High-energy and ultra-high-energy cosmic neutrinos:
2. Astrophysics, particle physics, future

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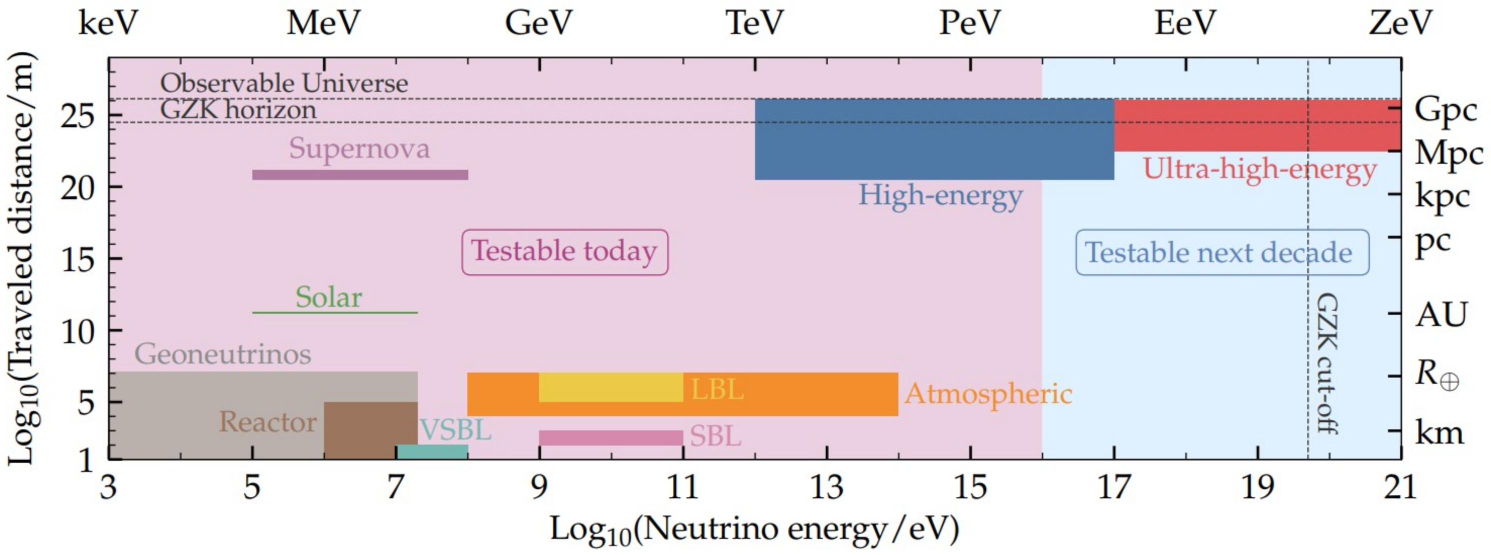
Mexican Astro-Particle School (MAPS)
July 01, 2021

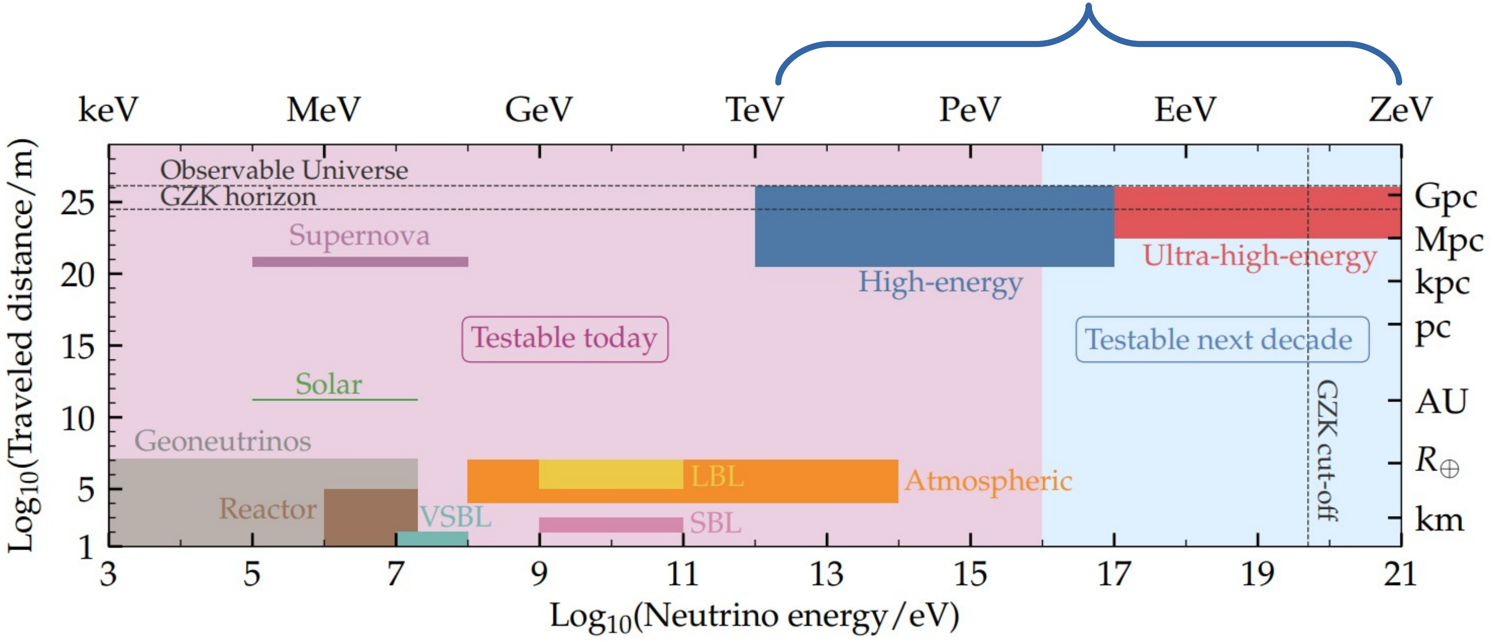
What makes high-energy cosmic ν exciting?



Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

What makes high-energy cosmic ν exciting?

They have the highest energies



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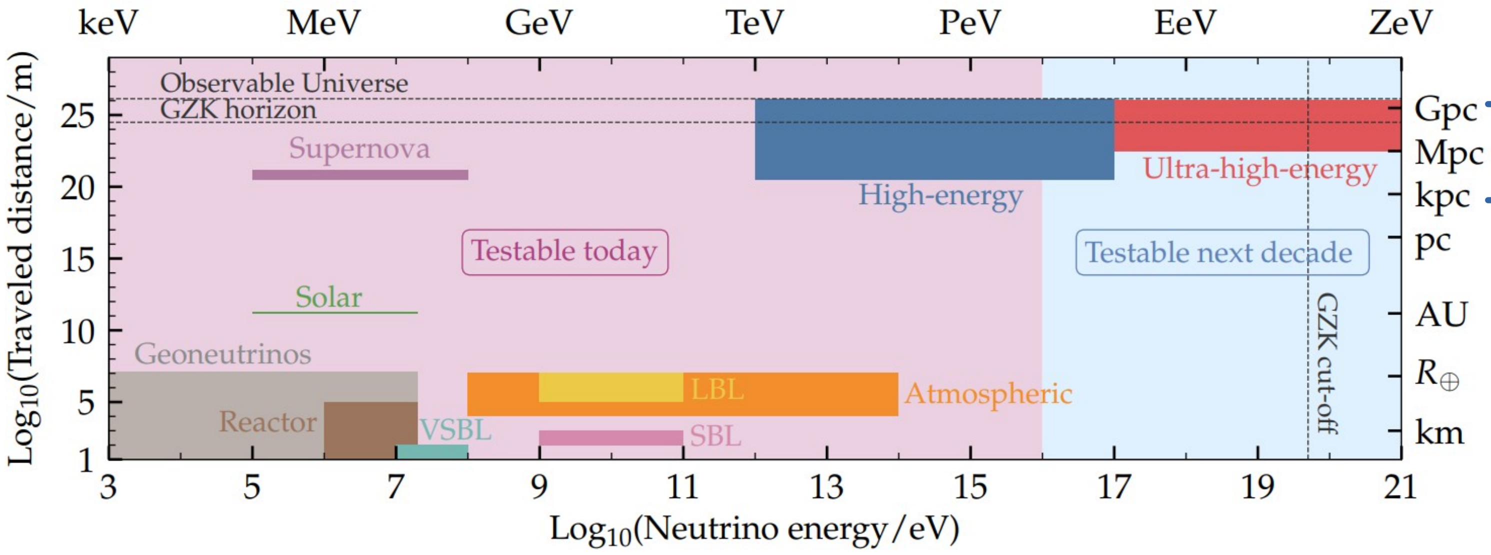
They have the highest energies

They travel the longest distances



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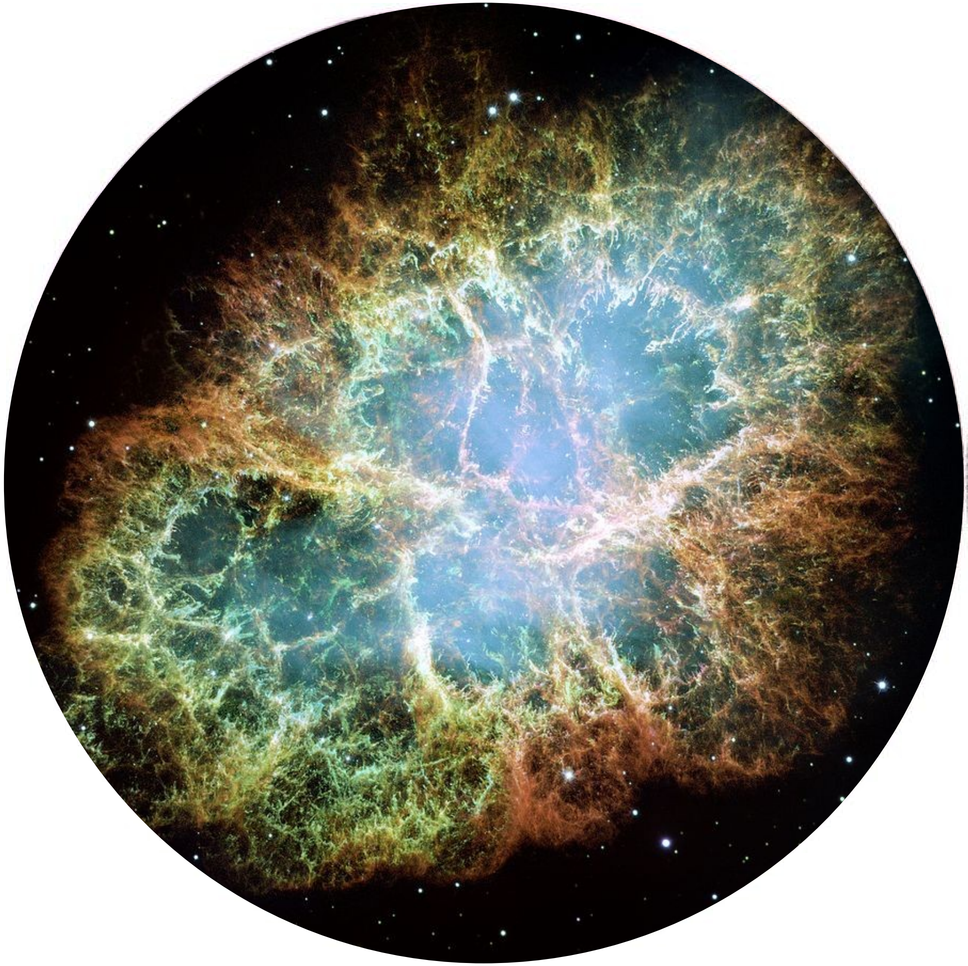

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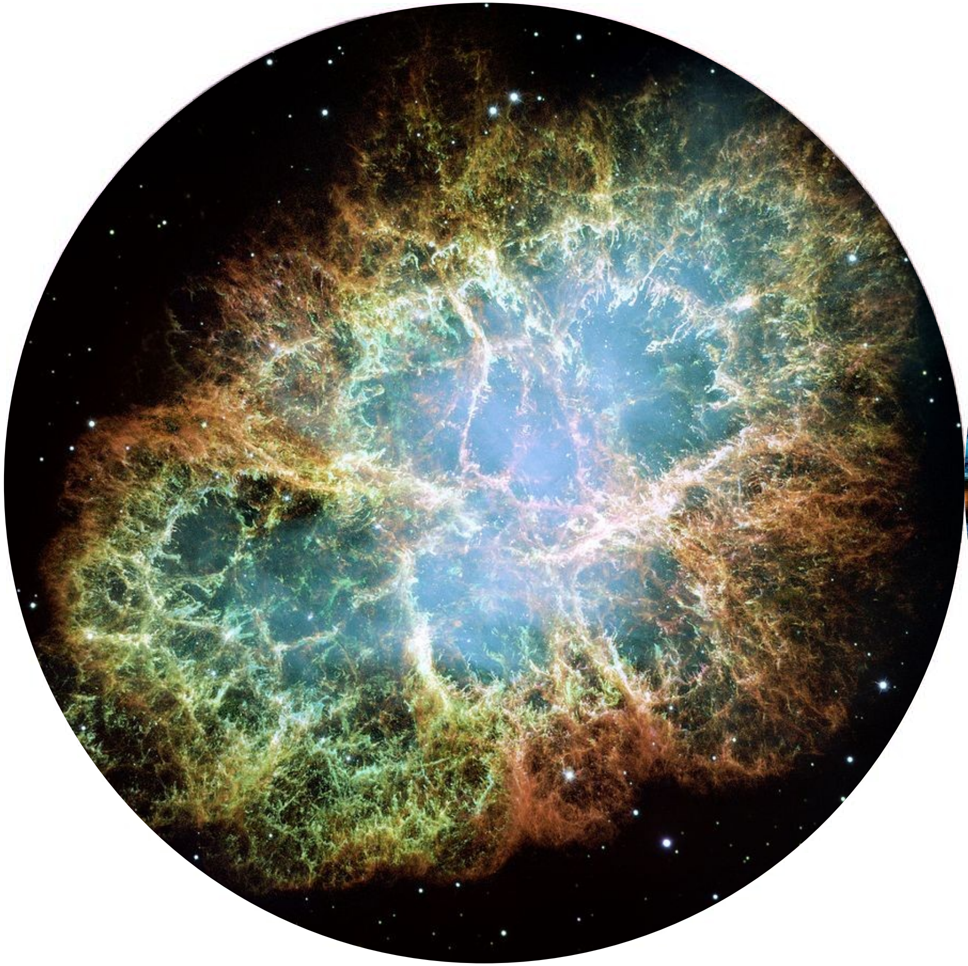

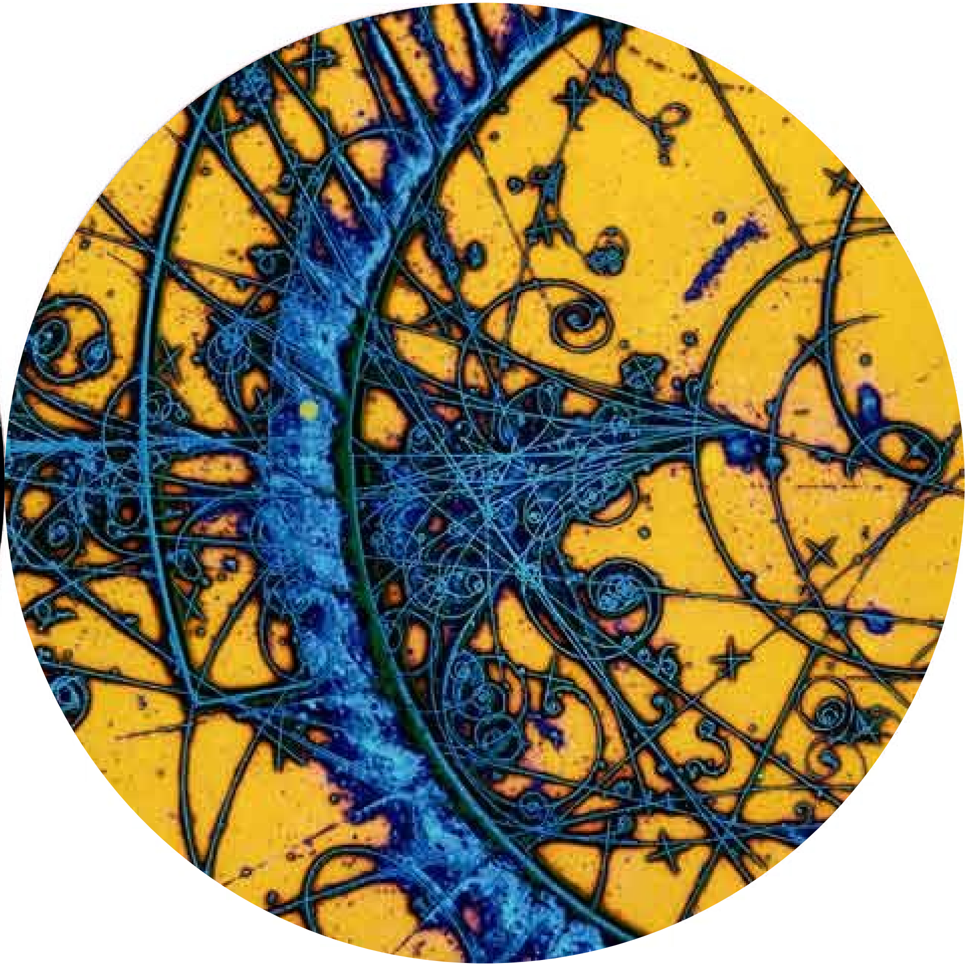

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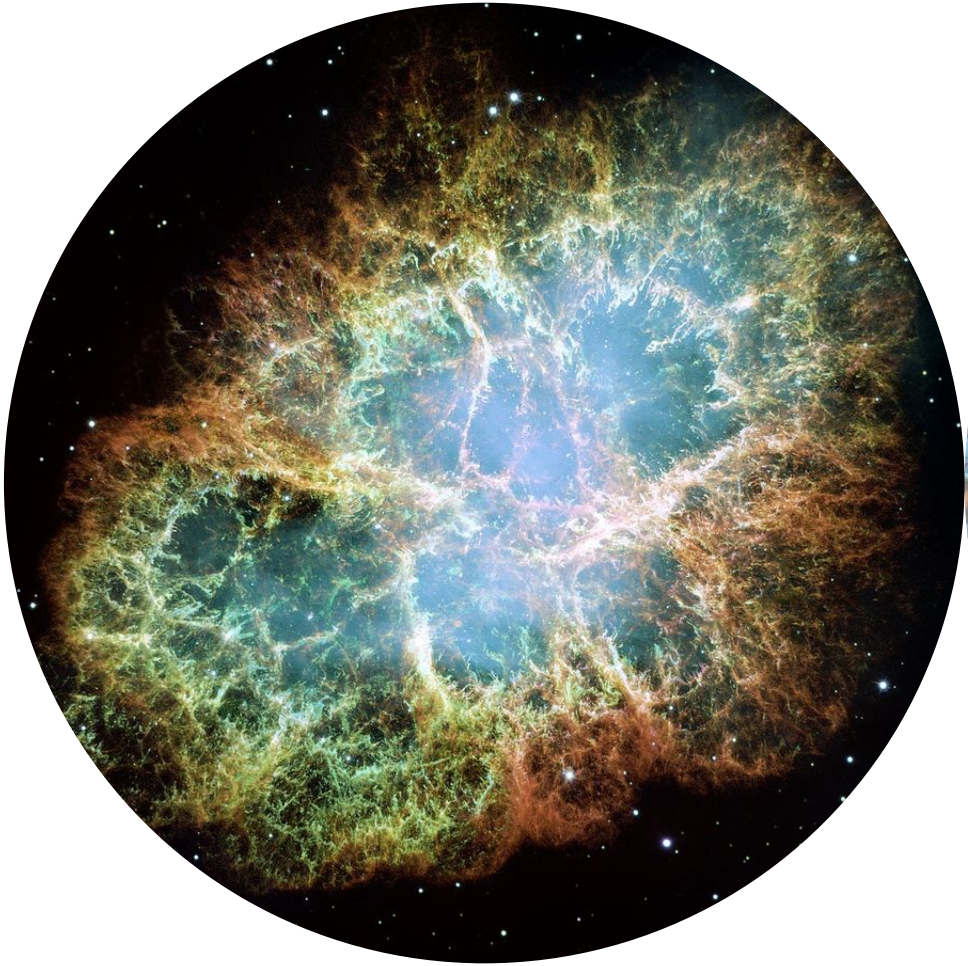
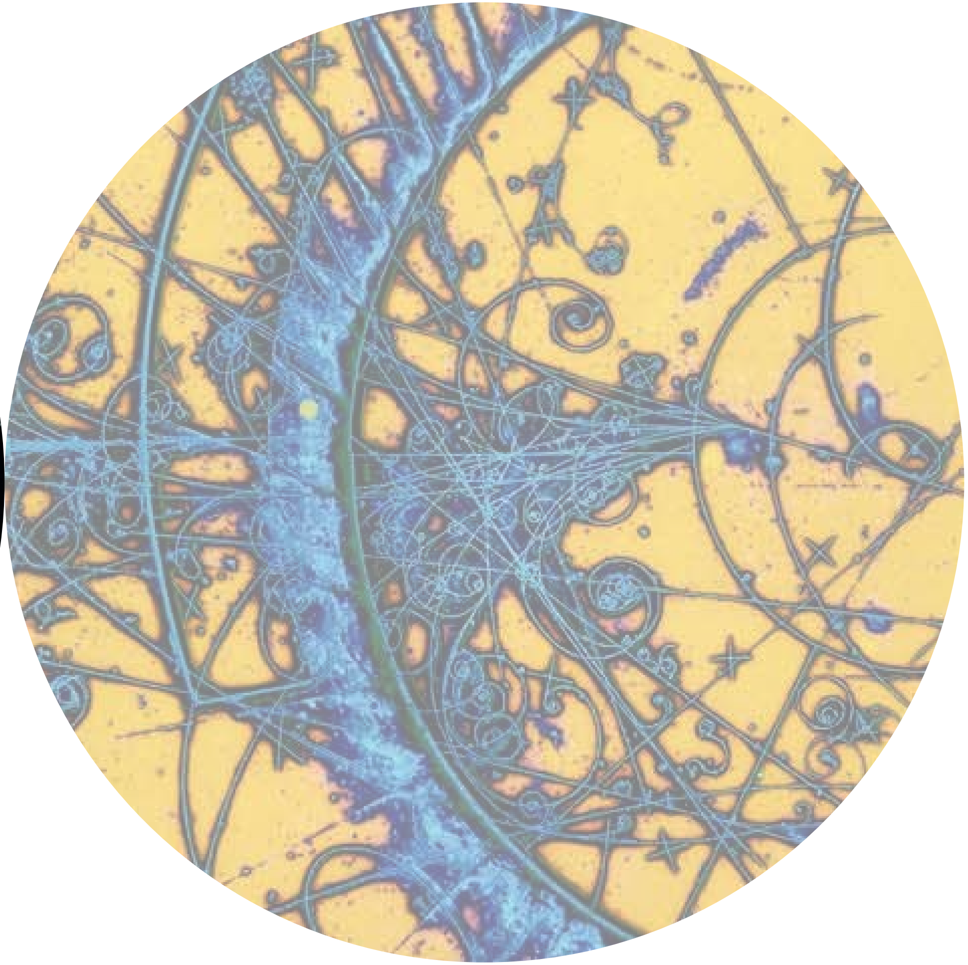
III.
What have we learned about *astrophysics*





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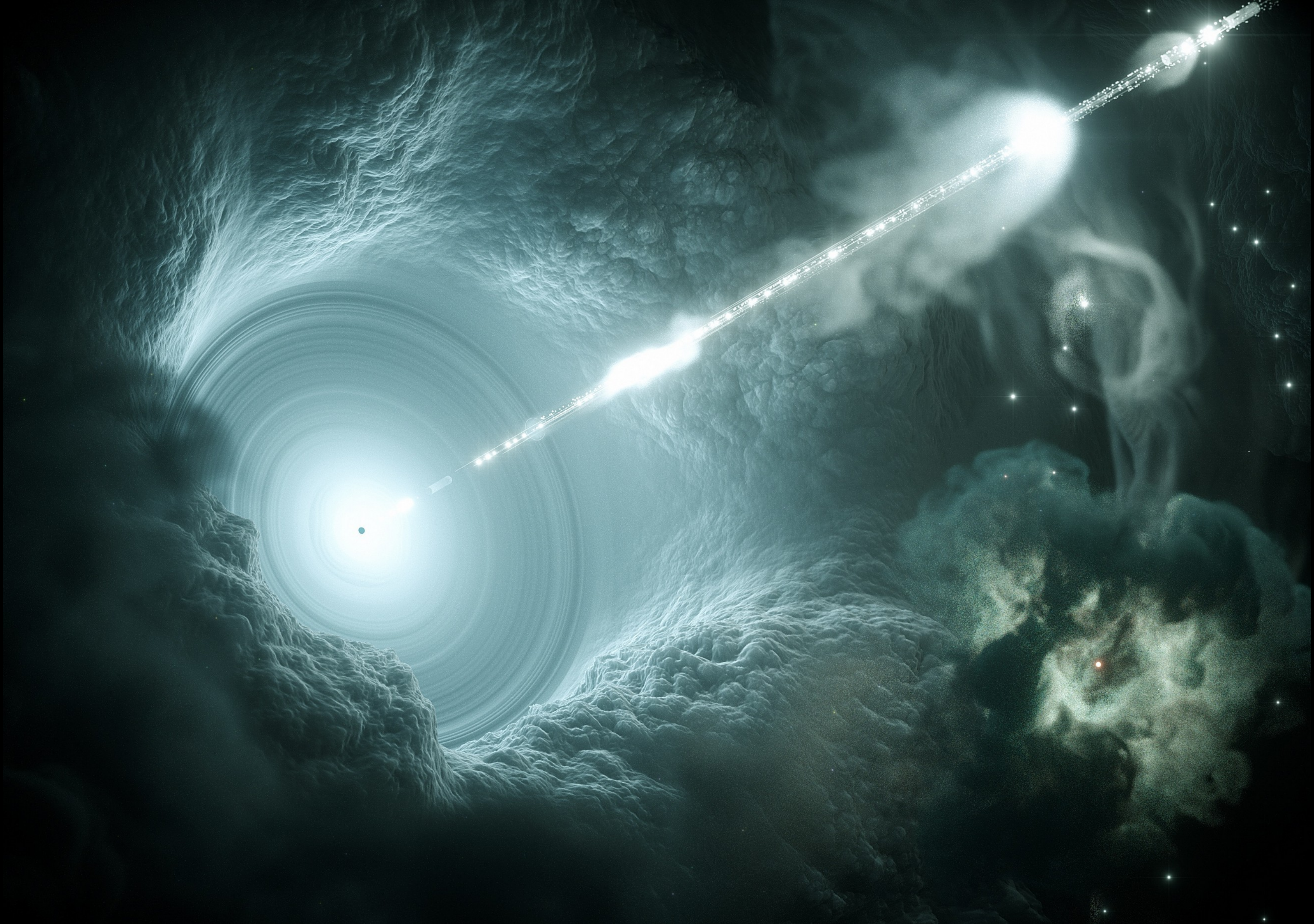
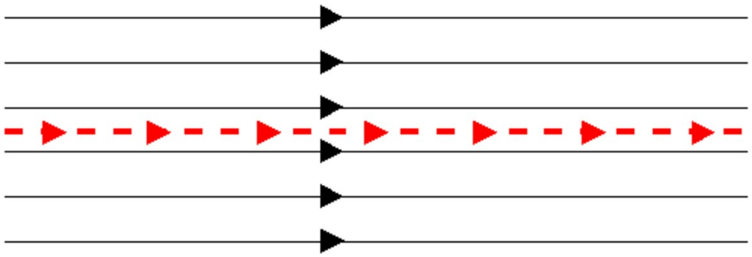
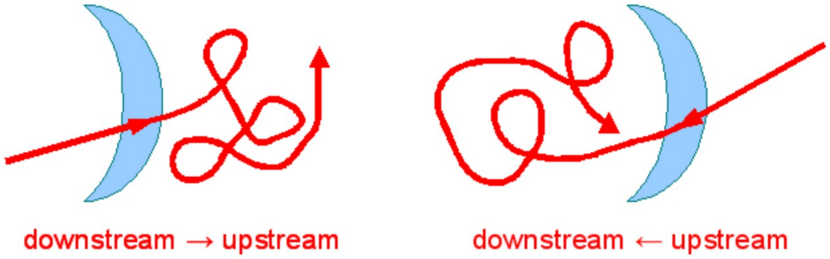

DESY

Luckily, UHECR Sources Should Be Wasteful…

	Man-made accelerators	Astrophysical accelerators
		
Acceleration	In vacuum	In a medium
E.m. fields	Ordered	Messy
Beam dumps	Precisely regulated	Fully unregulated

Astrophysical accelerators *inevitably* make high-energy secondaries

The Hillas criterion

- Necessary condition for a source to accelerate cosmic rays

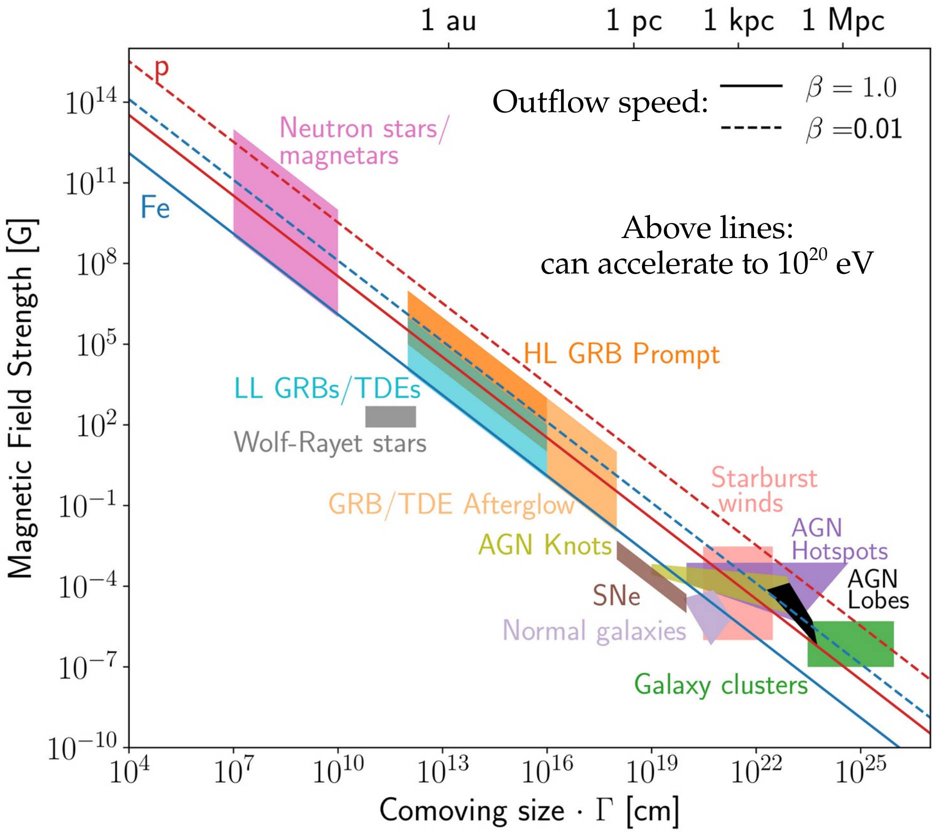
- Particles must stay confined:

Larmor radius < Size of acceleration region

$$R_L = E/(Z\,e\,B) < (R\,\Gamma)$$

- Maximum energy:

$$E_{\max} \approx \left(3 \cdot 10^{20}\ \mathrm{eV}\right) \eta^{-1} \beta_{\rm sh} Z \left(\frac{\Gamma R}{10^{16}\ \mathrm{cm}}\right) \left(\frac{B}{100\ \mathrm{G}}\right)$$



Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista, **MB** *et al.*, *Frontiers* 2019
See also: Winter, *PRD* 2011

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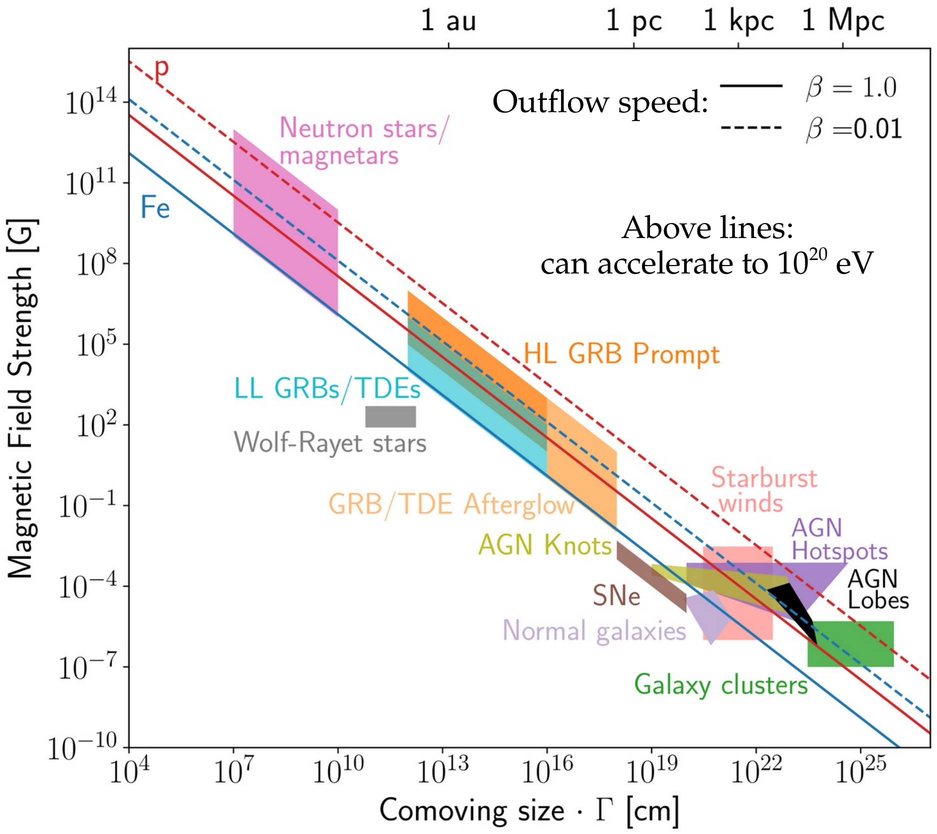

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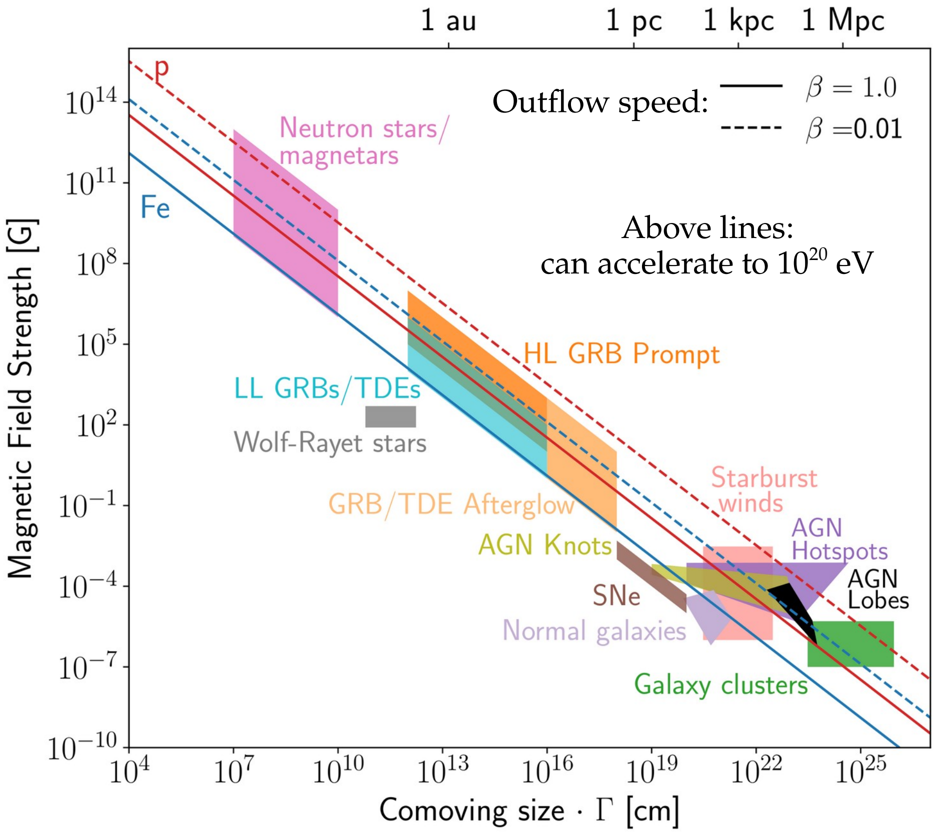
- ▶ Maximum energy:

Acceleration efficiency ($\eta = 1$ for perfect efficiency)

$$E_{\rm max} \approx \left(3\cdot 10^{20}~{\rm eV}\right)\eta^{-1}\beta_{\rm sh} Z \left(\frac{\Gamma R}{10^{16}~{\rm cm}}\right)\left(\frac{B}{100~{\rm G}}\right)$$

Speed $v_{\rm sh}/c$ of the outflow



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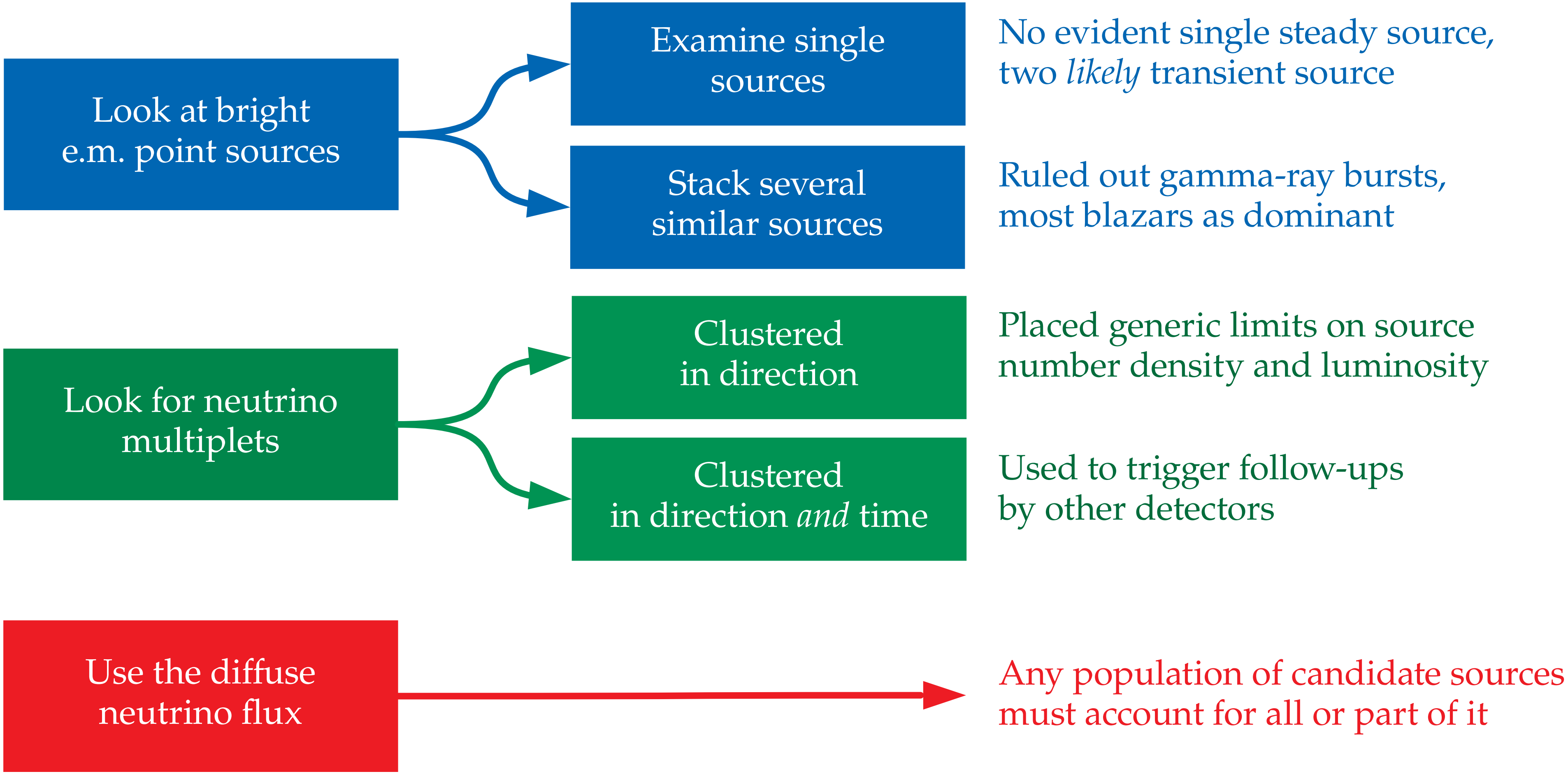
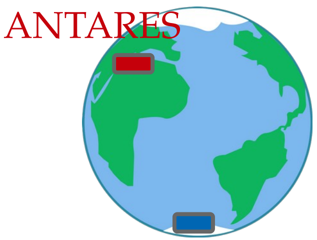
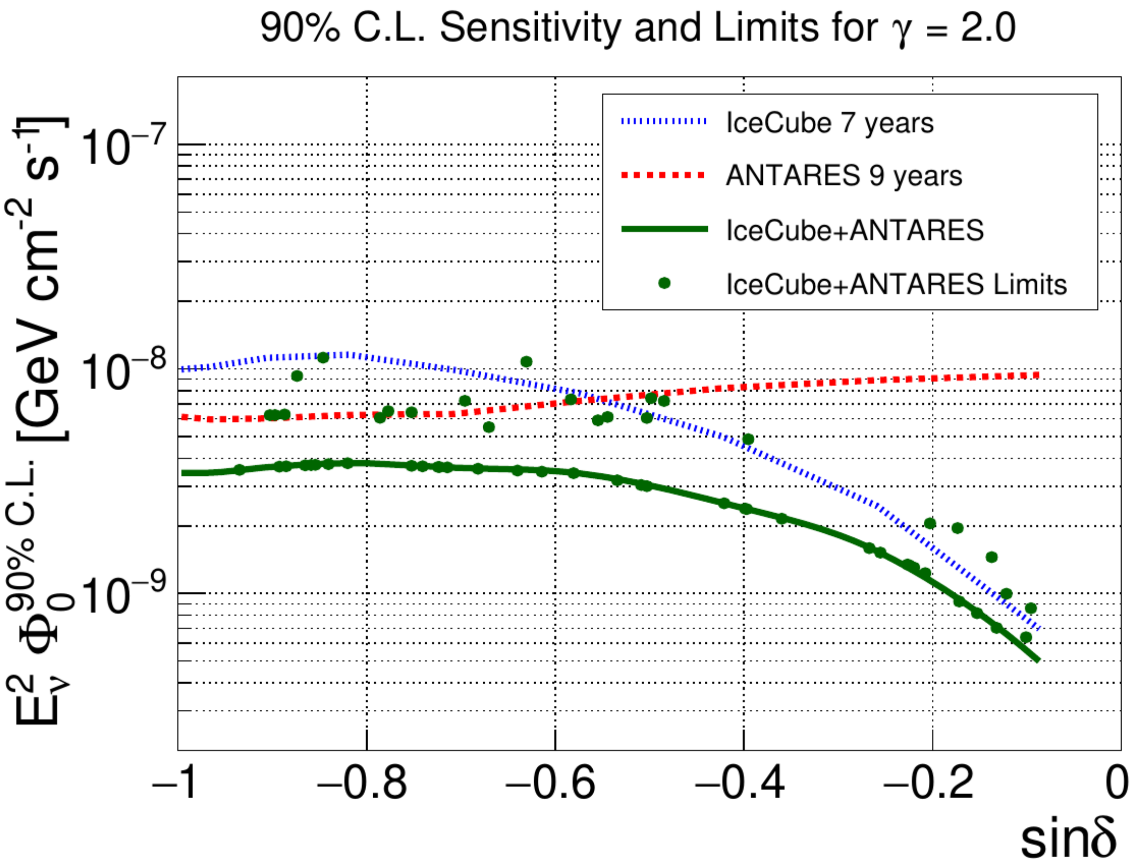
Three strategies to reveal sources of TeV–PeV ν



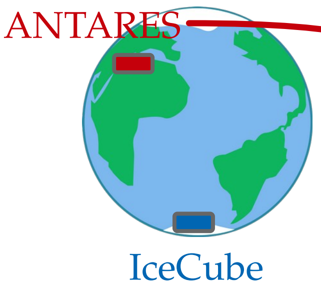
Point-source upper limits

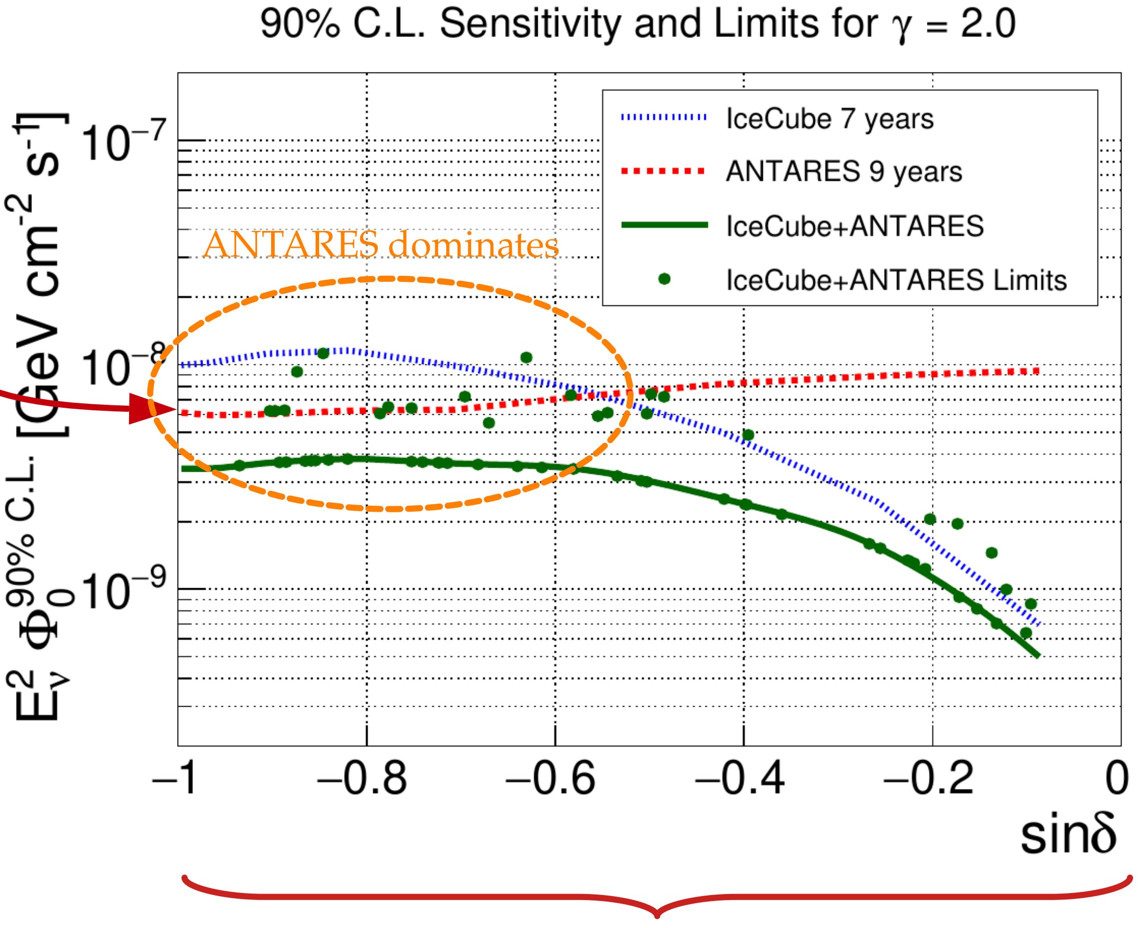




Sources in the Southern sky

Point-source upper limits





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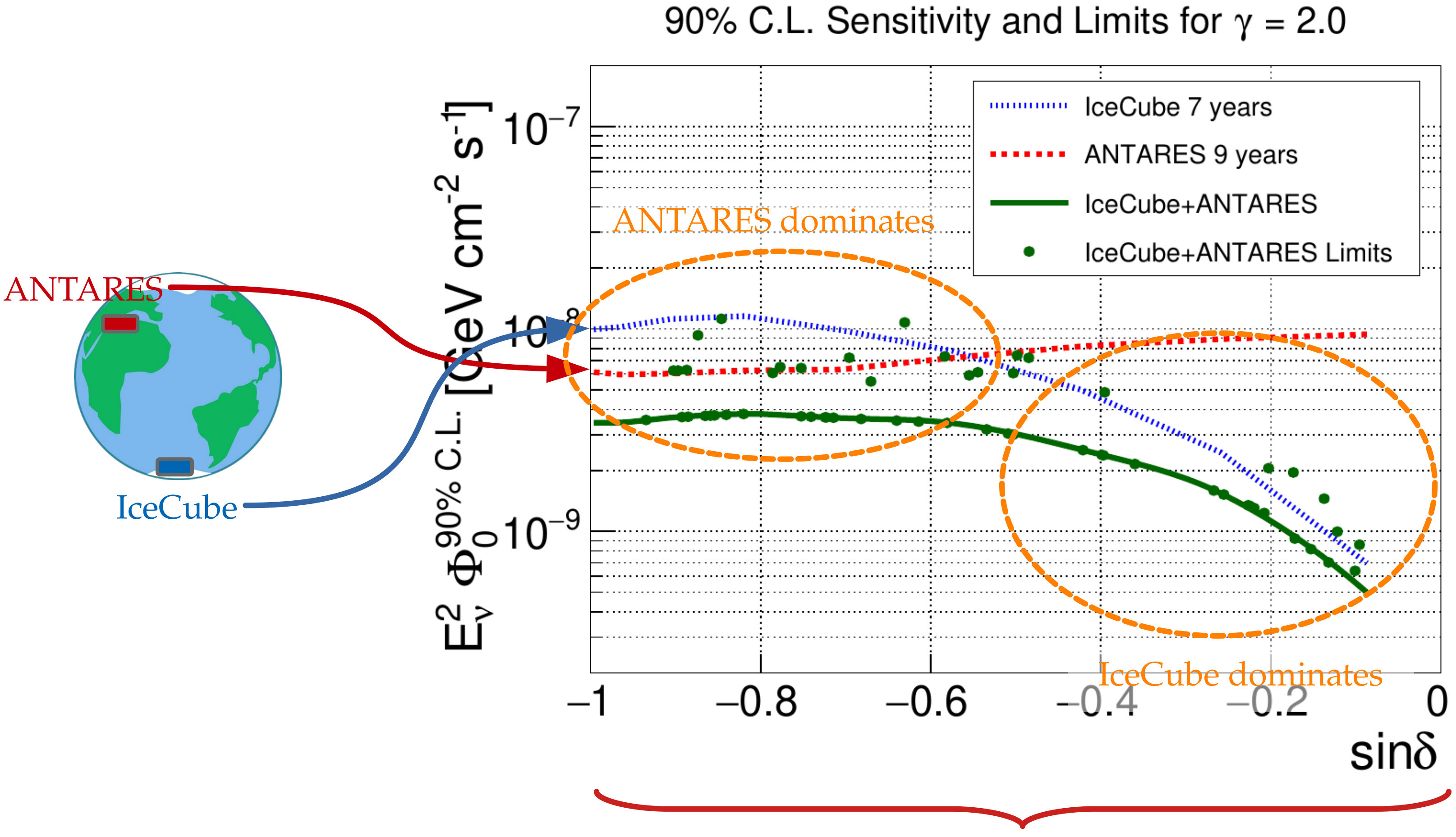
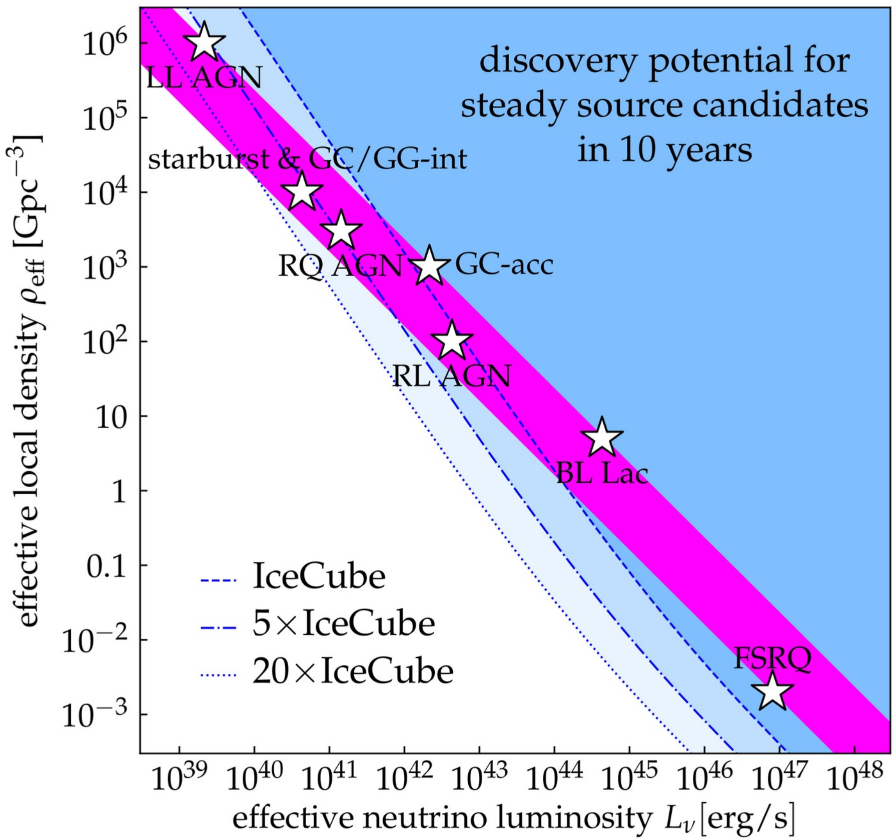


Sources in the Southern sky

Source discovery potential: today and in the future

Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

Closest source with $E^2\phi_{\nu_\mu+\bar{\nu}_\mu} = 10^{-9}\ \mathrm{GeV cm^{-2} s^{-1}}$

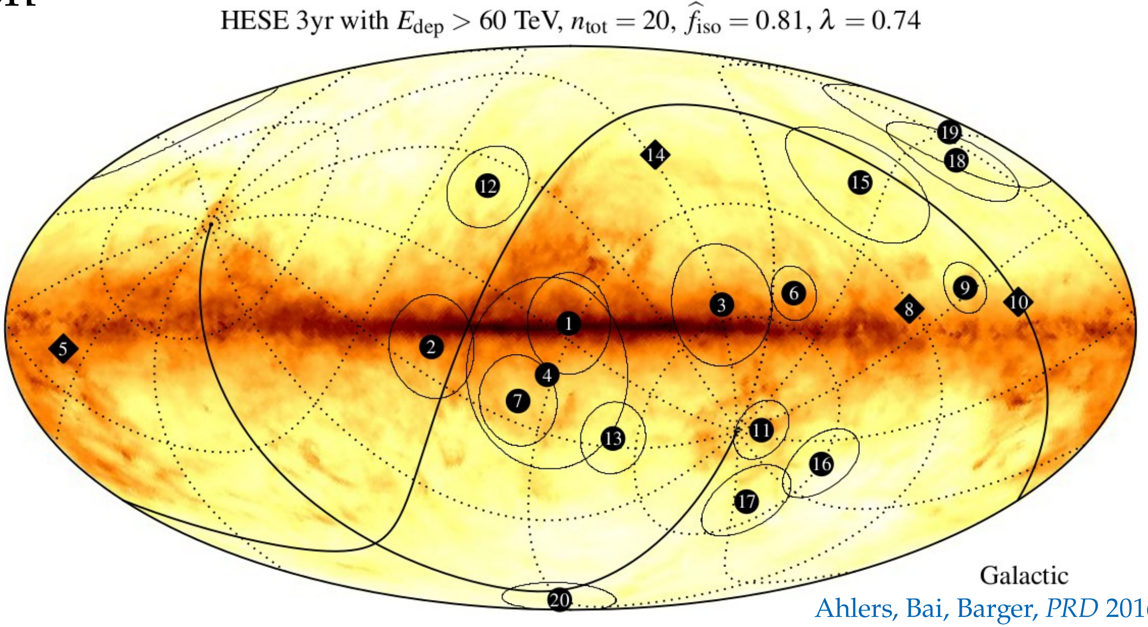


Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333) – See also: Silvestri & Barwick, *PRD* 2010; Murase & Waxman, *PRD* 2016

PeV neutrino sources in the Milky Way?

Candidates for full or partial contribution:

- Diffuse Galactic gamma-ray emission
- Unidentified gamma-ray sources
- Fermi bubbles
- Supernova remnants
- Pulsars
- Microquasars
- Sagitarius A*
- Galactic halo
- Heavy dark matter decay



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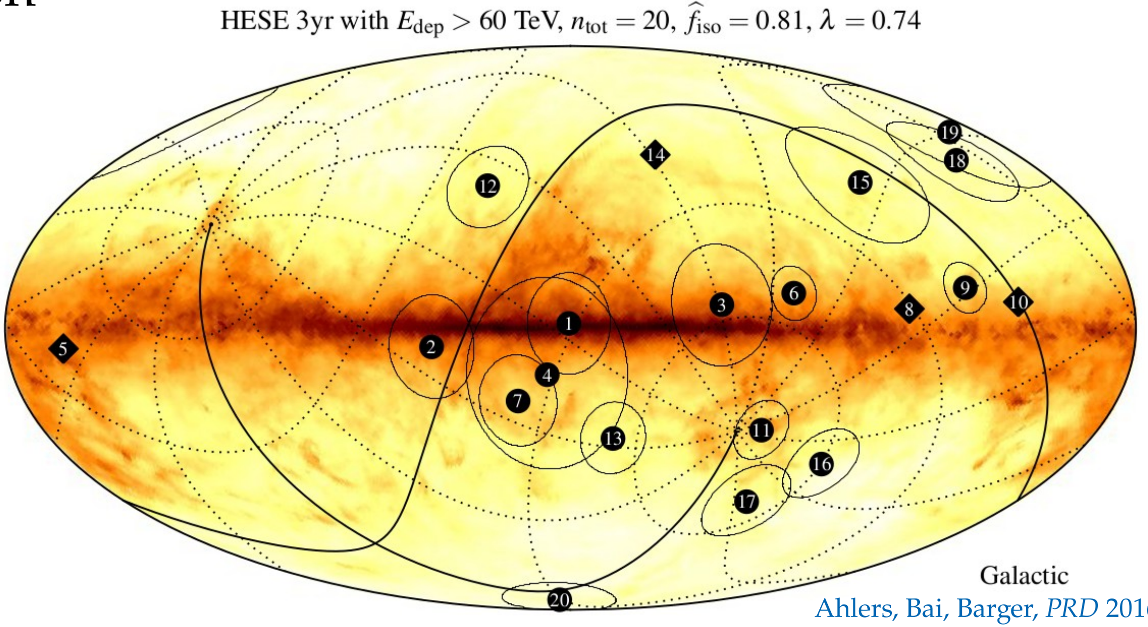

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Contribution from Galactic sources: < 14%

IceCube, *ApJ* 2017

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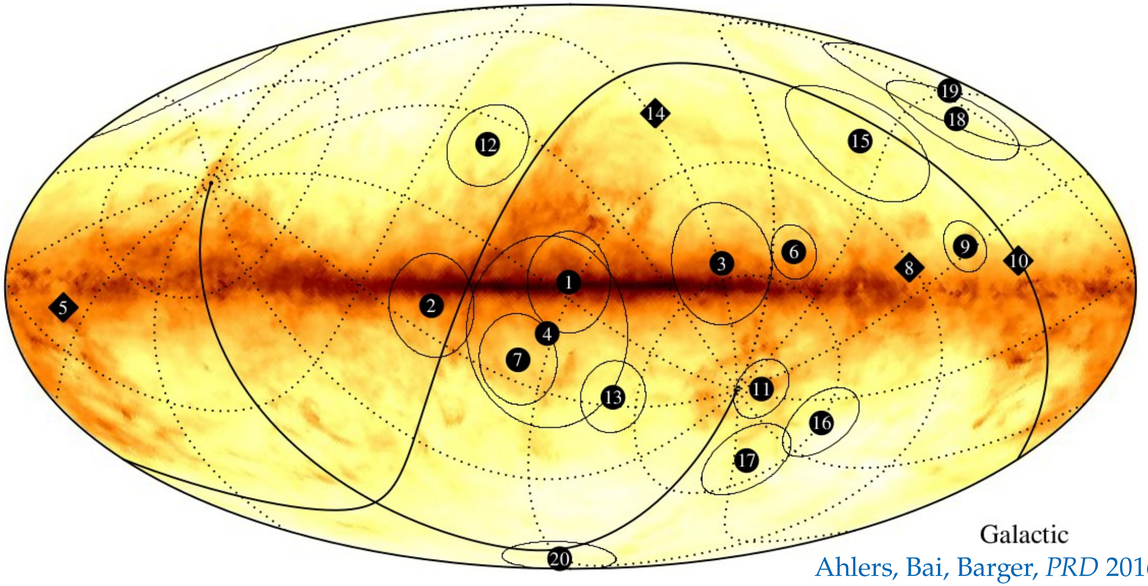
Q: What about the 0.1–1 PeV Galactic gamma rays seen by Tibet ASGamma (PRL 2021)?

HESE 3yr with $E_{\rm dep} > 60$ TeV, $n_{\rm tot} = 20$, $\widehat{f}_{\rm iso} = 0.81$, $\lambda = 0.74$



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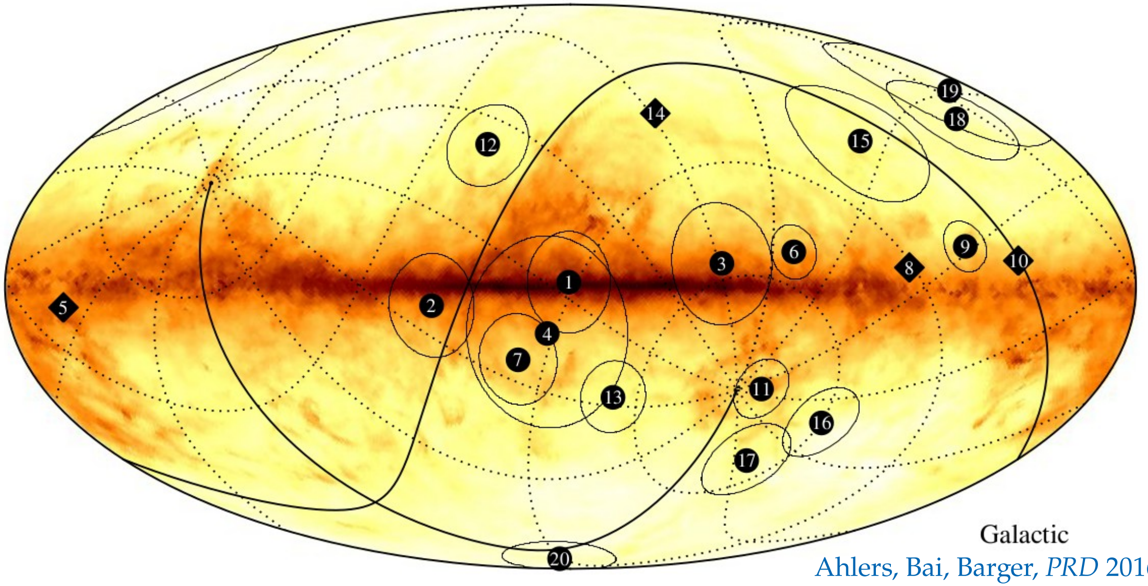

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Q: What about the 0.1–1 PeV Galactic gamma rays seen by Tibet ASGamma (PRL 2021)?

A: The accompanying ν emission from the Galactic Plane is < 5–10% of the diffuse ν flux seen by IceCube (2104.09491)

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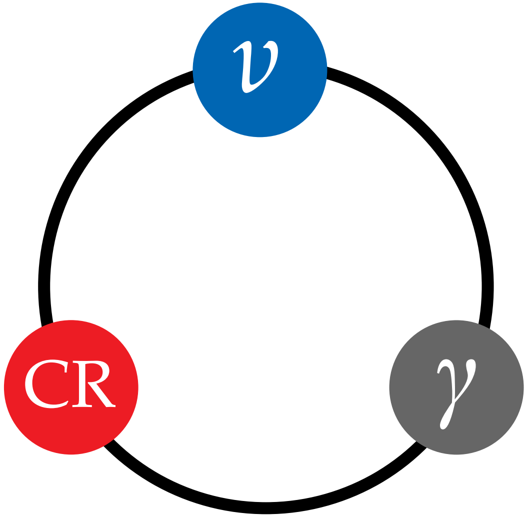
IceCube, *ApJ* 2017

Bright in gamma rays, bright in high-energy neutrinos (?)

Energy in neutrinos ∝ energy in gamma rays

Waxman & Bahcall, *PRL* 1997



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Fudge factors:
Source properties (*e.g.*, baryonic loading)
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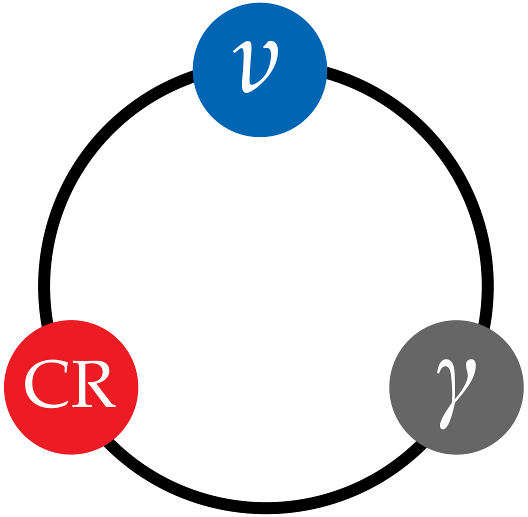

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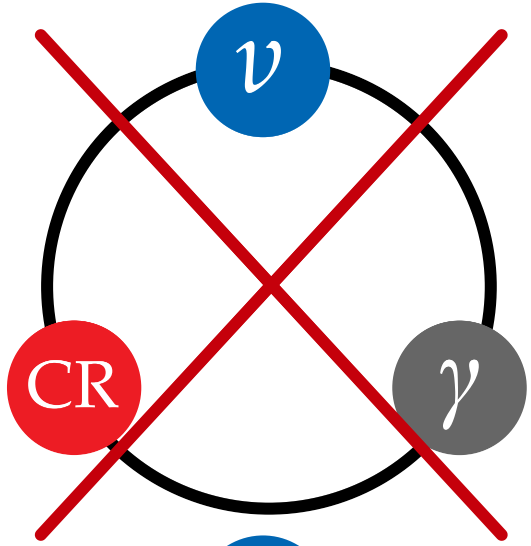
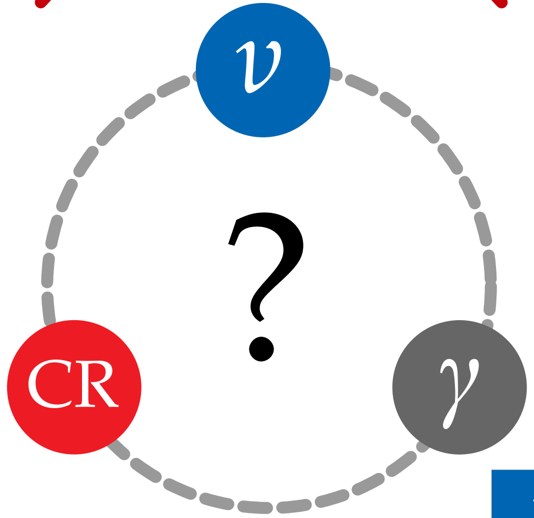


But the correlation between ν and γ may be more nuanced:

Gao, Pohl, Winter, *ApJ* 2017



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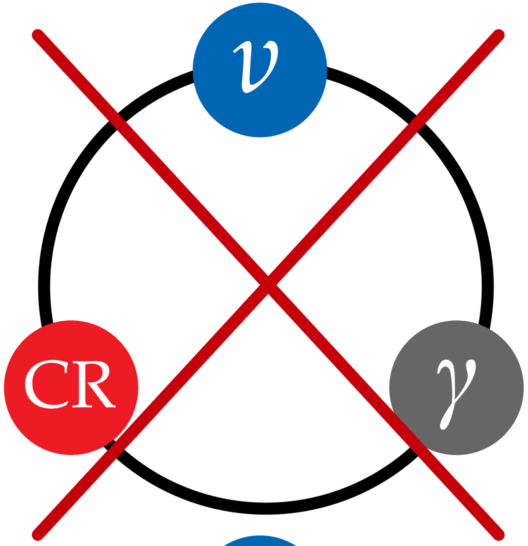

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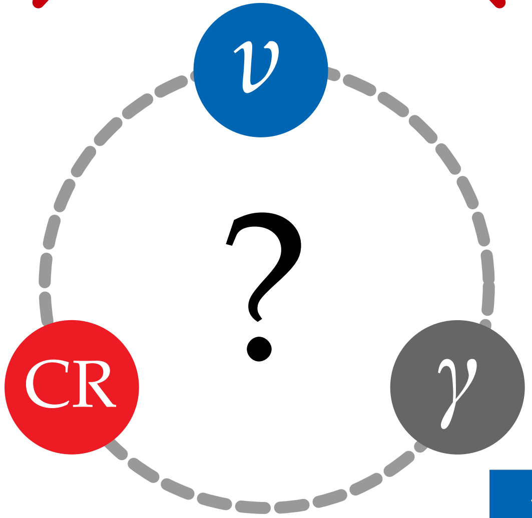
Sources that make neutrinos via *p*γ
may be opaque to 1–100 MeV gamma rays

Murase, Guetta, Ahlers, *PRL* 2016

Modeling of *p*γ interactions & nuclear cascading
in the sources is complex and uncertain

Morejon, Fedynitch, Boncioli, Winter, *JCAP* 2019
Boncioli, Fedynitch, Winter, *Sci. Rep.* 2017



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Energy in neutrinos $\propto$ energy in gamma rays

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D. Guetta *et al.*, *Astropart. Phys.* 2004

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Baryonic loading

Optical depth to $p\gamma$: $$\tau_{p\gamma} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\mathrm{erg}\,\mathrm{s}^{-1}}\right)\left(\frac{0.01}{t_{\mathrm{v}}}\right)\left(\frac{300}{\Gamma}\right)^4\left(\frac{\mathrm{MeV}}{\epsilon_{\gamma,\mathrm{break}}}\right)$$

E. Waxman & J. Bahcall, *PRL* 1997
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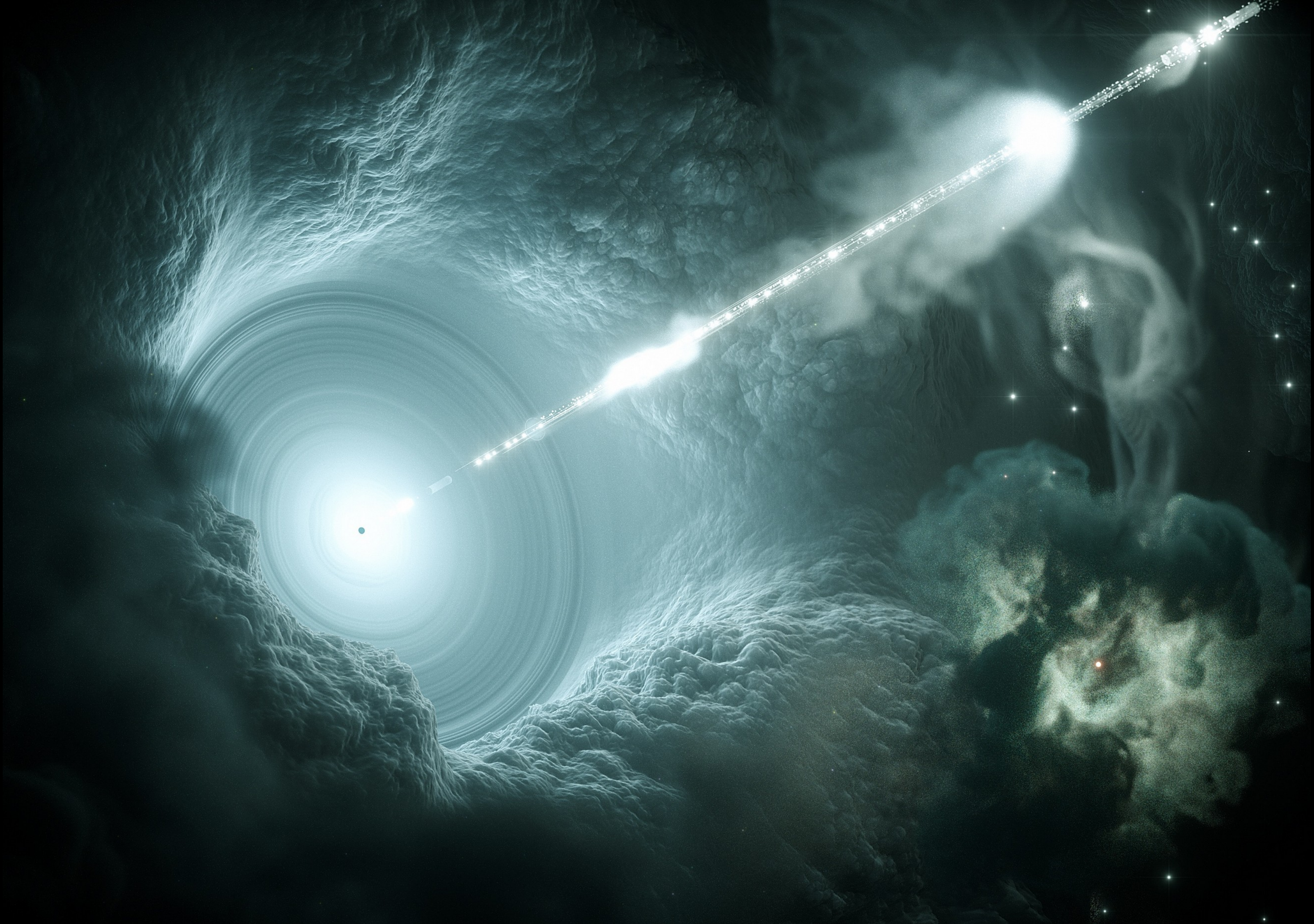
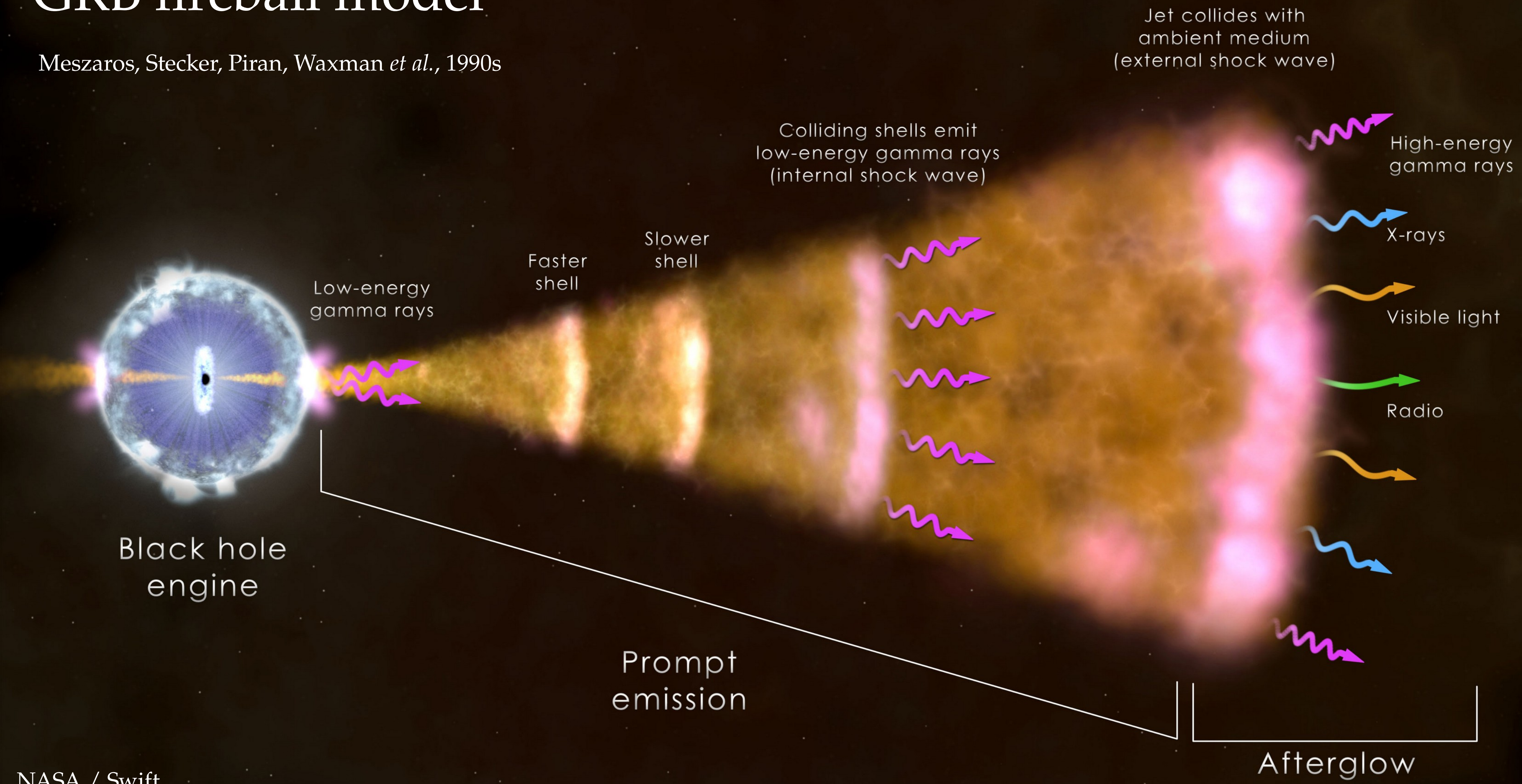

DESY

GRB fireball model

Meszaros, Stecker, Piran, Waxman *et al.*, 1990s



NASA / Swift

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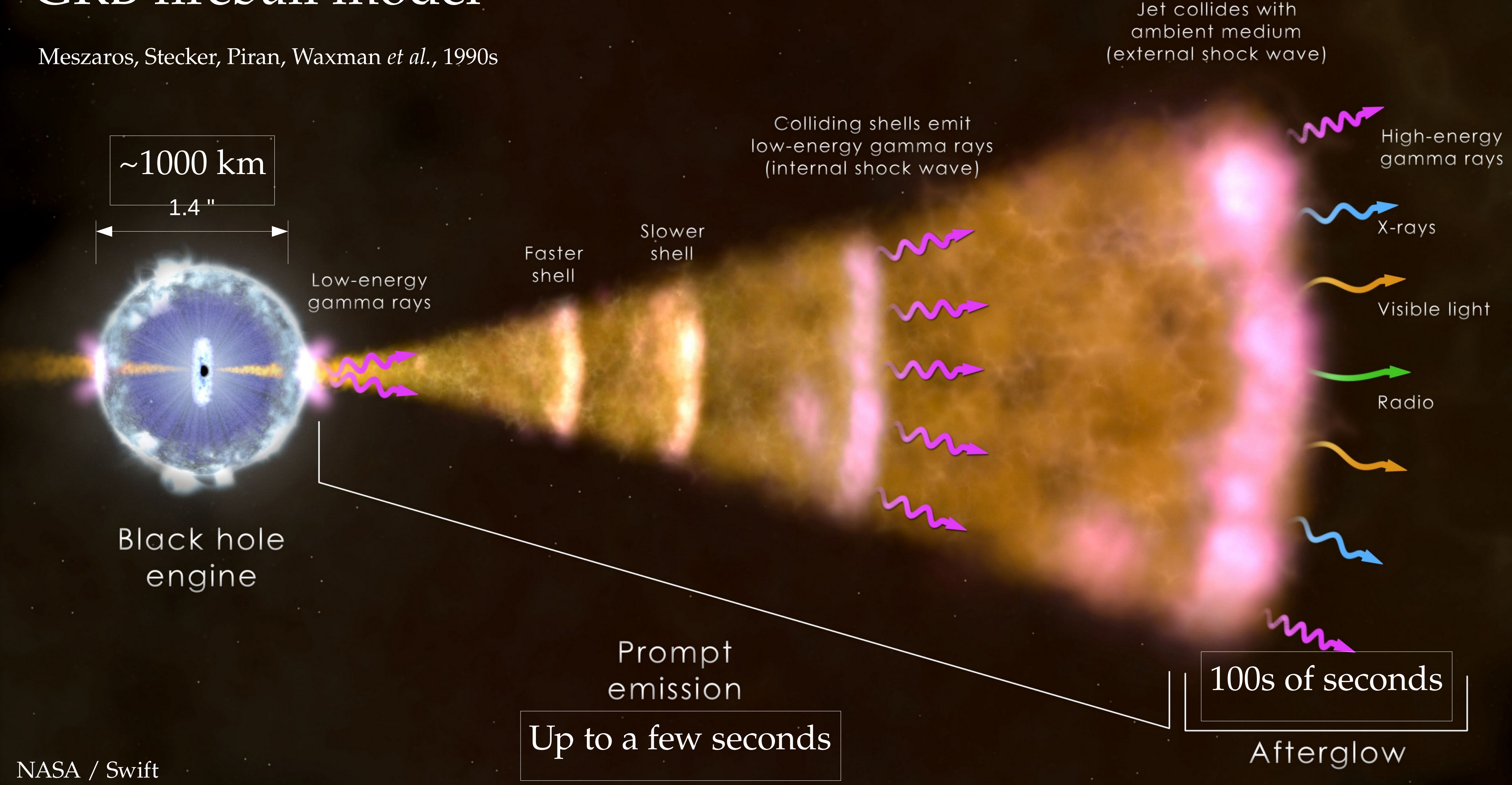

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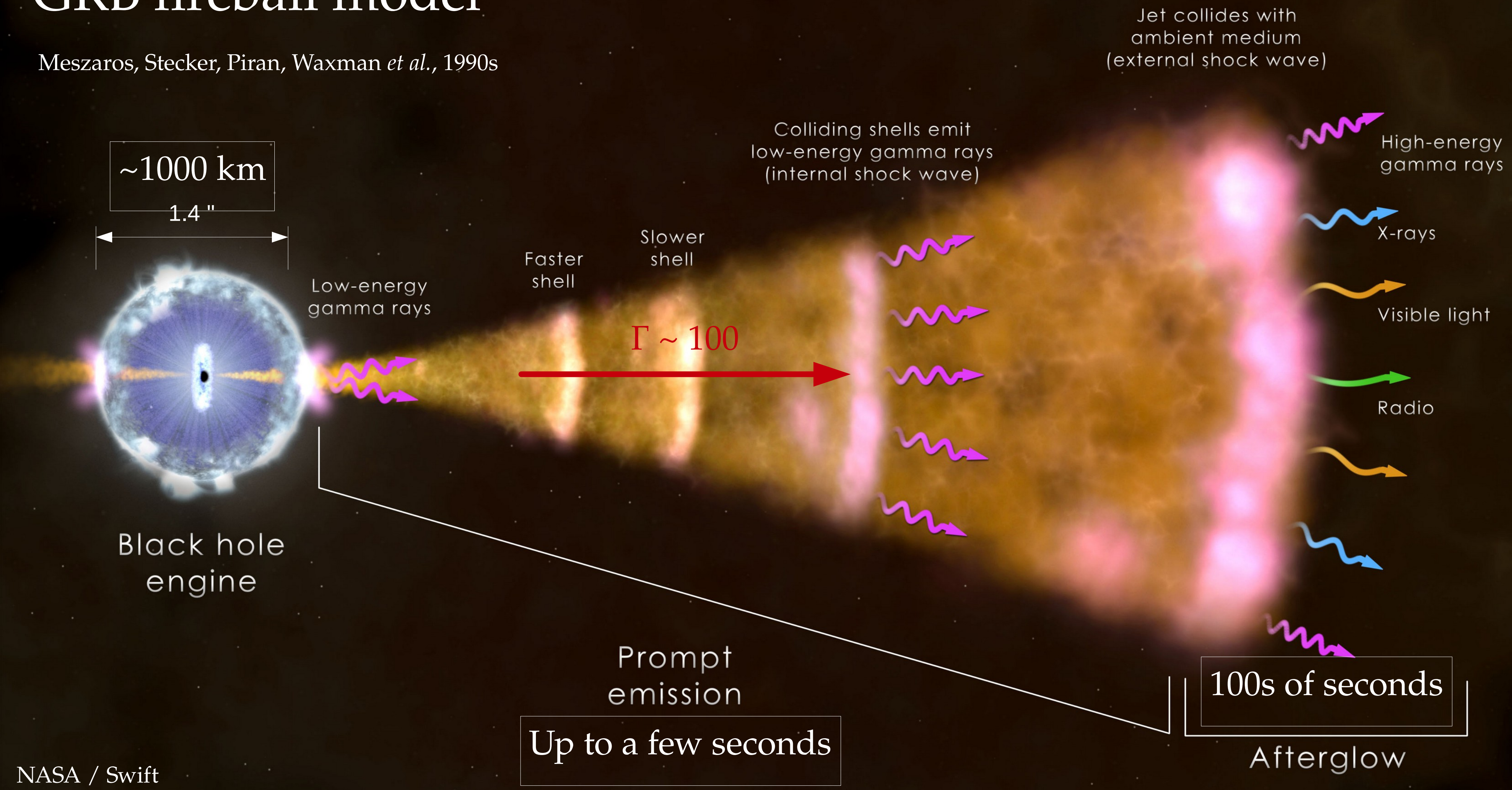

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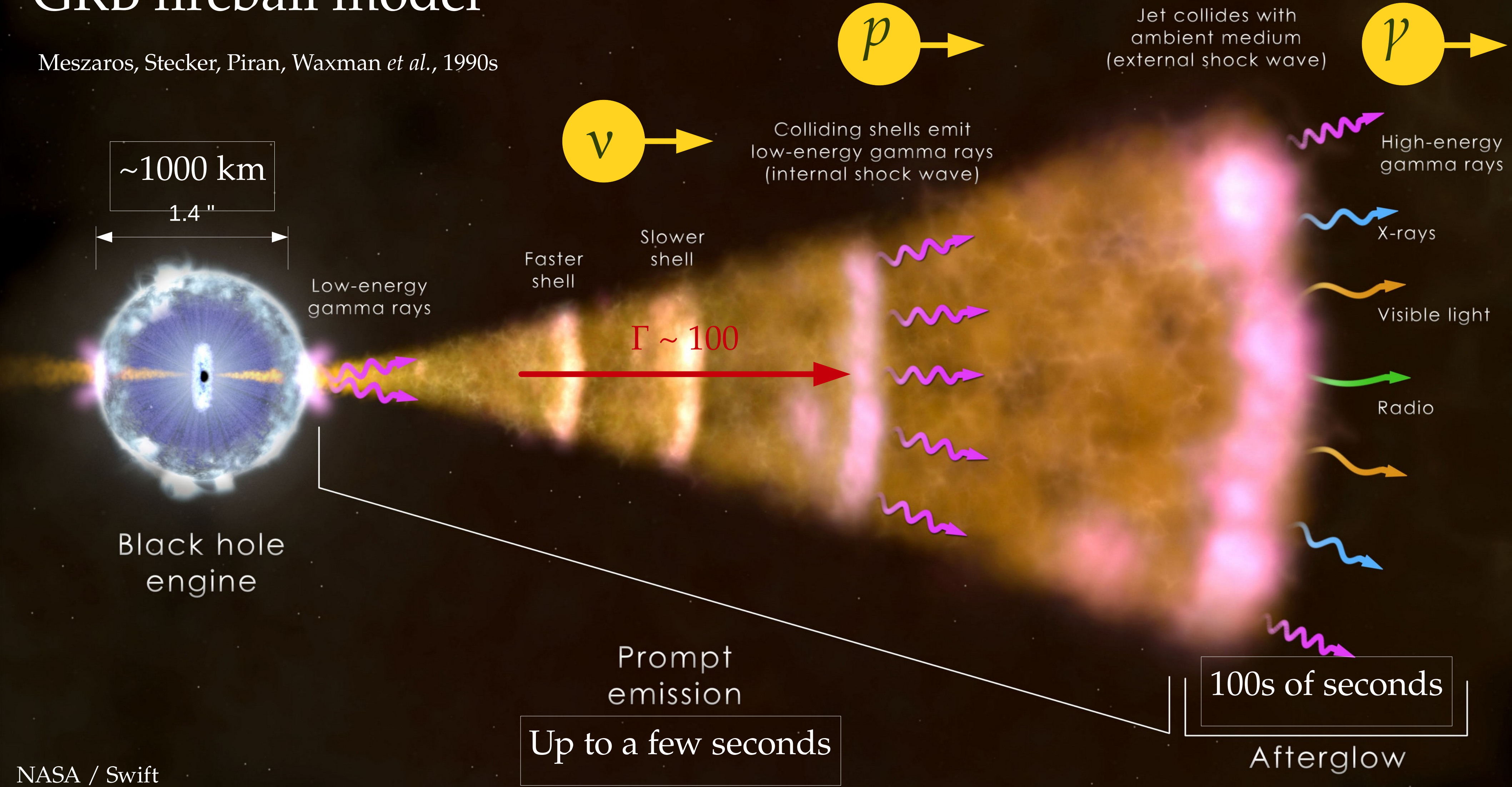
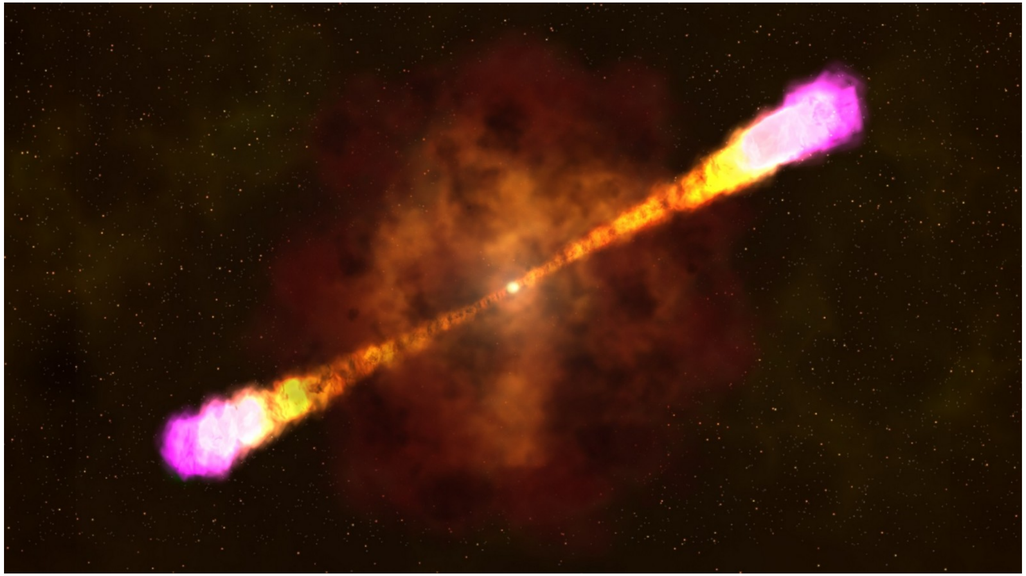


NASA / Swift

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



Blazars

Gamma-ray bursts and blazars – *not* dominant

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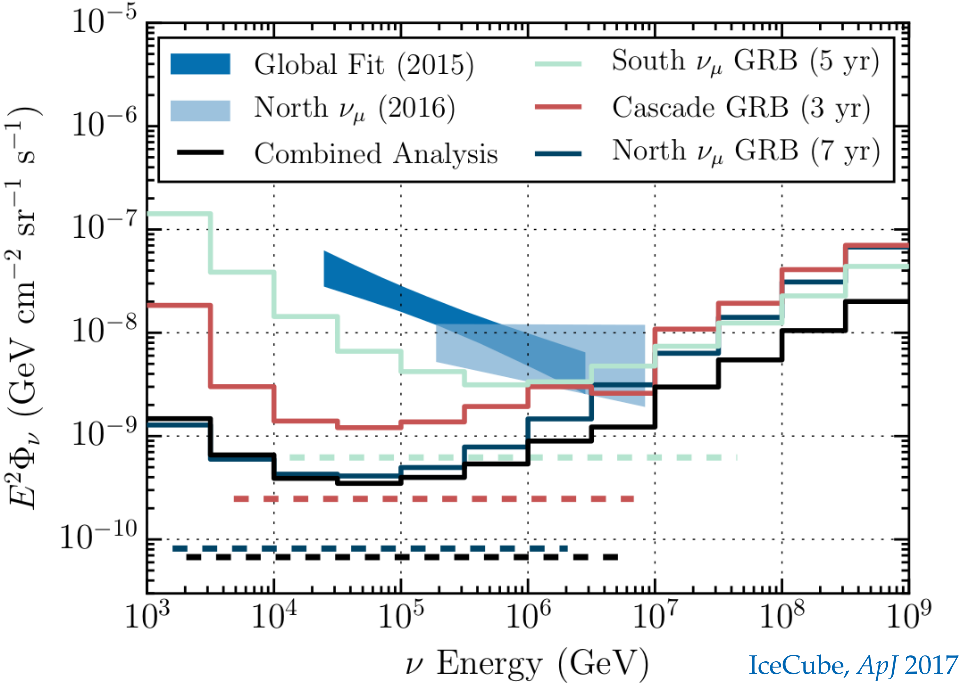
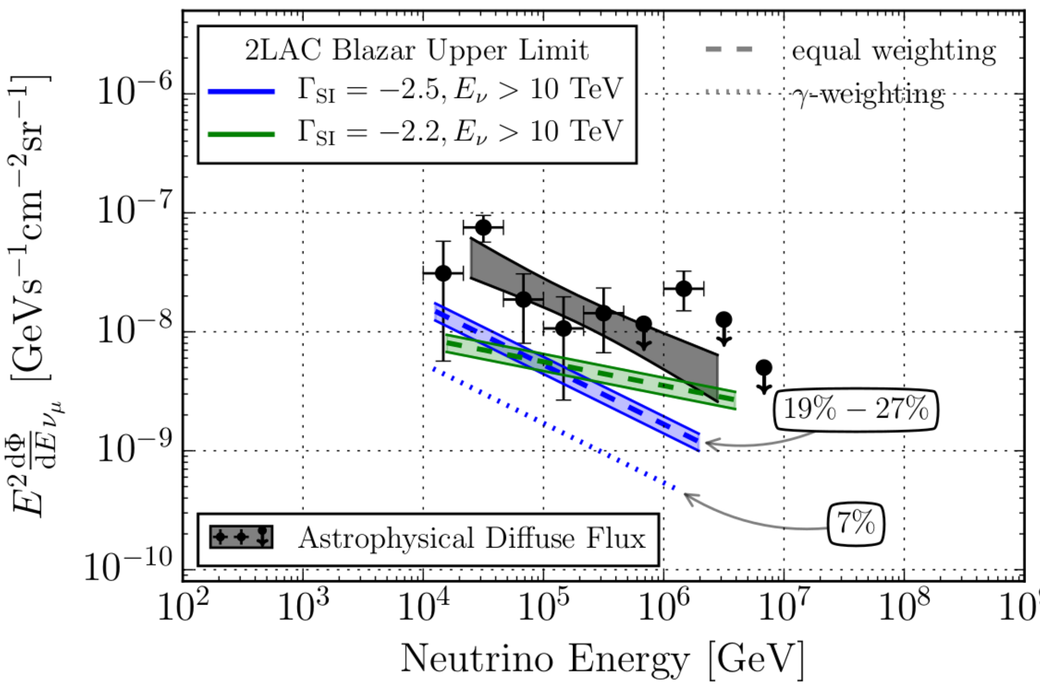


1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars



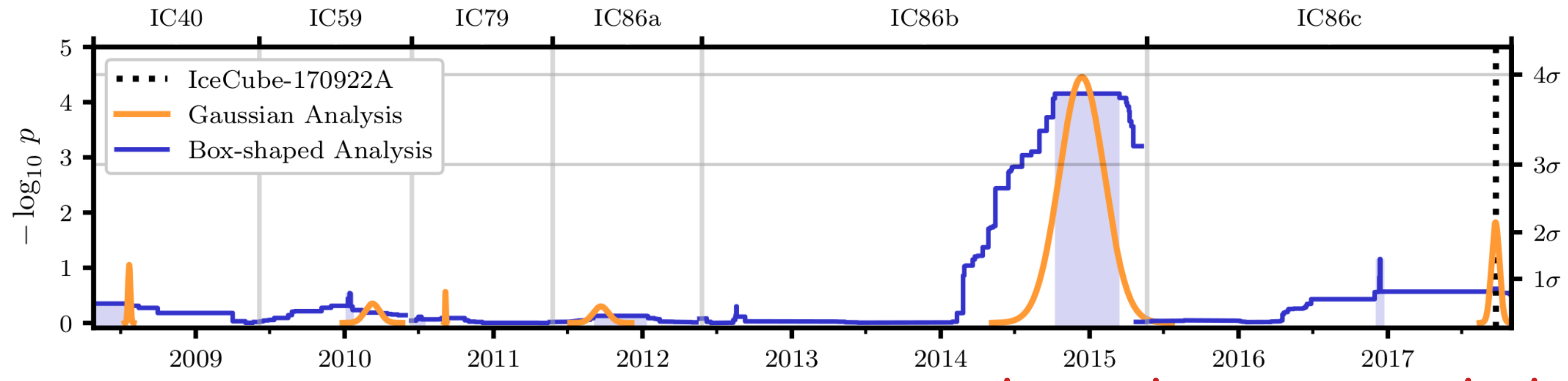
862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

… but we have seen *one* blazar neutrino flare!

Blazar TXS 0506+056:

IceCube, *Science* 2018



2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

2017: one 290-TeV ν + X-ray flare
1.4σ significance of correlation

Combined (pre-trial): 4.1σ

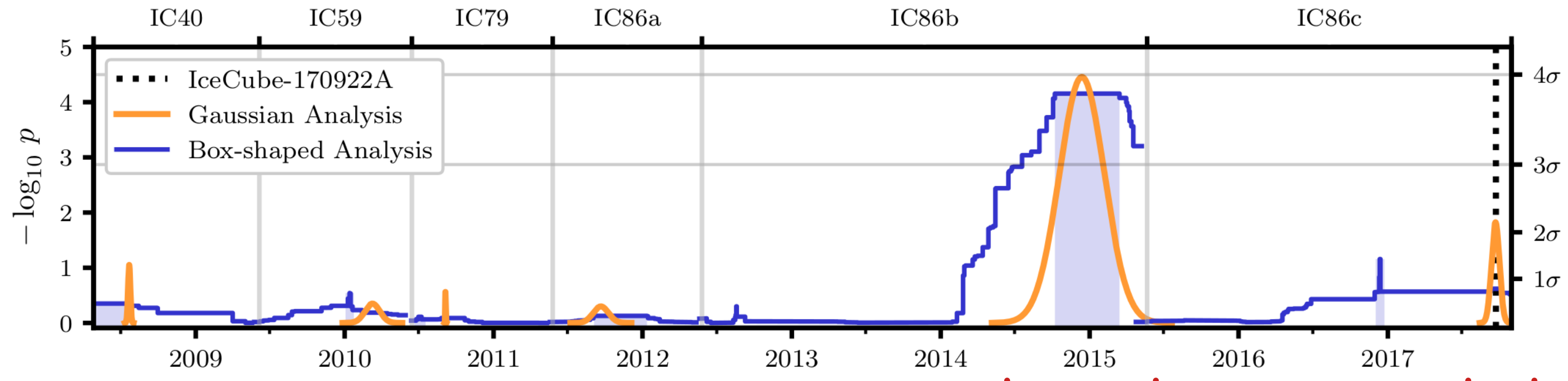
Hard fluence: $E^2 J_{100} = 2.1^{+0.9}_{-0.7} \left(\frac{E}{100~\mathrm{TeV}}\right)^{-2.1\pm0.2}~\mathrm{TeV~cm^{-2}}$

Joint modeling of the two periods is challenging!

… but we have seen *one* blazar neutrino flare!

Blazar TXS 0506+056:

IceCube, *Science* 2018



2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

2017: one 290-TeV ν + X-ray flare
1.4σ significance of correlation

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If every blazar produced neutrinos as TXS 0506+056, the diffuse ν flux would be 20x higher than observed!

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Blazar TXS 0506+056:

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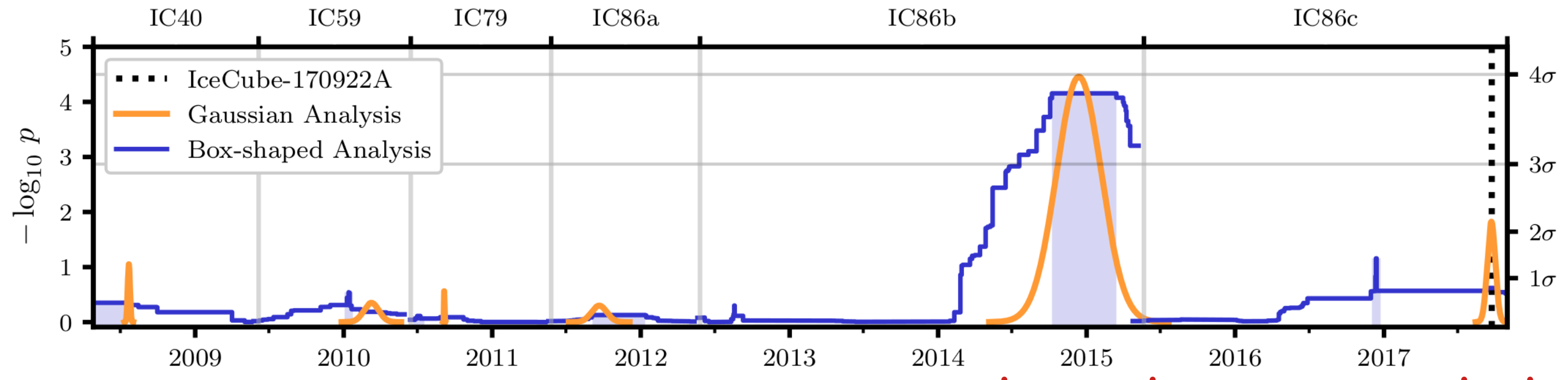

After re-analysis (2101.09836), significance dropped from $p=7\times10^{-5}$ to $p=8\times10^{-3}$

2014–2015: 13±5 ν flare, no X-ray flare
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If every blazar produced neutrinos as TXS 0506+056, the diffuse ν flux would be 20x higher than observed!

Joint modeling of the two periods is challenging!

