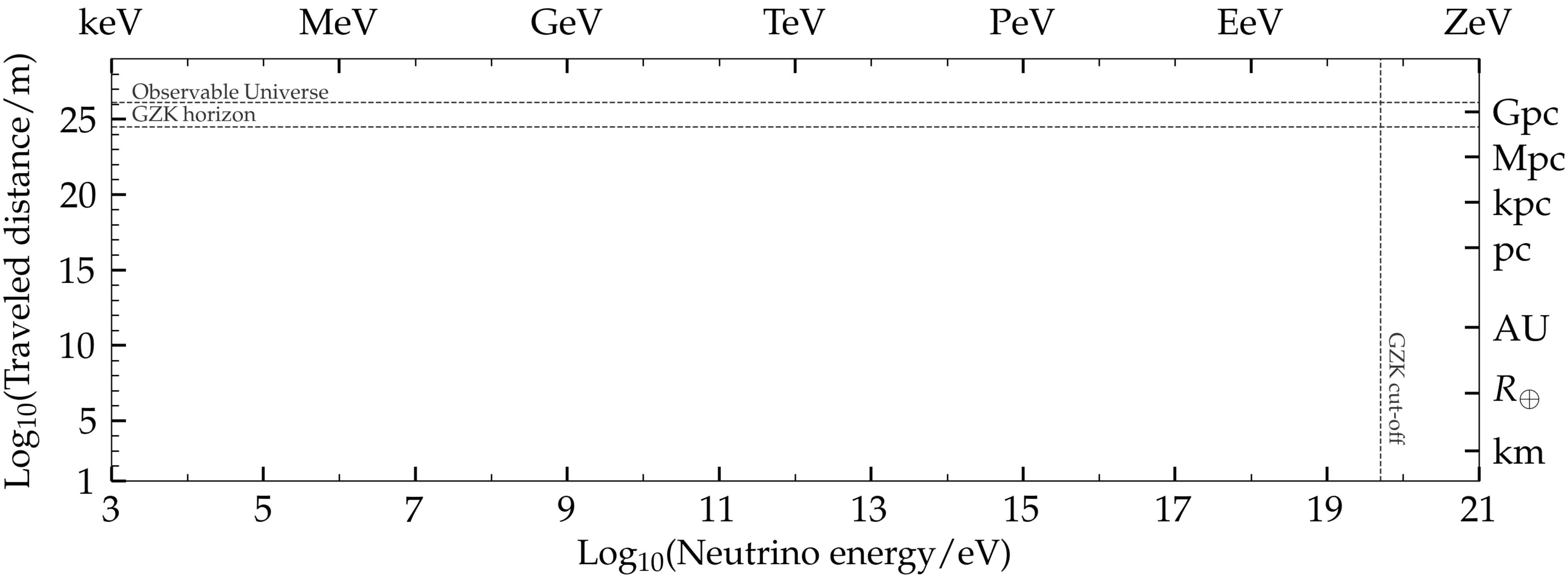
Beyond-the-Standard-Model physics from KM3-230213A and beyond

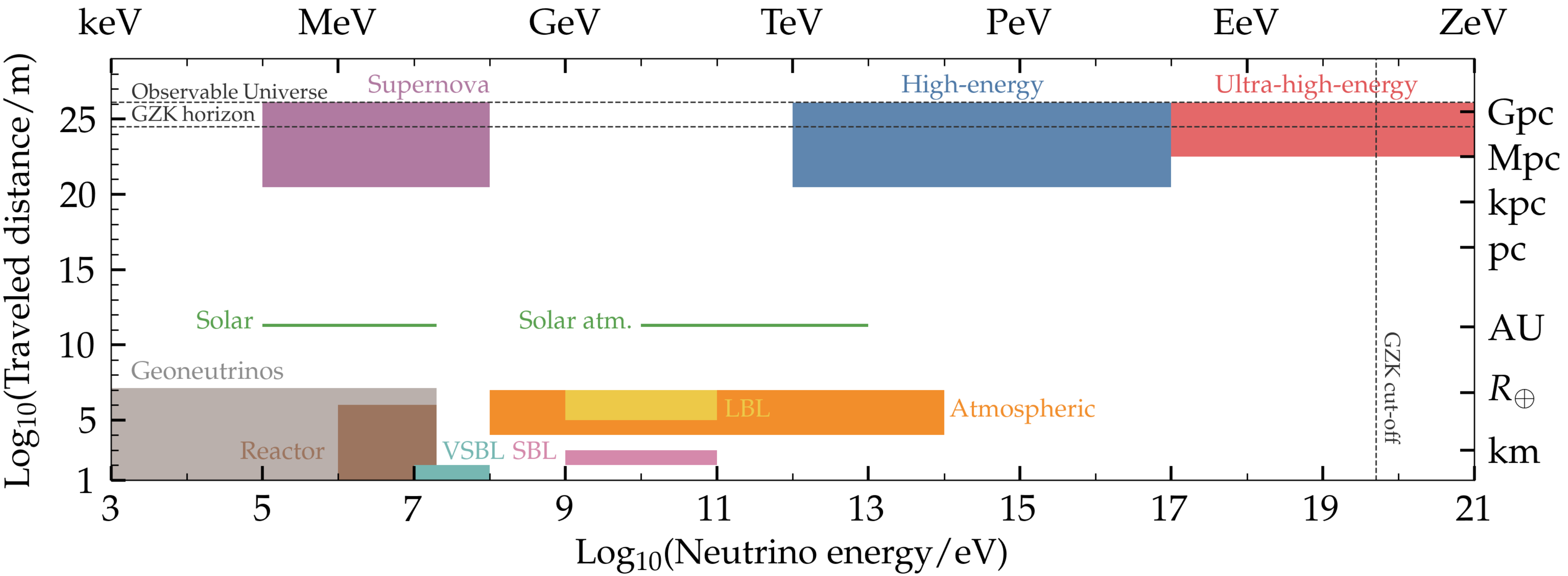
Mauricio Bustamante
Niels Bohr Institute, University of Copenhagen

UNIVERSITY OF COPENHAGEN
VILLUM FONDEN

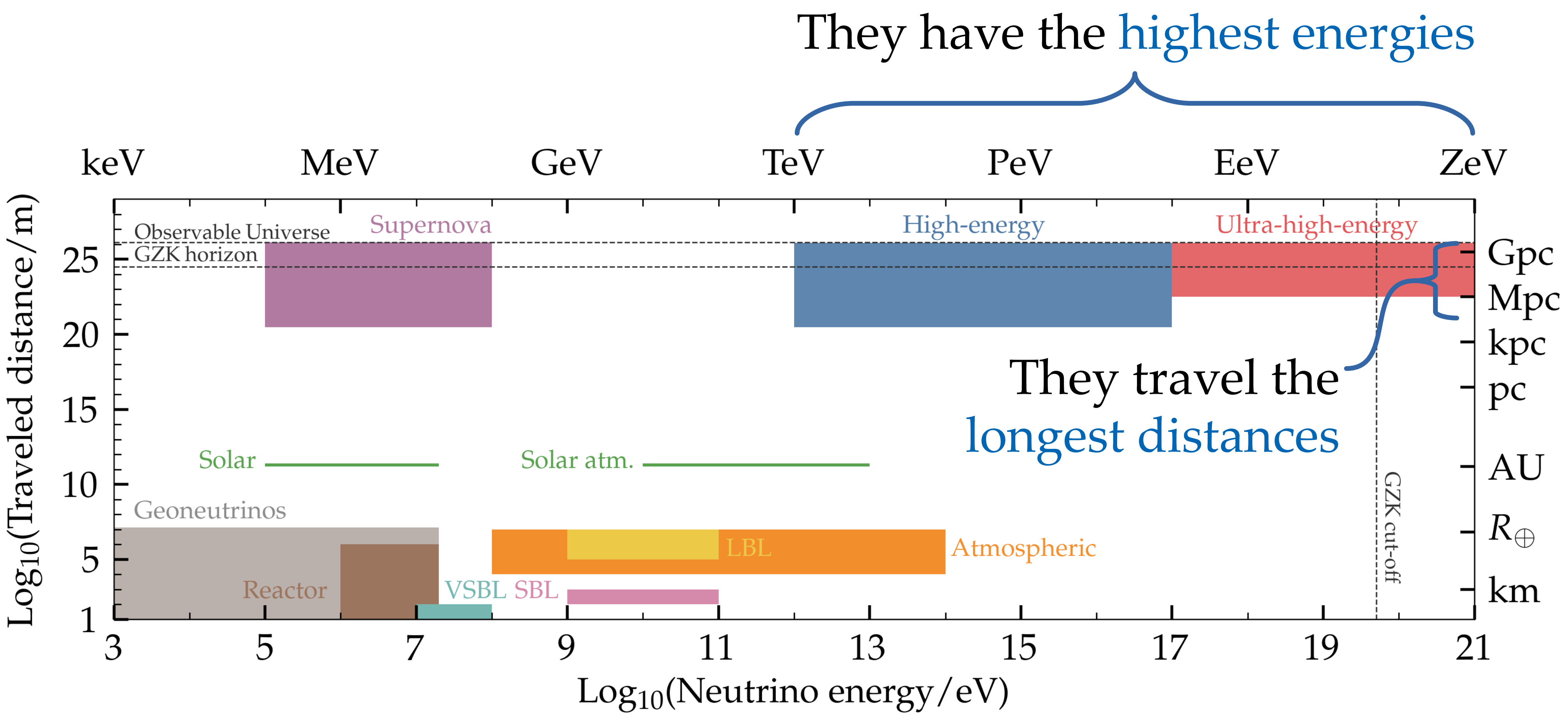
3rd Town Hall KM3NeT Meeting
Les Houches, April 16, 2025



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



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



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

Fundamental physics with high-energy cosmic neutrinos

Numerous new ν physics effects grow as ~ $\kappa_n \cdot E^n \cdot L$

If BSM effects are comparable in size to SM effects, then we can probe

$$\kappa_n \sim 10^{-47} \left(\frac{E}{\mathrm{PeV}} \right)^{-n} \left(\frac{L}{\mathrm{Gpc}} \right)^{-1} \mathrm{PeV}^{1-n}$$

With 1-PeV ν: $\kappa_2 \sim 10^{-47}$ PeV^{-1}

With 100-PeV ν: $\kappa_2 \sim 10^{-51}$ PeV^{-1}

Orders-of-magnitude improvement

Fundamental physics with high-energy cosmic neutrinos

Numerous new ν physics effects grow as ~ $\kappa_n \cdot E^n \cdot L$

E.g.,
n = -1: neutrino decay
n = 0: CPT-odd Lorentz violation
n = +1: CPT-even Lorentz violation

If BSM effects are comparable in size to SM effects, then we can probe

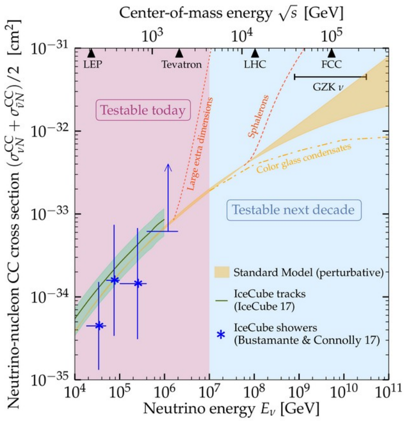
$$\kappa_n \sim 10^{-47} \left(\frac{E}{\mathrm{PeV}} \right)^{-n} \left(\frac{L}{\mathrm{Gpc}} \right)^{-1} \mathrm{PeV}^{1-n}$$

With 1-PeV ν: $\kappa_2 \sim 10^{-47}$ PeV^{-1}

With 100-PeV ν: $\kappa_2 \sim 10^{-51}$ PeV^{-1}

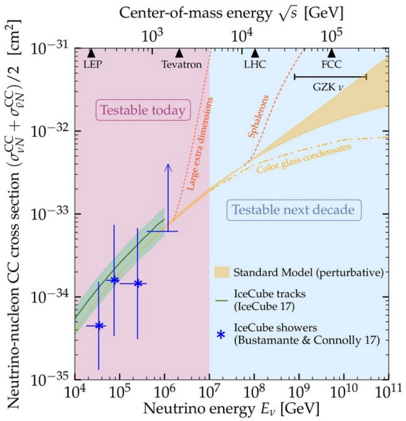
Orders-of-magnitude improvement

TeV–EeV ν cross sections



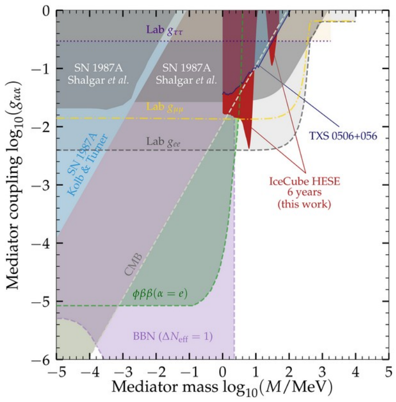
MB & Connolly, *PRL* 2019

TeV–EeV ν cross sections



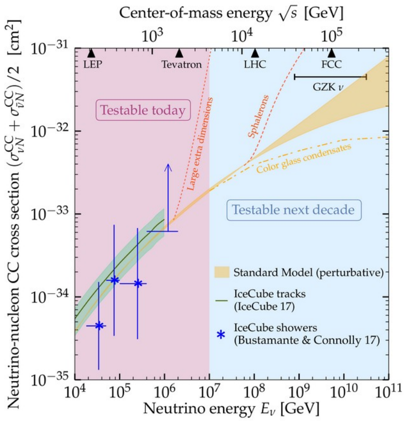
MB & Connolly, *PRL* 2019

ν self-interactions



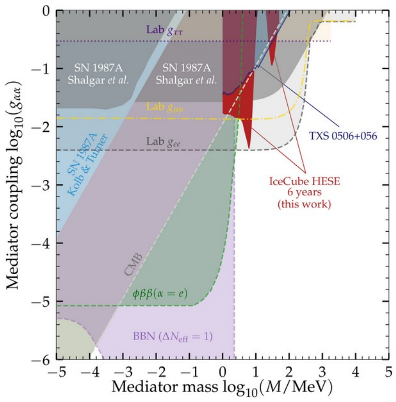
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

TeV–EeV ν cross sections



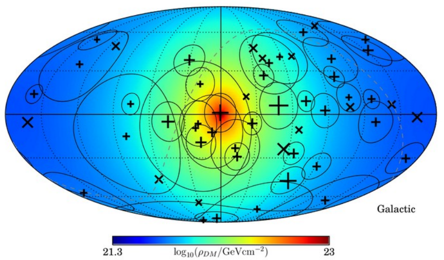
MB & Connolly, *PRL* 2019

ν self-interactions



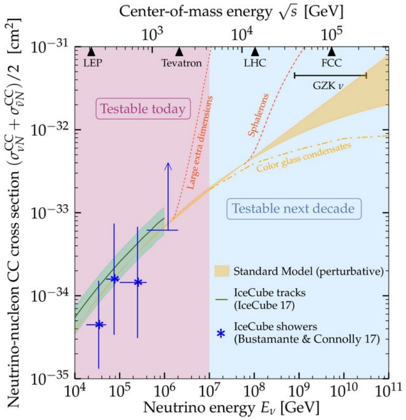
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



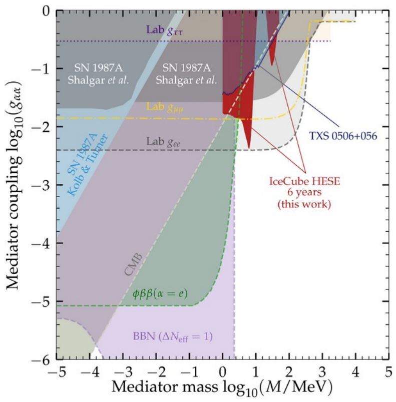
Argüelles, Kheirandish, Vincent, *PRL* 2017

TeV–EeV ν cross sections



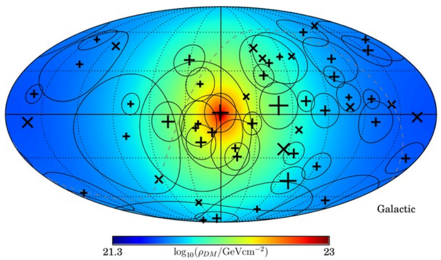
MB & Connolly, *PRL* 2019

ν self-interactions



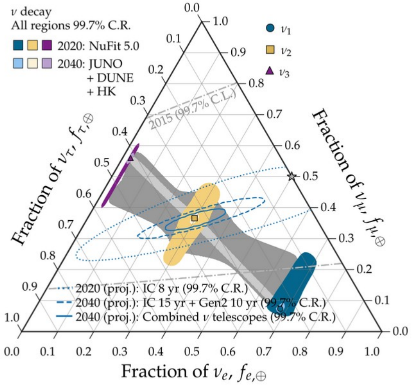
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



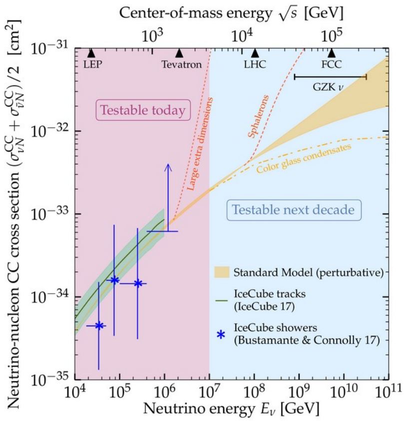
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



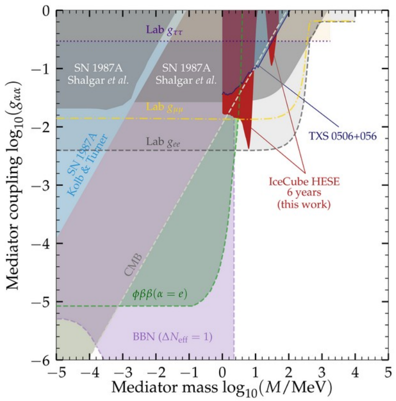
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

TeV–EeV ν cross sections



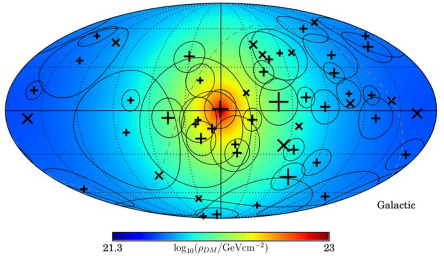
MB & Connolly, *PRL* 2019

ν self-interactions



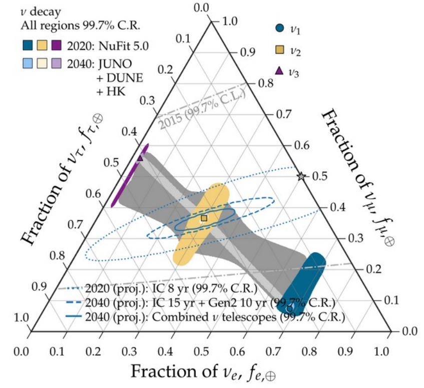
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



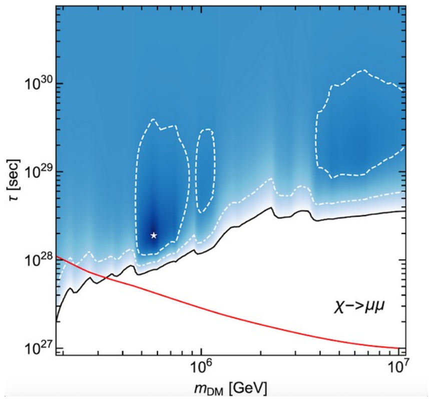
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



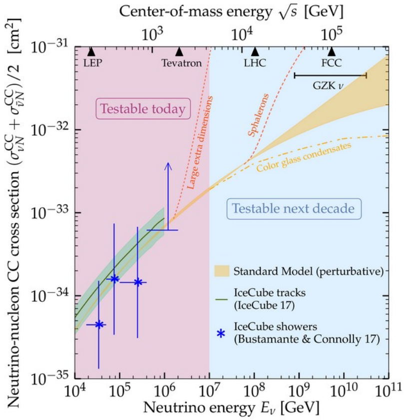
Song, Li, Argüelles, MB, Vincent, *JCAP* 2021

Dark matter decay



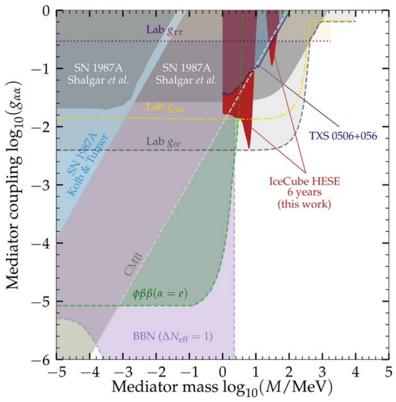
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

TeV–EeV ν cross sections



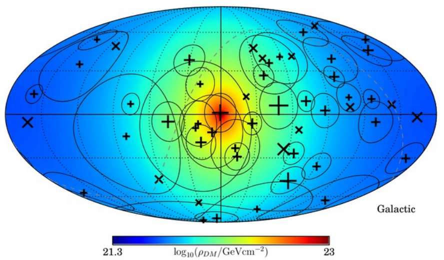
MB & Connolly, *PRL* 2019

ν self-interactions



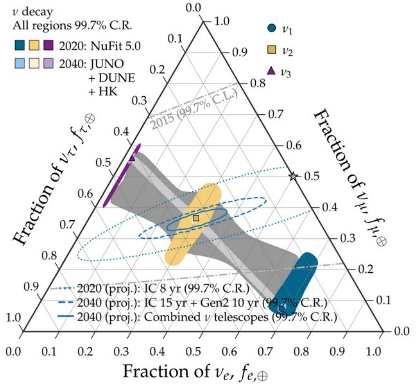
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



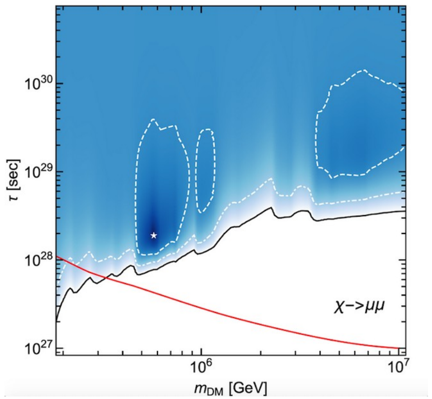
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



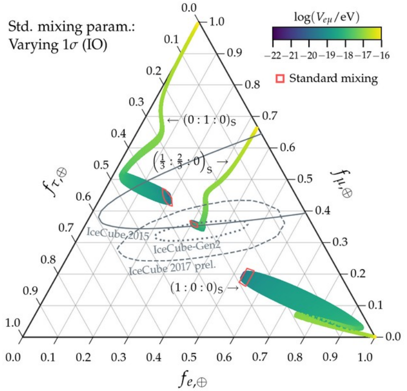
Song, Li, Argüelles, MB, Vincent, *JCAP* 2021

Dark matter decay



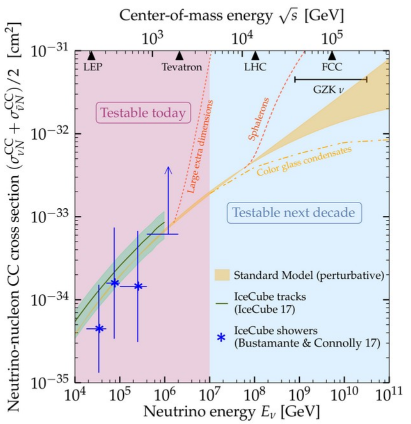
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



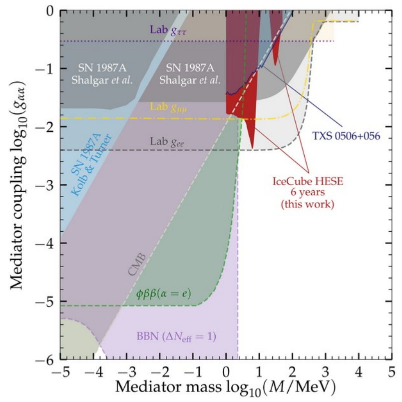
MB & Agarwalla, *PRL* 2019

TeV–EeV ν cross sections



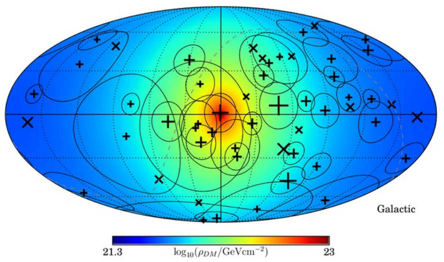
MB & Connolly, *PRL* 2019

ν self-interactions



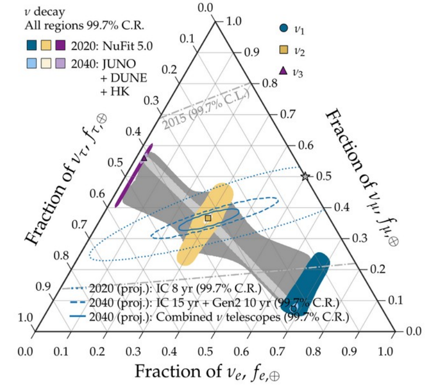
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



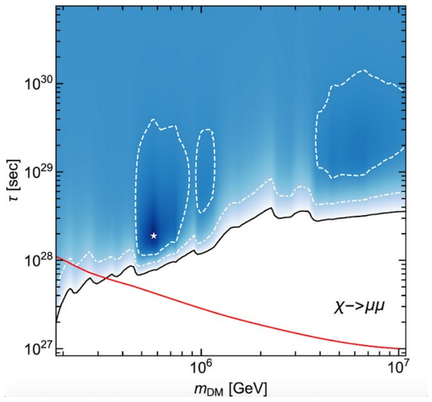
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



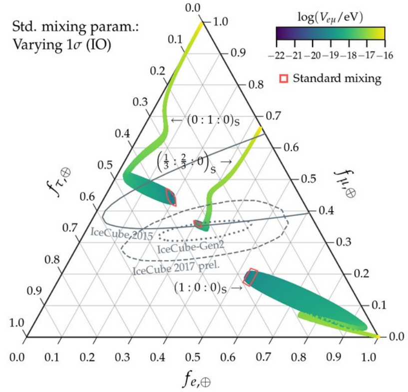
Song, Li, Argüelles, MB, Vincent, *JCAP* 2021

Dark matter decay



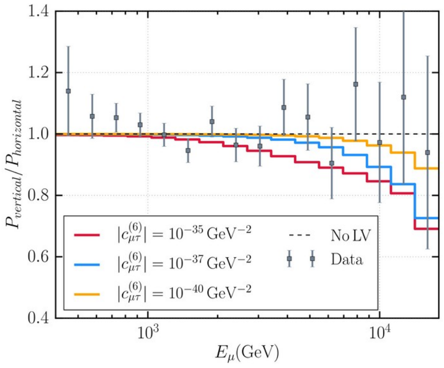
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



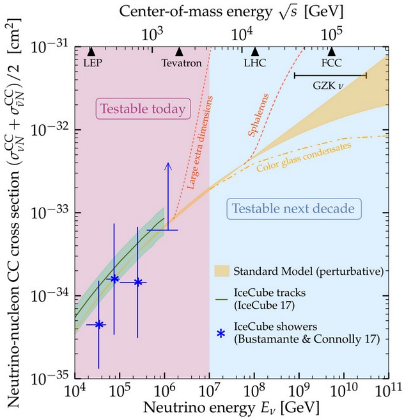
MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



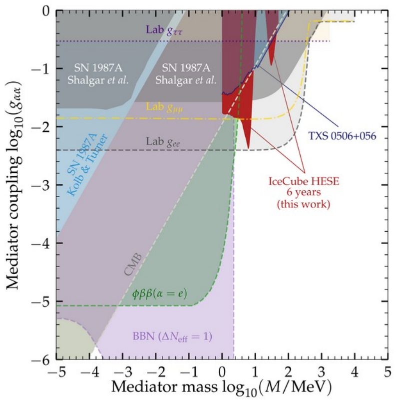
IceCube, *Nature Phys.* 2018

TeV–EeV ν cross sections



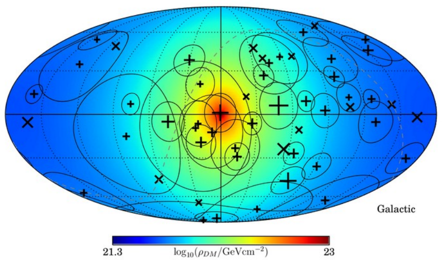
MB & Connolly, *PRL* 2019

ν self-interactions



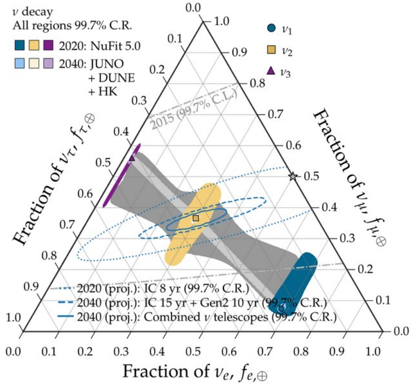
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



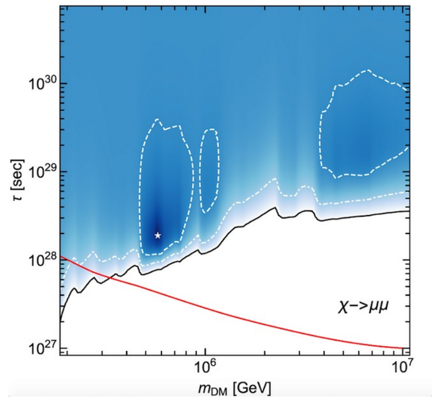
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



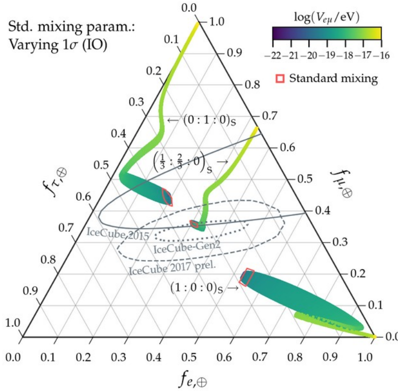
Song, Li, Argüelles, MB, Vincent, *JCAP* 2021

Dark matter decay



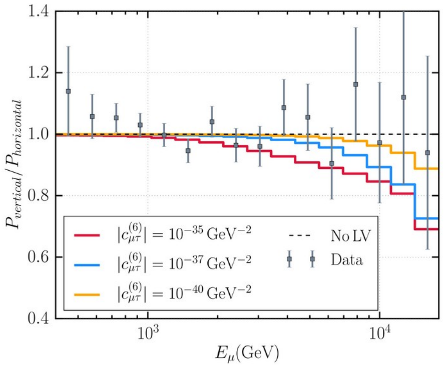
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



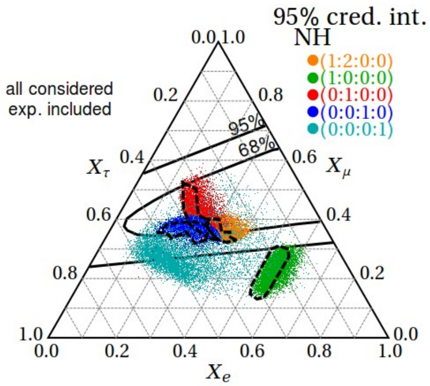
MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation

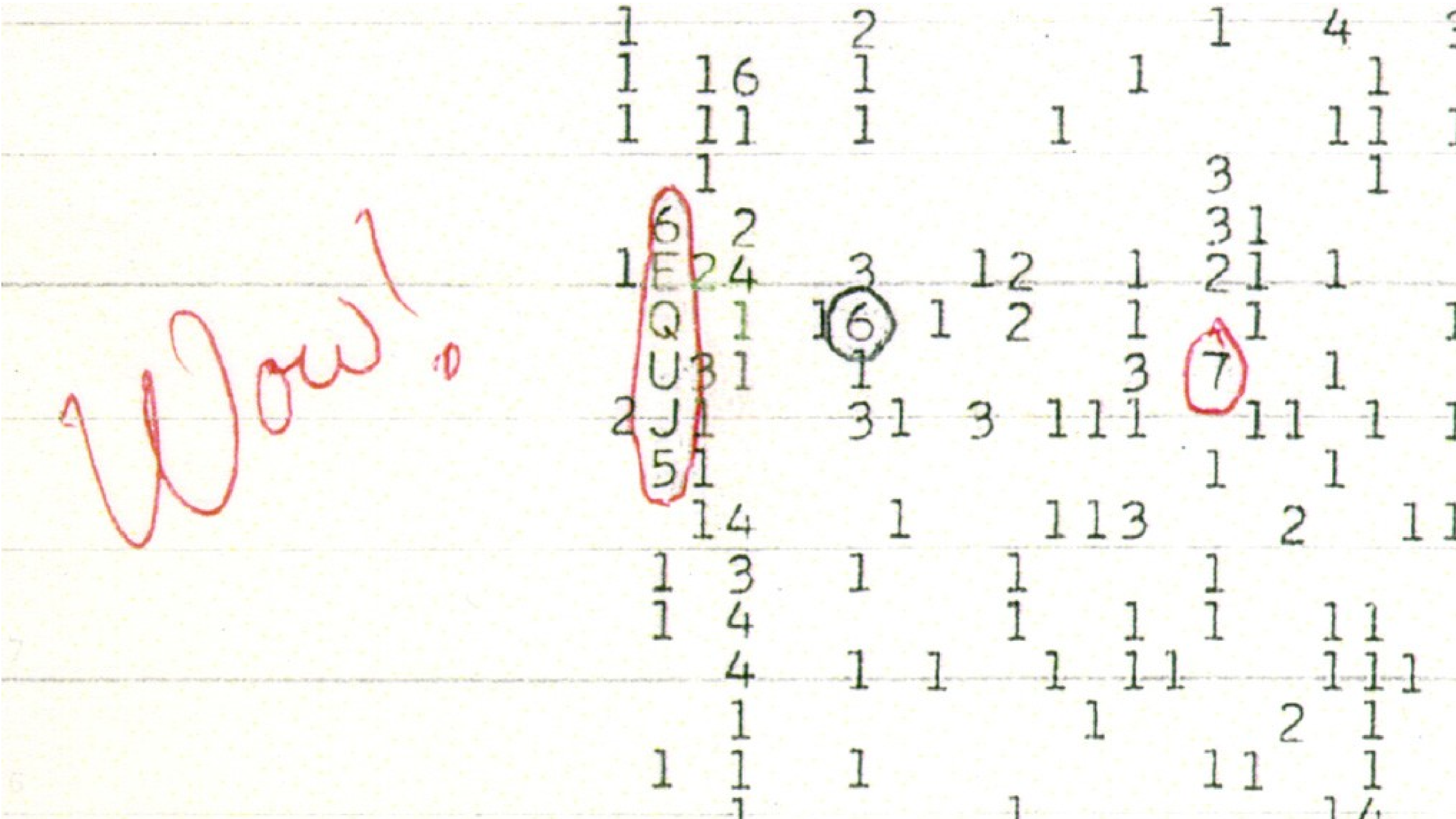


IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017


Wow!

