

High-energy and ultra-high-energy cosmic neutrinos: *great today, better tomorrow*

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UNIVERSITY OF
COPENHAGEN



VILLUM FONDEN







2021 (*we are here*):
TeV–PeV ν discovered
First possible sources



2020s (*we are getting there*):
More source candidates
Characterize the ν flux precisely

2021 (*we are here*):
TeV–PeV ν discovered
First possible sources

2030s (*under planning*):
Discovering EeV neutrinos

2020s (*we are getting there*):
More source candidates
Characterize the ν flux precisely

2021 (*we are here*):
TeV–PeV ν discovered
First possible sources

I.

The story so far

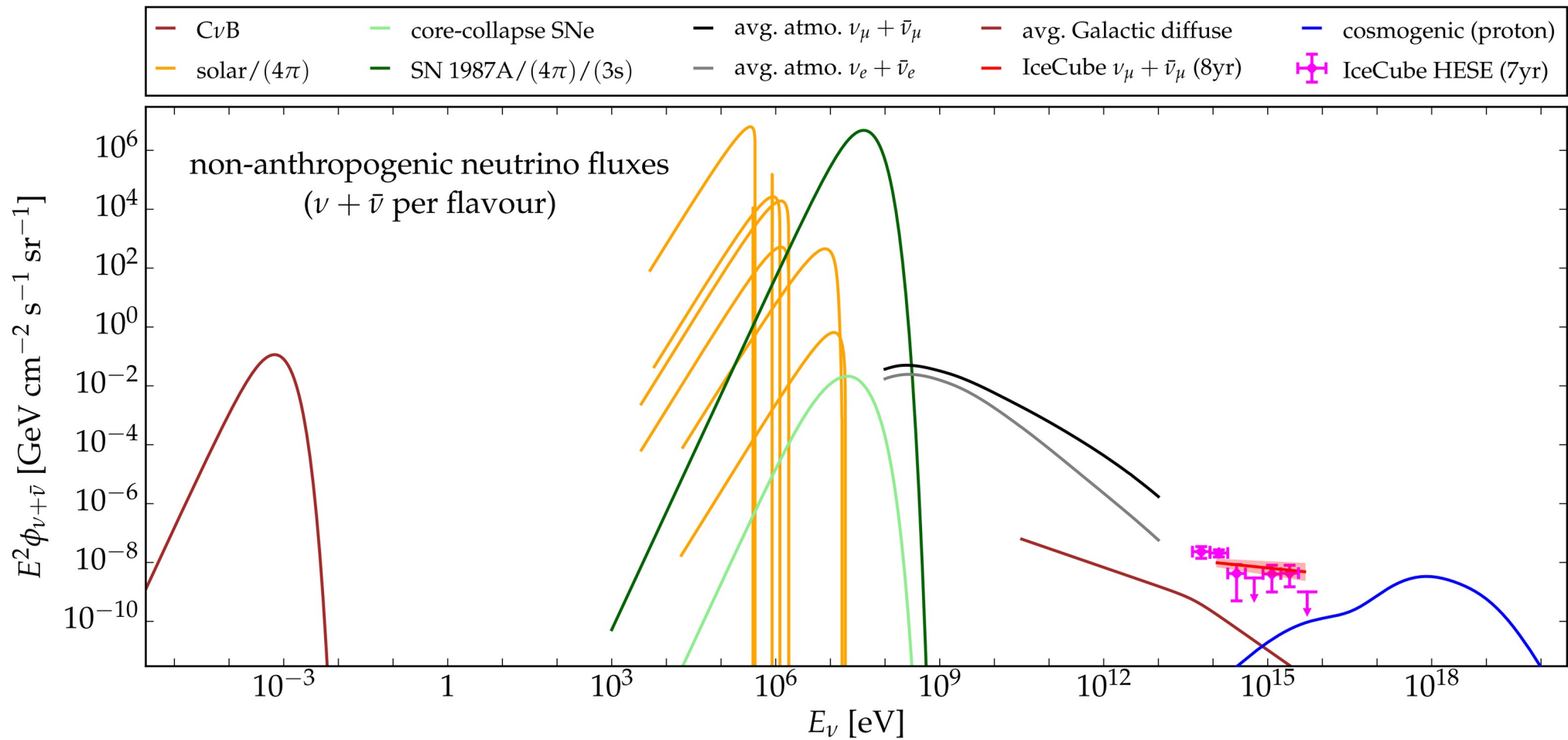


Figure courtesy of Markus Ahlers
Maoloud, De Wasseige, Ahlers, MB, Van Elewyck, PoS(ICRC2019), 1023

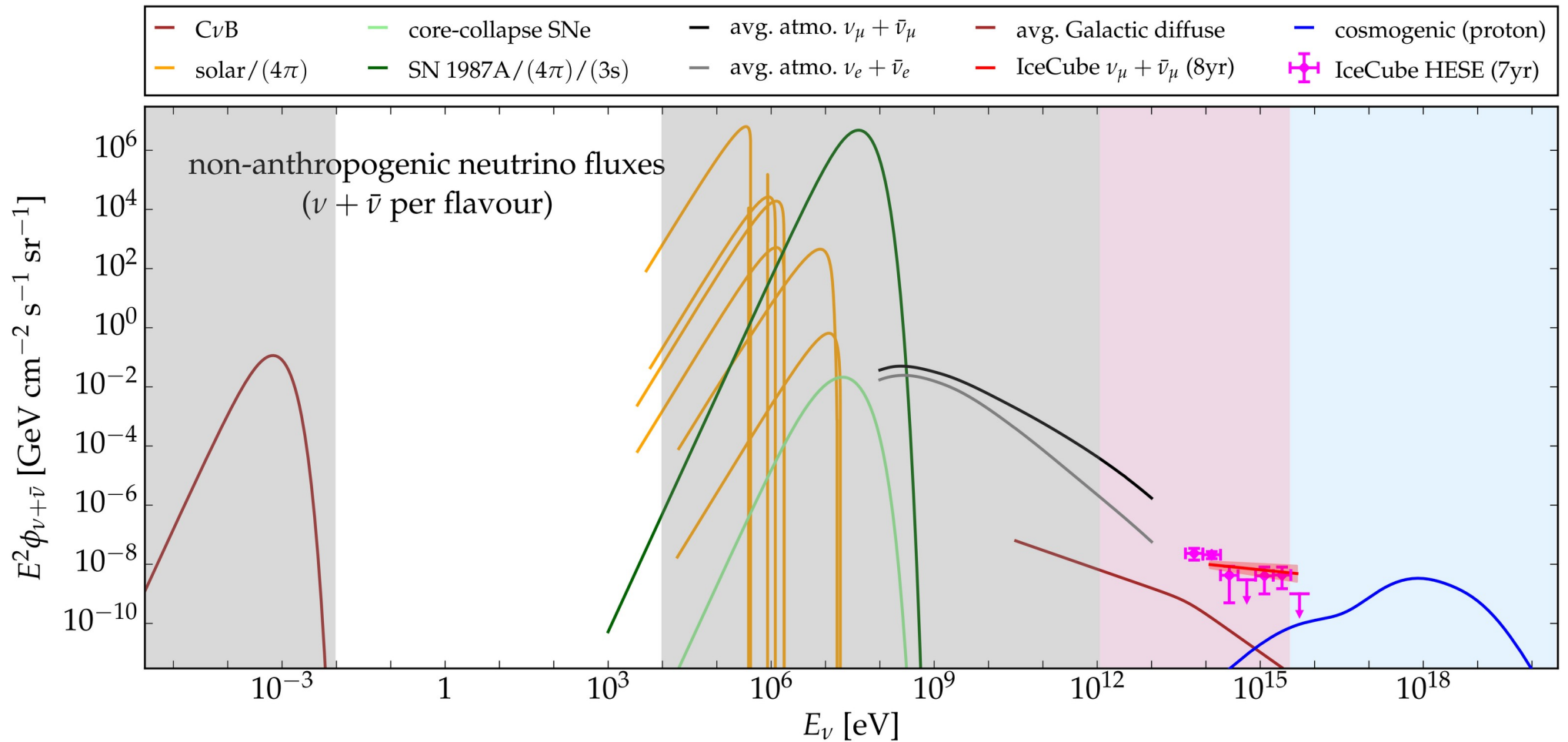


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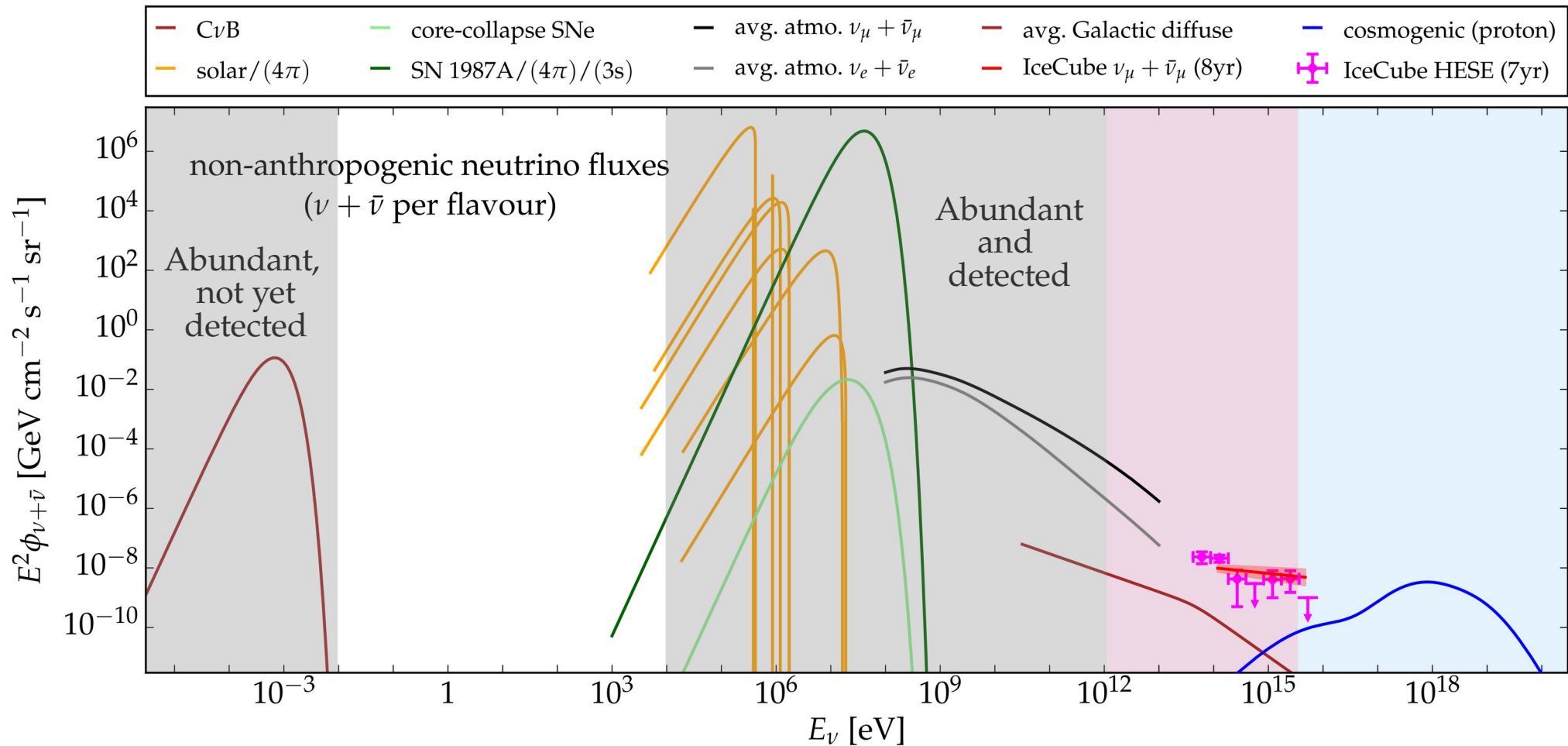


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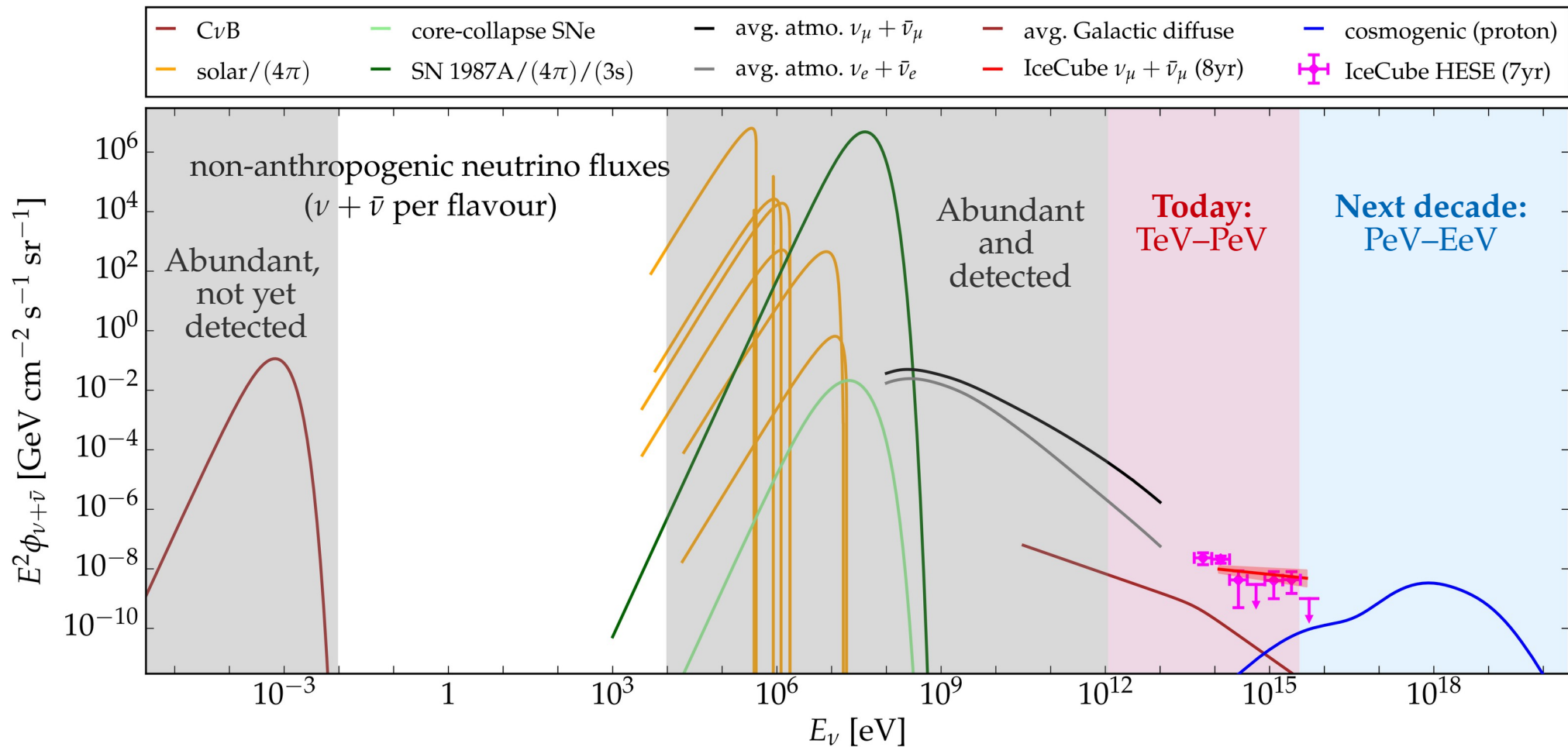


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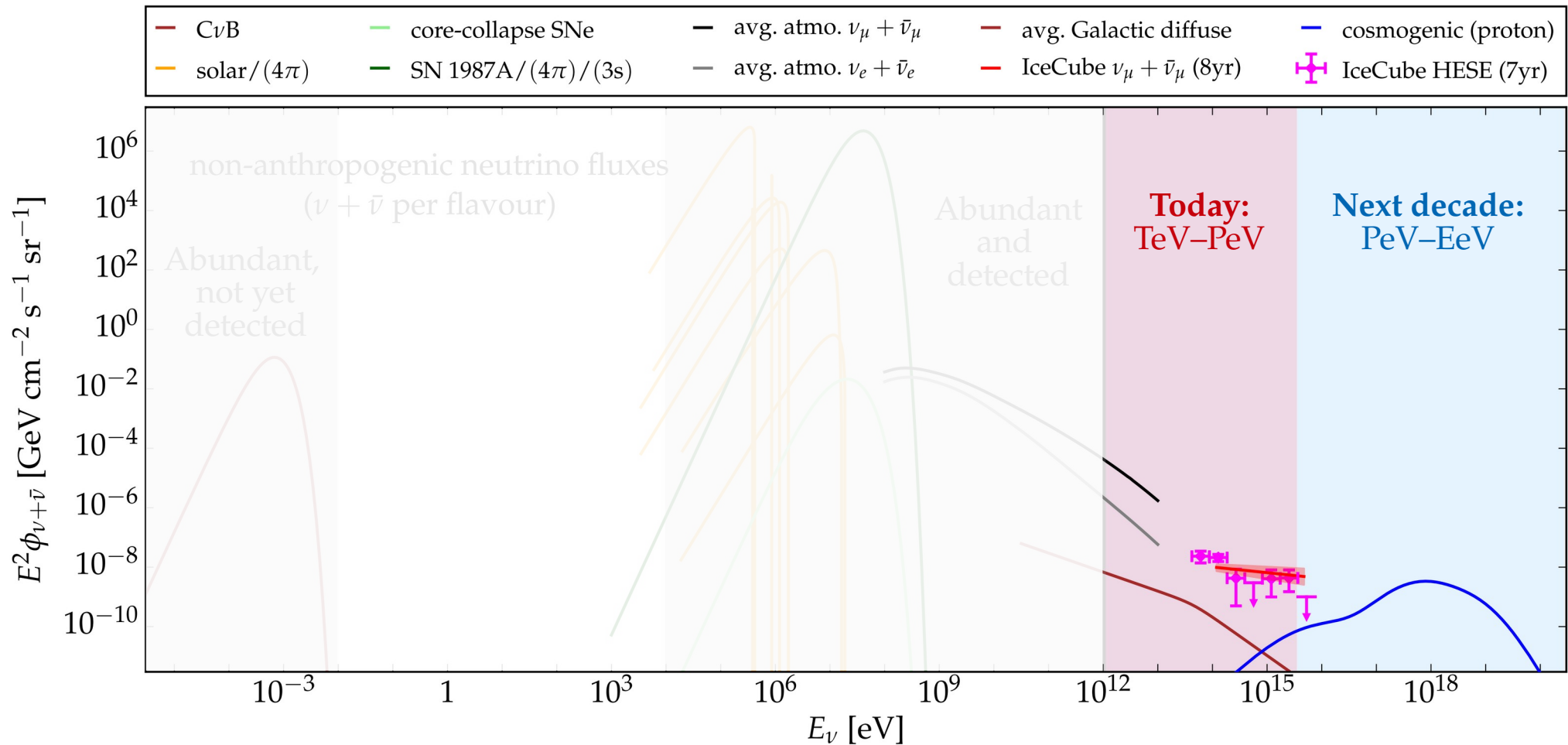
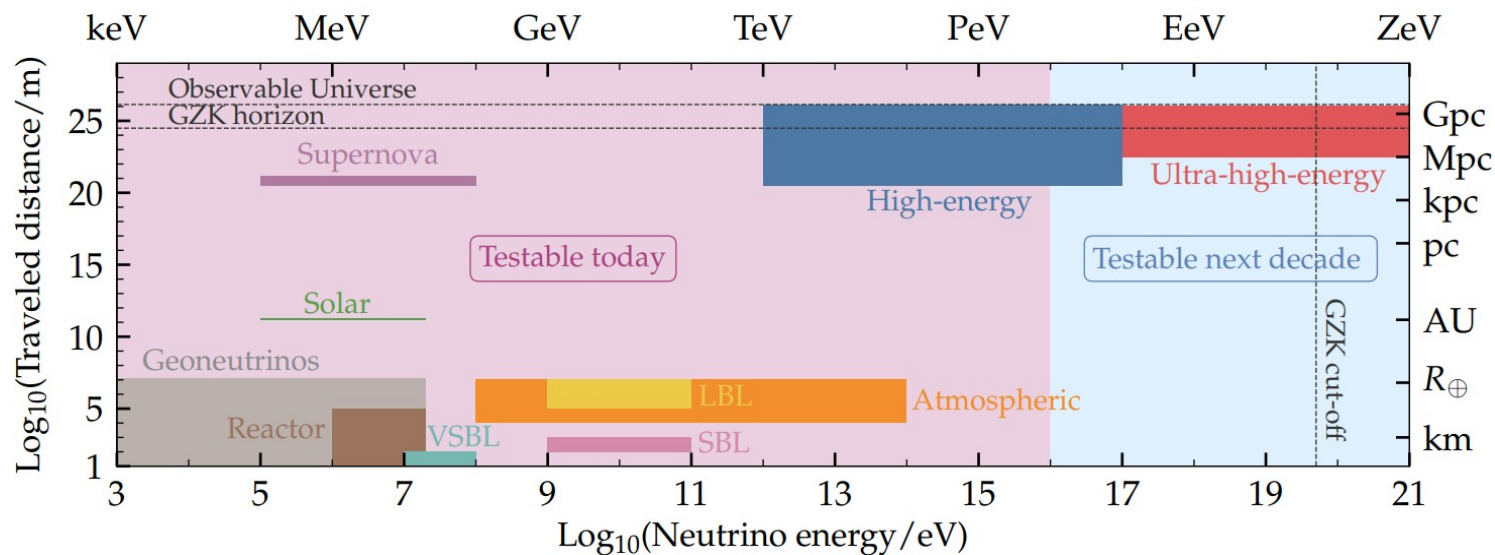


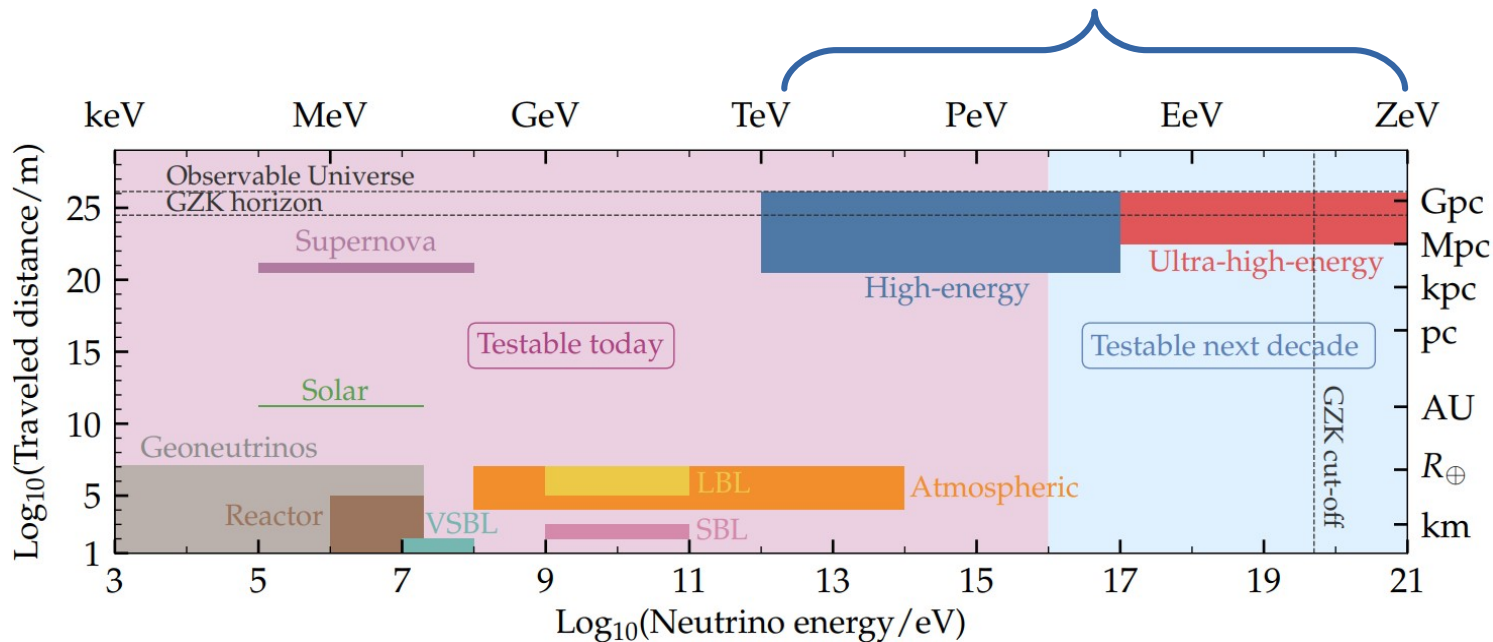
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What makes high-energy cosmic ν exciting?



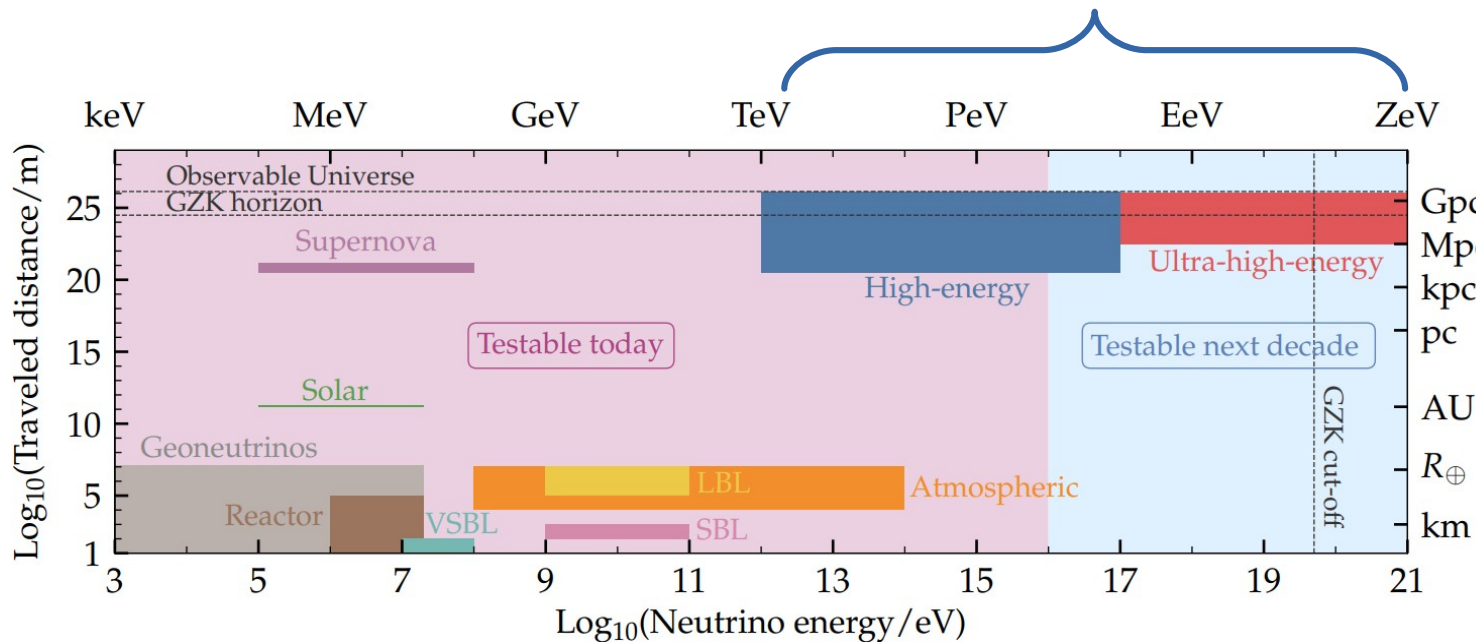
What makes high-energy cosmic ν exciting?

They have the **highest energies**



What makes high-energy cosmic ν exciting?

They have the **highest energies**



They travel the **longest distances**

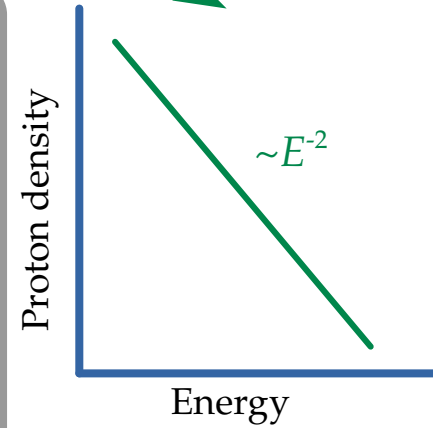
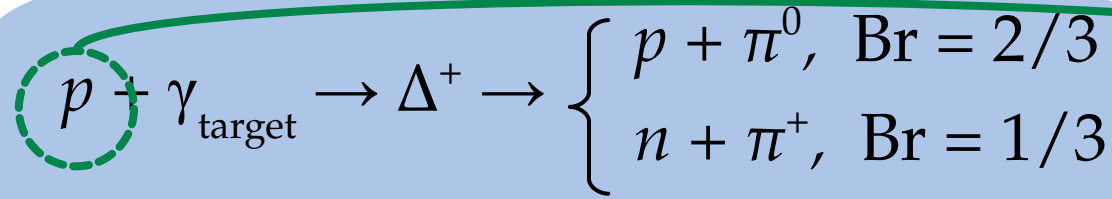
The multi-messenger connection: a simple picture

(or $p + p$)

$$p + \gamma_{\text{target}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

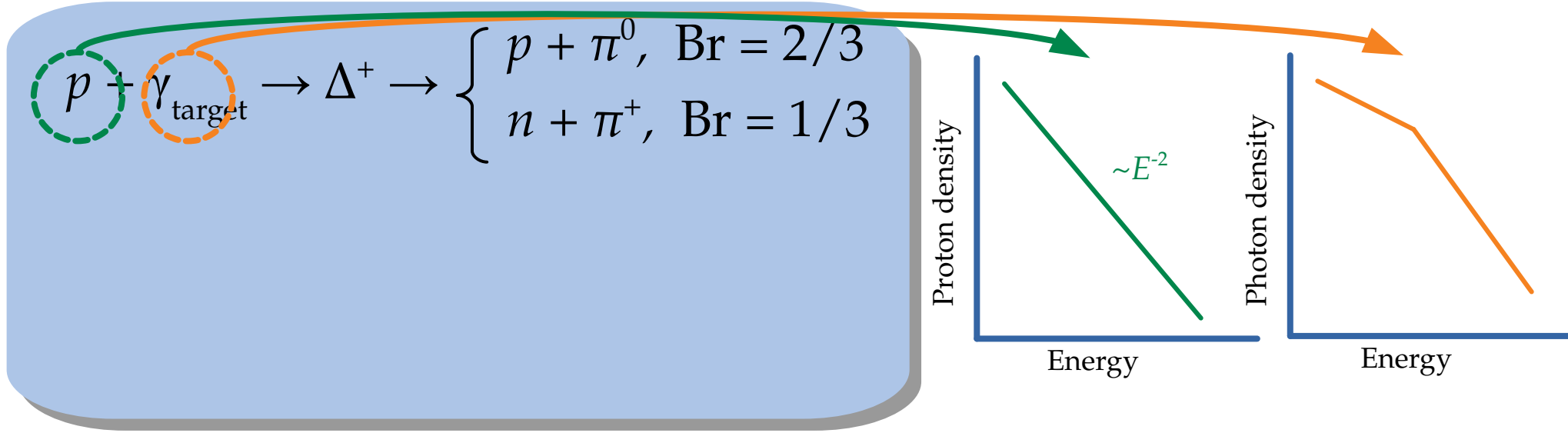
The multi-messenger connection: a simple picture

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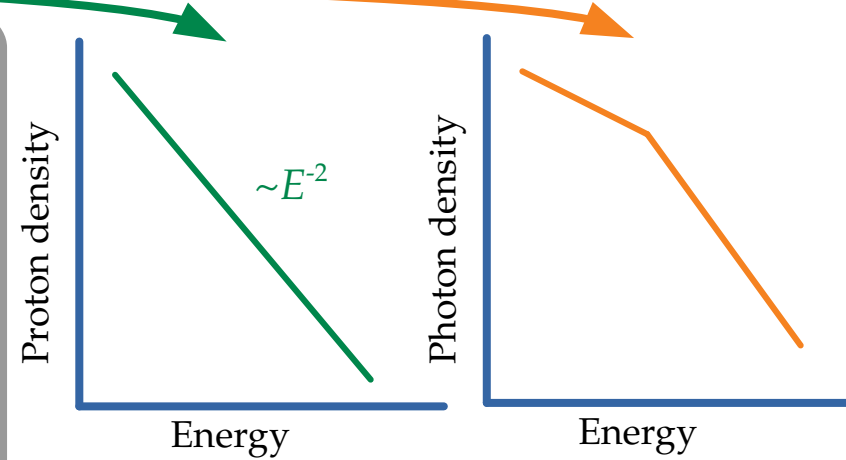
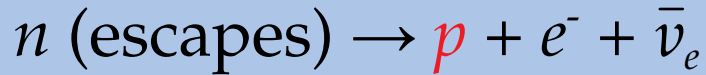
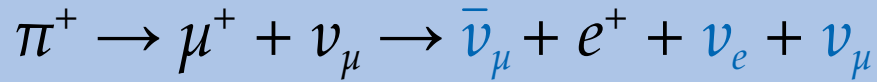
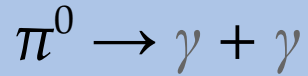
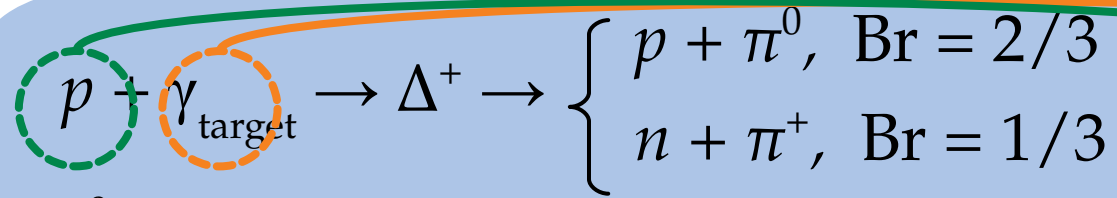
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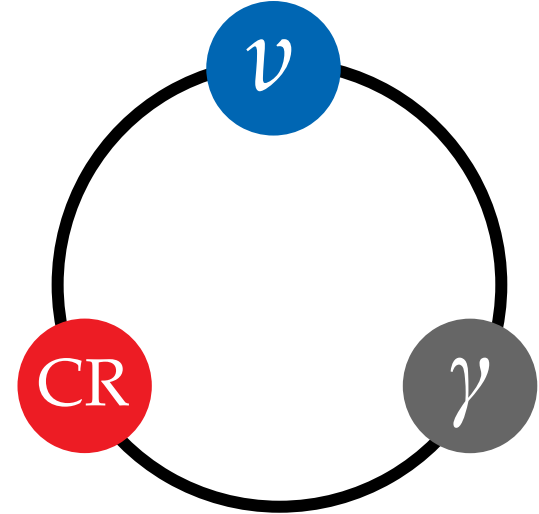
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$$\pi^0 \rightarrow \gamma + \gamma$$

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

$$n \text{ (escapes)} \rightarrow \textcolor{red}{p} + e^- + \bar{\nu}_e$$



Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

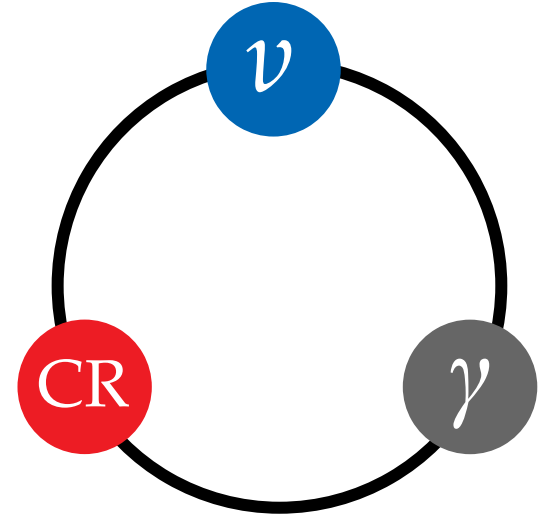
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1 PeV

20 PeV

Neutrino energy = Proton energy / 20

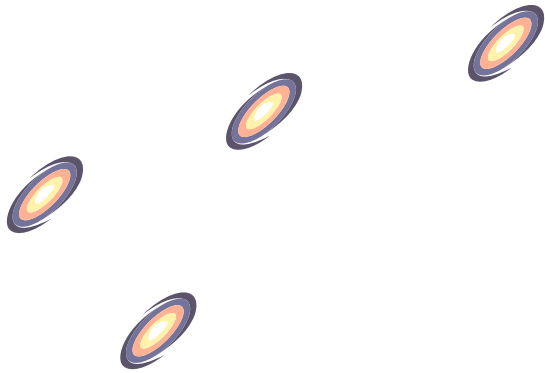
Gamma-ray energy = Proton energy / 10

Redshift



$z = 0$

Note: v sources can be steady-state or transient



Redshift

$z = 0$

Discovered

MeV γ

PeV p

TeV–PeV ν

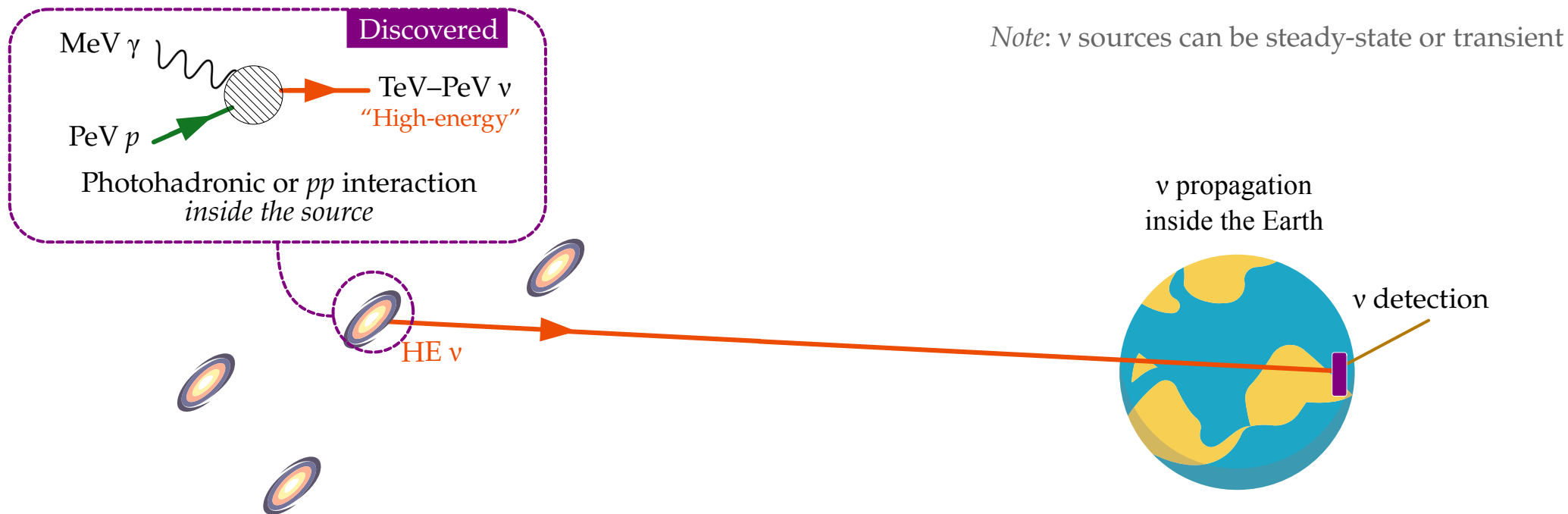
“High-energy”

Photohadronic or pp interaction
inside the source

Note: ν sources can be steady-state or transient

ν propagation
inside the Earth

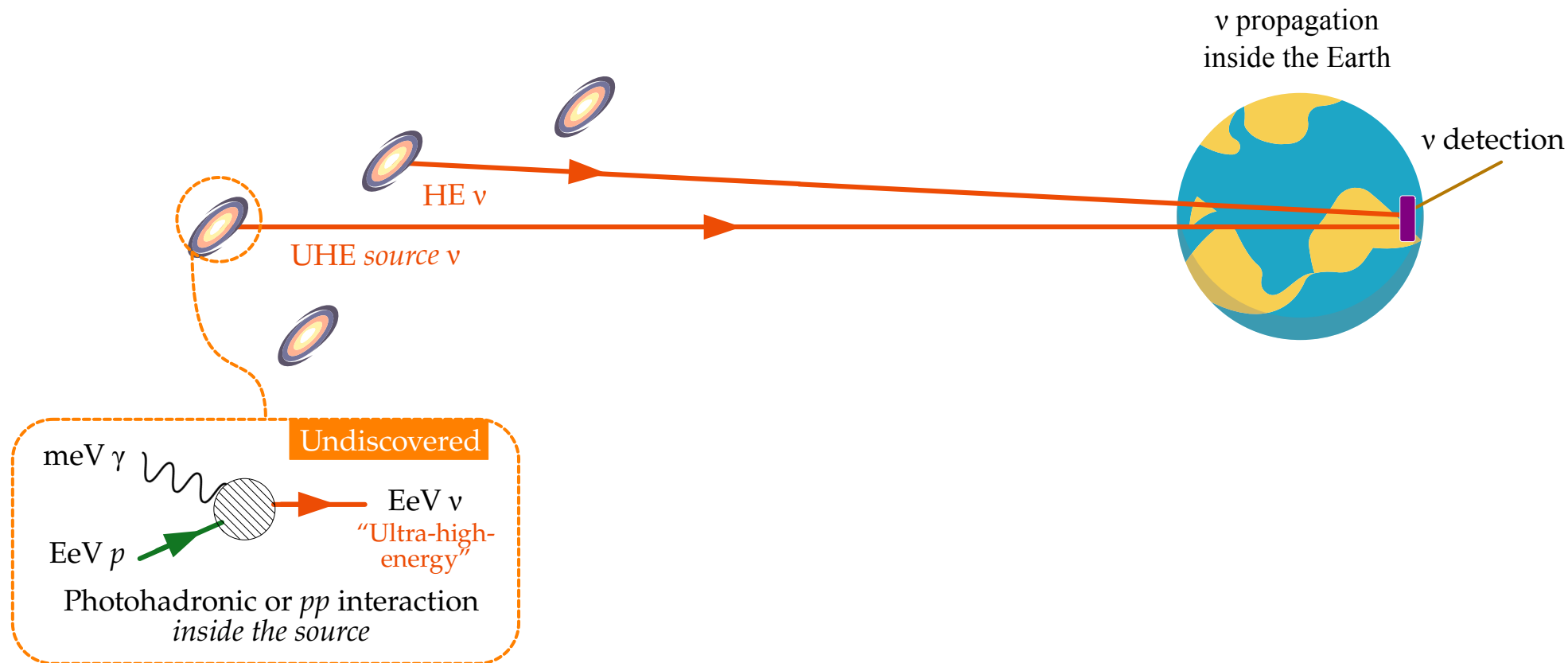
ν detection



Redshift

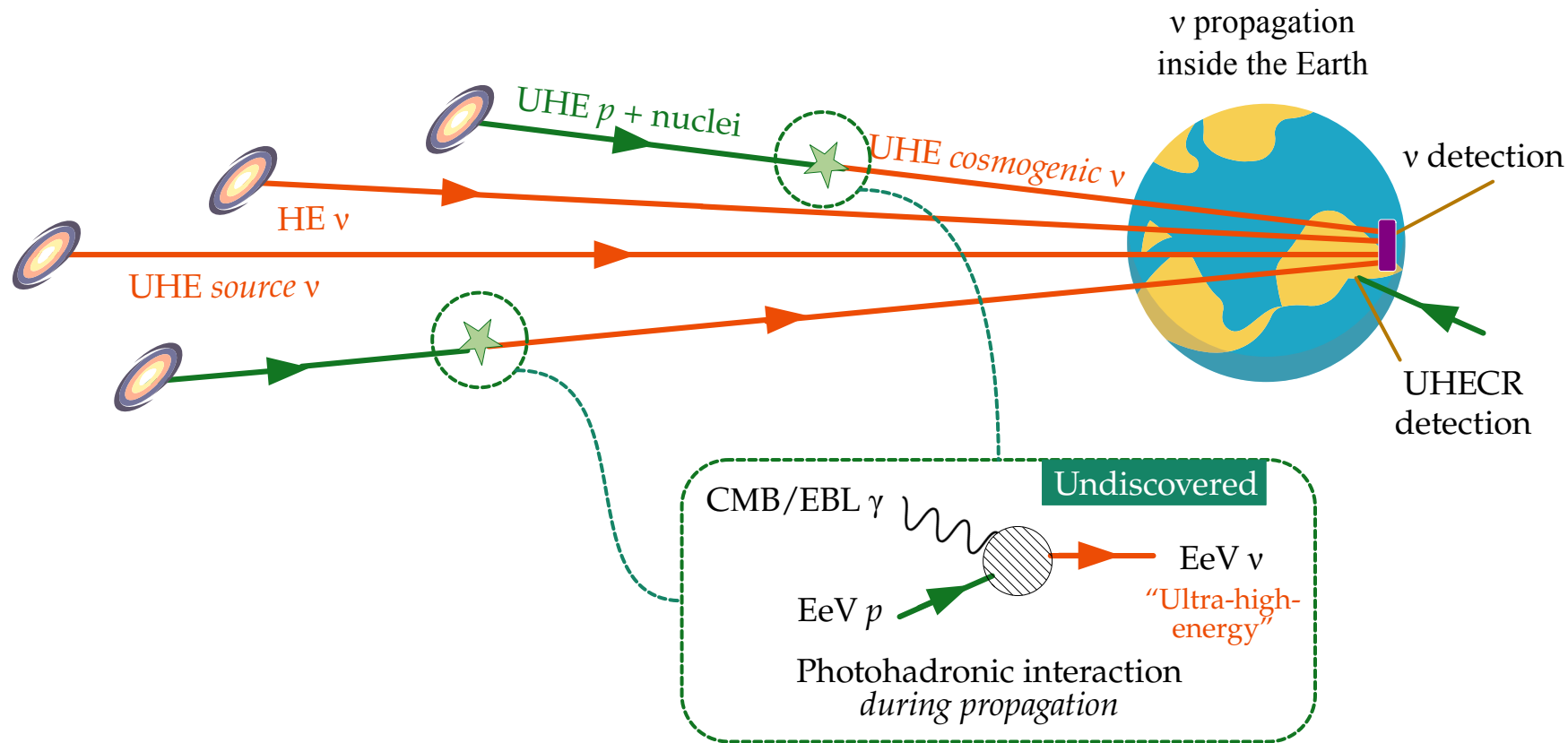
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Redshift ← $z = 0$

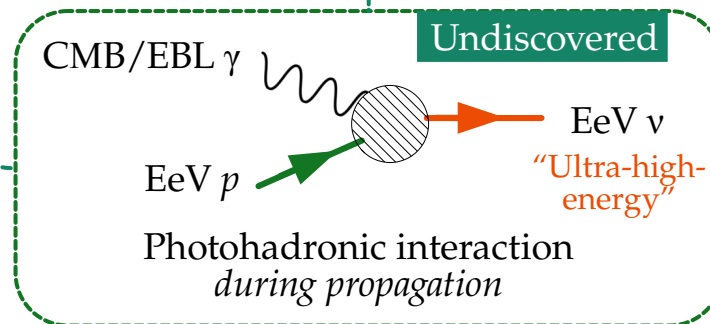
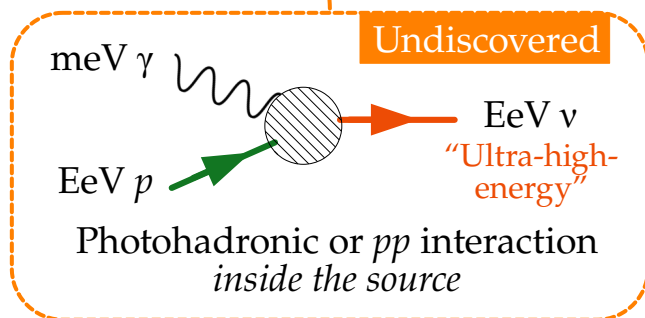
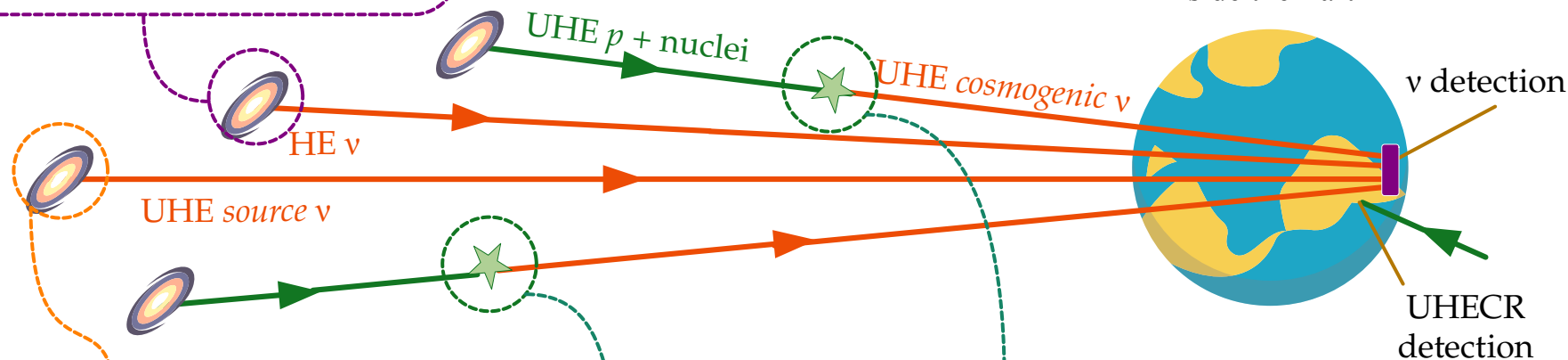
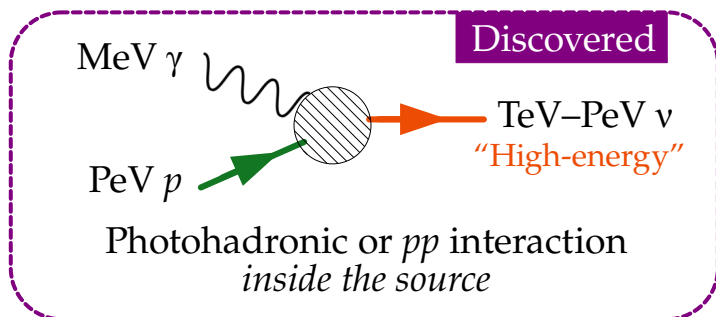
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Redshift $\leftarrow$

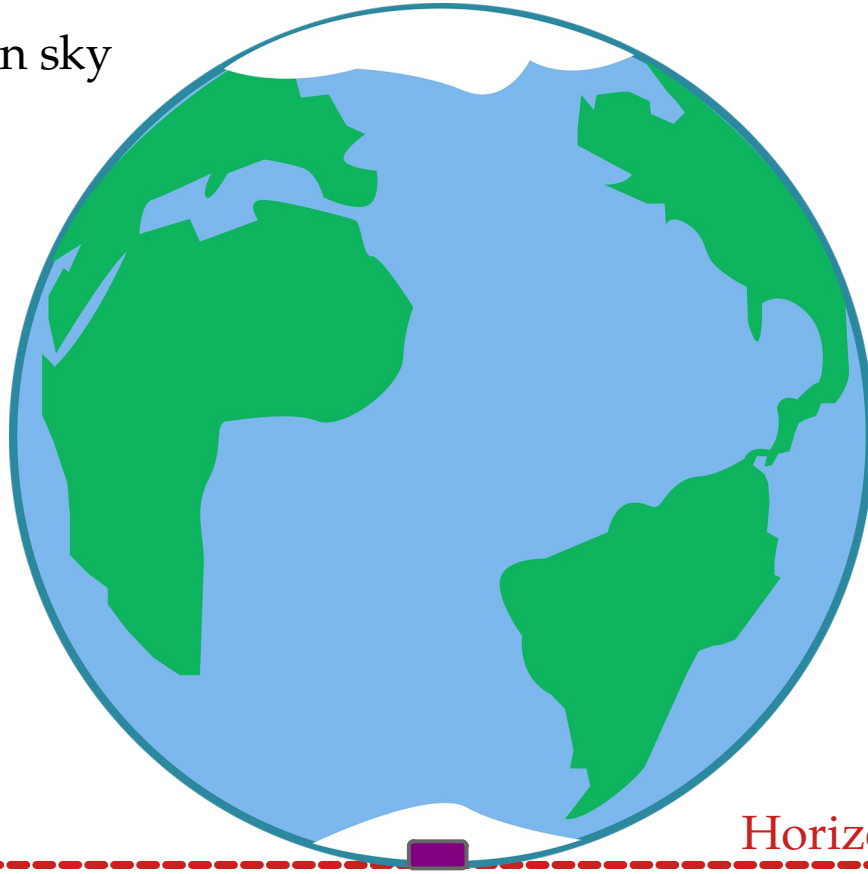
$z = 0$

Note: ν sources can be steady-state or transient



Upgoing *vs.* downgoing neutrinos

Northern sky



Horizon

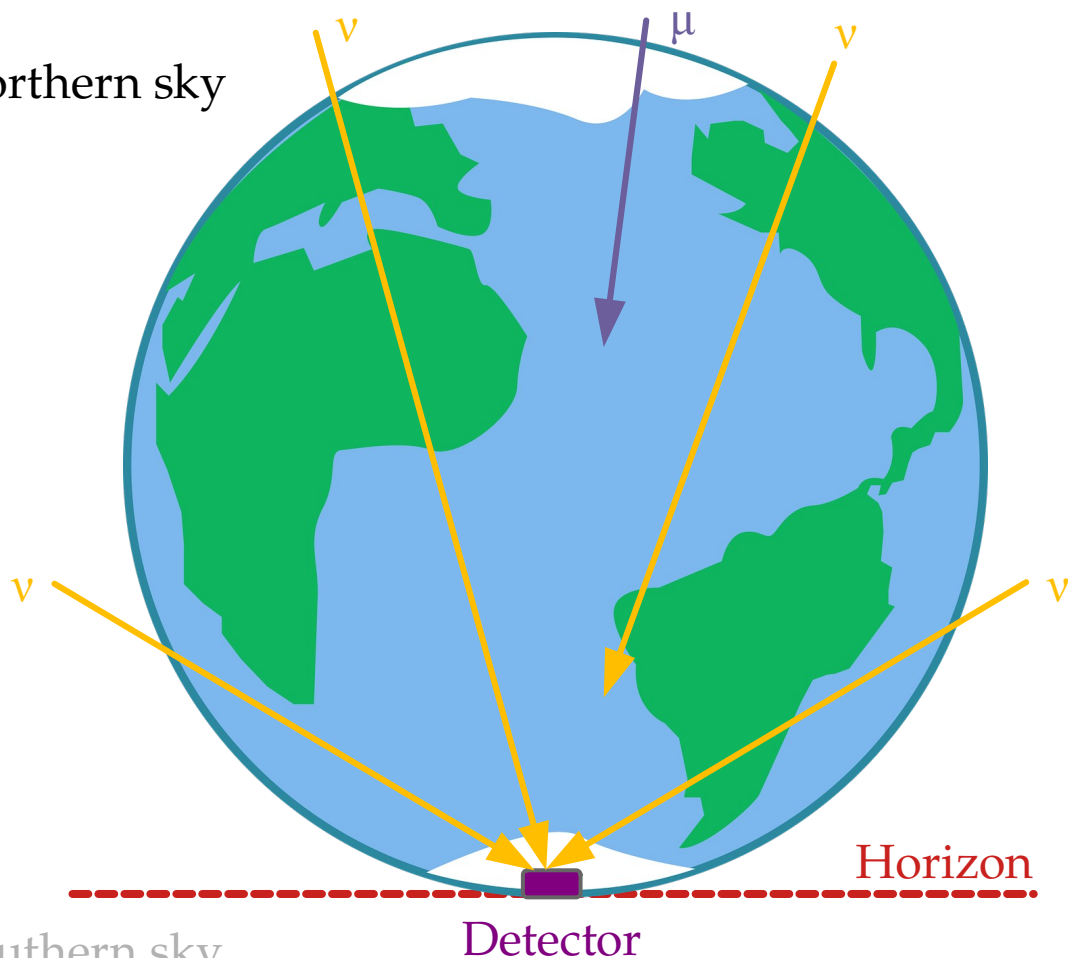
Detector

Southern sky

(Galactic Center is here)

Upgoing vs. downgoing neutrinos

Northern sky



Southern sky

(Galactic Center is here)

Detector

Horizon

Neutrinos from the Northern sky

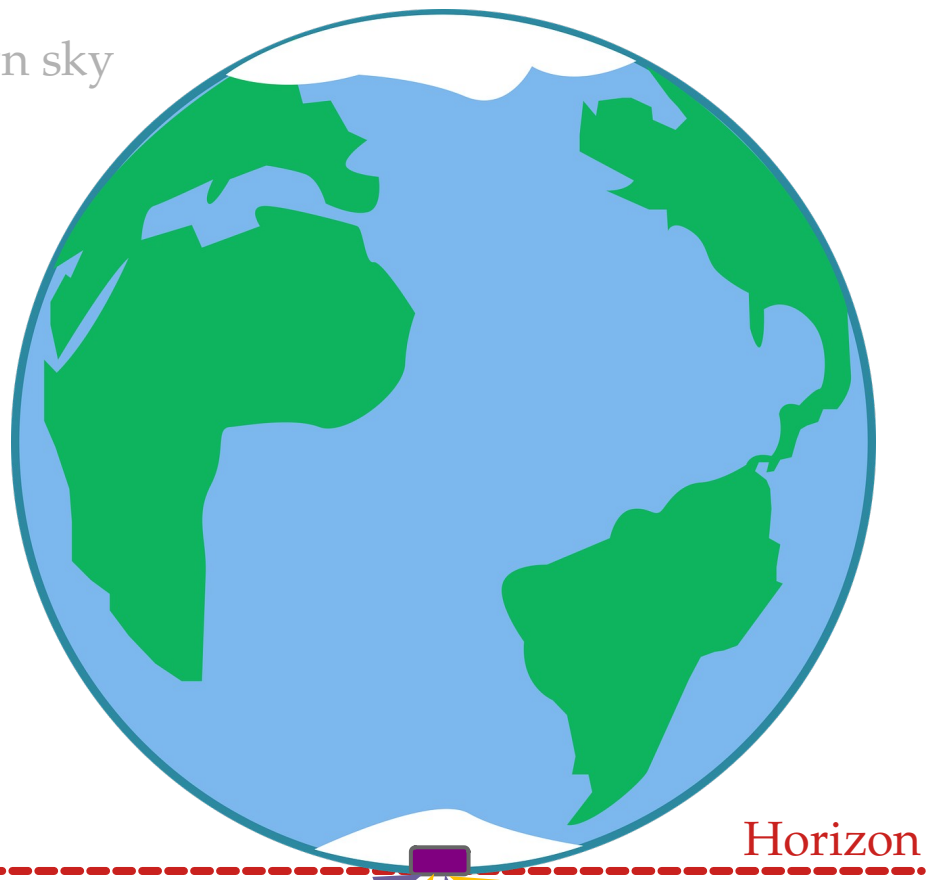
≡

Upgoing neutrinos

- ▶ Atmospheric μ ons stopped
- ▶ Dominated by atmospheric ν
- ▶ High-energy ν flux attenuated
- ▶ High statistics
- ▶ Good for finding sources with through-going muon tracks

Downgoing vs. upgoing neutrinos

Northern sky



Southern sky
(Galactic Center is here)

Neutrinos from the **Southern sky**

≡

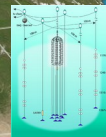
Downgoing neutrinos

- ▶ Need to mitigate atmospheric **muons** and **ν** :
 - ▶ Use higher-energy events
 - ▶ Use starting a self-veto
- ▶ Dominated by astrophysical ν (*after* event selection)
- ▶ Low statistics
- ▶ **Good for measuring the diffuse flux of astrophysical ν**

TeV–PeV ν
telescopes, 2021

ANTARES

- ▶ Mediterranean Sea
- ▶ Completed 2008
- ▶ $V_{\text{eff}} \sim 0.2 \text{ km}^3$ (10 TeV)
- ▶ $V_{\text{eff}} \sim 1 \text{ km}^3$ (10 PeV)
- ▶ 12 strings, 900 OMs
- ▶ Sensitive to ν from the Southern sky