Tidal disruption events

Solar-mass star disrupted by SMBH ($>10^5\ M_\odot$)

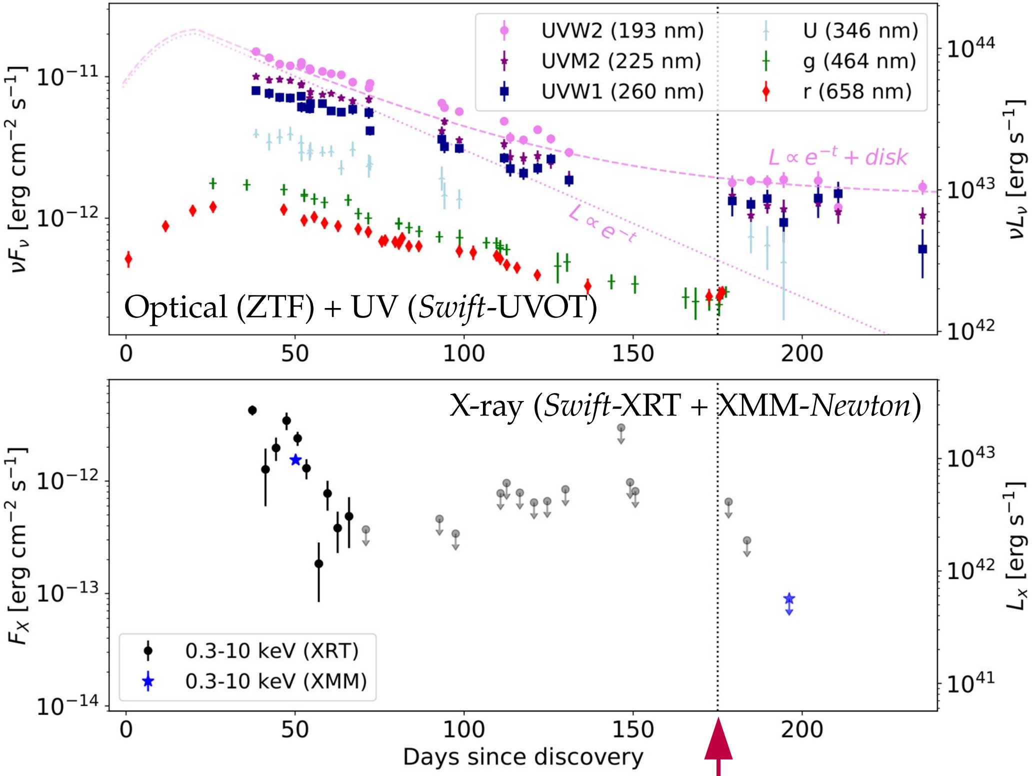
~50% of the debris bound to the SMBH, creates a flare (occasionally a jet)

NASA

An apparent TDE neutrino source

Radio-emitting TDE AT2019dsg coincident with neutrino event IC191001A:

AT2019dsg: Apr 9, 2019 / $z = 0.051$ (230 Mpc) / $M_{\rm BH} = 3 \times 10^7\, M_\odot$

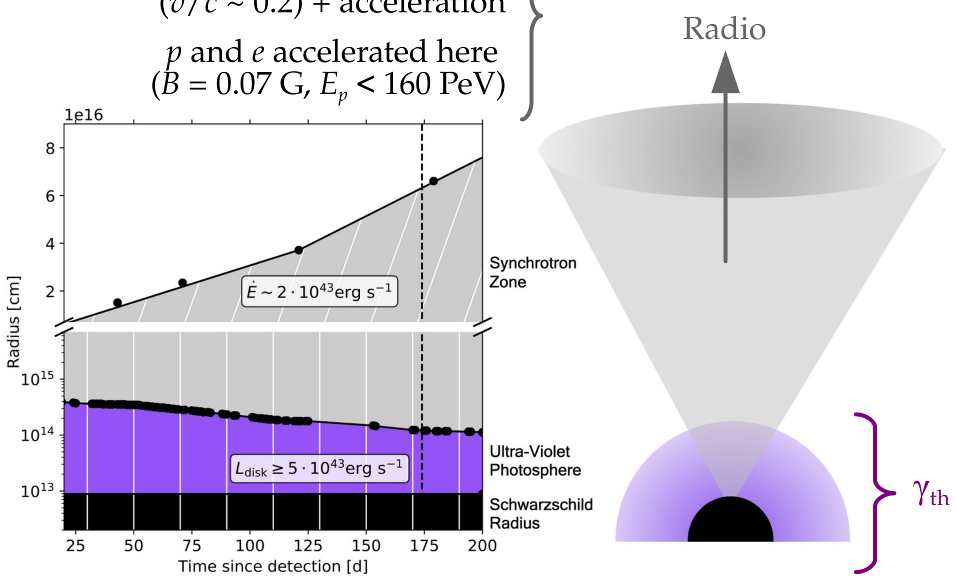


IC191001A, ~200 TeV

Multi-zone model:

From radio:
mildly relativistic expansion ($v/c \sim 0.2$) + acceleration

p and e accelerated here ($B = 0.07$ G, $E_p < 160$ PeV)

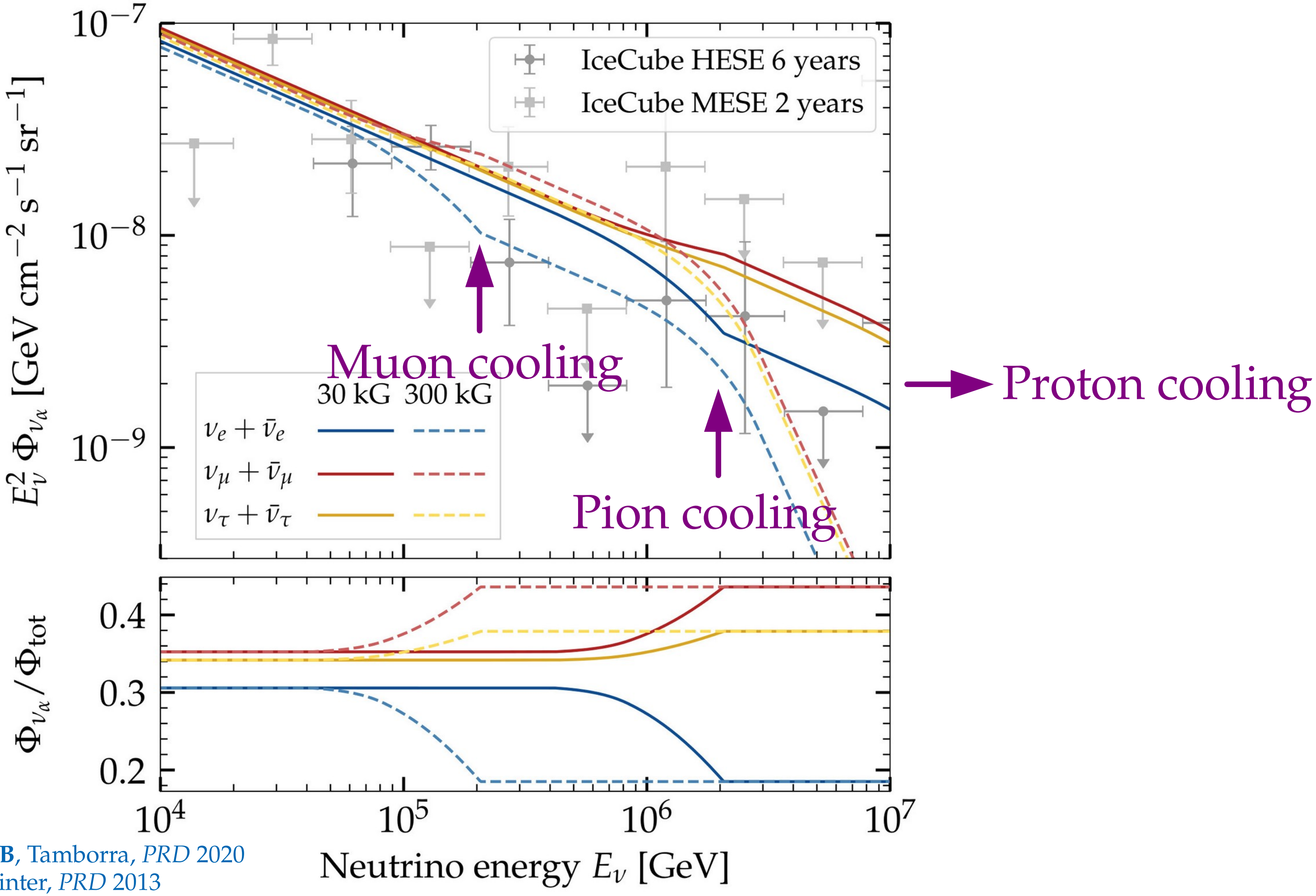


$$p + \gamma_{\rm th}\ (\text{or } p) \rightarrow \nu$$

Stein *et al.*, *Nature Astron.* 2021 – See also: Winter & Lunardini, *Nature Astron.* 2021; Murase, Kimura, Zhang, Oikonomou, Petropoulou, *ApJ* 2020

Using high-energy neutrinos as magnetometers

If sources have strong magnetic fields, charged particles cool via synchrotron:



MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

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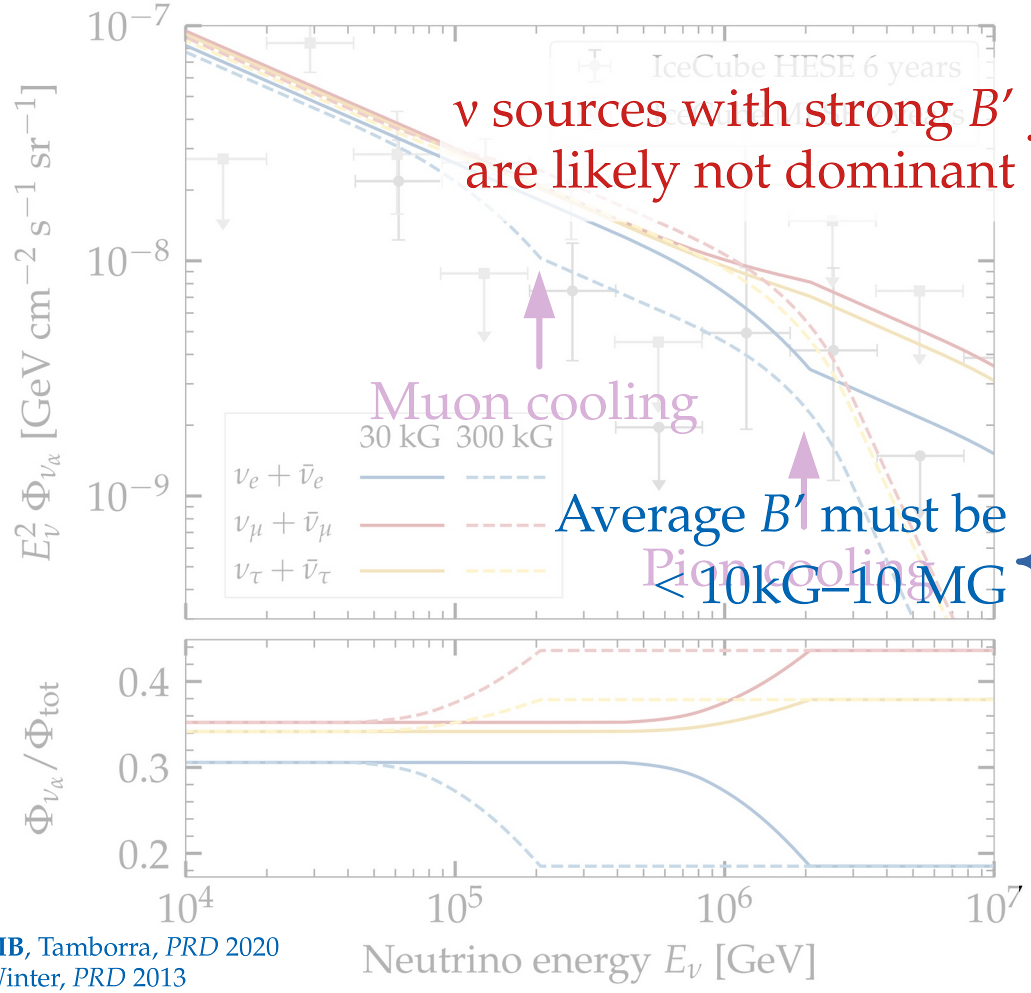
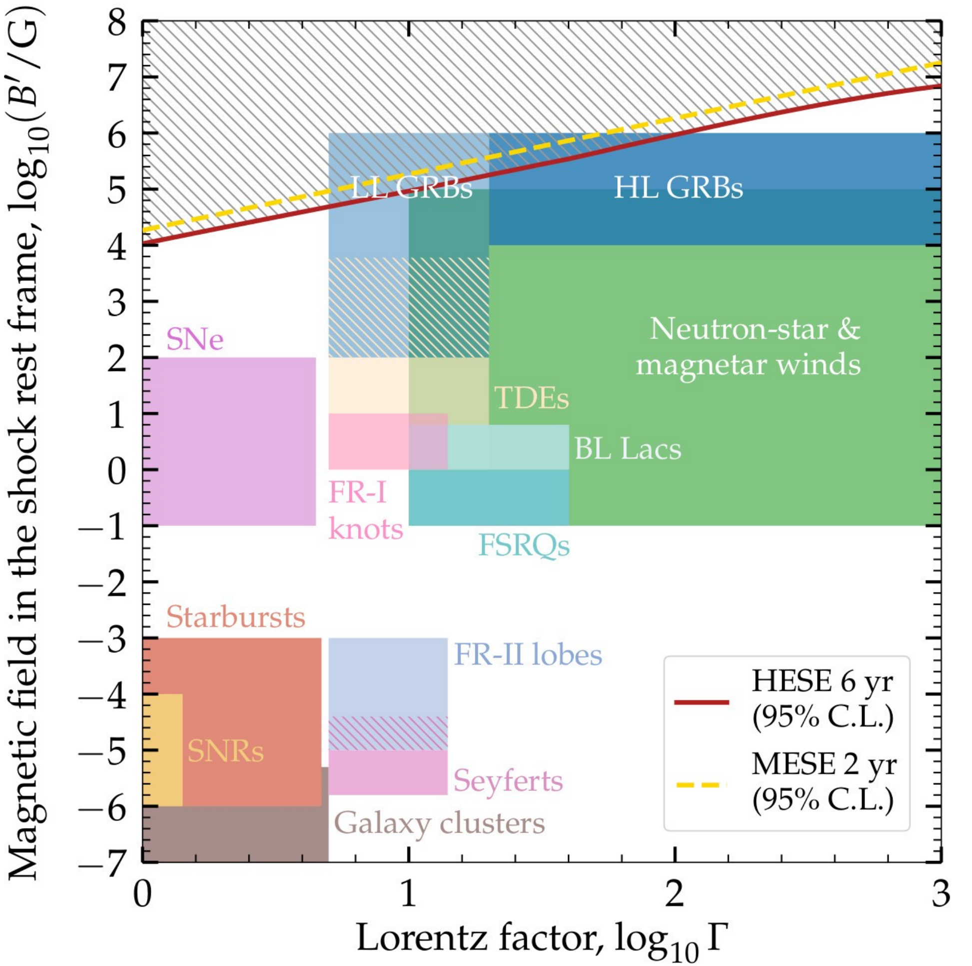
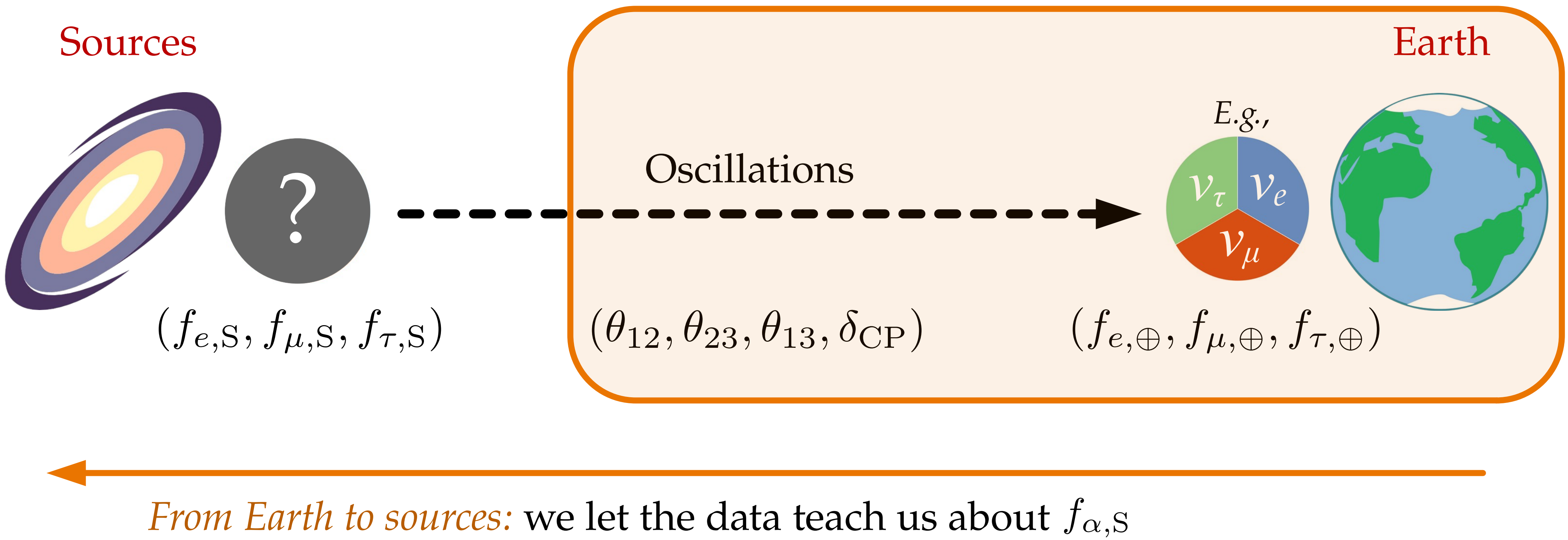


ν sources with strong B' are likely not dominant

Average B' must be < 10kG–10 MG



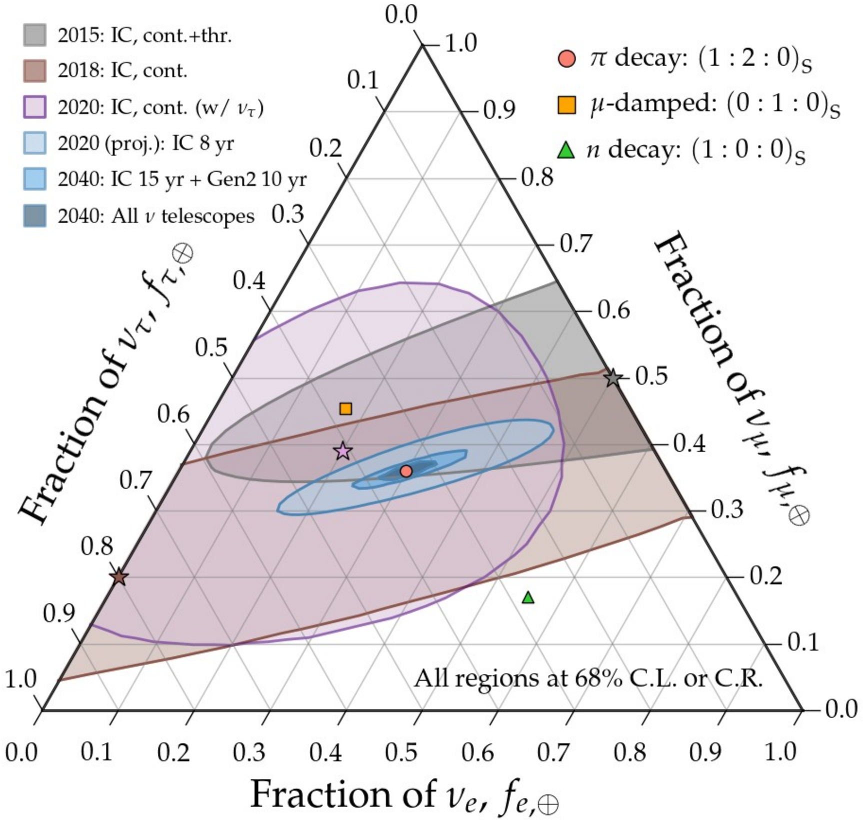
MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013



Sources
Earth
E.g.,
Oscillations
ν_τ
ν_e
ν_μ
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

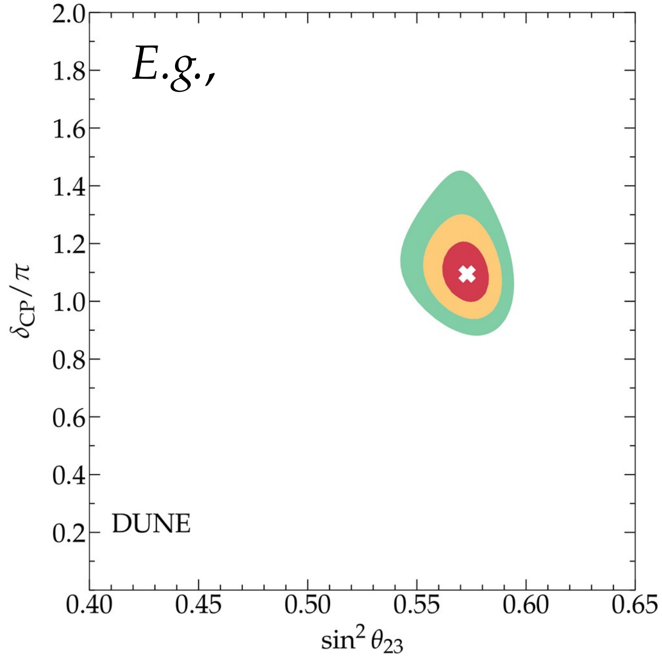
Inferring the flavor composition at the sources

Ingredient #1:
Flavor ratios measured at Earth,
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

$\mathcal{L}(\boldsymbol{\vartheta})$



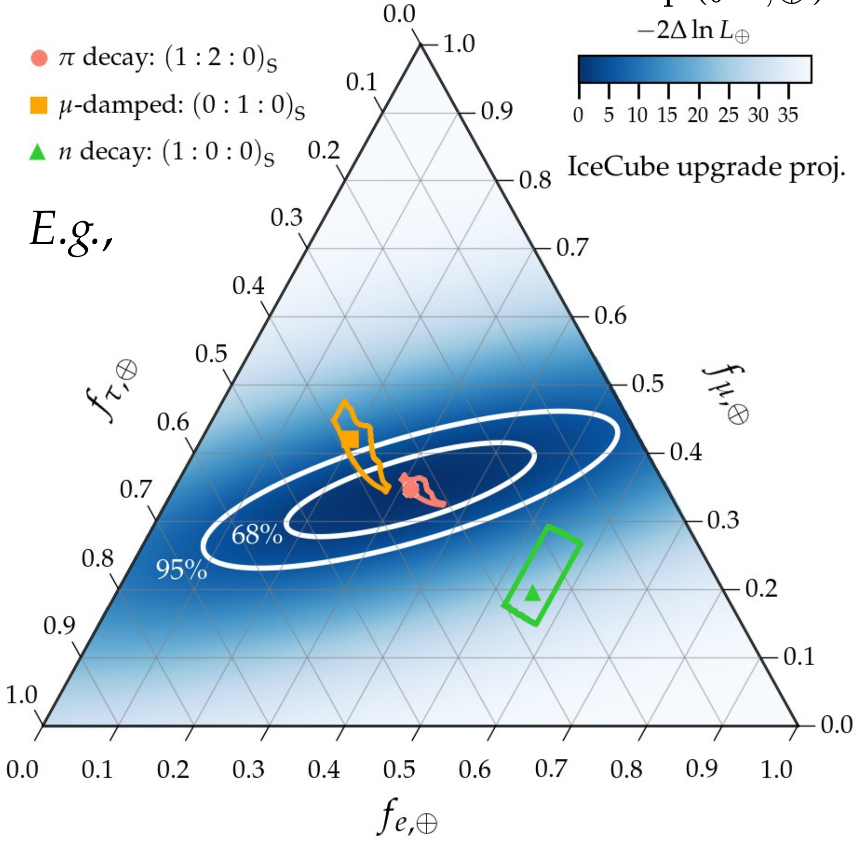
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

Ingredient #1:
Flavor ratios measured at Earth,
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

$\mathcal{P}_{\rm exp}(f_{\alpha,\oplus})$

E.g.,



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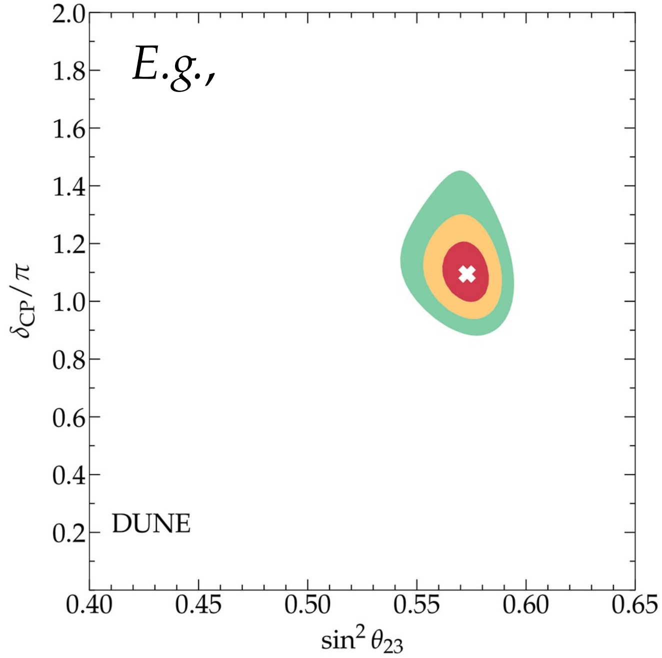
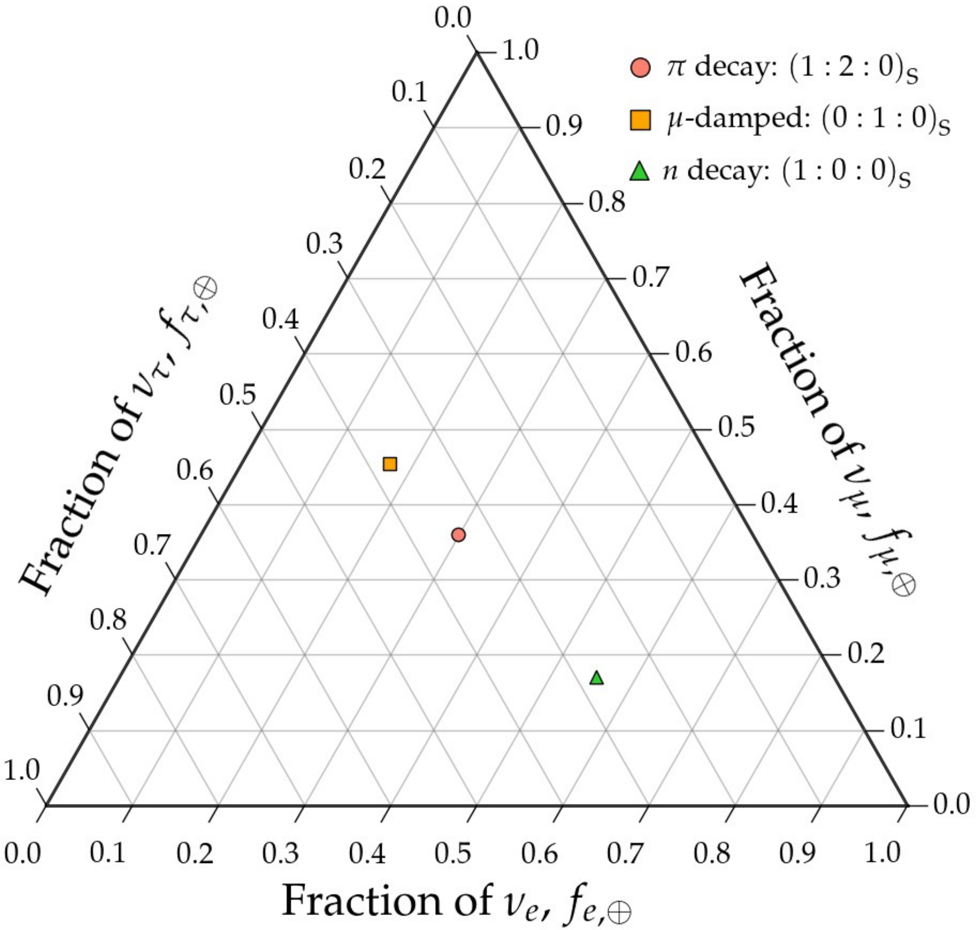


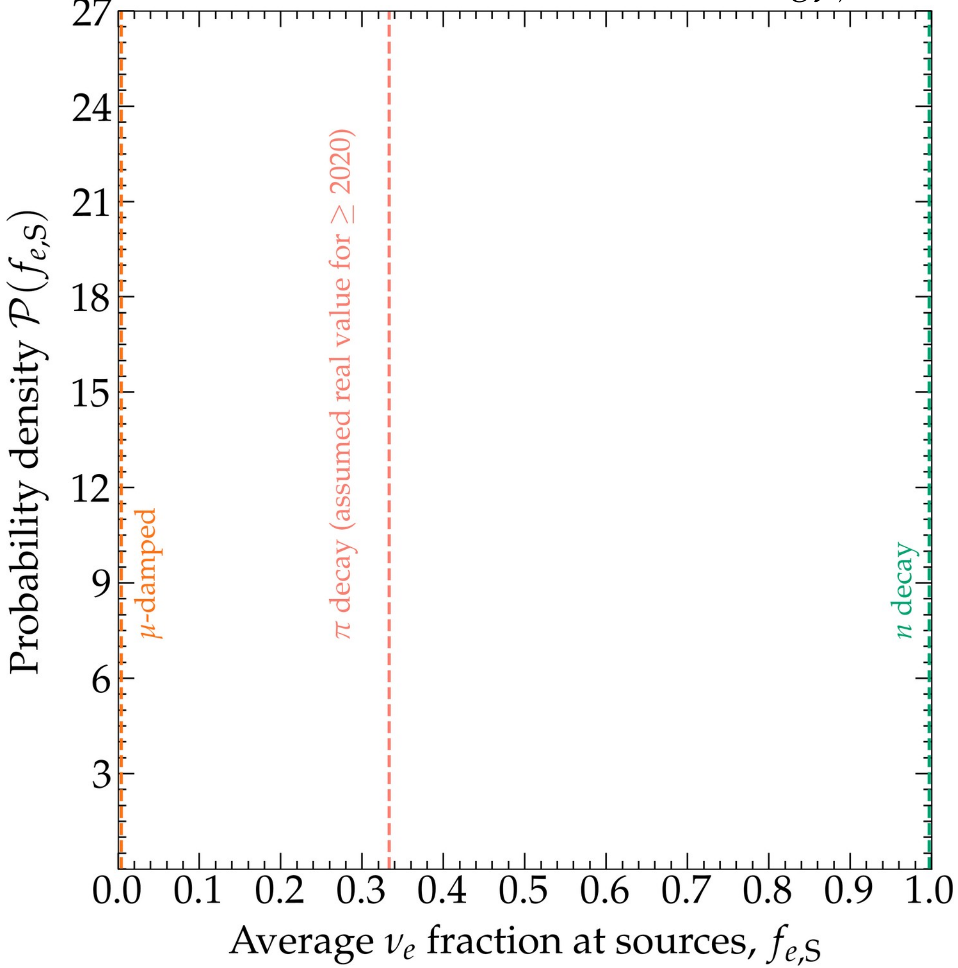
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

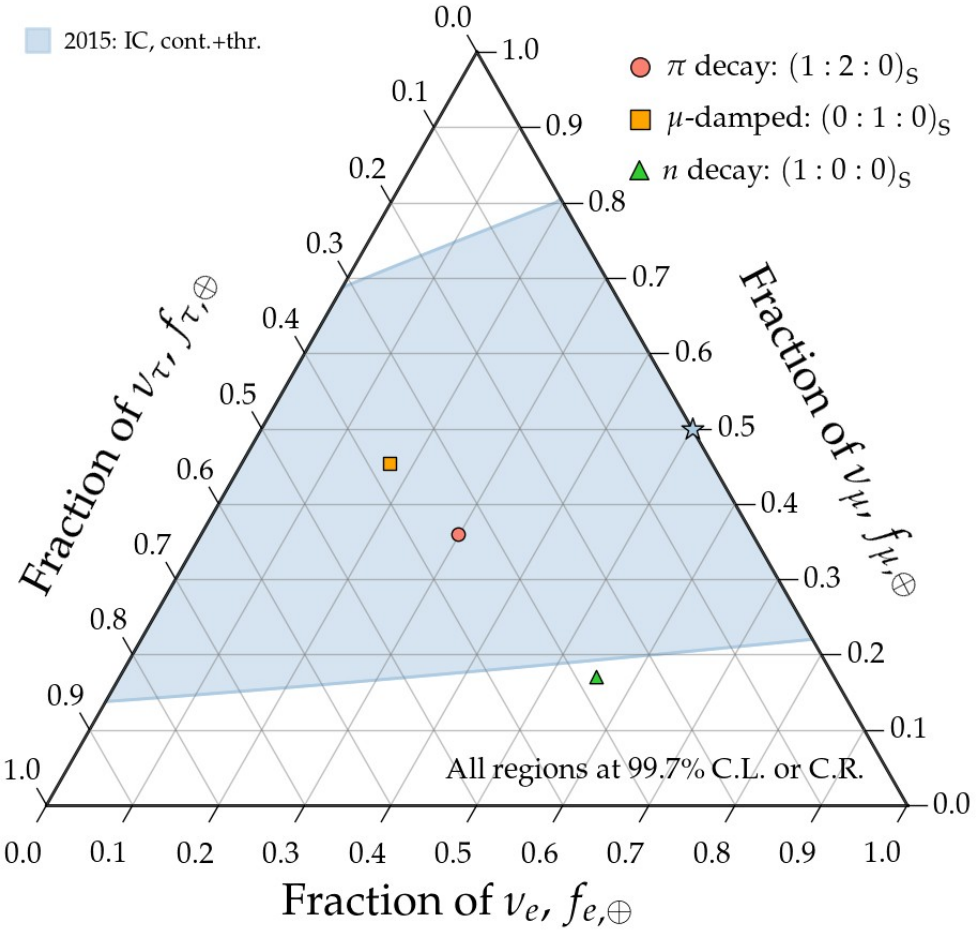
Inferring the flavor composition at the sources



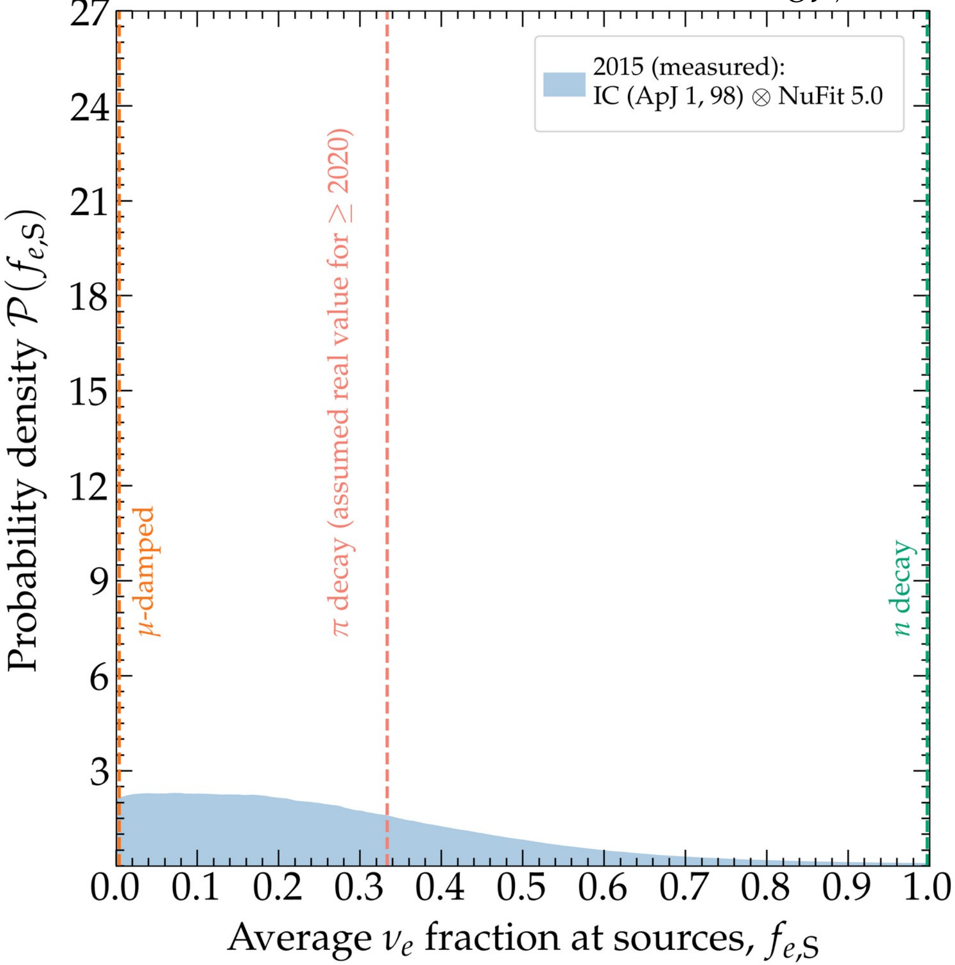


Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

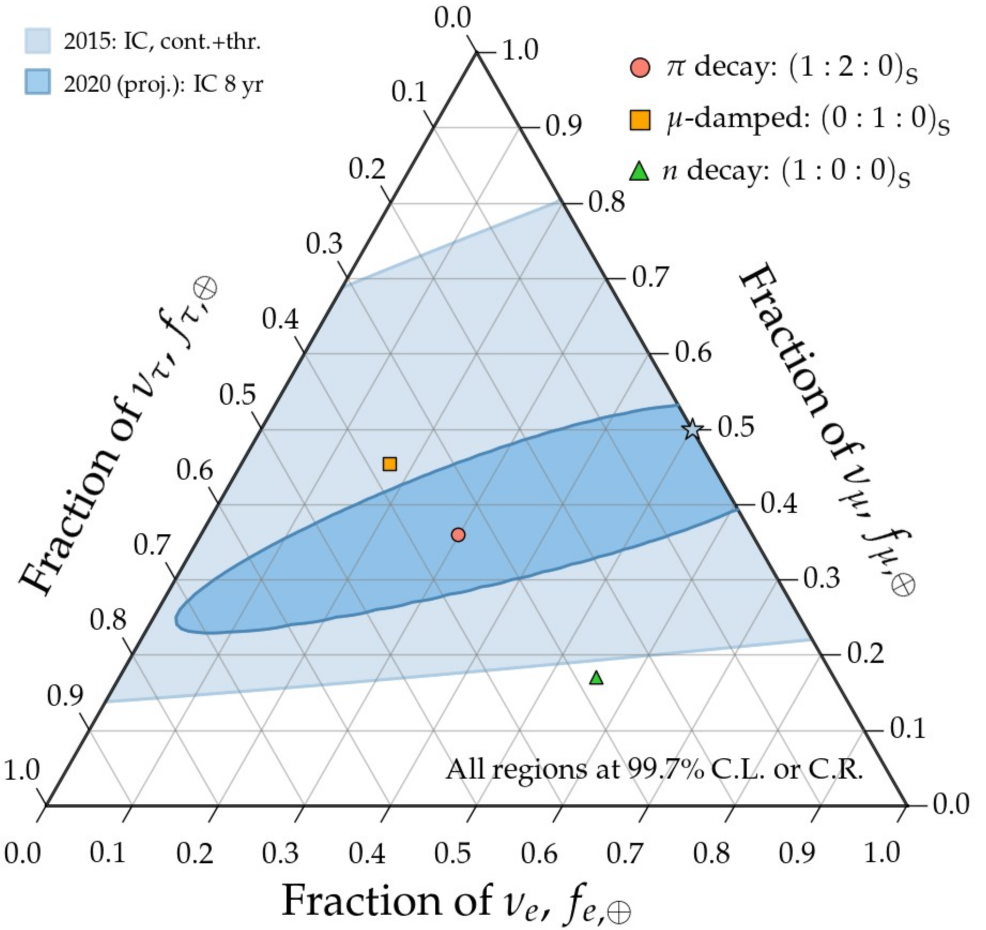


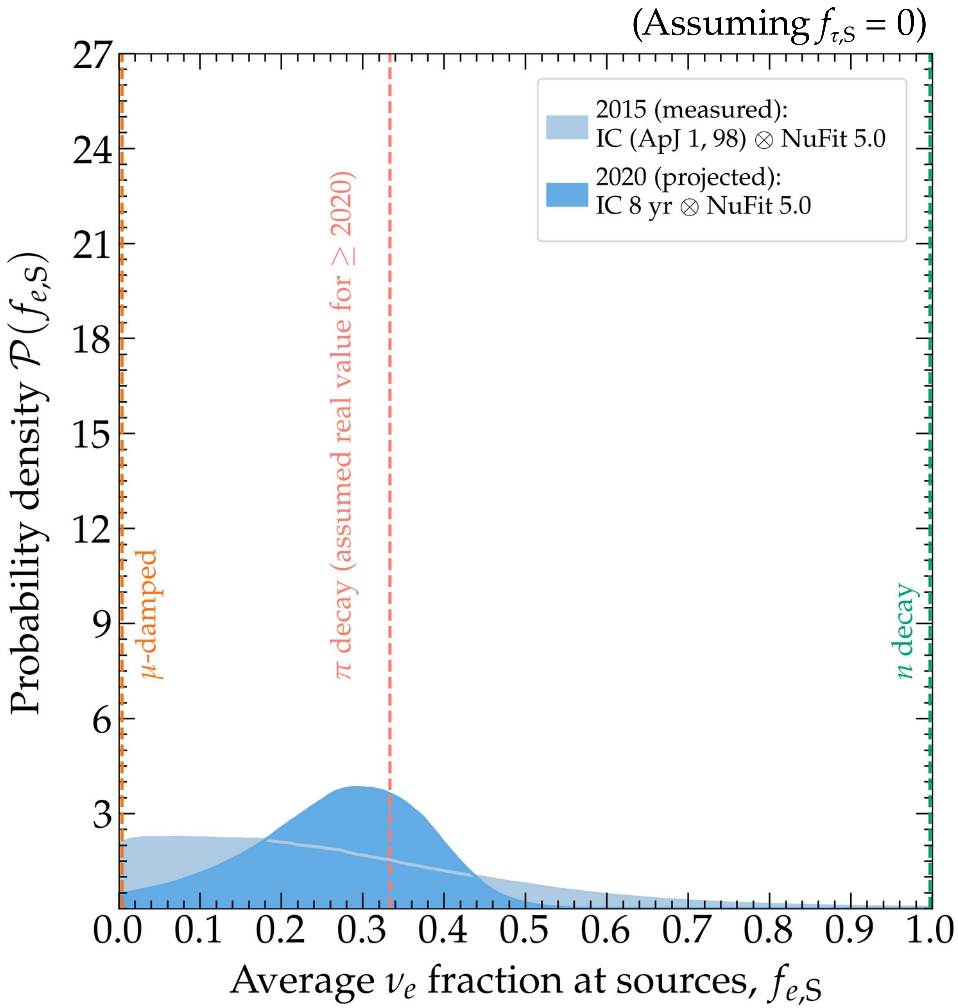
(Assuming $f_{\tau,S} = 0$)



Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources





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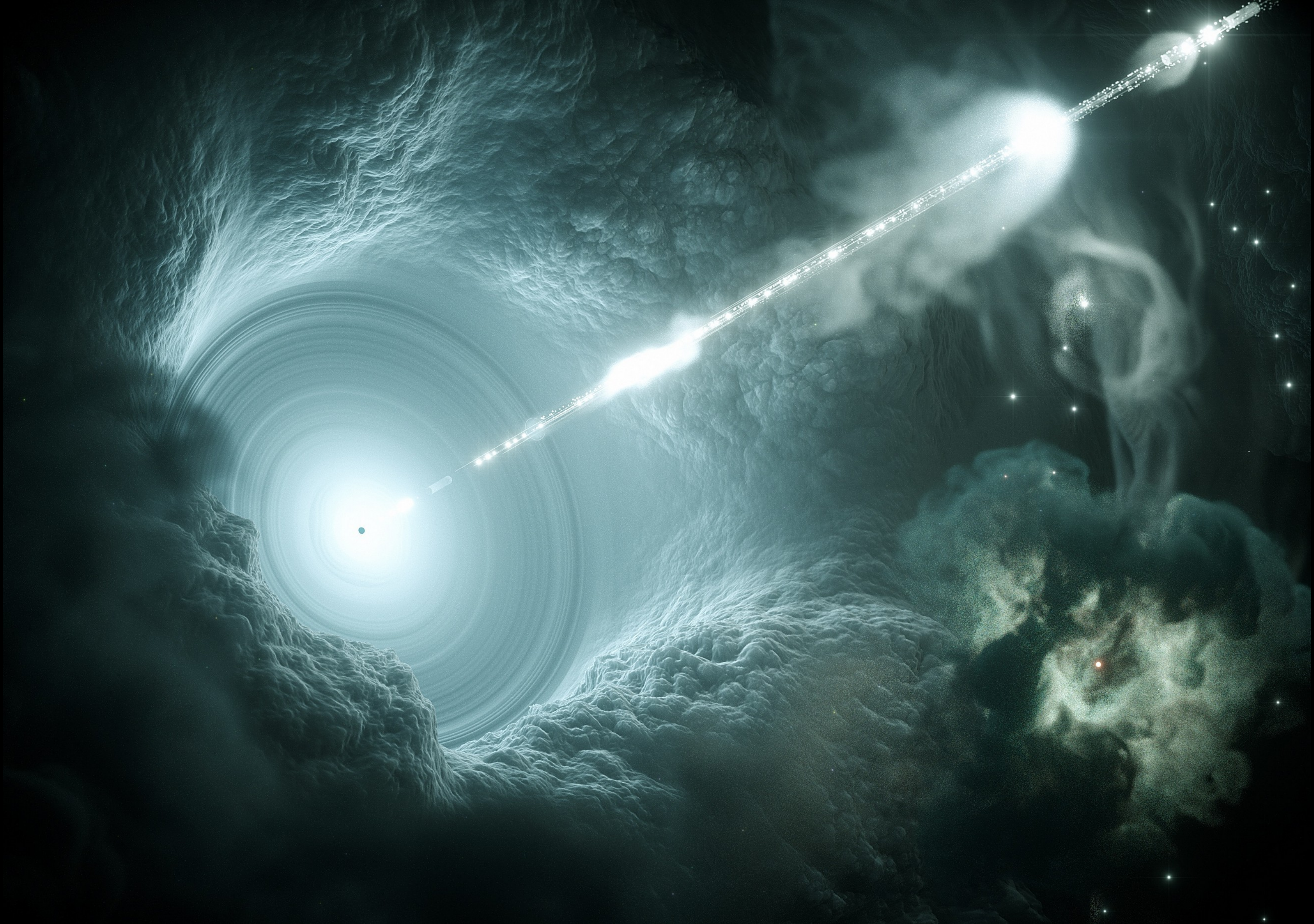
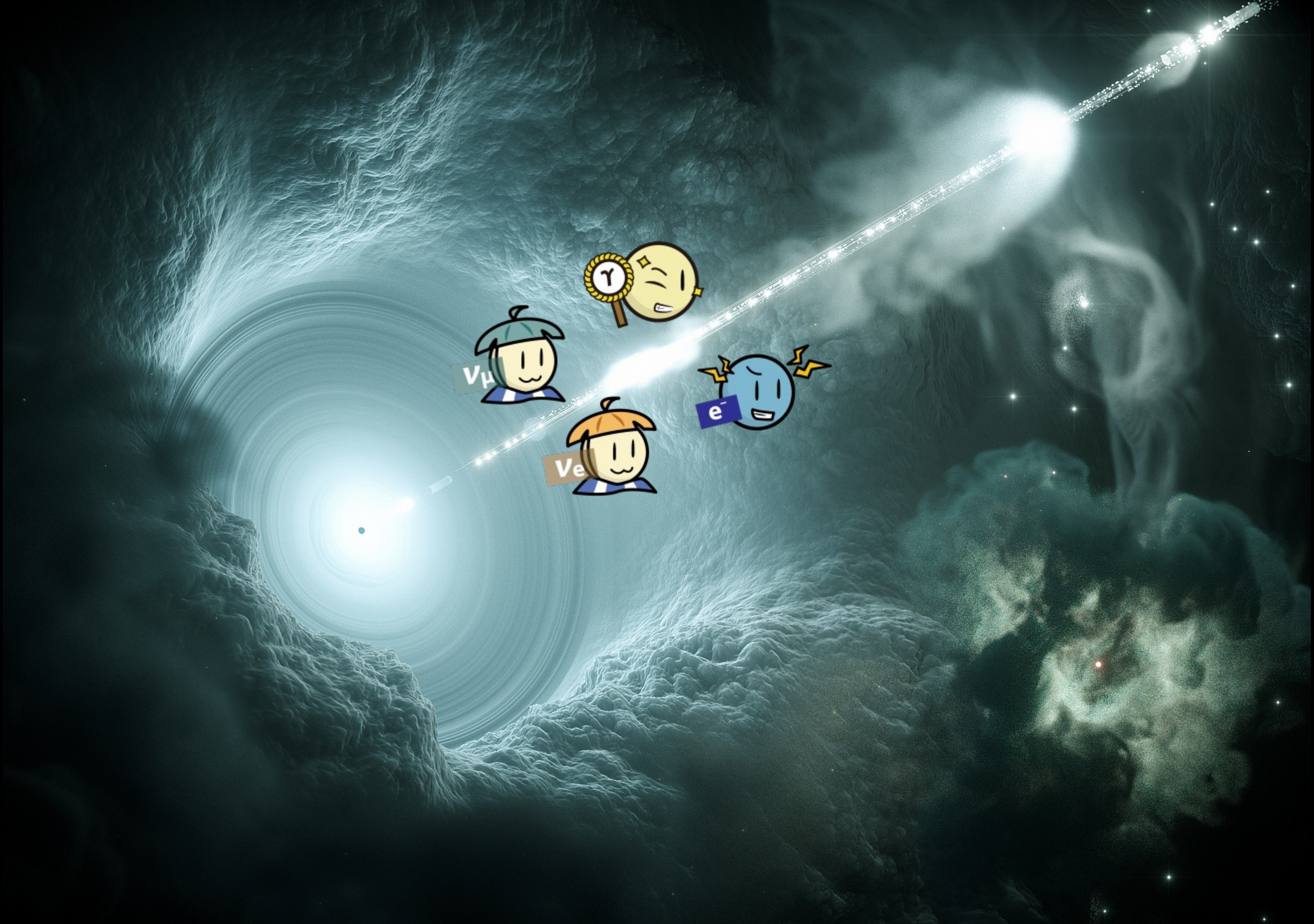


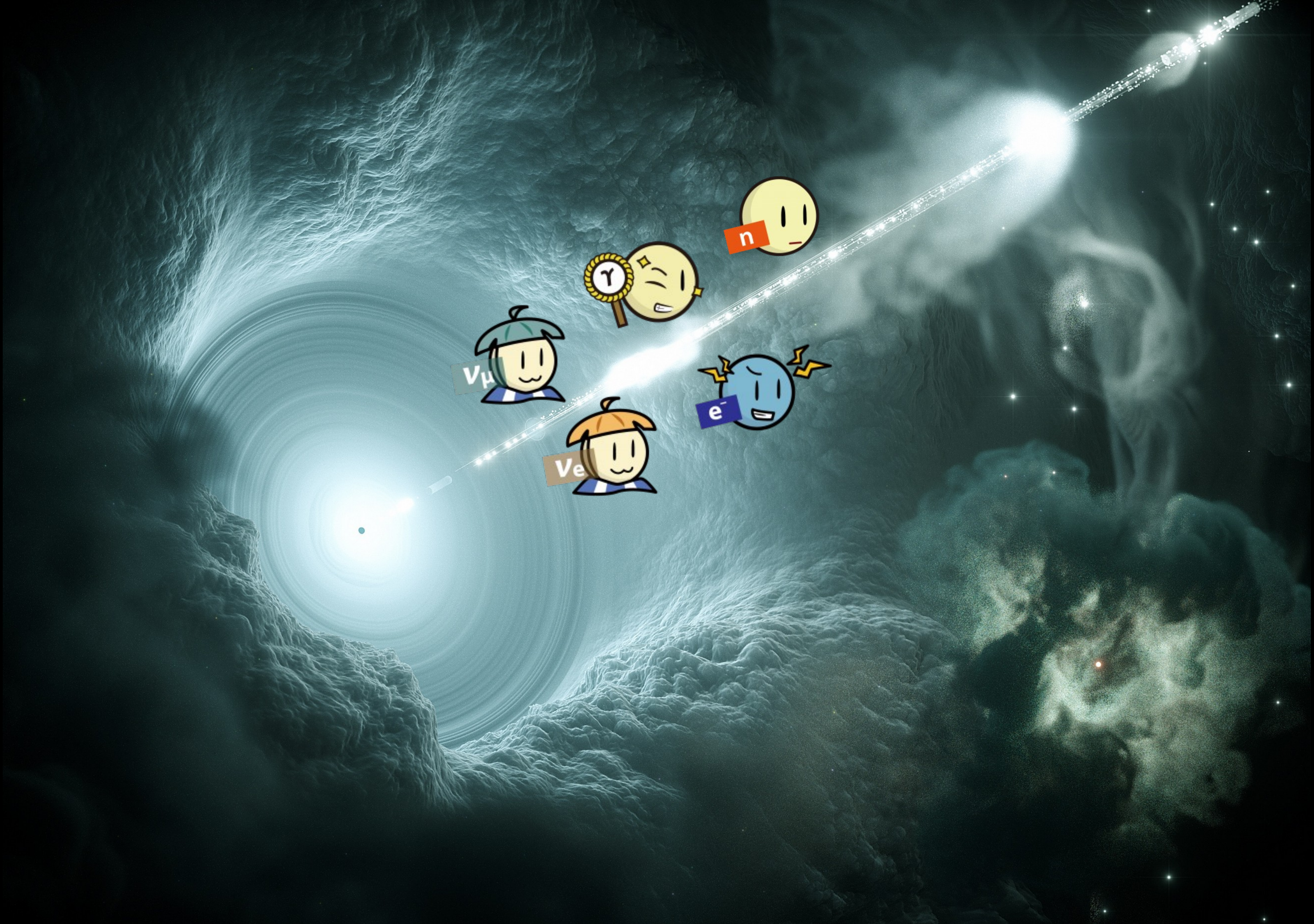
DESY

DESY

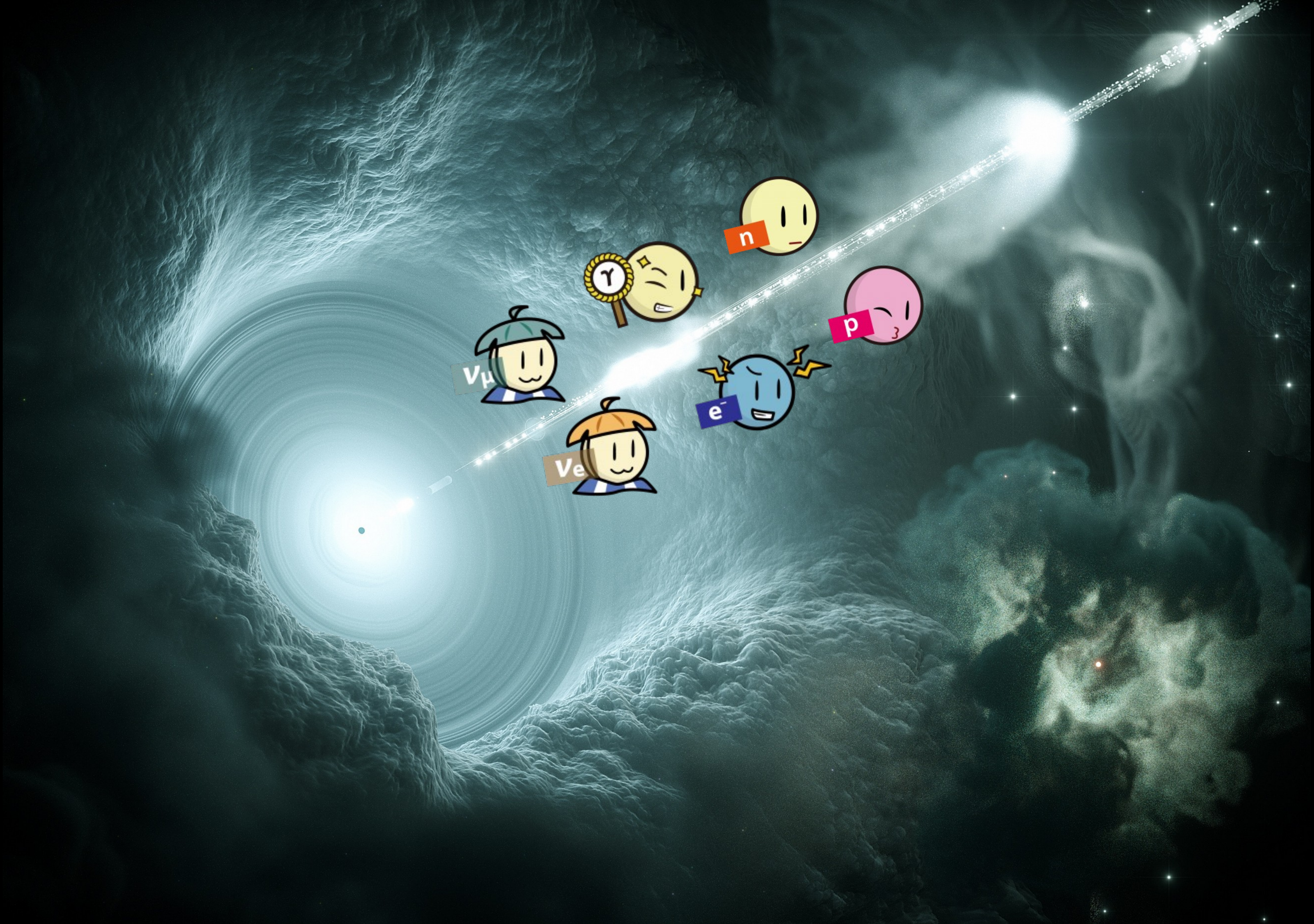
DESY



DESY



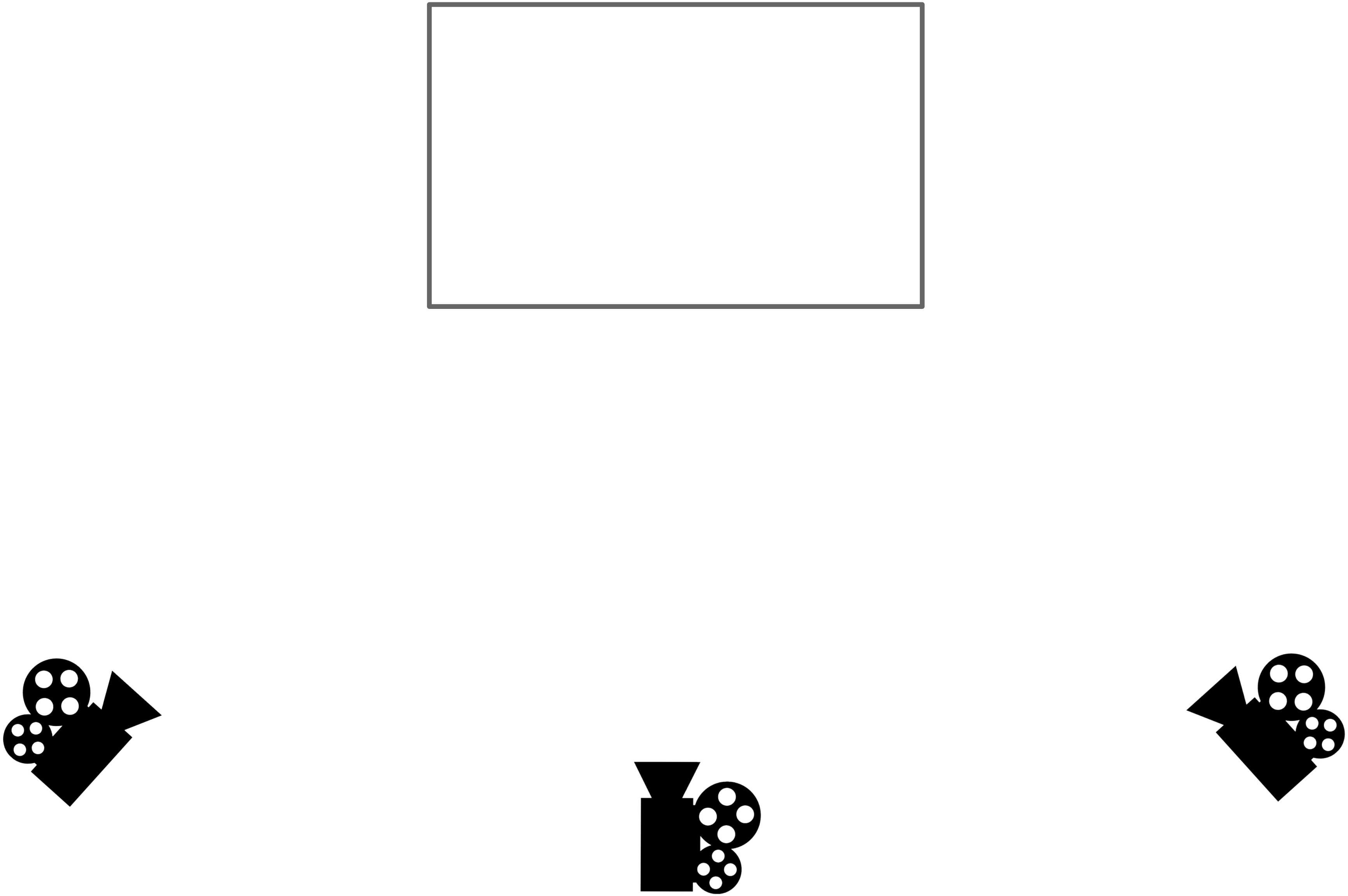
DESY

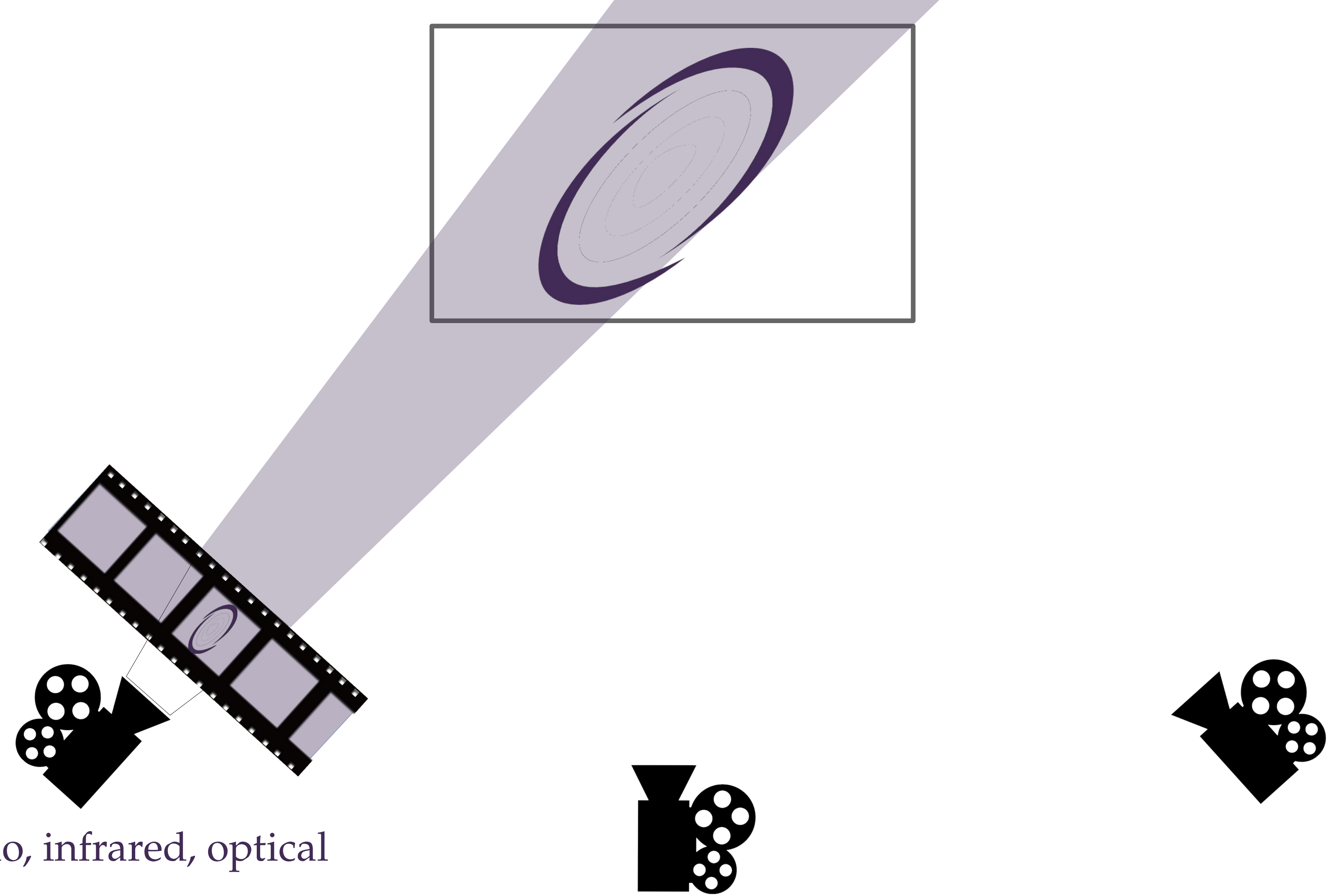


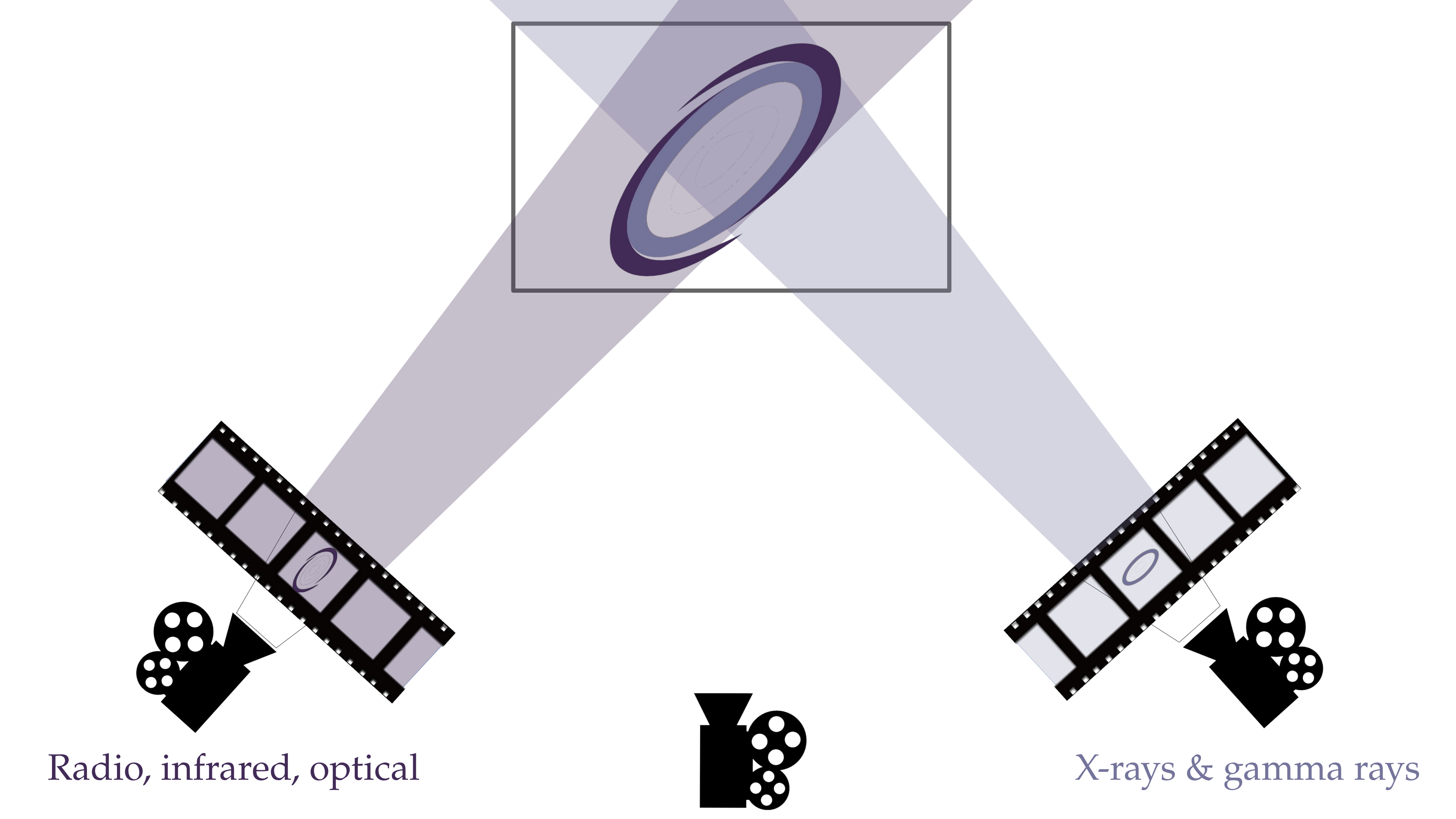
DESY

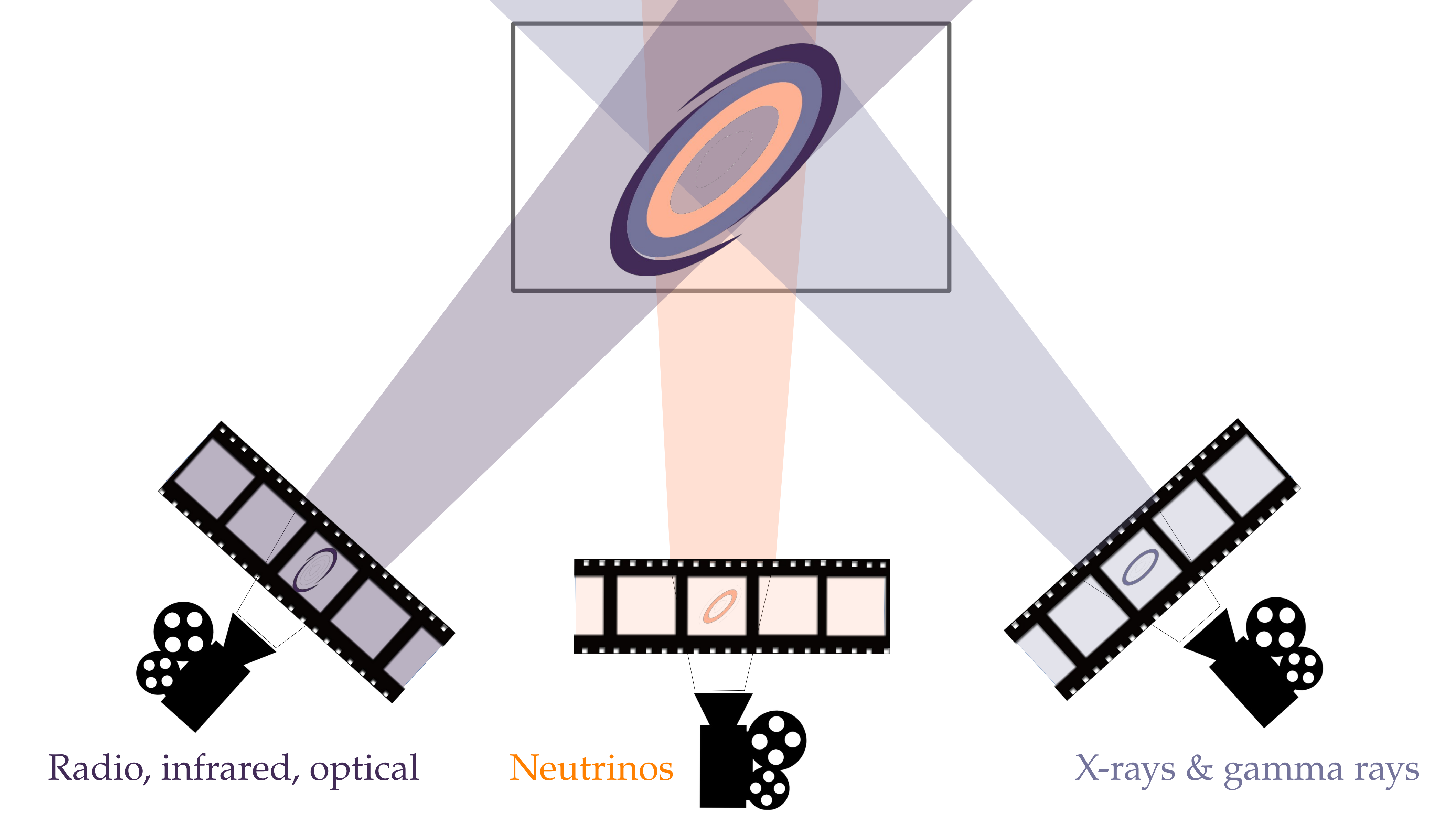
Multi-messenger astrophysics

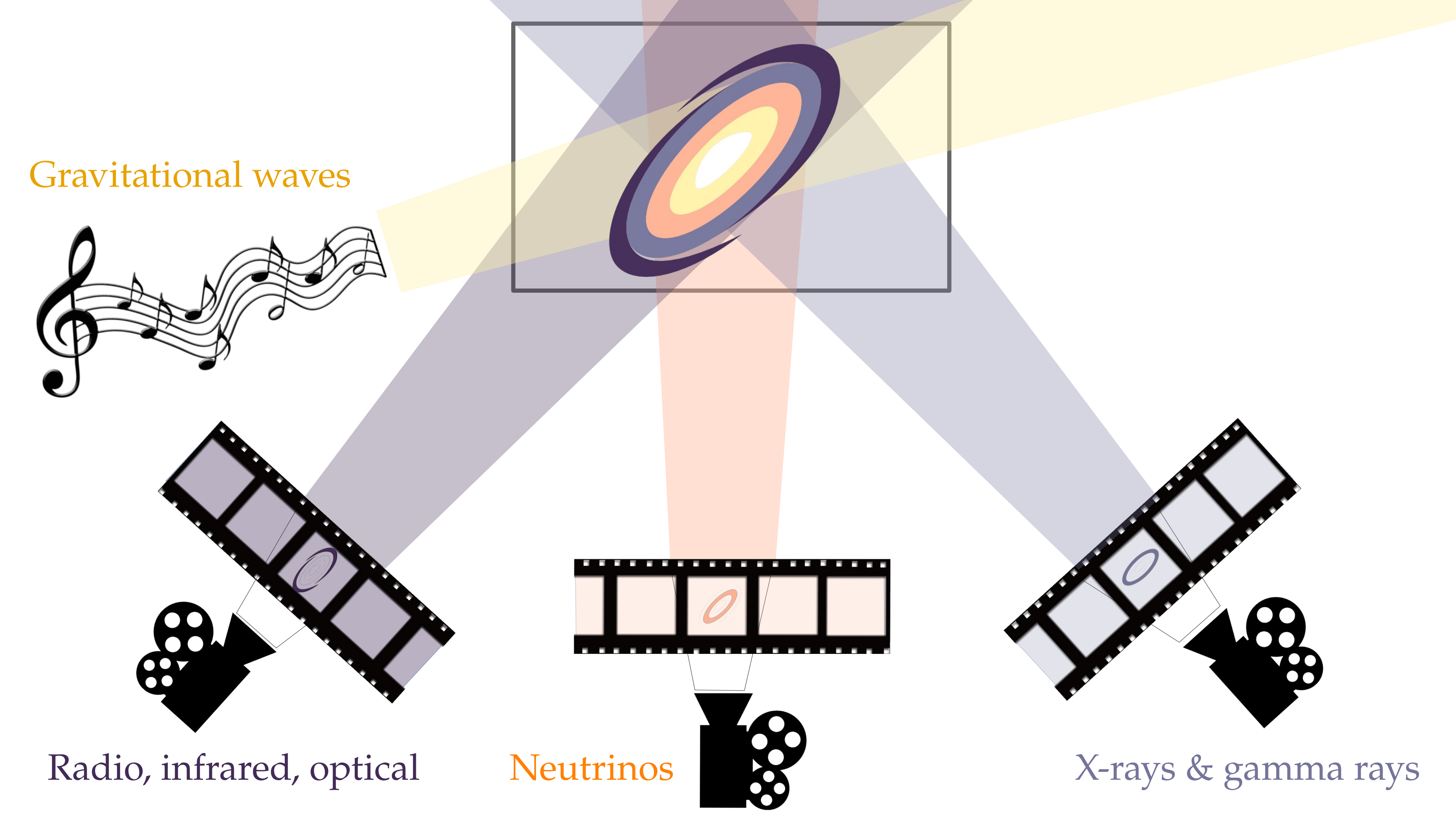
DESY



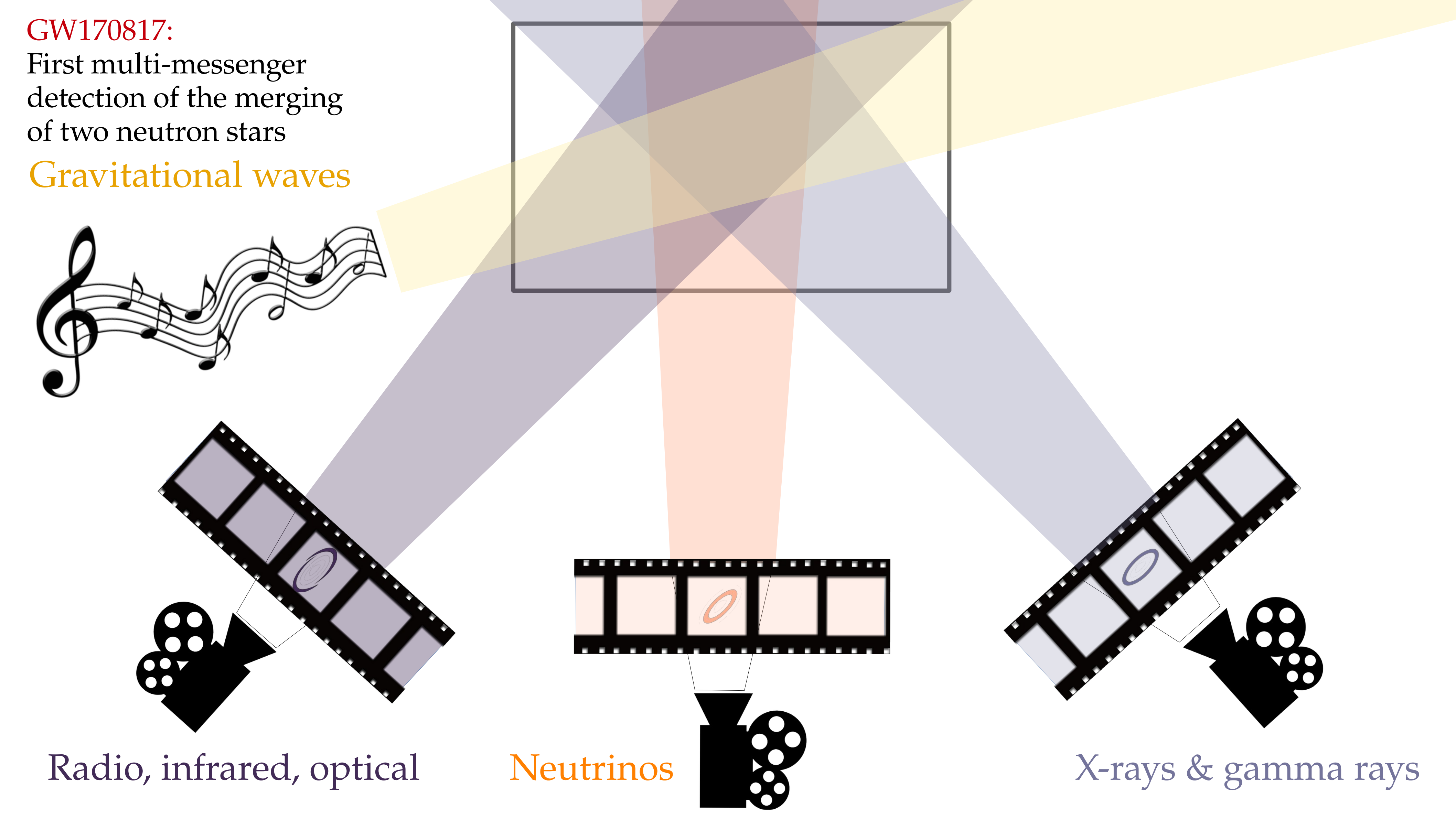

Radio, infrared, optical

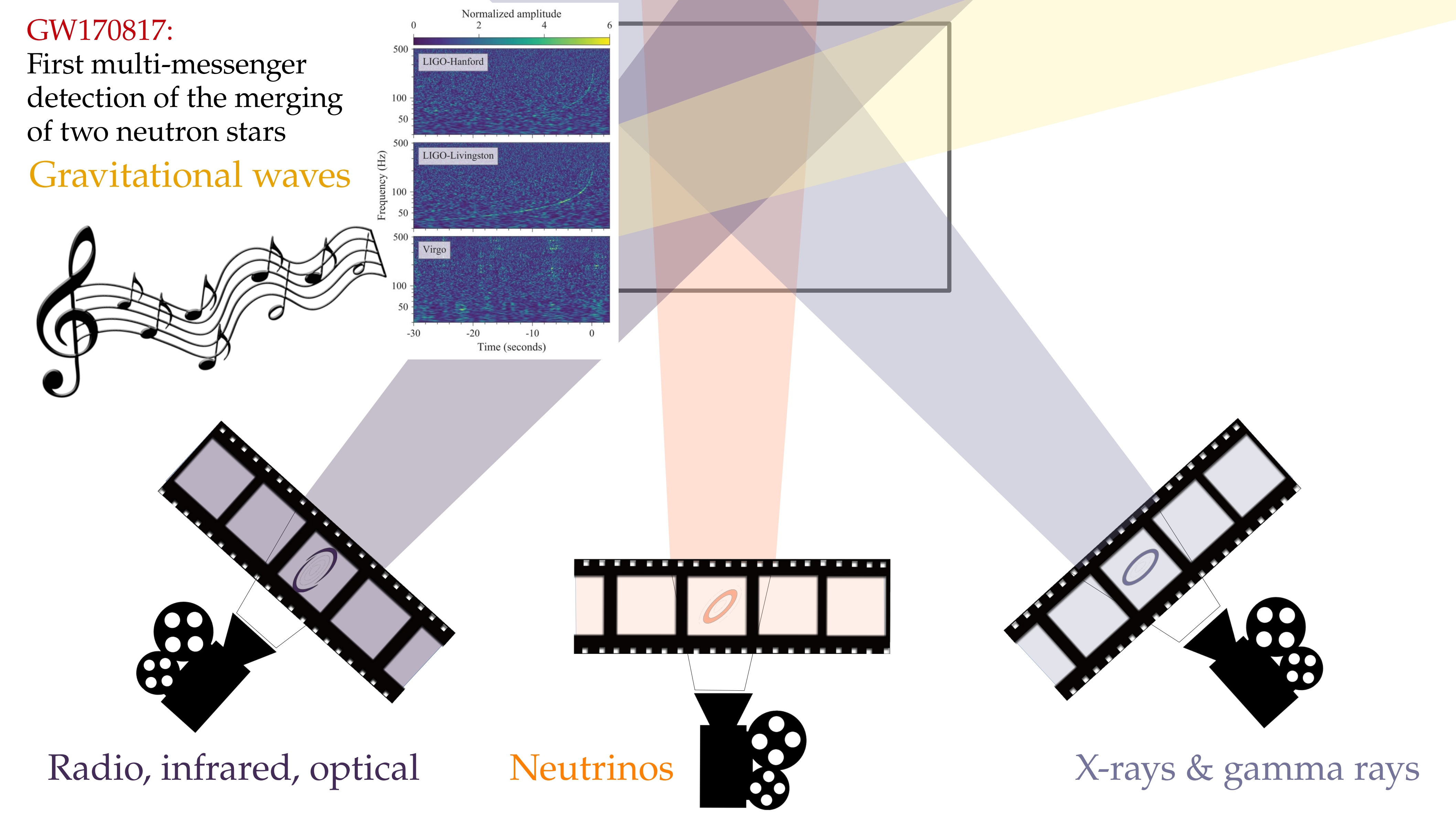

Radio, infrared, optical
X-rays & gamma rays


Radio, infrared, optical
Neutrinos
X-rays & gamma rays

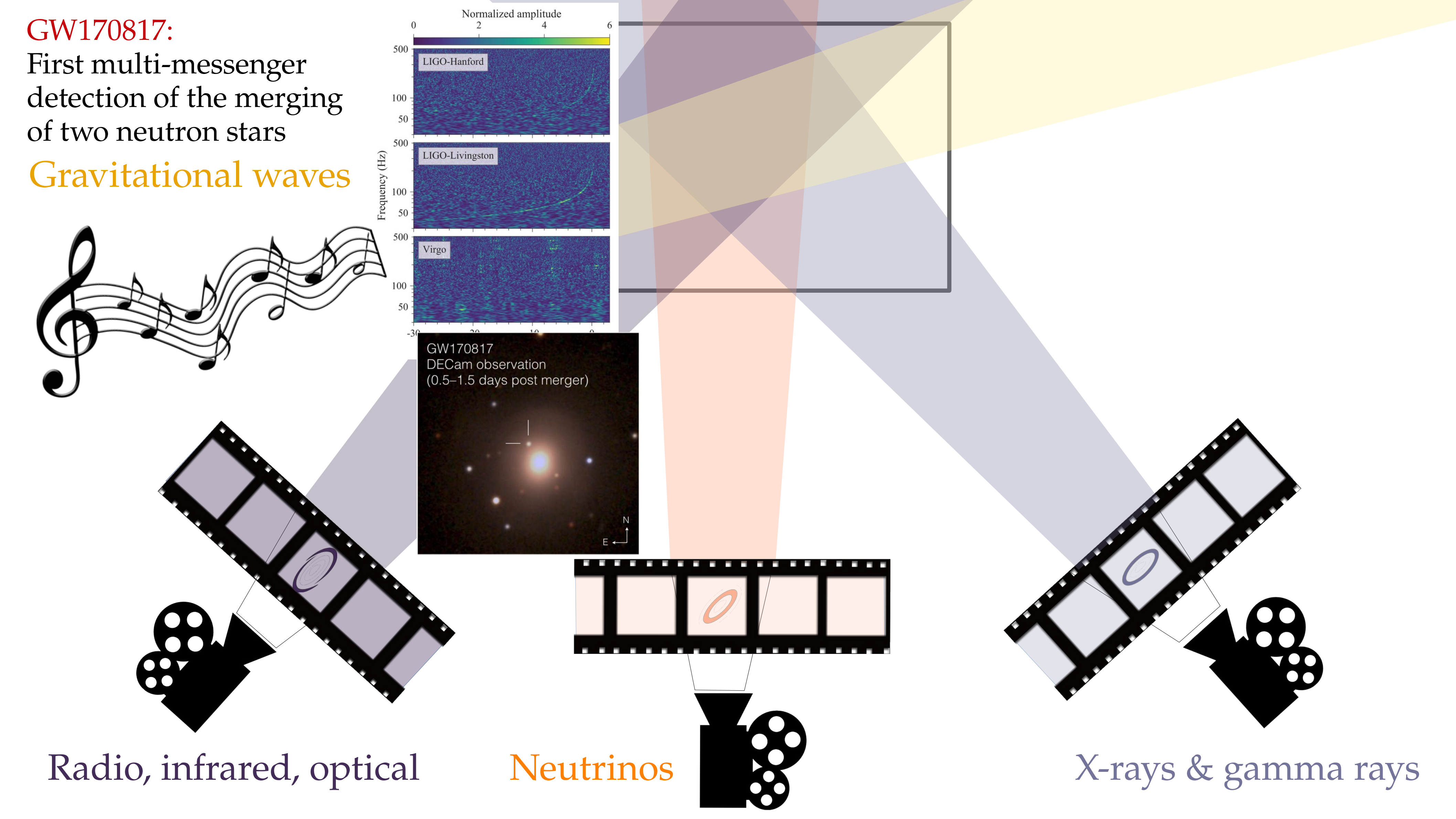


Gravitational waves
Radio, infrared, optical
Neutrinos
X-rays & gamma rays


GW170817:
First multi-messenger detection of the merging of two neutron stars
Gravitational waves
Radio, infrared, optical
Neutrinos
X-rays & gamma rays



GW170817:
First multi-messenger detection of the merging of two neutron stars
Gravitational waves
Normalized amplitude
0
2
4
6
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
500
100
50
-30
-20
-10
0
Time (seconds)
Radio, infrared, optical
Neutrinos
X-rays & gamma rays



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Virgo
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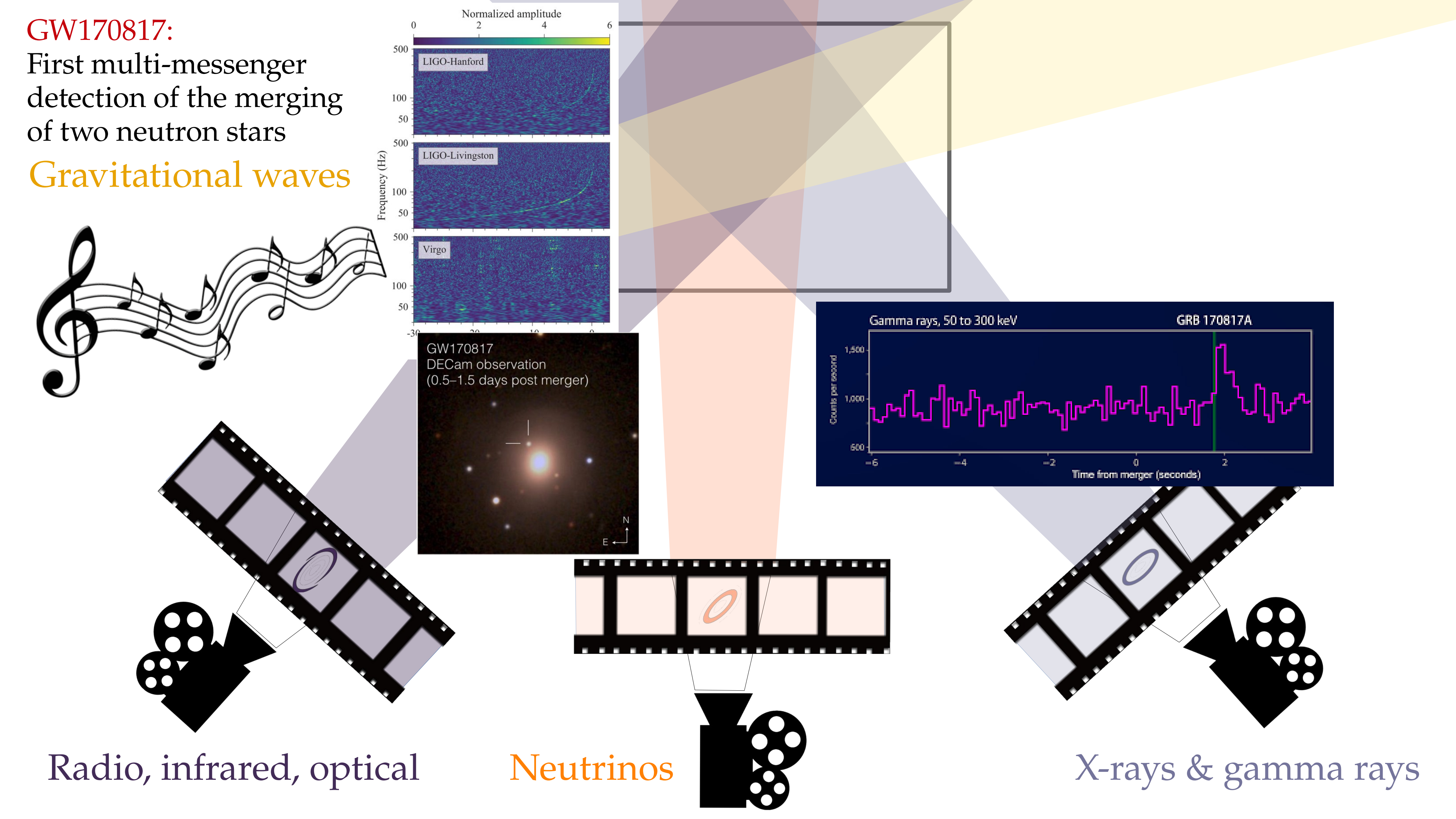
GW170817
DECam observation
(0.5–1.5 days post merger)
N
E
Radio, infrared, optical
Neutrinos
X-rays & gamma rays



GW170817:
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Gravitational waves
Normalized amplitude
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LIGO-Livingston
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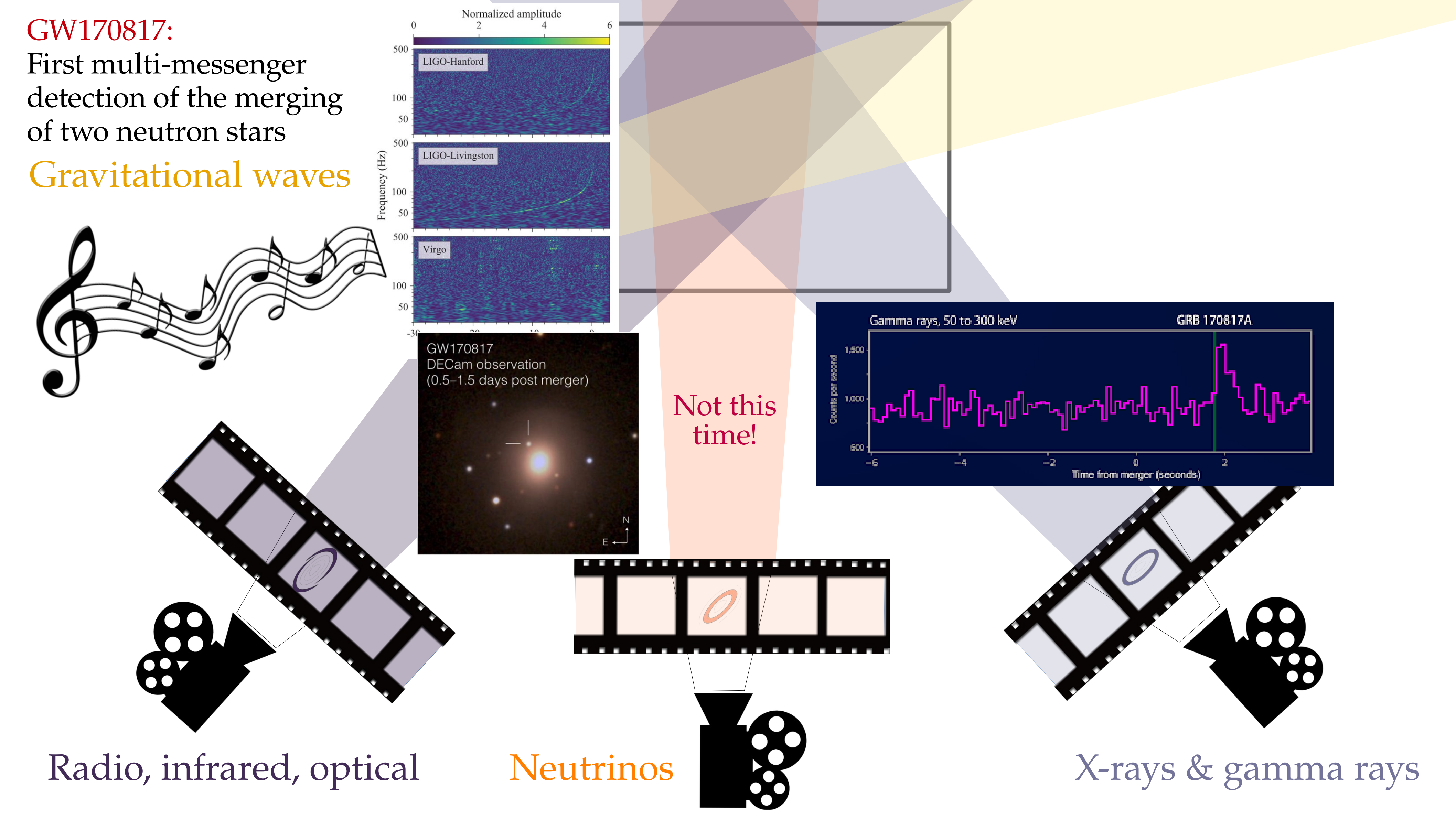
GW170817
DECam observation
(0.5–1.5 days post merger)
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
Time from merger (seconds)
Radio, infrared, optical
Neutrinos
X-rays & gamma rays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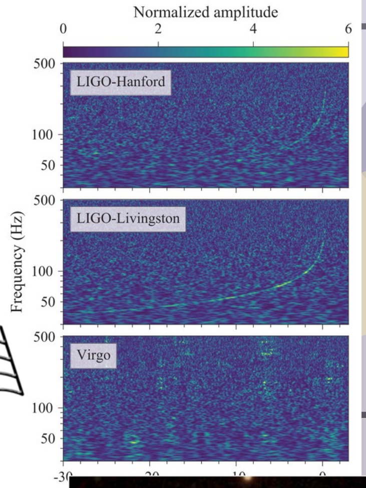
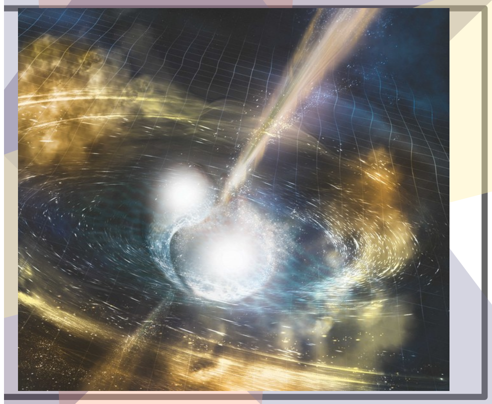
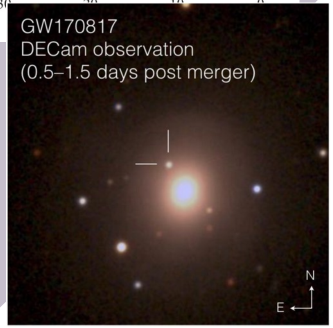
LIGO-Livingston
Virgo
Frequency (Hz)
500
100
50
GW170817
DECam observation
(0.5–1.5 days post merger)
N
E
Not this time!
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
600
−6
−4
−2
0
2
Time from merger (seconds)
Radio, infrared, optical
Neutrinos
X-rays & gamma rays

GW170817:
First multi-messenger detection of the merging of two neutron stars

Gravitational waves







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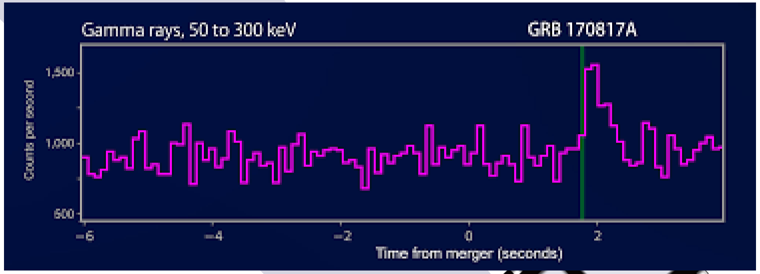
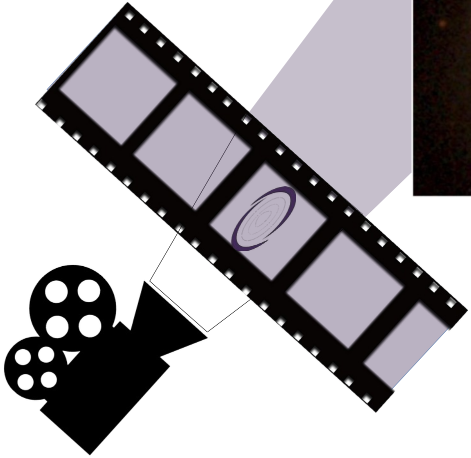
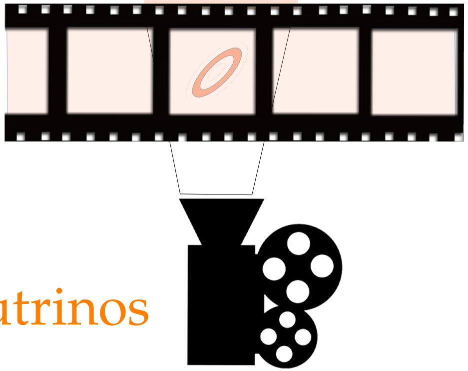
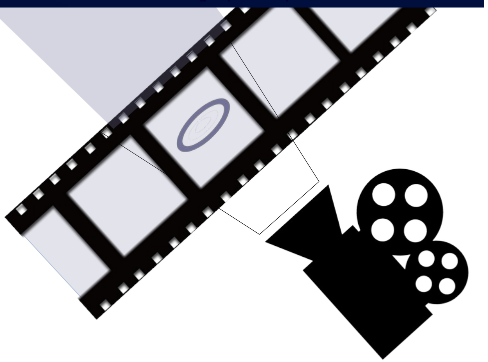








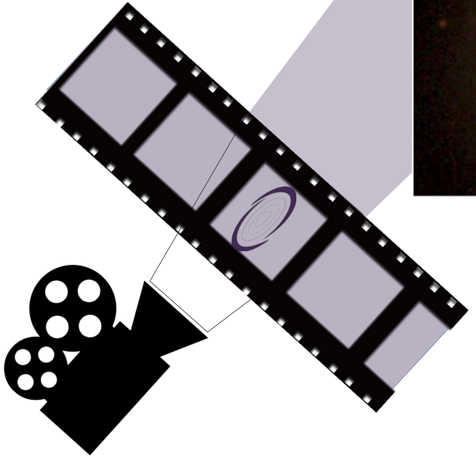
Radio, infrared, optical

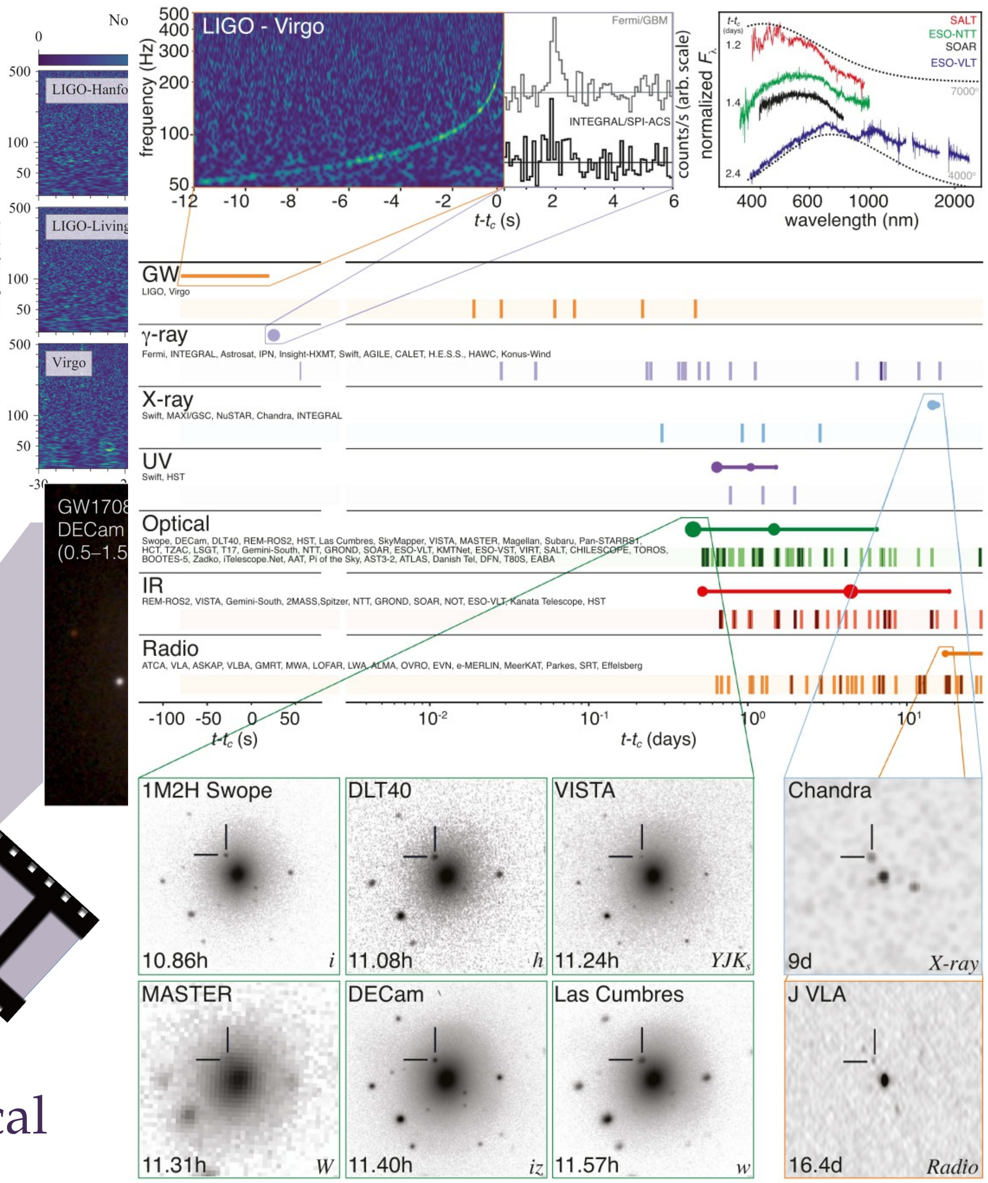
Neutrinos

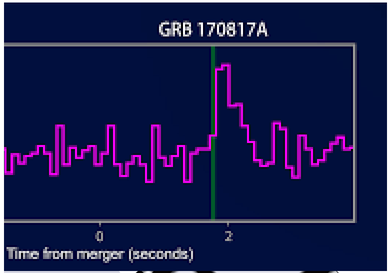
X-rays & gamma rays

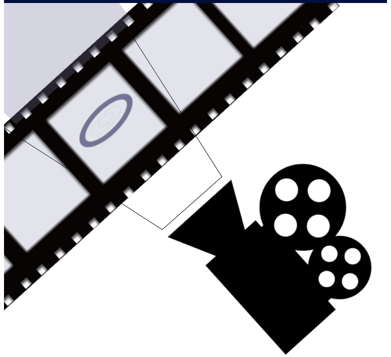
GW170817:
First multi-messenger detection of the merging of two neutron stars

Gravitational waves





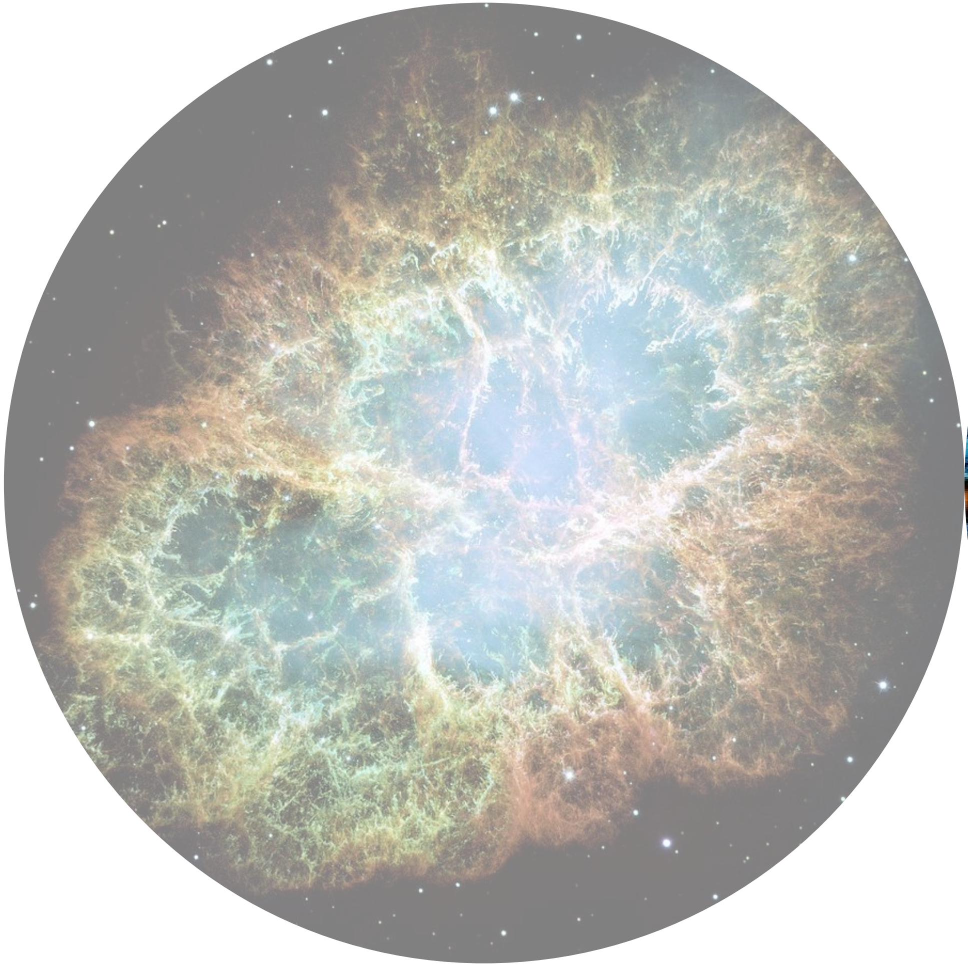


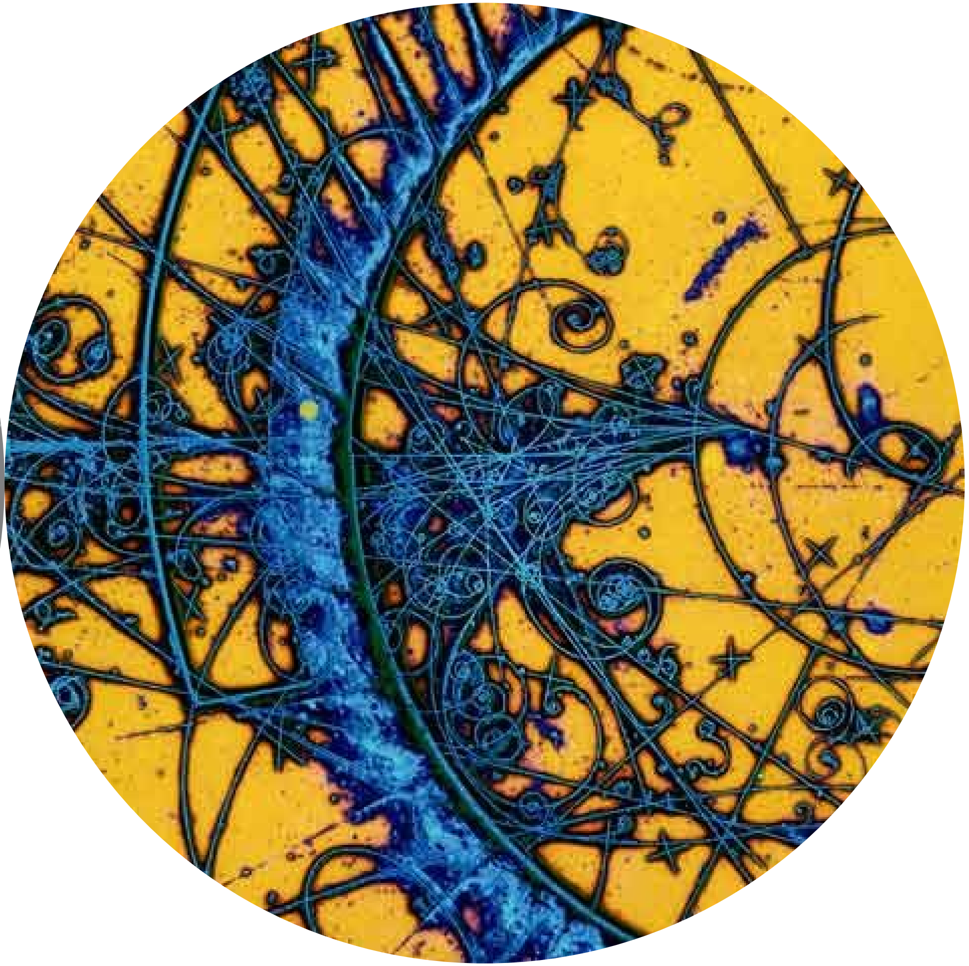


Radio, infrared, optical

X-rays & gamma rays

IV.
What have we learned about *particle physics*





Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine

In the face of astrophysical unknowns,
can we extract fundamental TeV–PeV ν physics?

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can we extract fundamental TeV–PeV ν physics?

Yes.

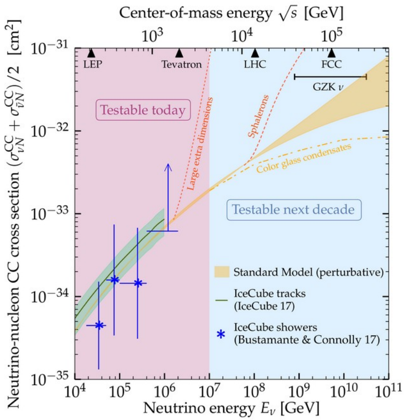
In the face of astrophysical unknowns,
can we extract fundamental TeV–PeV ν physics?

Yes.

Already today.

