Perspectives of multimessenger astrophysics

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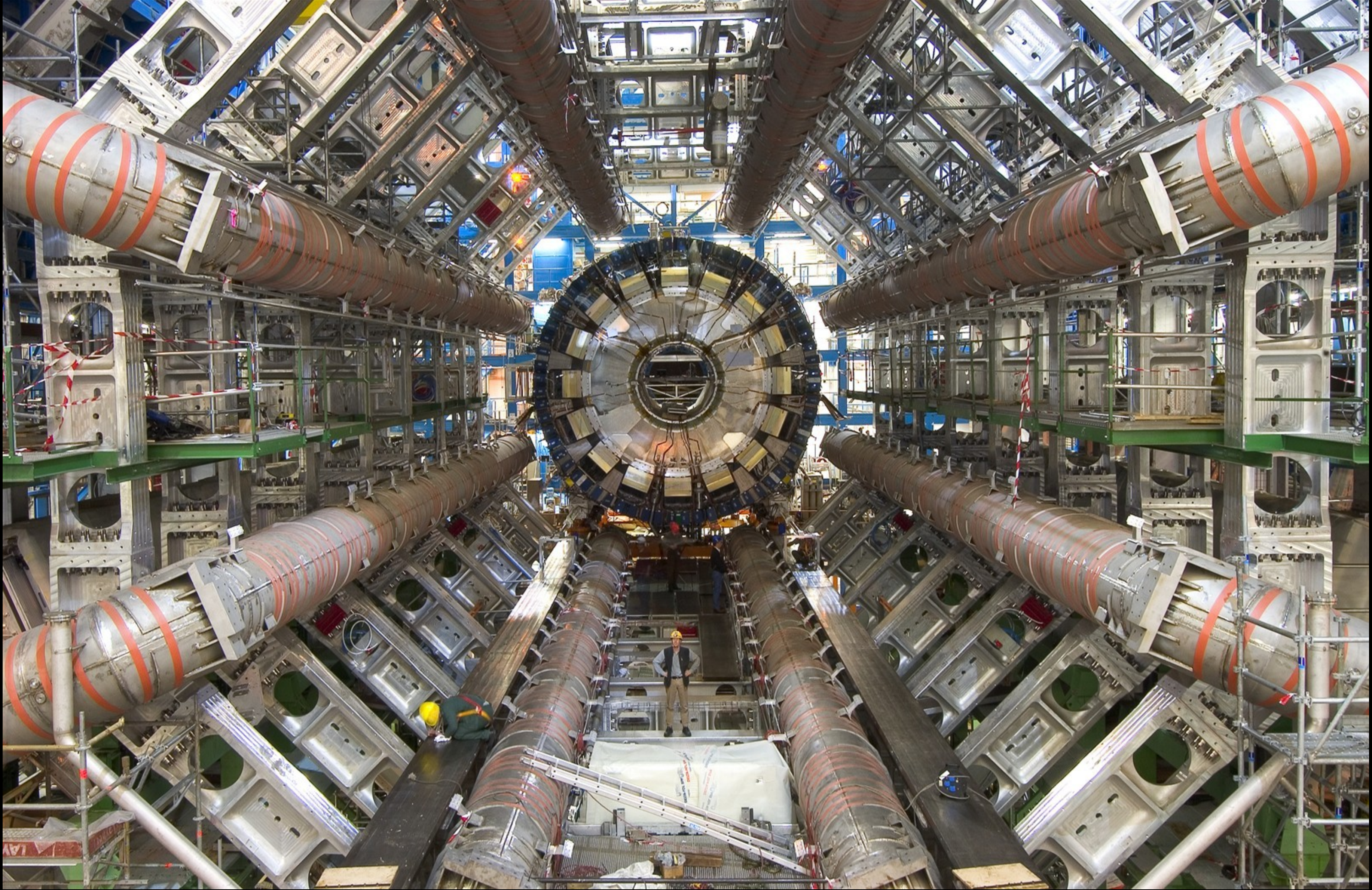
Niels Bohr Institute, University of Copenhagen

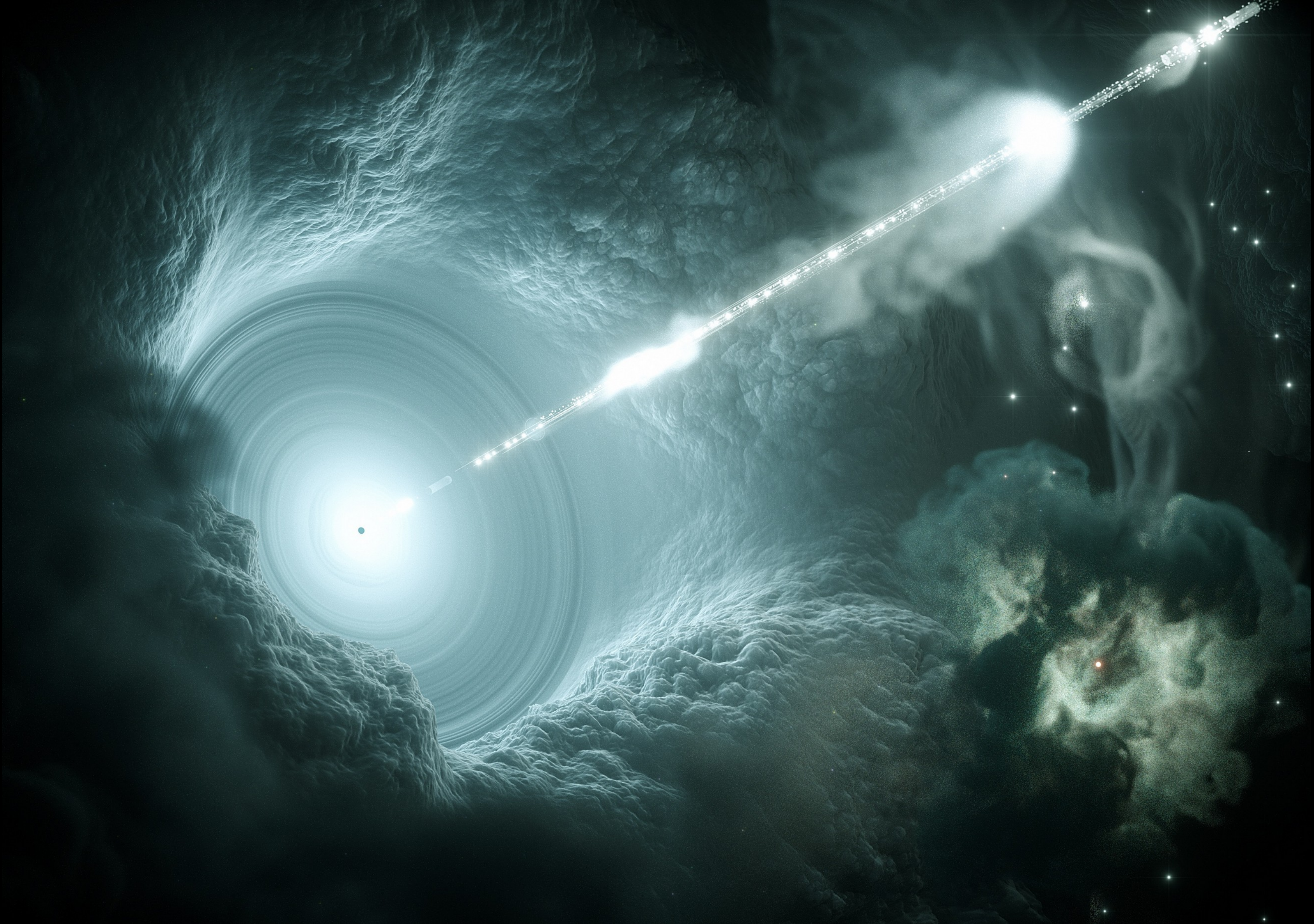
Invisibles23 School
August 21–26, 2023

UNIVERSITY OF
COPENHAGEN

VILLUM FONDEN

High-energy cosmic neutrinos


ATLAS



DESY

DESY

Neutrinos are elementary particles,

electrically neutral,

very light,

and superbly antisocial

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Neutrinos are $\underbrace{\text{elementary particles}}_{=\ \textit{indivisible}}$,

$\underbrace{\text{electrically neutral}}_{=\ \textit{no electric charge}}$,

$\underbrace{\text{very light}}_{=\ \textit{so light that we don't know their mass!}}$,

and $\underbrace{\text{superbly antisocial}}_{=\ \textit{barely interact with matter}}$

Neutrinos are everywhere: even *you* make them!

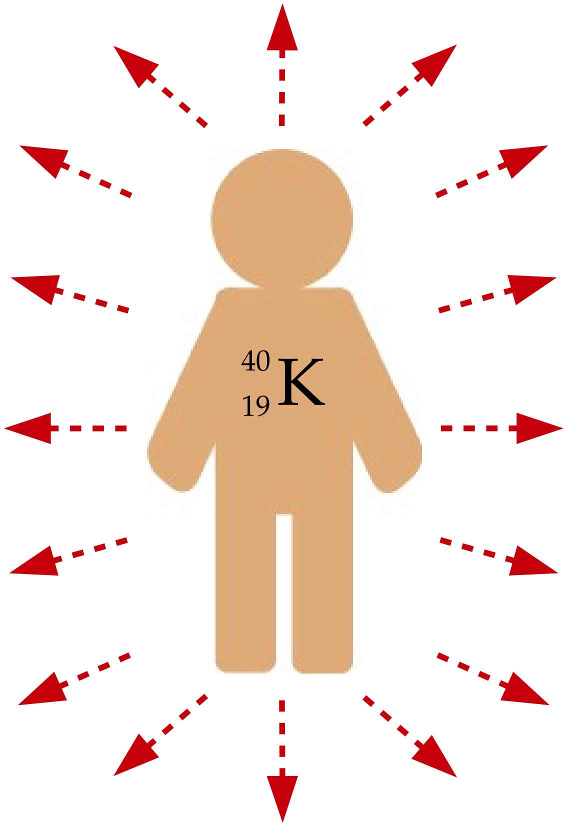
Some of the potassium
in bananas is radioactive

Potassium-40 has a half-life
of ~ 1 billion years:

$$e^- + {}^{40}_{19}\mathrm{K} \longrightarrow {}^{40}_{18}\mathrm{Ar} + \nu_e$$

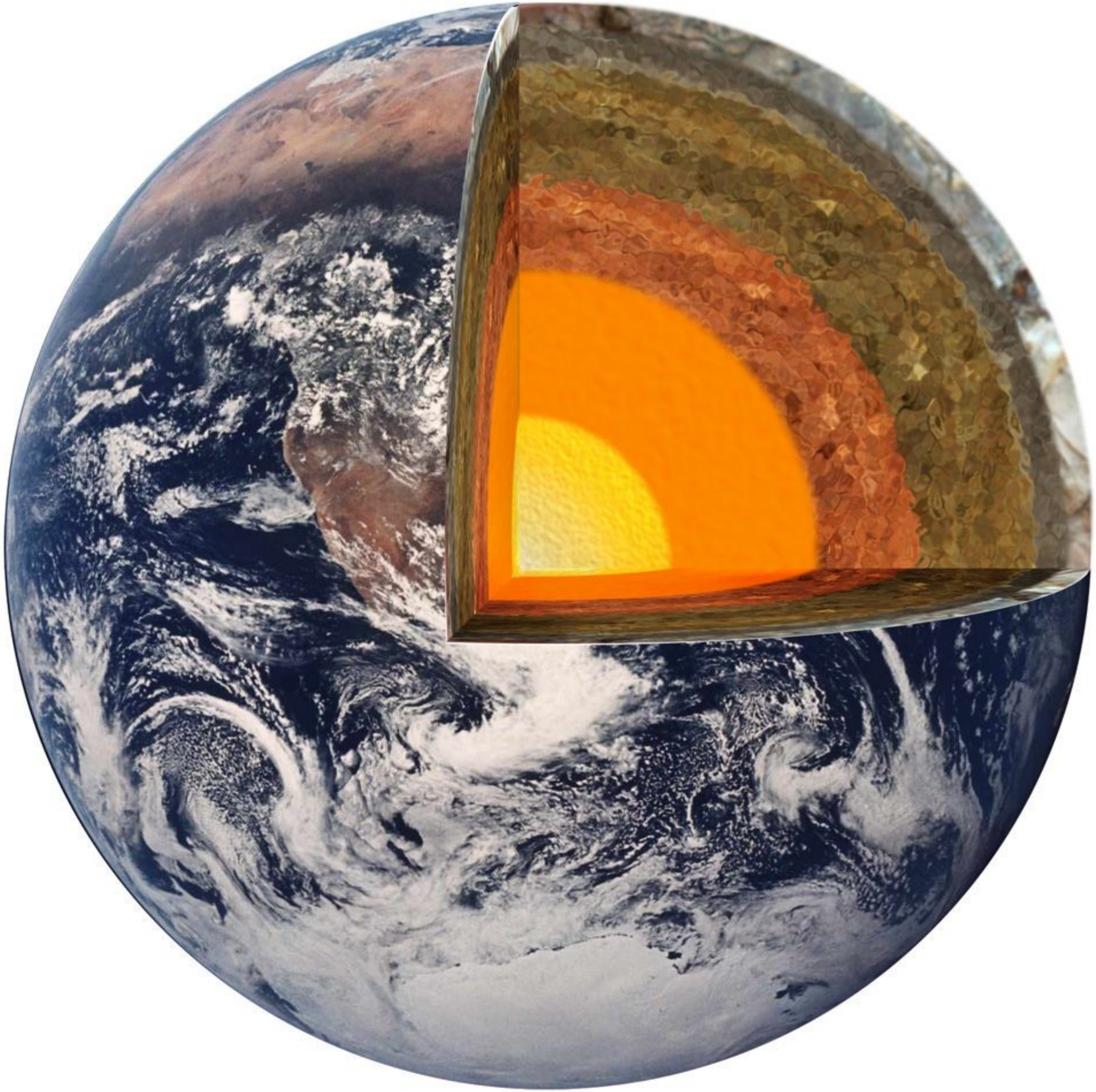
$$ {}^{40}_{19}\mathrm{K} \longrightarrow {}^{40}_{18}\mathrm{Ar} + e^+ + \nu_e + \gamma$$

$$ {}^{40}_{19}\mathrm{K} \longrightarrow {}^{40}_{20}\mathrm{Ca} + e^- + \overline{\nu}_e$$

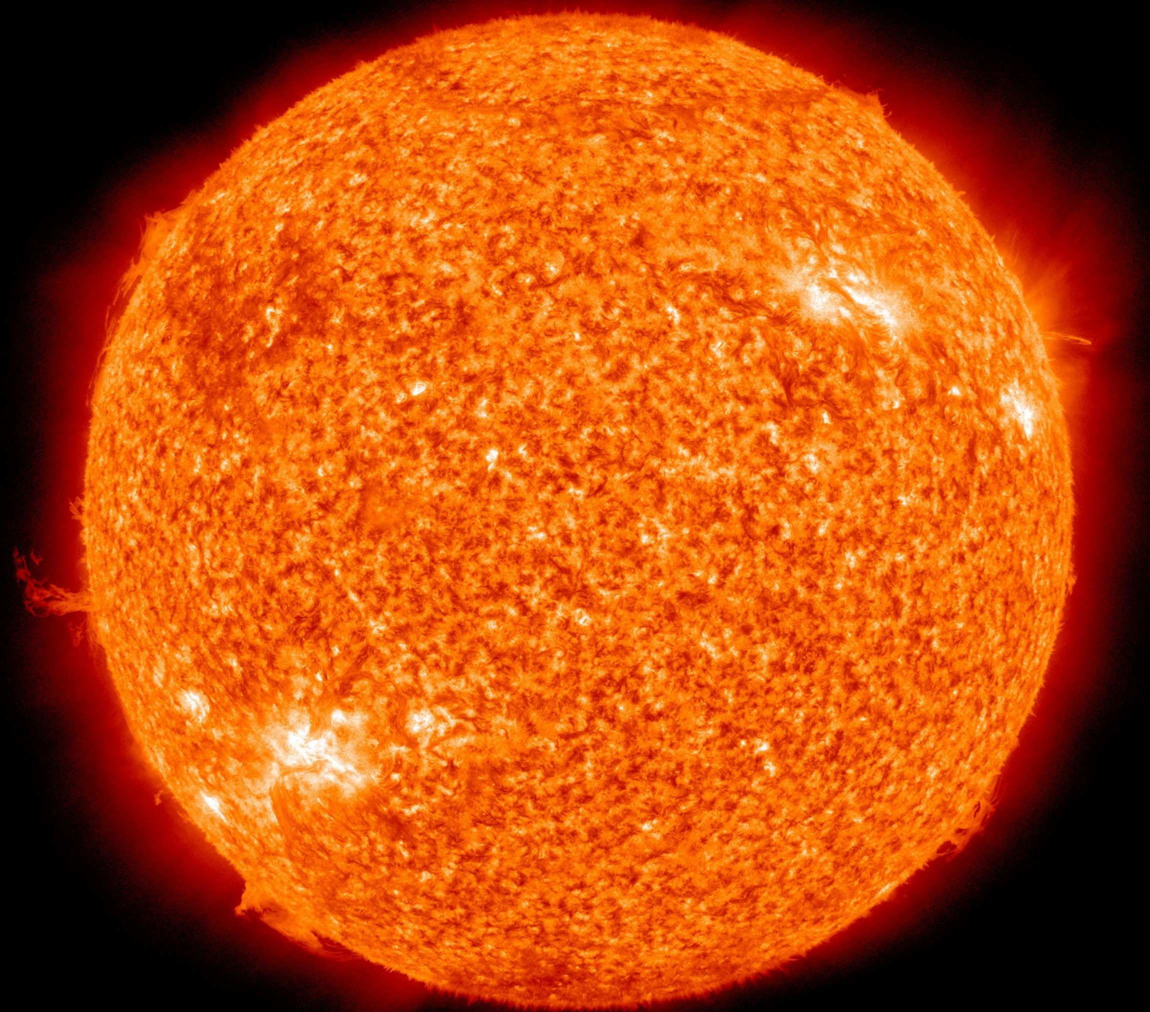


4000+ neutrinos emitted each second by a 70-kg person

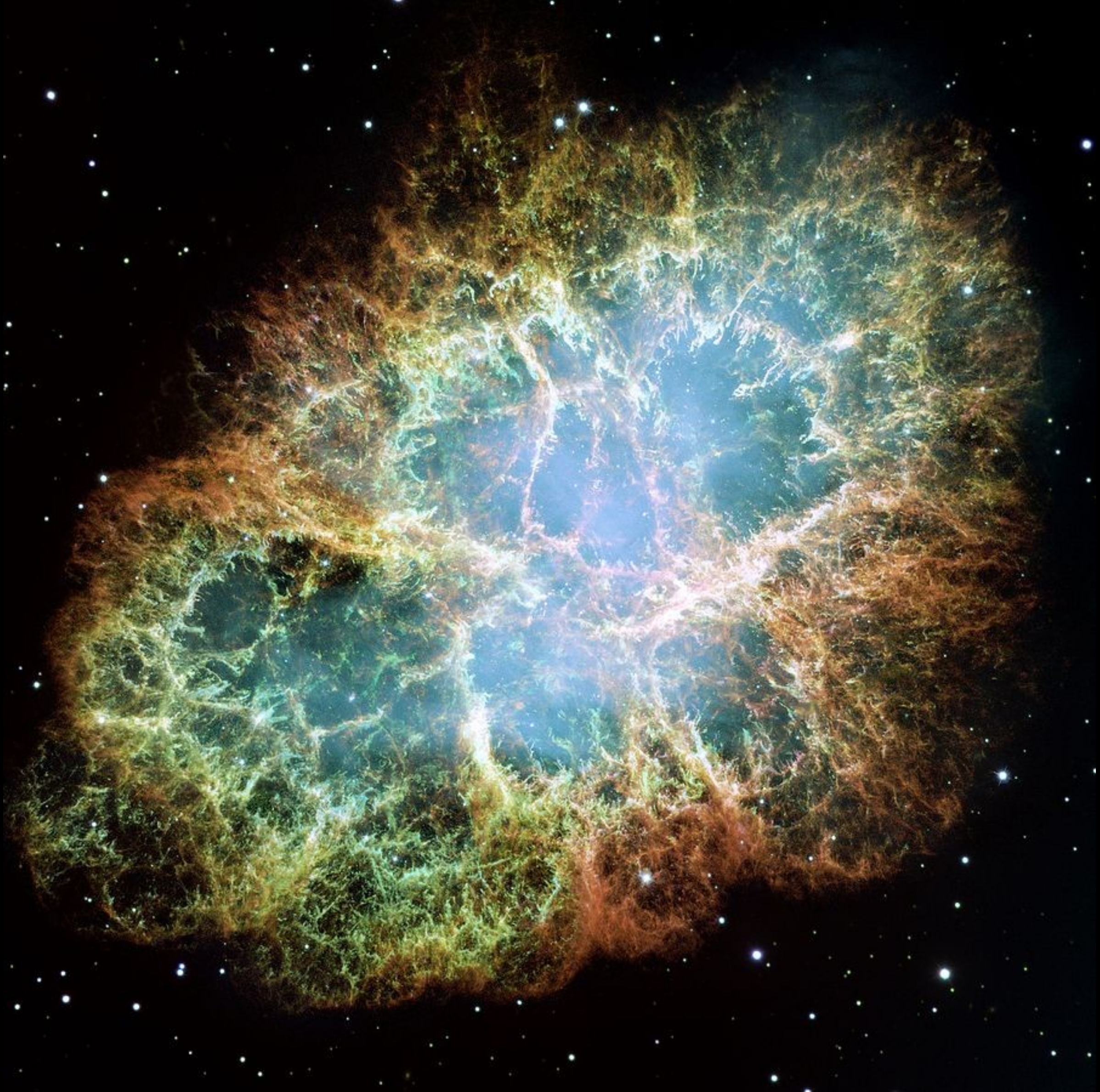
Avda



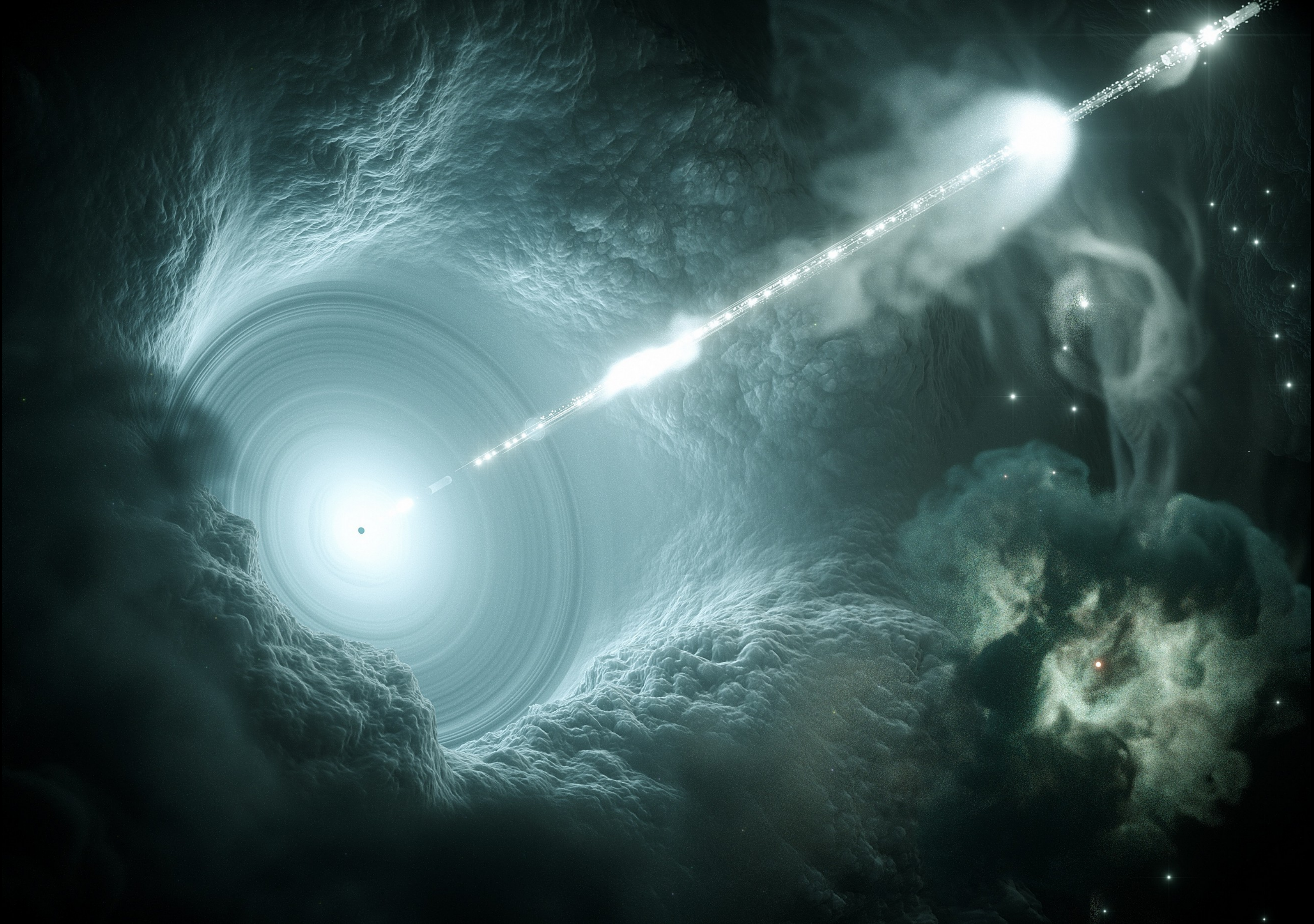
Australian National University



NASA



NASA, ESA



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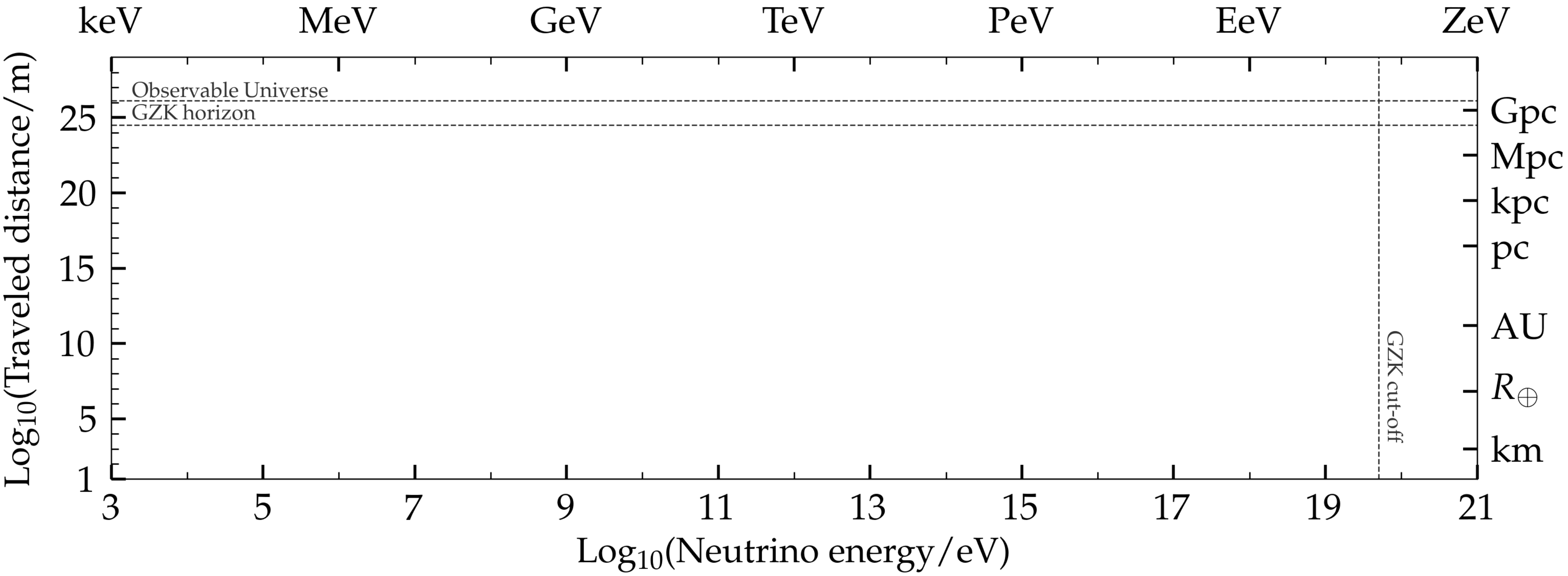
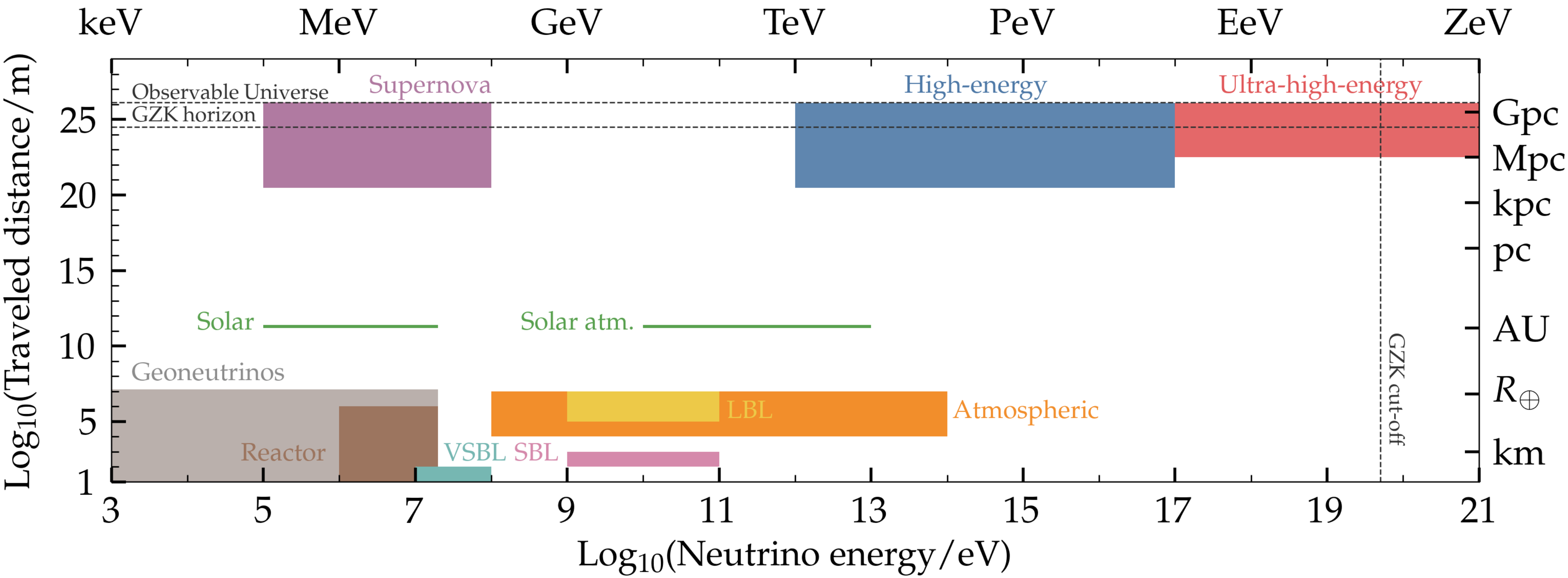
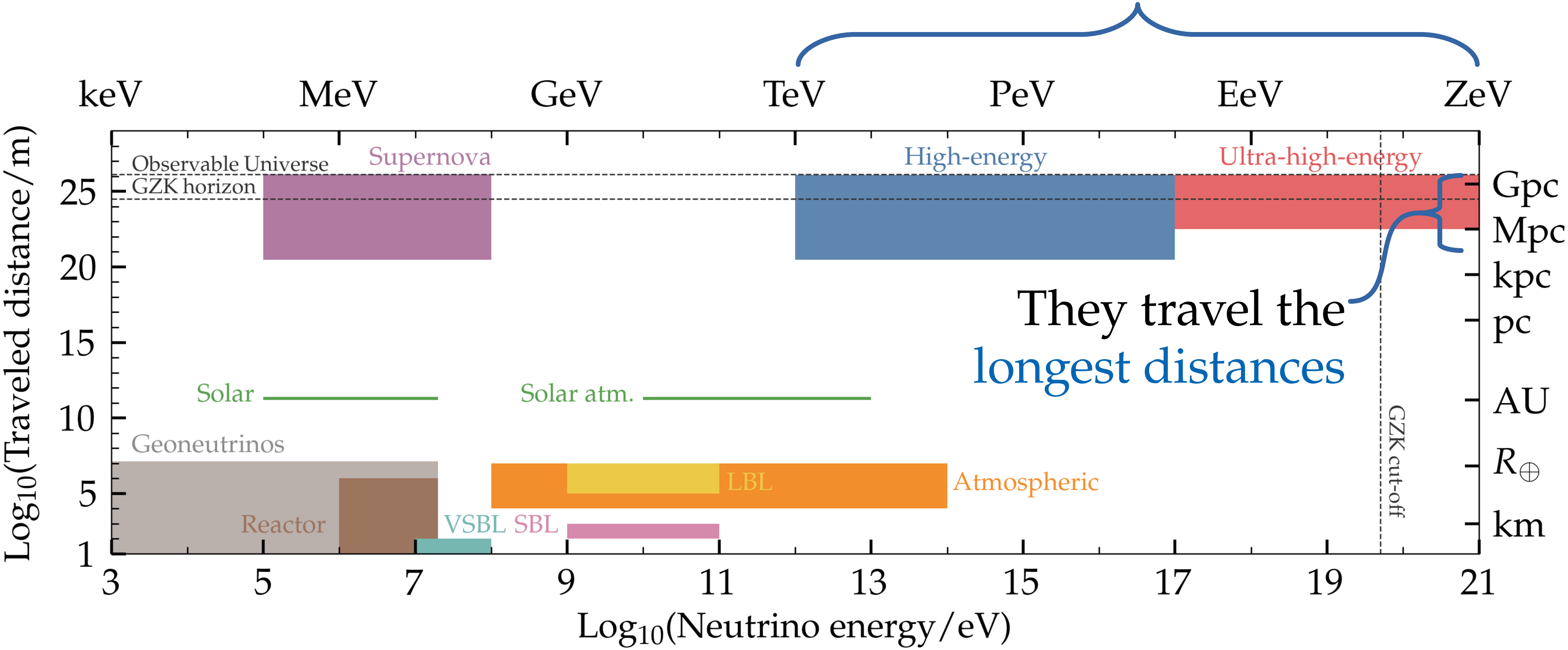


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



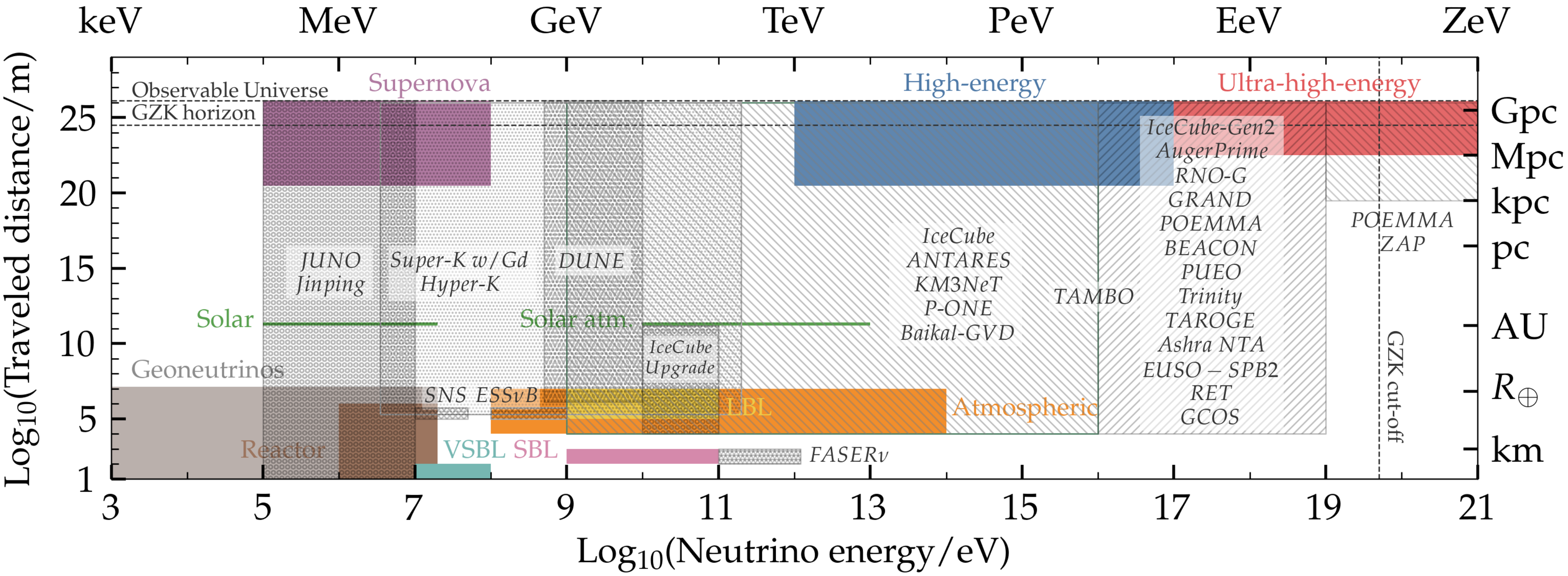
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

They have the highest energies



They travel the longest distances

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



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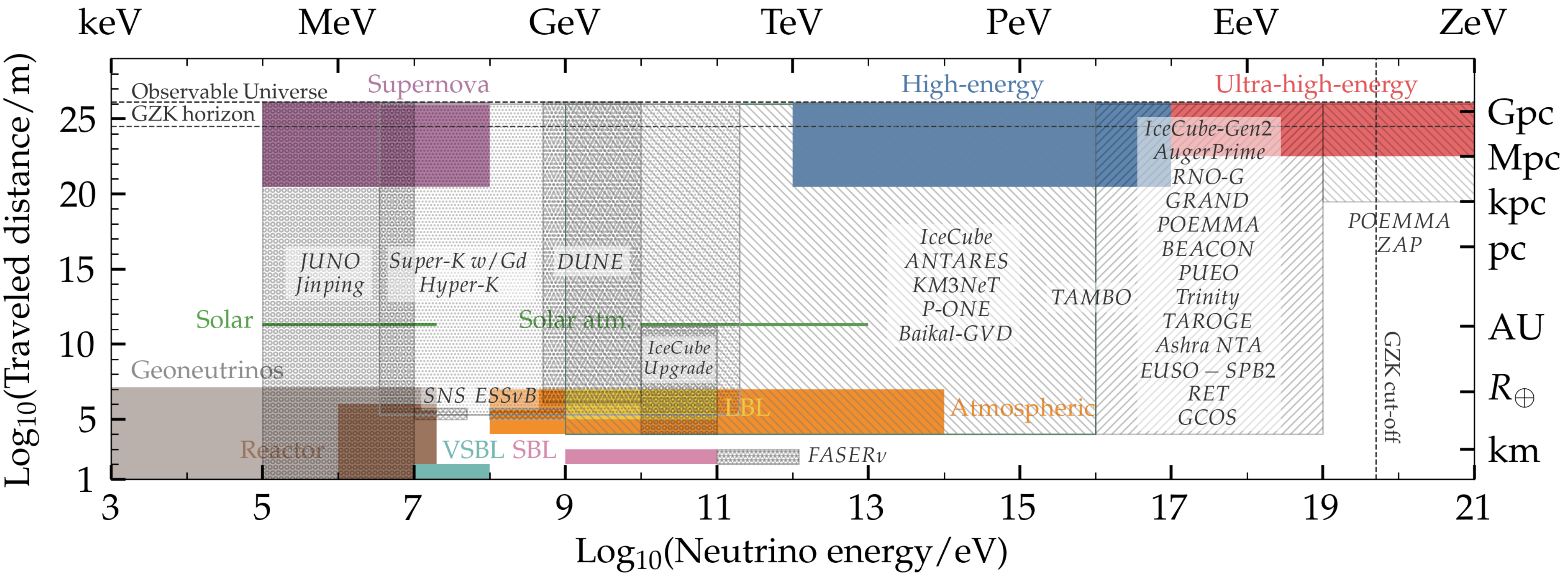
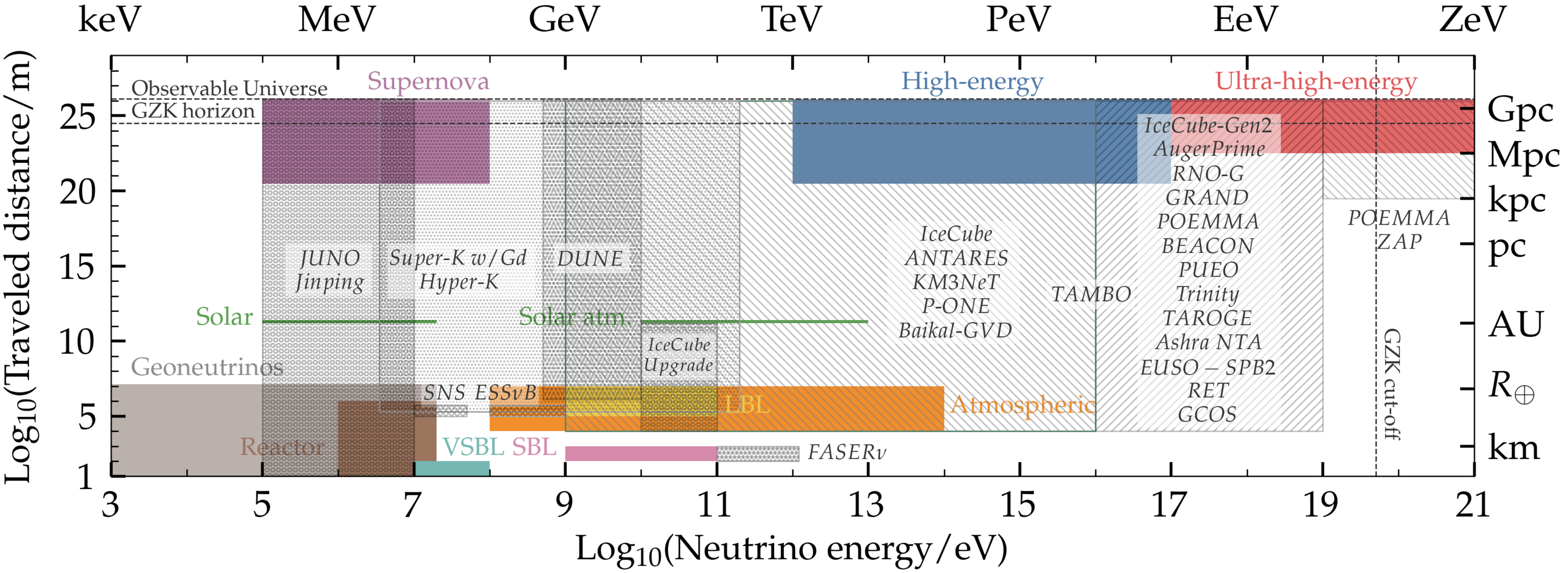


Synergies with lower energies

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

Discovered in 2013
by IceCube



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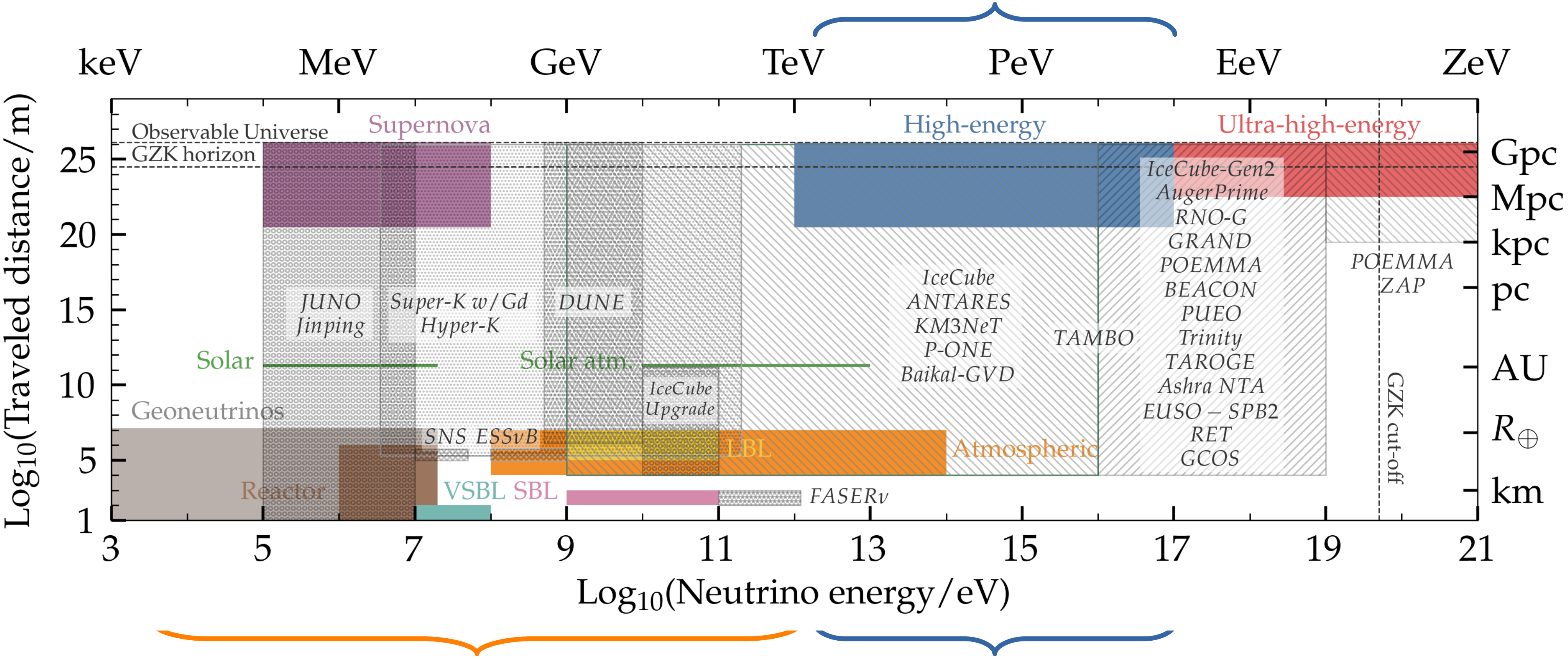

Synergies with lower energies

Increase TeV–PeV
ν statistics

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

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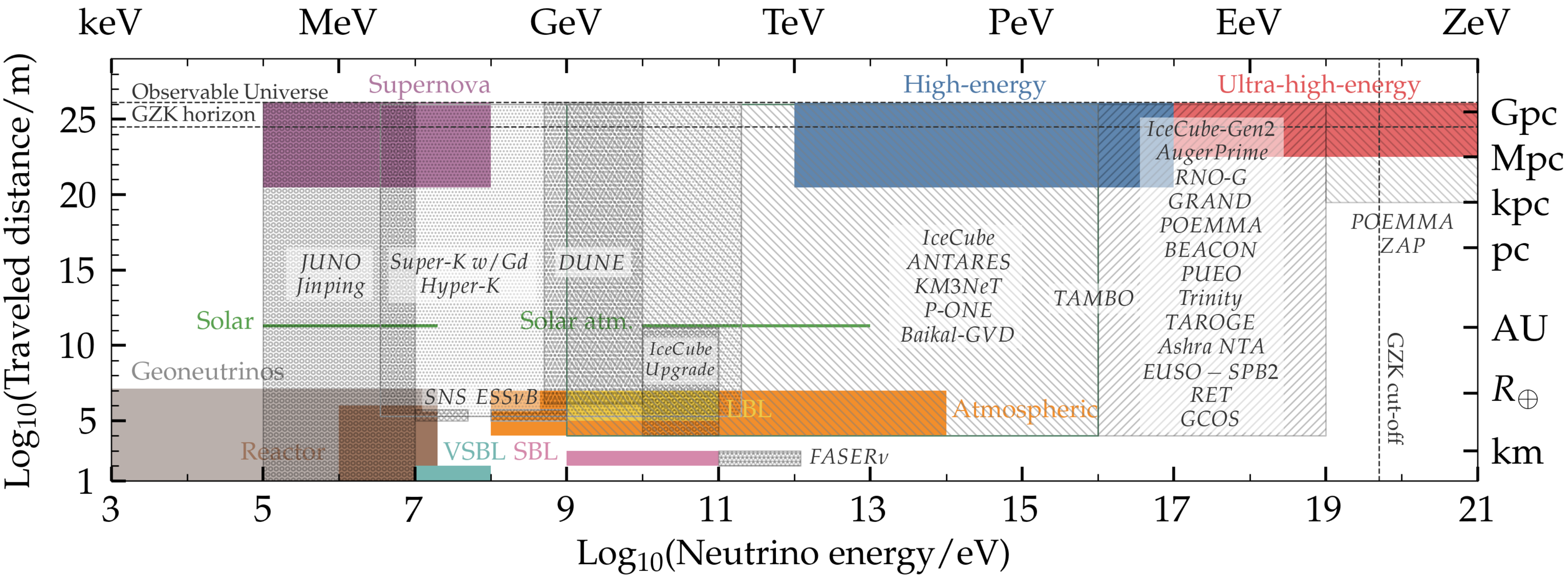

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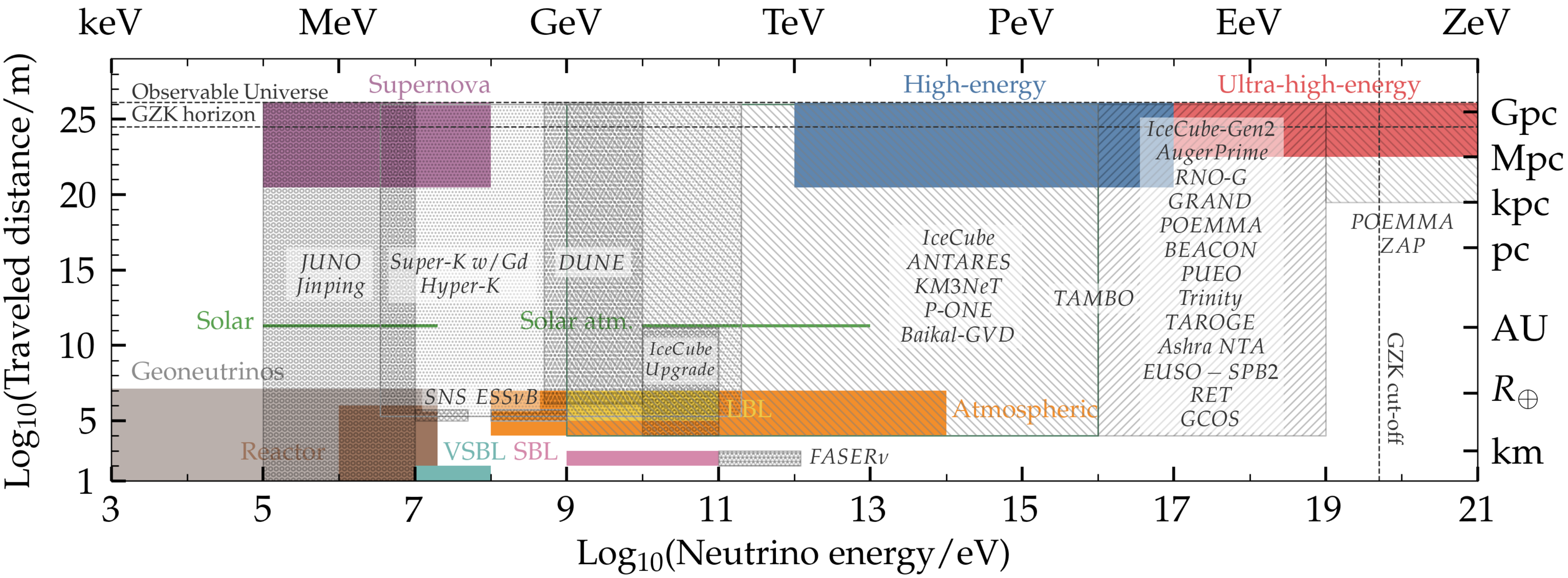

Synergies with lower energies

Increase TeV–PeV
ν statistics

Discover > EeV ν

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

Today

TeV–PeV ν

Next decade

$>$ 100-PeV ν

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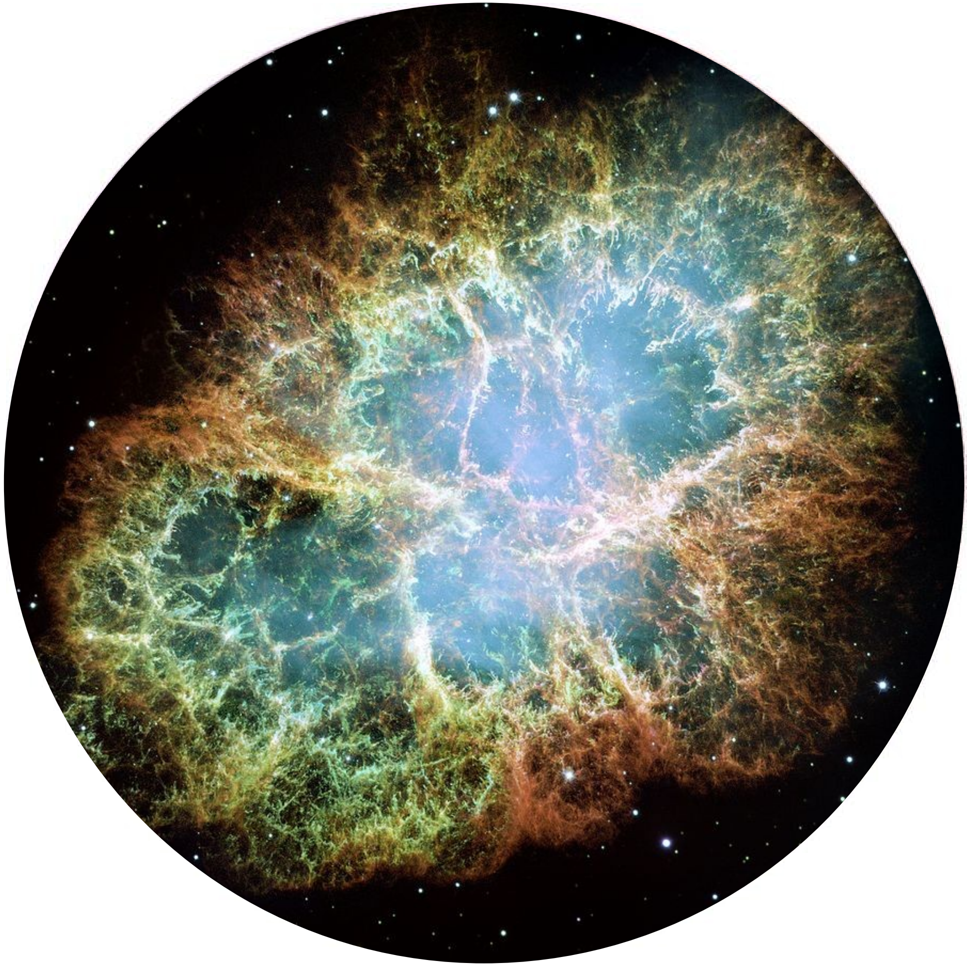

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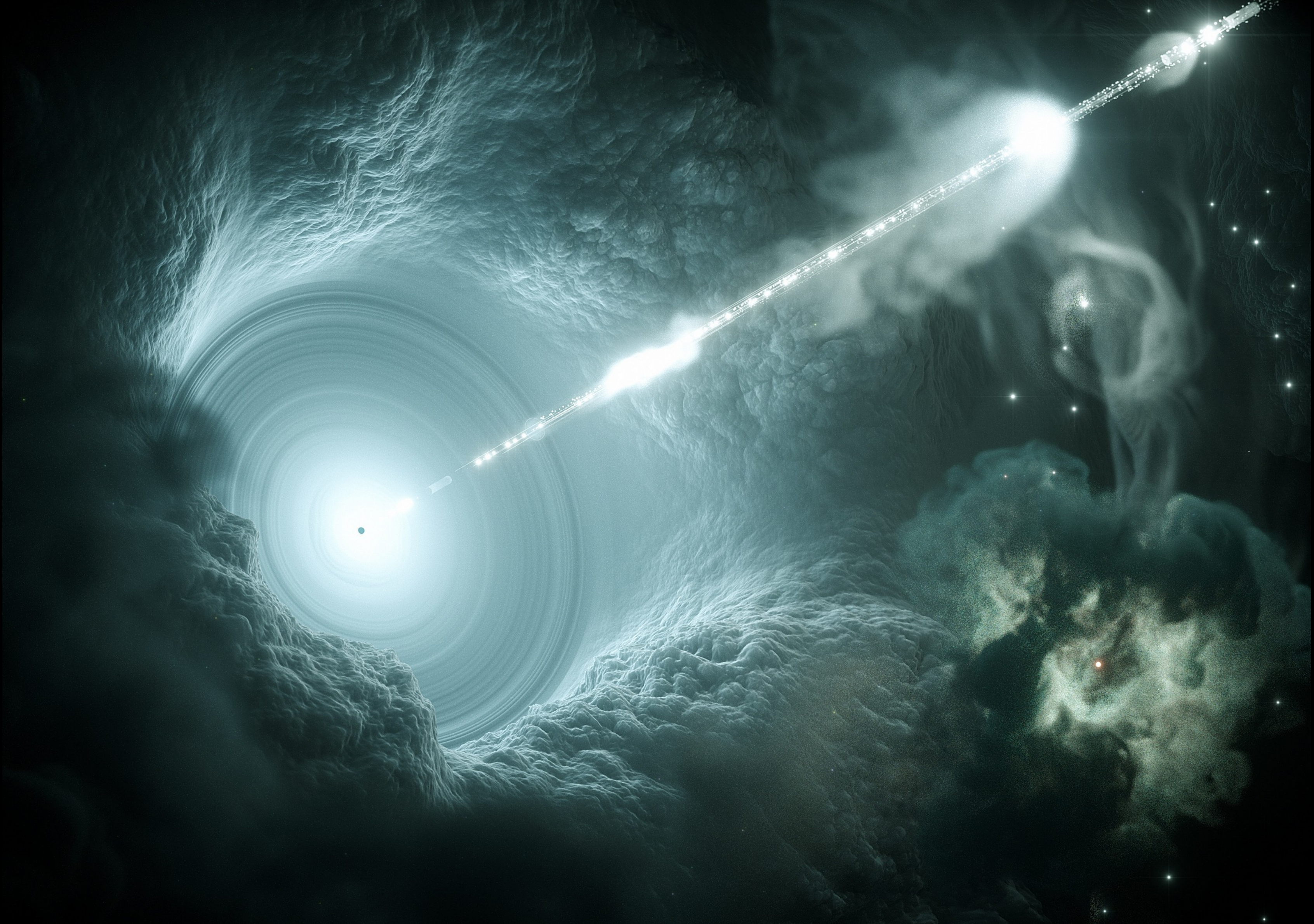

DESY

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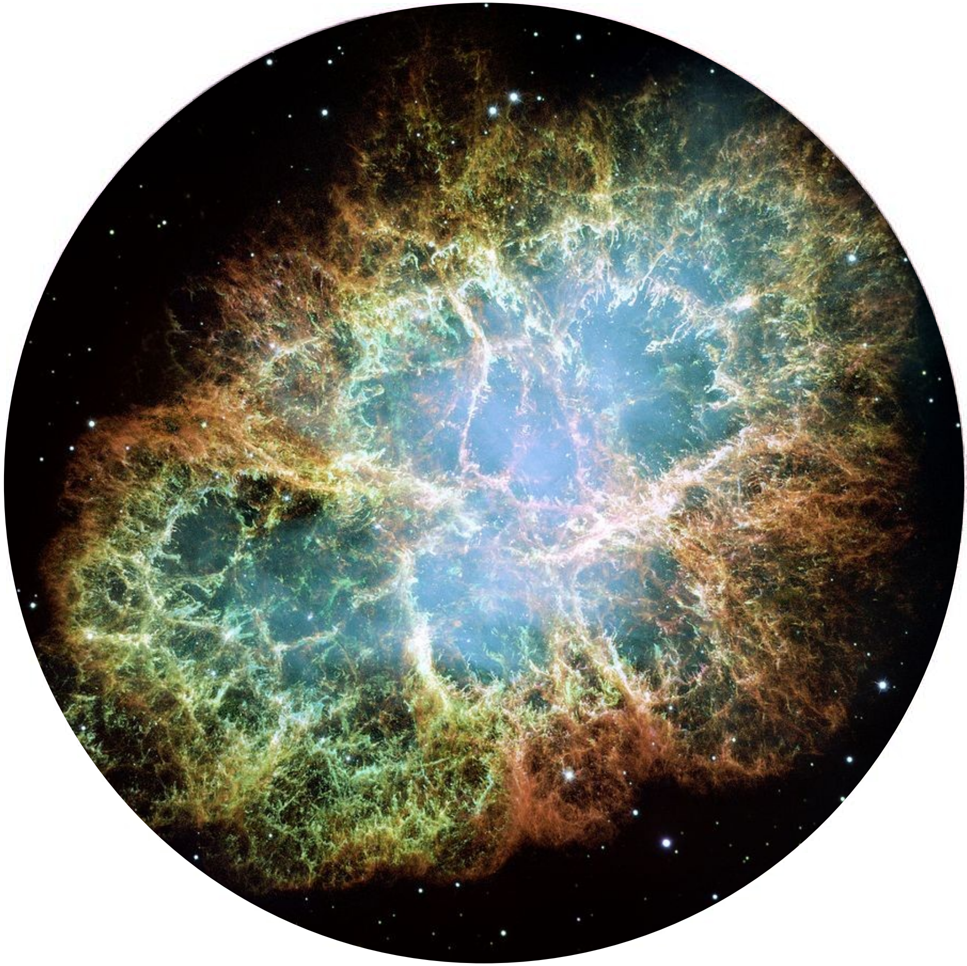

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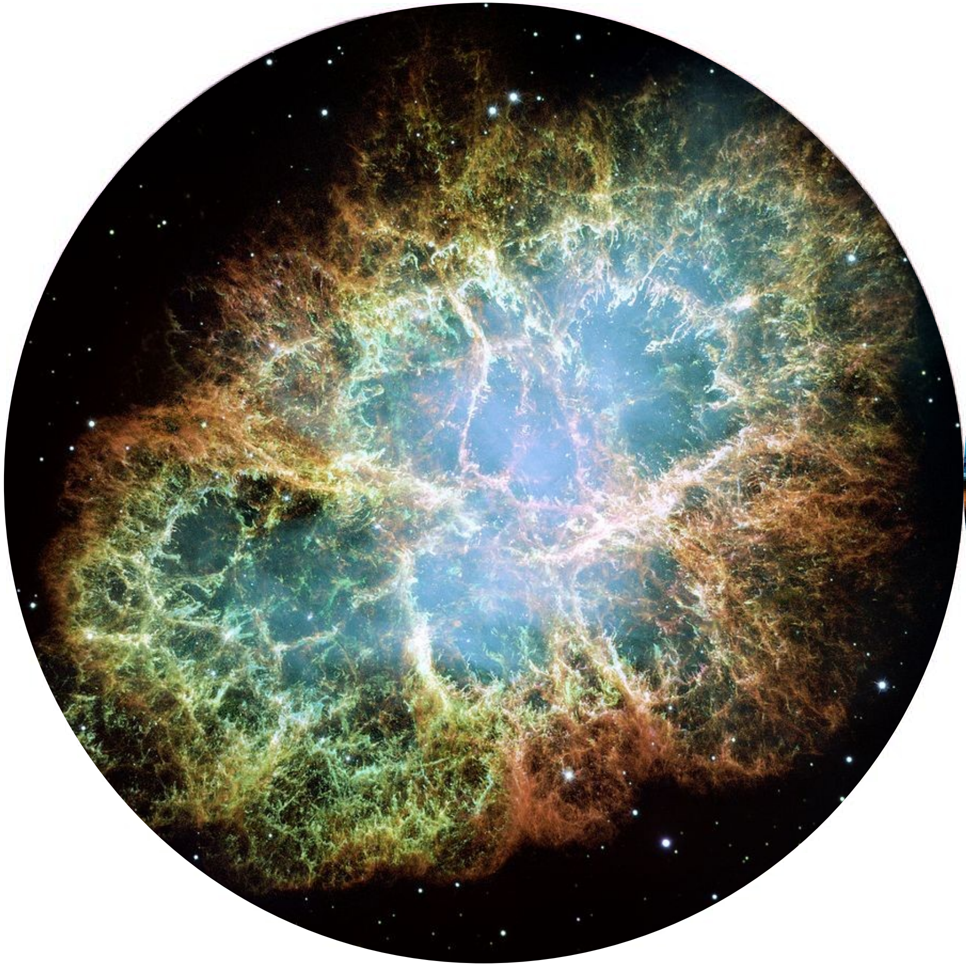

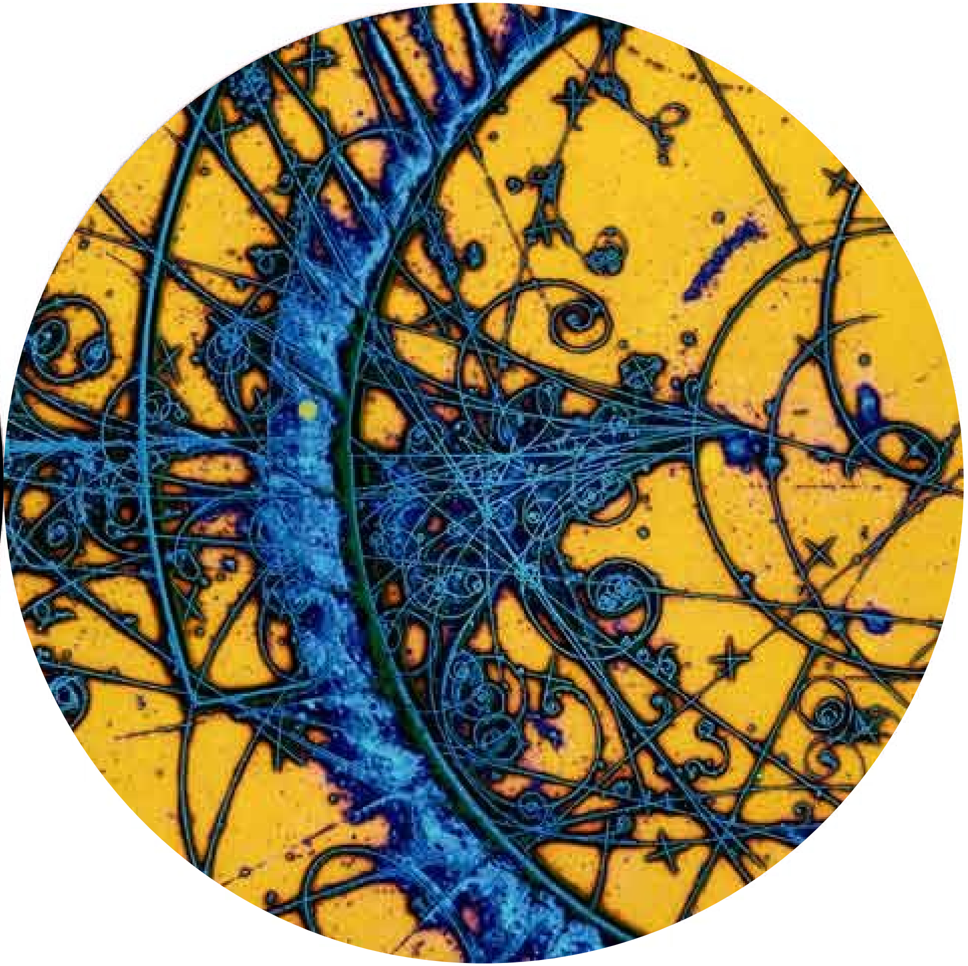

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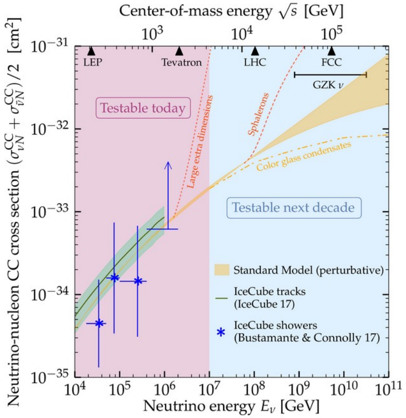
TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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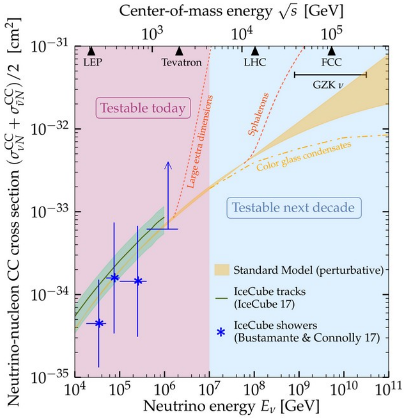
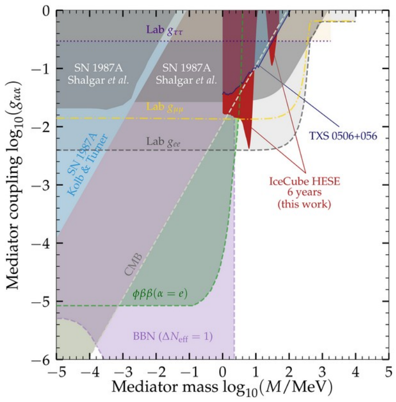


MB & Connolly, *PRL* 2019

ν self-interactions



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

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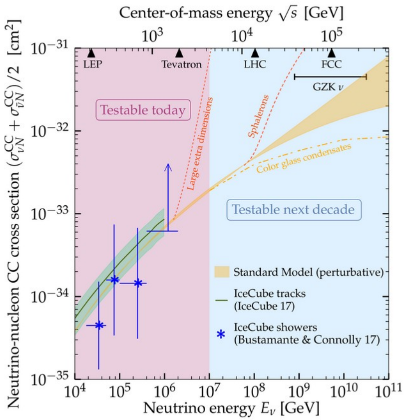

MB & Connolly, *PRL* 2019

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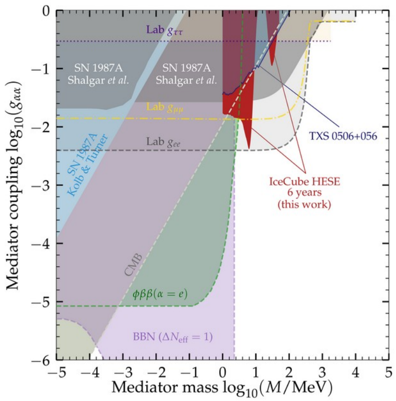
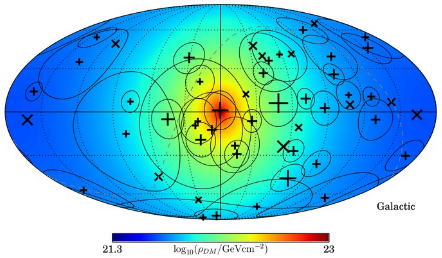


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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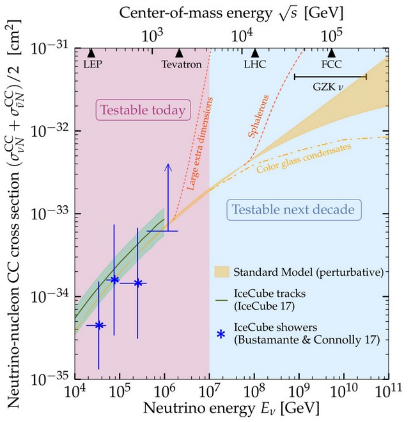

MB & Connolly, *PRL* 2019

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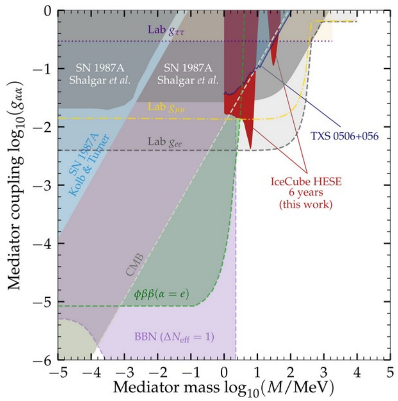

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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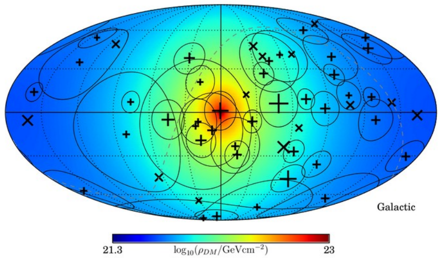
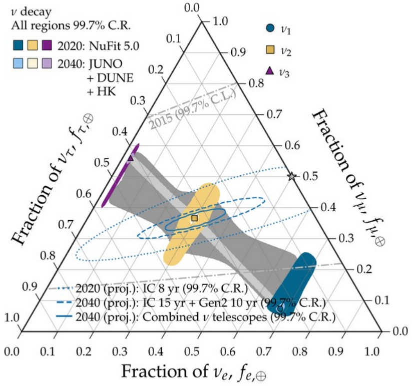


Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



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

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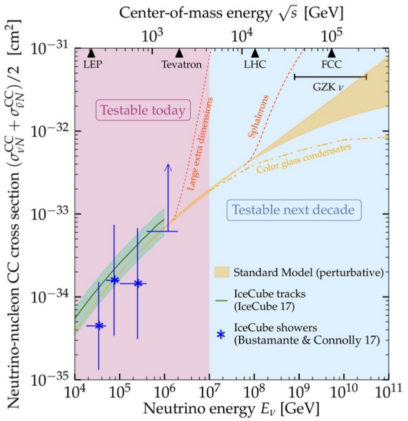

MB & Connolly, *PRL* 2019

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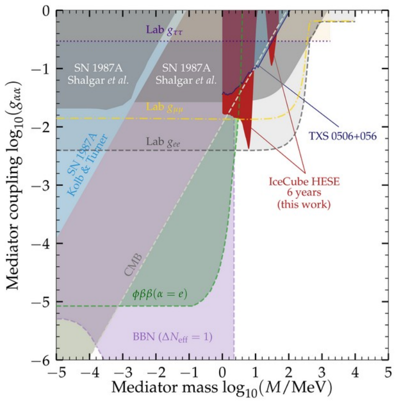

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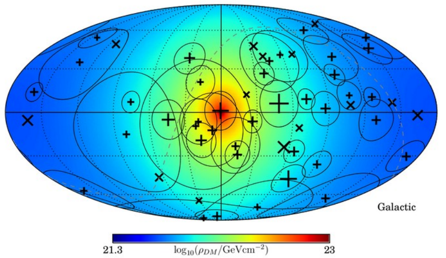

Argüelles, Kheirandish, Vincent, *PRL* 2017

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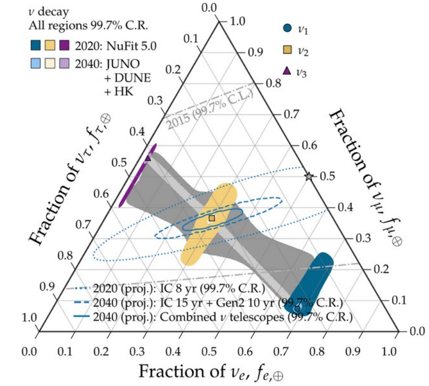
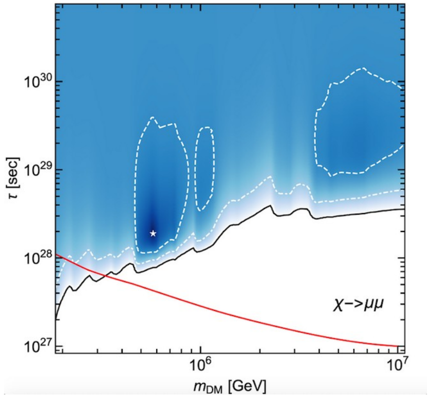