I. A warning

about how to search for BSM physics

I. A warning

about how to search for BSM physics

II. A survey

of UHE BSM studies with KM3-230213A

I. A warning

about how to search for BSM physics

II. A survey

of UHE BSM studies with KM3-230213A

III. A hope

for the future of UHE ν fundamental physics

I.
A warning

Evidence for BSM

Evidence for BSM
Evidence for SM

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

If $B \ll 1$: SM is favored

If $B \gg 1$: BSM is favored

If $B \sim 1$: No preference

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

$$\mathcal{Z}_{\mathrm{SM}} = \int \mathcal{L}(\theta_{\mathrm{SM}}, \theta_{\mathrm{astro}}, \theta_{\mathrm{det}})\pi(\theta_{\mathrm{SM}}, \theta_{\mathrm{astro}}, \theta_{\mathrm{det}})\mathrm{d}\theta_{\mathrm{SM}}\mathrm{d}\theta_{\mathrm{astro}}\mathrm{d}\theta_{\mathrm{det}}$$

Account for particle-physics + astrophysical + detector uncertainties

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

$$\mathcal{Z}_{\rm SM} = \int \overbrace{\mathcal{L}(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det})}^{\text{Likelihood}} \overbrace{\pi(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det})}^{\text{Prior}} \mathrm{d}\theta_{\rm SM} \mathrm{d}\theta_{\rm astro} \mathrm{d}\theta_{\rm det}$$

Account for particle-physics + astrophysical + detector uncertainties

$$\mathcal{Z}_{\rm BSM} = \int \mathcal{L}(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det}, \theta_{\rm BSM}) \pi(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det}, \theta_{\rm BSM}) \times d\theta_{\rm SM} d\theta_{\rm astro} d\theta_{\rm det} d\theta_{\rm BSM}$$

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

$$\mathcal{Z}_{\rm SM} = \int \overbrace{\mathcal{L}(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det})}^{\text{Likelihood}} \overbrace{\pi(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det})}^{\text{Prior}} d\theta_{\rm SM} d\theta_{\rm astro} d\theta_{\rm det}$$

Account for particle-physics + astrophysical + detector uncertainties

$$\mathcal{Z}_{\rm BSM} = \int \mathcal{L}(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det}, \theta_{\rm BSM})\pi(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det}, \theta_{\rm BSM}) \times {\rm d}\theta_{\rm SM}{\rm d}\theta_{\rm astro}{\rm d}\theta_{\rm det}{\rm d}\theta_{\rm BSM}$$

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

$$\mathcal{Z}_{\rm SM} = \int \overbrace{\mathcal{L}(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det})}^{\text{Likelihood}}\overbrace{\pi(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det})}^{\text{Prior}}{\rm d}\theta_{\rm SM}{\rm d}\theta_{\rm astro}{\rm d}\theta_{\rm det}$$

Account for particle-physics + astrophysical + detector uncertainties

Use the blackboard

Recommendation #1

BSM searches must comprehensively include SM, astrophysical, and detector uncertainties, using unbiased priors.

Recommendation #1

BSM searches must comprehensively include SM, astrophysical, and detector uncertainties, using unbiased priors.

"When you have eliminated all which is impossible, then whatever remains, however improbable, must be the truth."

— Arthur Conan Doyle, The Case-Book of Sherlock Holmes

II.
A survey

BSM models in connection to KM3-230213A

Lorentz-invariance violation

Superluminal neutrinos (2502.09548, 2502.12070, 2502.18256)
Time delay (14 years!) *vs.* gamma rays from a GRB (2502.13093, 2503.14471)
From the muon surviving enhanced $\mu \to e + \gamma$ while traveling underground (2502.13201)

Decay of heavy dark matter

Decay of 400-PeV DM (2503.00097, 2503.04464, 2503.14332, 2503.18737, 2504.01447)
Heavy scalar decays into sterile ν that decays into active ν (2503.07776)

Sterile-active neutrino transition

Motivated by observation in KM3NeT, but not IceCube (2502.21299)

Primordial black hole evaporation

Possibly with "memory burden" to lengthen PBH life (2502.19245, 2503.19227, 2503.21740)

Mirror neutrons

UHE $n' \to n \to \nu$ reconciles heavy UHECR masses with high cosmogenic ν flux (2503.14419)

Do we live in a simulation? (2504.08461)

Lorentz-invariance violation — from superluminal speeds

A superluminal ν loses energy via pair production, *i.e.*,

$$\nu \to \nu + e^+ + e^-$$

Cohen & Glashow, *PRL* 2011

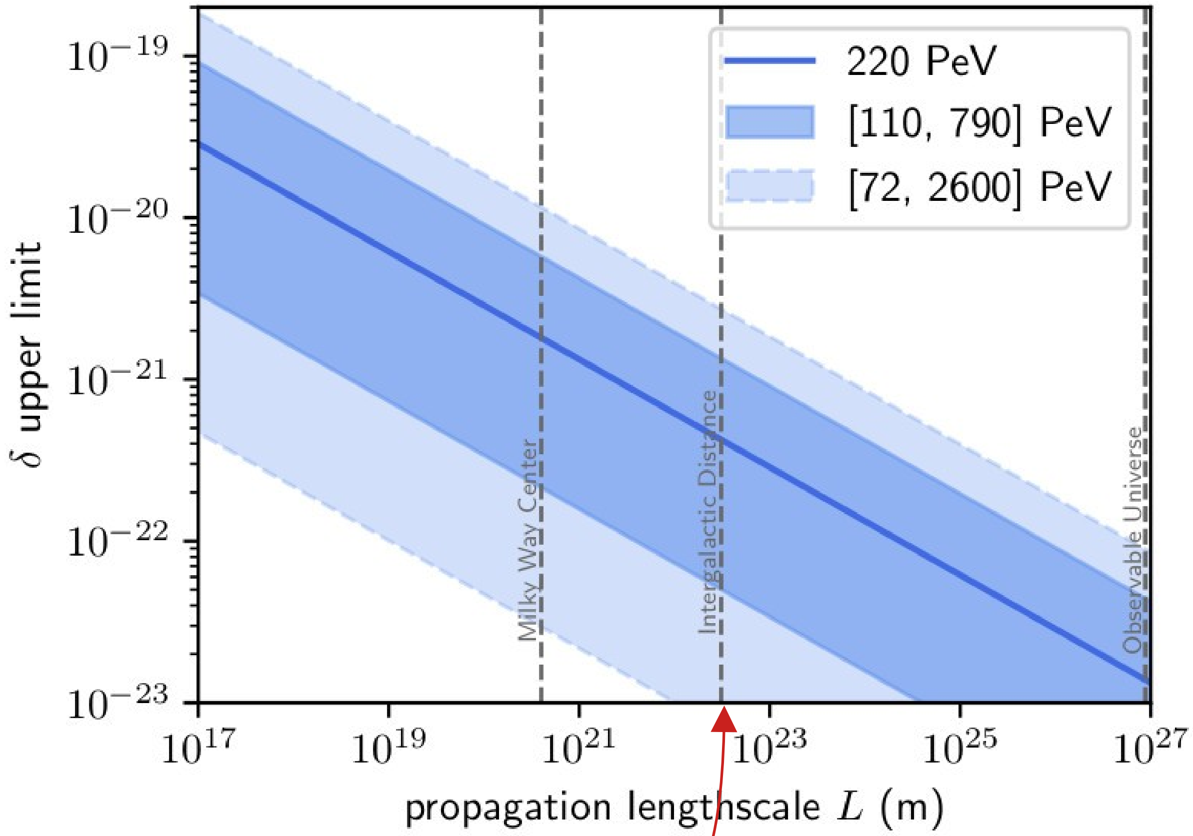
Excess over light speed: $\delta = c_\nu - 1$

Decay length: $L_{dec} = c_\nu / \Gamma \propto E^{-5} \delta^{-3}$

Decay width (↑ Γ)

Demanding that the travel distance $L < 10\, L_{dec}$ sets upper limits on δ

KM3NeT Collab., 2502.12070



New limit is ~1000 times stronger than previous one from TXS 0506+056

Lorentz-invariance violation — from a GRB association

GRB emitted neutrinos & photons simultaneously

Time delay induced by dispersion of neutrinos on spacetime foam:

Neutrino energy

$$\Delta t = D(z)\frac{E}{\Lambda} \approx 14 \text{ years}$$

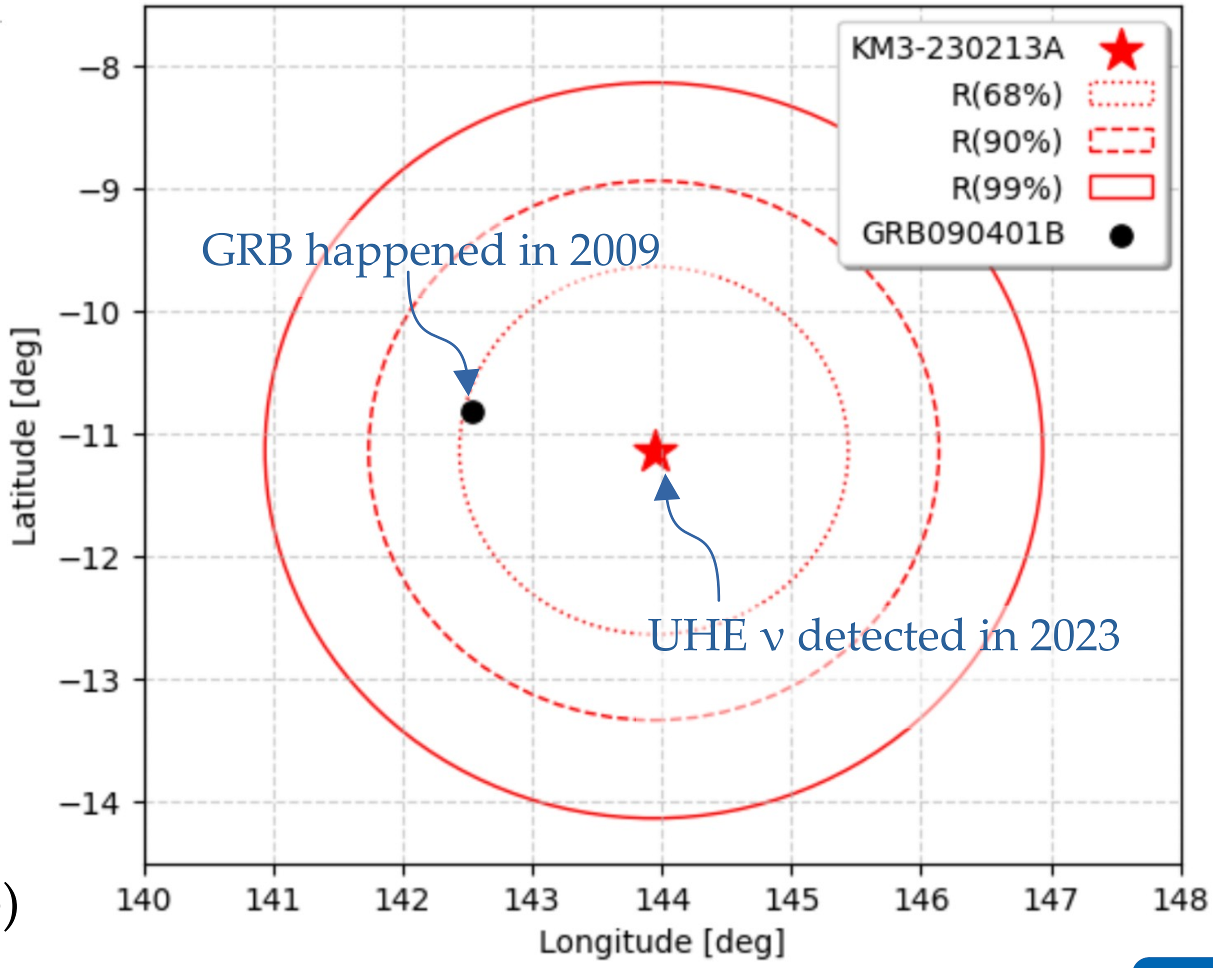
Cosmological expansion

Energy scale of LIV (10^{14}–10^{15} GeV)

GRB-ν association: 2.4σ

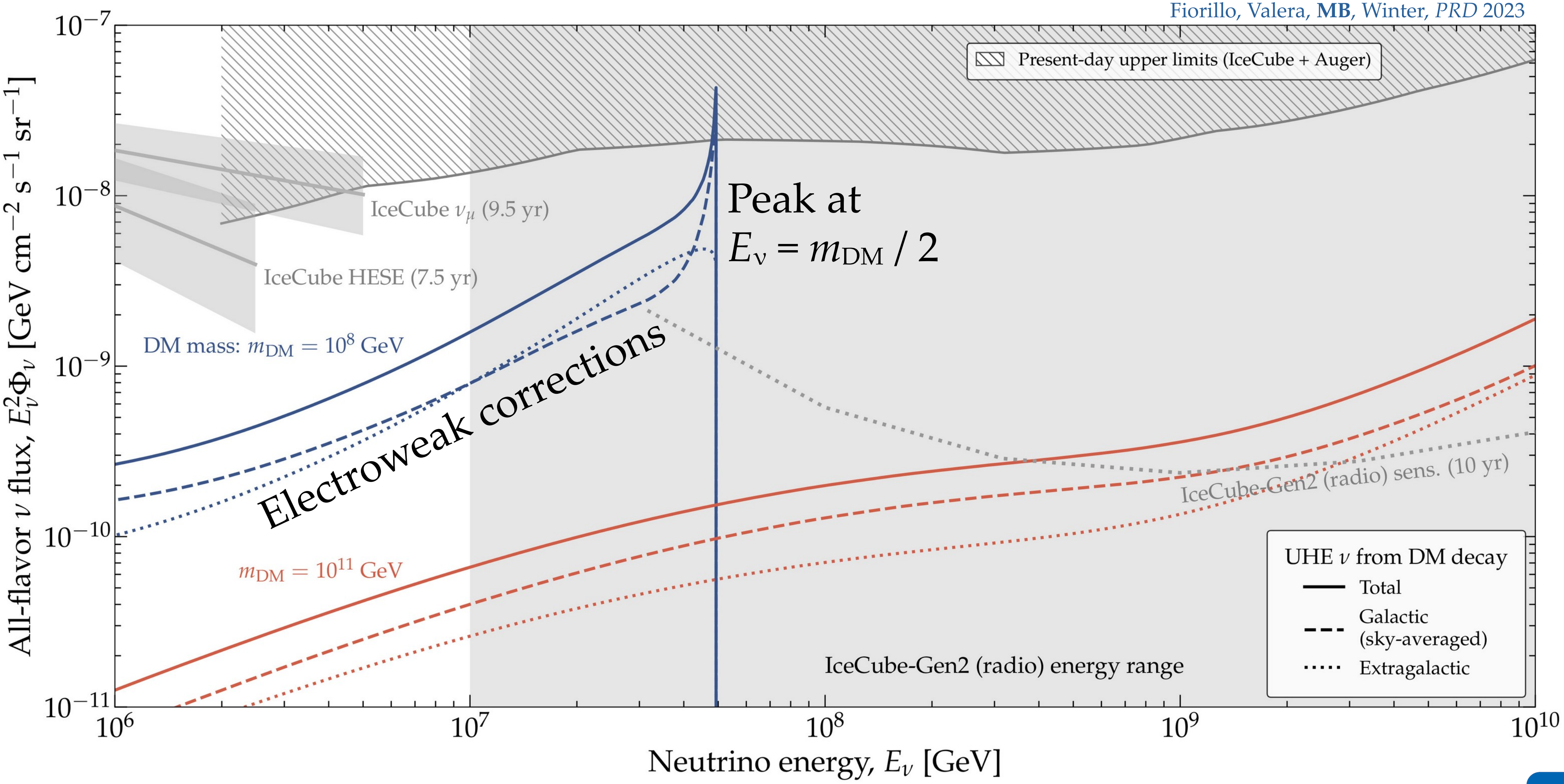
(p-value of 0.015)

Amelino-Camelia *et al.*, 2502.13093



Decay of heavy dark matter (DM → ν + ν)

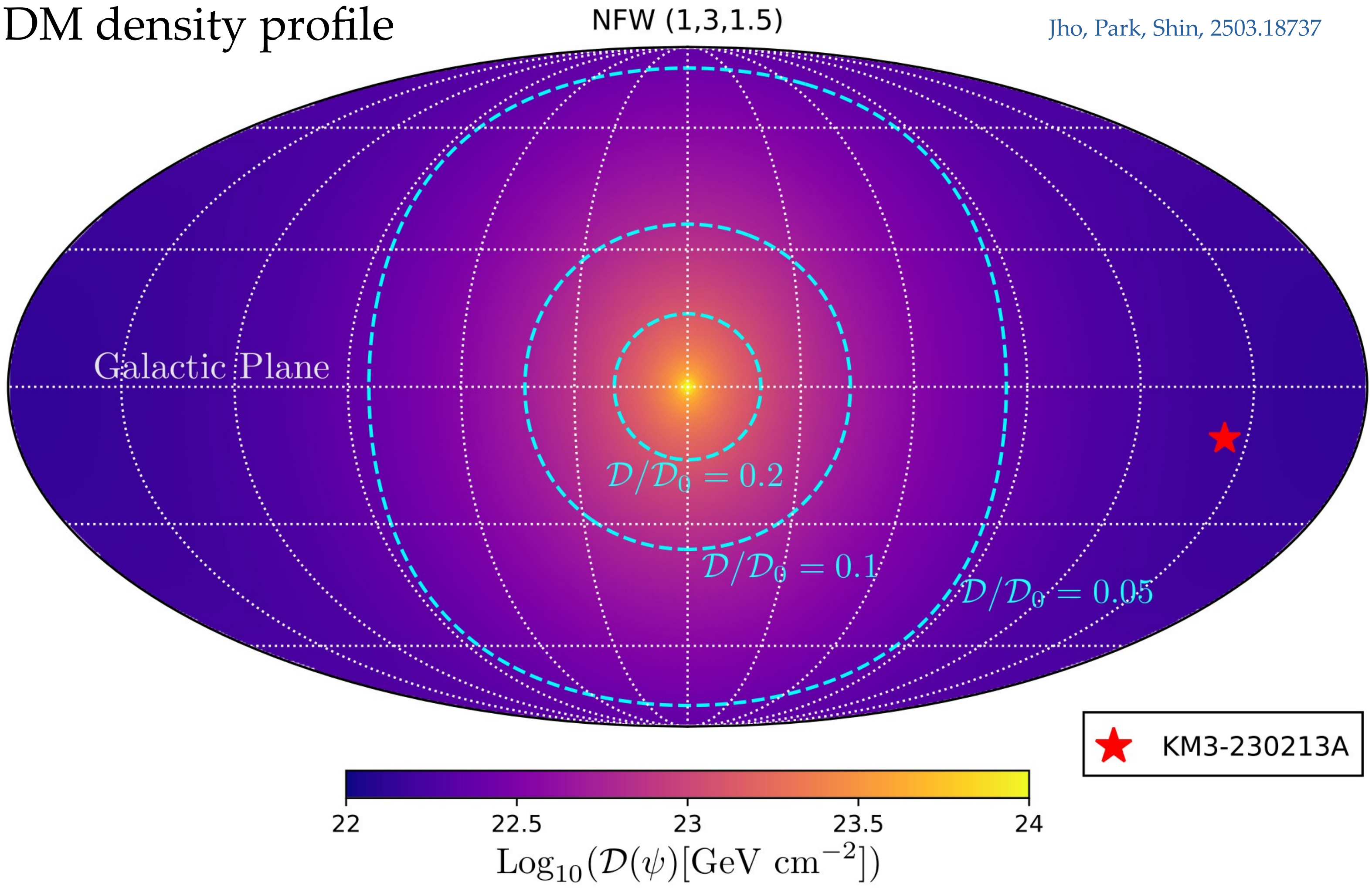
Fiorillo, Valera, **MB**, Winter, *PRD* 2023



Decay of heavy dark matter (DM → ν + ν)

Galactic DM density profile

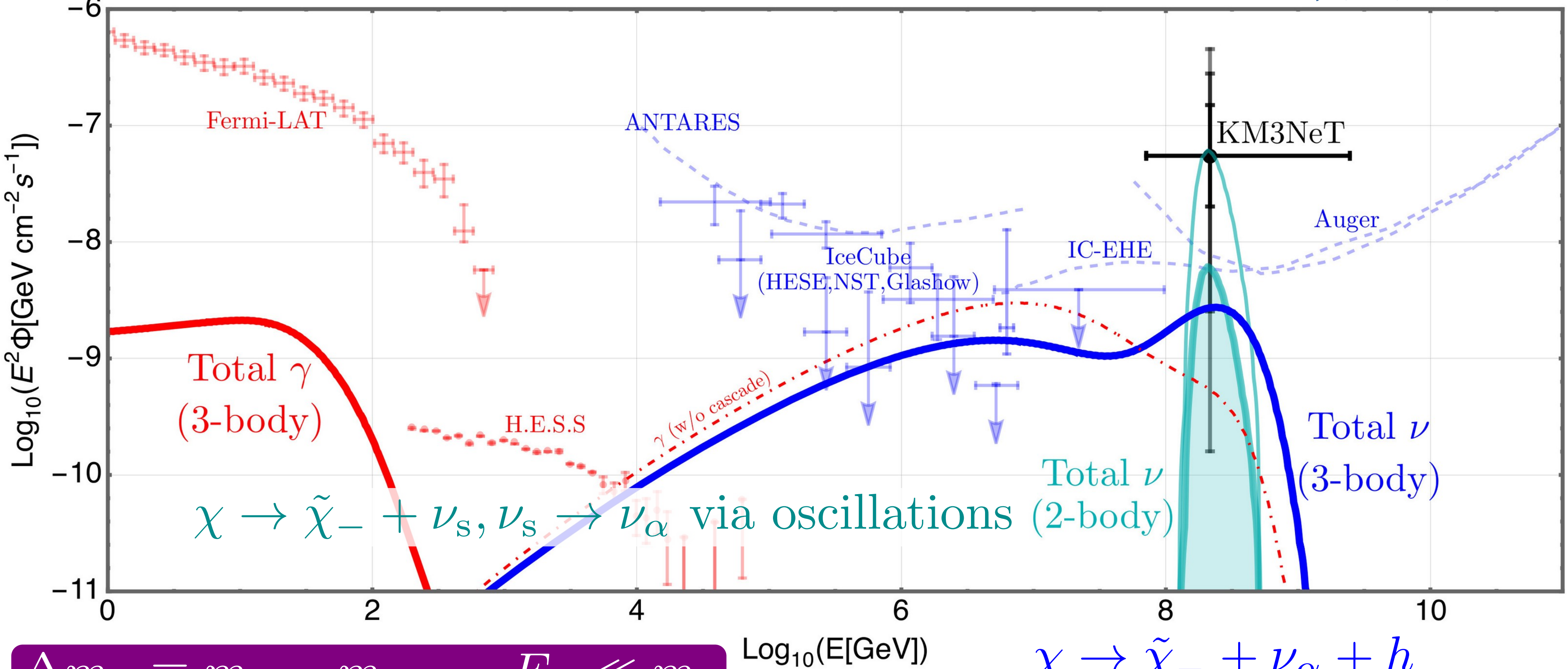
Jho, Park, Shin, 2503.18737



Decay of heavy dark matter — supersymmetric

Multi-component DM: heavy (χ, unstable) & lighter ($\tilde{\chi}_-$, stable)

Jho, Park, Shin, 2503.18737



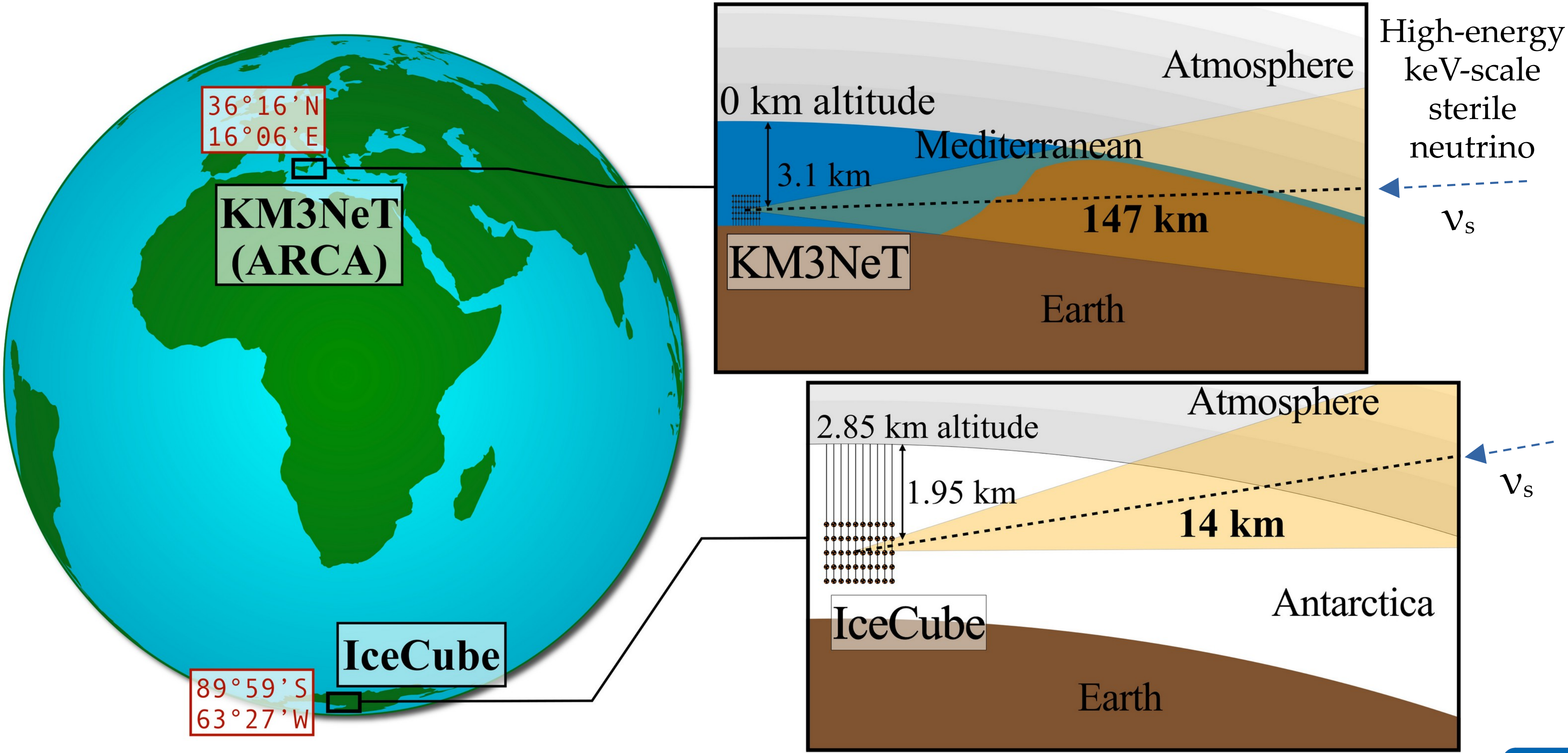
$$\Delta m_\chi \equiv m_\chi - m_{\tilde{\chi}_-} \sim E_\nu \ll m_\chi$$

$$\chi \to \tilde{\chi}_- + \nu_\alpha + h$$

(Higgs decays into γ)

Sterile-active ν transitions

Brdar & Chattopadhyay, 2502.21299



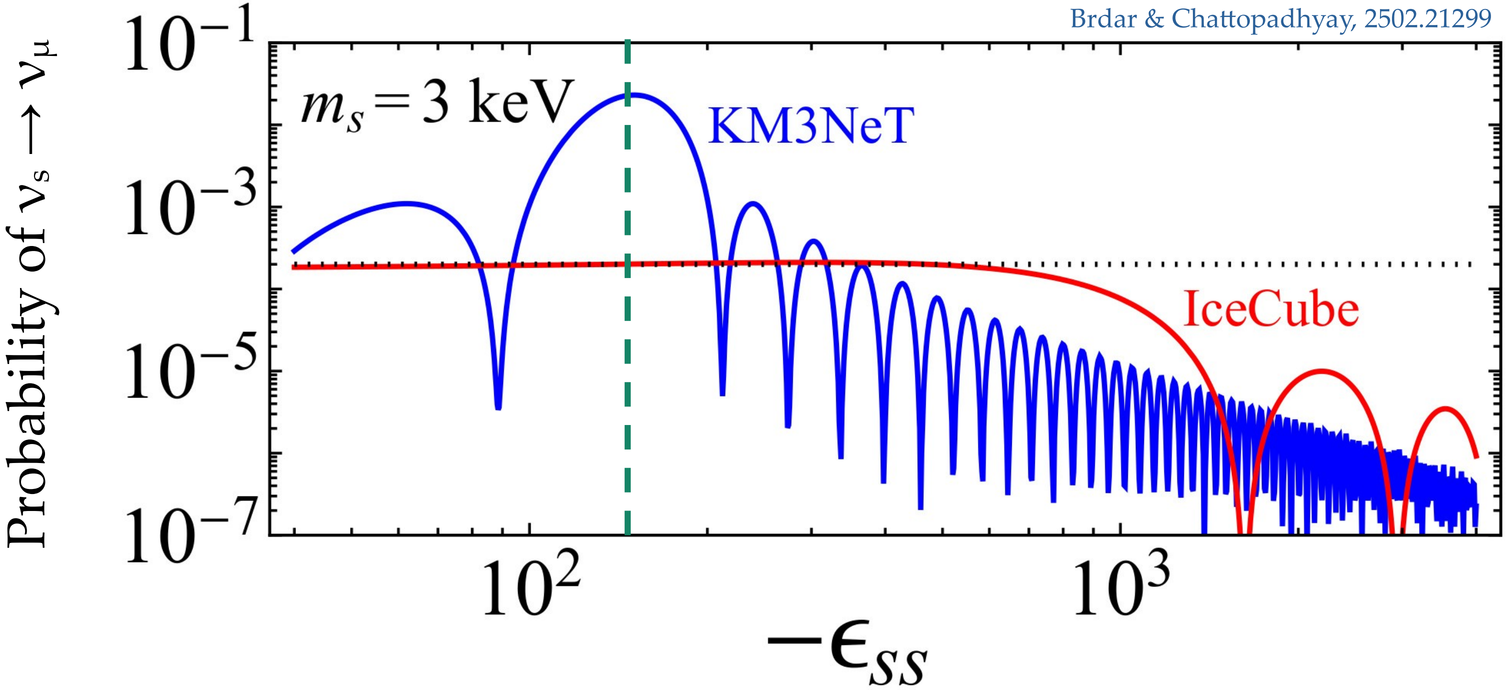
Sterile-active ν transitions

New neutrino-baryon interactions inside Earth (by gauging $U(1)_B$ symmetry)

Relative strength *vs.* standard weak interaction: $\epsilon_{ss} = G_B/(\sqrt{2}G_F)$

For $-\epsilon_{ss} = 150$, transitions are resonant in KM3NeT,
but not in IceCube

Brdar & Chattopadhyay, 2502.21299



Primordial black hole evaporation

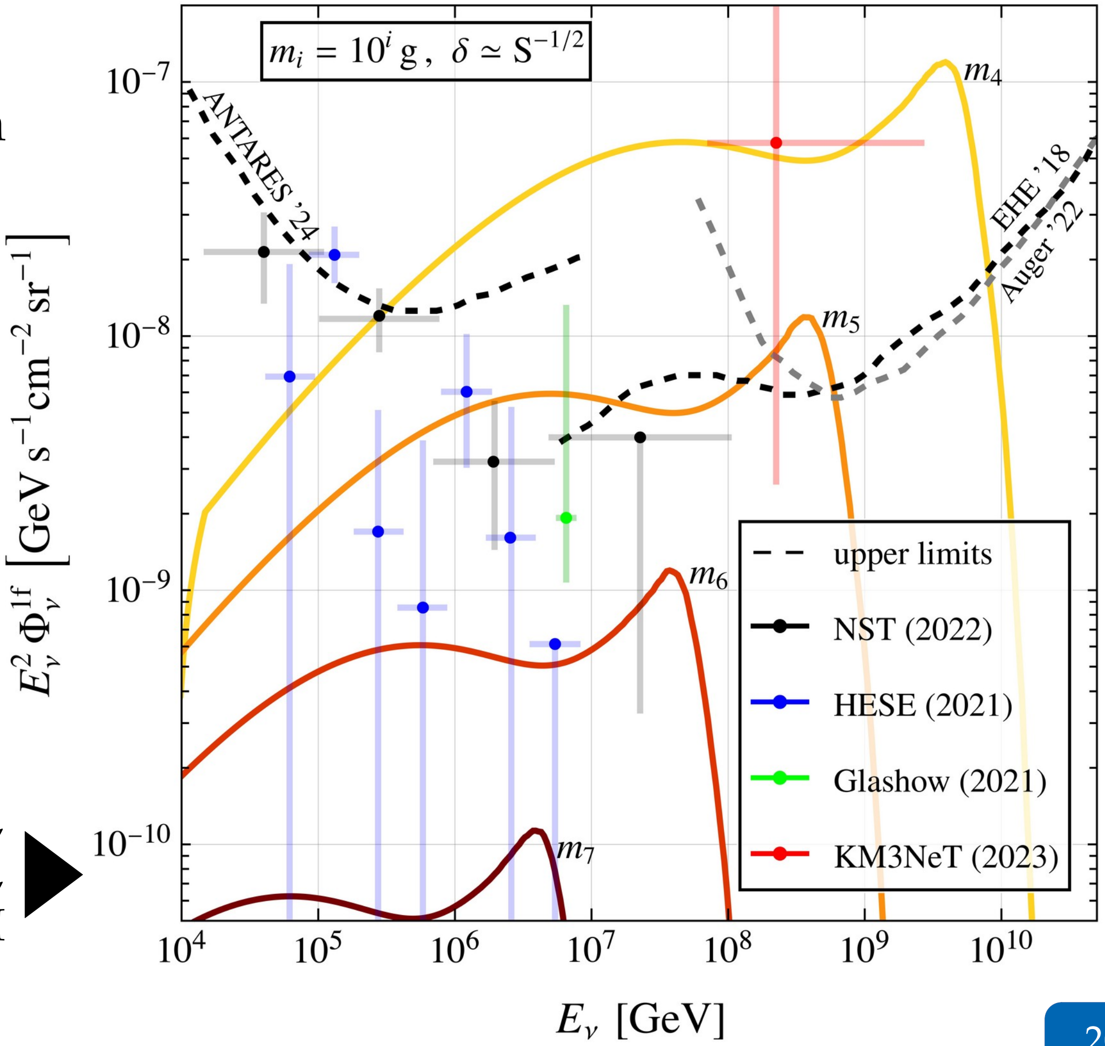
Primordial black holes (PBHs) evaporate through Hawking radiation

