The wondrous life and times of high-energy astrophysical neutrinos

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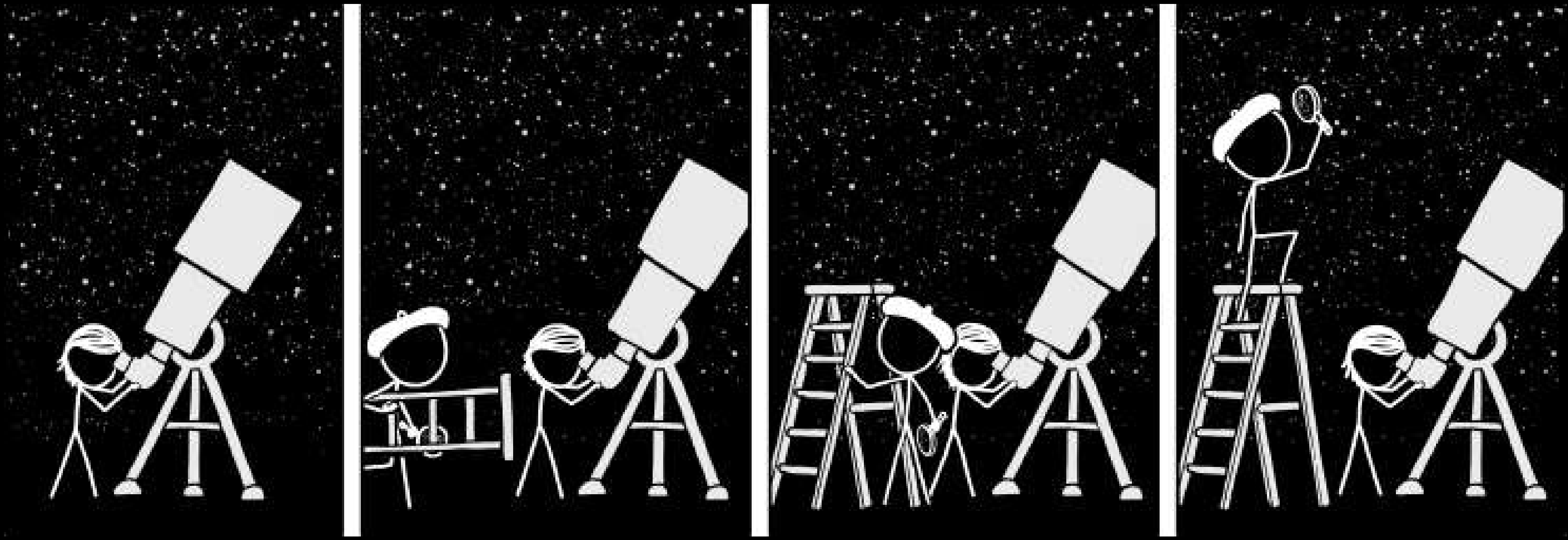
UNIVERSITY OF COPENHAGEN



xkcd

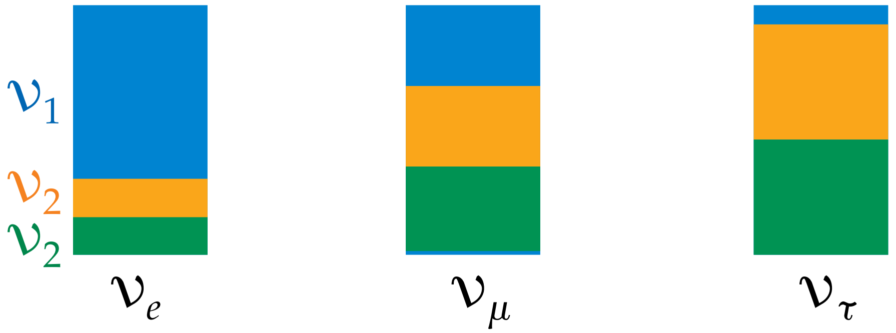
Symmetry Magazine

Neutrinos are wonderfully weird

1. They are lighter than any other massive particle we know of
2. They are notoriously anti-social
3. They retain their quantum nature over long distances
4. (We think) they reach us with energies higher than anything else

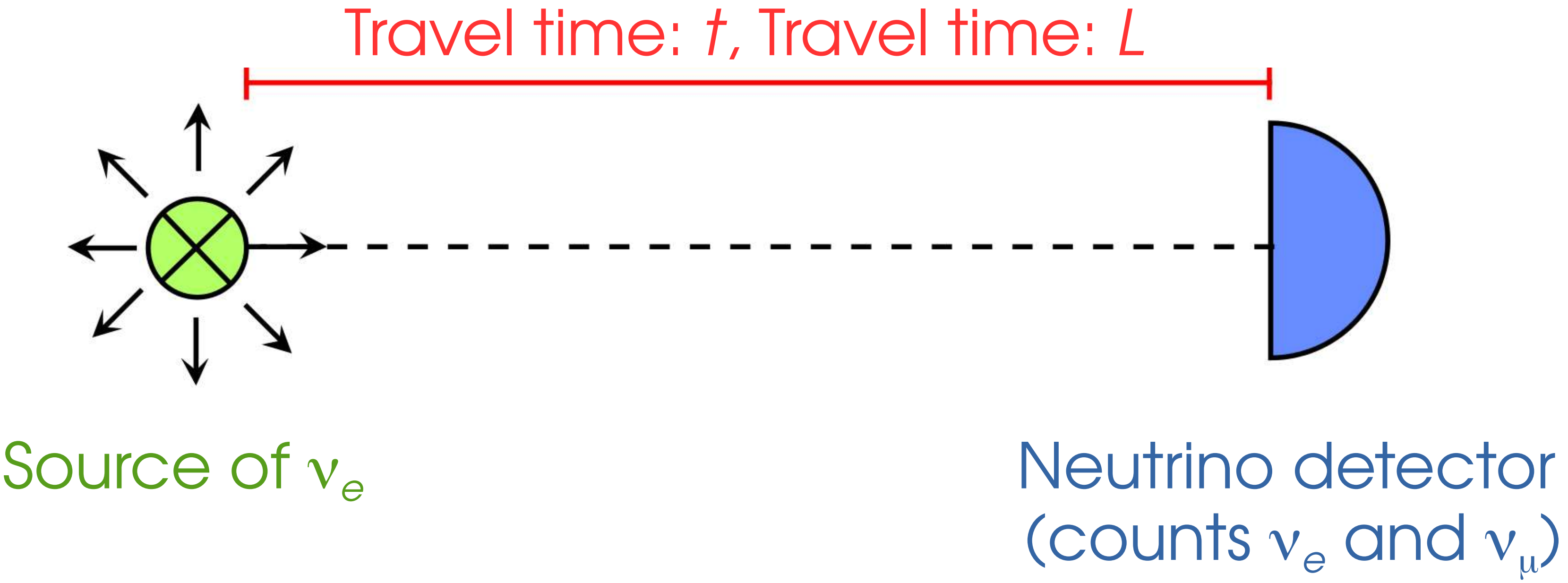
Quintessential quantum particles

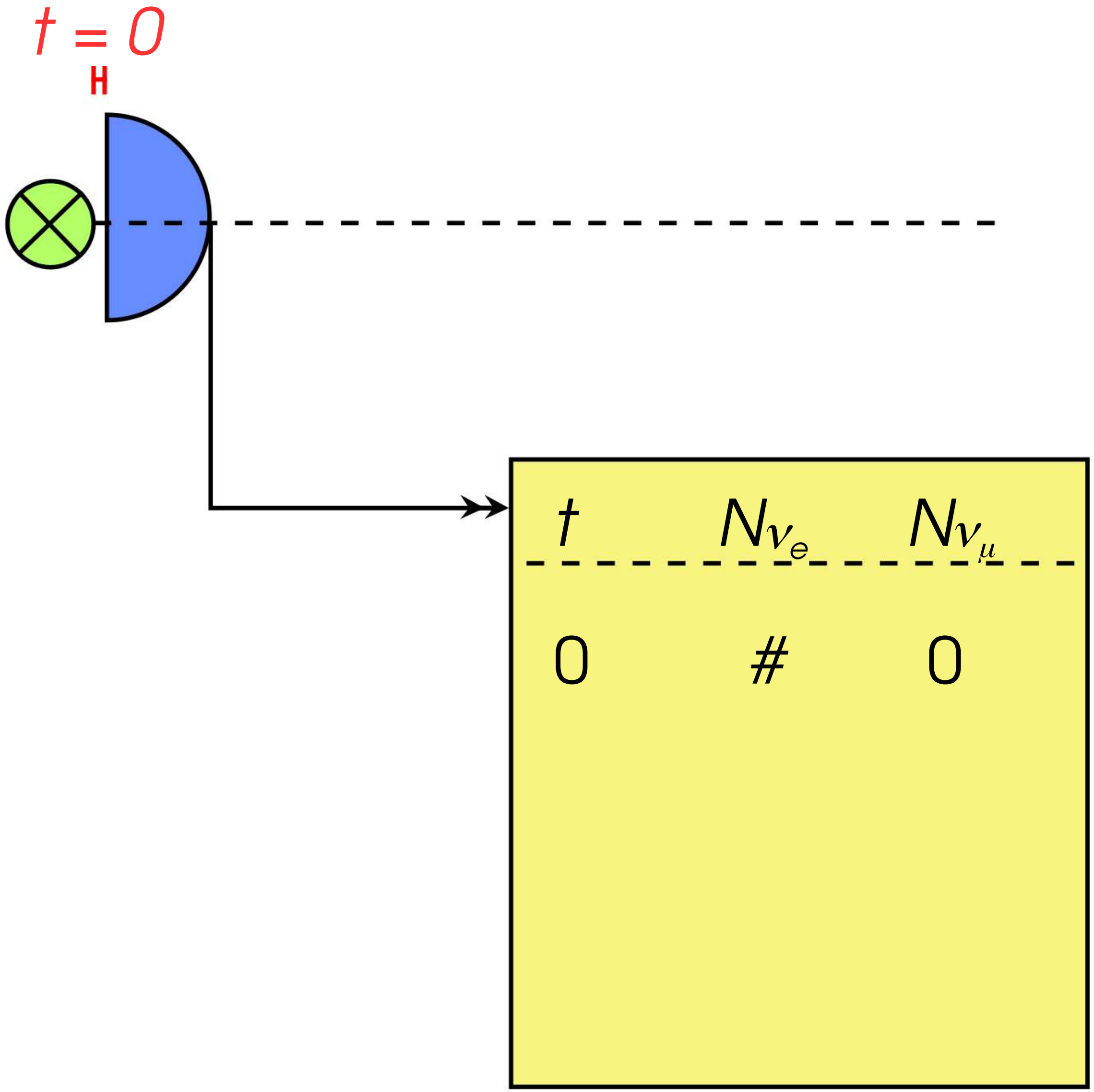
Neutrinos are created and detected as interactions states –



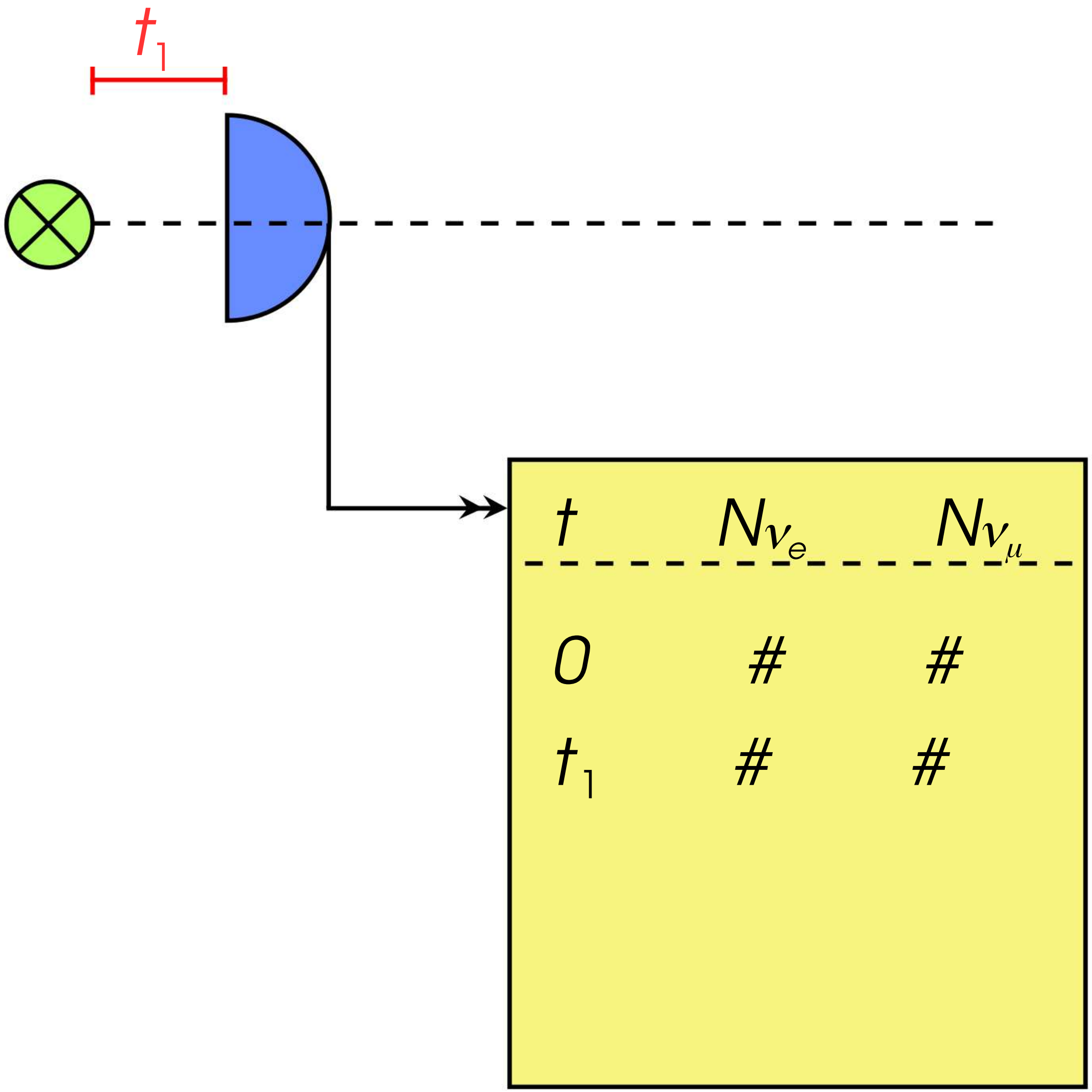
ν_1, ν_2, ν_3 have different masses $\rightarrow$ they travel at different speeds

Their superposition changes with time –

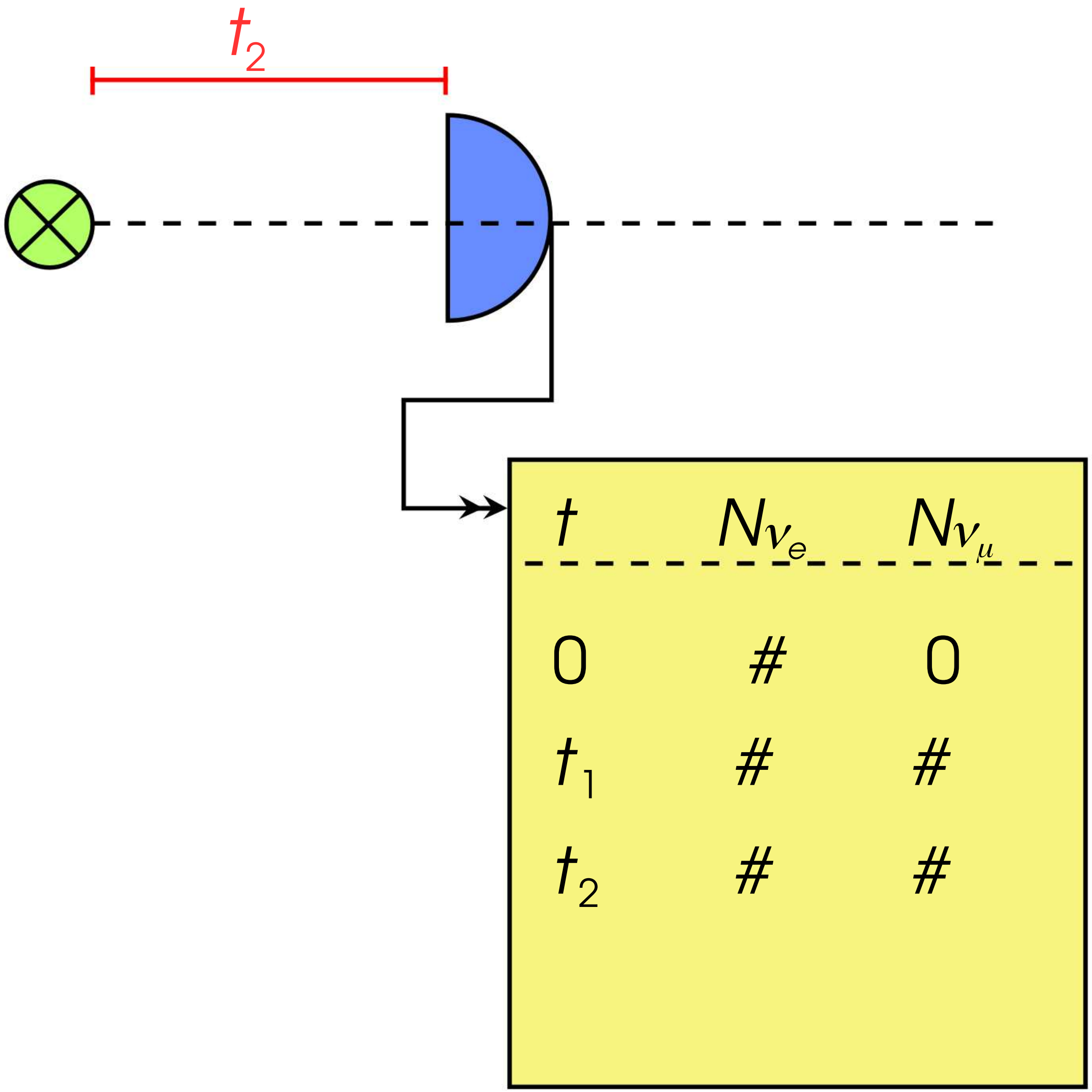

Travel time: t, Travel time: L
Source of νe
Neutrino detector
(counts νe and νμ)

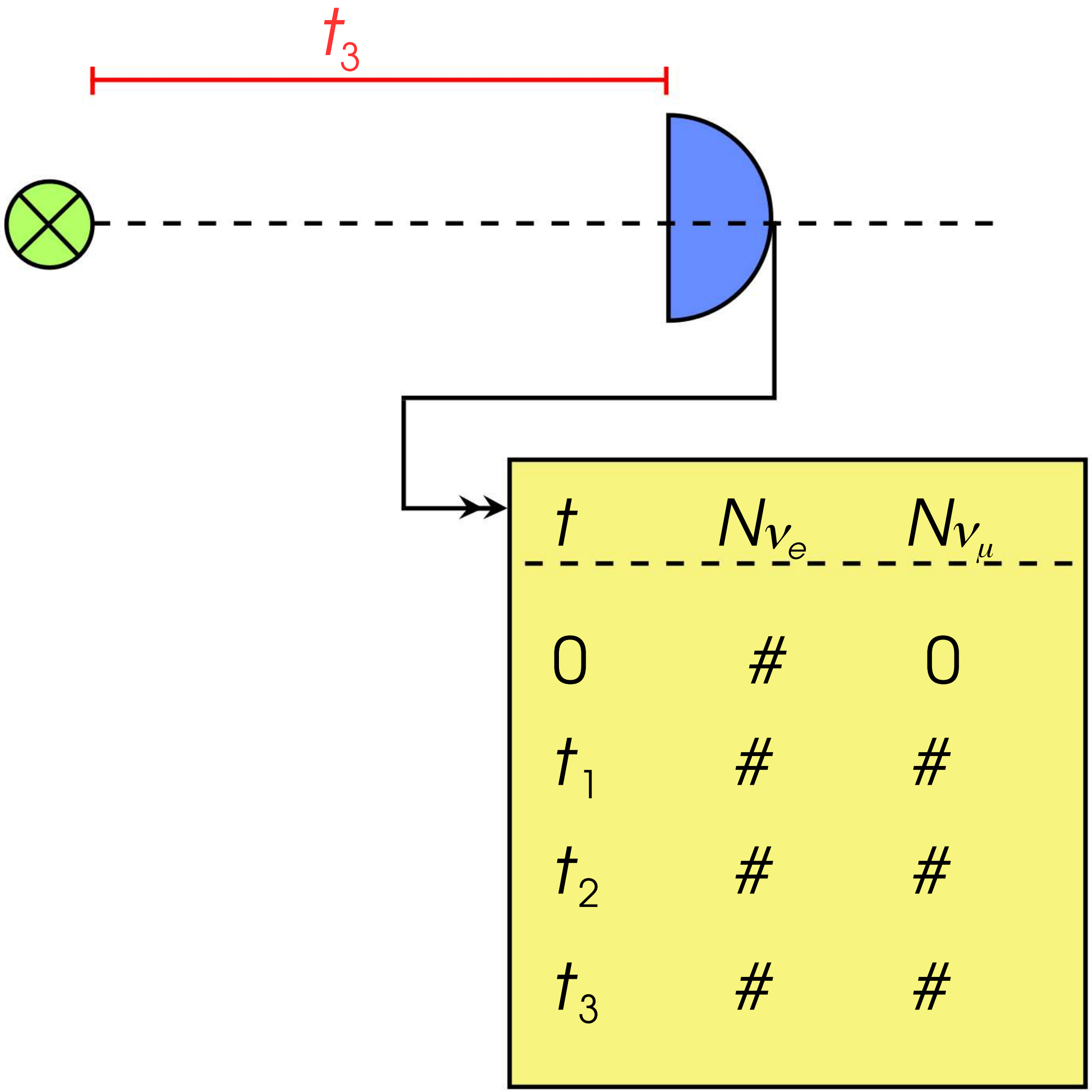


$t = 0$
H
t
N_{ν_e}
N_{ν_μ}
0
#
0



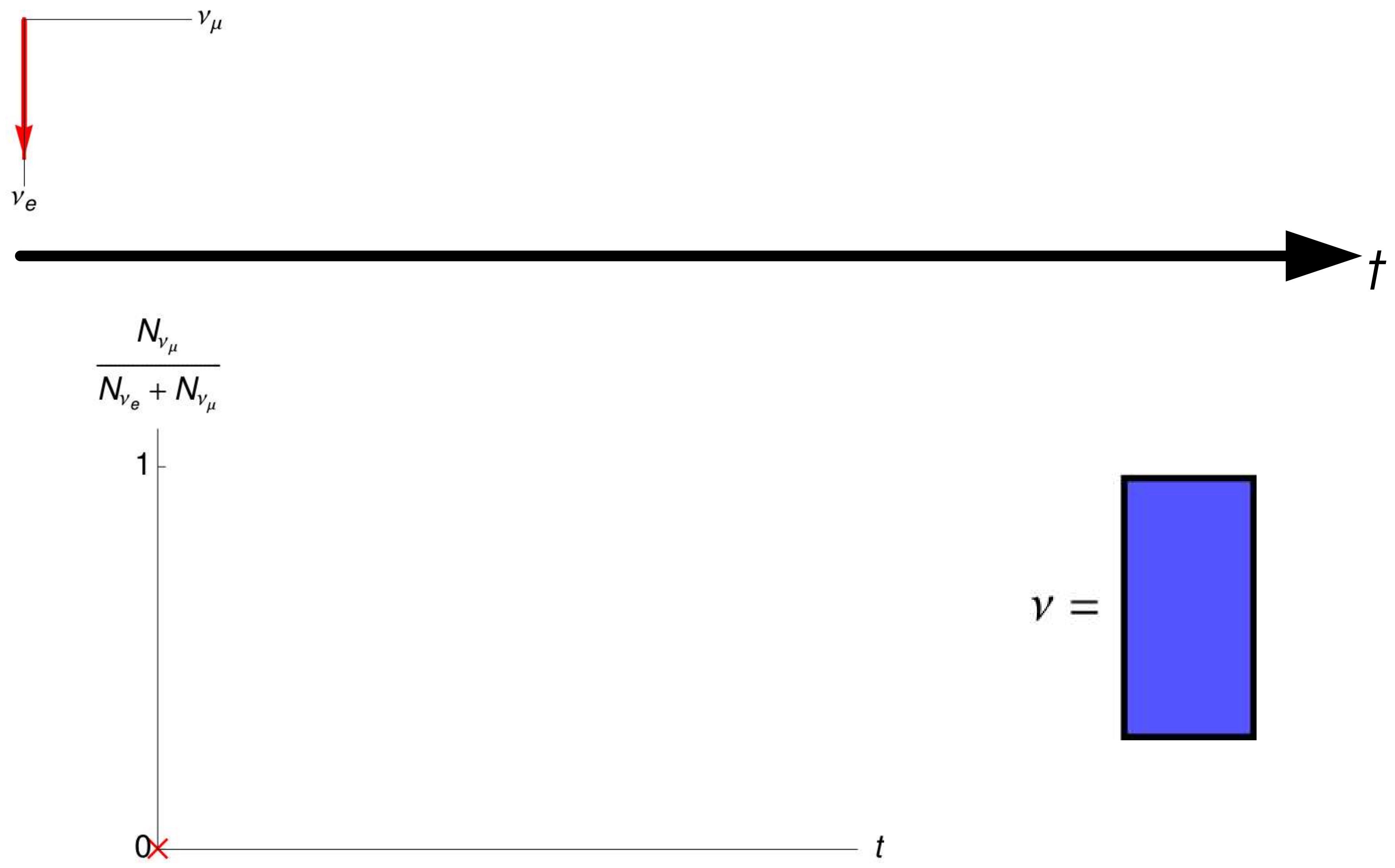
t_1
t N_{ν_e} N_{ν_μ}
0 # #
t_1 # #


t_2
t N_{ν_e} N_{ν_μ}
0 # 0
t_1 # #
t_2 # #

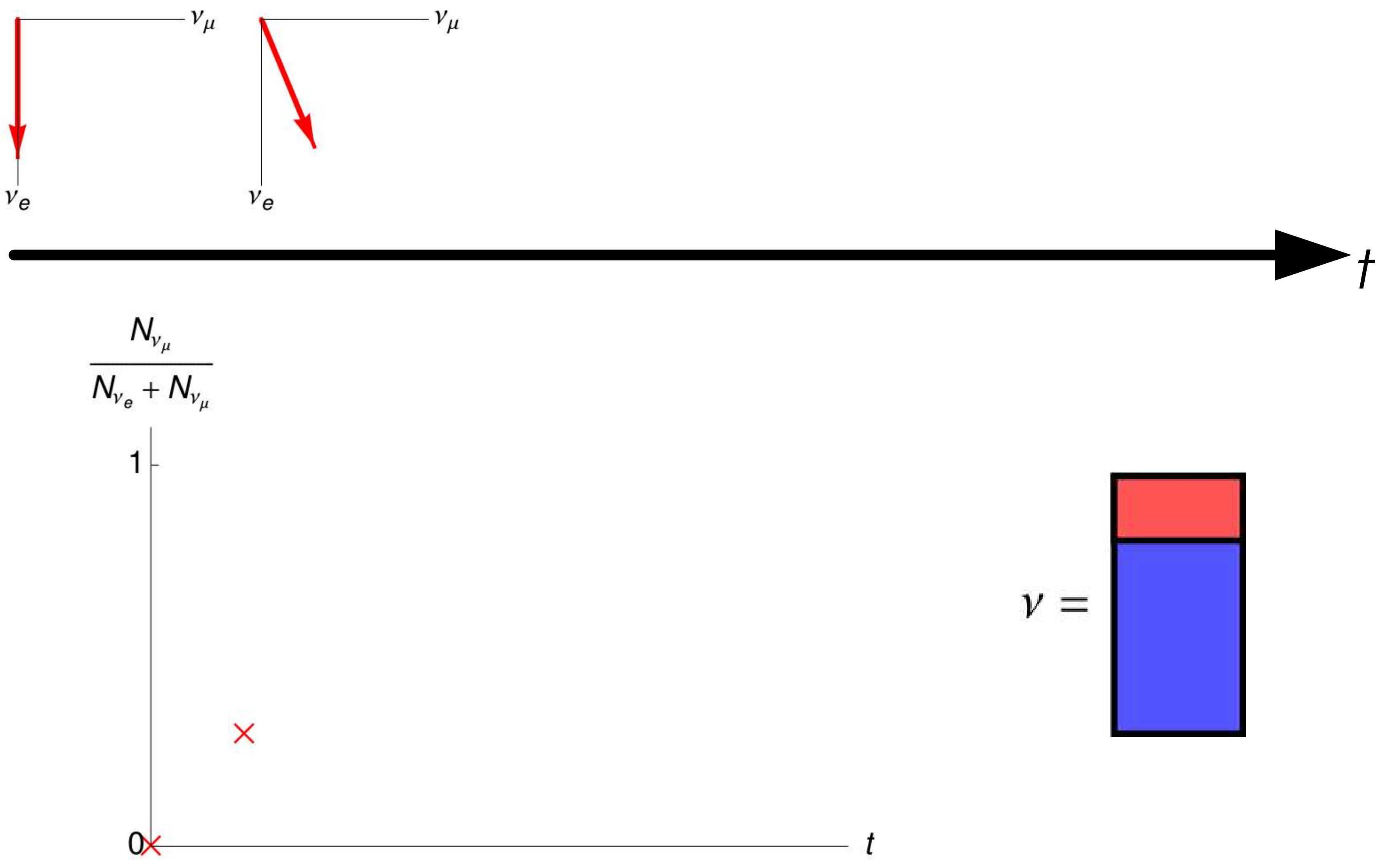


t_3
t
N_{ν_e}
N_{ν_μ}
0
#
0
t_1
#
#
t_2
#
#
t_3
#
#

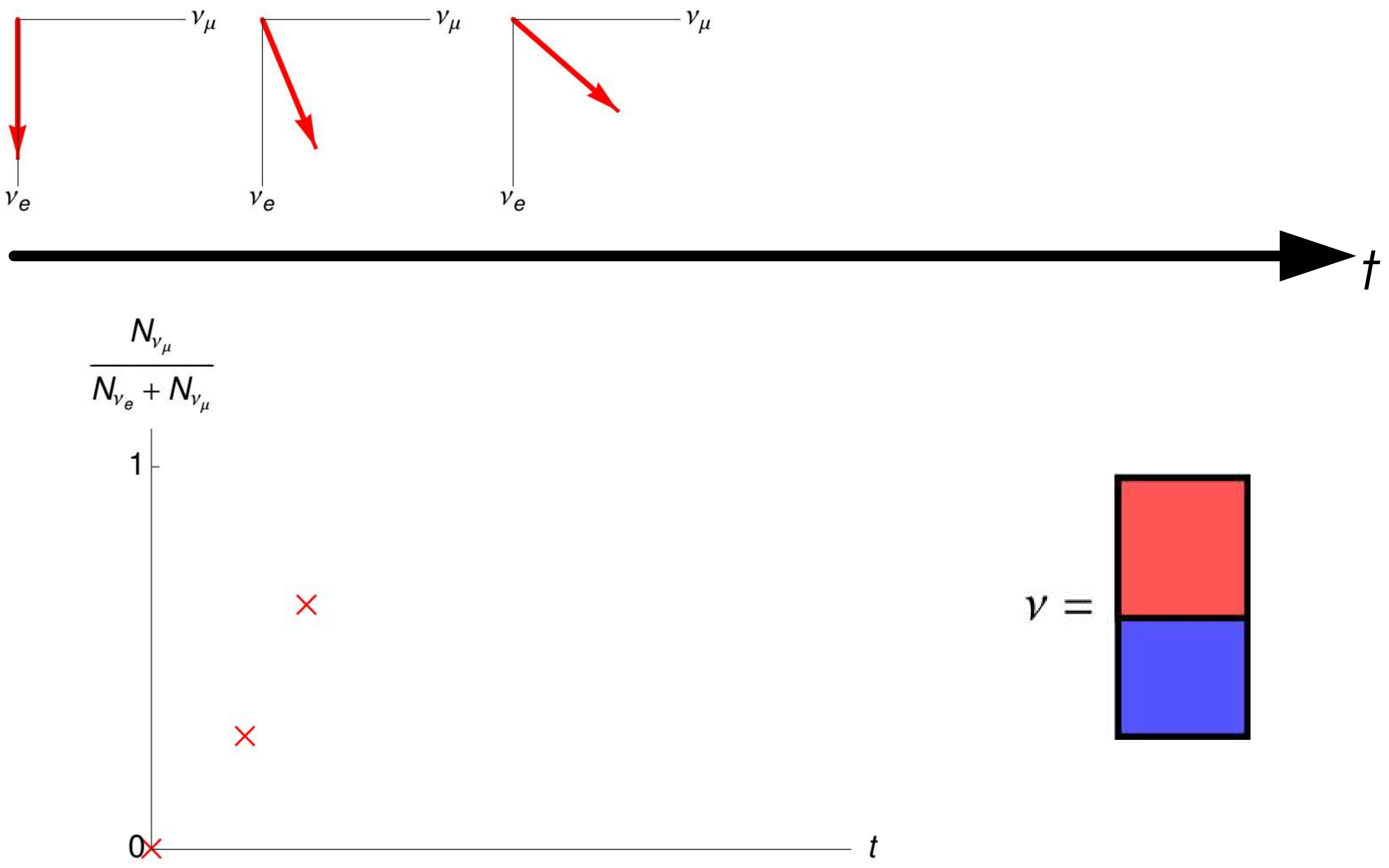

t



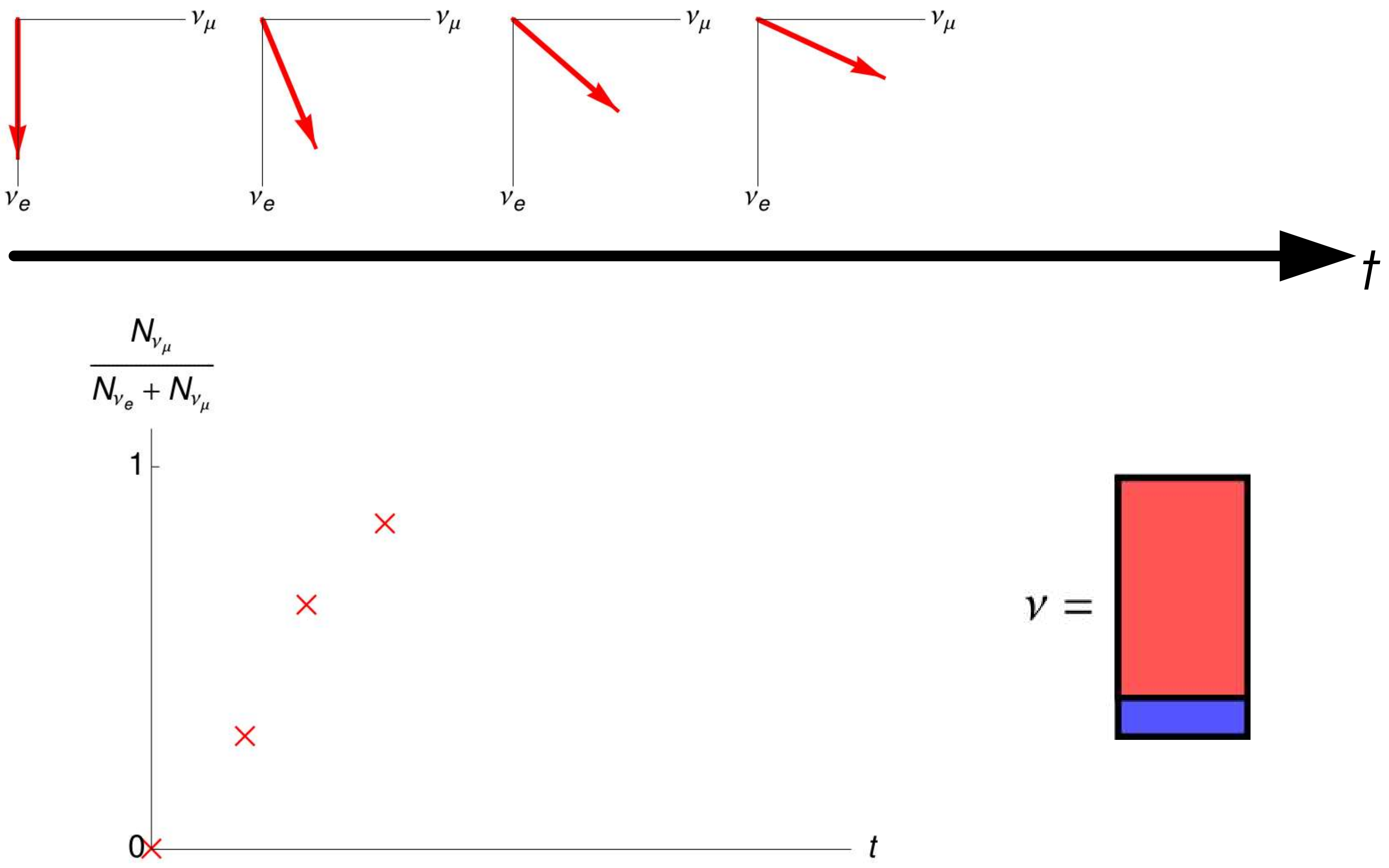
ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t
$\nu =$



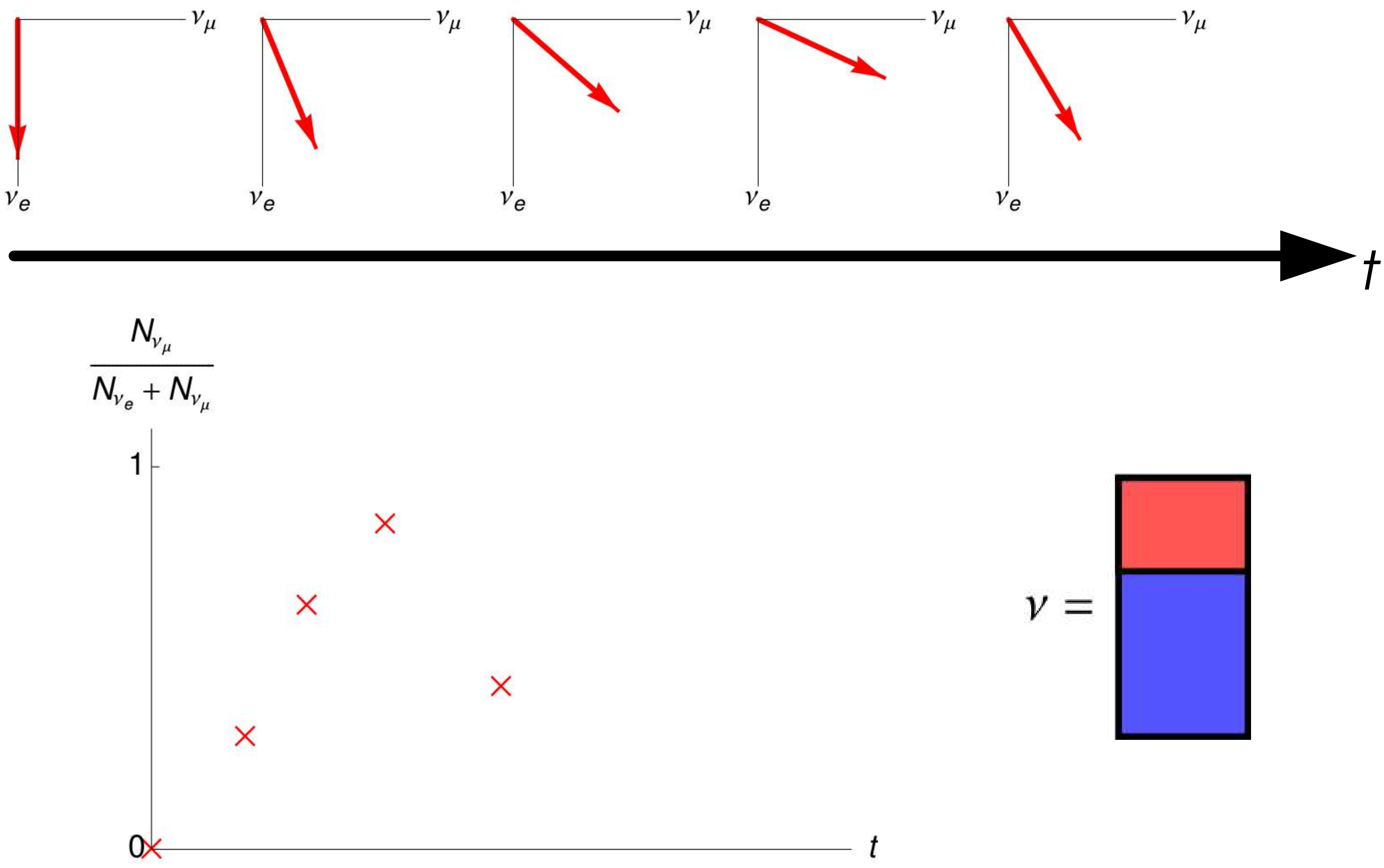
ν_μ
ν_e
ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t
$\nu =$



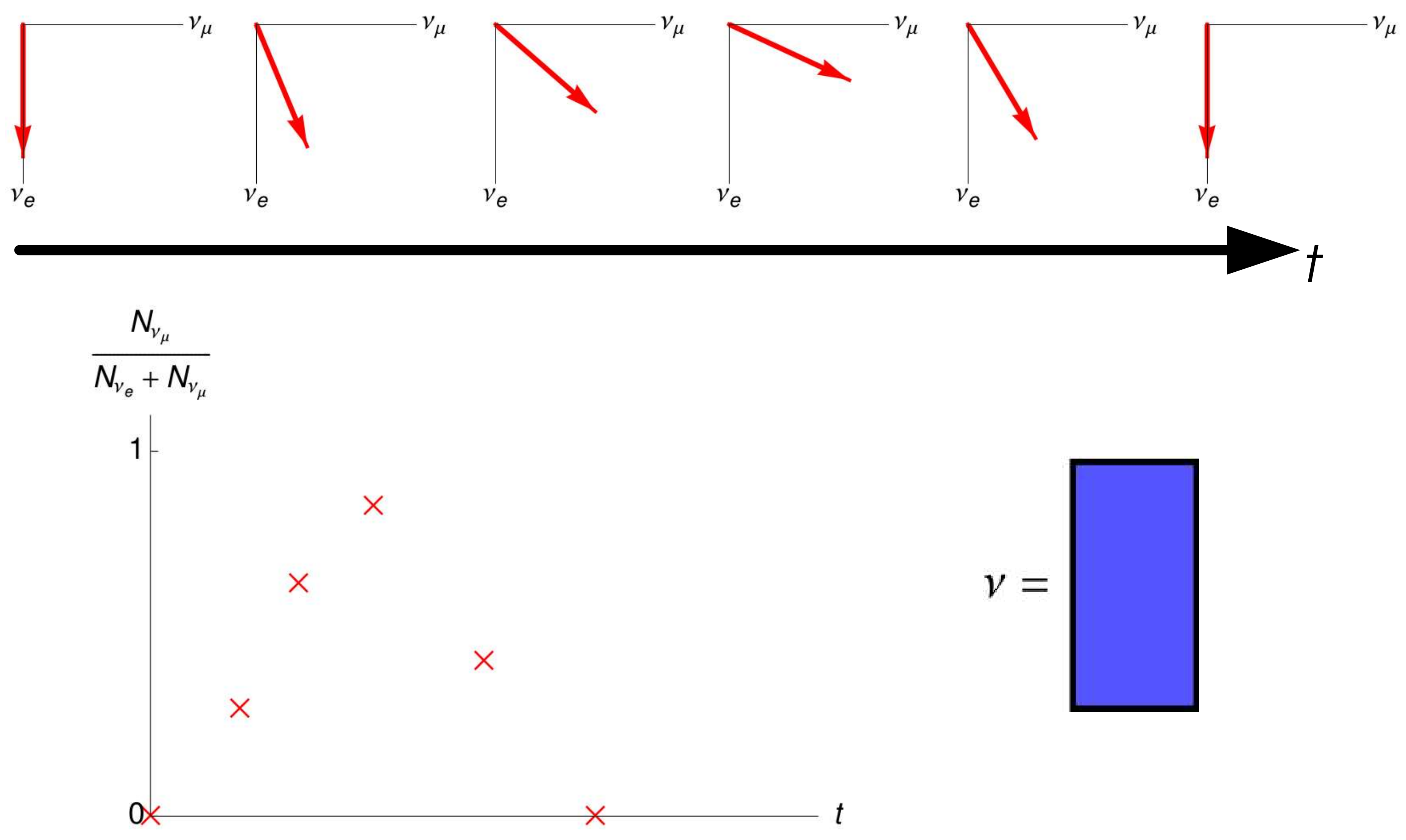
ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e}+N_{\nu_\mu}}$
1
0
$\nu =$



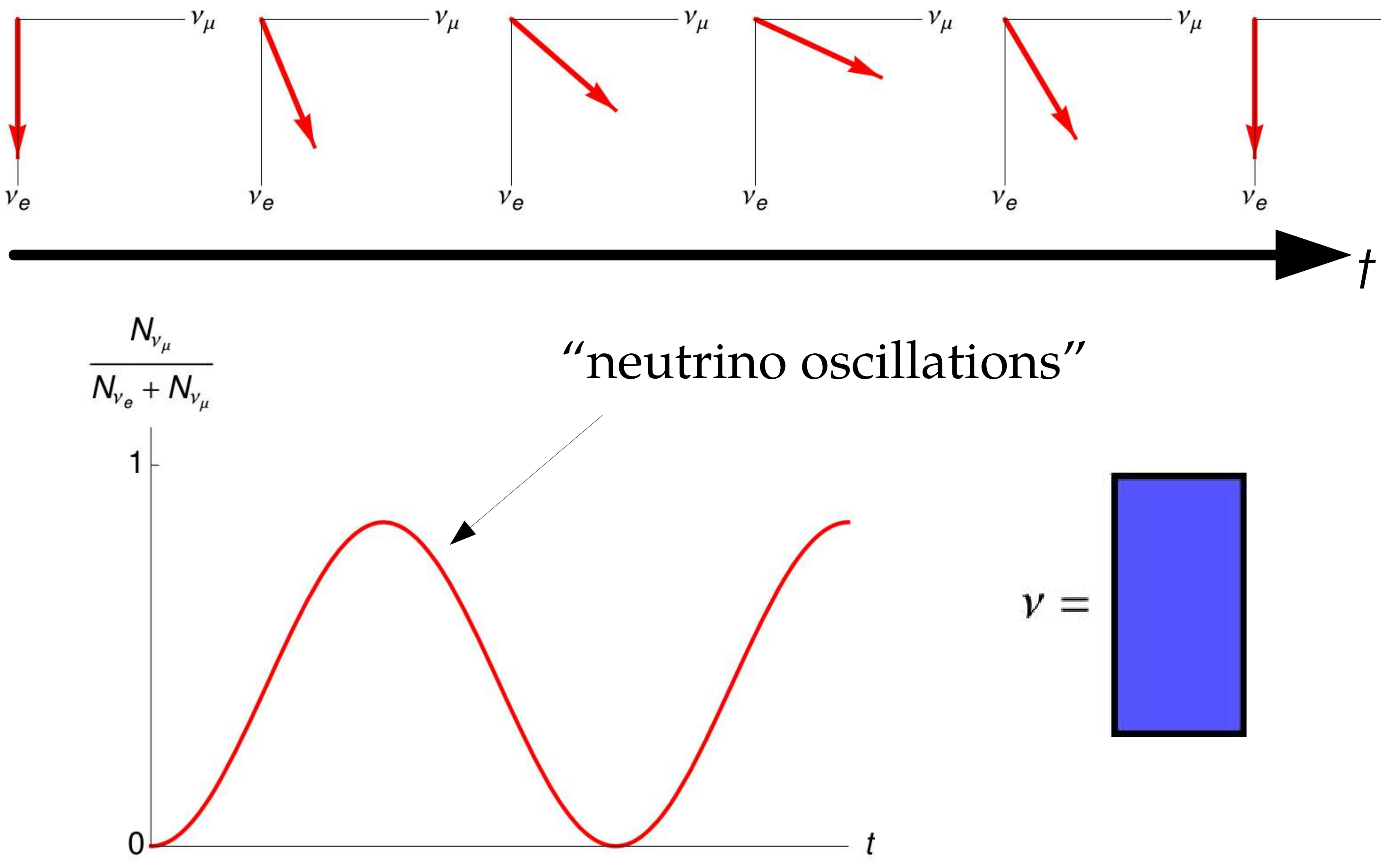
ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t
$\nu =$

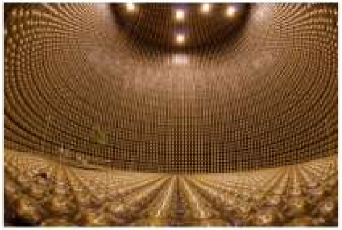


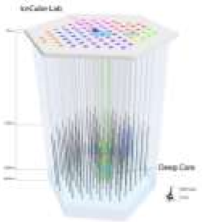
ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e}+N_{\nu_\mu}}$
1
0
t
$\nu =$

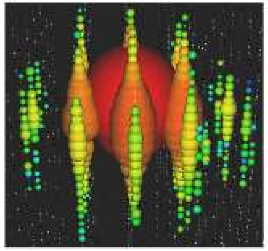


ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t
$\nu =$

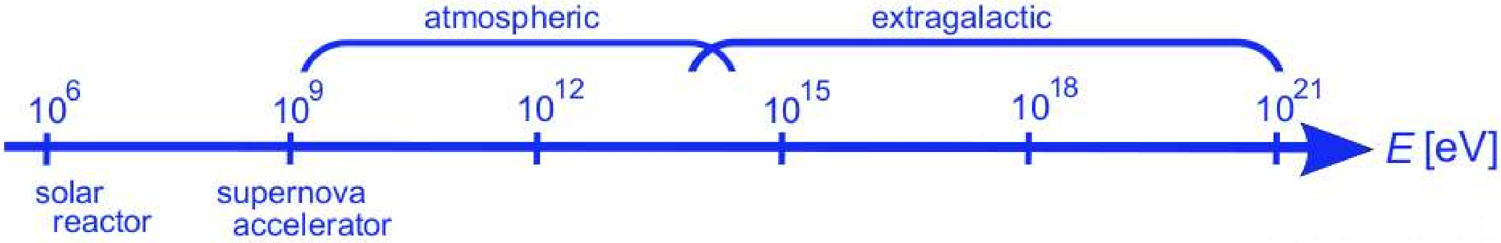

ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t
“neutrino oscillations”
$\nu =$

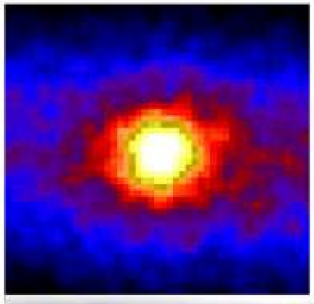






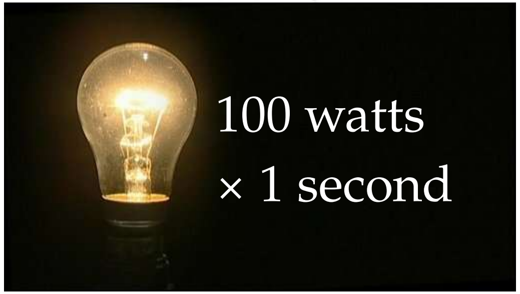
2013+

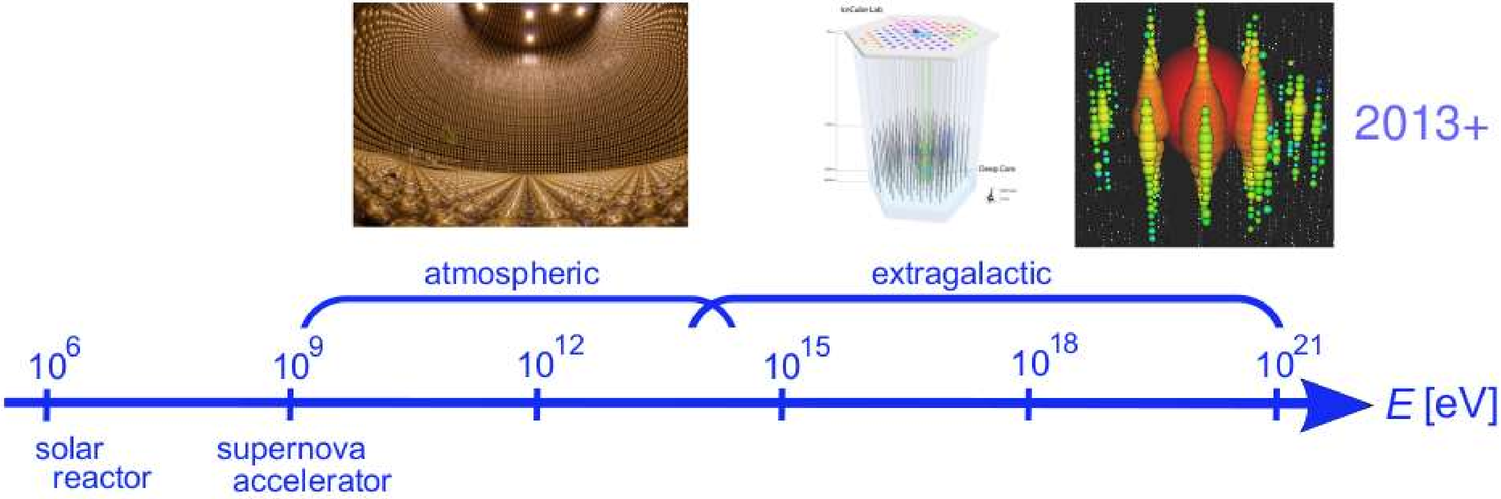


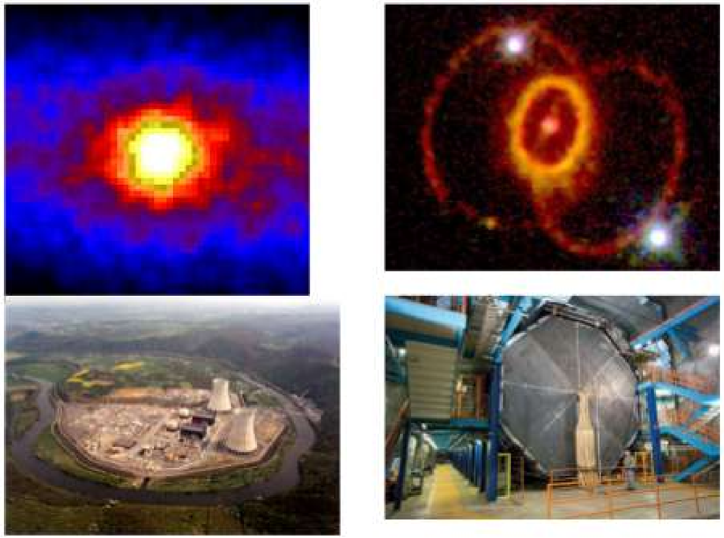


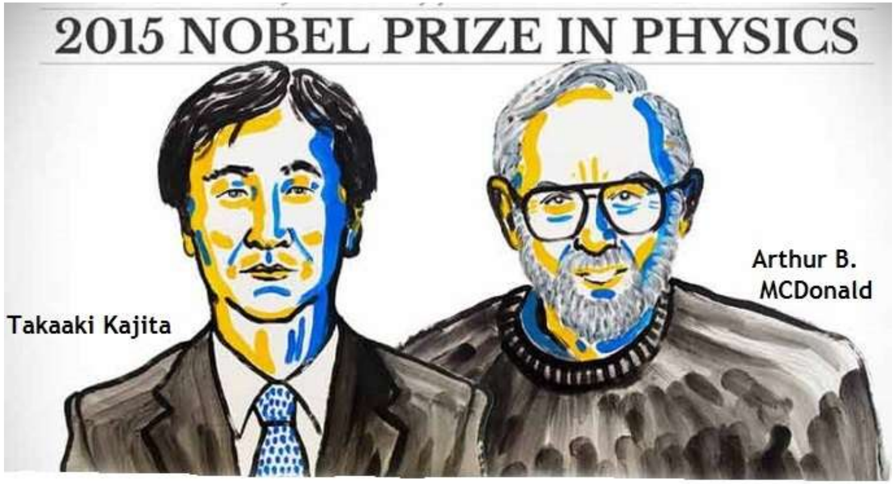
10^{12} eV $\rightarrow$

6×10^{20} eV $\rightarrow$









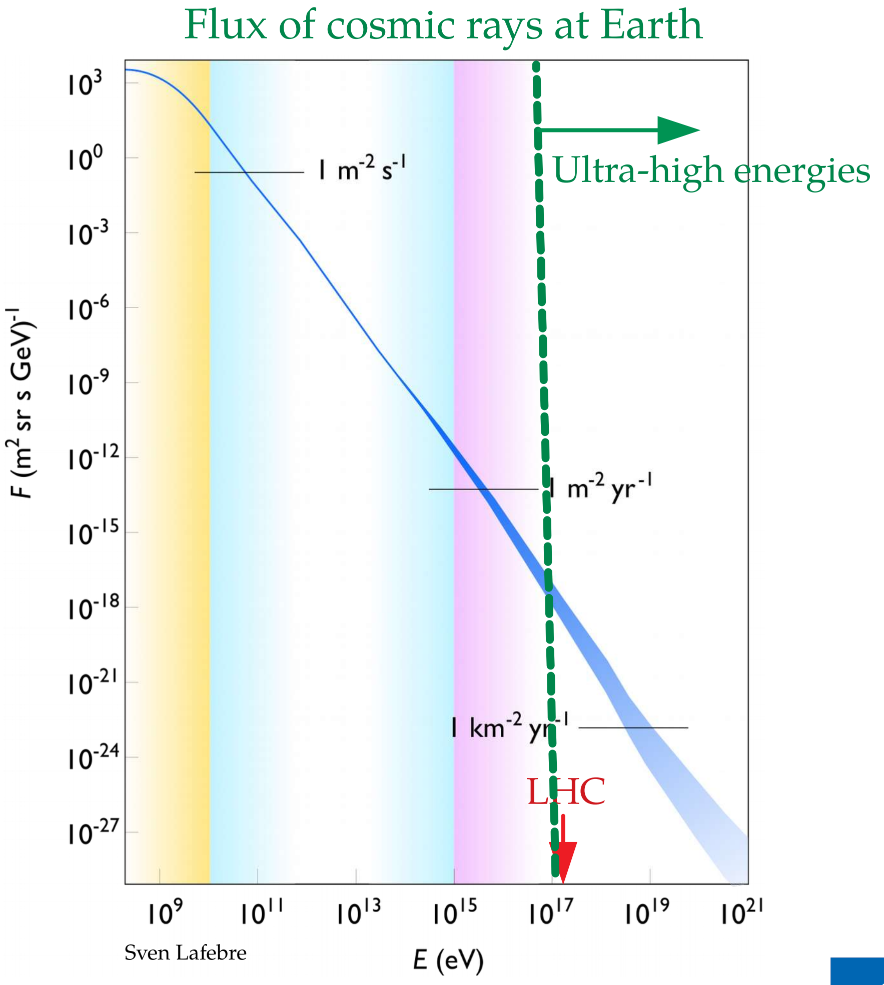
Next ν-Nobel for high-energy ν's?

Why study high-energy astrophysical neutrinos?

They are key to answering two major questions –

1. What makes the most energetic particles we detect?

2. How does particle physics look at these energies?



Sven Lafebre

A mystery 50+ years old

Where are the most energetic cosmic rays coming from?

1962: First cosmic rays with $>10^{18}$ eV

- 1991, Fly's Eye:

  "Oh-my-God" particle

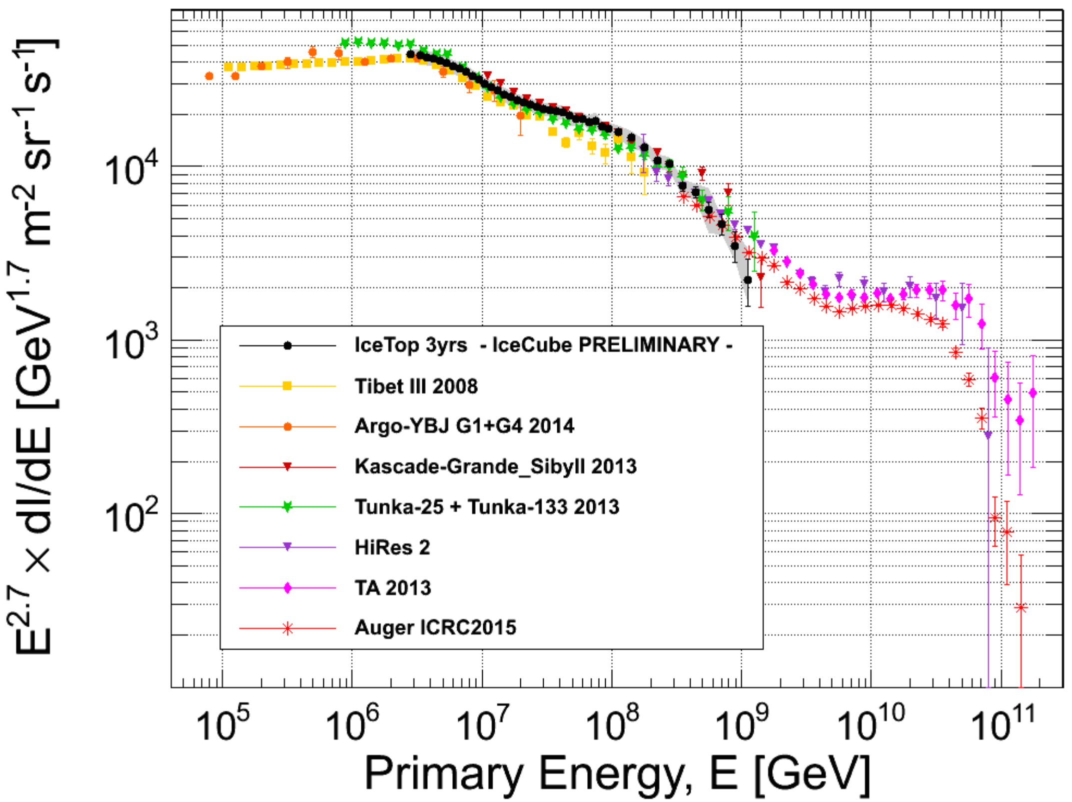
  $3 \cdot 10^{20}$ eV ≈ 50 J

- $E_{\rm kin}$ of a baseball at 58 mph

  … in $(1\ \mathrm{fm})^3$

- 40 million × LHC proton

What *do* we know about UHECRs?