Baikal NT200+

- ▶ Lake Baikal
- ▶ Completed 1998 (upgraded 2005)
- ▶ $V_{\text{eff}} \sim 10^{-4} \text{ km}^3$ (10 TeV)
- ▶ $V_{\text{eff}} \sim 0.01 \text{ km}^3$ (10 PeV)
- ▶ 8 strings, 192+ OMs

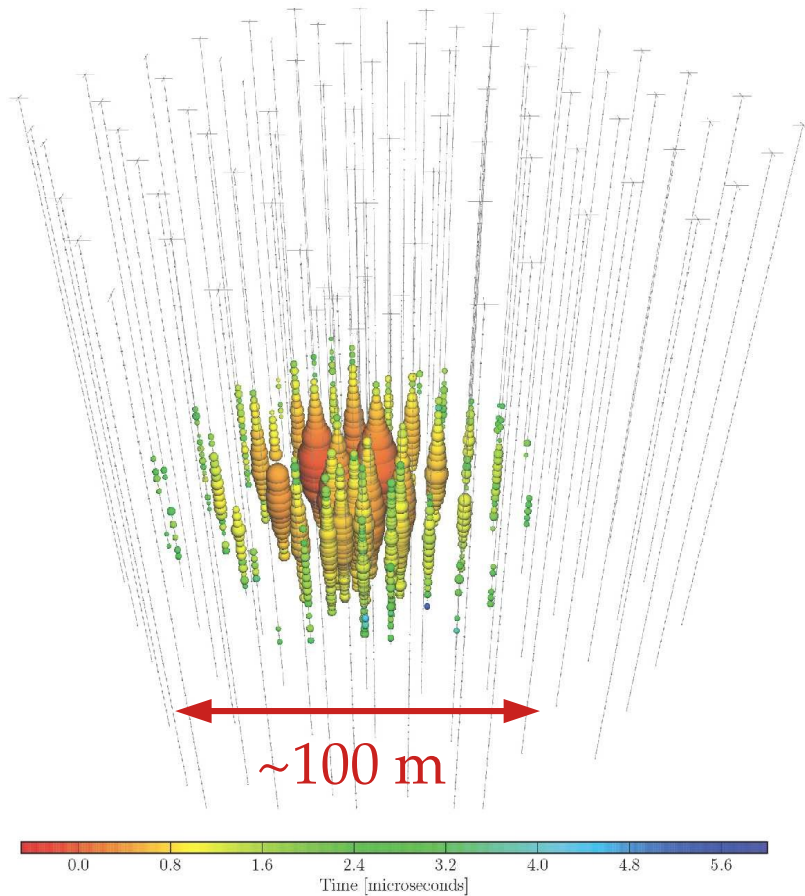
IceCube

- ▶ South Pole
- ▶ Completed 2011
- ▶ $V_{\text{eff}} \sim 0.01 \text{ km}^3$ (10 TeV)
- ▶ $V_{\text{eff}} \sim 1 \text{ km}^3$ ($> 1 \text{ PeV}$)
- ▶ 86 strings, 5000+ OMs
- ▶ Sees high-energy astrophysical ν



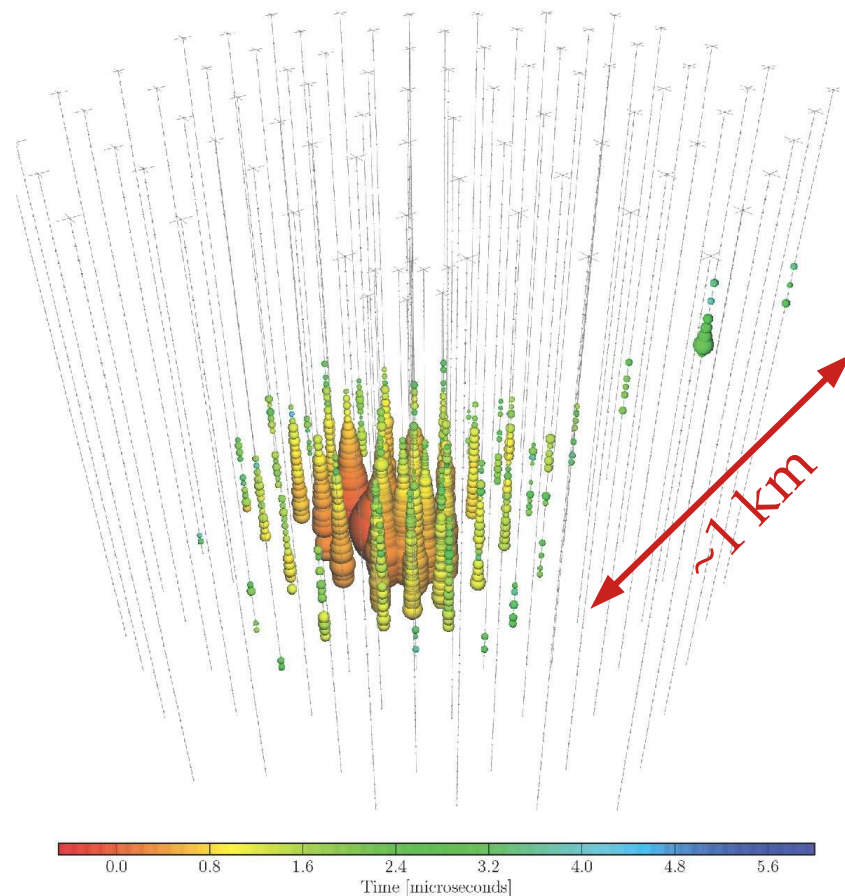
OM: optical module

Shower
(mainly from ν_e and ν_τ)

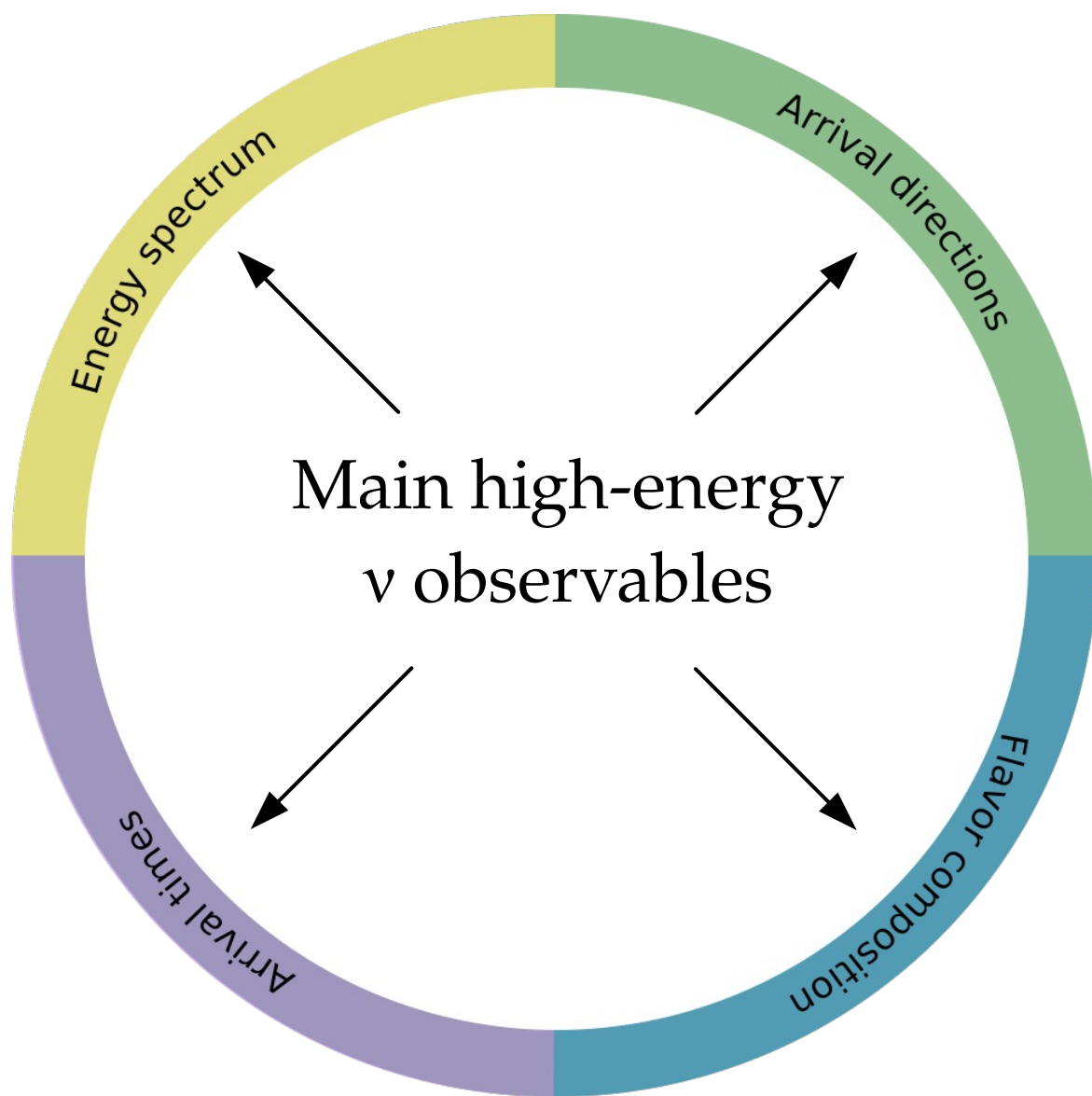


Poor angular resolution: $\sim 10^\circ$

Track
(mainly from ν_μ)



Angular resolution: $< 1^\circ$

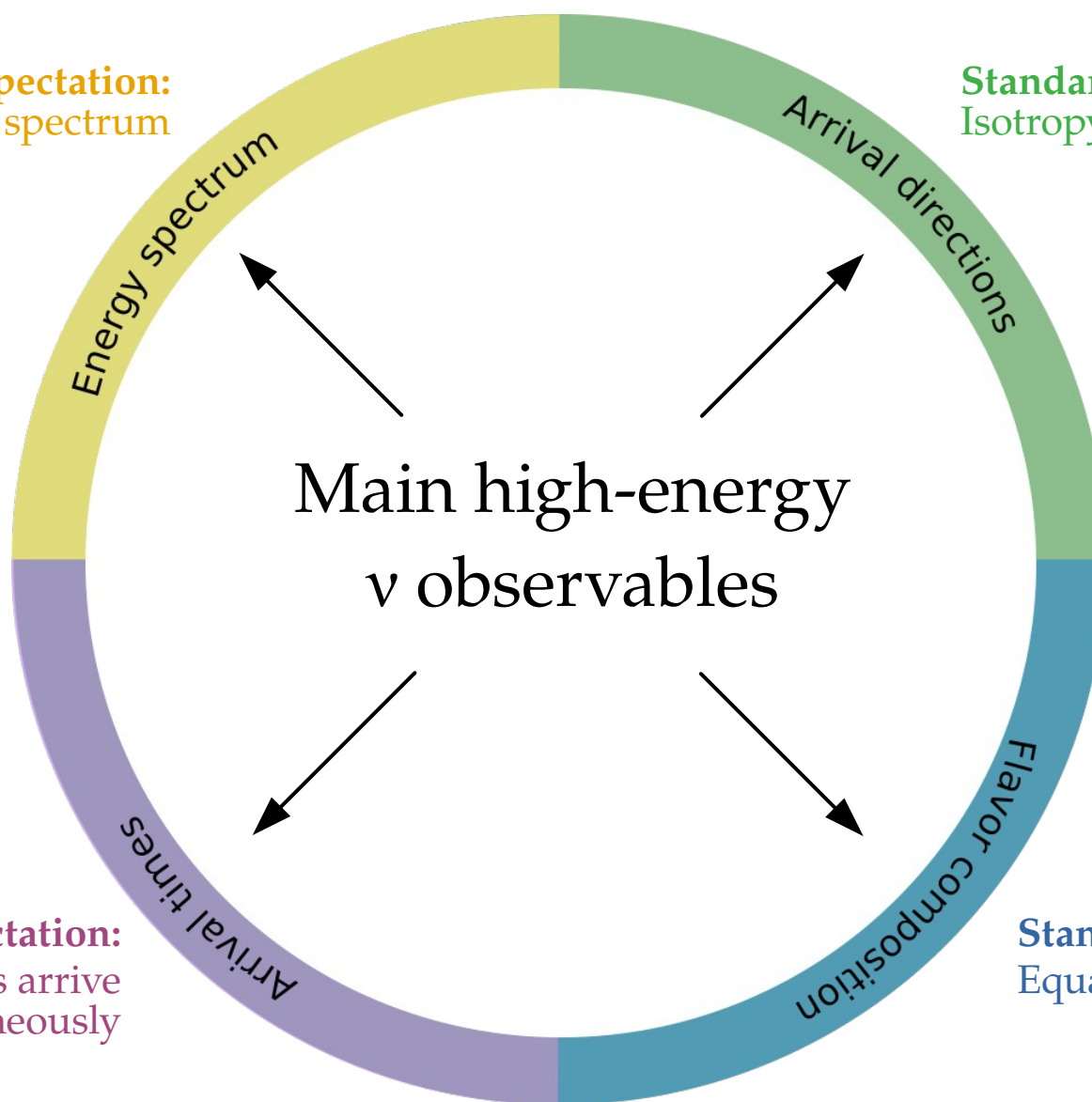


Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
 ν and γ from transients arrive
simultaneously

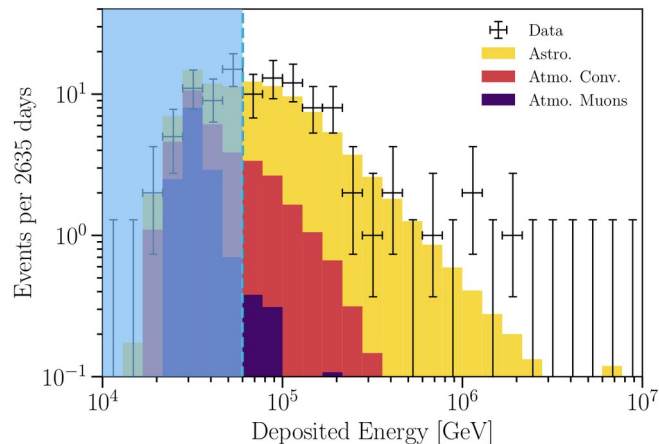
Standard expectation:
Equal number of ν_e , ν_μ , ν_τ



Neutrino energy spectrum (7.5 yr)

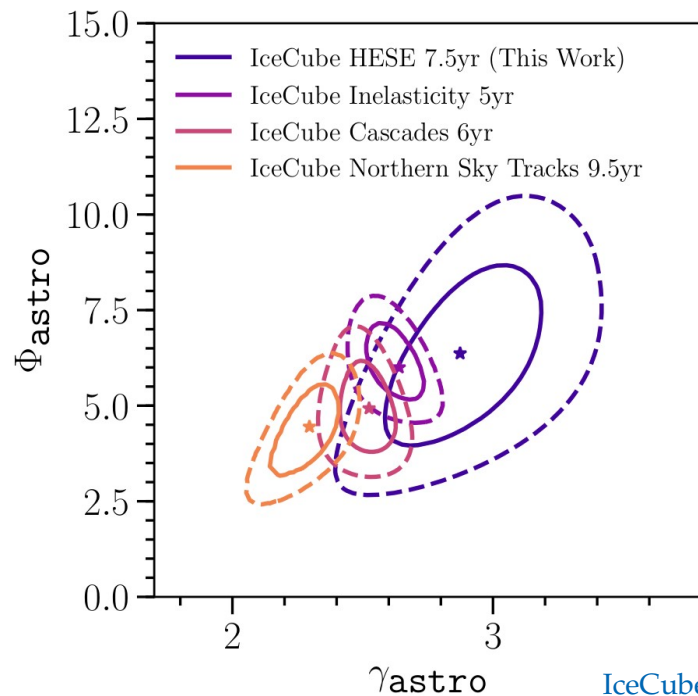
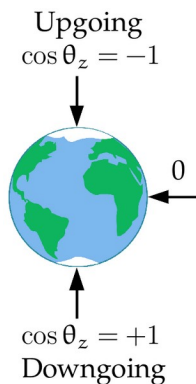
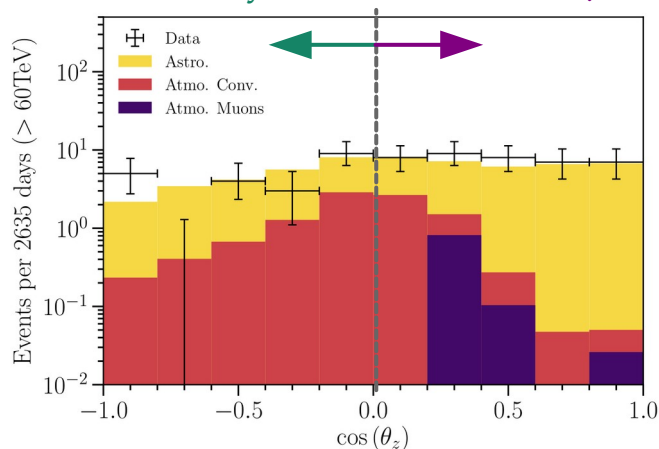
100+ contained events above 60 TeV:

Data is fit well by a single power law:



$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

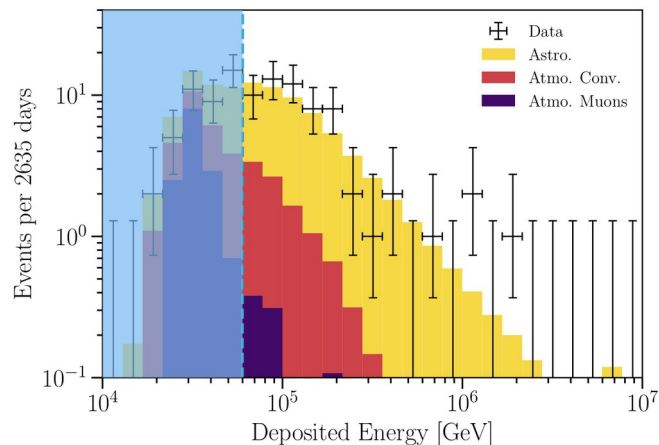
ν attenuated by Earth Atm. ν and μ vetoed



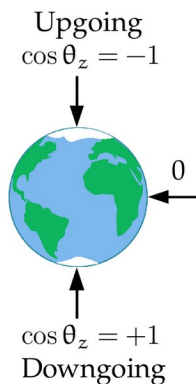
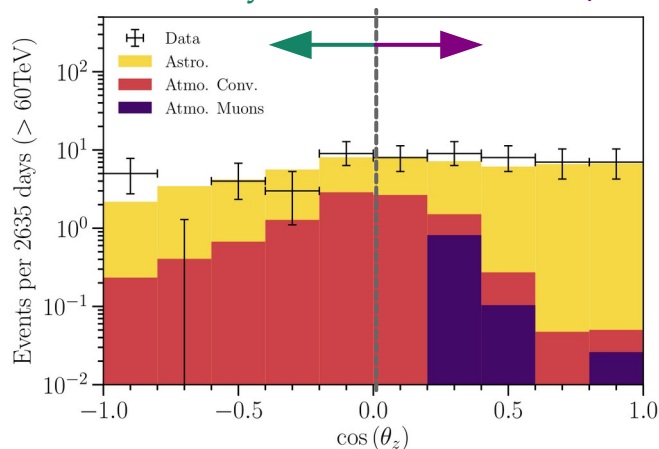
IceCube, 2011.03545

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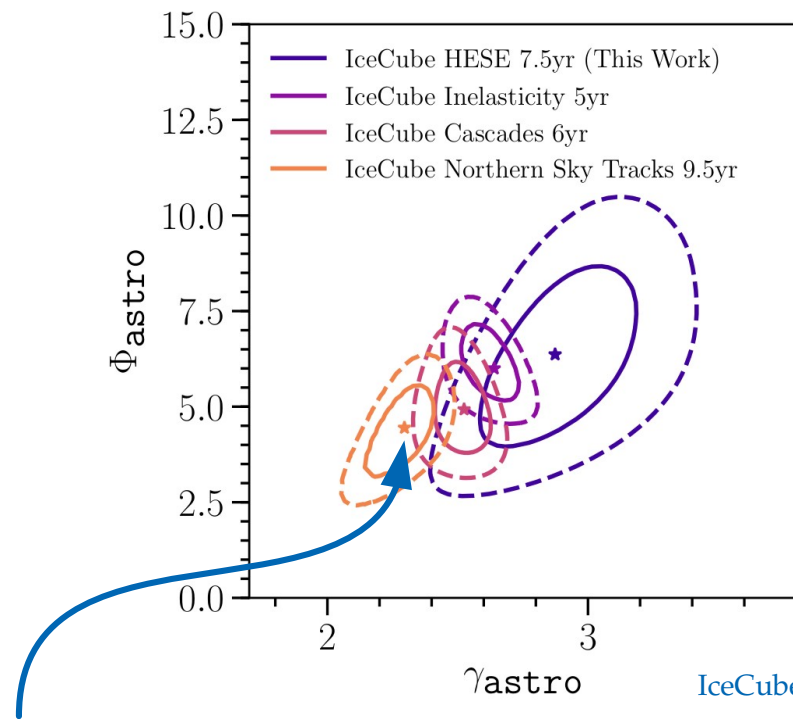


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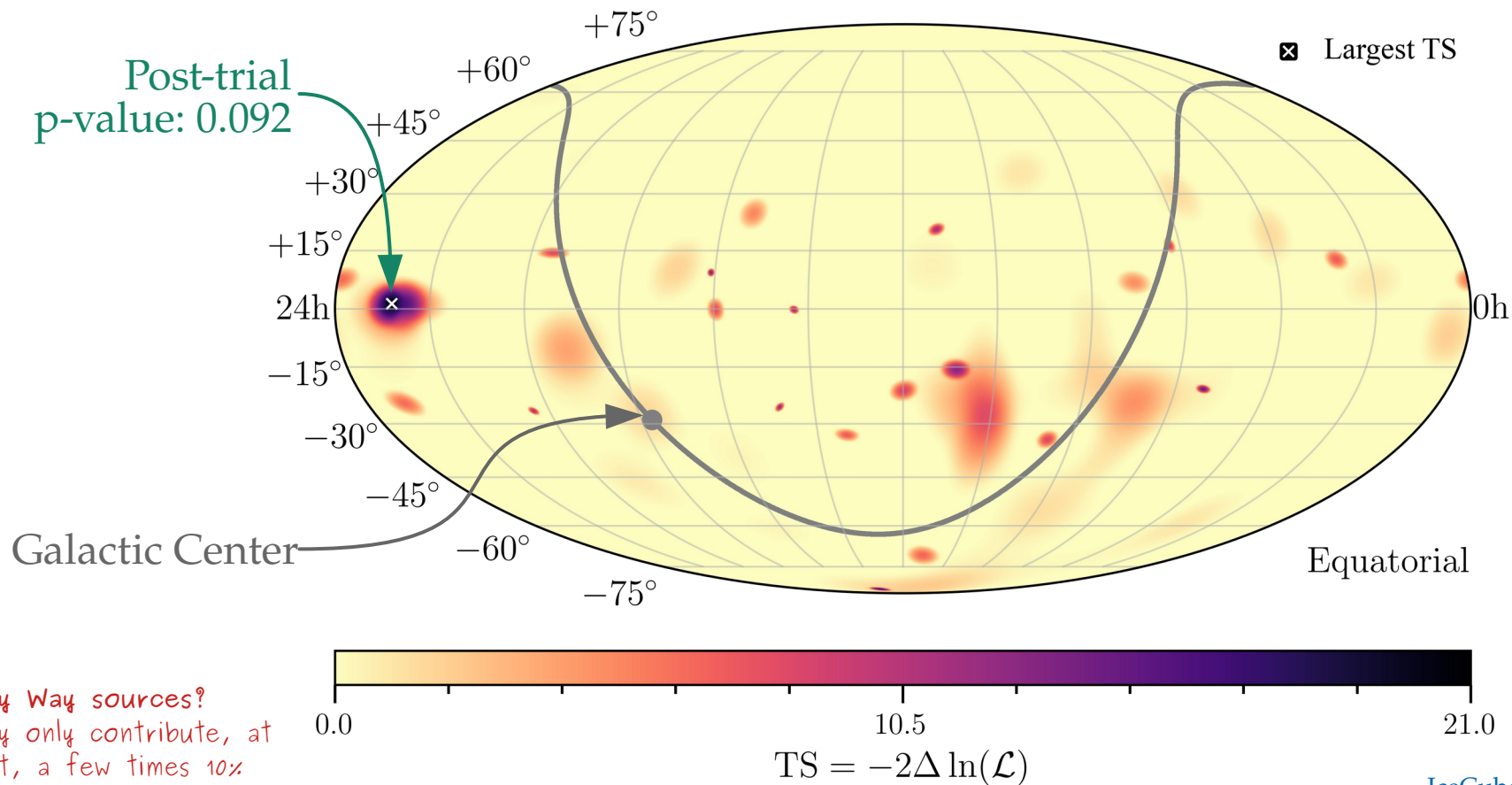


IceCube, 2011.03545

Spectrum looks harder for through-going ν_μ

Distribution of arrival directions (7.5 yr)

No significant excess in the neutrino skymap:



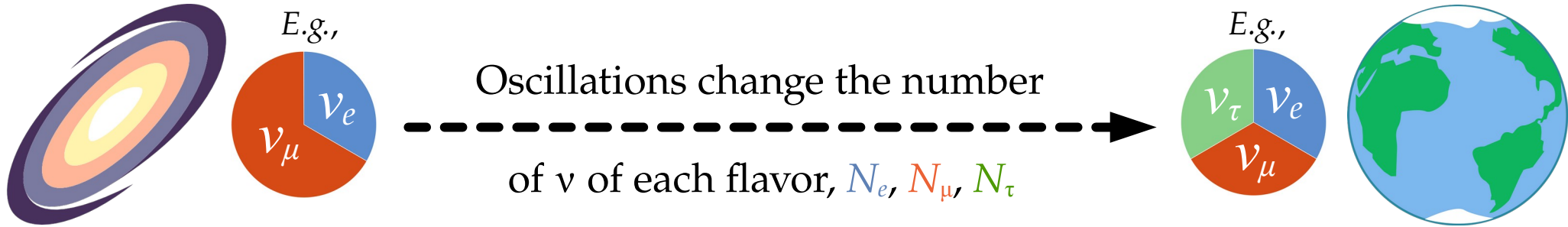
Milky Way sources?
They only contribute, at
most, a few times 10%
of the total diffuse flux

IceCube, 2011.03545

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S}) / N_{\text{tot}}$$

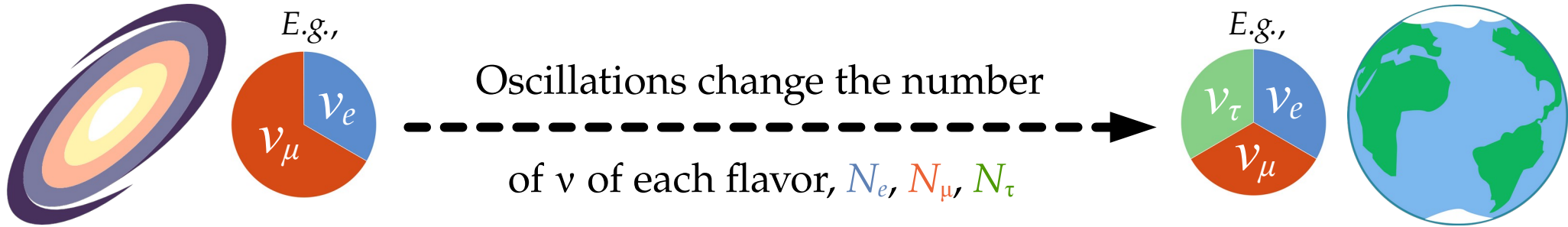
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

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Up to a few Gpc



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Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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Standard oscillations
or
new physics

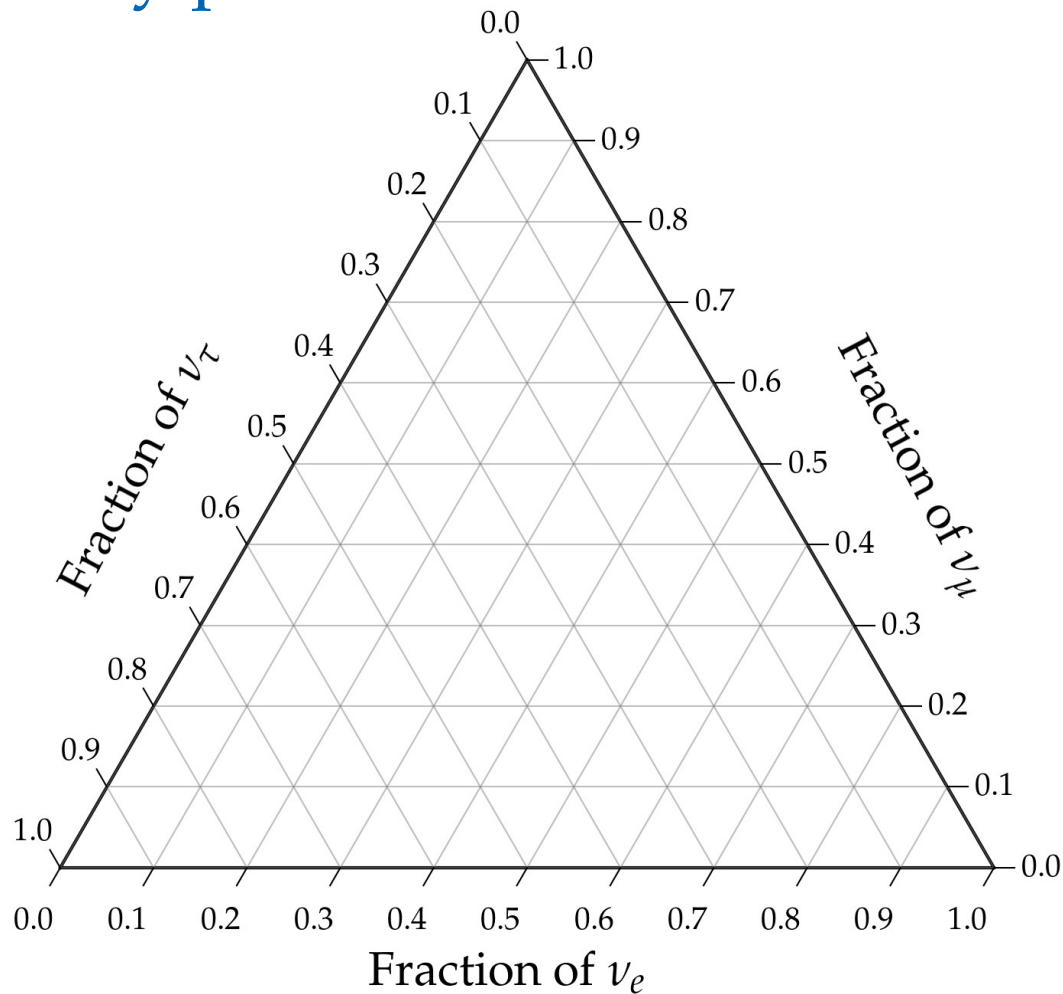
Quick aside: how to read a ternary plot

Assumes underlying unitarity –
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



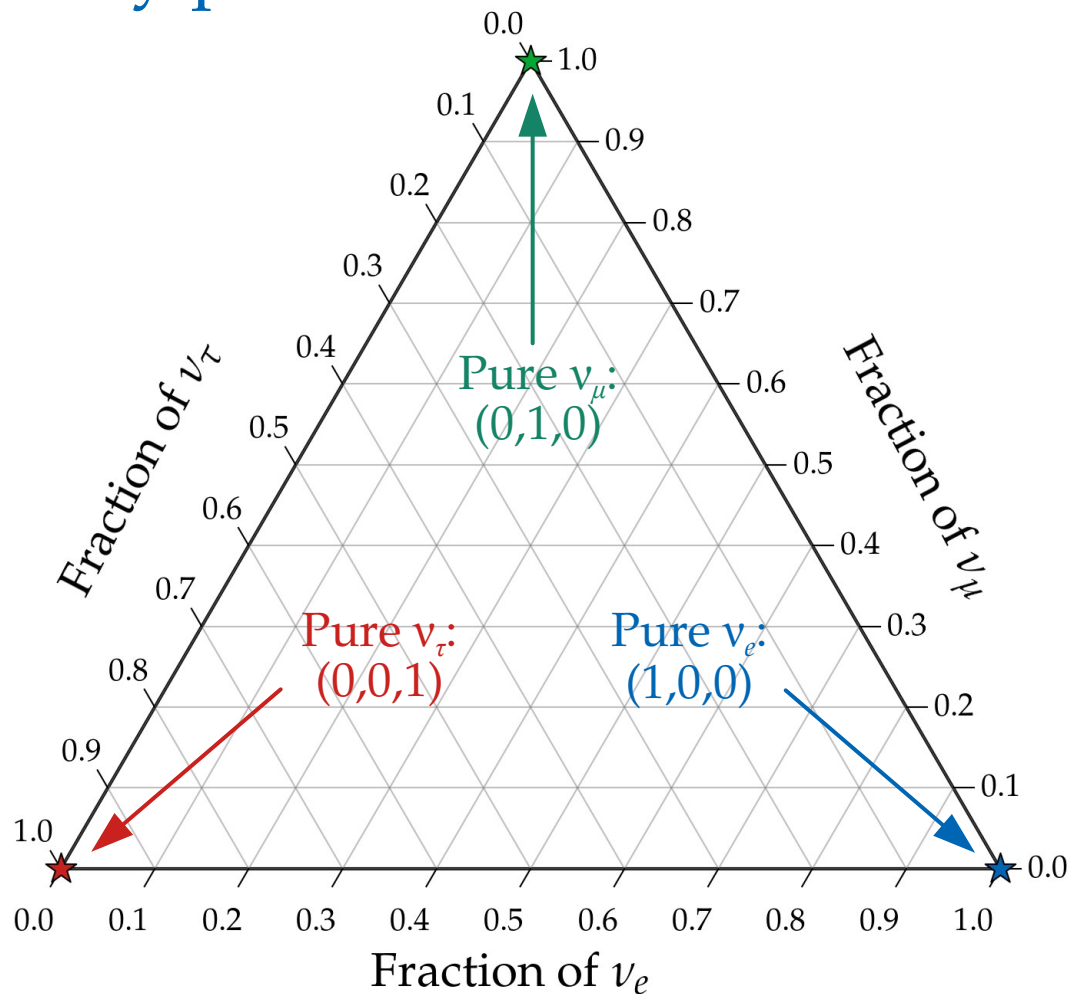
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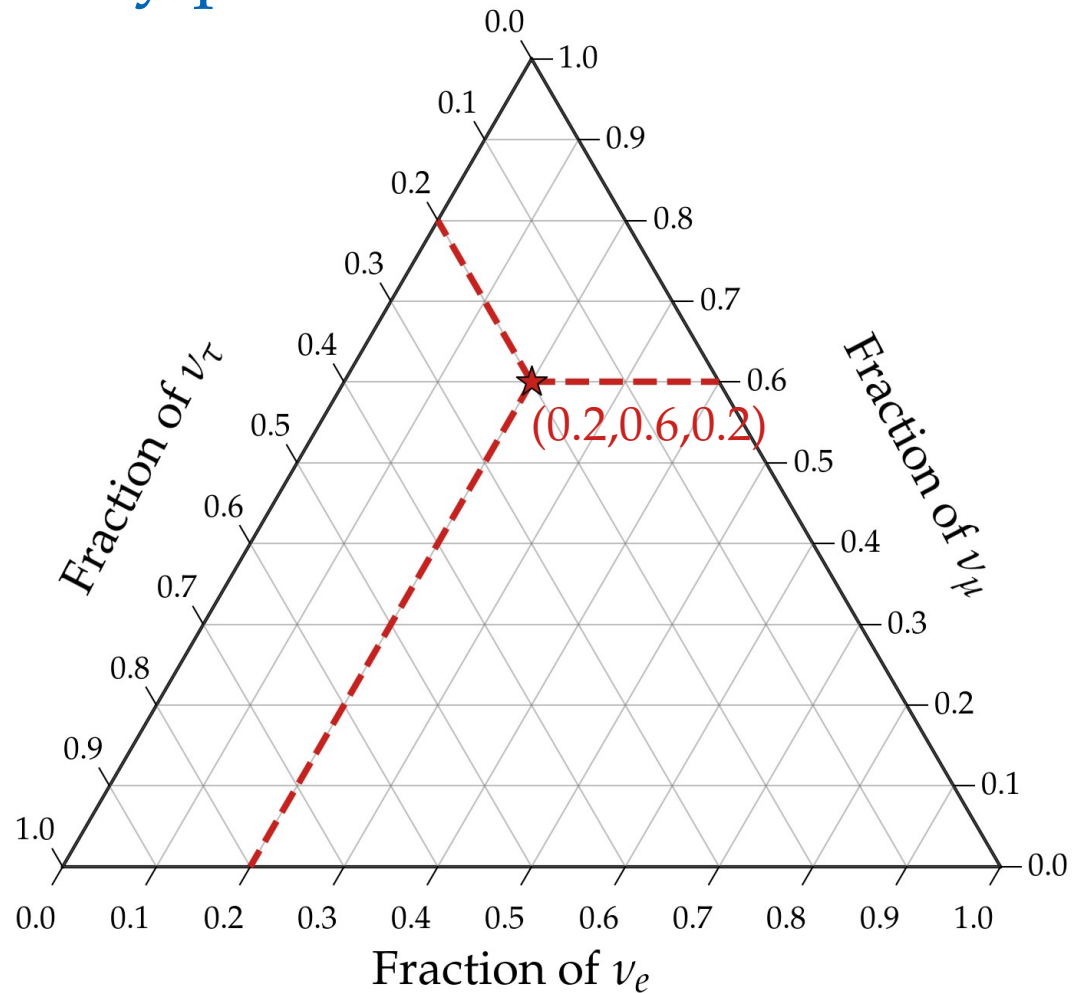
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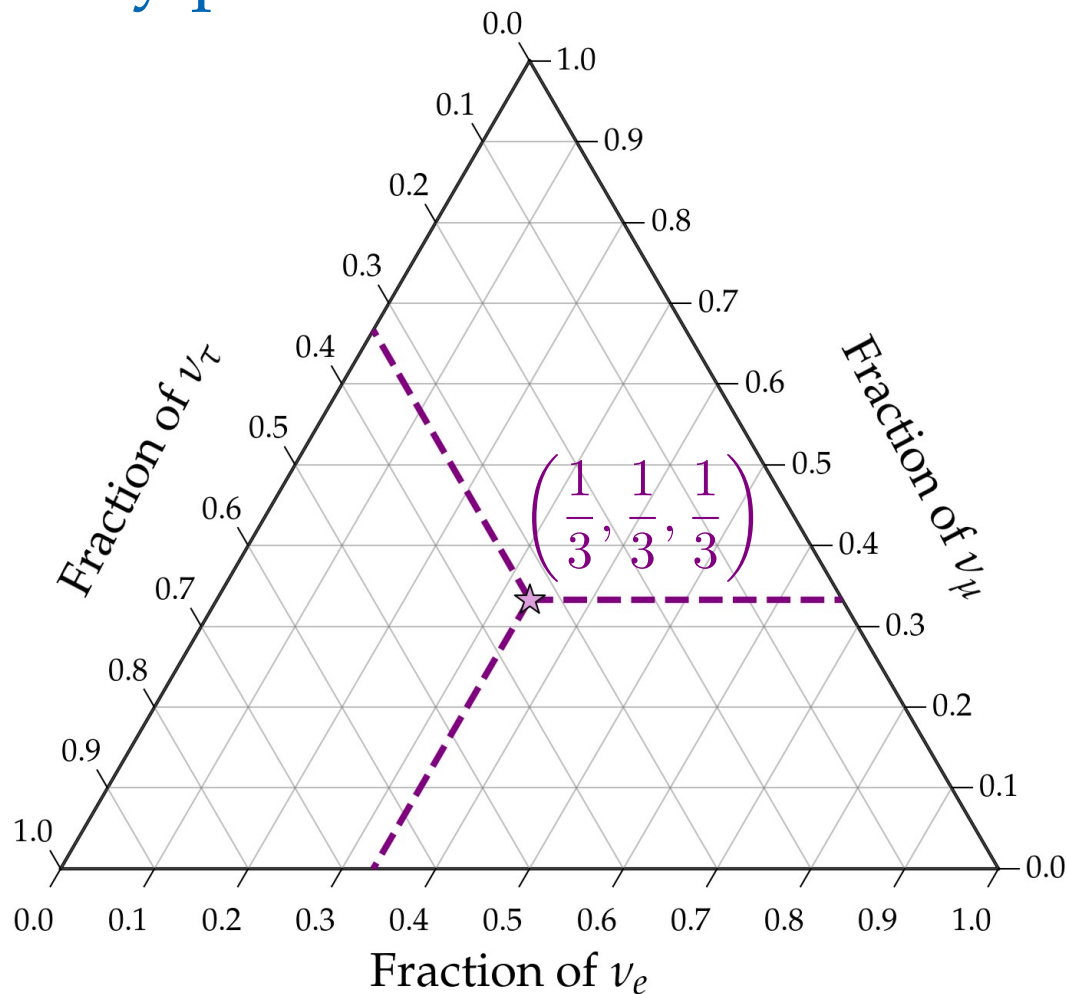
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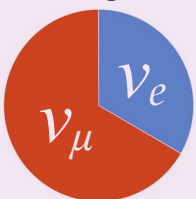


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$

Sources



E.g.,



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

Oscillations

$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

Earth



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

One likely TeV–PeV ν production scenario:

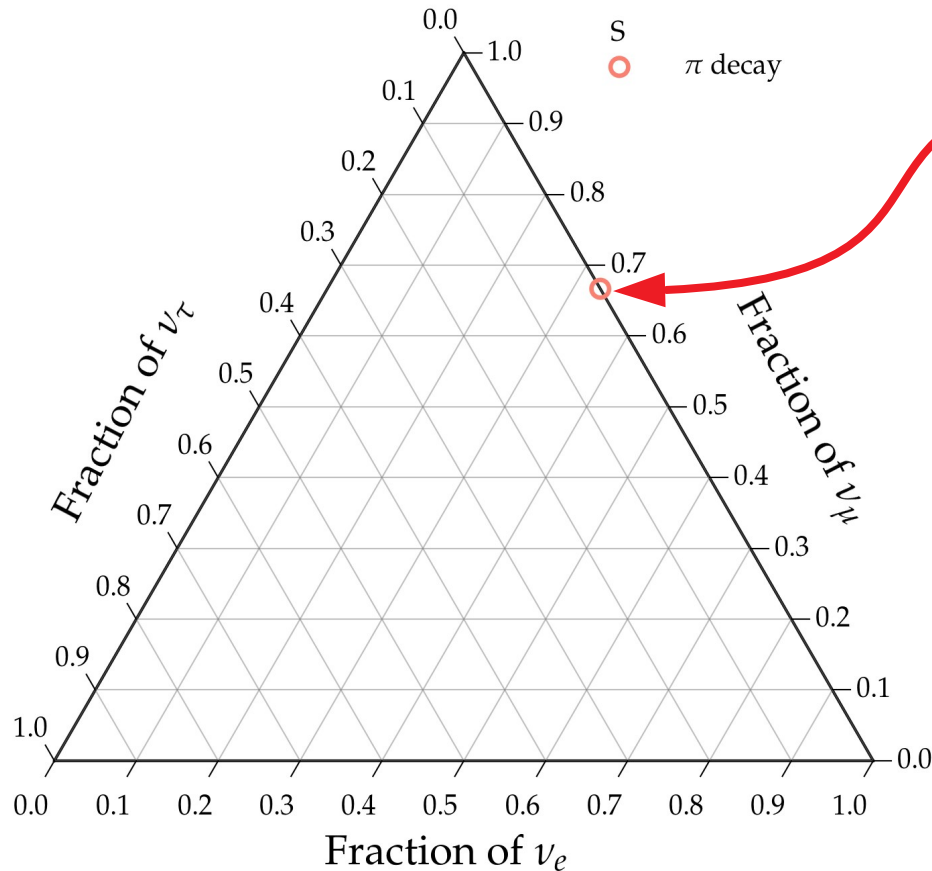
$$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \text{ followed by } \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Full π decay chain

$$(1/3:2/3:0)_S$$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable
in neutrino telescopes

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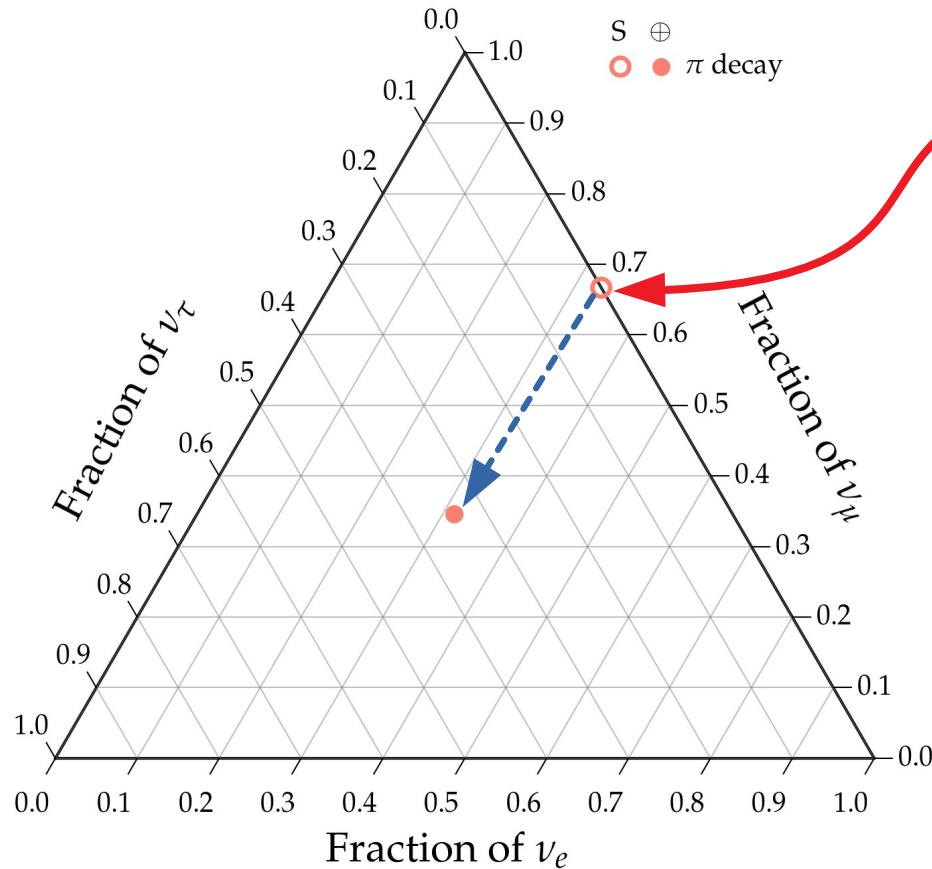


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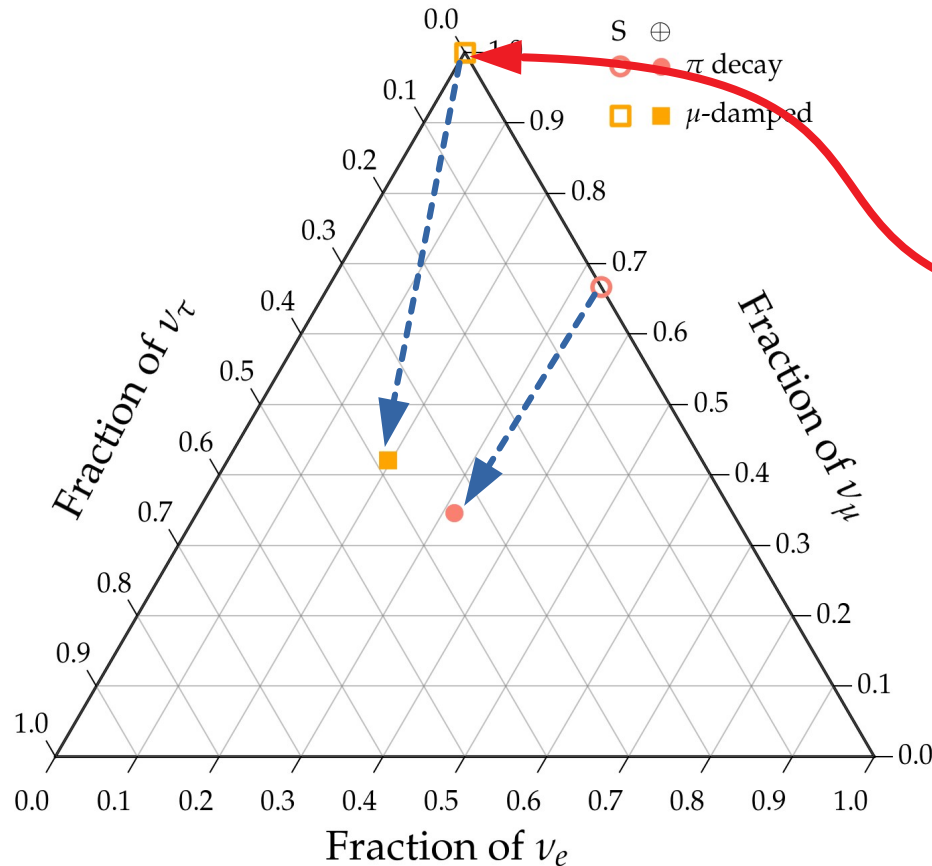


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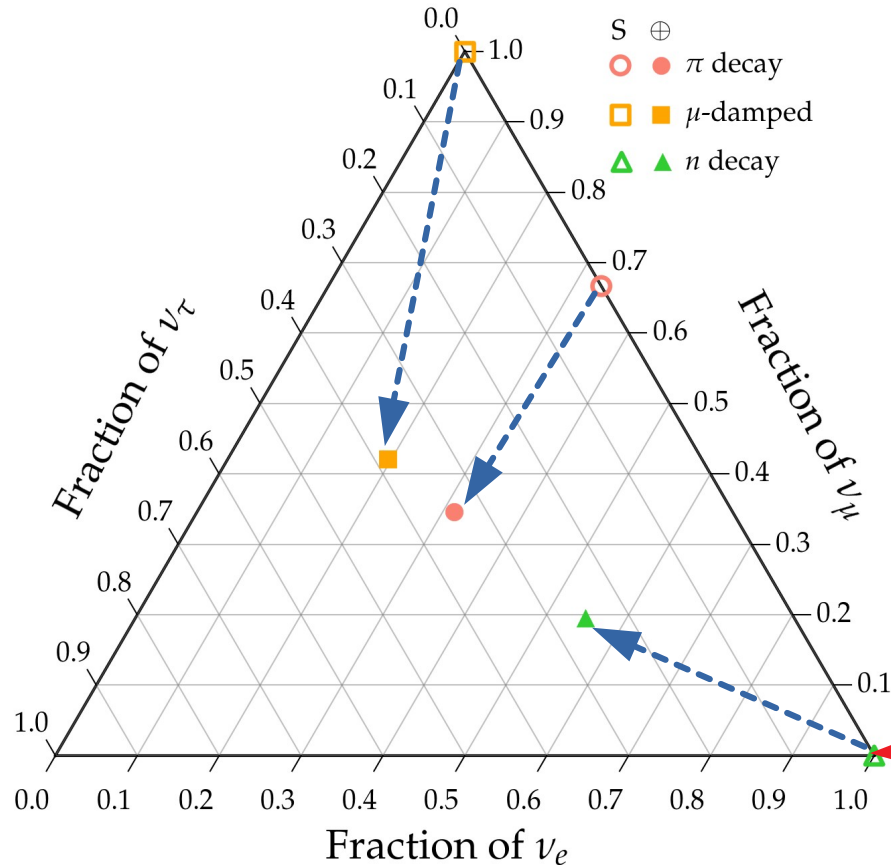
Muon damped

$(0:1:0)_S$

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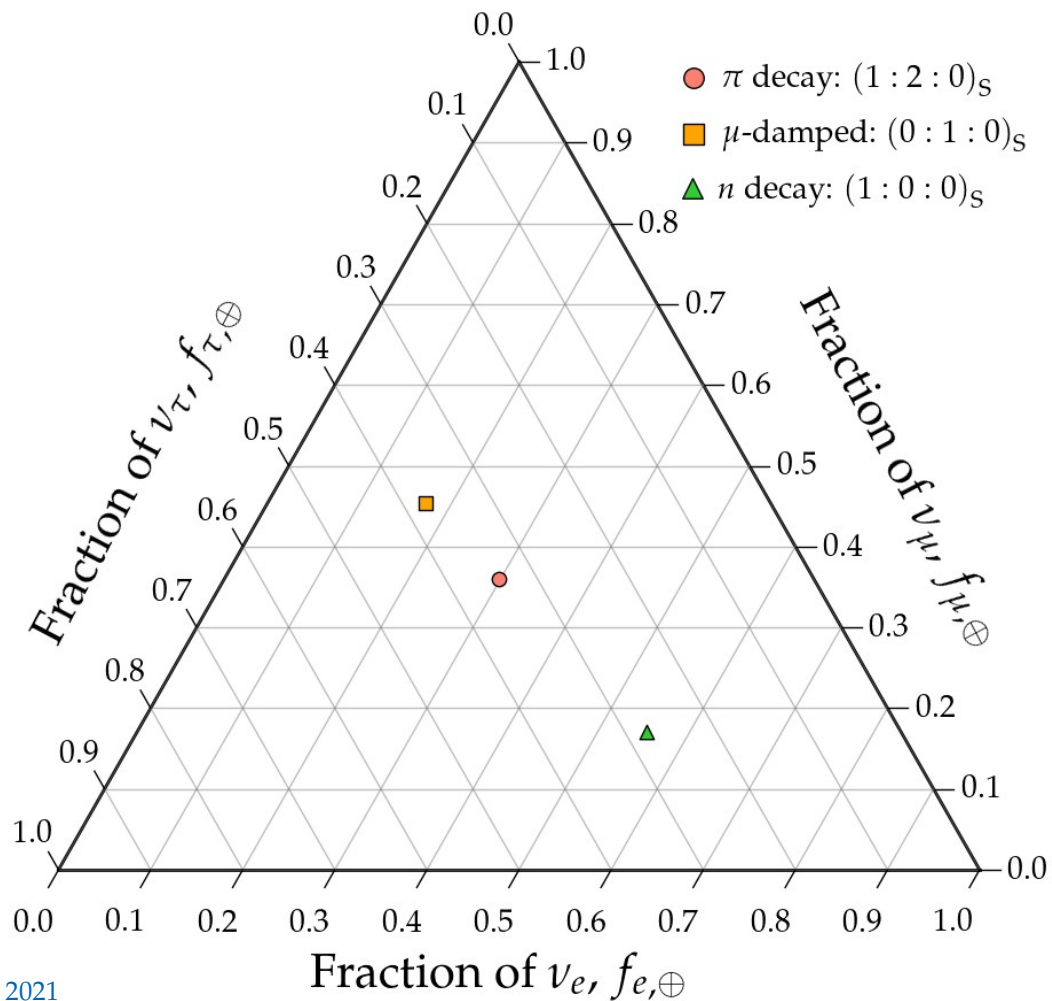
Neutron decay

$$(1:0:0)_S$$

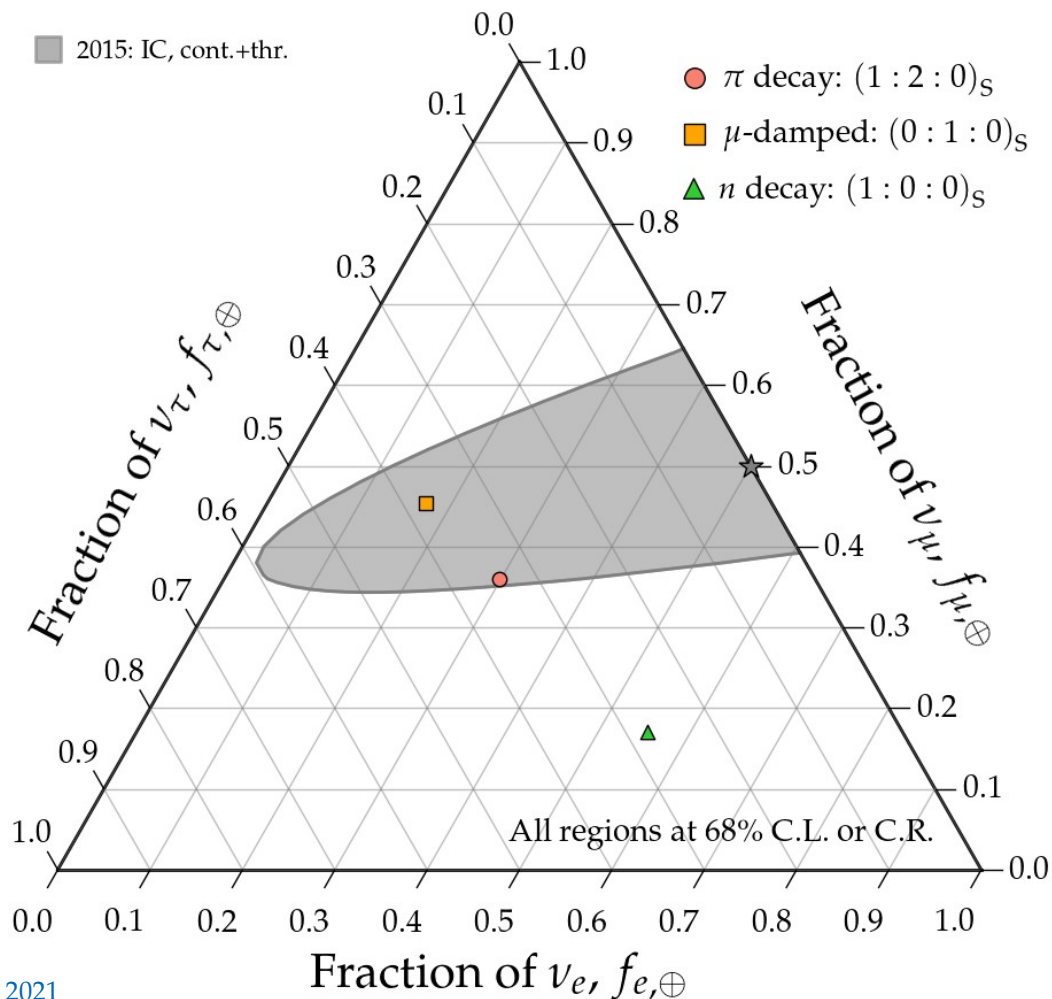
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Measuring flavor composition: 2015–2040

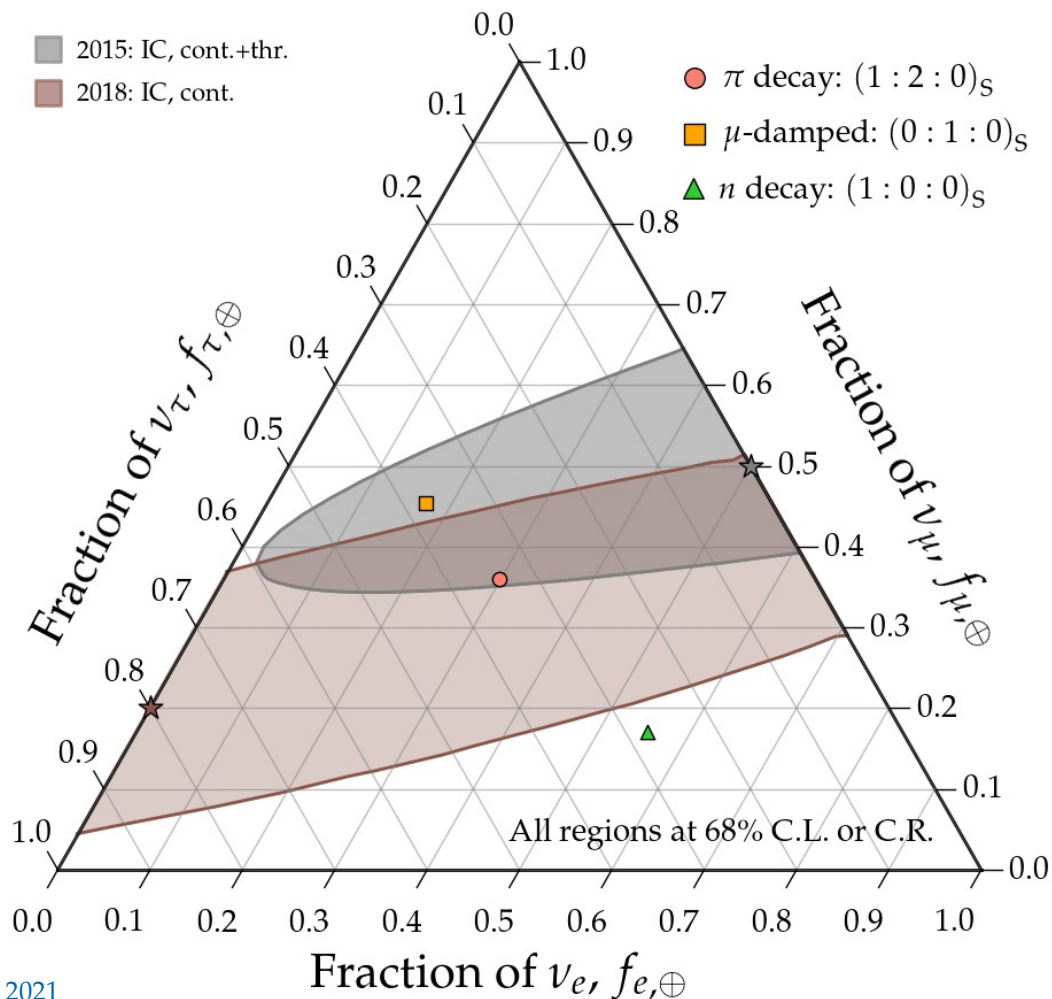
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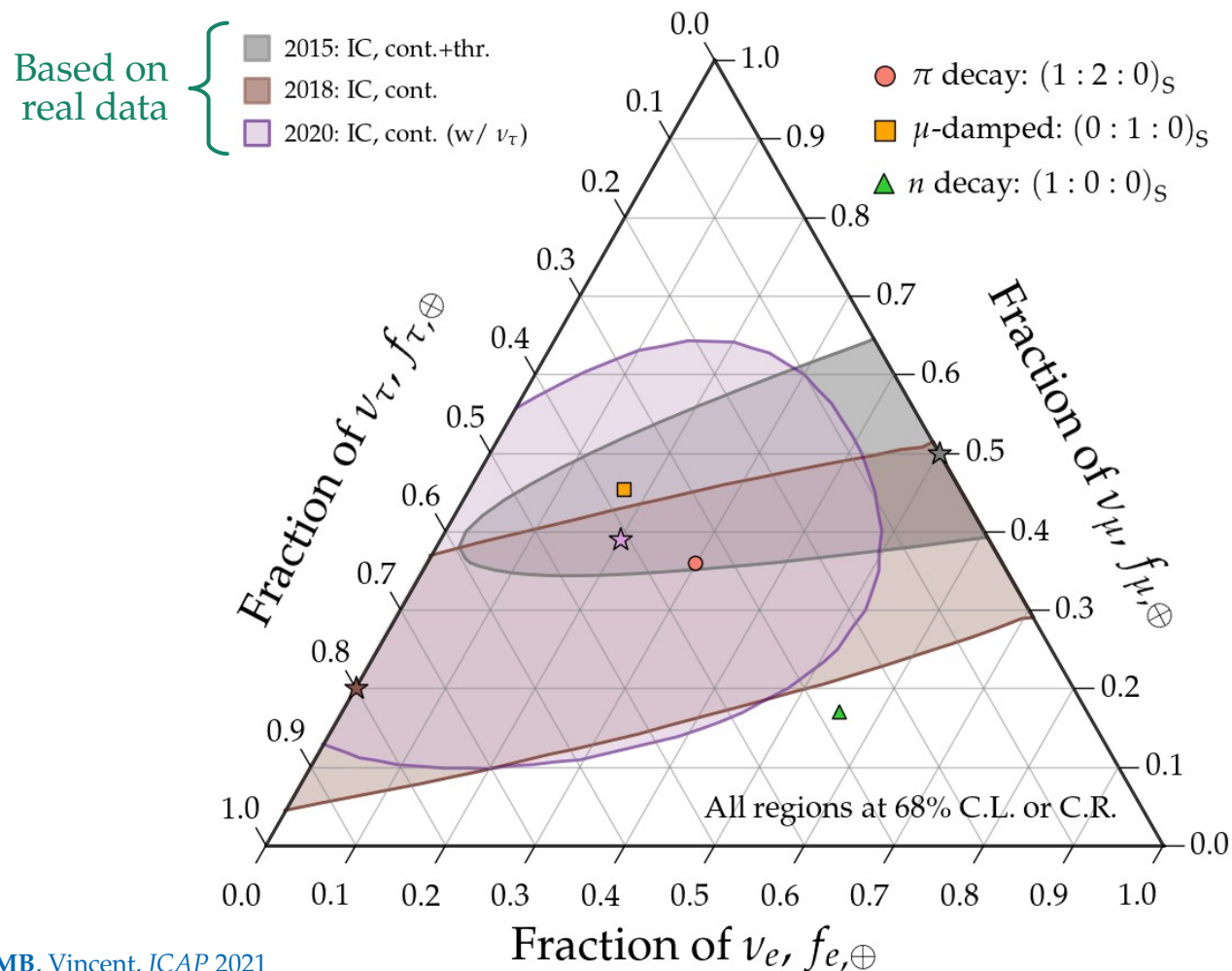
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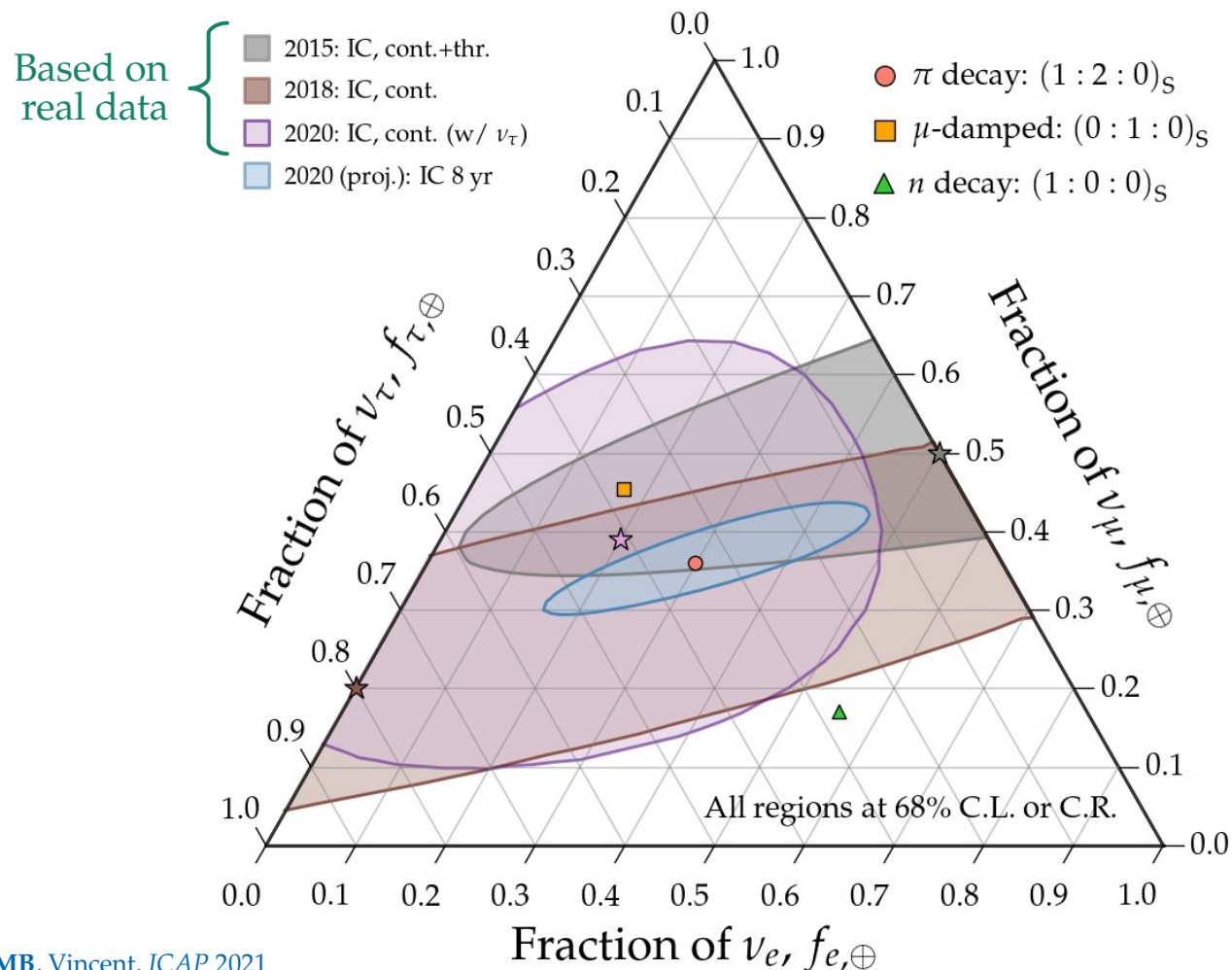


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Measurements are compatible with standard expectations (but errors are large!)