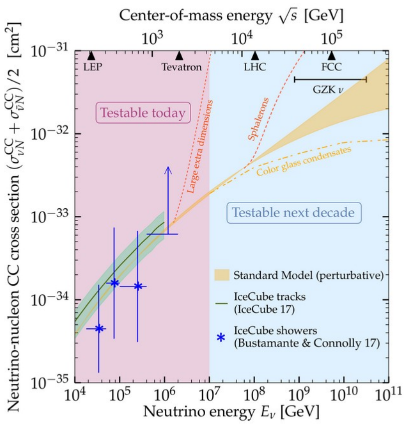

Neutrino physicist

TeV–EeV ν cross sections



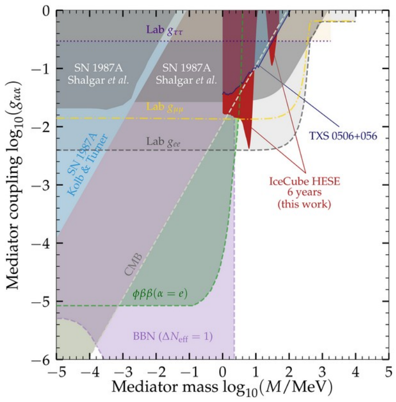
MB & Connolly, *PRL* 2019

TeV–EeV ν cross sections



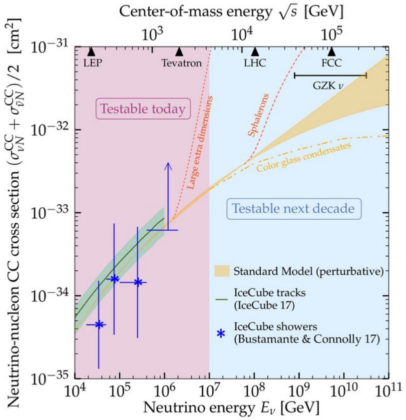
MB & Connolly, *PRL* 2019

ν self-interactions



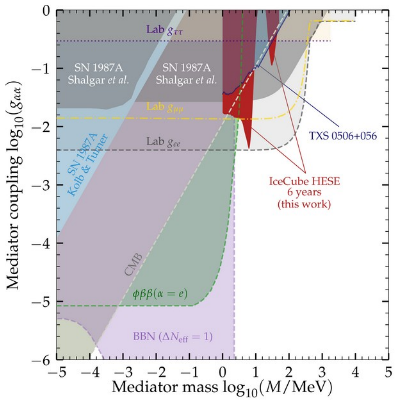
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

TeV–EeV ν cross sections



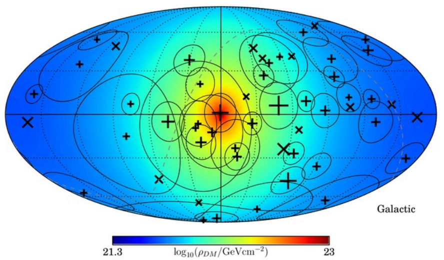
MB & Connolly, *PRL* 2019

ν self-interactions



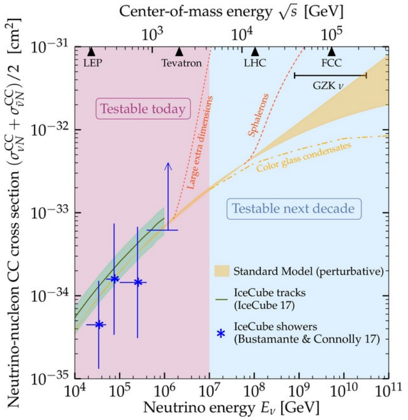
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



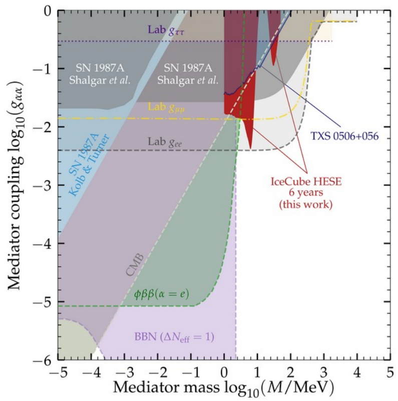
Argüelles, Kheirandish, Vincent, *PRL* 2017

TeV–EeV ν cross sections



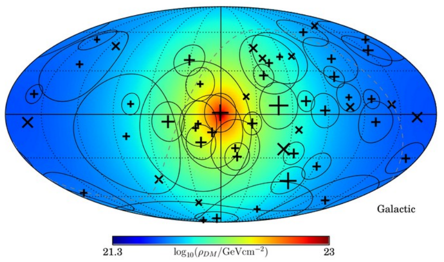
MB & Connolly, *PRL* 2019

ν self-interactions



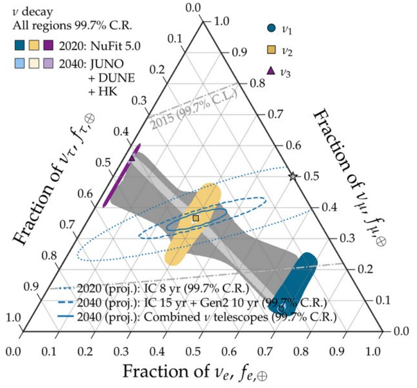
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



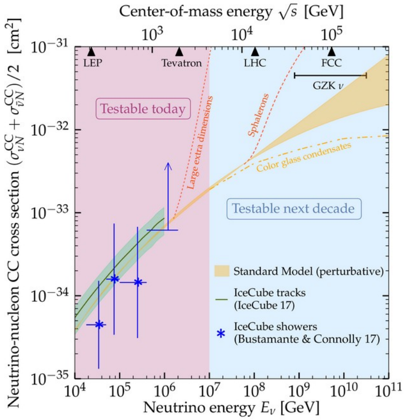
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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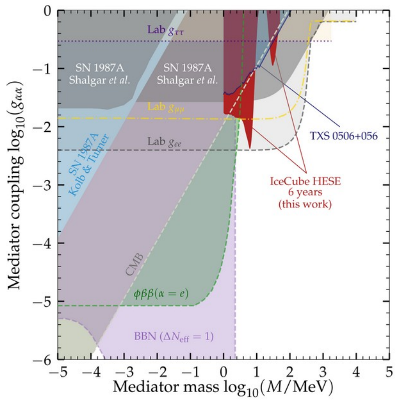

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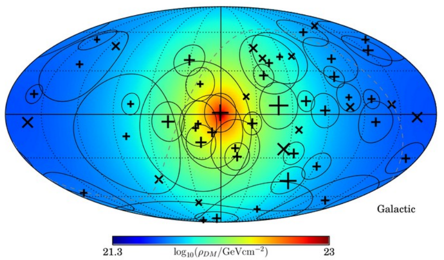

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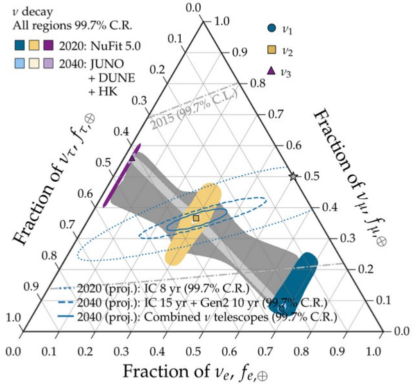

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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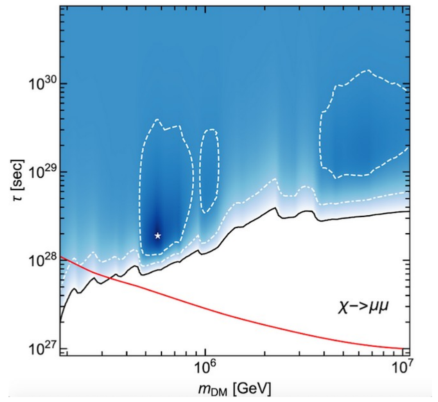

Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

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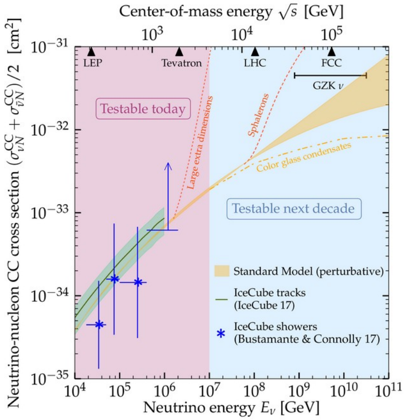

MB & Connolly, *PRL* 2019

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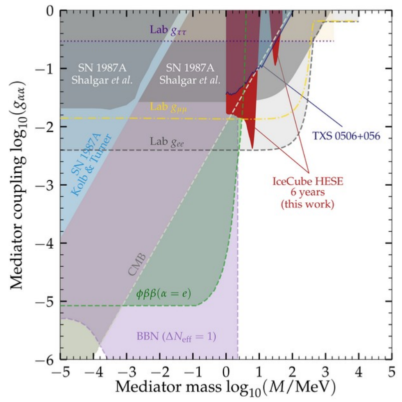

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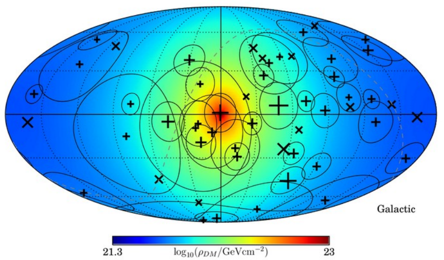

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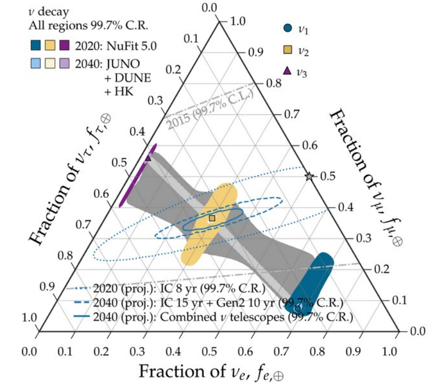

Song, Li, Argüelles, MB, Vincent, *JCAP* 2021

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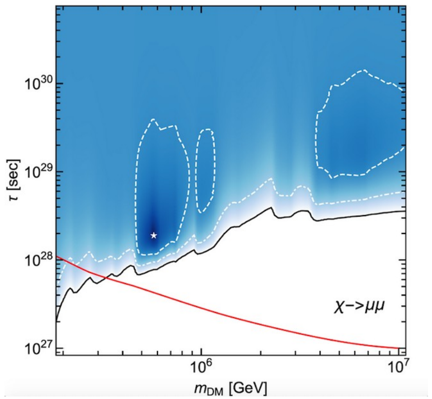

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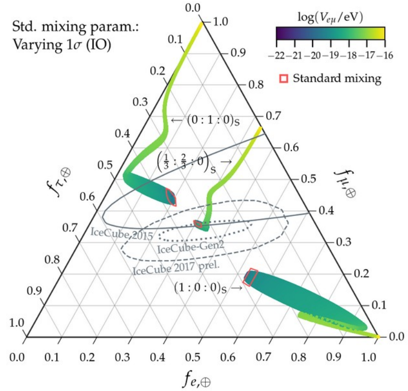

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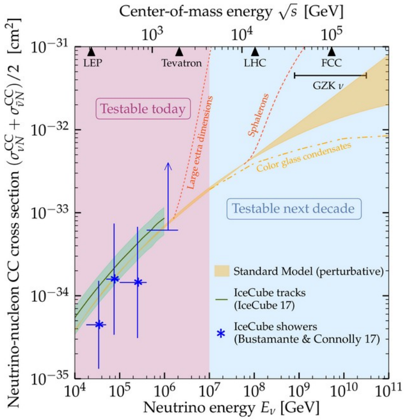

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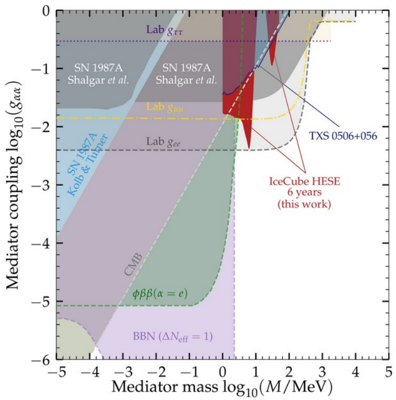

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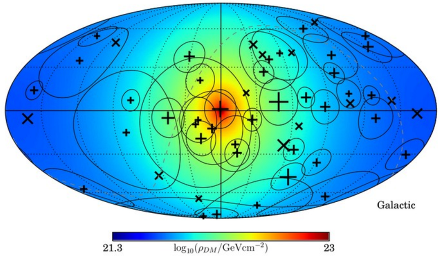

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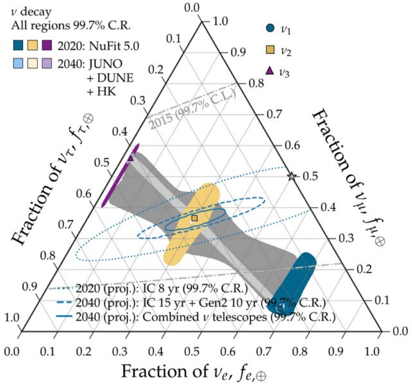
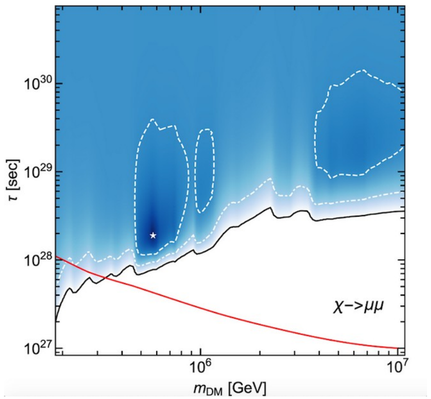


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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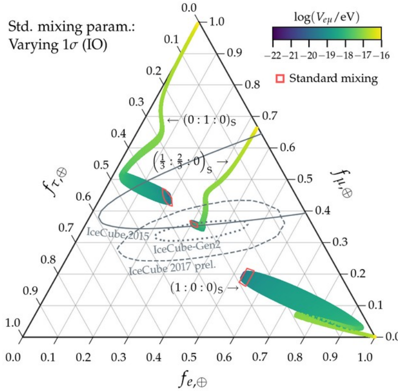
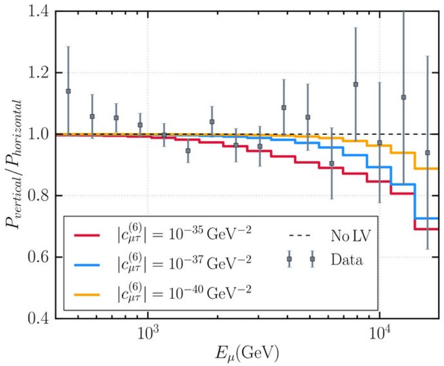


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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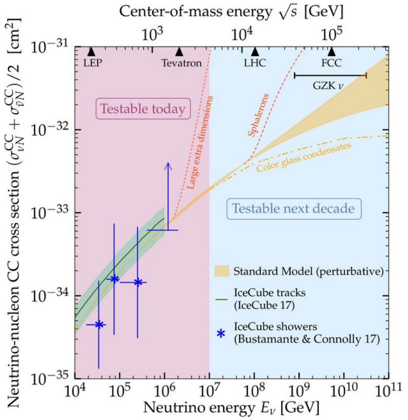

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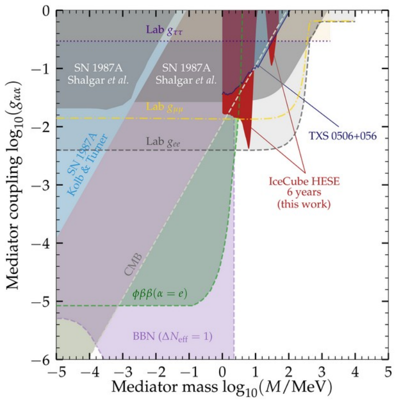

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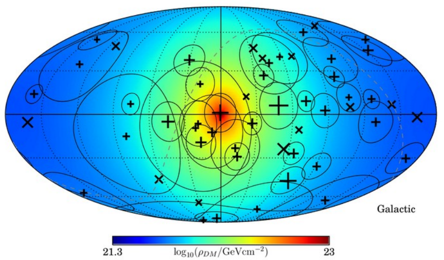

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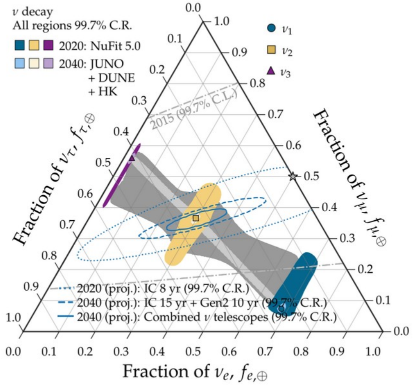
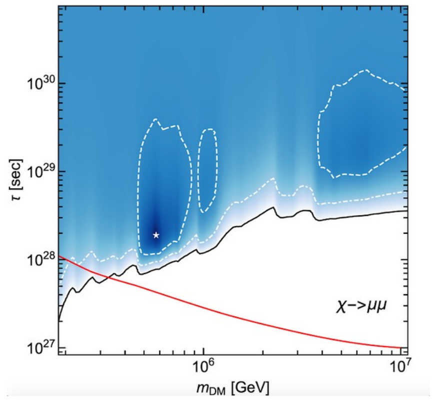


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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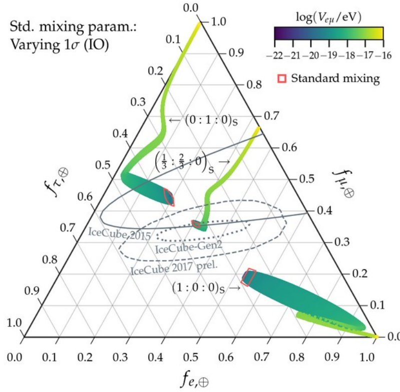

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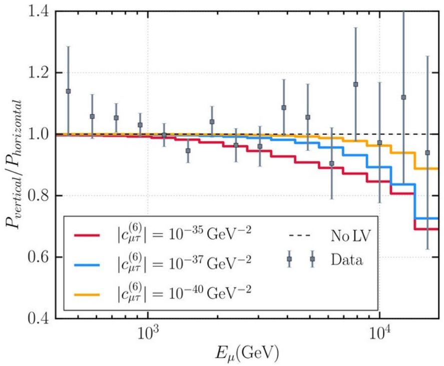
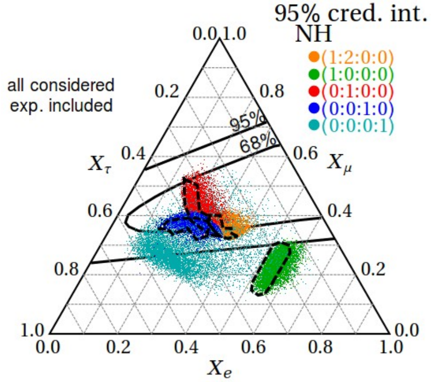
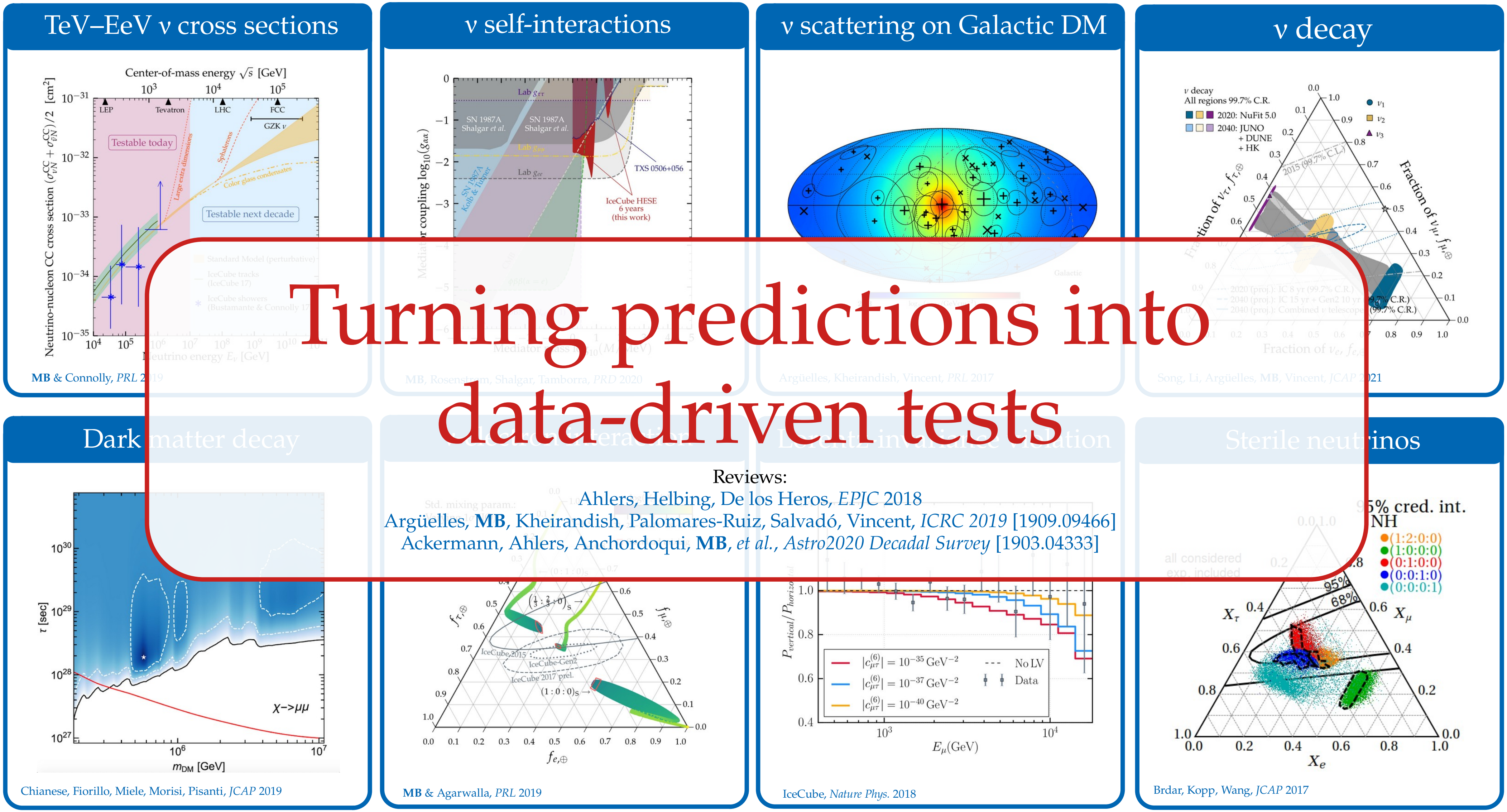


IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017



TeV–EeV ν cross sections
ν self-interactions
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Turning predictions into data-driven tests
Reviews:
Ahlers, Helbing, De los Heros, EPJC 2018
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, ICRC 2019 [1909.09466]
Ackermann, Ahlers, Anchordoqui, MB, et al., Astro2020 Decadal Survey [1903.04333]

Note: Not an exhaustive list

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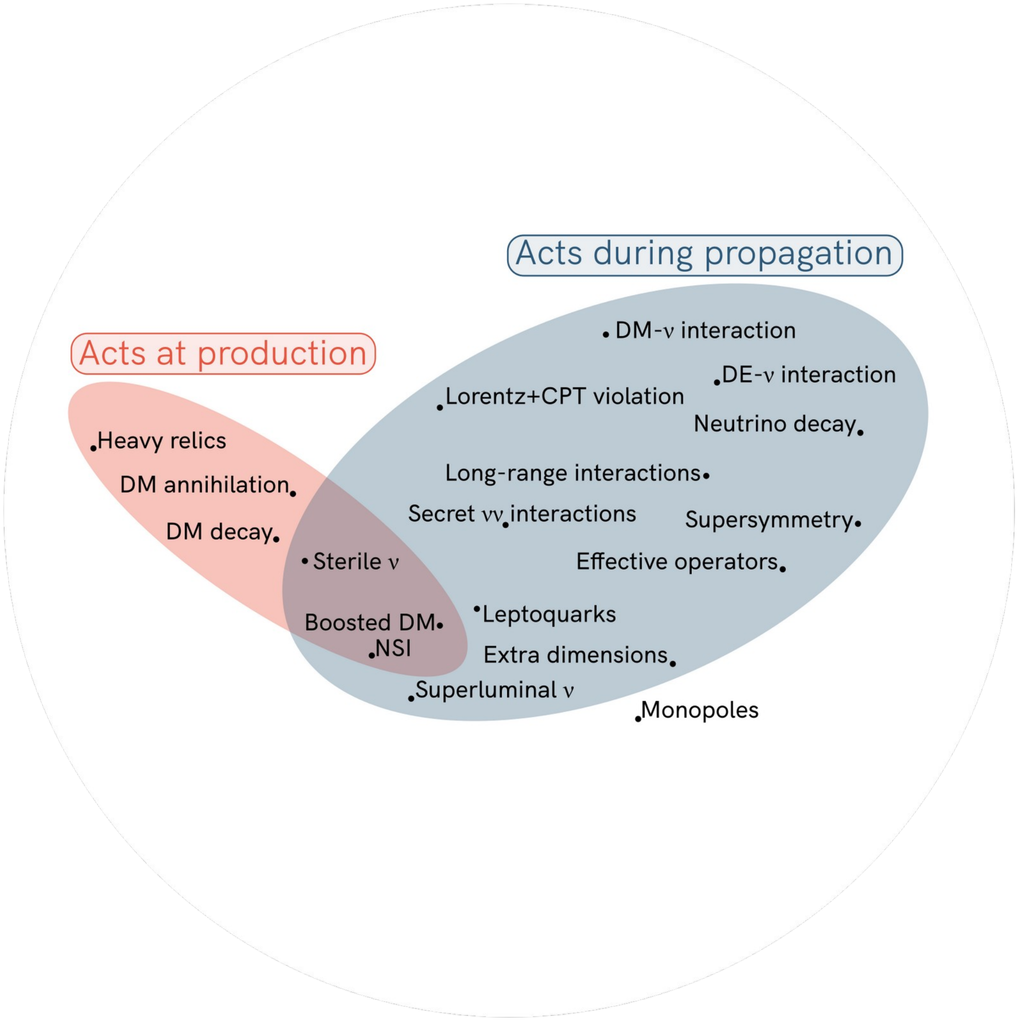

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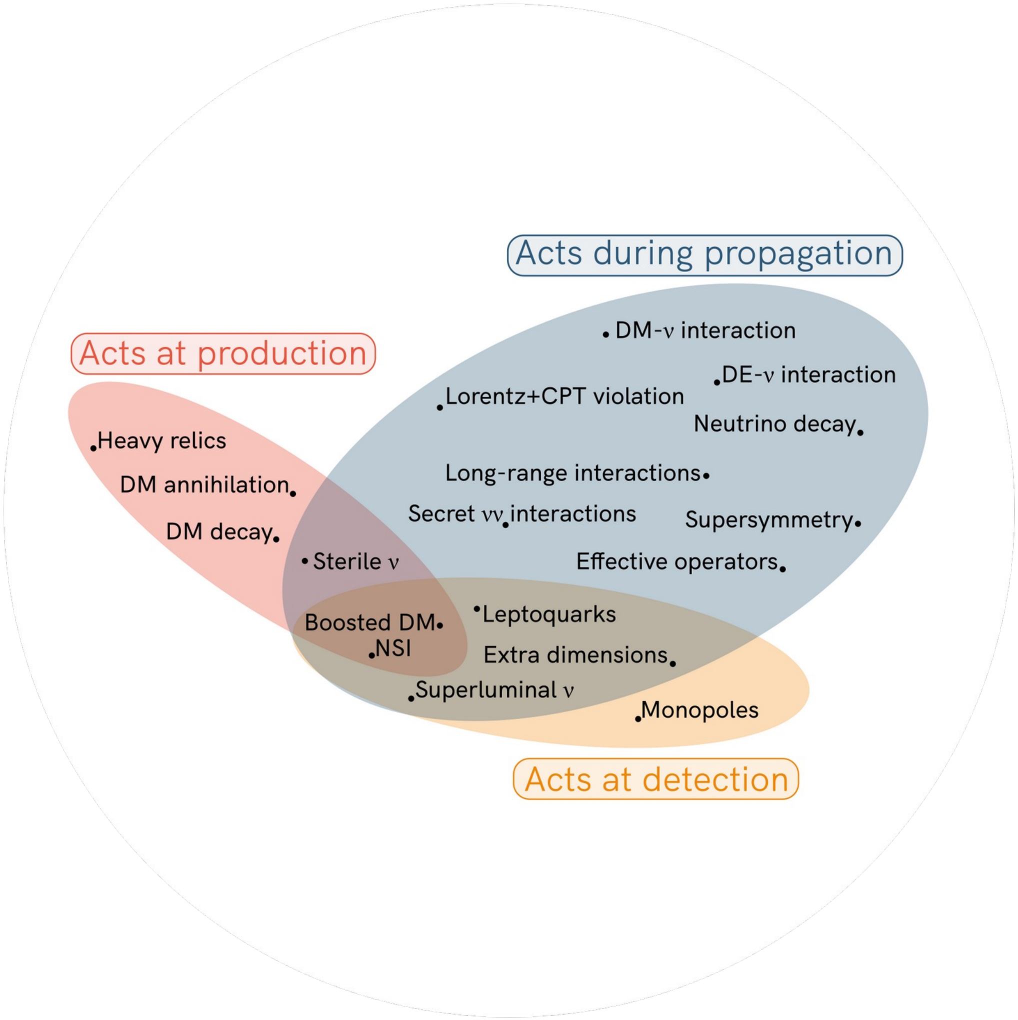

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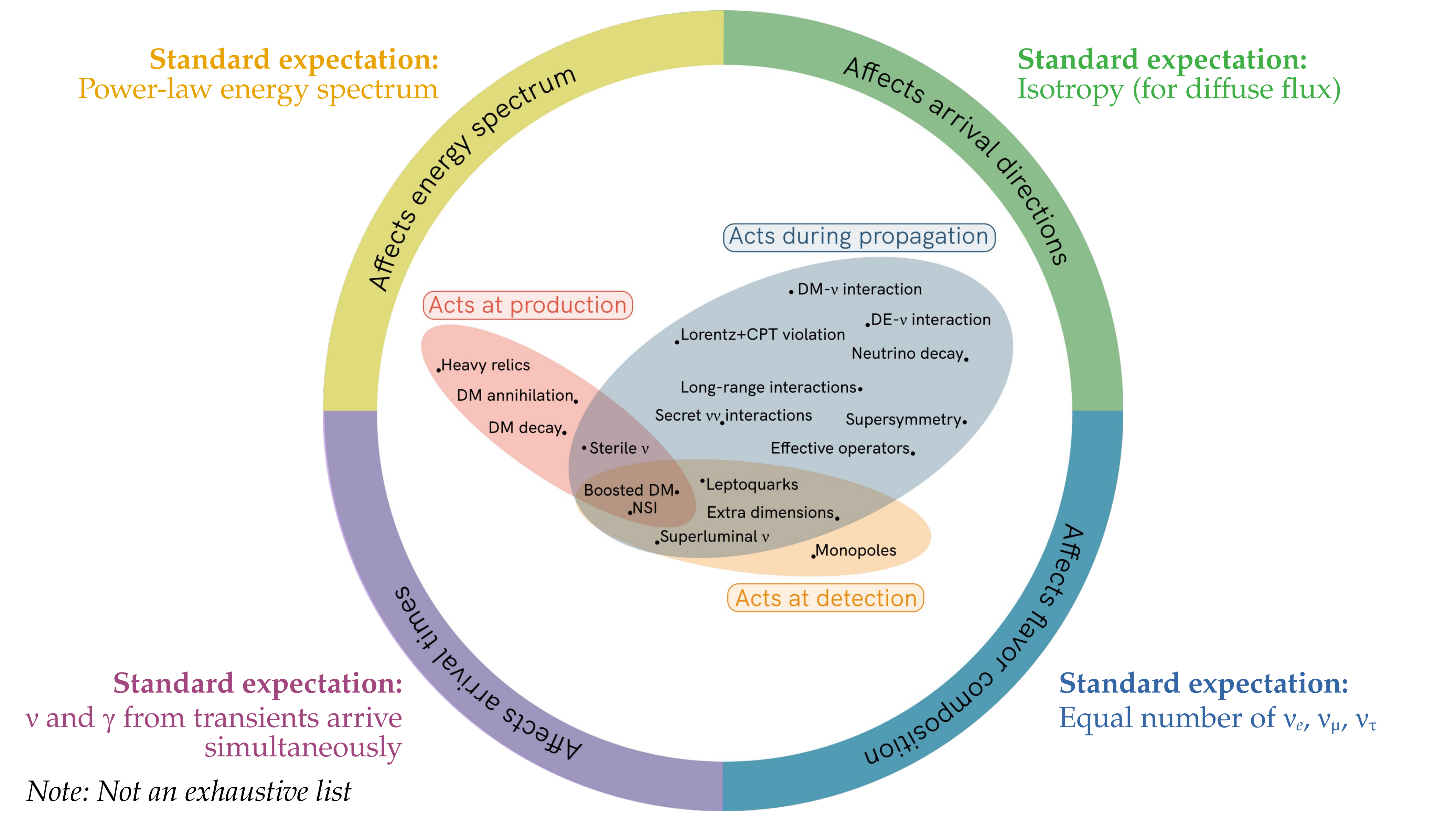
Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Acts during propagation
Acts at production
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay
Long-range interactions
Secret νν interactions
Supersymmetry
Sterile ν
Effective operators
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NSI
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Extra dimensions
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Standard expectation:
ν and γ from transients arrive simultaneously
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Equal number of ν_e, ν_μ, ν_τ
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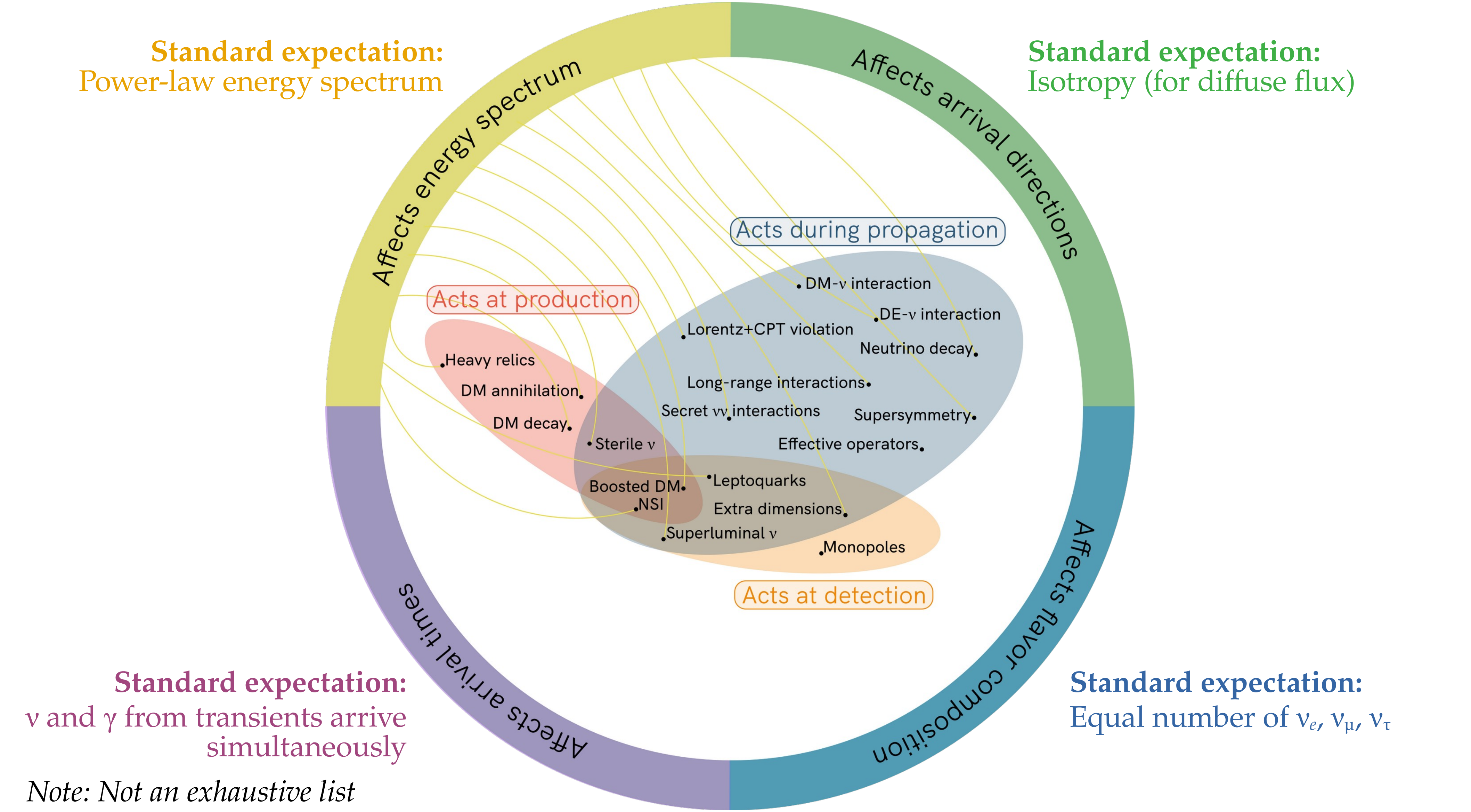

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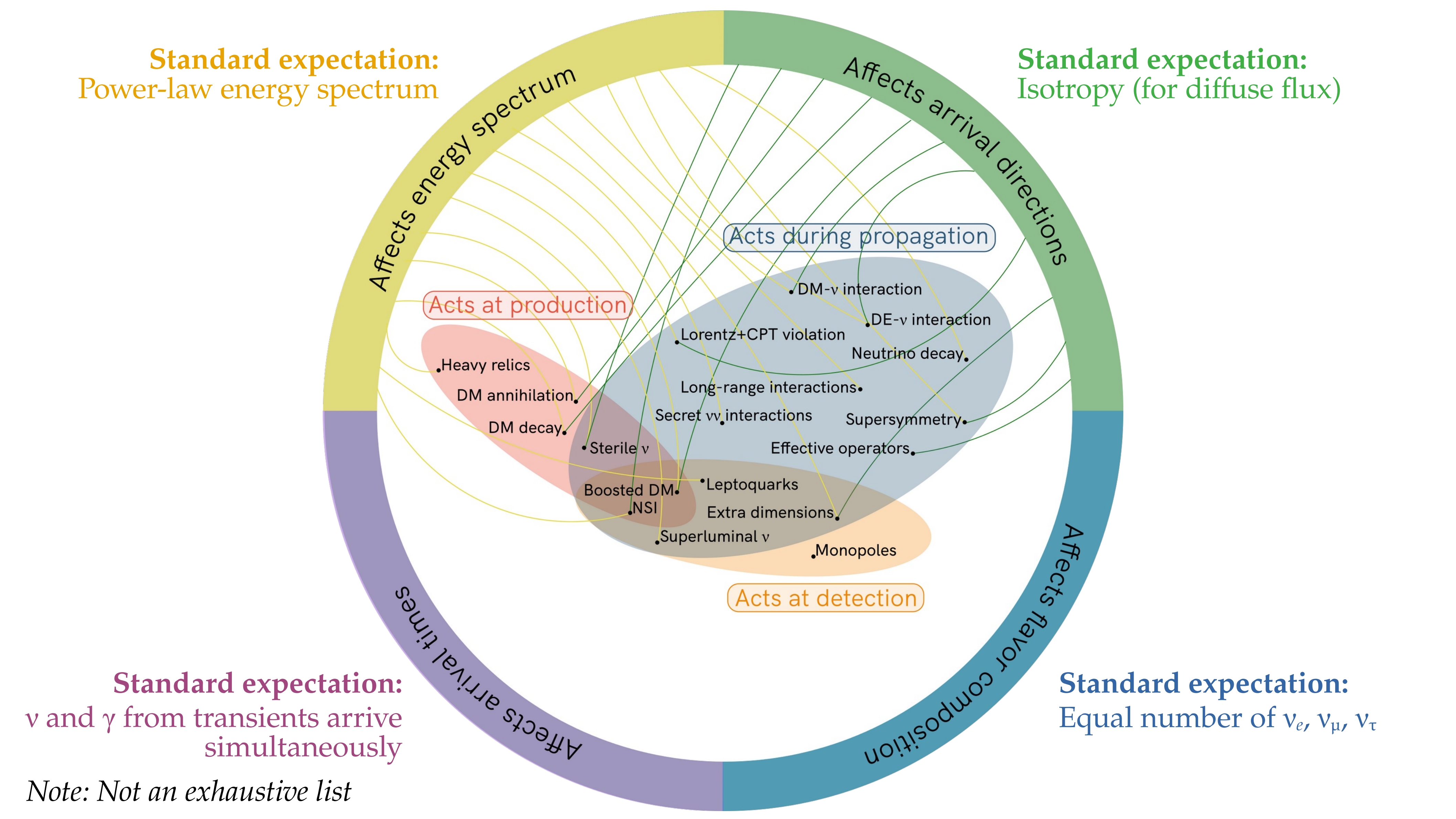
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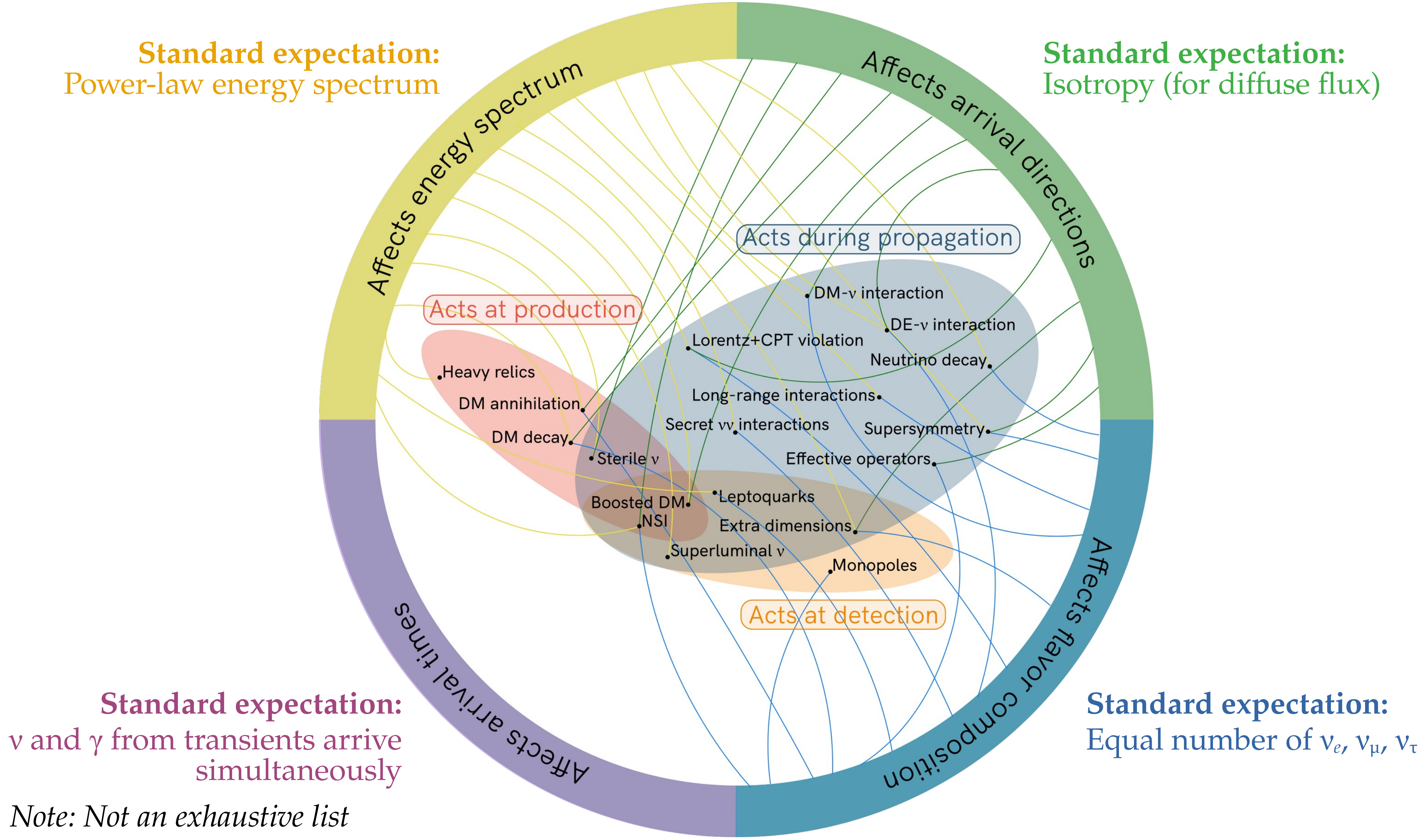

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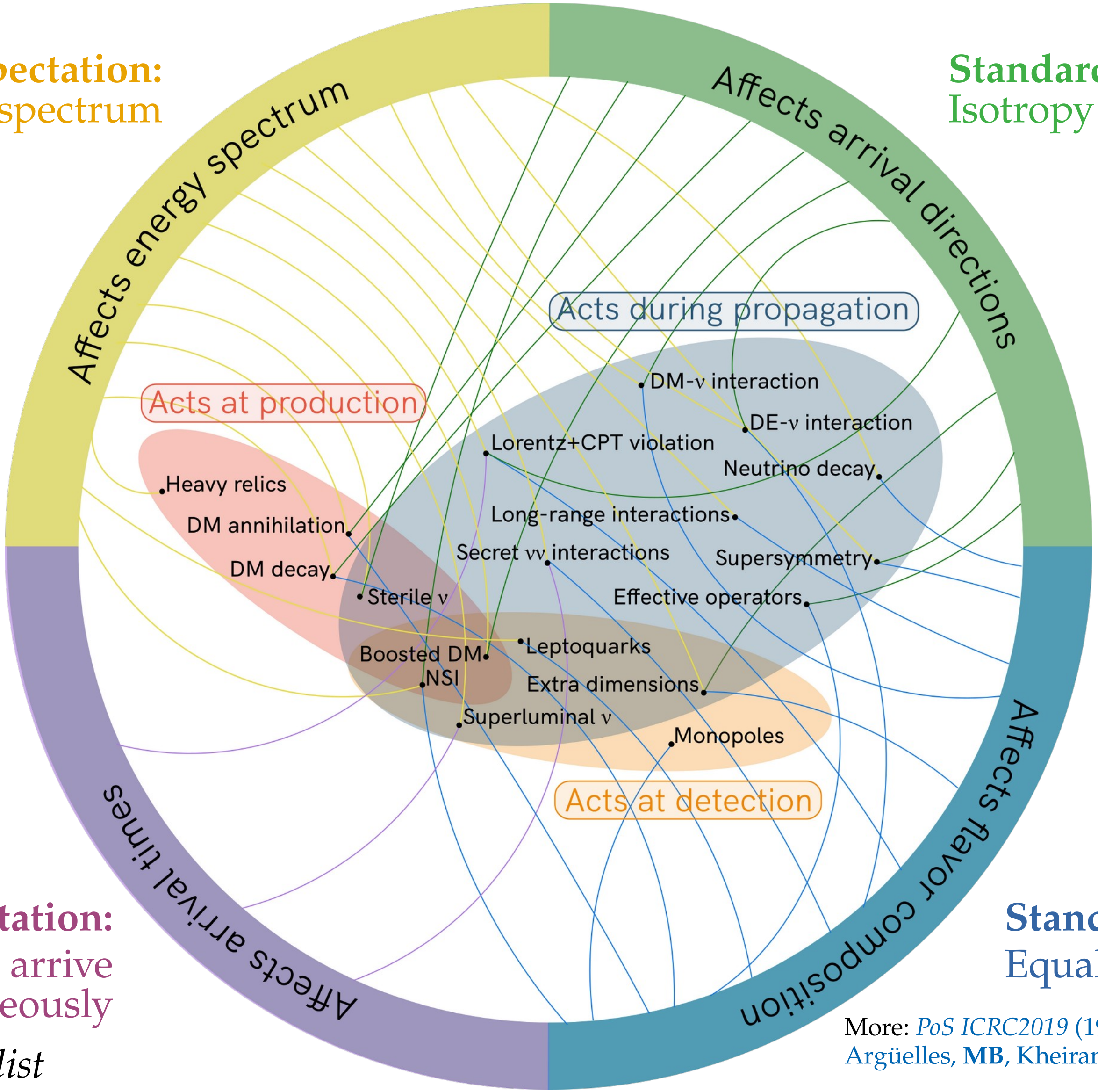

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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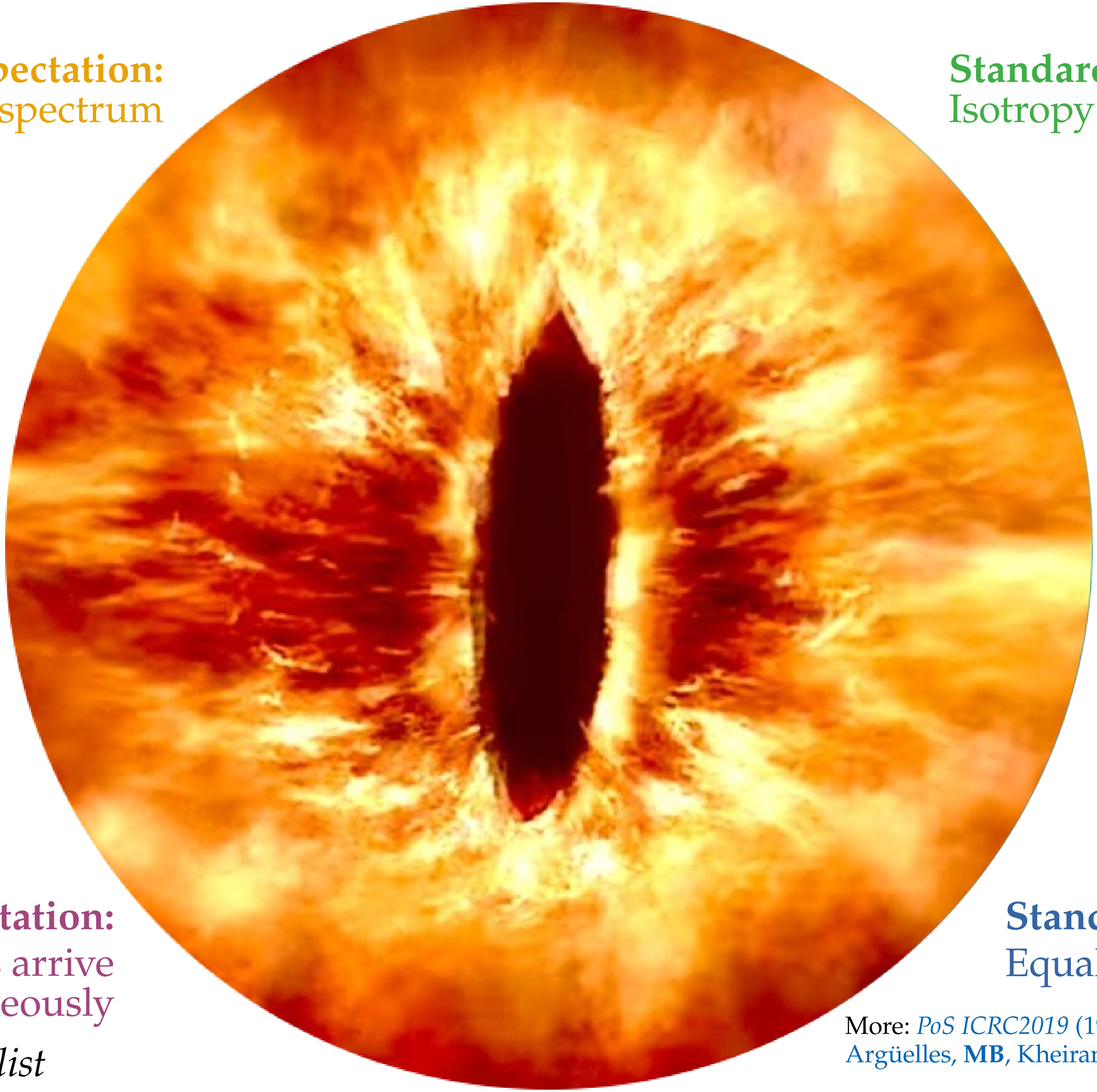

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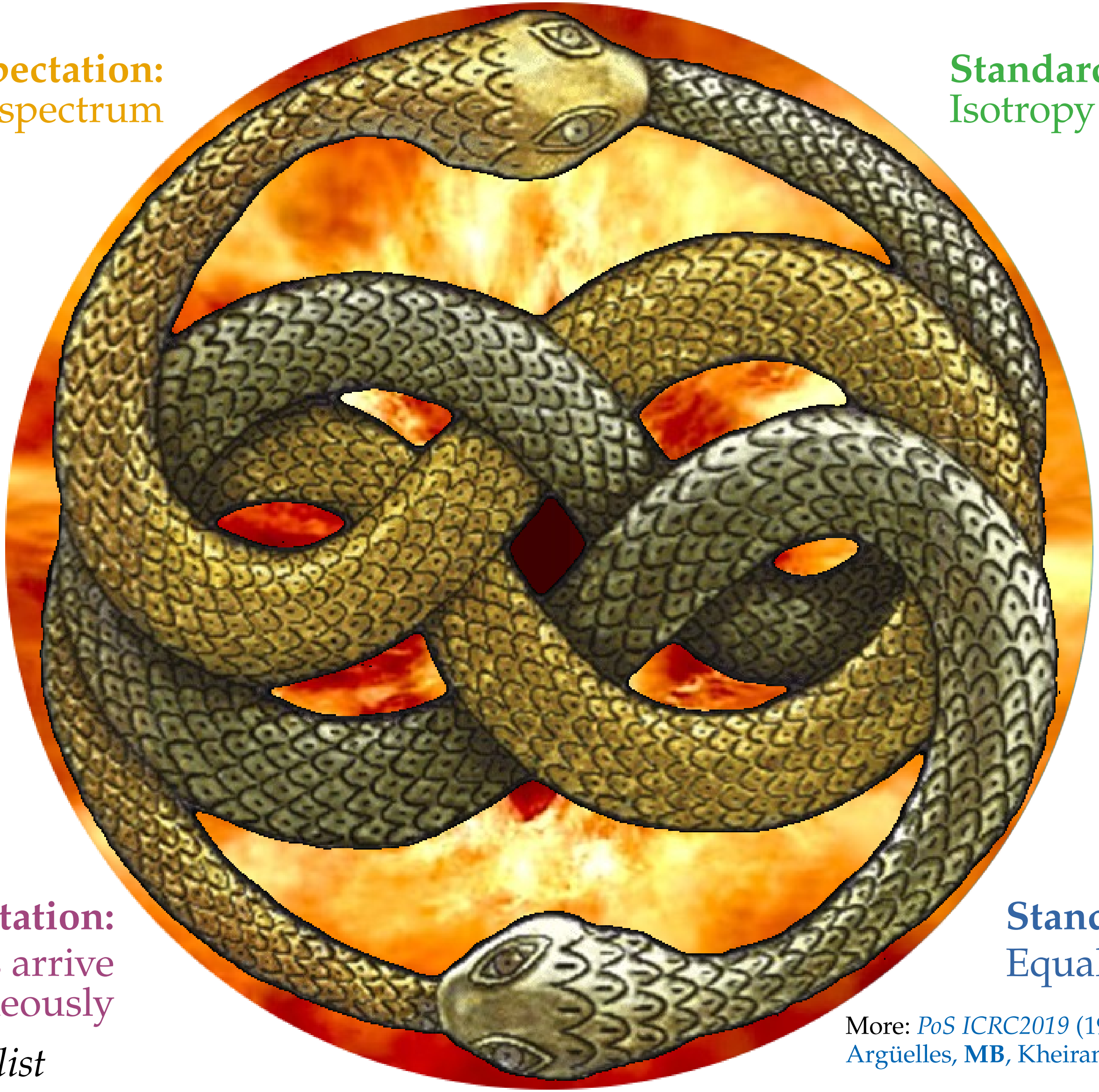

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Fundamental physics with HE cosmic neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\mathrm{PeV})^{-n} (L/\mathrm{Gpc})^{-1}\ \mathrm{PeV}^{1-n}$
- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$
- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
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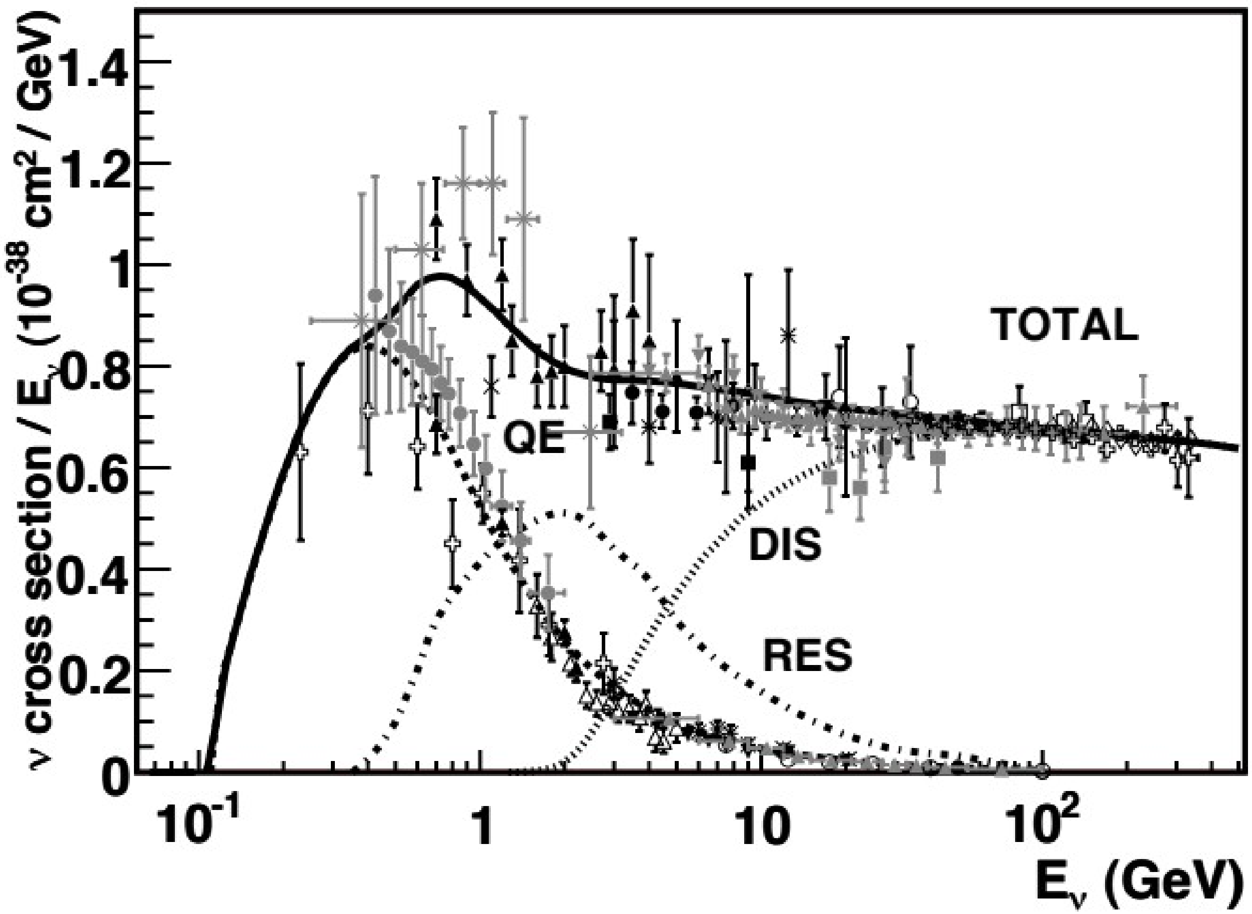
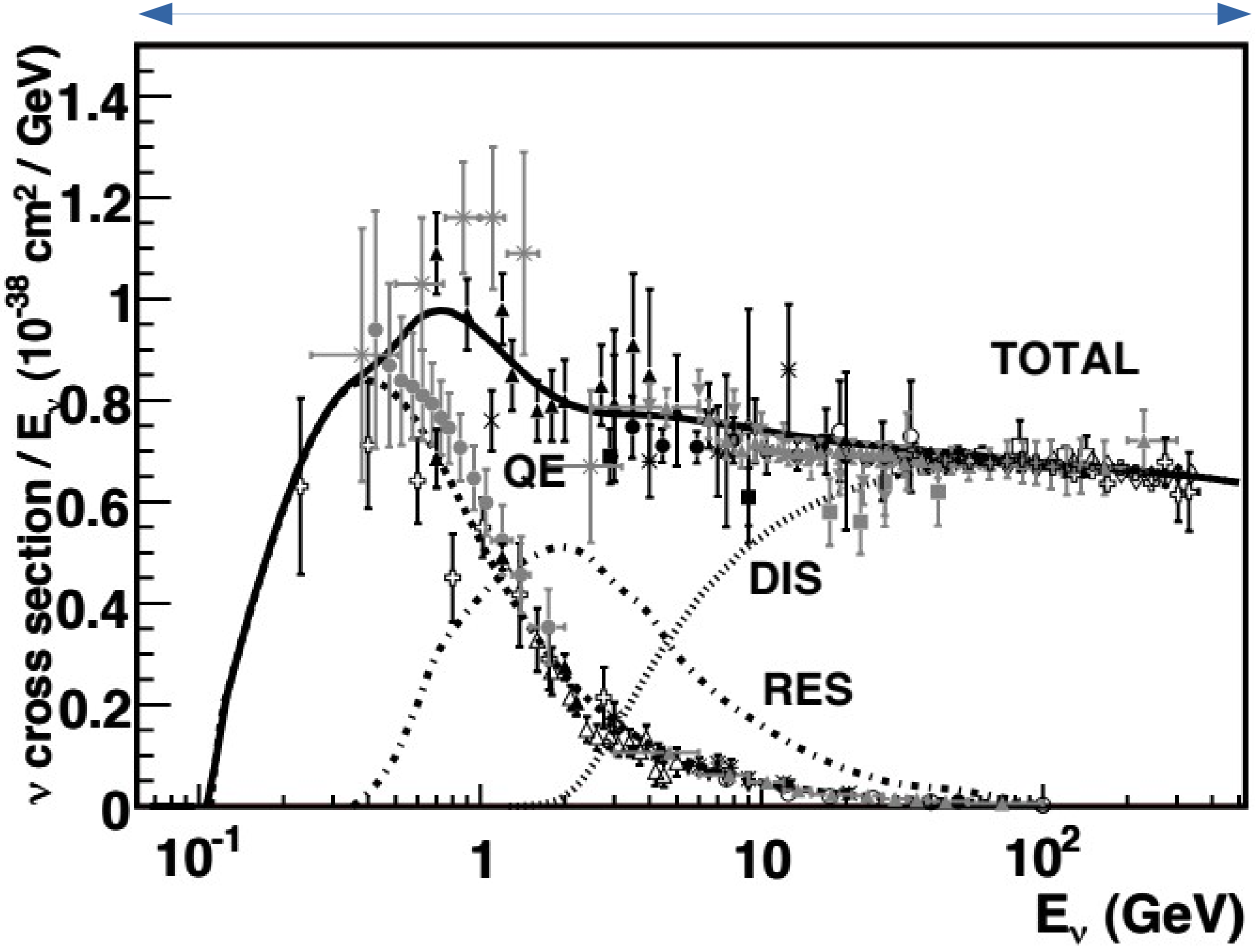
  In spite of
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns

Example 1:
Measuring TeV–PeV ν cross sections



Particle Data Group

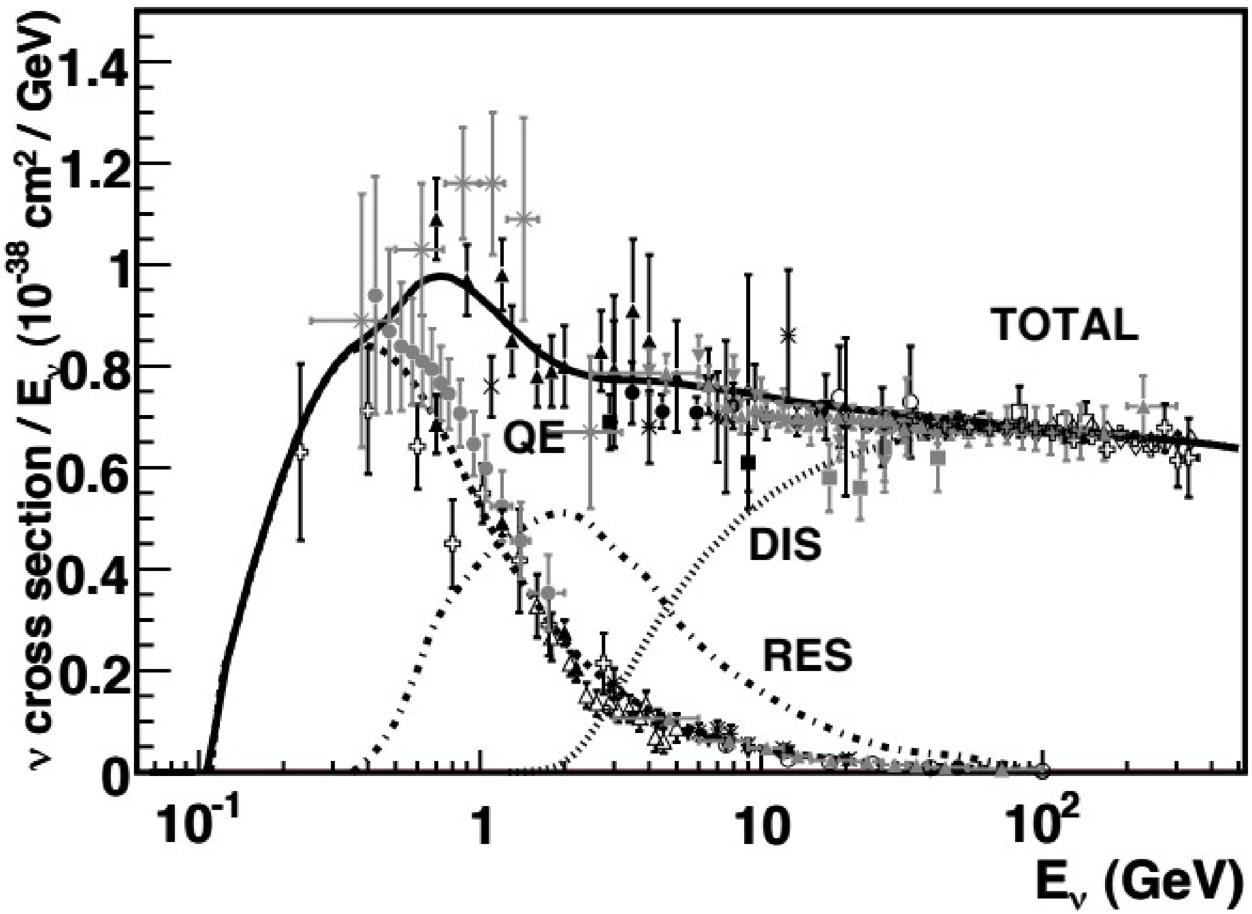
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group

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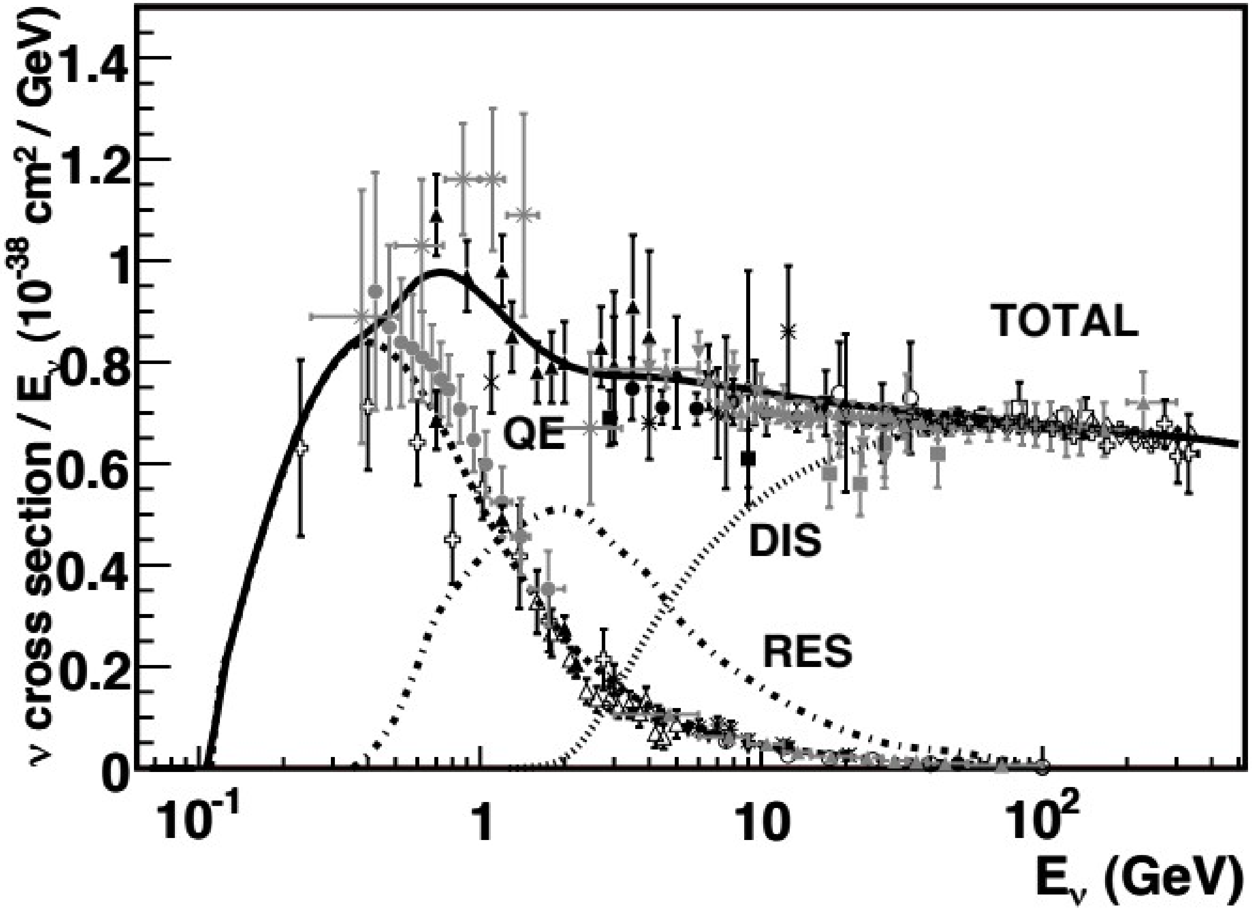


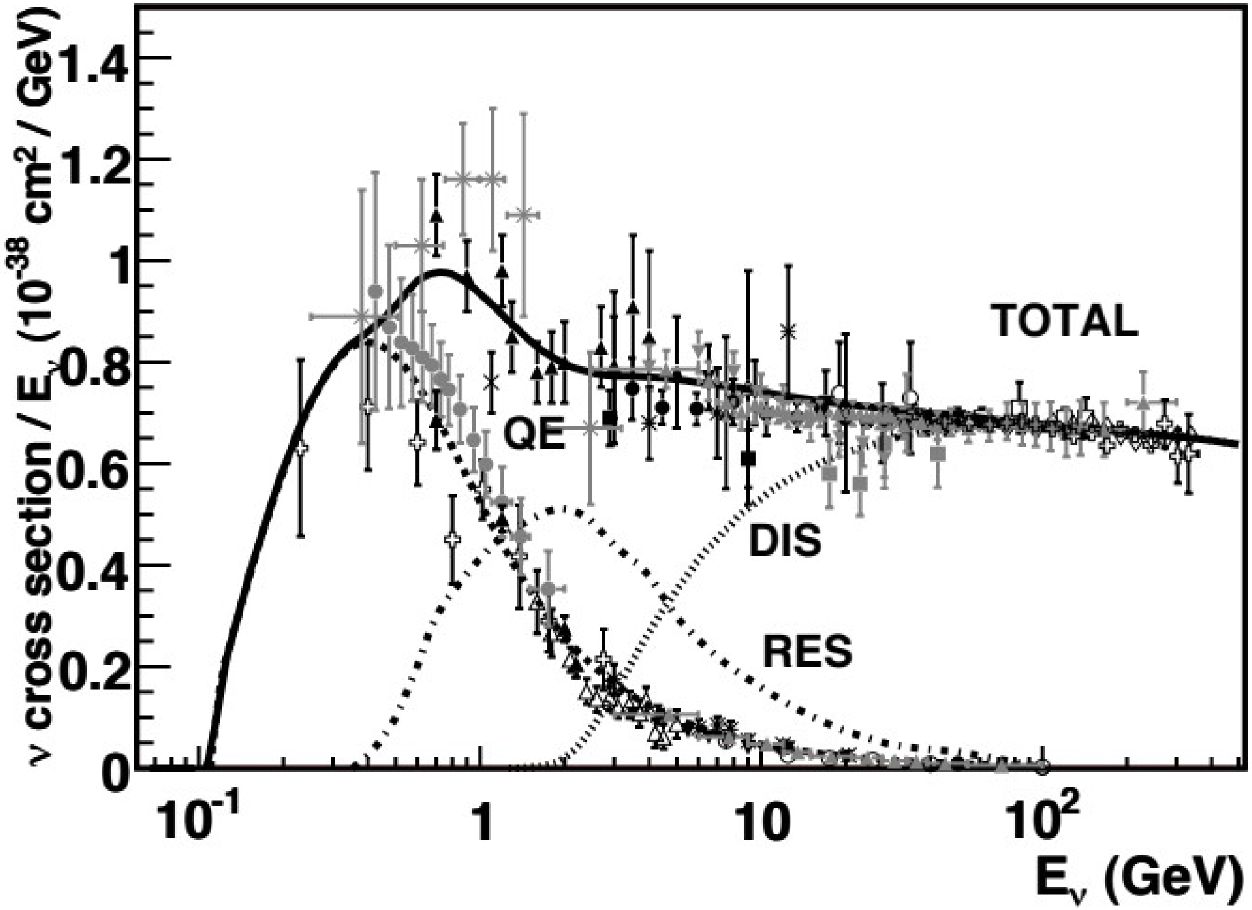
One recent measurement (COHERENT)

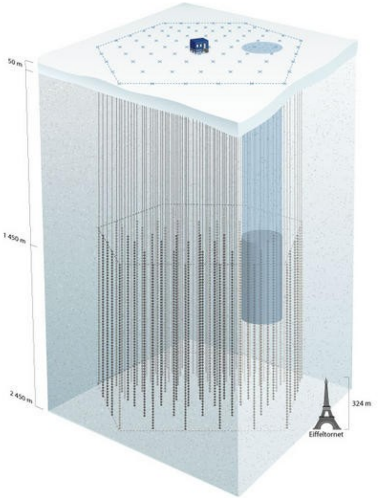
No measurements … until recently!

Particle Data Group

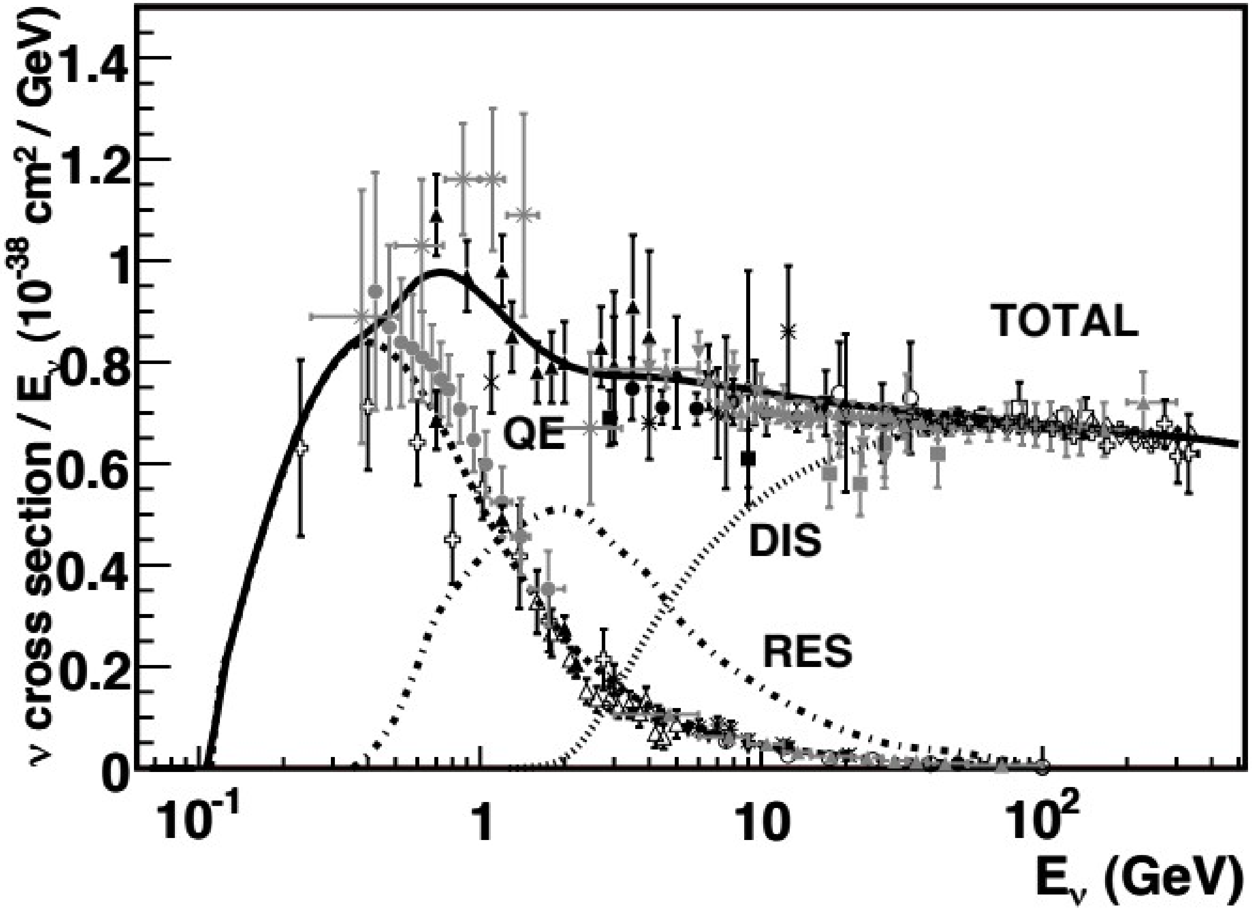
Accelerator experiments

One recent measurement (COHERENT)





Particle Data Group

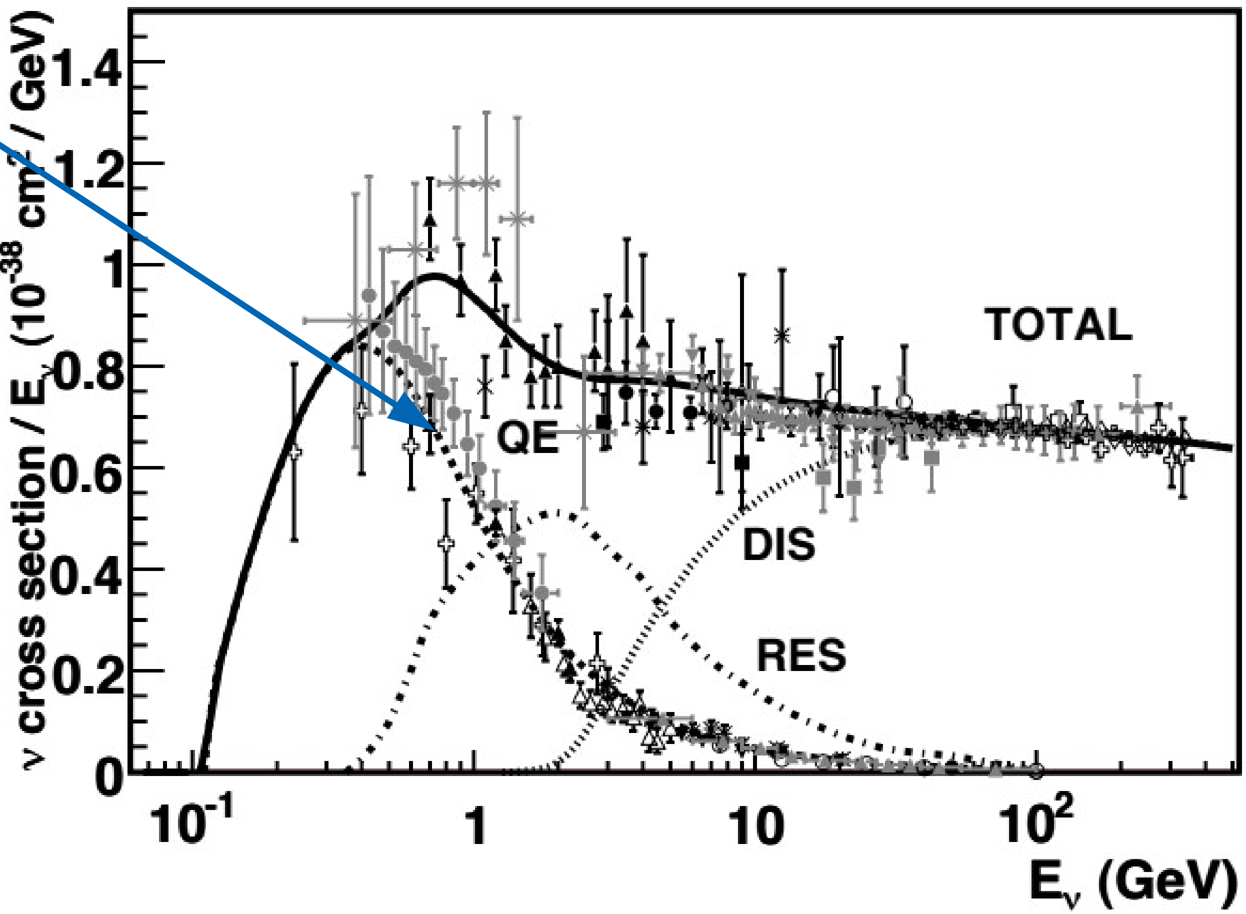


Particle Data Group

Quasi-elastic scattering:

$\nu_l + n \rightarrow l^- + p$

$\bar{\nu}_l + p \rightarrow l^+ + n$



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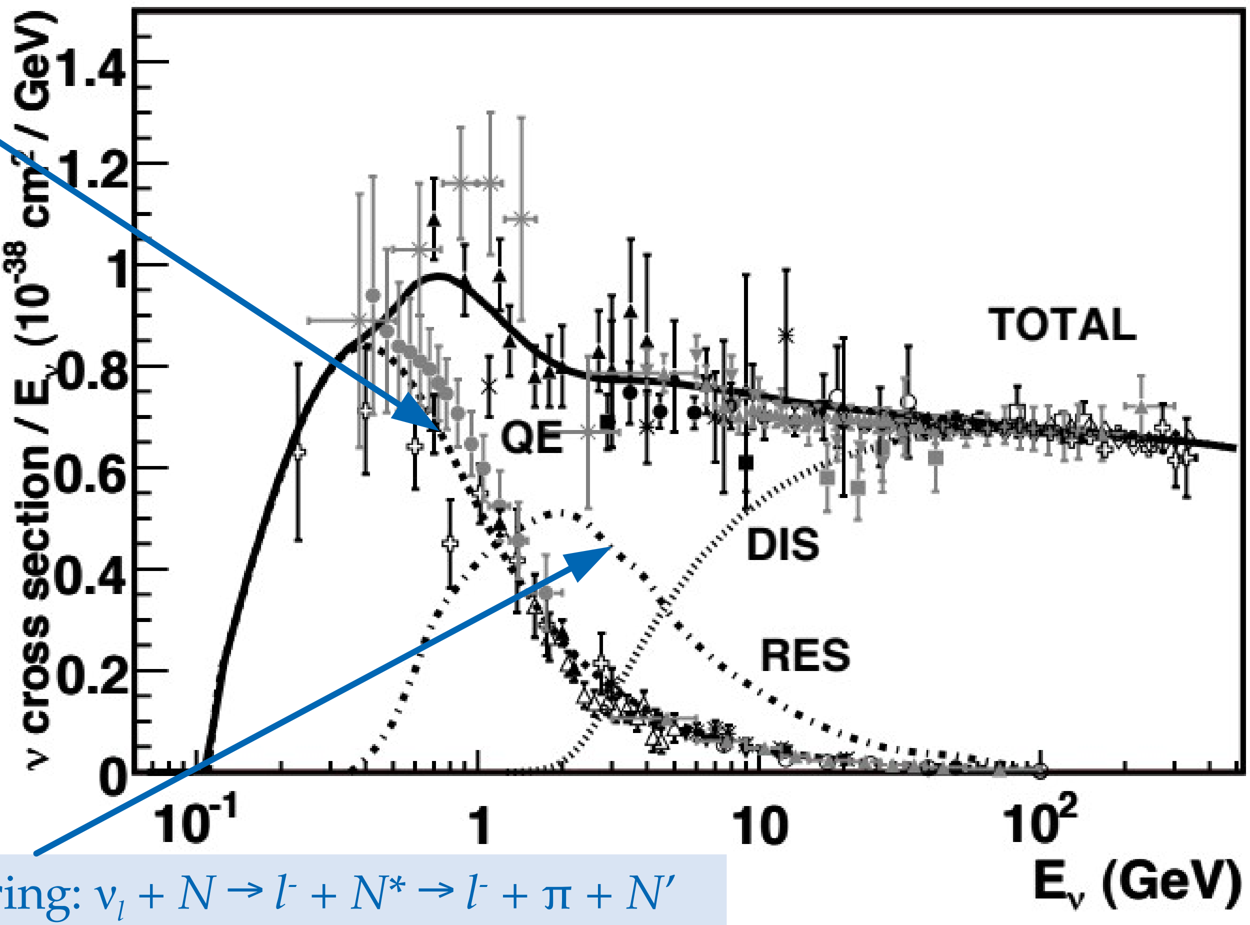

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

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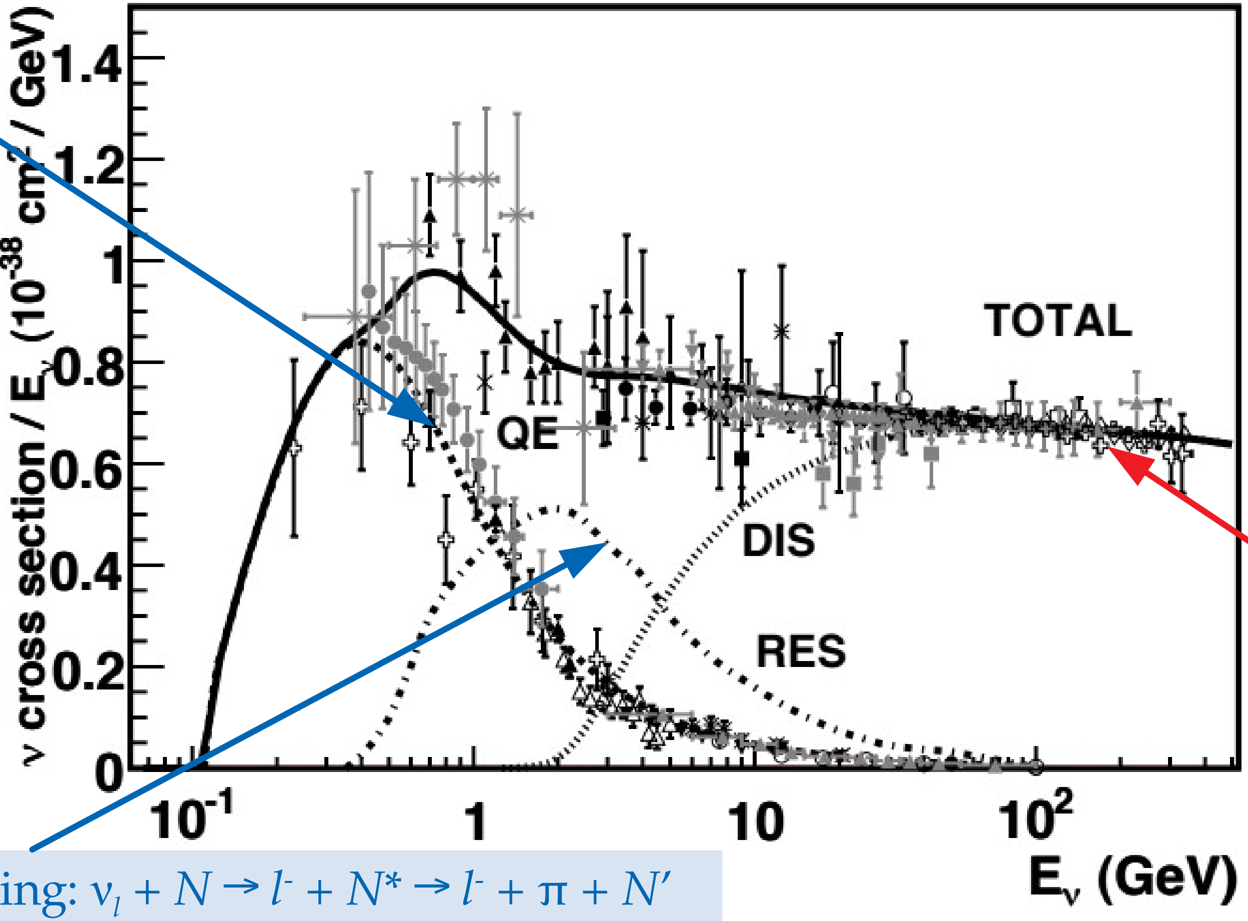


Deep inelastic scattering:

$\nu_l + N \rightarrow l^- + X$

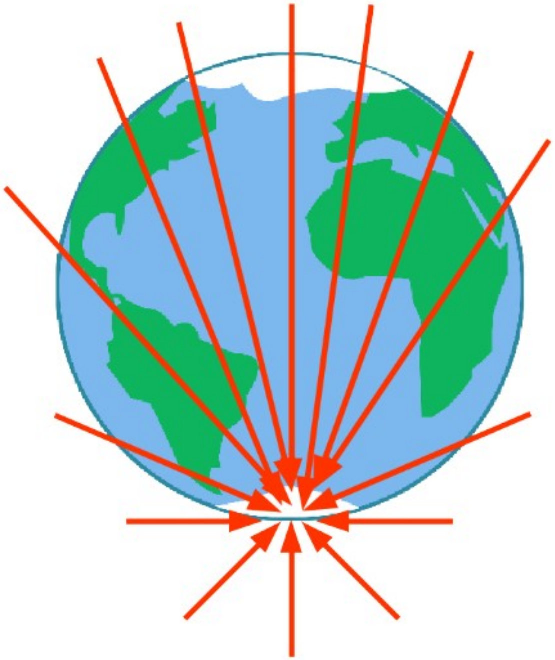
$\bar{\nu}_l + N \rightarrow l^+ + X$

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

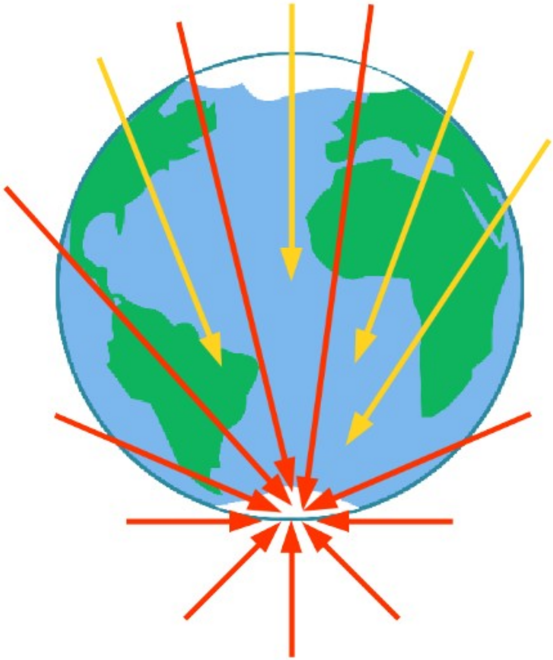
Particle Data Group

Measuring the high-energy cross section

Below ~ 10 TeV: Earth is transparent



Above ~ 10 TeV: Earth is opaque



Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy cross section

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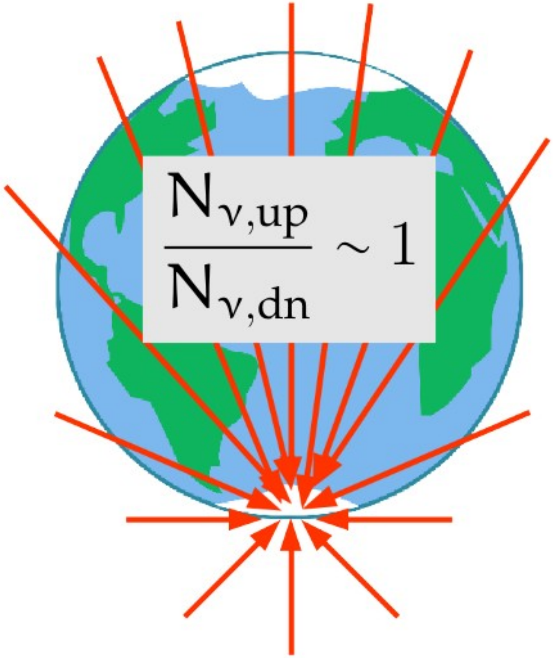
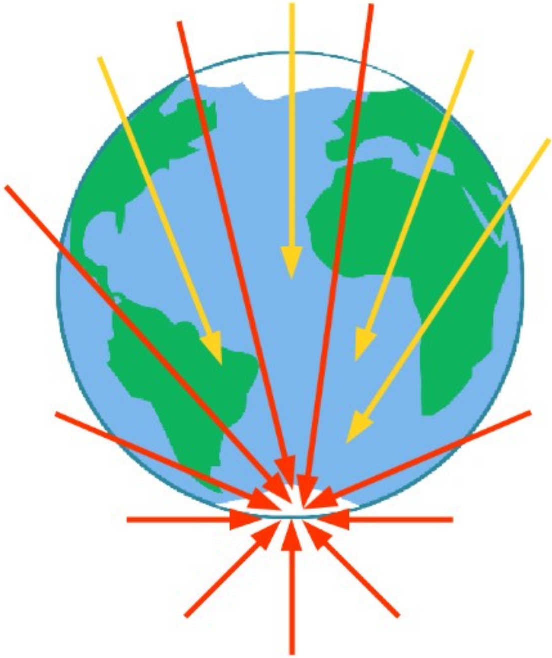


Above ~ 10 TeV: Earth is opaque



Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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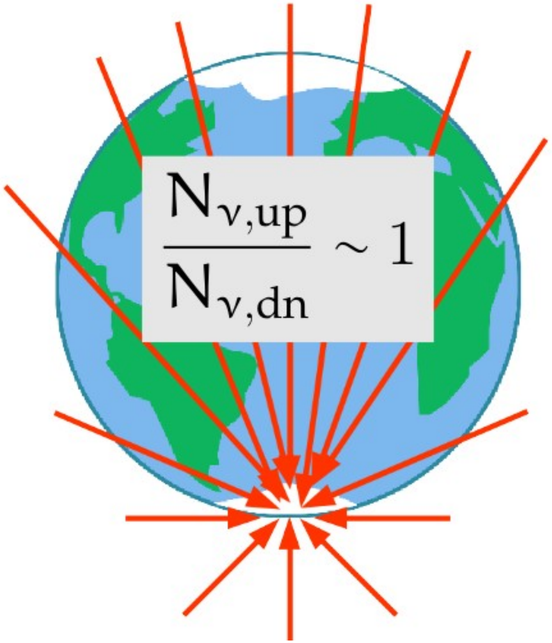
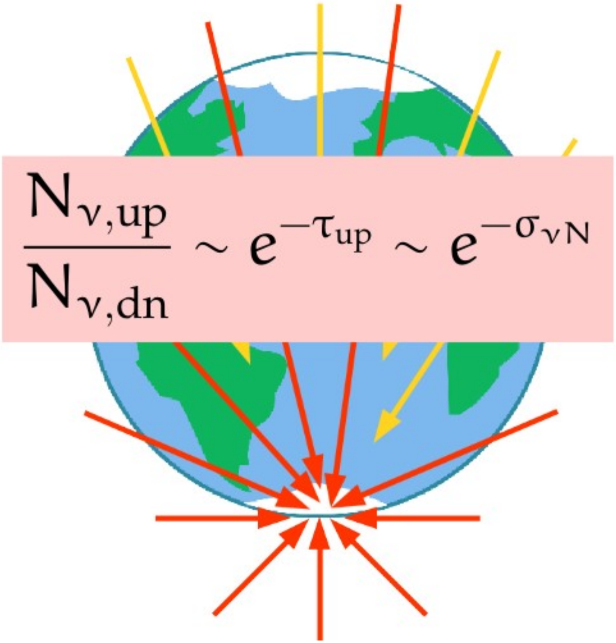


Above ~ 10 TeV: Earth is opaque

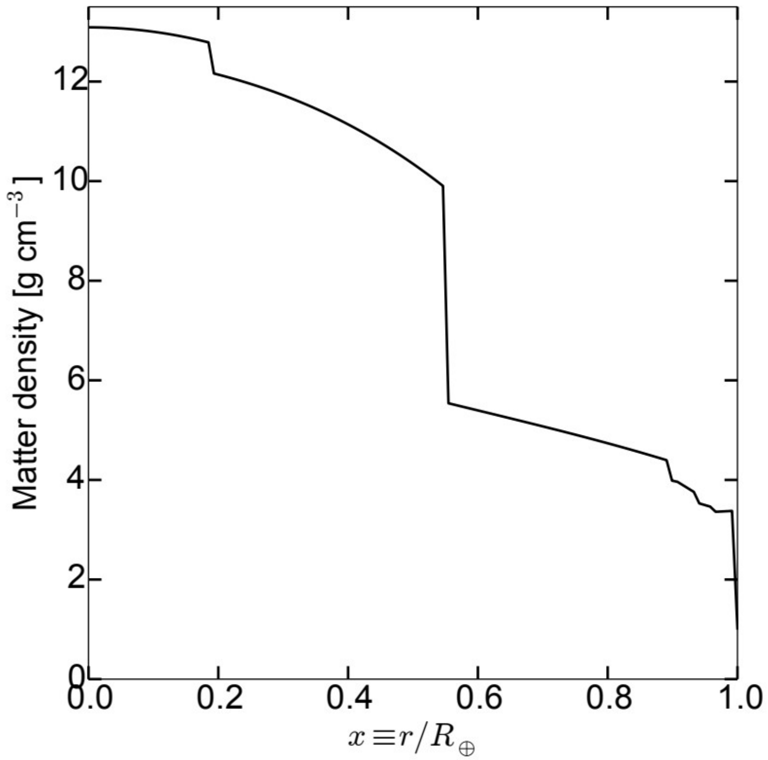


Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

A feel for the in-Earth attenuation

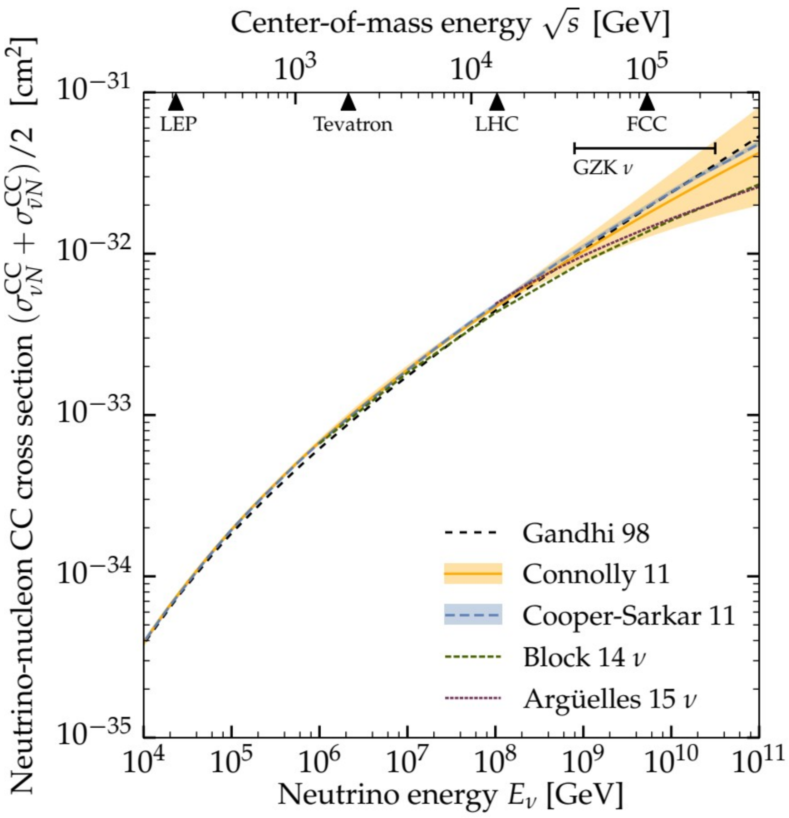
Earth matter density

(Preliminary Reference Earth Model)



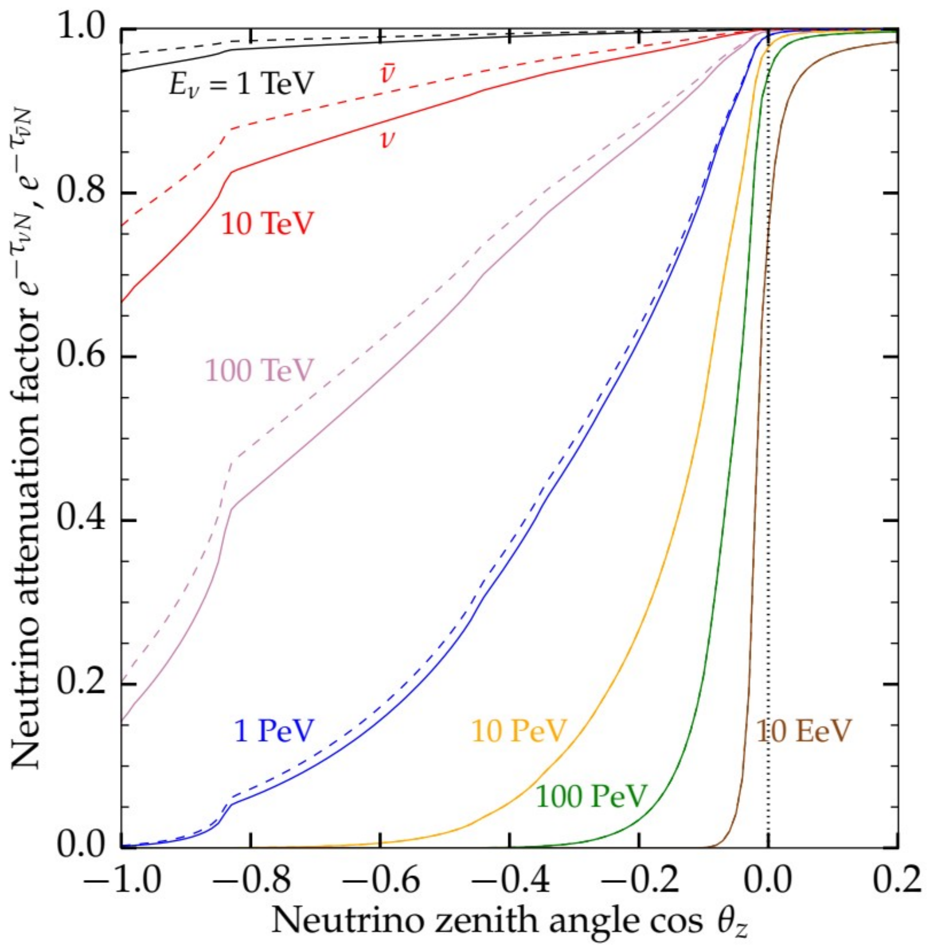
+

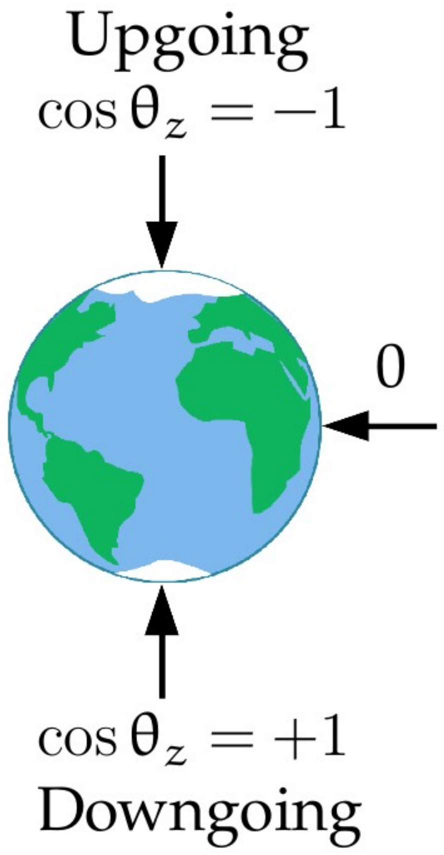
Neutrino-nucleon cross section

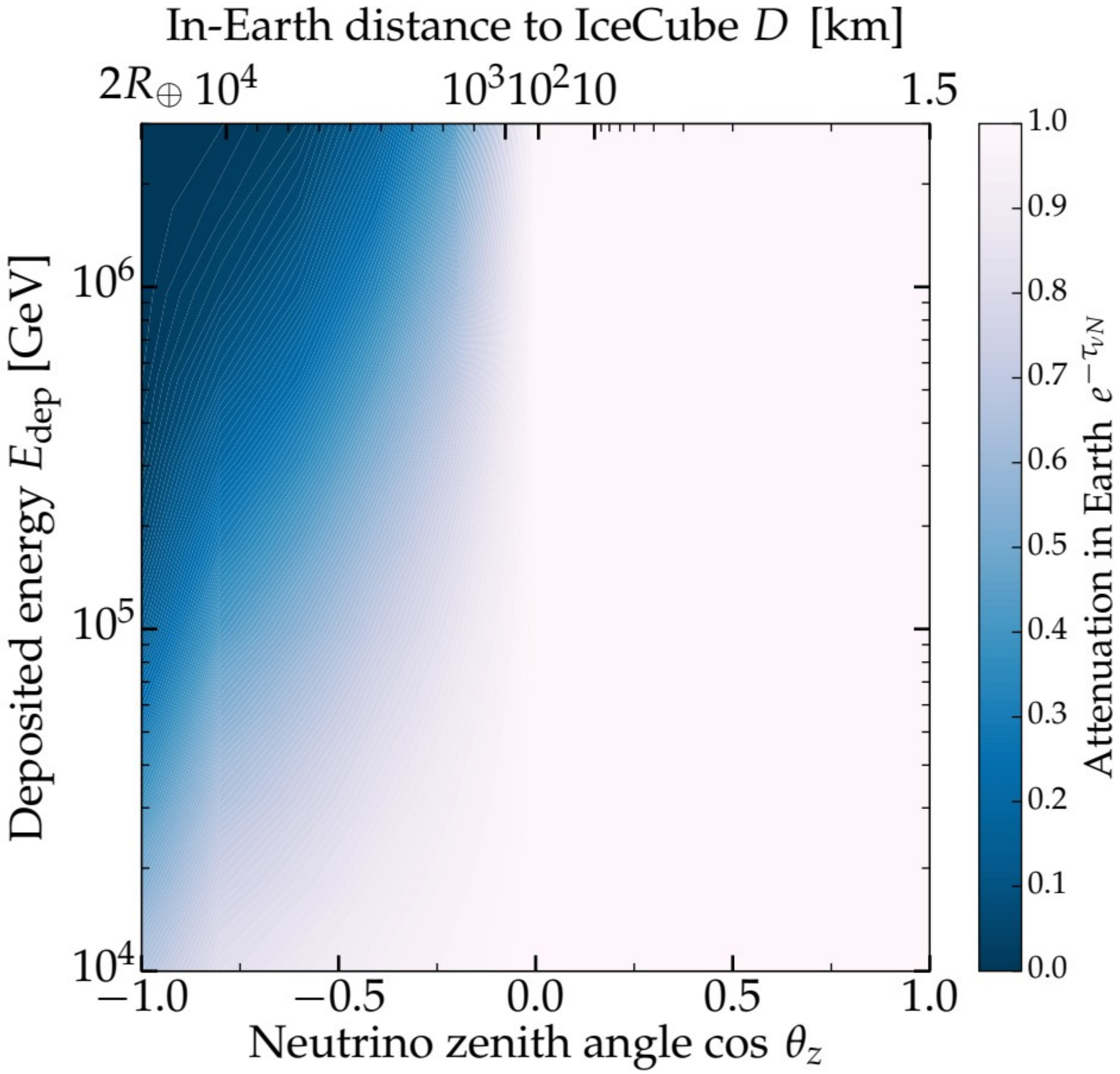


A feel for the in-Earth attenuation

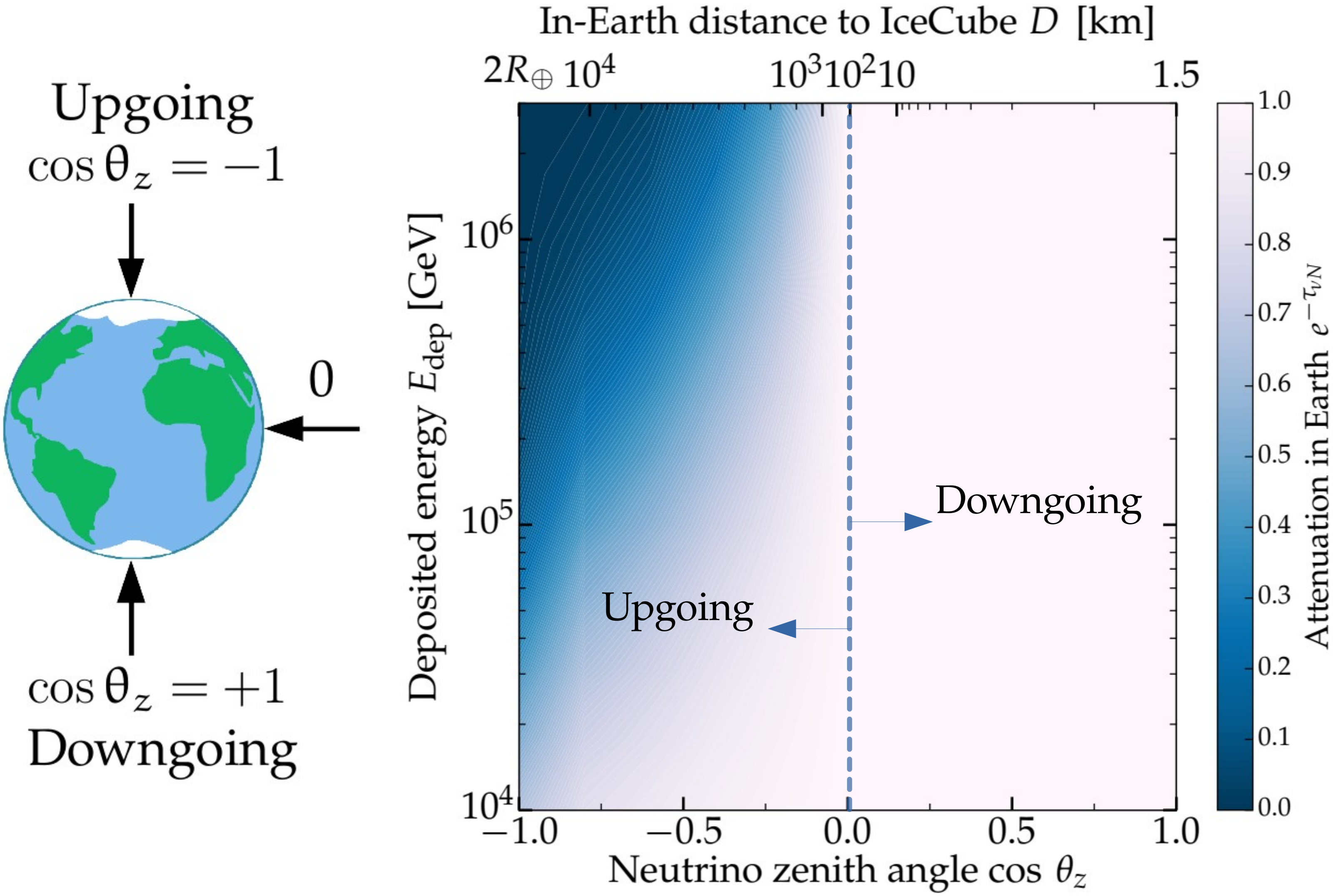
=



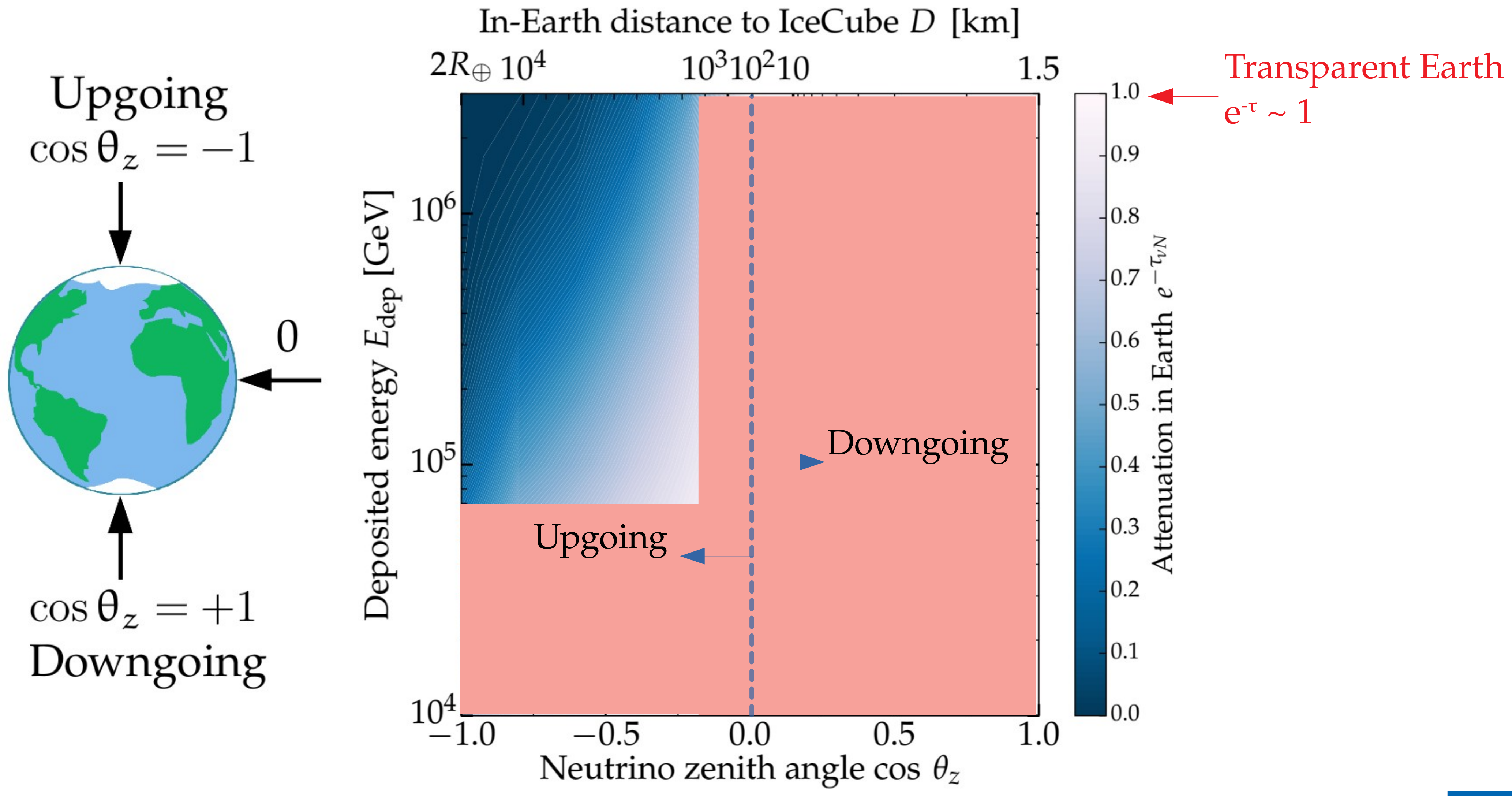




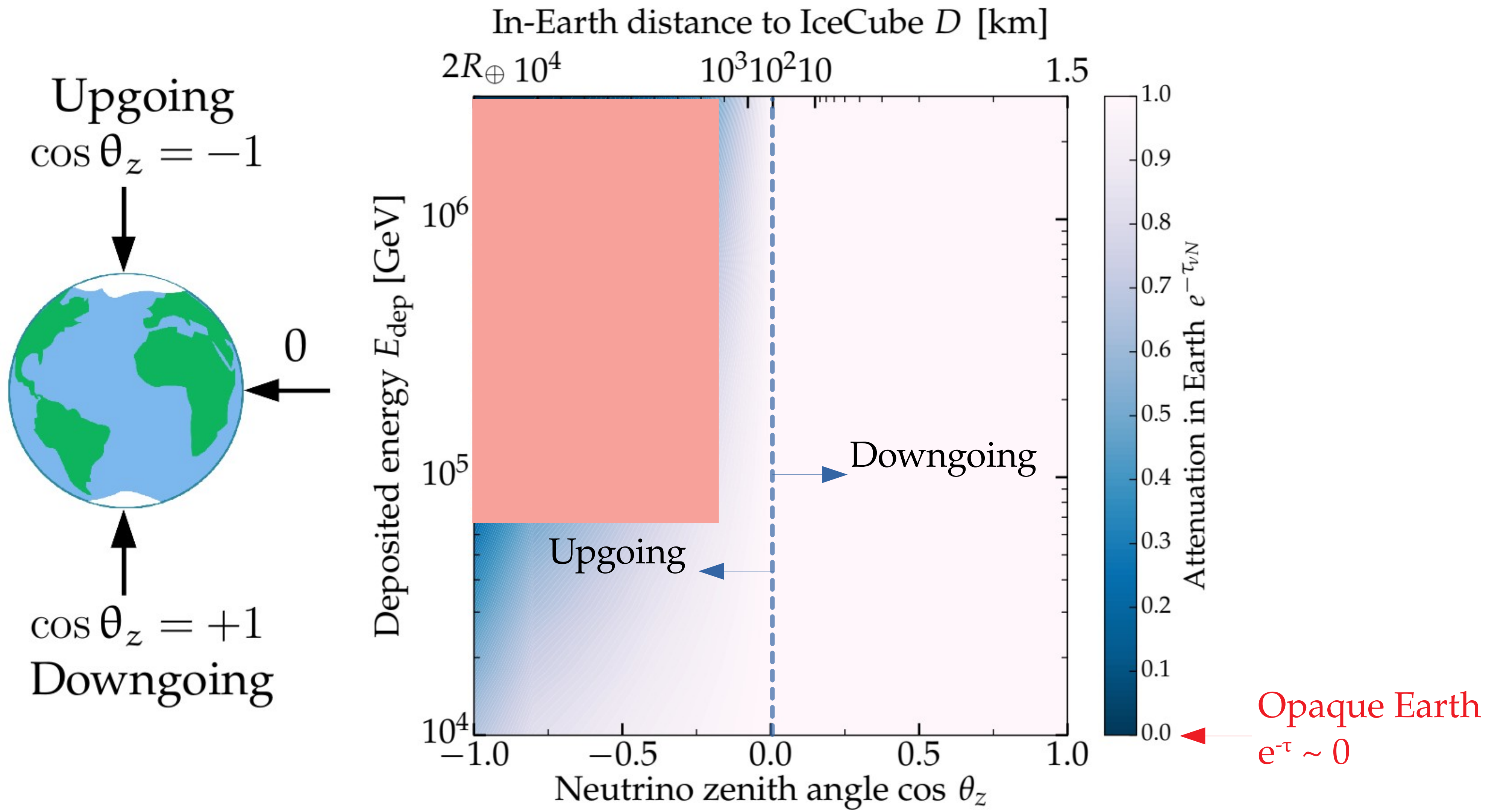
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



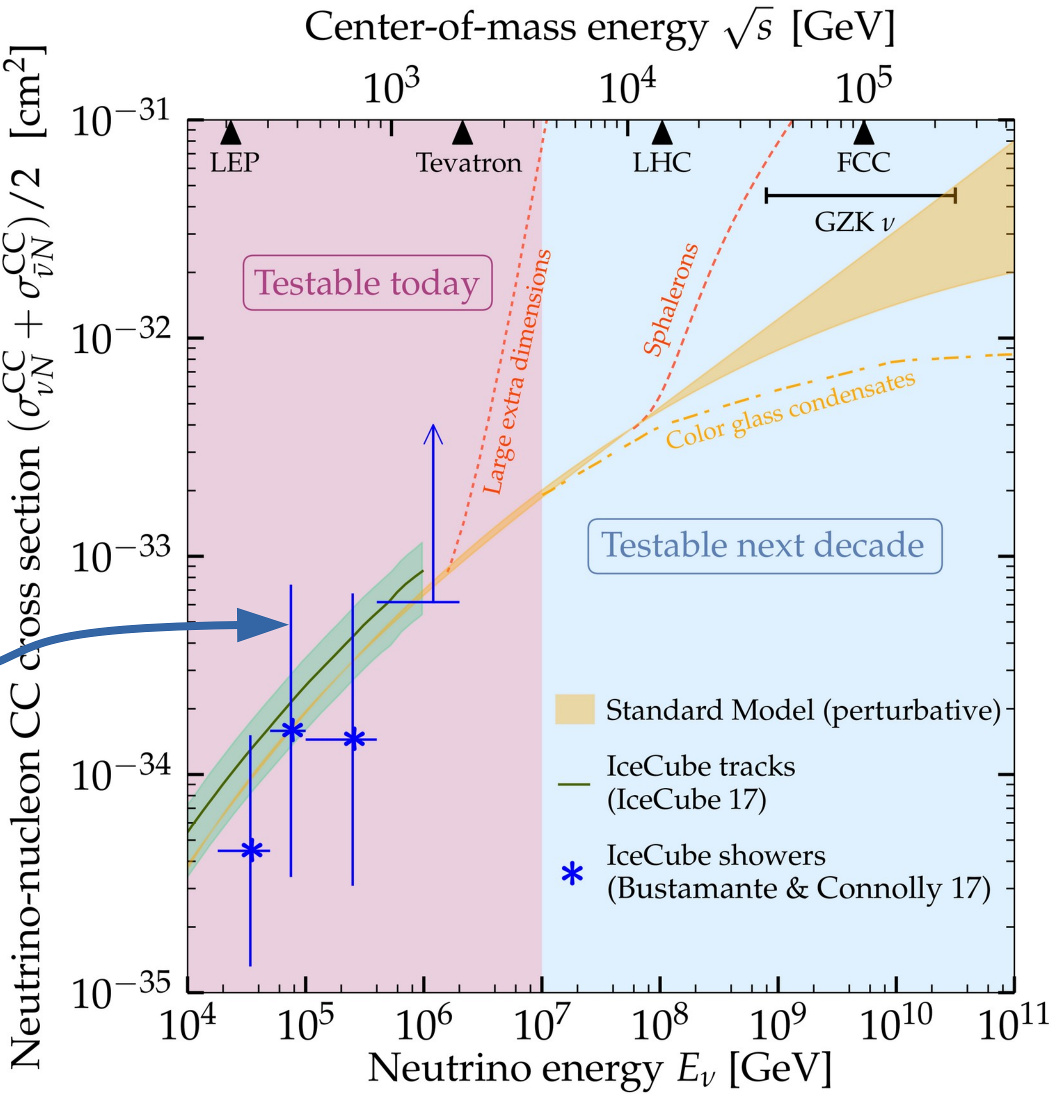
Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0



Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Transparent Earth
$e^{-\tau} \sim 1$


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Opaque Earth
$e^{-\tau} \sim 0$

- Fold in astrophysical unknowns (spectral index, normalization)
- Compatible with SM predictions
- Still room for new physics
- Today, using IceCube:
  - Extracted from ~60 showers in 6 yr
  - Limited by statistics
- Future, using IceCube-Gen2:
  - $\times$ 5 volume $\Rightarrow$ 300 showers in 6 yr
  - Reduce statistical error by 40%

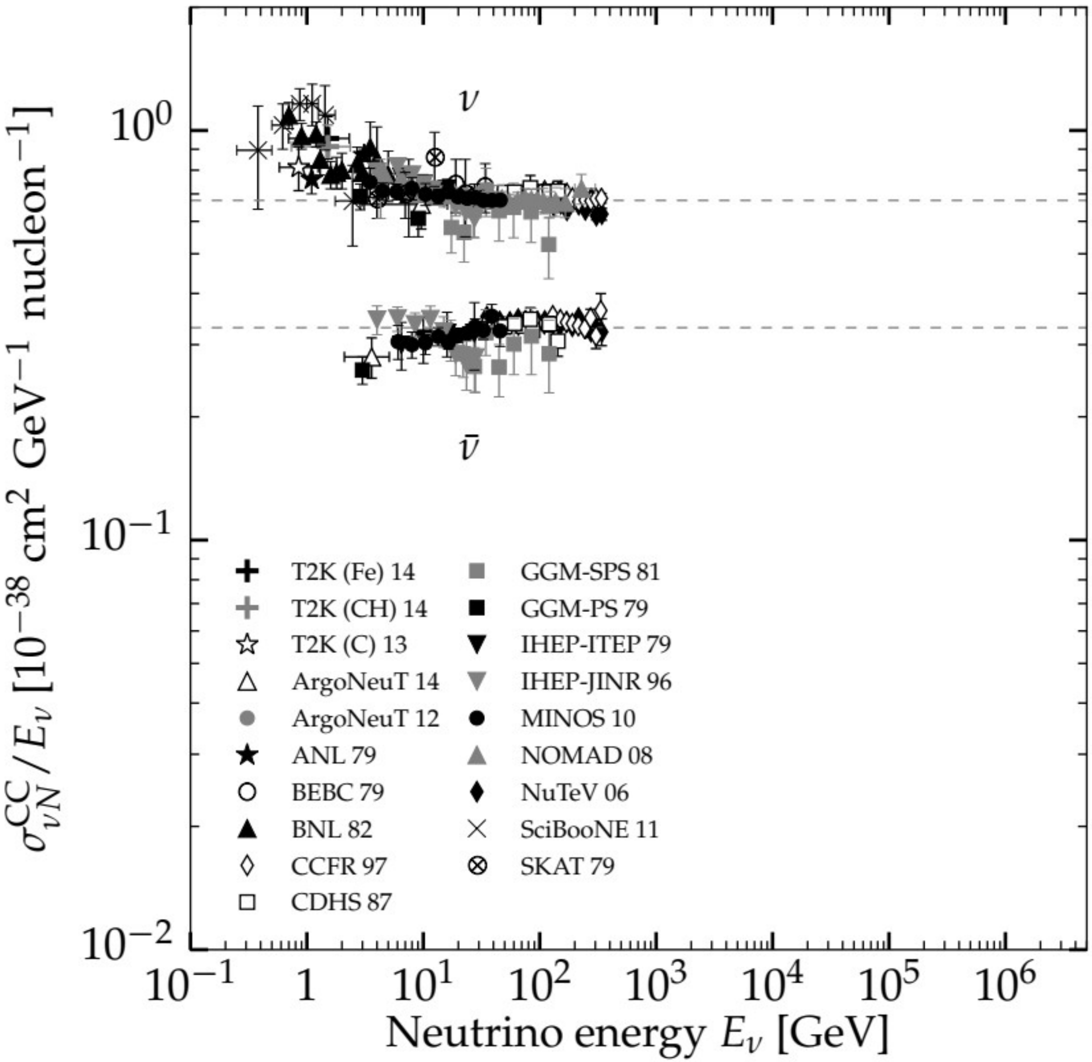


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

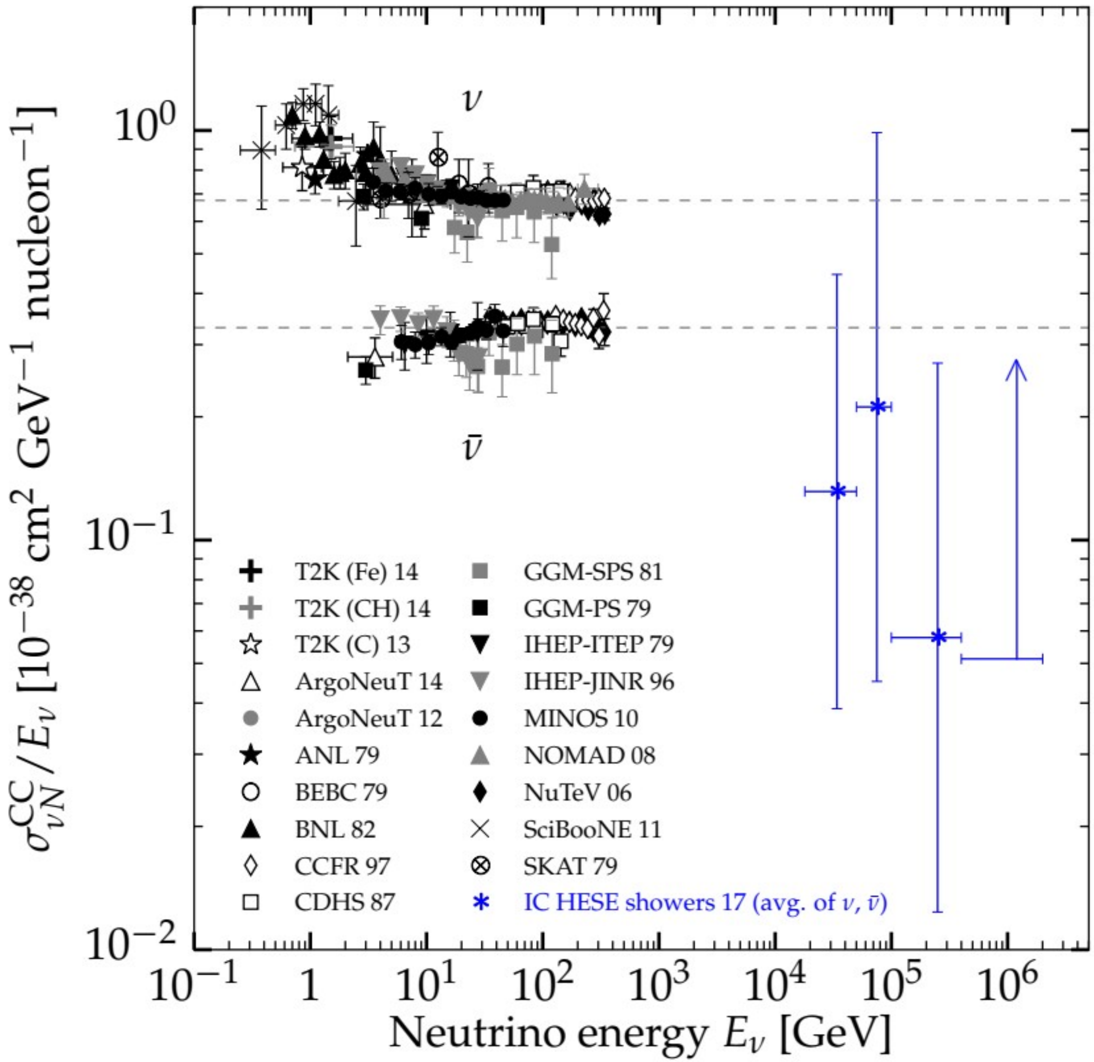
Cross sections from:
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

Recent update:
IceCube, 2011.03560

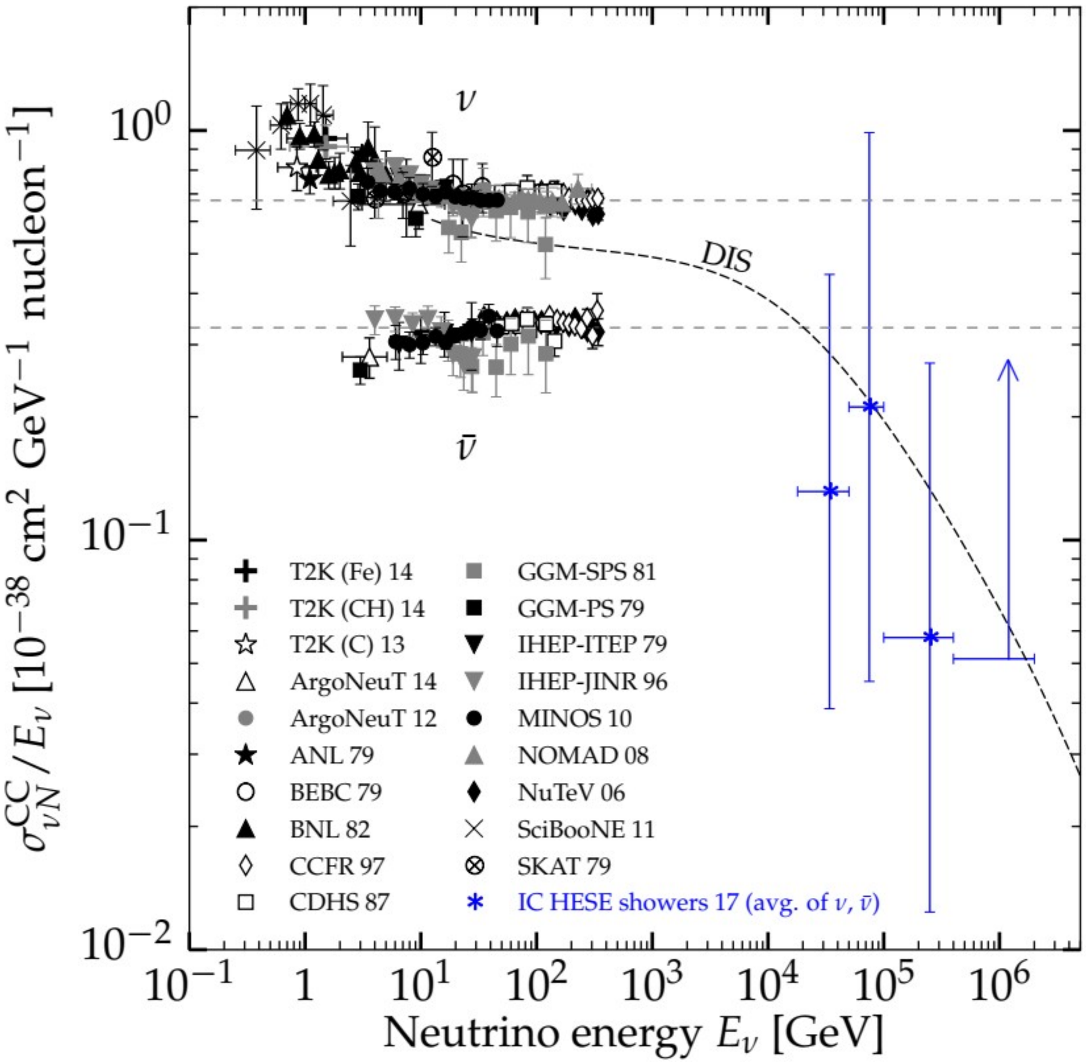
MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



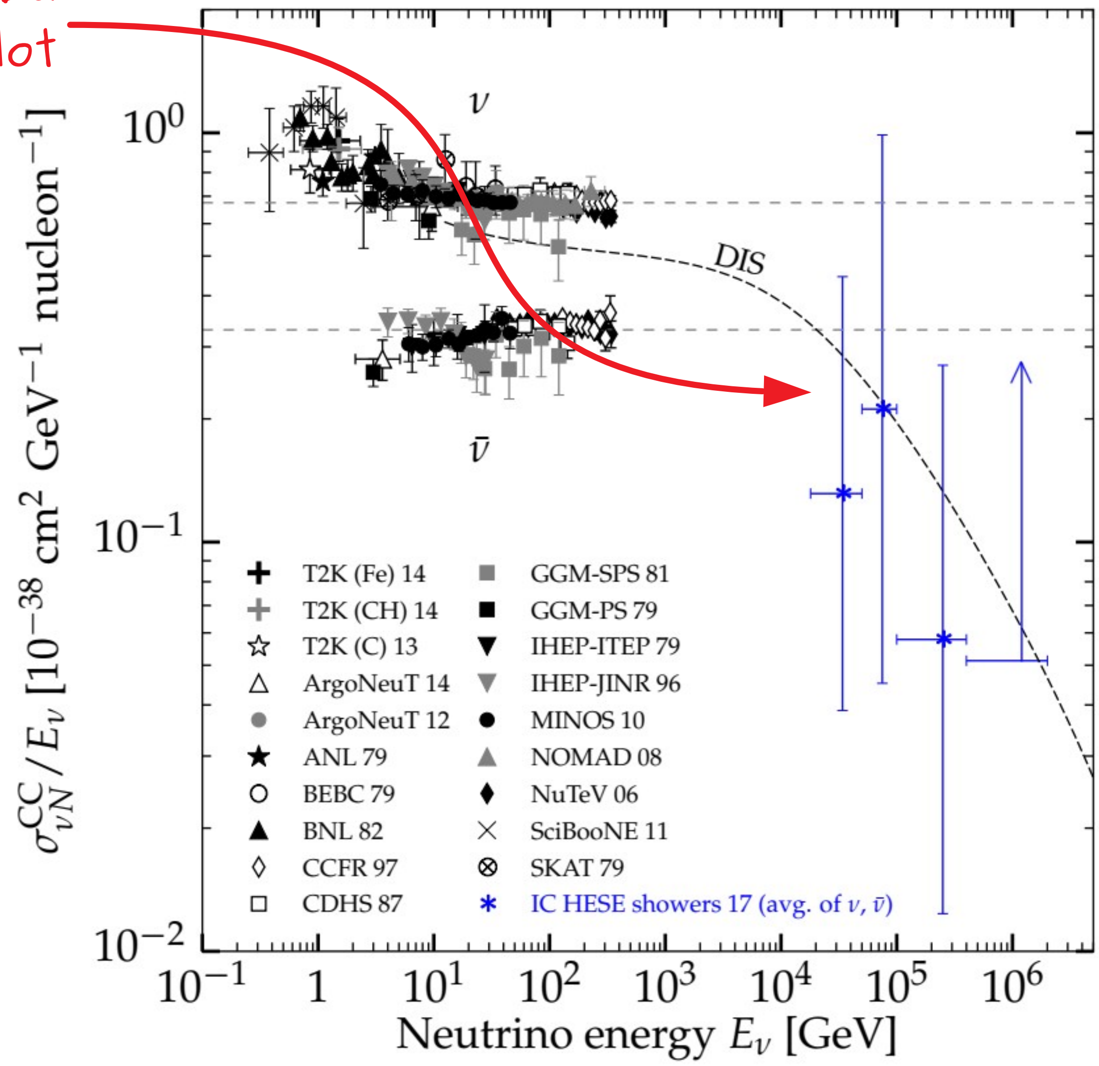
MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



Extending the PDG cross-section plot



MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

Example 2:
Secret neutrino interactions

Astrophysical neutrino sources

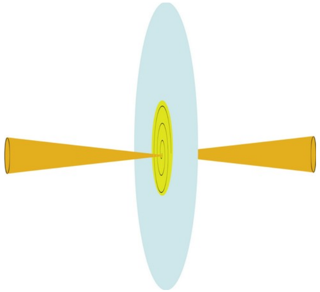
Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance

Astrophysical neutrino sources

Earth

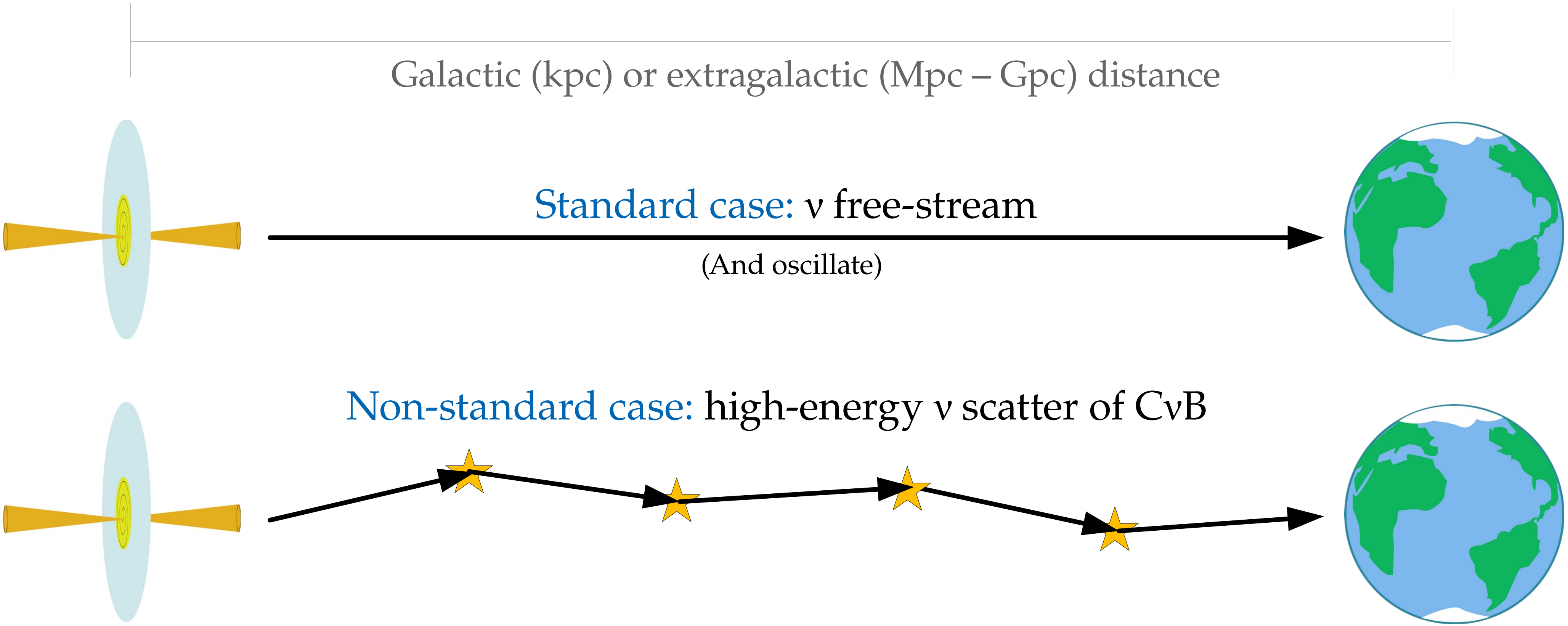
Galactic (kpc) or extragalactic (Mpc – Gpc) distance

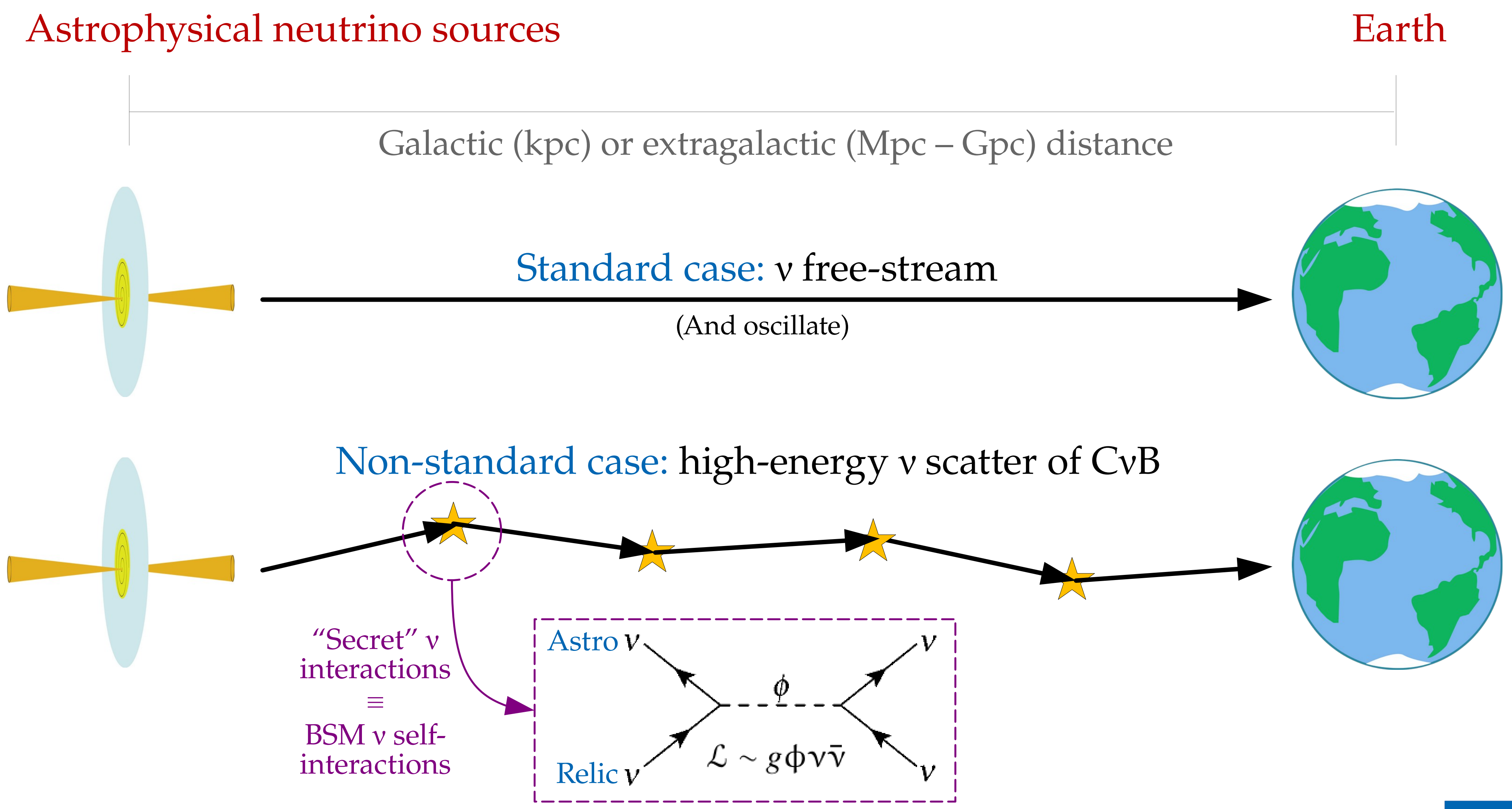


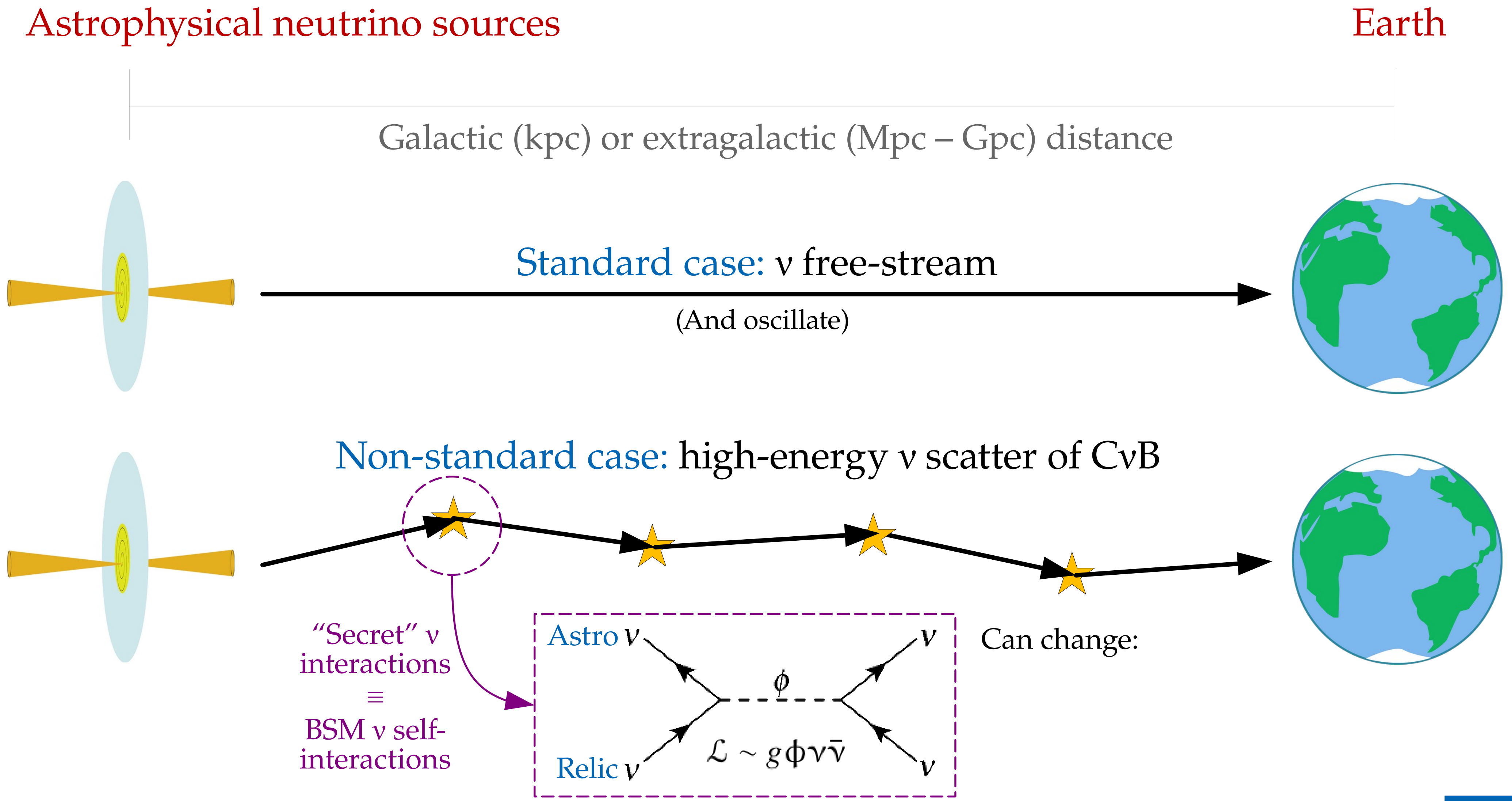
Standard case: ν free-stream

(And oscillate)

Astrophysical neutrino sources Earth




Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions
≡
BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$



Astrophysical neutrino sources
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Standard case: ν free-stream
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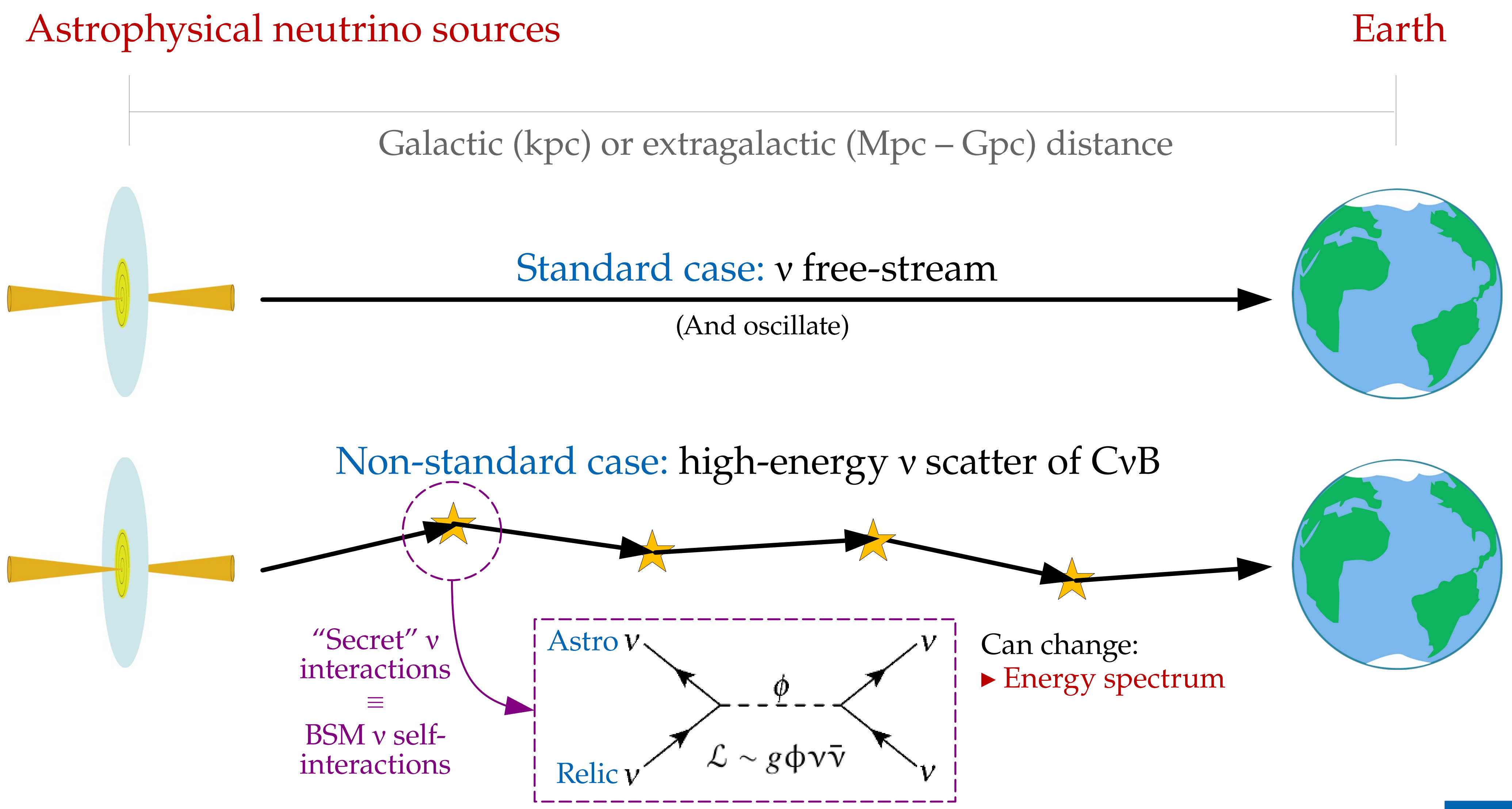
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:


Astrophysical neutrino sources
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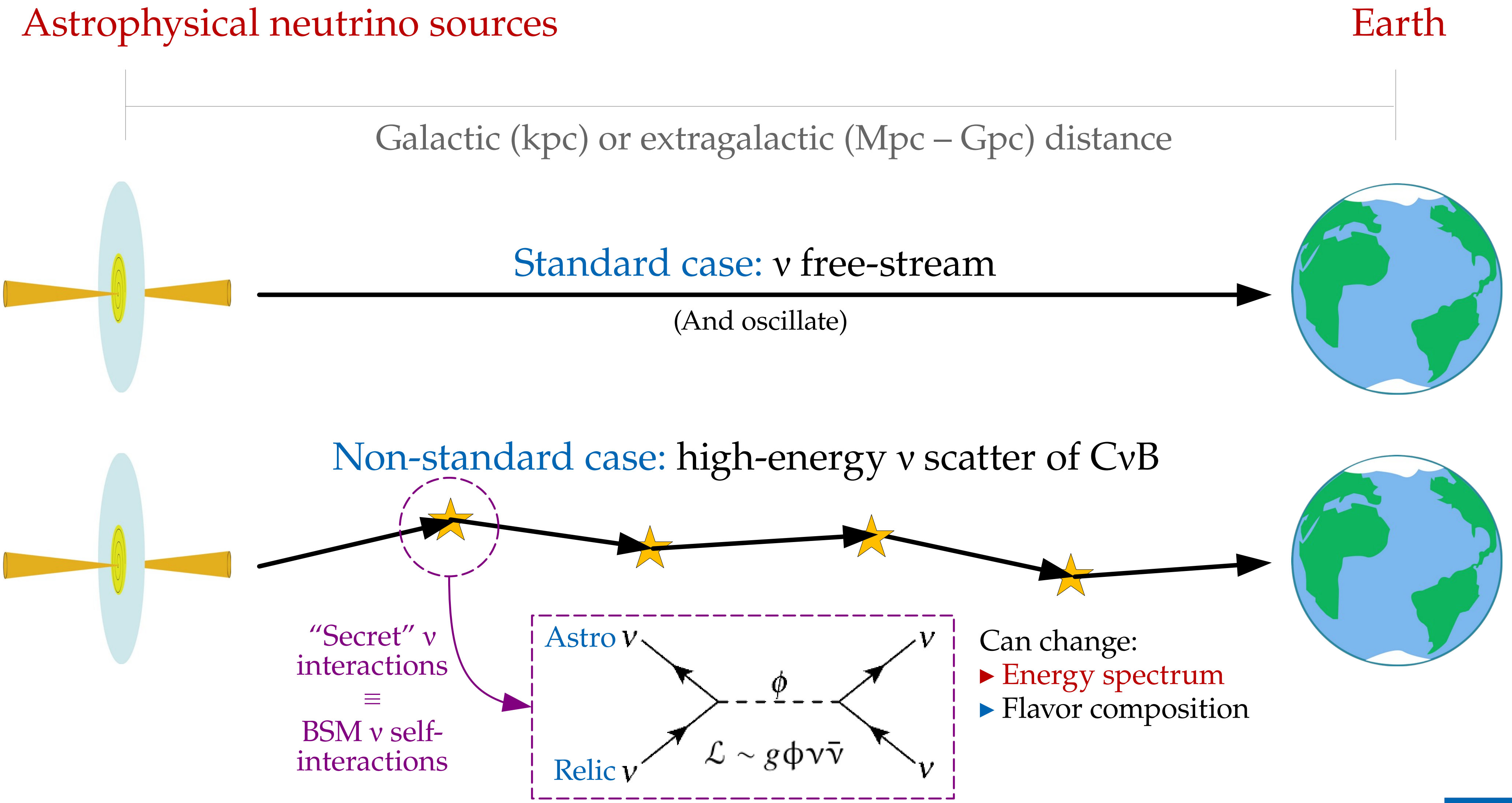
"Secret" ν interactions
≡
BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum



Astrophysical neutrino sources
Earth
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Standard case: ν free-stream
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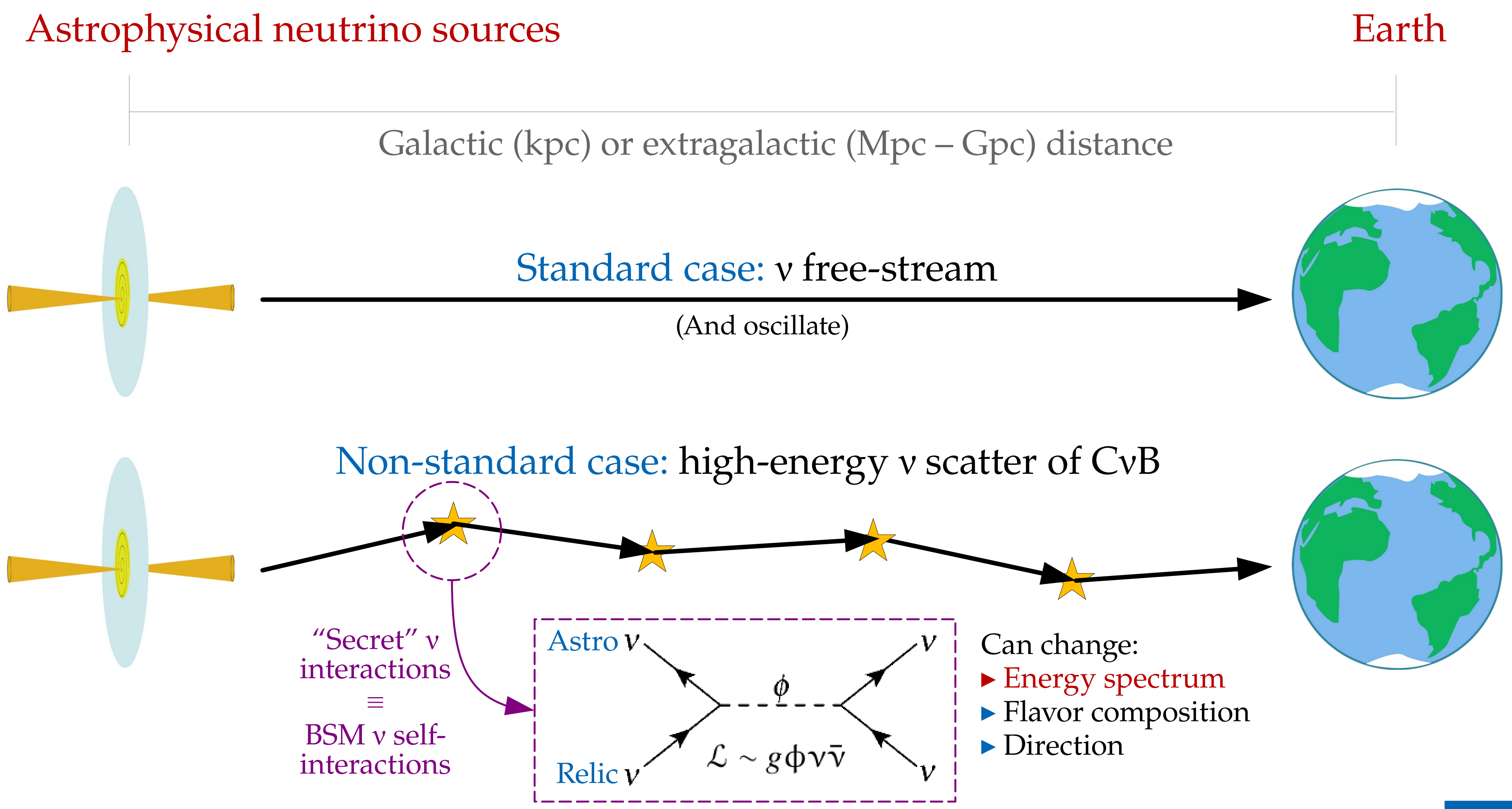
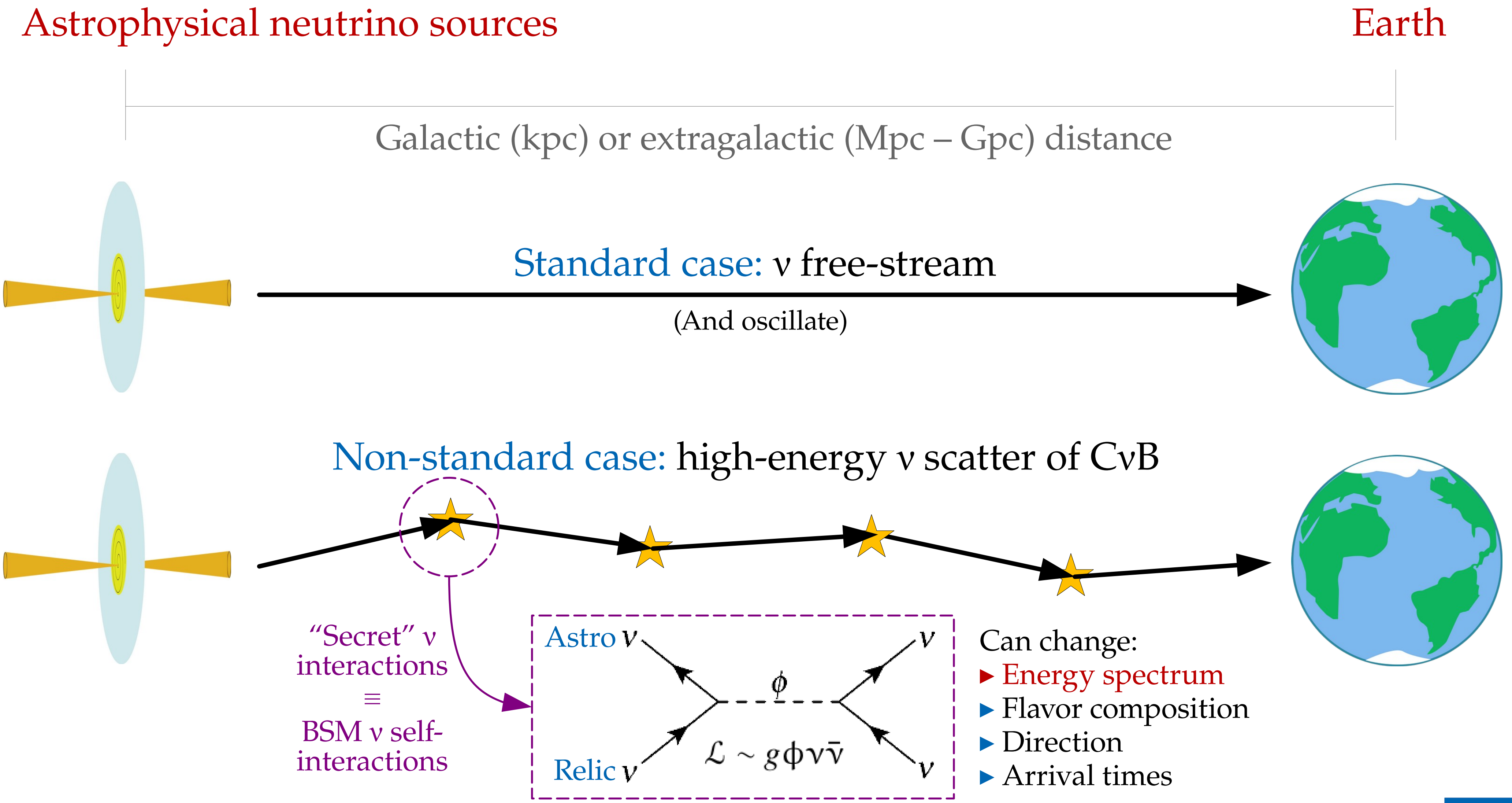
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum
▸ Flavor composition



Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
ℒ ~ gϕνν̄
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction



Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
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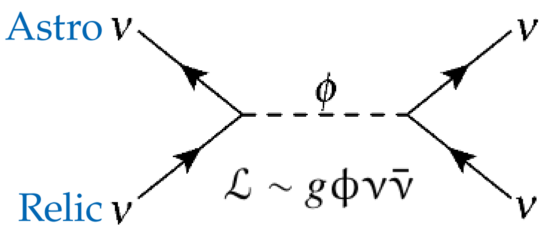
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction
▸ Arrival times

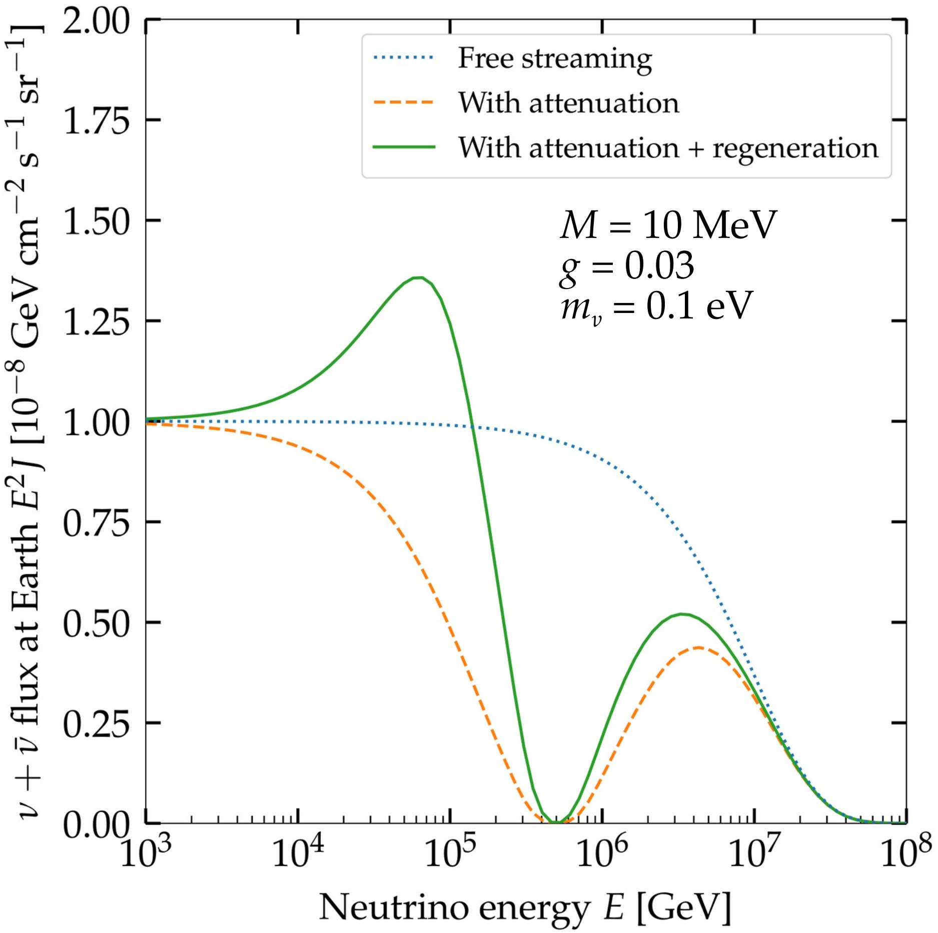
Secret interactions of high-energy astrophysical neutrinos

"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



Cross section: $\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$

Resonance energy: $E_{\rm res} = \frac{M^2}{2m_\nu}$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

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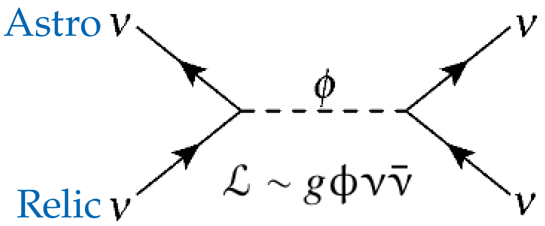
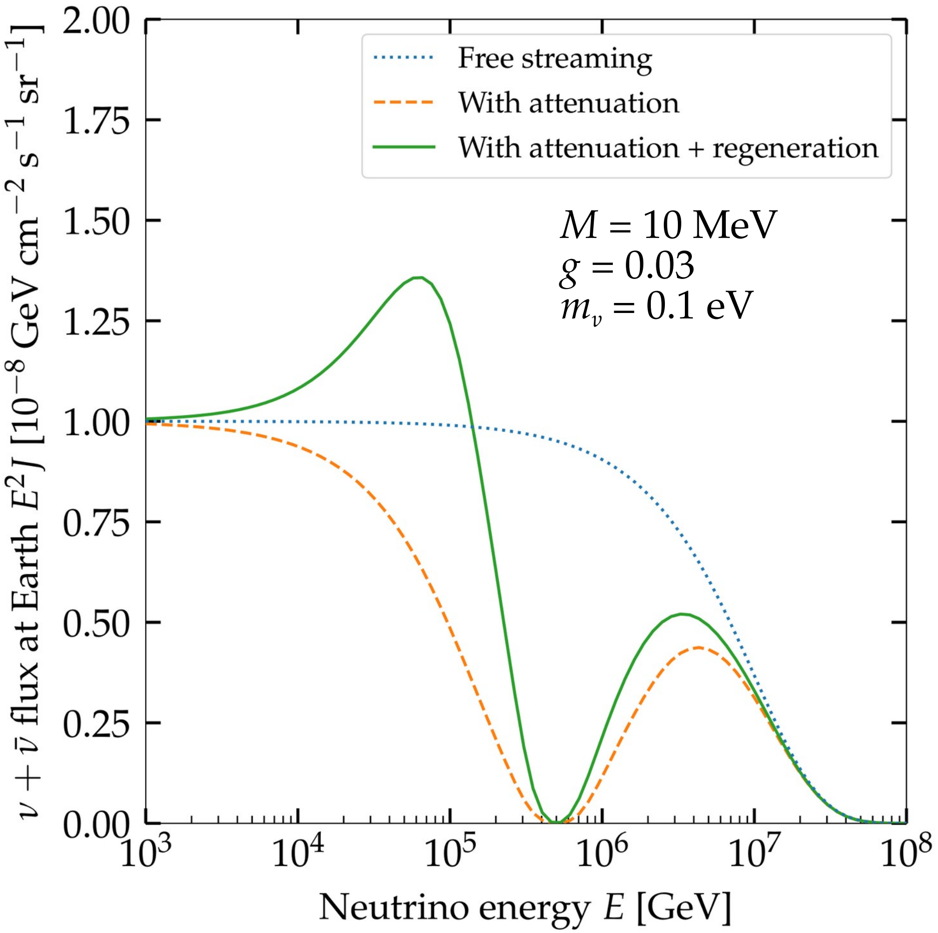


New coupling

Cross section: $$\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$$

Mediator mass

Resonance energy: $$E_{\text{res}} = \frac{M^2}{2m_\nu}$$



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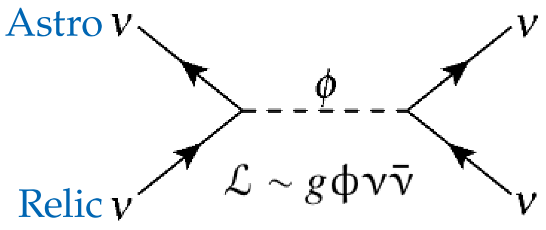
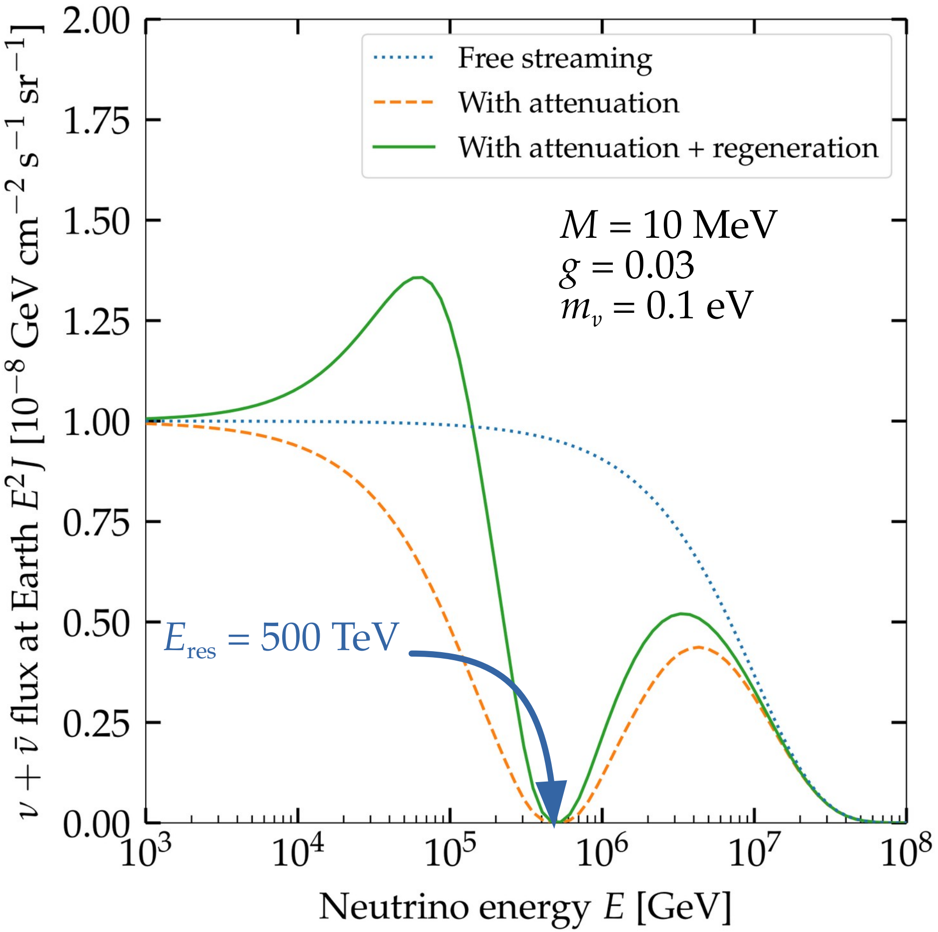


New coupling

Cross section: $\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$

Mediator mass

Resonance energy: $E_{\rm res} = \frac{M^2}{2m_\nu}$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
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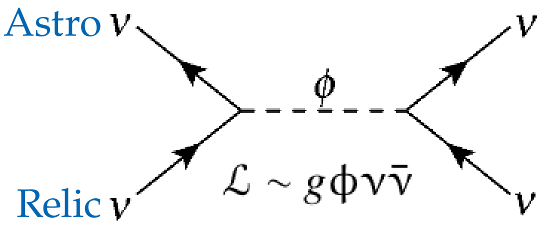

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Mediator mass

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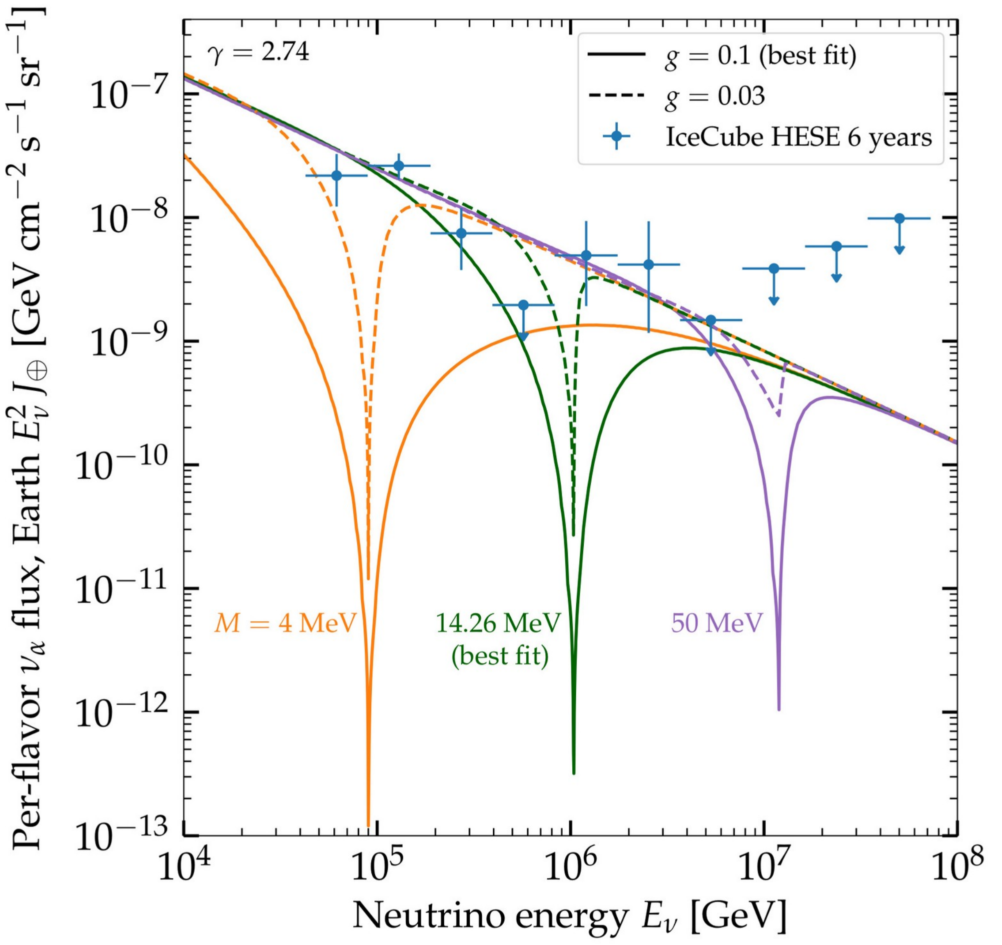

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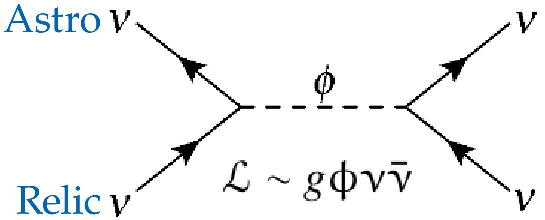

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Cross section: $$\sigma = \frac{g^4}{4\pi}\frac{s}{(s - M^2)^2 + M^2\Gamma^2}$$

Mediator mass

Resonance energy: $$E_{\mathrm{res}} = \frac{M^2}{2m_\nu}$$

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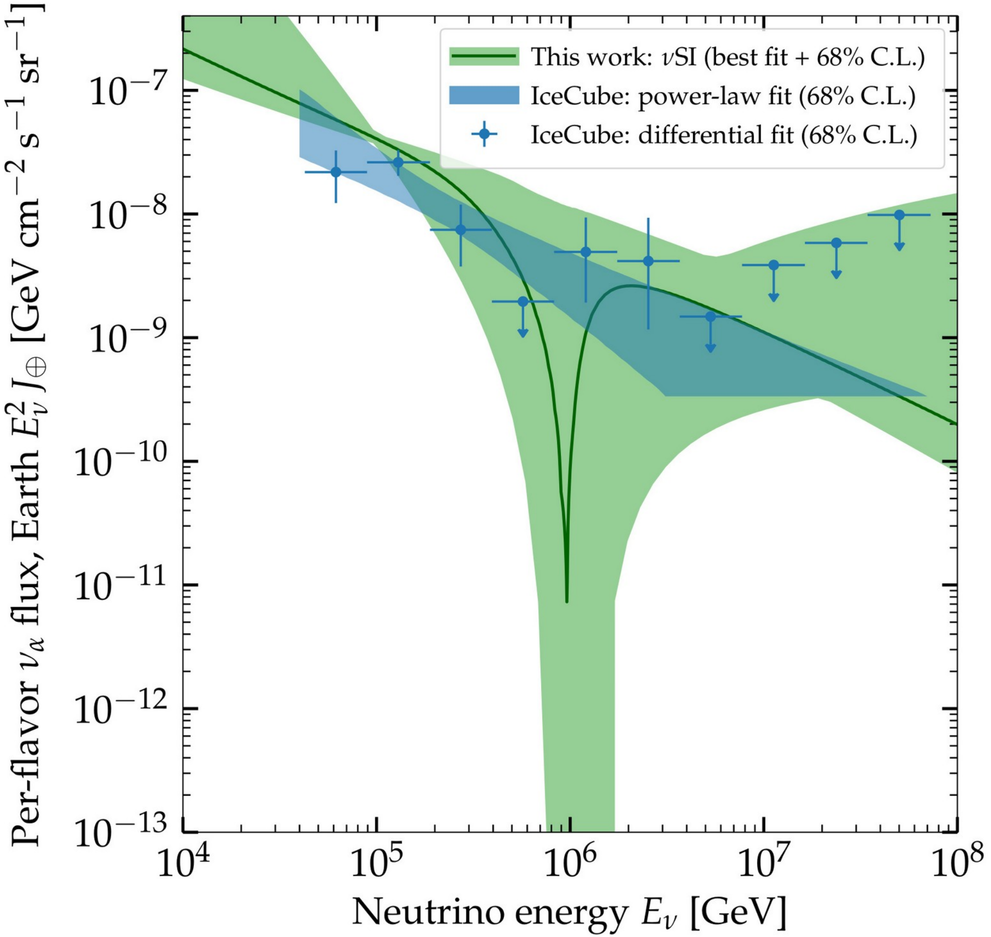
See also: Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Looking for evidence of νSI

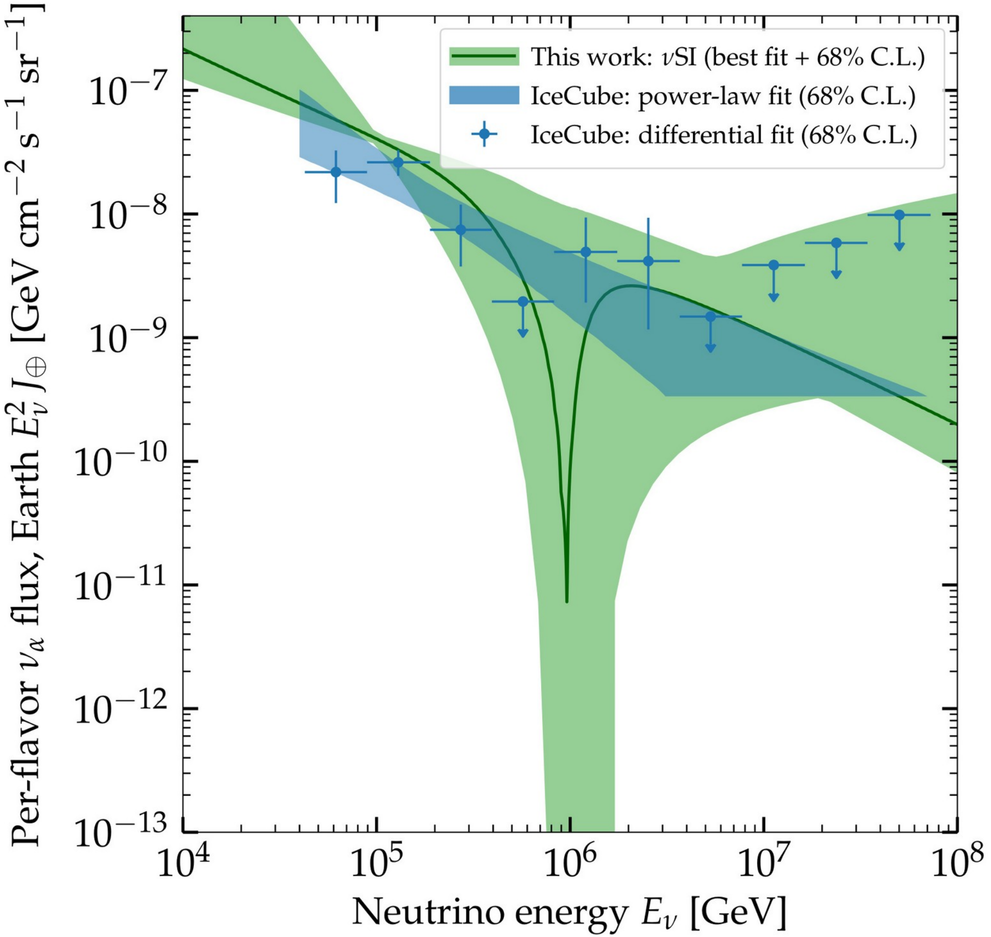
- Look for dips in 6 years of public IceCube data (HESE)
- 80 events, 18 TeV–2 PeV
- Assume flavor-diagonal and universal: $g_{\alpha\alpha} = g\,\delta_{\alpha\alpha}$
- Bayesian analysis varying M, g, shape of emitted flux (γ)
- Account for atmospheric ν, in-Earth propagation, detector uncertainties

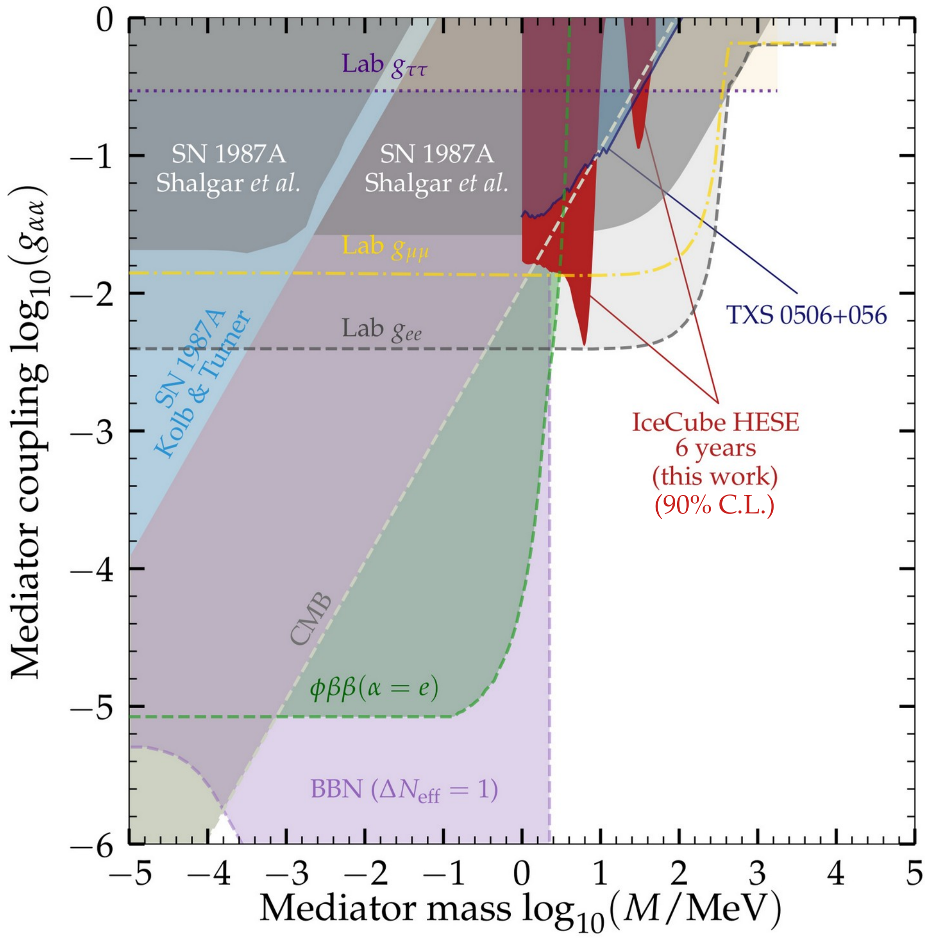
No significant (> 3σ) evidence for a spectral dip …



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, 1912.09115

No significant (> 3σ) evidence for a spectral dip … … so we set upper limits on the coupling g





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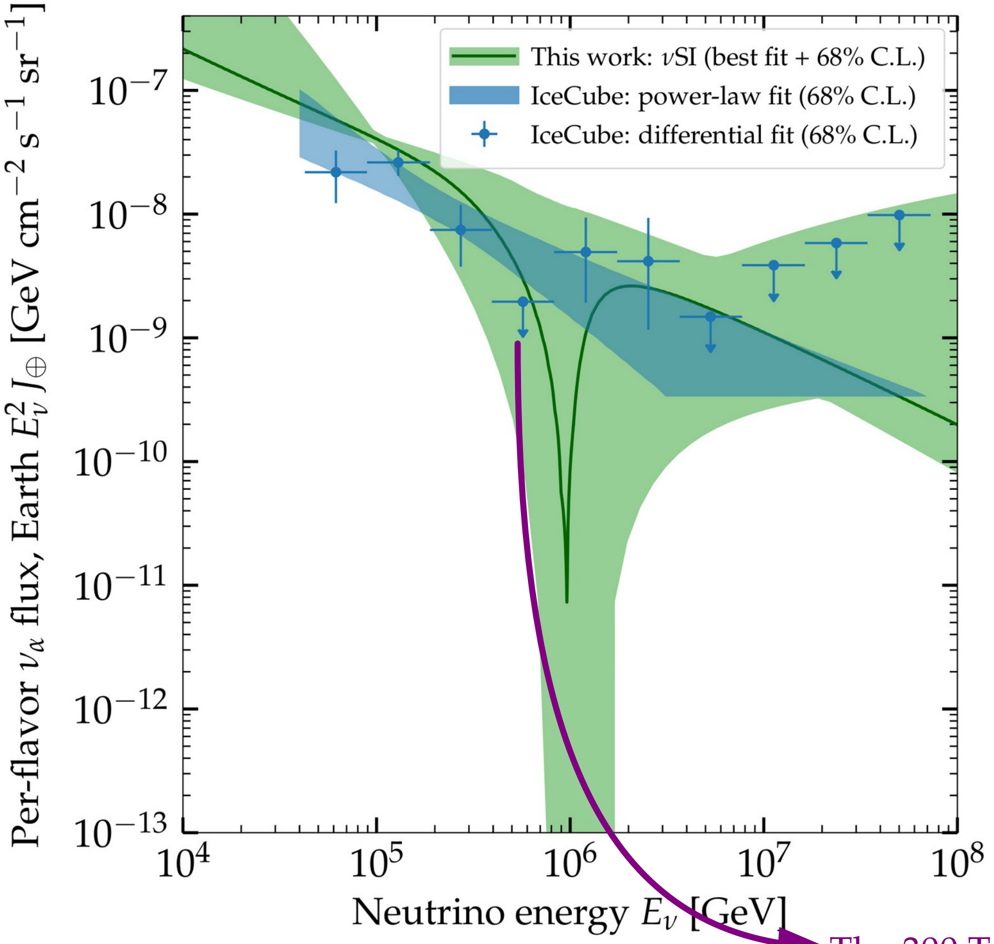
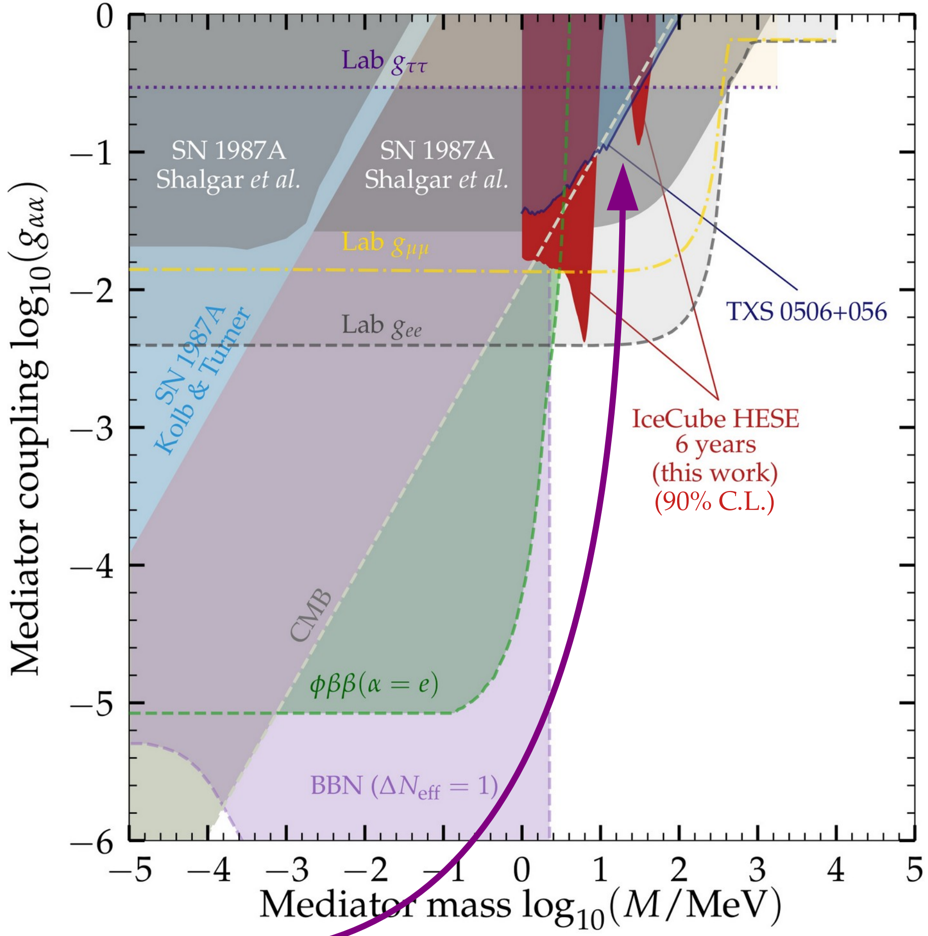
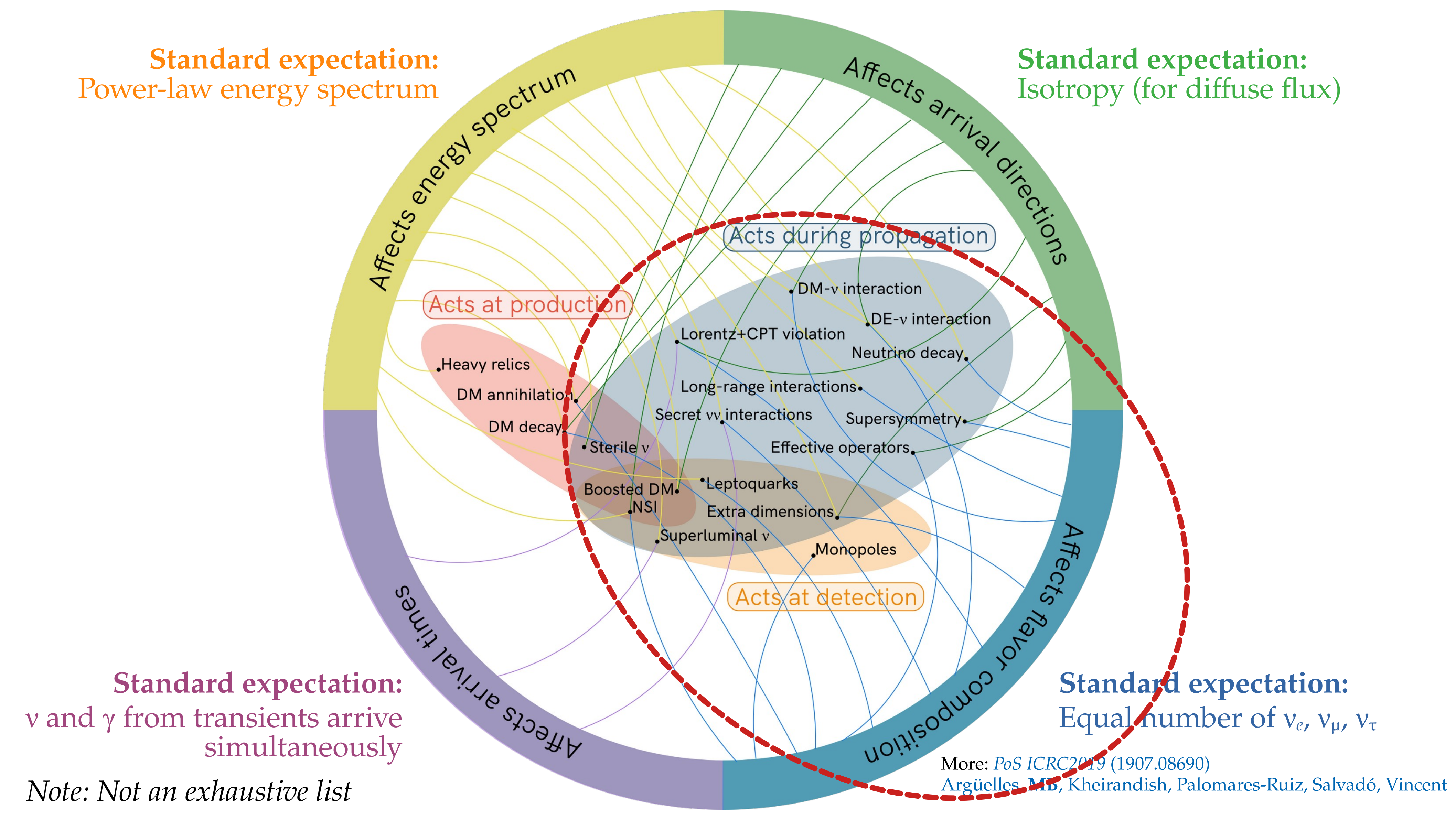




The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, 1912.09115

Example 3: New physics in flavor



Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
Long-range interactions
Secret νν interactions
Supersymmetry
DM decay
Sterile ν
Effective operators
Leptoquarks
Boosted DM
NSI
Extra dimensions
Superluminal ν
Monopoles
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ
Note: Not an exhaustive list
More: PoS ICRC2019 (1907.08690)
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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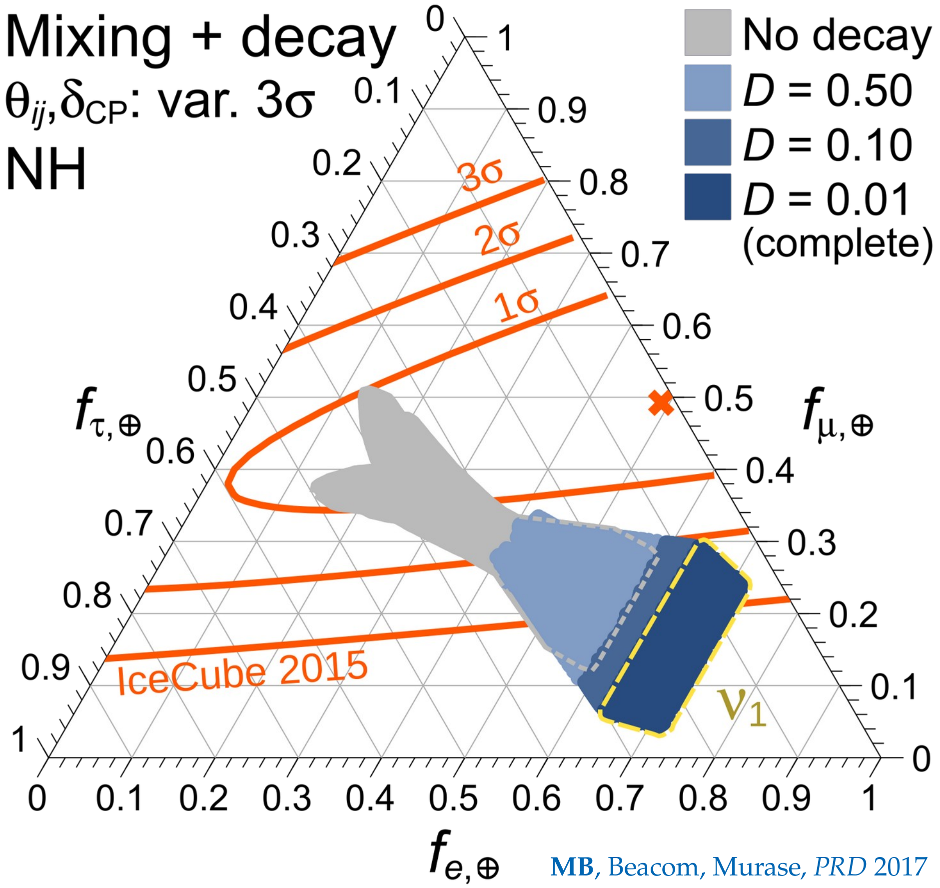

MB, Beacom, Murase, *PRD* 2017

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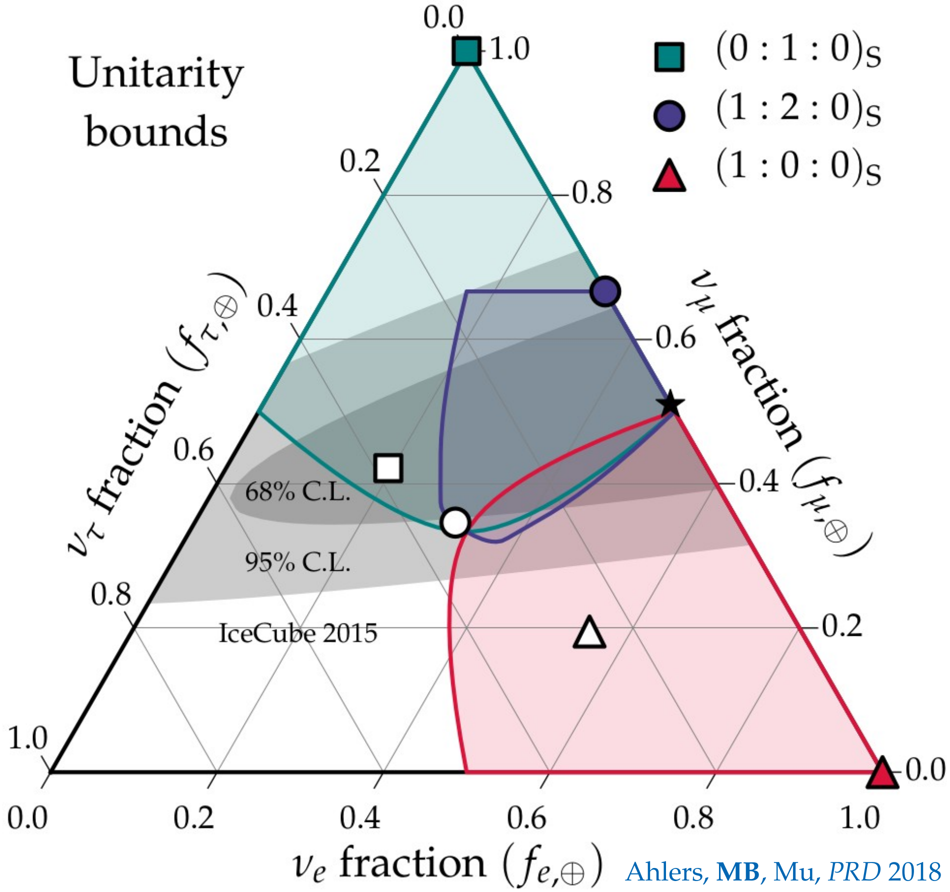

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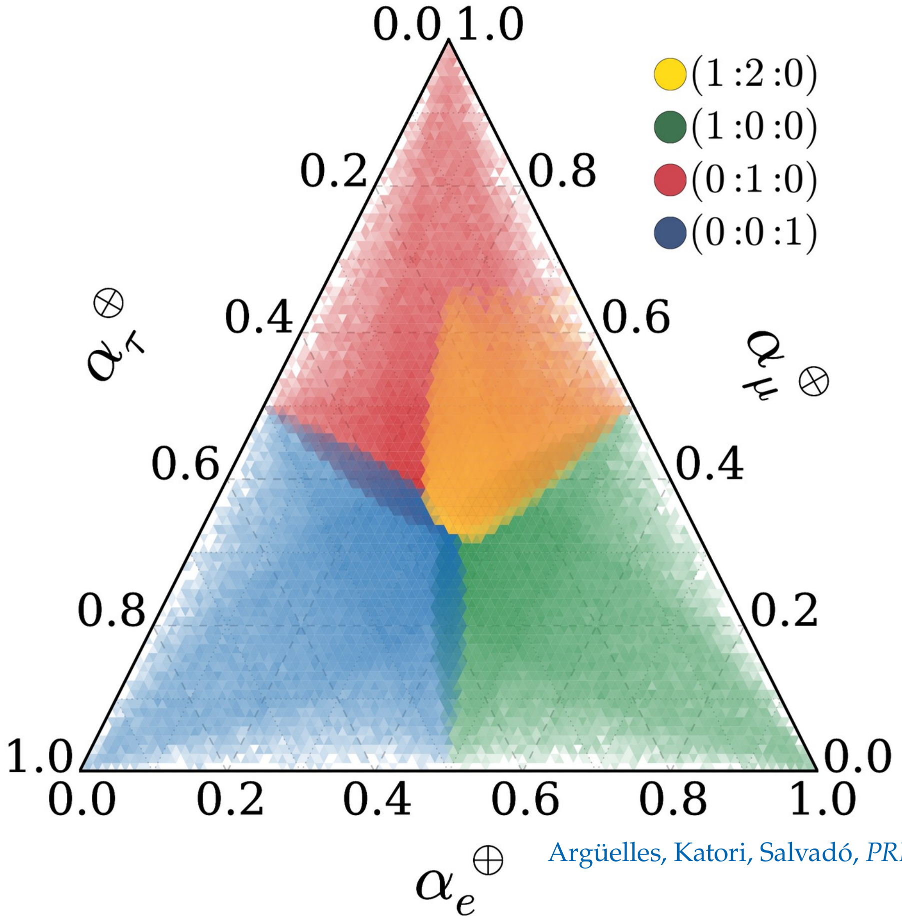

Argüelles, Katori, Salvadó, *PRL* 2015

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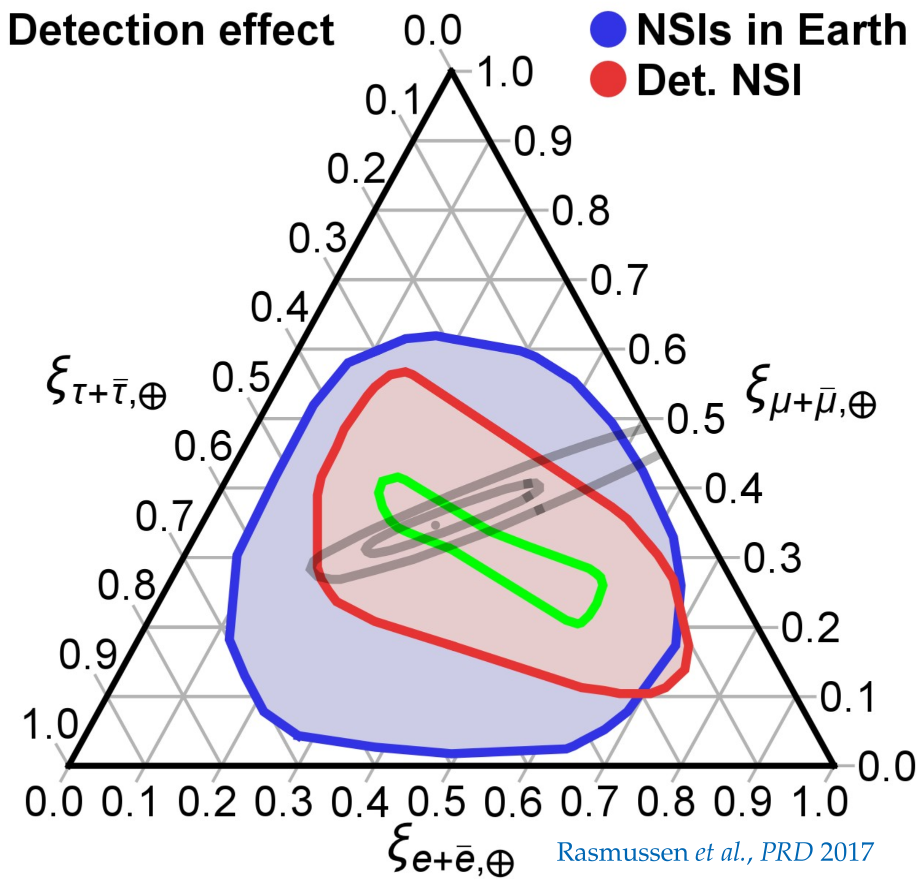

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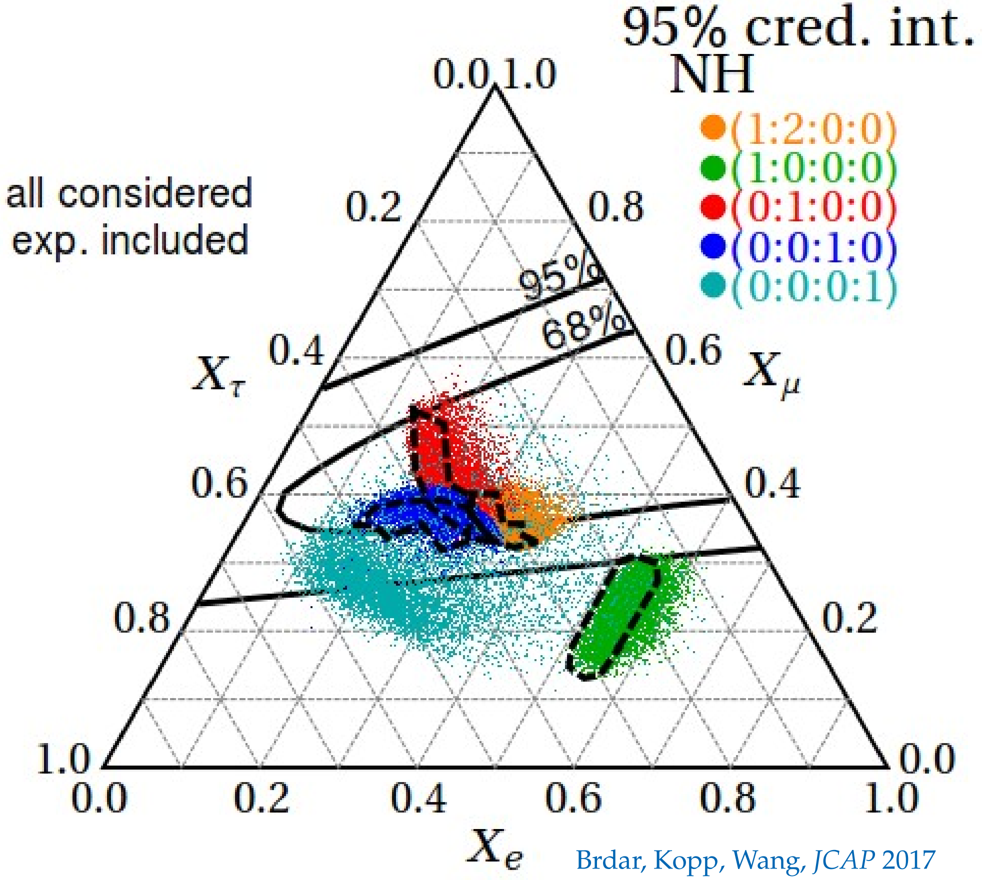

Brdar, Kopp, Wang, *JCAP* 2017

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Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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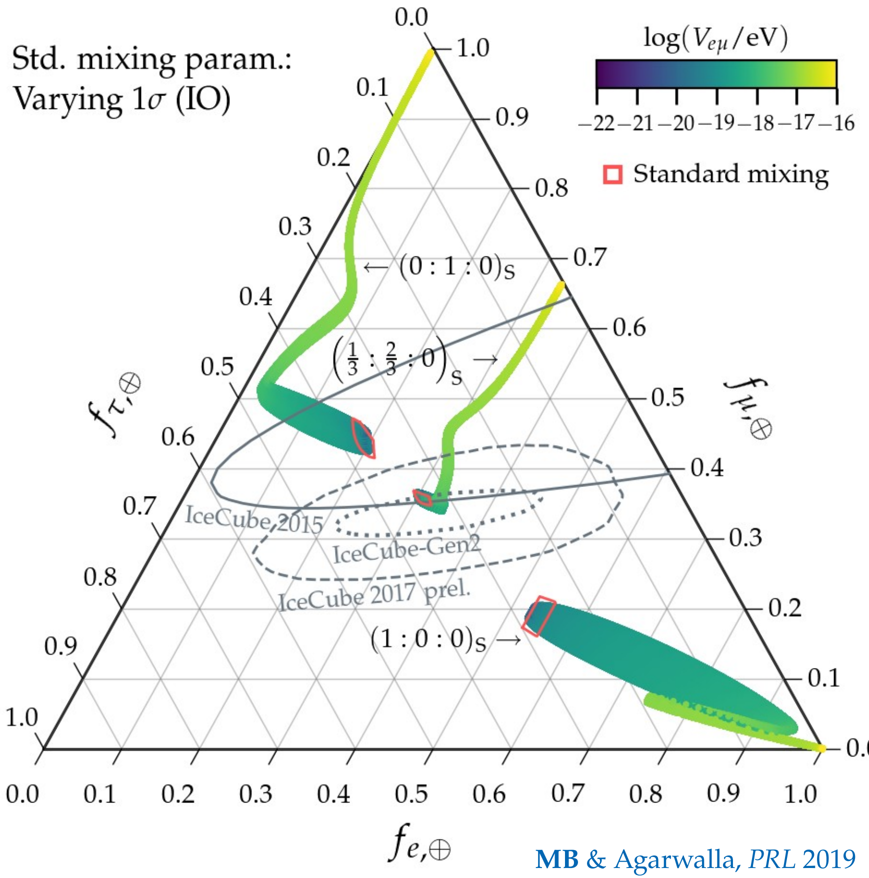
- ▸ Long-range *e*ν interactions
  [**MB** & Agarwalla, *PRL* 2019]

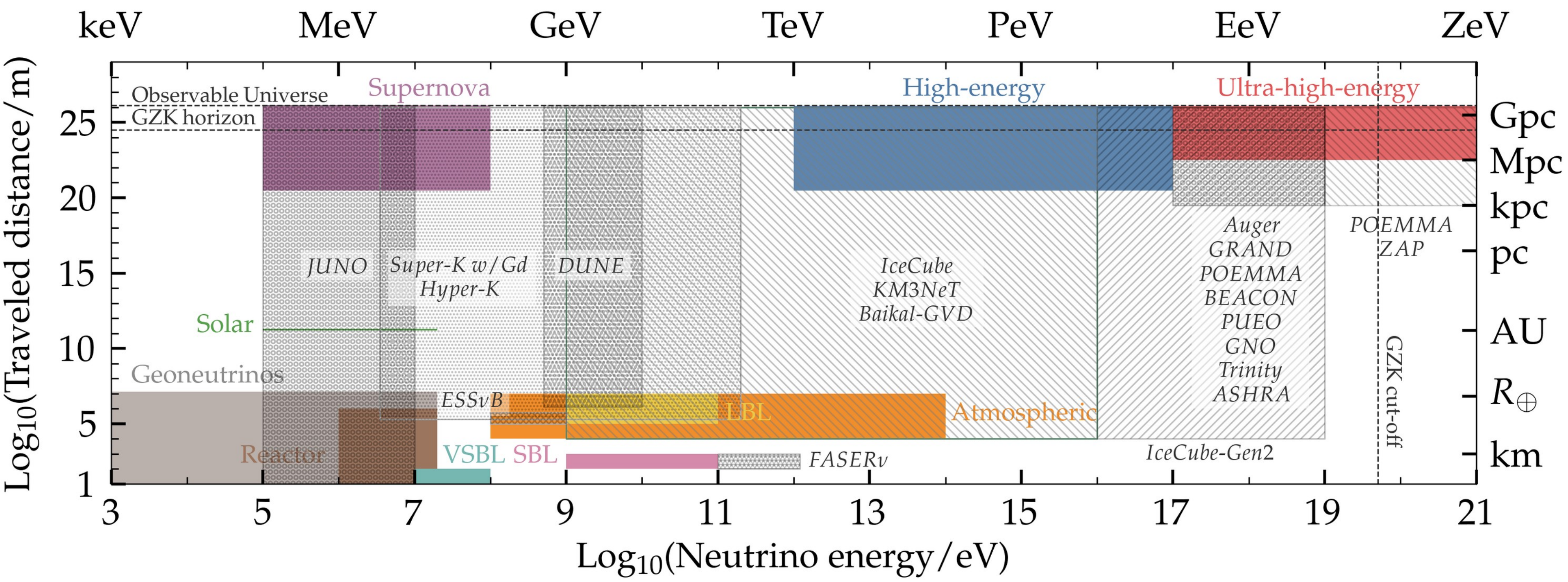
Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017



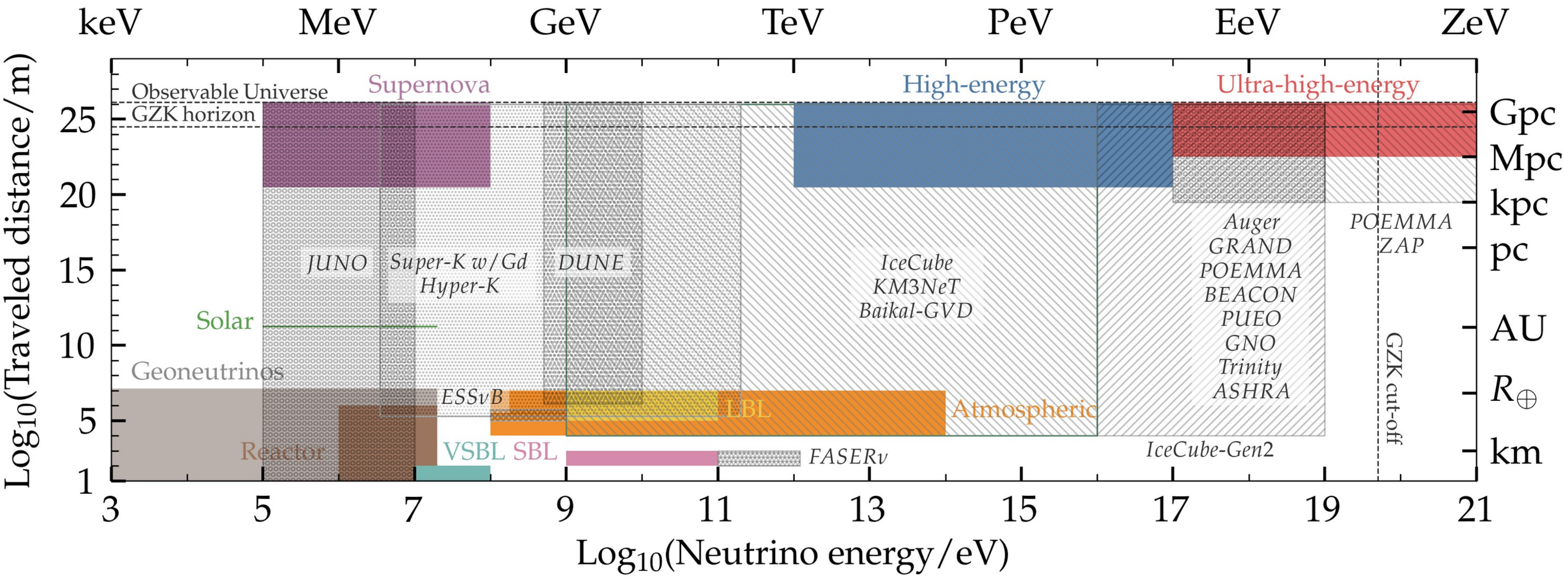
MB & Agarwalla, *PRL* 2019

IV.
The future

Next decade: a host of planned neutrino detectors



Next decade: a host of planned neutrino detectors

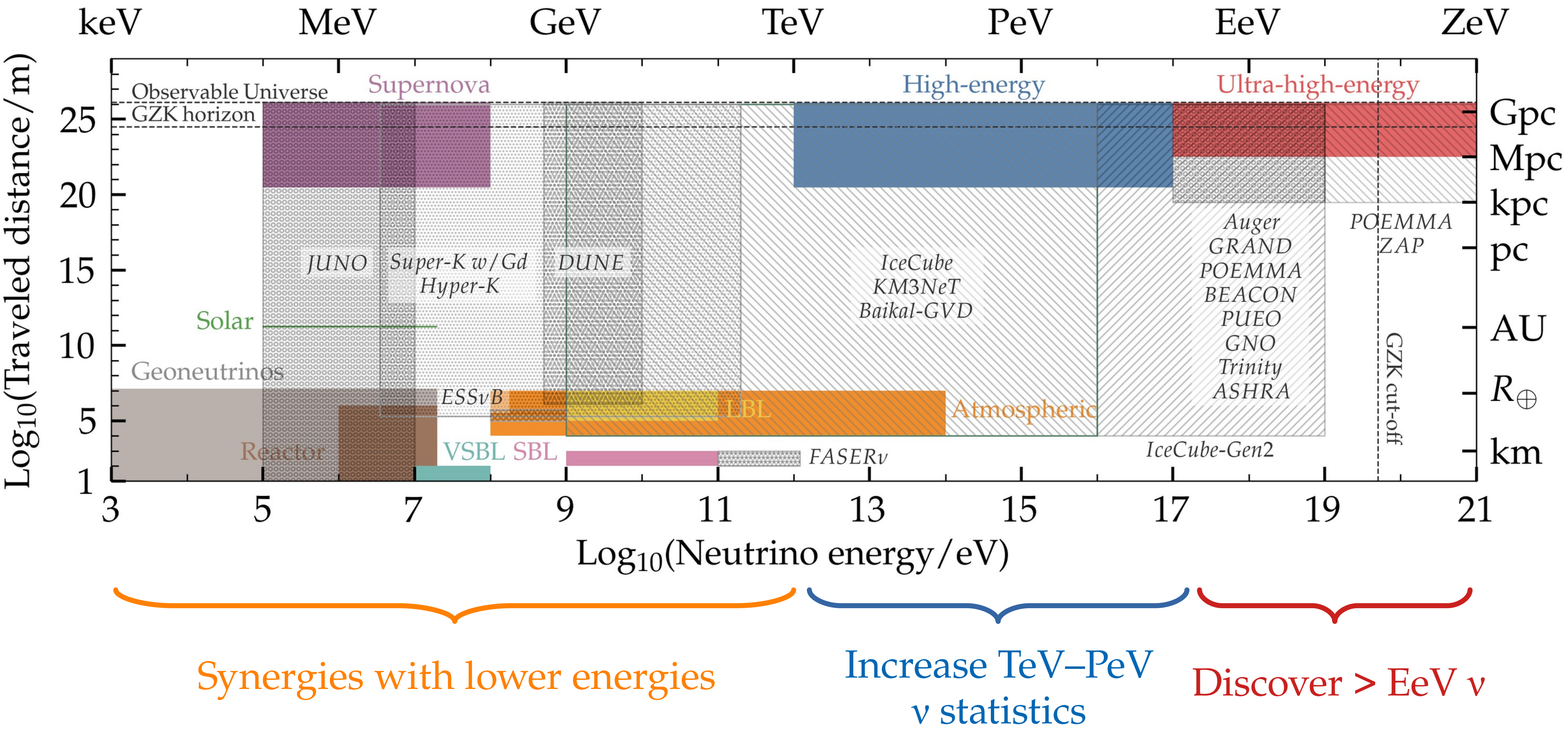


Increase TeV–PeV
ν statistics

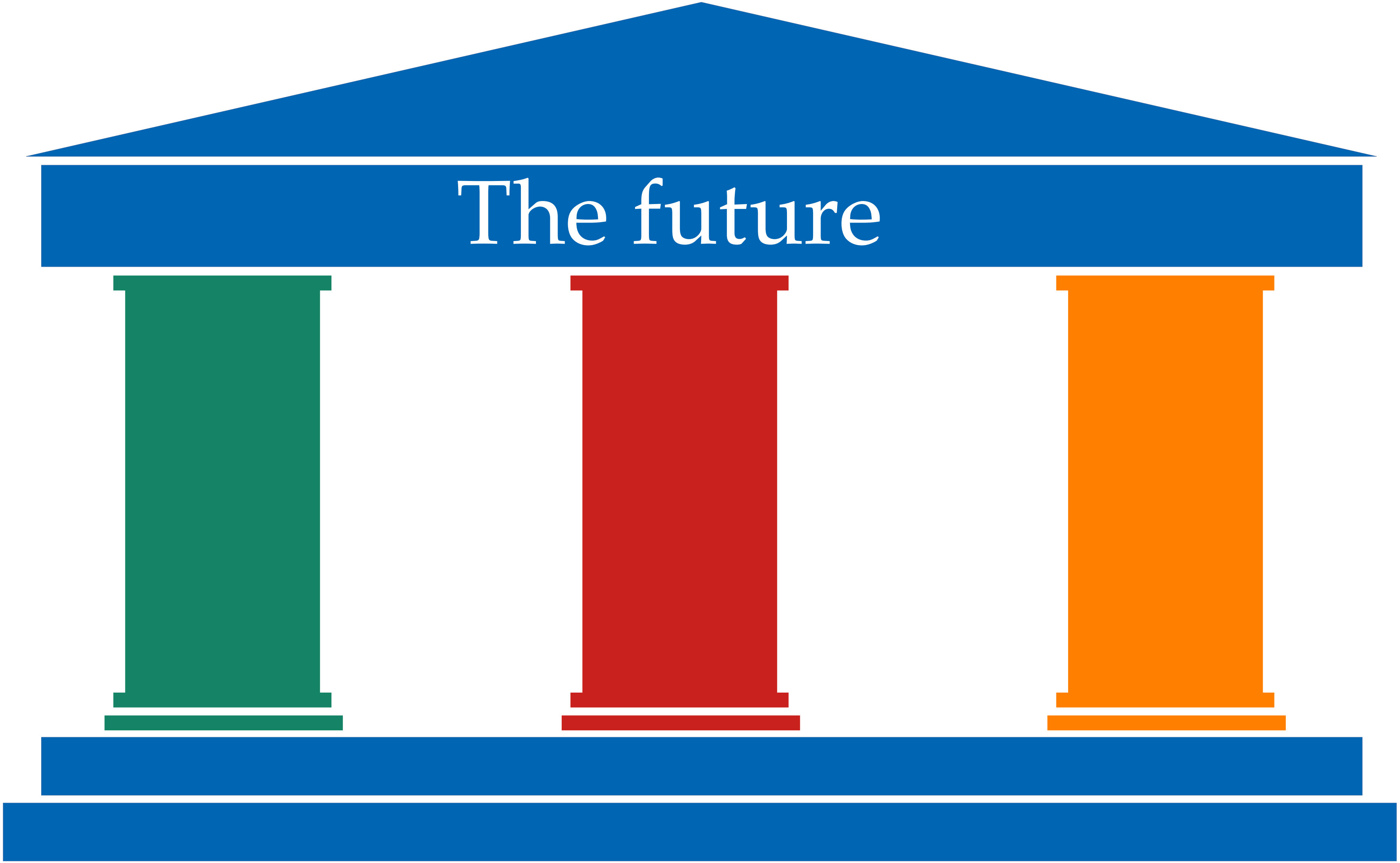
Discover > EeV ν

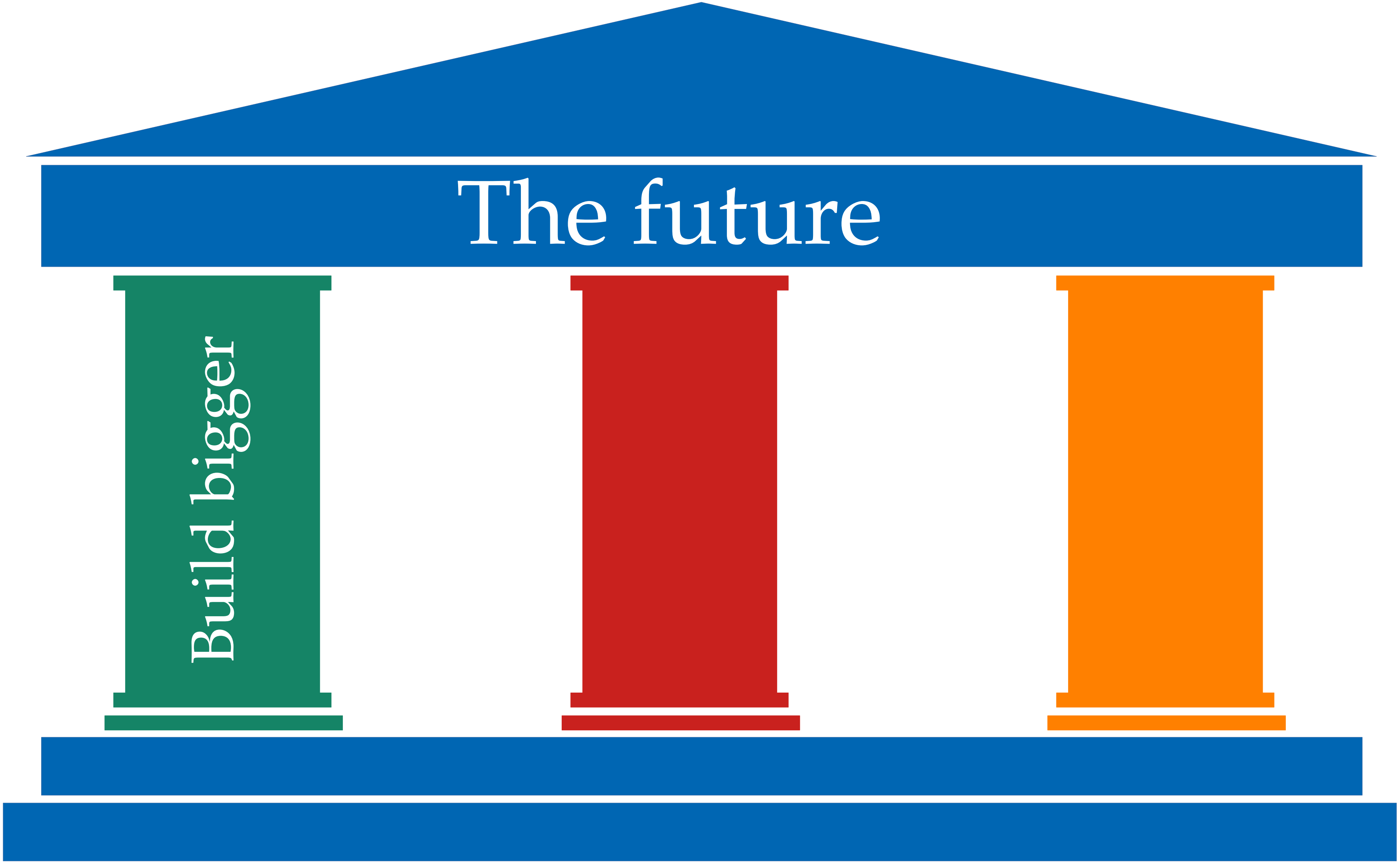
MB *et al.*, Snowmass 20201 Letter of interest

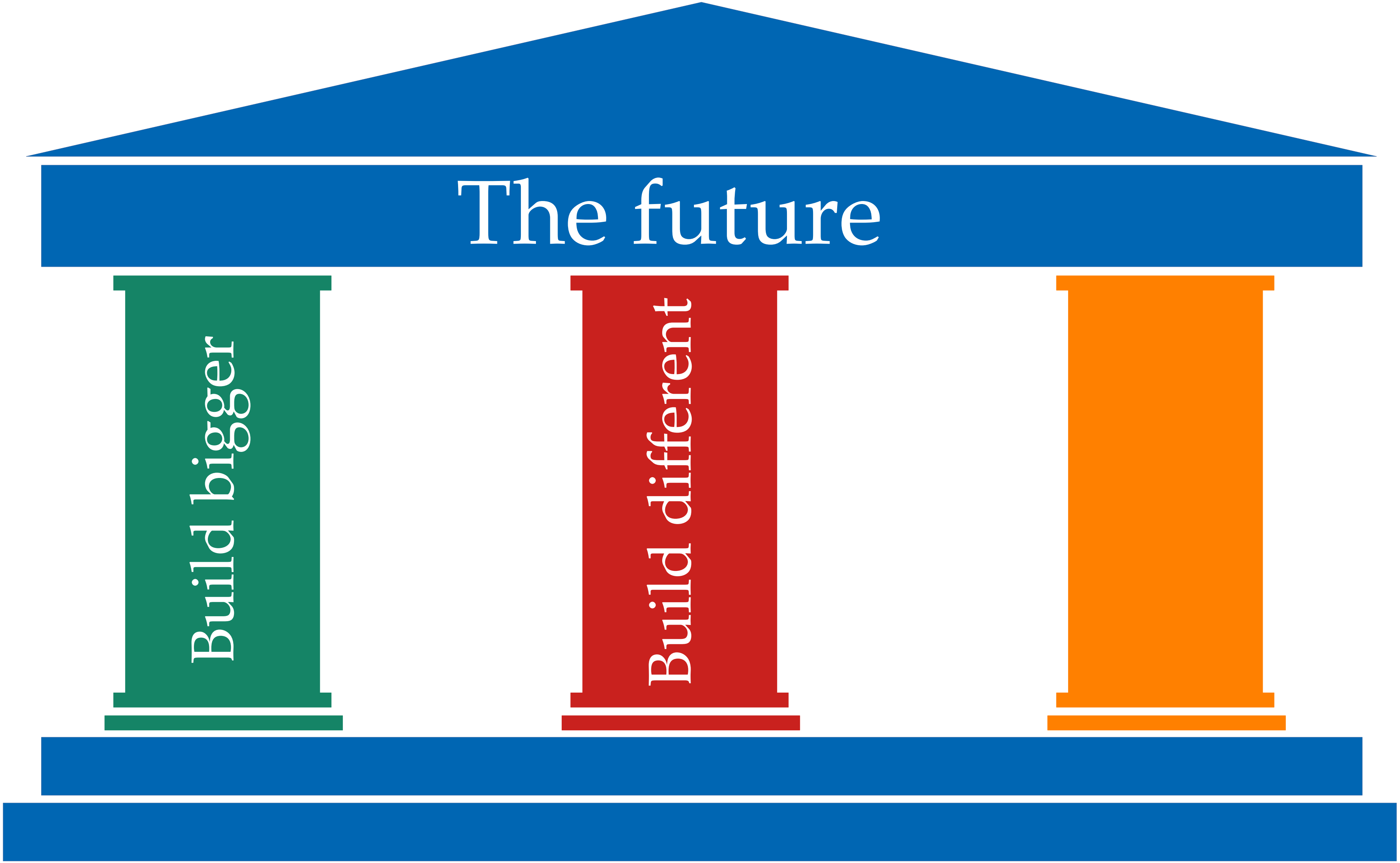
Next decade: a host of planned neutrino detectors