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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

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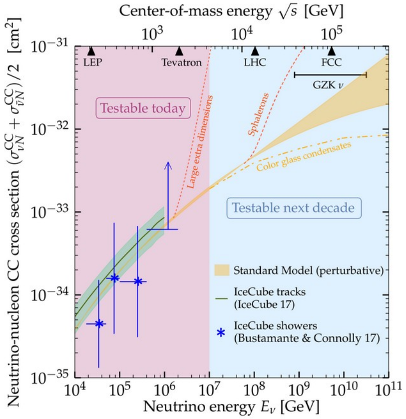

MB & Connolly, *PRL* 2019

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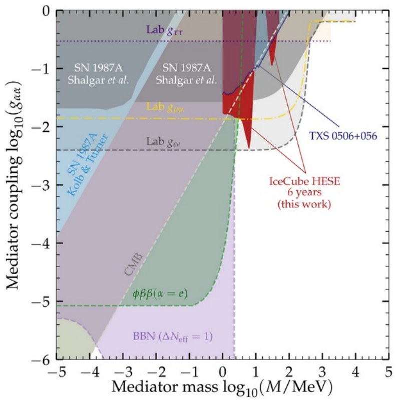
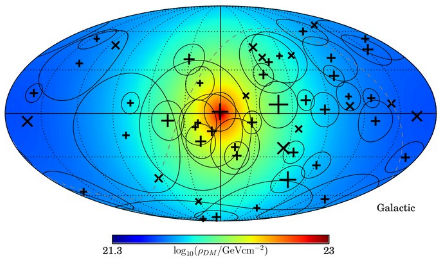


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



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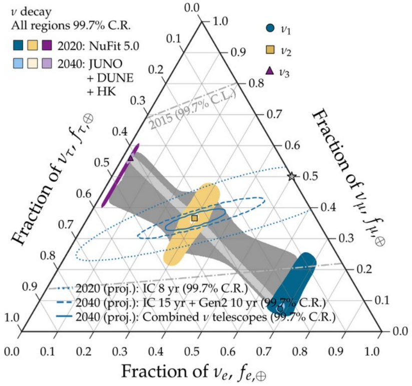

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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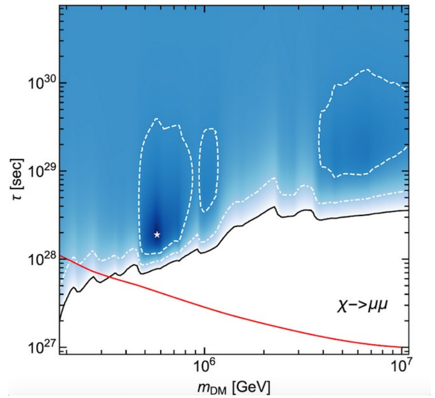
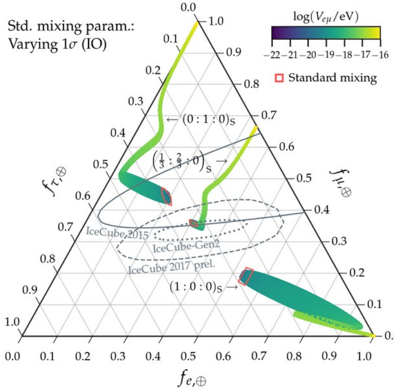


Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



MB & Agarwalla, *PRL* 2019

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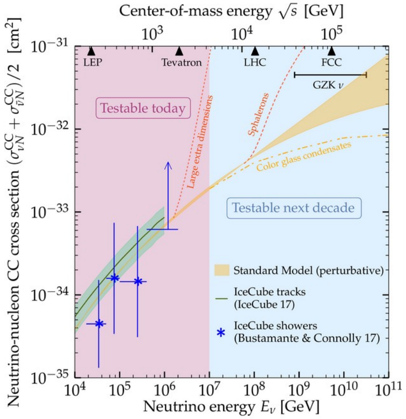

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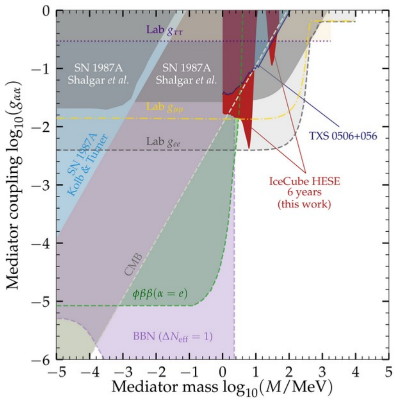

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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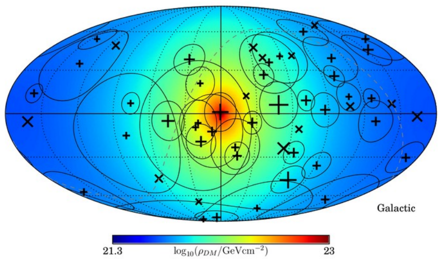

Argüelles, Kheirandish, Vincent, *PRL* 2017

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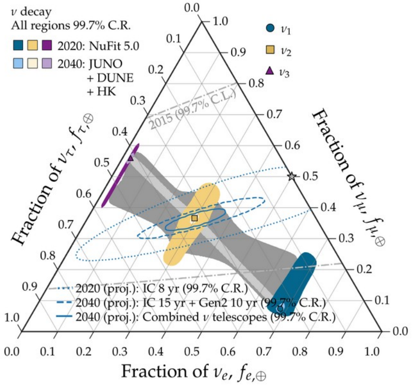

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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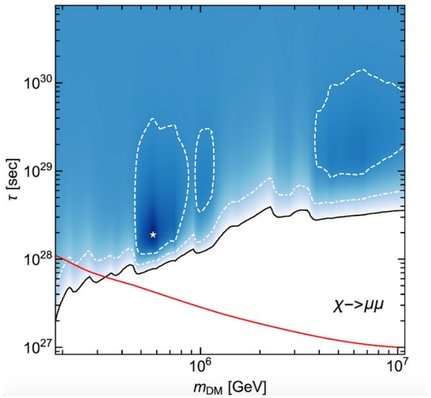

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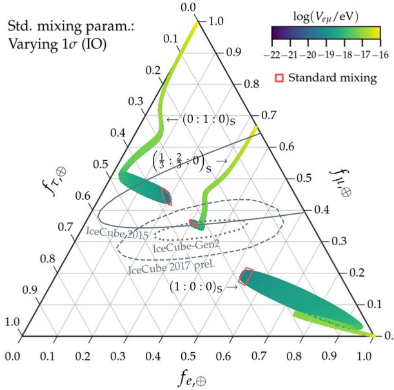
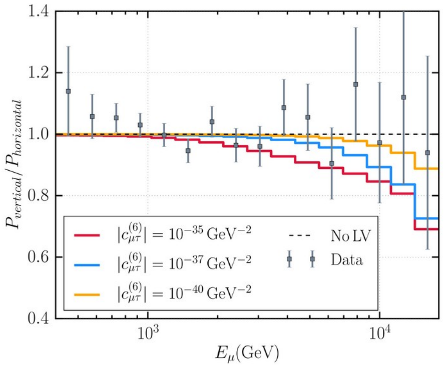


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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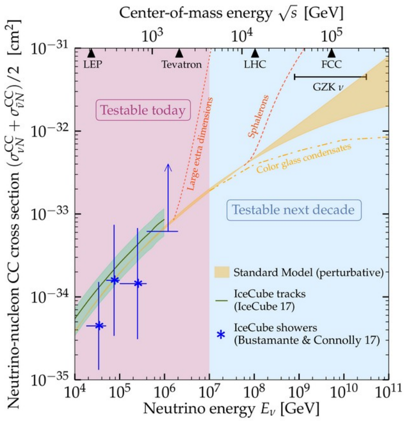

MB & Connolly, *PRL* 2019

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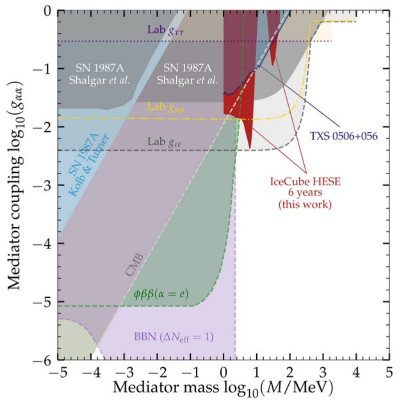

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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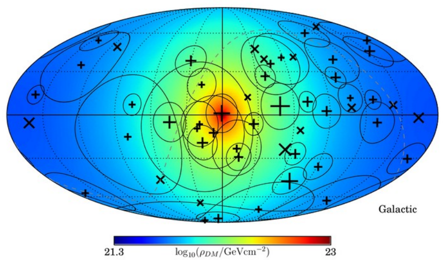

Argüelles, Kheirandish, Vincent, *PRL* 2017

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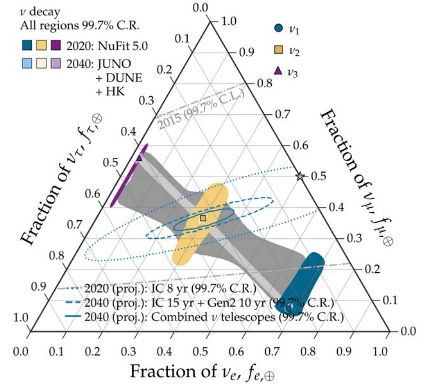

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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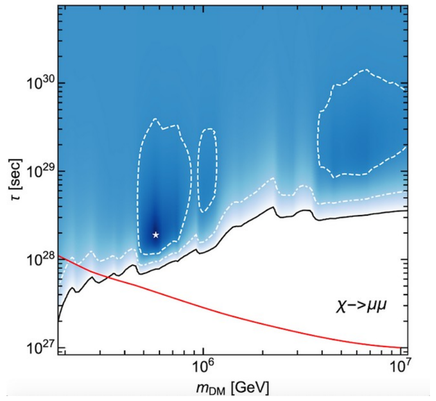

Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

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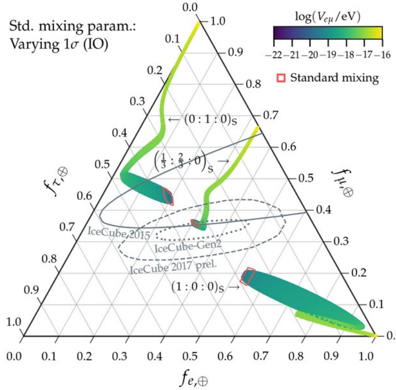

MB & Agarwalla, *PRL* 2019

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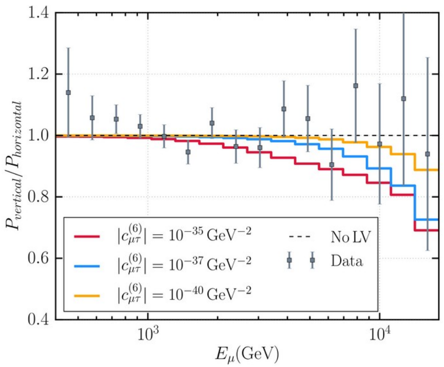
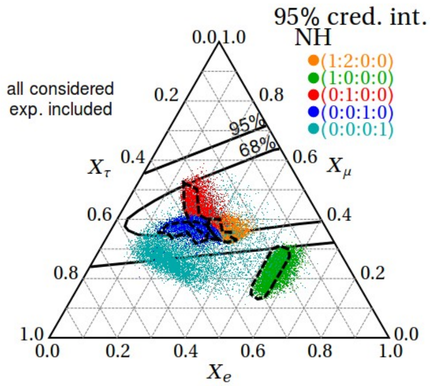


IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

Making high-energy astrophysical neutrinos: a toy model

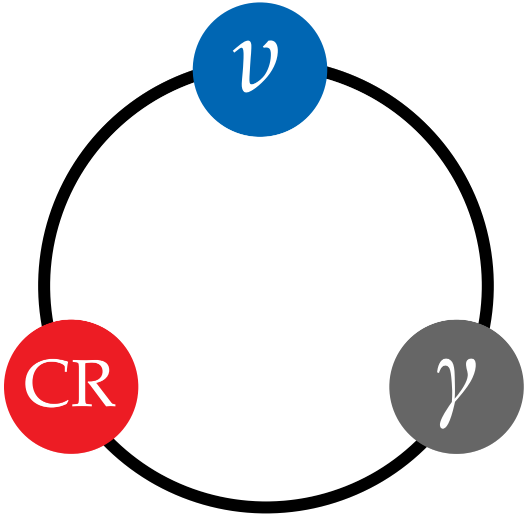
(or $p + p$)

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

$$\pi^0 \longrightarrow \gamma + \gamma$$

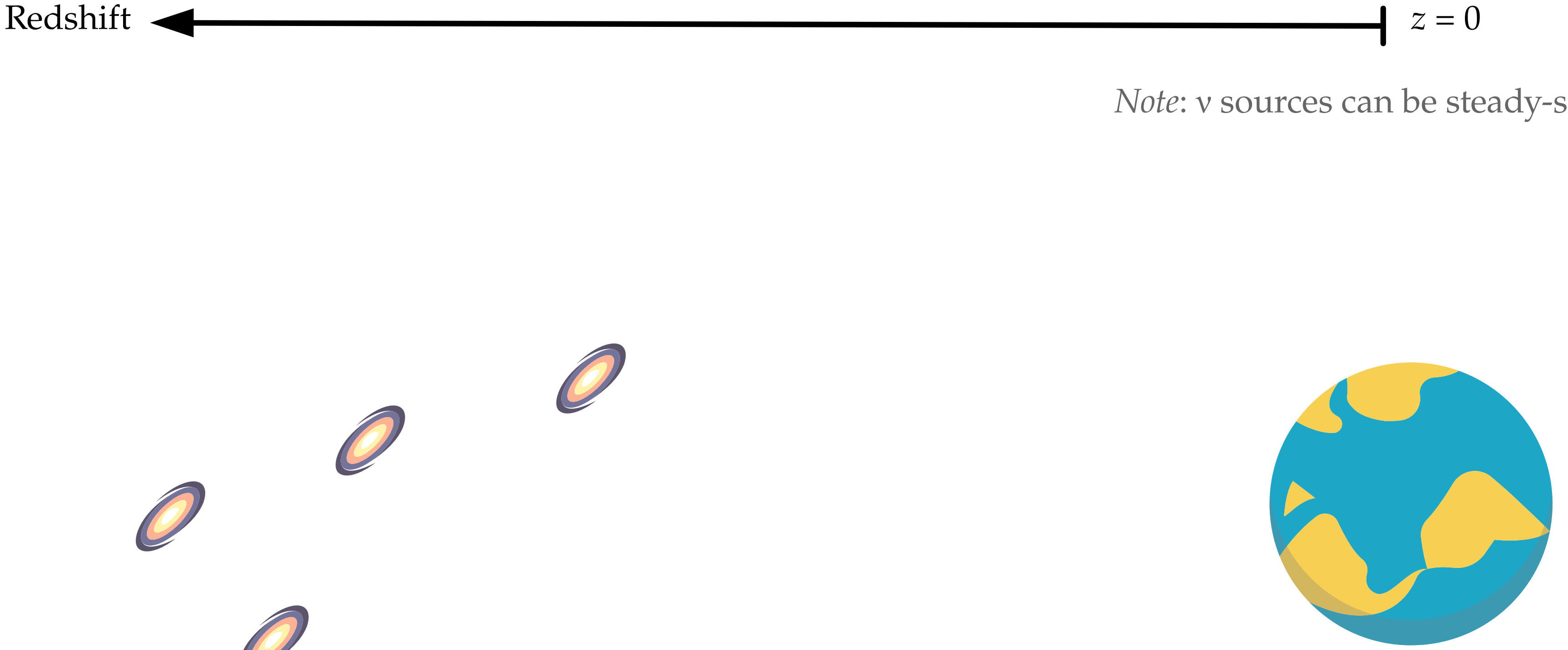
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

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

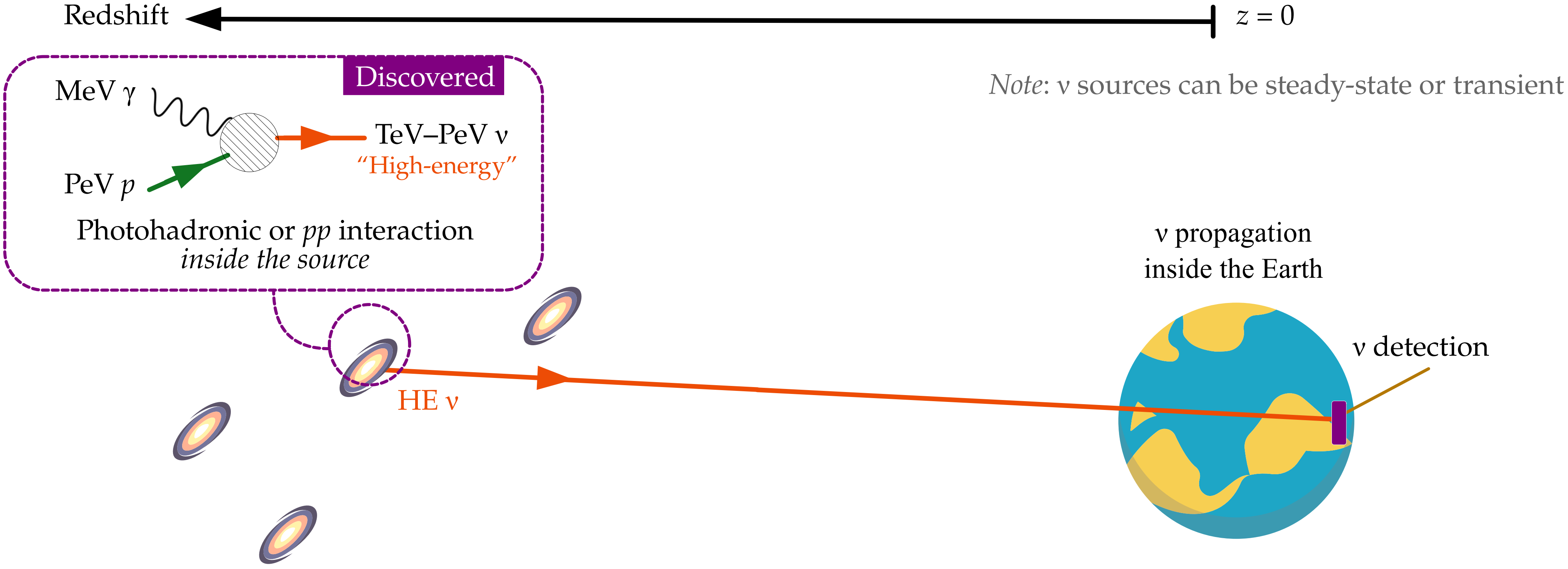


Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10



Note: ν sources can be steady-state or transient


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

How many neutrinos? The Waxman-Bahcall bound

- Energy production rate of extragalactic cosmic-ray protons in the energy range 10^{19}–10^{20} eV:

$$\dot{\varepsilon}_{\rm CR}^{[10^{19},10^{21}]} \sim 5 \cdot 10^{44}~{\rm erg~Mpc^{-3}~yr^{-1}}$$

- So, the energy-dependent generation rate of cosmic rays is $E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}} = \frac{\dot{\varepsilon}_{\rm CR}^{[10^{19},10^{21}]}}{\ln(10^{21}/10^{19})} \approx 10^{44}~{\rm erg~Mpc^{-3}~yr^{-1}}$

- Protons lose a fraction $\epsilon < 1$ in photohadronic production of pions in the sources

- Present-day energy density of $\nu_\mu + \bar{\nu}_\mu$: $E_\nu^2 \frac{dN_\nu}{dE_\nu} \approx \underbrace{\frac{1}{4}}\epsilon\, \underbrace{t_{\rm H}}\, E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}$

$\mathrm{Br}(p + \gamma \to \pi^+) = 0.5$ × Fraction of π energy going to $\nu_\mu + \bar{\nu}_\mu$

Hubble time: $t_{\rm H} \sim 10^{10}$ yr

- Maximum neutrino intensity is for $\epsilon = 1$: $I_{\rm max} \approx \frac{1}{4}\, \xi_z\, t_{\rm H} \frac{c}{4\pi} E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}} \approx 1.5 \cdot 10^{-8} \xi_z~{\rm GeV~cm^{-2}~s^{-1}~sr^{-1}}$

- So the expected neutrino flux is $E_\nu^2 \Phi_{\nu_\mu} \equiv \frac{c}{4\pi} E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{1}{2} \epsilon I_{\rm max}$

Waxman & Bahcall, *PRD* 1999

Waxman-Bahcall bound: $E_\nu^2 \Phi_{\nu_\mu} \approx 0.75 \cdot 10^{-8} \xi_z\, \epsilon~{\rm GeV~cm^{-2}~s^{-1}~sr^{-1}}$

The need for km-scale detectors

Predicted by Waxman-Bahcall 1998

- Neutrino flux at TeV–PeV: $E^2 \cdot \Phi \sim 10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$

- Neutrino-nucleon cross section: $\sigma_{\nu p} \sim 10^{-35}\ \mathrm{cm}^2\ (E/\mathrm{GeV})^{0.36}$

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

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

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

- To detect $N > 10$ neutrinos, we need

$$V_{\mathrm{det}} > 1\ \mathrm{km}^3$$

The need for km-scale detectors

Predicted by Waxman-Bahcall 1998

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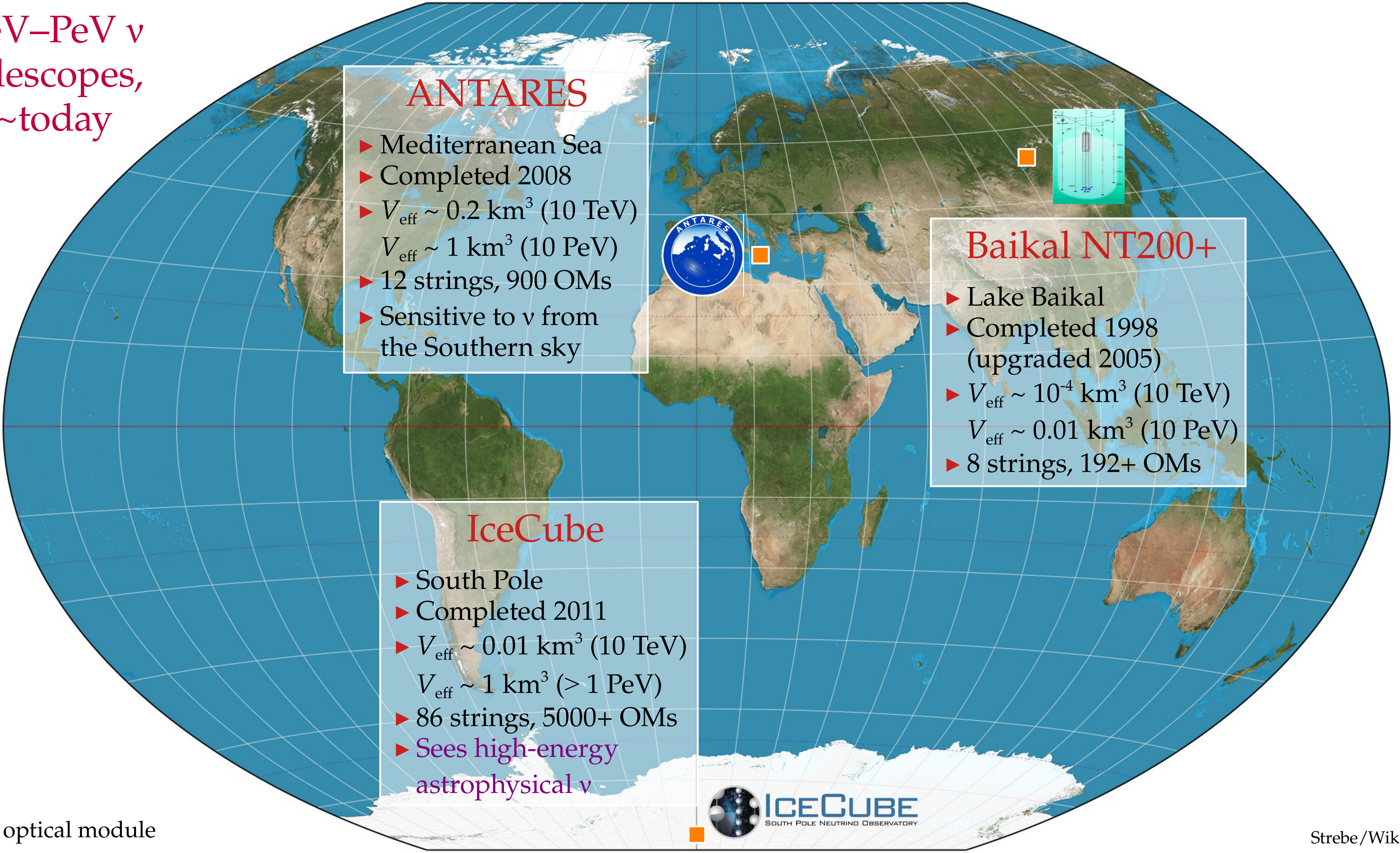
Number density of nucleons: $\sim N_{\mathrm{Av}}$ cm^3

Detector volume

- To detect $N > 10$ neutrinos, we need

$$V_{\mathrm{det}} > 1\ \mathrm{km}^3$$

TeV–PeV ν telescopes, ~today



ANTARES

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

Baikal NT200+

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

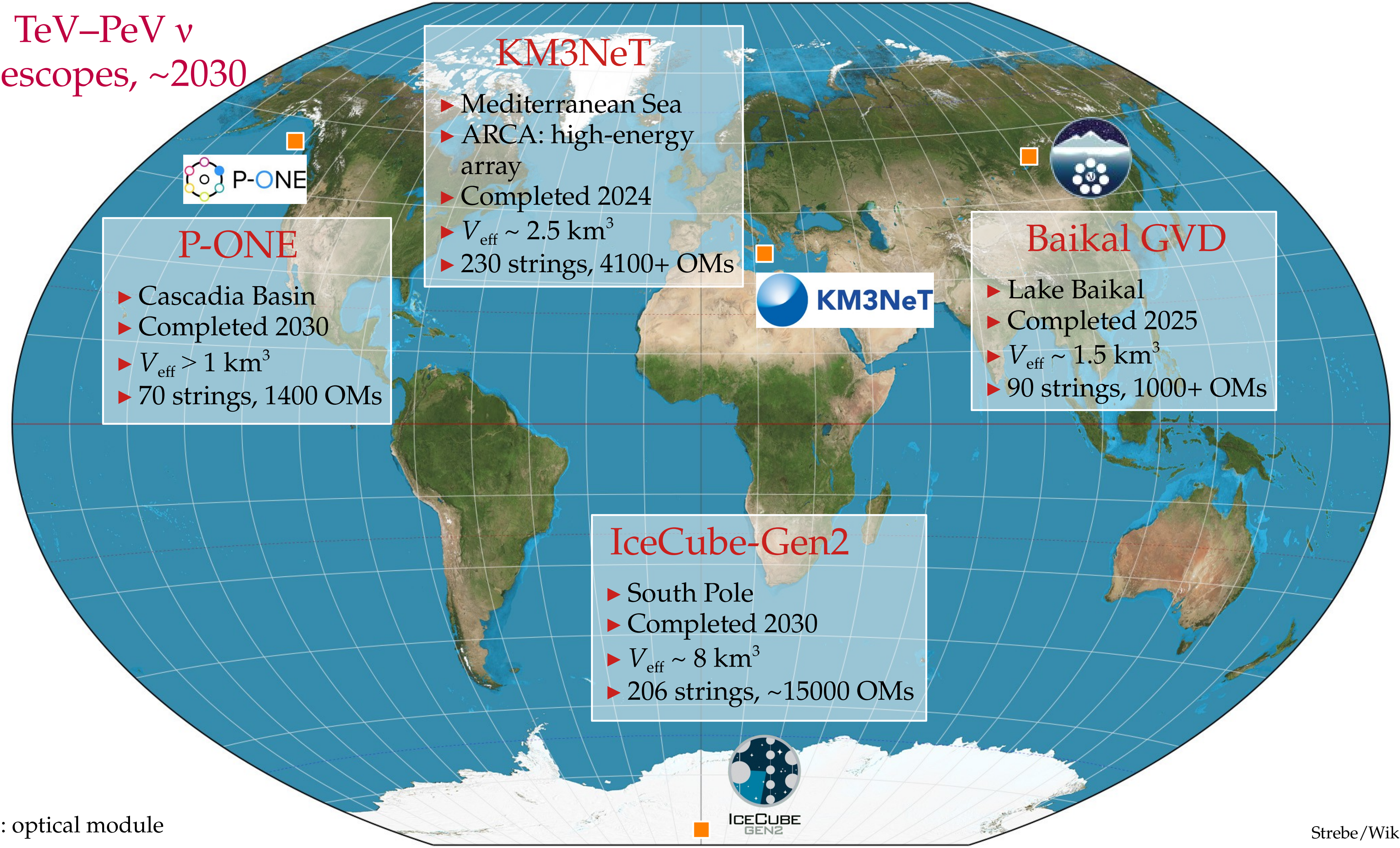
IceCube

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

OM: optical module

Strebe/Wikipedia

TeV–PeV ν telescopes, ~2030



KM3NeT

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

P-ONE

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

Baikal GVD

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

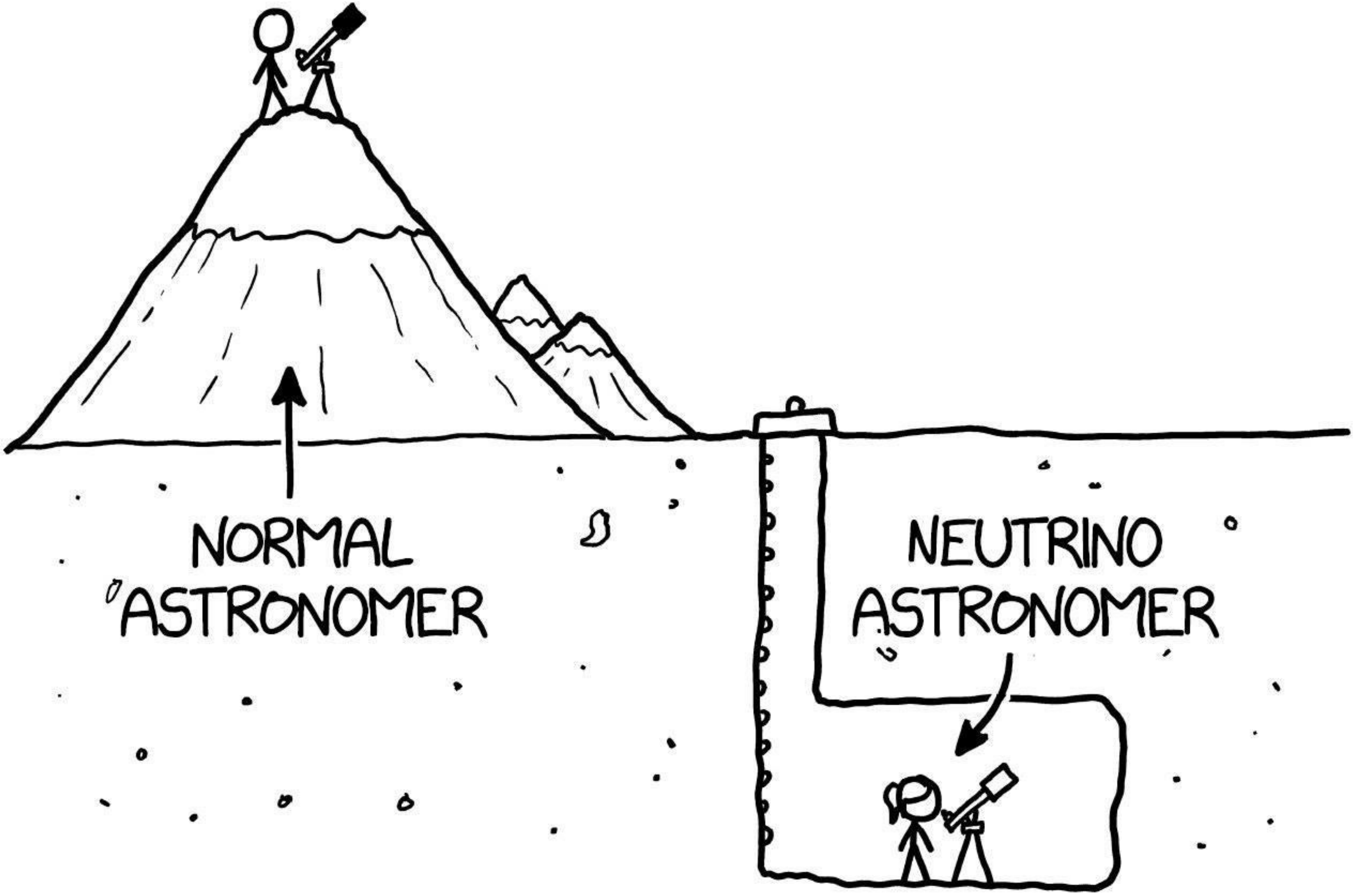
IceCube-Gen2

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

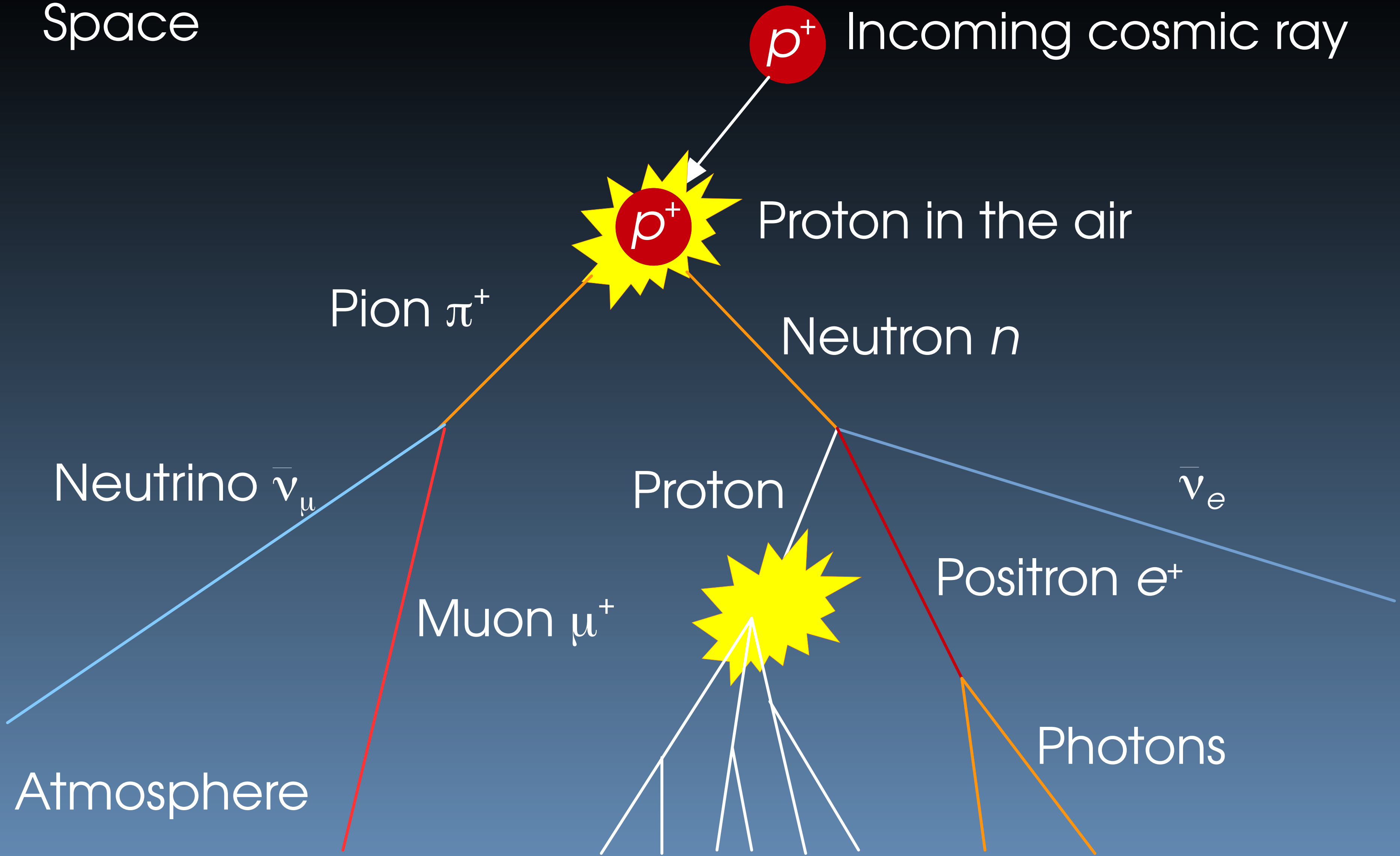
OM: optical module

Strebe/Wikipedia

Yuya Makino, IceCube/NSF



xkcd



Space

p^+ Incoming cosmic ray

p^+ Proton in the air

Pion π^+

Neutron n

Neutrino $\bar{\nu}_\mu$

Proton

$\bar{\nu}_e$

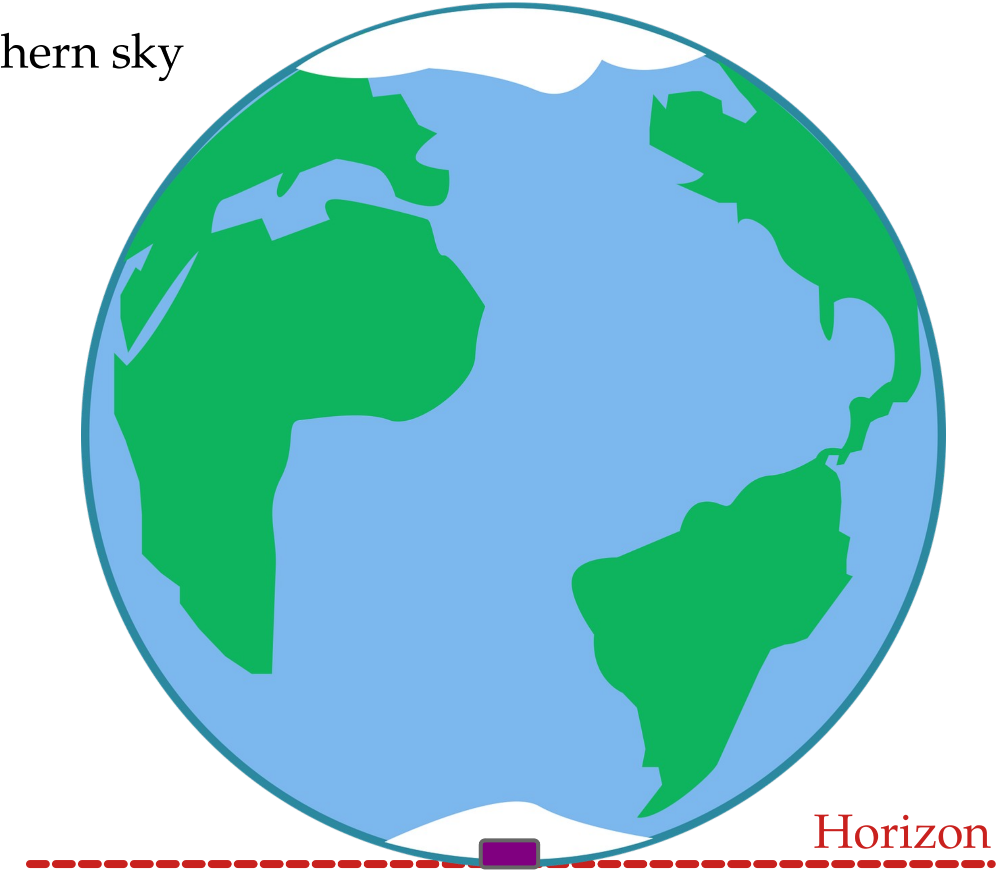
Positron e^+

Muon μ^+

Photons

Atmosphere

Upgoing *vs.* downgoing neutrinos



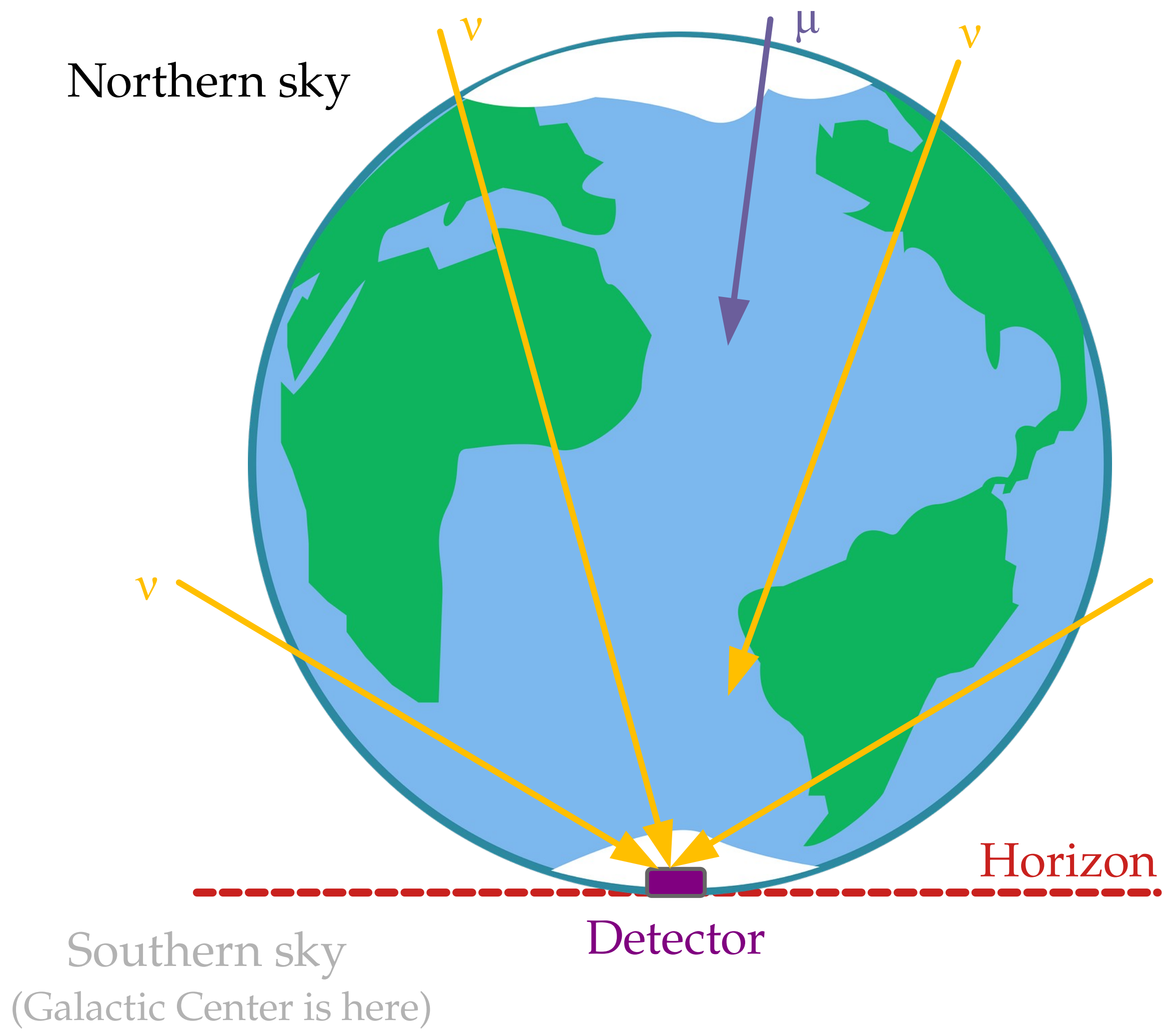
Northern sky

Horizon

Detector

Southern sky
(Galactic Center is here)

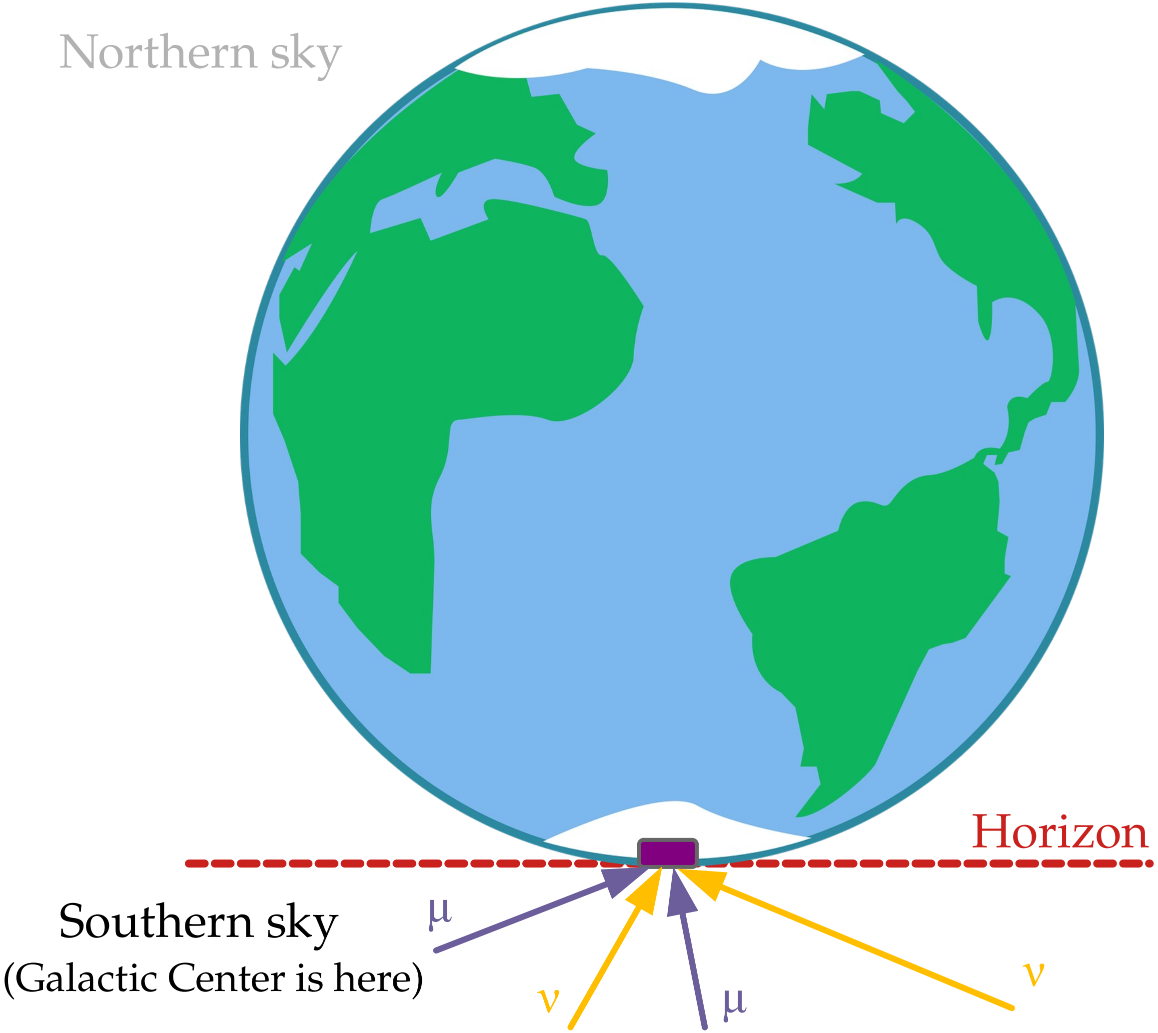
Upgoing *vs.* downgoing neutrinos



Neutrinos from the Northern sky
≡
Upgoing neutrinos

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

Downgoing *vs.* upgoing neutrinos



Neutrinos from the Southern sky

≡

Downgoing neutrinos

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

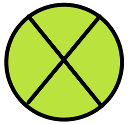
Detecting the undetectable

Neutrino source

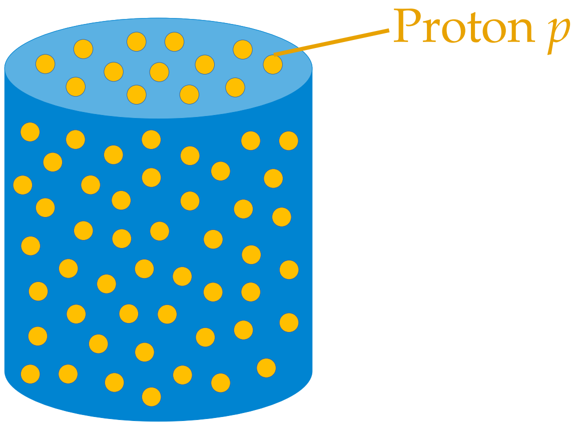
Water tank

Detecting the undetectable

Neutrino source



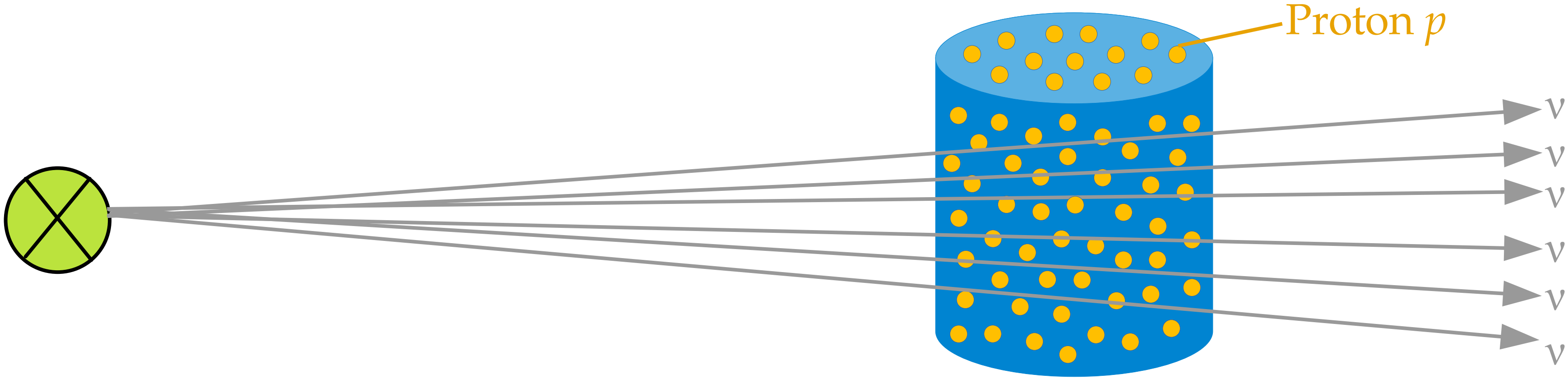
Water tank



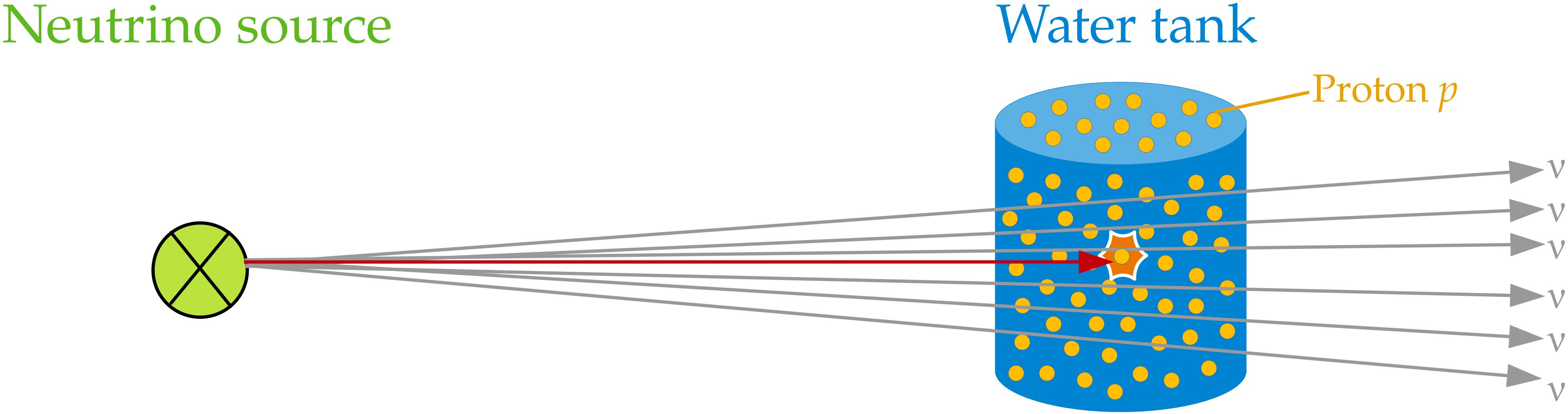
Detecting the undetectable

Neutrino source

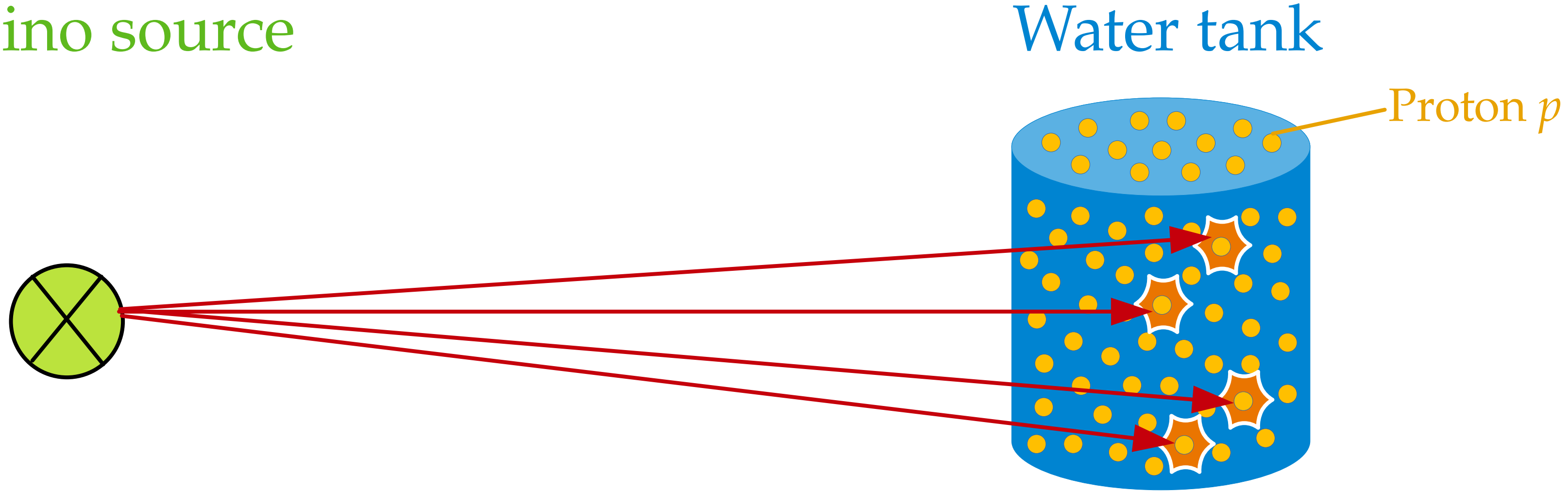
Water tank



Detecting the undetectable



Detecting the undetectable

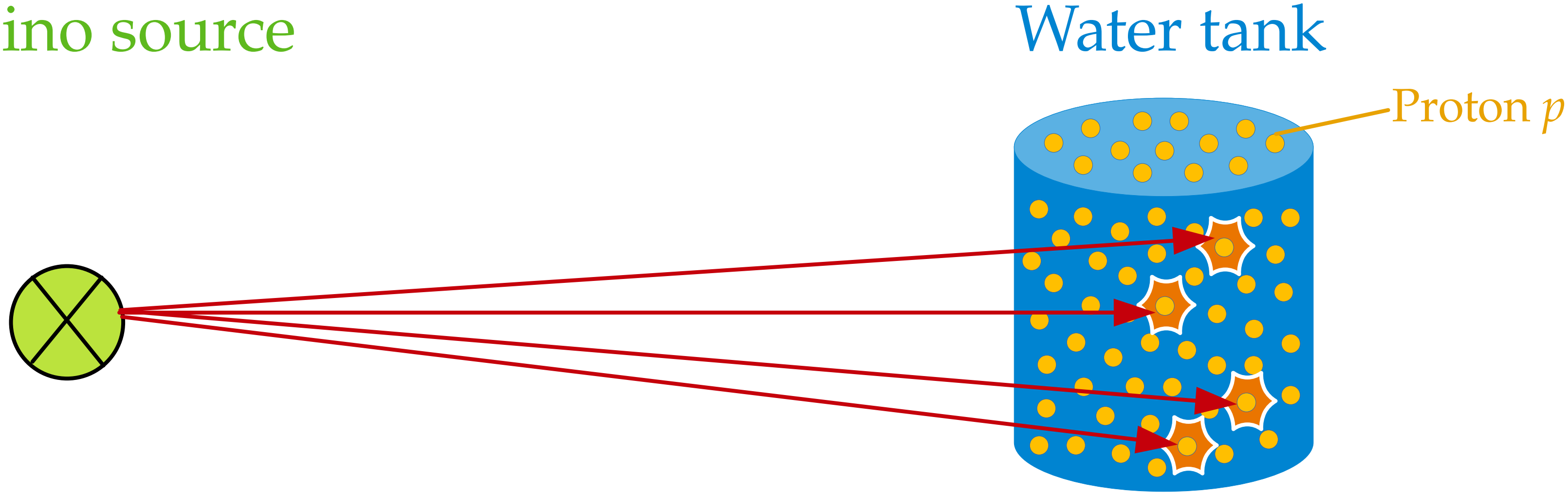


Neutrino source

Water tank

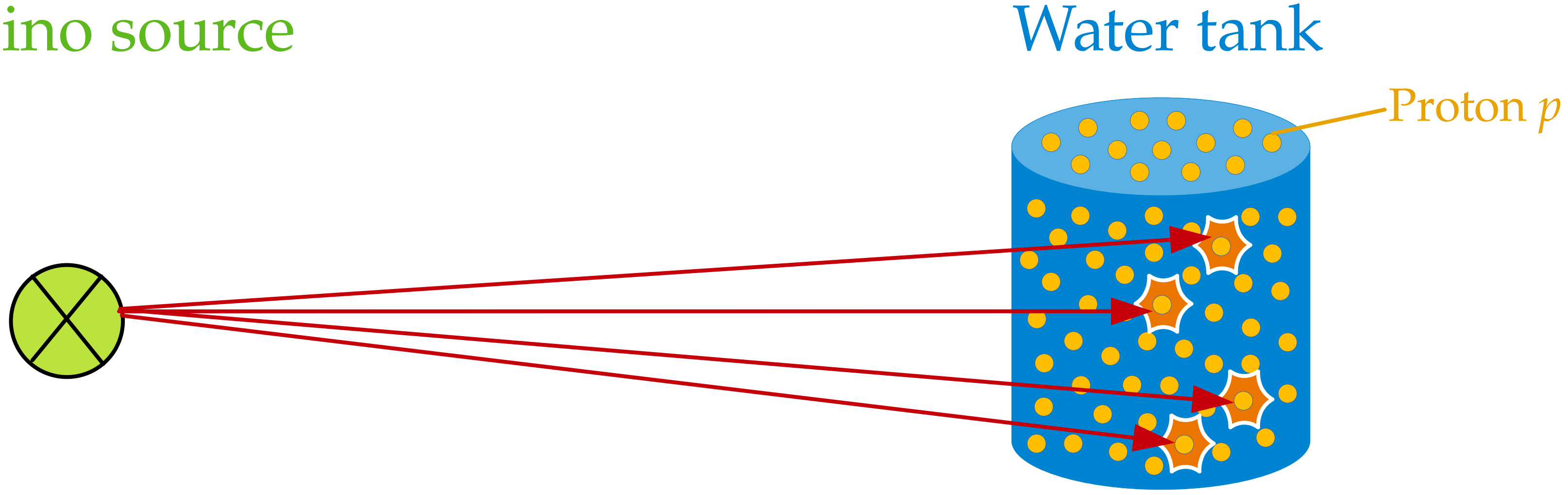
Proton p

Detecting the undetectable



Number of interacting ν =

Detecting the undetectable

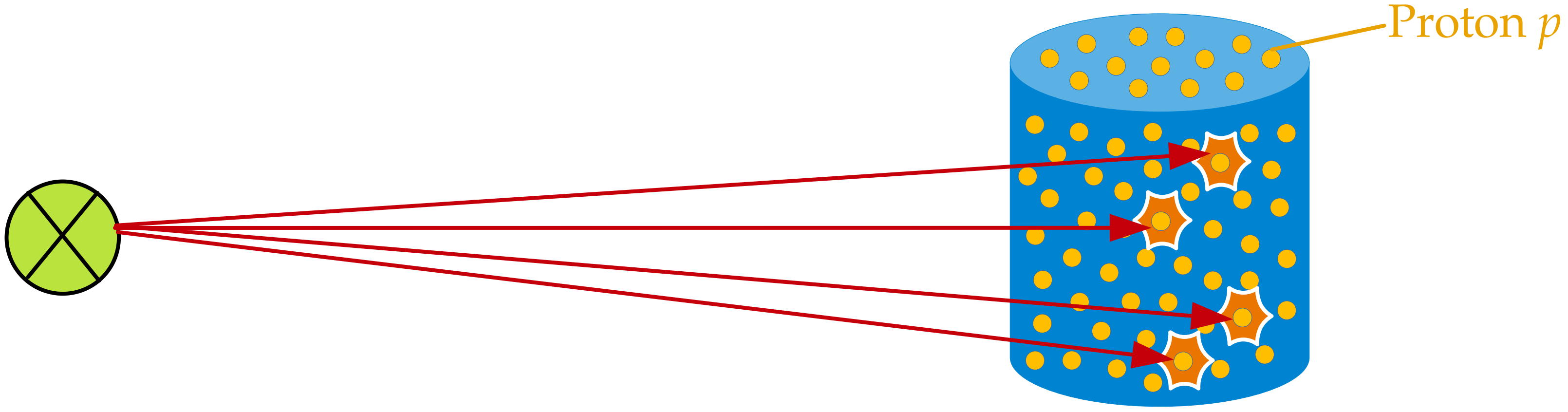


Number of interacting ν = Chance that one ν interacts with one p

Detecting the undetectable

Neutrino source

Water tank

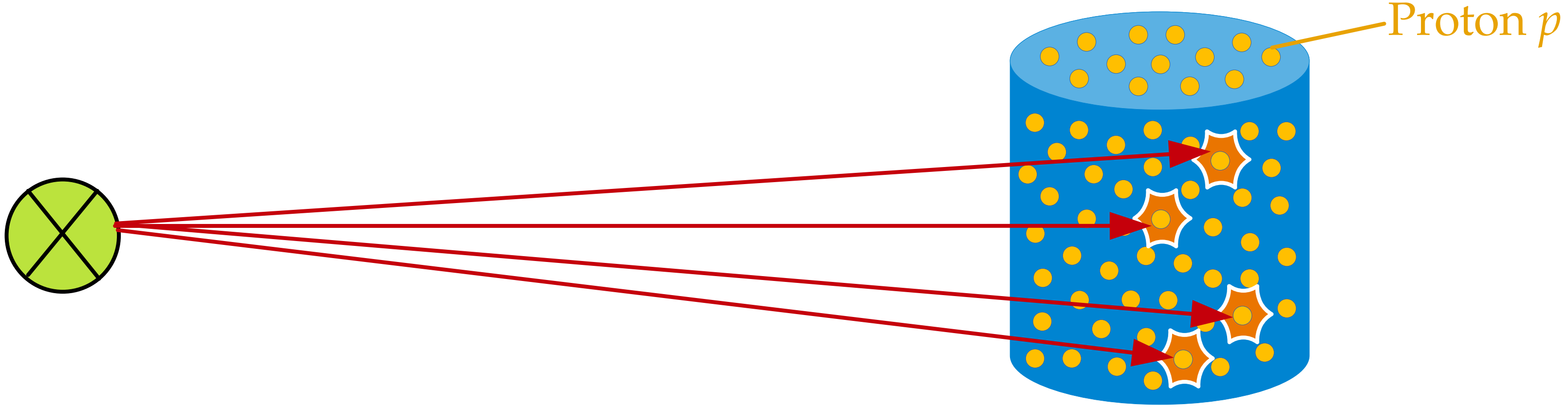


$$\begin{array}{c}\text{Number of} \\ \text{interacting } \nu\end{array} = \underbrace{\begin{array}{c}\text{Chance that one } \nu \\ \text{interacts with one } p\end{array}}_{\begin{array}{c}\text{Fixed by Nature} \\ \text{(weak interactions):} \\ \textit{neutrino-proton cross section}\end{array}}$$

Detecting the undetectable

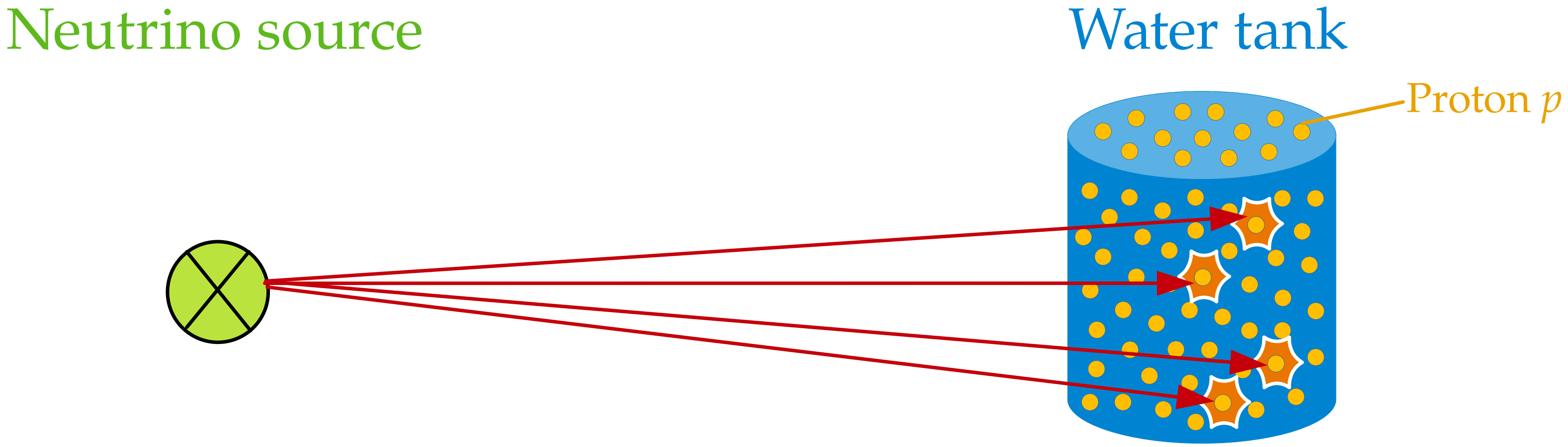
Neutrino source

Water tank



$$\text{Number of interacting } \nu = \underbrace{\text{Chance that one } \nu \text{ interacts with one } p}_{\substack{\text{Fixed by Nature} \\ \text{(weak interactions):} \\ \textit{neutrino-proton cross section}}} \times \text{Number of } \nu \text{ that reach the tank}$$

Detecting the undetectable

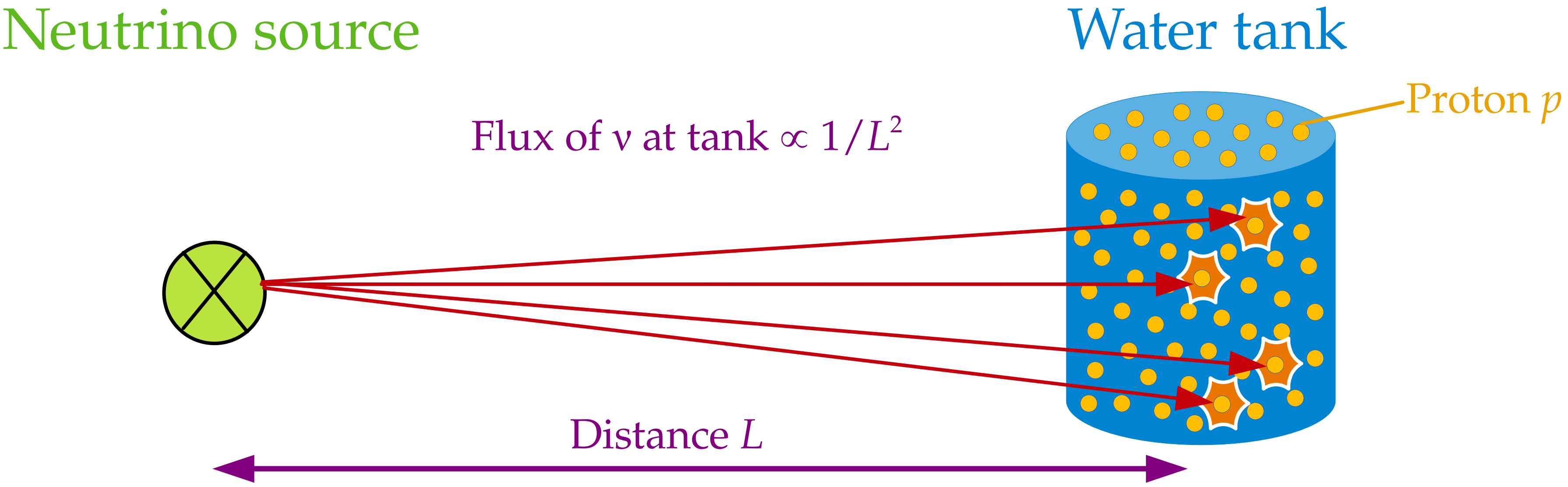


$$\text{Number of interacting } \nu = \underbrace{\text{Chance that one } \nu \text{ interacts with one } p}_{\text{Fixed by Nature (weak interactions): neutrino-proton cross section}} \times \underbrace{\text{Number of } \nu \text{ that reach the tank}}_{\text{Use an intense source, place the tank close to it, and be patient}}$$

Fixed by Nature
(weak interactions):
neutrino-proton cross section

Use an intense source,
place the tank close to it,
and be patient

Detecting the undetectable



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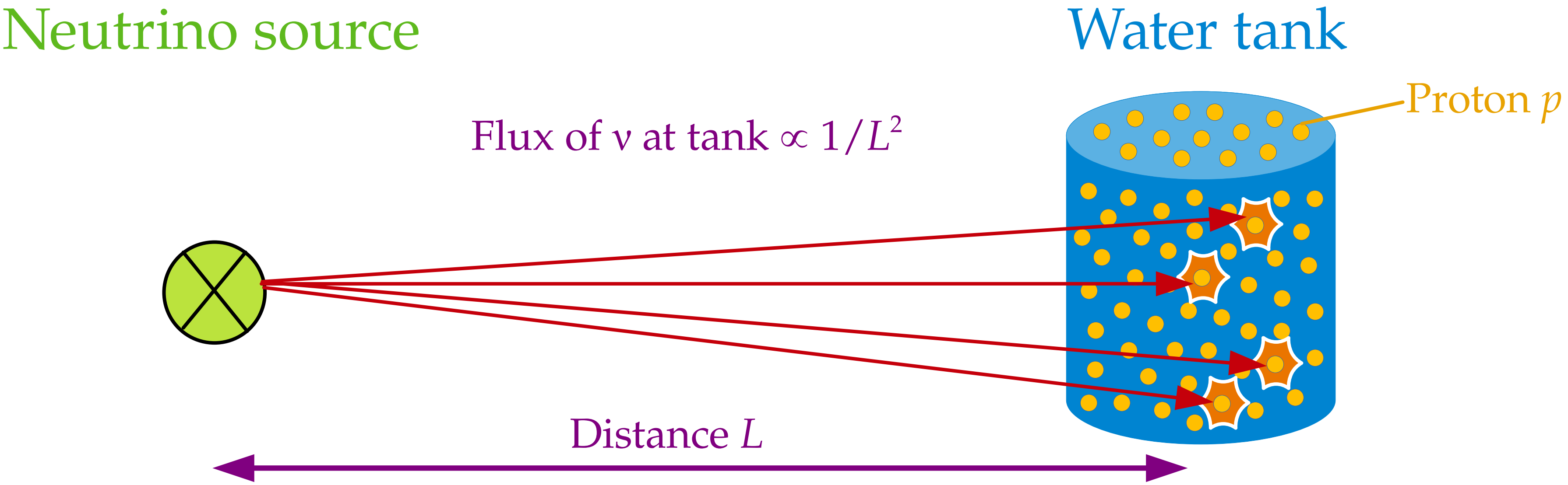
Detecting the undetectable



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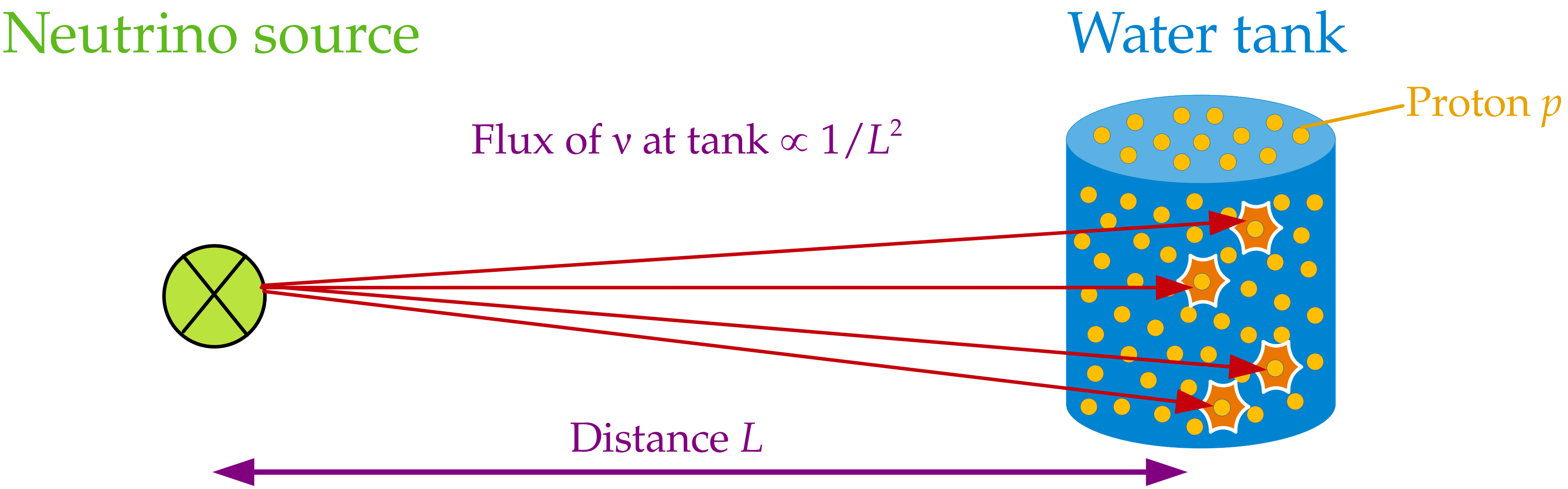
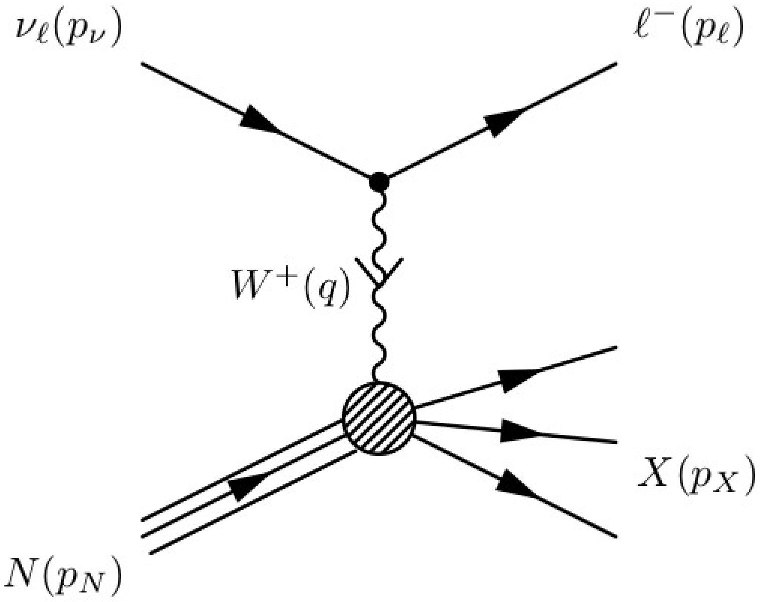
Detecting the undetectable