“Memory burden” effect: quantum back-reaction lengthens the life of the black hole

Most of the contribution is from intermediate-mass PBHs, transitioning to memory burden

Galactic + extragalactic contributions, monochromatic mass spectrum, PBHs make up all of DM

Dvali, Zantedeschi, Zell, 2503.21740

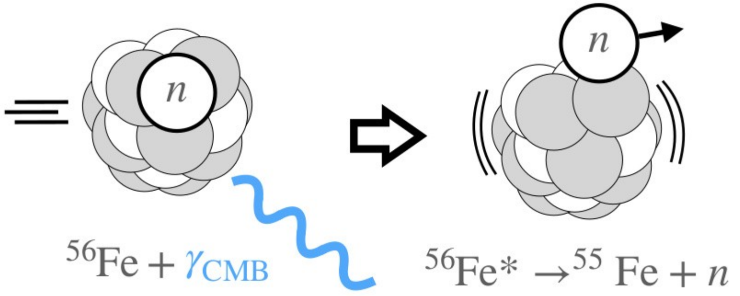


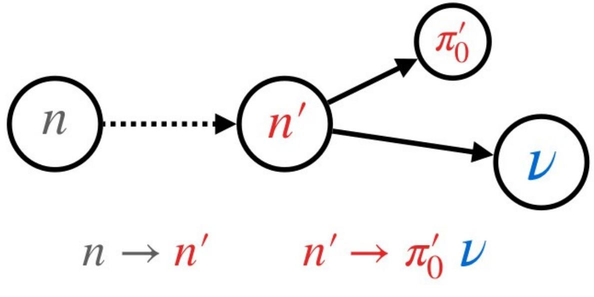
Mirror neutrons

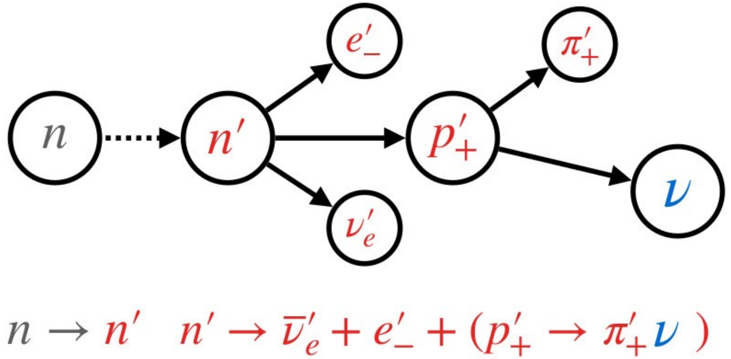
Can reconcile large cosmogenic ν flux inspired by KM3-230213A and heavy UHECR mass composition

But cannot explain lack of IceCube events

Joint fits to Auger UHECR data + neutrino data from IceCube and KM3NeT

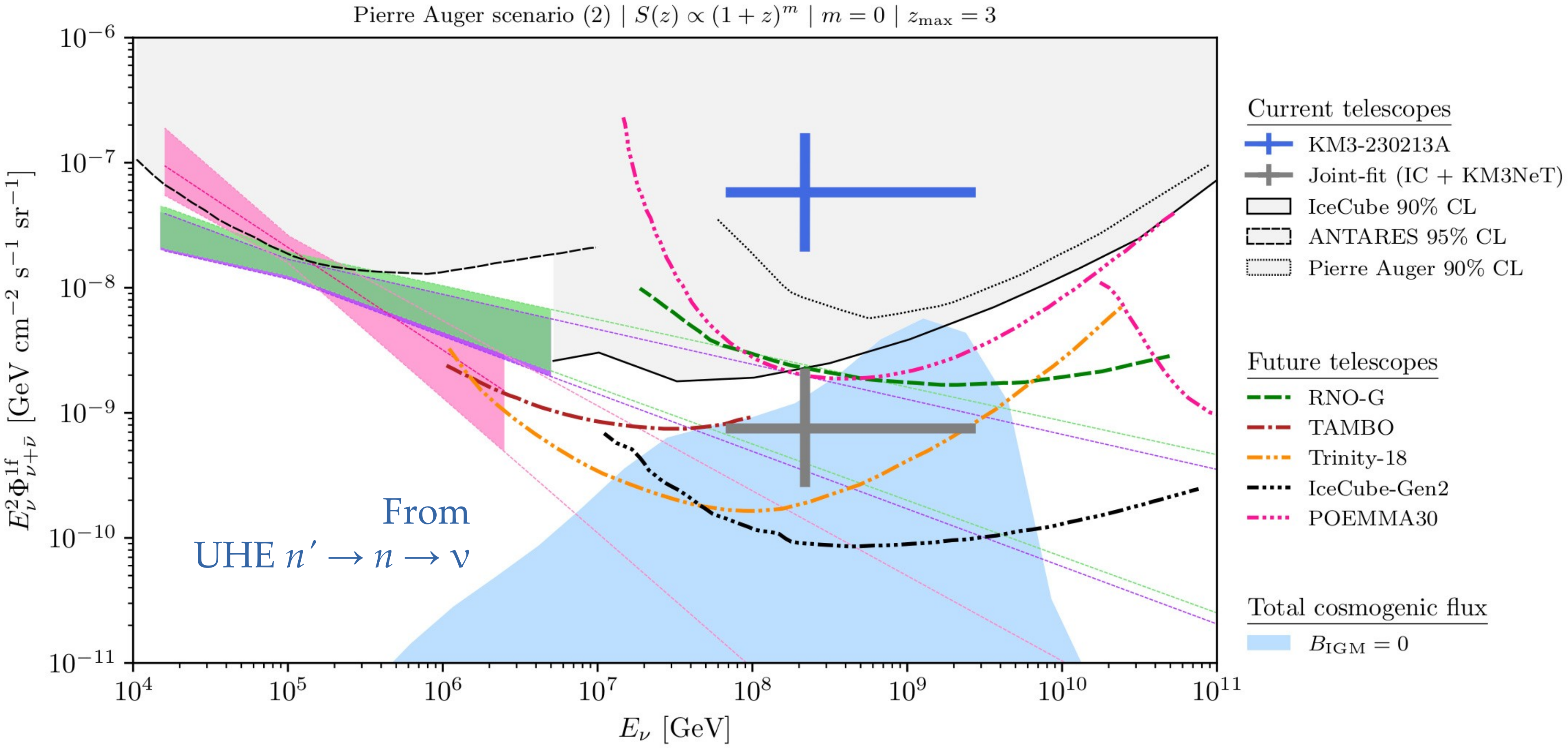






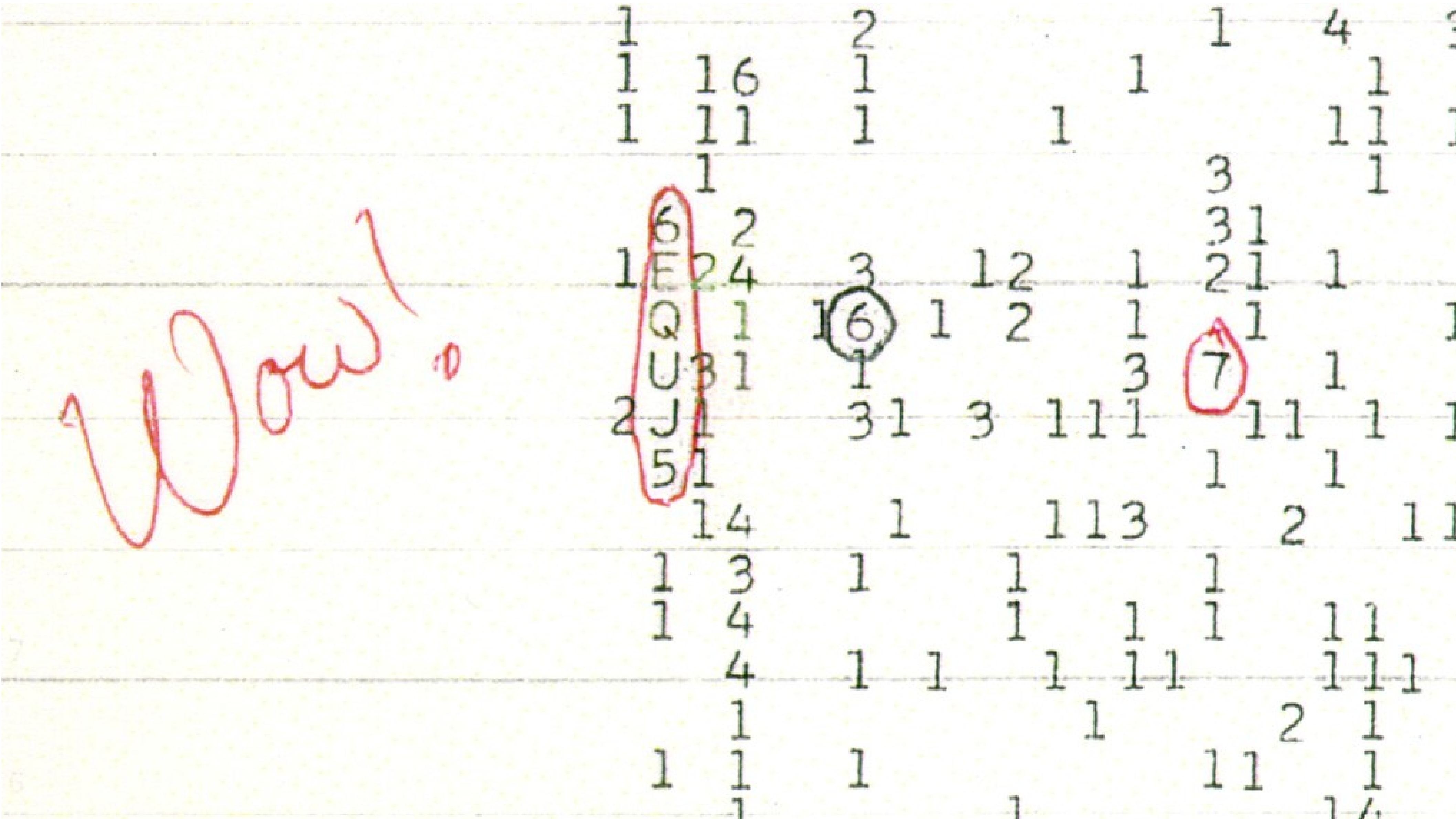
Alves, Hostert, Pospelov, 2503.14419

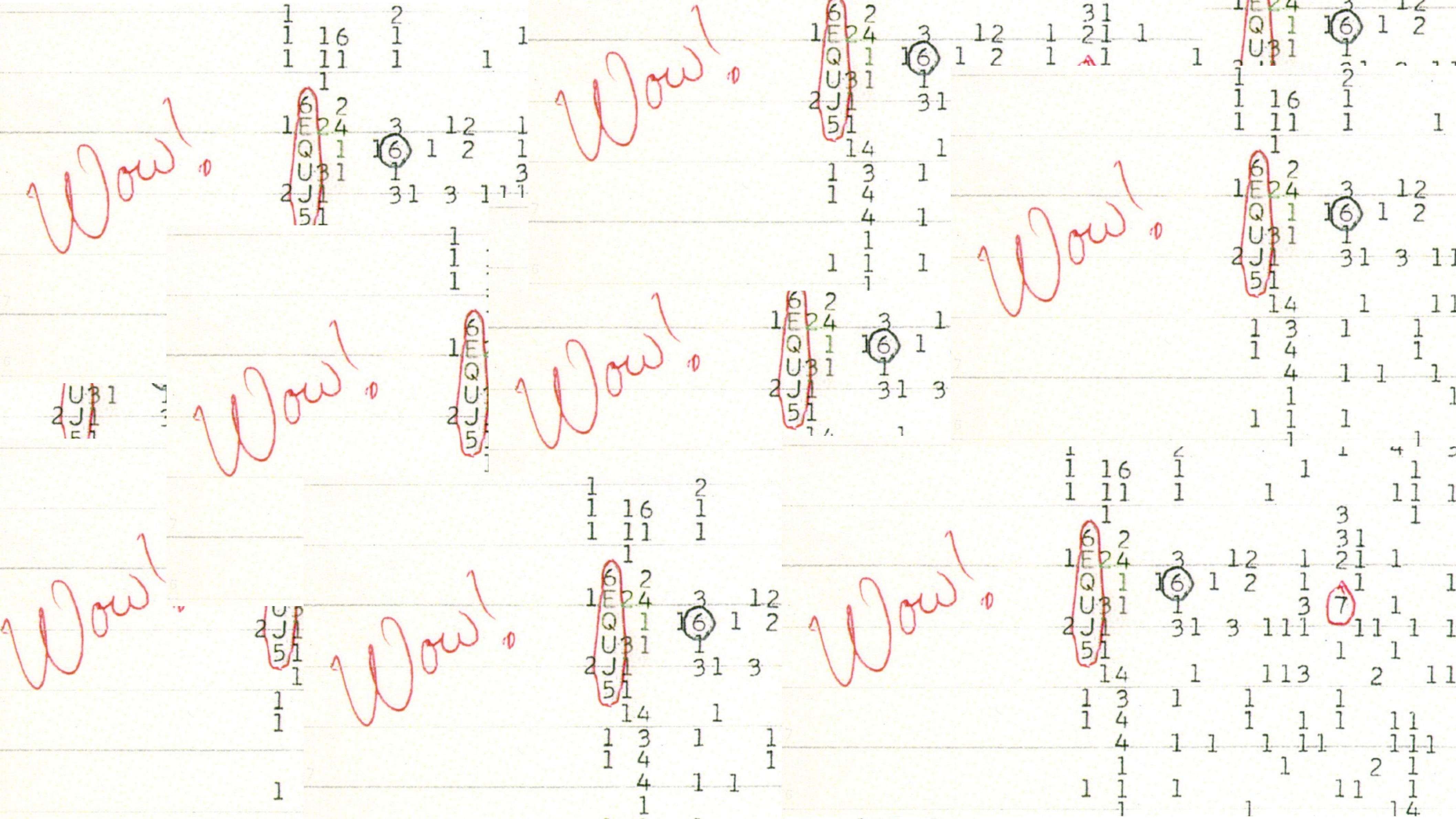
Mirror neutrons

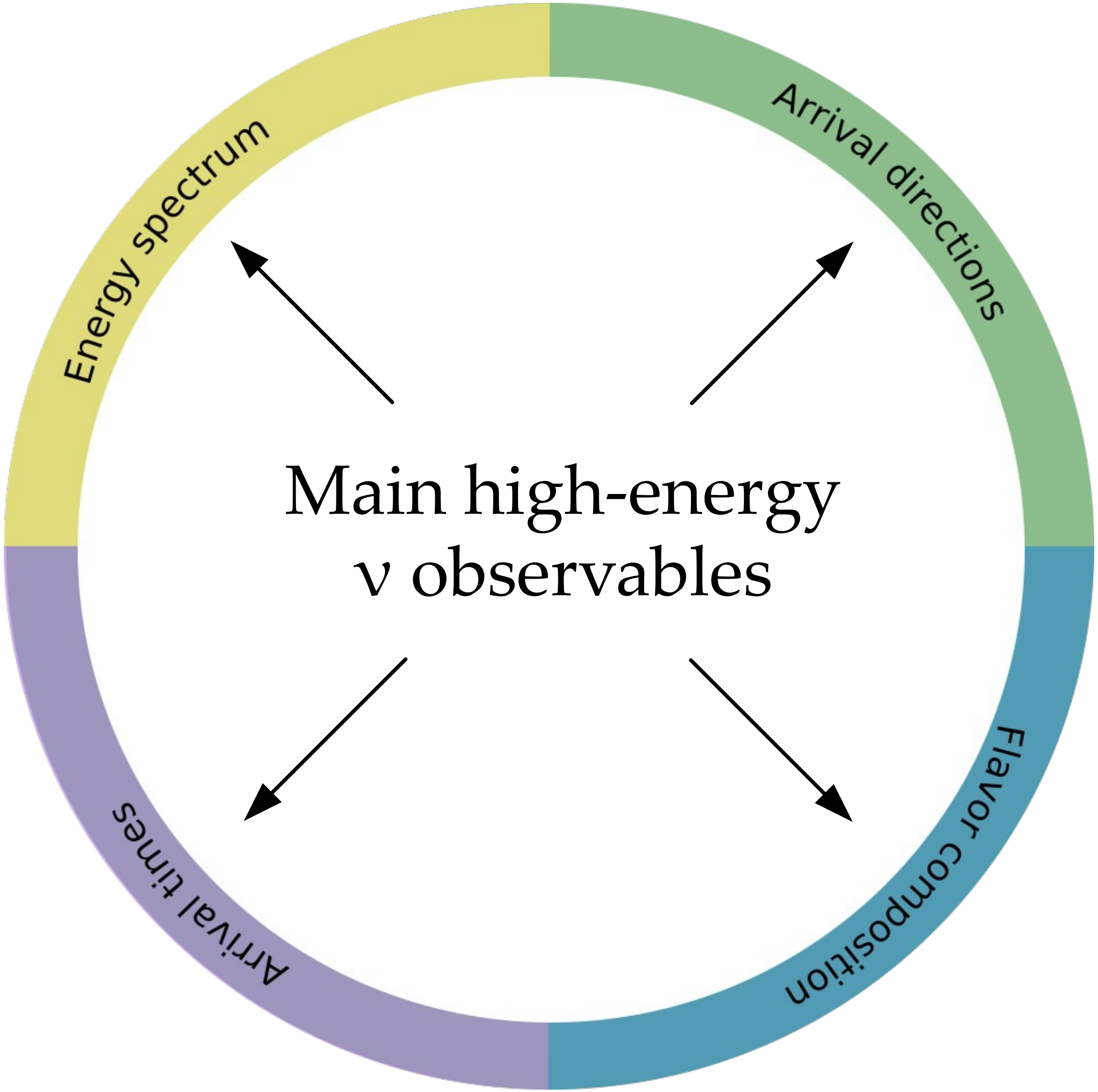


Alves, Hostert, Pospelov, 2503.14419

III.
A hope


Wow!
6EQUJ5

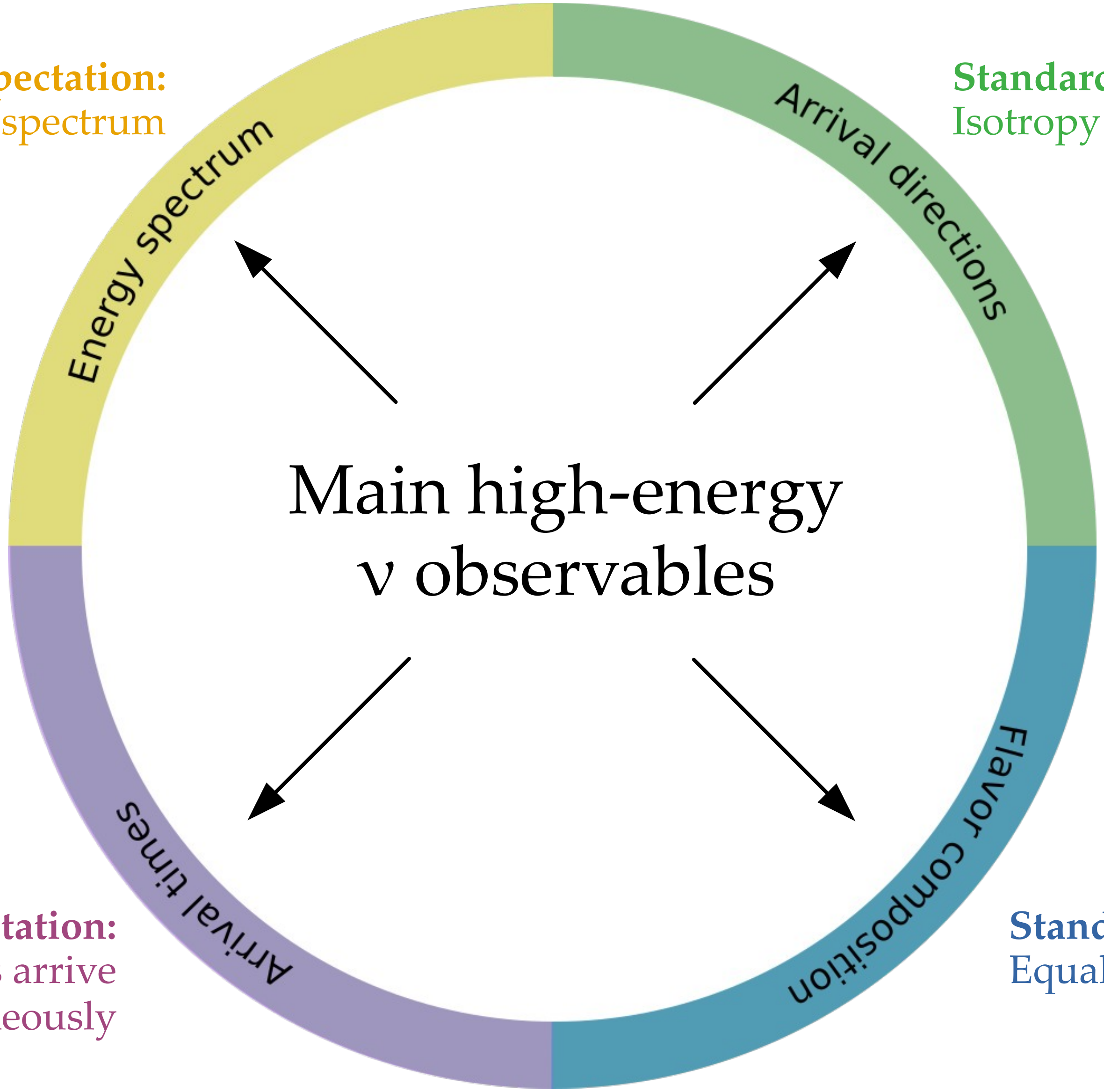

Wow!



Energy spectrum
Arrival directions
Main high-energy ν observables
Arrival times
Flavor composition

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

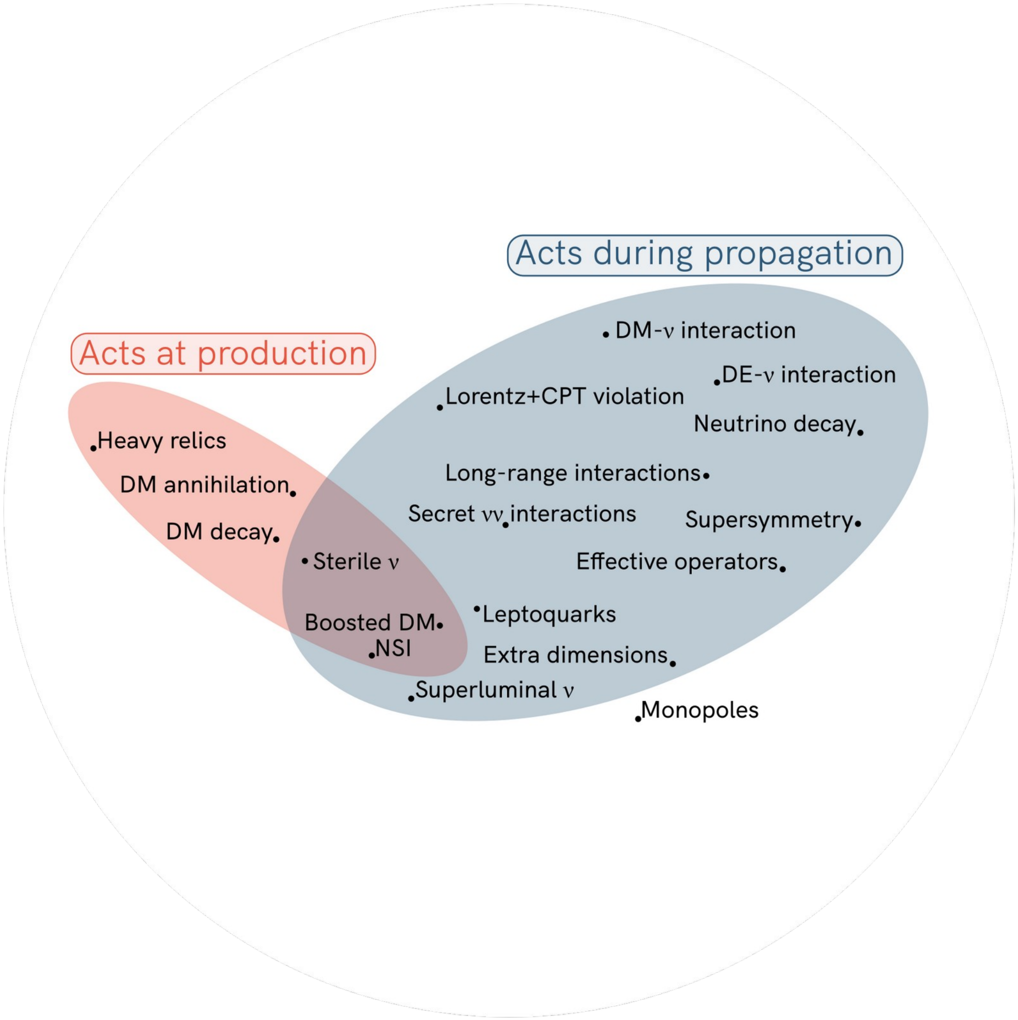


Standard expectation:
ν and γ from transients arrive simultaneously

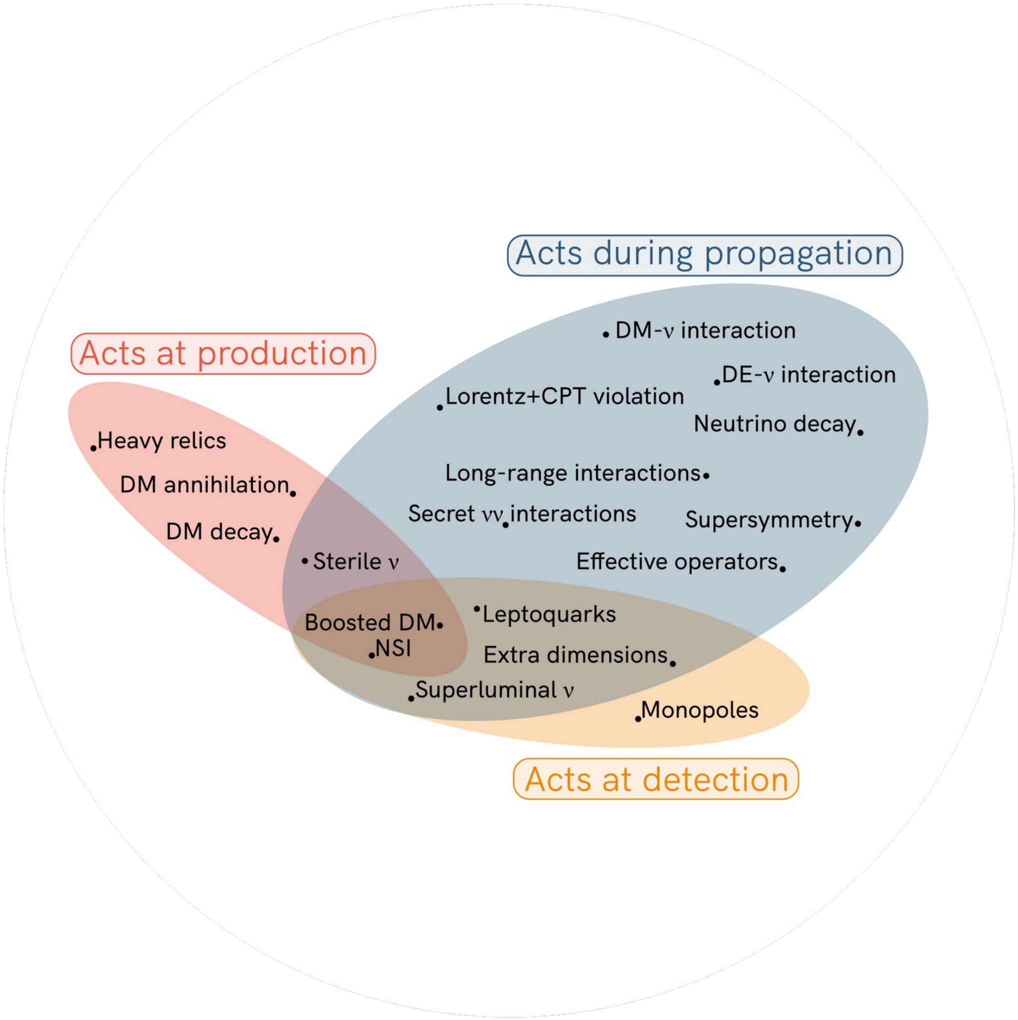
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

