High-energy cosmic neutrinos:

Current status and future prospects

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

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CERN, October 11, 2019

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

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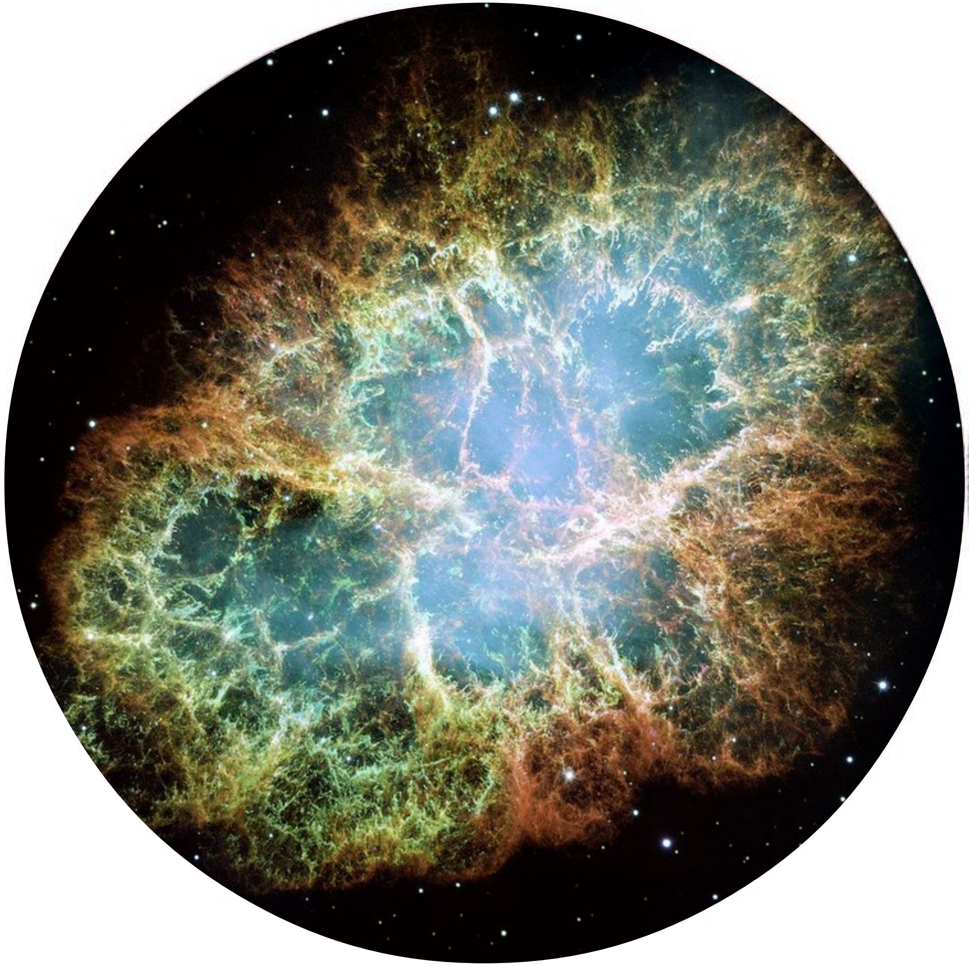

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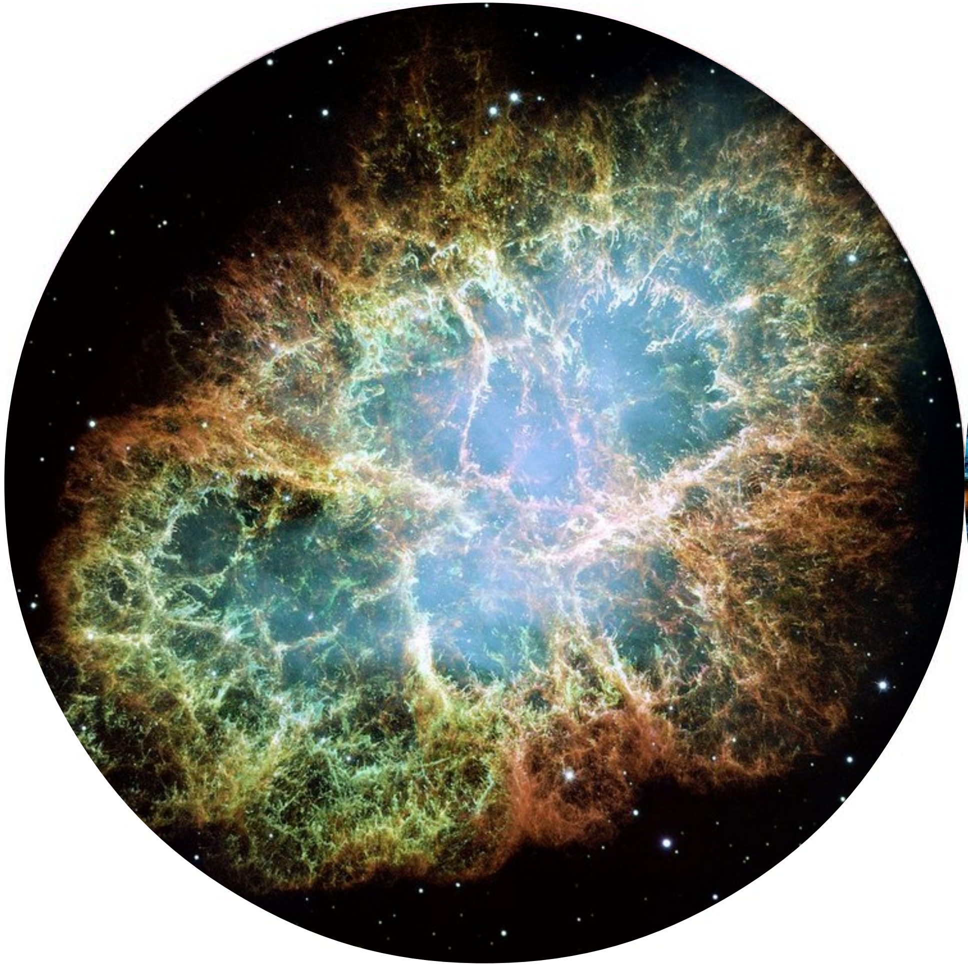

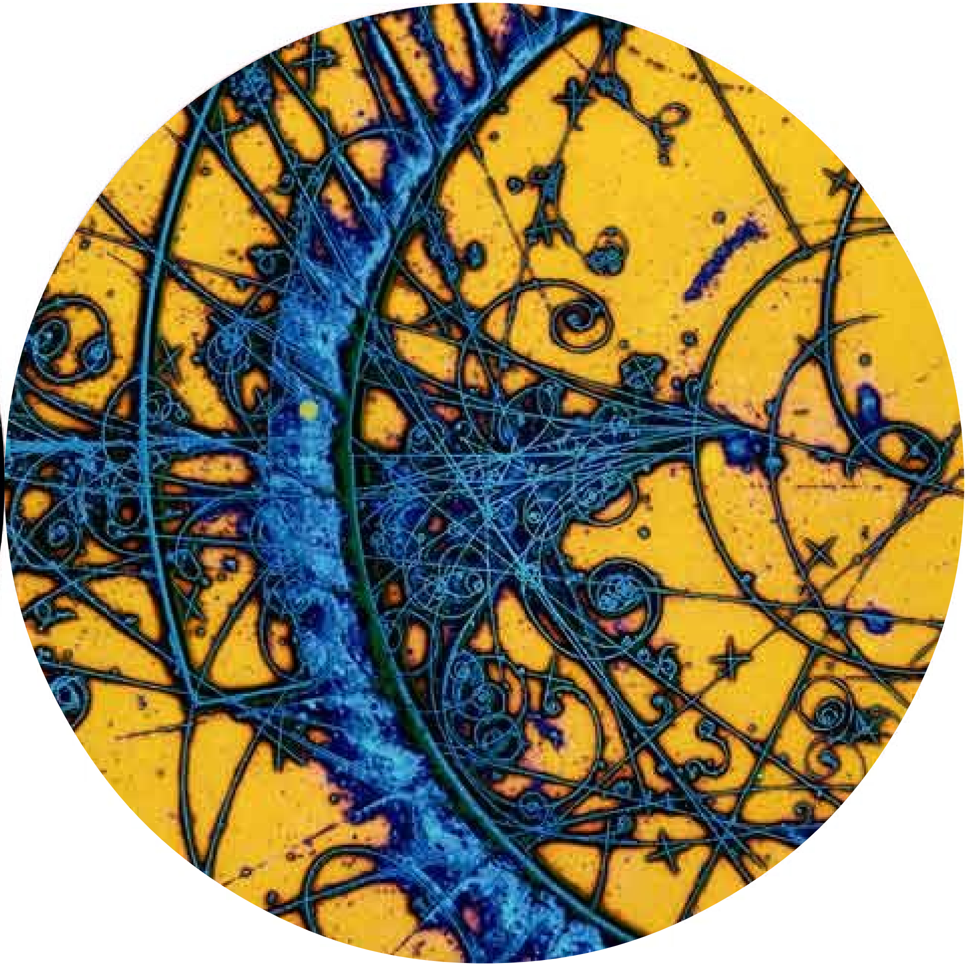

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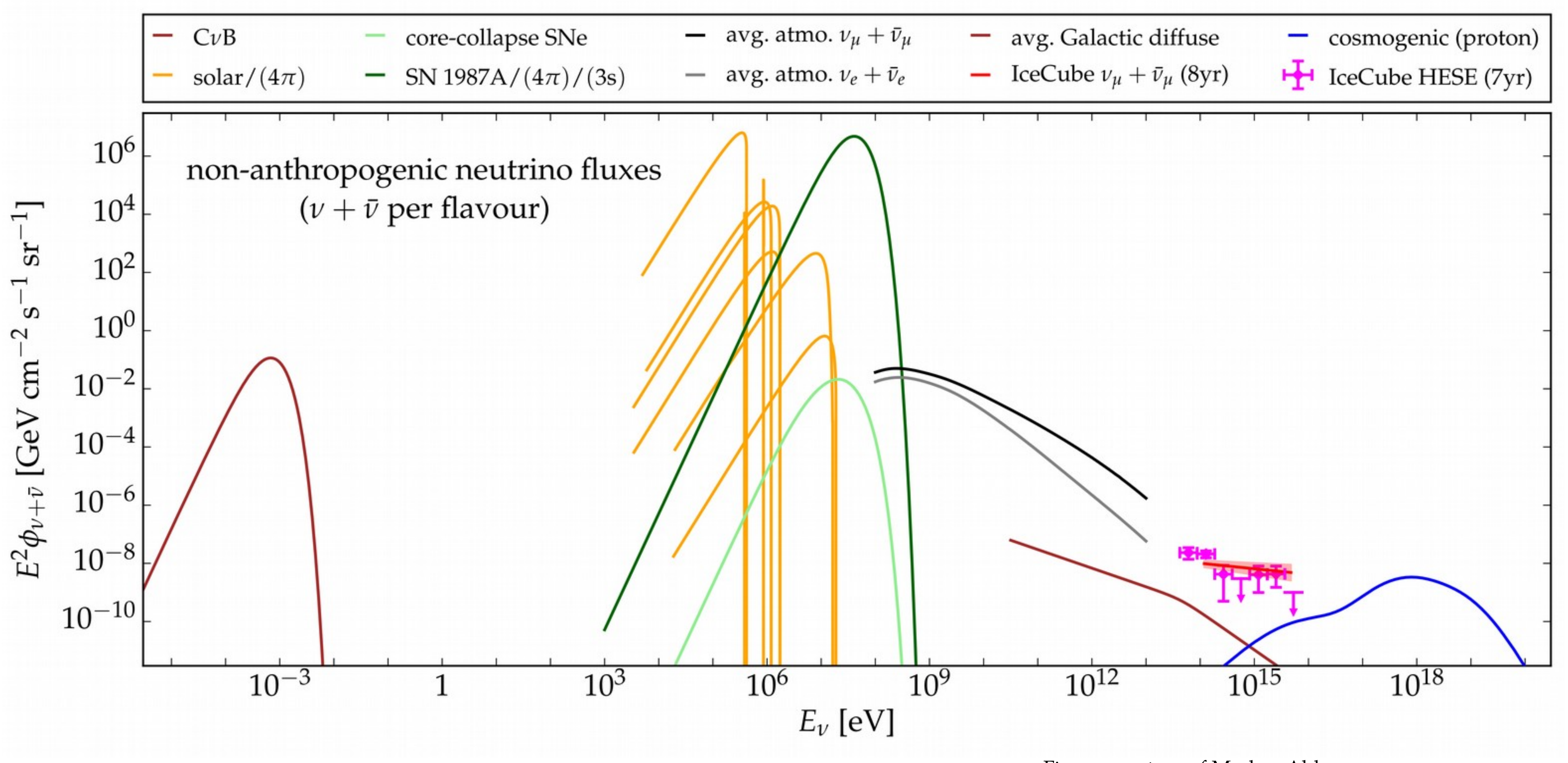
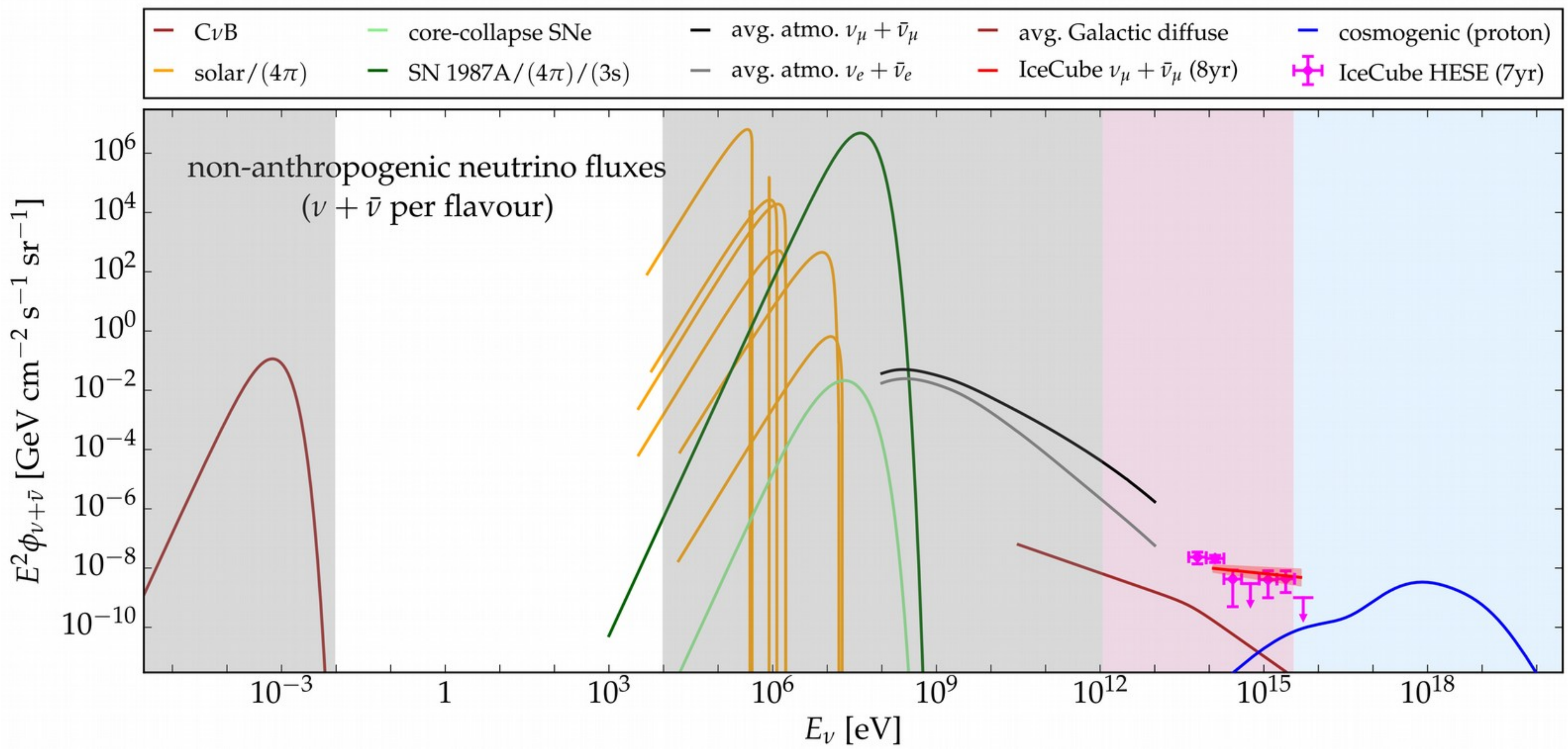


Figure courtesy of Markus Ahlers
Also in: Van Elewyck, **MB** *et al.*, PoS(ICRC2019), 1023



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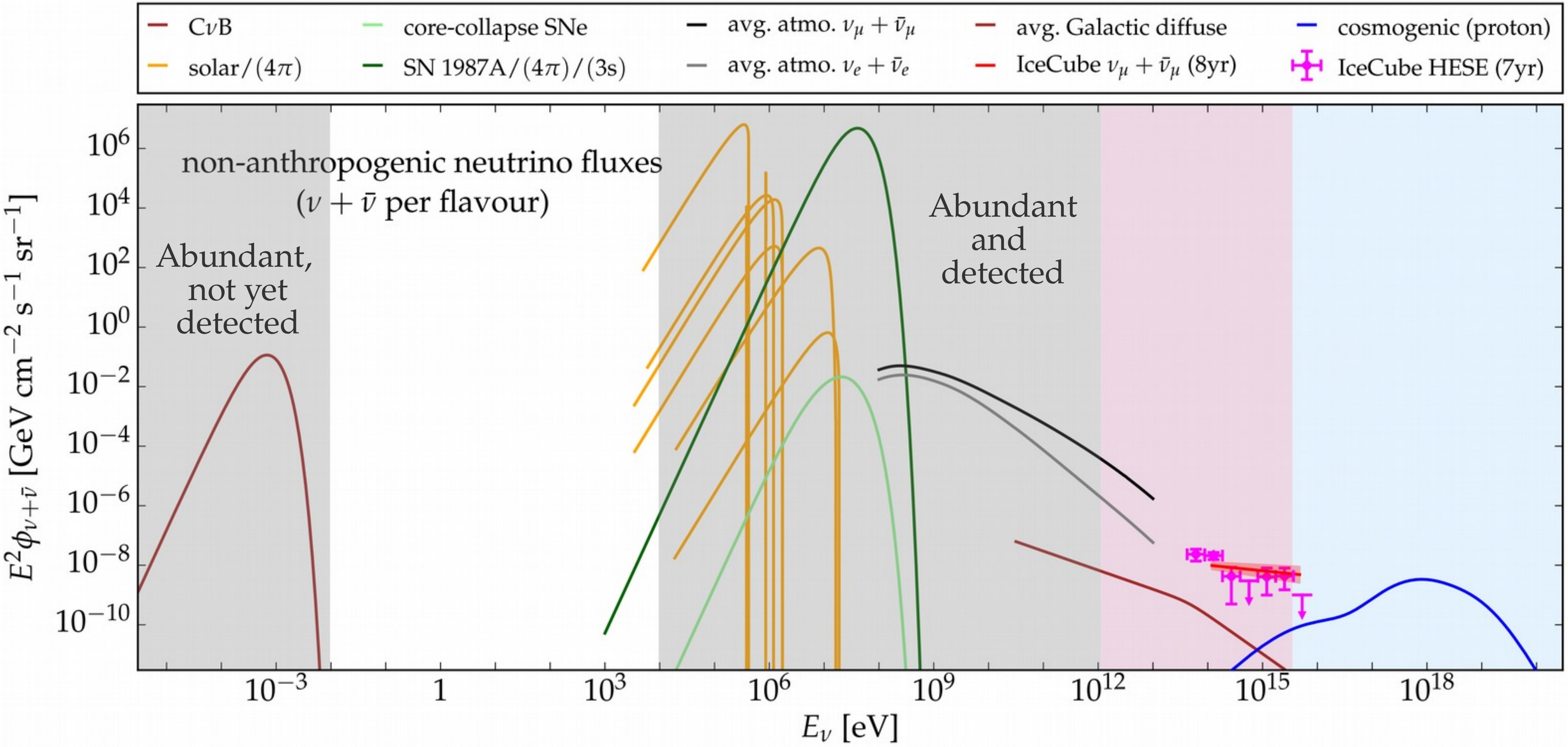

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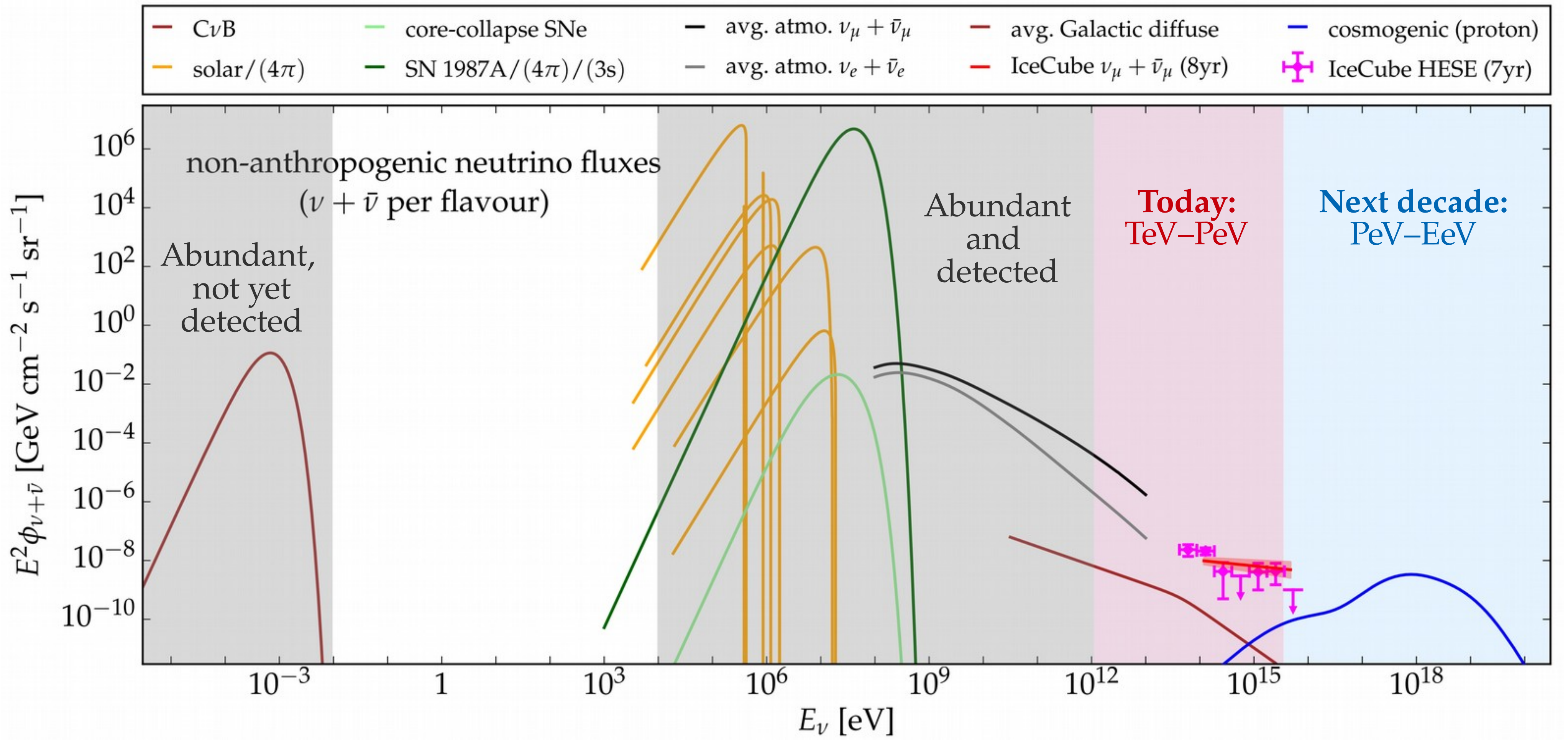

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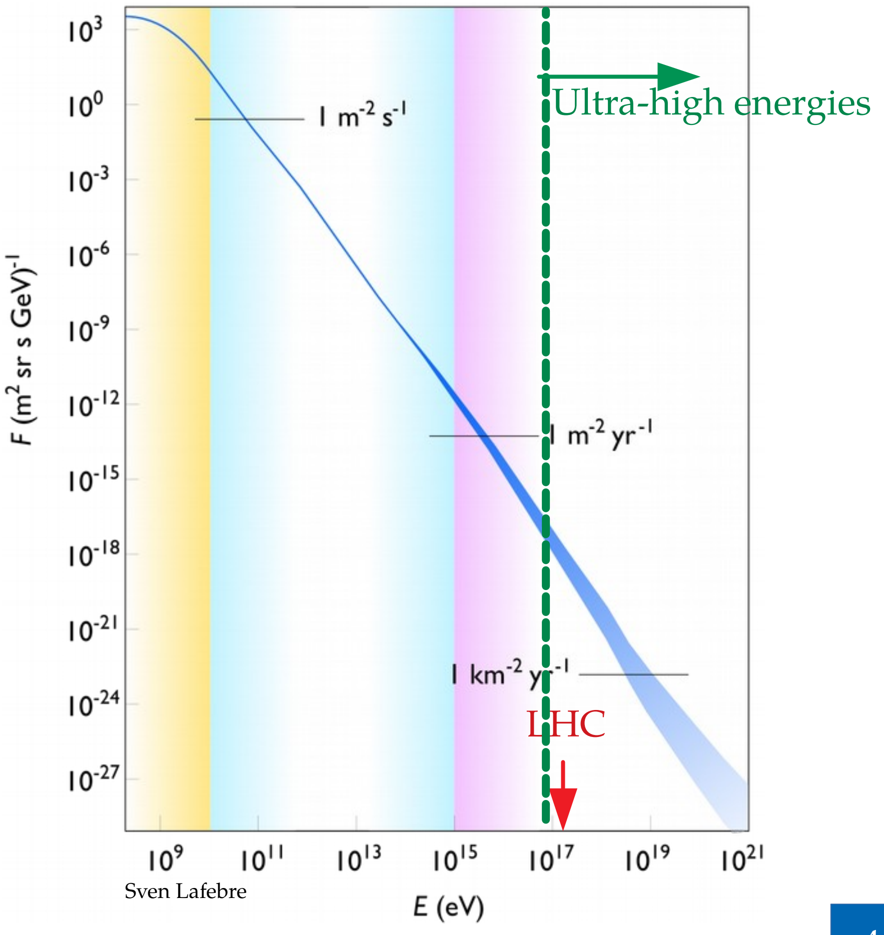
Why study high-energy astrophysical neutrinos?

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?

Flux of cosmic rays at Earth



Sven Lafebre

What makes high-energy astrophysical neutrinos unique?

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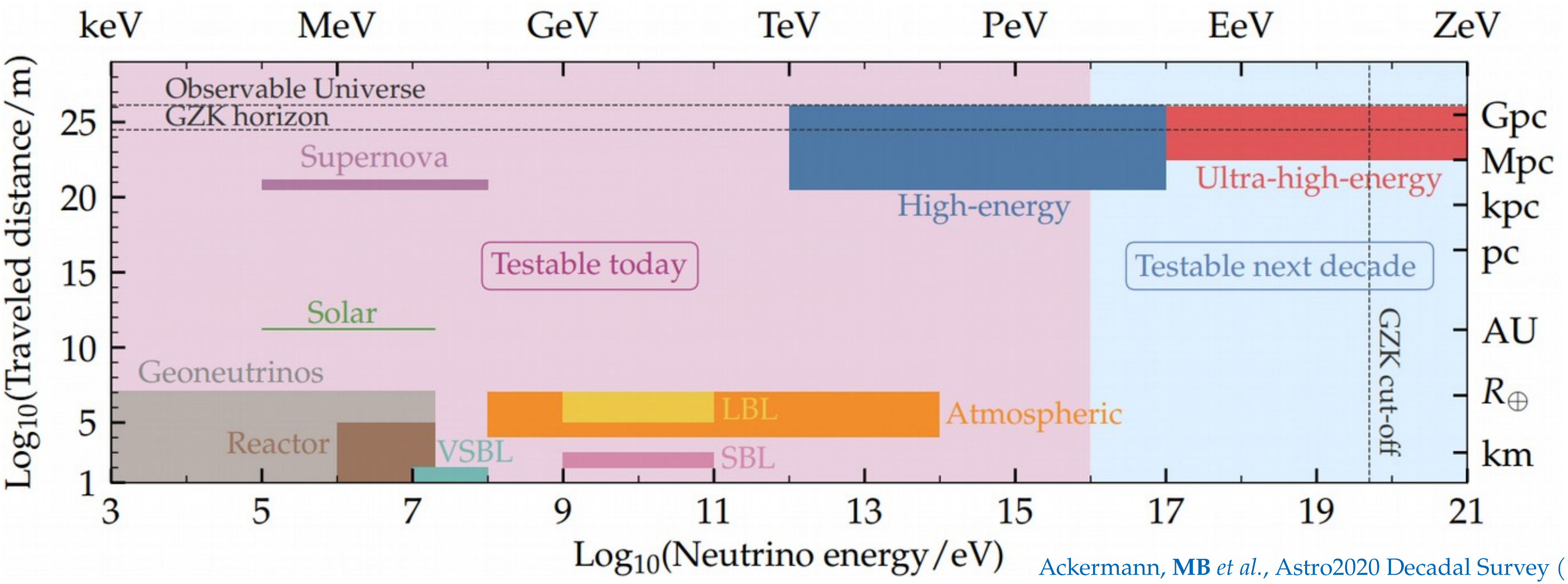

Ackermann, **MB** *et al.*, Astro2020 Decadal Survey (1903.04333)

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3 Neutrinos are weakly interacting
$\mapsto$ They bring untainted information across cosmological scales
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4 Neutrinos have a unique quantum number: flavor
$\mapsto$ Powerful probe of astrophysics and neutrino physics
$\mapsto$ But flavor is hard to reconstruct

The multi-messenger connection: a simple picture

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

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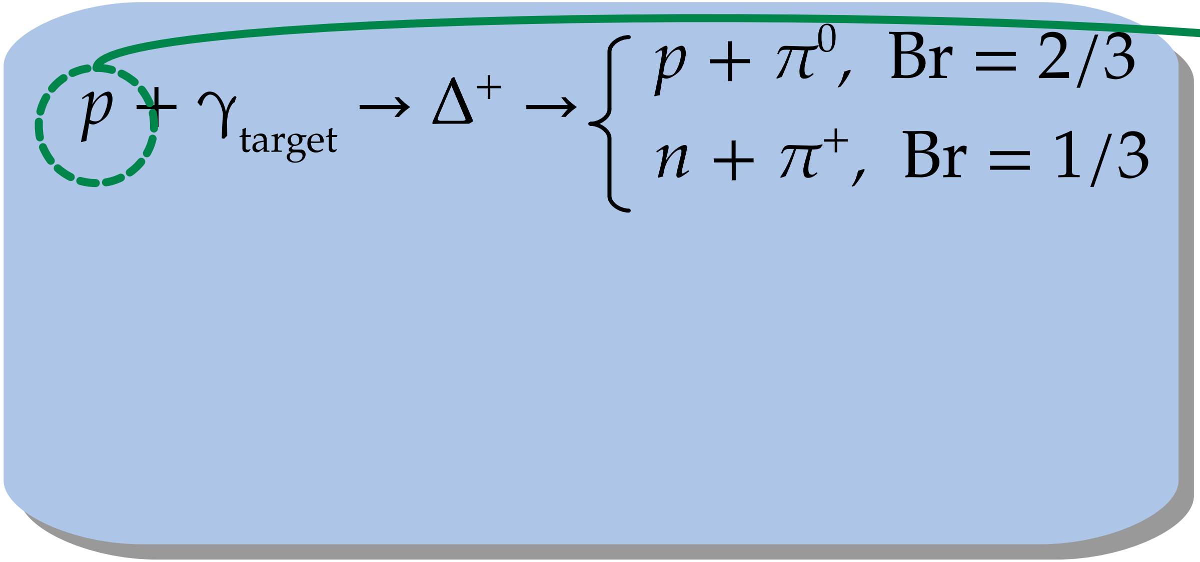

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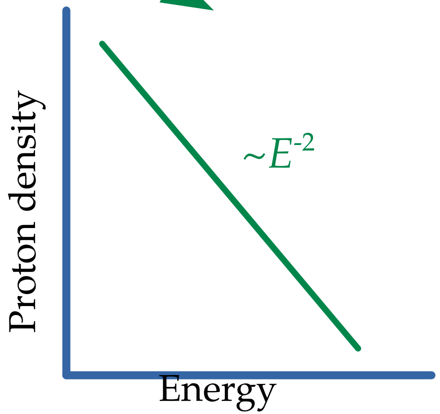

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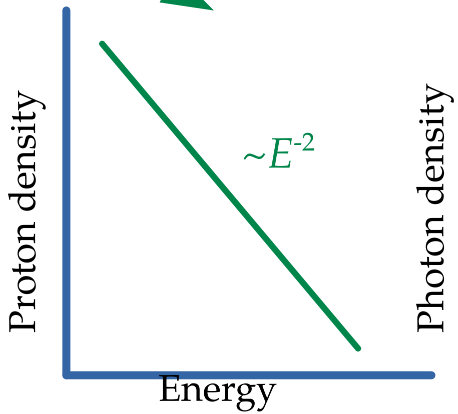

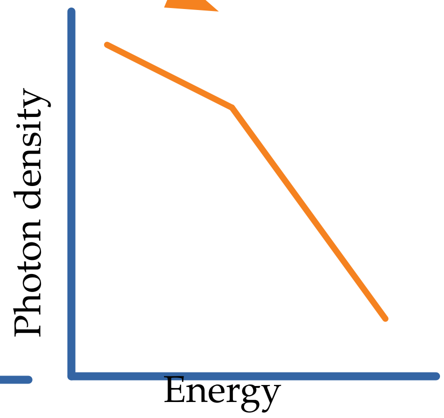

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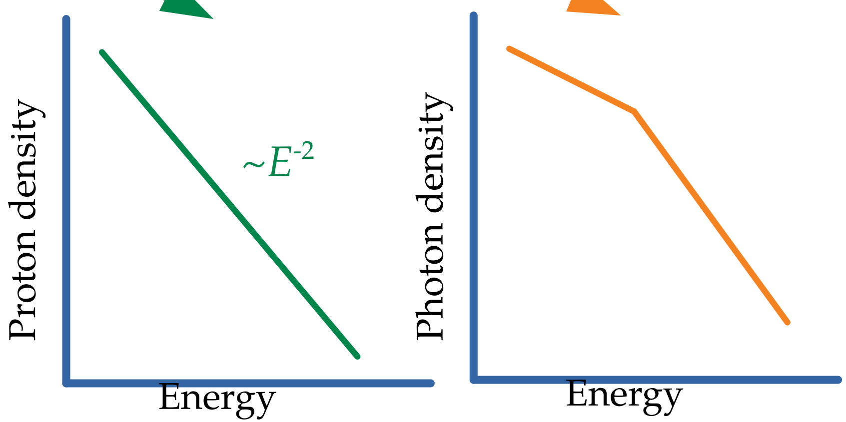
$$\pi^{0} \rightarrow \gamma + \gamma$$

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

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



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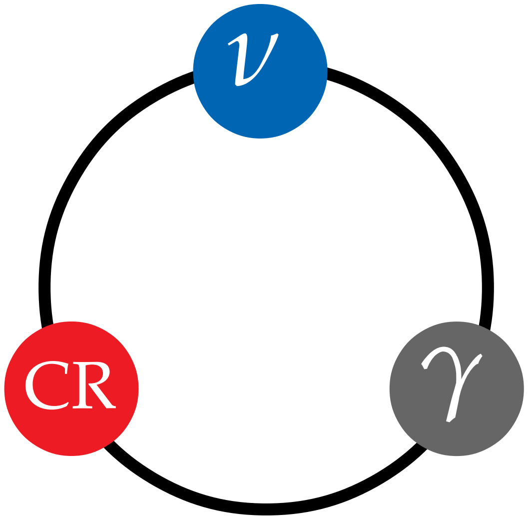

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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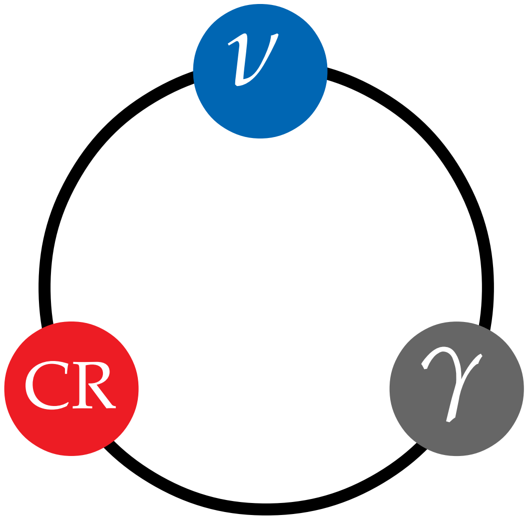

1 PeV 20 PeV

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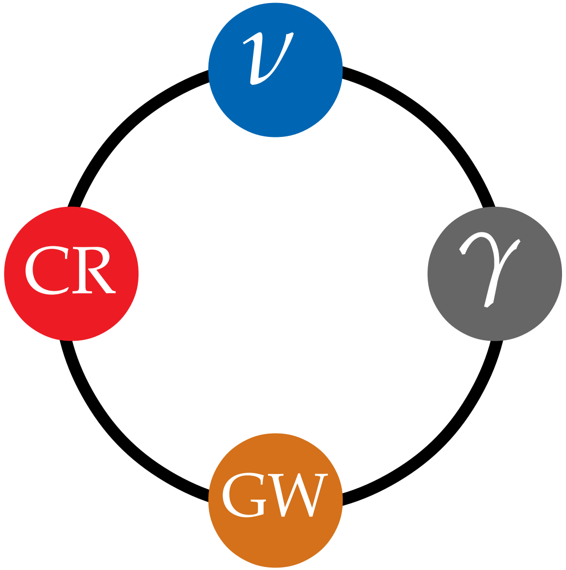

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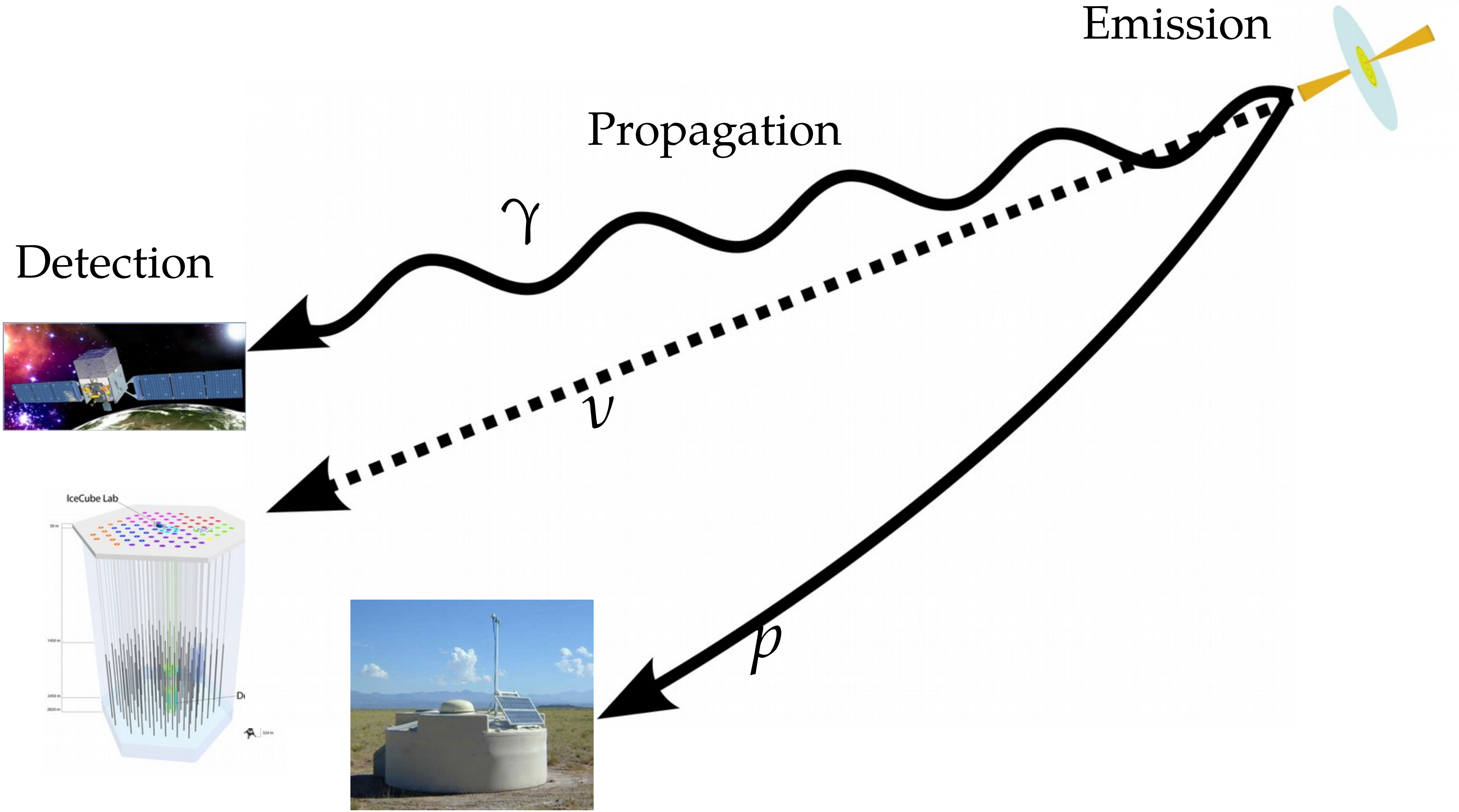
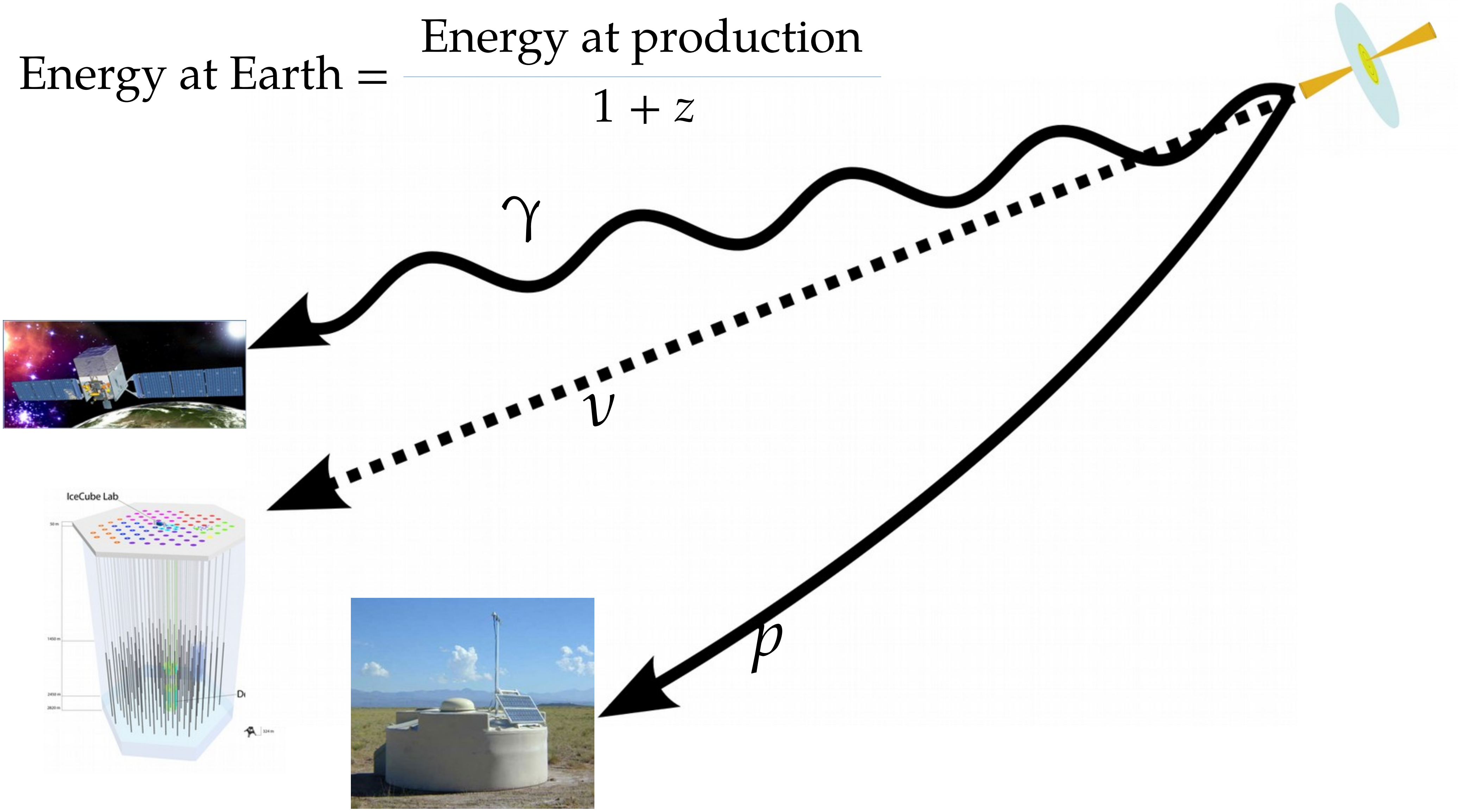


Emission
Propagation
γ
Detection
ν
IceCube Lab
p

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



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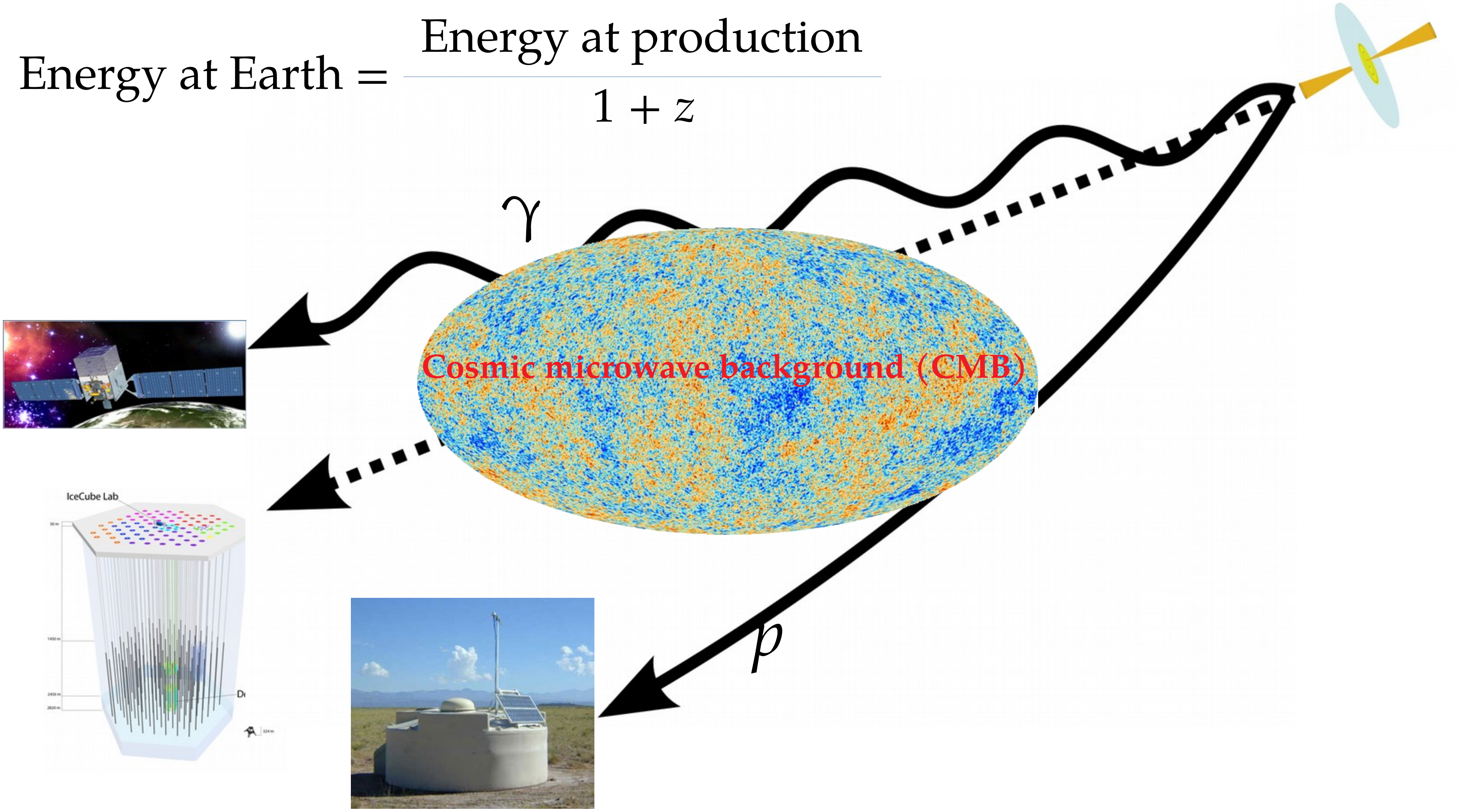
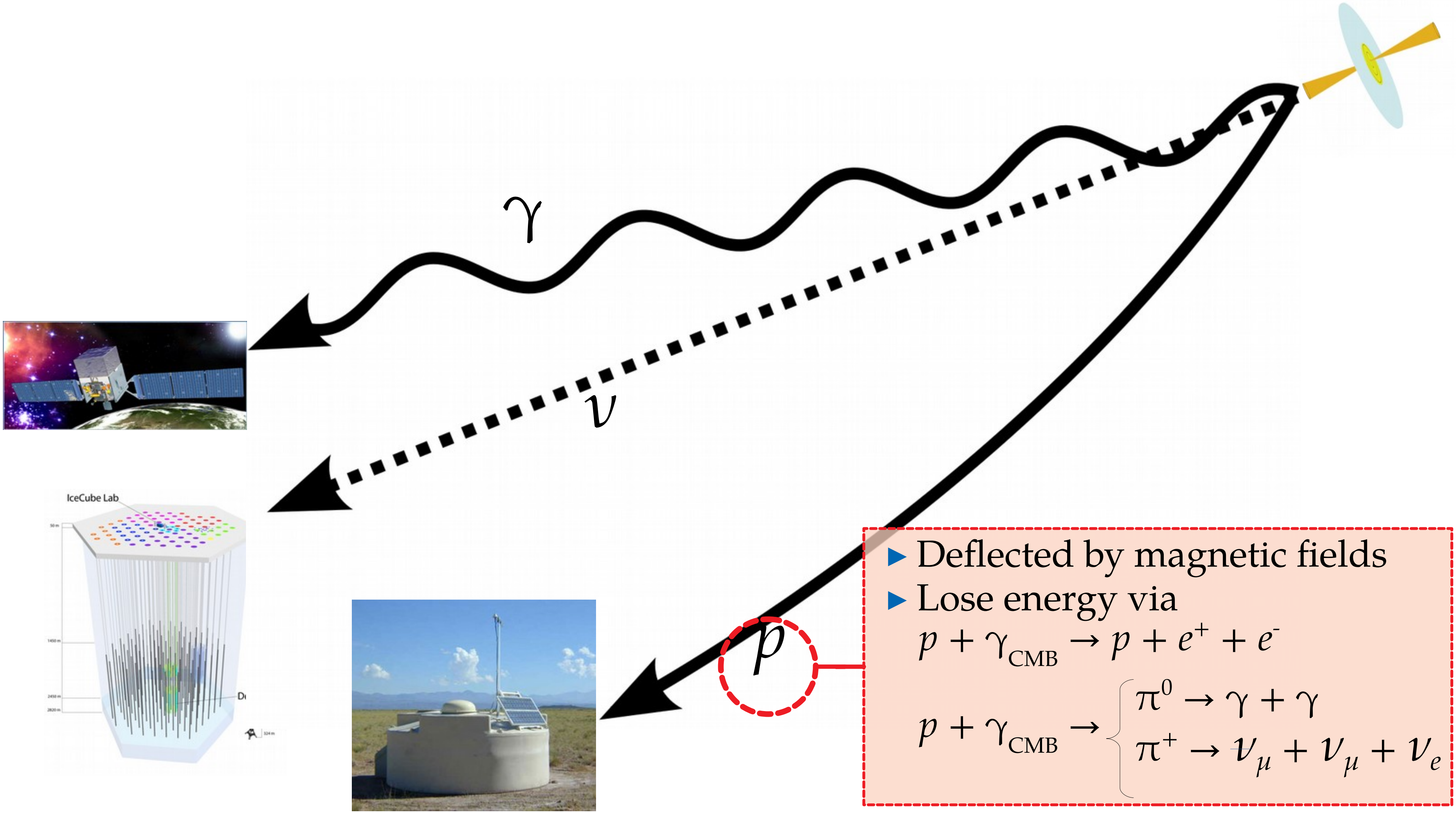
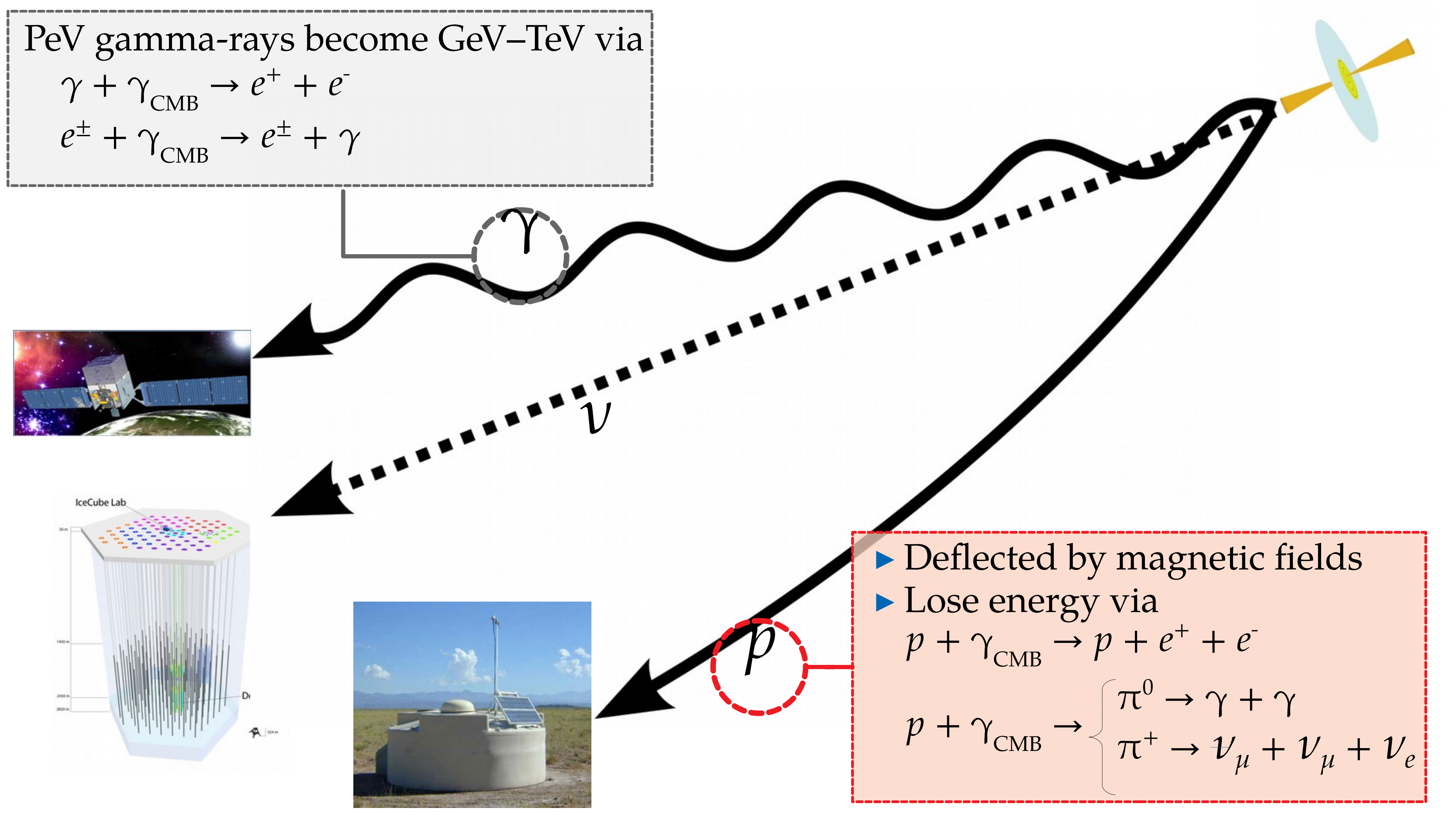



γ
ν
p
IceCube Lab
▸ Deflected by magnetic fields
▸ Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^{0} \rightarrow \gamma + \gamma \\ \pi^{+} \rightarrow \nu_{\mu} + \nu_{\mu} + \nu_{e} \end{cases}$



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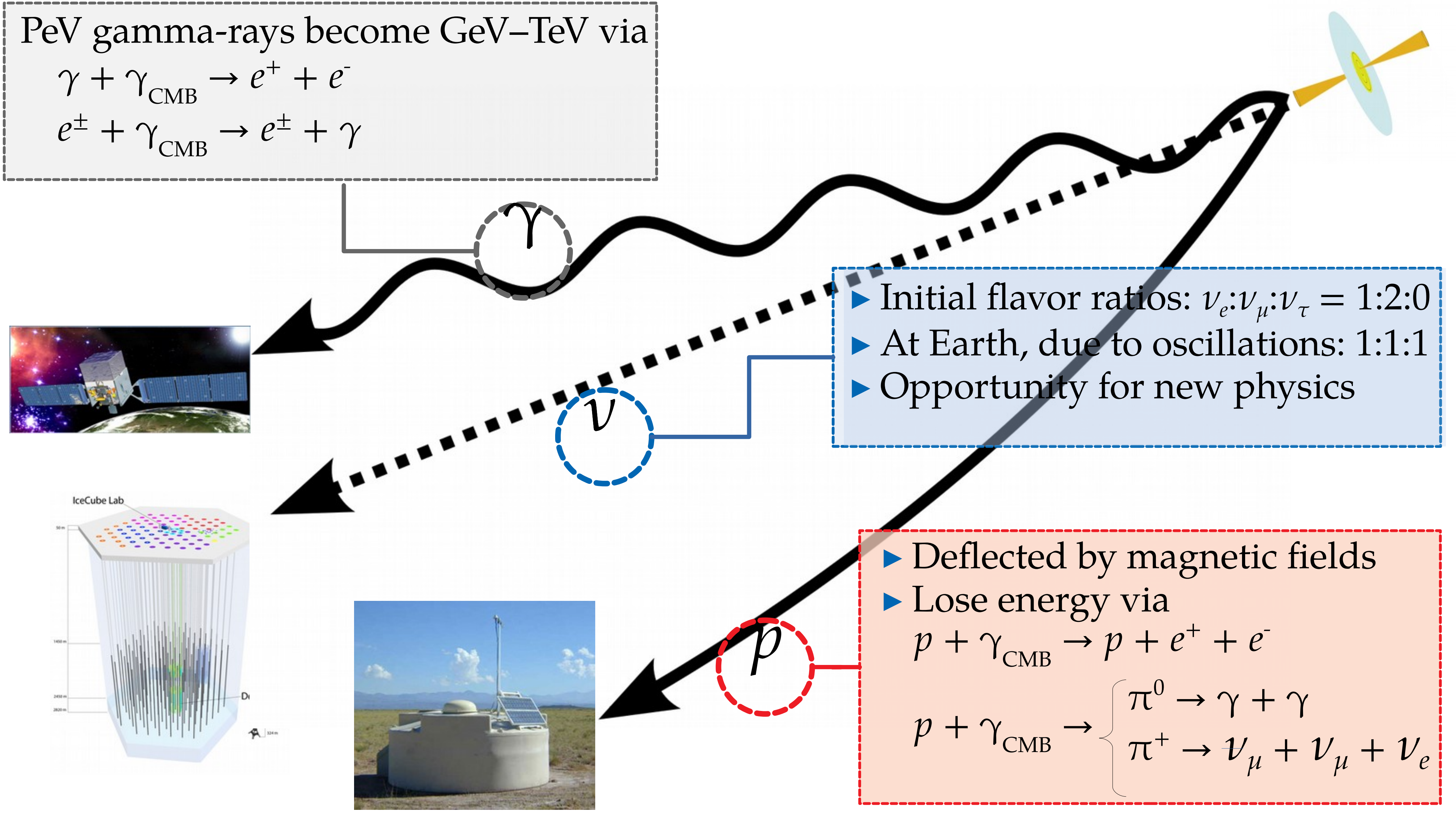
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$\gamma + \gamma_{\rm CMB} \rightarrow e^{+} + e^{-}$
$e^{\pm} + \gamma_{\rm CMB} \rightarrow e^{\pm} + \gamma$
γ
ν
p
▶ Initial flavor ratios: $\nu_e{:}\nu_\mu{:}\nu_\tau = 1{:}2{:}0$
▶ At Earth, due to oscillations: 1:1:1
▶ Opportunity for new physics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

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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Neutrinos – The ultimate smoking gun

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

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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 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation	Severe	Tiny	Severe
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
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Note: This is a simplified view

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

$$\nu_l + N \rightarrow \nu_l + X$$

Charged current (CC)

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

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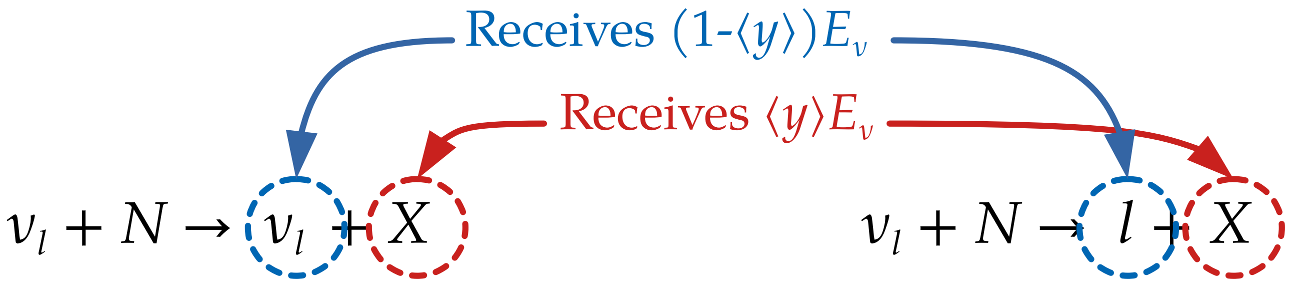

At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25–0.30$

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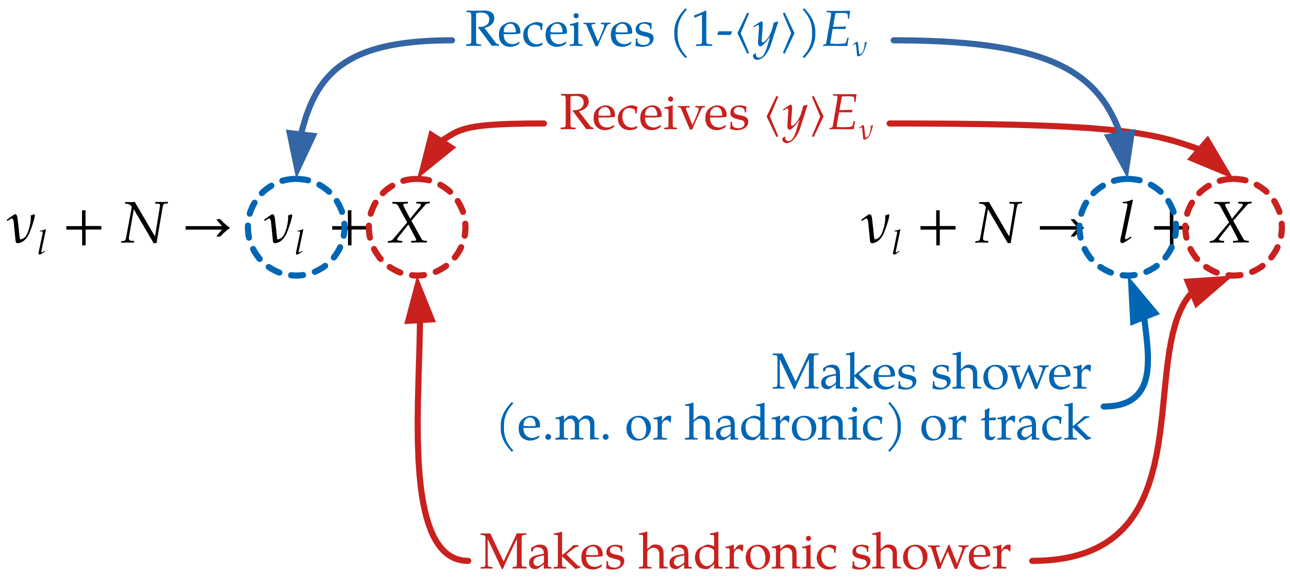

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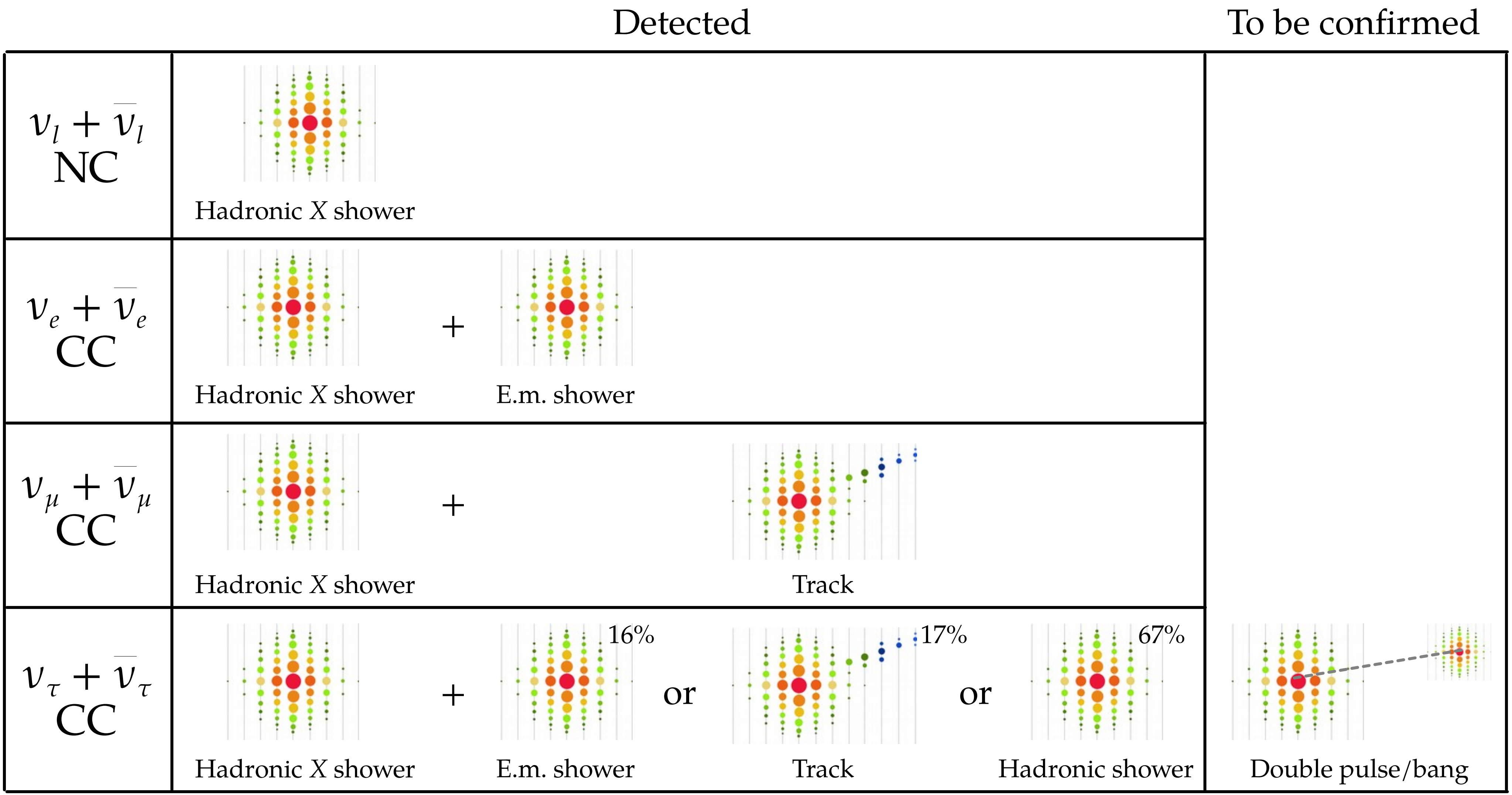
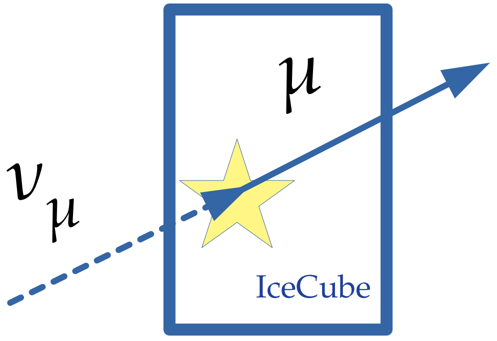


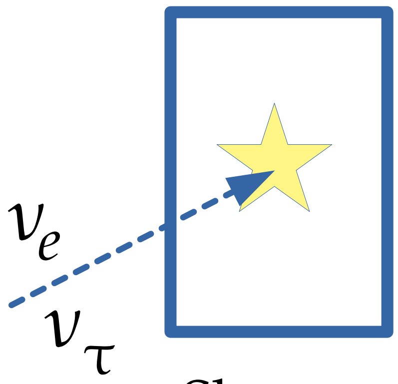
Detected
To be confirmed
$\nu_l + \bar{\nu}_l$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

Contained *vs.* uncontained events

Contained events



Starting track

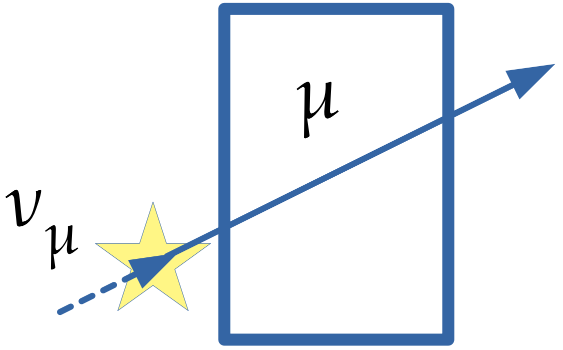


Shower

Pro: Clean determination of E_ν

Con: Few events (~100 in 8yr)

Uncontained events



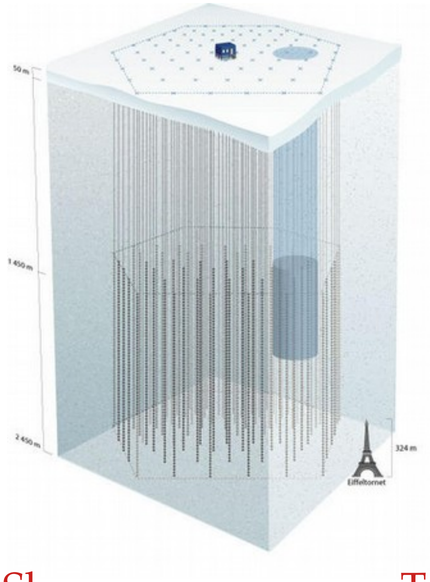
Through-going muon

Pro: Lots of events (few 10k in 8 yr)

Con: Uncertain estimates of E_ν

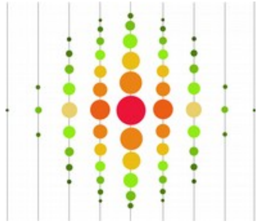
IceCube (8 years)

km³ in-ice
Cherenkov detector



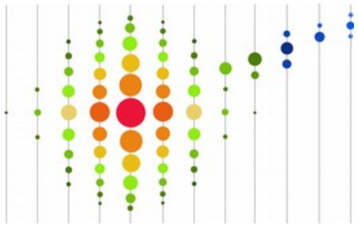
Showers

(mostly from ν_e, ν_τ)

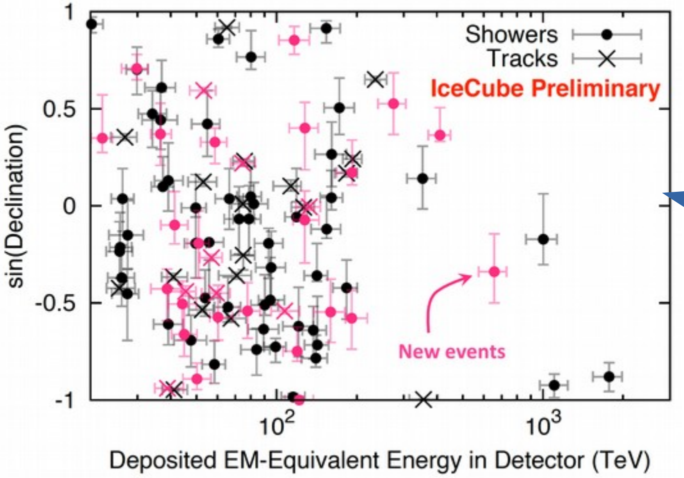


Tracks

(from ν_μ)



103 contained events, 15 TeV–2 PeV



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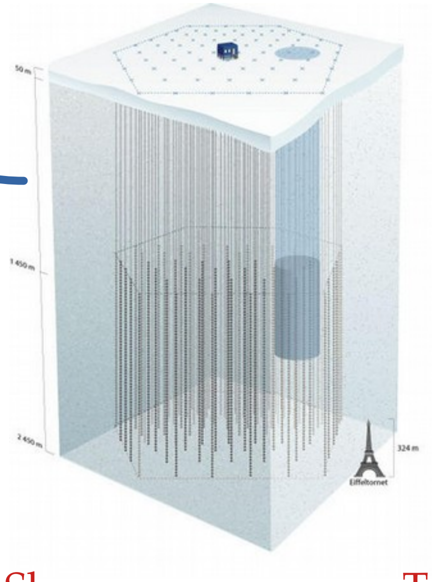
km^3 in-ice
Cherenkov detector



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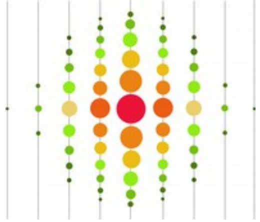

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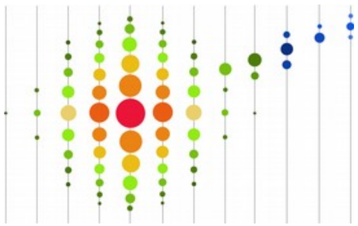

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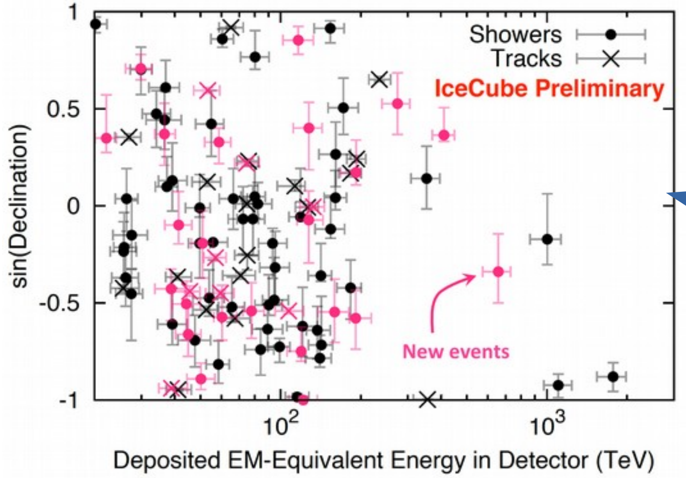

IceCube (8 years)

km³ in-ice
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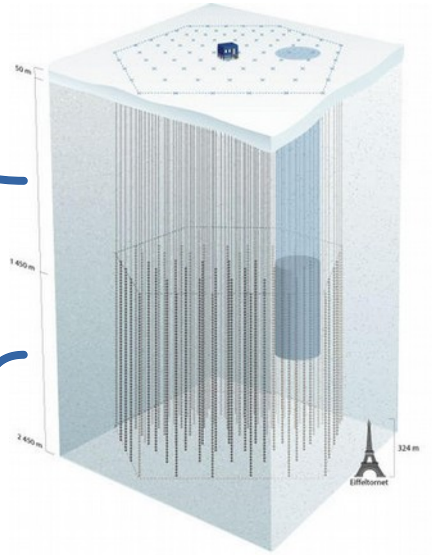
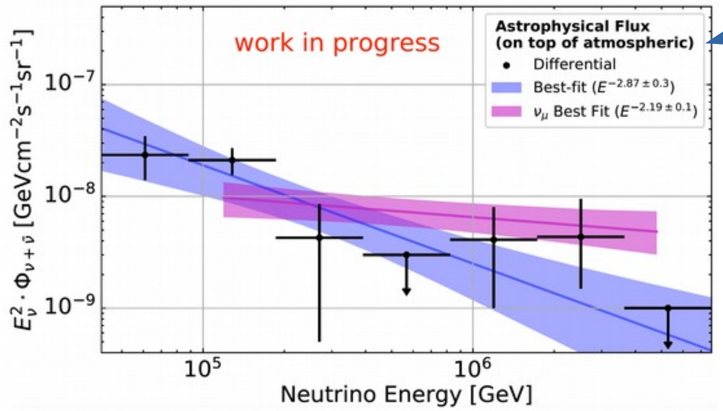


Astrophysical ν flux detected at $> 7\sigma$



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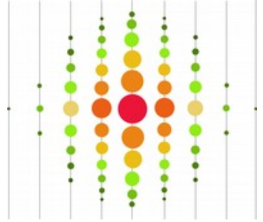

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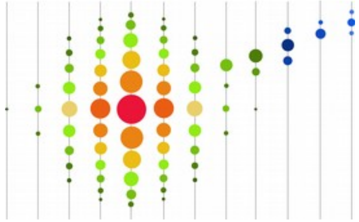

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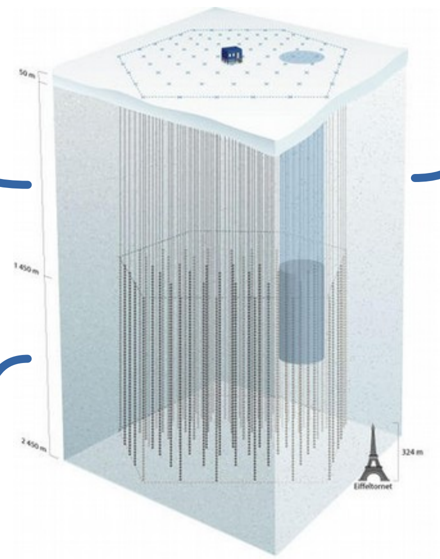

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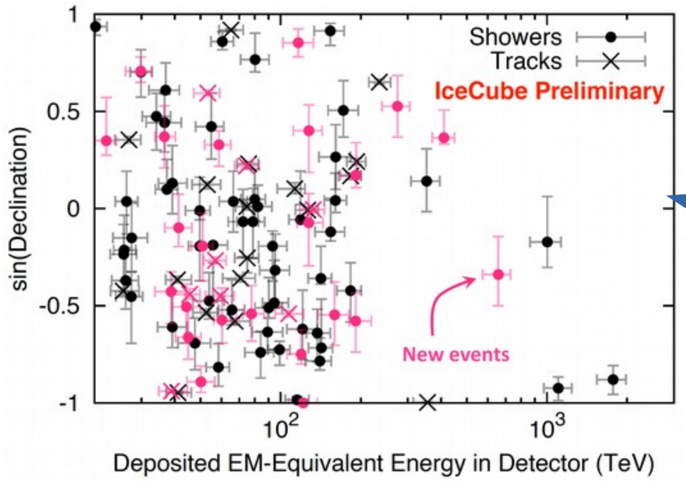
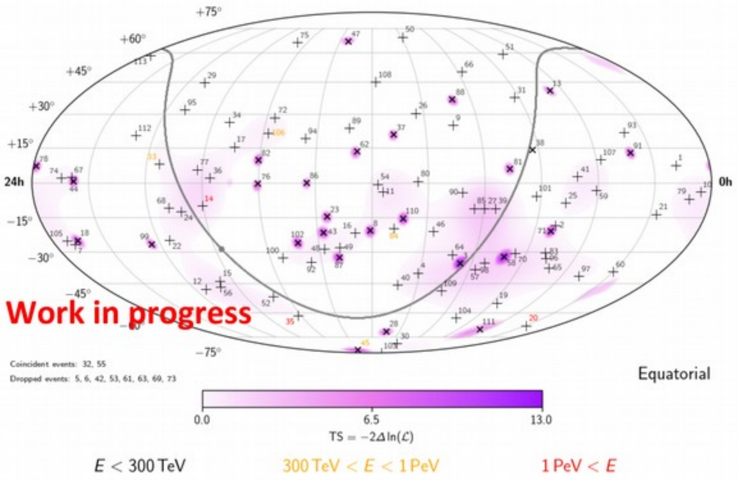


Arrival directions compatible with isotropy



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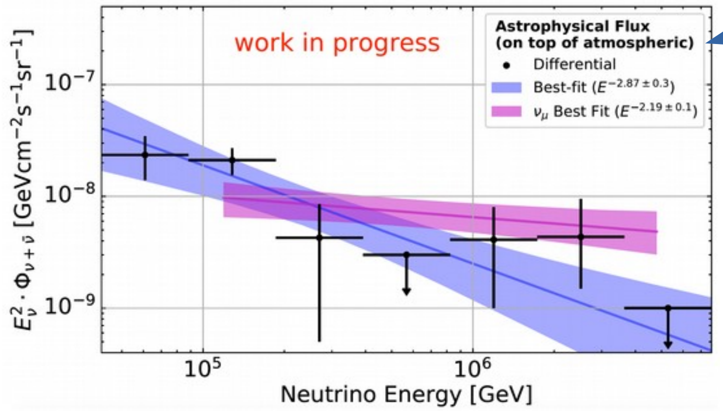

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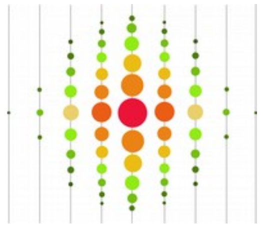
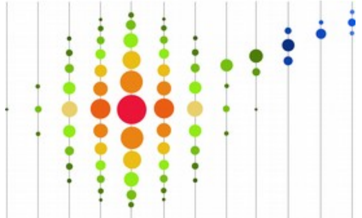
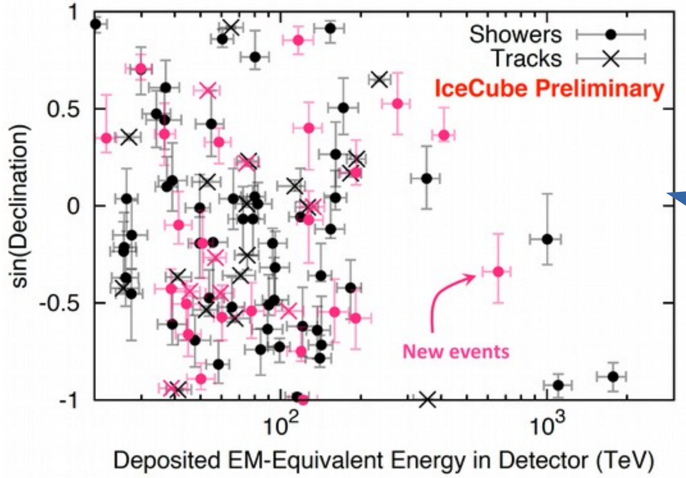


Tracks
(from ν_μ)

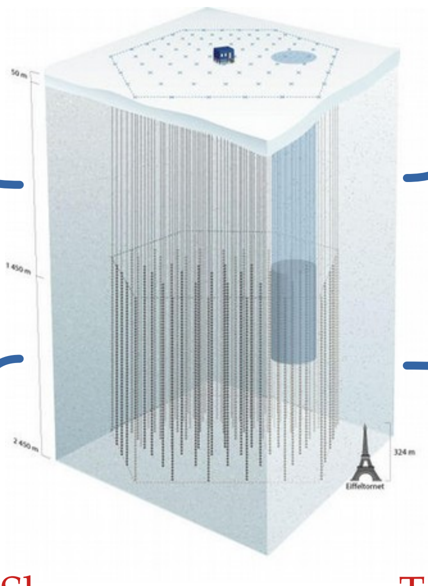


103 contained events, 15 TeV–2 PeV

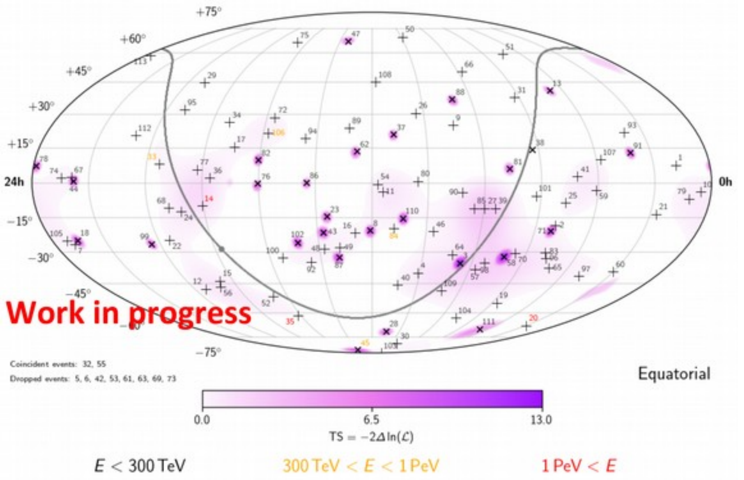


IceCube (8 years)

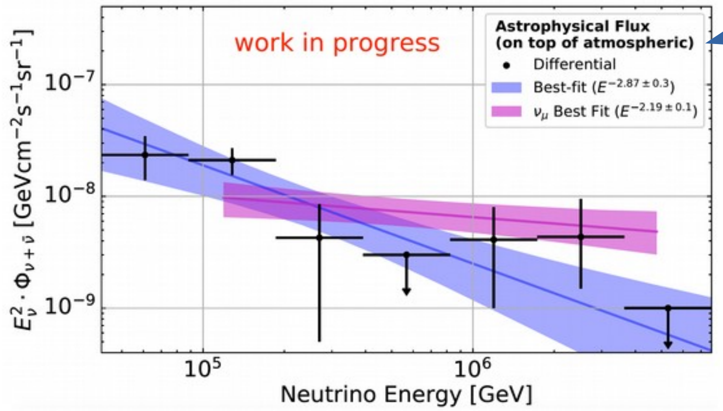
km³ in-ice Cherenkov detector



Arrival directions compatible with isotropy



Astrophysical ν flux detected at > 7σ



Showers

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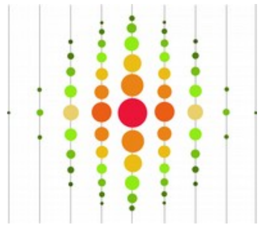

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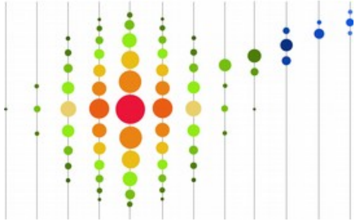
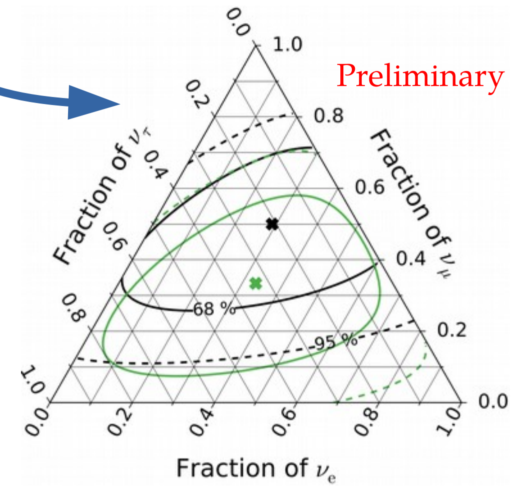


Flavor composition



Status quo of high-energy cosmic neutrinos

What we know

- Isotropic distribution of sources
- Spectrum is a power law $\propto E^{-p}$
- At least some sources are gamma-ray transients
- No correlation between directions of cosmic rays and neutrinos
- Flavor composition: compatible with equal number of ν_e, ν_μ, ν_τ
- No evident new physics

What we don't know

- The sources of the diffuse ν flux
- The ν production mechanism
- The spectral index of the spectrum
- A spectral cut-off at a few PeV?
- Are there Galactic ν sources?
- The precise flavor composition
- Is there new physics?