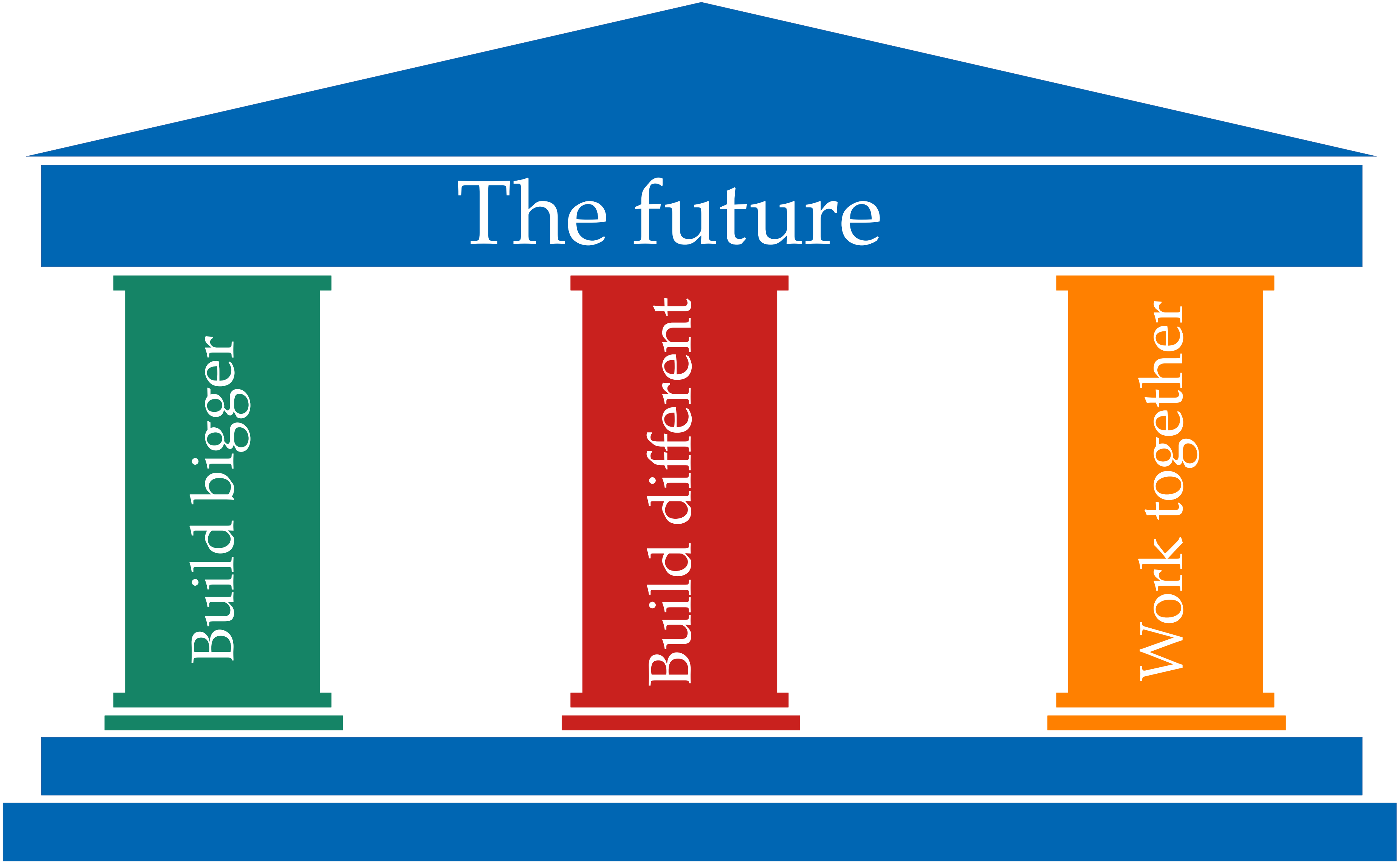


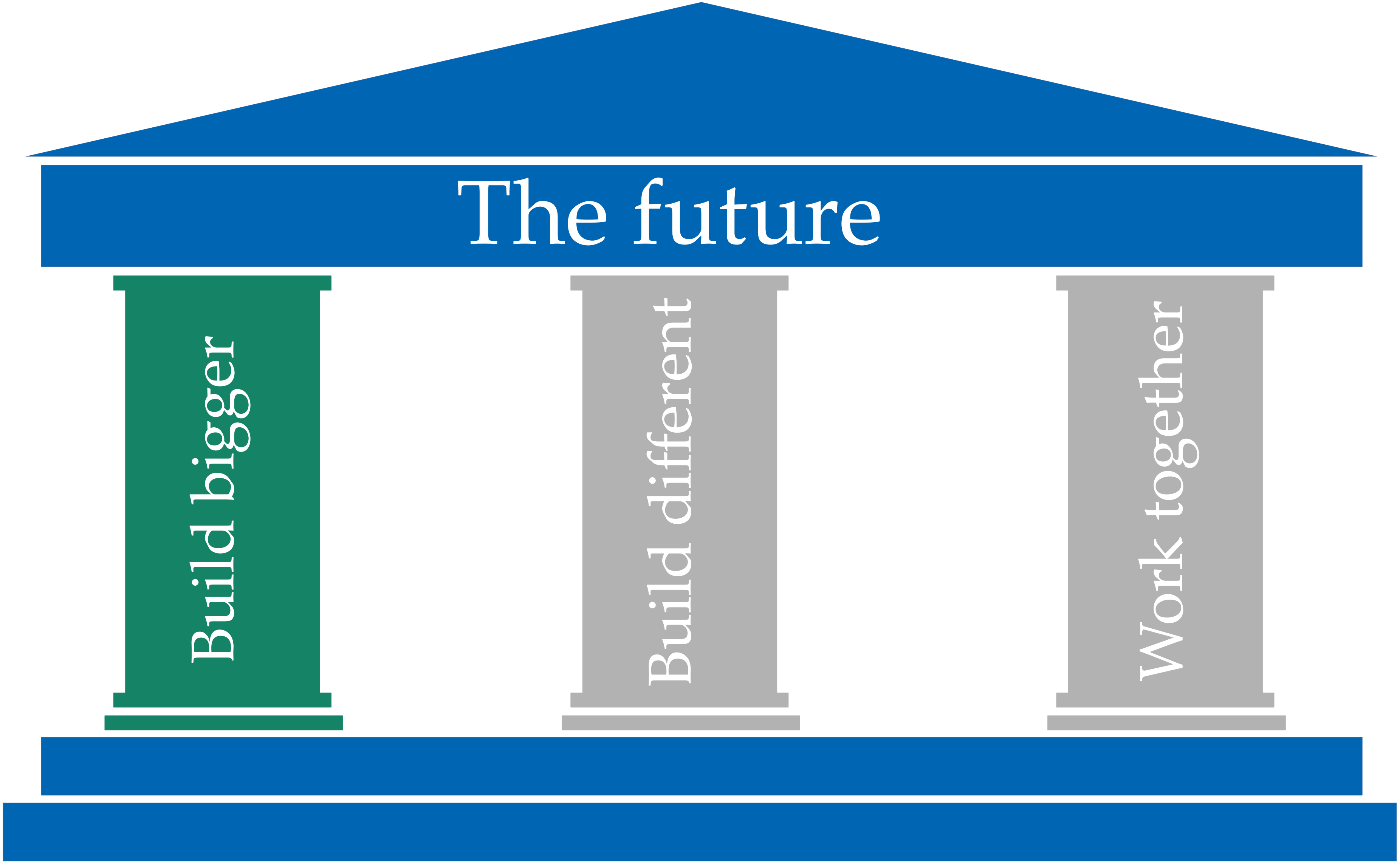
MB *et al.*, Snowmass 20201 Letter of interest


The future


The future
Build bigger


The future
Build bigger
Build different


The future
Build bigger
Build different
Work together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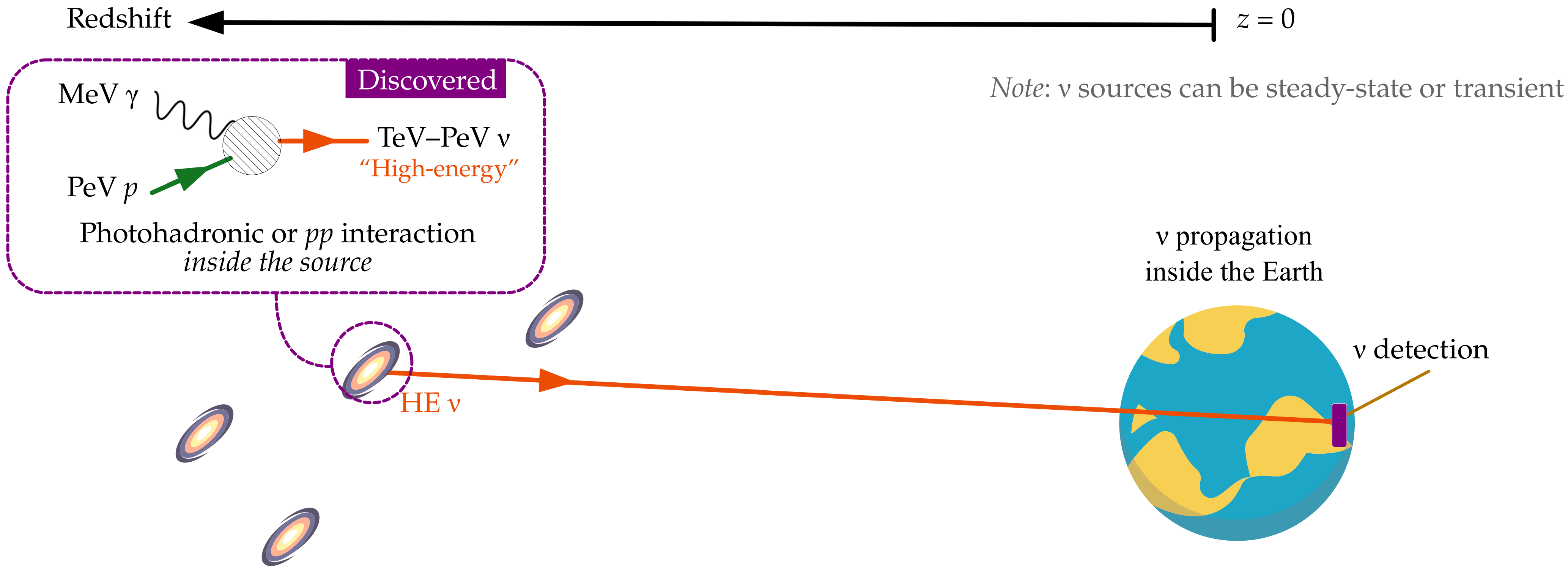
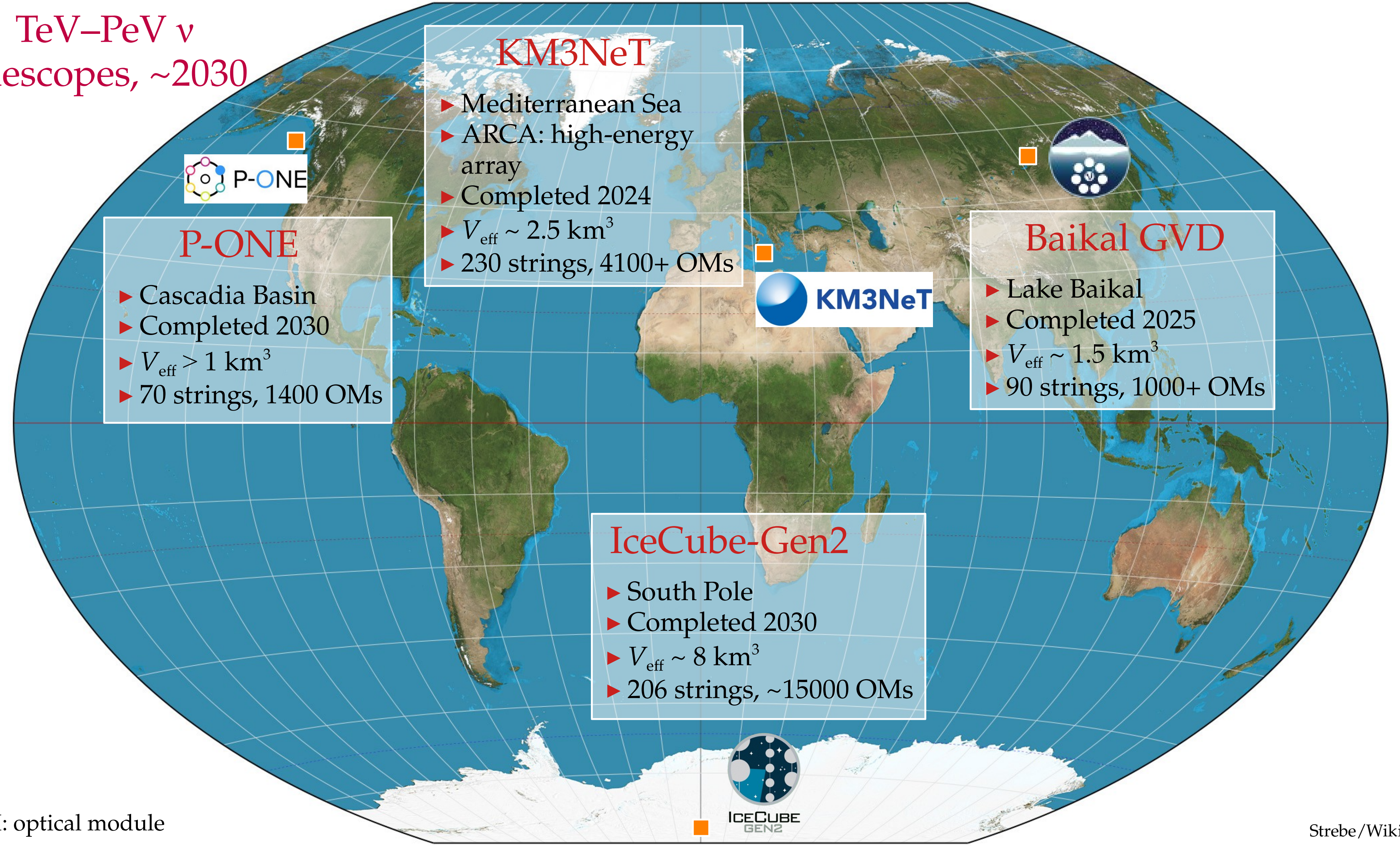

Redshift
z = 0
Discovered
Note: ν sources can be steady-state or transient
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
ν propagation
inside the Earth
ν detection
HE ν

TeV–PeV ν telescopes, ~2030



KM3NeT

- Mediterranean Sea
- ARCA: high-energy array
- Completed 2024
- $V_{\mathrm{eff}} \sim 2.5\ \mathrm{km}^3$
- 230 strings, 4100+ OMs

P-ONE

- Cascadia Basin
- Completed 2030
- $V_{\mathrm{eff}} > 1\ \mathrm{km}^3$
- 70 strings, 1400 OMs

Baikal GVD

- Lake Baikal
- Completed 2025
- $V_{\mathrm{eff}} \sim 1.5\ \mathrm{km}^3$
- 90 strings, 1000+ OMs

IceCube-Gen2

- South Pole
- Completed 2030
- $V_{\mathrm{eff}} \sim 8\ \mathrm{km}^3$
- 206 strings, ~15000 OMs

OM: optical module

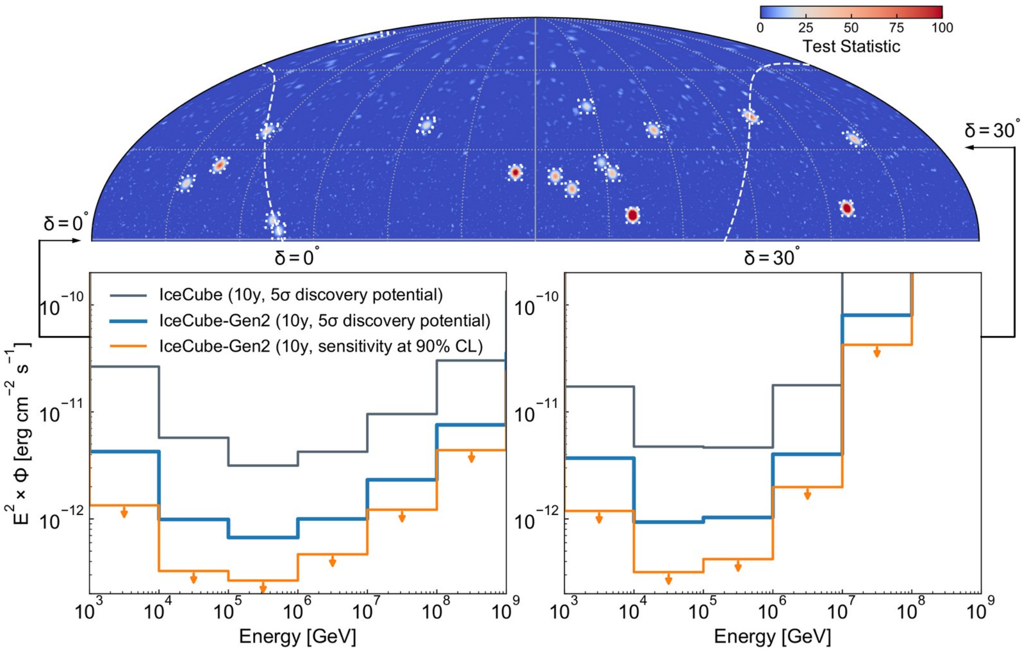
Strebe/Wikipedia

Point-source limits

Point-source limits

IceCube-Gen2 (optical)

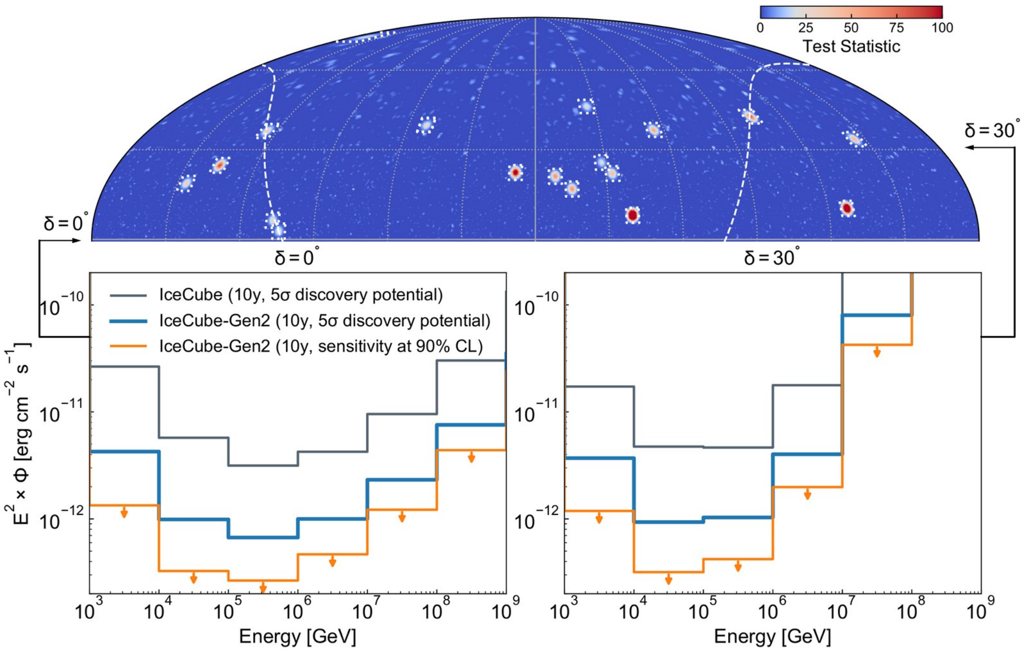
Northern sky



IceCube-Gen2, *J. Phys. G* 2021

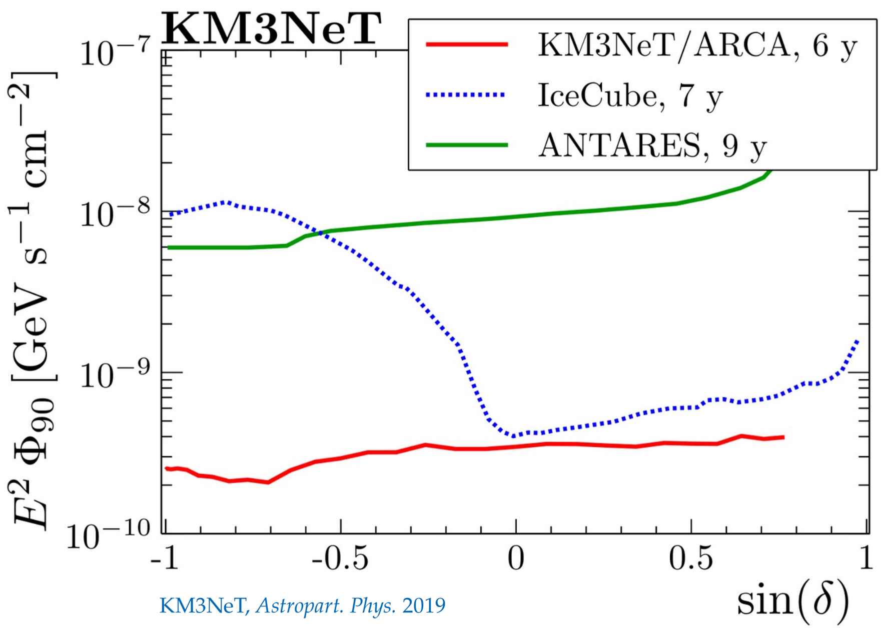
Point-source limits

IceCube-Gen2 (optical)
Northern sky



IceCube-Gen2, *J. Phys. G* 2021

KM3NeT
Southern sky



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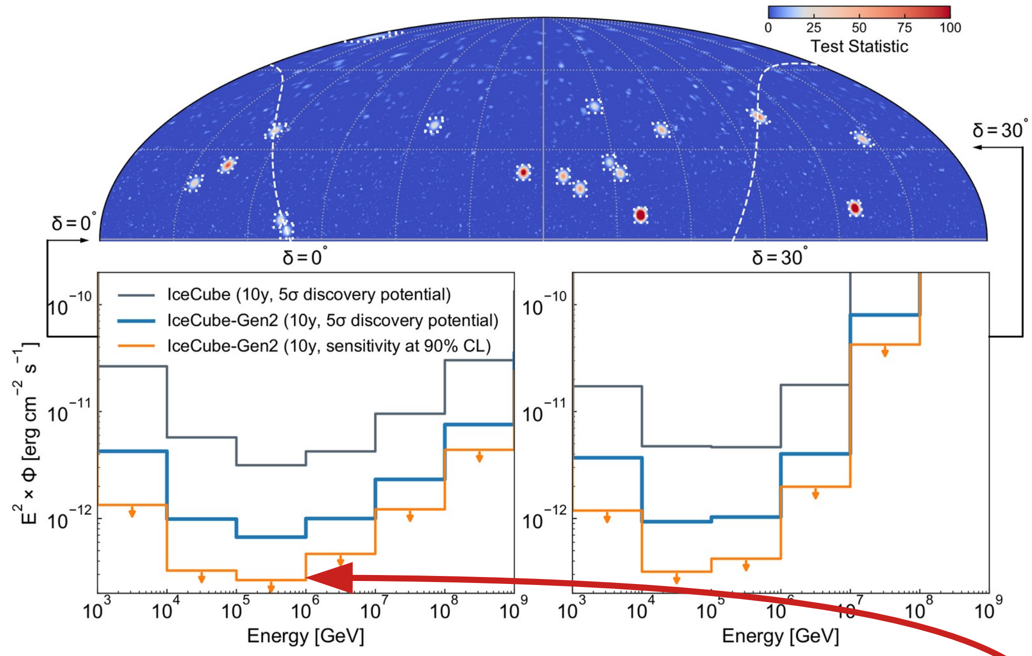

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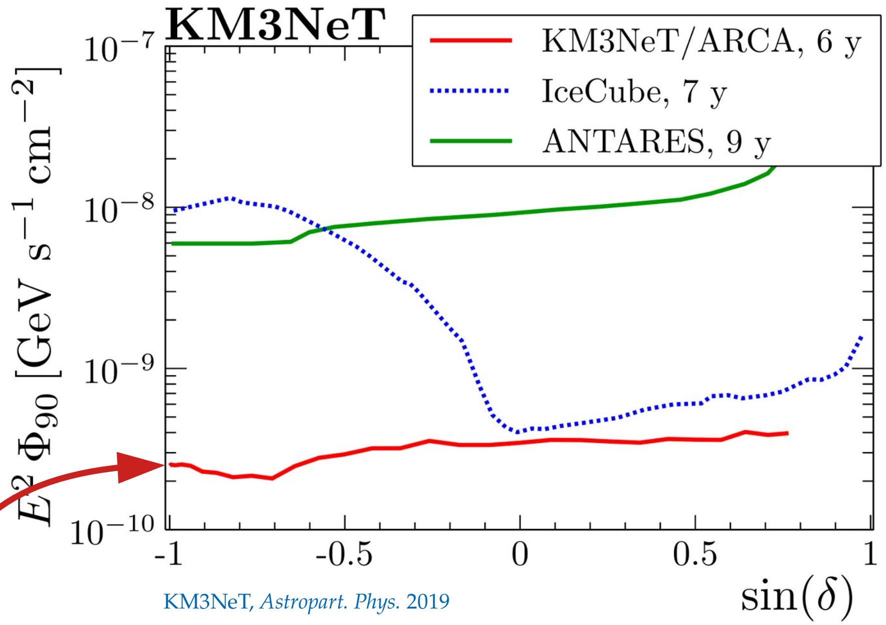
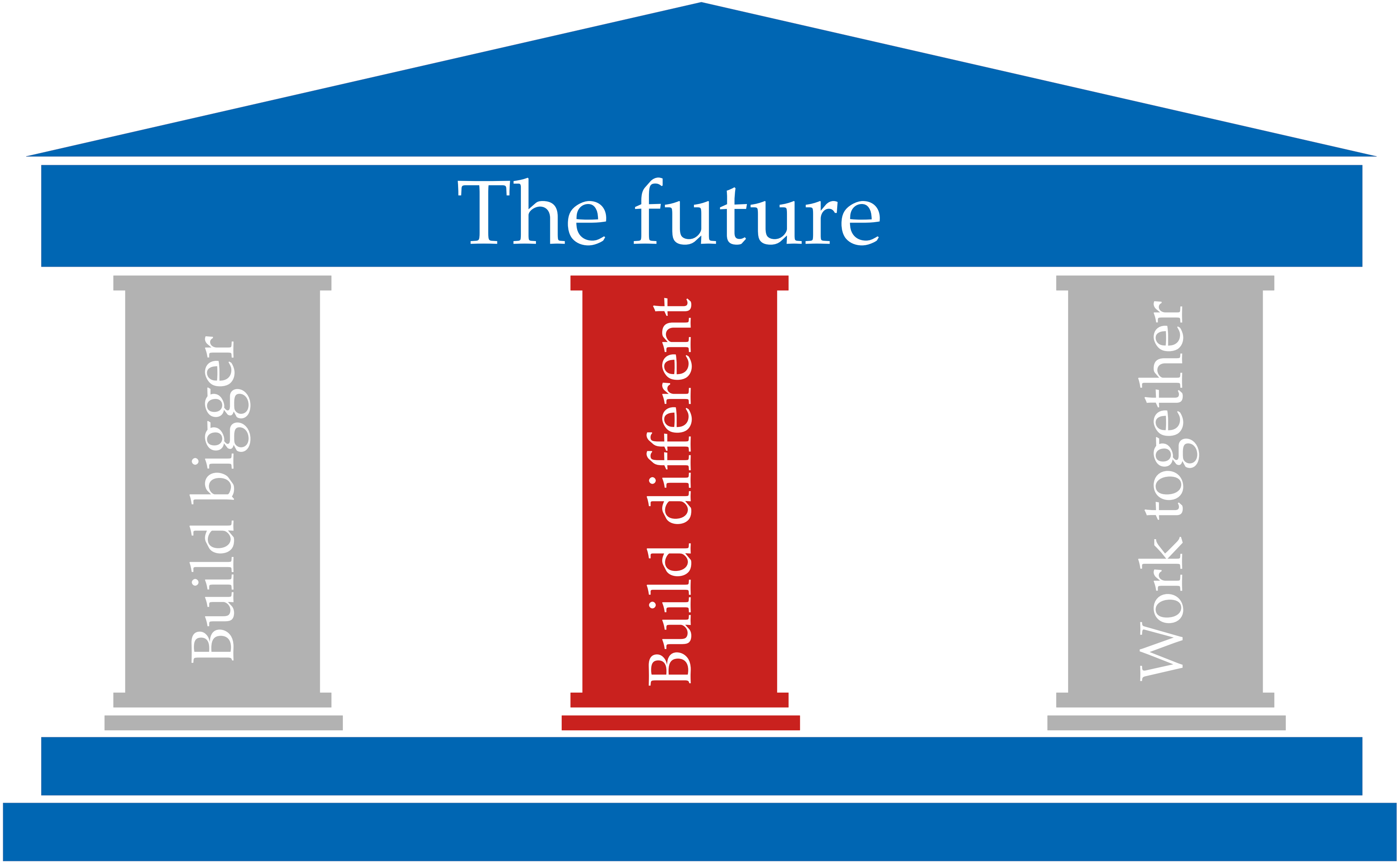


KM3NeT, *Astropart. Phys.* 2019

We will reach comparable sensitivity in both hemispheres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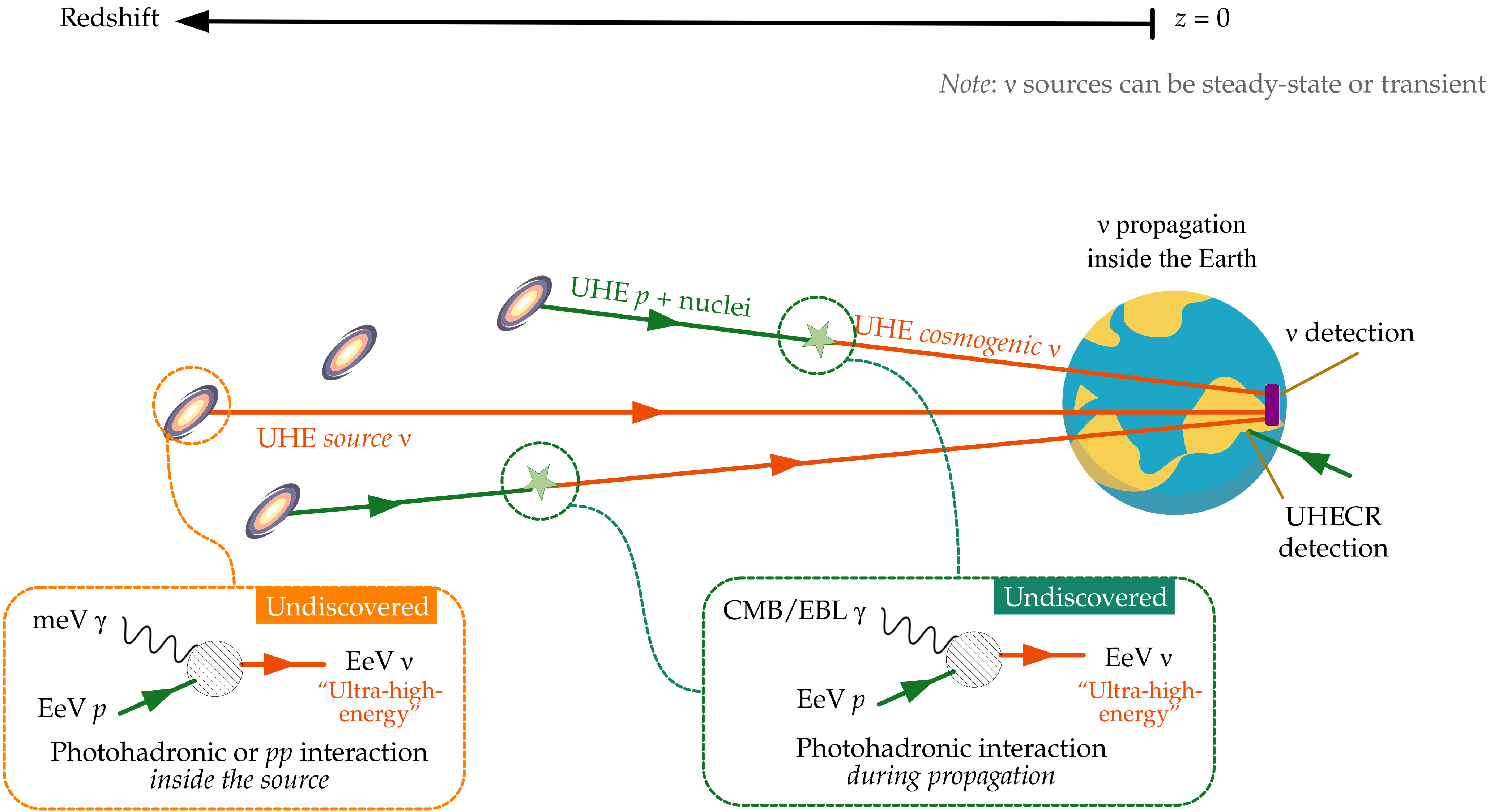

Redshift
z = 0
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
UHE p + nuclei
UHE cosmogenic ν
ν detection
UHE source ν
UHECR
detection
Undiscovered
meV γ
EeV ν
"Ultra-high-
energy"
EeV p
Photohadronic or pp interaction
inside the source
Undiscovered
CMB/EBL γ
EeV ν
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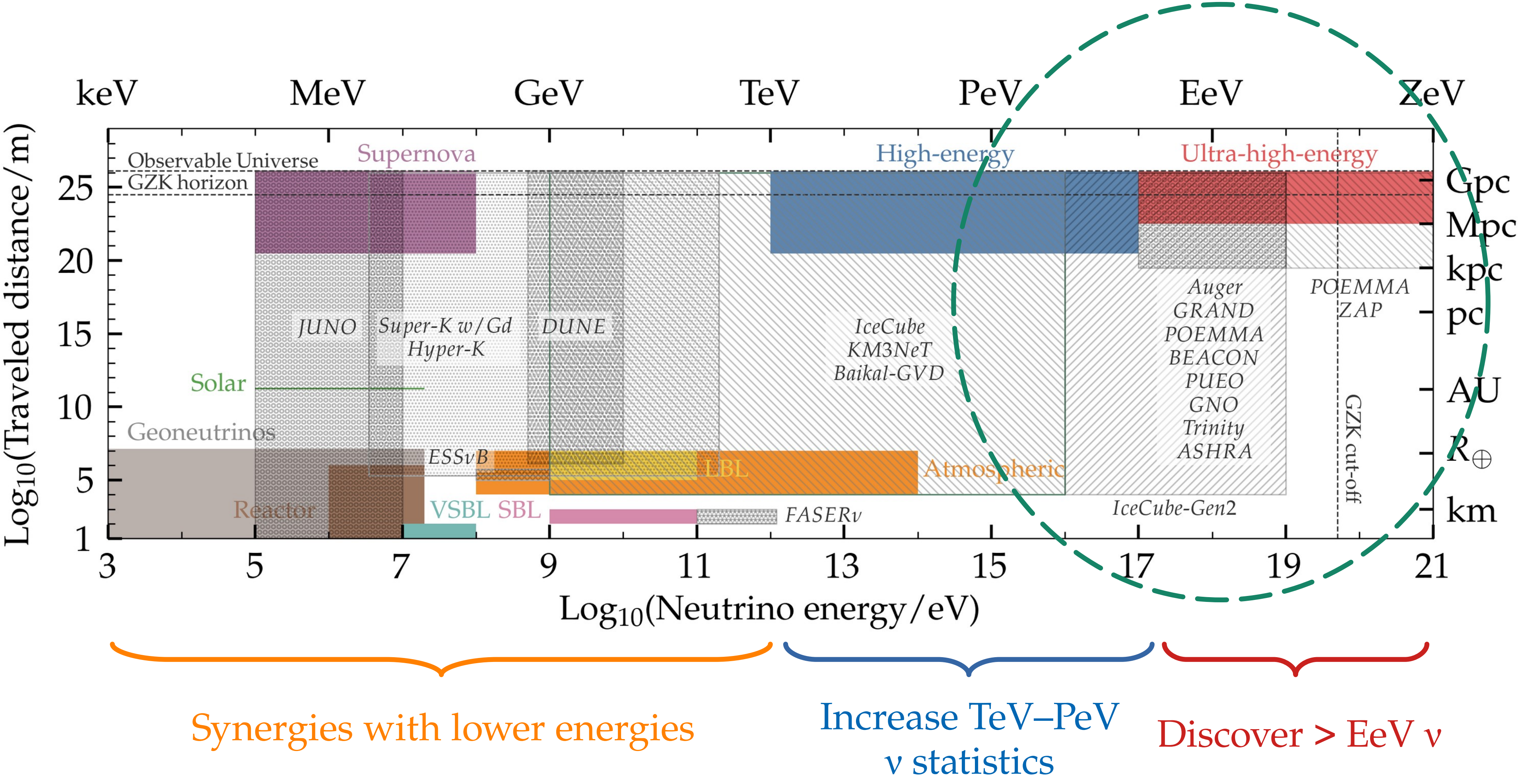
Photohadronic interaction
during propagation

Next decade: a host of planned neutrino detectors



MB *et al.*, Snowmass 20201 Letter of interest

Detection of UHE ν in ice and water

Optical detection in ice or water

⚙ IceCube → IceCube-Gen2 🚧
⚙ ANTARES → KM3NeT 🚧
⚙ NT200+ → Baikal GVD 🚧
P-ONE 🚧

Radio detection in ice

ARA ⚙
ARIANNA ⚙
RNO-G 🚧
IceCube-Gen2 🚧

Radio detection from the air or space

✓ ANITA → PUEO 🚧
NuMoon ✓

Detection of air showers from UHE ν_τ

Surface particle detection

⚙ Auger → AugerPrime 🚧
⚙ TA → TA×4 🚧
HAWC ⚙
TAMBO 🚧

Radio detection in the atmosphere

✓ ANITA → PUEO 🚧
BEACON 🚧
GRAND 🚧
TAROGE & TAROGE-M 🚧

Air-shower imaging from the ground

Trinity 🚧
MAGIC ⚙
CTA 🚧
ASHRA NTA 🚧

Cherenkov/fluorescence from air or space

EUSO-SPB2 🚧
POEMMA 🚧

Denton, **MB**, Wissel *et al.*, Snowmass 20201 Letter of interest

⚙ Operating 🚧 Proposed or under construction ✓ Completed

PHYSICS

Searching for the Universe's Most Energetic Particles, Astronomers Turn on the Radio

New radio-based observatories could soon detect ultrahigh-energy neutrinos, opening a new window on extreme cosmic physics

By Katrina Miller on April 27, 2021

Artist's composite of the IceCube Neutrino Observatory in Antarctica, accompanied by a distant astrophysical source emitting neutrinos that are detected in IceCube's subsurface sensors. Credit: IceCube and NSF

Ever since their discovery in the 1960s, ultrahigh-energy cosmic rays have

Katrina Miller for *Scientific American*, April 27, 2021 [link]

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ARIANNA

RNO-G

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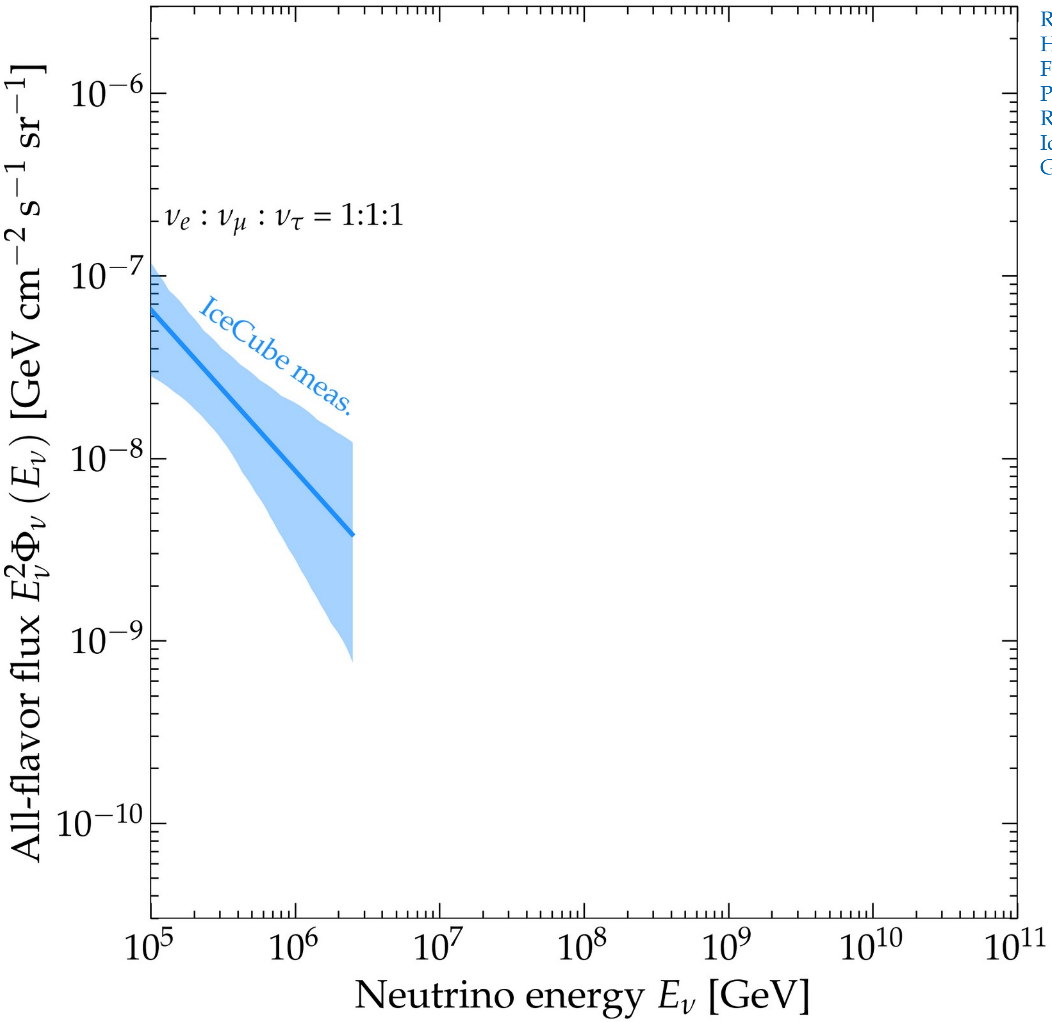
Denton, **MB**, Wissel *et al.*, Snowmass 20201 Letter of interest

UHE neutrinos: *steady-state sources*



Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
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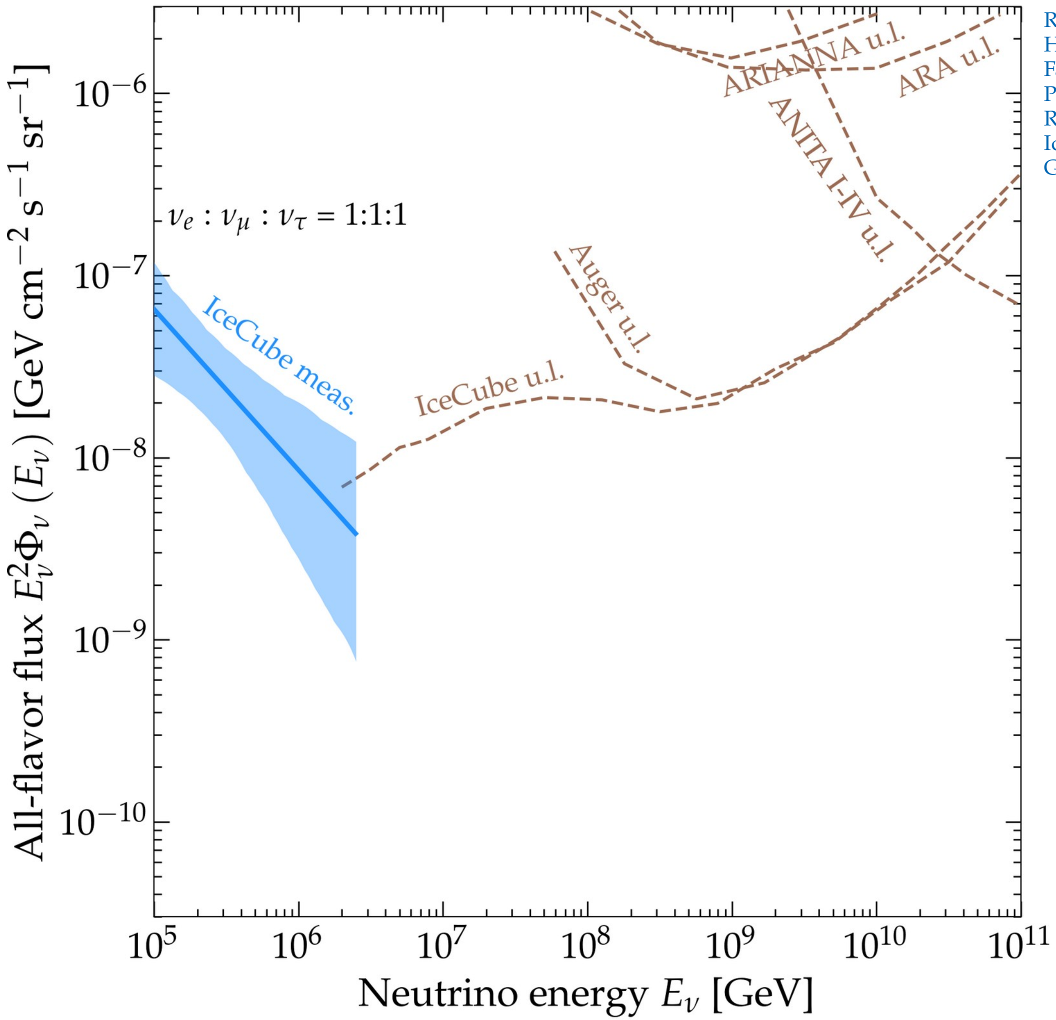

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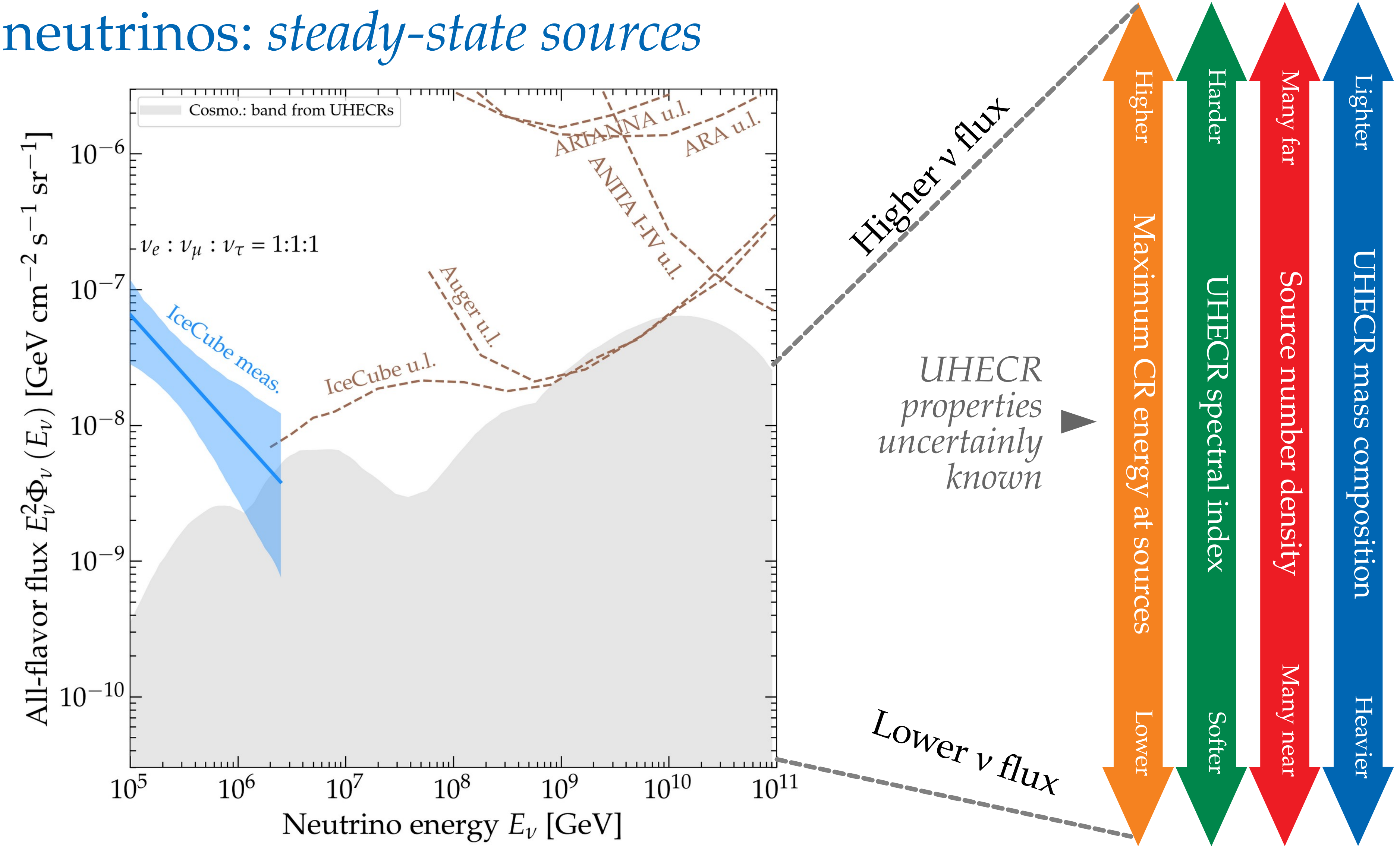

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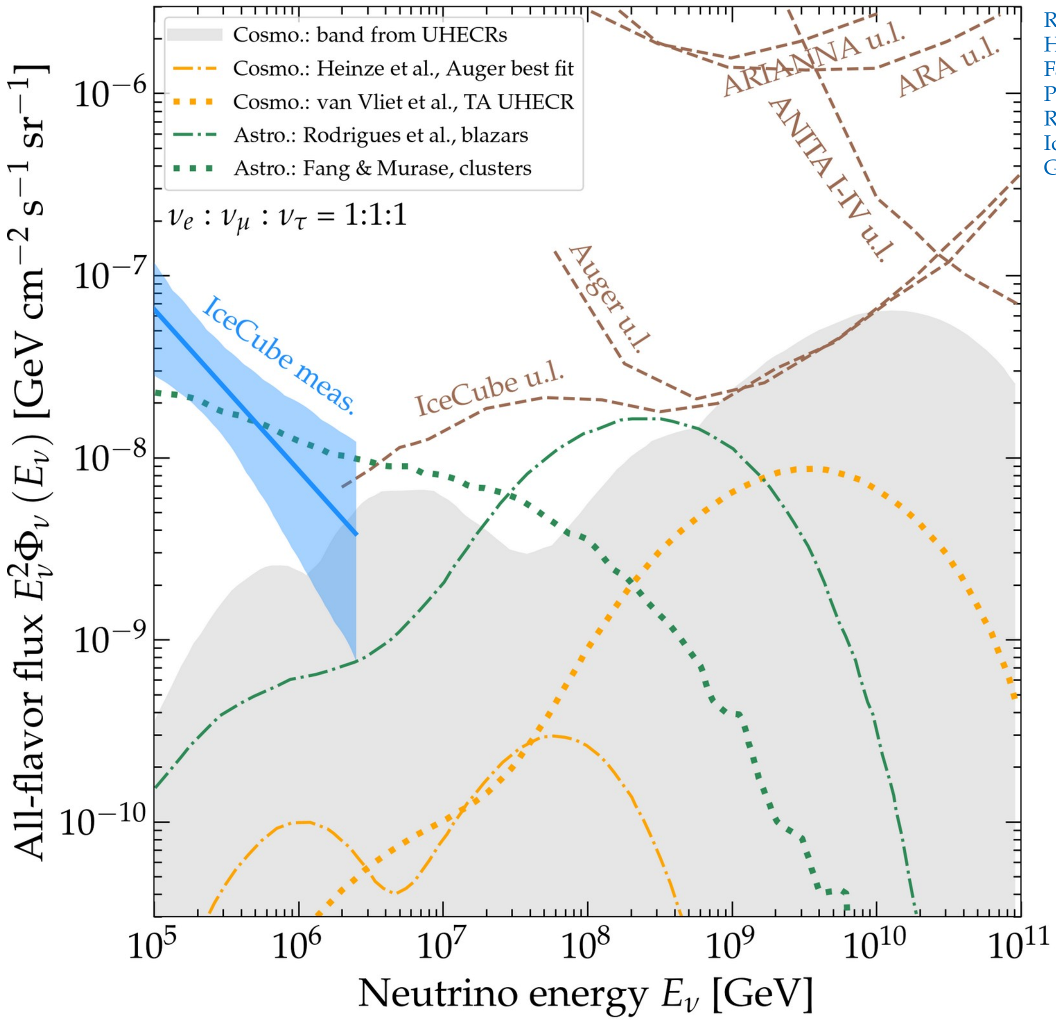

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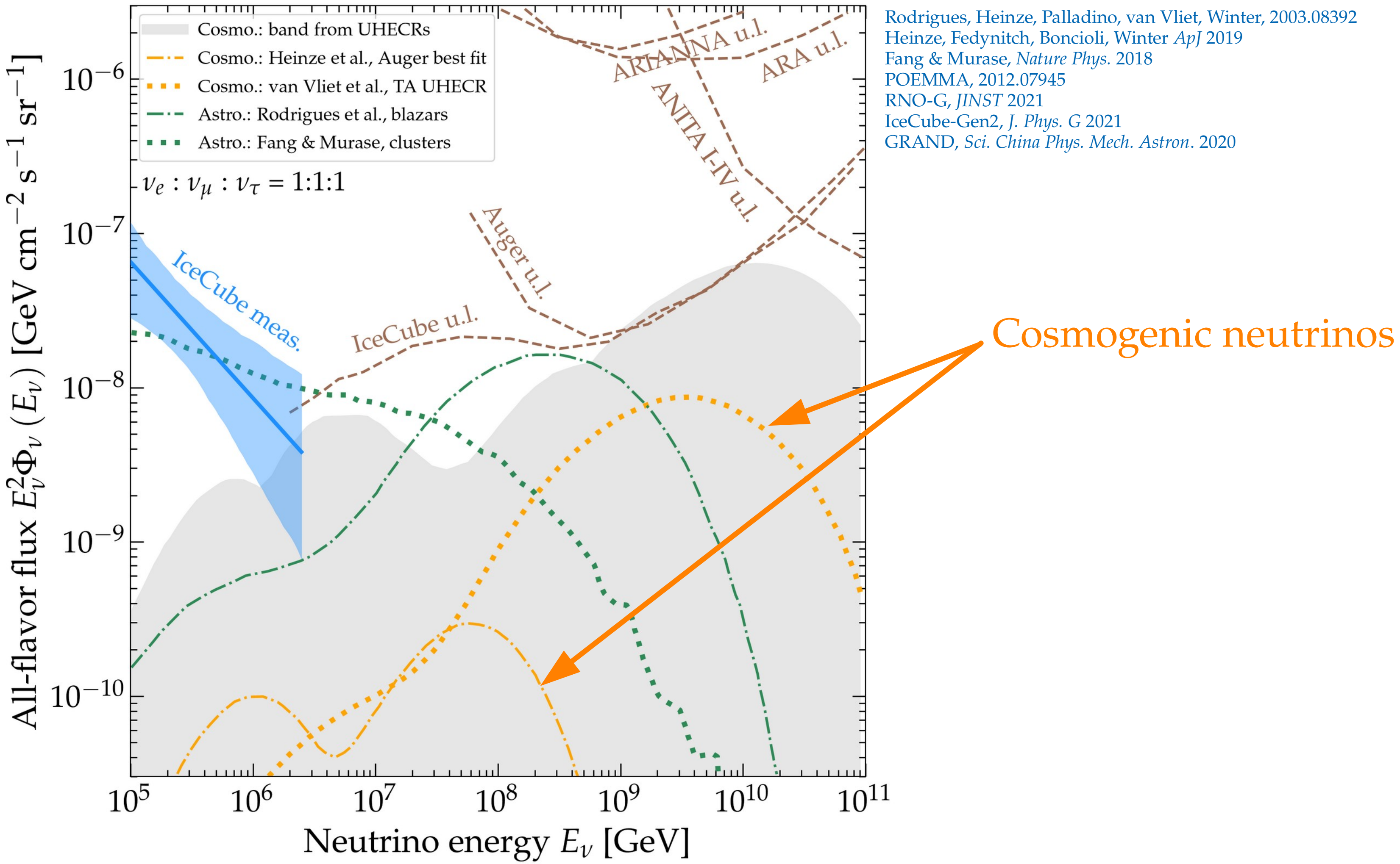

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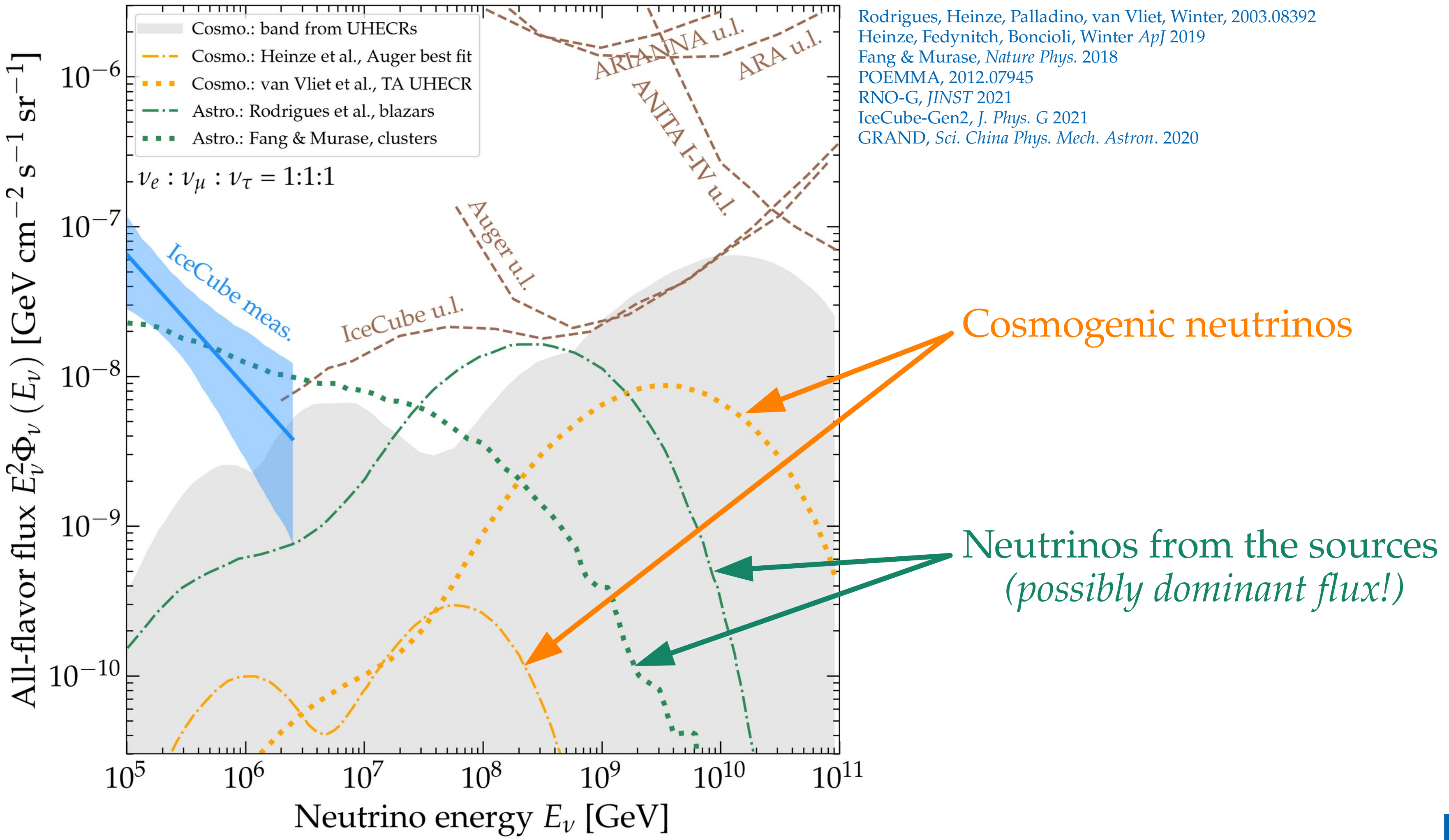

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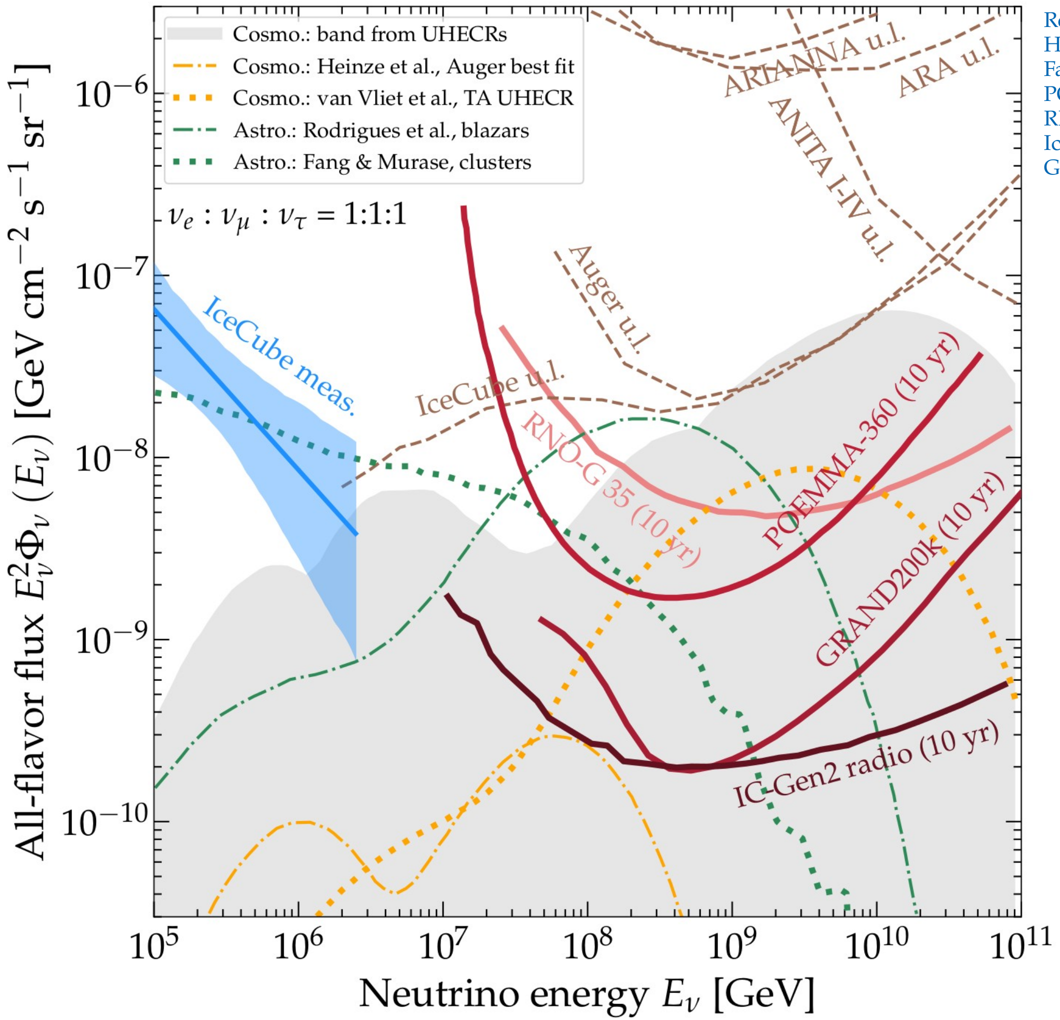

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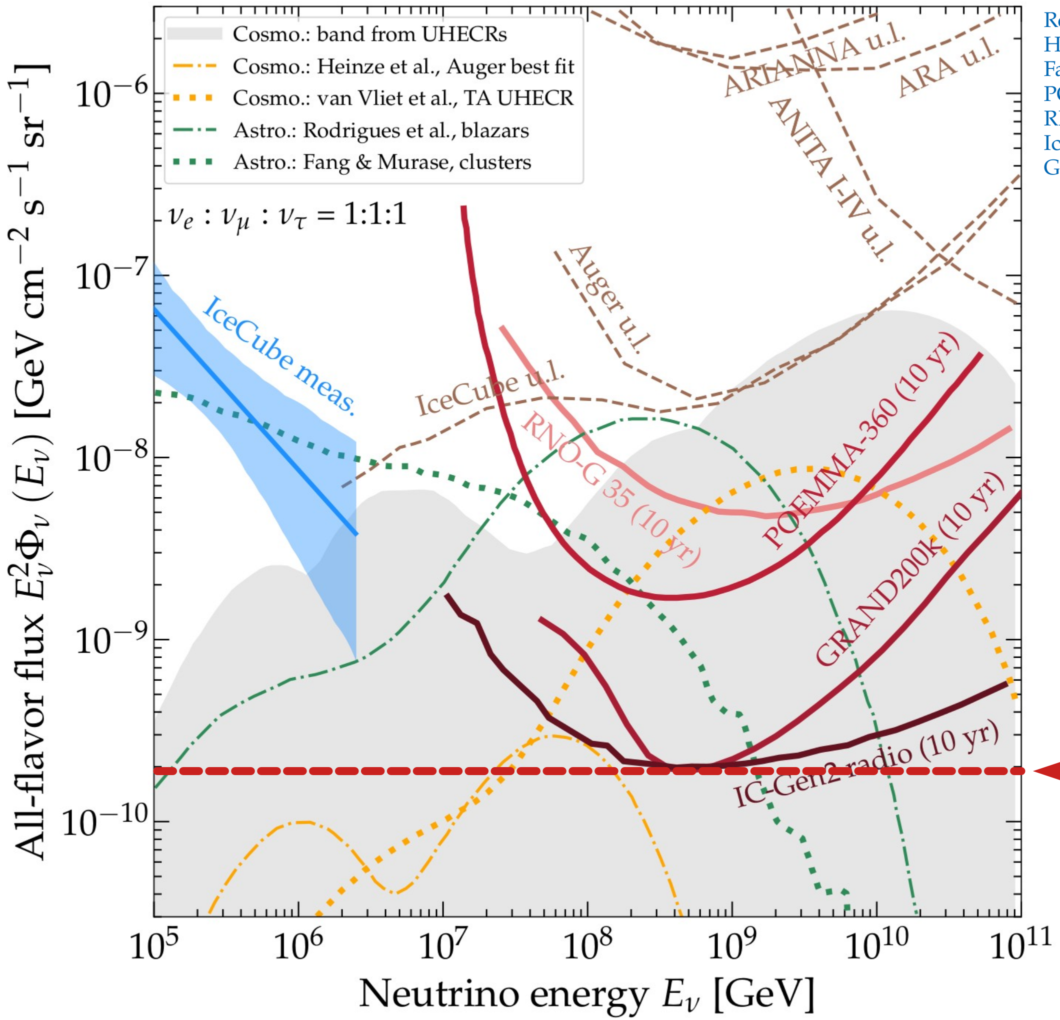

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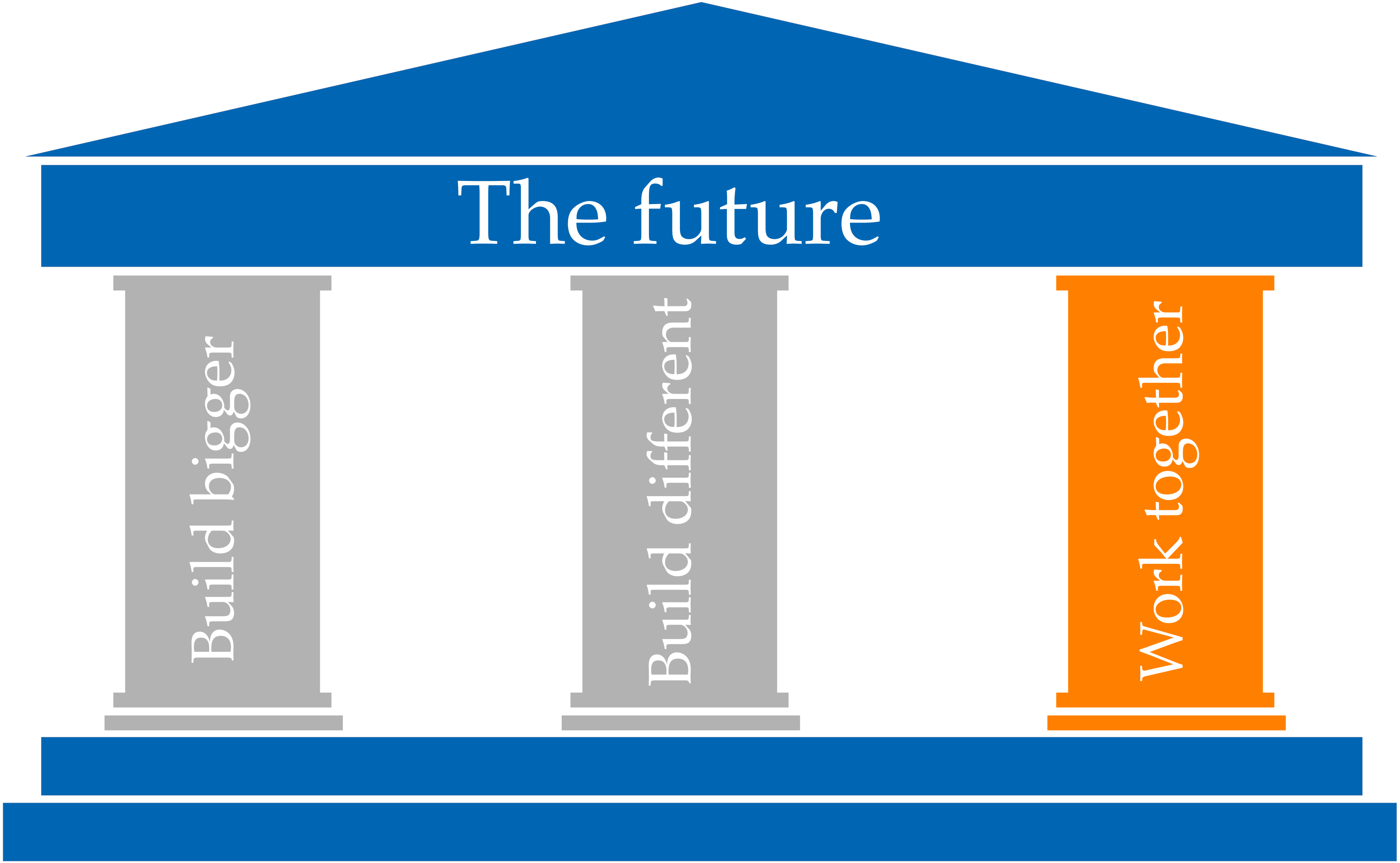
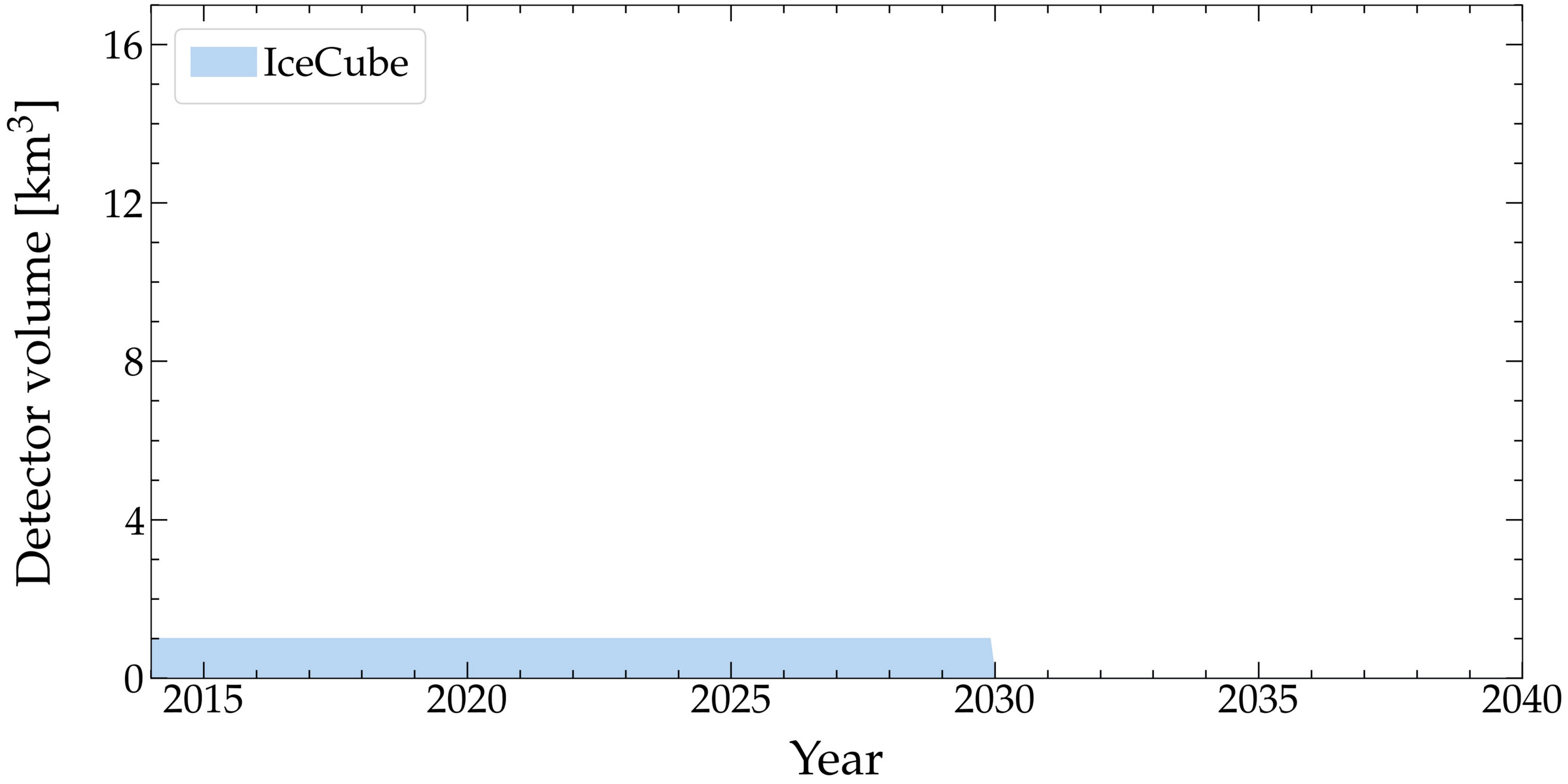
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron*. 2020

Ultimate target sensitivity for next-gen detectors

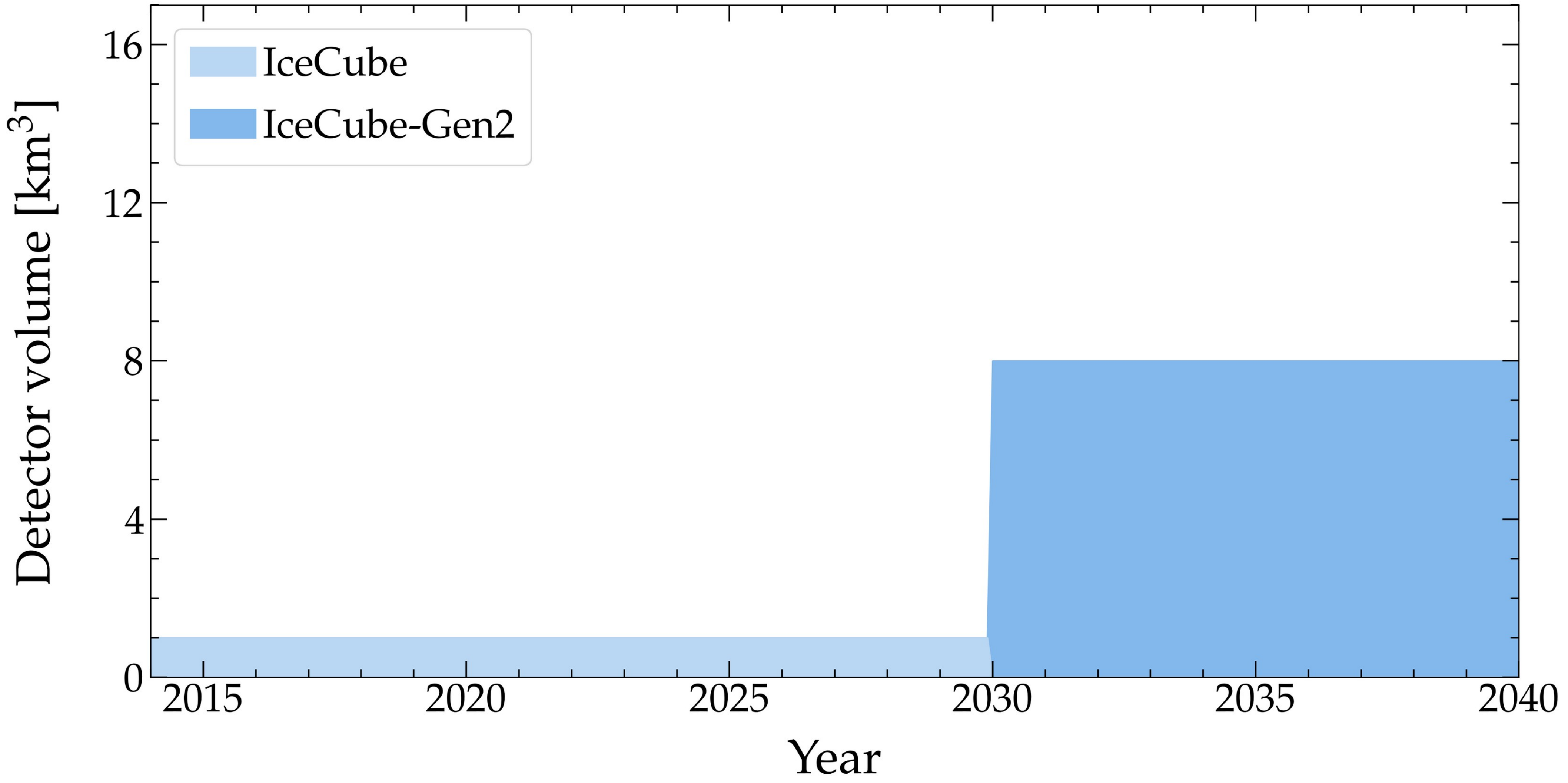
(if protons are ~10% of the highest-energy UHECRs)



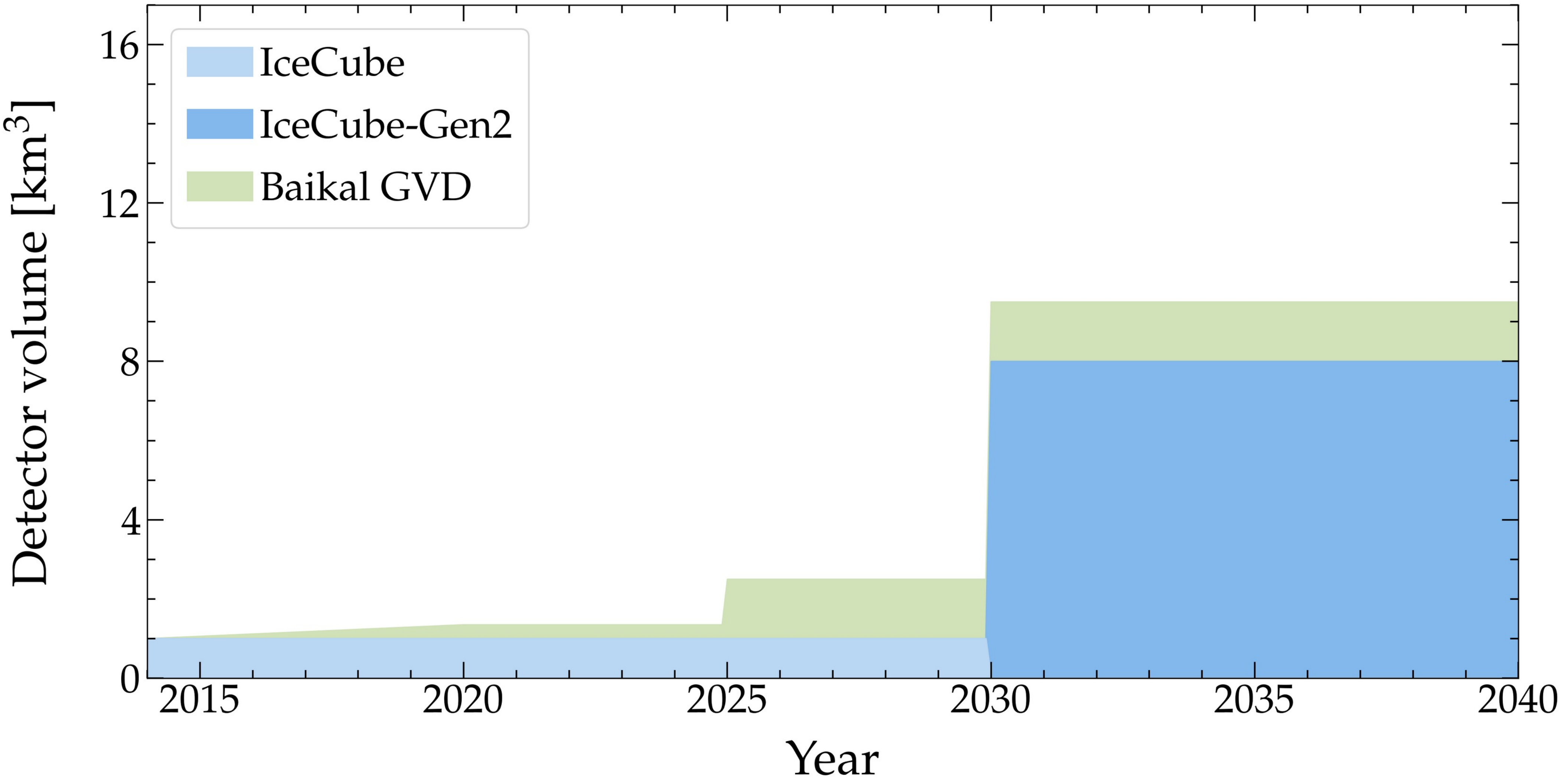
The future
Build bigger
Build different
Work together



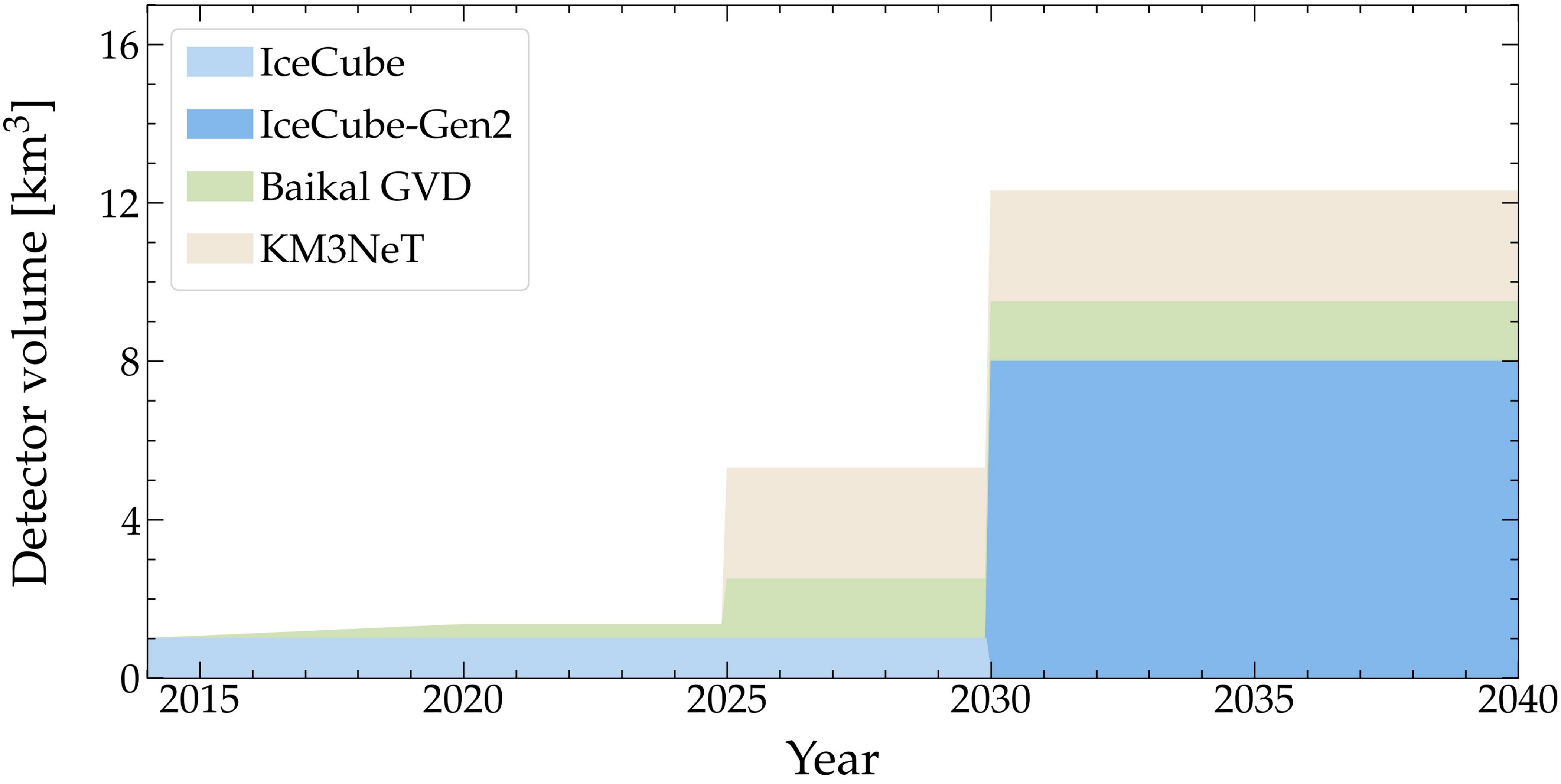
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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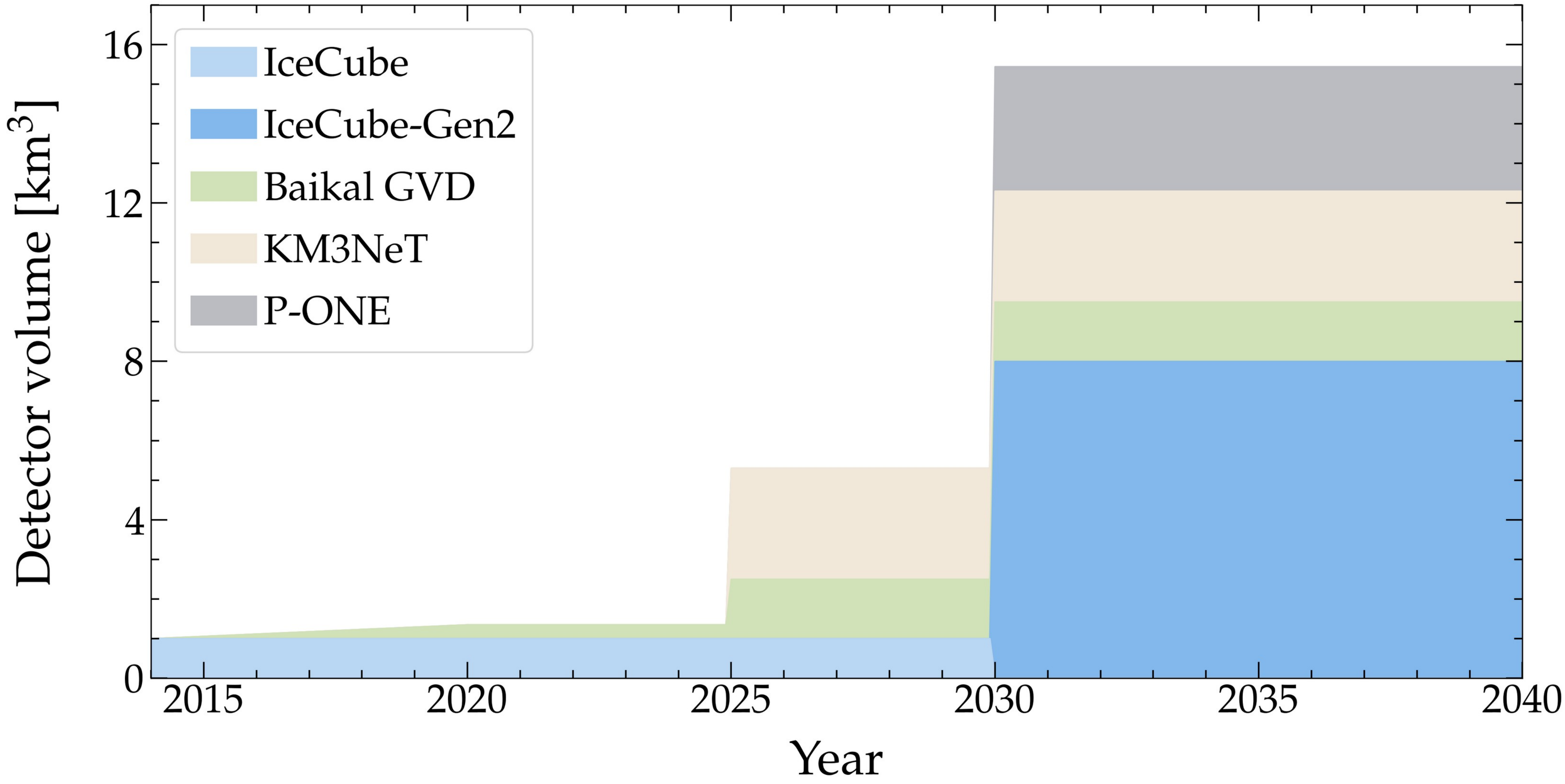

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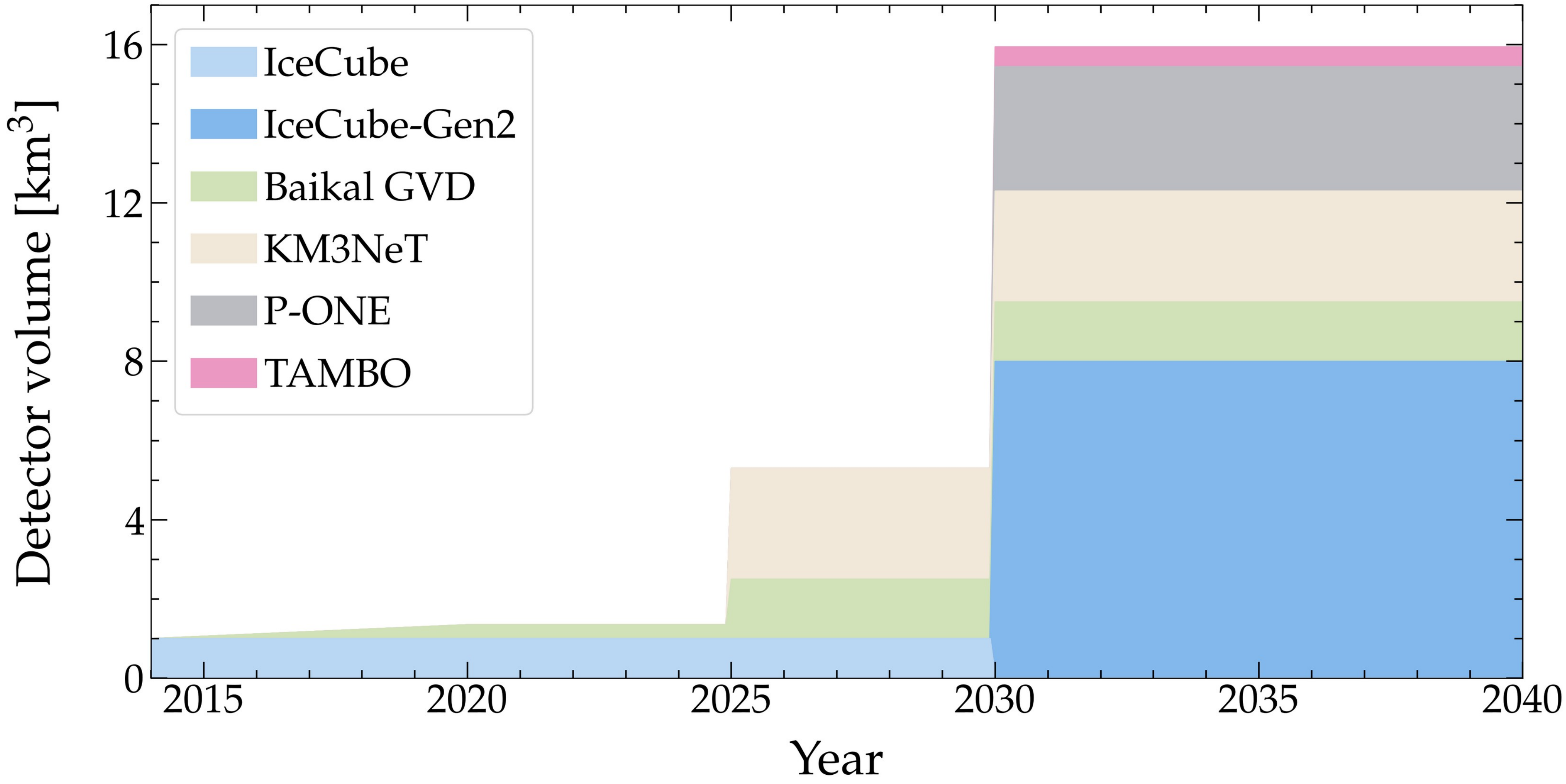

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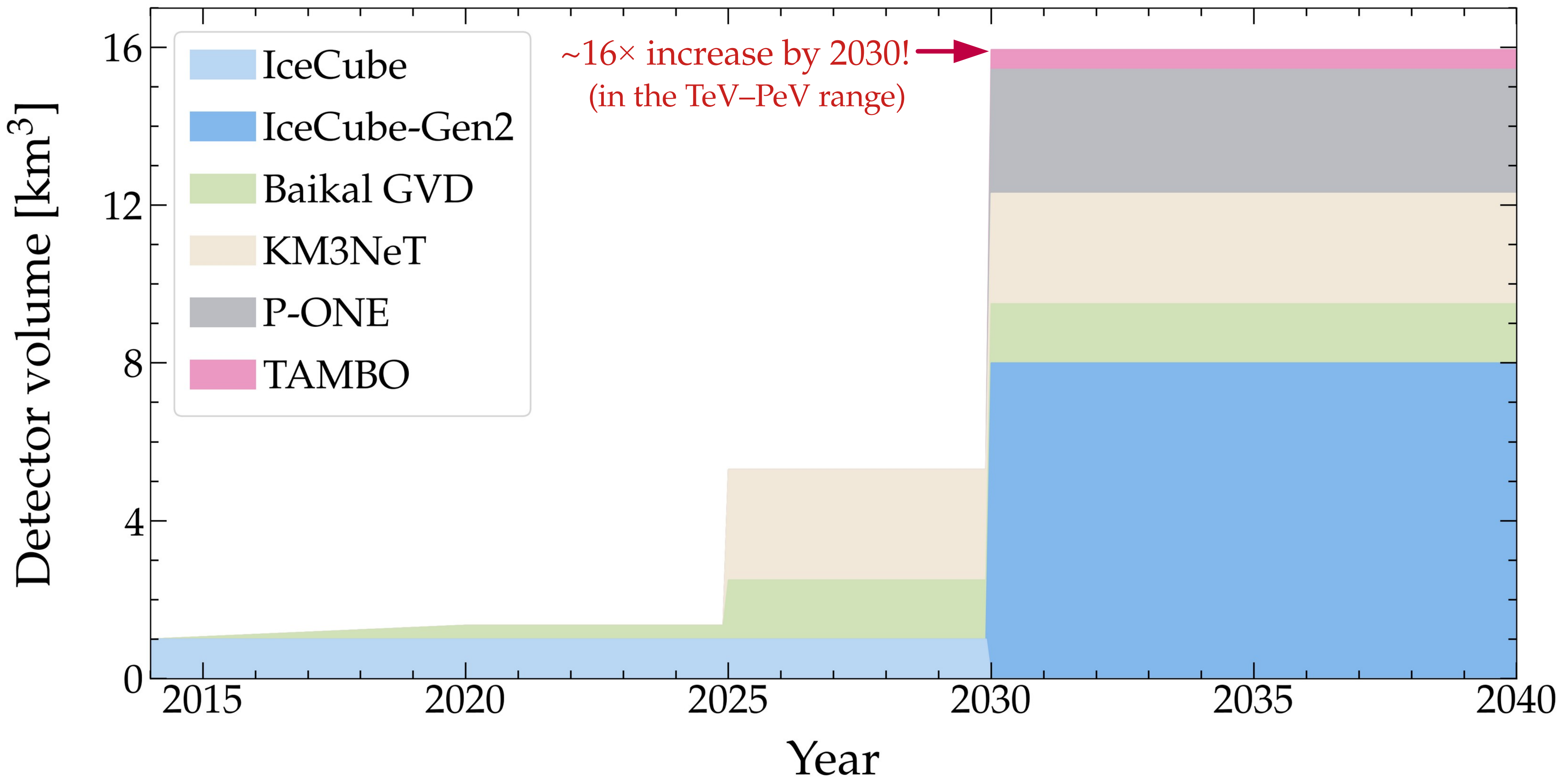
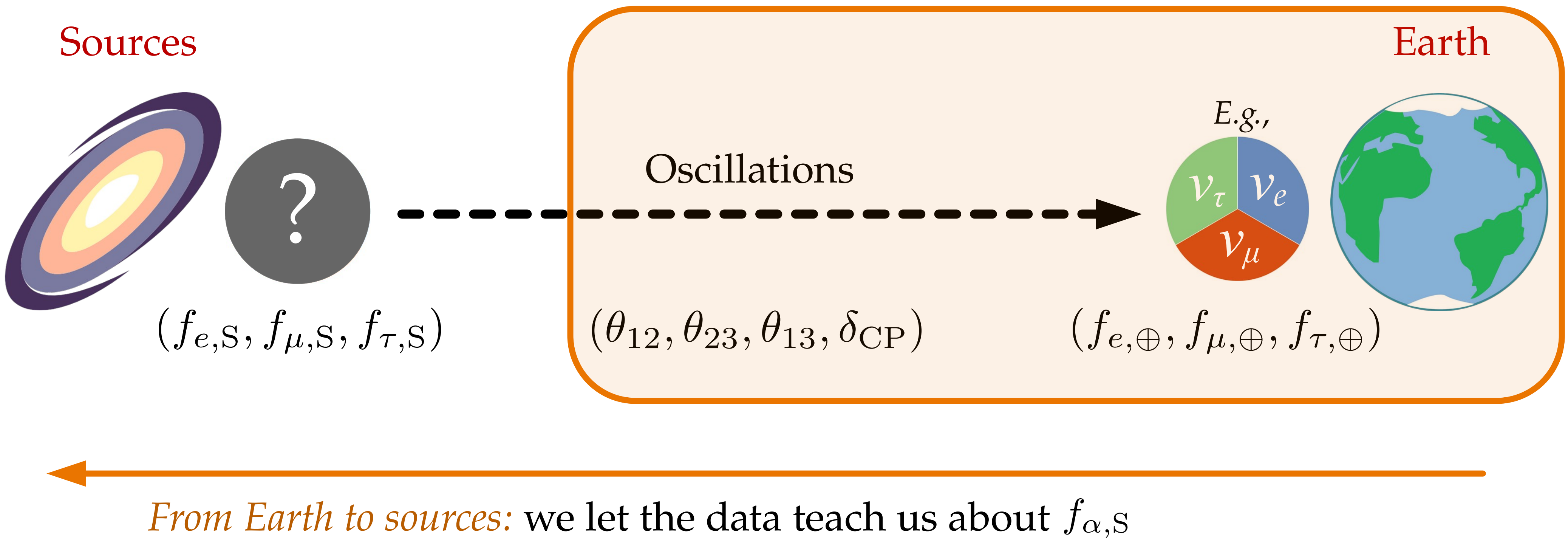


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



Sources
Earth
E.g.,
Oscillations
ν_τ ν_e ν_μ
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

Inferring the flavor composition at the sources

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

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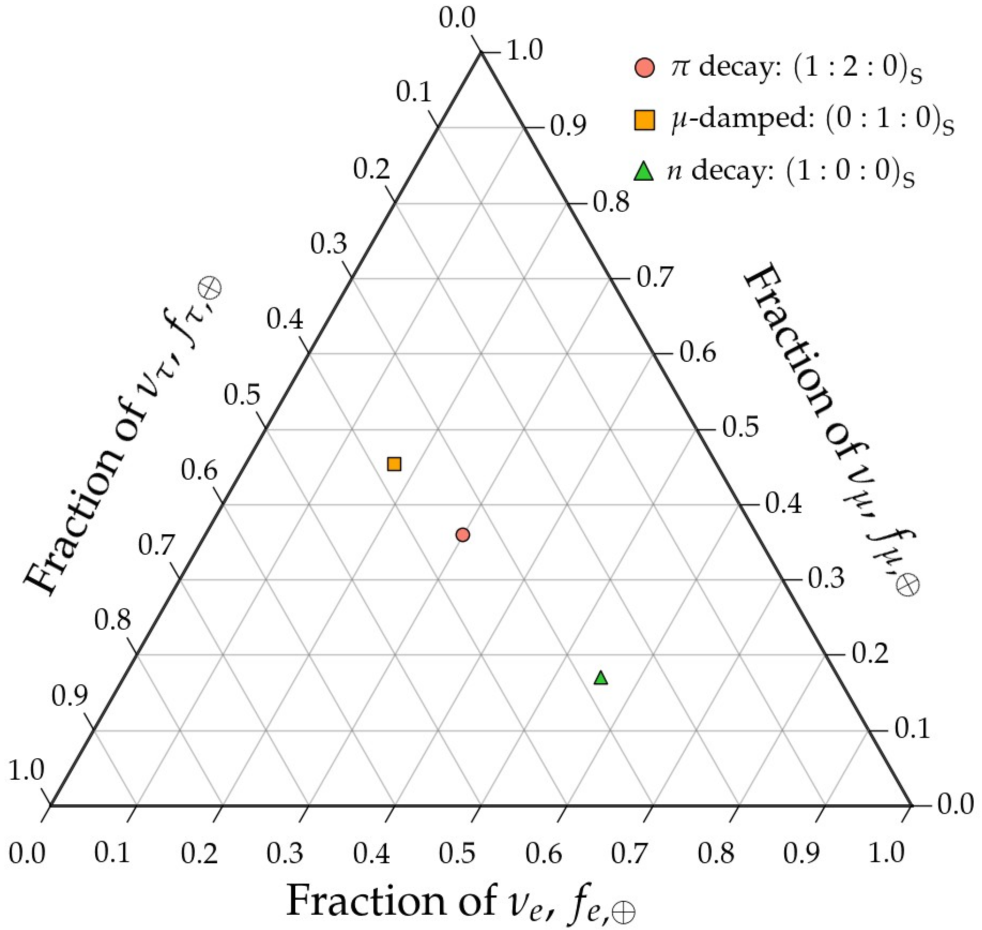

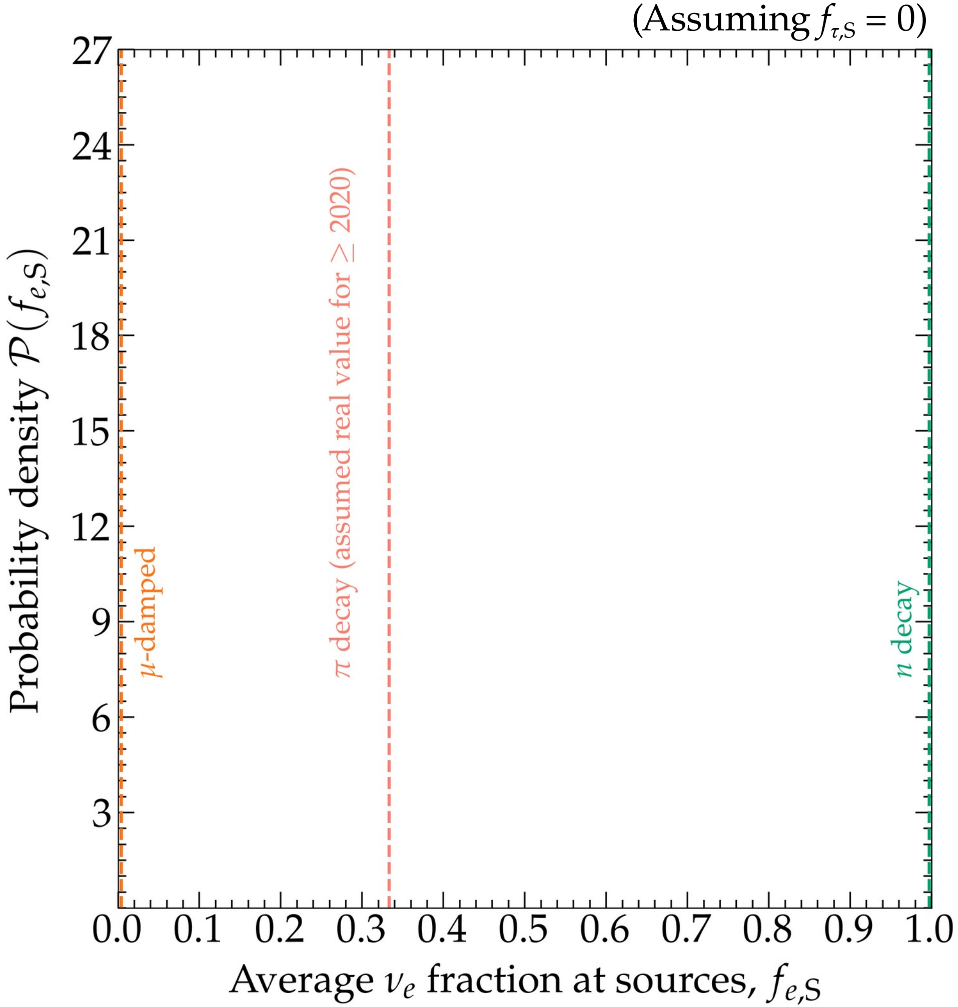

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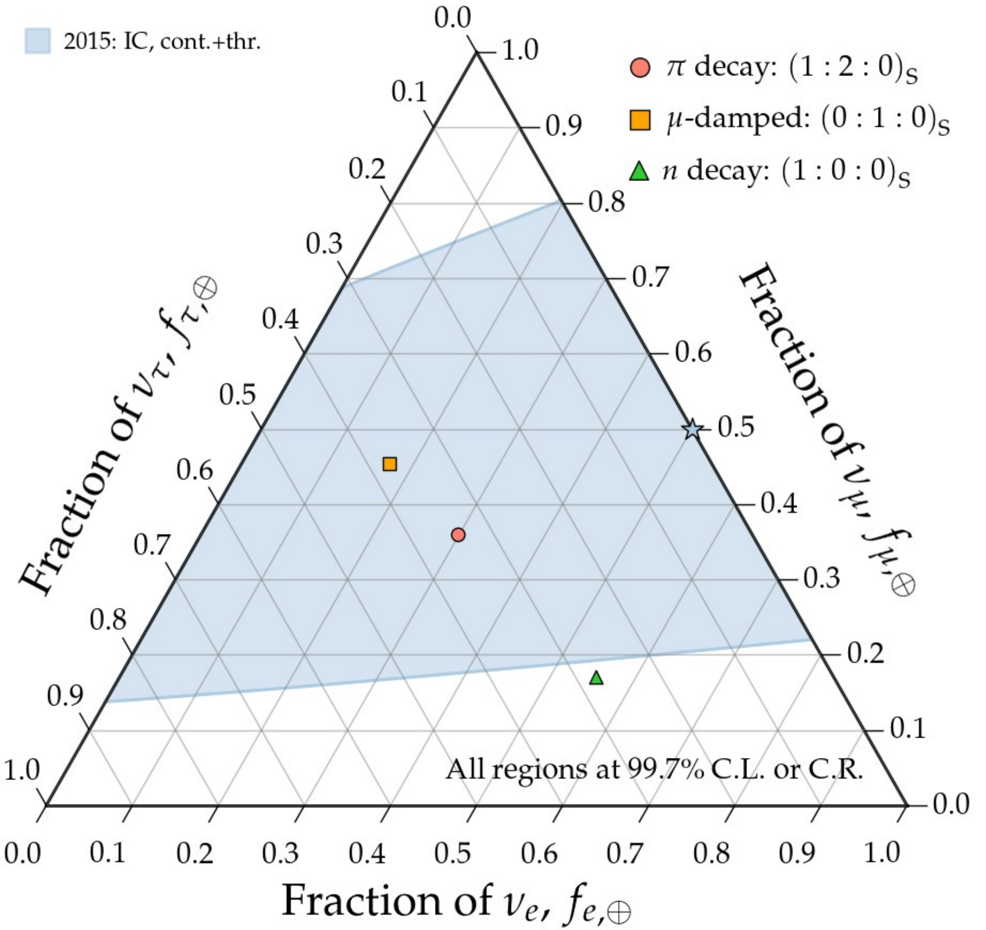
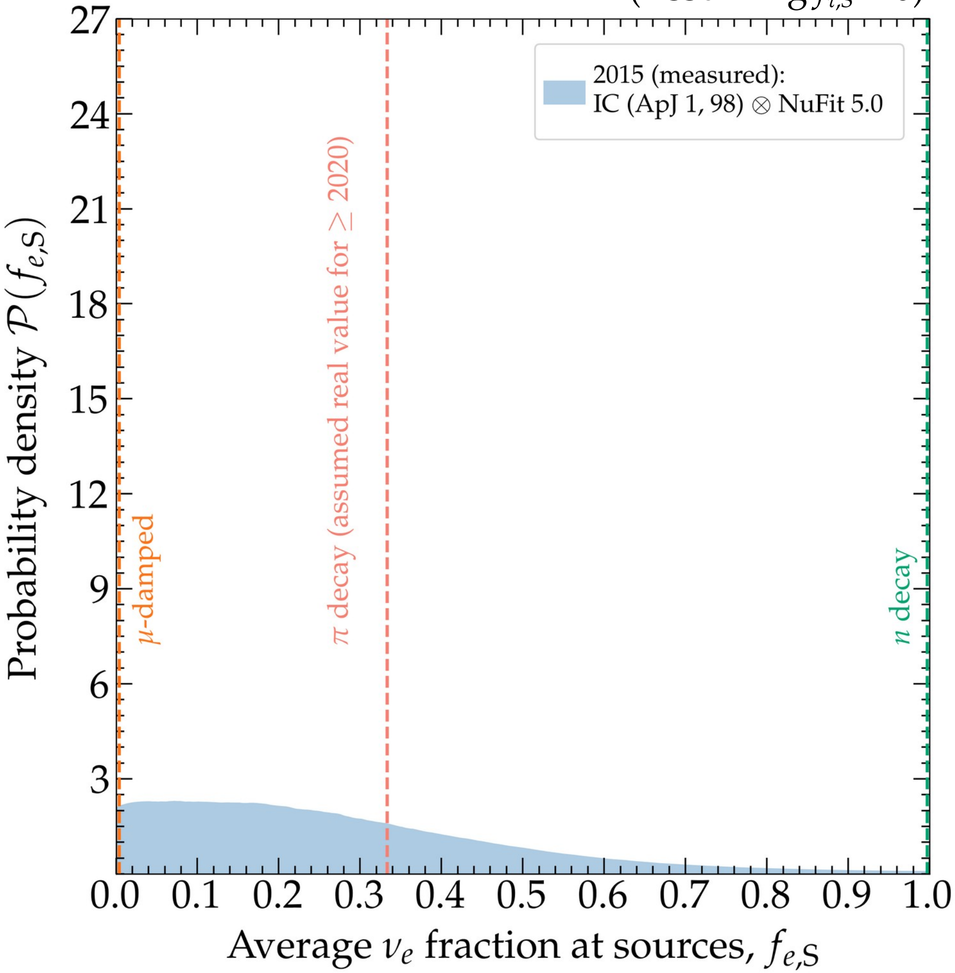


(Assuming $f_{\tau,S} = 0$)