- Their spectrum
  – A power law with kinks
- Their mass composition (sort of)
  – Light → heavy → medium
- Their arrival directions
  – Isotropic
  … save one significant excess

All of these are interesting, but insufficient to solve the mystery

Using UHECRs to find their sources is tough

- The Universe is opaque to UHECRs
  - CRs lose energy by scattering on the cosmic microwave background (CMB):

$$p + \gamma_{\mathrm{CMB}} \to p + e^{+} + e^{-}$$

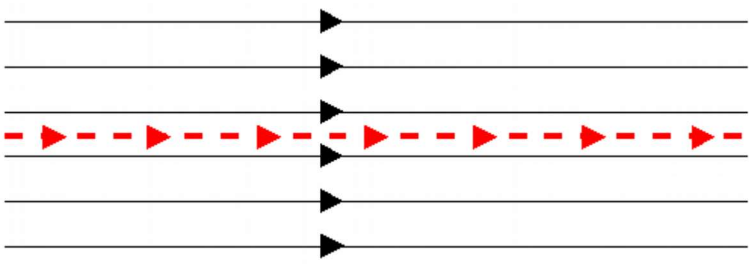
  - Protons above $4 \cdot 10^9$ GeV do not survive more than ~100 Mpc

- Cosmic rays do not point back at their sources
  - Magnetic fields: μG (Milky Way) – nG (extragalactic)
  - Deflections of up to tens of degrees

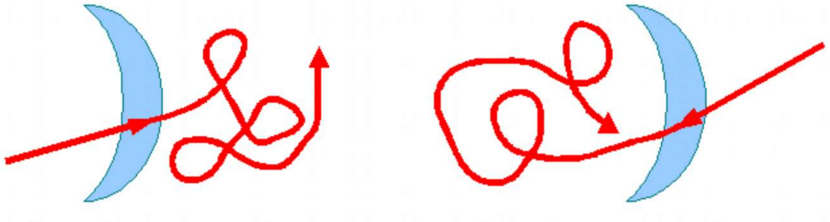
- Uncertainties about how high-energy particle showers work

UHECR sources are wasteful…

Man-made accelerators



Astrophysical accelerators



	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


Jellyfish Nebula , NASA

… And one man's garbage is another man's treasure

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

… And one man's garbage is another man's treasure

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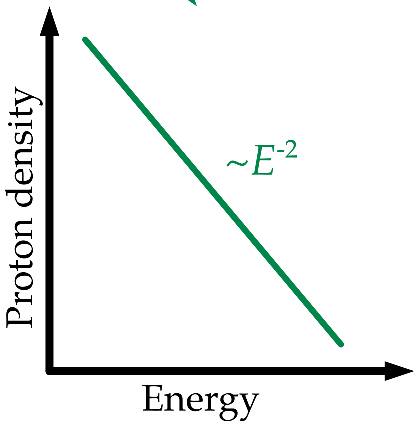

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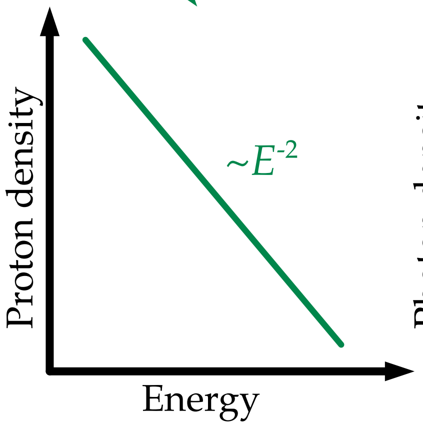

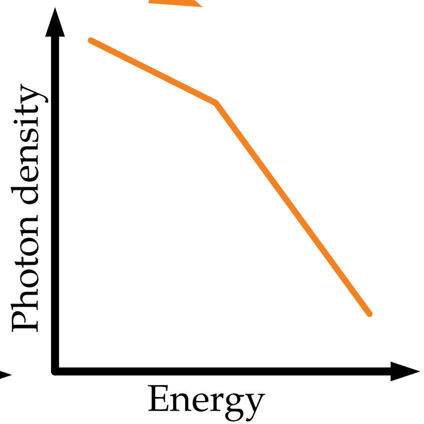

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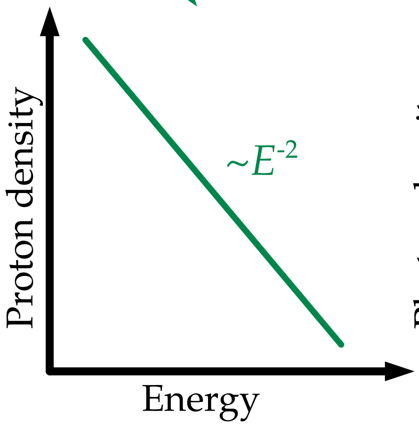
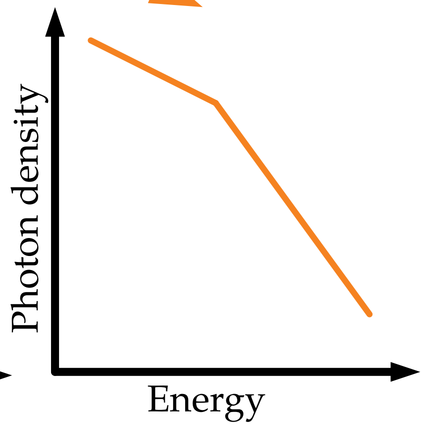
$$\pi^0 \to \gamma + \gamma$$

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

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





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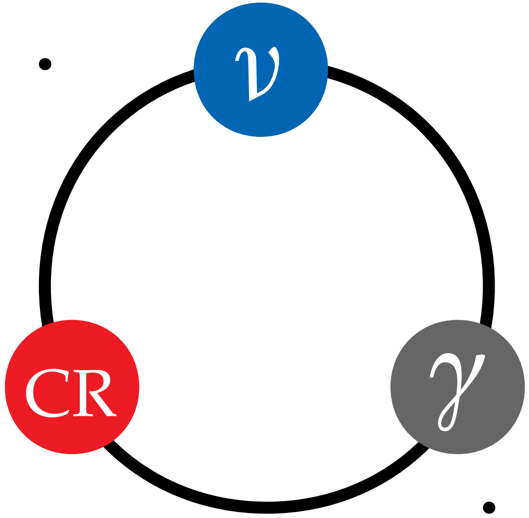

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

… And one man's garbage is another man's treasure

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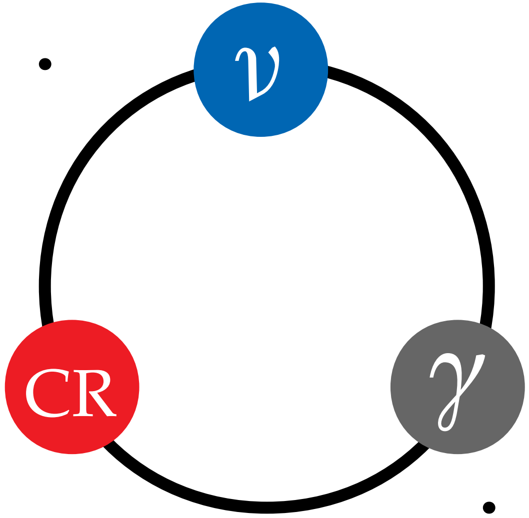

1 PeV — 20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

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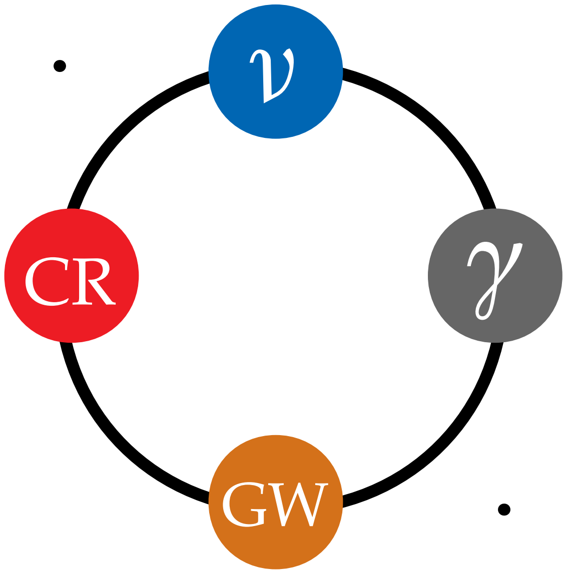

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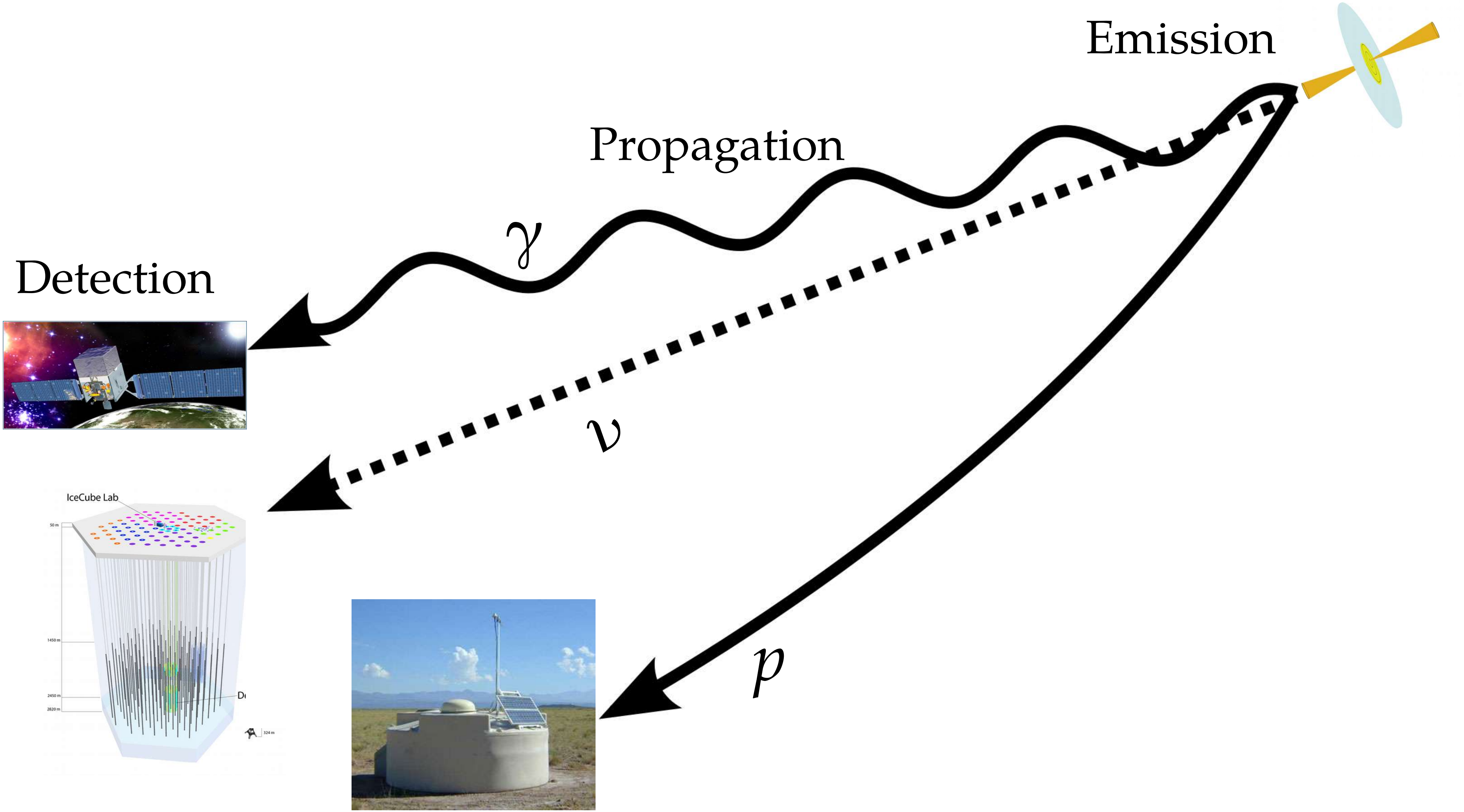
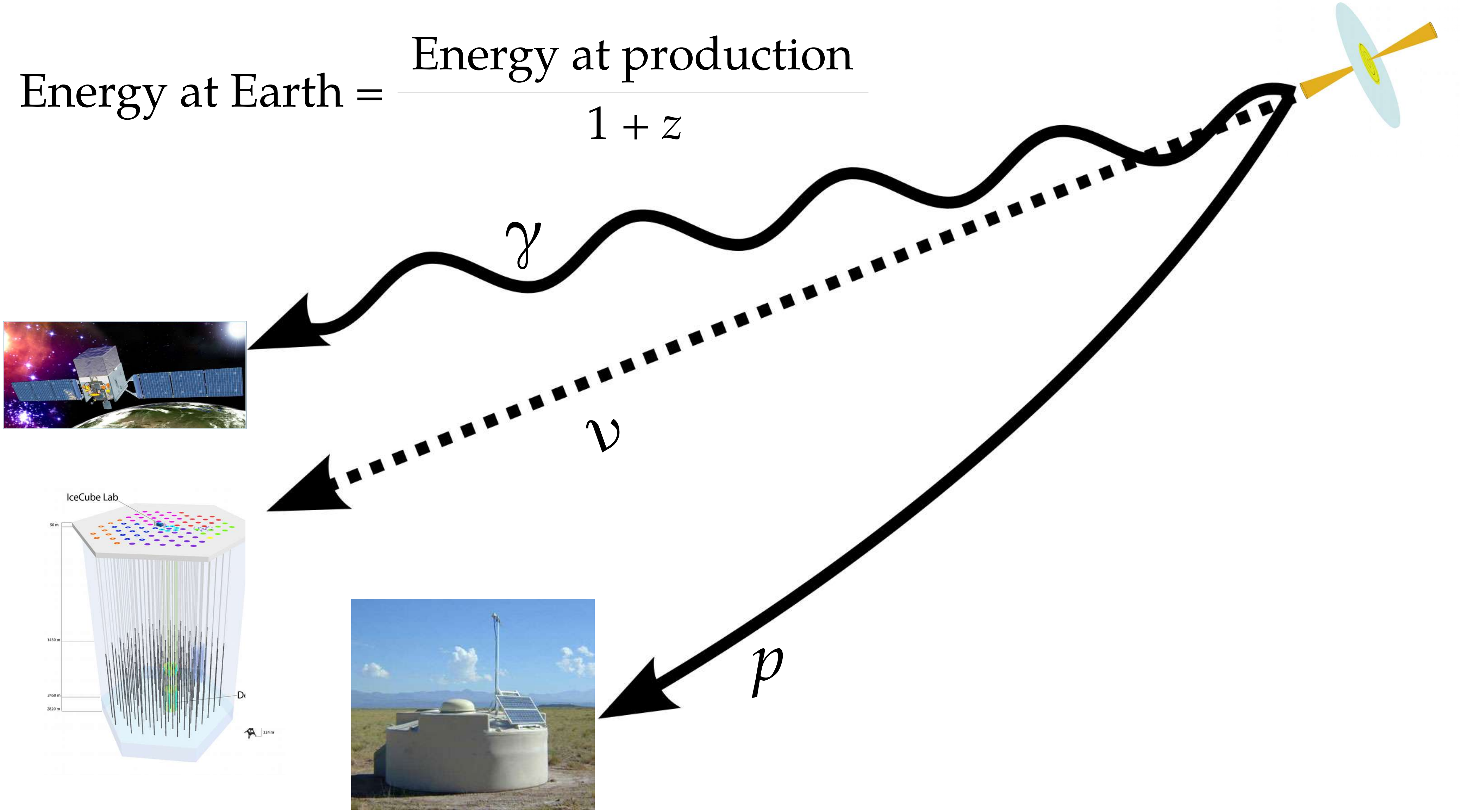

Emission
Propagation
Detection
γ
ν
p
IceCube Lab

$$\text{Energy at Earth} = \frac{\text{Energy at production}}{1 + z}$$



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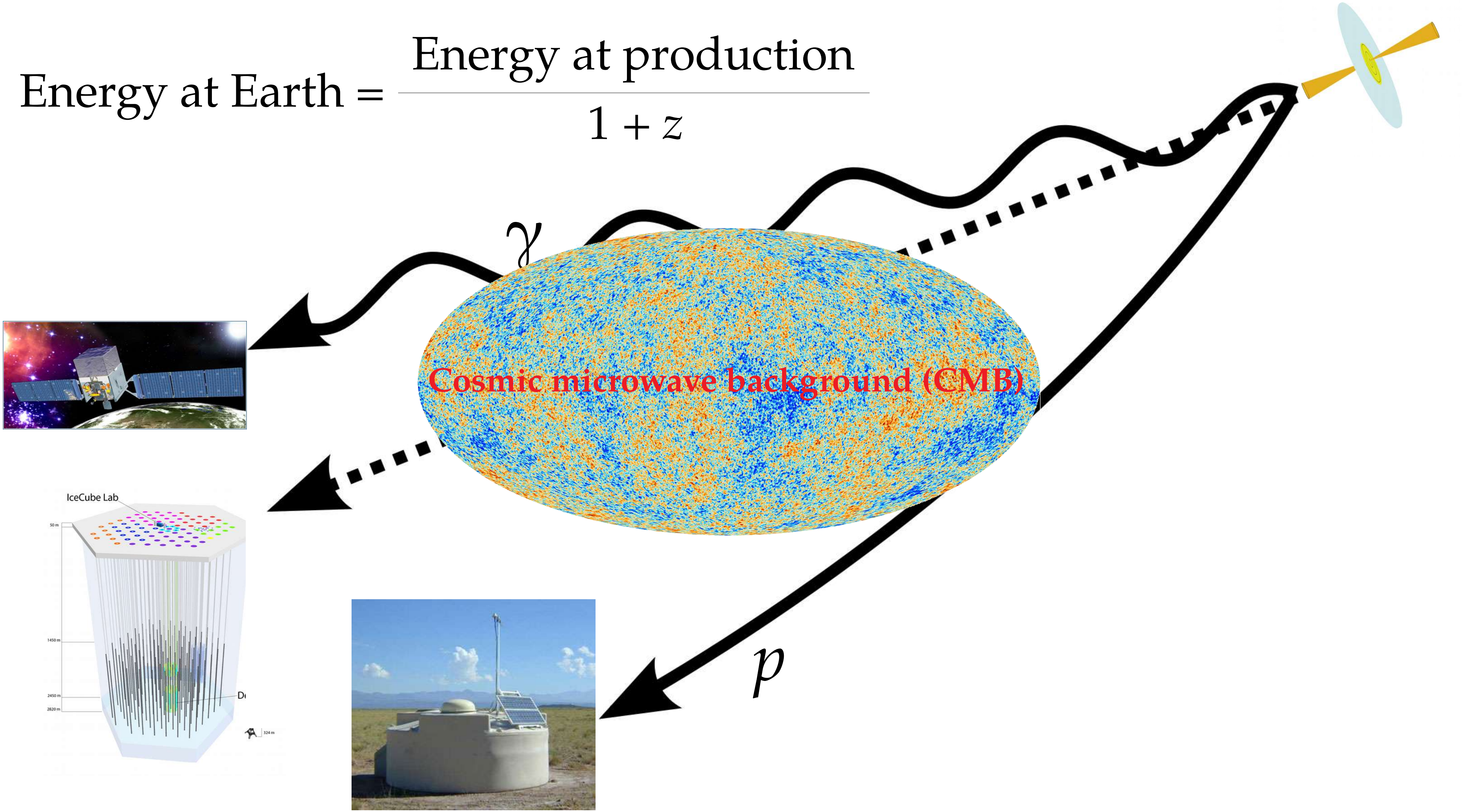
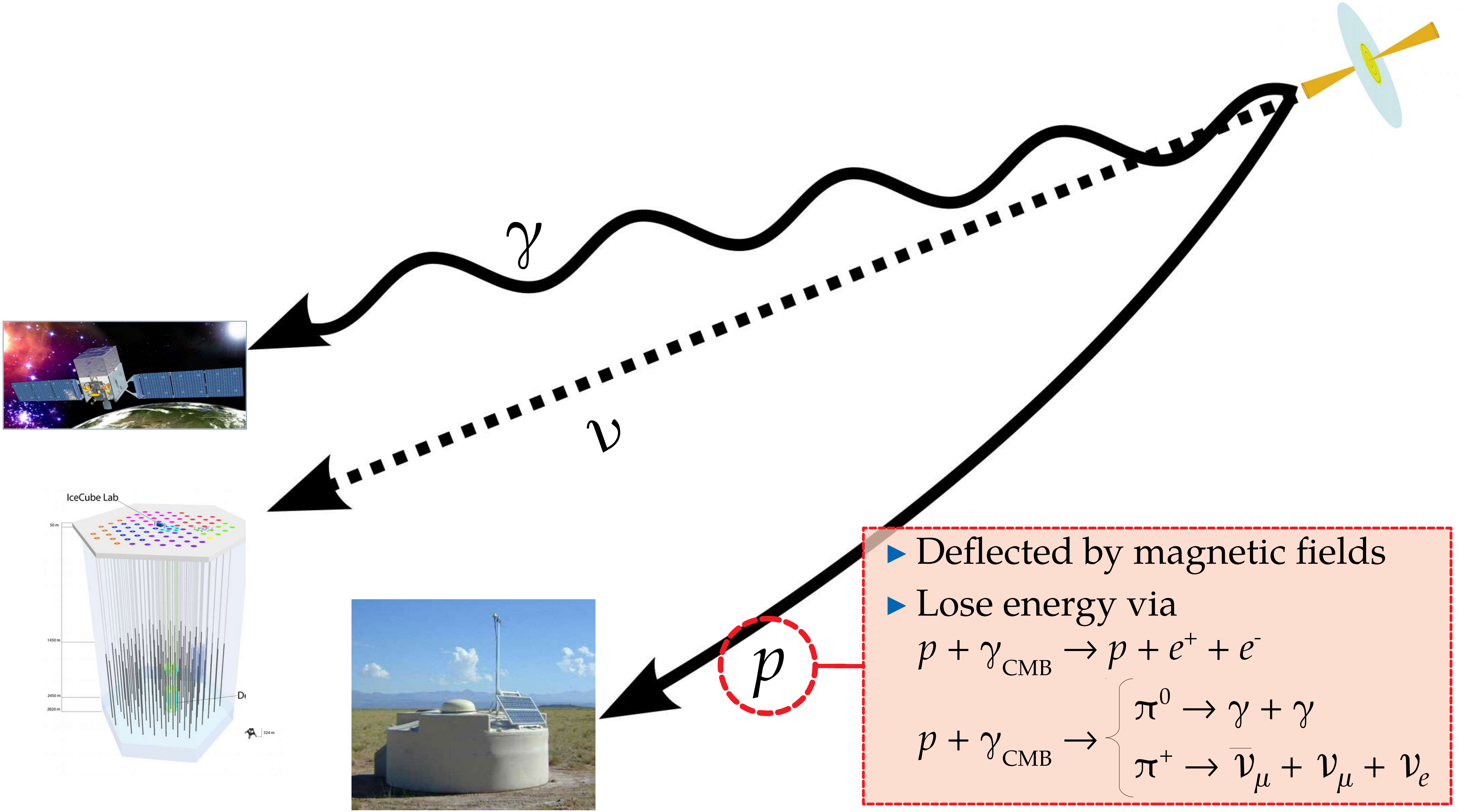
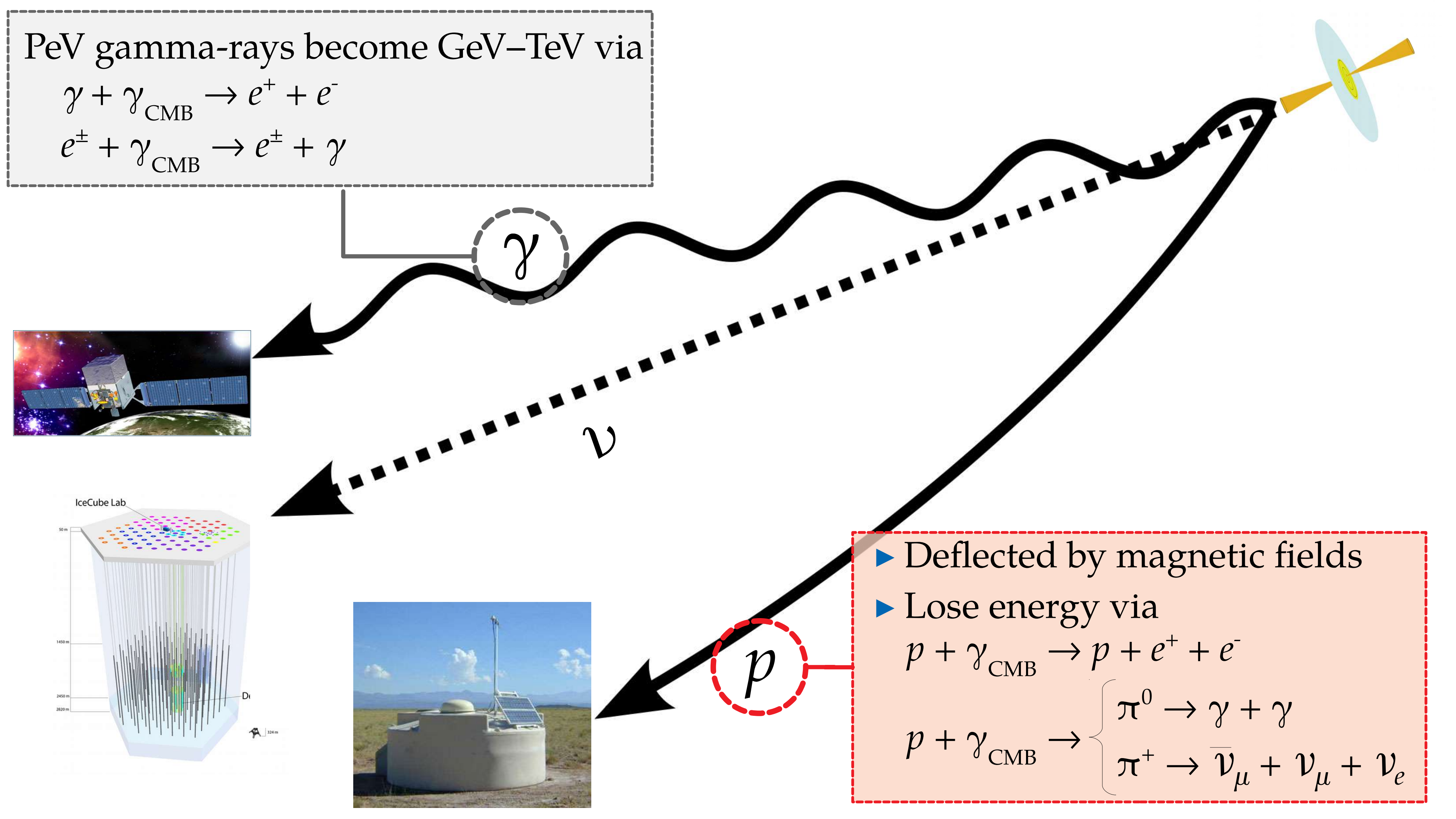



γ
ν
IceCube Lab
p
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^{0} \rightarrow \gamma + \gamma \\ \pi^{+} \rightarrow \bar{\nu}_{\mu} + \nu_{\mu} + \nu_{e} \end{cases}$


PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$
$e^{\pm} + \gamma_{CMB} \rightarrow e^{\pm} + \gamma$
γ
ν
p
IceCube Lab
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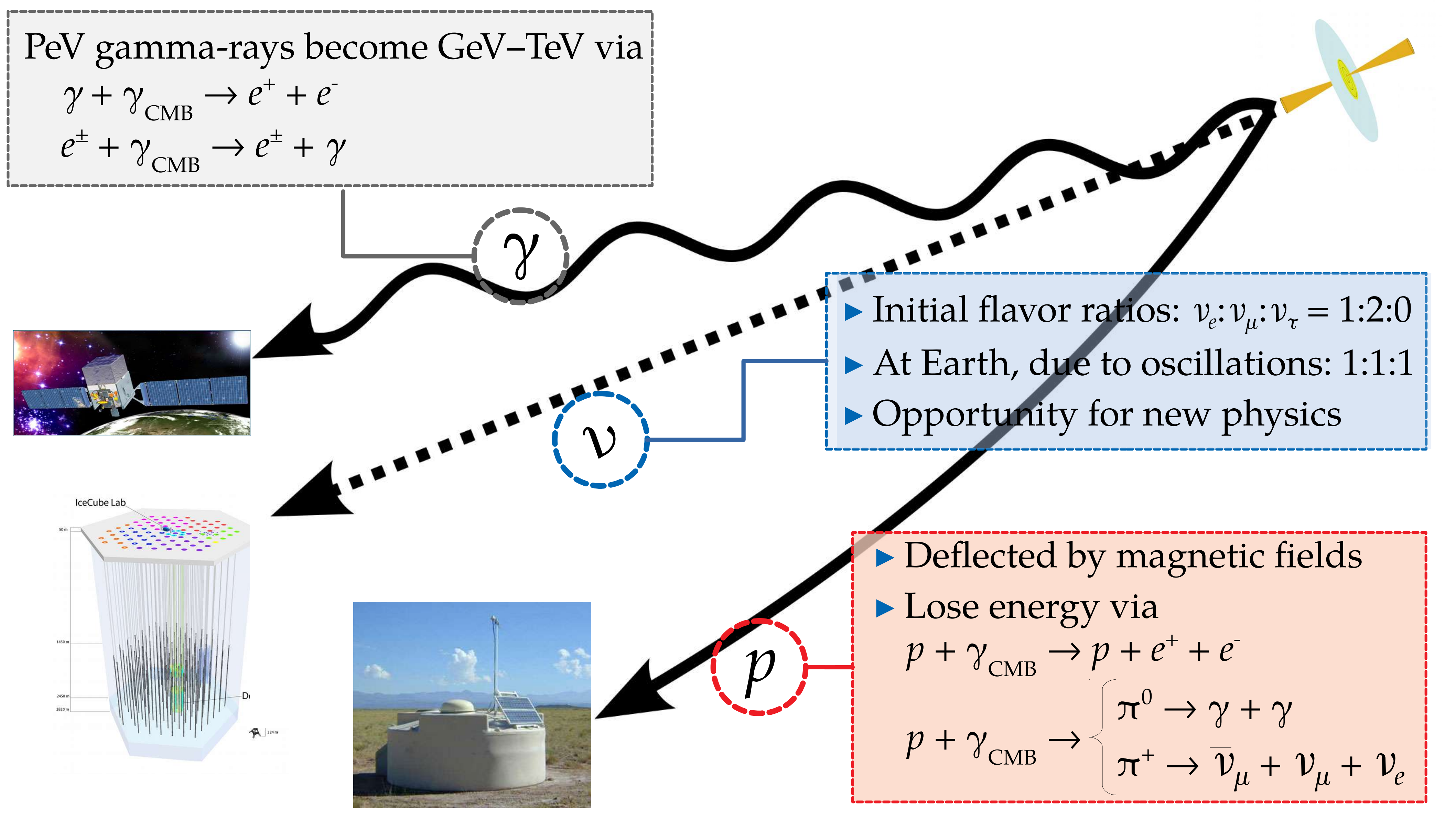
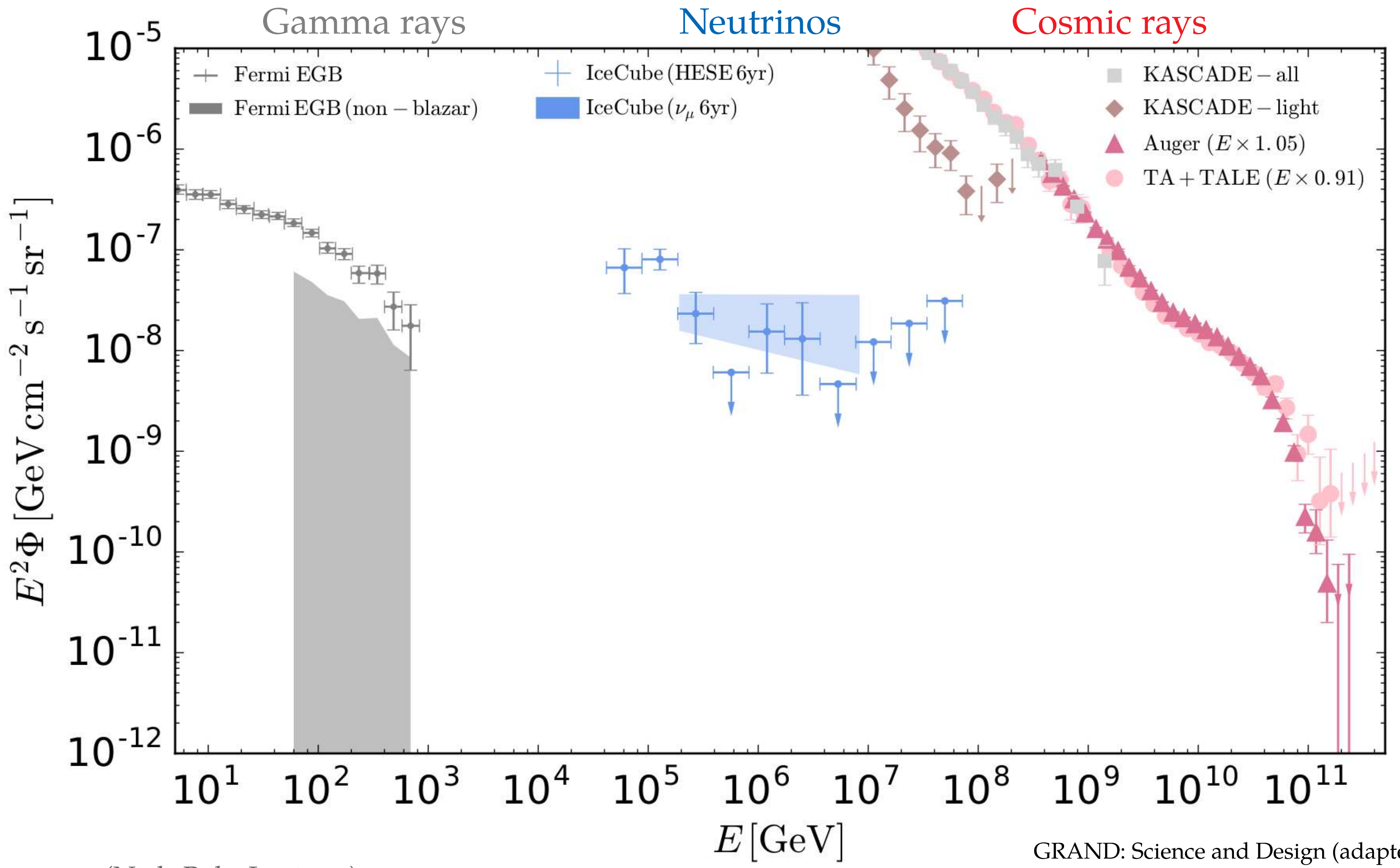

PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
$e^\pm + \gamma_{CMB} \rightarrow e^\pm + \gamma$
γ
ν
p
Initial flavor ratios: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$
At Earth, due to oscillations: 1:1:1
Opportunity for new physics
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^+ + e^-$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^+ \rightarrow \bar{\nu}_\mu + \nu_\mu + \nu_e \end{cases}$
IceCube Lab

Fluxes at Earth



GRAND: Science and Design (adapted)

Neutrinos – the ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources			
Size of horizon			
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – the ultimate smoking gun

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Point back at sources	Yes	Yes	No
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Neutrinos – the ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 kpc (at PeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation			
Relative ease to detect			

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Neutrinos – the ultimate smoking gun

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Relative ease to detect			

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The need for km-scale detectors

Predicted by Waxman-Bahcall 1997

- Neutrino flux at TeV–PeV: $E^2 \cdot \Phi \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
- Neutrino-nucleon cross section: $\sigma_{\nu p} \sim 10^{-35}$ cm^2 $(E/\mathrm{GeV})^{0.36}$

At center-of-mass energy of 1 GeV:
$\sigma_{pp} \sim 10^{-28}$ cm^2
$\sigma_{\gamma p} \sim 10^{-29}$ cm^2
$\sigma_{\nu p} \sim 10^{-38}$ cm^2

- Number of detected neutrinos from half the sky in 1 yr:

$$N = (n_{\mathrm{nucl}} \cdot V_{\mathrm{det}}) \cdot (2\pi) \cdot (1\ \mathrm{yr}) \cdot \int_{100\ \mathrm{TeV}} \Phi(E) \cdot \sigma_{\nu p}(E)\, \mathrm{d}E$$

- To detect $N > 1$ neutrino, we needed

$$V_{\mathrm{det}} > 0.1\ \mathrm{km}^3$$

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$\sigma_{\nu p} \sim 10^{-38}$ cm^2

- Number of detected neutrinos from half the sky in 1 yr:

$$N = (n_{\rm nucl}) \cdot (V_{\rm det}) \cdot (2\pi) \cdot (1\ \mathrm{yr}) \cdot \int_{100\ \mathrm{TeV}} \Phi(E) \cdot \sigma_{\nu p}(E)\, \mathrm{d}E$$

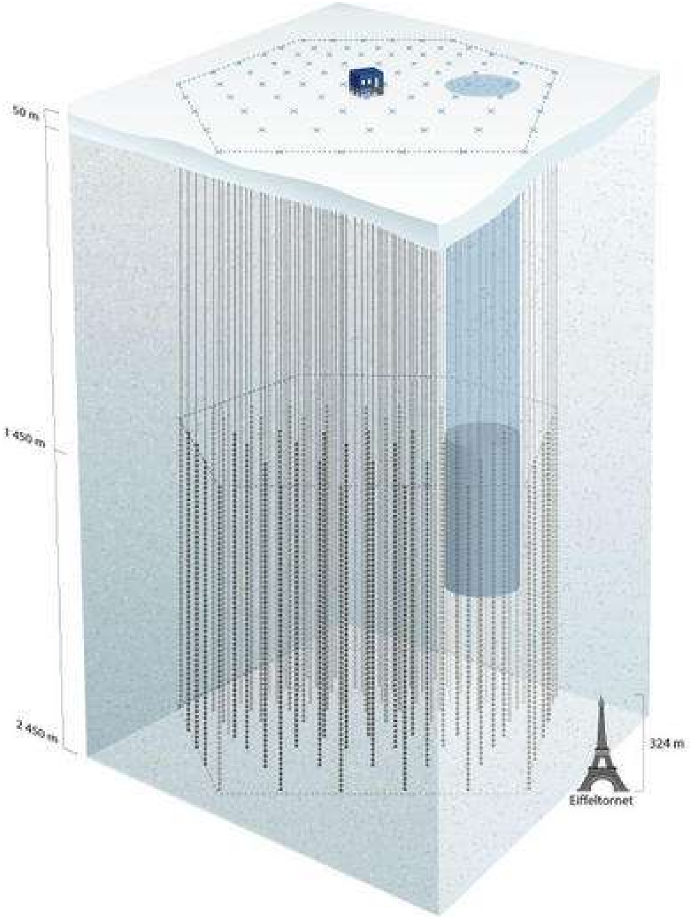
Number density of nucleons: $\sim N_{\rm Av}$ cm^3

Detector volume

- To detect $N > 1$ neutrino, we needed

$$V_{\rm det} > 0.1\ \mathrm{km}^3$$

IceCube – What is it?



- Km^3 in-ice Cherenkov detector in Antarctica
- >5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies > 10 GeV

How does IceCube see neutrinos?

Two types of fundamental interactions . . .

Charged-current (CC)

$\nu_l + N \to l + \text{hadrons}$

Neutral-current (NC)

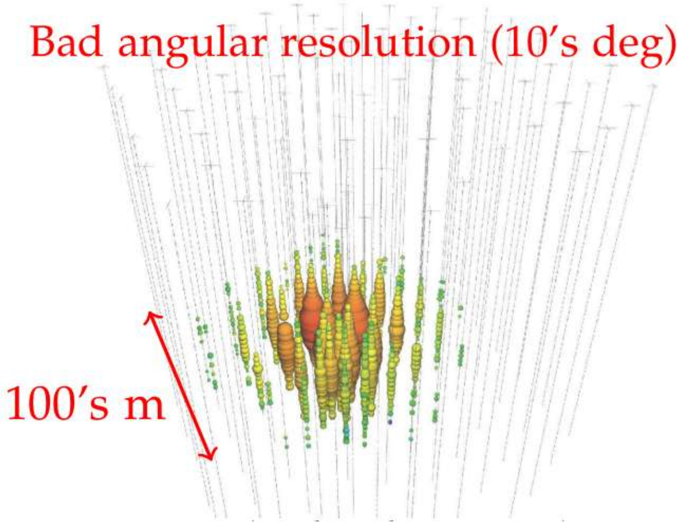
$\nu_l + N \to \nu_l + \text{hadrons}$

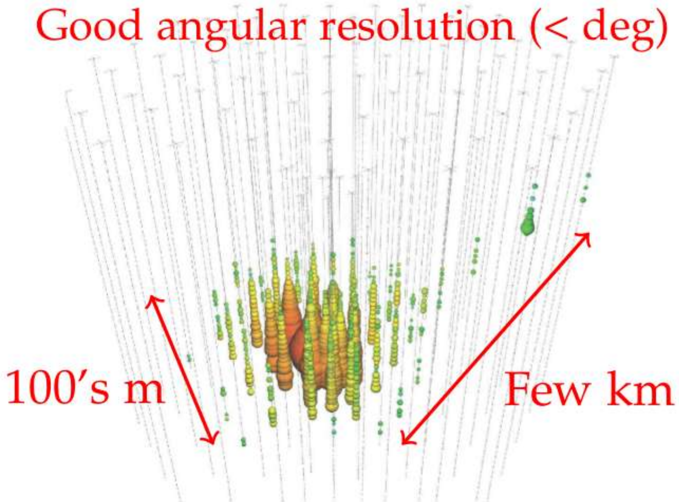
These shower and make light

. . . create two event topologies . . .

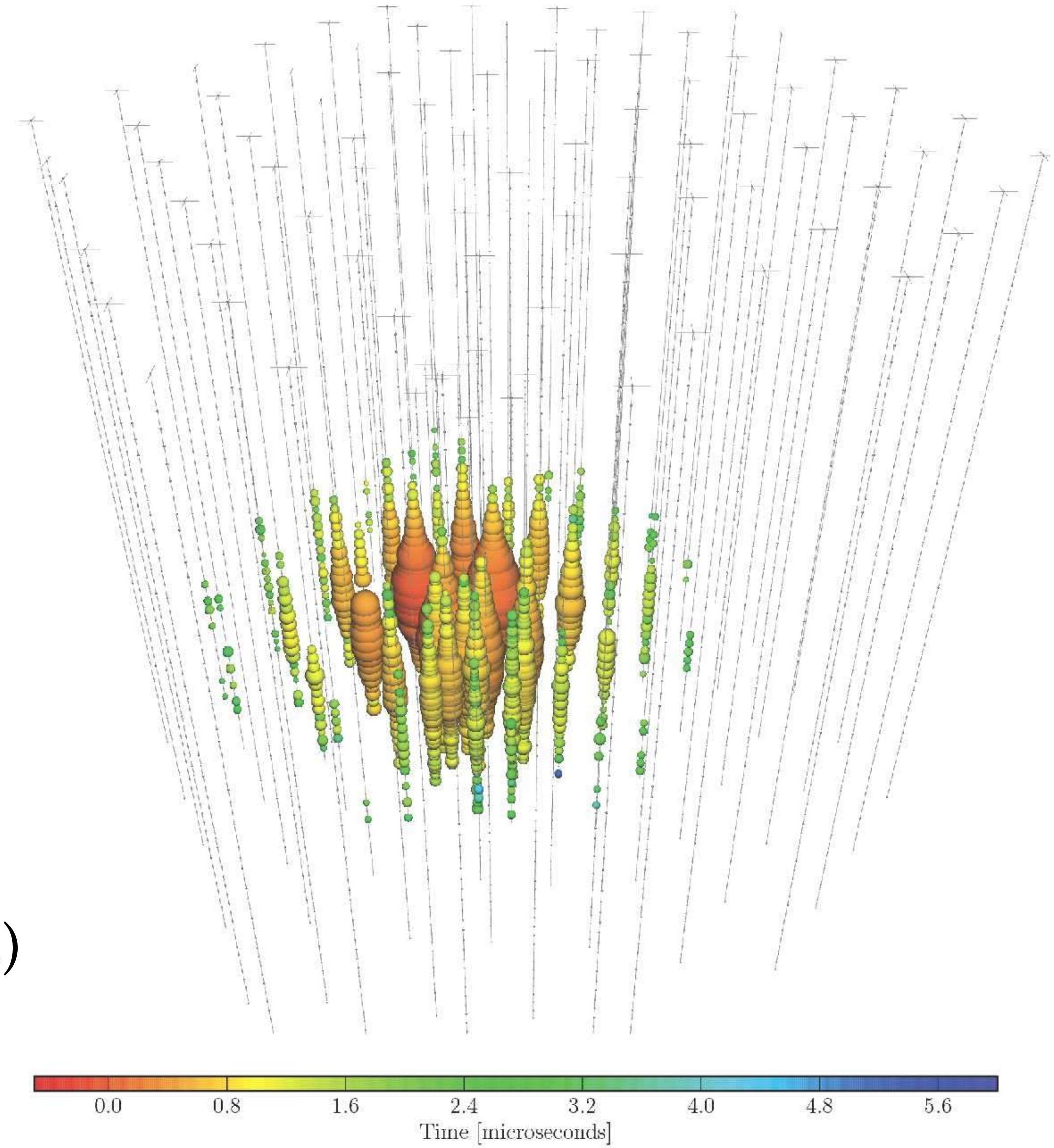
Showers — From CC ν_e or ν_τ, or NC ν_x

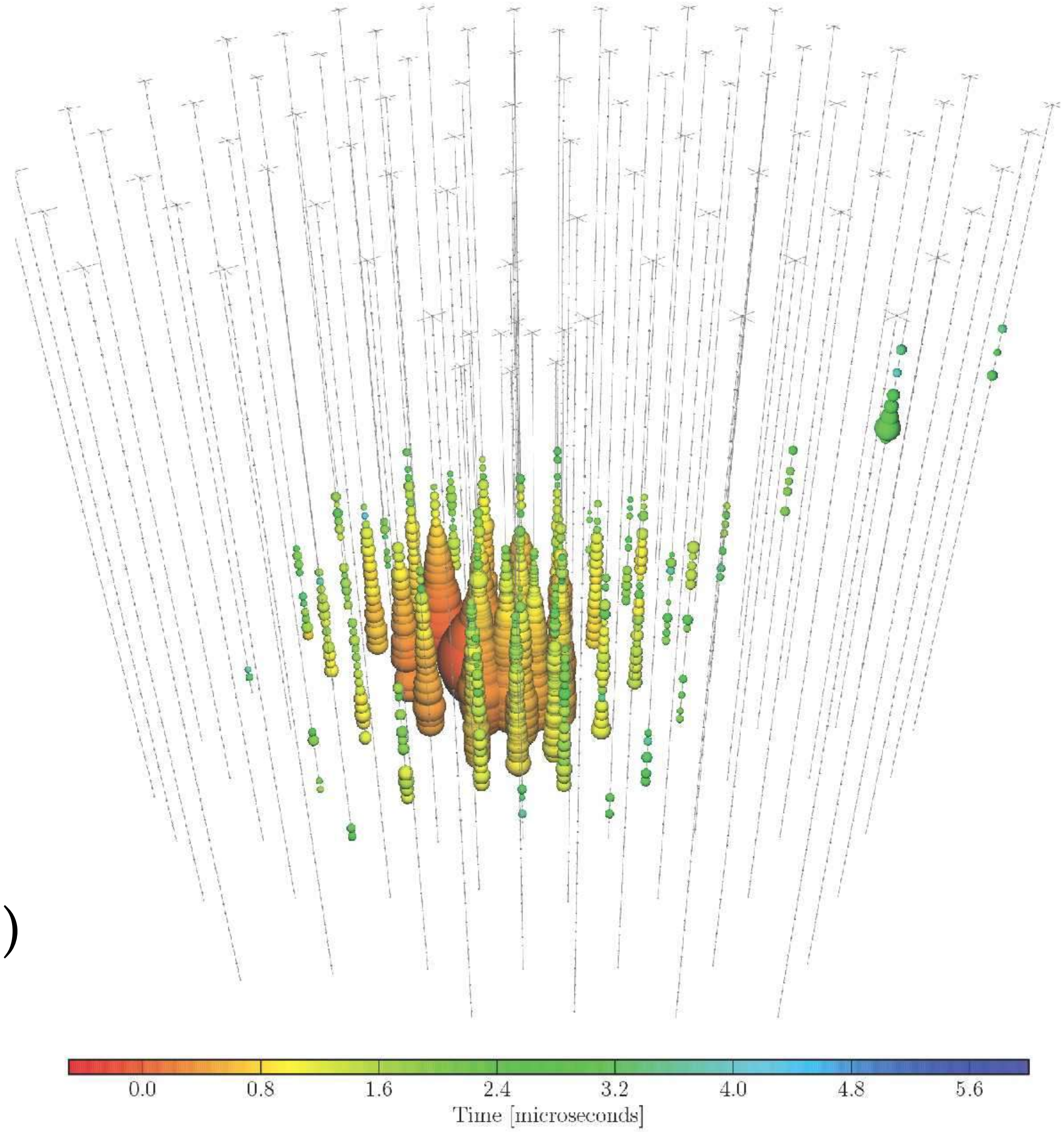
Tracks — From CC ν_μ mainly





Shower
(IceCube event #22)

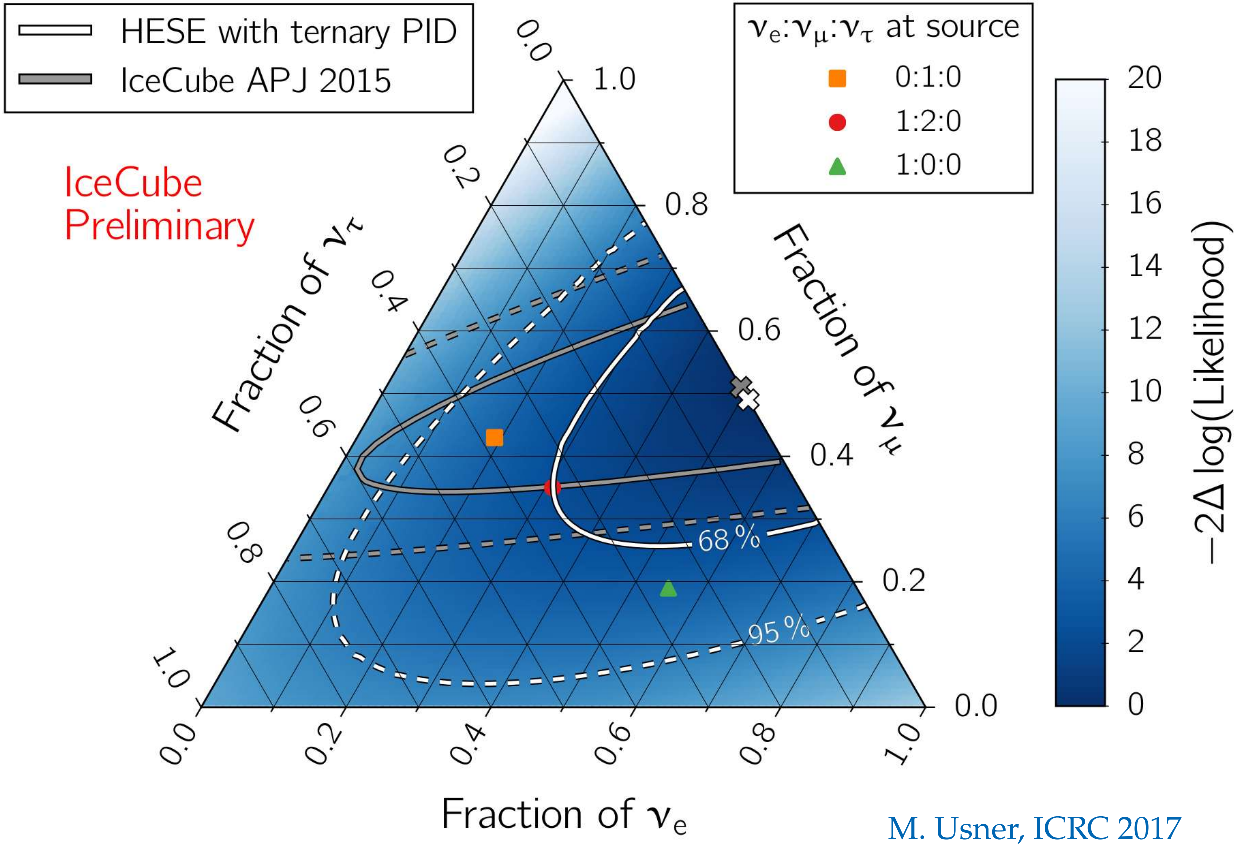




Track
(IceCube event #15)

What has IceCube found so far (6 years)?

Flavor composition compatible with equal proportion of each flavor



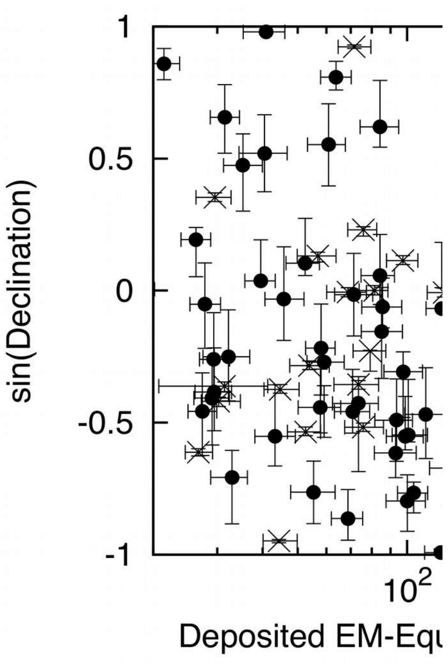
M. Usner, ICRC 2017

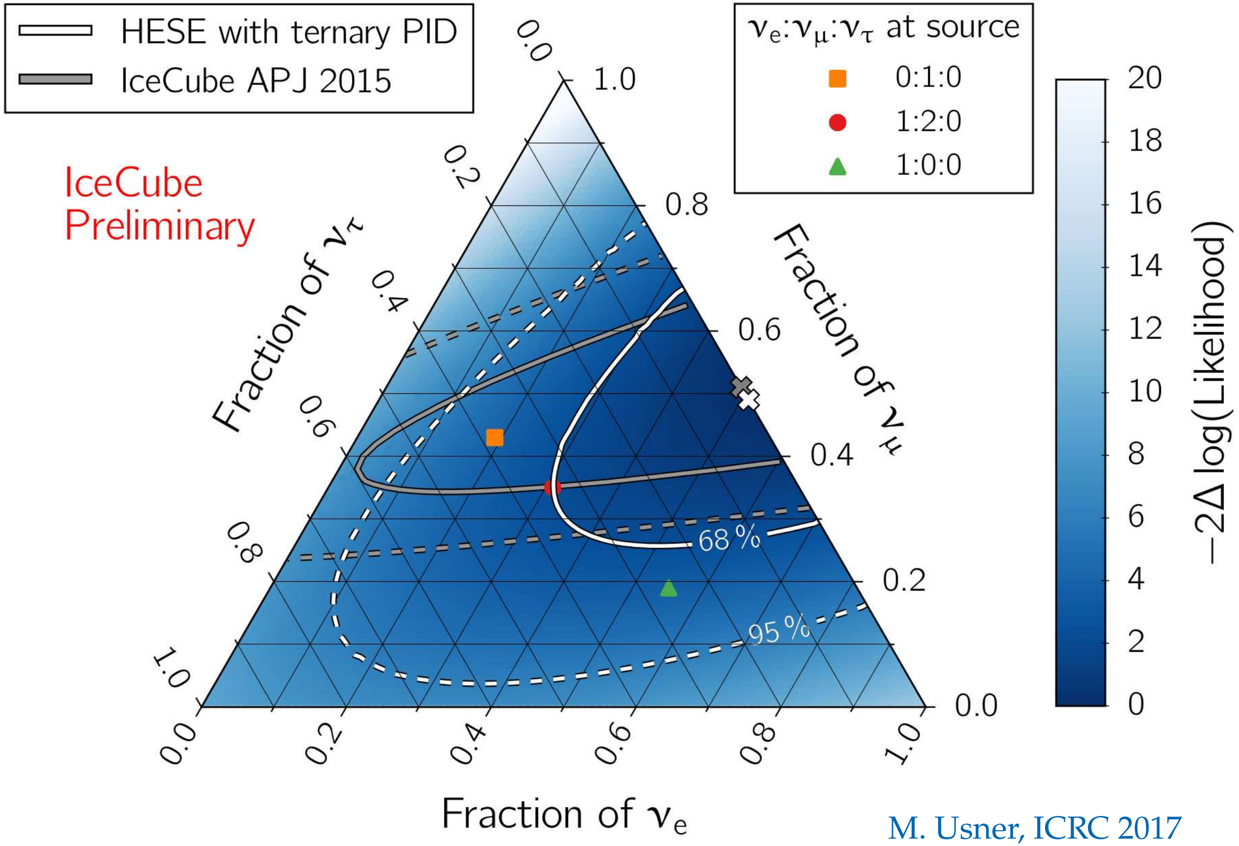
What has IceCube found so far (6 years)?

80 contained events between 18 TeV – 2 PeV

Flavor composition compatible with equal proportion of each flavor

(16 atm. neutr





M. Usner, ICRC 2017

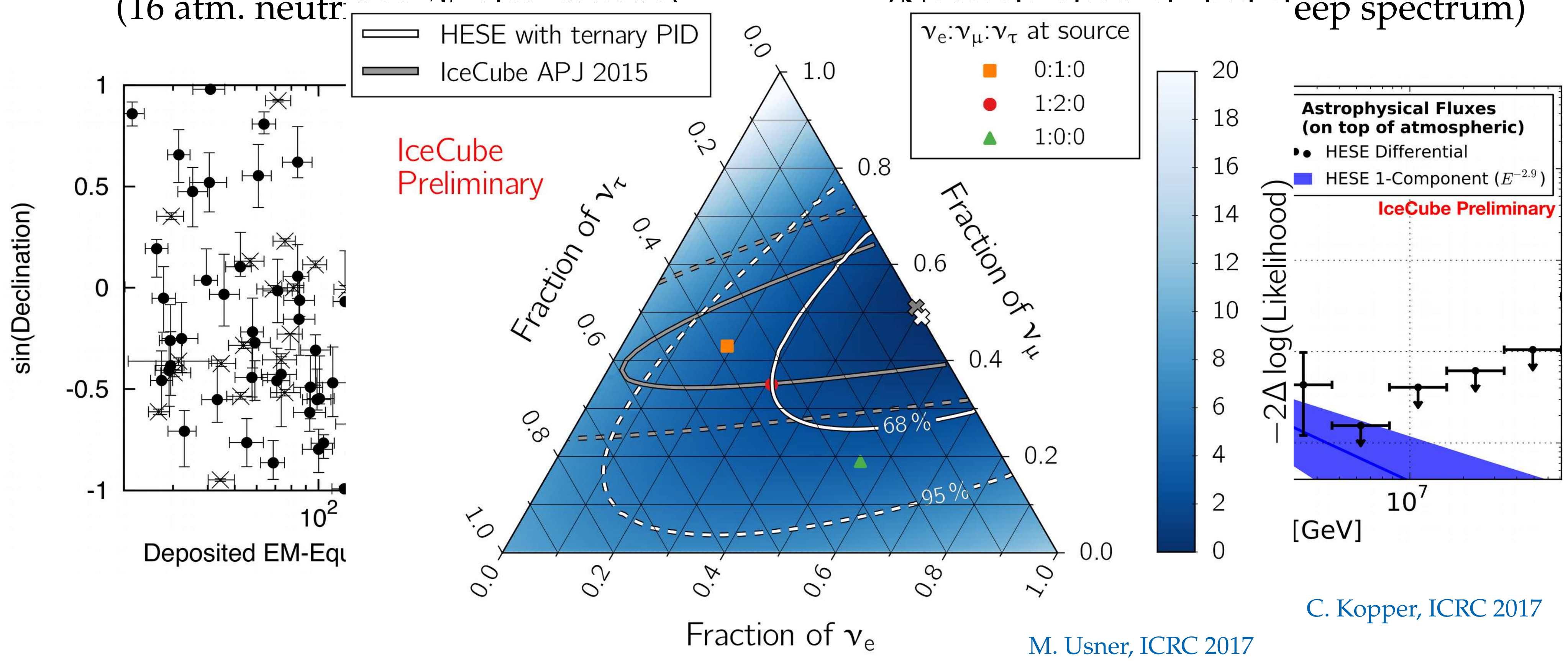
C. Kopper, ICRC 2017

What has IceCube found so far (6 years)?

80 contained events between 18 TeV – 2 PeV
(16 atm. neutri…

Flavor composition compatible with equal proportions of each flavor

Astrophysical flux detected at > 7σ
…eep spectrum)



C. Kopper, ICRC 2017

M. Usner, ICRC 2017

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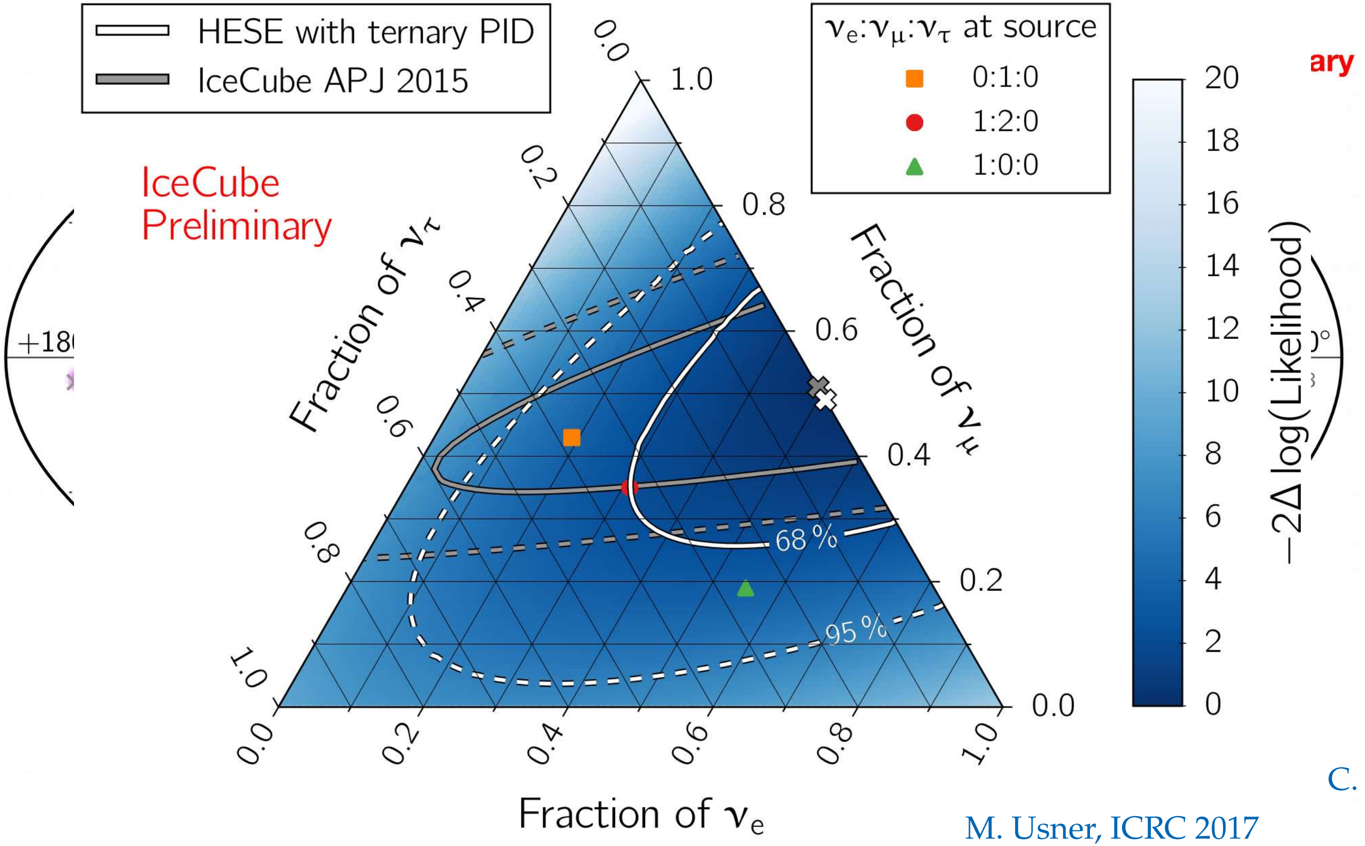
Arrival directions compatible with isotropy



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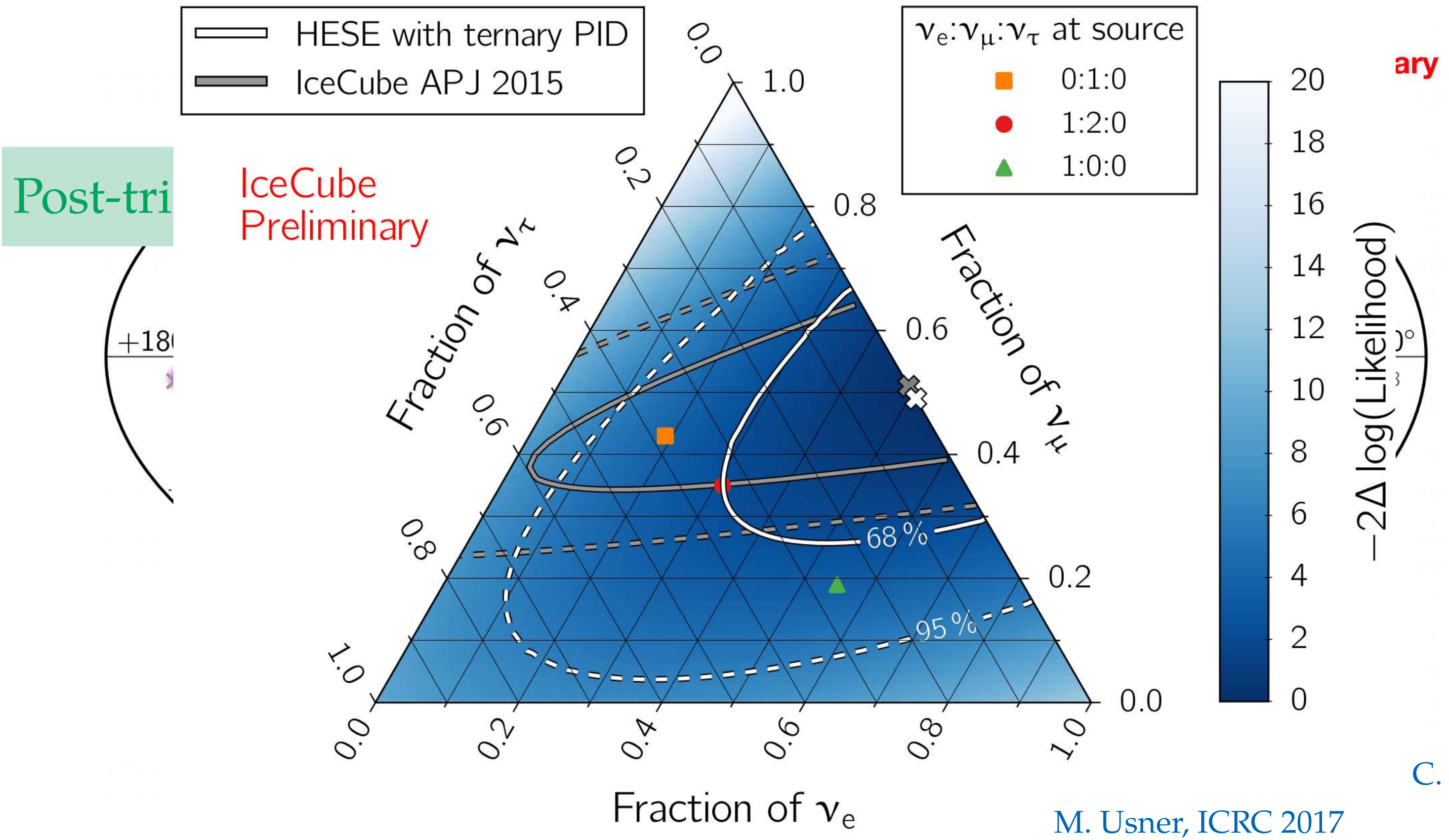

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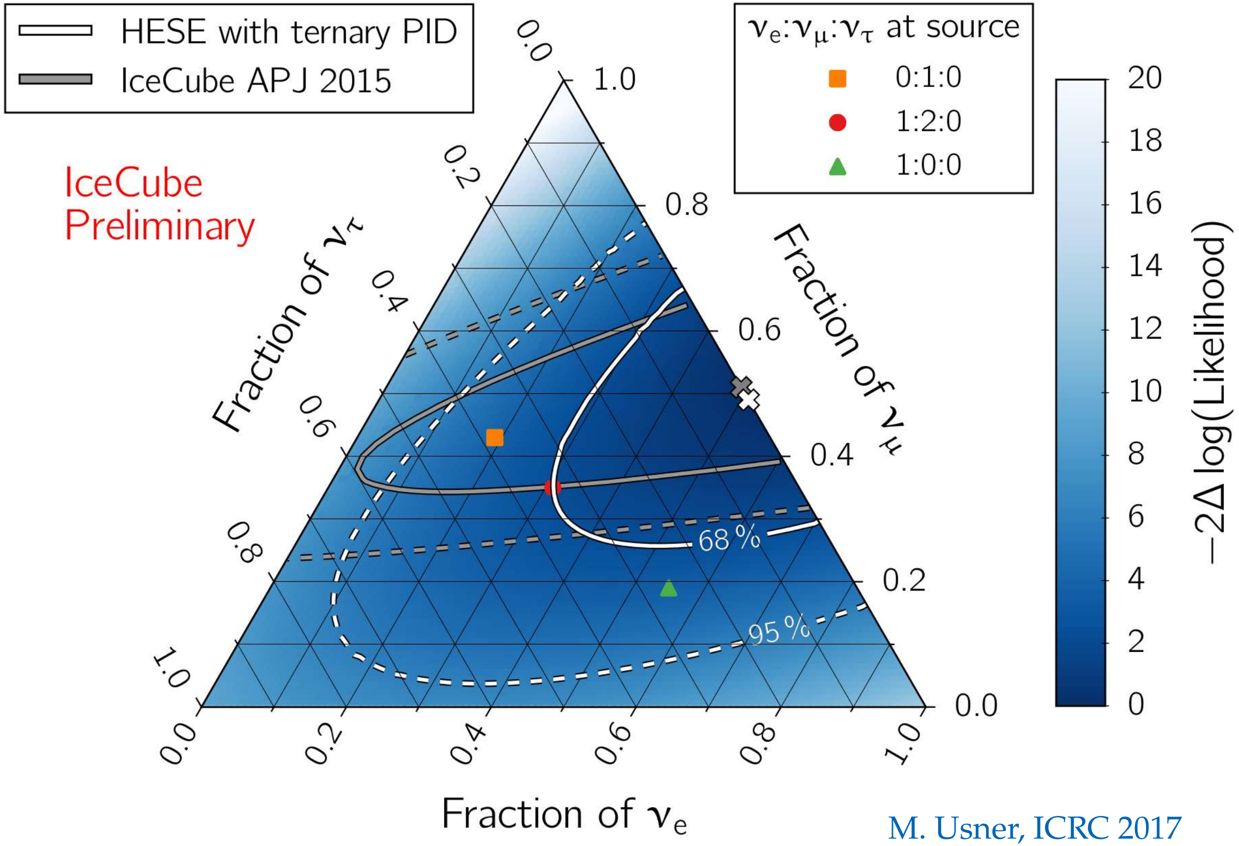
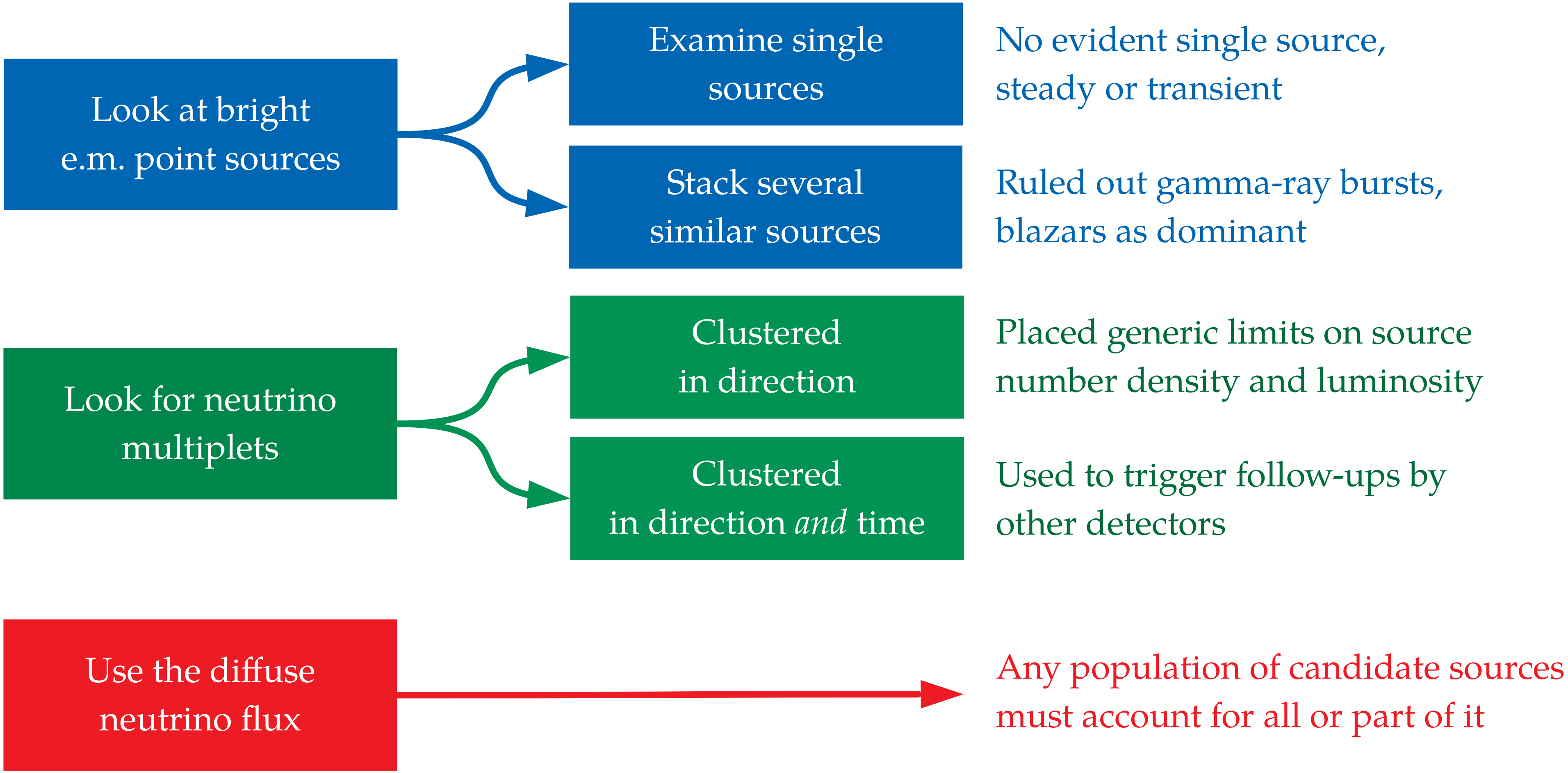


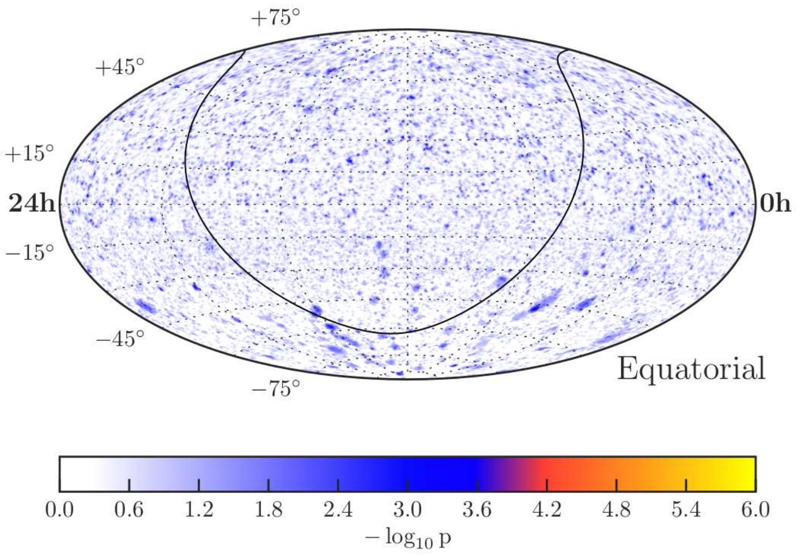
M. Usner, ICRC 2017

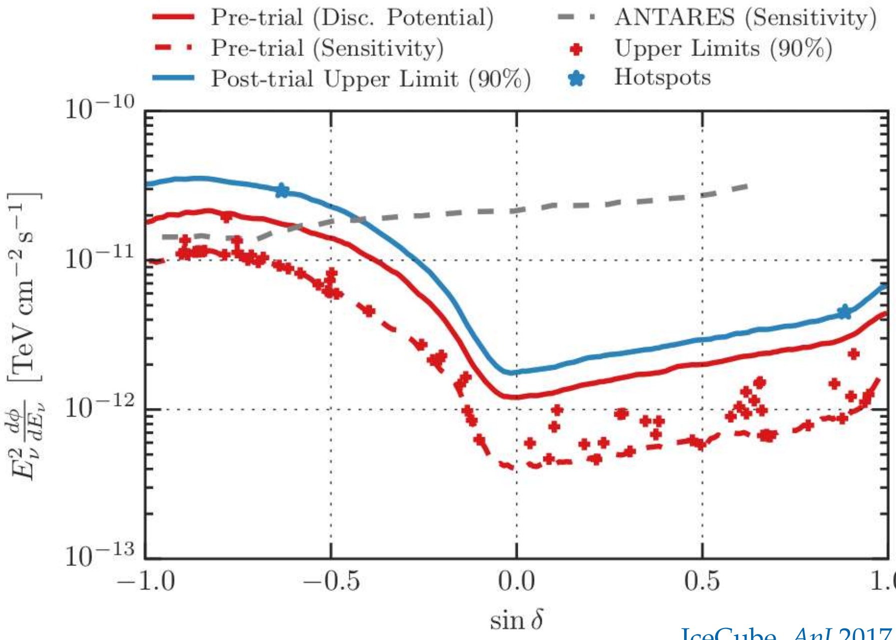
Three strategies to reveal sources using TeV–PeV ν



Upper limits on point sources

No neutrino point source has been identified –





IceCube, *ApJ* 2017

▲ (Pre-trial) p-values

Chance of background fluctuation:

17% (Southern Hem.) – 29% (Northern Hem.)

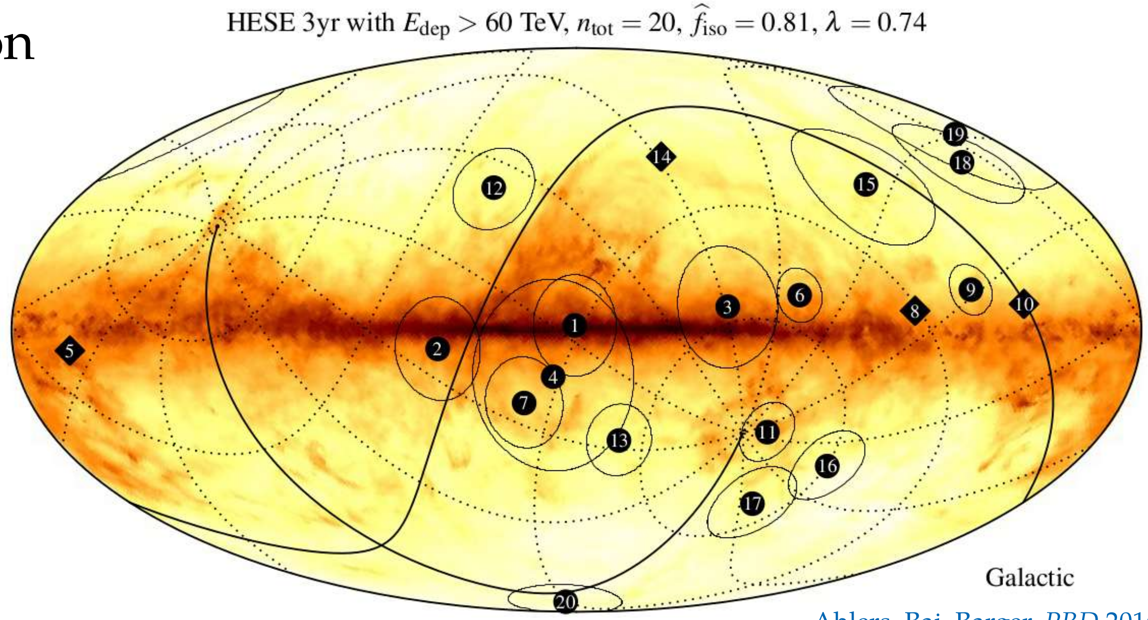
▲ Point flux upper limits

Close to gamma-ray point-source fluxes

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



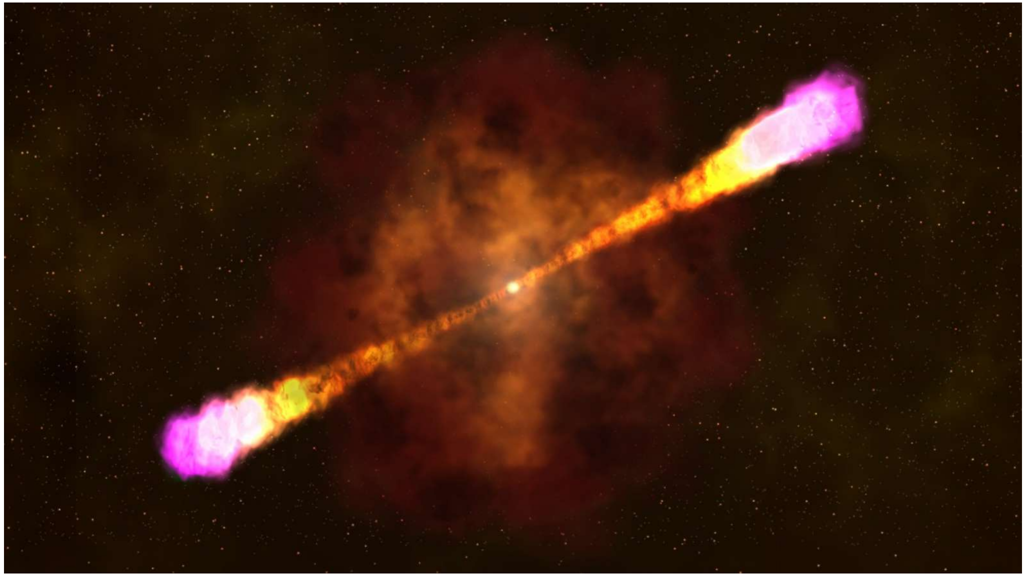
Ahlers, Bai, Barger, *PRD* 2016

Contribution from Galactic sources: < 14%

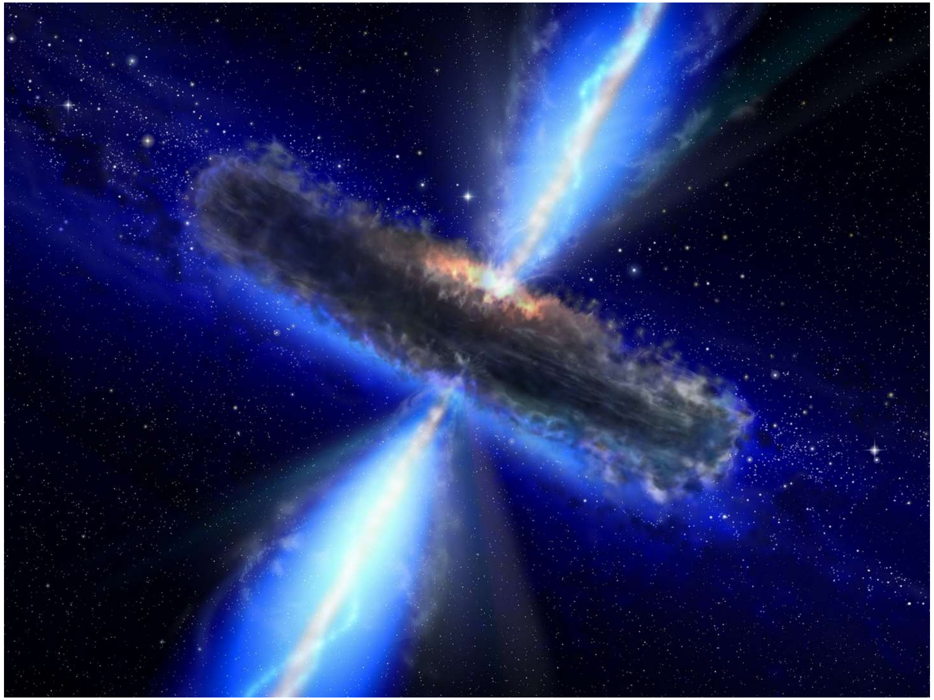
IceCube, *ApJ* 2017

Extragalactic PeV neutrino sources?