Status quo of high-energy cosmic neutrinos

But we have solid theory expectations
+ fast experimental progress

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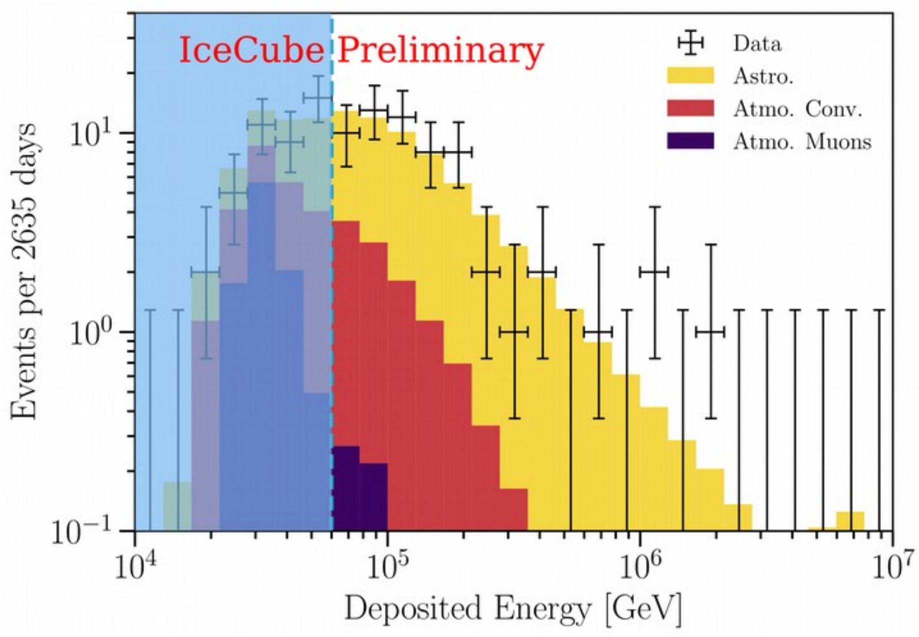
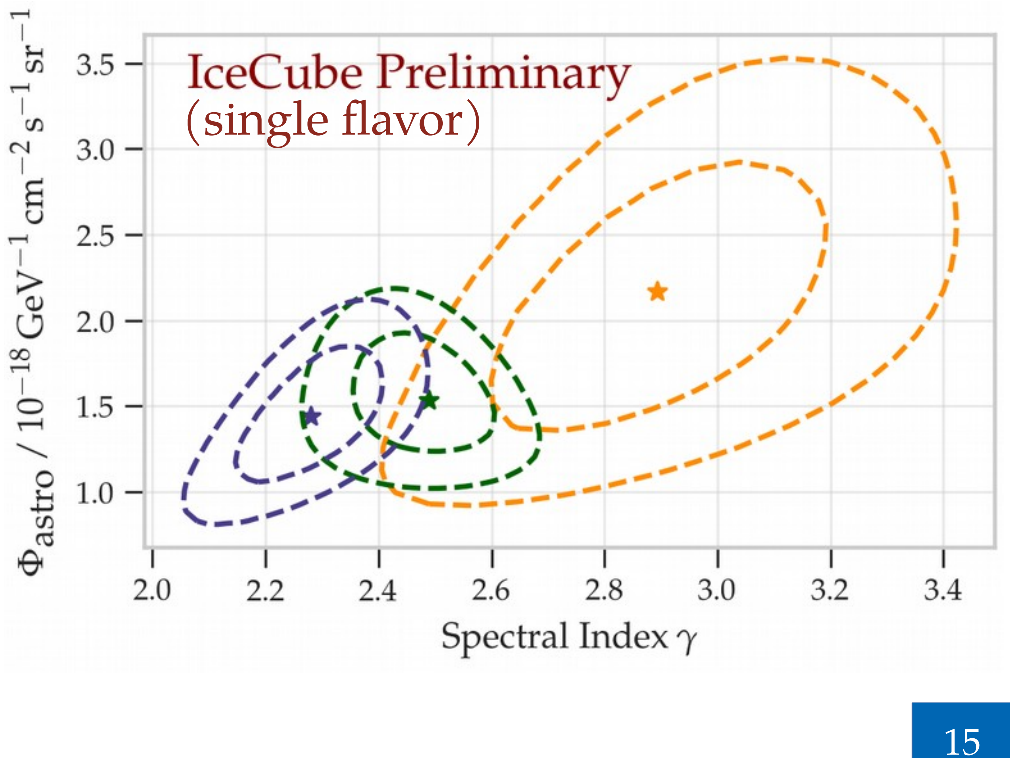
IceCube results: Energy spectrum

100+ contained events above 60 TeV (8 yr):



Data is fit well by a single power law:

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = \Phi \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-\gamma} 10^{-18}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$



IceCube Collab., ICRC 2019
Schneider, ICRC 2019

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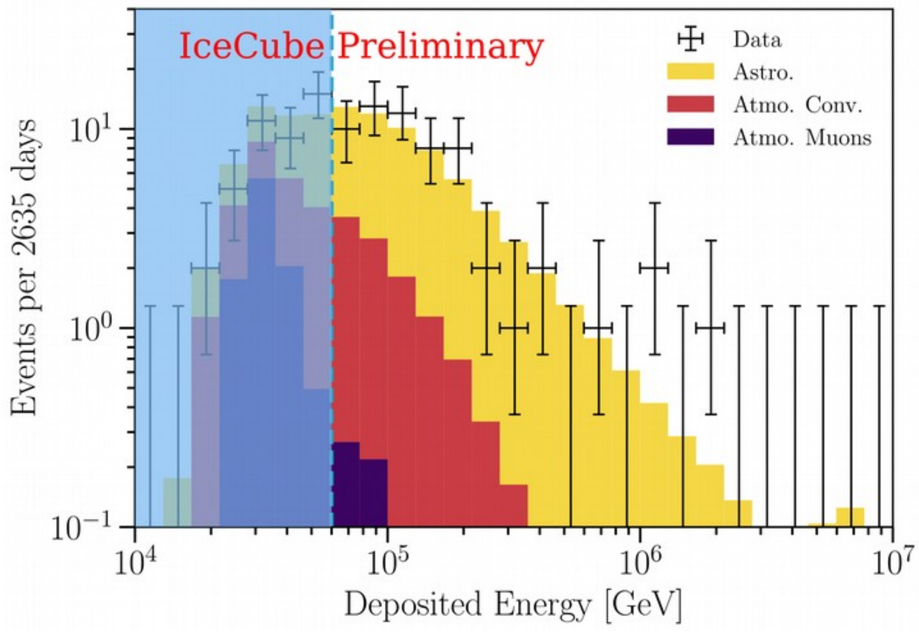

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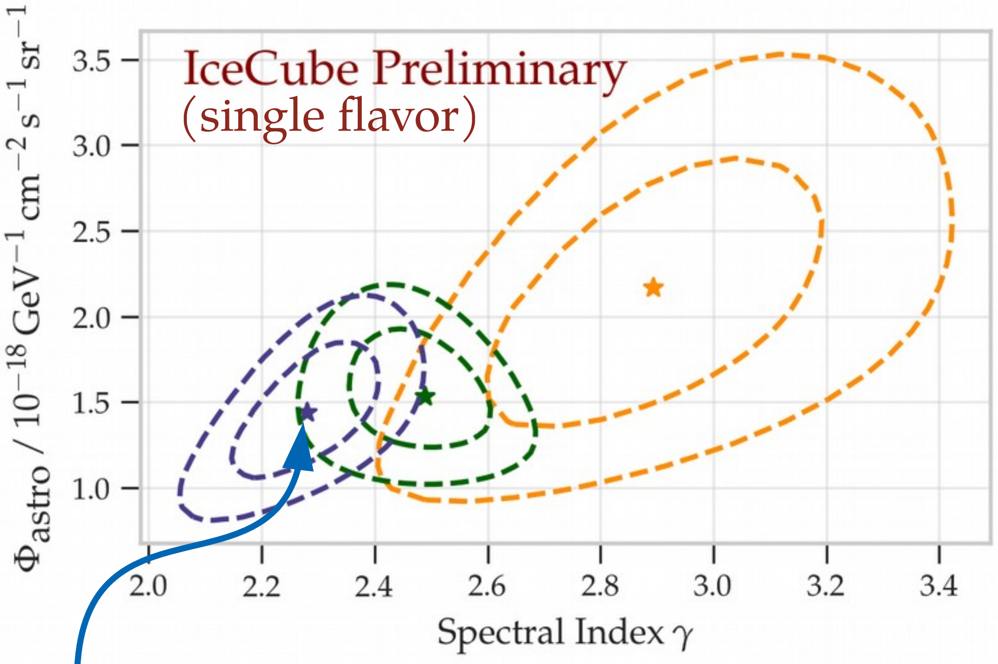
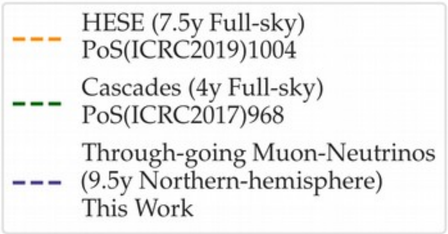


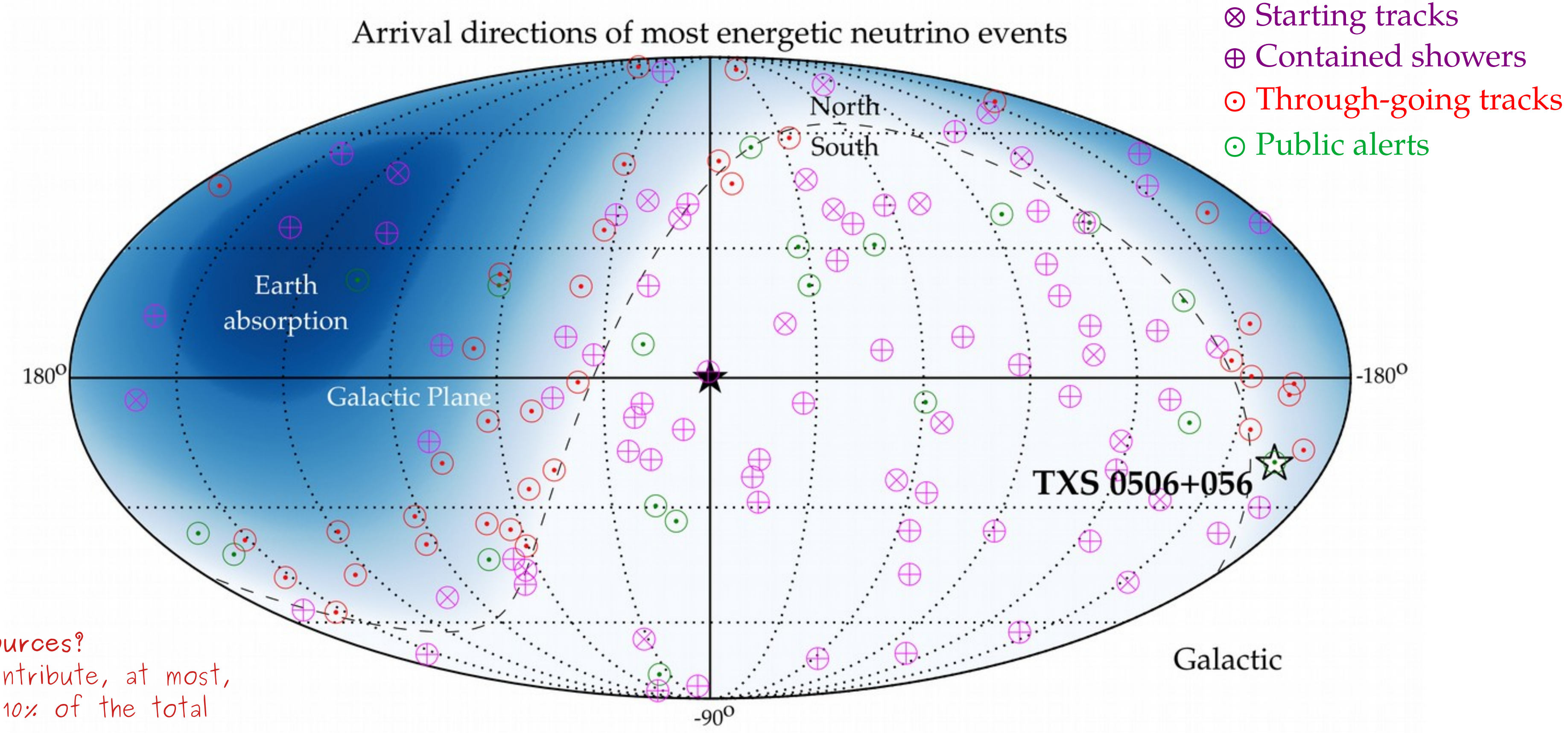


Spectrum looks harder for through-going ν_μ

IceCube Collab., ICRC 2019
Schneider, ICRC 2019

IceCube results: Arrival directions

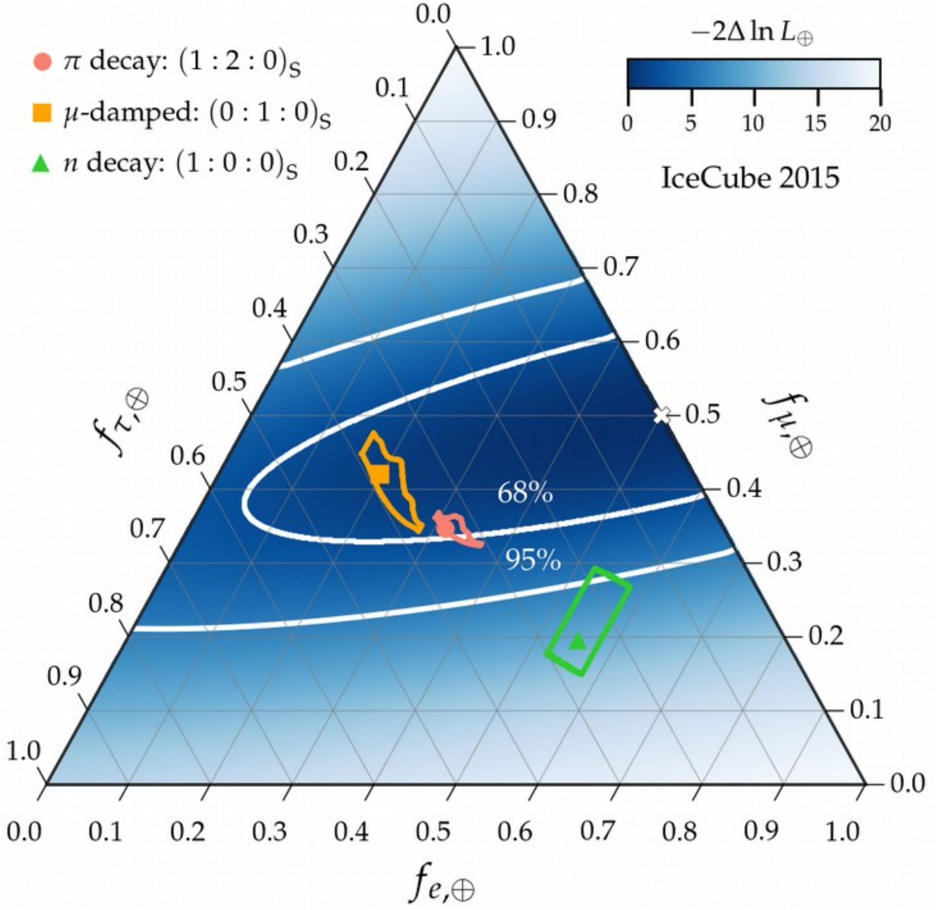
Distribution of arrival directions (8 yr) is compatible with an isotropic distribution of sources:



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

Ackermann, **MB** *et al.*, Astro2020 Decadal Survey (1903.04334)

IceCube results: Flavor composition



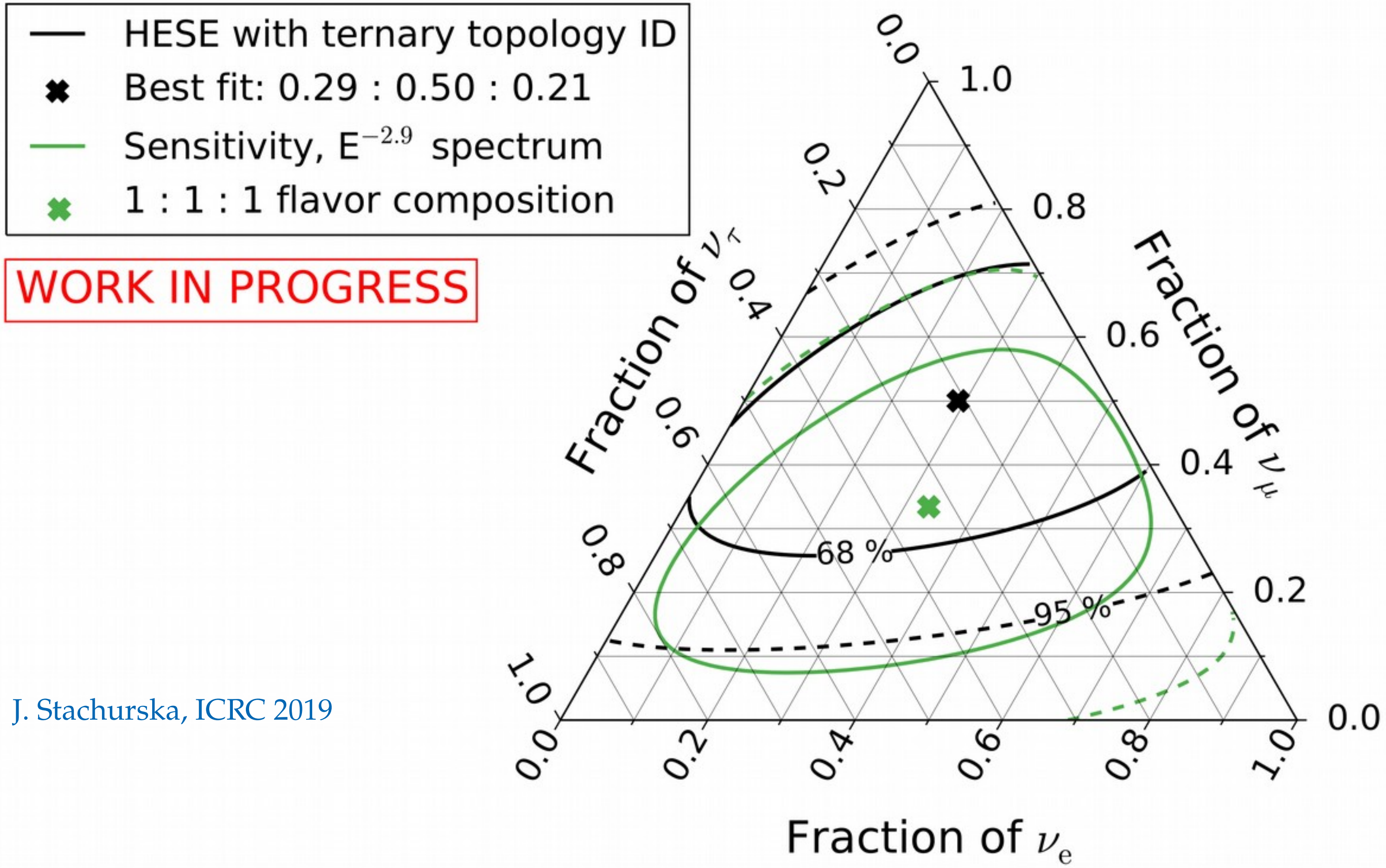
- Compare number of tracks (ν_μ) *vs.* showers (all flavors)
- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.5 : 0.5 : 0)_\oplus$
- Compatible with standard source compositions
- Lots of room for improvement: more statistics, better flavor-tagging

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

MB & Ahlers, *PRL* 2019
Adapted from: IceCube, *ApJ* 2015

IceCube results: Flavor composition

There are 2 ν_τ candidate events which change the flavor composition:



J. Stachurska, ICRC 2019

Three strategies to find the sources of TeV–PeV ν

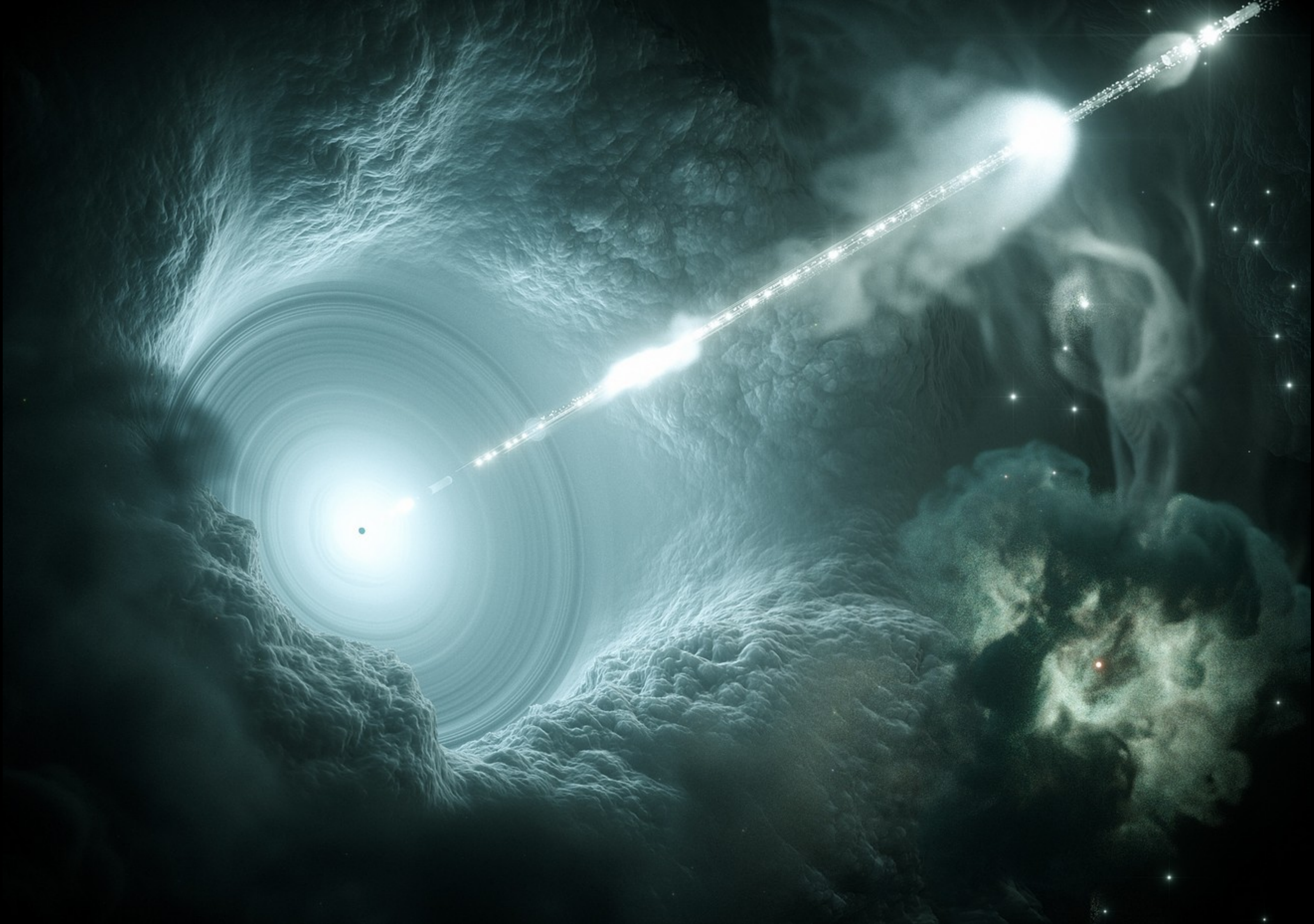
Look at bright e.m. point sources

- **Examine single sources** → No evident single steady source, *one* transient source
- **Stack several similar sources** → Ruled out gamma-ray bursts, blazars as dominant

Look for neutrino multiplets

- **Clustered in direction** → Placed generic limits on source number density and luminosity
- **Clustered in direction *and* time** → Used to trigger follow-ups by other detectors

Use the diffuse neutrino flux → Any population of candidate sources must account for all or part of it

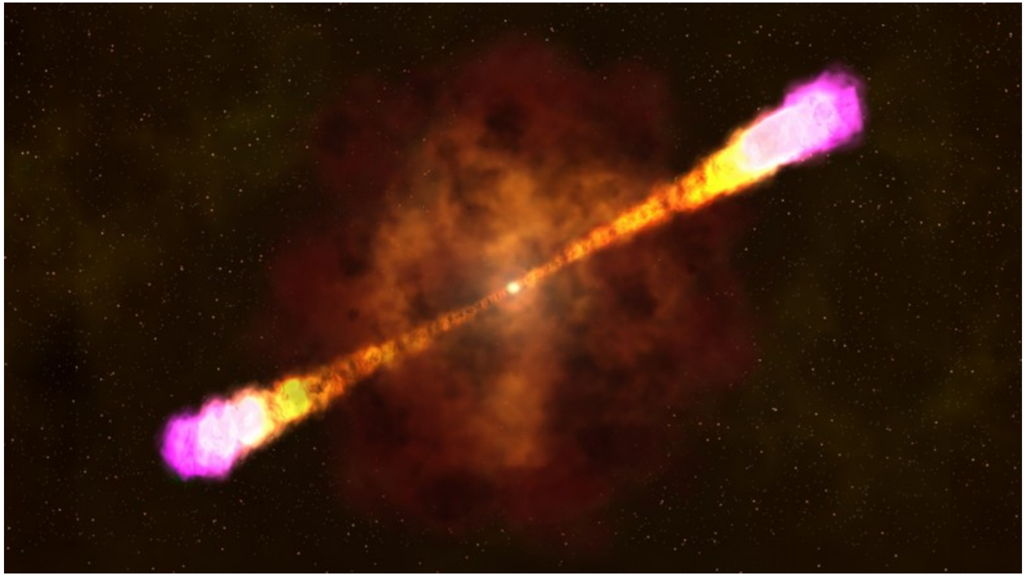


DESY

DESY

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

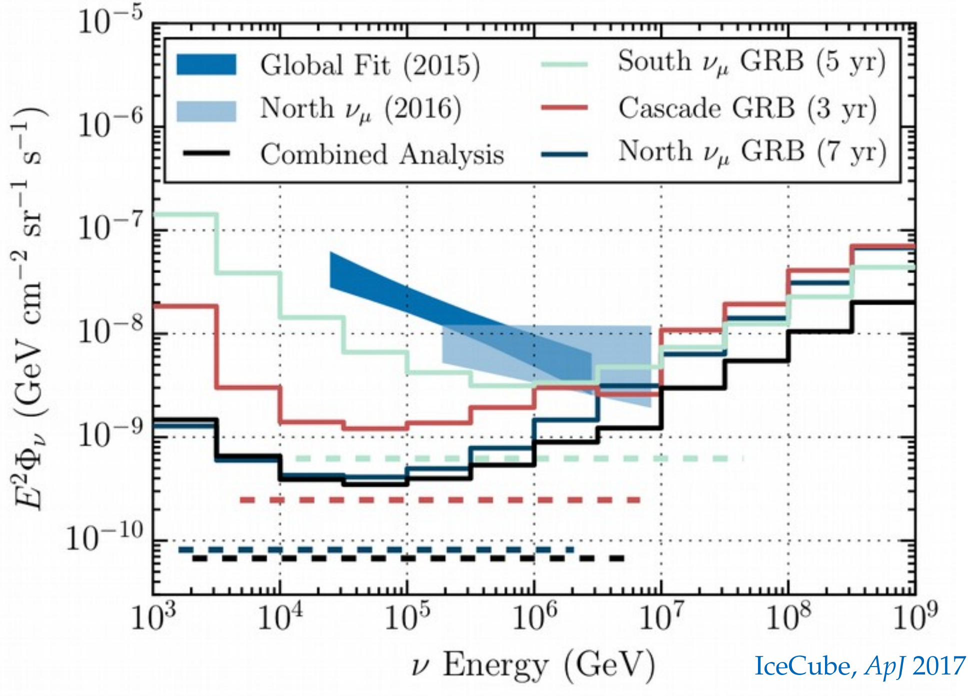


Blazars

GRB ν emission: *e.g.*, Kobayashi & Piran, *ApJ* 1997; Murase & Nagataki, *PRD* 2006; Guetta *et al.*, *ApJ* 2011
Baerwald, Hümmer, Winter, *PRD* 2011; **MB** *et al.*, *Nature Commun.* 2015; ; **MB** *et al.*, *ApJ* 2017

Gamma-ray bursts and blazars – *not* dominant

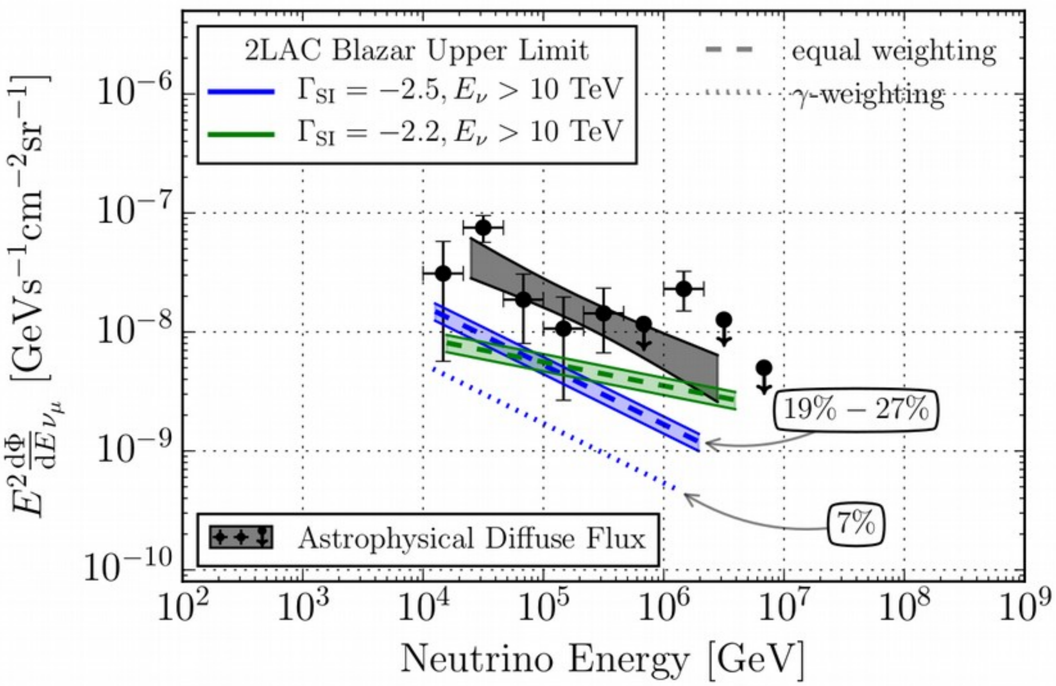
Gamma-ray bursts



1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars



862 blazars inspected, no correlation found

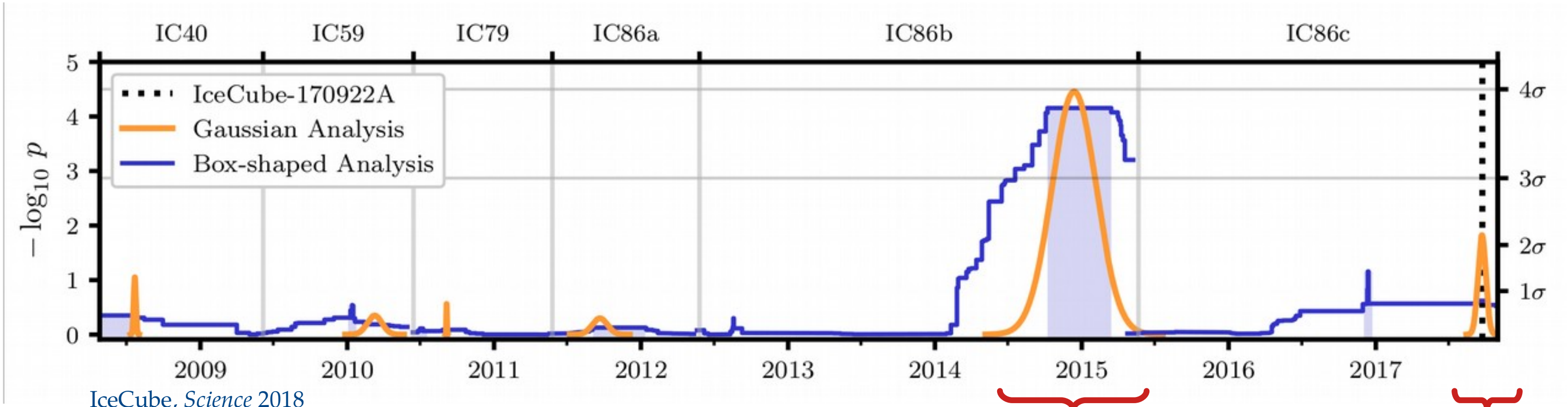
< 27% contribution to diffuse flux

GRB ν emission: *e.g.*, Kobayashi & Piran, *ApJ* 1997; Murase & Nagataki, *PRD* 2006; Guetta *et al.*, *ApJ* 2011
Baerwald, Hümmer, Winter, *PRD* 2011; **MB** *et al.*, *Nature Commun.* 2015; ; **MB** *et al.*, *ApJ* 2017

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

Recent news:
The starburst Seyfert galaxy NGC 1068 is also a potential neutrino source candidate (1908.05993)

Blazar TXS 0506+056:



IceCube, *Science* 2018

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

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

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

Combined (pre-trial): 4.1σ

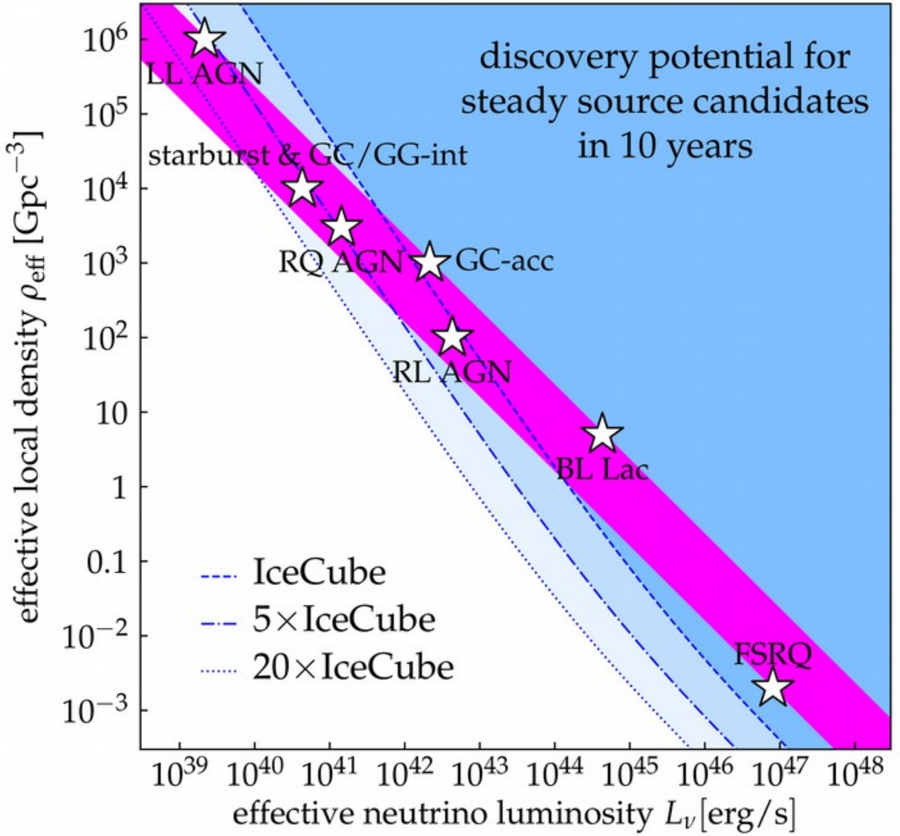
Hard fluence: $E^2 J_{100} = 2.1^{+0.9}_{-0.7} \left(\frac{E}{100\ \text{TeV}}\right)^{-2.1\pm0.2}\ \text{TeV cm}^{-2}$

Joint modeling of the two periods is challenging; see ICRC 2019 talk by Walter Winter

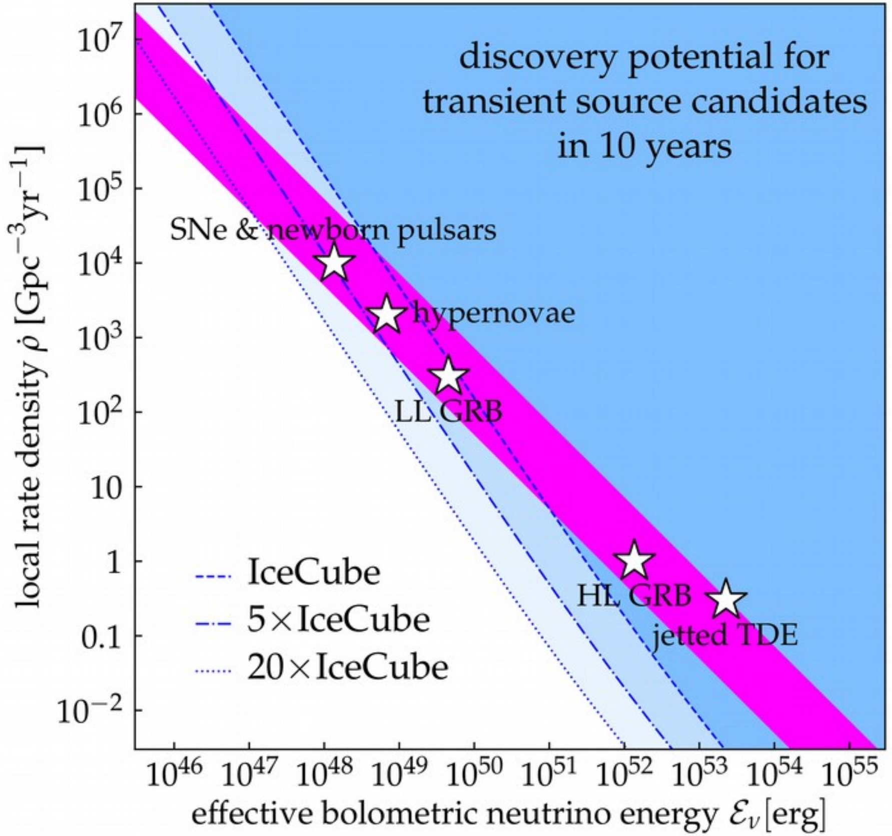
Source discovery potential: today and in the future

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

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



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



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

In the face of astrophysical unknowns,
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Yes.

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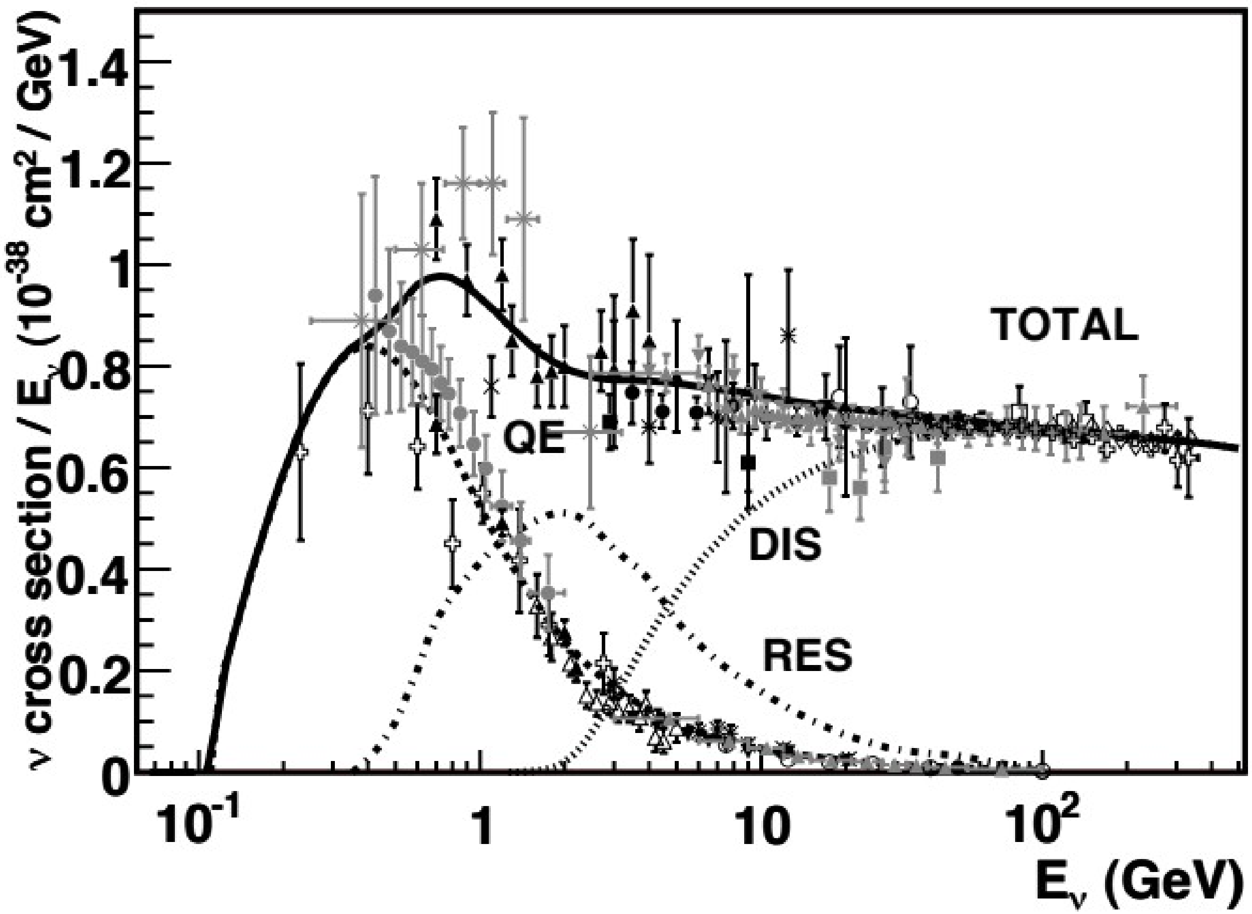
Yes.

Already today.

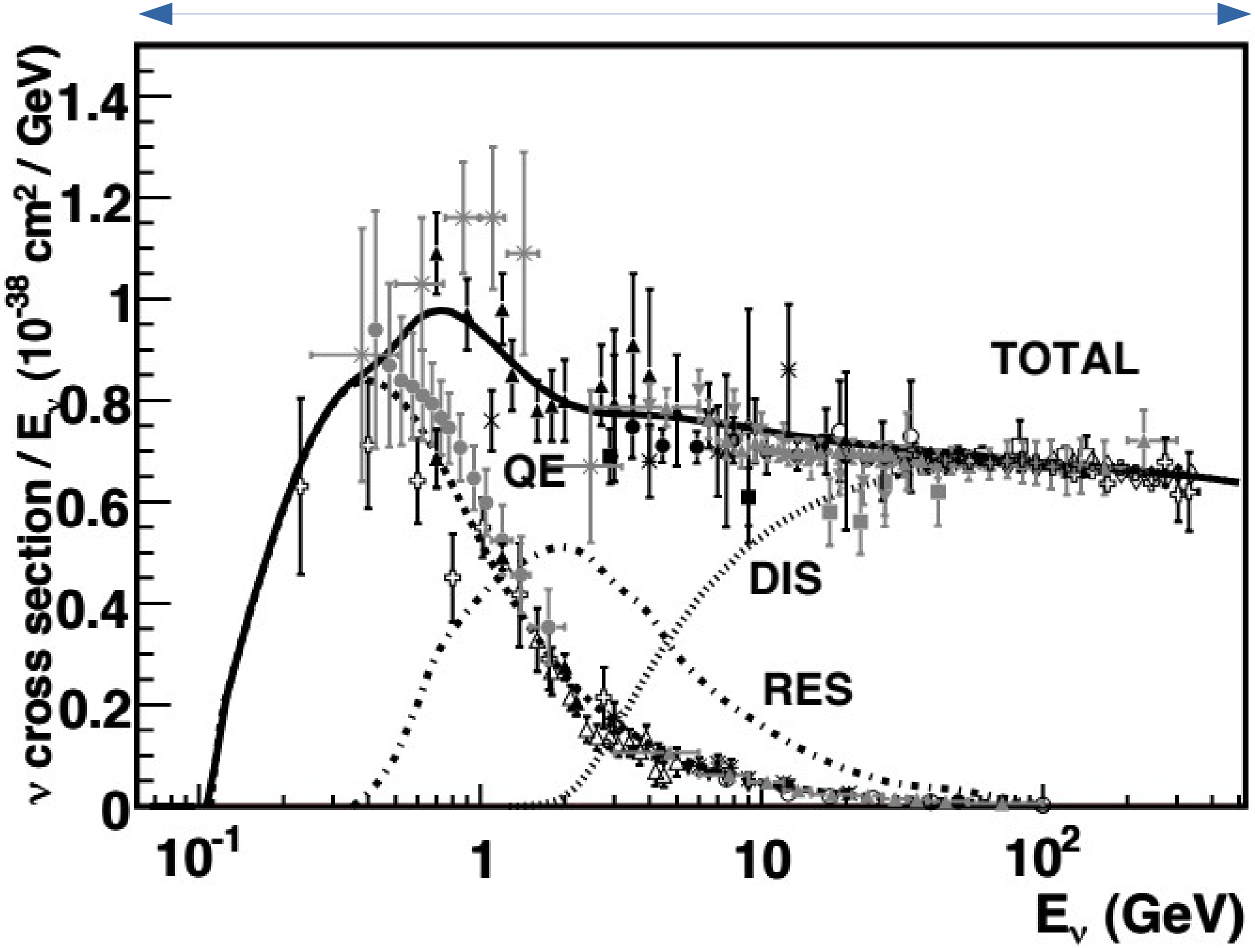
Netflix

Netflix



Particle Data Group

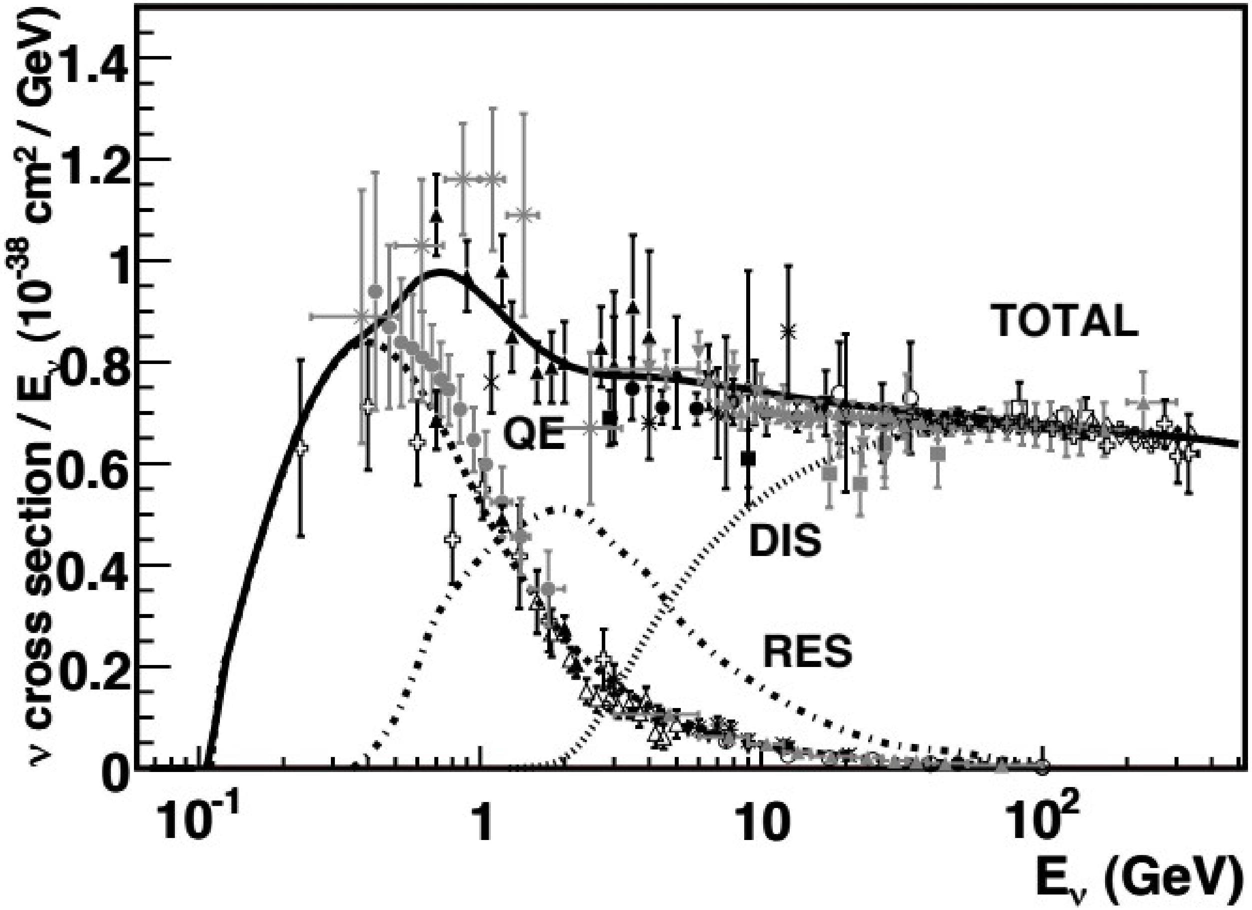
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



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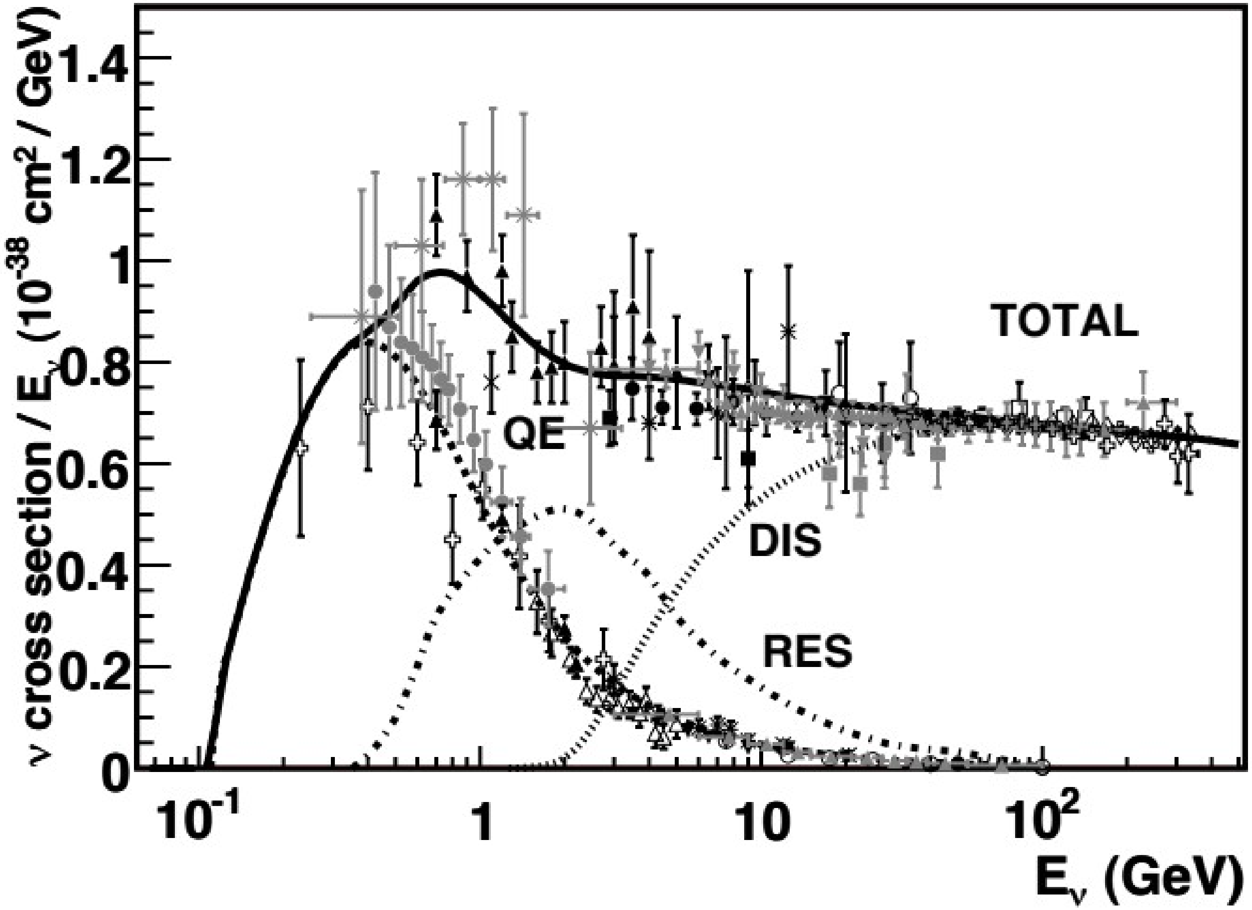

No measurements

… until recently!

Particle Data Group

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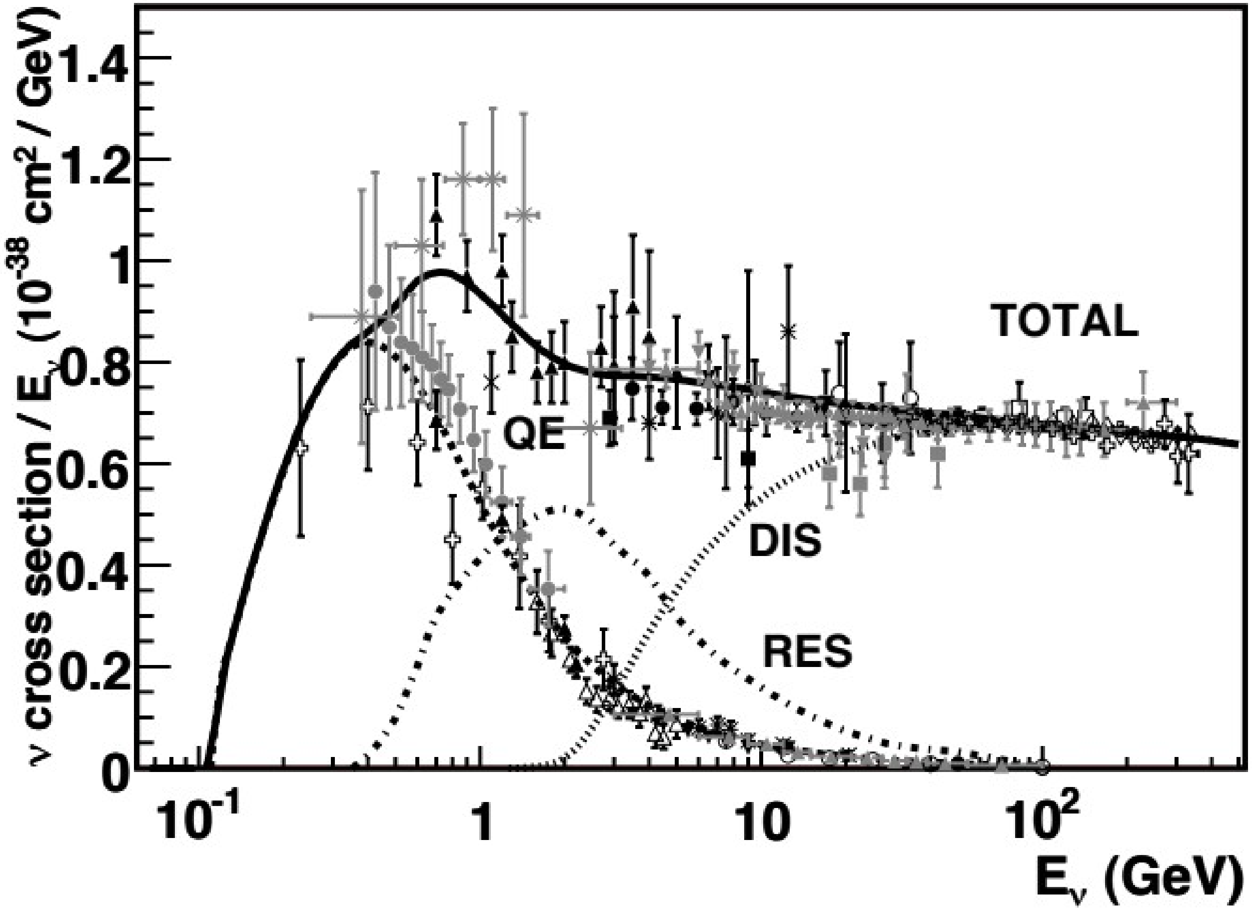
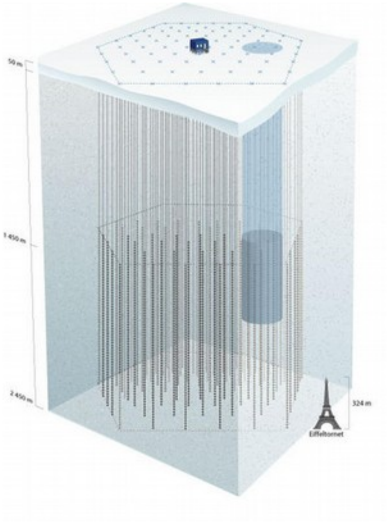
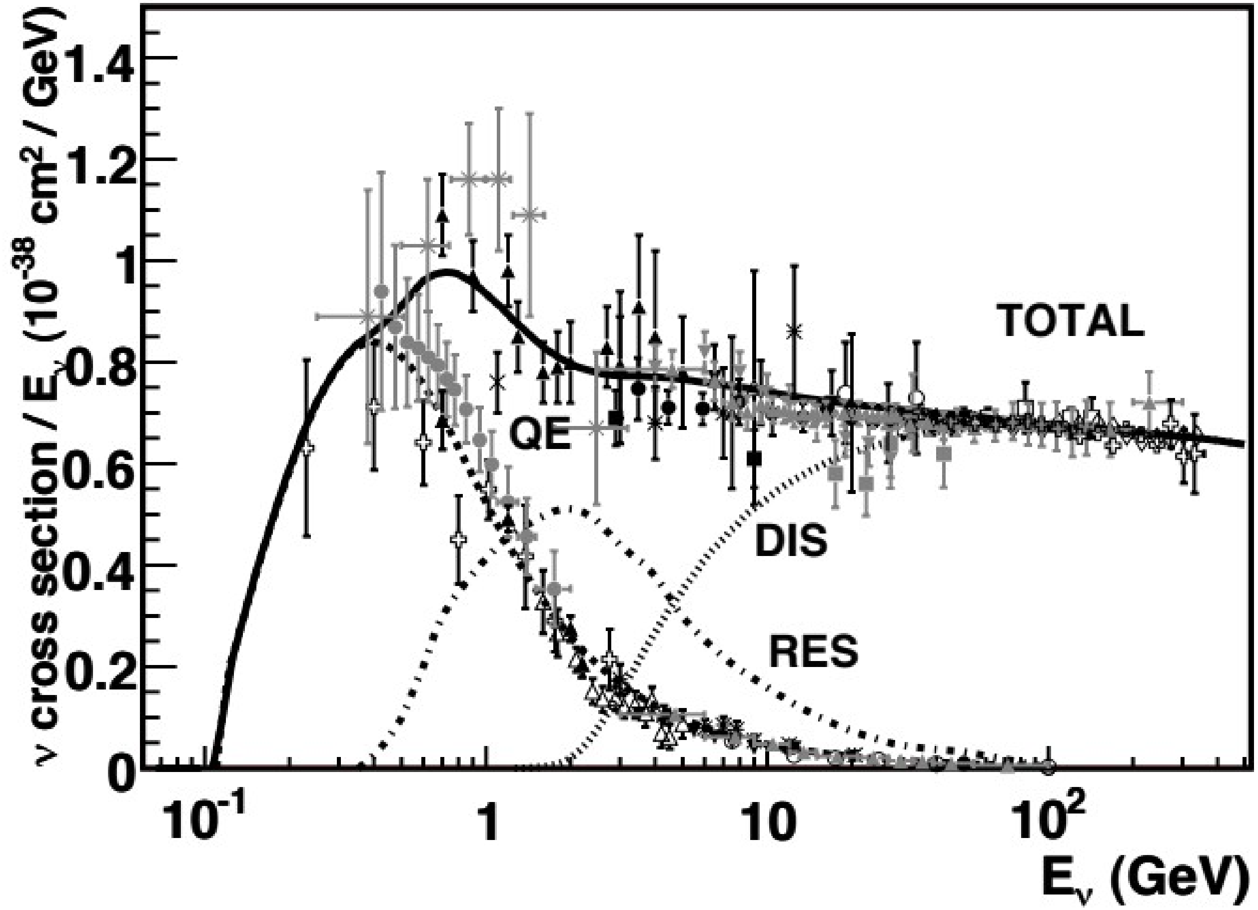


Particle Data Group



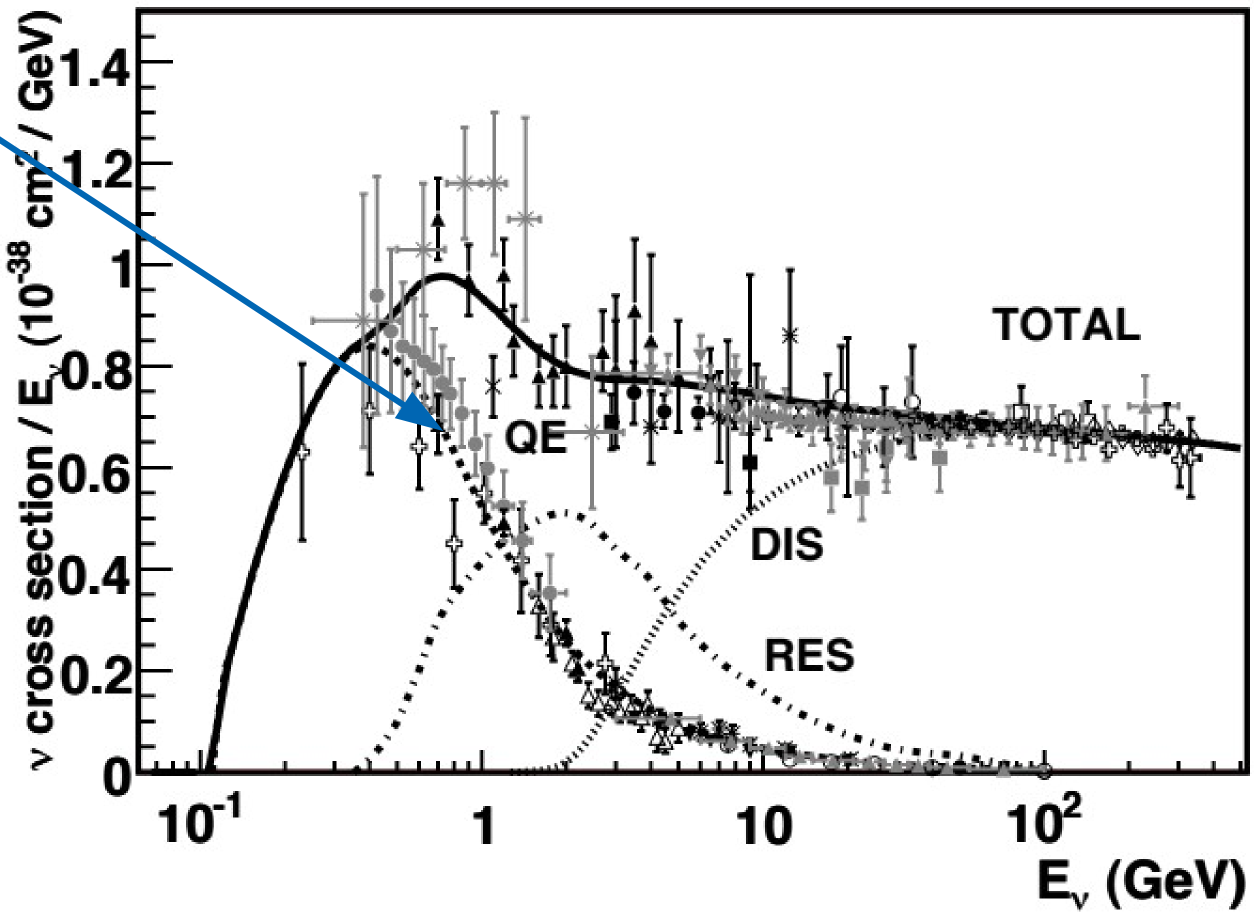


Particle Data Group

Quasi-elastic scattering:

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

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



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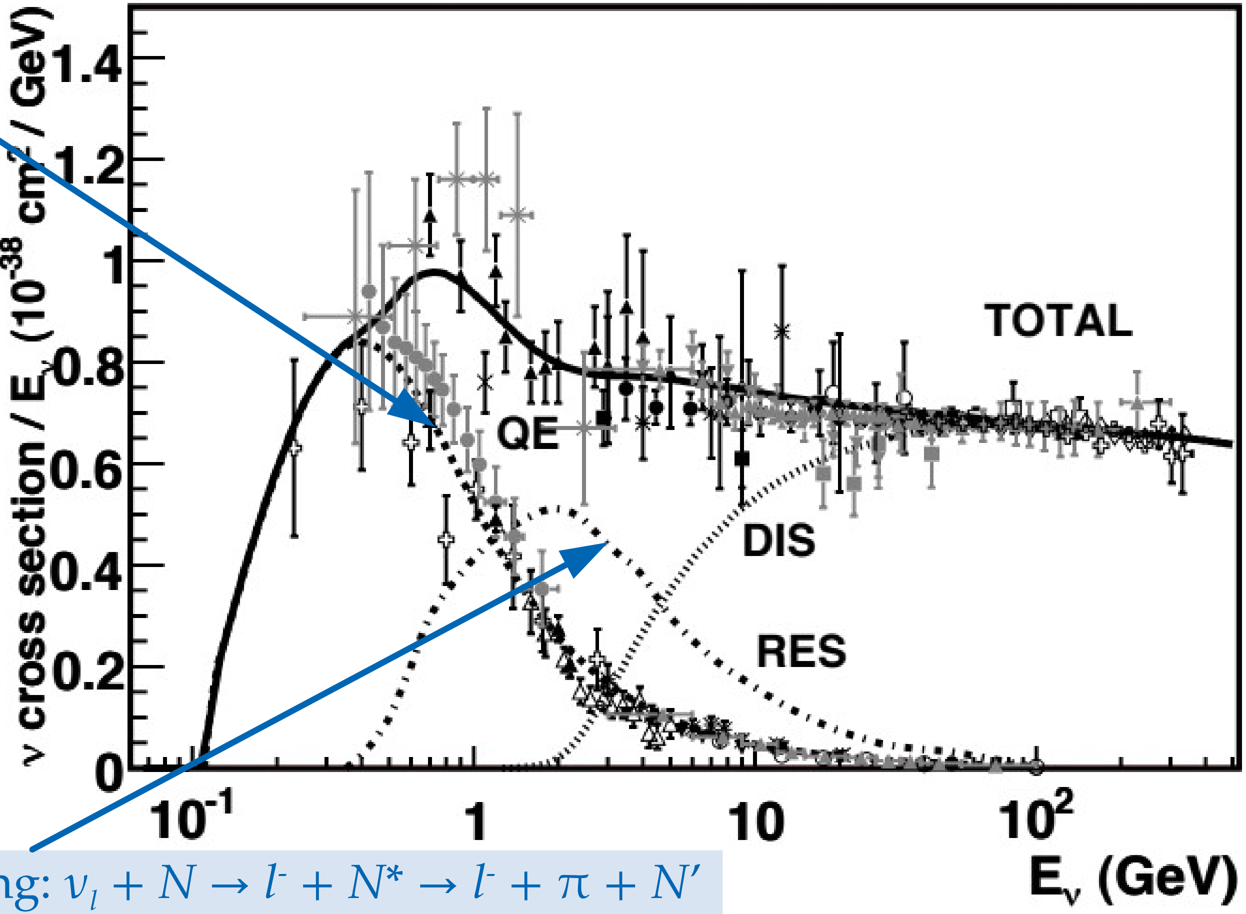

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

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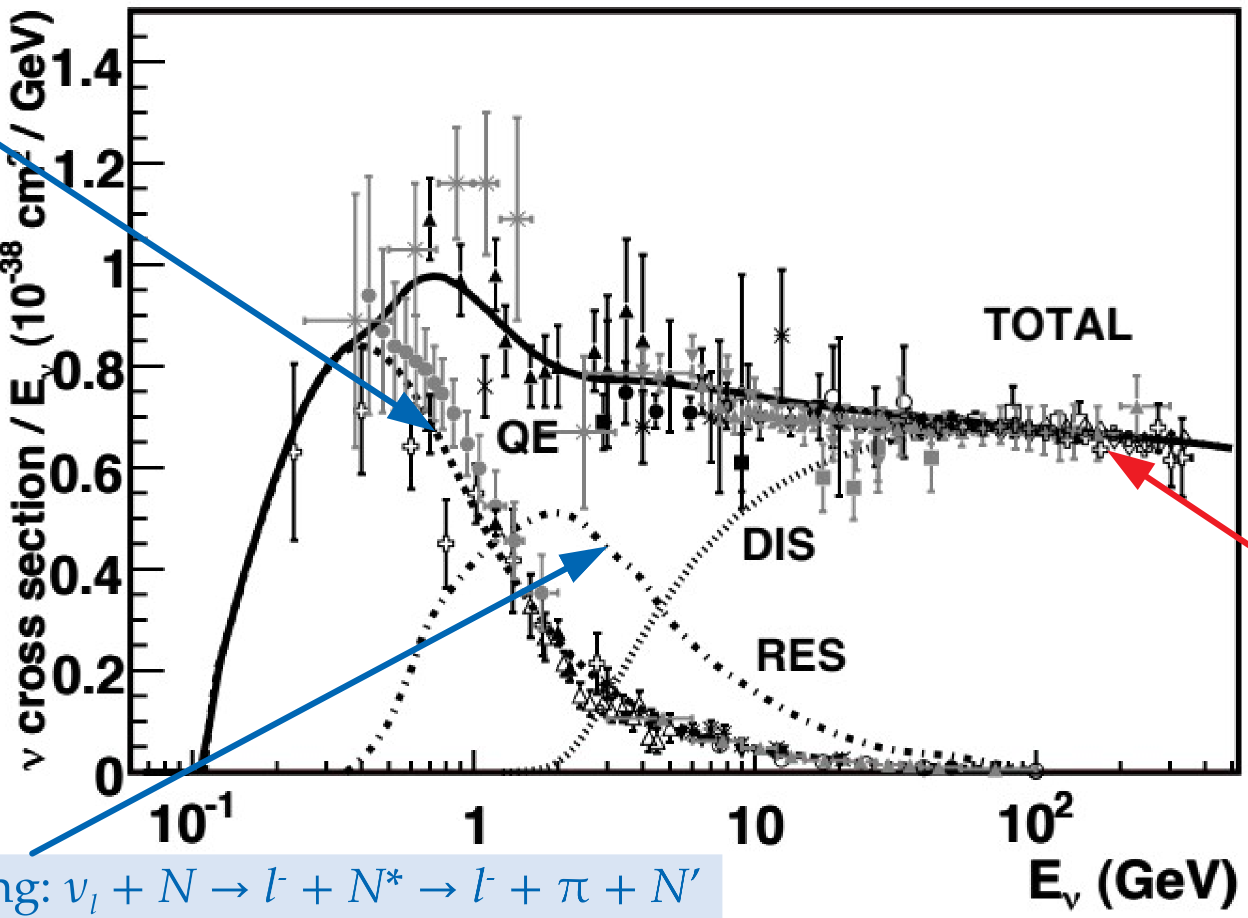