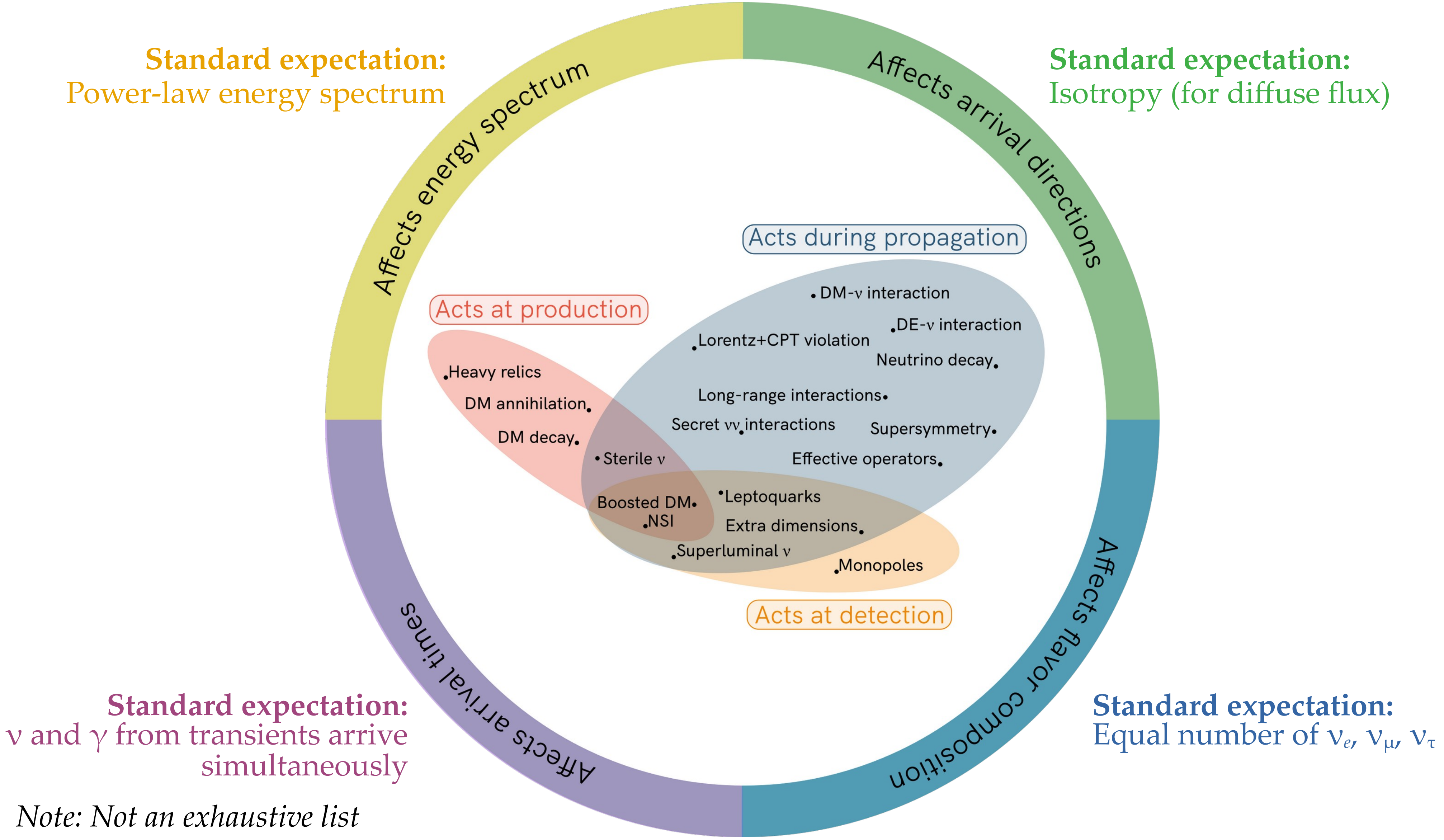
Note: Not an exhaustive list

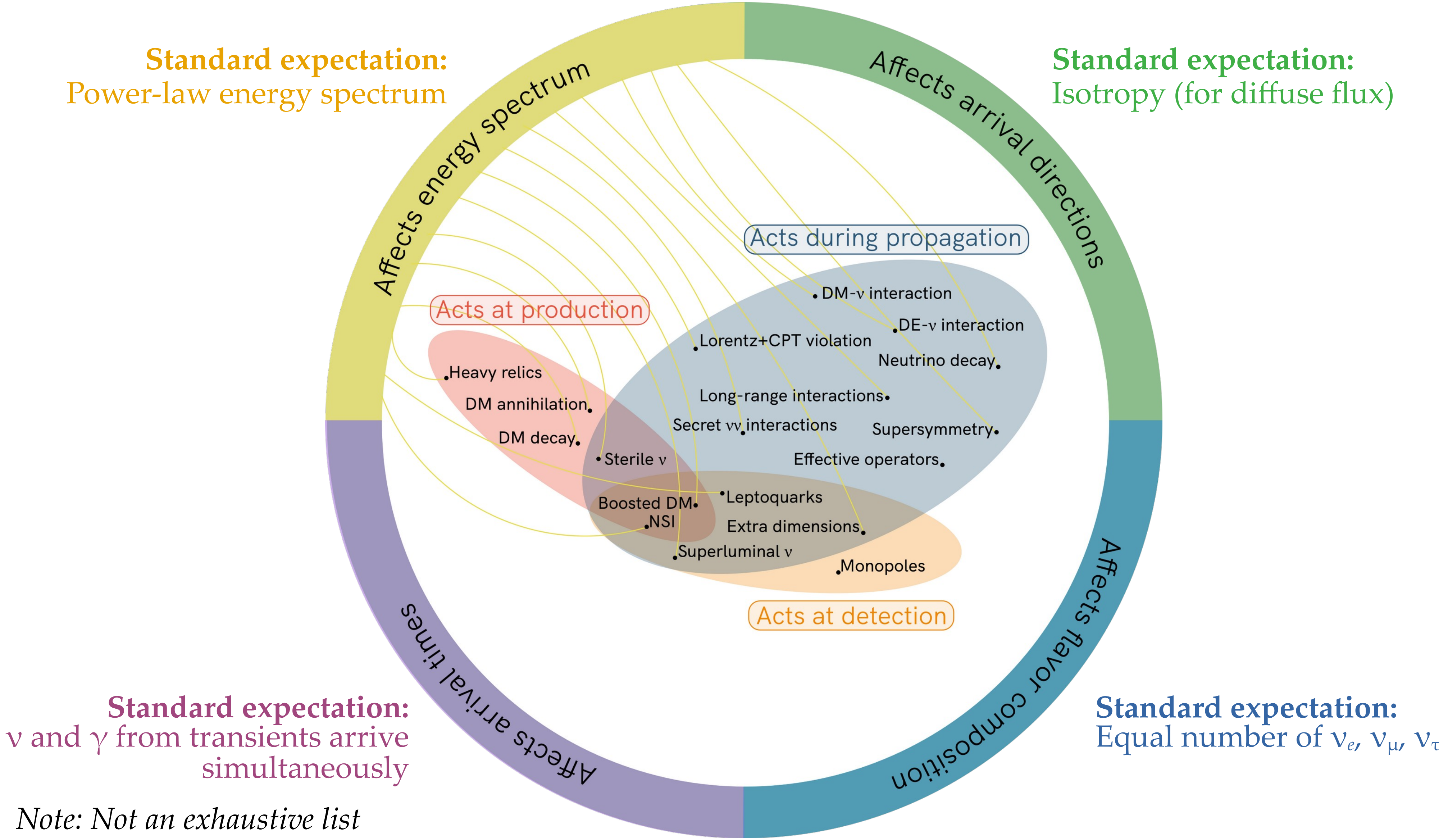


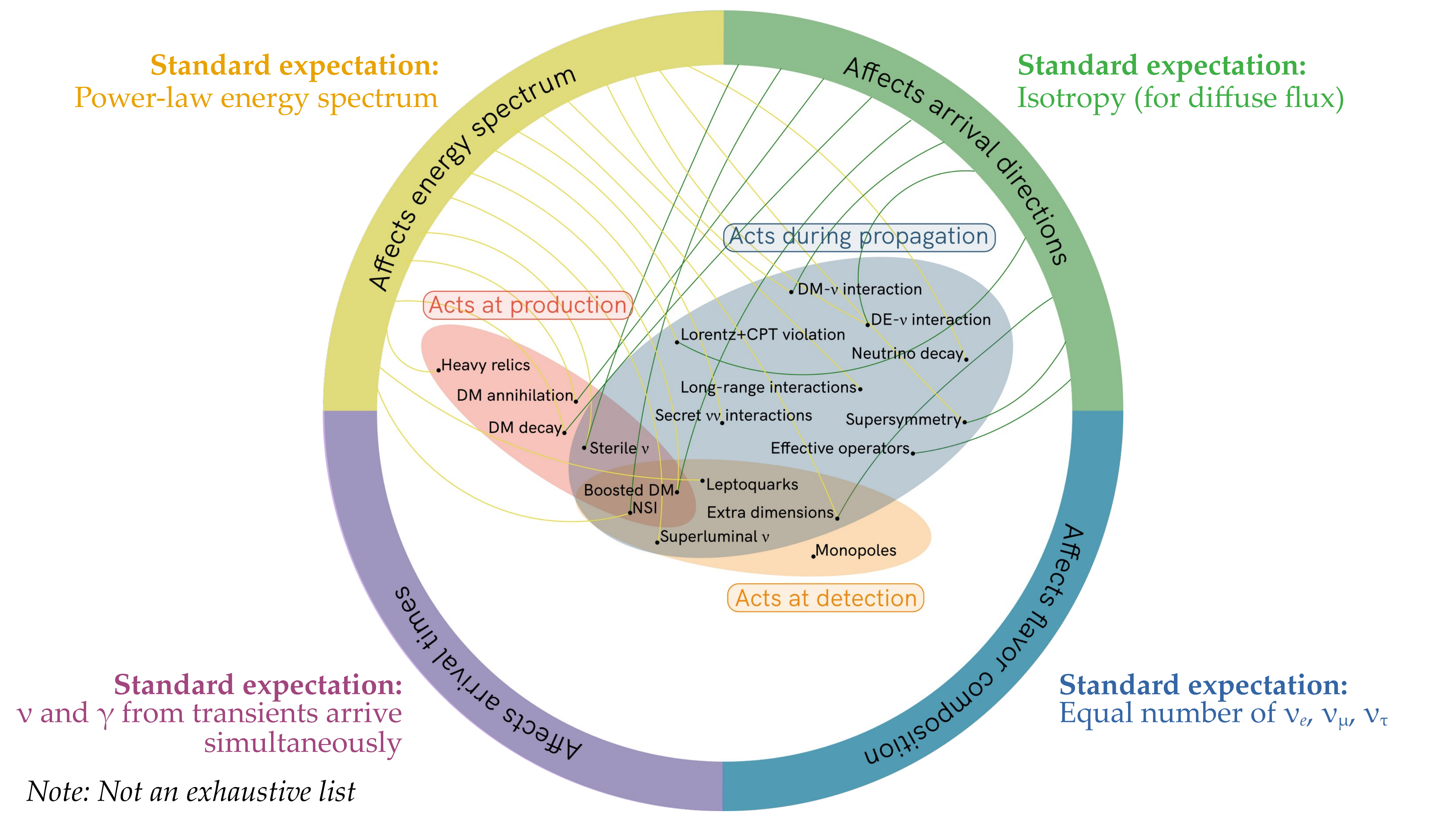
Note: Not an exhaustive list

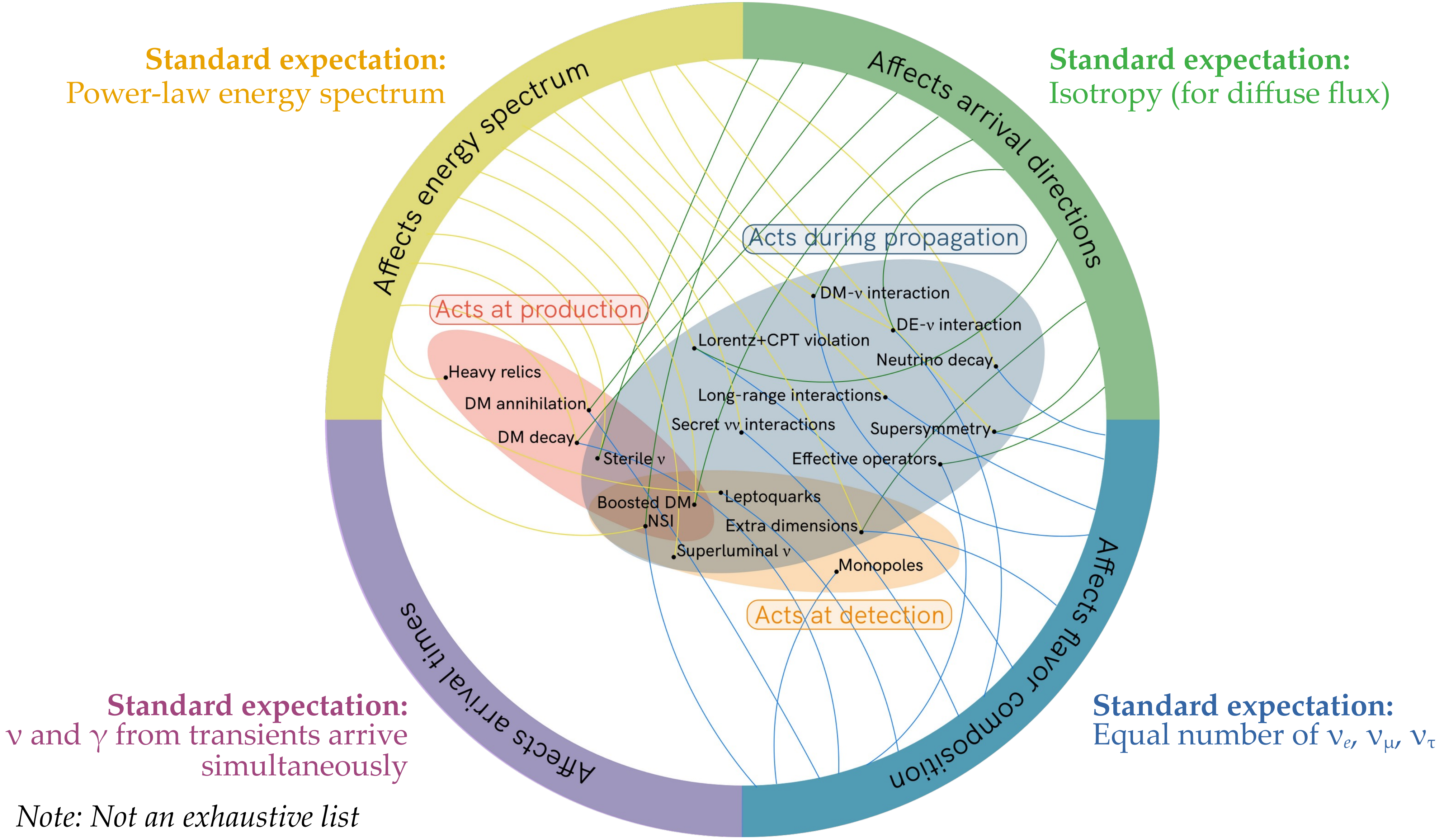


Note: Not an exhaustive list


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

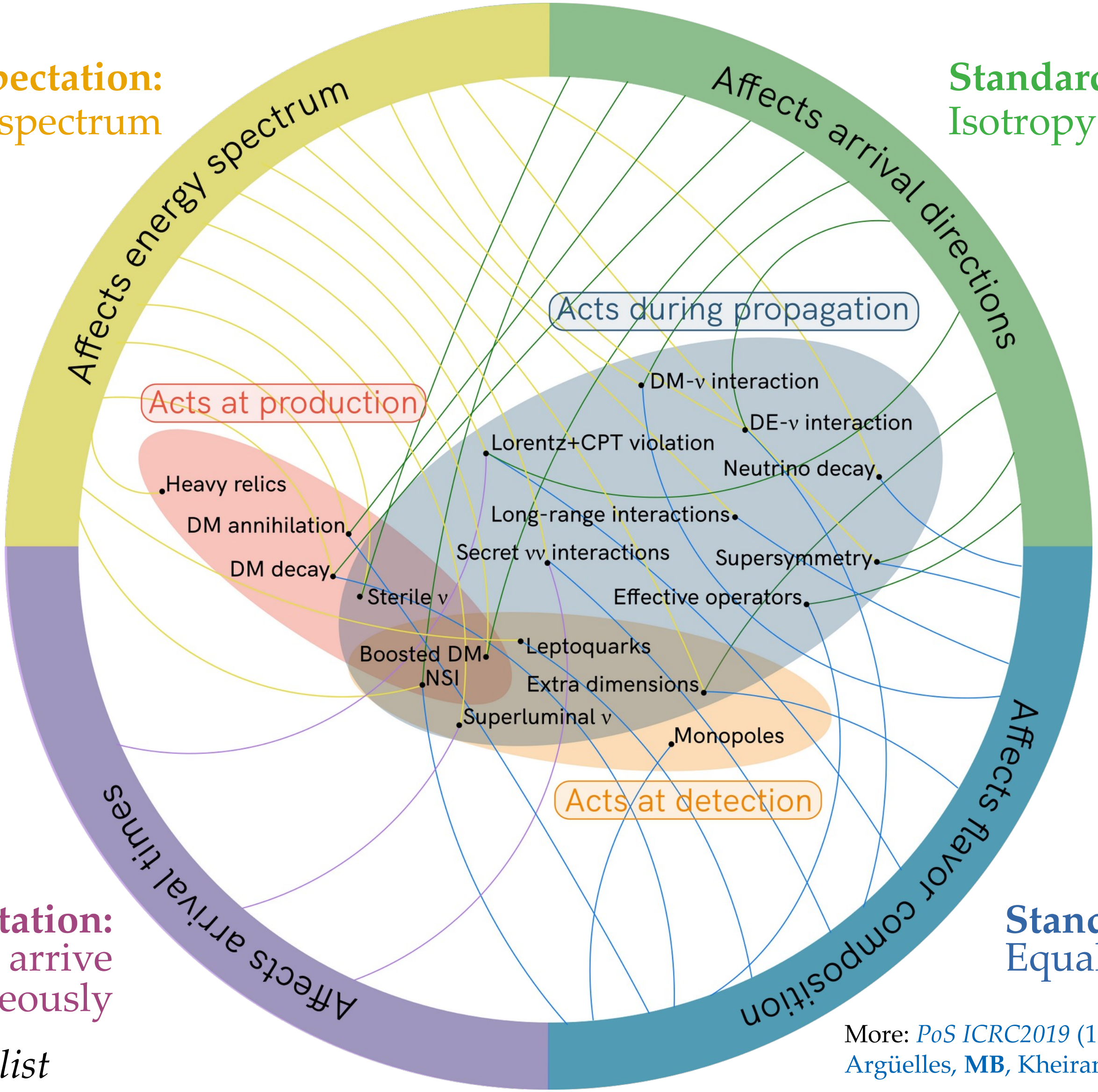

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT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


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
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts at production
Acts during propagation
Acts at detection
Heavy relics
DM annihilation
DM decay
Sterile ν
Boosted DM
NSI
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Long-range interactions
Secret νν interactions
Supersymmetry
Effective operators
Leptoquarks
Extra dimensions
Superluminal ν
Monopoles
Note: Not an exhaustive list


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
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts at production
Acts during propagation
Acts at detection
Heavy relics
DM annihilation
DM decay
Sterile ν
Boosted DM
NSI
Superluminal ν
Leptoquarks
Extra dimensions
Monopoles
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Long-range interactions
Secret νν interactions
Supersymmetry
Effective operators
Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

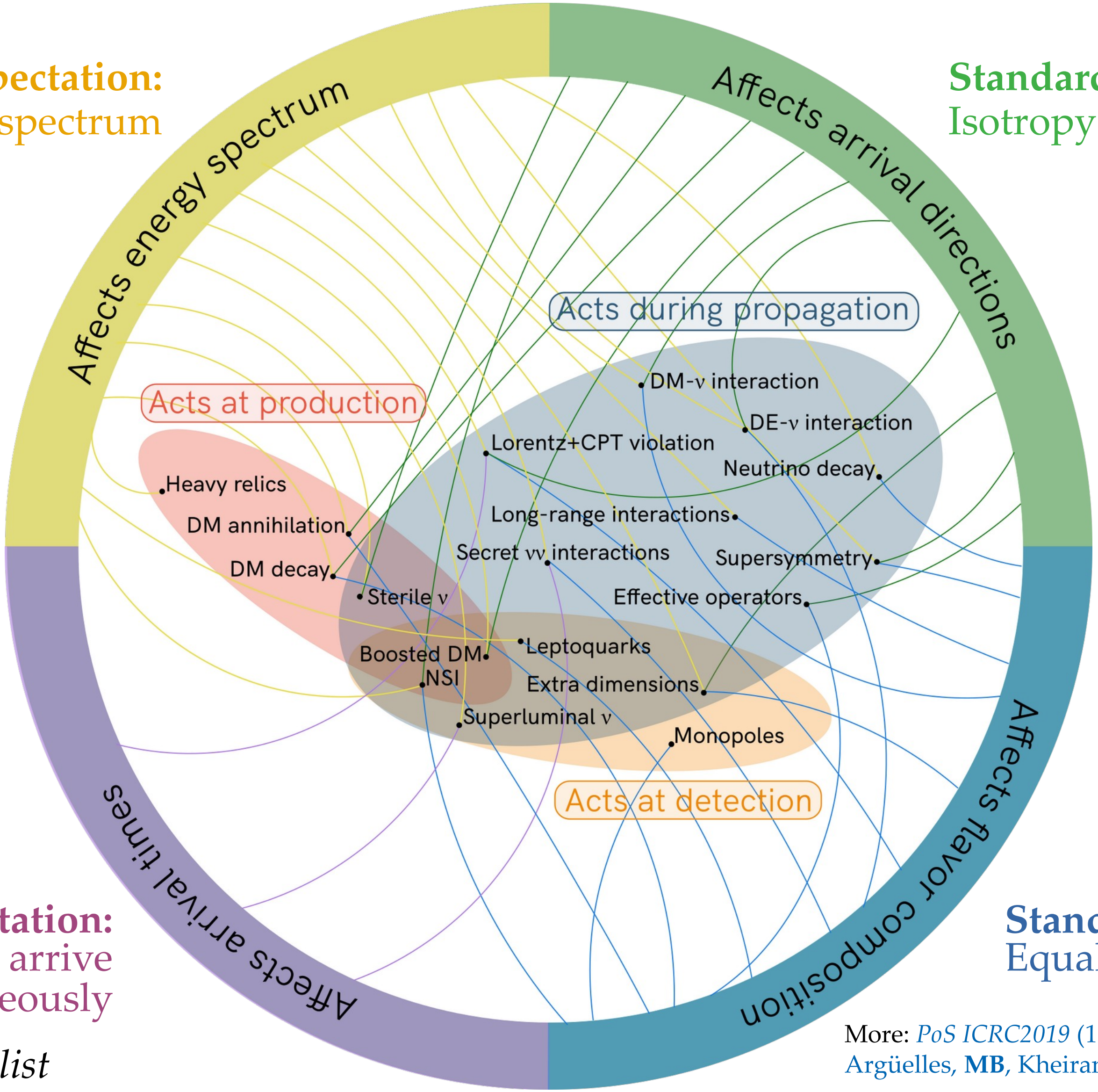
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

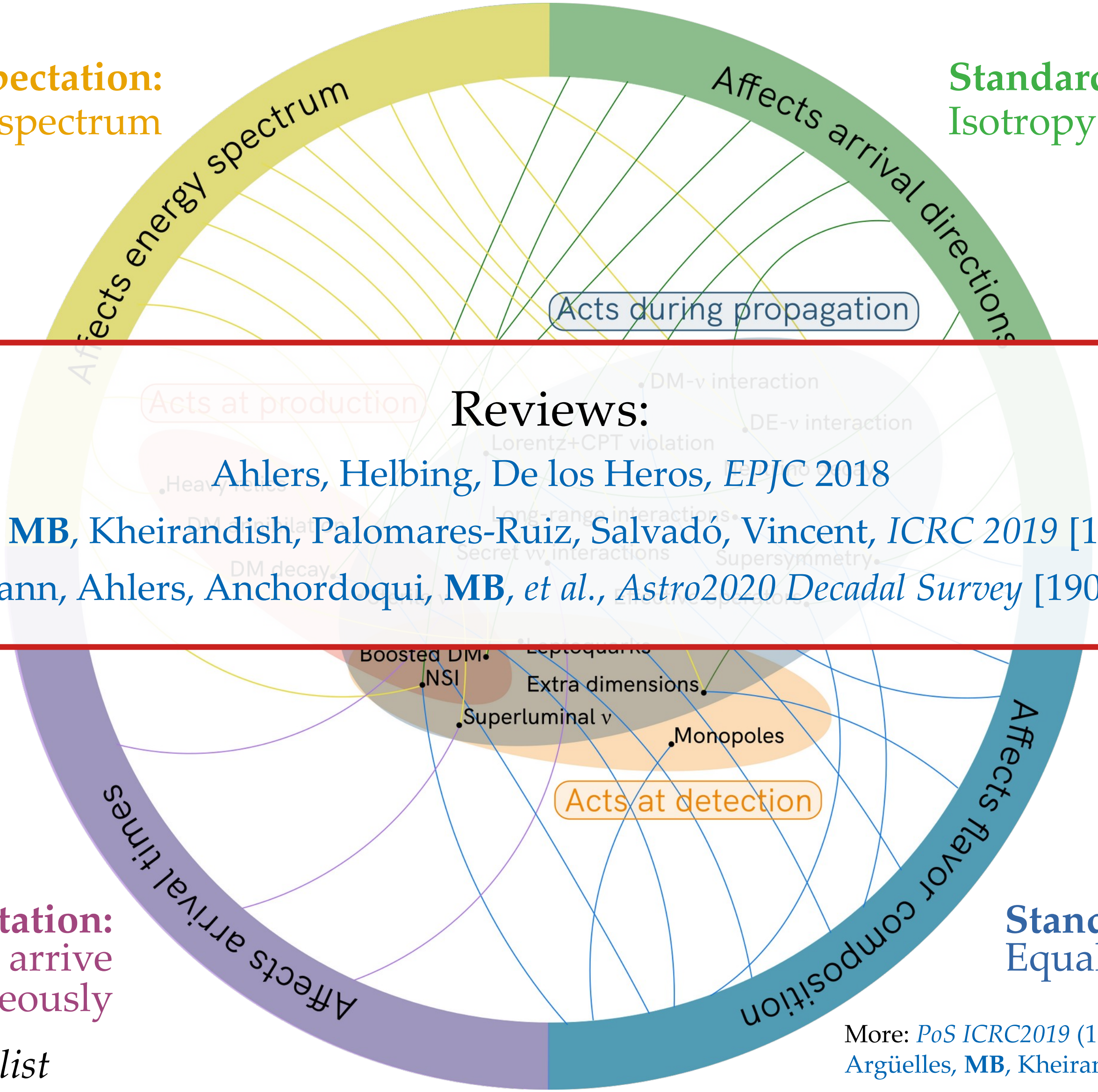
Note: Not an exhaustive list

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Reviews:

Ahlers, Helbing, De los Heros, *EPJC* 2018

Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC 2019* [1907.08690]

Ackermann, Ahlers, Anchordoqui, **MB**, *et al.*, *Astro2020 Decadal Survey* [1903.04333]

Standard expectation:
ν and γ from transients arrive simultaneously

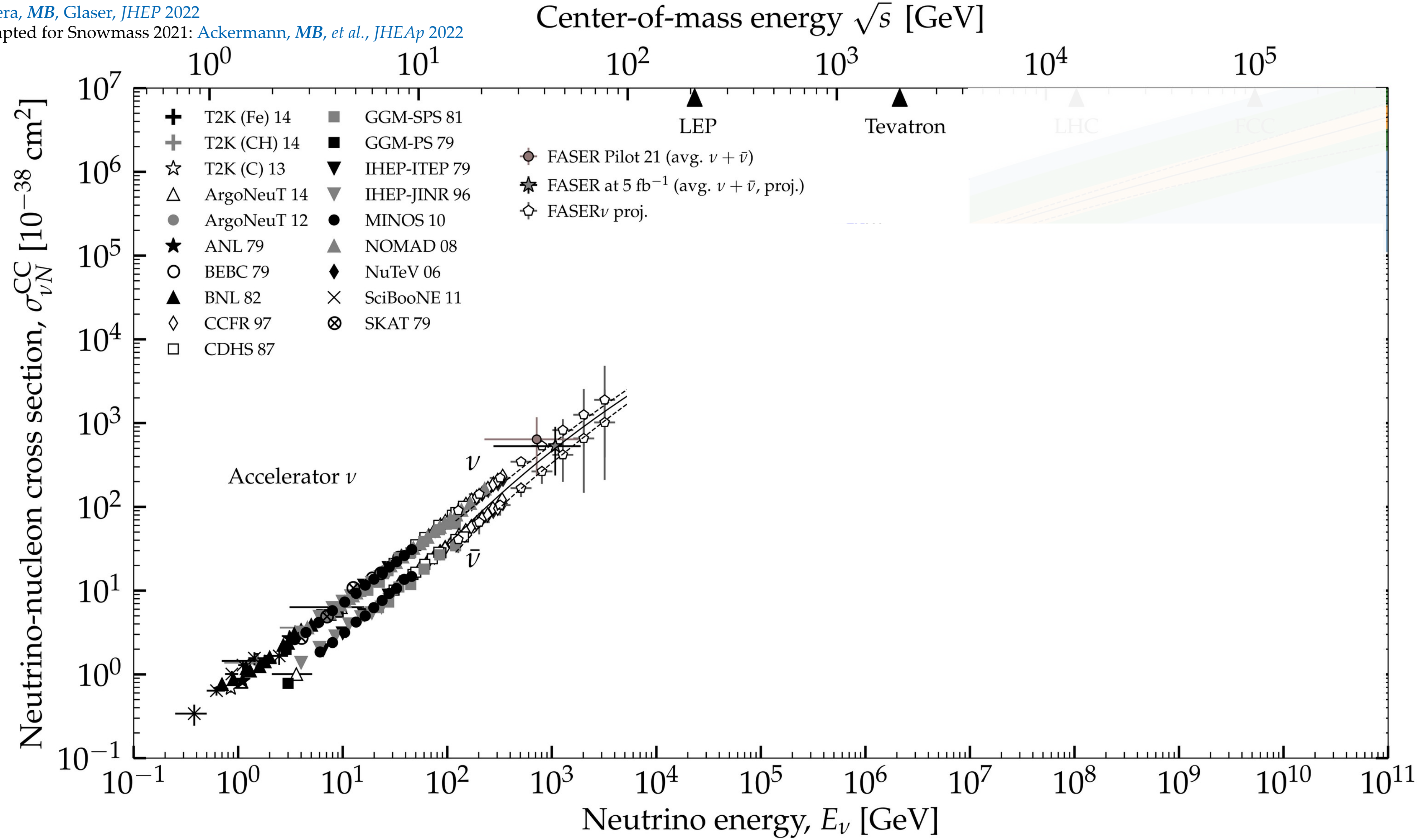
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

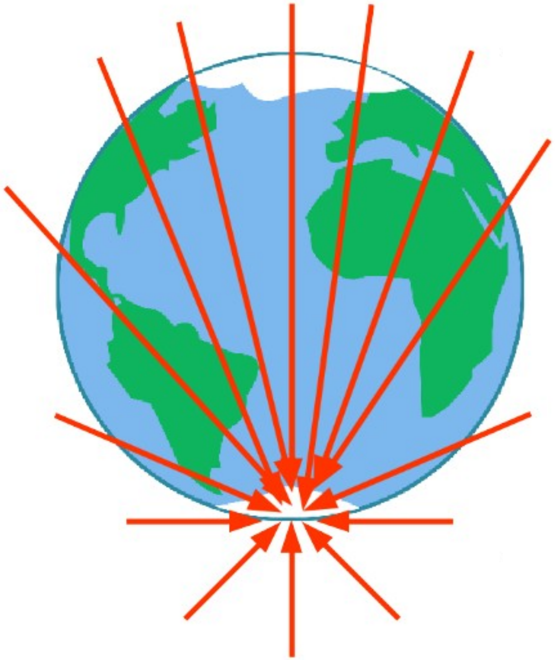
Measuring the UHE νN cross section

Valera, ***MB***, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, ***MB***, *et al.*, *JHEAp* 2022

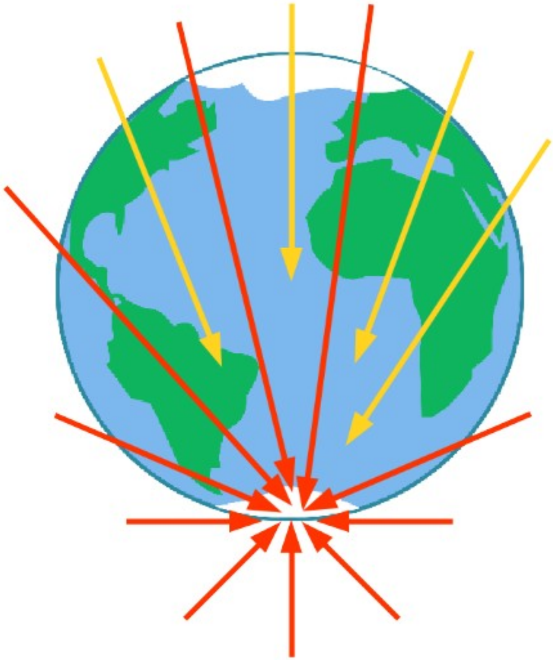


Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



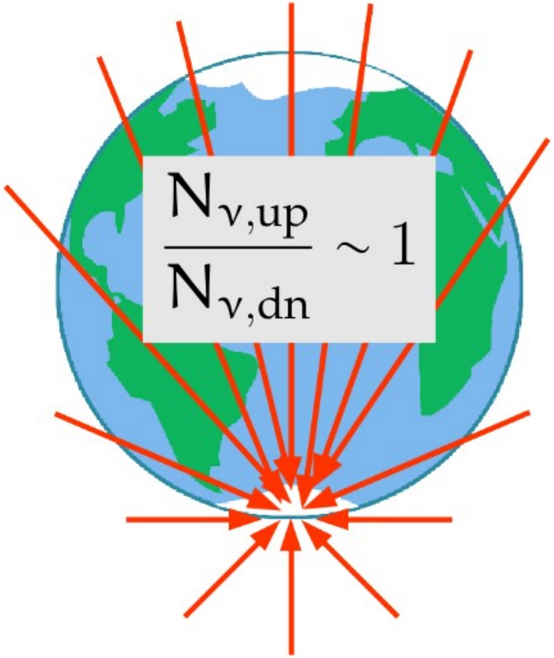
Above ~ 10 TeV: Earth is opaque



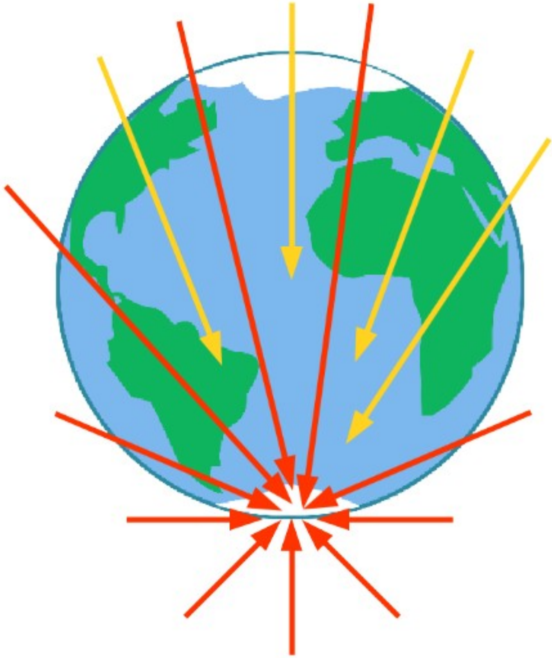
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



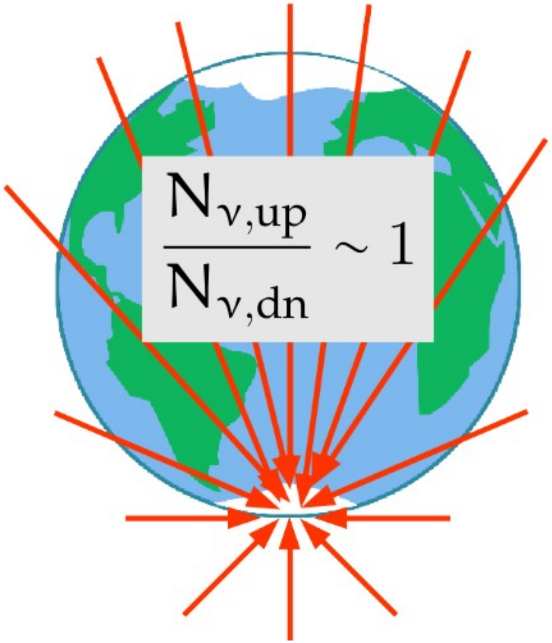
Above ~ 10 TeV: Earth is opaque



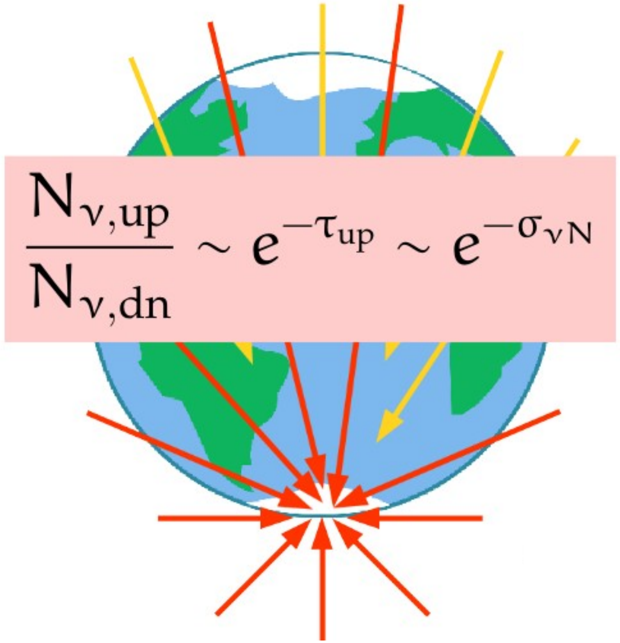
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent

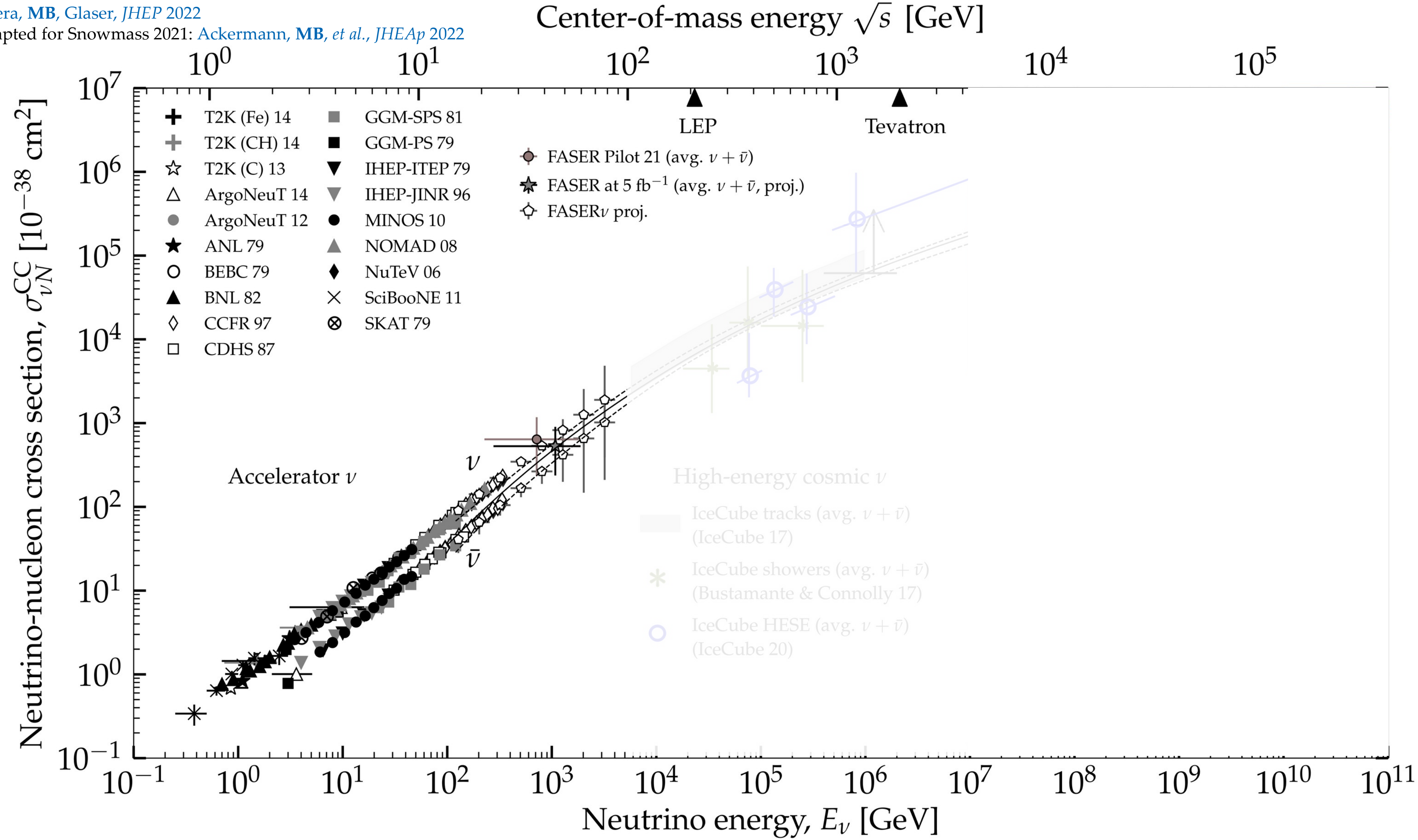


Above ~ 10 TeV: Earth is opaque

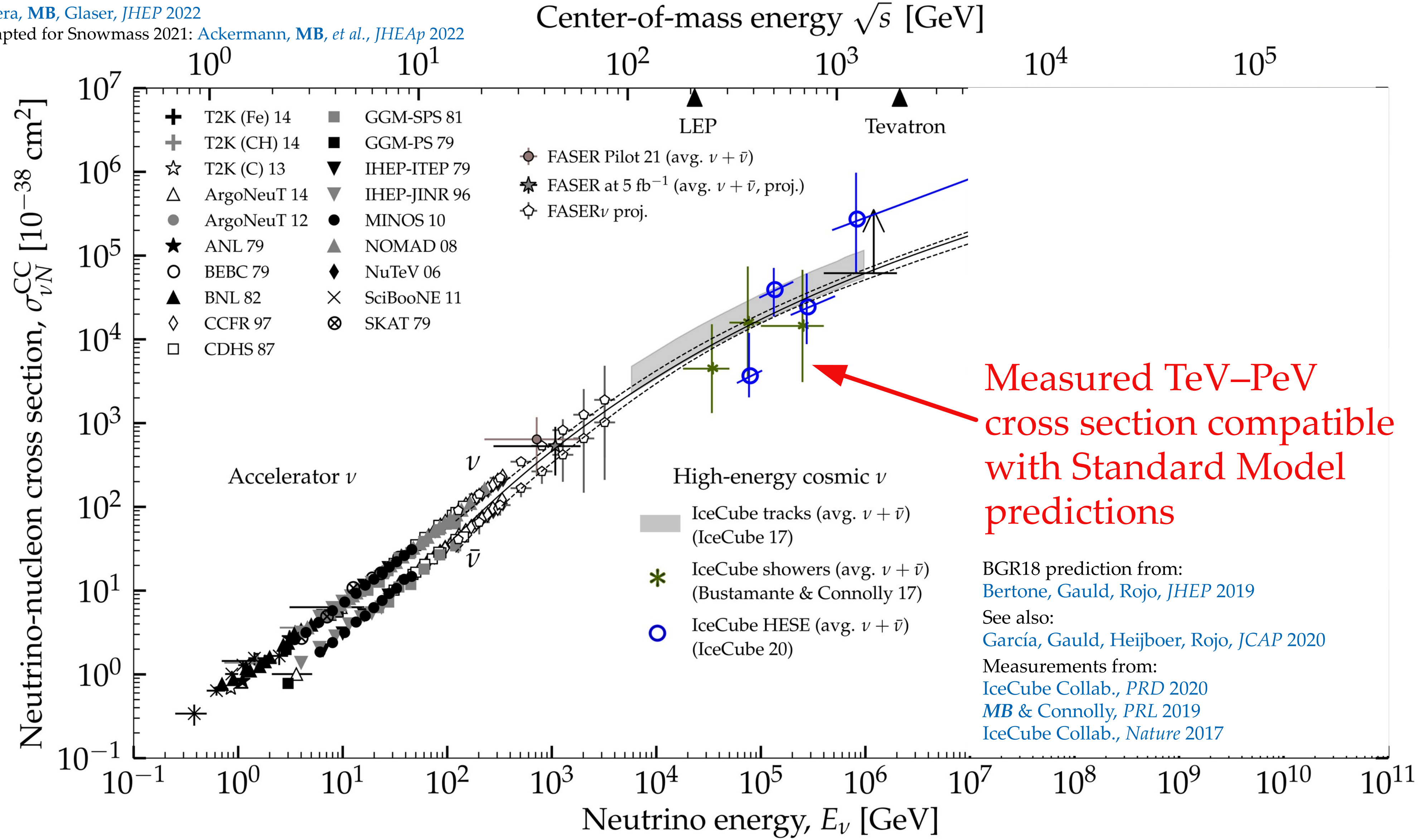


Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

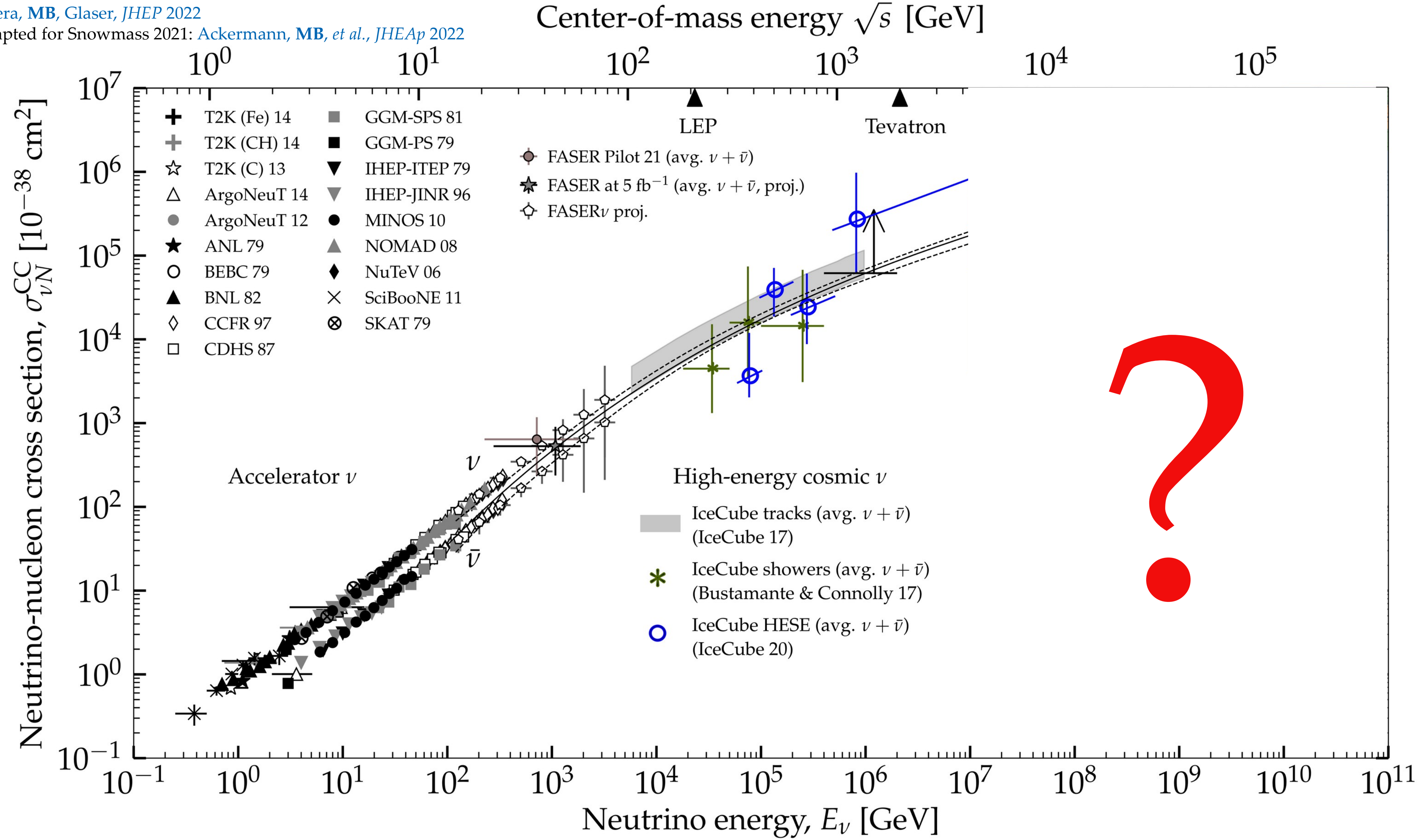
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



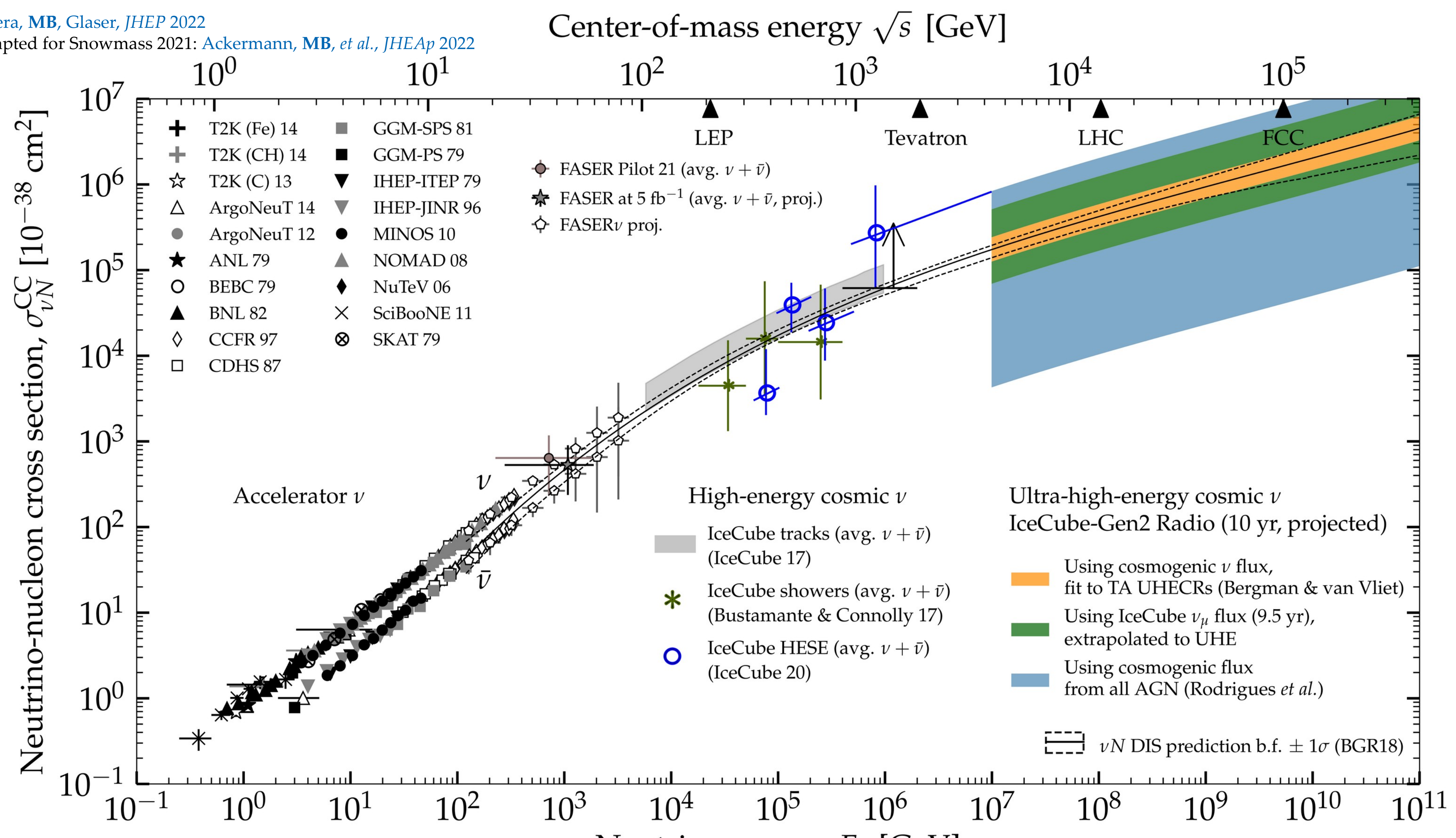
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022

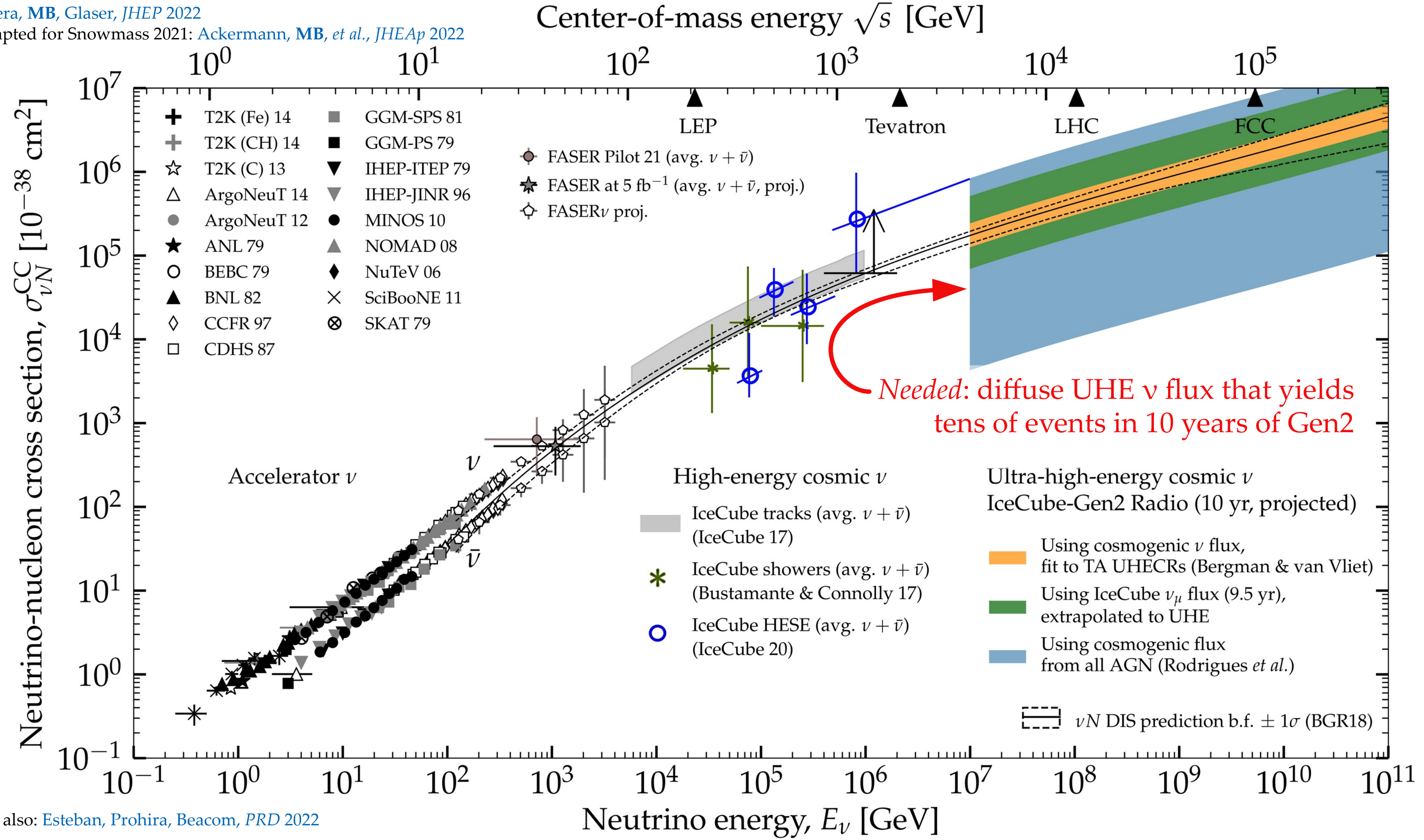


Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



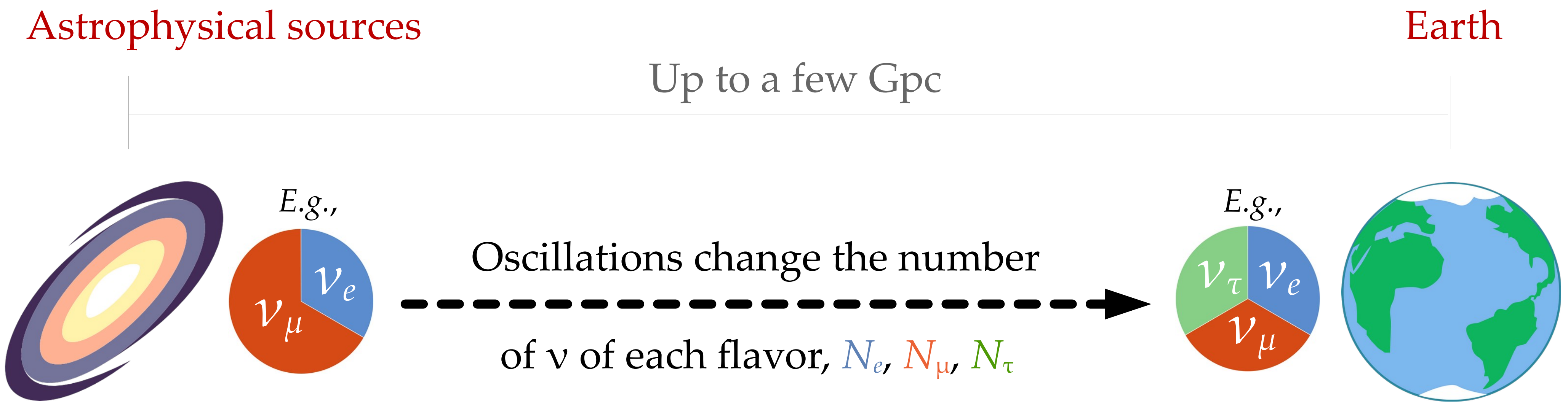
See also: Esteban, Prohira, Beacom, *PRD* 2022

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



See also: Esteban, Prohira, Beacom, *PRD* 2022

Measuring the UHE flavor composition

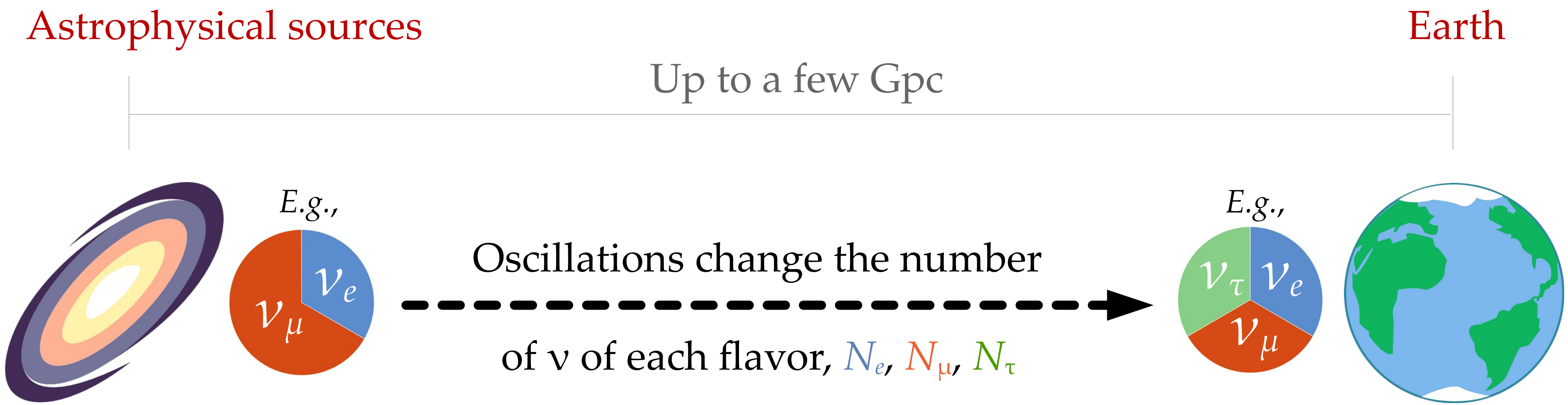


Different production mechanisms yield different flavor ratios:

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

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

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



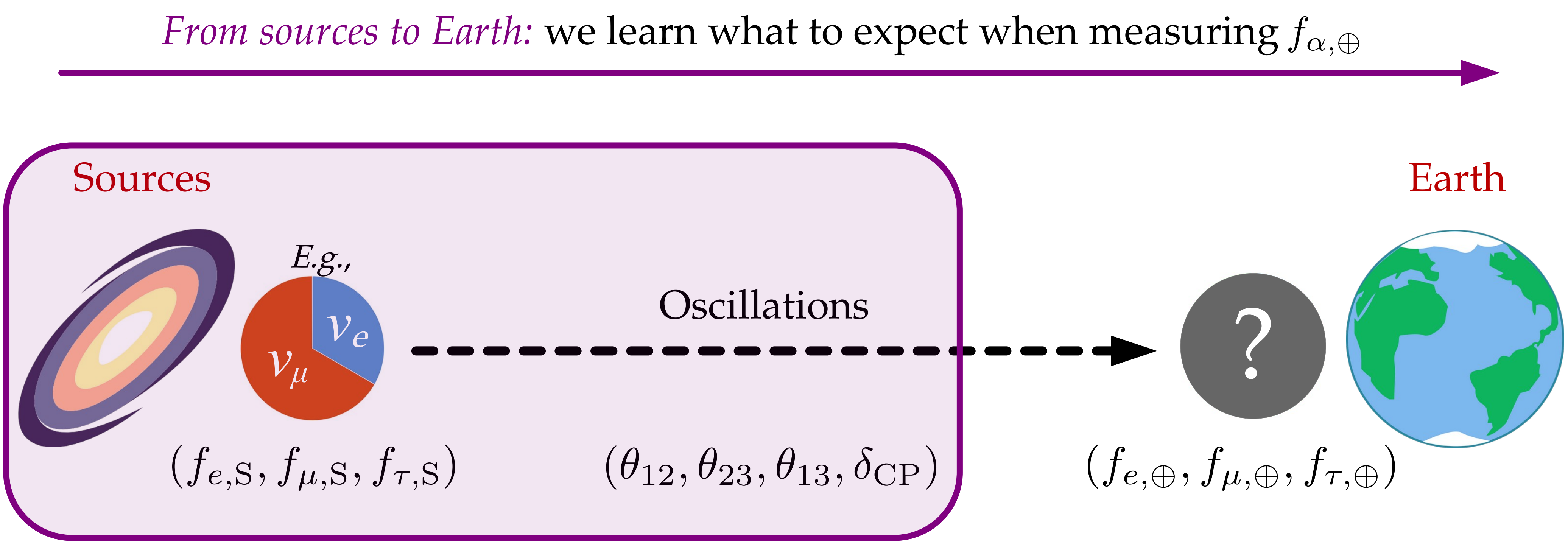
Different production mechanisms yield different flavor ratios:

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

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

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

Standard oscillations
or
new physics



From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

One likely TeV–PeV ν production scenario:

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

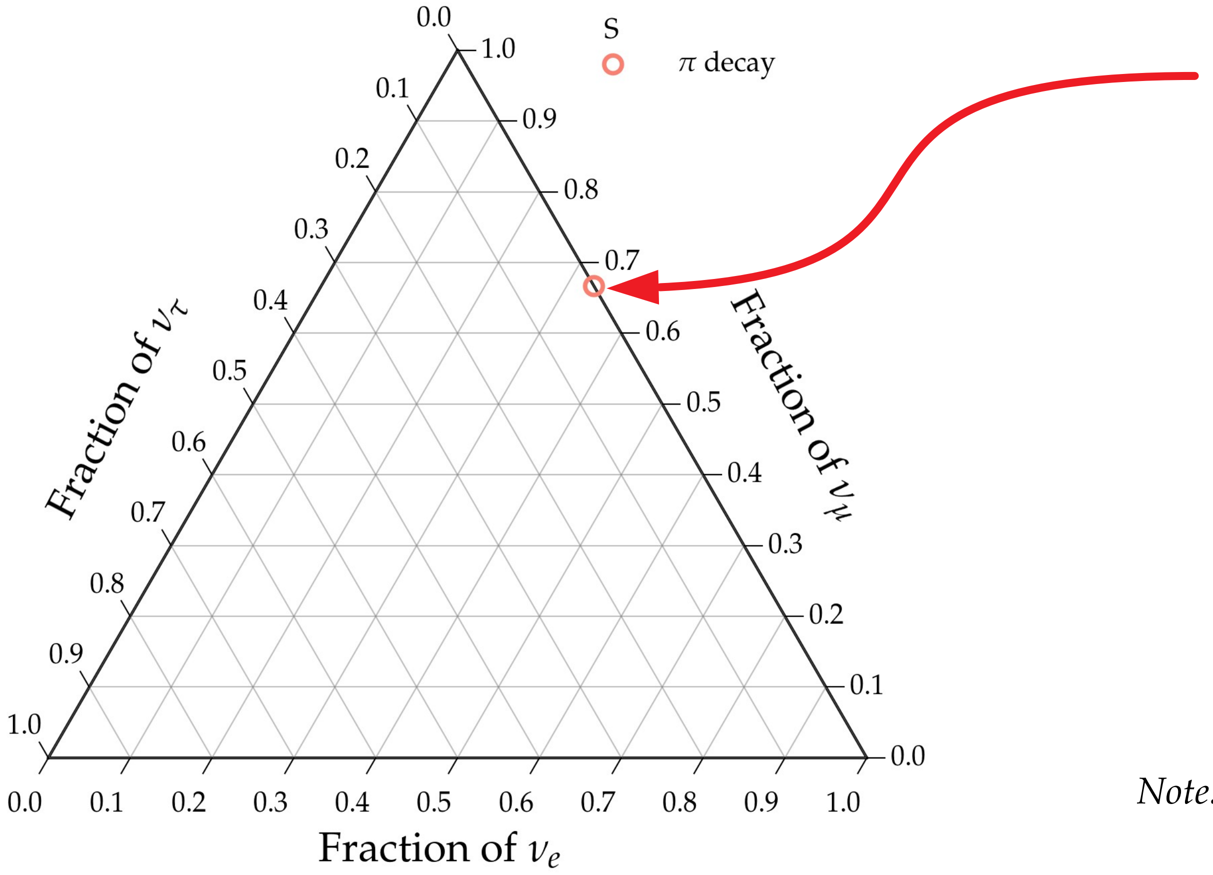
Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

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



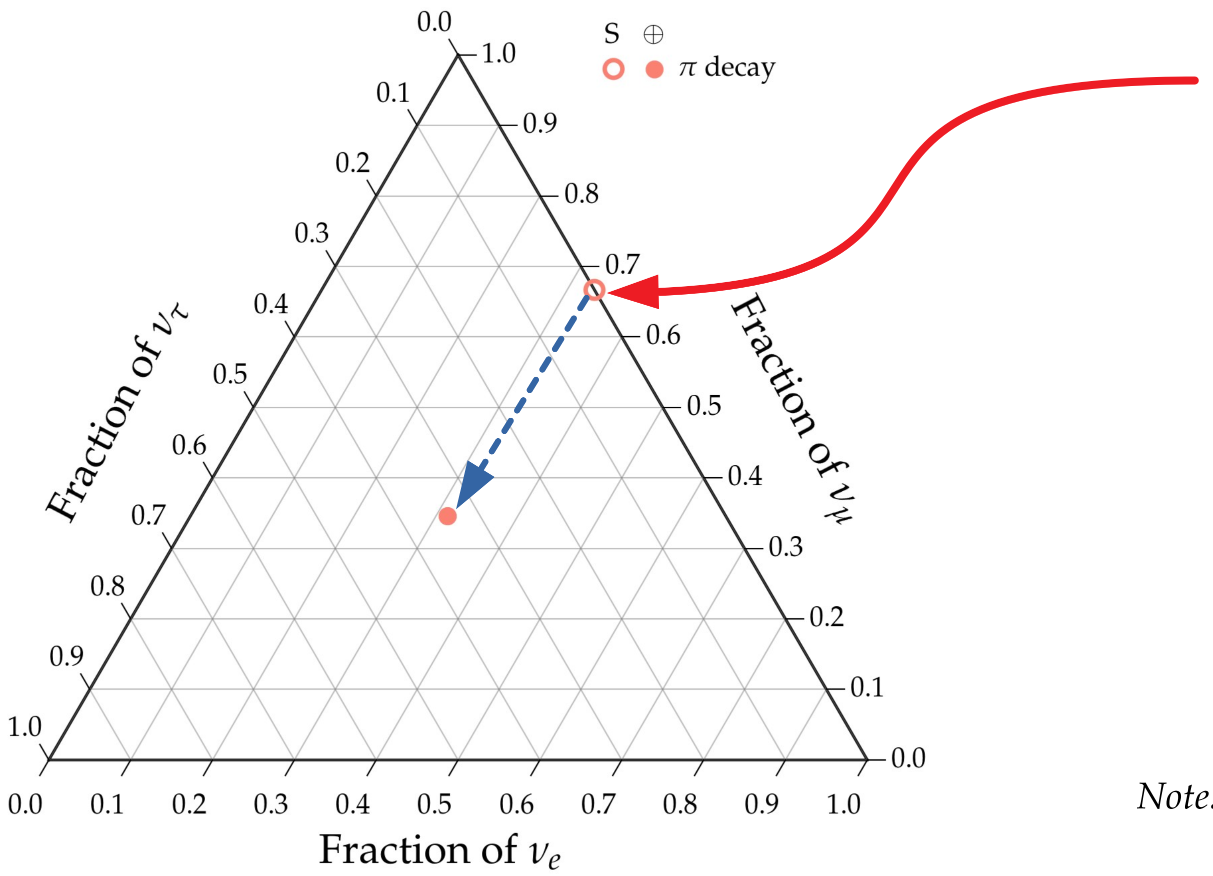
Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

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



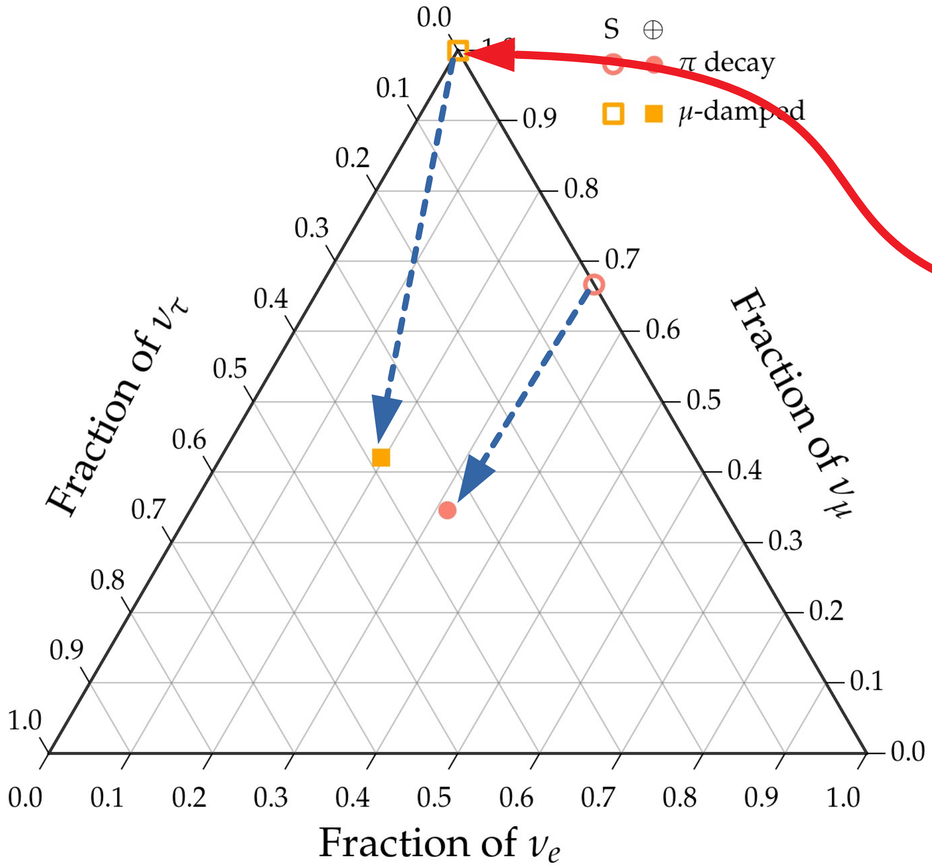
Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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