Gamma-ray bursts



Blazars



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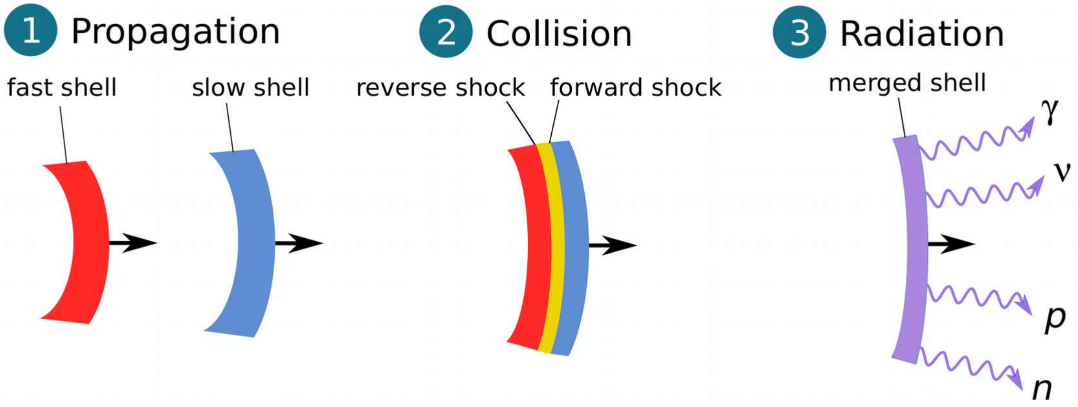

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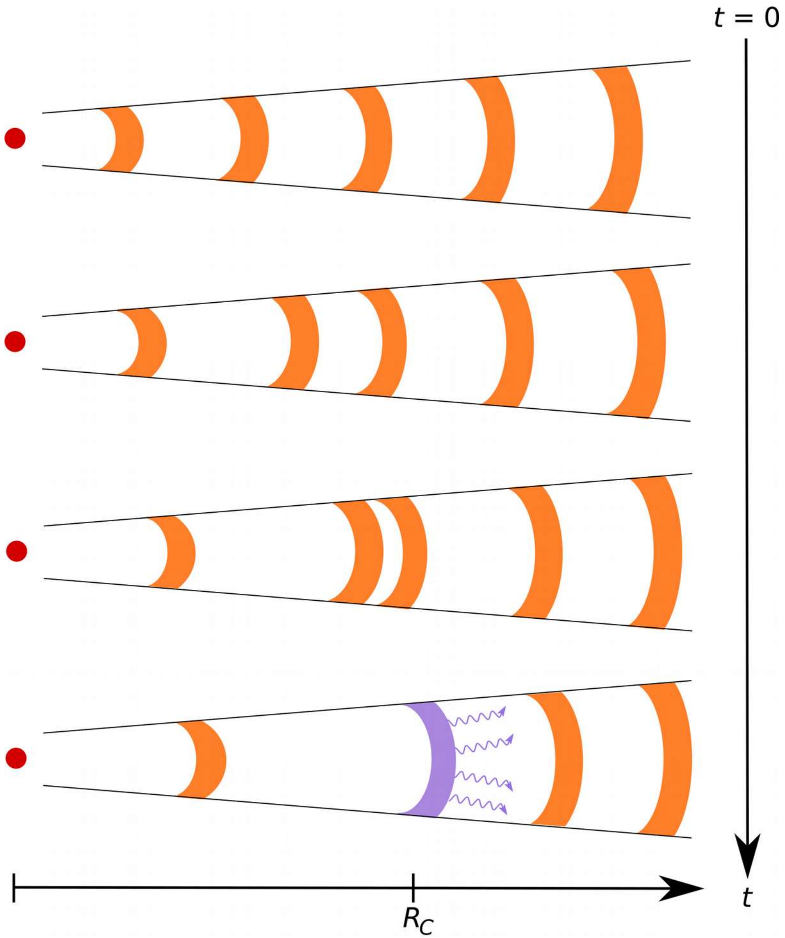

PeV neutrino production via $p\gamma$

MB, Murase, Winter, Heinze, *ApJ* 2017
MB, Baerwald, Murase, Winter, *Nature Commun.* 2015
Baerwald, **MB**, Winter, *ApJ* 2013

Extragalactic PeV neutrino sources?

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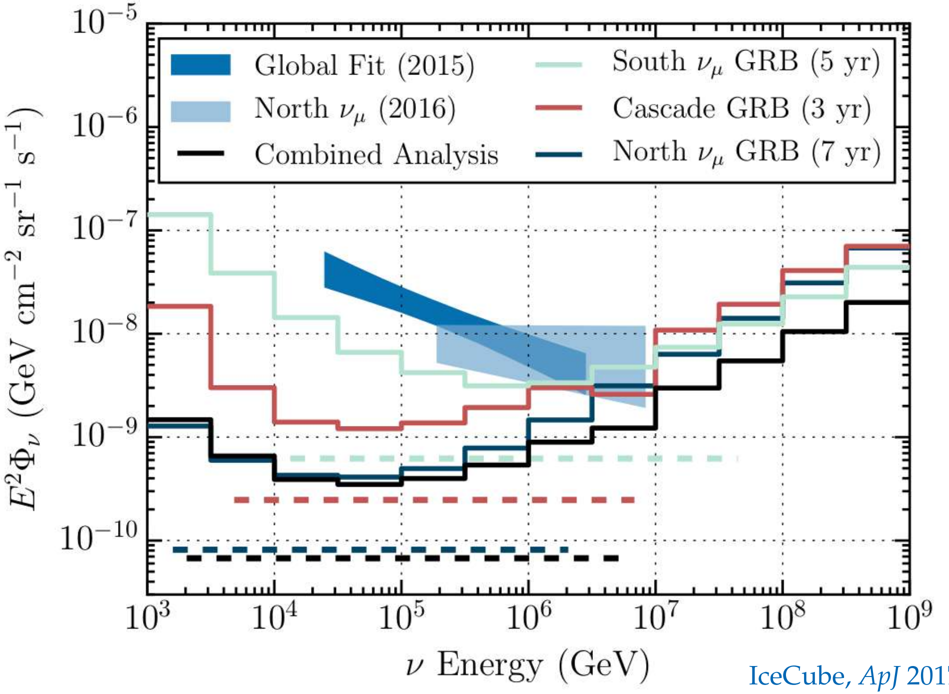
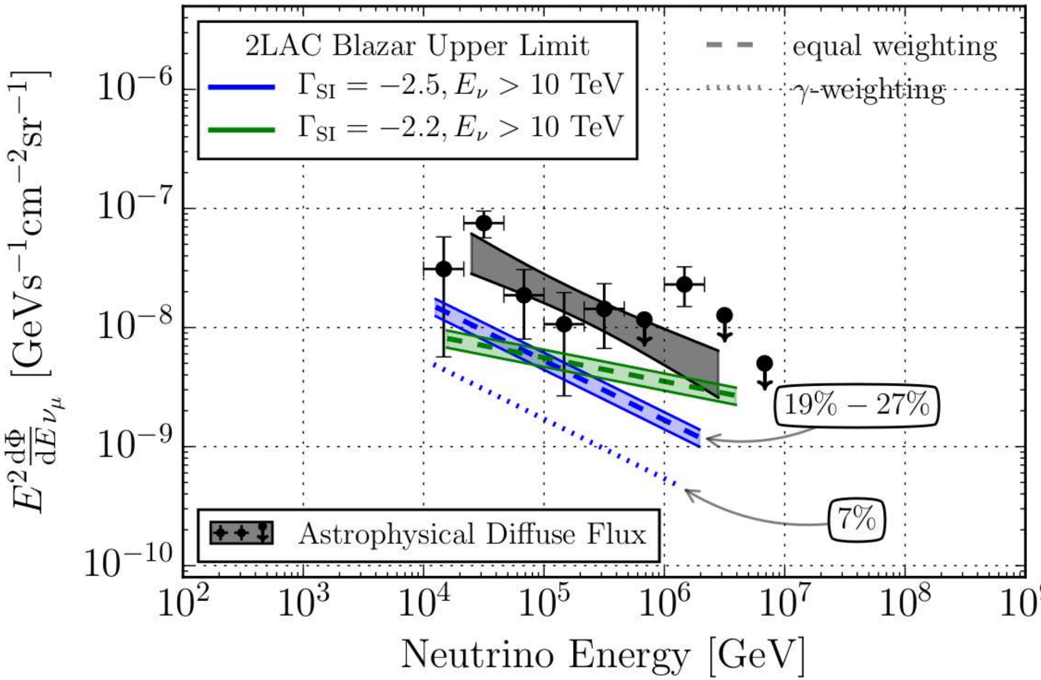


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

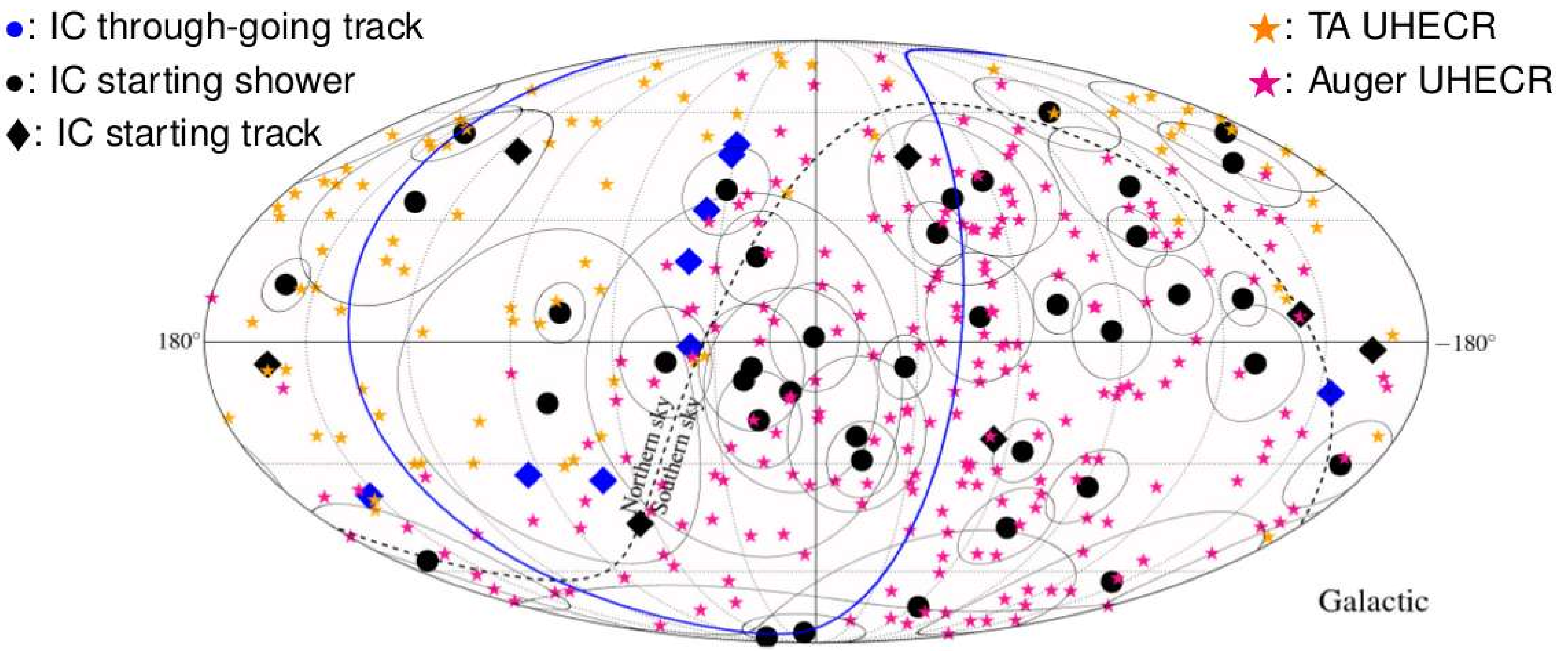
Blazars



862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

Spatial correlation between neutrinos and UHECRs?

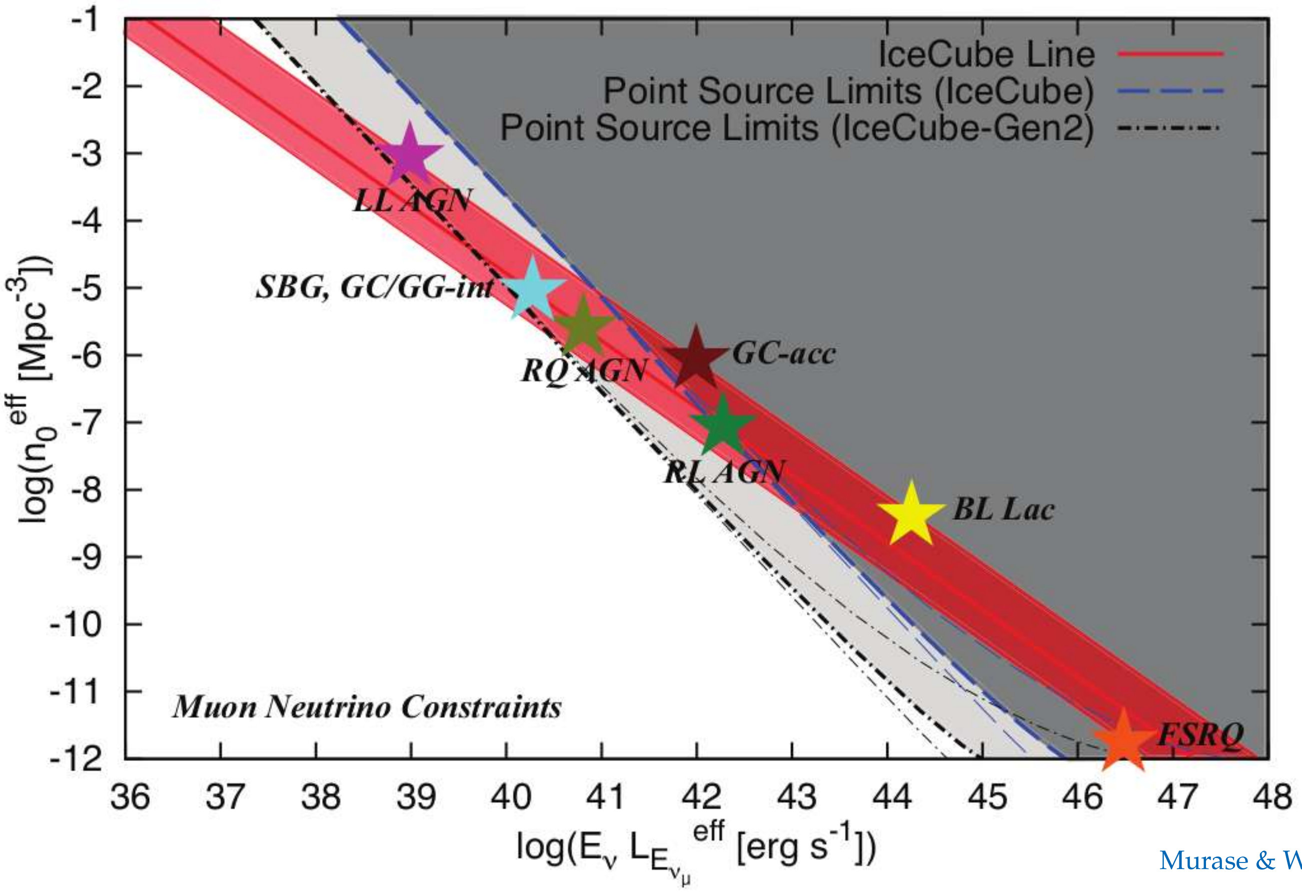


IceCube, *JCAP* 2015 [1511.09408]

No significant correlation with UHECRs (<3.3σ)

Needed: many dim neutrino sources

Absence of neutrino multiplets means sources are likely many and dim –



Murase & Waxman, *PRD* 2016

A long time ago in a galaxy, far, far away….

many galaxies

A long time ago in ~~a galaxy~~, far, far away….

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.


Neutrino physicist

Fundamental physics with HE astrophysical 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 current limits: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$
- Fundamental physics can be extracted from:
  - Spectral shape
  - Angular distribution
  - Flavor information

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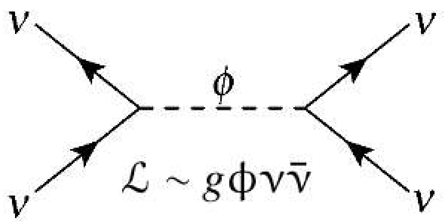
In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns

New physics in the spectral shape? $\nu\nu$ interactions

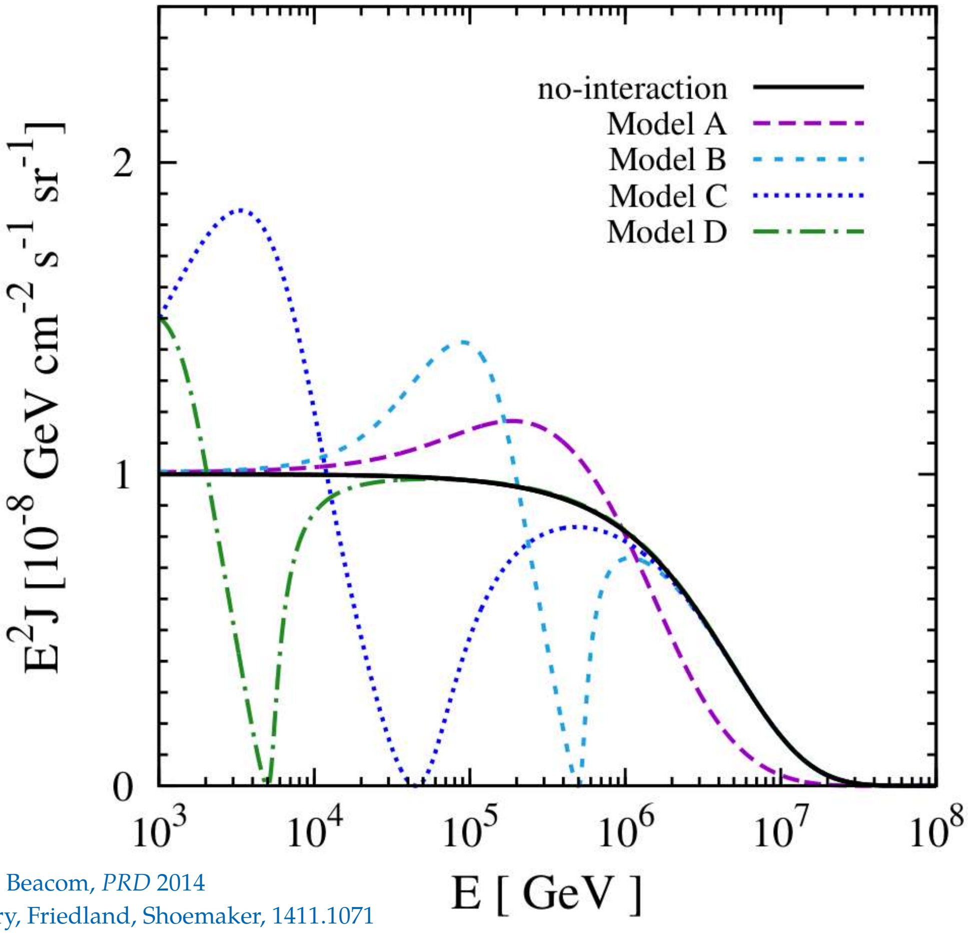
Secret neutrino interactions between astrophysical neutrinos (PeV) and relic neutrinos (0.1 meV):



$$\mathcal{L} \sim g\phi\nu\bar{\nu}$$

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

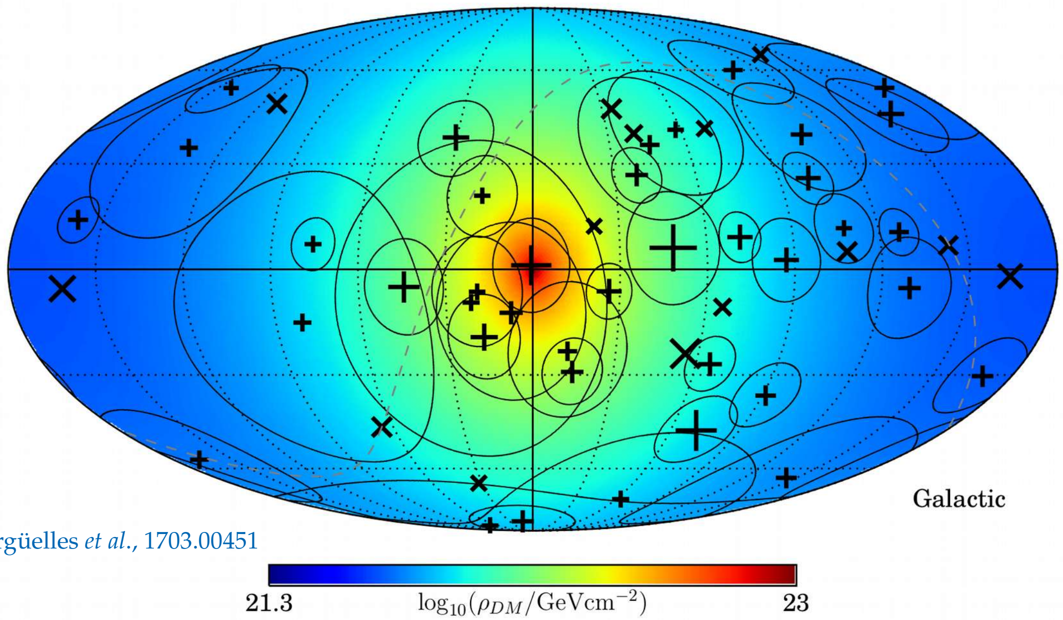
Resonance energy: $$E_{\rm res} = \frac{M^2}{2m_\nu}$$



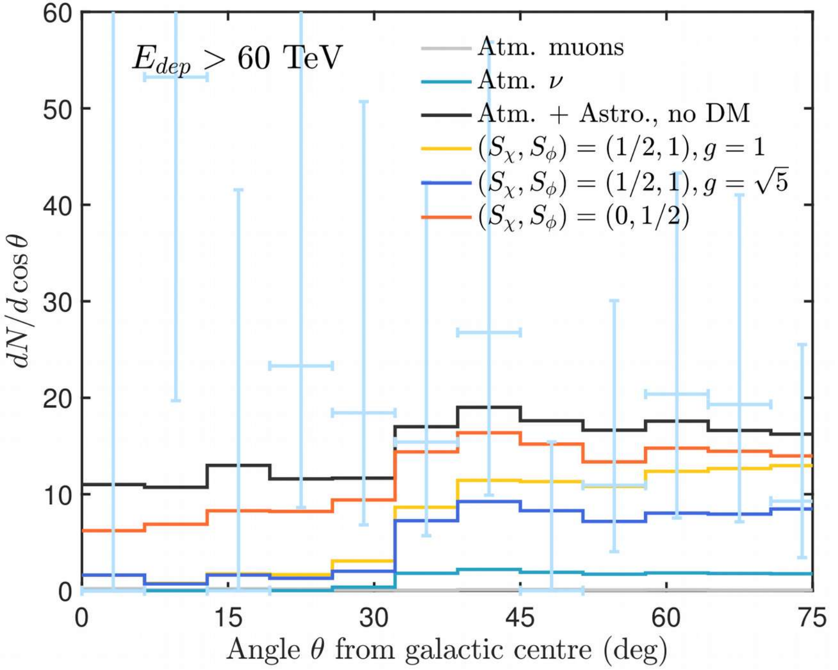
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

New physics in the angular distribution? ν-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile:



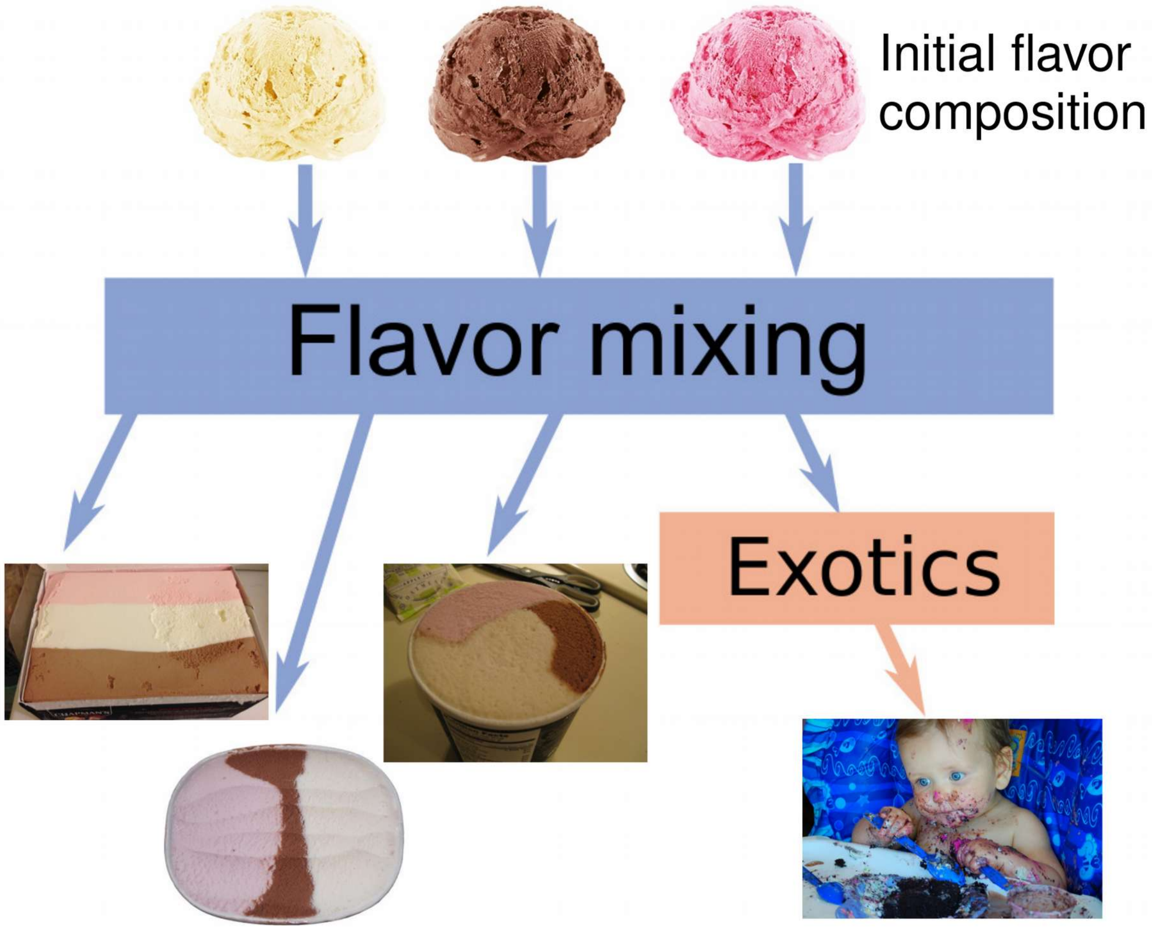
Argüelles *et al.*, 1703.00451



Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

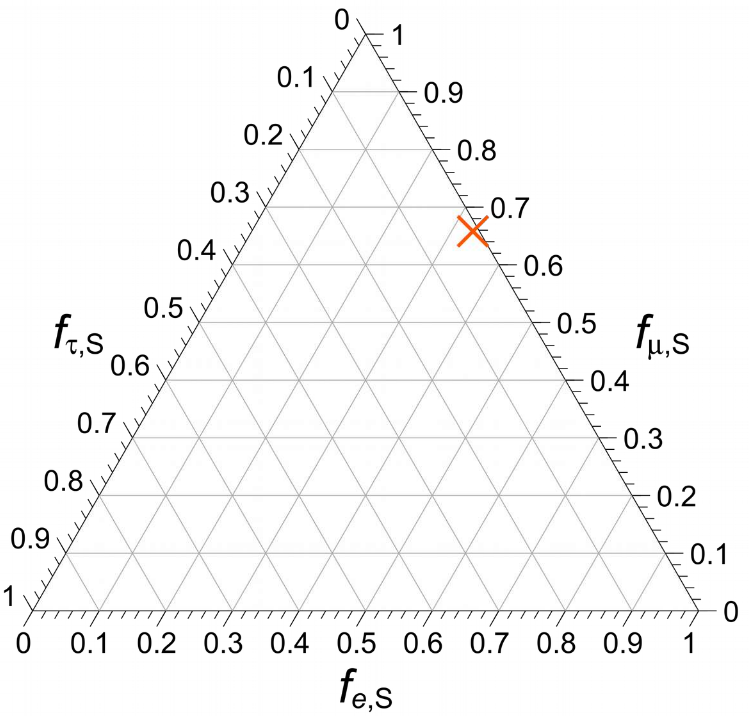
New physics in the flavor composition?



Flavor – there and here

At the sources

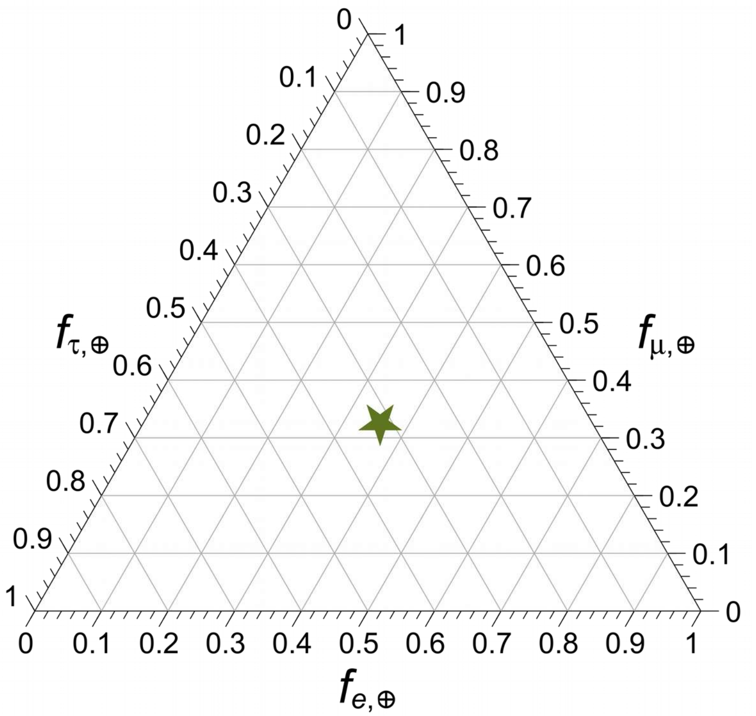
$$(f_e{:}f_\mu{:}f_\tau)_S = (1/3 : 2/3 : 0)_S$$



Neutrino oscillations

At Earth

$$(0.36 : 0.32 : 0.32)_\oplus$$



Flavor – there and here

$p + \gamma \rightarrow \bar{\nu}_\mu + \nu_\mu + \nu_e$

At the sources

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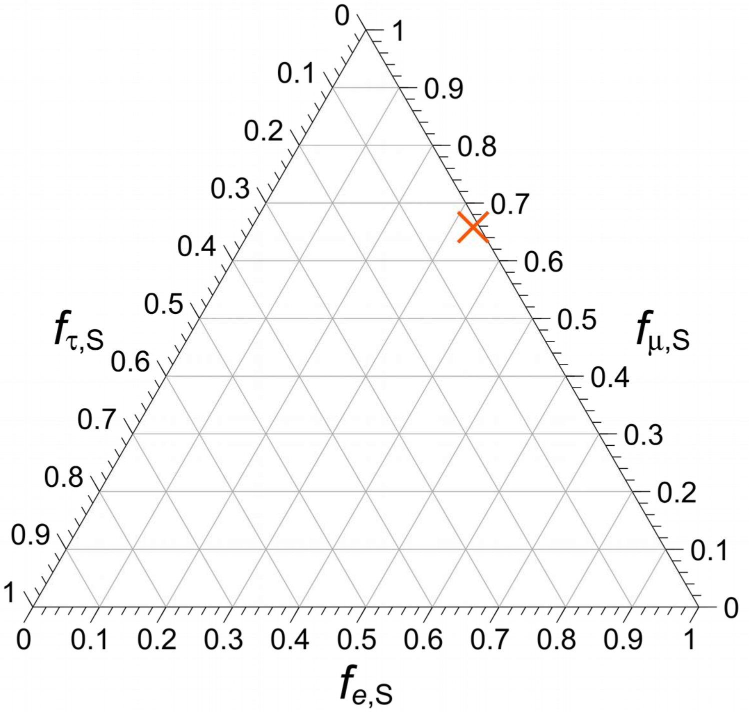

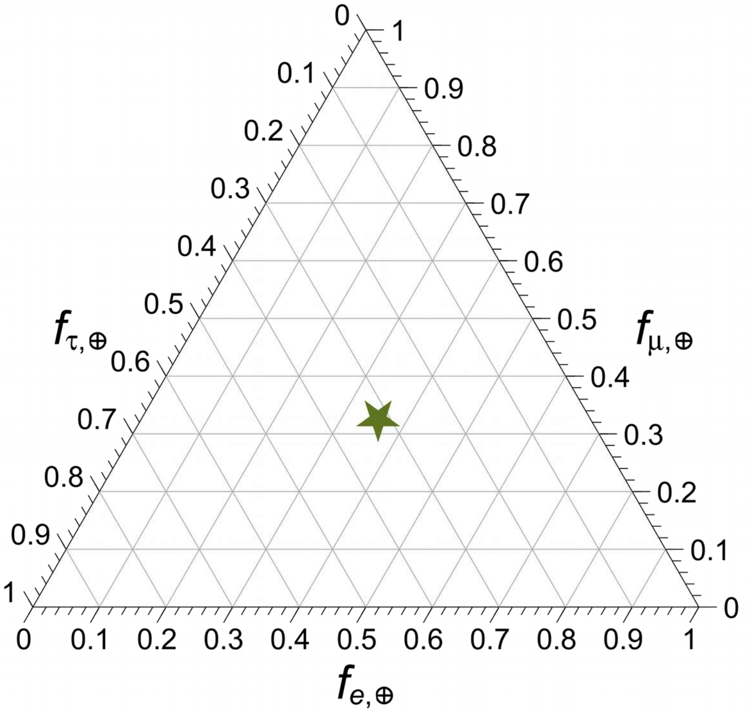

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Neutrino oscillations →

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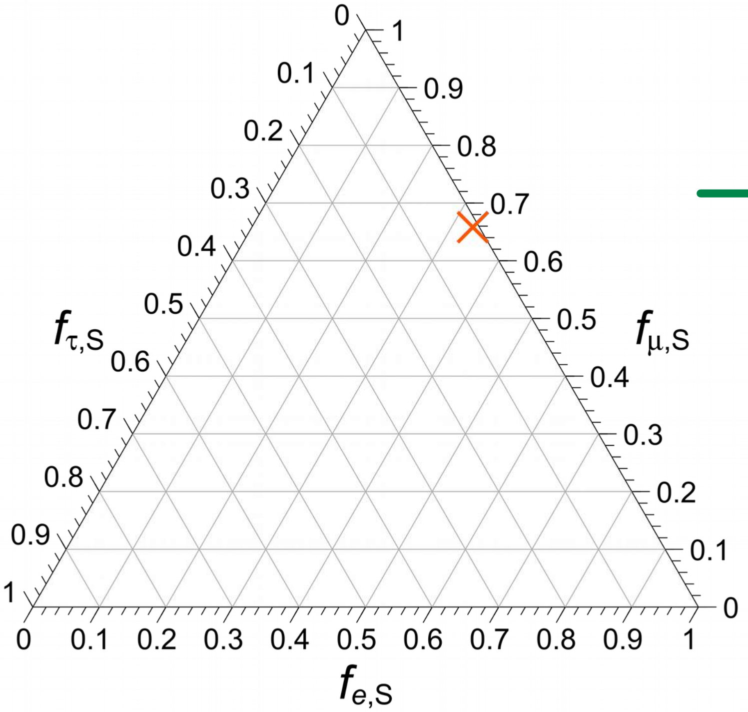
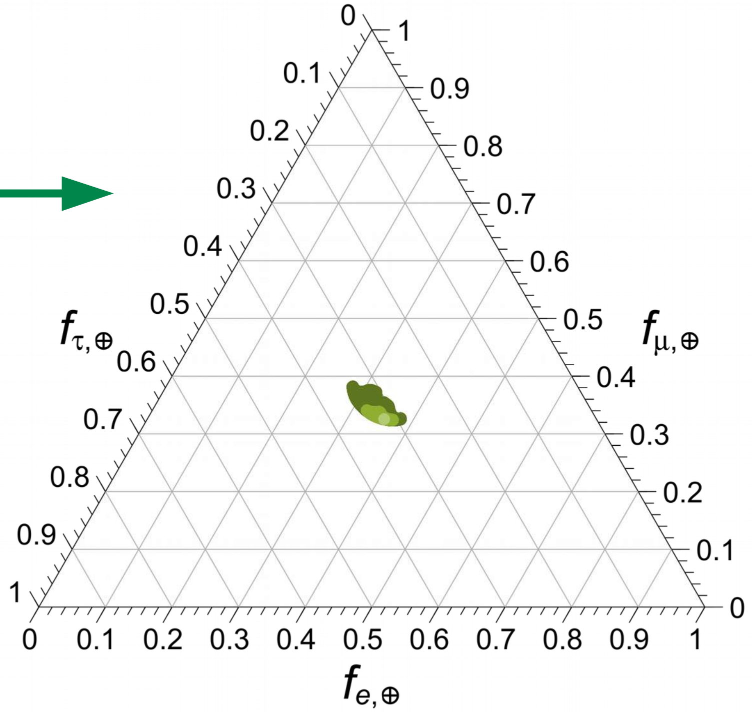


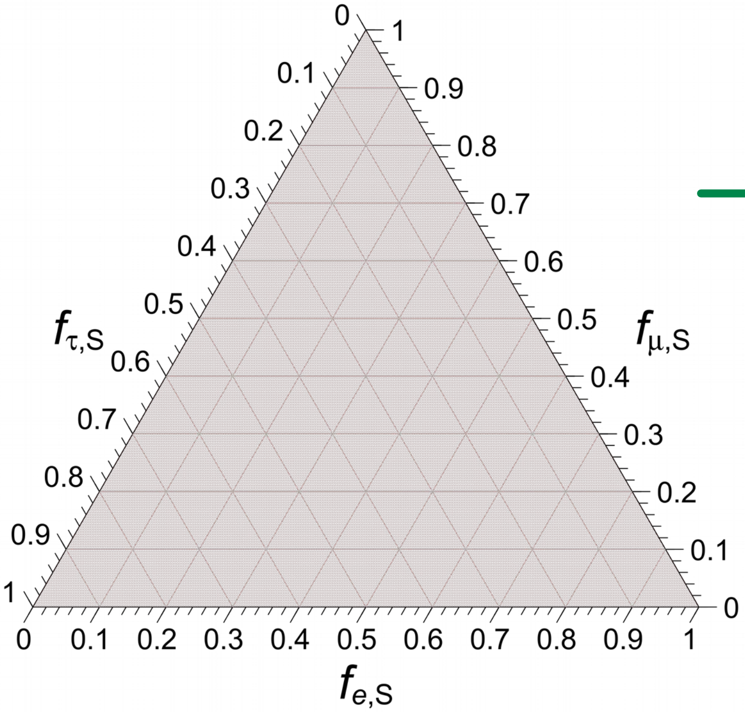
Uncertainties in values of mixing parameter (1σ, 3σ) →



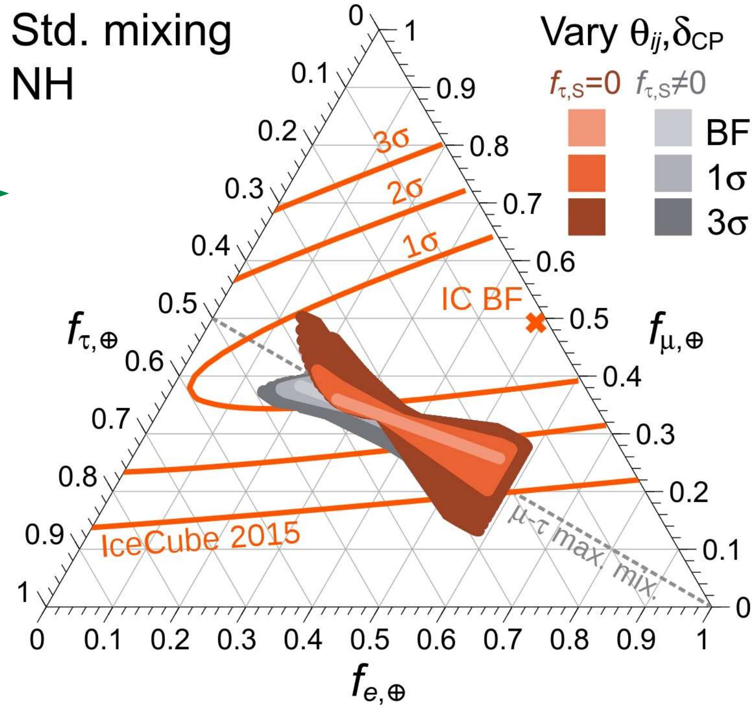
Flavor composition – standard allowed region

At the sources

All possible flavor ratios



At Earth



MB, Beacom, Winter *PRL* 2015

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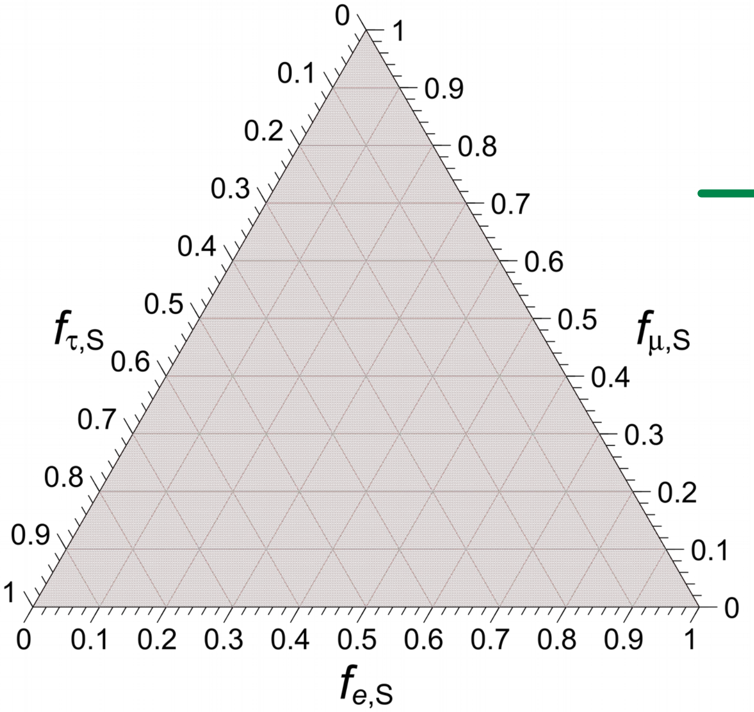
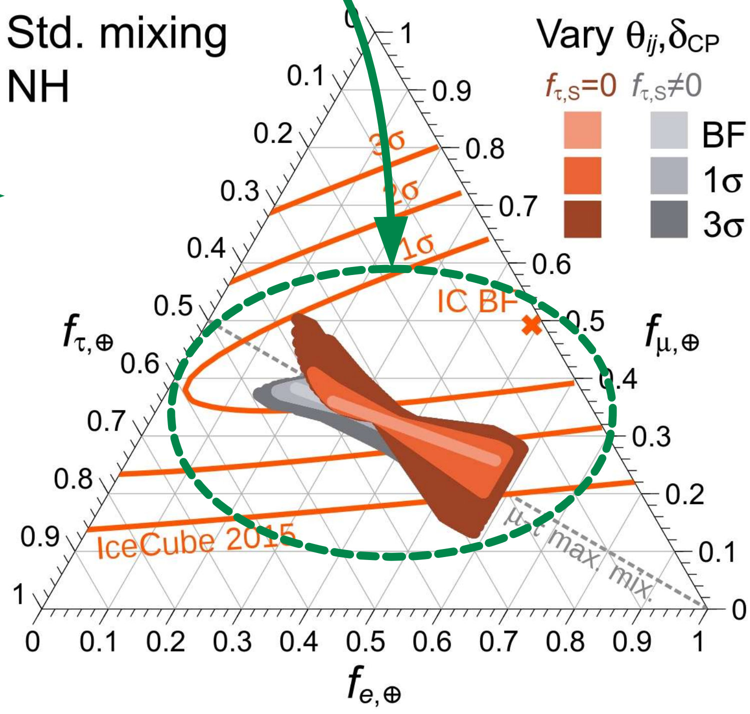


Only 10% of parameter space

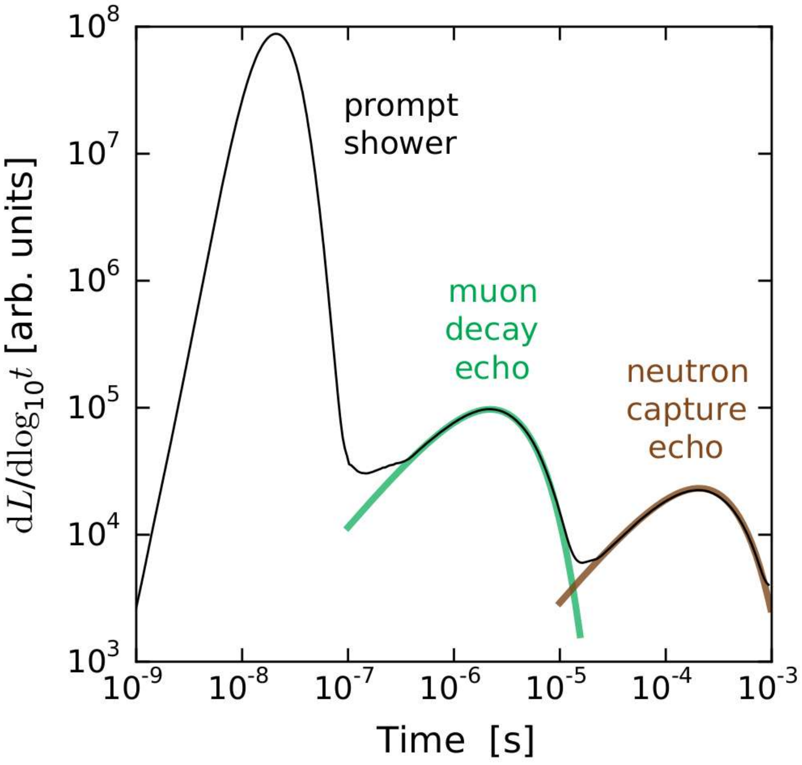
At Earth

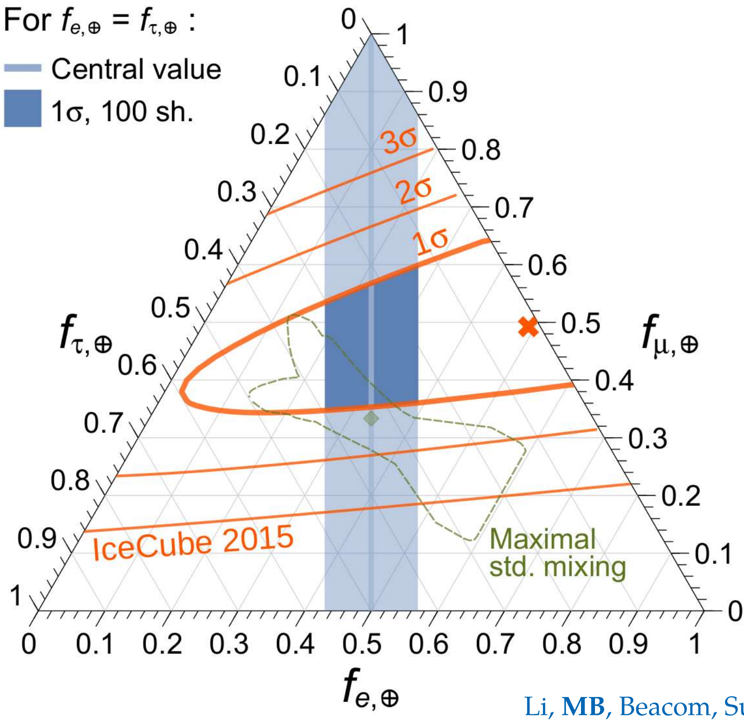


MB, Beacom, Winter *PRL* 2015

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, Sub. to *PRL*

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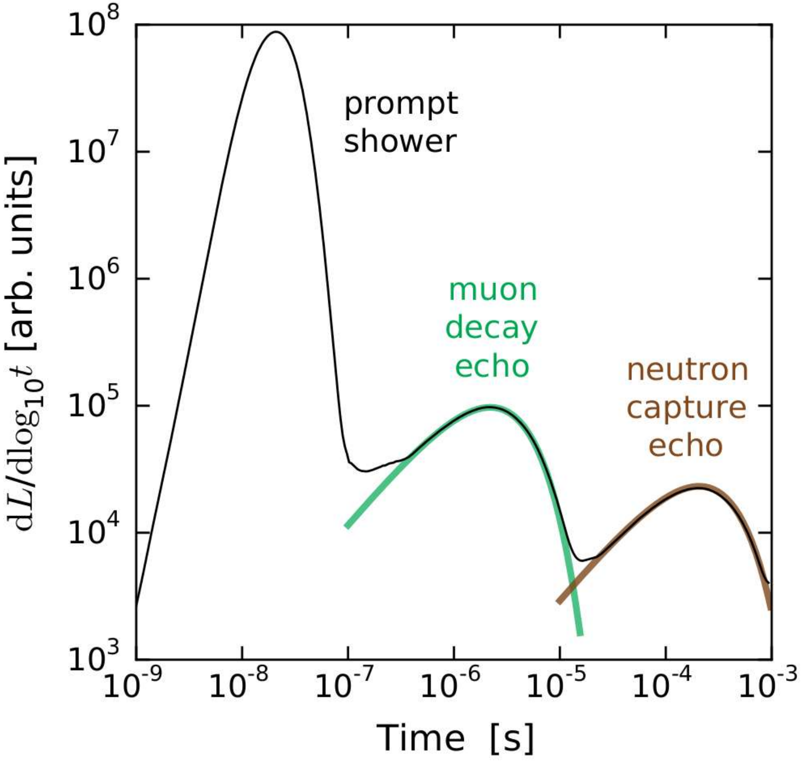

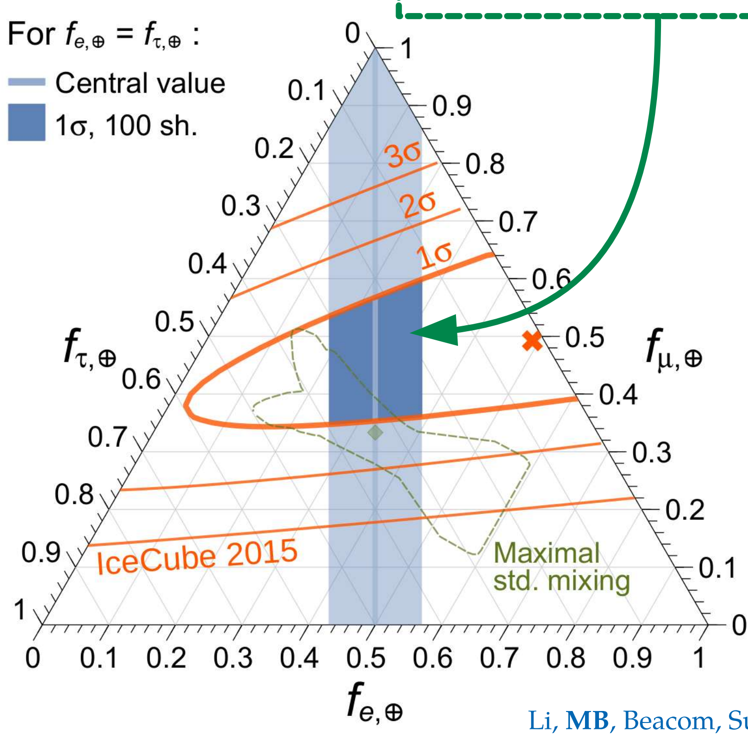

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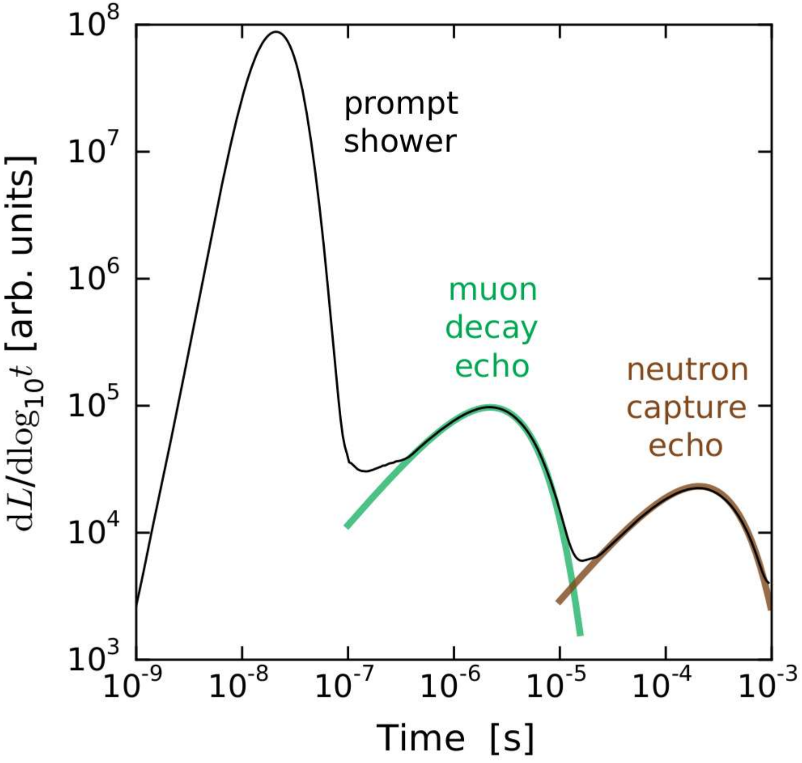

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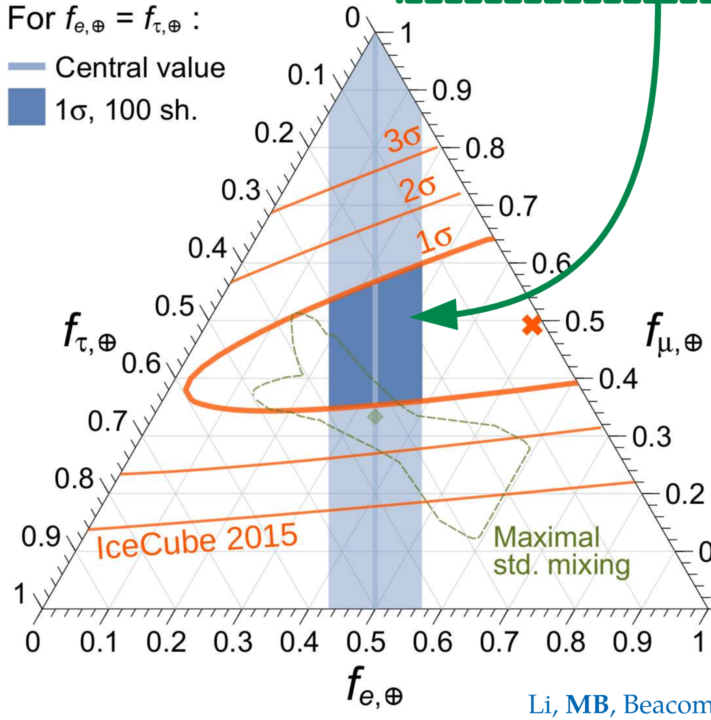
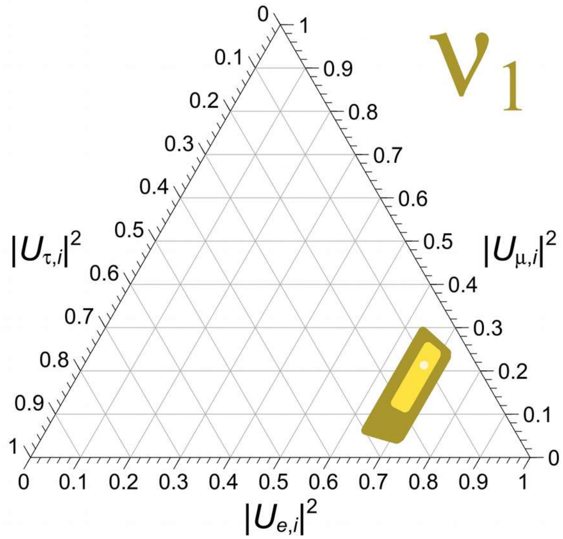


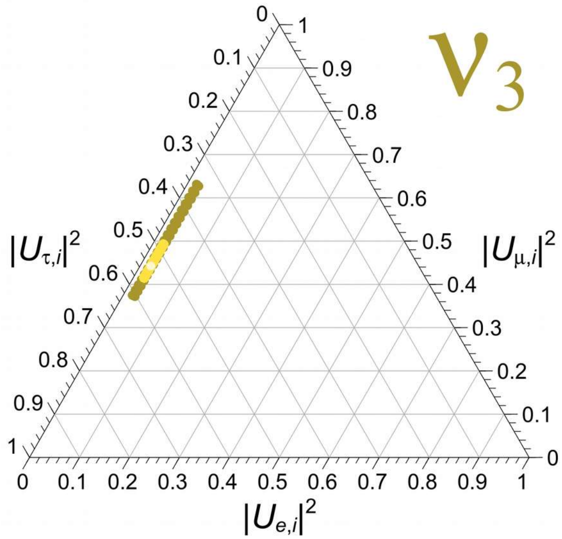
Li, **MB**, Beacom, Sub. to *PRL*

Measuring the neutrino lifetime

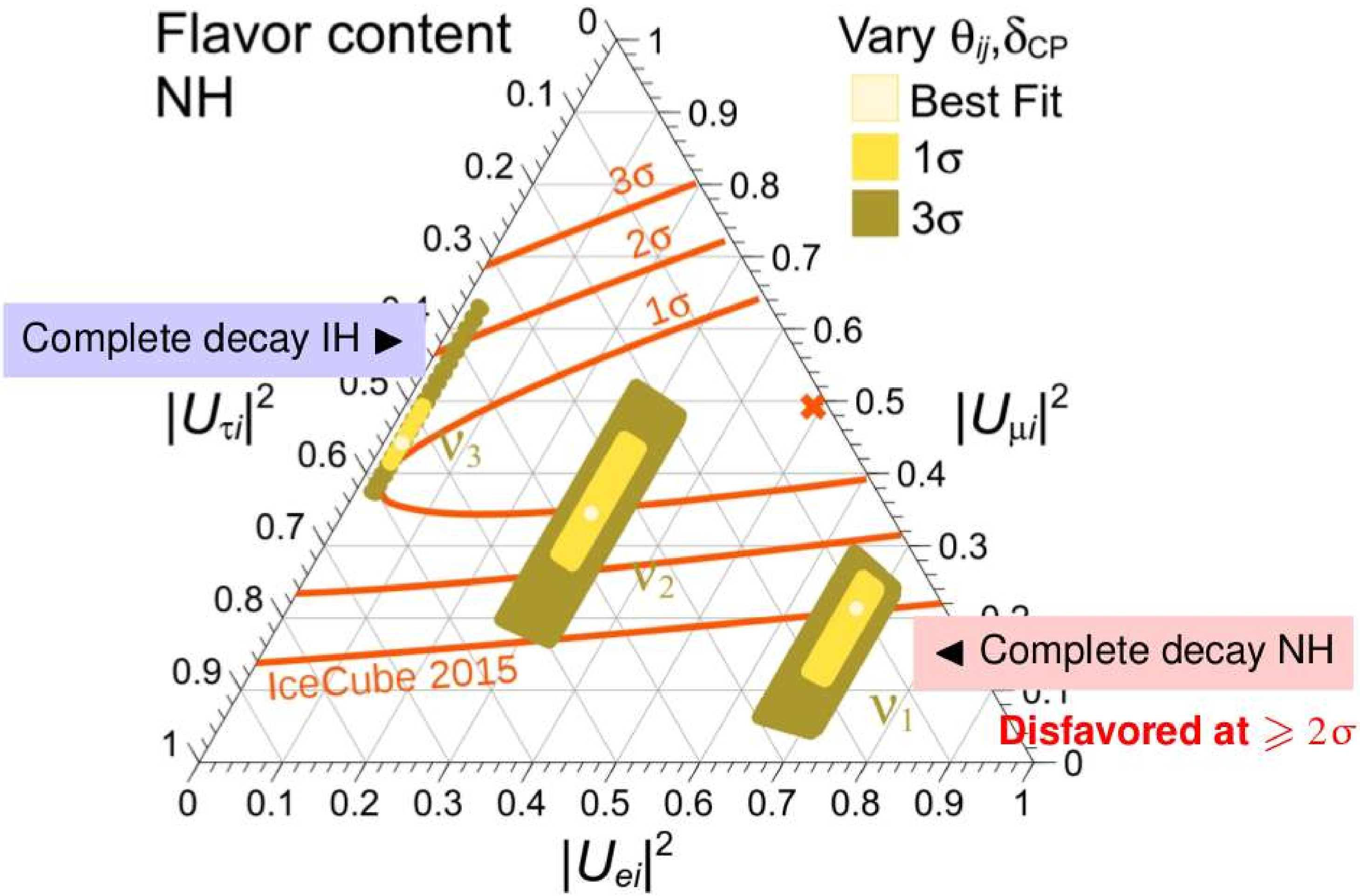
- In the Standard Model, neutrinos are essentially stable (lifetime > 10^{36} yr)
- But new physics could lower the lifetime

$$\underbrace{\nu_2, \nu_3 \to \nu_1}_{\nu_1 \text{ lightest and stable}} \qquad \underbrace{\nu_1, \nu_2 \to \nu_3}_{\nu_3 \text{ lightest and stable}}$$





Measuring the neutrino lifetime



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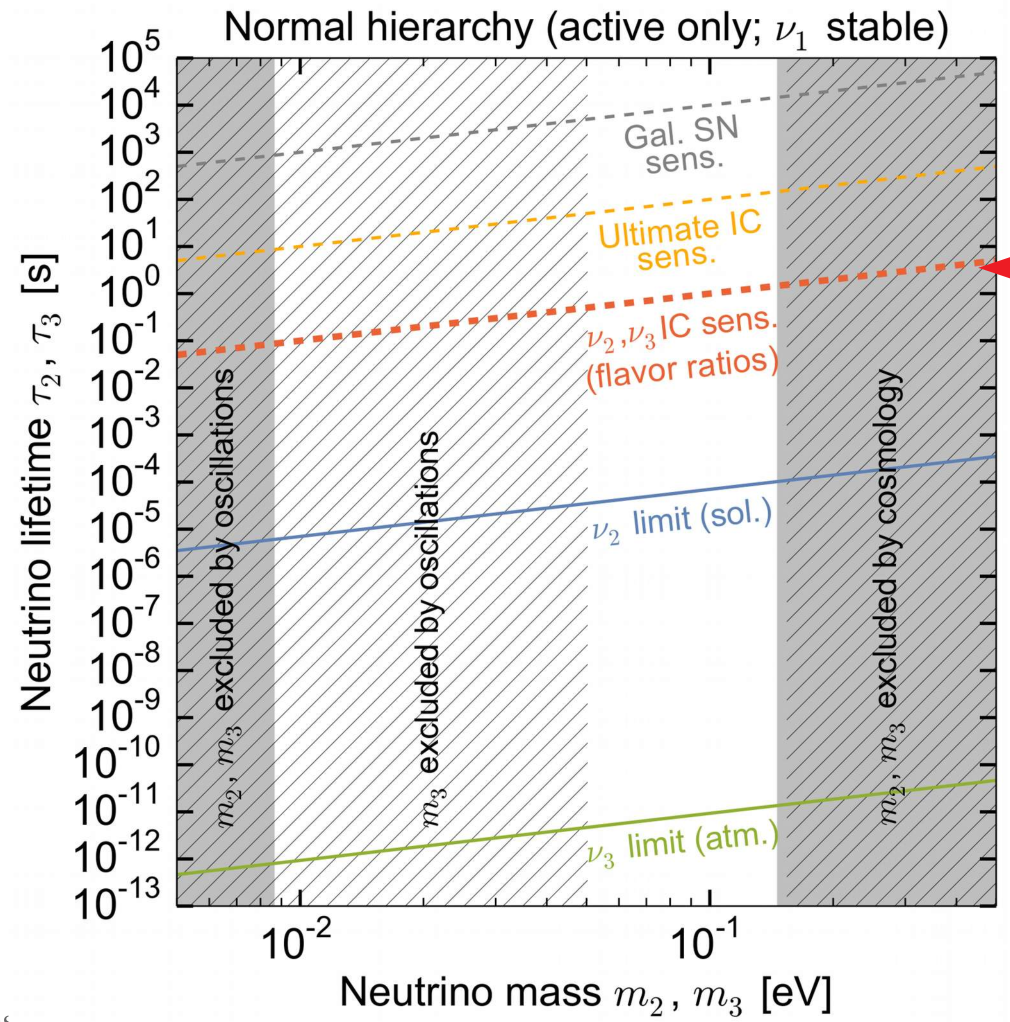
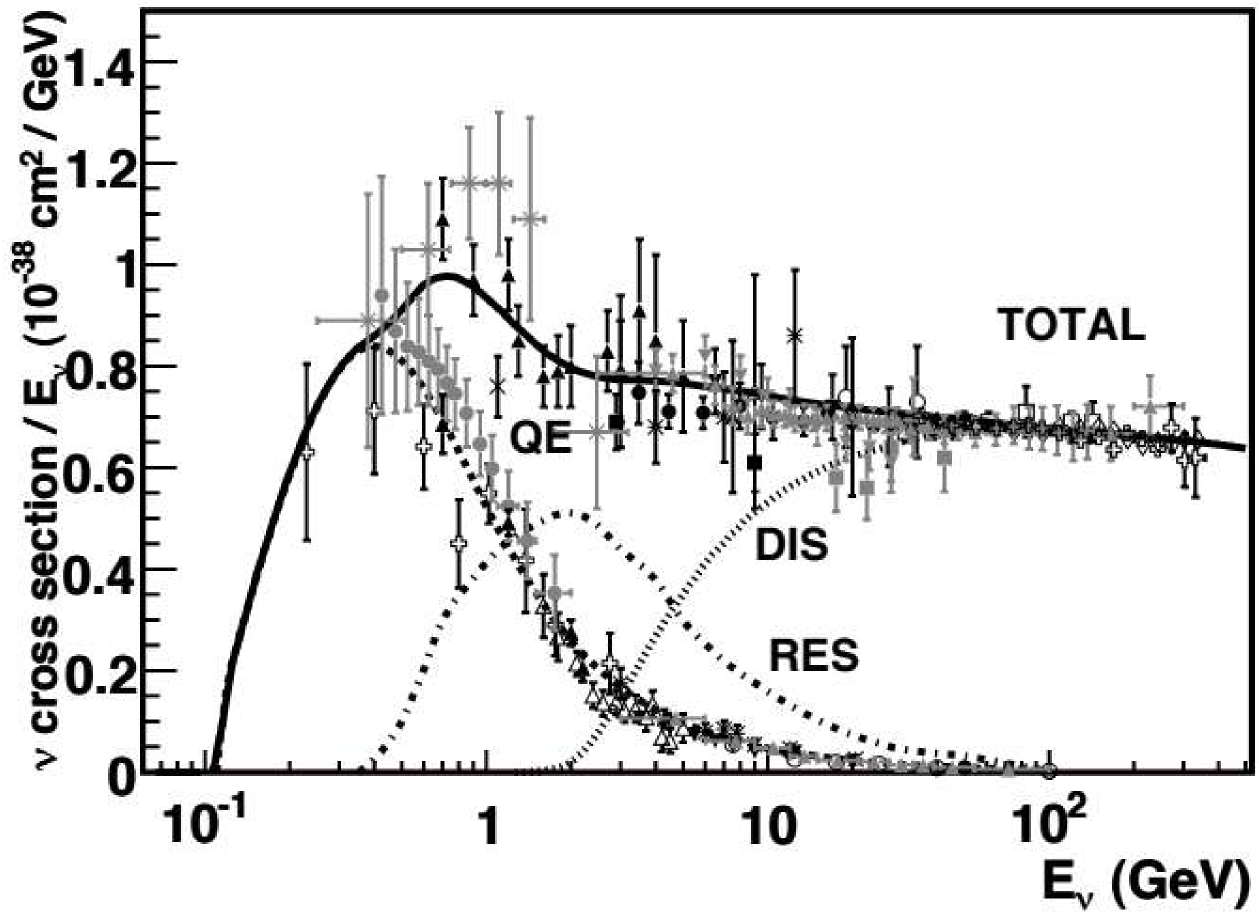


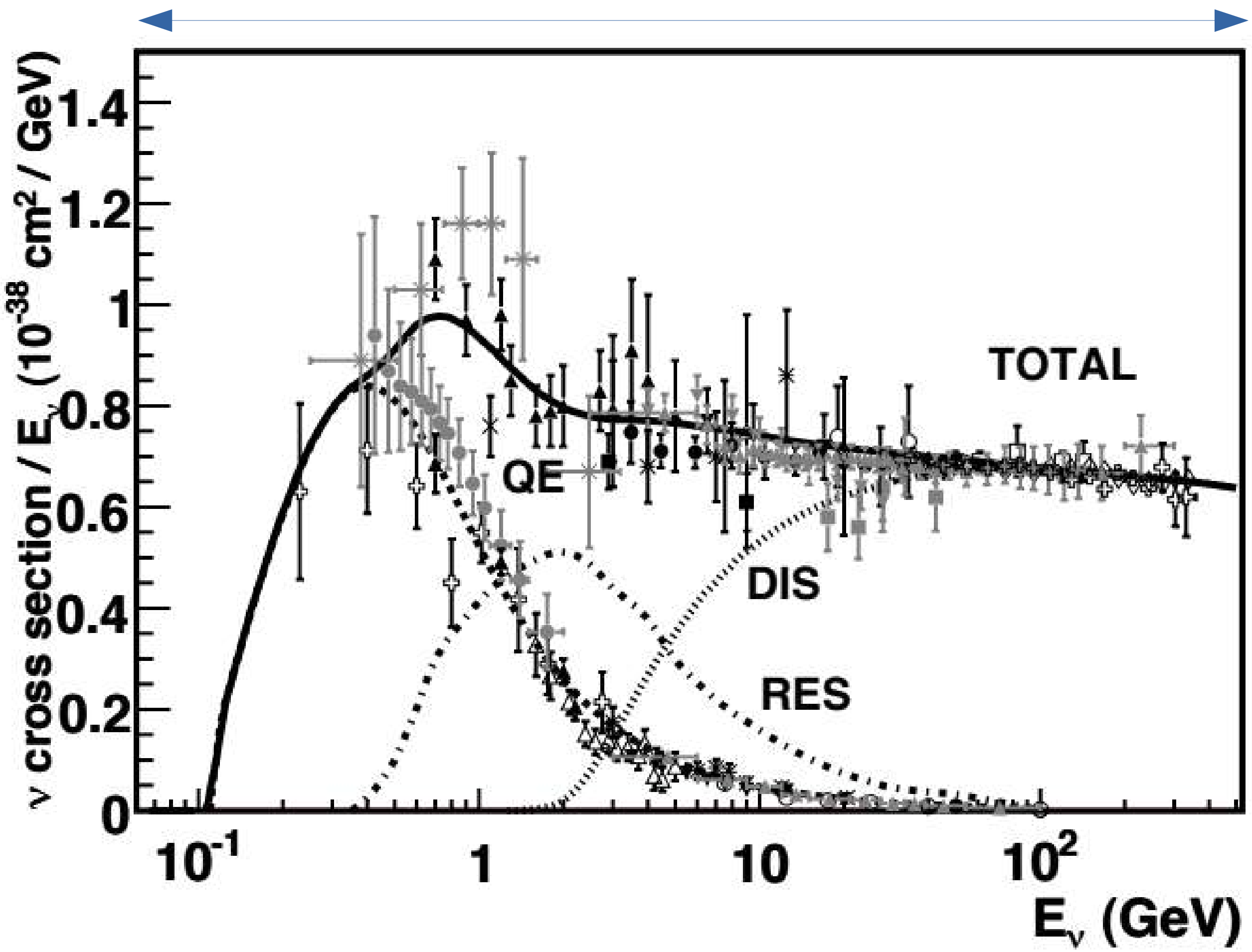
Our result

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



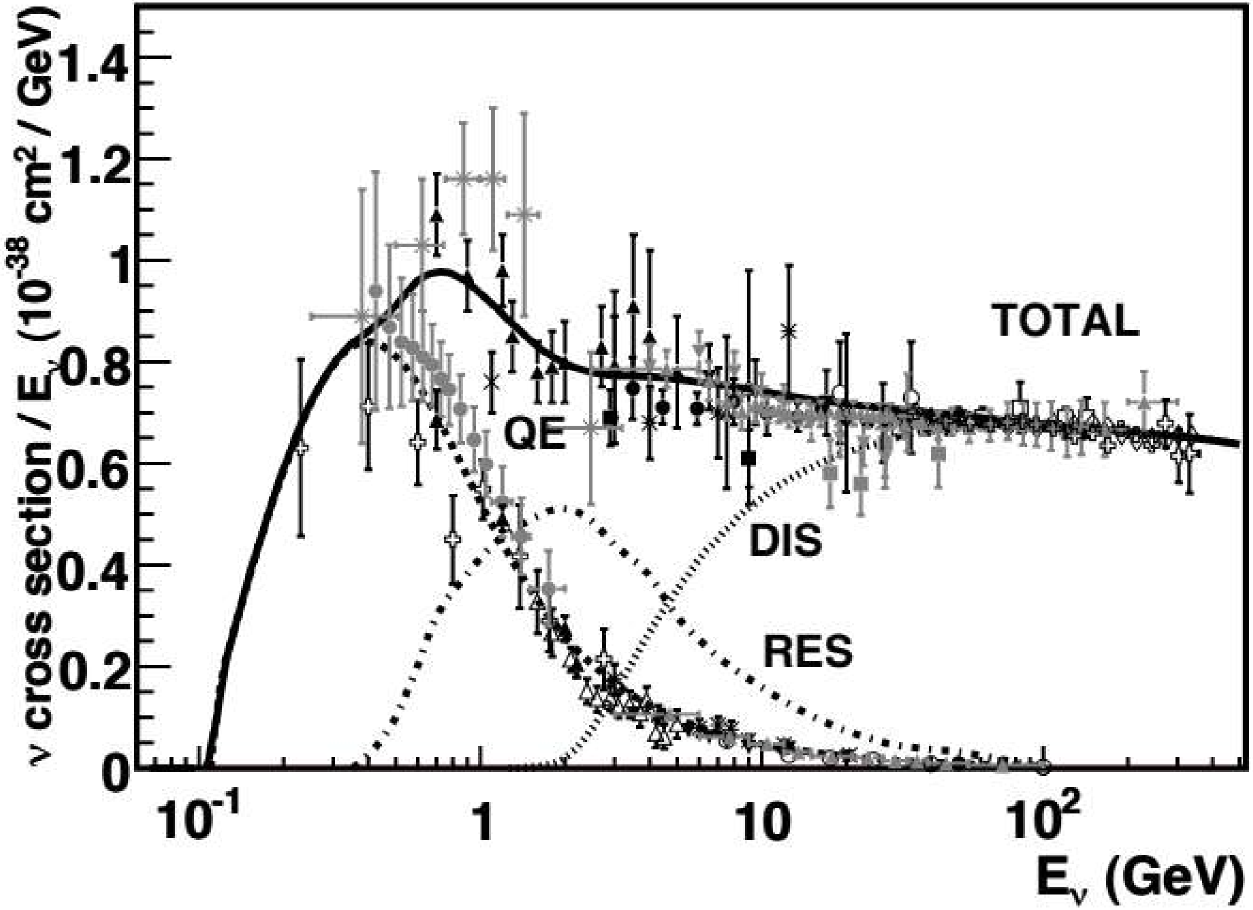
Particle Data Group

Accelerator experiments



Particle Data Group

Accelerator experiments



Particle Data Group

One recent measurement (COHERENT)