Deep inelastic scattering:
$\nu_l + N \rightarrow l^- + X$
$\bar{\nu}_l + N \rightarrow l^+ + X$

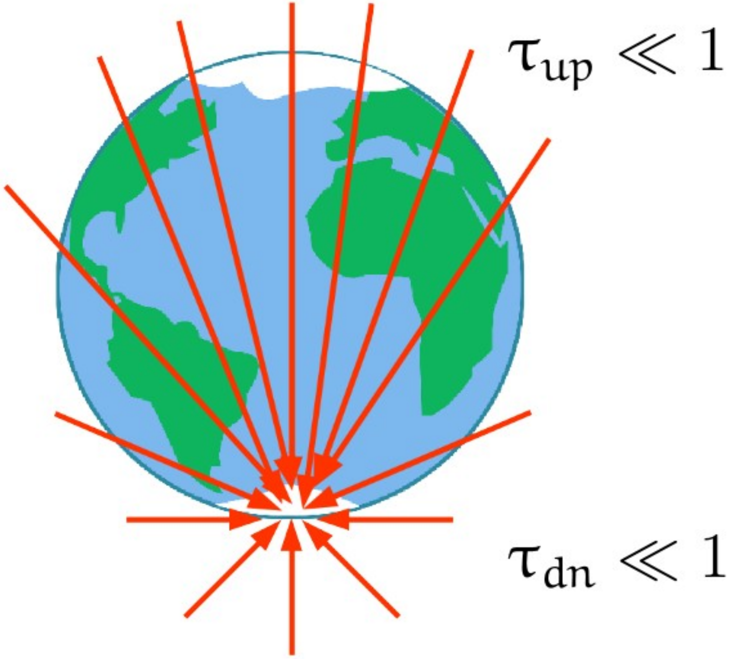
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

High-energy neutrinos are attenuated inside Earth

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

Below ~ 10 TeV: Earth is transparent



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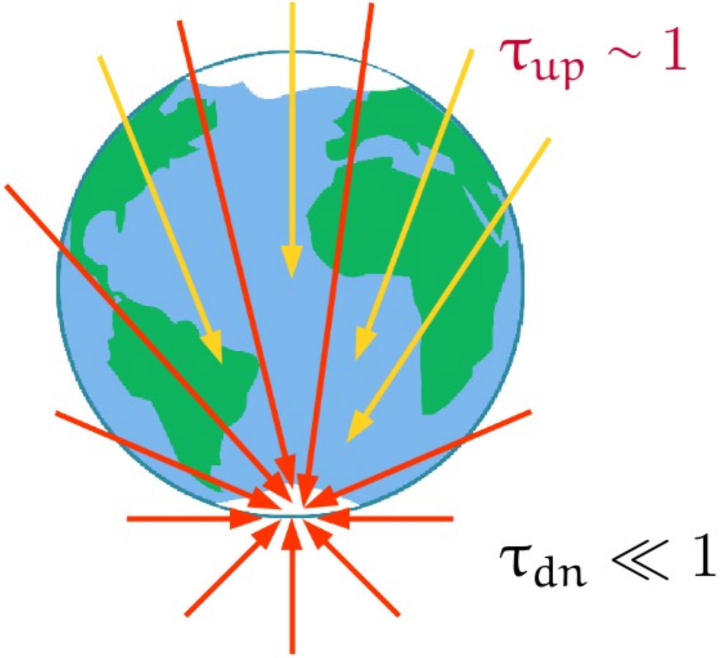

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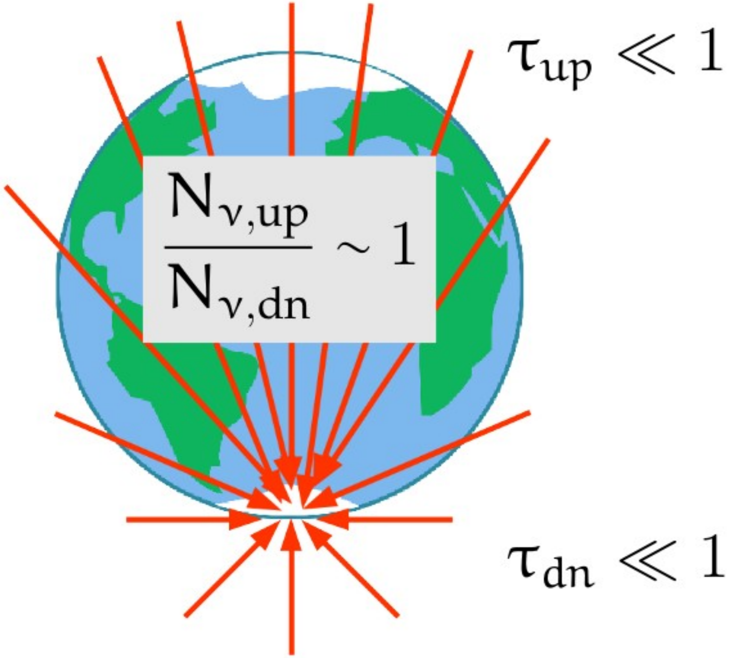

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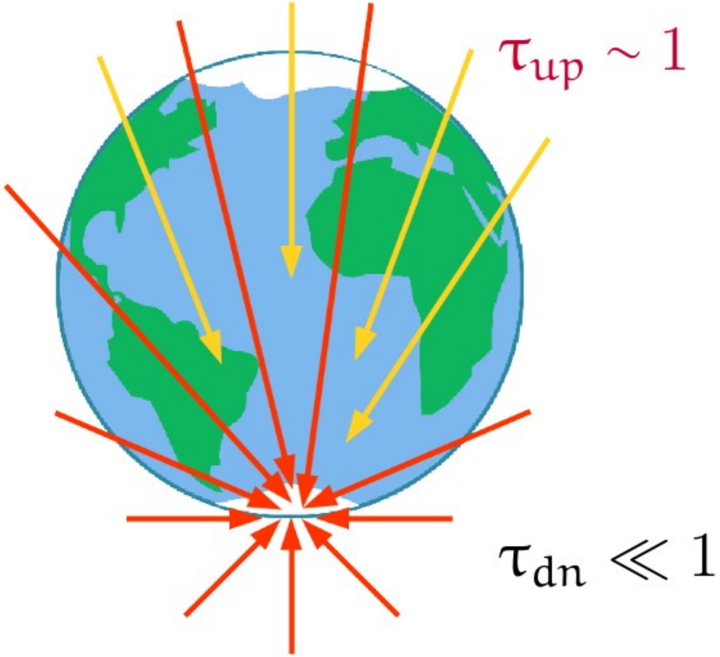

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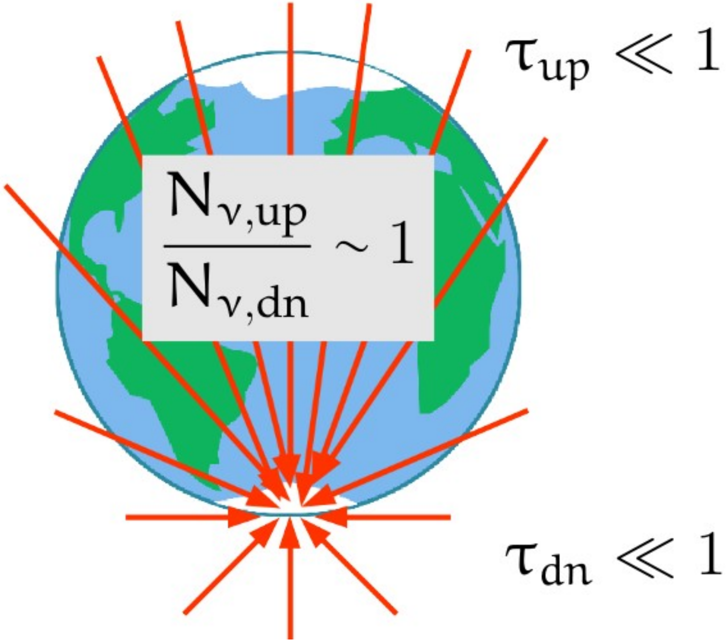

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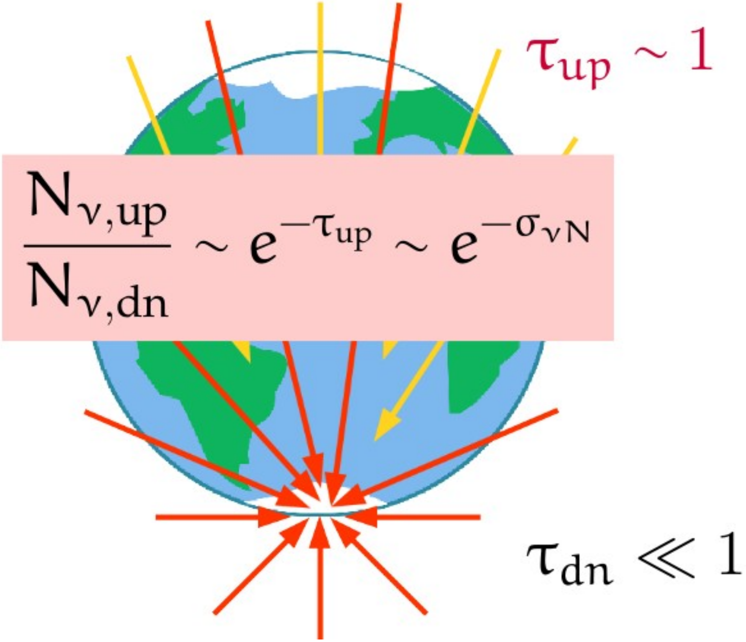
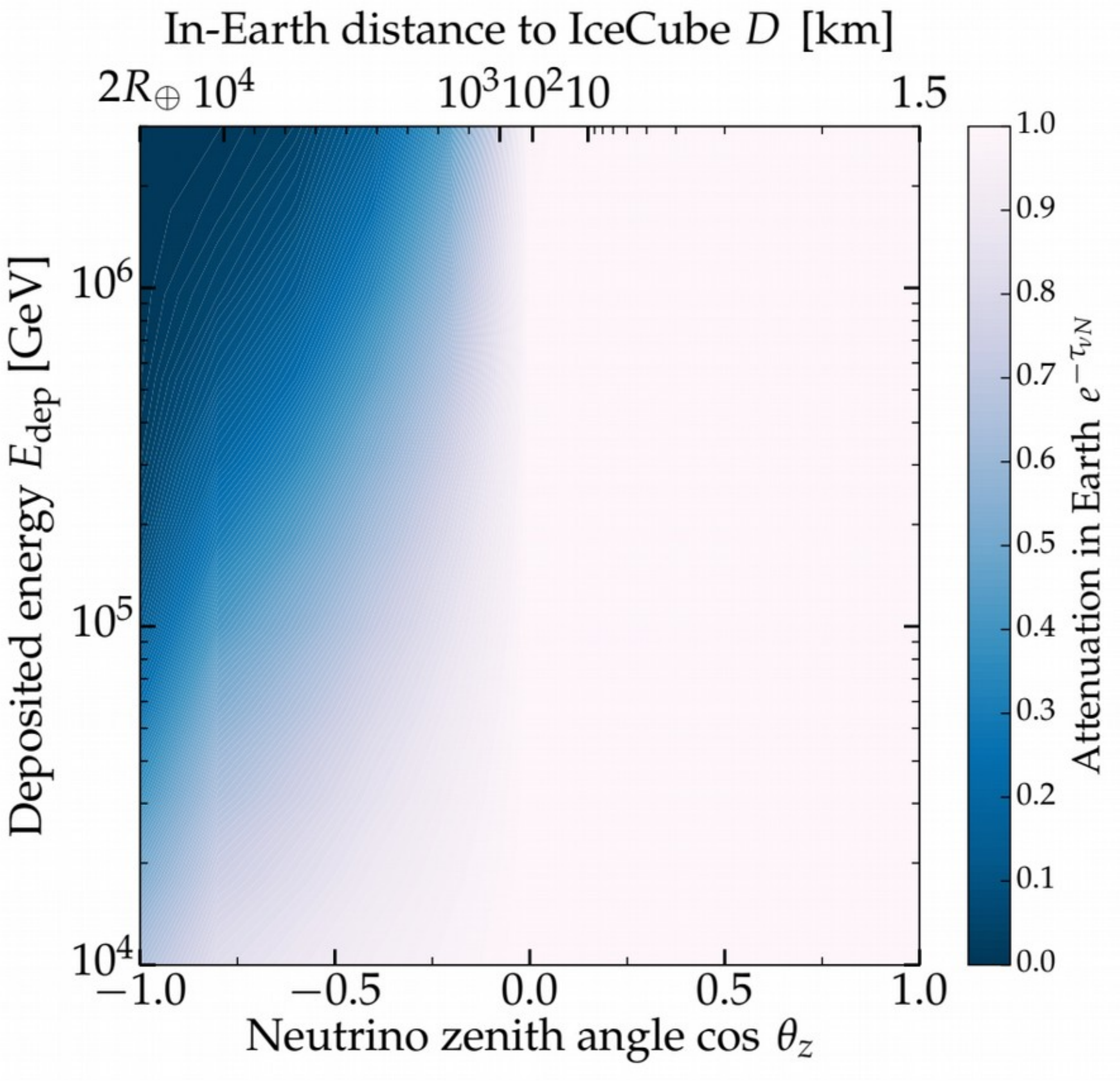
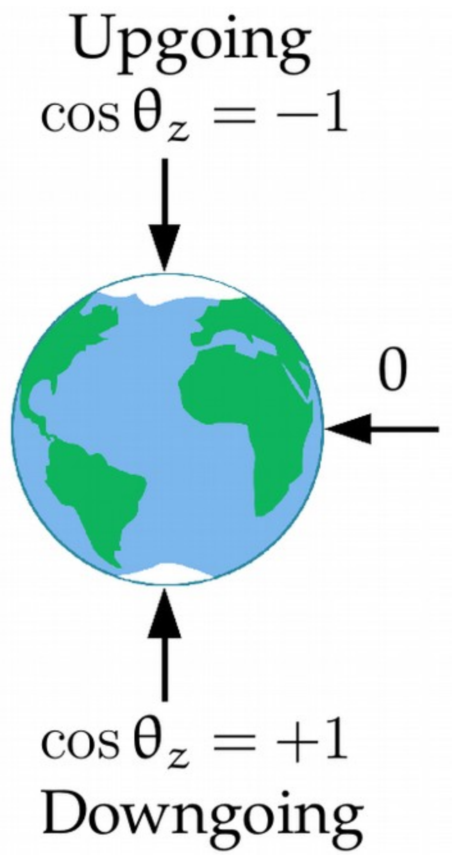
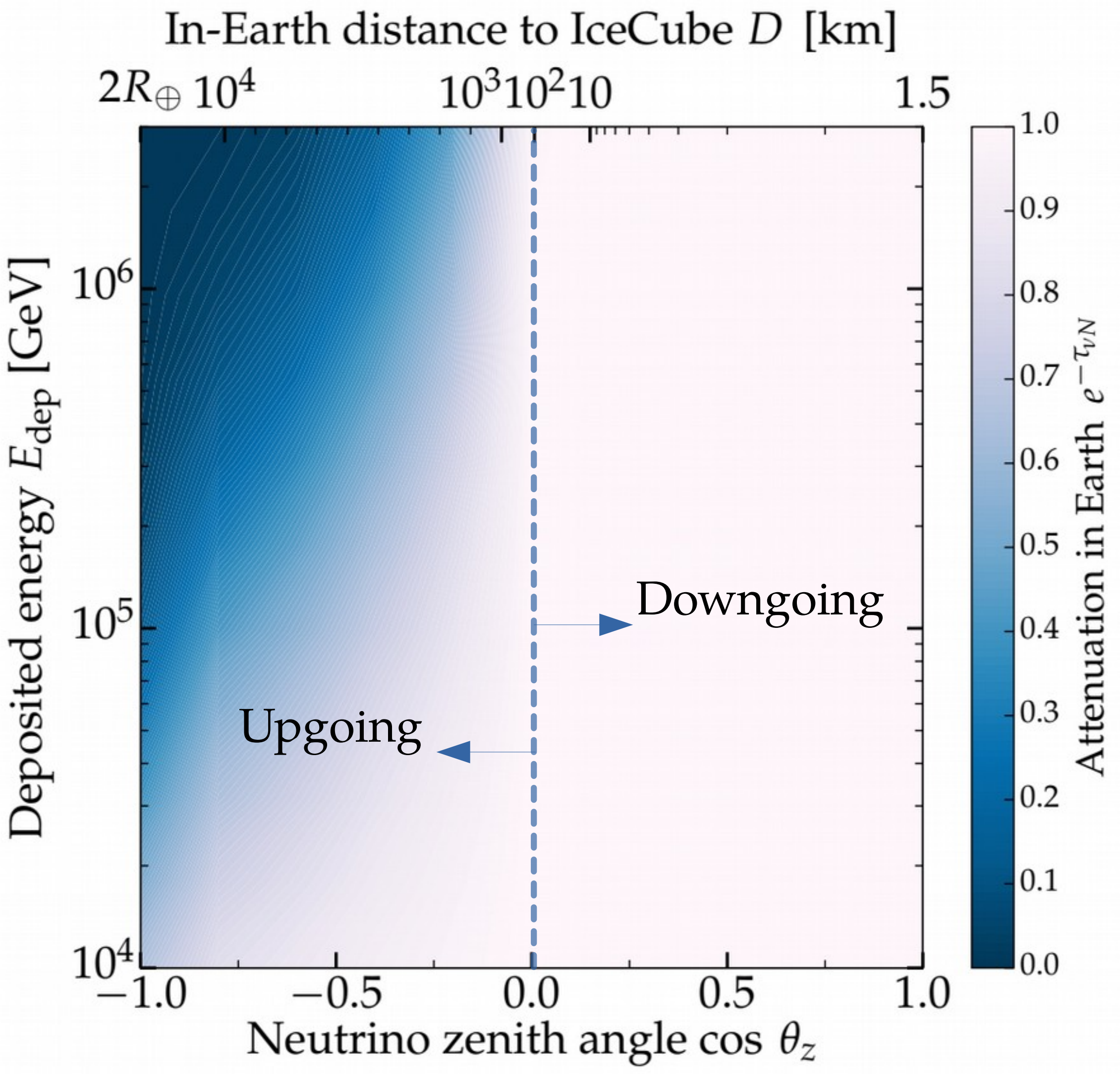




Assume the matter density inside the Earth from the Preliminary Reference Earth Model (Dziewonski & Anderson 1981)





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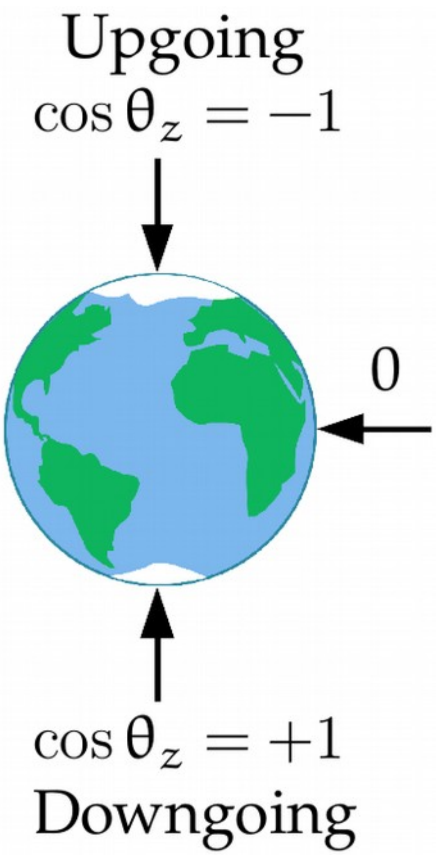
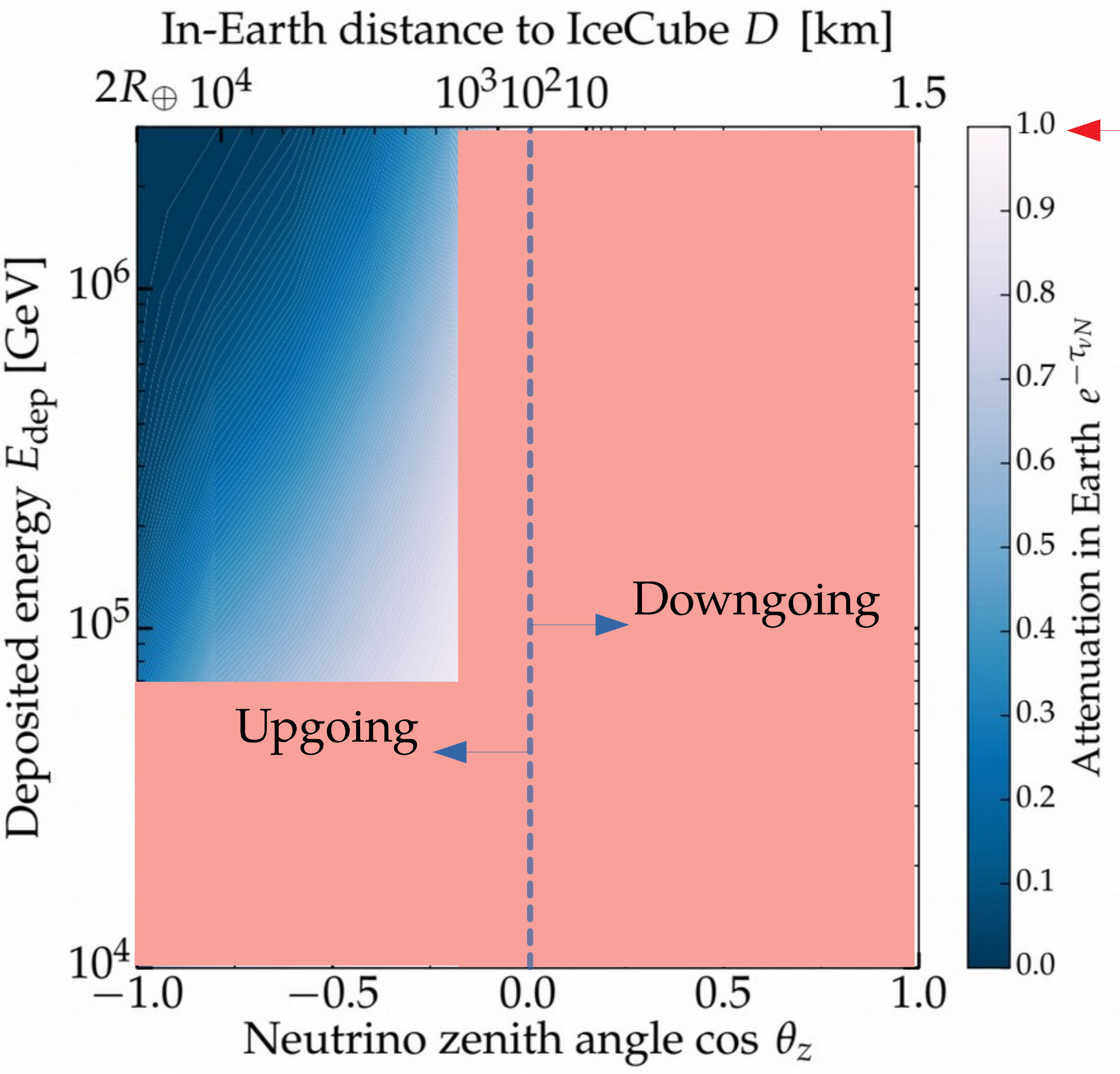
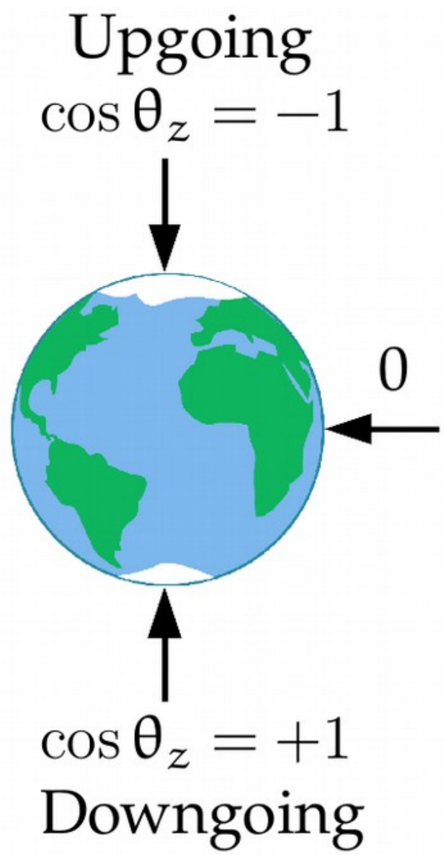
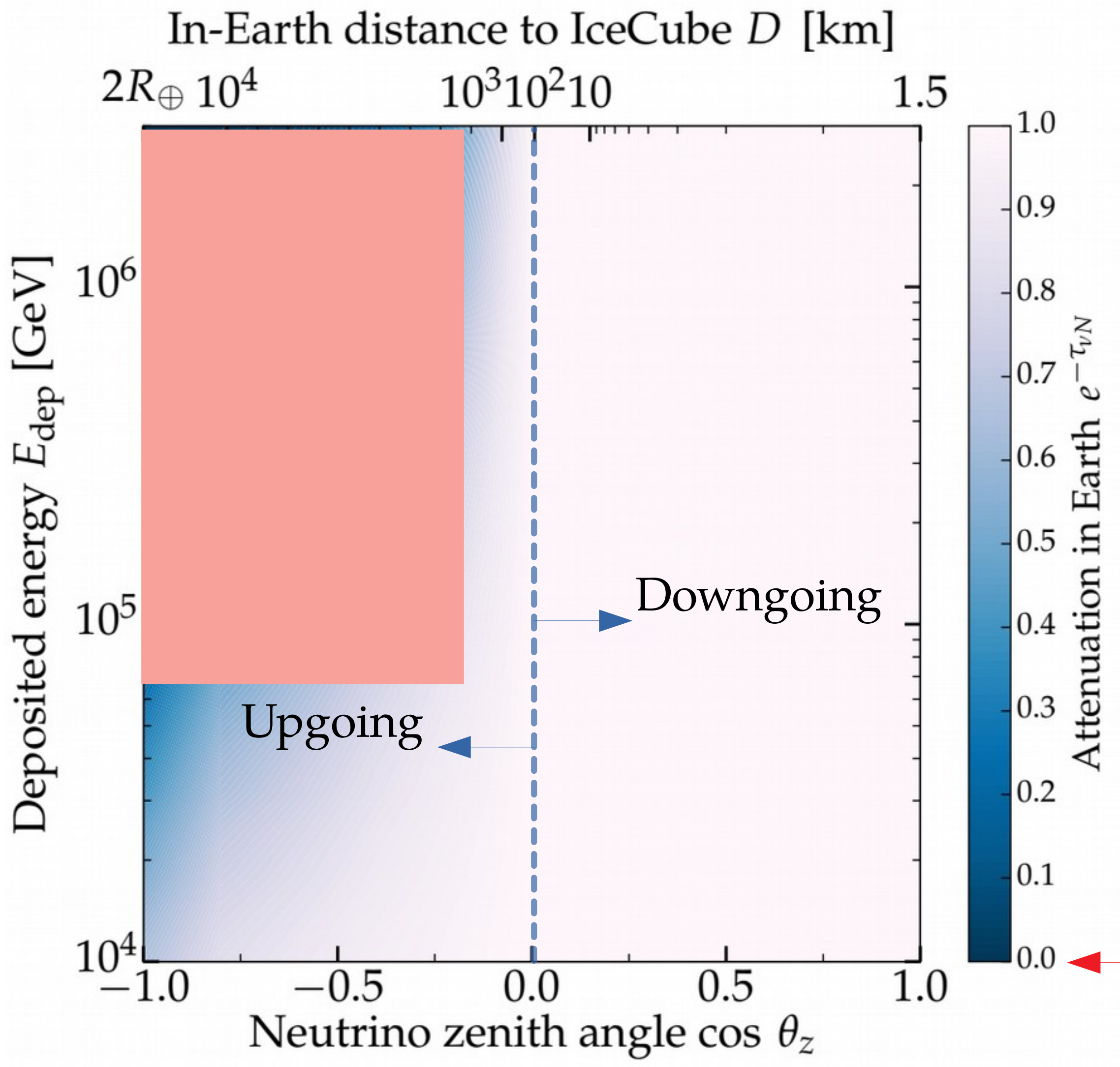




Transparent Earth
$e^{-\tau} \sim 1$

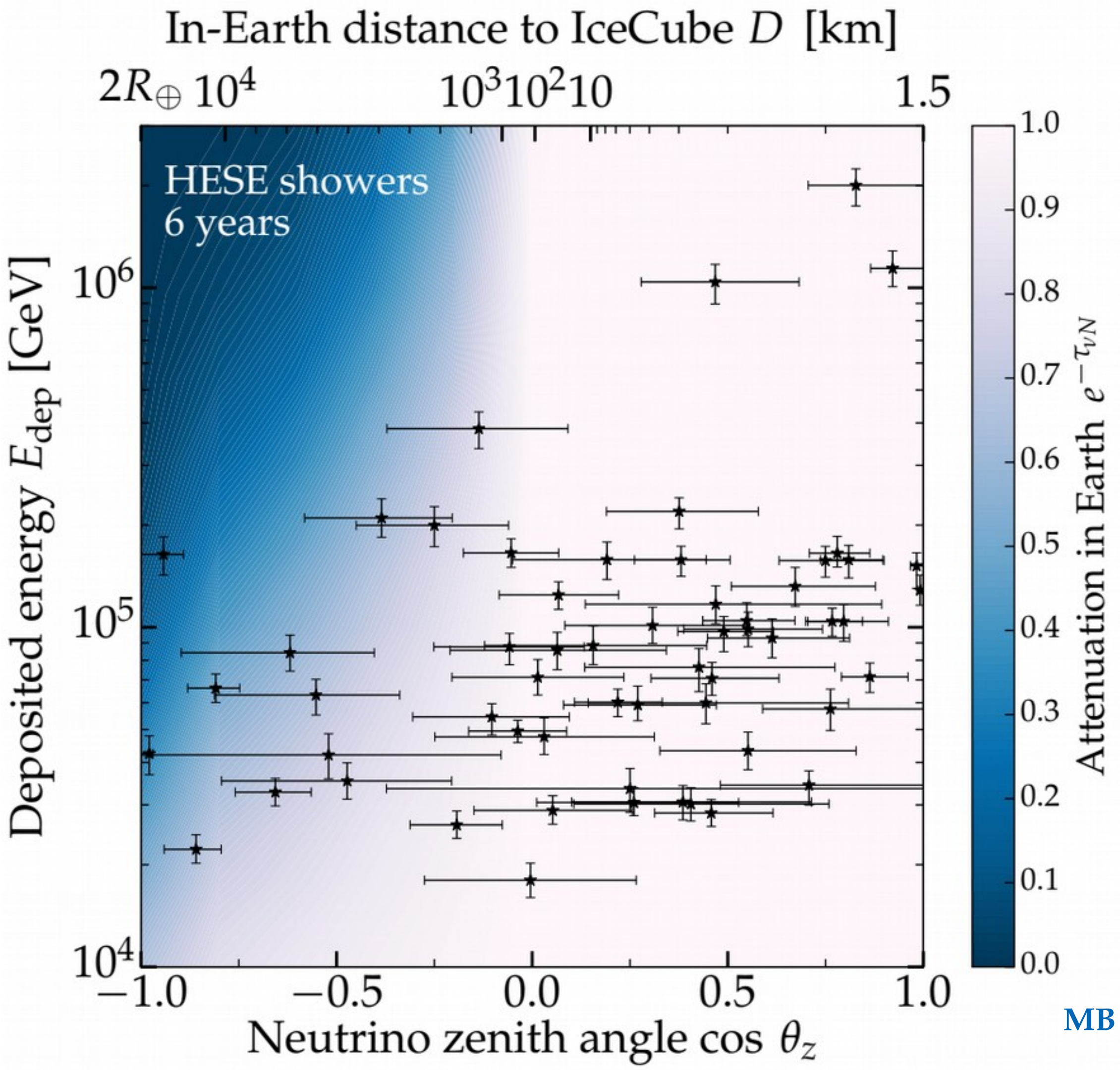
Assume the matter density inside the Earth from the Preliminary Reference Earth Model (Dziewonski & Anderson 1981)



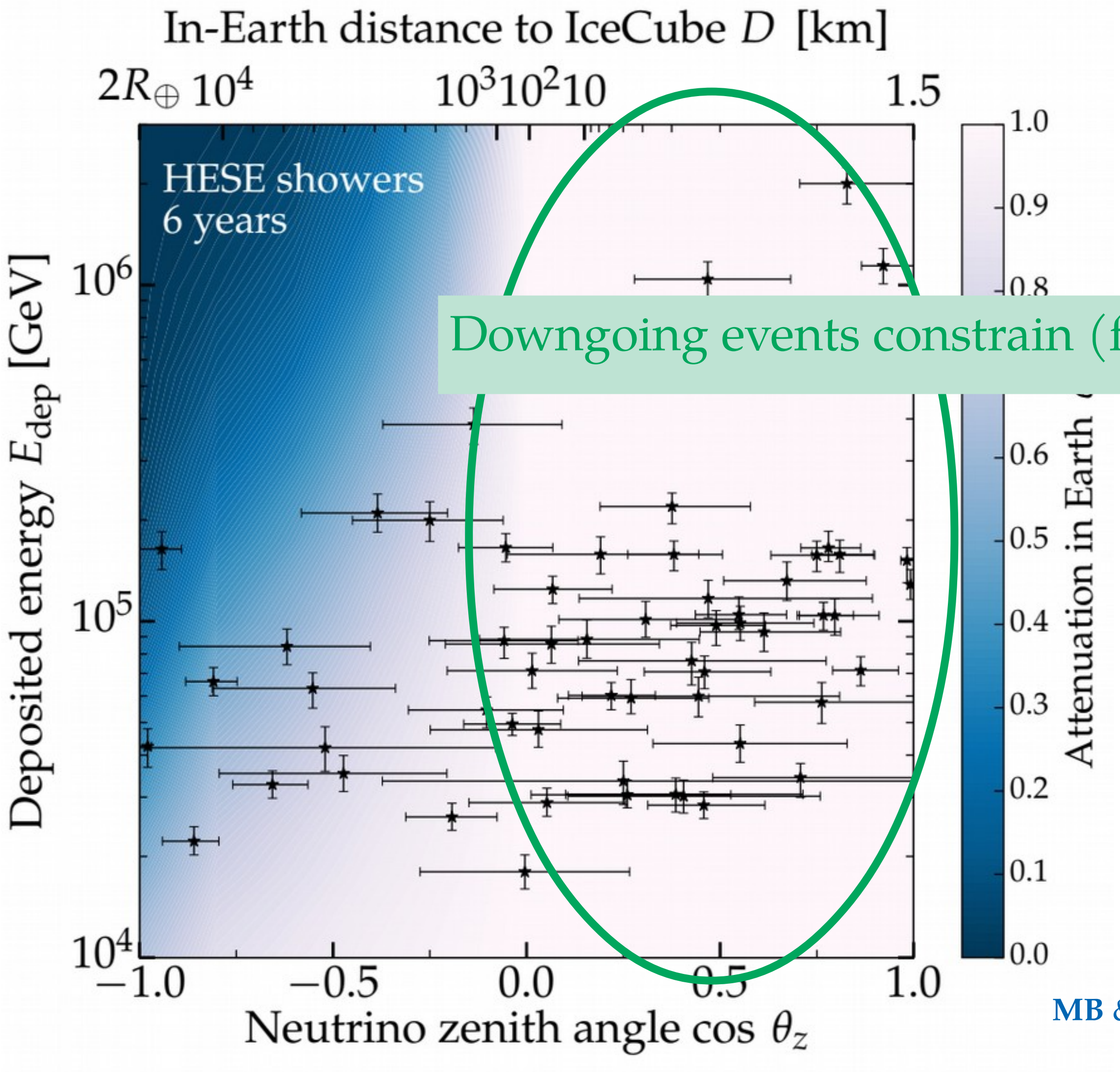


Assume the matter density inside the Earth from the Preliminary Reference Earth Model (Dziewonski & Anderson 1981)

Opaque Earth
$e^{-\tau} \sim 0$

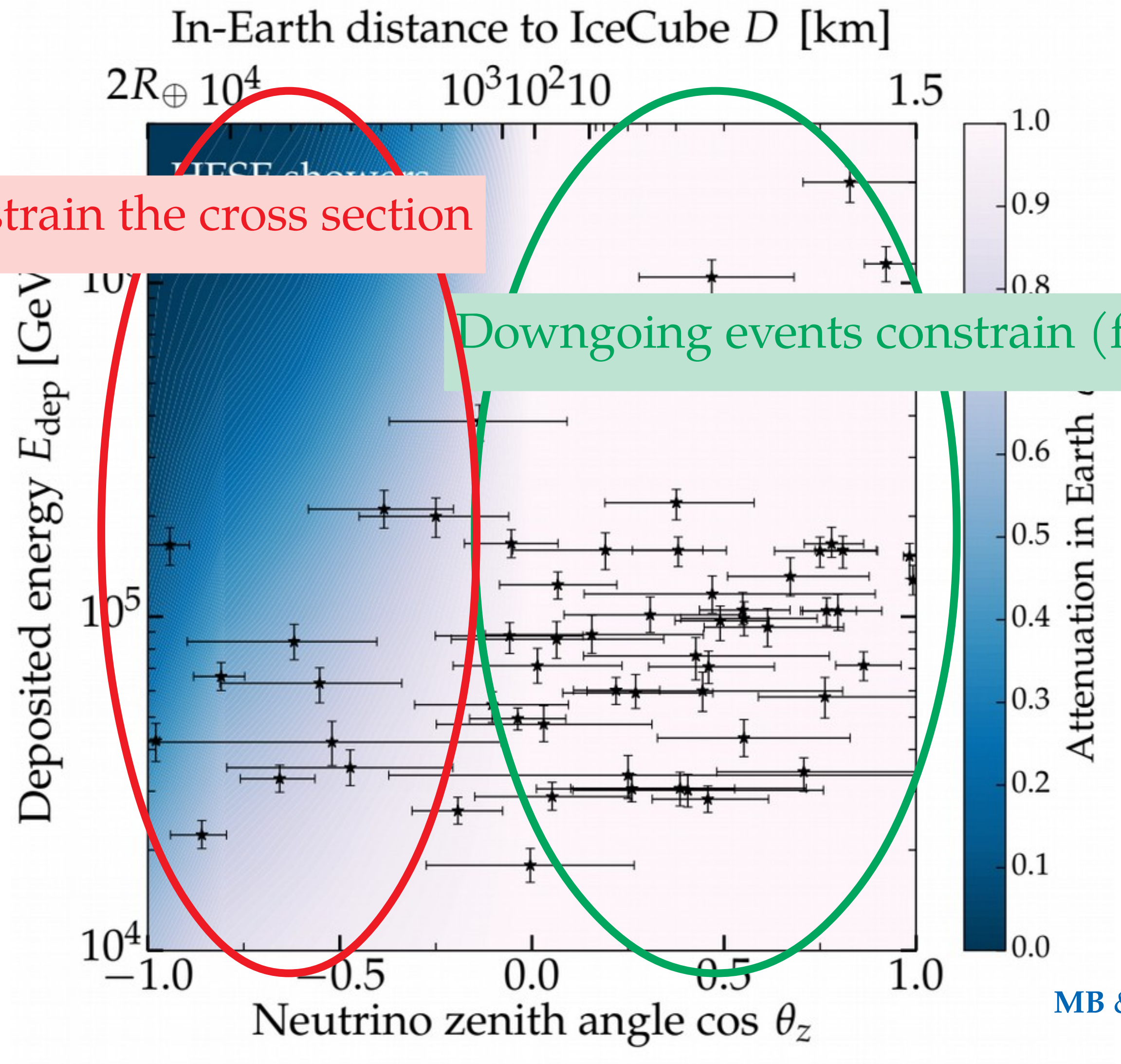


MB & Connolly, *PRL* 2019

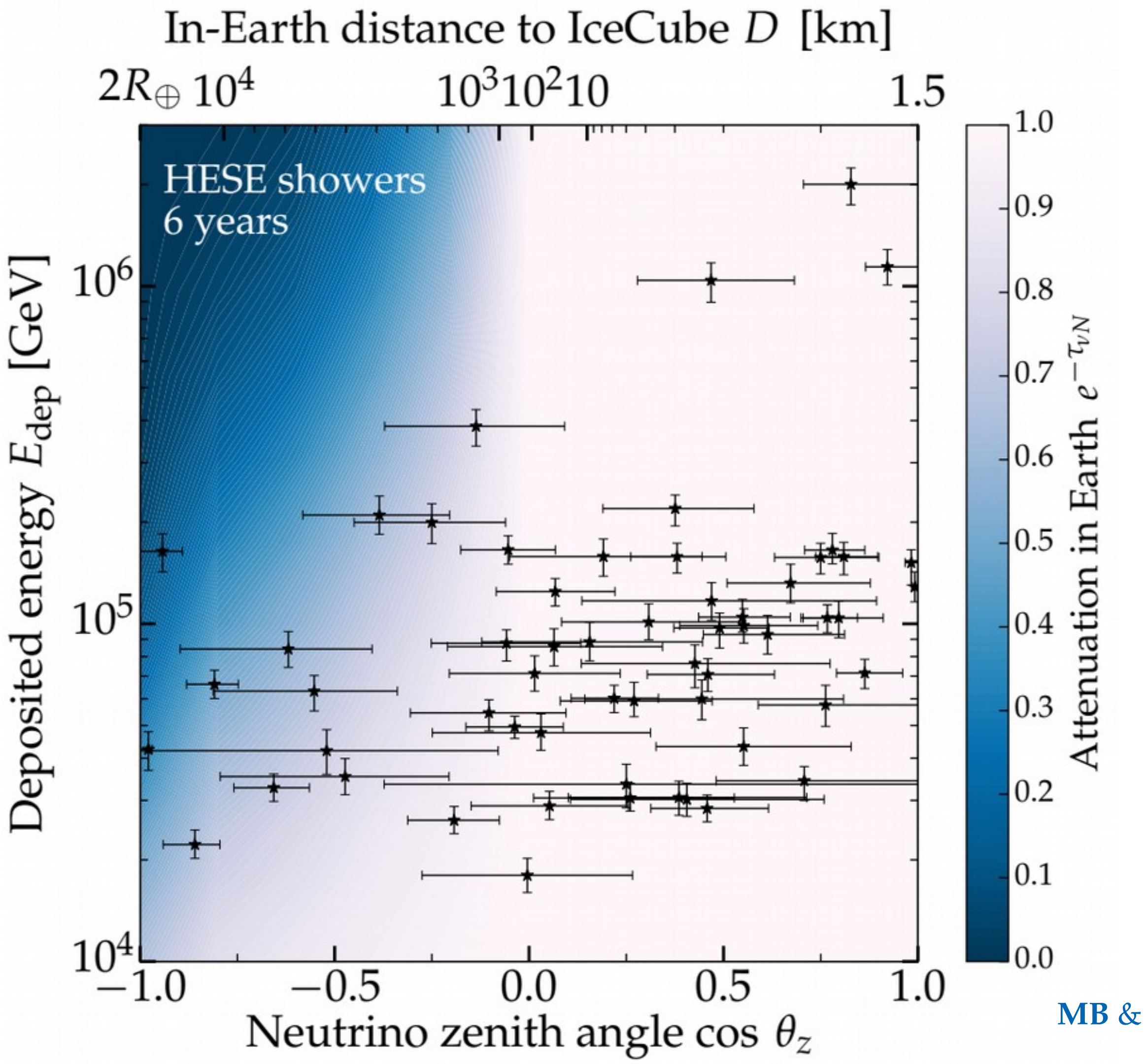


Downgoing events constrain (flux x cross section)

MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019



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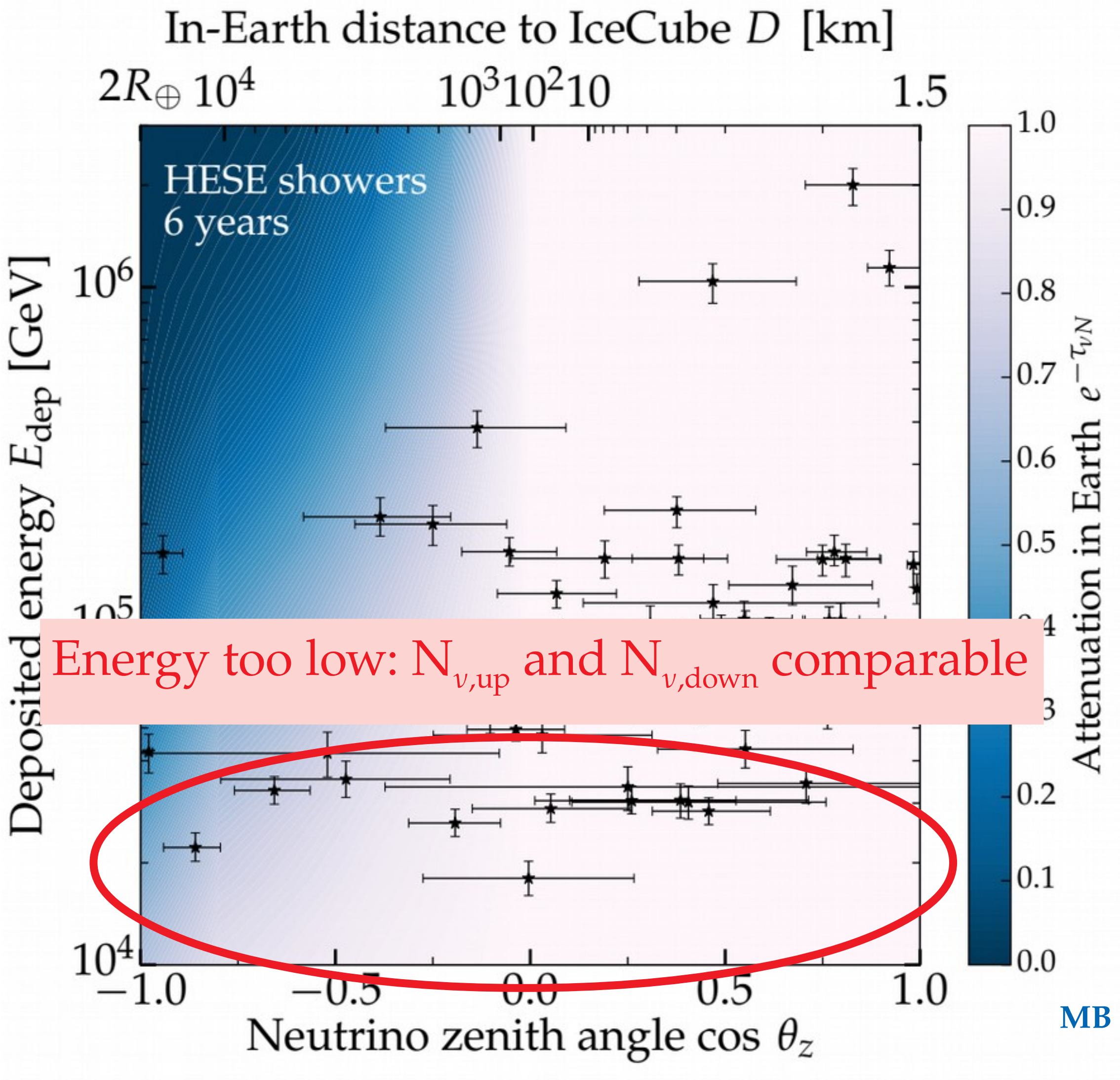
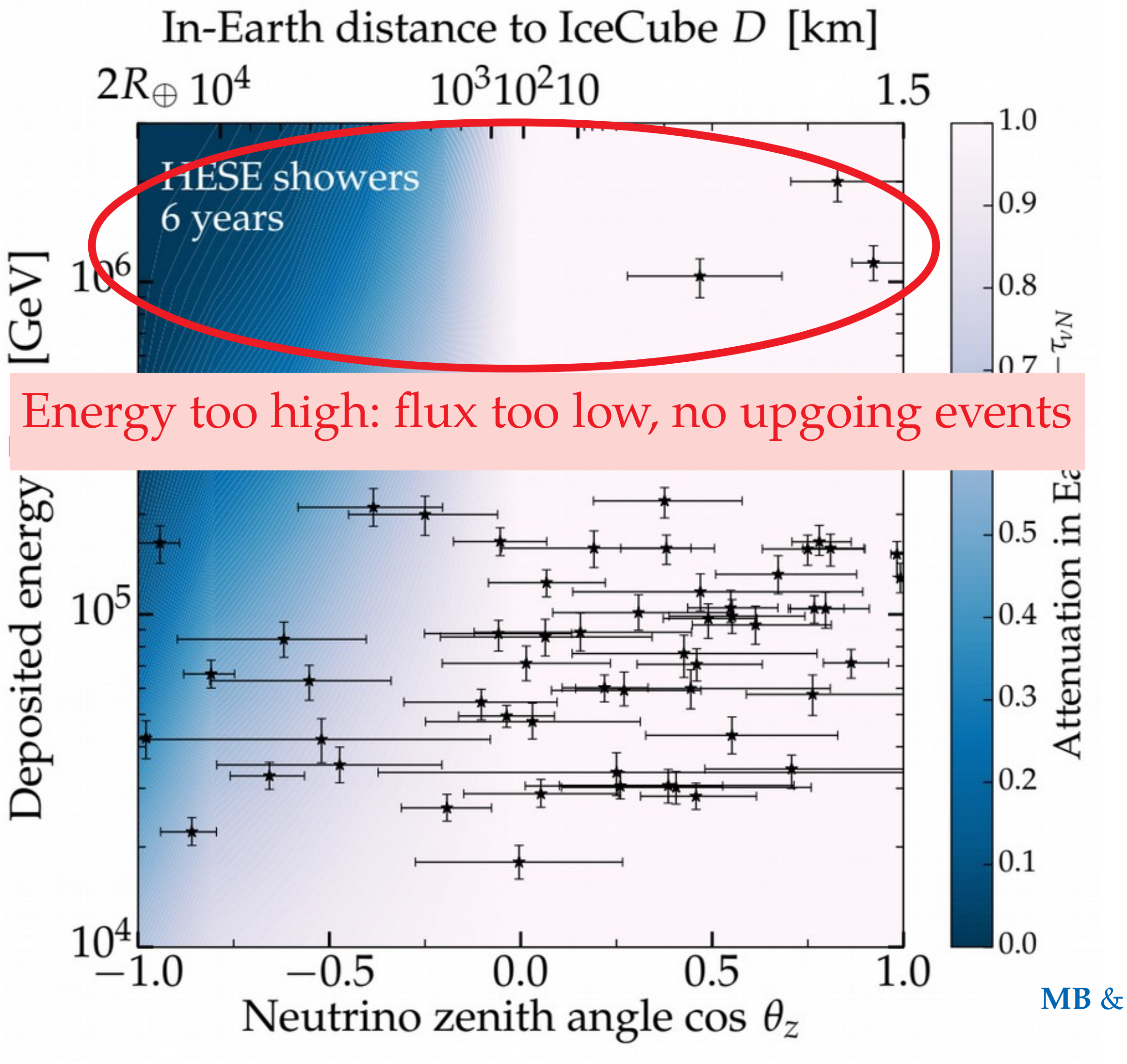
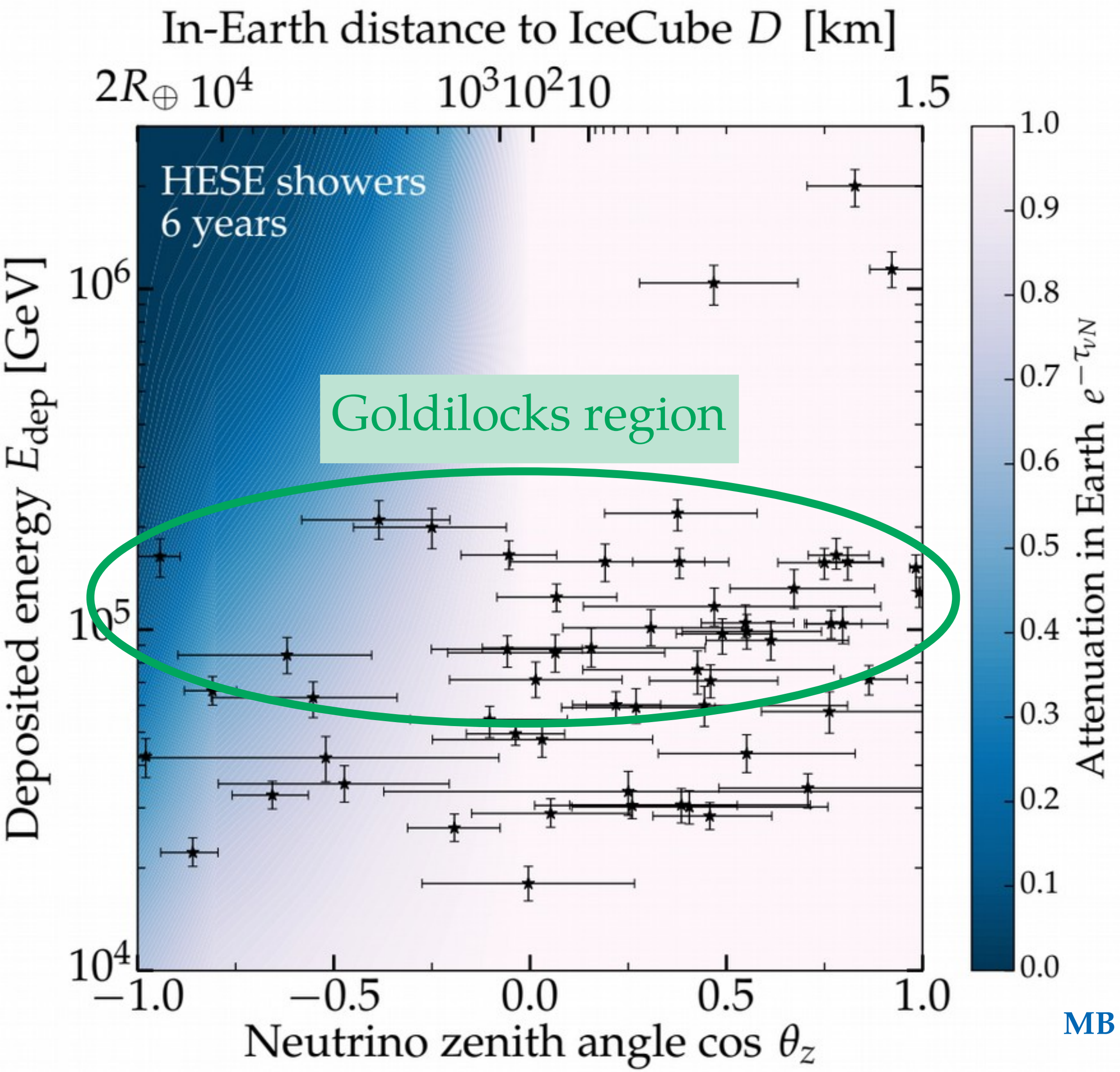


Energy too low: $N_{\nu,up}$ and $N_{\nu,down}$ comparable

MB & Connolly, *PRL* 2019

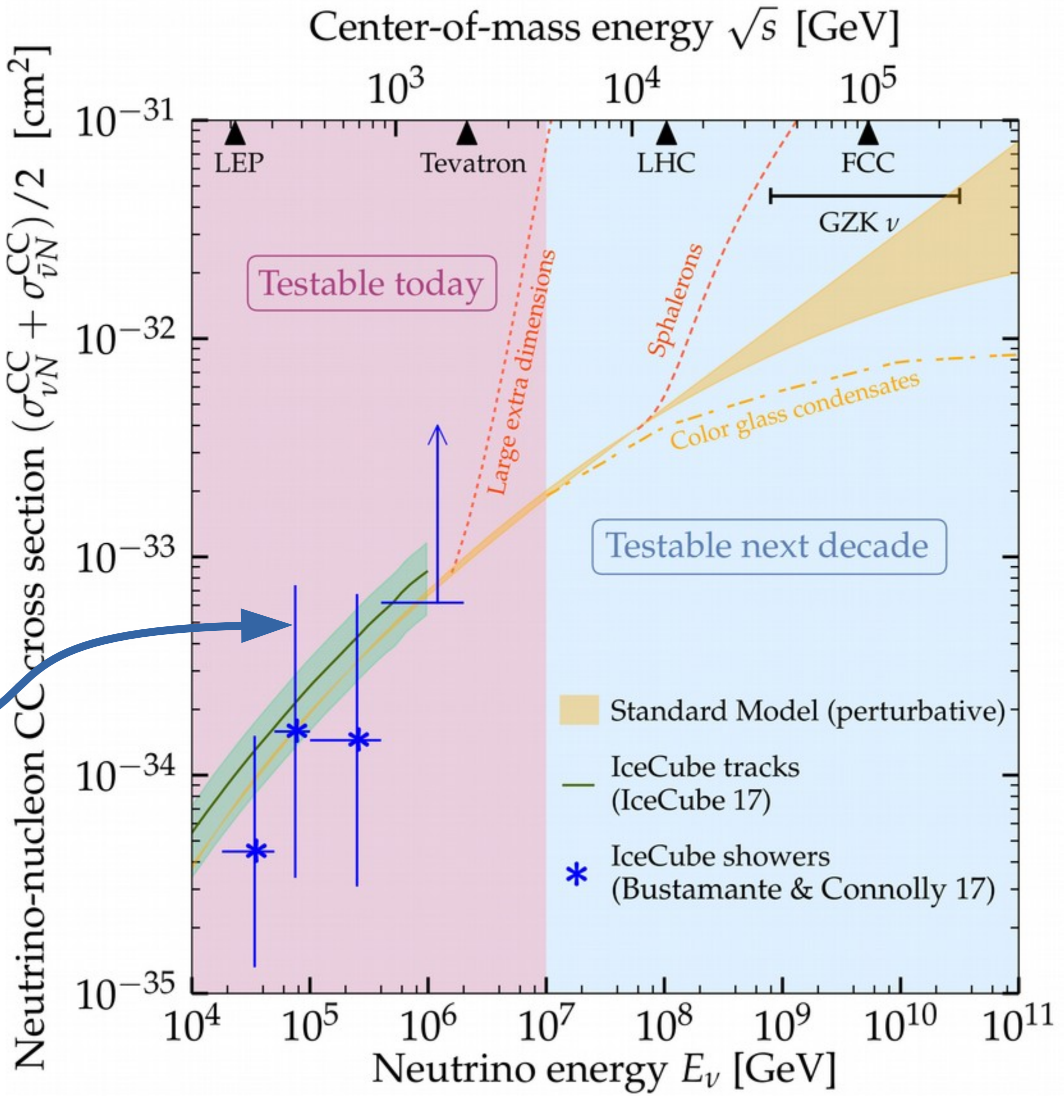


MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

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



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

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

UHE uncertainties can be smaller:
Cooper-Sarkar, Mertsch, Sarkar *et al.*, *JHEP* 2011

- Fold in astrophysical unknowns (spectral index, normalization)
- Compatible with SM predictions
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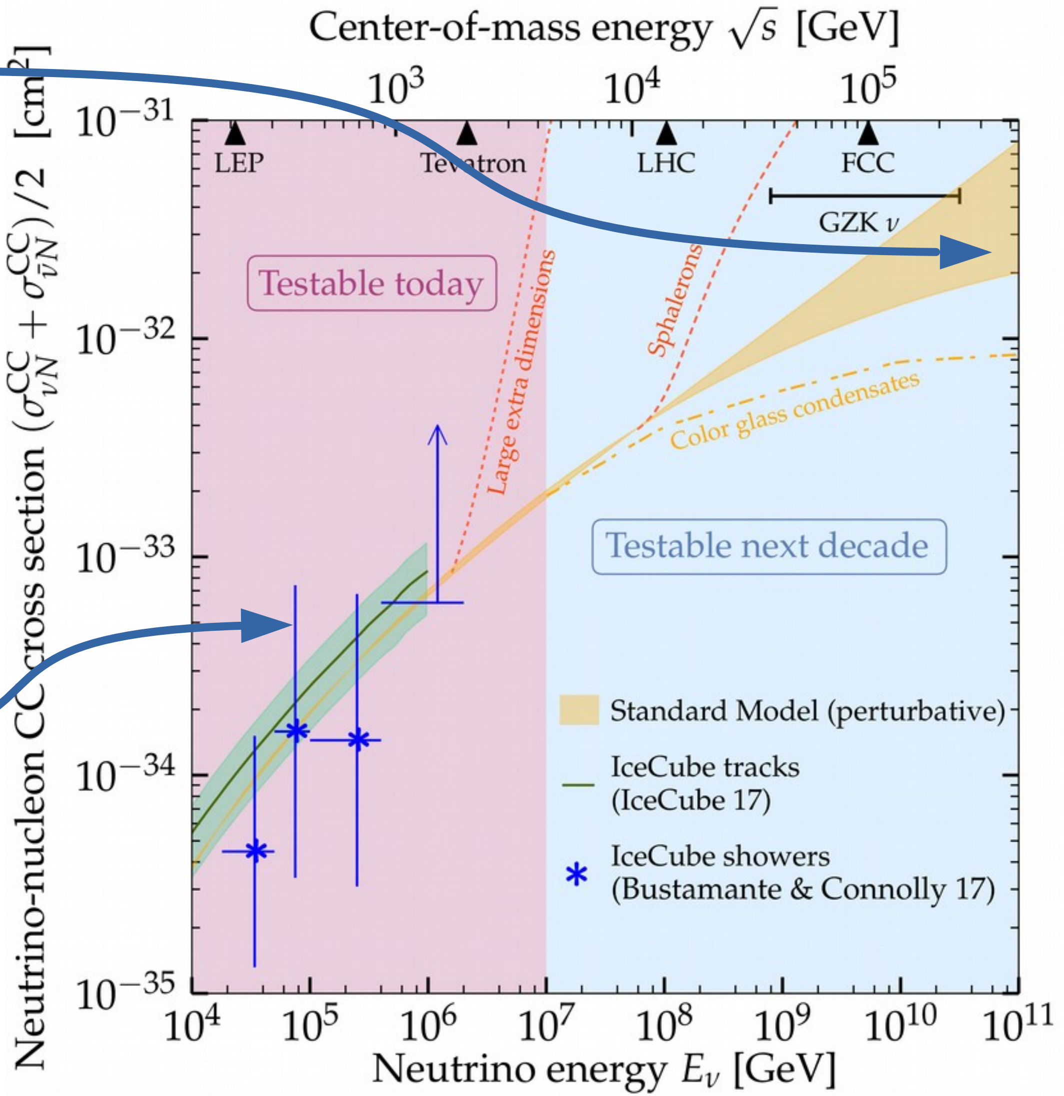
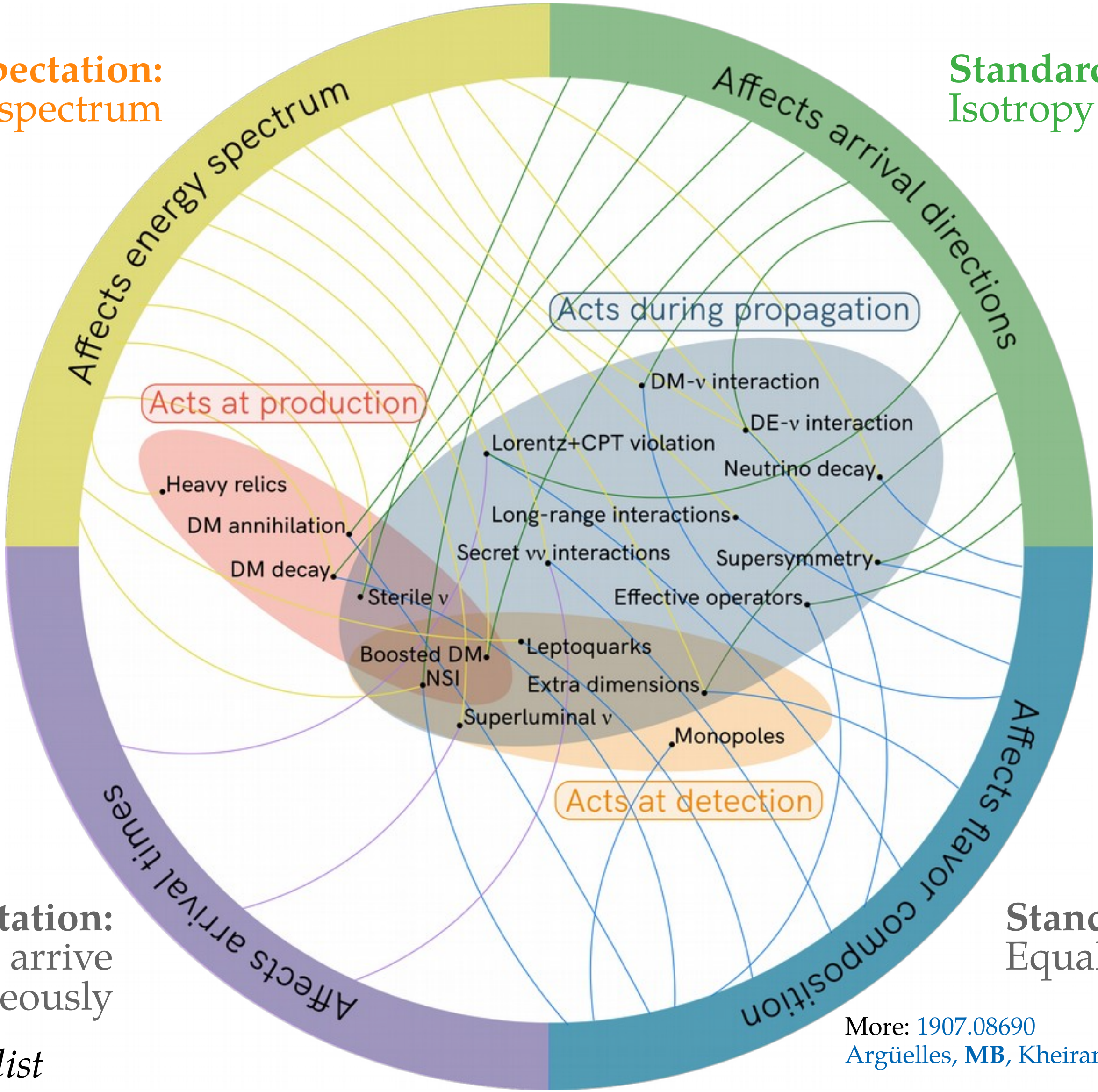


Cross sections from:
MB & Connolly *PRL* 2019
IceCube, *Nature* 2017

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



See talk by Carlos Argüelles

Standard expectation:
ν and γ from transients arrive simultaneously

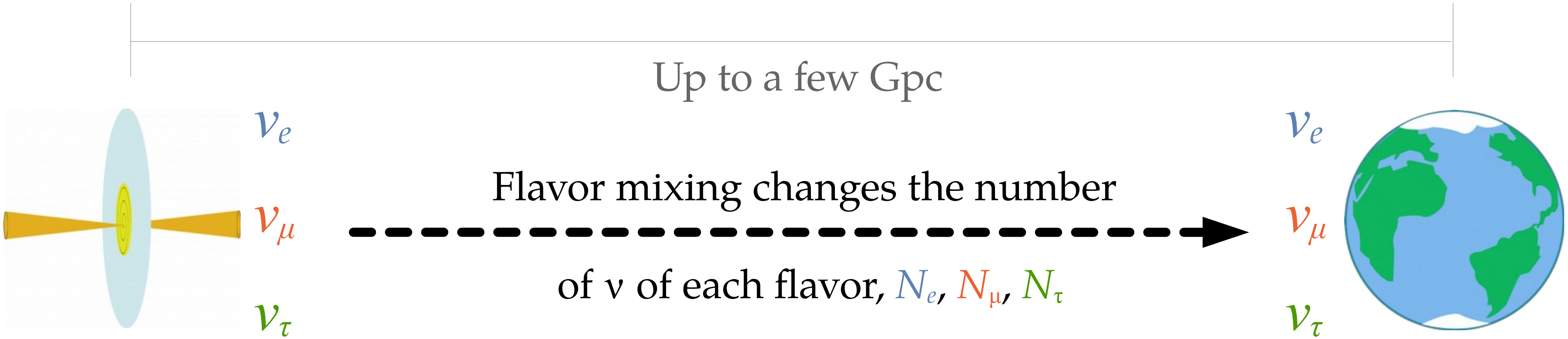
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

More: 1907.08690
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

Flavor composition

Astrophysical neutrino sources | Earth



- Different processes yield different ratios of neutrinos of each flavor:

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

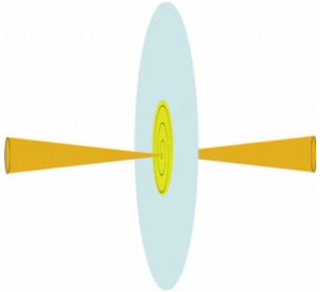
- Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Flavor composition

Astrophysical neutrino sources — Earth

Up to a few Gpc



ν_e, ν_μ, ν_τ

Flavor mixing changes the number of ν of each flavor, N_e, N_μ, N_τ

ν_e, ν_μ, ν_τ

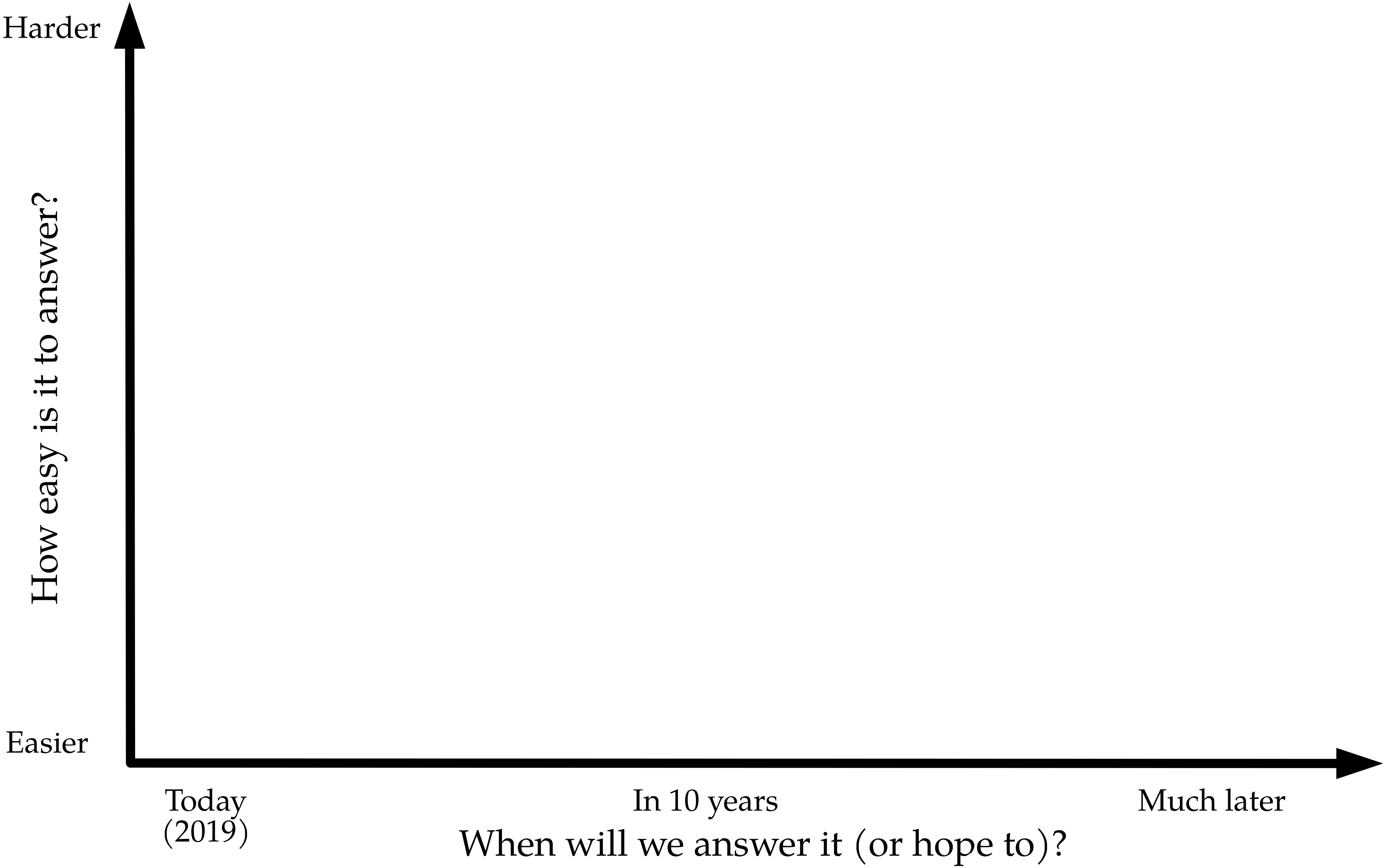
- Different processes yield different ratios of neutrinos of each flavor:

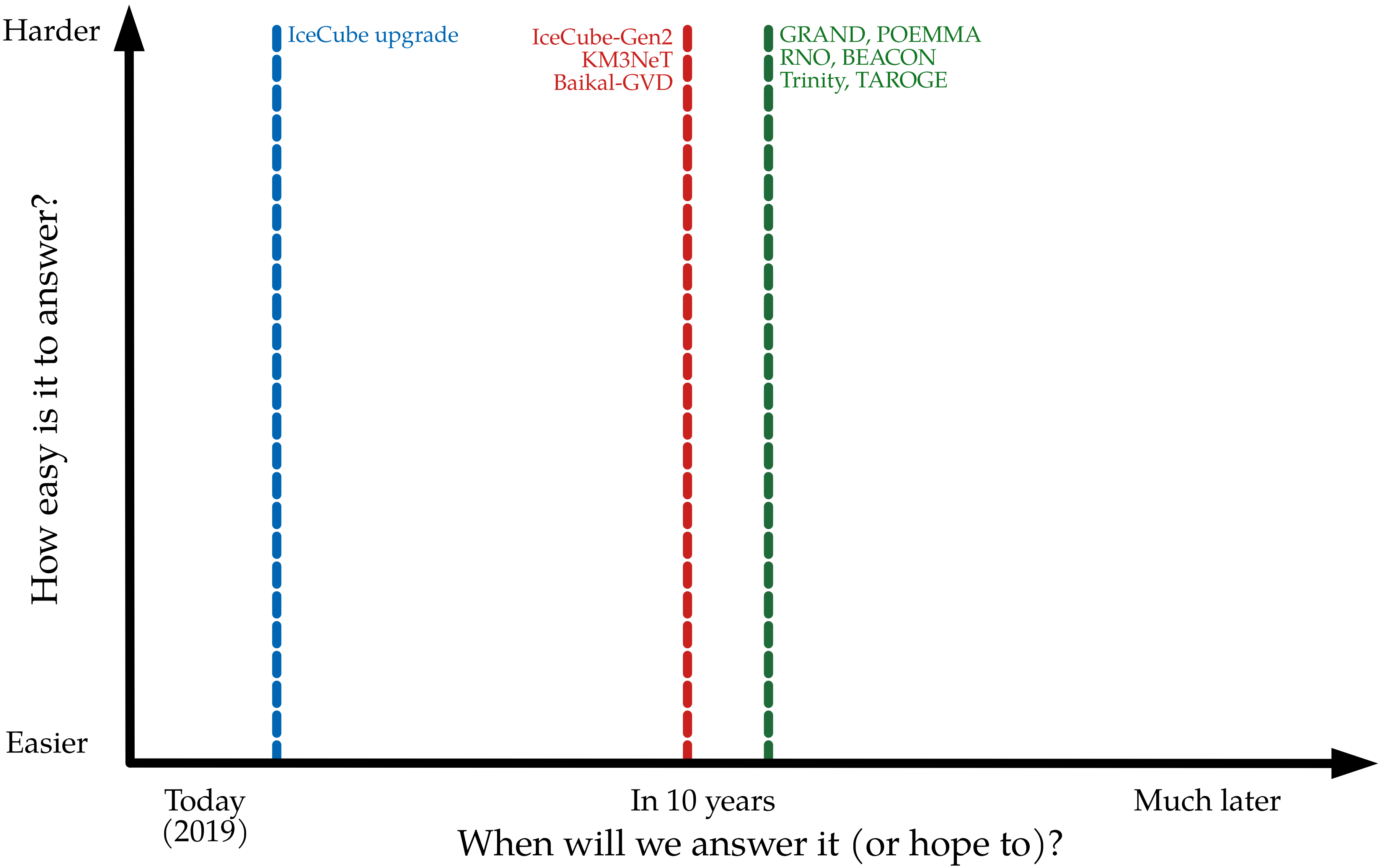
$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{\rm tot}$$

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

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

Standard oscillations
or
new physics


Harder
How easy is it to answer?
Easier
Today
(2019)
In 10 years
Much later
When will we answer it (or hope to)?