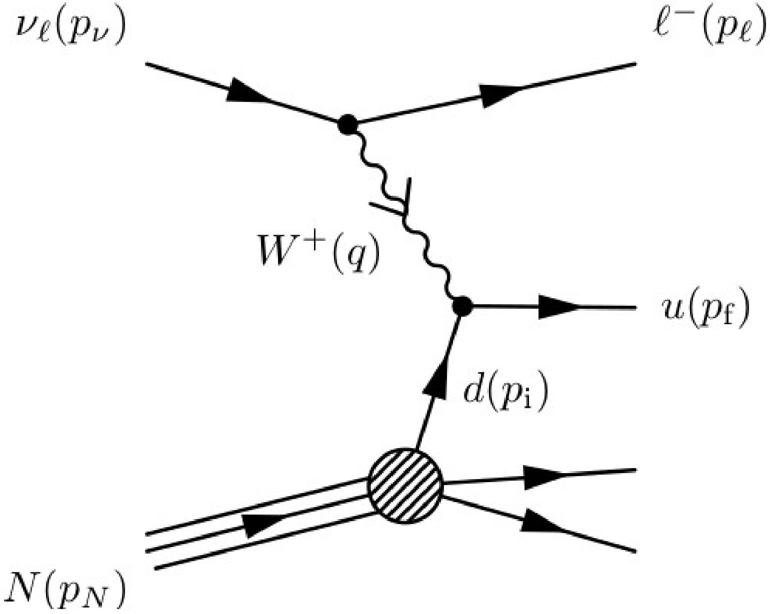
$$\substack{\text{Number of}\\ \text{interacting } \nu} = \underbrace{\substack{\text{Chance that one } \nu\\ \text{interacts with one } p}}_{\substack{\text{Fixed by Nature}\\ \text{(weak interactions):}\\ \textit{neutrino-proton cross section}}} \times \underbrace{\substack{\text{Number of } \nu \text{ that}\\ \text{reach the tank}}}_{\substack{\text{Use an intense source,}\\ \text{place the tank close to it,}\\ \text{and be patient}}} \times \underbrace{\substack{\text{Number of } p\\ \text{in the tank}}}_{\substack{\text{Build as big a}\\ \text{water tank as}\\ \text{possible}}}$$

Neutrino-nucleon deep inelastic scattering

What you see



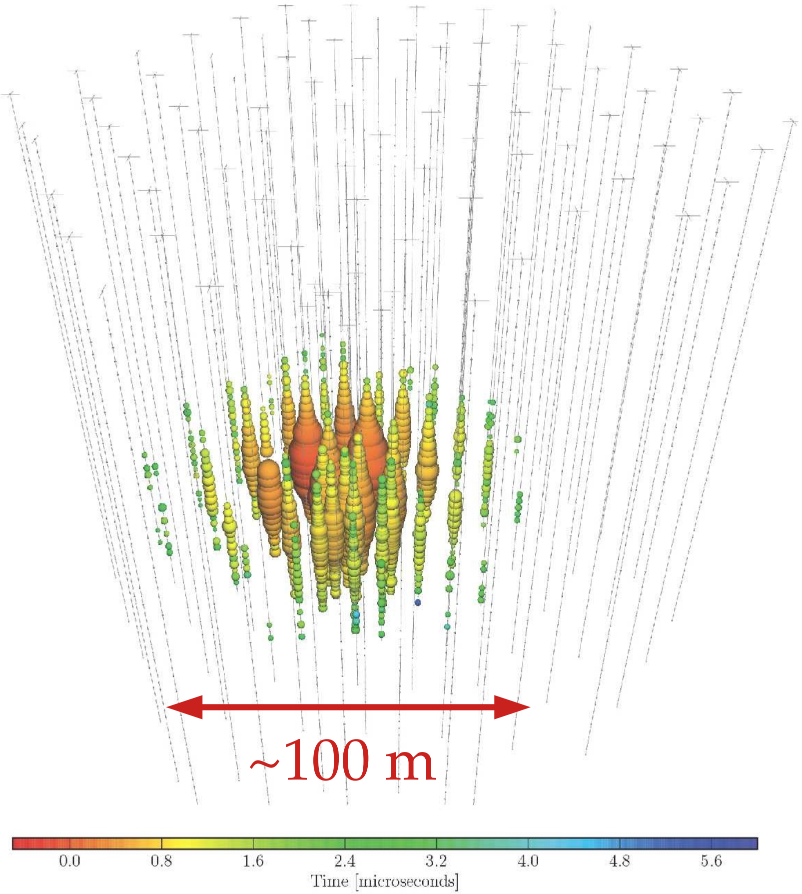
Beneath the hood



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

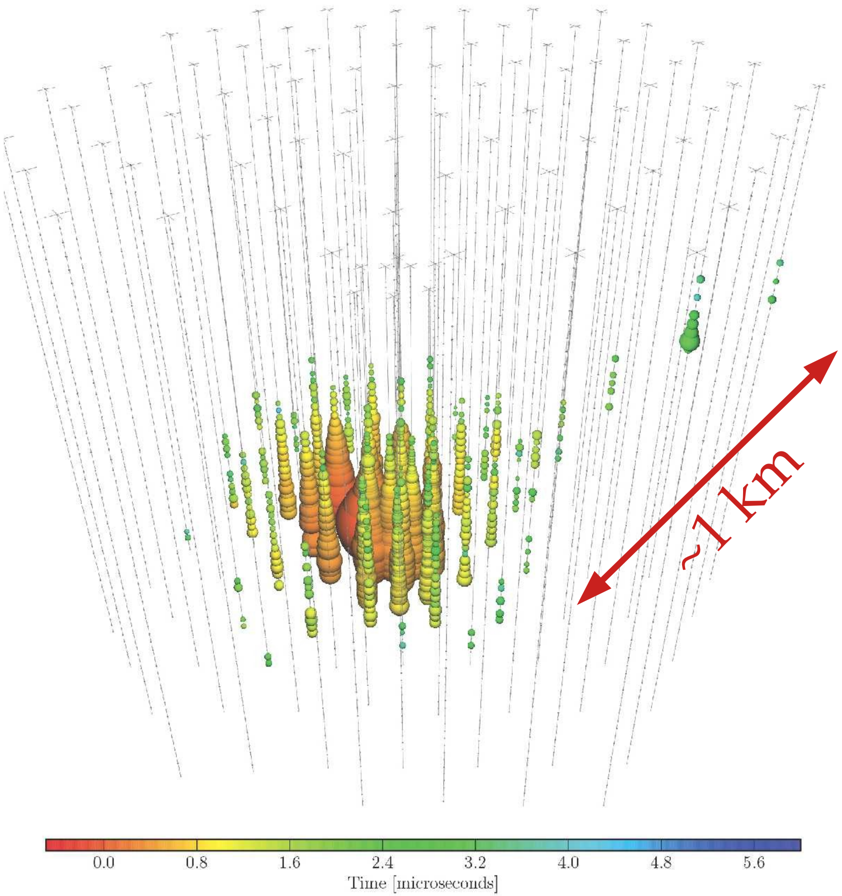
Giunti & Kim, *Fundamentals of Neutrino Physics & Astrophysics*

Shower
(mainly from ν_e and ν_τ)



Poor angular resolution: ~10°

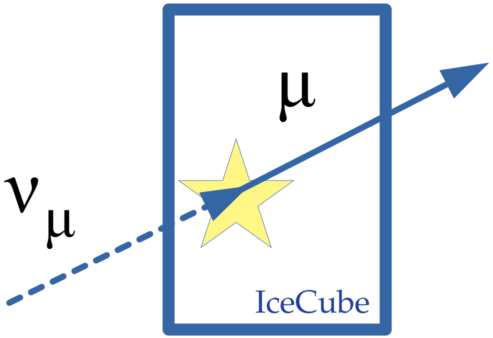
Track
(mainly from ν_μ)



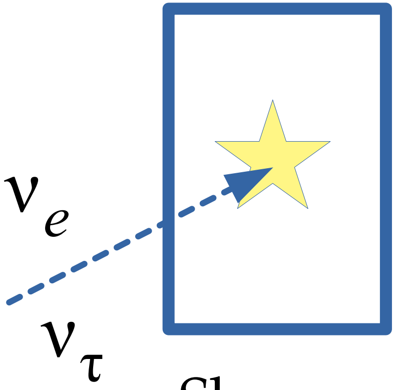
Angular resolution: < 1°

Contained *vs.* uncontained events

Contained events

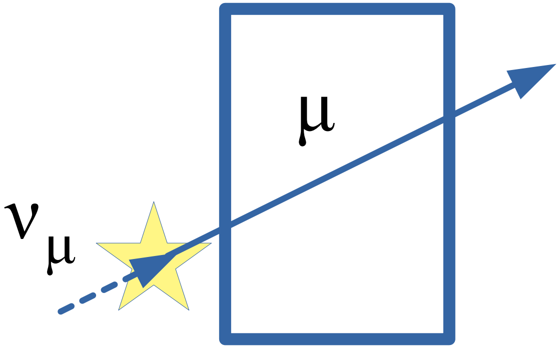


Starting track



Shower

Through-going muons



Through-going muon

Pro: Clean determination of E_ν

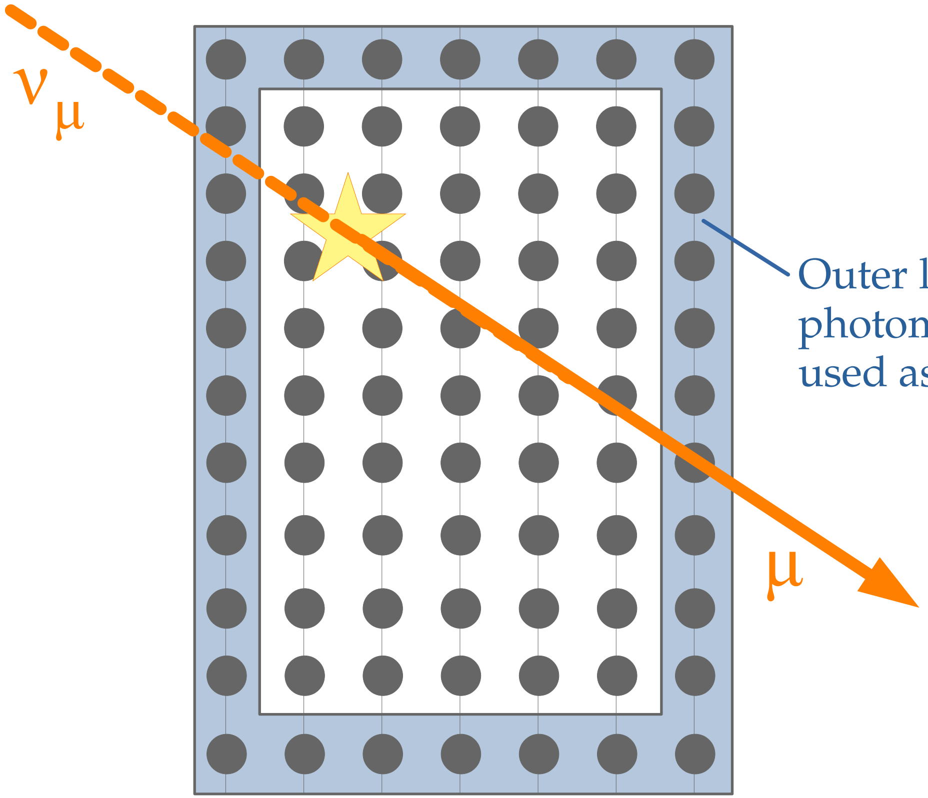
Con: Few events (~100 in 10 yr)

Pro: Lots of events (few 100k)

Con: Uncertain estimates of E_ν

IceCube self-veto: High-Energy Starting Events (HESE)

Astrophysical neutrino
(High-Energy Starting Event)



Outer layer of
photomultipliers
used as veto

IceCube

Schönert, Gaisser, Resconi, Schulz, *PRD* 2008
Gaisser, Jero, Karle, van Santen, *PRD* 2014

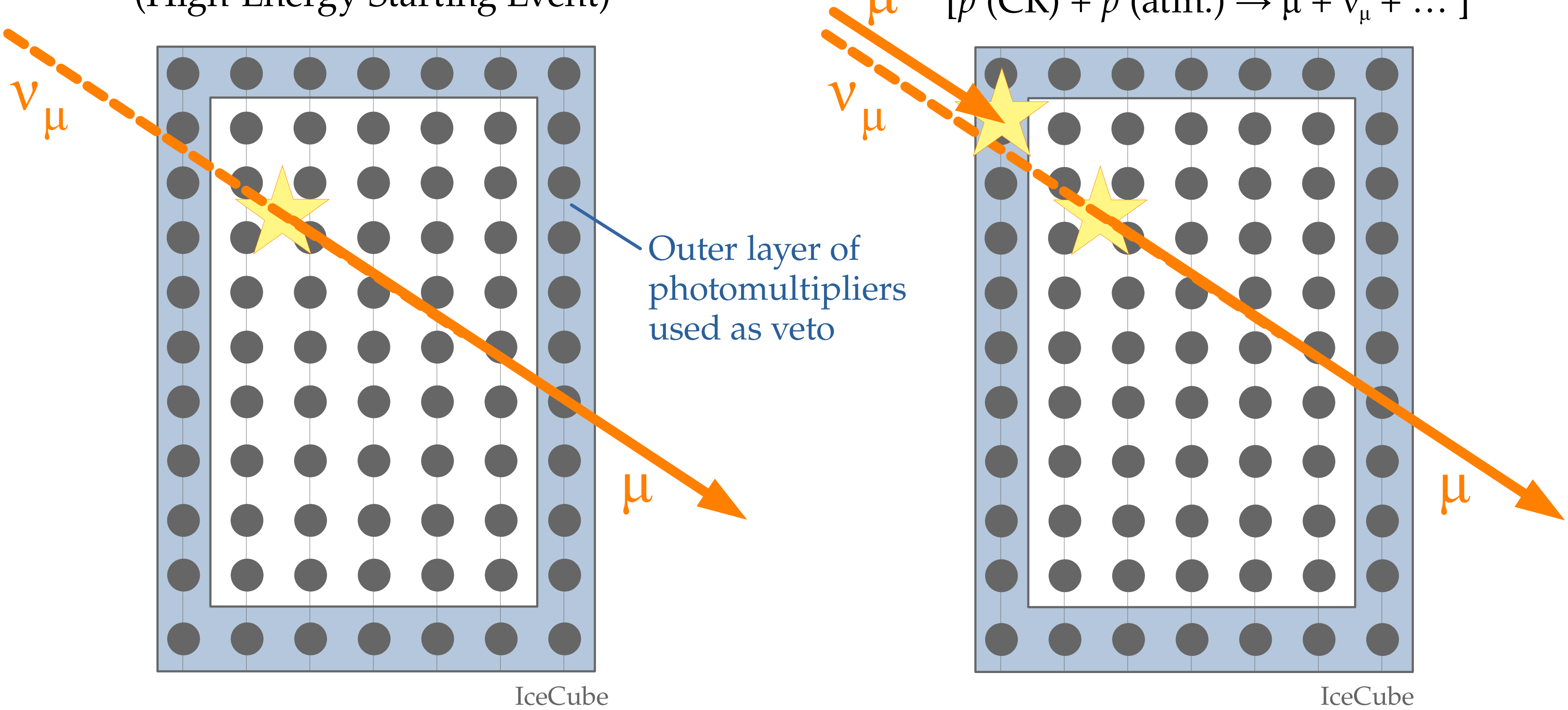
IceCube self-veto: High-Energy Starting Events (HESE)

Astrophysical neutrino

(High-Energy Starting Event)

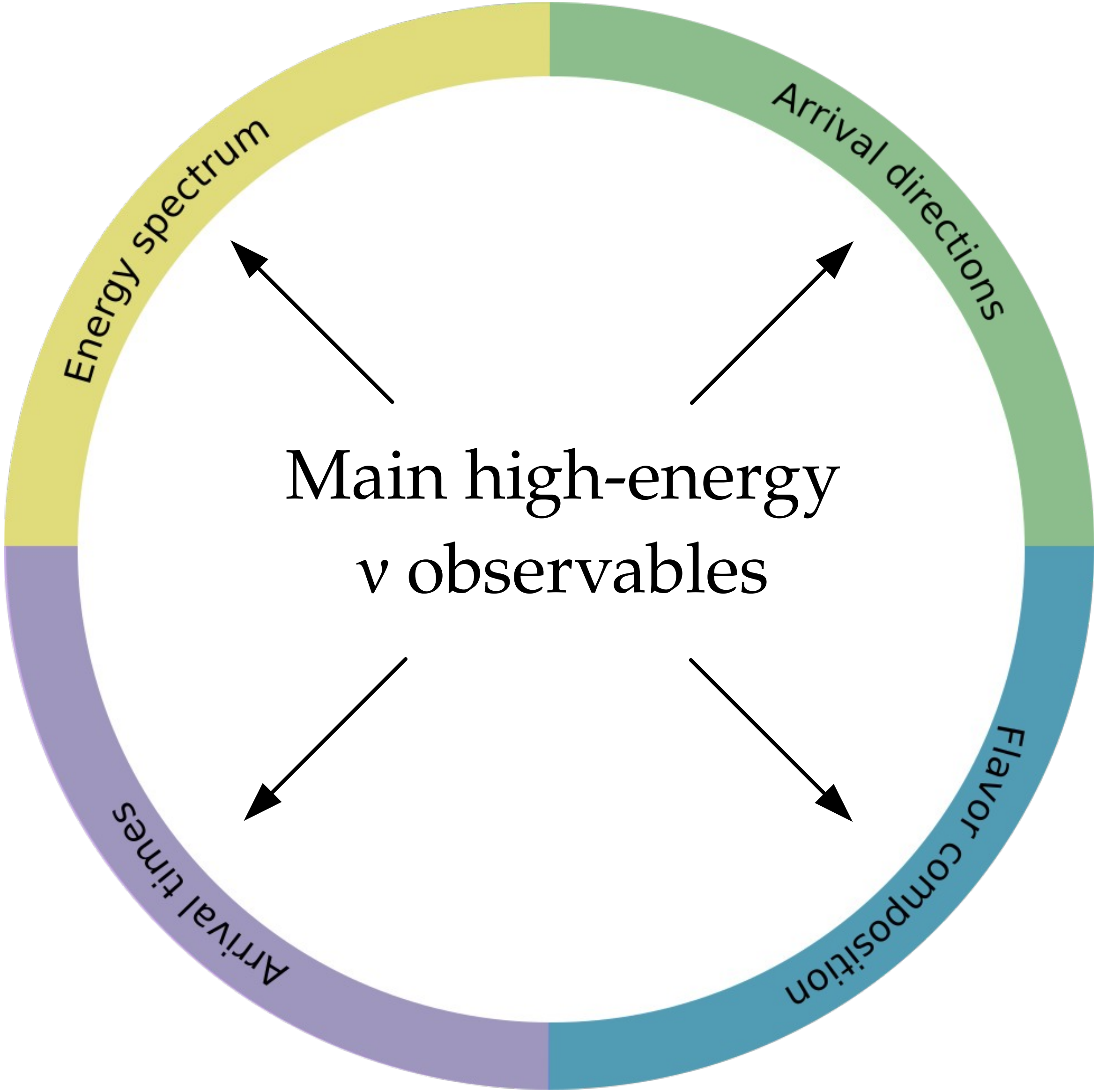
Atmospheric neutrino

$[p\ (\mathrm{CR}) + p\ (\mathrm{atm.}) \rightarrow \mu + \nu_\mu + \ldots\ ]$



Outer layer of photomultipliers used as veto

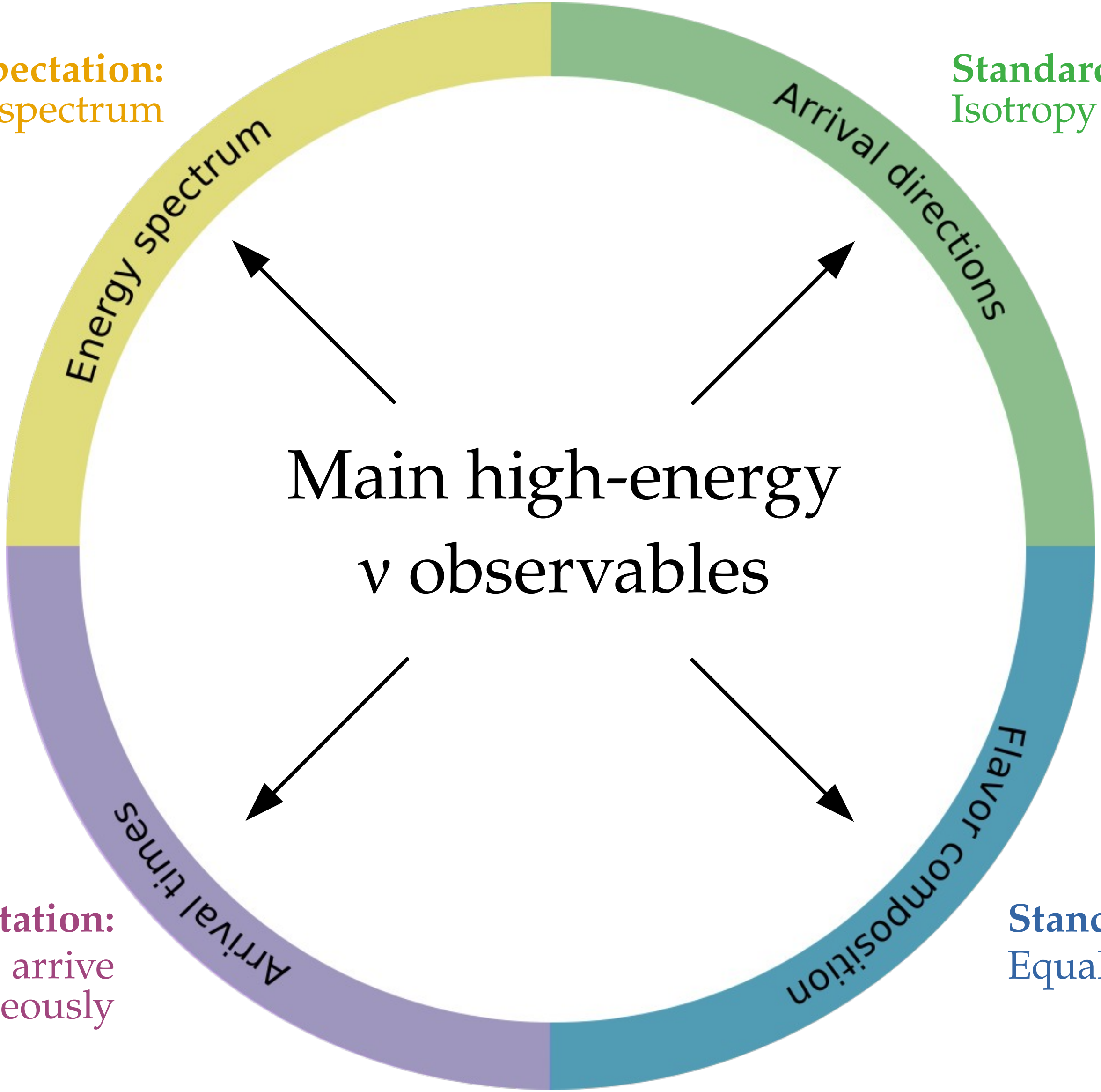
Schönert, Gaisser, Resconi, Schulz, *PRD* 2008
Gaisser, Jero, Karle, van Santen, *PRD* 2014



Main high-energy
ν observables

Standard expectation:
Power-law energy spectrum

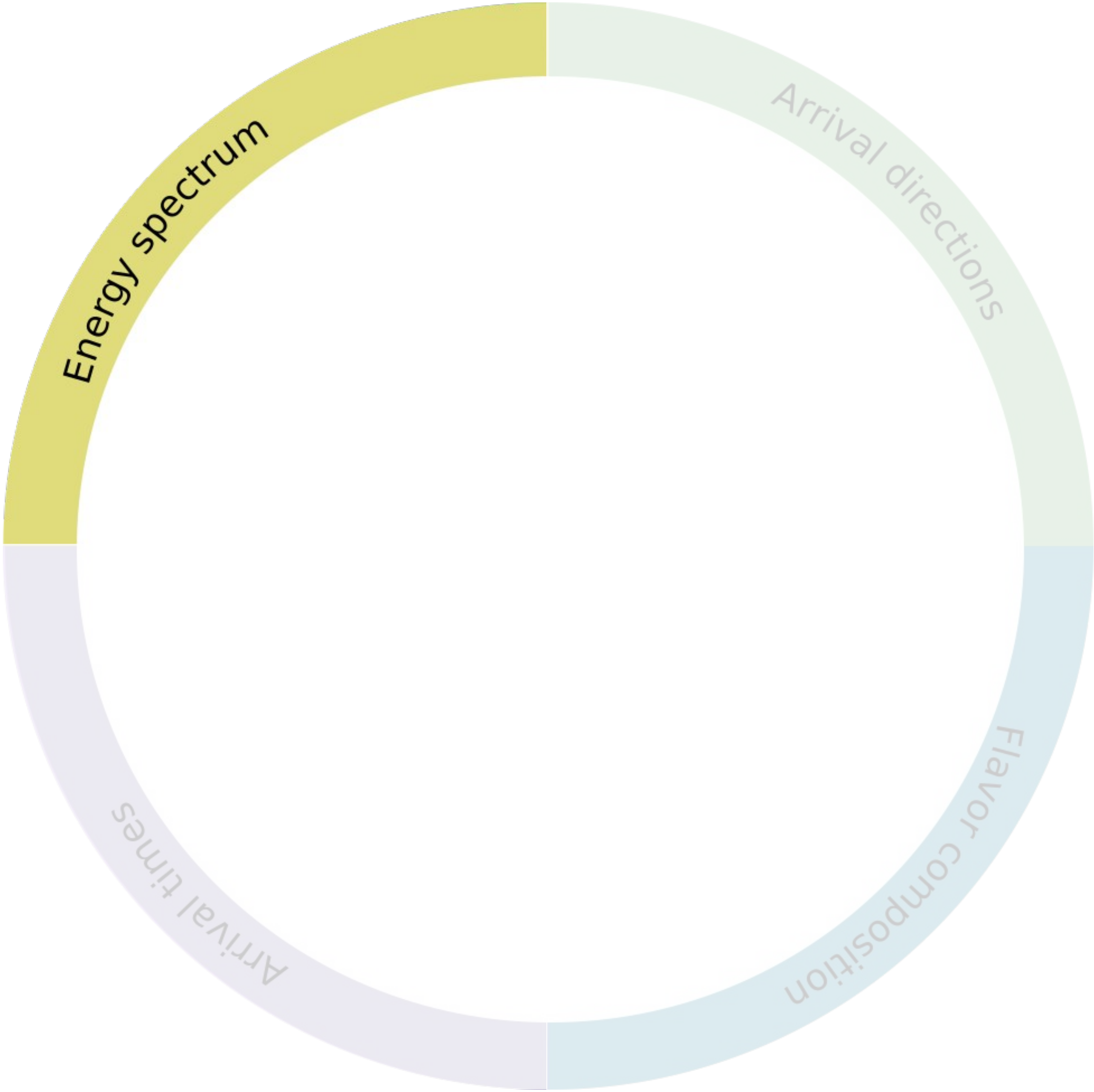
Standard expectation:
Isotropy (for diffuse flux)



Main high-energy ν observables

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

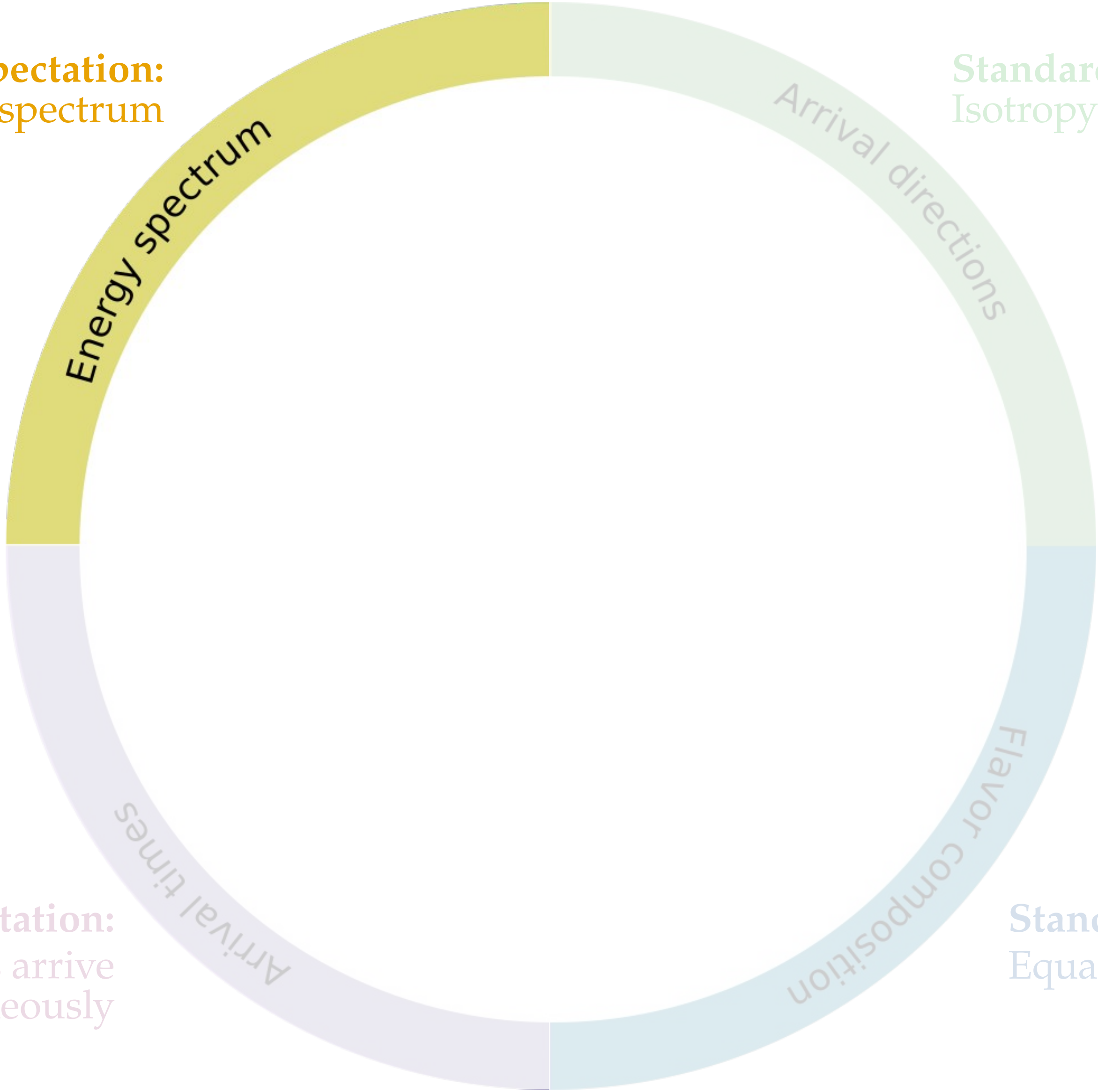


Energy spectrum

Arrival directions

Flavor composition

Arrival times



Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

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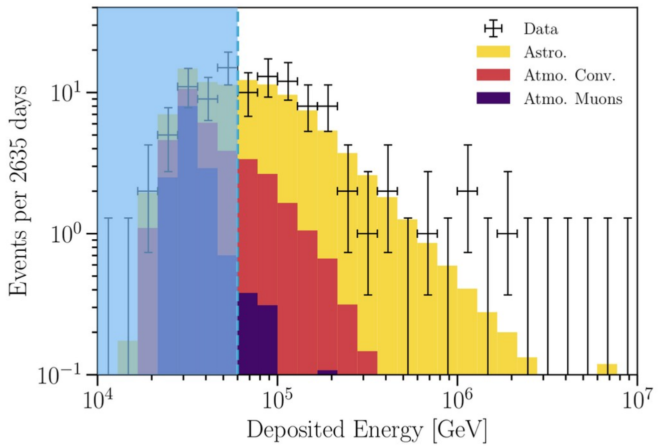
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

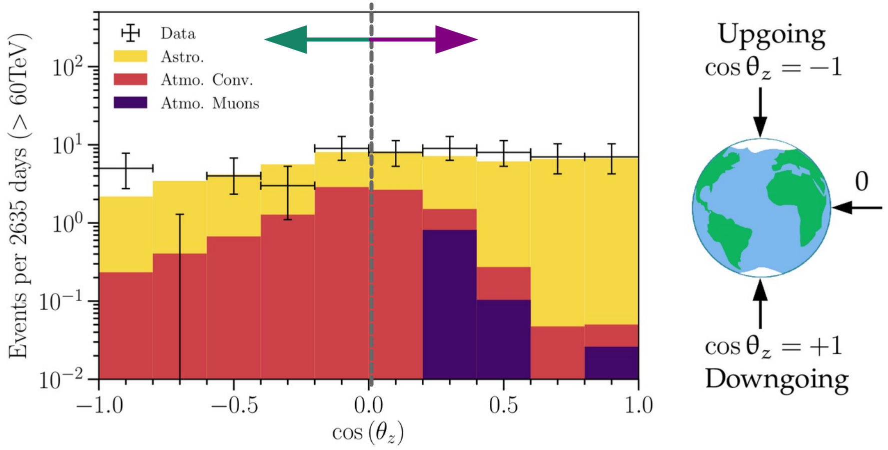
Energy spectrum (7.5 yr)

100+ contained events above 60 TeV:



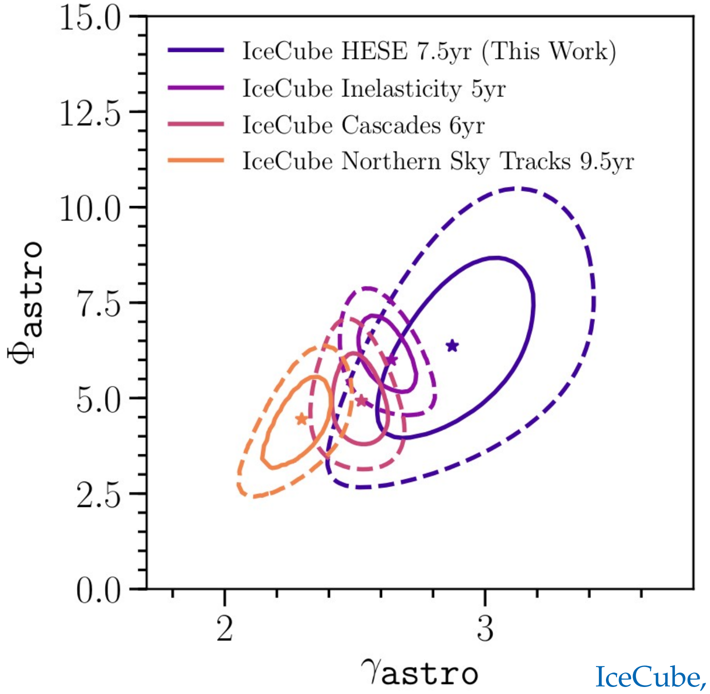
ν attenuated by Earth

Atm. ν and μ vetoed



Data is fit well by a single power law:

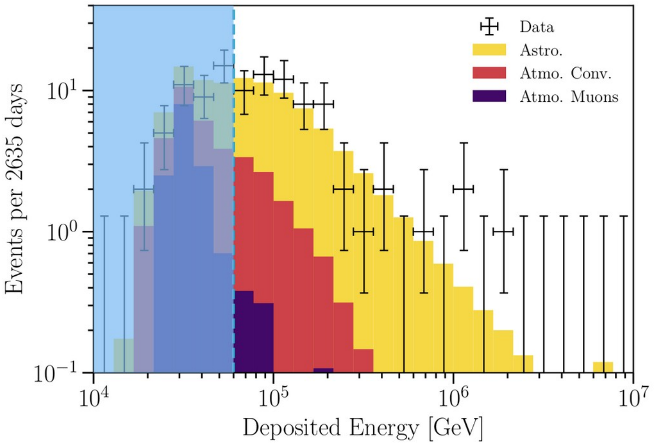
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$



IceCube, *PRD* 2021

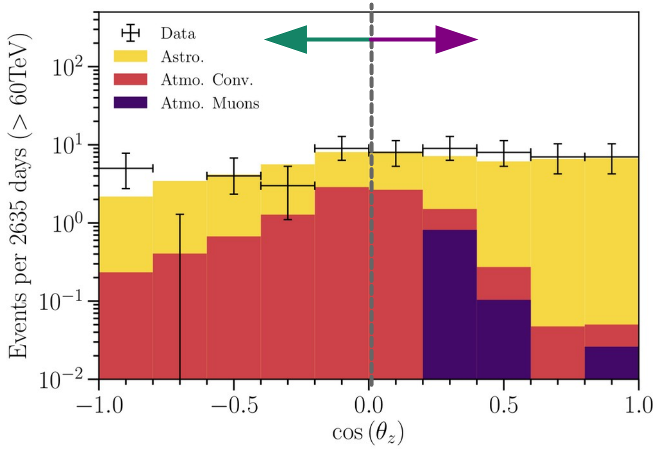
Energy spectrum (7.5 yr)

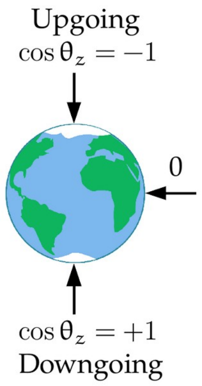
100+ contained events above 60 TeV:



ν attenuated by Earth

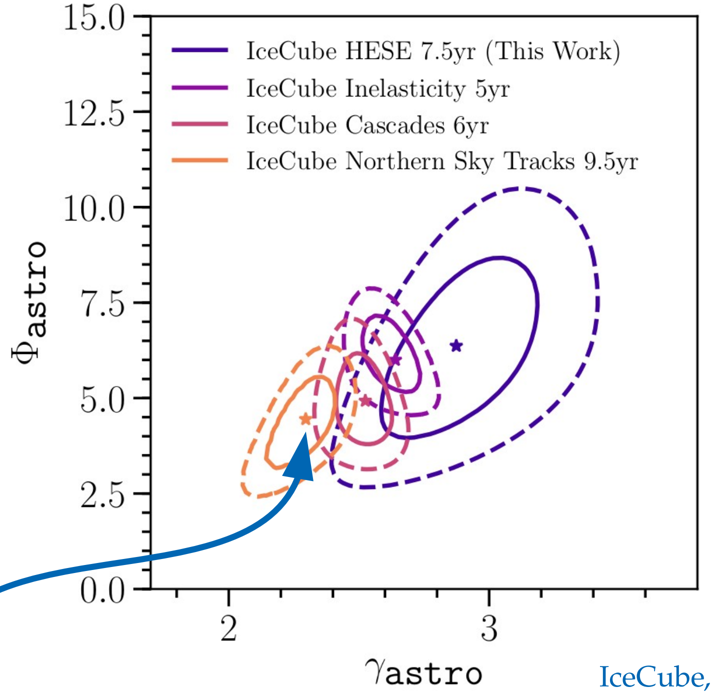
Atm. ν and μ vetoed





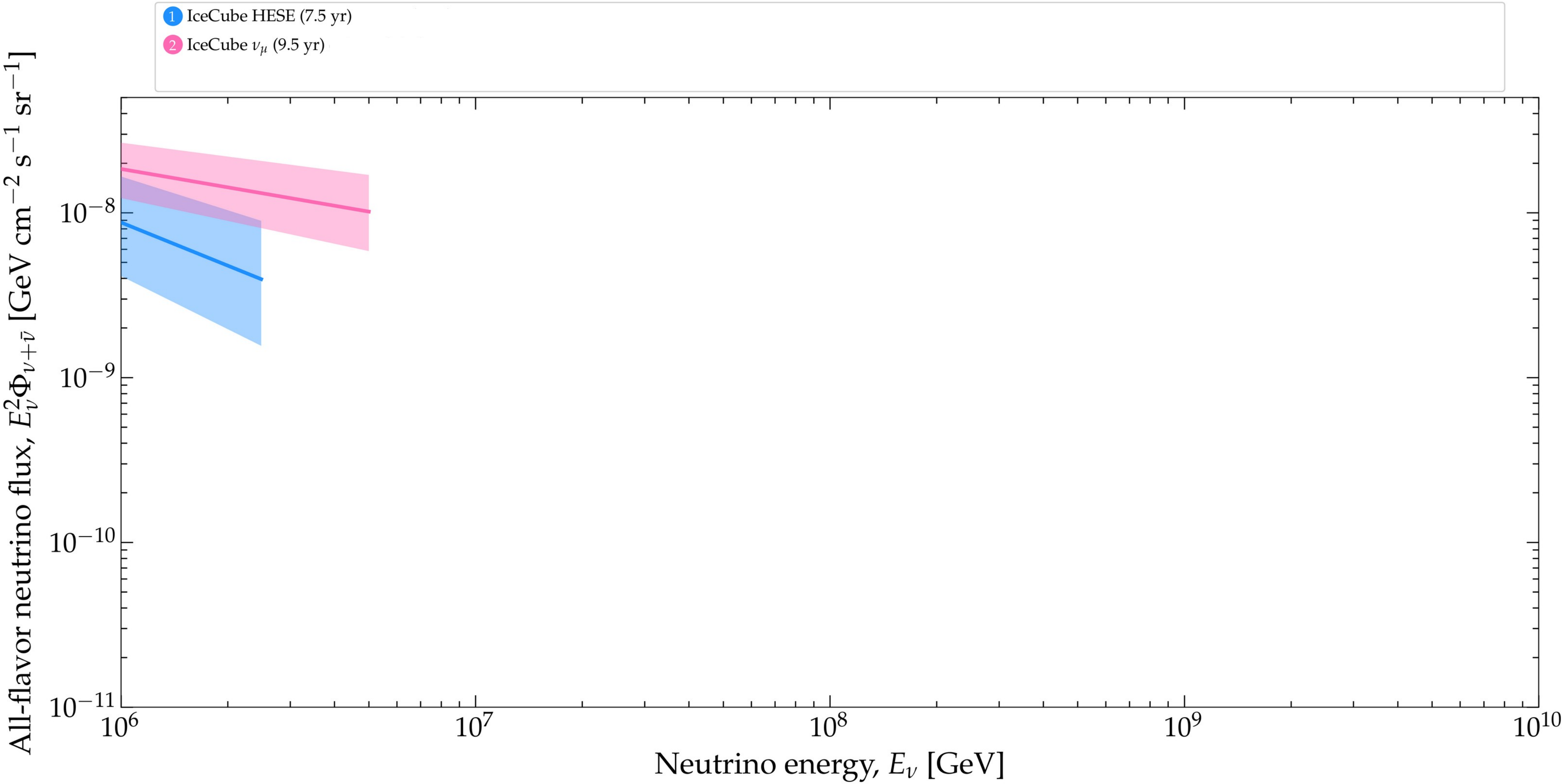
Data is fit well by a single power law:

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



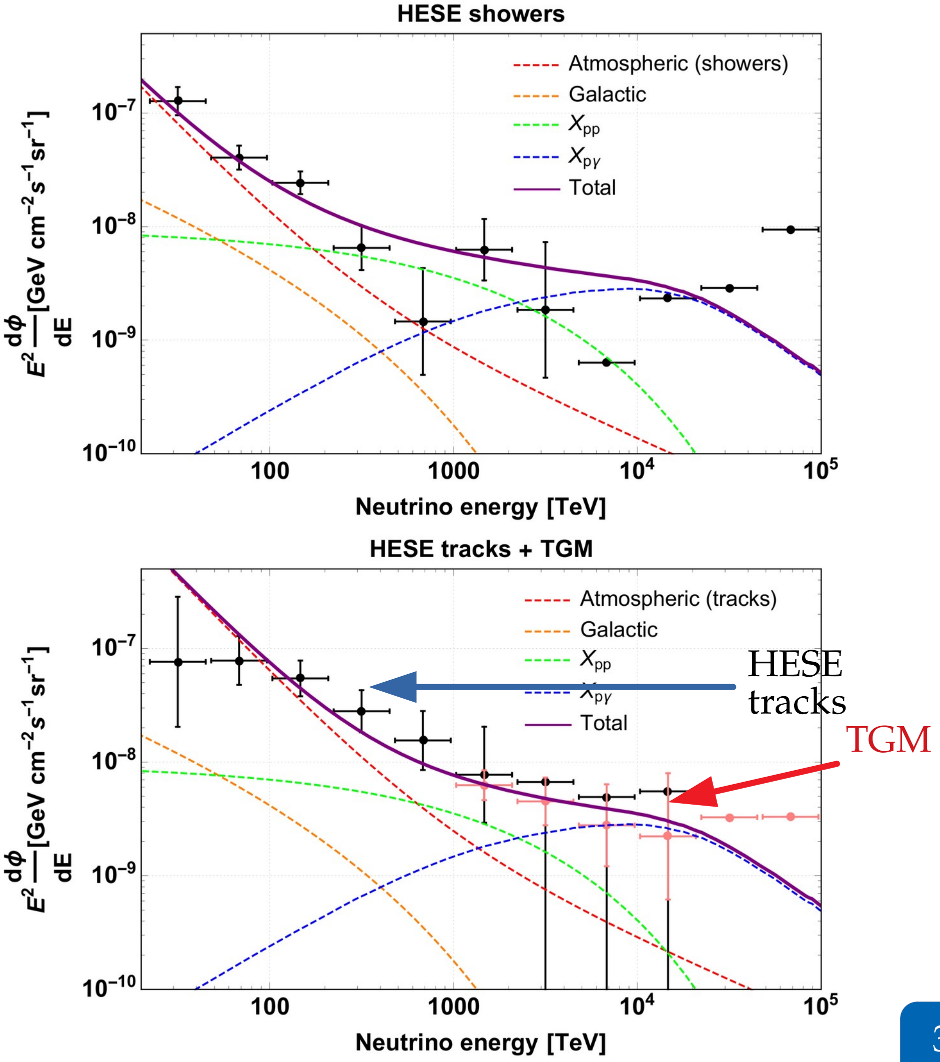
IceCube, *PRD* 2021

Spectrum looks harder for through-going ν_μ


① IceCube HESE (7.5 yr)
② IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

Multi-component model of astrophysical neutrinos

- Four diffuse components:
    - Residual atmospheric (0.2–0.5 PeV): Conv. ($E^{-3.7}$) & prompt ($E^{-2.7}$) ν + muons
    - Galactic ν (≲ PeV): *pp* with disc gas ($E^{-2.6}$), confined to $|b| < 5°$, $|l| < 45°$
    - Extragalactic ν from *pp*, *Ap*: *á la* starbursts (E^{-2})
    - Extragalactic ν from *pγ*, *Aγ*: *á la* TDE (peaked around a few PeV)
- Simultaneous fit to HESE showers, tracks, through-going muons (TGM)



Palladino & Winter, *A&A* 2018

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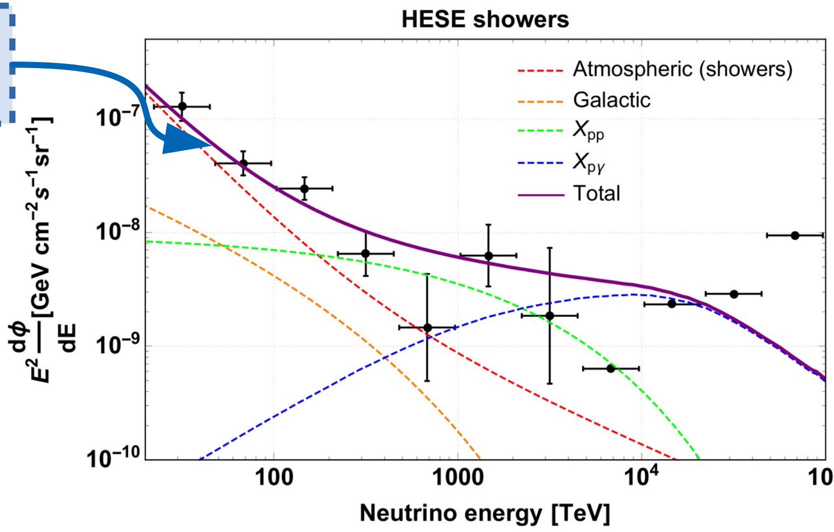
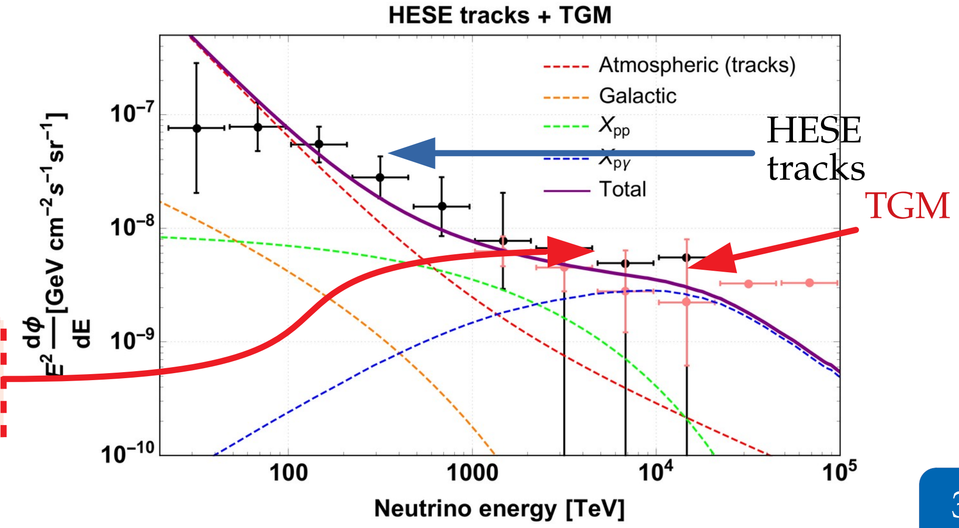
Describes astrophysical ν better at low energies





Describes astrophysical ν better at high energies

Palladino & Winter, *A&A* 2018

Multi-component model of astrophysical neutrinos

- Four diffuse components:
  - Residual atmospheric (0.2–0.5 PeV): Conv. ($E^{-3.7}$) & prompt ($E^{-2.7}$) ν + muons
  - Galactic ν ($\lesssim$ PeV): *pp* with disc gas ($E^{-2.6}$), confined to $|b| < 5°$, $|l| < 45°$
  - Extragalactic ν from *pp*, *Ap*: *á la* starbursts (E^{-2})
  - Extragalactic ν from *pγ*, *Aγ*: *á la* TDE (peaked around a few PeV)
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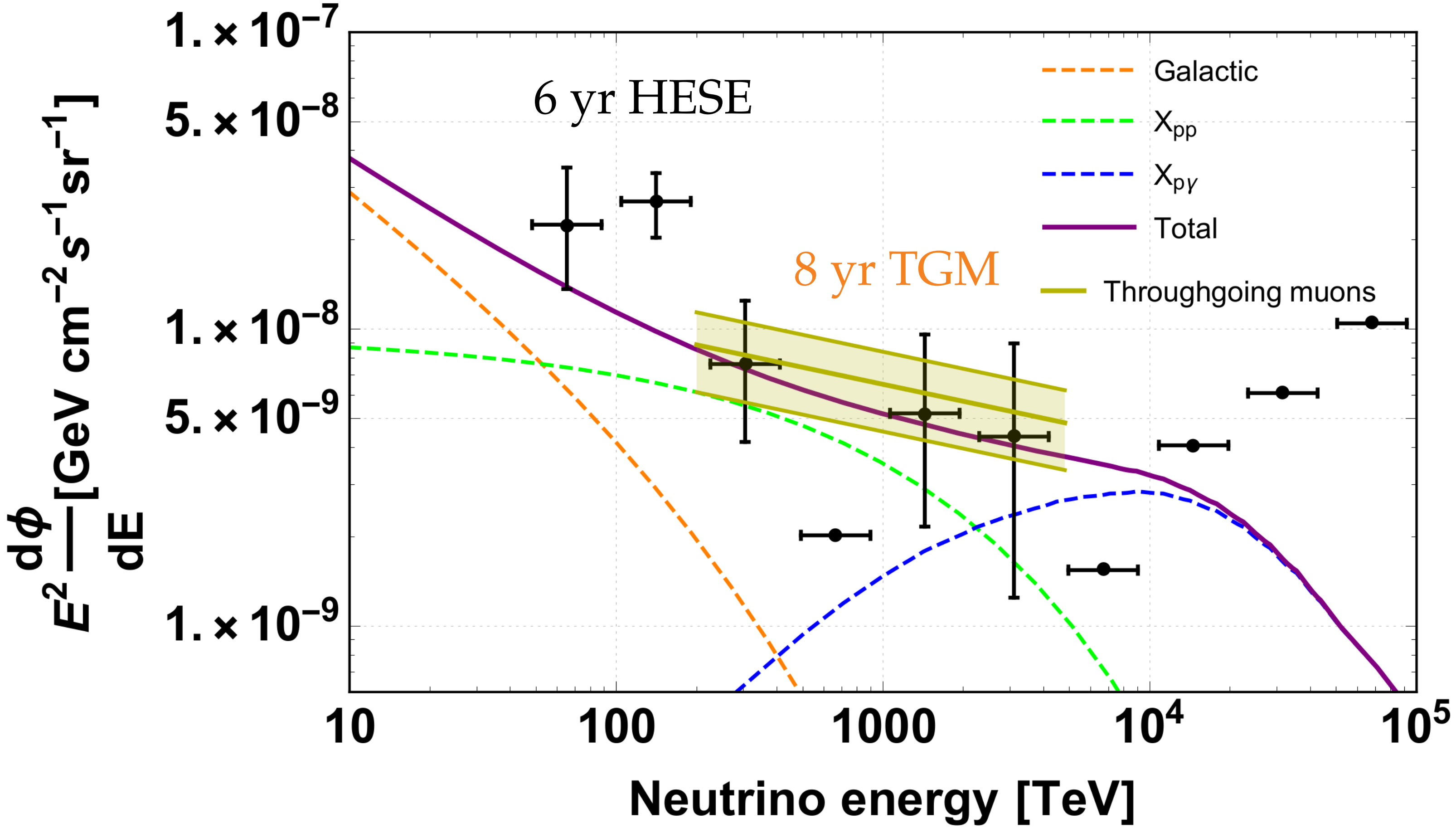

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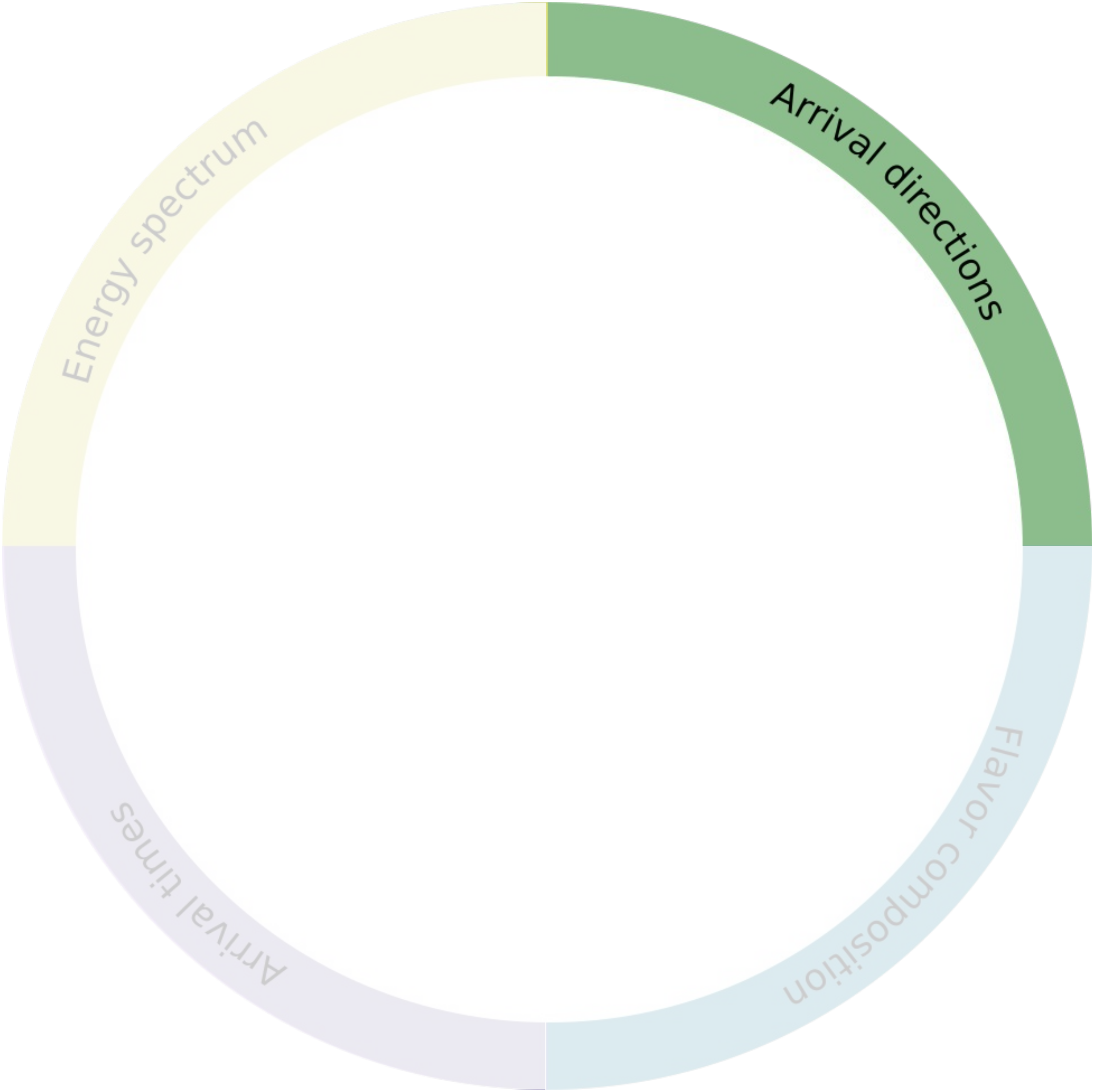


Energy spectrum

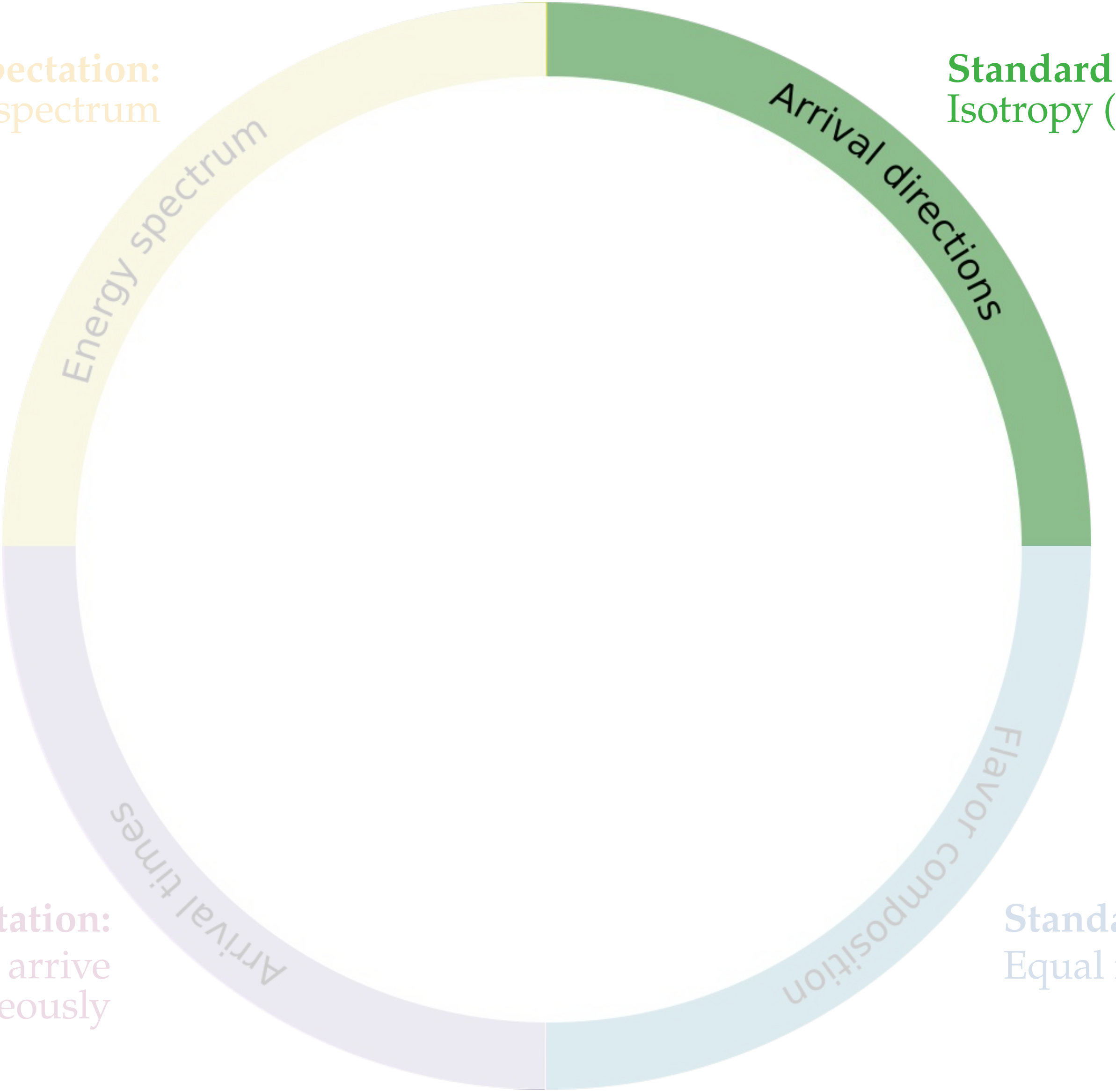
Arrival directions

Flavor composition

Arrival times

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

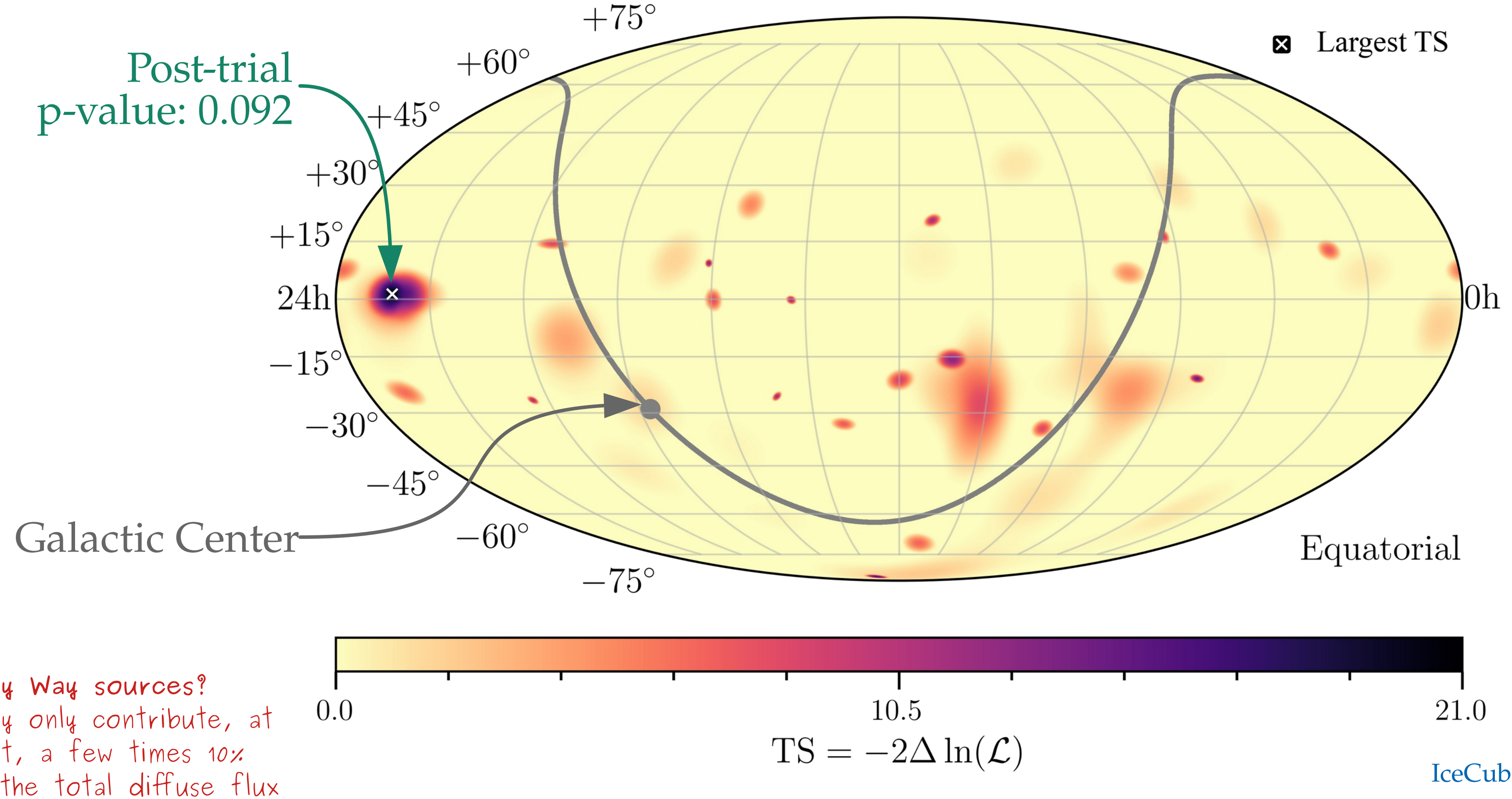


Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Arrival directions (7.5 yr)

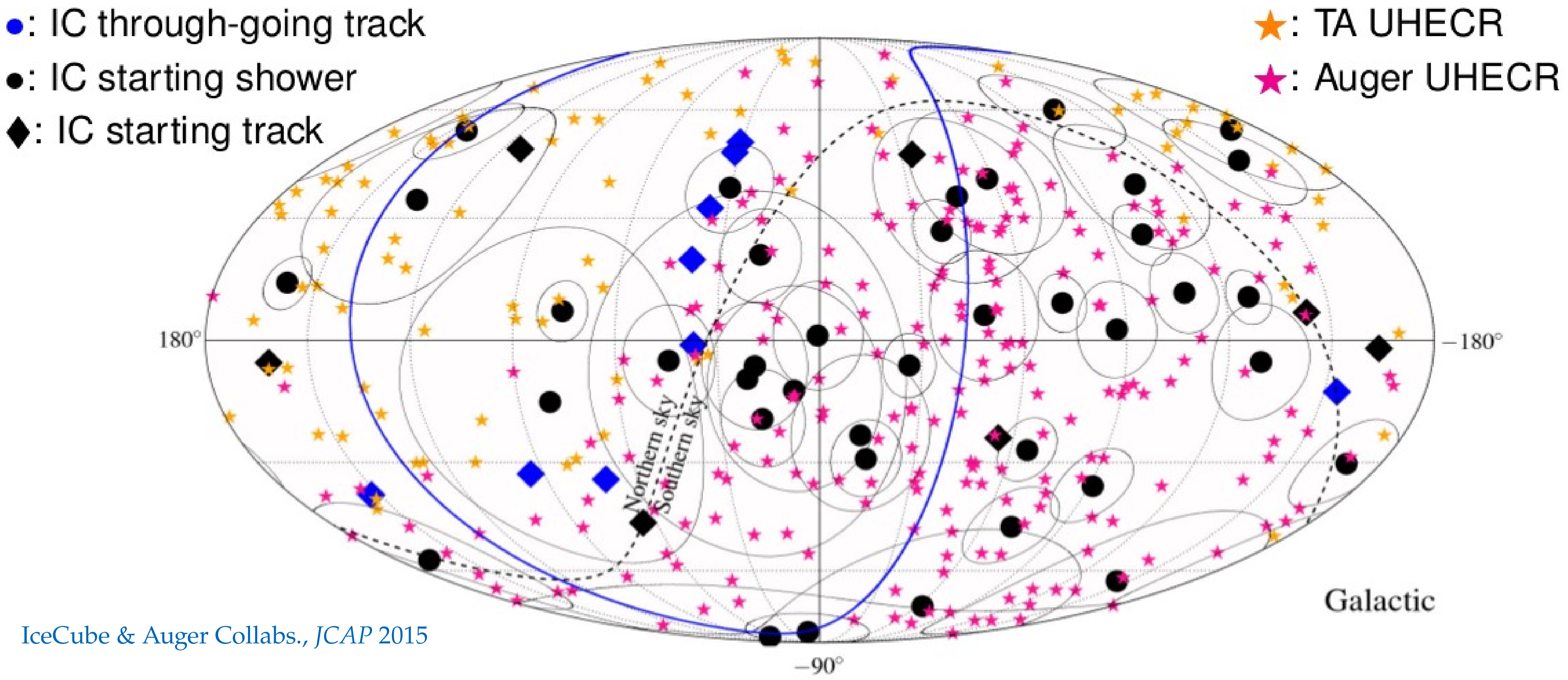
No significant excess in the neutrino sky map:



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

IceCube, *PRD* 2021

Neutrino–UHECR angular correlation?