Accelerator experiments

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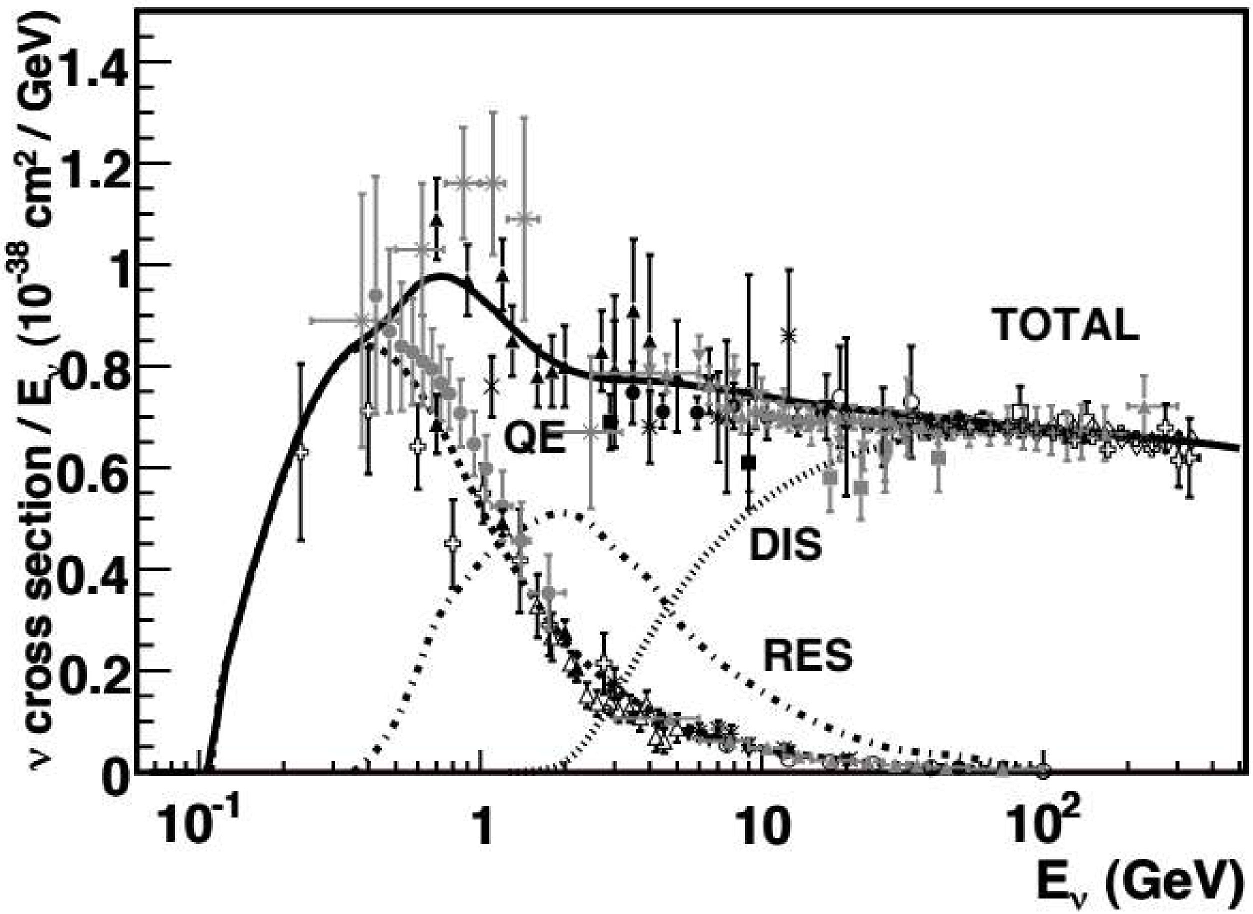
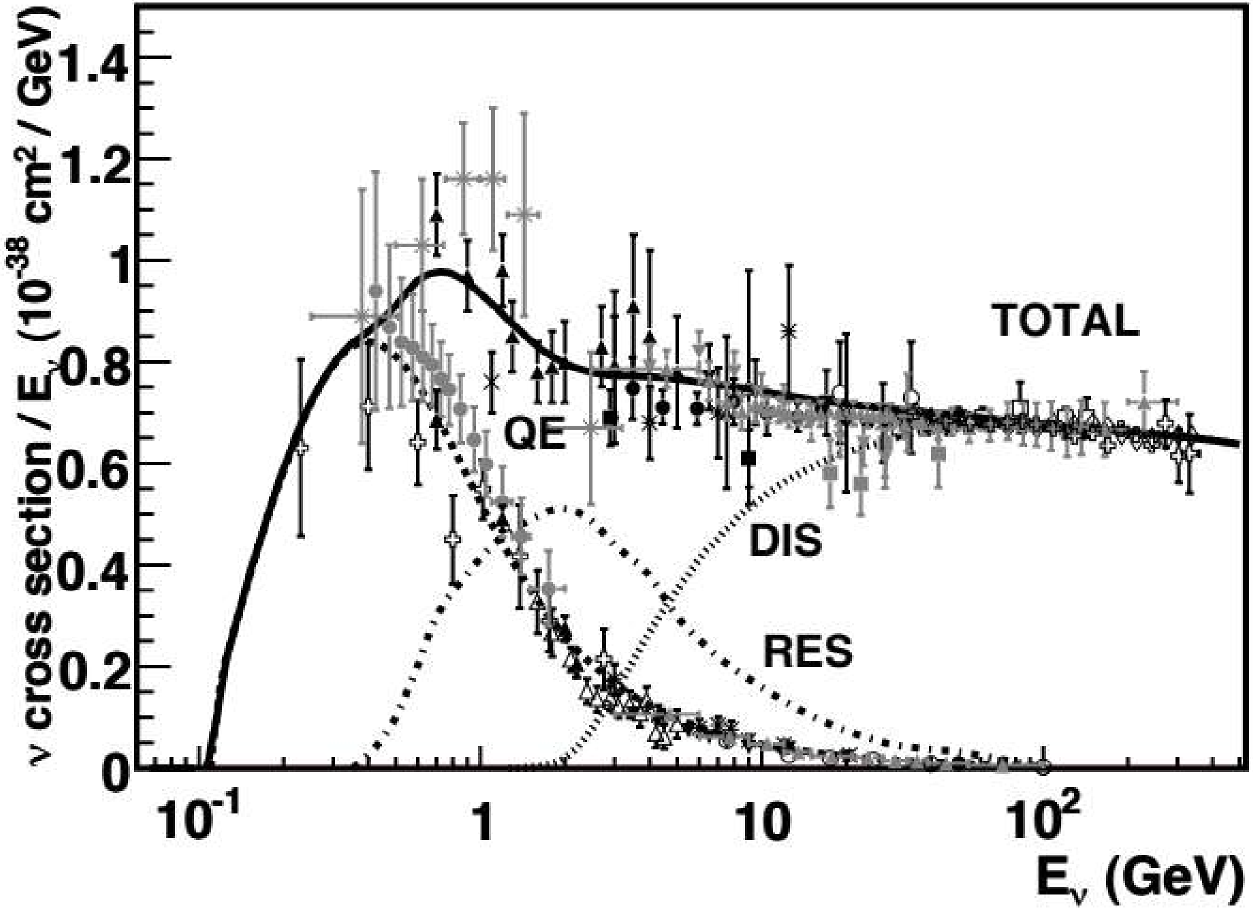


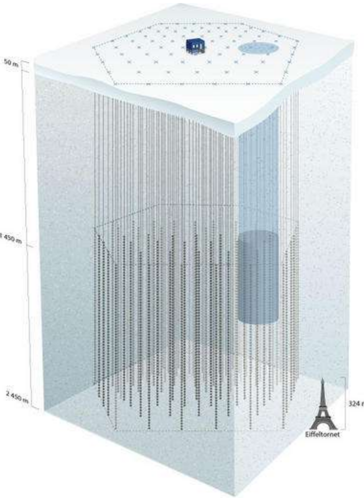
Particle Data Group

No measurements … until now!

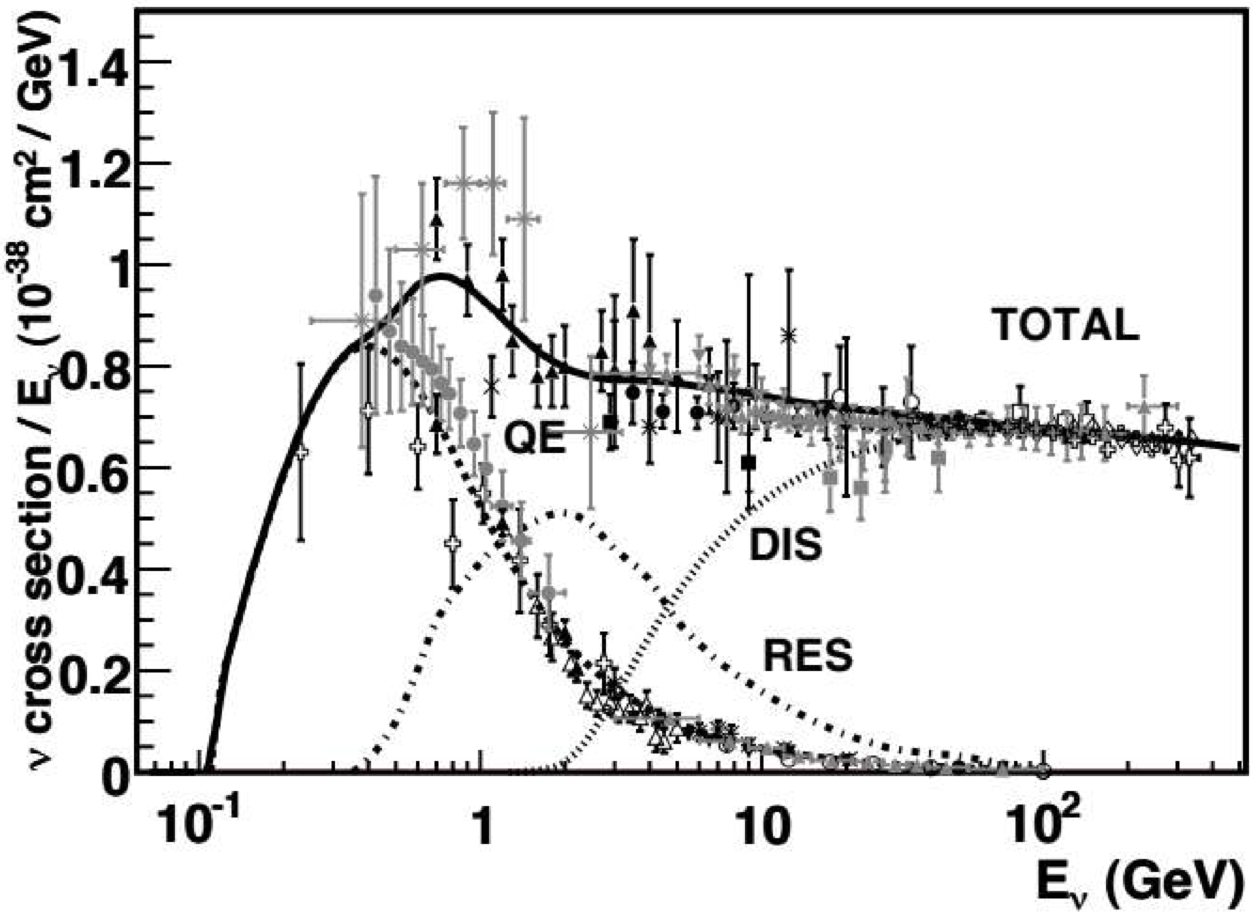
Accelerator experiments

One recent measurement (COHERENT)





Particle Data Group

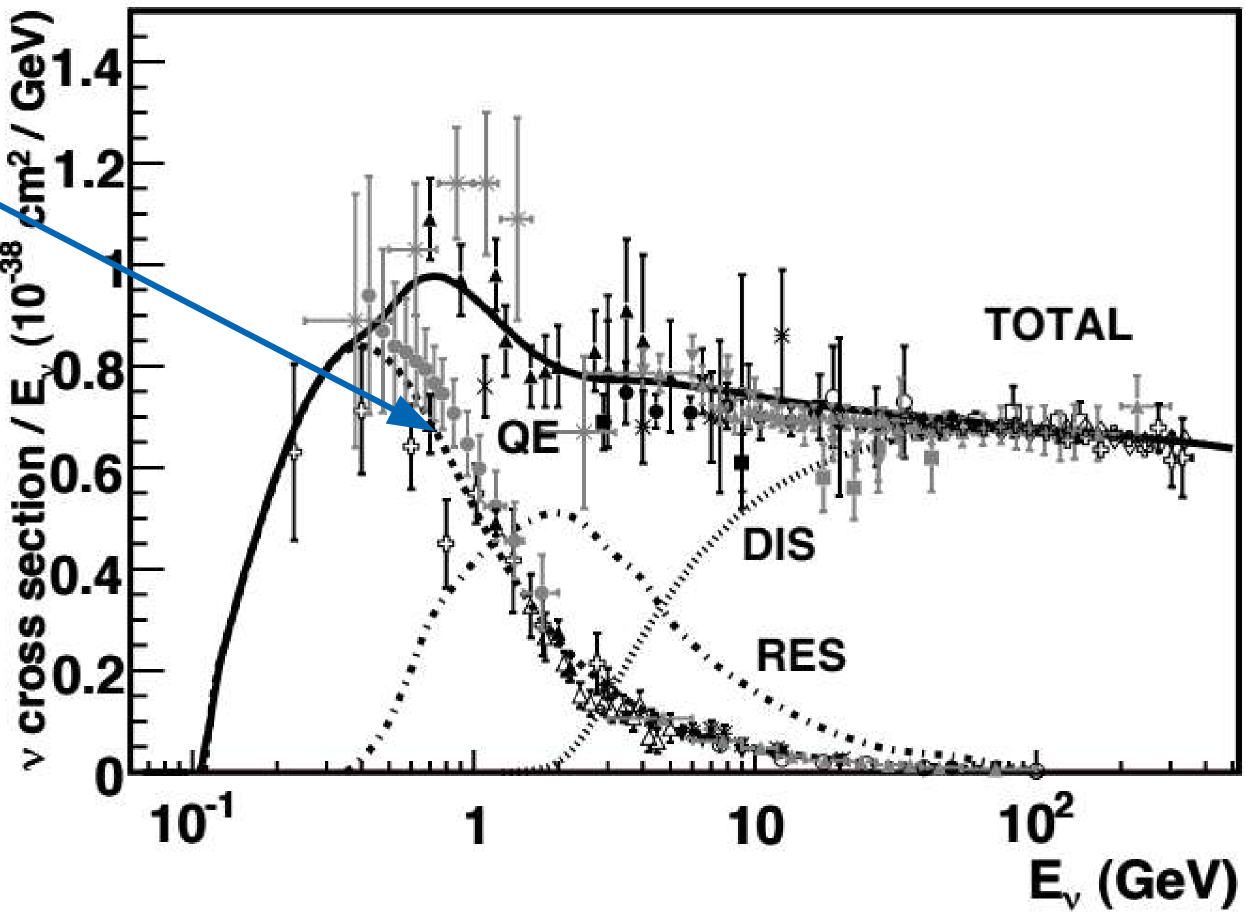


Particle Data Group

Quasi-elastic scattering:

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

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



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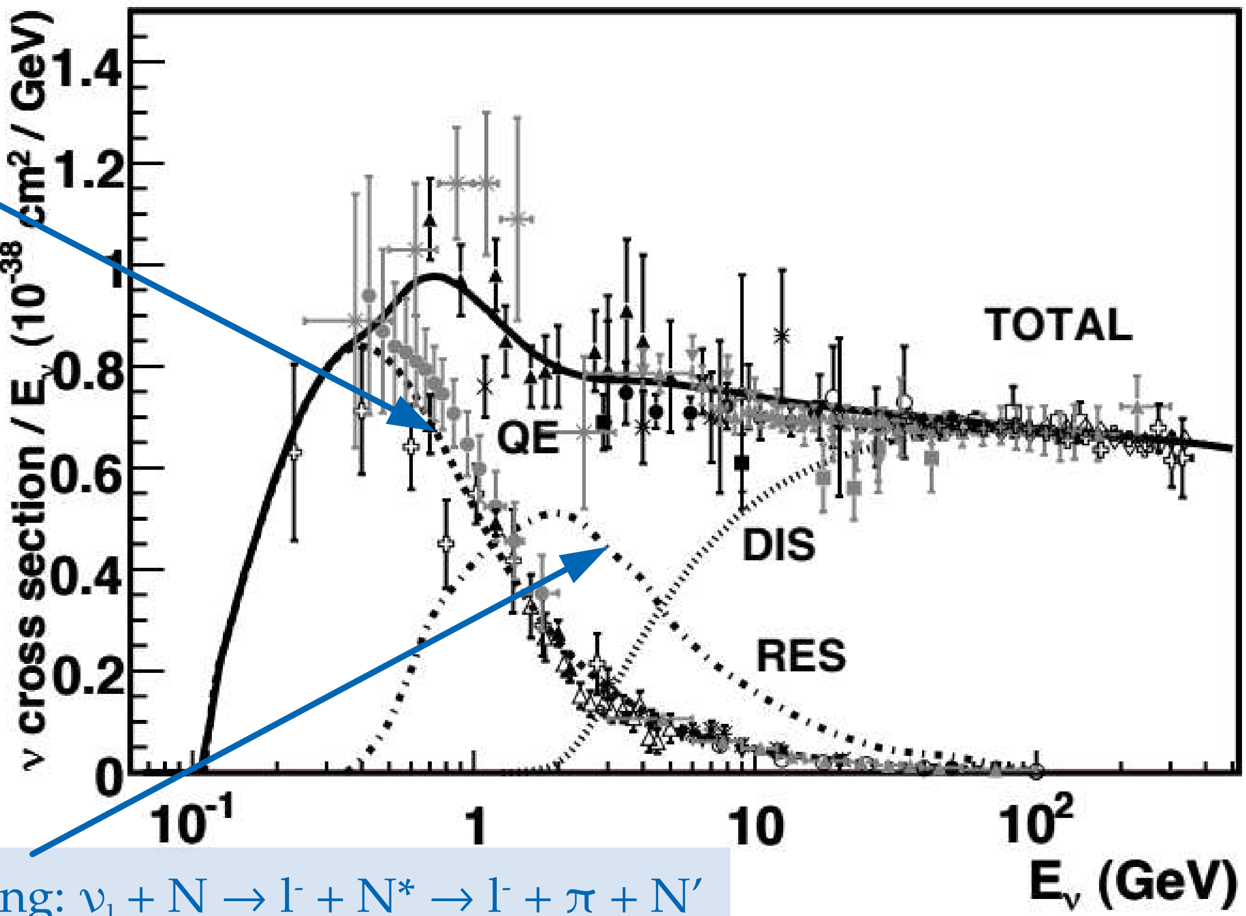


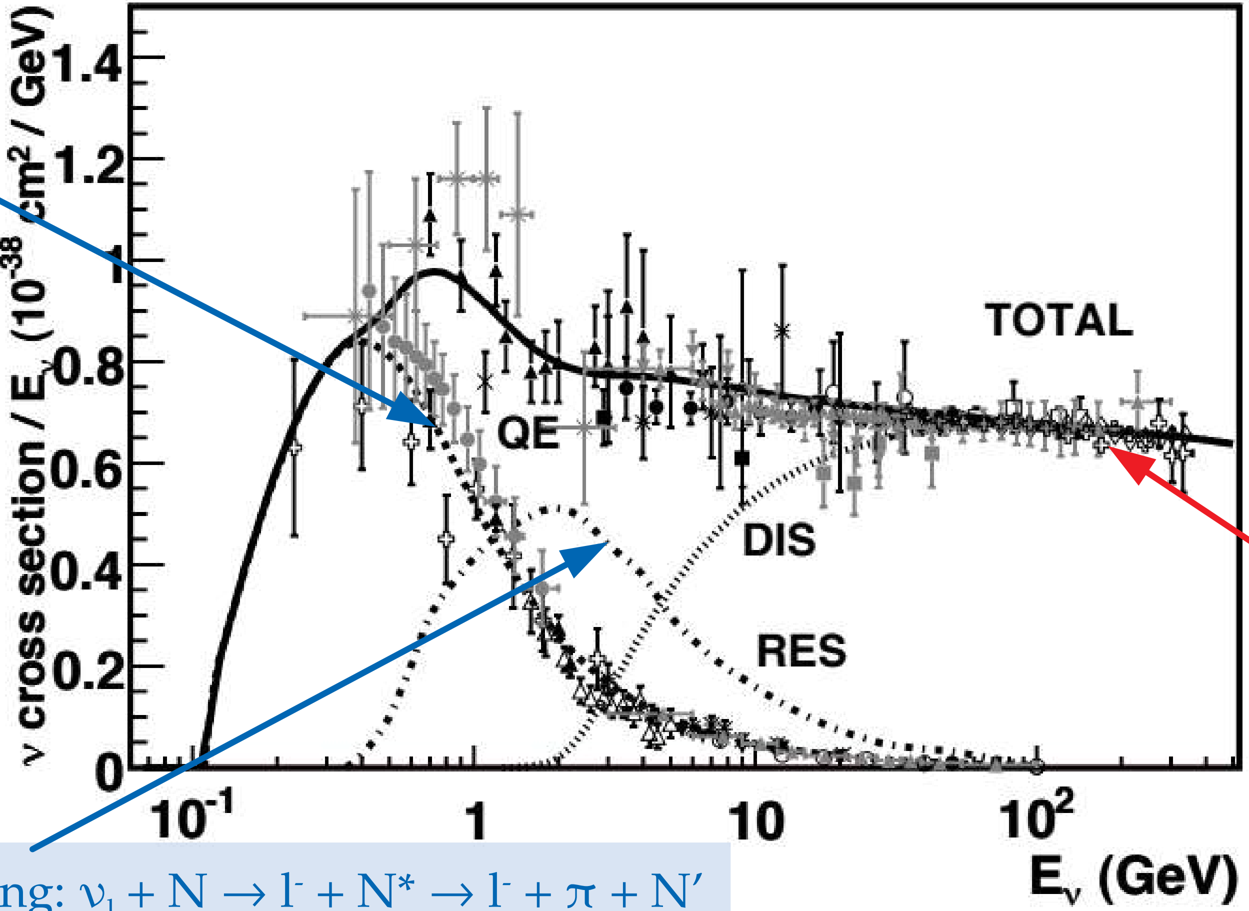
Resonant scattering: $\nu_l + N \to l^- + N^* \to l^- + \pi + N'$

Particle Data Group

Quasi-elastic scattering:

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

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



Deep inelastic scattering:

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

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

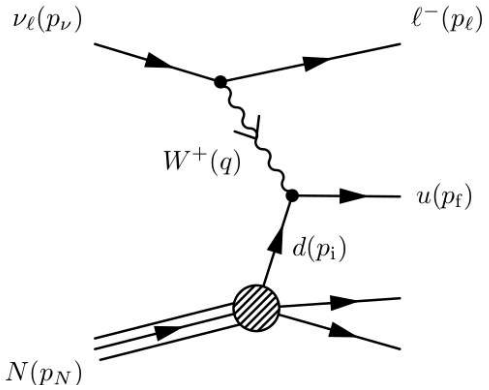
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Extrapolating the cross section to high energies

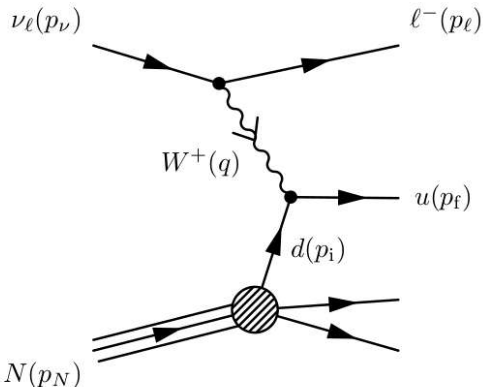
Extrapolating the cross section to high energies

SM



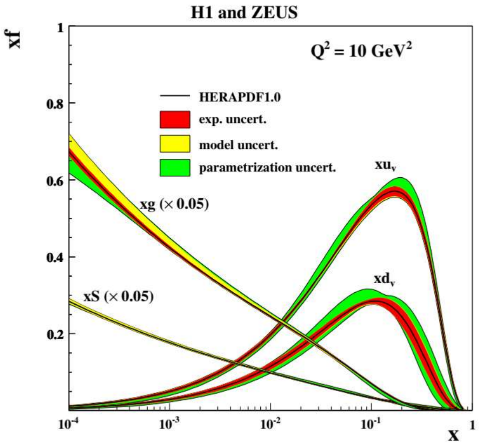
Extrapolating the cross section to high energies

SM



+

PDFs



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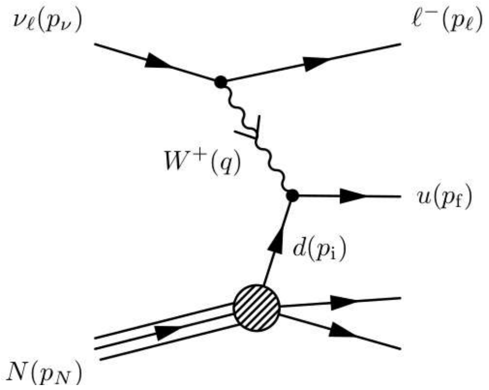

+

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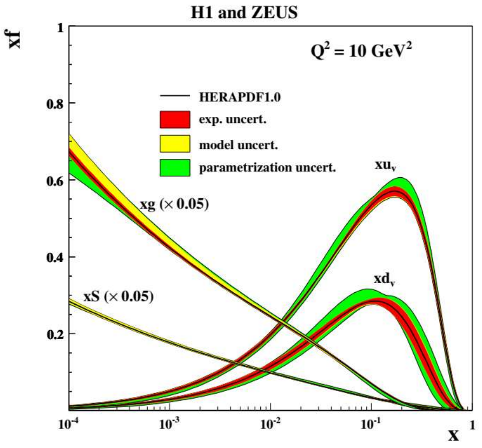
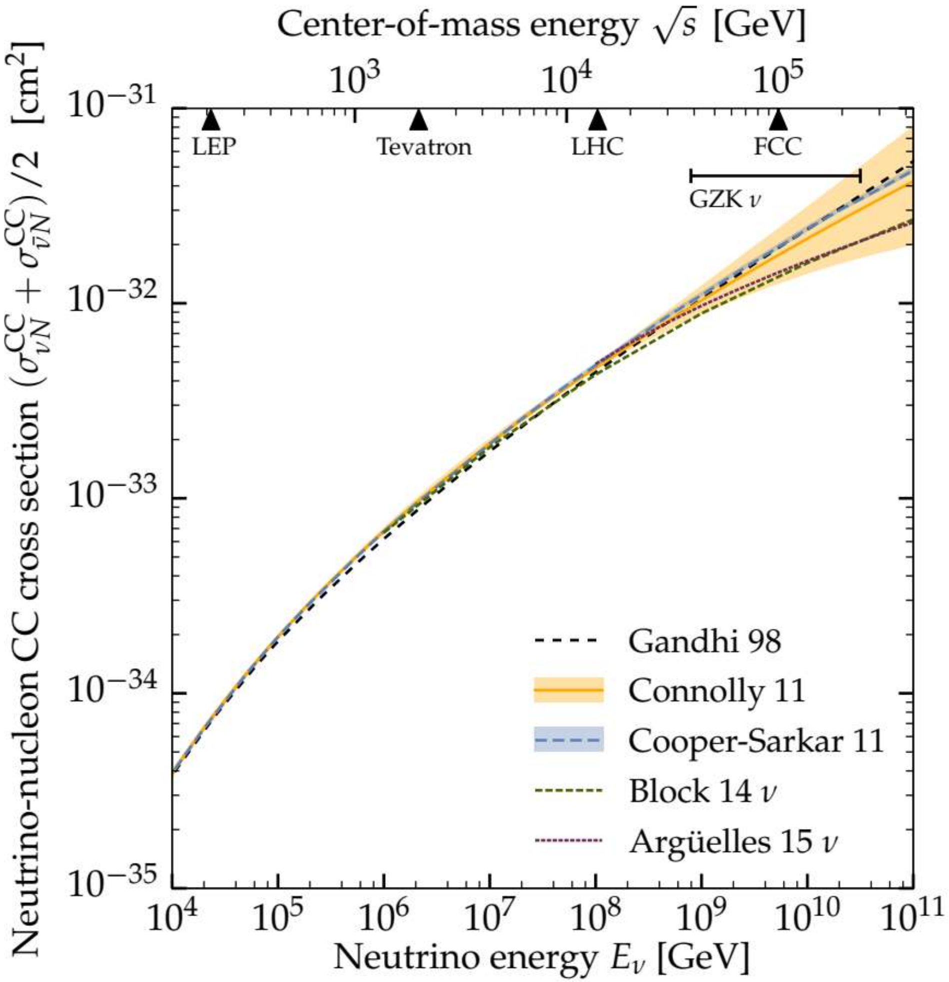
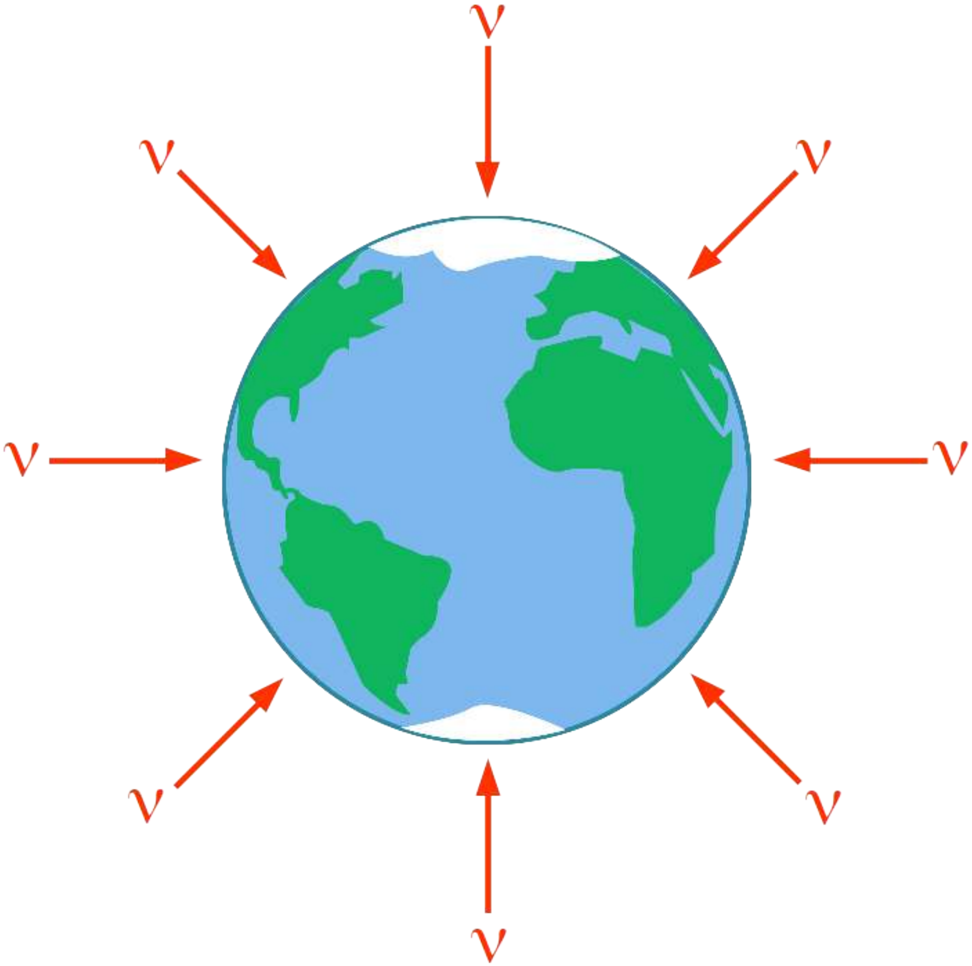


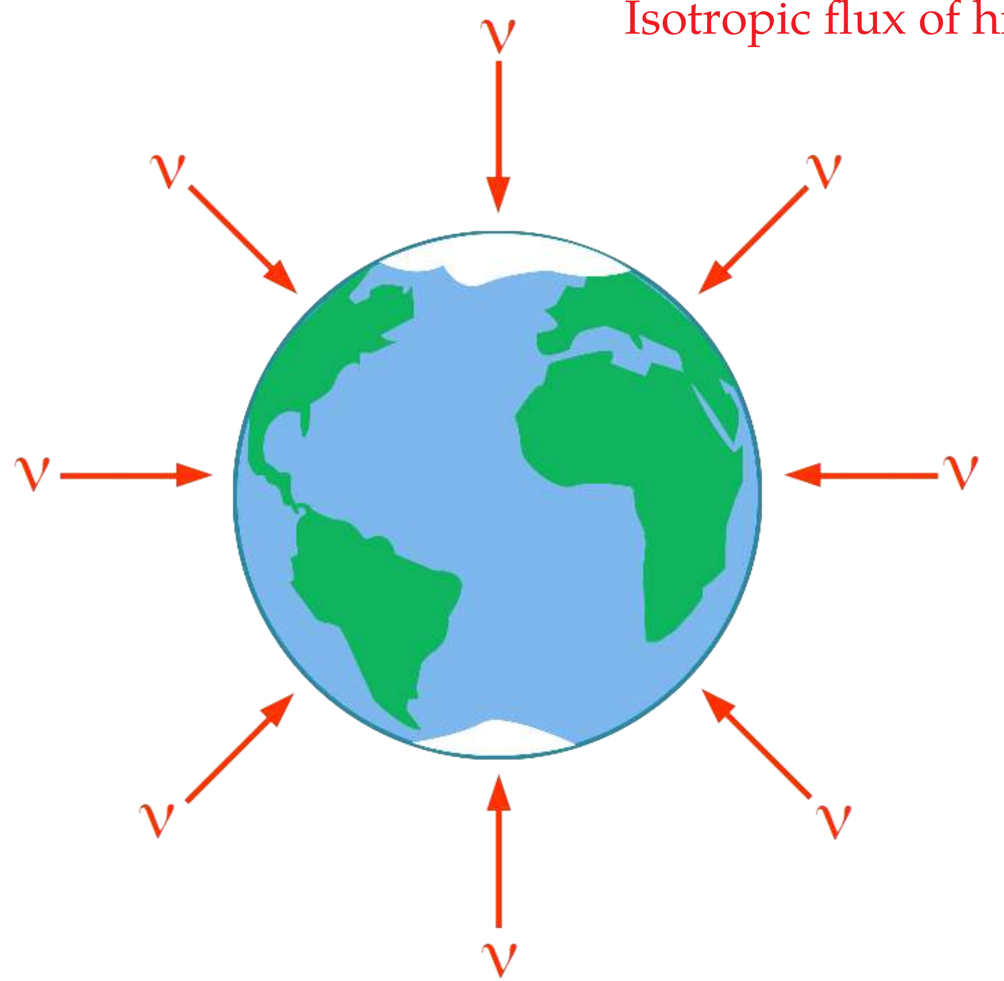
=



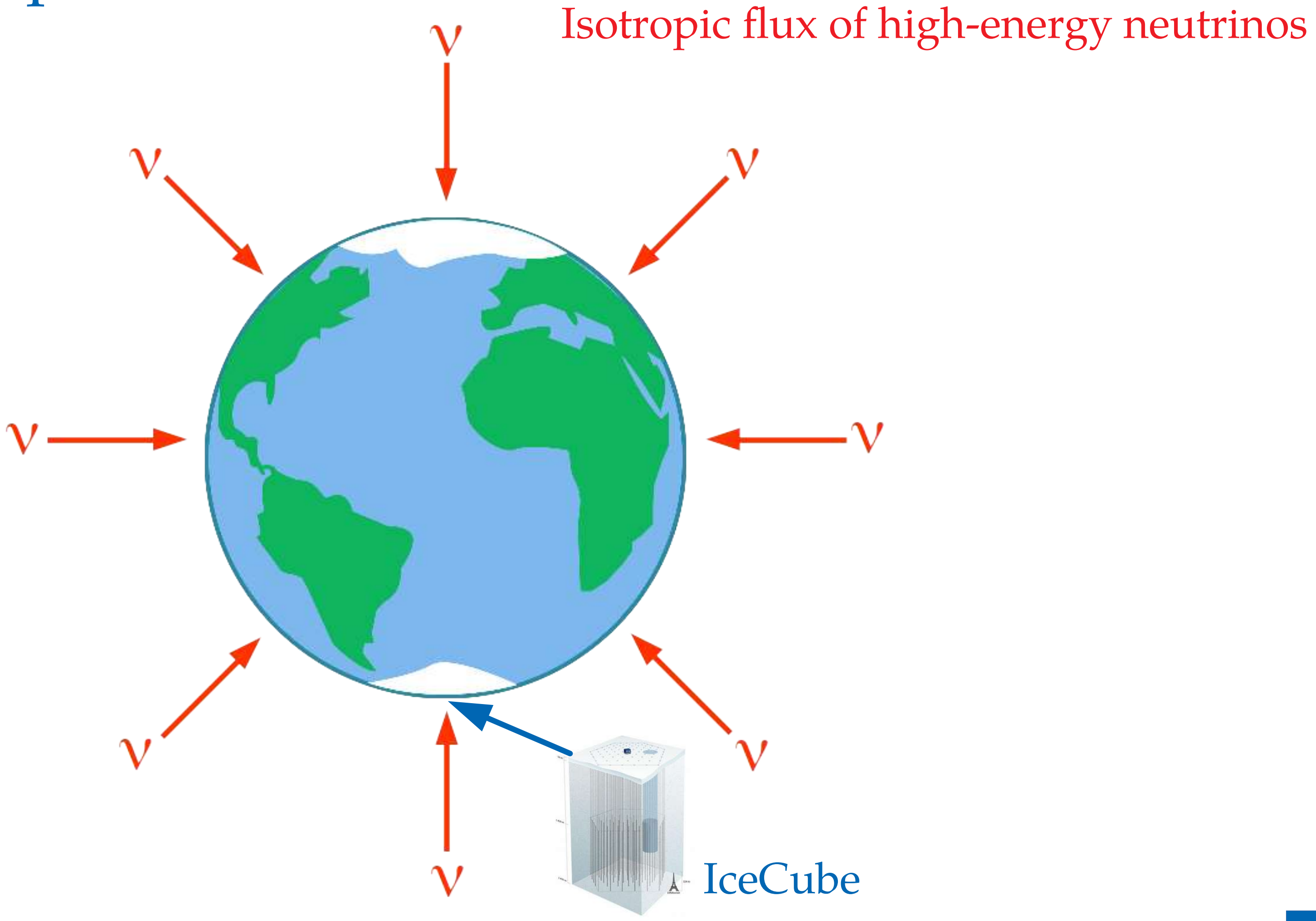
Neutrino, interrupted



Neutrino, interrupted



Neutrino, interrupted



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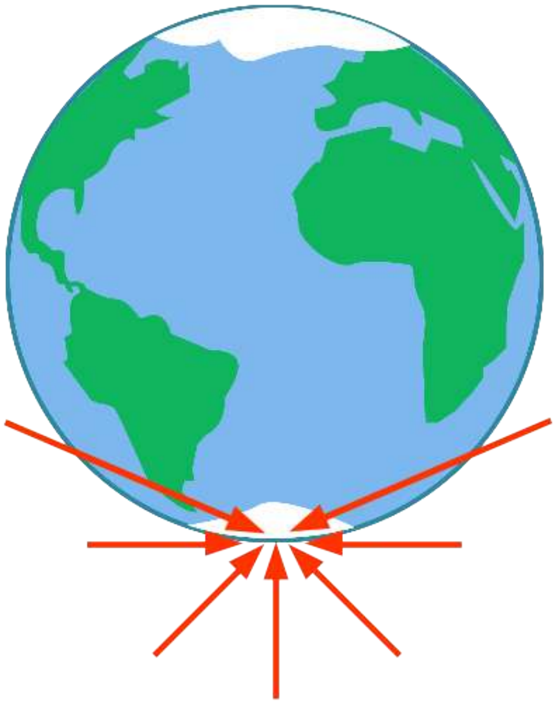
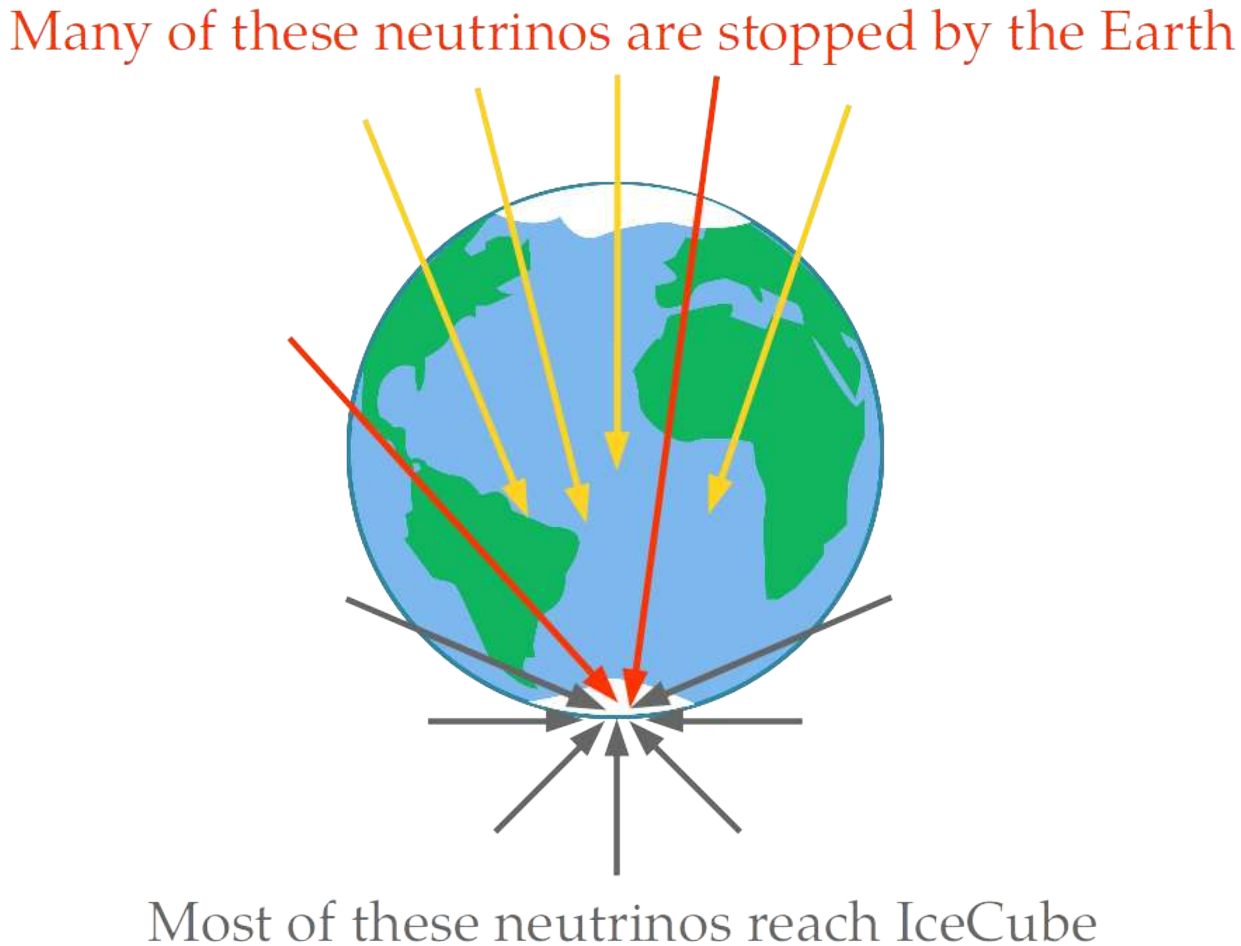


Most of these neutrinos reach IceCube

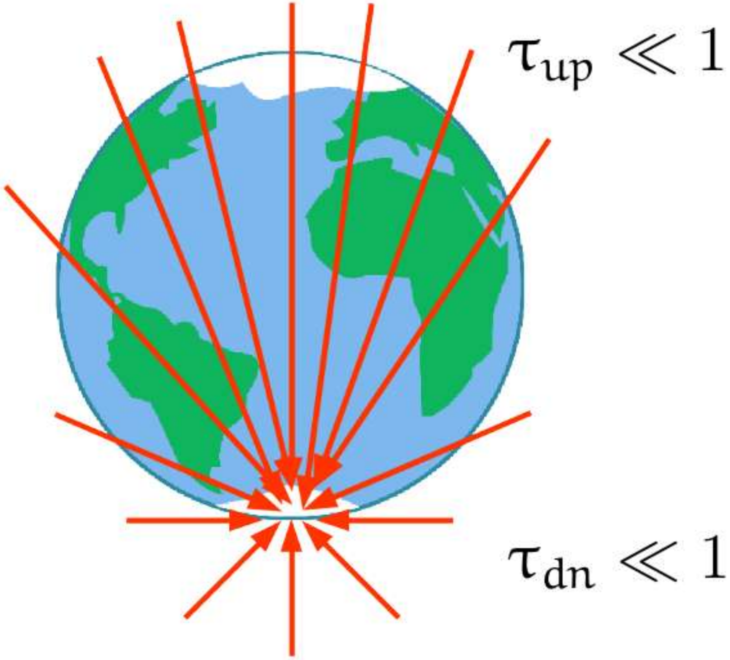
Neutrino, interrupted



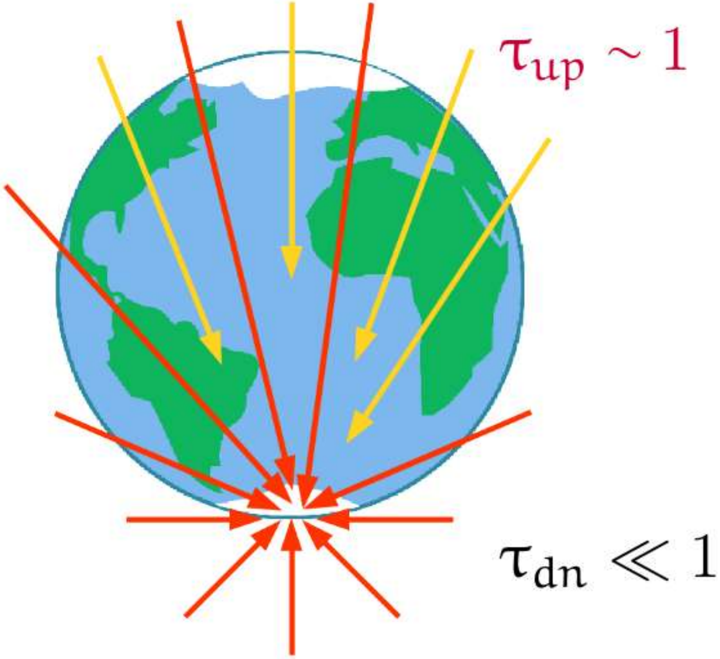
Measuring the high-energy cross section

$$\text{Optical depth to } \nu N \text{ int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent



Above ~ 10 TeV: Earth is opaque



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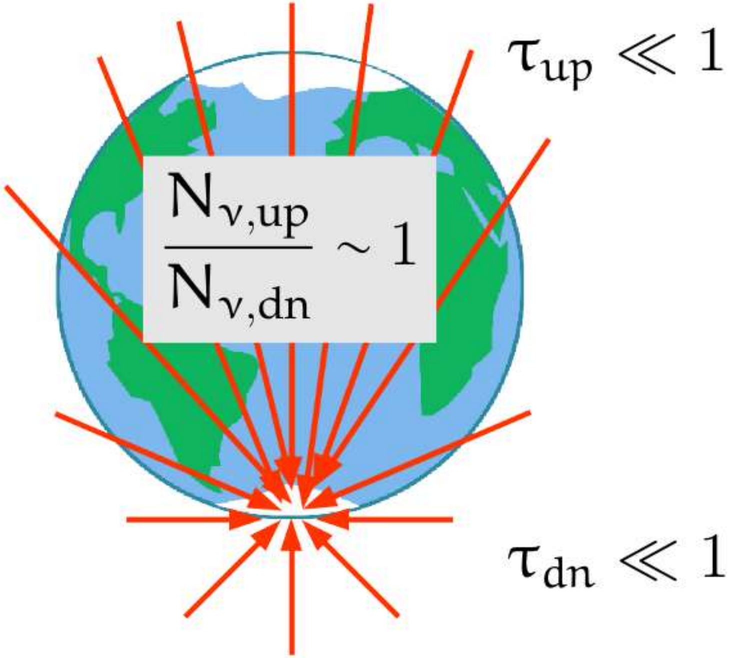

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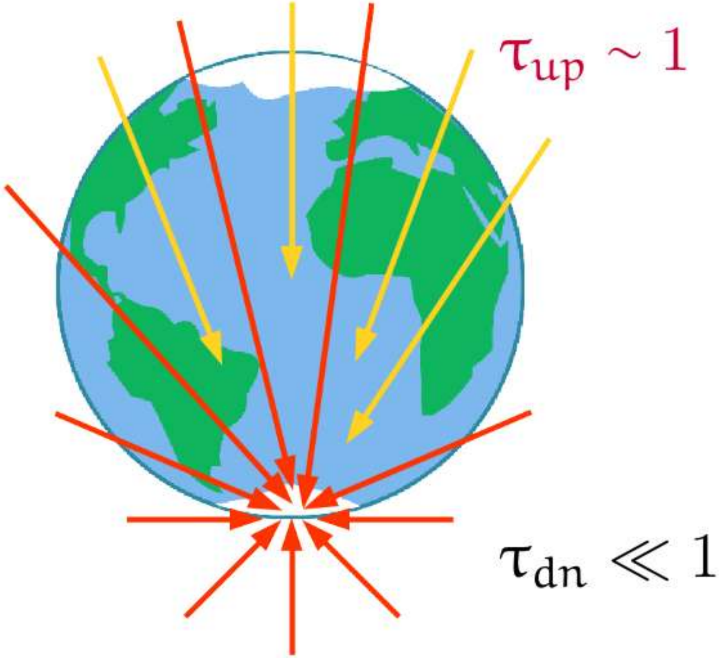

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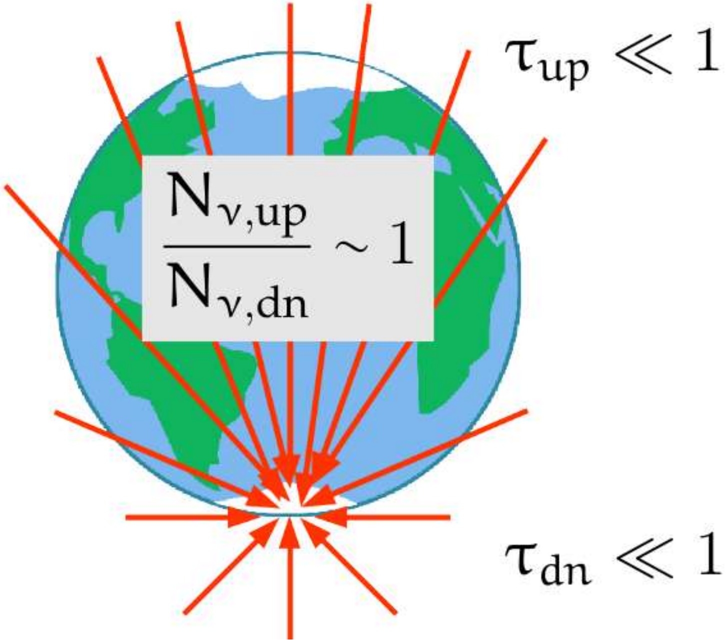

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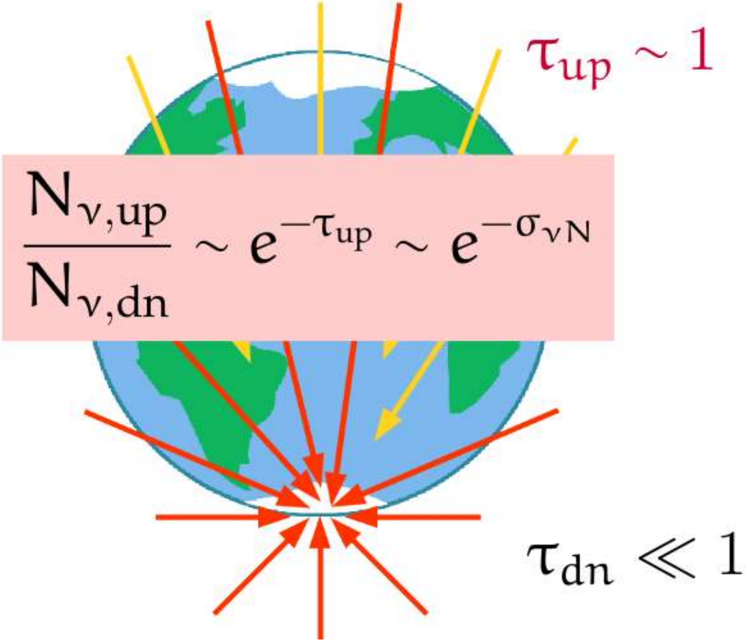
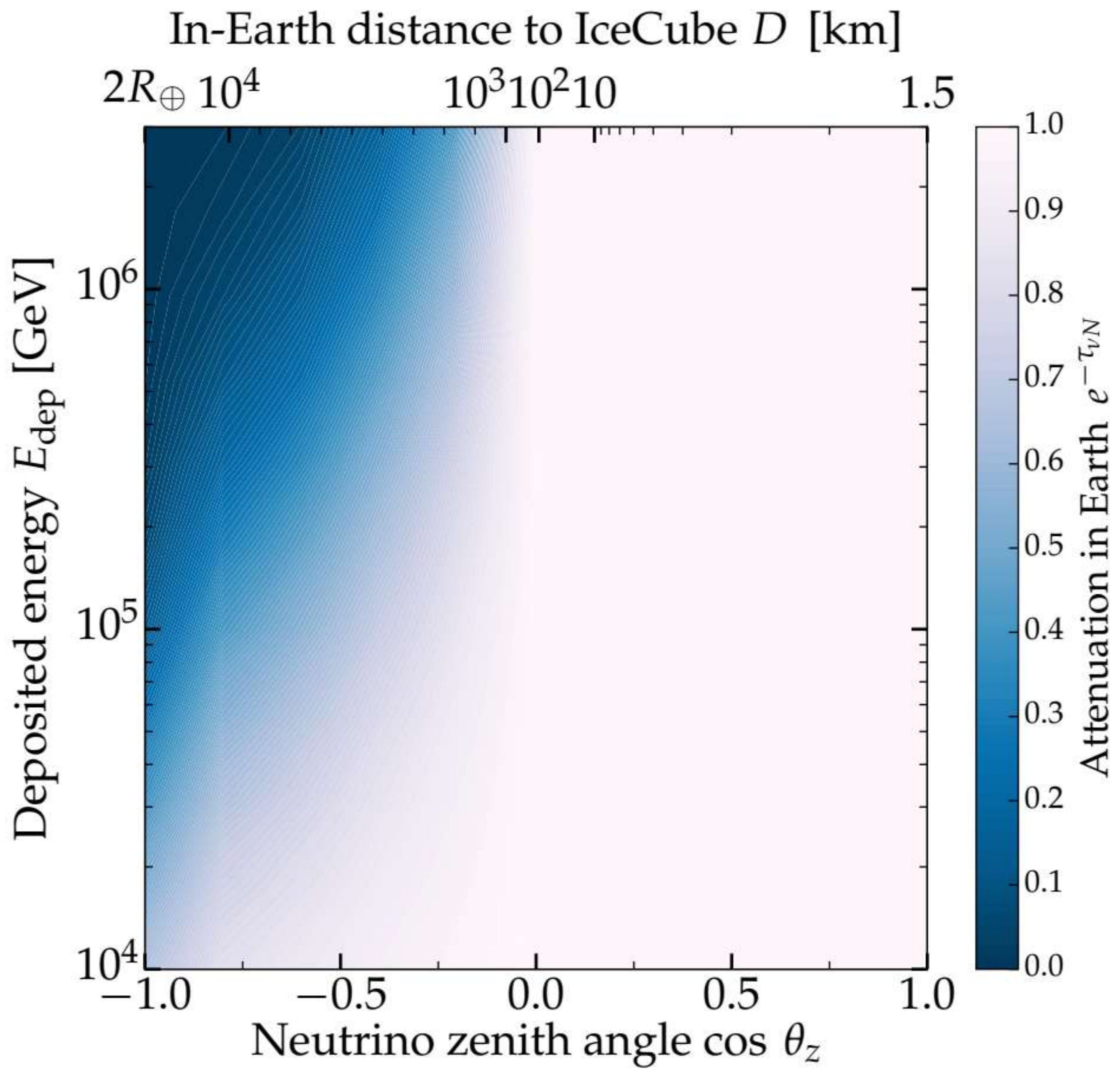
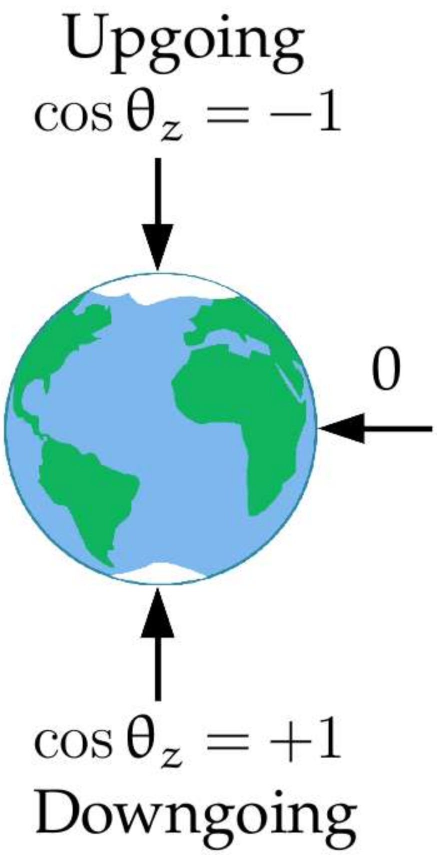
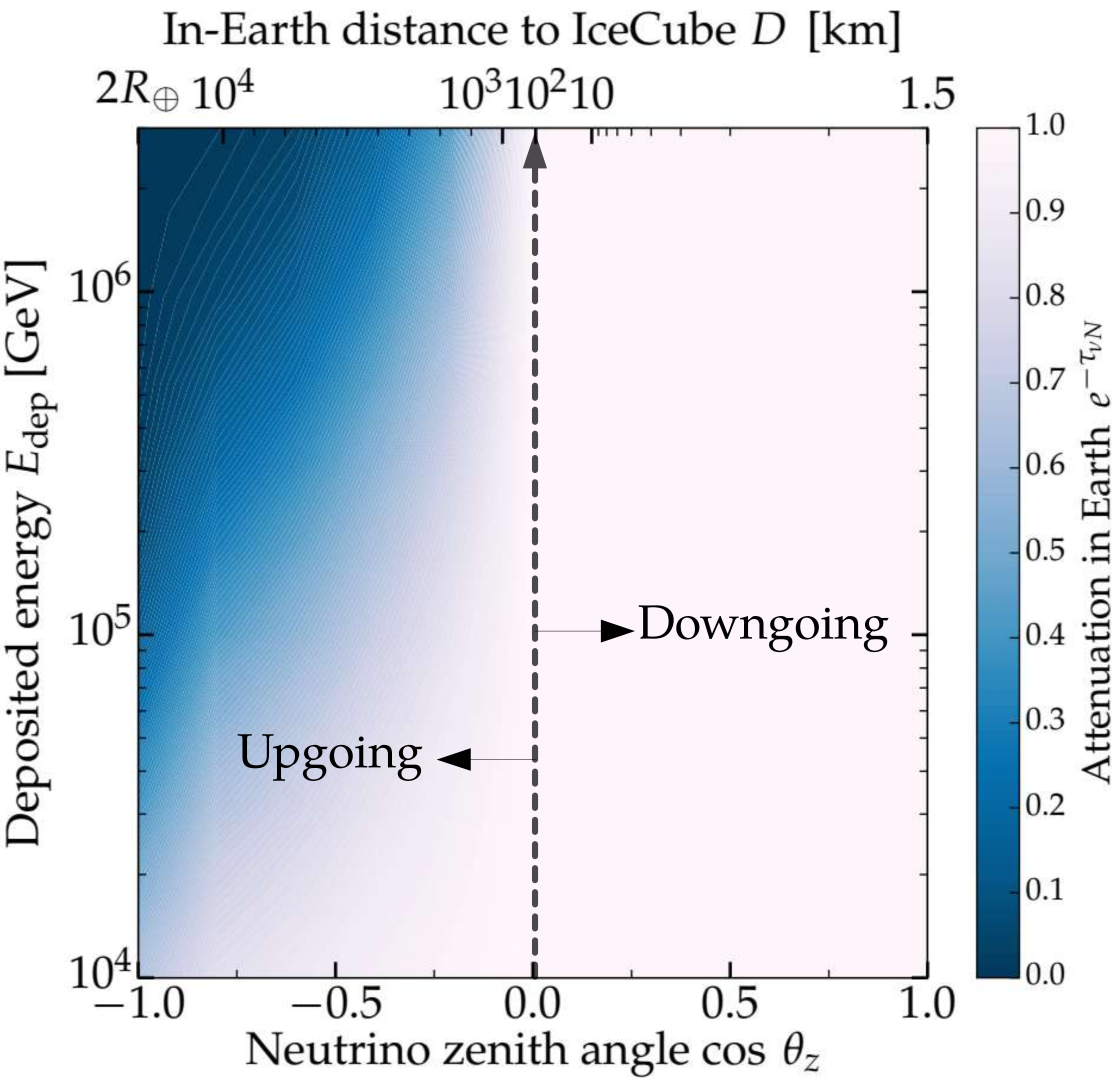
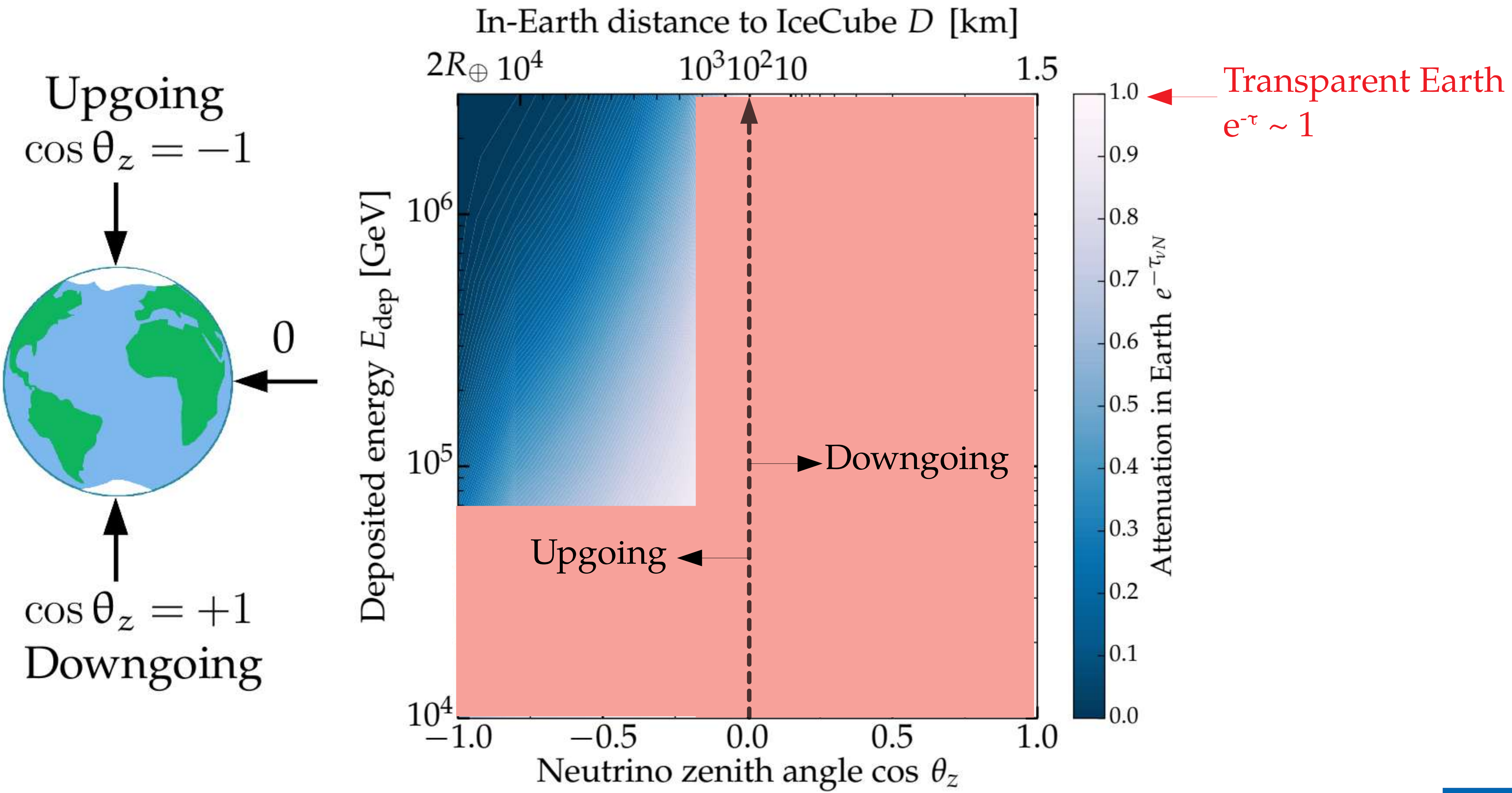




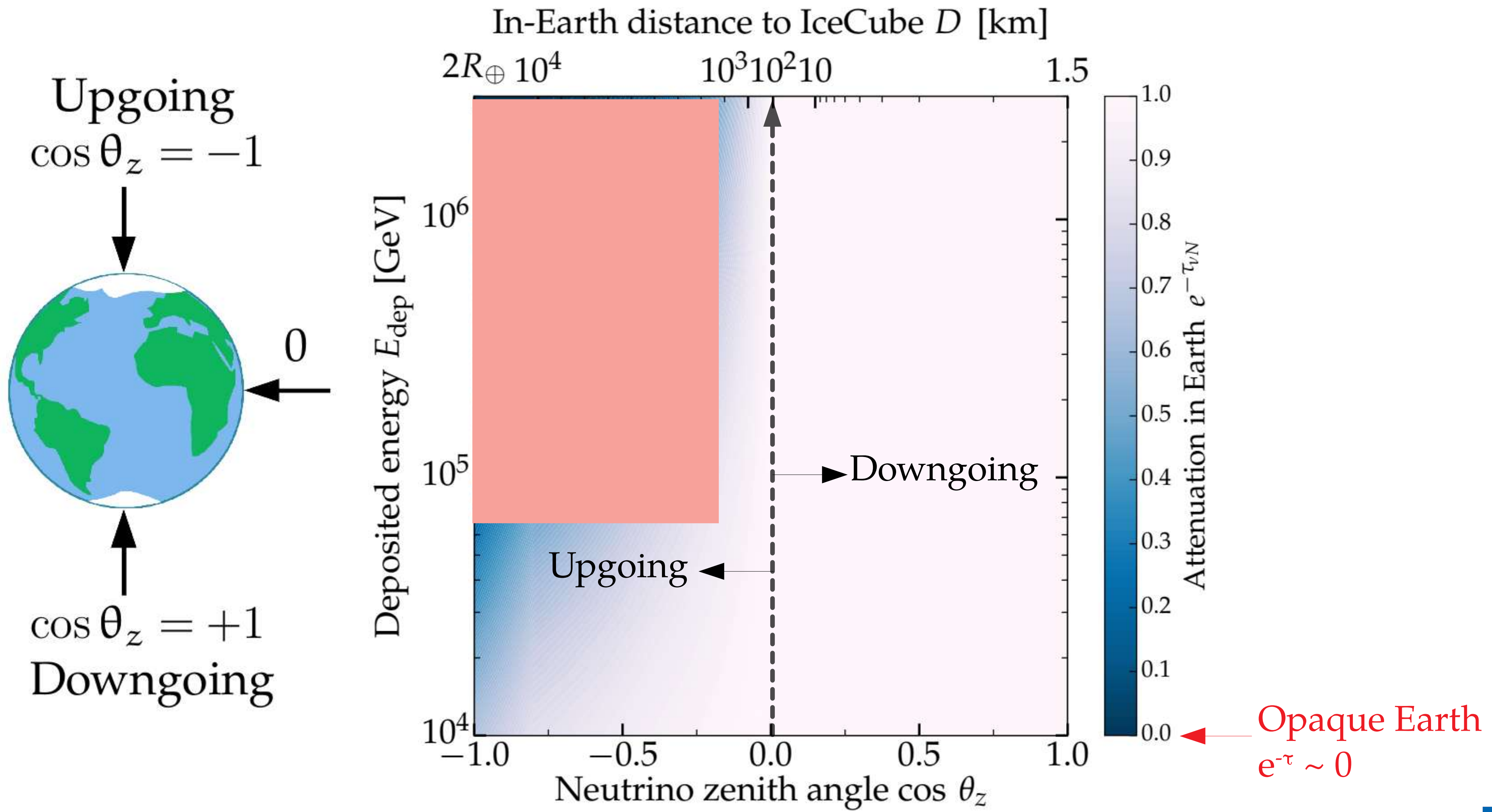
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing

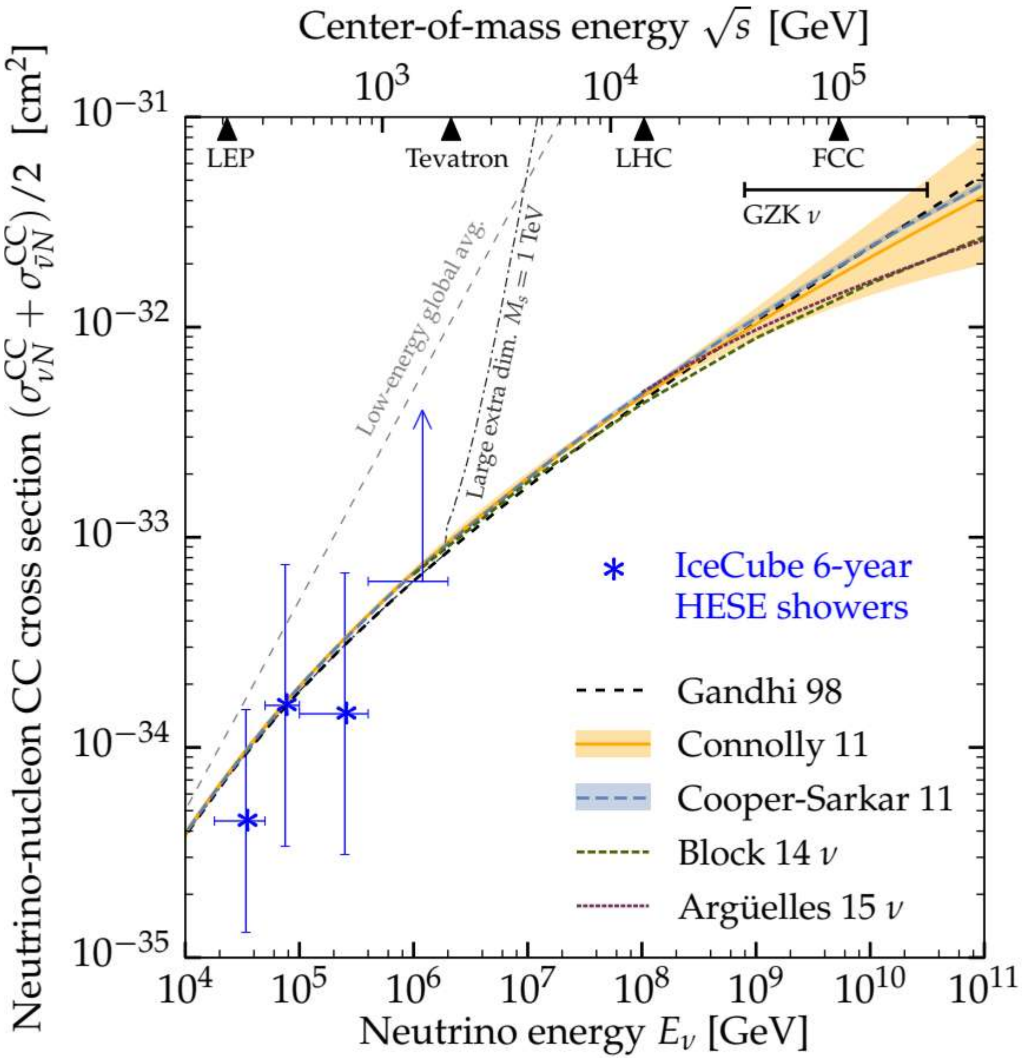

In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



Upgoing
cos θ_z = −1
0
cos θ_z = +1
Downgoing
In-Earth distance to IceCube D [km]
2R⊕ 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
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth e^{−τ_νN}
Transparent Earth
e^{-τ} ~ 1

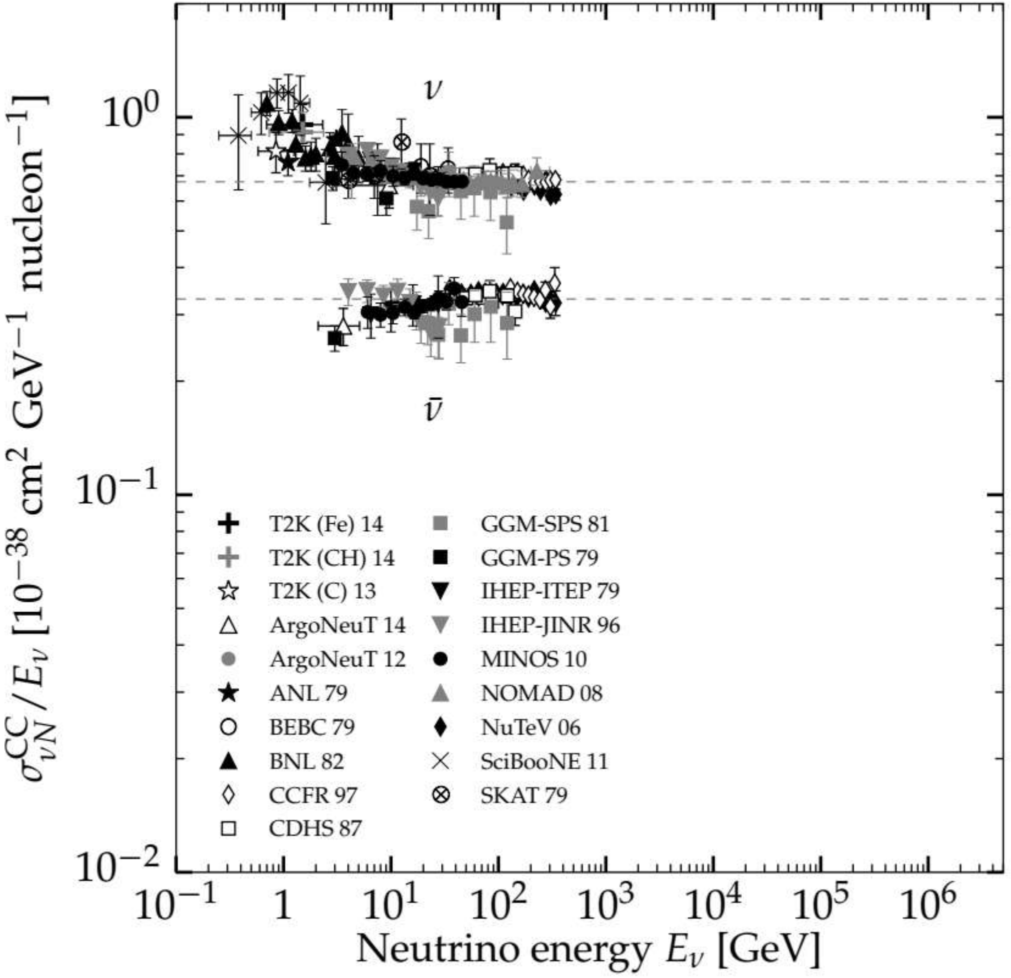

Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Attenuation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

Our result



MB & Connolly, 1711.11043

Extending cross section measurements



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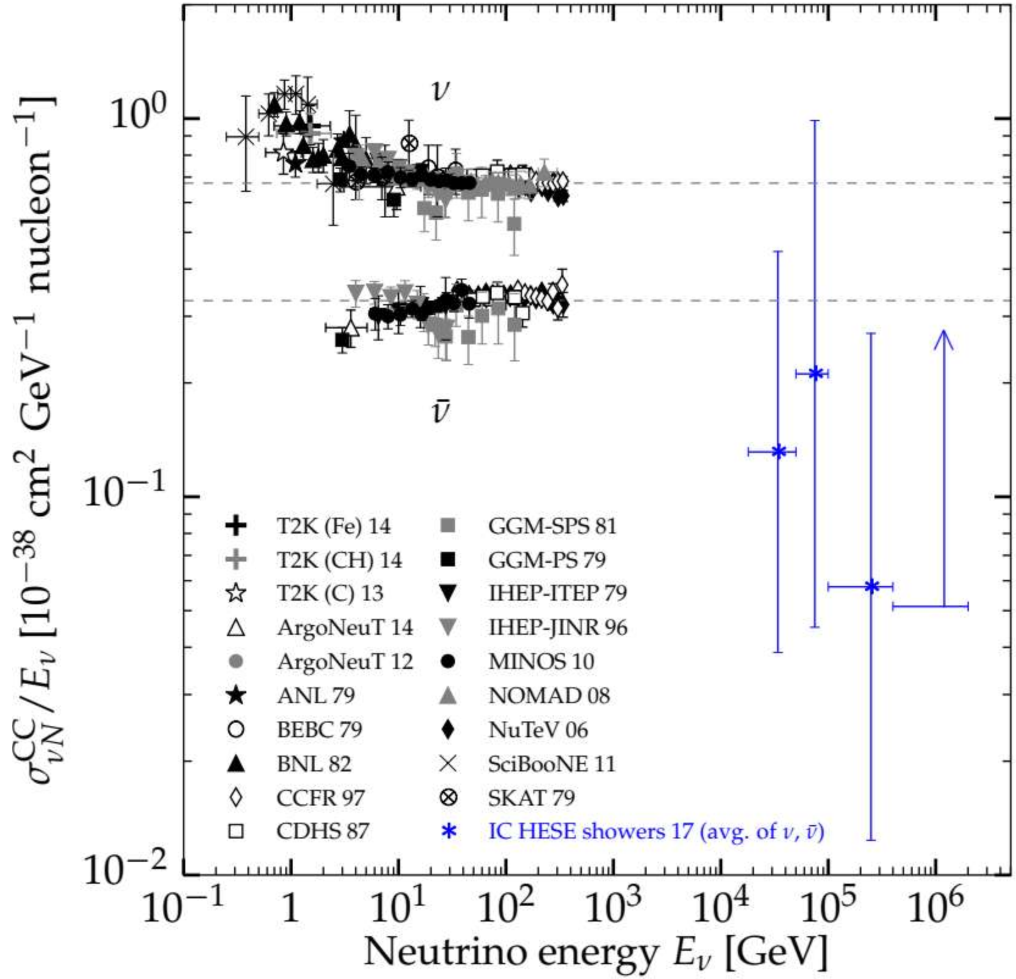
Extending cross section measurements



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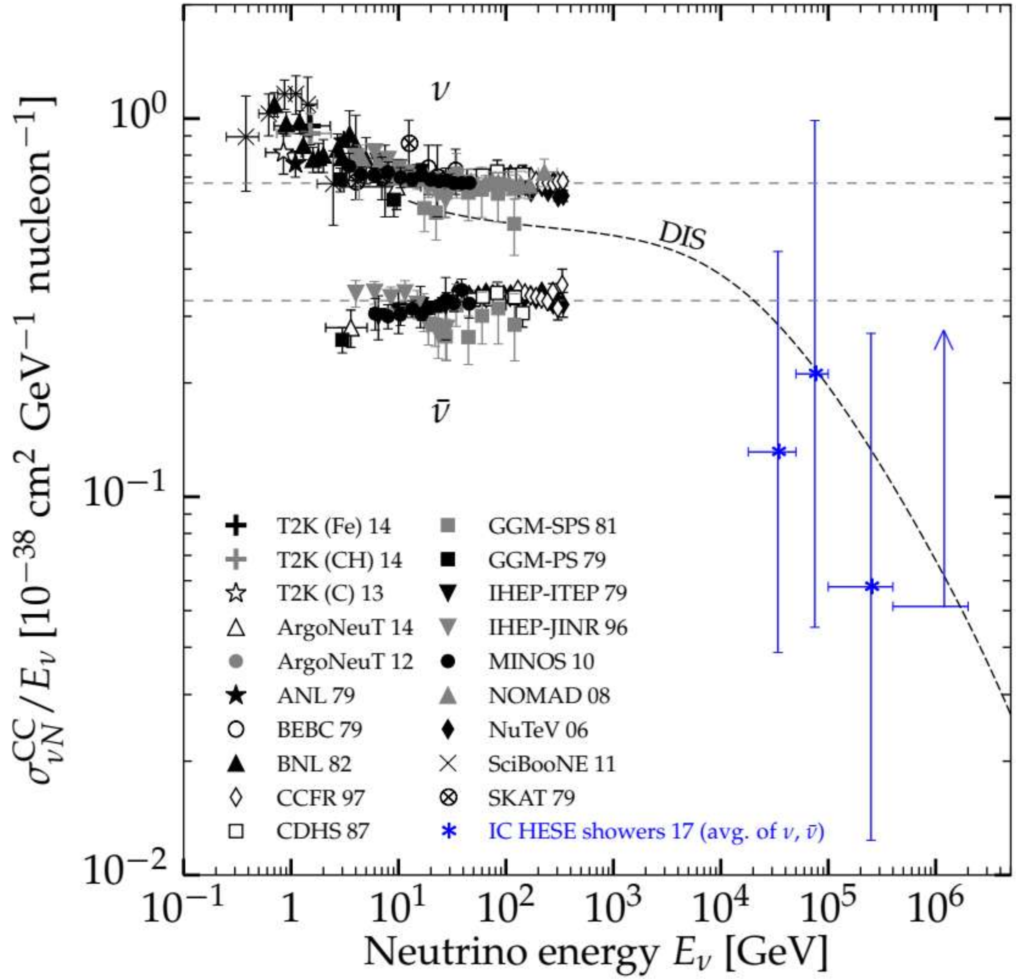
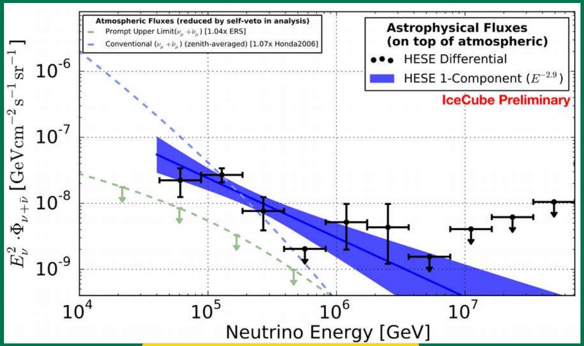
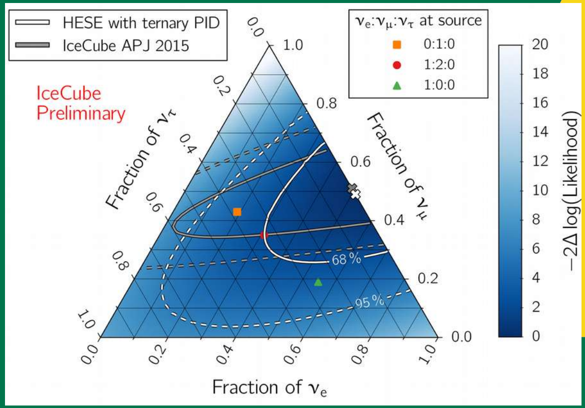
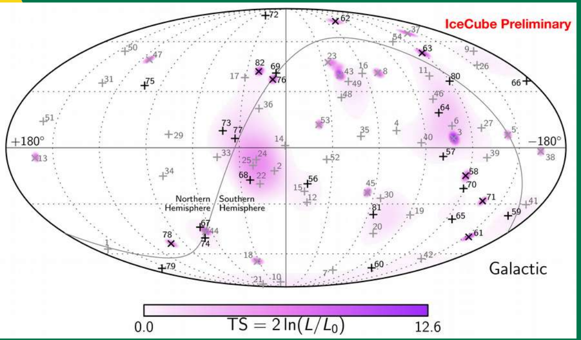
Extending cross section measurements

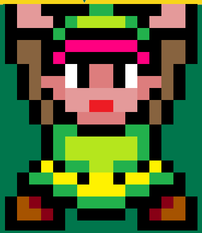


MB & Connolly, 1711.11043


Atmospheric Fluxes (reduced by self-veto in analysis)
Prompt Upper Limit [1.04x ERS]
Conventional (zenith-averaged) [1.07x Honda2006]
Astrophysical Fluxes
(on top of atmospheric)
HESE Differential
HESE 1-Component ($E^{-2.9}$)
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino Energy [GeV]


HESE with ternary PID
IceCube APJ 2015
$\nu_e:\nu_\mu:\nu_\tau$ at source
0:1:0
1:2:0
1:0:0
IceCube
Preliminary
Fraction of ν_τ
Fraction of ν_μ
Fraction of ν_e
68 %
95 %
$-2\Delta\log$(Likelihood)


IceCube Preliminary
+180°
−180°
Northern Hemisphere
Southern Hemisphere
Galactic
TS = $2\ln(L/L_0)$
0.0
12.6



Quo vadis?

Recall the threshold condition for $p\gamma \to \pi$ ($\to \nu$):

$$E_p \cdot E_{\gamma_{\rm target}} = 0.2 \text{ GeV}^2$$

Quo vadis?

$E_\nu = E_p/20$

Recall the threshold condition for $p\gamma \to \pi$ ($\to \nu$):

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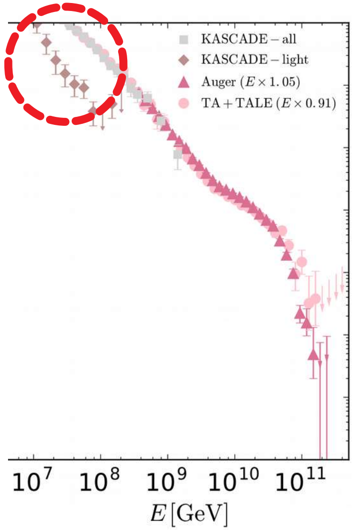
- Inside sources: Protons: $20 \cdot 10^6$ GeV; Photons: 10^{-8} GeV → Neutrinos: 10^6 GeV

Quo vadis?



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Recall the threshold condition for $p\gamma \to \pi$ ($\to \nu$):

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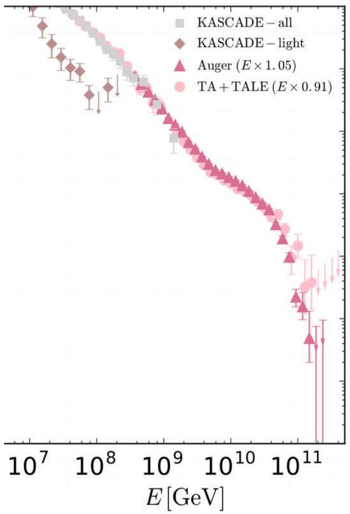

- Inside sources: { Protons: $20 \cdot 10^6$ GeV; Photons: 10^{-8} GeV } → Neutrinos: 10^6 GeV
- CR propagation: { Protons: 10^{11} GeV; Photons: 10^{-12} GeV } → Neutrinos: ~10^{10} GeV

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$E_\nu = E_p/20$

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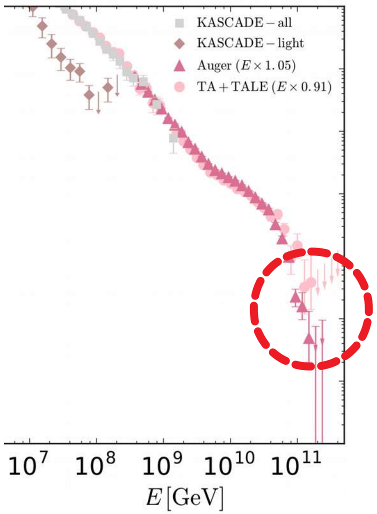
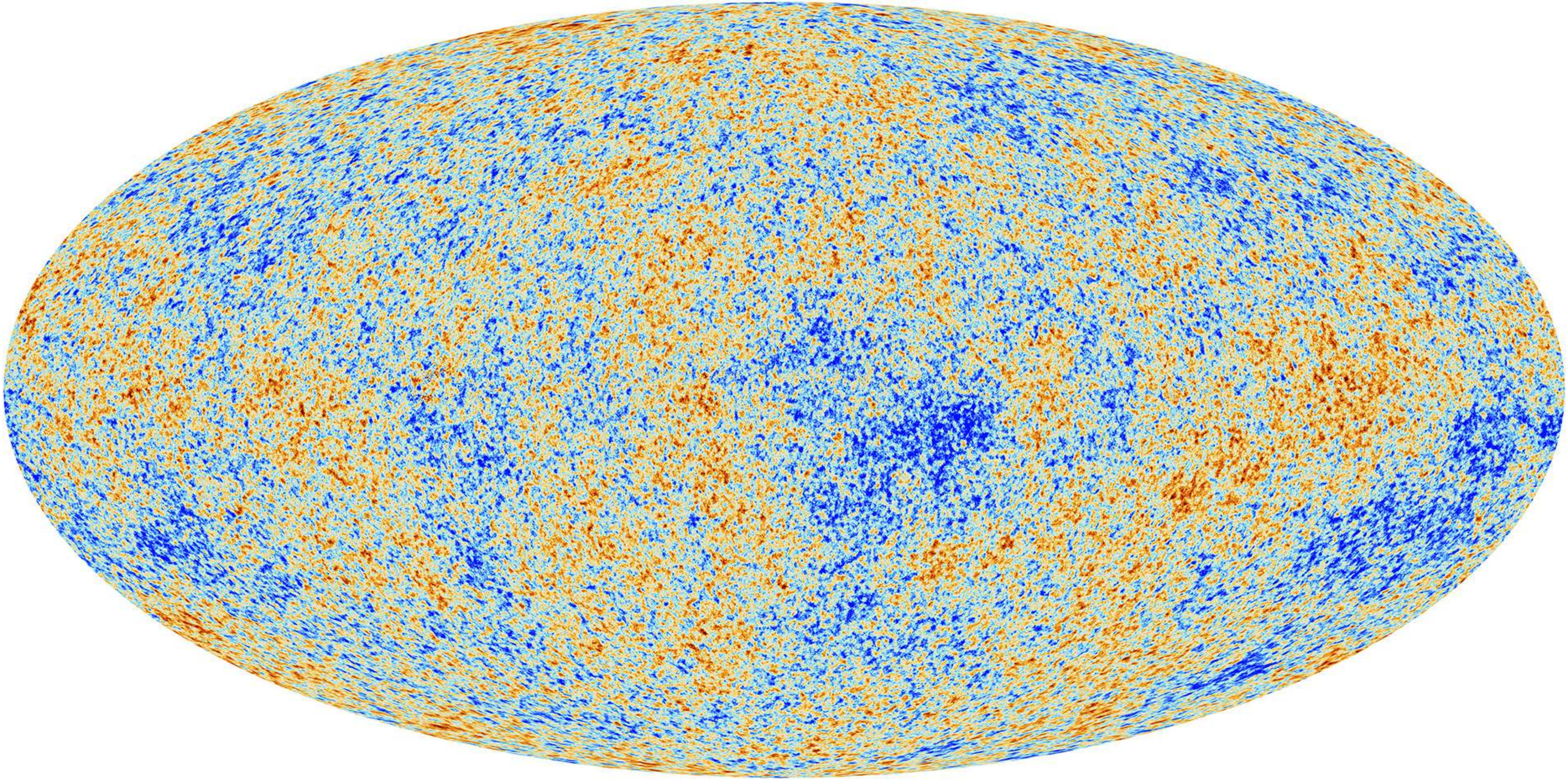


$$E_p \cdot E_{\gamma_{\rm target}} = 0.2\ \mathrm{GeV}^2$$

- Inside sources: Protons: $20 \cdot 10^6$ GeV; Photons: 10^{-8} GeV → Neutrinos: 10^6 GeV
- CR propagation: Protons: 10^{11} GeV; Photons: 10^{-12} GeV → Neutrinos: $\sim 10^{10}$ GeV



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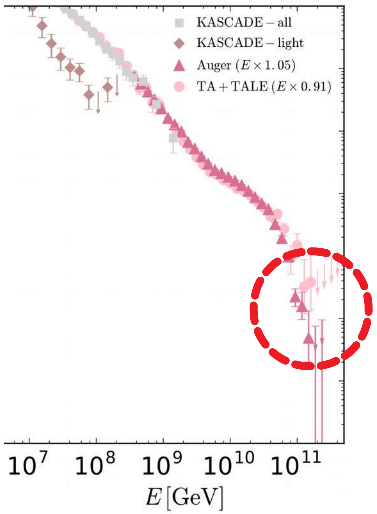

$$E_p \cdot E_{\gamma_{\text{target}}} = 0.2\ \text{GeV}^2$$

- Inside sources: Protons: $20 \cdot 10^6$ GeV; Photons: 10^{-8} GeV → Neutrinos: 10^6 GeV
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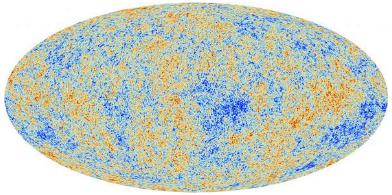
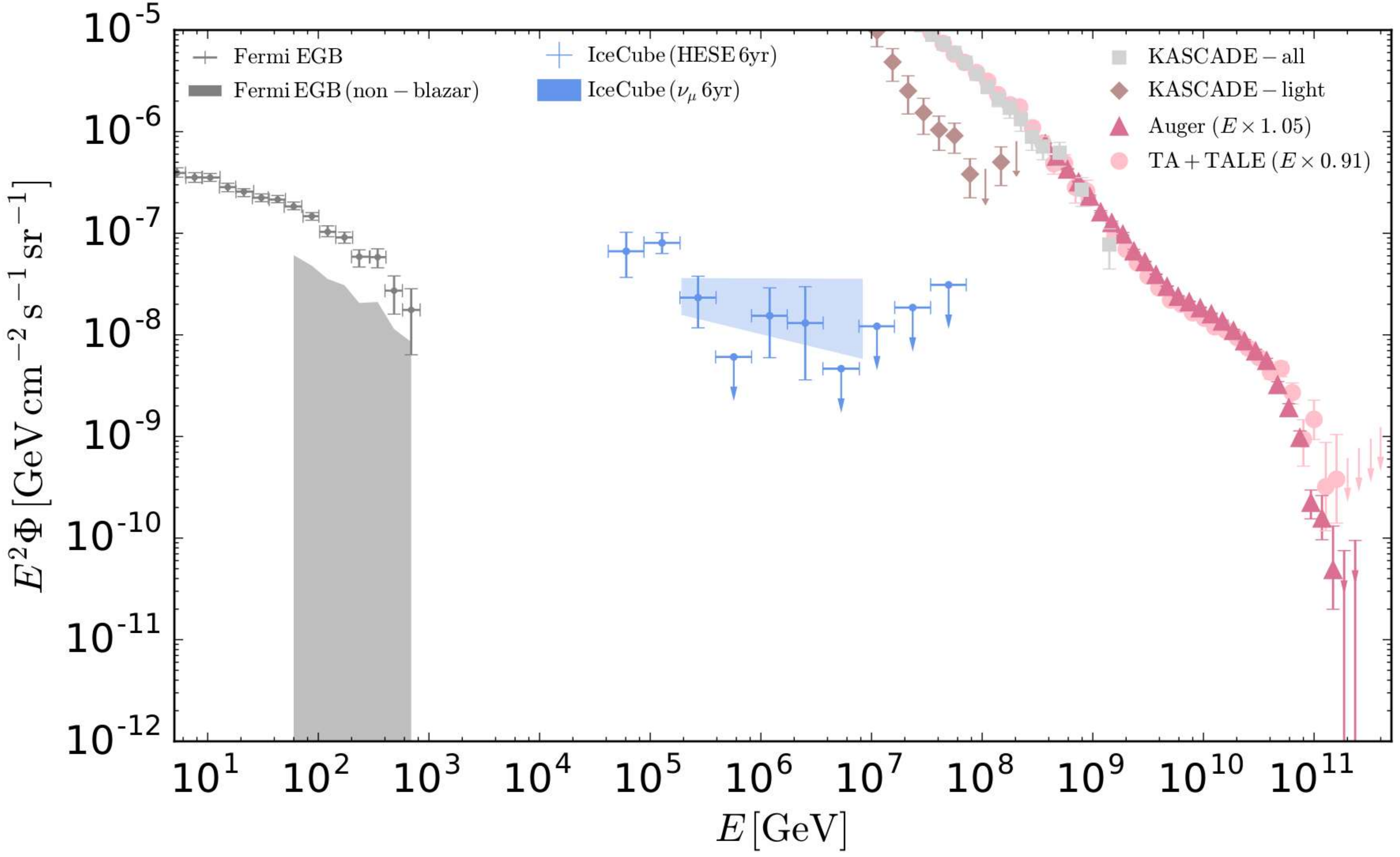
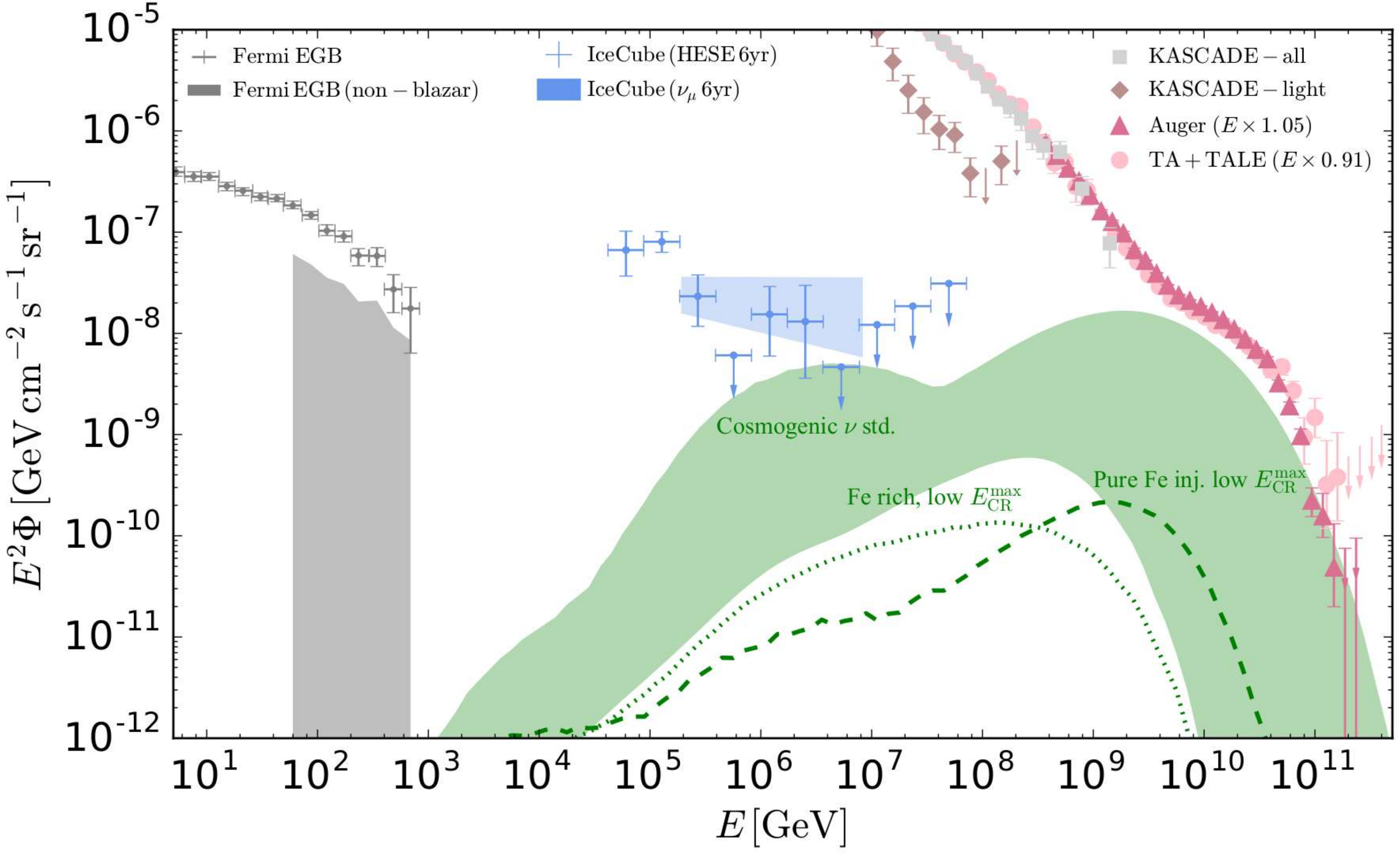
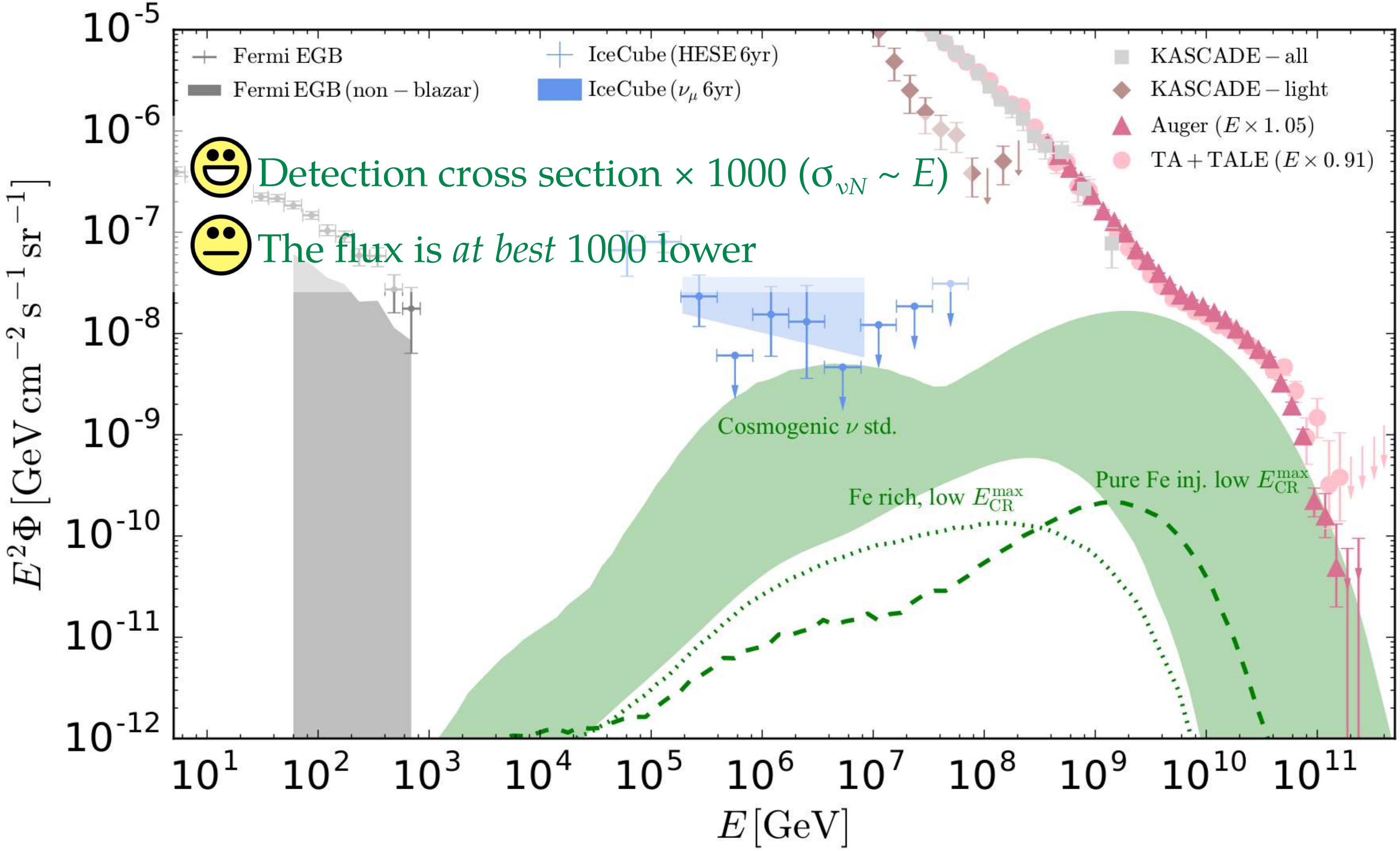


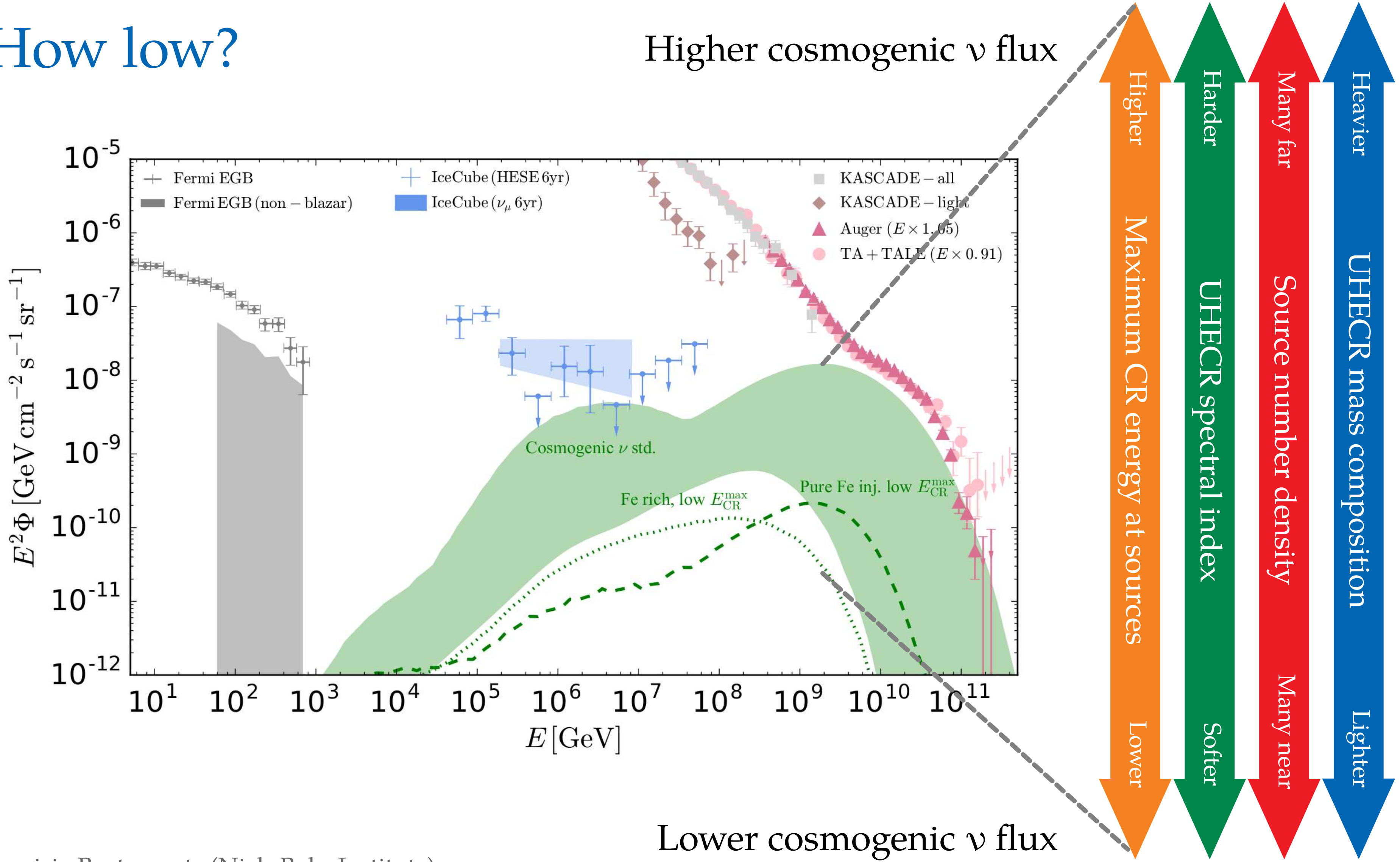

Fermi EGB
Fermi EGB (non − blazar)
IceCube (HESE 6yr)
IceCube (ν_μ 6yr)
KASCADE − all
KASCADE − light
Auger ($E \times 1.05$)
TA + TALE ($E \times 0.91$)
$E^2\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}



Fermi EGB
Fermi EGB (non − blazar)
IceCube (HESE 6yr)
IceCube (ν_μ 6yr)
KASCADE − all
KASCADE − light
Auger ($E \times 1.05$)
TA + TALE ($E \times 0.91$)
Cosmogenic ν std.
Fe rich, low $E_{\rm CR}^{\rm max}$
Pure Fe inj. low $E_{\rm CR}^{\rm max}$
$E^2\Phi\,[\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}]$
$E\,[\rm GeV]$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}


Fermi EGB
Fermi EGB (non – blazar)
IceCube (HESE 6yr)
IceCube (ν_μ 6yr)
KASCADE – all
KASCADE – light
Auger ($E \times 1.05$)
TA + TALE ($E \times 0.91$)
Detection cross section × 1000 ($\sigma_{\nu N} \sim E$)
The flux is *at best* 1000 lower
Cosmogenic ν std.
Fe rich, low E_{CR}^{max}
Pure Fe inj. low E_{CR}^{max}
$E^2\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]

How low?

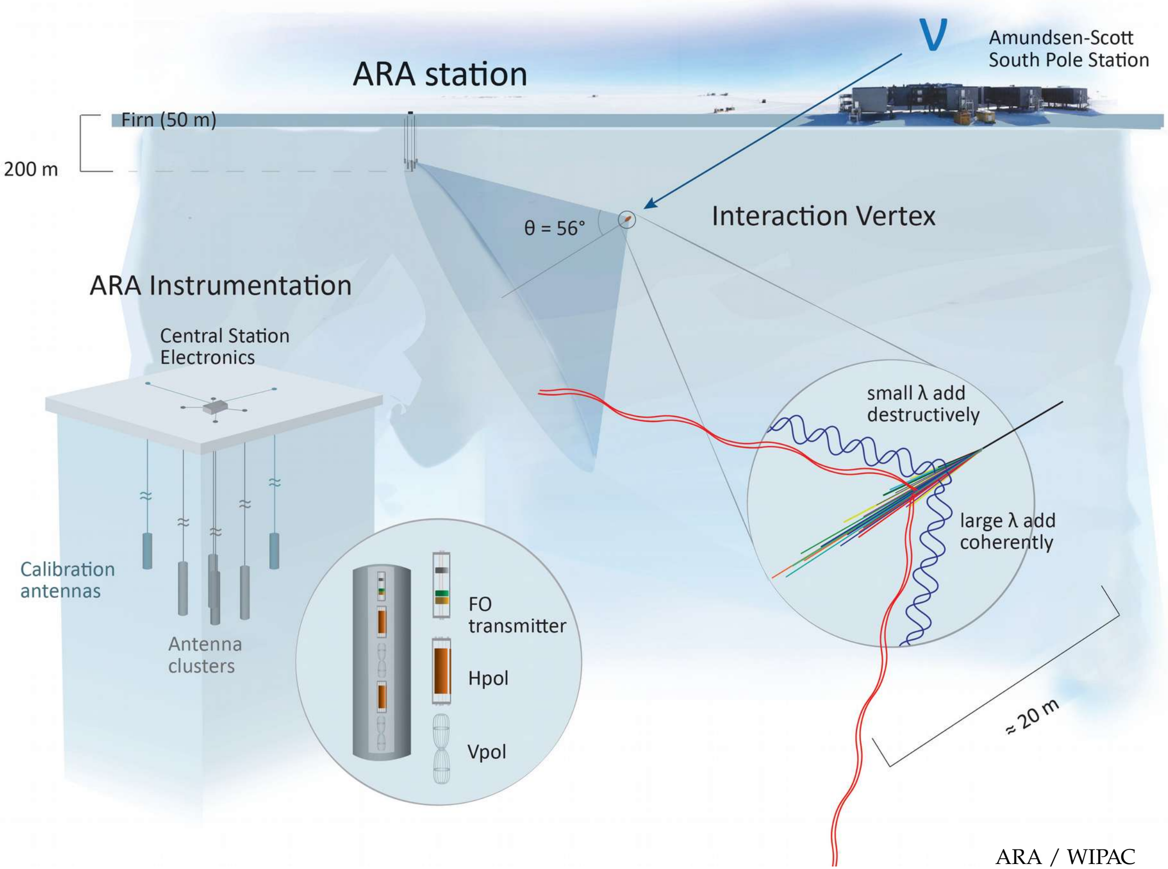

Higher cosmogenic ν flux
Lower cosmogenic ν flux
Fermi EGB
Fermi EGB (non – blazar)
IceCube (HESE 6yr)
IceCube (ν_μ 6yr)
KASCADE – all
KASCADE – light
Auger ($E \times 1.05$)
TA + TALE ($E \times 0.91$)
Cosmogenic ν std.
Fe rich, low E_{CR}^{max}
Pure Fe inj. low E_{CR}^{max}
$E^2\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Heavier
UHECR mass composition
Lighter

Radio detection of UHE neutrinos

- ▸ Radio attenuation length in ice: few km (*vs.* 100 m for light)
- ▸ Larger monitored volume than IceCube
- ▸ ARA, ARIANNA: antennas buried in ice
- ▸ ANITA: antennas mounted on a balloon

No ν detected yet

(But UHECRs detected regularly!)



ARA / WIPAC

Radio detection of UHE neutrinos

- Radio attenuation length in ice: few km (*vs.* 100 m for light)
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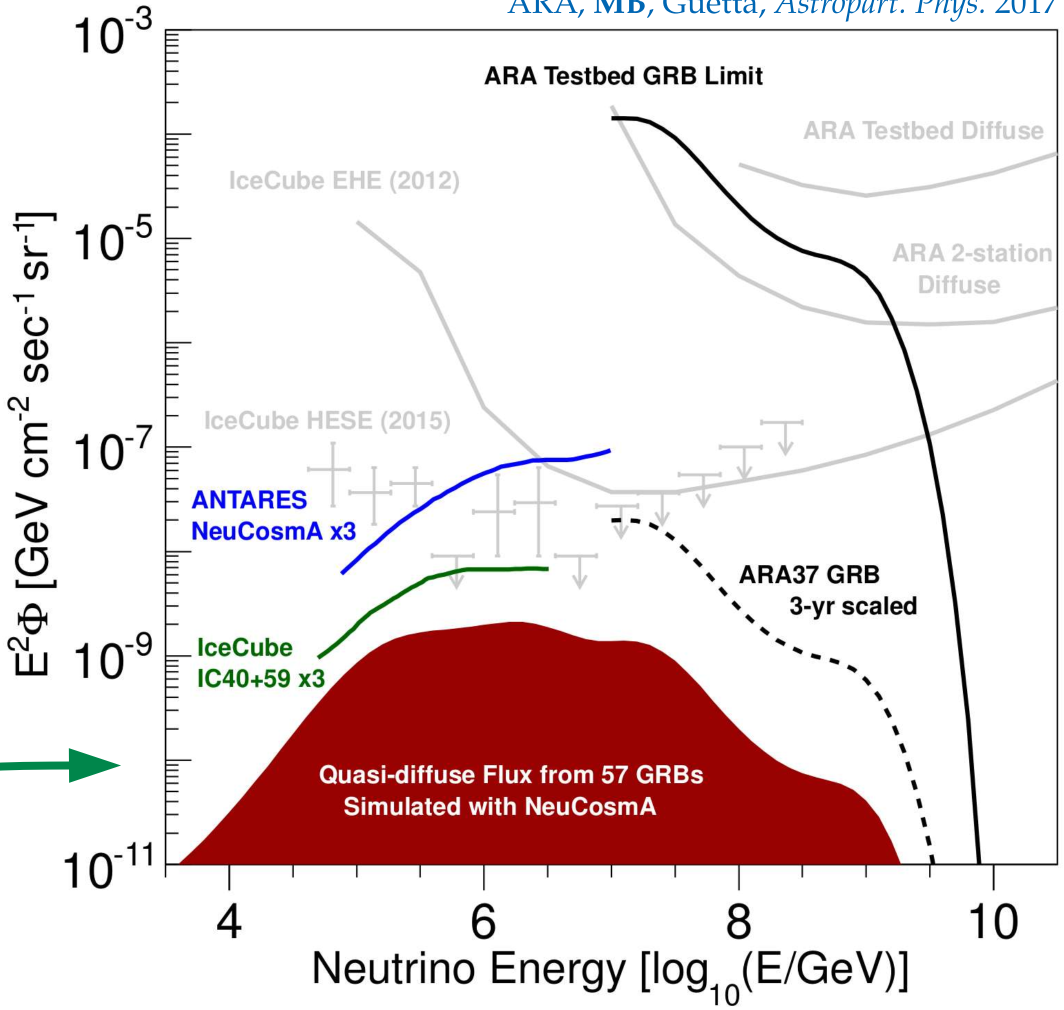
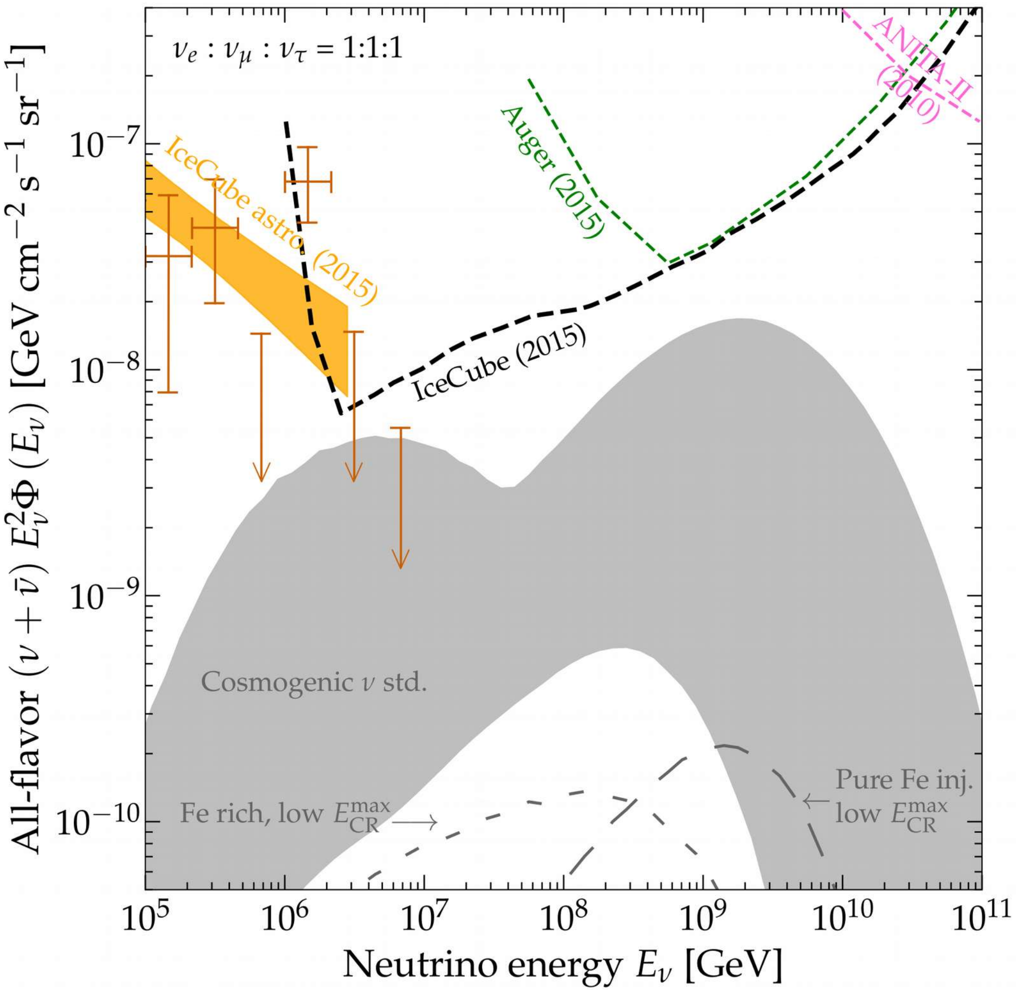
First search for prompt GRB neutrinos with ARA

ARA, **MB**, Guetta, *Astropart. Phys.* 2017



The way forward – think *big*



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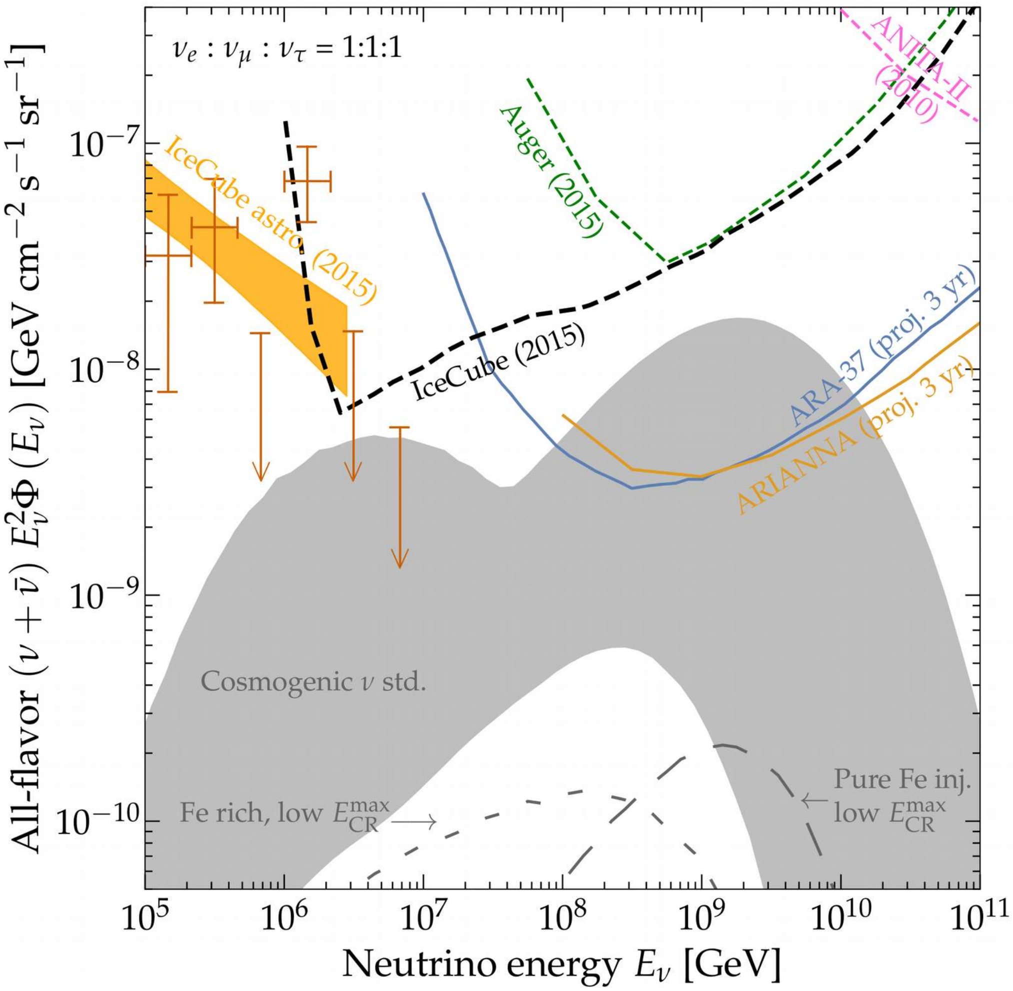
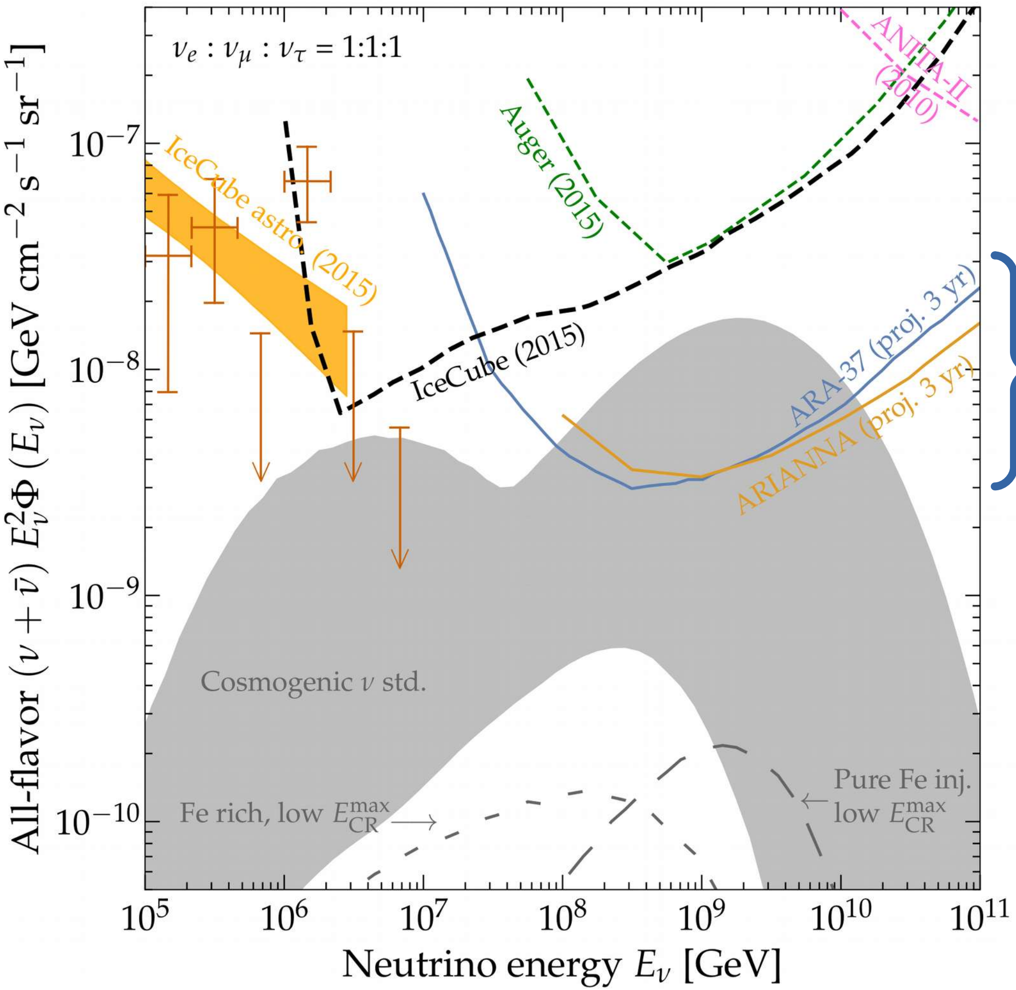
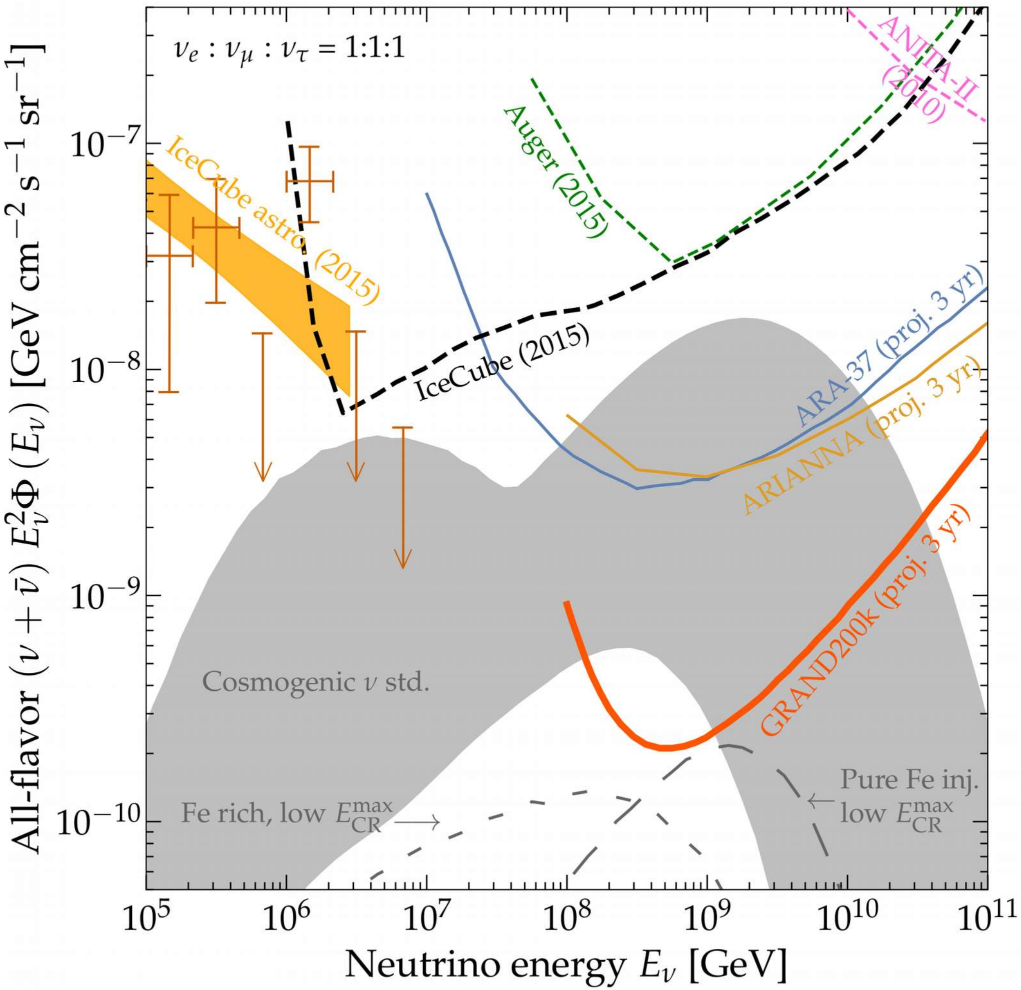


The way forward – think *big*



Possible future upgrades of ARA, ARIANNA

The way forward – think *big*



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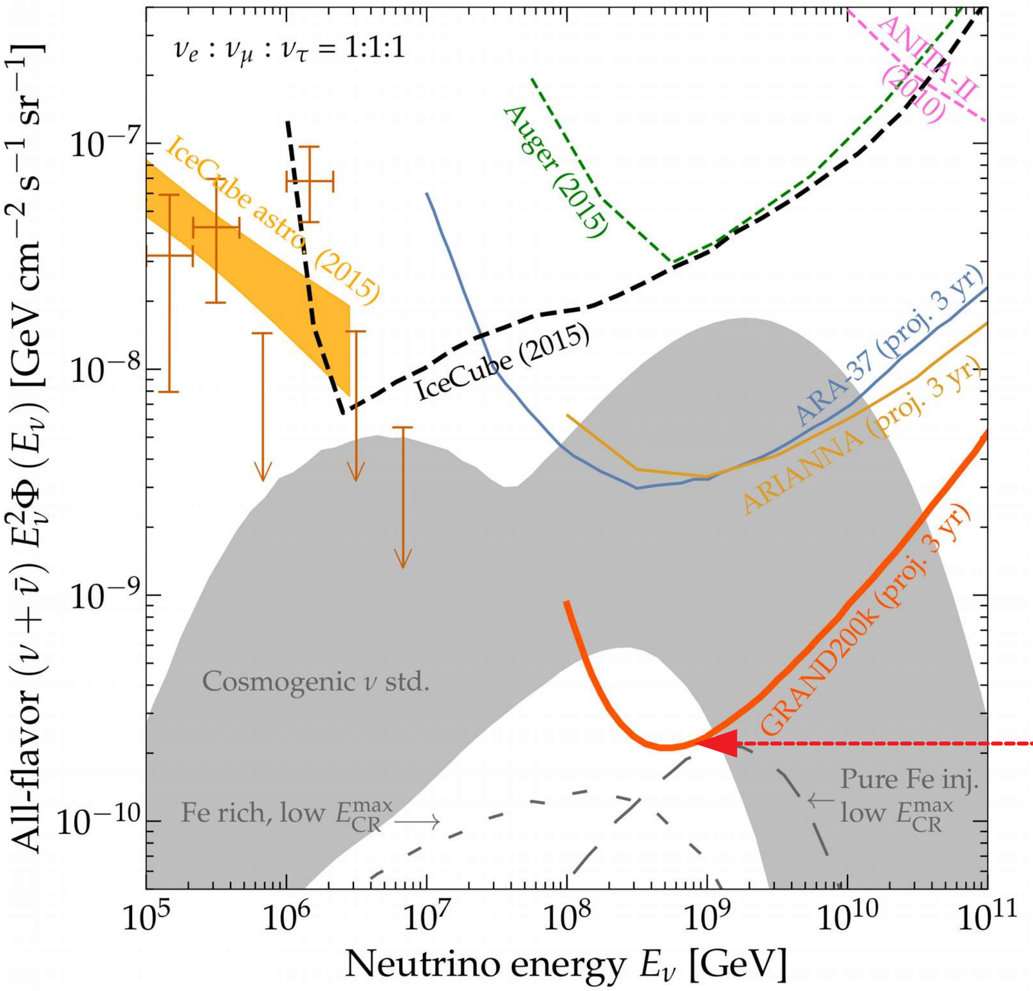
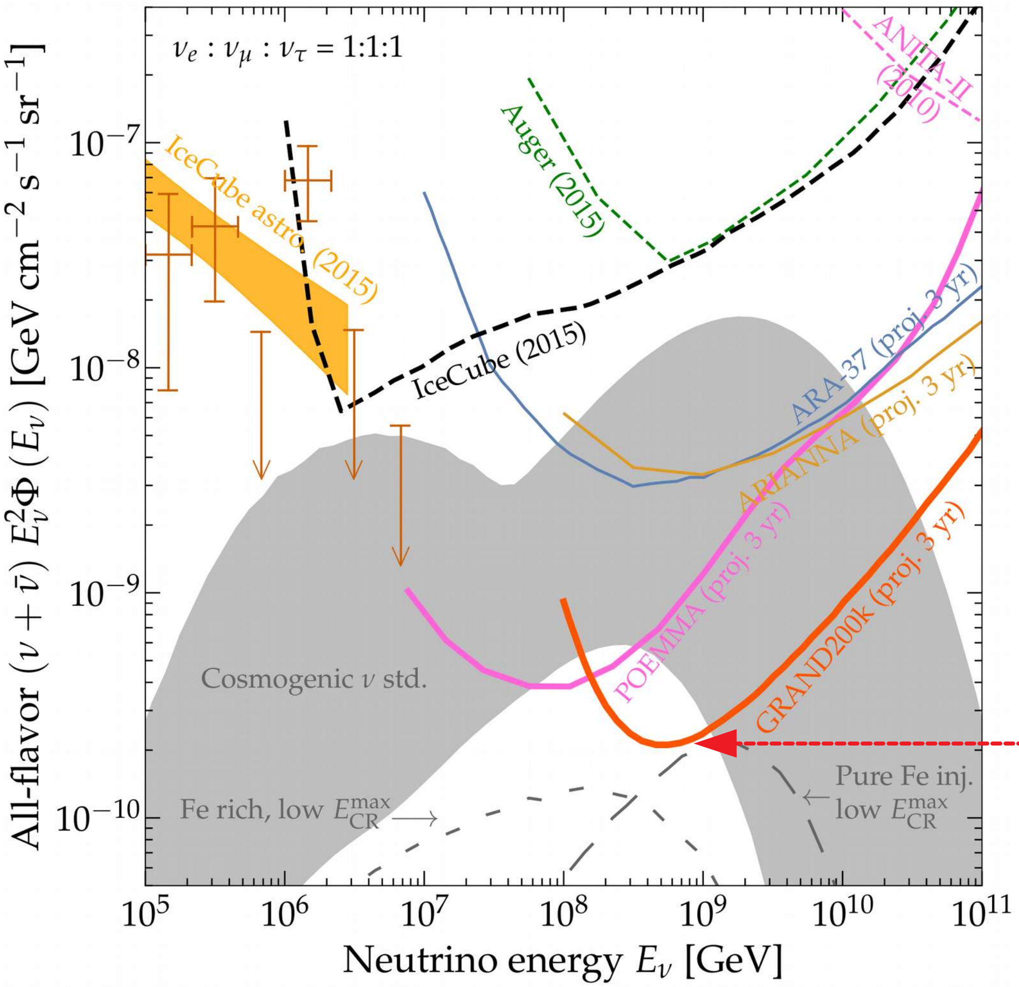


Only GRAND will probe *very* low fluxes at ~10^9 GeV

The way forward – think *big*



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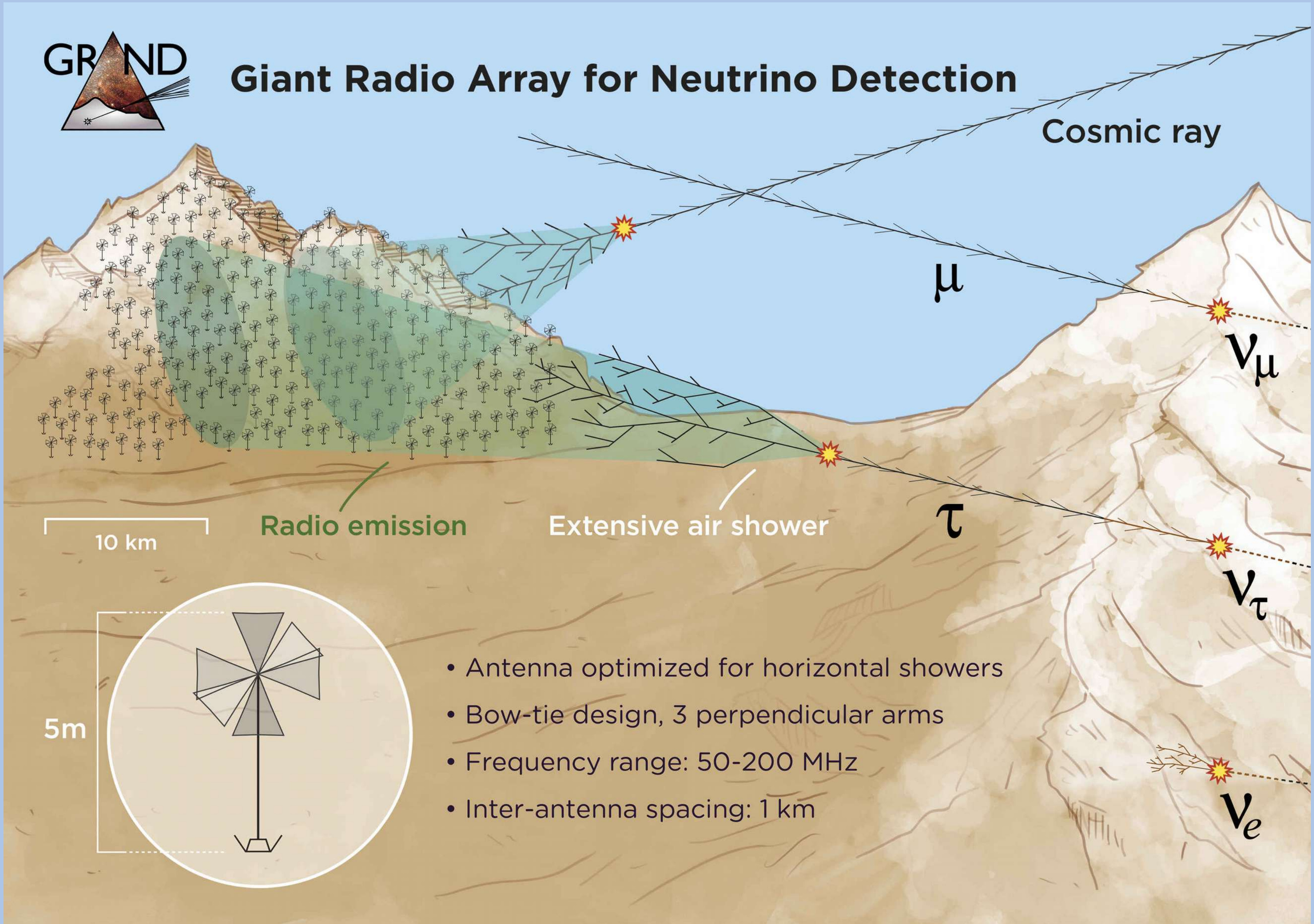

GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
ν_μ
τ
ν_τ
ν_e
Radio emission
Extensive air shower
10 km
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km

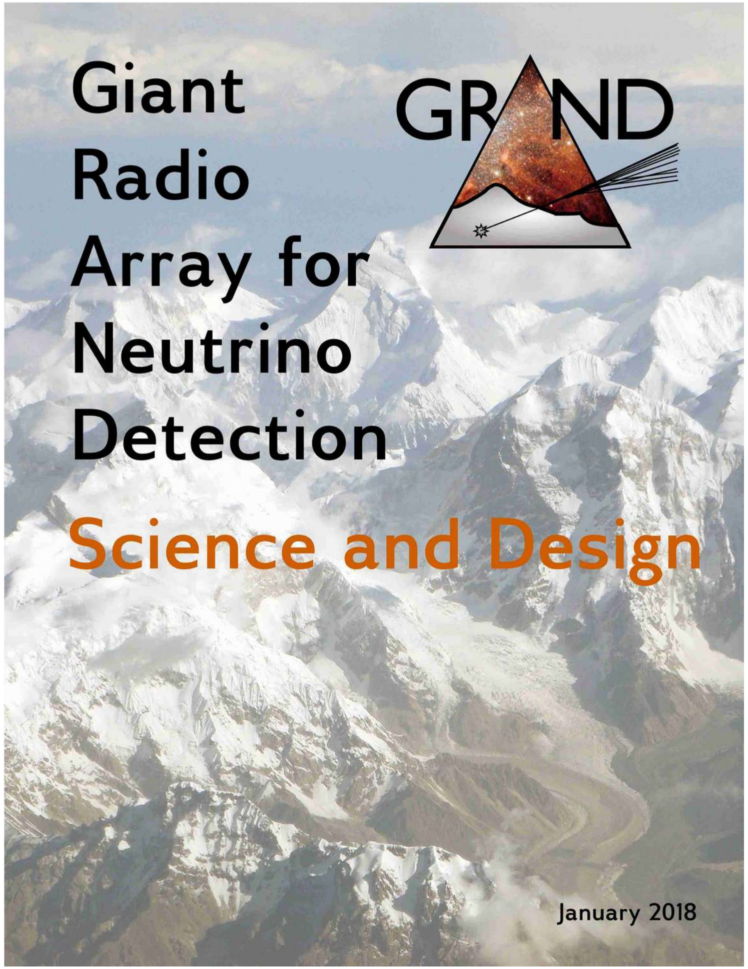
Status of GRAND

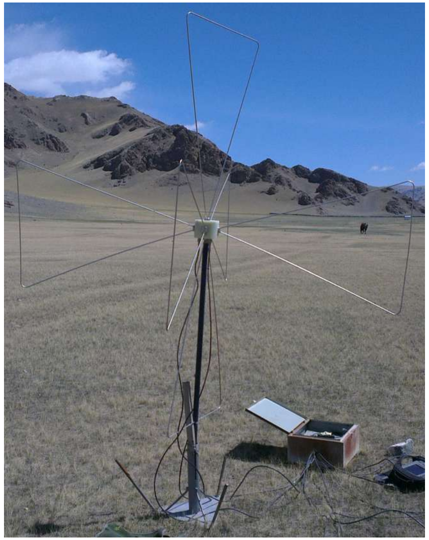
Science runs

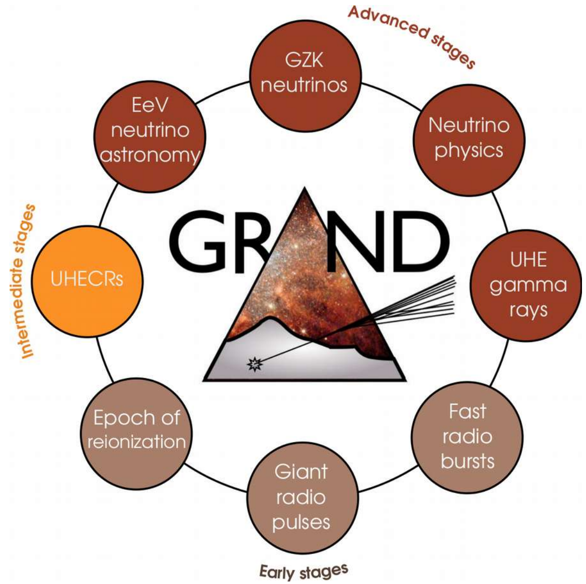
2018 2019 2025 203X

Number of antennas deployed

35	300	10k	20 × 10k
GRANDProto35	GRANDProto300	GRANDProto10k	GRANDProto200k







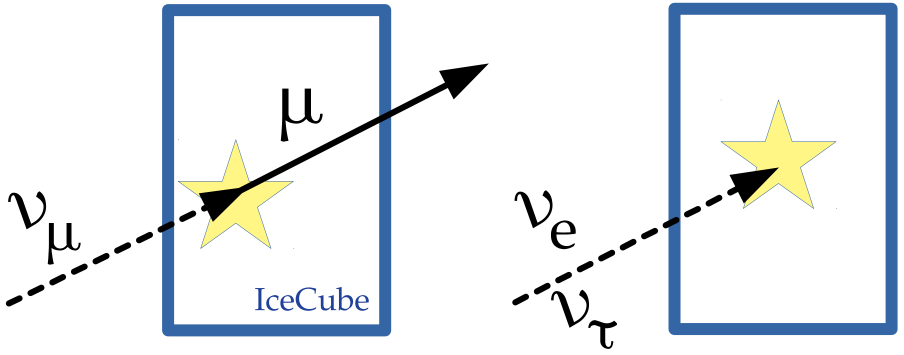
What are you taking home?