Harder
Easier
How easy is it to answer?
IceCube upgrade
IceCube-Gen2
KM3NeT
Baikal-GVD
GRAND, POEMMA
RNO, BEACON
Trinity, TAROGE
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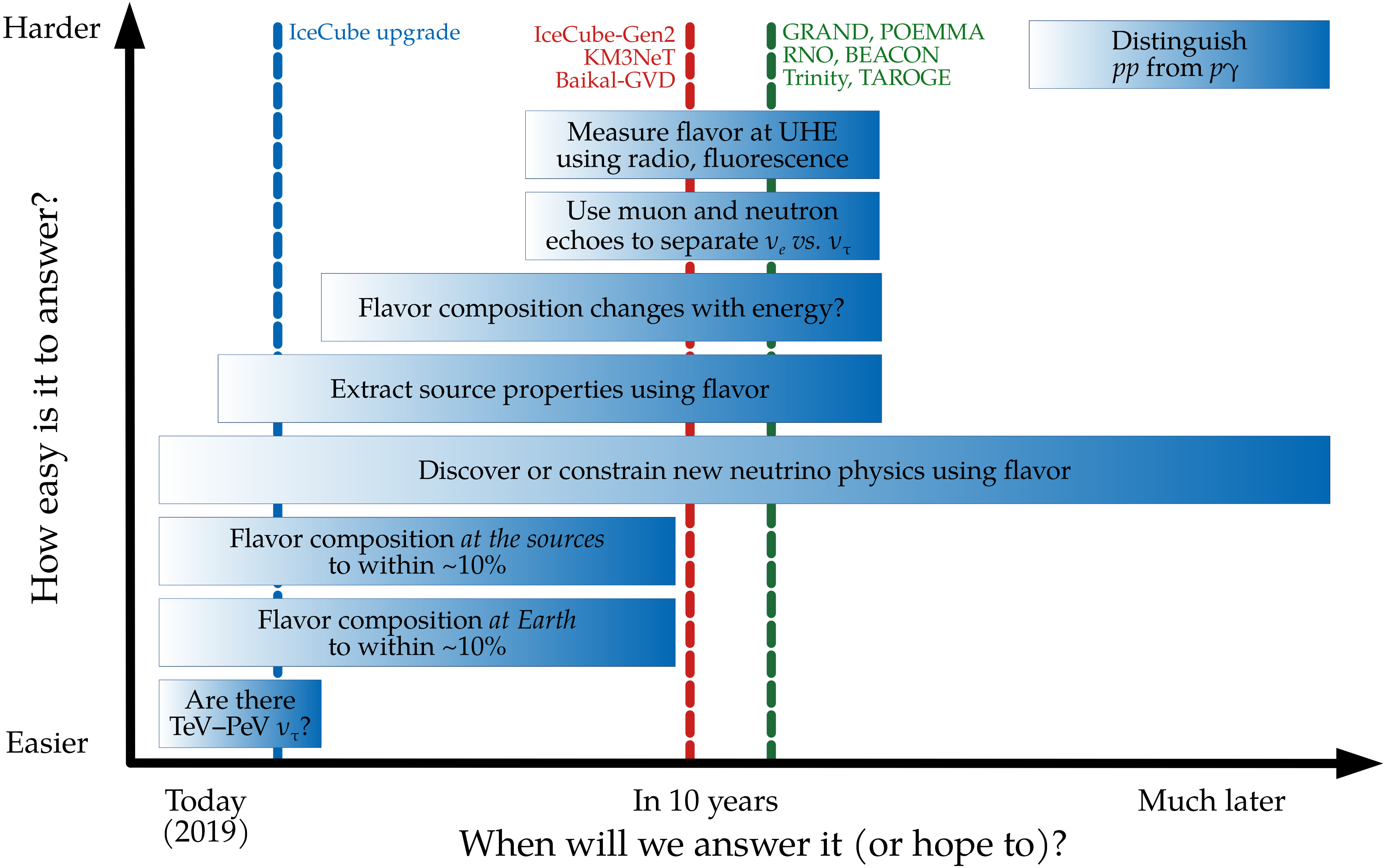
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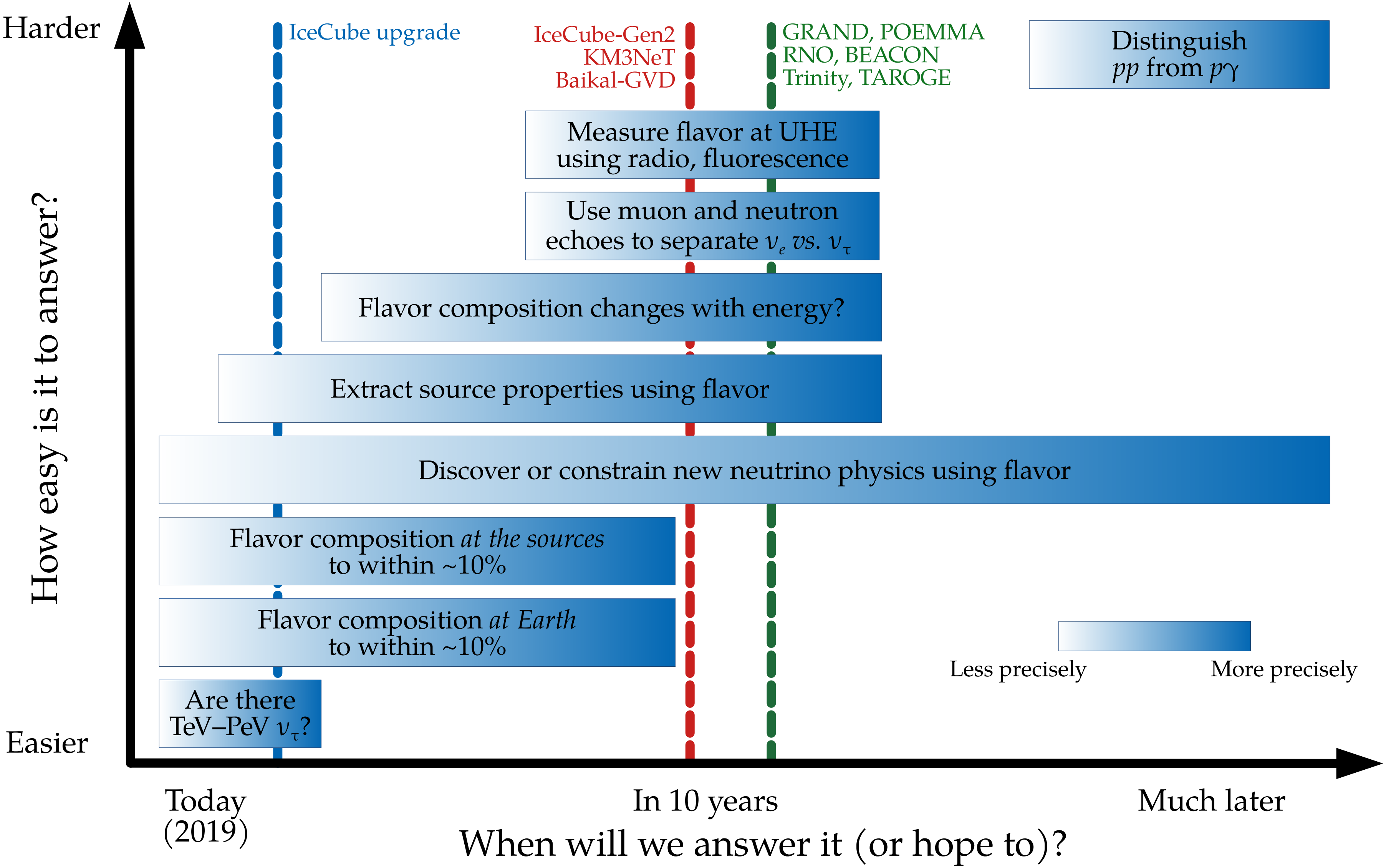
Distinguish pp from $p\gamma$
Measure flavor at UHE using radio, fluorescence
Use muon and neutron echoes to separate ν_e *vs.* ν_τ
Flavor composition changes with energy?
Extract source properties using flavor
Discover or constrain new neutrino physics using flavor
Flavor composition *at the sources* to within ~10%
Flavor composition *at Earth* to within ~10%
Are there TeV–PeV ν_τ?
Today (2019)
In 10 years
Much later
When will we answer it (or hope to)?



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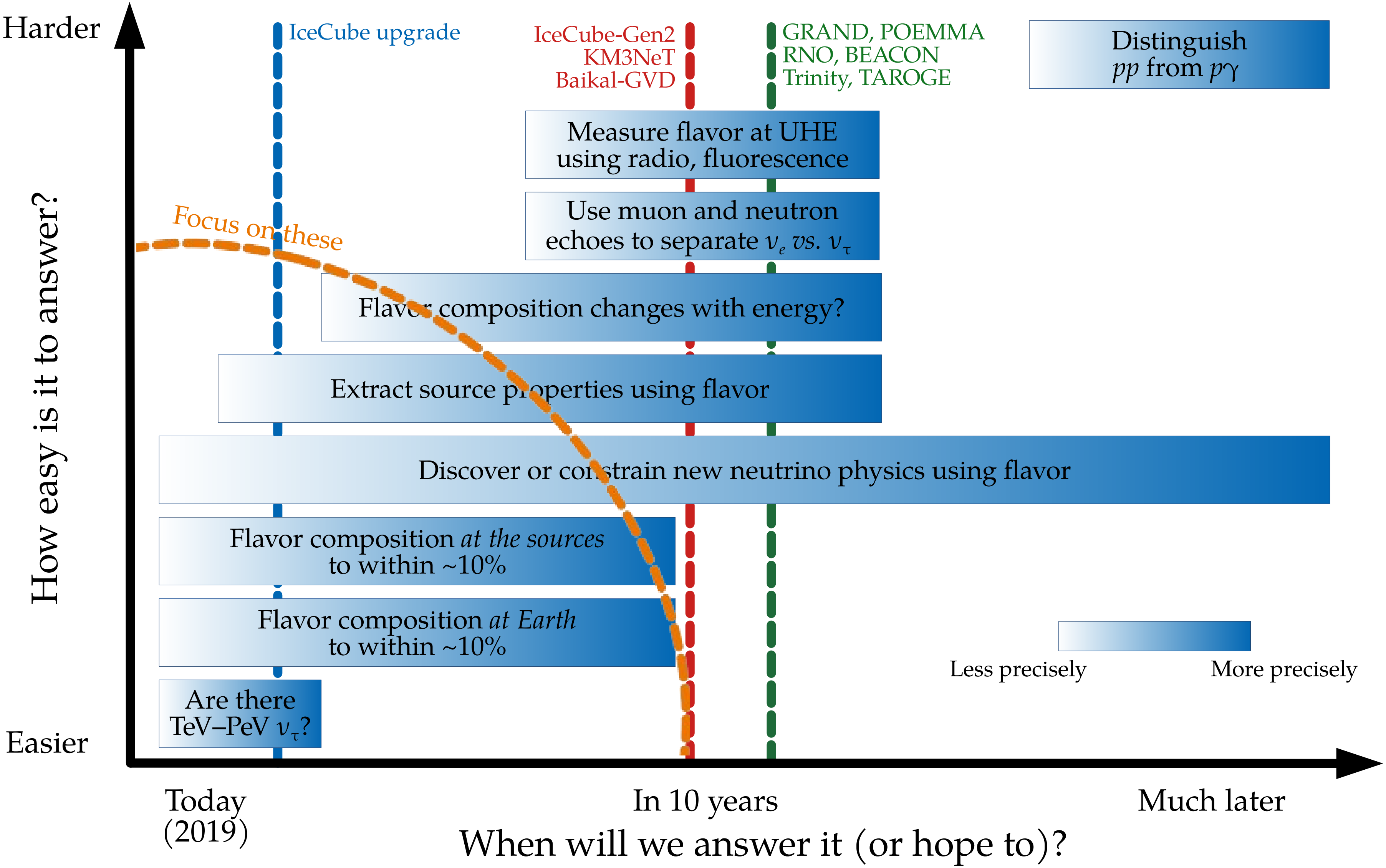
TeV–PeV ντ?
Less precisely
More precisely
Today
(2019)
In 10 years
Much later
When will we answer it (or hope to)?



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Distinguish
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Focus on these
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Less precisely
More precisely
Today
(2019)
In 10 years
Much later
When will we answer it (or hope to)?

One likely TeV–PeV ν production scenario:

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

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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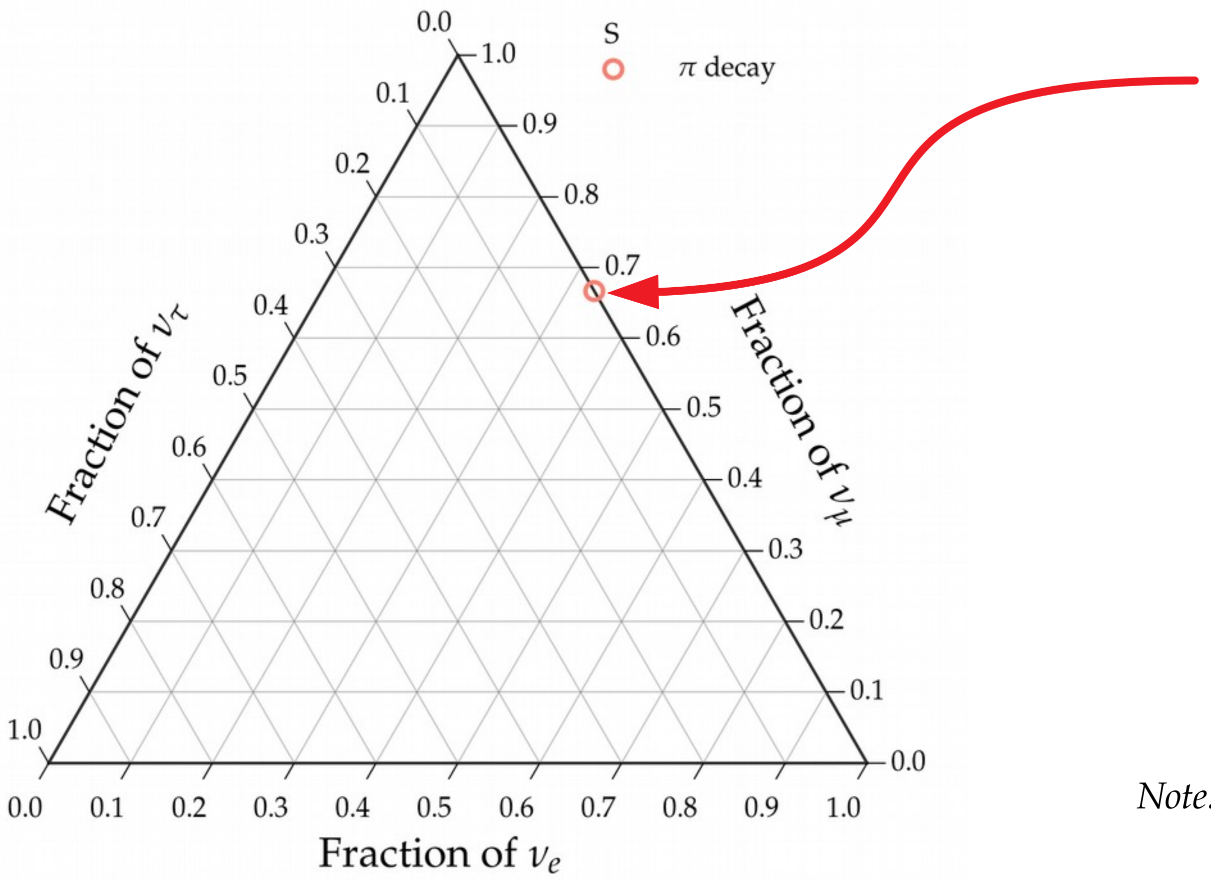

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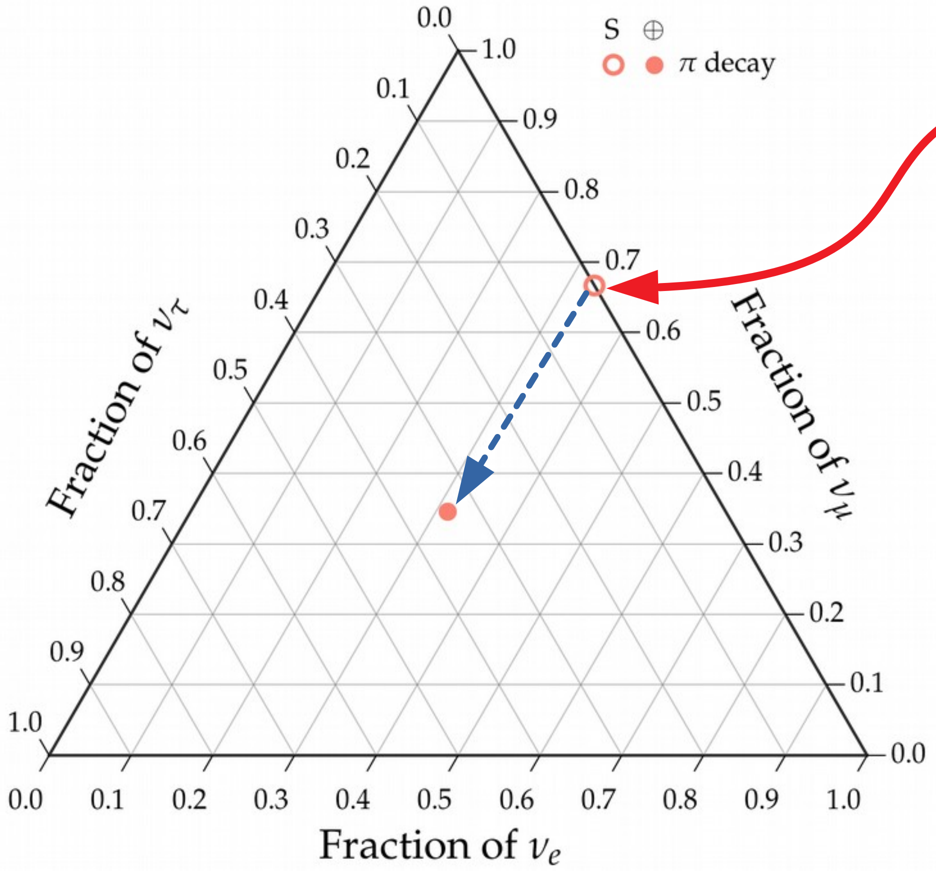

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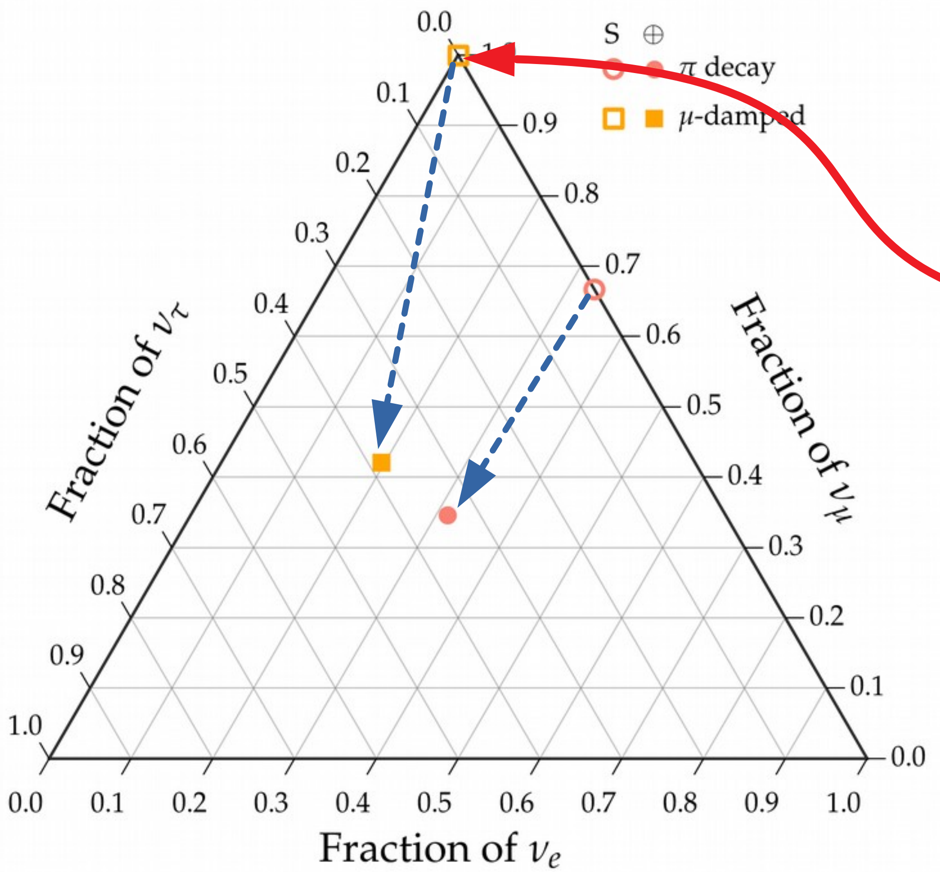

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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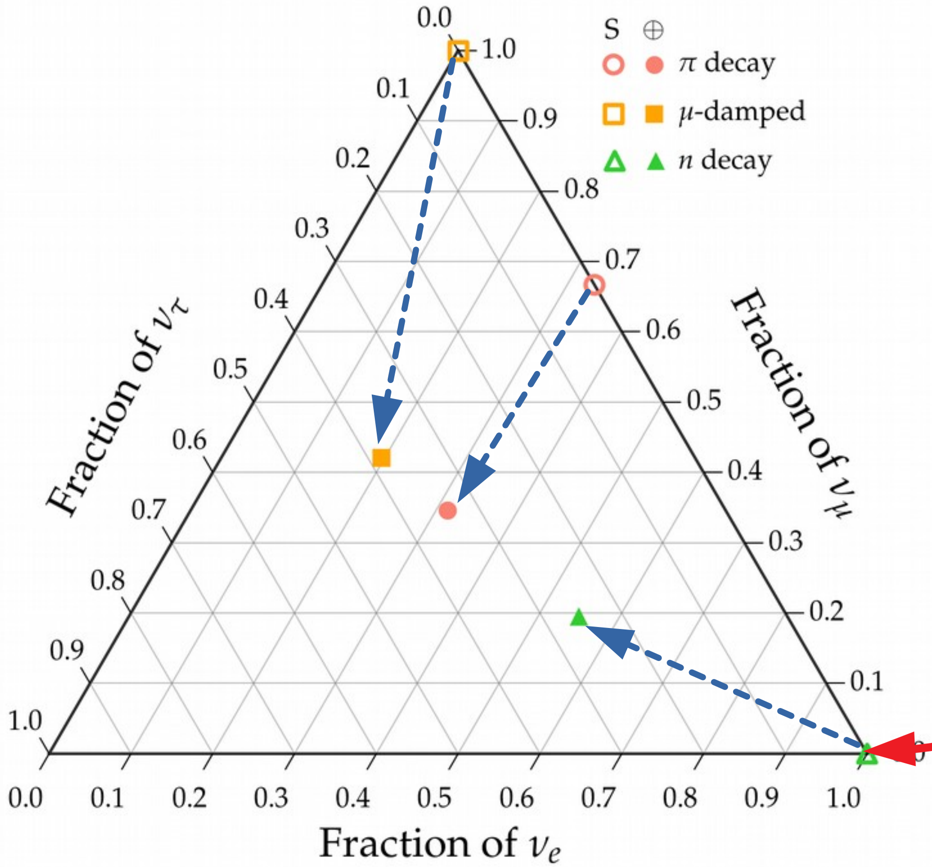

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Muon damped

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Neutron decay

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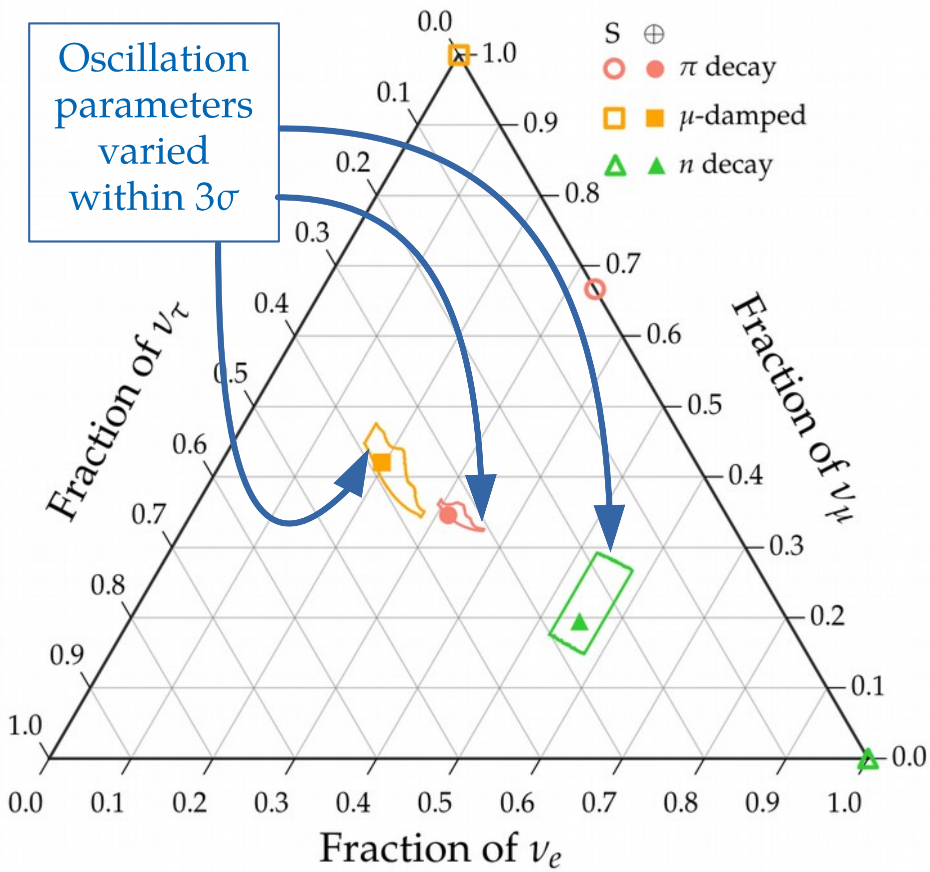

Full π decay chain

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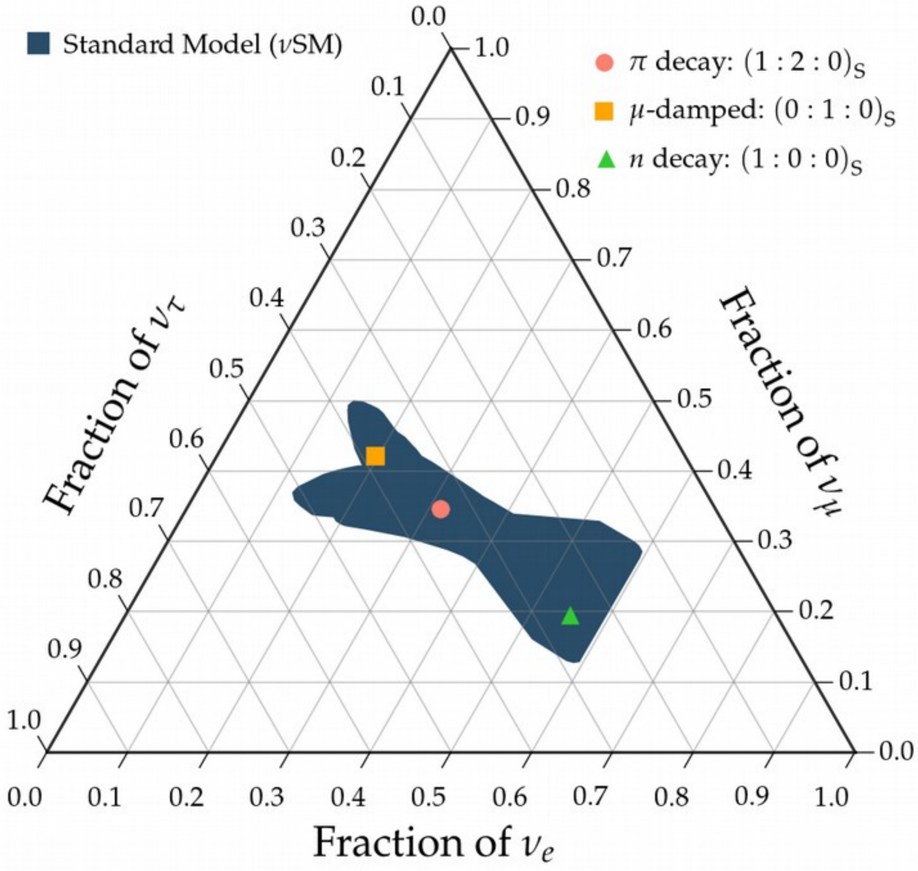


All possible flavor ratios at the sources

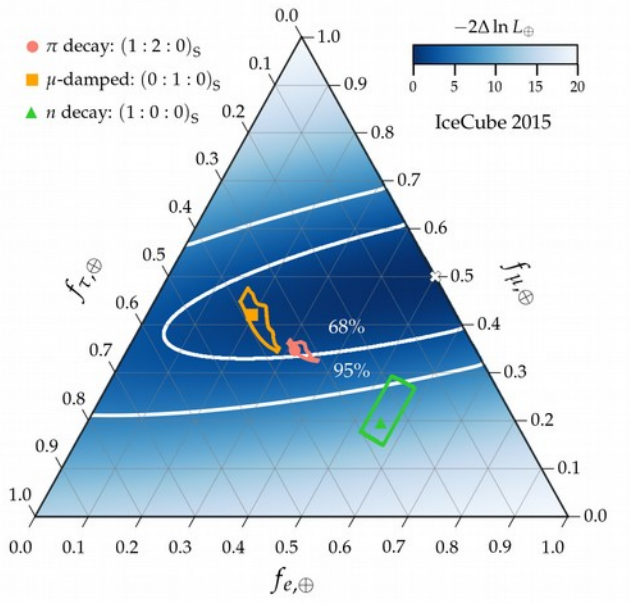
+

Vary oscillation parameters within 3σ

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

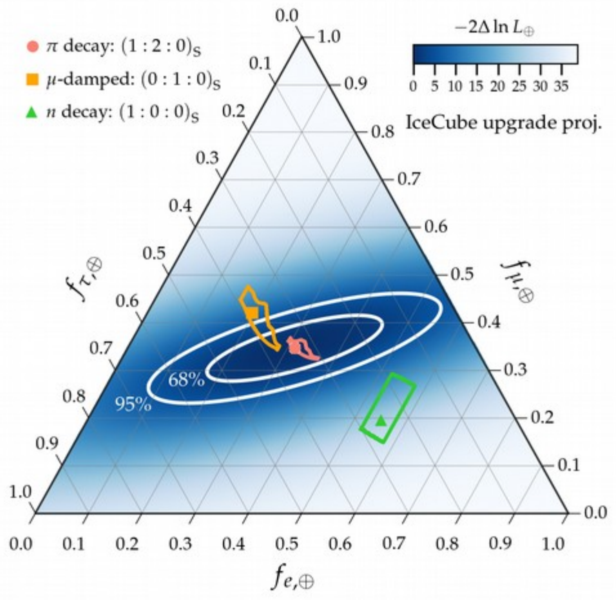
Flavor composition: now and in the future

Today
IceCube

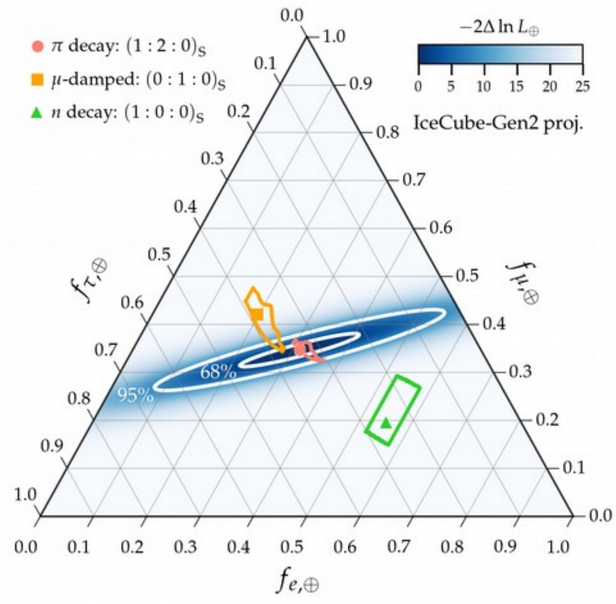


- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.5 : 0.5 : 0)_\oplus$
- Compatible with standard source compositions
- Hints of one ν_τ (not shown)

Near future (2022)
IceCube upgrade

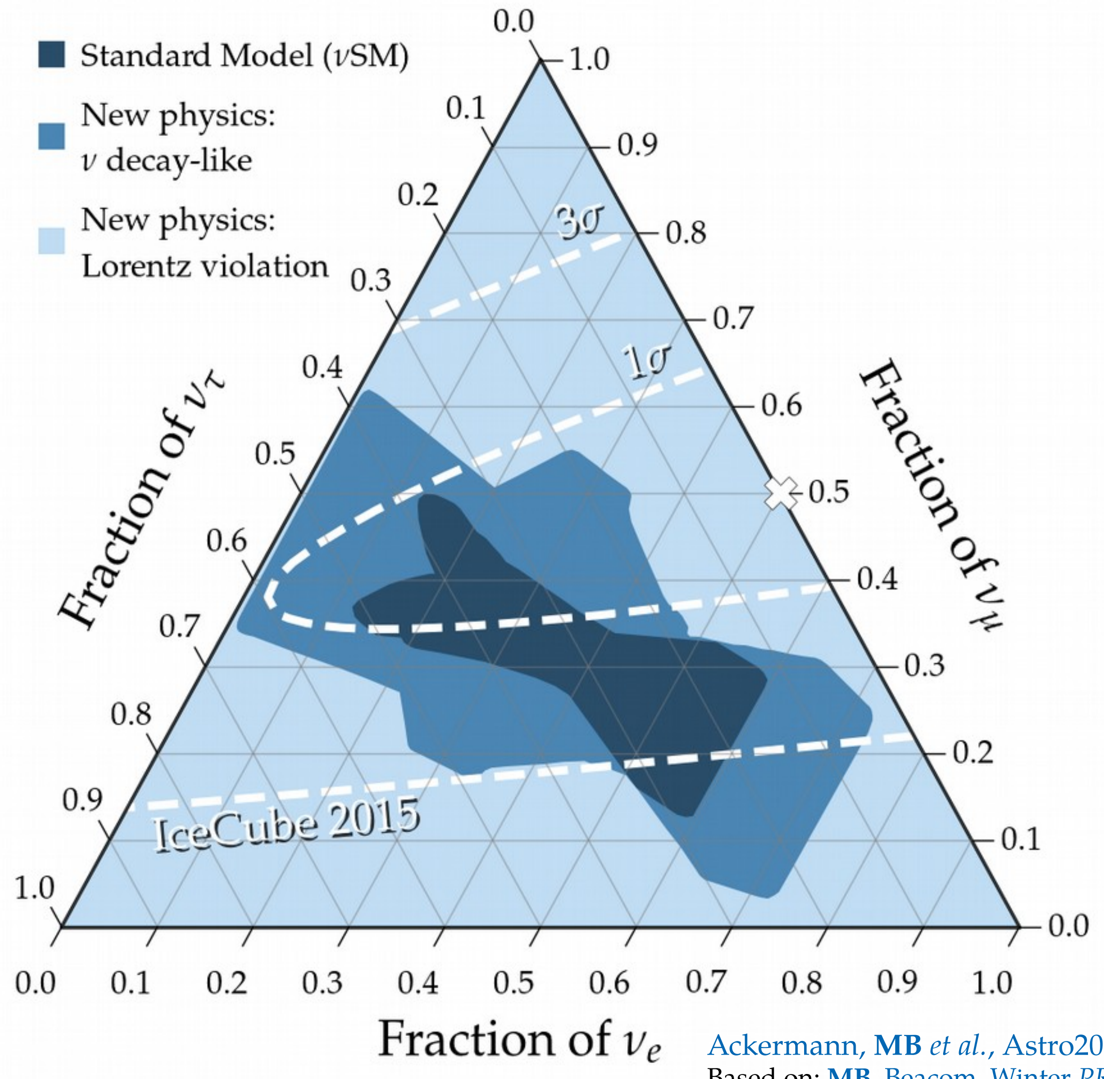


In 10 years (2030s)
IceCube-Gen2



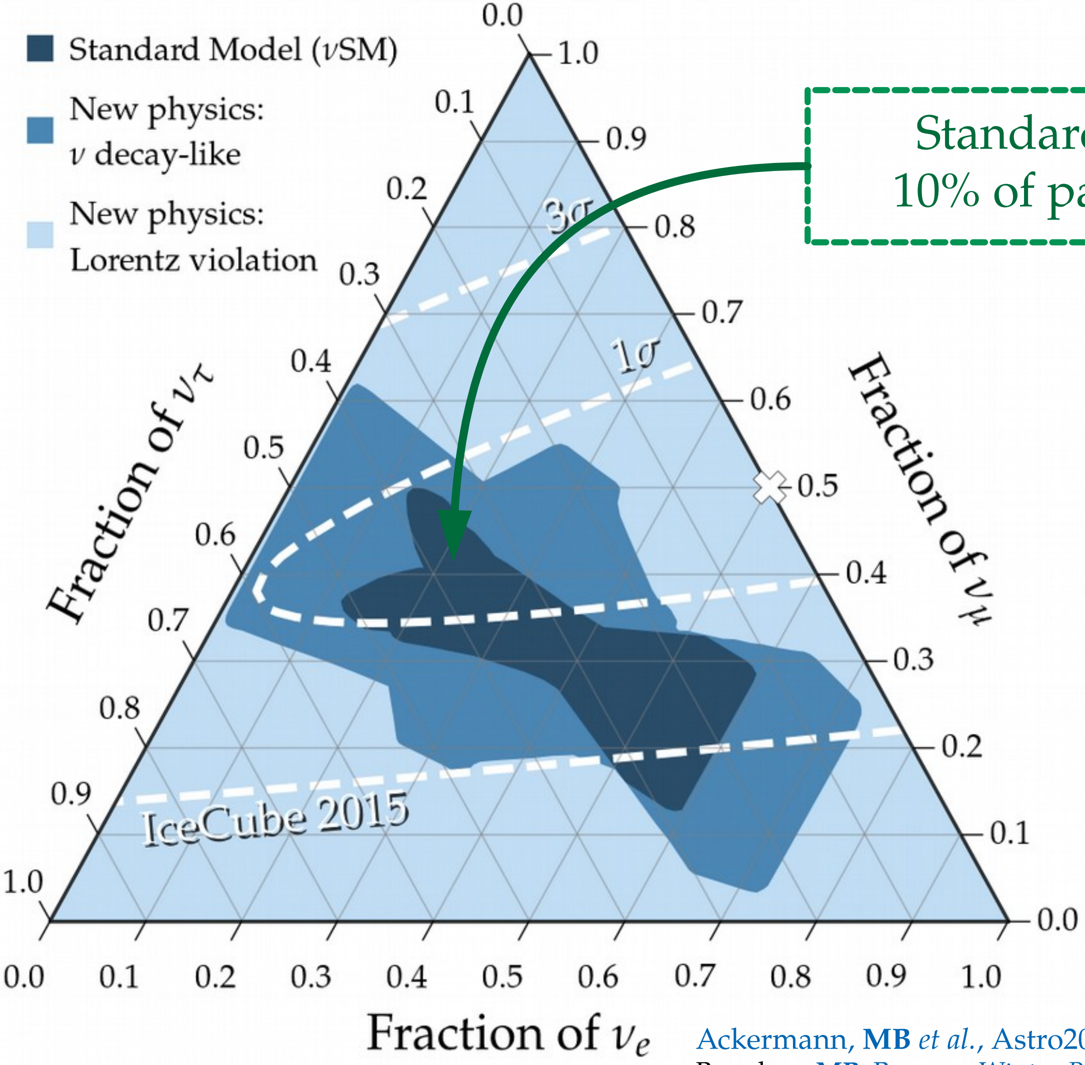
Assuming production by the full pion decay chain

Plus possibly better flavor-tagging, *e.g.*, muon and neutron echoes
[Li, **MB**, Beacom *PRL* 2019]



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

Based on: **MB**, Beacom, Winter *PRL* 2015



Standard oscillations:
10% of parameter space

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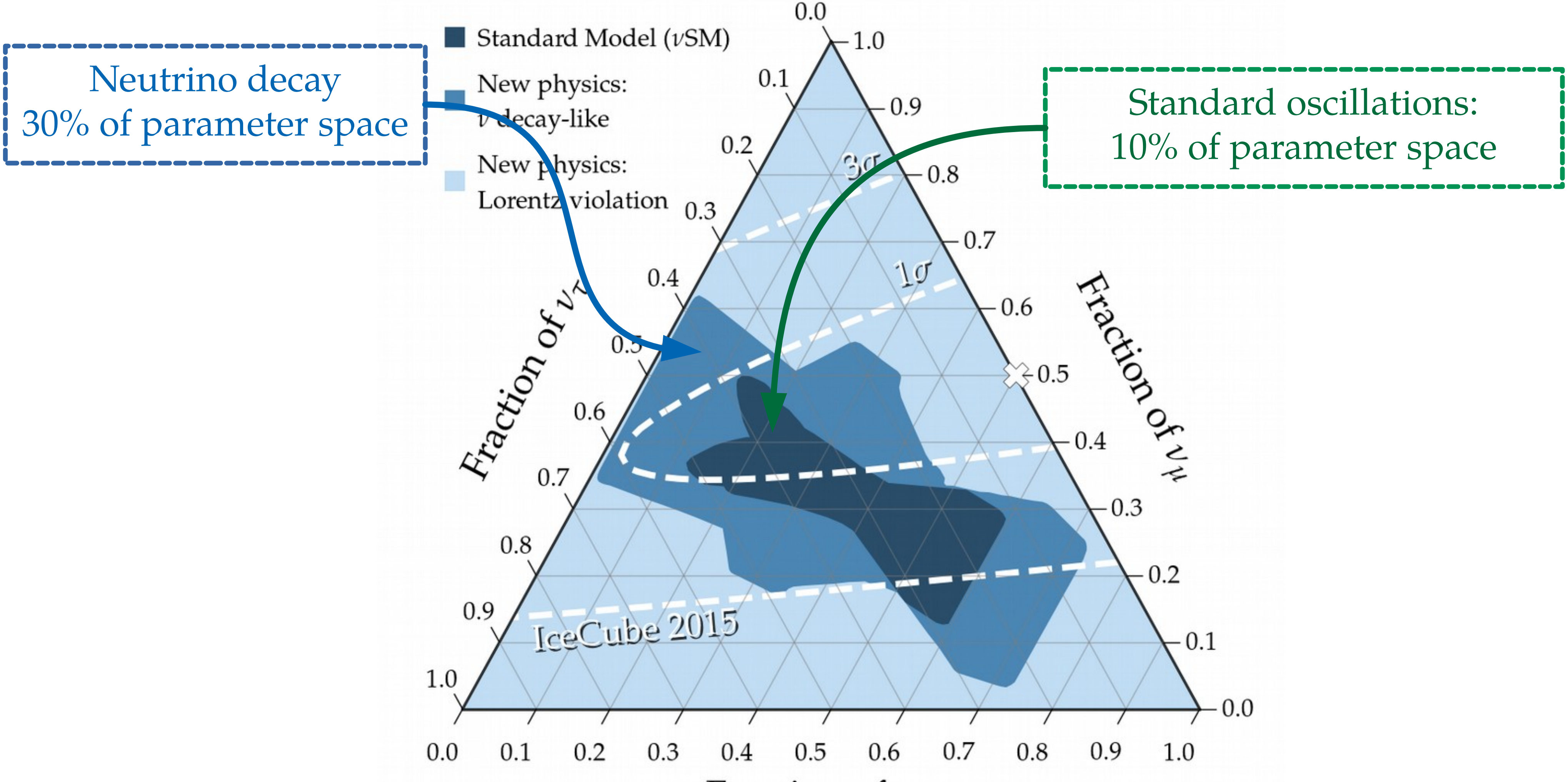

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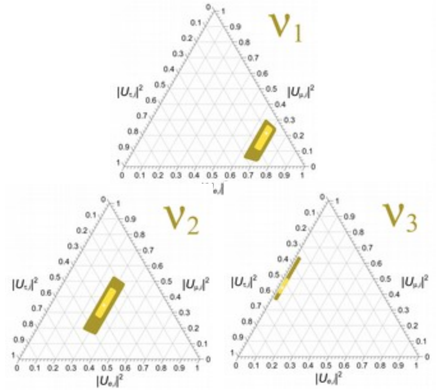
Neutrino decay
30% of parameter space

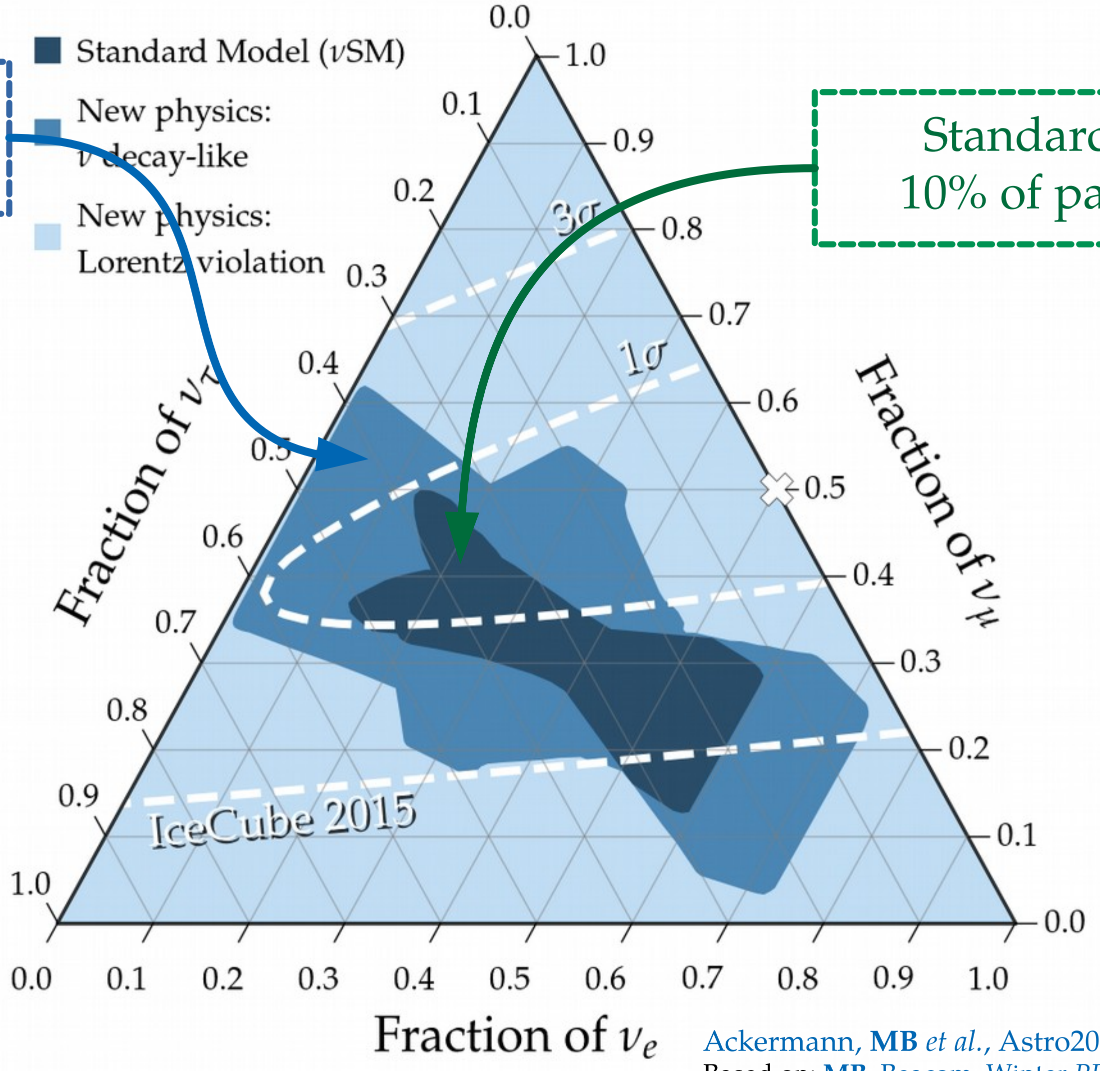
$\nu_2, \nu_3 \rightarrow \nu_1$ or $\nu_1, \nu_2 \rightarrow \nu_3$

Flavor ratios determined by how many ν_1, ν_2, ν_3 survive:



$\tau_2/m_2, \tau_3/m_3 > 10$ s eV^{-1}

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



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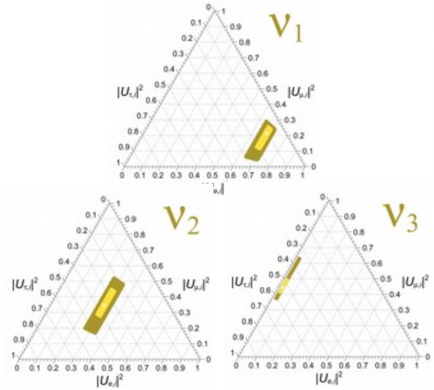

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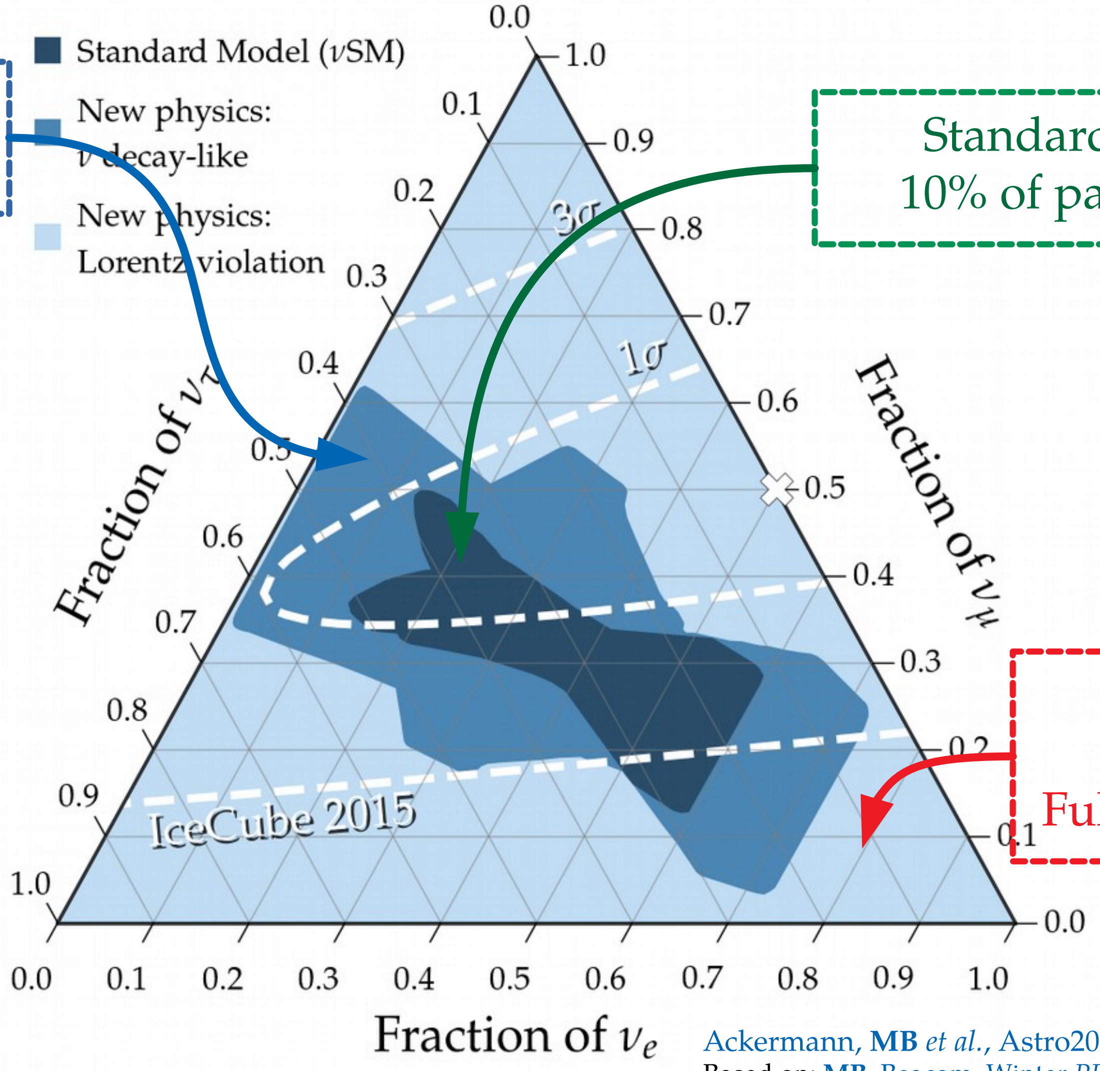

Standard oscillations:
10% of parameter space

Lorentz, CPT violation, etc:
Full parameter space

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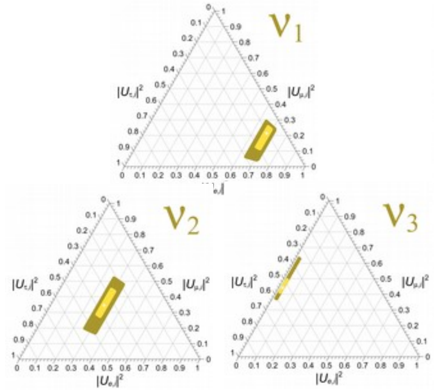

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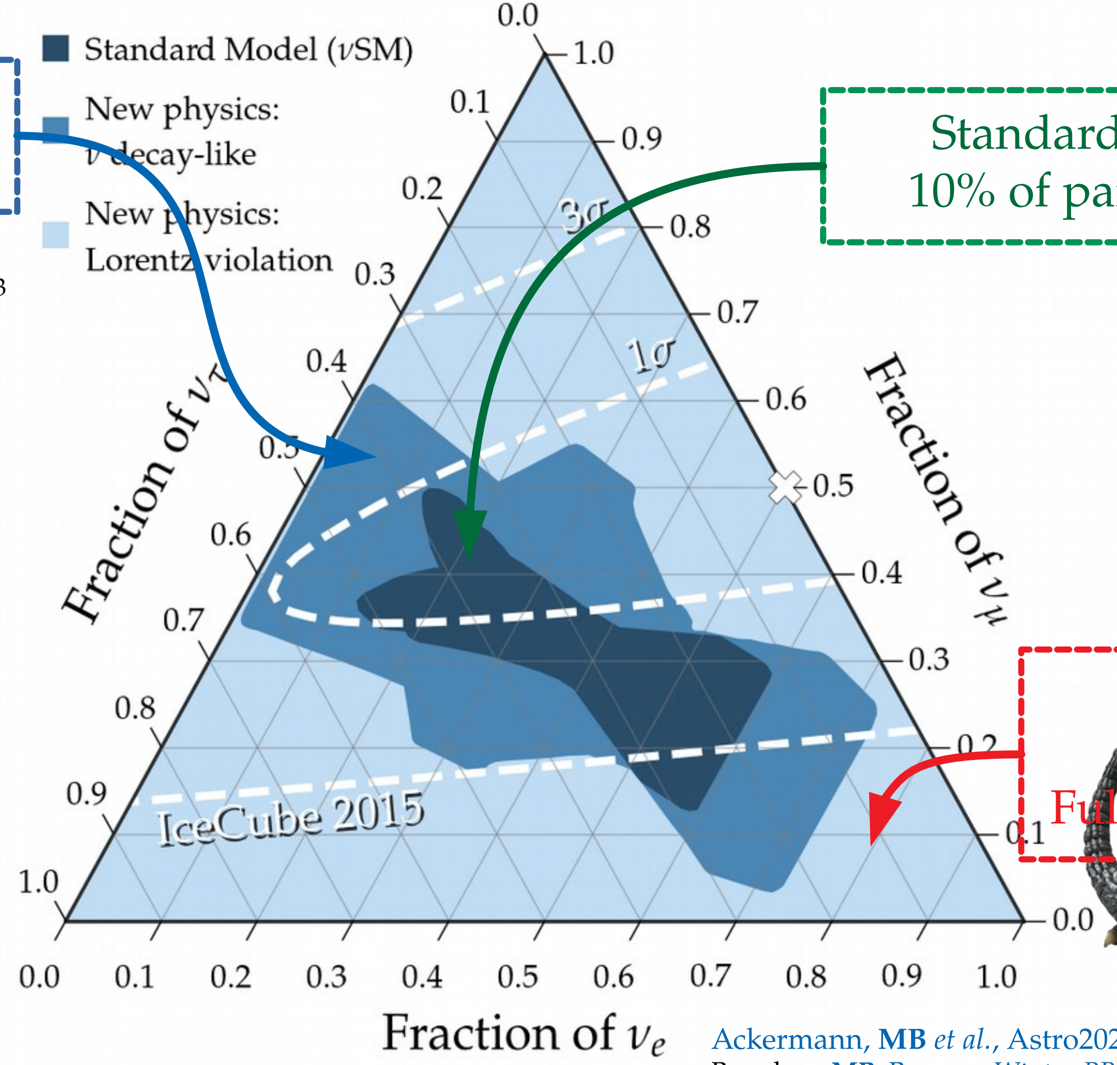

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Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015

How to access all of the flavor triangle? *Pick your monster*

- High-energy effective field theories
  - Violation of Lorentz and CPT invariance
    [Barenboim & Quigg, *PRD* 2003; Kostelecky & Mewes 2004; **MB**, Gago, Peña-Garay, *JHEP* 2010]
  - Violation of equivalence principle
    [Gasperini, *PRD* 1989; Glashow *et al.*, *PRD* 1997]
  - Coupling to a gravitational torsion field
    [De Sabbata & Gasperini, *Nuovo Cim.* 1981]
  - Renormalization-group-running of mixing parameters
    [**MB**, Gago, Jones, *JHEP* 2011]
  - General non-unitary propagation
    [Ahlers, **MB**, Mu, *PRD* 2018]

- Active-sterile mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, *JCAP* 2017; Argüelles *et al.*, 1909.05341]

- Flavor-violating physics
  - New neutrino-electron interactions Click if time allows
    [**MB** & Agarwalla, *PRL* 2019]
  - New $\nu\nu$ interactions
    [Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]

- …

Toho Company Ltd.

New physics – High-energy effects

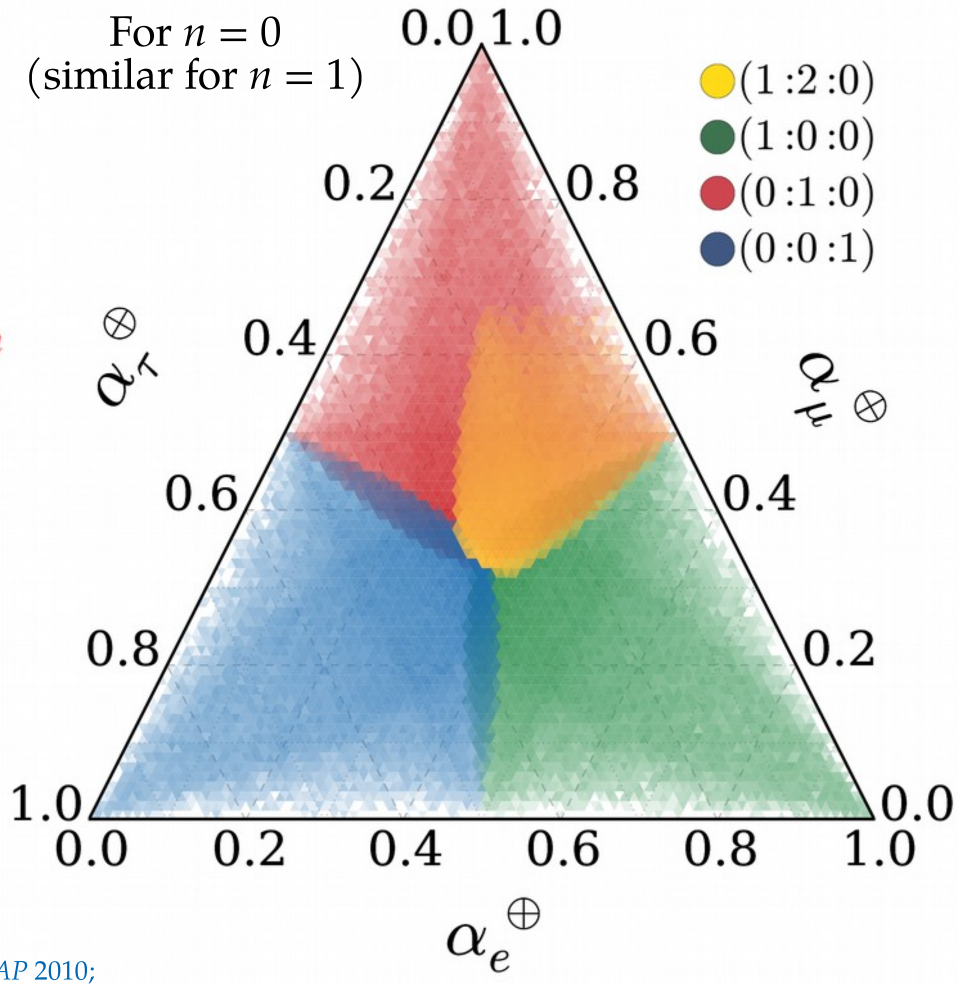
$$H_{\rm tot} = H_{\rm std} + H_{\rm NP}$$

$$H_{\rm std} = \frac{1}{2E} U^\dagger_{\rm PMNS}\, \mathrm{diag}\left(0, \Delta m^2_{21}, \Delta m^2_{31}\right) U_{\rm PMNS}$$

$$H_{\rm NP} = \sum_n \left(\frac{E}{\Lambda_n}\right)^n U_n^\dagger\, \mathrm{diag}\left(O_{n,1}, O_{n,2}, O_{n,3}\right) U_n$$

This can populate *all* of the triangle –

- Use current atmospheric bounds on $O_{n,i}$:
  $O_0 < 10^{-23}$ GeV, $O_1/\Lambda_1 < 10^{-27}$ GeV
- Sample the unknown new mixing angles



Argüelles, Katori, Salvadó, *PRL* 2015

See also: Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

New physics – High-energy effects

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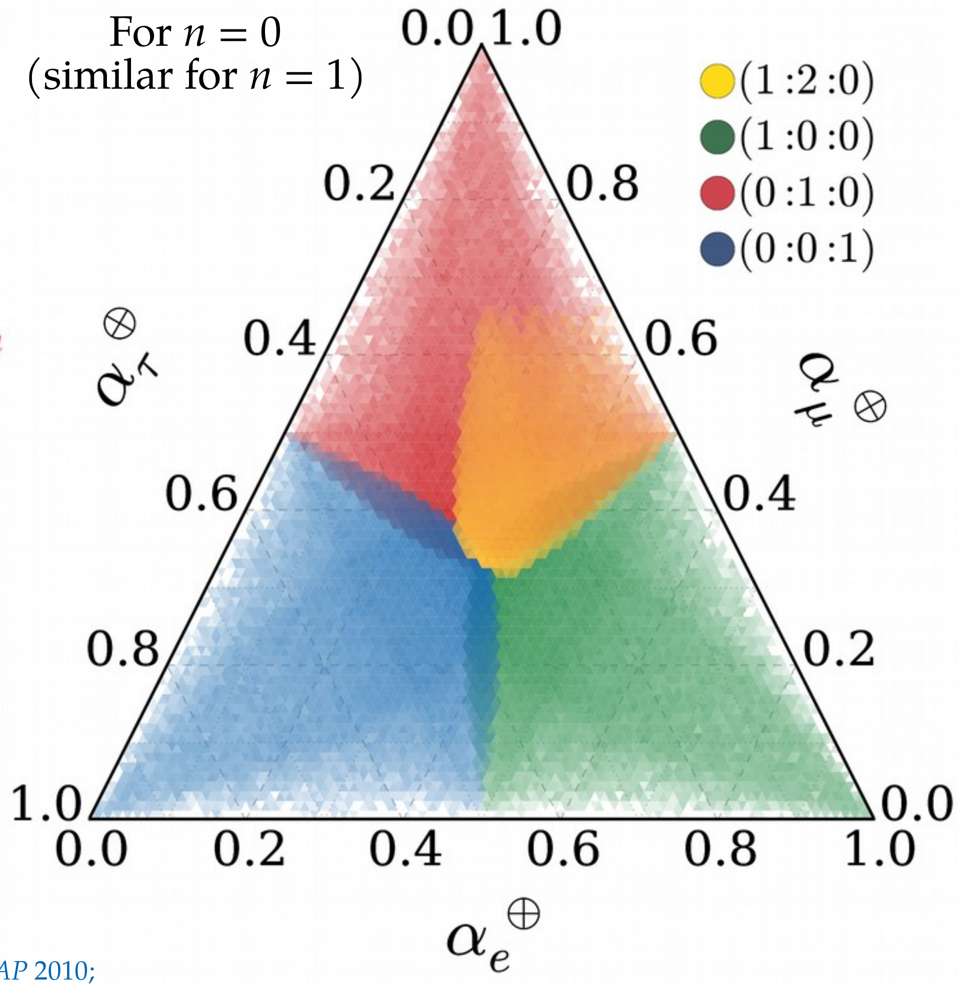

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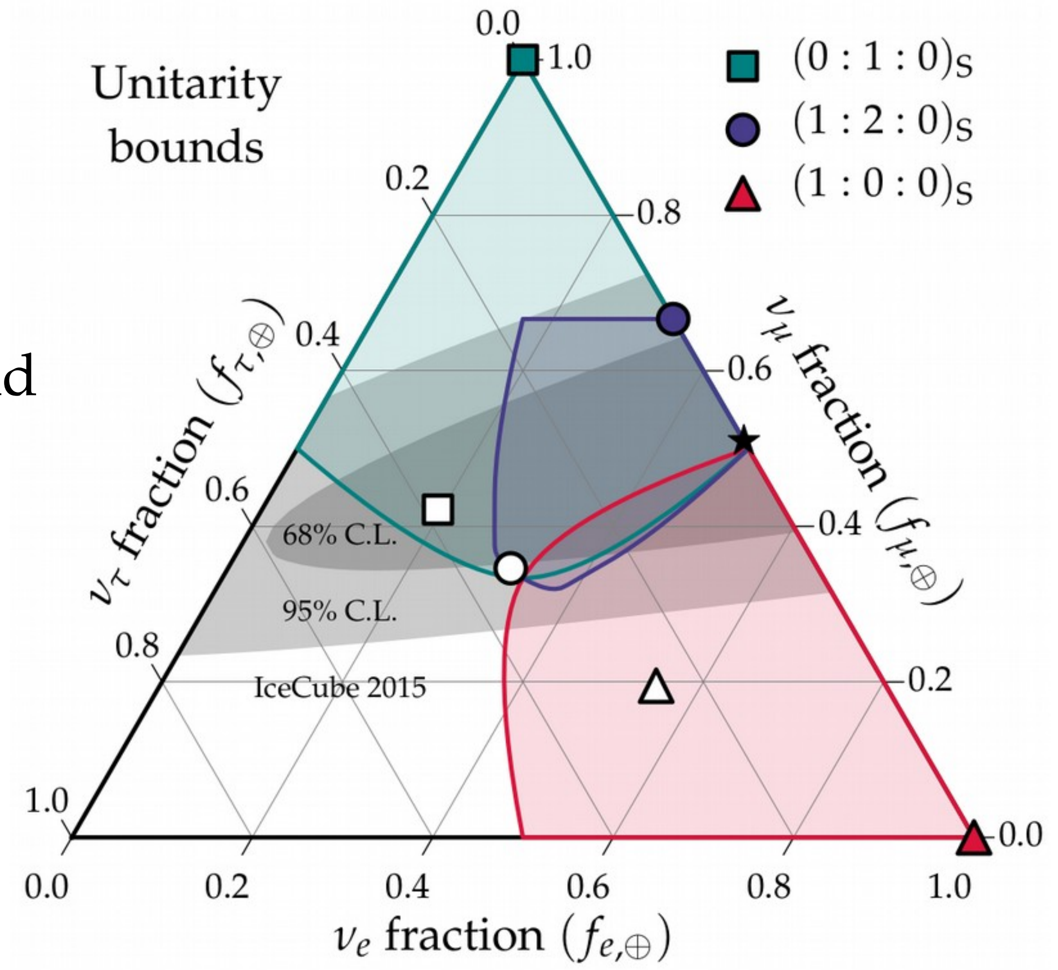
Using unitarity to constrain new physics

$$H_{tot} = H_{std} + H_{NP}$$

- New mixing angles unconstrained
- Use unitarity ($U_{NP}U^{\dagger}_{NP} = 1$) to bound all possible flavor ratios at Earth
- Can be used as prior in new-physics searches in IceCube



Ahlers, **MB**, Mu, *PRD* 2018
See also: Xu, He, Rodejohann, *JCAP* 2014

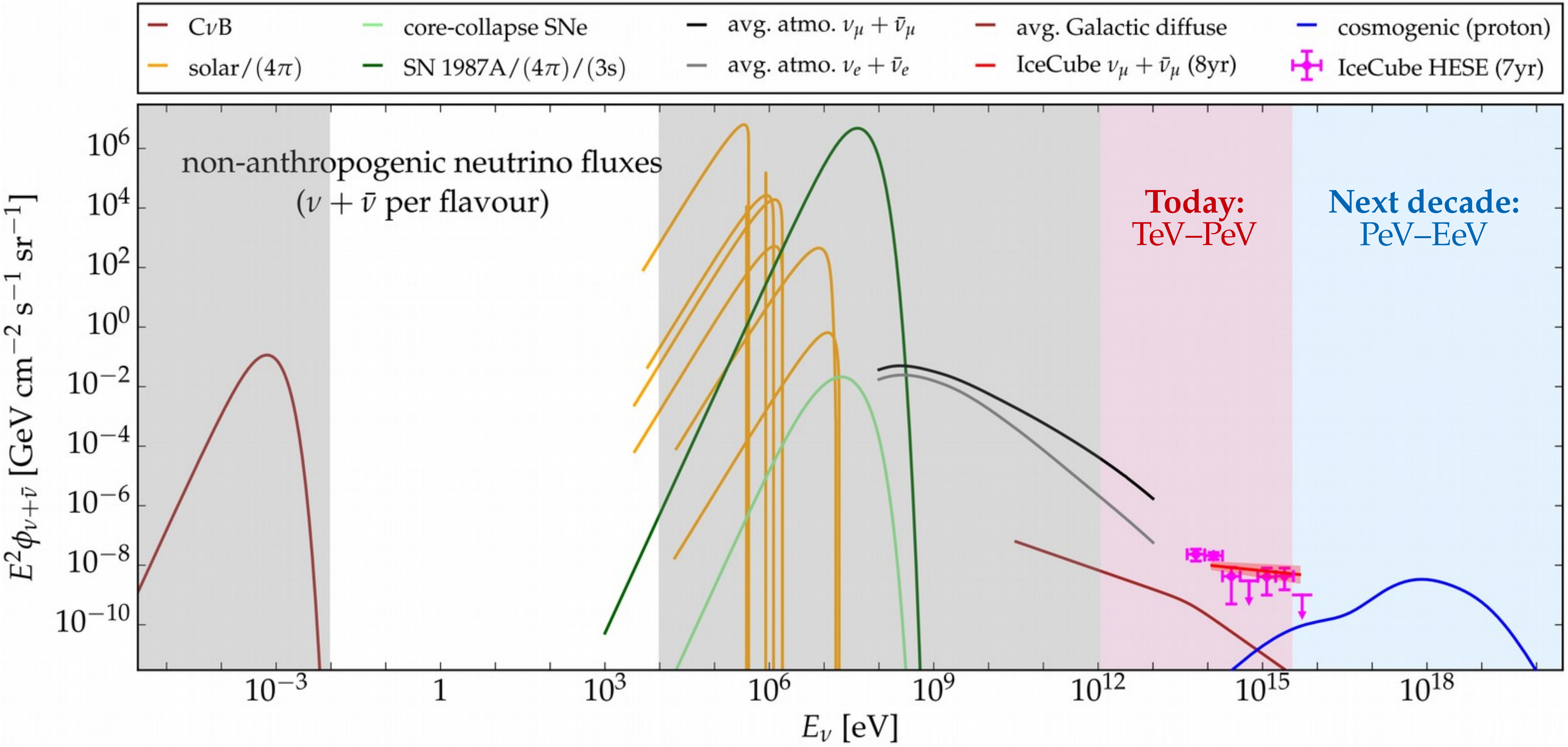
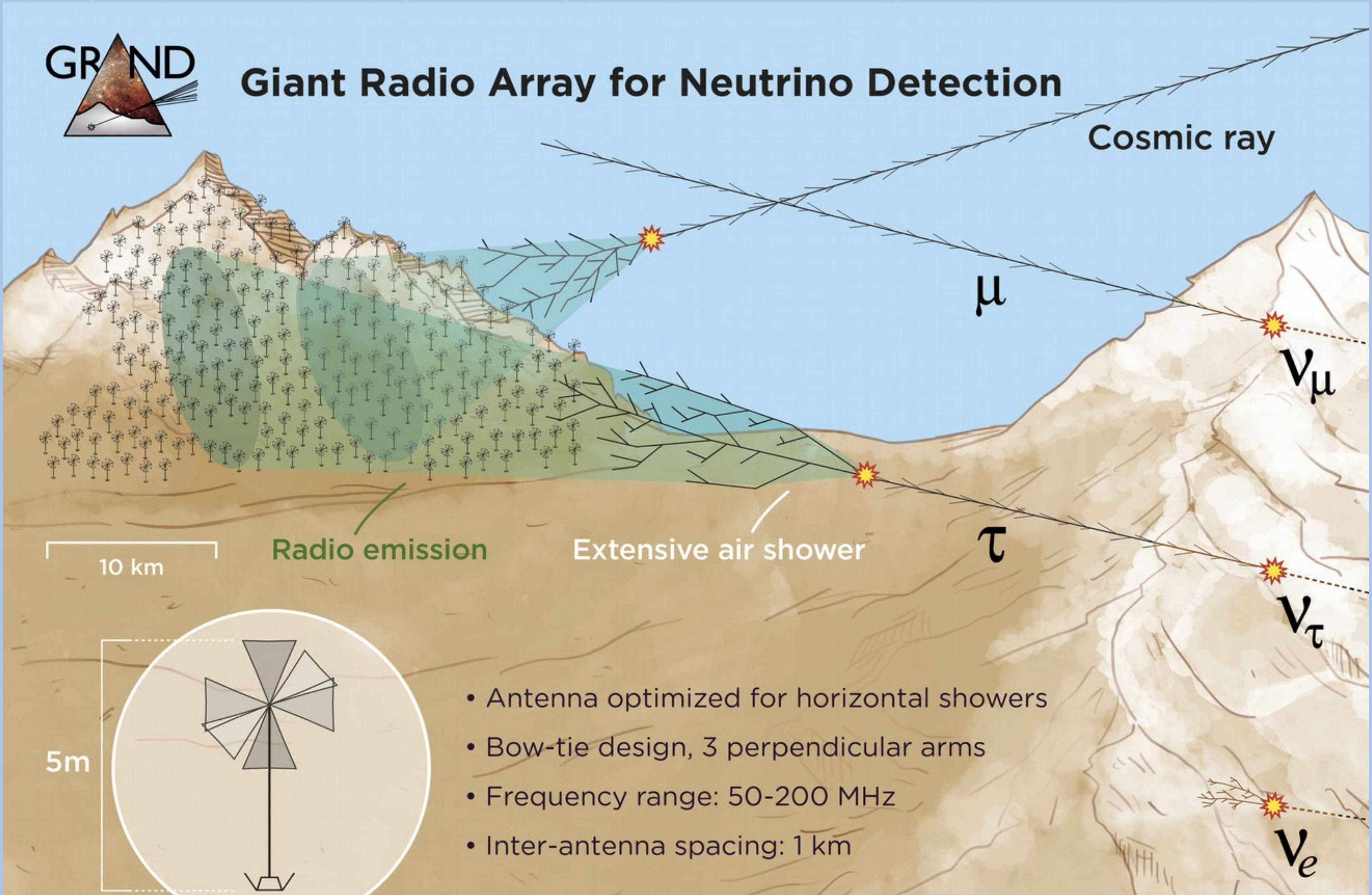
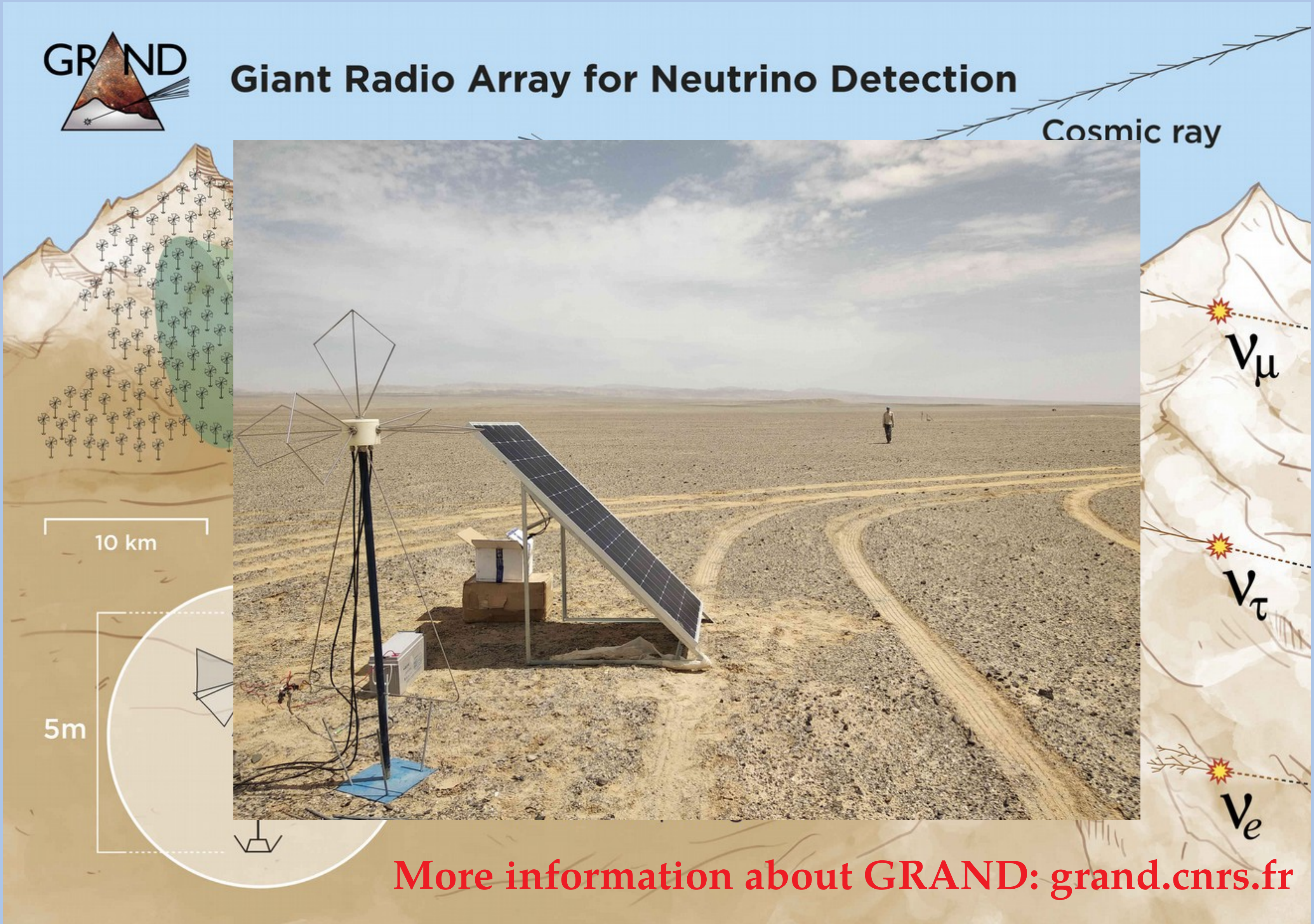


Figure courtesy of Markus Ahlers
Also in: Van Elewyck, **MB** *et al.*, PoS(ICRC2019), 1023



More information about GRAND: grand.cnrs.fr


GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
10 km
5m
ν_μ
ν_τ
ν_e
More information about GRAND: grand.cnrs.fr

What are you taking home?

- Cosmic TeV–PeV neutrinos:
  Powerful probes of the non-thermal Universe and high-energy particle physics

- Huge potential to test high-energy neutrino physics – *accessible already today*

- Still unknown, but getting there:
  - Where do most neutrinos come from?
  - What are, precisely, their spectrum, arrival directions, flavor composition?

- Coming decade: larger statistics, better reconstruction, higher energies

More?