IceCube & Auger Collabs., *JCAP* 2015

No significant correlation with UHECRs (<3.3σ)

A null neutrino-UHECR correlation *makes sense*

UHECRs trace sources within $\lambda_{\mathrm{GZK}} \approx 100$ Mpc

Neutrinos come from anywhere inside the Hubble horizon $D_{\mathrm{H}} \approx 4$ Gpc

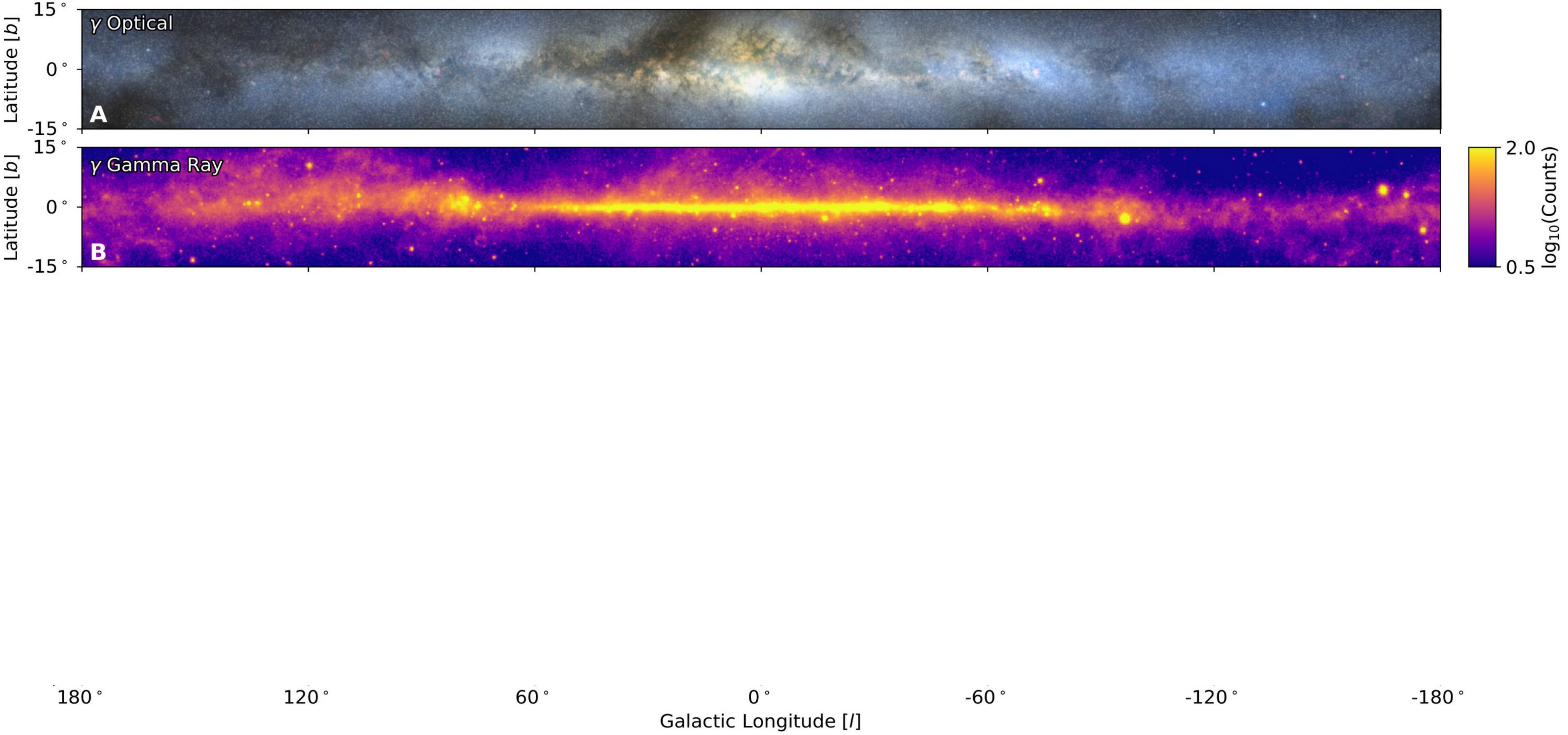
So the maximum possible correlation is $\dfrac{\lambda_{\mathrm{GZK}}}{D_{\mathrm{H}}} \approx 2.5\%$

Current number of IceCube high-energy starting tracks (HESE): ~100

∴ Expected UHECR correlation with only ~3 neutrinos

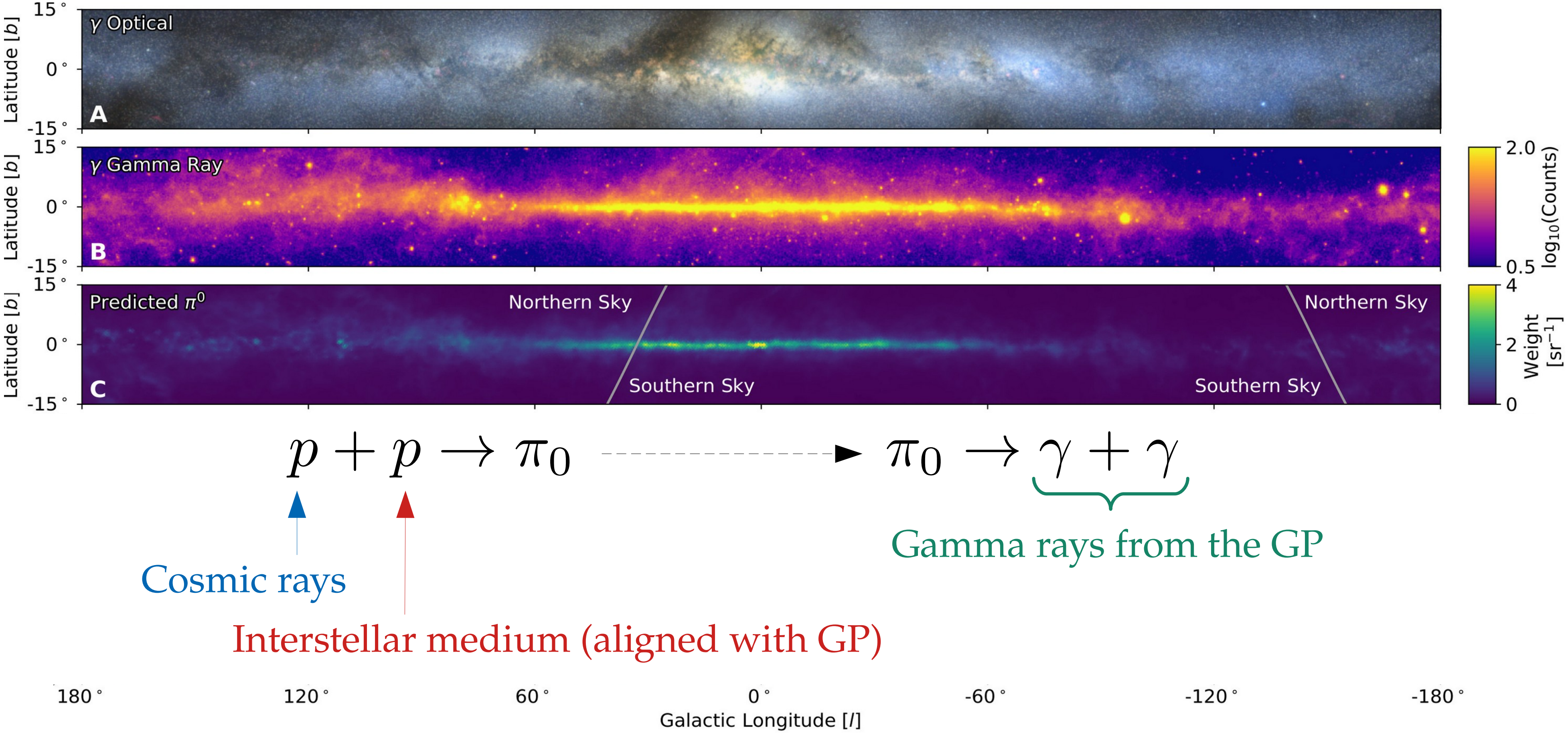
(Also, potential correlation is weakened by magnetic deflection, angular resolution, *etc.*)

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



$$p + p \to \pi_0 \dashrightarrow \pi_0 \to \underbrace{\gamma + \gamma}$$

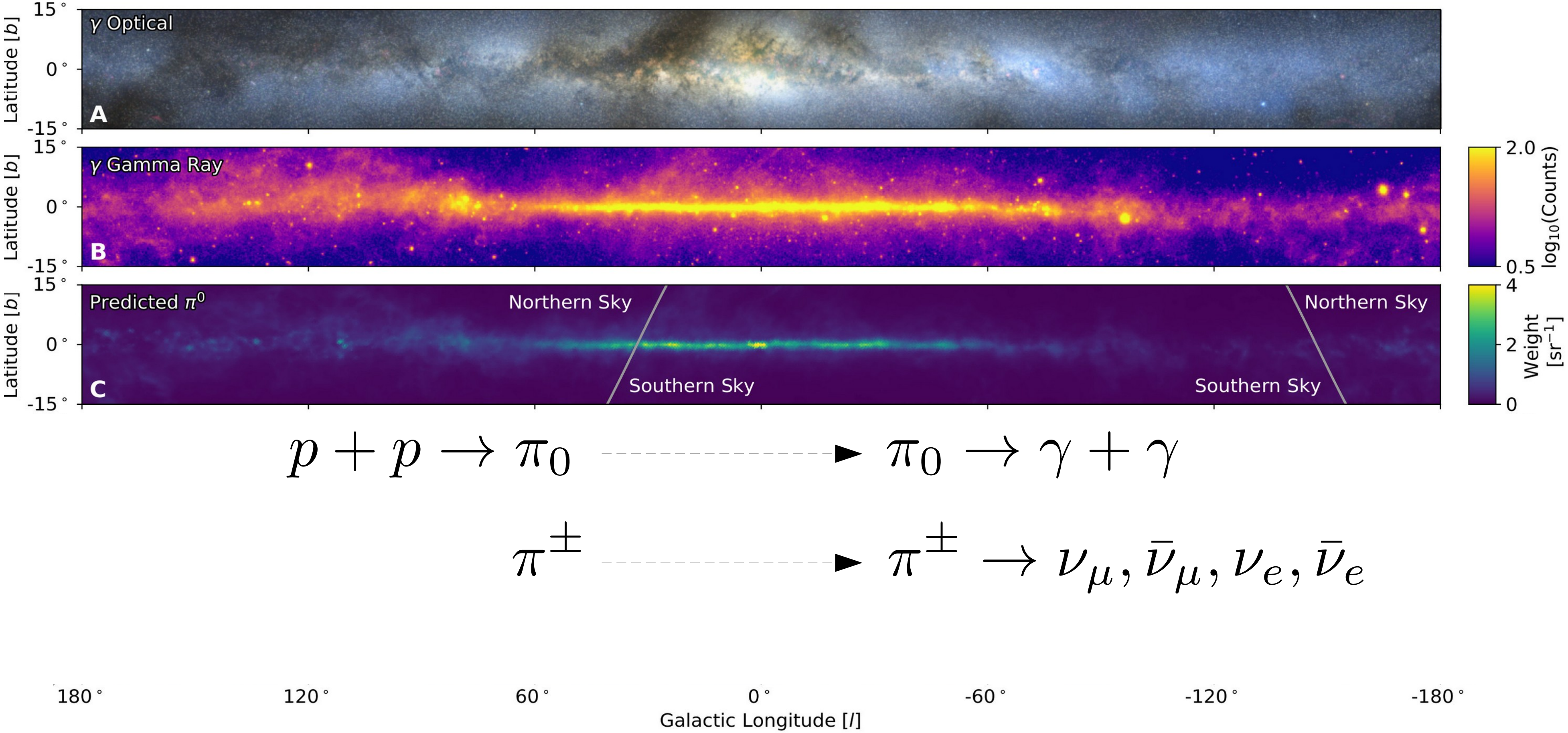
Cosmic rays

Interstellar medium (aligned with GP)

Gamma rays from the GP

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane

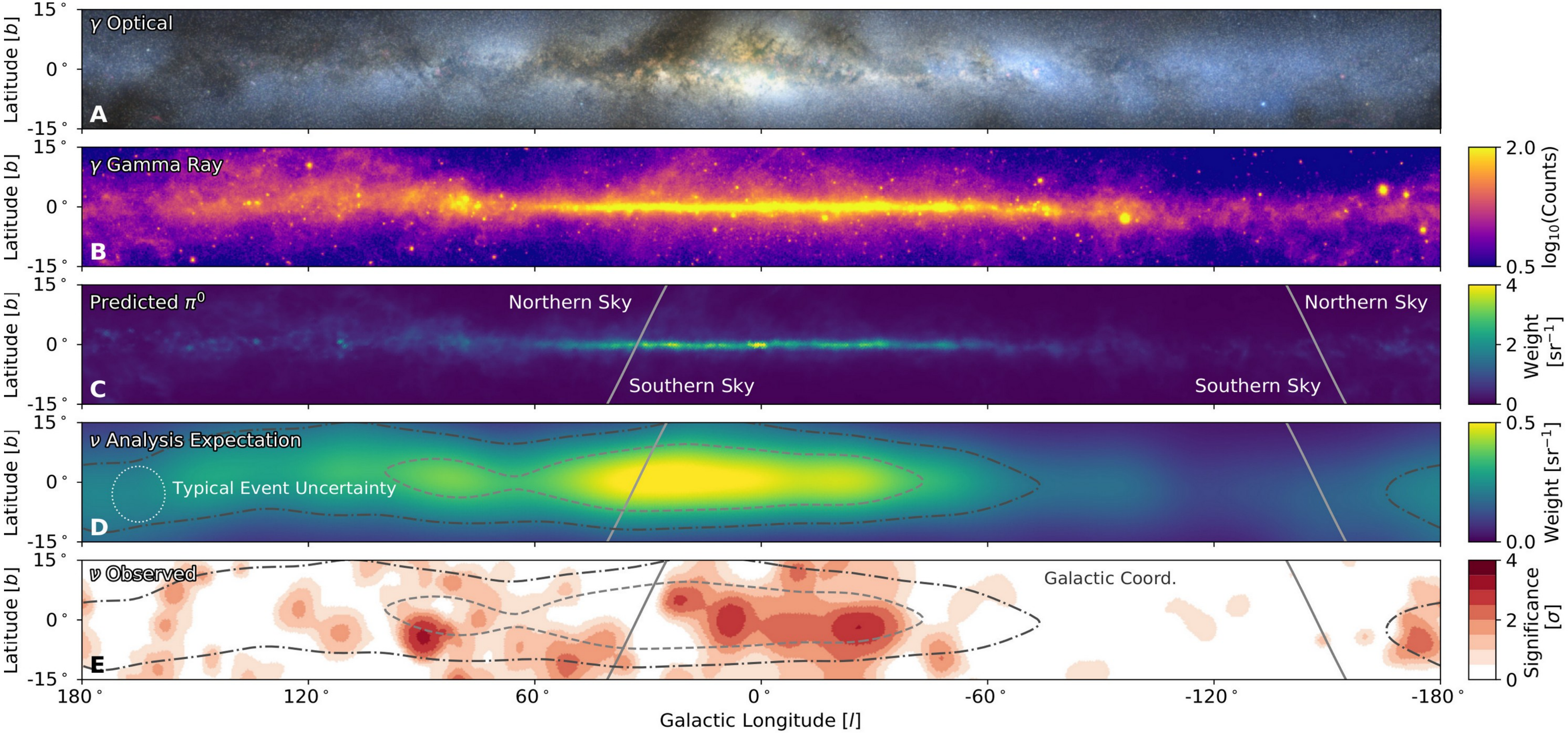


$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \gamma + \gamma$$

$$\pi^{\pm} \dashrightarrow \pi^{\pm} \rightarrow \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$$

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

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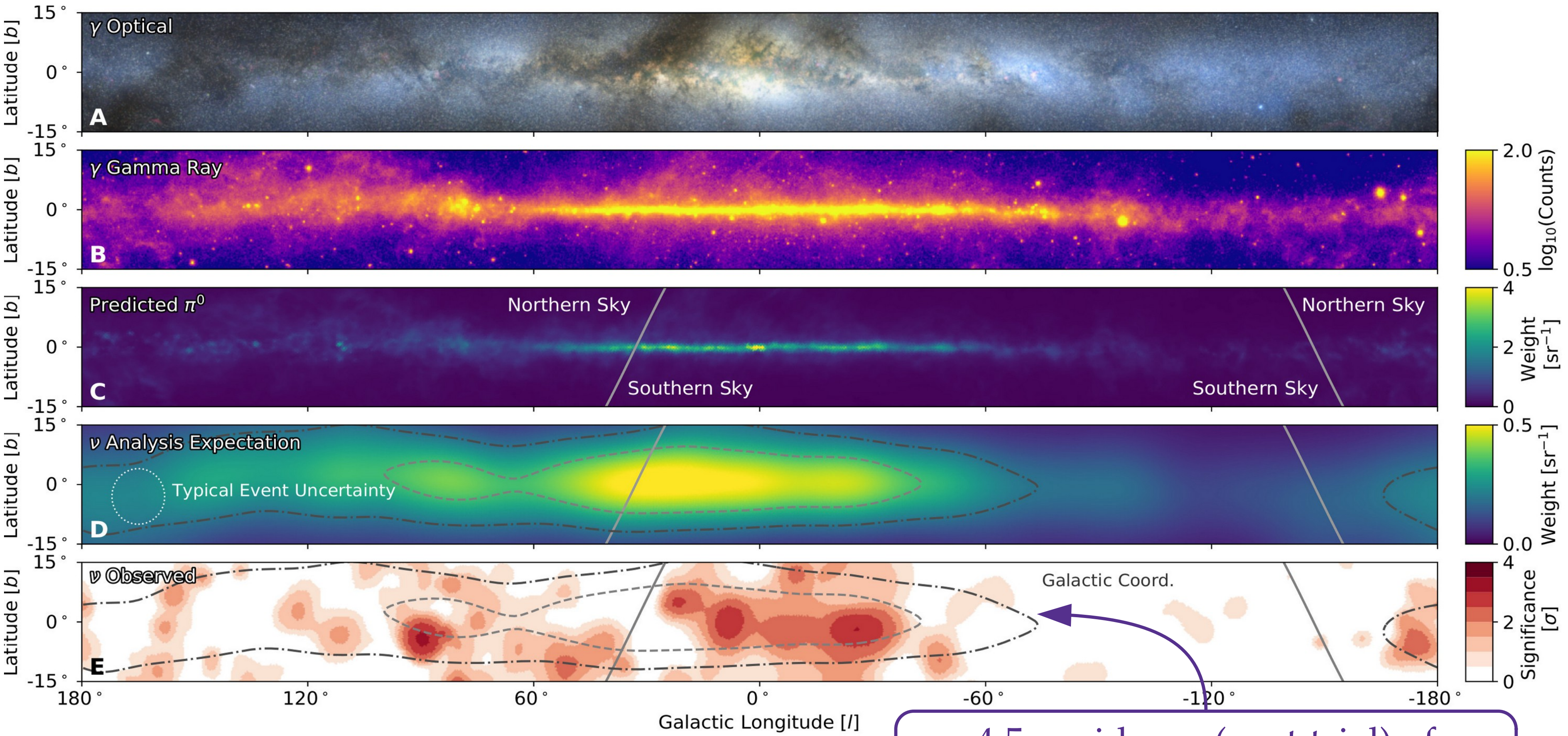
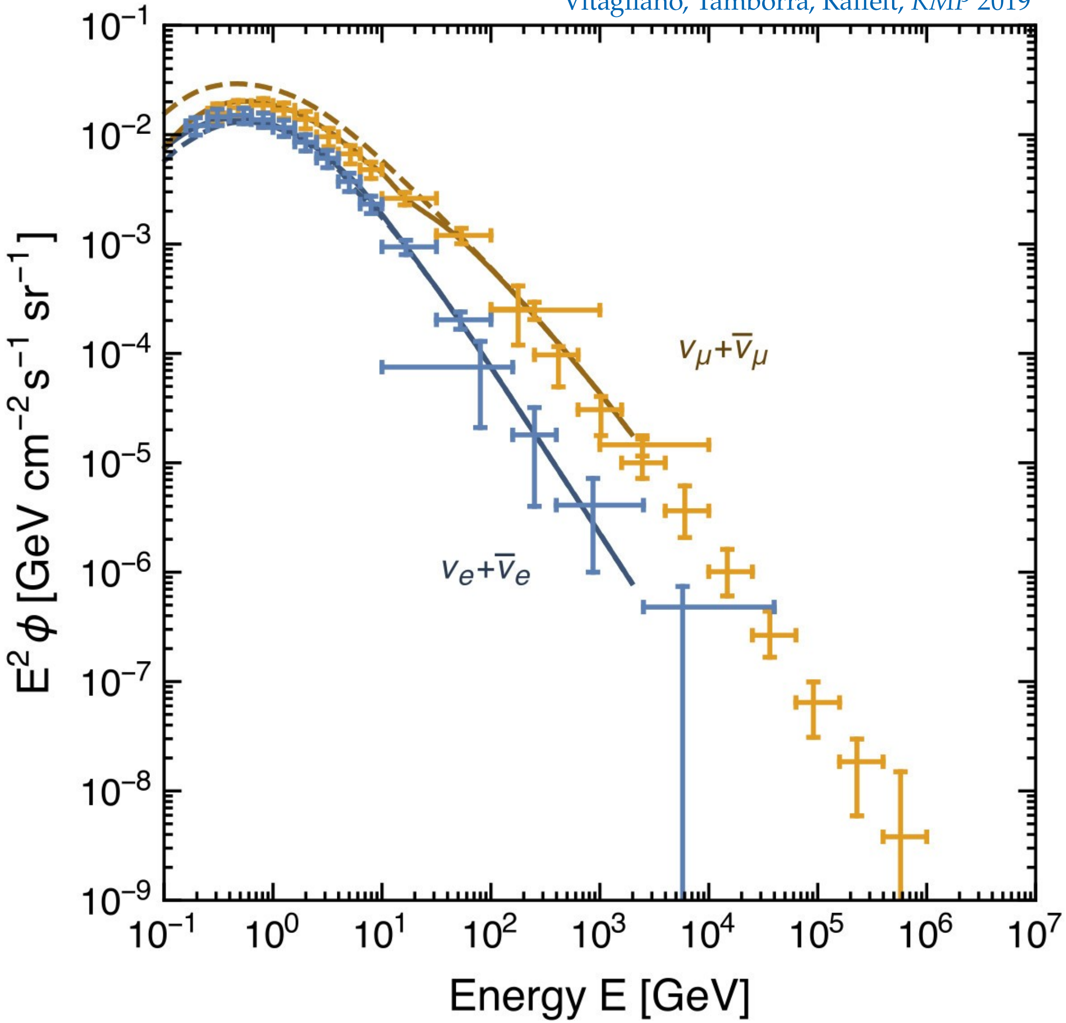


4.5σ evidence (post-trial) of diffuse flux of > TeV ν from the GP

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane

Vitagliano, Tamborra, Raffelt, *RMP* 2019



See also: Beacom & Candia, *JCAP* 2004

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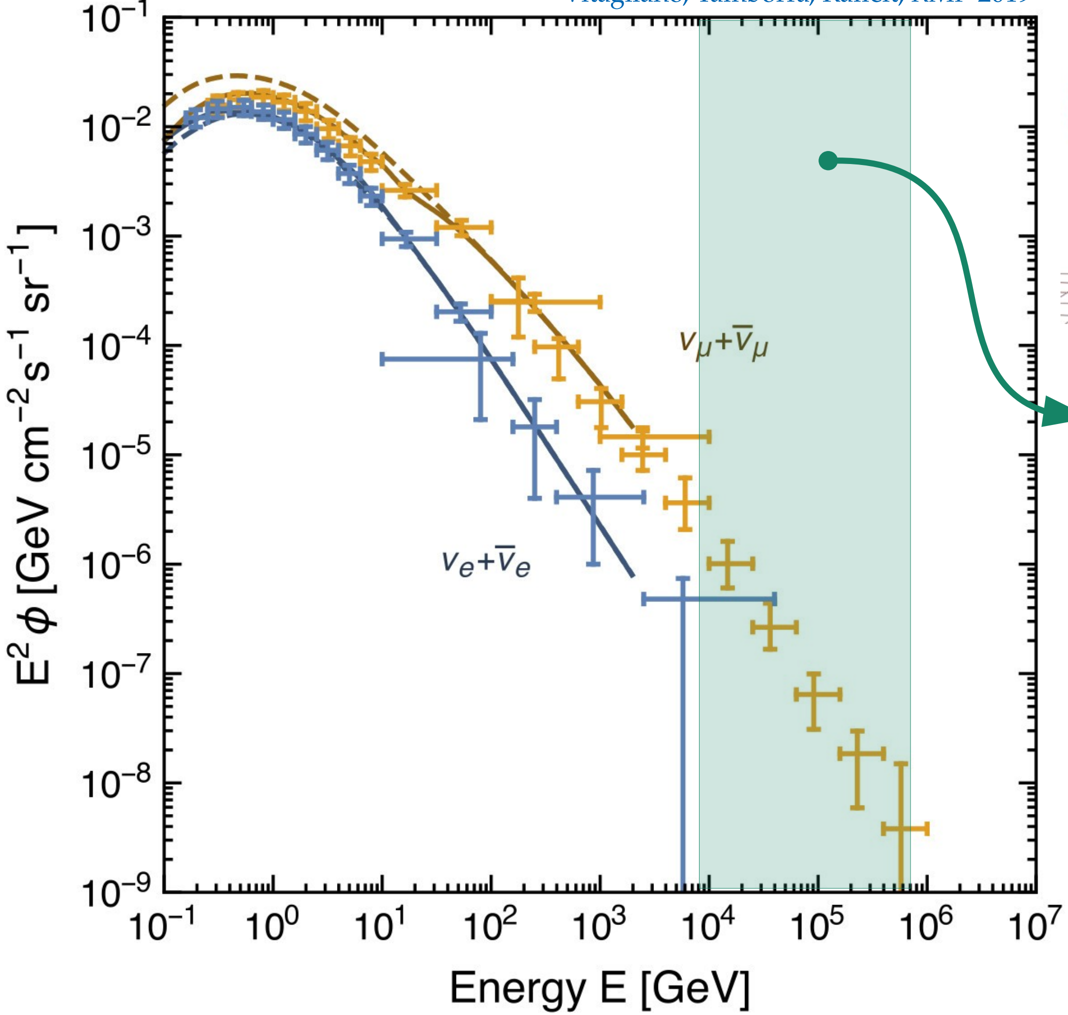
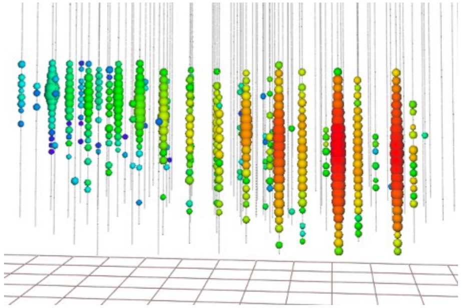


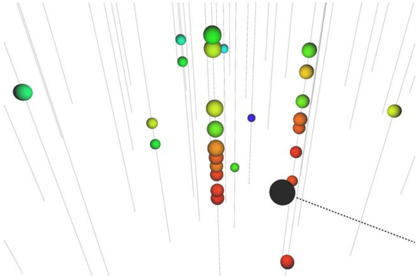


Search for **>10-TeV** astrophysical ν

- Use **muon tracks**
- Pointing accuracy: ~1°
- Atm. bg. is mostly ν_μ
- Self-veto screens for atm. muons to cut ν bg.

See also: Beacom & Candia, *JCAP* 2004

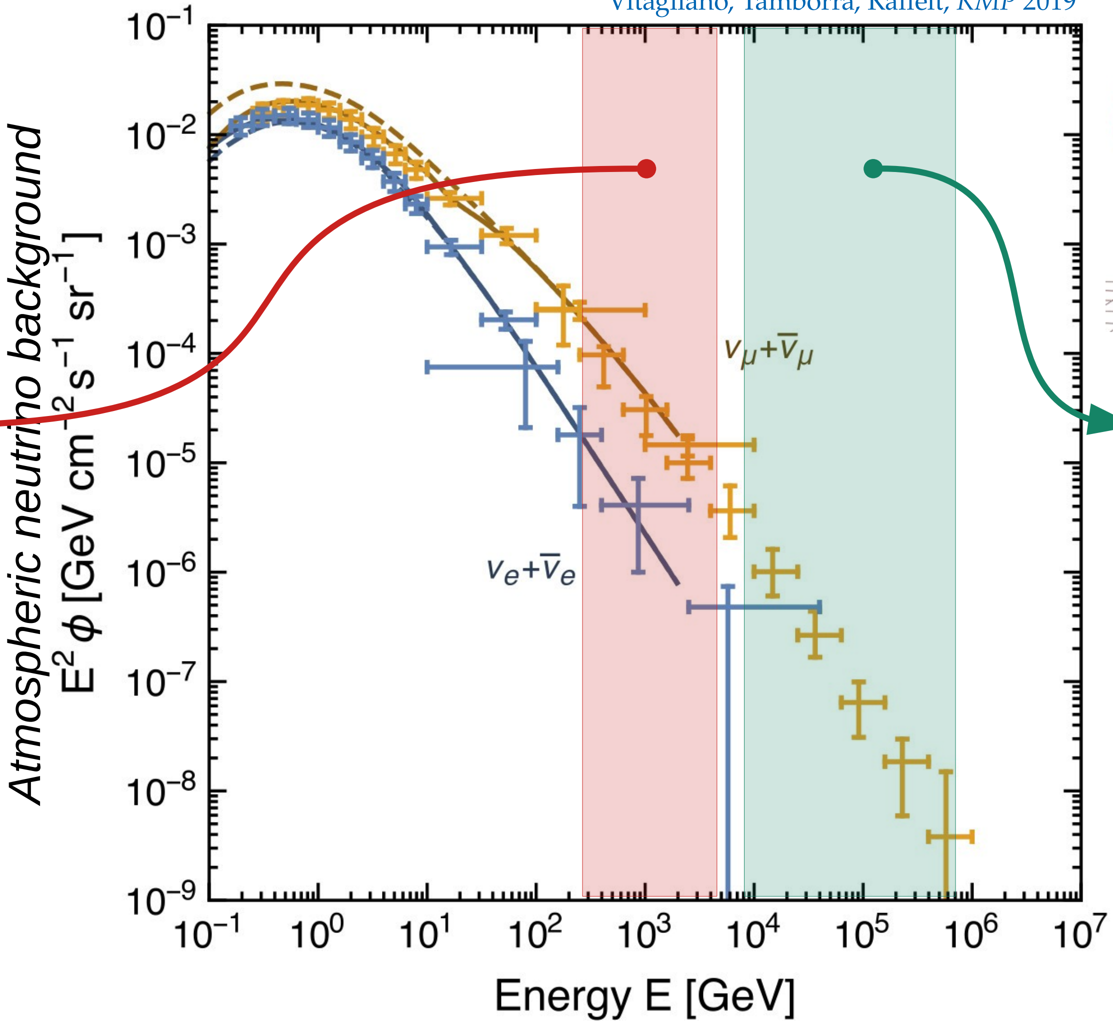
High-energy neutrinos from the Galactic Plane

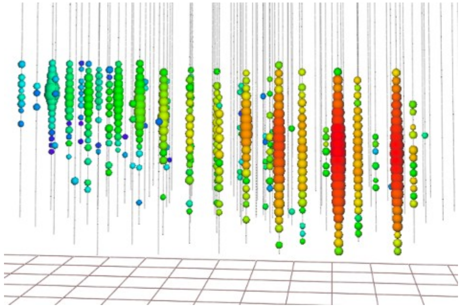


Search for **TeV** astrophysical ν

- But GP ν are TeV
- Use **cascades**
- Atm. ν_e bg. ×10 lower
- Bg.-to-signal: 10^8:1
- *Deep learning retains 20 times more events, ×2 better angular res.*

Vitagliano, Tamborra, Raffelt, *RMP* 2019





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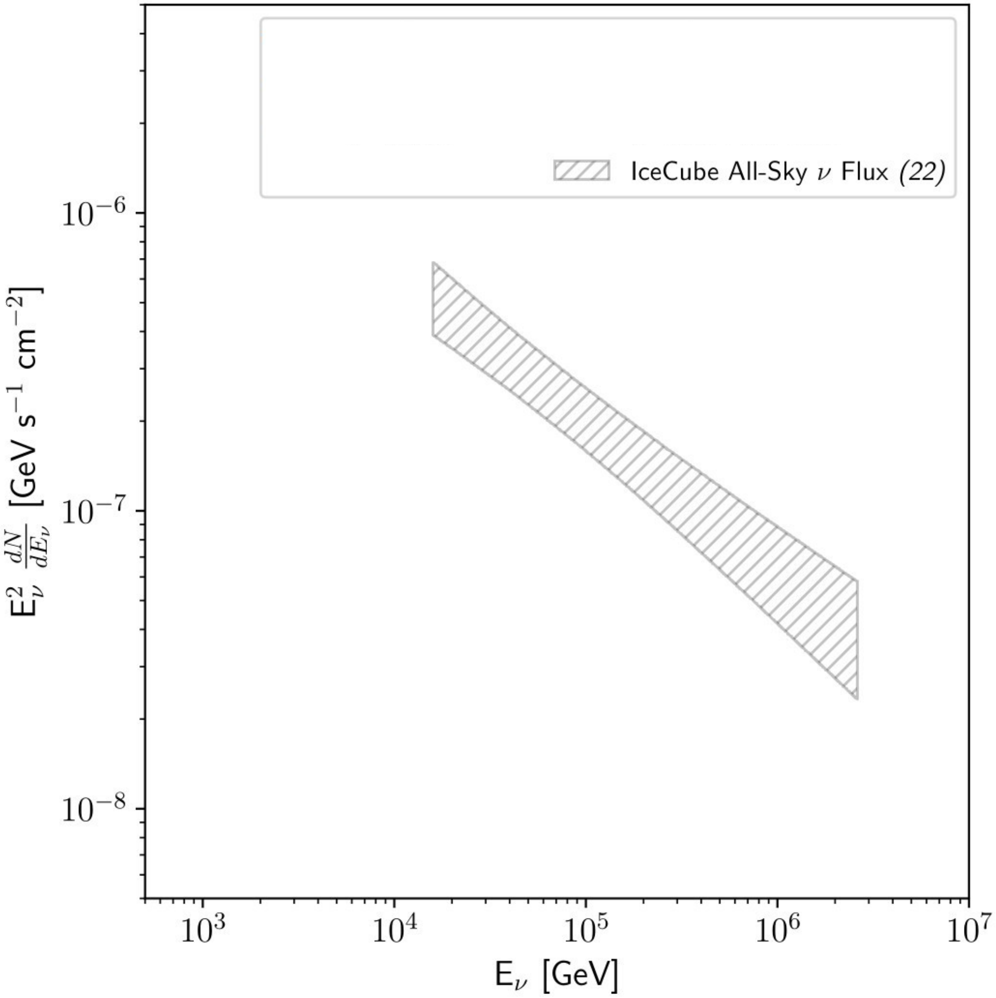

IceCube Collab., *Science* 2023

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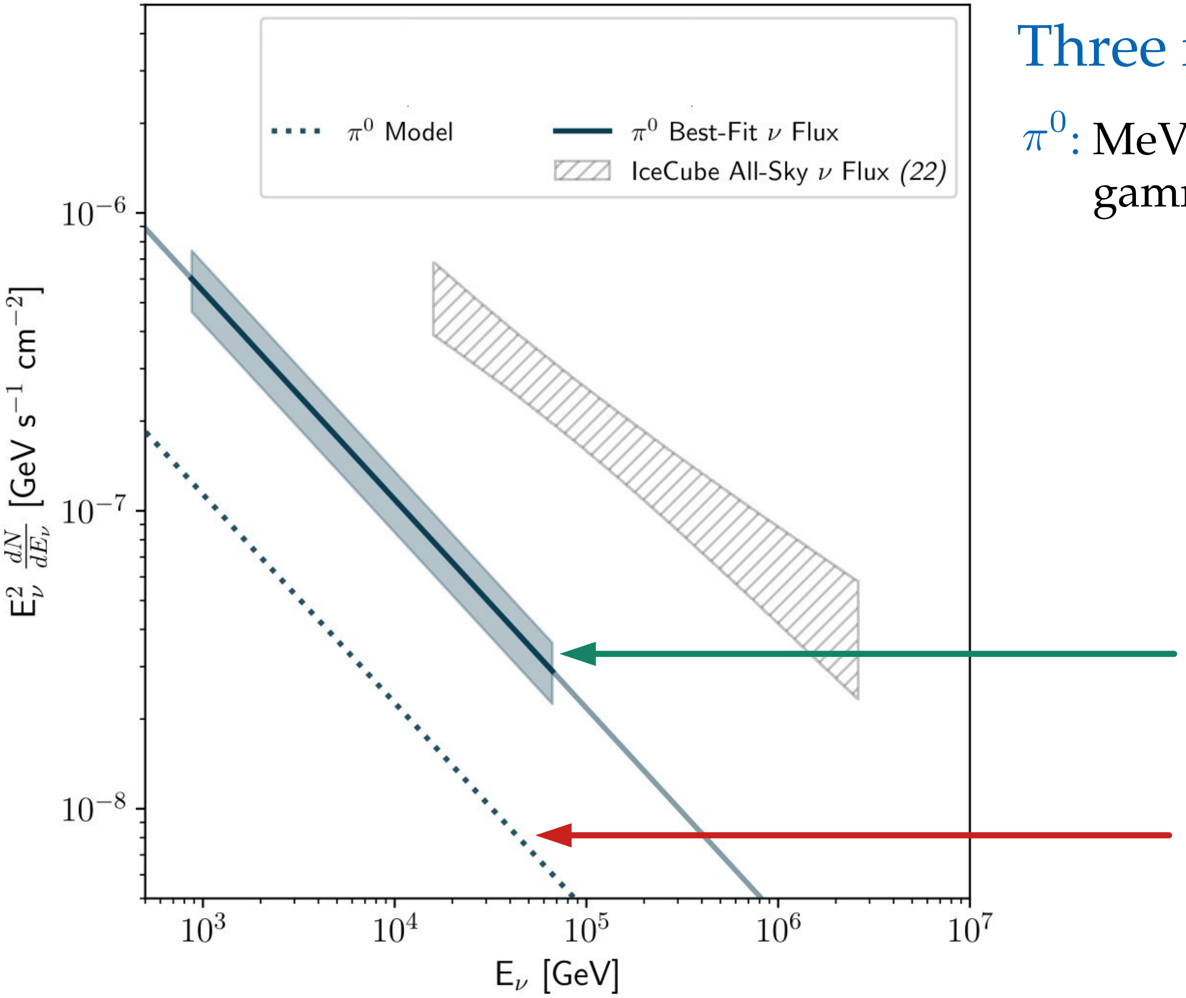


Three models of Galactic diffuse ν:

π^0: MeV–GeV π^0 template inferred from gamma rays extrapolated to TeV

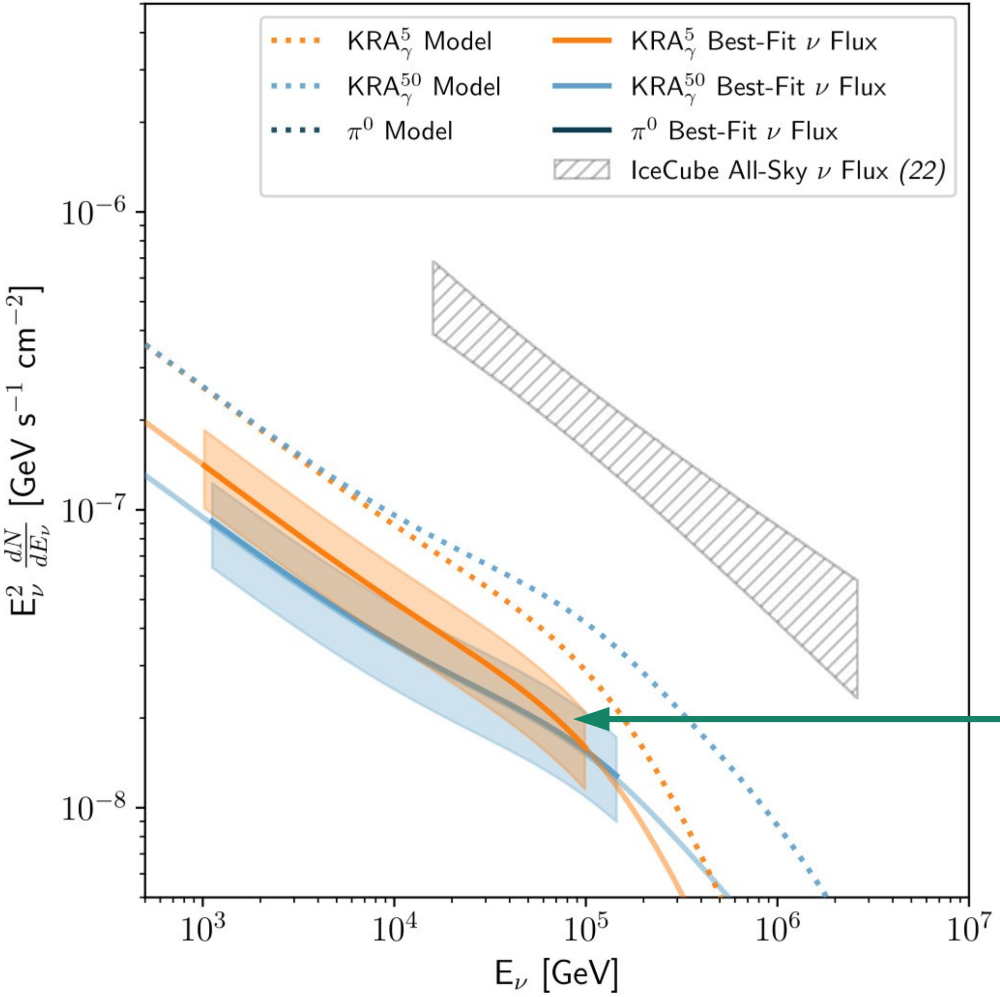
Observed (× 5 model)

Consistent with 100-TeV observations by Tibet Air Shower Array

Model

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



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KRA_γ^5 : Spectrum varies spatially, harder ν spectrum, cut-off at 5 PeV in CR energy

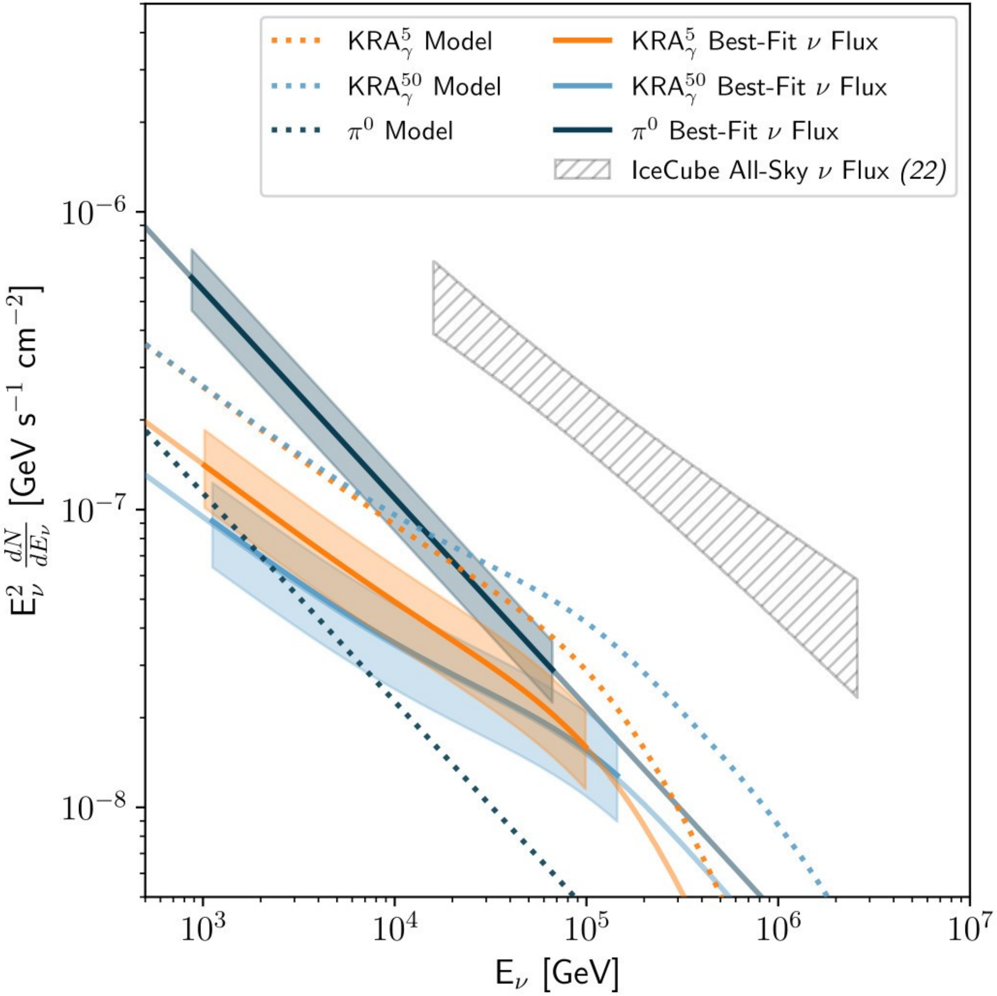
KRA_γ^{50} : Cut-off at 50 PeV in CR energy

Observed (× 0.5 model)

Cut-off energy could be different from the 5 and 50 PeV tested

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

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KRA_γ^5 : Spectrum varies spatially, harder ν spectrum, cut-off at 5 PeV in CR energy

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None of the models matched data

(caveat: there are relatively simple models)

No Galactic ν source identified

(likely diffuse + source: Fang & Murase, 2307.02905)

GP flux is 6–13% of all-sky at 30 TeV

Energy spectrum

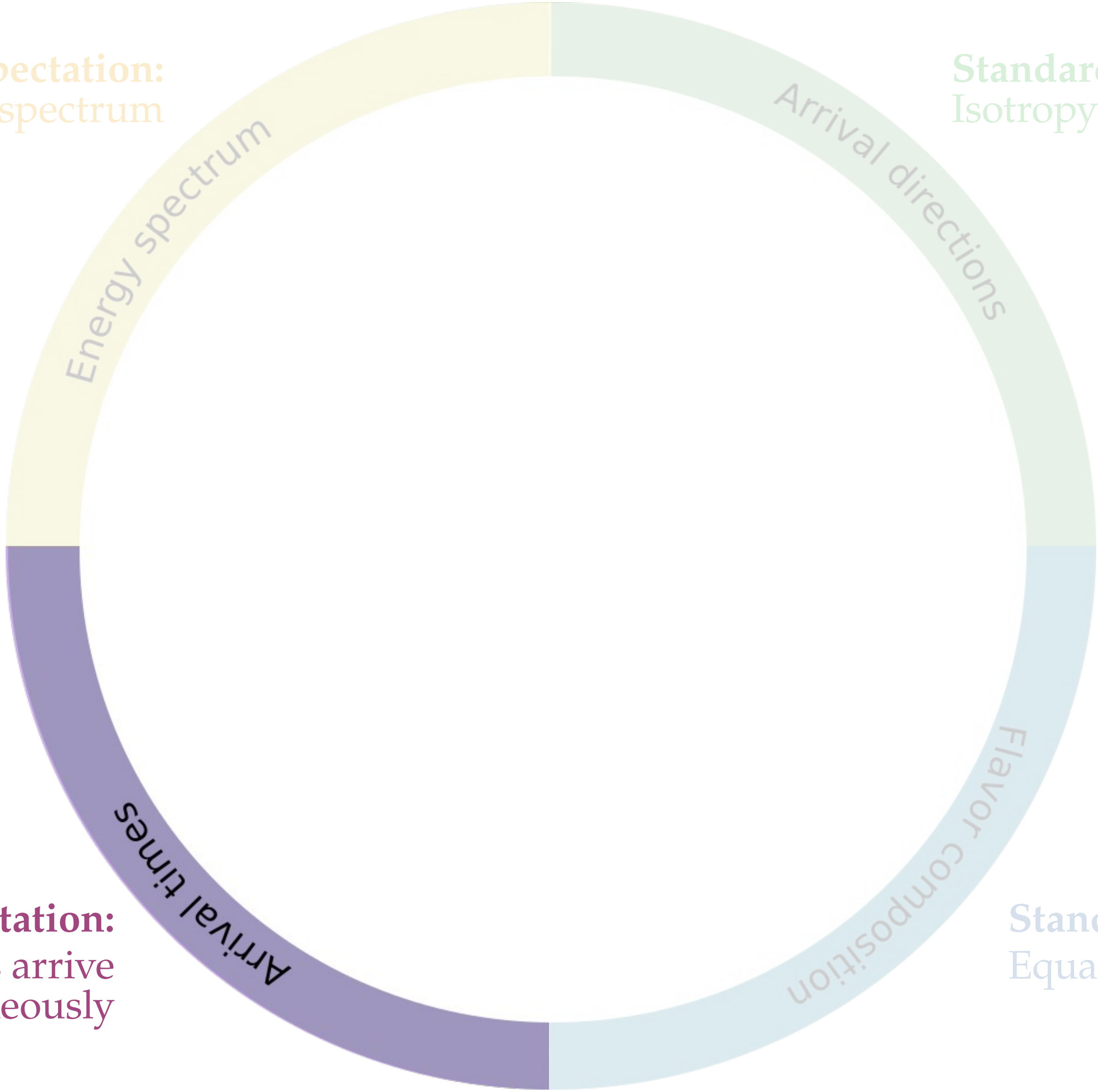
Arrival directions

Flavor composition

Arrival times

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Bright in gamma rays, bright in high-energy neutrinos

Energy in neutrinos ∝ 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 *p* energy given to π
in one interaction (~20%)

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Baryonic loading

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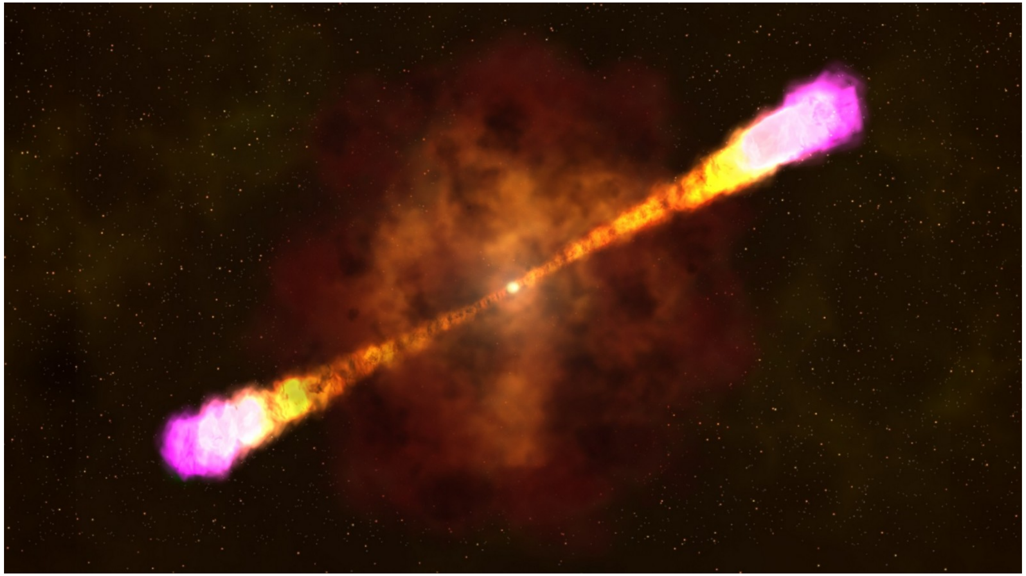
Baryonic loading

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

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

Gamma-ray bursts and blazars – *not* dominant

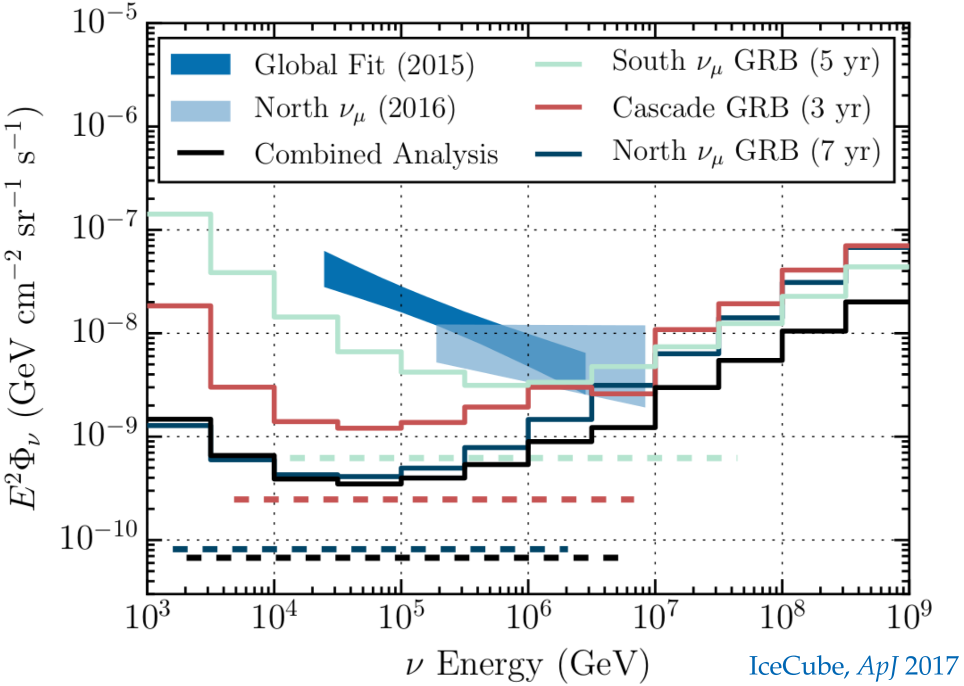
Gamma-ray bursts



Blazars

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

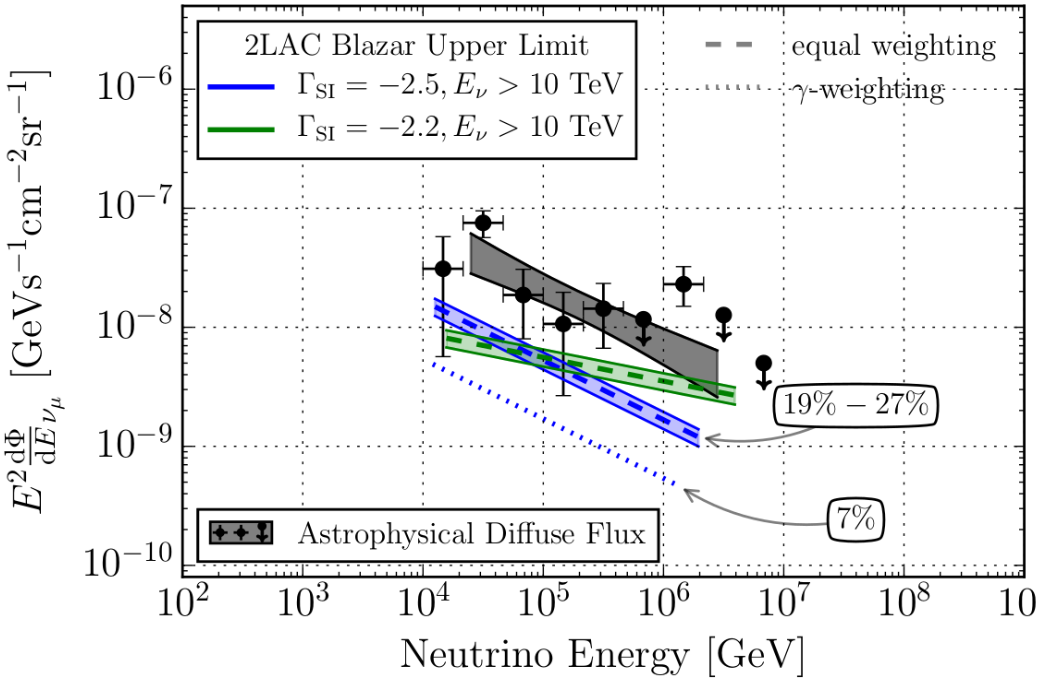


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

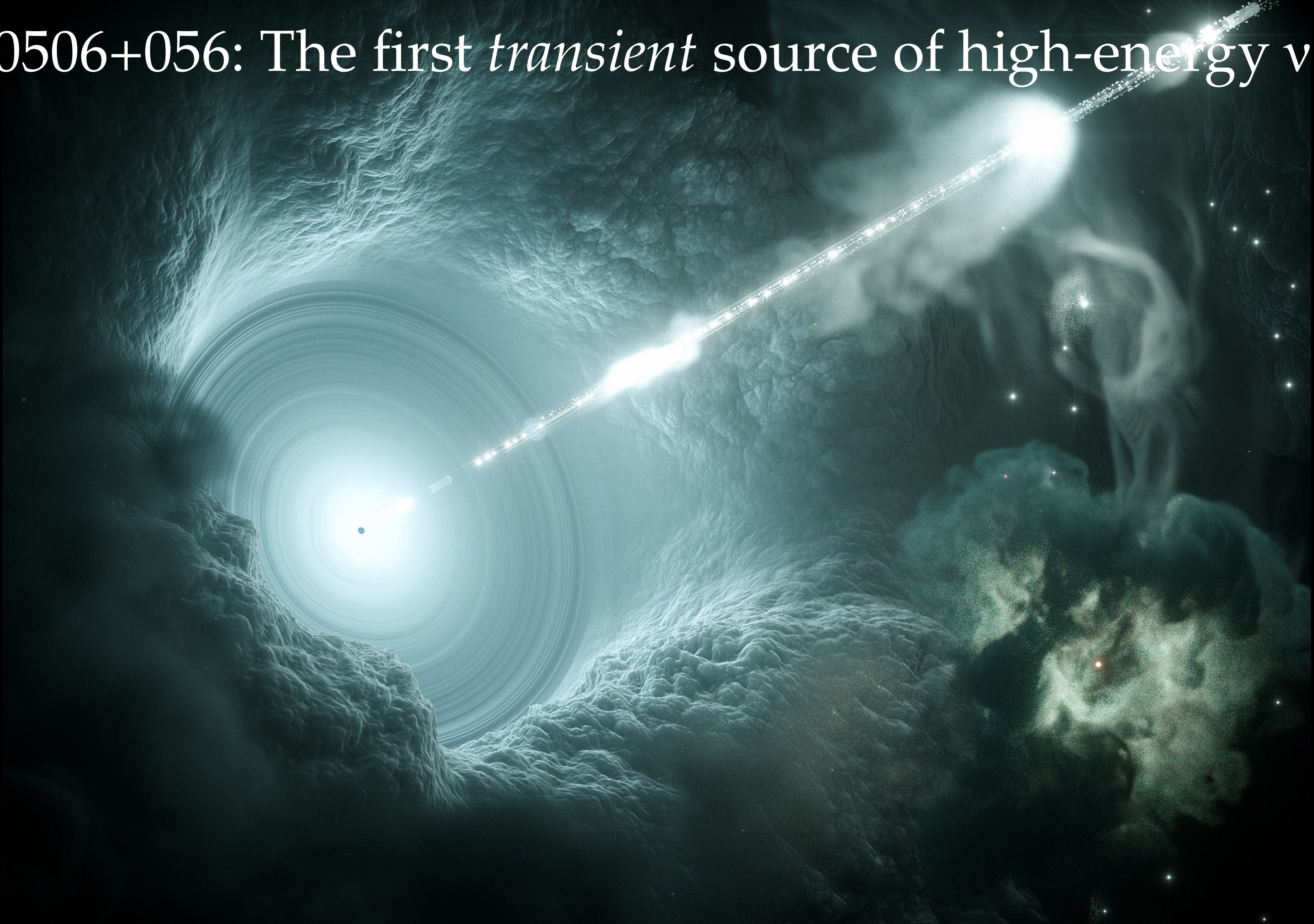
Blazars



862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

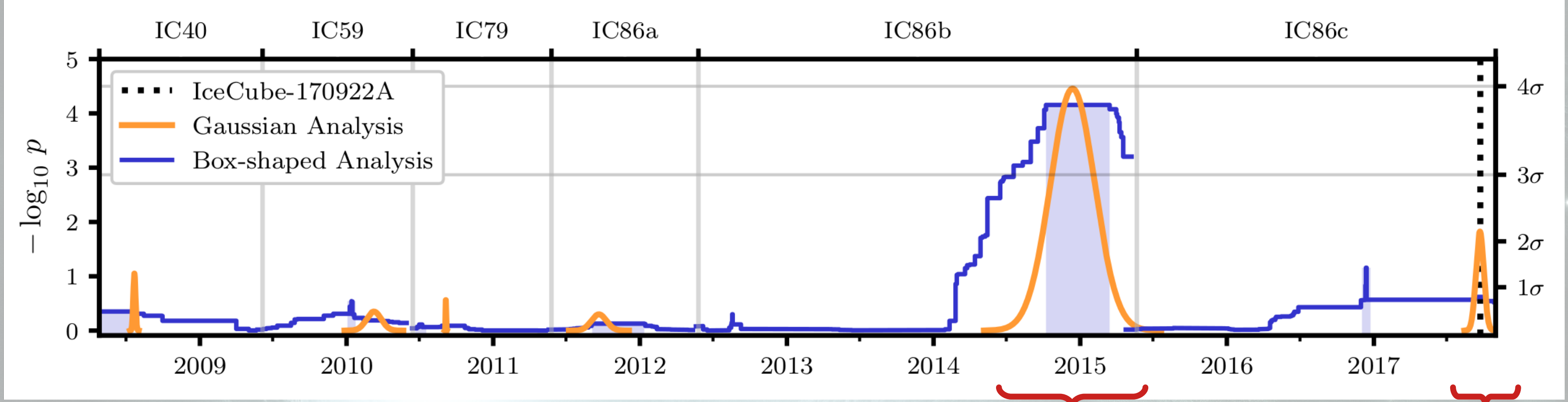
TXS 0506+056: The first *transient* source of high-energy ν



DESY

TXS 0506+056: The first *transient* source of high-energy ν

Blazar TXS 0506+056:



IceCube, *Science* 2018

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

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

Combined (pre-trial): 4.1σ

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

Tidal disruption events

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

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

NASA

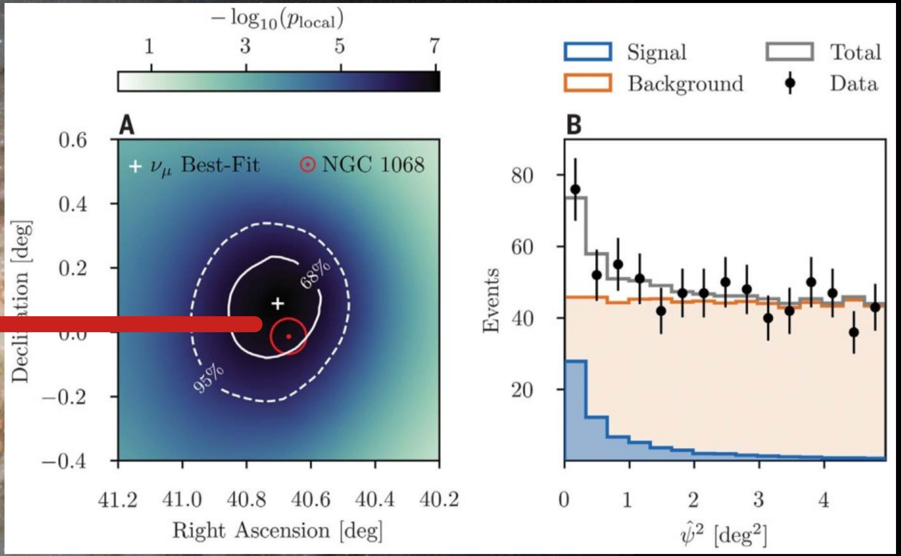
NGC1068: The first *steady-state* source of high-energy ν

Active galactic nucleus

Brightest type-2 Seyfert

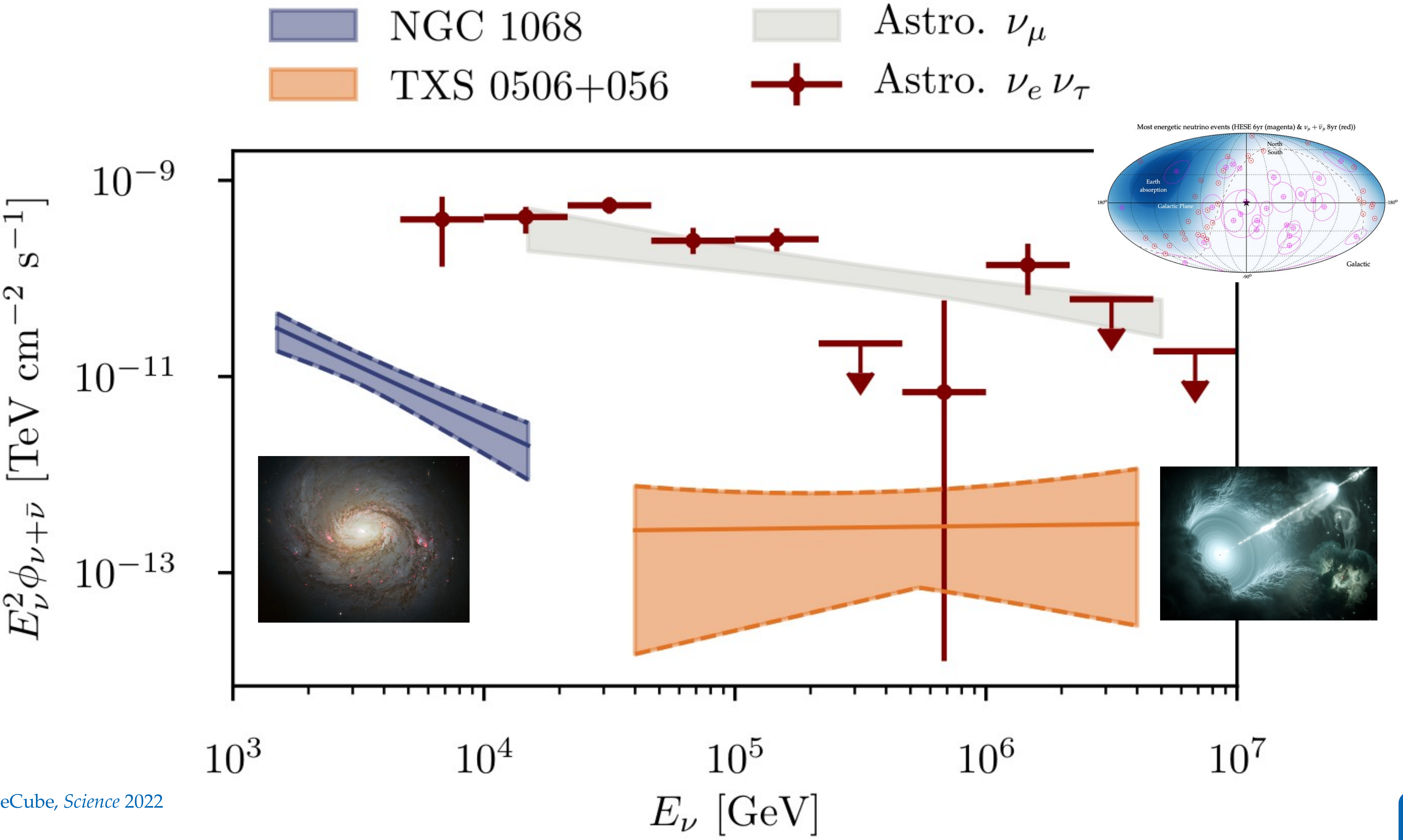
79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



IceCube Collab., *Science* 378, 538 (2022)

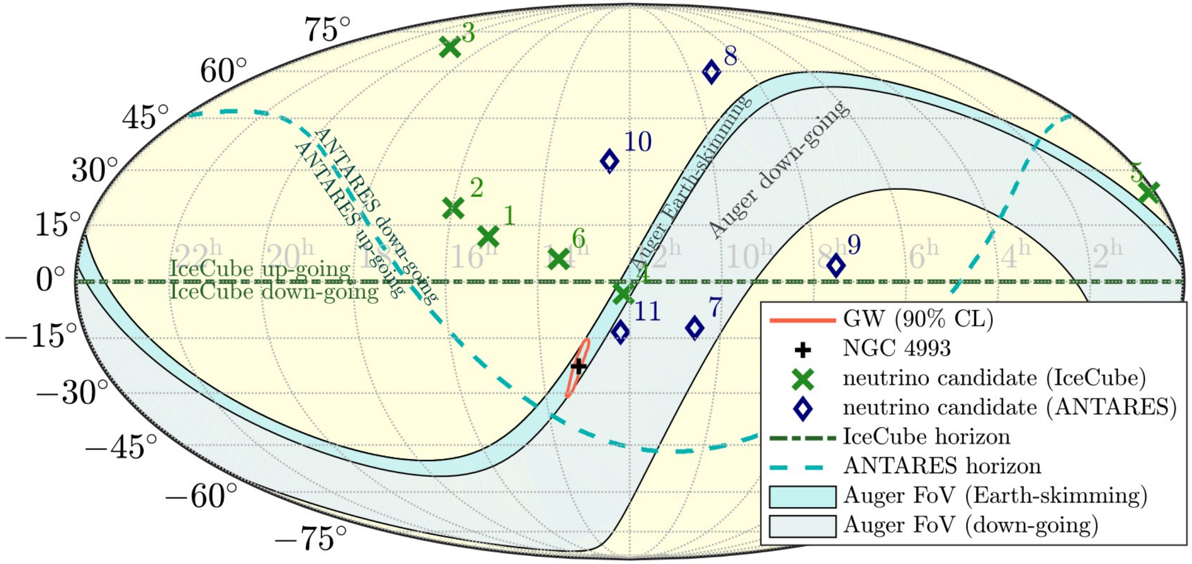
Hubble Space Telescope,
NASA, ESA & A. van der Hoeven

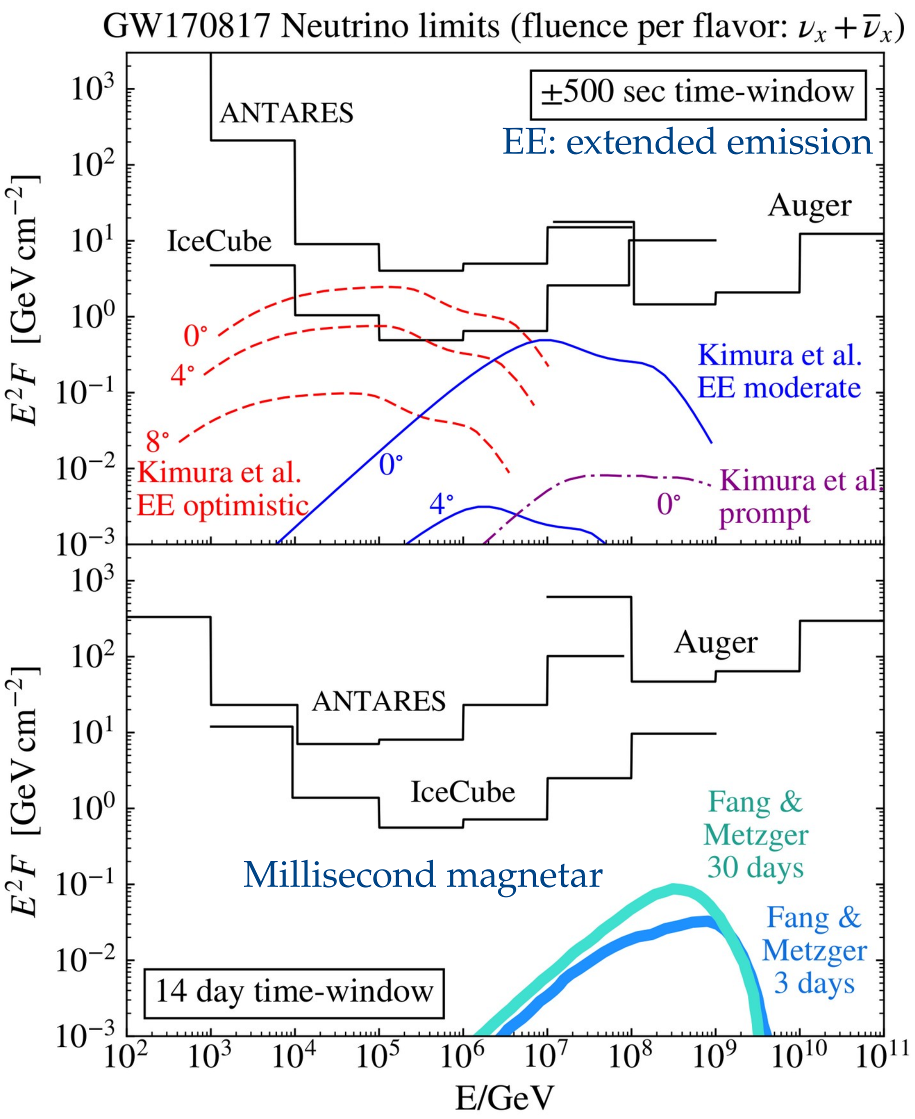


IceCube, *Science* 2022

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



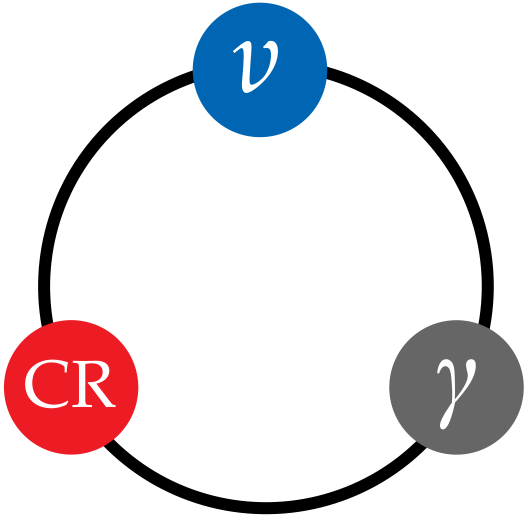


ANTARES, IceCube, Pierre Auger Collab., *ApJL* 2017

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

Energy in neutrinos $\propto$ energy in gamma rays

Waxman & Bahcall, *PRL* 1997



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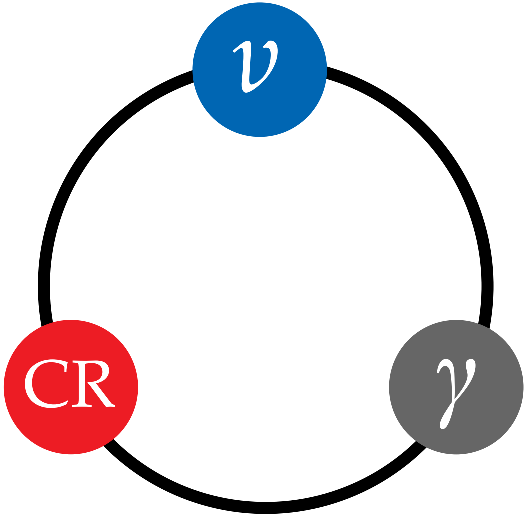
Source properties (*e.g.*, baryonic loading)
Particle effects (*e.g.*, ν-producing channels)



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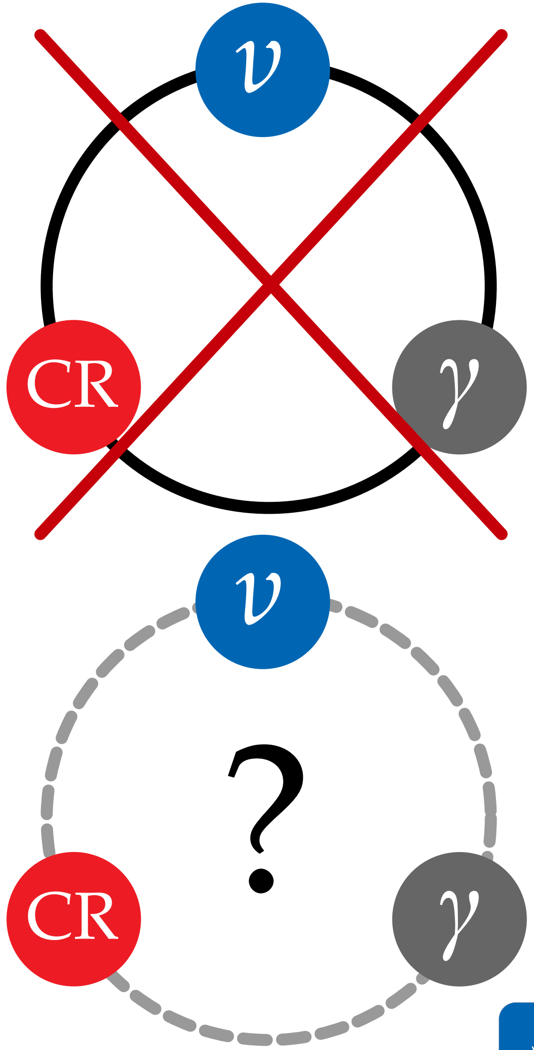

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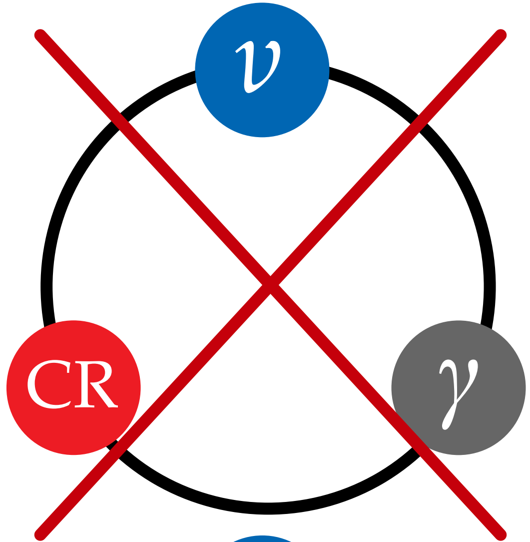

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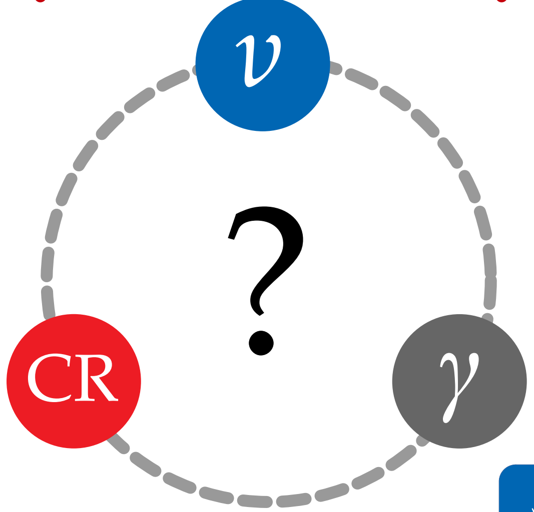
Sources that make neutrinos via *p*γ
may be opaque to 1–100 MeV gamma rays

Murase, Guetta, Ahlers, *PRL* 2016

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

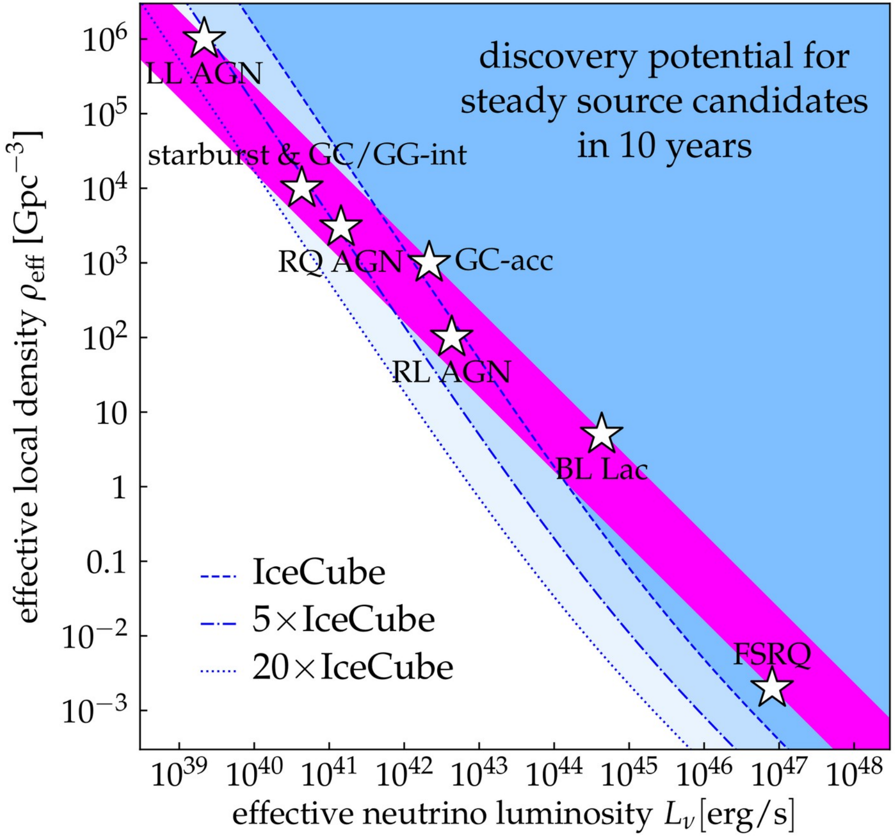
Morejon, Fedynitch, Boncioli, Winter, *JCAP* 2019
Boncioli, Fedynitch, Winter, *Sci. Rep.* 2017



Source discovery potential: today and in the future

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

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



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

Energy spectrum

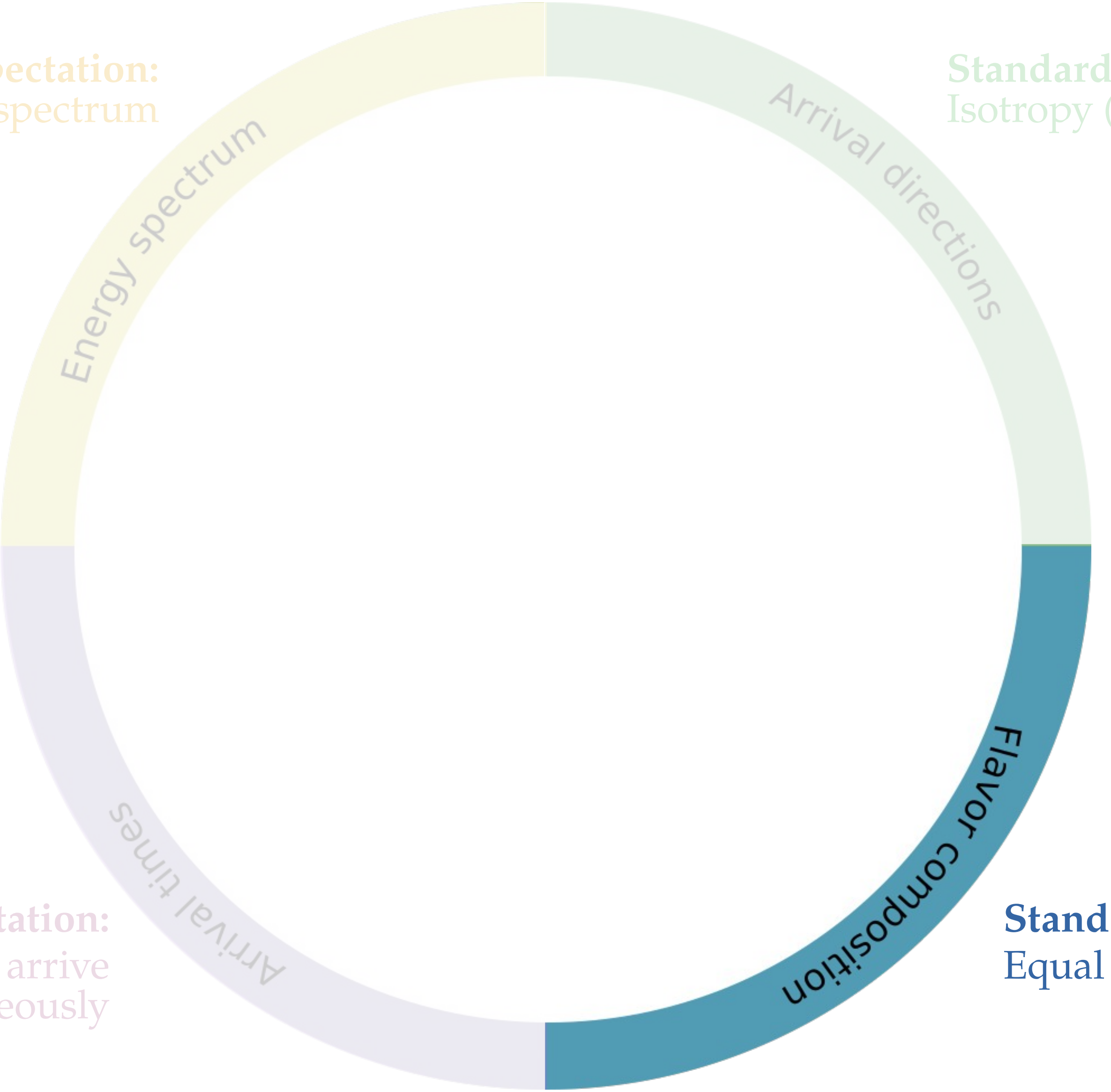
Arrival directions

Flavor composition

Arrival times

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Neutrinos are quintessential quantum particles

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A neutrino is created
with *one* definite flavor, *e.g.*,

ν_e

Neutrino source

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ν_e

It travels a long
distance to the detector

Neutrino source

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A neutrino is created
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But may be detected with a
different flavor, with some probability

ν_e

It travels a long
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ν_e or ν_μ or ν_τ

Neutrino source

Neutrino detector

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“flavor oscillations”

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(Nobel Prize 2002, 2015)

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It travels a long
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Neutrino source

"flavor oscillations"
(Nobel Prize 2002, 2015)

Neutrino detector

We use quantum mechanics to compute probabilities over *macroscopic* distances!