- We are finally edging closer to find the sources of UHECRs with > 10 PeV
- But the solution will need ingenuity… and multiple messengers
- Fundamental TeV–PeV neutrino physics? Yes! *Already today*
- The future is GRAND (pun intended) – UHE neutrinos are the next frontier

Contained vs. uncontained νN interactions

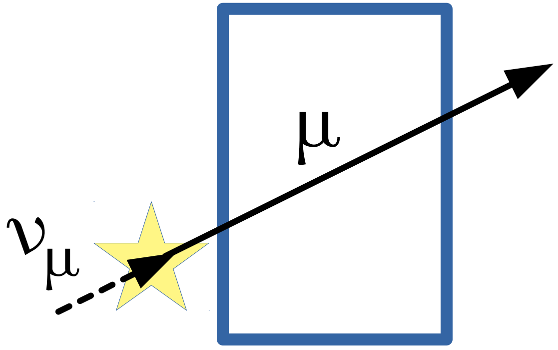
Contained events

Uncontained events



Starting track

Shower



Through-going muon

Pro: Clean determination of E_ν

Con: Few events (<100)

Ref.: MB & A. Connolly, 1711.11043

Pro: Lots of events (~10k used)

Con: Uncertain estimates of E_ν

Ref.: IceCube, Nature 2017, 1711.08119

Backup slides

Fundamental Physics with HE Astrophysical Neutrinos

What:

Extract fundamental TeV–EeV physics from astrophysical ν

Why:

Man-made neutrinos are limited to GeV and ~1000 km

How:

Look for changes to all relevant observables, use data when available

- 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 current limits: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$
- Fundamental physics can be extracted from:
  - Spectral shape
  - Angular distribution
  - Flavor information

Fundamental Physics with HE Astrophysical Neutrinos

↦ Background

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

  - n = -1: neutrino decay
  - n = 0: CPT-odd Lorentz violation
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In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns

Fundamental Physics with HE Astrophysical Neutrinos

↦ Research experience

Fundamental Physics with HE Astrophysical Neutrinos

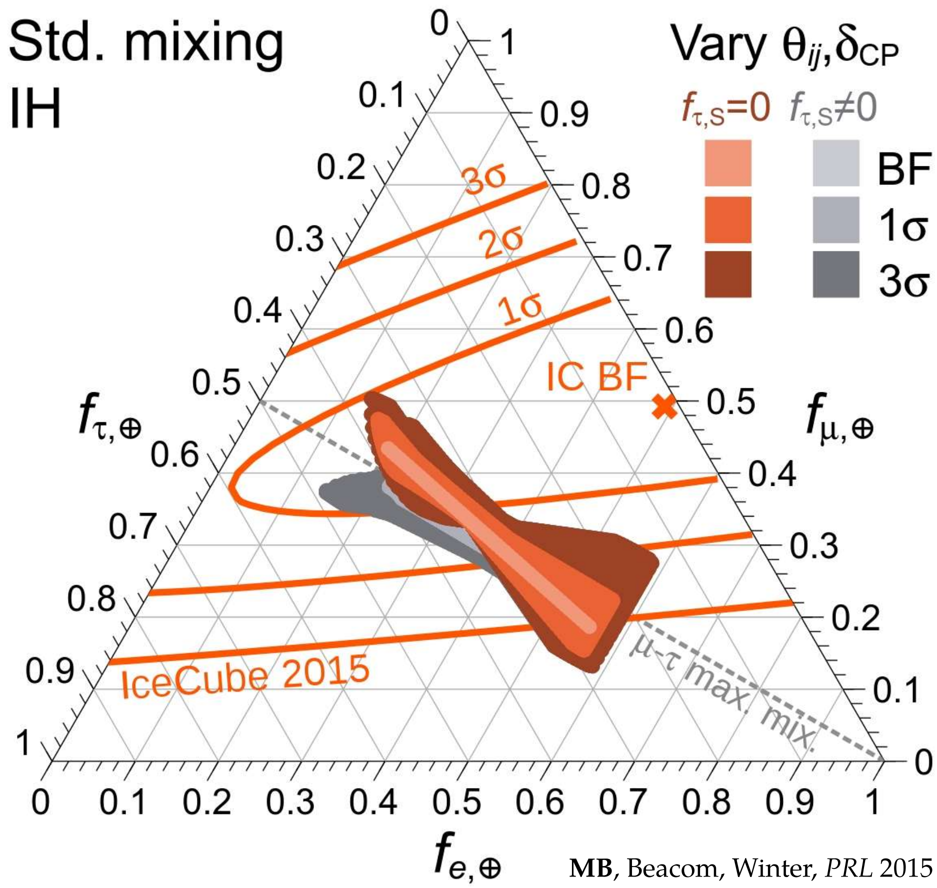
↦ Research experience

- New physics from flavor ratios

Fundamental Physics with HE Astrophysical Neutrinos

↦ Research experience

- New physics from flavor ratios



MB, Beacom, Winter, *PRL* 2015

Fundamental Physics with HE Astrophysical Neutrinos

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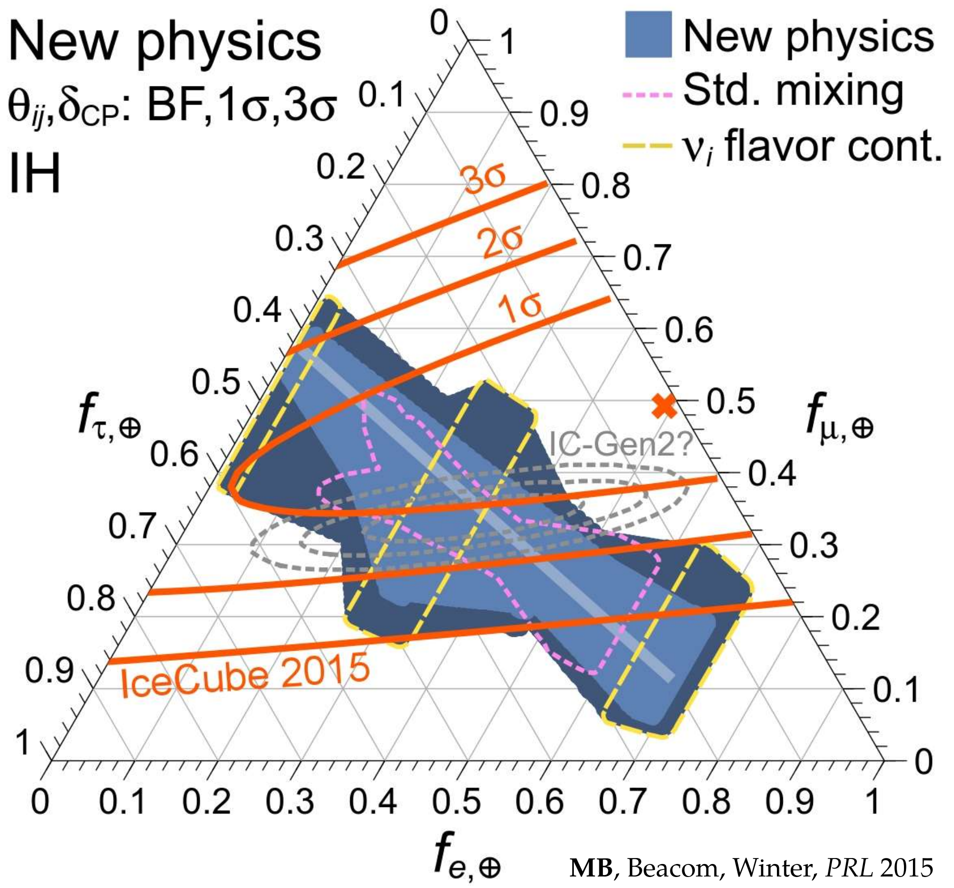
- ▸ New physics from flavor ratios



MB, Beacom, Winter, *PRL* 2015

Fundamental Physics with HE Astrophysical Neutrinos

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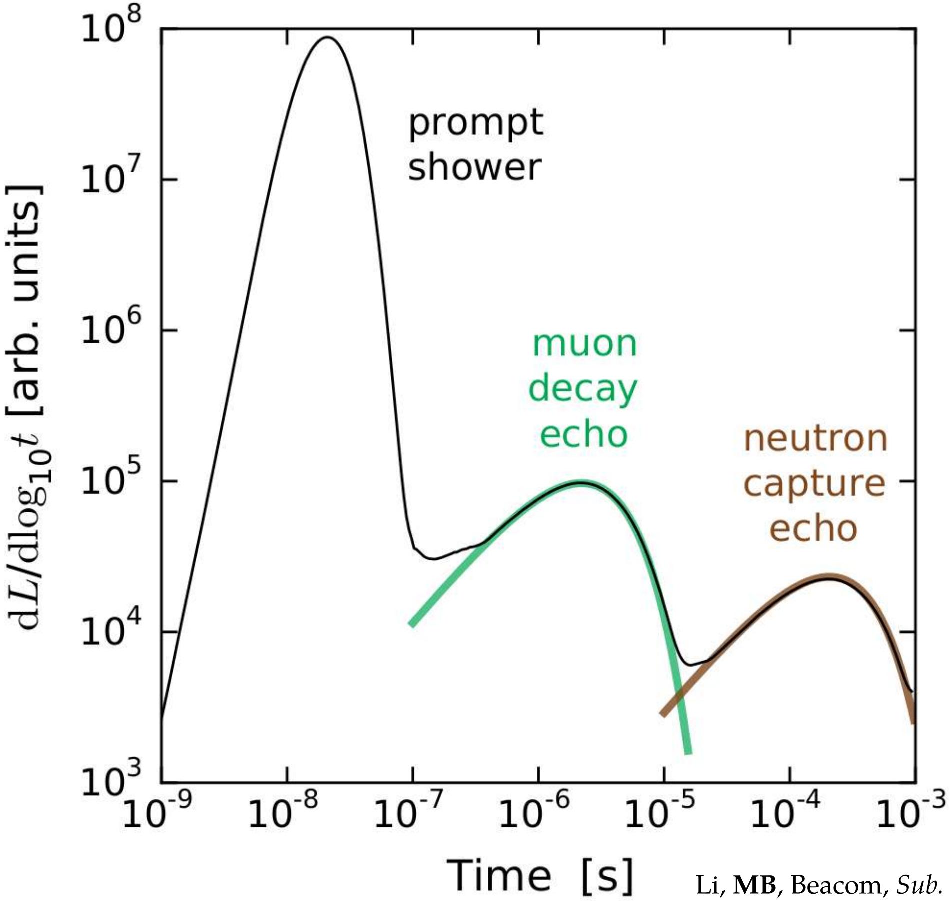
- New physics from flavor ratios
- Improved flavor tagging: echoes



Li, **MB**, Beacom, *Sub. to PRL*

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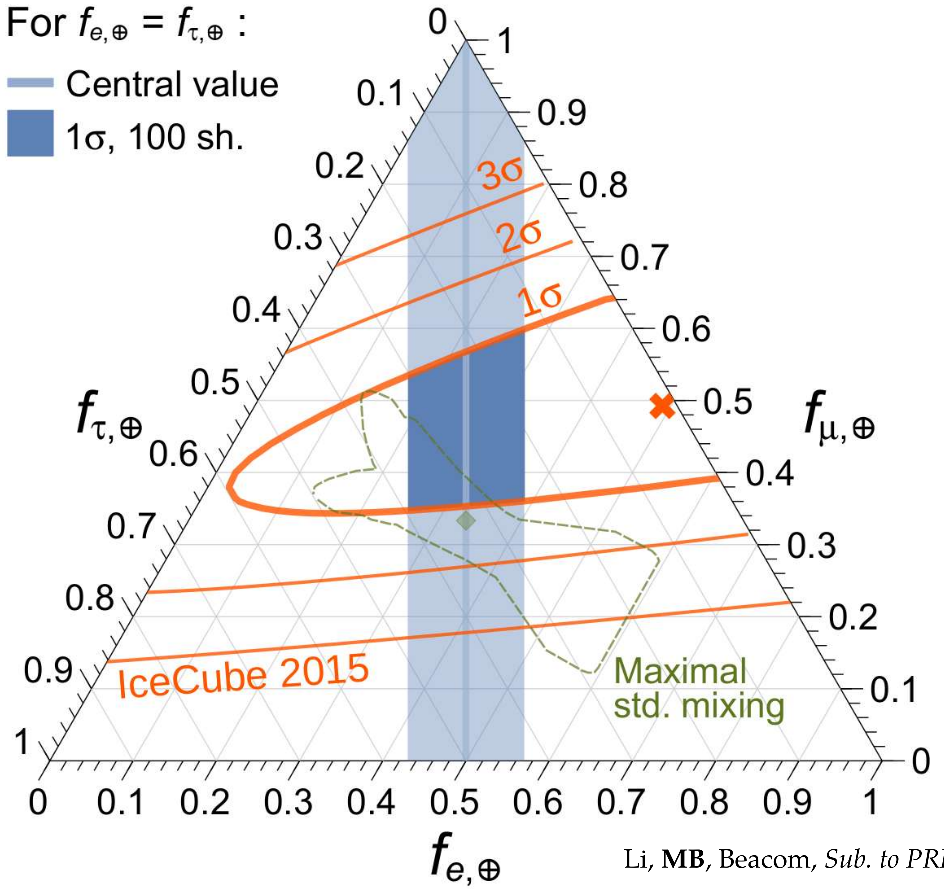
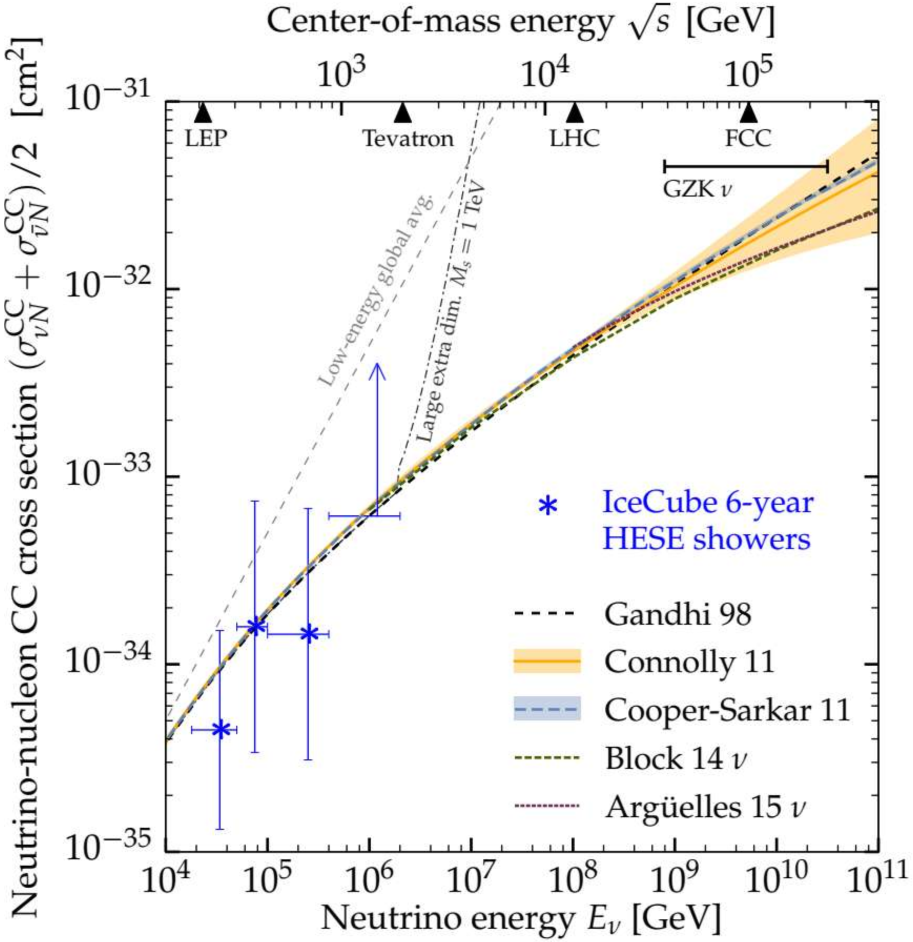


Li, **MB**, Beacom, *Sub. to PRL*

Fundamental Physics with HE Astrophysical Neutrinos

↦ Research experience

- ▸ New physics from flavor ratios
- ▸ Improved flavor tagging: echoes
- ▸ TeV–PeV ν cross section



MB, Connolly, 1711.11043, *Sub. to PRL*

Fundamental Physics with HE Astrophysical Neutrinos

↦ Research experience

- New physics from flavor ratios

- Improved flavor tagging: echoes

- TeV–PeV ν cross section

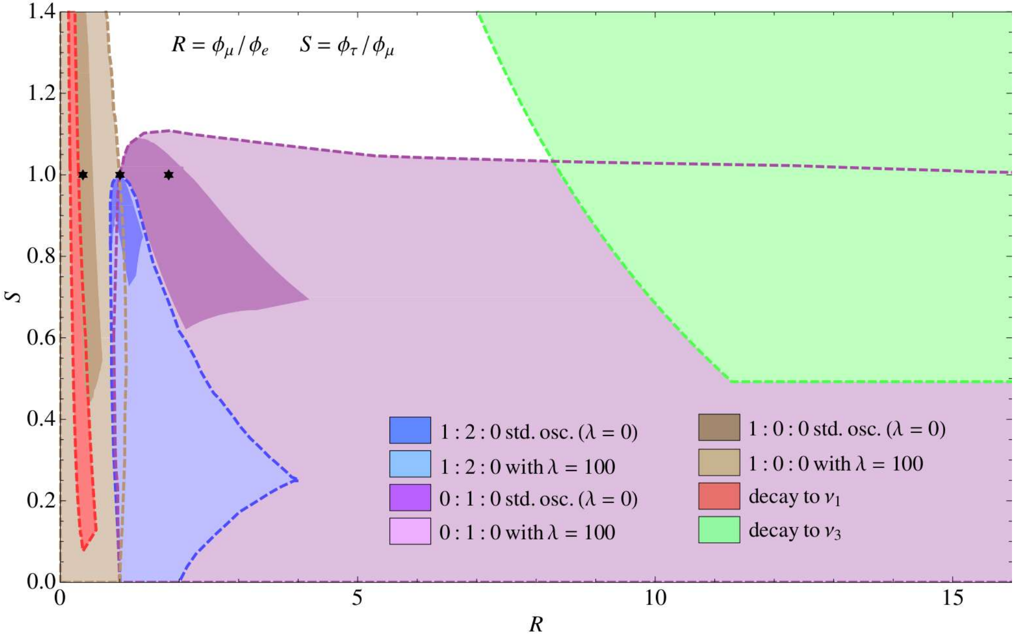
- New-physics models explored –

Fundamental Physics with HE Astrophysical Neutrinos

↦ Research experience

- New physics from flavor ratios
- Improved flavor tagging: echoes
- TeV–PeV ν cross section
- New-physics models explored –
  - Energy-independent new-physics effects

$\lambda = 0 \to$ CPT conserved $\quad \lambda = 100 \to$ CPT broken



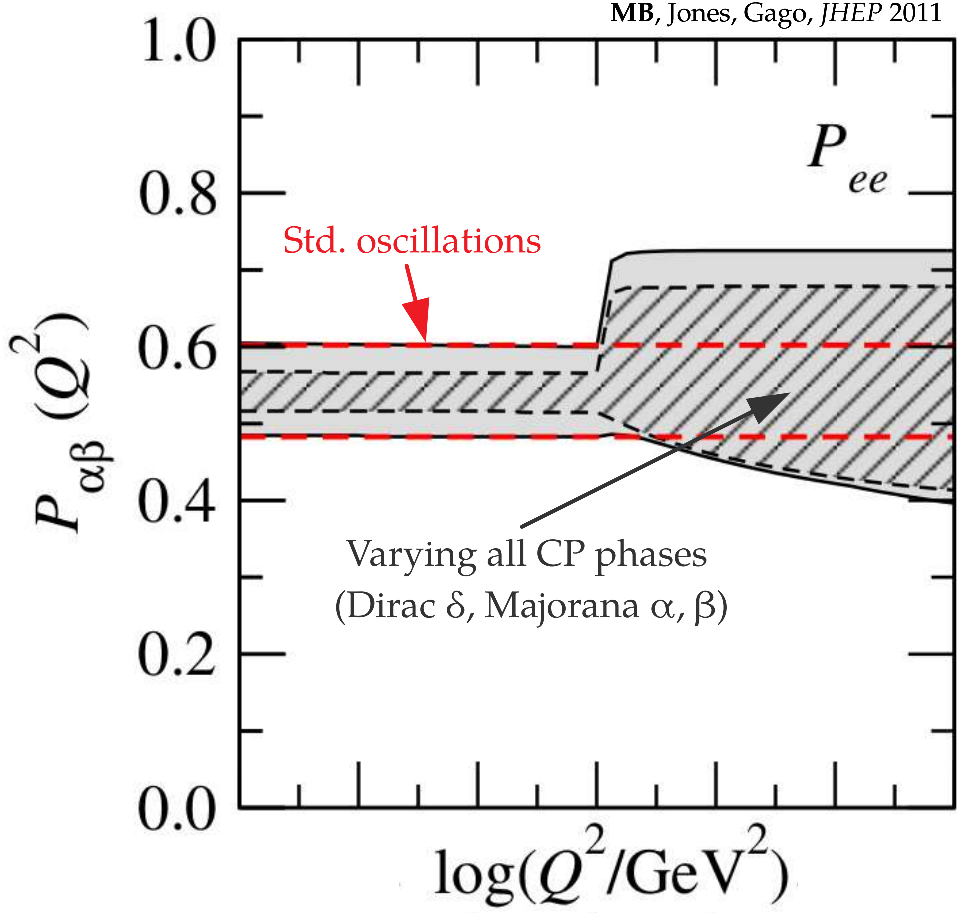
MB, Gago, Peña-Garay, *JHEP* 2010
MB *et al.*, IJMPA 2009

Fundamental Physics with HE Astrophysical Neutrinos

↦ Research experience

- New physics from flavor ratios
- Improved flavor tagging: echoes
- TeV–PeV ν cross section
- New-physics models explored –
  - Energy-independent new-physics effects
  - RGE running of ν mixing parameters

MB, Jones, Gago, *JHEP* 2011



Fundamental Physics with HE Astrophysical Neutrinos

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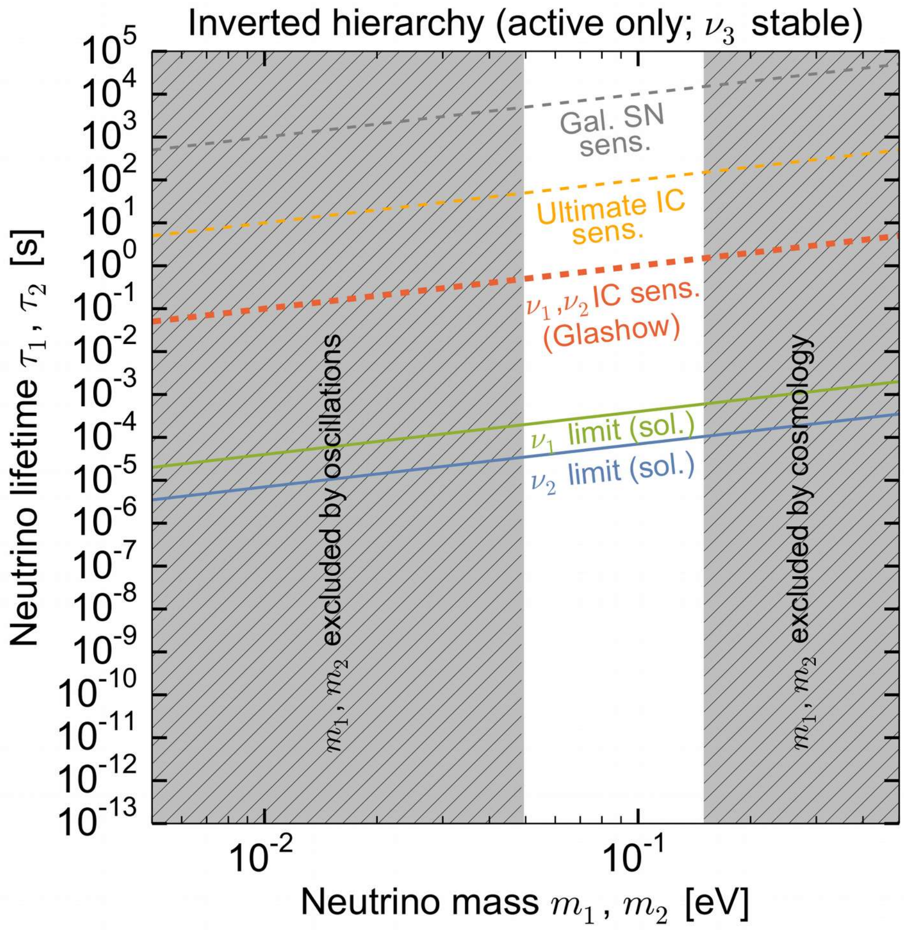
- New physics from flavor ratios
- Improved flavor tagging: echoes
- TeV–PeV ν cross section
- New-physics models explored –
  - Energy-independent new-physics effects
  - RGE running of ν mixing parameters
  - Neutrino decay



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

Fundamental Physics with HE Astrophysical Neutrinos

↦ Future work

- Settle whether there is new TeV–EeV neutrino physics
- Use all available observables: spectral shape, anisotropies, flavor, timing
- Combine with other messengers: cosmic rays, gamma rays
- Potential projects –
  - Extending statistics and energy range of ν cross section measurements
  - Generalizing ν decay formalism
  - Constraining ν lifetime using IceCube and *Fermi*
  - Ultra-long-range ν interactions

What:

What is making TeV–PeV neutrinos, EeV CRs, GeV–TeV gamma rays?

Why:

All the **usual** suspects have turned out not to be the sources

How:

Probe the **unusual** suspects

Modeling and Constraining Multi-Messenger Sources

↦ Background

Modeling and Constraining Multi-Messenger Sources

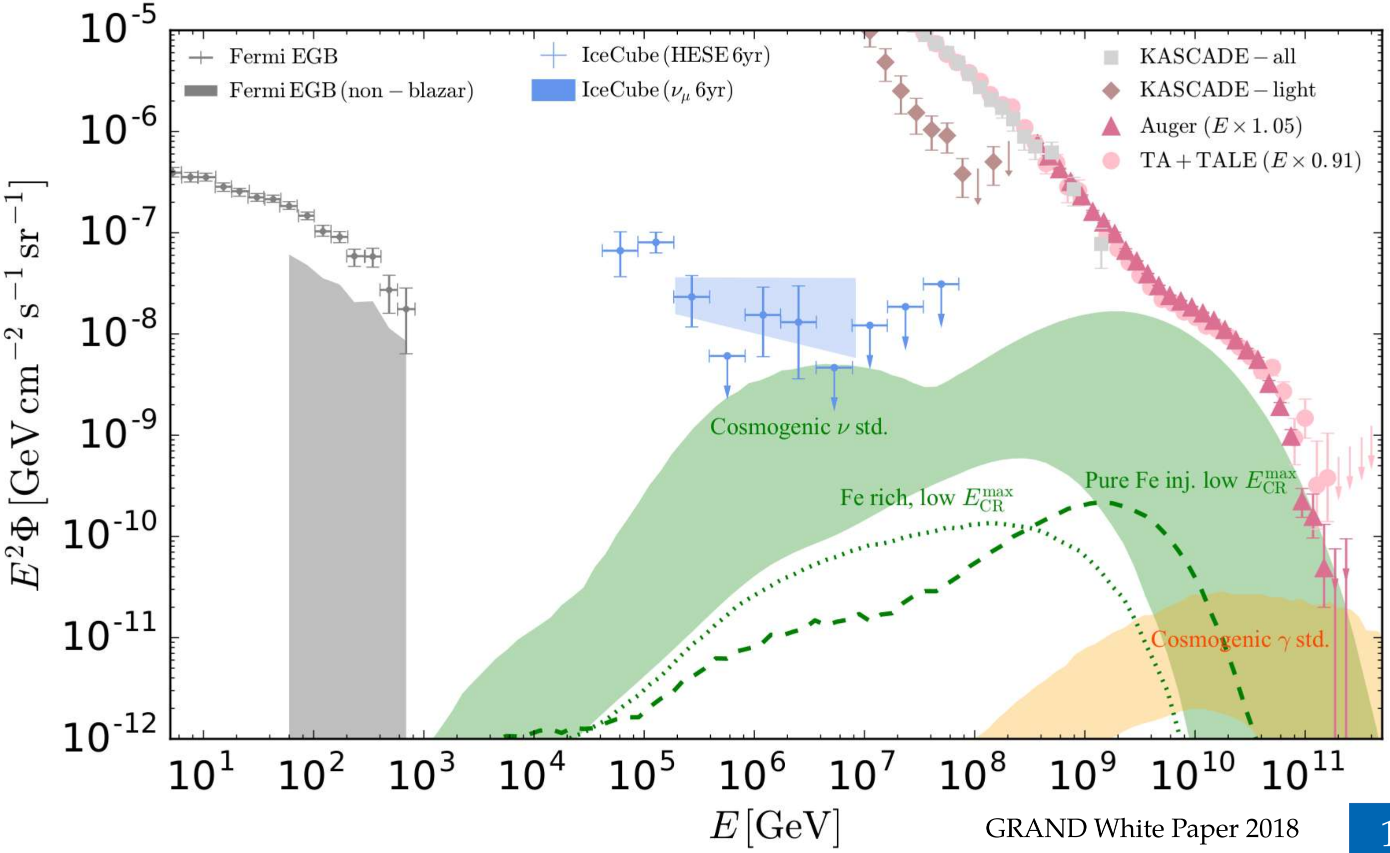
↦ Background

- Cosmic-ray sources must also make neutrinos and gamma rays

$E_\gamma = E_p/10$

$$pp, p\gamma \rightarrow \begin{cases} \pi^\pm \rightarrow \gamma\gamma \\ \pi^0 \rightarrow \nu_e \nu_\mu \nu_\mu \end{cases}$$

$E_\nu = E_p/20$



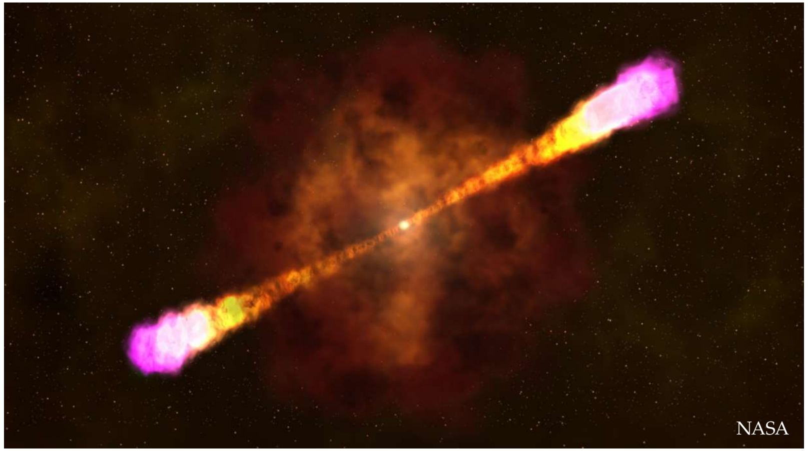
GRAND White Paper 2018

Modeling and Constraining Multi-Messenger Sources

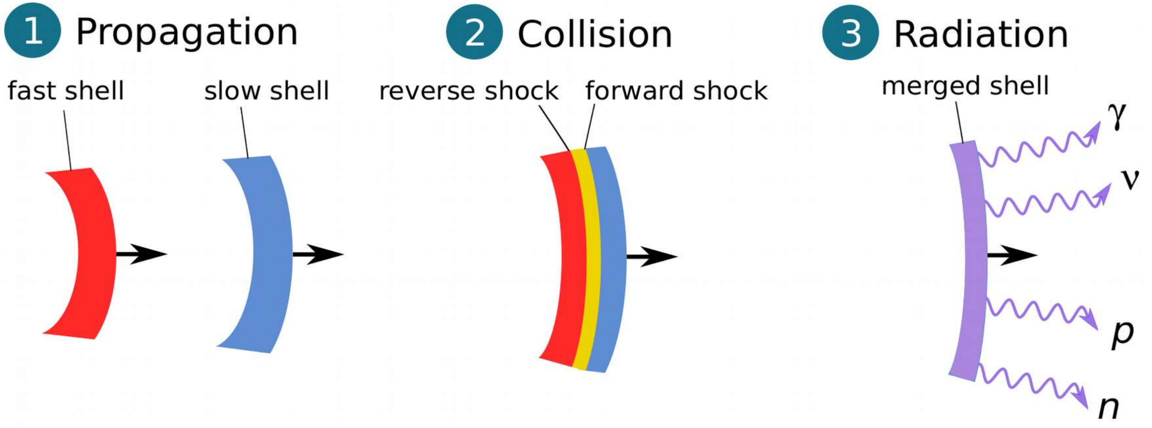
↦ Background

- Cosmic-ray sources must also make neutrinos and gamma rays
- Two ingredients: particle physics + astrophysics

- Cosmic-ray sources must also make neutrinos and gamma rays
- Two ingredients: particle physics + astrophysics
- Gamma-ray bursts (GRBs) – representative of relativistic emission



Fireball model – internal collisions

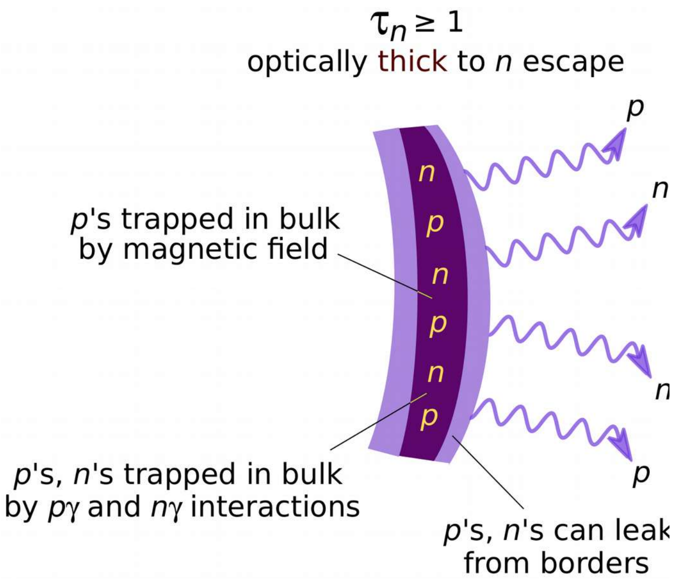


Modeling and Constraining Multi-Messenger Sources

↦ Research experience

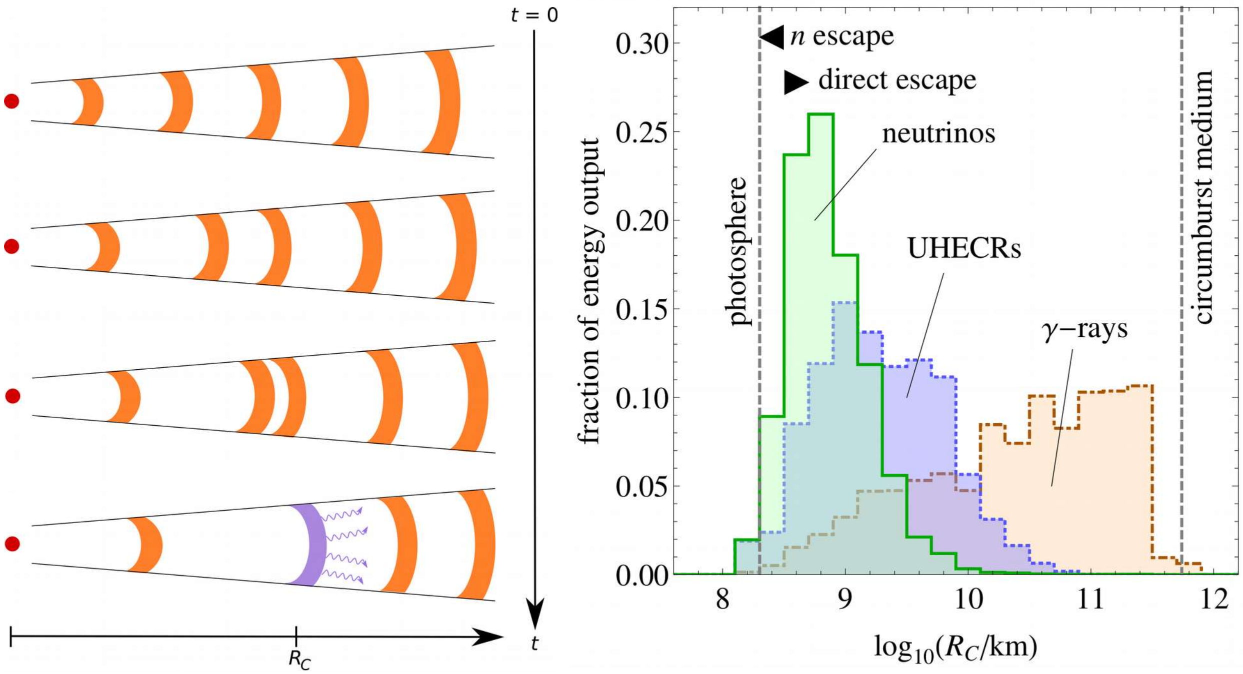
Revised CR and ν production in gamma-ray bursts (GRBs)

Revised particle emission



Baerwald, **MB**, Winter, *ApJ* 2013

Multiple collisions in GRB jet

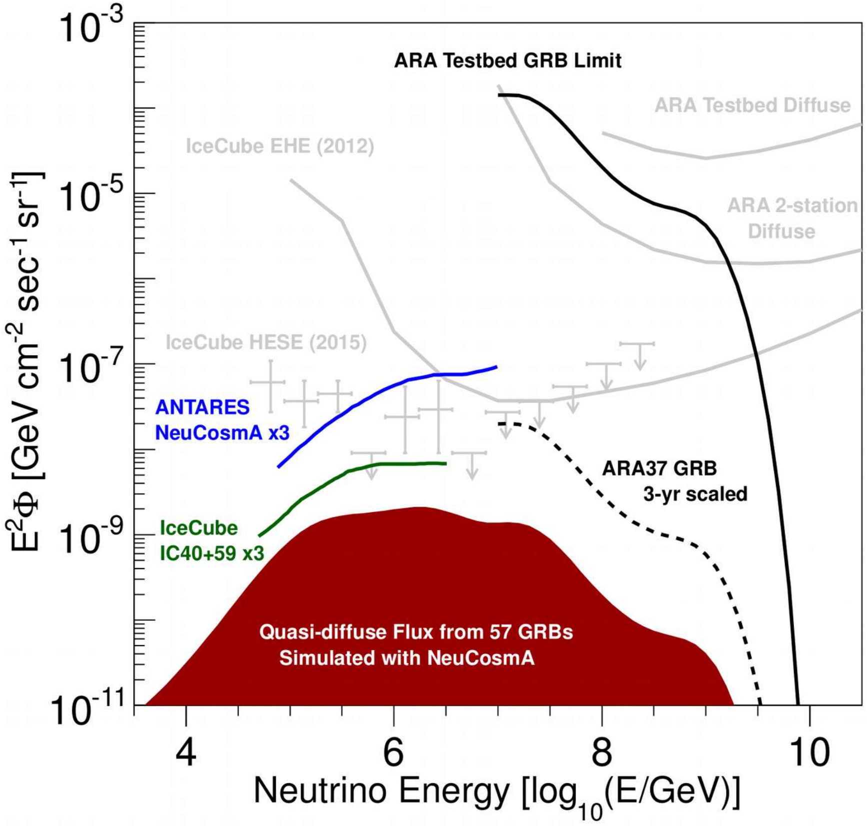


MB, Baerwald, Murase, Winter, *Nature Commun.* 2015
MB, Murase, Winter, Heinze, *ApJ* 2017

Modeling and Constraining Multi-Messenger Sources

↦ Research experience

Work with experimental collaborations



← First search for GRB neutrinos from ARA

ARA, **MB**, Guetta, *Astropart. Phys.* 2017

Modeling and Constraining Multi-Messenger Sources

↦ Future work

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- Explore more ν source classes
  - Transient and steady, dark and bright

Modeling and Constraining Multi-Messenger Sources

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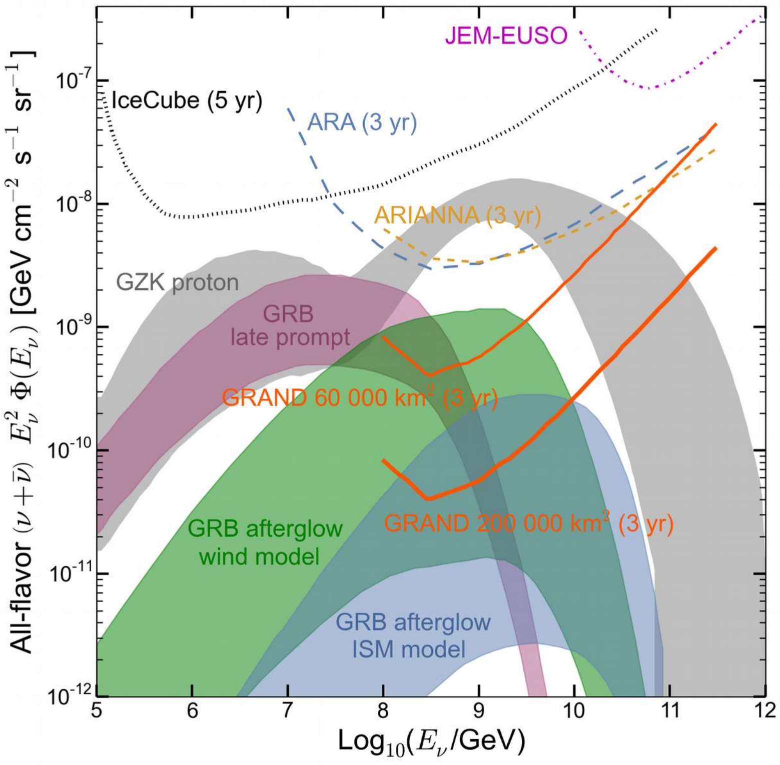
Neutrinos from GRB afterglows



MB & I. Tamborra, *In prep.*

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- Constrain sources with public IceCube data
  – Predict for next-gen detectors

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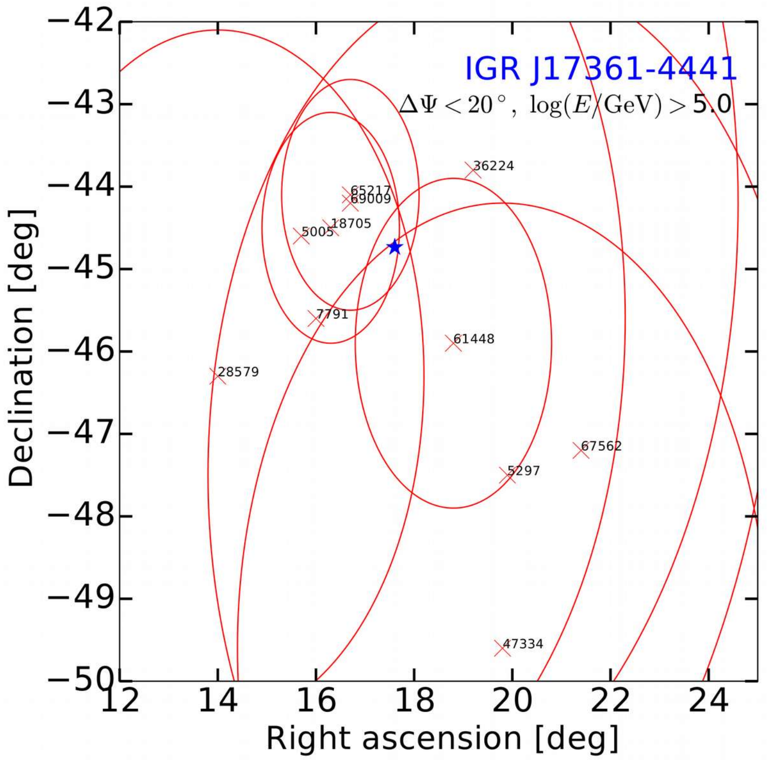
Neutrinos from tidal disruption events



MB & K. Auchettl, *In prep.*

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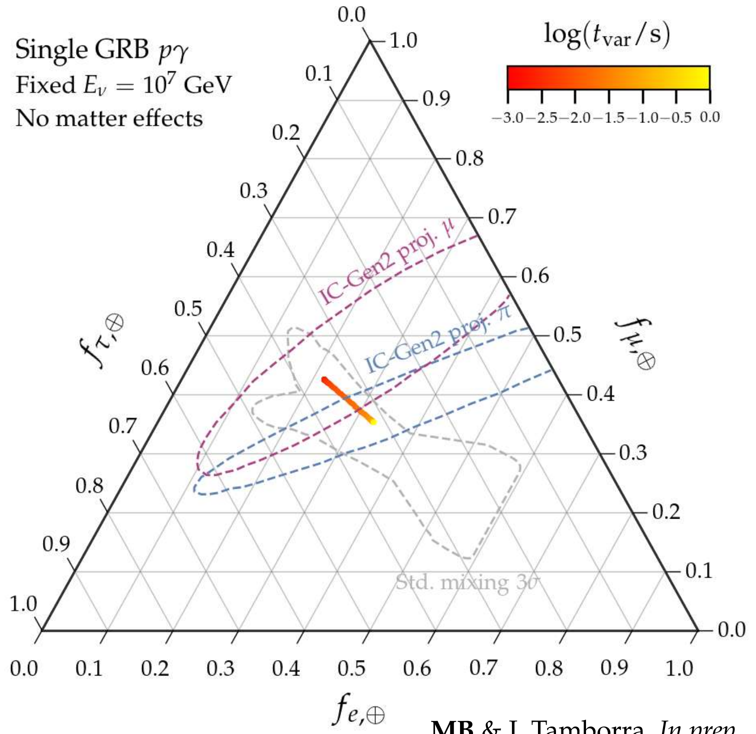
Constraining sources using flavor



MB & I. Tamborra, *In prep.*

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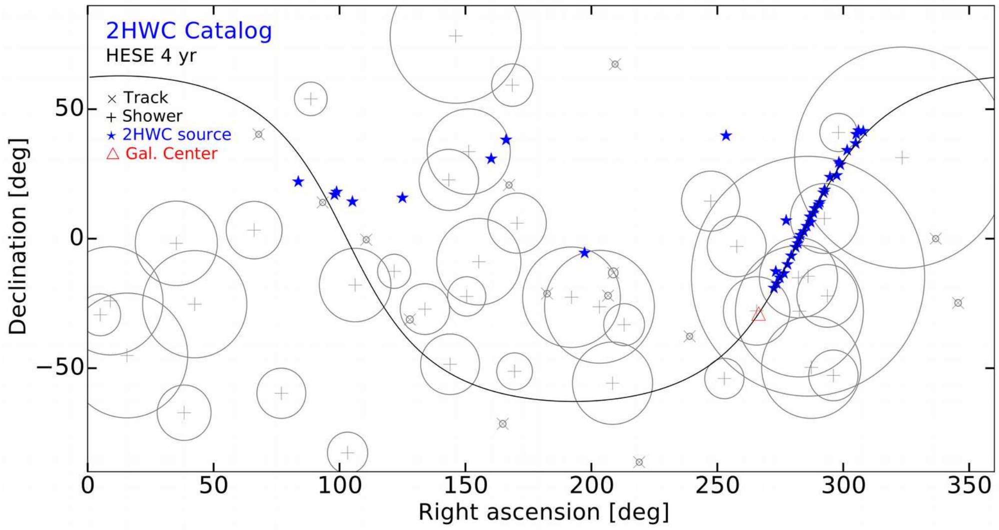
- Galactic sources of TeV–PeV neutrinos

MB, Li, Linden, Beacom, *In prep.*



Modeling and Constraining Multi-Messenger Sources

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- Explore more ν source classes
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- Galactic sources of TeV–PeV neutrinos
- Work with experimental collaborations –
  - ANITA: First search for EeV neutrinos from GRBs
  - ANTARES: Include more GRB emission mechanisms
  - Auger (tentative): EeV neutrinos from GRBs
  - GRAND (future)

Constraining UHECRs with UHE Neutrinos

What:

What is making the most energetic UHECRs, over 100 EeV?

Why:

Hard to discover directly using CRs (GZK, magnetic deflection)

How:

Use the accompanying EeV neutrinos

Constraining UHECRs with UHE Neutrinos

↦ Background

UHECR sources are hard to find:

- Magnetic deflection: few × 10°, composition-dependent
- GZK horizon: $p\gamma_{\rm CMB}$ scattering kills CRs with > 40 EeV after 100 Mpc

How to find them?

- Look for UHECR (> few EeV) arrival-direction anisotropies
- Look for UHE (> 10 EeV) gamma rays and neutrinos from $p\gamma$

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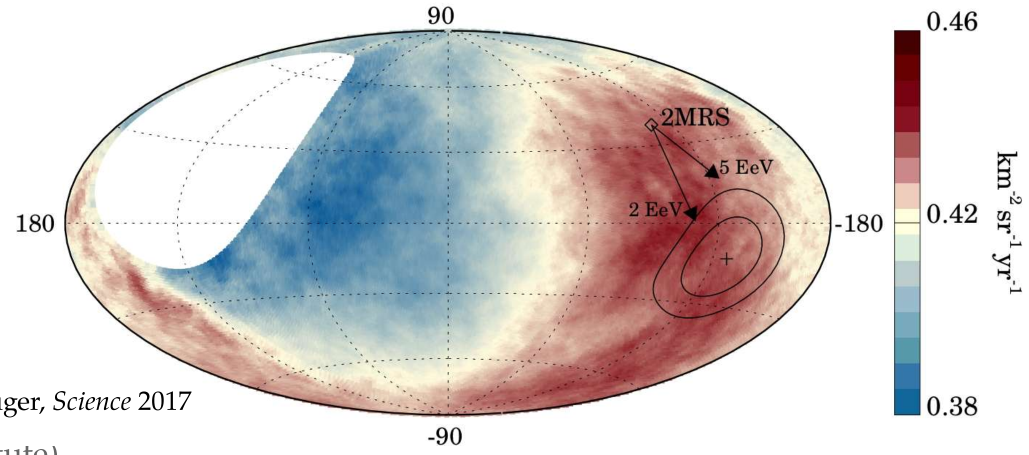

Auger, *Science* 2017

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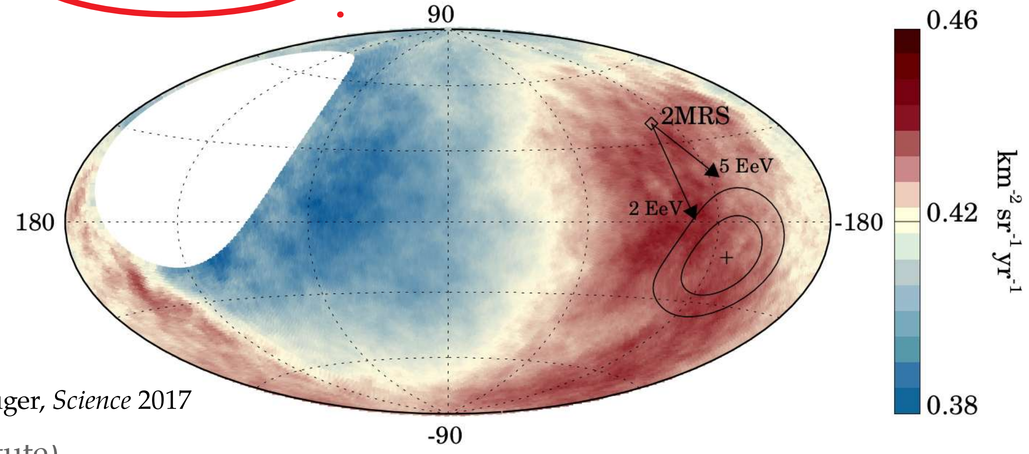
Can only find nearby sources because of gamma-ray opacity of Universe



Auger, *Science* 2017

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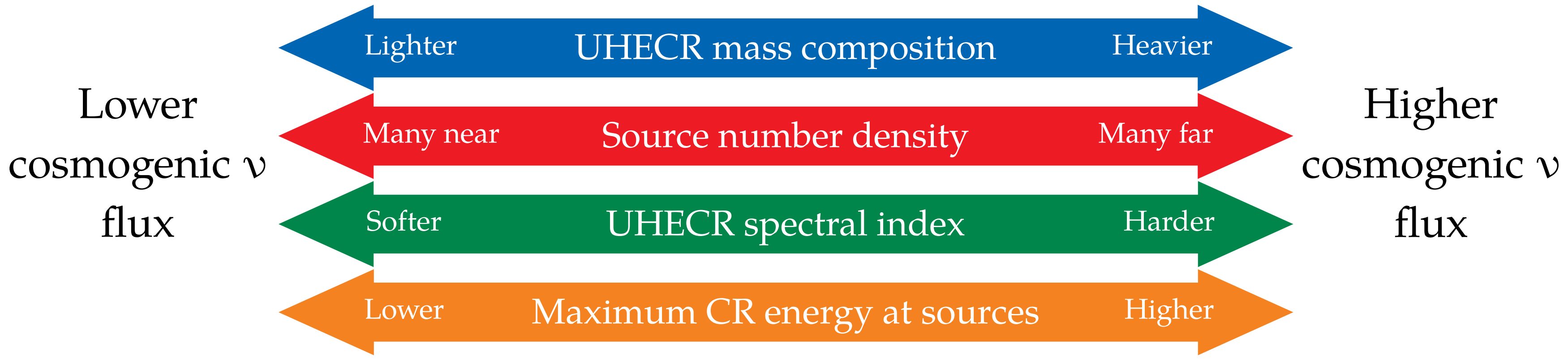


Constraining

↦ Background

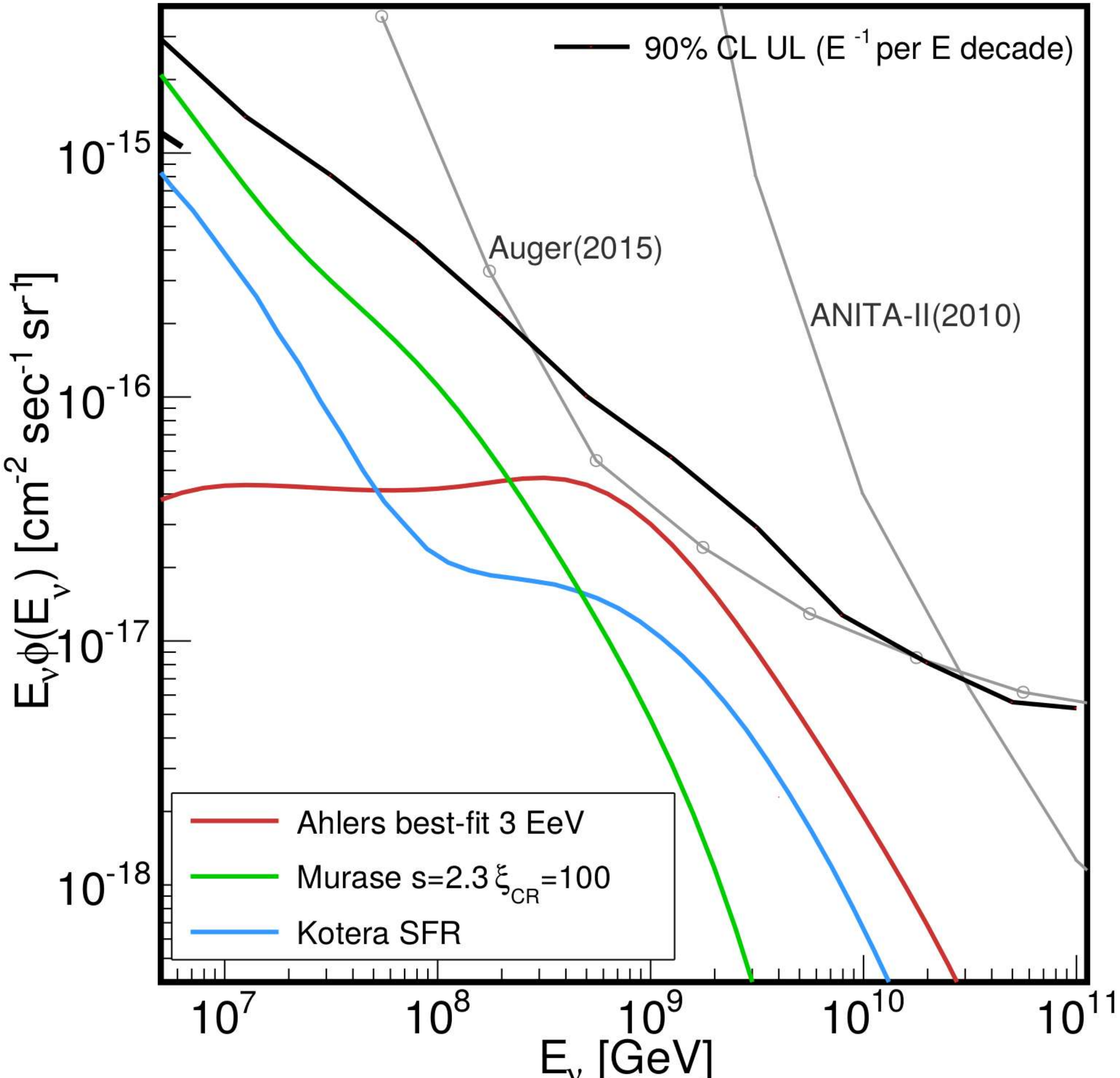
UHECR sources

- Magnetic deflecti
- GZK horizon: $p\gamma_C$

How to find the

- Look for UHECR
- Look for UHE (>

Lower cosmogenic flux



Higher osmogenic ν flux

Constraining UHECRs with UHE Neutrinos

↦ Research experience

Distribution of sources → Propagate CRs to Earth → Normalize to UHECR spectrum

Constraining UHECRs with UHE Neutrinos

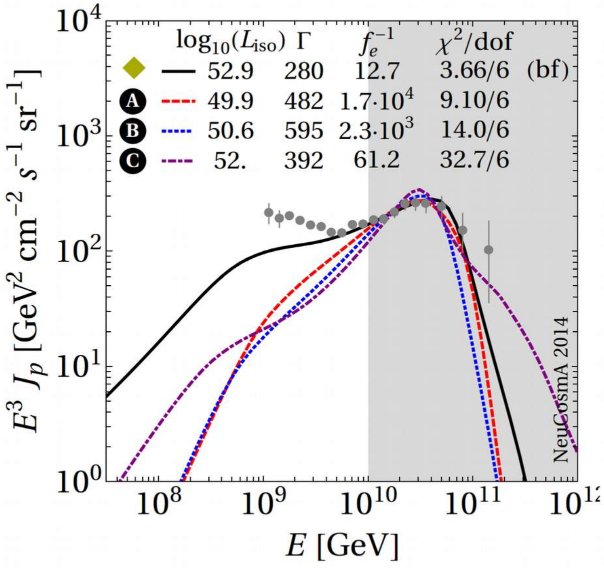
↦ Research experience

Distribution of sources → Propagate CRs to Earth → Normalize to UHECR spectrum

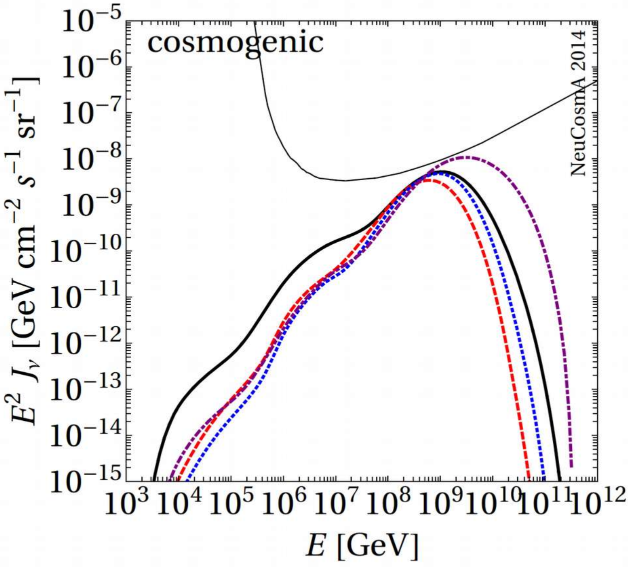
Are GRBs the UHECR sources?

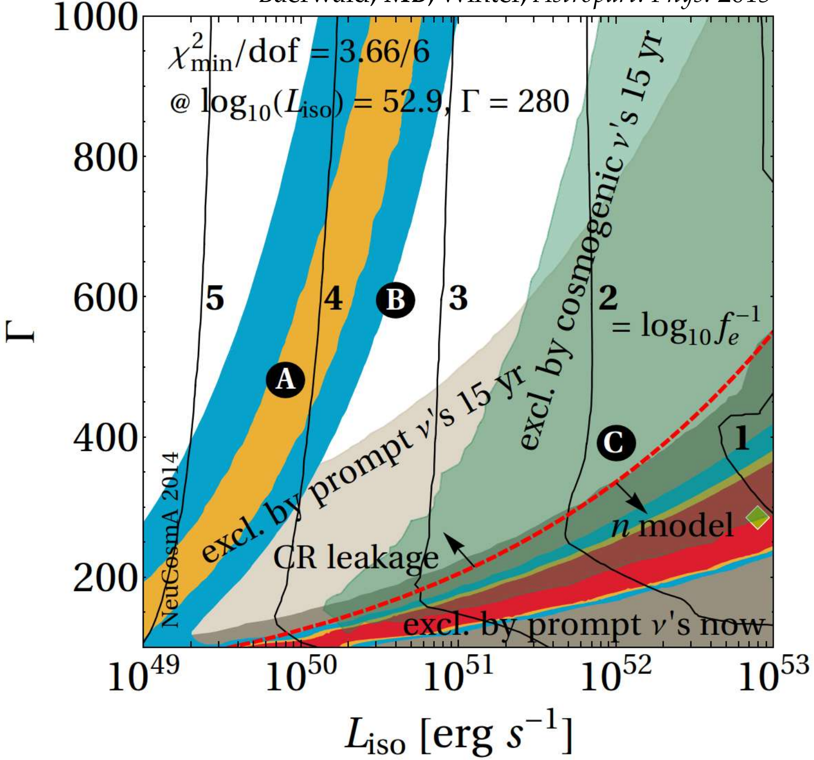
Baerwald, **MB**, Winter, *Astropart. Phys.* 2015

GRBs emit UHE protons and neutrons



Compare associated cosmogenic ν flux to limit





Constraining UHECRs with UHE Neutrinos

↦ Research experience

Distribution of sources → Propagate CRs to Earth → Normalize to UHECR spectrum

Are GRBs the UHECR sources?

GRBs emit
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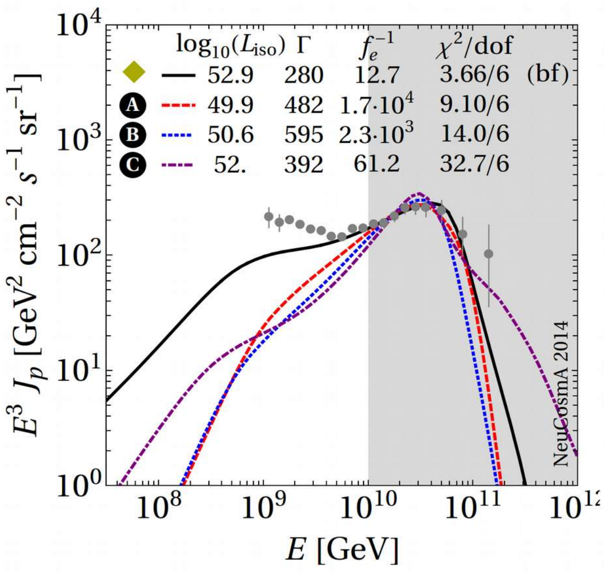

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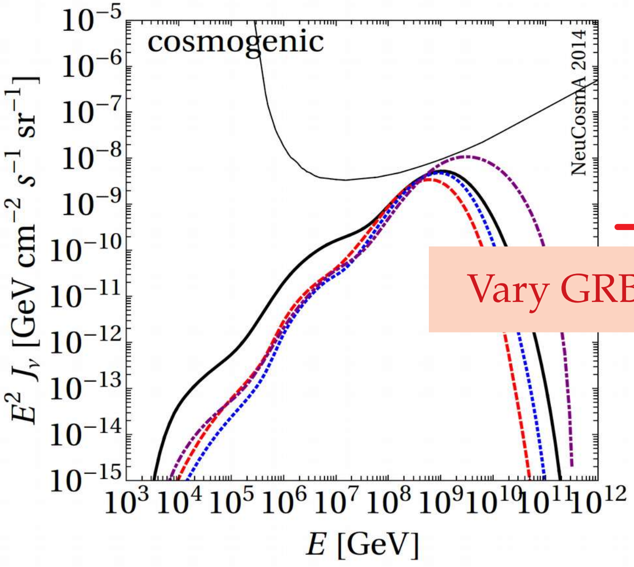
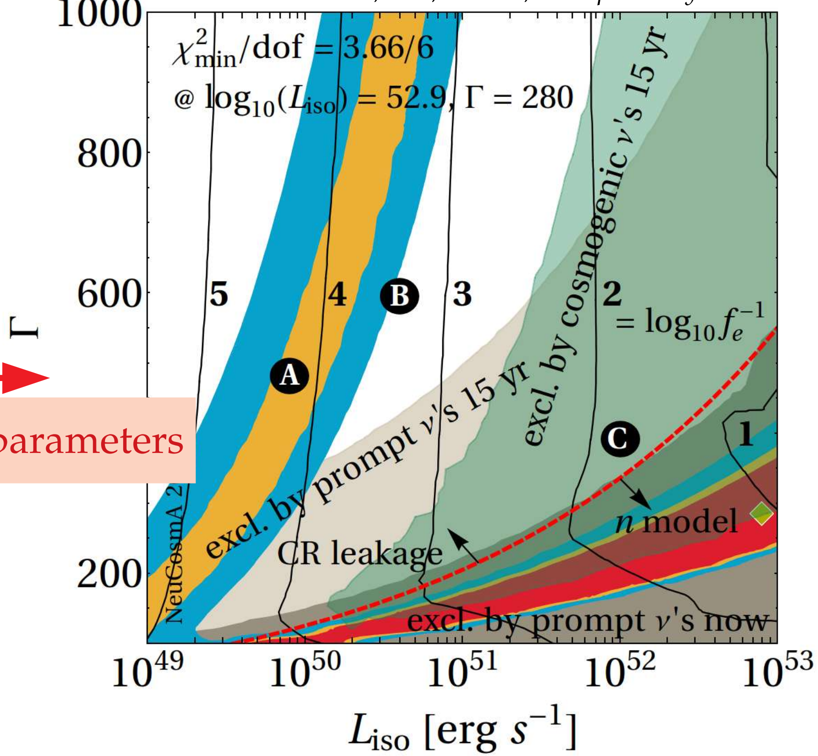


Vary GRB parameters

Baerwald, **MB**, Winter, *Astropart. Phys.* 2015



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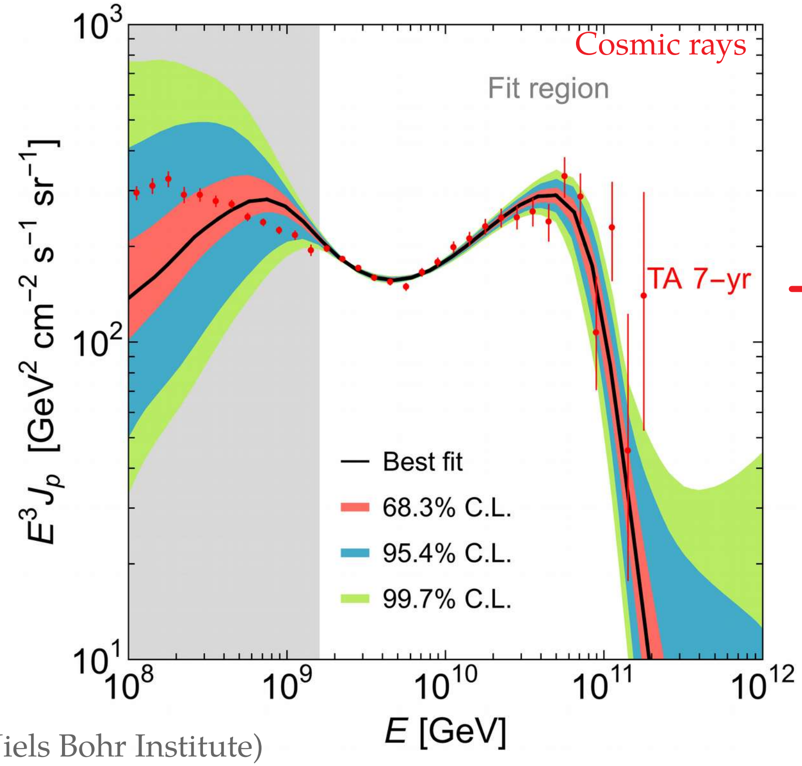
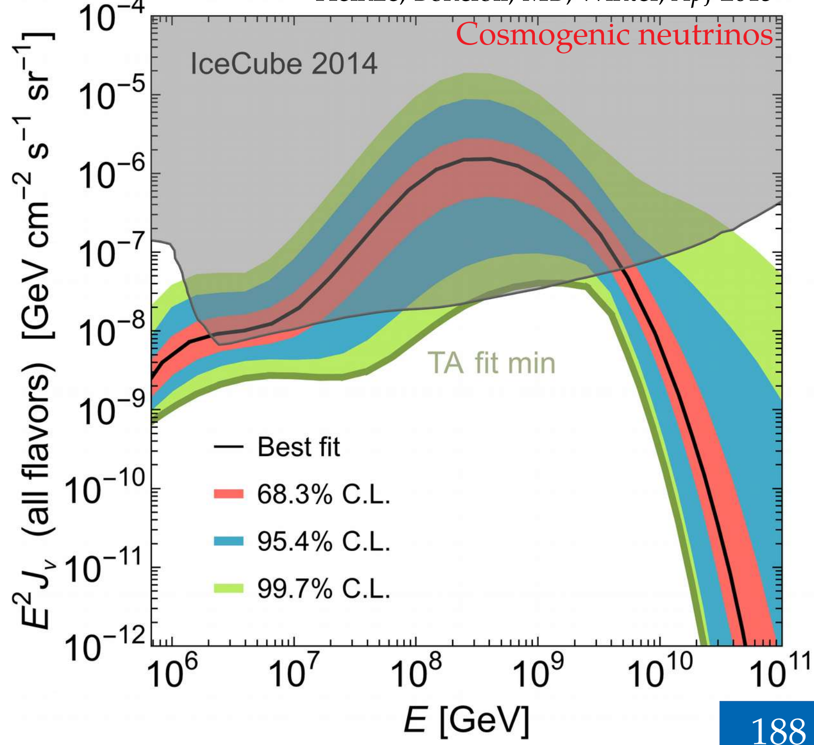
Are UHECRs at >10^9 GeV protons?