- Ackermann, **MB**, *et al.*, *Fundamental physics with high-energy cosmic neutrinos*, **1903.04333**
- Ackermann, **MB**, *et al.*, *Astrophysics uniquely enabled by observations of high-energy cosmic neutrinos*, **1903.04334**
- Argüelles, **MB**, *et al.*, *Fundamental physics with high-energy cosmic neutrinos today and in the future*, **1907.08690**

Backup slides

Ultra-long-range flavorful interactions

- Simple extension of the SM: Promote the global lepton-number symmetries L_e-L_μ, L_e-L_τ to local symmetries

- They introduce new interaction between electrons and ν_e and ν_μ or ν_τ mediated by a new neutral vector boson (Z'):
  - Affects oscillations
  - If the Z' is *very* light, *many* electrons can contribute

X.-G. He, G.C. Joshi, H. Lew, R. R. Volkas, *PRD* 1991 / R. Foot, X.-G. He, H. Lew, R. R. Volkas, *PRD* 1994
A. Joshipura, S. Mohanty, *PLB* 2004 / J. Grifols & E. Massó, PLB 2004 / A. Bandyopadhyay, A. Dighe, A. Joshipura, *PRD* 2007
M.C. González-García, P..C. de Holanda, E. Massó, R. Zukanovich Funchal, *JCAP* 2007 / A. Samanta, *JCAP* 2011
S.-S. Chatterjee, A. Dasgupta, S. Agarwalla, *JHEP* 2015

The new potential sourced by an electron

Under the L_e-L_μ or L_e-L_τ symmetry, an electron sources a Yukawa potential —

$$V \sim \frac{g'^2_{e\beta}}{r} e^{-m'_{e\beta} r}$$

A neutrino "feels" all the electrons within the interaction range $\sim(1/m')$

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Under the L_e-L_μ or L_e-L_τ symmetry, an electron sources a Yukawa potential —

Z′ coupling

Z′ mass

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Distance to neutrino

A neutrino "feels" all the electrons within the interaction range $\sim(1/m')$

Electron-neutrino interactions can kill oscillations

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$$H_{\text{tot}} = \underbrace{H_{\text{vac}}}$$

Standard oscillations:
Neutrinos change flavor
because this is non-diagonal

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$$\downarrow$$

$$P_{\nu_\alpha \to \nu_\beta}\left(\theta_{ij}, \delta_{\mathrm{CP}}\right)$$

Electron-neutrino interactions can kill oscillations

$$= \mathrm{diag}(V_{e\mu}, -V_{e\mu}, 0)$$

$$\mathrm{H_{tot}} = \mathrm{H_{vac}} + \underbrace{\mathrm{V}_{e\beta}}$$

New neutrino-electron interaction:
This is diagonal

Electron-neutrino interactions can kill oscillations

$$\mathrm{H_{tot}} = \mathrm{H_{vac}} + \mathrm{V}_{e\beta} = \mathrm{diag}(V_{e\mu}, -V_{e\mu}, 0)$$

New neutrino-electron interaction:
This is diagonal

Z' parameters

$$P_{\nu_\alpha \to \nu_\beta}\left(\theta_{ij}, \delta_{\mathrm{CP}}, \Delta m^2_{ij}, E_\nu, g'_{e\mu}, m'_{e\mu}\right)$$

Electron-neutrino interactions can kill oscillations

$$= \mathrm{diag}(V_{e\mu}, -V_{e\mu}, 0)$$

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Z' parameters

$$P_{\nu_\alpha \to \nu_\beta}\left(\theta_{ij}, \delta_{\mathrm{CP}}, \Delta m^2_{ij}, E_\nu, \overbrace{g'_{e\mu}, m'_{e\mu}}\right)$$

If $\mathrm{V}_{e\beta}$ dominates ($g' \gg 1$, $m' \ll 1$), oscillations turn off

Electron-neutrino interactions can kill oscillations

$$\mathrm{H_{tot}} = \mathrm{H_{vac}} + \mathrm{V}_{e\beta}$$

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~$1/E$

Energy-independent

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$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \mathrm{V}_{e\beta}$$

~$1/E$

Energy-independent

∴ We can use high-energy astrophysical neutrinos

Electrons in the local and distant Universe

Potential:

$$V_{e\beta} \propto \frac{1}{r} e^{-m'_{e\beta} r}$$

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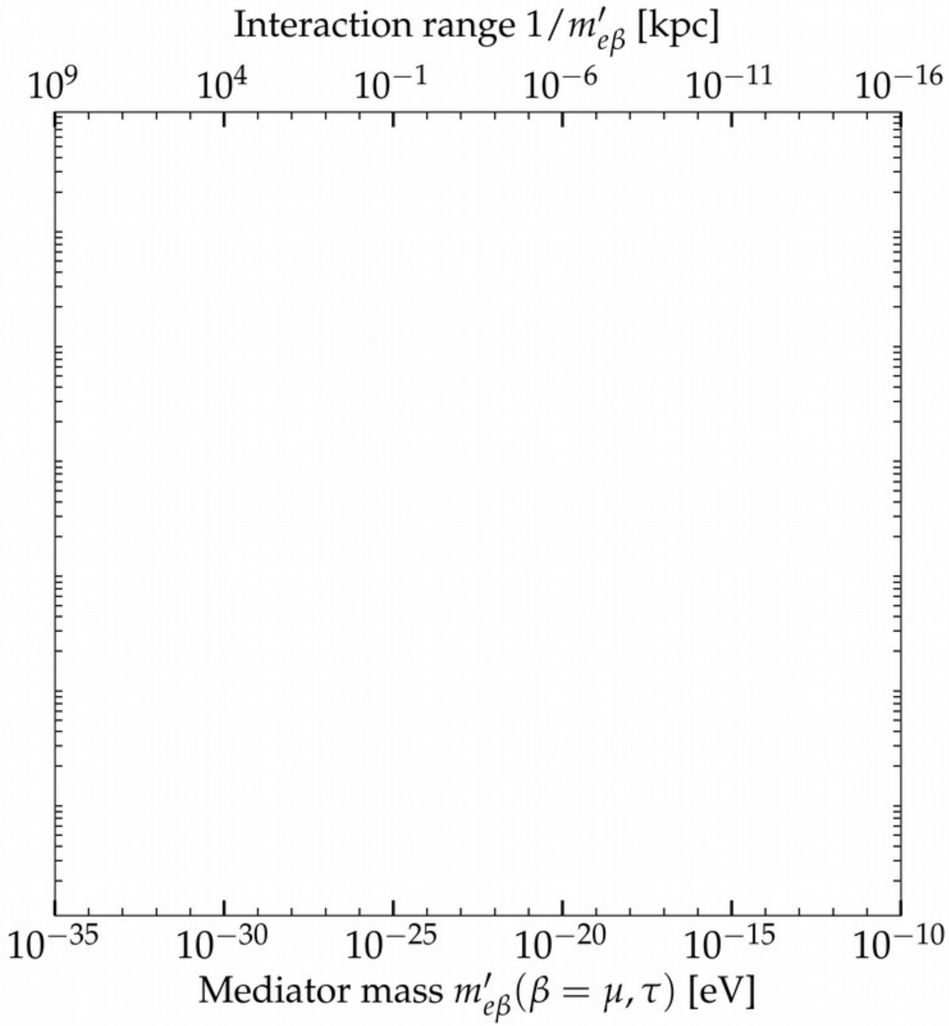
Interaction range: $\frac{1}{m'_{e\beta}}$

Electrons in the local and distant Universe



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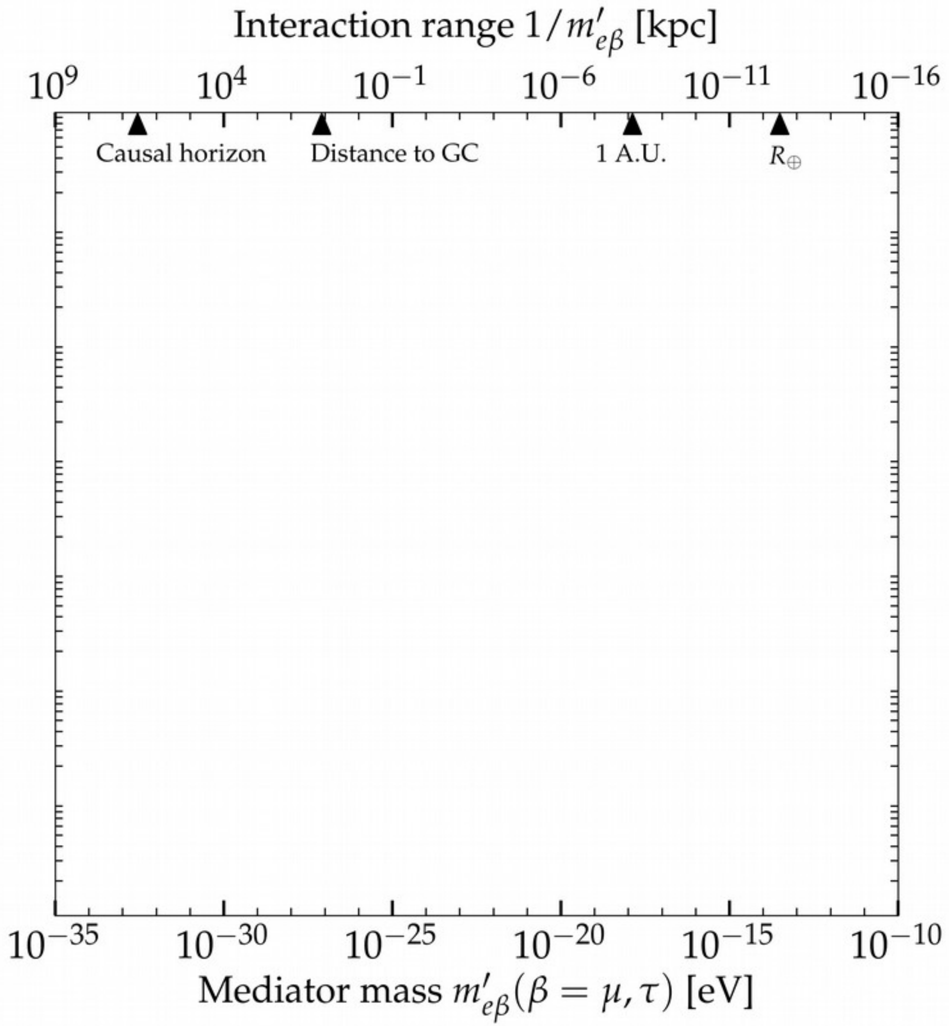

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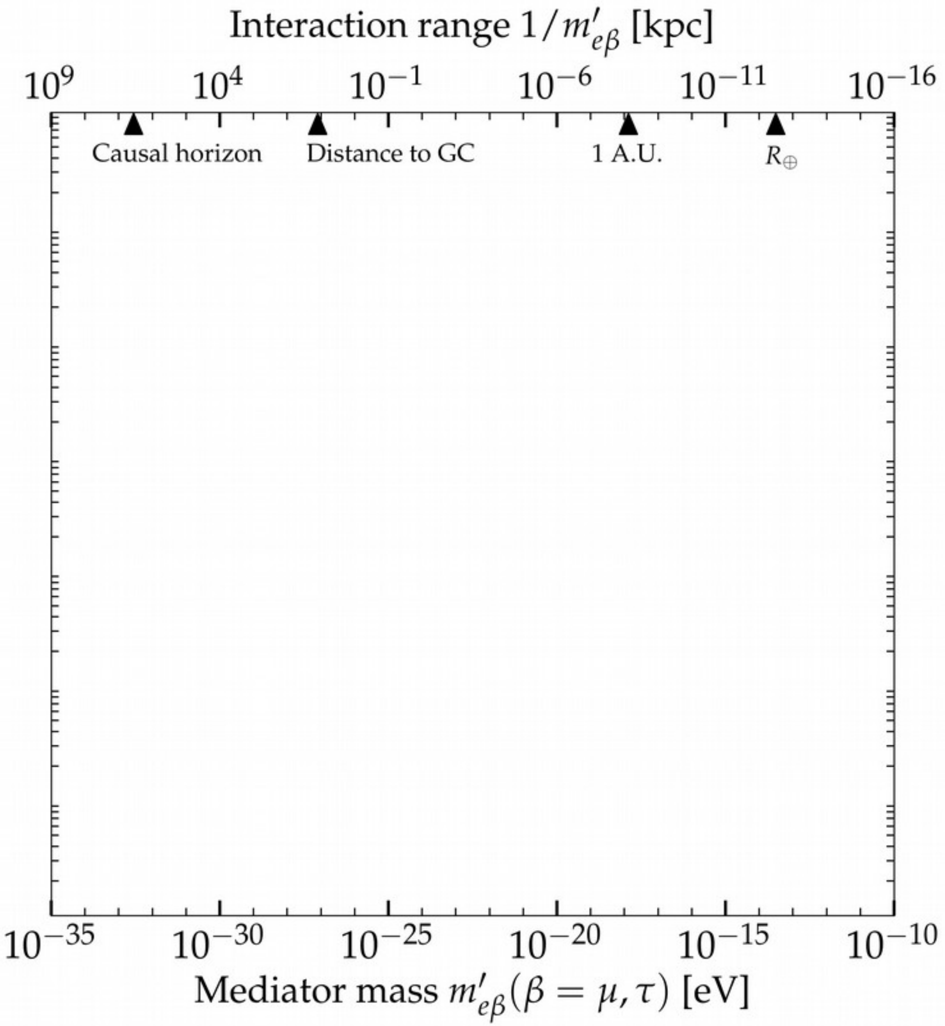

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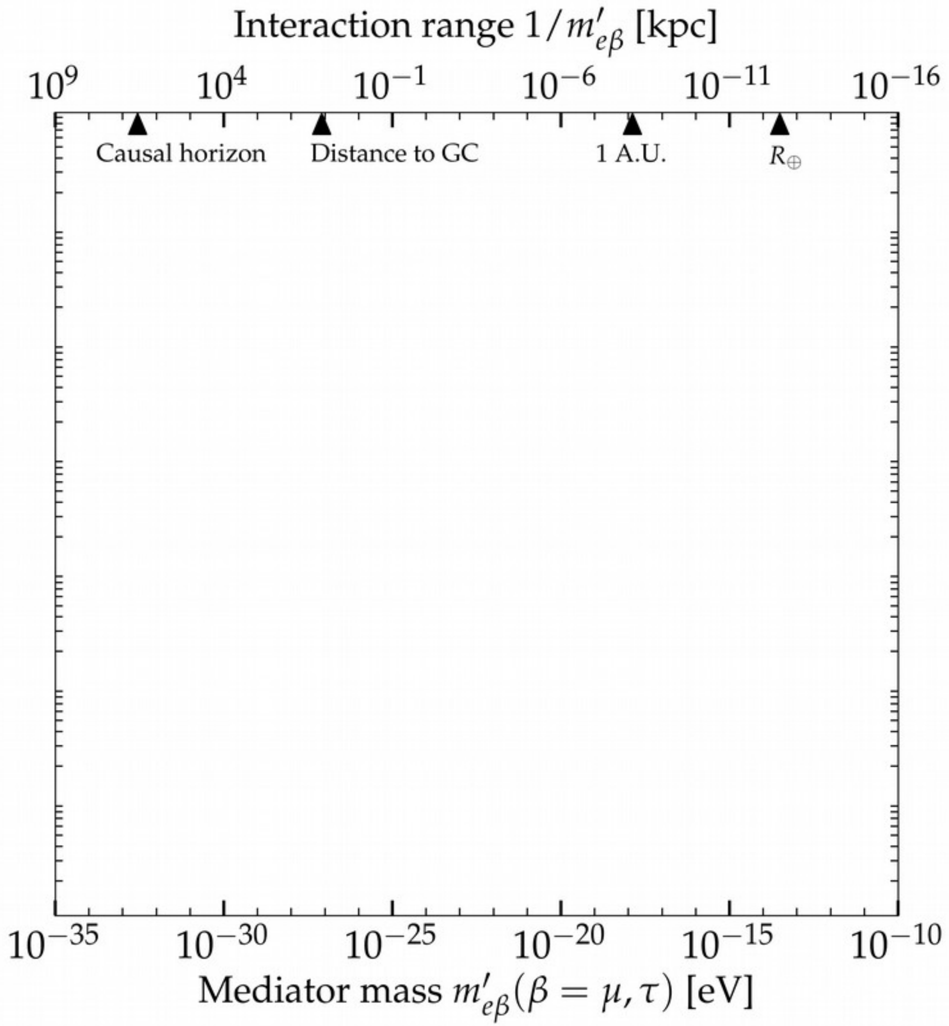
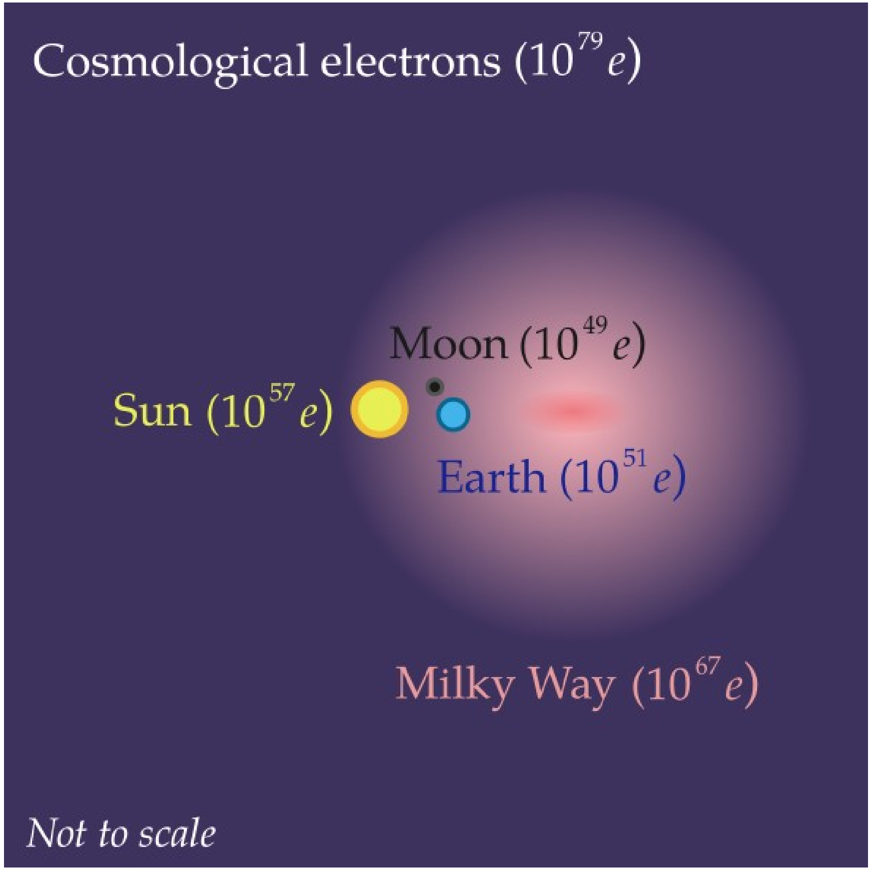
Interaction range: $\dfrac{1}{m'_{e\beta}}$

Light mediators
$\Rightarrow$ Long interaction ranges

Electrons in the local and distant Universe





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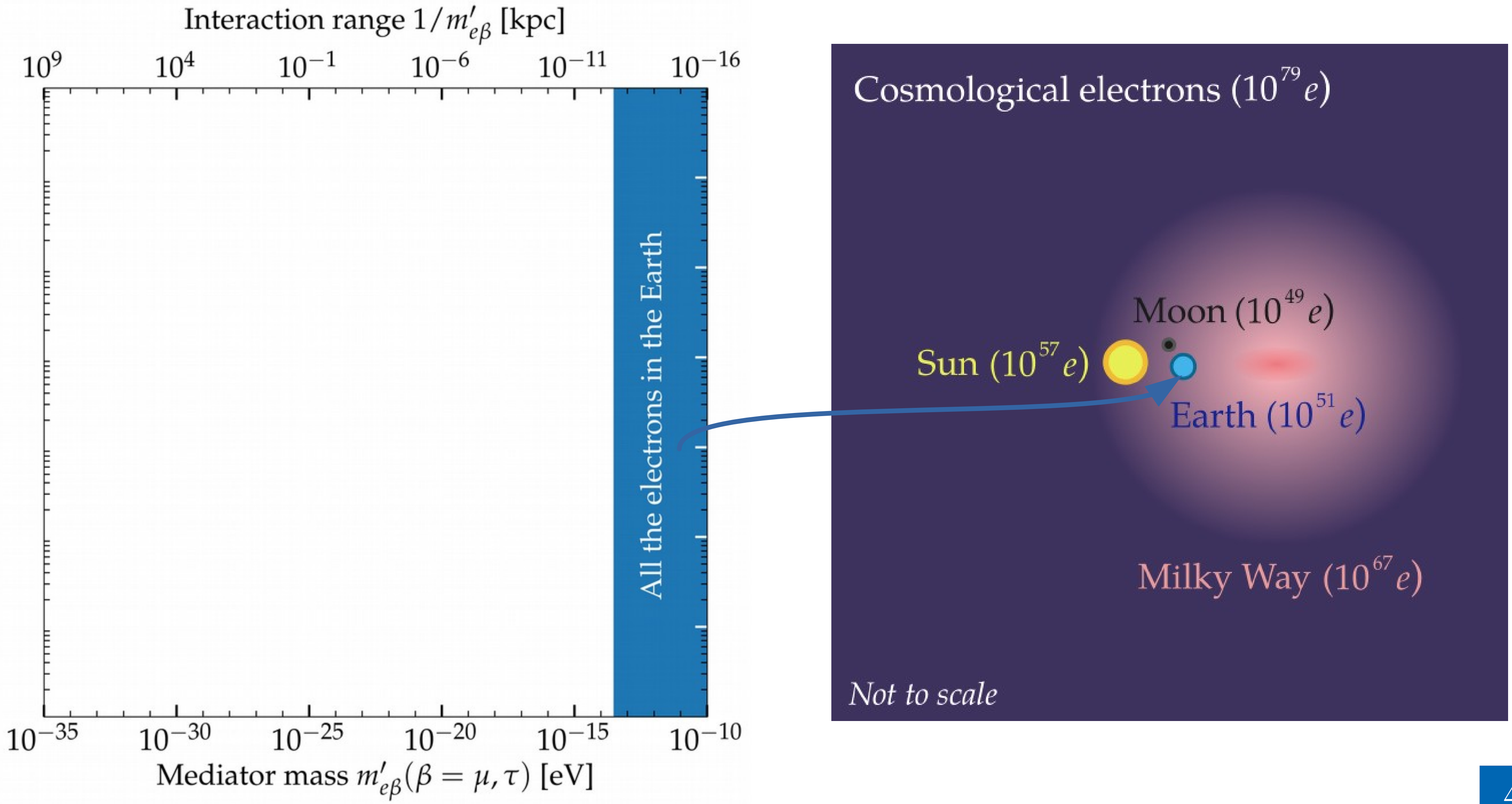

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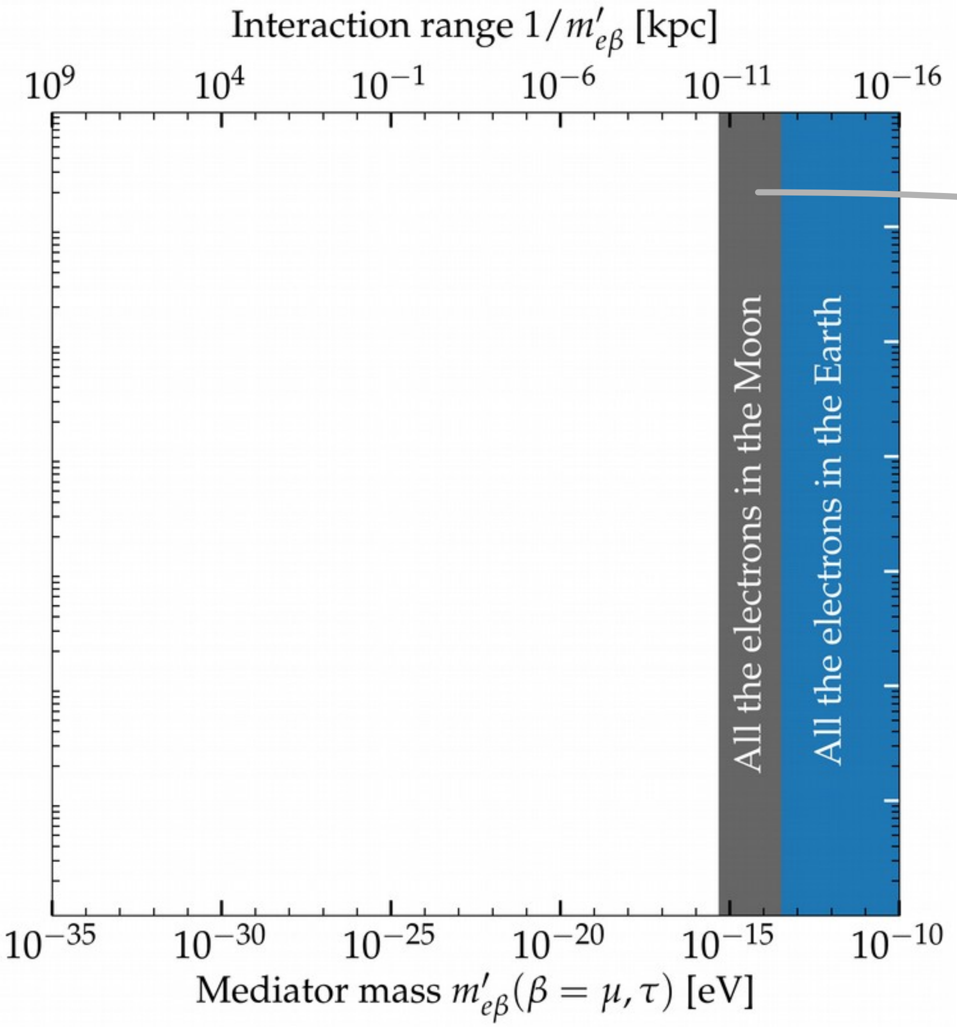

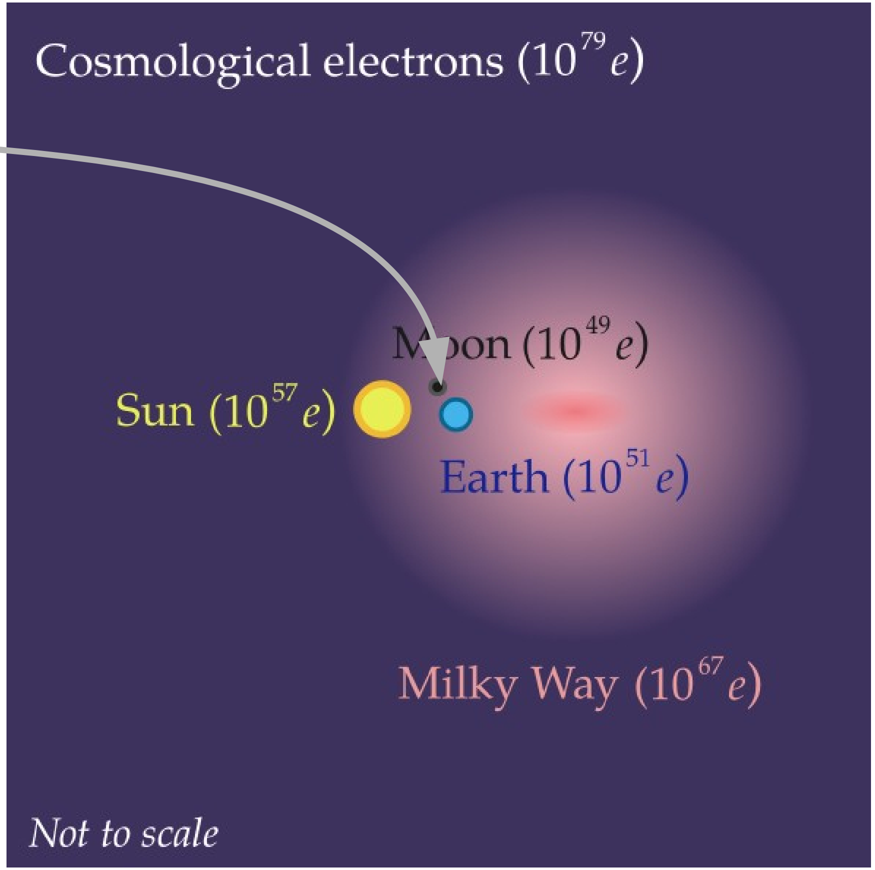

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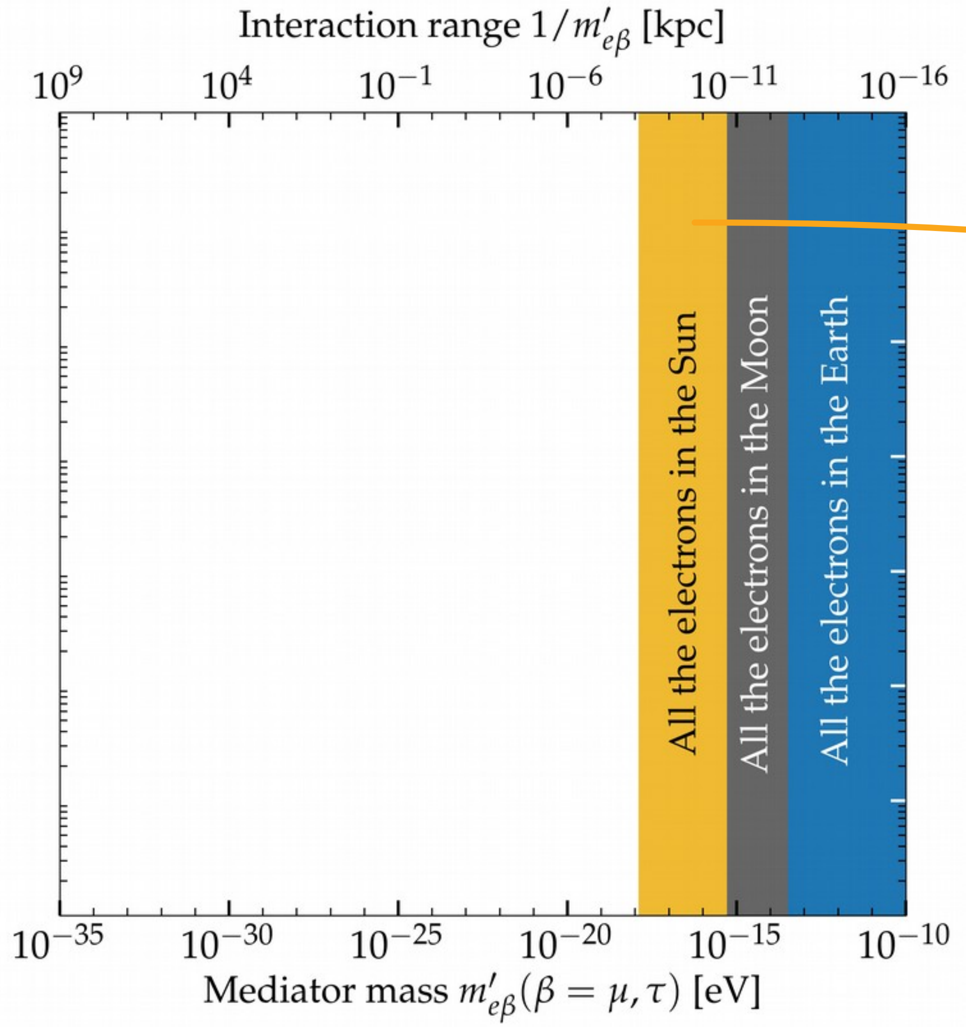

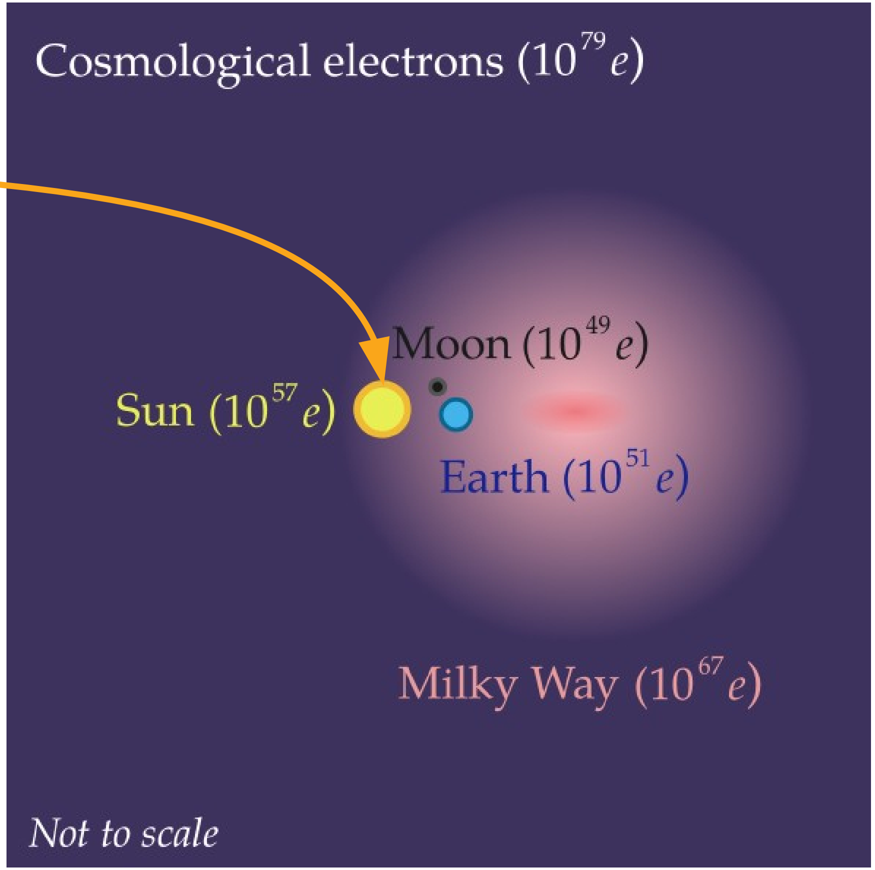

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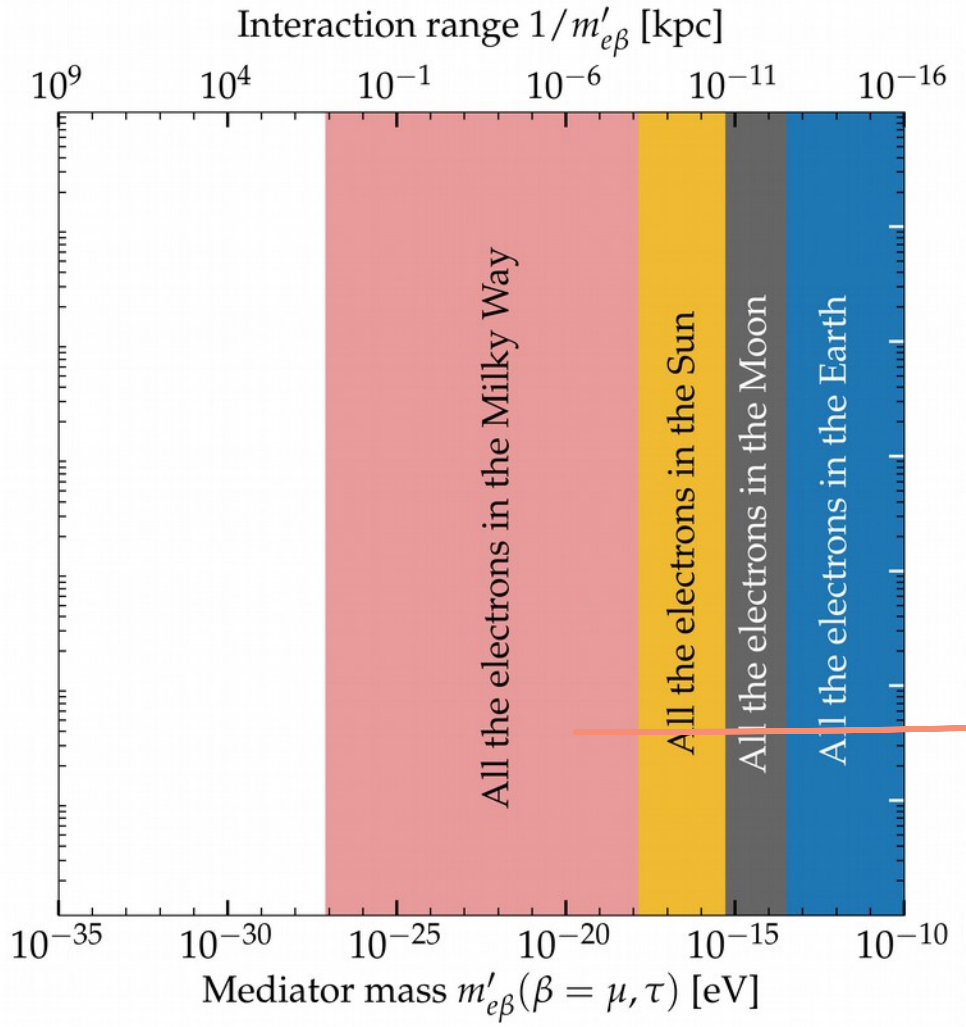

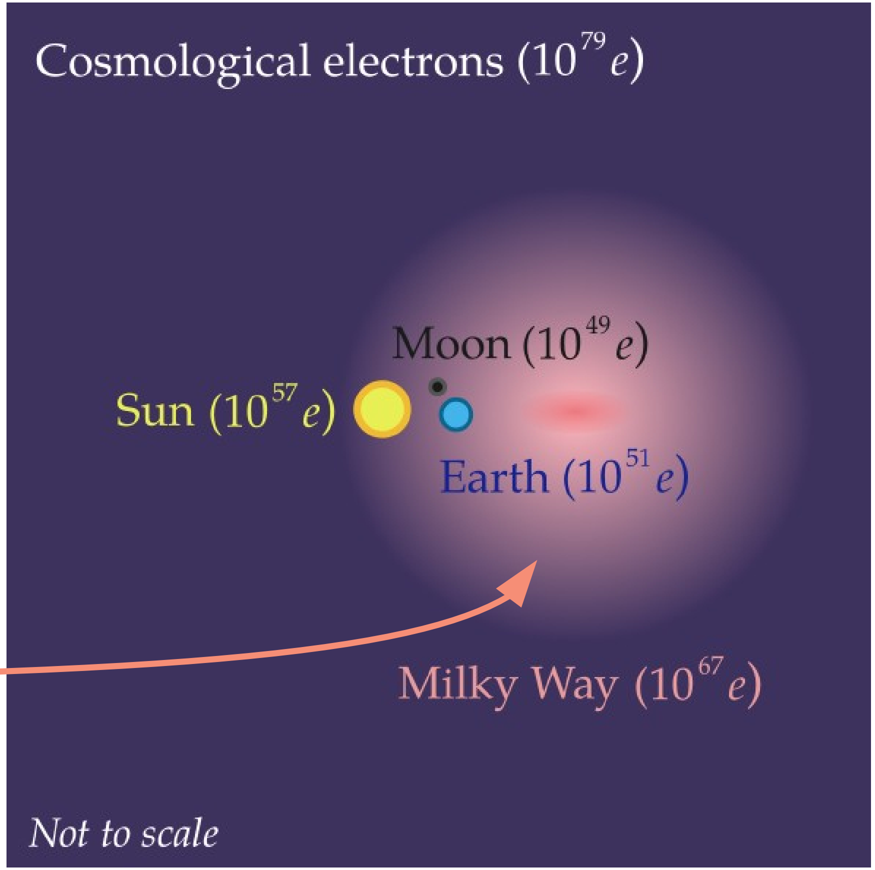

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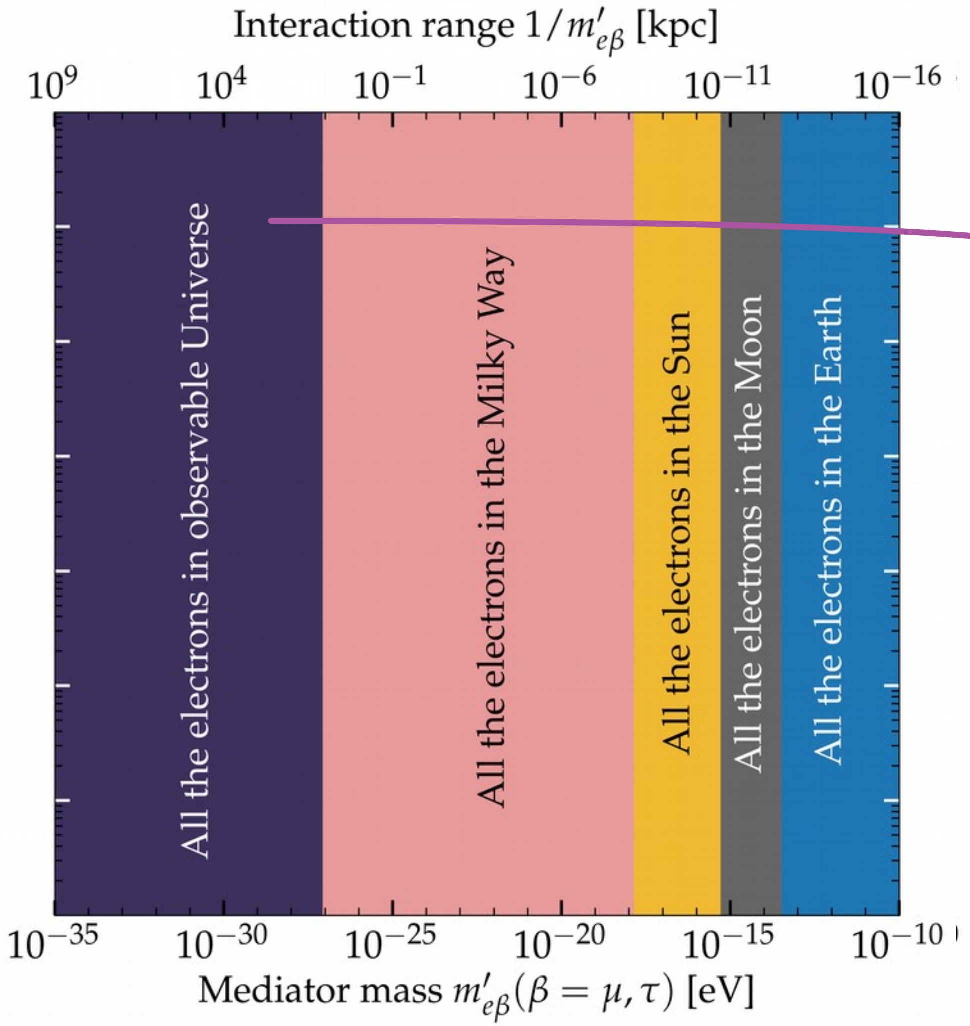

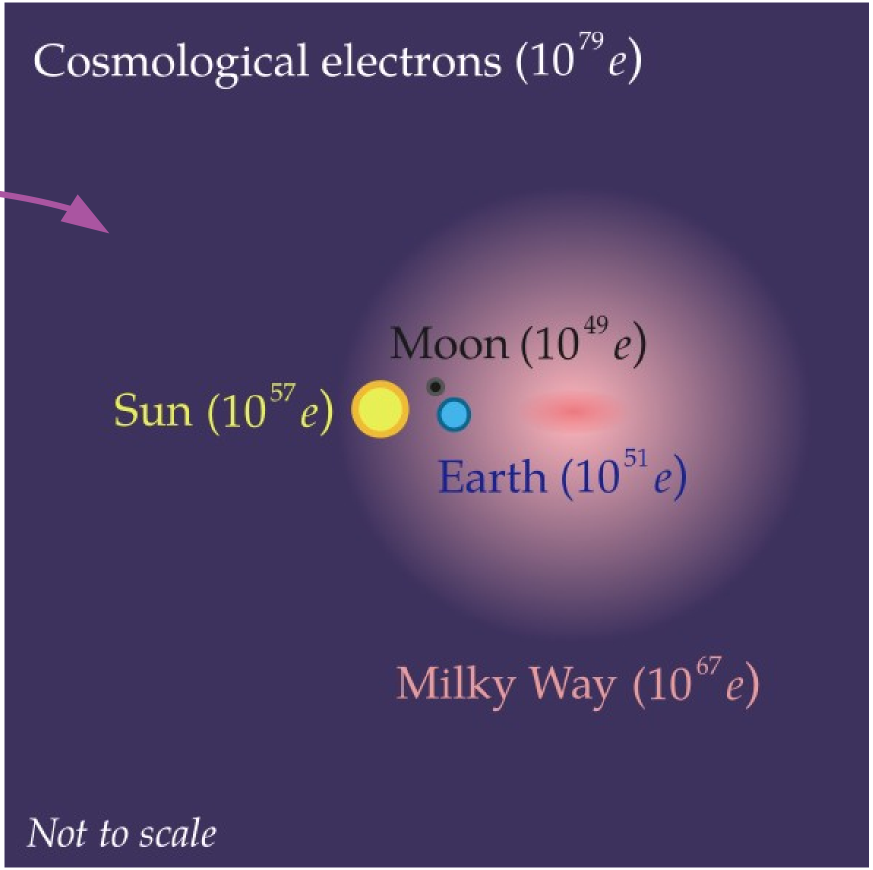

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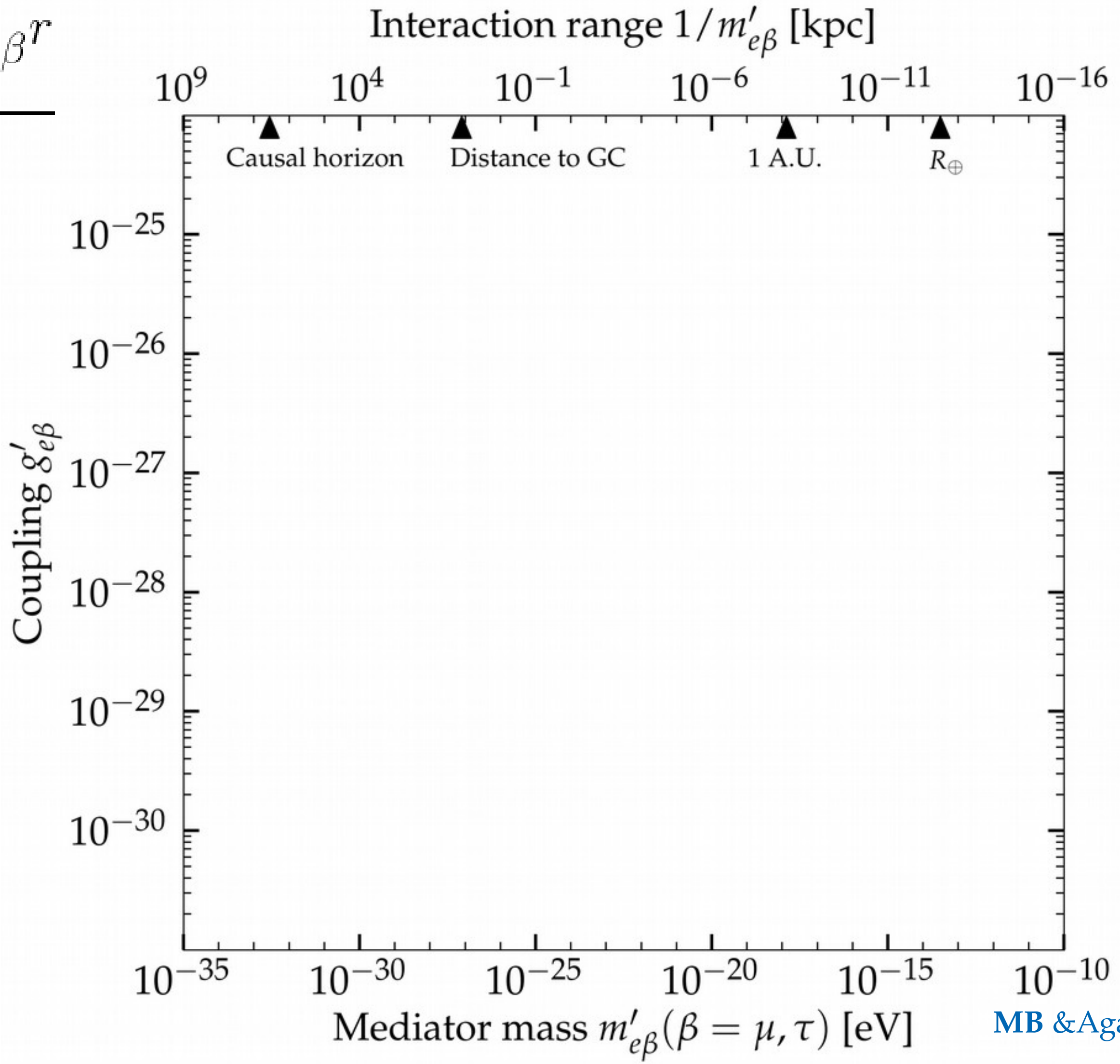

MB &Agarwalla, *PRL* 2019

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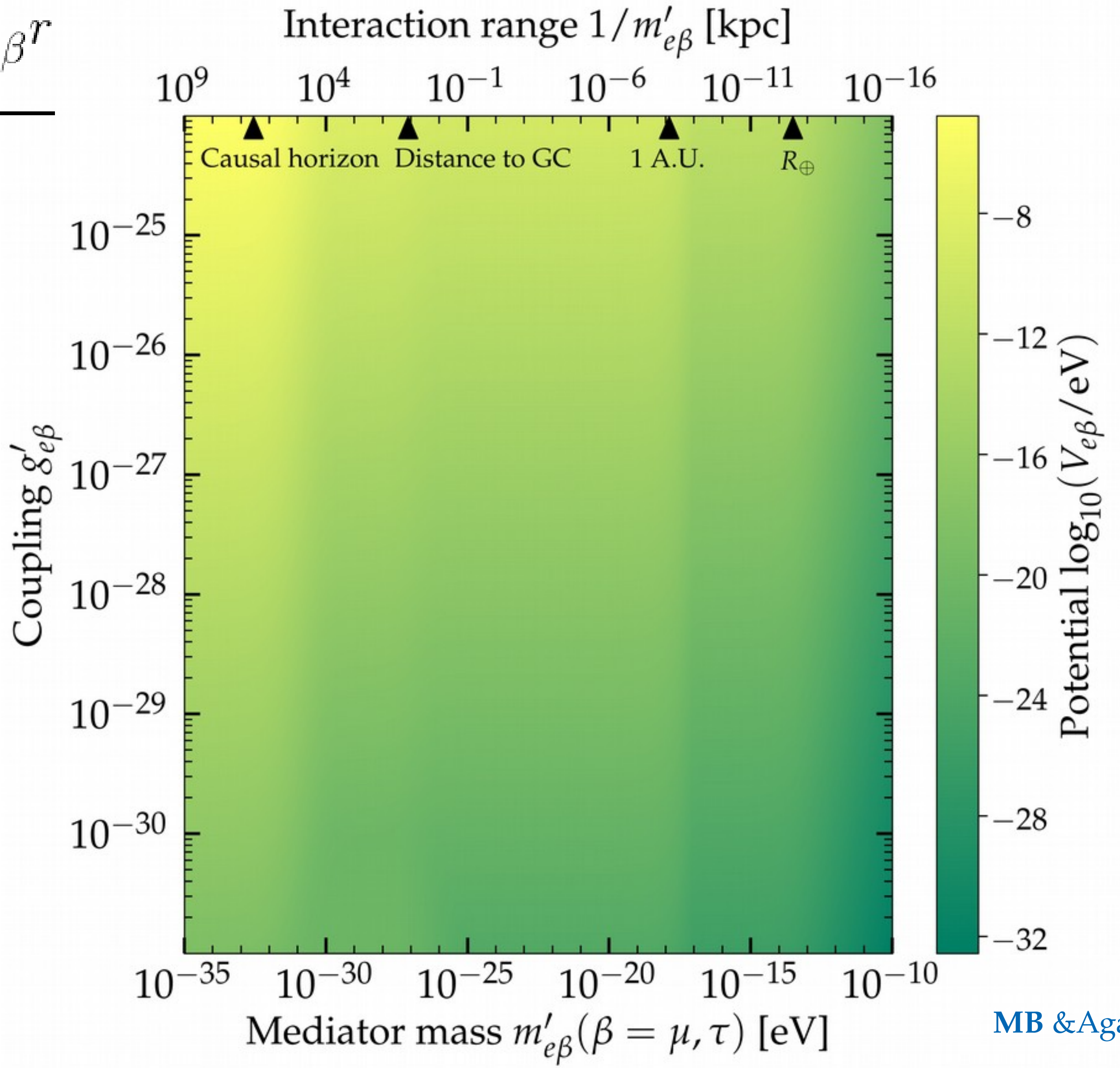
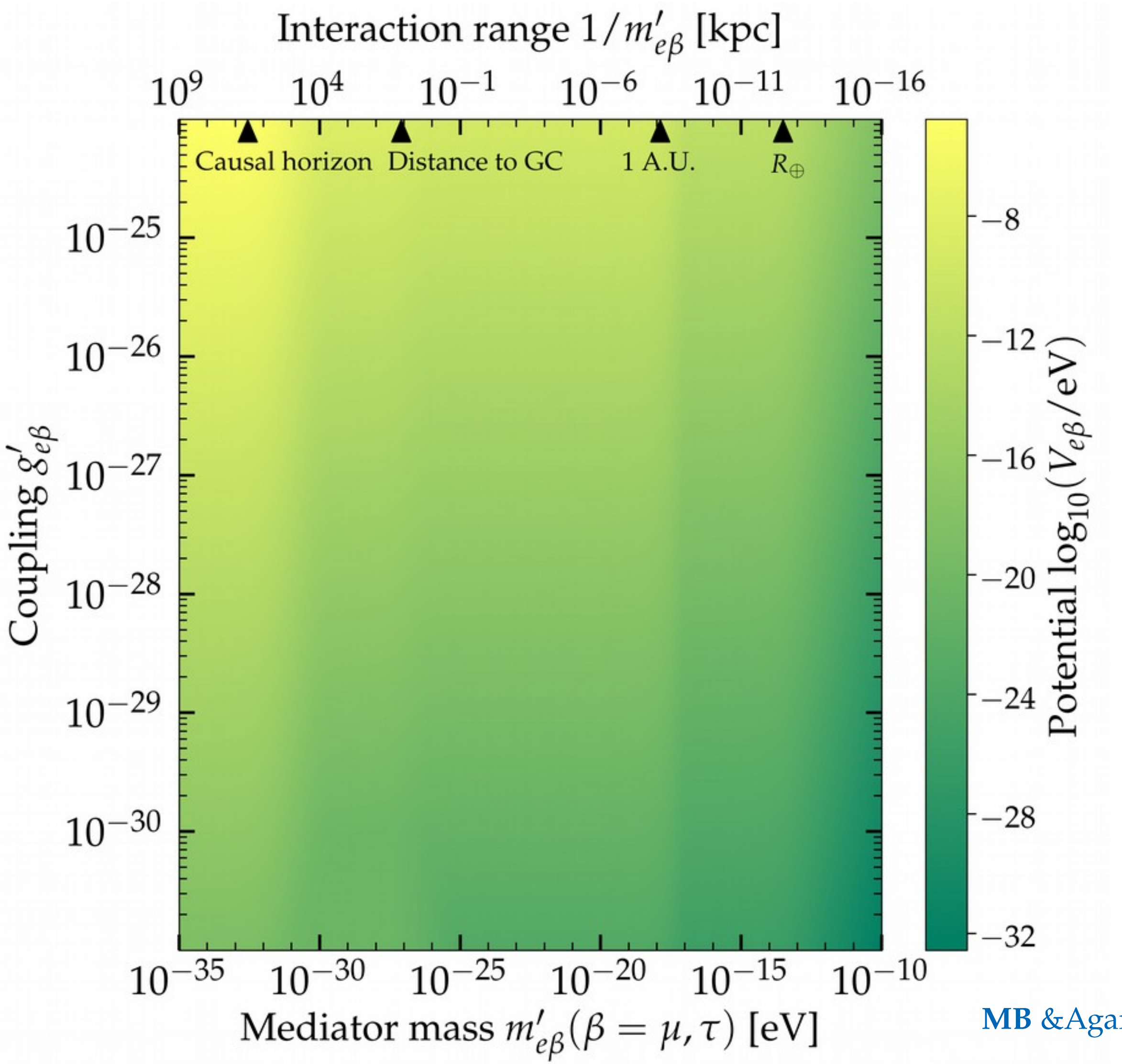


MB &Agarwalla, *PRL* 2019

$g_{\text{strong}} \sim 13.5$
$g_{\text{e.m.}} \sim 0.3$
$g_{\text{weak}} \sim 0.01$
$g_{\text{gravity}} \sim 10^{-19}$



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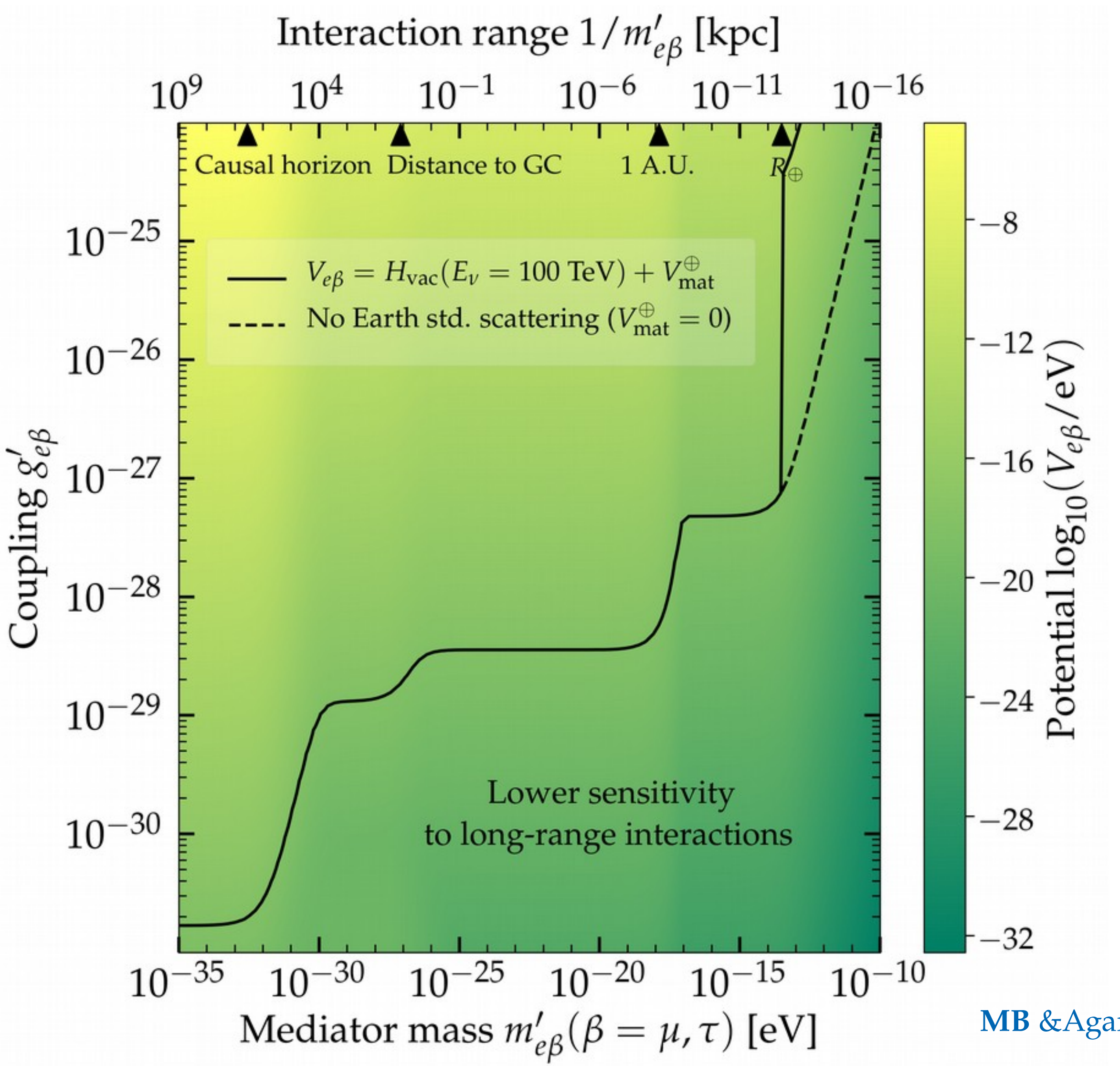

MB &Agarwalla, *PRL* 2019

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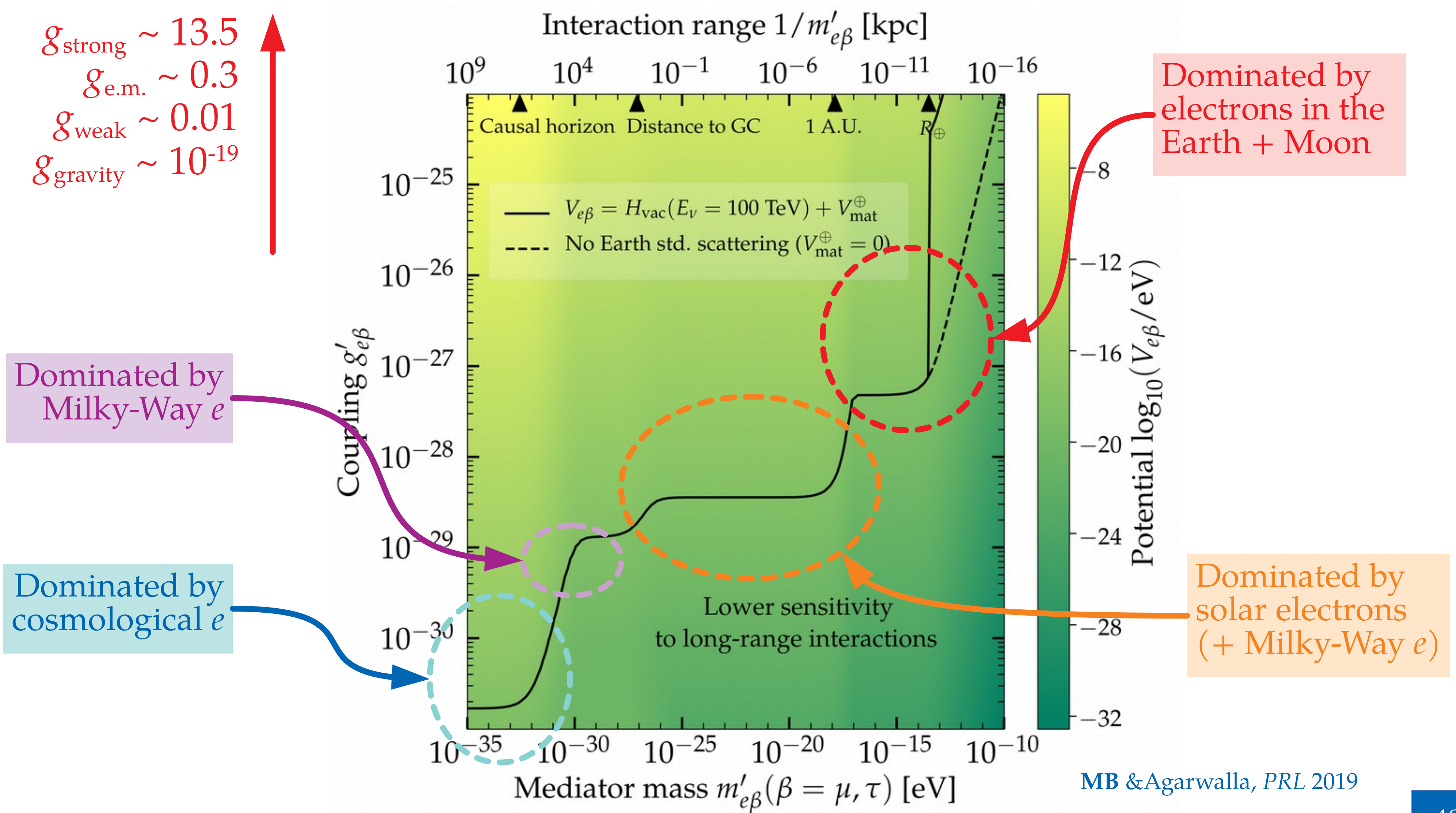
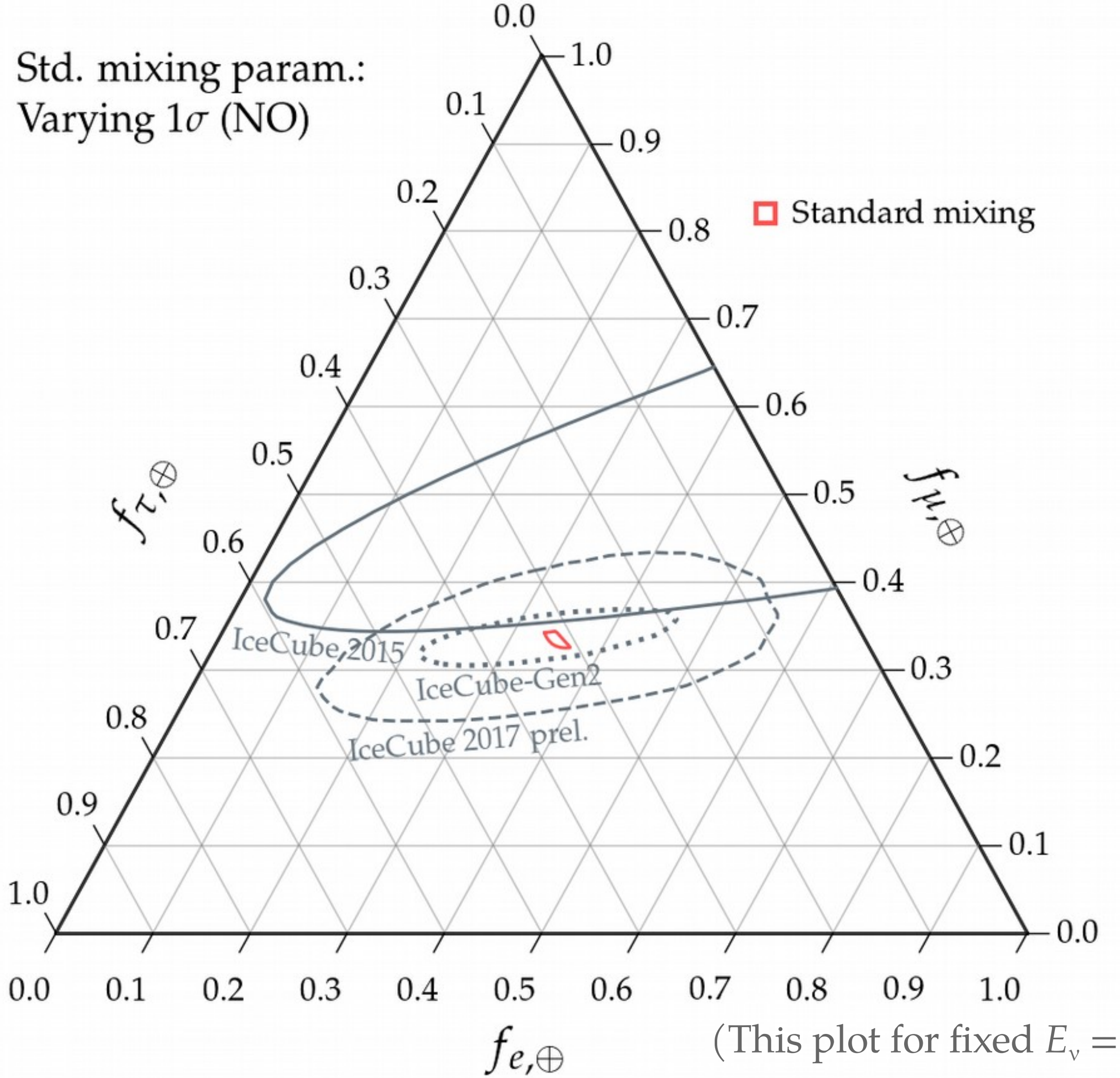
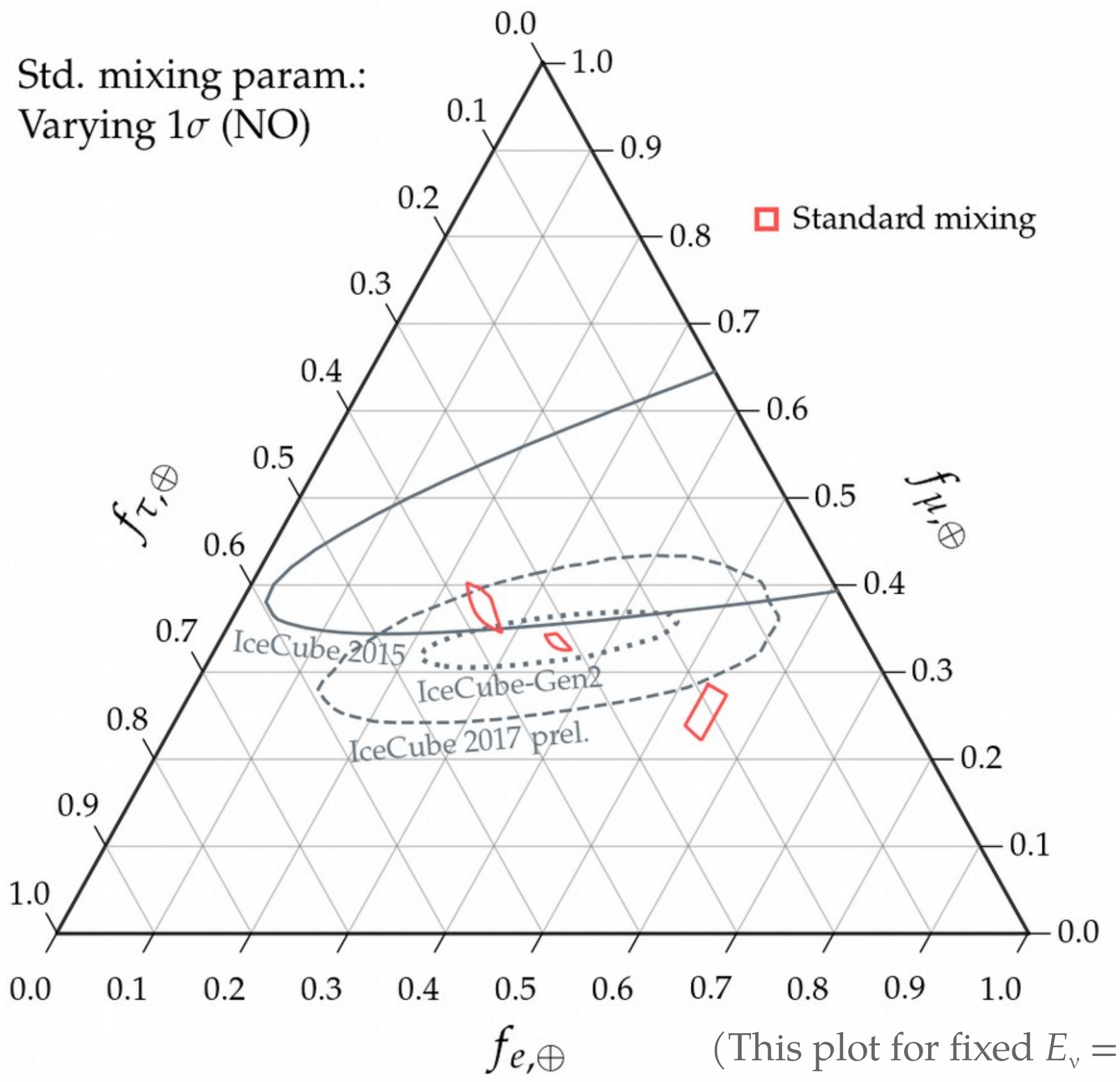


MB &Agarwalla, *PRL* 2019



MB & Agarwalla, *PRL* 2019

(This plot for fixed $E_\nu = 100$ TeV)



MB & Agarwalla, *PRL* 2019

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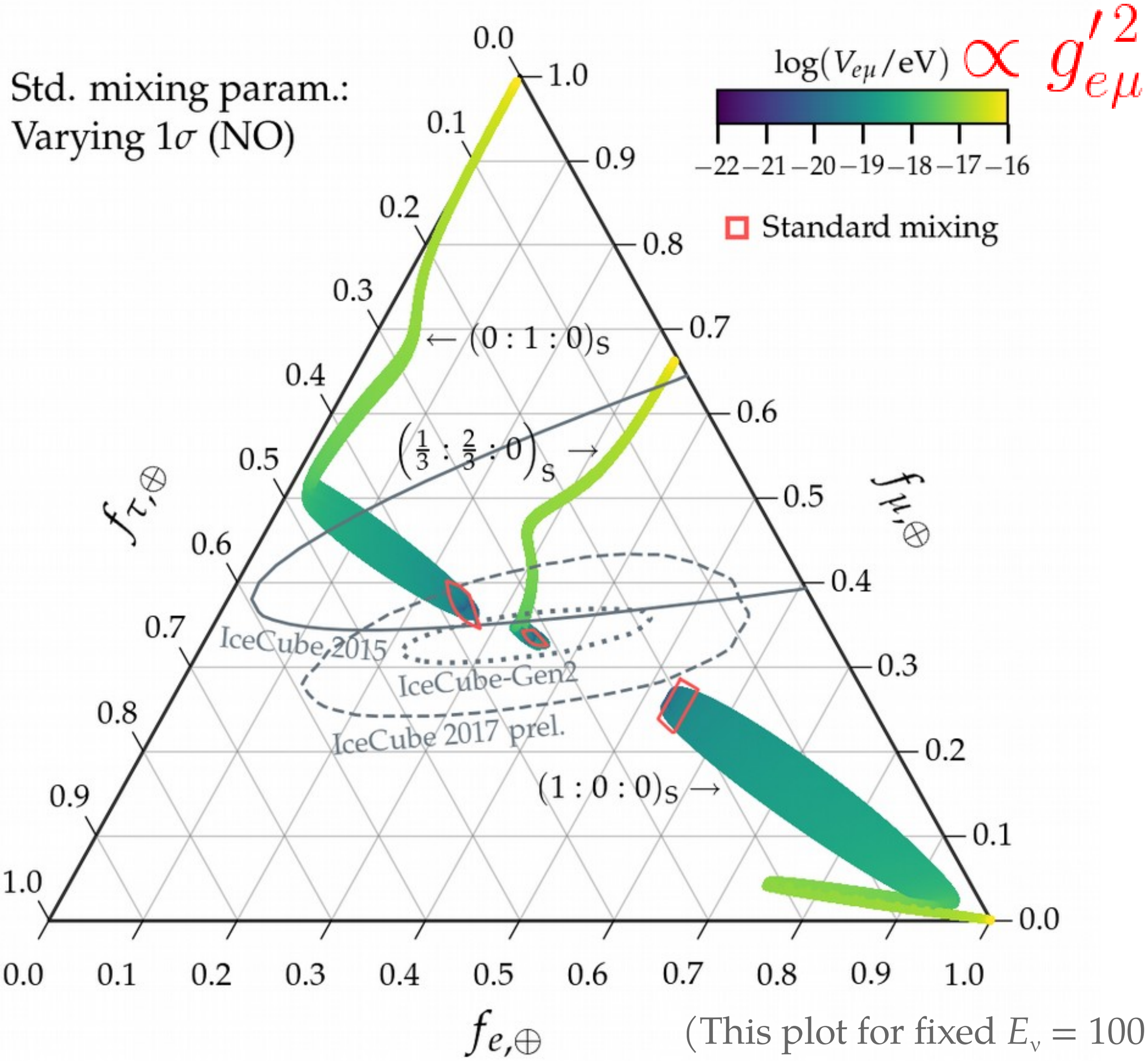

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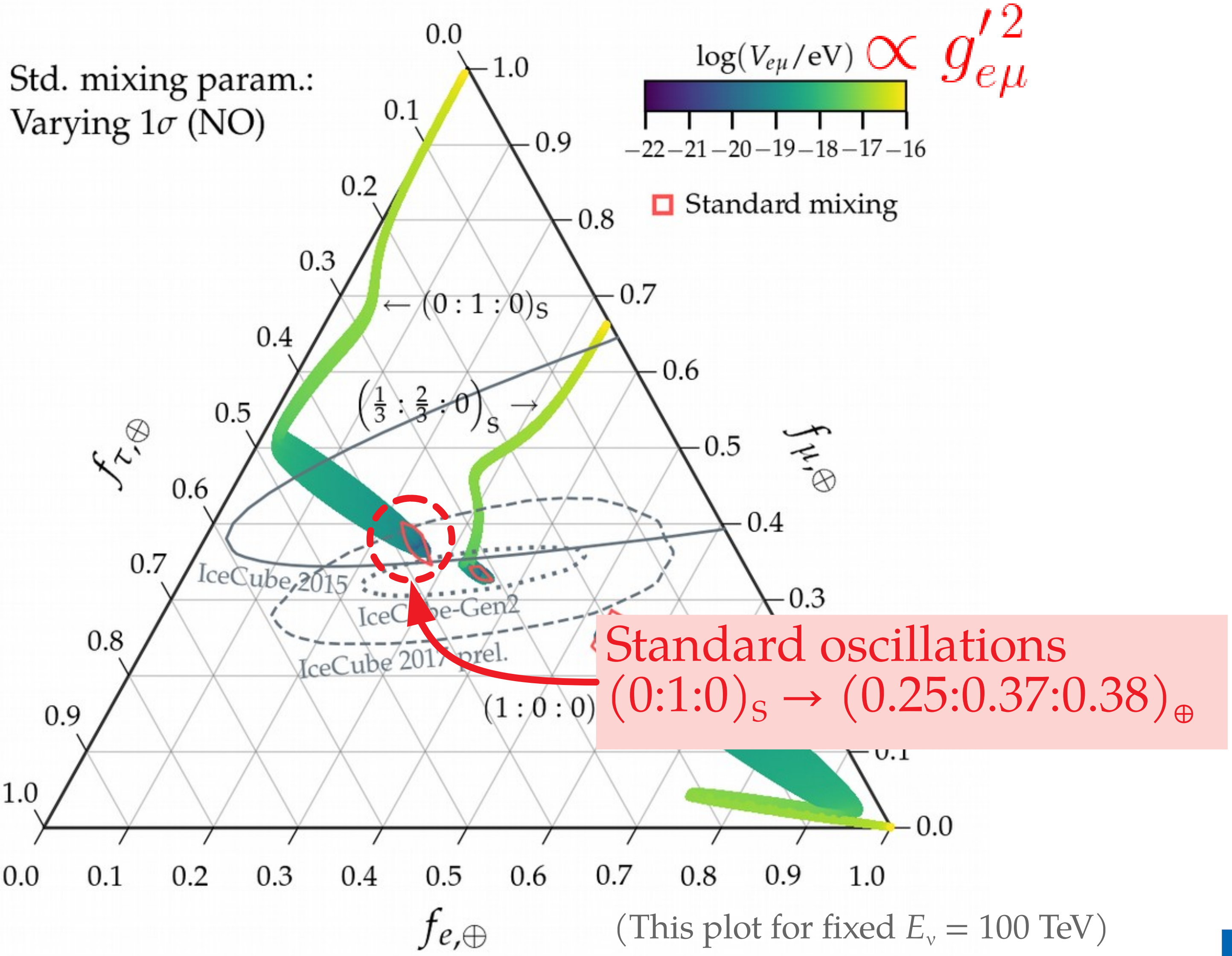