Flavor-transition probability: the quick and dirty of it

- In matrix form: $$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U^*_{e1} & U^*_{e2} & U^*_{e3}\\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3}\\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$
- Pontecorvo-Maki-Nakagawa-Sakata matrix ($c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$):

$$U = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{Cross mixing}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \underbrace{\begin{pmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Majorana CP phases}}$$

- Probability for $\nu_\alpha \to \nu_\beta$: $$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right)$$ $$+\,2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

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$\theta_{23} \approx 48°$

$\theta_{13} \approx 9°$

$\theta_{12} \approx 34°$

$\delta \approx 222°$

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… But high-energy neutrinos oscillate *fast*

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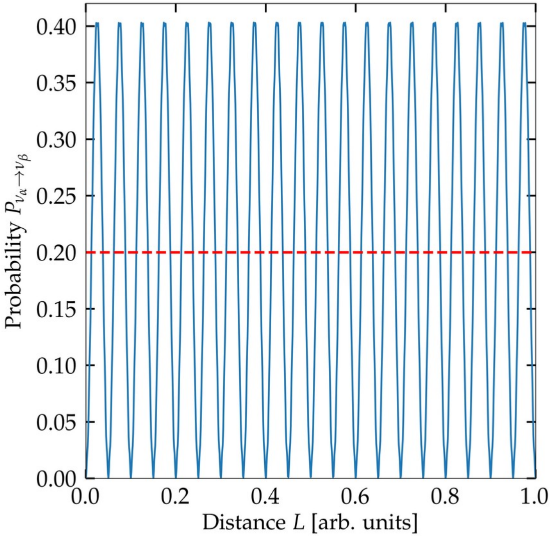

Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2 \sim 0.1$ pc

~ 8% of the way to Proxima Centauri
⋘ Distance to Galactic Center (8 kpc)
⋘ Distance to Andromeda (1 Mpc)
⋘ Cosmological distances (few Gpc)

We cannot resolve oscillations, so we use instead the average probability:

$$\langle P_{\nu_\alpha\to\nu_\beta}\rangle = \sum_{i=1}^{3}|U_{\alpha i}|^2\,|U_{\beta i}|^2$$

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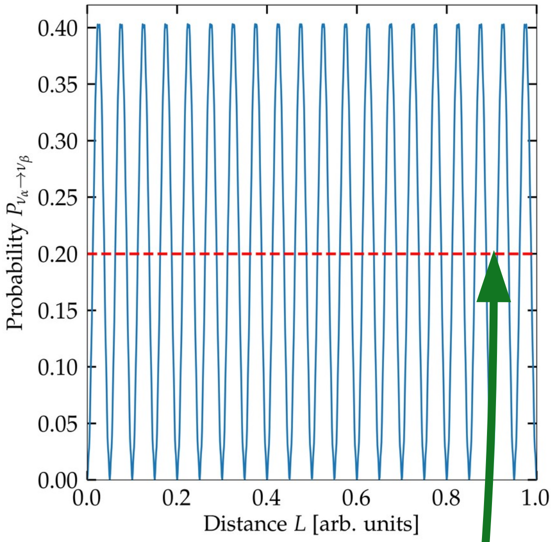

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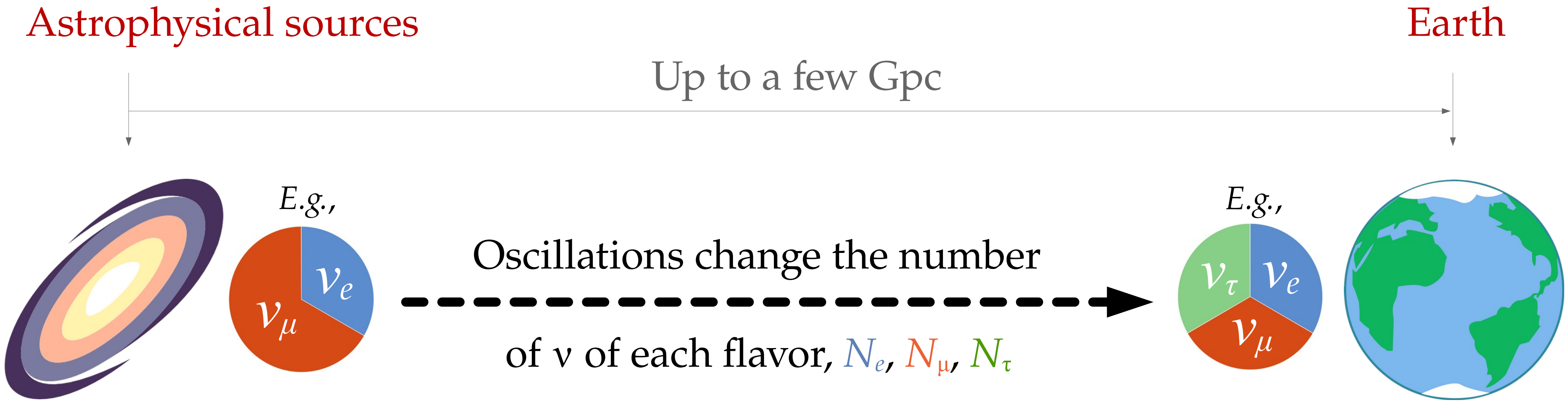

Astrophysical sources

Earth

Up to a few Gpc

Oscillations change the number of ν of each flavor, N_e, N_μ, N_τ

Different production mechanisms yield different flavor ratios:

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

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

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

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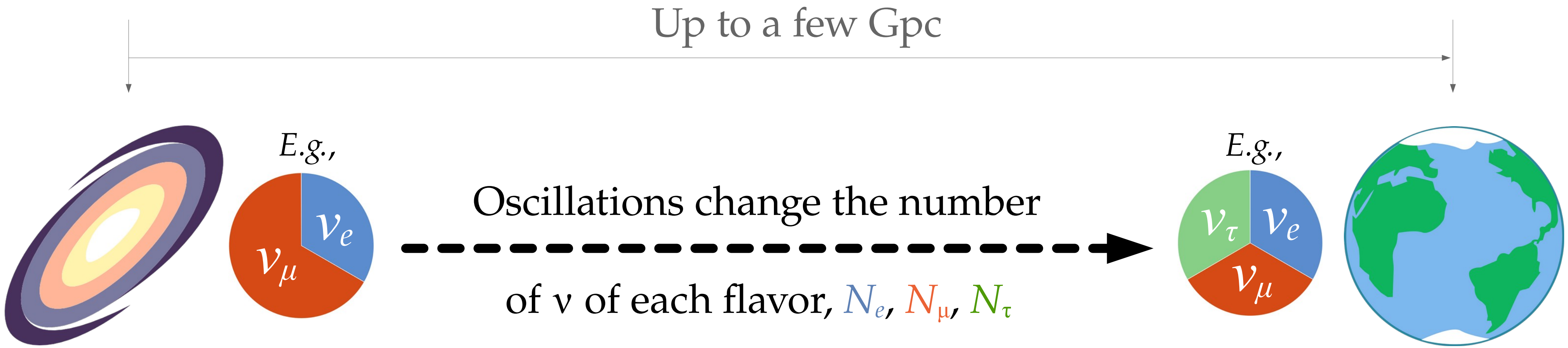

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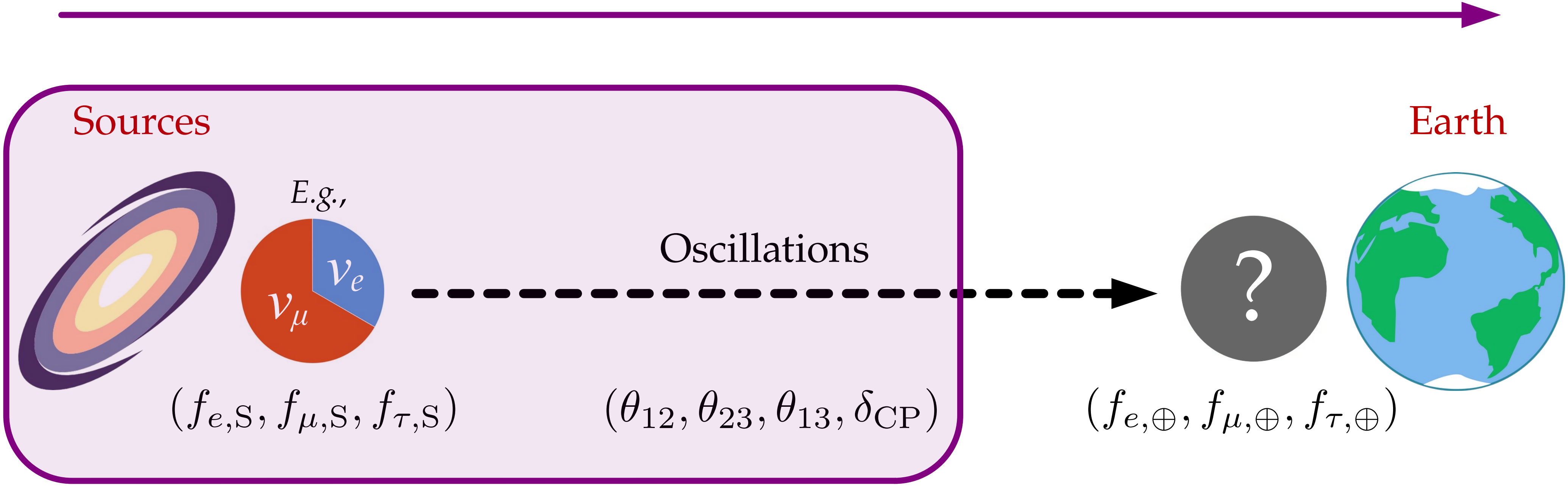
Standard oscillations
or
new physics

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



Sources

E.g.,

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

Oscillations

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

Earth

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

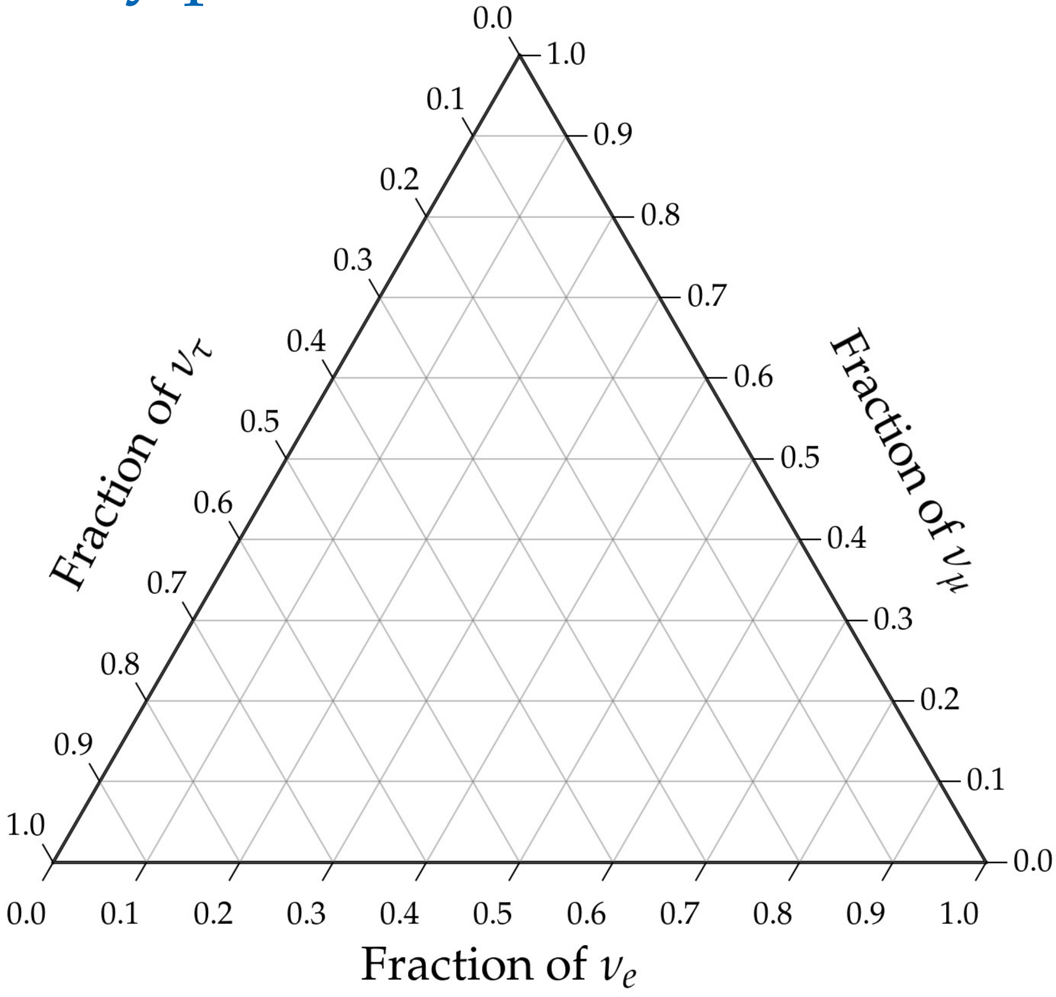
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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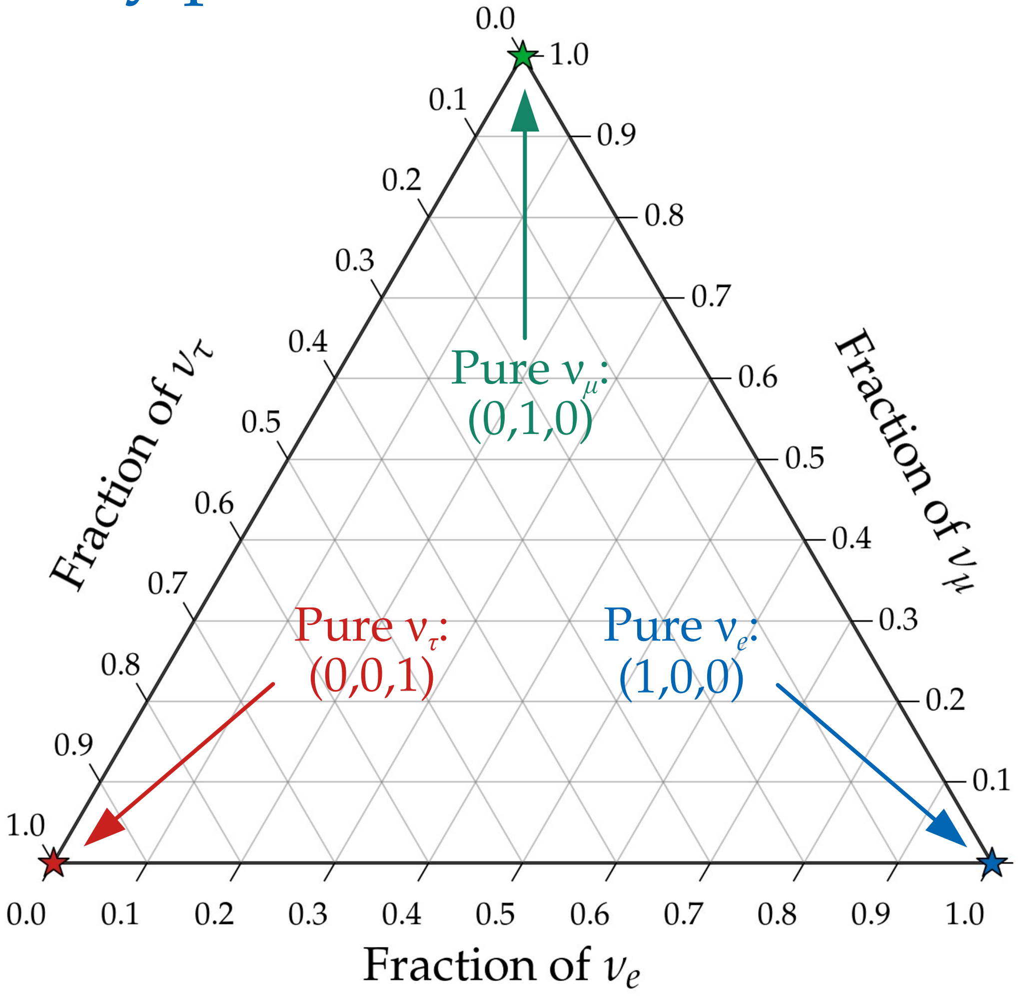

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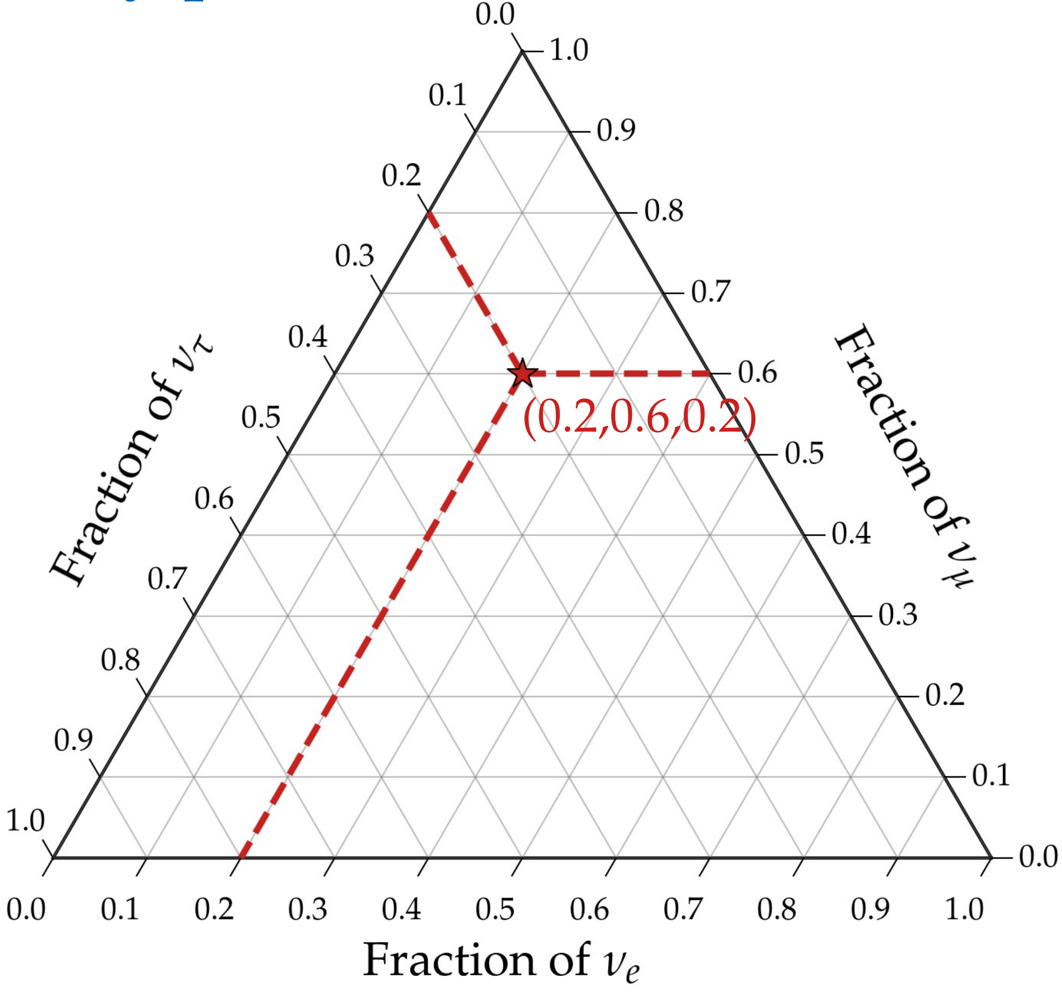

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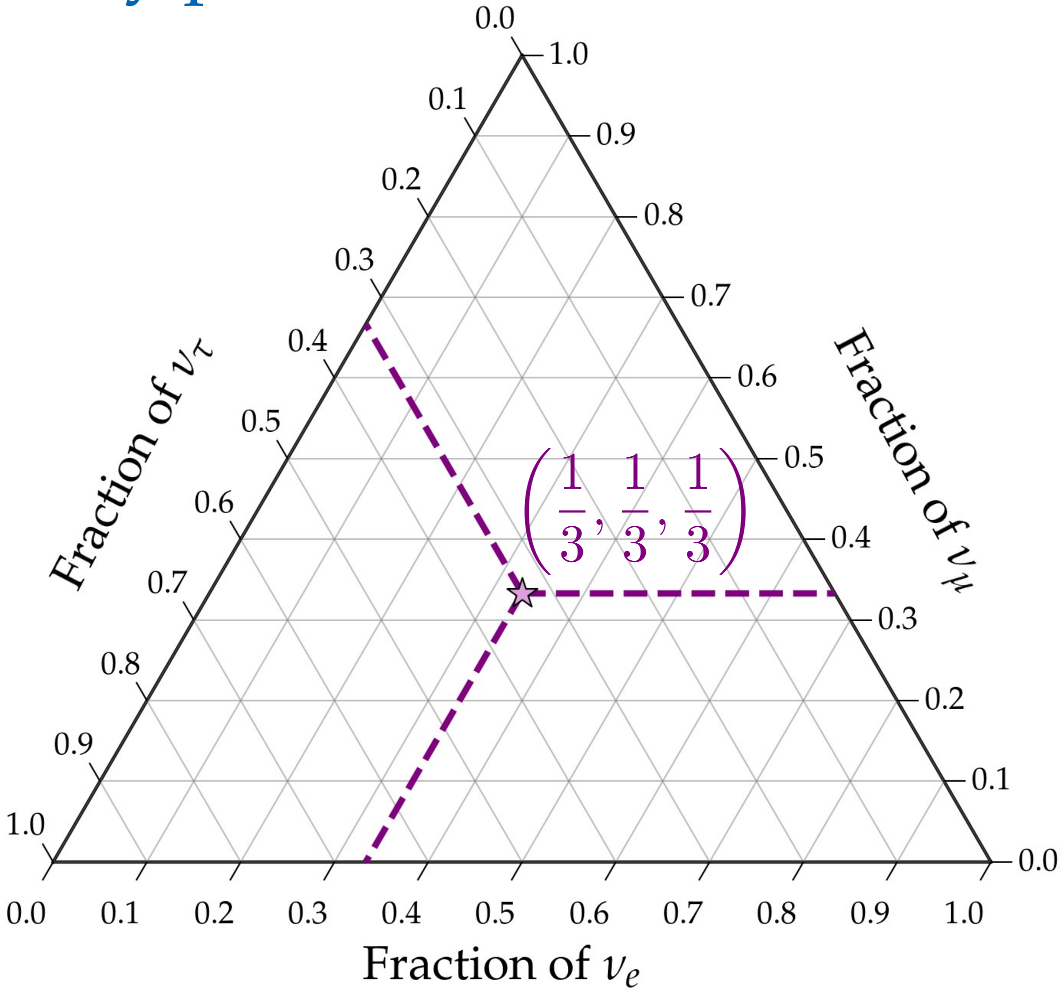

One likely TeV–PeV ν production scenario:

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

Full π decay chain

$(1/3:2/3:0)_\mathrm{S}$

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

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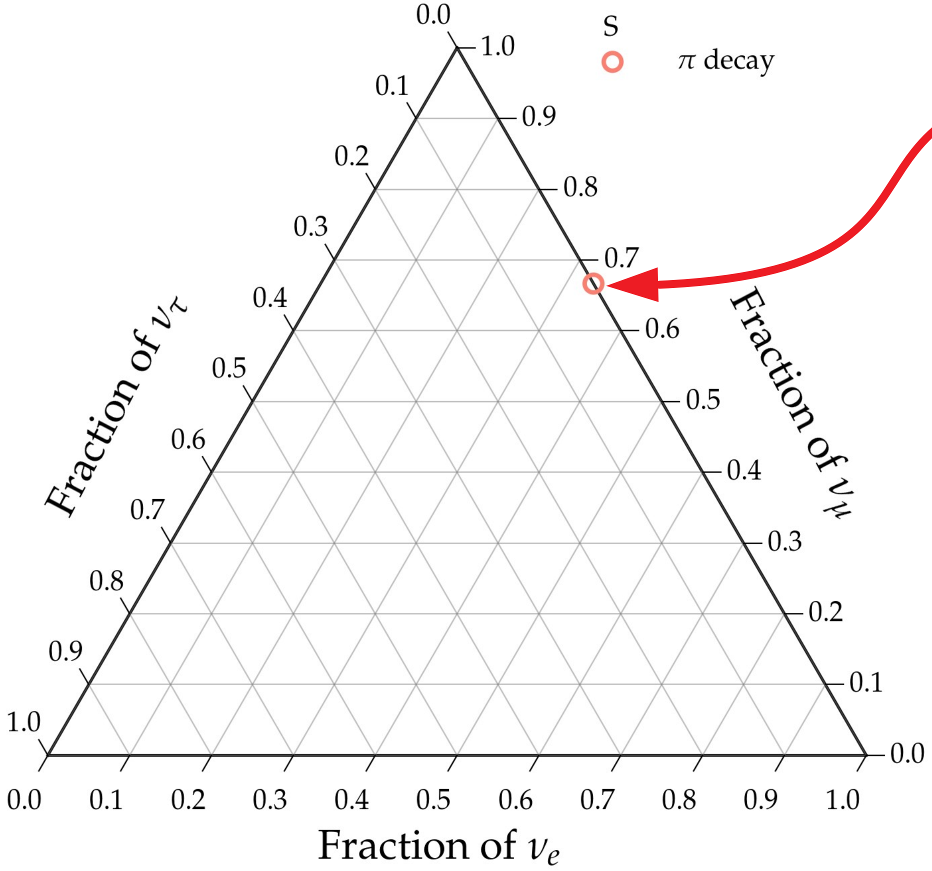

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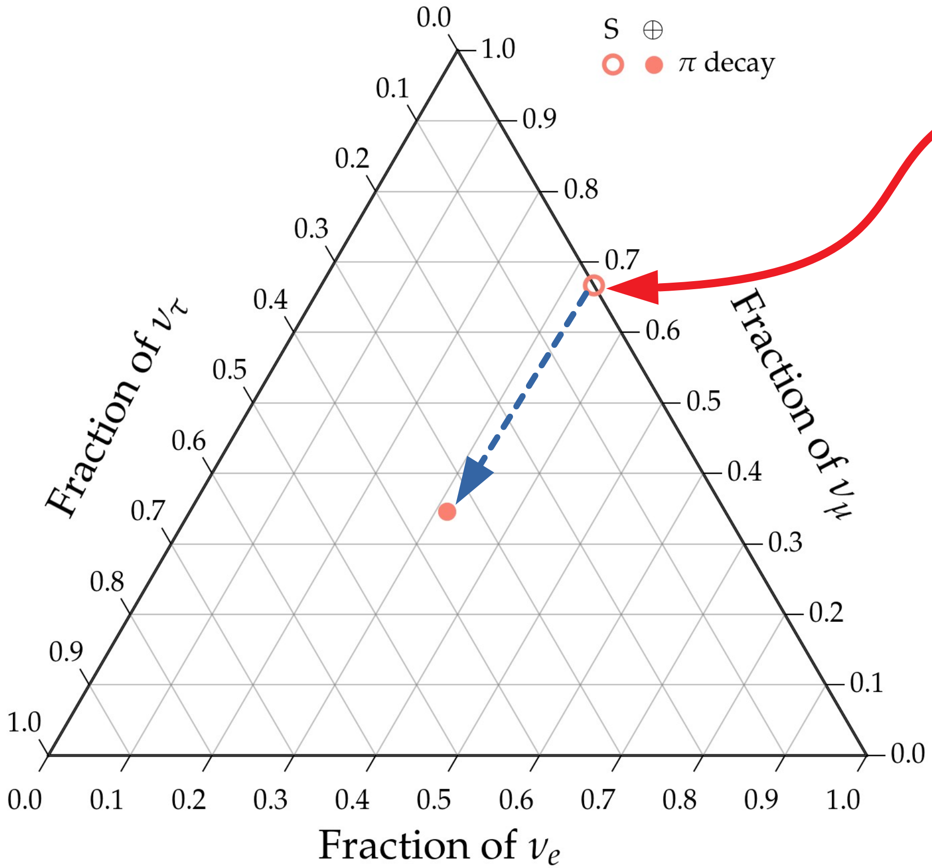

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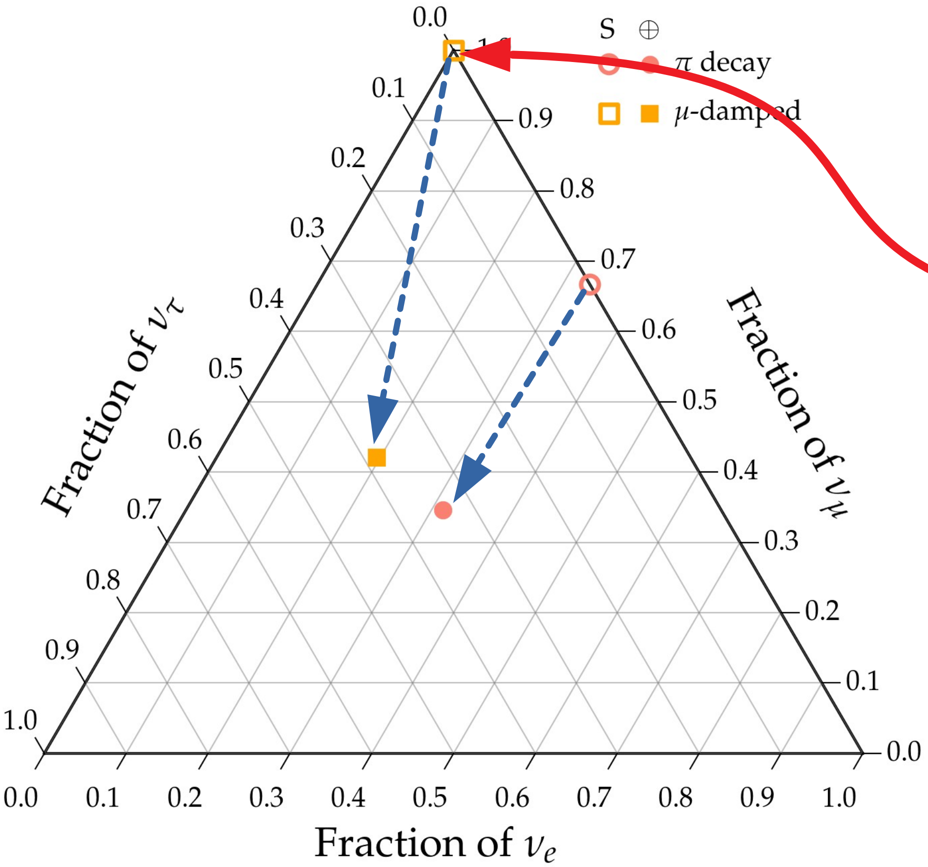

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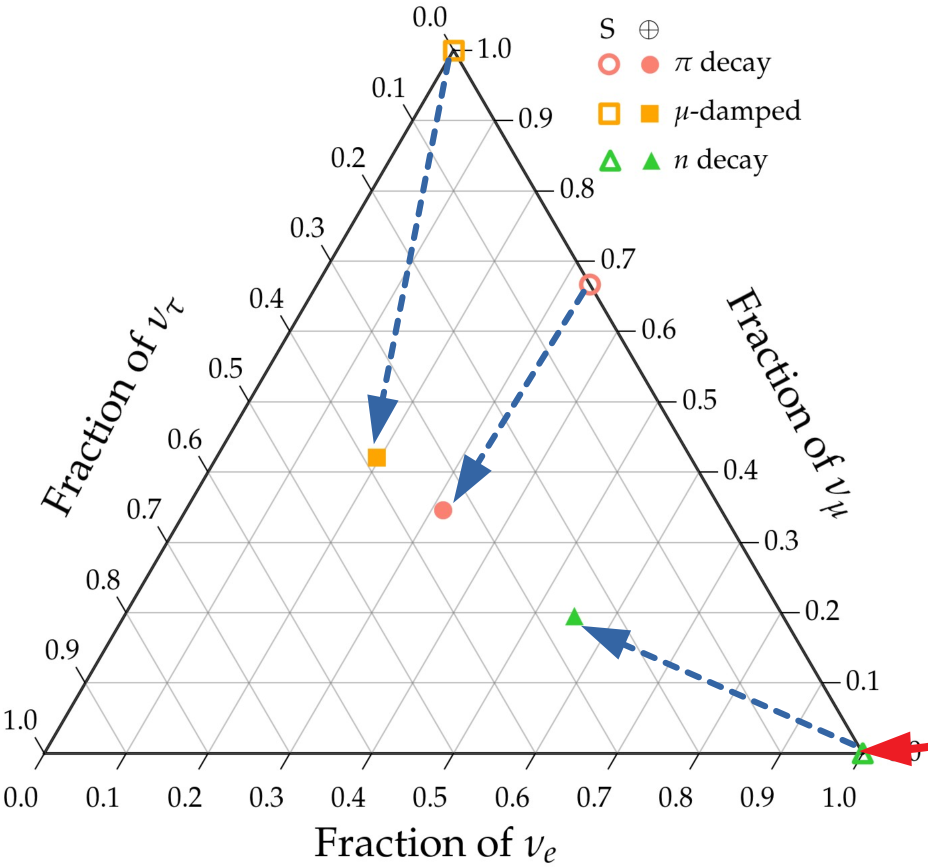

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Neutron decay

$(1:0:0)_S$

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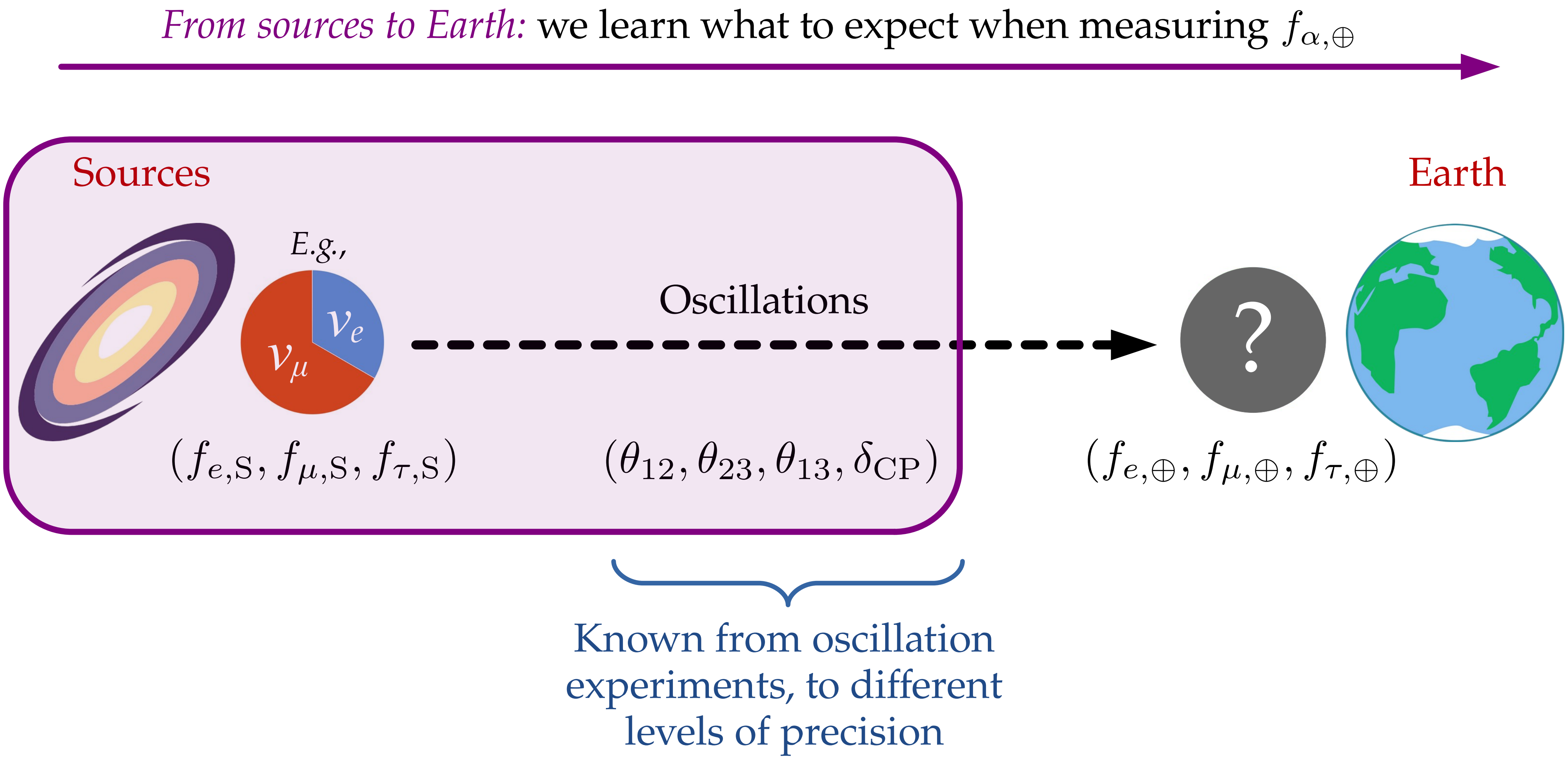


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$

Sources

E.g.,

ν_e

ν_μ

Oscillations

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

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

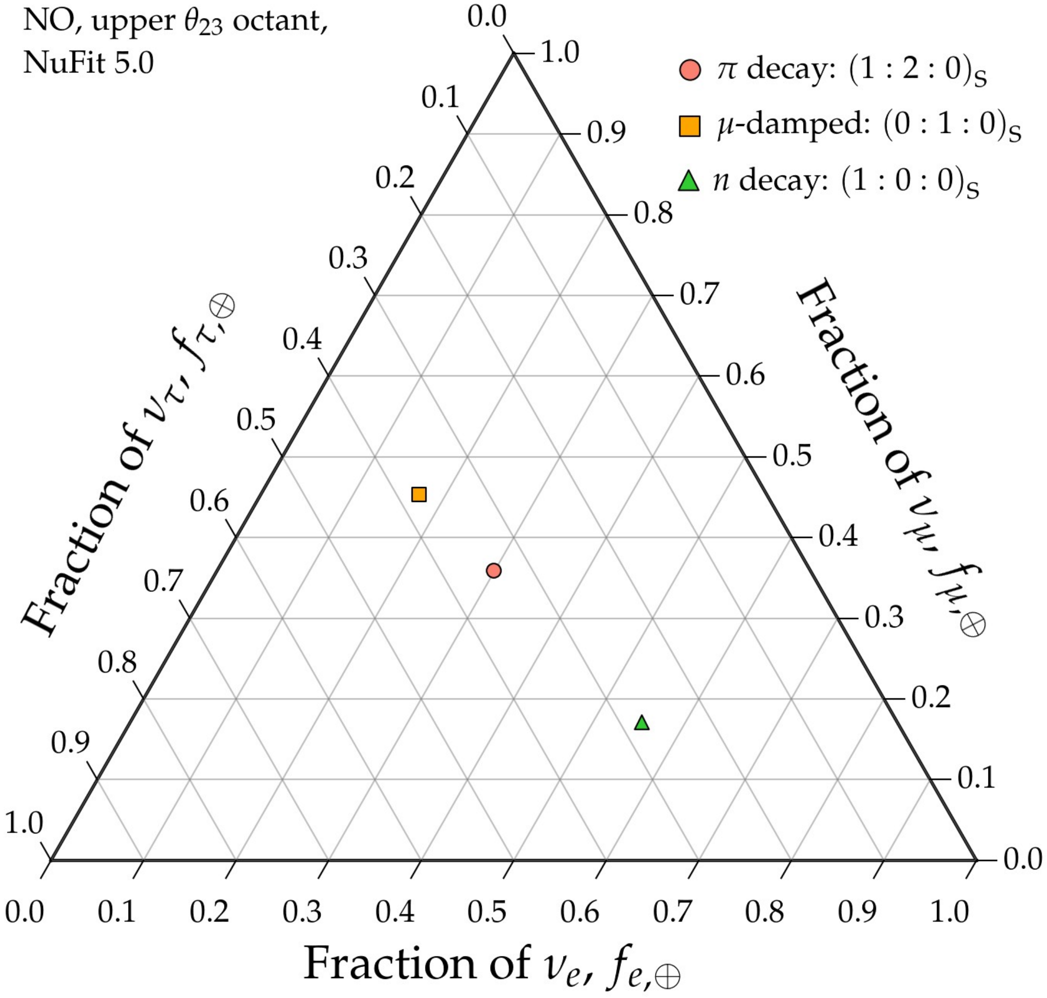
Earth

?

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

Known from oscillation
experiments, to different
levels of precision

Theoretically palatable regions: today



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

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
See also: **MB**, Beacom, Winter, *PRL* 2015

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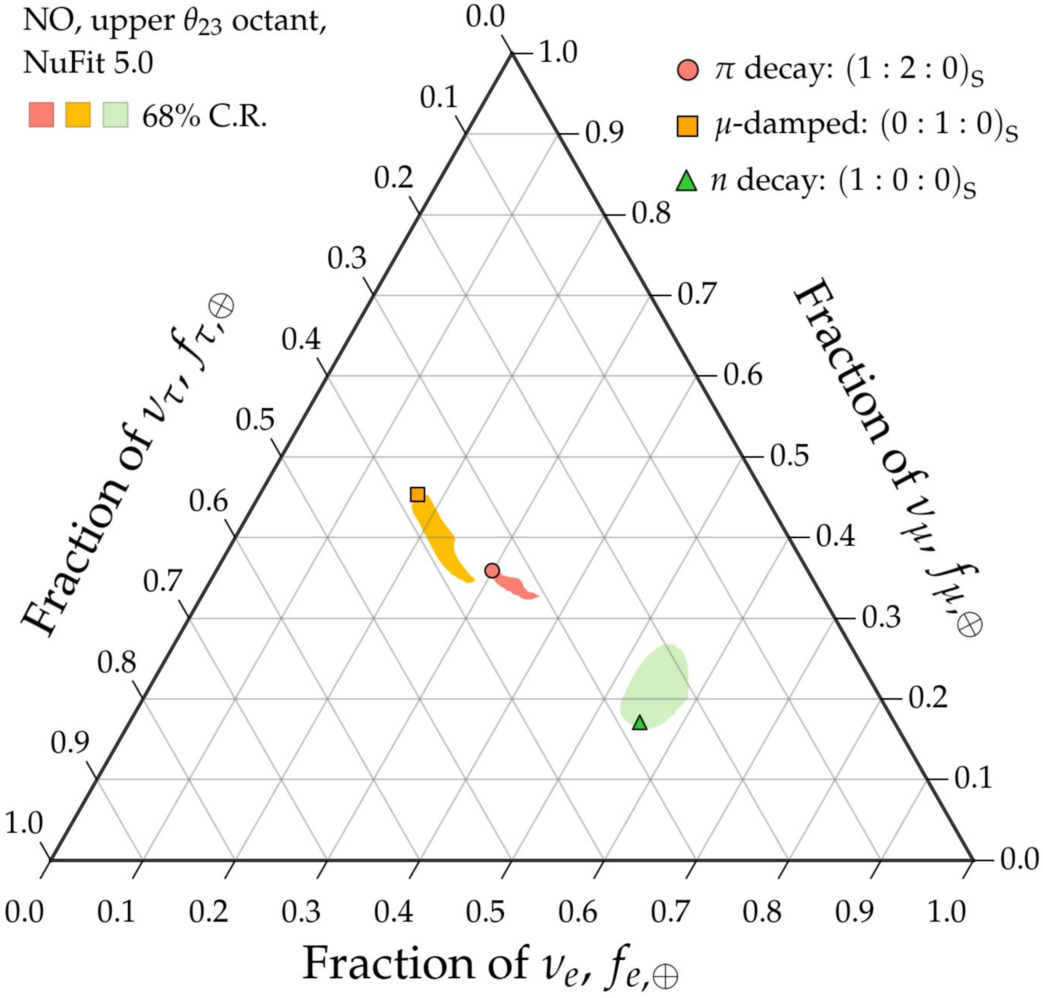

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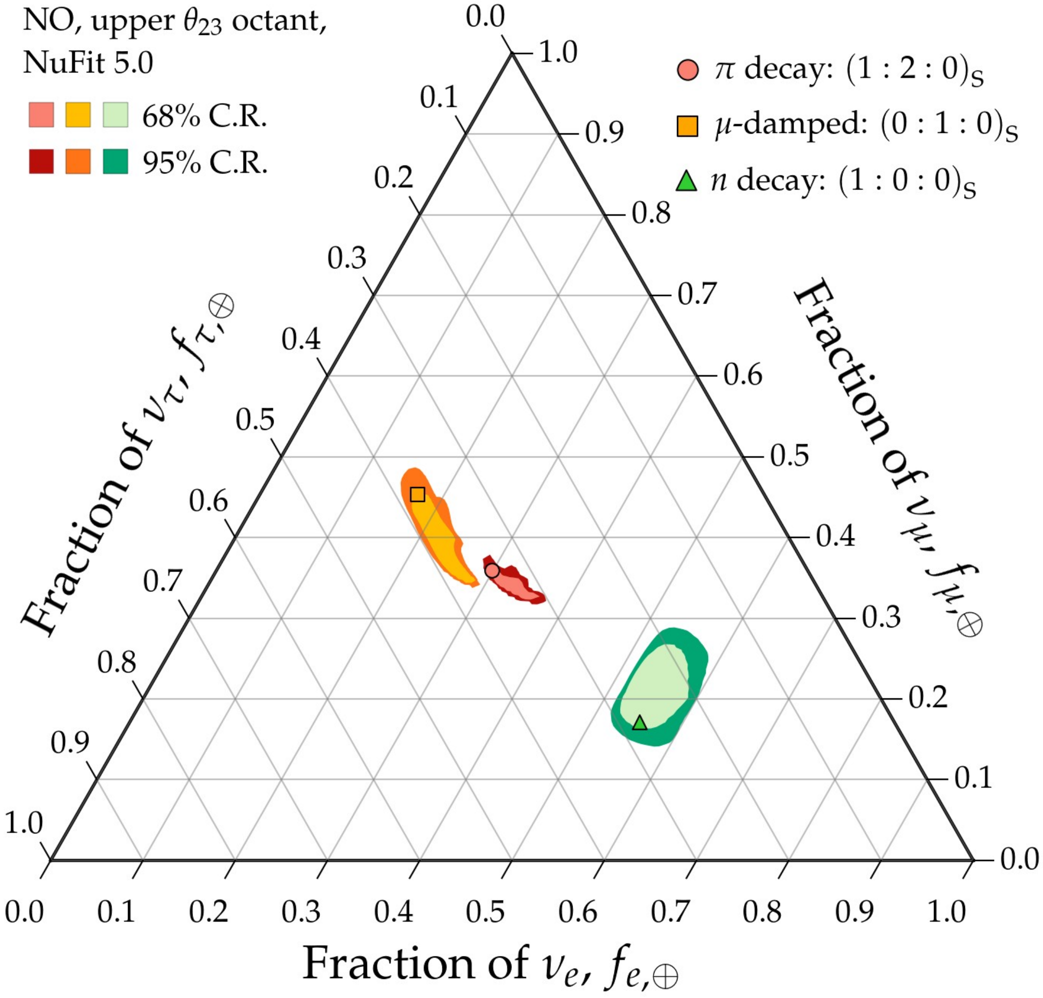

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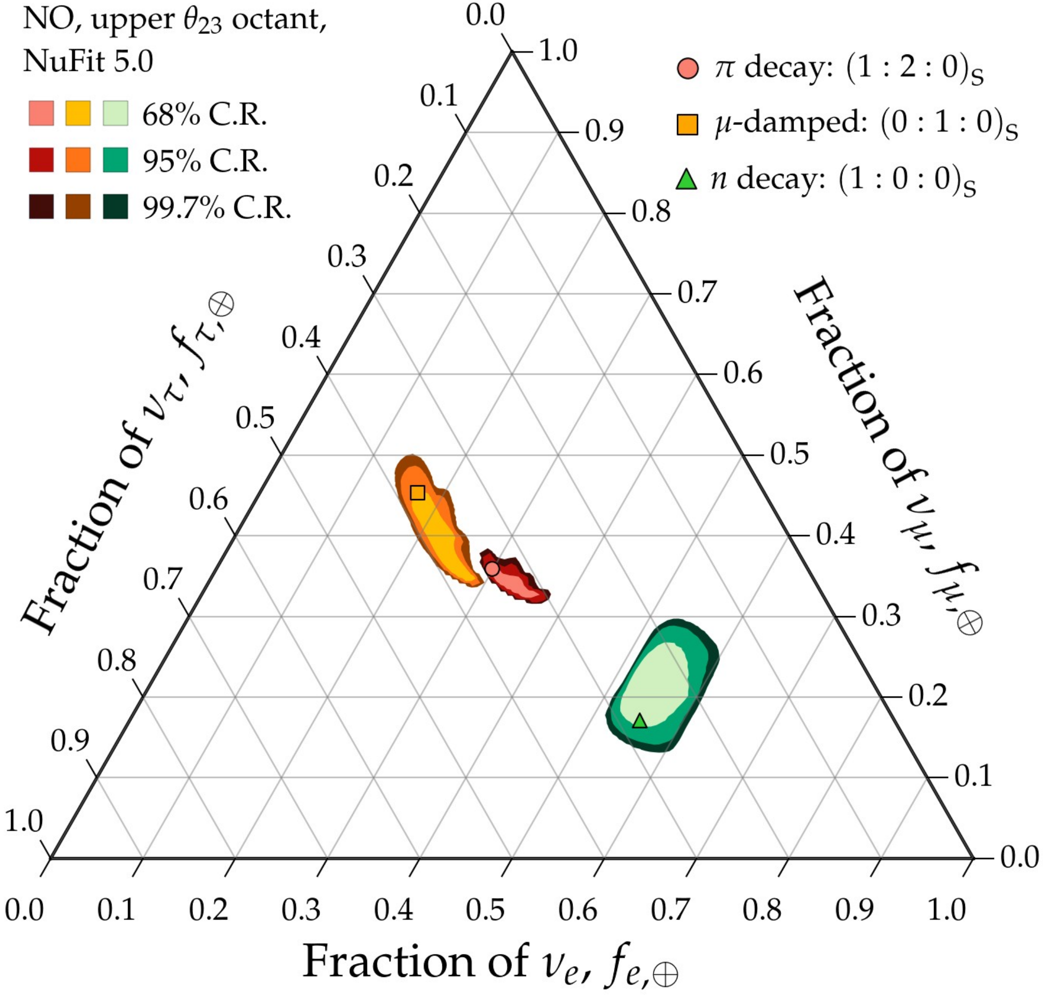

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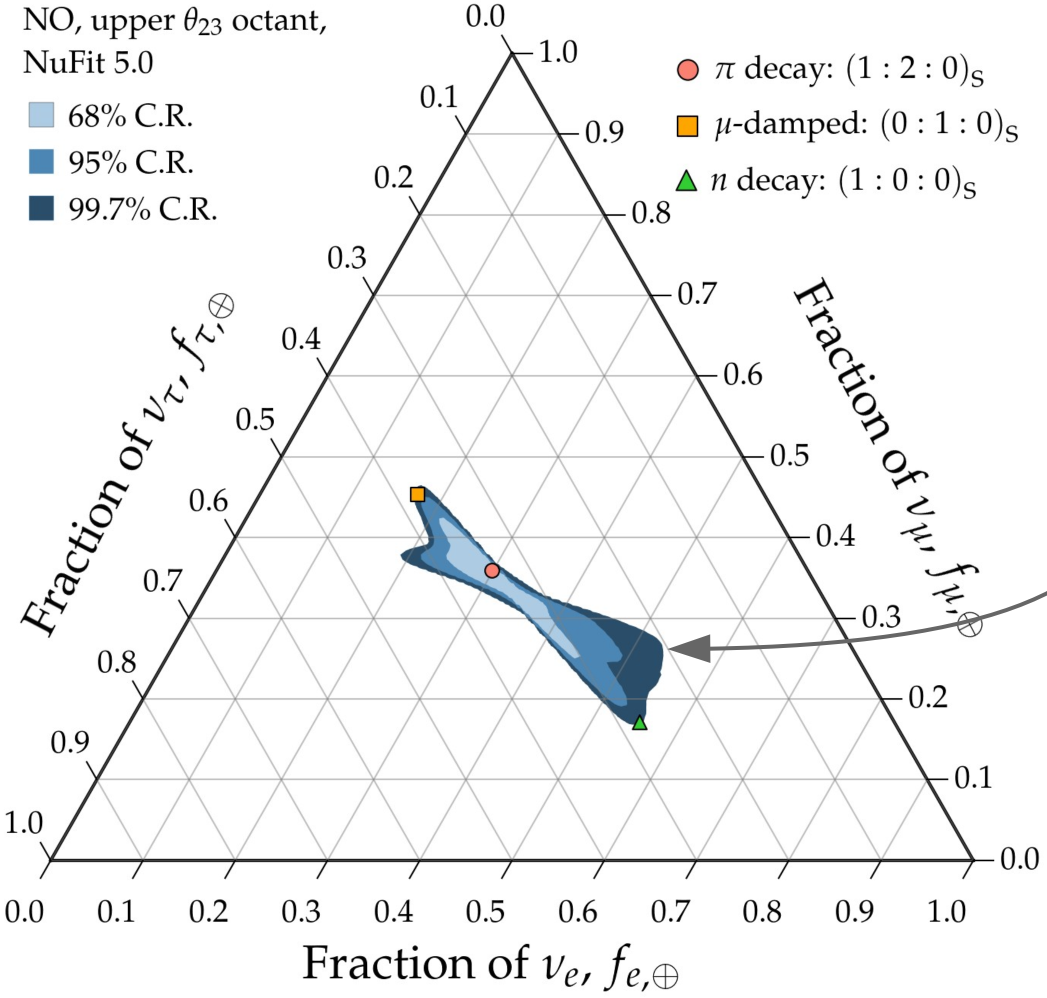

Varying over all possible flavor ratios at the source

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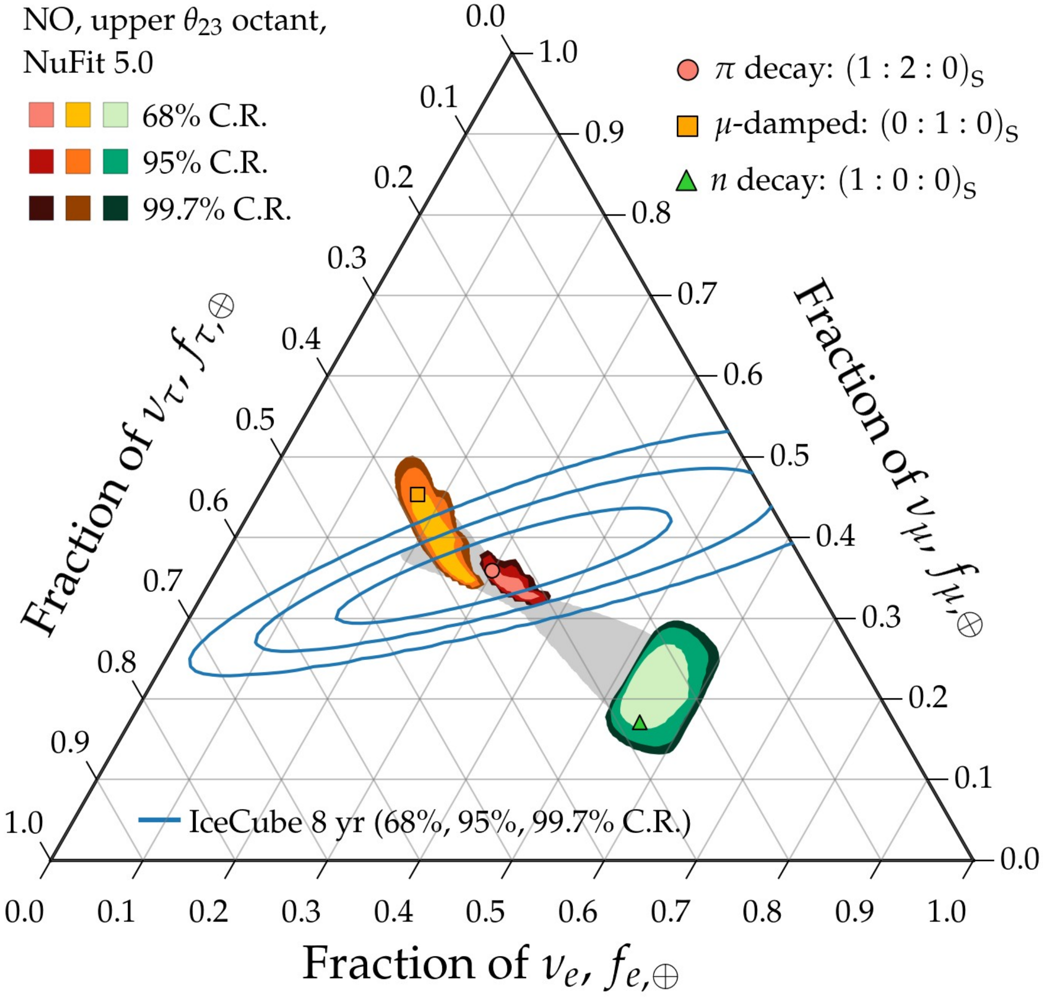
Theoretically palatable regions: today



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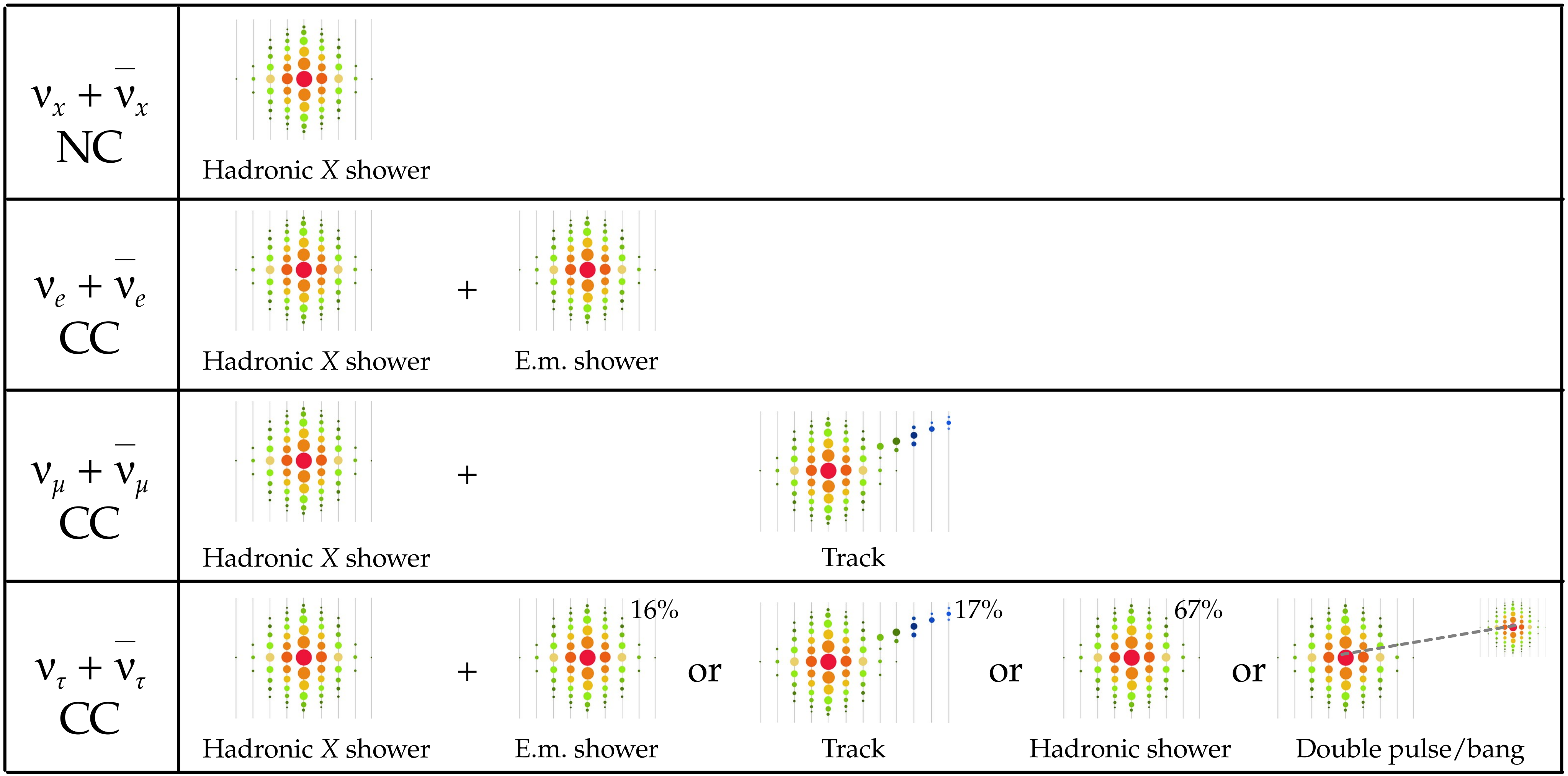
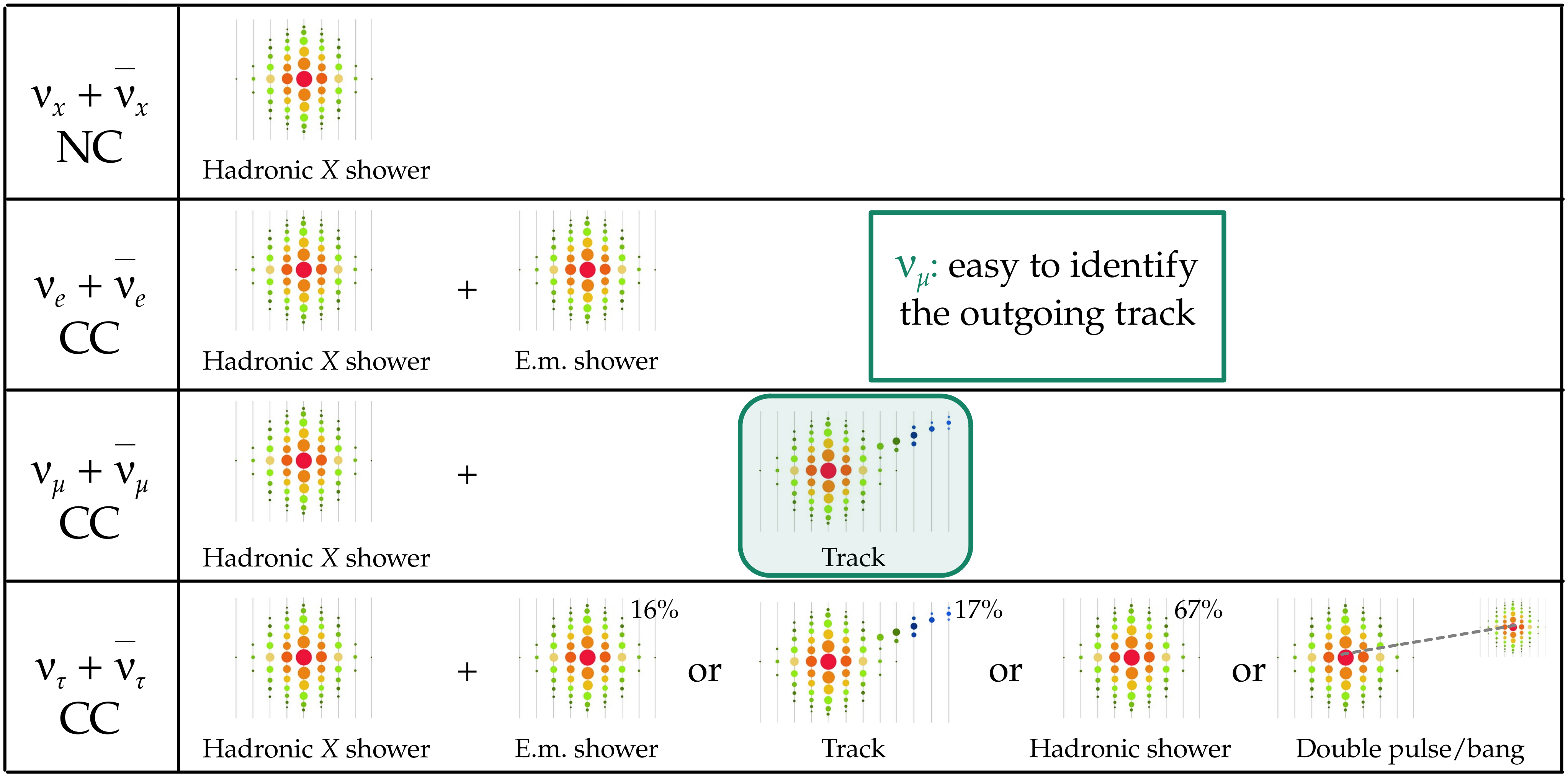
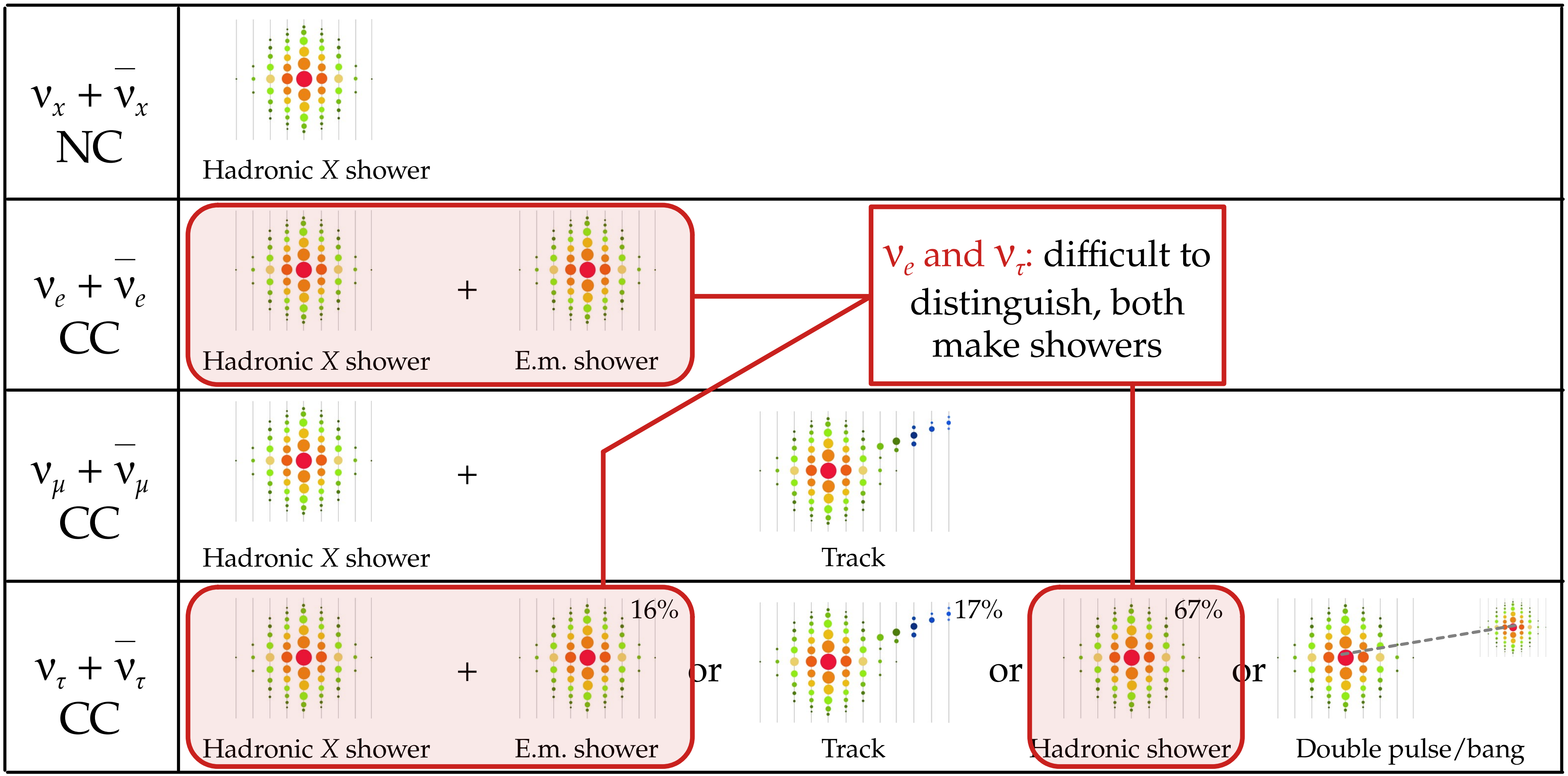

$\nu_x + \bar{\nu}_x$
NC
Hadronic *X* shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic *X* shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic *X* shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic *X* shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or
Double pulse/bang