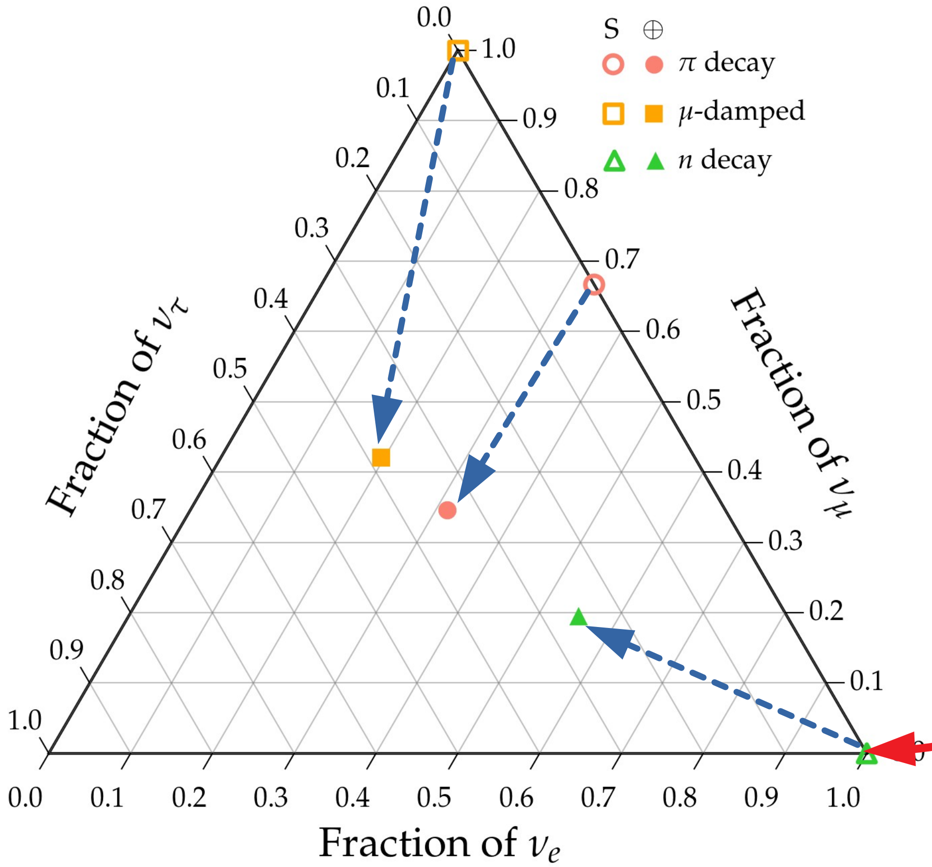
Muon damped

$(0:1:0)_S$

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

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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

Muon damped

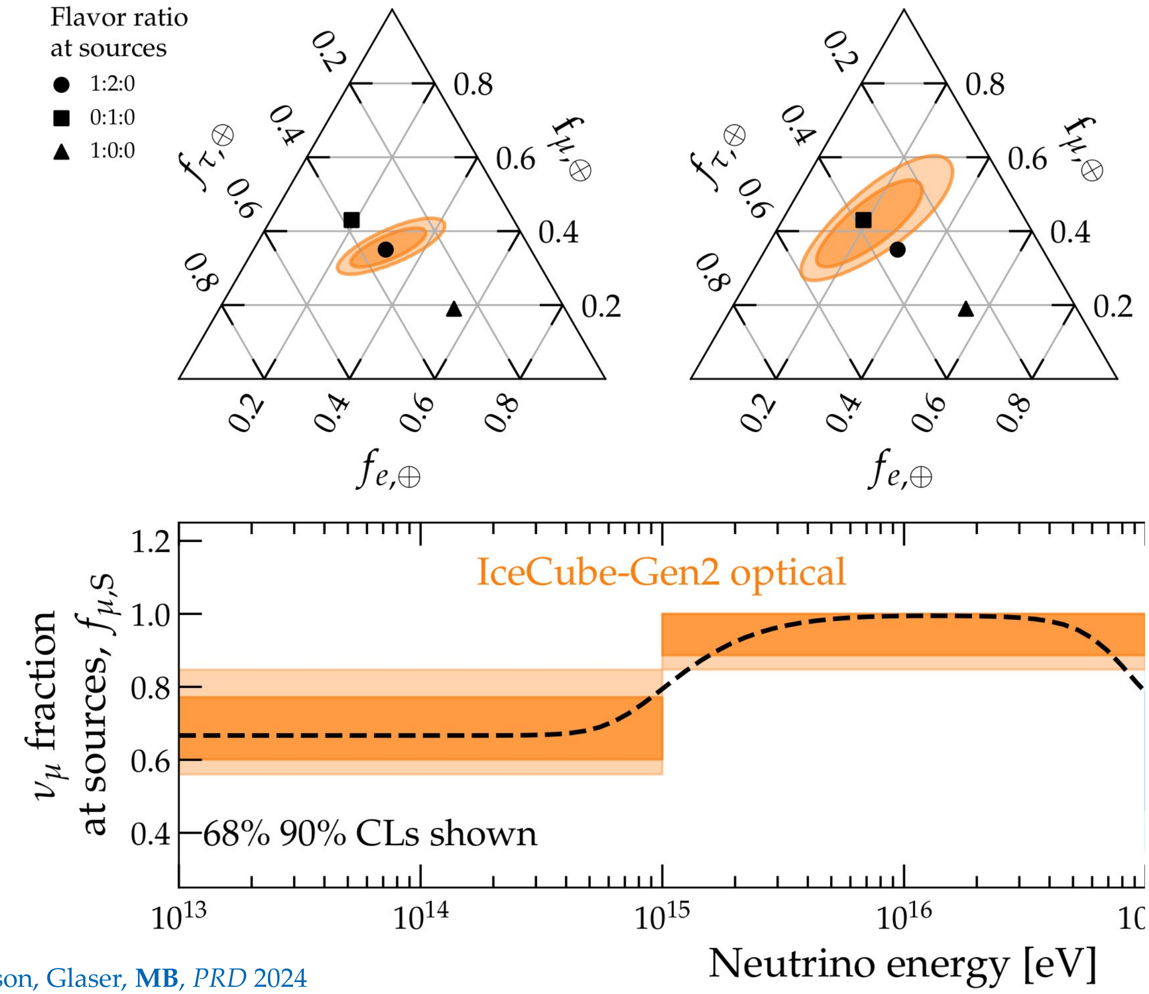
$(0 : 1 : 0)_S$

Neutron decay

$(1 : 0 : 0)_S$

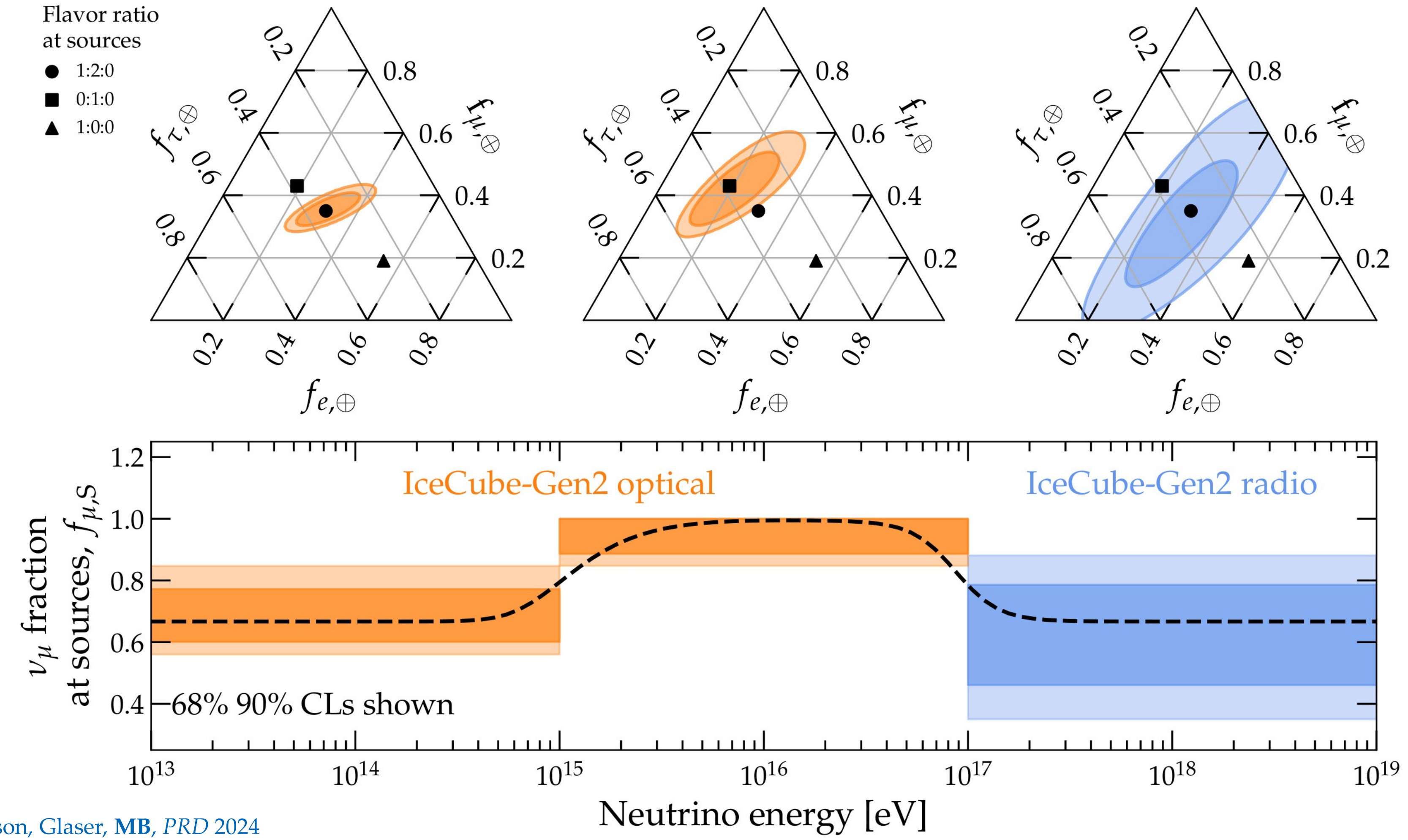
Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

Measuring the ultra-high-energy νN cross section



Coleman, Ericsson, Glaser, **MB**, *PRD* 2024
Testagrossa, Fiorillo, **MB**, *PRD* 2024

Measuring the ultra-high-energy νN cross section



Coleman, Ericsson, Glaser, **MB**, *PRD* 2024
Testagrossa, Fiorillo, **MB**, *PRD* 2024

New physics in flavor composition

Use the flavor sensitivity to test new physics:

New physics in flavor composition

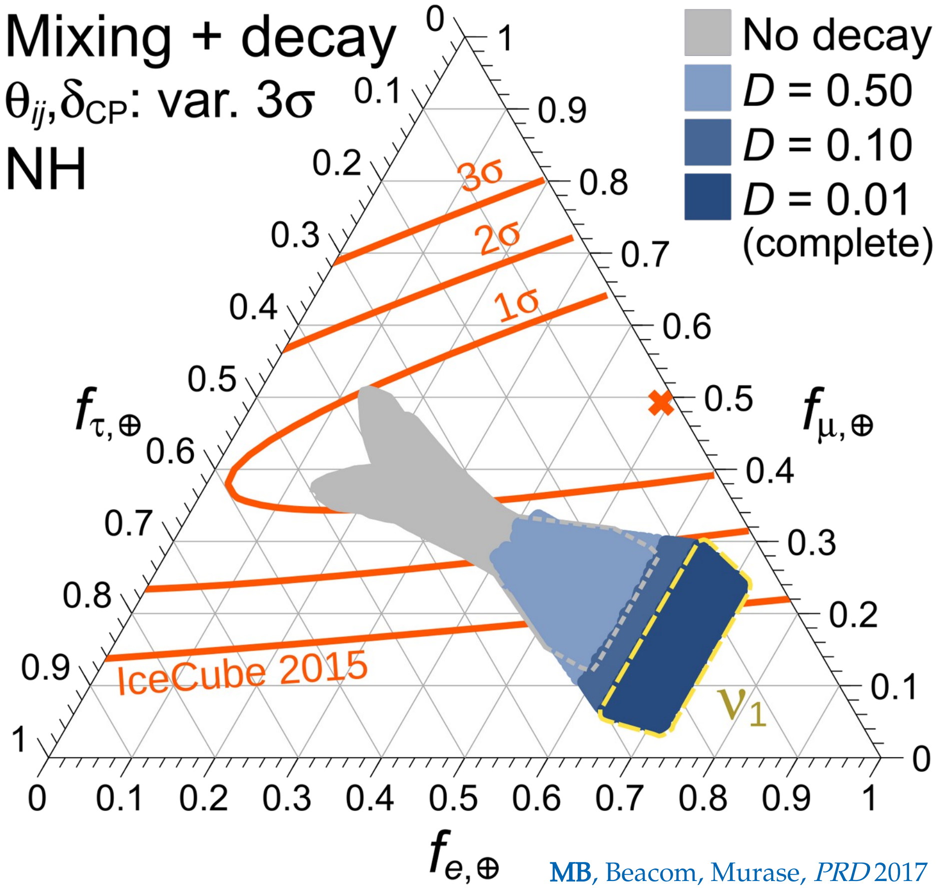
Use the flavor sensitivity to test new physics:

Reviews: Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Use the flavor sensitivity to test new physics:

- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, ***MB***, Winter, JCAP 2010; ***MB***, Beacom, Winter, *PRL* 2015; ***MB***, Beacom, Murase, *PRD* 2017]



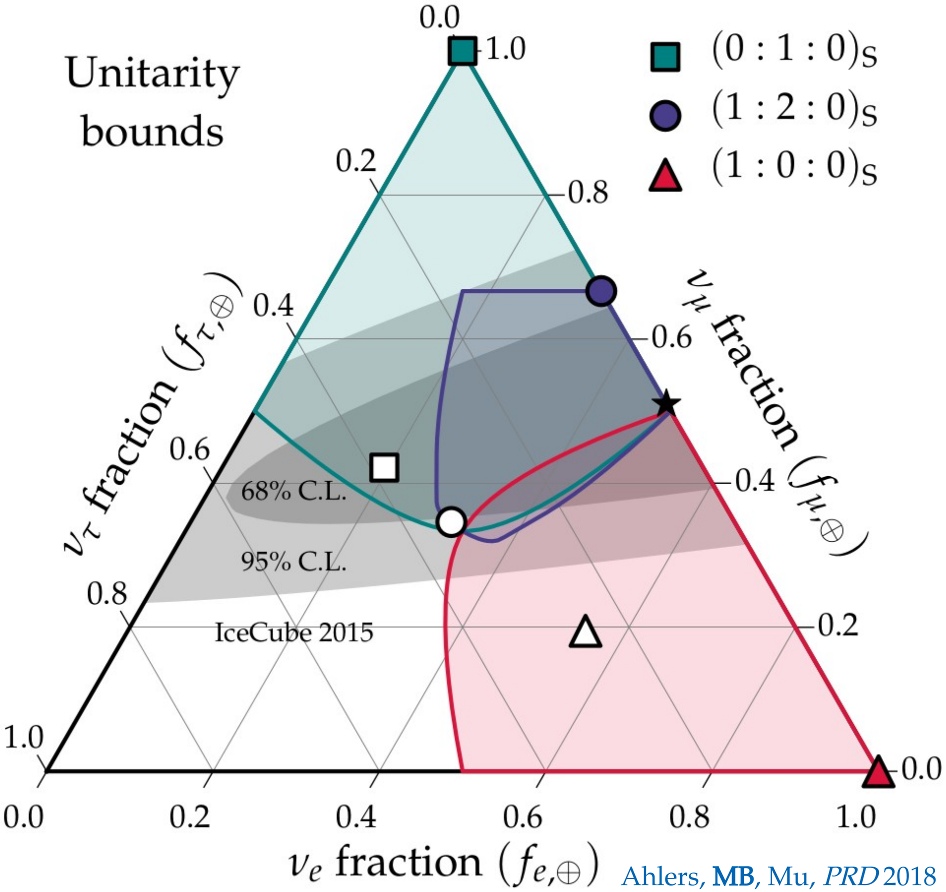
MB, Beacom, Murase, *PRD* 2017

Reviews: Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Use the flavor sensitivity to test new physics:

- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, ***MB***, Winter, JCAP 2010; ***MB***, Beacom, Winter, *PRL* 2015; ***MB***, Beacom, Murase, *PRD* 2017]
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, ***MB***, Mu, *PRD* 2018; Ahlers, ***MB***, Nortvig, *JCAP* 2021]



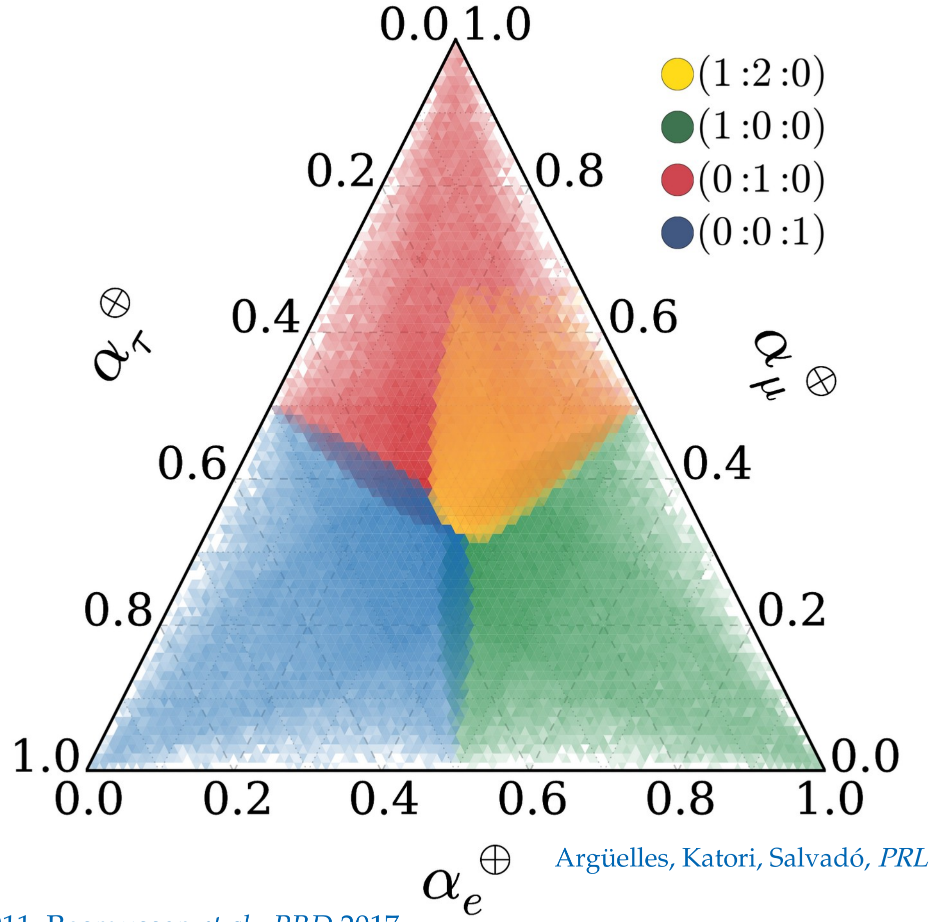
Ahlers, **MB**, Mu, *PRD* 2018

Reviews: Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Use the flavor sensitivity to test new physics:

- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, ***MB***, Winter, JCAP 2010; ***MB***, Beacom, Winter, *PRL* 2015; ***MB***, Beacom, Murase, *PRD* 2017]
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, ***MB***, Mu, *PRD* 2018; Ahlers, ***MB***, Nortvig, *JCAP* 2021]
- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; ***MB***, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]



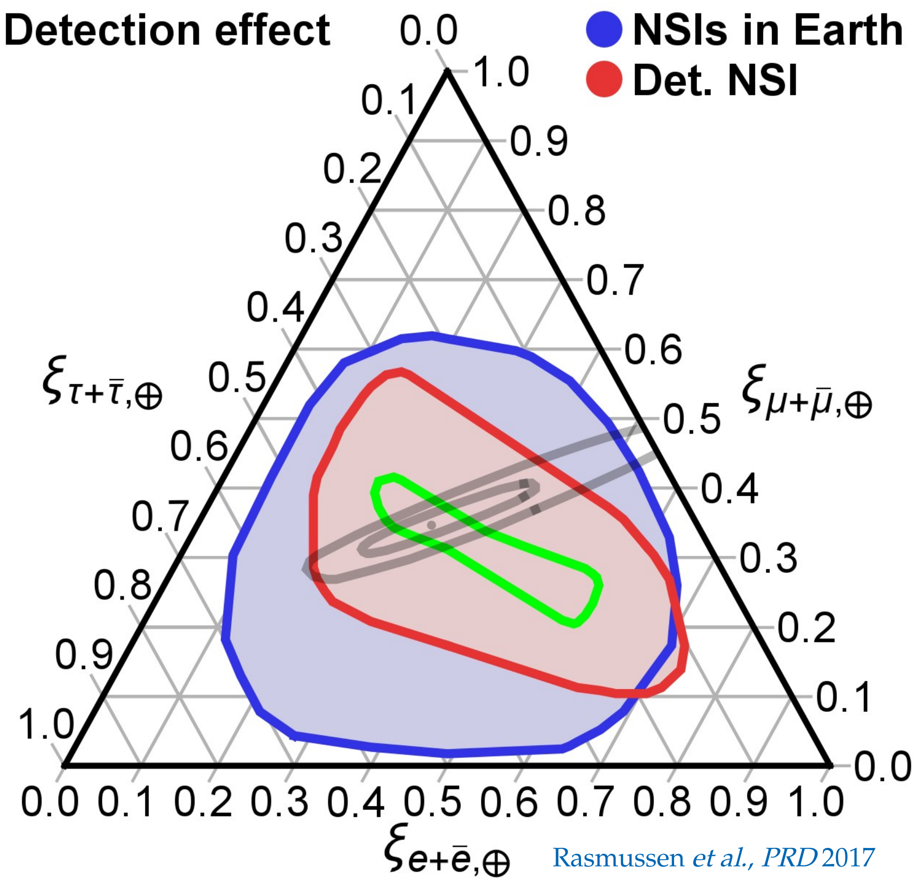
Argüelles, Katori, Salvadó, *PRL* 2015

Reviews: Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Use the flavor sensitivity to test new physics:

- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, ***MB***, Winter, JCAP 2010; ***MB***, Beacom, Winter, *PRL* 2015; ***MB***, Beacom, Murase, *PRD* 2017]
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, ***MB***, Mu, *PRD* 2018; Ahlers, ***MB***, Nortvig, *JCAP* 2021]
- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; ***MB***, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]
- Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]



Rasmussen *et al.*, *PRD* 2017

Reviews: Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Use the flavor sensitivity to test new physics:

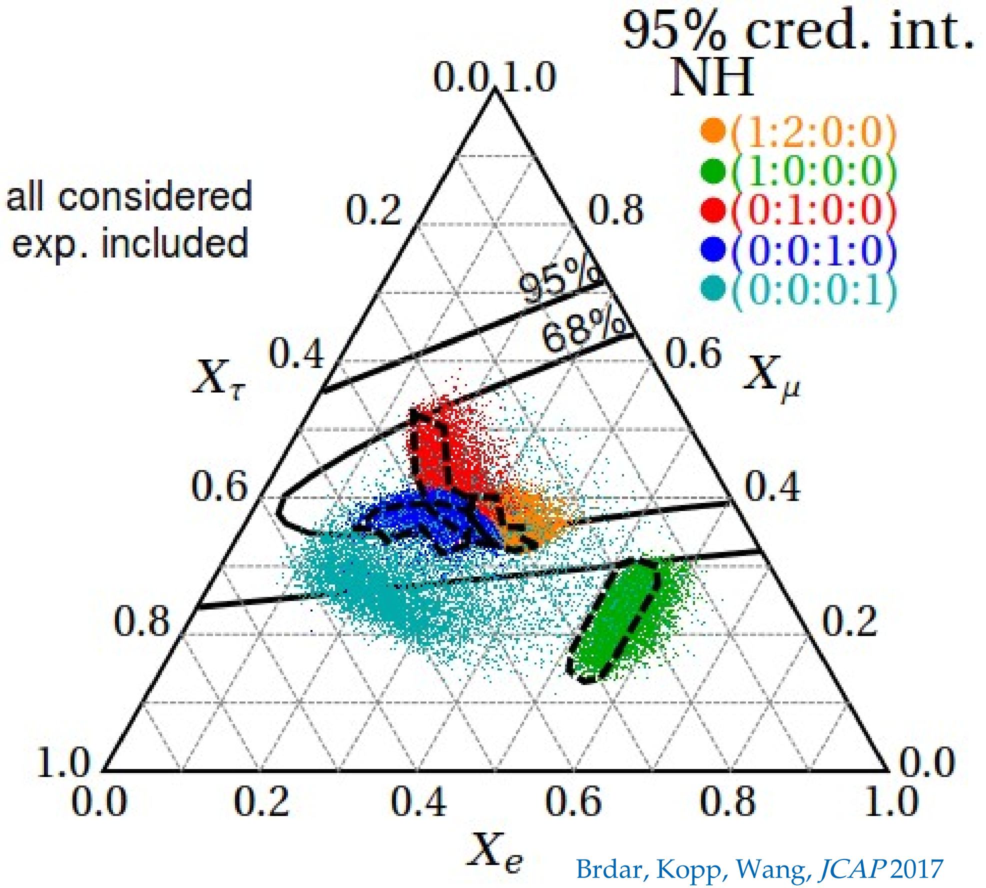
- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, ***MB***, Winter, JCAP 2010; ***MB***, Beacom, Winter, *PRL* 2015; ***MB***, Beacom, Murase, *PRD* 2017]

- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, ***MB***, Mu, *PRD* 2018; Ahlers, ***MB***, Nortvig, *JCAP* 2021]

- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; ***MB***, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]

- Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]

- Active-sterile ν mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, ***MB***, *JCAP* 2021]



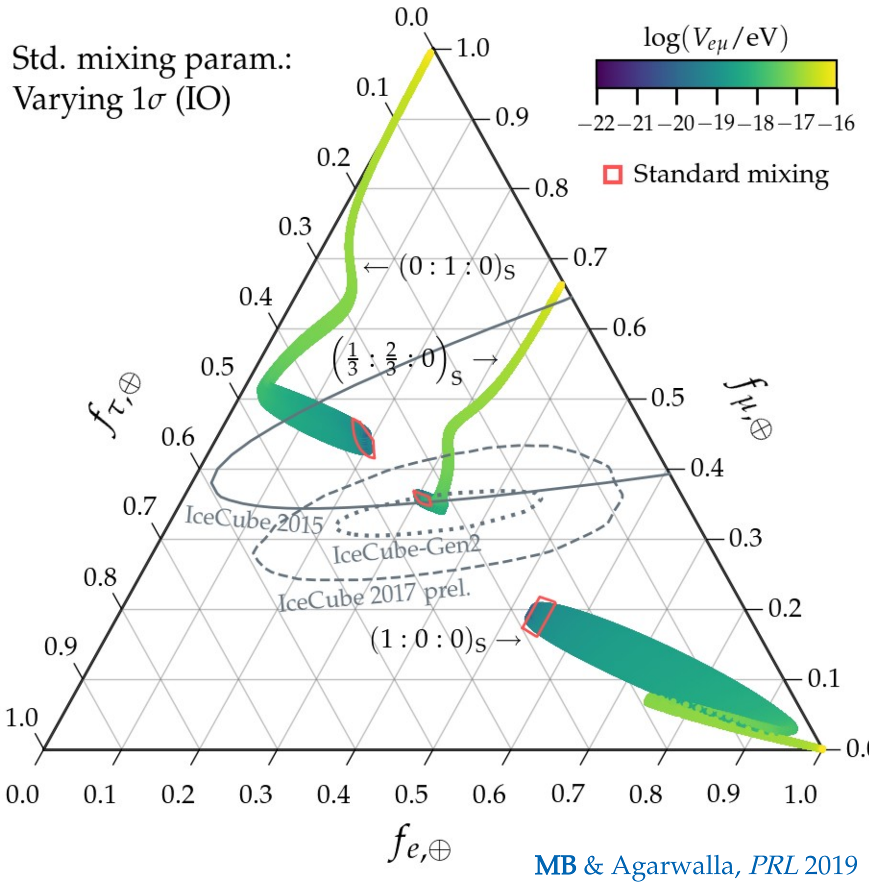
Brdar, Kopp, Wang, *JCAP* 2017

Reviews: Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Use the flavor sensitivity to test new physics:

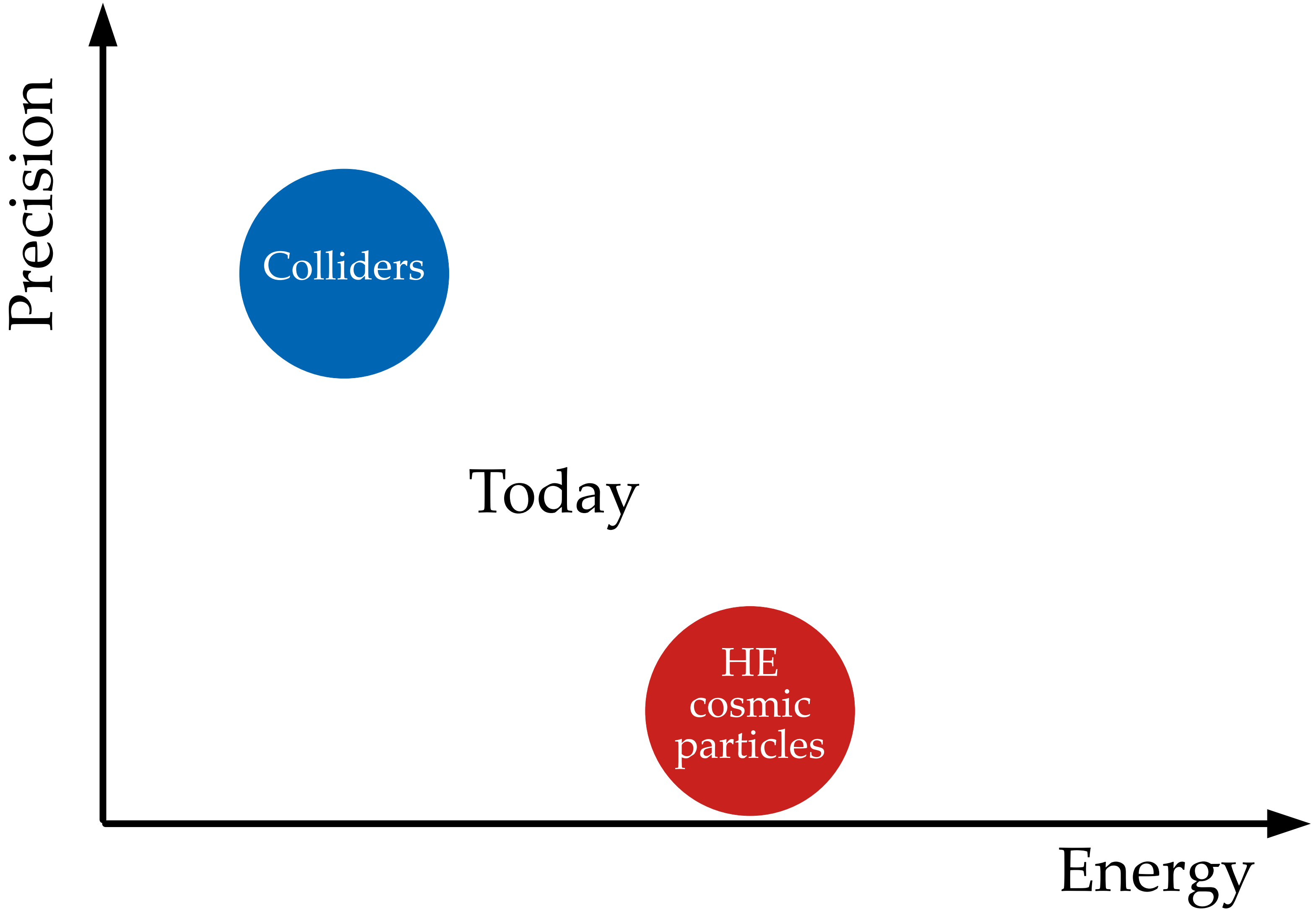
- ▶ Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, ***MB***, Winter, JCAP 2010; ***MB***, Beacom, Winter, *PRL* 2015; ***MB***, Beacom, Murase, *PRD* 2017]
- ▶ Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, ***MB***, Mu, *PRD* 2018; Ahlers, ***MB***, Nortvig, *JCAP* 2021]
- ▶ Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; ***MB***, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]
- ▶ Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]
- ▶ Active-sterile ν mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, ***MB***, *JCAP* 2021]
- ▶ Long-range *e*ν interactions
  [***MB*** & Agarwalla, *PRL* 2019]

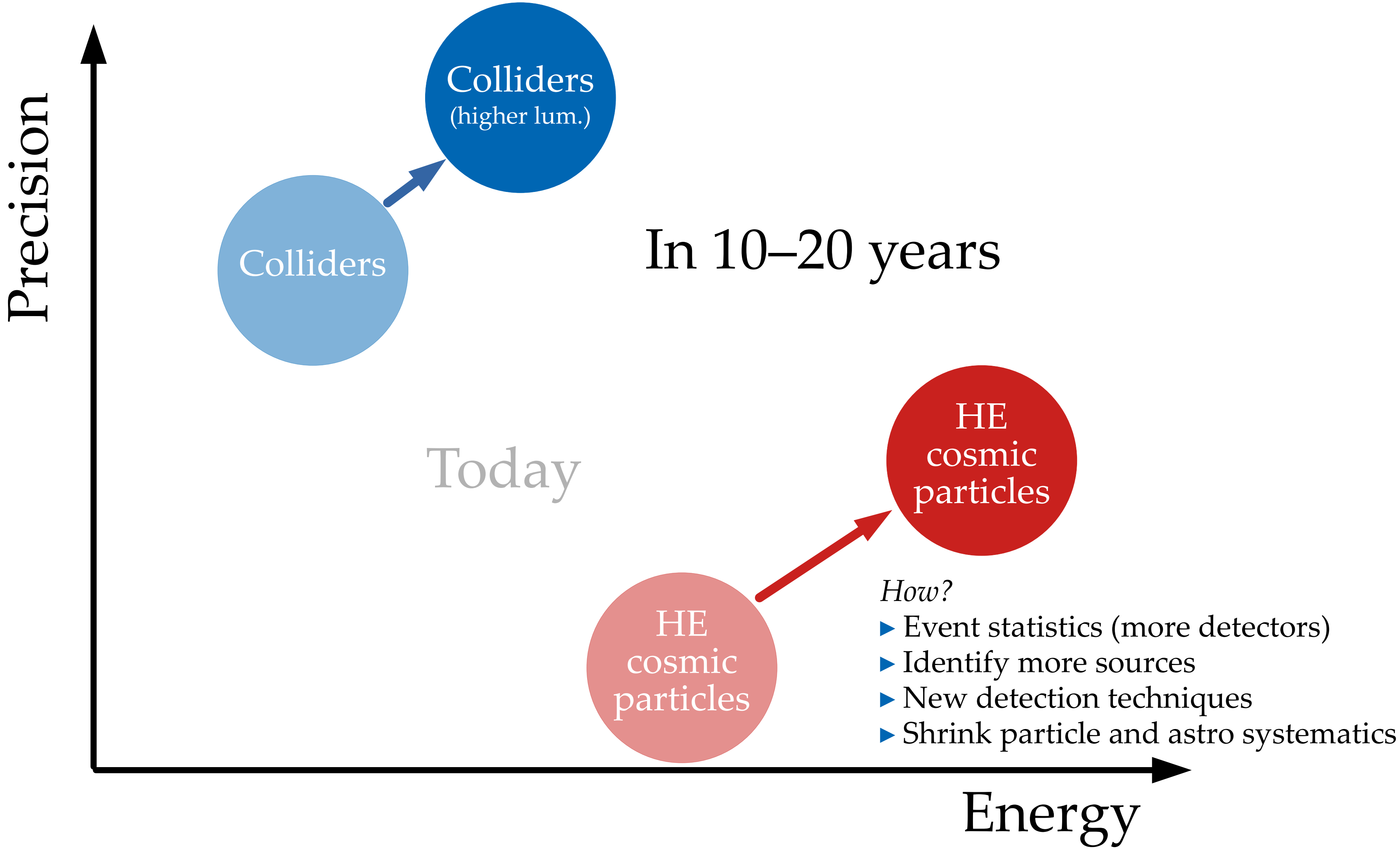


MB & Agarwalla, *PRL* 2019

Reviews: Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

Closing thoughts


Precision
Colliders
Today
HE
cosmic
particles
Energy


Precision
Colliders
(higher lum.)
Colliders
In 10–20 years
Today
HE cosmic particles
HE cosmic particles
How?
▸ Event statistics (more detectors)
▸ Identify more sources
▸ New detection techniques
▸ Shrink particle and astro systematics
Energy

Recommendation #1: Embrace the mess

BSM searches must comprehensively include SM, astrophysical, and detector uncertainties, using unbiased priors.