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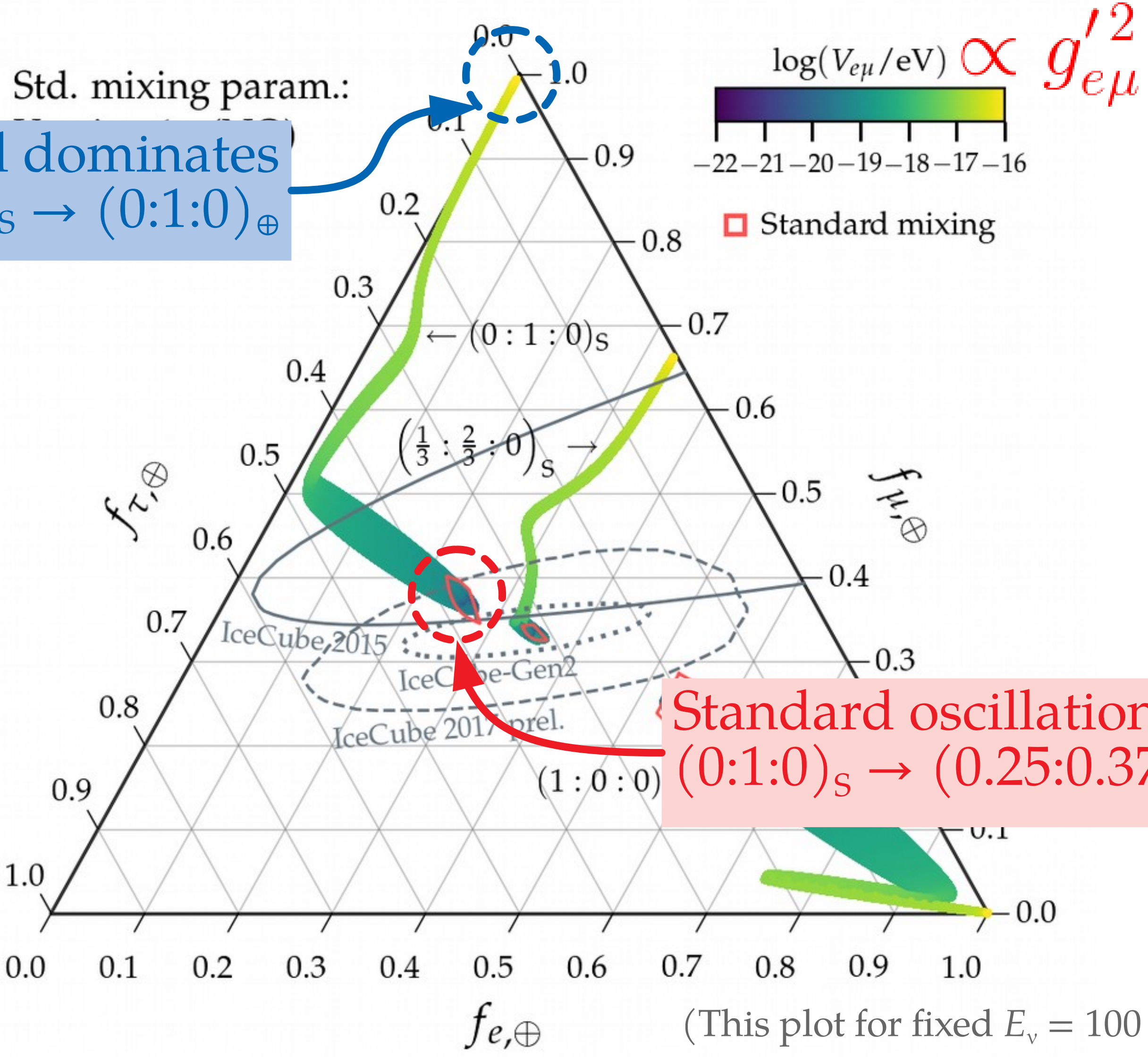
$(0{:}1{:}0)_S \rightarrow (0{:}1{:}0)_\oplus$



Standard oscillations
$(0{:}1{:}0)_S \rightarrow (0.25{:}0.37{:}0.38)_\oplus$

MB & Agarwalla, *PRL* 2019

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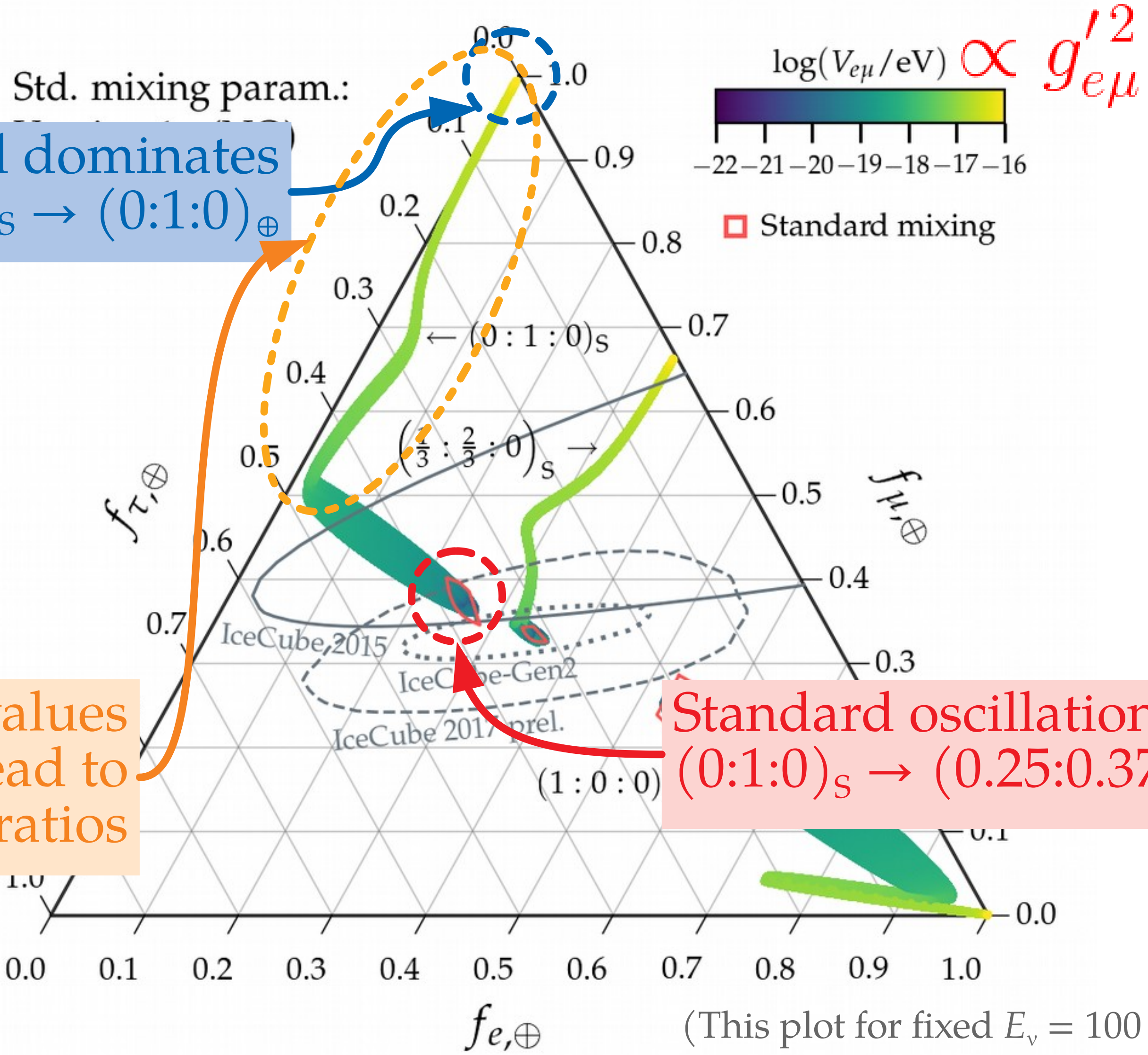

New potential dominates
$(0{:}1{:}0)_S \rightarrow (0{:}1{:}0)_\oplus$

We can disfavor all values of m' and g' that lead to these flavor ratios

Standard oscillations
$(0{:}1{:}0)_S \rightarrow (0.25{:}0.37{:}0.38)_\oplus$

MB & Agarwalla, *PRL* 2019

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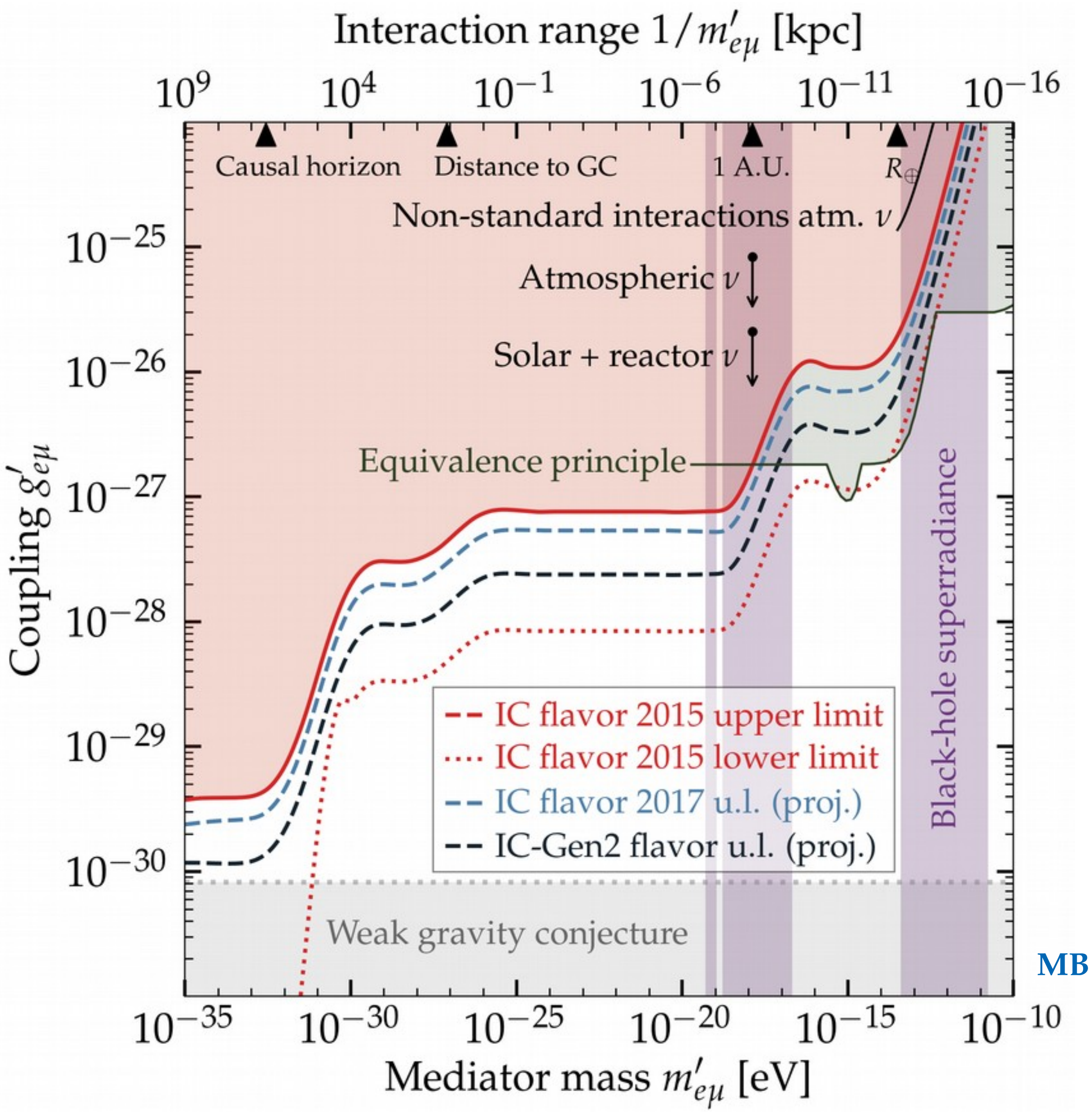
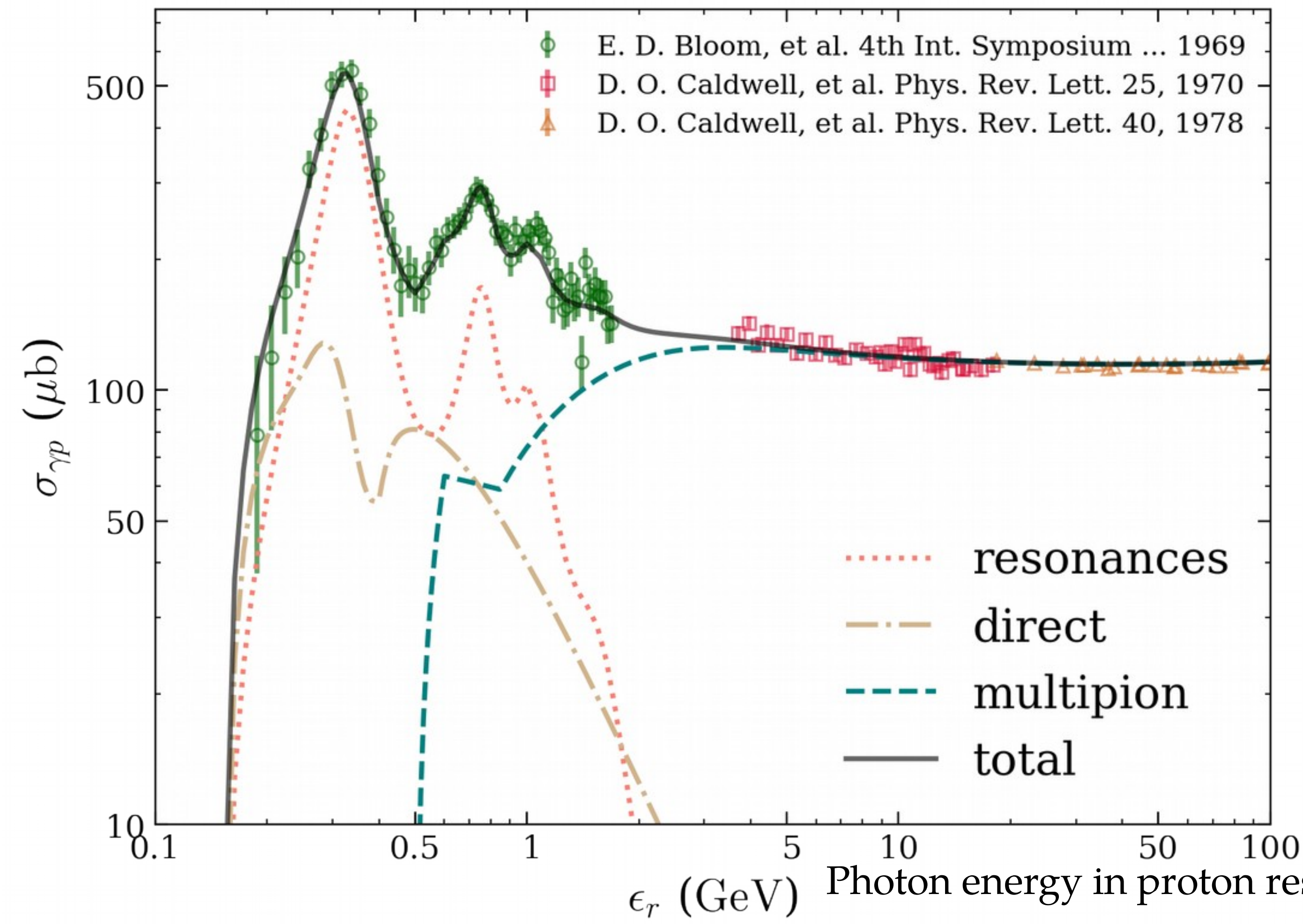


MB &Agarwalla, *PRL* 2019

Beyond the Δ resonance (1/2)

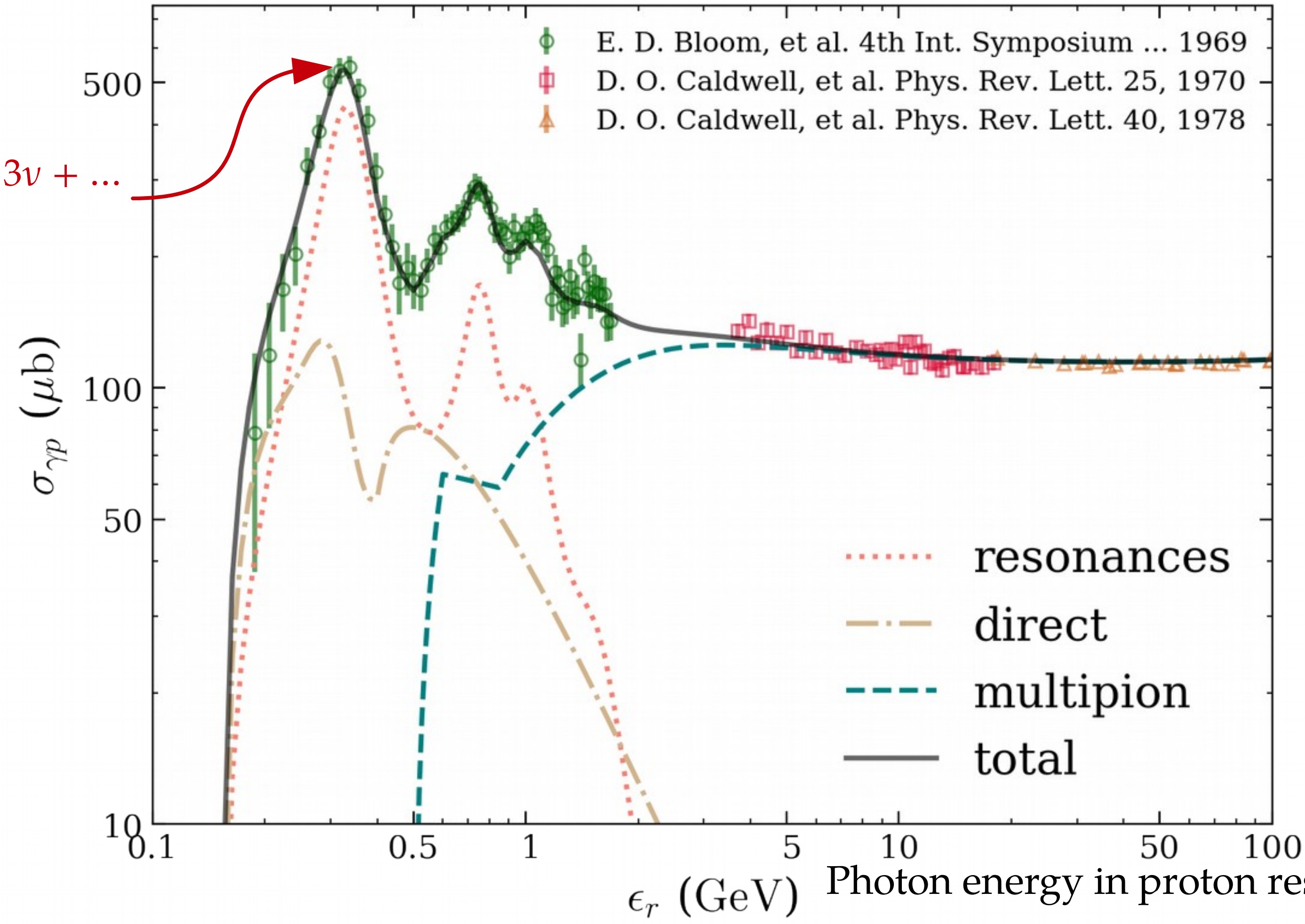


Photon energy in proton rest frame

Morejón *et al.*, 1904.07999

Beyond the Δ resonance (1/2)

Delta resonance:
$p + \gamma \rightarrow \Delta \rightarrow \pi^+ \rightarrow 3\nu + \ldots$



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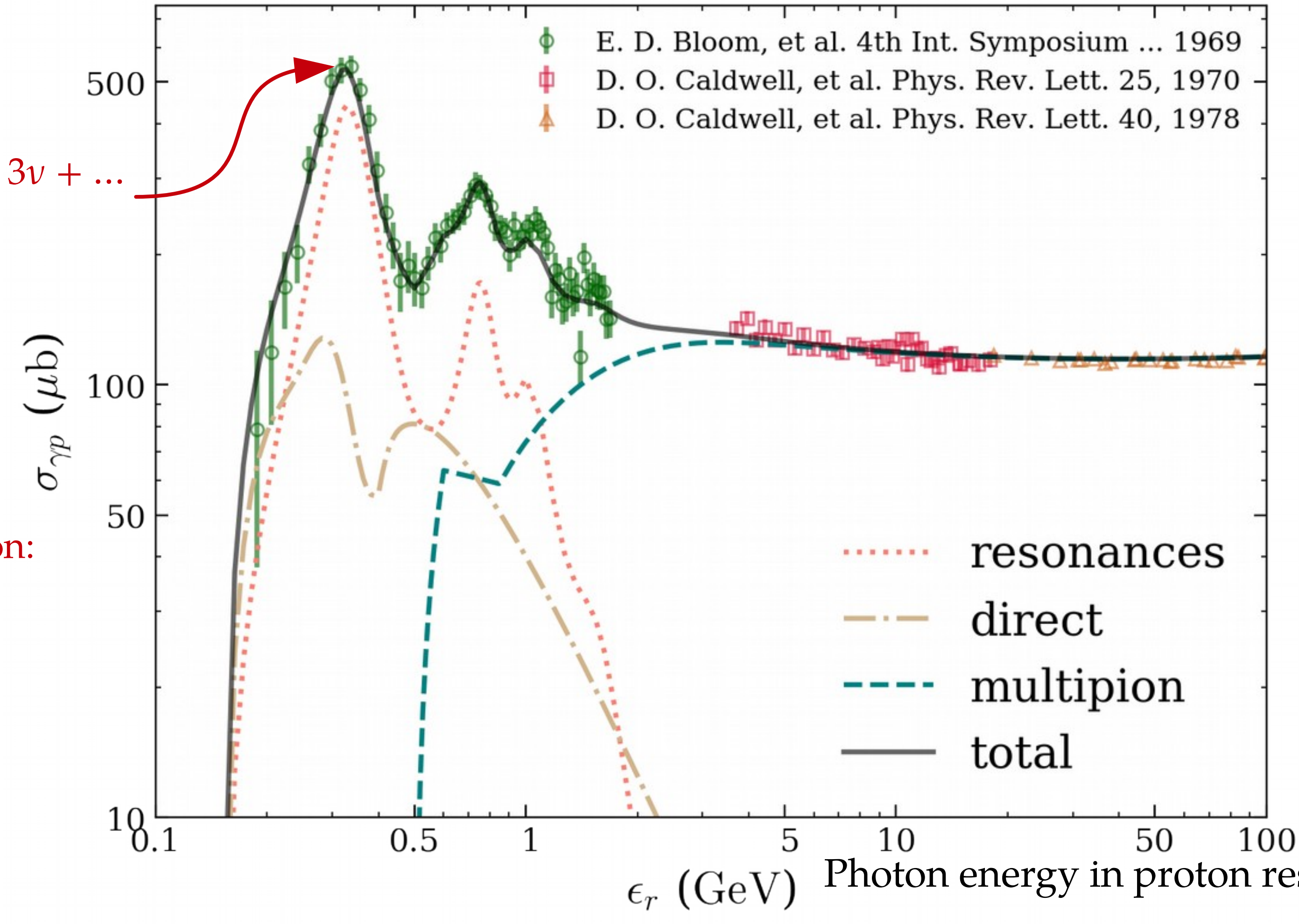
Resonance condition:
$E_p \times E_\nu \sim 0.2\ \mathrm{GeV}^2$



Photon energy in proton rest frame

Morejón *et al.*, 1904.07999

Beyond the Δ resonance (2/2)

(1) Δ-resonance region

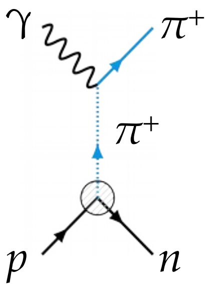
$$p + \gamma \xrightarrow{\Delta(1232)} p' + \pi$$

(2) Higher resonances

$$p + \gamma \xrightarrow{\Delta, N} \Delta' + \pi \ , \quad \Delta' \to p' + \pi$$

(3) Direct production (t channel)

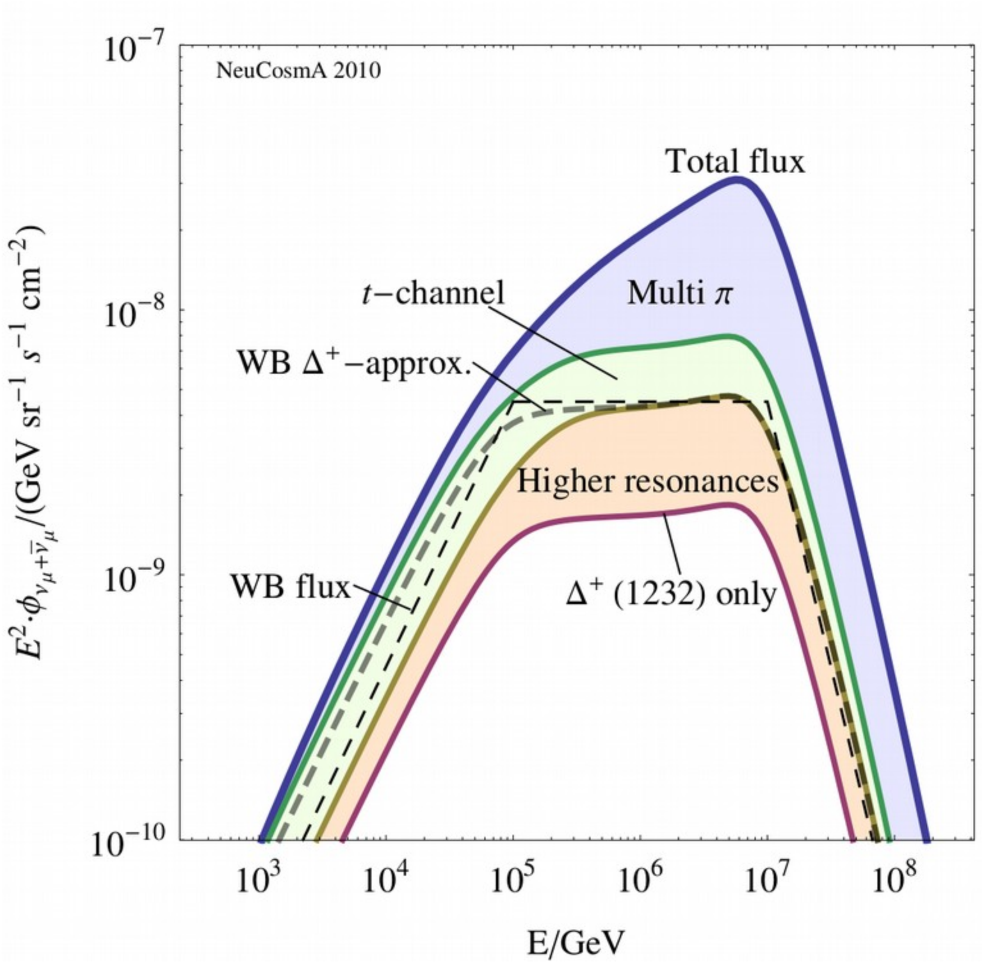
Same as (1) and (2), but in the
t channel, *i.e.*,
with a virtual pion



(4) Multi-pion production

Statistical production of two or more pions

E.g., neutrinos from a gamma-ray burst:



Mücke *et al.*, *Comput. Phys. Comm.* 2000
Hümmer *et al.*, *ApJ* 2010; Baerwald, Hümmer, Winter, *PRD* 2011

The Hillas criterion

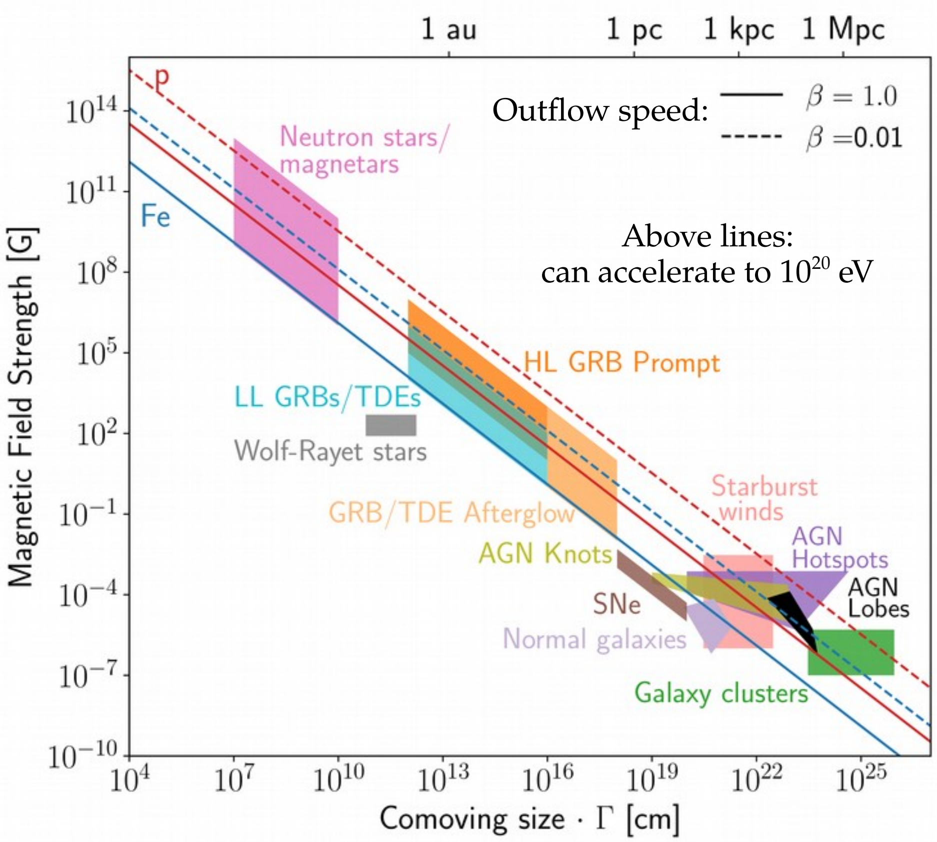
- Necessary condition for a source to accelerate cosmic rays

- Particles must stay confined:

Larmor radius < Size of acceleration region

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

- Maximum energy:



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

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

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

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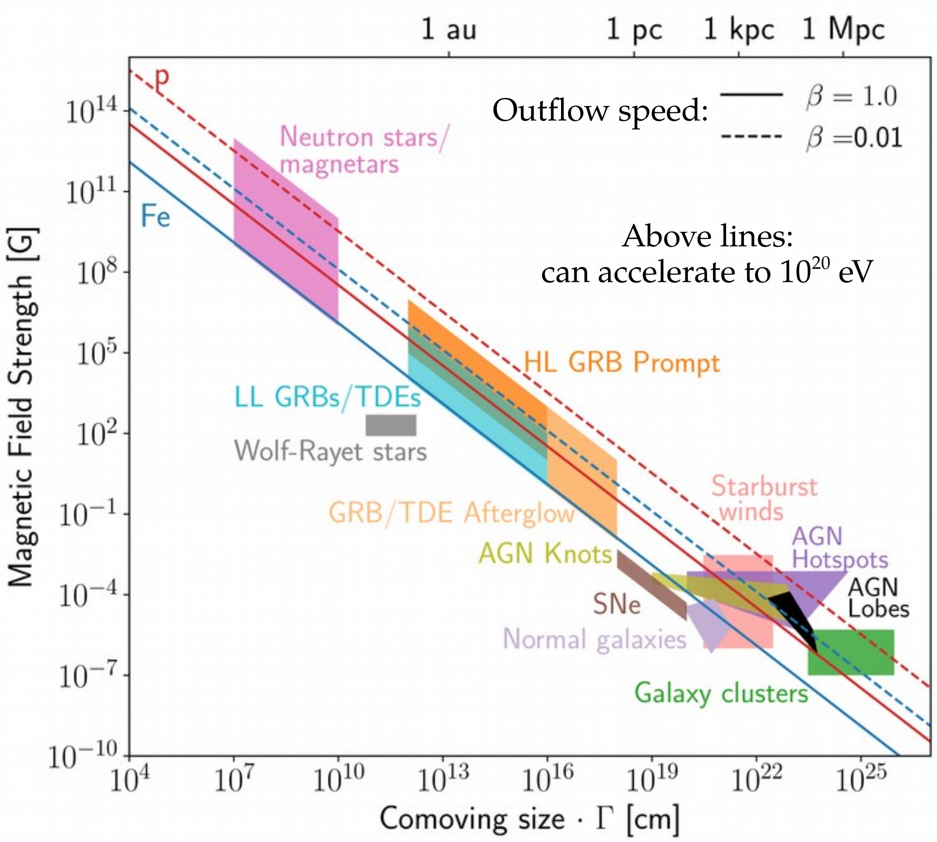

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- Maximum energy:

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

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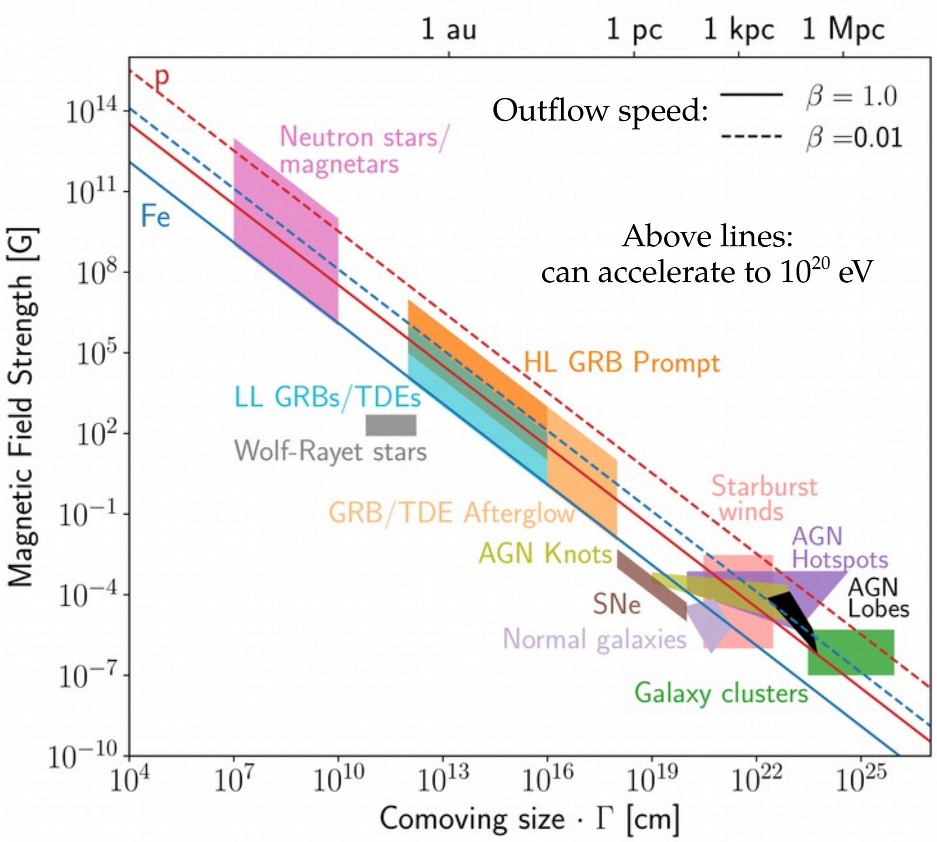
Speed $v_{\rm sh}/c$ of the outflow



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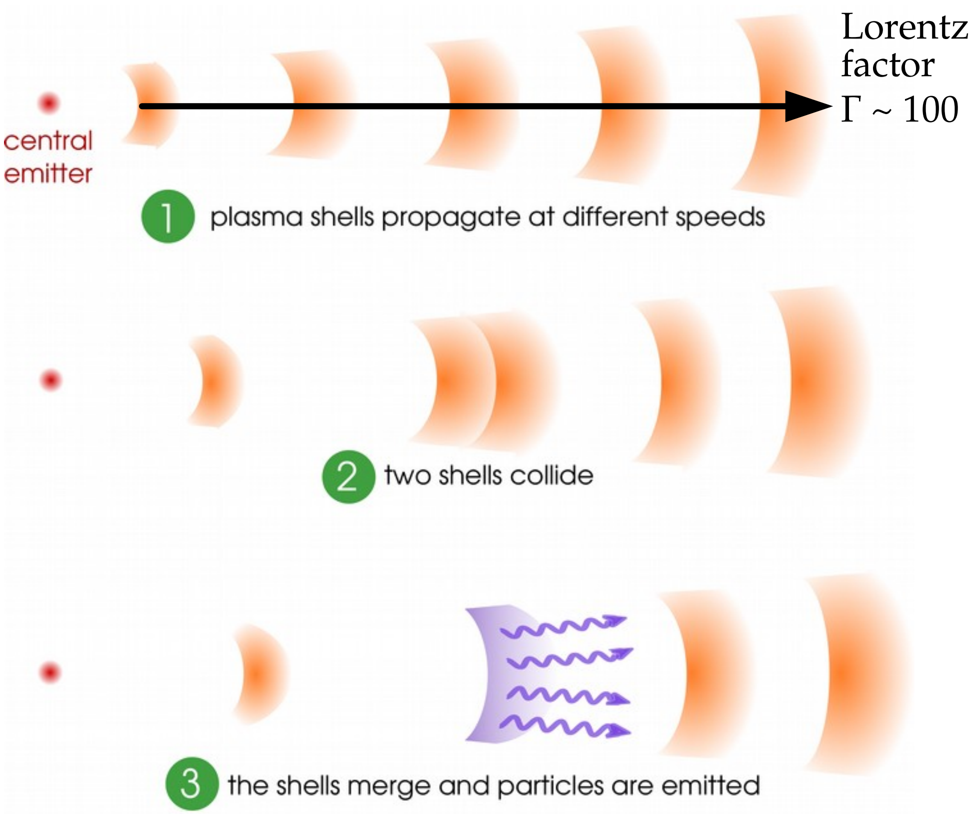
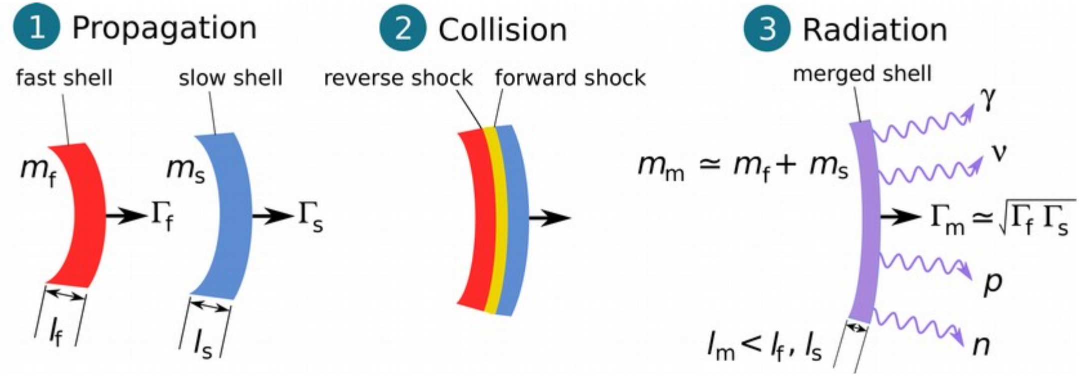
General anatomy of particle emission from a relativistic jet

Fireball model, internal collisions:





Part of the initial kinetic energy is radiated as γ, ν, and cosmic rays:

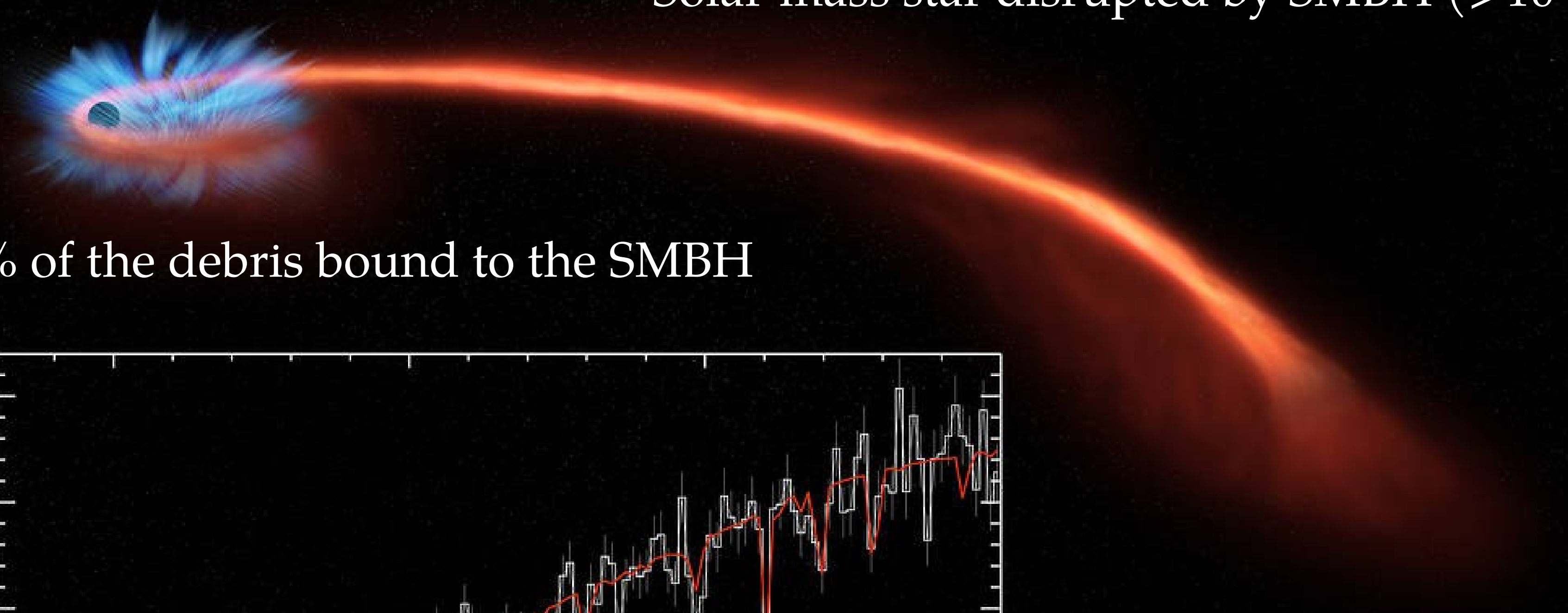
f_e : Fraction of energy in photons
f_p : Fraction of energy in protons
f_B : Fraction of energy in magnetic field

} Uncertainly known

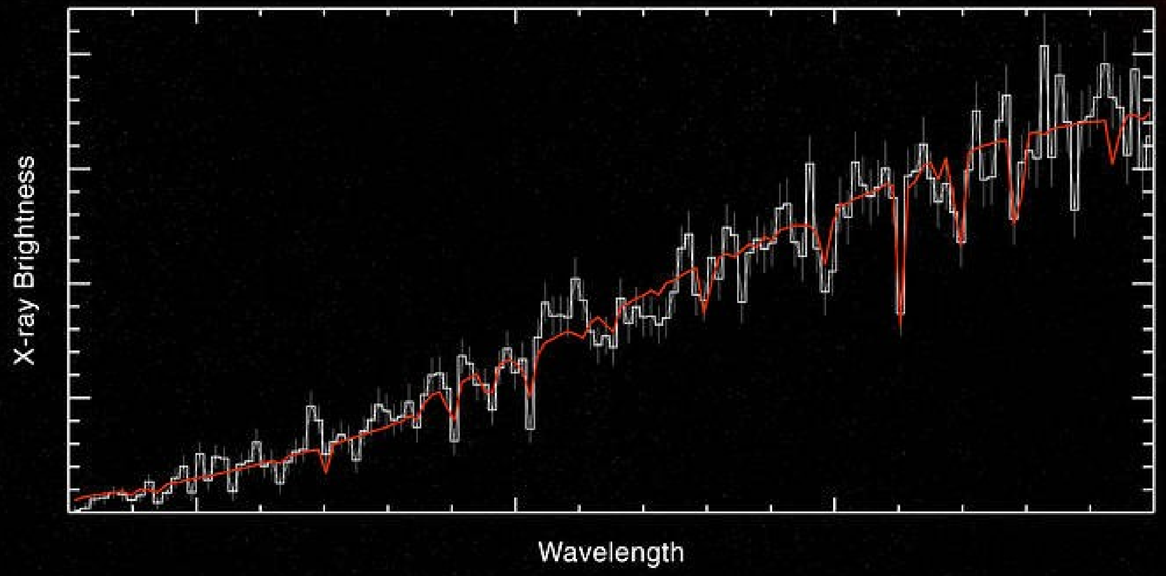
Kobayashi & Piran, *ApJ* 1997; Murase & Nagataki, *PRD* 2006; Guetta *et al.*, *ApJ* 2011
Baerwald, Hümmer, Winter, *PRD* 2011; **MB** *et al.*, *Nature Commun.* 2015

Tidal disruption events

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



~50% of the debris bound to the SMBH



NASA
ILLUSTRATION

Tidal disruption events

- Mid-to-heavy star chemical composition might explain Auger composition
- Particles produced in internal collisions in jet (only 2 jetted TDEs seen so far)
- Inject ^{14}N and model nuclear cascades in jet
- TDEs follow the redshift evolution of SMBHs
- Fit to Auger UHECR spectrum + composition

$\sim(1+z)^{-3}$

Biehl, Boncioli, Lunardini, Winter, 1711.03555

See also: Lunardini & Winter, *PRD* 2017; Dai & Fang, *MNRAS* 2017; Guépin *et al.*, 1711.11274; Zhang, Murase, Oikonomou, Li, *PRD* 2017; Senno, Murase, Meszaros, *ApJ* 2017

Tidal disruption events

Baryonic loading

Local rate of jetted TDEs

$$G \equiv \xi_A \cdot \frac{\tilde{R}(0)}{0.1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}}$$

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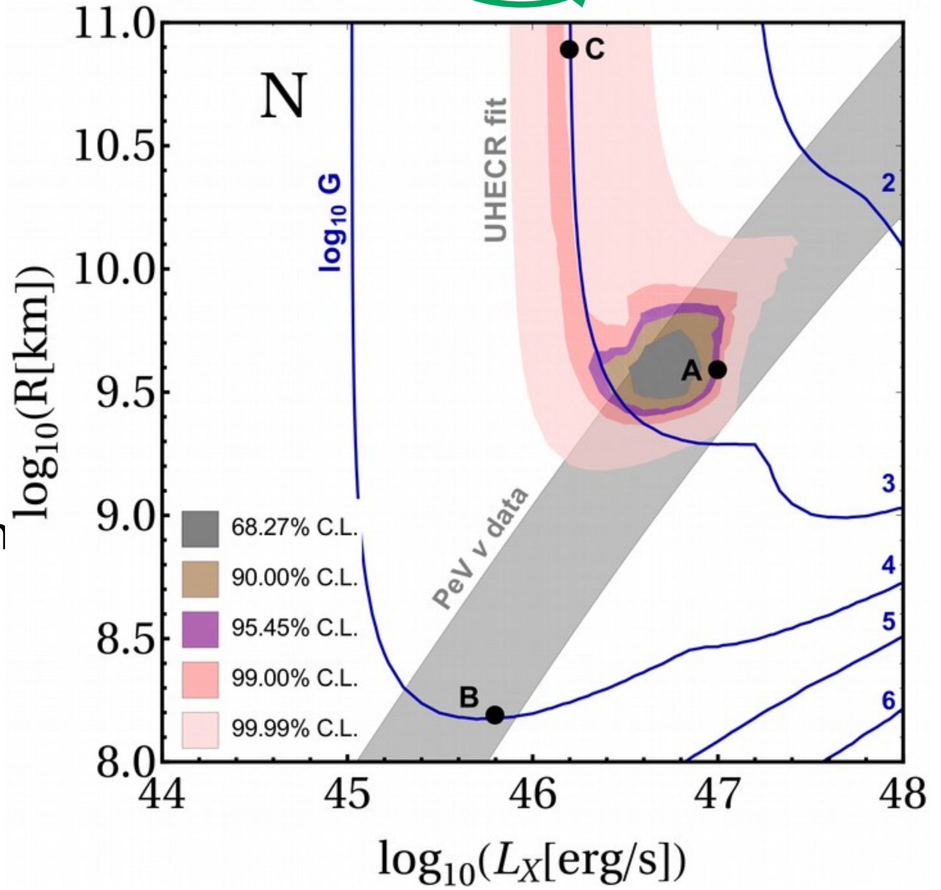

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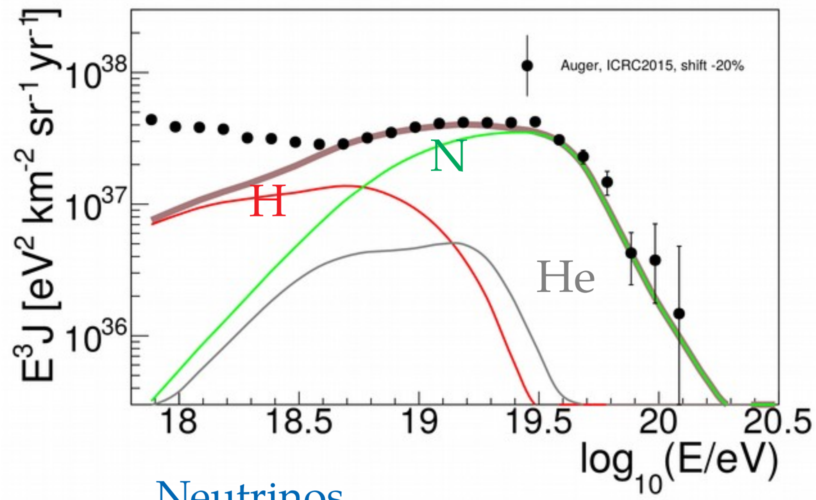
Tidal disruption events

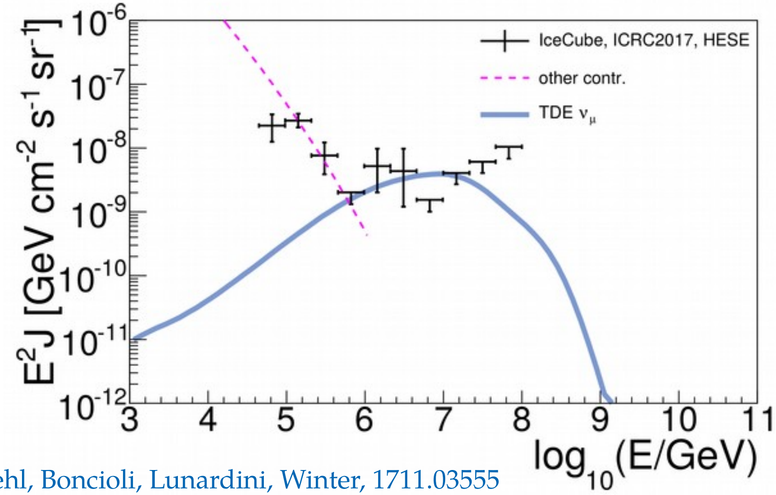
- Mid-to-heavy star chemical composition might explain Auger composition
- Particles produced in internal collisions in jet (only 2 jetted TDEs seen so far)
- Inject ^{14}N and model nuclear cascades in jet
- TDEs follow the redshift evolution of SMBHs
- Fit to Auger UHECR spectrum + composition

$\sim(1+z)^{-3}$

Cosmic rays



Neutrinos

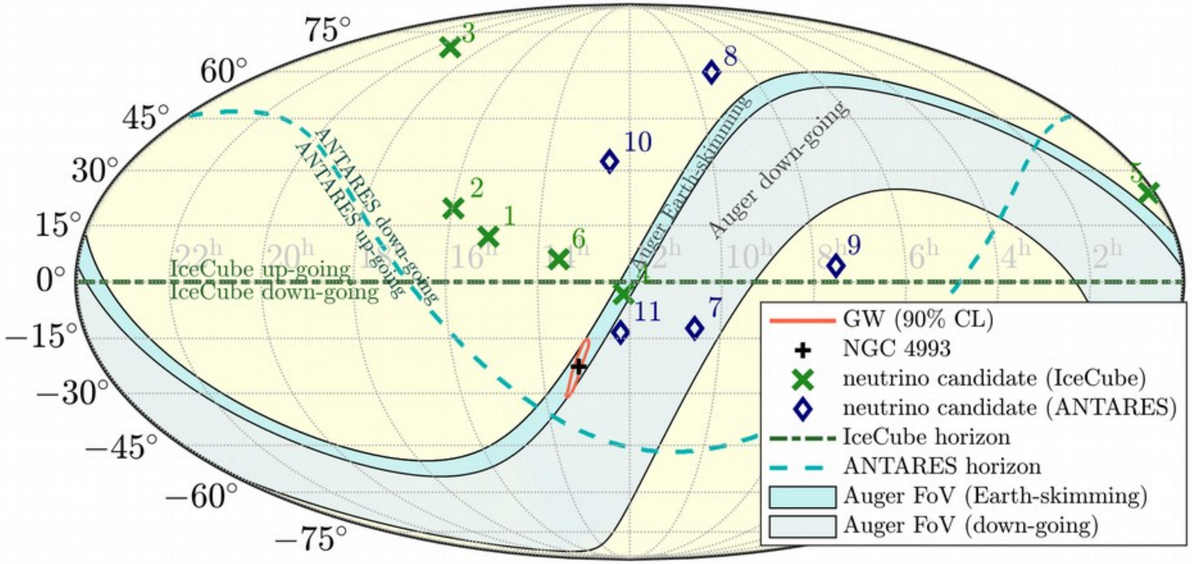


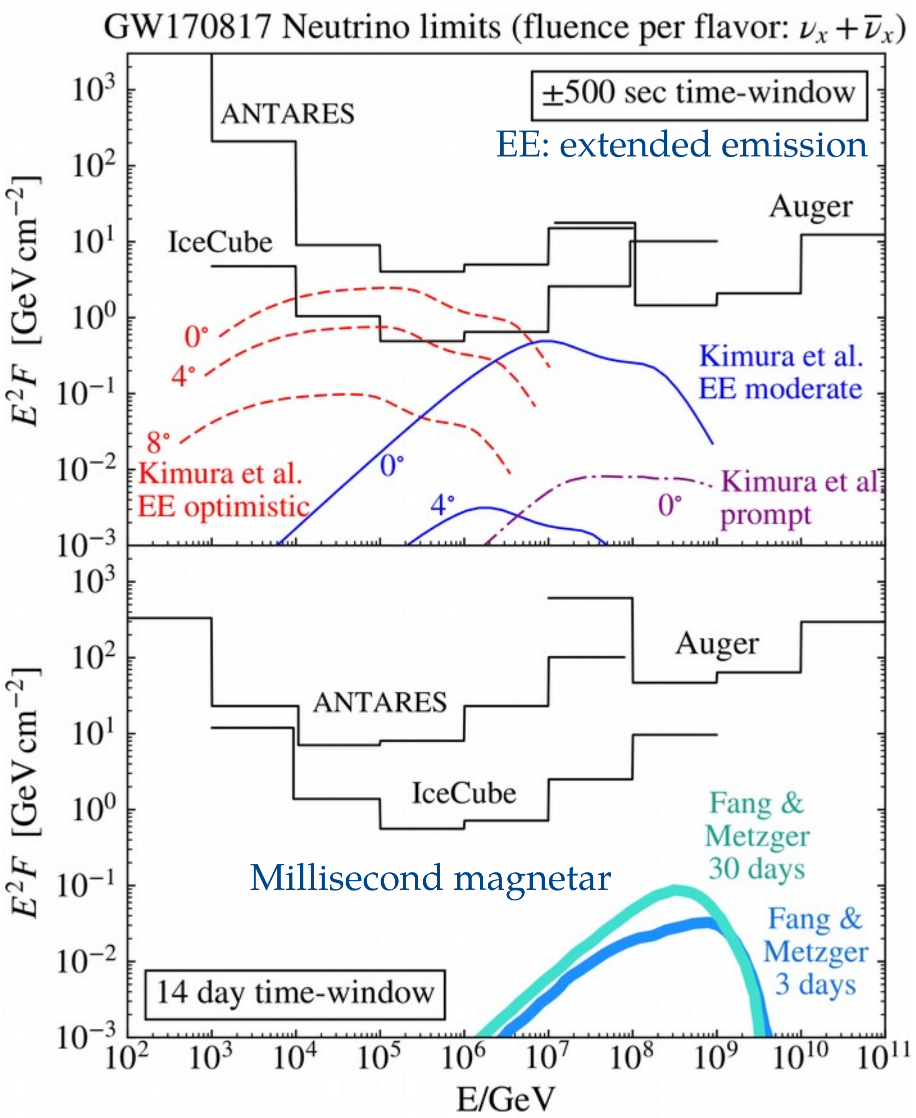
Biehl, Boncioli, Lunardini, Winter, 1711.03555

See also: Lunardini & Winter, *PRD* 2017; Dai & Fang, *MNRAS* 2017; Guépin *et al.*, 1711.11274; Zhang, Murase, Oikonomou, Li, *PRD* 2017; Senno, Murase, Meszaros, *ApJ* 2017

GW170817 (NS-NS merger)

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



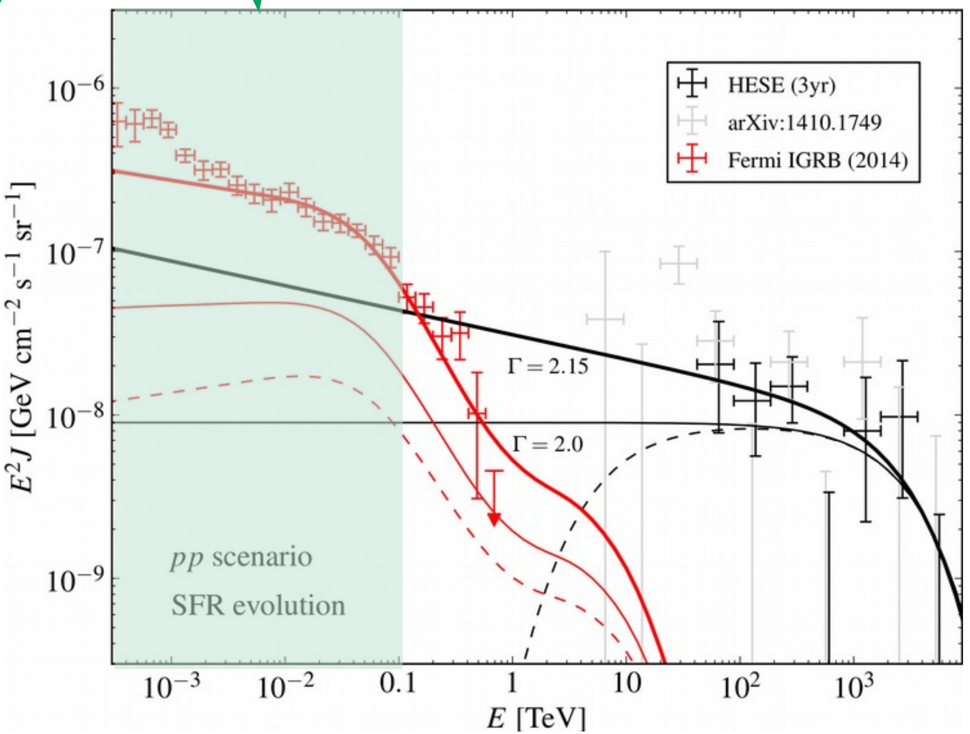


ANTARES, IceCube, Pierre Auger Collab., *ApJL* 2017

Constraints from the gamma-ray background

- Production via *pp*: ν and gamma-ray spectra follow the CR spectrum $E^{-\Gamma}$
- Gamma-ray interactions on the CMB make them pile up at GeV
- *Fermi* gamma-ray background is not exceeded only if $\Gamma < 2.2$
- But IceCube found $\Gamma = 2.5$–2.7
- Therefore, production via *pp* is disfavored between 10–100 TeV

Murase, Ahlers, Lacki, *PRD* 2013



The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} p + \pi^0 \; (\pi^0 \rightarrow \gamma + \gamma) \\ n + \pi^+ \; (\pi^+ \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+) \end{cases}$$

Pair production:

$$p + \gamma \rightarrow p + e^- + e^+$$

Greisen-Zatsepin-Kuzmin (GZK) cut-off:

$$E_p \approx \frac{0.16\ \text{GeV}}{0.66\ \text{meV}} \approx 2 \cdot 10^{11}\ \text{GeV}$$

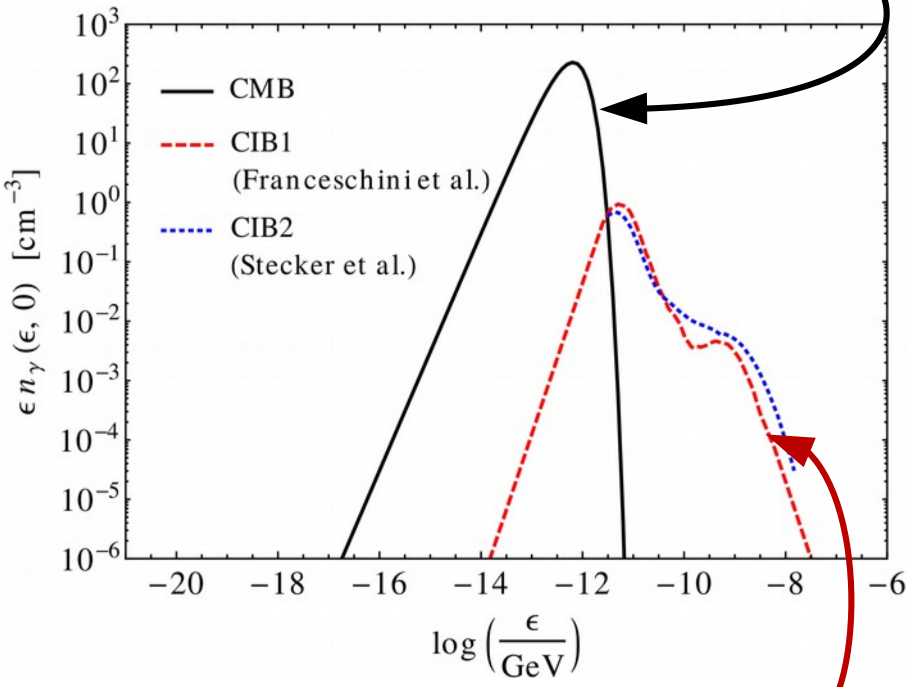
(Assuming only photohadronic interaction)

Accounting also for pair production and CMB width:

$$E_p \approx 5 \cdot 10^{10}\ \text{GeV}$$

Target photon spectra (at $z = 0$):

CMB: Microwave (black body, <ϵ> ~ 0.66 meV)



CIB: optical (stars) + infrared (dust remission)

$n_\gamma(z) = (1+z)^3\, n_\gamma(z=0)$ (exact only for CMB)

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} p + \pi^0 \quad \Rsh \gamma + \gamma \\ n + \pi^+ \quad \Lsh \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{cases}$$

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Mean free path:

$$(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} = (413\ \mathrm{cm}^{-3} \times 200\ \mu\mathrm{barn})^{-1} \approx 10^{25}\ \mathrm{cm} \approx 4\ \mathrm{Mpc}$$

Energy-loss scale:

$$L = (E/\Delta E)(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} \approx (1/0.2) \times 4\ \mathrm{Mpc} \approx 20\ \mathrm{Mpc}$$

A more detailed calculation yields

$$L_{\mathrm{GZK}} = 50\ \mathrm{Mpc}$$

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

Photohadronic processes:

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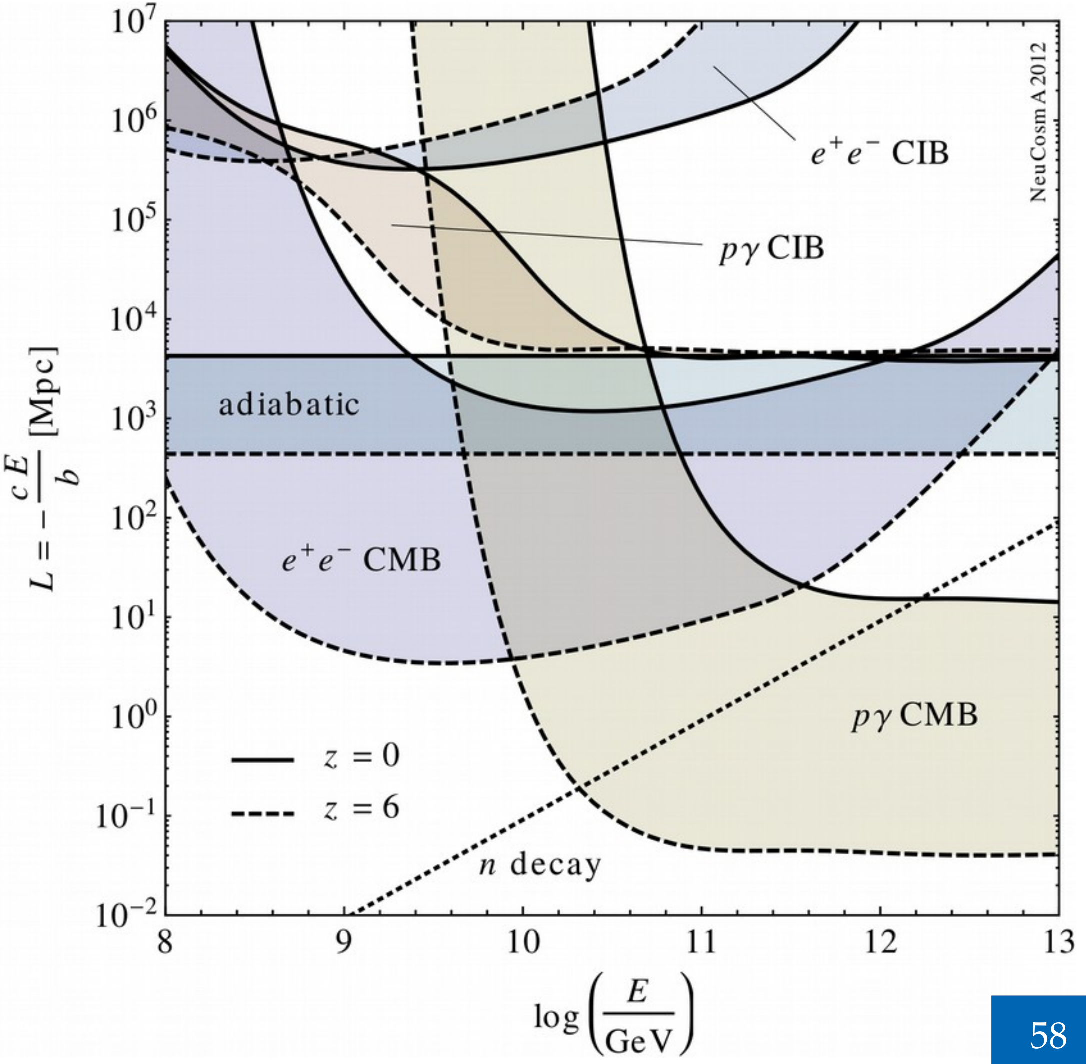


Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is *also* opaque to PeV gamma rays

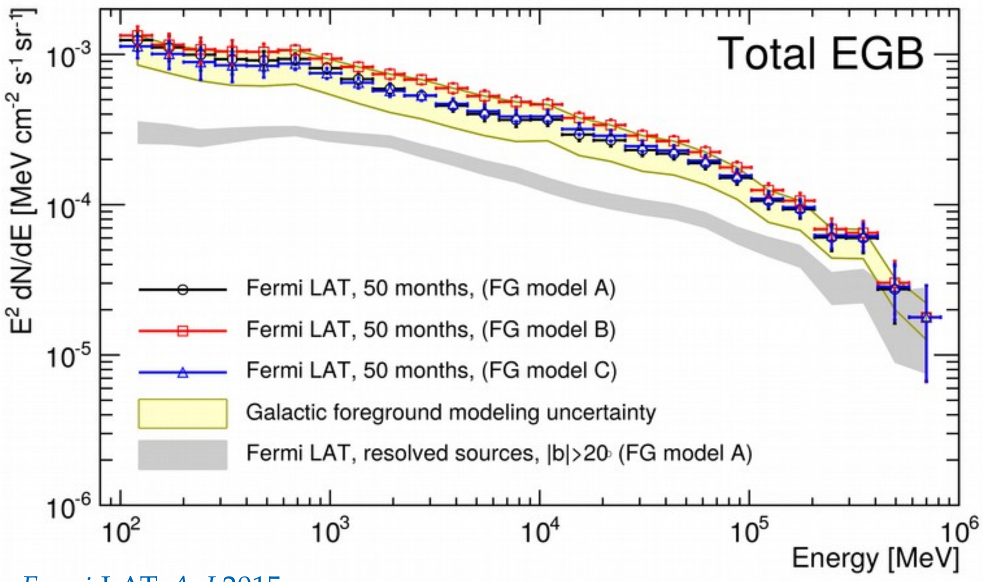
Pair production:

$$\gamma_{\text{astro}} + \gamma_{\text{cosmo}} \rightarrow e^- + e^+$$

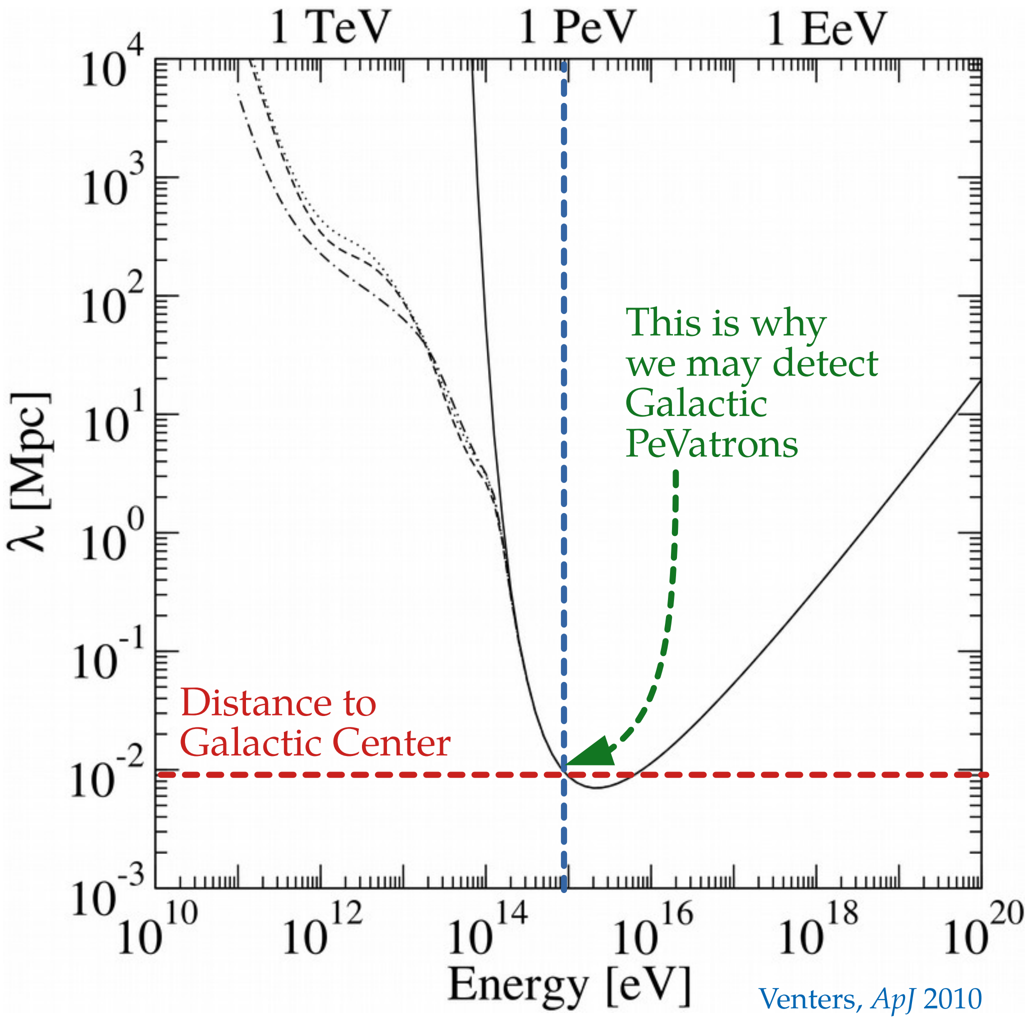
Inverse Compton scattering:

$$e^{\pm} + \gamma_{\text{cosmo}} \rightarrow e^{\pm} + \gamma$$

PeV gamma rays cascade down to MeV–GeV:



Fermi-LAT, *ApJ* 2015



Venters, *ApJ* 2010

Neutrinos from gamma-ray observations

Energy in neutrinos $\propto$ energy in gamma rays

$$\int_0^\infty \mathrm{d}E_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8}\left[1 - \left(1 - \langle x_{p\to\pi}\rangle\right)^{\tau_{p\gamma}}\right] \frac{f_p}{f_e} \int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} \mathrm{d}E_\gamma E_\gamma F_\gamma(E_\gamma)$$

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

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Fraction of total p energy
given to pions

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Fraction of p energy given to π in one interaction (~20%)

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Fraction of total p energy given to pions

Baryonic loading

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

Neutrinos from gamma-ray observations

Energy in neutrinos ∝ energy in gamma rays

Fraction of p energy given to π in one interaction (~20%)

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Fraction of total p energy given to pions

Baryonic loading

Optical depth to $p\gamma$:

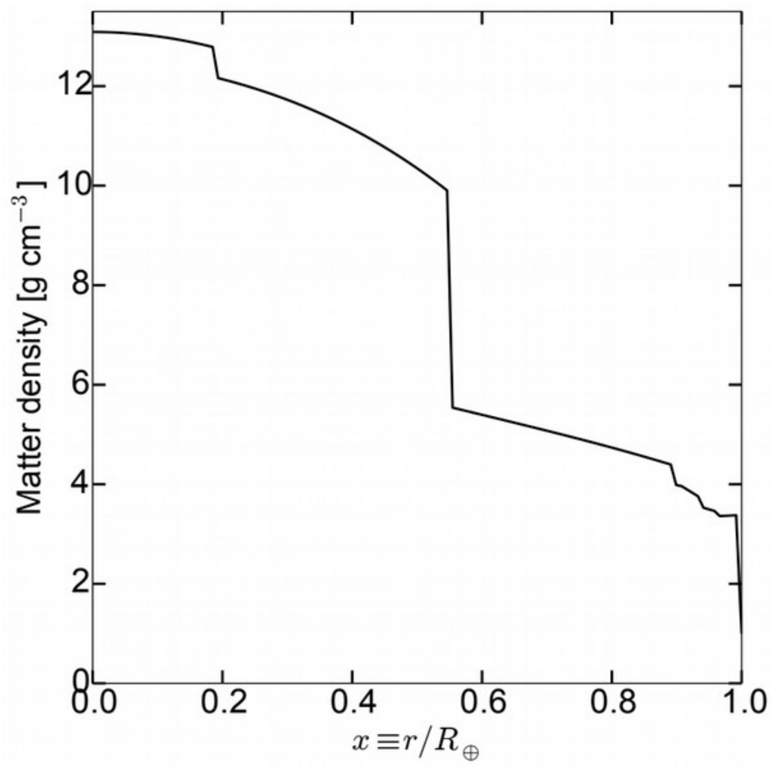
$$\tau_{p\gamma} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\mathrm{erg\,s}^{-1}}\right)\left(\frac{0.01}{t_\mathrm{v}}\right)\left(\frac{300}{\Gamma}\right)^4\left(\frac{\mathrm{MeV}}{\epsilon_{\gamma,\mathrm{break}}}\right)$$

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

A feel for the in-Earth attenuation

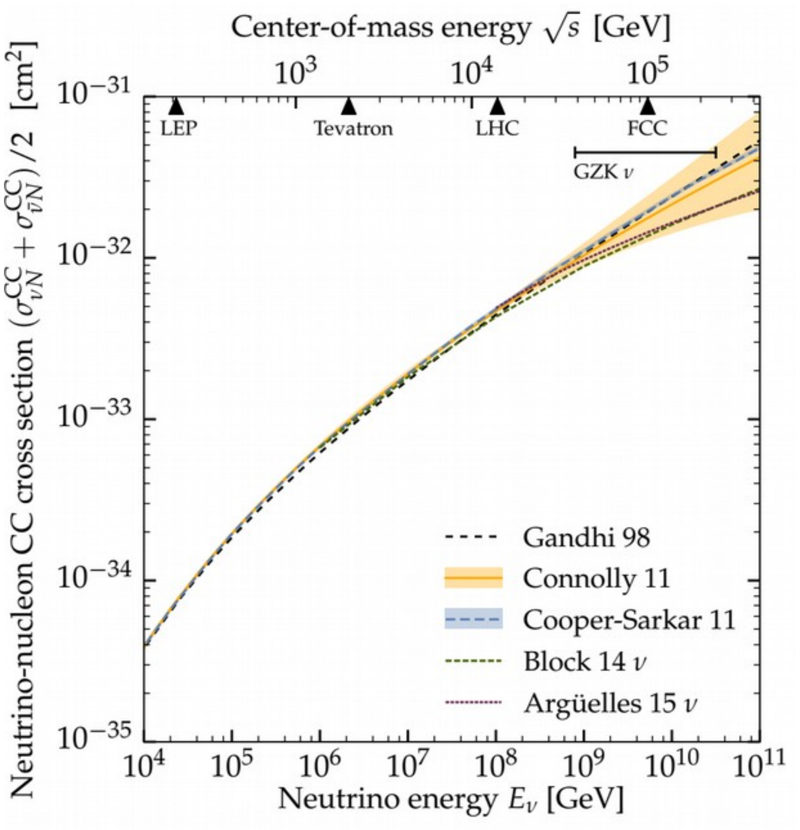
Earth matter density

(Preliminary Reference Earth Model)