Proton-dip model: CRs are extragalactic protons above 10^9 GeV



Heinze, Boncioli, **MB**, Winter, *ApJ* 2015



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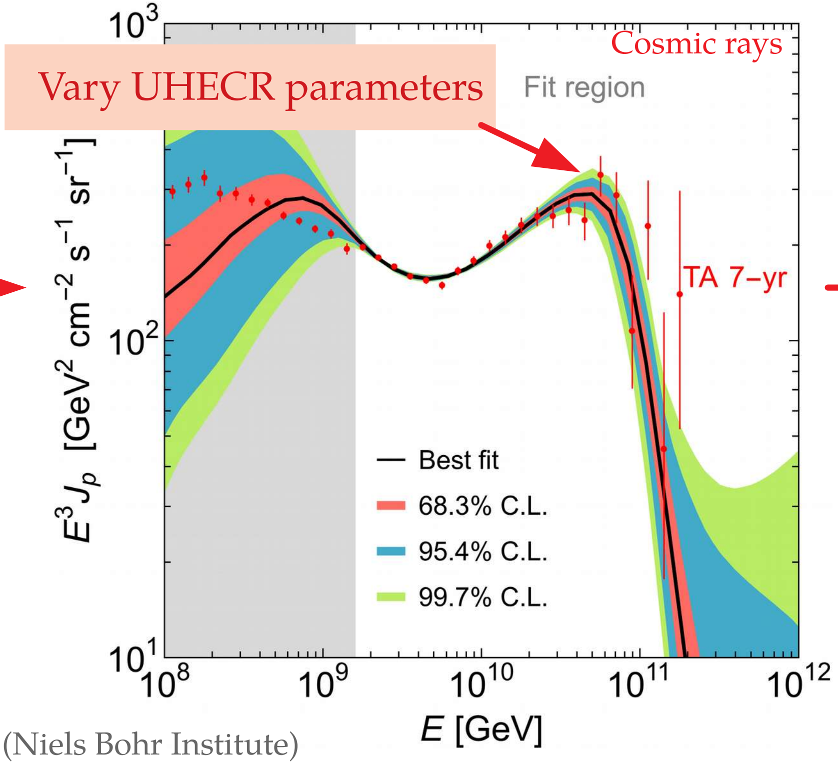

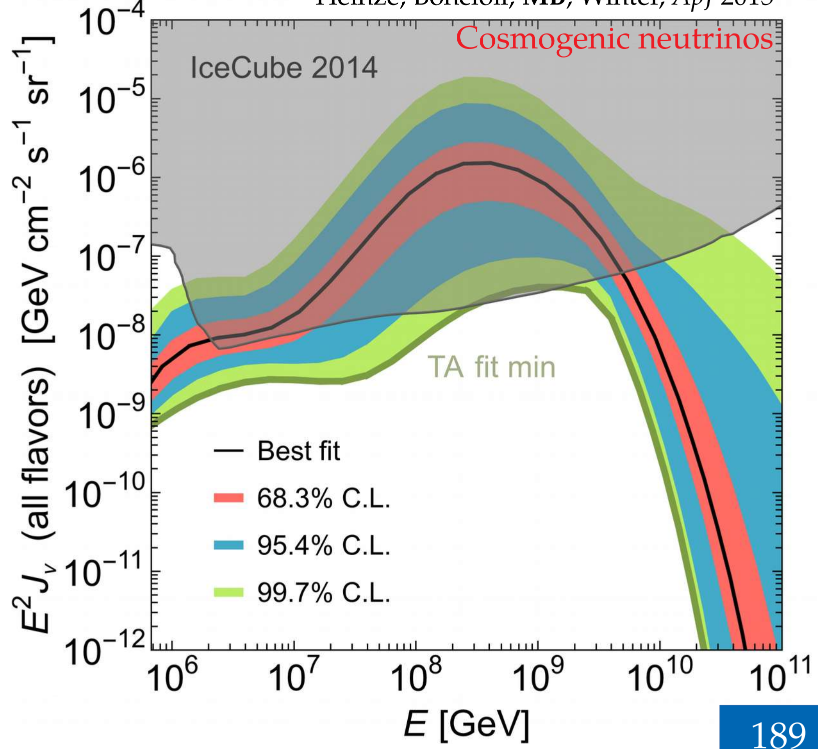

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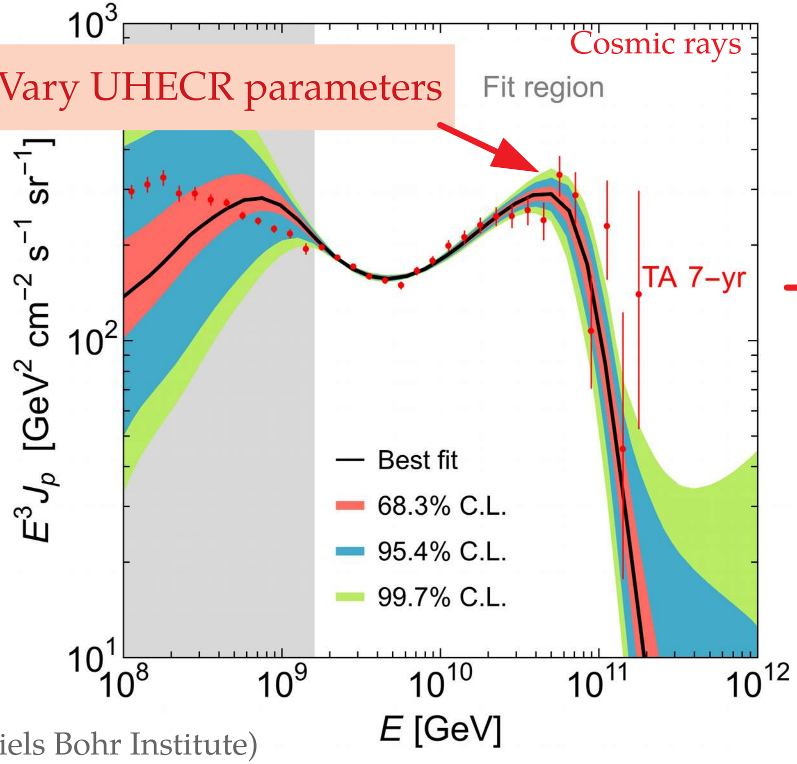
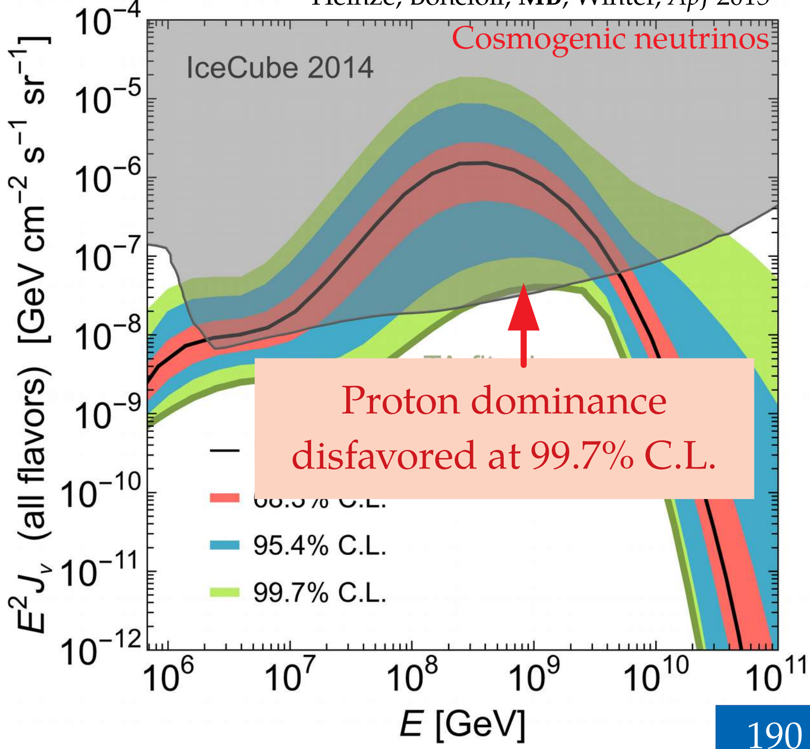




Constraining UHECRs with UHE Neutrinos

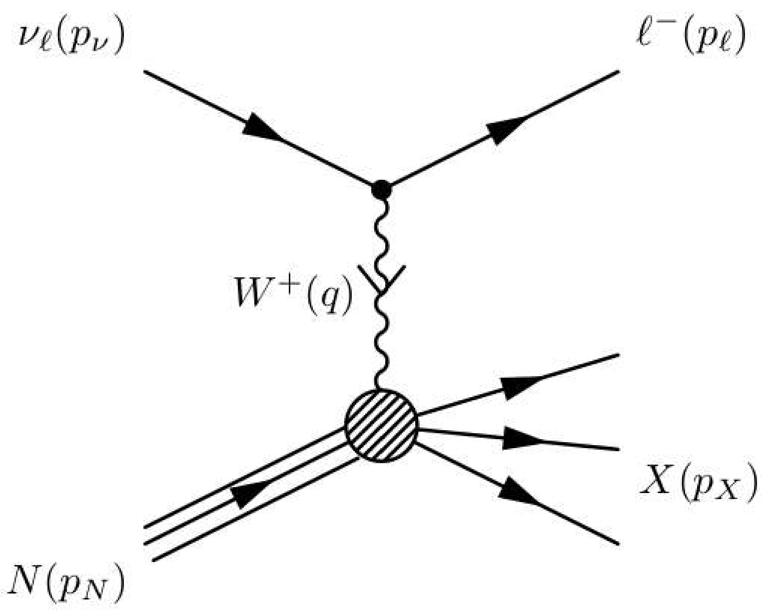
↦ Future work

- Near future for cosmogenic ν: stronger limits *or* discovery
  ↦ Find implications for identity of UHECR sources

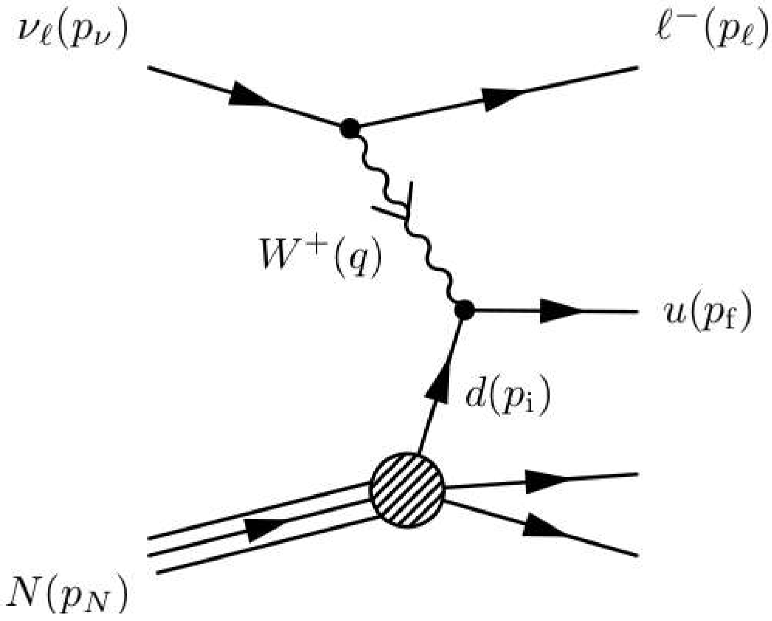
- Be comprehensive –
  - Mixed CR mass composition (collab. with DESY)
  - Use UHECR anisotropy
  - Combine with GeV–TeV and EeV gamma-ray data
  - Explore the *ankle* UHECR model (extragalactic dominance at lower energy)

How does DIS probe nucleon structure?

What you see

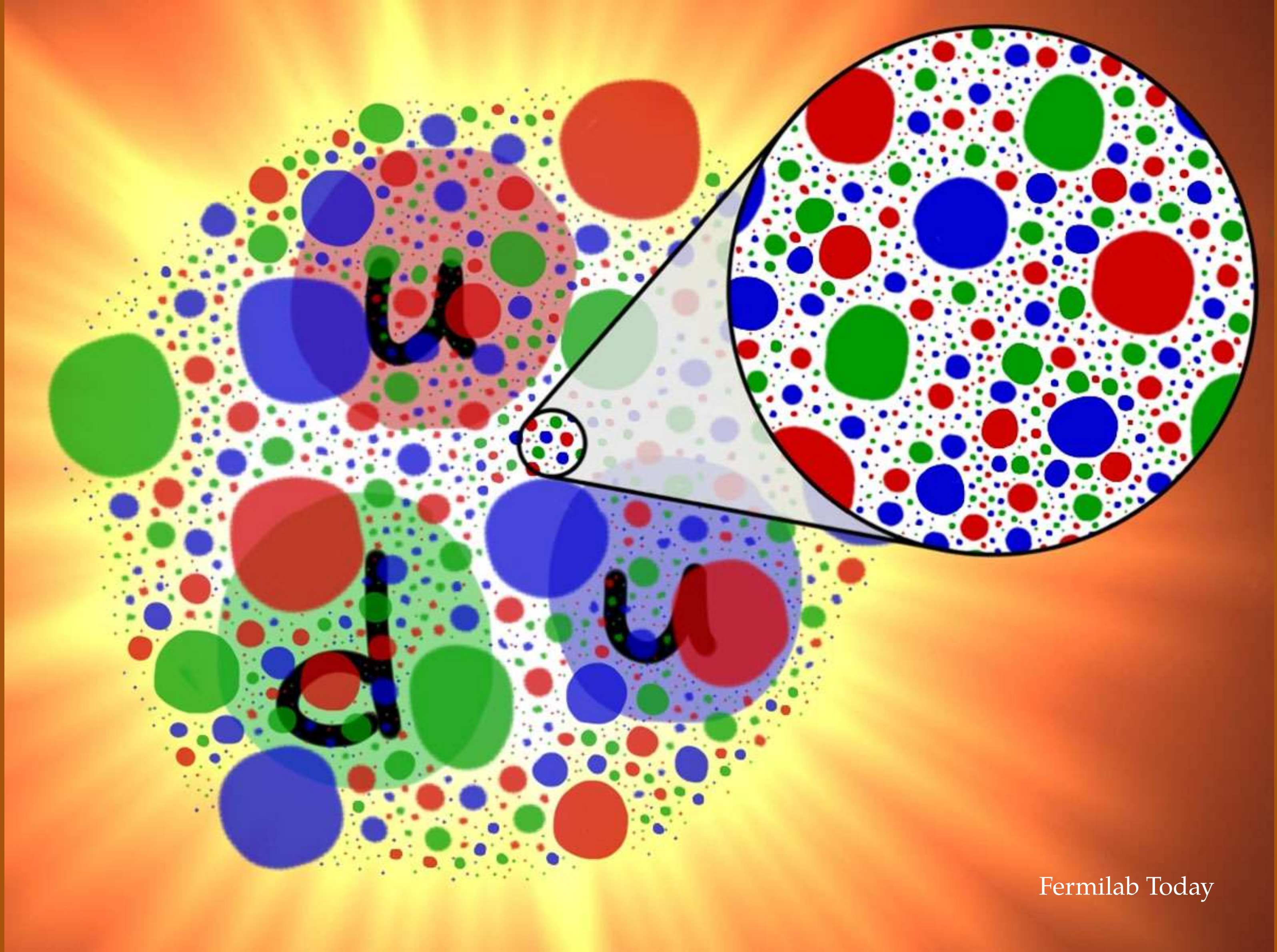


Beneath the hood



(Plus the equivalent neutral-current process (Z-exchange))

Giunti & Kim, *Fundamentals of Neutrino Physics & Astrophysics*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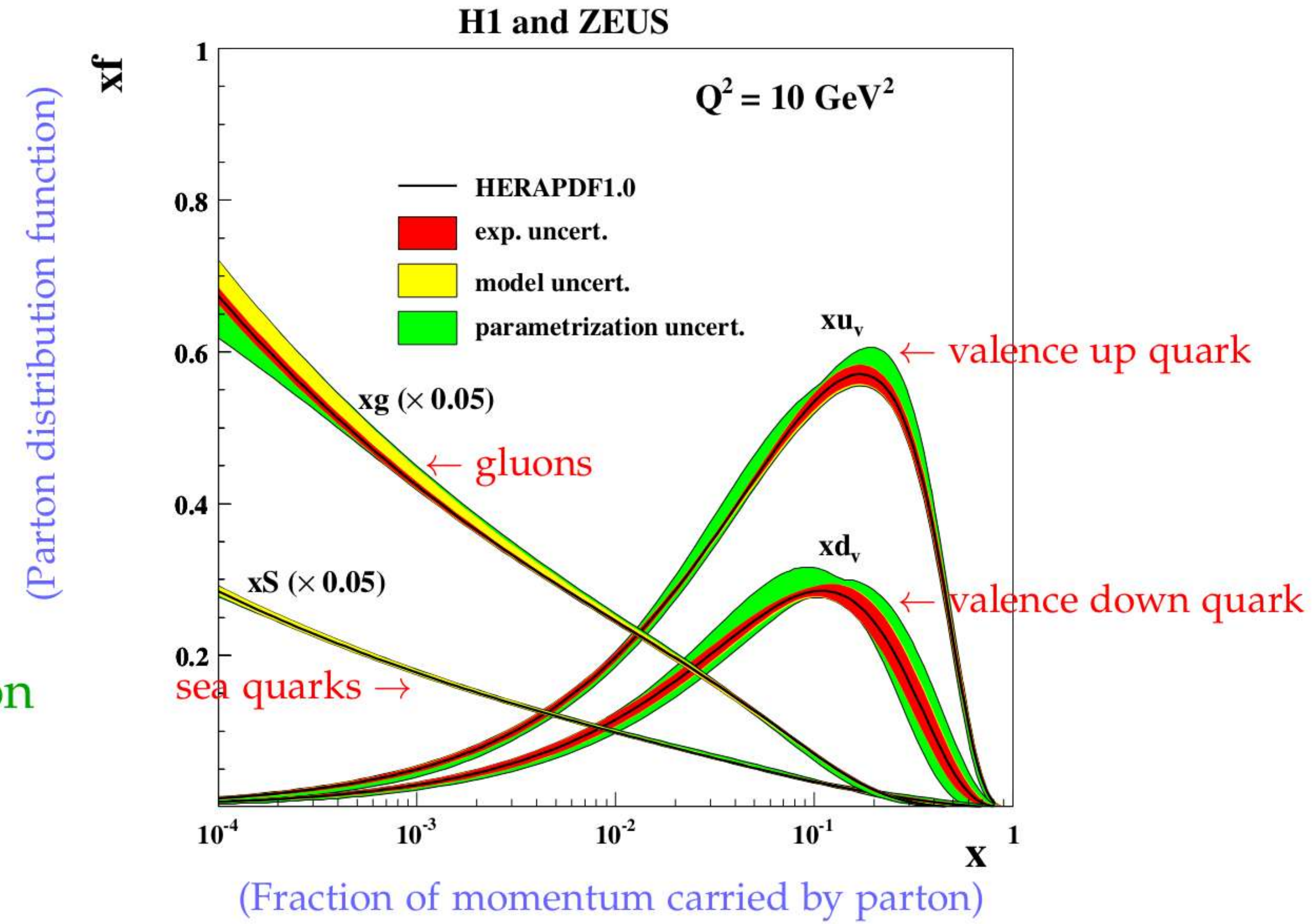
Fermilab Today

Peeking inside a proton



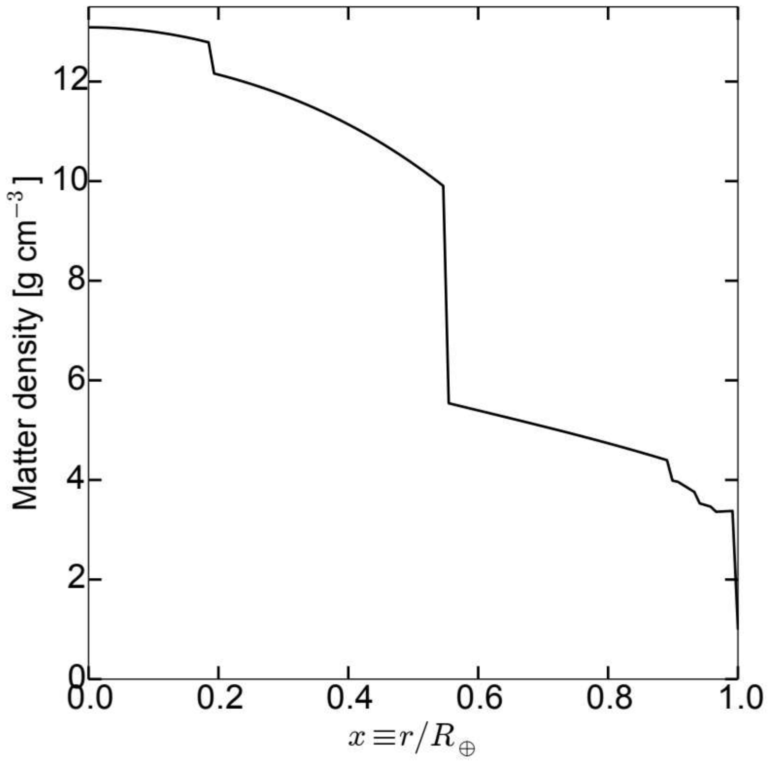
← Extrapolation

A. Cooper-Sarkar 2012

A feel for the in-Earth attenuation

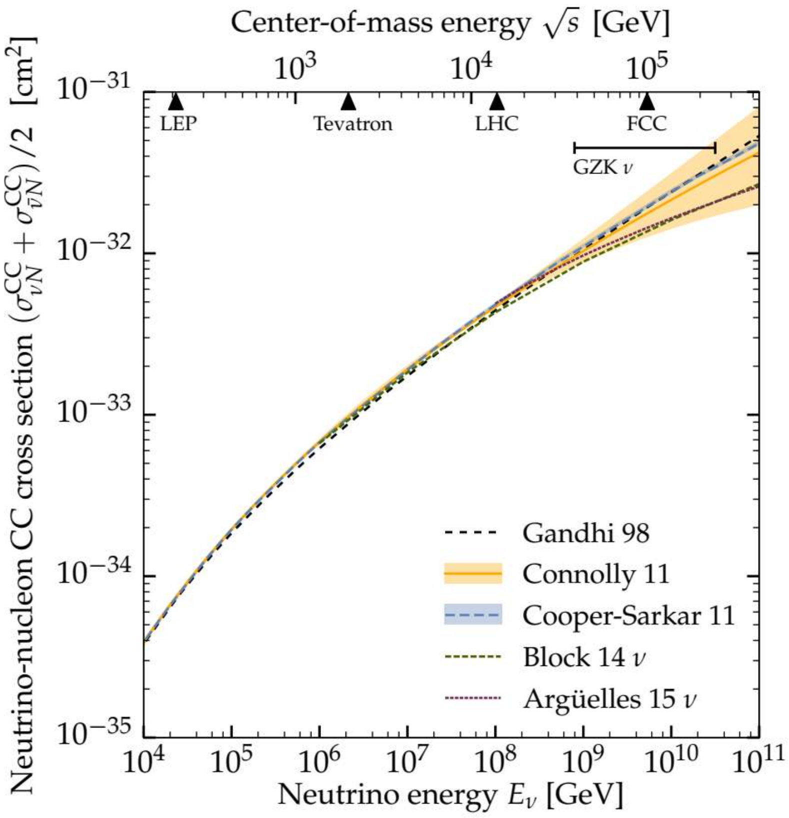
Earth matter density

(Preliminary Reference Earth Model)



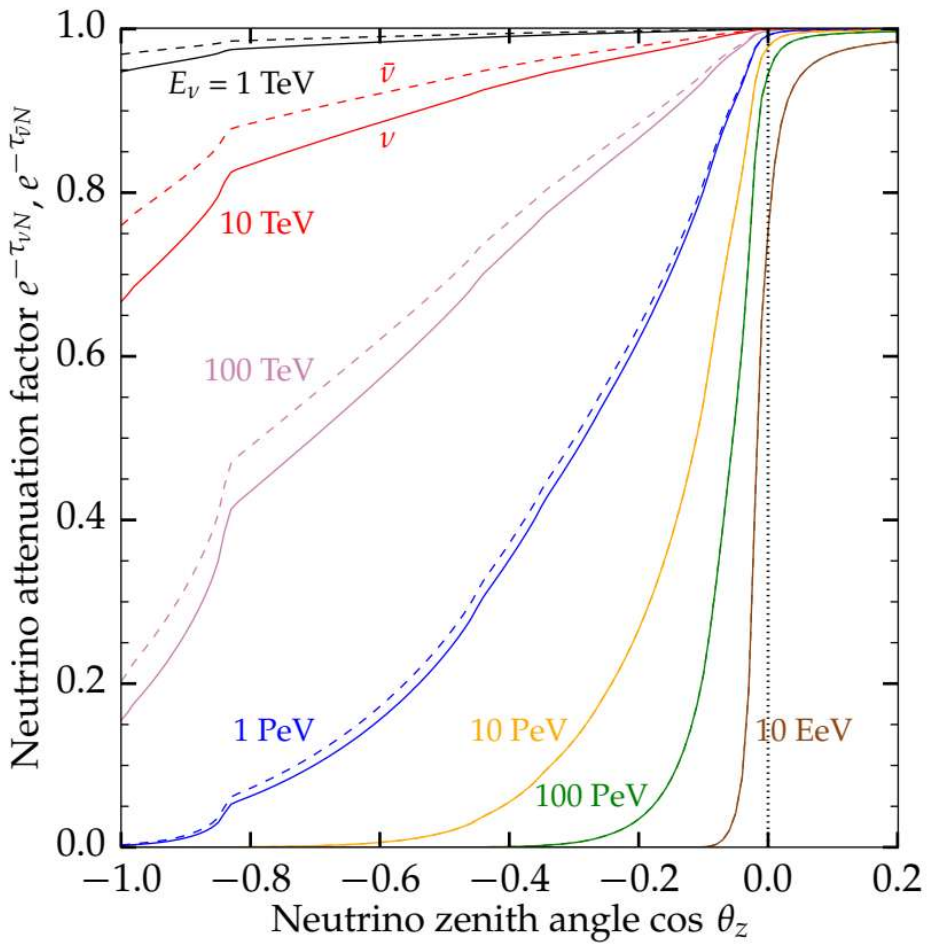
+

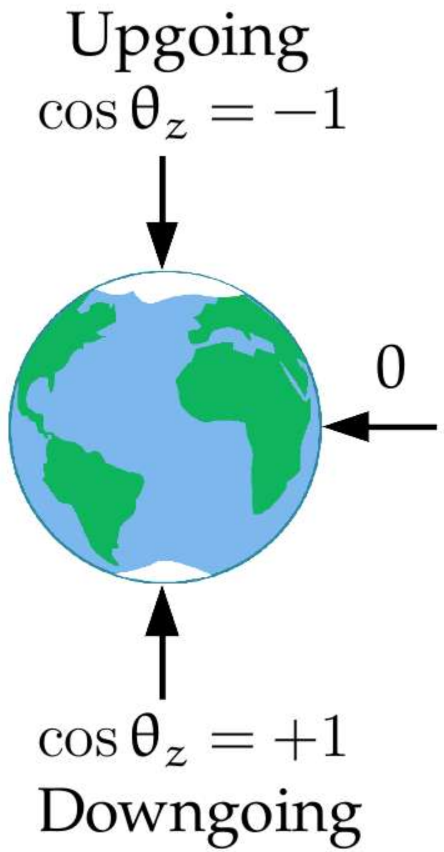
Neutrino-nucleon cross section



A feel for the in-Earth attenuation

=





Cross section from contained events

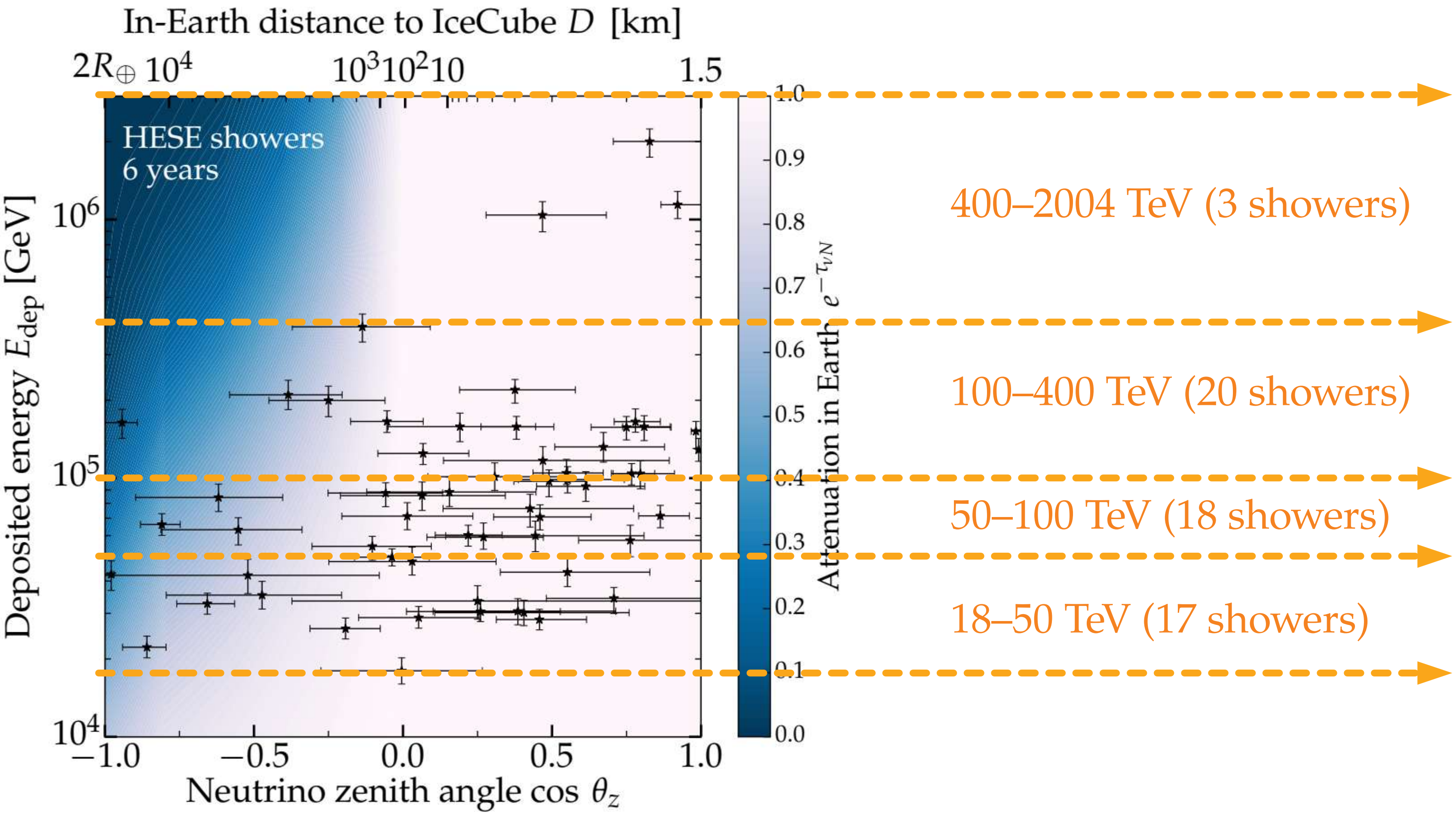
- $\sigma_{\nu N}$ varies with neutrino energy ⇒ use events where E_ν is well-reconstructed

- These are IceCube High-Energy Starting Events (HESE):
  - νN interaction occurs inside the detector
  - ☑ **Showers:** completely contained in the detector ($E_{dep} \approx E_\nu$)
  - ☒ **Tracks:** partially contained ($E_{dep} < E_\nu$)

- We use the 58 publicly available HESE showers (6-year sample)

- HESE tracks *could* be used
  – but we would need non-public data to reconstruct E_ν without bias

Bin-by-bin analysis



Sensitivity to σ in each bin

Number of contained events in an energy bin:

$$N_\nu \sim \Phi_\nu \cdot \sigma_{\nu N} \cdot e^{-\tau} = \Phi_\nu \cdot \sigma_{\nu N} \cdot e^{-L\sigma_{\nu N} n_N}$$

Downgoing (no matter)

$$N_{\nu,\mathrm{dn}} \sim \Phi_\nu \cdot \sigma_{\nu N}$$

Downgoing events fix the product $\Phi_\nu \cdot \sigma_{\nu N}$

Upgoing (lots of matter)

$$N_{\nu,\mathrm{up}} \sim N_{\nu,\mathrm{dn}} \cdot e^{-\tau}$$

Upgoing events measure $\sigma_{\nu N}$ via τ

Reality check:
Few events (per energy bin), so we are statistics-limited

The fine print

- High-energy ν's: astrophysical (isotropic) + atmospheric (**anisotropic**)
  ↦ We take into account the shape of the atmospheric contribution

- The shape of the astrophysical ν **energy spectrum** is still uncertain
  ↦ We take a $E^{-\gamma}$ spectrum in *narrow* energy bins

- **NC showers** are sub-dominant to **CC showers**, but they are indistinguishable
  ↦ Following Standard-Model predictions, we take $\sigma_{NC} = \sigma_{CC}/3$

- IceCube does not **distinguish ν from $\bar{\nu}$**, and their cross-sections are different
  ↦ We assume equal fluxes, expected from production via pp collisions
  ↦ We assume the avg. ratio $<\sigma_{\bar{\nu}N}/\sigma_{\nu N}>$ in each bin known, from SM predictions

- The **flavor composition** of astrophysical neutrinos is still uncertain
  ↦ We assume equal flux of each flavor, compatible with theory and observations

What goes into the (likelihood) mix?

- Inside each energy bin, we freely vary
  - N_{ast} (showers from astrophysical neutrinos)
  - N_{atm} (showers from atmospheric neutrinos)
  - γ (astrophysical spectral index)
  - σ_{CC} (neutrino-nucleon charged-current cross section)
- For each combination, we generate the angular and energy shower spectrum…
- … and compare it to the observed HESE spectrum via a likelihood
- Maximum likelihood yields σ_{CC} (marginalized over nuisance parameters)
- Bins are independent of each other – there are no (significant) cross-bin correlations

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Including detector resolution (10% in energy, 15° in direction)

- For each combination, we generate the angular and energy shower spectrum…
- … and compare it to the observed HESE spectrum via a likelihood
- Maximum likelihood yields σ_{CC} (marginalized over nuisance parameters)
- Bins are independent of each other – there are no (significant) cross-bin correlations

How to do better / more?

- Currently, we are statistics-limited
  ↦ Solvable with more data from IceCube, IceCube-Gen2, KM3NeT

- Large errors in arrival direction (~10°) give errors in attenuation
  ↦ Solvable with ongoing IceCube improvements + KM3NeT

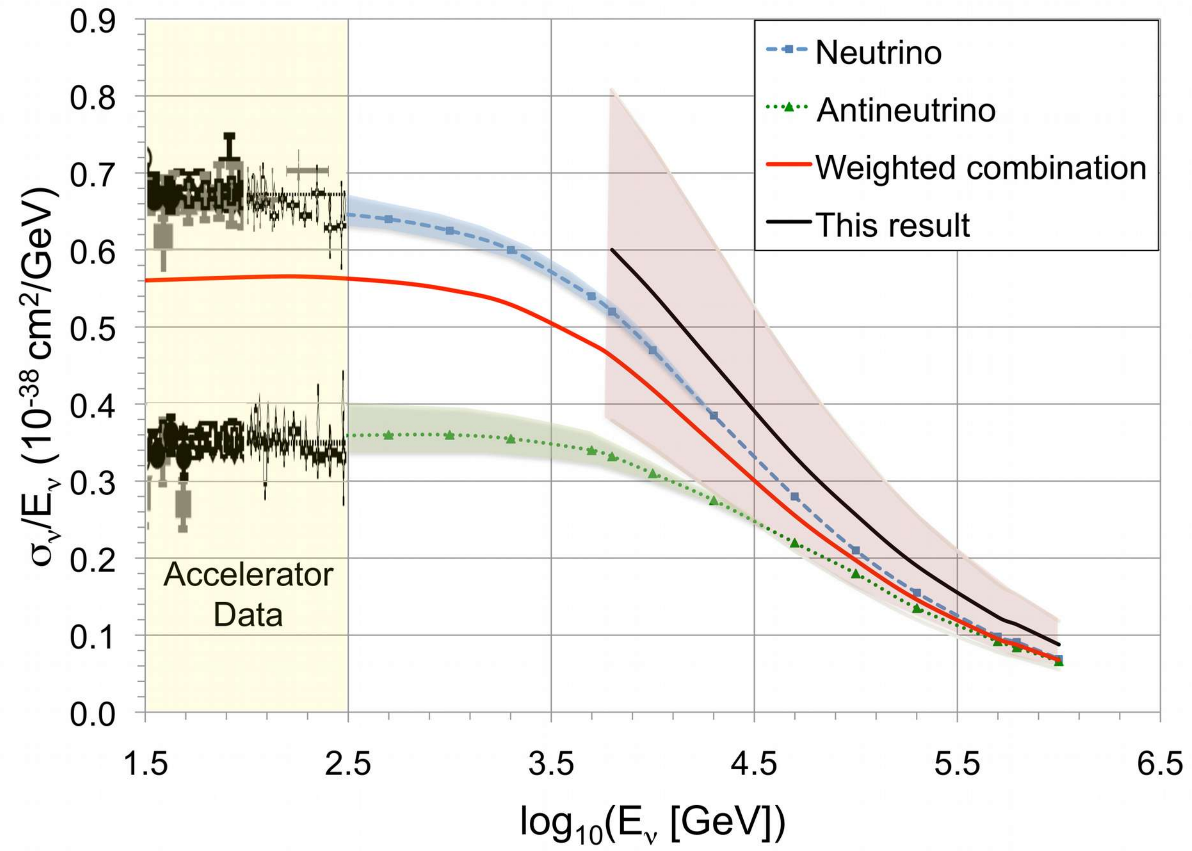
- Charged-current + neutral-current cross sections are indistinguishable
  ↦ Solvable (?) with muon and neutron echoes (Li, MB, Beacom 16)

- Cannot separate ν from $\bar{\nu}$
  ↦ Wait to detect Glashow resonance (~6.3 PeV), sensitive only to $\bar{\nu}_e$

- Use starting tracks / through-going muons
  ↦ Doable / done by IceCube (more next)

Using through-going muons instead

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



IceCube, Nature, 1711.08119

Summary: fundamental physics with astrophysical ν

- We extracted the neutrino-nucleon cross section from 18 TeV to 2 PeV
  $\mapsto$ Previously known up to 350 GeV

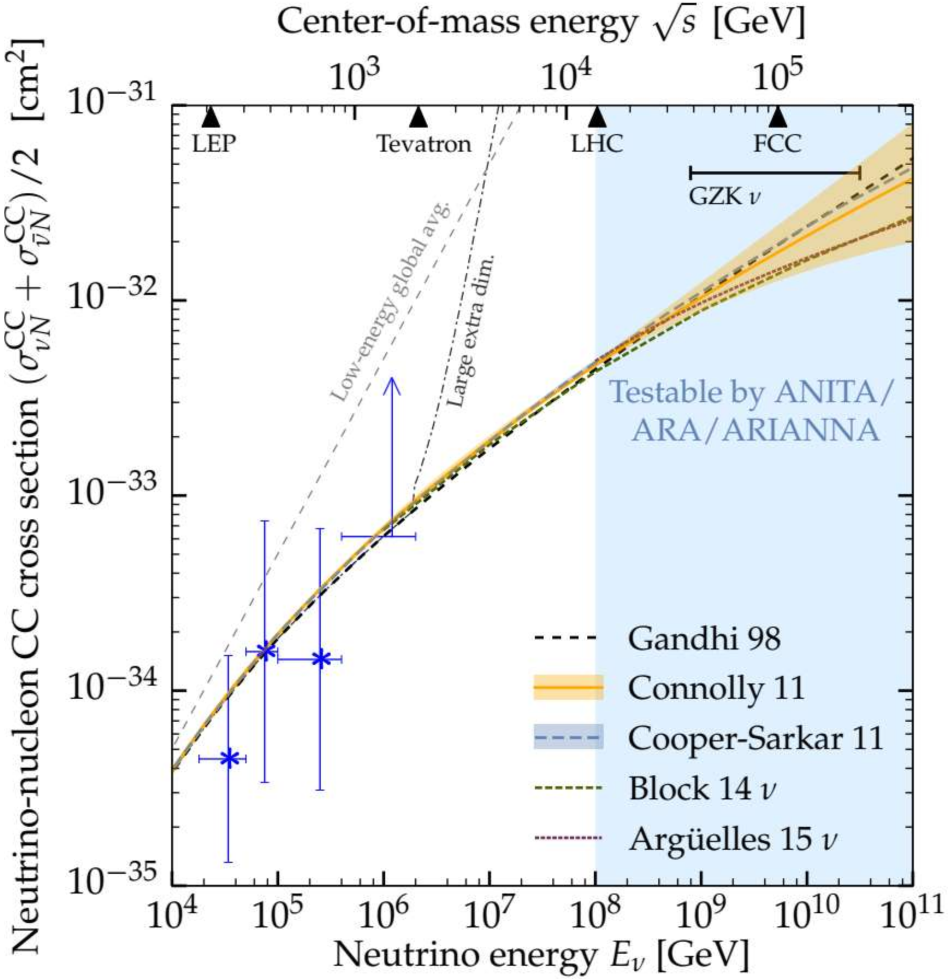
- Found consistency with Standard-Model predictions

- Errors are still large due to statistics and astrophysical unknowns

- But both will be improved in the future

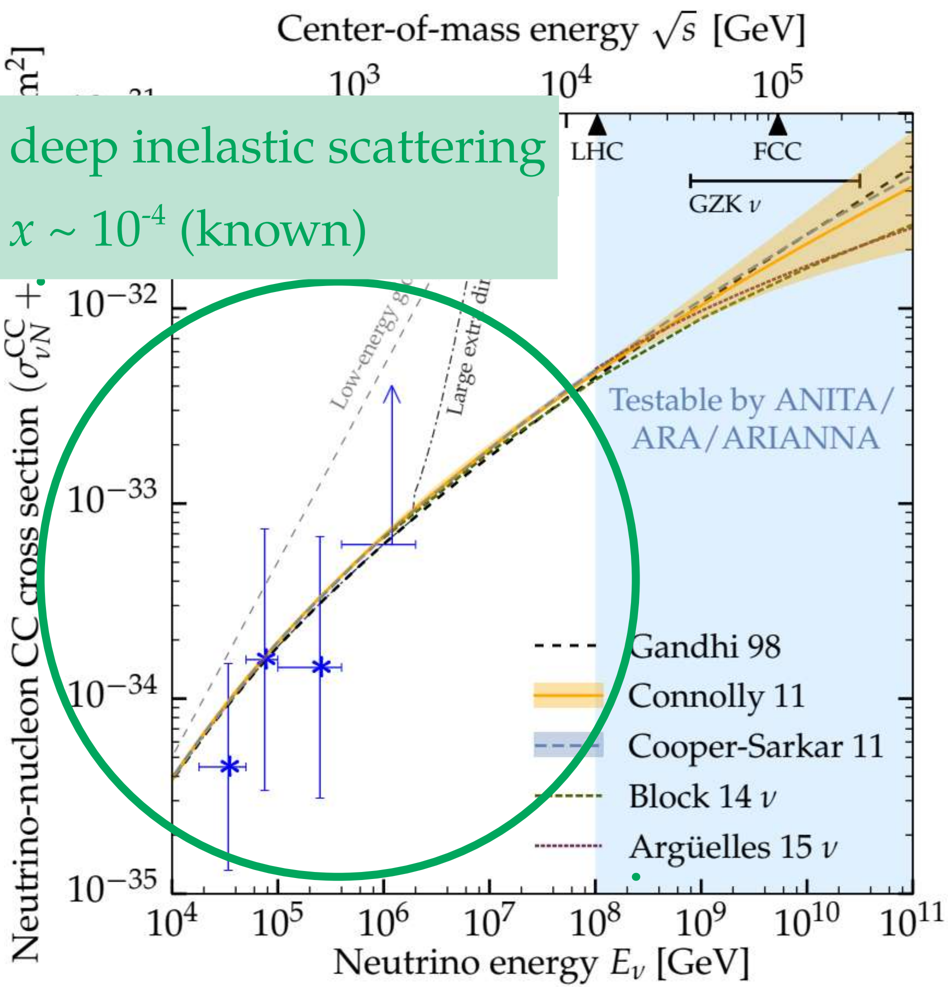
Neutrino telescopes can probe fundamental particle physics
(cross section, flavor composition, anisotropies)

Quo vadis: IceCube vs. ANITA / ARA / ARIANNA



Quo vadis: IceCube vs. ANITA / ARA / ARIANNA

Test predictions of deep inelastic scattering – down to PDFs at $x \sim 10^{-4}$ (known)



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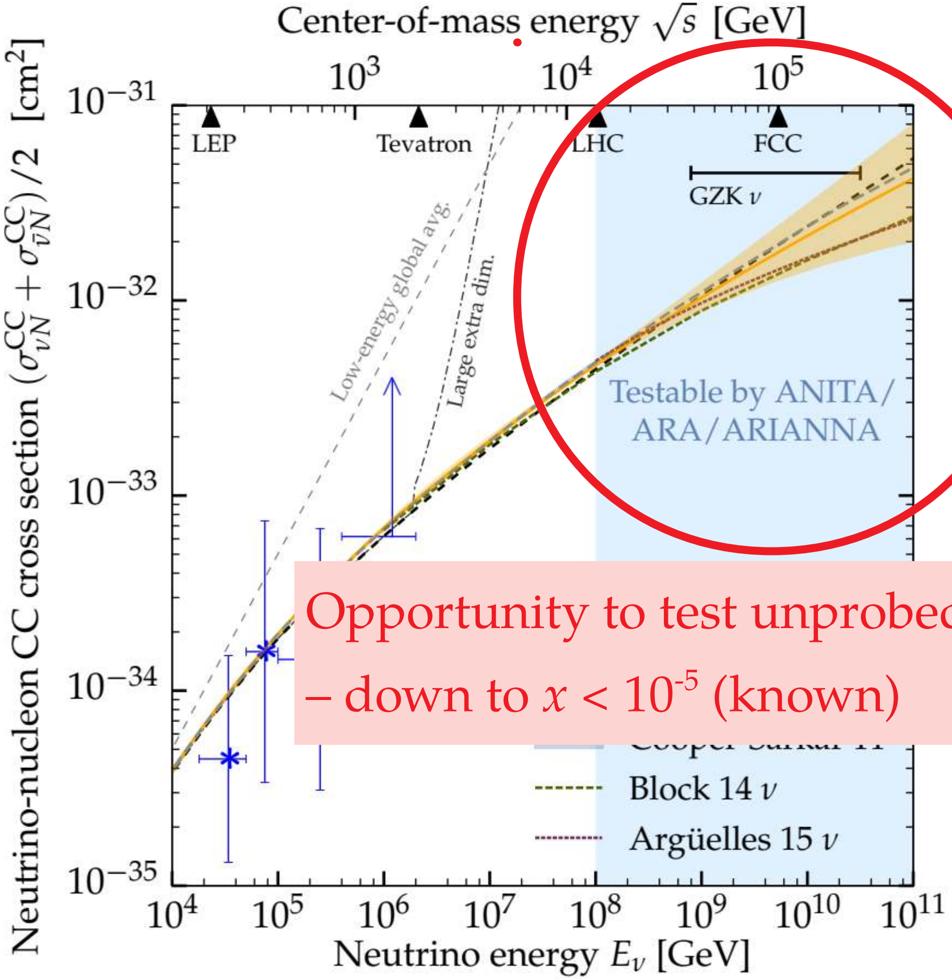


Opportunity to test unprobed nucleon structure – down to $x < 10^{-5}$ (known)

Marginalized cross section in each bin

TABLE I. Neutrino-nucleon charged-current inclusive cross sections, averaged between neutrinos ($\sigma_{\nu N}^{\rm CC}$) and anti-neutrinos ($\sigma_{\bar{\nu} N}^{\rm CC}$), extracted from 6 years of IceCube HESE showers. To obtain these results, we fixed $\sigma_{\bar{\nu} N}^{\rm CC} = \langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle \cdot \sigma_{\nu N}^{\rm CC}$ — where $\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$ is the average ratio of $\bar{\nu}$ to ν cross sections calculated using the standard prediction from Ref. [60] — and $\sigma_{\nu N}^{\rm NC} = \sigma_{\nu N}^{\rm CC}/3$, $\sigma_{\bar{\nu} N}^{\rm NC} = \sigma_{\bar{\nu} N}^{\rm CC}/3$. Uncertainties are statistical plus systematic, added in quadrature.

E_ν [TeV]	$\langle E_\nu \rangle$ [TeV]	$\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$	$\log_{10}[\frac{1}{2}(\sigma_{\nu N}^{\rm CC} + \sigma_{\bar{\nu} N}^{\rm CC})/{\rm cm}^2]$
18–50	32	0.752	-34.35 ± 0.53
50–100	75	0.825	-33.80 ± 0.67
100–400	250	0.888	-33.84 ± 0.67
400–2004	1202	0.957	> -33.21 (1σ)

MB & A. Connolly, 1711.11043

Neutrino zenith angle distribution

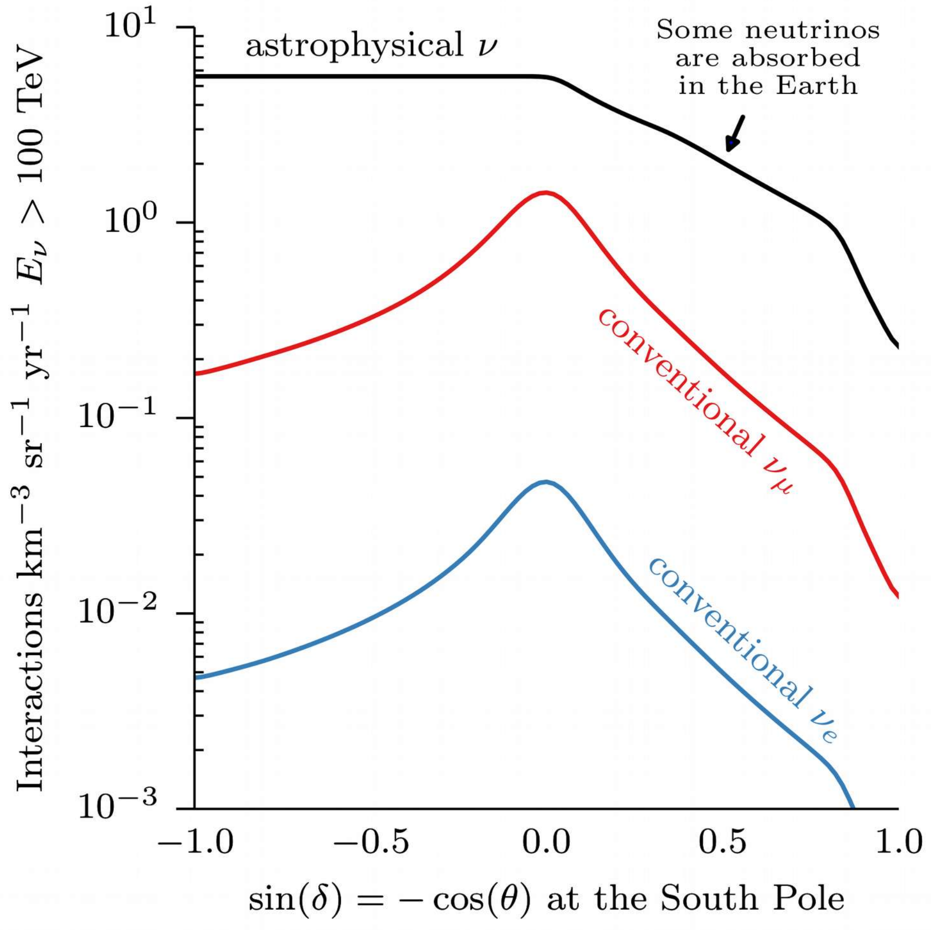


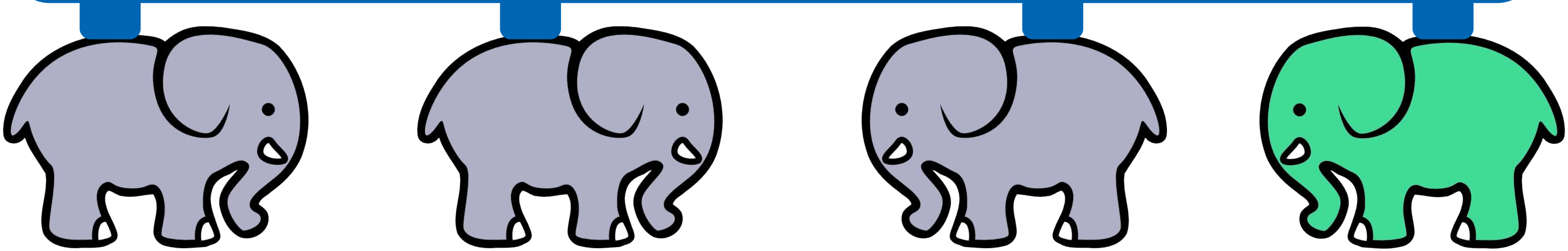
Figure by
Jakob Van Santen
ICRC 2017

GRAND construction timeline

GRANDProto300

	GRANDProto35		GRAND10k	GRAND200k
	2018	2020	2025	203X
Goals	**Standalone** radio detection of EAS Very good **background rejection**	Standalone radio detection of **very inclined showers** (θ>65°) induced by high energy cosmic rays (>10^9 GeV)	First GRAND subarray, **sensitivity comparable to ARA/ARIANNA on similar time scale,** allowing potential 1st discovery of cosmogenic neutrinos	**First neutrino detection at 10^9 GeV even with pessimistic fluxes and/or neutrino astronomy**
Setup	35 radio antennas 21 scintillators	• 300 Horizon Antennas over 300 km² • Fast DAQ • Solar pannels (day use) + WiFi data transfer • TBD: Array of surface muon detectors	DAQ with discrete elements, but mature design for trigger, data transfer, consumption	200'000 antennas over 200'000 km² Hotspots could be in different continents
Budget & stage	160k€, fully funded by NAOC+IHEP, deployment 2018 @ Ulastai	1.3 M€ to be deployed in 2019	1500€ / detection unit	**Industrial scale allows to cut costs down: 500€/unit** **➔ 120M€ in total**

High-Energy Astroparticle Physics: Neutrinos, Cosmic rays, Gamma rays



Fundamental Physics with High-Energy Astrophysical Neutrinos

Modeling and Constraining Multi-Messenger Sources

Constraining UHECRs with UHE Neutrinos

Giant Radio Array for Neutrino Detection (GRAND)

Constraining UHECRs with UHE Neutrinos

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Distribution of sources → Propagate CRs to Earth → Normalize to UHECR spectrum

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Baerwald, **MB**, Winter, *Astropart. Phys.* 2015

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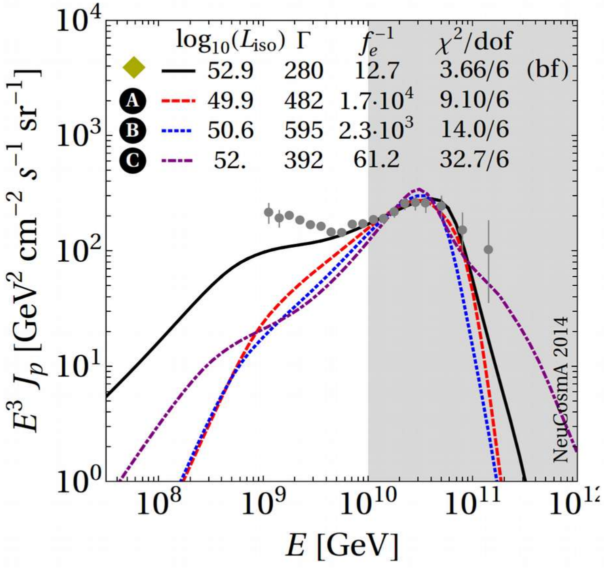

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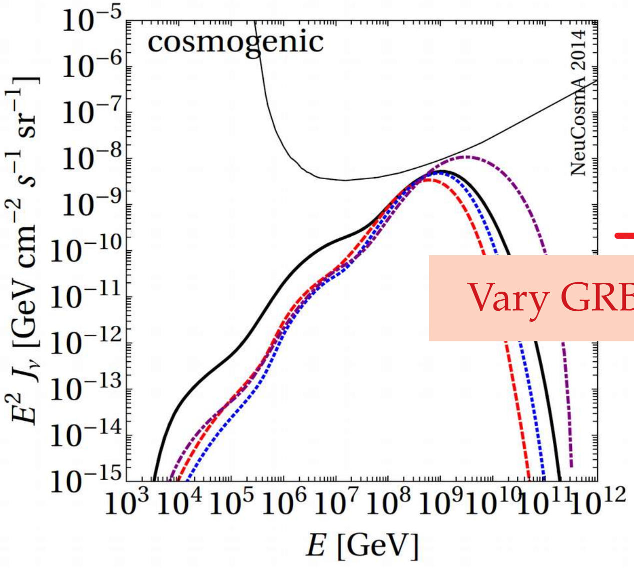

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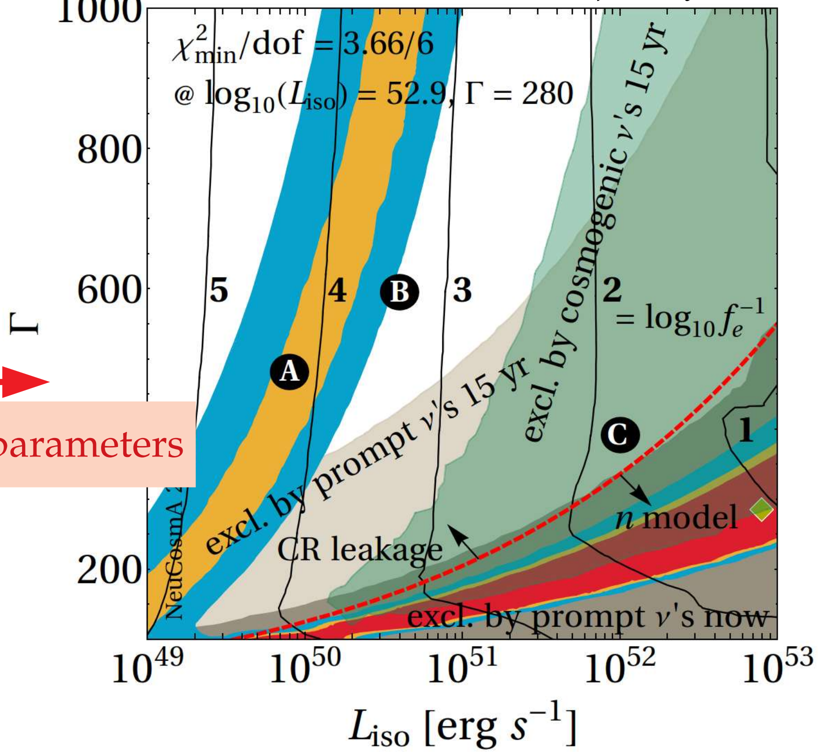

Modeling and Constraining Multi-Messenger Sources

↦ Future work

- Explore more ν source classes
  - Transient and steady, dark and bright
- Constrain sources with public IceCube data
  - Predict for next-gen detectors
- Galactic sources of TeV–PeV neutrinos
- Work with experimental collaborations –
  - ANITA: First search for EeV neutrinos from GRBs
  - ANTARES: Include more GRB emission mechanisms
  - Auger (tentative): EeV neutrinos from GRBs
  - GRAND (future)

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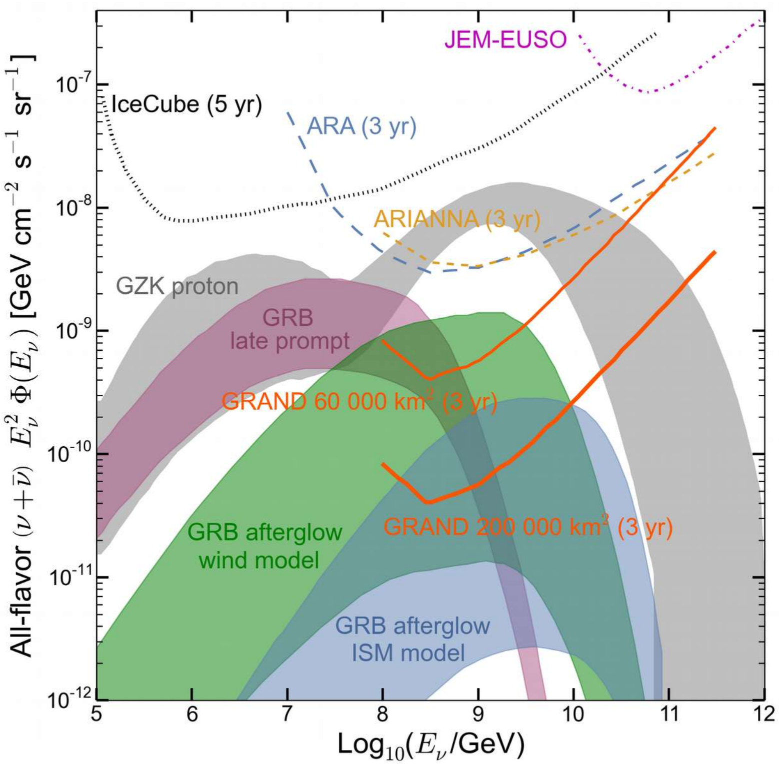
Neutrinos from GRB afterglows



MB & I. Tamborra, *In prep.*

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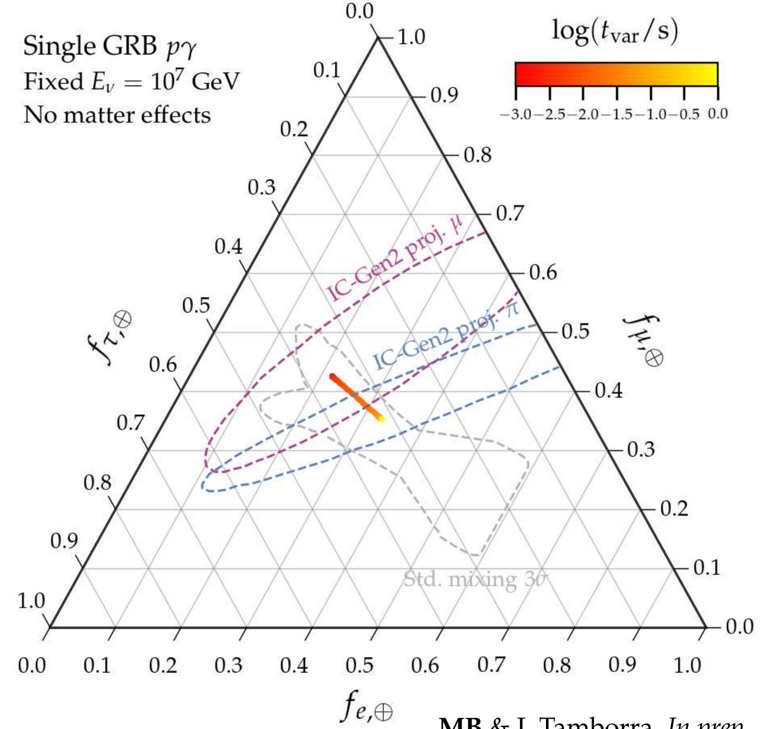
Neutrinos from tidal disruption events

Constraining sources using flavor



MB & I. Tamborra, *In prep.*

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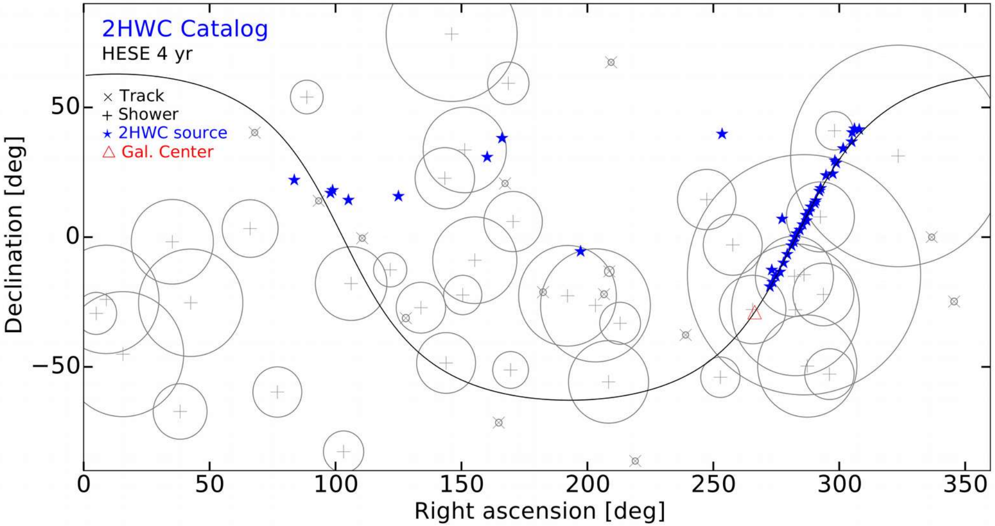
MB, Li, Linden, Beacom, *In prep.*



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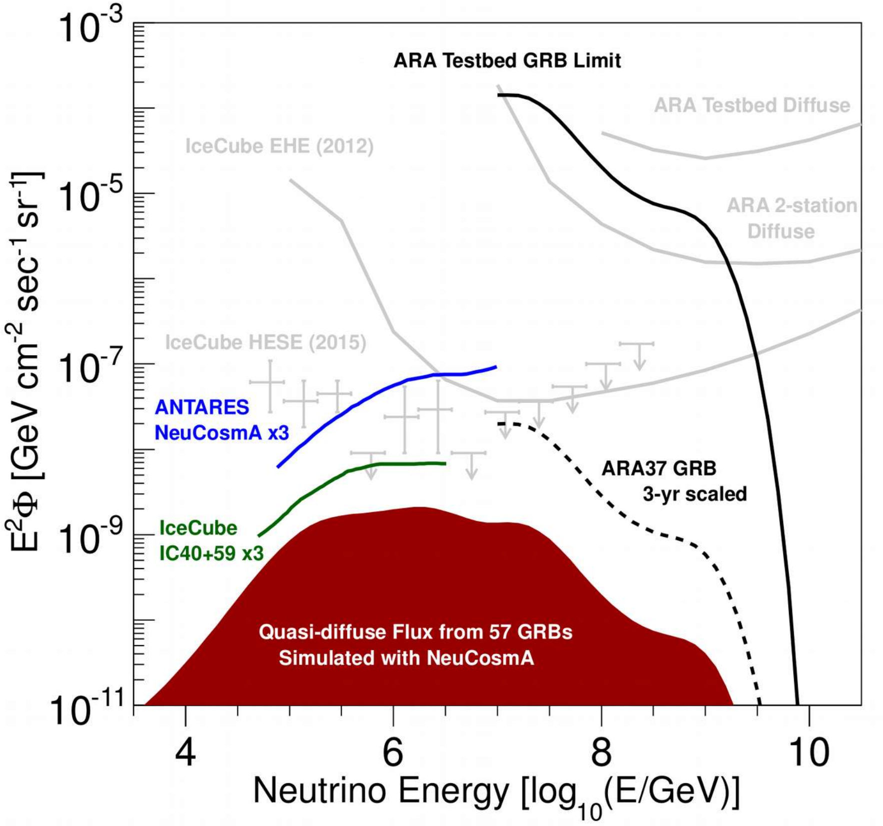
Modeling and Constraining Multi-Messenger Sources

↦ Research experience

Work with experimental collaborations



← First search for GRB neutrinos from ARA

ARA, **MB**, Guetta, *Astropart. Phys.* 2017

Modeling and Constraining Multi-Messenger Sources

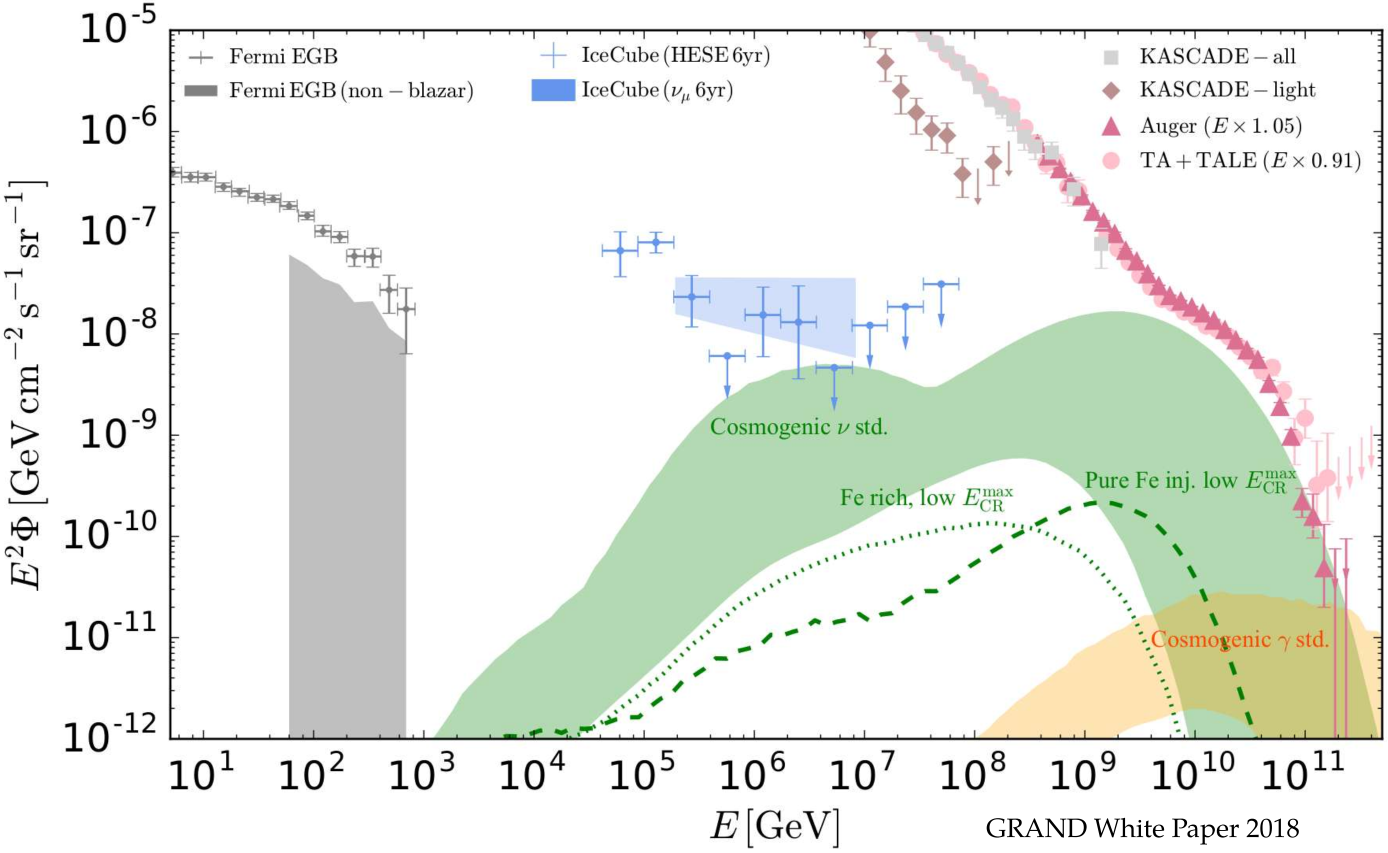
↦ Background

- Cosmic-ray sources must also make neutrinos and gamma rays

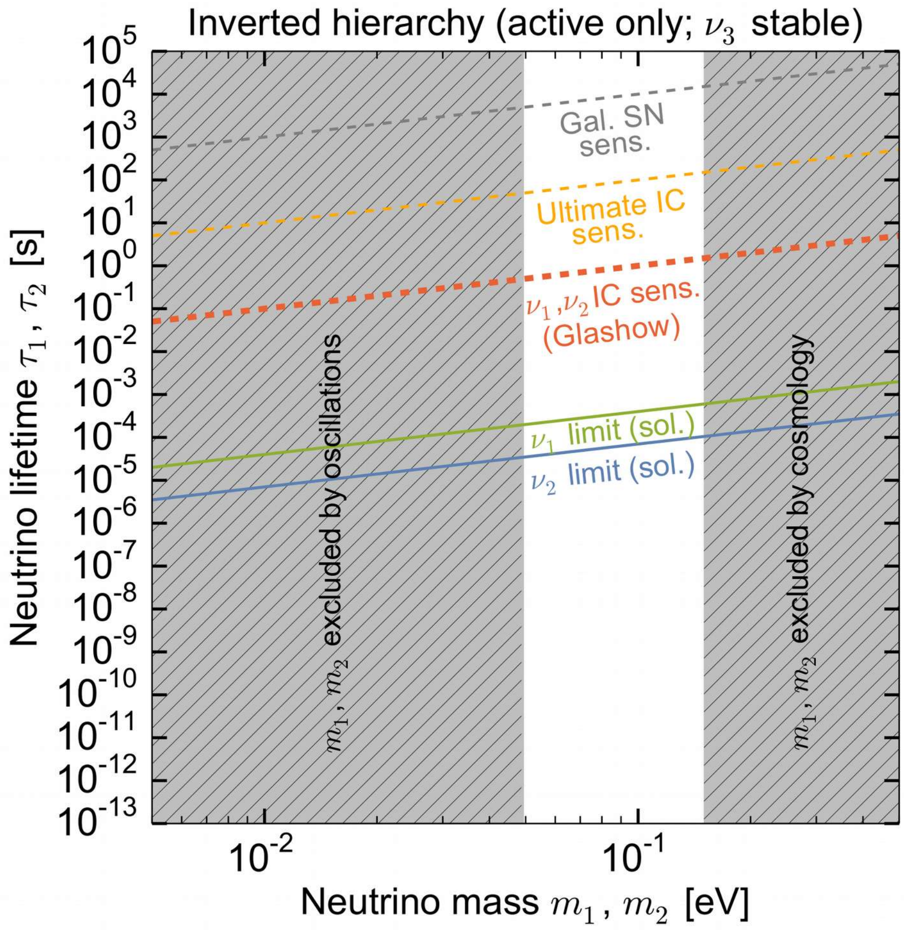
$$pp, p\gamma \to \begin{cases} \pi^{\pm} \to \gamma\gamma \\ \pi^{0} \to \nu_e \nu_\mu \nu_\mu \end{cases}$$