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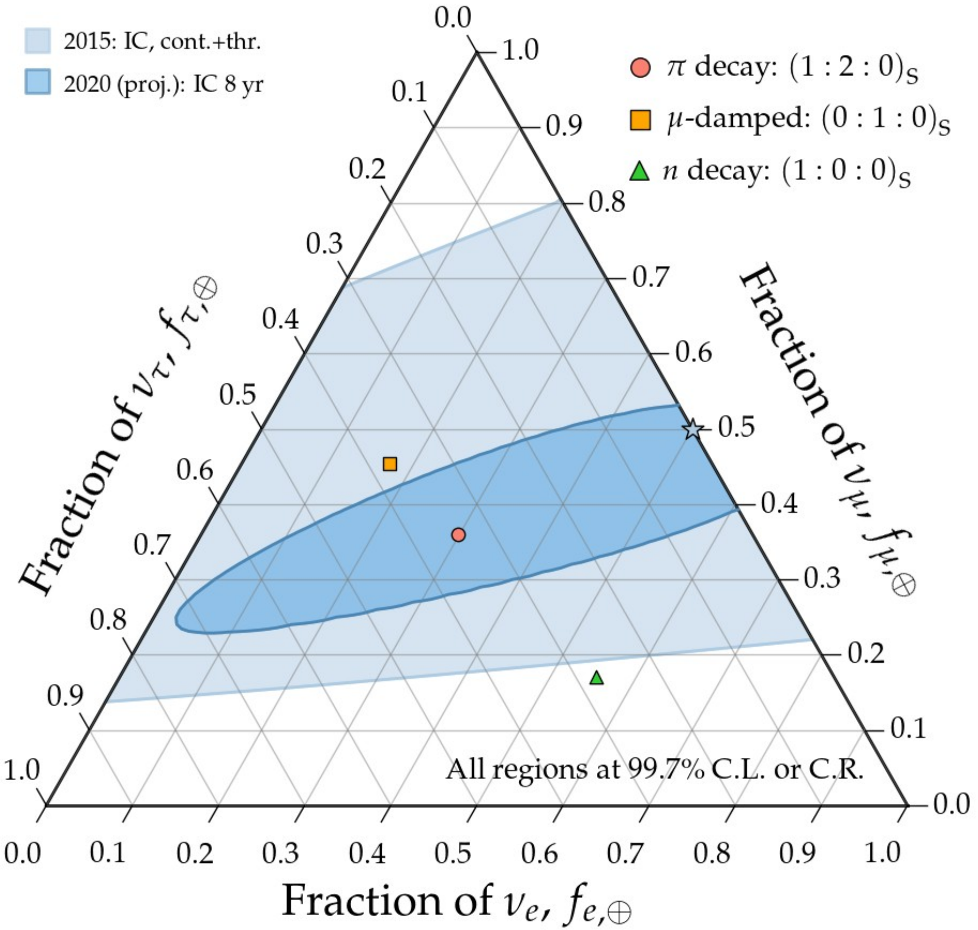

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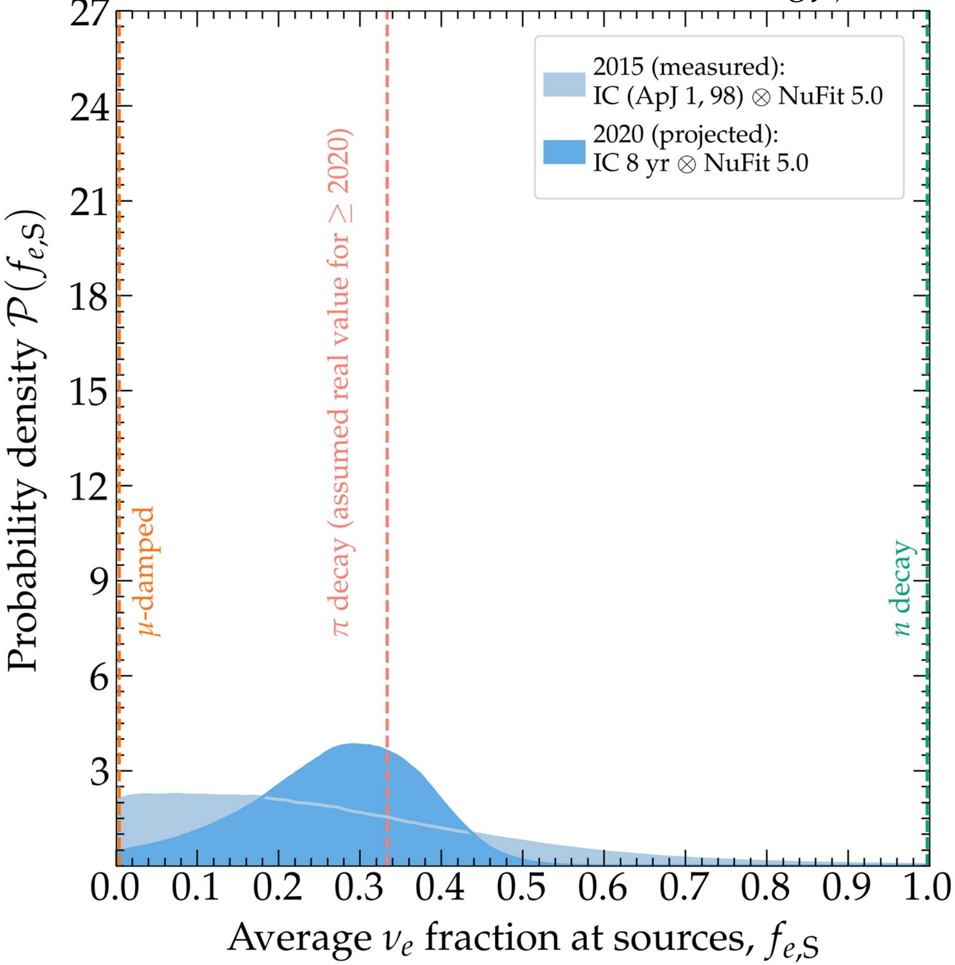

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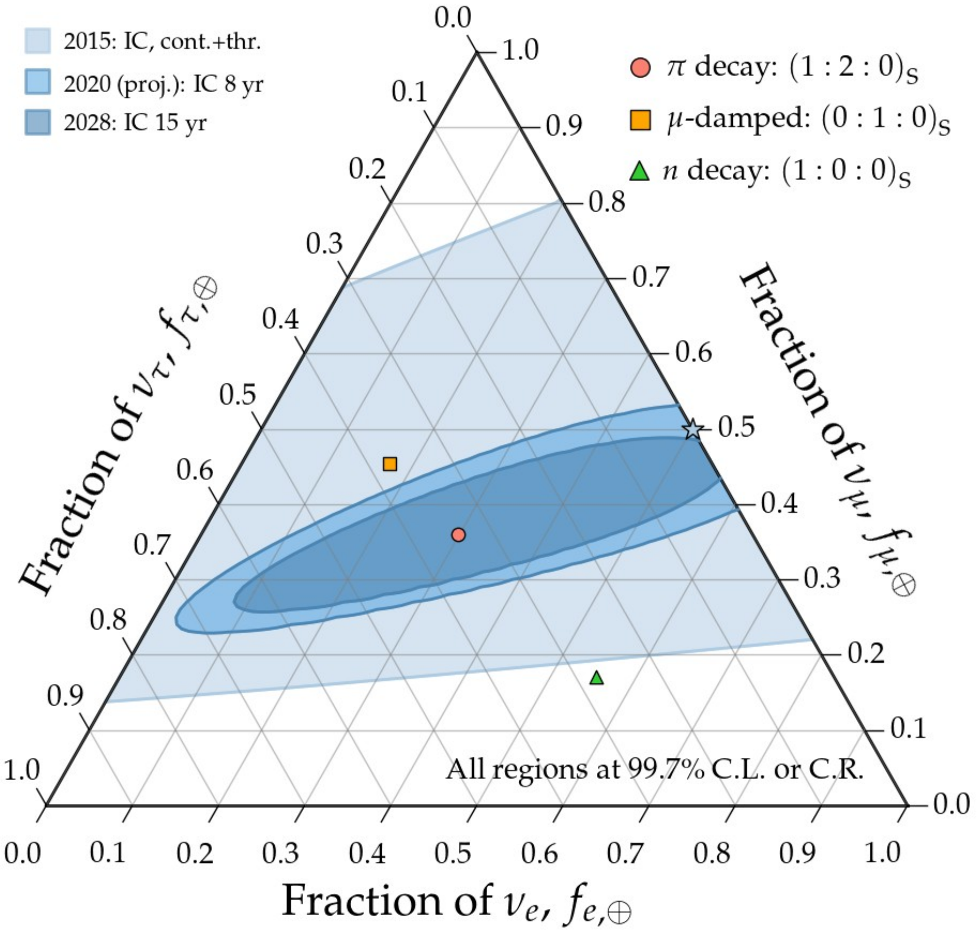

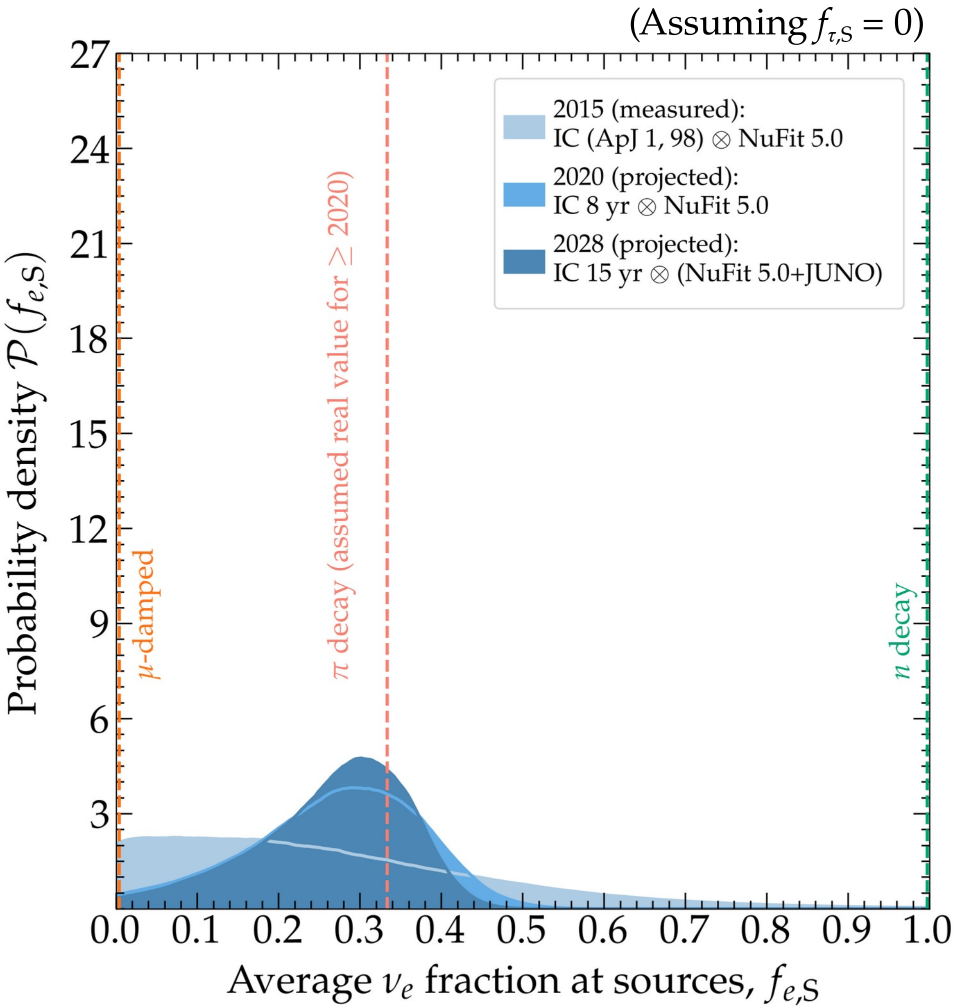

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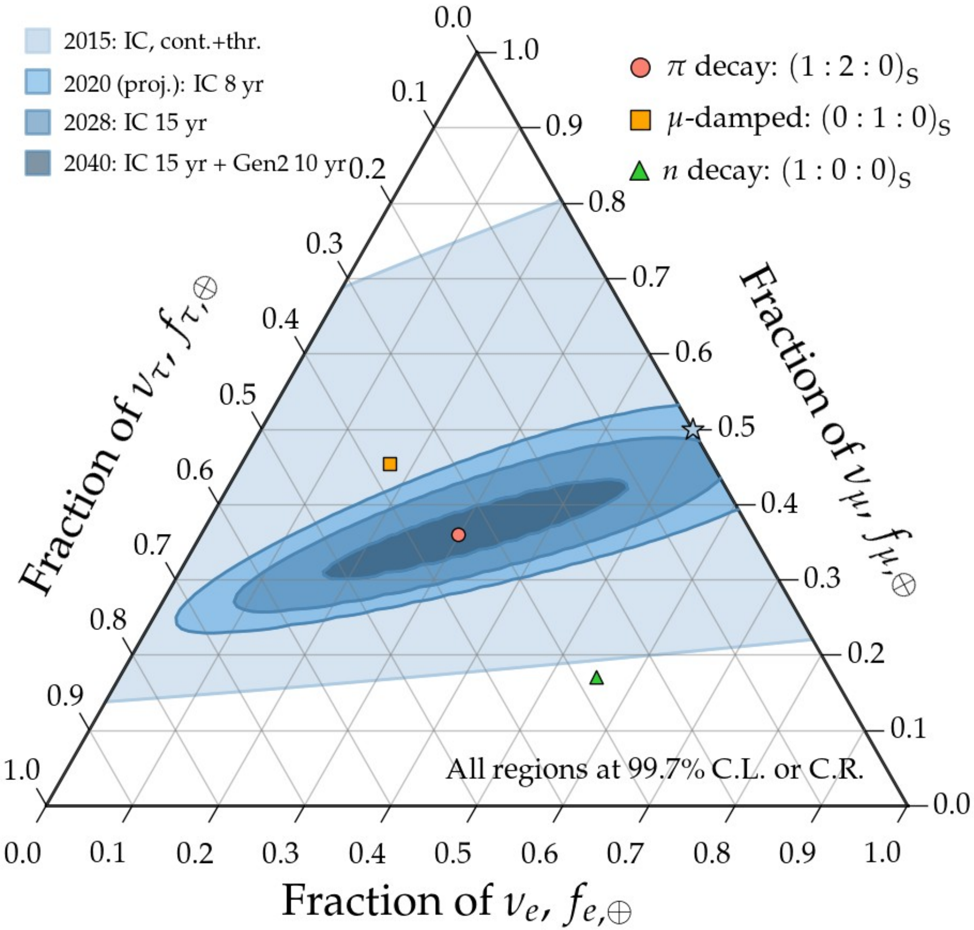

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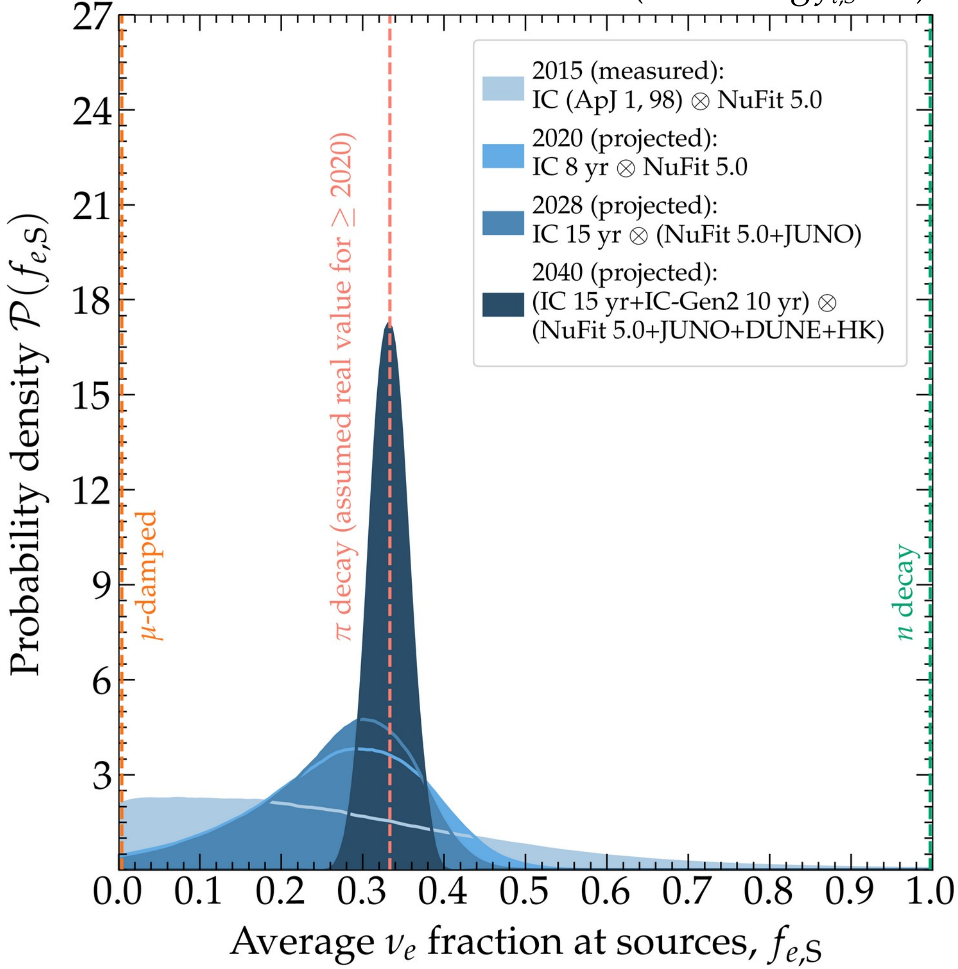

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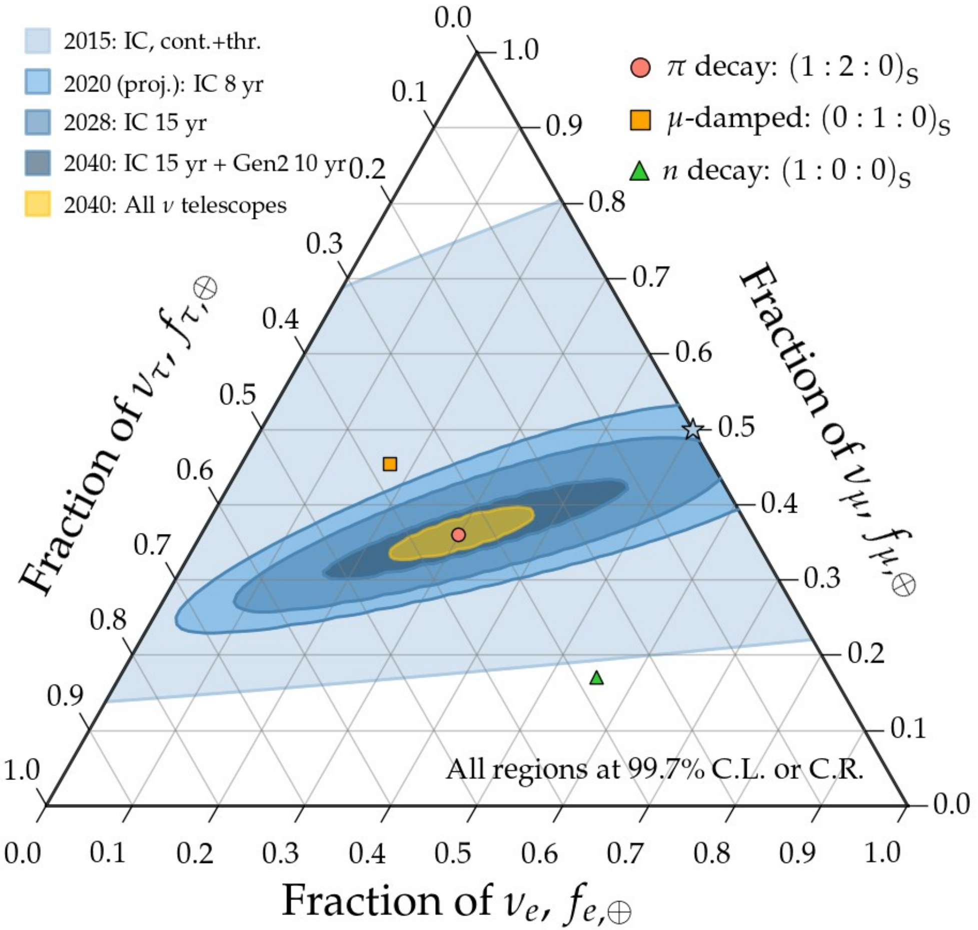

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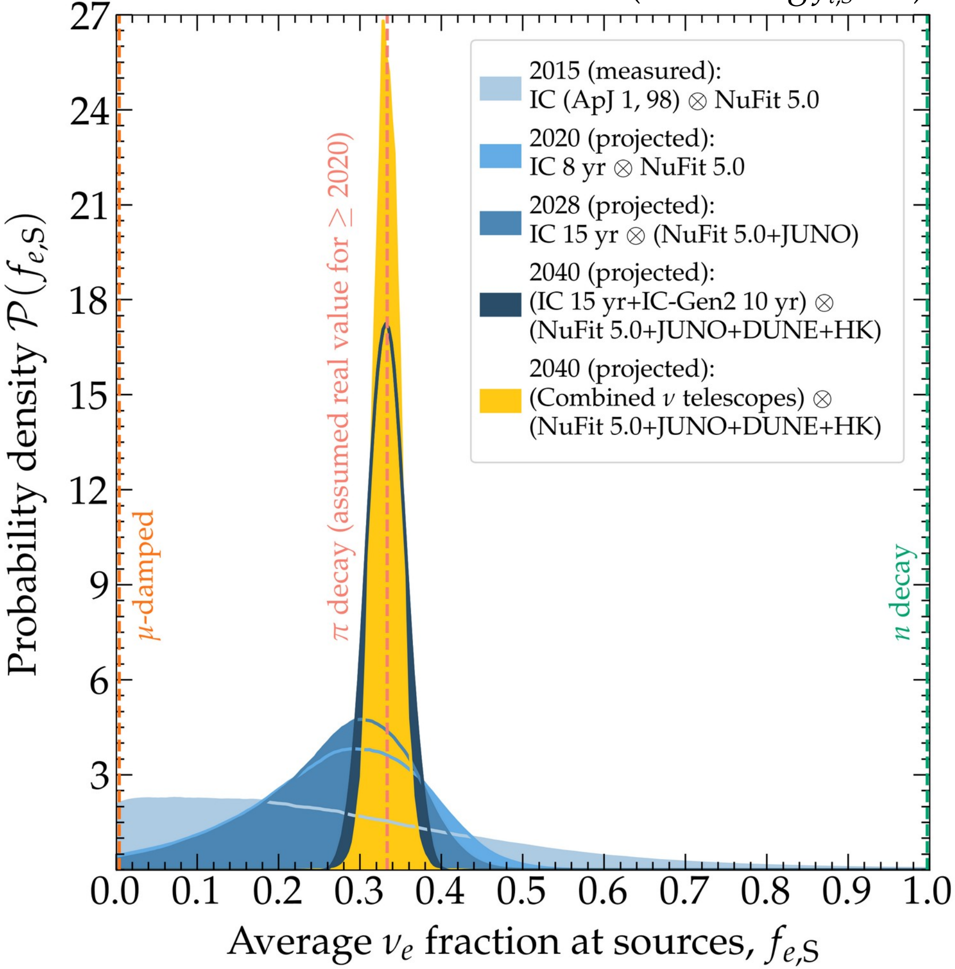

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

TeV–PeV ν telescopes, ~2030

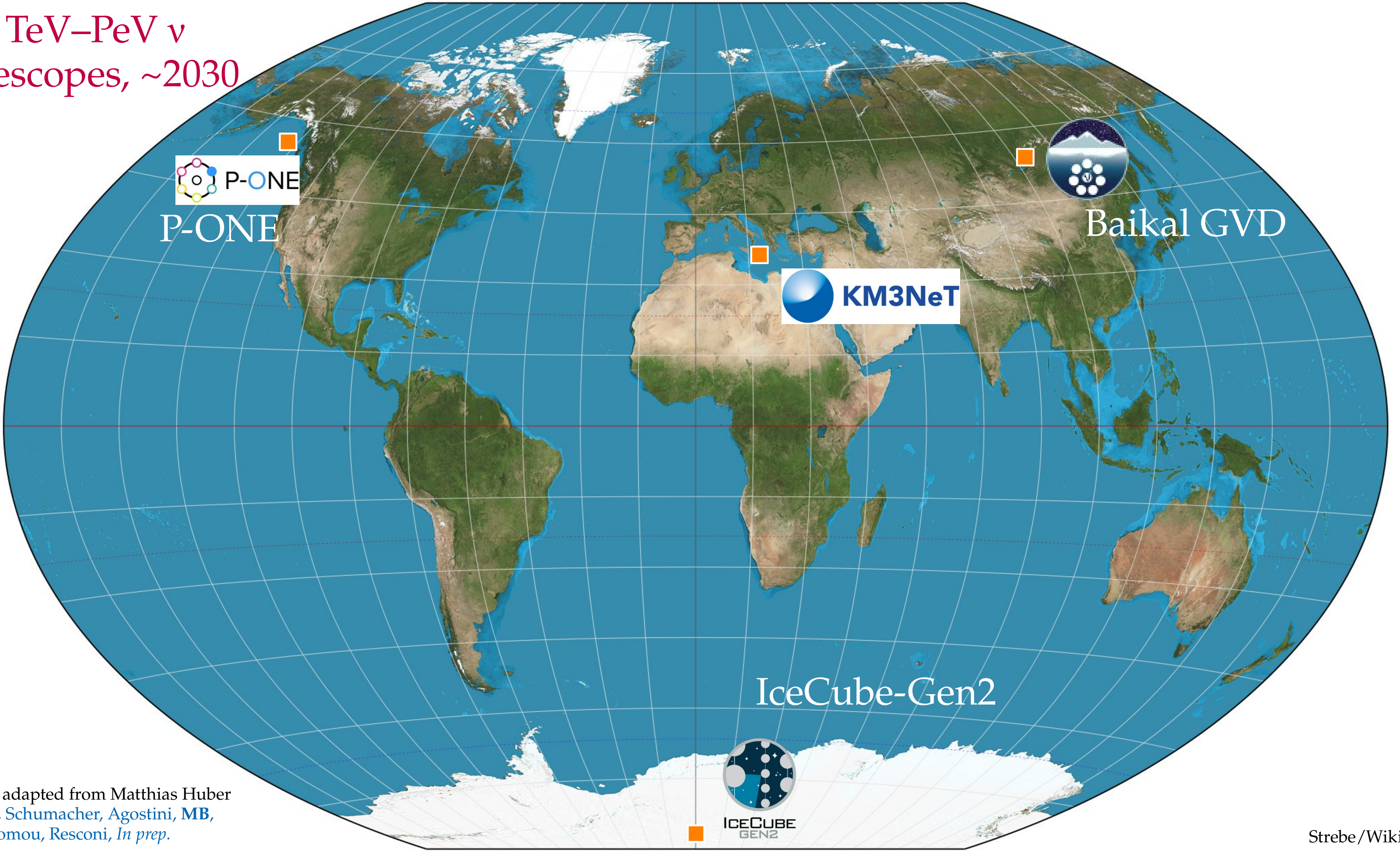

Figure adapted from Matthias Huber
Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Strebe/Wikipedia

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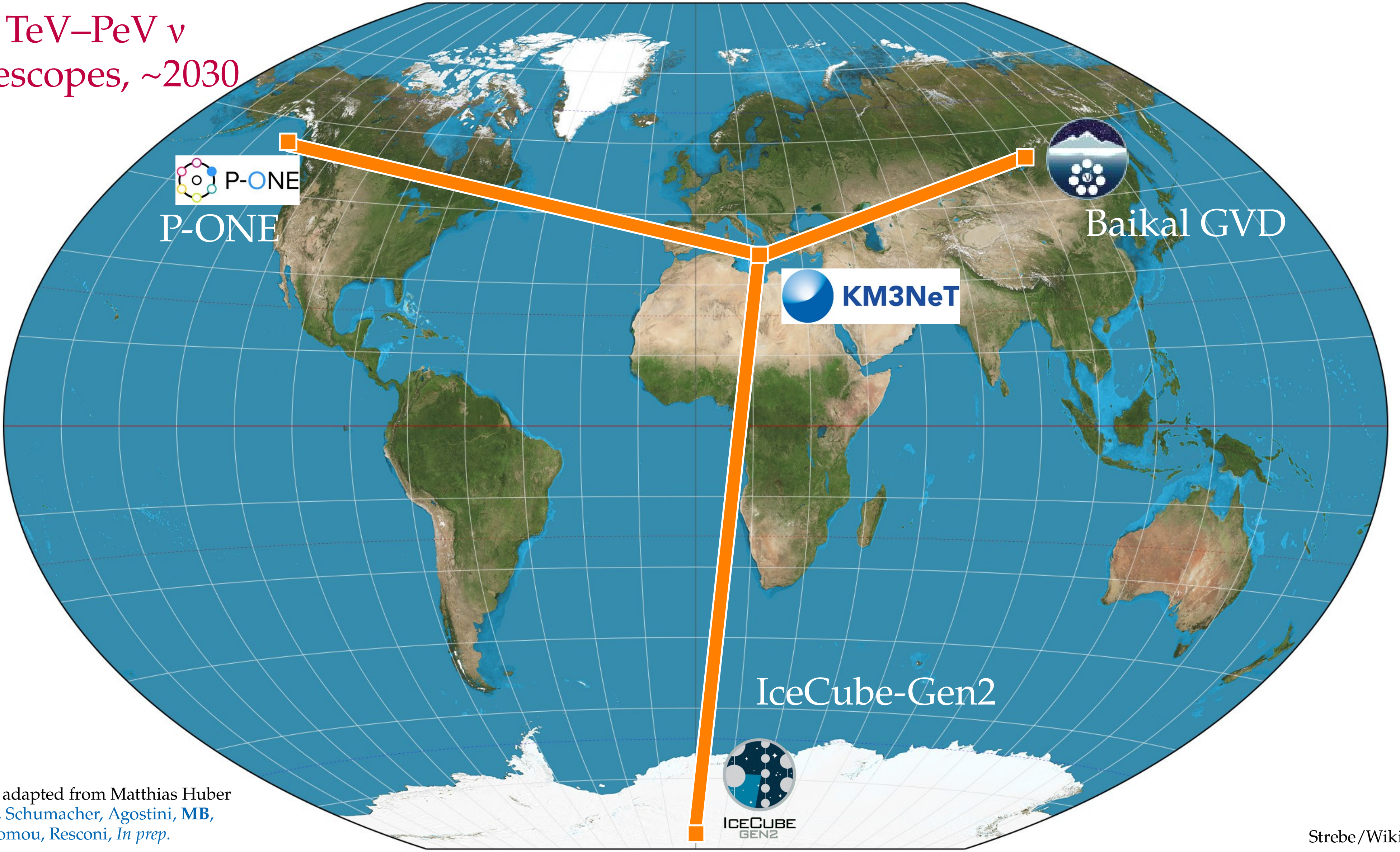

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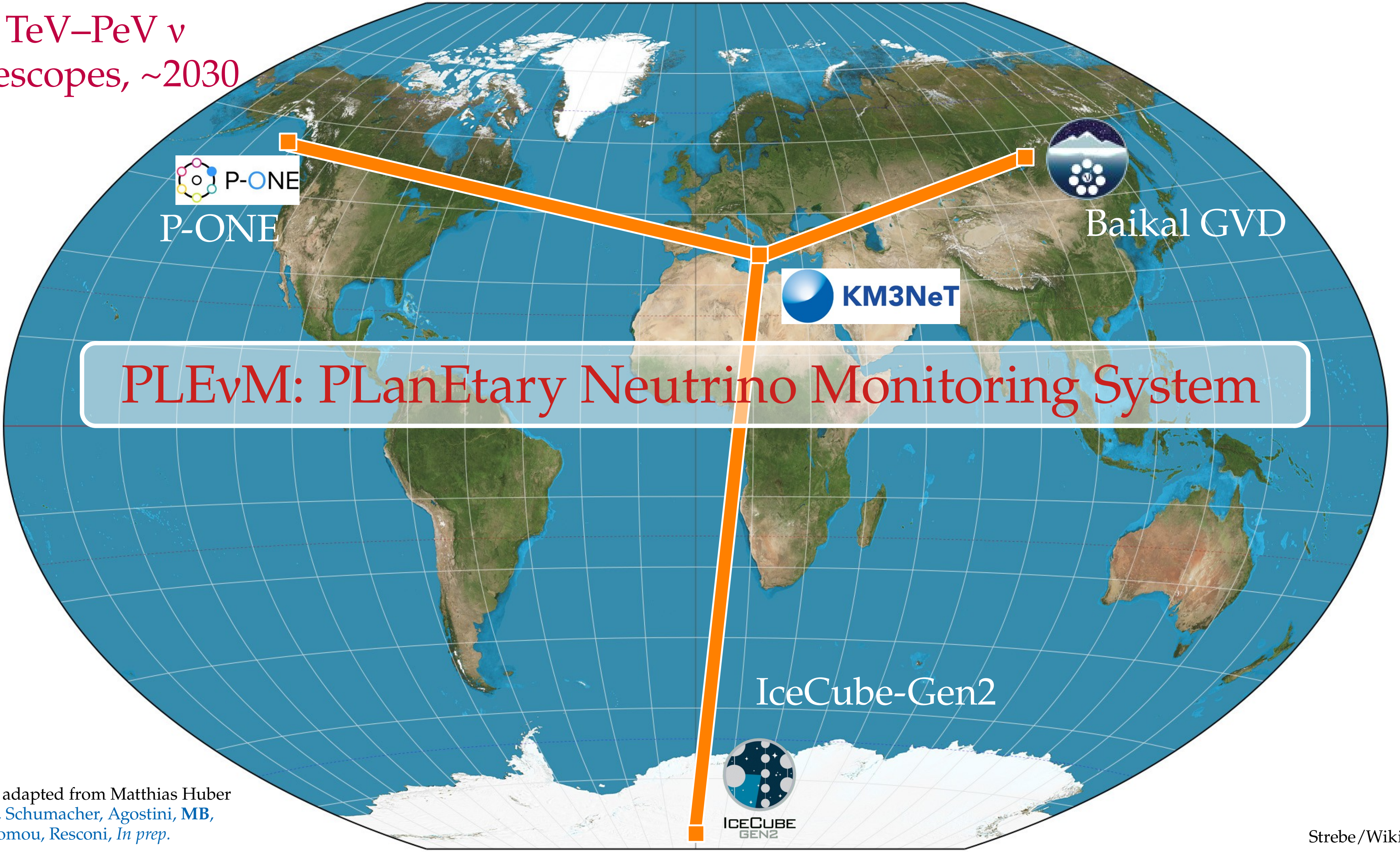


Figure adapted from Matthias Huber
Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Strebe/Wikipedia

Characterizing the diffuse power-law flux in PLEνM

$$E^2\phi = \phi_{100\text{TeV}} \left(\frac{E}{100\text{ TeV}}\right)^{2-\gamma}$$

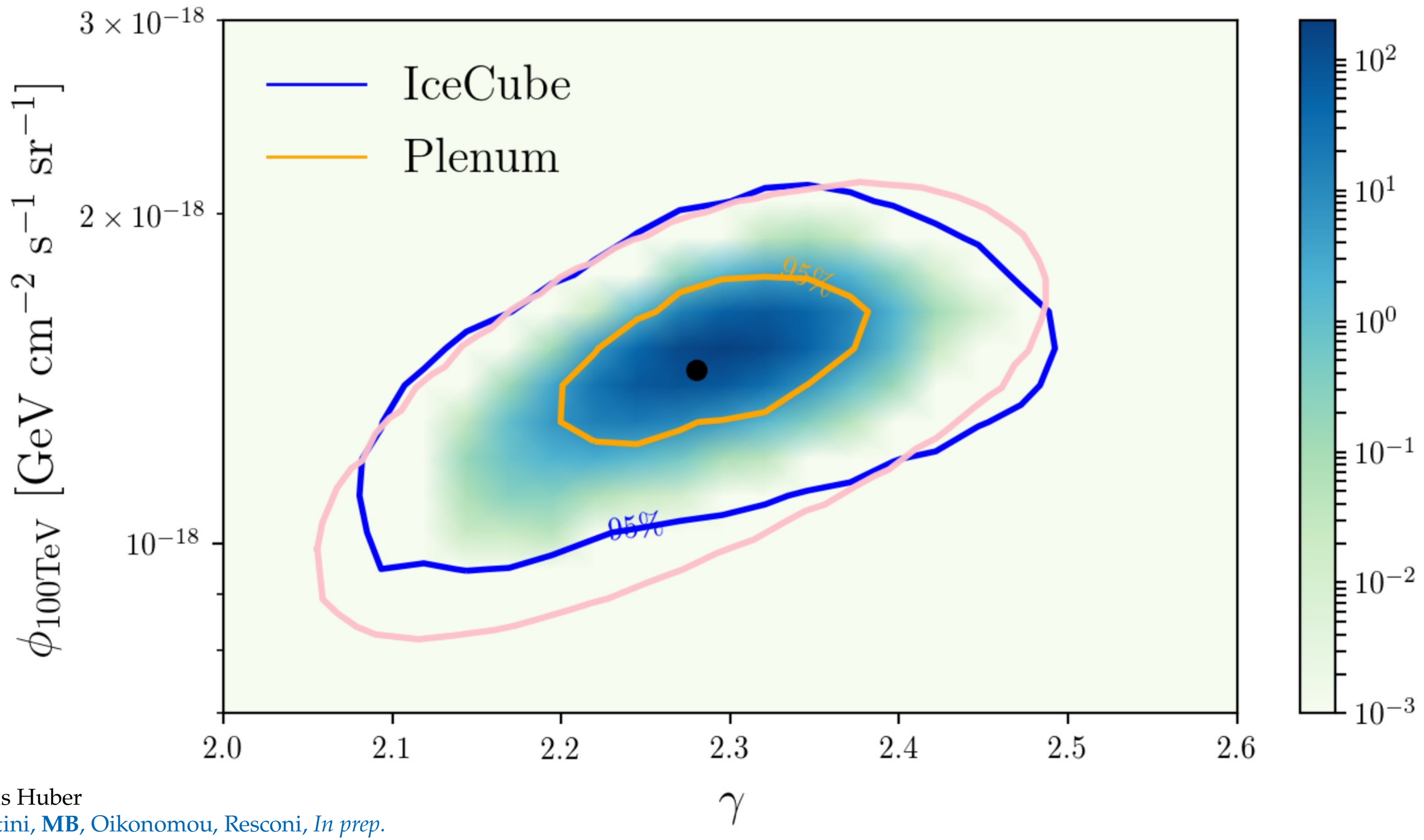
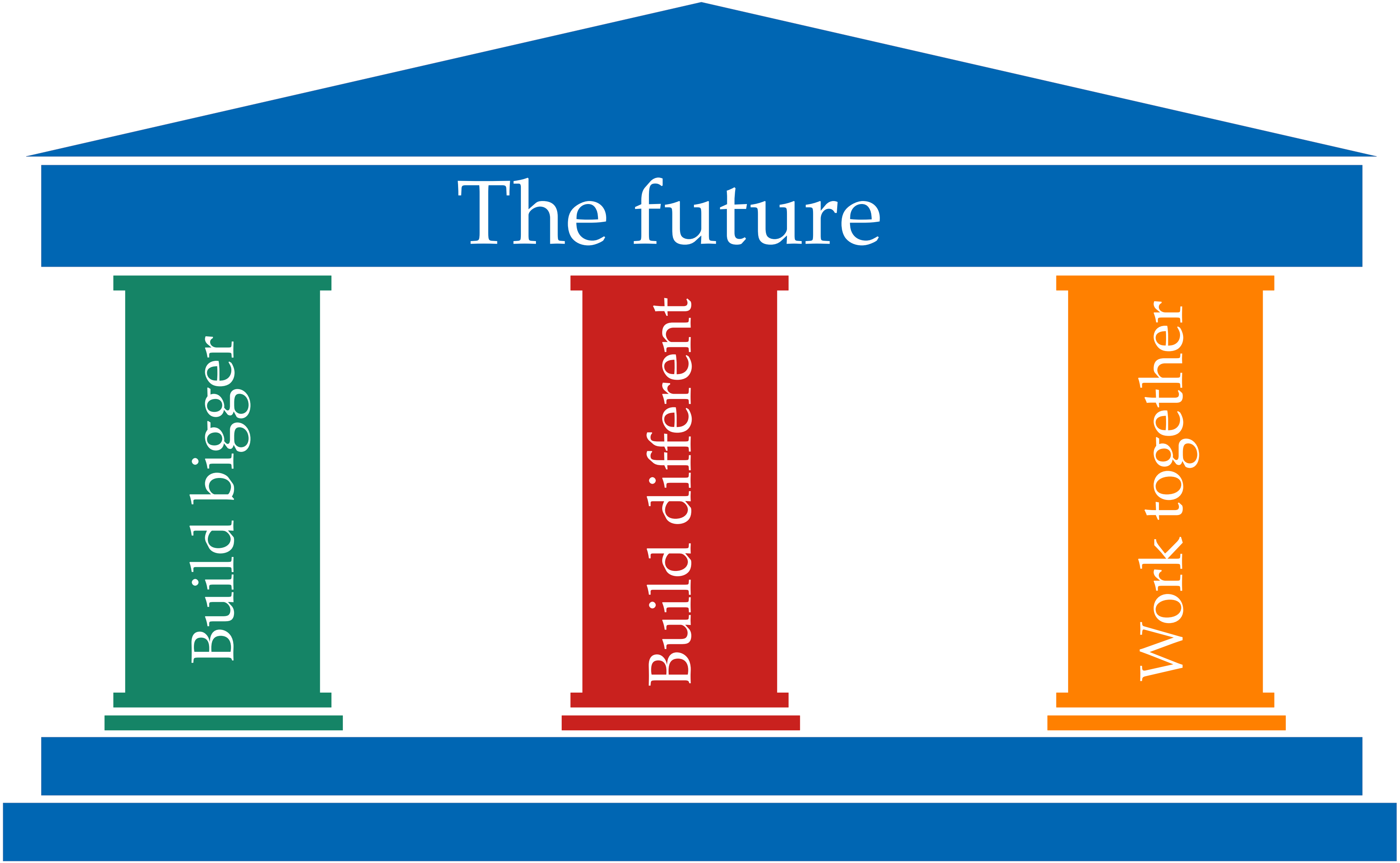


Figure courtesy of Matthias Huber

Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*


The future
Build bigger
Build different
Work together

V.
What now?

What theorists give

Well-motivated target sensitivity to aim for: flux, energy resolution, angular resolution, flavor

What should detectors optimize for: event rate, source discovery, *etc.*

What experimentalists give

Realistic instrument sensitivity (in useful form, *e.g.*, effective volume *vs.* shower energy)

Realistic projected event rates, including backgrounds


Photo by @aleozh


2021 (we are here):
TeV–PeV ν discovered
First possible sources
Photo by @aleozh


2020s (we are getting there):
More source candidates
Characterize the ν flux precisely
2021 (we are here):
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Photo by @aleozh


2030s (under planning):
Discovering EeV neutrinos
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> 2040:
????
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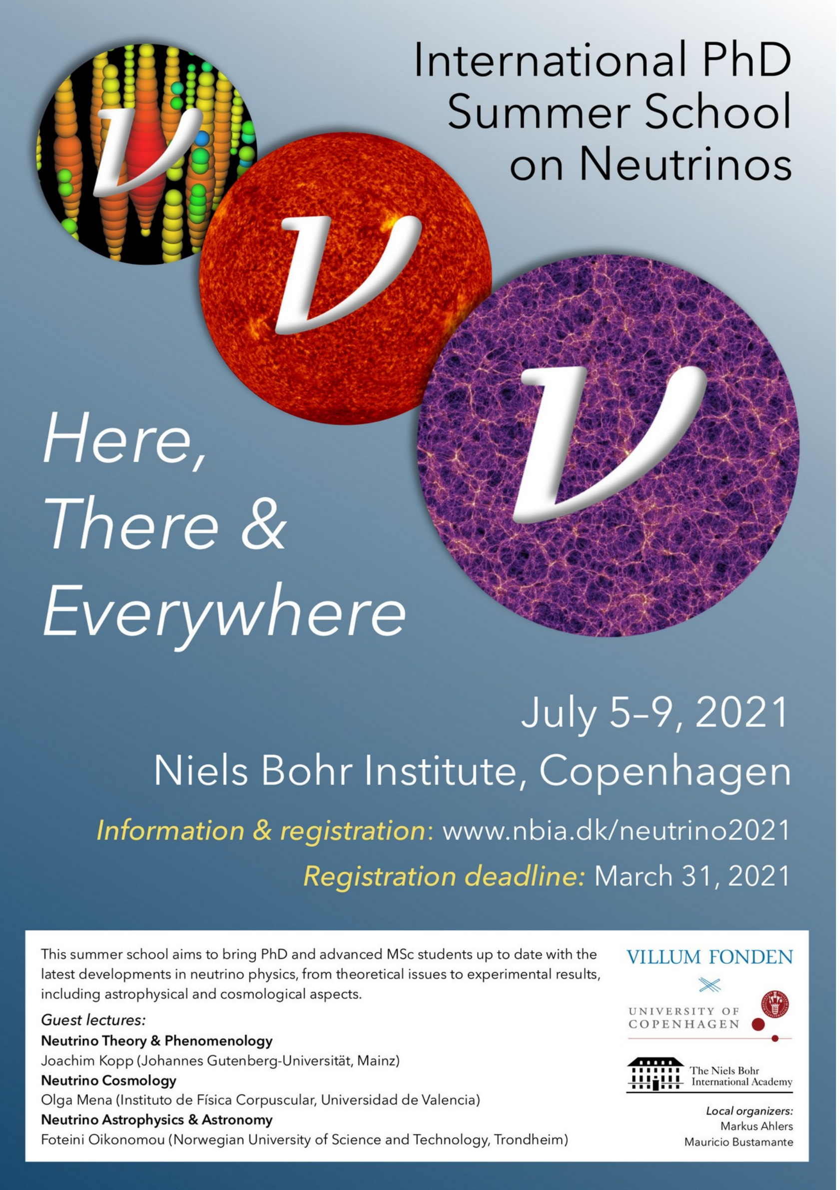
Photo by @aleozh

End



- For PhD and advanced MSc students
- Neutrino theory & phenomenology
  Neutrino cosmology
  Neutrino astrophysics & astronomy
  \+ Local talks
  \+ Student talks
- No participation fee
- Registration deadline: ~~March 31, 2021~~

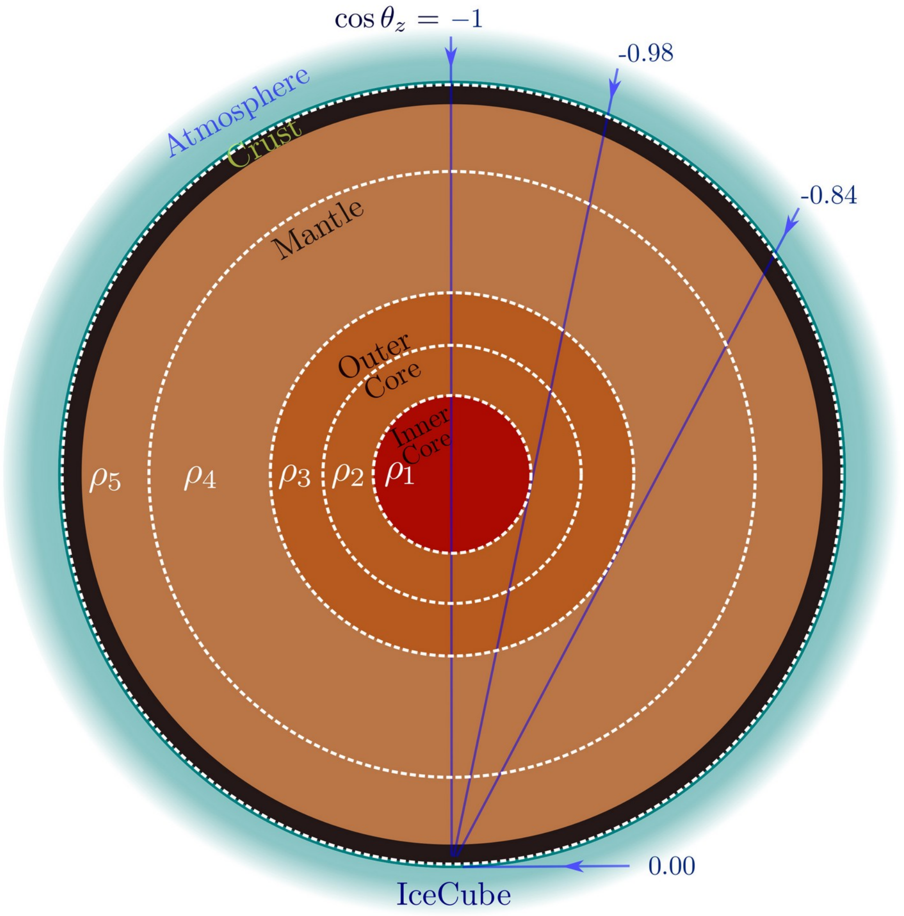
Re-opened until Thursday, July 1

- Fully online

www.nbia.dk/neutrino2021

Backup slides

Tomography of the Earth



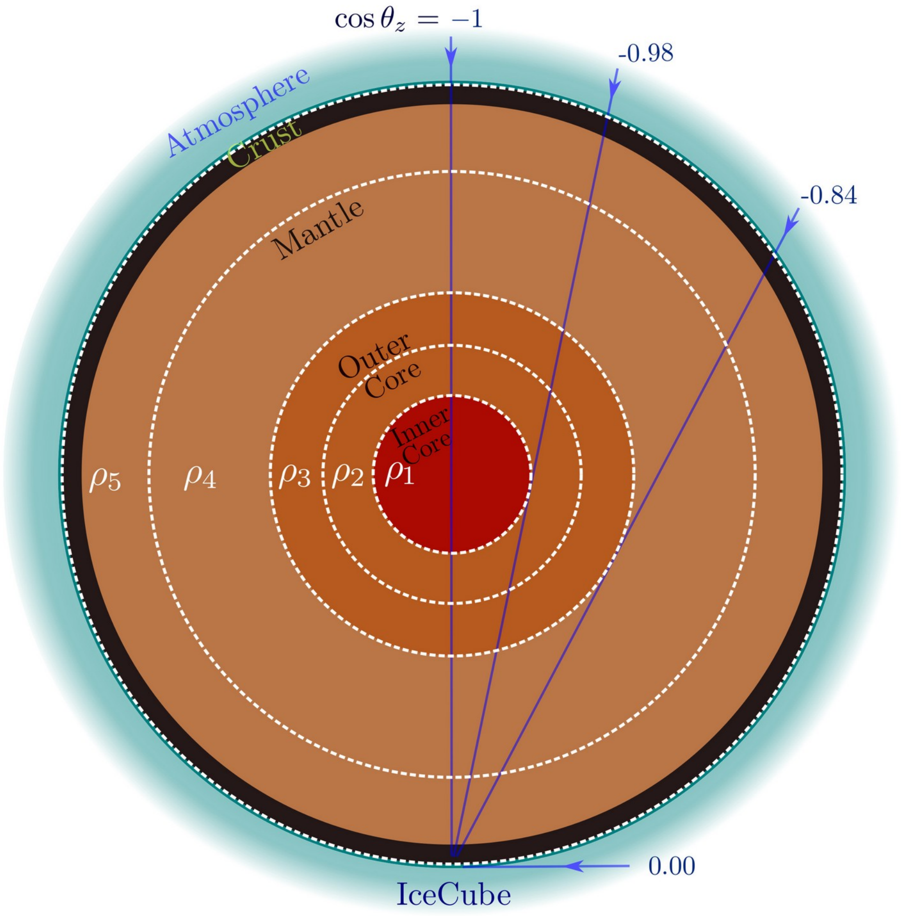
Neutrinos are more likely to interact while traveling inside the Earth …

… the higher their energy, and

… the longer the distance they travel.

Donini, Palomares-Ruiz, Salvadó, *Nature Phys.* 2019

Tomography of the Earth



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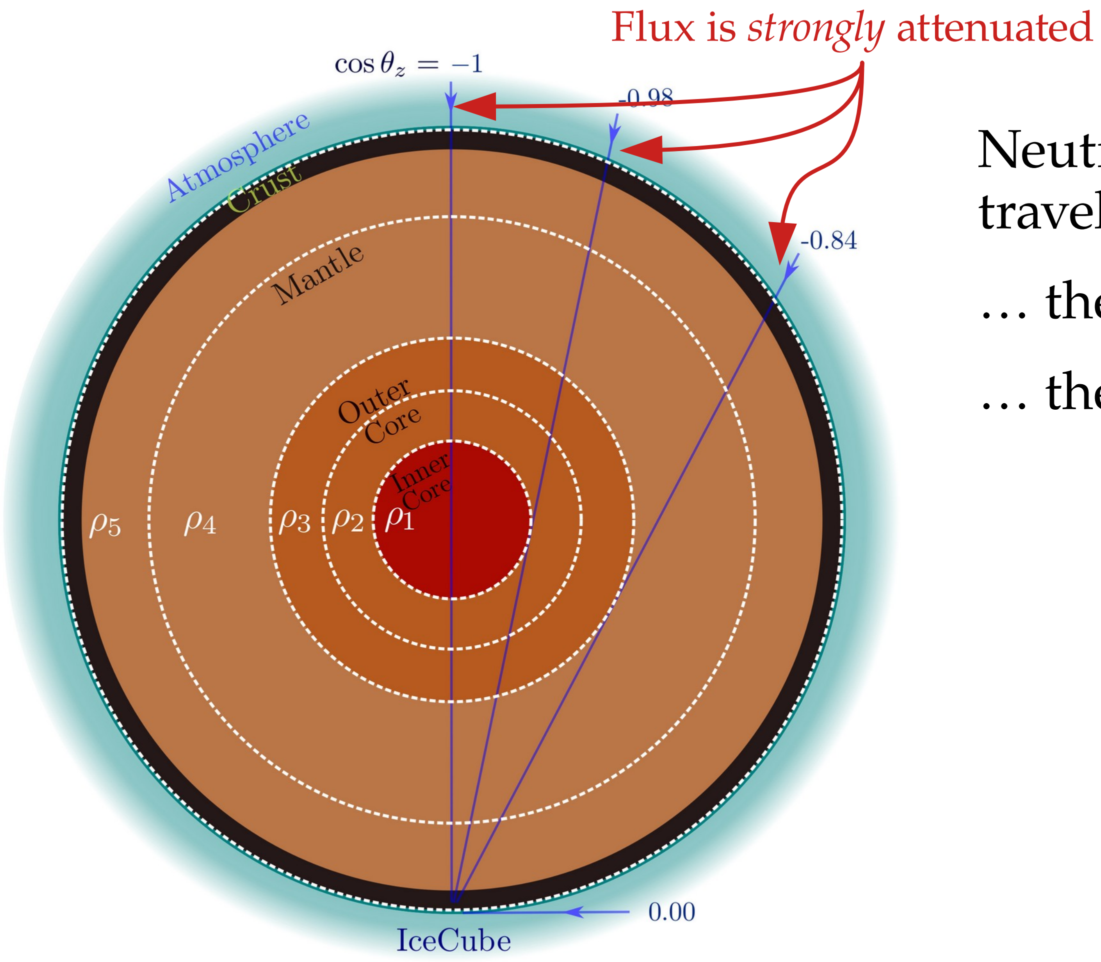

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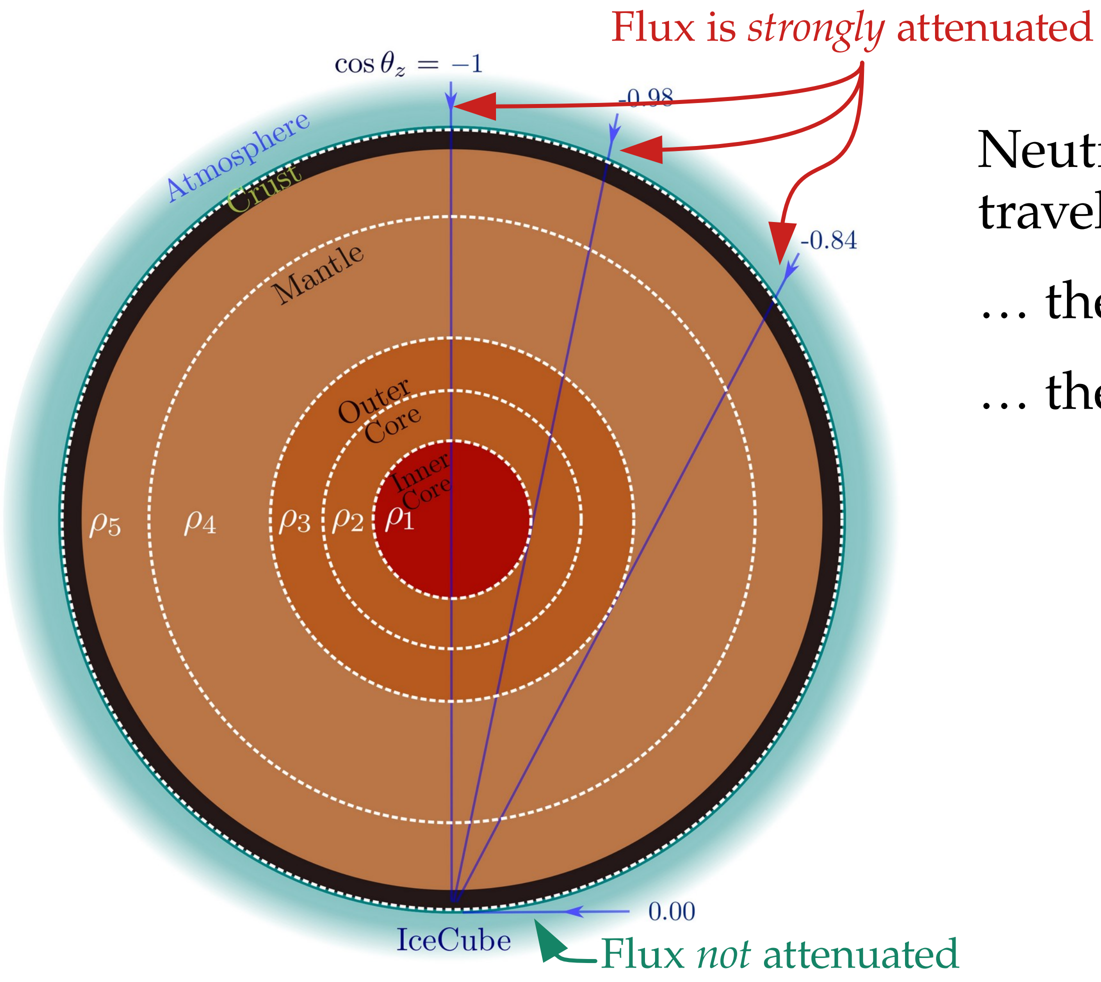

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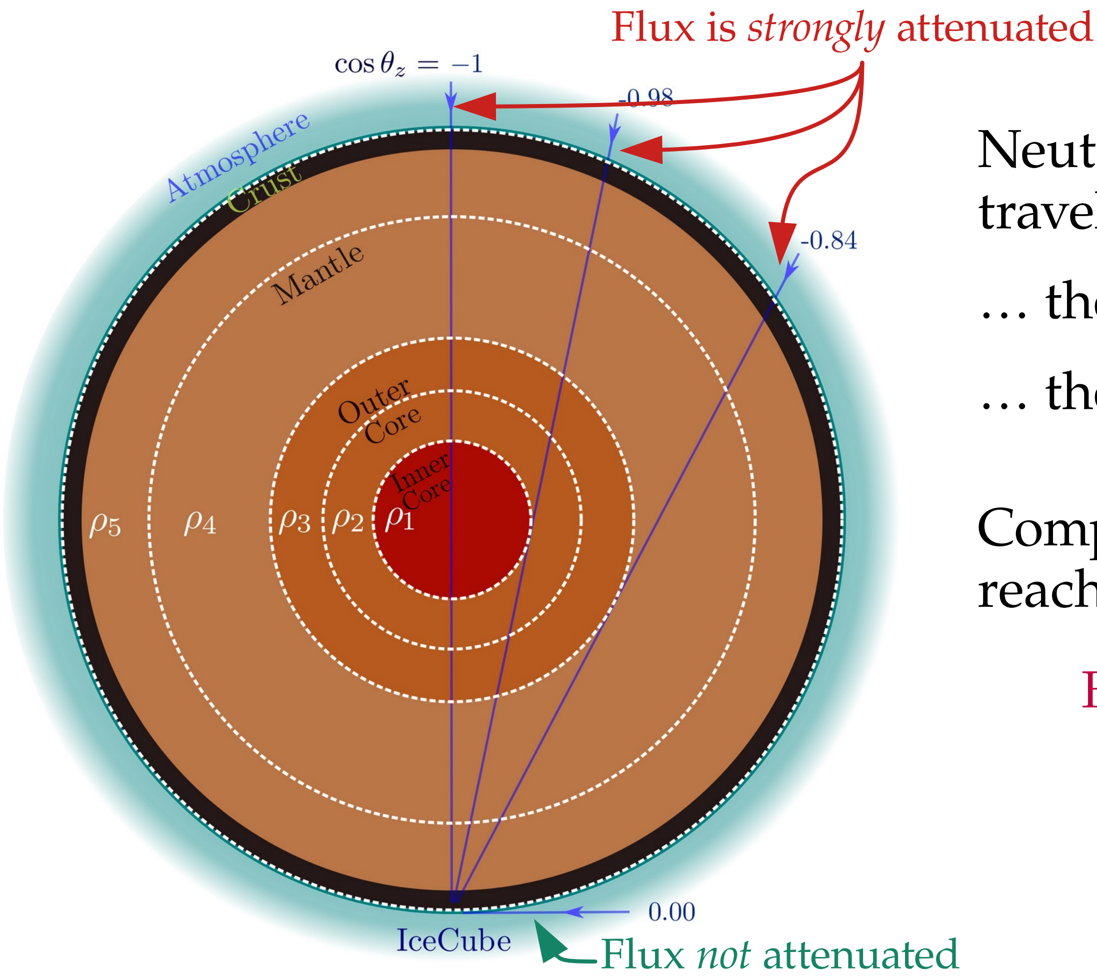

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Comparing atmospheric neutrino fluxes reaching IceCube from different directions:

$$\text{Earth's mass} = 6.0^{+1.6}_{-1.3} \times 10^{24}\ \text{kg}$$

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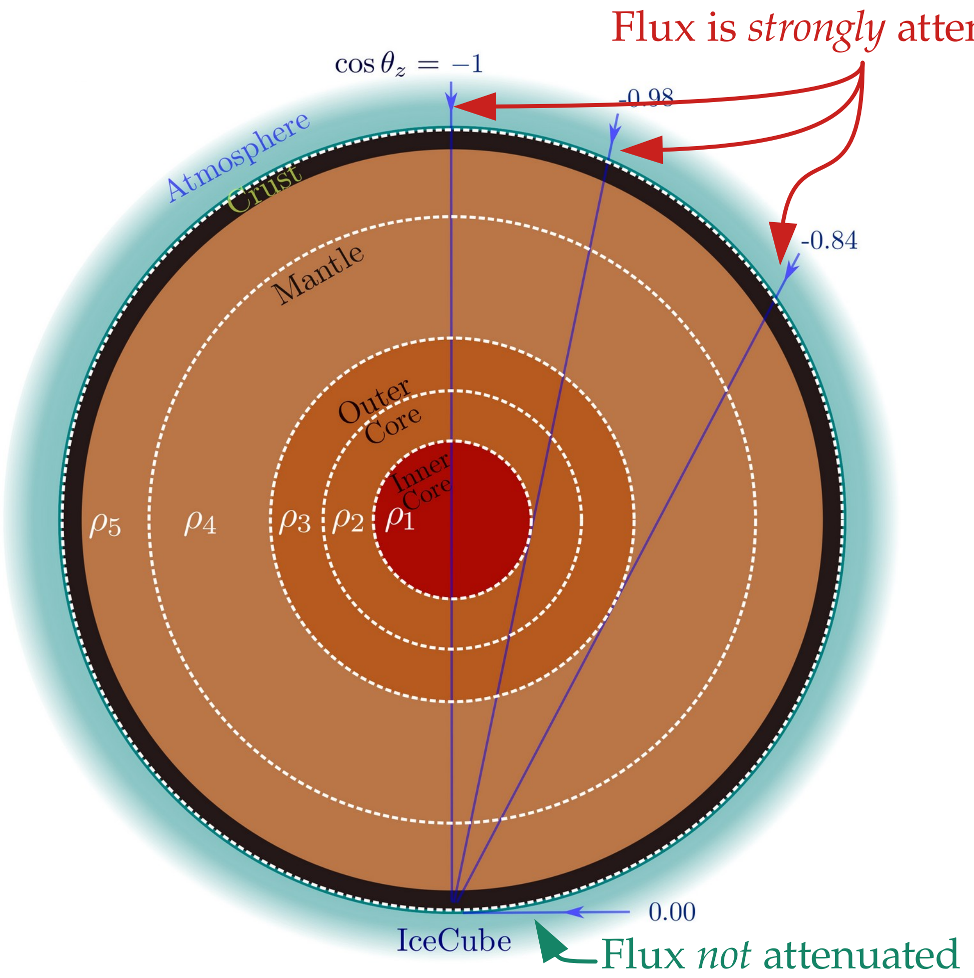

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[*Vs.* gravitational measurements: $(5.9722 \pm 0.0006) \times 10^{24}$ kg]

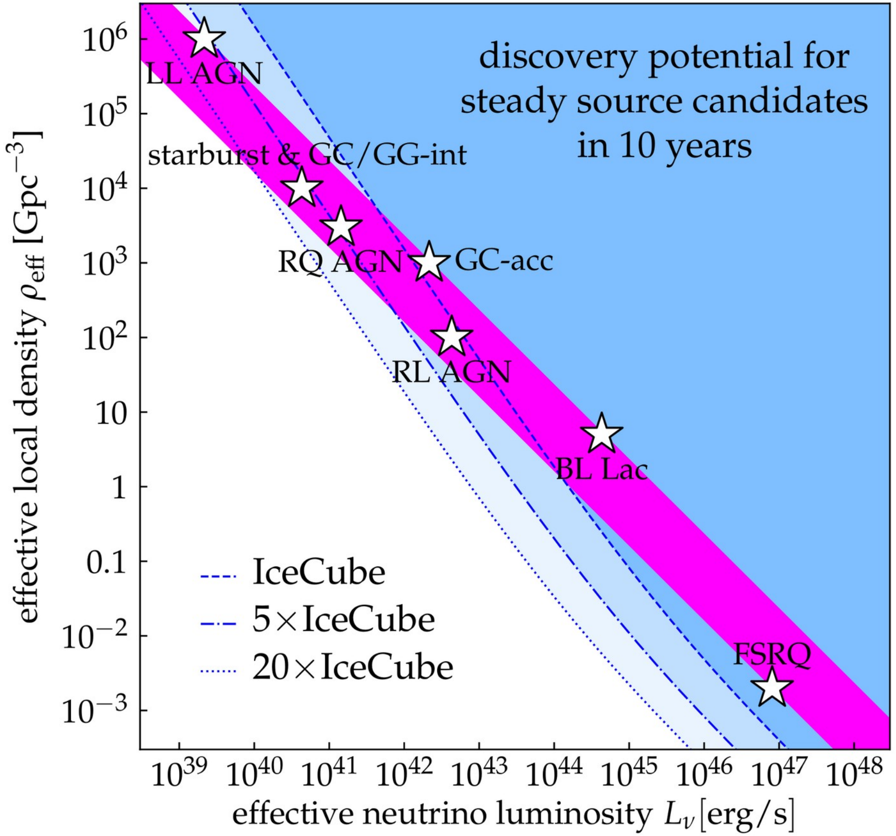
Donini, Palomares-Ruiz, Salvadó, *Nature Phys.* 2019

Sources

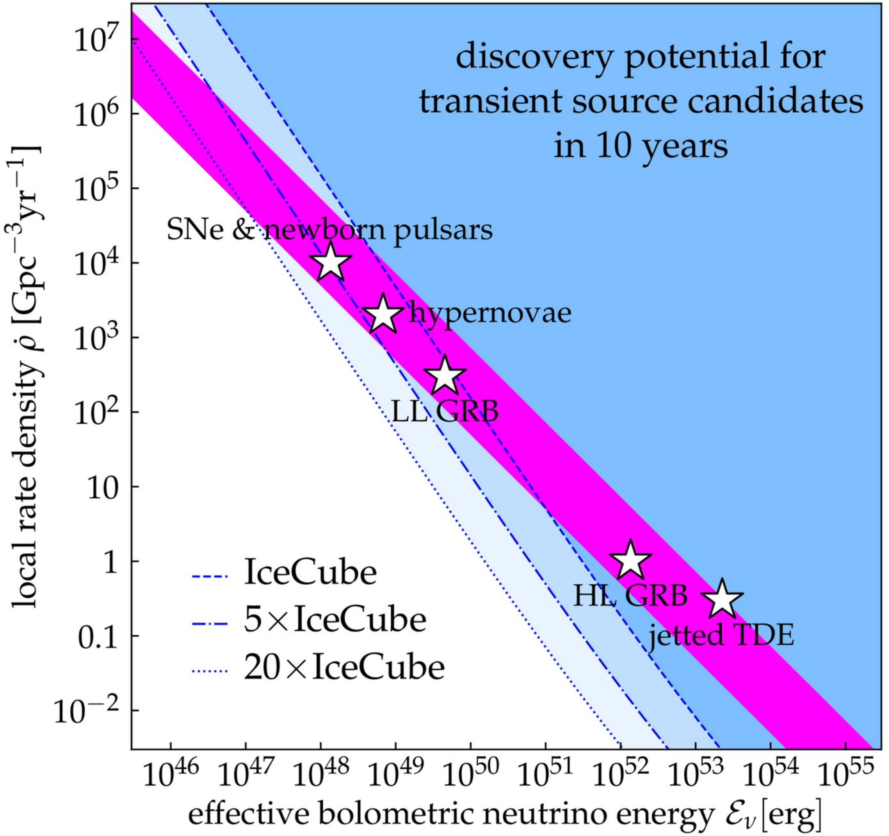
Source discovery potential: today and in the future

Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

Closest source with $E^2\Phi_{\nu_\mu+\bar{\nu}_\mu} = 10^{-12}$ TeV cm^{-2} s^{-1}



Closest source with $E^2F_{\nu_\mu+\bar{\nu}_\mu} = 0.1$ GeV cm^{-2}



Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333) – See also: Silvestri & Barwick, *PRD* 2010; Murase & Waxman, *PRD* 2016

Using high-energy neutrinos as magnetometers

If sources have strong magnetic fields, charged particles cool via synchrotron:

$$p + \gamma(p) \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

MB, Tamborra, *PRD* 2020

Using high-energy neutrinos as magnetometers

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Proton cooling

Induce a high-energy cut-off in the emitted ν spectrum:

$$E_\nu'^2 \frac{dN_\nu}{dE_\nu'} \propto E_\nu'^{2-\alpha_\nu} e^{-E_\nu'/E_\nu'^{\max}}$$

$$E_\nu^{\max} \approx \frac{10^{10}\Gamma \text{ GeV}}{\sqrt{B'/\text{G}}}$$

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Muon cooling

Change flavor composition:

$$(f_{e,\text{S}}, f_{\mu,\text{S}}, f_{\tau,\text{S}}) = \begin{cases} (\frac{1}{3}, \frac{2}{3}, 0), & \text{if } E_\nu < E_{\nu,\mu}^{\text{sync}} \\ (0, 1, 0), & \text{if } E_\nu \geq E_{\nu,\mu}^{\text{sync}} \end{cases}$$

$$E_{\nu,\mu}^{\text{sync}} \approx 10^9 \Gamma \frac{\text{G}}{B'} \text{ GeV}$$

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MB, Tamborra, *PRD* 2020

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$$E^{\text{sync}}_{\nu,\mu} \approx 10^9 \Gamma \frac{\text{G}}{B'} \text{ GeV}$$

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$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

Pion cooling

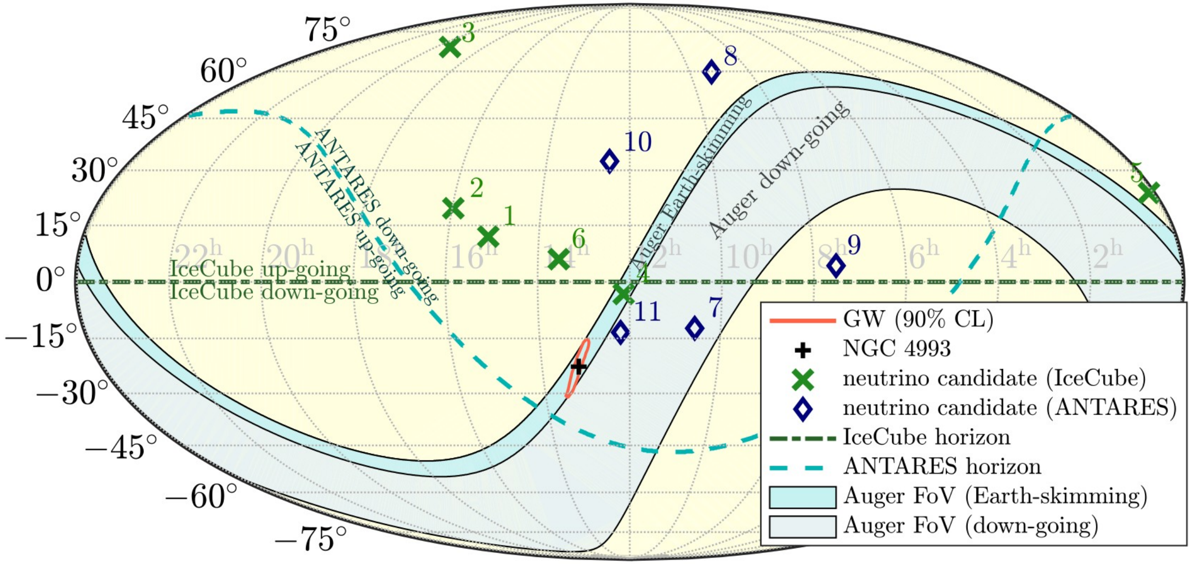
Steepen the ν spectrum: $\alpha_\nu = \begin{cases} \gamma, & \text{if } E_\nu < E^{\text{sync}}_{\nu,\pi} \\ \gamma + 2, & \text{if } E_\nu \geq E^{\text{sync}}_{\nu,\pi} \end{cases}$

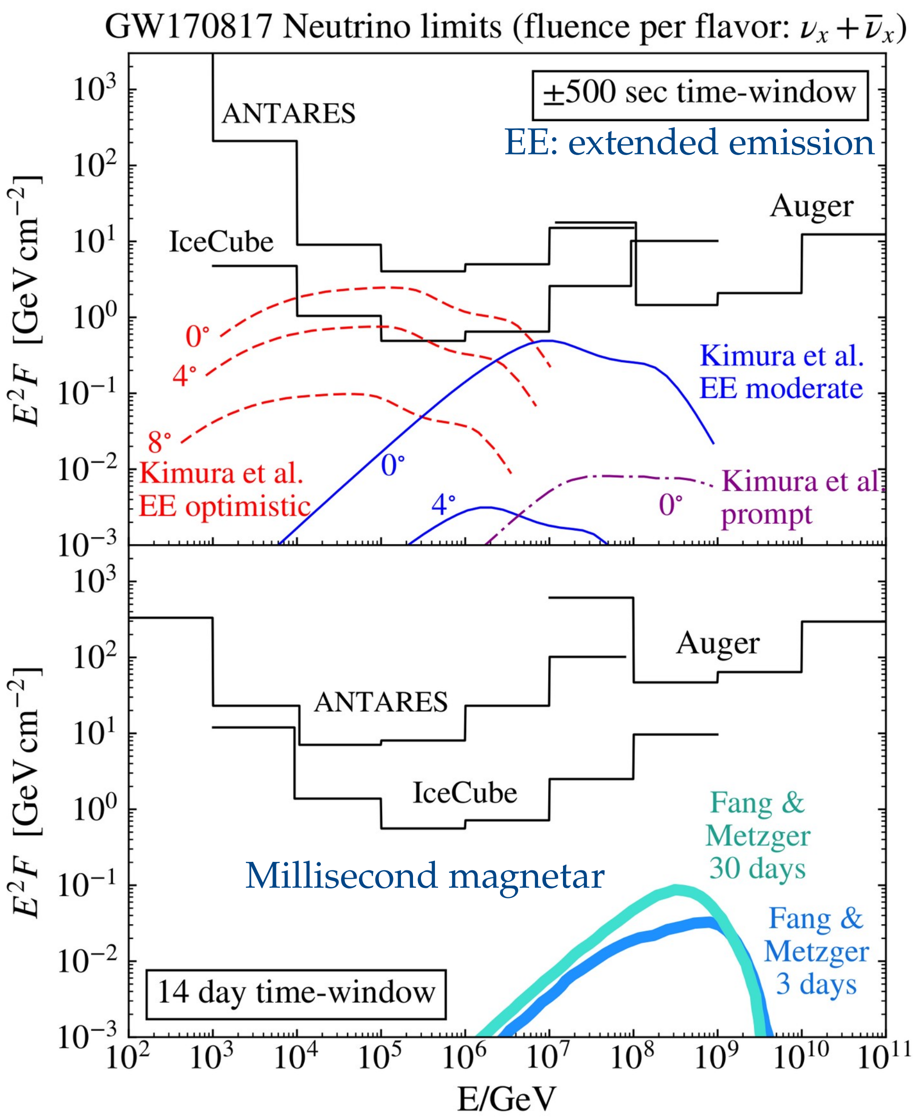
$$E^{\text{sync}}_{\nu,\pi} \approx 10^{10} \Gamma \frac{\text{G}}{B'} \text{ GeV}$$

MB, Tamborra, *PRD* 2020

GW170817 (NS-NS merger)

- Short GRB seen in *Fermi*-GBM, INTEGRAL
- Neutrino search by IceCube, ANTARES, and Auger
- MeV–EeV neutrinos, 14-day window
- Non-detection consistent with off-axis





ANTARES, IceCube, Pierre Auger Collab., *ApJL* 2017

Are GRBs still good UHECR source candidates?

- High-luminosity bursts: Not so much
- Low-luminosity bursts: Yes!

	HL GRBs	LL GRBs
Luminosity (erg s^{-1})	$> 10^{49}$	$< 10^{49}$
Rate (Gpc^{-3} yr^{-1})	1	300 (predicted)
Survival of heavy nuclei in jet?	Unlikely	Likely
Can explain IceCube ν?	No	Yes

D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

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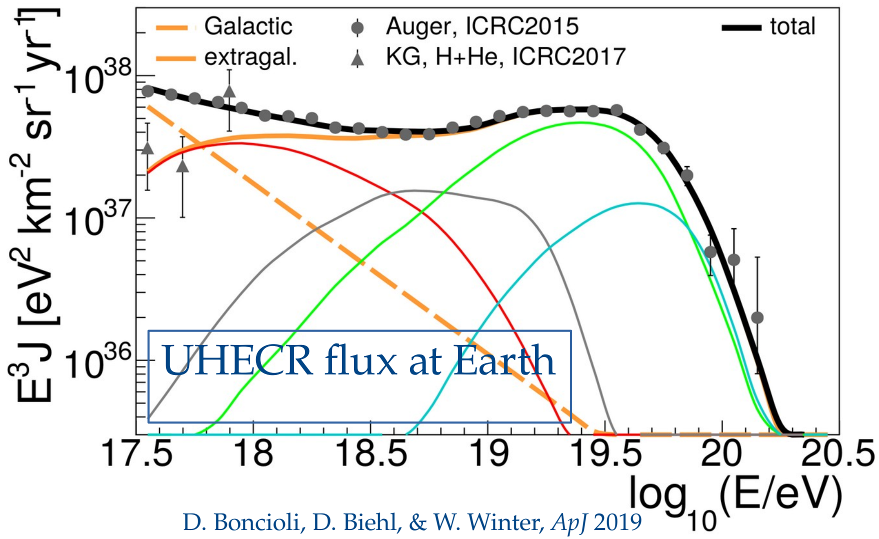

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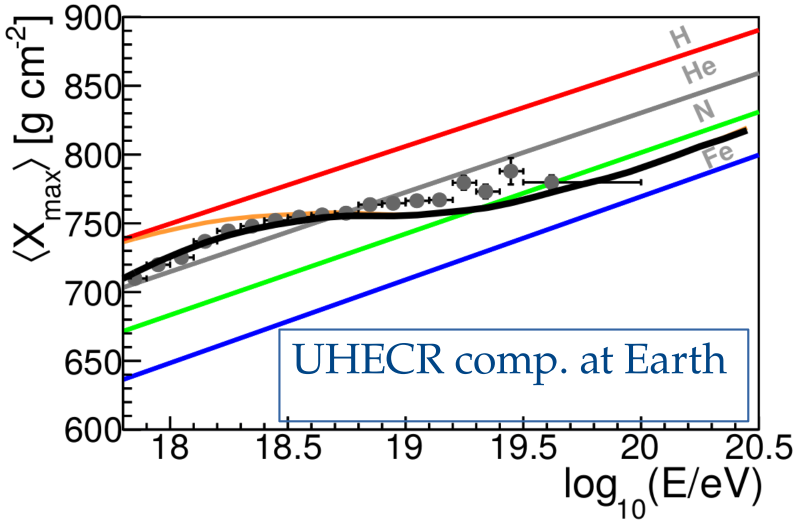

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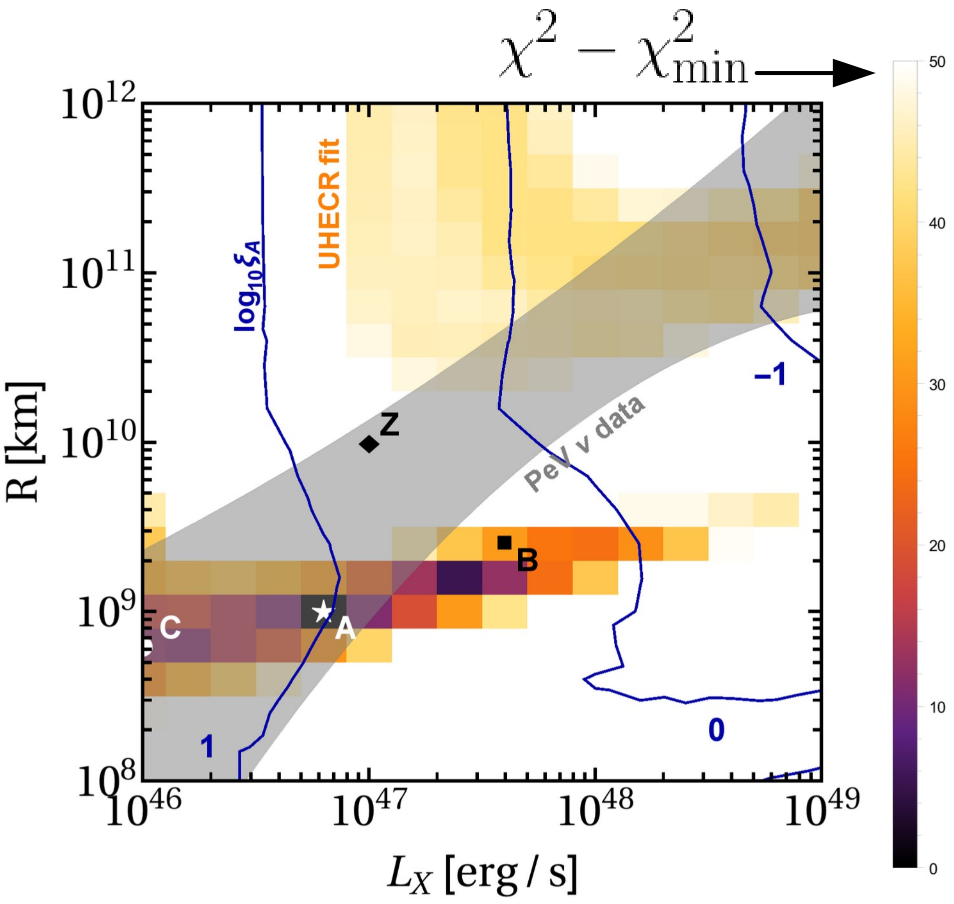
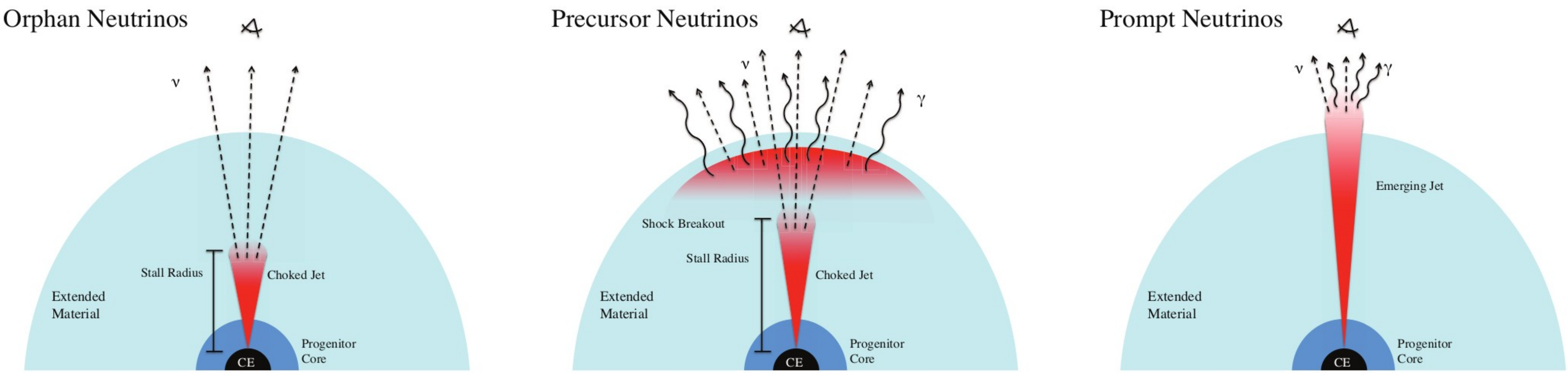


D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

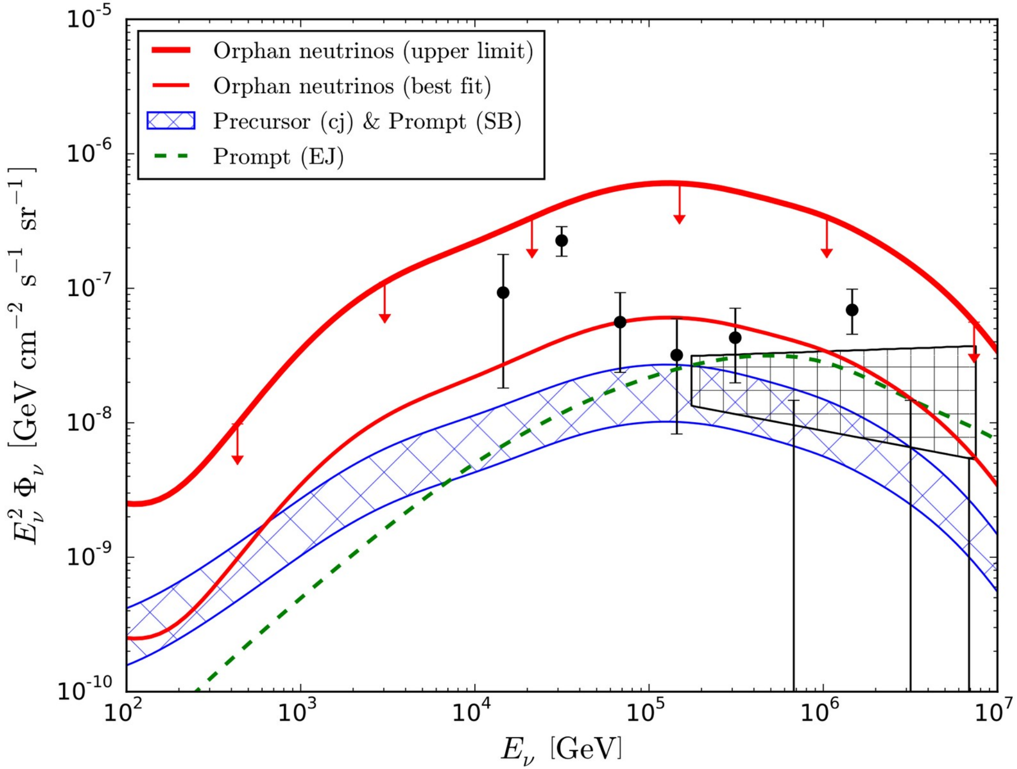
Low-luminosity and dark GRBs

In jetted supernovae, the jet might be choked —

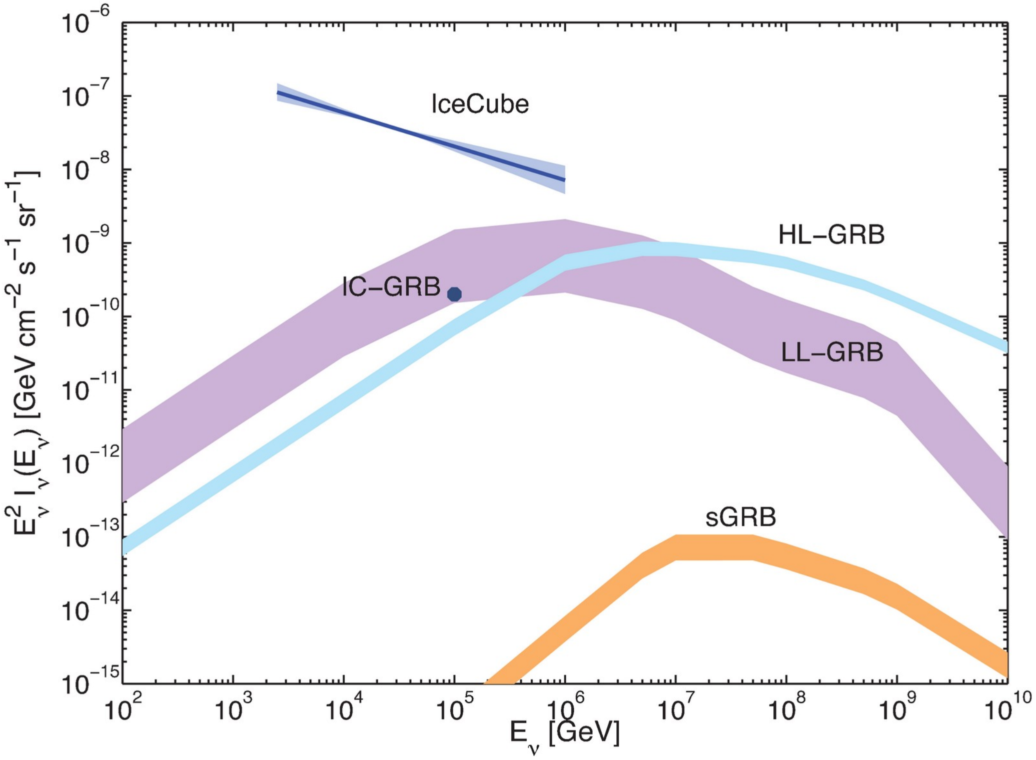


N. Senno, K. Murase, & P. Meszaros, *PRD* 2016

Low-luminosity and dark GRBs



N. Senno, K. Murase, & P. Meszaros, *PRD* 2016

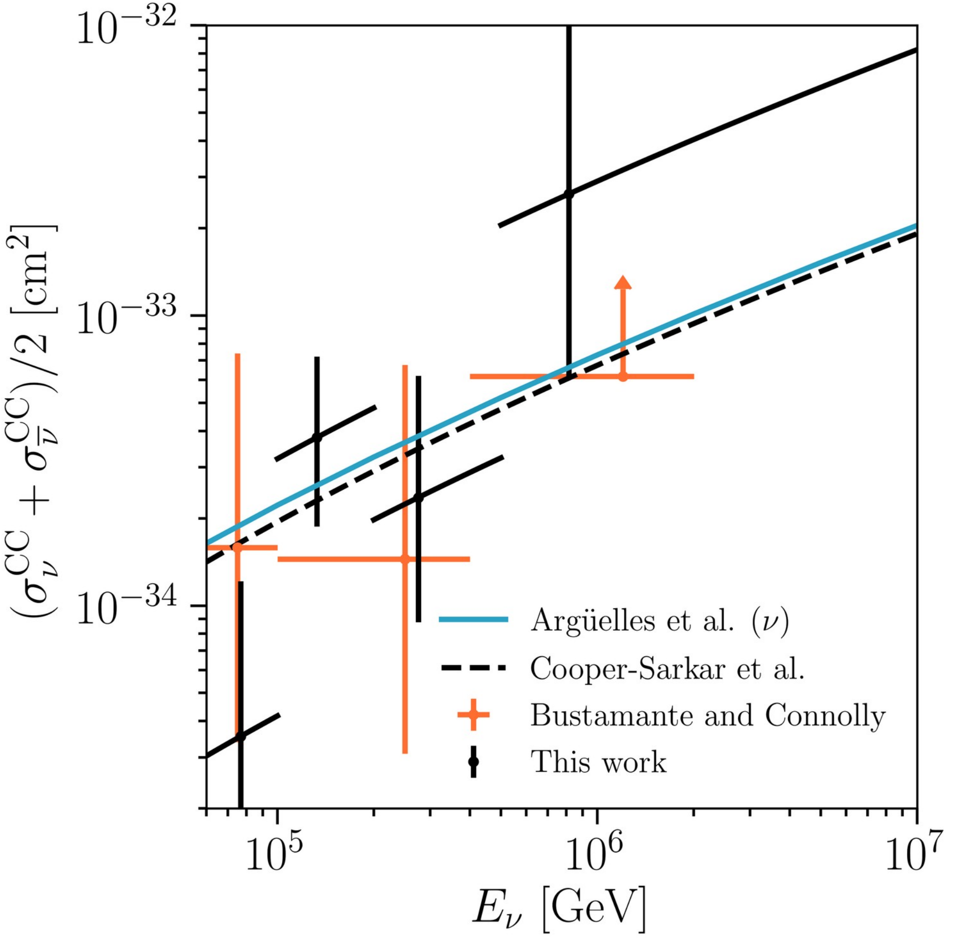


I. Tamborra & S. Ando, *JCAP* 2015

Example 1:
Measuring TeV–PeV ν cross sections

Updated cross section measurement

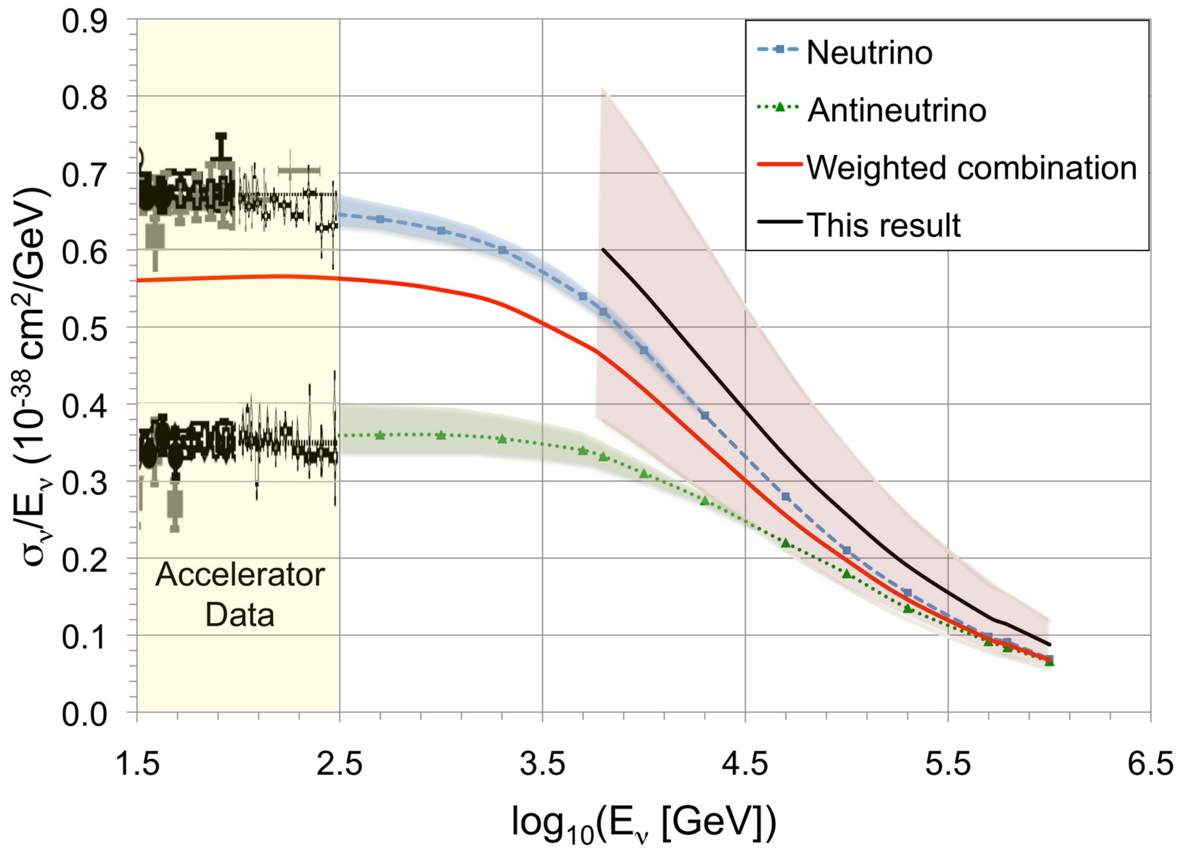
- Uses 7.5 years of IceCube data
- Uses starting showers + tracks
  - *Vs.* starting showers only in Bustamante & Connolly 2017
  - *Vs.* throughgoing muons in IceCube 2017
- Extends measurement to 10 PeV
- Still compatible with Standard Model predictions
- Higher energies? Work in progress by Valera & MB



IceCube, 2011.03560

Using through-going muons instead

- Use ~10^4 through-going muons
- Measured: $\mathrm{d}E_\mu/\mathrm{d}x$
- Inferred: $E_\mu \approx \mathrm{d}E_\mu/\mathrm{d}x$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30\,^{+0.21}_{-0.19}(\mathrm{stat.})\,^{+0.39}_{-0.43}(\mathrm{syst.})$
- All events grouped in a single energy bin 6–980 TeV



IceCube, *Nature* 2017

Bonus: Measuring the inelasticity $\langle y \rangle$

- Inelasticity in CC ν_μ interaction $\nu_\mu + N \to \mu + X$:

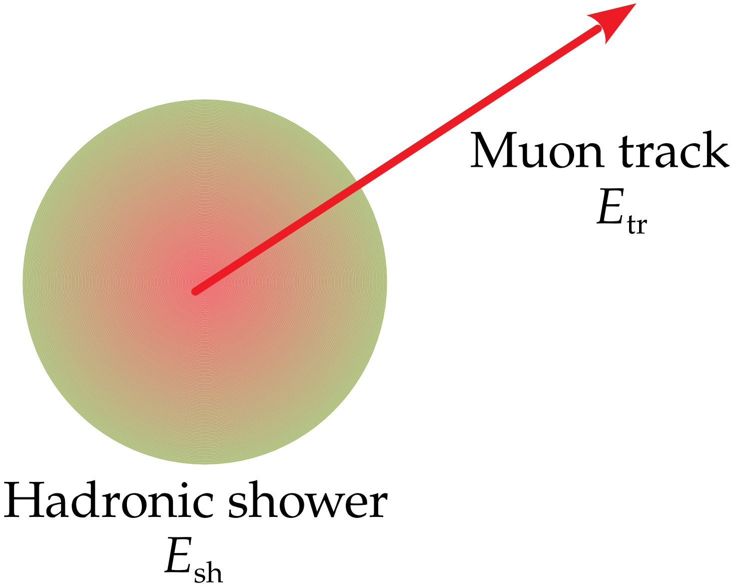
  $E_X = y\, E_\nu$ and $E_\mu = (1-y)\, E_\nu \;\Rightarrow\; y = (1 + E_\mu / E_X)^{-1}$

- The value of y follows a distribution $d\sigma/dy$

- In a HESE starting track:

  $E_X = E_{sh}$ (energy of shower)
  $E_\mu = E_{tr}$ (energy of track)
  $\Big\}\; y = (1 + E_{tr}/E_{sh})^{-1}$

- New IceCube analysis:
  - 5 years of starting-track data (2650 tracks)
  - Machine learning separates shower from track
  - Different y distributions for ν and $\bar{\nu}$



IceCube, *PRD* 2019

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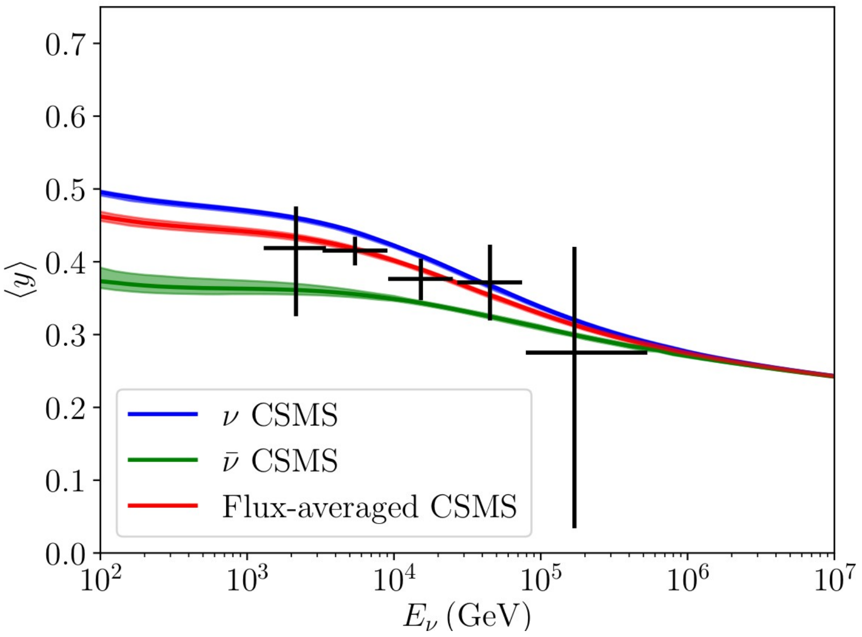


IceCube, *PRD* 2019

Example 4: Neutrino decay

Are neutrinos forever?