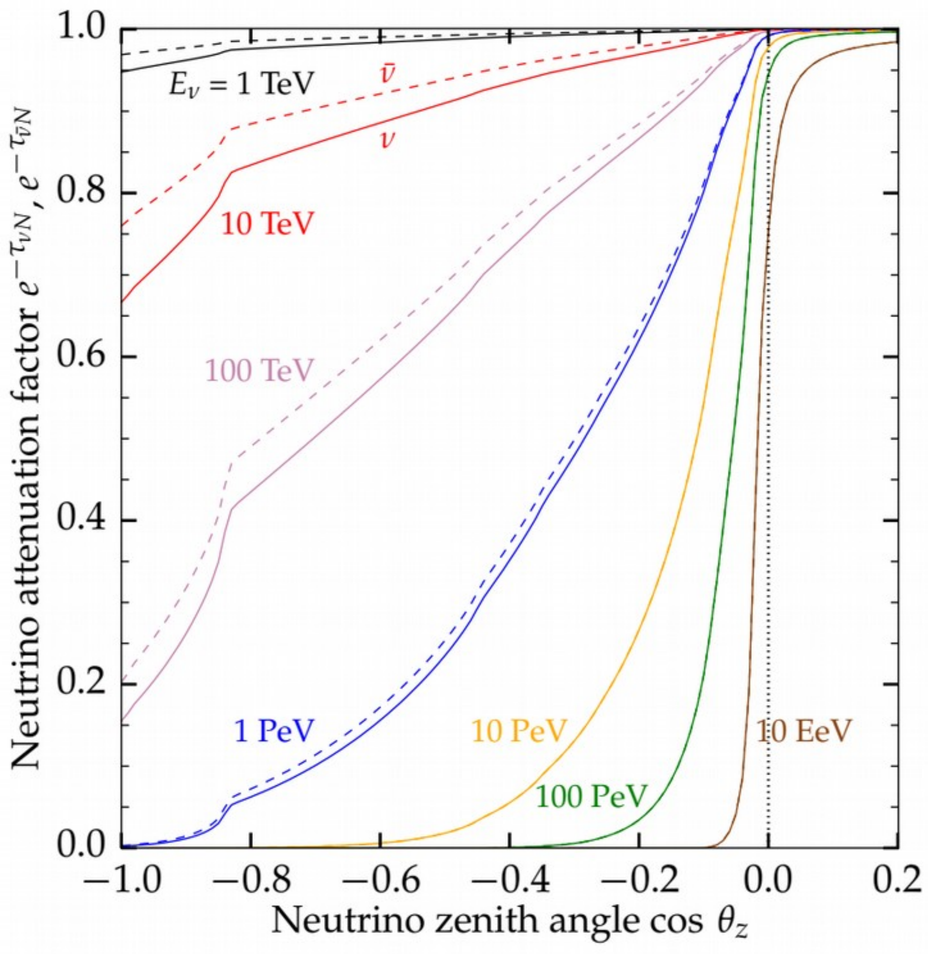
+

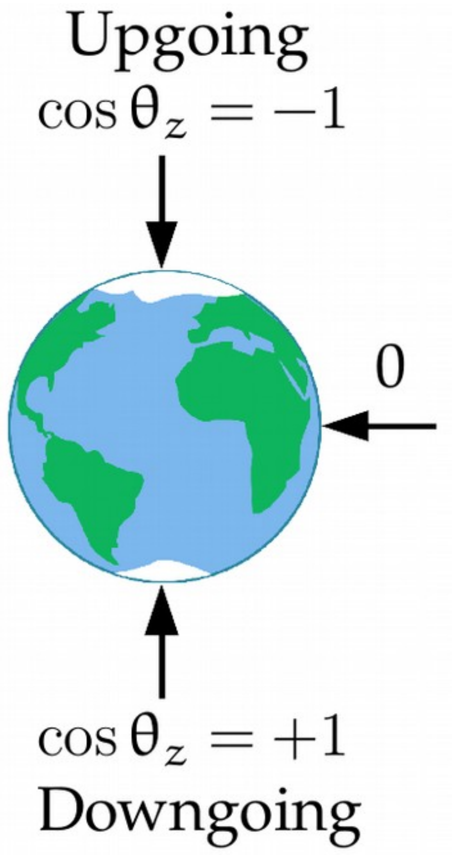
Neutrino-nucleon cross section

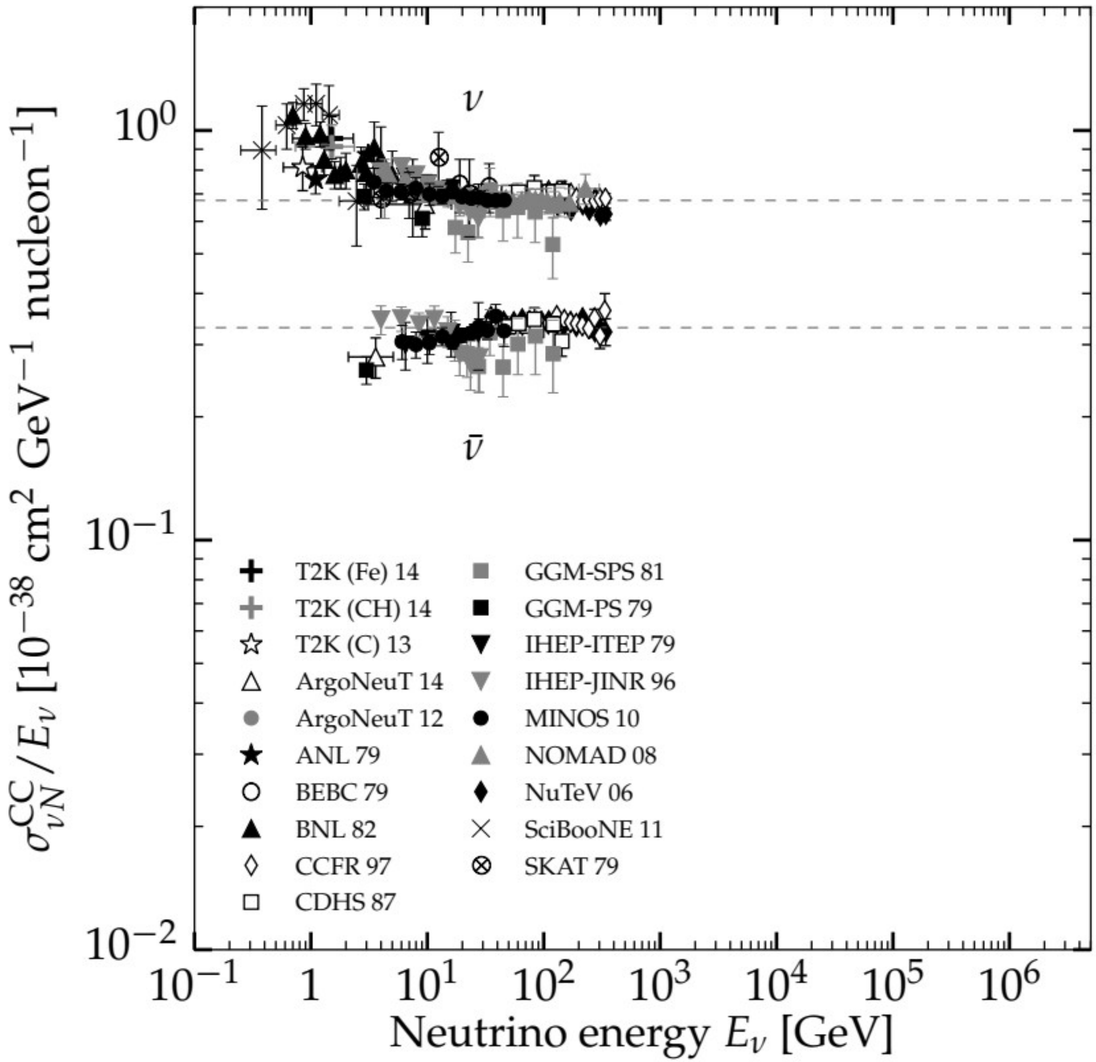


A feel for the in-Earth attenuation

=







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

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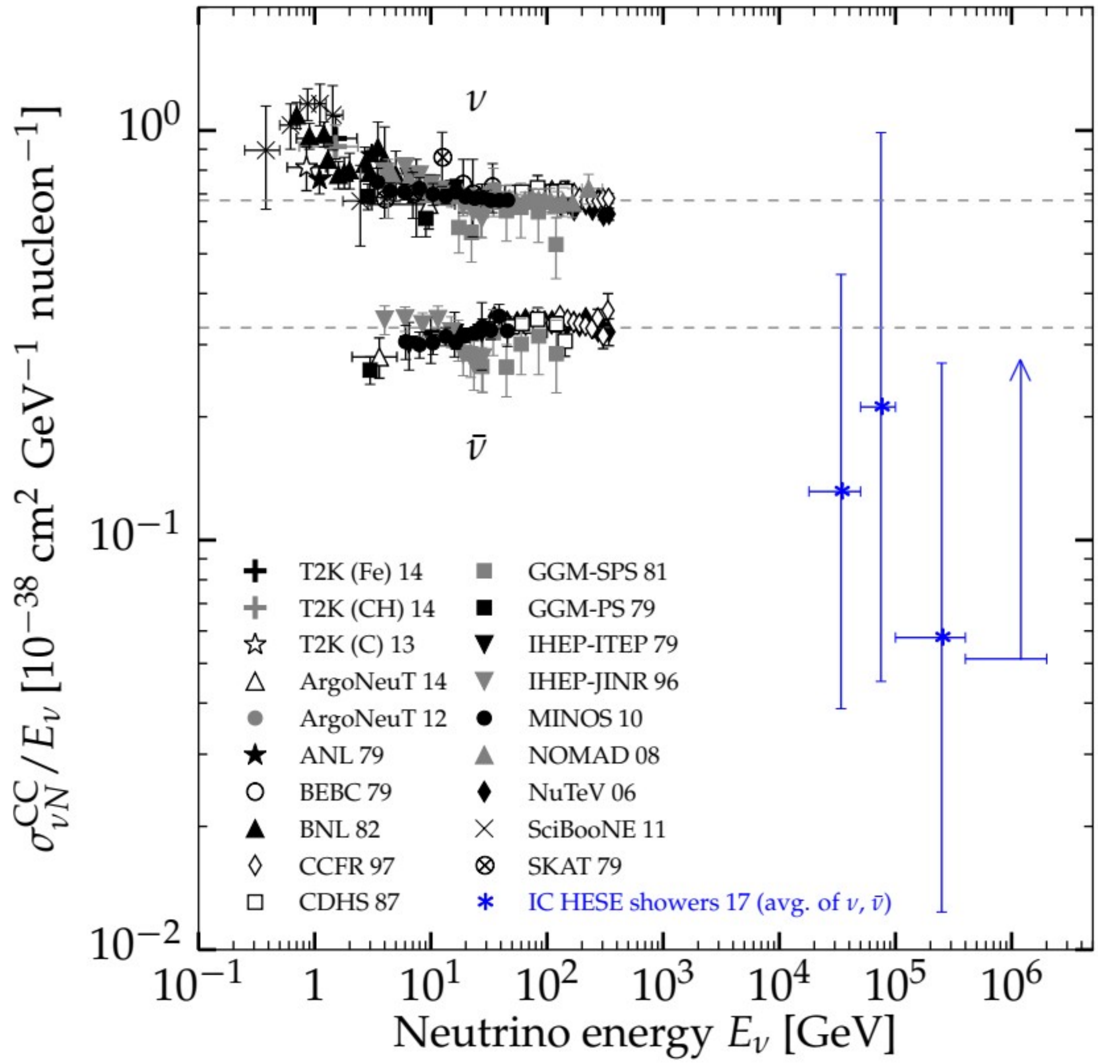

MB & A. Connolly *PRL* 2019
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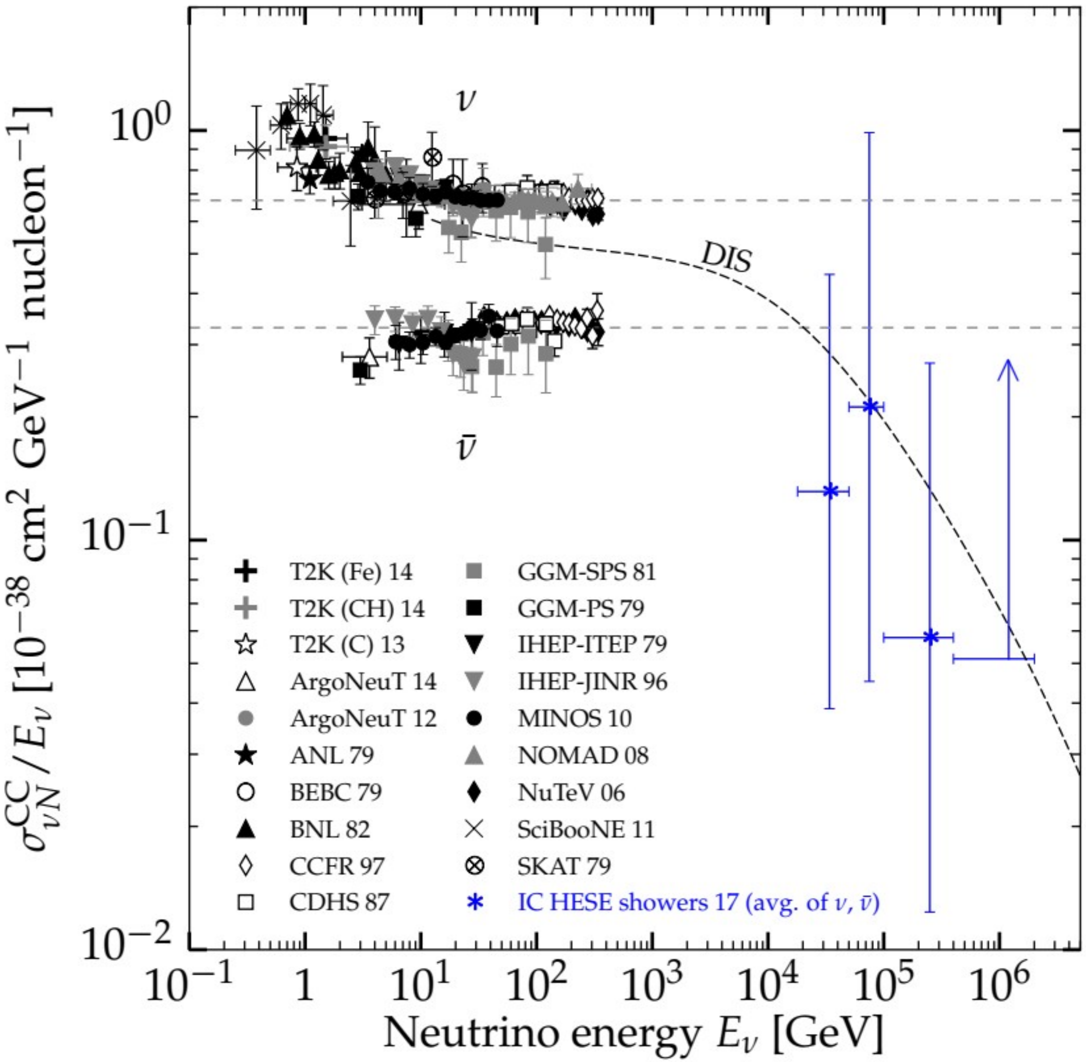
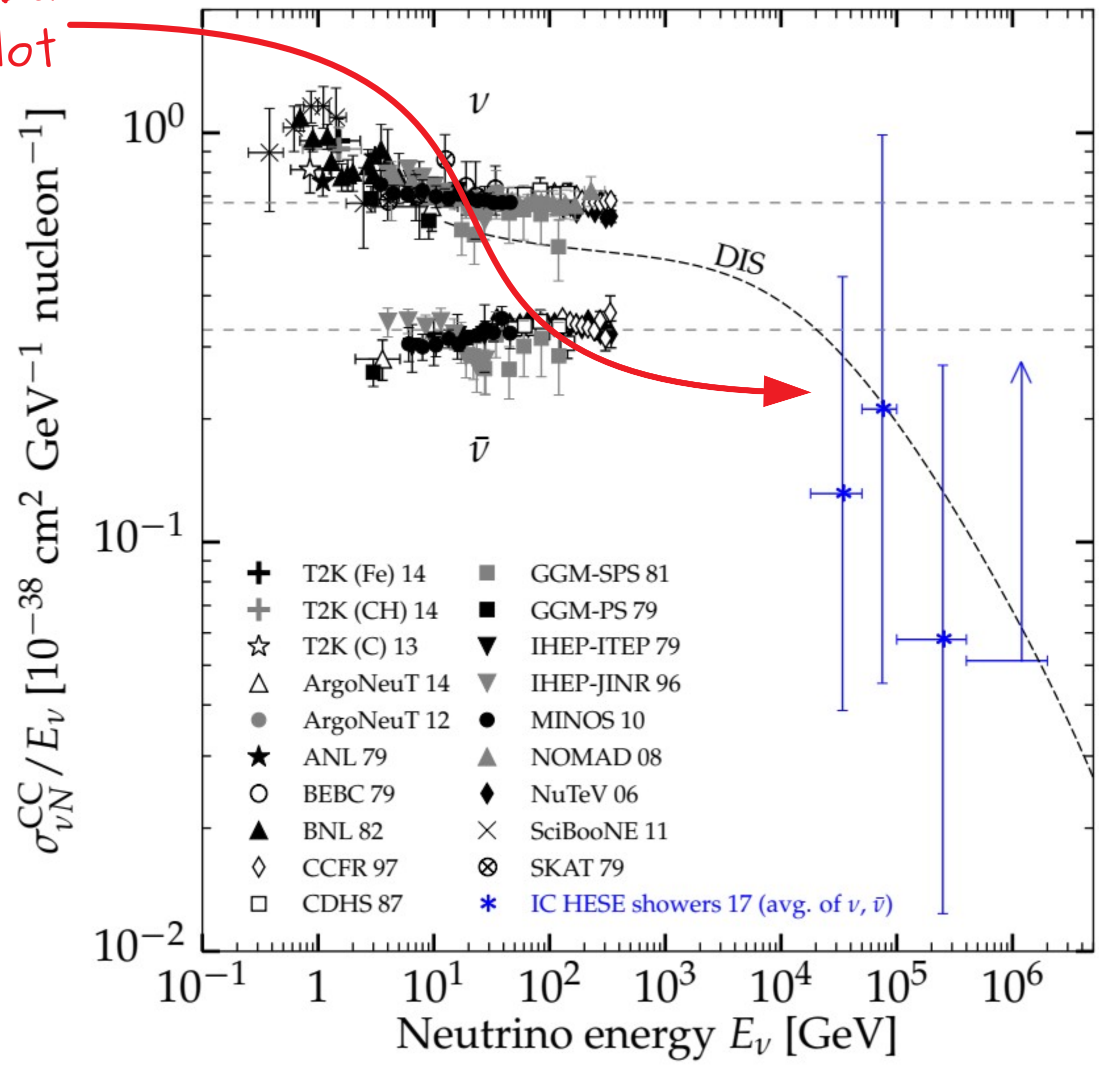


Extending the PDG cross-section plot

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

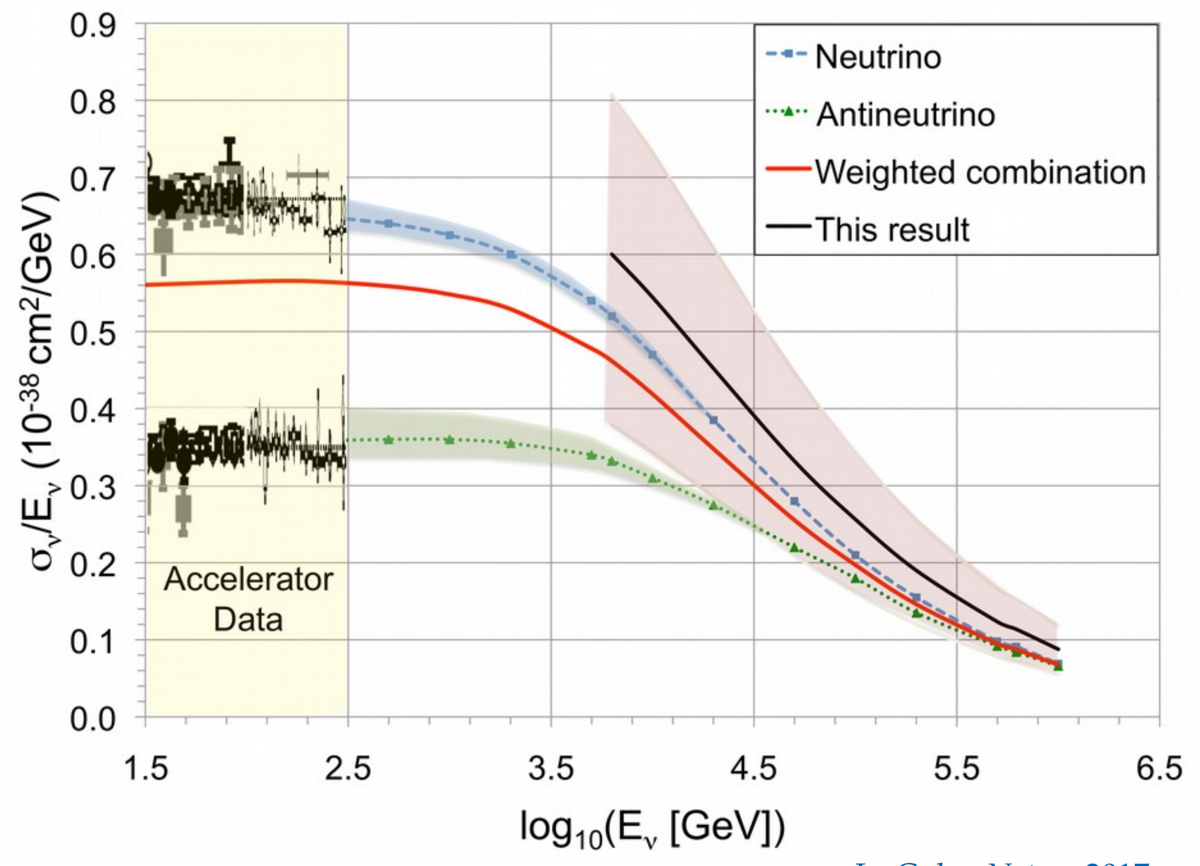


The fine print

- 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 $<\sigma_{\nu N}/\bar{\sigma}_{\nu N}>$ 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

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}
  $1.30\,^{+0.21}_{-0.19}(\text{stat.})\,^{+0.39}_{-0.43}(\text{syst.})$
- All events grouped in a single energy bin 6–980 TeV



IceCube, *Nature* 2017

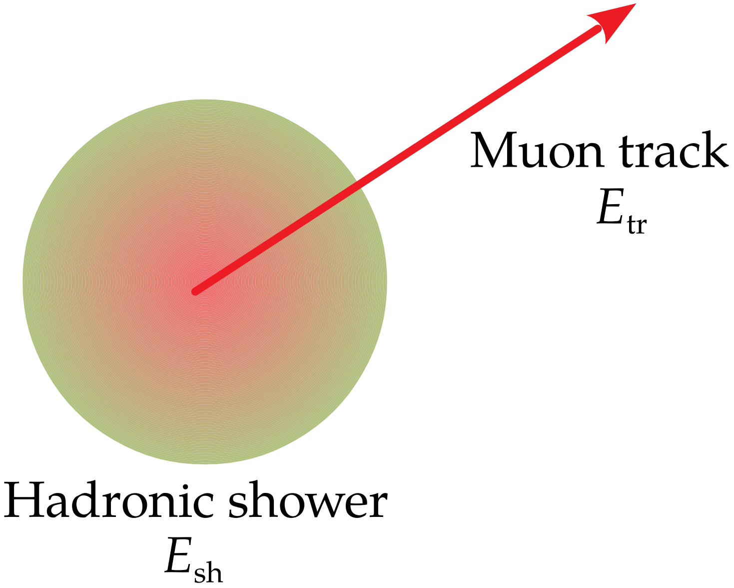
Bonus: Measuring the inelasticity $\langle y \rangle$

- Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:
  $E_X = y\, E_\nu$ and $E_\mu = (1\text{-}y)\, E_\nu \;\Rightarrow\; y = (1 + E_\mu/E_X)^{-1}$

- The value of y follows a distribution $\mathrm{d}\sigma/\mathrm{d}y$

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

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



IceCube, *PRD* 2019

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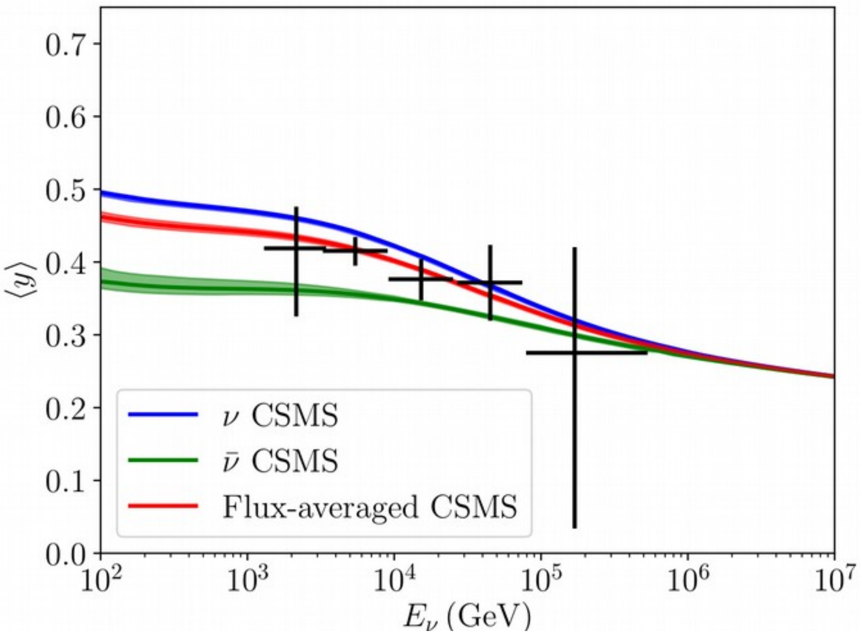


IceCube, *PRD* 2019

Neutrino zenith angle distribution

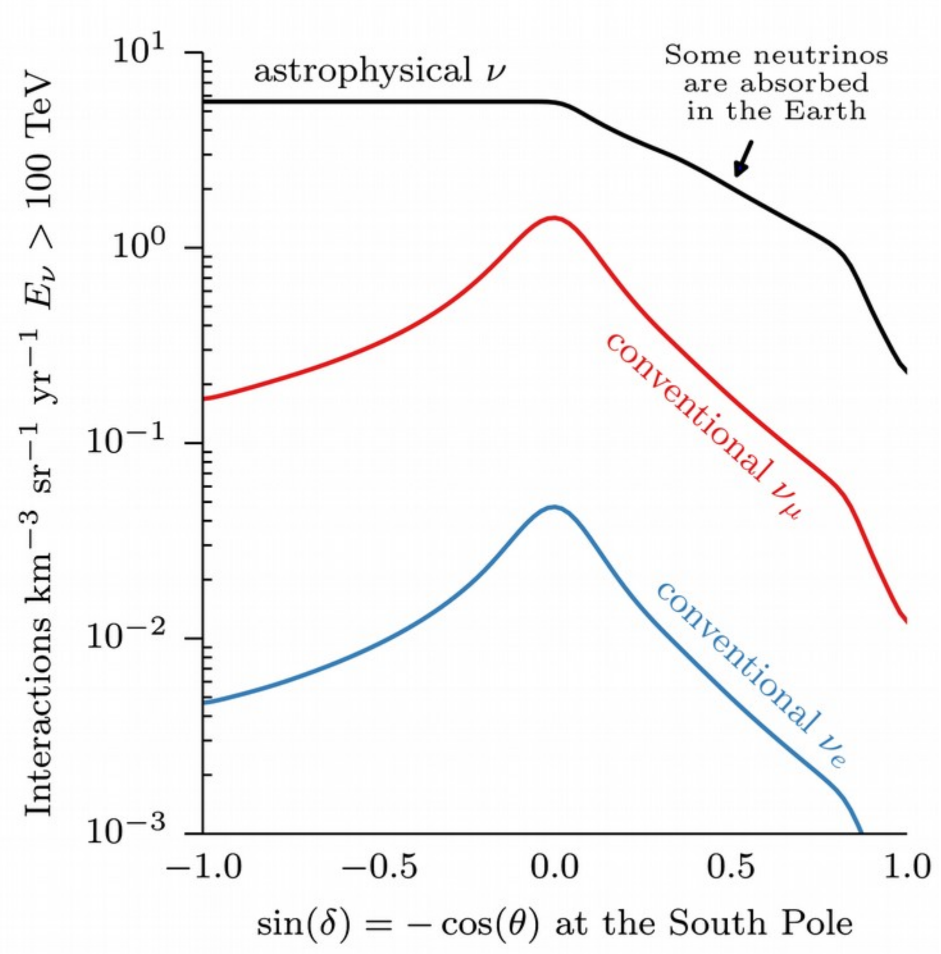
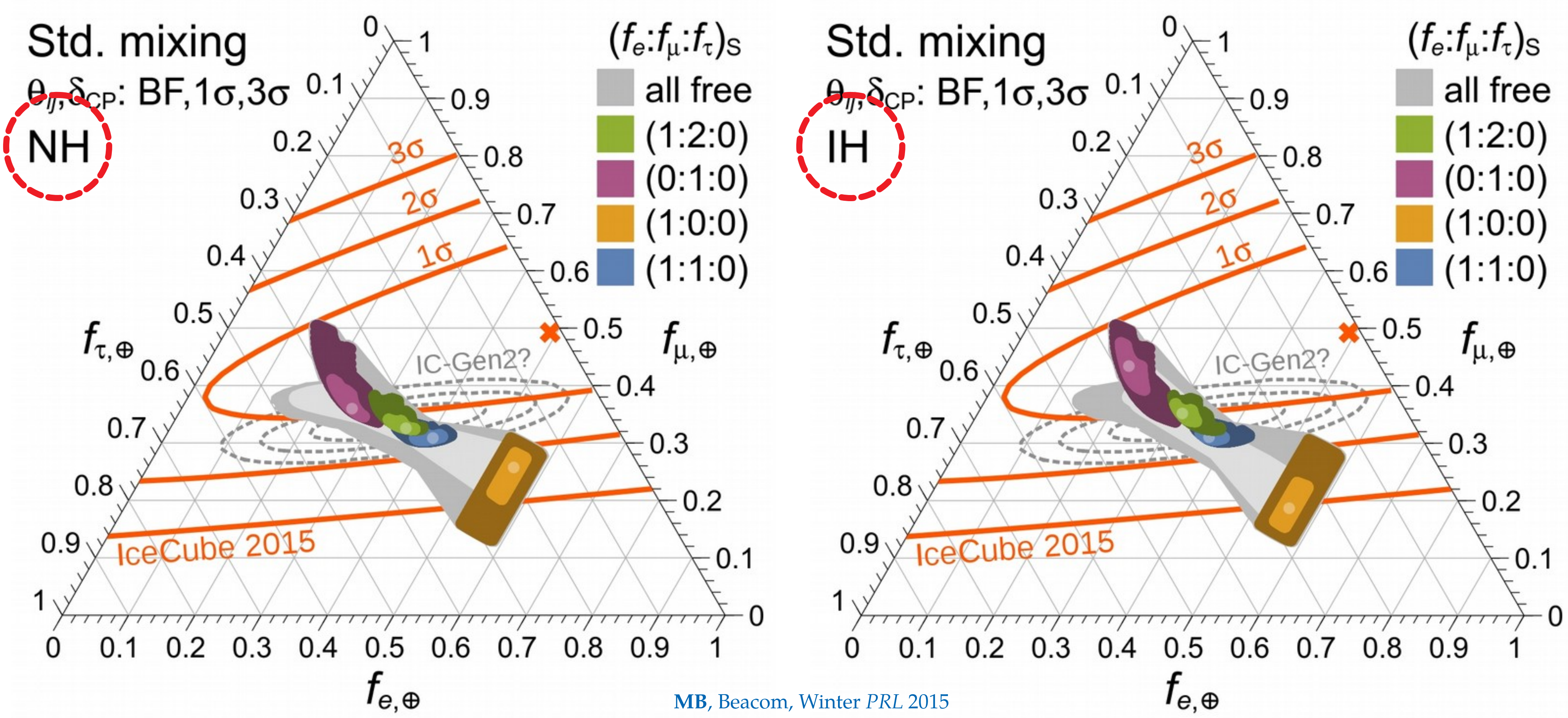


Figure by
Jakob Van Santen
ICRC 2017

Flavor composition – a few source choices

Flavor composition – a few source choices

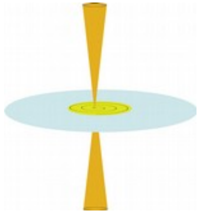


MB, Beacom, Winter *PRL* 2015

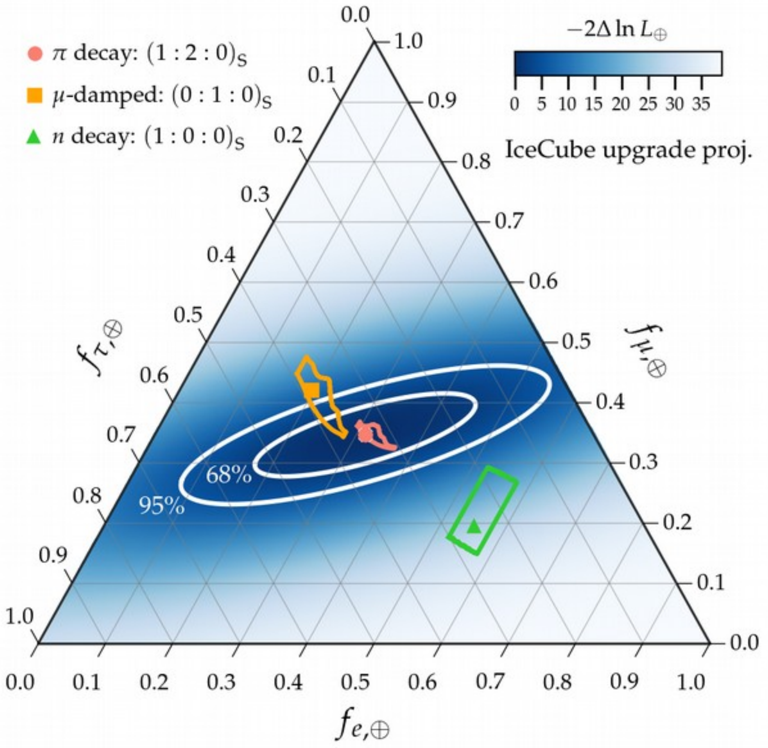
Inferring the flavor composition at the sources

Measured:
Flavor ratios at Earth

Invert flavor oscillations



Inferred:
Flavor ratios at astrophysical sources



MB & Ahlers, *PRL* 2019

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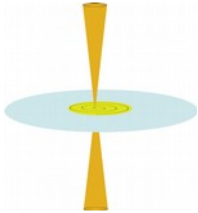

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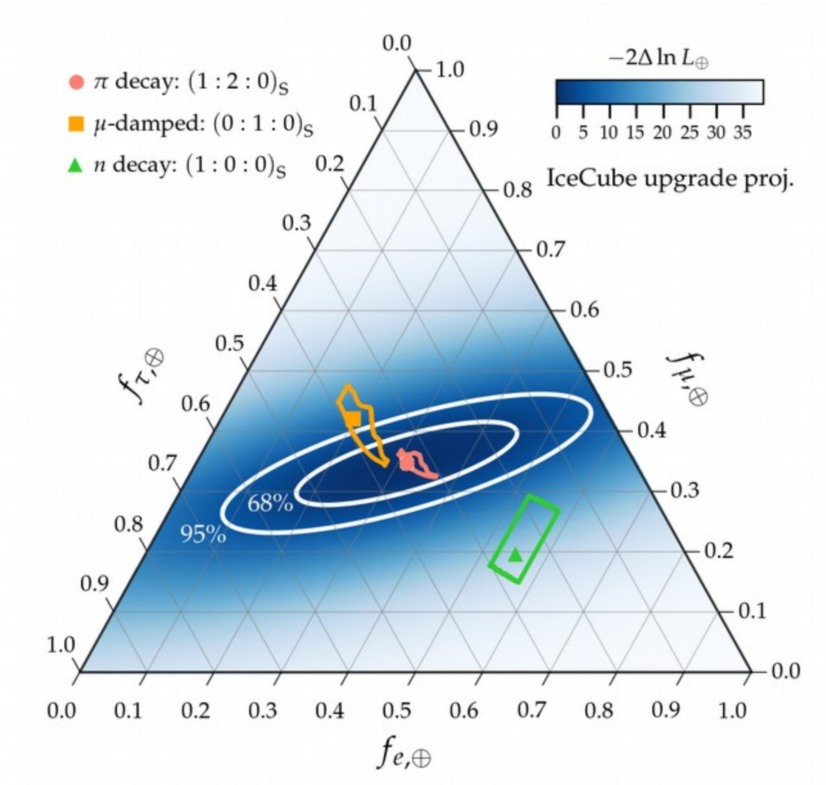

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MB & Ahlers, *PRL* 2019

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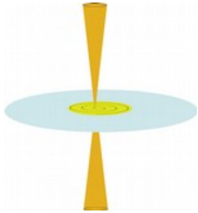
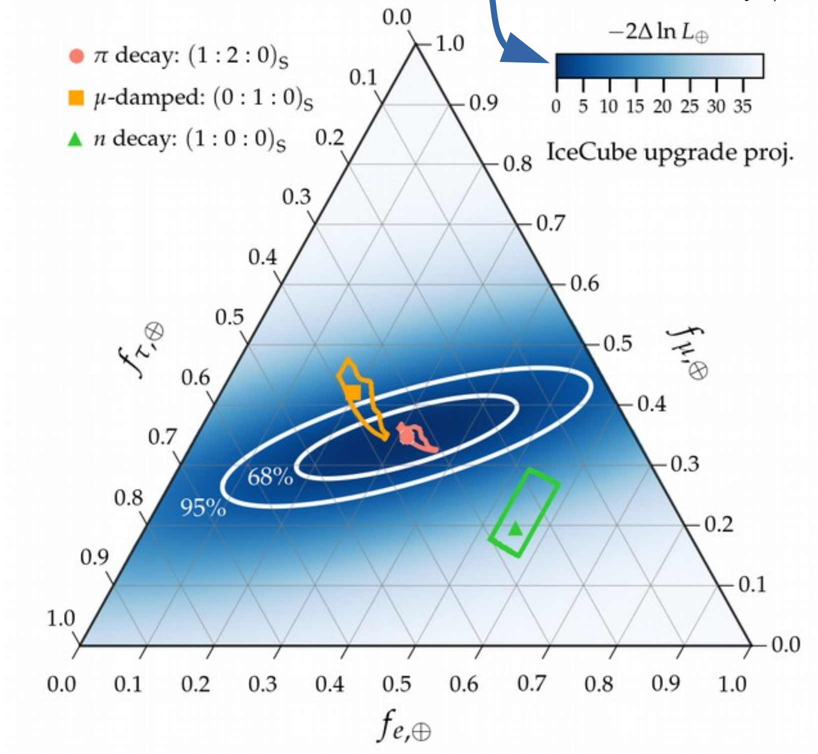


Inferred:
Flavor ratios at astrophysical sources

More likely

Likelihood of $f_{\alpha,\oplus}$



MB & Ahlers, *PRL* 2019

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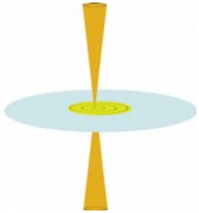

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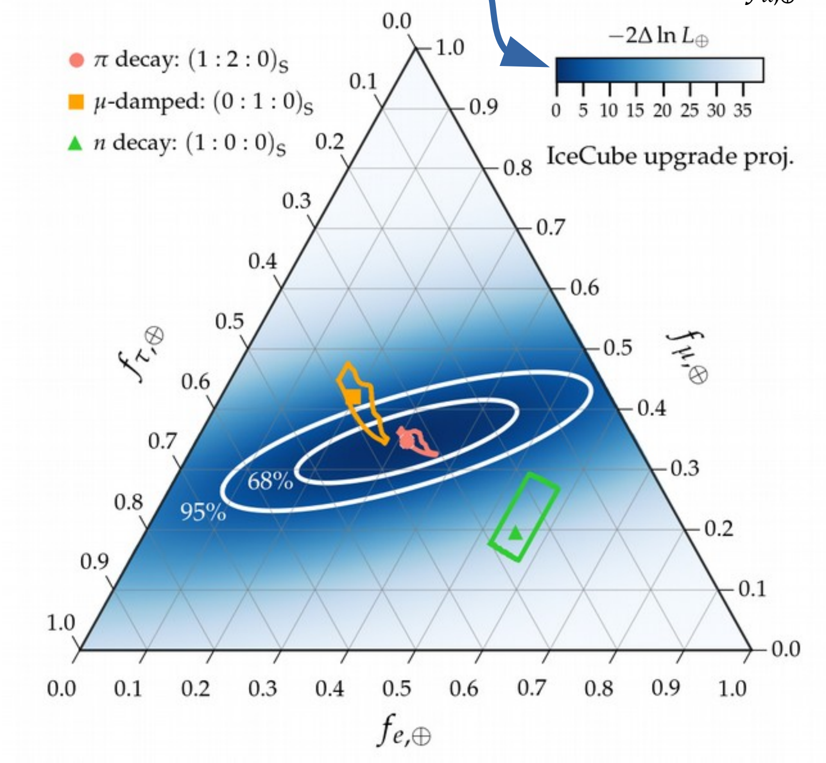
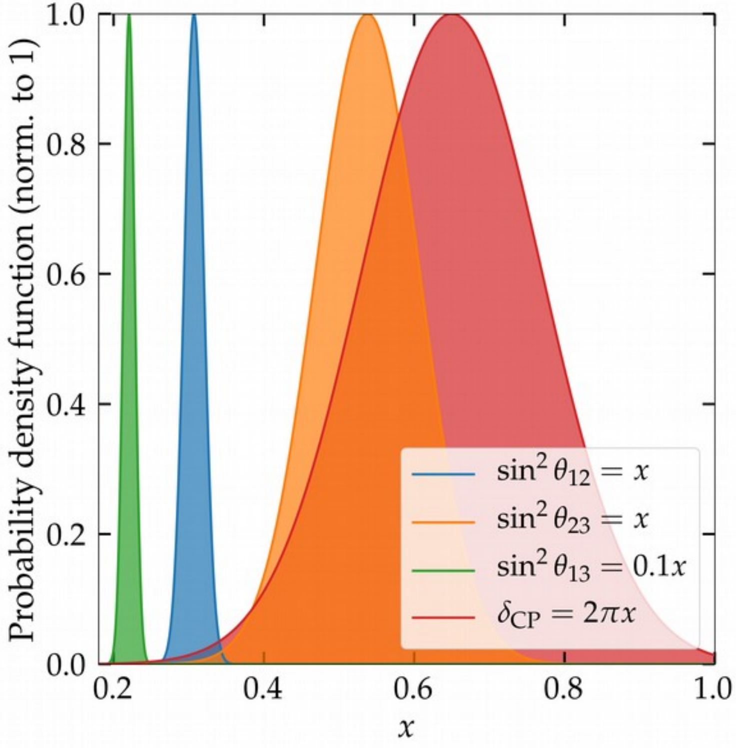


PDFs of mixing parameters



MB & Ahlers, *PRL* 2019

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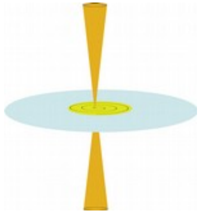

Inferred:
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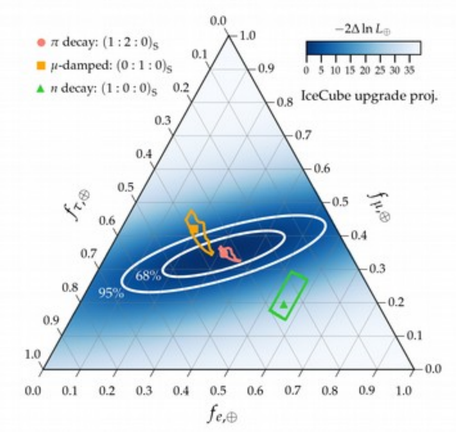

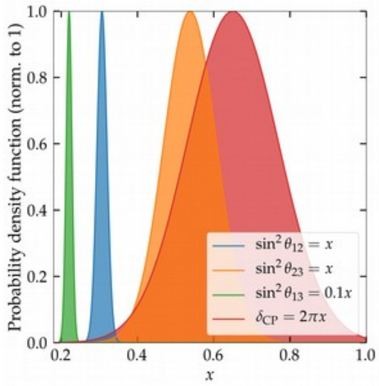

Posterior probability density of $f_{\alpha,\mathrm{S}}$ being the flavor ratios at the sources:

$$\mathcal{P}\left(f_{\alpha,\mathrm{S}}\right) \equiv \int d\boldsymbol{\theta} \frac{\mathcal{P}(\boldsymbol{\theta})}{\mathcal{N}(\boldsymbol{\theta})} \mathcal{L}_{\oplus}\left[f_{e,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta})\right]$$

$$\boldsymbol{\theta} \equiv (\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$$

Normalization: $\mathcal{N}(\boldsymbol{\theta}) \equiv \int_0^1 df_{e,\mathrm{S}} \int_0^{1-f_{e,\mathrm{S}}} df_{\mu,\mathrm{S}}\ \mathcal{L}_{\oplus}\left[f_{e,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta})\right]$

MB & Ahlers, *PRL* 2019

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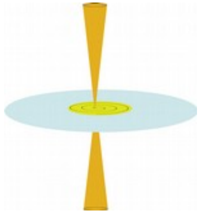
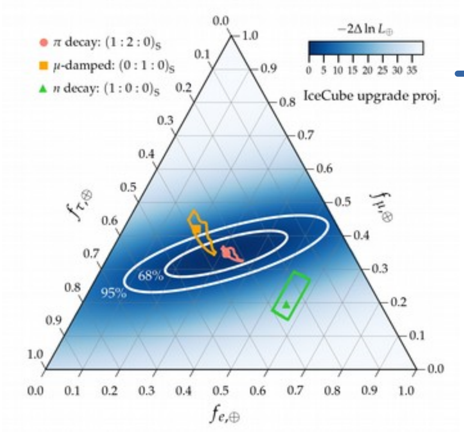
Flavor ratios at Earth

Invert flavor oscillations



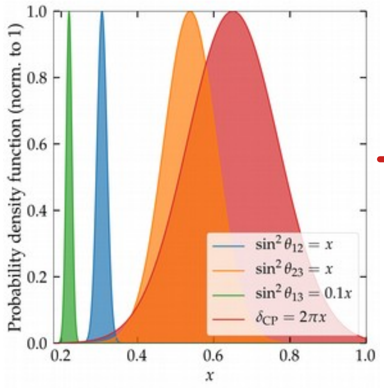
Inferred:
Flavor ratios at astrophysical sources



Posterior probability density of $f_{\alpha,\mathrm{S}}$ being the flavor ratios at the sources:

$$\mathcal{P}\left(f_{\alpha,\mathrm{S}}\right) \equiv \int \mathrm{d}\boldsymbol{\theta} \frac{\mathcal{P}(\boldsymbol{\theta})}{\mathcal{N}(\boldsymbol{\theta})} \mathcal{L}_{\oplus}\left[f_{e,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta})\right]$$

$$\boldsymbol{\theta} \equiv (\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$$



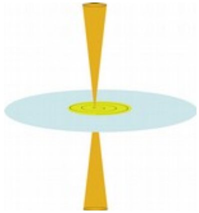
Normalization: $\mathcal{N}(\boldsymbol{\theta}) \equiv \int_0^1 \mathrm{d}f_{e,\mathrm{S}} \int_0^{1-f_{e,\mathrm{S}}} \mathrm{d}f_{\mu,\mathrm{S}}\ \mathcal{L}_{\oplus}\left[f_{e,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta})\right]$

MB & Ahlers, *PRL* 2019

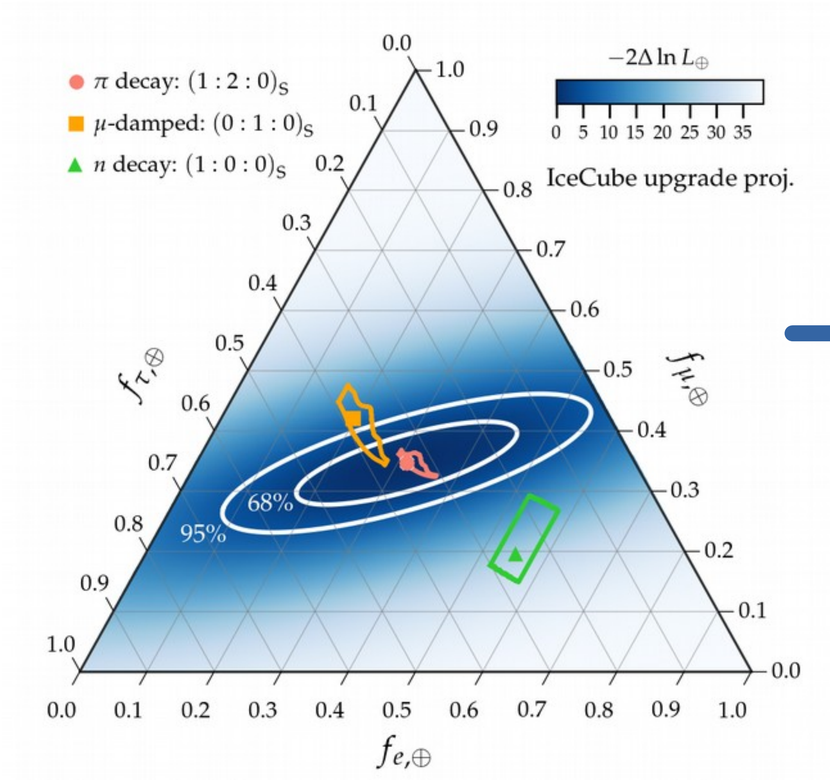
Inferring the flavor composition at the sources

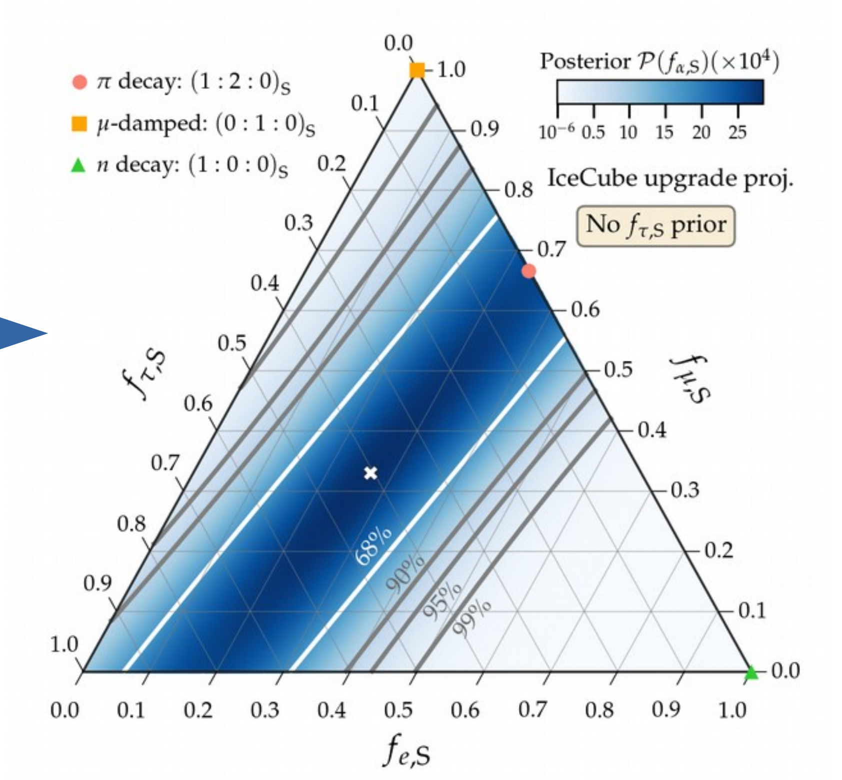
Measured:
Flavor ratios at Earth

Invert flavor oscillations



Inferred:
Flavor ratios at astrophysical sources



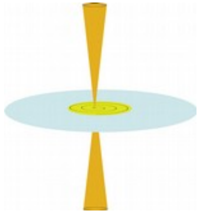


MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

Measured:
Flavor ratios at Earth

Invert flavor oscillations



Inferred:
Flavor ratios at
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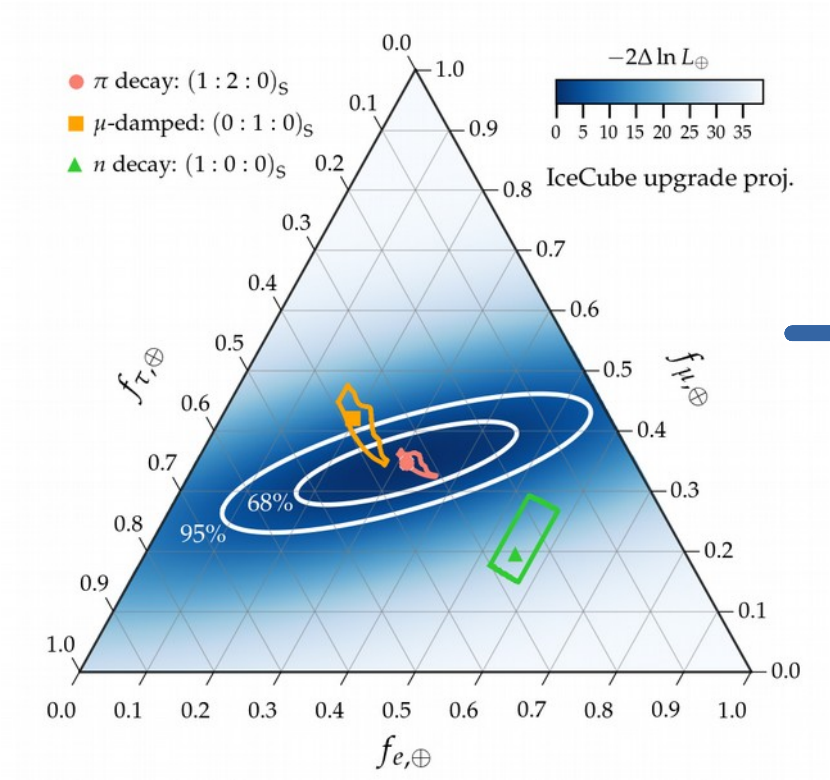
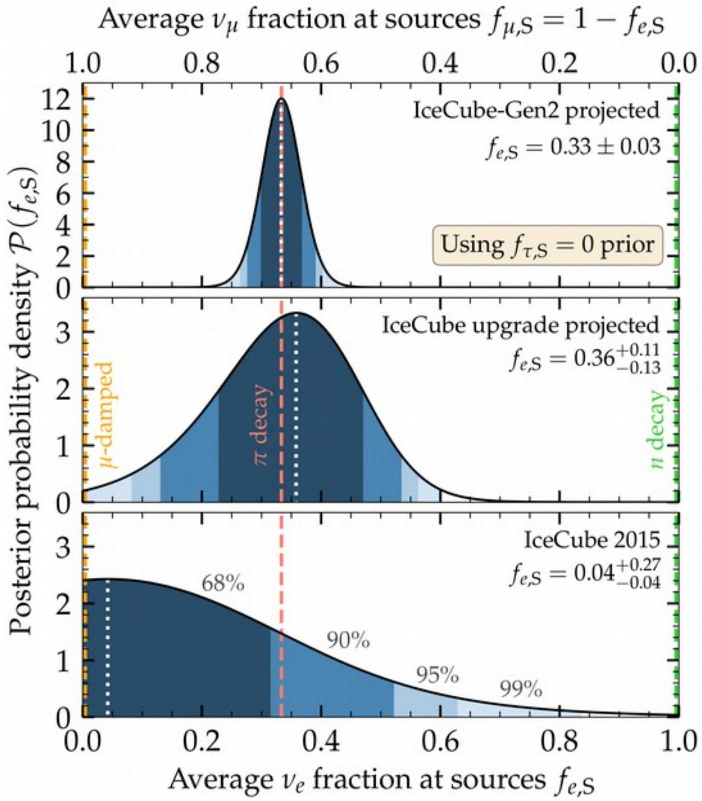




MB & Ahlers, *PRL* 2019

Flavor content of neutrino mass eigenstates

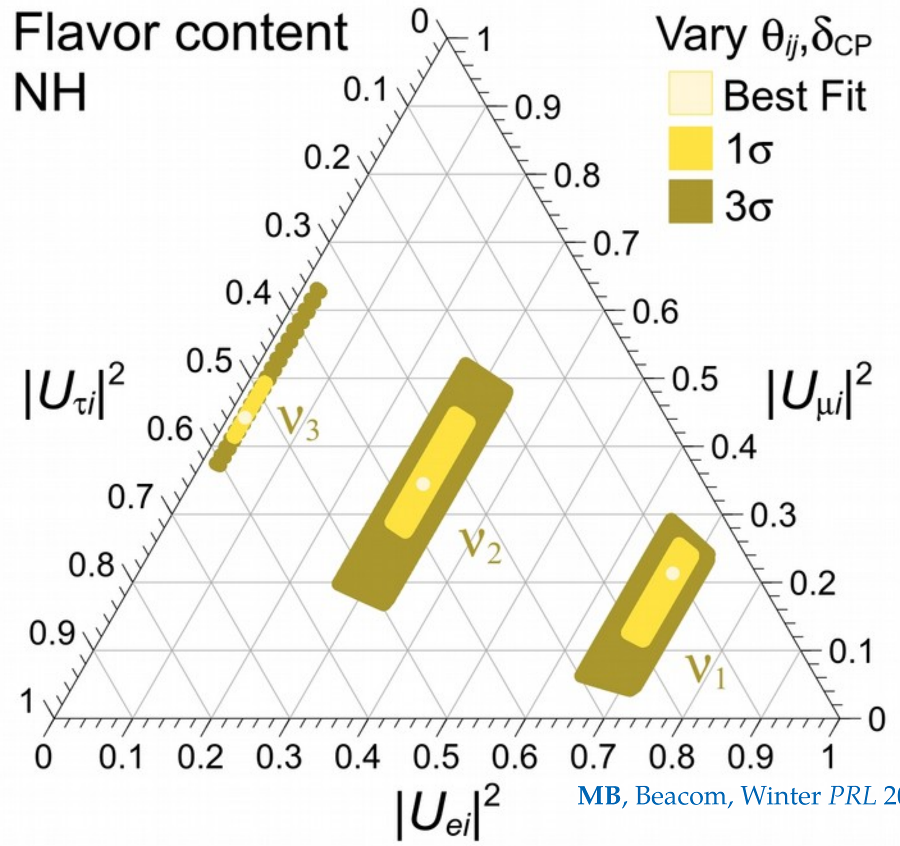
Flavor content for every allowed combination of mixing parameters –

Known to within 2%

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

Known to within 8%

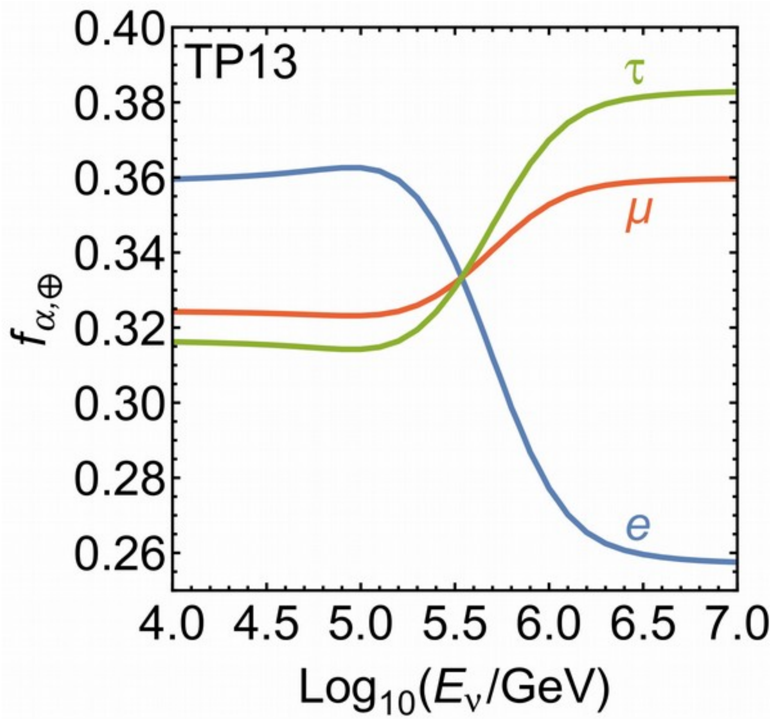
Known to within 20% (or worse)

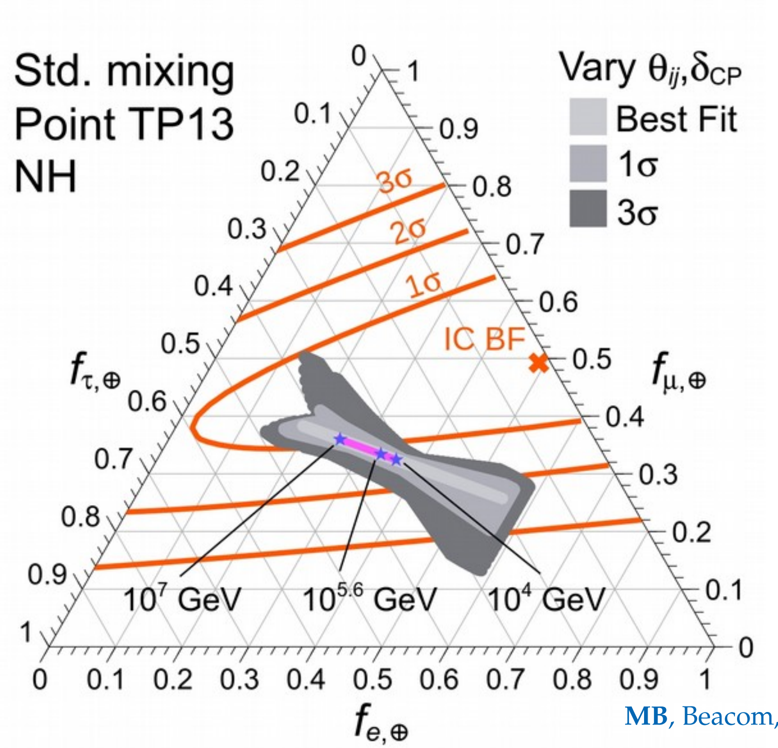


MB, Beacom, Winter *PRL* 2015

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –





MB, Beacom, Winter *PRL* 2015

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

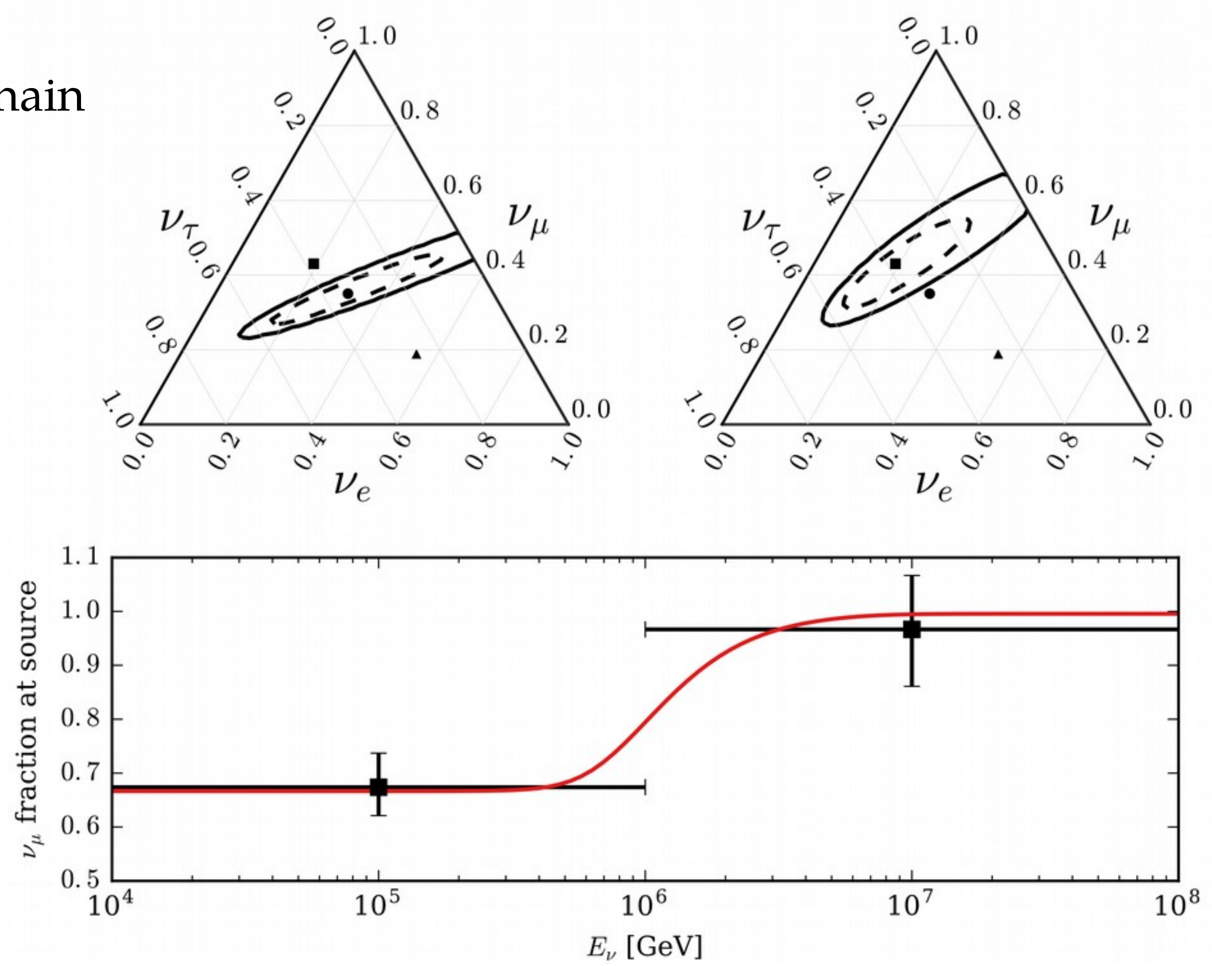
… Observable in IceCube-Gen2?

< PeV:
Full pion decay chain

$(f_e : f_\mu : f_\tau)_\oplus$
≈
(⅓:⅓:⅓)

> PeV:
Muon damping

$(f_e : f_\mu : f_\tau)_\oplus$
≈
(0.2:0.4:0.4)



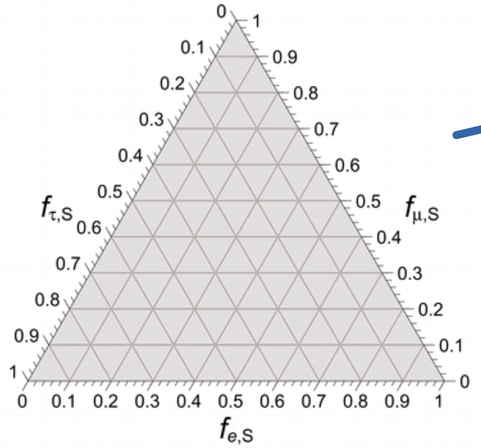
More detailed studies are required

Borrowed from J. van Santen & M. Kowalski

Measuring the neutrino lifetime

Earth

Sources



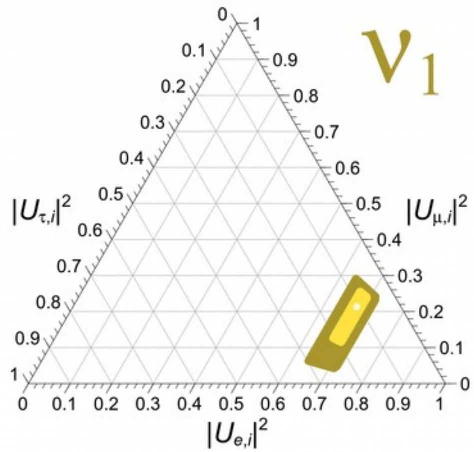
$\nu_2, \nu_3 \to \nu_1$

ν_1 lightest and stable

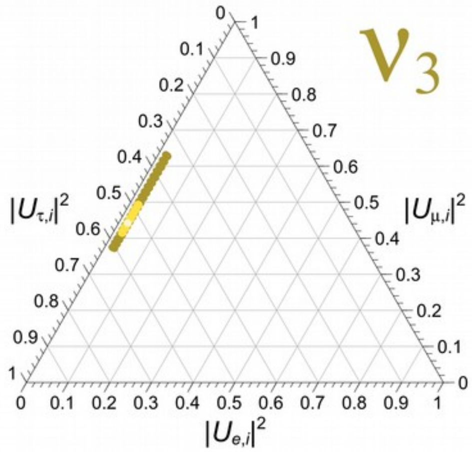
If all unstable neutrinos decay

$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable



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



$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$

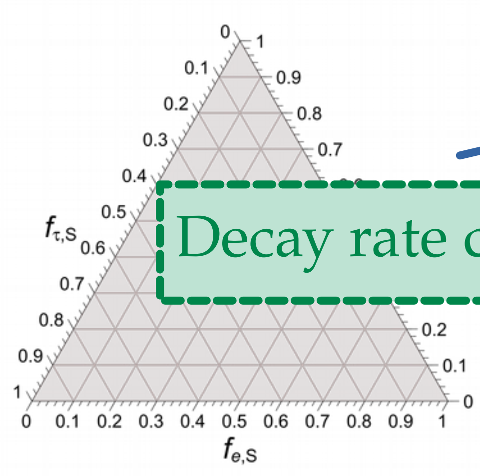
Measuring the neutrino lifetime

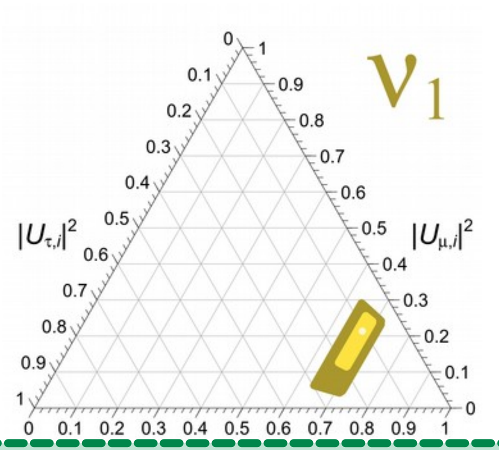
Earth

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable

Sources

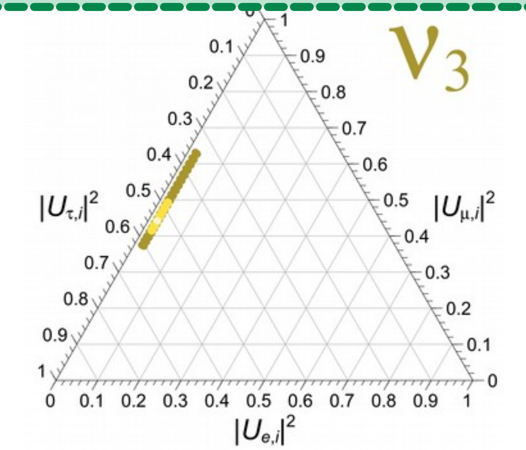




$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$

If all unstable

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



$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable

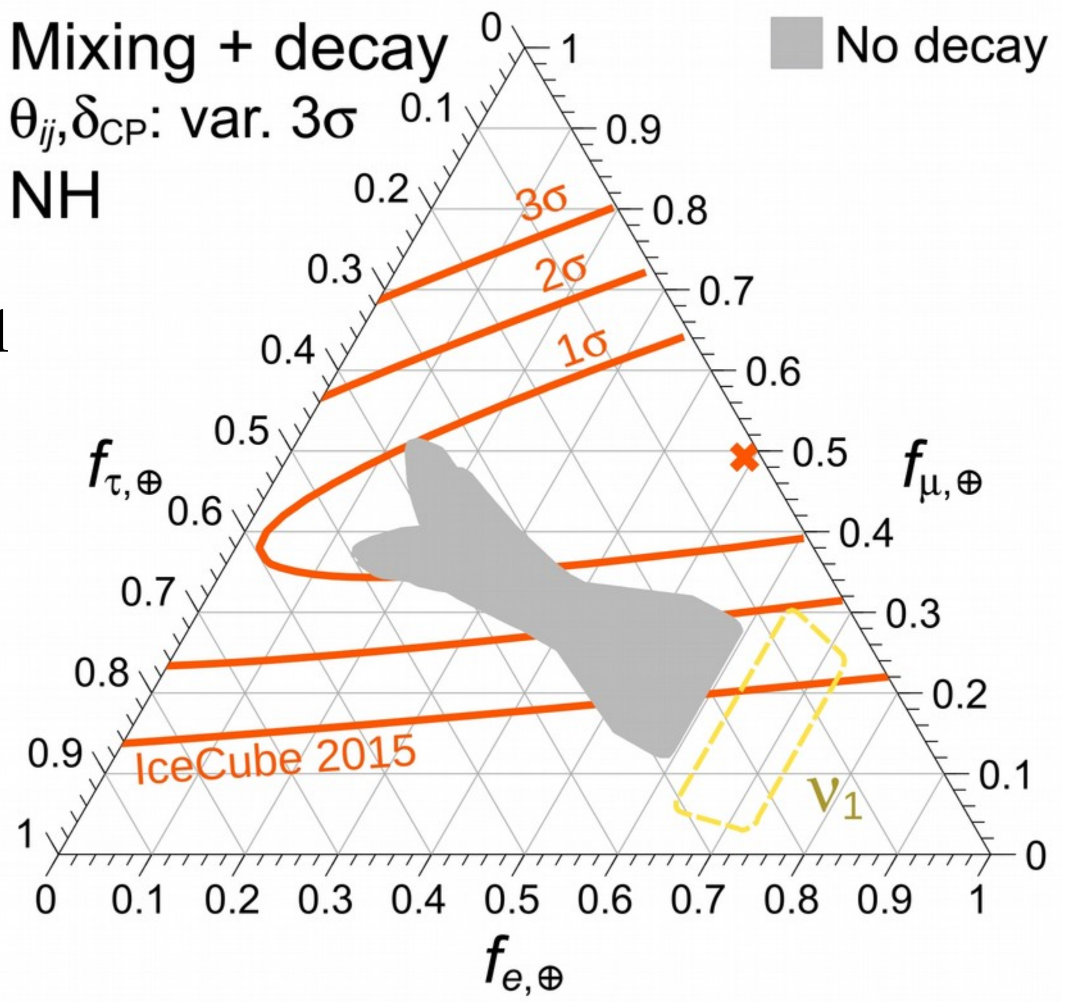
Measuring the neutrino lifetime

Find the value of D so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- Any value of mixing parameters; and
- Any flavor ratios at the sources

(Assume equal lifetimes of ν_2, ν_3)

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



Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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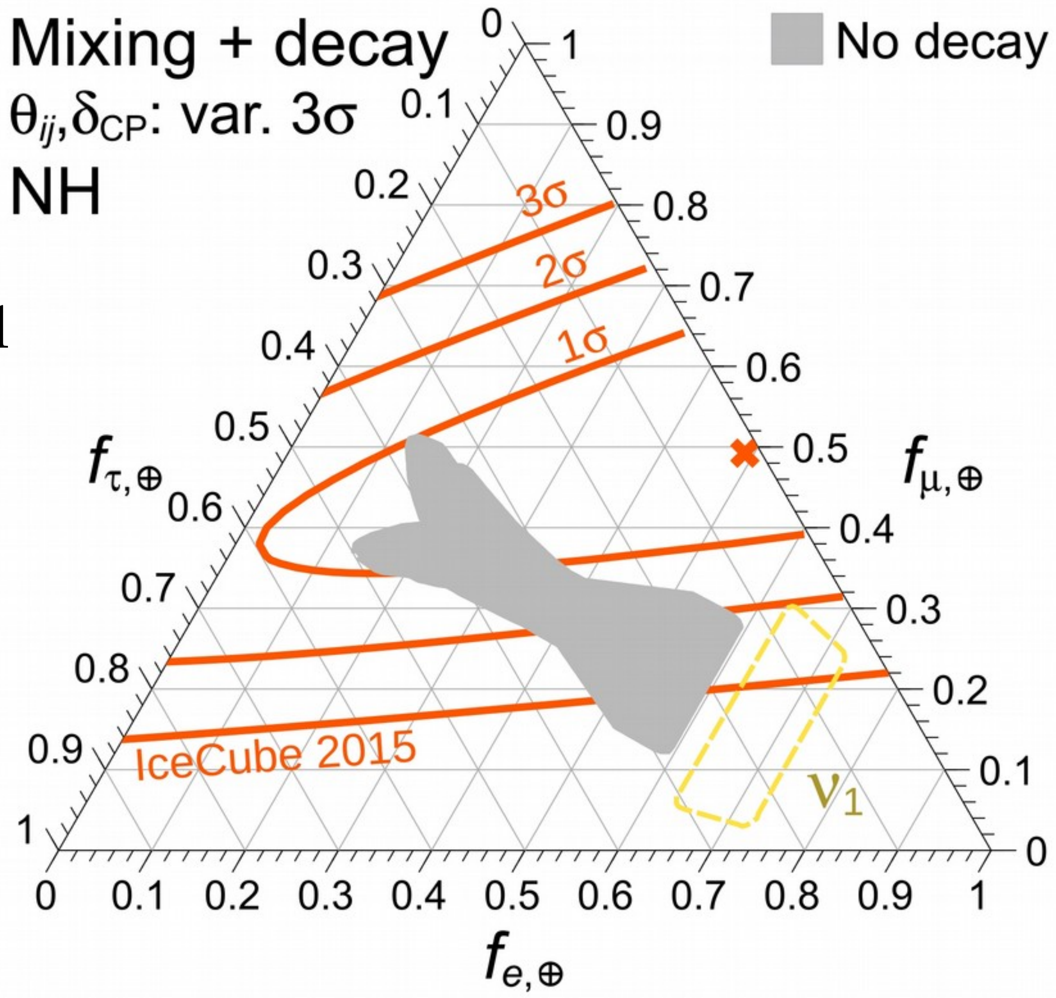

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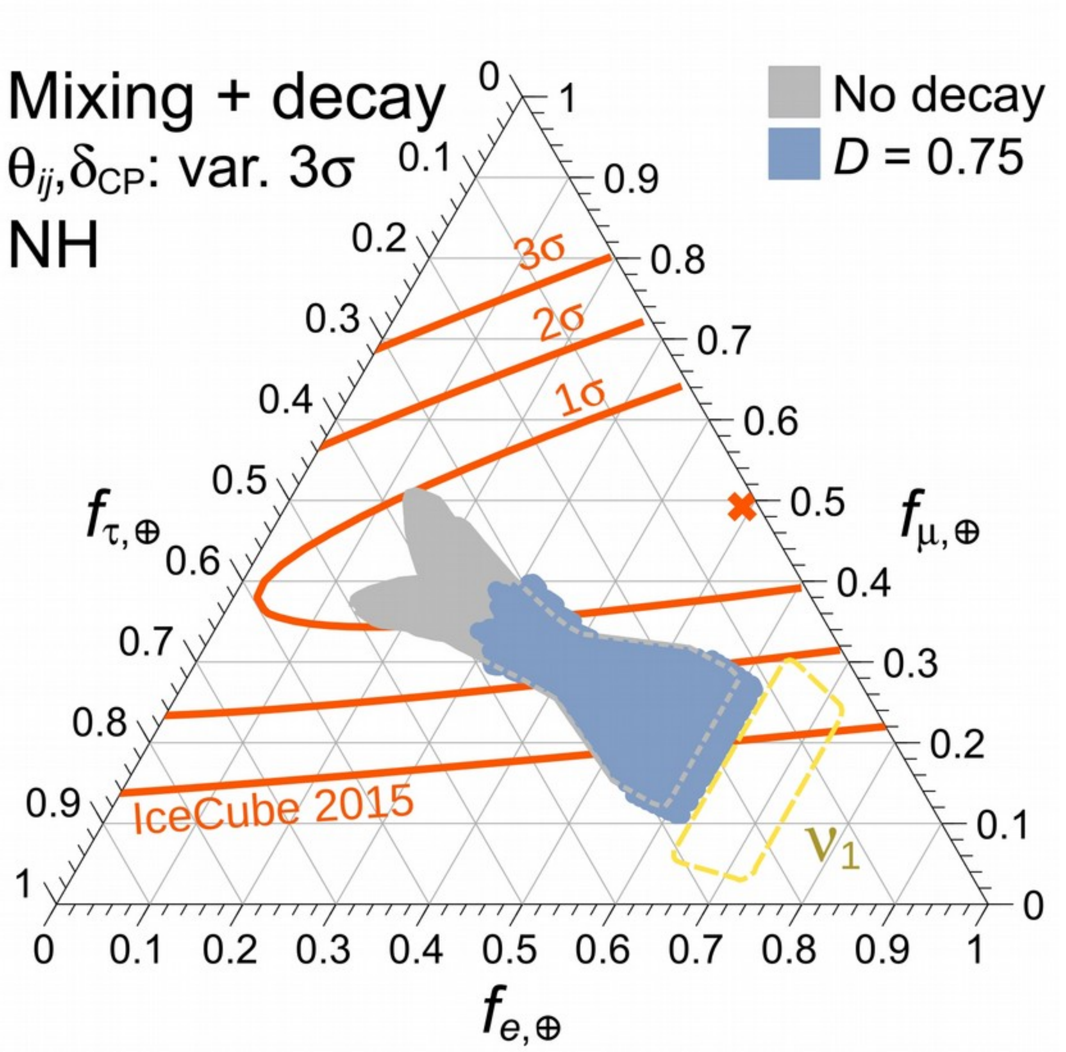