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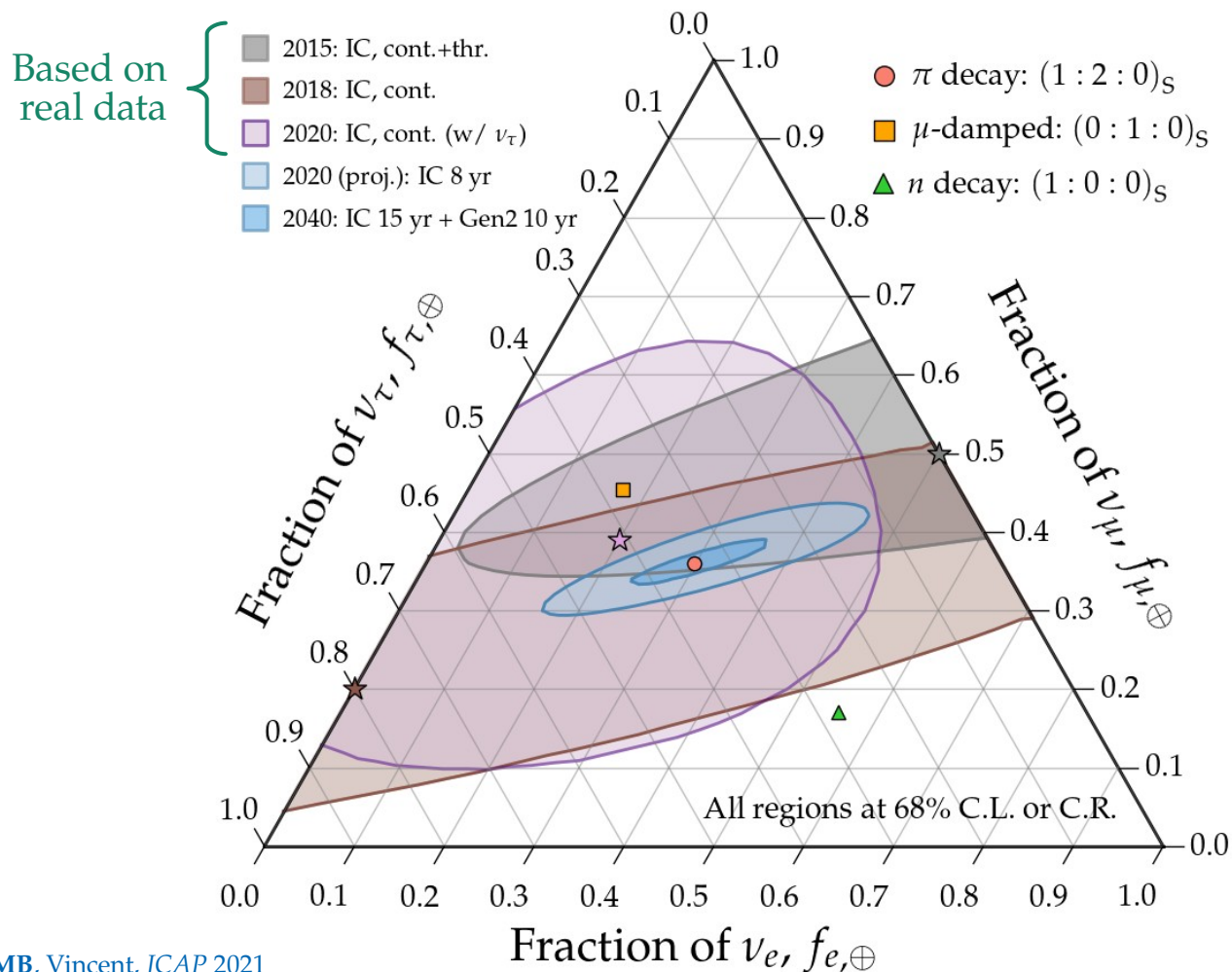
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Projections:

Near future (~2020):

× 5 reduction using 8 yr of IC contained + thru.

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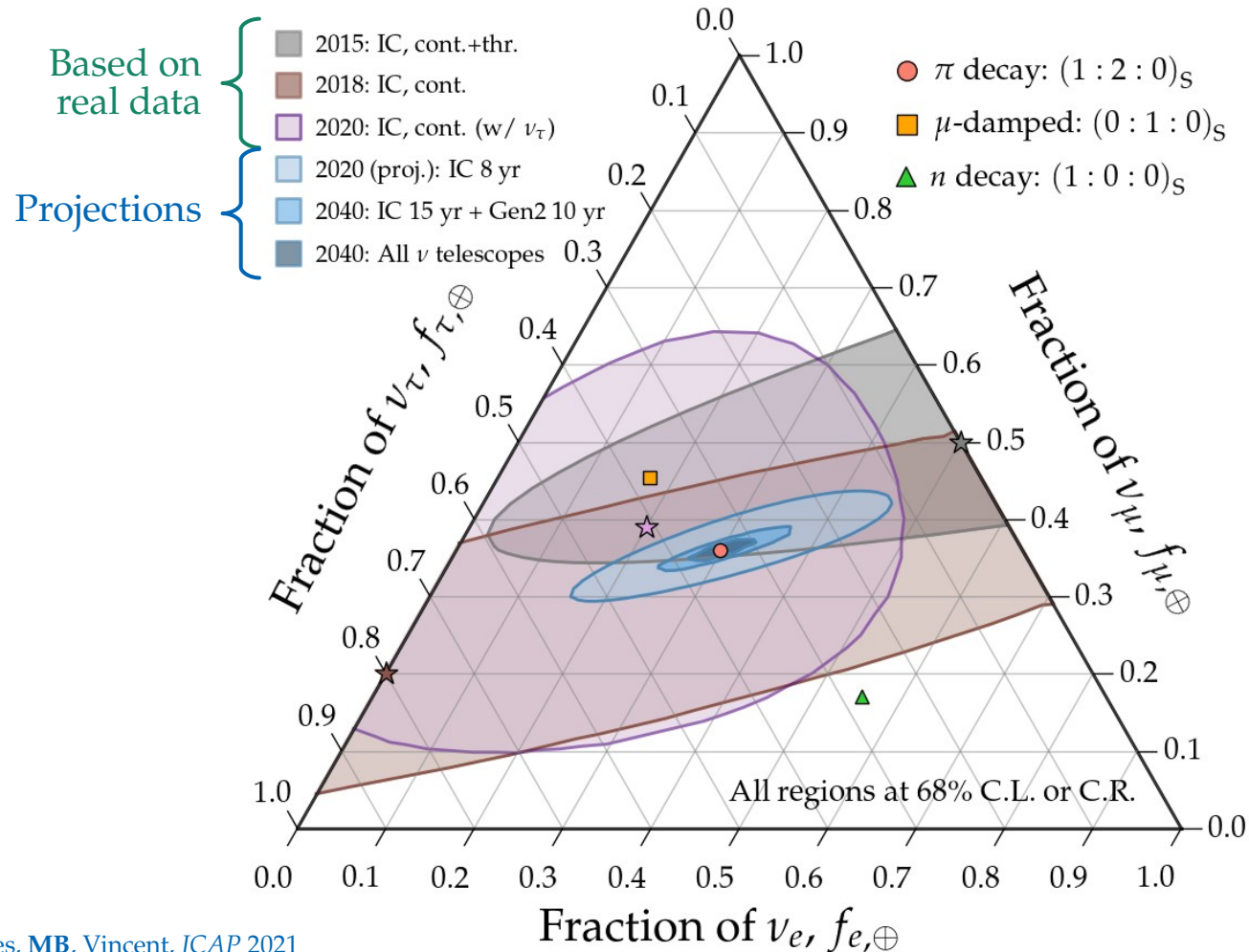
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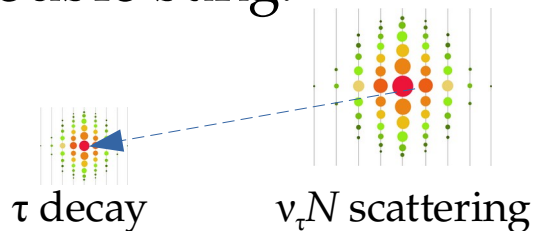
× 5 reduction using 8 yr of IC contained + thru.

Coming up (~2040):

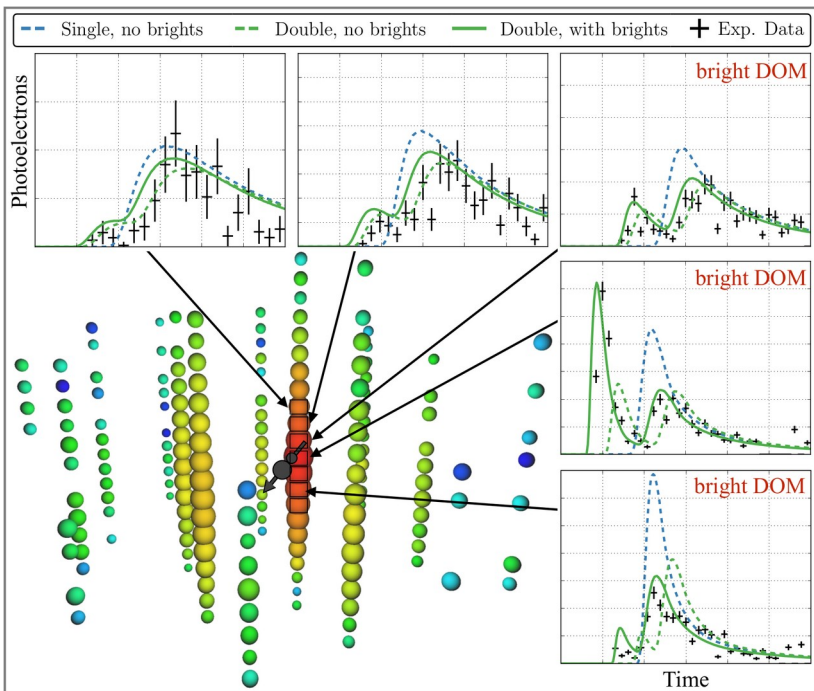
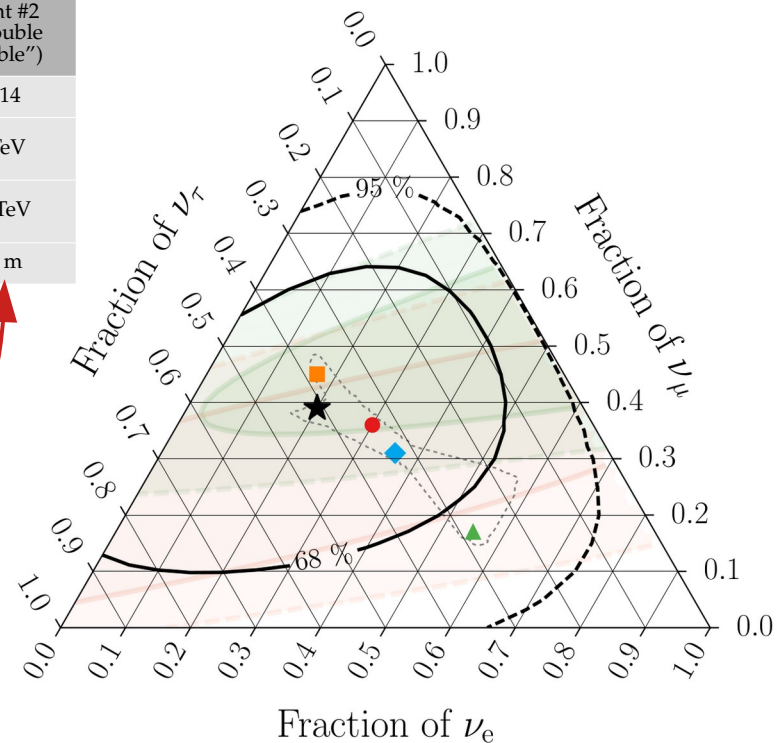
× 10 reduction using Gen2 and all ν telescopes

First identified high-energy astrophysical ν_τ

Double bang:



	Event #1 ("Big Bird")	Event #2 ("Double Double")
Year	2012	2014
Energy 1st cascade	1.2 PeV	9 TeV
Energy 2nd cascade	0.6 PeV	80 TeV
Length	16 m	17 m

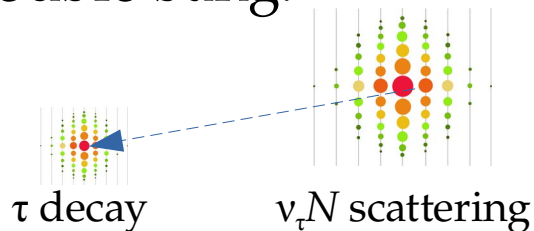


- HESE with ternary topology ID
- ★ Best fit: 0.20 : 0.39 : 0.42
- Global Fit (IceCube, APJ 2015)
- Inelasticity (IceCube, PRD 2019)
- 3ν -mixing 3σ allowed region

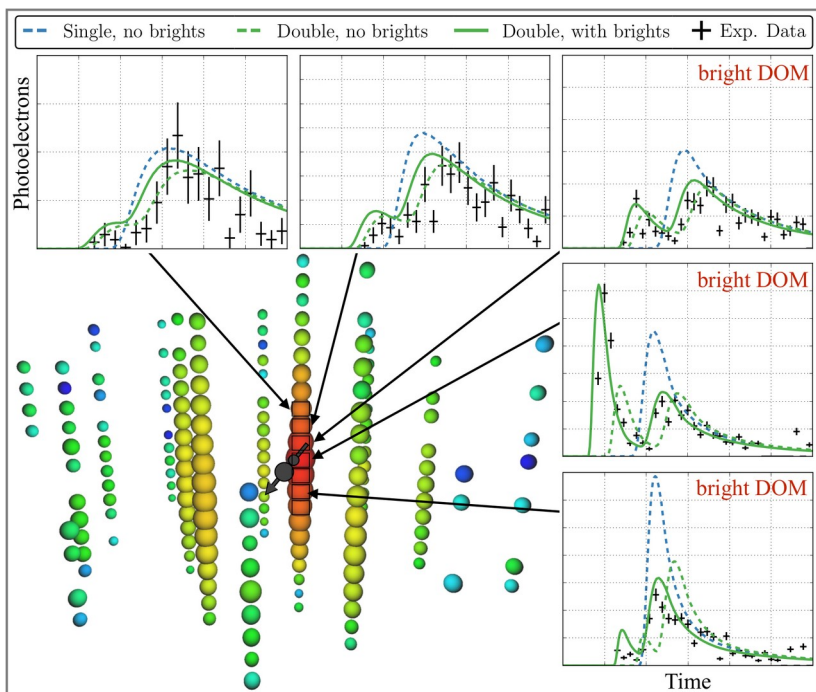
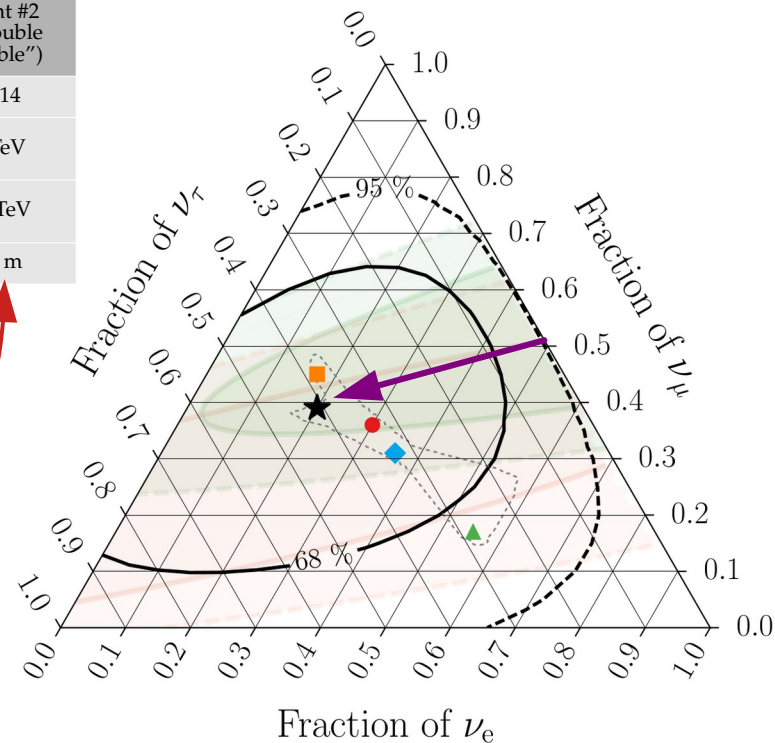
- $\nu_e : \nu_\mu : \nu_\tau$ at source $\rightarrow$ on Earth:
- 0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
 - 1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
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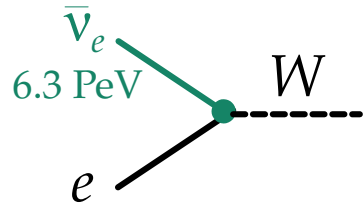
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First observation of a Glashow resonance

Predicted in 1960:

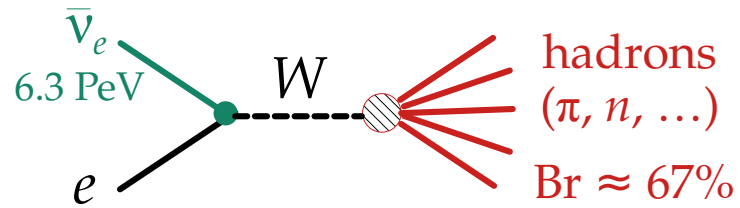
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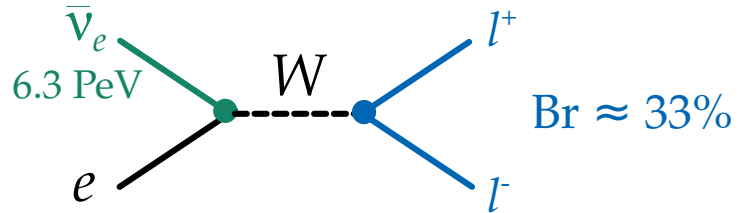
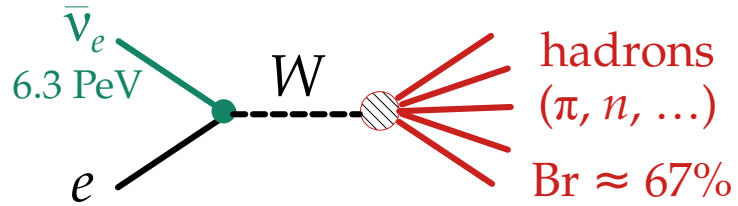
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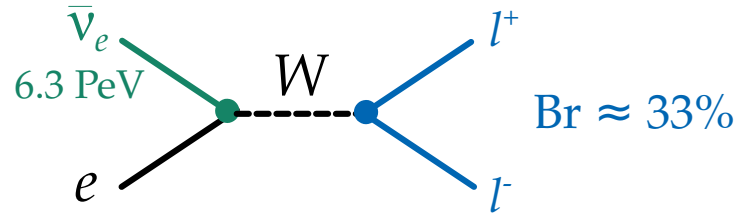
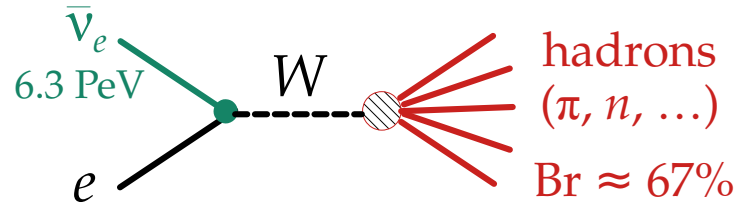
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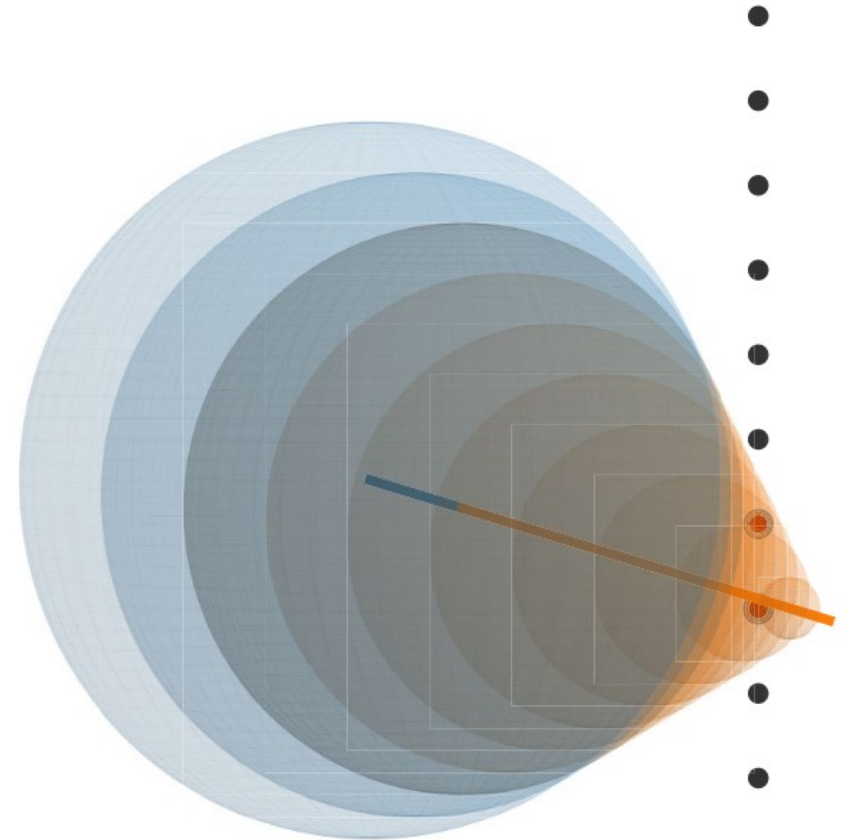


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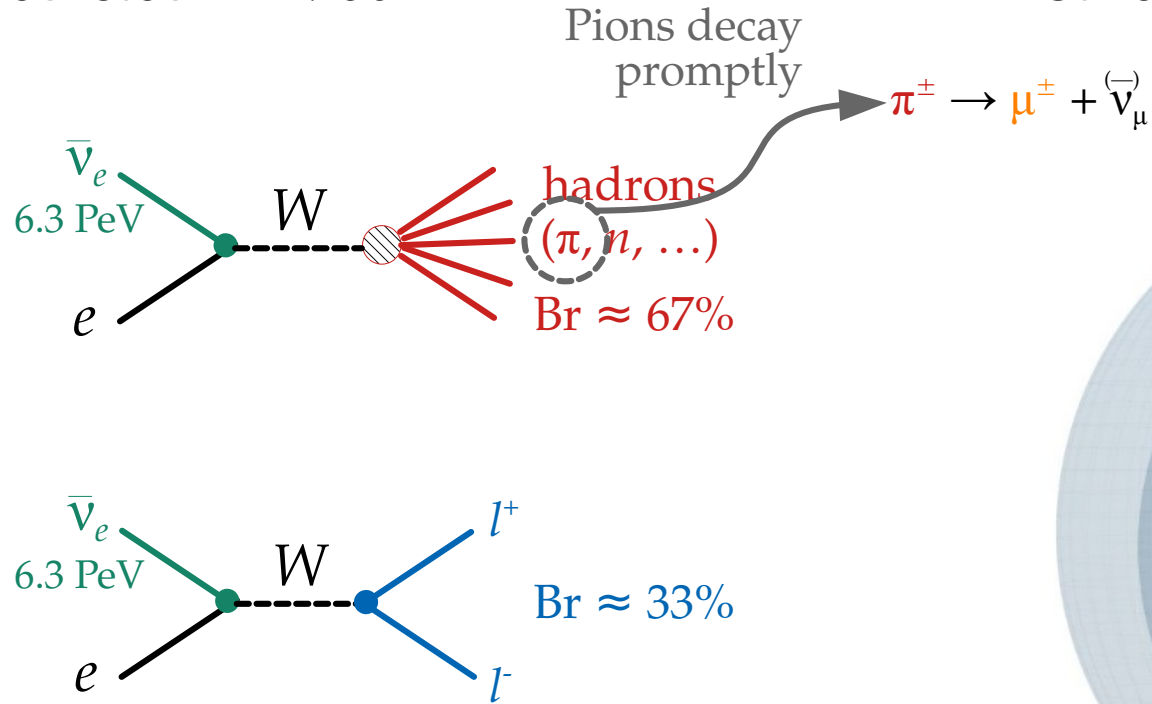


First reported by IceCube in 2021:

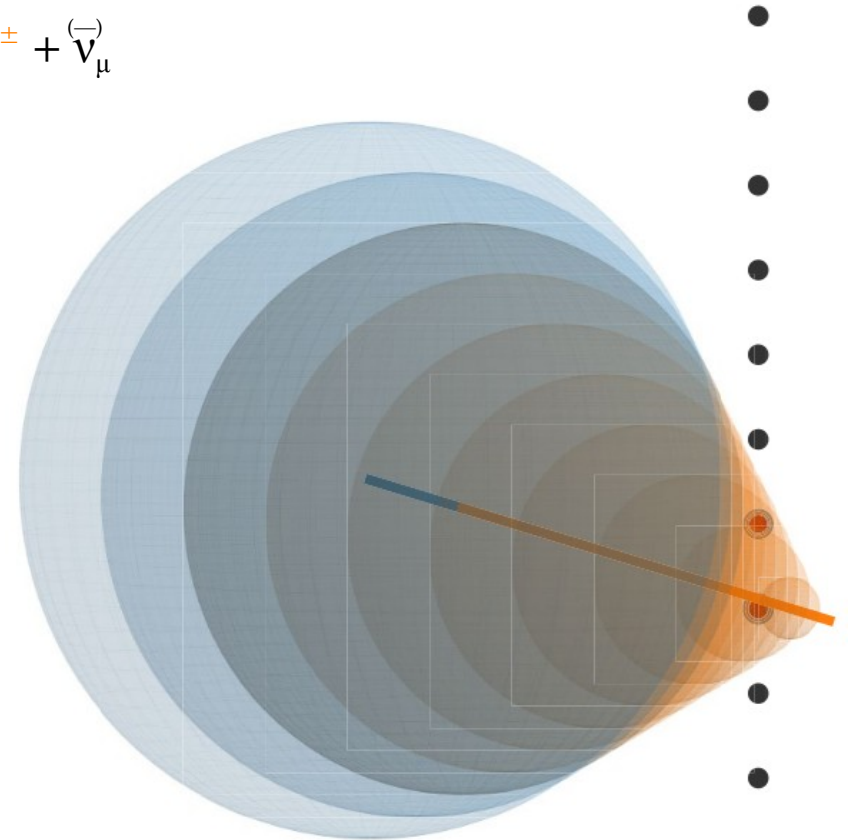


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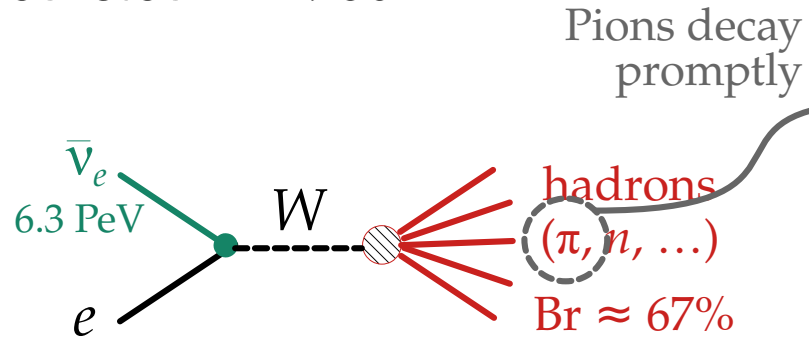


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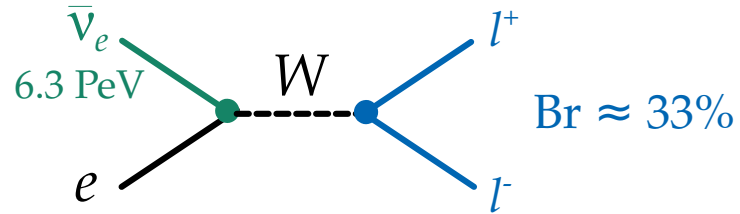


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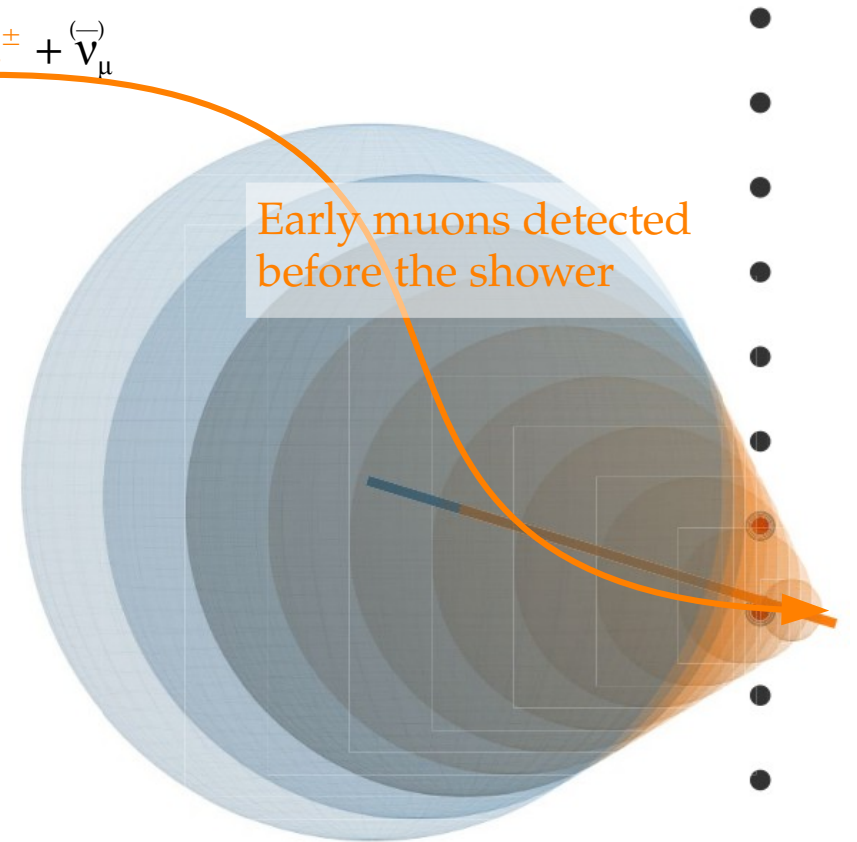


$\text{Br} \approx 67\%$



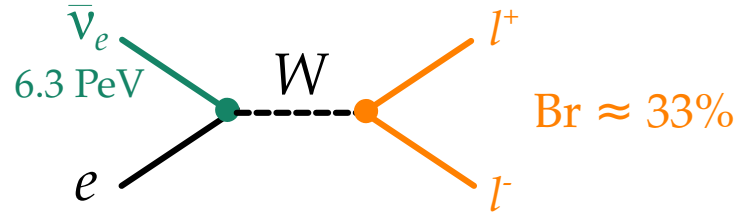
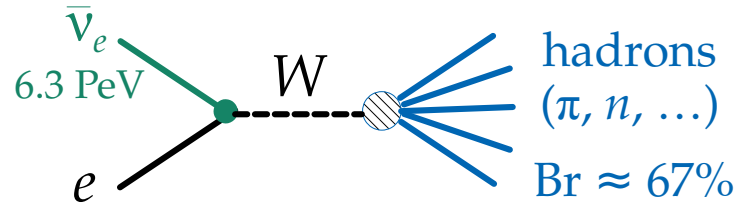
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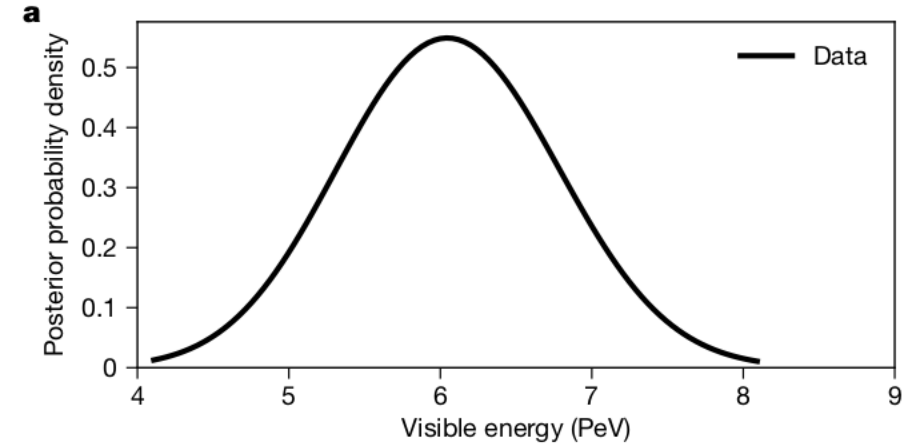


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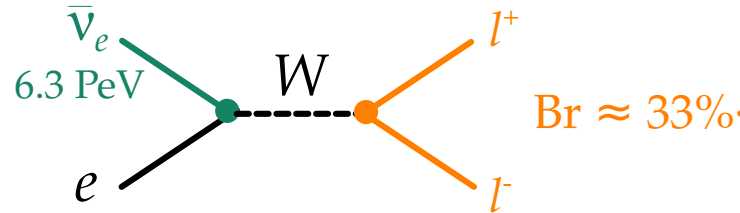
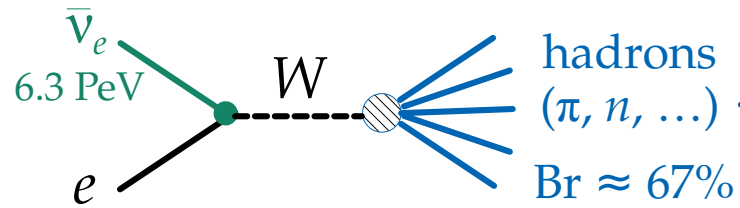


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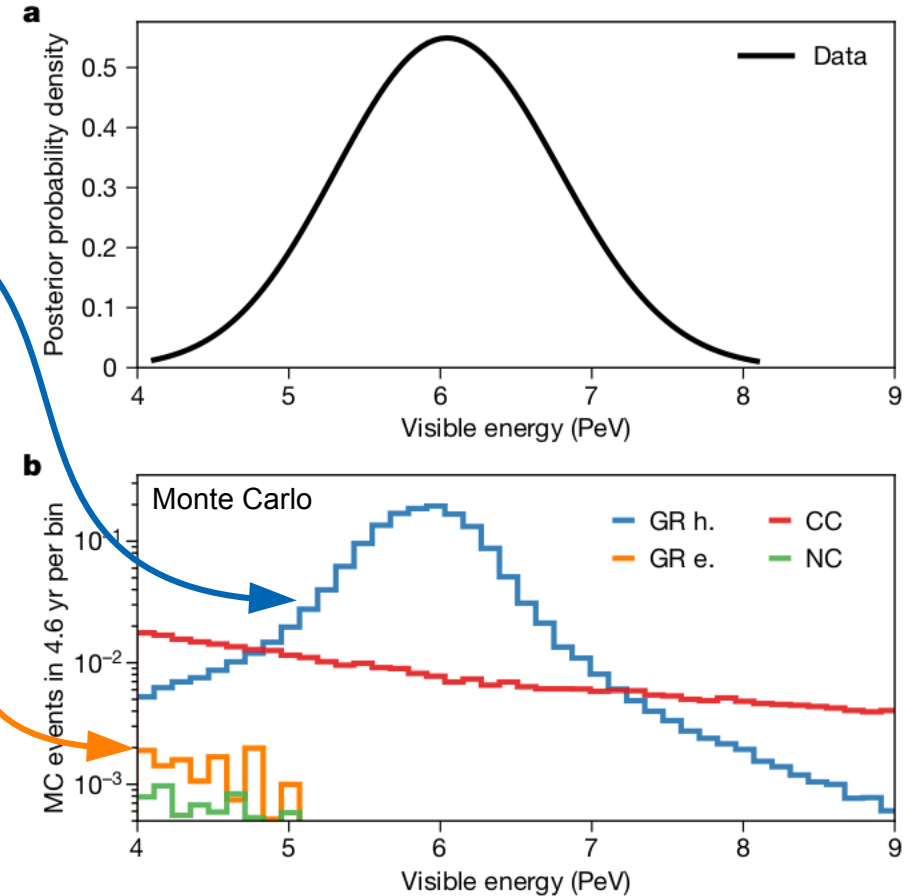


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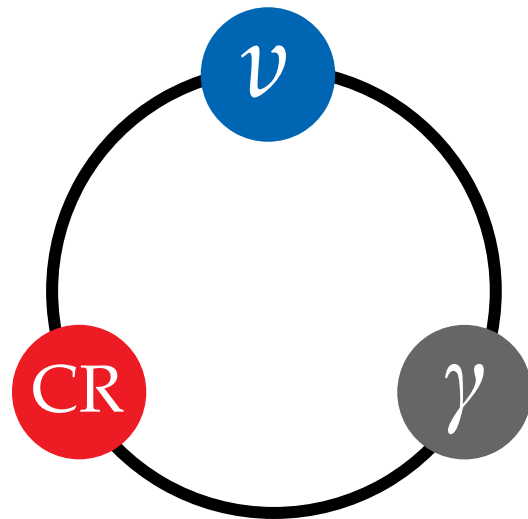
II.

What have we learned
about *astrophysics*

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

Energy in neutrinos $\propto$ energy in gamma rays

Waxman & Bahcall, *PRL* 1997



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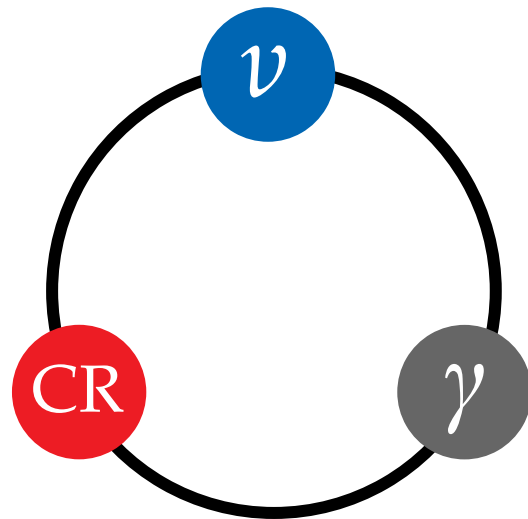
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Source properties (*e.g.*, baryonic loading)

Particle effects (*e.g.*, ν -producing channels)



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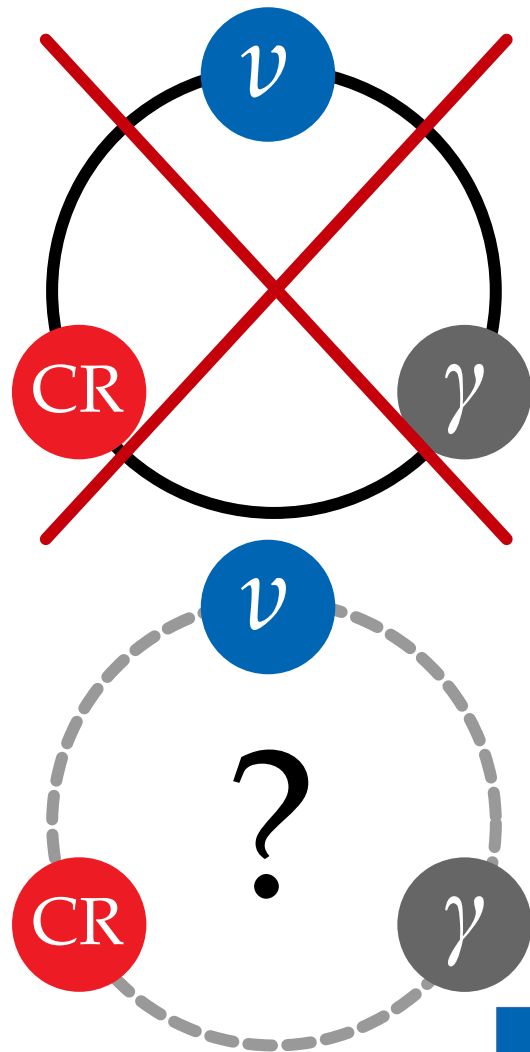
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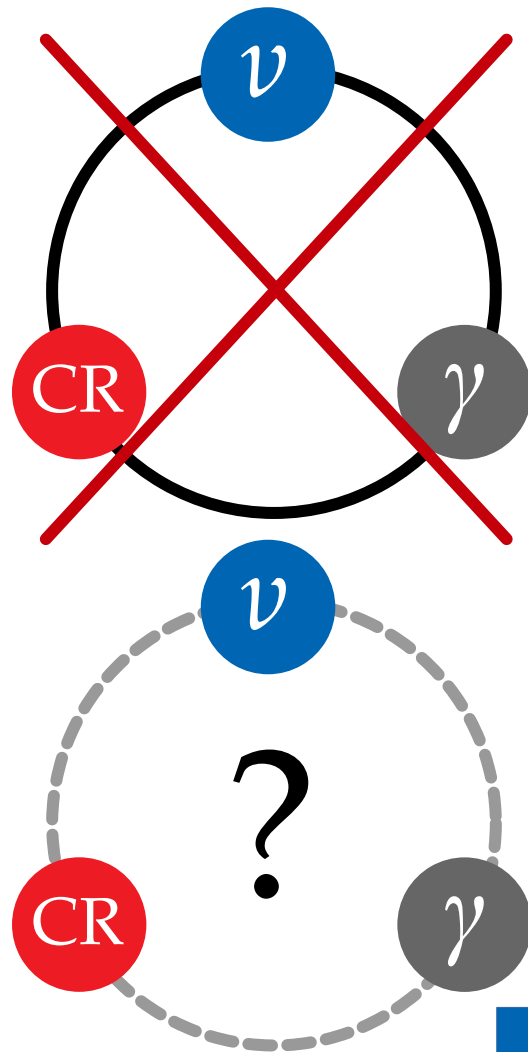
Sources that make neutrinos via $p\gamma$
may be opaque to 1–100 MeV gamma rays

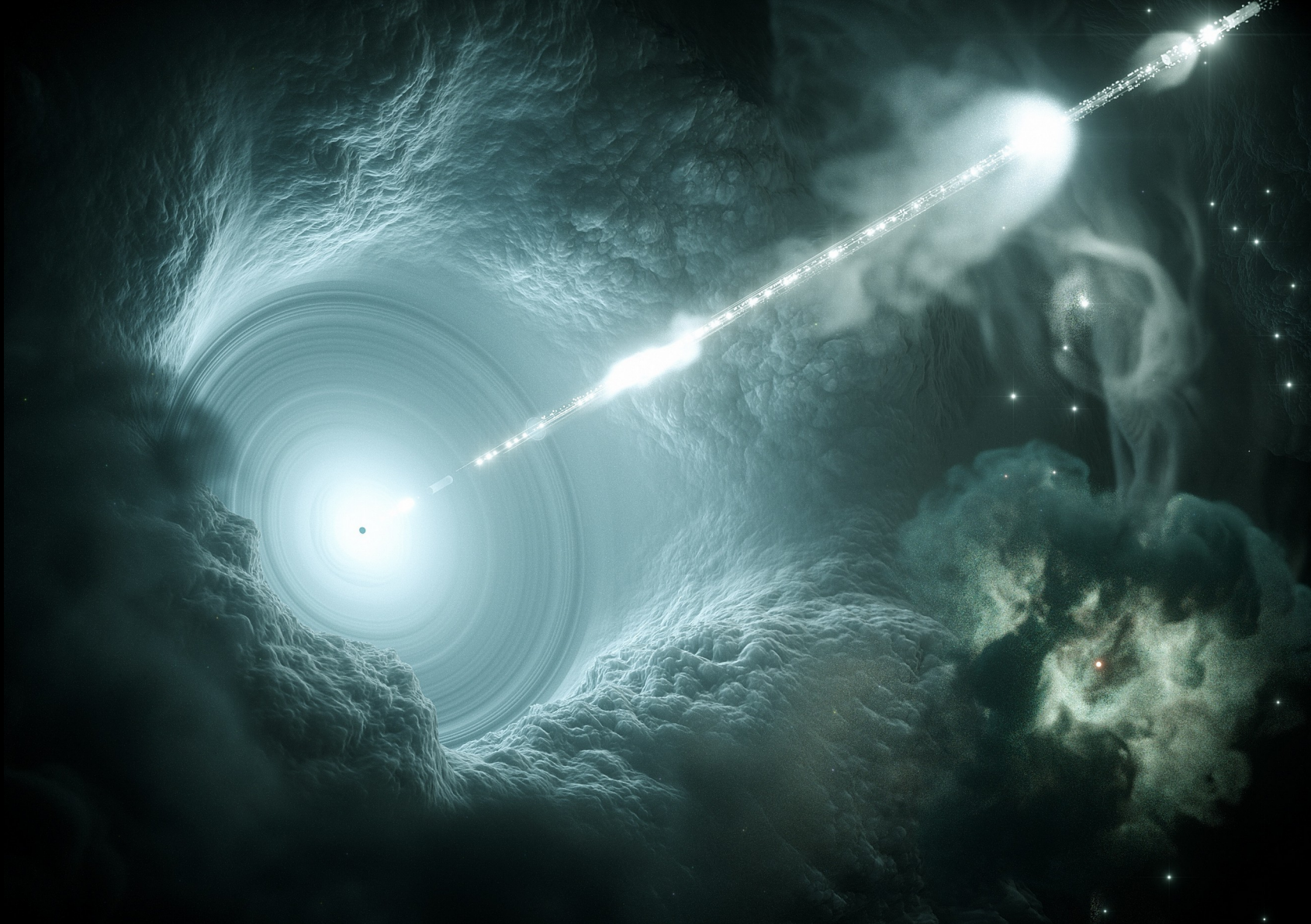
Murase, Guetta, Ahlers, *PRL* 2016

Modeling of $p\gamma$ interactions & nuclear cascading
in the sources is complex and uncertain

Morejon, Fedynitch, Boncioli, Winter, *JCAP* 2019

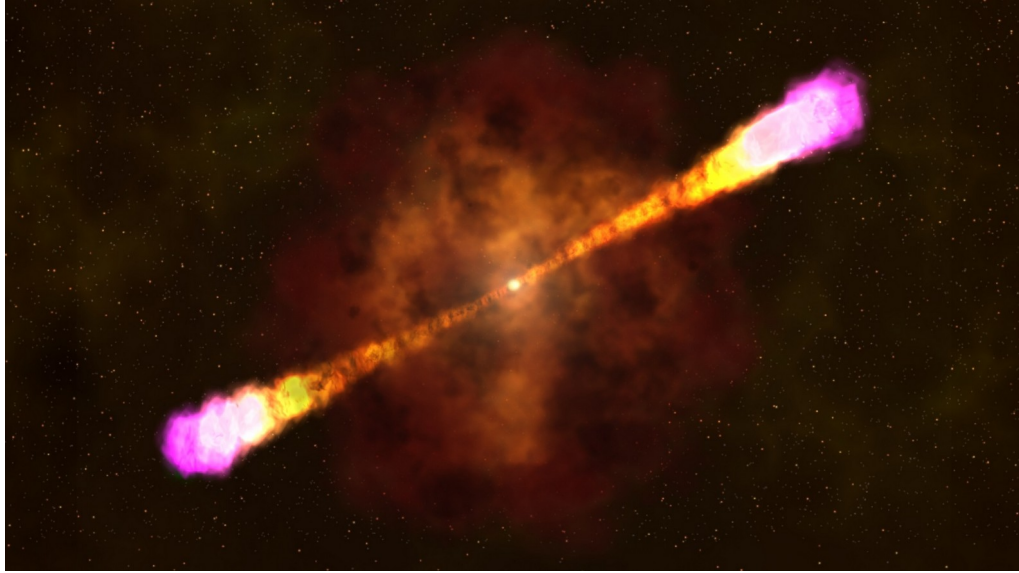
Boncioli, Fedynitch, Winter, *Sci. Rep.* 2017





Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

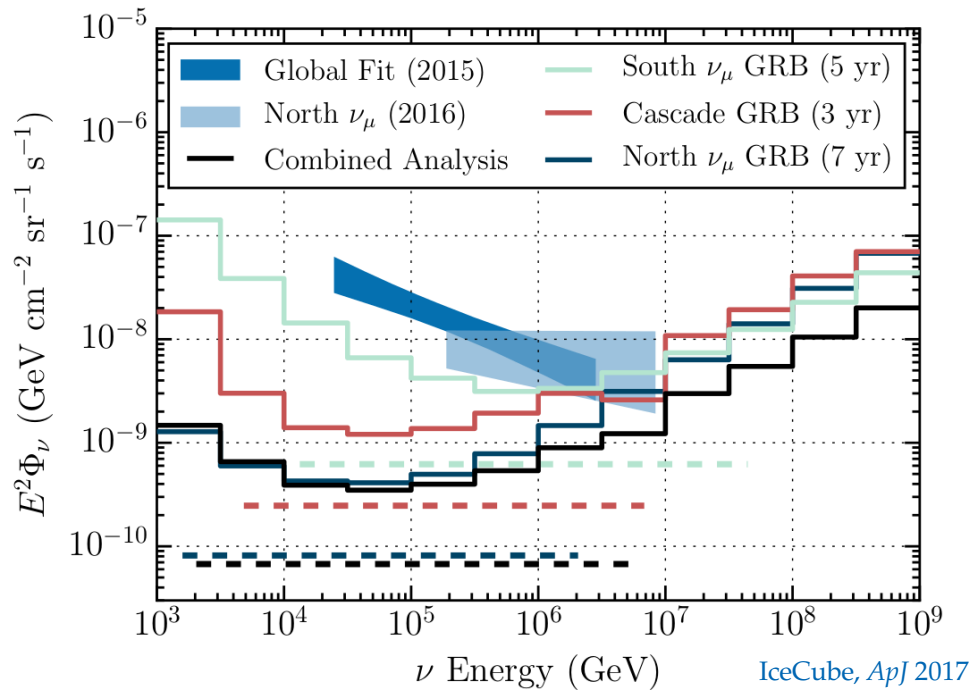


Blazars



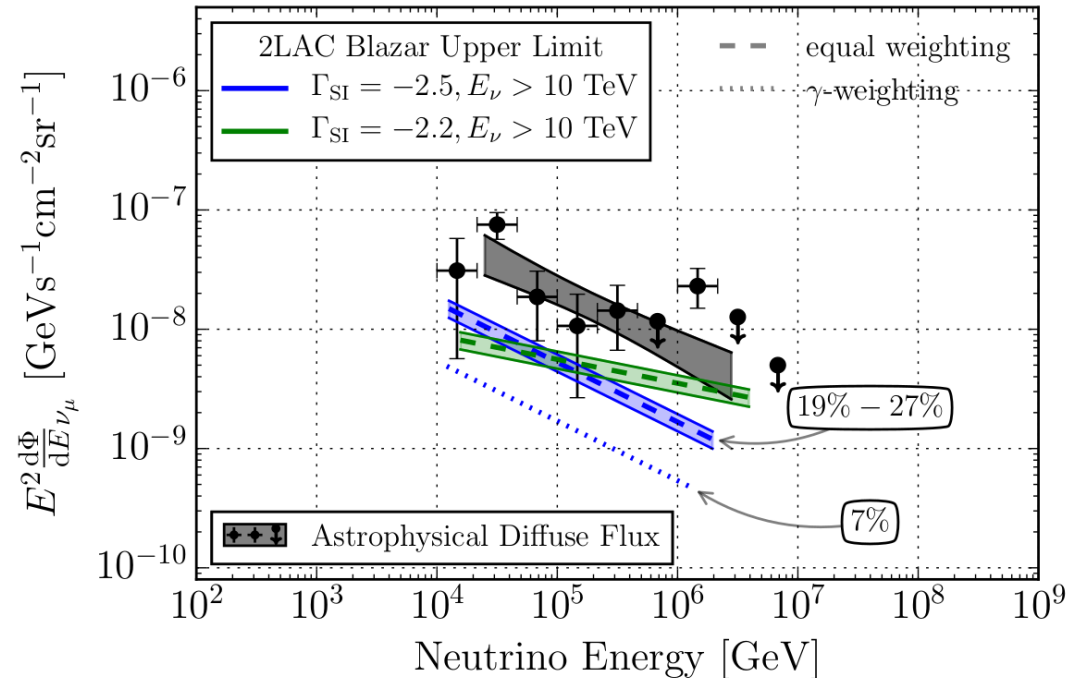
Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