- In the Standard Model (νSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):
  - One-photon decay ($\nu_i \to \nu_j + \gamma$): $\tau > 10^{36}\,(m_i/\text{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \to \nu_j + \gamma + \gamma$): $\tau > 10^{57}\,(m_i/\text{eV})^{-9}$ yr
  - Three-neutrino decay ($\nu_i \to \nu_j + \nu_k + \bar{\nu}_k$): $\tau > 10^{55}\,(m_i/\text{eV})^{-5}$ yr

  » Age of Universe (~ 14.5 Gyr)

- BSM decays may have significantly higher rates: $\nu_i \to \nu_j + \varphi$

- φ: Nambu-Goldstone boson of a broken symmetry (*e.g.*, Majoron)

- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors

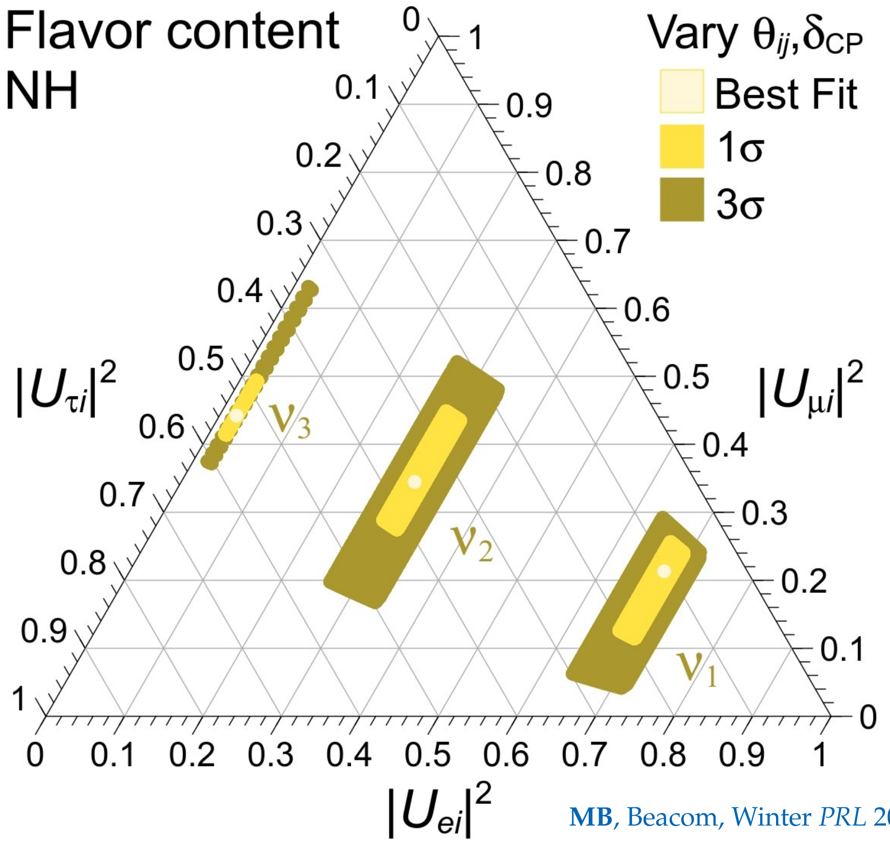
Flavor content of neutrino mass eigenstates

Known to within 2%

$$|U_{\alpha i}|^2 = |U_{\alpha i}(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})|^2$$

Known to within 8%

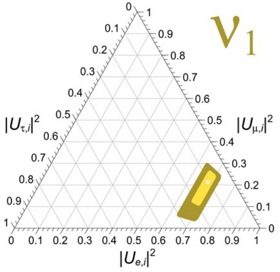
Known to within 20%
(or worse)



MB, Beacom, Winter *PRL* 2015

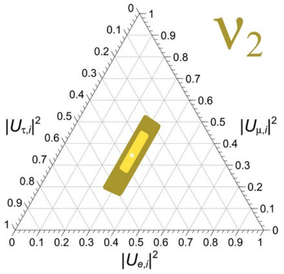
Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3 —

w_1



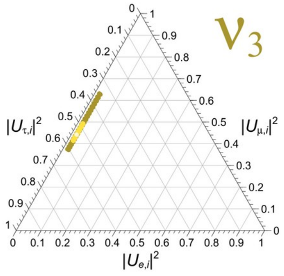
+

w_2

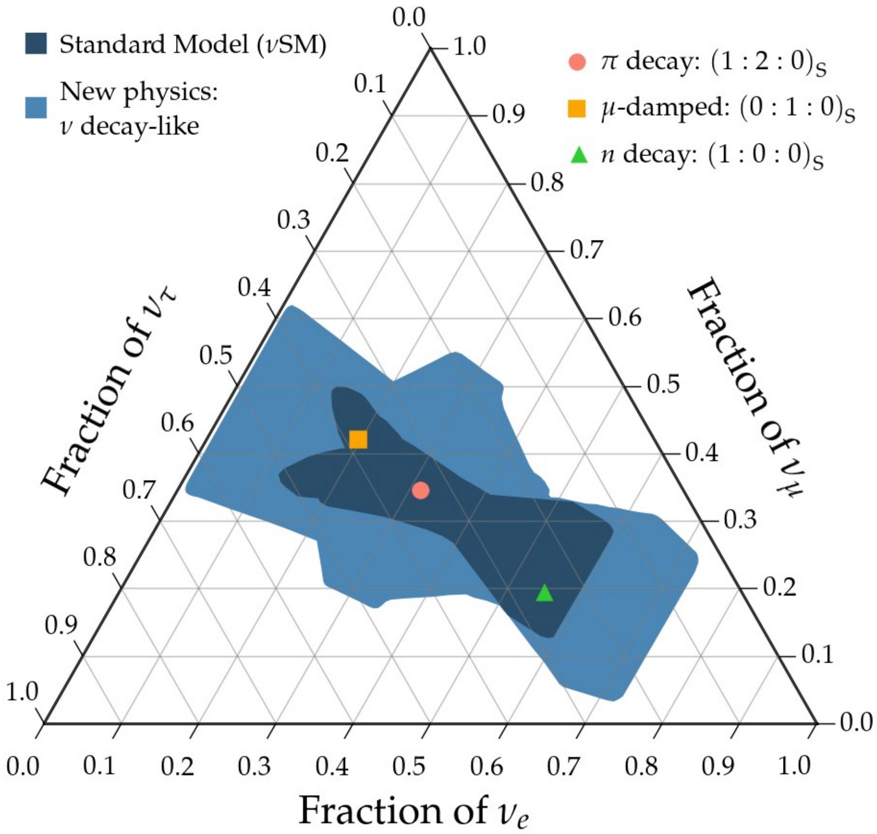


+

w_3



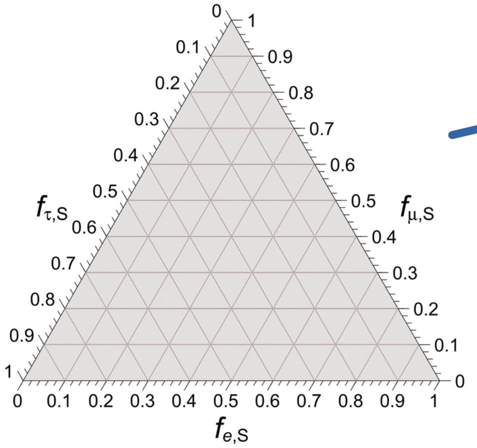
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights ▸ with striking consequences for flavor

Measuring the neutrino lifetime

Sources



$$\underbrace{\nu_2, \nu_3 \rightarrow \nu_1}$$

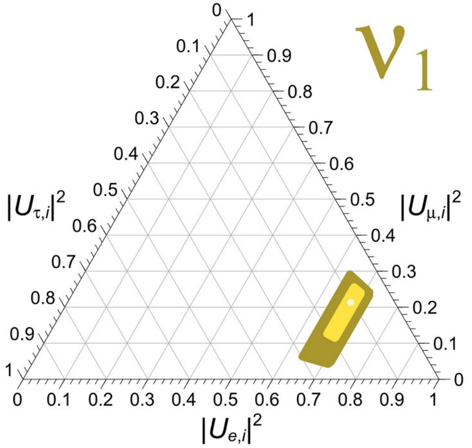
ν_1 lightest and stable (normal mass ordering)

If all unstable neutrinos decay

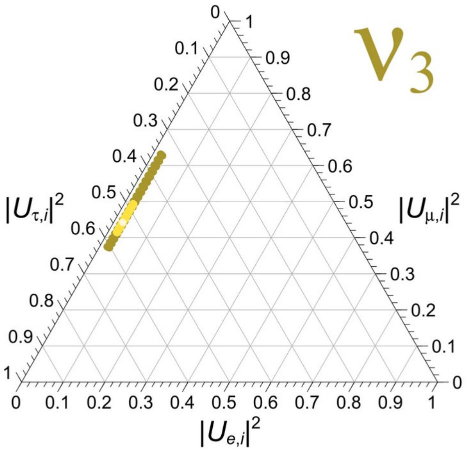
$$\underbrace{\nu_1, \nu_2 \rightarrow \nu_3}$$

ν_3 lightest and stable (inverted mass ordering)

Earth



$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$
$(w_1 \sim 1; w_2, w_3 \sim 0)$



$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$
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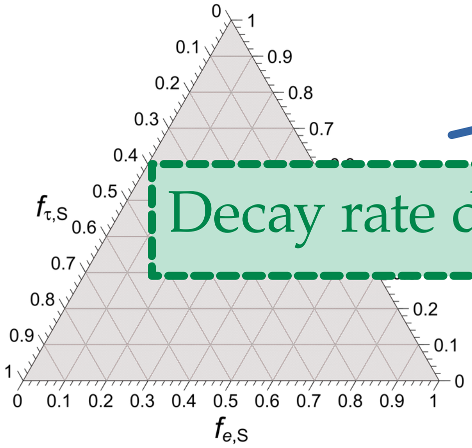
Measuring the neutrino lifetime

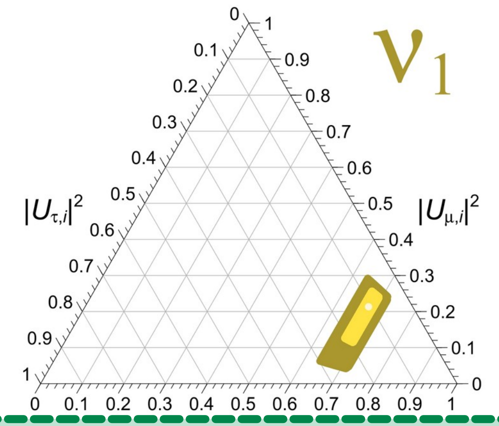
Earth

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)

Sources



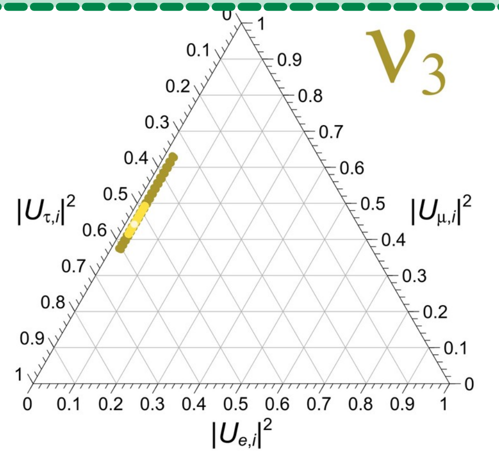


ν_1

$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$

$(w_1 \sim 1; w_2, w_3 \sim 0)$

Decay rate depends on $\exp[-\, t \,/\, (\gamma\, \tau_i)] = \exp[-\, (L/E) \cdot (m_i/\tau_i)]$



ν_3

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$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
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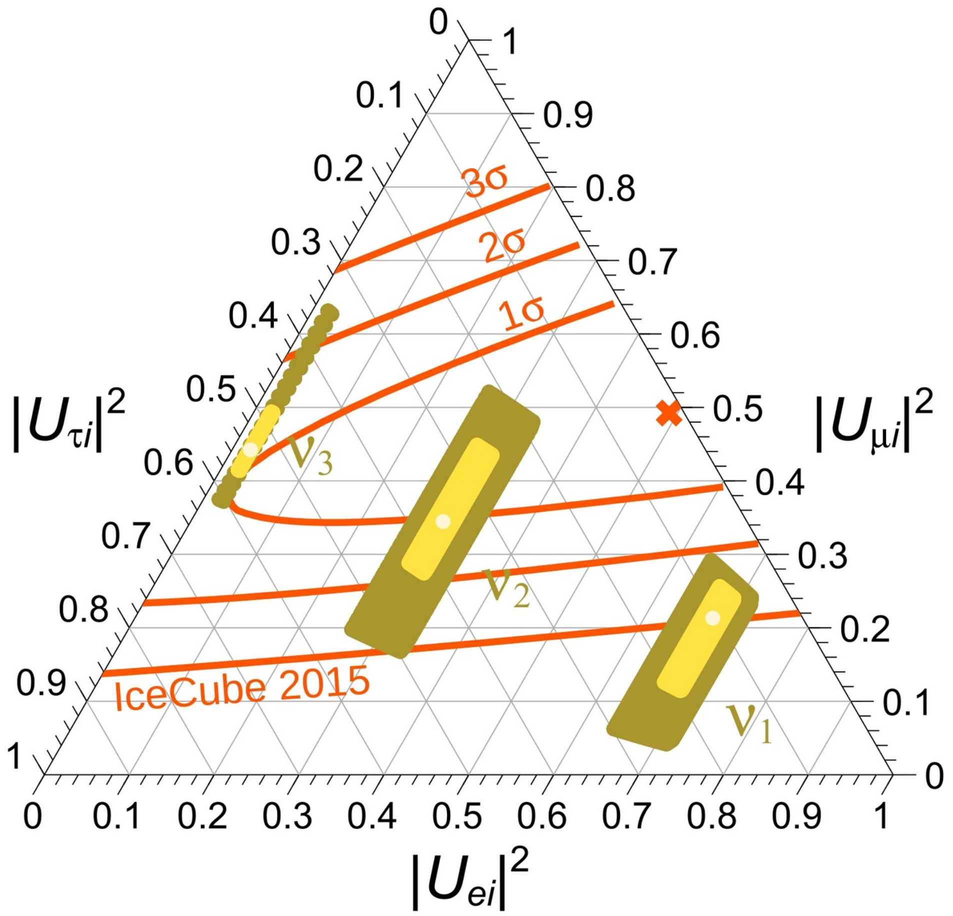
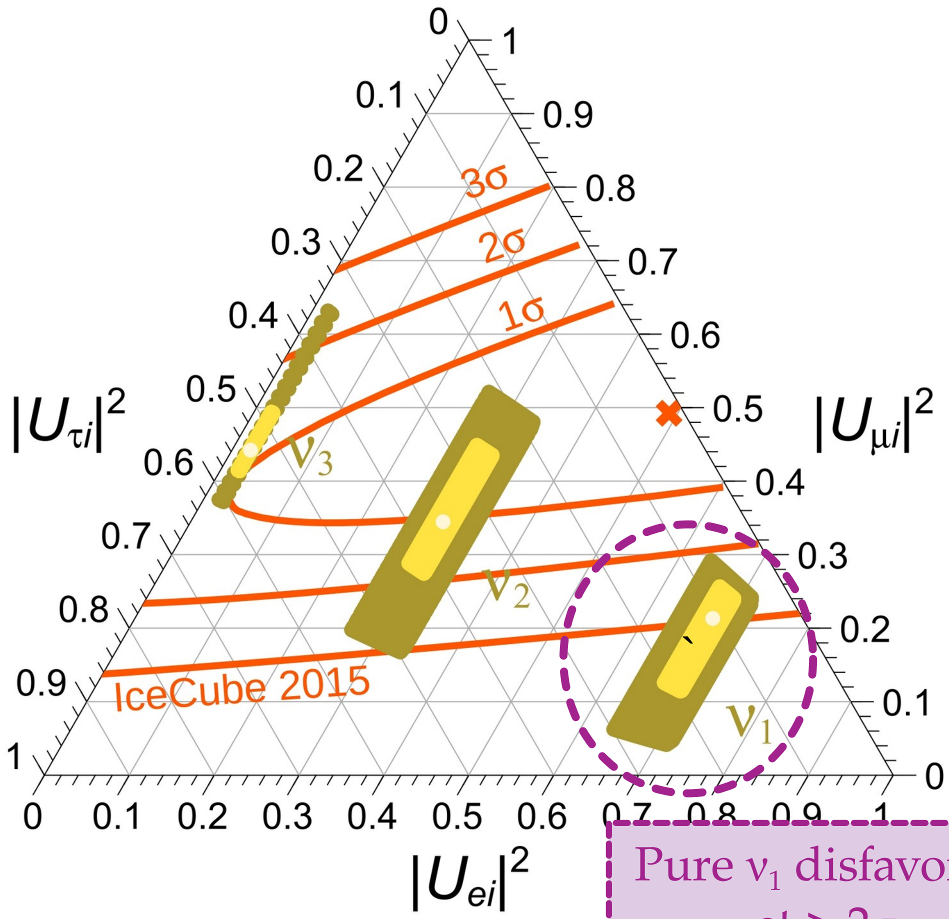


MB, Beacom, Murase, *PRD* 2017

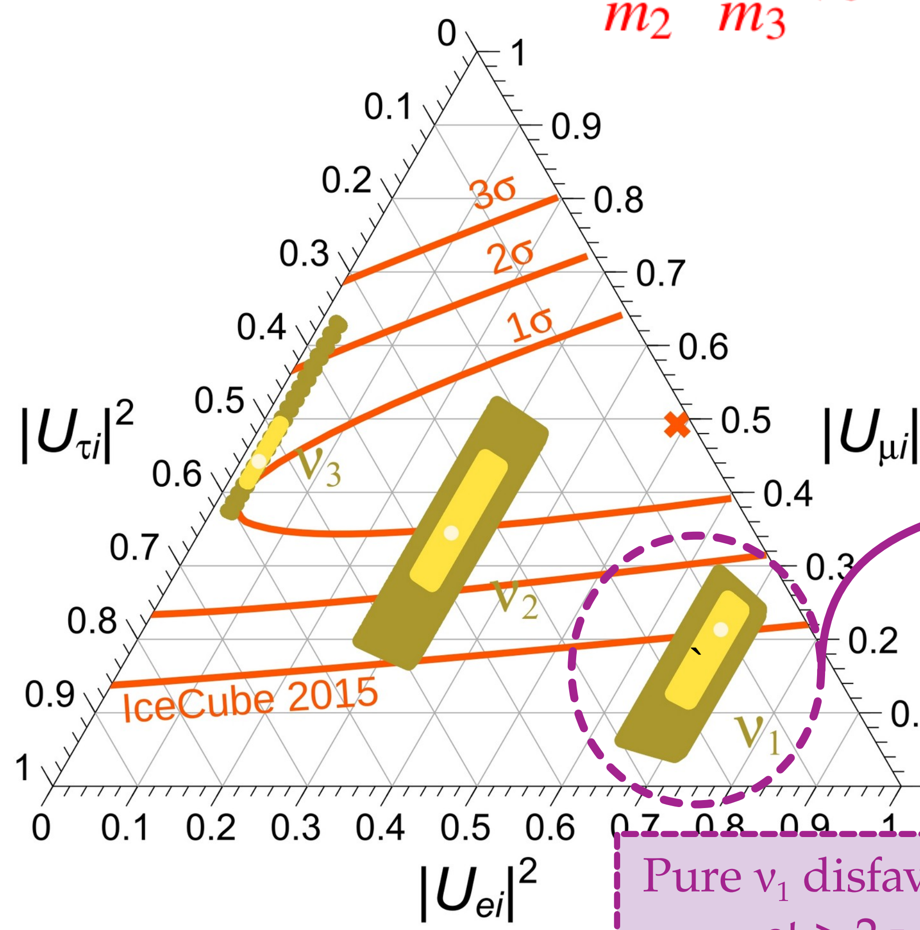
Baerwald, **MB**, Winter, *JCAP* 2012

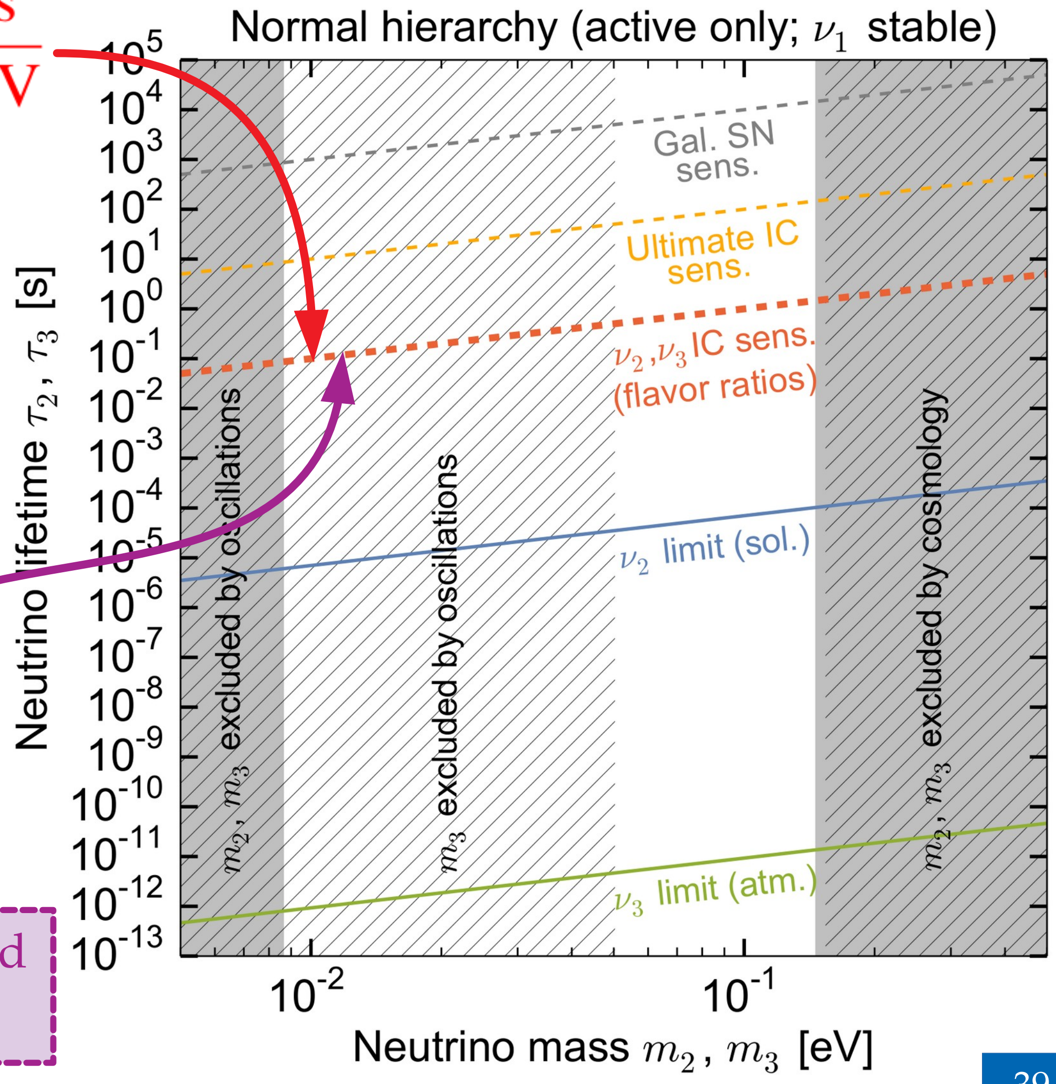


Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

$$\frac{\tau_2}{m_2}, \frac{\tau_3}{m_3} \gtrsim 10 \, \frac{\text{s}}{\text{eV}}$$





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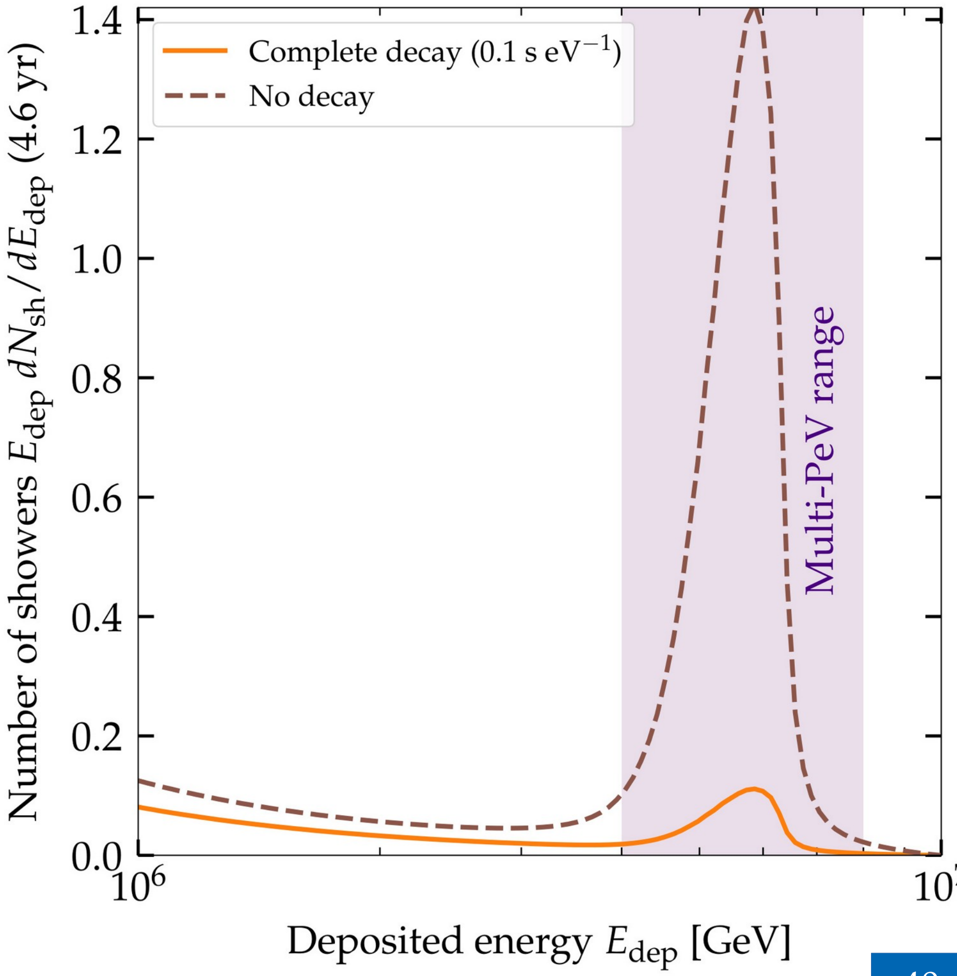
Using the Glashow resonance to test decay

- At 6.3 PeV, the Glashow resonance ($\bar{\nu}_e + e \to W$) should trigger showers in IceCube
- … unless ν_1, ν_2 decay to ν_3 en route to Earth (the surviving ν_3 have little electron content)
- IceCube has seen 1 shower in the 4–8 PeV range, so ν_1, ν_2 *must* make it to Earth
- So we set *lower* limits on their lifetimes (in the inverted mass ordering)
- Translated into *upper* limits on coupling



MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

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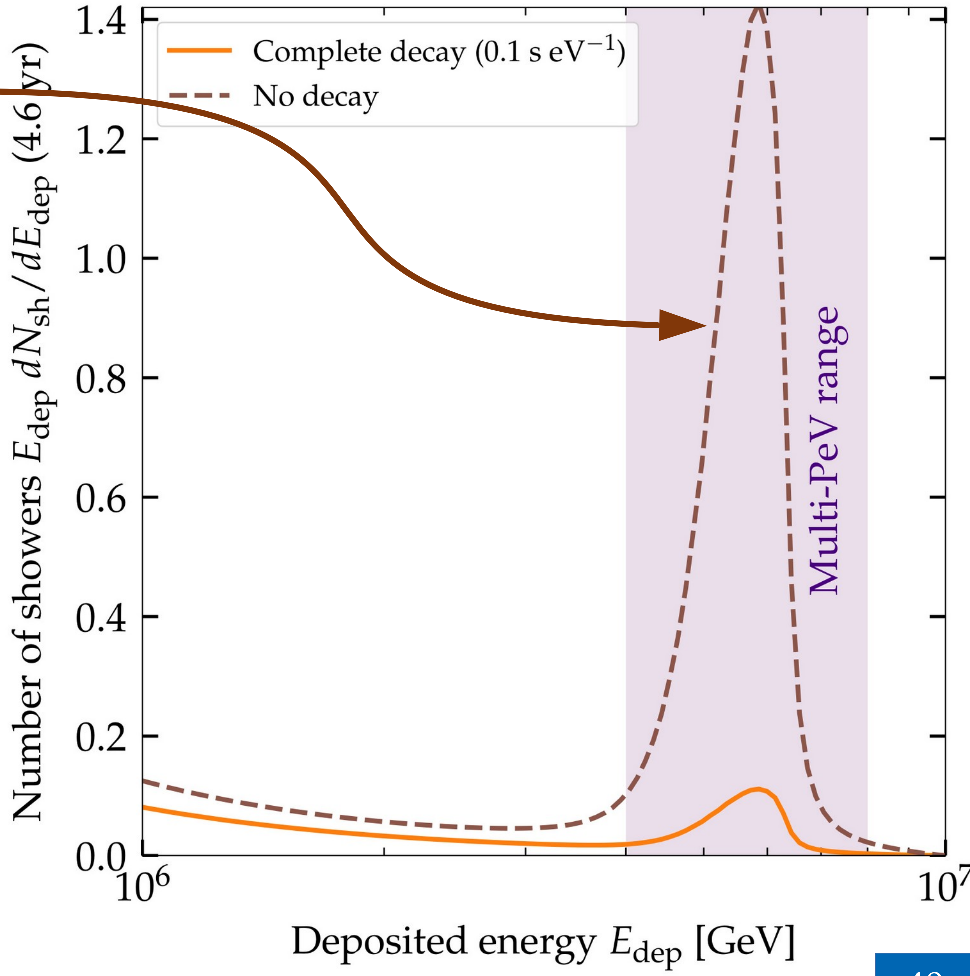

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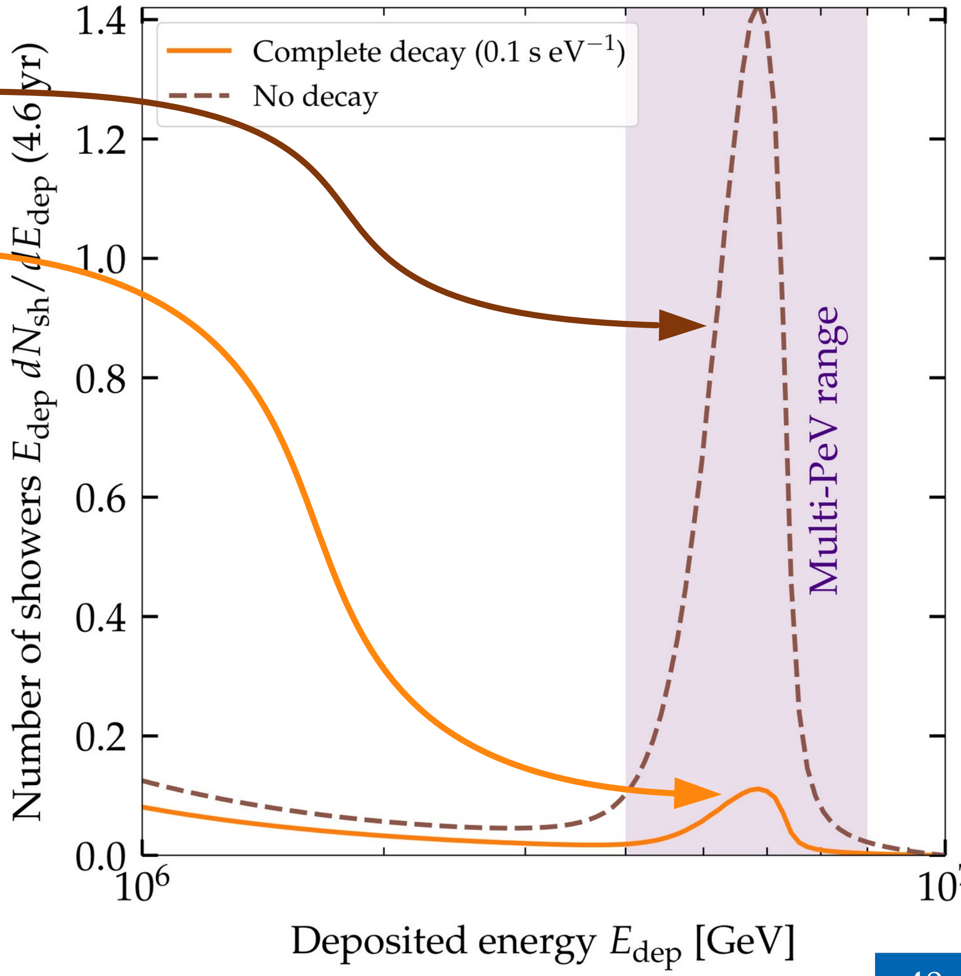

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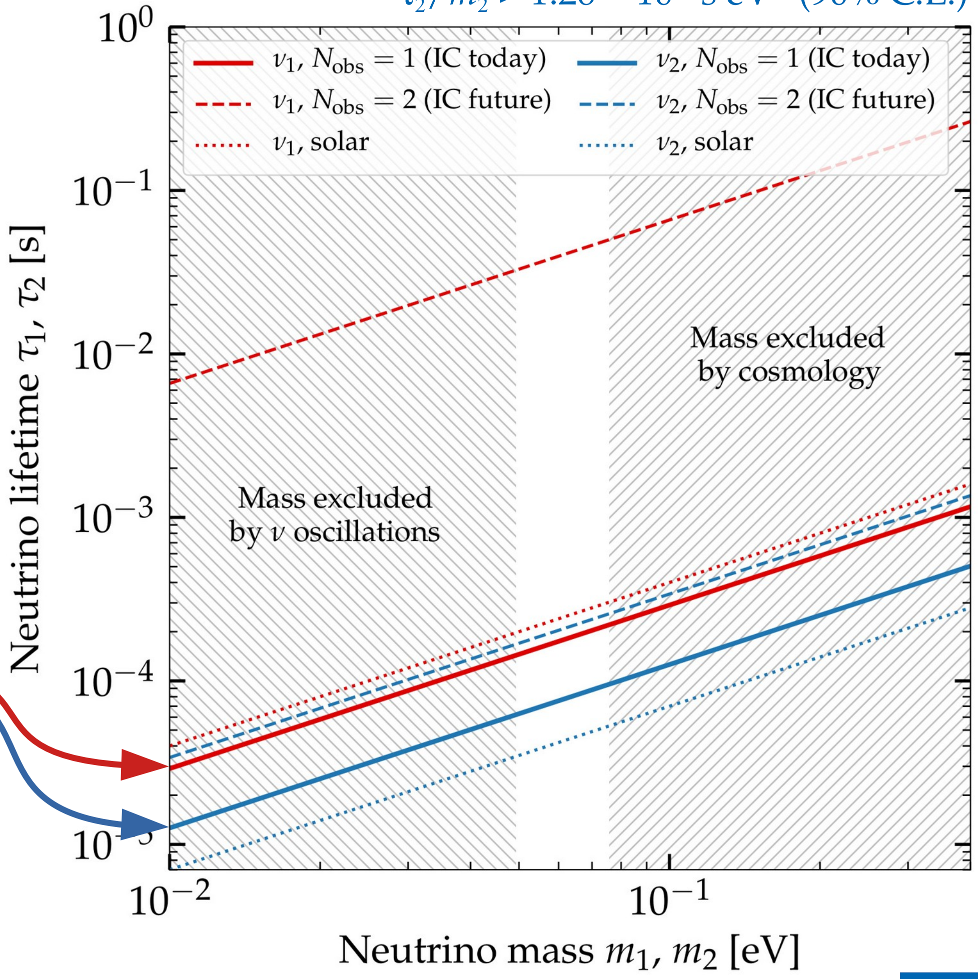
$\tau_1/m_1 > 2.91 \times 10^{-3}$ s eV^{-1} (90% C.L.)
$\tau_2/m_2 > 1.26 \times 10^{-3}$ s eV^{-1} (90% C.L.)



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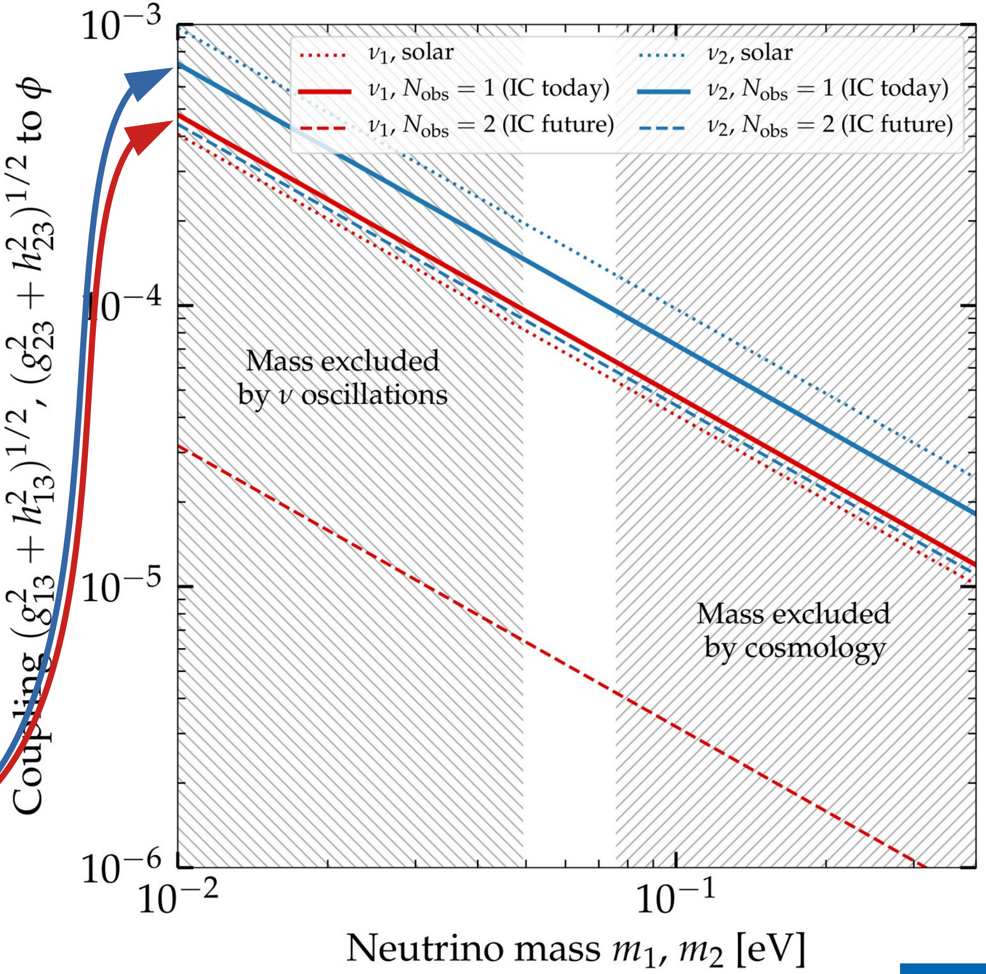
$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$



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Flavor composition

Inferring the flavor composition at the sources

Ingredient #1:
Flavor ratios measured at Earth,
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

Ingredient #2:
Probability density of mixing parameters (θ_{12}, θ_{23}, θ_{13}, $\delta_{\rm CP}$)

Posterior probability of $f_{\alpha,\rm S}$ [**MB** & Ahlers, *PRL* 2019]:

$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \mathcal{L}(\boldsymbol{\vartheta}) \mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}, \boldsymbol{\vartheta}))$$

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

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$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\beta\to\alpha} f_{\beta,{\rm S}}$$

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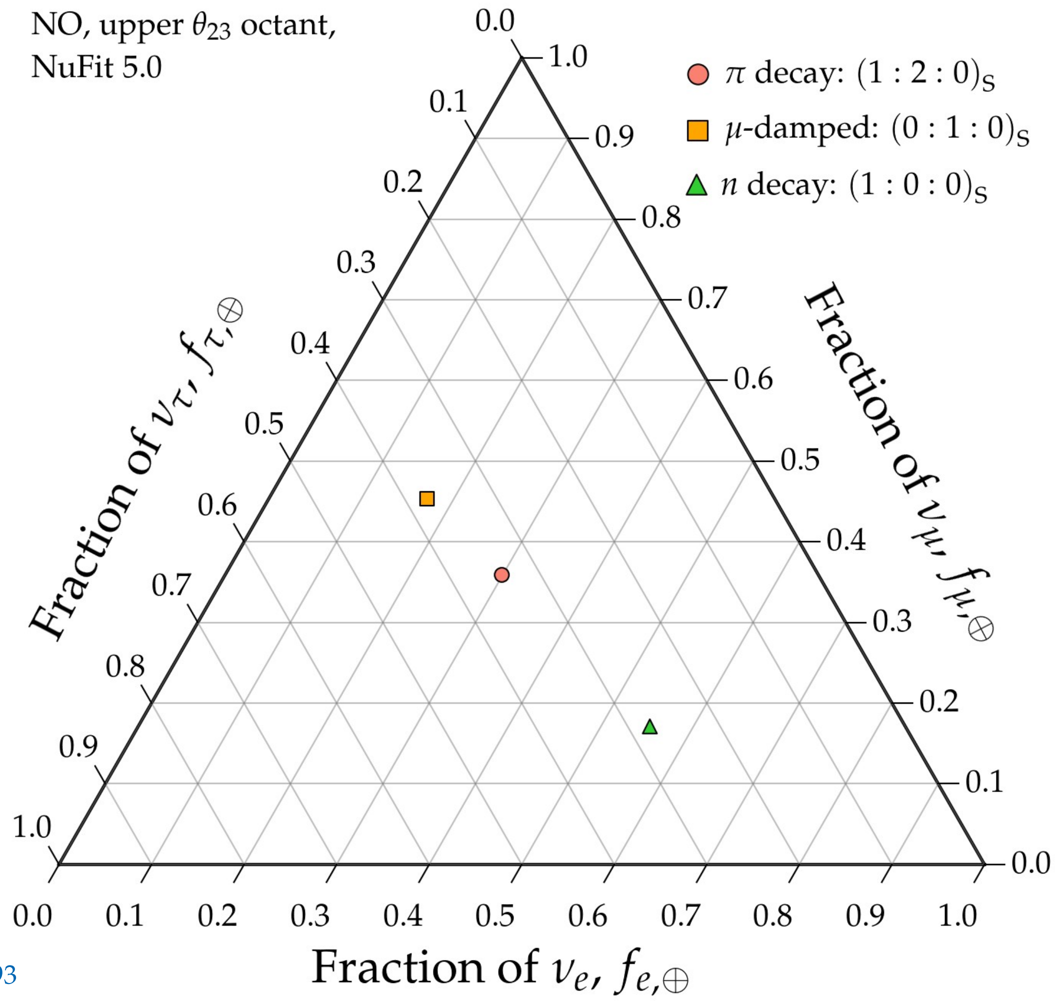
Oscillation experiments Neutrino telescopes

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

Theoretically palatable regions: today (2020)



Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

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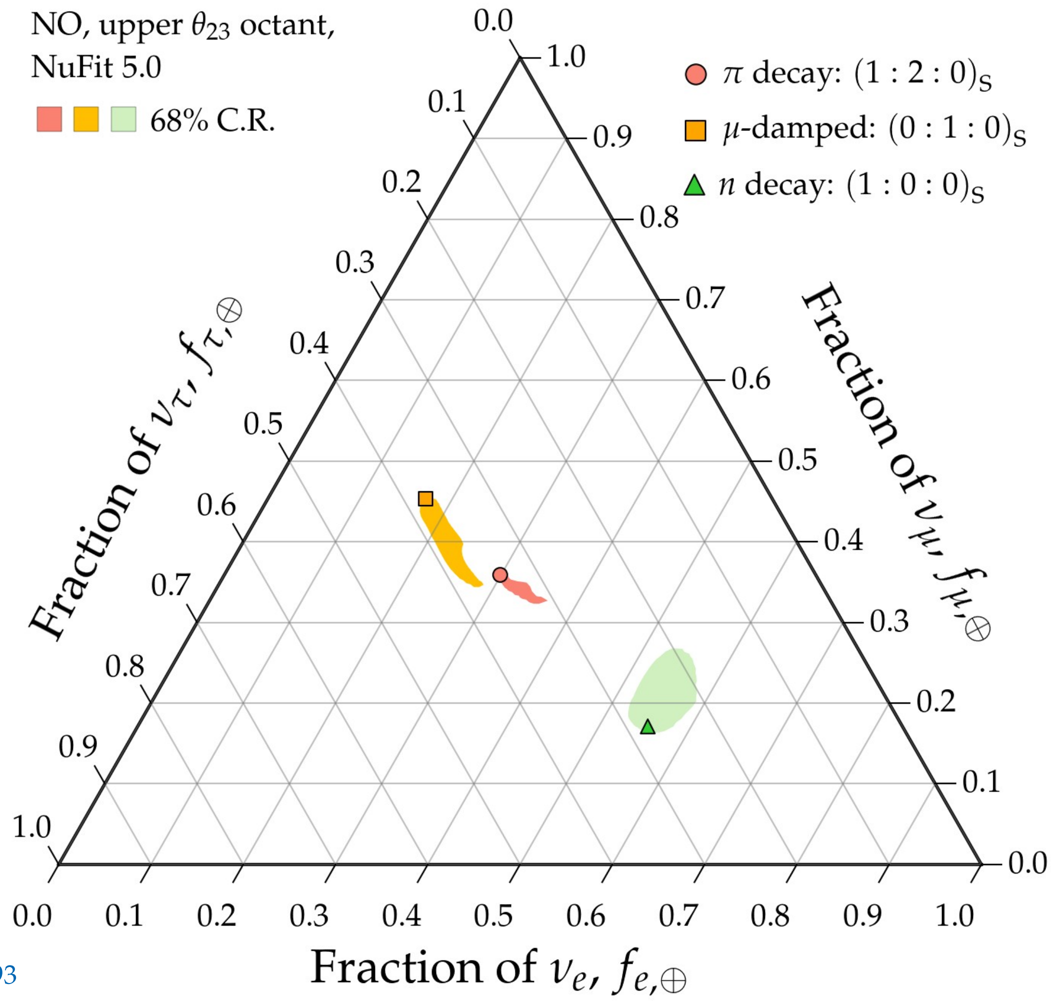

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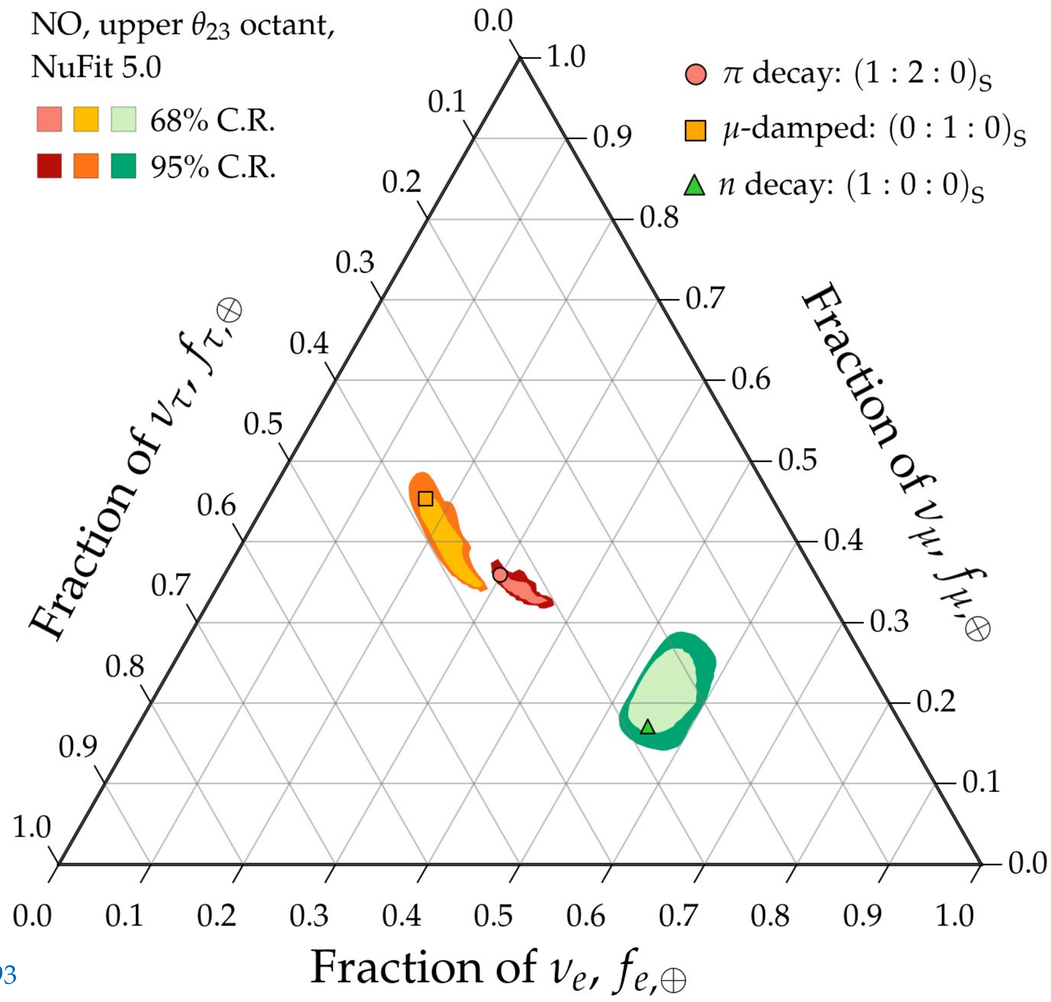

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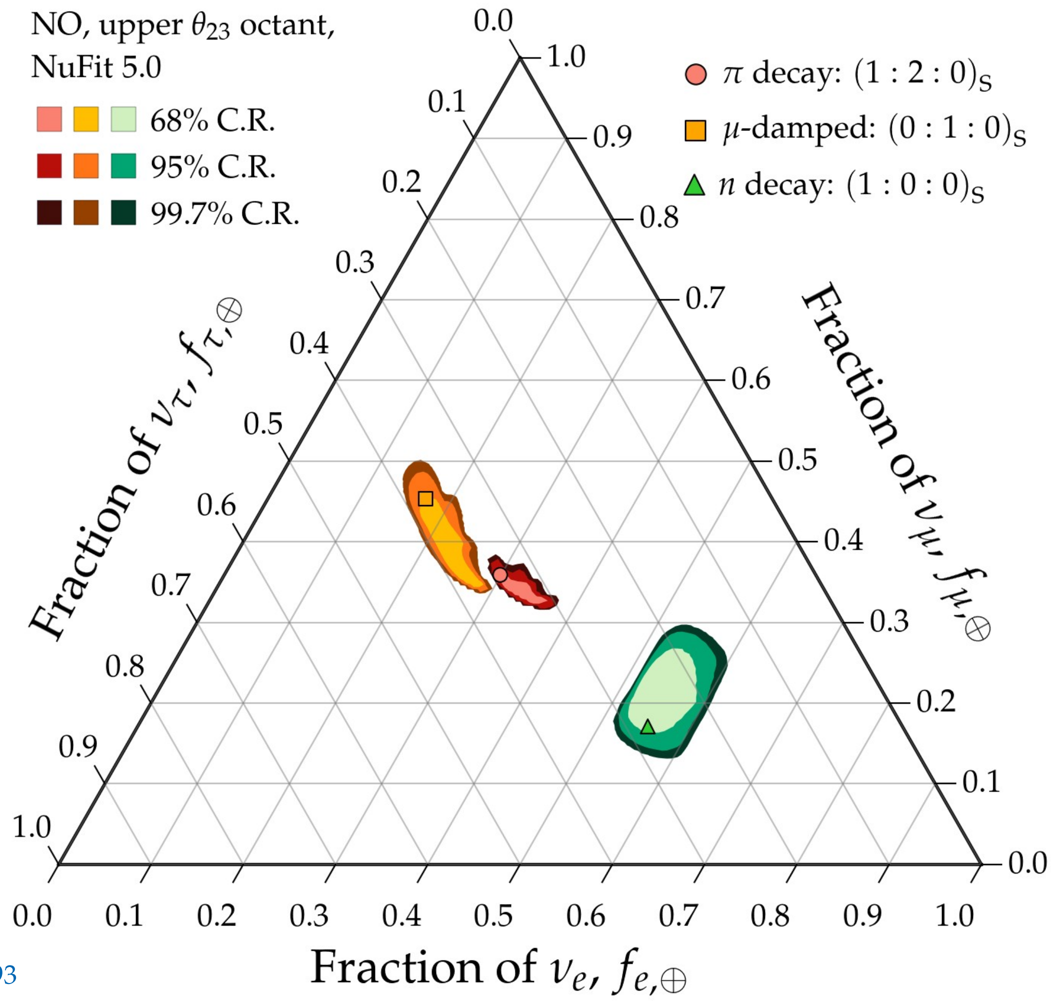

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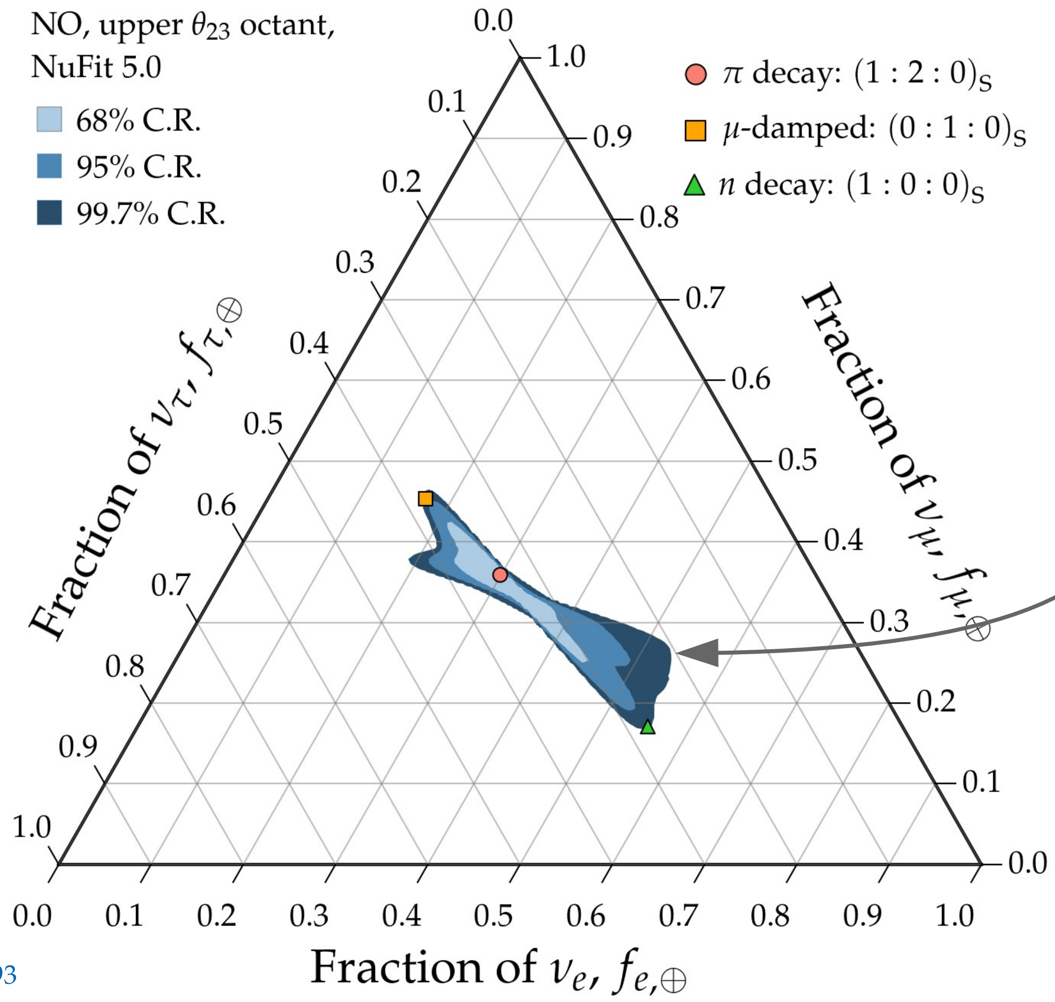

Varying over all possible flavor ratios at the source

Note:
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Song, Li, Argüelles, **MB**, Vincent, 2012.12893
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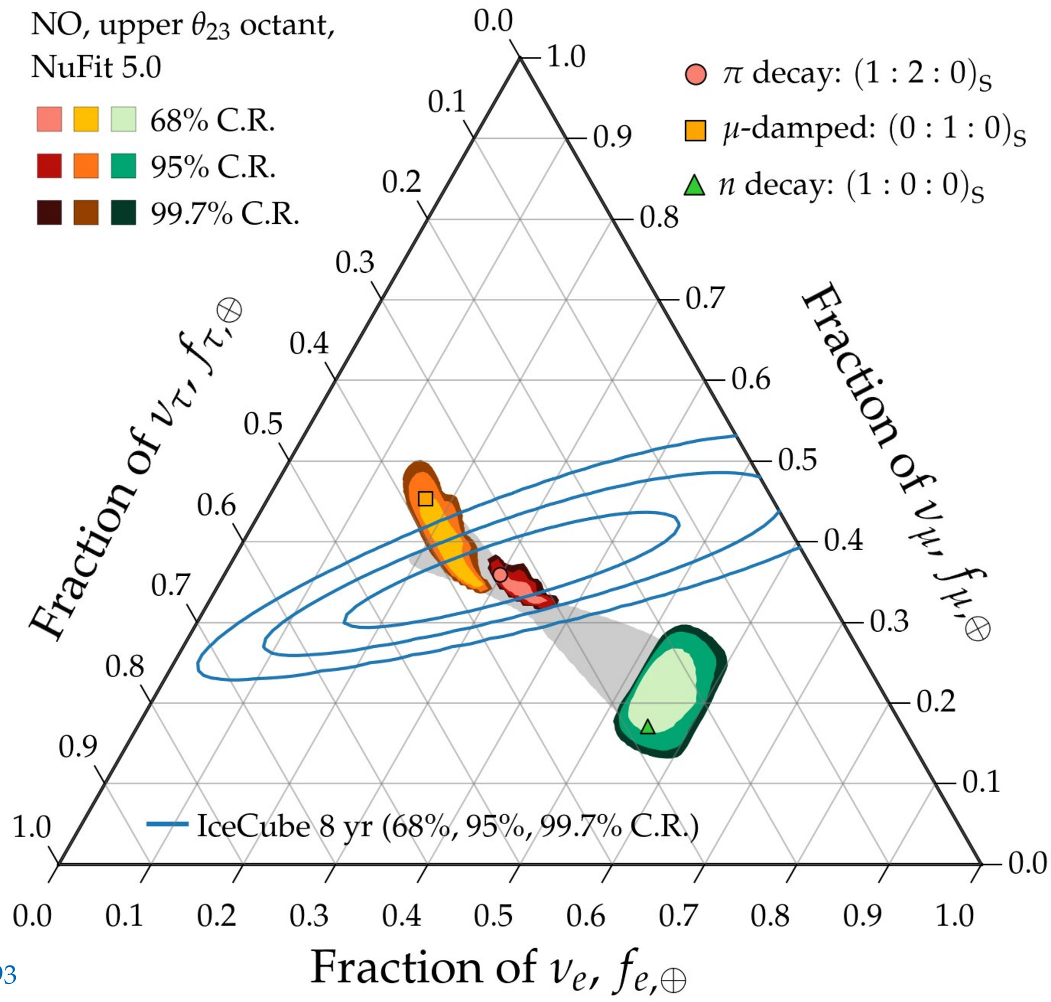

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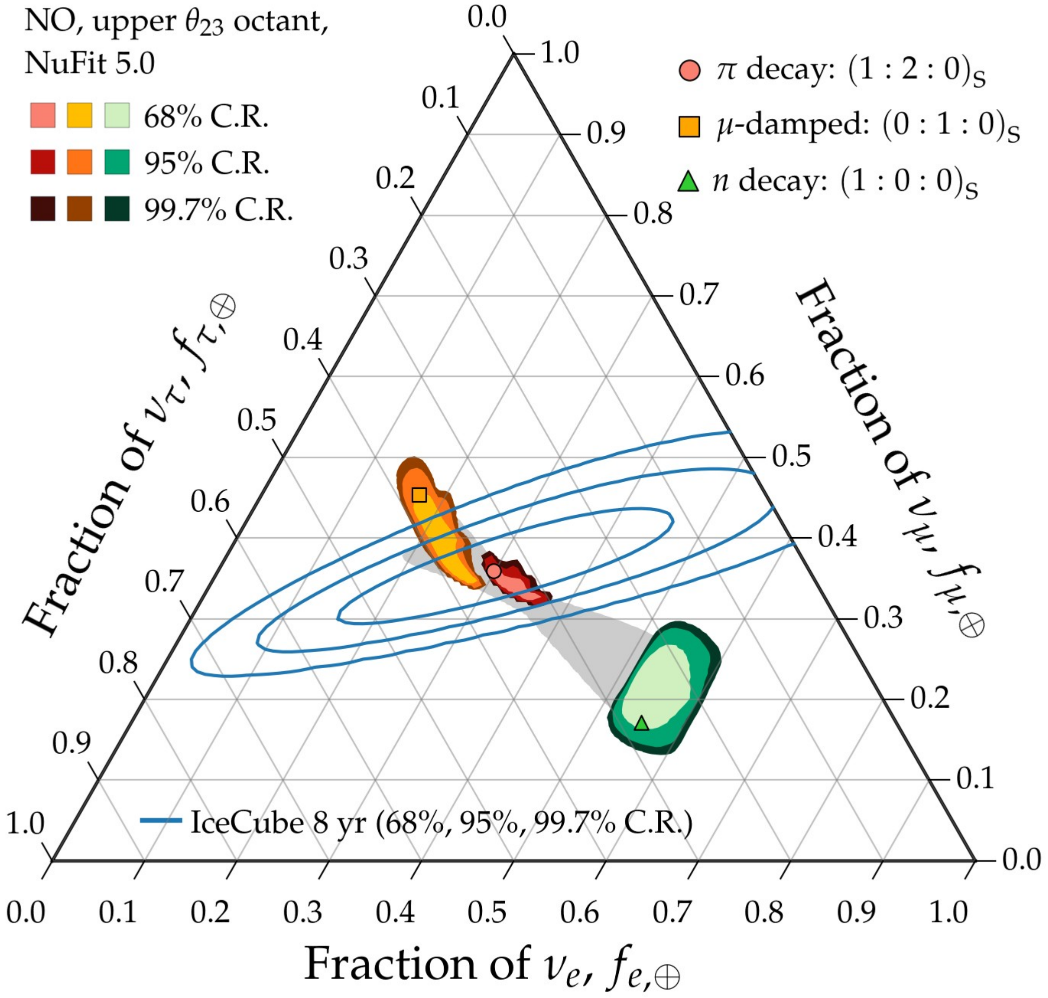

Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

Measurement of flavor ratios –
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
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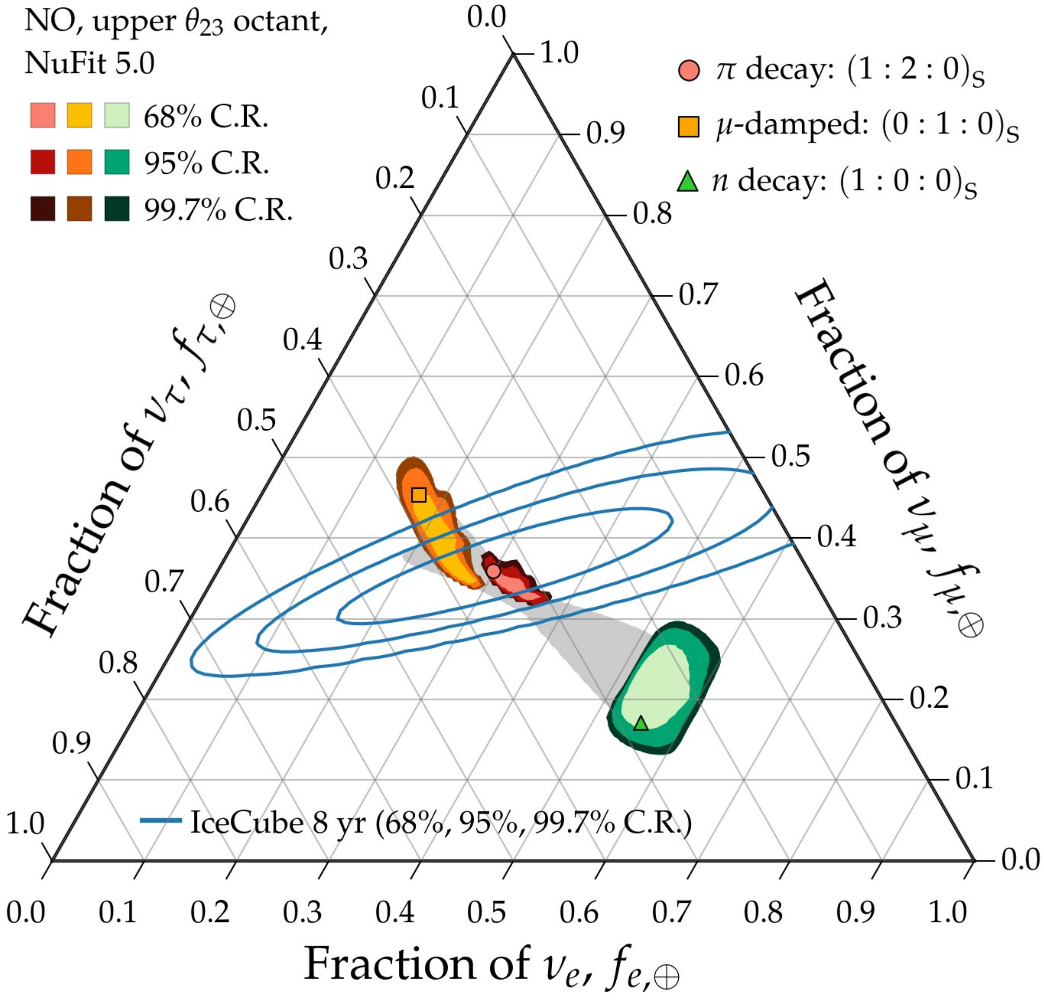

Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

Will be overcome by 2030

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Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

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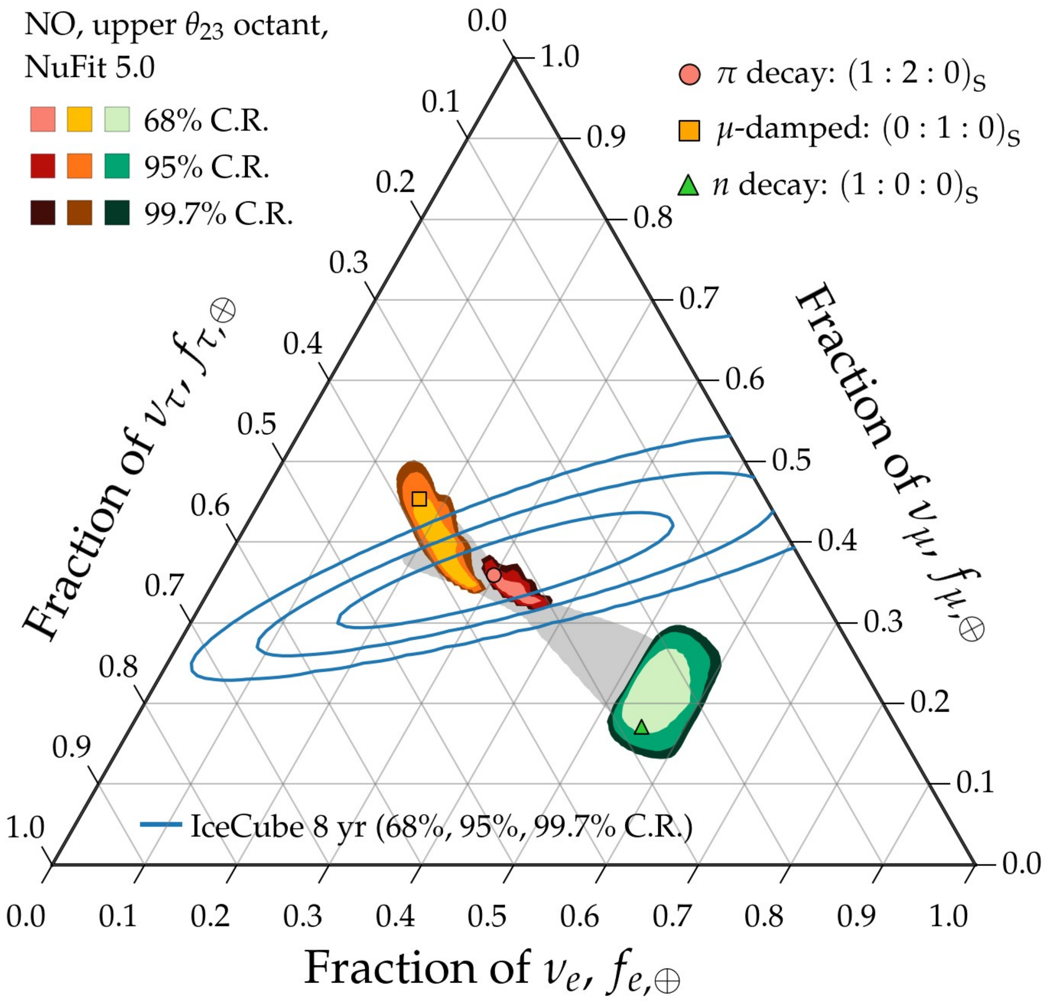

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Will be overcome by 2040

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Note:
The original palatable regions were frequentist [**MB**, Beacom, Winter, *PRL* 2015];
the new ones are Bayesian

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

$(f_{e,S}, f_{\mu,S}, f_{\tau,S})$

Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

Note:
The original palatable regions were frequentist [**MB**, Beacom, Winter, *PRL* 2015]; the new ones are Bayesian

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

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Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$

Note:
The original palatable regions were frequentist [**MB**, Beacom, Winter, *PRL* 2015]; the new ones are Bayesian

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:
Flavor ratios at the source,
$(f_{e,S}, f_{\mu,S}, f_{\tau,S})$

Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

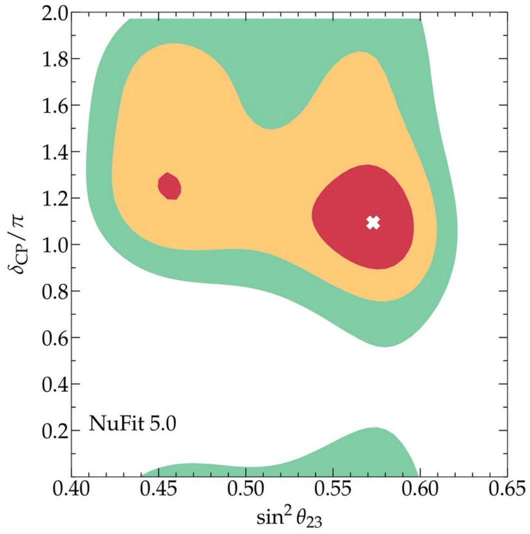
or

Explore all possible combinations

Ingredient #2:
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

Esteban *et al.*, *JHEP* 2020
www.nu-fit.org



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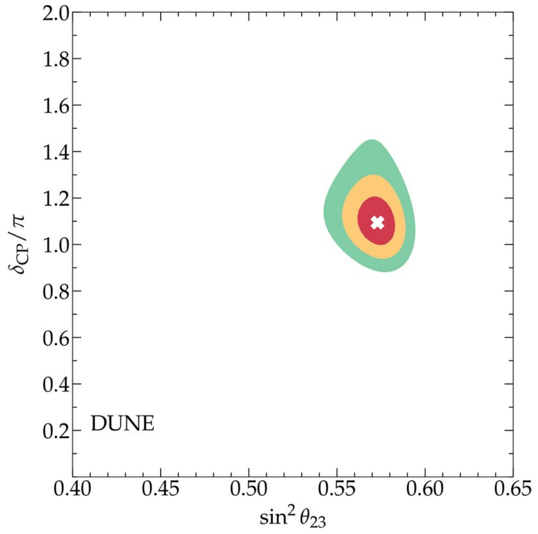
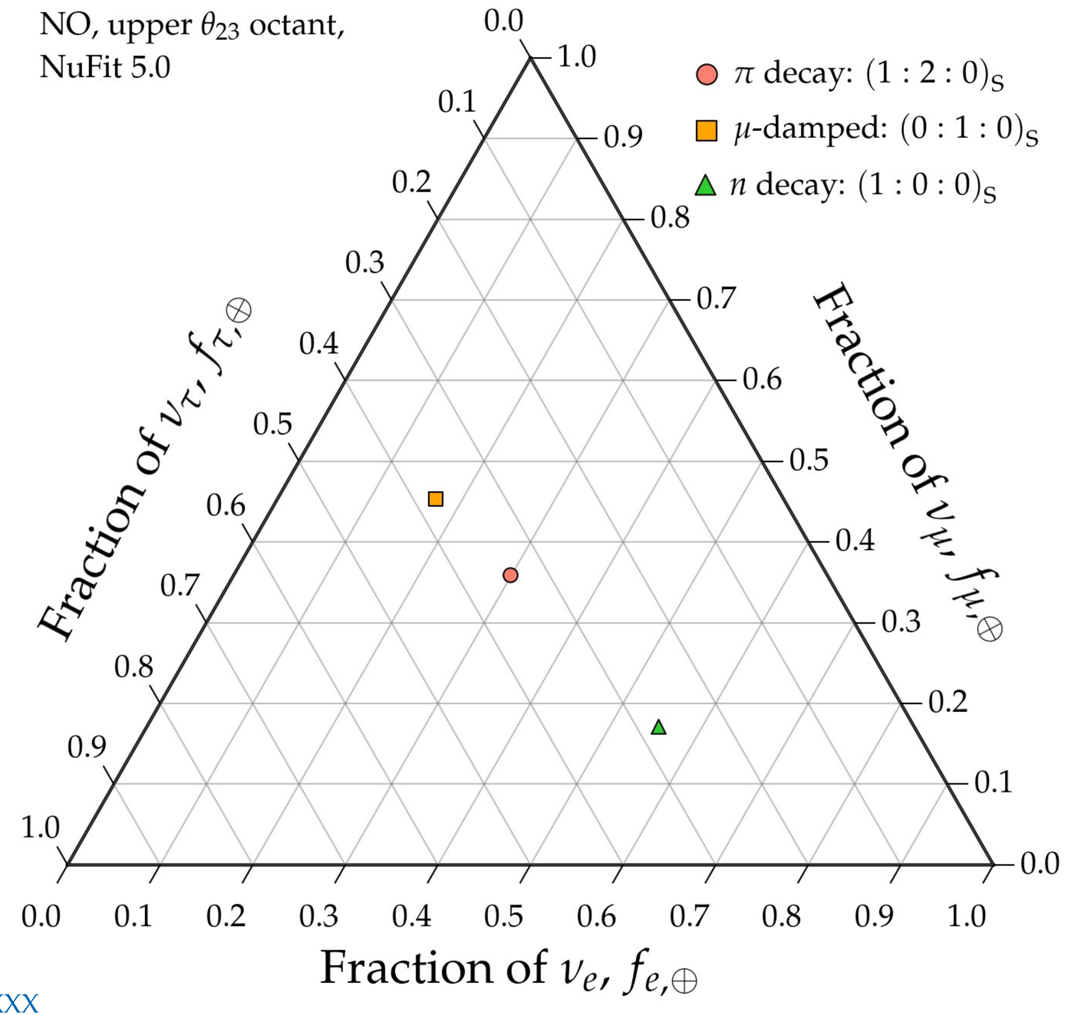
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

An *et al.*, *J. Phys. G* 2016
DUNE, 2002.03005
Huber, Lindner, Winter, *Nucl. Phys. B* 2002



Theoretically palatable regions: today (2020)



Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

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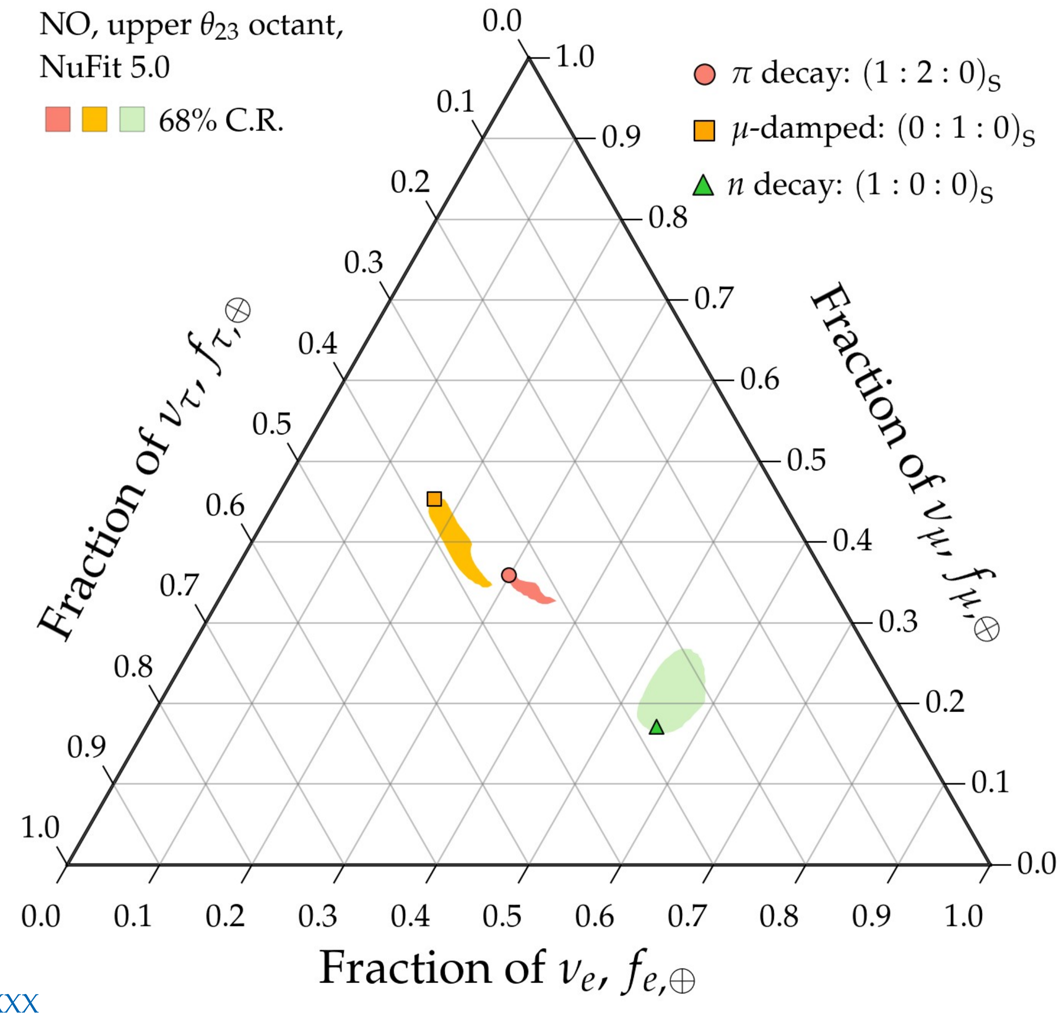

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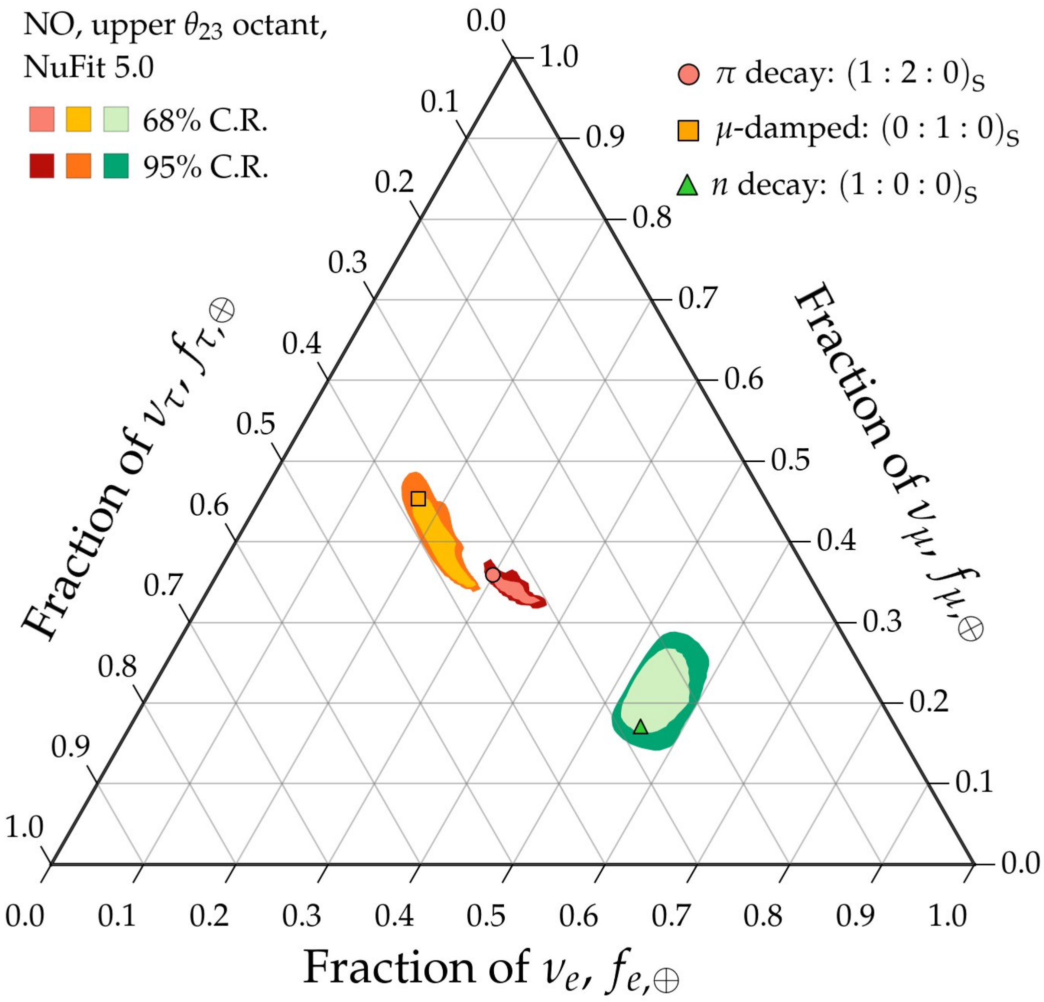

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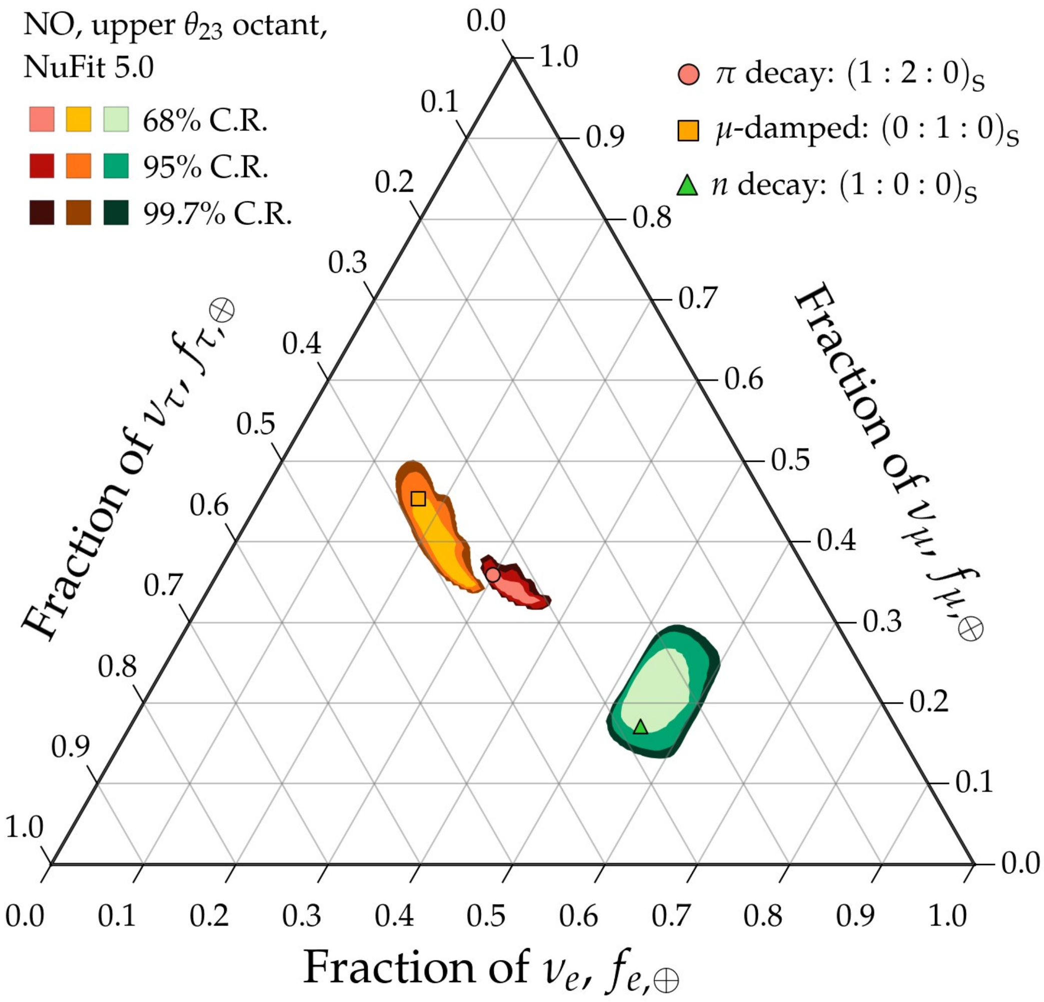

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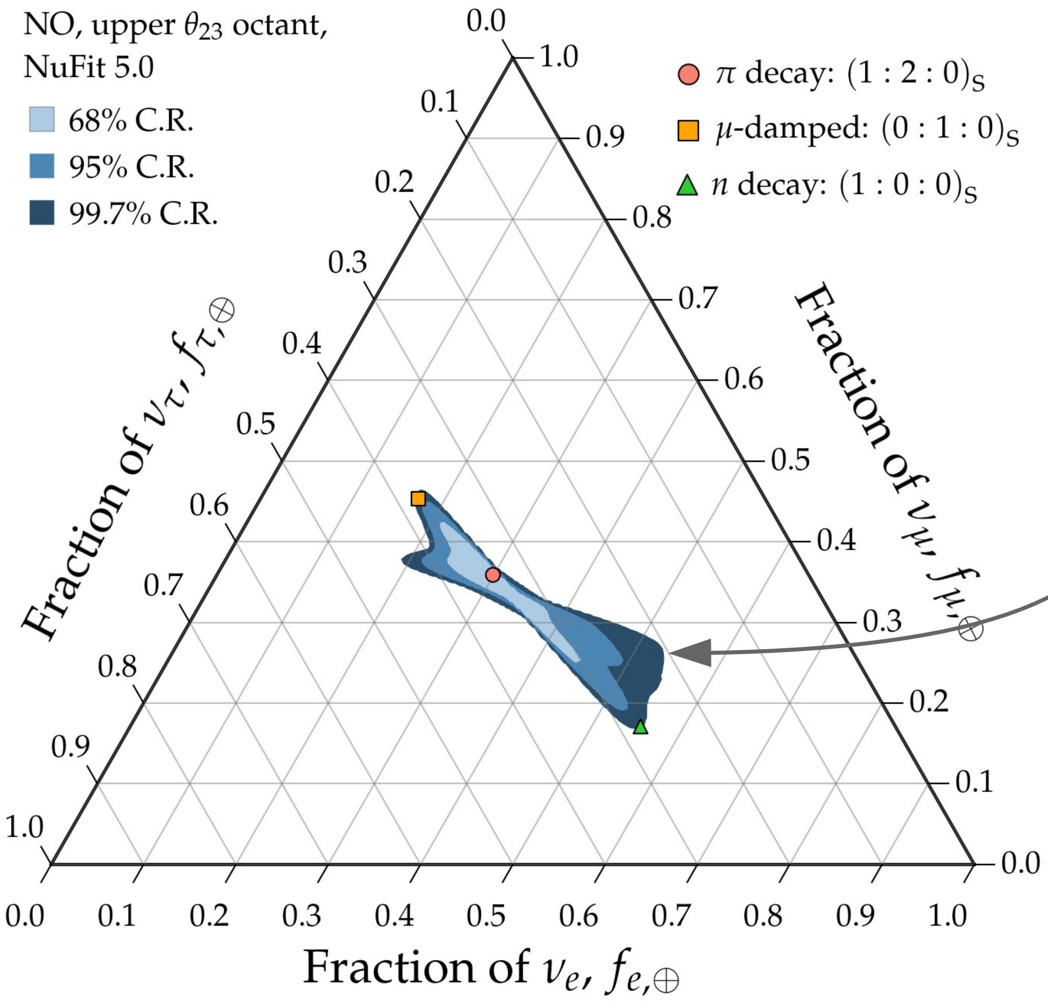
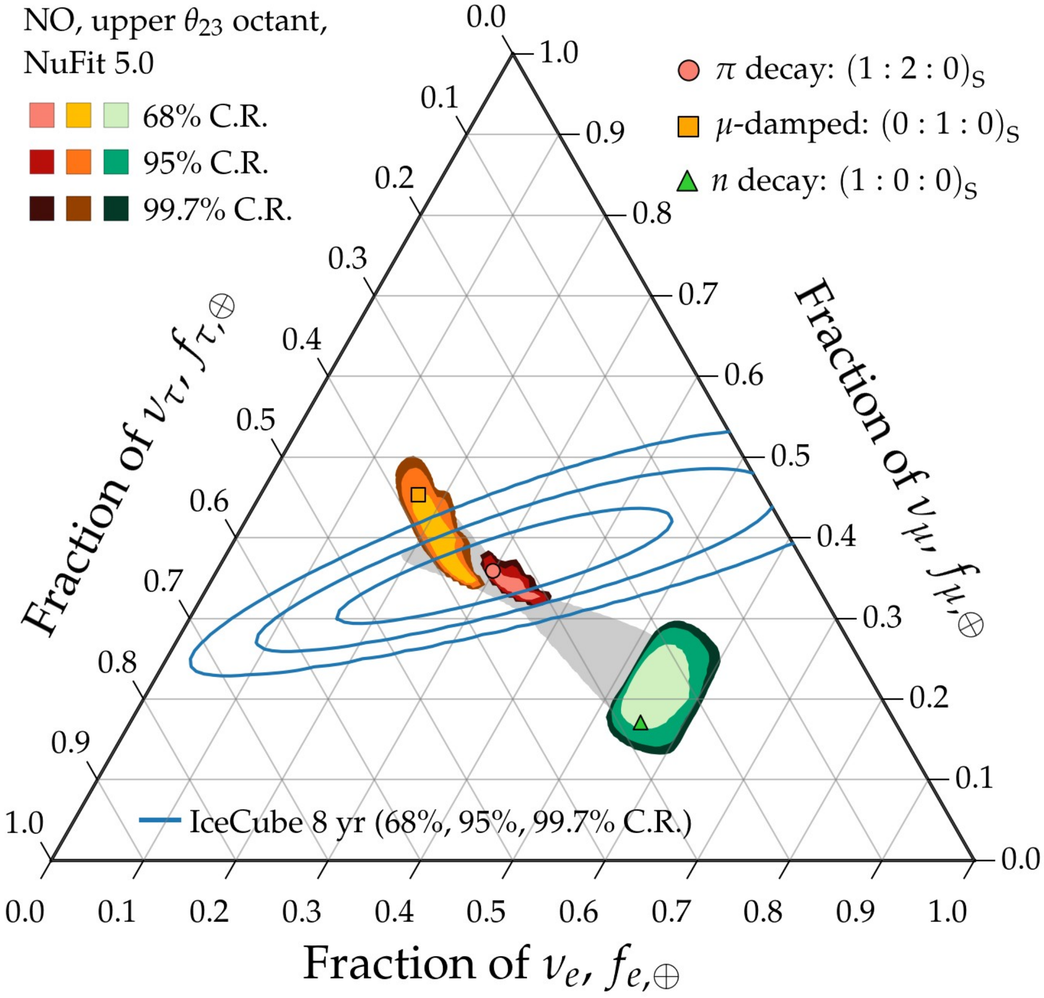


Varying over all possible flavor ratios at the source

Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: today (2020)



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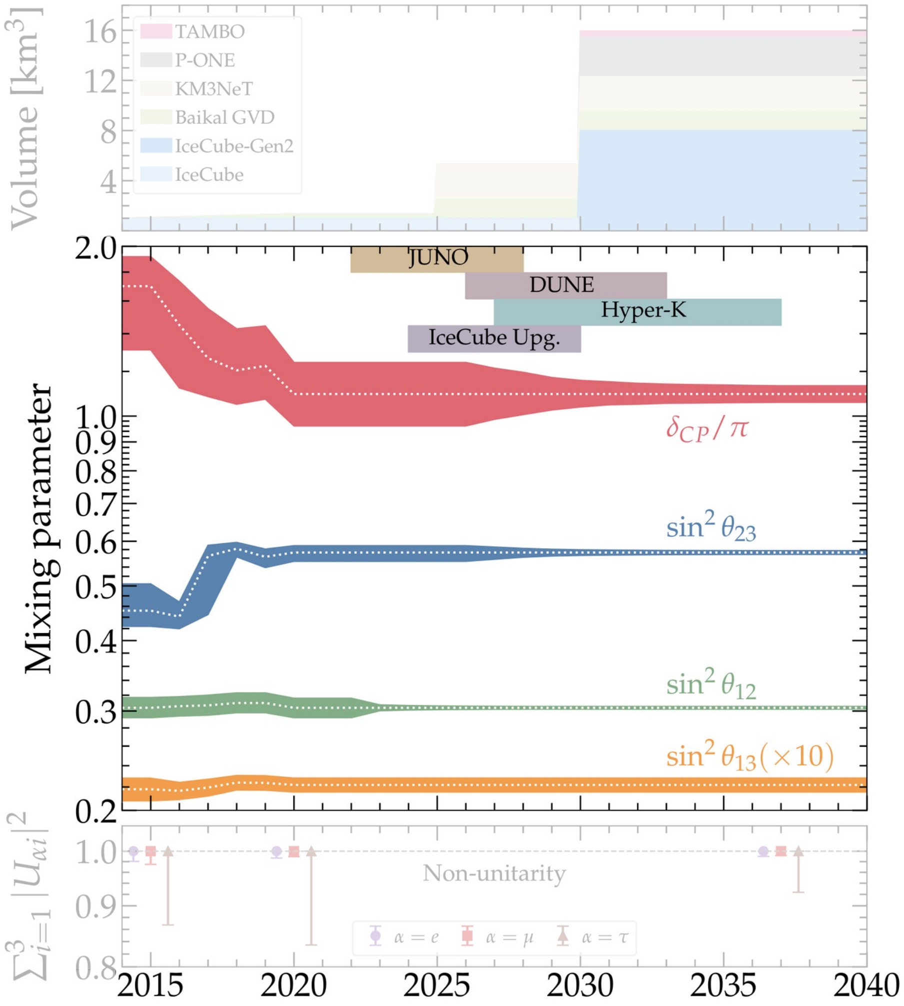
How knowing the mixing parameters better helps

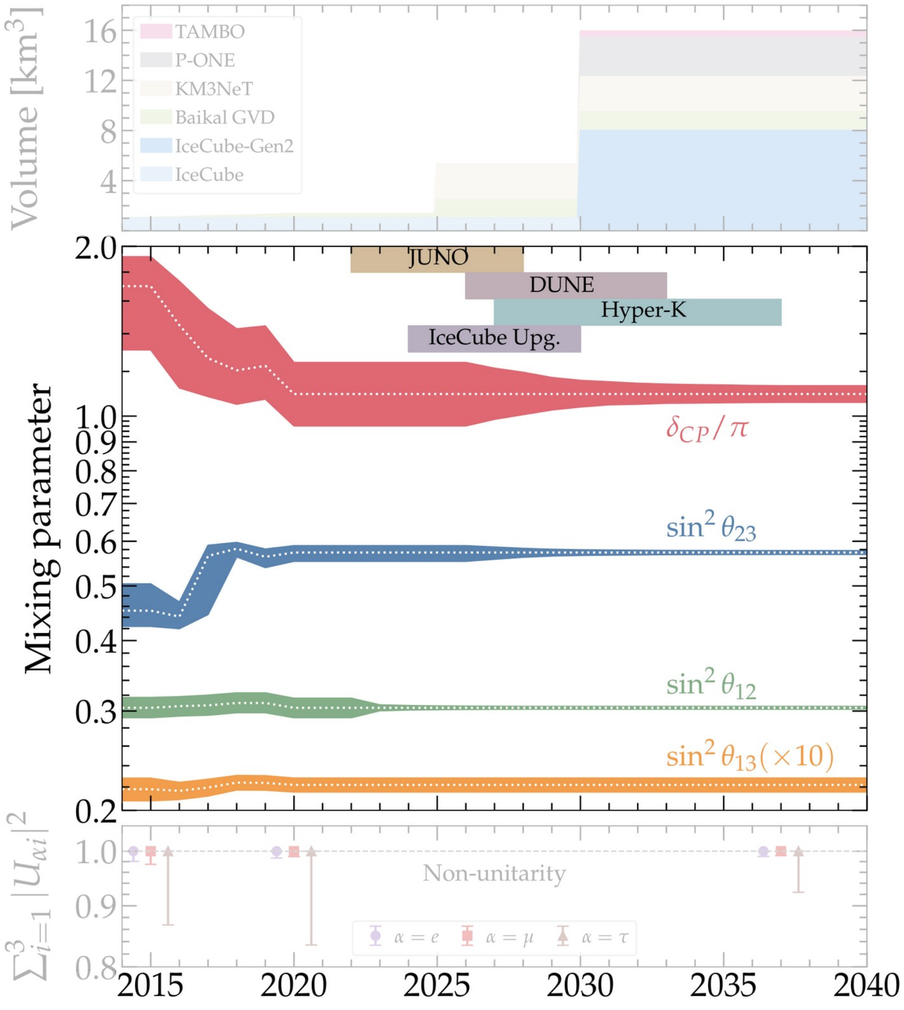


We can compute the oscillation probability more precisely:

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\beta\alpha} f_{\beta,\mathrm{S}}$$

So we can convert back and forth between source and Earth more precisely

How knowing the mixing parameters better helps



For a future experiment
ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

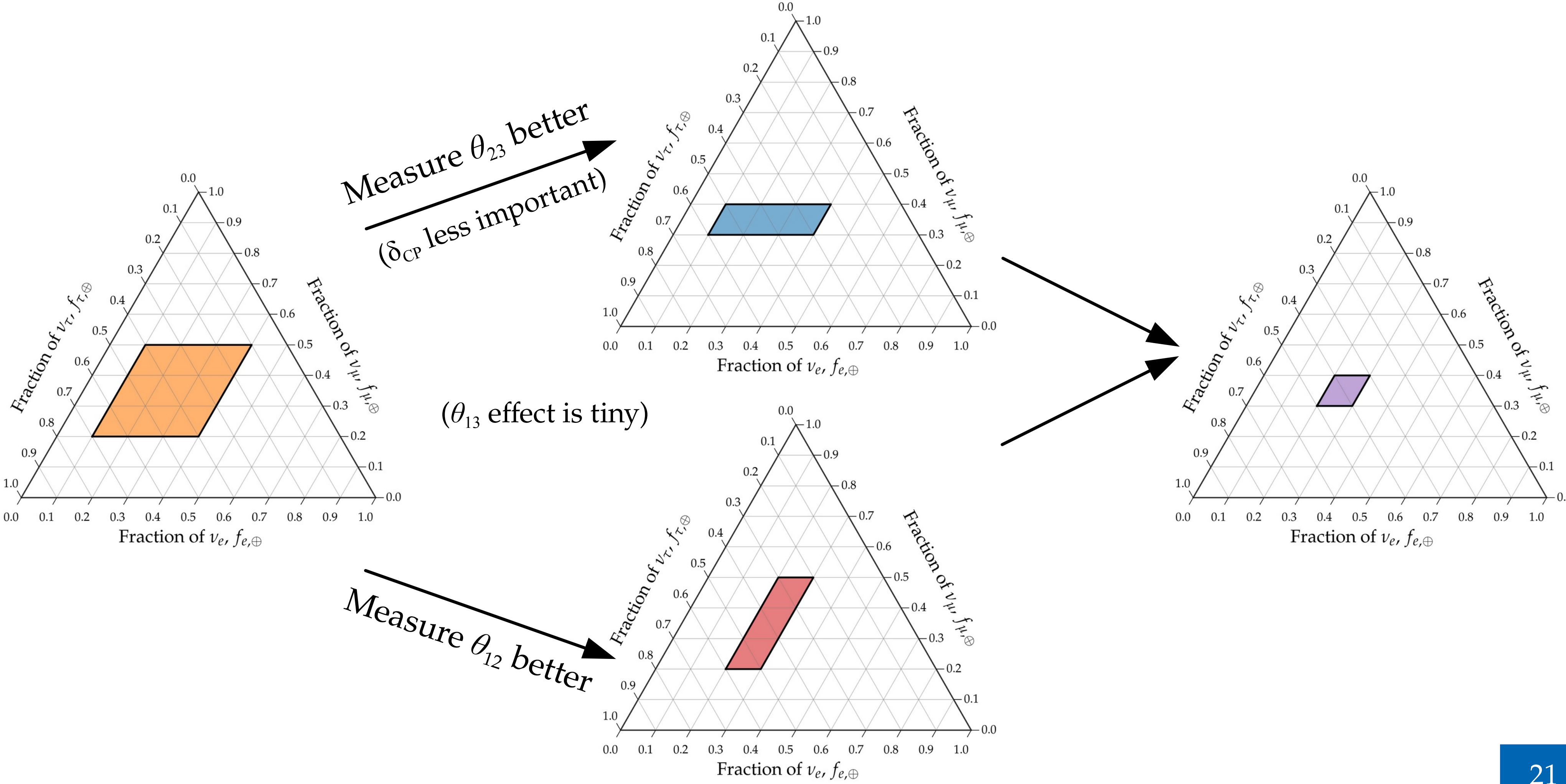
$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

$$-2\log\mathcal{L}(\boldsymbol{\theta}) = \sum_\varepsilon \chi^2_\varepsilon(\boldsymbol{\vartheta})$$

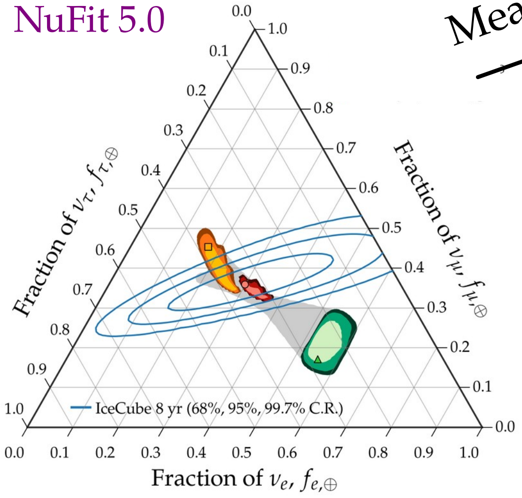
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

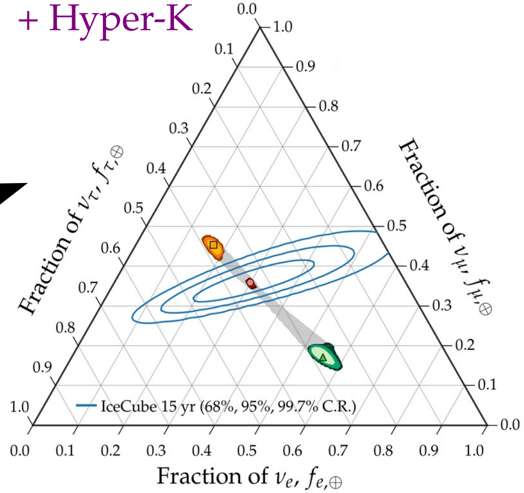
2020

NuFit 5.0



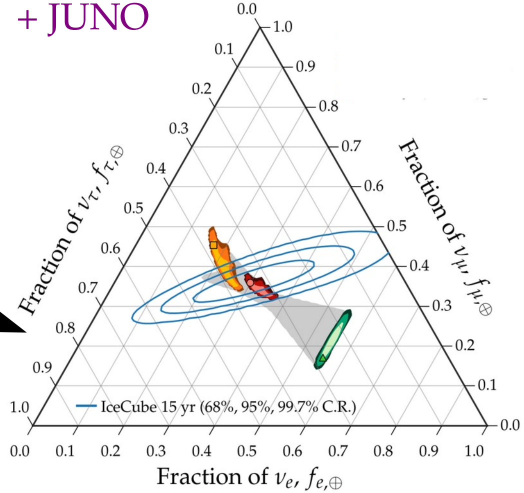
Measure θ_{23} better

+ Hyper-K



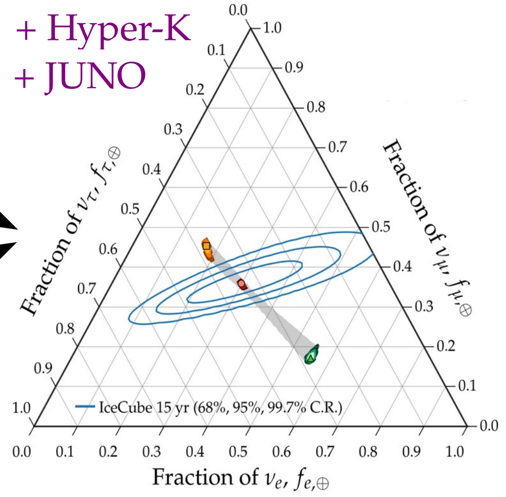
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

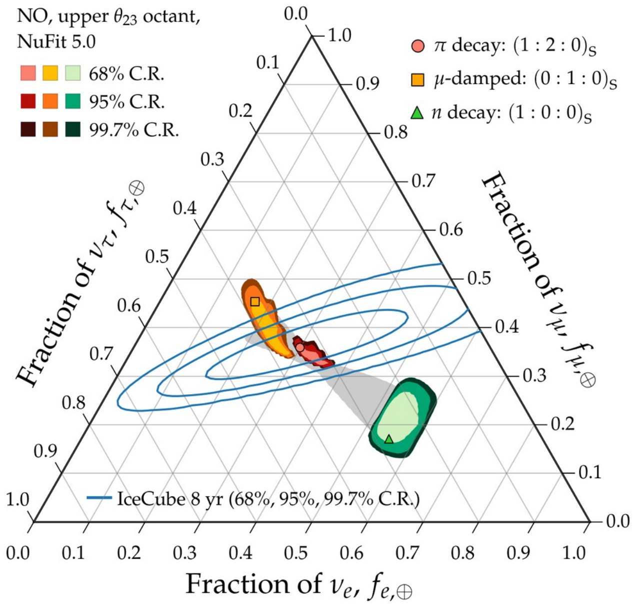
Marginal improvement til 2040

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

Theoretically palatable regions: 2020 → 2030 → 2040

2020



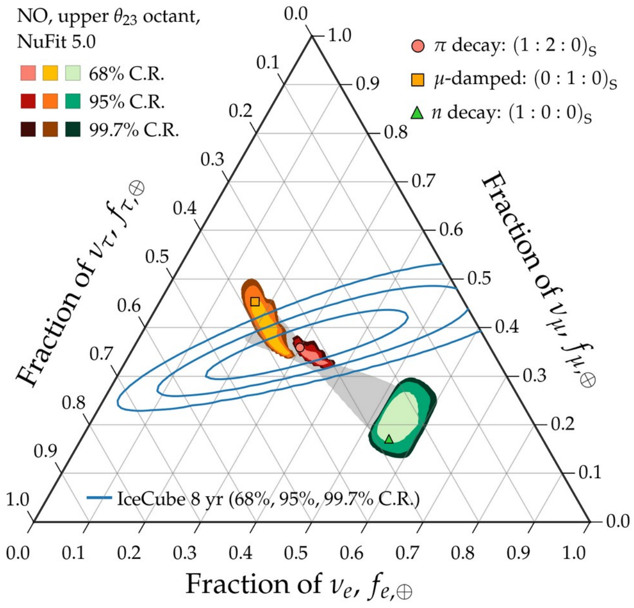
Allowed regions: overlapping

Measurement: imprecise

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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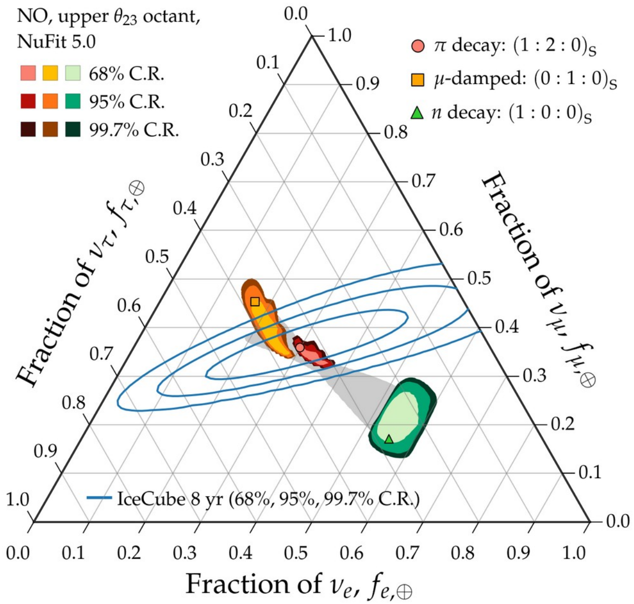
Measurement: imprecise

Not ideal

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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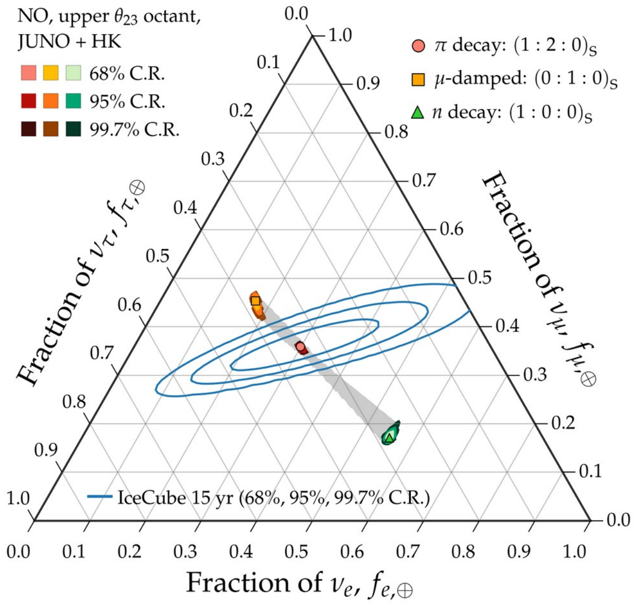
2030



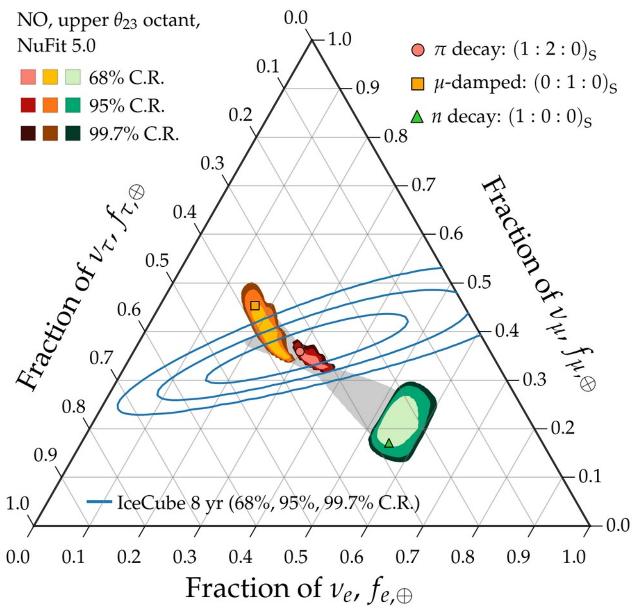
Allowed regions: well separated

Measurement: improving

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

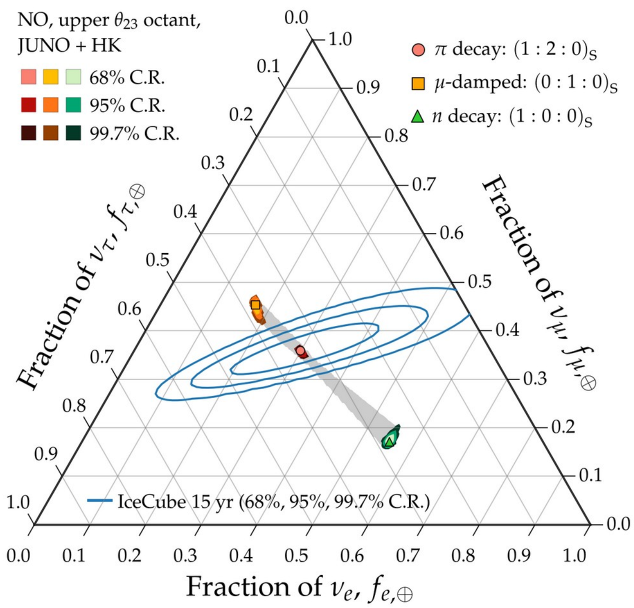


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



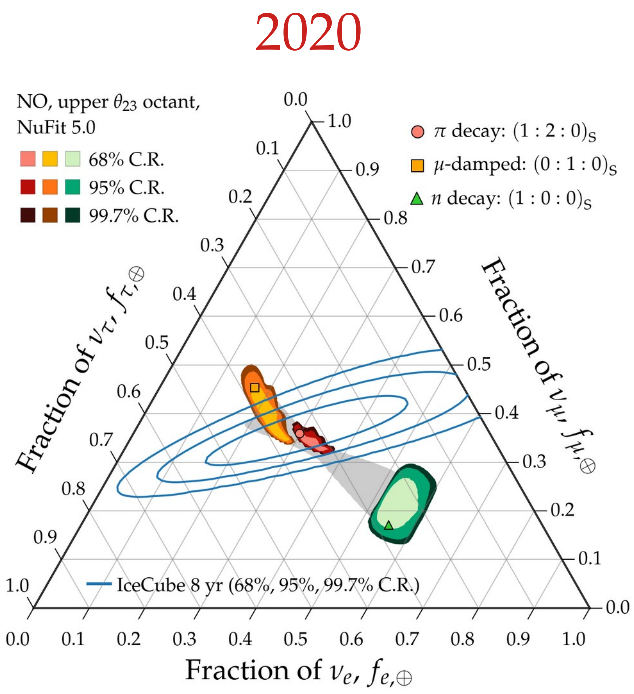
Allowed regions: well separated

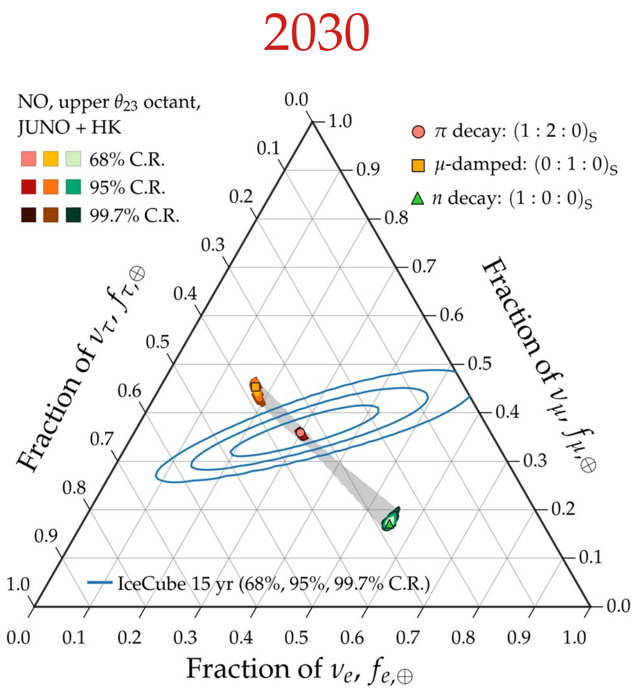
Measurement: improving

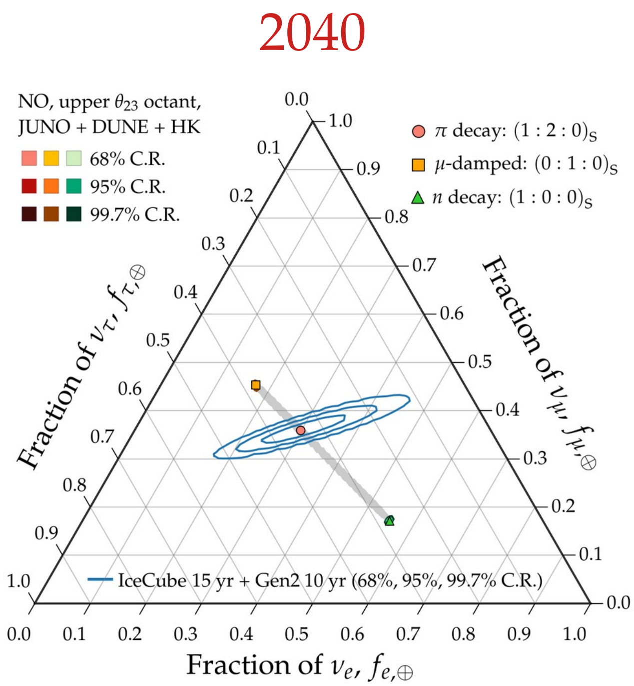
Nice

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040







2020 — Allowed regions: overlapping. Measurement: imprecise. *Not ideal*

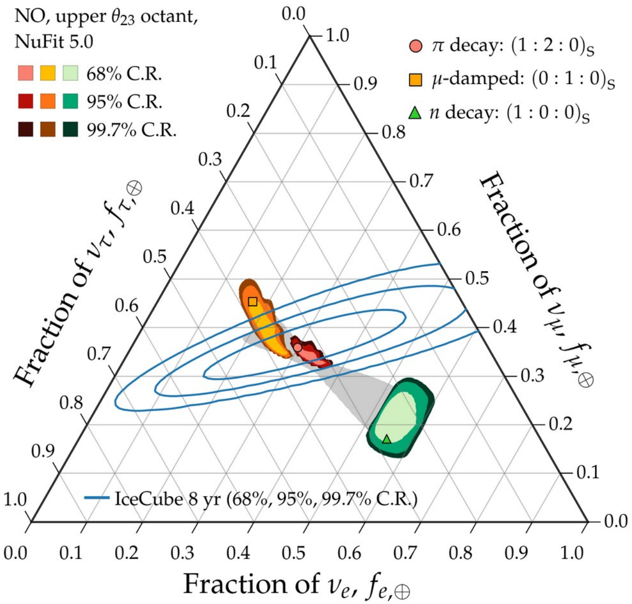
2030 — Allowed regions: well separated. Measurement: improving. *Nice*

2040 — Allowed regions: well separated. Measurement: precise.