$E_\gamma = E_p/10$

$E_\nu = E_p/20$

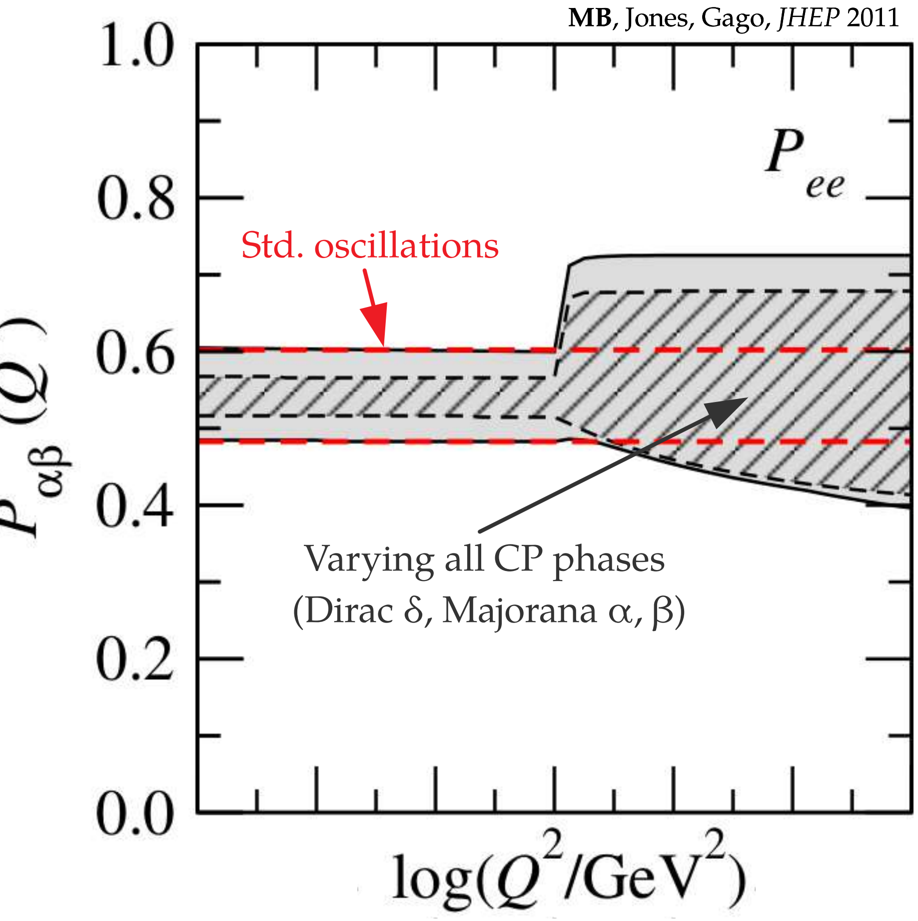


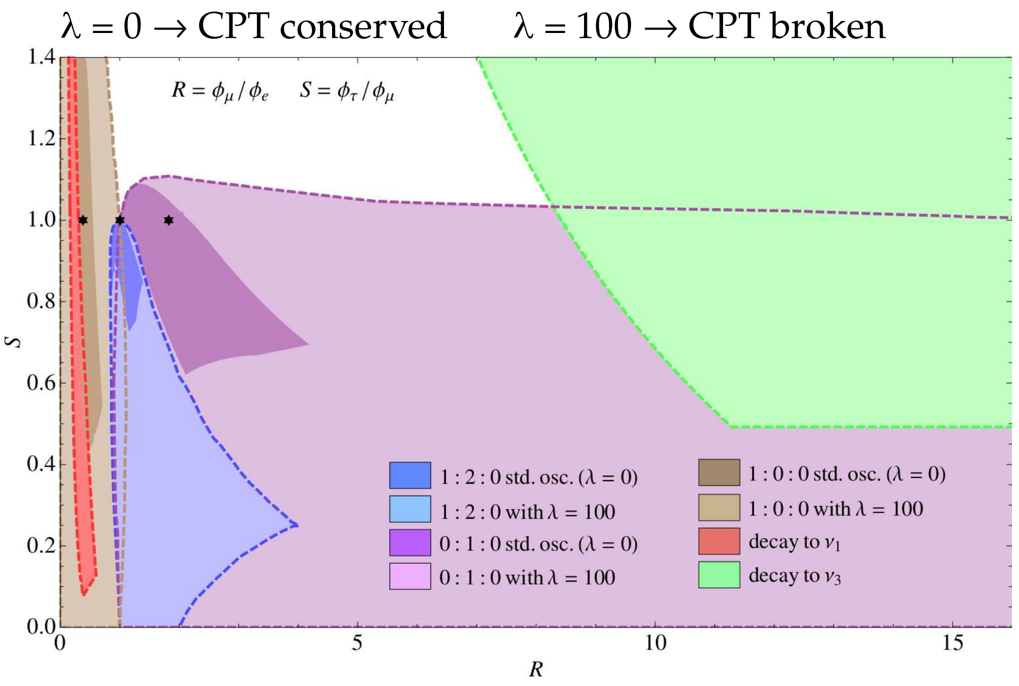
GRAND White Paper 2018



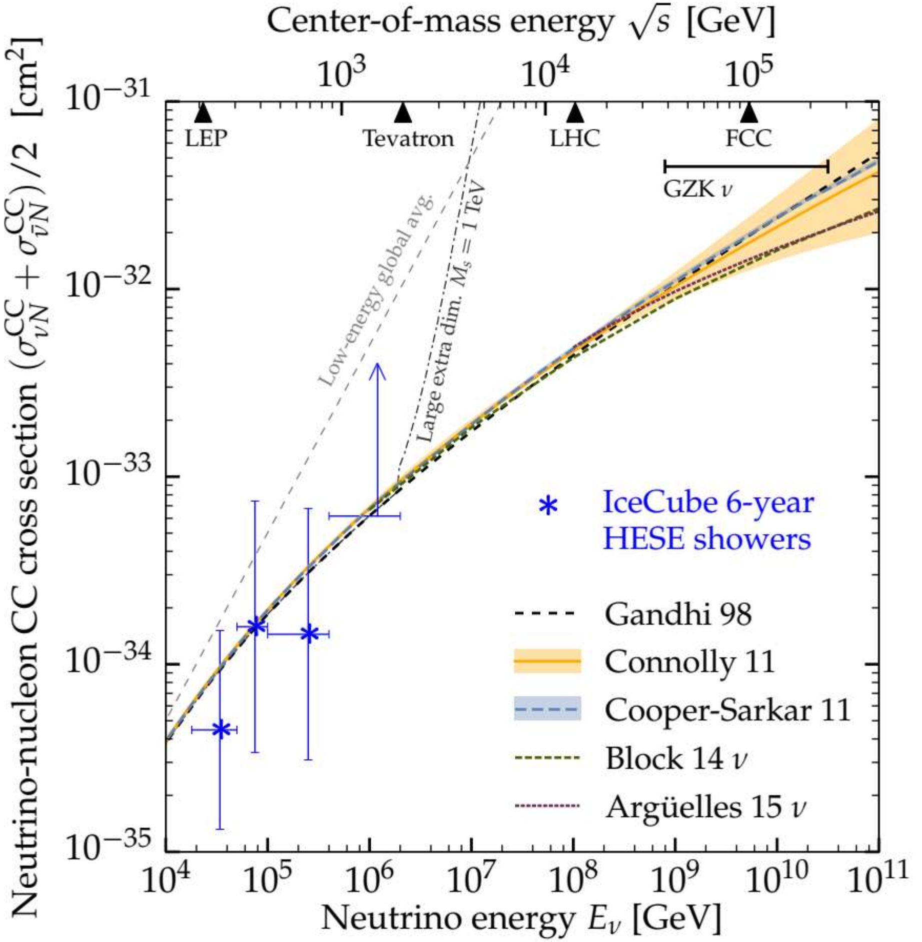
MB, Beacom, Murase, *PRD* 2017

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

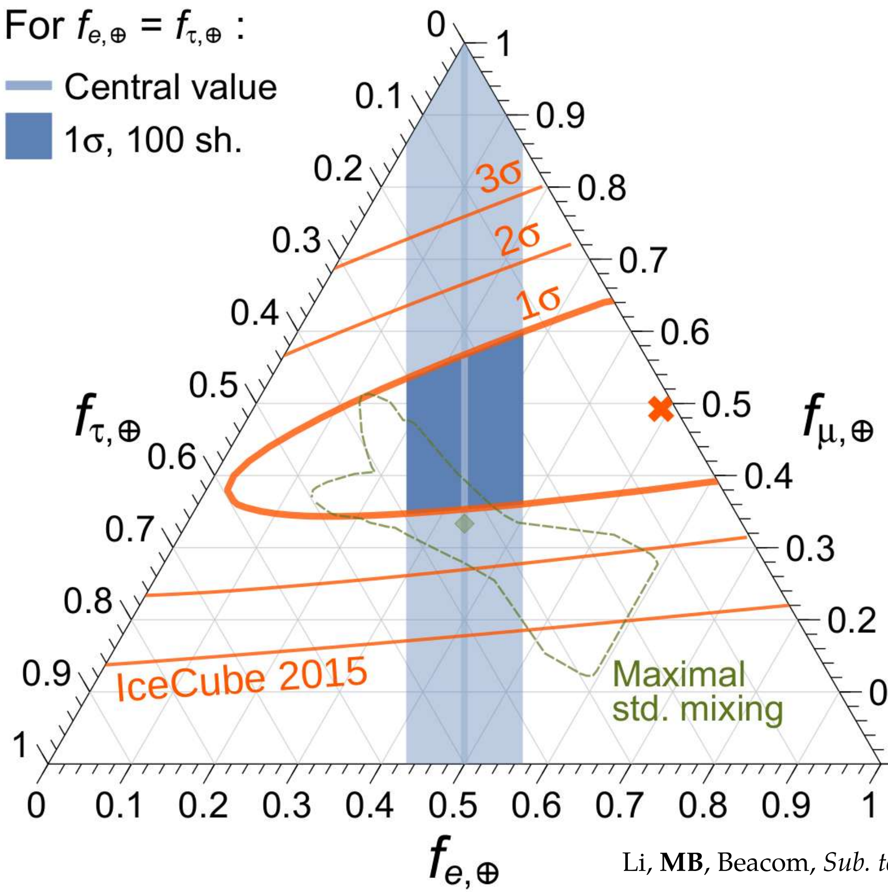




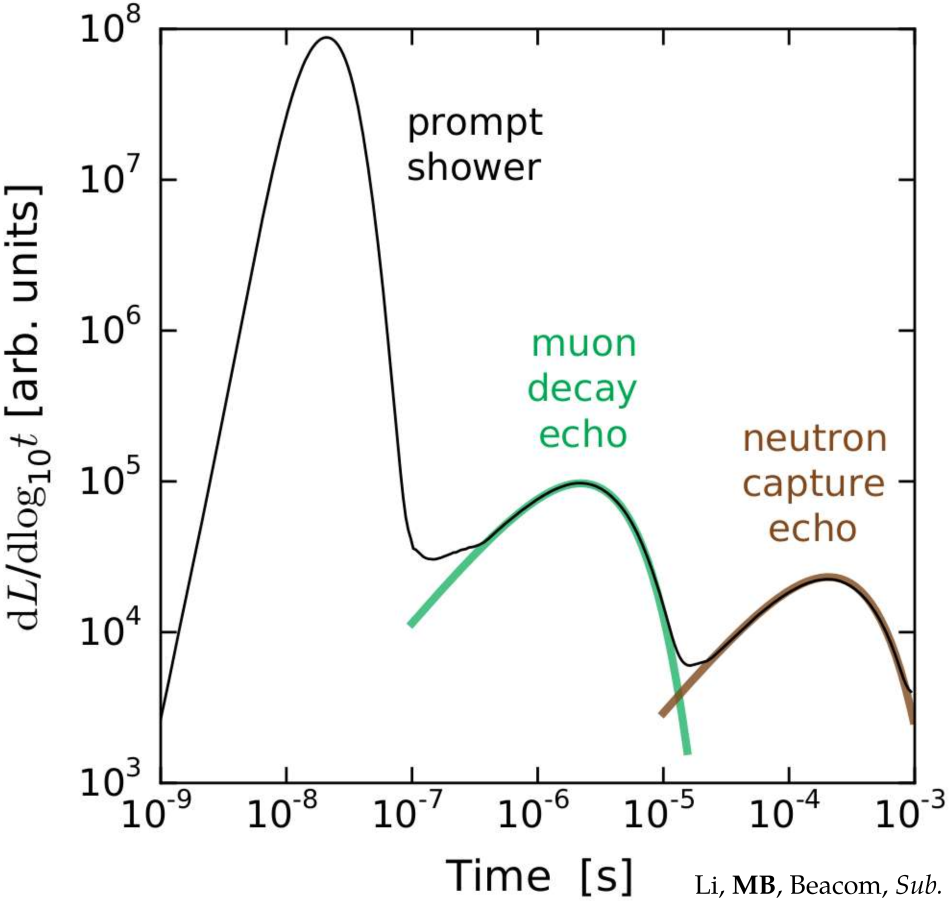
MB, Gago, Peña-Garay, *JHEP* 2010
MB *et al.*, IJMPA 2009



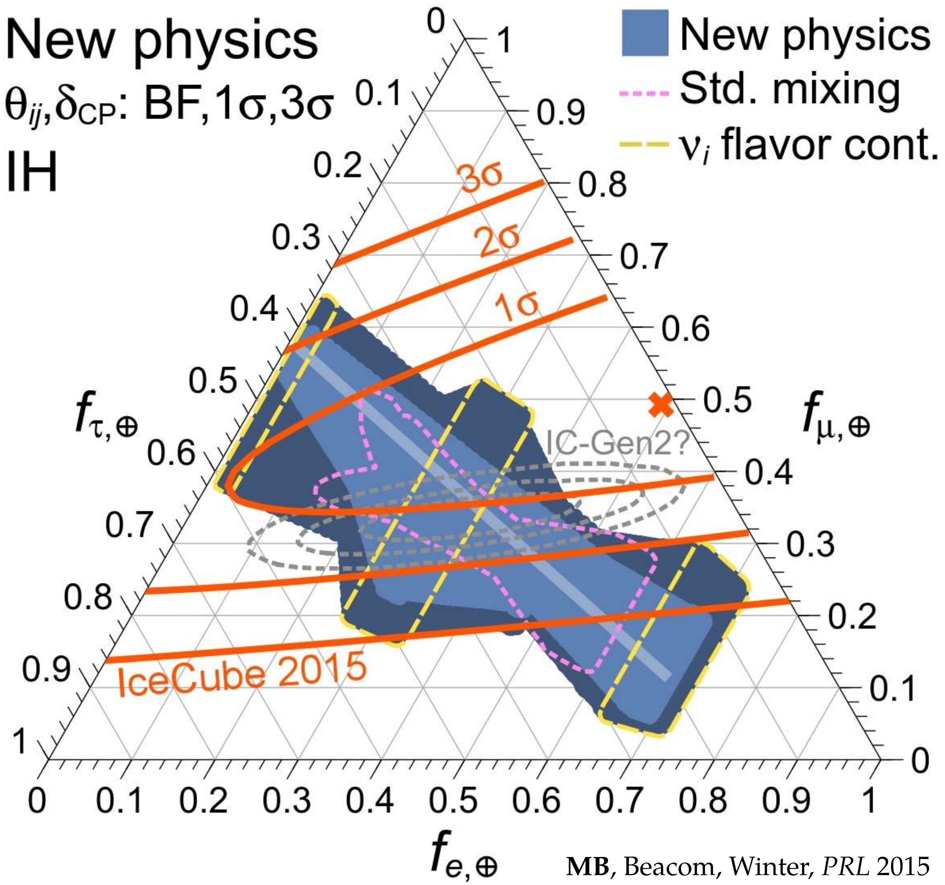
MB, Connolly, 1711.11043, *Sub. to PRL*



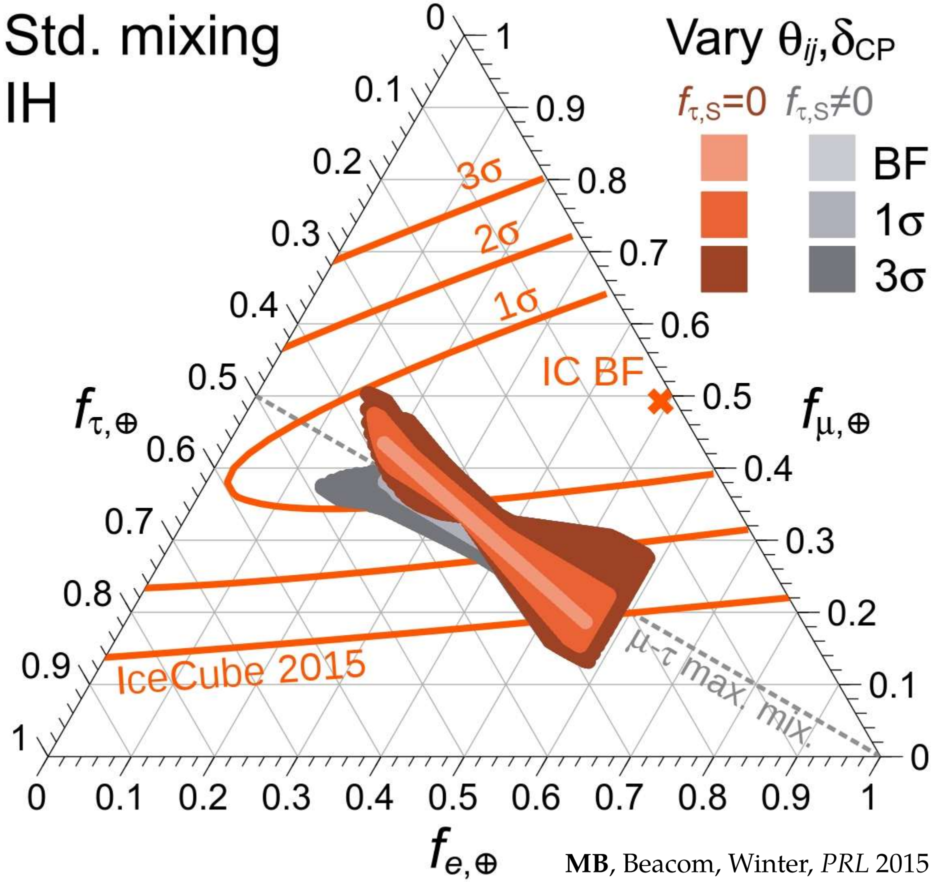
Li, **MB**, Beacom, *Sub. to PRL*



Li, **MB**, Beacom, *Sub. to PRL*



MB, Beacom, Winter, *PRL* 2015



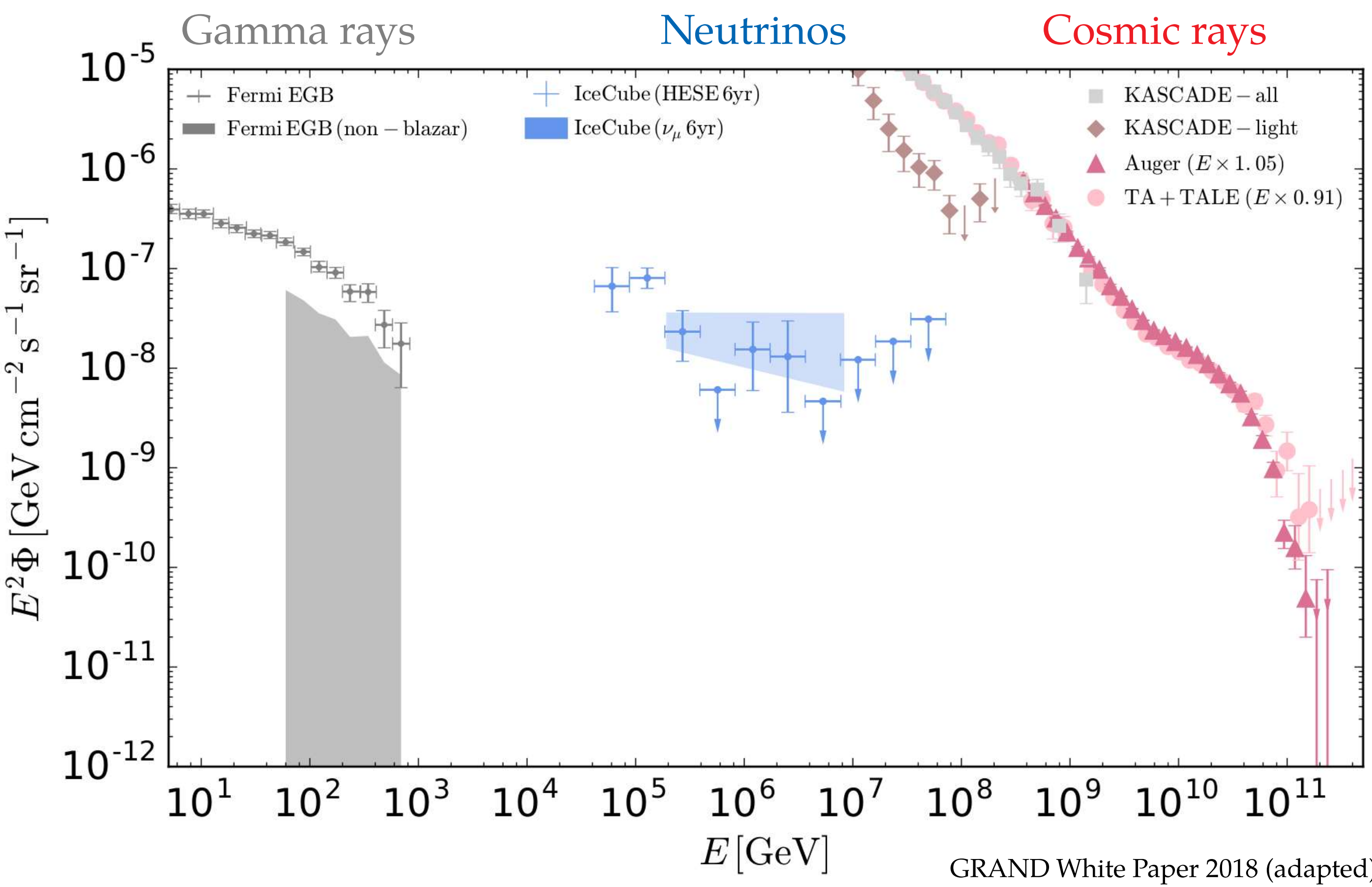
MB, Beacom, Winter, *PRL* 2015

Neutrinos – smoking guns of UHECR sources

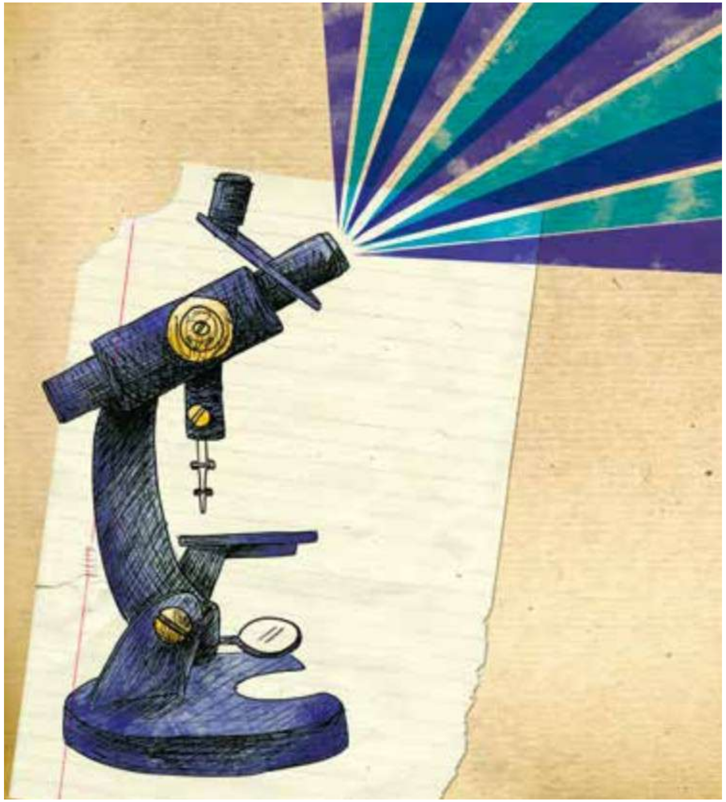
$E_\gamma = E_p/10$

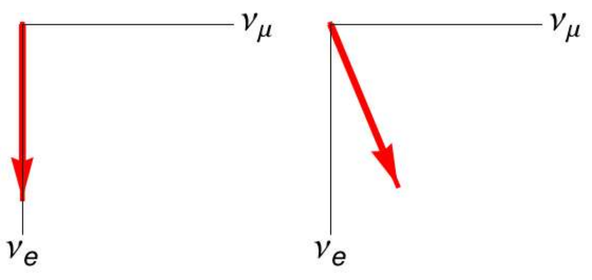
$$pp, p\gamma \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^\pm \rightarrow \nu_e \nu_\mu \nu_\mu \end{cases}$$

$E_\nu = E_p/20$

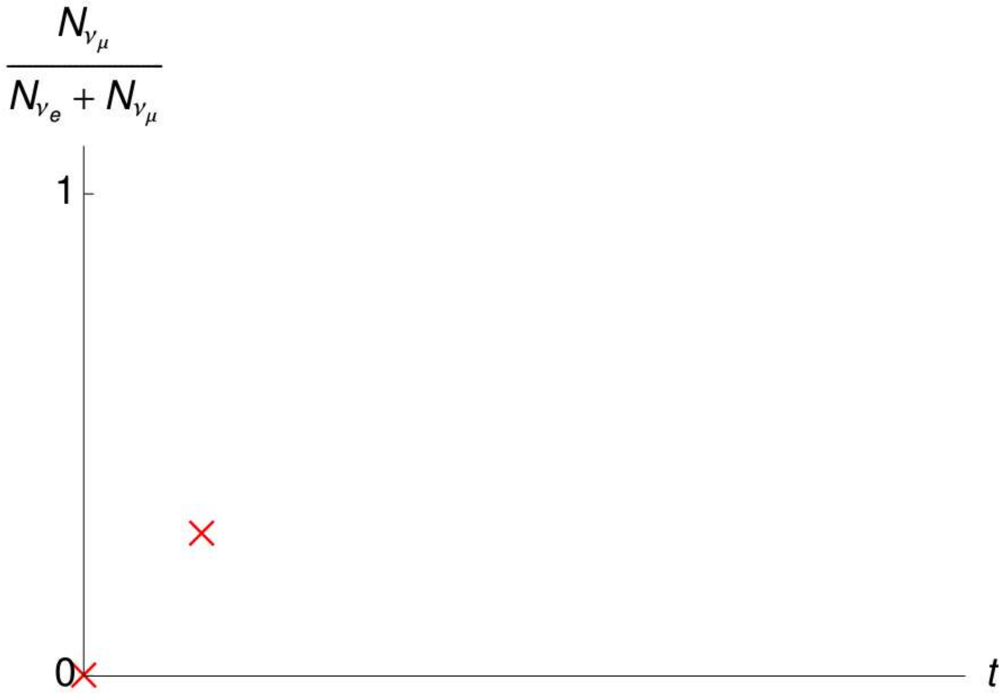


GRAND White Paper 2018 (adapted)

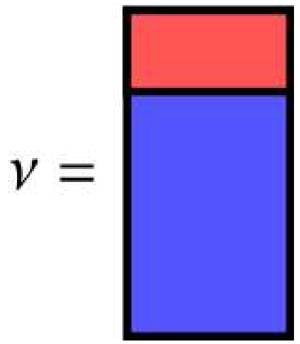




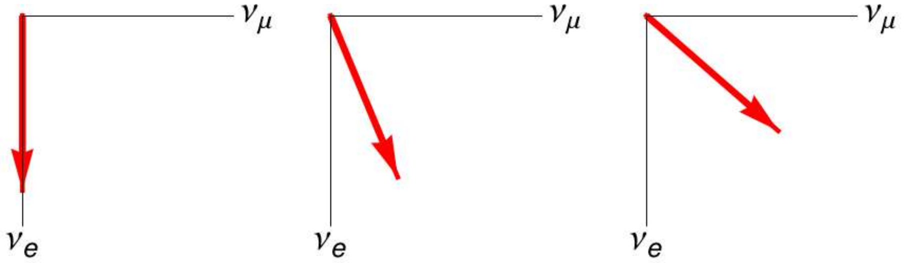
ν_μ
ν_e
ν_μ
ν_e



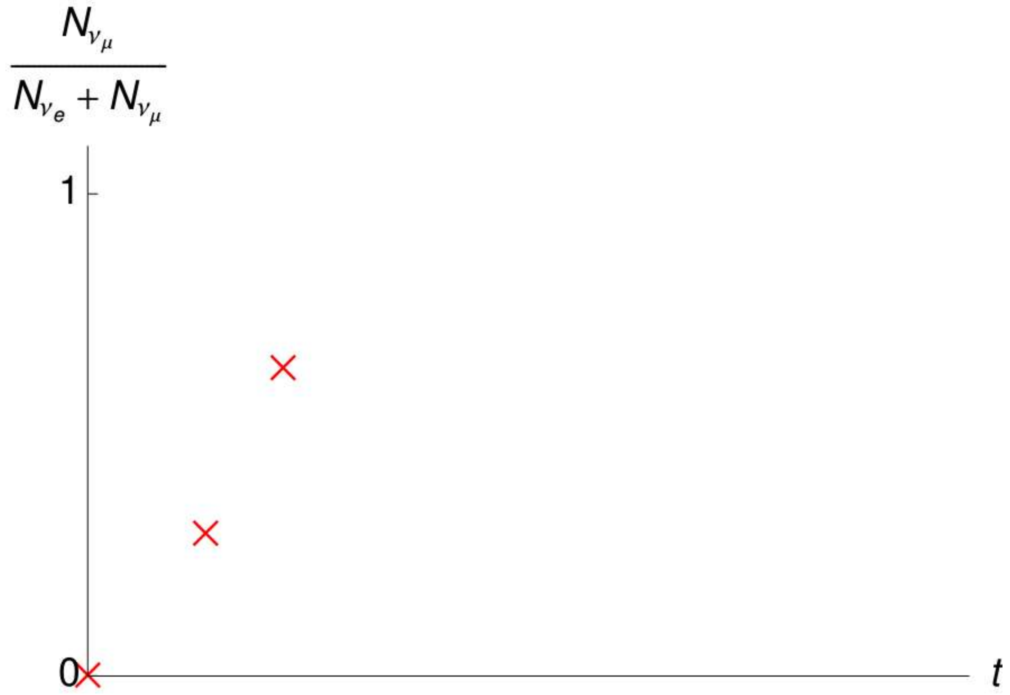
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t



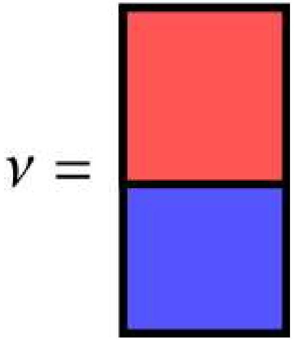
$\nu =$



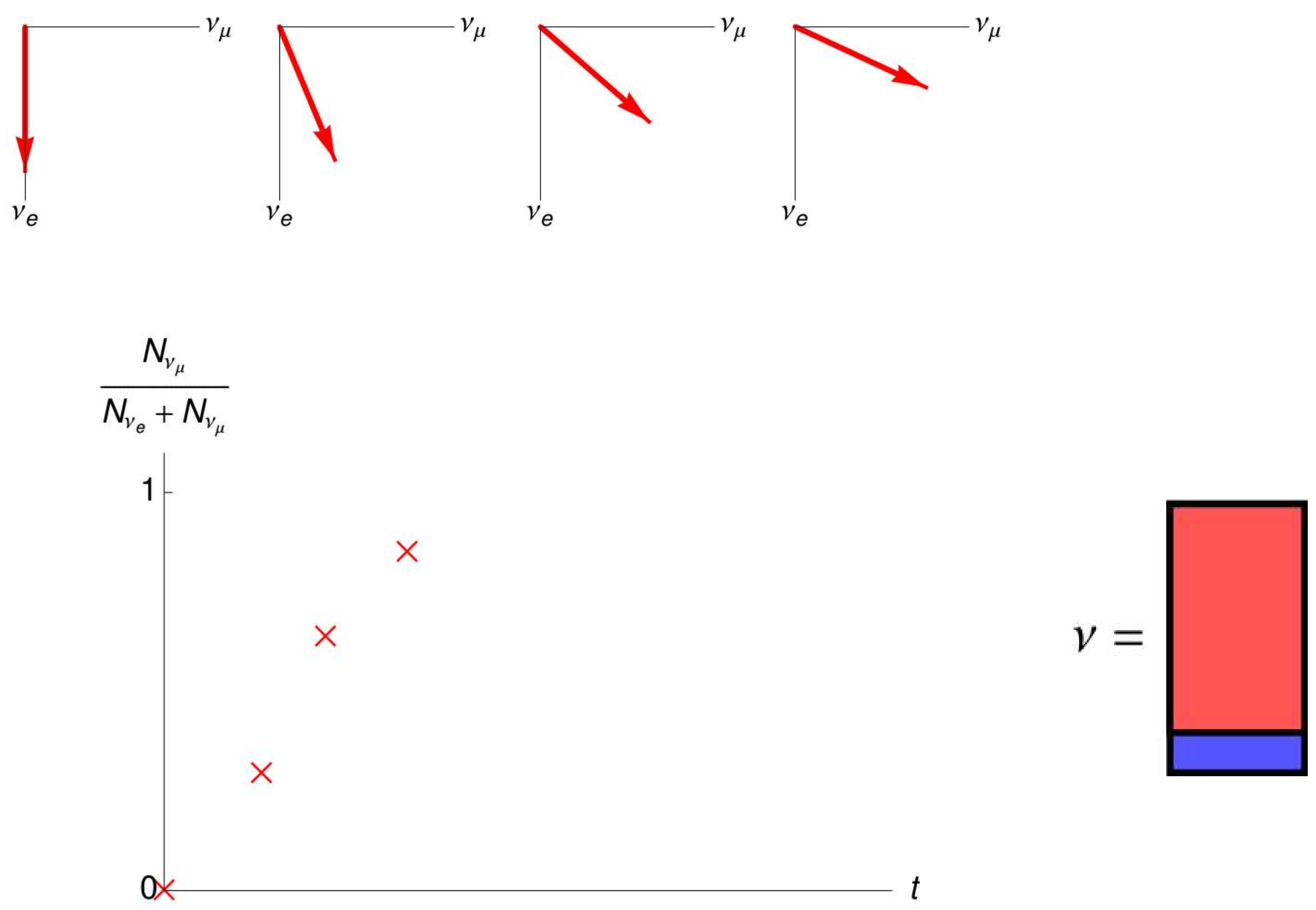
ν_μ
ν_e
ν_μ
ν_e
ν_μ
ν_e



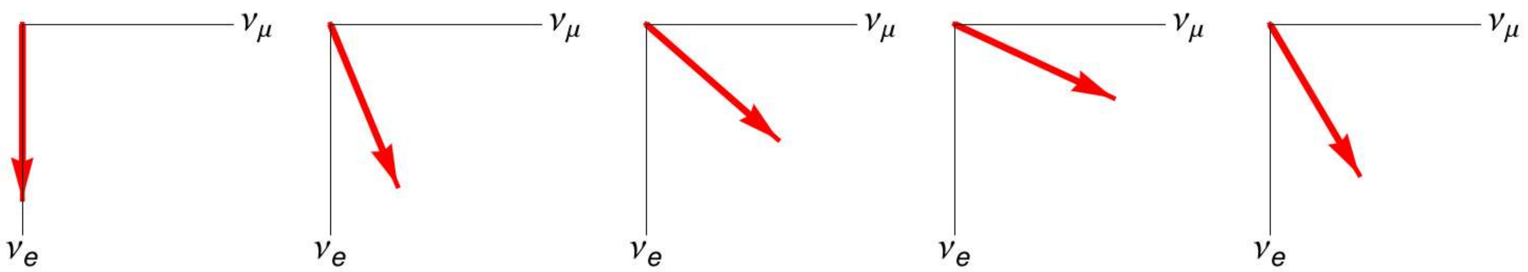
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t



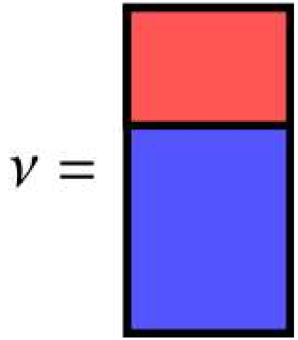
$\nu =$

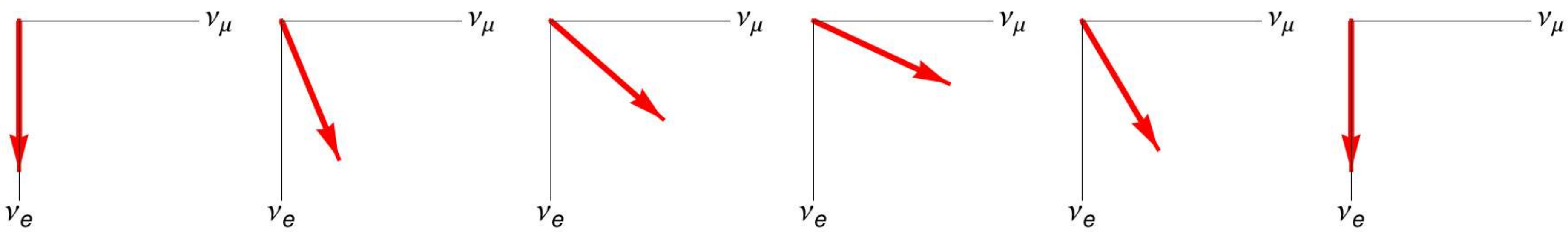


ν_μ
ν_e
ν_μ
ν_e
ν_μ
ν_e
ν_μ
ν_e
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t
$\nu =$


ν_μ
ν_e

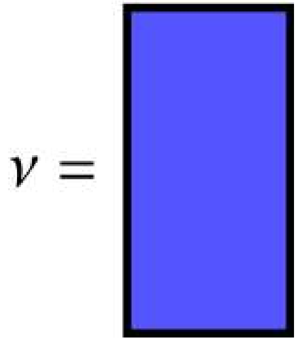

$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t


$\nu =$



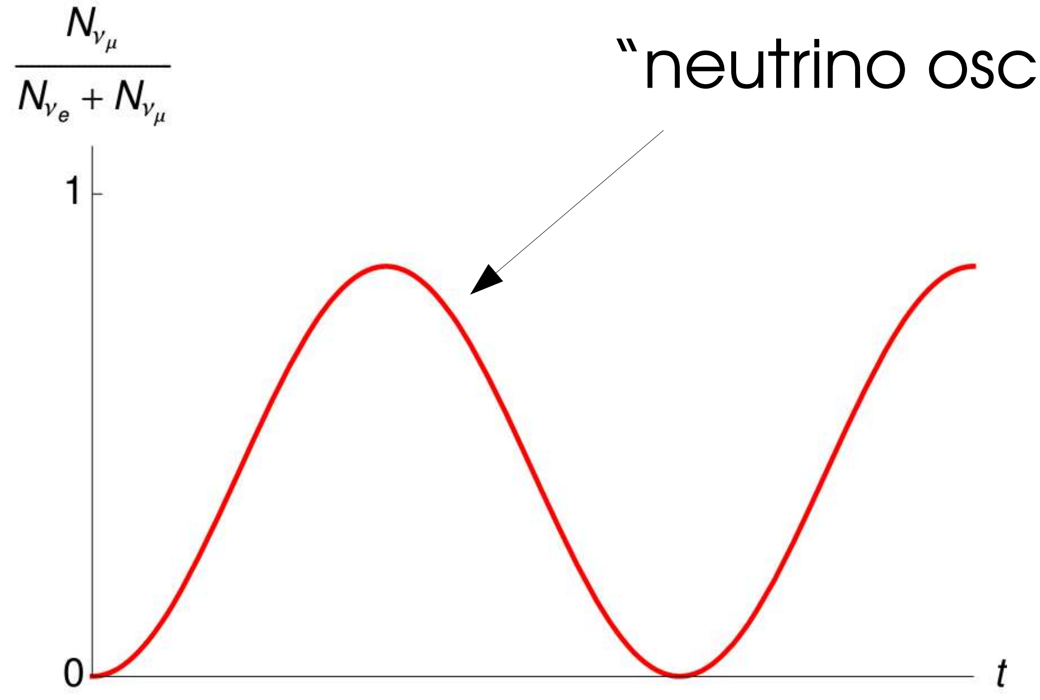
ν_μ
ν_e

$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t

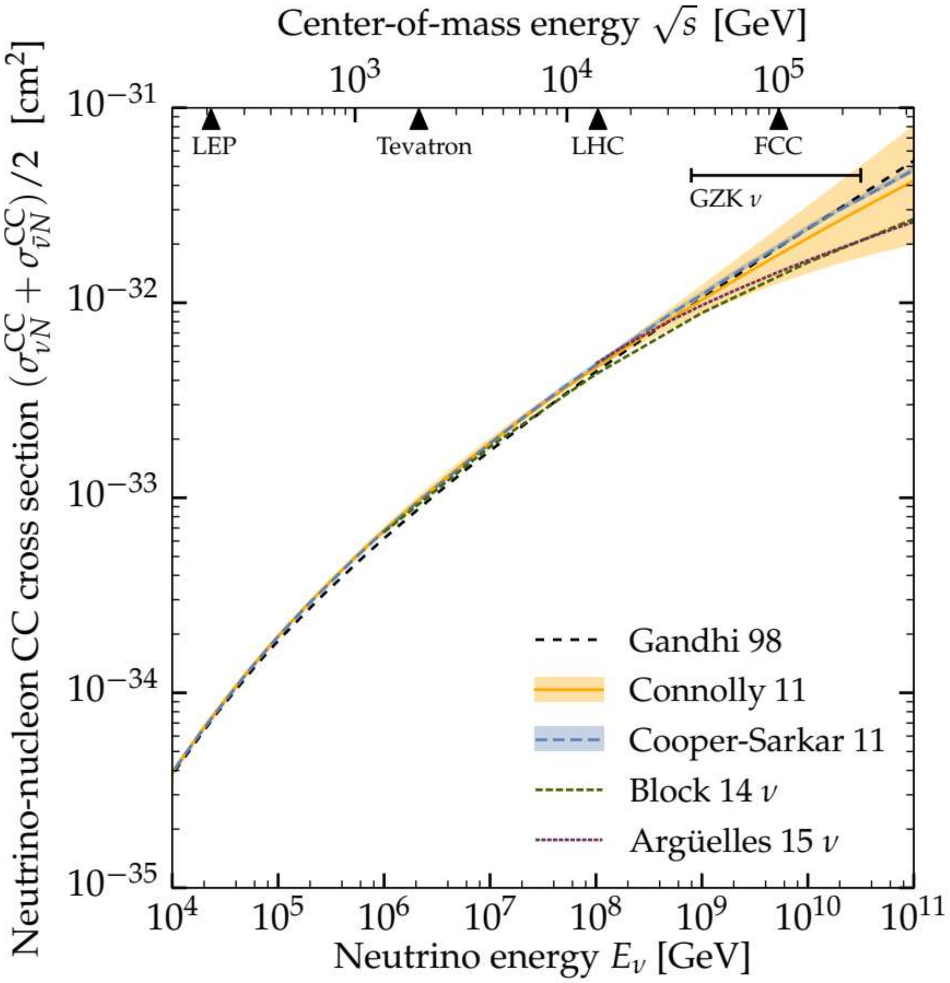


$\nu =$

“neutrino oscillations”

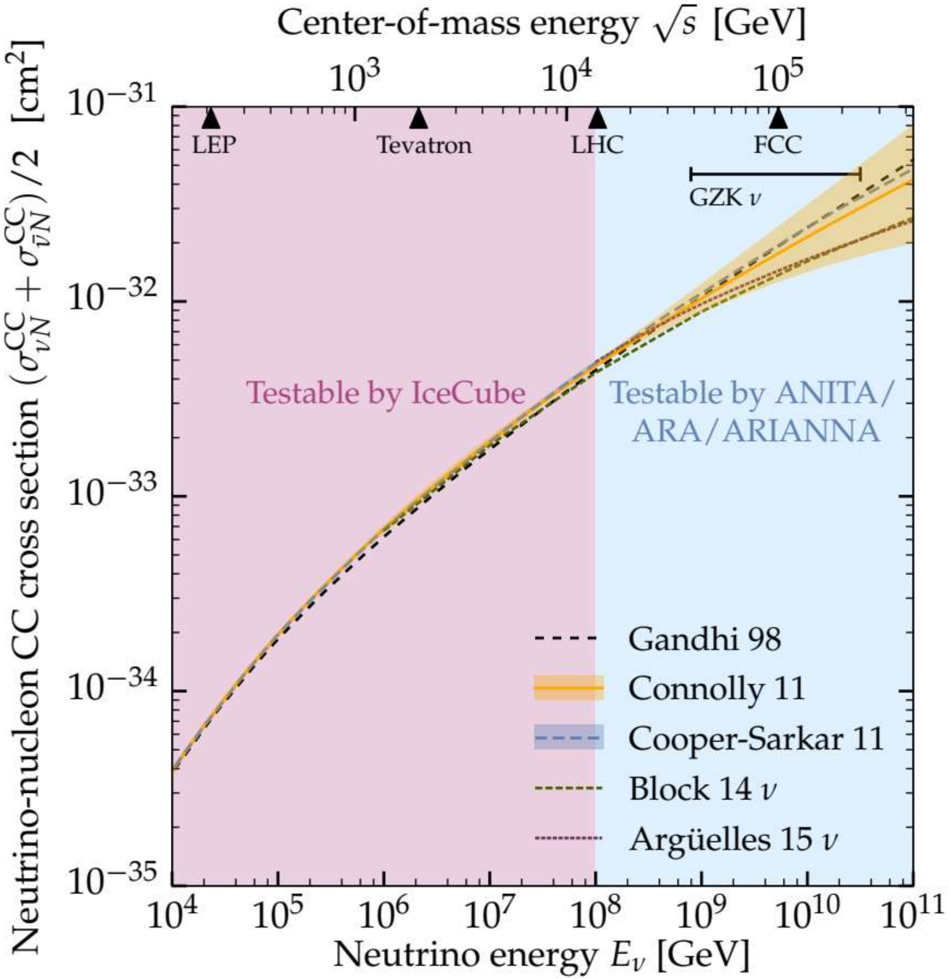


What can we measure *now* and later?

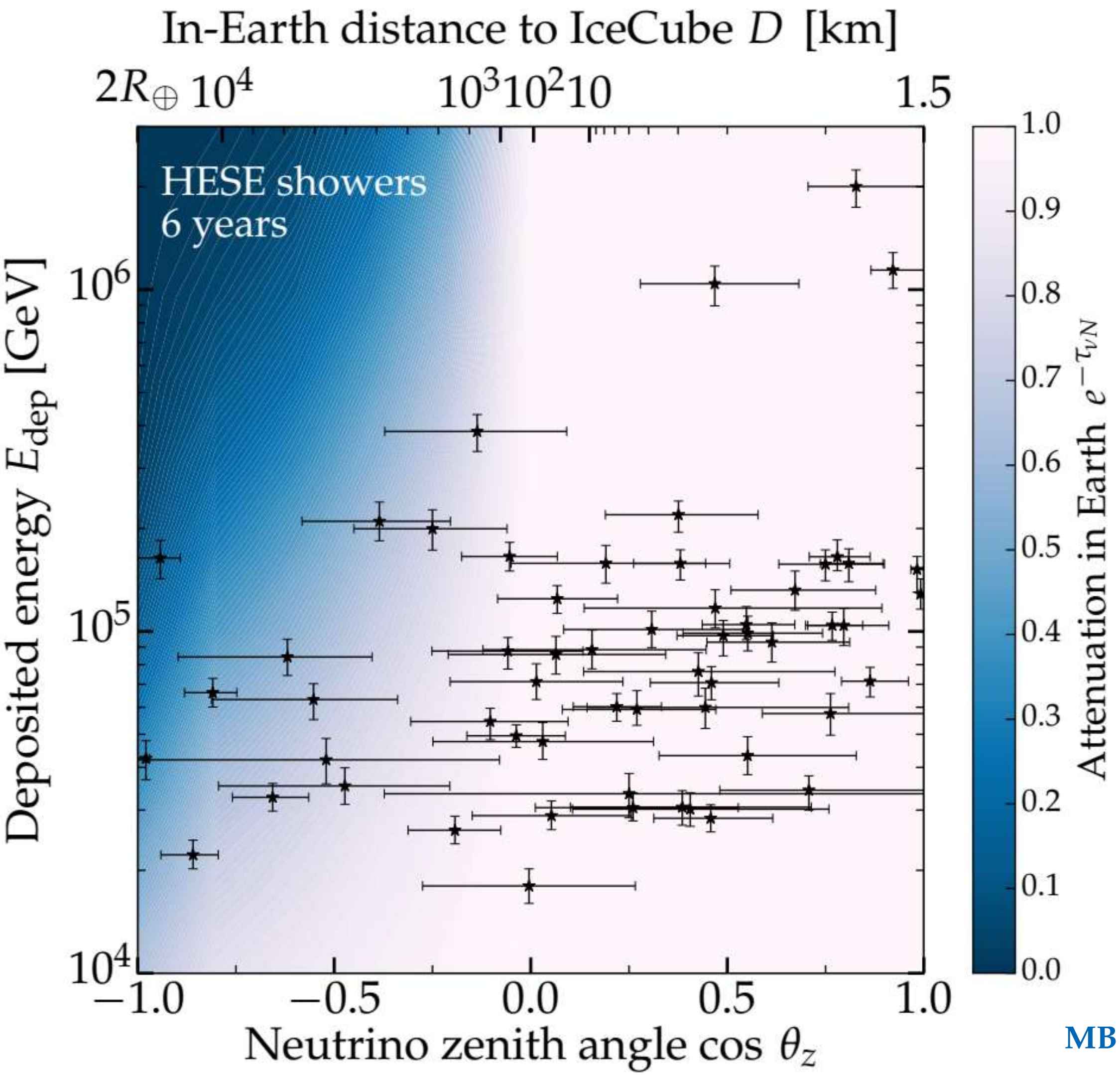


MB & Connolly, 1711.11043

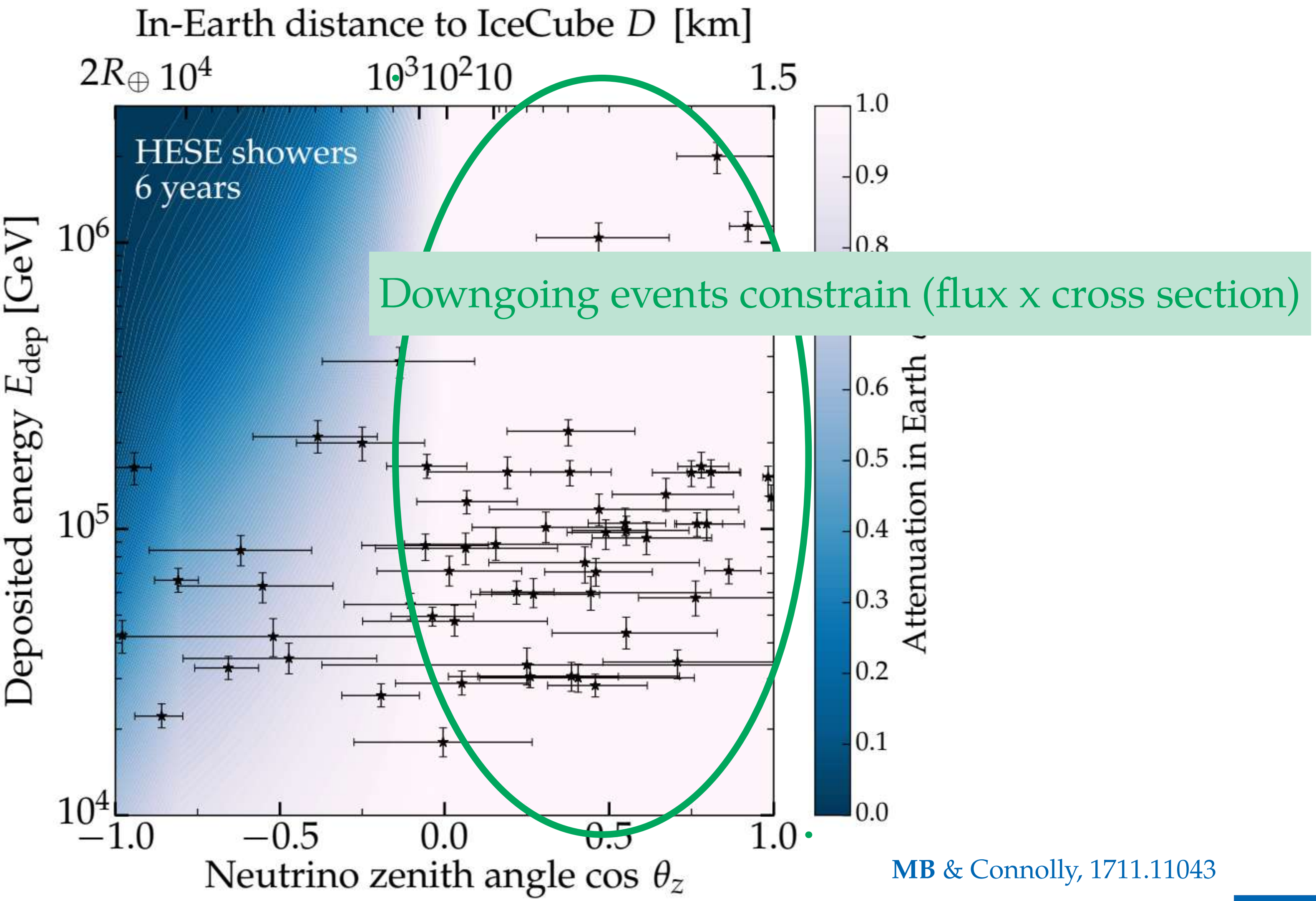
What can we measure *now* and later?



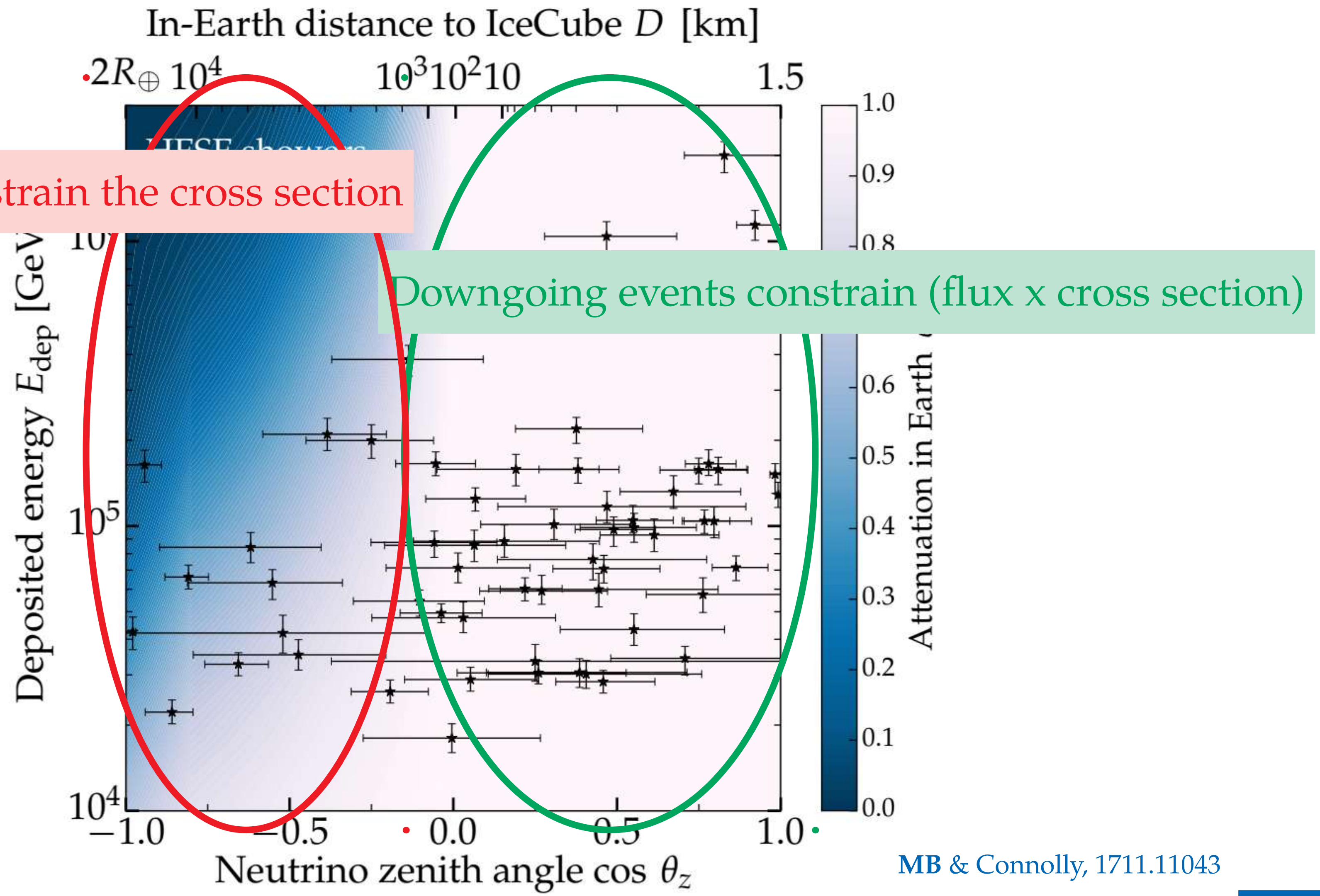
MB & Connolly, 1711.11043



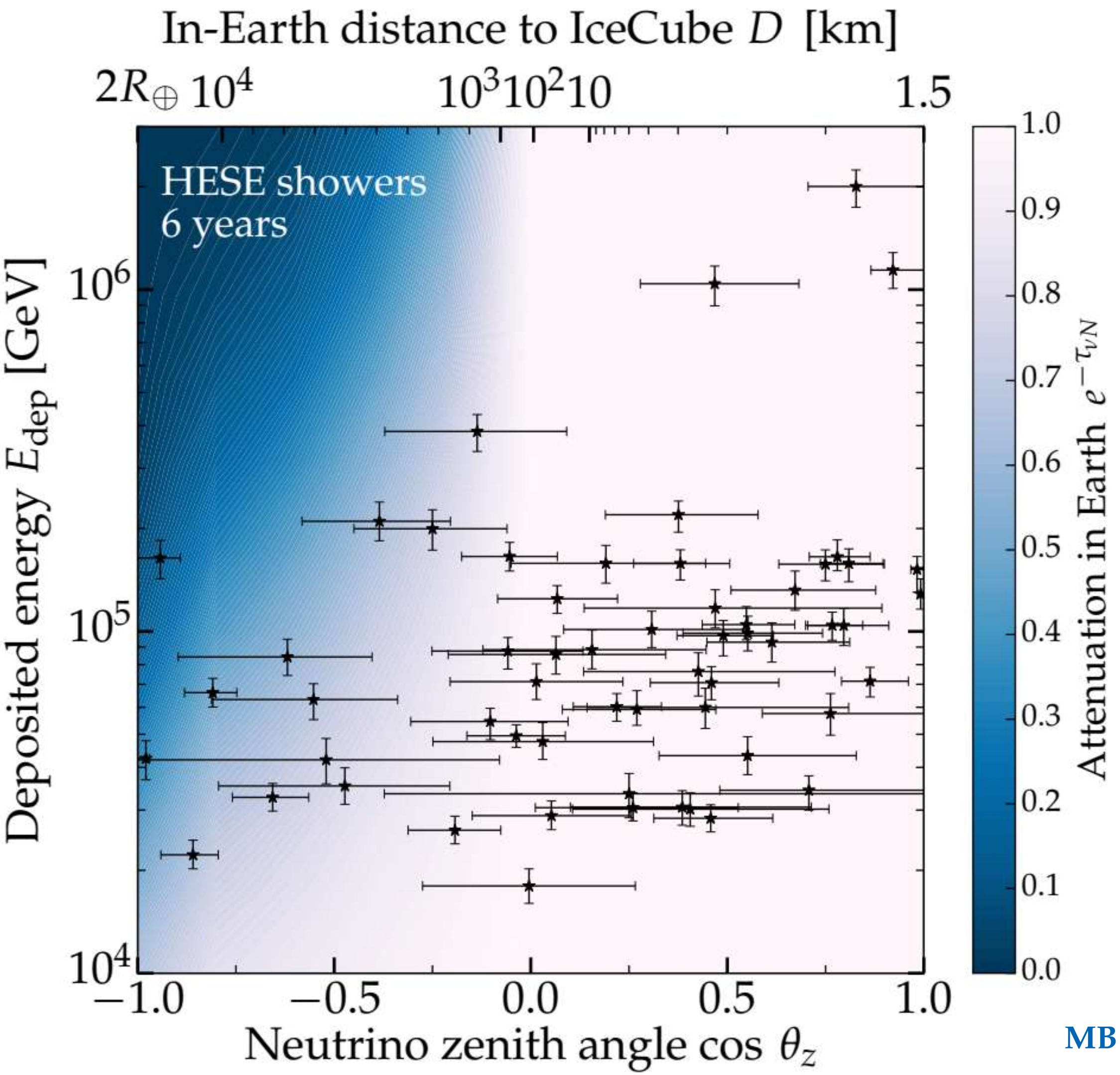
MB & Connolly, 1711.11043



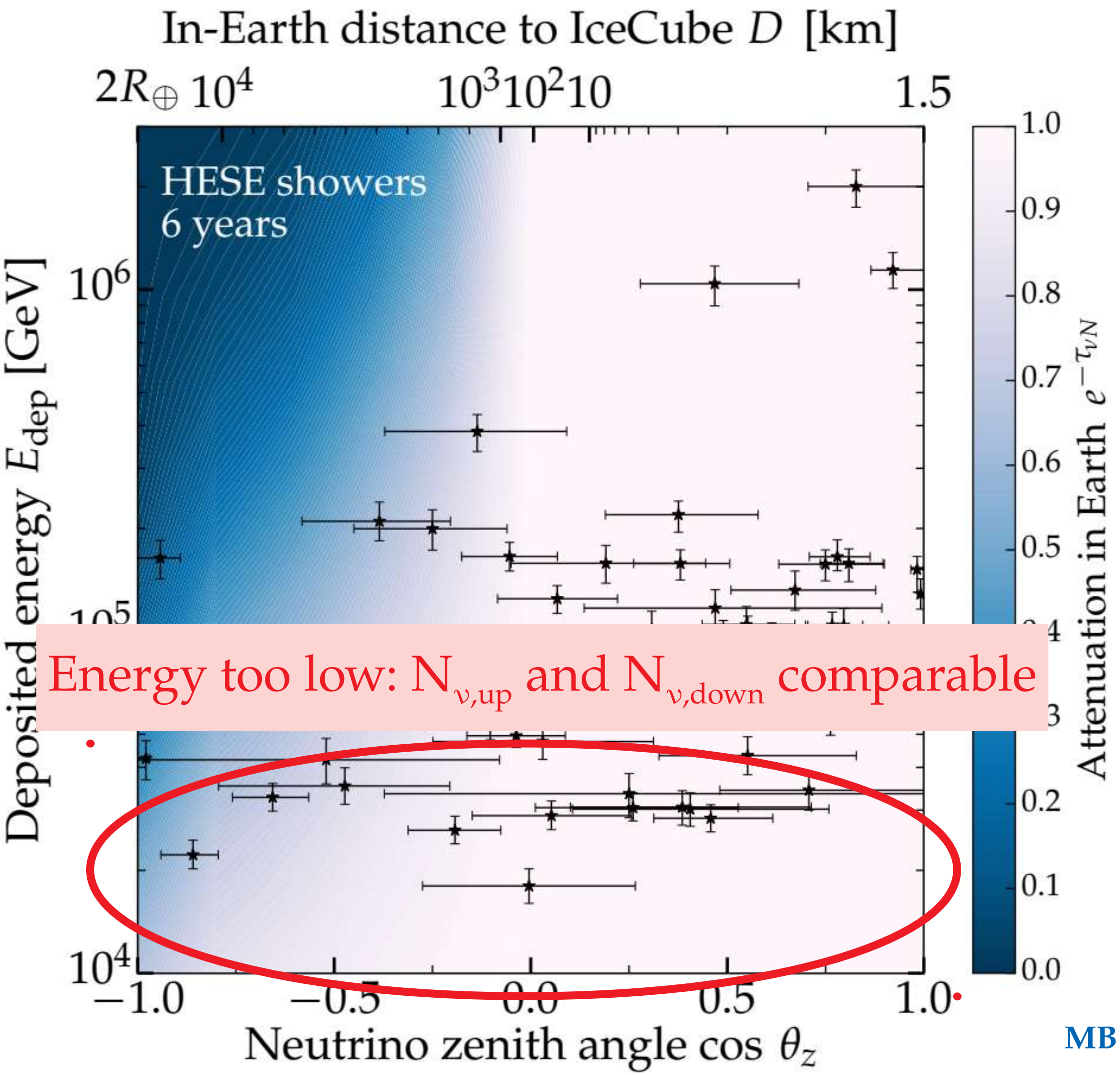
MB & Connolly, 1711.11043



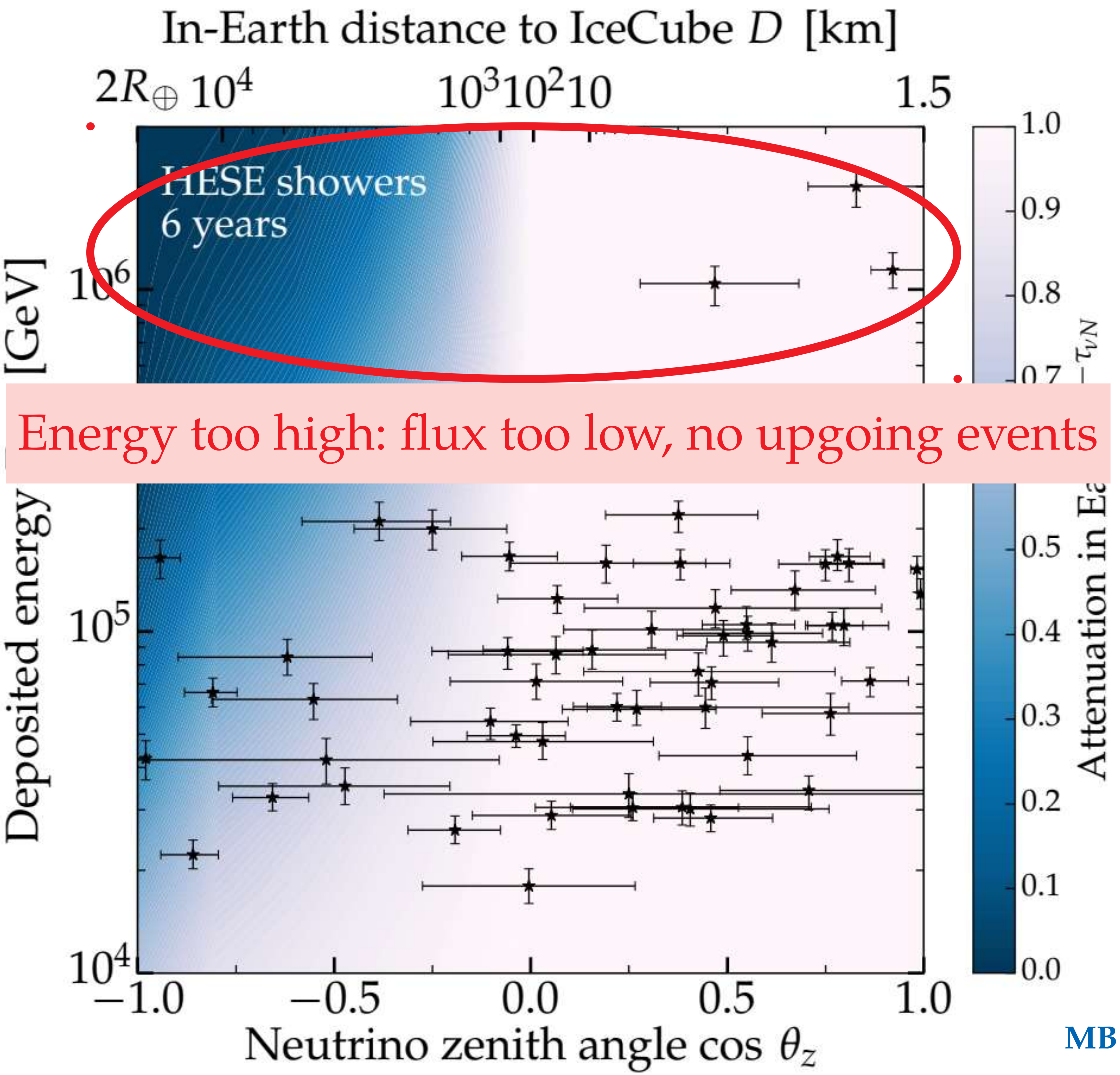
MB & Connolly, 1711.11043



MB & Connolly, 1711.11043

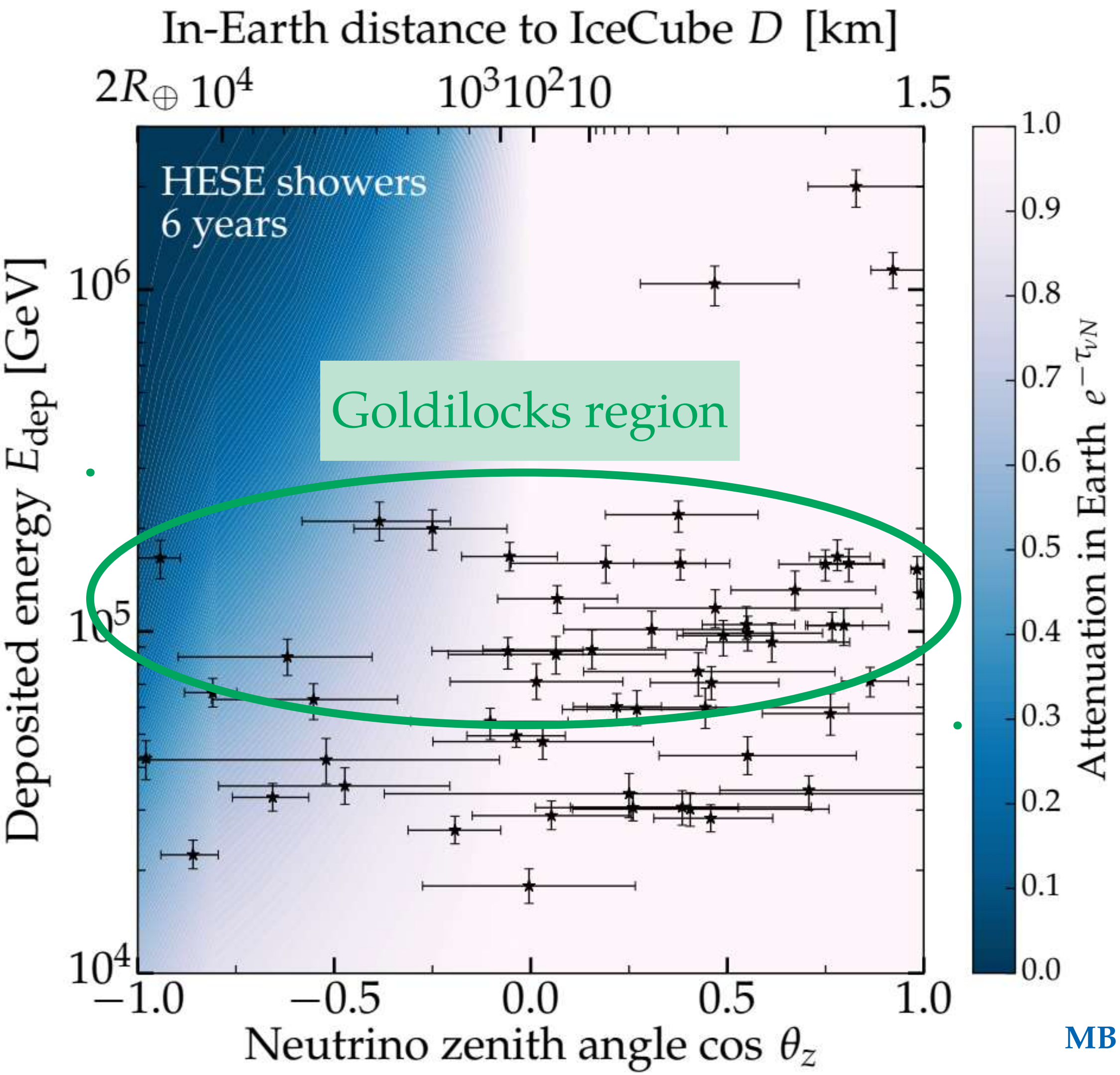


MB & Connolly, 1711.11043



Energy too high: flux too low, no upgoing events

MB & Connolly, 1711.11043



MB & Connolly, 1711.11043