Recommendation #1: Embrace the mess

BSM searches must comprehensively include SM, astrophysical, and detector uncertainties, using unbiased priors.

Recommendation #2: Work together more

More joint analyses of IceCube + KM3NeT (+ others?) mean higher chances of more UHE data (or constraints) faster.

Recommendation #1: Embrace the mess

BSM searches must comprehensively include SM, astrophysical, and detector uncertainties, using unbiased priors.

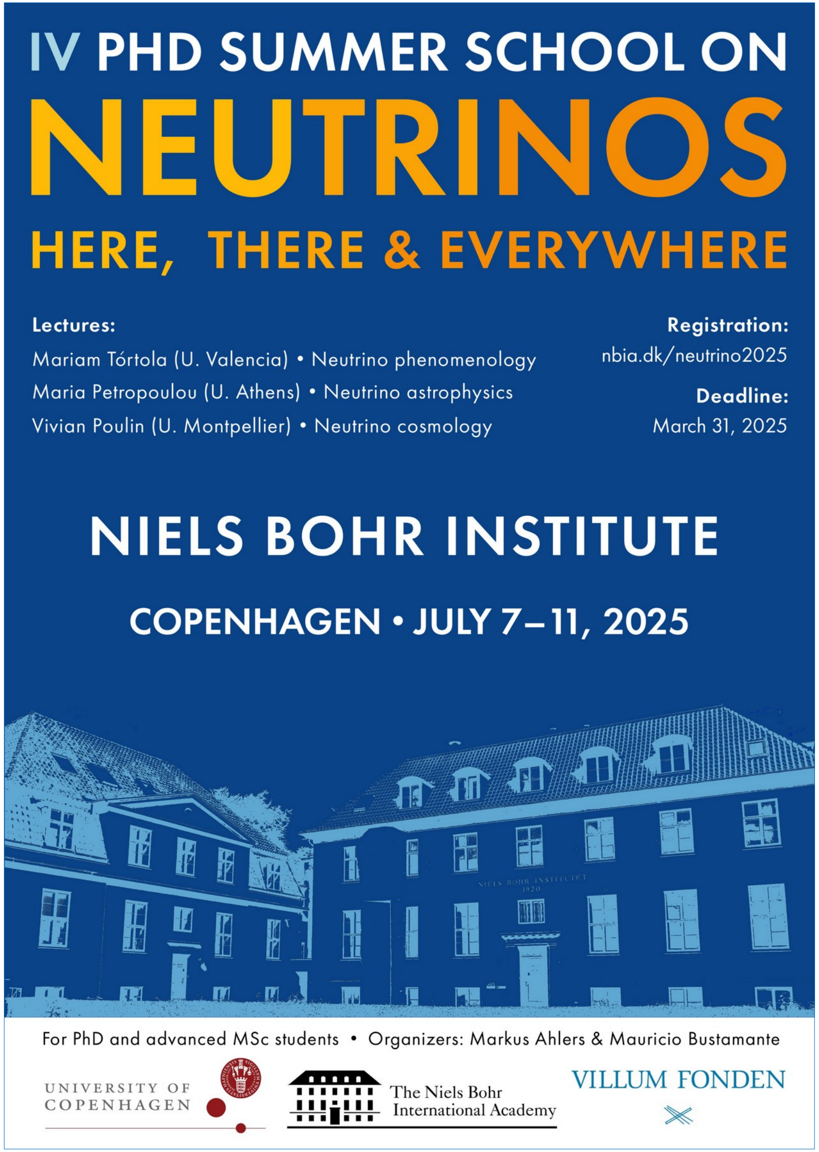
Recommendation #2: Work together more

More joint analyses of IceCube + KM3NeT (+ others?) mean higher chances of more UHE data (or constraints) faster.

Recommendation #3: Make detailed detector response public

Provide phenomenologists with effective areas, smearing matrices, Monte Carlo samples of detected events.

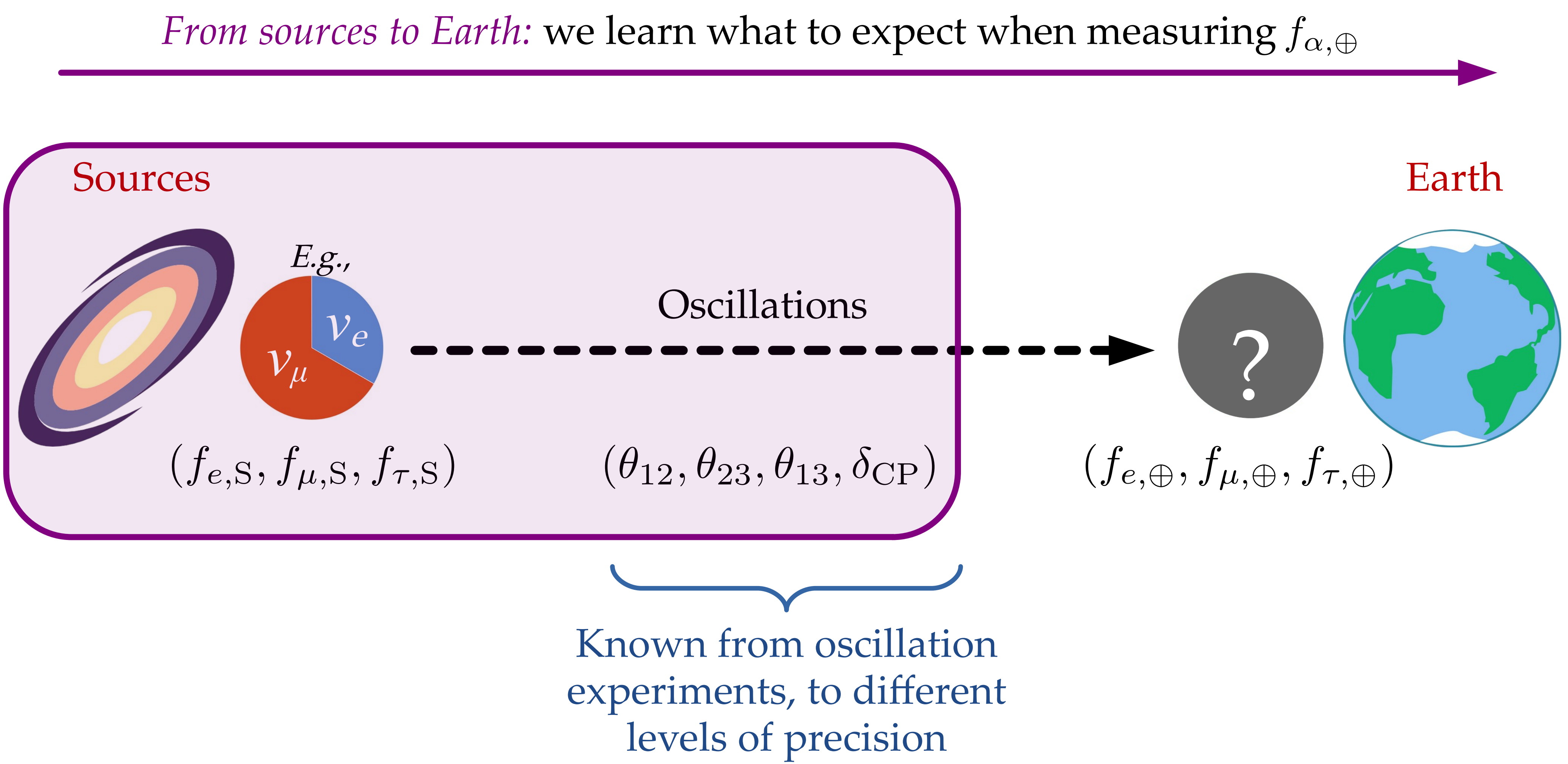
Thanks!



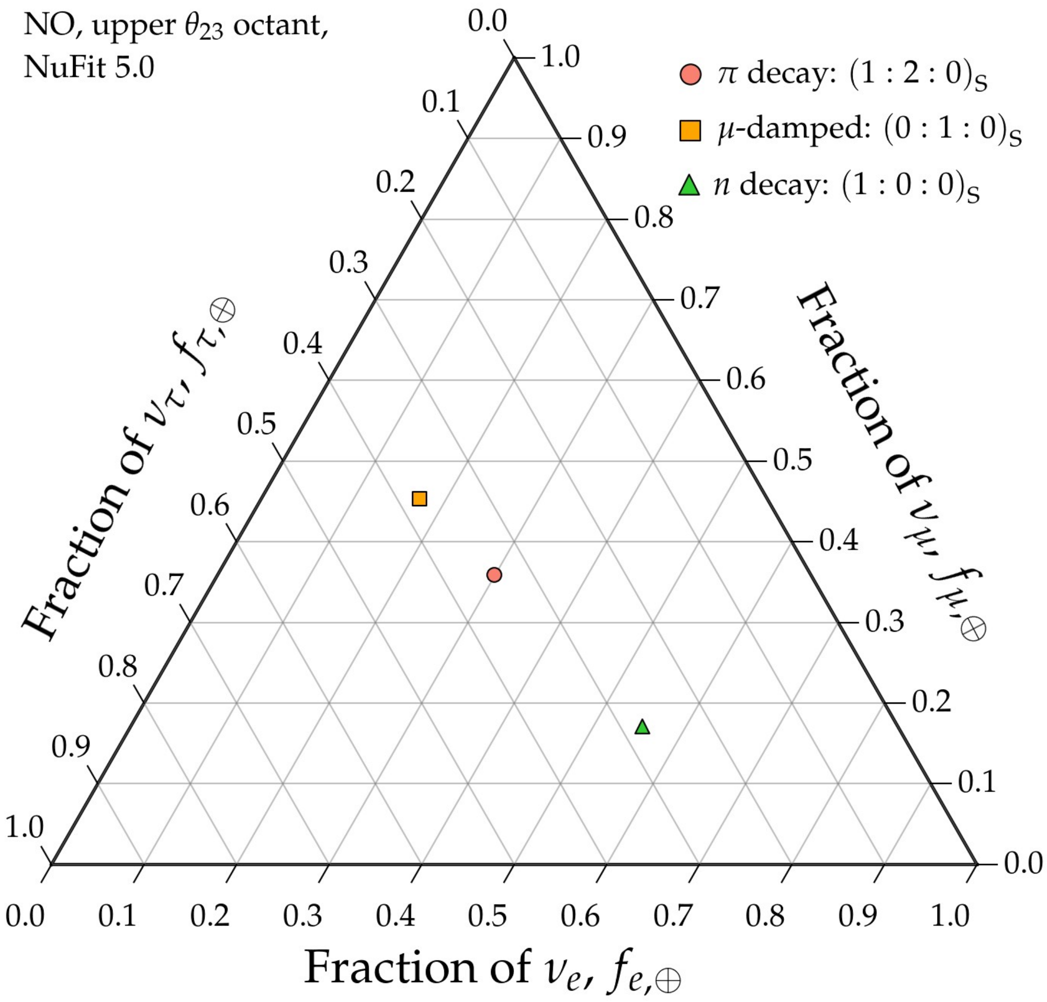
- Three tracks:
  - Neutrino phenomenology: Mariam Tórtola (Valencia)
  - Neutrino astrophysics: Maria Petropoulou (Athens)
  - Neutrino cosmology: Vivian Poulin (Montpellier)
- Plus topical seminars & student talks
- Registration remains open for remote participation (no charge!)

nbia.dk/neutrino2025

Backup slides


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
Known from oscillation experiments, to different levels of precision

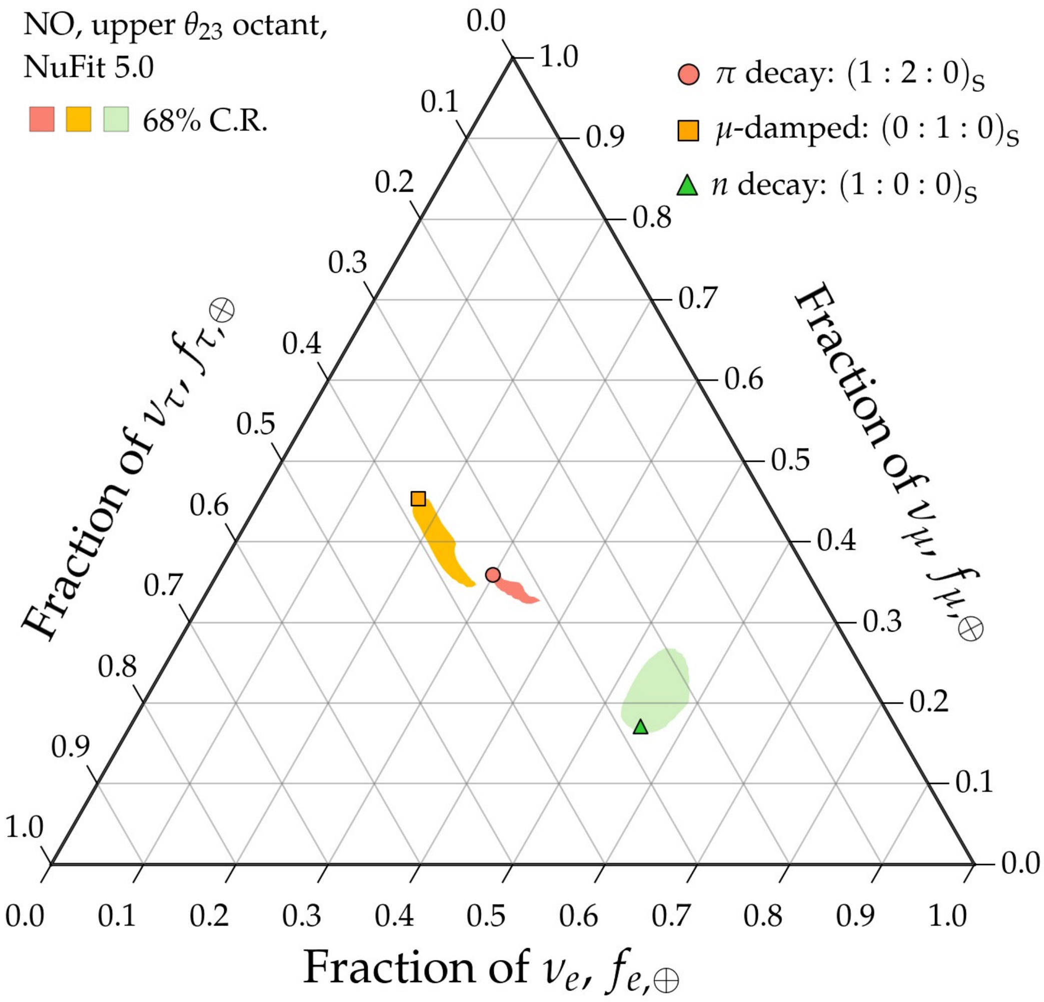
Theoretically palatable regions



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

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

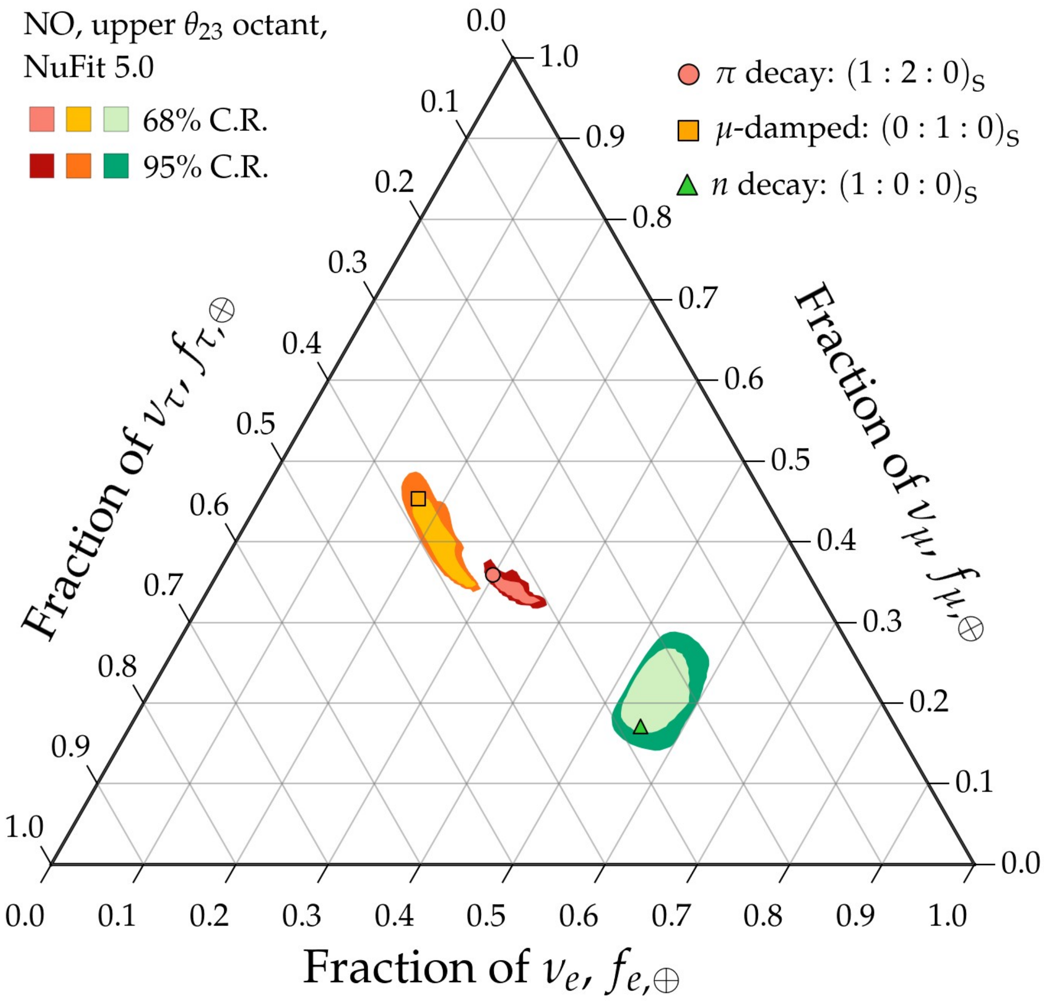
Theoretically palatable regions



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

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

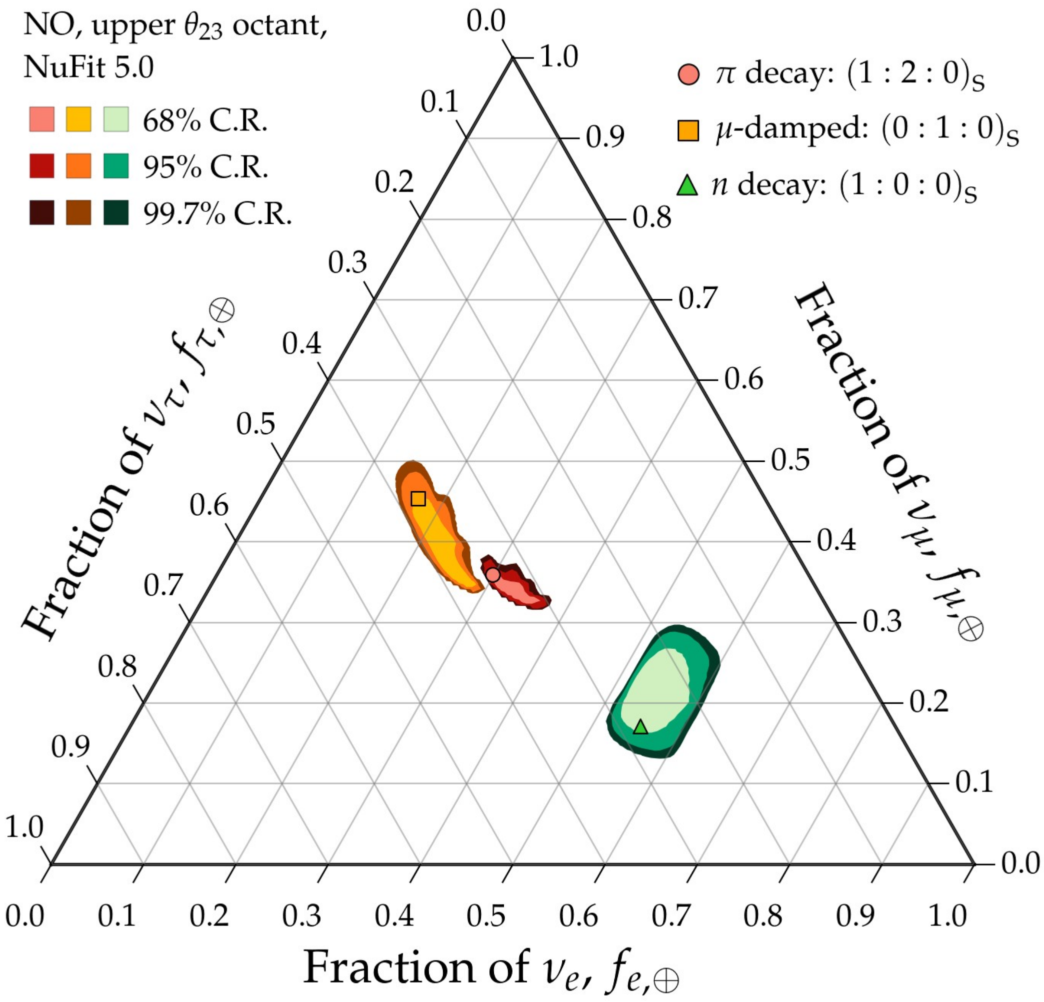
Theoretically palatable regions



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

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

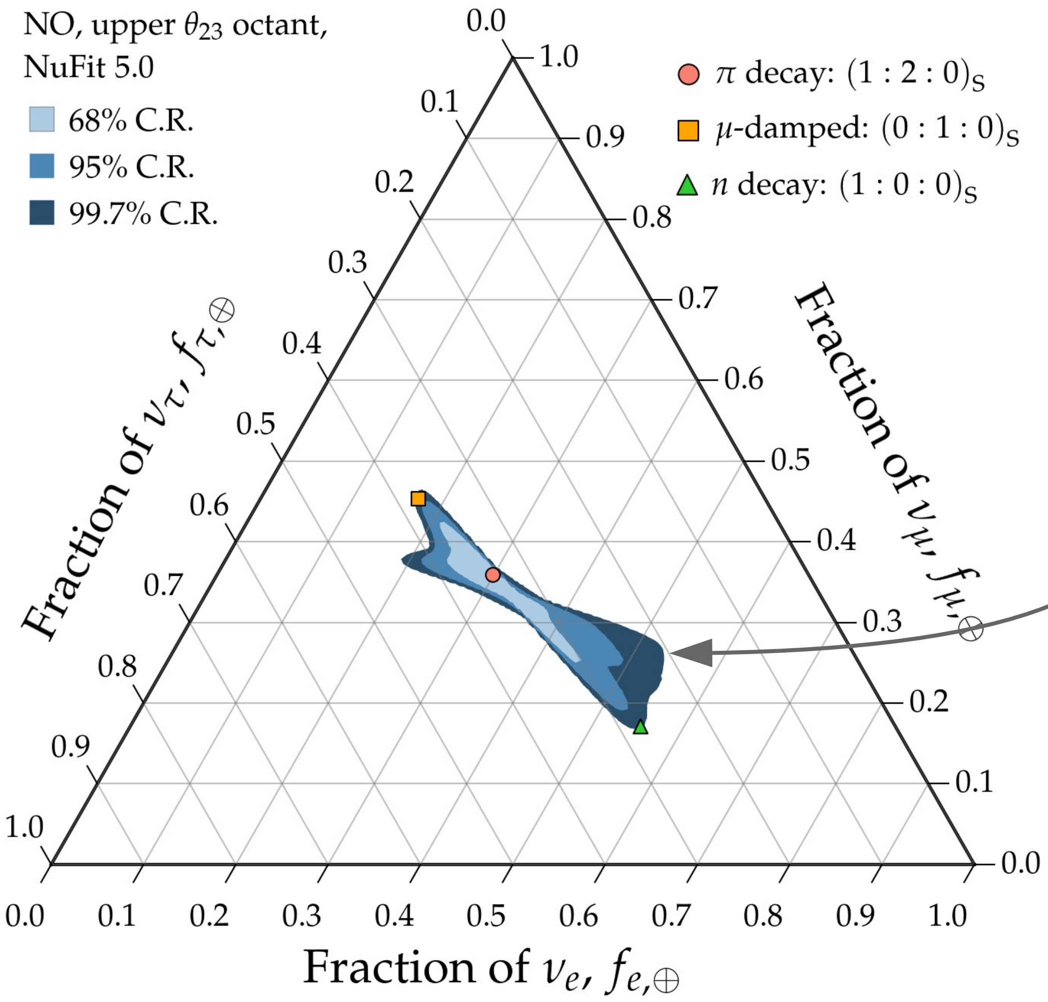
Theoretically palatable regions



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

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

Theoretically palatable regions



Varying over all possible flavor ratios at the source

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

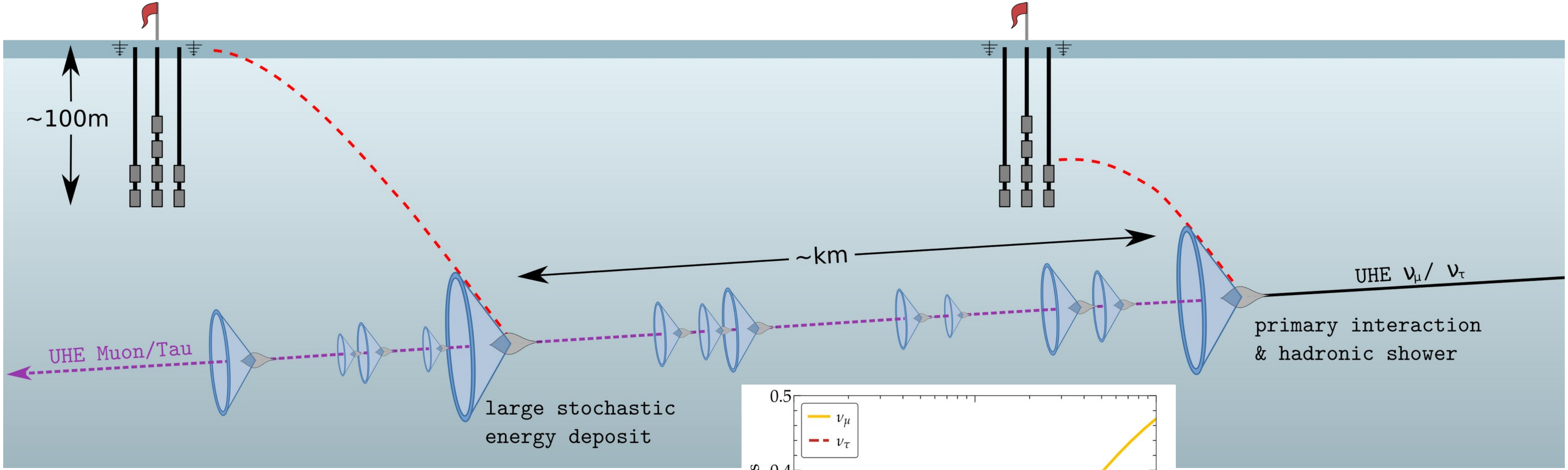
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB, Beacom, Winter, *PRL* 2015

Theoretically palatable regions

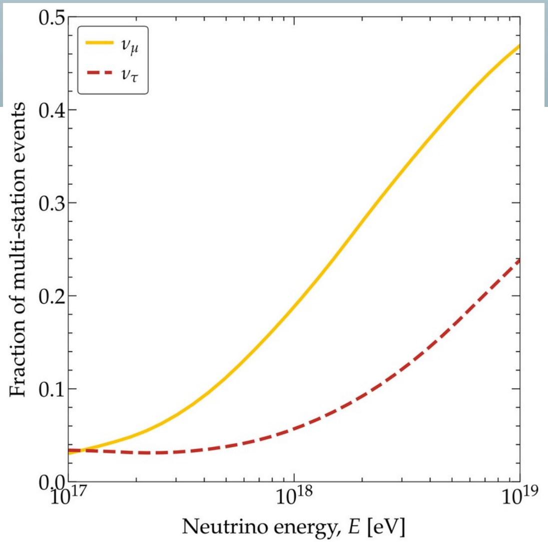
Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

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

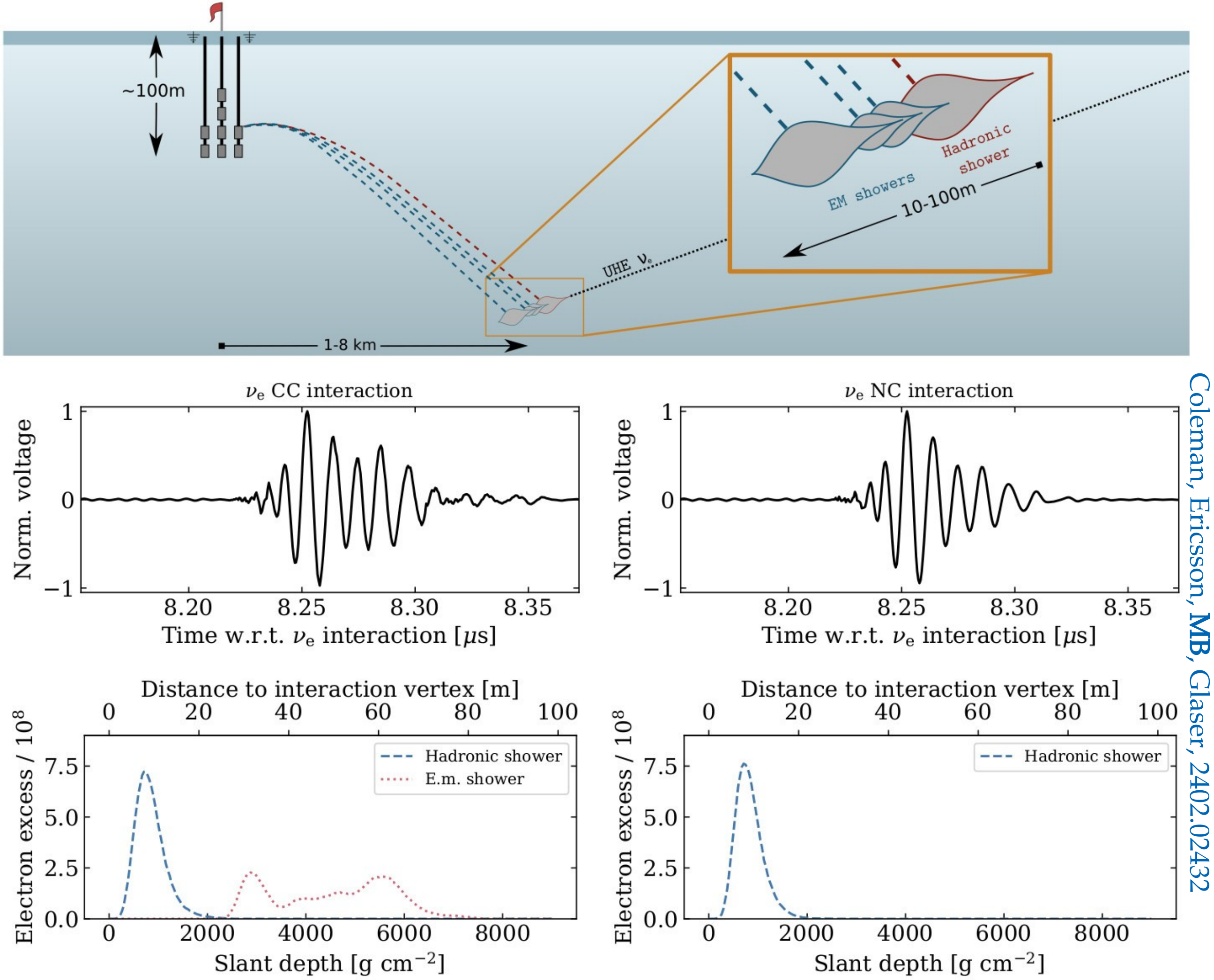
Multi-shower events from $\nu_\mu + \nu_\tau$ in IceCube-Gen2 (radio)