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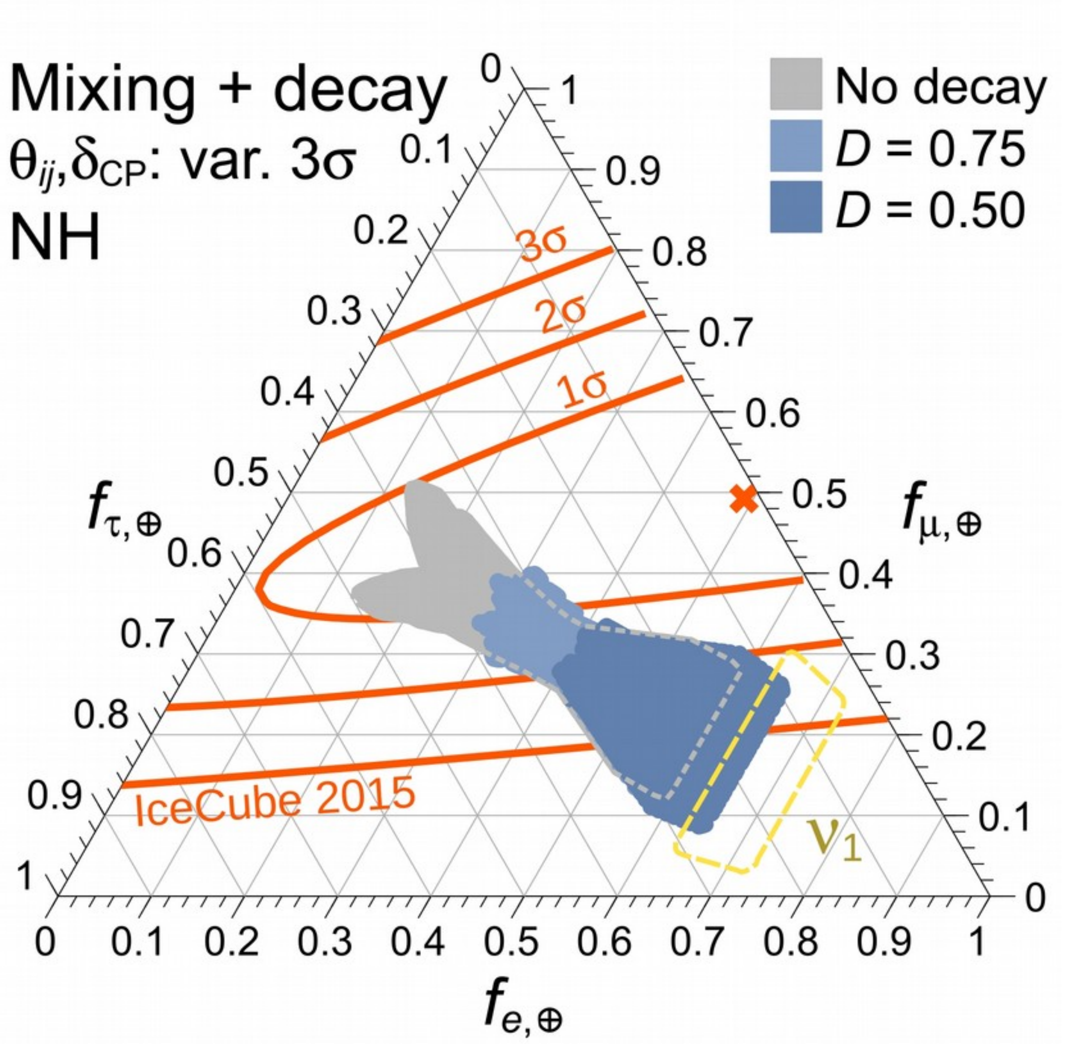

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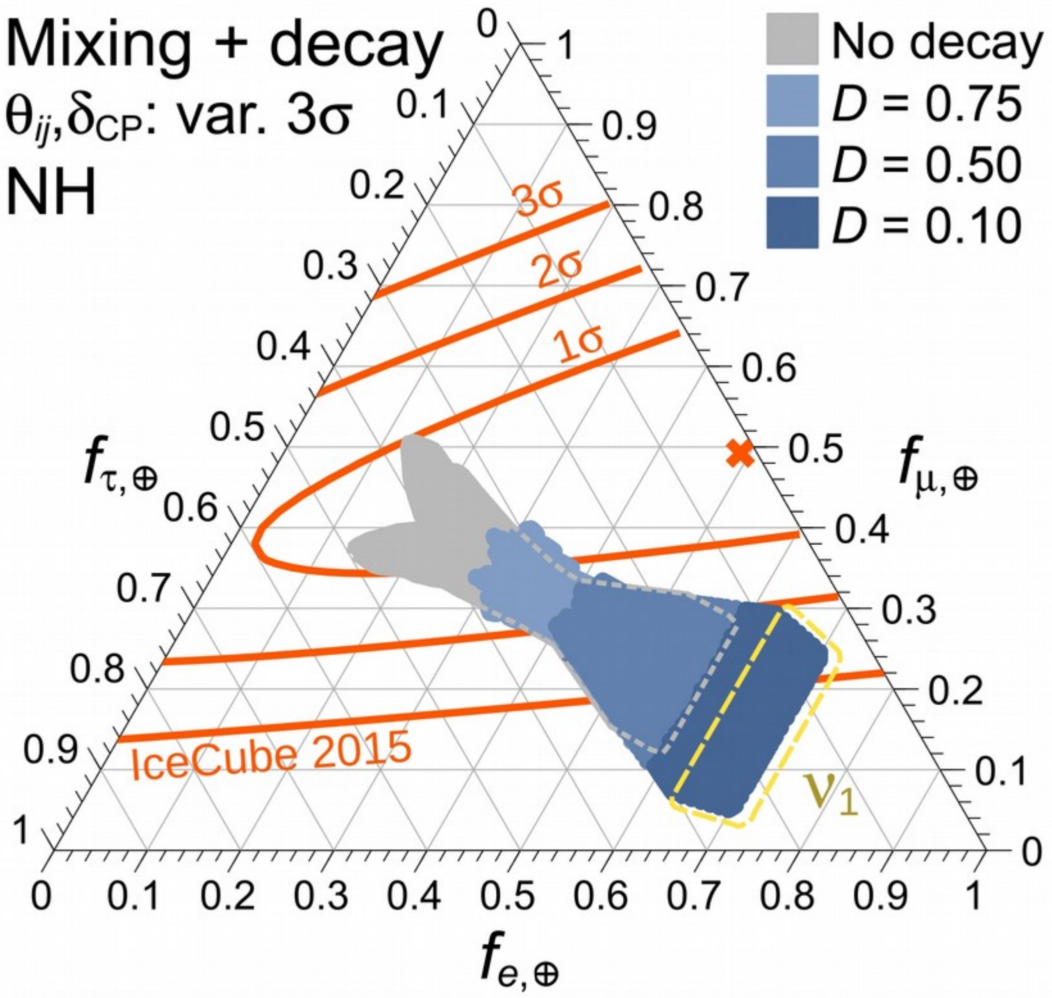

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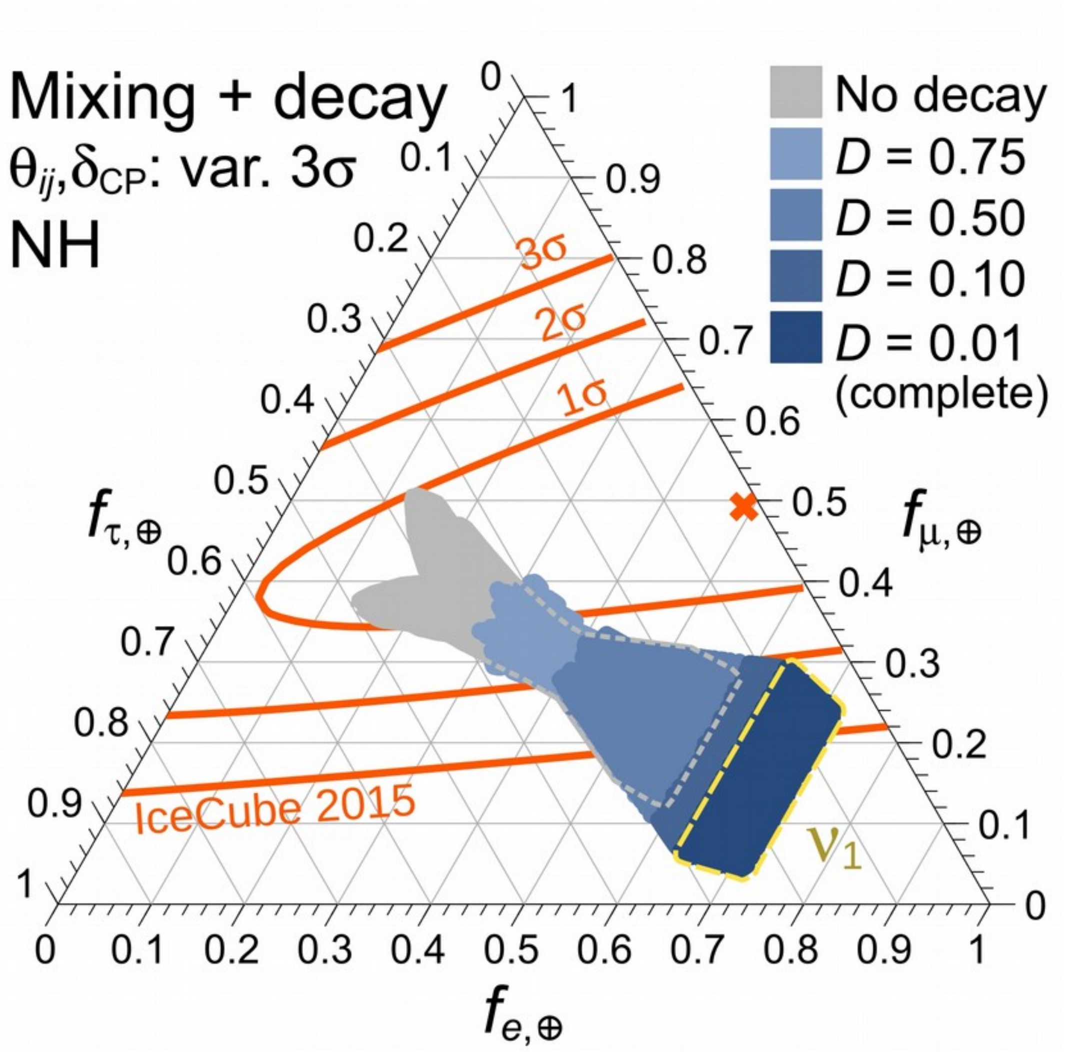

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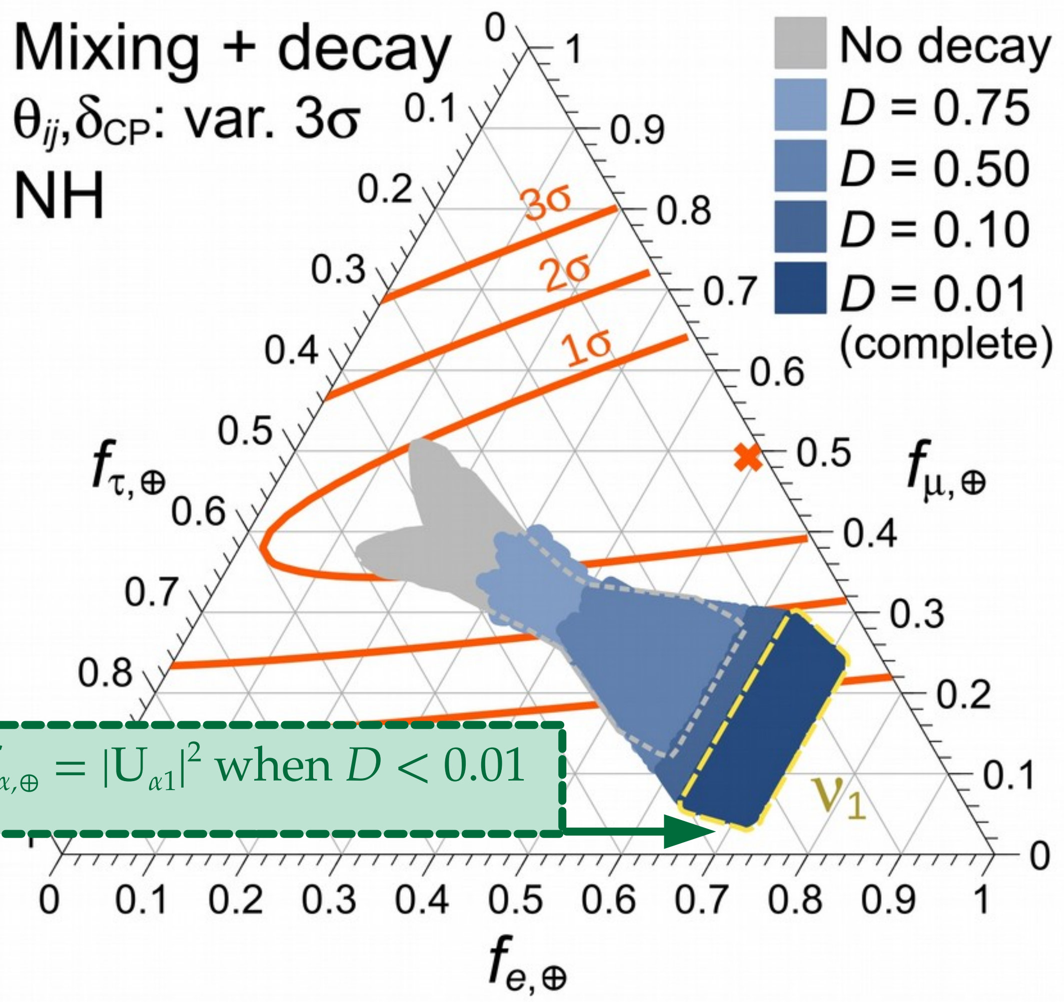
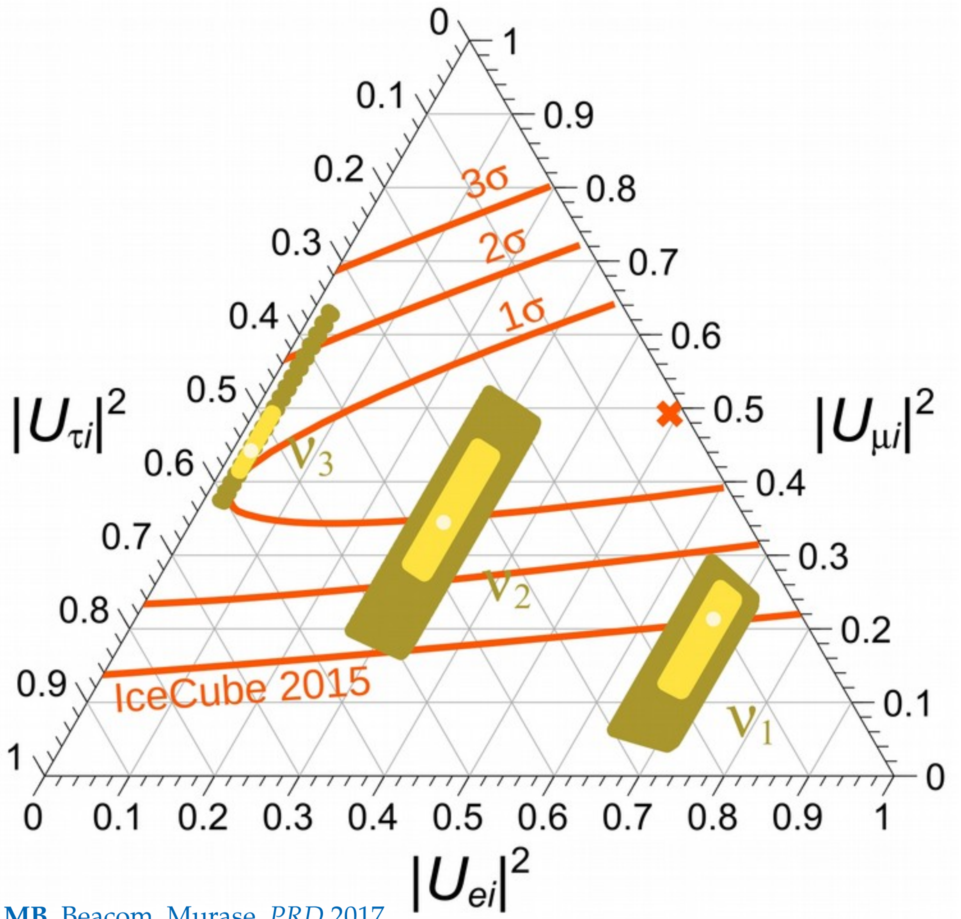
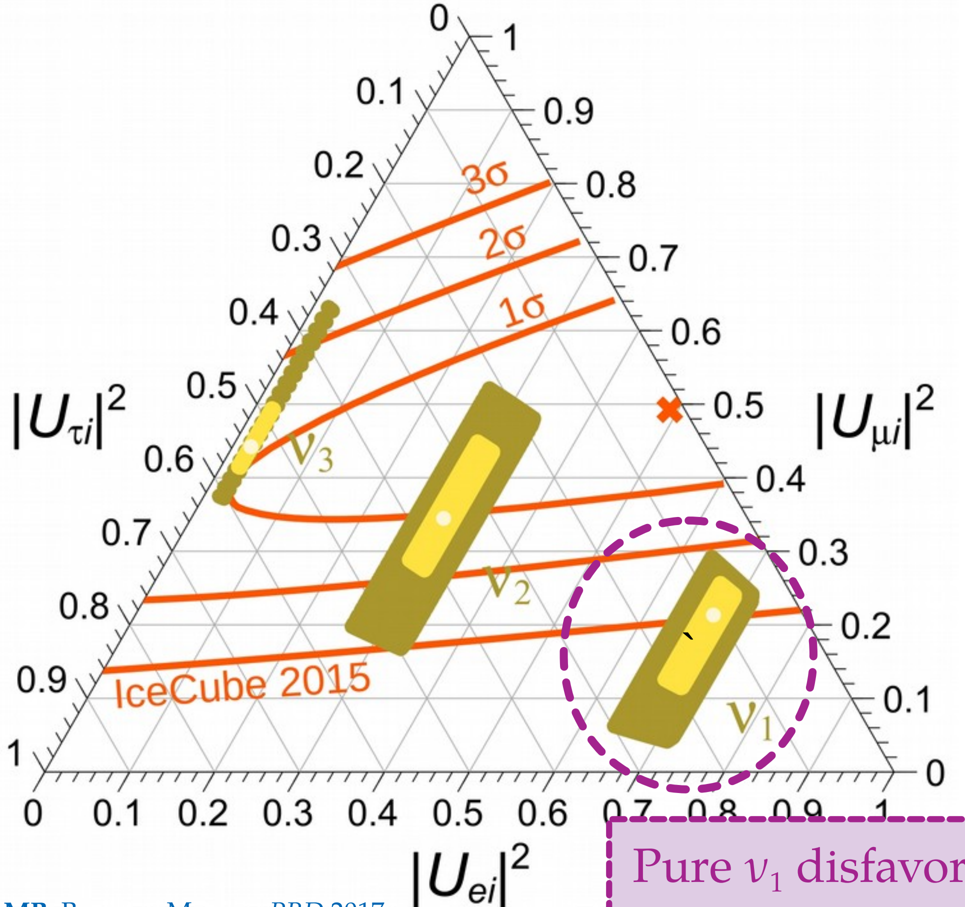


$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D < 0.01$

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



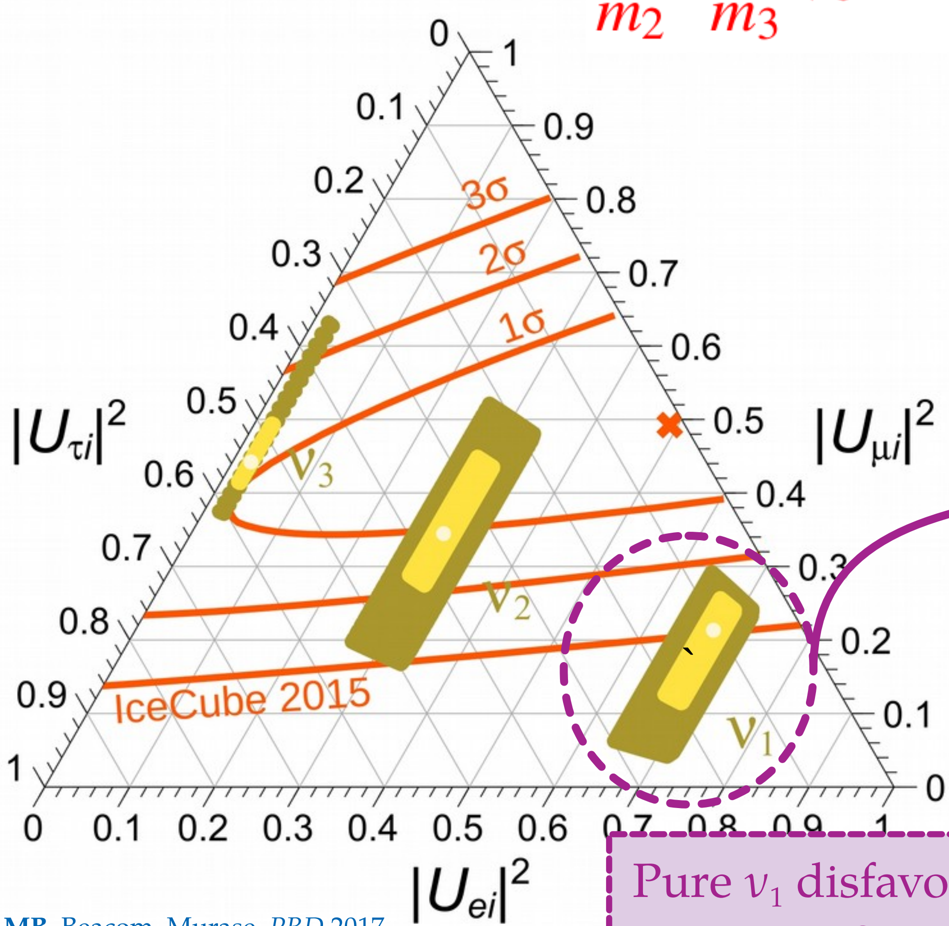
MB, Beacom, Murase, *PRD* 2017

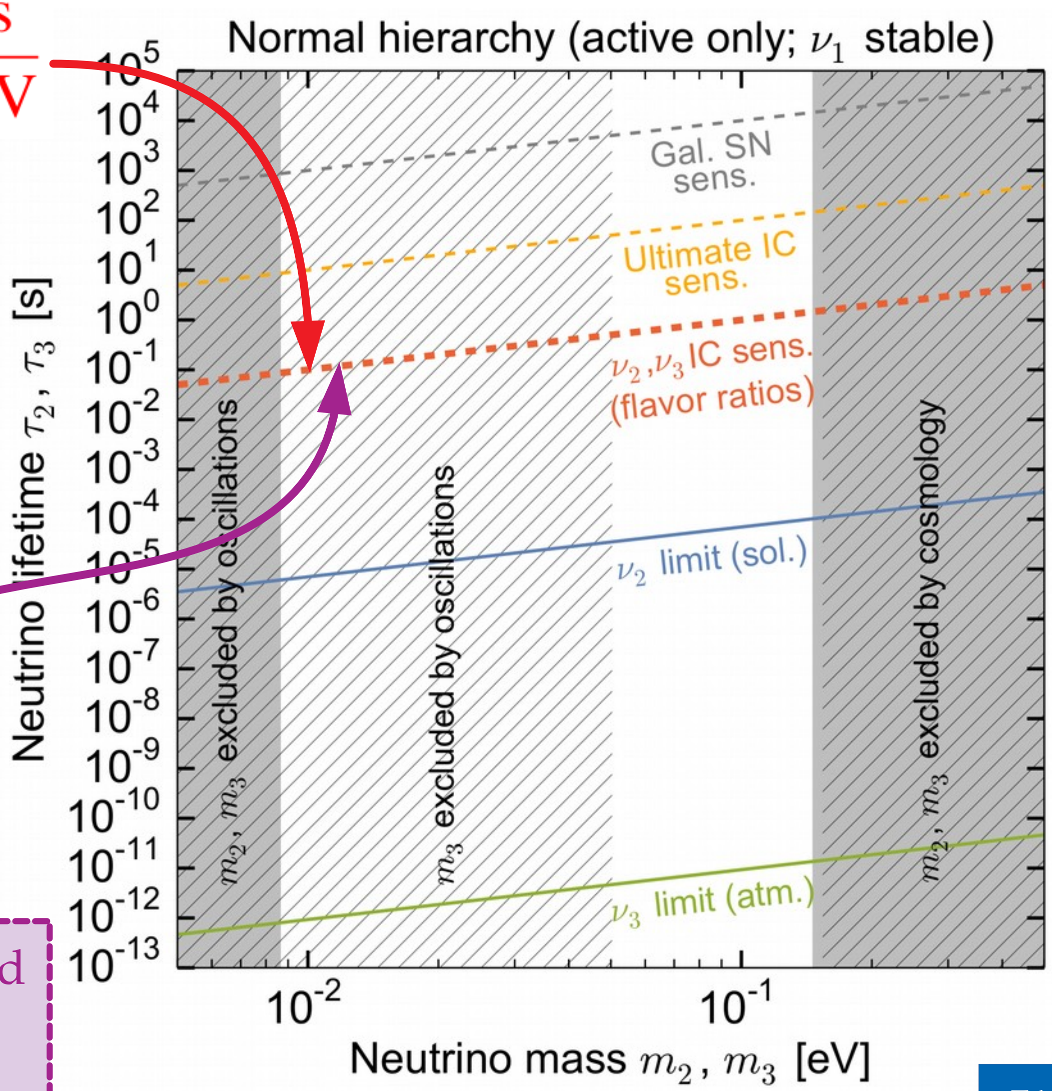


MB, Beacom, Murase, *PRD* 2017

Pure ν_1 disfavored at > 2σ

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





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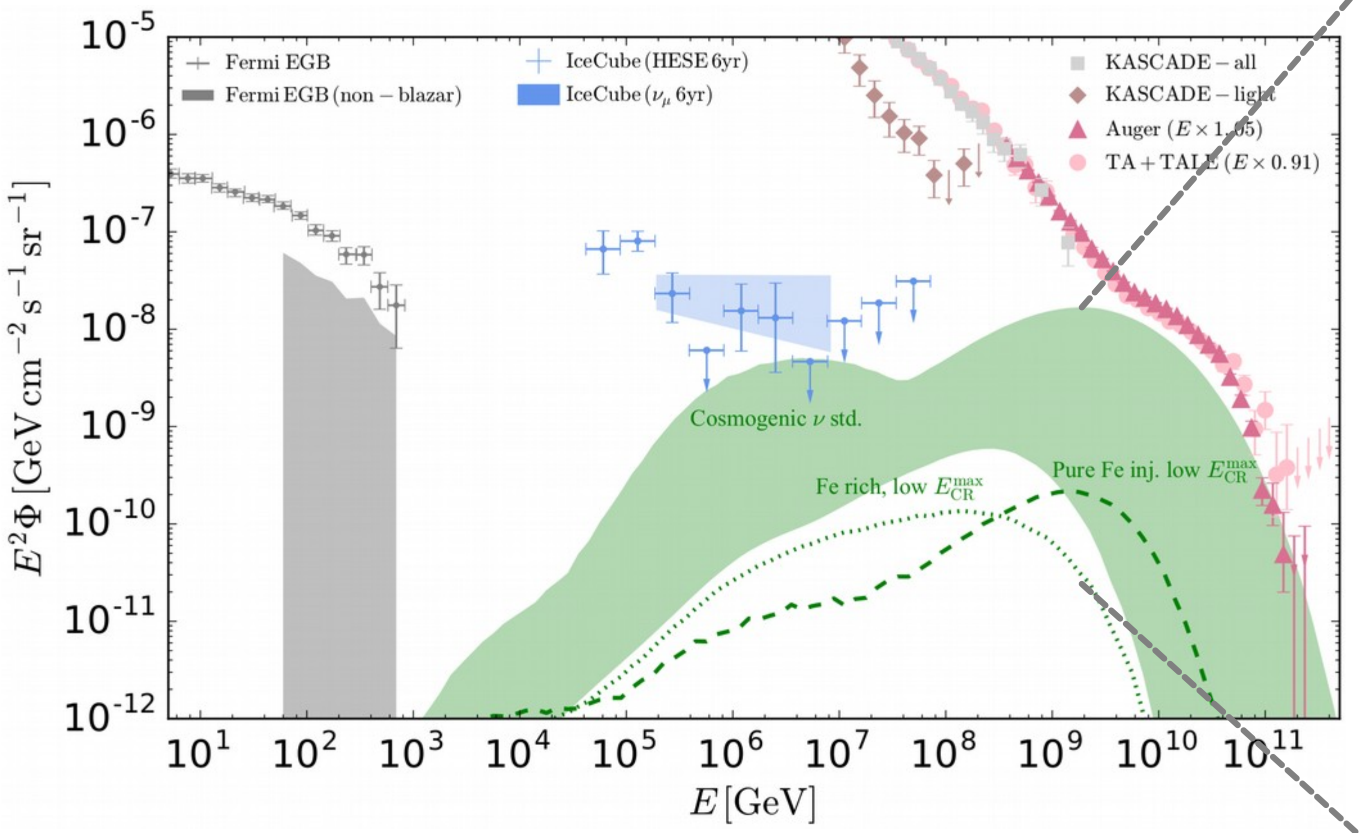
MB, Beacom, Murase, *PRD* 2017

UHE ν flux – how low?

Higher cosmogenic ν flux



Lower cosmogenic ν flux

The proton fraction is the driver

Ahlers & Halzen, *PRD* 2012

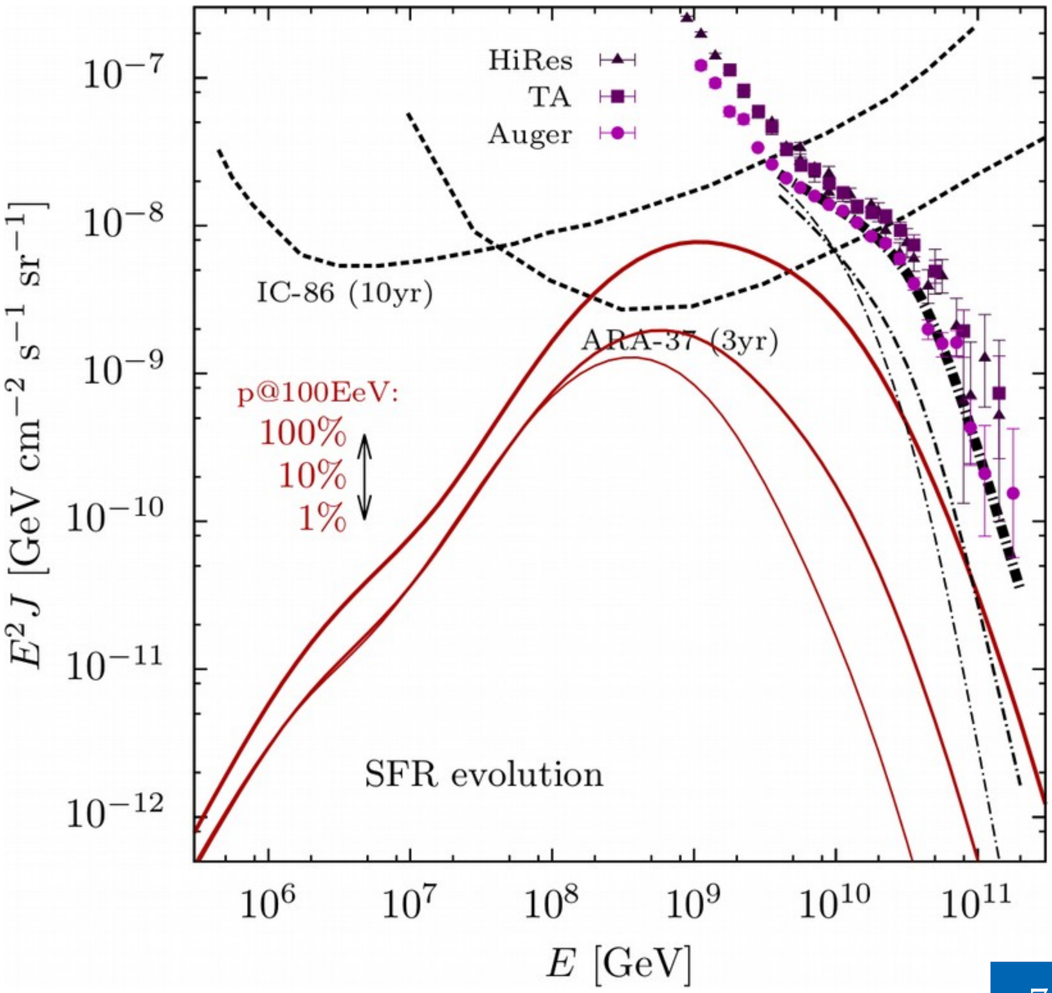
- Cosmogenic ν production is mainly due to UHECR protons

- Consider a mixed mass composition

- Proton fraction:

$$f_p = 1 - \left(1 + \left(\frac{E}{10^{19}\ \mathrm{eV}}\right)^{-\alpha}\right)^{-1}$$

- Nuclei fraction: $f_A = 1 - f_p$



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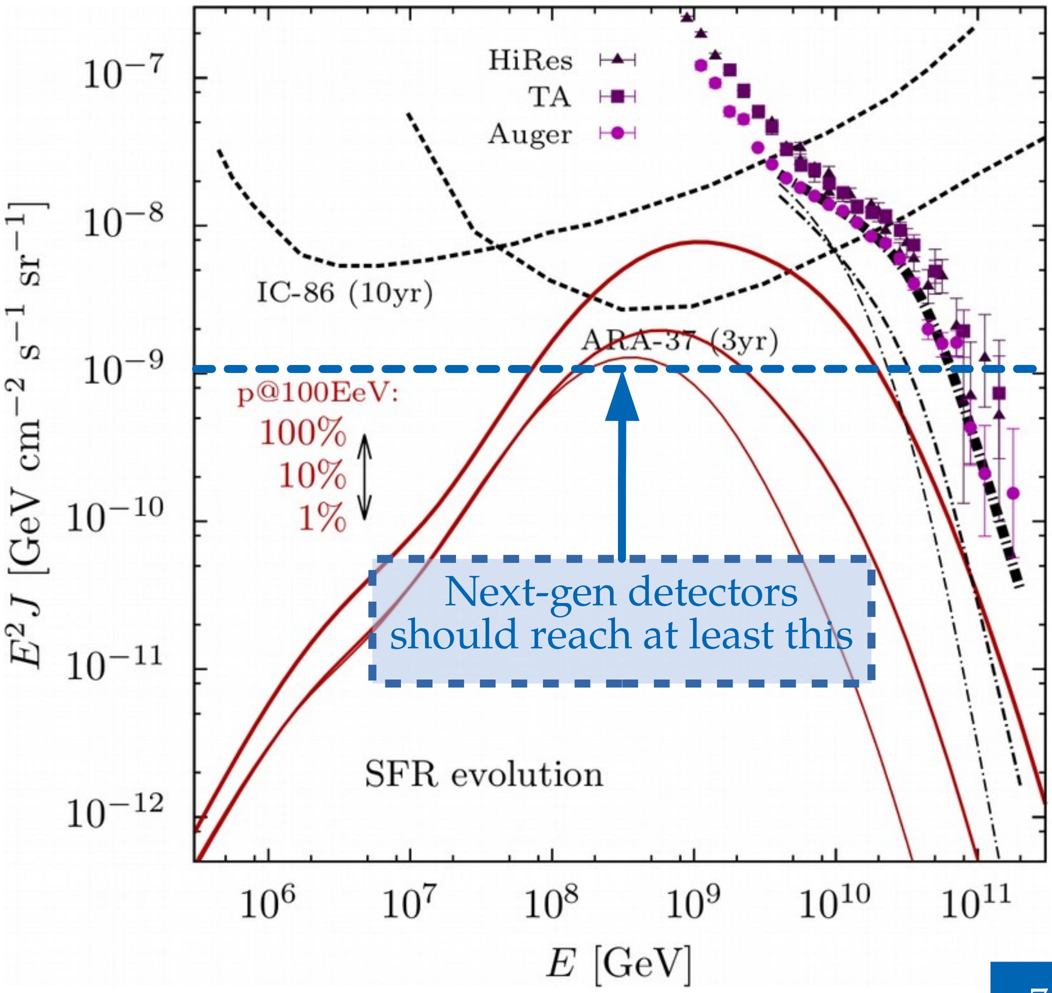


Updated cosmogenic ν fluxes

Plot from GRAND Collab., *Sci. China Phys. Mech. Astron.* 2020

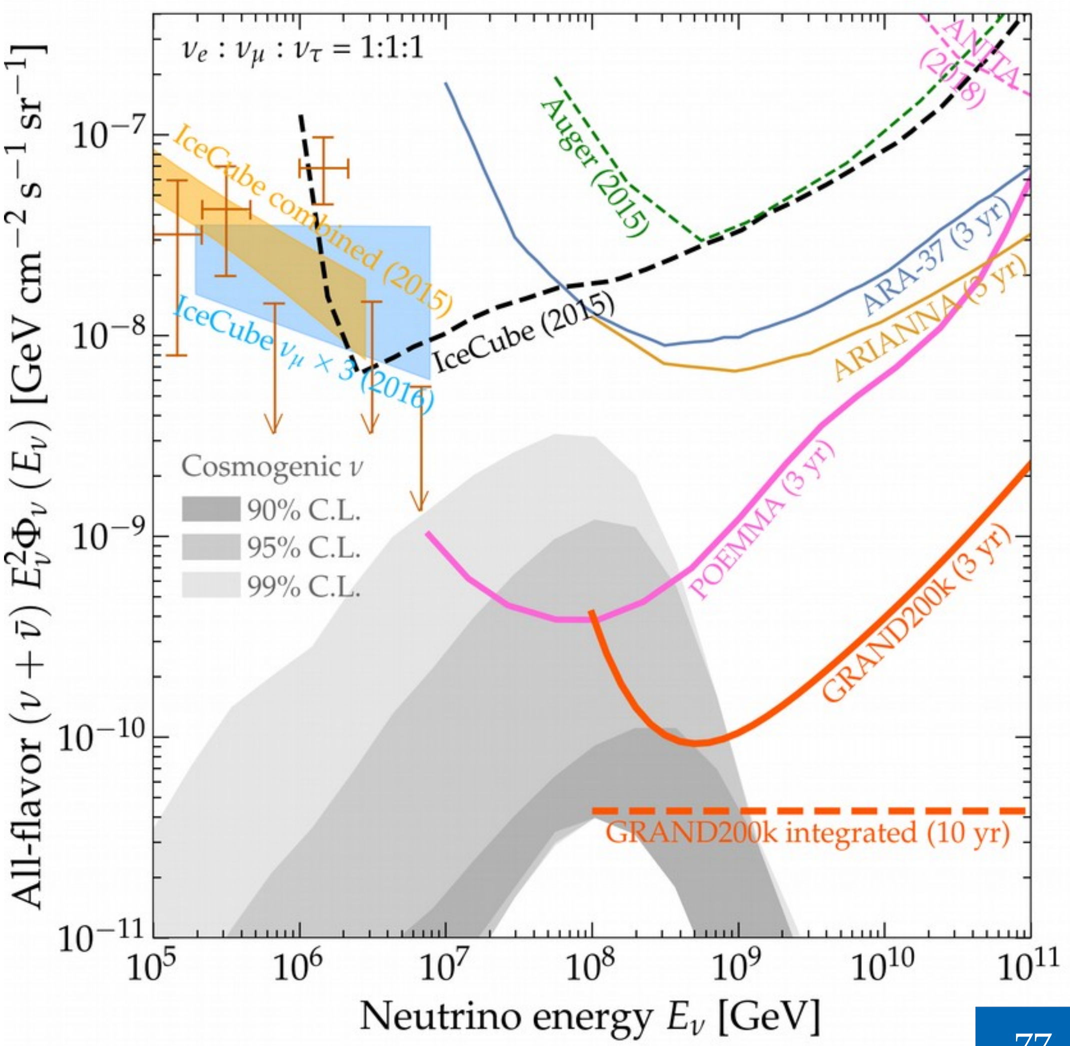
- Predictions from fits to 2017 Auger UHECR spectrum & composition

  [Pierre Auger Collab., *JCAP* 2017]

- Simultaneously vary (CRPropa):
  - Spectral index γ (*i.e.*, $E^{-\gamma}$)
  - Source evolution m (*i.e.*, $(1+z)^m$)
  - Maximum rigidity $R_{\rm cut}$ (*i.e.*, $e^{-R/R_{\rm cut}}$)

- Best-fit values:
  $\gamma = 1$, $m = -1.5$, $\log_{10}(R_{\rm cut}/{\rm V}) = 18.69$

- The ν fluxes are ~10 × lower, mainly due to low $R_{\rm cut}$ and negative m



Alves Batista *et al.*, *JCAP* 2019
See also: Heinze *et al.*, *ApJ* 2019

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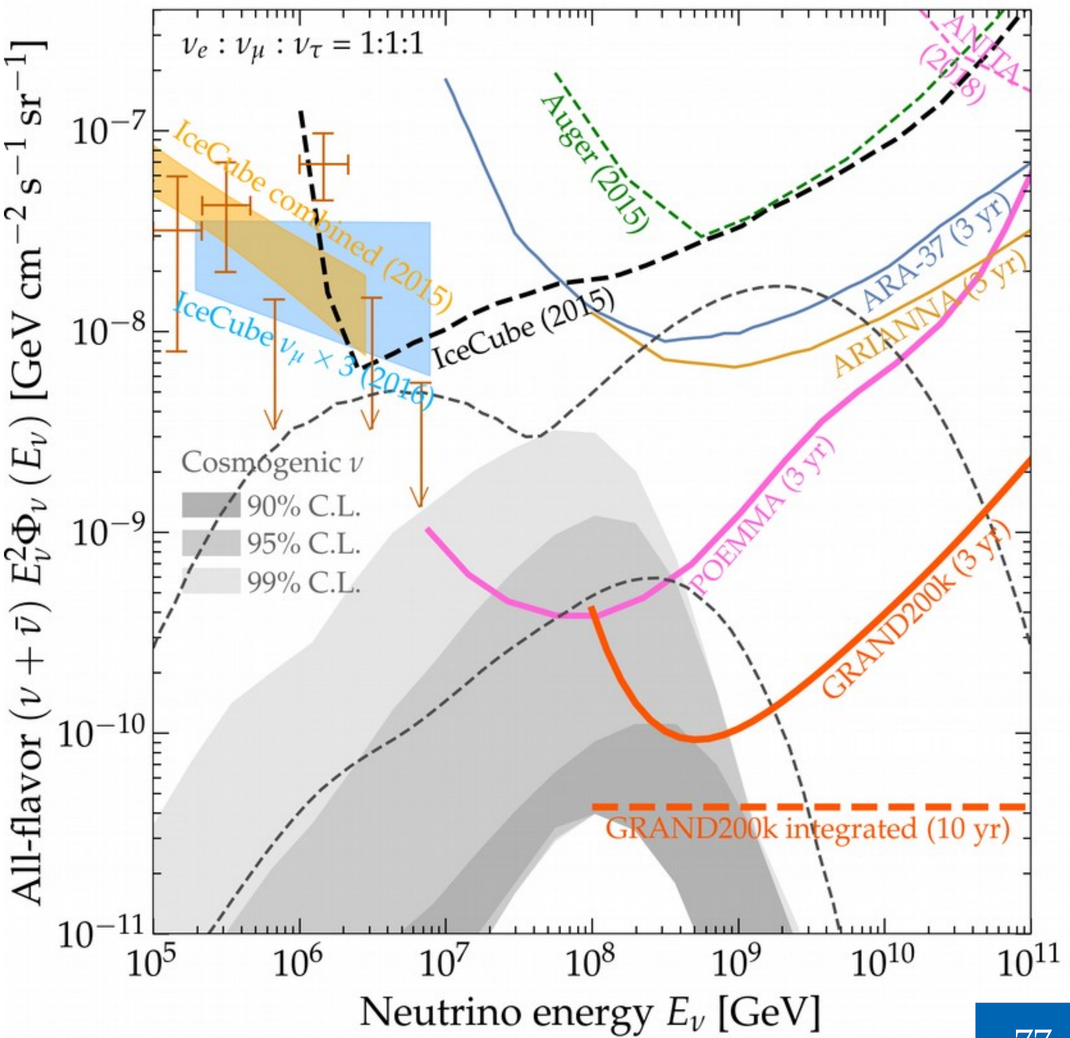
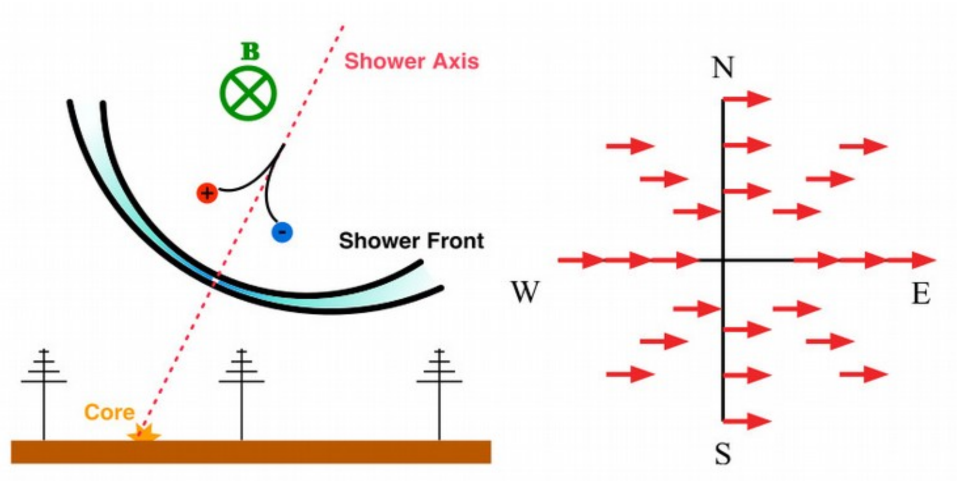


Alves Batista *et al.*, *JCAP* 2019
See also: Heinze *et al.*, *ApJ* 2019

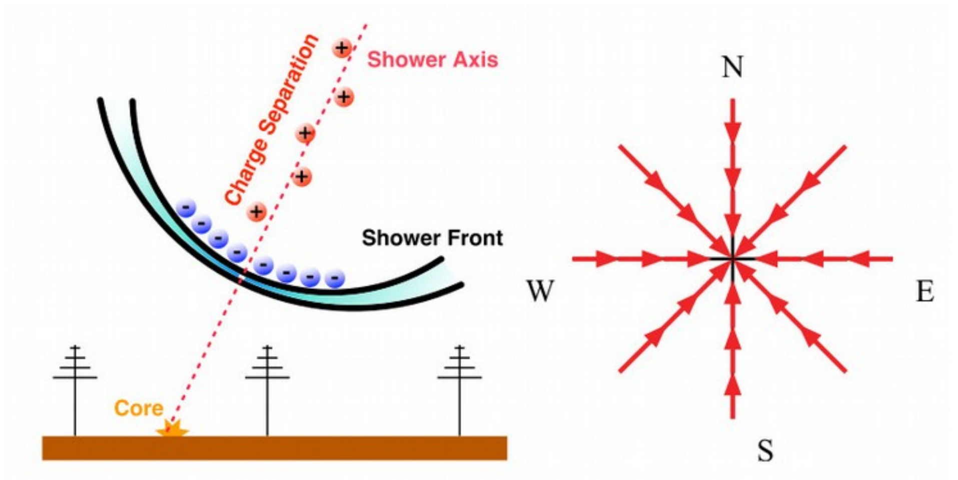
Radio emission: geomagnetic and Askaryan

Geomagnetic



- Time-varying transverse current
- Linearly polarized parallel to Lorentz force
- Dominant in air showers

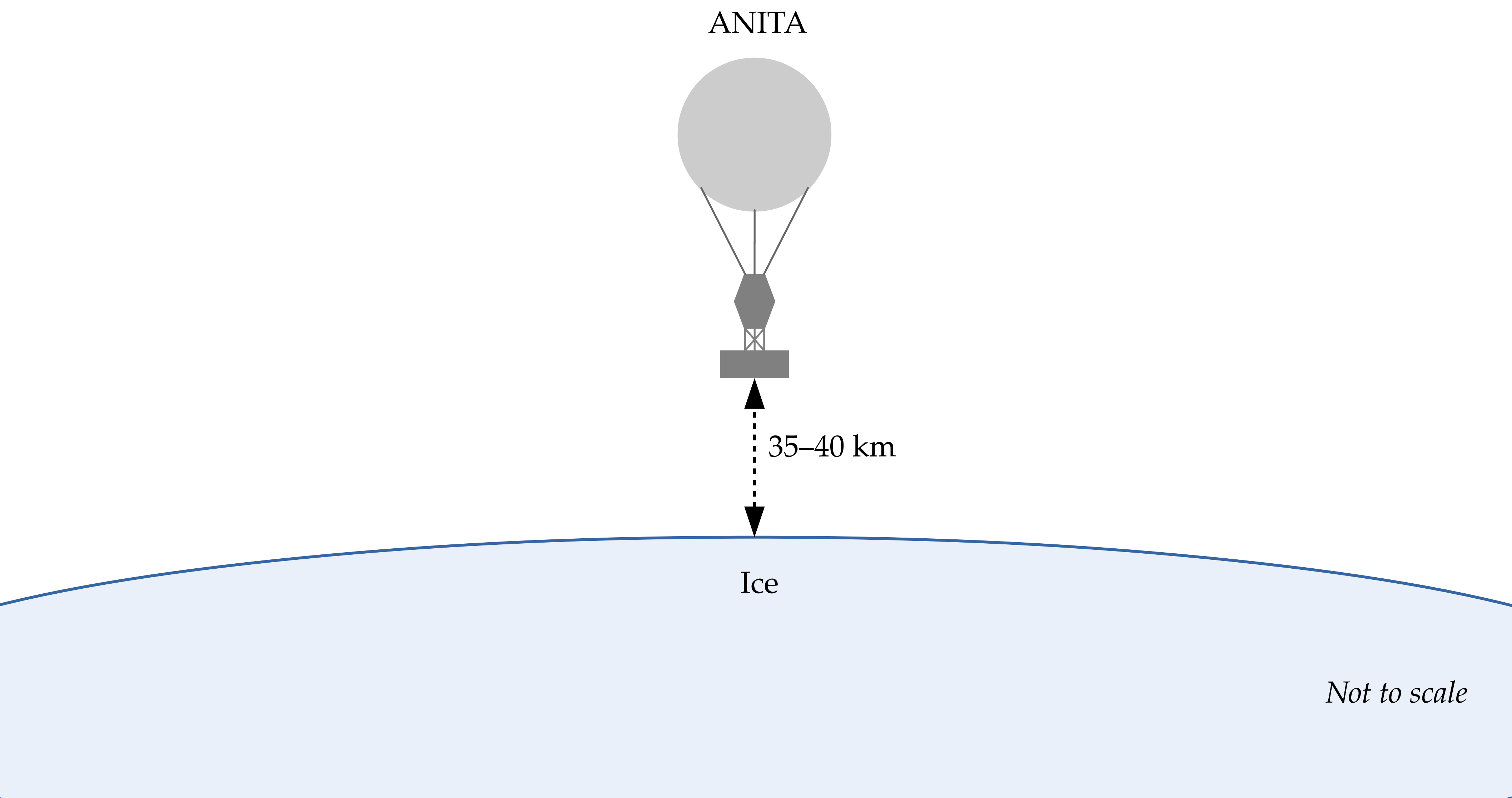
Askaryan

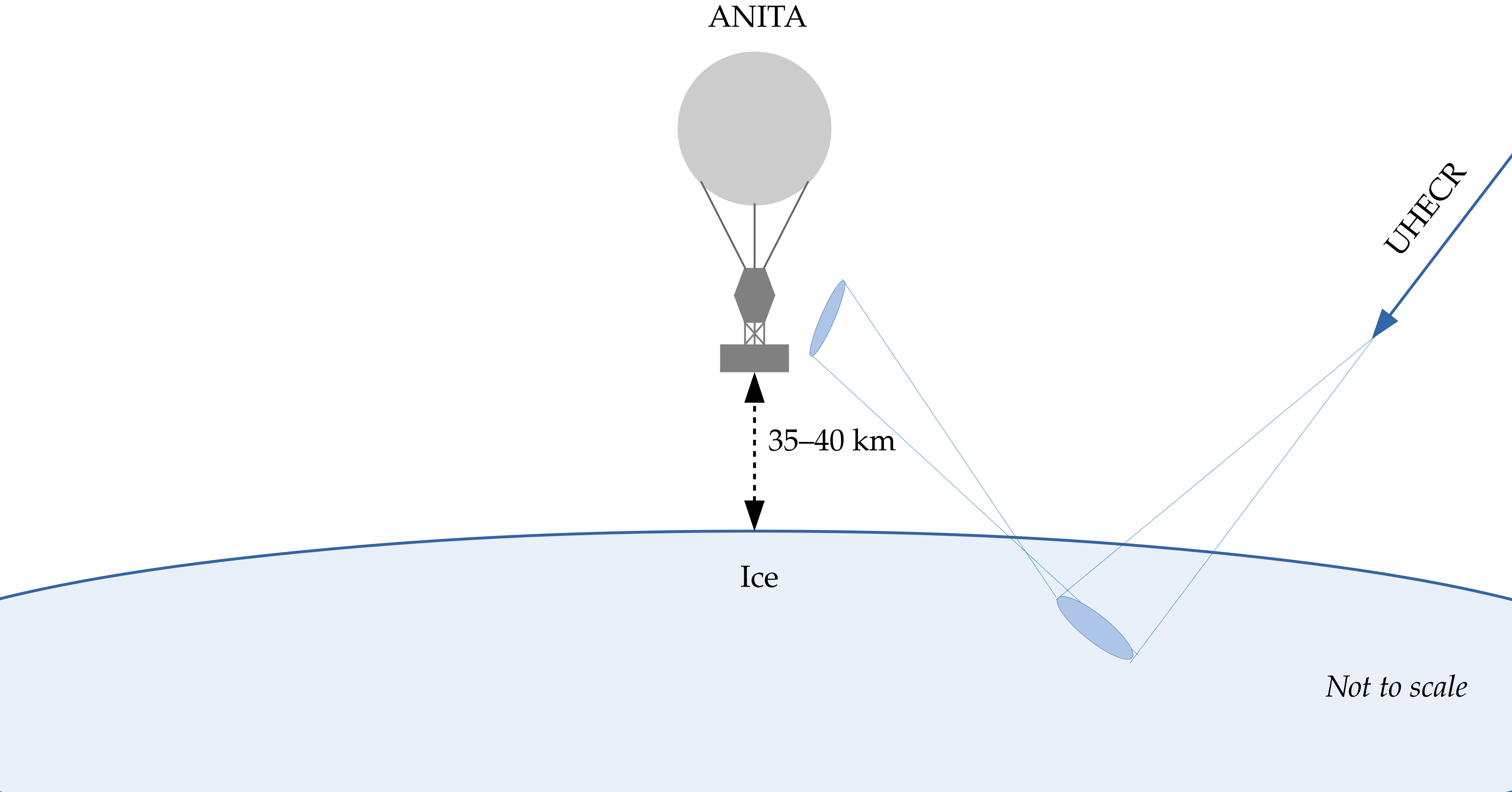


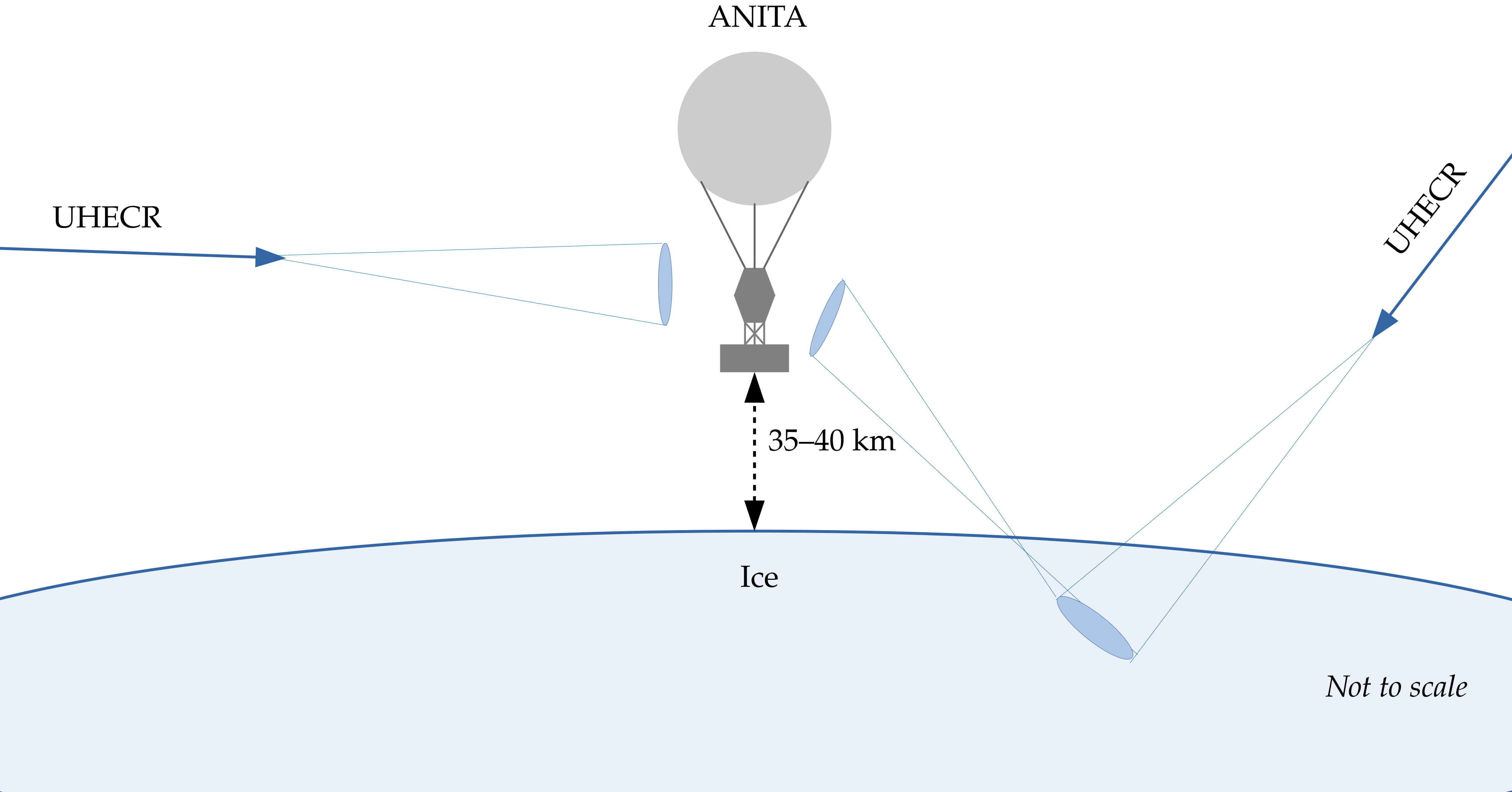
- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

Figures by H. Schoorlemmer and K. D. de Vries

Radio emission: geomagnetic and Askaryan


ANITA
35–40 km
Ice
Not to scale


ANITA
UHECR
35–40 km
Ice
Not to scale


ANITA
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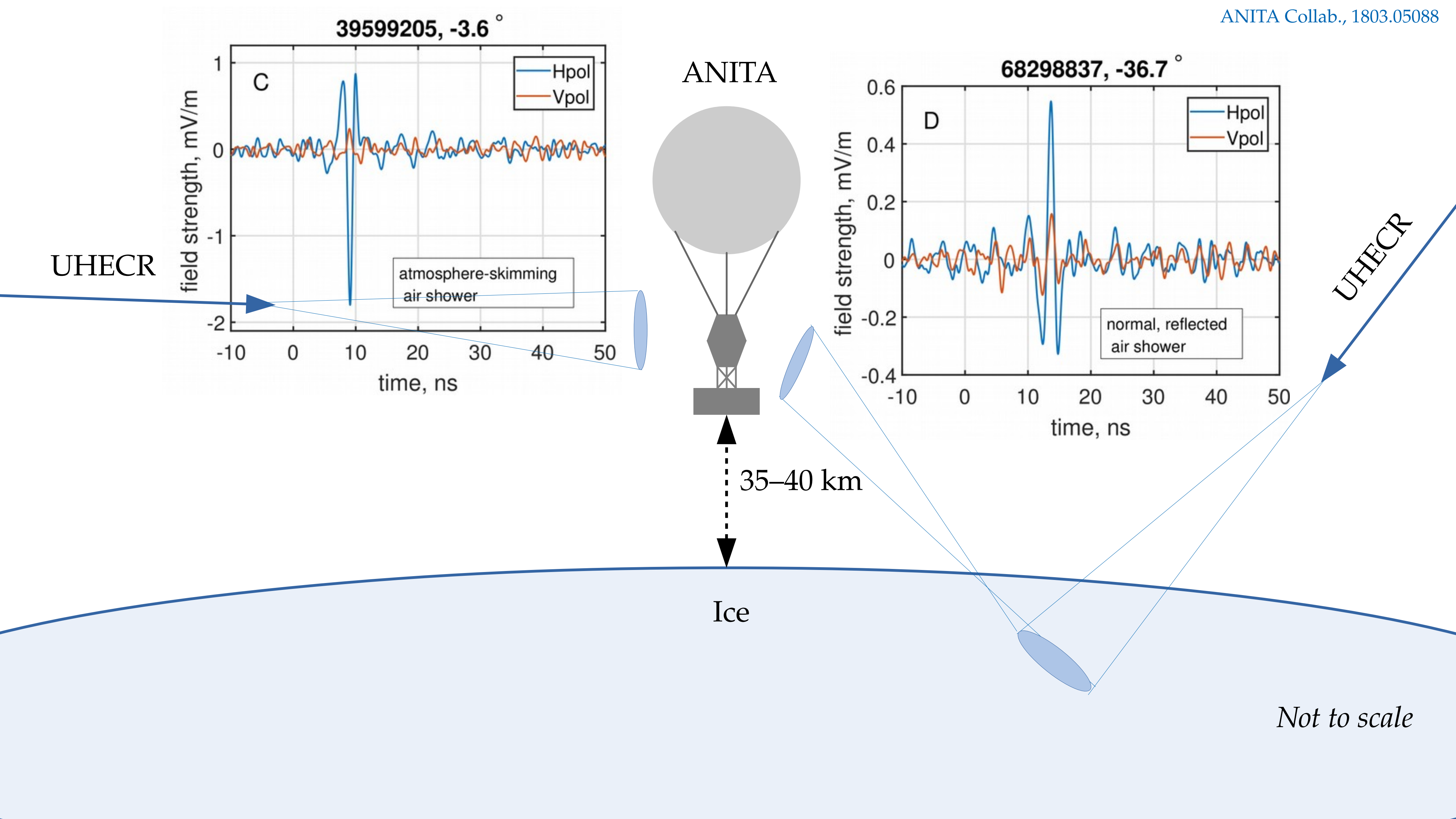
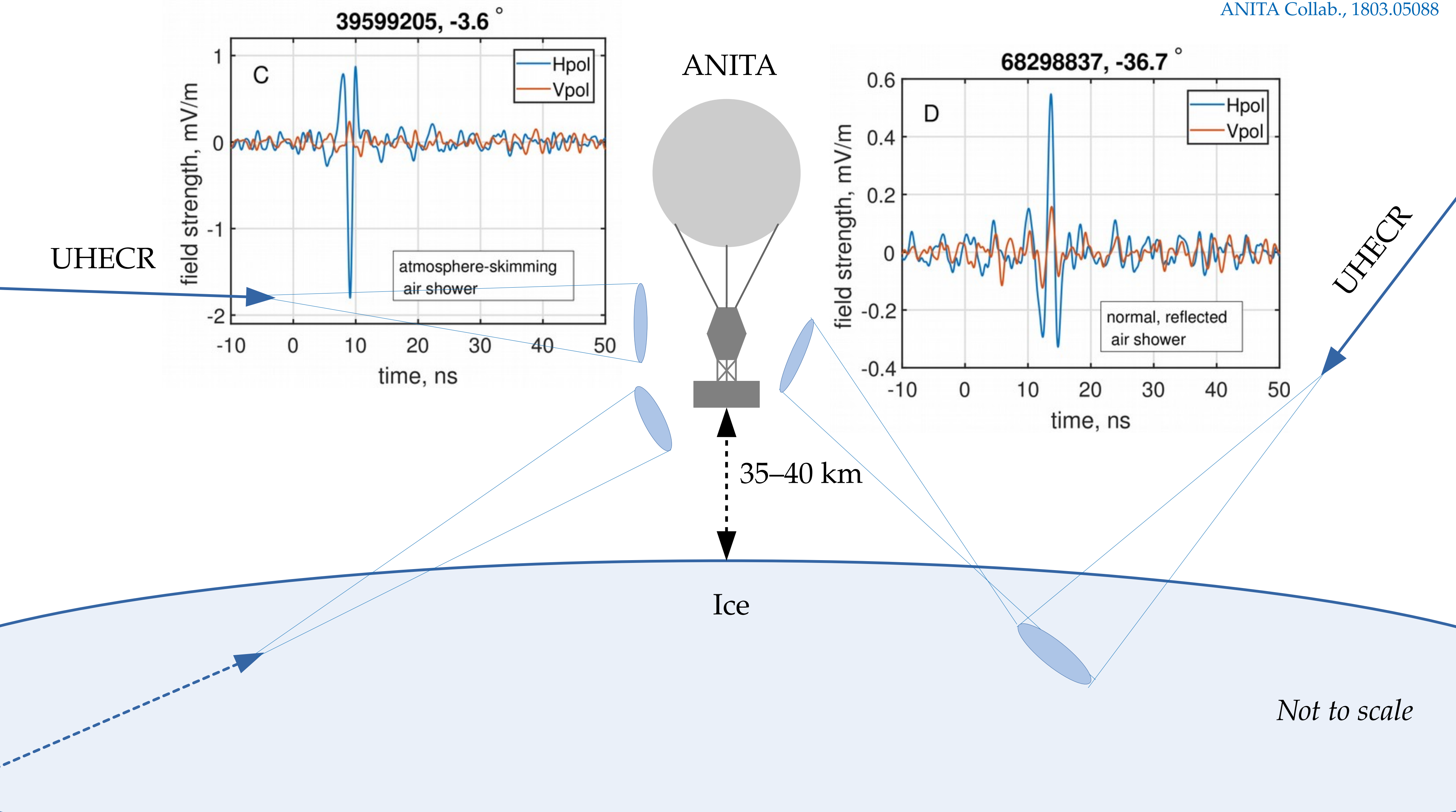
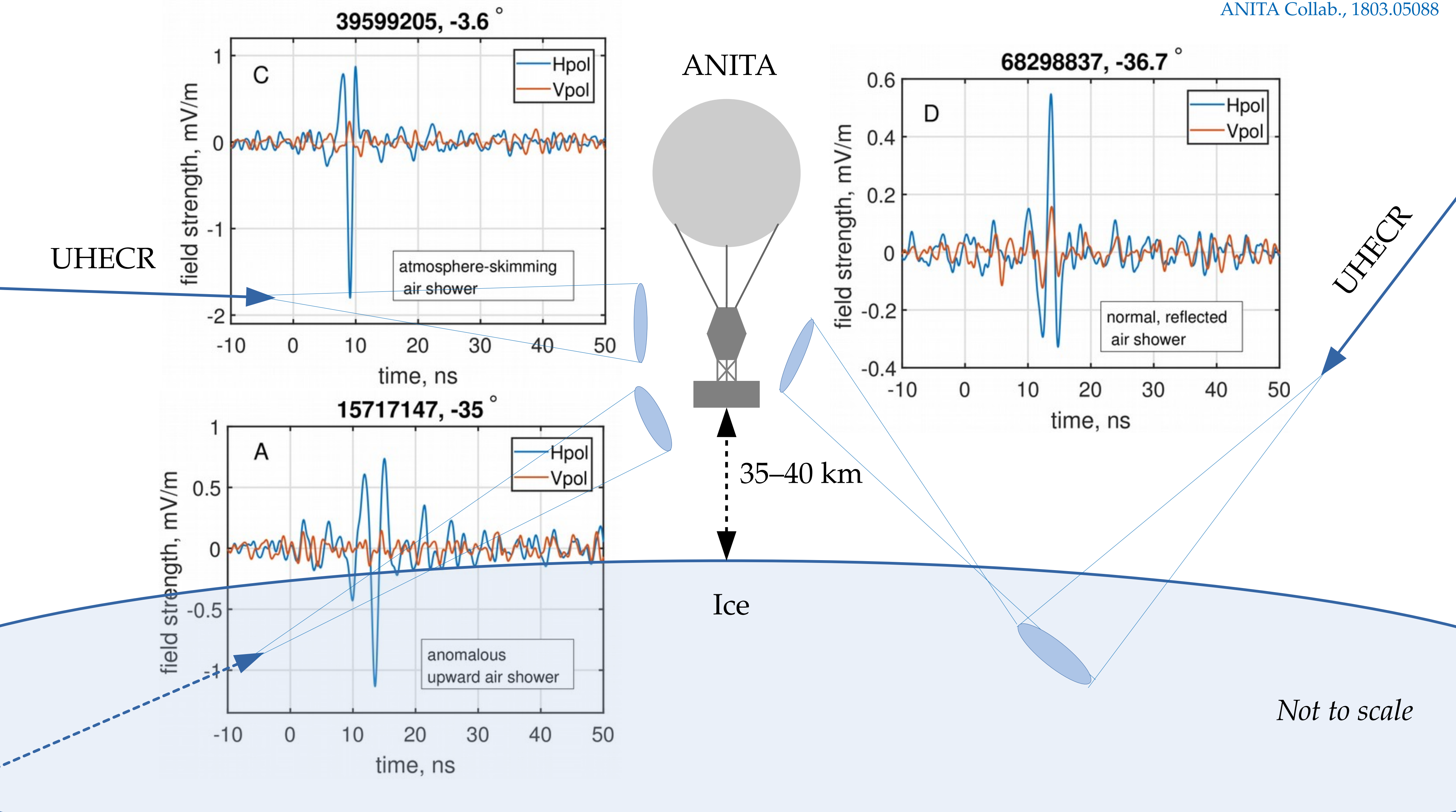
Not to scale


ANITA Collab., 1803.05088
39599205, -3.6 °
C
Hpol
Vpol
field strength, mV/m
time, ns
atmosphere-skimming air shower
UHECR
ANITA
68298837, -36.7 °
D
normal, reflected air shower
35–40 km
Ice
Not to scale

ANITA Collab., 1803.05088




39599205, -3.6 °
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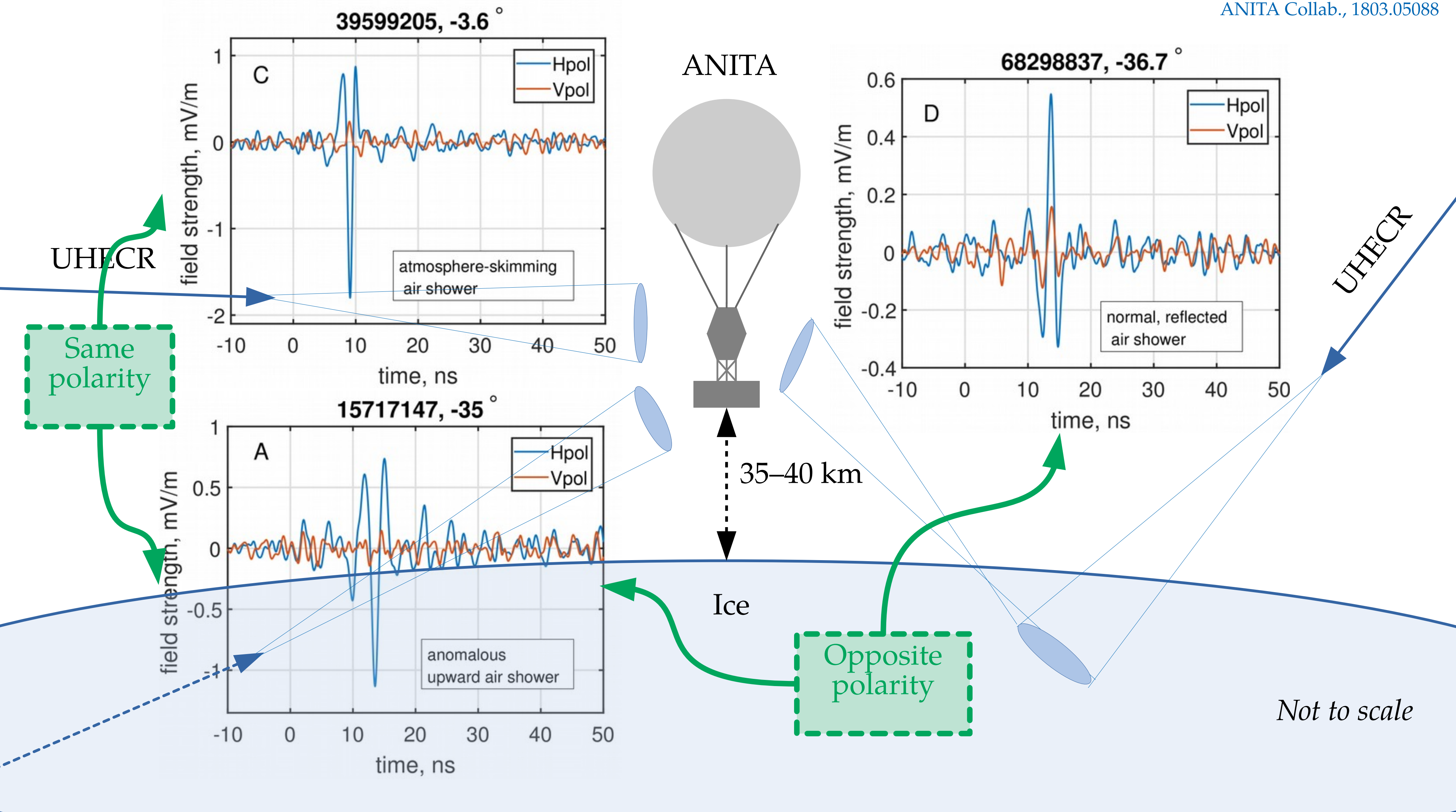
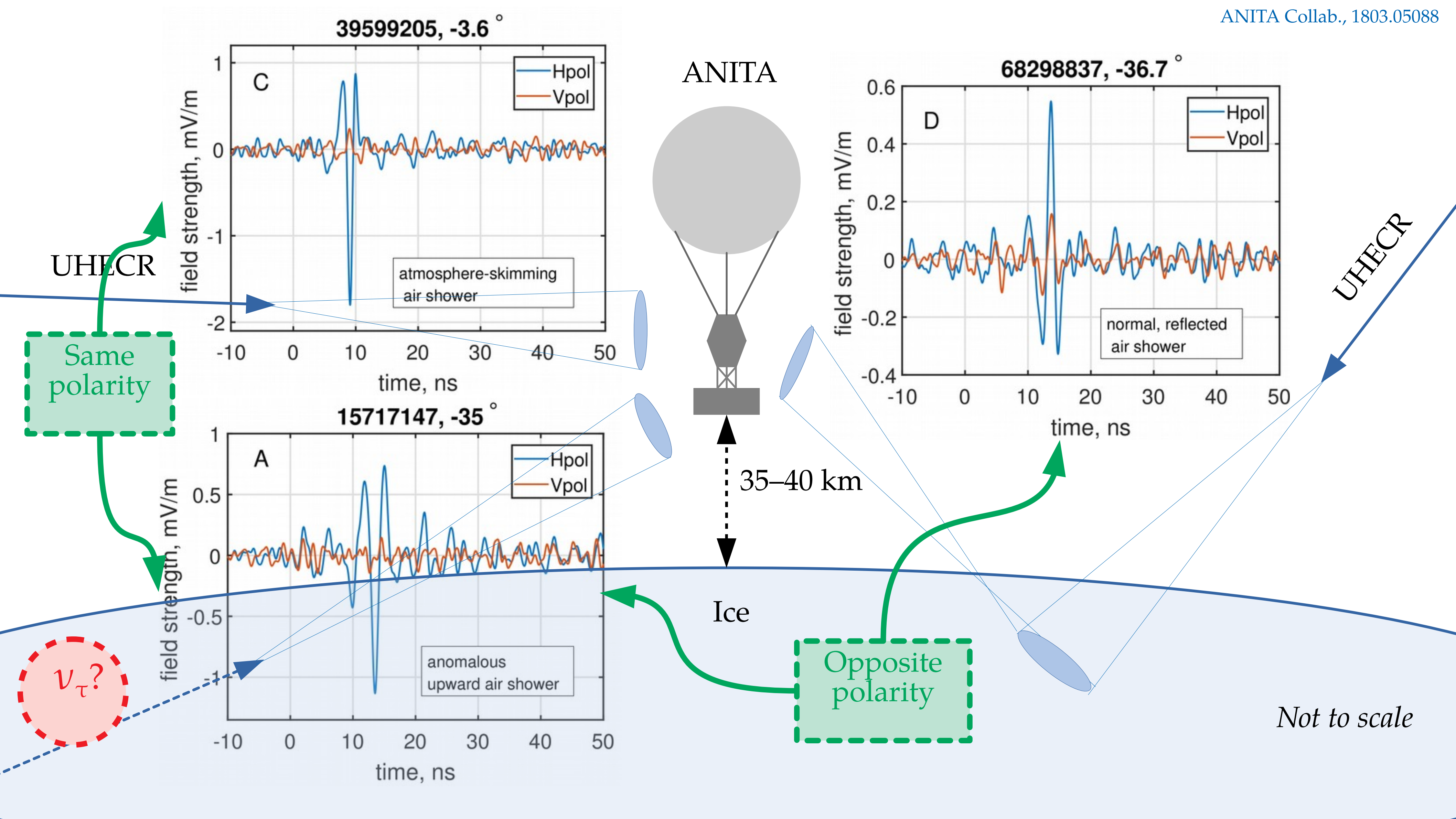
air shower
field strength, mV/m
time, ns
UHECR
ANITA
68298837, -36.7 °
D
Hpol
Vpol
normal, reflected
air shower
field strength, mV/m
time, ns
UHECR
15717147, -35 °
A
Hpol
Vpol
anomalous
upward air shower
field strength, mV/m
time, ns
35–40 km
Ice
Not to scale


39599205, -3.6 °
C
Hpol
Vpol
atmosphere-skimming air shower
field strength, mV/m
time, ns
15717147, -35 °
A
Hpol
Vpol
anomalous upward air shower
field strength, mV/m
time, ns
68298837, -36.7 °
D
Hpol
Vpol
normal, reflected air shower
field strength, mV/m
time, ns
ANITA
UHECR
UHECR
Same polarity
Opposite polarity
35–40 km
Ice
Not to scale


ANITA Collab., 1803.05088
39599205, -3.6 °
C
Hpol
Vpol
atmosphere-skimming air shower
field strength, mV/m
time, ns
ANITA
68298837, -36.7 °
D
normal, reflected air shower
15717147, -35 °
A
anomalous upward air shower
UHECR
Same polarity
35–40 km
Ice
Opposite polarity
ν_τ?
Not to scale

Mystery ANITA events – First UHE ν detected?

- Two upgoing, unflipped-polarity showers:
  - ANITA-1 (2006): 20°±0.3° dec., 0.60±0.4 EeV
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- Estimated background rate: $< 10^{-2}$ events

- Were these showers due to ν_τ? *Unlikely*

- Optical depth to νN interactions at EeV:

$$\frac{\text{Chord inside Earth}}{\text{Interaction length in Earth}} = \frac{7000\text{ km}}{390\text{ km}} = 18$$

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ANITA Collab., *PRL* 2016 + 1803.05088

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Transient astrophysical event?

- **ANITA-1 event:** none associated
- **ANITA-3 event:**
  - Type-Ia SN2014dz ($z = 0.017$)
  - Within 1.9°, 5 hours before event
  - Probability of chance SN: 3×10^{-3}
  - ν luminosity must exceed bolometric luminosity of 4×10^{42} erg s^{-1}

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