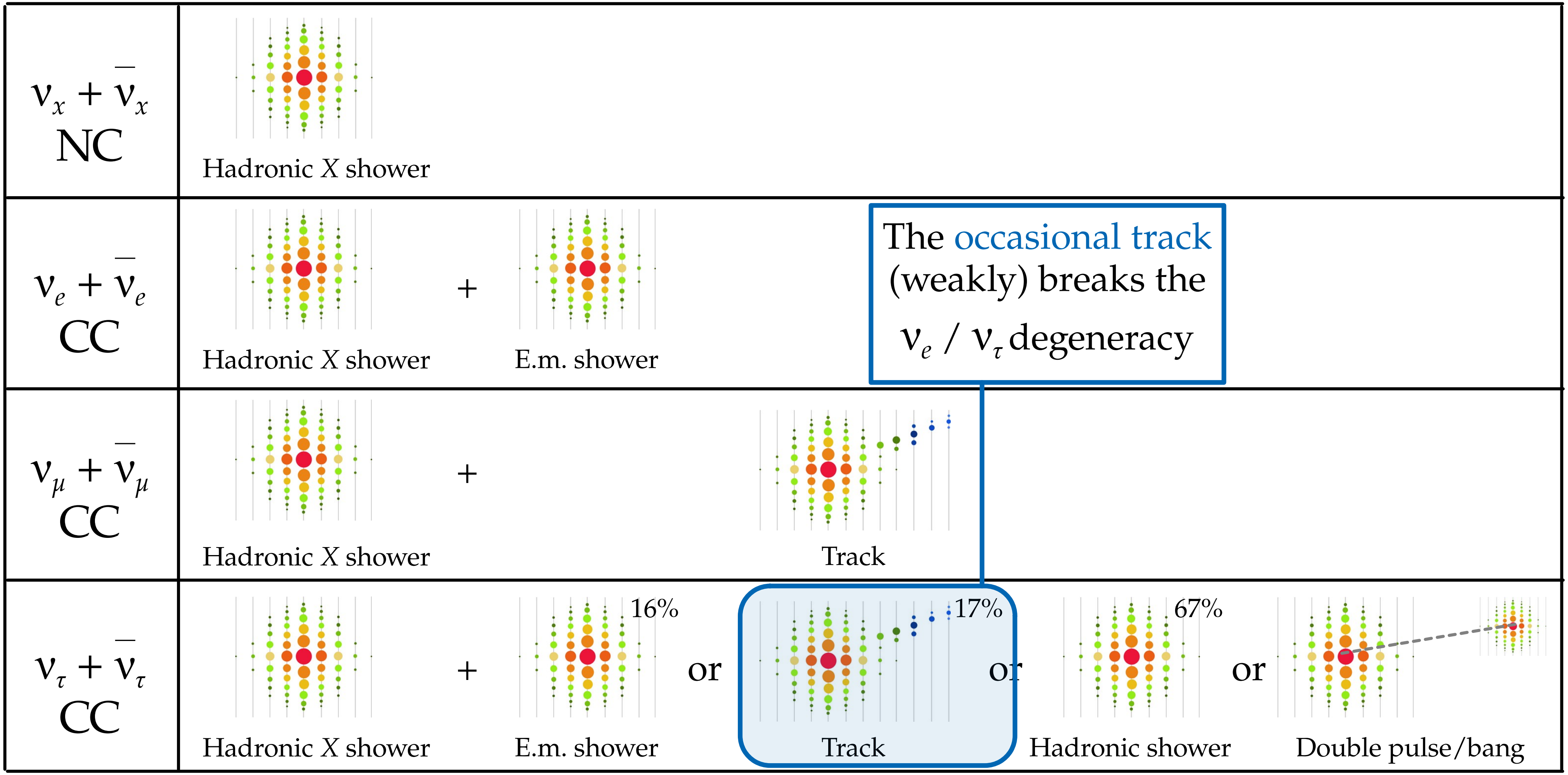
$\nu_x + \bar{\nu}_x$ NC	Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC	Hadronic X shower + E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC	Hadronic X shower + Track
$\nu_\tau + \bar{\nu}_\tau$ CC	Hadronic X shower + E.m. shower 16% or Track 17% or Hadronic shower 67% or Double pulse/bang

ν_μ: easy to identify the outgoing track



$\nu_x + \bar{\nu}_x$ 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 + E.m. shower 16% or Track 17% or Hadronic shower 67% or Double pulse/bang

ν_e and ν_τ: difficult to distinguish, both make showers

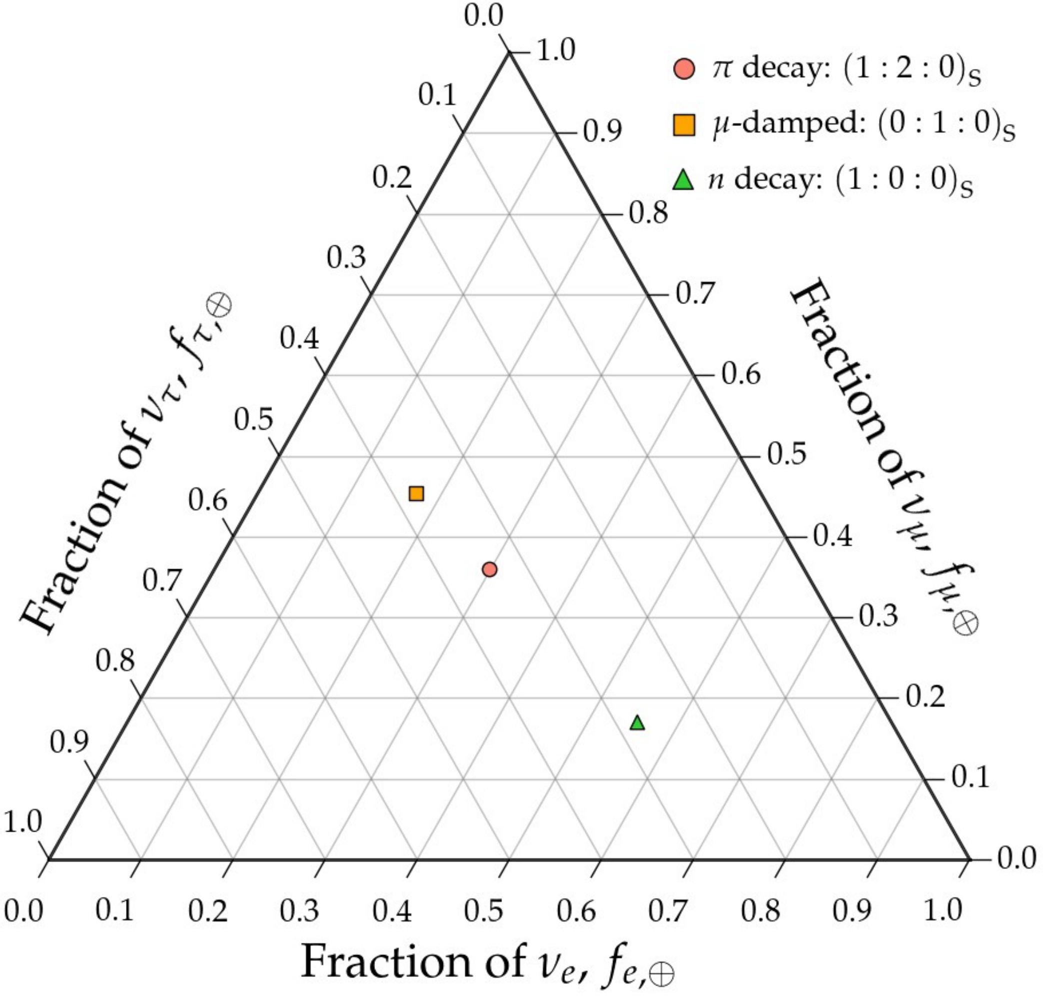


The occasional track (weakly) breaks the ν_e / ν_τ degeneracy

Measuring flavor composition: 2015–2040

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

Measuring flavor composition: 2015–2040



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

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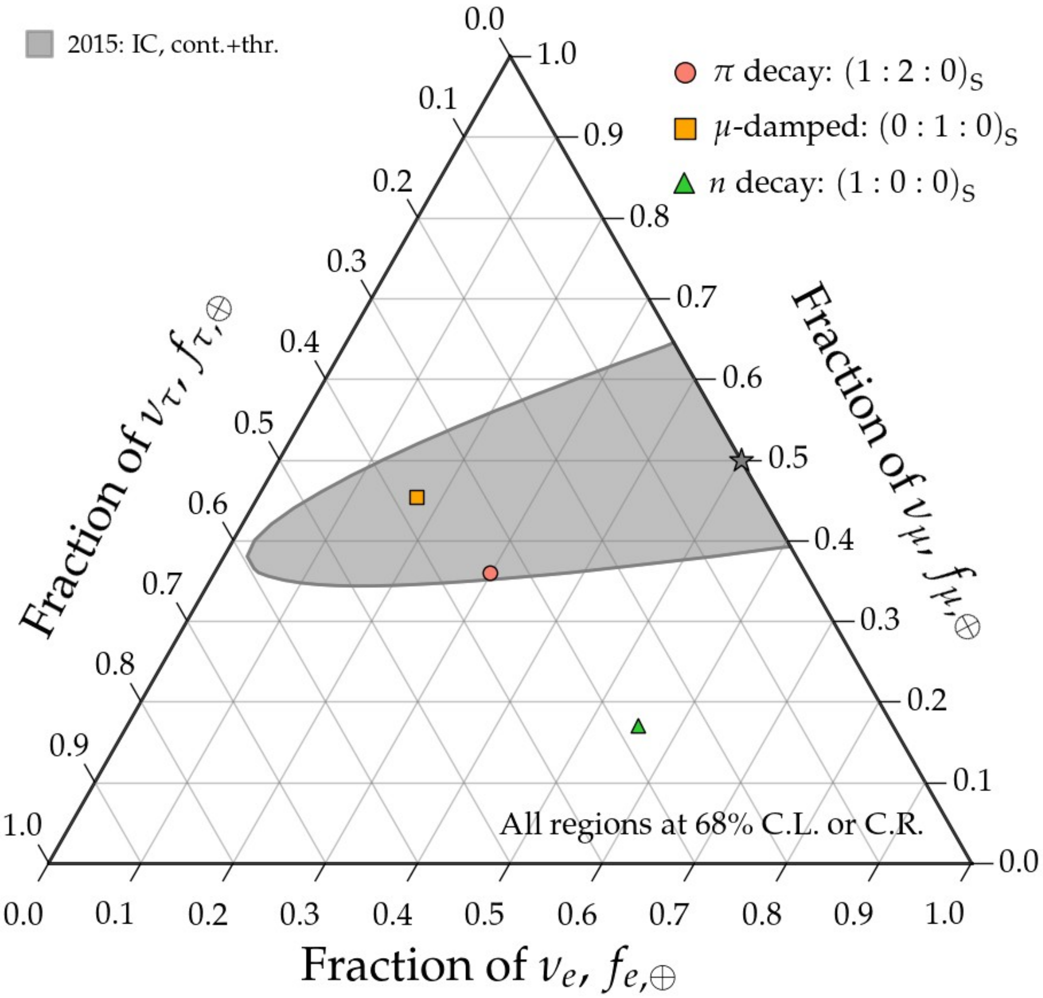

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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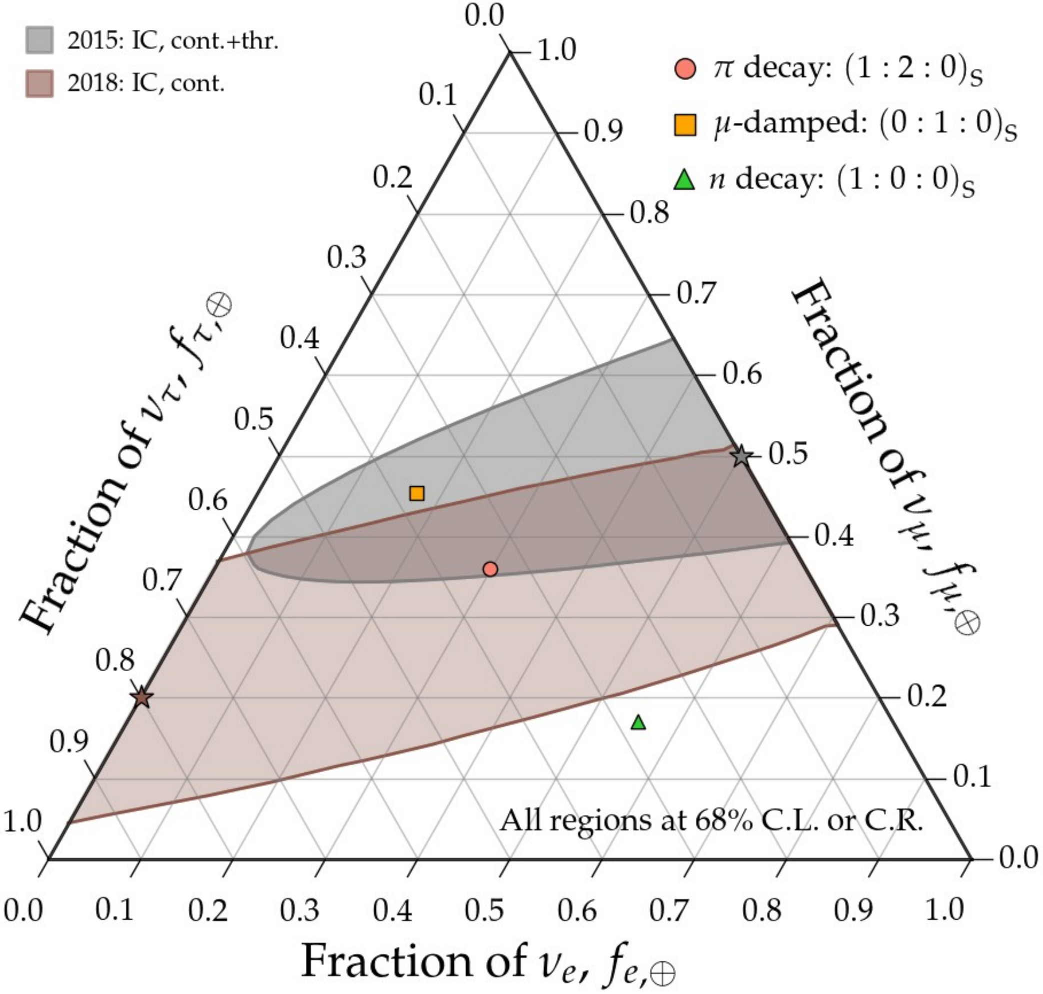
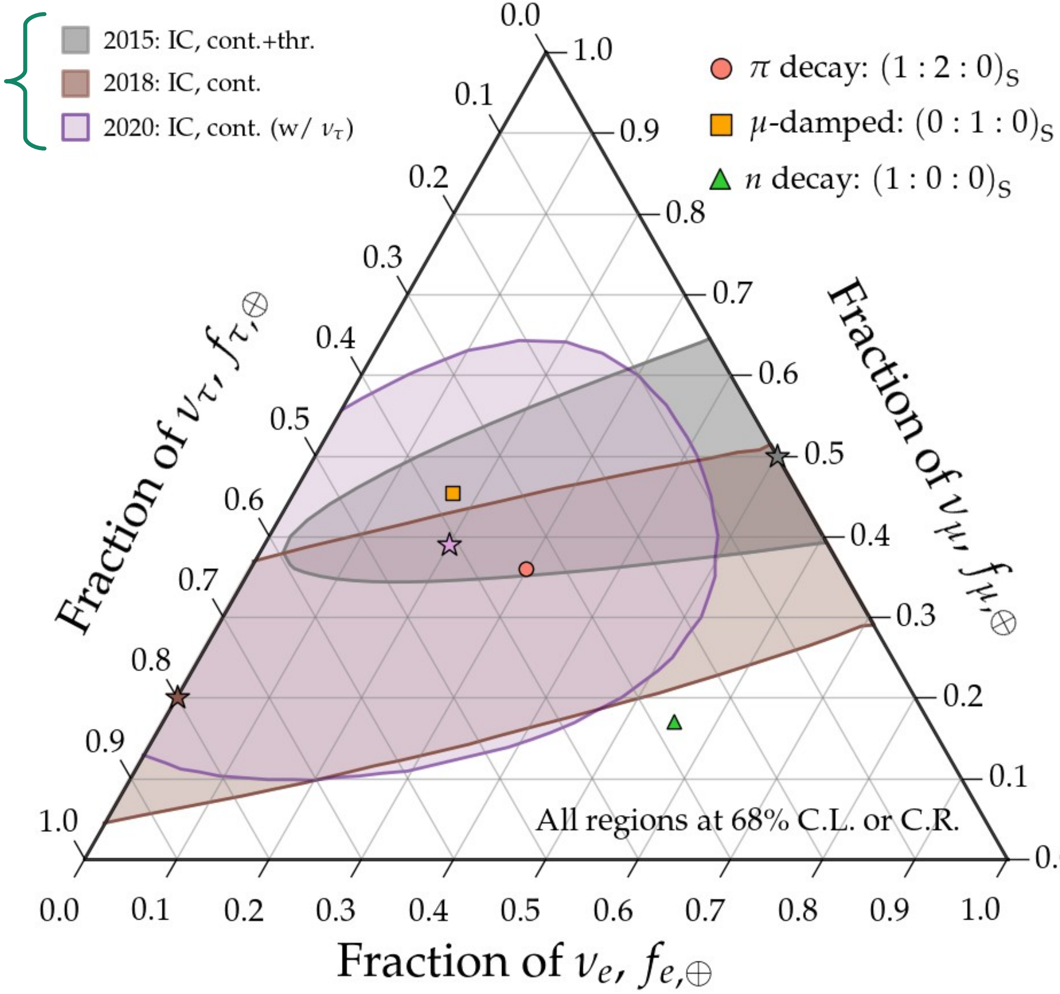


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring flavor composition: 2015–2040

Based on real data



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

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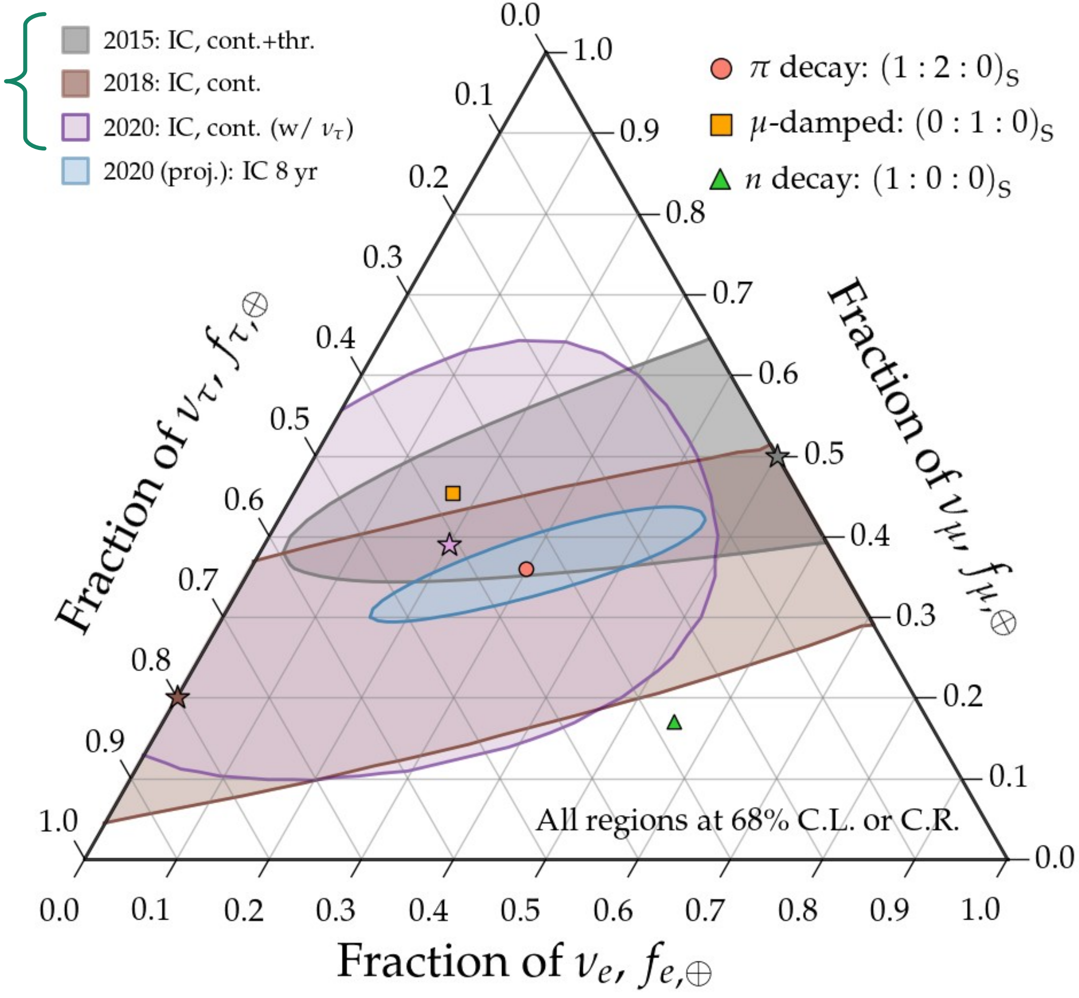

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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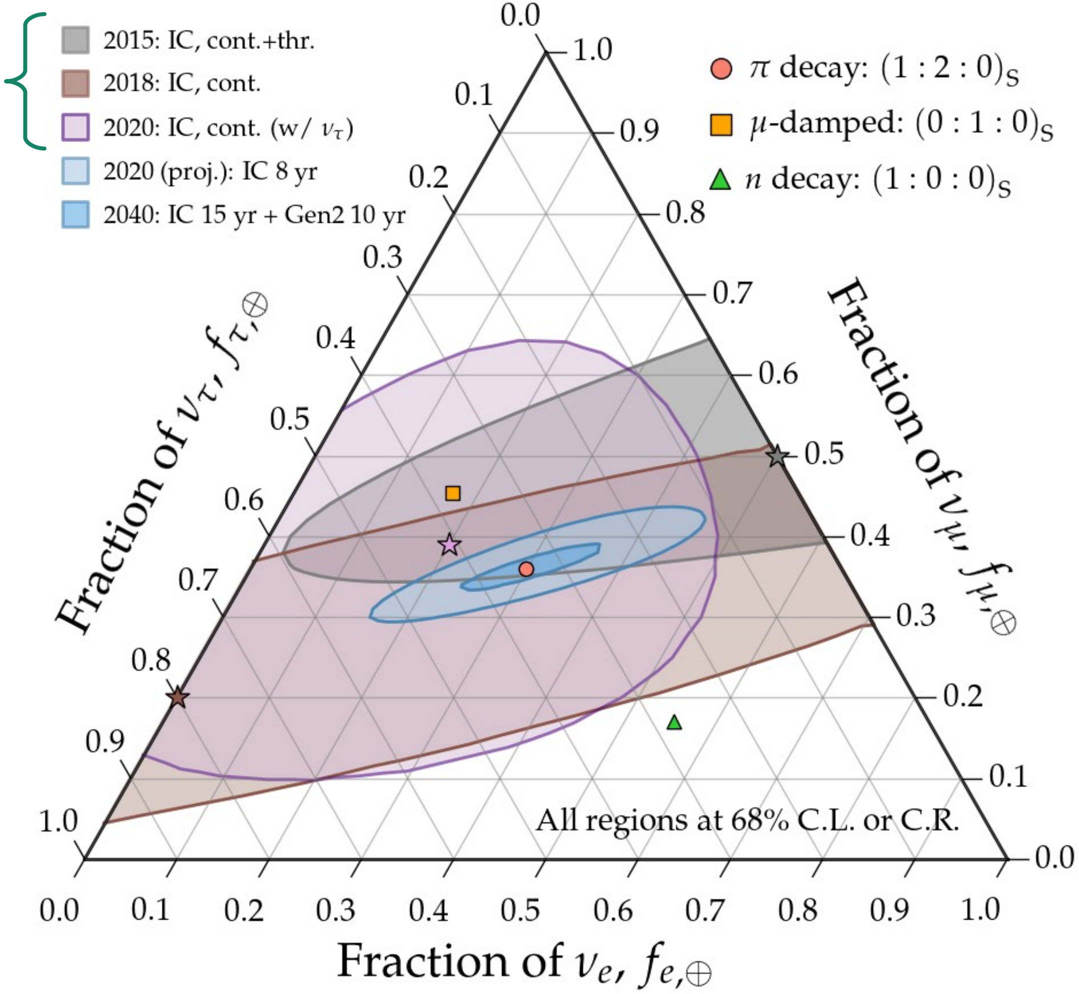
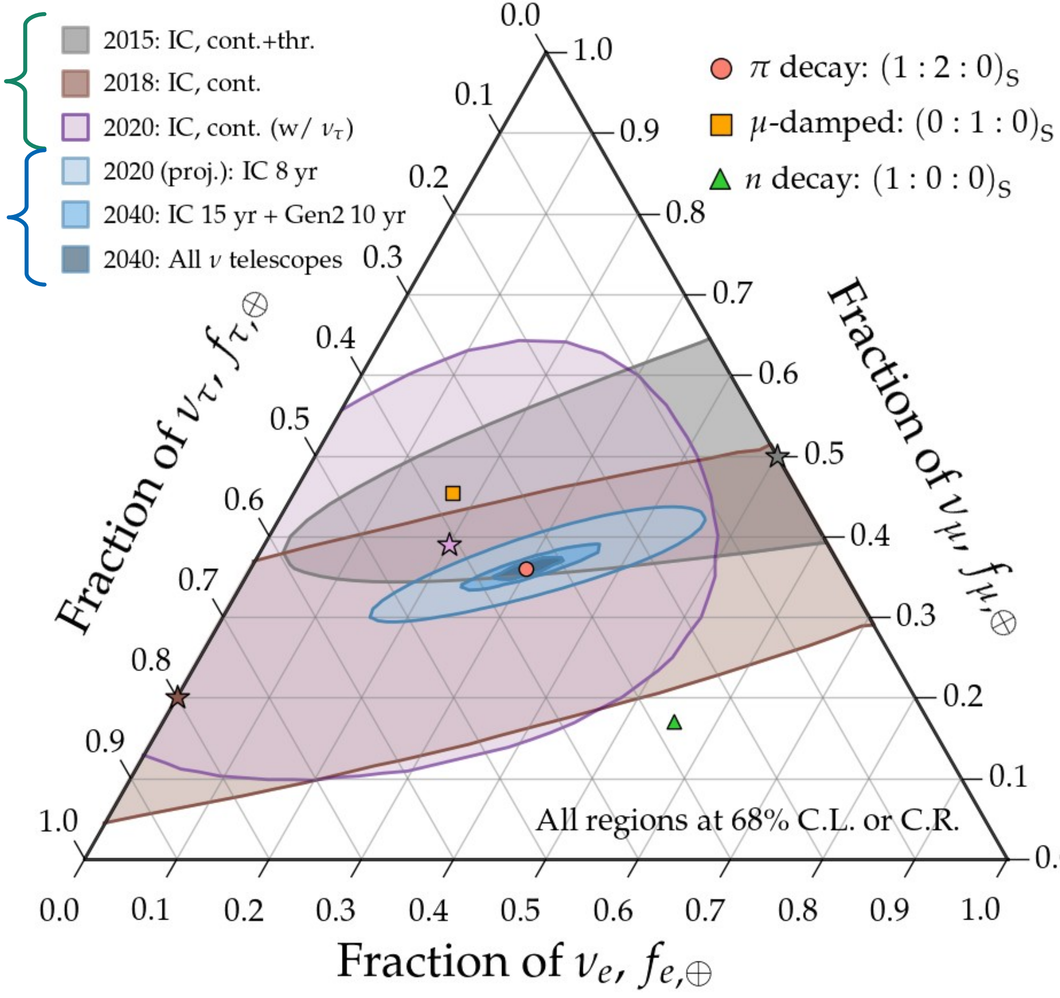


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring flavor composition: 2015–2040



Based on real data

Projections

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

Today

TeV–PeV ν

Today

TeV–PeV ν

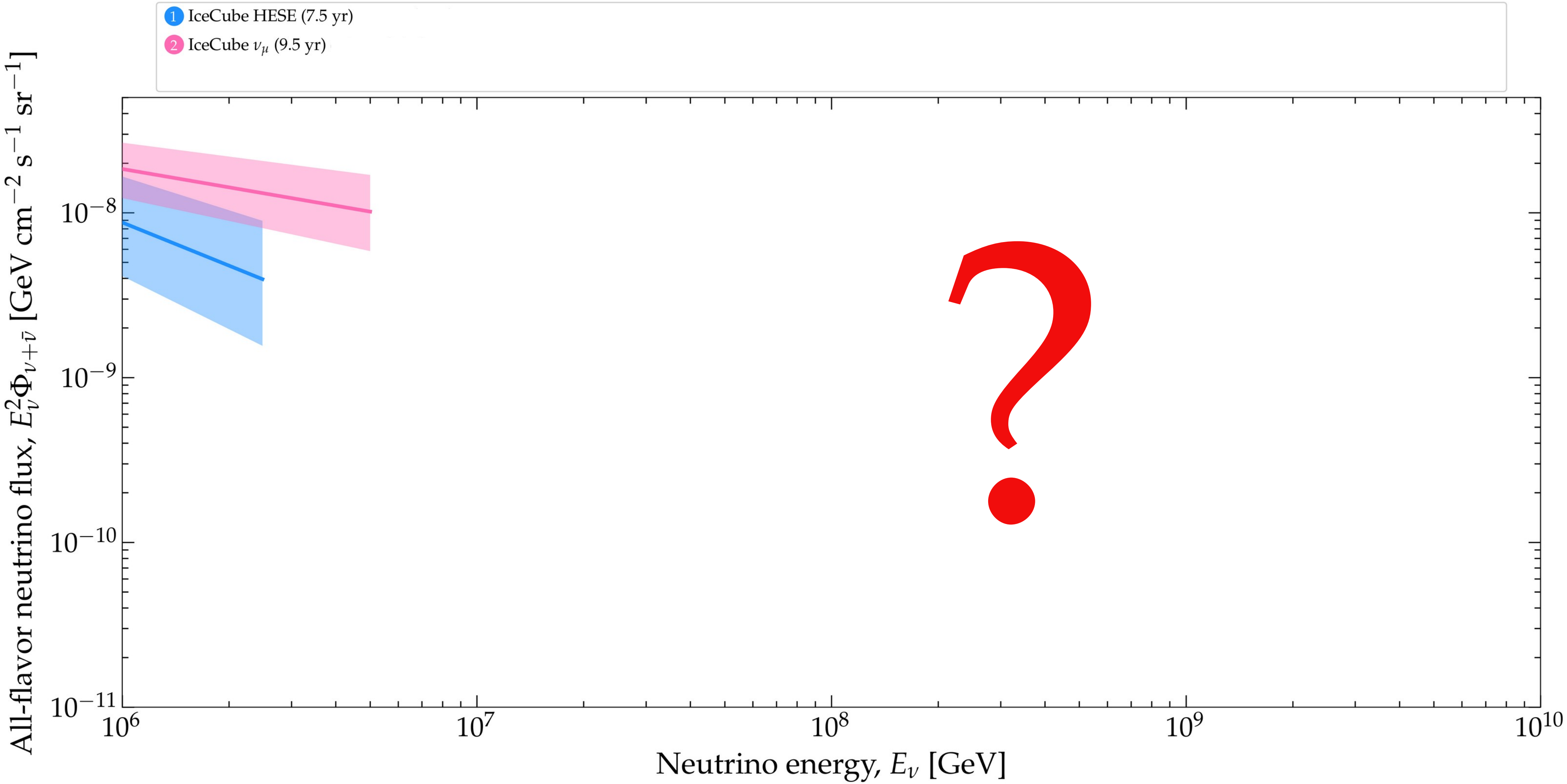
Turn predictions
into data-driven tests

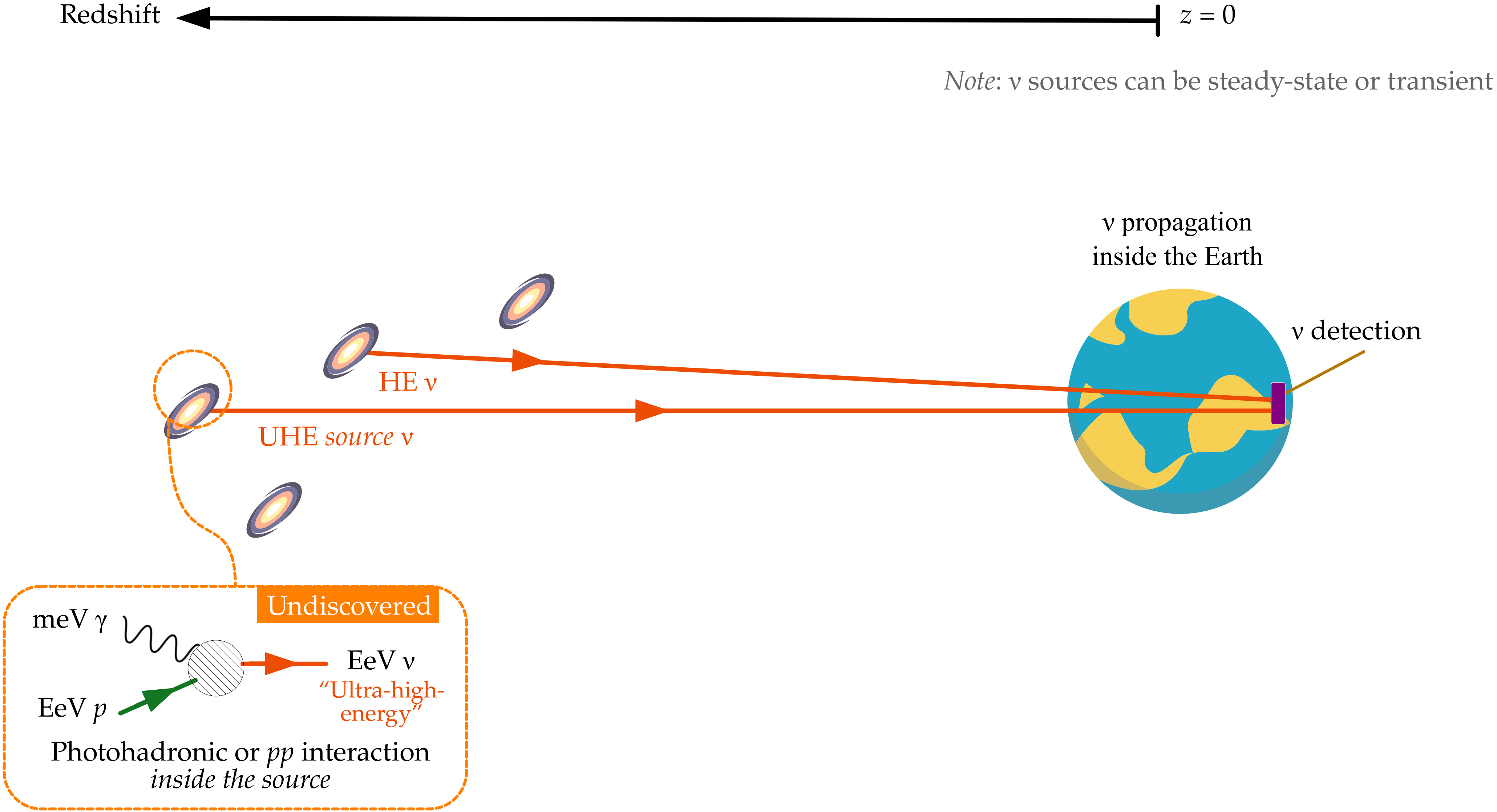
Today

TeV–PeV ν

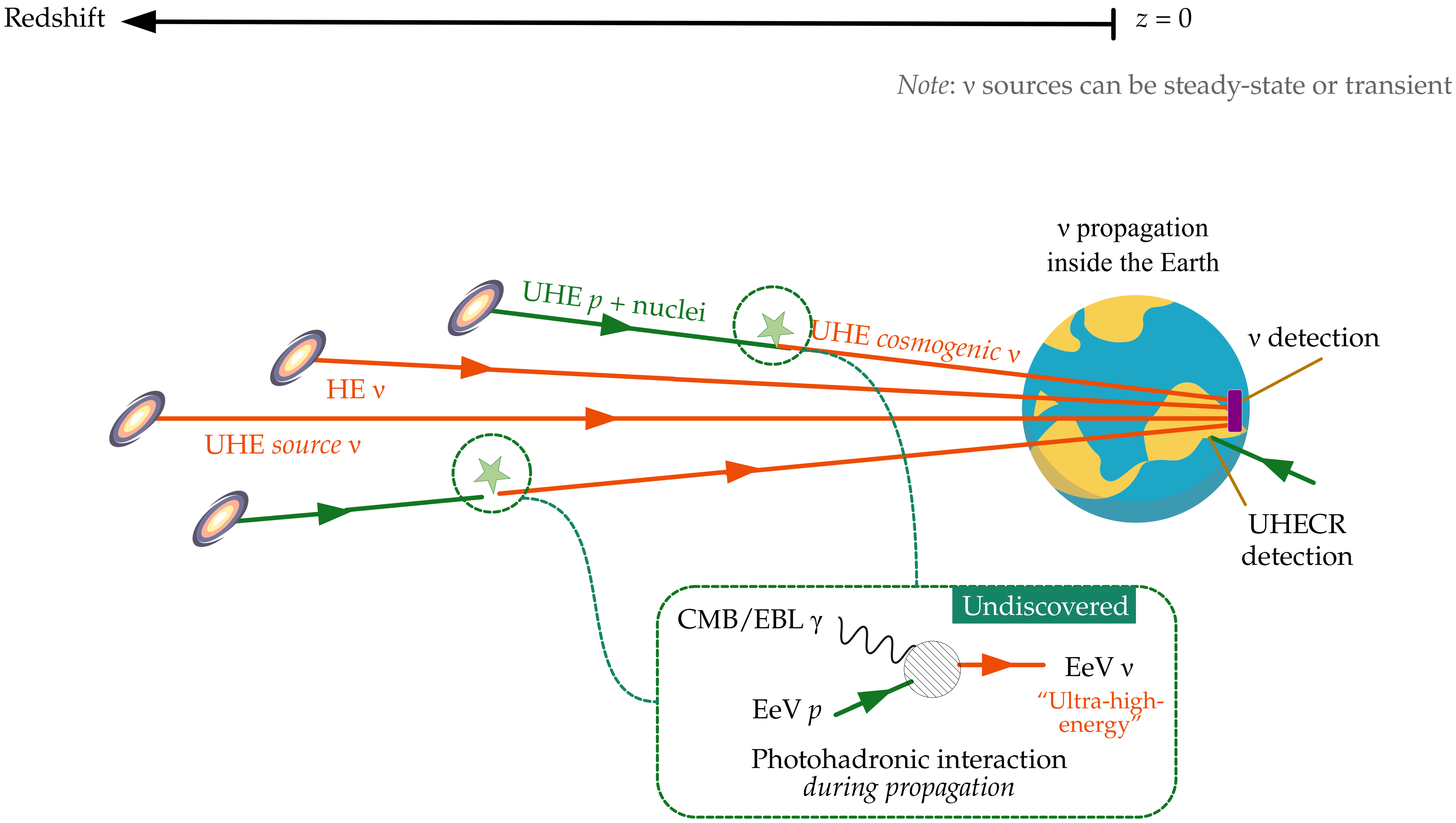
Turn predictions
into data-driven tests

Key developments:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

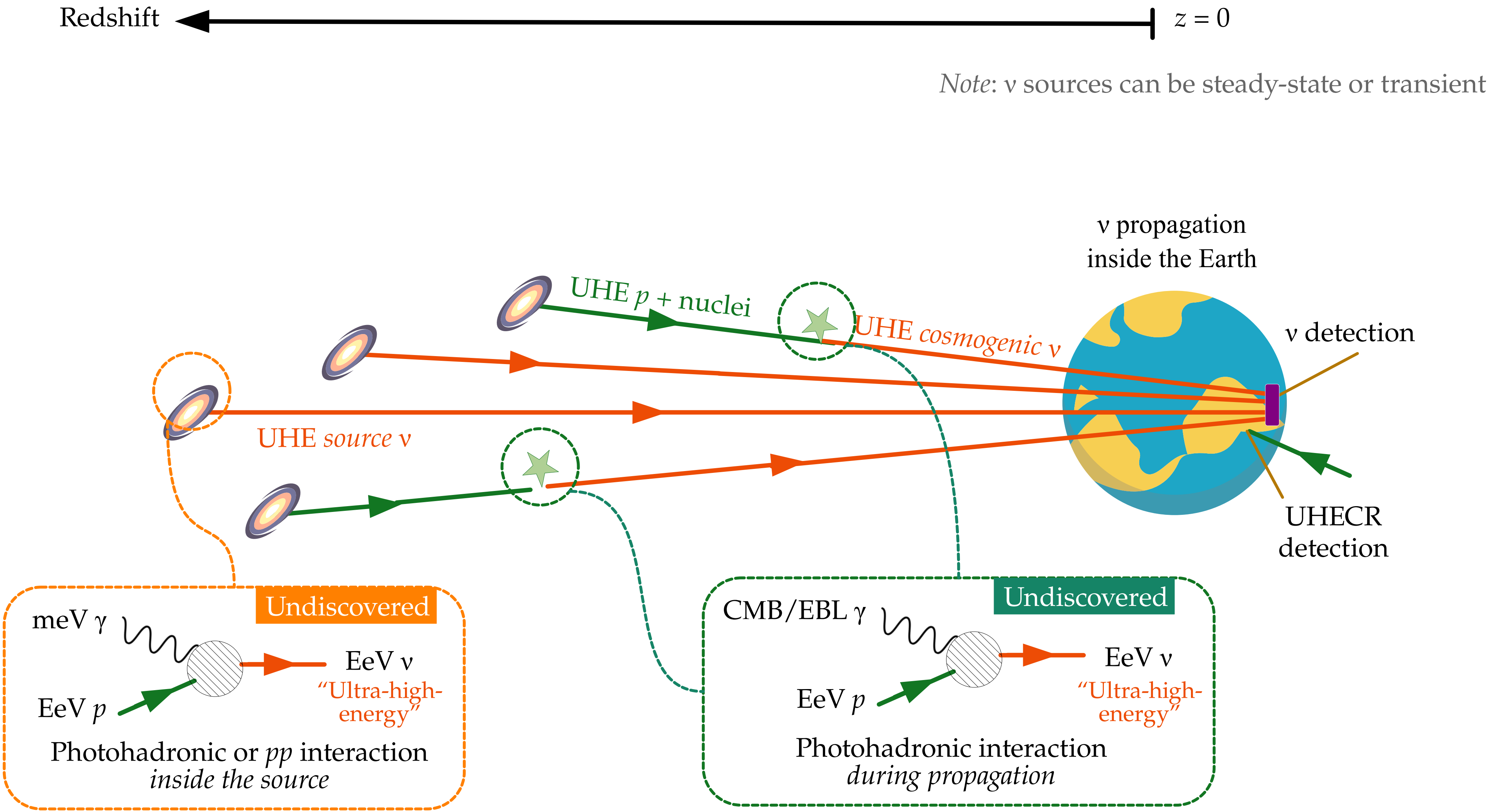

① IceCube HESE (7.5 yr)
② IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]
?



Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation inside the Earth
ν detection
HE ν
UHE *source* ν
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV *p*
Photohadronic or *pp* interaction
inside the source



Note: ν sources can be steady-state or transient


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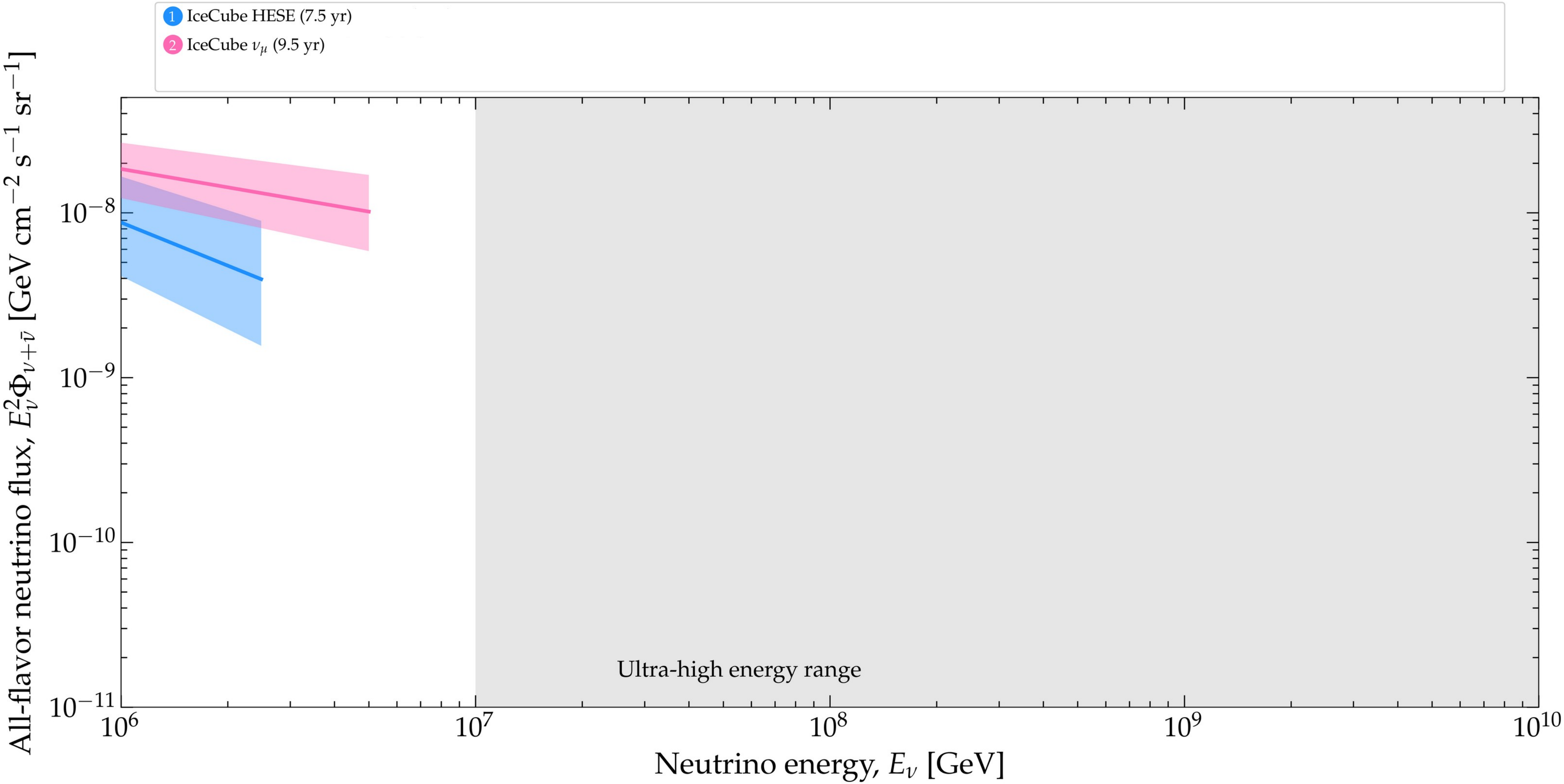
EeV p
Photohadronic or pp interaction inside the source
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic interaction during propagation



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10^6
10^7
10^8
10^9
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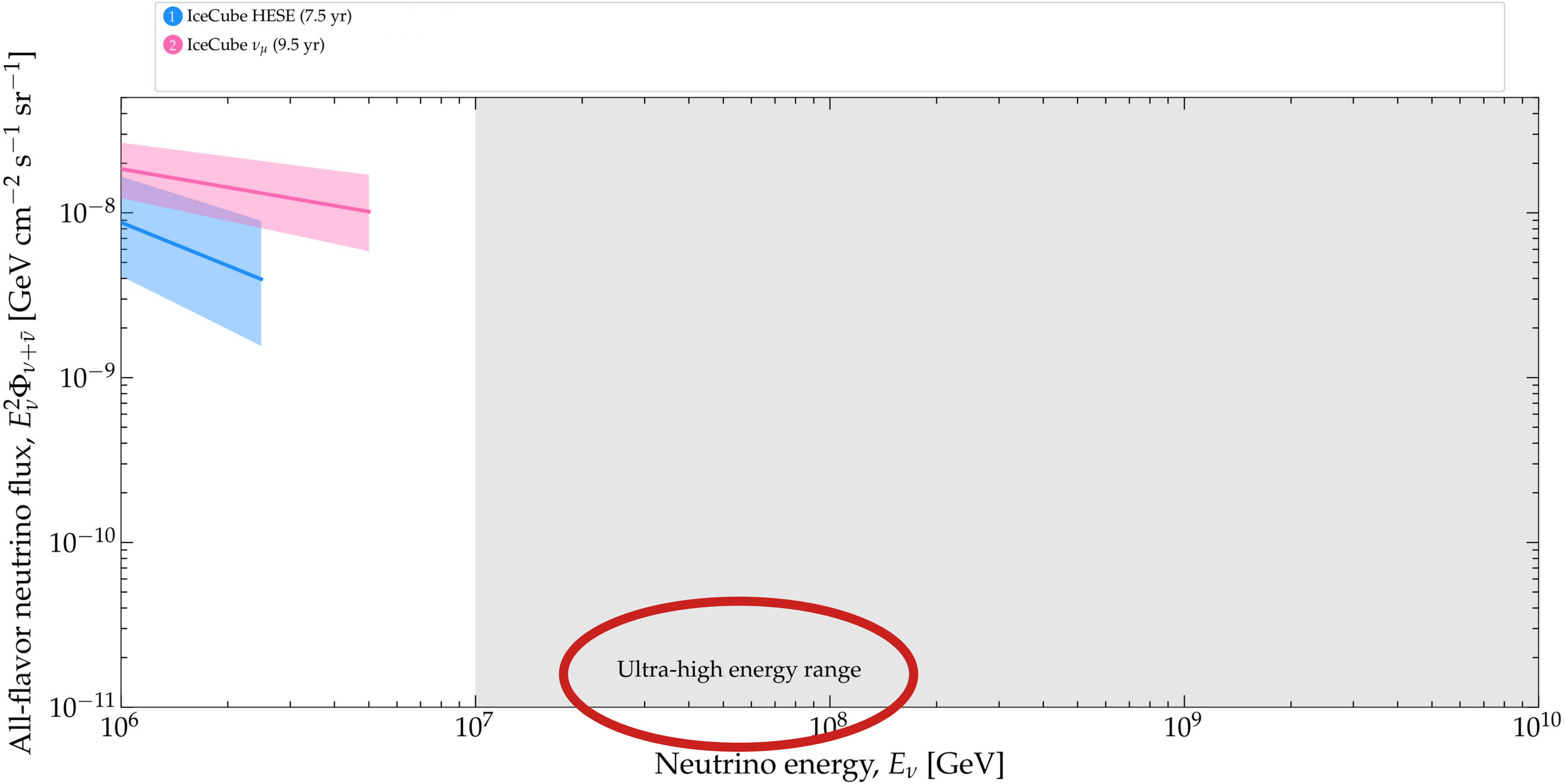
Neutrino energy, E_ν [GeV]
Ultra-high energy range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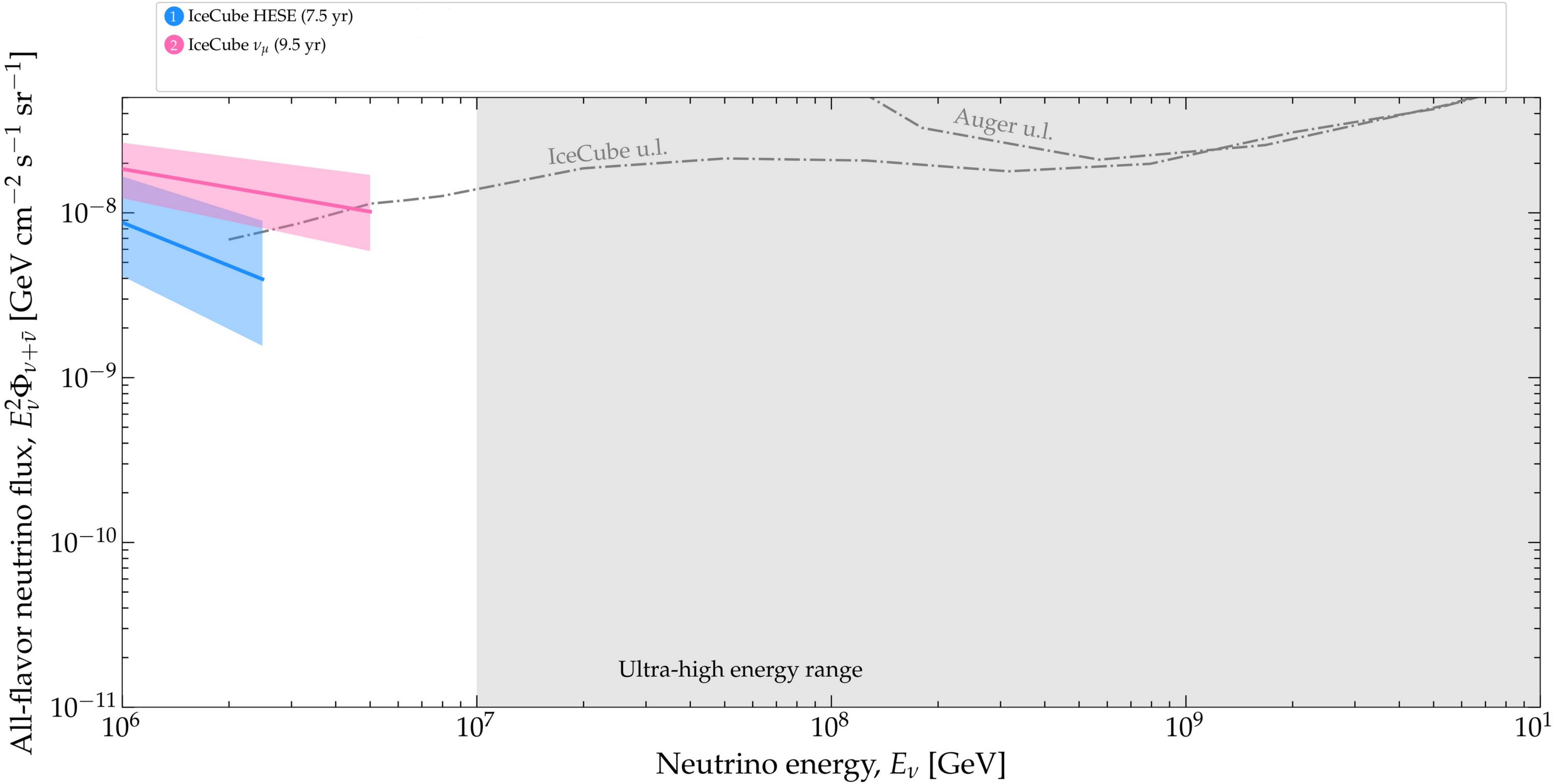

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IceCube u.l.
Auger u.l.
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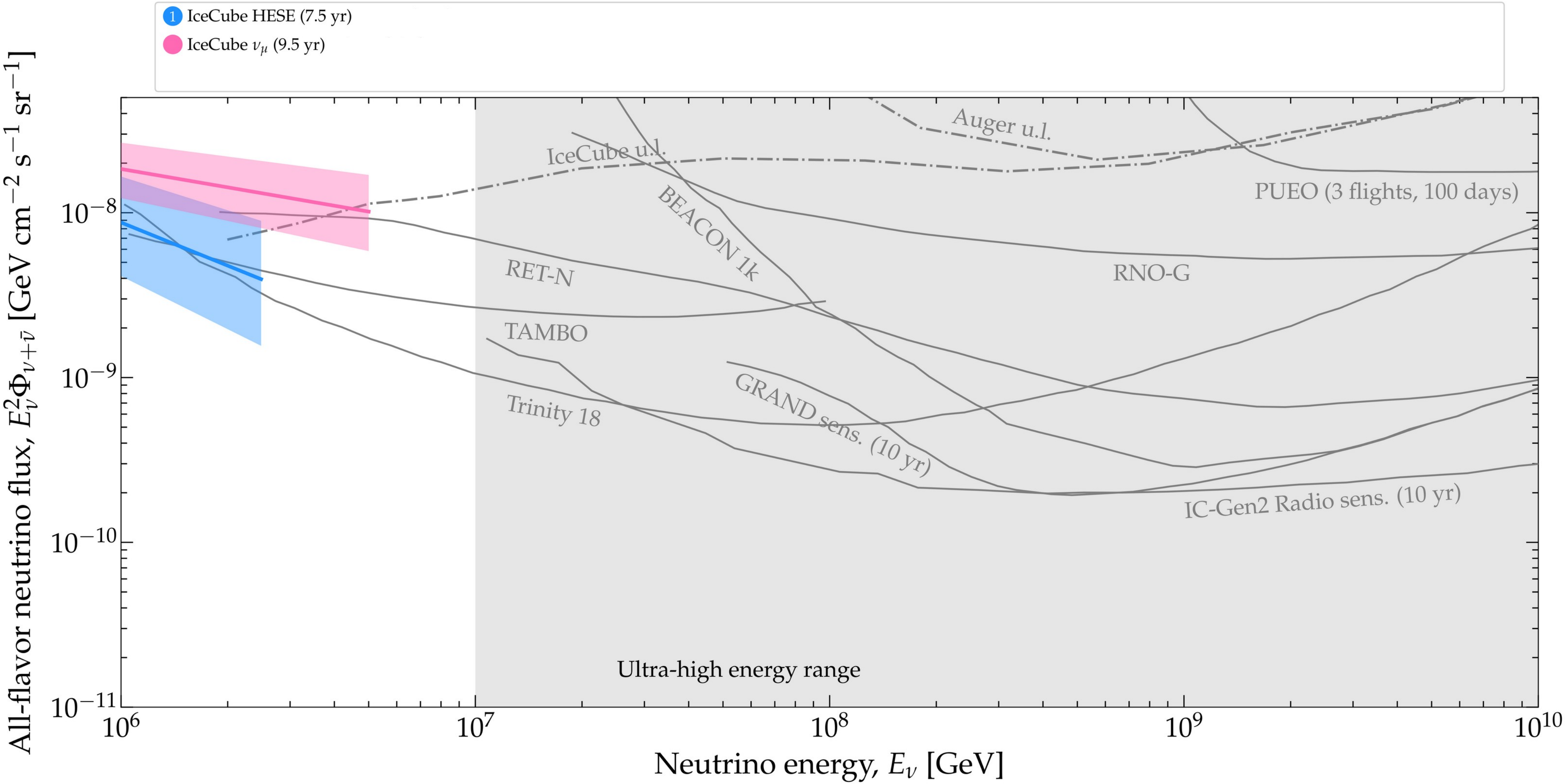
1 IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
PUEO (3 flights, 100 days)
BEACON 1k
RET-N
RNO-G
TAMBO
GRAND sens. (10 yr)
Trinity 18
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
10^{-8}
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10^{-10}
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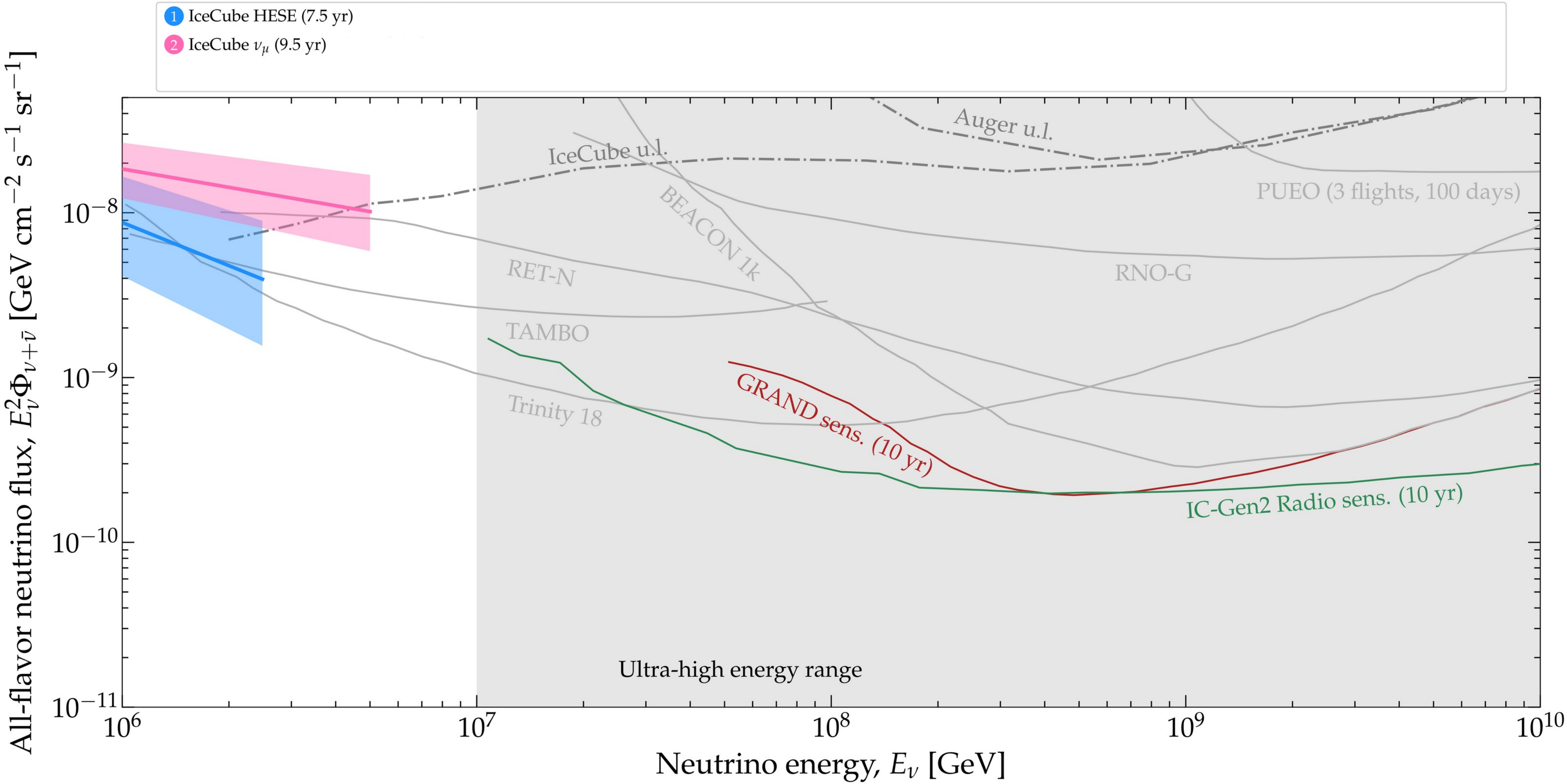
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10^6
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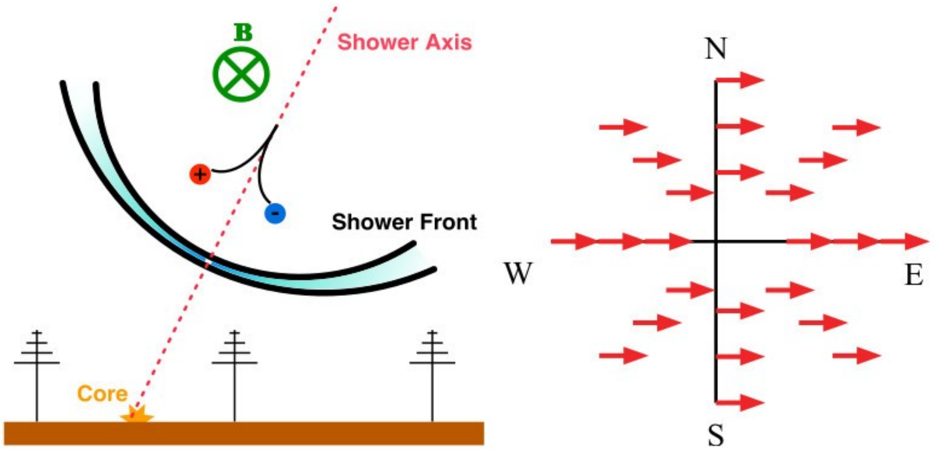
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

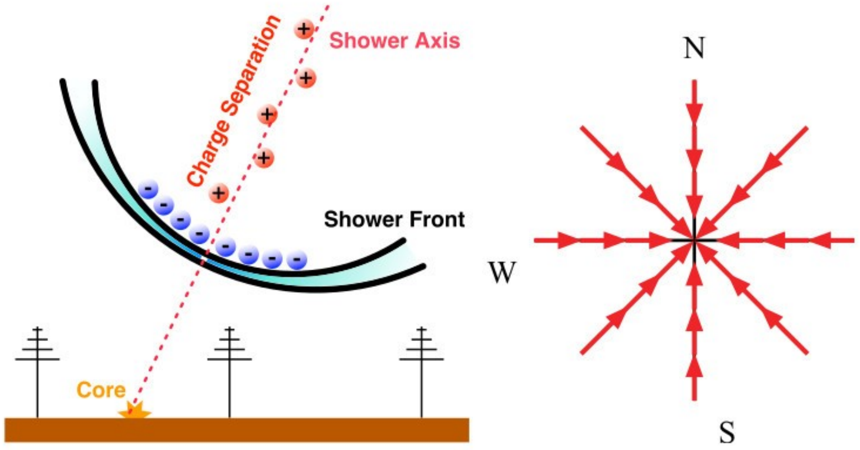
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

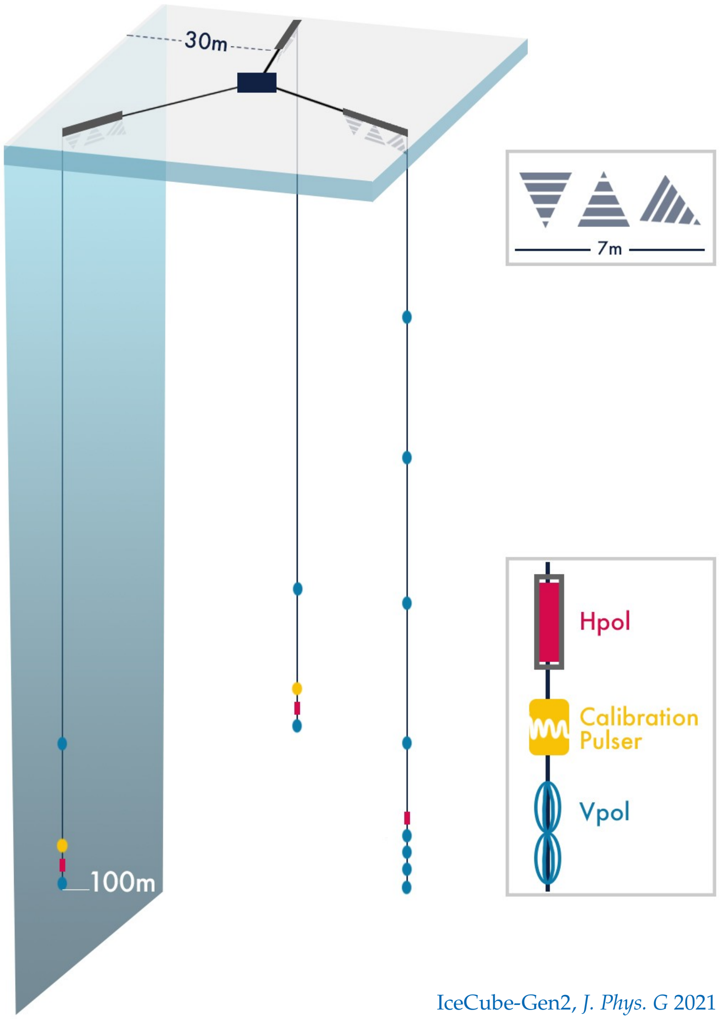
Askaryan



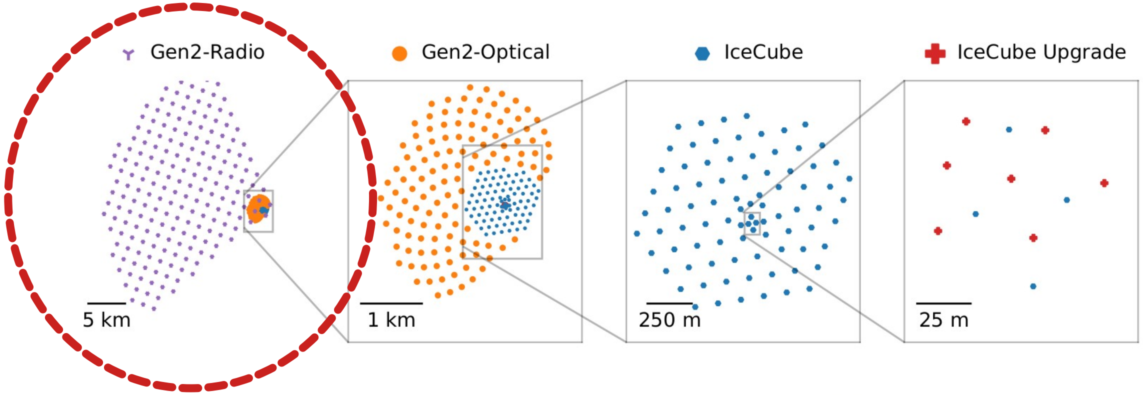
- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

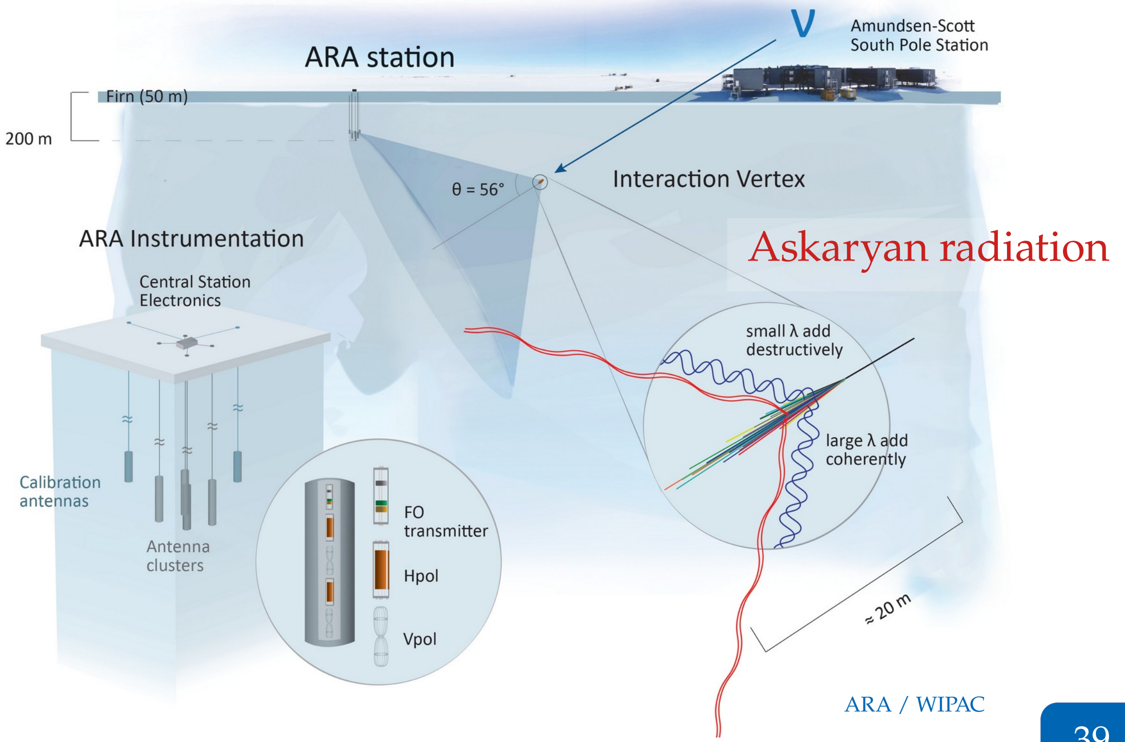
Figures by H. Schoorlemmer and K. D. de Vries