1172 GRBs inspected, no correlation found
< 1% contribution to diffuse flux

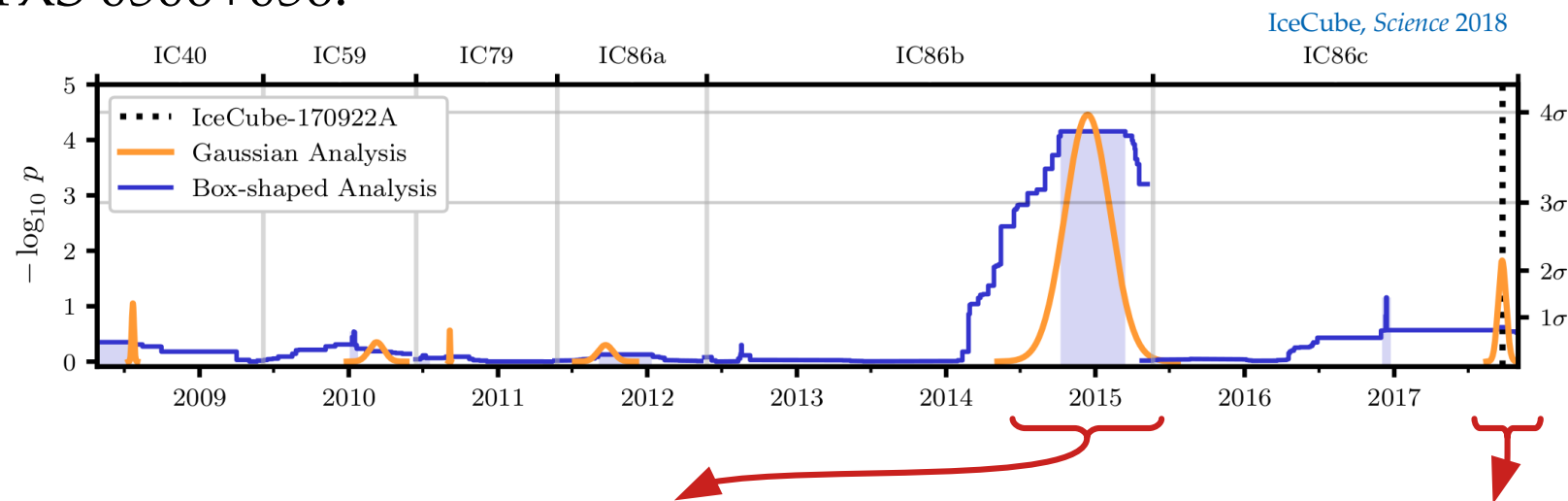
Blazars



862 blazars inspected, no correlation found
< 27% contribution to diffuse flux

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

Blazar TXS 0506+056:



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

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

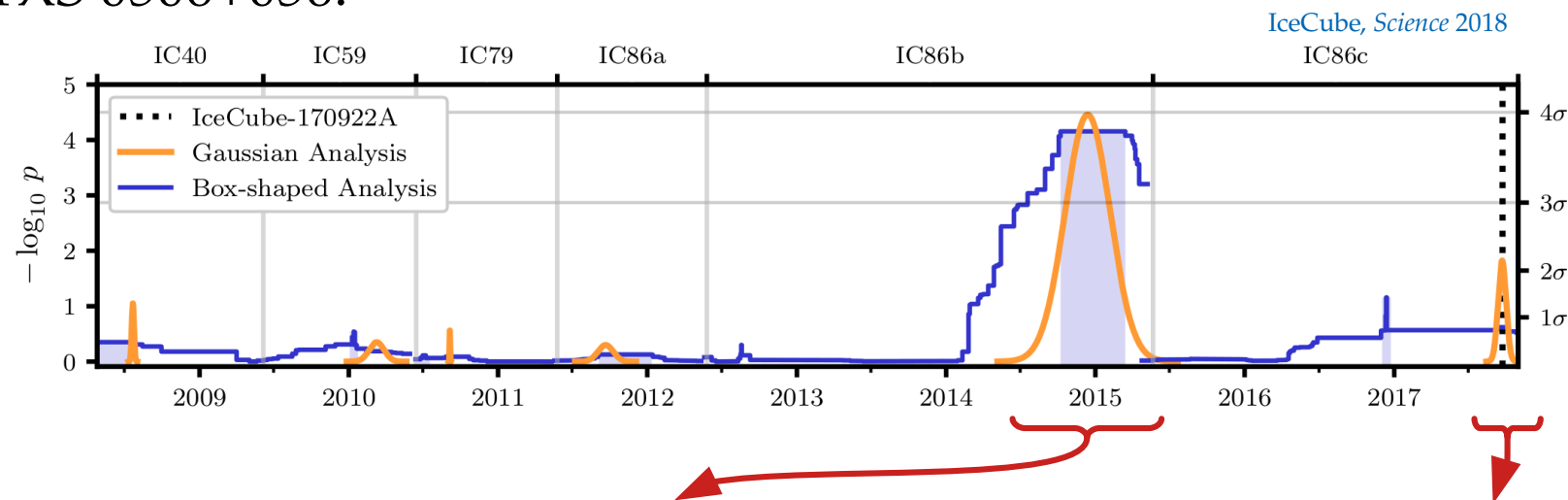
Combined (pre-trial): 4.1 σ

Hard fluence: $E^2 J_{100} = 2.1^{+0.9}_{-0.7} \left(\frac{E}{100 \text{ TeV}} \right)^{-2.1 \pm 0.2} \text{ TeV cm}^{-2}$

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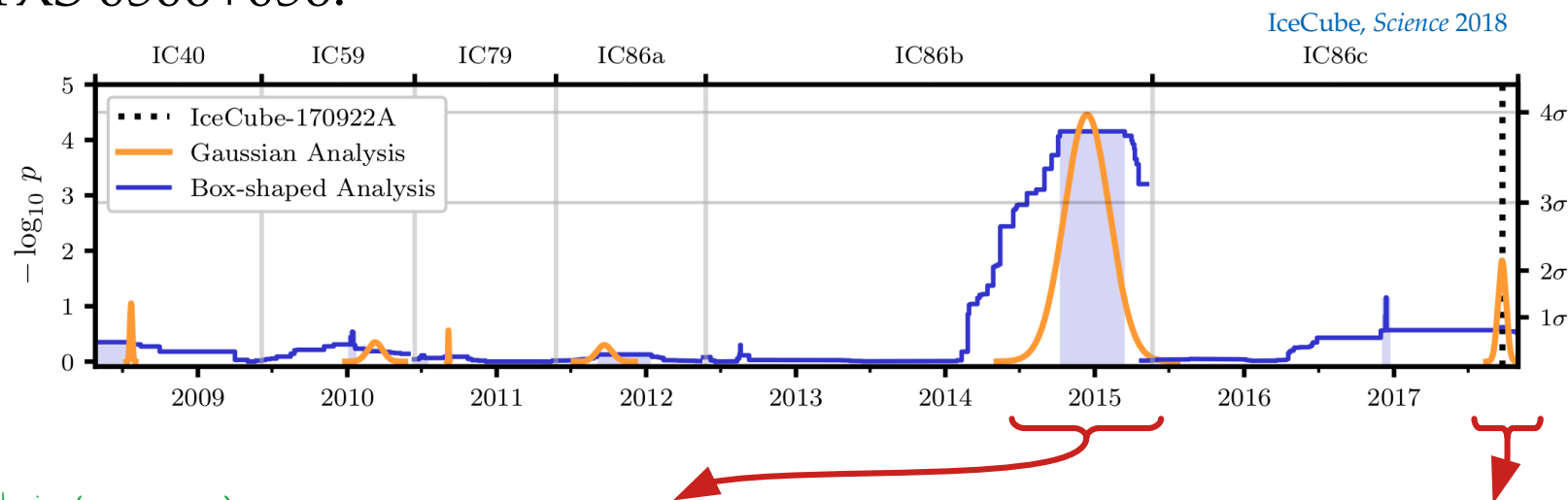
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Blazar TXS 0506+056:



After re-analysis (2101.09836),
significance dropped
from $p=7 \times 10^{-5}$ to $p=8 \times 10^{-3}$

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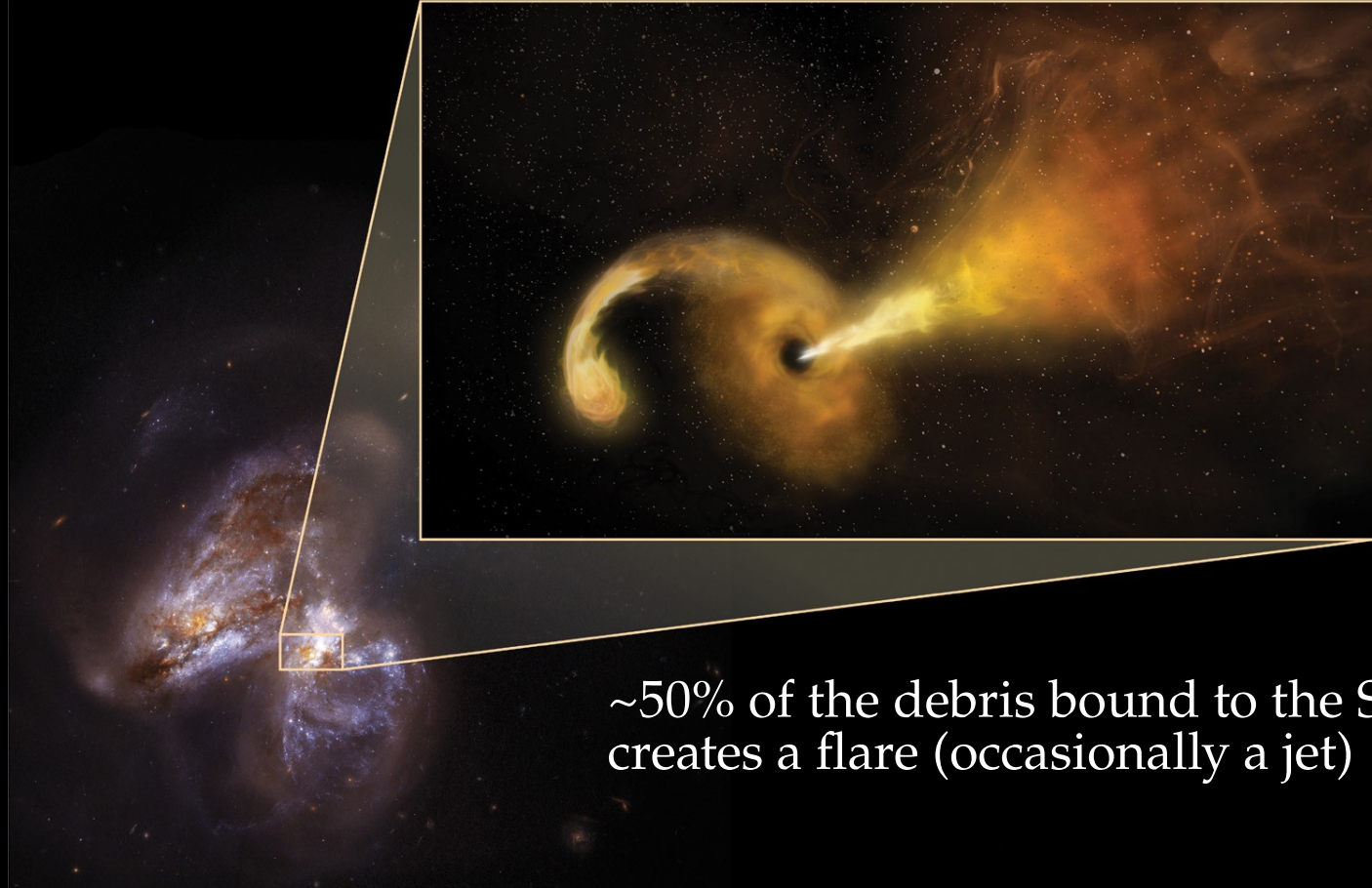
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Tidal disruption events

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

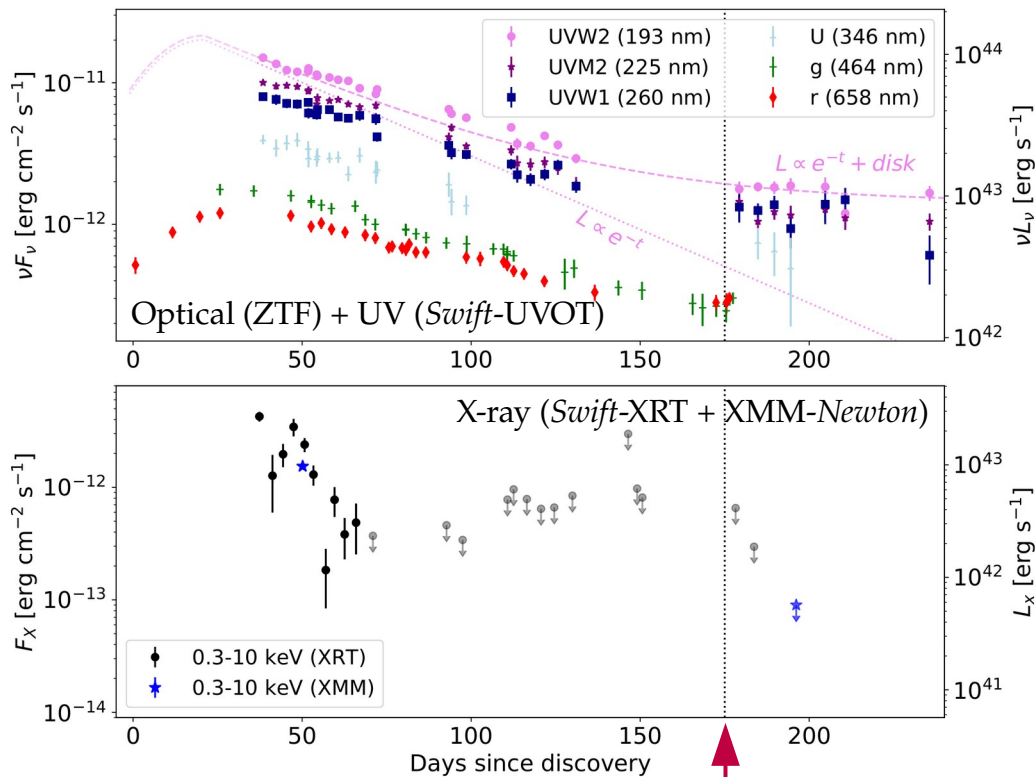


~50% of the debris bound to the SMBH,
creates a flare (occasionally a jet)

An apparent TDE neutrino source

Radio-emitting TDE AT2019dsg coincident with neutrino event IC191001A:

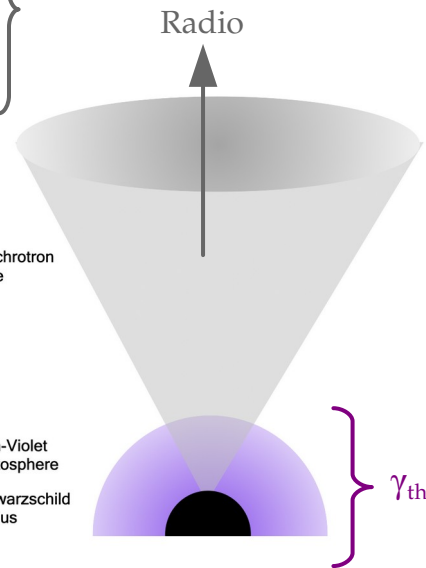
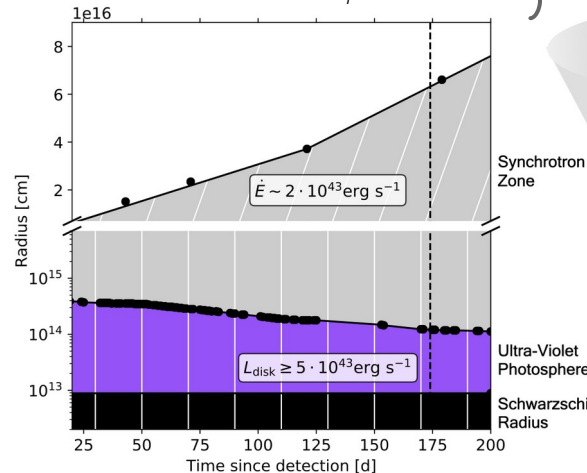
AT2019dsg: Apr 9, 2019 / $z = 0.051$ (230 Mpc) / $M_{\text{BH}} = 3 \times 10^7 M_{\odot}$



IC191001A, ~200 TeV

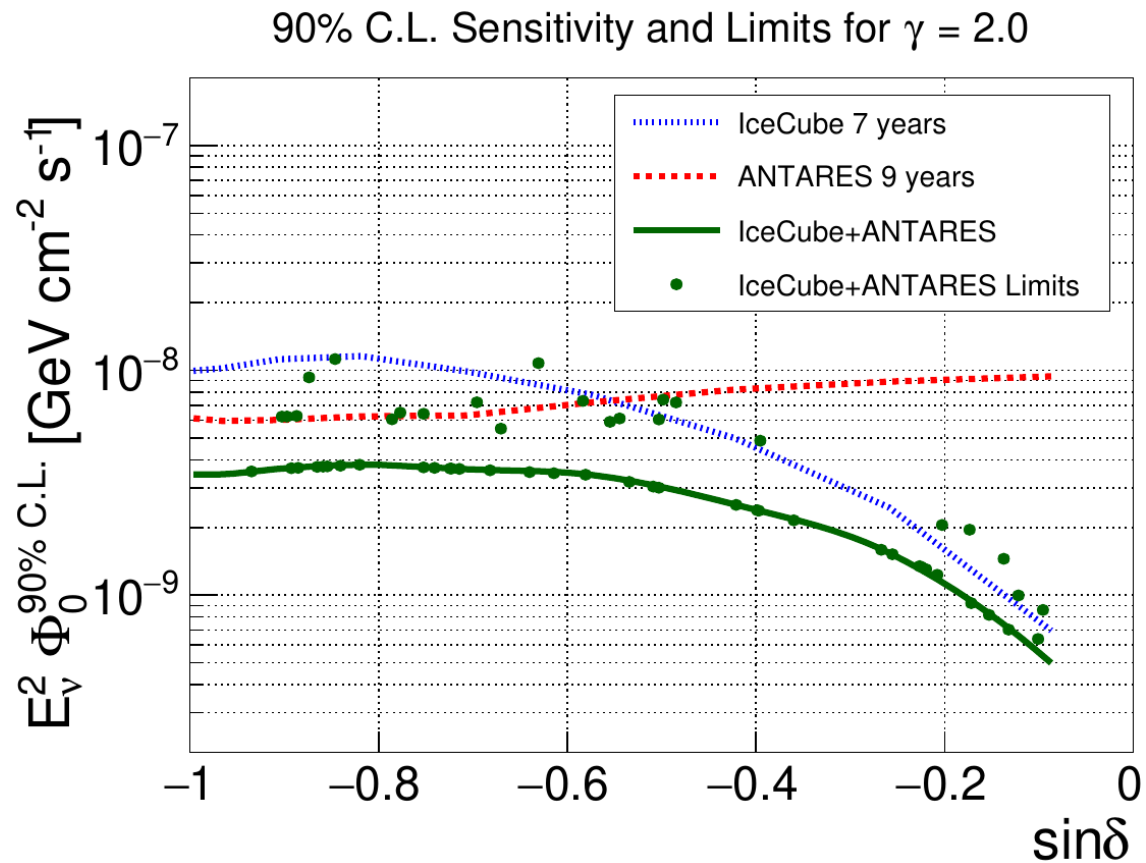
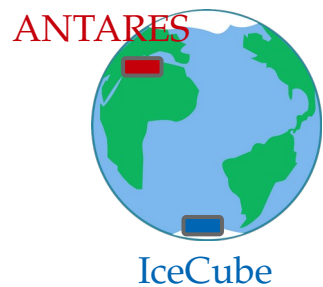
Multi-zone model:

From radio:
mildly relativistic expansion
($v/c \sim 0.2$) + acceleration
 p and e accelerated here
($B = 0.07$ G, $E_p < 160$ PeV)



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

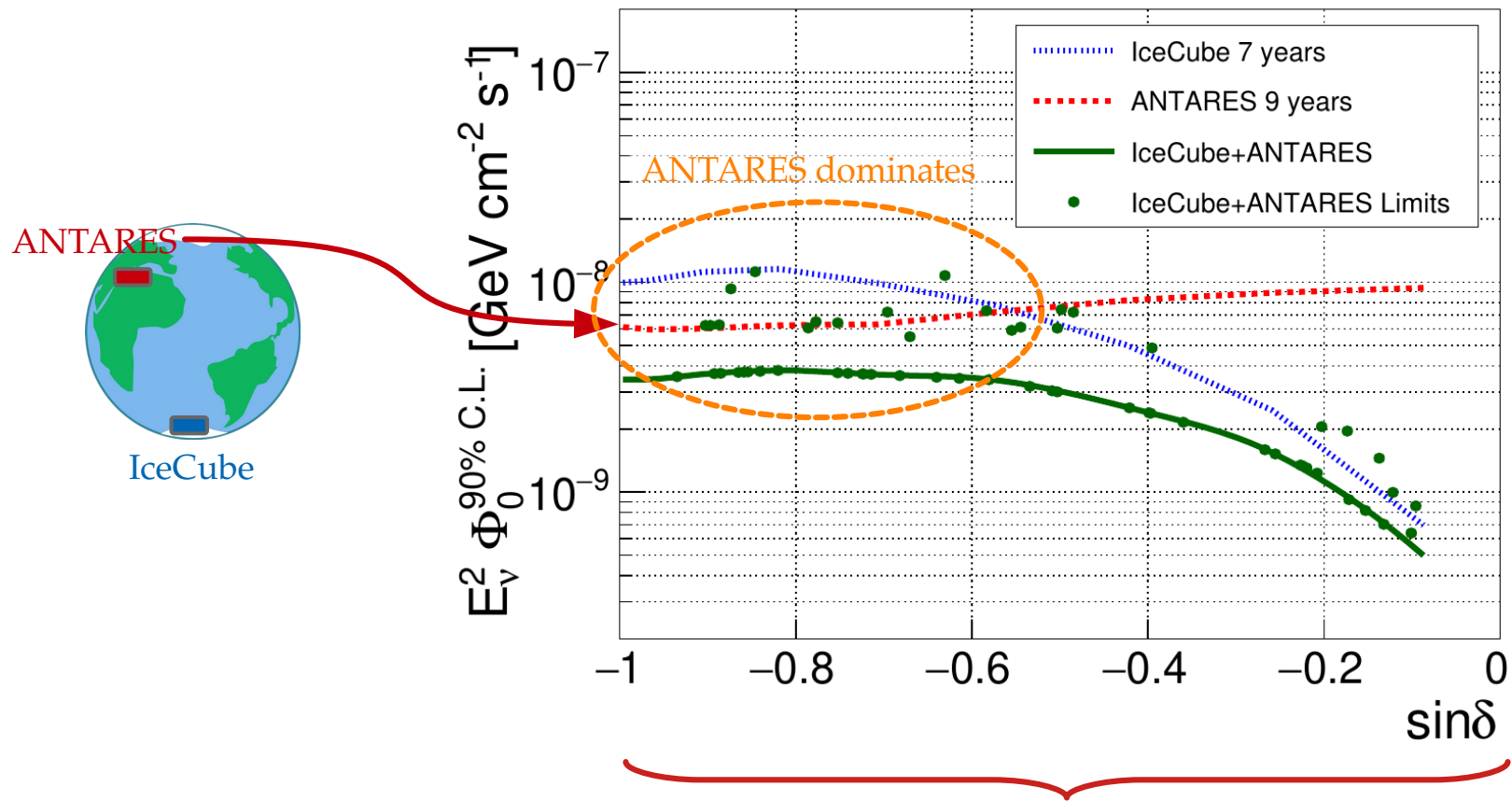
Point-source upper limits



Sources in the Southern sky

Point-source upper limits

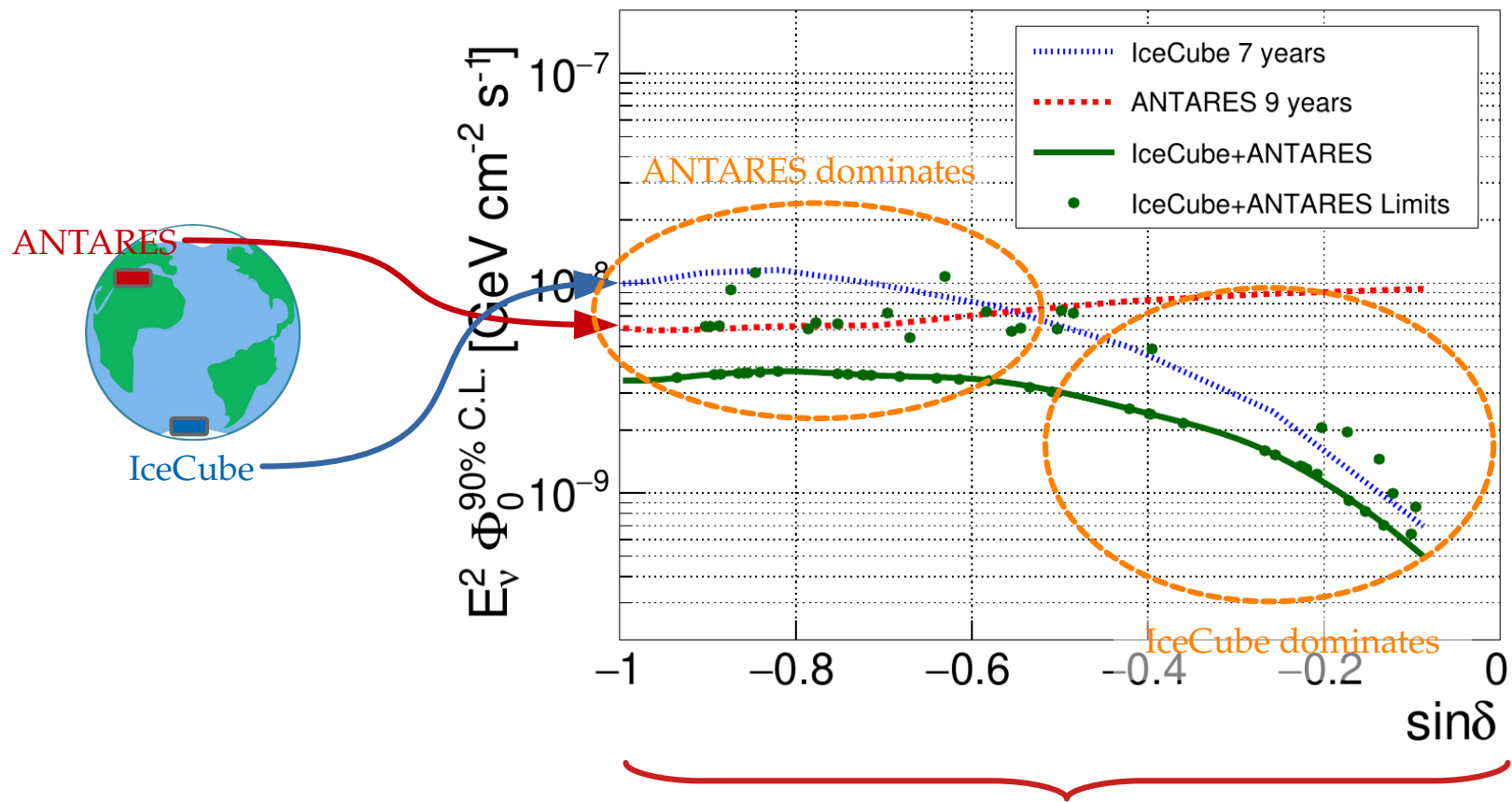
90% C.L. Sensitivity and Limits for $\gamma = 2.0$



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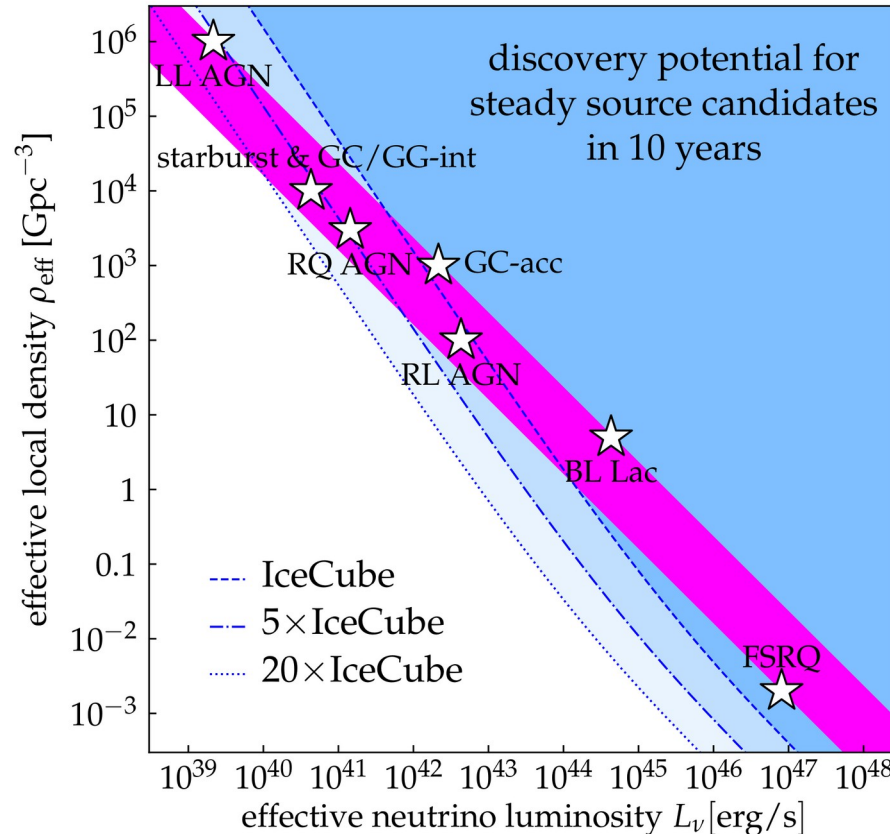


Sources in the Southern sky

Source discovery potential: today and in the future

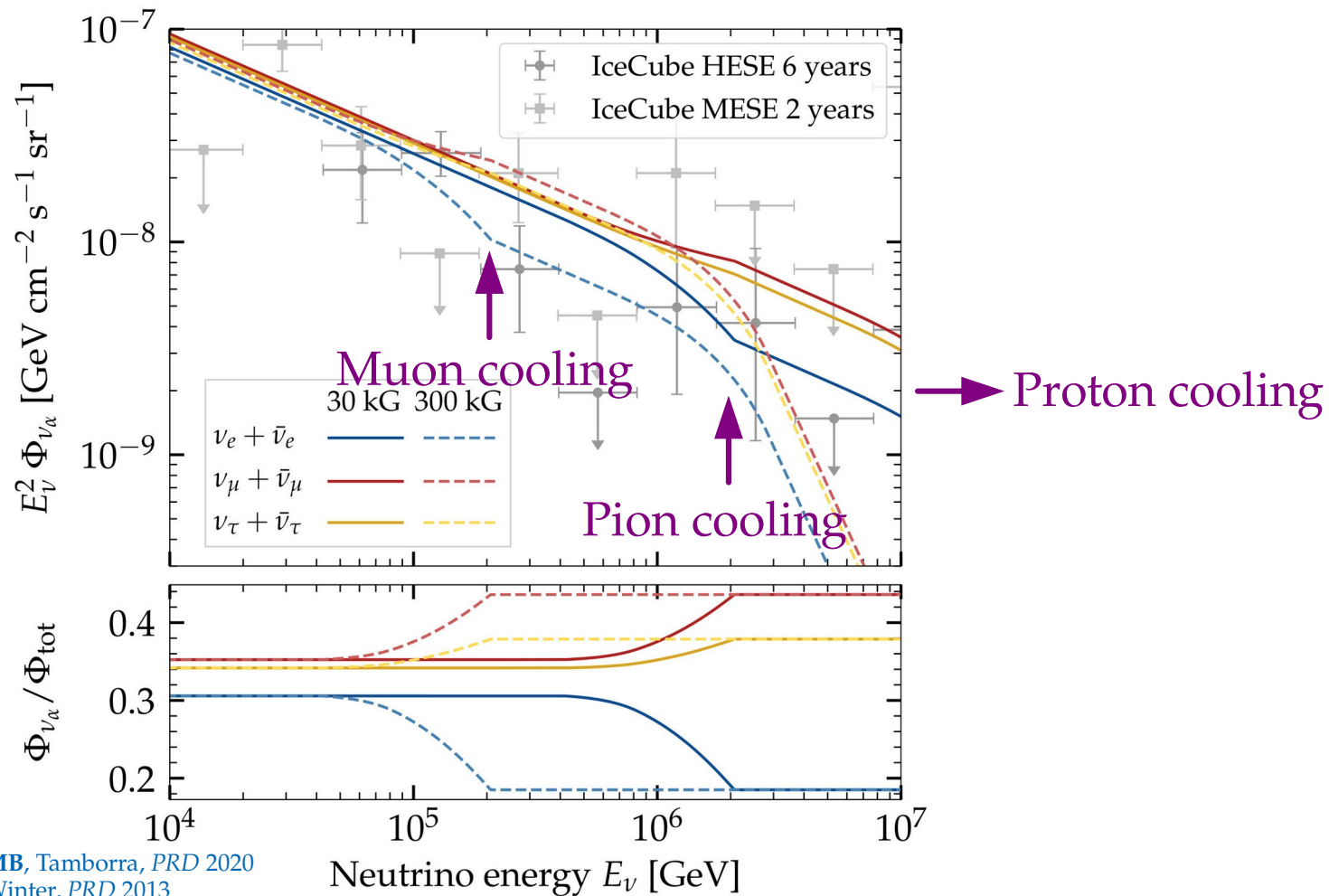
■ Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

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



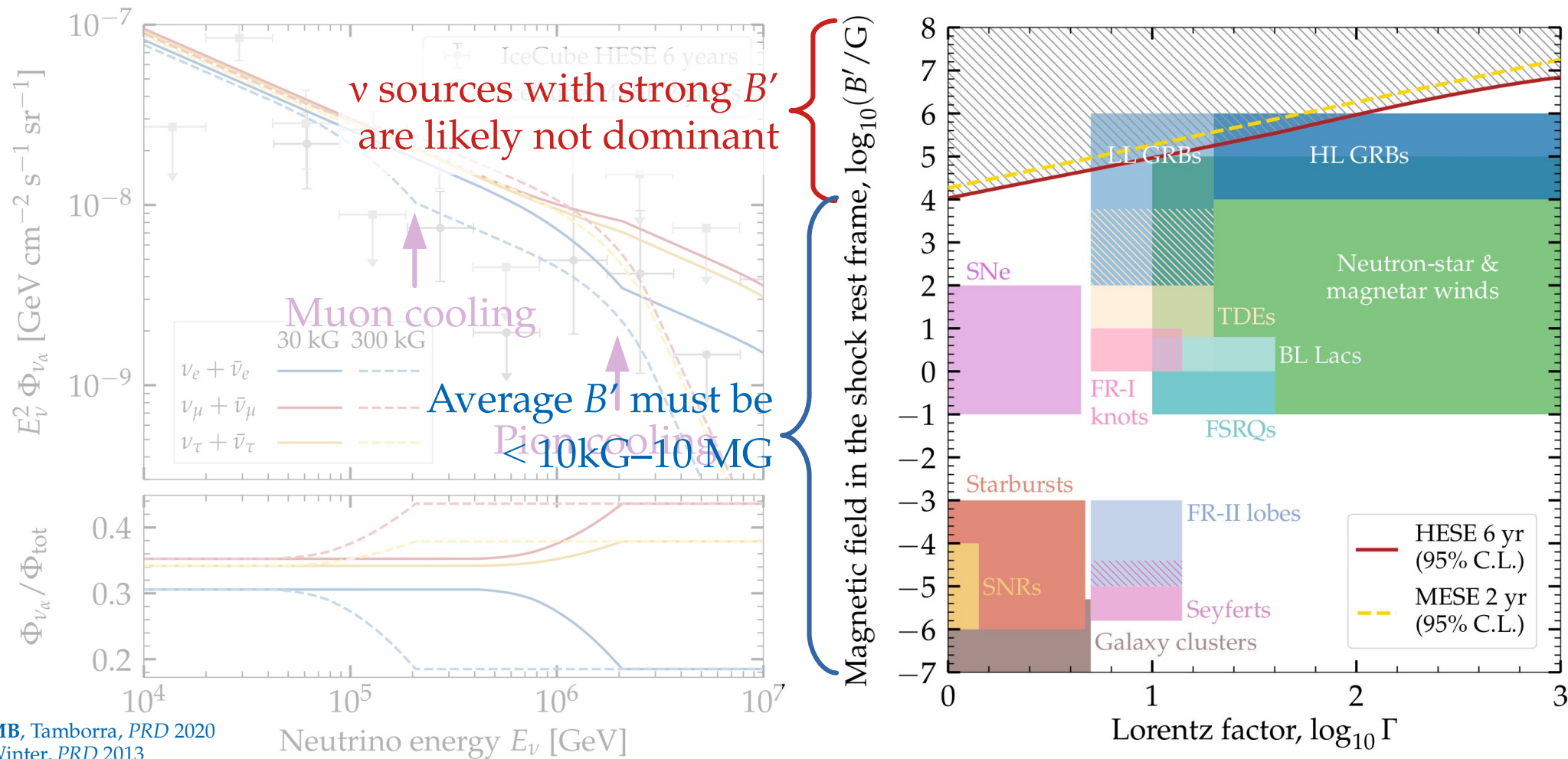
Using high-energy neutrinos as magnetometers

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



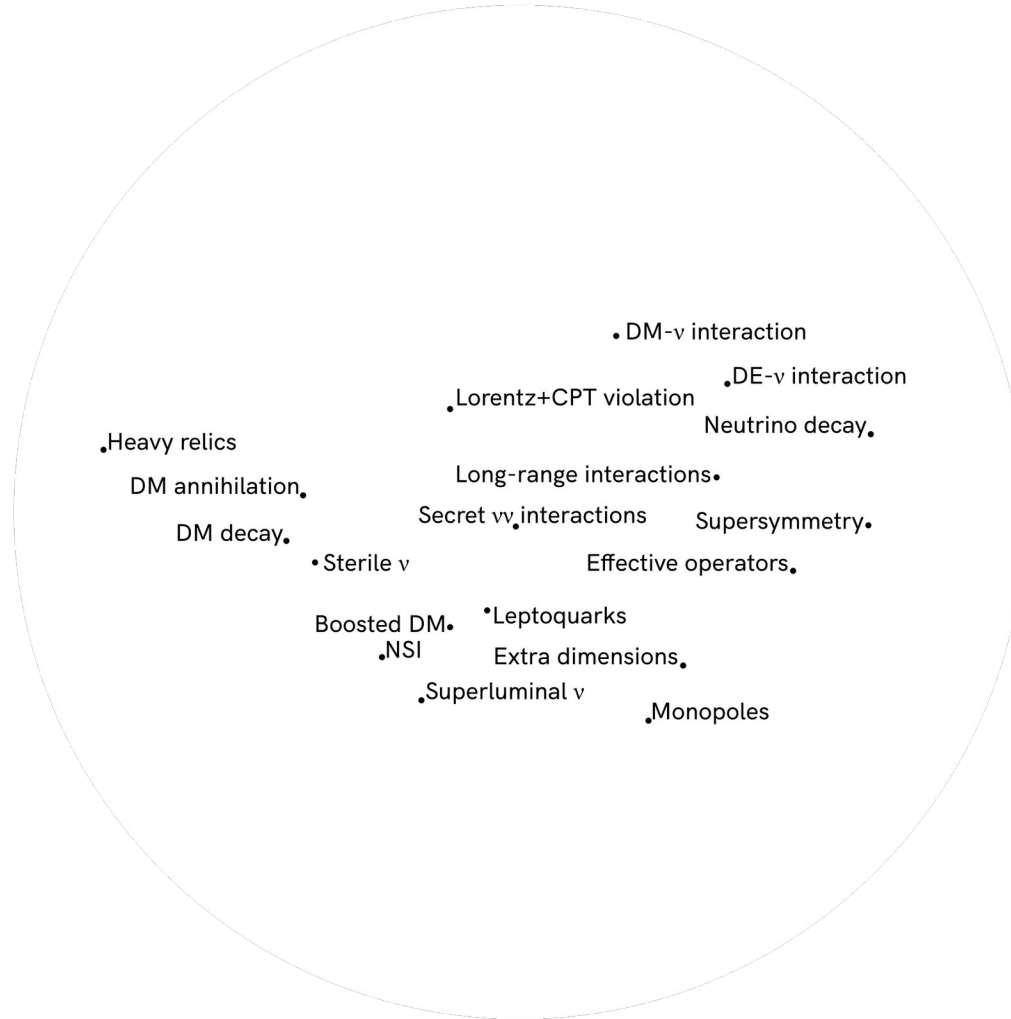
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III.

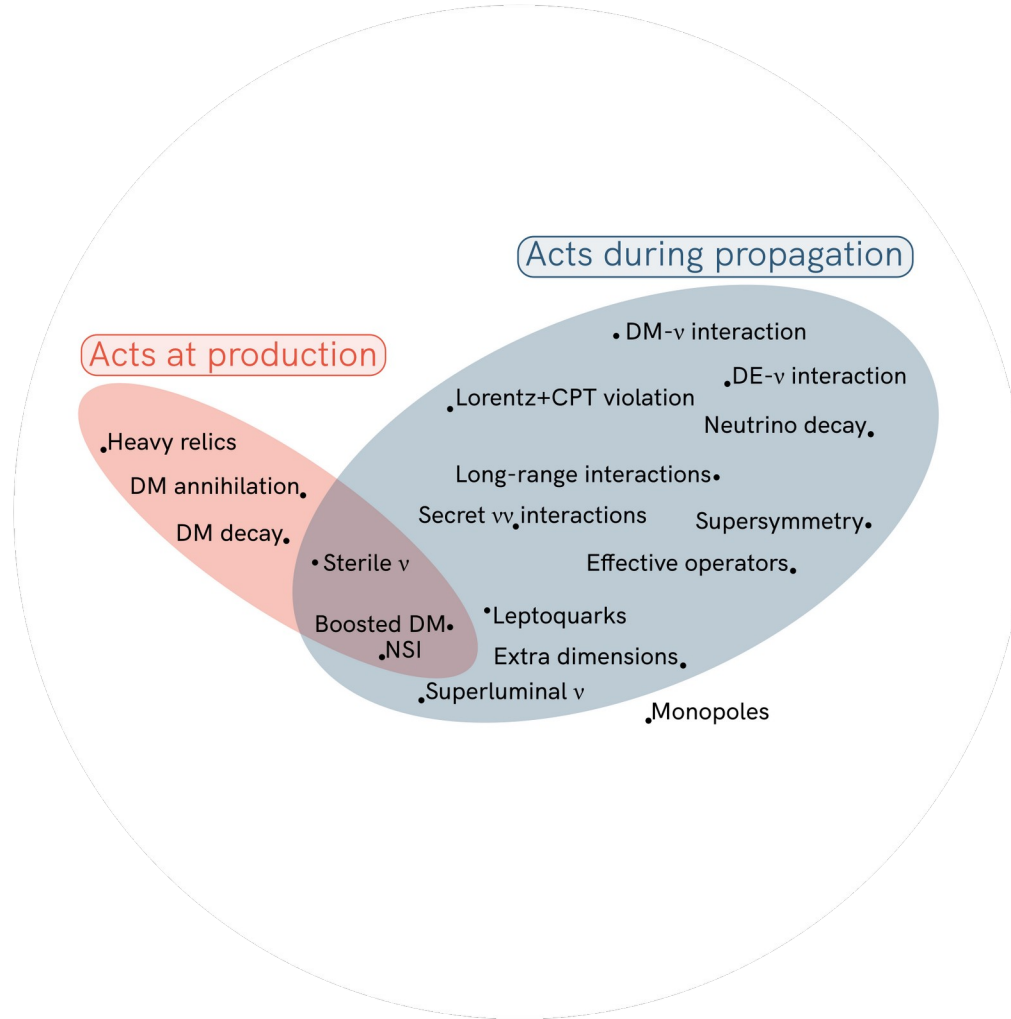
What have we learned
about *particle physics*



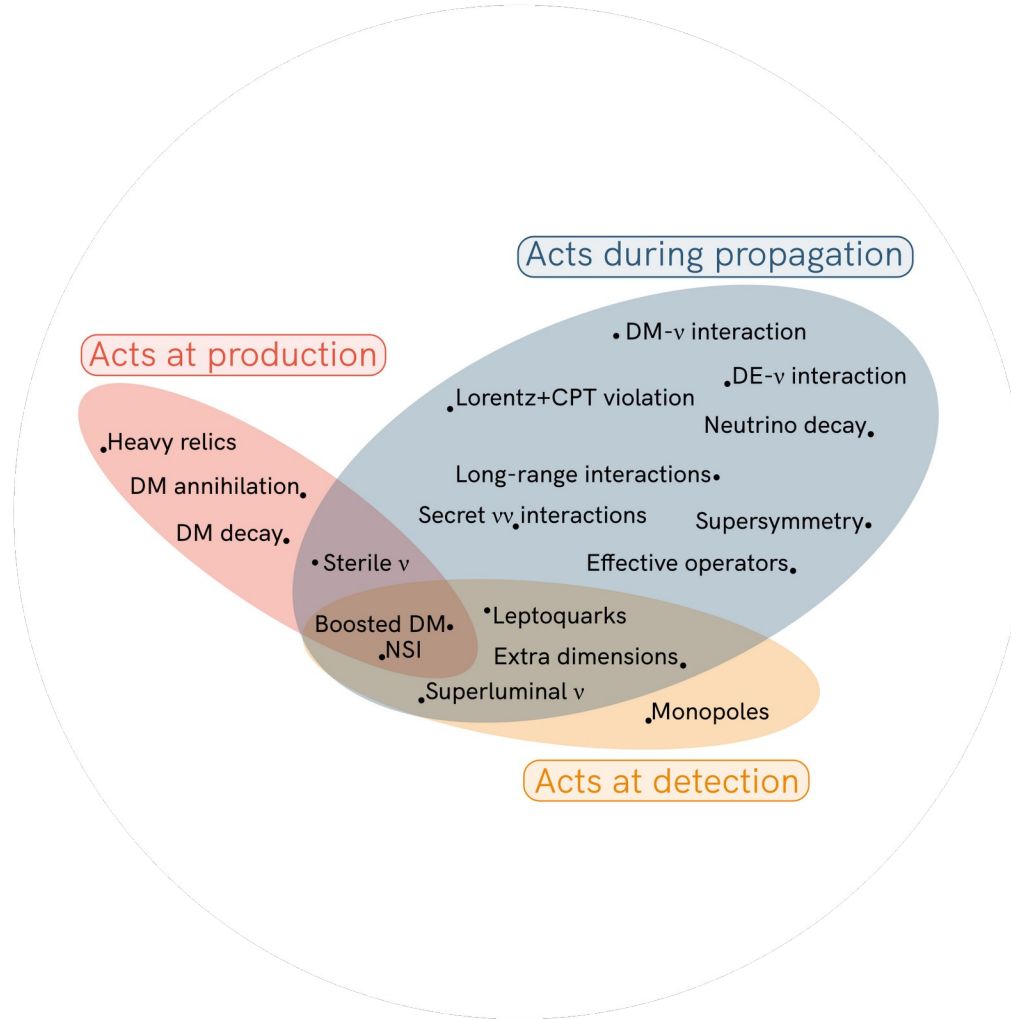
Note: Not an exhaustive list



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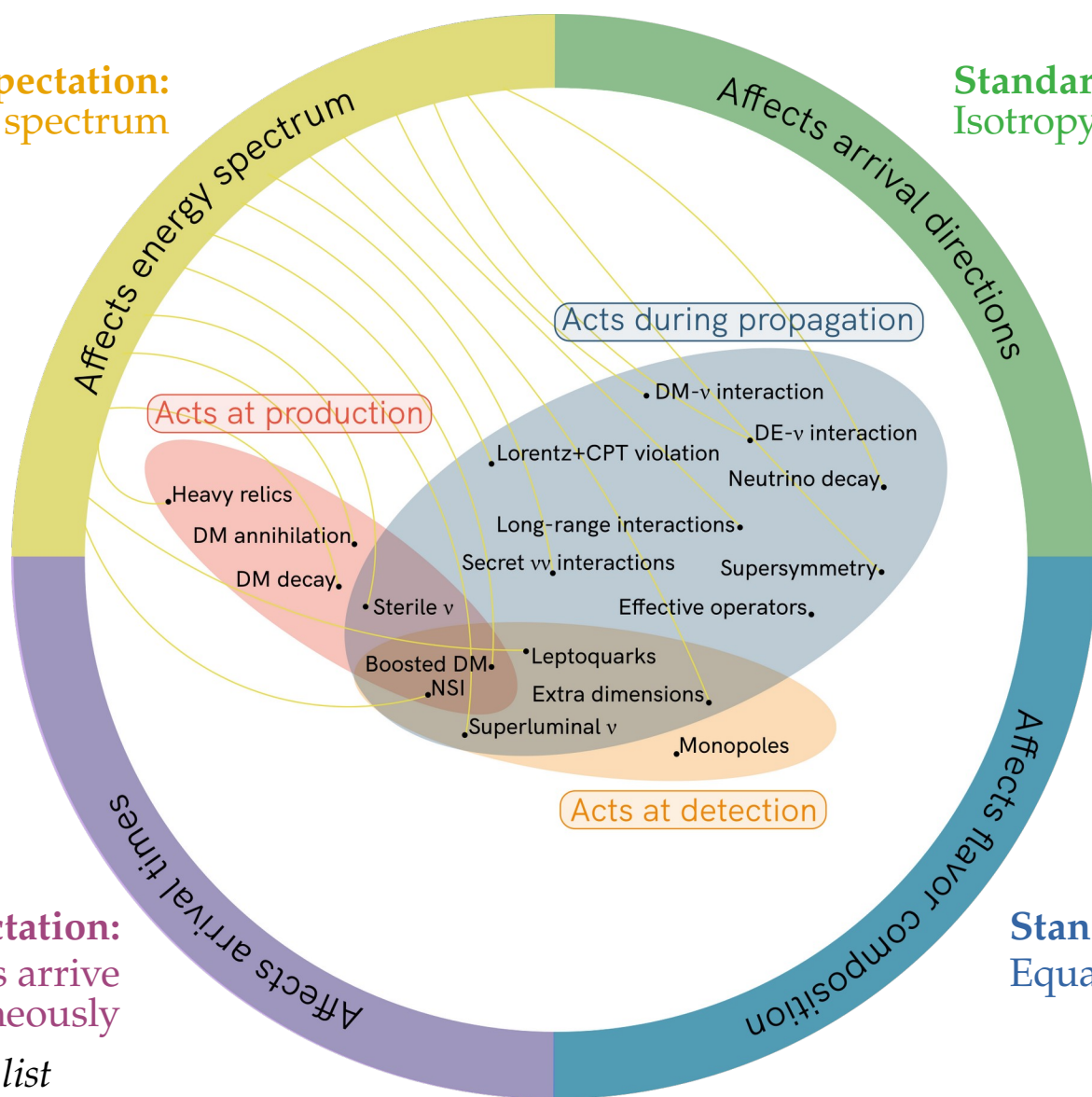
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

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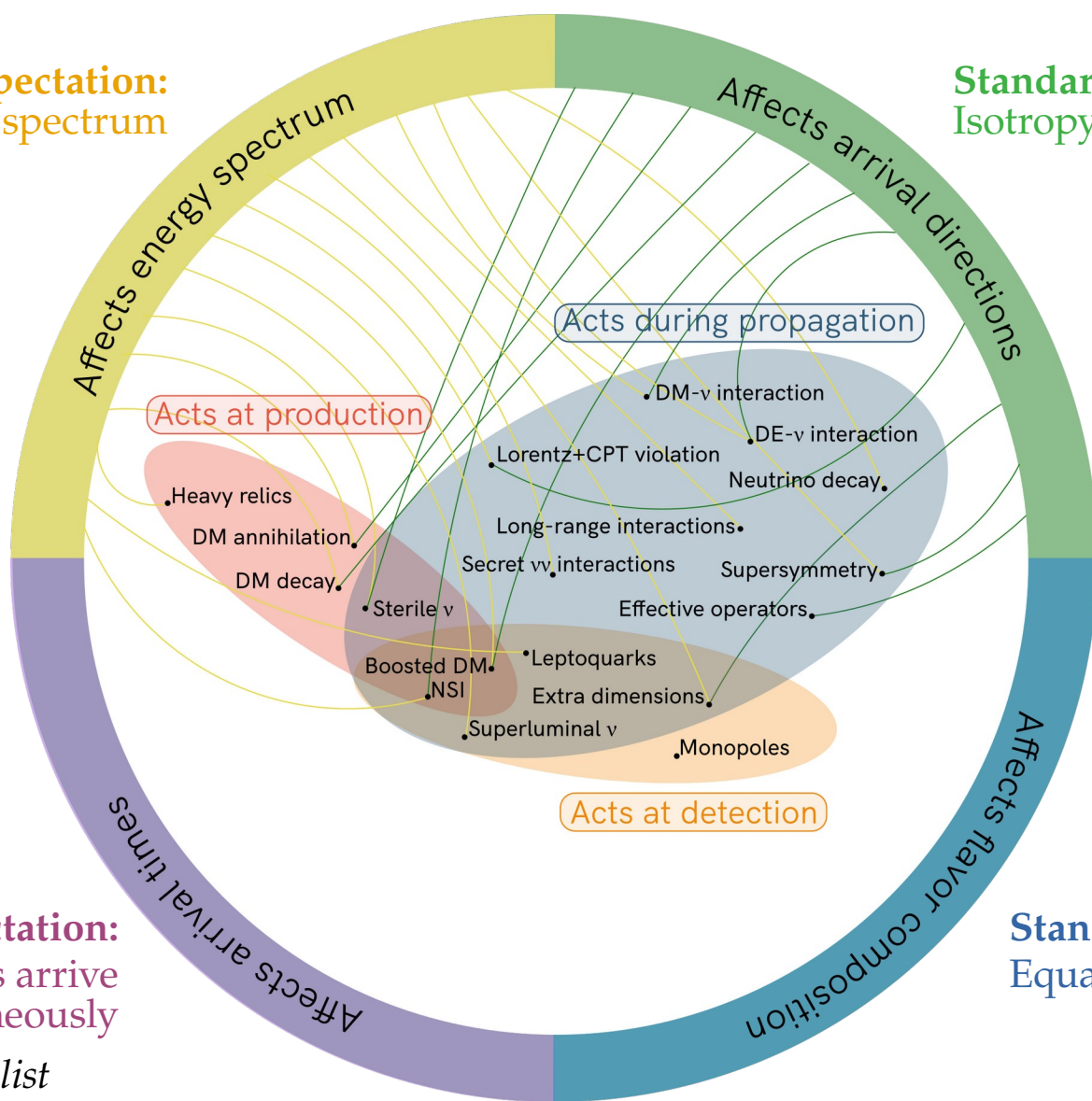
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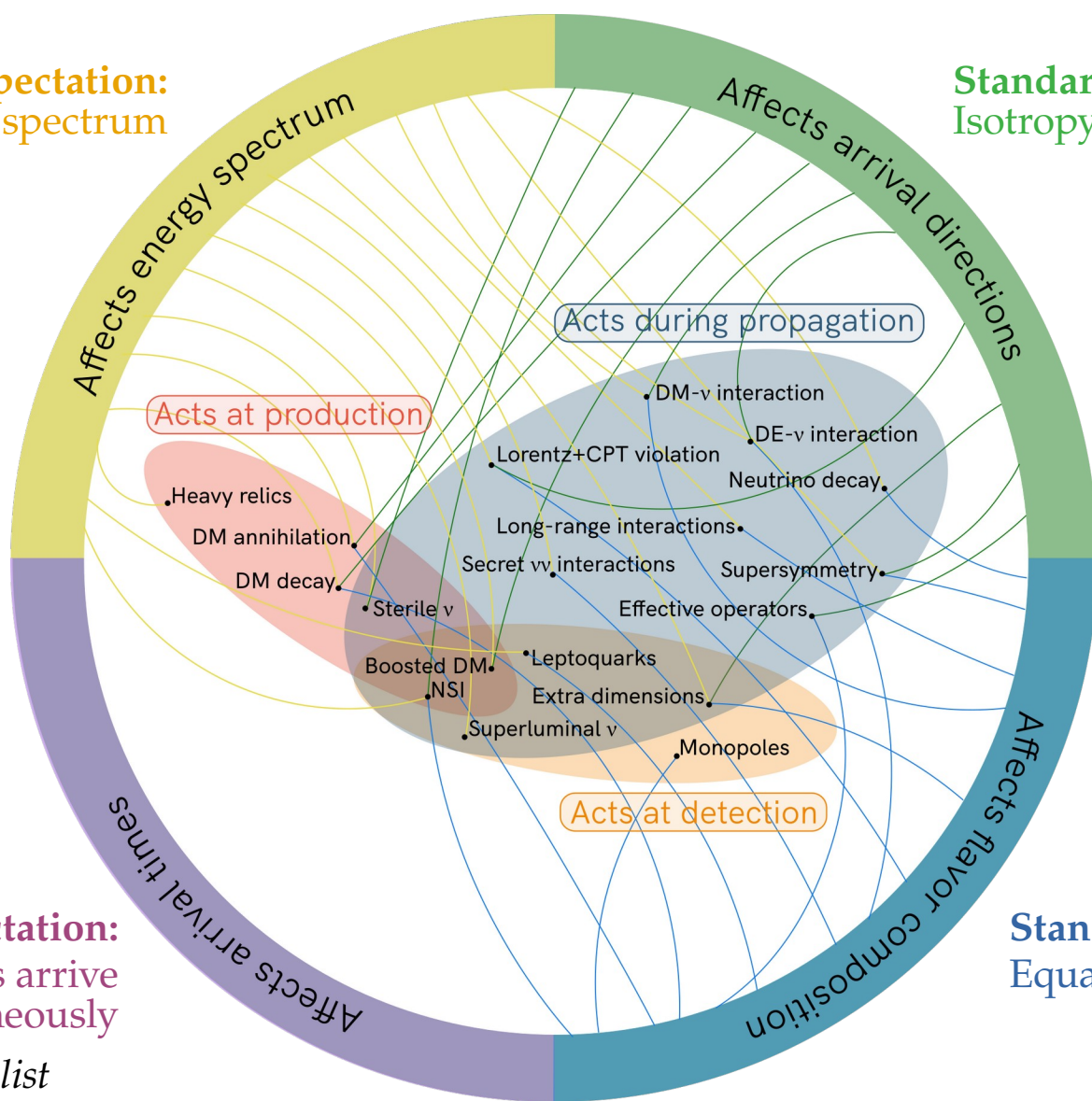
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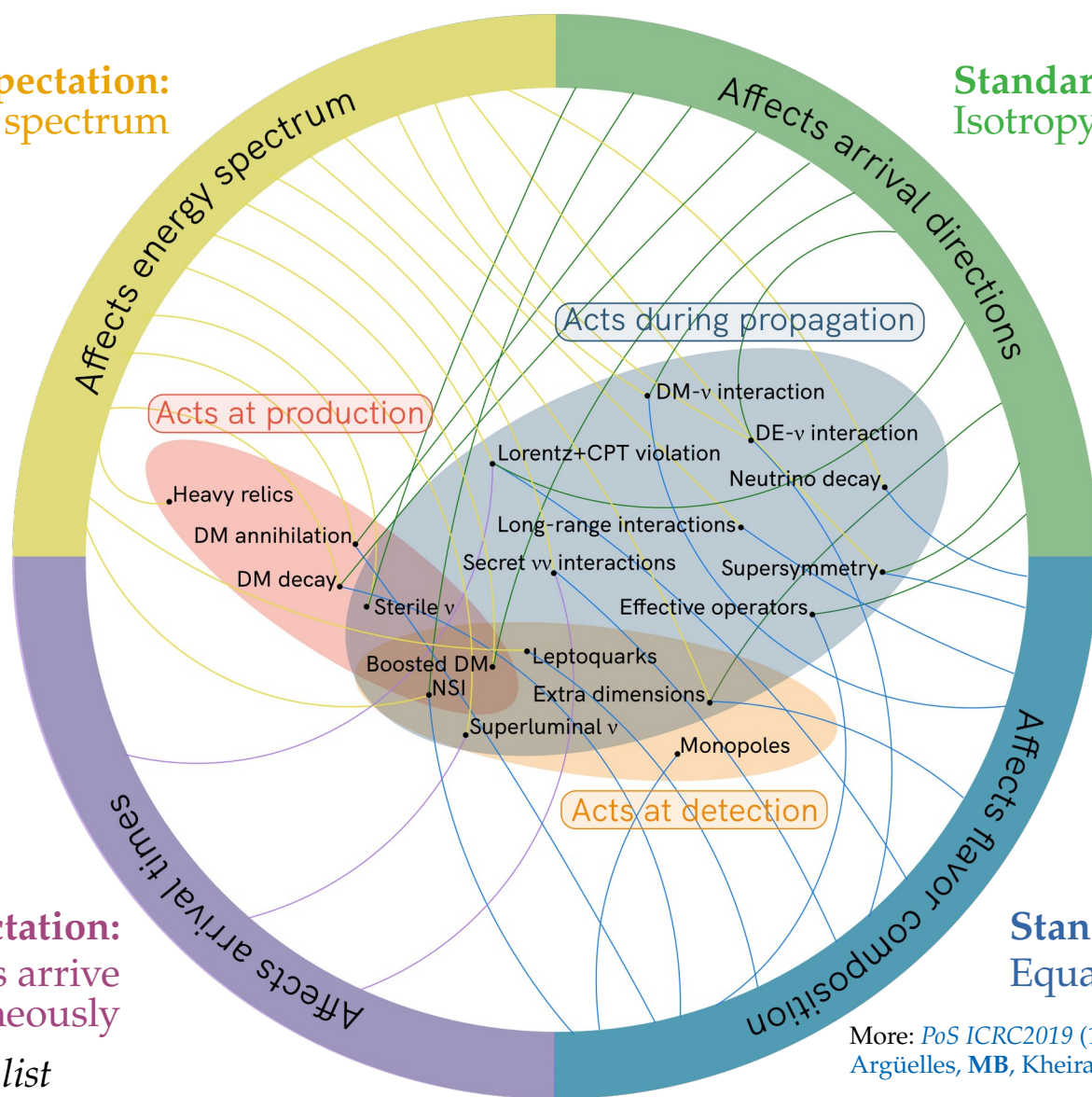
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More: *PoS ICRC2019* (1907.08690)

Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

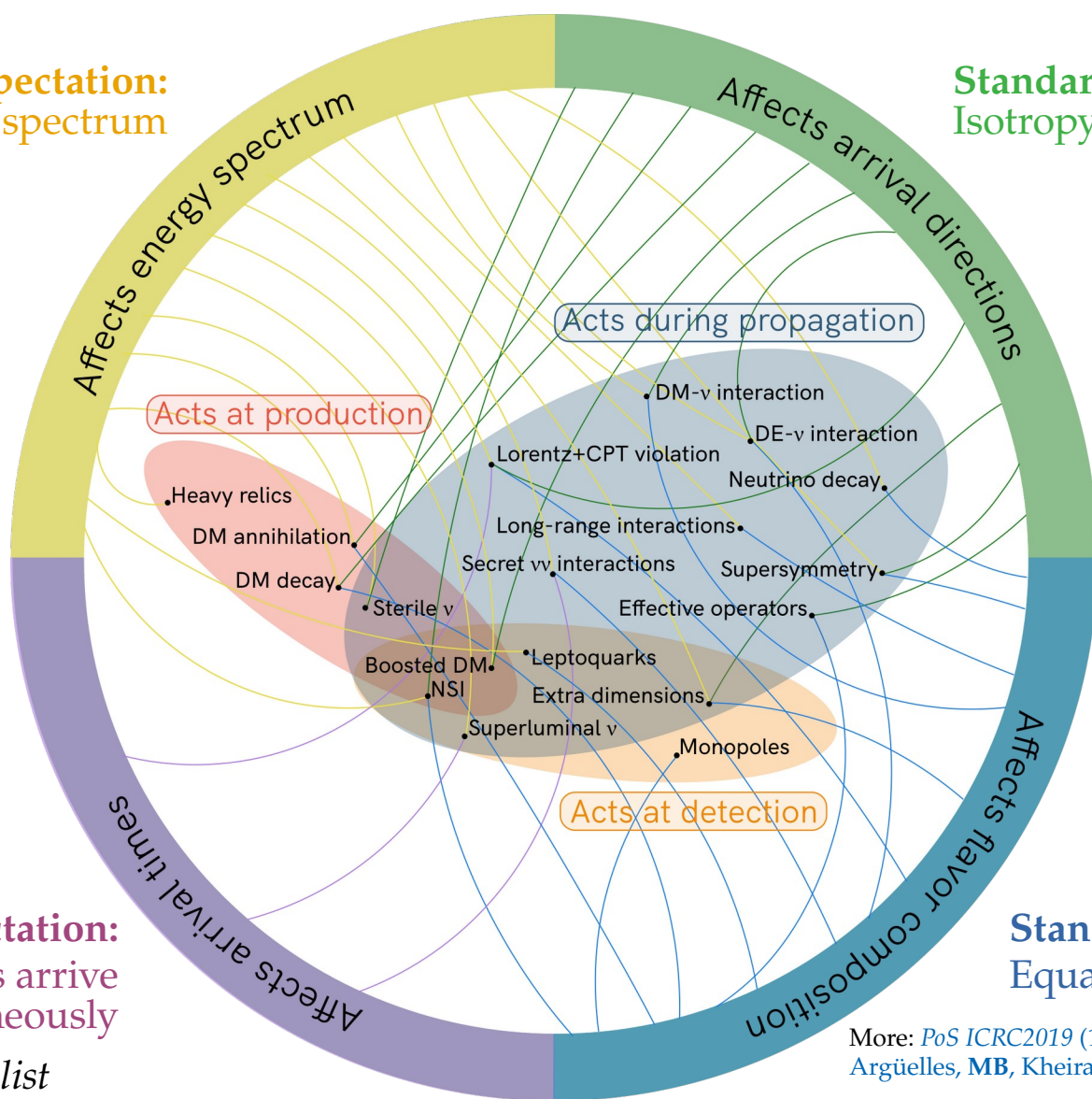
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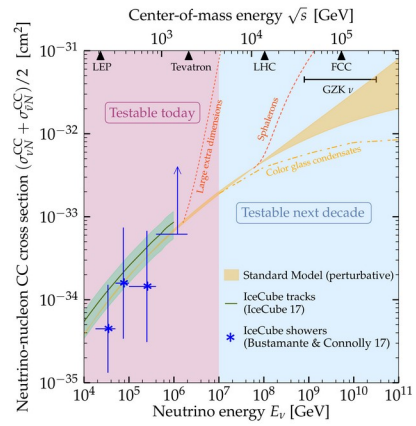
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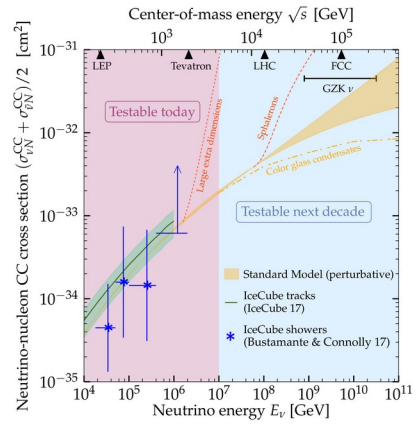
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

TeV–EeV ν cross sections



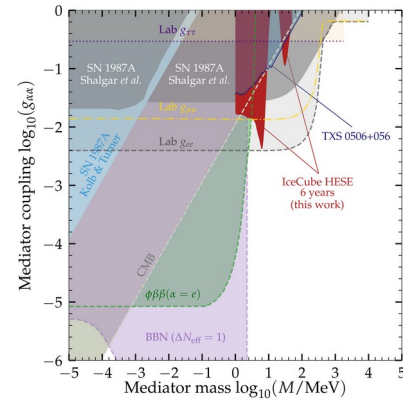
MB & Connolly, *PRL* 2019

TeV–EeV ν cross sections



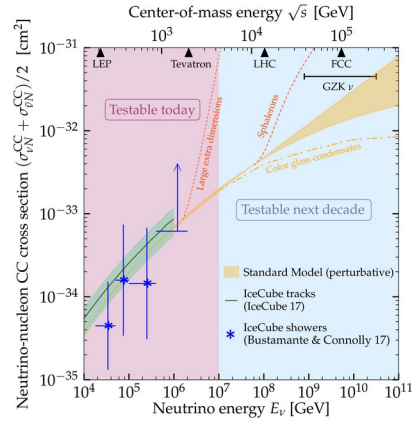
MB & Connolly, *PRL* 2019

ν self-interactions



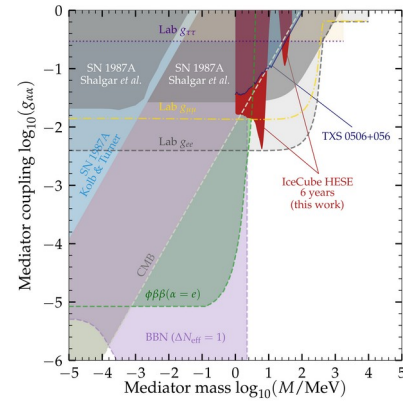
MB, Rosenström, Shalgar, Tamborra, *PRD* 2020

TeV–EeV ν cross sections



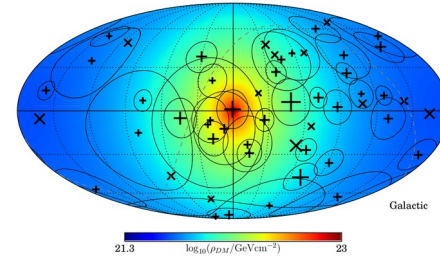
MB & Connolly, *PRL* 2019

ν self-interactions



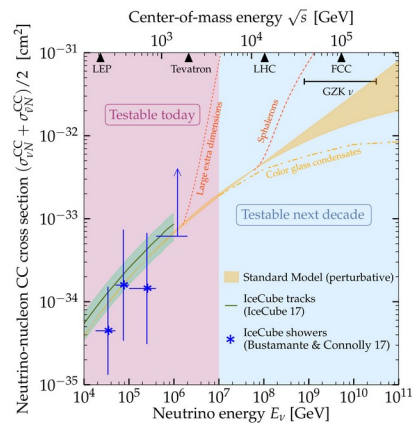
MB, Rosenström, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



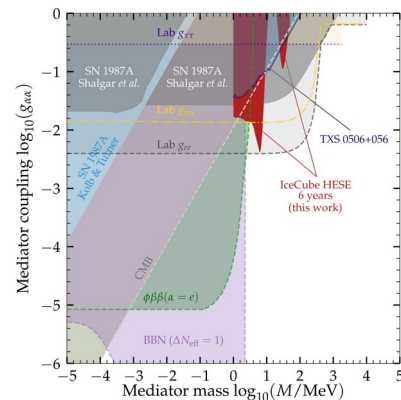
Argüelles, Kheirandish, Vincent, *PRL* 2017

TeV–EeV ν cross sections



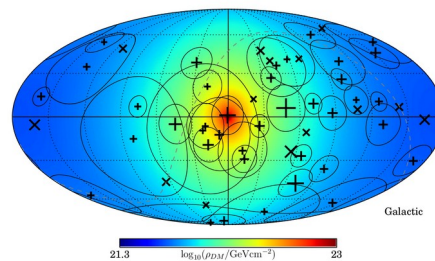
MB & Connolly, PRL 2019

ν self-interactions



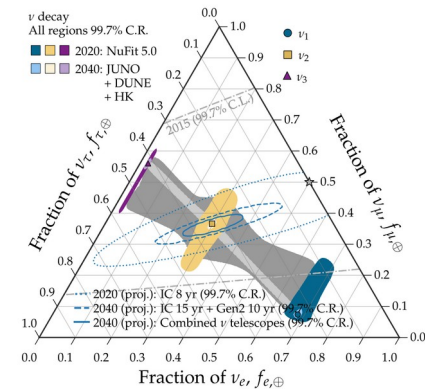
MB, Rosenström, Shalgar, Tamborra, PRD 2020

ν scattering on Galactic DM



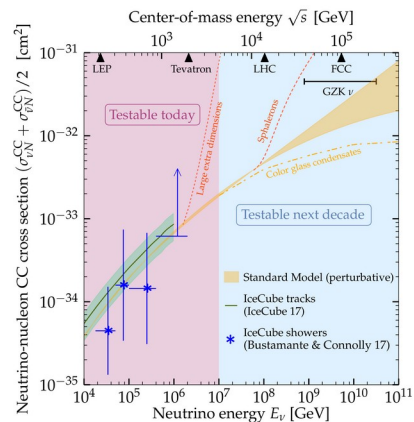
Argüelles, Kheirandish, Vincent, PRL 2017

ν decay



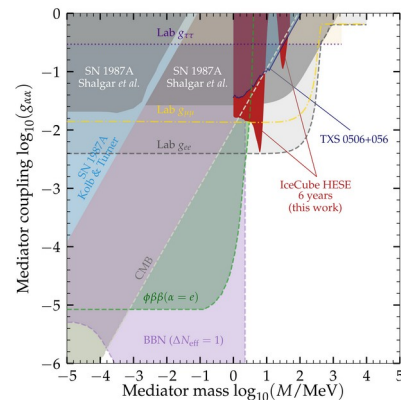
Song, Li, Argüelles, MB, Vincent, JCAP 2021

TeV–EeV ν cross sections



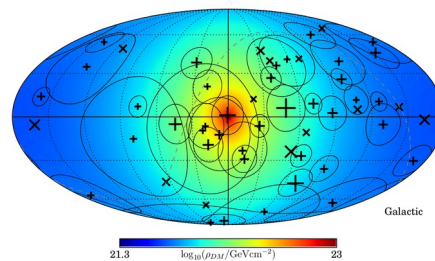
MB & Connolly, PRL 2019

ν self-interactions



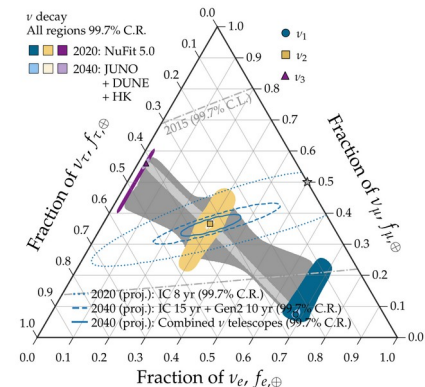
MB, Rosenström, Shalgar, Tamborra, PRD 2020

ν scattering on Galactic DM



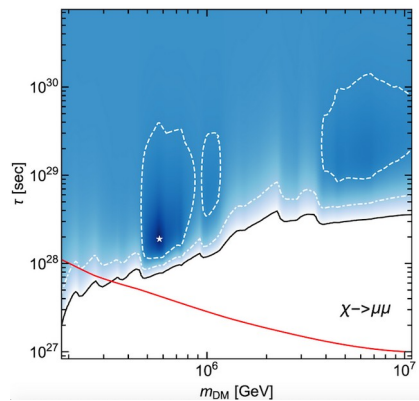
Argüelles, Kheirandish, Vincent, PRL 2017

ν decay



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

Dark matter decay



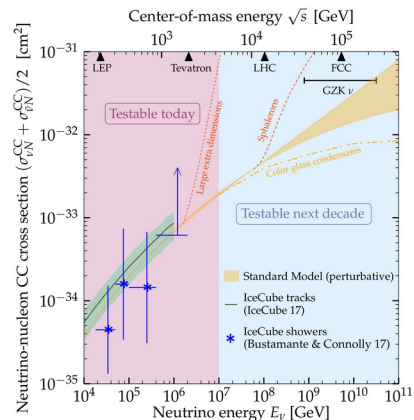
Chianese, Fiorillo, Miele, Morisi, Pisanti, JCAP 2019

Figure 1 is a log-log plot showing the neutrino-nucleon CC cross section $(\sigma_{\nu N}^{CC} + \sigma_{\nu N}^{CC})/2$ [cm²] versus Neutrino energy E_ν [GeV]. The y-axis ranges from 10^{-35} to 10^{-31} , and the x-axis ranges from 10^4 to 10^{11} GeV. The plot is divided into regions for different physical processes: 'Testable today' (pink), 'Testable next decade' (blue), and 'Standard Model (perturbative)' (yellow). Key features include 'Large extra dimensions' (dashed red line), 'Spontaneous' (dashed orange line), and 'Color glass condensates' (dashed orange line). Experimental constraints are shown for LEP, Tevatron, LHC, FCC, and GZK. IceCube tracks (green line) and IceCube showers (blue stars) are also plotted.

Figure 1 is a ternary plot showing the fraction of neutrino flavors (ν_e , ν_μ , ν_τ) for different neutrino experiments. The plot is a triangle with axes labeled "Fraction of ν_e , $f_{e,\oplus}$ ", "Fraction of ν_μ , $f_{\mu,\oplus}$ ", and "Fraction of ν_τ , $f_{\tau,\oplus}$ ". The plot shows the 2015 99.7% C.L. region for ν_1 (blue circle), ν_2 (orange square), and ν_3 (purple triangle). It also shows the 2020 (proj.) IC 15 yr (99.7% C.R.) region (blue dashed line), the 2040 (proj.) IC 15 yr Gen2 10 yr (99.7% C.R.) region (orange dashed line), and the 2040 (proj.) Combined ν telescopes (99.7% C.R.) region (blue solid line). The plot is labeled "ν decay" and "All regions 99.7% C.R."

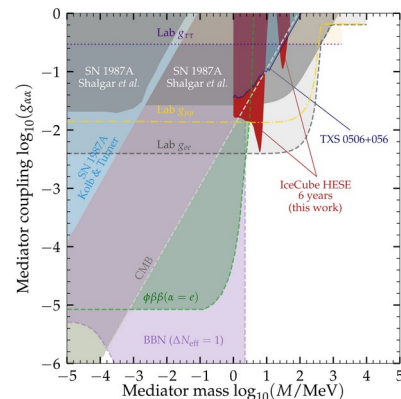
MB & Agarwalla, PRL 2019

TeV–EeV ν cross sections



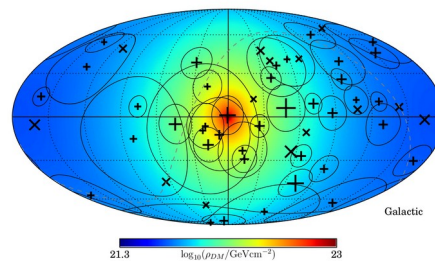
MB & Connolly, PRL 2019

ν self-interactions



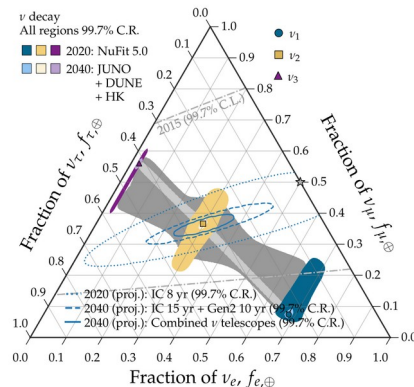
MB, Rosenström, Shalgar, Tamborra, PRD 2020

ν scattering on Galactic DM



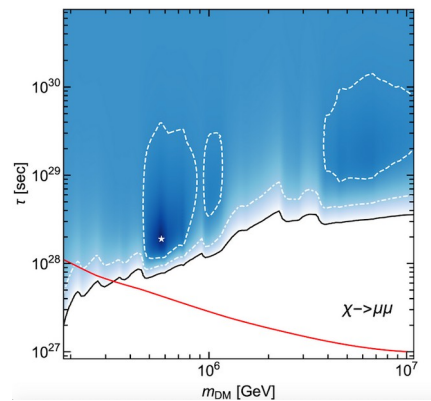
Argüelles, Kheirandish, Vincent, PRL 2017

ν decay



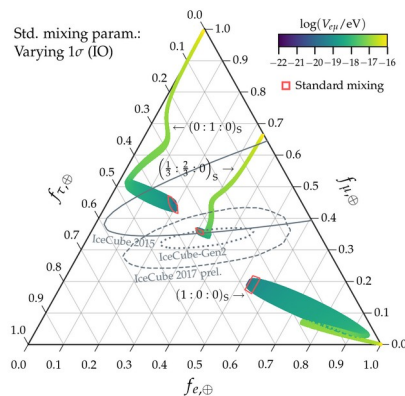
Song, Li, Argüelles, MB, Vincent, JCAP 2021

Dark matter decay



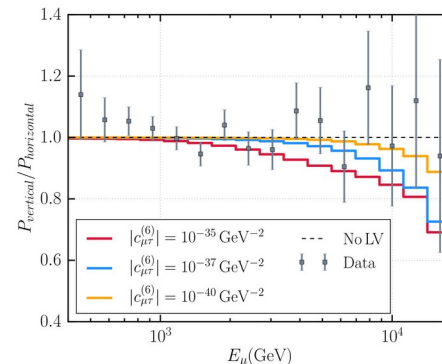
Chianese, Fiorillo, Miele, Morisi, Pisanti, JCAP 2019

ν -electron interaction



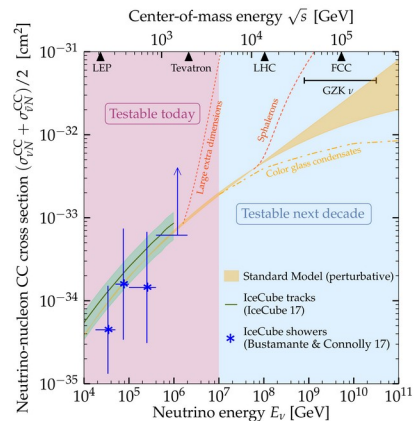
MB & Agarwalla, PRL 2019

Lorentz-invariance violation



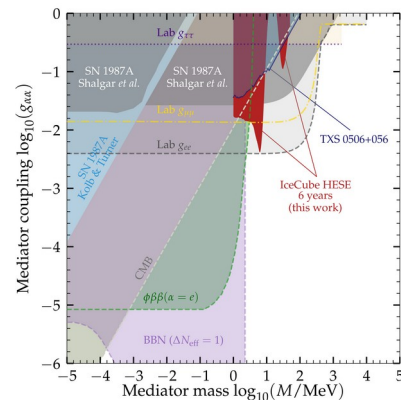
IceCube, Nature Phys. 2018

TeV–EeV ν cross sections



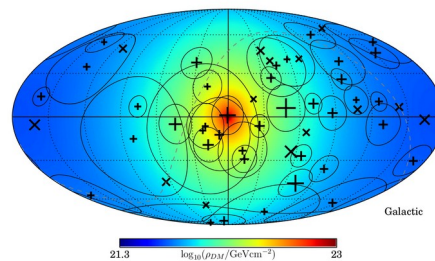
MB & Connolly, PRL 2019

ν self-interactions



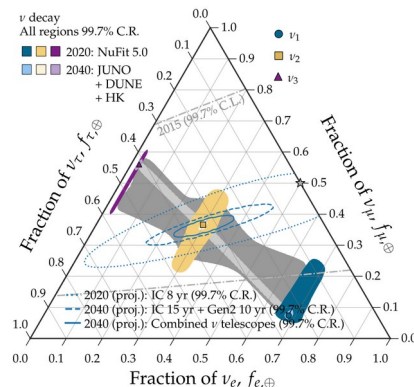
MB, Rosenström, Shalgar, Tamborra, PRD 2020

ν scattering on Galactic DM



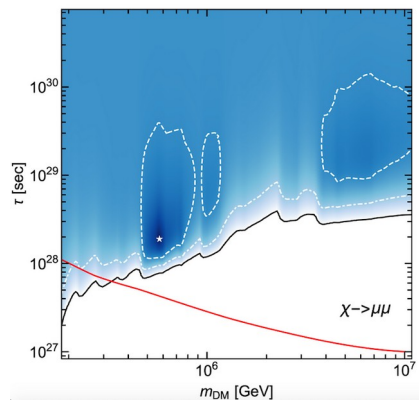
Argüelles, Kheirandish, Vincent, PRL 2017

ν decay



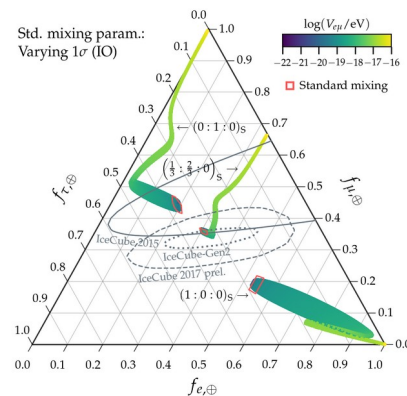
Song, Li, Argüelles, MB, Vincent, JCAP 2021

Dark matter decay



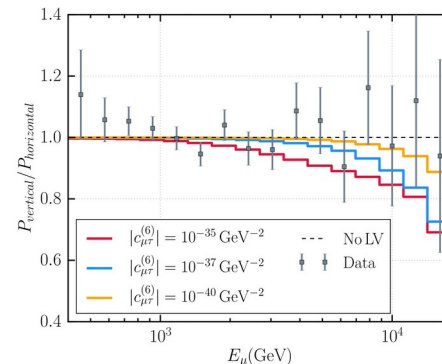
Chianese, Fiorillo, Miele, Morisi, Pisanti, JCAP 2019

ν -electron interaction



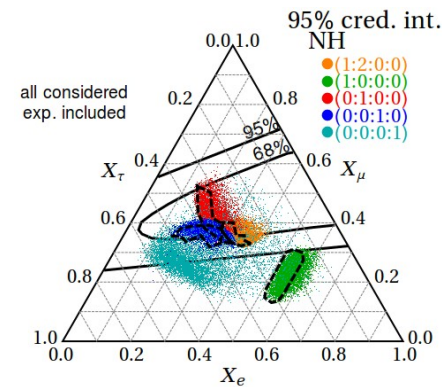
MB & Agarwalla, PRL 2019

Lorentz-invariance violation



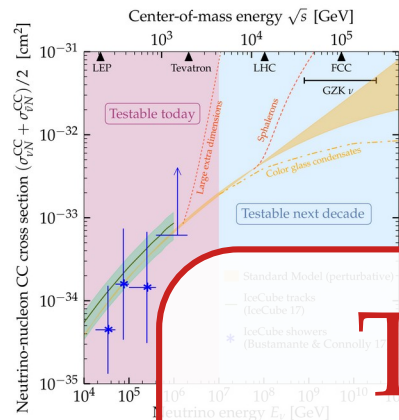
IceCube, Nature Phys. 2018

Sterile neutrinos



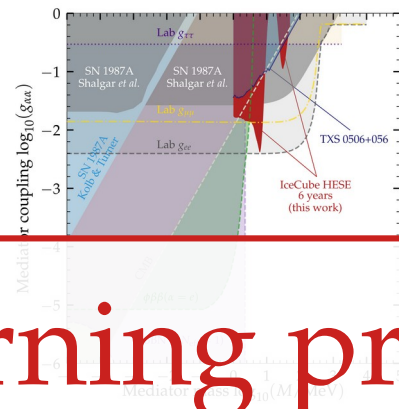
Brdar, Kopp, Wang, JCAP 2017

TeV–EeV ν cross sections



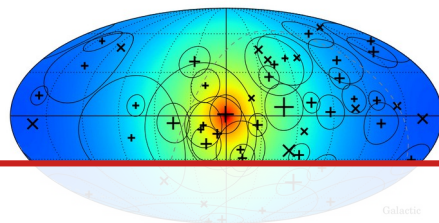
MB & Connolly, PRL 2019

ν self-interactions



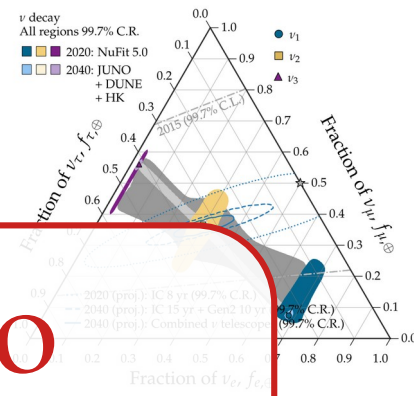
MB, Rosenbaum, Shalgar, Tamborra, PRD 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, PRL 2017

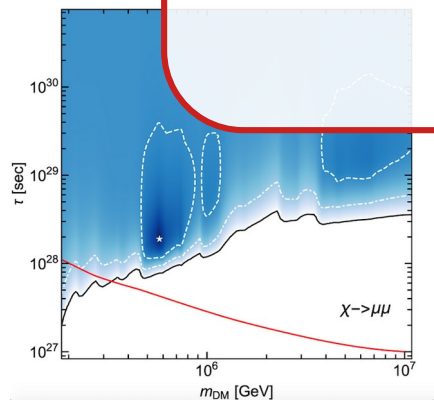
ν decay



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

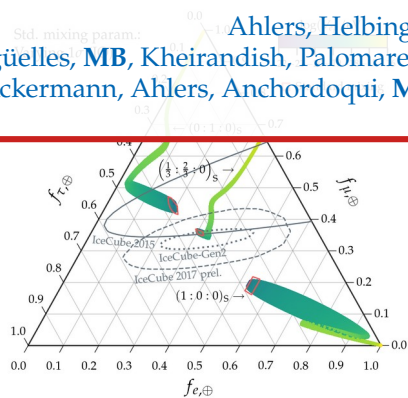
Turning predictions into data-driven tests

Dark matter decay



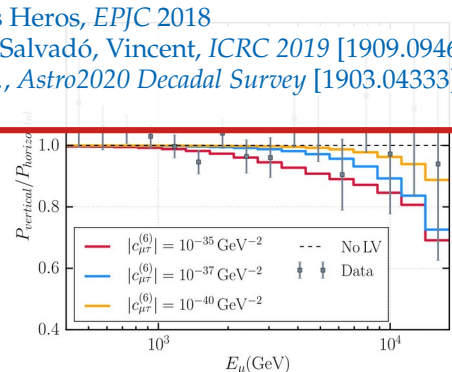
Chianese, Fiorillo, Miele, Morisi, Pisanti, JCAP 2019

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]



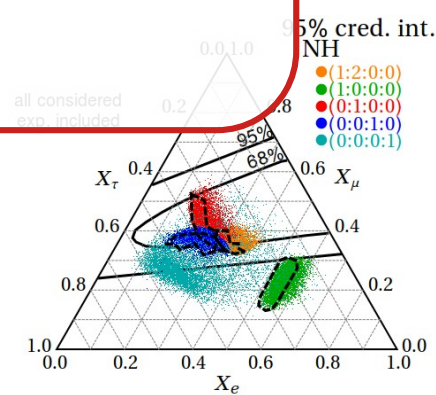
MB & Agarwalla, PRL 2019

Light in the dark sector



IceCube, Nature Phys. 2018

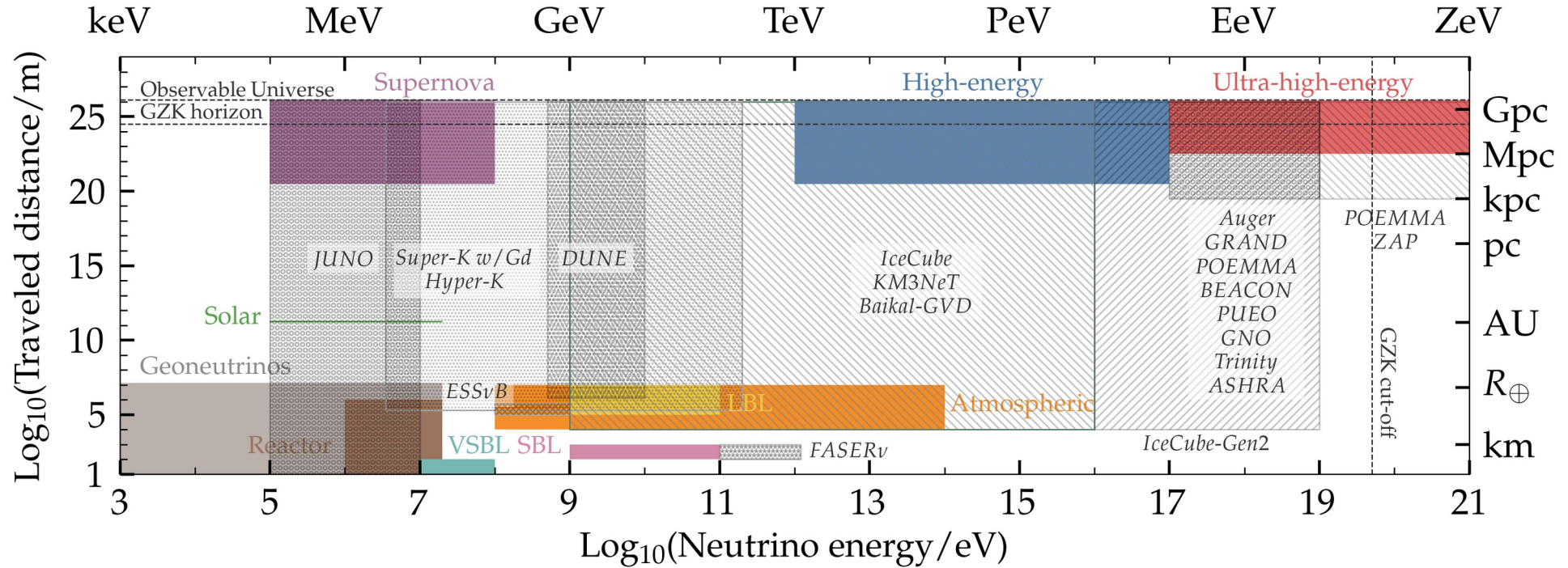
Sterile neutrinos



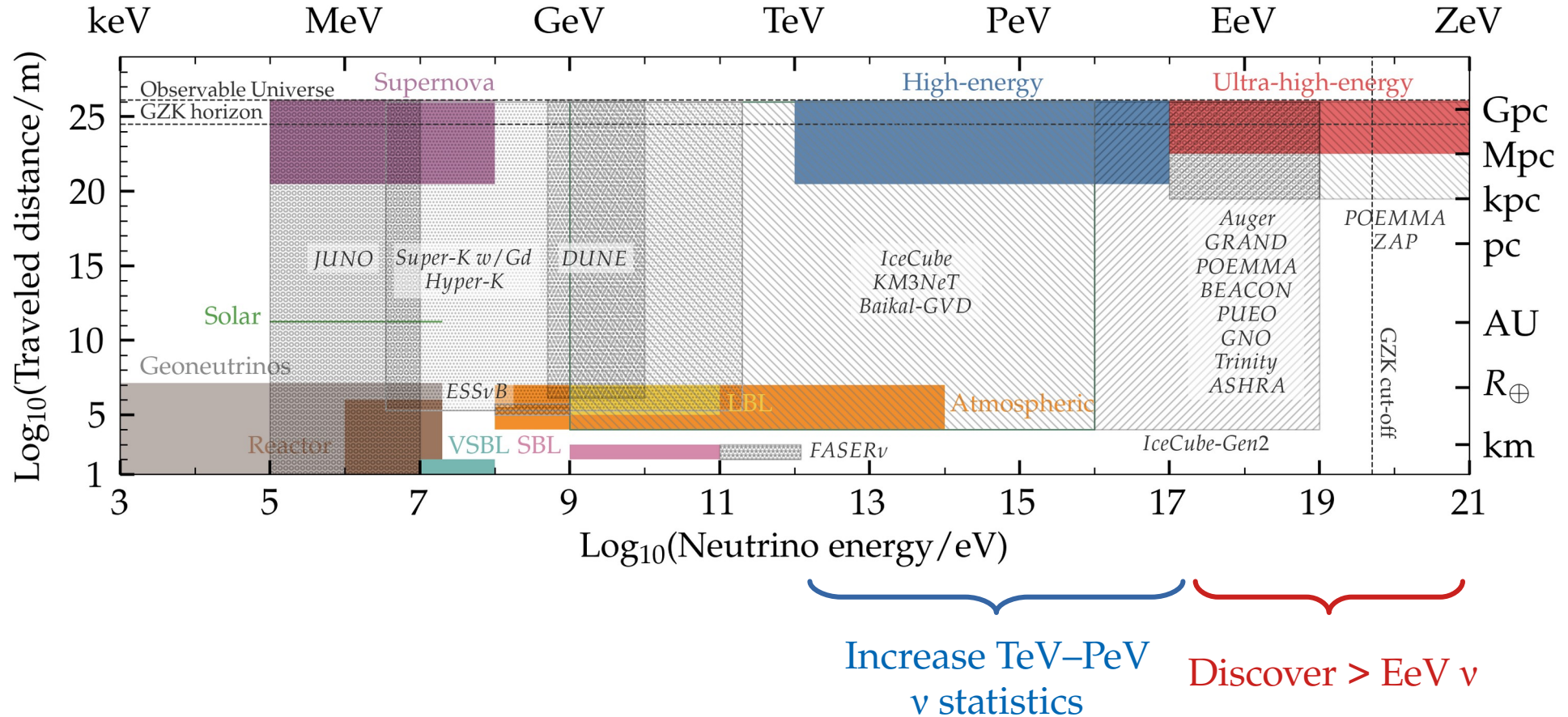
Brdar, Kopp, Wang, JCAP 2017

IV. The future

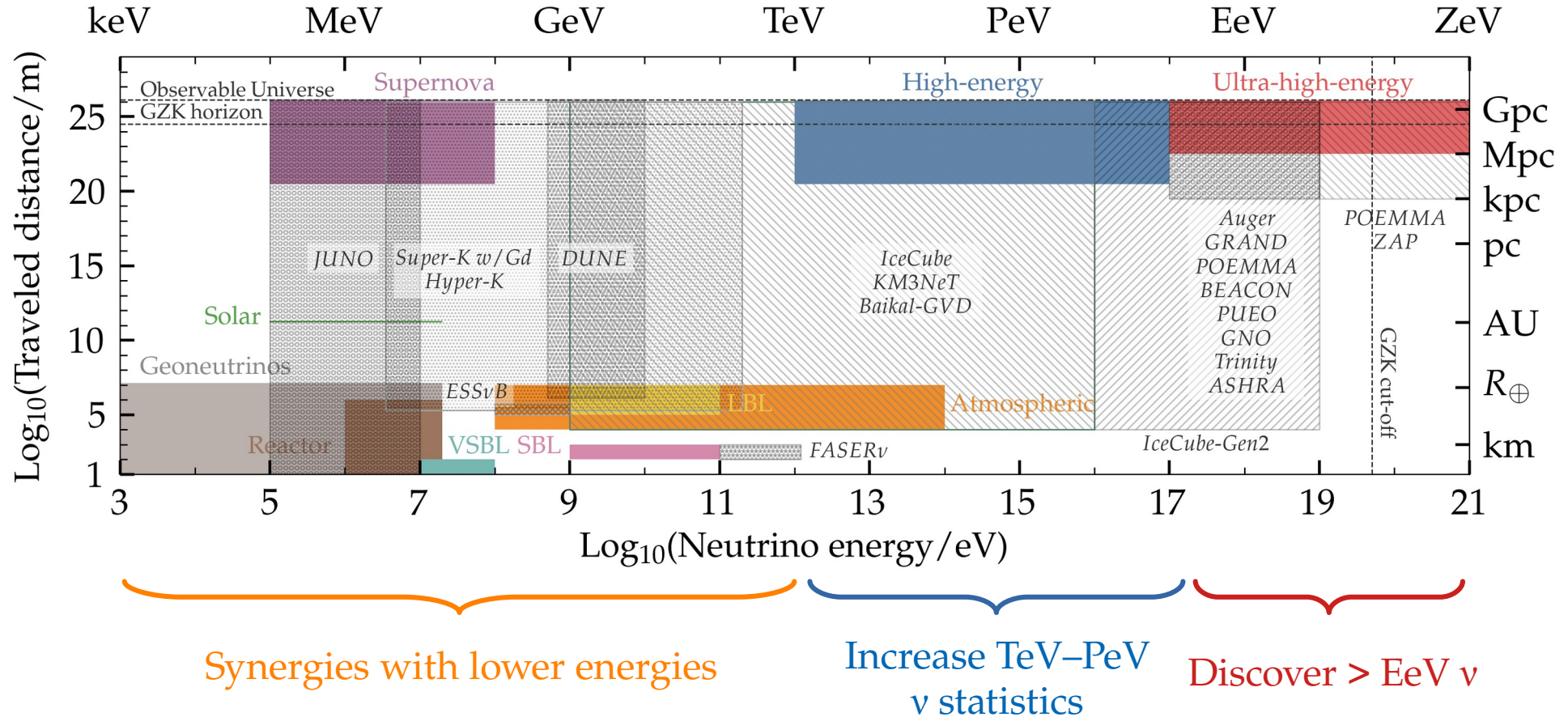
Next decade: a host of planned neutrino detectors

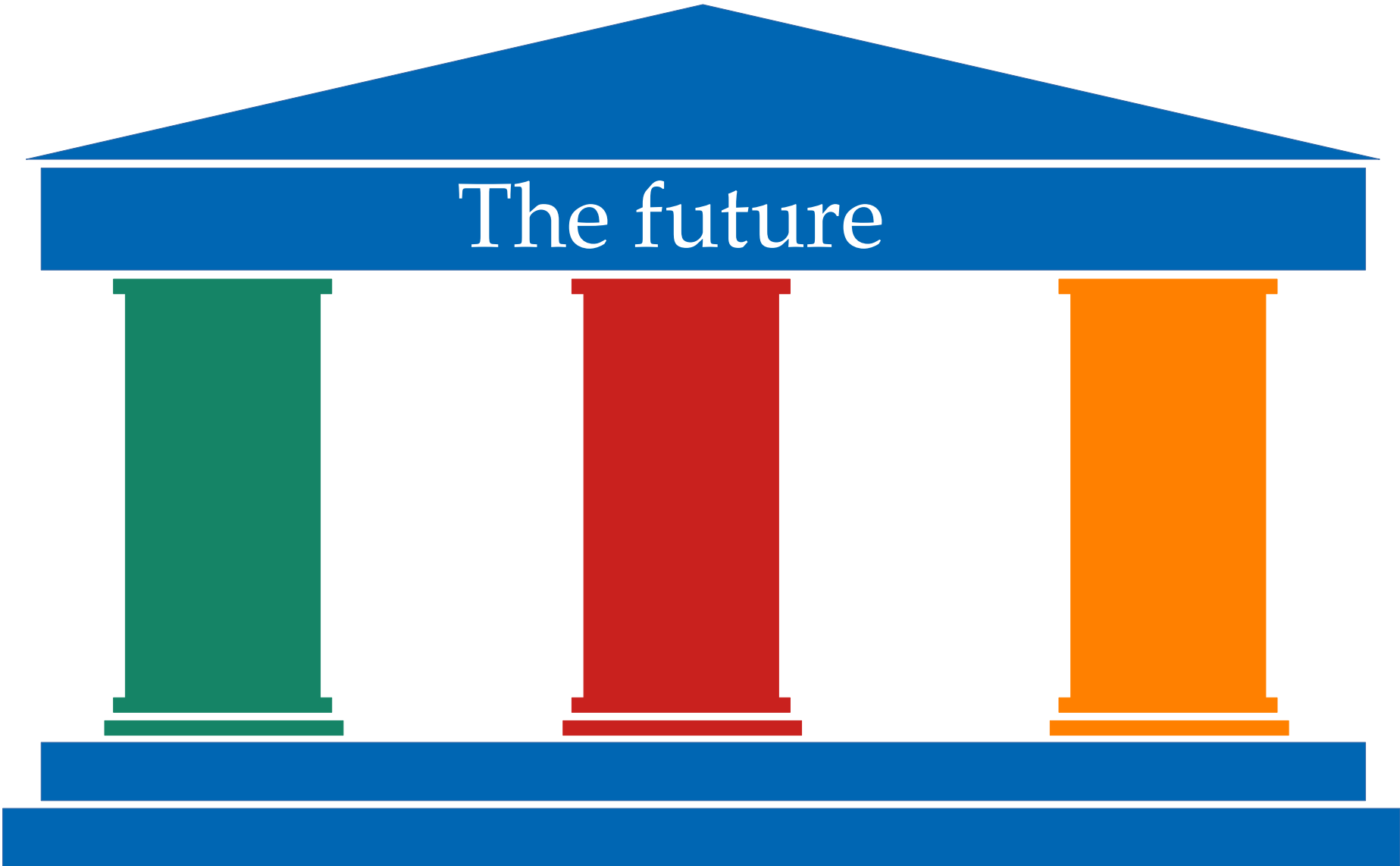


Next decade: a host of planned neutrino detectors

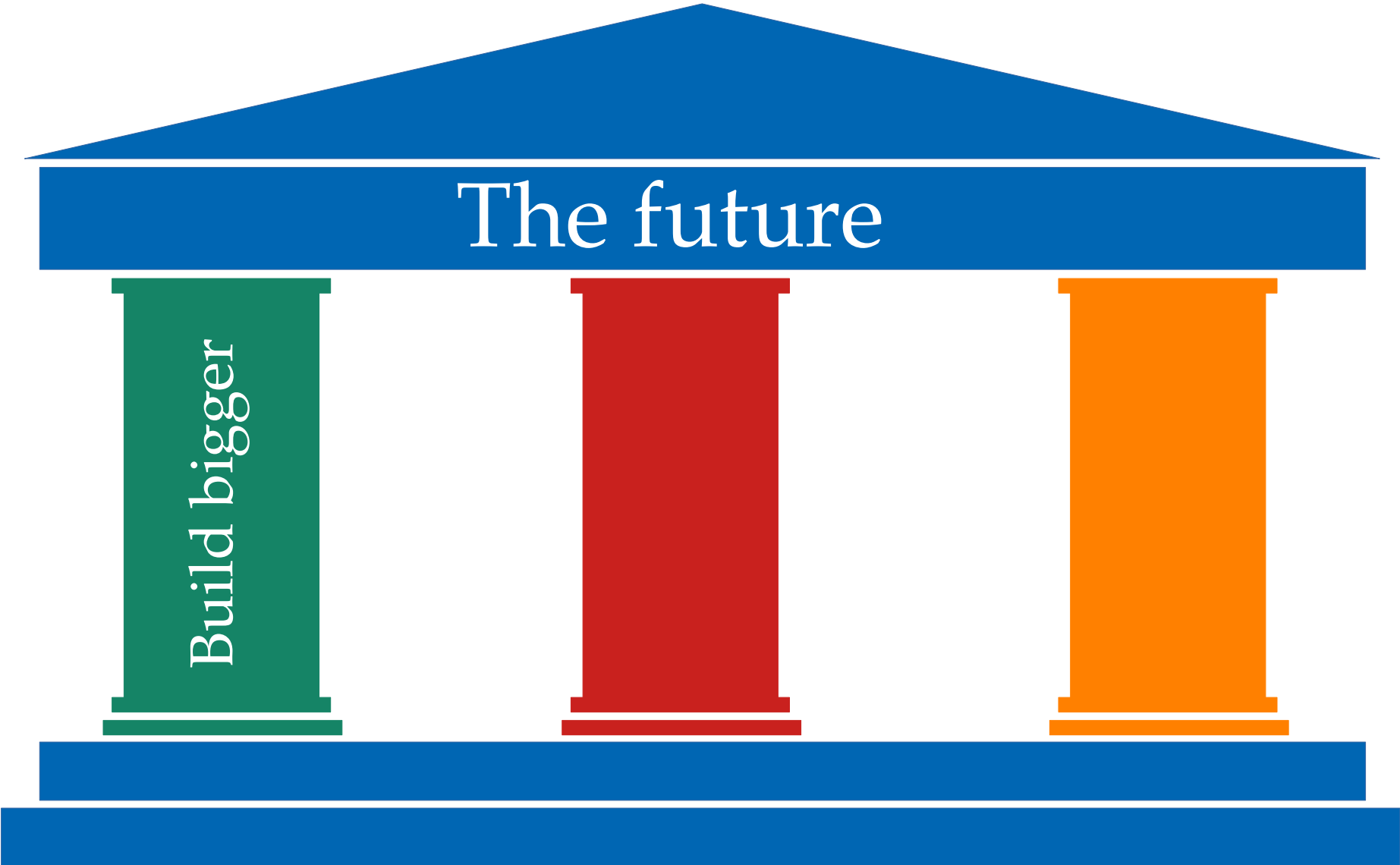


Next decade: a host of planned neutrino detectors



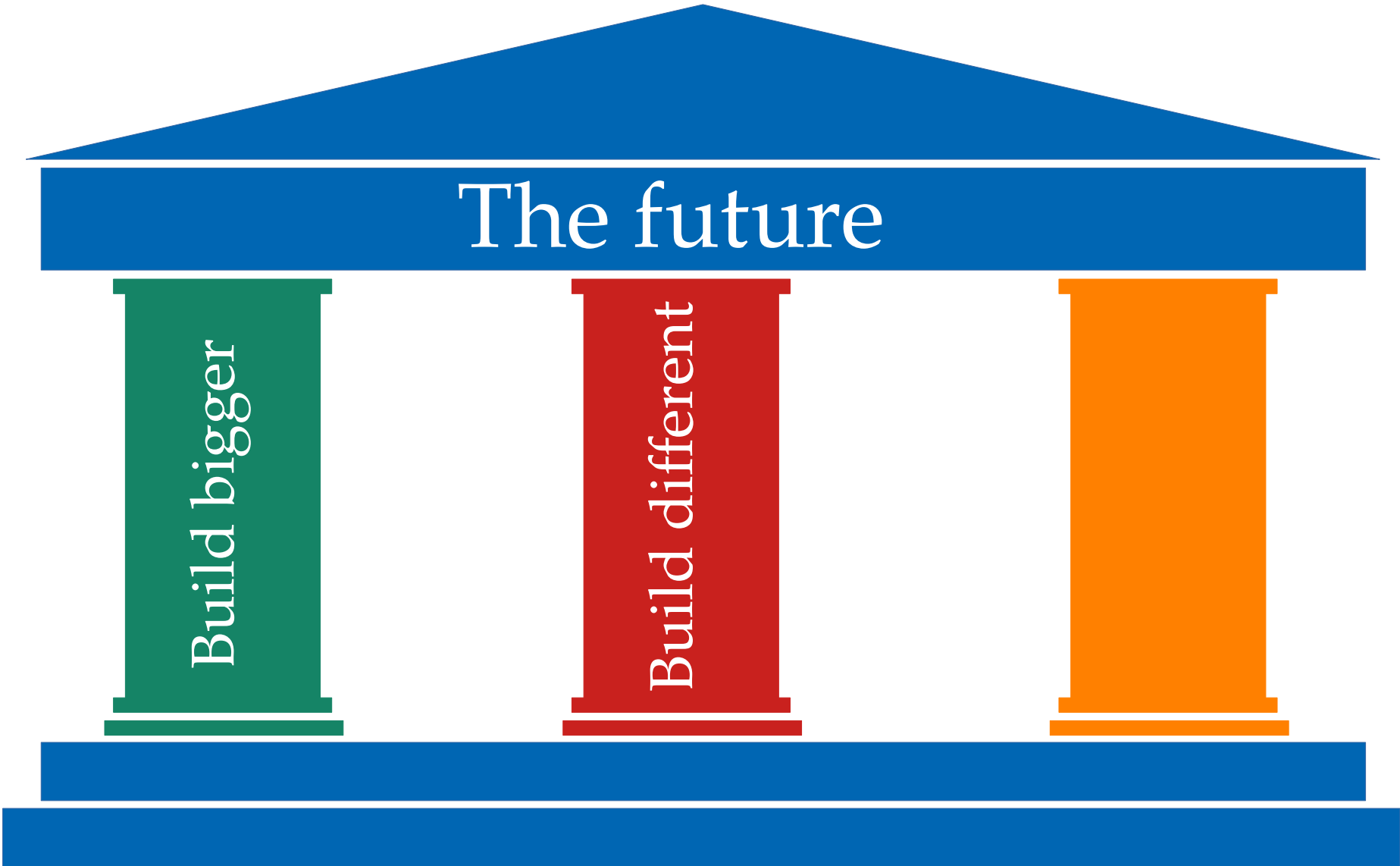


The future



The future

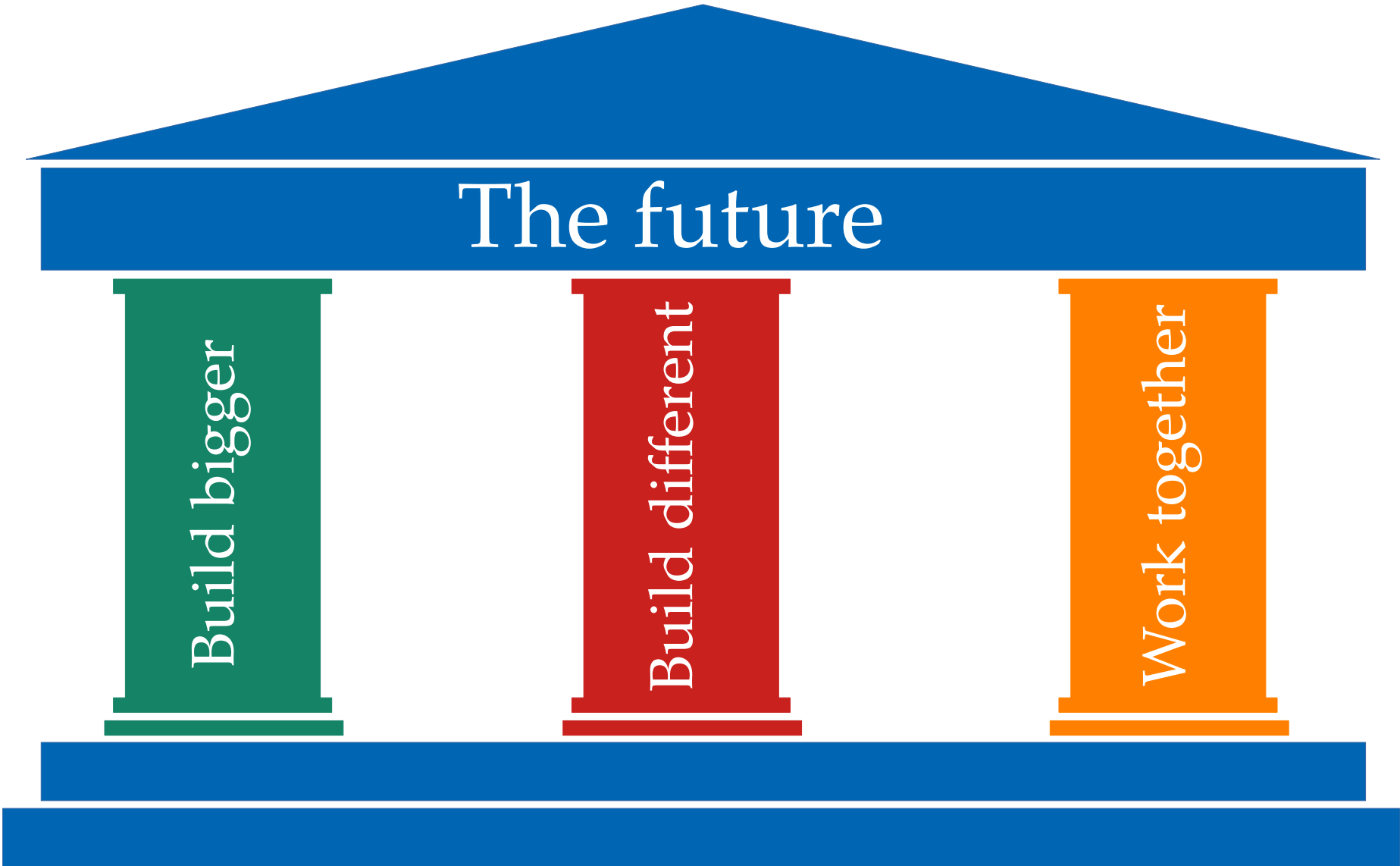
Build bigger



The future

Build bigger

Build different

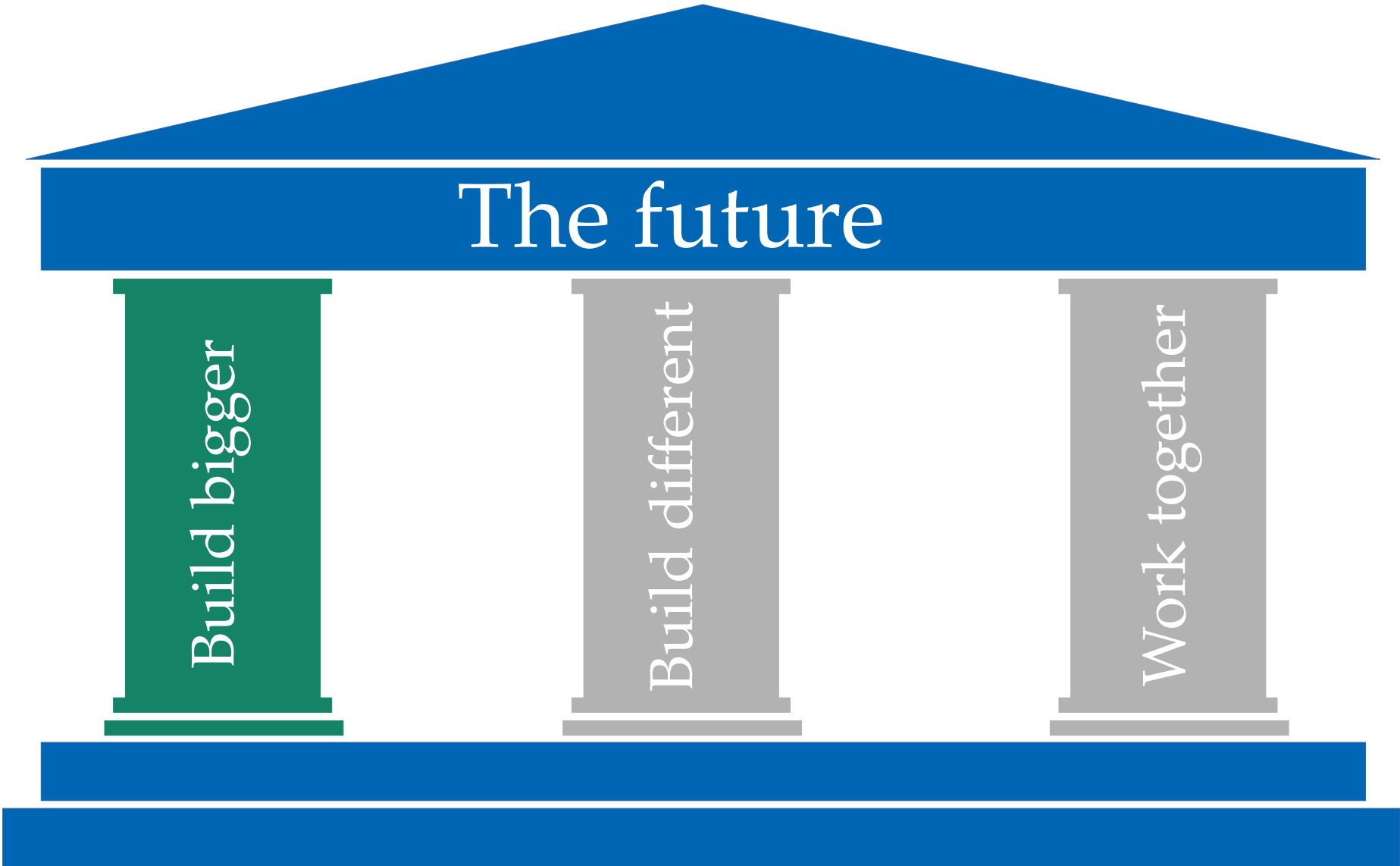


The future

Build bigger

Build different

Work together



The future

Build bigger

Build different

Work together

Redshift

$z = 0$

Discovered

MeV γ

PeV p

TeV–PeV ν

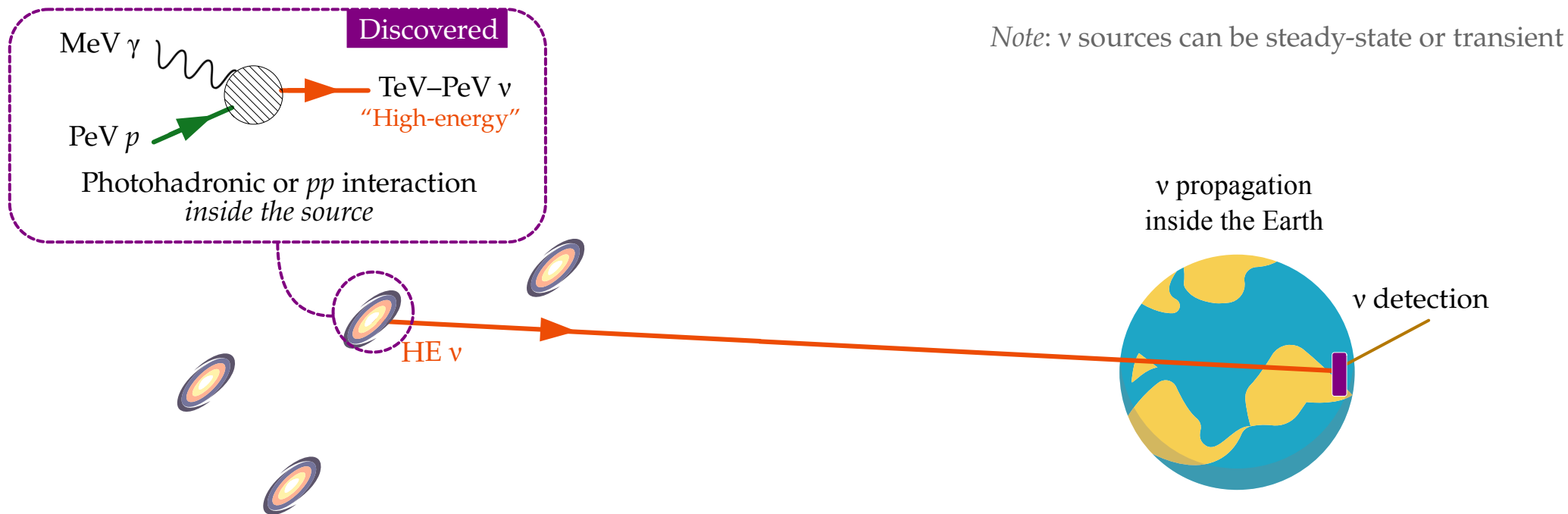
“High-energy”