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

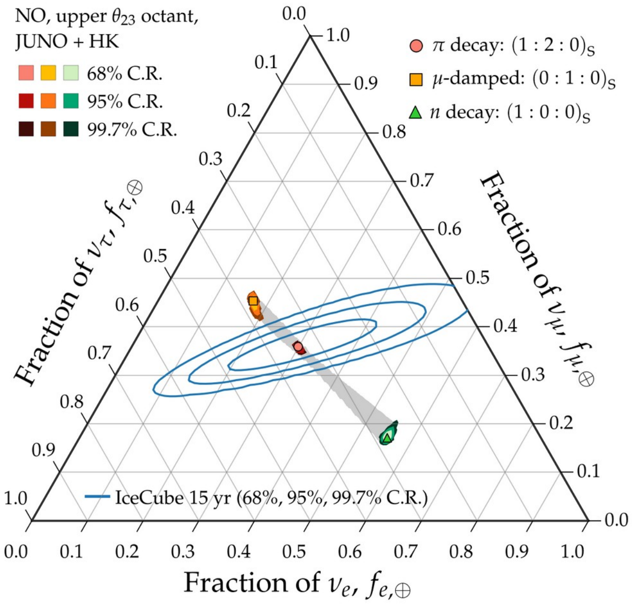
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

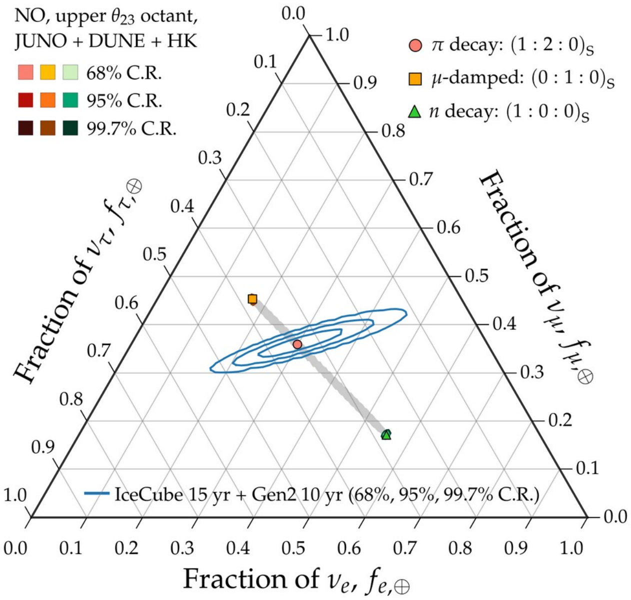
2030



Allowed regions: well separated
Measurement: improving

Nice

2040

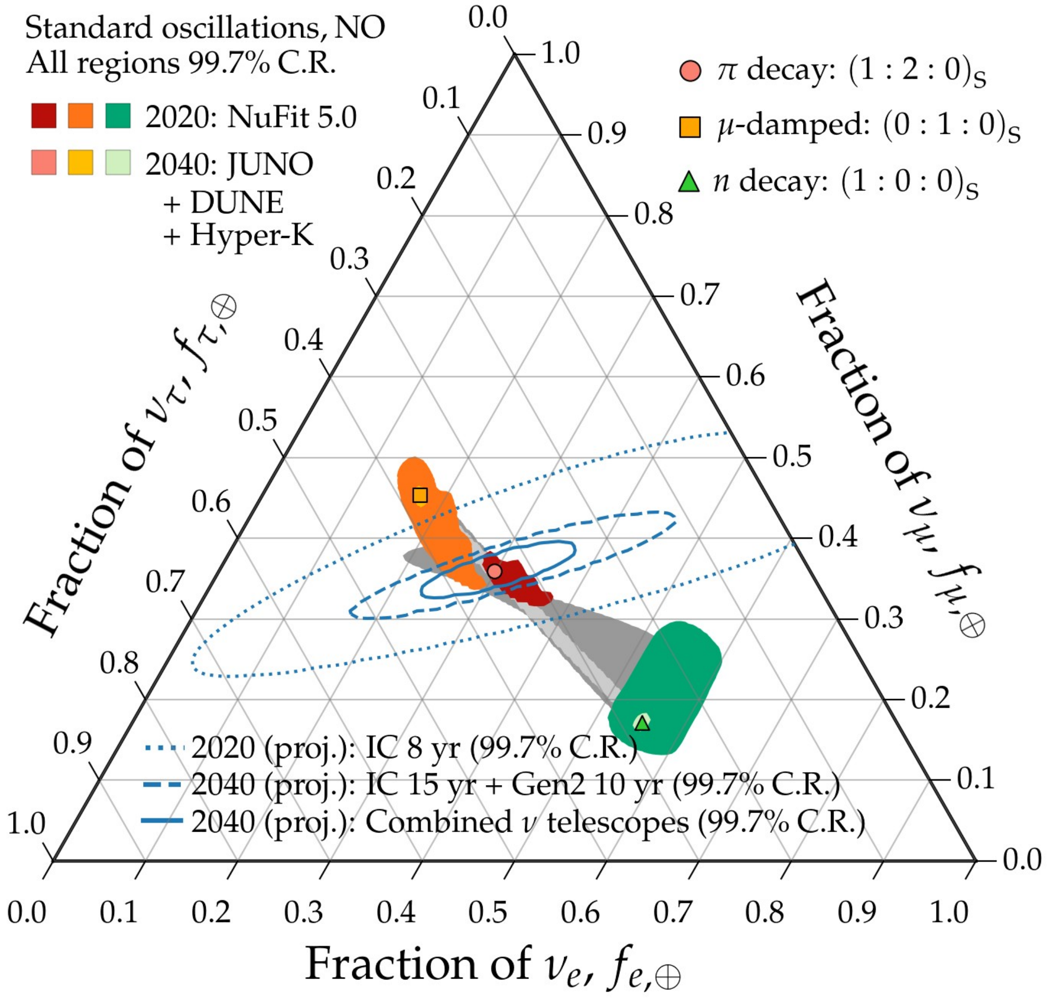


Allowed regions: well separated
Measurement: precise

Success

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

Theory –
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

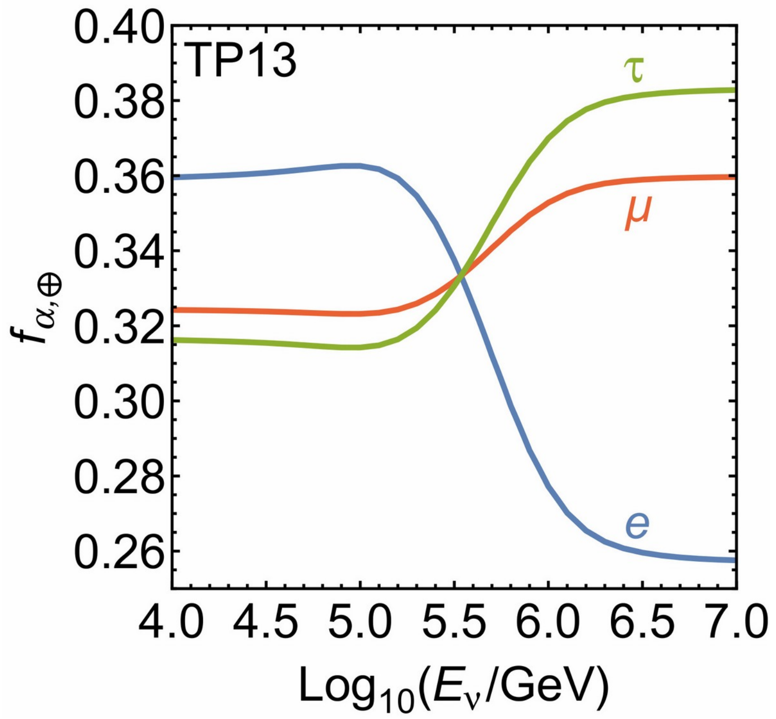
Measurement of flavor ratios –
Can distinguish between similar predictions at 99.7% C.R. (3σ)

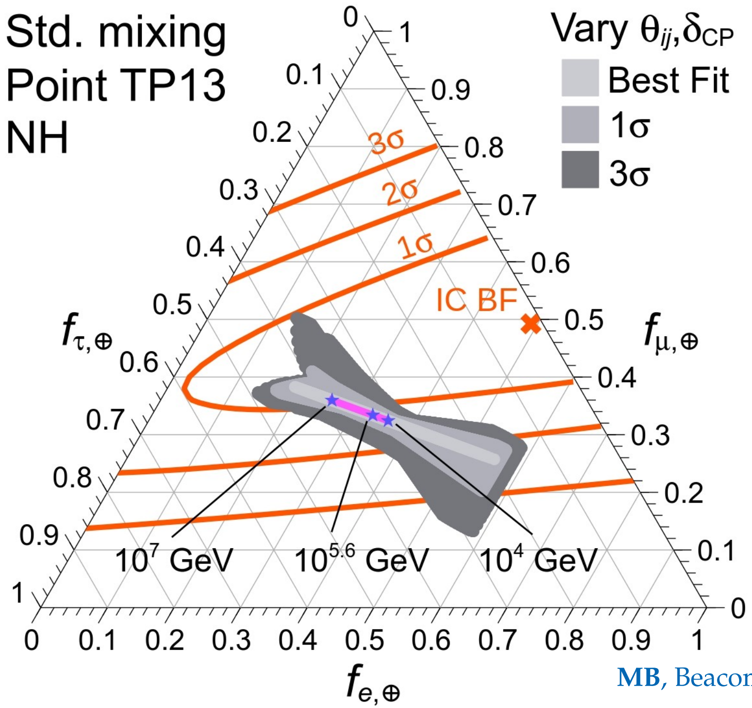
Can finally use the full power of flavor composition for astrophysics and neutrino physics

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



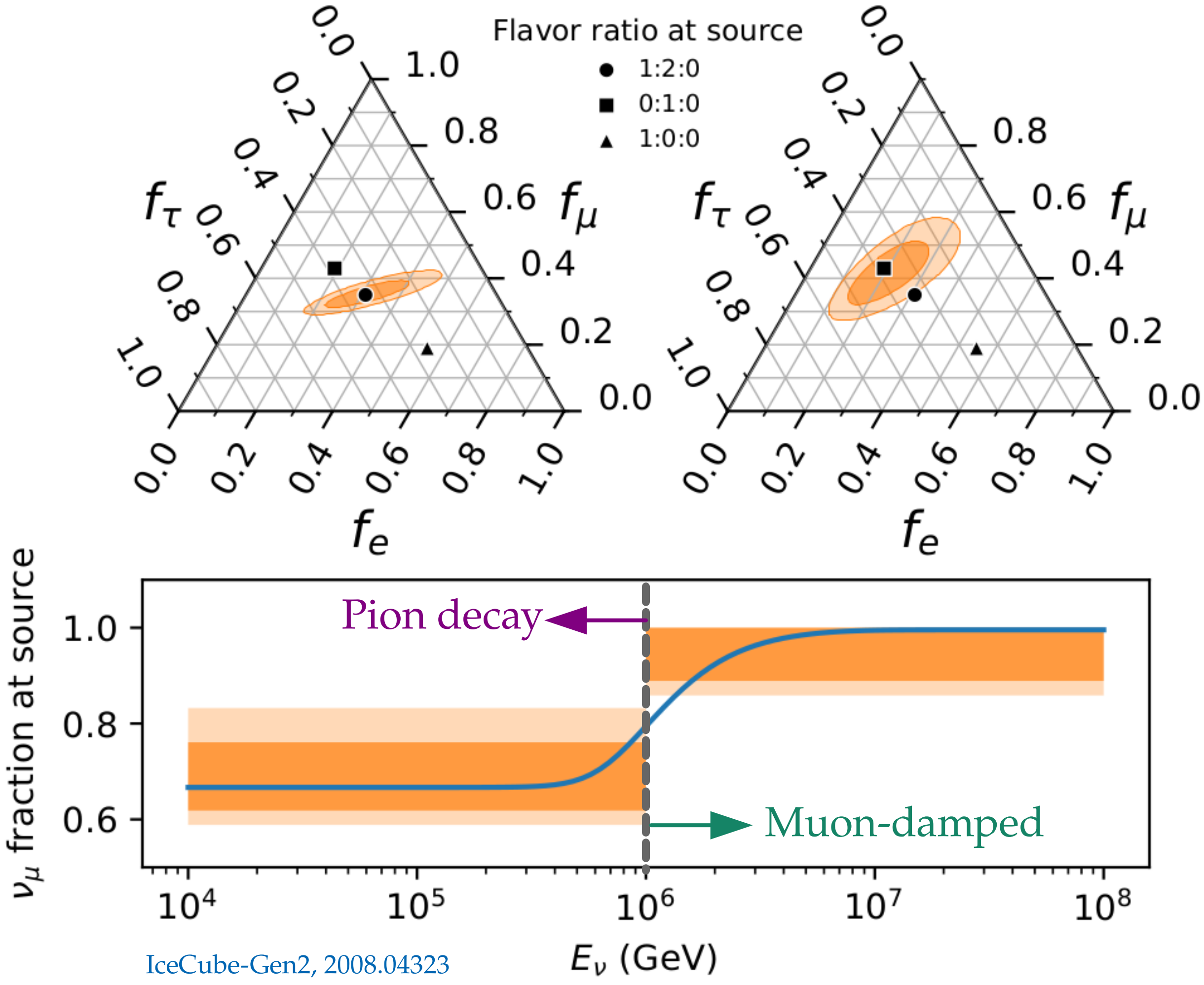


MB, Beacom, Winter, *PRL* 2015

- ▸ TP13: $p\gamma$ model, target photons from e^-e^+ annihilation [Hümmer+, *Astropart. Phys.* 2010]
- ▸ Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

Energy dependence of flavor ratios – in IceCube-Gen2

Measured:



IceCube-Gen2, 2008.04323

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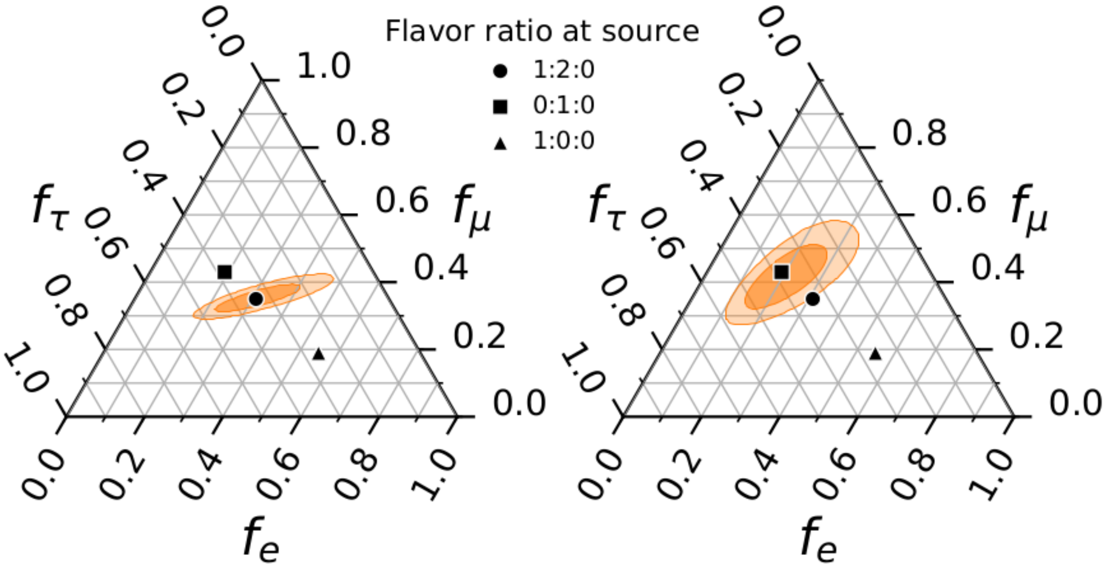

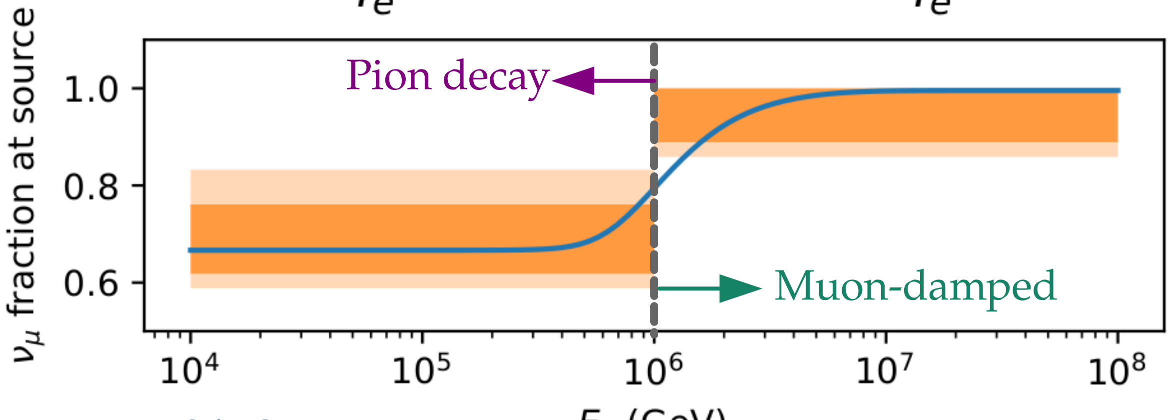

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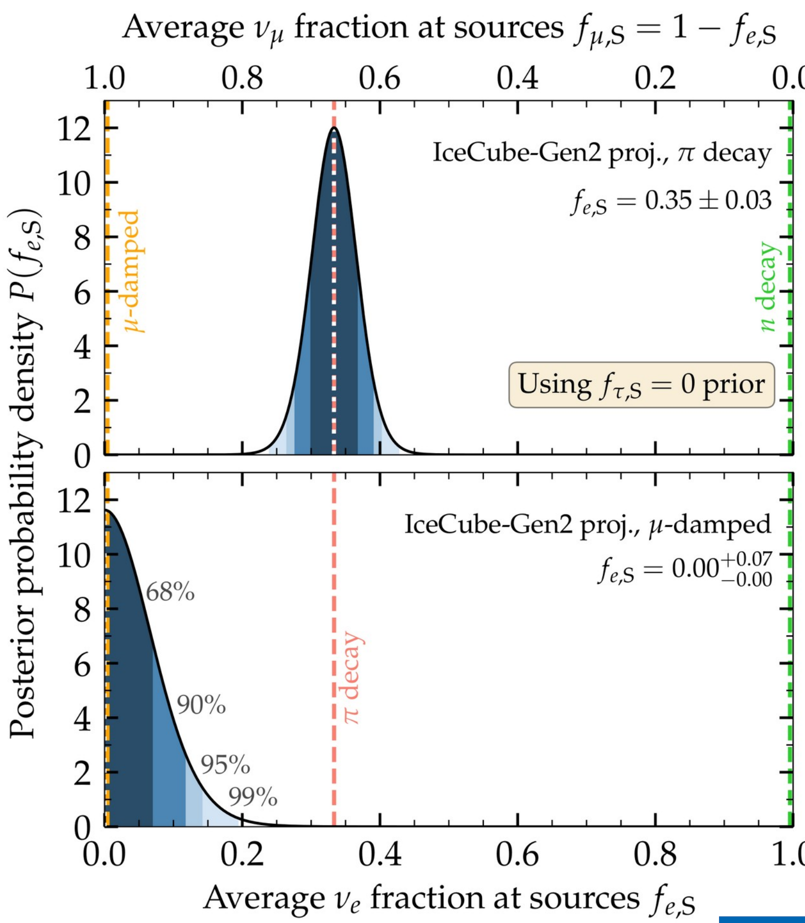
Inferred (at sources):



MB & Ahlers, *PRL* 2019

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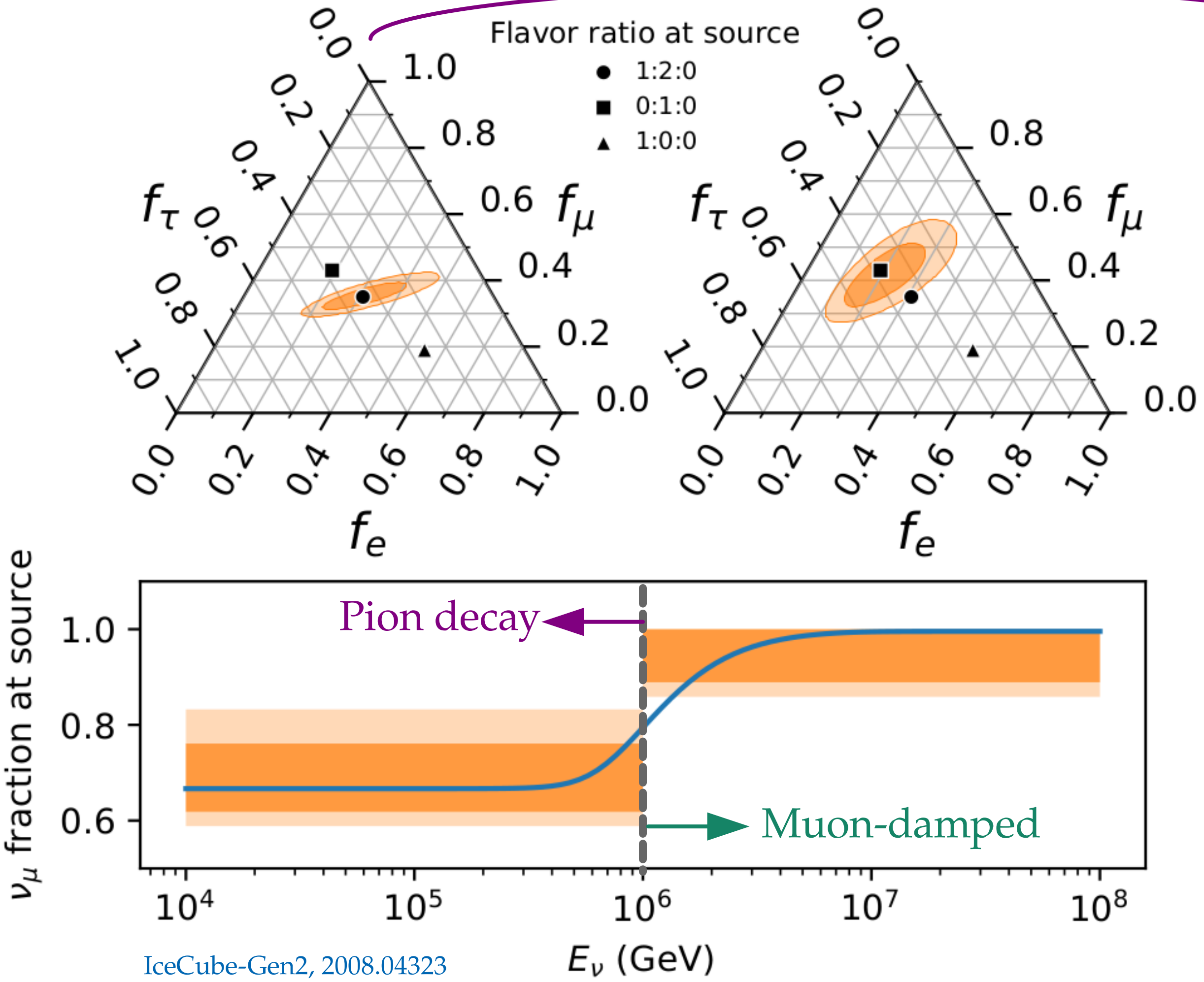

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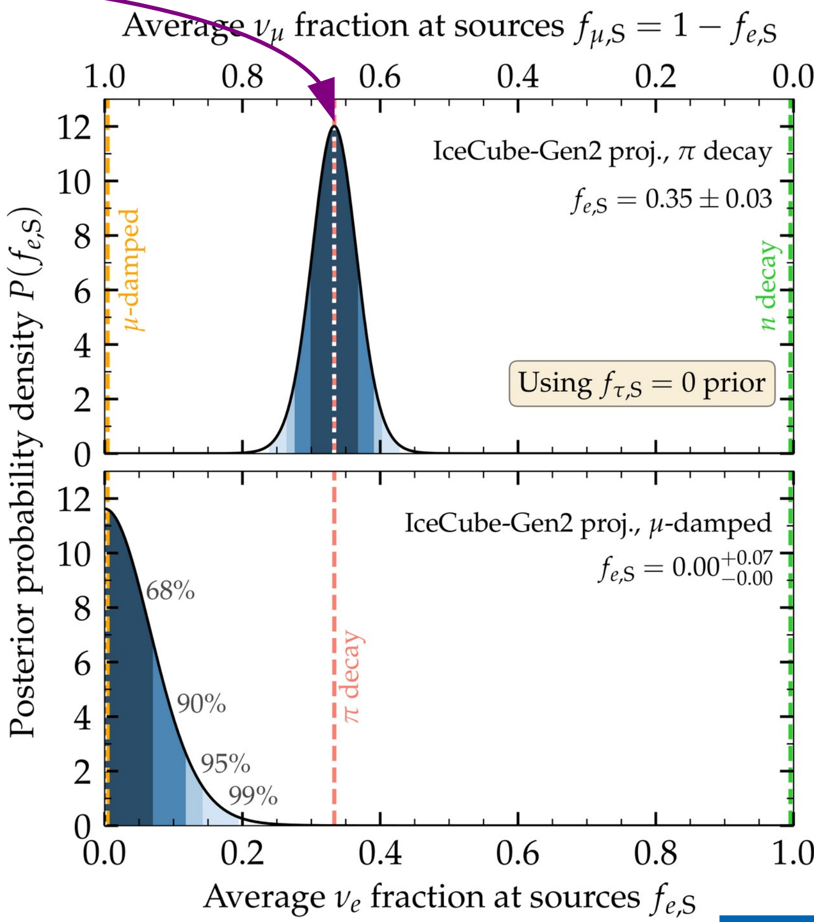

MB & Ahlers, *PRL* 2019

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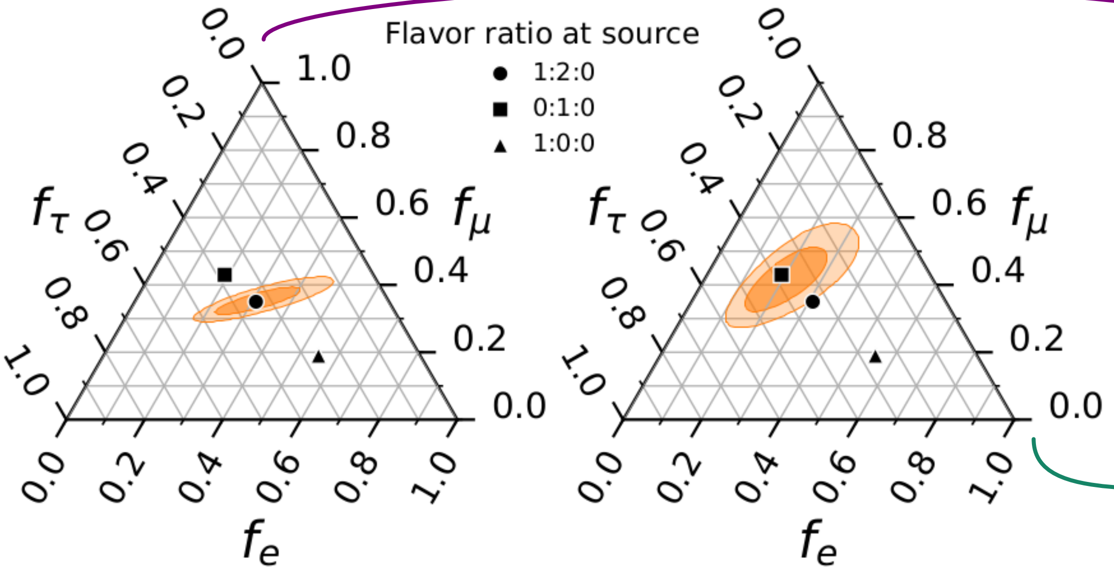

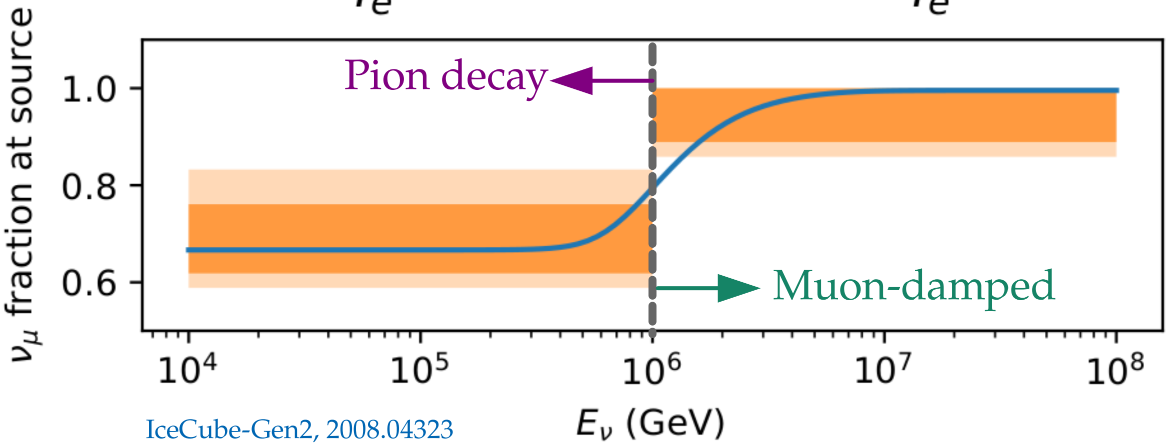

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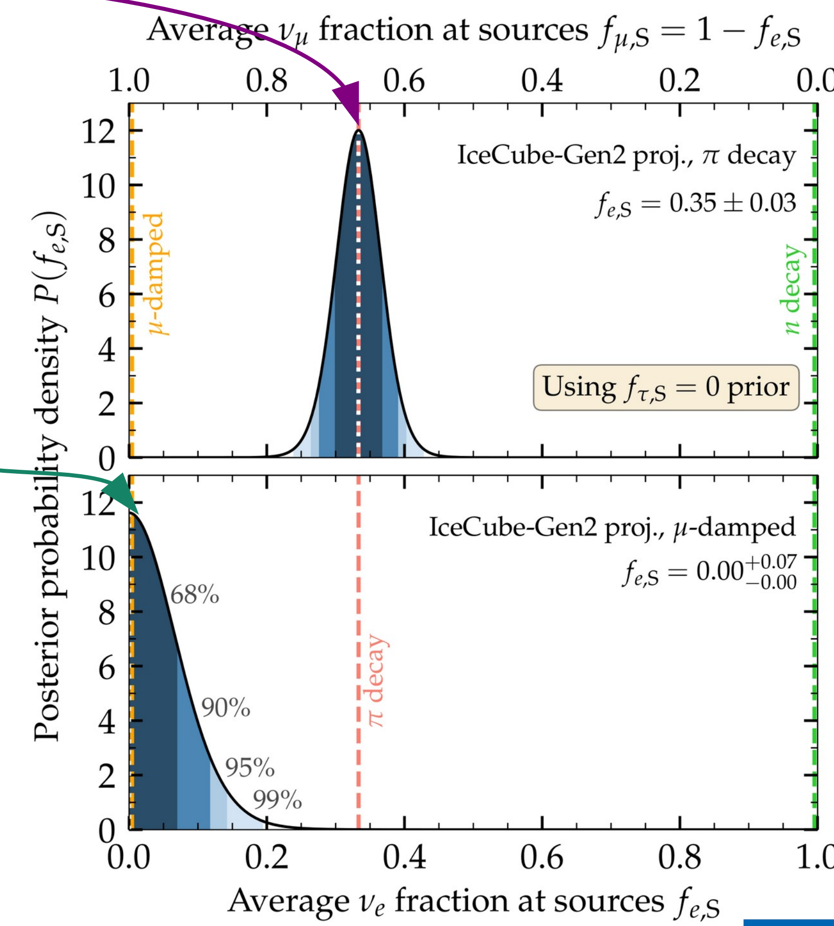

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MB & Ahlers, *PRL* 2019

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = \underbrace{k_\pi \boldsymbol{f}_{\rm S}^\pi}_{} + \underbrace{k_\mu \boldsymbol{f}_{\rm S}^\mu}_{} + \underbrace{k_n \boldsymbol{f}_{\rm S}^n}_{}$$

π decay: (1/3, 2/3, 0) μ damped: (0, 1, 0) *n* decay: (1, 0, 0)

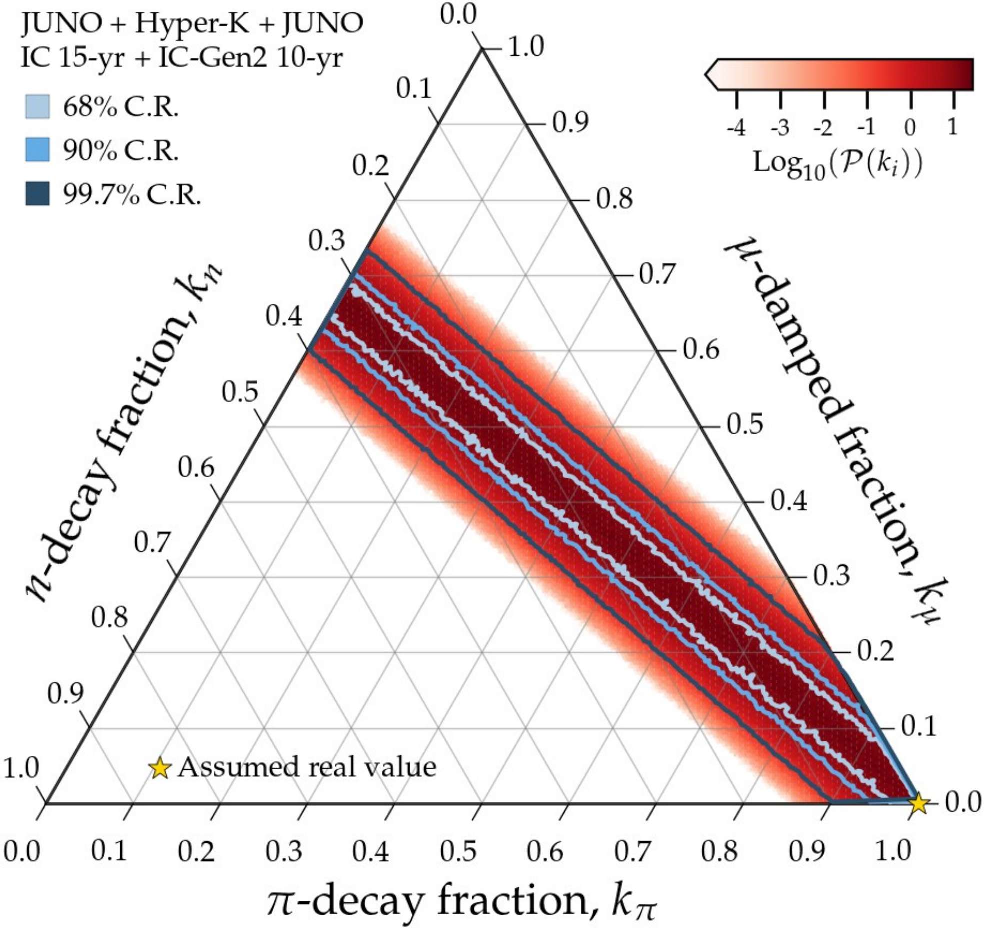
Propagate to Earth

$\boldsymbol{f}_\oplus$

Assume real value $k_\pi = 1$ ($k_\mu = k_n = 0$)

By 2040, how well will we recover the real value?

[Adding spectrum information (not shown) will likely help]



Song, Li, Argüelles, **MB**, Vincent, 2012.12893

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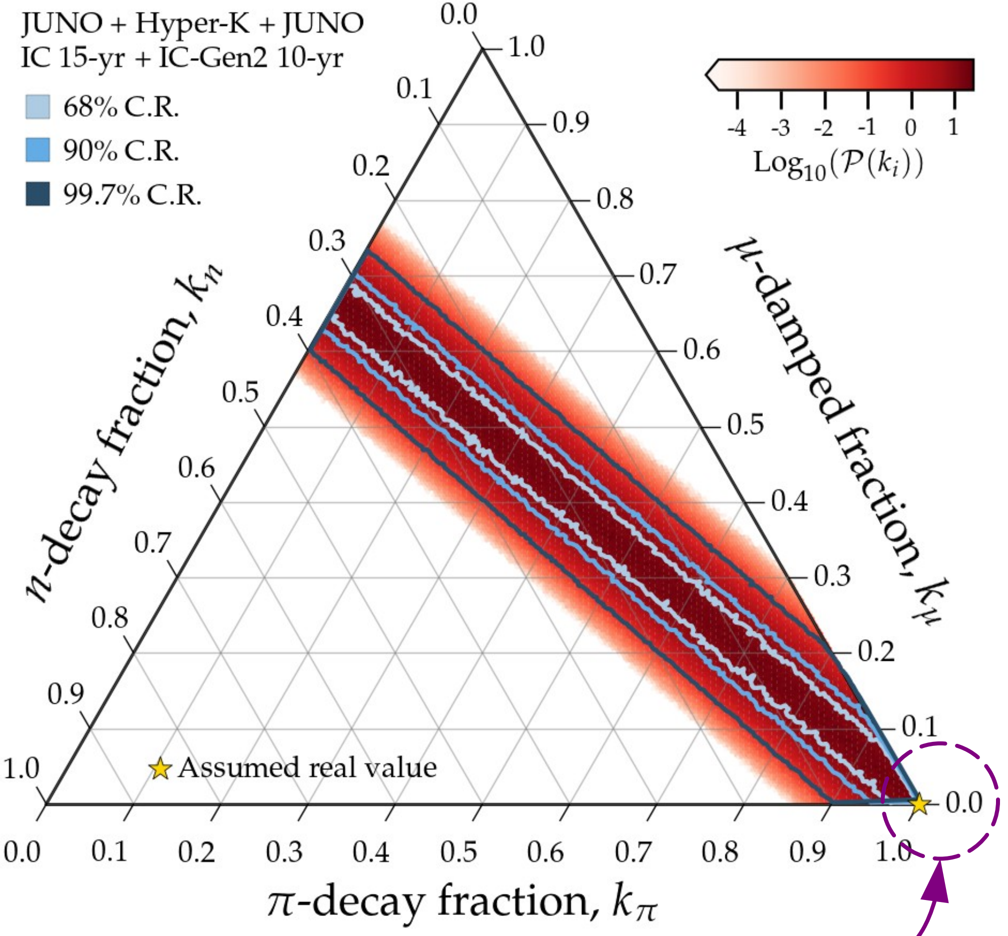

We do recover the real value

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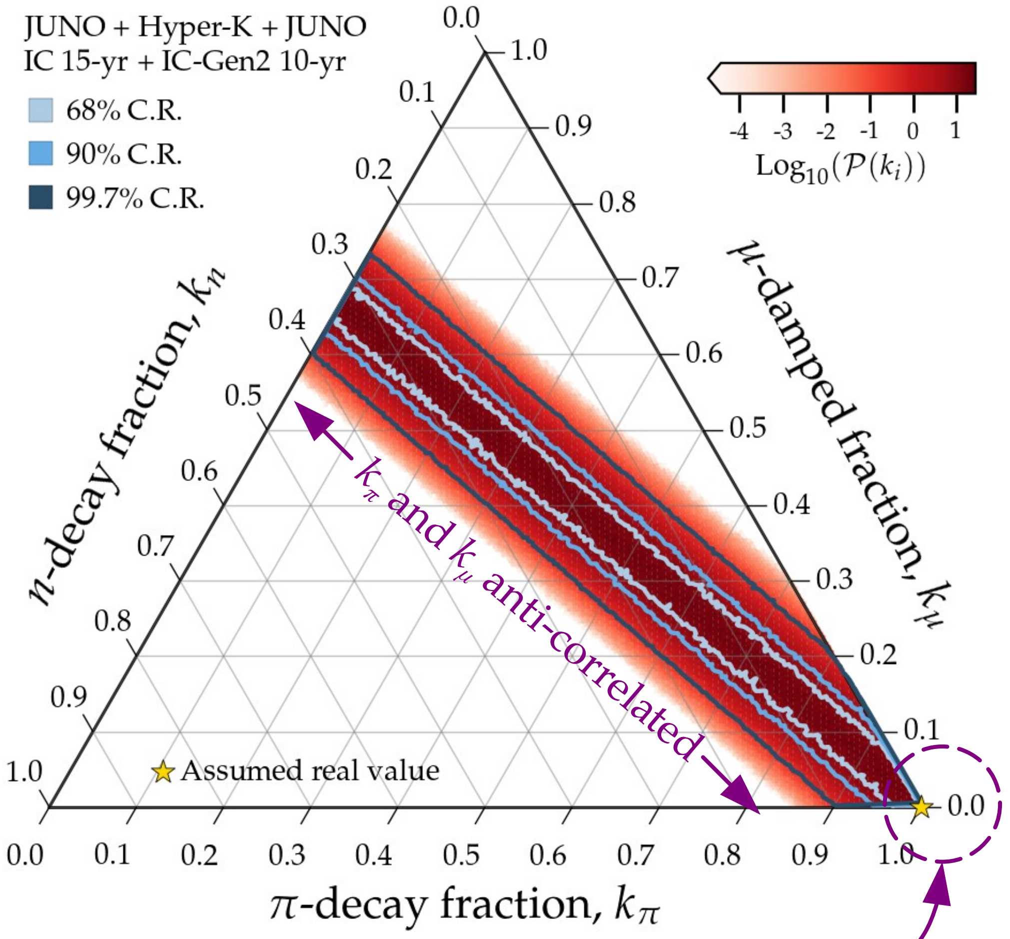

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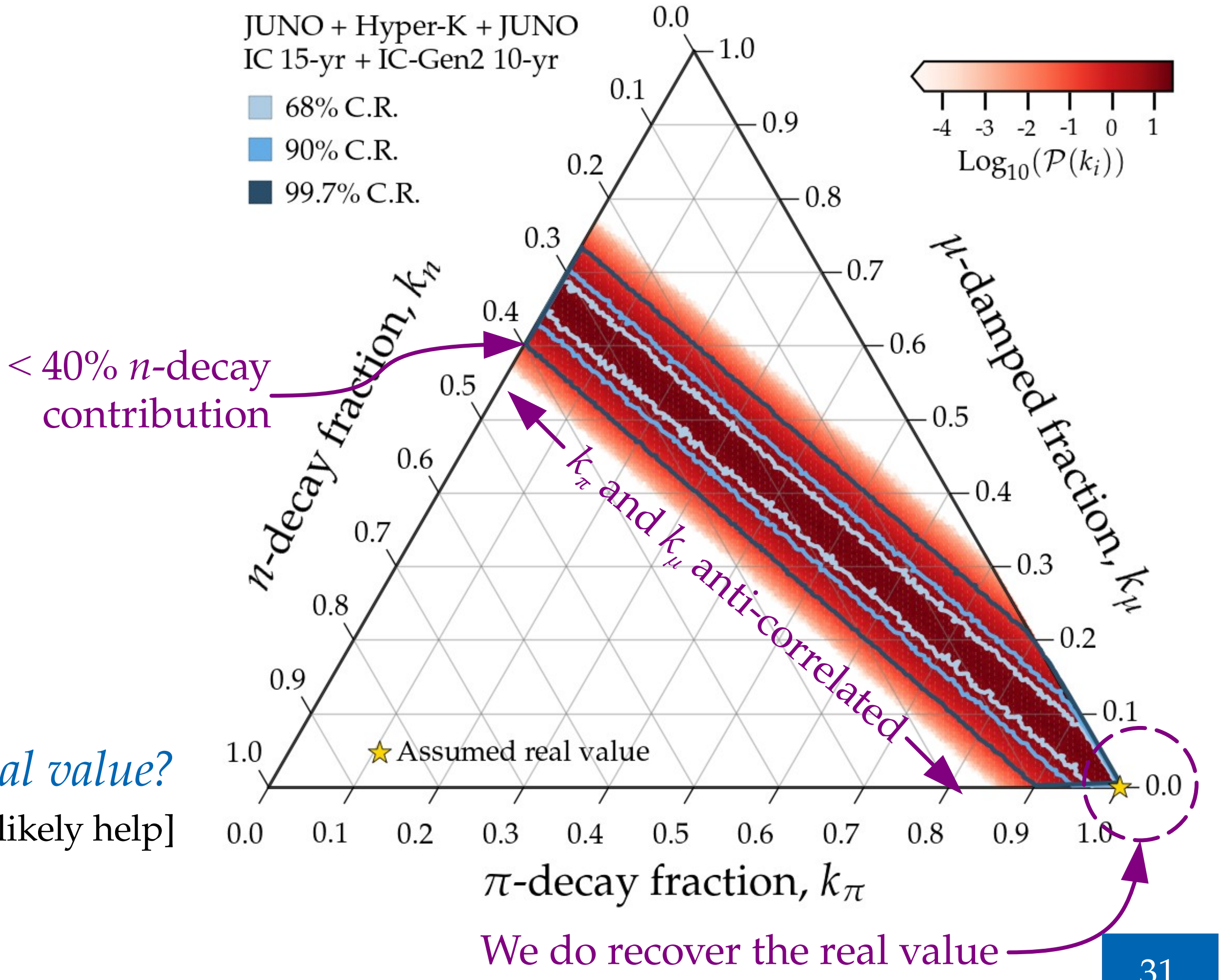

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Propagate to Earth ↓

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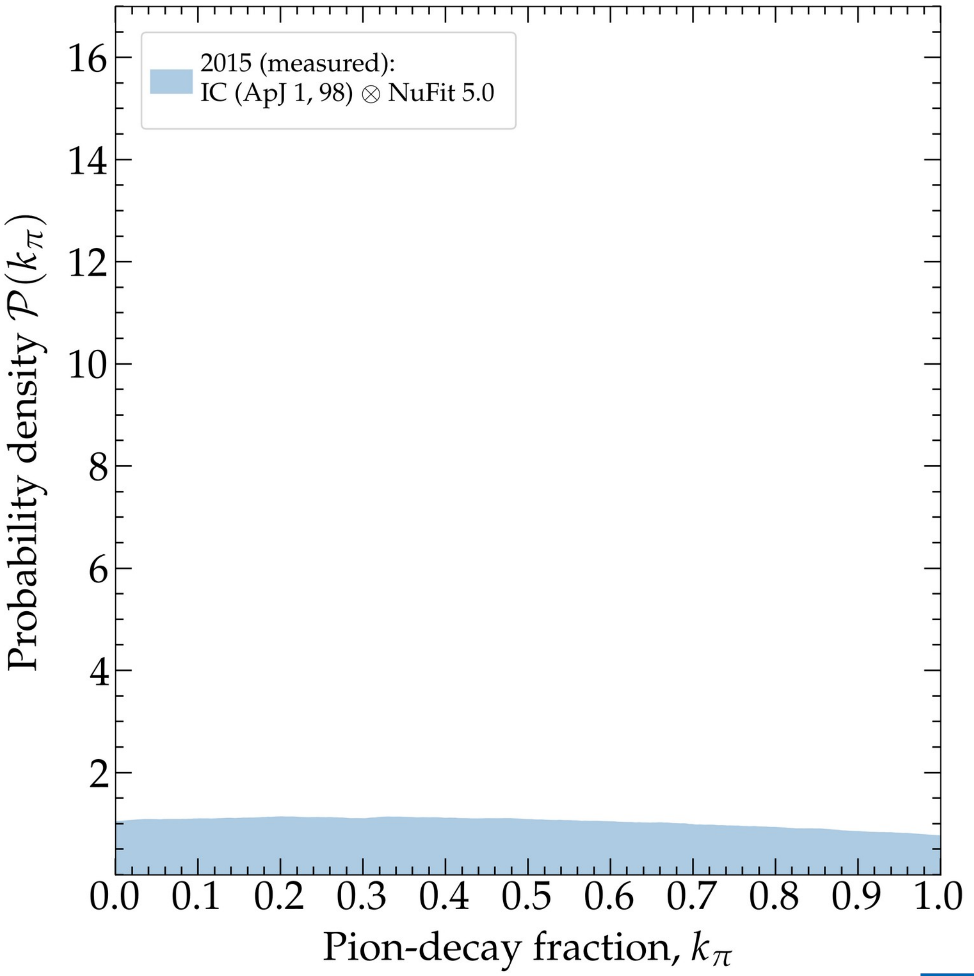

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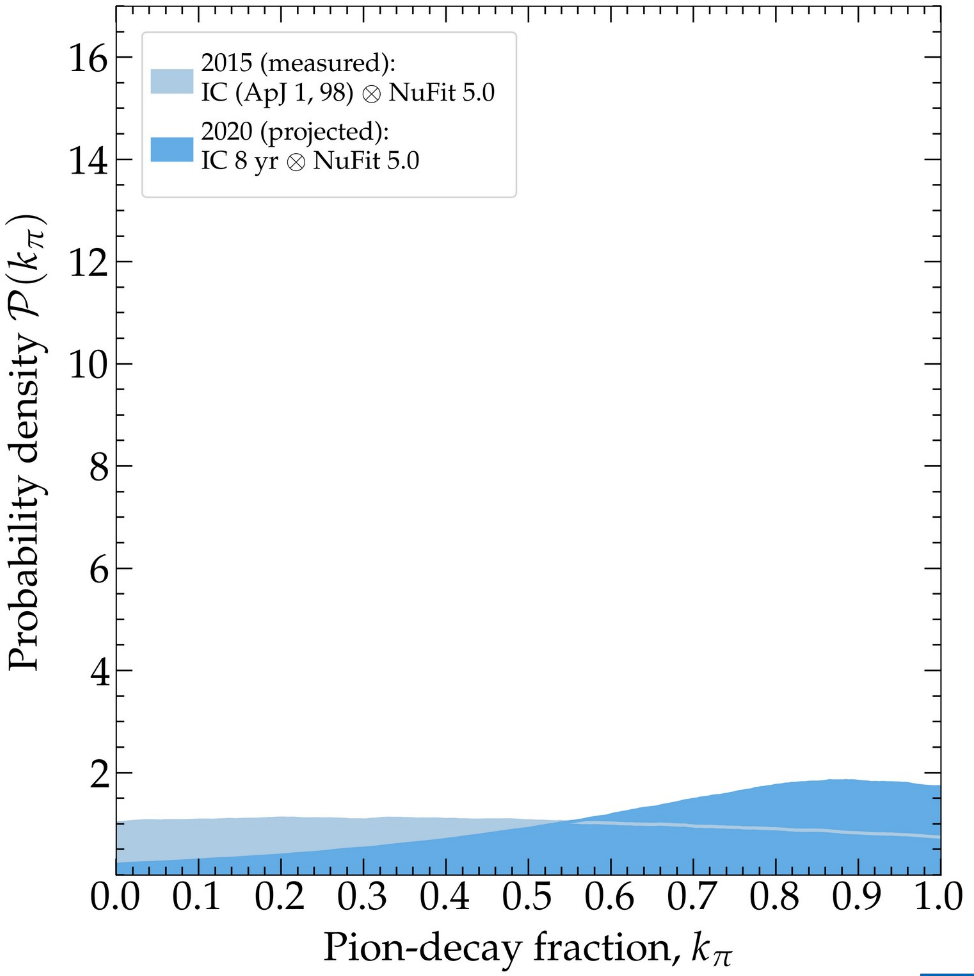

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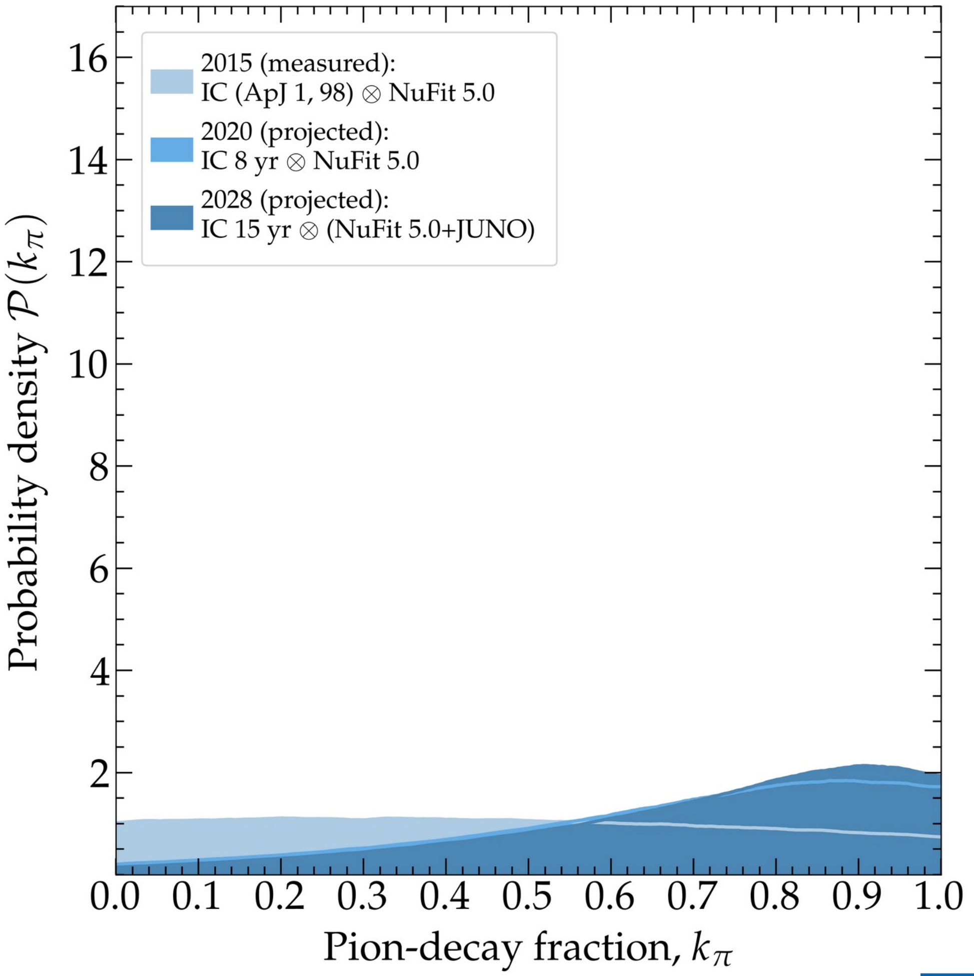

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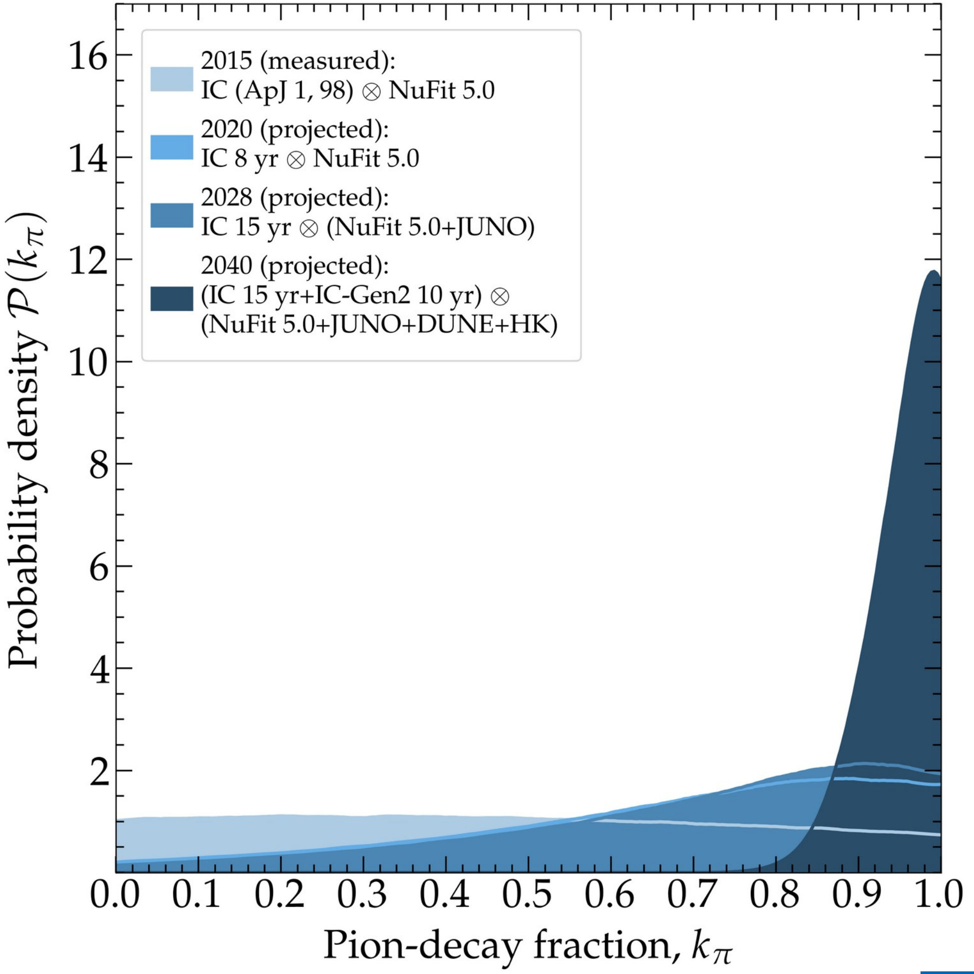

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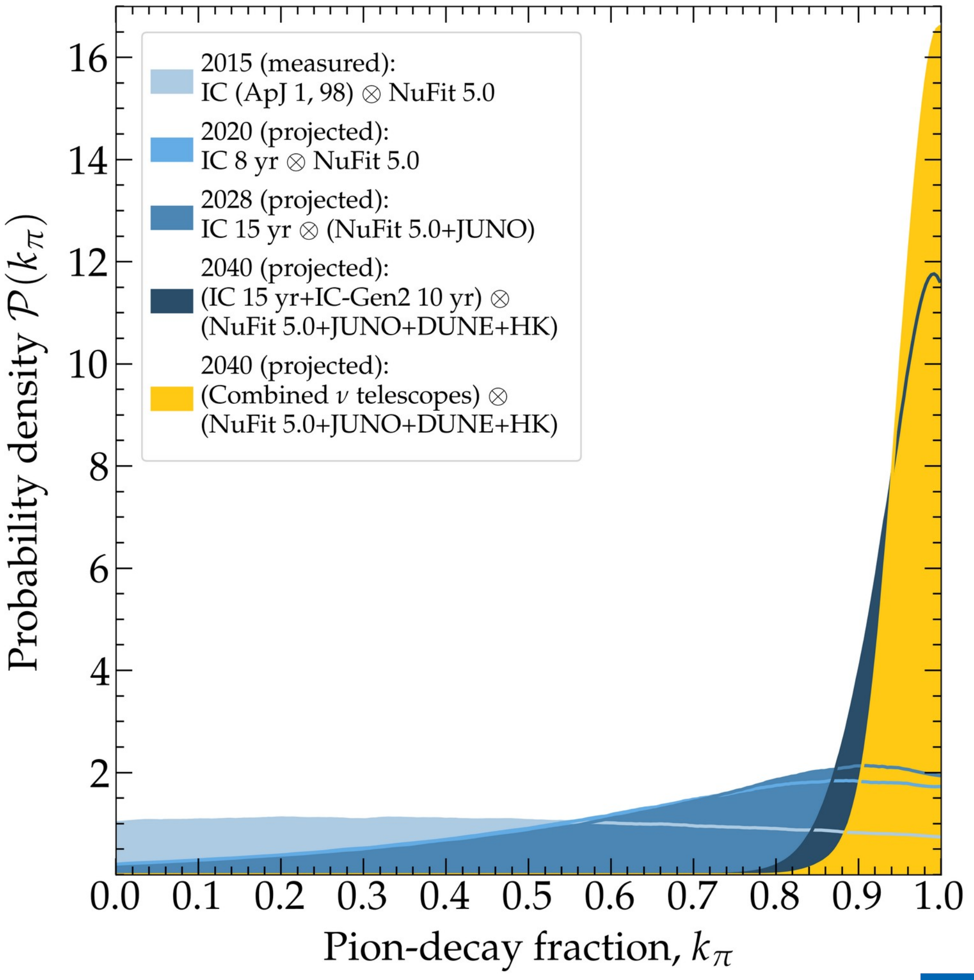
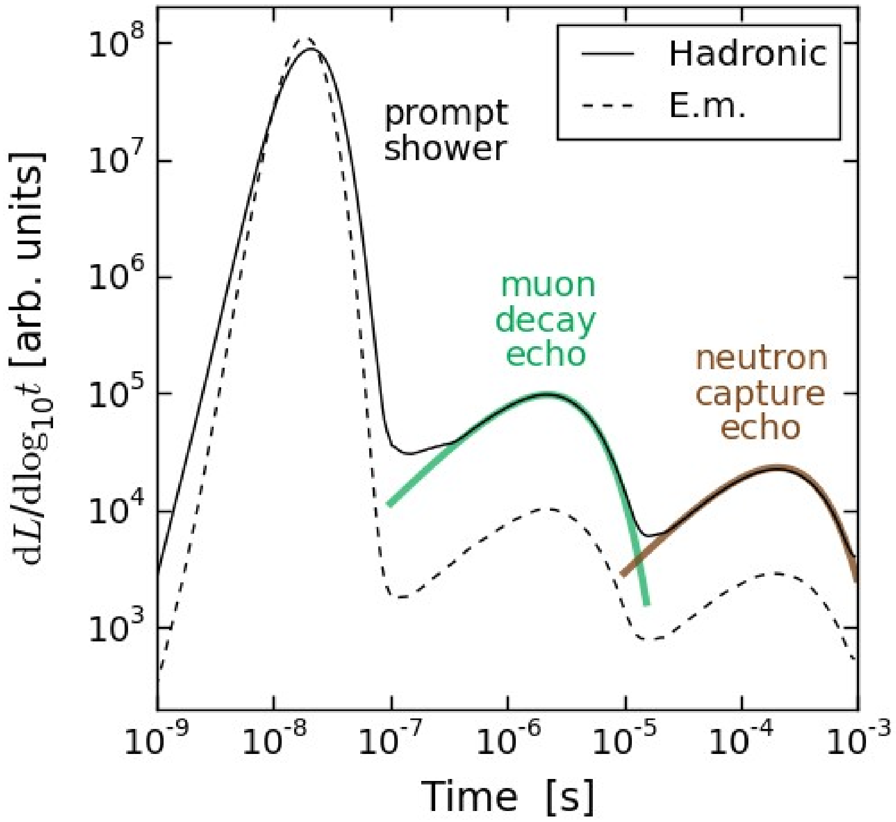
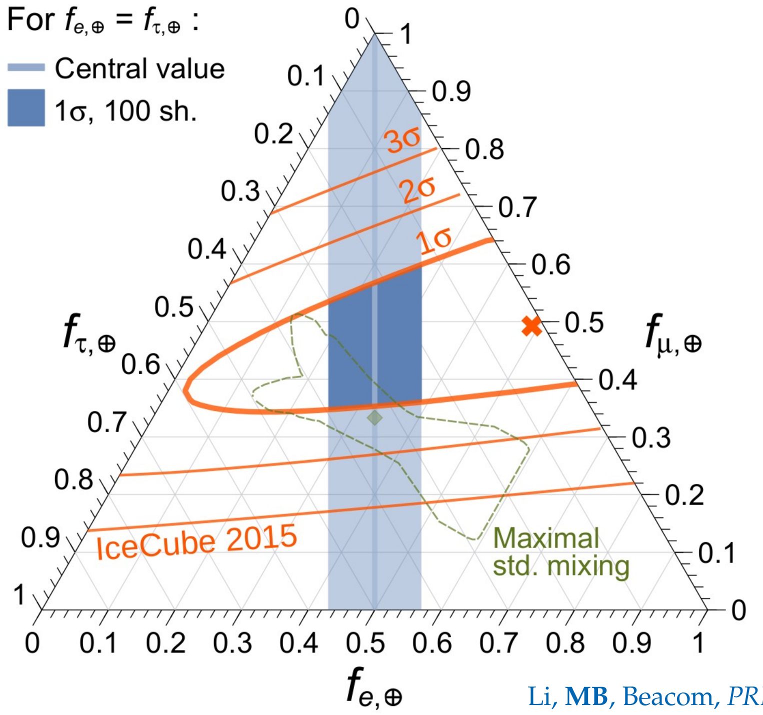


Song, Li, Argüelles, **MB**, Vincent, 2012.12893

Side note: Improving flavor-tagging using *echoes*

Late-time light (*echoes*) from muon decays and neutron captures can separate showers made by ν_e and ν_τ –





Li, **MB**, Beacom, *PRL* 2019

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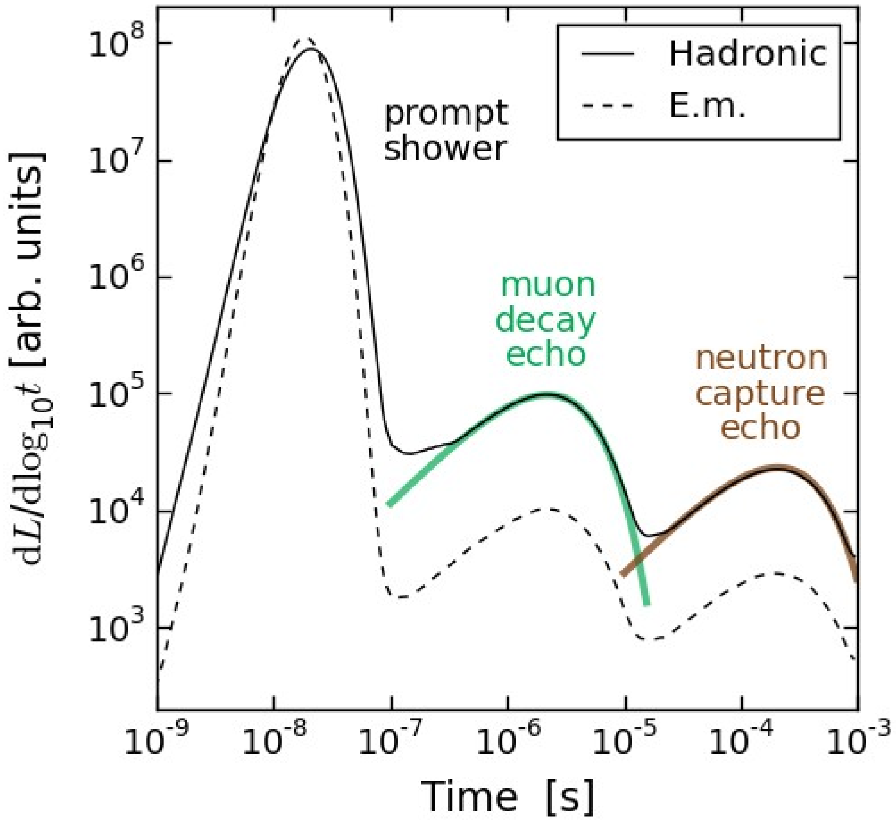
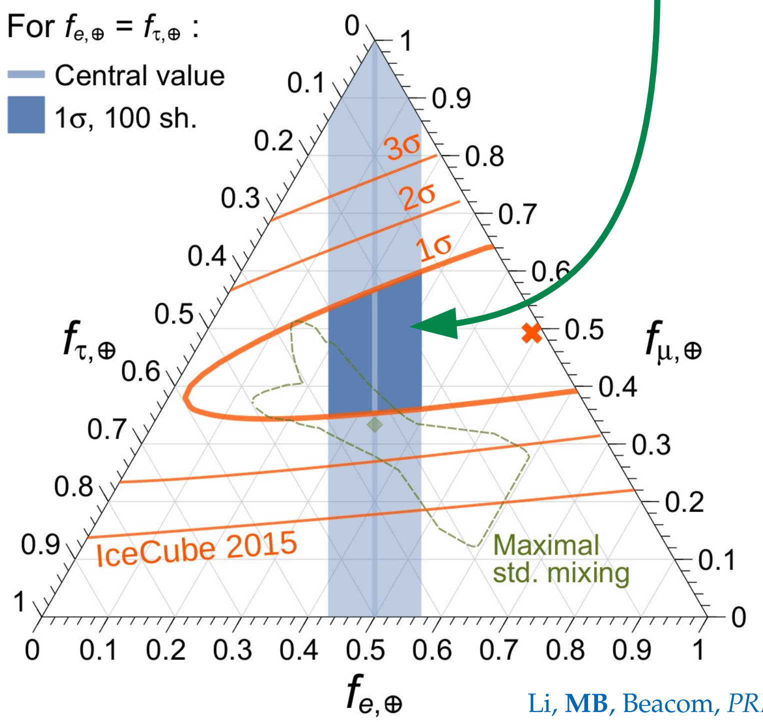


~10 × improvement over current measurement



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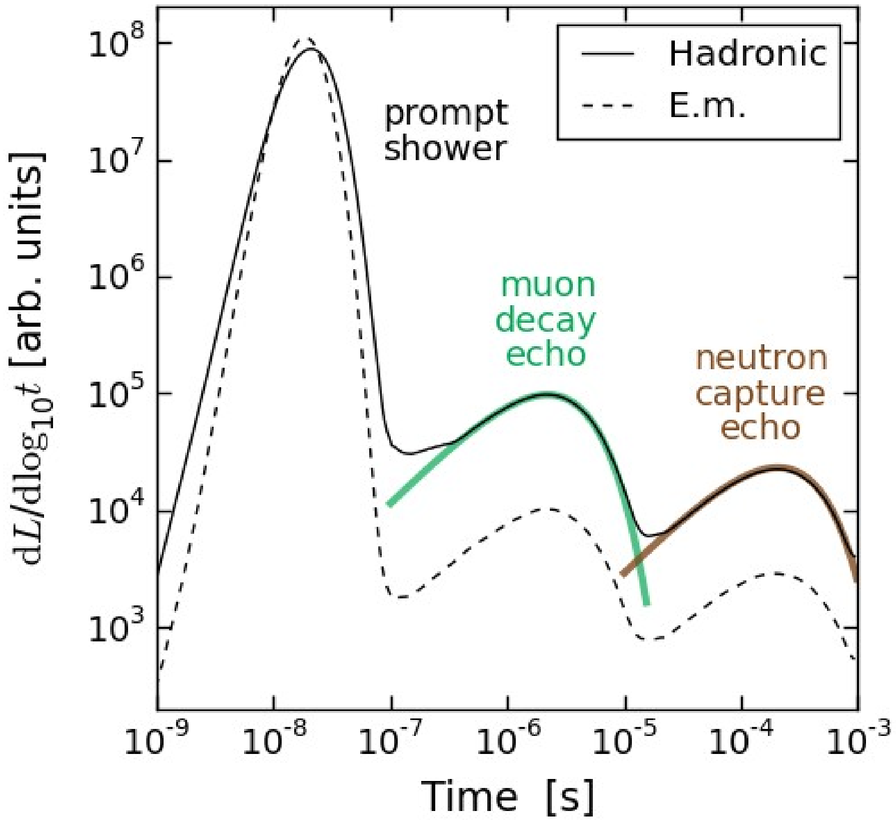

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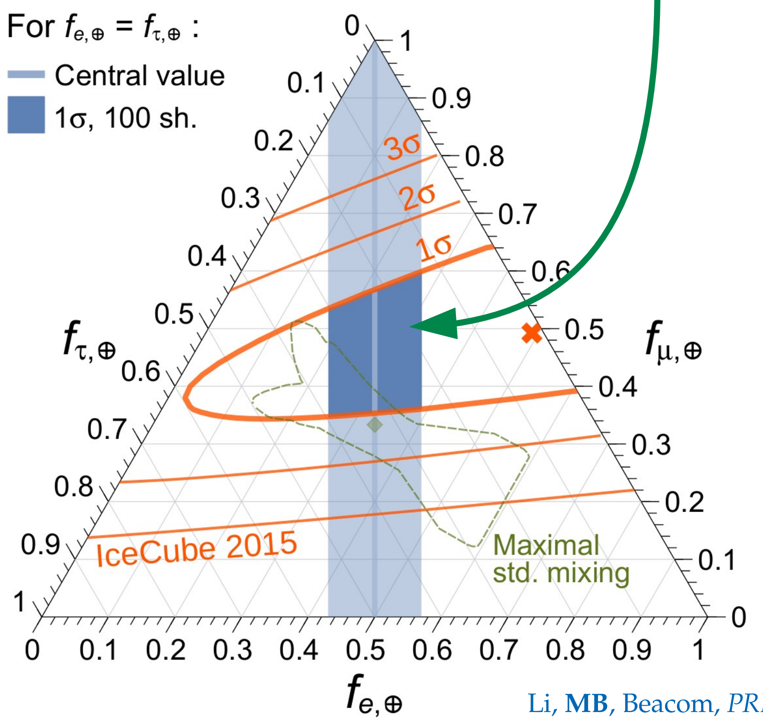
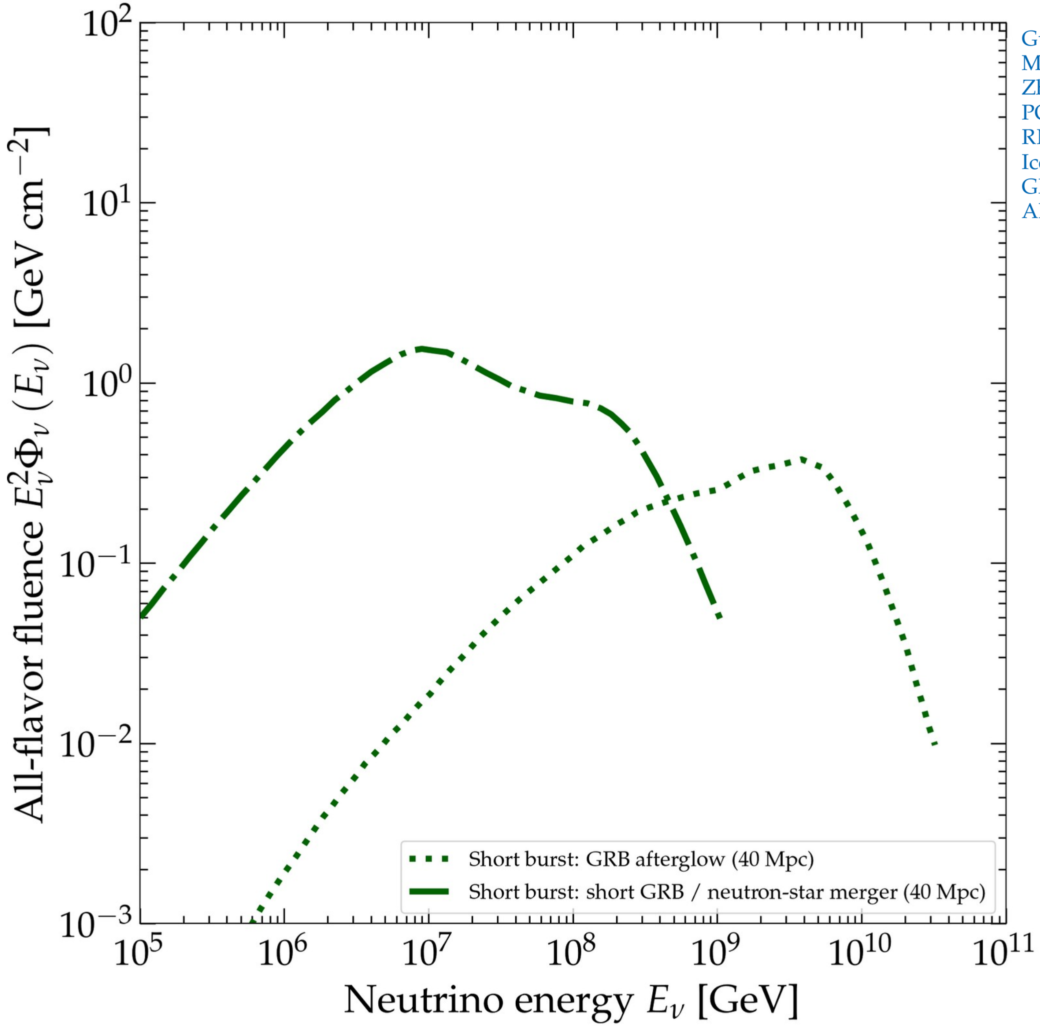


Li, **MB**, Beacom, *PRL* 2019

The future

UHE neutrinos: *transient sources*



Guépin, Kotera, Barausse, Fang, Murase, *A&A* 2018
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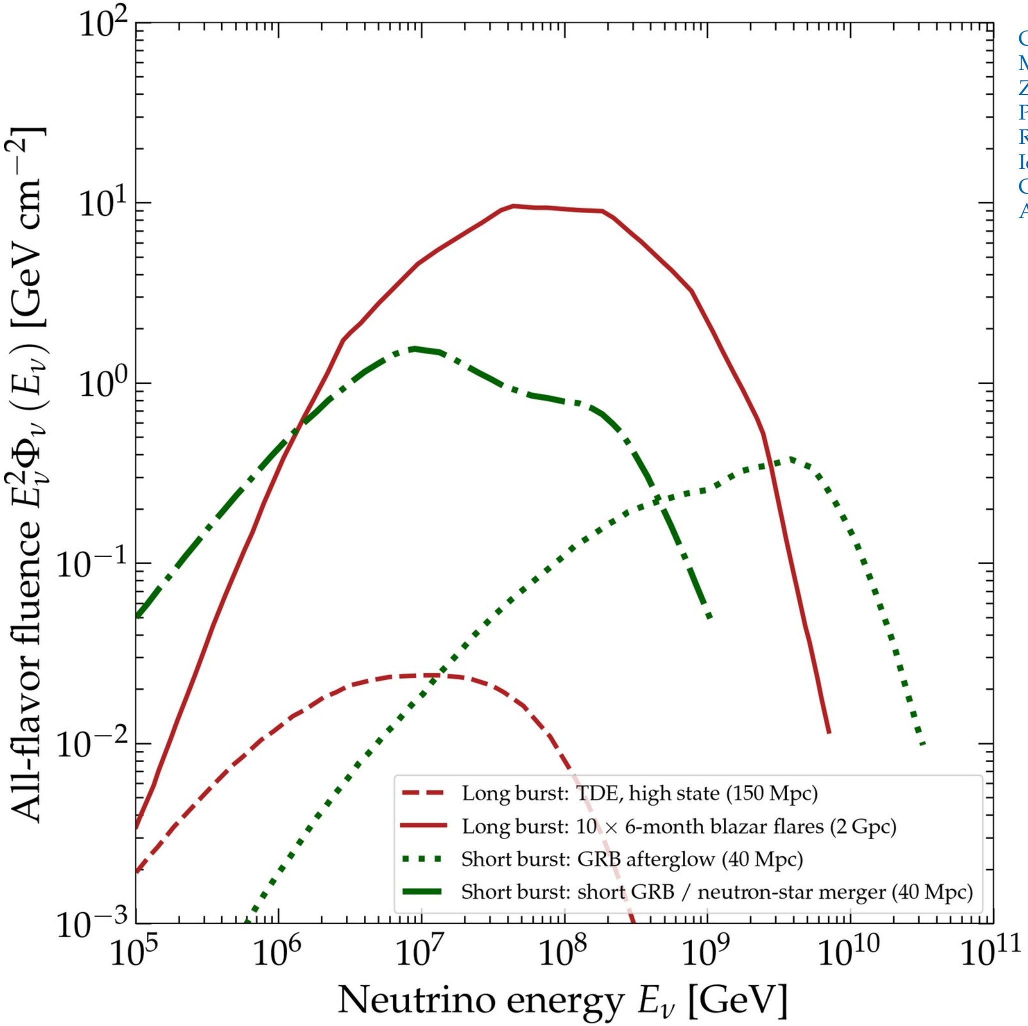

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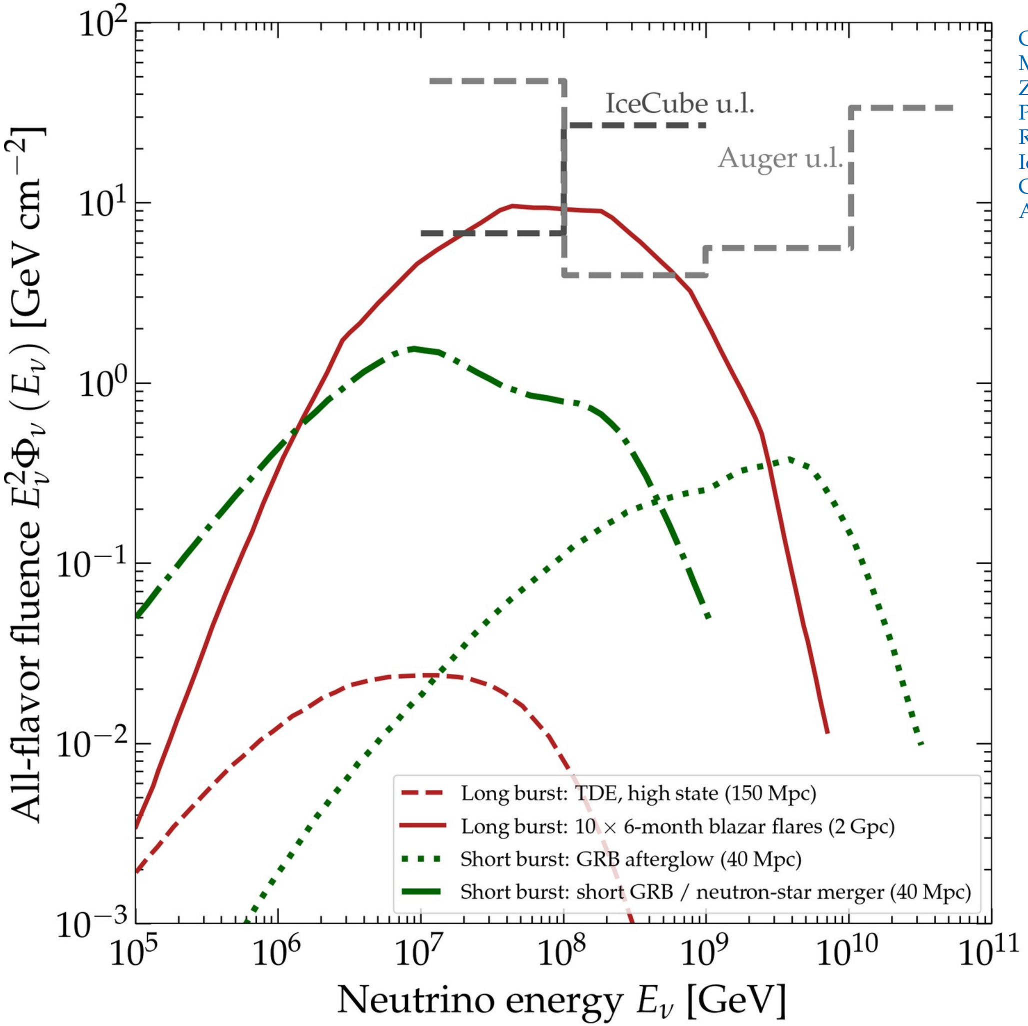

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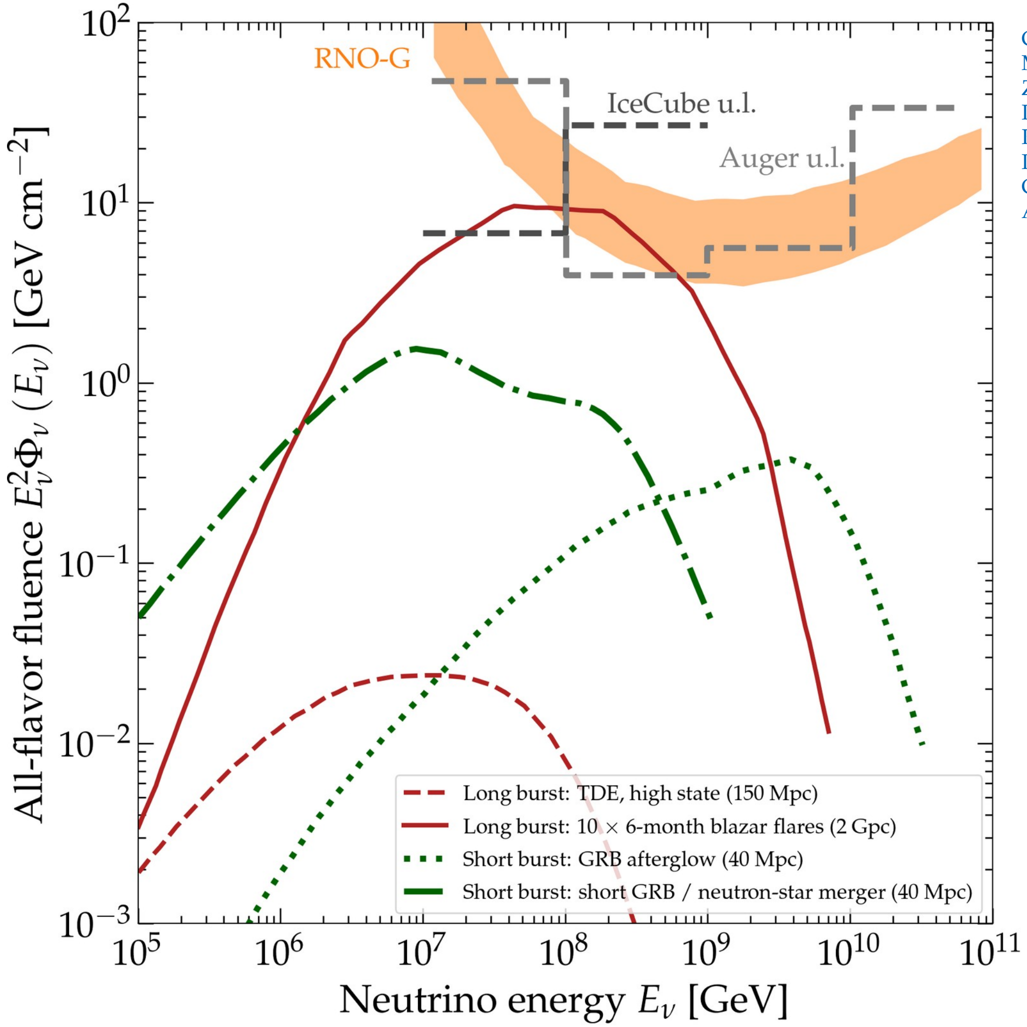

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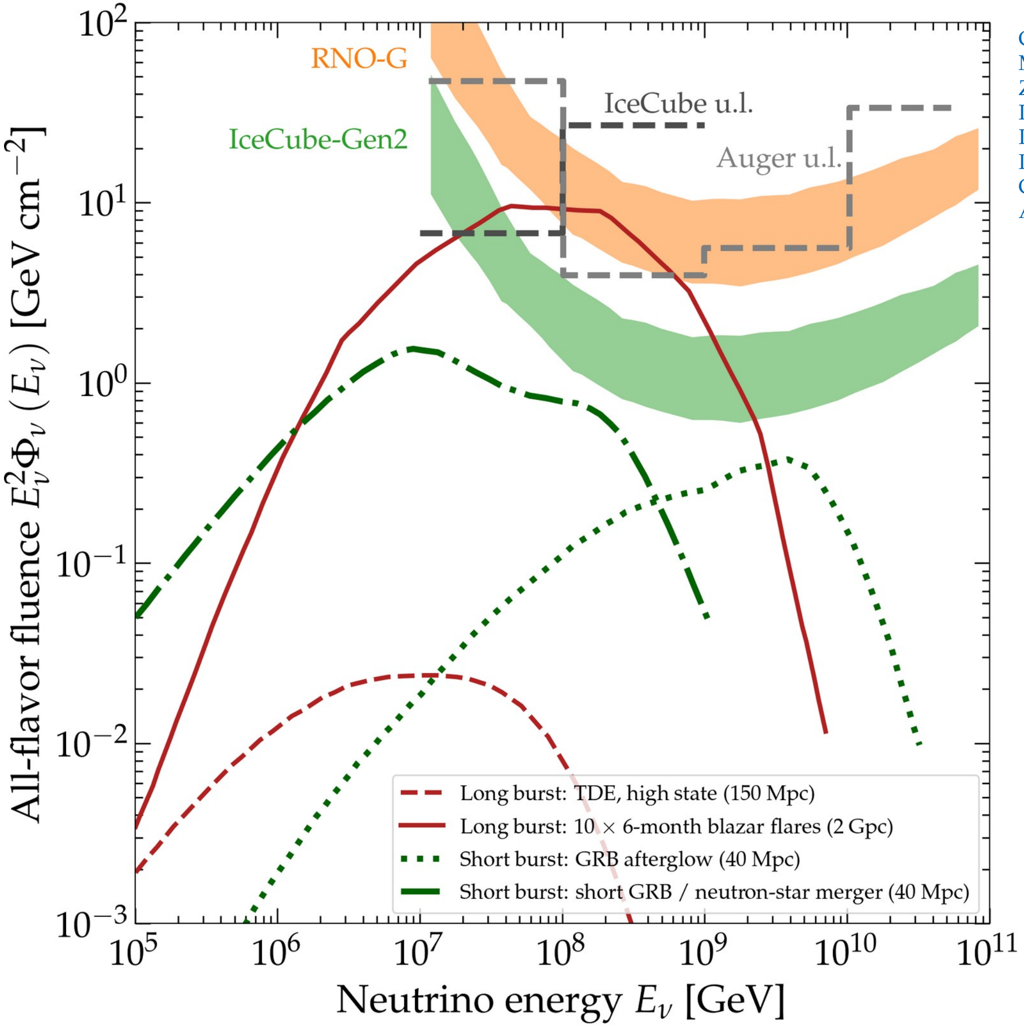

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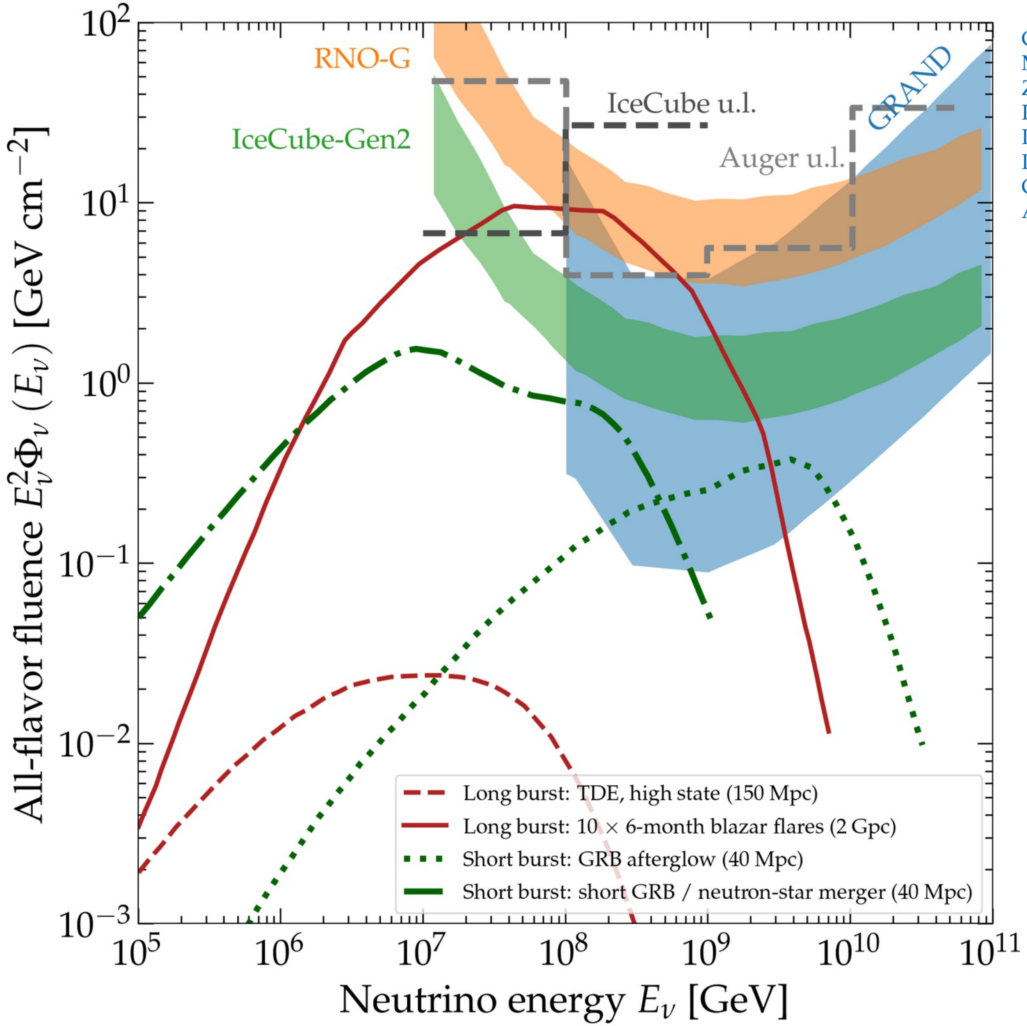

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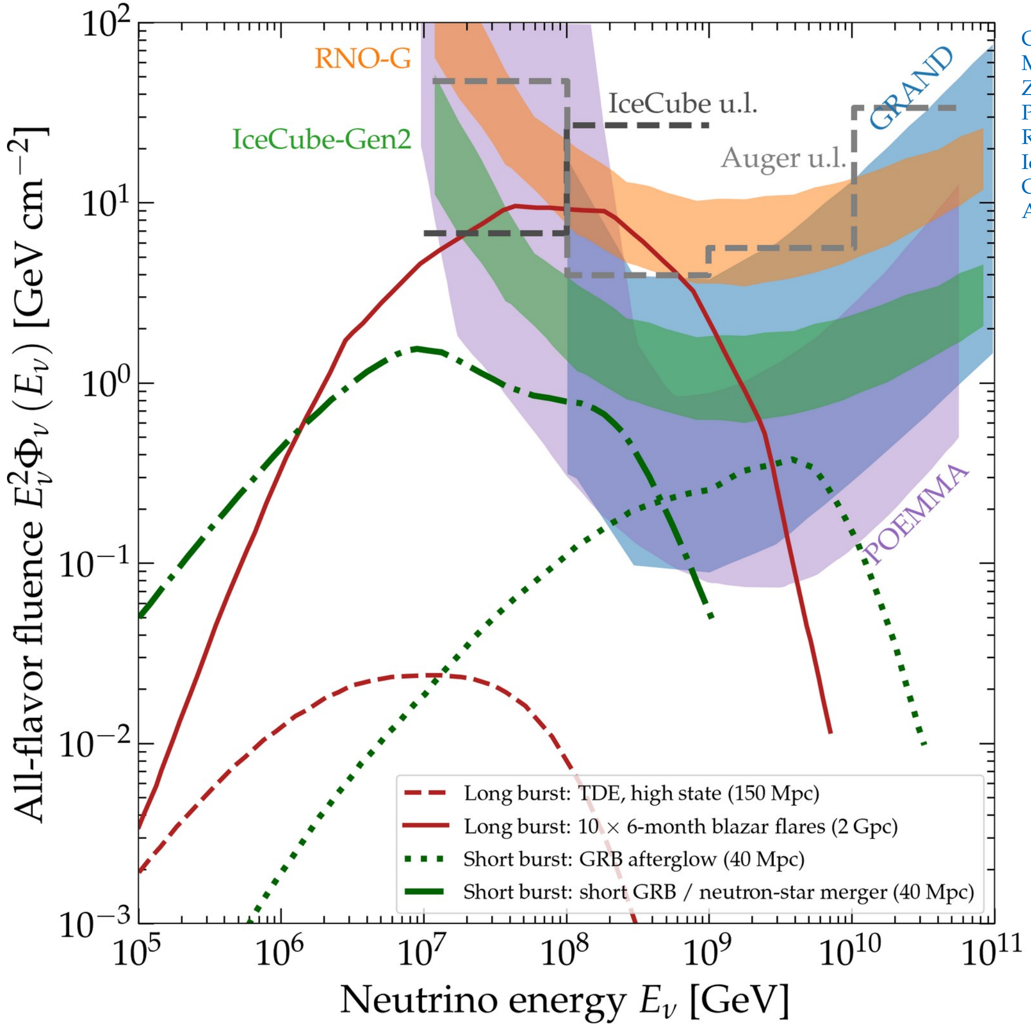

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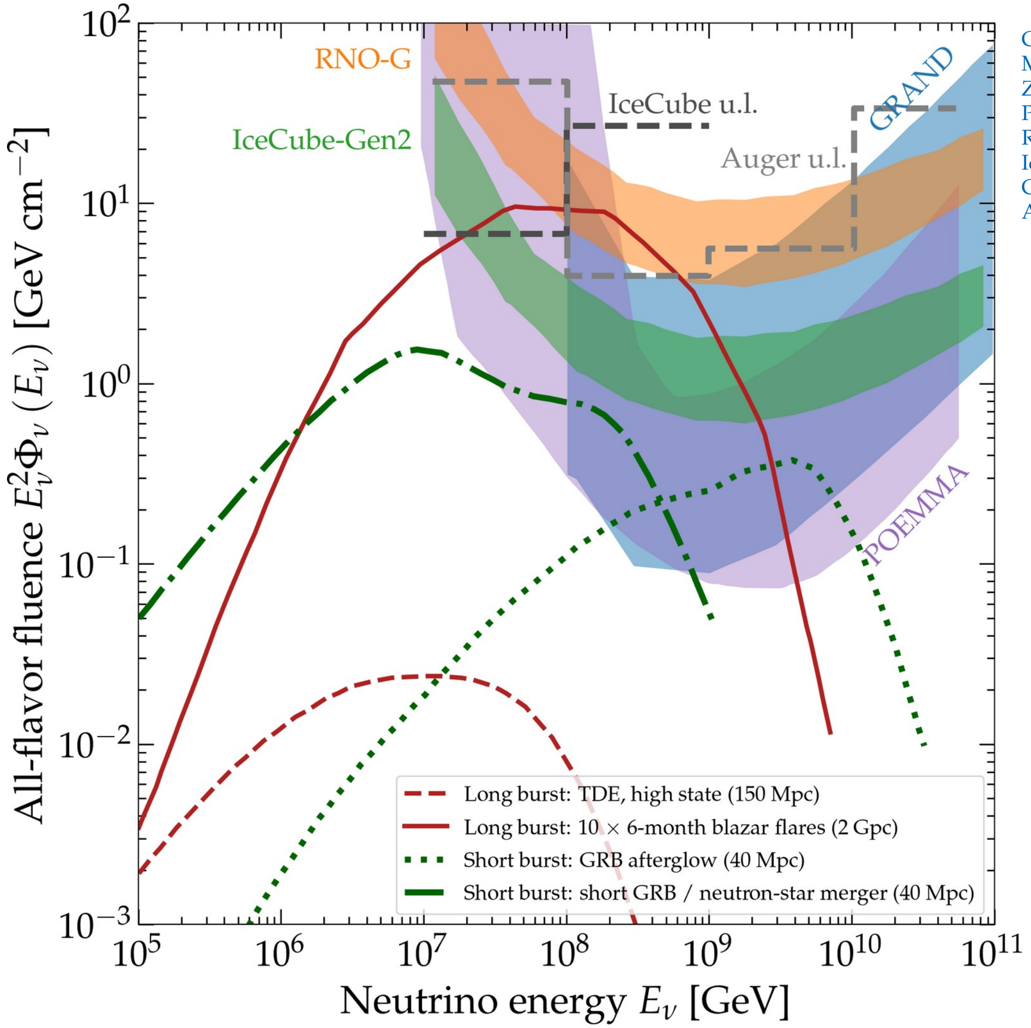

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Take-home message

We might see an UHE ν burst before we see a diffuse flux

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[Adding spectrum information (not shown) will likely help]

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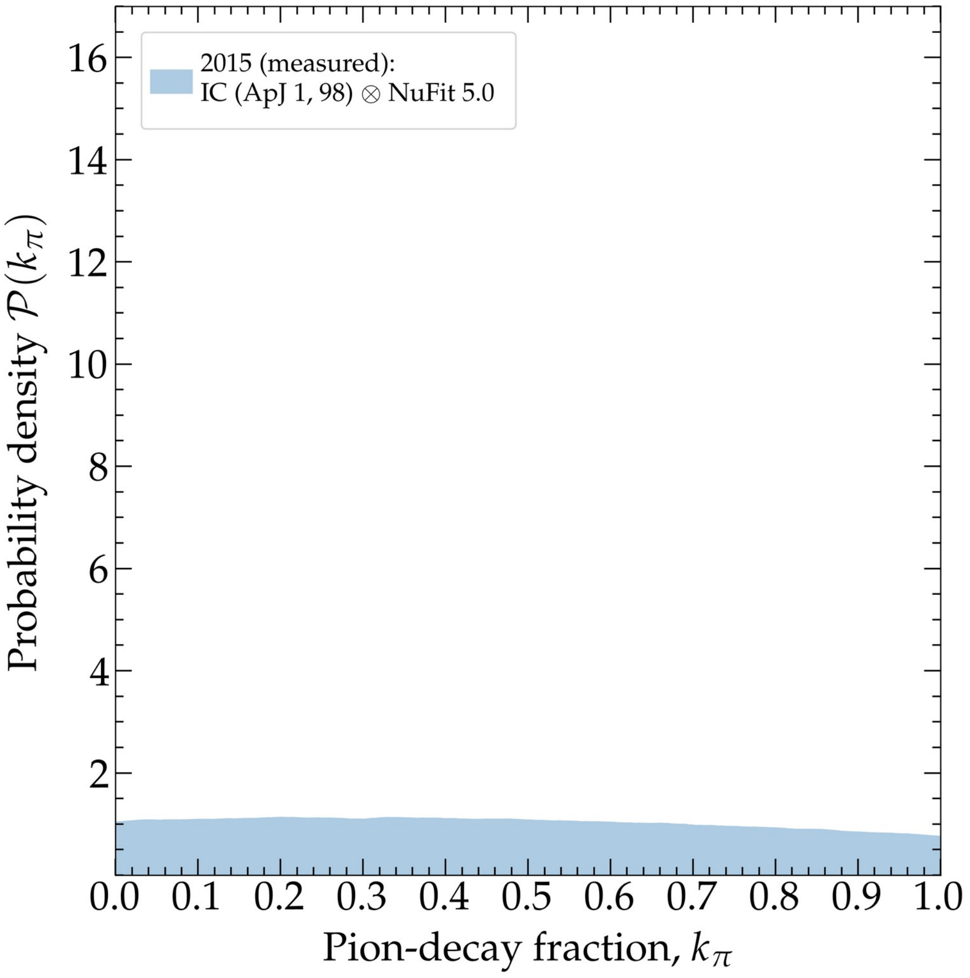

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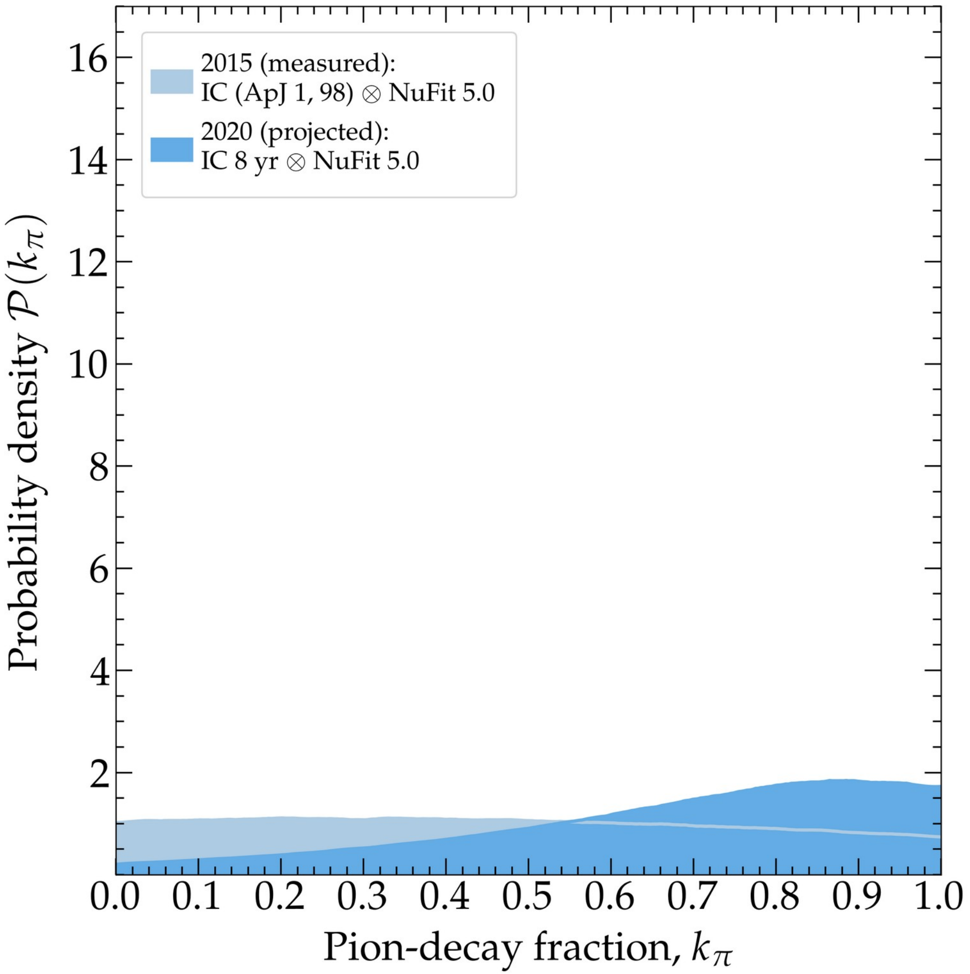

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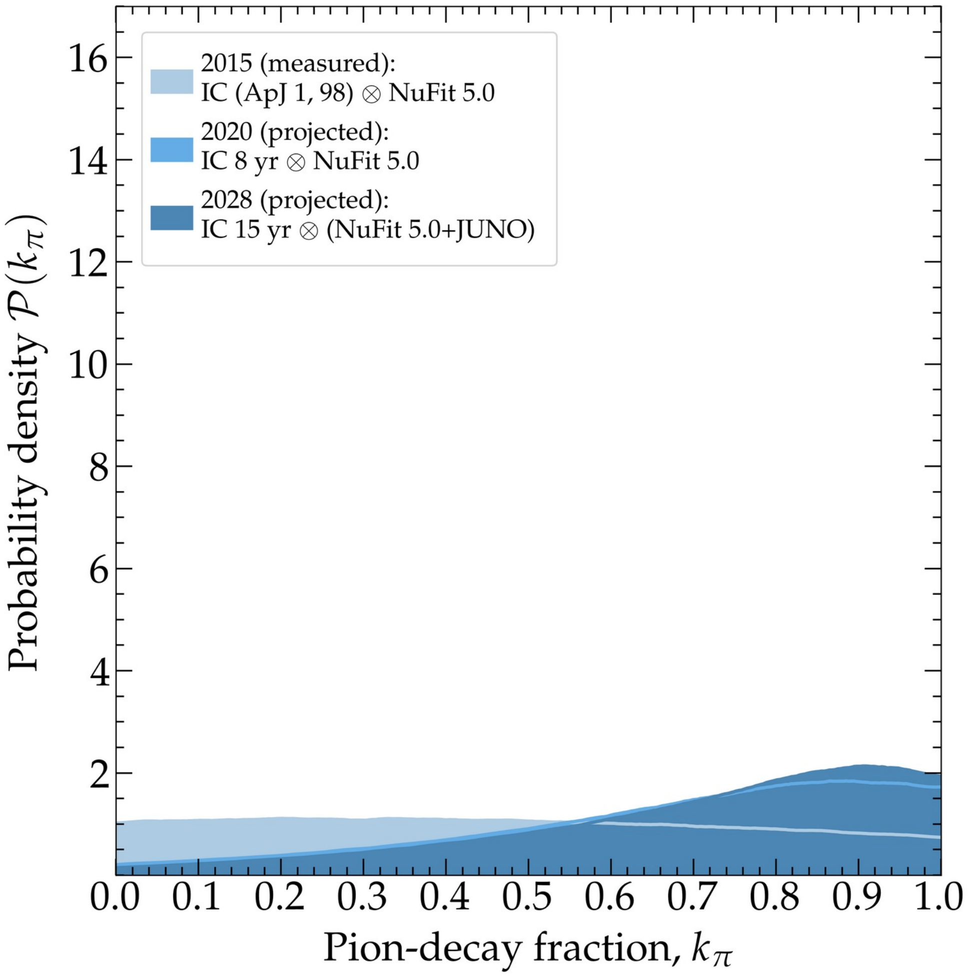

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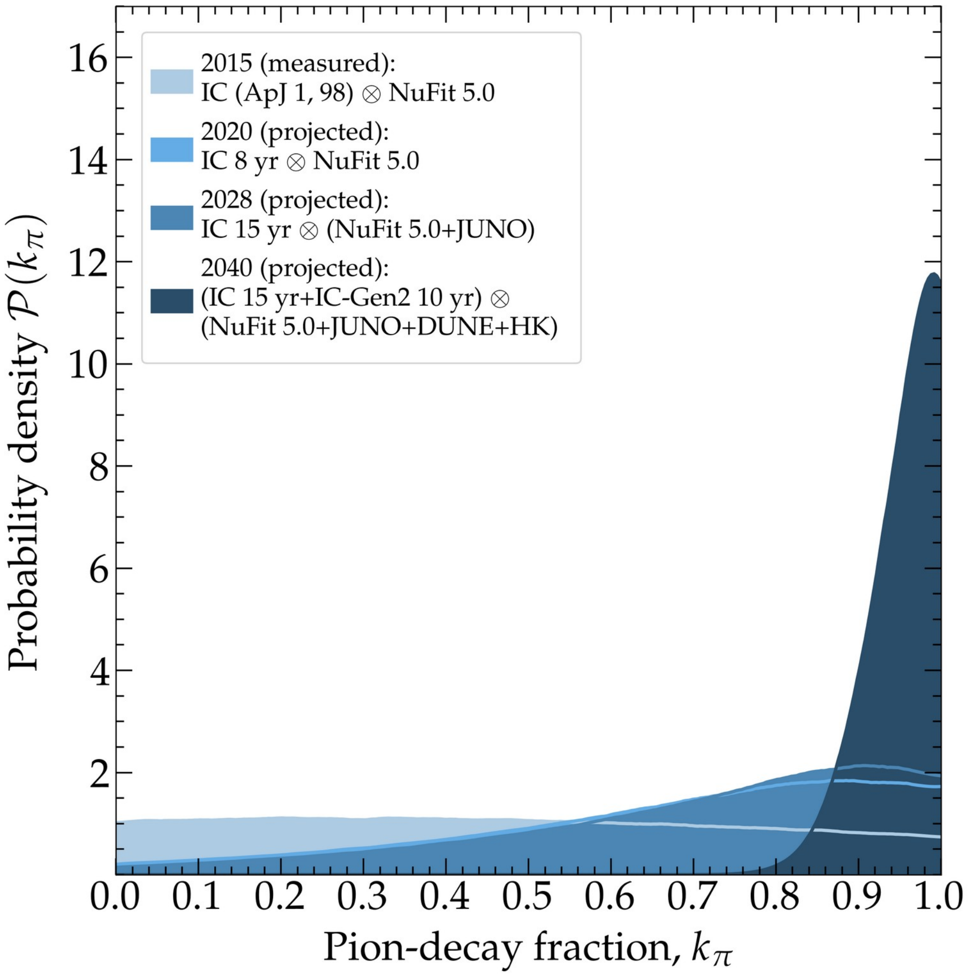

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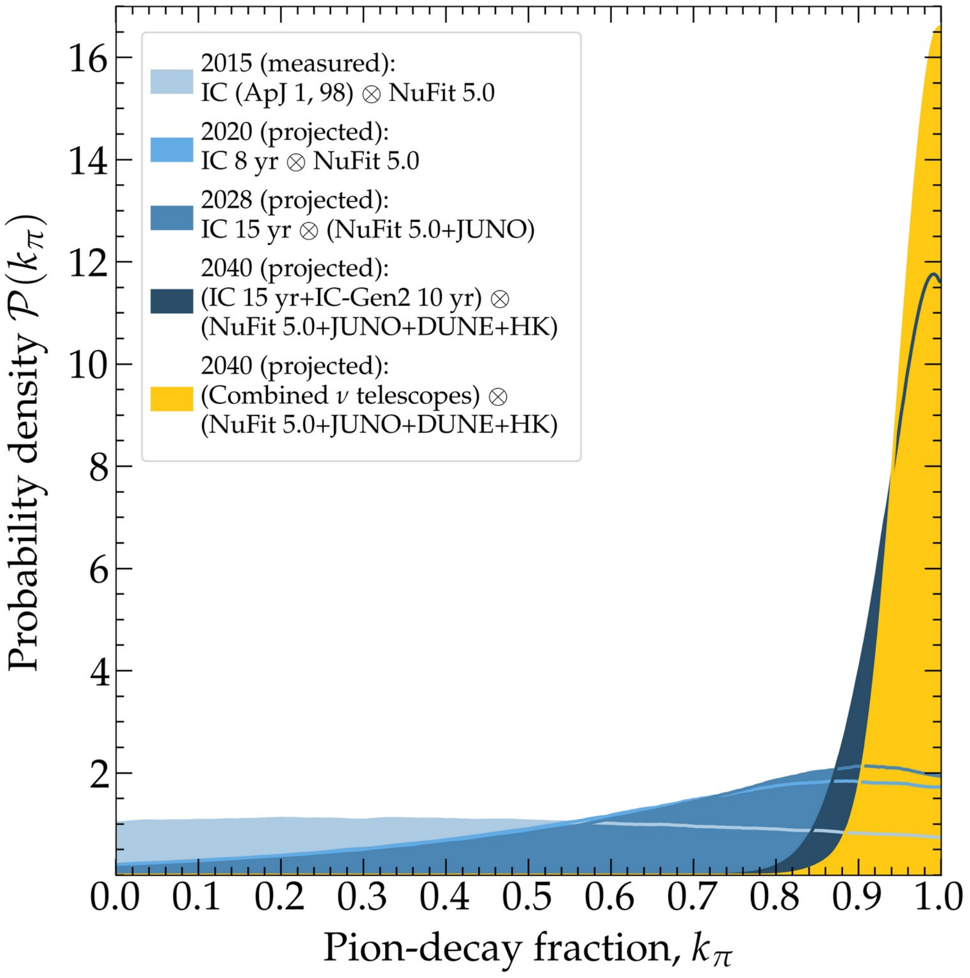

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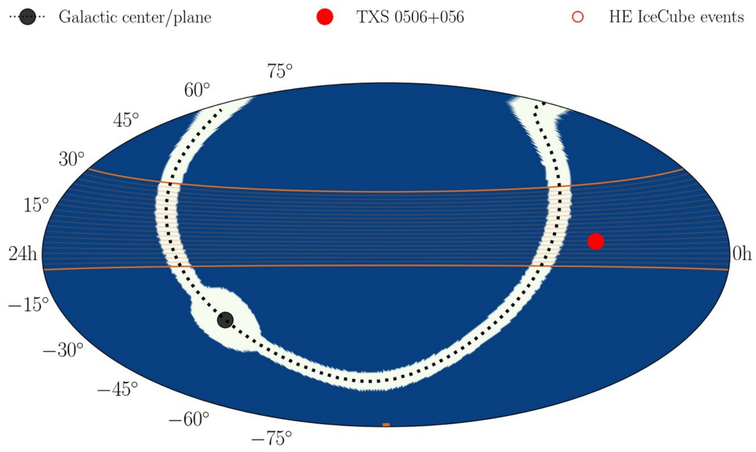
Discovering a Galactic ν flux in PLEνM

Galactic emission template:



Flux uniformly distributed:

$$E^2\phi = \phi_{100\text{TeV}} \left(\frac{E}{100\ \text{TeV}}\right)^{2-\gamma}$$

5σ discovery potential (GC only)

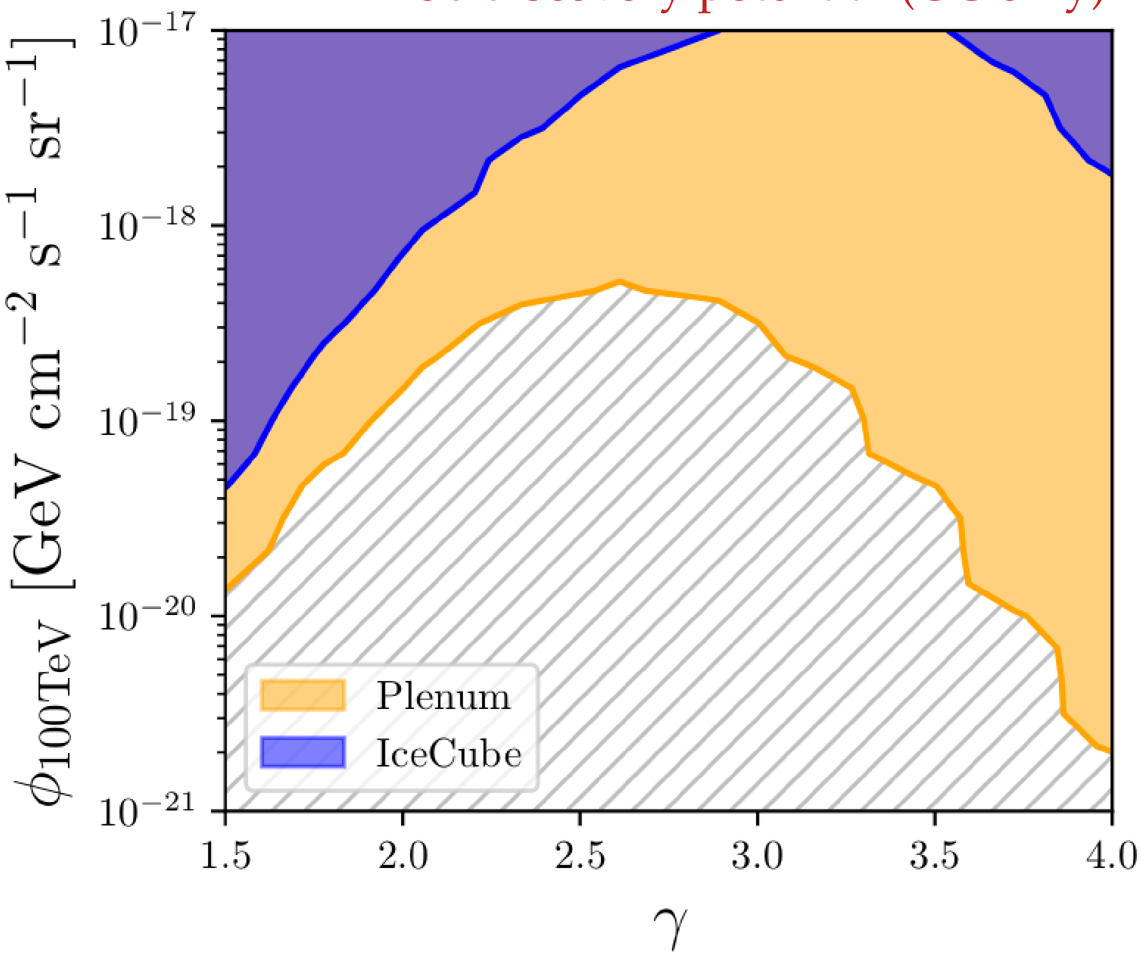


Figure courtesy of Matthias Huber

Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*