IceCube-Gen2 Radio



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

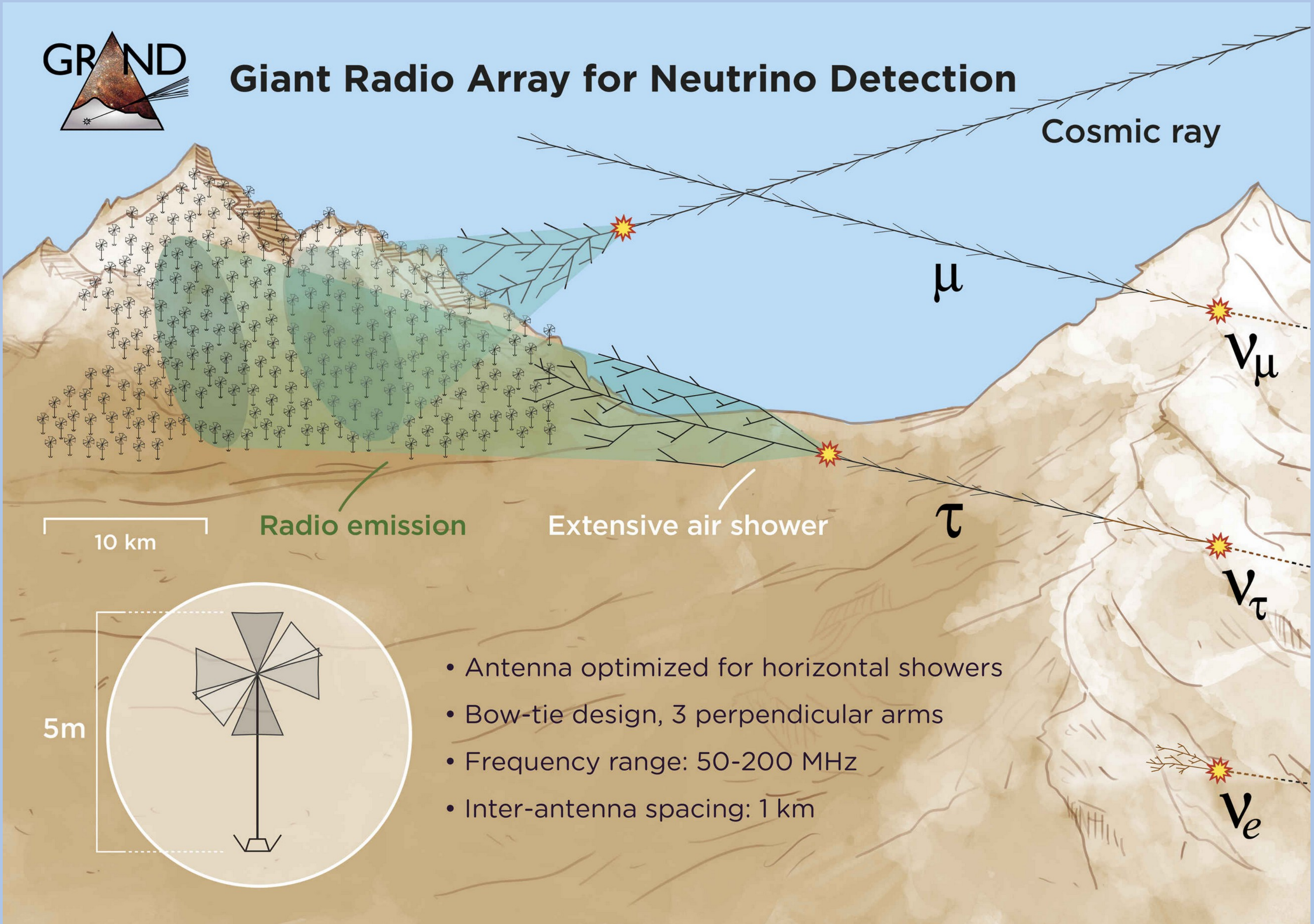




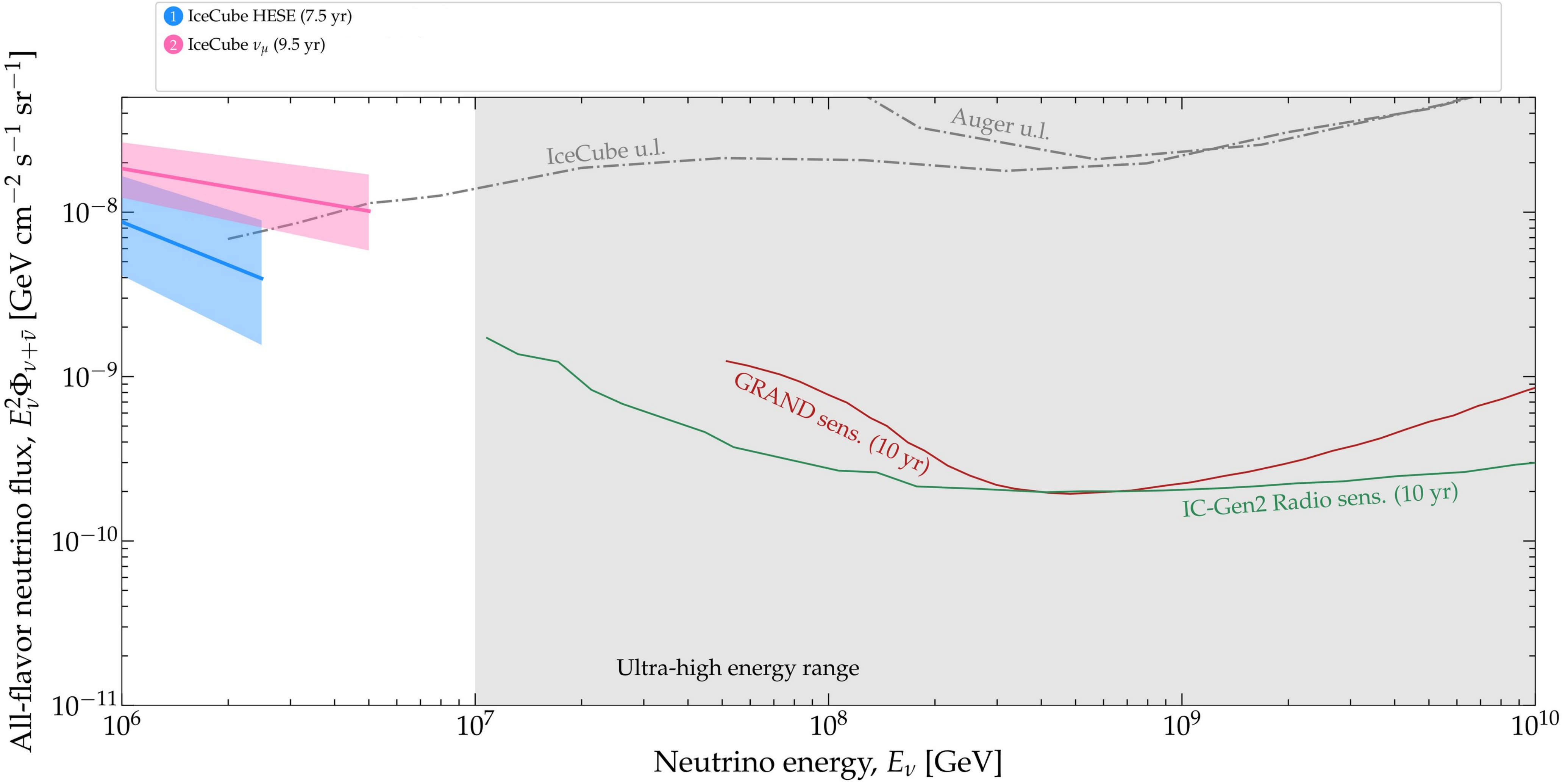
Askaryan radiation

ARA / WIPAC

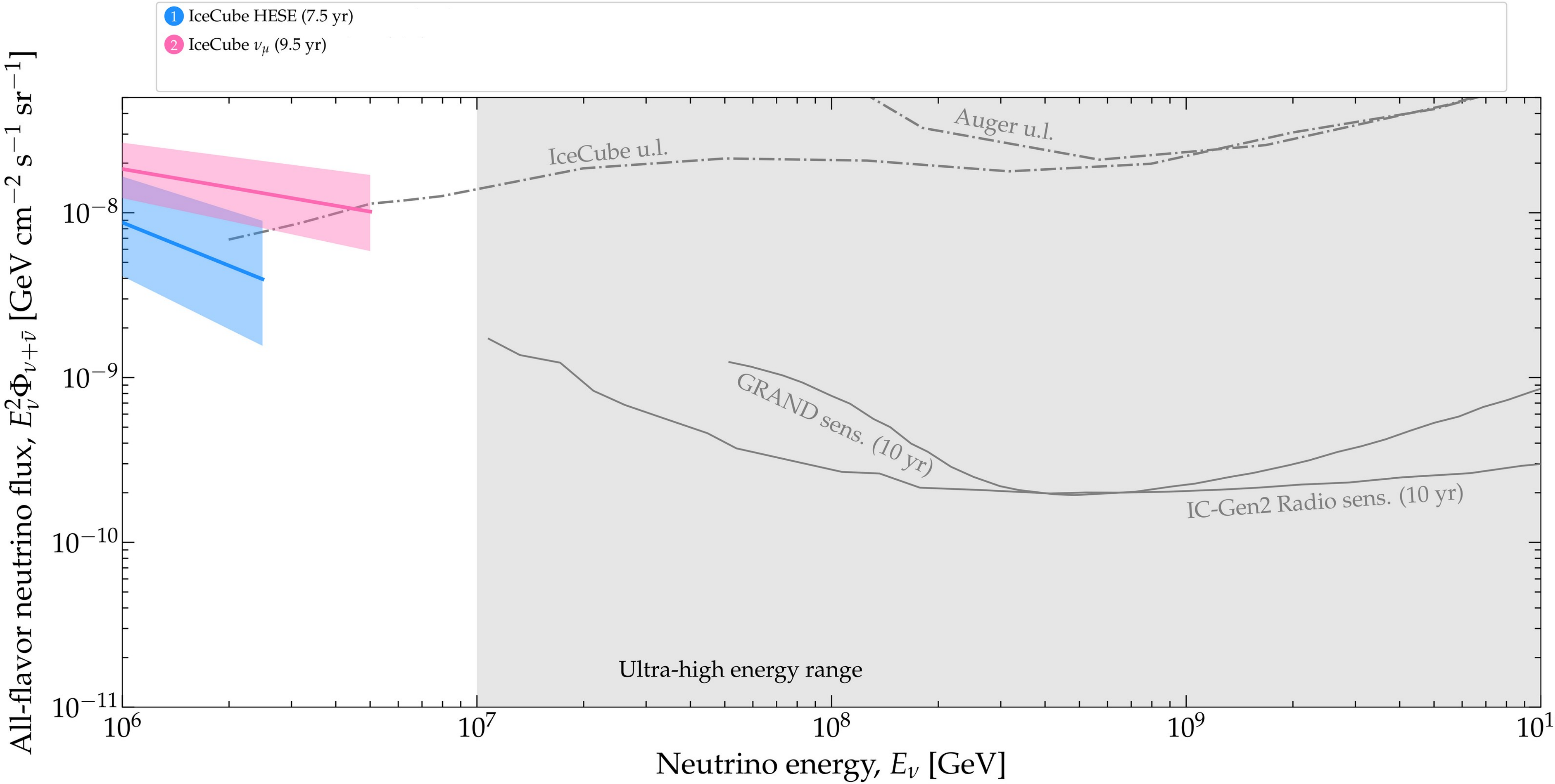
Giant Radio Array for Neutrino Detection



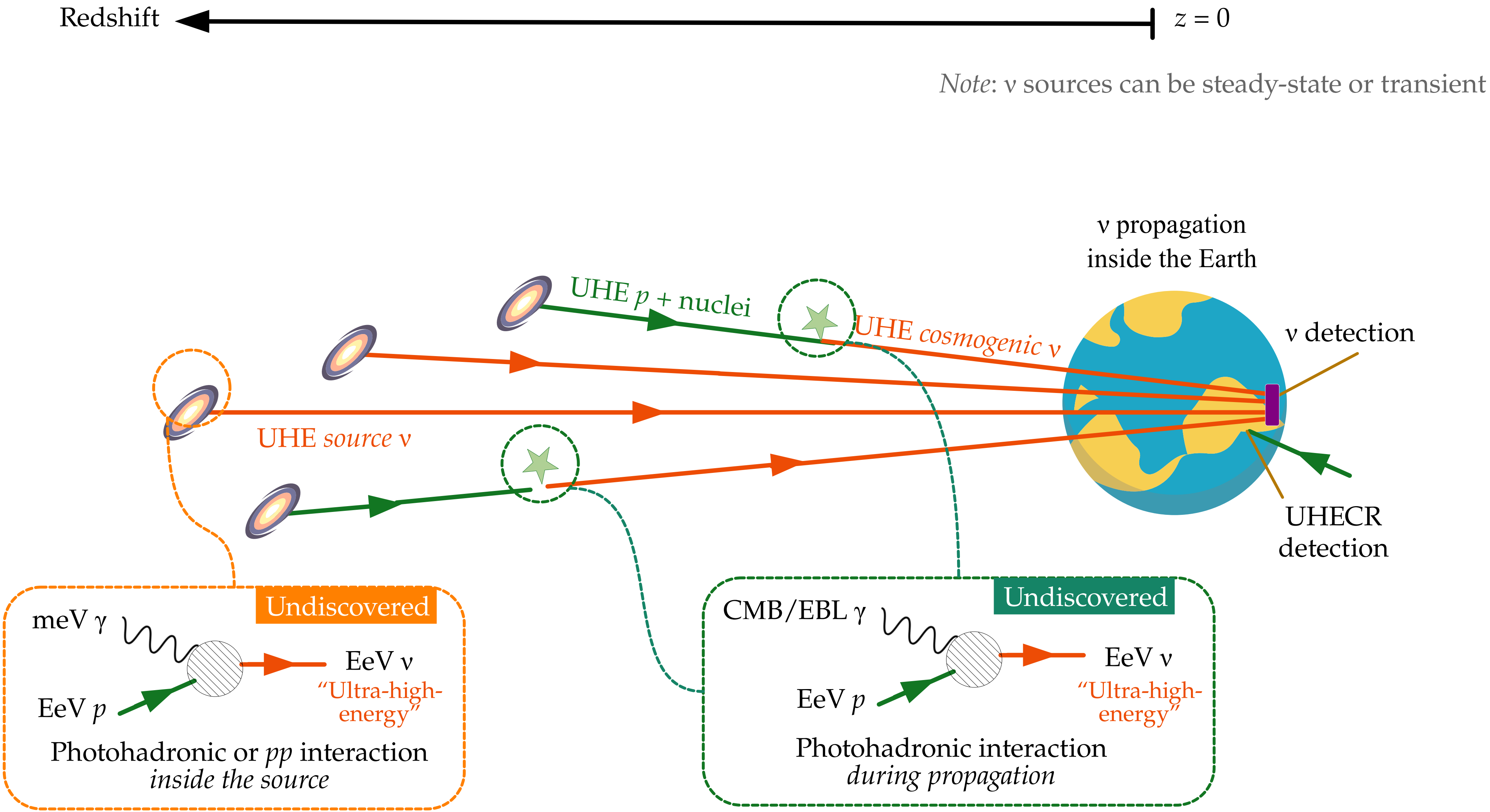
- Antenna optimized for horizontal showers
- Bow-tie design, 3 perpendicular arms
- Frequency range: 50-200 MHz
- Inter-antenna spacing: 1 km



Valera, **MB**, Glaser, *PRD* 2023



Valera, **MB**, Glaser, *PRD* 2023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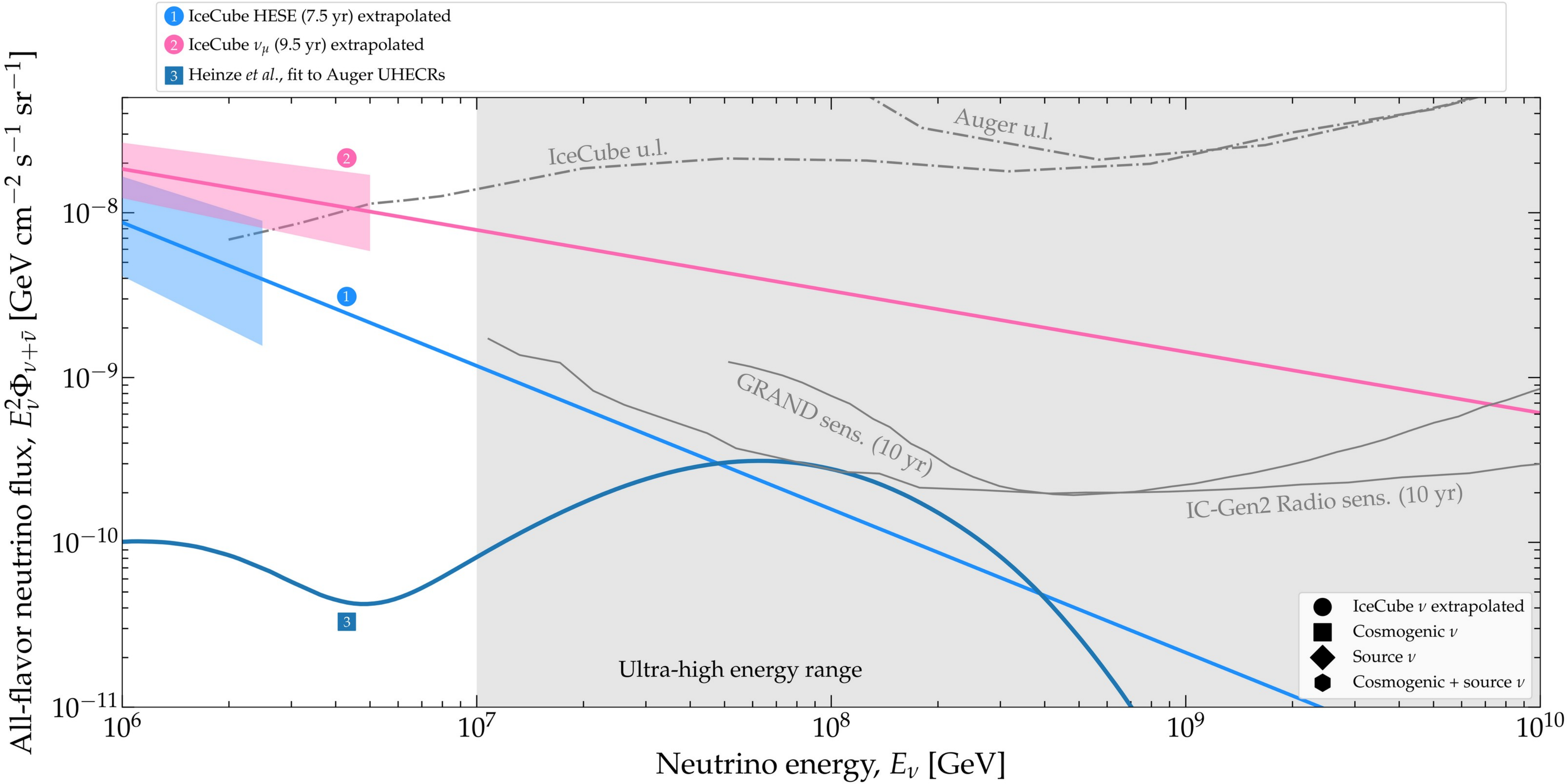
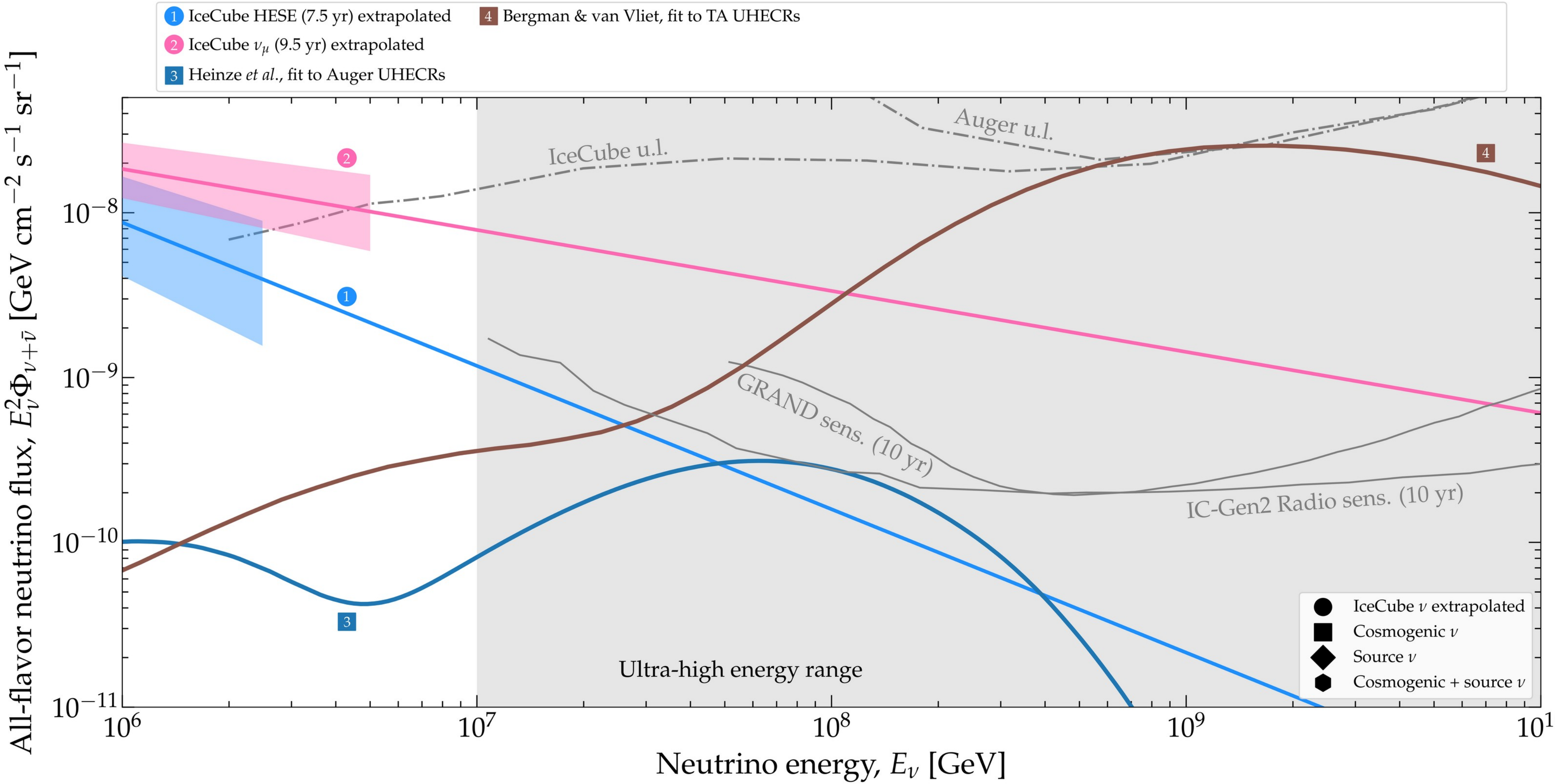
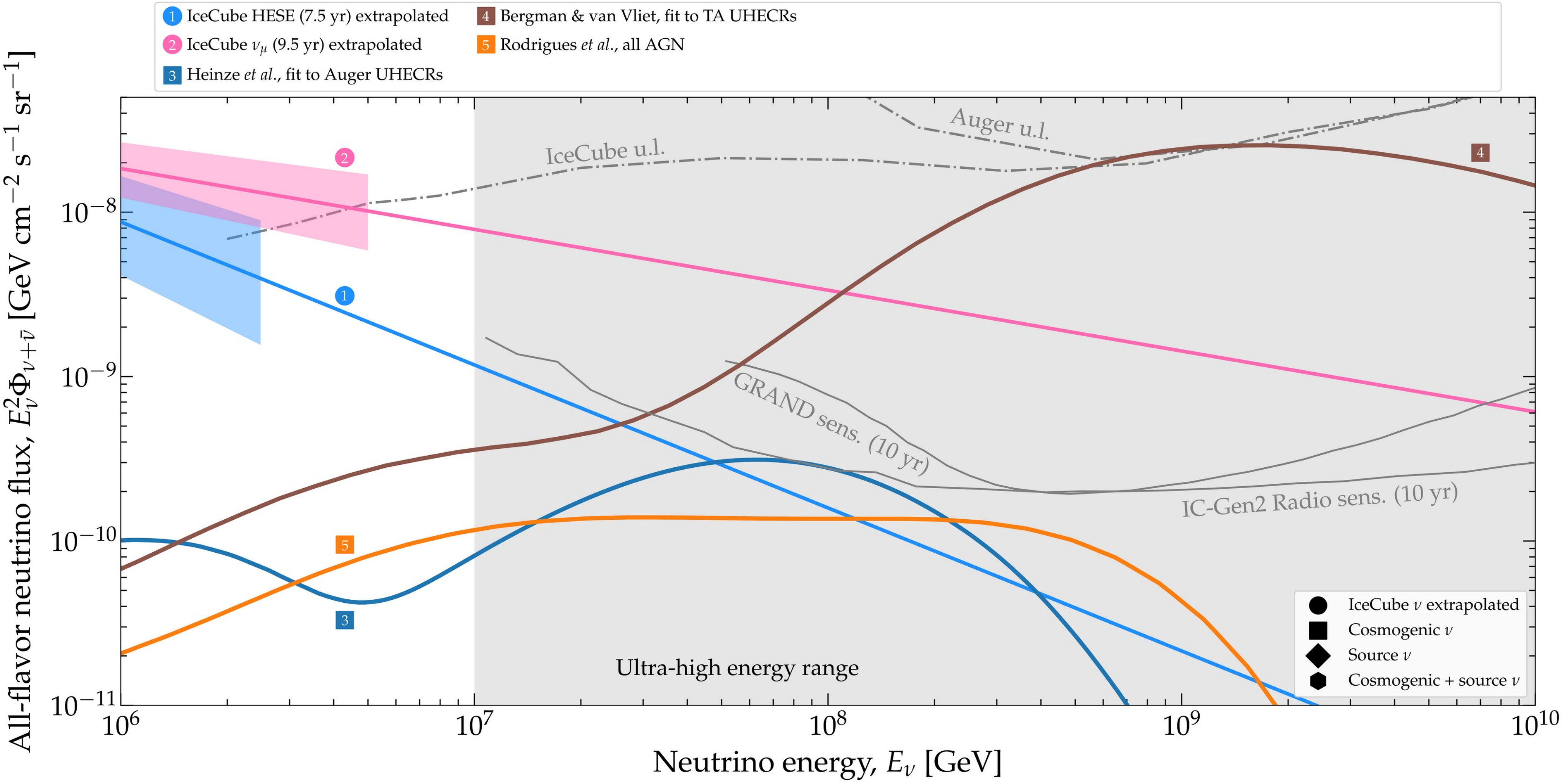
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation



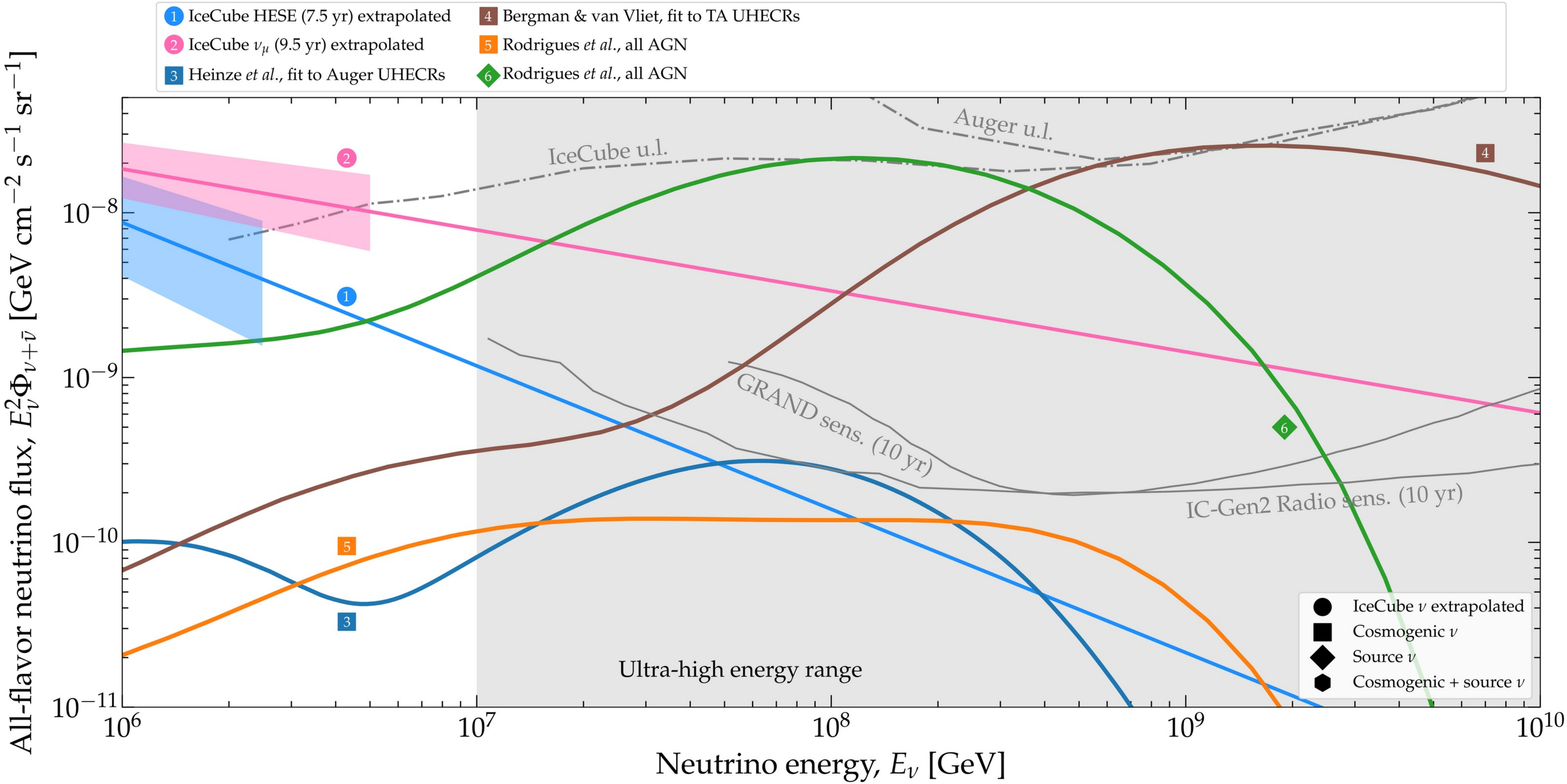
Valera, **MB**, Glaser, *PRD* 2023



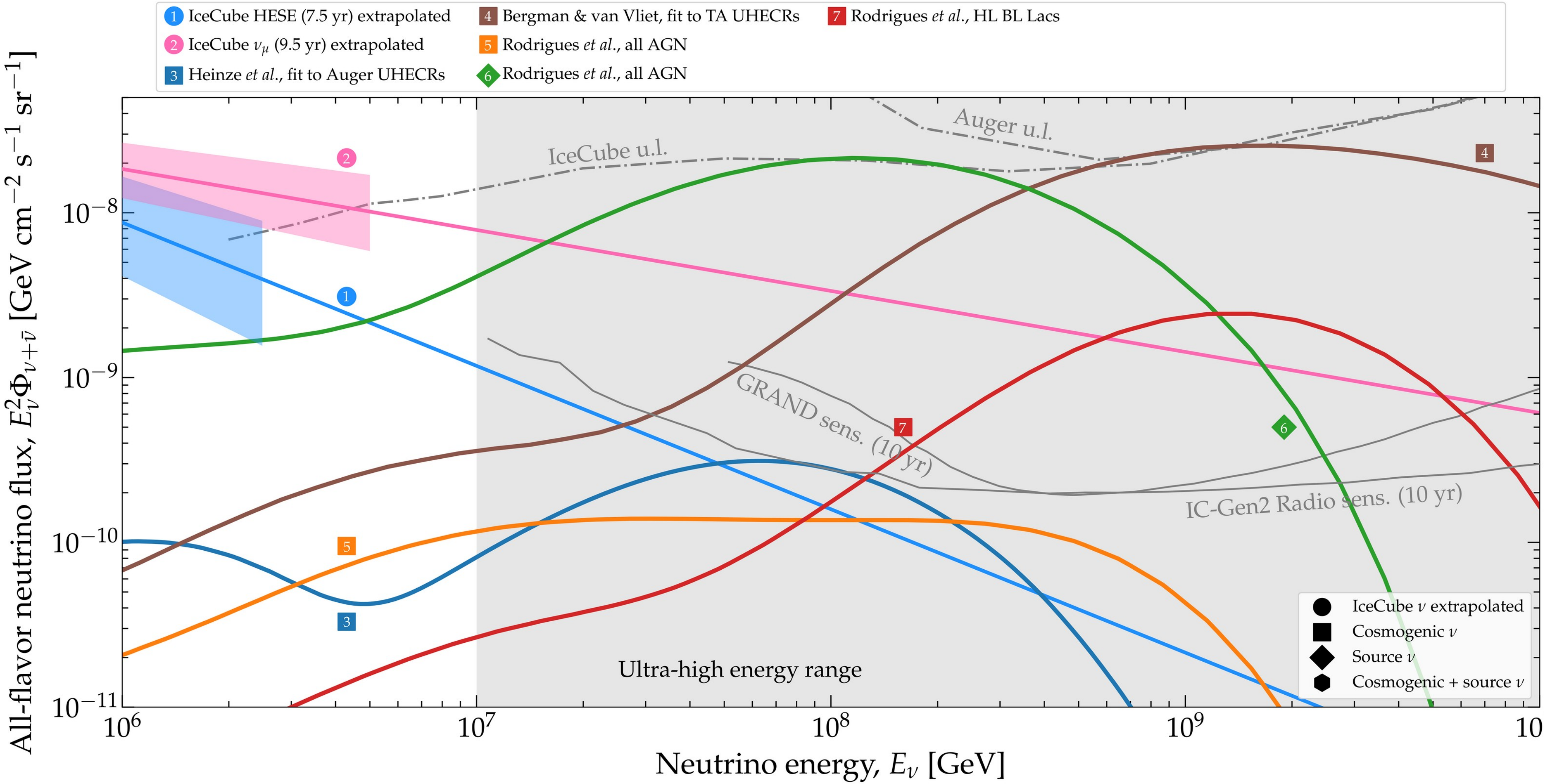
Valera, **MB**, Glaser, *PRD* 2023



Valera, **MB**, Glaser, *PRD* 2023



Valera, **MB**, Glaser, *PRD* 2023



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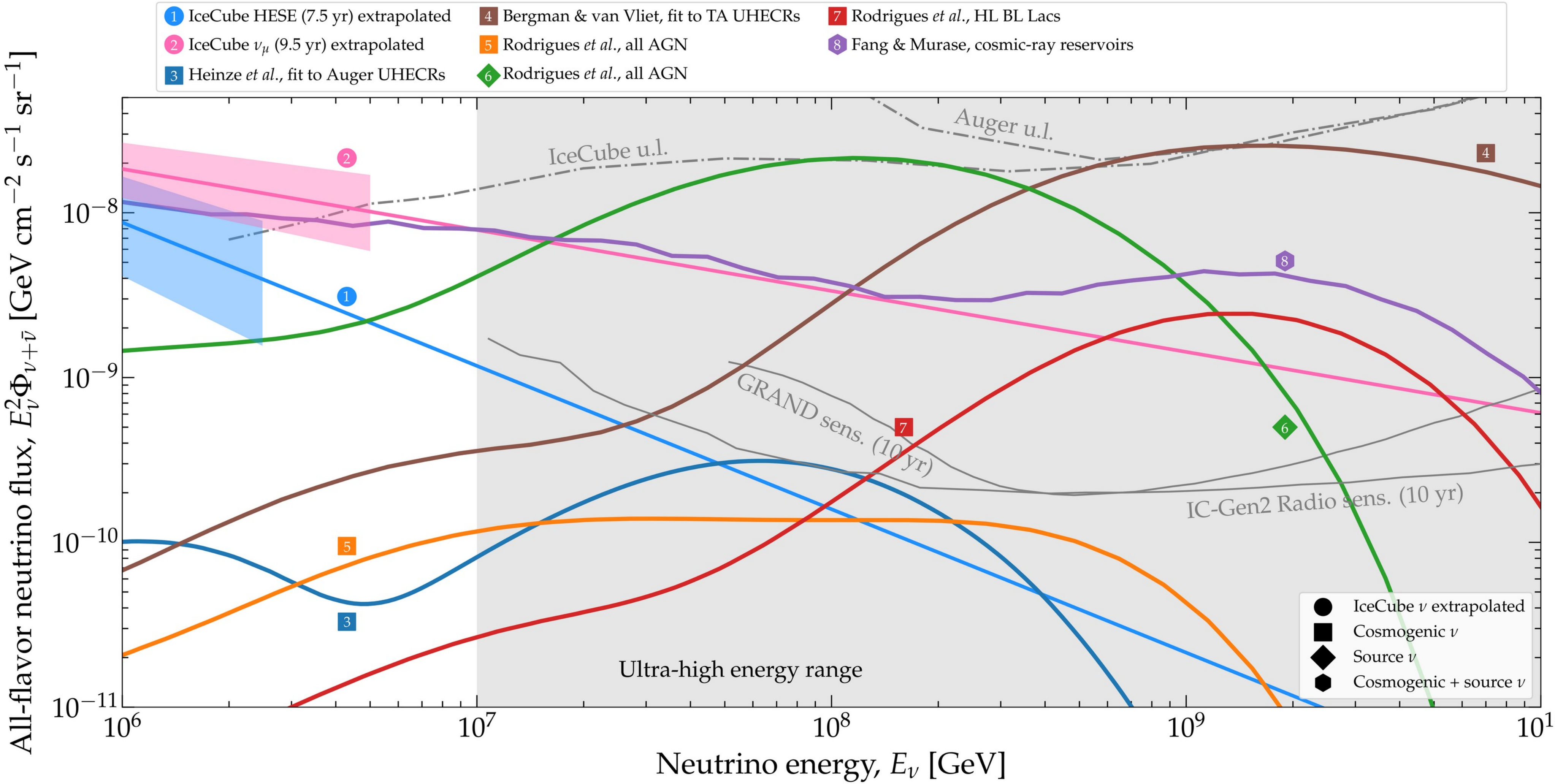

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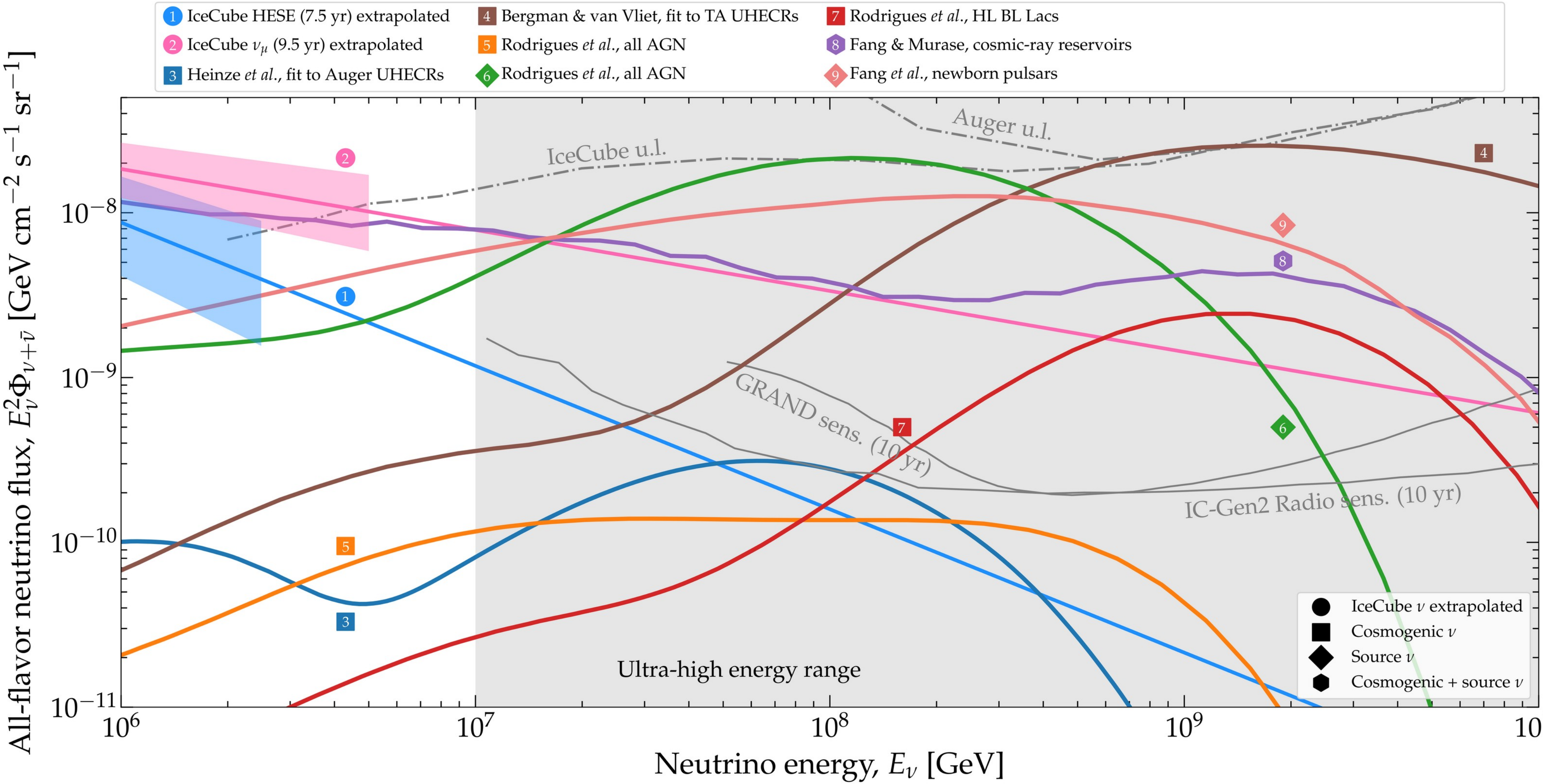

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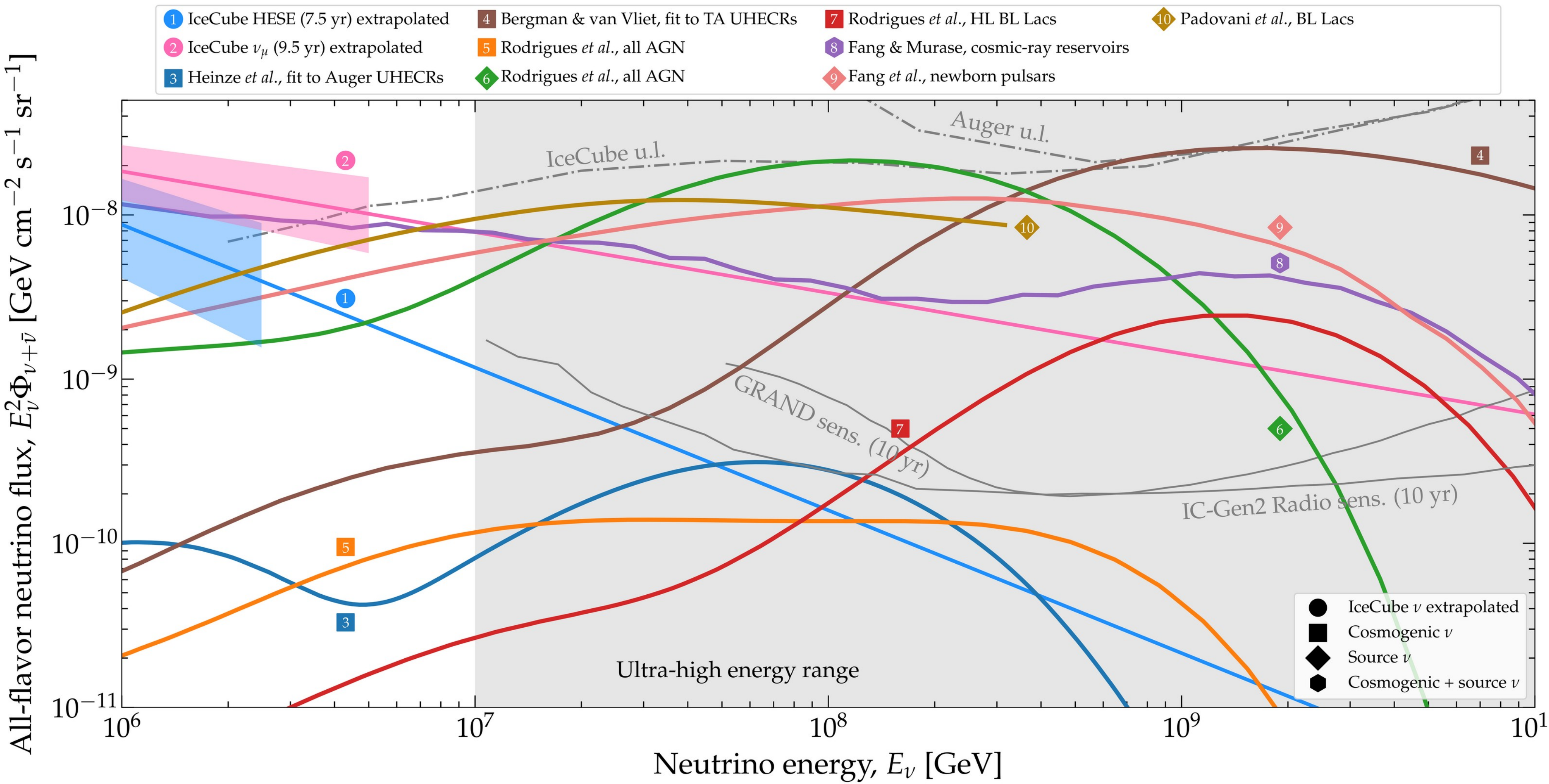

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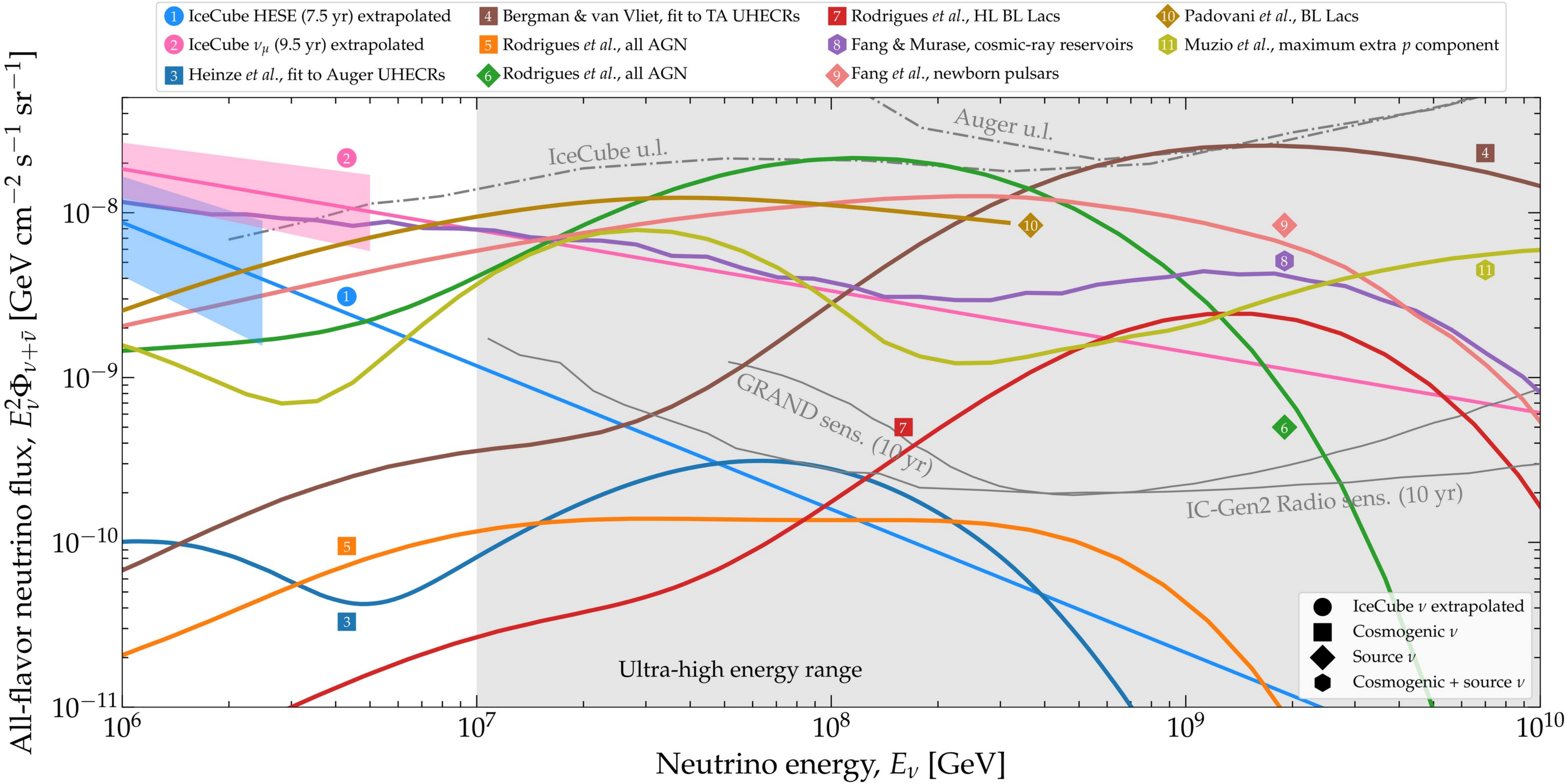

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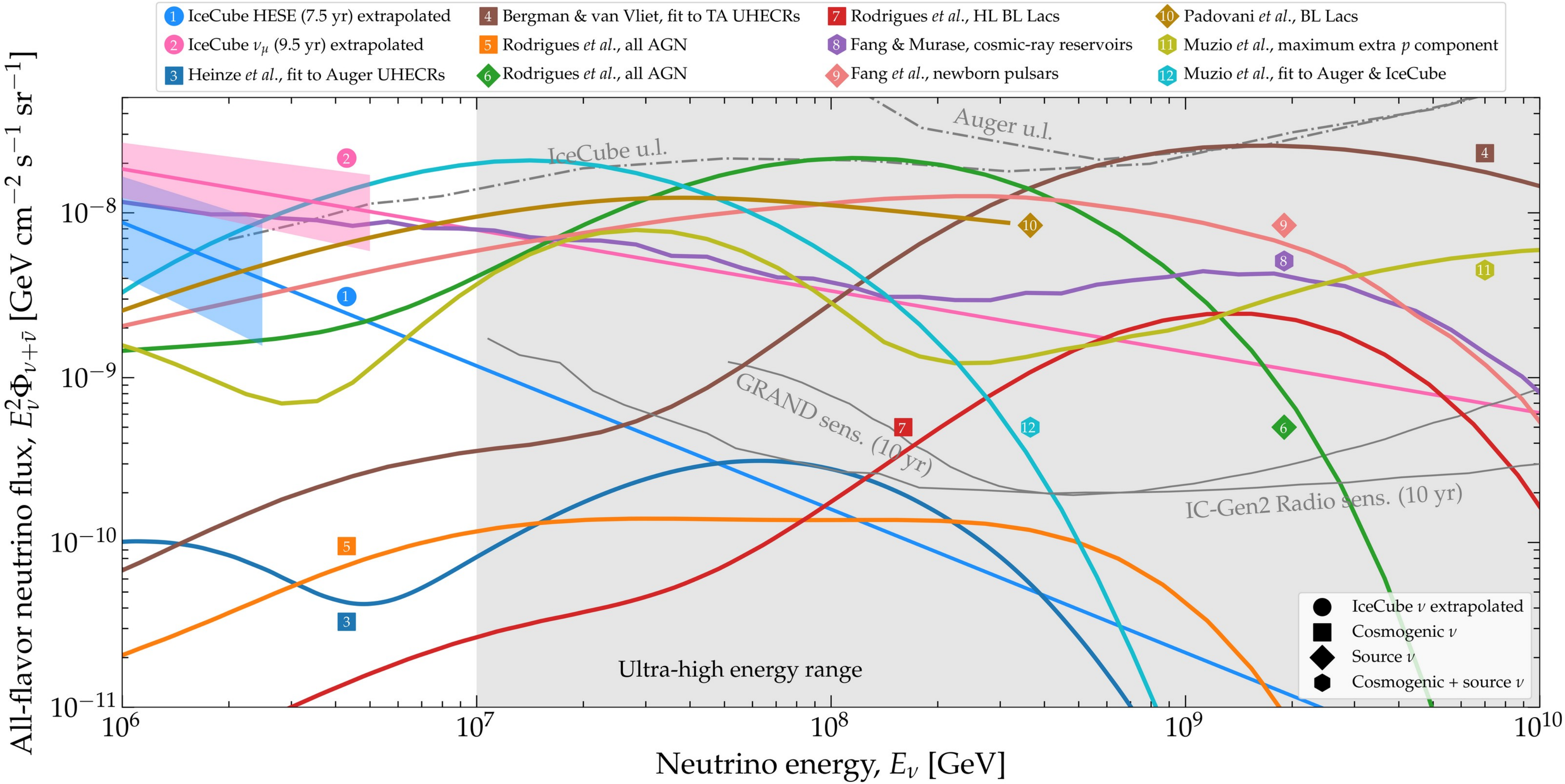
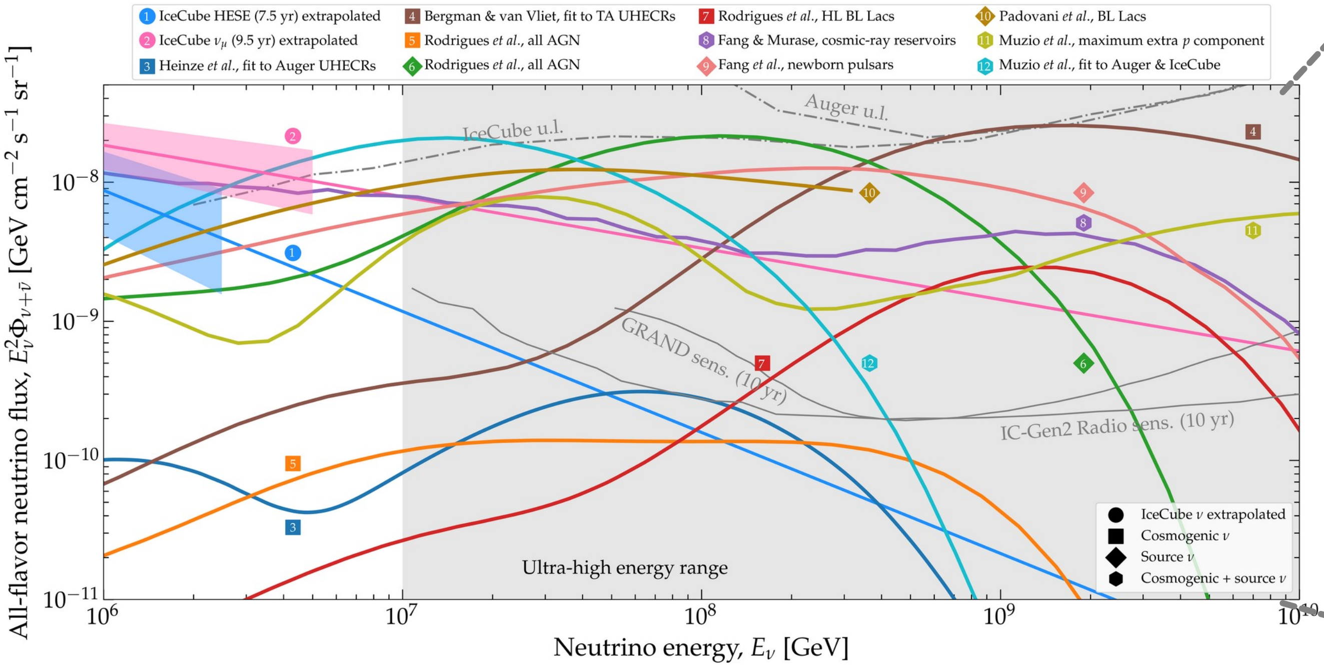


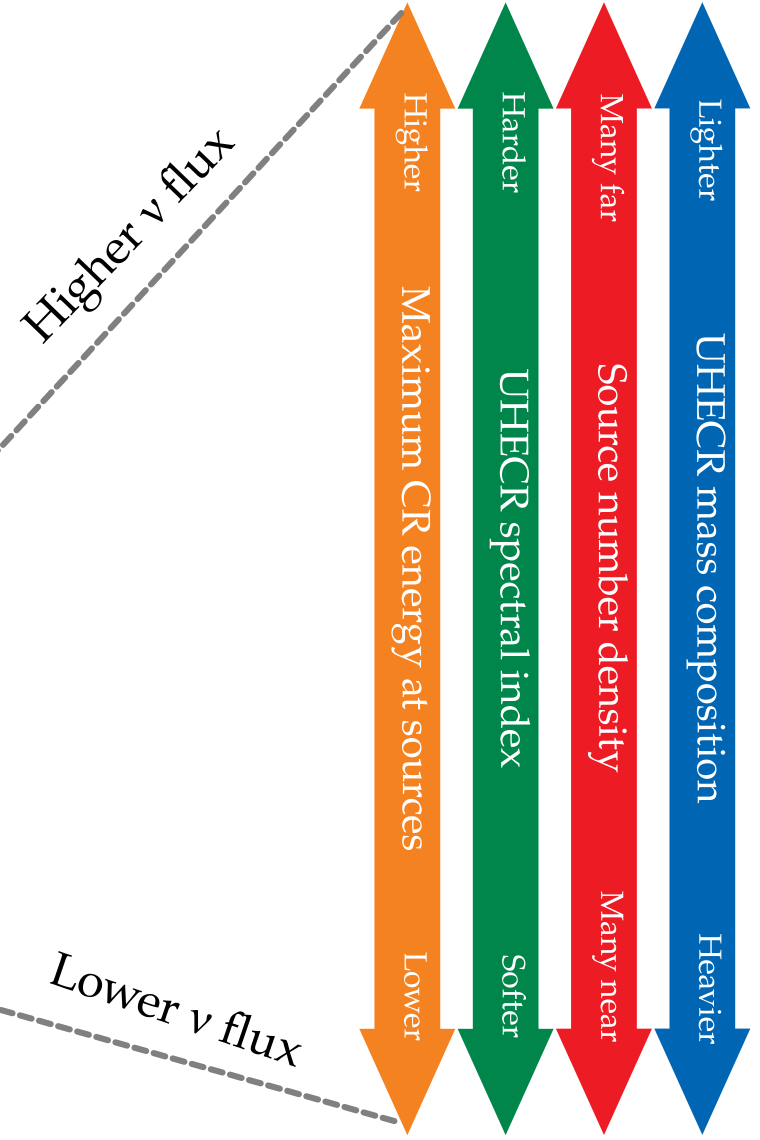
Valera, **MB**, Glaser, *PRD* 2023

Uncertainty in UHECR properties

▼

Uncertainty in predicted UHE neutrino flux





Higher ν flux

Lower ν flux

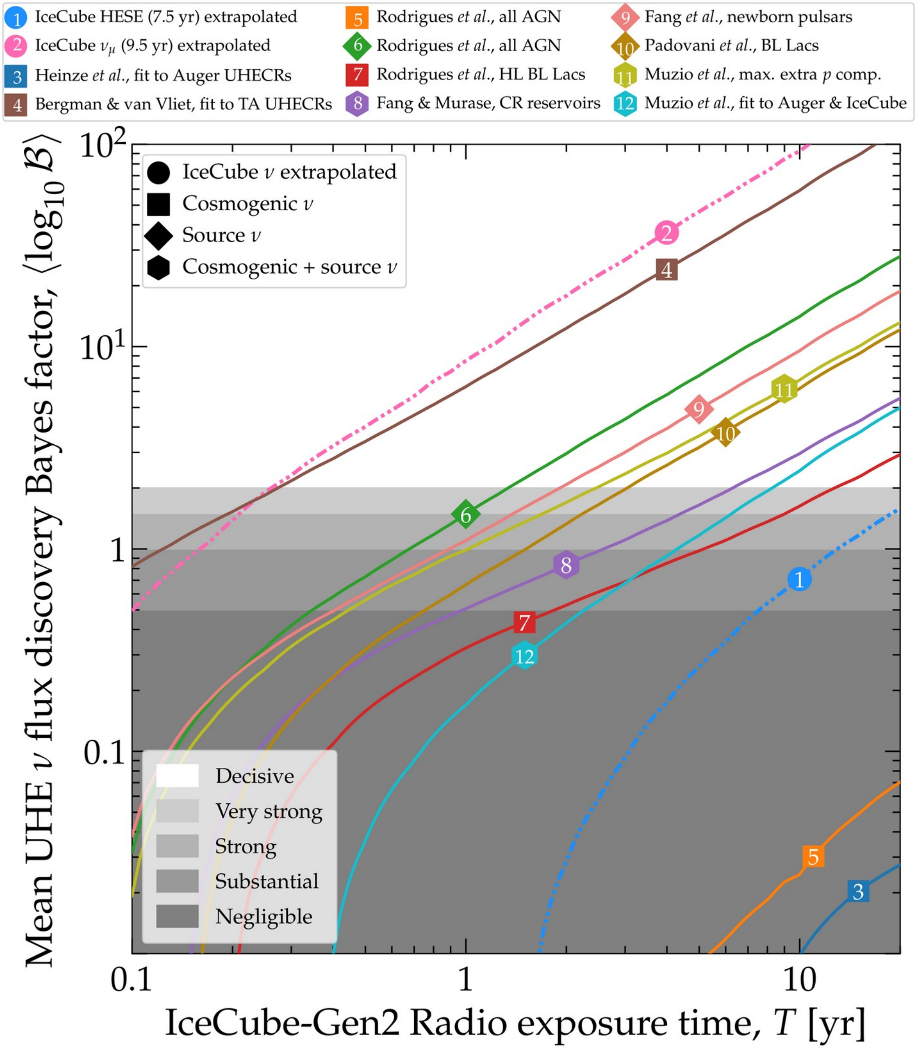
Higher
Maximum CR energy at sources
Lower

Harder
UHECR spectral index
Softer

Many far
Source number density
Many near

Lighter
UHECR mass composition
Heavier

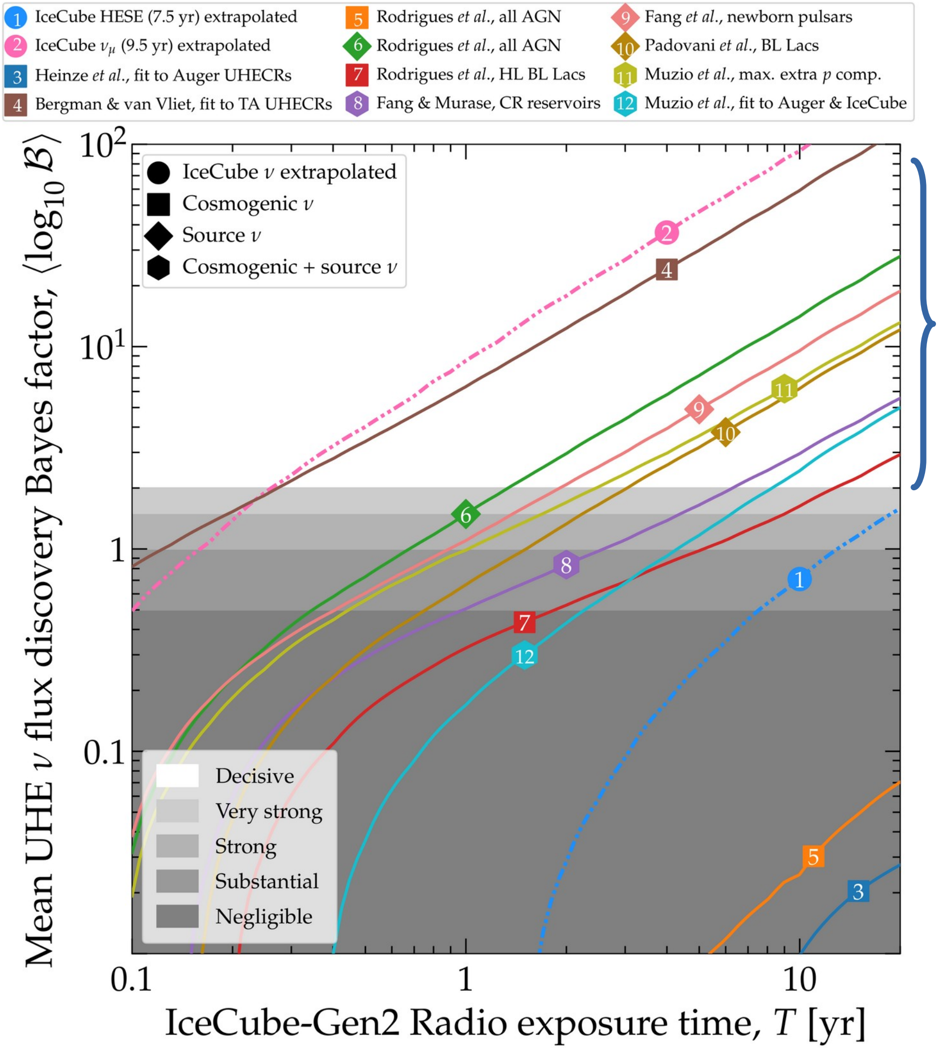
Discovering the diffuse flux of UHE neutrinos



Valera, **MB**, Glaser, *PRD* 2023

Discovering the diffuse flux of UHE neutrinos

Bayes factor compares signal+bkg. *vs.* bkg.-only



Large Bayes factor
=
decisive flux discover

Valera, **MB**, Glaser, *PRD* 2023

Discovering the diffuse flux of UHE neutrinos

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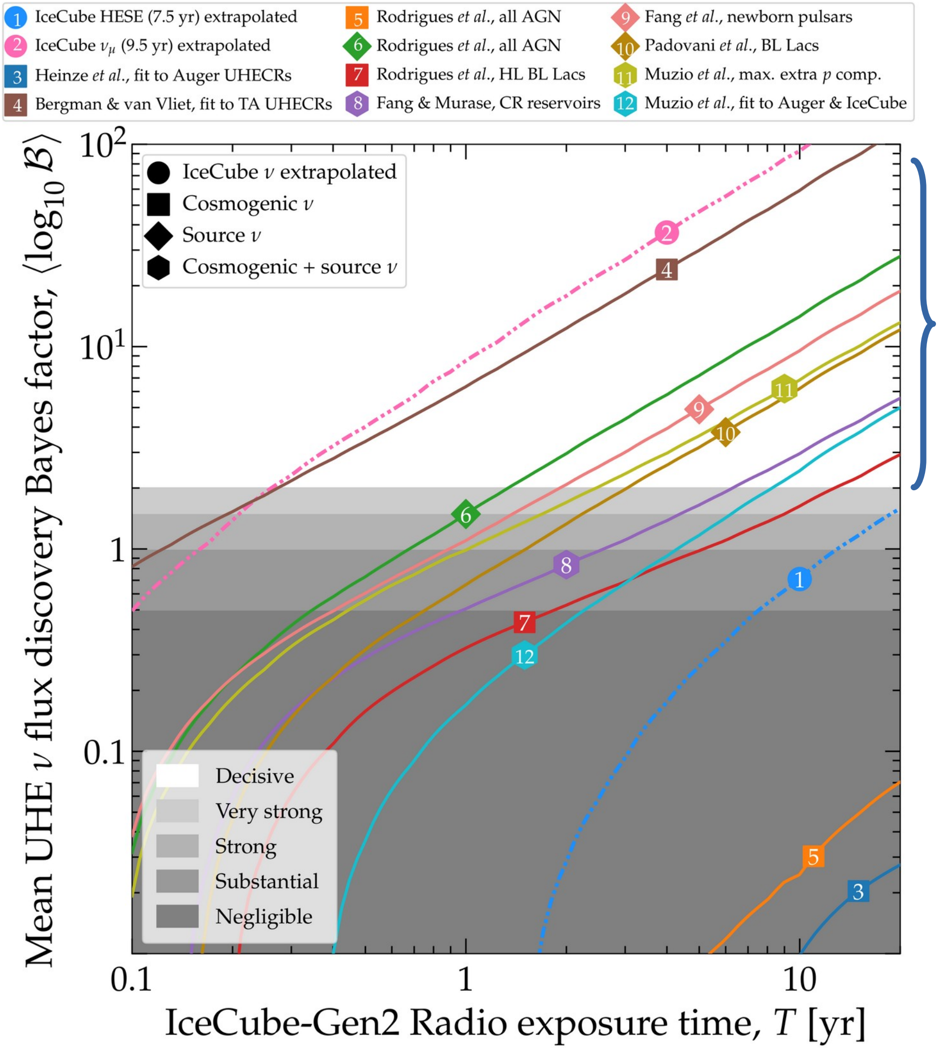


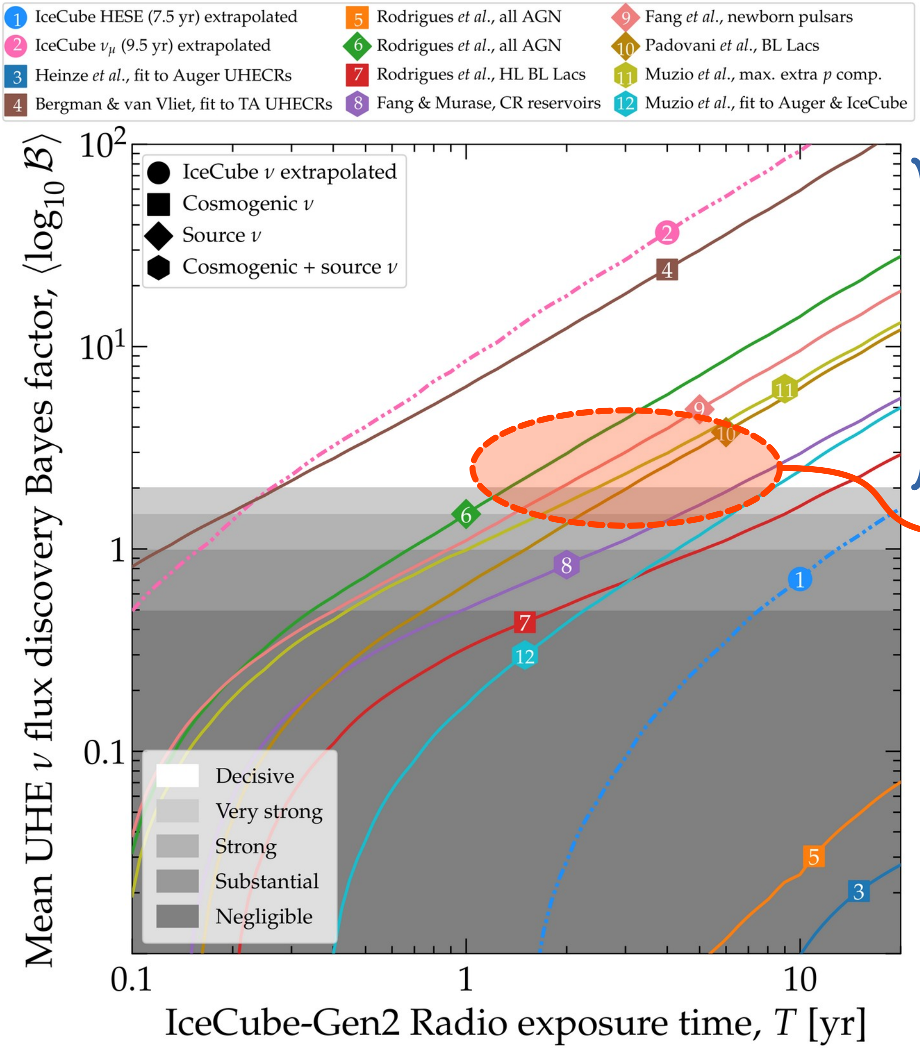
Large Bayes factor
=
decisive flux discover

Forecasts are state-of-the-art:
- Neutrino propagation inside Earth
- Detailed simulation of radio in ice
- Detailed antenna response
- Detector energy & angular resolution
- Statistical fluctuations

Valera, **MB**, Glaser, *PRD* 2023

Discovering the diffuse flux of UHE neutrinos

Bayes factor compares signal+bkg. *vs.* bkg.-only



Large Bayes factor = decisive flux discover

Most flux models are discoverable with a few years

Forecasts are state-of-the-art:
- Neutrino propagation inside Earth
- Detailed simulation of radio in ice
- Detailed antenna response
- Detector energy & angular resolution
- Statistical fluctuations

Valera, **MB**, Glaser, *PRD* 2023

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

Today

TeV–PeV ν

Turn predictions
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<u>Key developments</u>:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Today

TeV–PeV ν

Turn predictions
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Key developments:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

Next decade

$>$ 100-PeV ν

Make predictions for
a new energy regime

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TeV–PeV ν

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Bigger detectors → larger statistics
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Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
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Key developments:
Discovery
New detection techniques
Better UHE ν flux predictions

Today

TeV–PeV ν

Turn predictions
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<u>Key developments</u>:
Bigger detectors → larger statistics
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Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
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<u>Key developments</u>:
Discovery
New detection techniques
Better UHE ν flux predictions

Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
a new energy regime

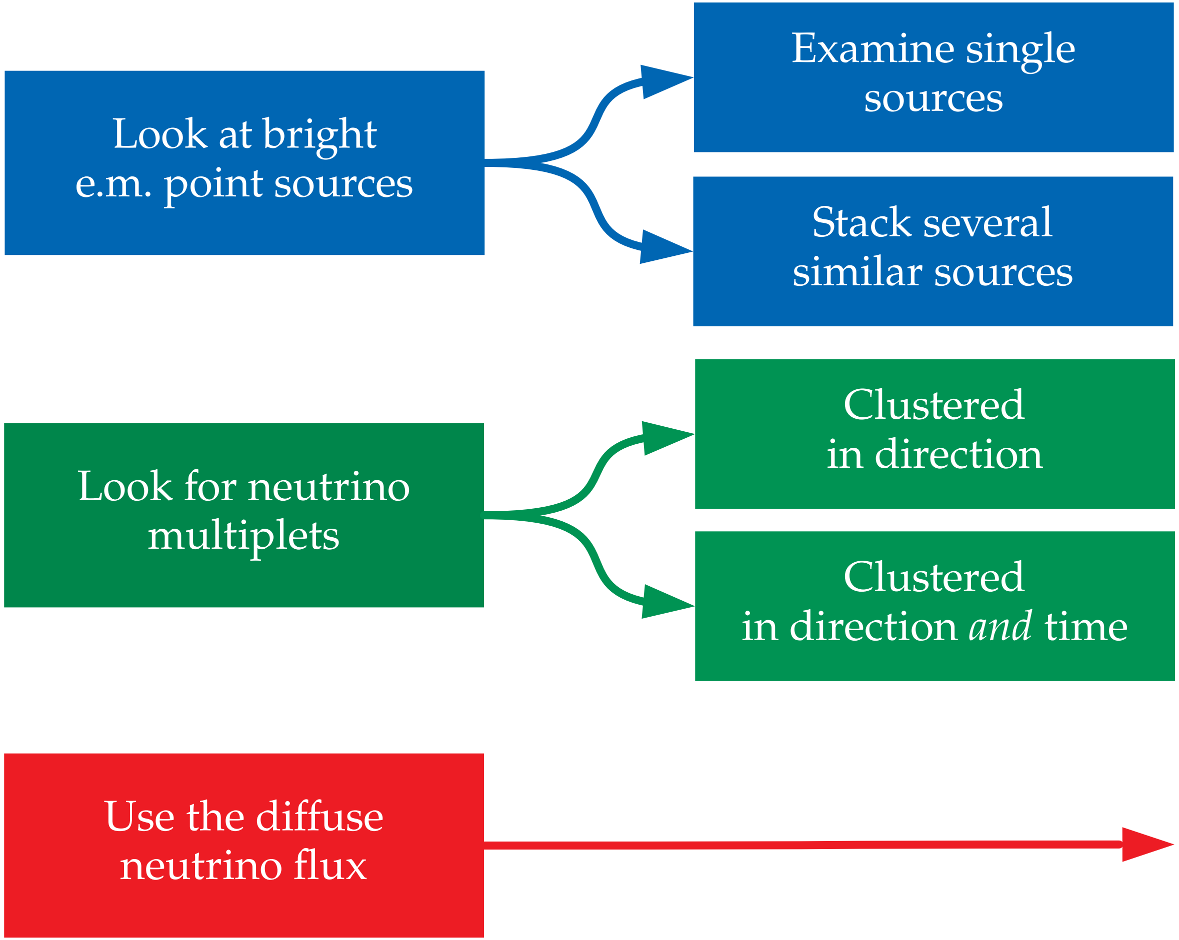
Key developments:
Discovery
New detection techniques
Better UHE ν flux predictions

Similar to the evolution of cosmology to a high-precision field in the 1990s

Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

Backup slides

Three Strategies to Reveal Sources Using 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