Photohadronic or pp interaction
inside the source

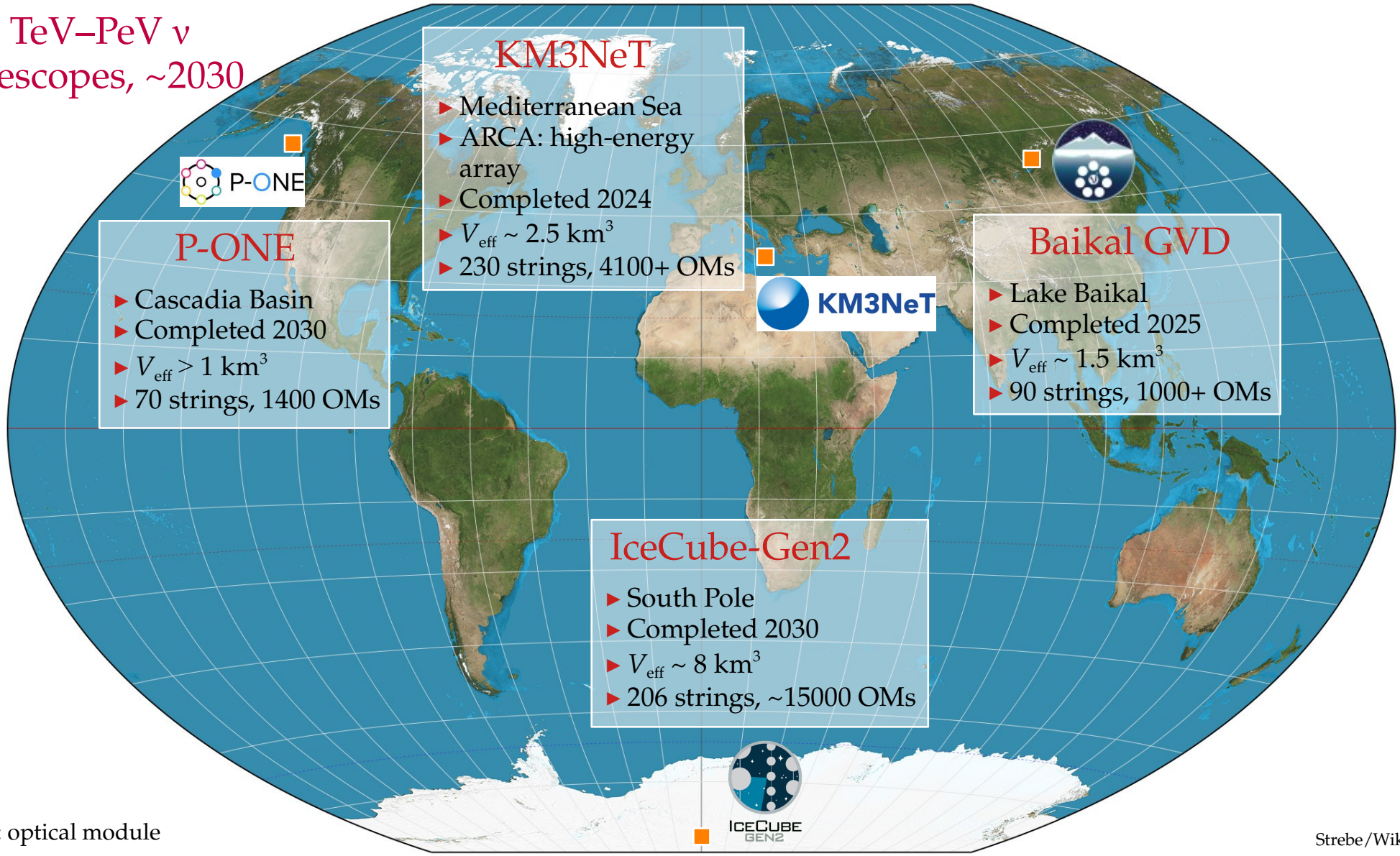
Note: ν sources can be steady-state or transient

ν propagation
inside the Earth

ν detection



TeV–PeV ν
telescopes, ~2030



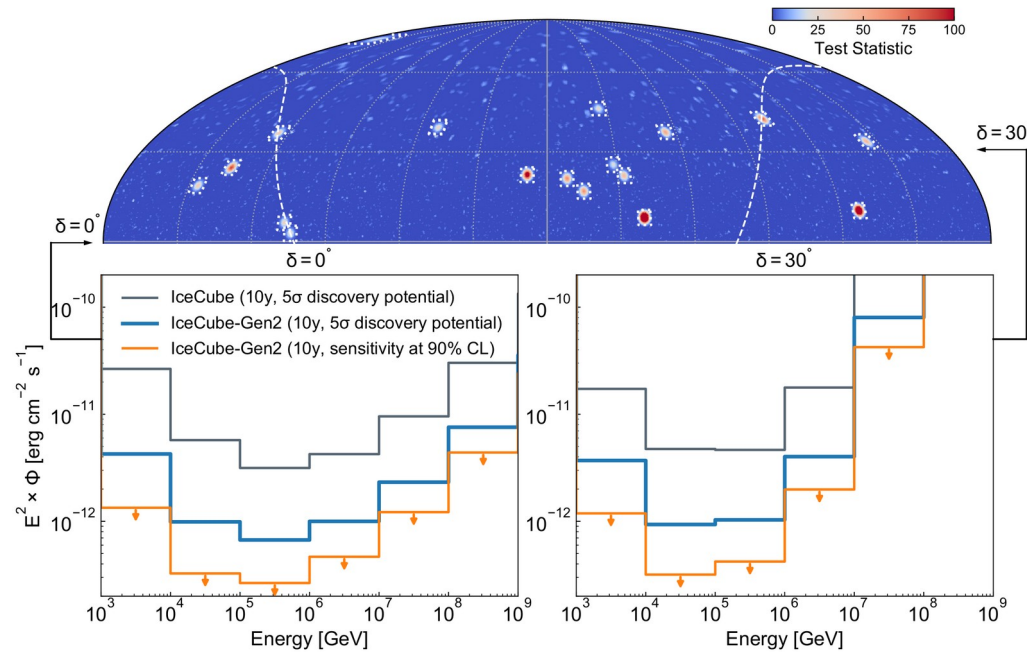
OM: optical module

Point-source limits

Point-source limits

IceCube-Gen2 (optical)

Northern sky

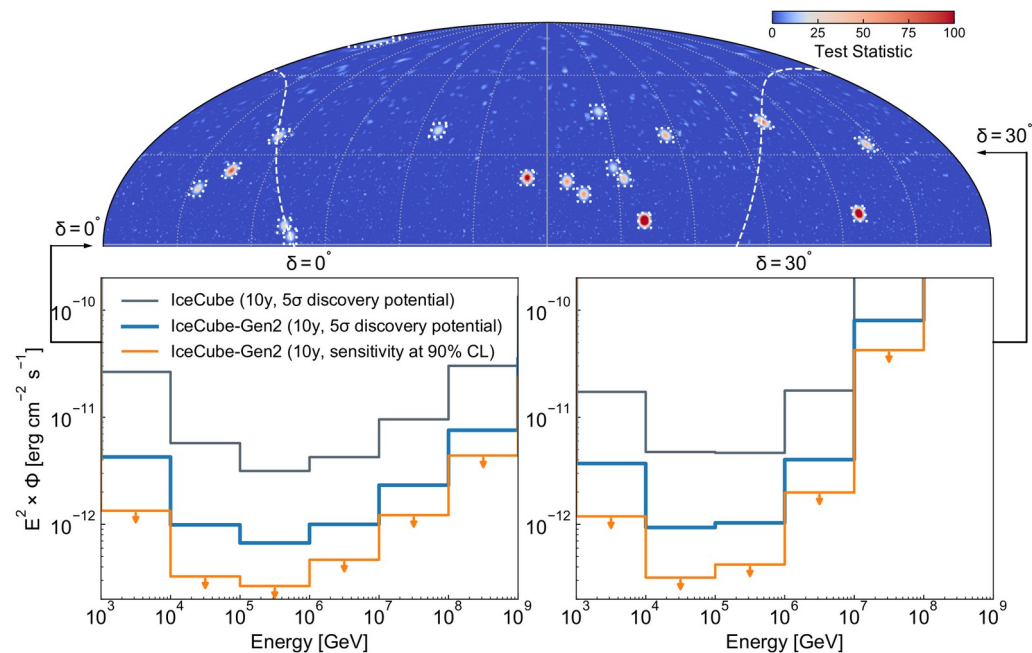


IceCube-Gen2, *J. Phys. G* 2021

Point-source limits

IceCube-Gen2 (optical)

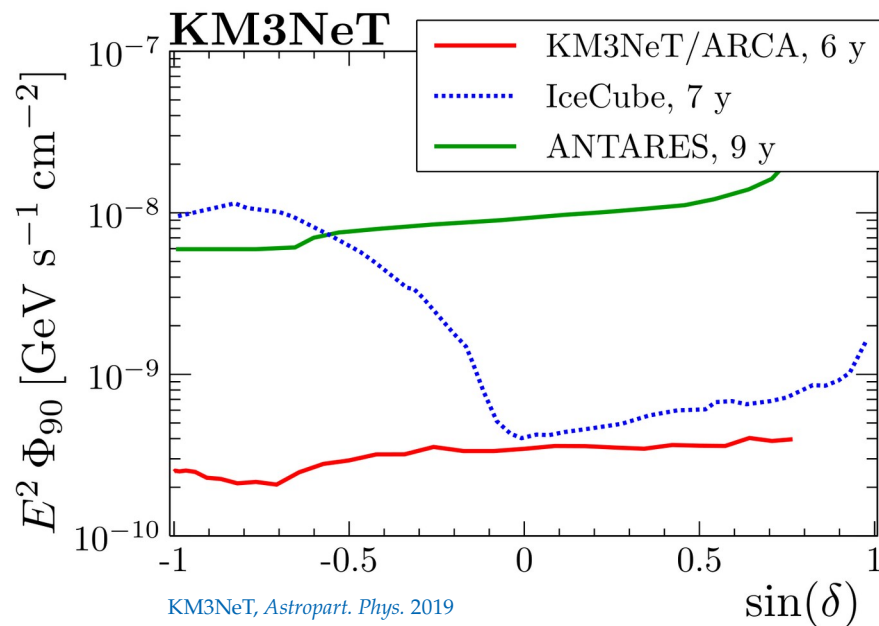
Northern sky



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

KM3NeT

Southern sky

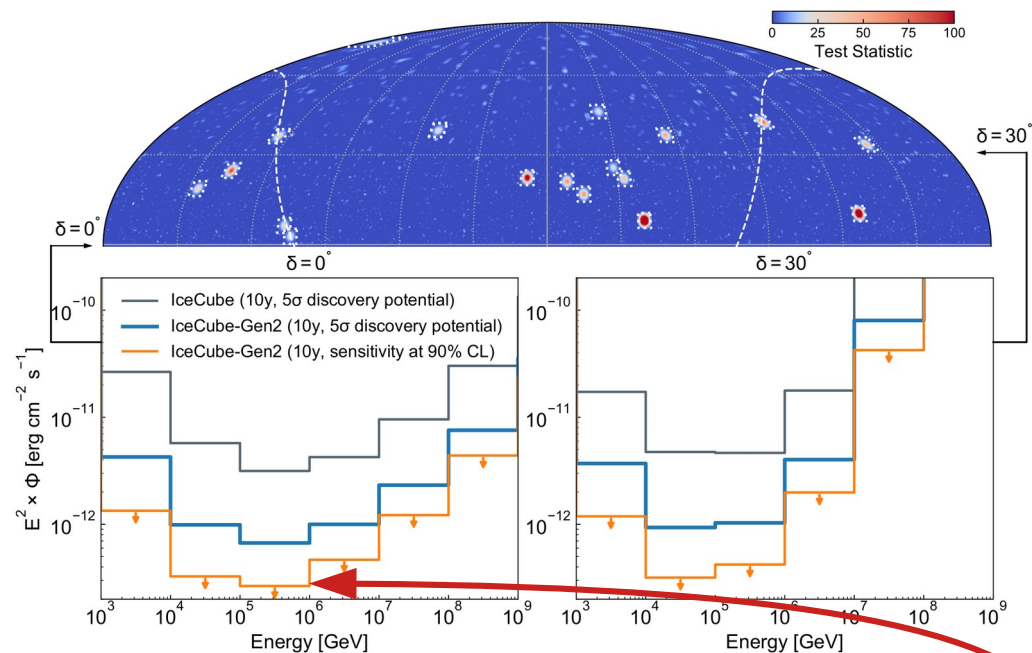


KM3NeT, *Astropart. Phys.* 2019

Point-source limits

IceCube-Gen2 (optical)

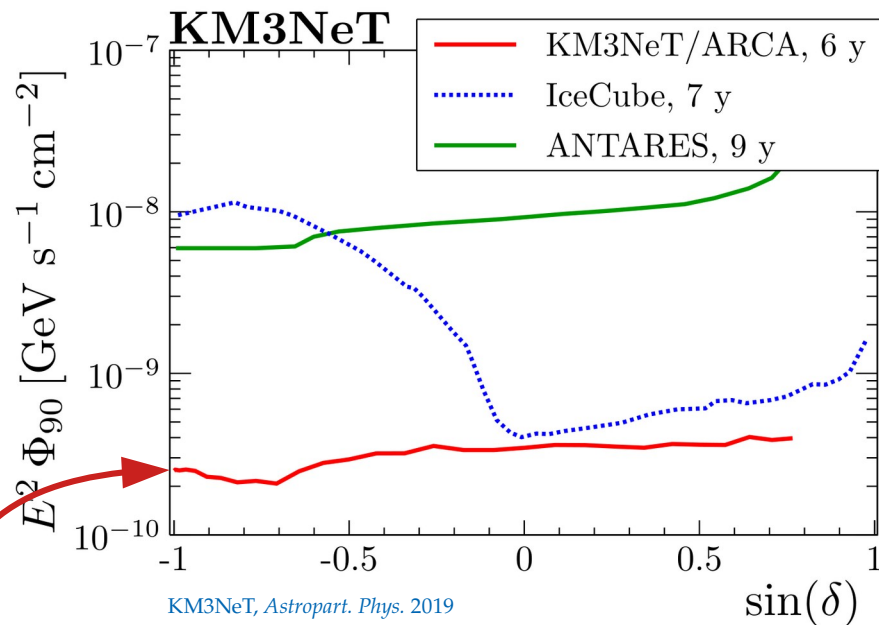
Northern sky



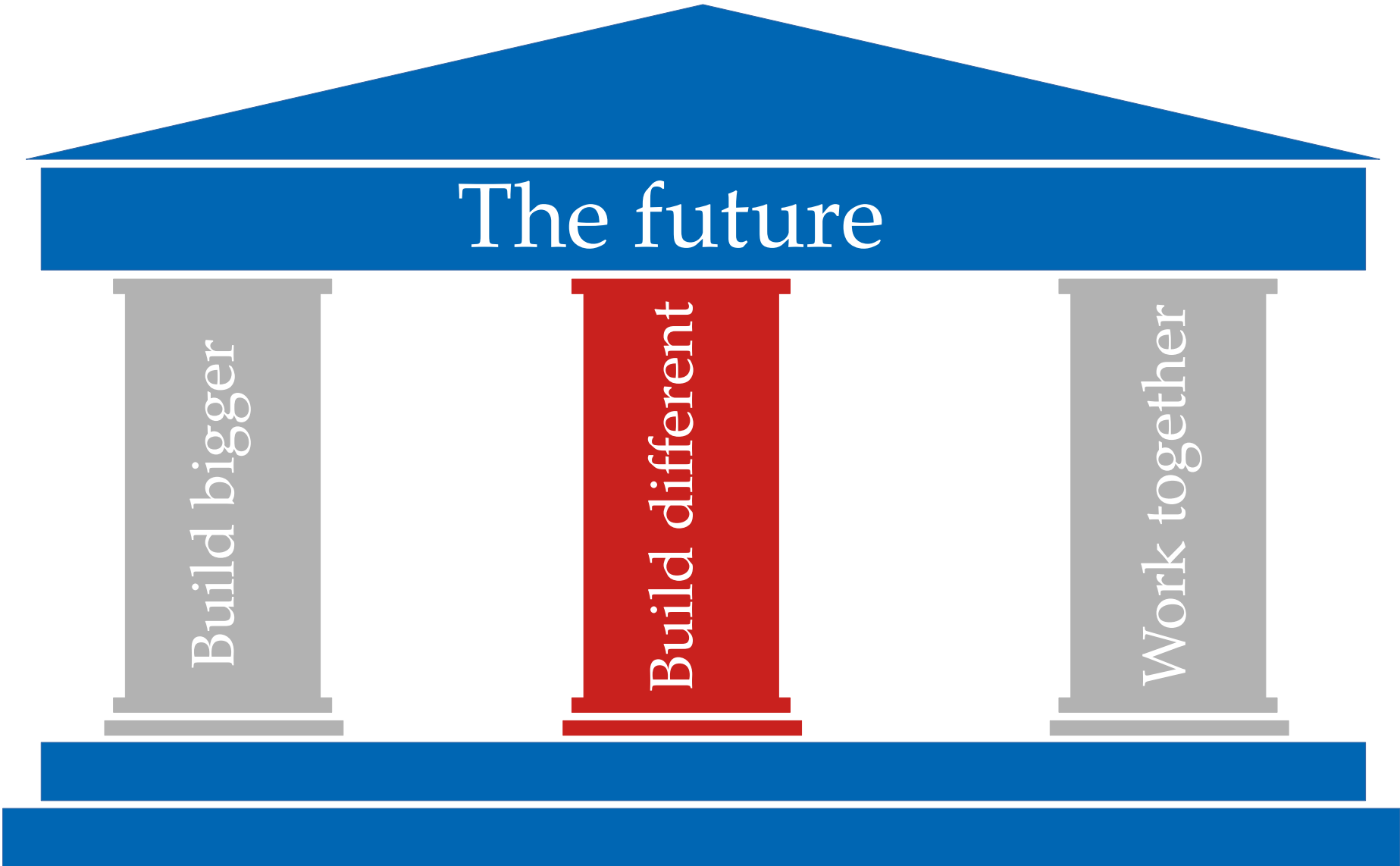
IceCube-Gen2, *J. Phys. G* 2021

KM3NeT

Southern sky



We will reach comparable sensitivity in both hemispheres



The future

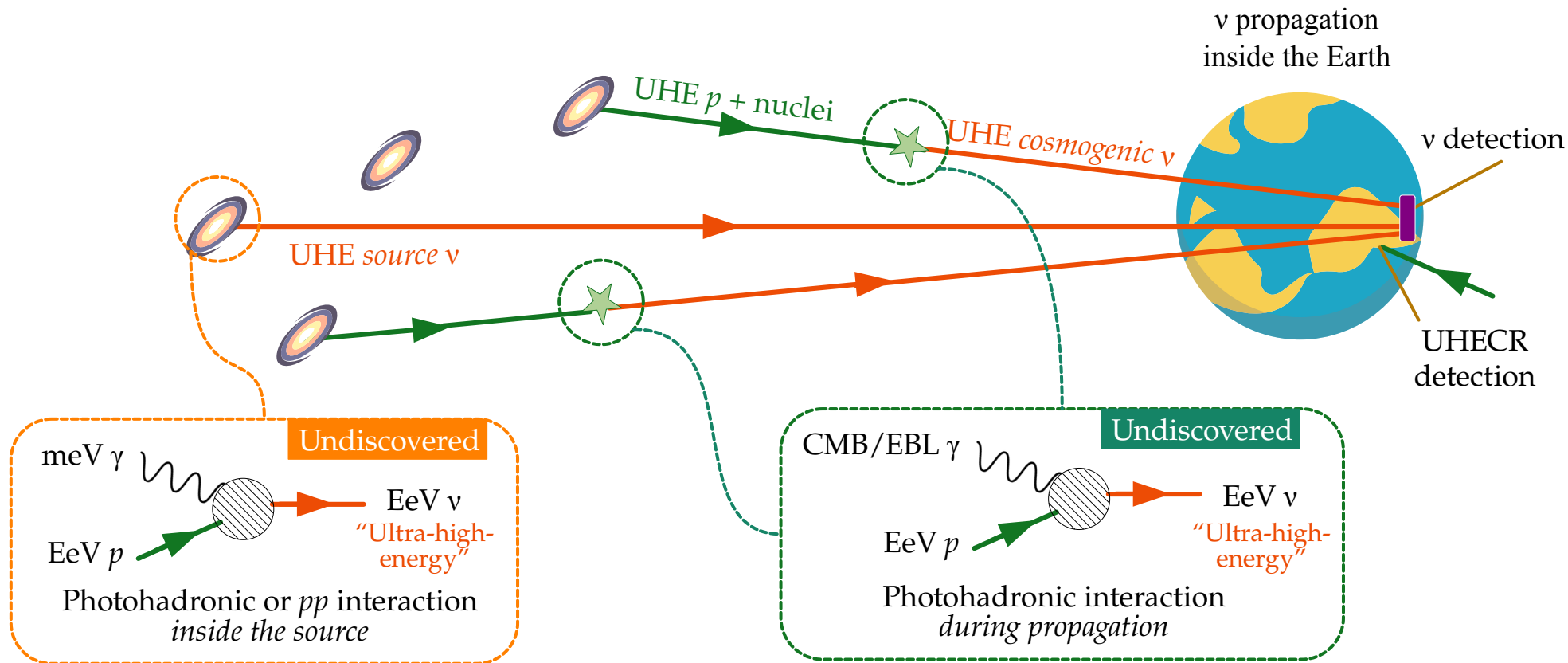
Build bigger

Build different

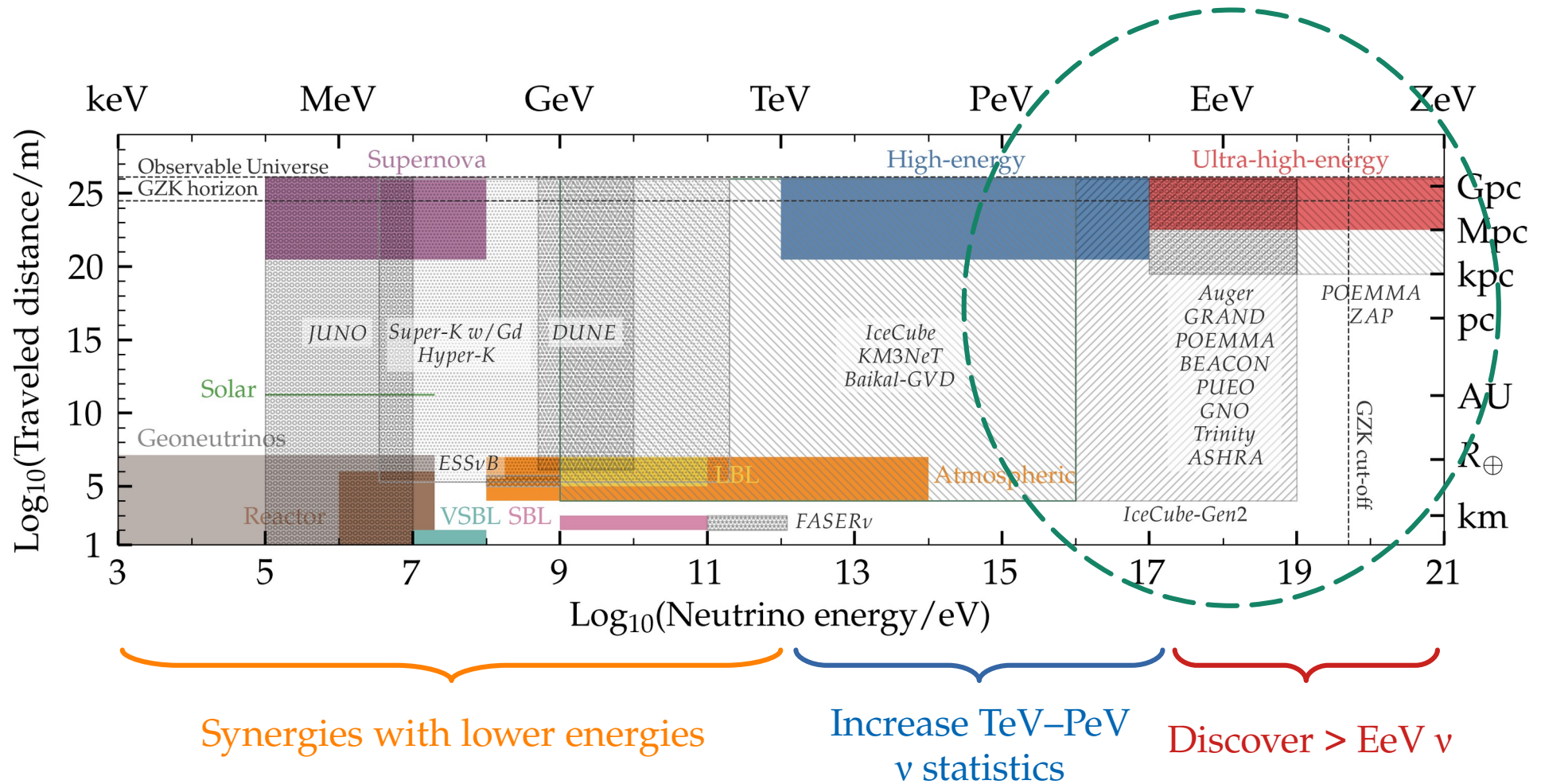
Work together

Redshift ← $z = 0$

Note: ν sources can be steady-state or transient



Next decade: a host of planned neutrino detectors



Detection of UHE ν in ice and water

Optical detection in ice or water

 IceCube $\rightarrow$ IceCube-Gen2 
 ANTARES $\rightarrow$ KM3NeT 
 NT200+ $\rightarrow$ Baikal GVD 
 P-ONE 

Radio detection in ice

ARA 
 ARIANNA 
 RNO-G 
 IceCube-Gen2 

Radio detection from the air or space

✓ ANITA $\rightarrow$ PUEO 
 NuMoon ✓

Detection of air showers from UHE ν_τ

Surface particle detection

 Auger $\rightarrow$ AugerPrime 
 TA $\rightarrow$ TA $\times$ 4 
 HAWC 
 TAMBO 

Radio detection in the atmosphere

✓ ANITA $\rightarrow$ PUEO 
 BEACON 
 GRAND 
 TAROGE & TAROGE-M 

Air-shower imaging from the ground

Trinity 
 MAGIC 
 CTA 
 ASHRA NTA 

Cherenkov/fluorescence from air or space

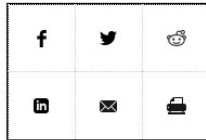
EUISO-SPB2 
 POEMMA 

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

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Katrina Miller for *Scientific American*,
April 27, 2021 [\[link\]](#)

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

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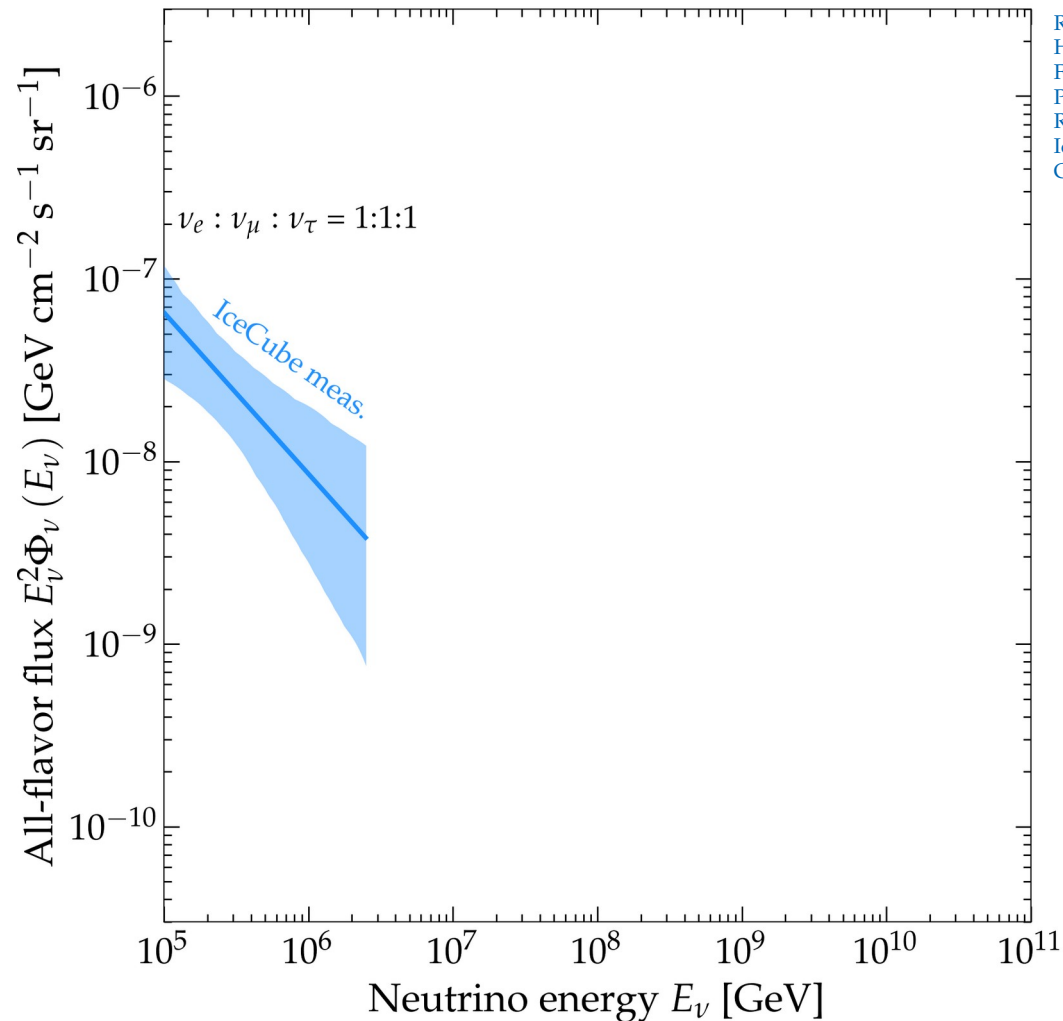
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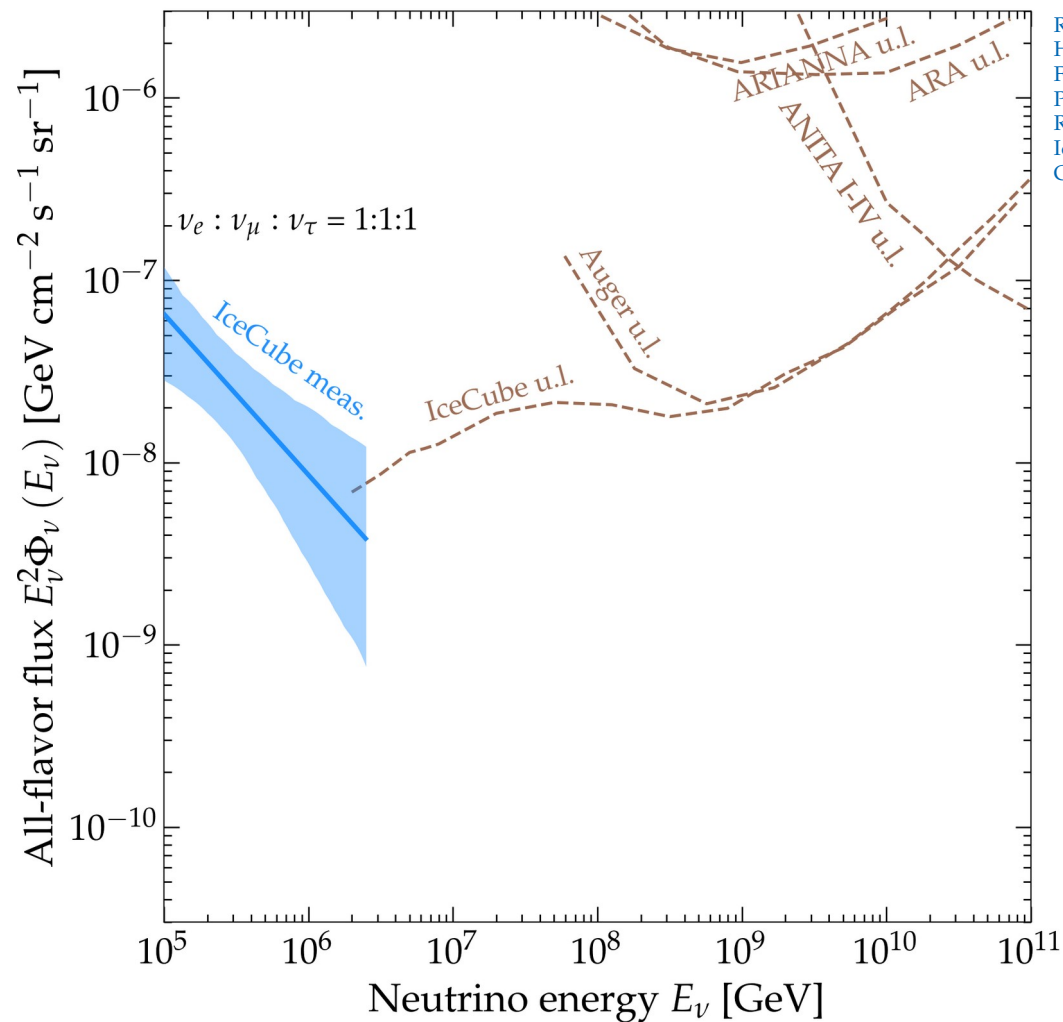
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UHE neutrinos: *steady-state sources*



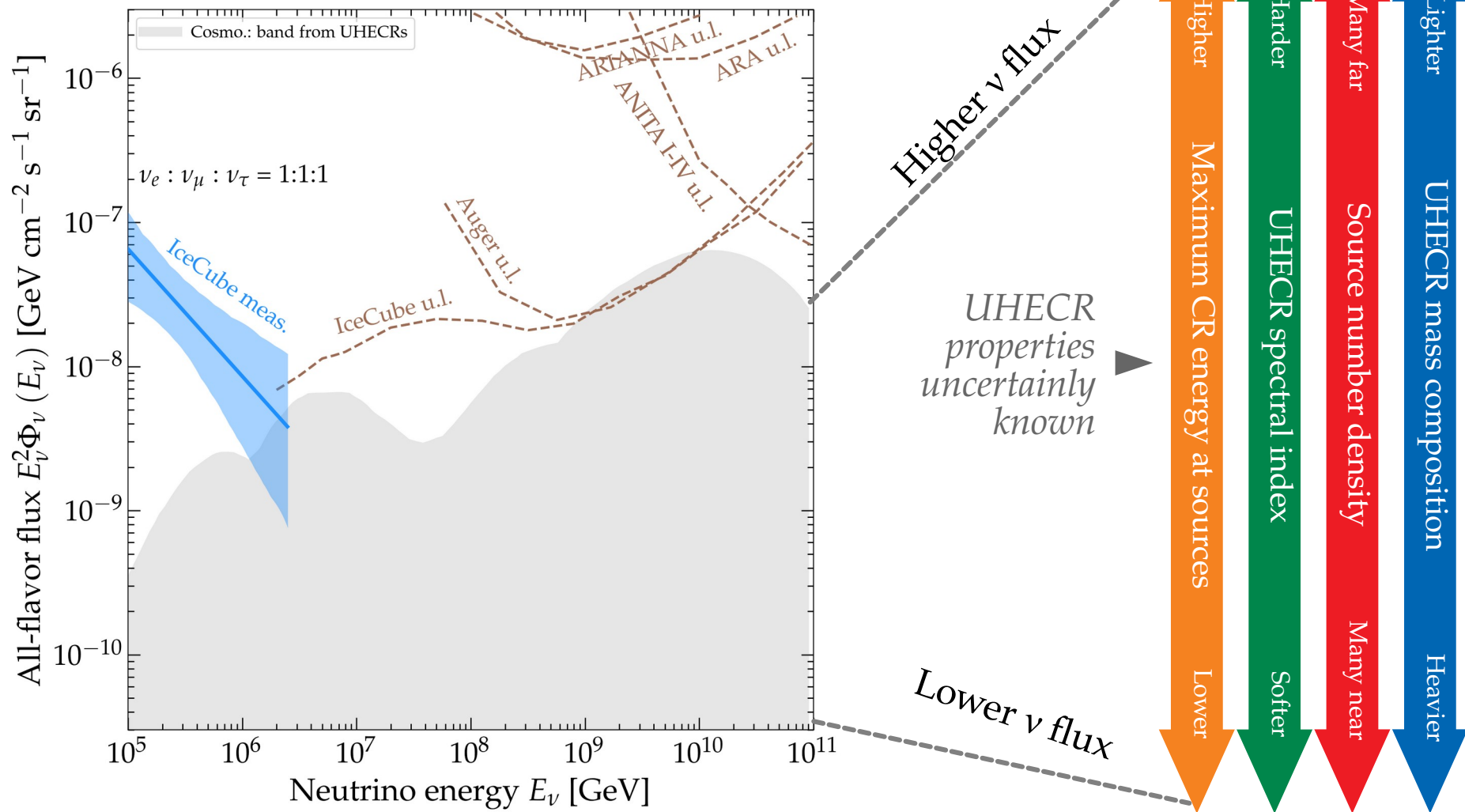
Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
Fang & Murase, *Nature Phys.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020

UHE neutrinos: *steady-state sources*

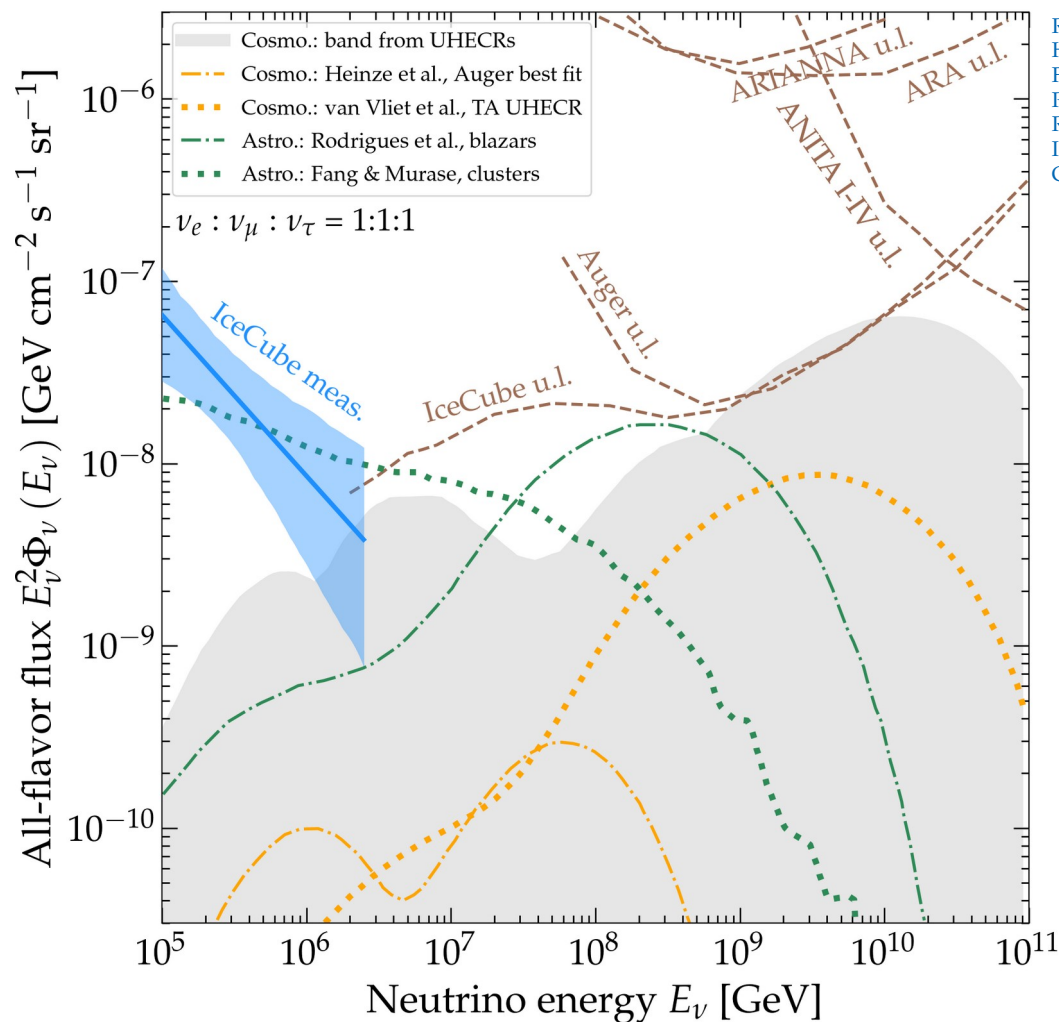


Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
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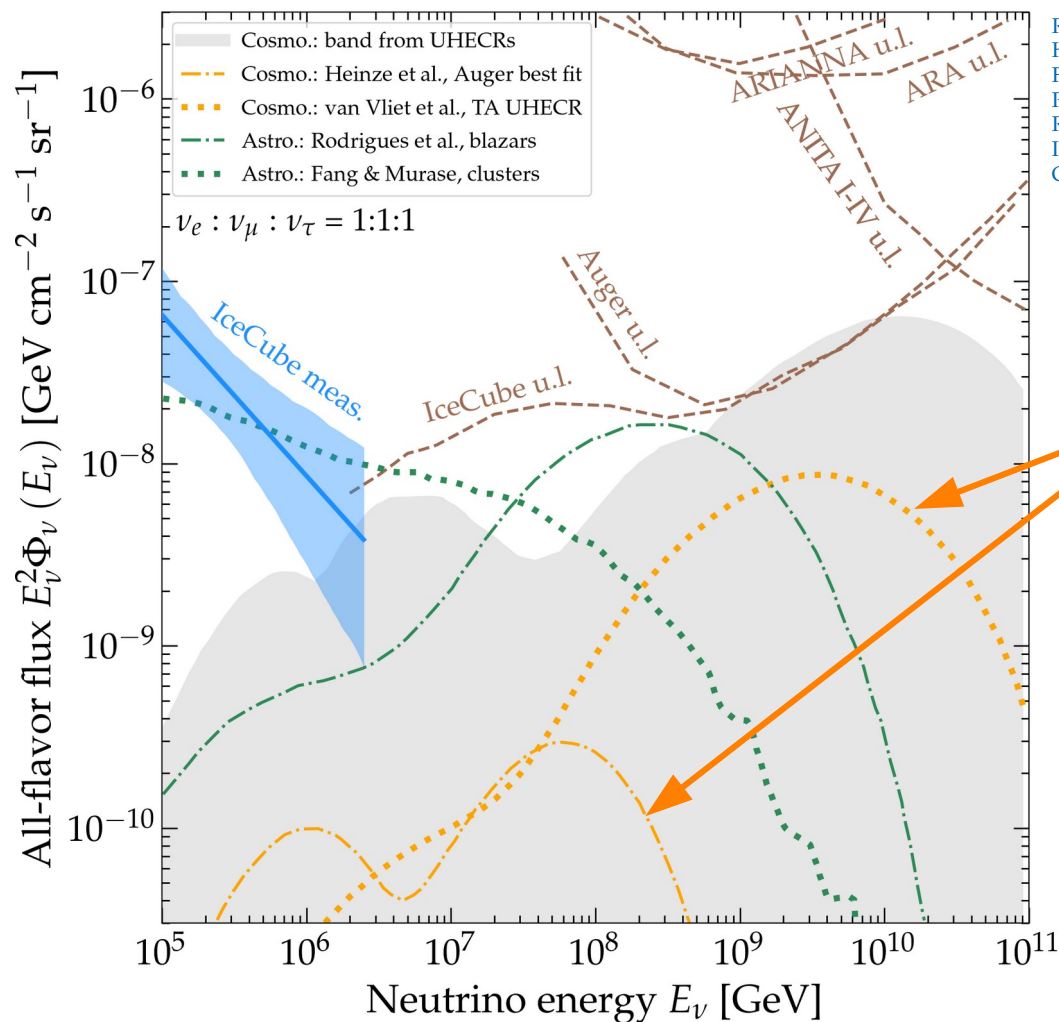


UHE neutrinos: *steady-state sources*



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 GRAND, *Sci. China Phys. Mech. Astron.* 2020

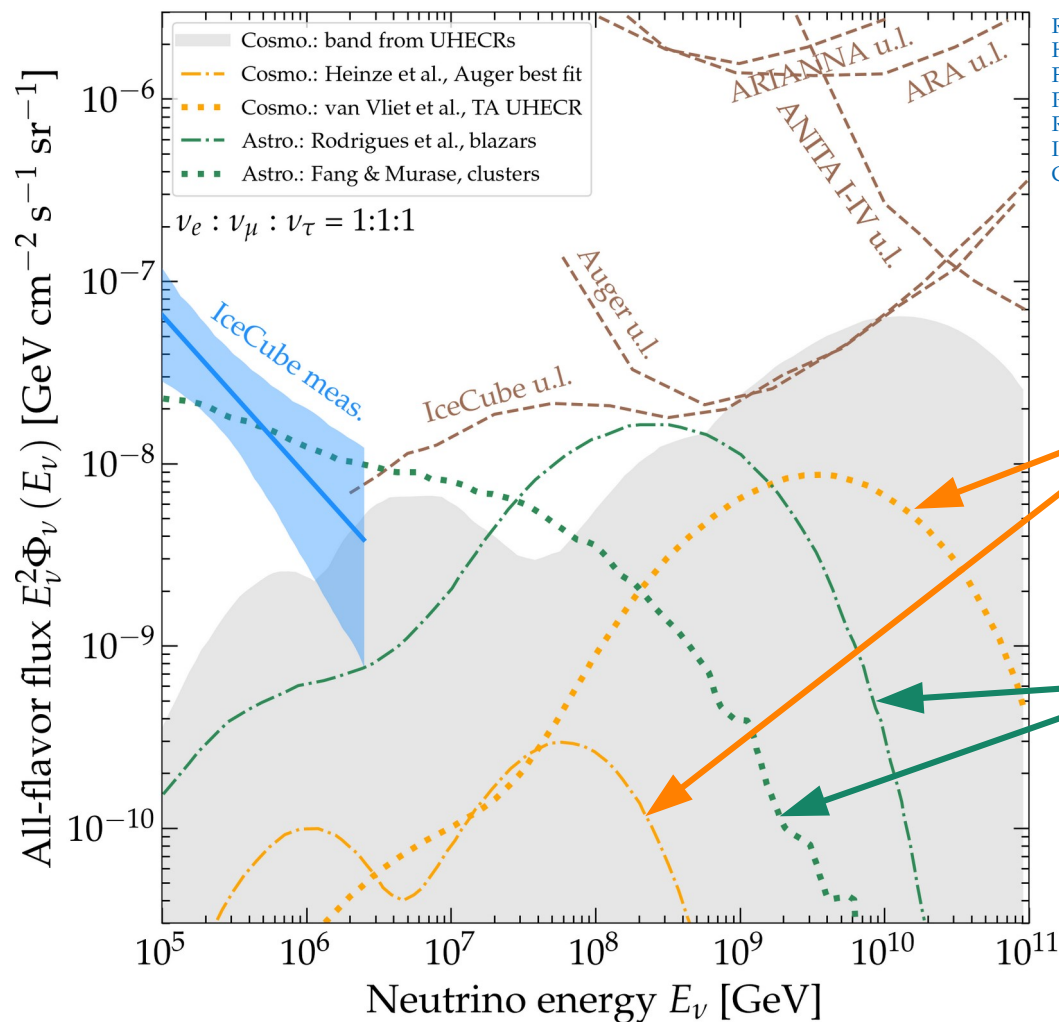
UHE neutrinos: *steady-state sources*



Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
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POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020

Cosmogenic neutrinos

UHE neutrinos: *steady-state sources*

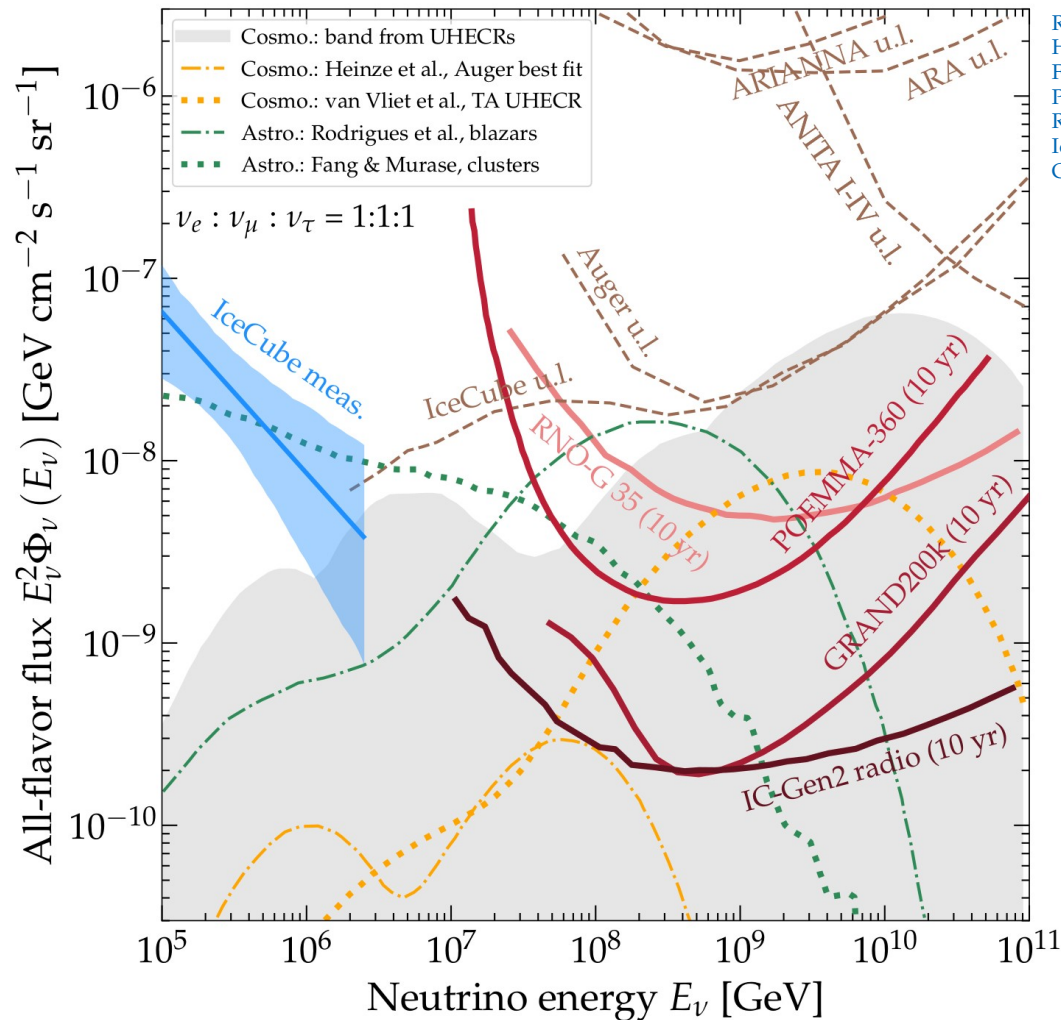


Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
Fang & Murase, *Nature Phys.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020

Cosmogenic neutrinos

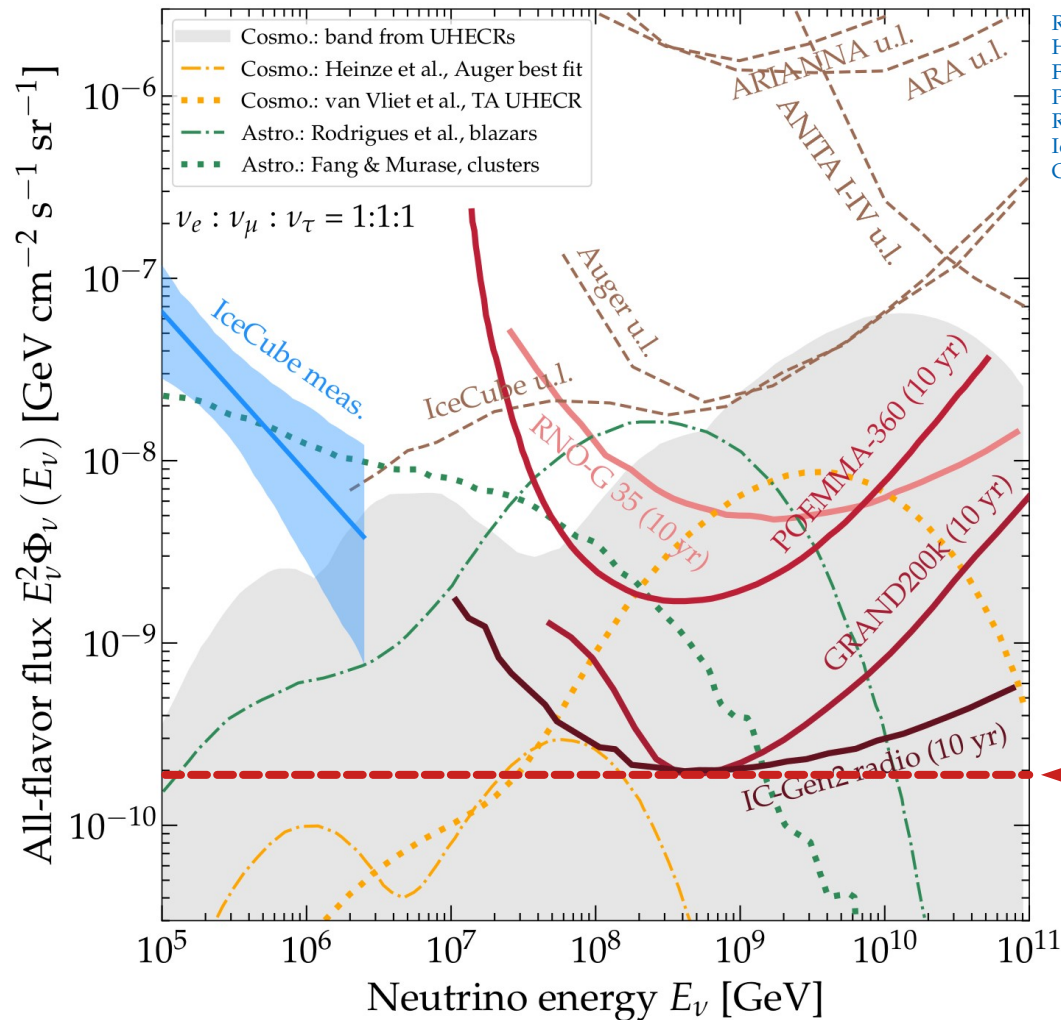
Neutrinos from the sources
(possibly dominant flux!)

UHE neutrinos: *steady-state sources*



Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
 Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
 Fang & Murase, *Nature Phys.* 2018
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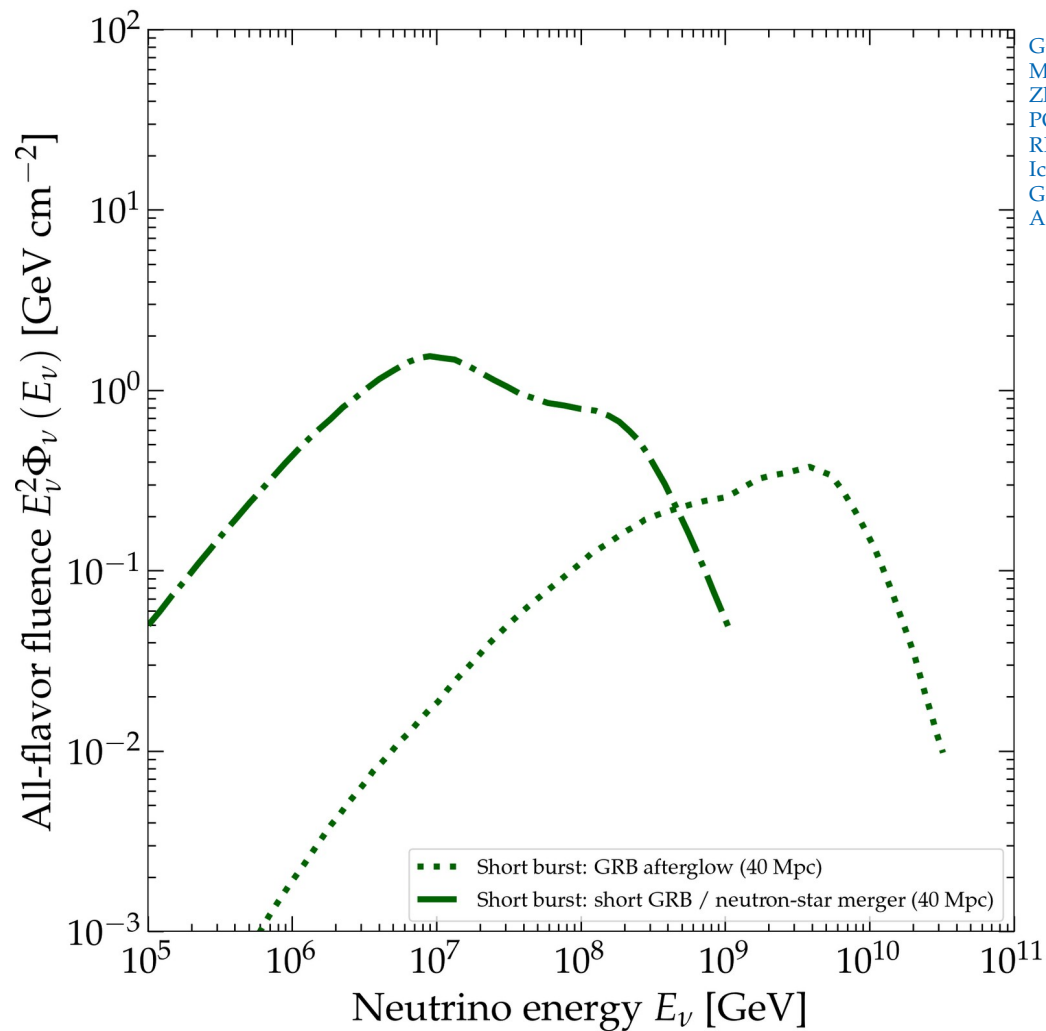
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IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020

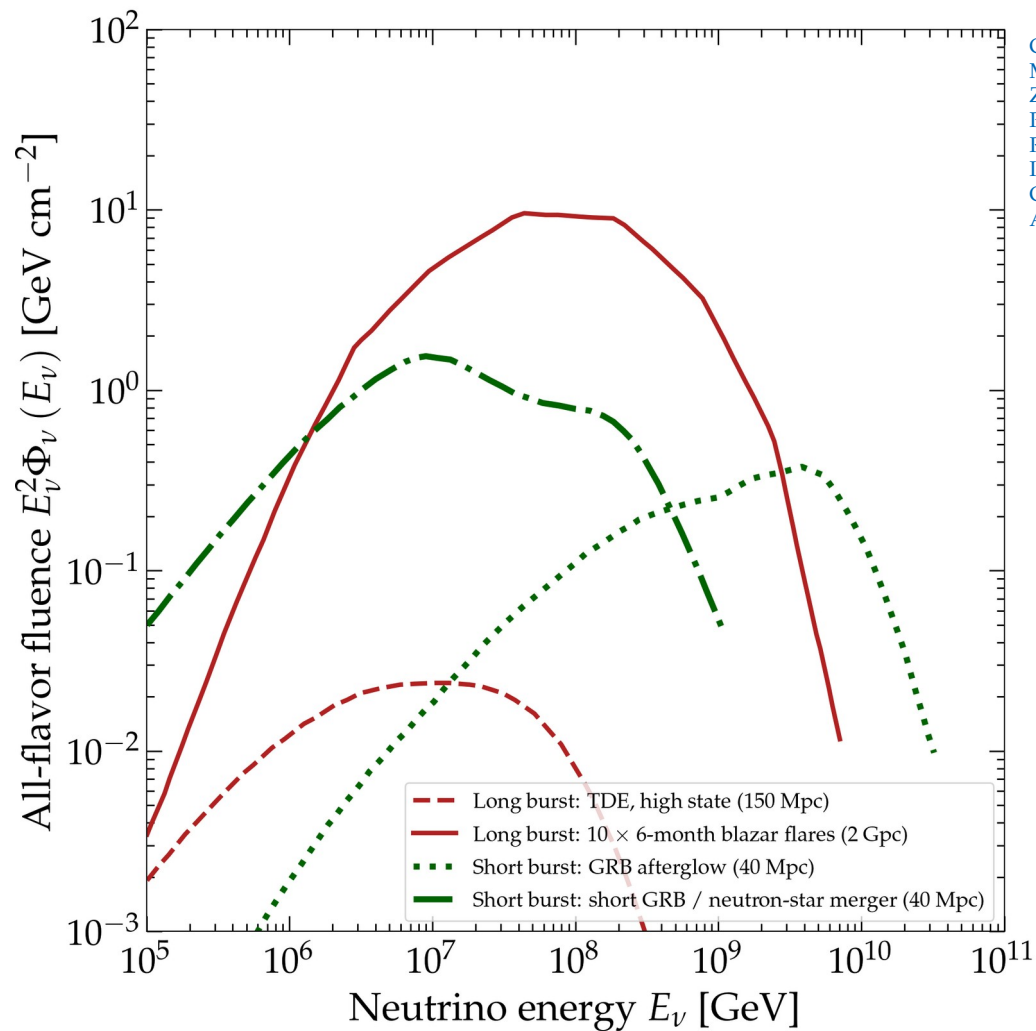
Ultimate target sensitivity
for next-gen detectors
(if protons are ~10% of the
highest-energy UHECRs)

UHE neutrinos: *transient sources*



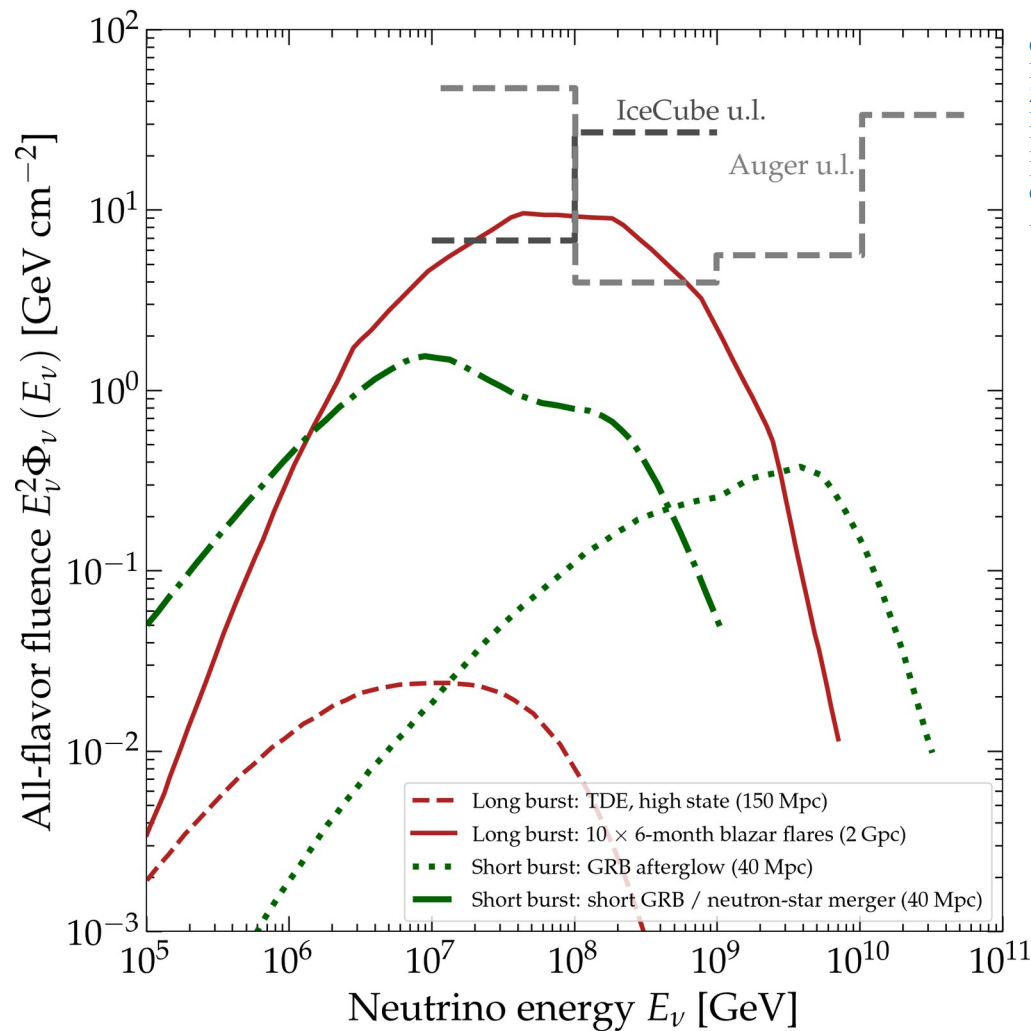
Guépin, Kotera, Barausse, Fang, Murase, *A&A* 2018
Murase, *PRD* 2017
Zhang *et al.*, *Nature Commun.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020
ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

UHE neutrinos: *transient sources*



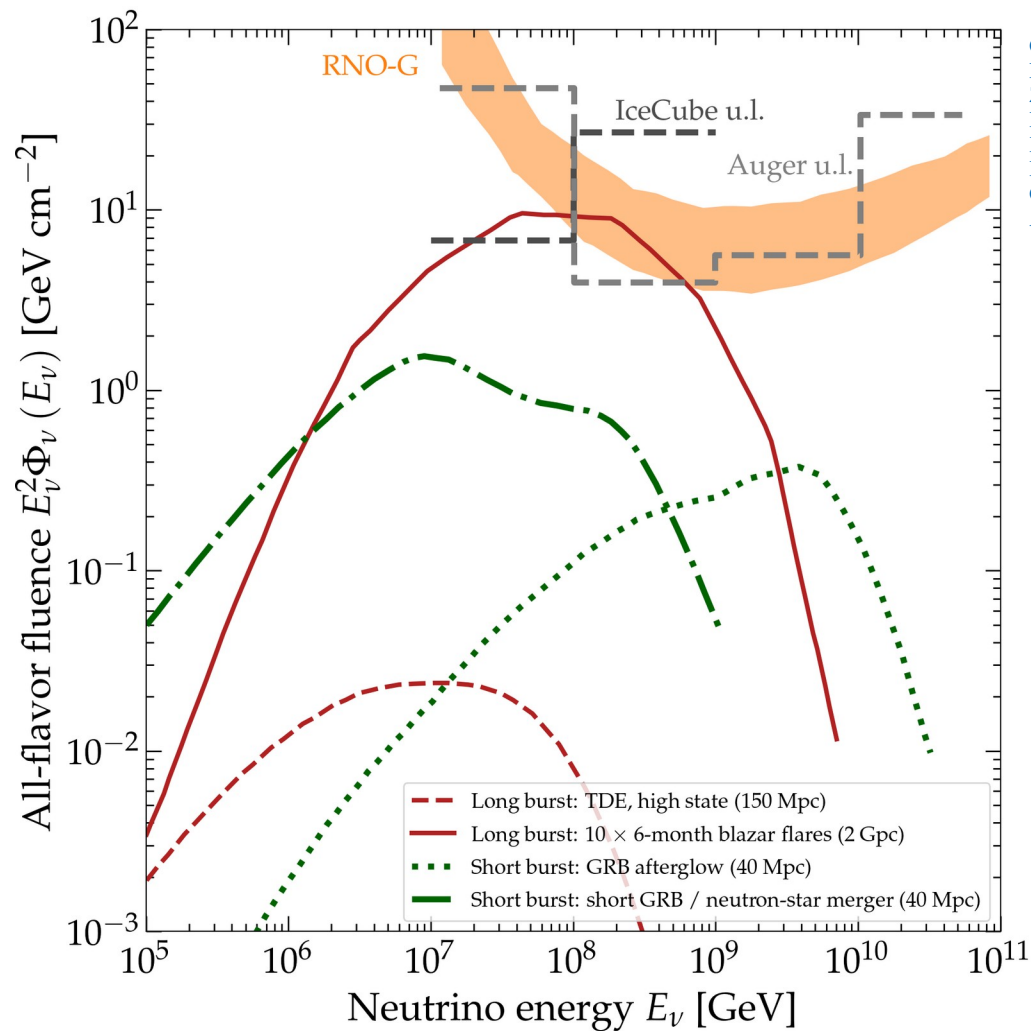
Guépin, Kotera, Barausse, Fang, Murase, *A&A* 2018
Murase, *PRD* 2017
Zhang *et al.*, *Nature Commun.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020
ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

UHE neutrinos: *transient sources*



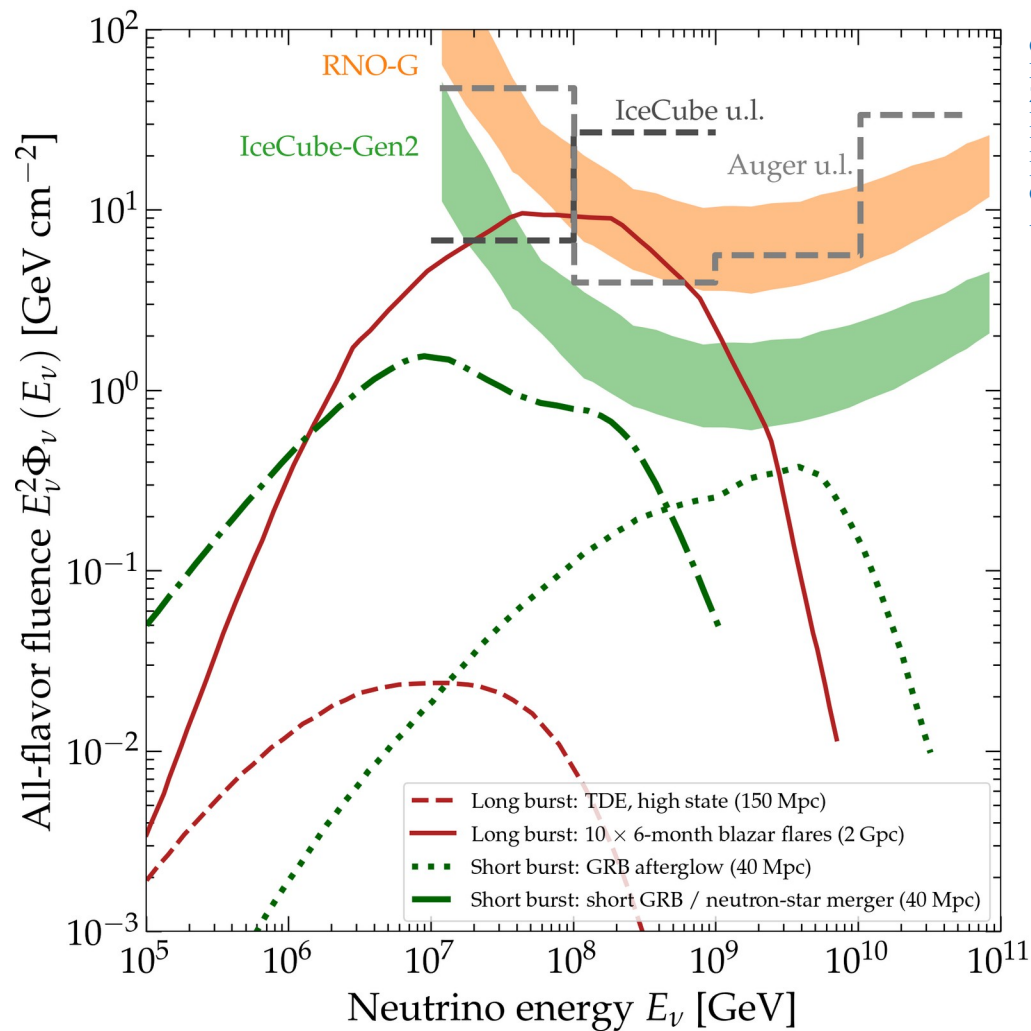
Guépin, Kotera, Barausse, Fang, Murase, *A&A* 2018
Murase, *PRD* 2017
Zhang *et al.*, *Nature Commun.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
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ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

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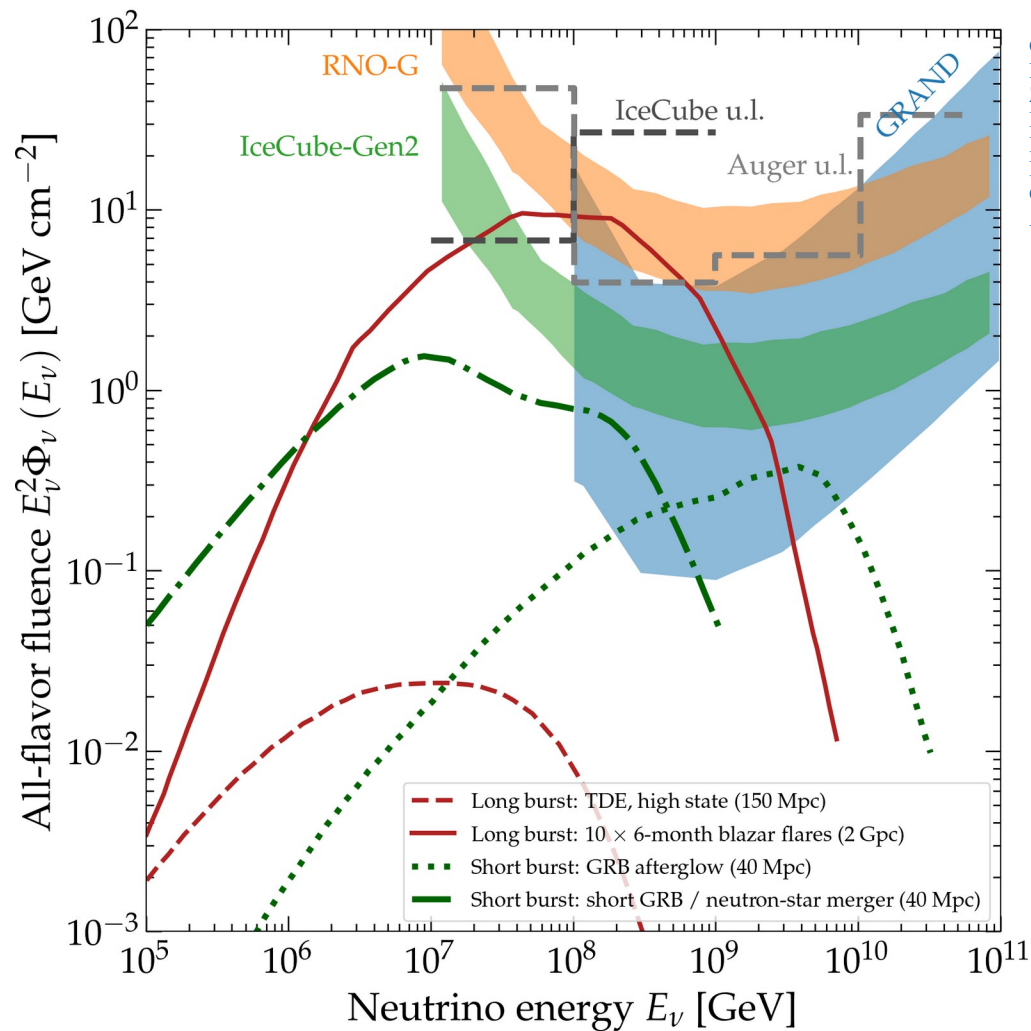
Guépin, Kotera, Barausse, Fang, Murase, *A&A* 2018
Murase, *PRD* 2017
Zhang *et al.*, *Nature Commun.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020
ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

UHE neutrinos: *transient sources*



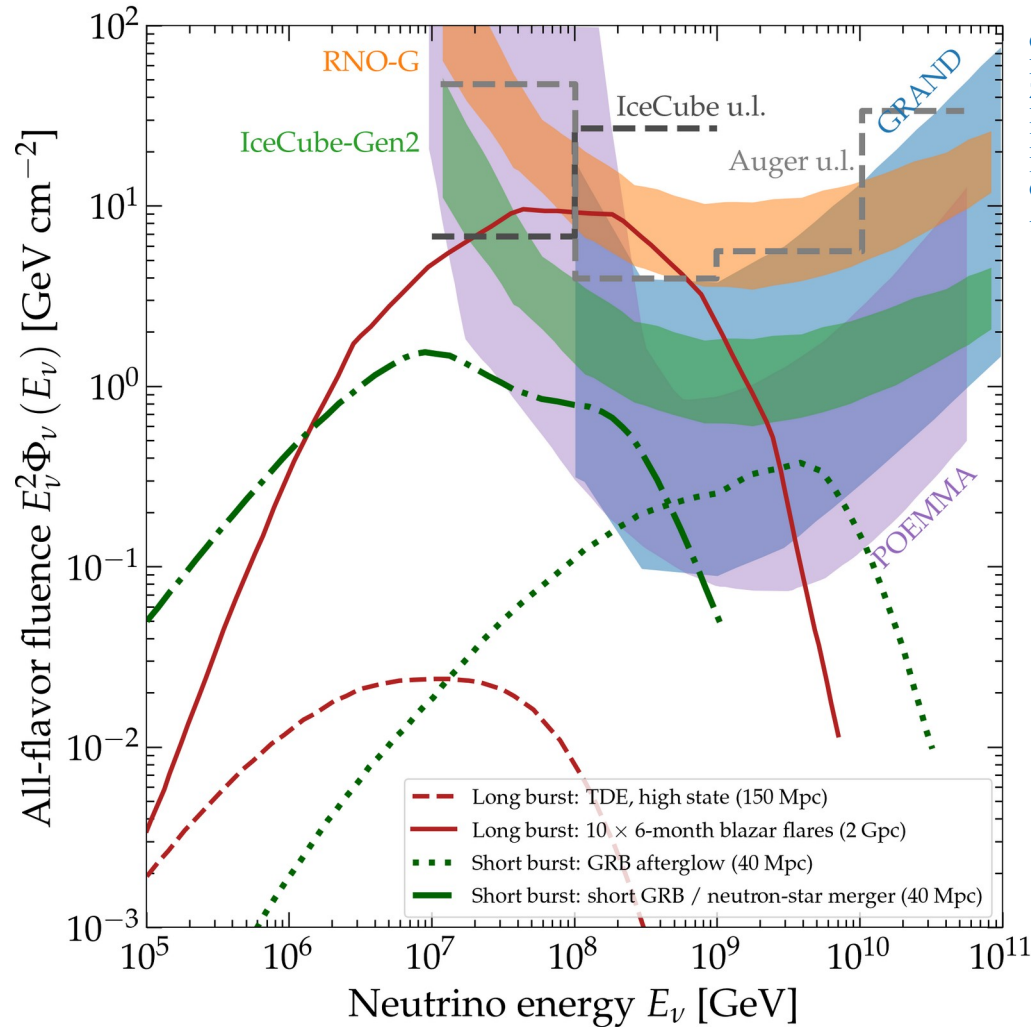
Guépin, Kotera, Barausse, Fang, Murase, *A&A* 2018
 Murase, *PRD* 2017
 Zhang *et al.*, *Nature Commun.* 2018
 POEMMA, 2012.07945
 RNO-G, *JINST* 2021
 IceCube-Gen2, *J. Phys. G* 2021
 GRAND, *Sci. China Phys. Mech. Astron.* 2020
 ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

UHE neutrinos: *transient sources*



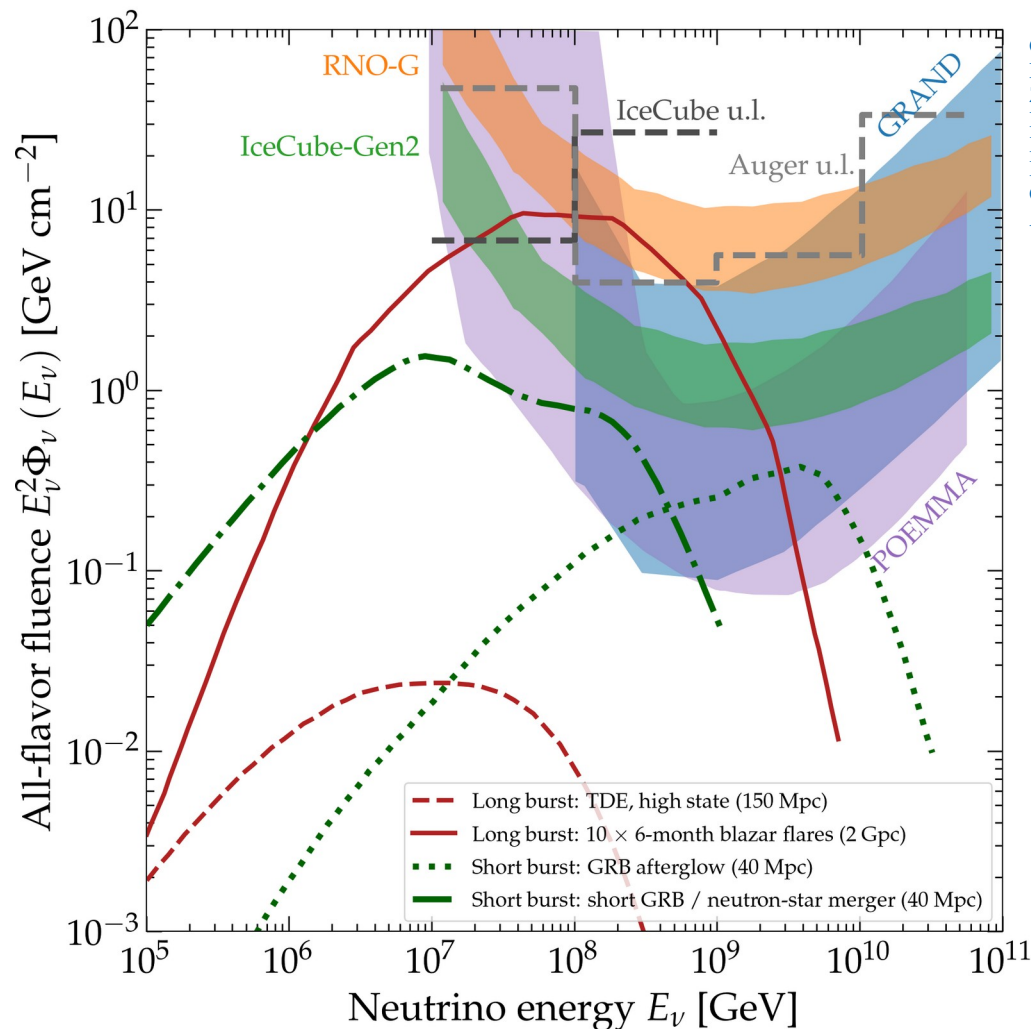
Guépin, Kotera, Barausse, Fang, Murase, *A&A* 2018
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 ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

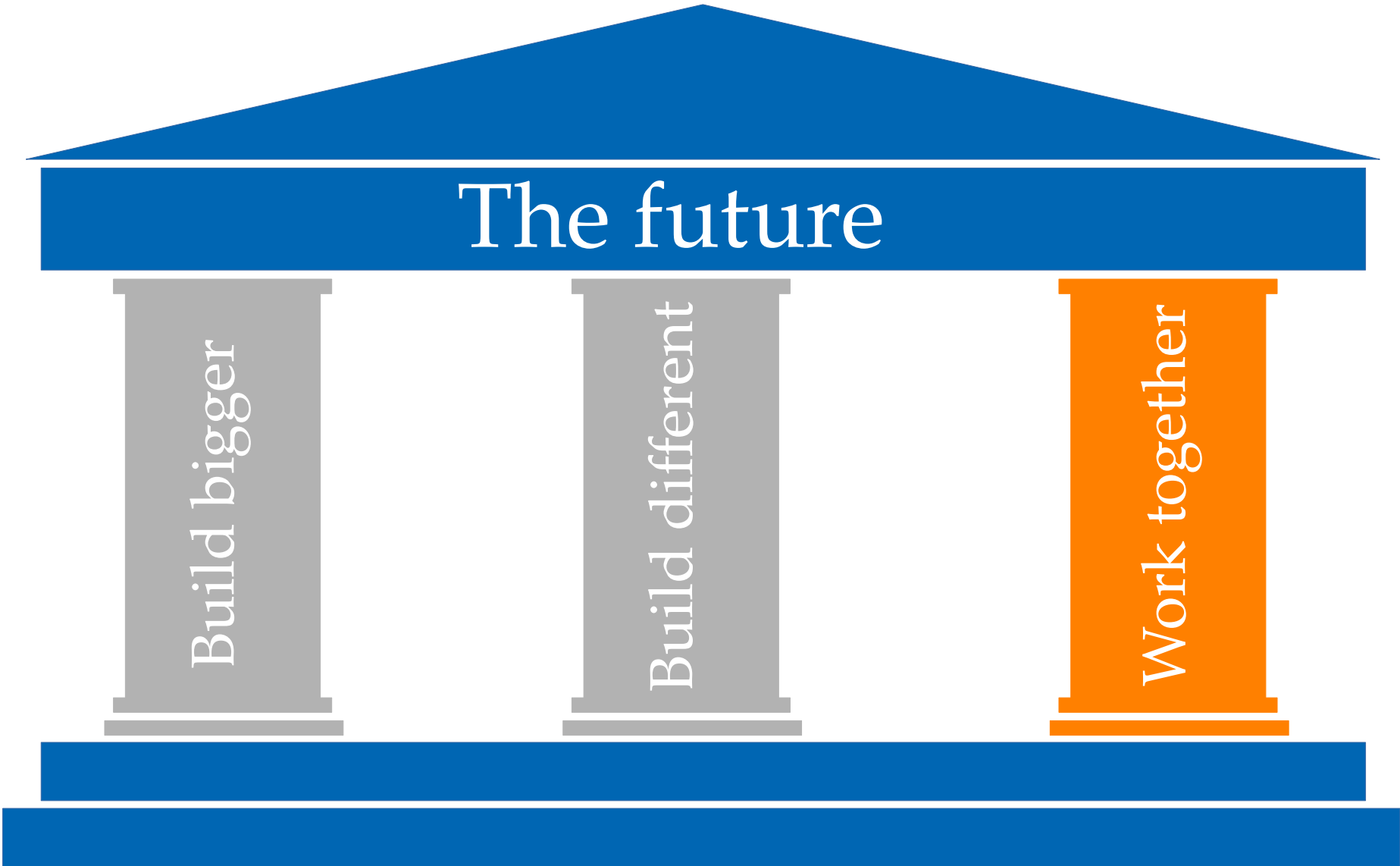
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GRAND, *Sci. China Phys. Mech. Astron.* 2020
ANTARES, IceCube, Auger, LIGO, *ApJ* 2017

Take-home message

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

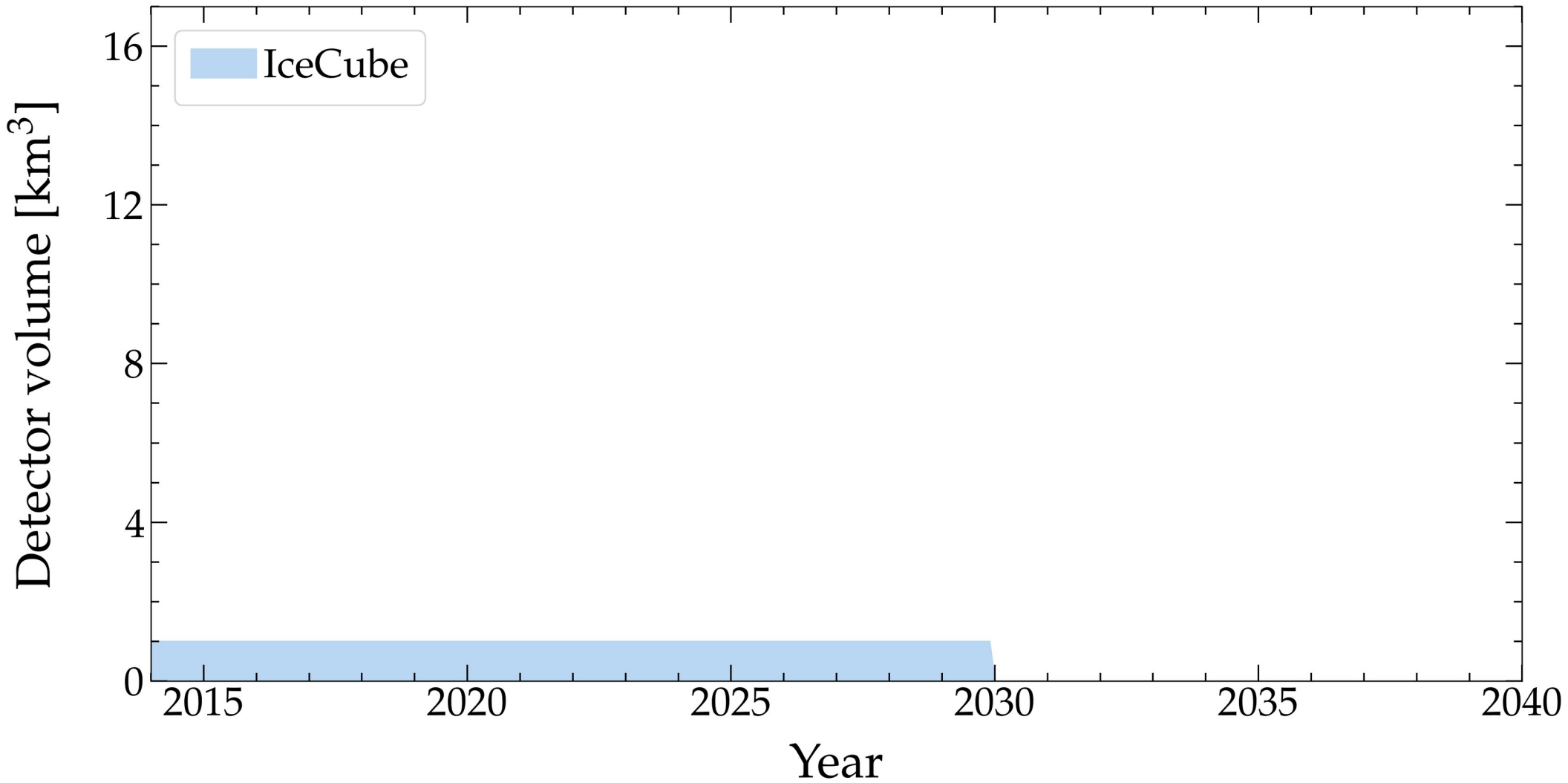


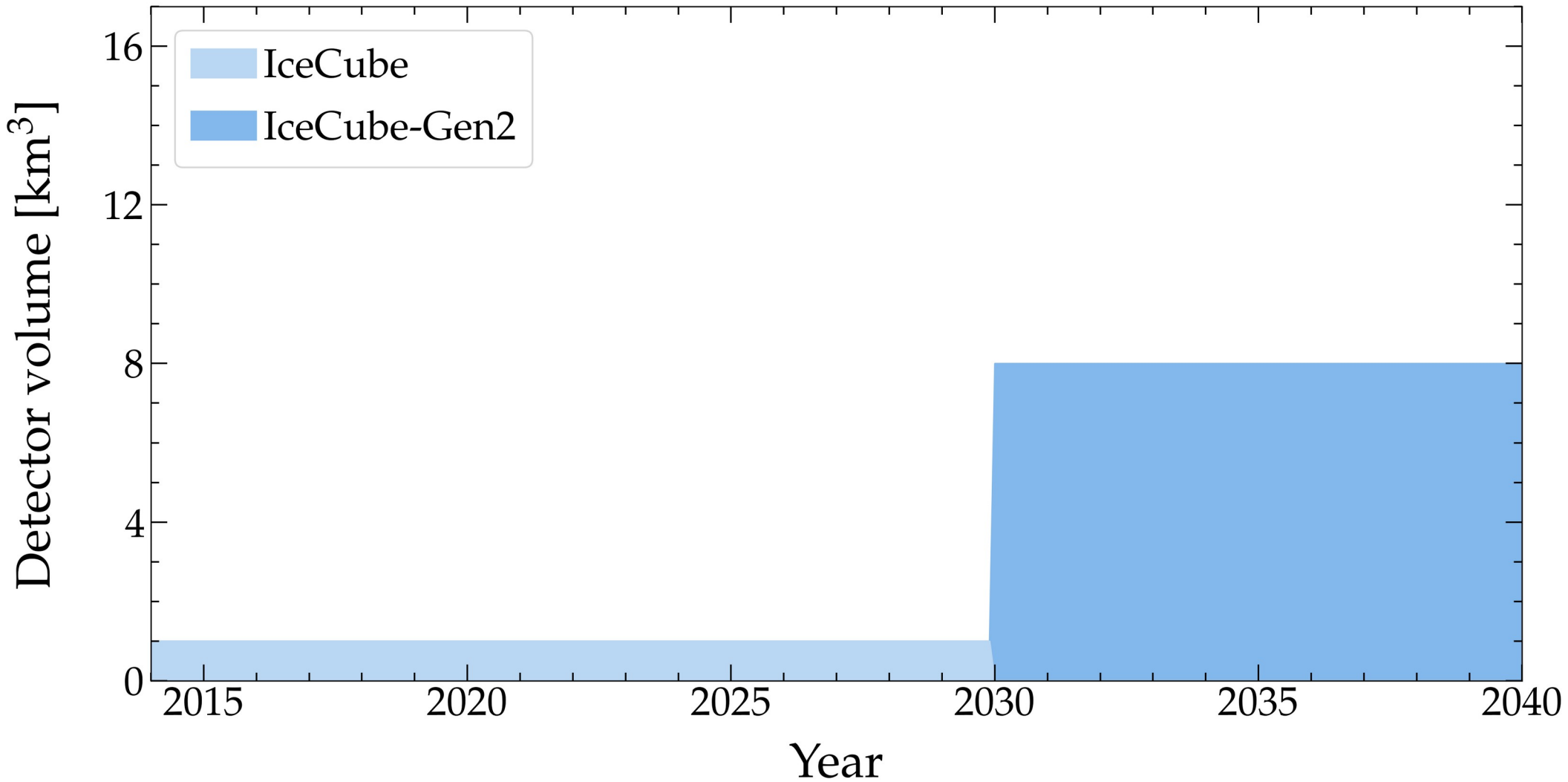
The future

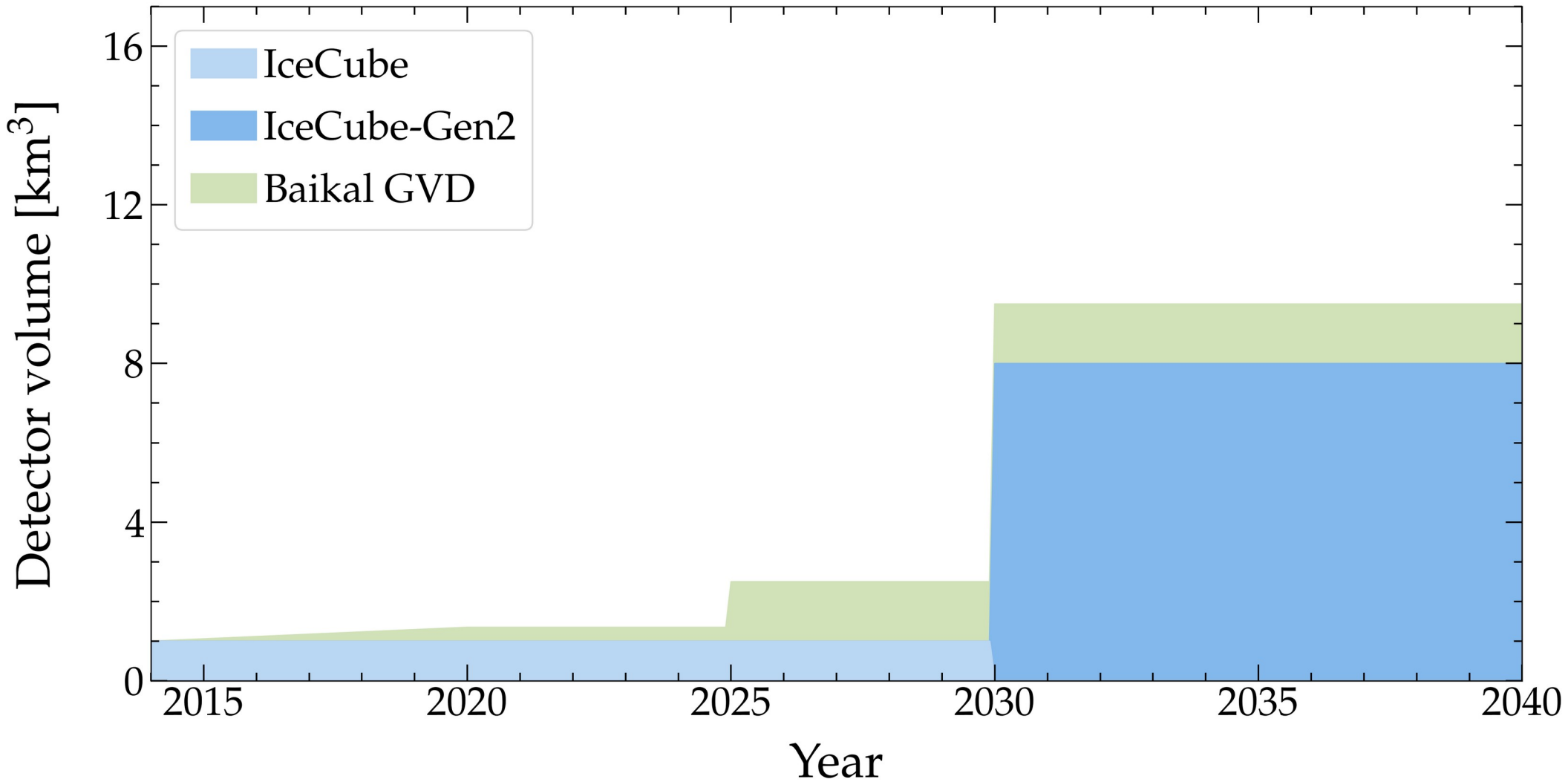
Build bigger

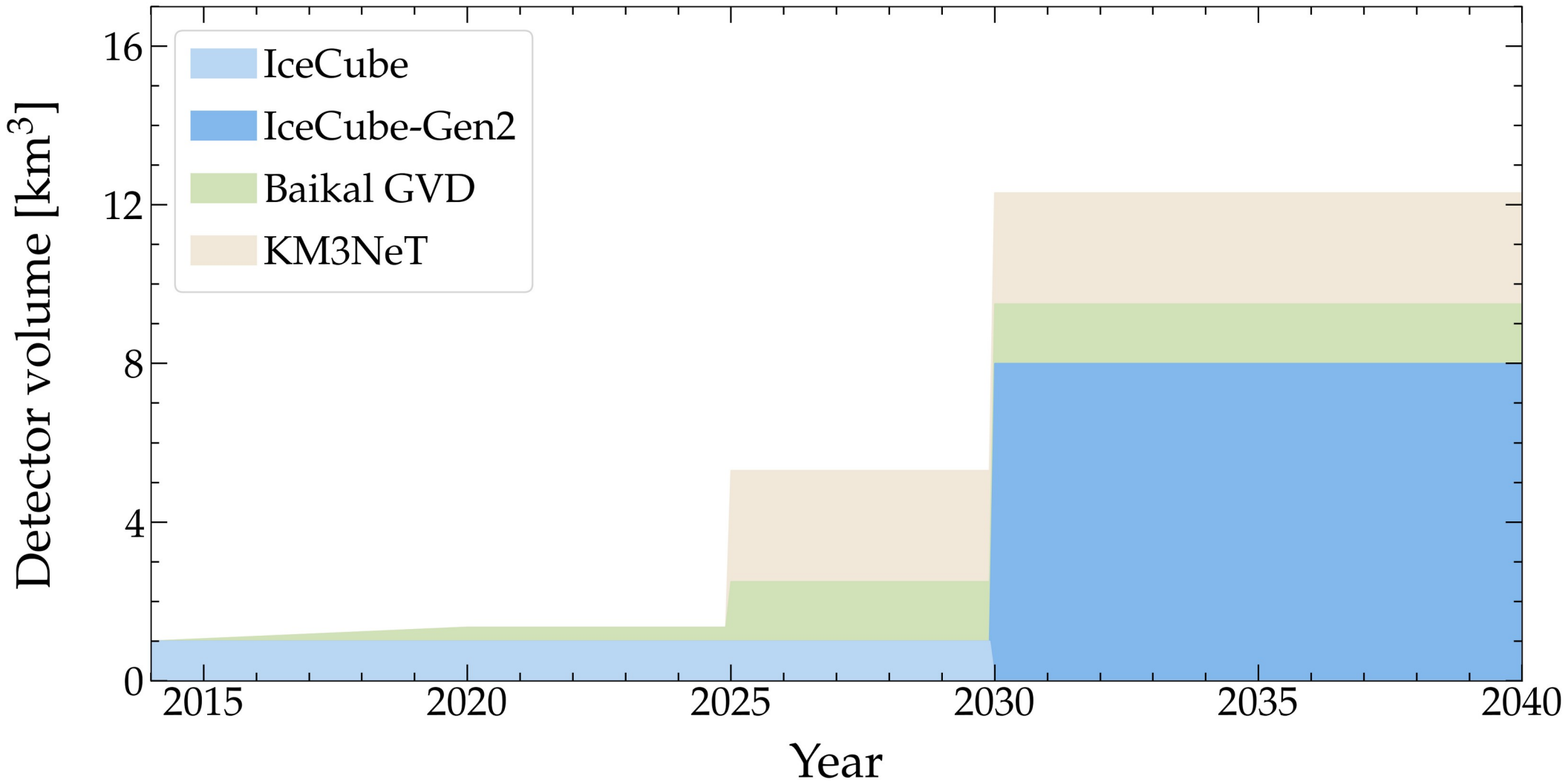
Build different

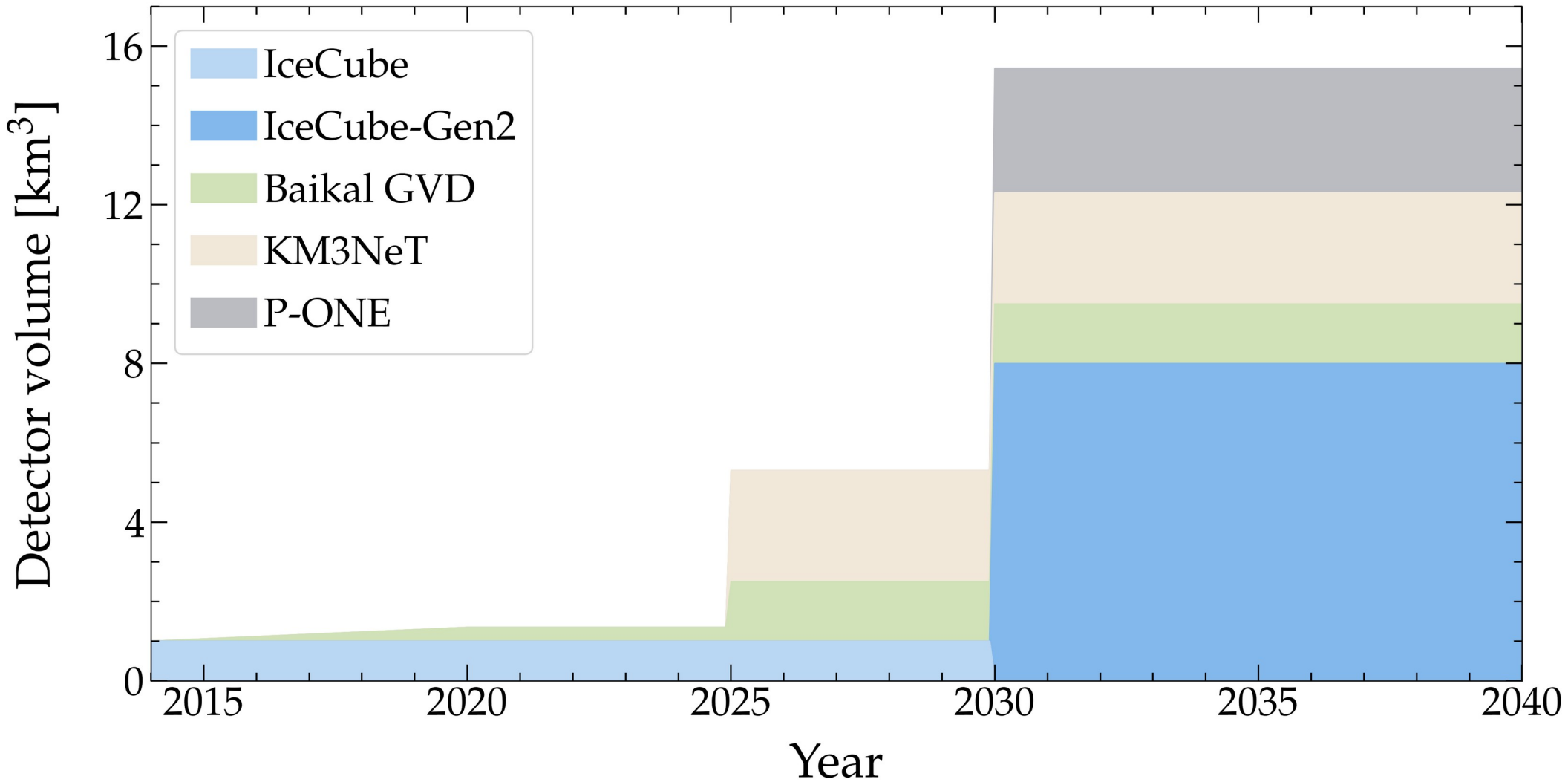
Work together

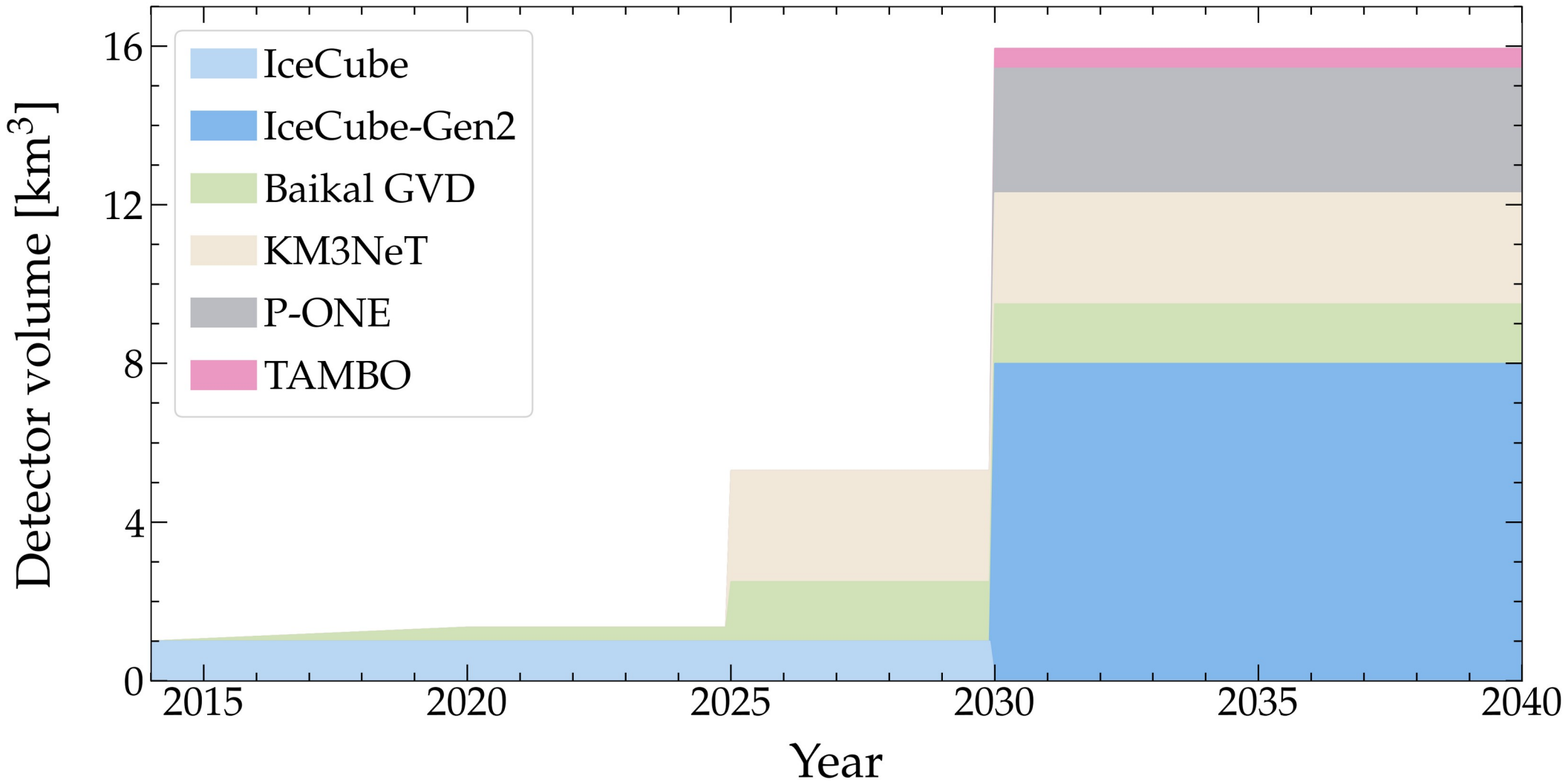


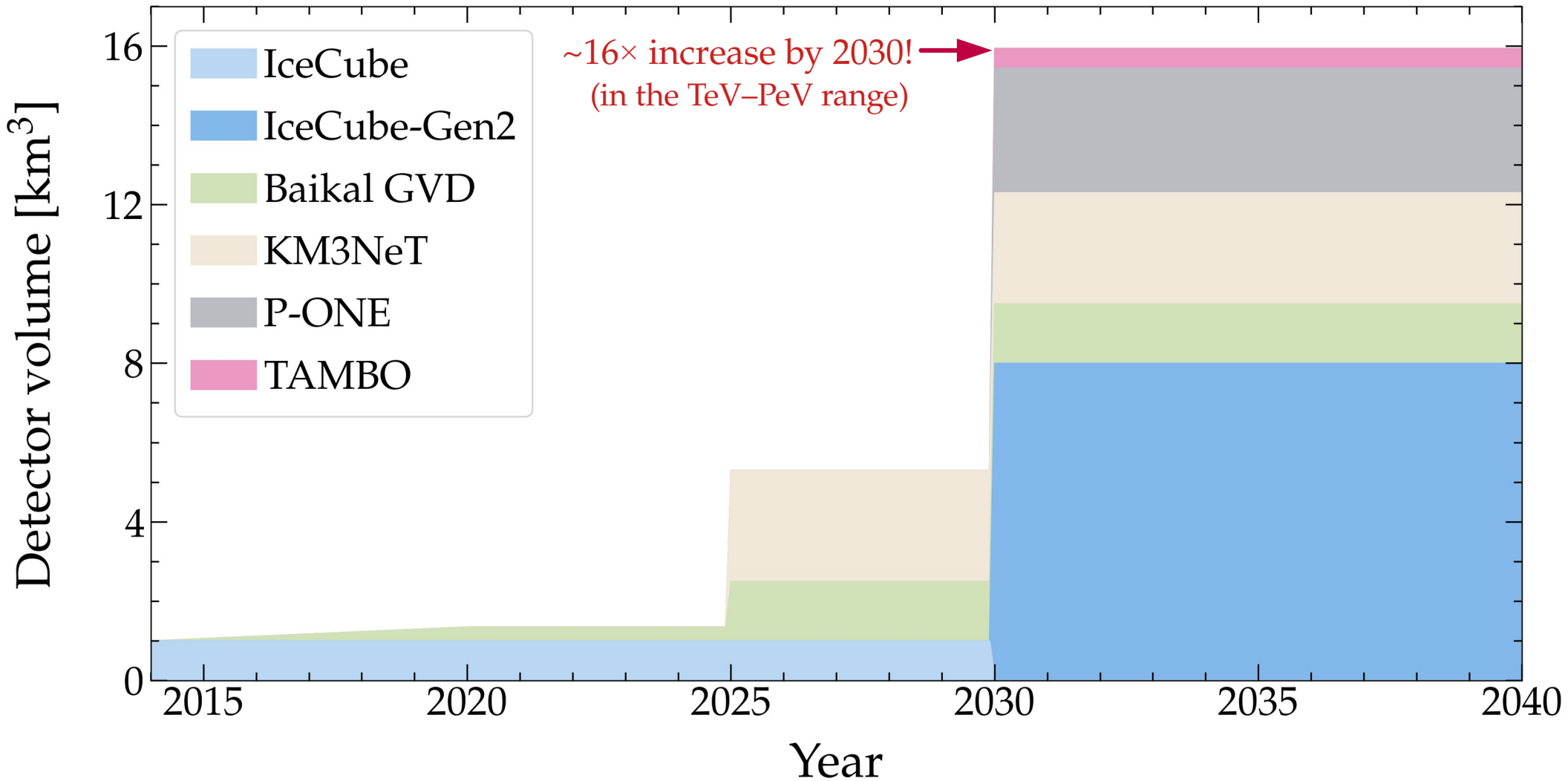


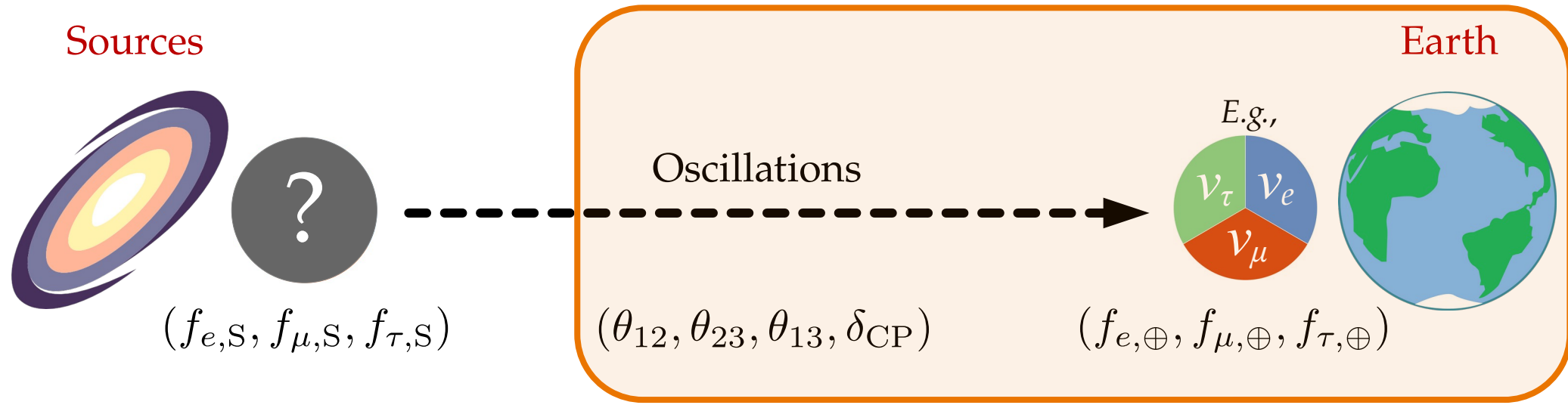








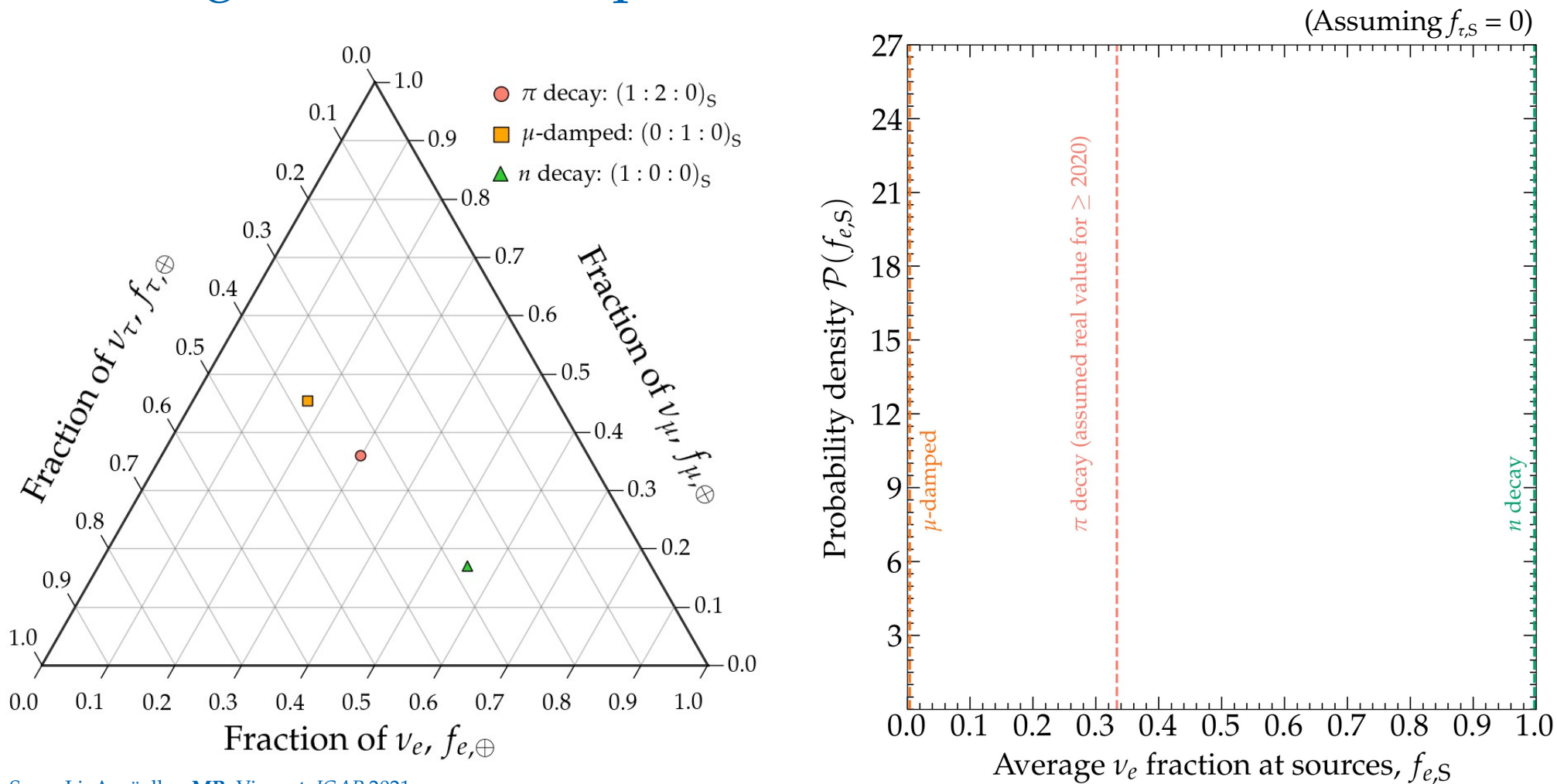




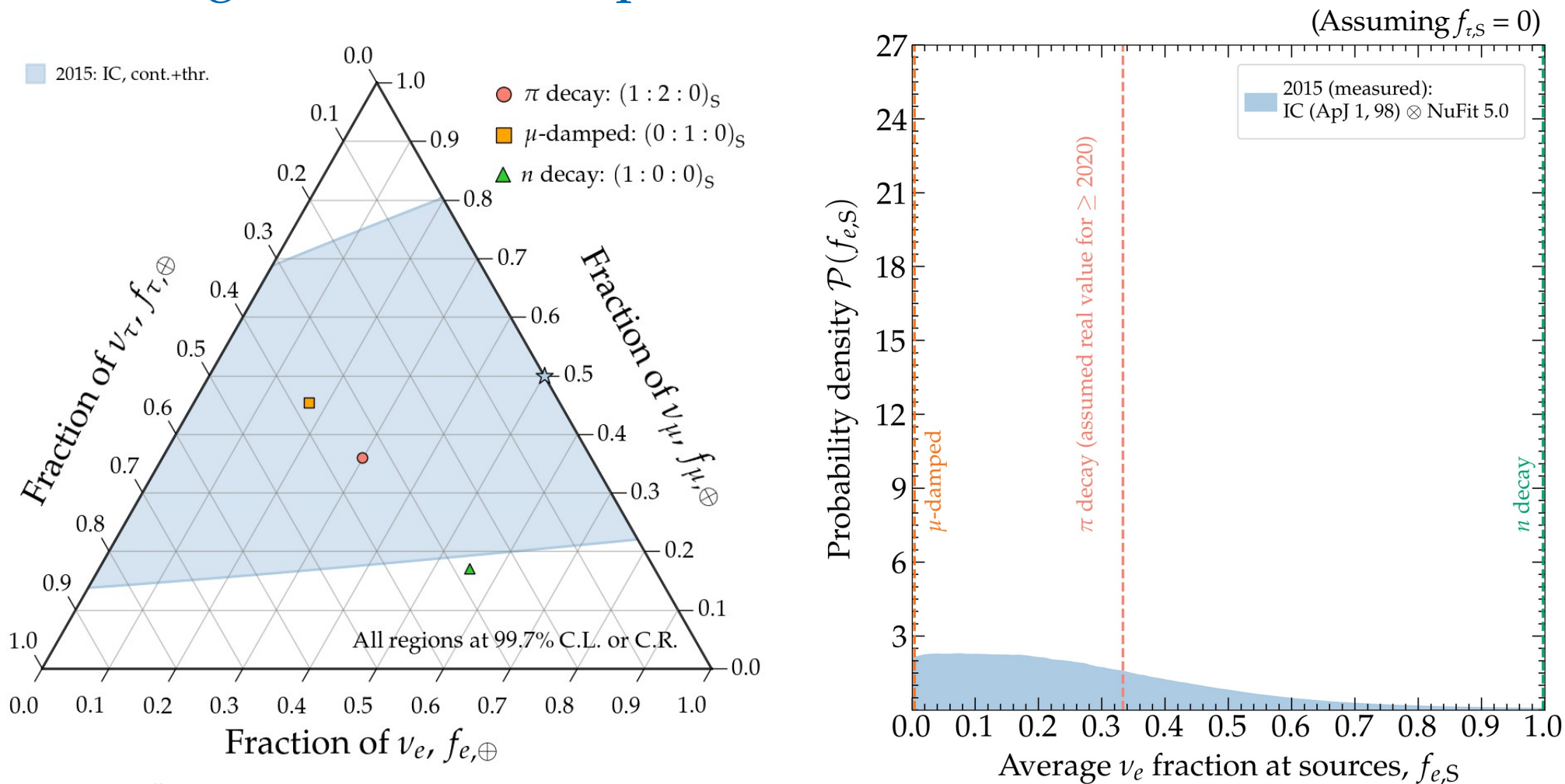
← *From Earth to sources:* we let the data teach us about $f_{\alpha,S}$