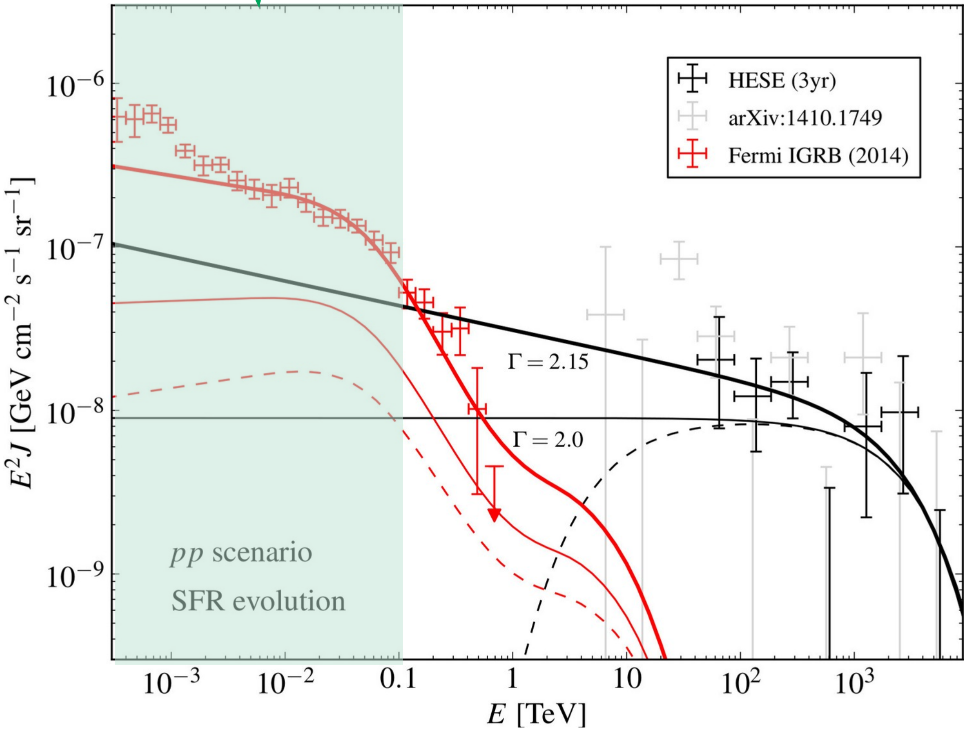
Use the diffuse neutrino flux

Any population of candidate sources must account for all or part of it

Constraints from the gamma-ray background

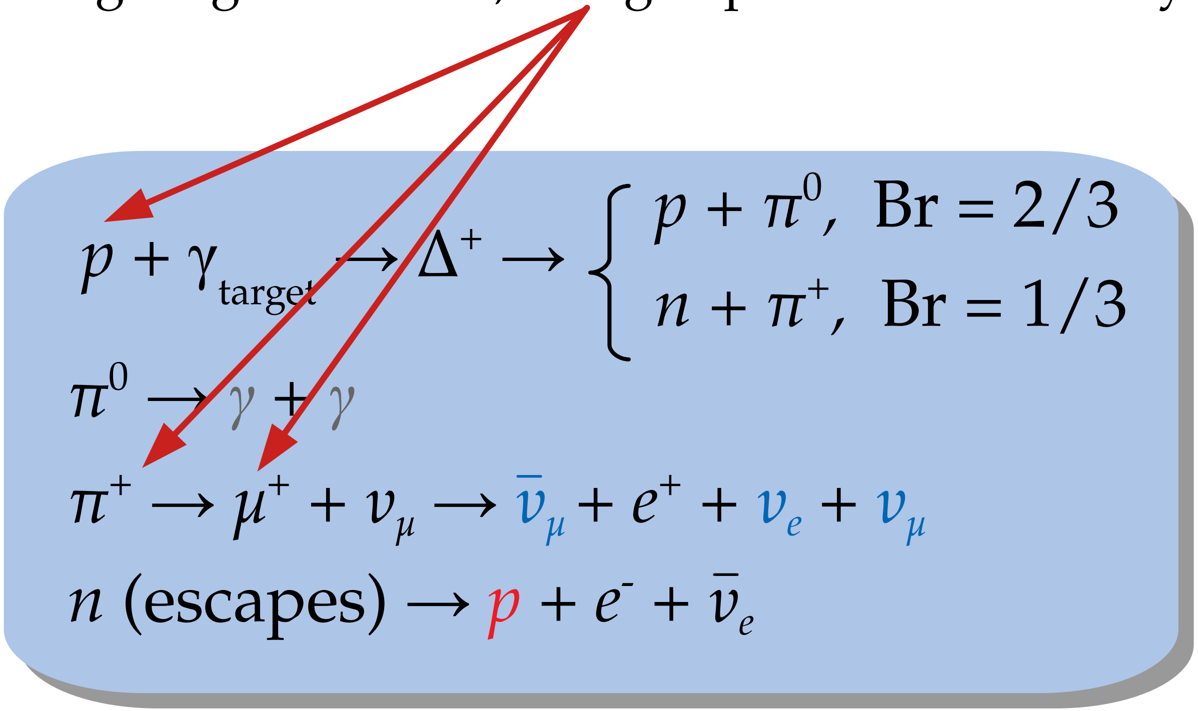
- Production via *pp*: ν and gamma-ray spectra follow the CR spectrum $E^{-\Gamma}$
- Gamma-ray interactions on the CMB make them pile up at GeV
- *Fermi* gamma-ray background is not exceeded only if $\Gamma < 2.2$
- But IceCube found Γ = 2.5–2.7
- Therefore, production via *pp* is disfavored between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

Murase, Ahlers, Lacki, *PRD* 2013



Using high-energy neutrinos as magnetometers

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



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

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

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

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

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

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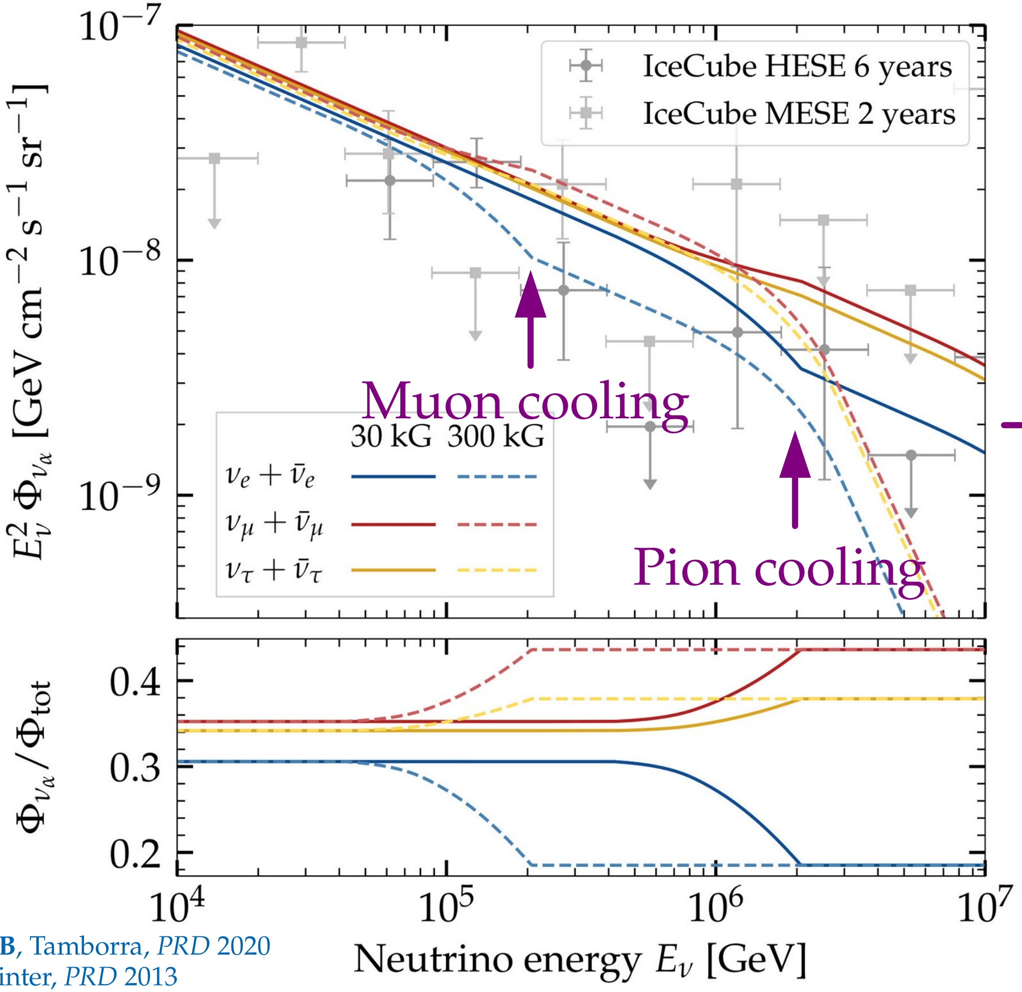

Muon cooling

Pion cooling

→ Proton cooling

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

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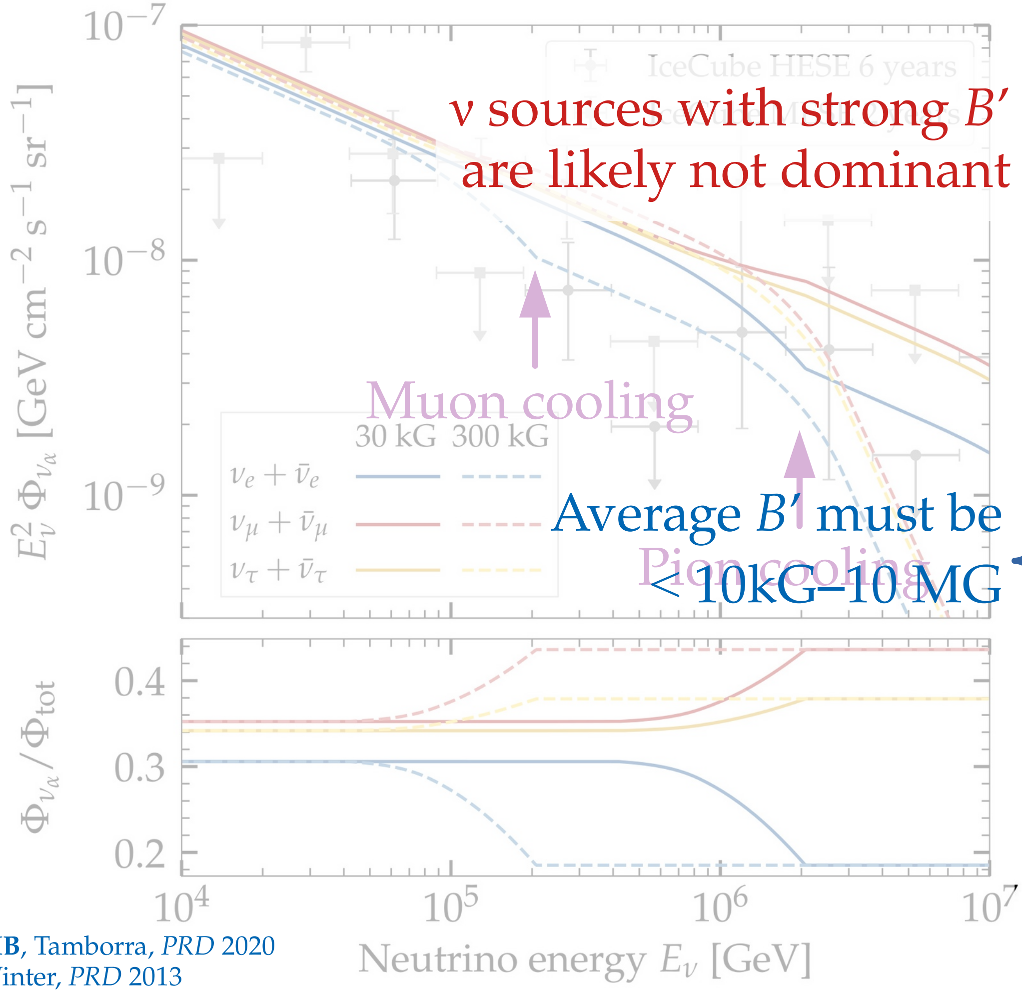
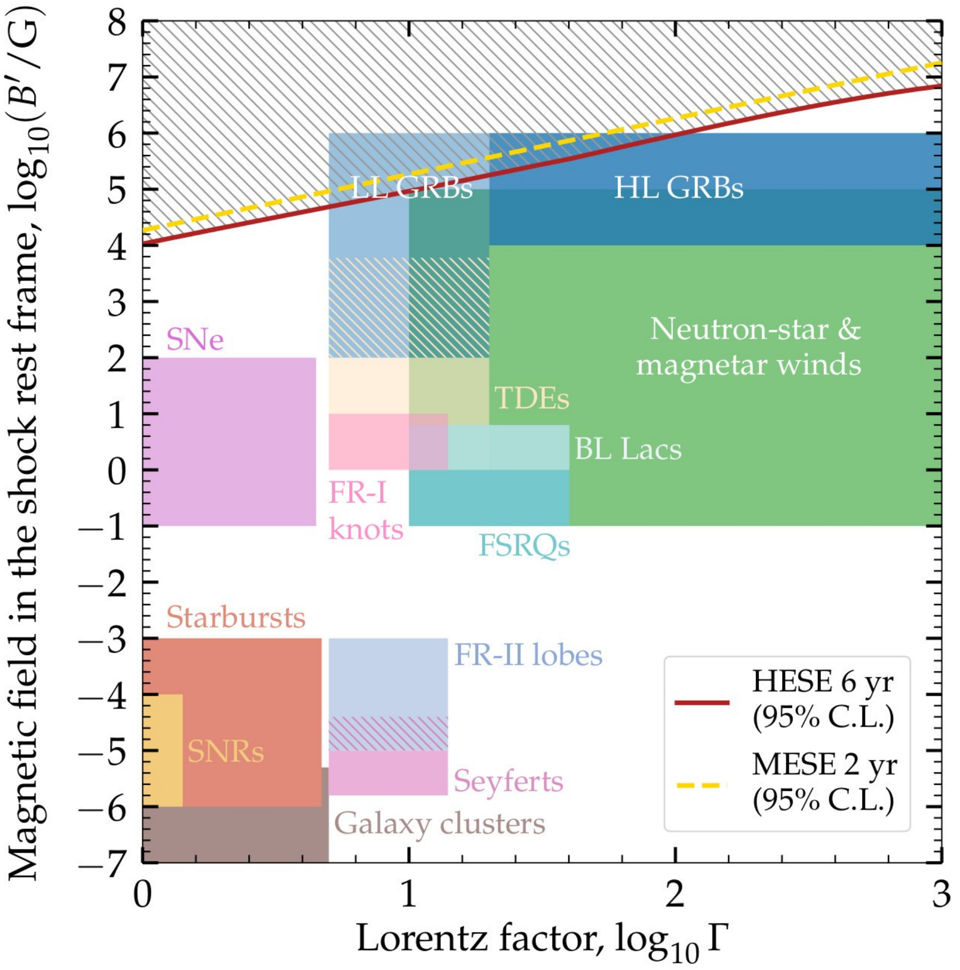


ν sources with strong B' are likely not dominant

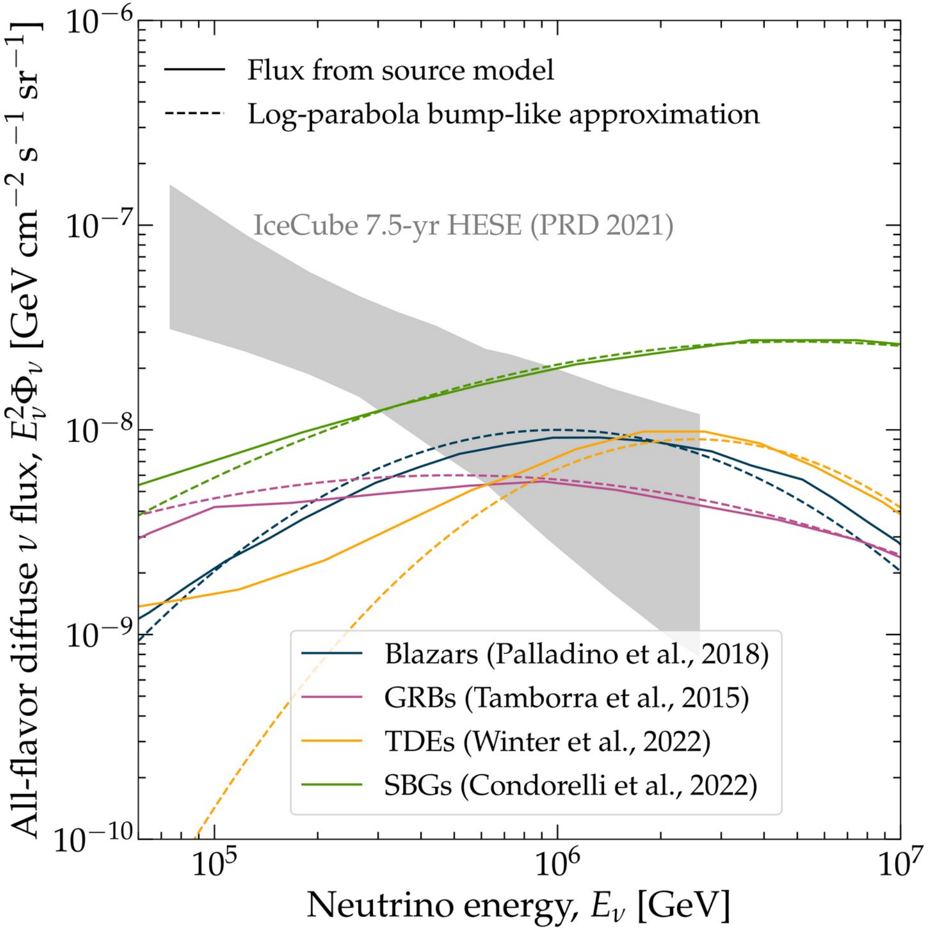
Average B' must be $<$ 10kG–10 MG



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

Bump-hunting in the diffuse flux of high-energy neutrinos

Bump-like spectra can reveal the presence of ν production via $p\gamma$:



Fiorillo, **MB**, *PRD* 2023

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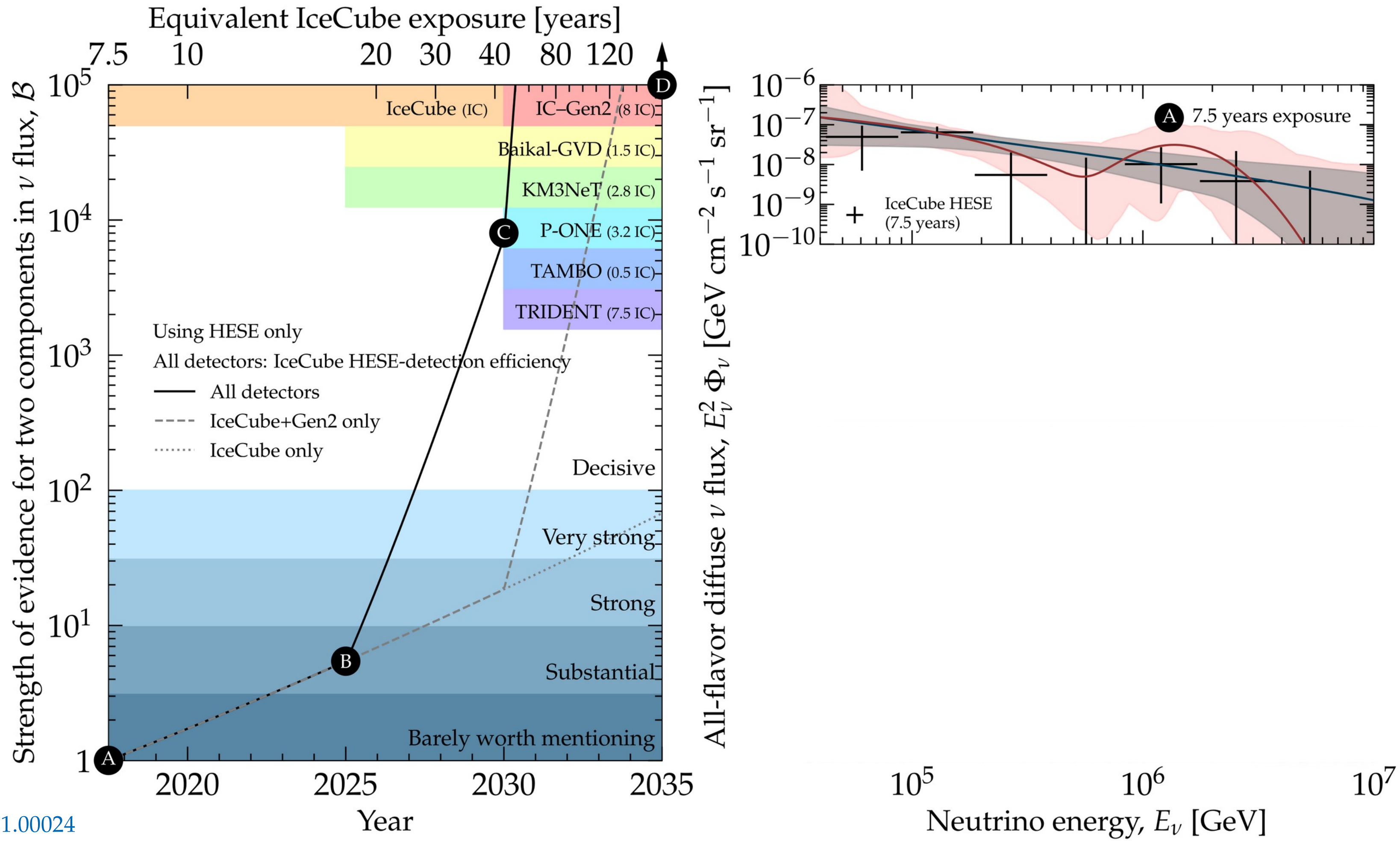

Fiorillo, **MB**, 2301.00024

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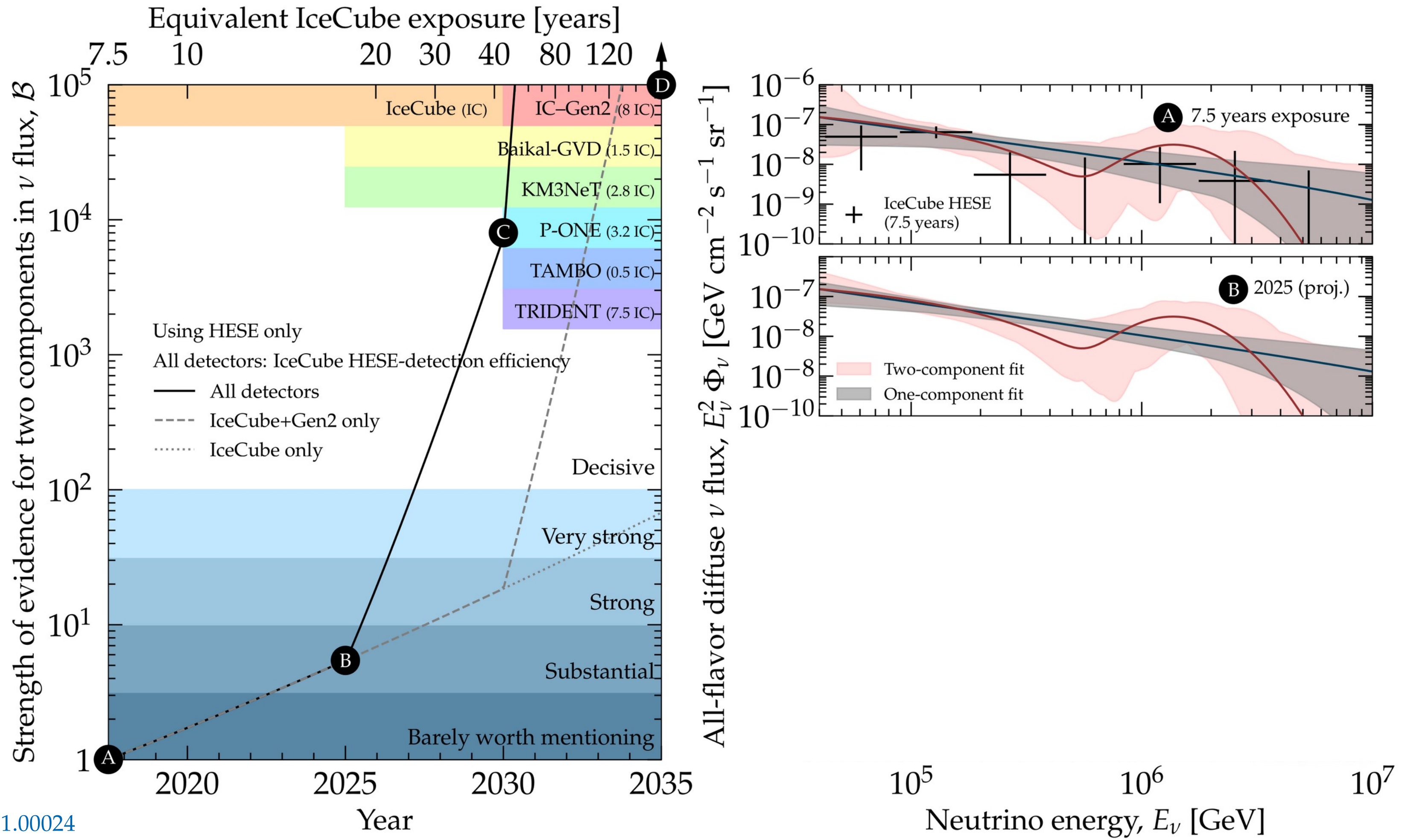

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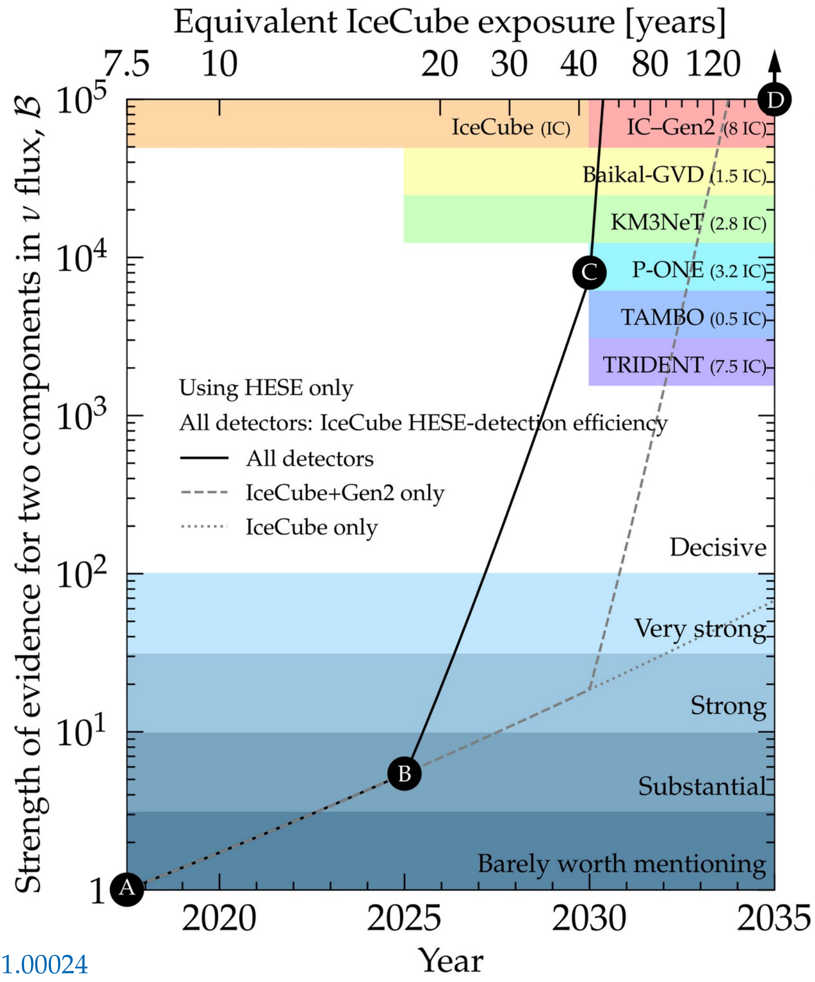

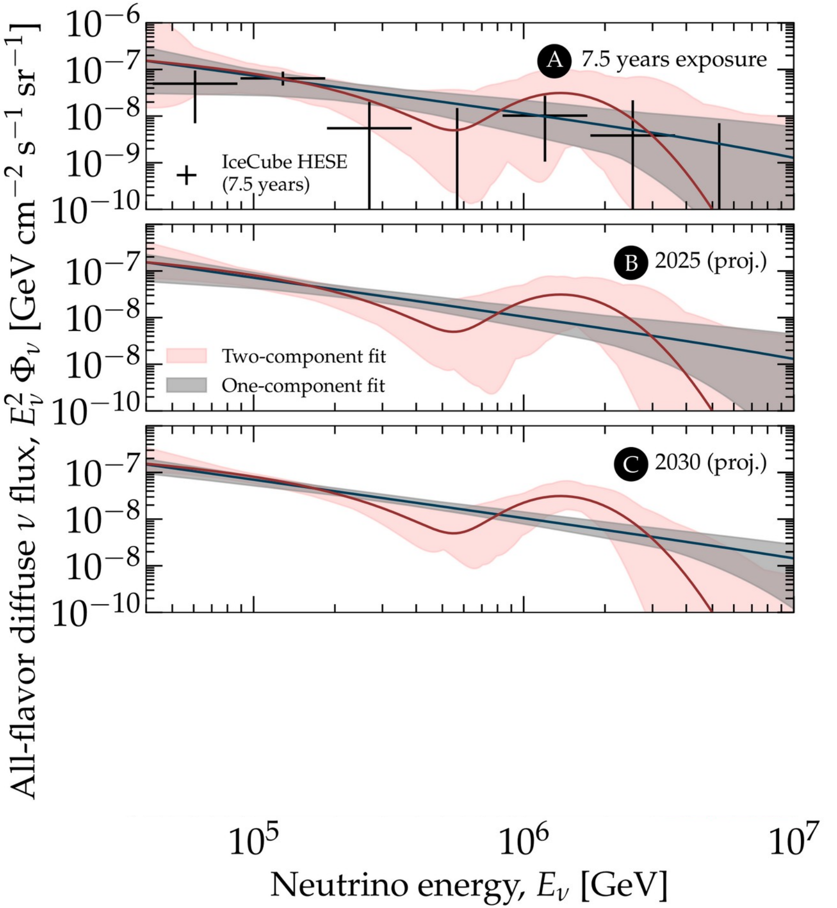

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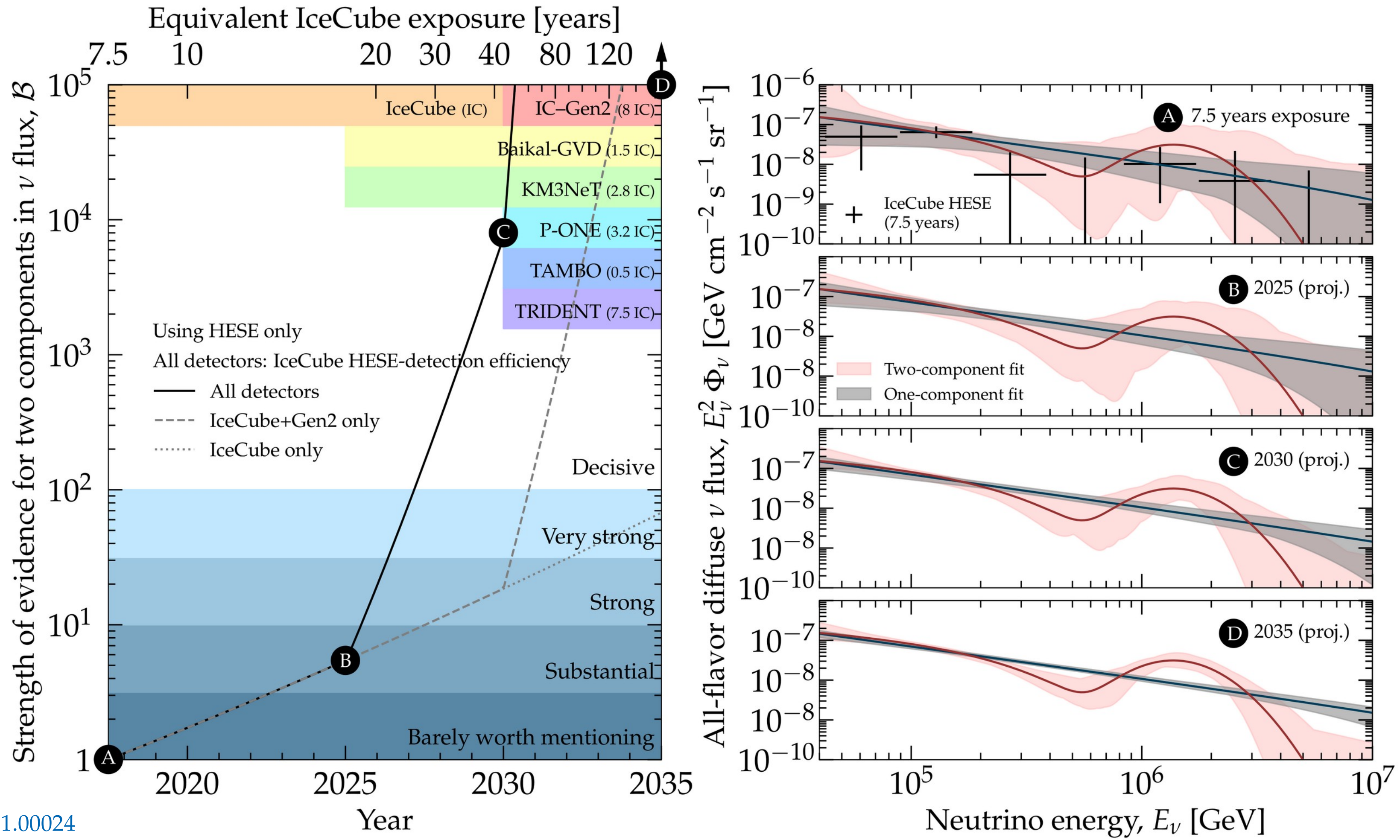


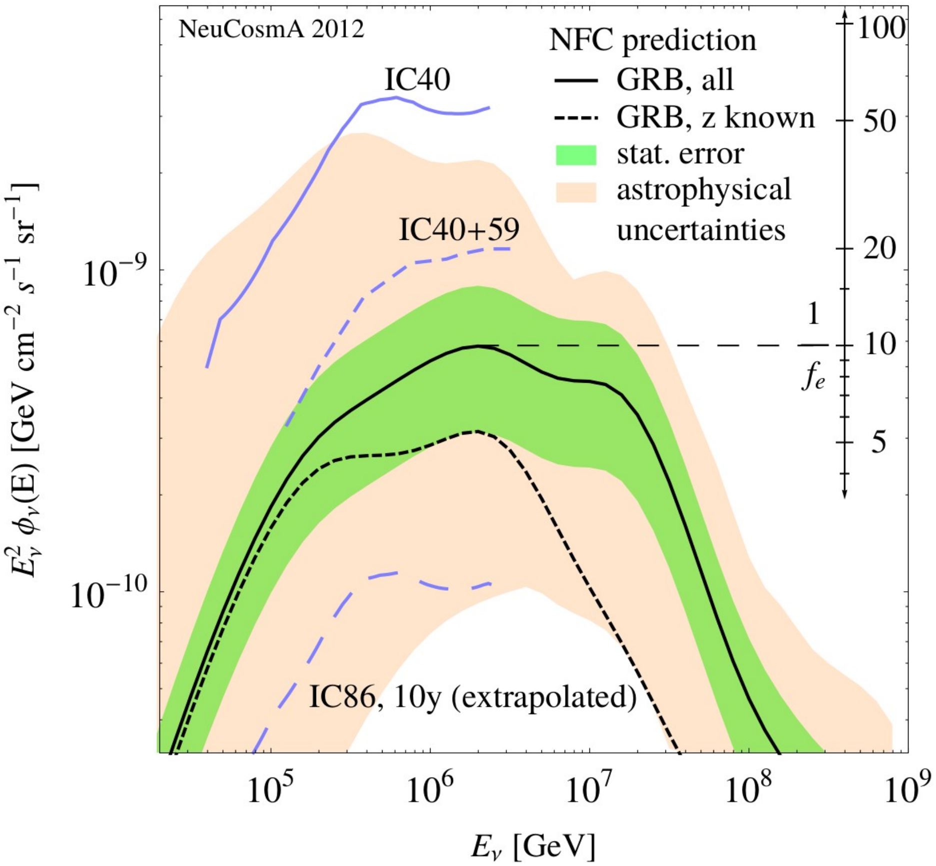
Fiorillo, **MB**, 2301.00024

Diffuse flux of neutrinos from GRBs

- How do we estimate it?
- Compute the expected ν fluence from a sample of N_{obs} observed GRBs
- Stack the fluences to obtain the total F_ν
- Quasi diffuse flux:

$$\phi_\nu(E_\nu) = F_\nu(E_\nu)\,\frac{1}{4\pi}\,\frac{1}{N_{\rm obs}}\,\frac{667\ \text{bursts}}{\text{yr}}$$

(N_{obs} = 117 in the plot)



S. Hümmer, P. Baerwald, & W. Winter, *PRL* 2012

Are GRBs still good UHECR source candidates?

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

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

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

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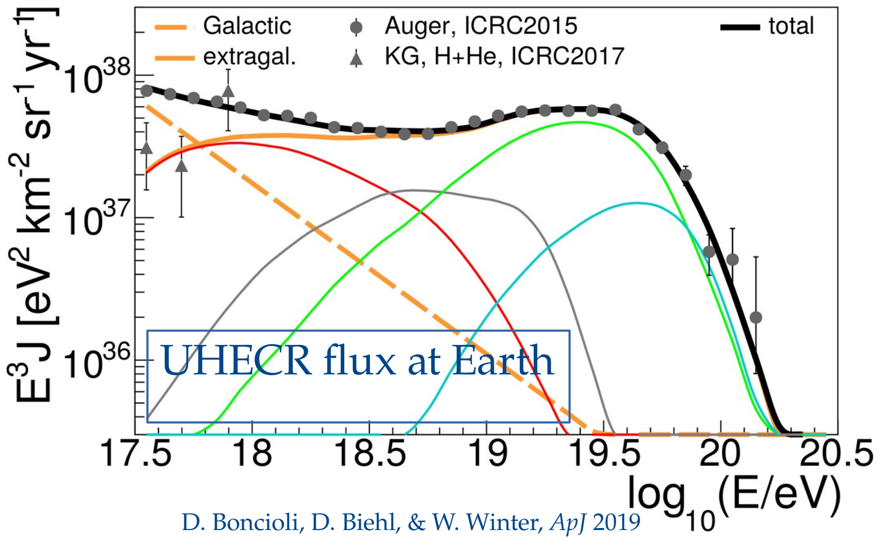
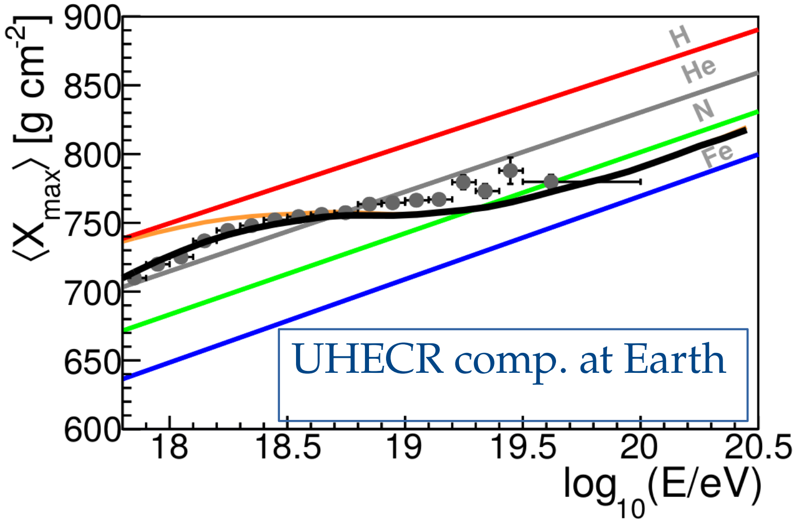


UHECR flux at Earth

D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019



UHECR comp. at Earth

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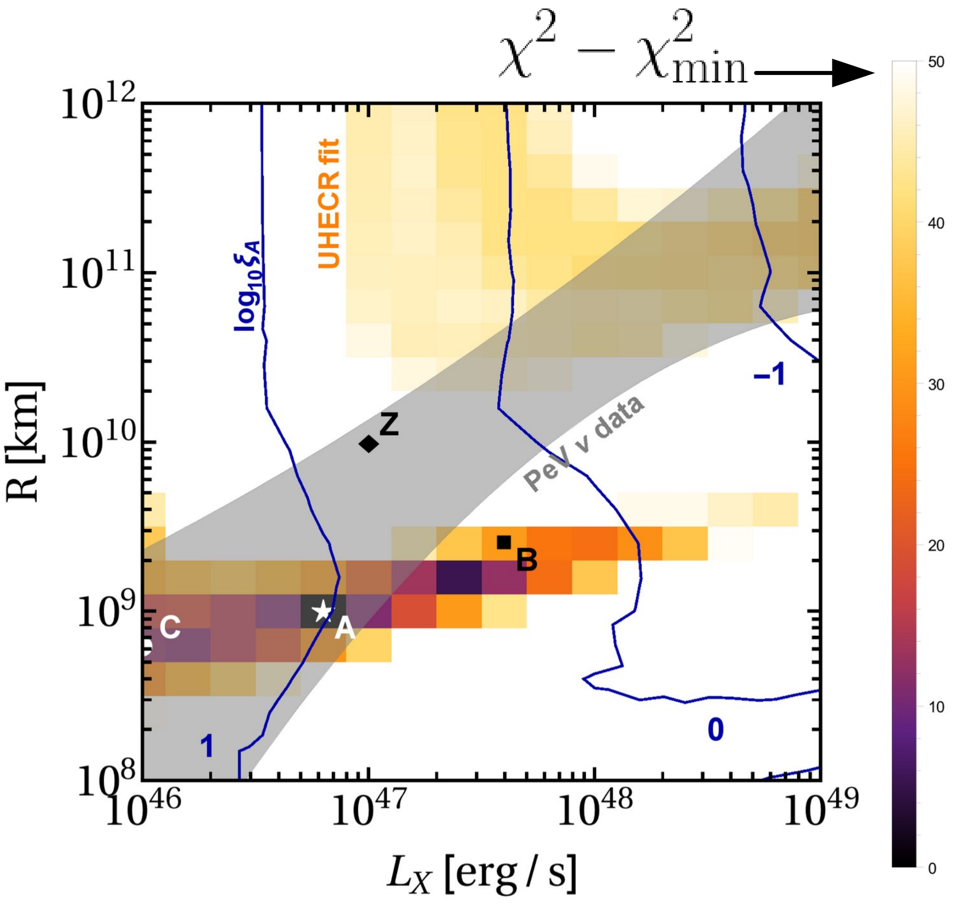


D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

Neutrino zenith angle distribution

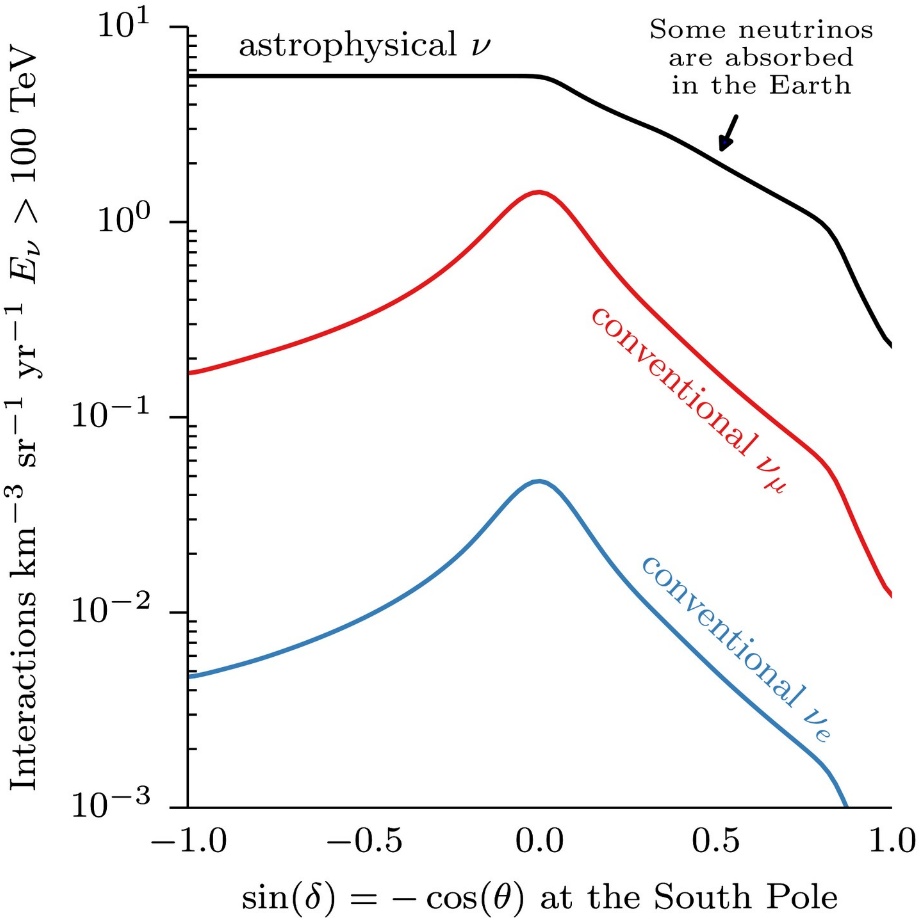
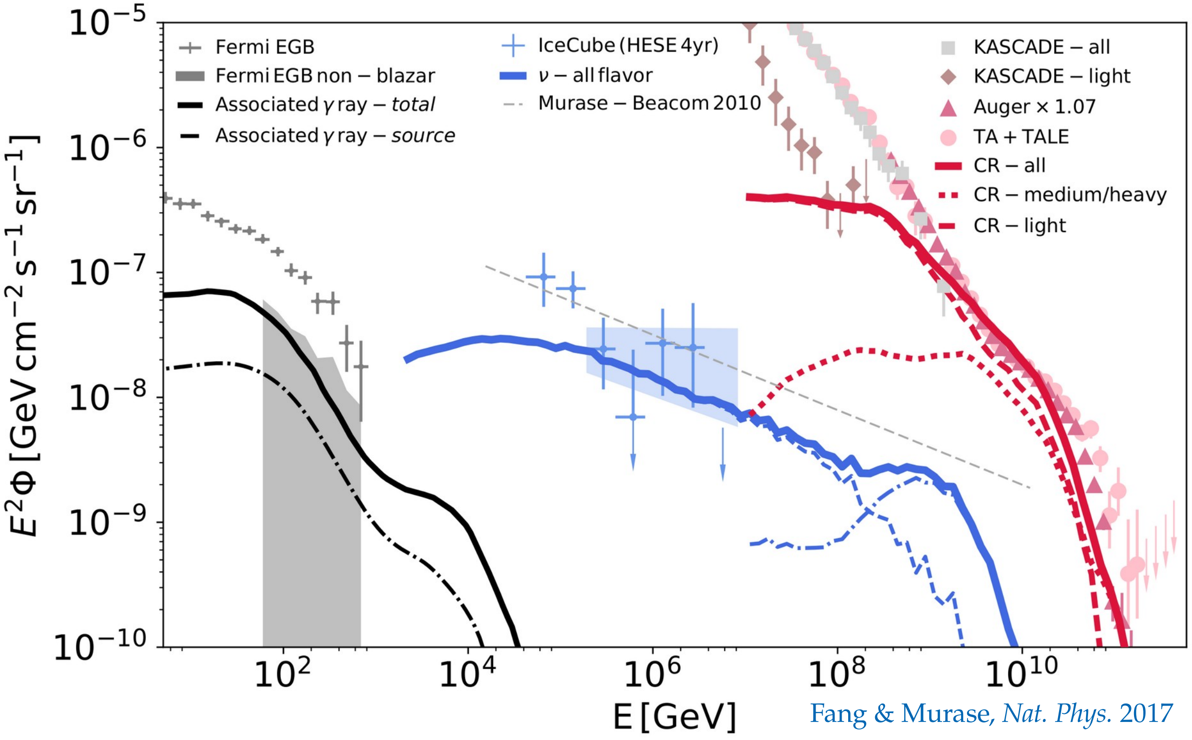


Figure by
Jakob Van Santen
ICRC 2017

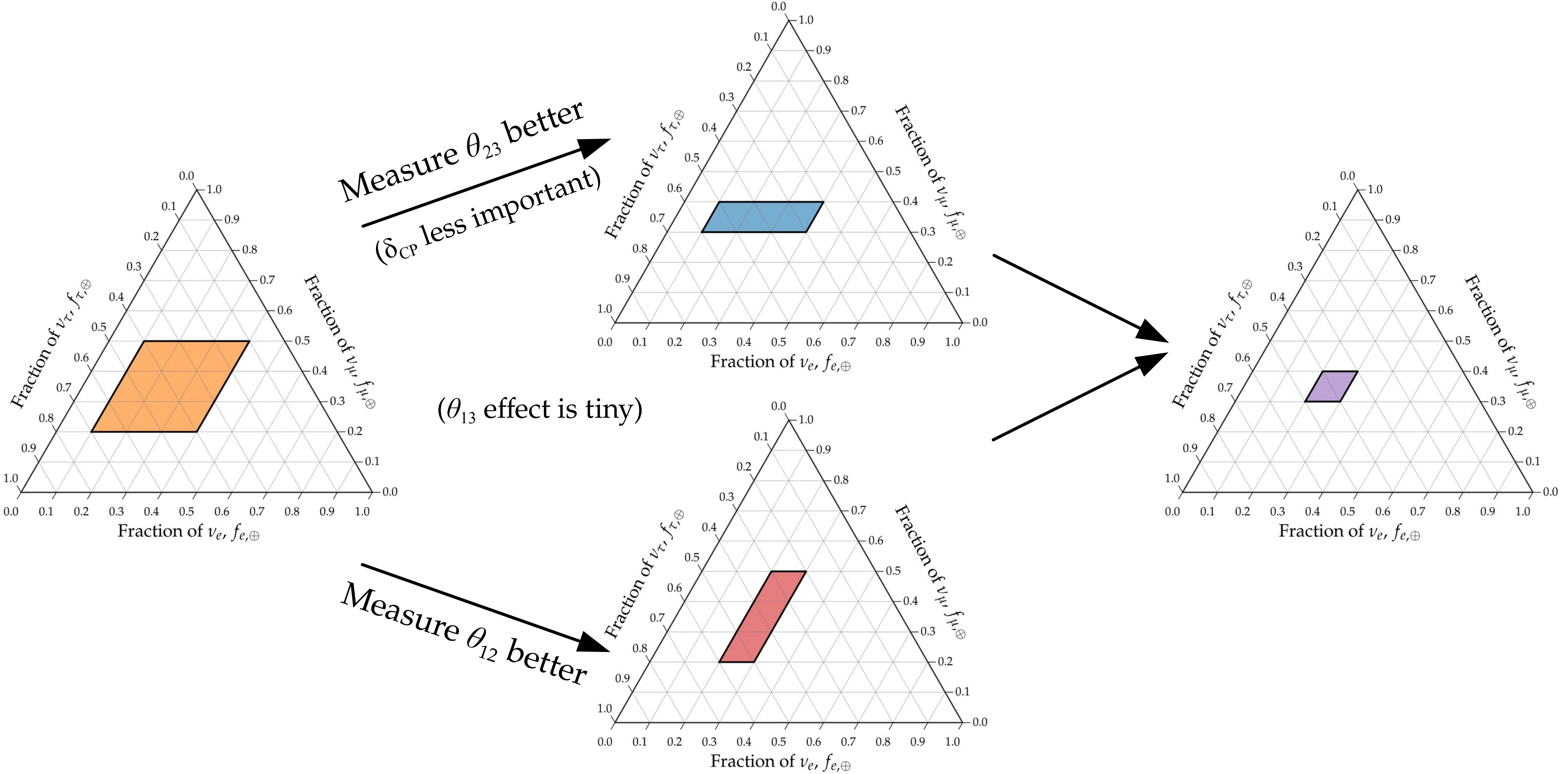
Grand-unified ν–UHECR–gamma-ray model

- Black-hole jets in galaxy clusters accelerate cosmic rays
- UHECRs make ν and γ in the magnetized cluster medium
- UHECRs above 0.1 EeV escape
- Consistent w/ observed UHECR spectrum, composition, isotropy
- Explains IceCube neutrinos
- Explains non-blazar *Fermi* EGB



Fang & Murase, *Nat. Phys.* 2017

How knowing the mixing parameters better helps



Measure θ_{23} better

(δ_{CP} less important)

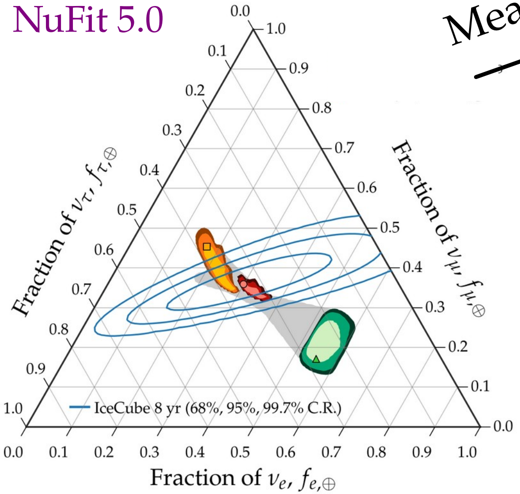
(θ_{13} effect is tiny)

Measure θ_{12} better

How knowing the mixing parameters better helps

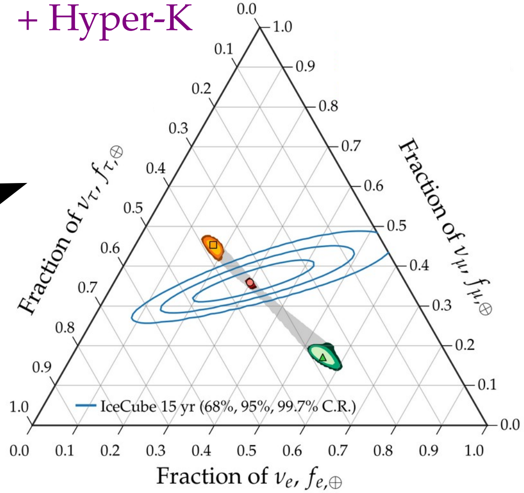
2020

NuFit 5.0

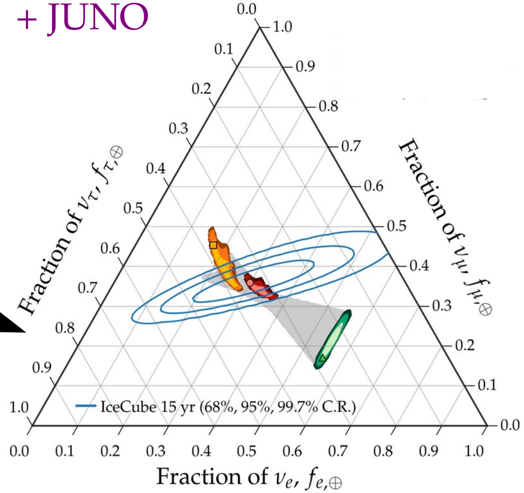


Measure θ_{23} better

+ Hyper-K



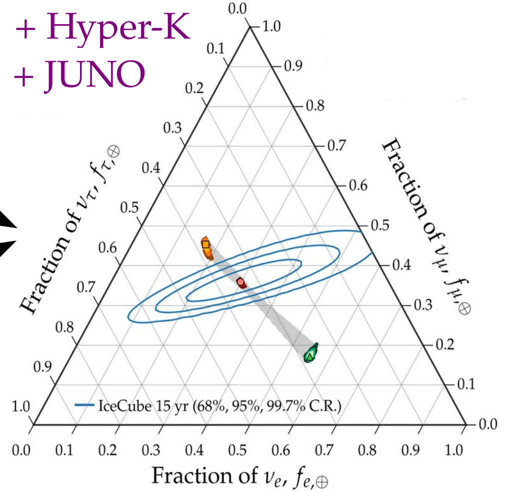
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO

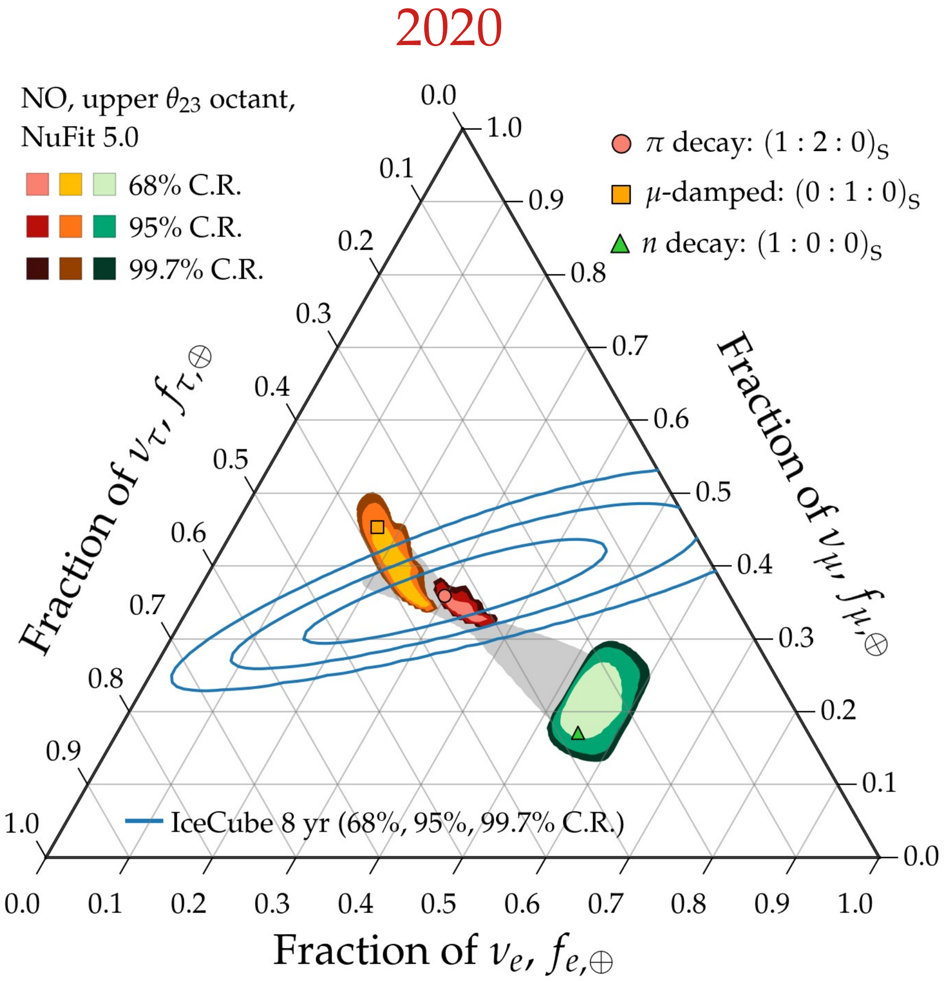


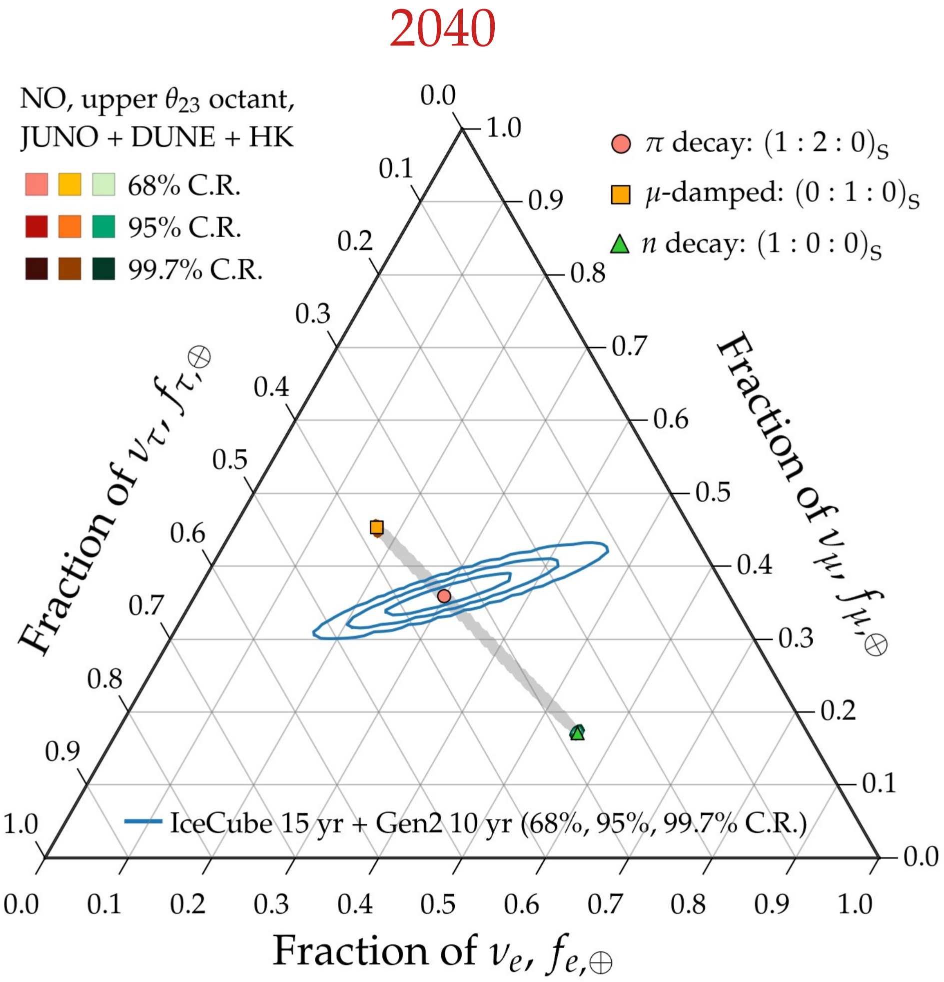
In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

Theoretically palatable regions: 2020 → 2040





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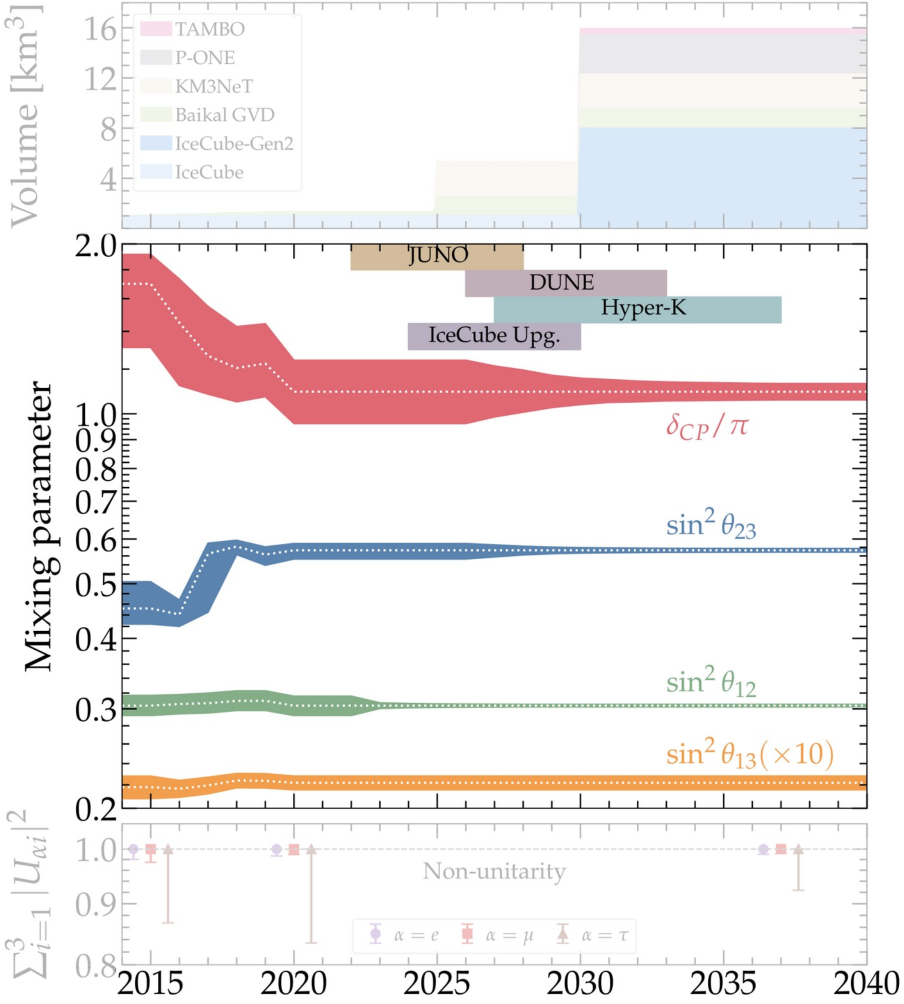

We can compute the oscillation probability more precisely:

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

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

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

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Ingredient #1:

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

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

or

Explore all possible combinations

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

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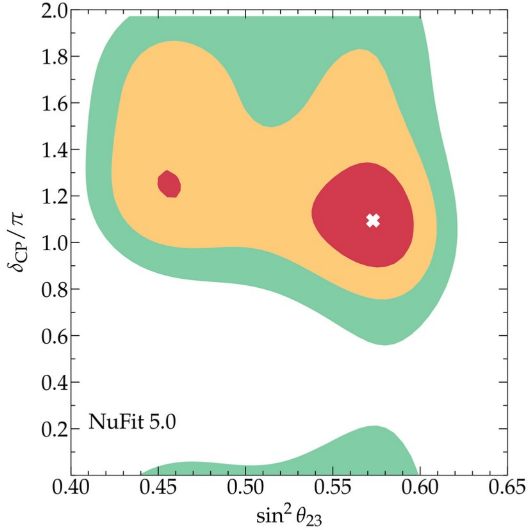
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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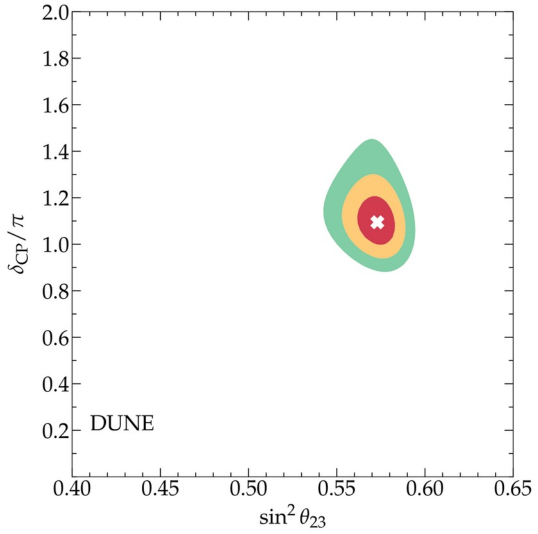
www.nu-fit.org

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

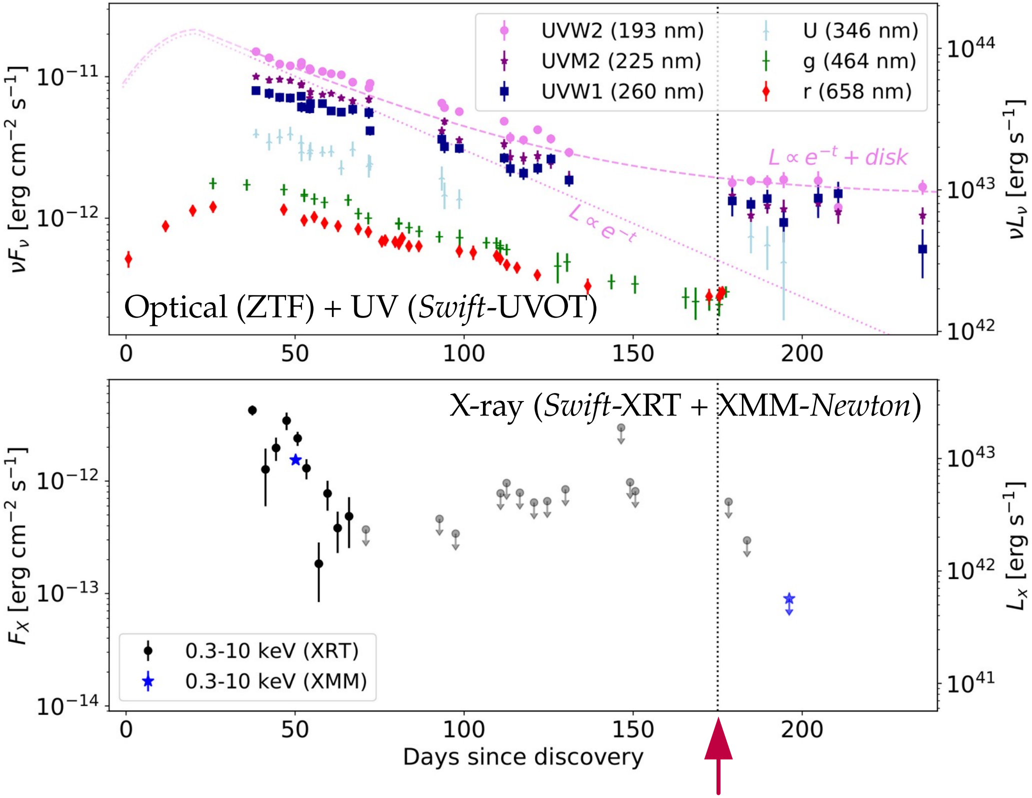
An *et al.*, *J. Phys. G* 2016
DUNE, 2002.03005
Huber, Lindner, Winter, *Nucl. Phys. B* 2002



An apparent TDE neutrino source

Radio-emitting TDE AT2019dsg coincident with neutrino event IC191001A:

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

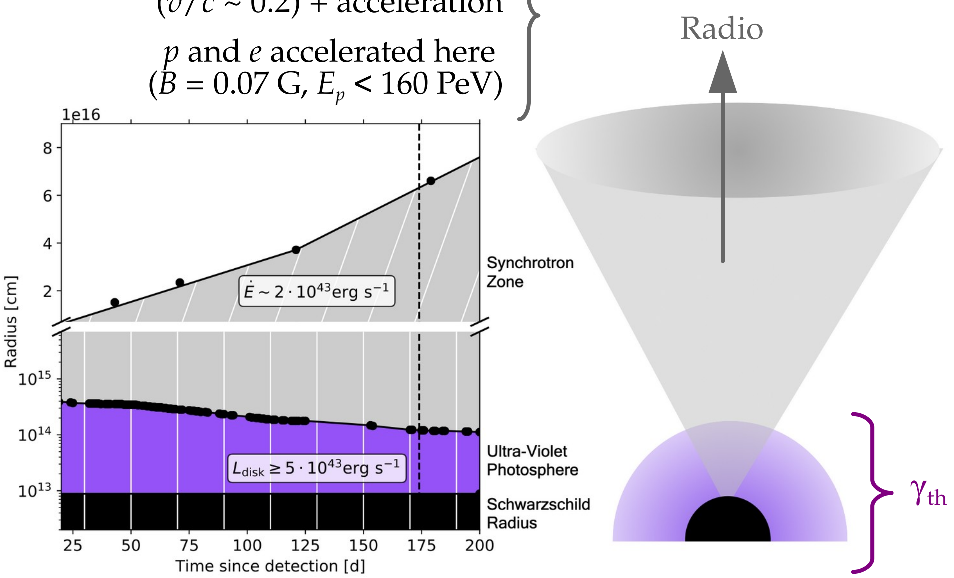


IC191001A, ~200 TeV

Multi-zone model:

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

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



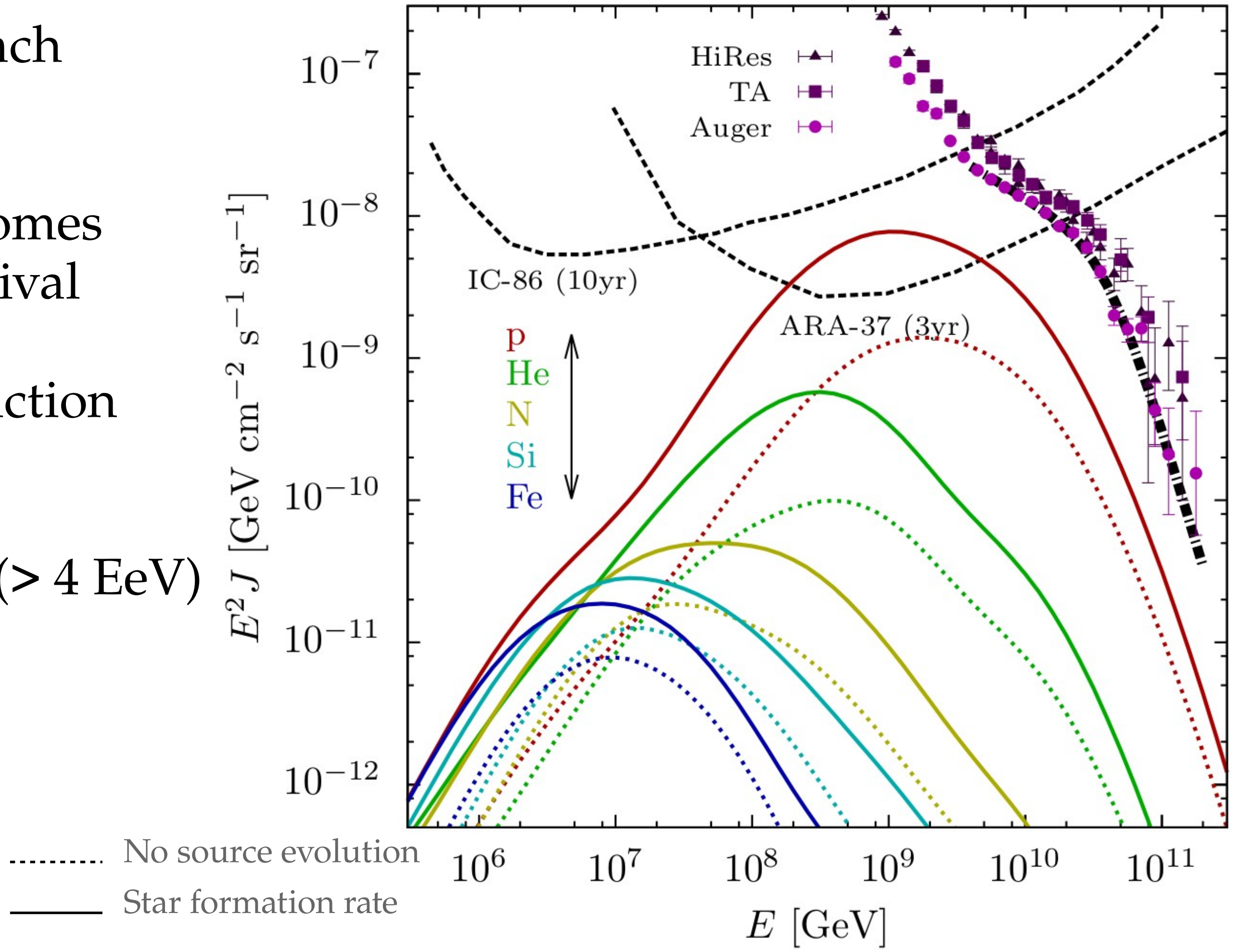
$$p + \gamma_{\rm th}\ (\text{or } p) \rightarrow \nu$$

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

The Cosmogenic Neutrino Floor

- In a nucleus A of energy E, each nucleon has energy E/A
- Minimal cosmogenic ν flux comes from maximizing nuclei survival
- *I.e.*, from minimizing p production from photo-disintegration
- ν fluxes from UHECR nuclei (> 4 EeV) are presently beyond reach

Ahlers & Halzen, *PRD* 2012



Many TeV–EeV
ν telescopes
in planning for
2020–2040

				Flavor		Technique			Neutrino Target					Geometry					
Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
KM3NeT	2021	TeV-PeV	Mediteranean		✓	✓			✓					✓					
Baikal-GVD	2021	TeV-PeV	Lake Baikal		✓	✓			✓					✓					
P-ONE	2020	TeV-PeV	Pacific Ocean		✓	✓			✓					✓					
IceCube-Gen2	2030+	TeV-EeV	South Pole		✓	✓	✓		✓					✓					
ARIANNA	2014	>30 PeV	Moore's Bay		✓		✓		✓					✓					
ARA	2011	>30 PeV	South Pole		✓		✓		✓					✓					
RNO-G	2021	>30 PeV	Greenland		✓		✓		✓					✓					
RET-N	2024	PeV-EeV	Antarctica		✓		✓		✓					✓					
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
PUEO	2024	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
GRAND	2020	EeV	China / Worldwide	✓			✓			✓	✓	✓			✓		✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓			✓				✓	✓					✓		
TAROGE-M	2018	EeV	Antarctica	✓			✓				✓	✓					✓		
SKA	2029	>100 EeV	Australia		✓		✓						✓		✓				
Trinity	2022	PeV-EeV	Utah, USA	✓		✓					✓						✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓				✓	✓								✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓					✓							✓	
Pierre Auger	2008	EeV	Argentina	✓	✓			✓		✓	✓	✓			✓				
AugerPrime	2022	EeV	Argentina	✓	✓		✓	✓		✓	✓	✓			✓				
Telescope Array	2008	EeV	Utah, USA	✓	✓			✓		✓					✓				
TAx4		EeV	Utah, USA	✓	✓			✓											
TAMBO	2025-2026	PeV-EeV	Peru	✓				✓				✓				✓			

Operational	□	Date full operations began
Prototype	▒	Date protoype operations began or begin
Planning	▓	Projected full operations

Abraham *et al.* (inc. **MB**),
J. Phys. G: Nucl. Part. Phys. 59, 11 (2022) [2203.05591]