Inferring the flavor composition at the sources

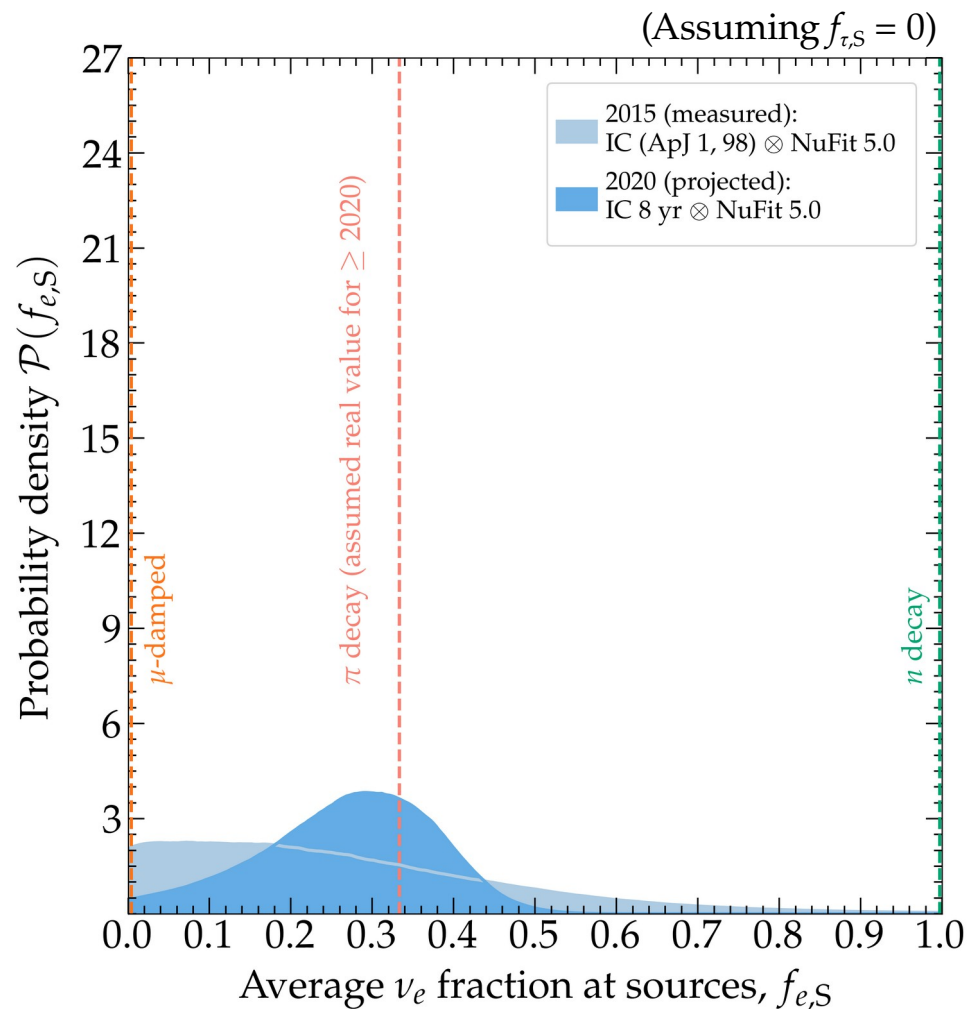
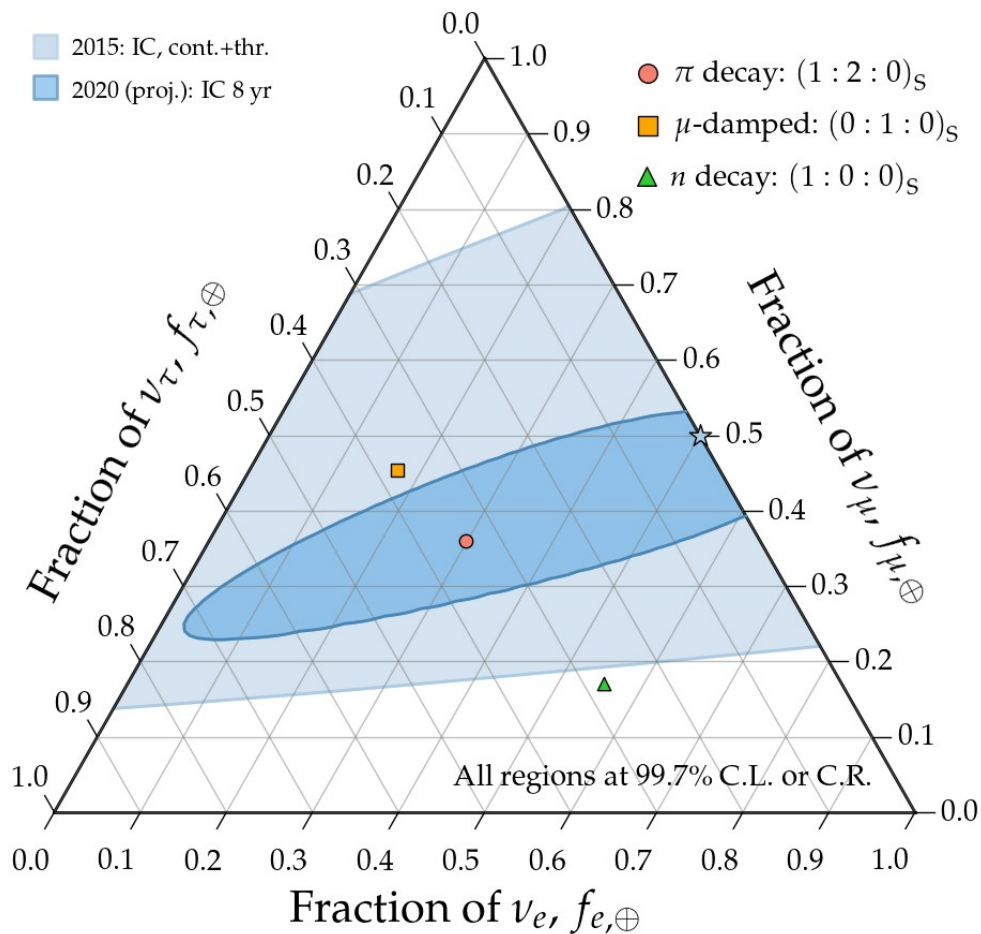
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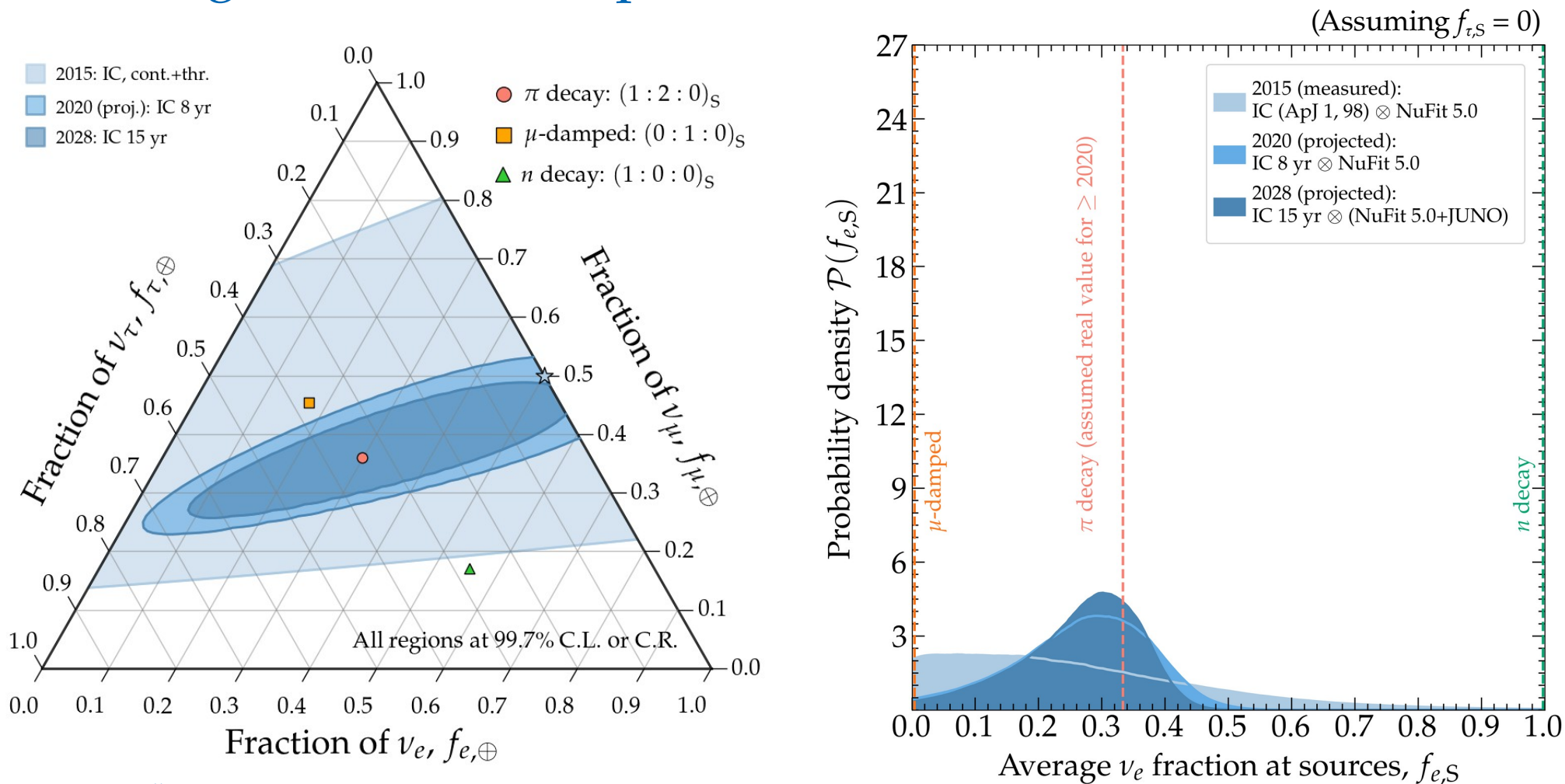
Inferring the flavor composition at the sources



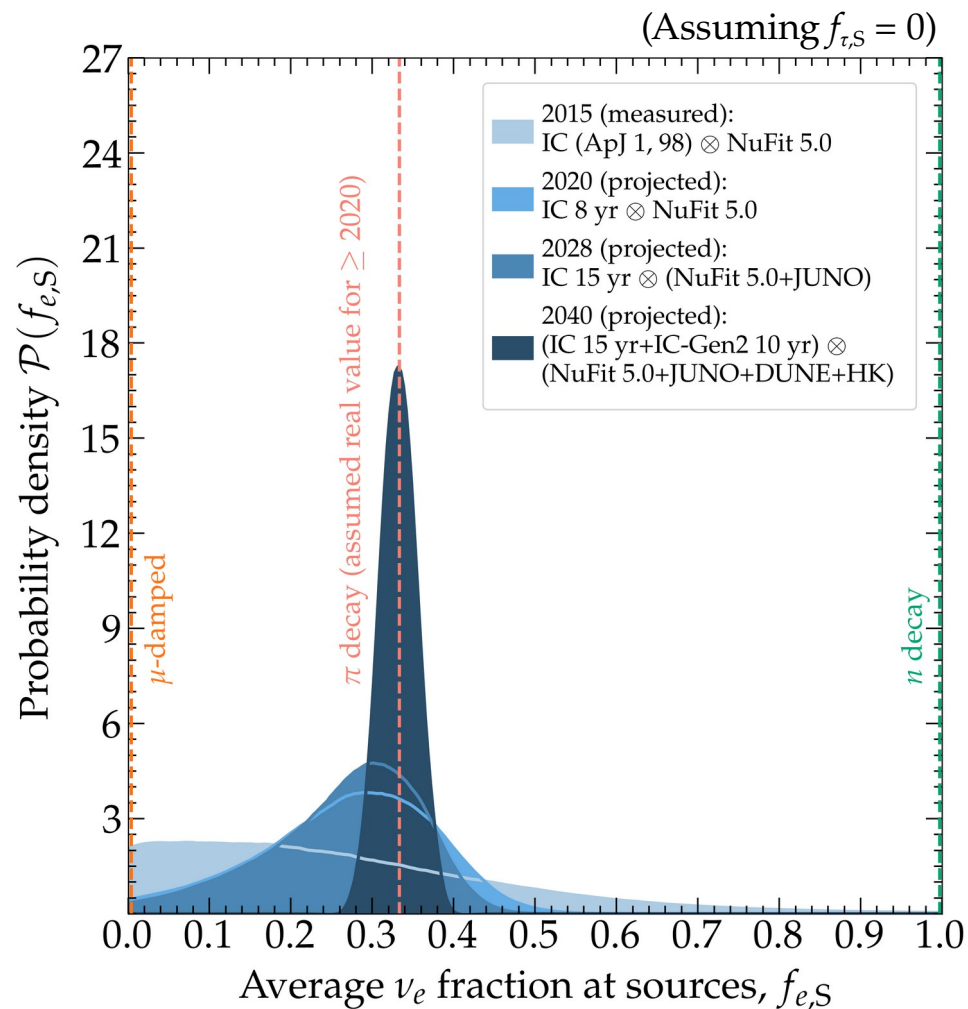
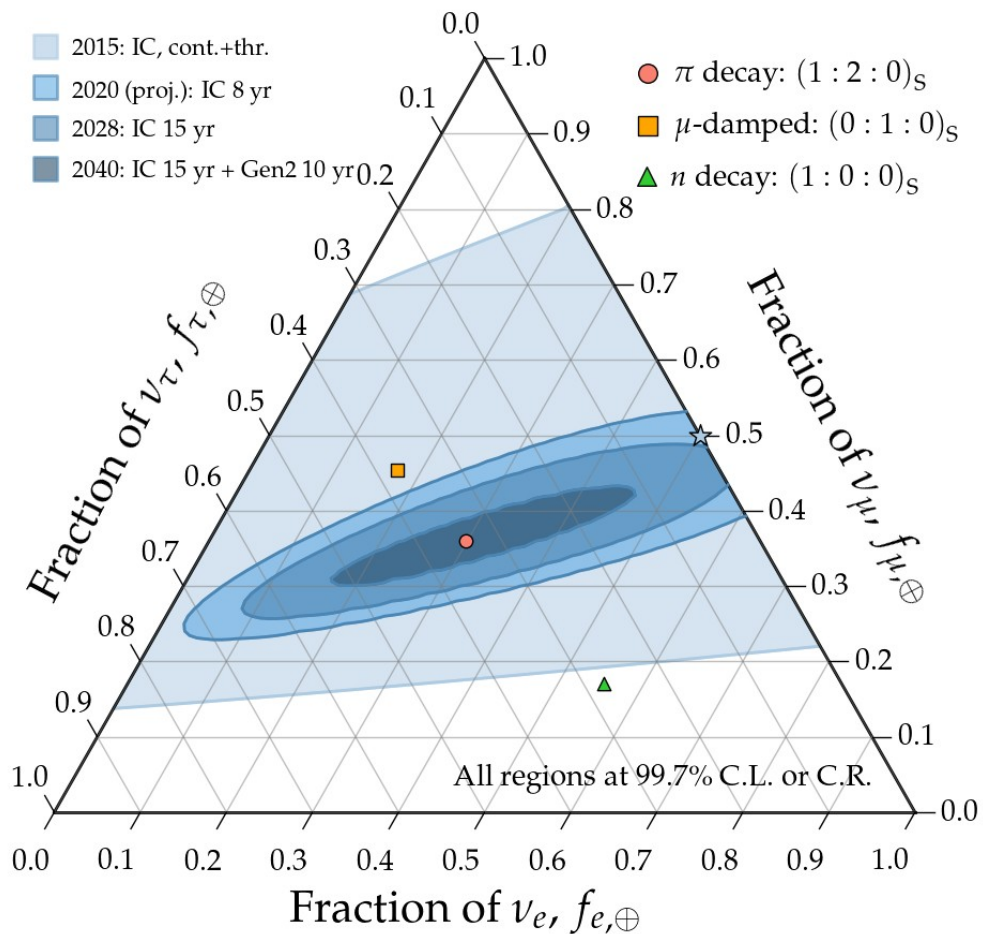
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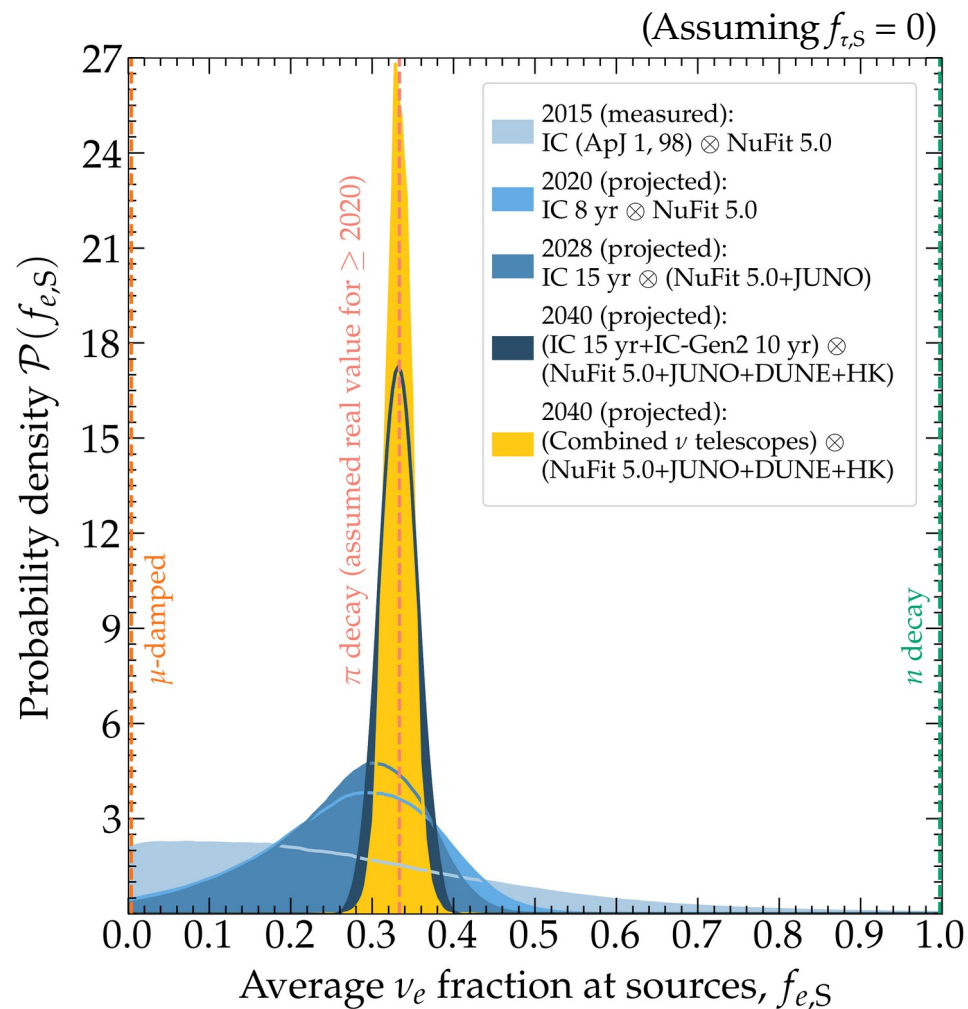
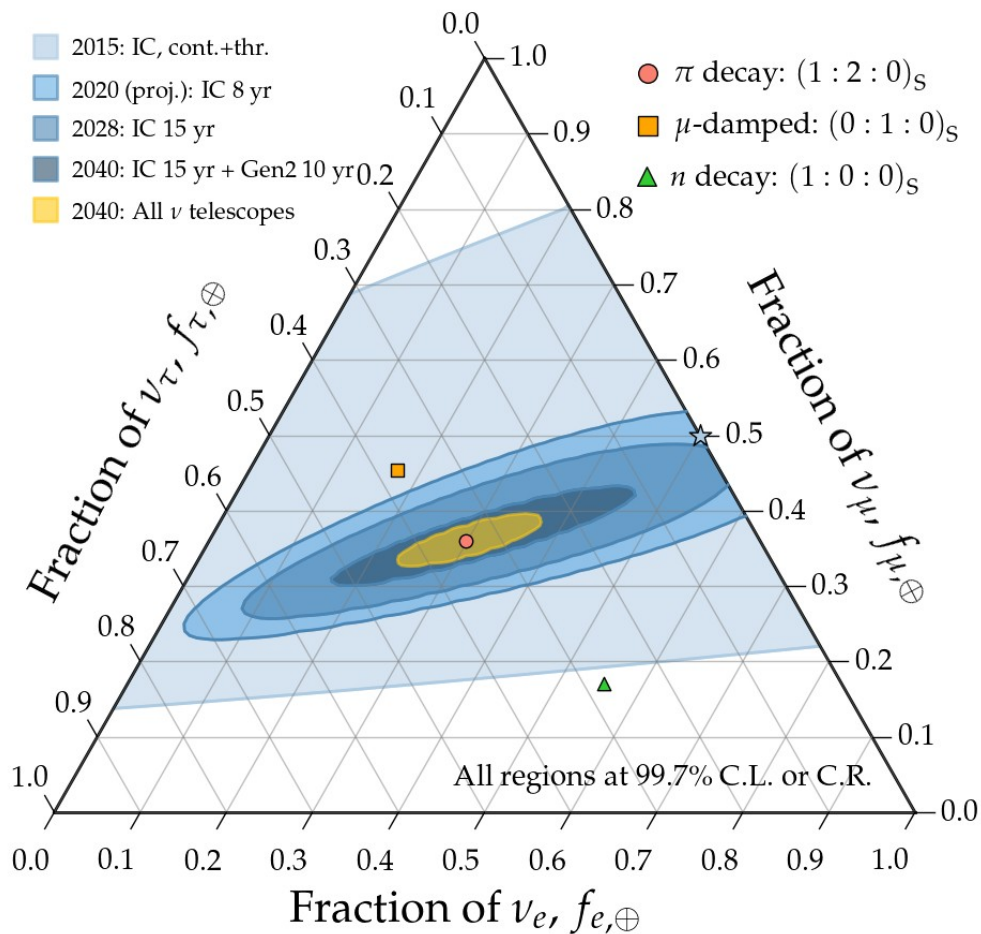
Inferring the flavor composition at the sources



Inferring the flavor composition at the sources



Inferring the flavor composition at the sources



More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$f_S = k_\pi \underbrace{f_S^\pi}_{\substack{\pi \text{ decay:} \\ (1/3, 2/3, 0)}} + k_\mu \underbrace{f_S^\mu}_{\substack{\mu \text{ damped:} \\ (0, 1, 0)}} + k_n \underbrace{f_S^n}_{\substack{n \text{ decay:} \\ (1, 0, 0)}}$$

Propagate to Earth
 $\downarrow$
 $f_\oplus$

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]

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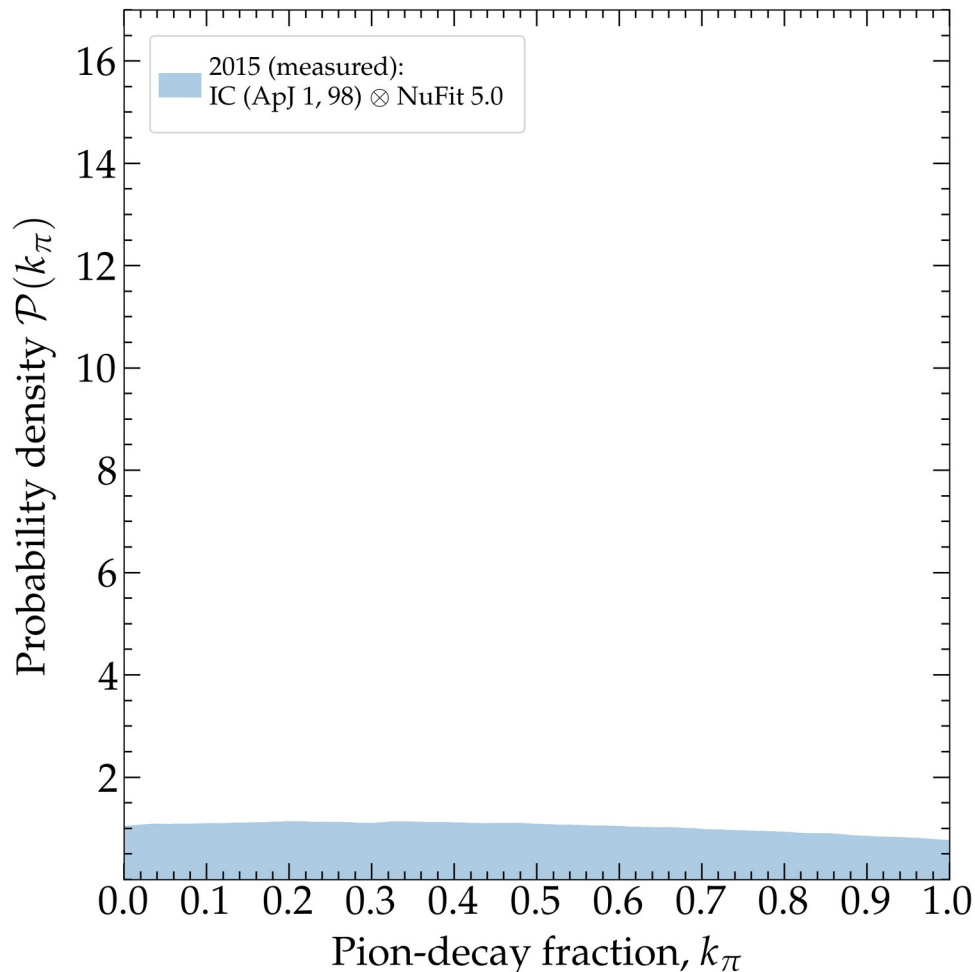
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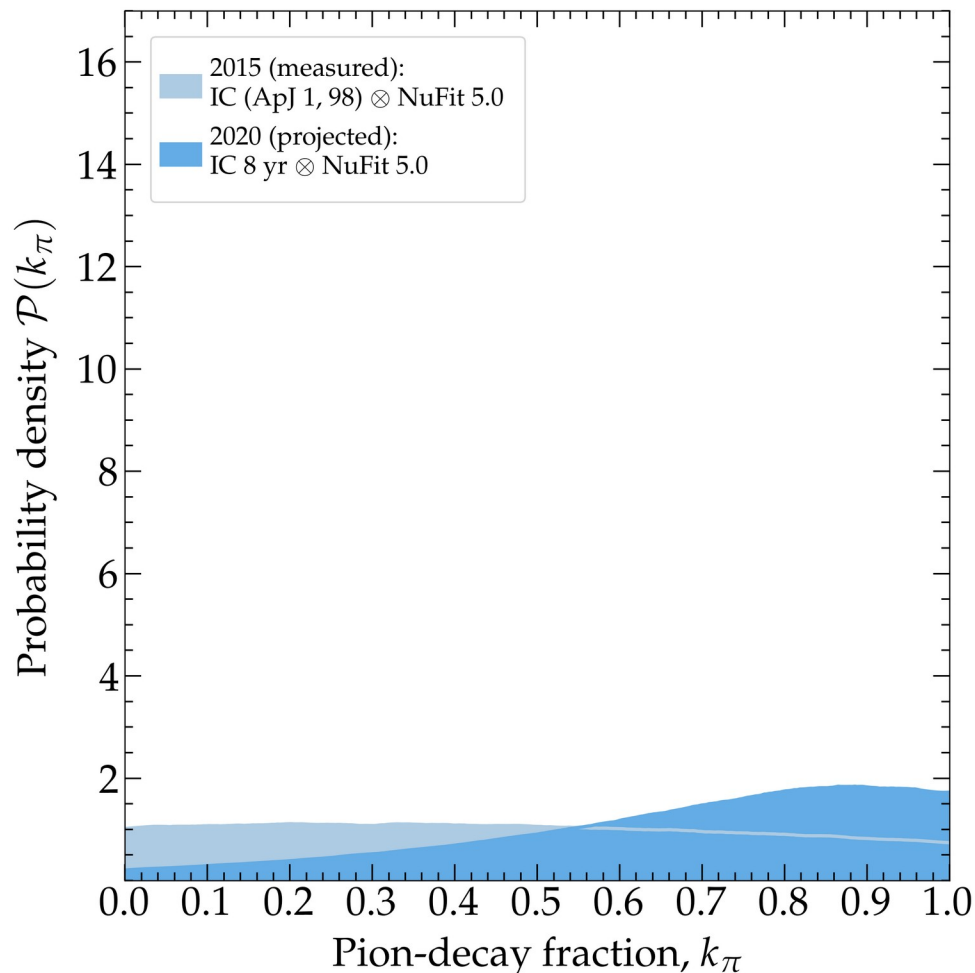
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Propagate to Earth

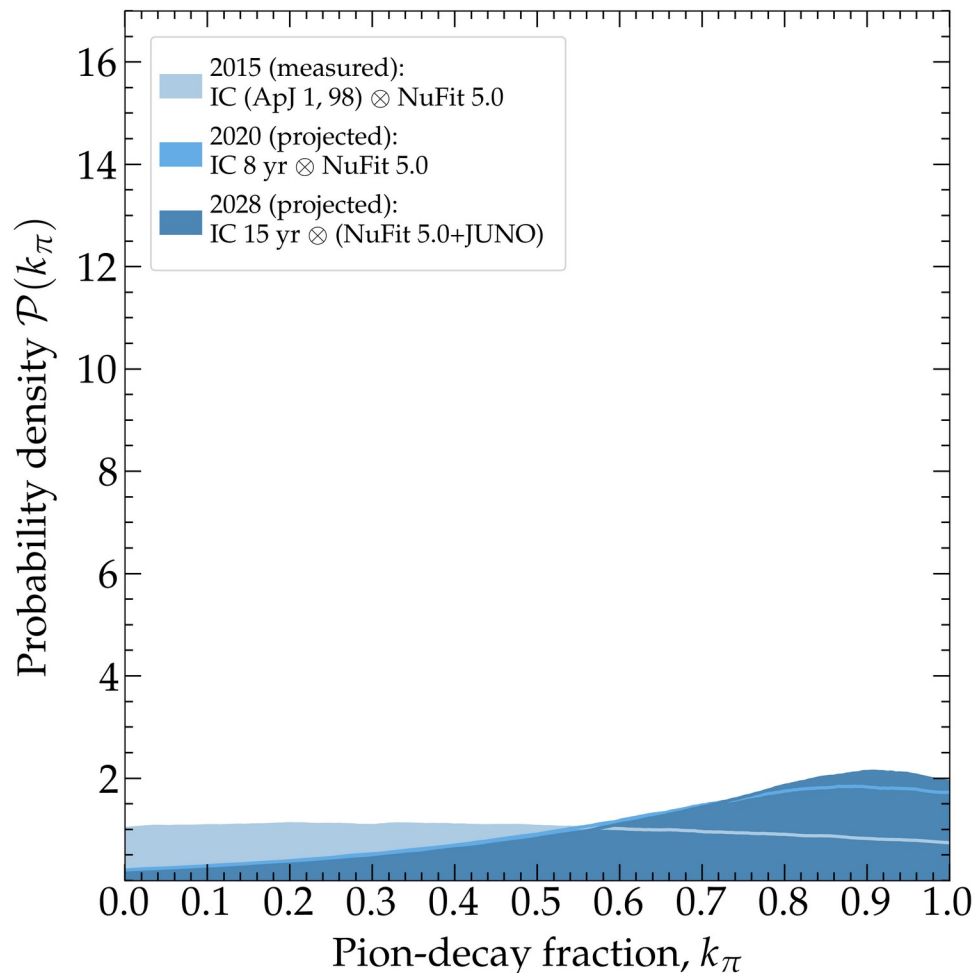
$$\downarrow$$

$$f_\oplus$$

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$$f_S = k_\pi \underbrace{f_S^\pi}_{\text{\color{red}\pi decay: (1/3, 2/3, 0)}} + k_\mu \underbrace{f_S^\mu}_{\text{\color{brown}\mu damped: (0, 1, 0)}} + k_n \underbrace{f_S^n}_{\text{\color{teal}n decay: (1, 0, 0)}}$$

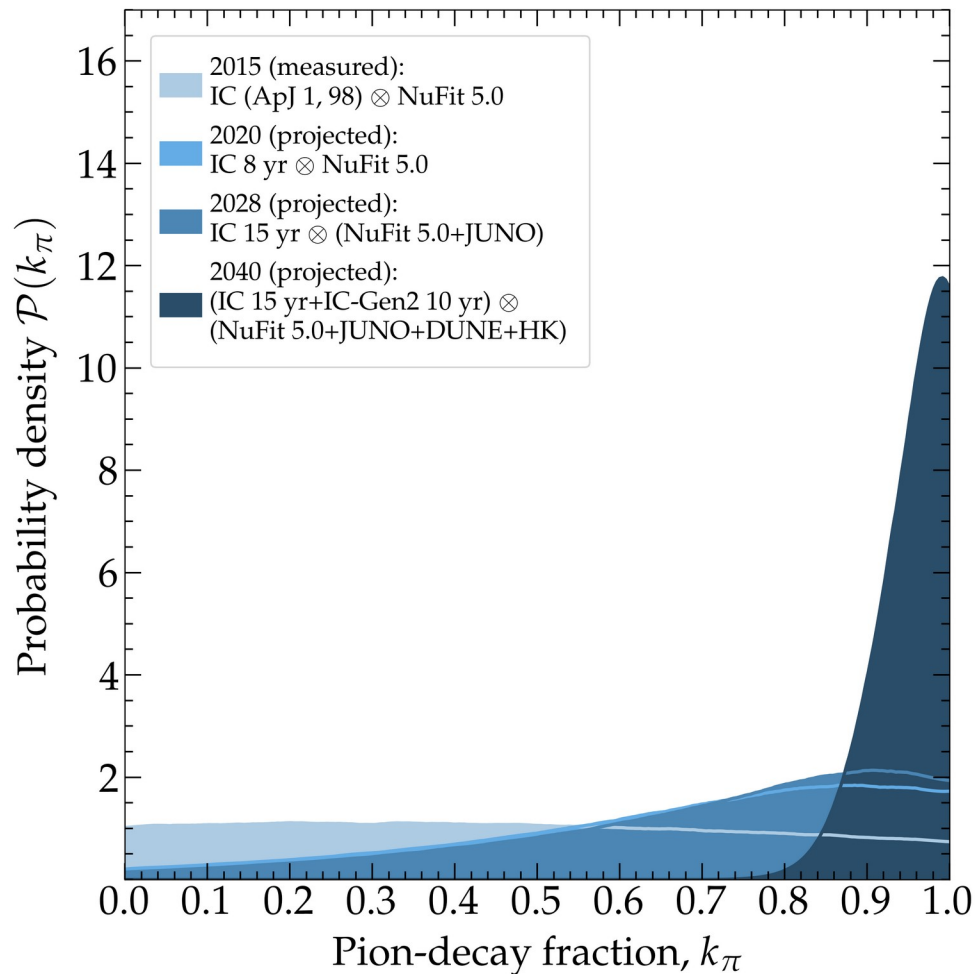
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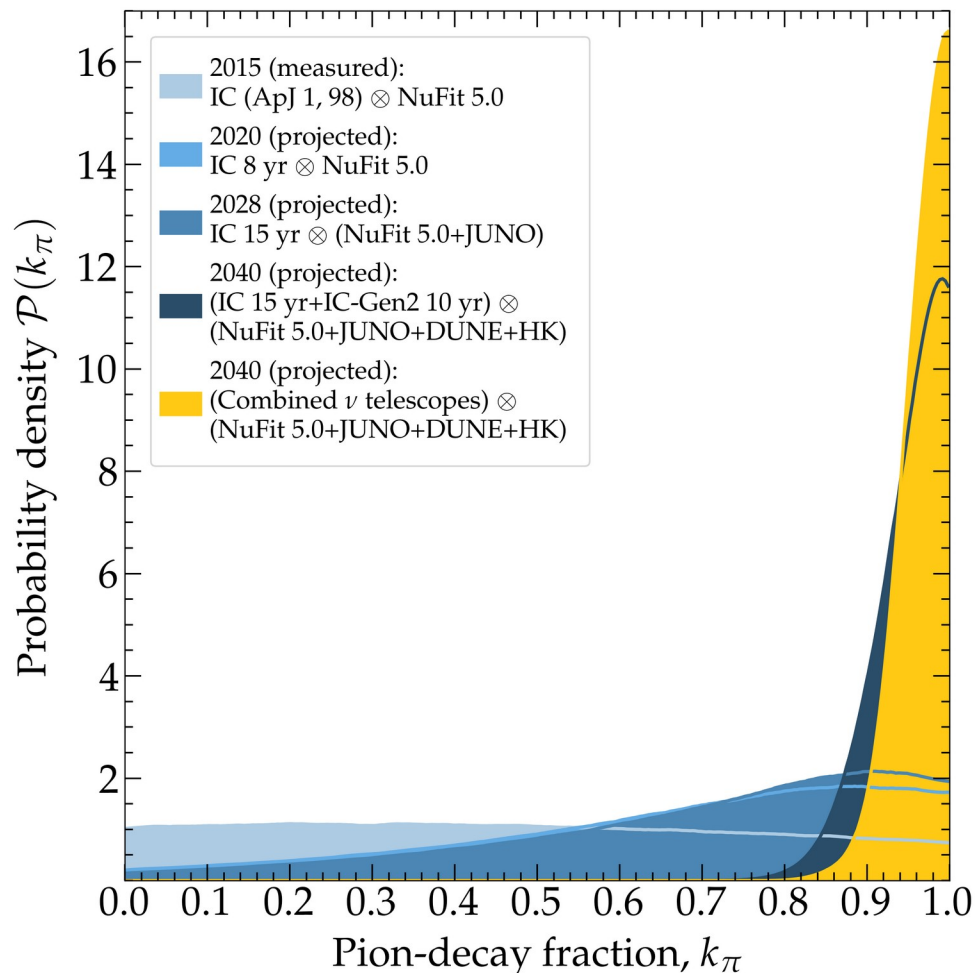
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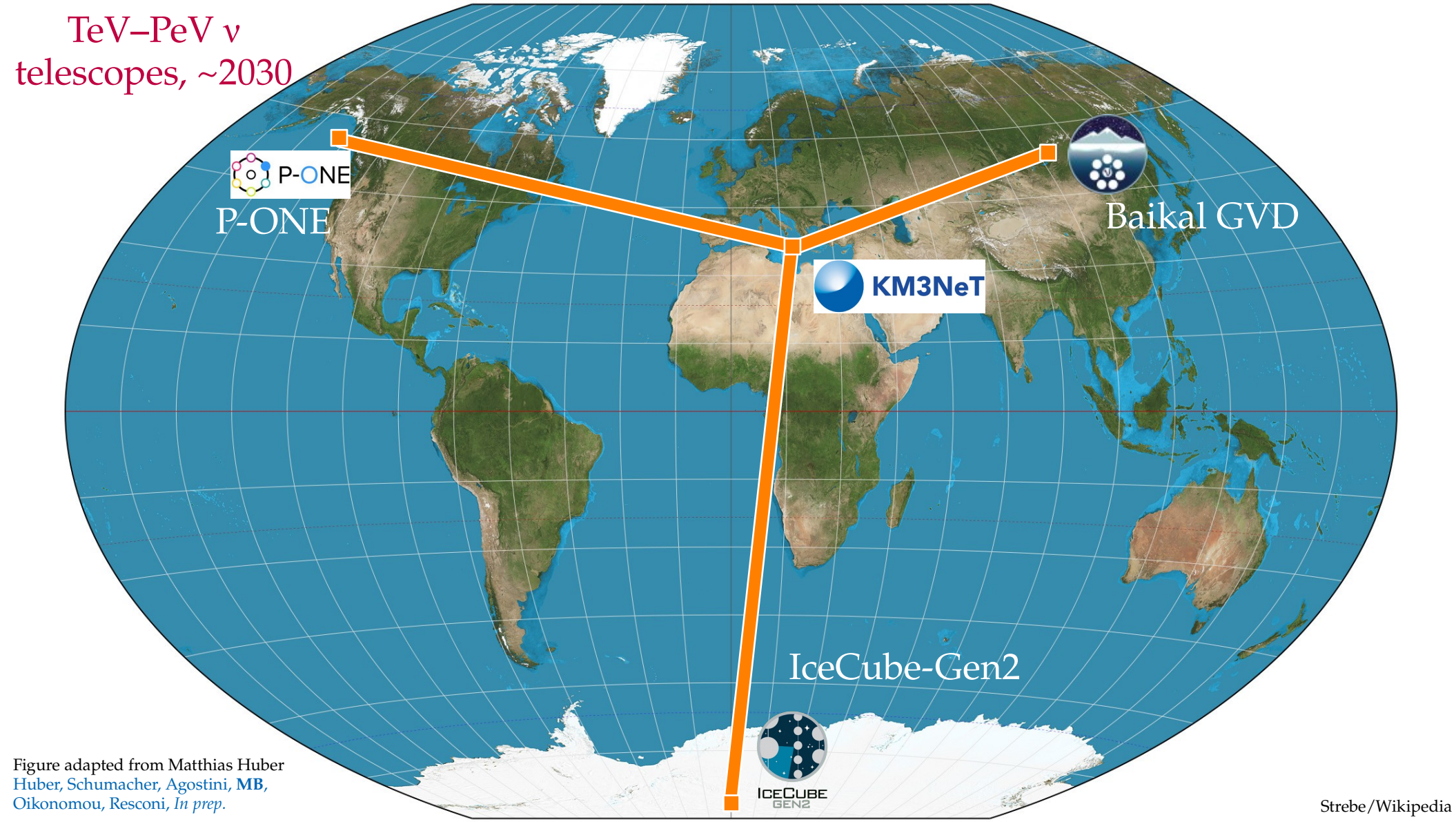
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TeV–PeV ν
telescopes, ~2030



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



TeV–PeV ν
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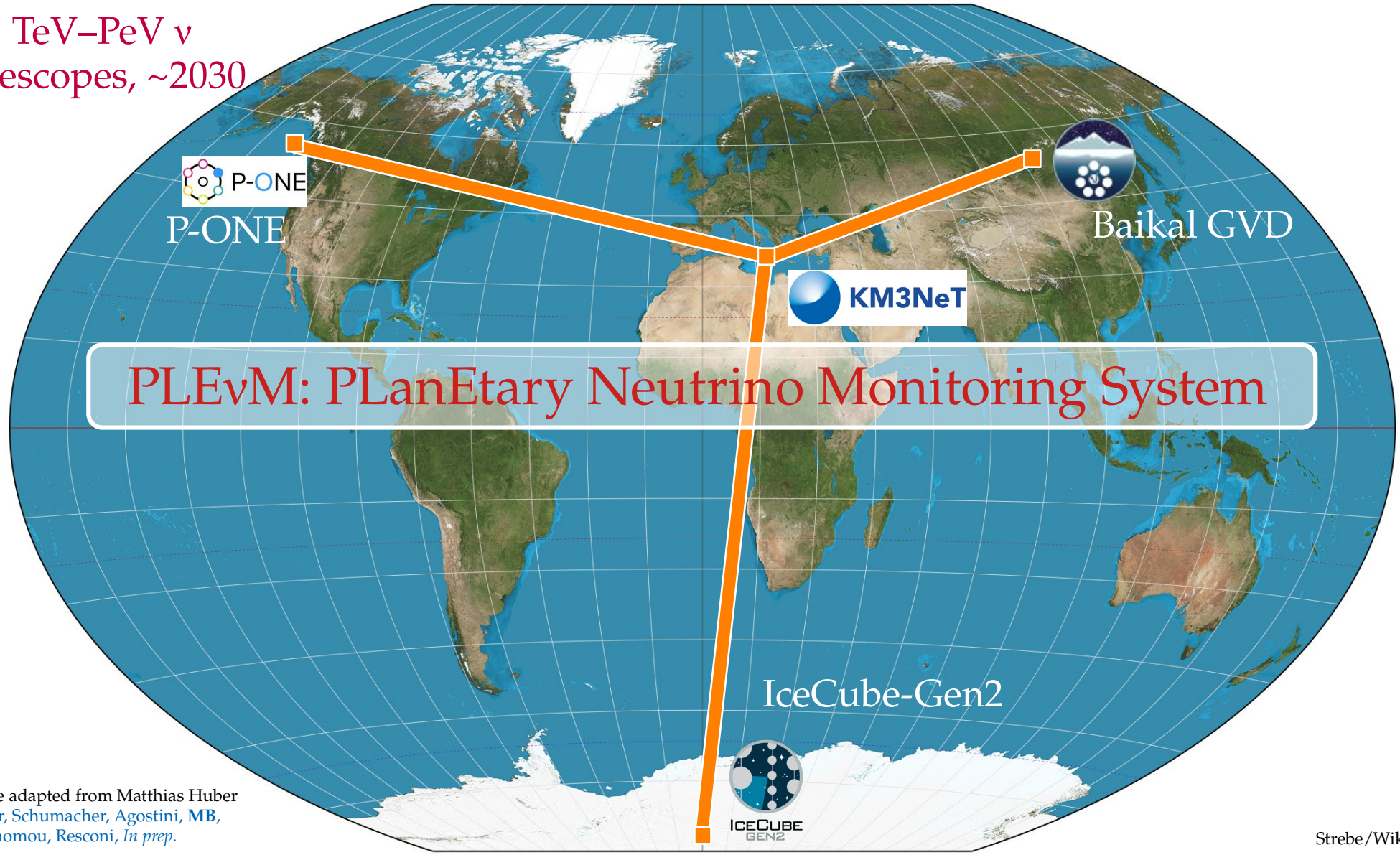
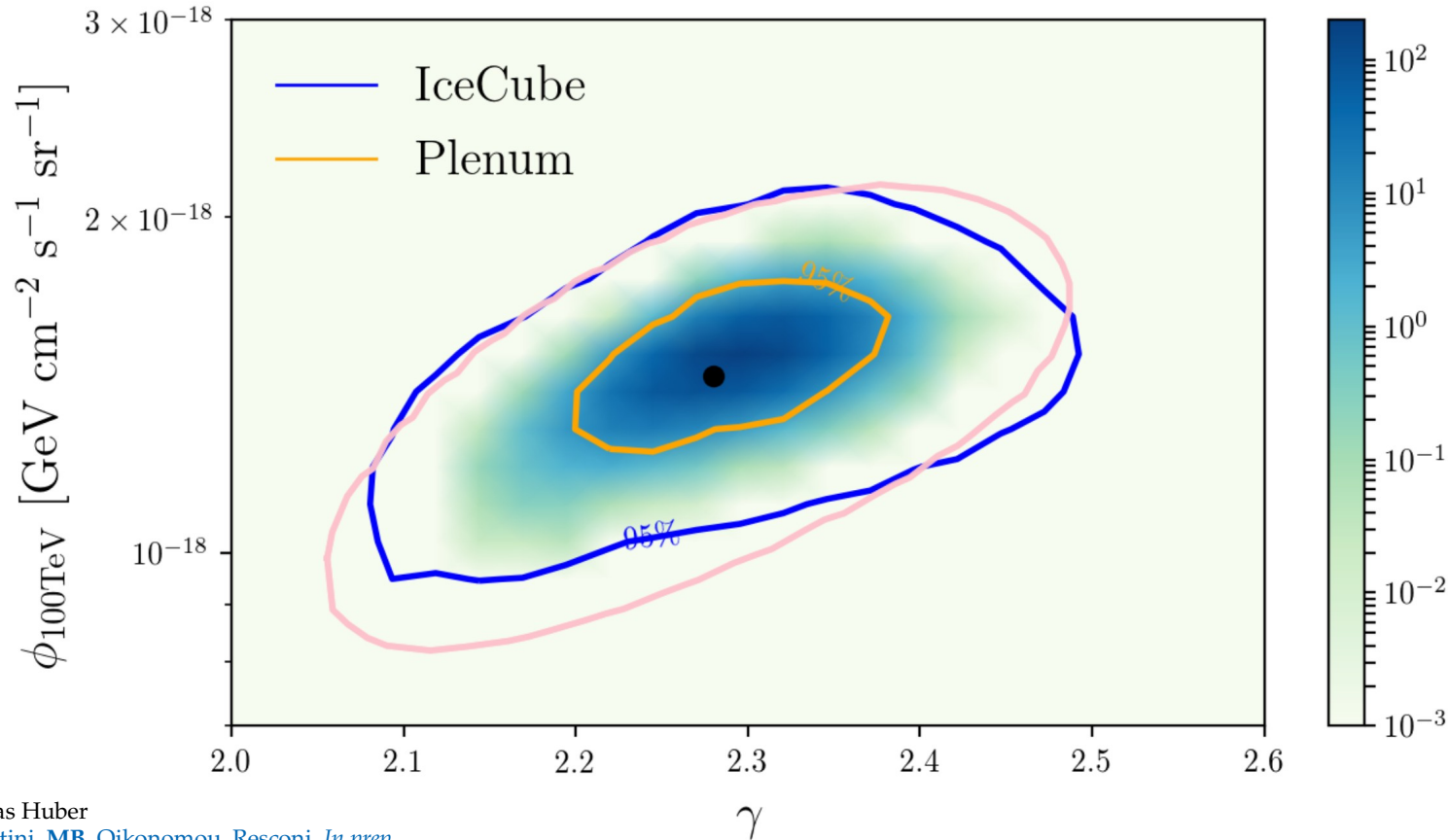


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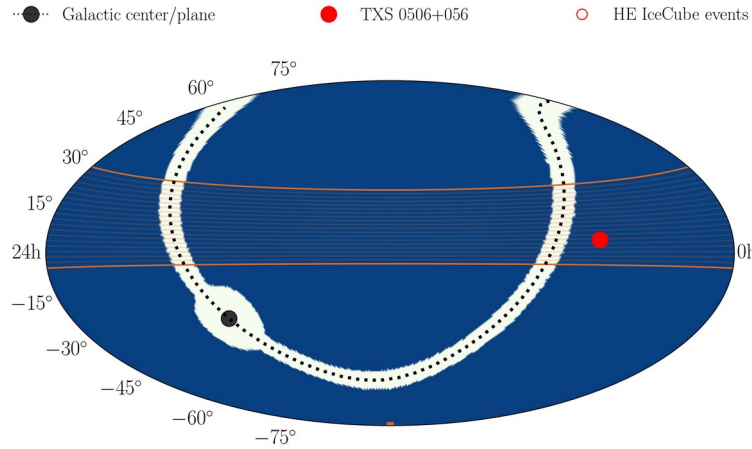
Characterizing the diffuse power-law flux in PLEvM

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



Discovering a Galactic ν flux in PLEvM

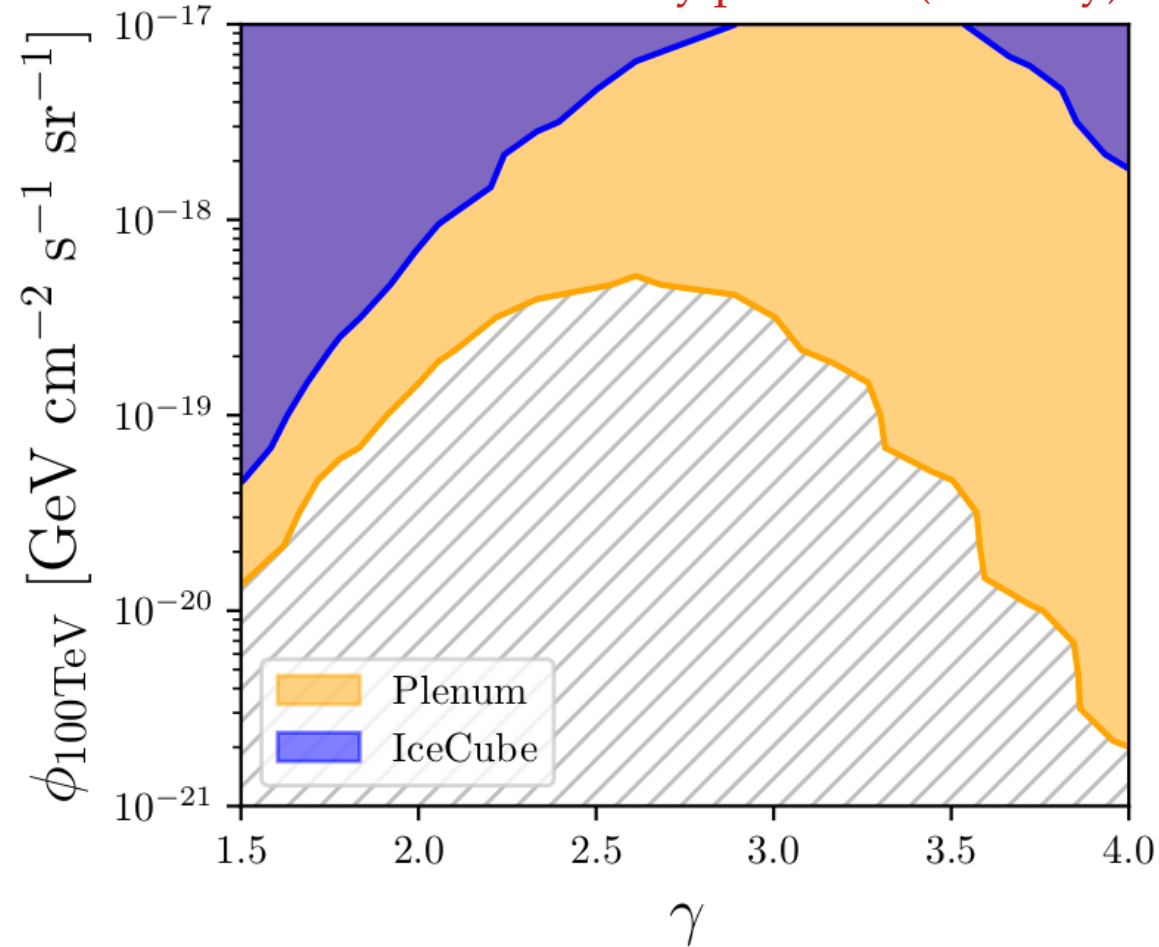
Galactic emission template:

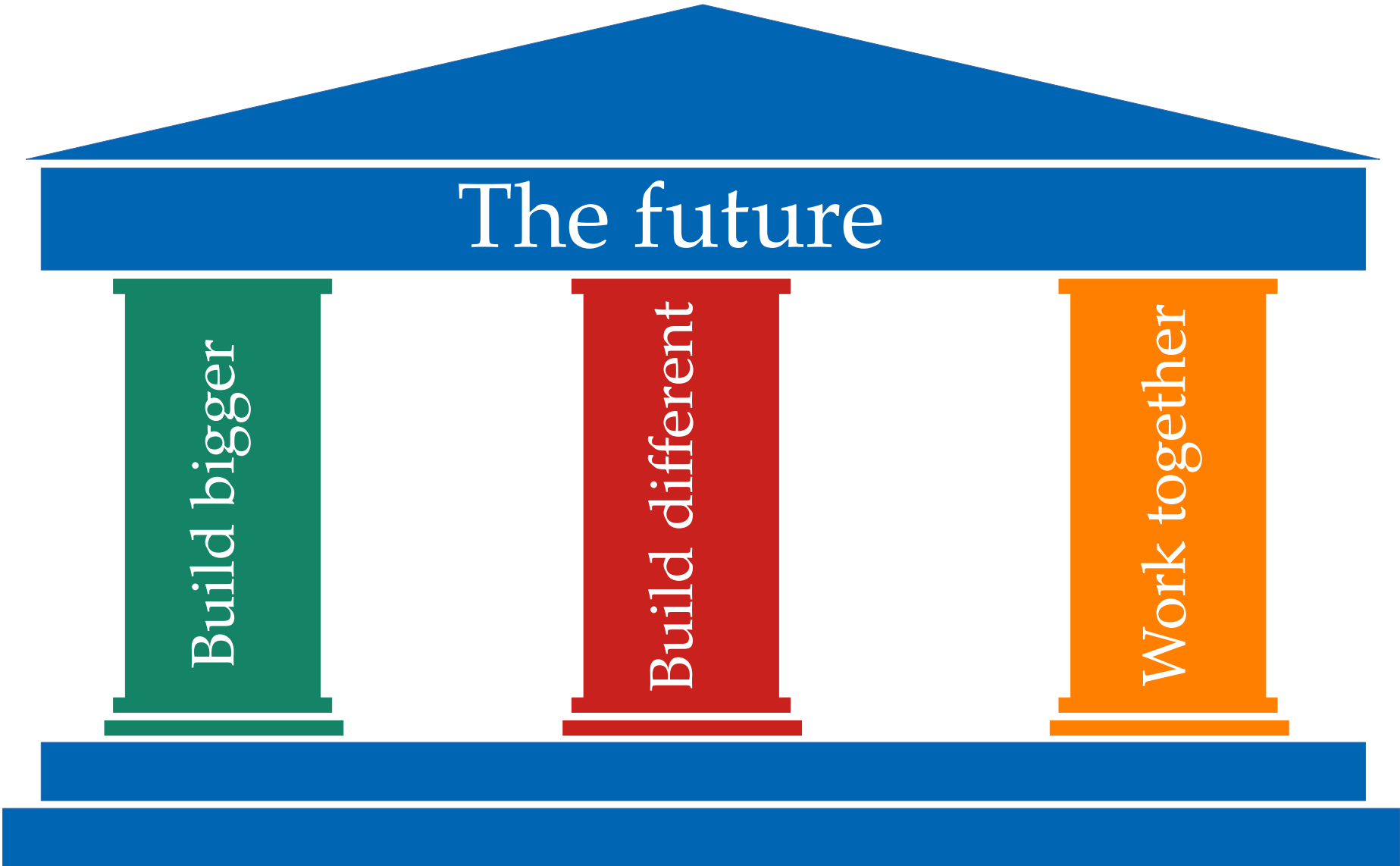


Flux uniformly distributed:

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

5 σ discovery potential (GC only)





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







2021 (*we are here*):
TeV–PeV ν discovered
First possible sources



2020s (*we are getting there*):
More source candidates
Characterize the ν flux precisely

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2030s (*under planning*):
Discovering EeV neutrinos

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> 2040:
????

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End