Coleman, Ericsson, **MB**, Glaser, 2402.02432



Multi-shower ν_e CC interactions in IceCube-Gen2 (radio)



Coleman, Ericsson, **MB**, Glaser, 2402.02432

Dark matter:
Annihilation and decay into ν

High-energy neutrinos from dark matter

Dark matter co-annihilation:

$$\chi + \chi \rightarrow \nu + \bar{\nu}$$

$$\chi + \chi \rightarrow \ldots \rightarrow \nu + \bar{\nu} + \ldots$$

$$E_{\rm max} = m_\chi$$

Dark matter decay:

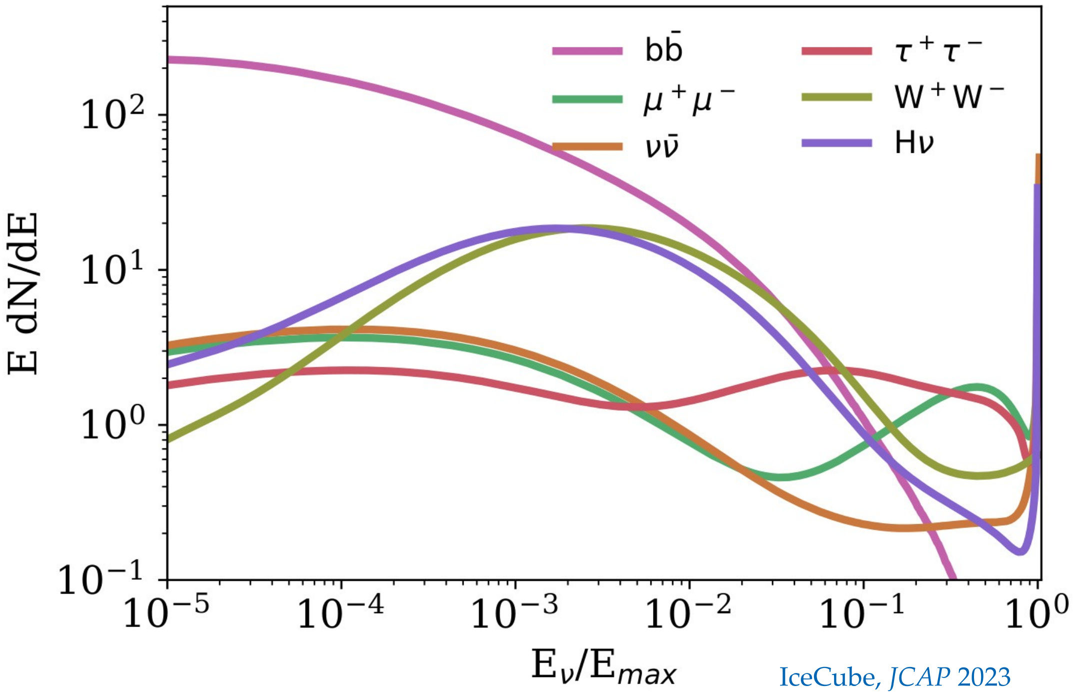
$$\chi \rightarrow \nu + \bar{\nu}$$

$$\chi \rightarrow \ldots \rightarrow \nu + \bar{\nu} + \ldots$$

$$E_{\rm max} = m_\chi/2$$

Electroweak corrections (off-shell *W* and *Z* emission) broaden the ν spectrum

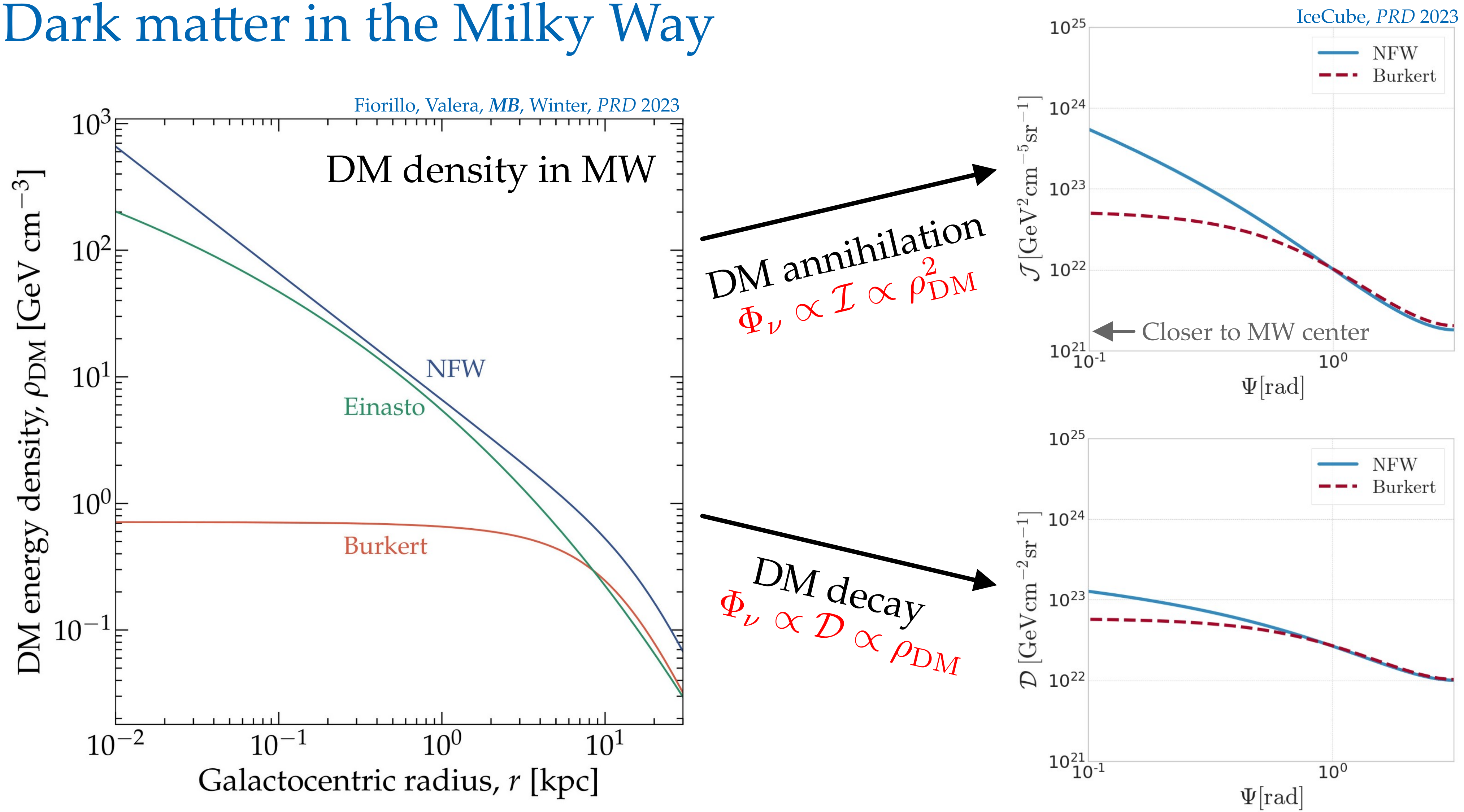
ν + ν yield from DM (at source)



IceCube, *JCAP* 2023

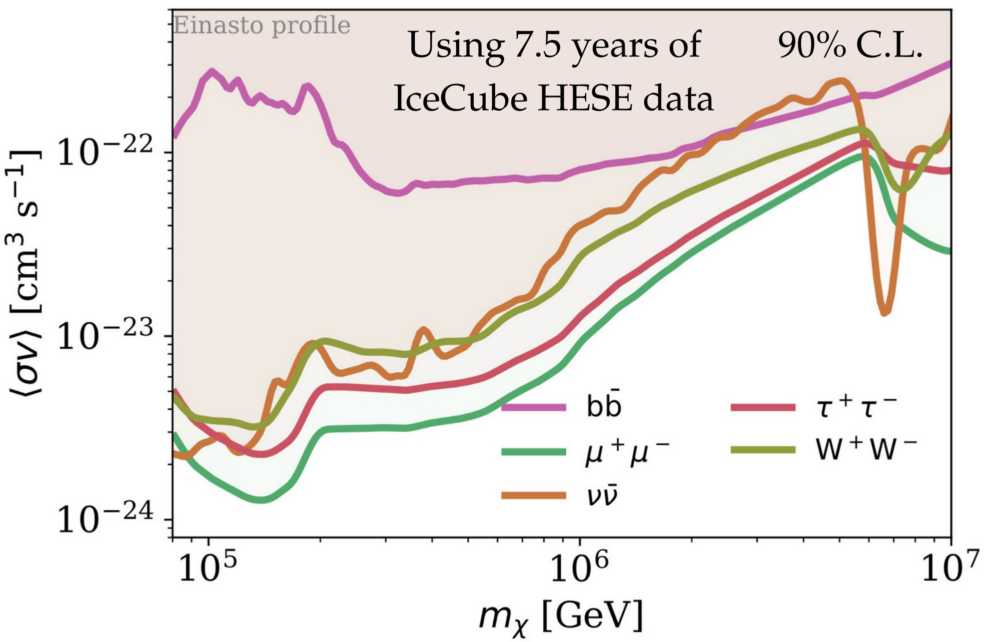
Approximate independence on m_χ valid for $m_\chi \approx$ 100 TeV–10 PeV

Dark matter in the Milky Way



Limits on dark matter annihilation

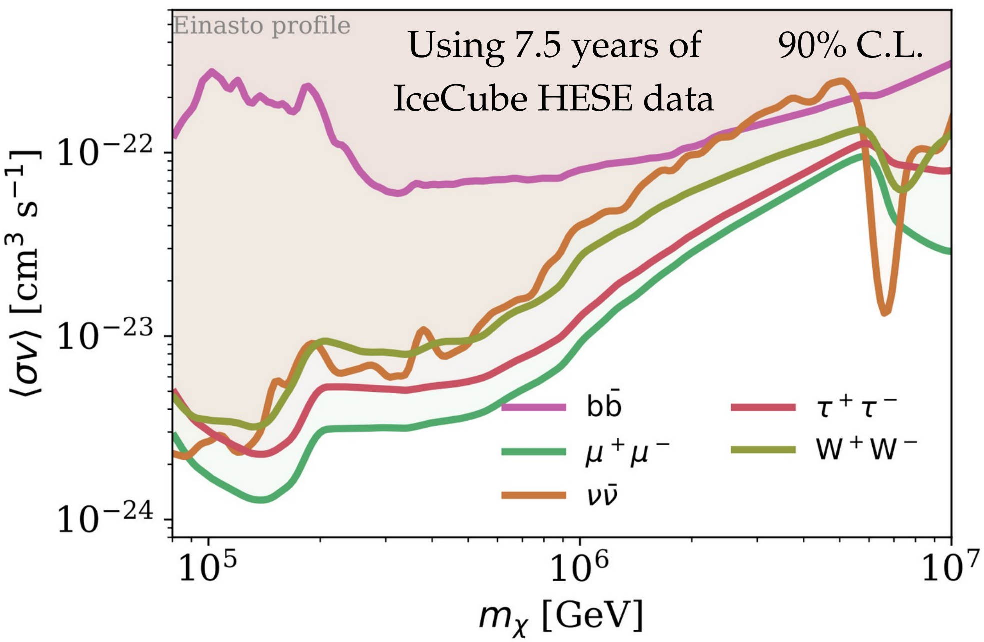
Per annihilation channel
(assuming 100% branching ratio)



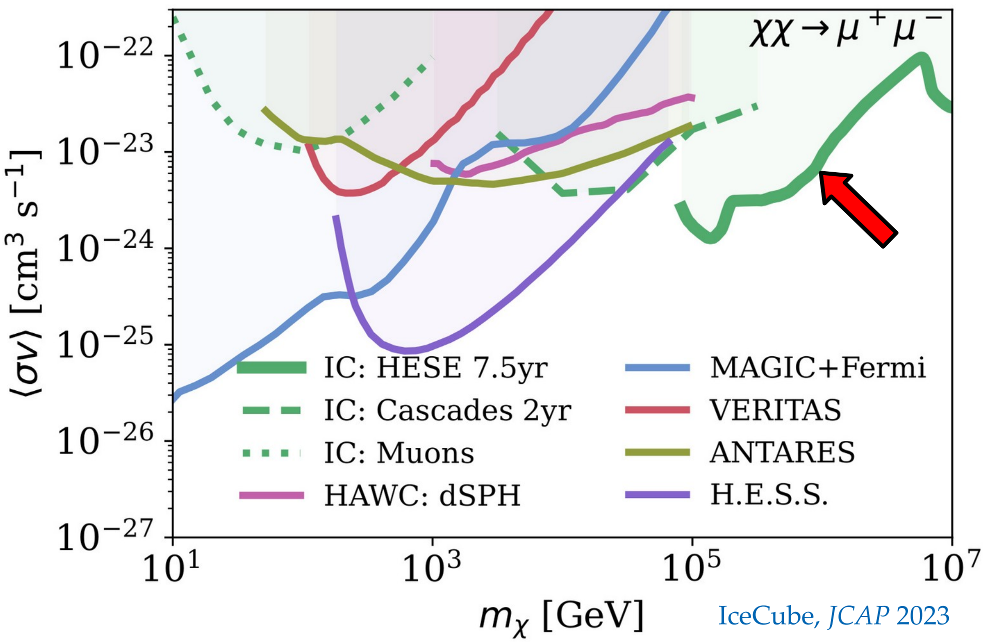
Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)
Plus background of atmospheric neutrinos (anisotropic, but different)

Limits on dark matter annihilation

Per annihilation channel
(assuming 100% branching ratio)



Compared to other limits
(assuming annihilation to muons)



IceCube, *JCAP* 2023

Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

New neutrino interactions:
Are there secret $\nu\nu$ interactions?

Astrophysical neutrino sources

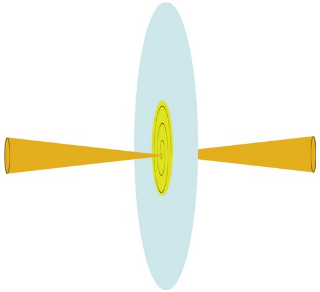
Earth

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

Astrophysical neutrino sources

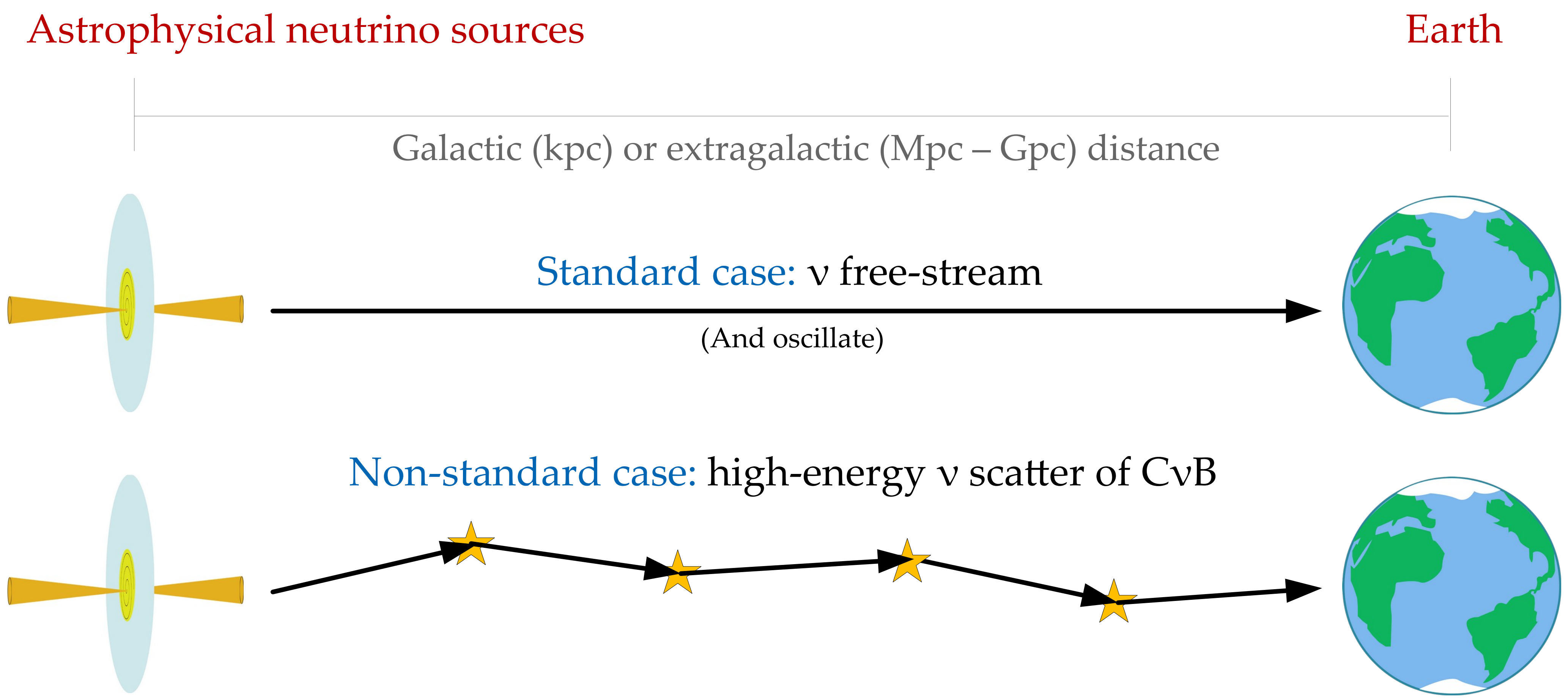
Earth

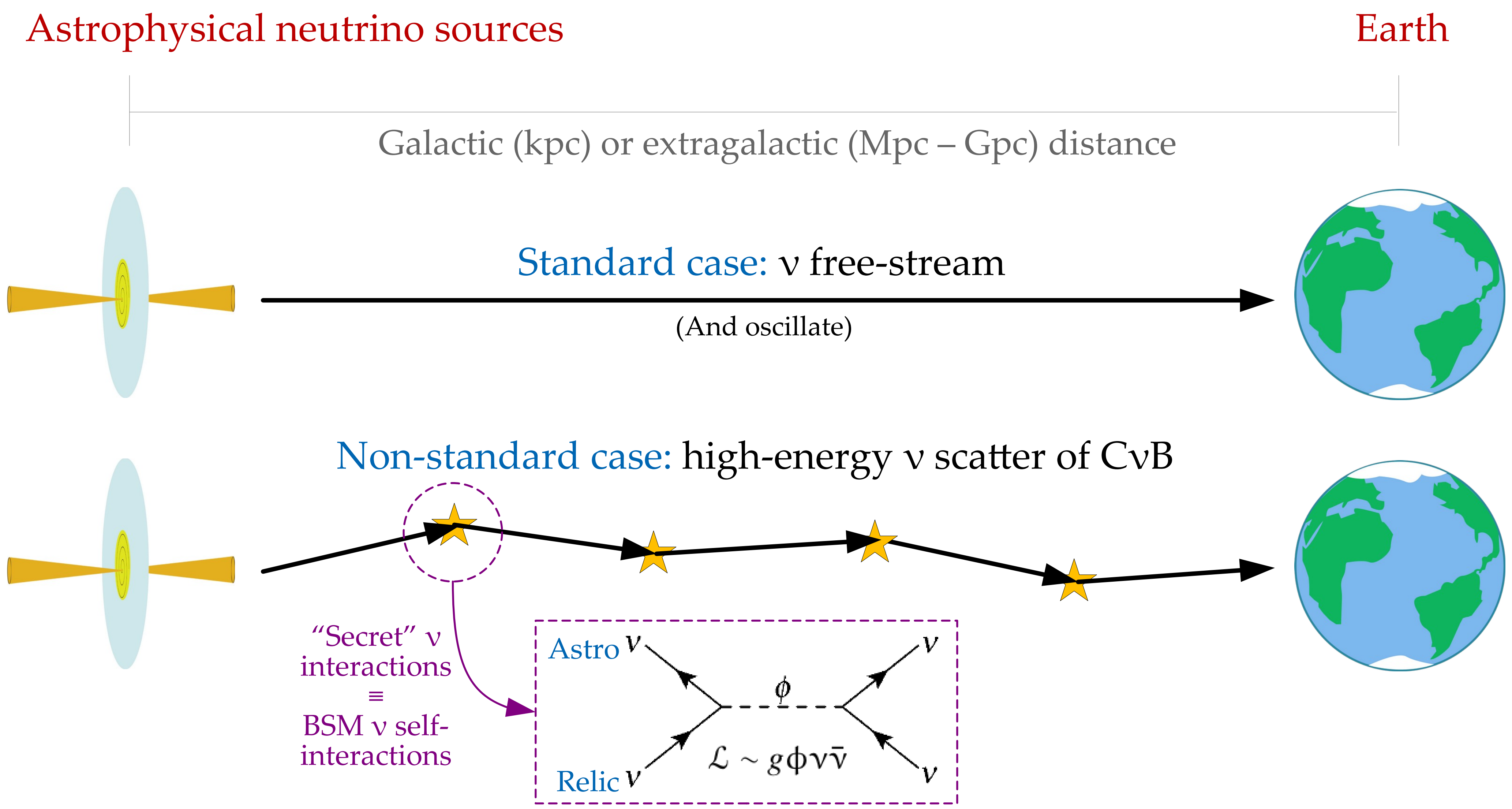
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



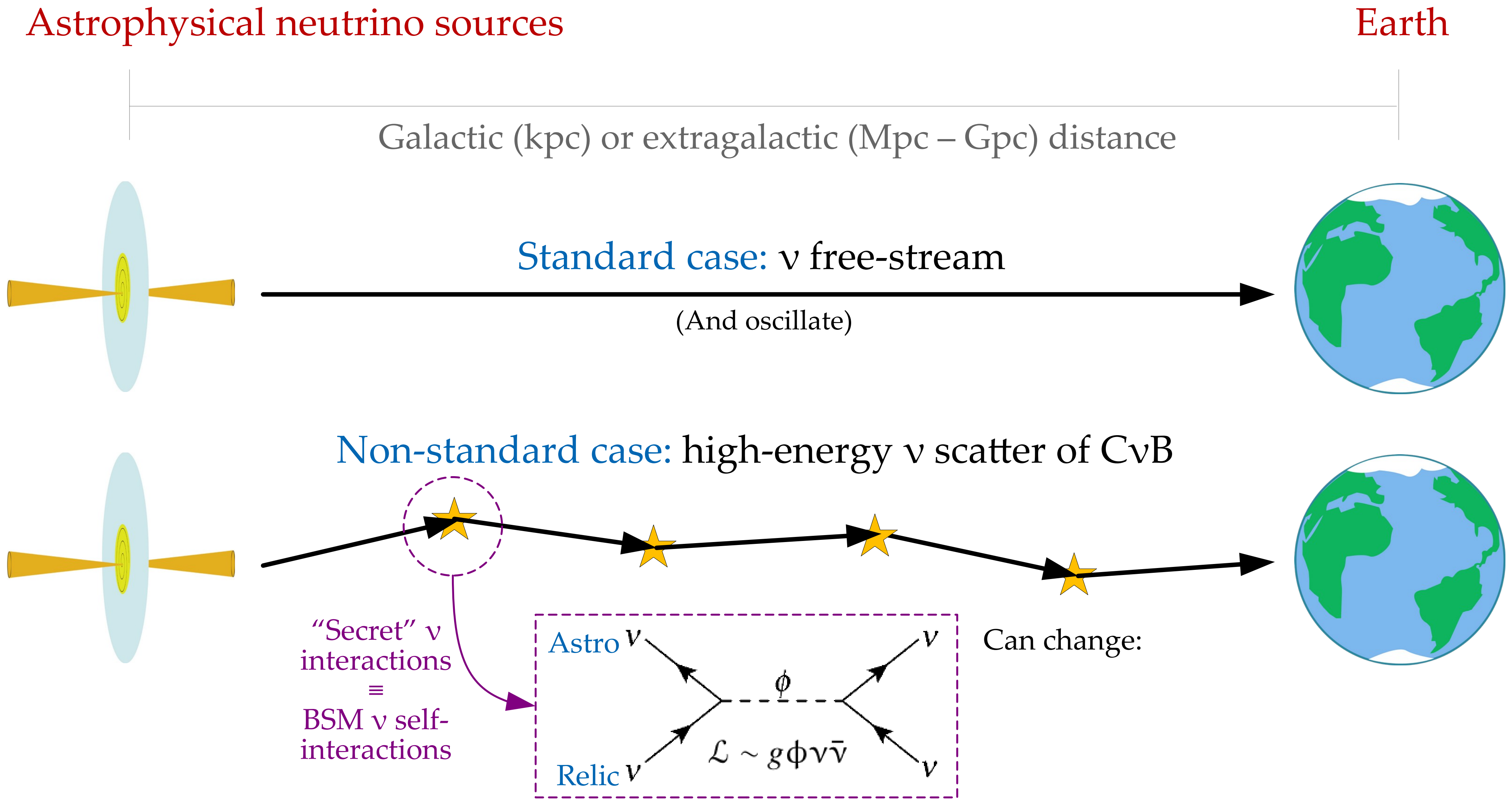
Standard case: ν free-stream

(And oscillate)

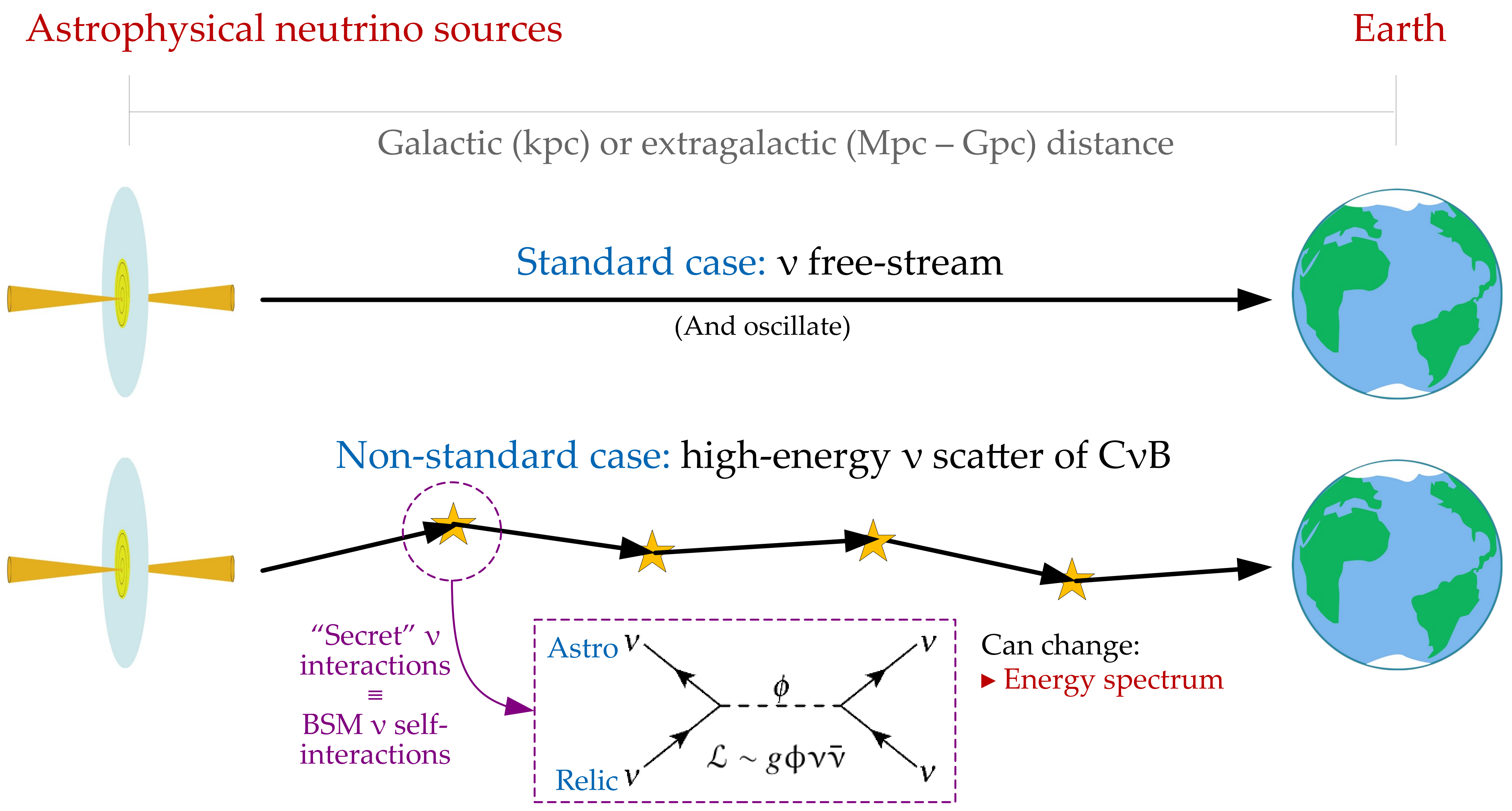

Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB



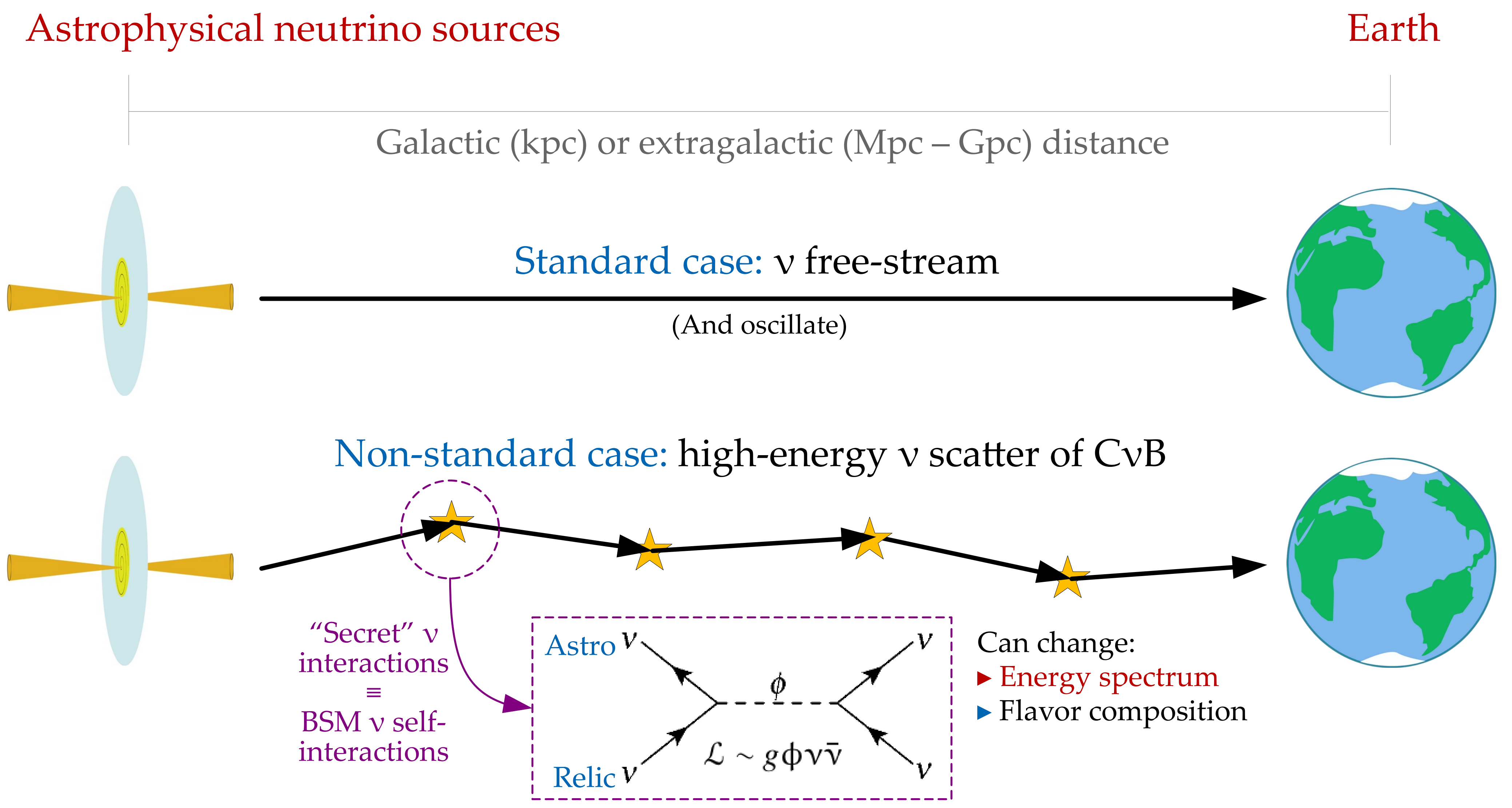
Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$



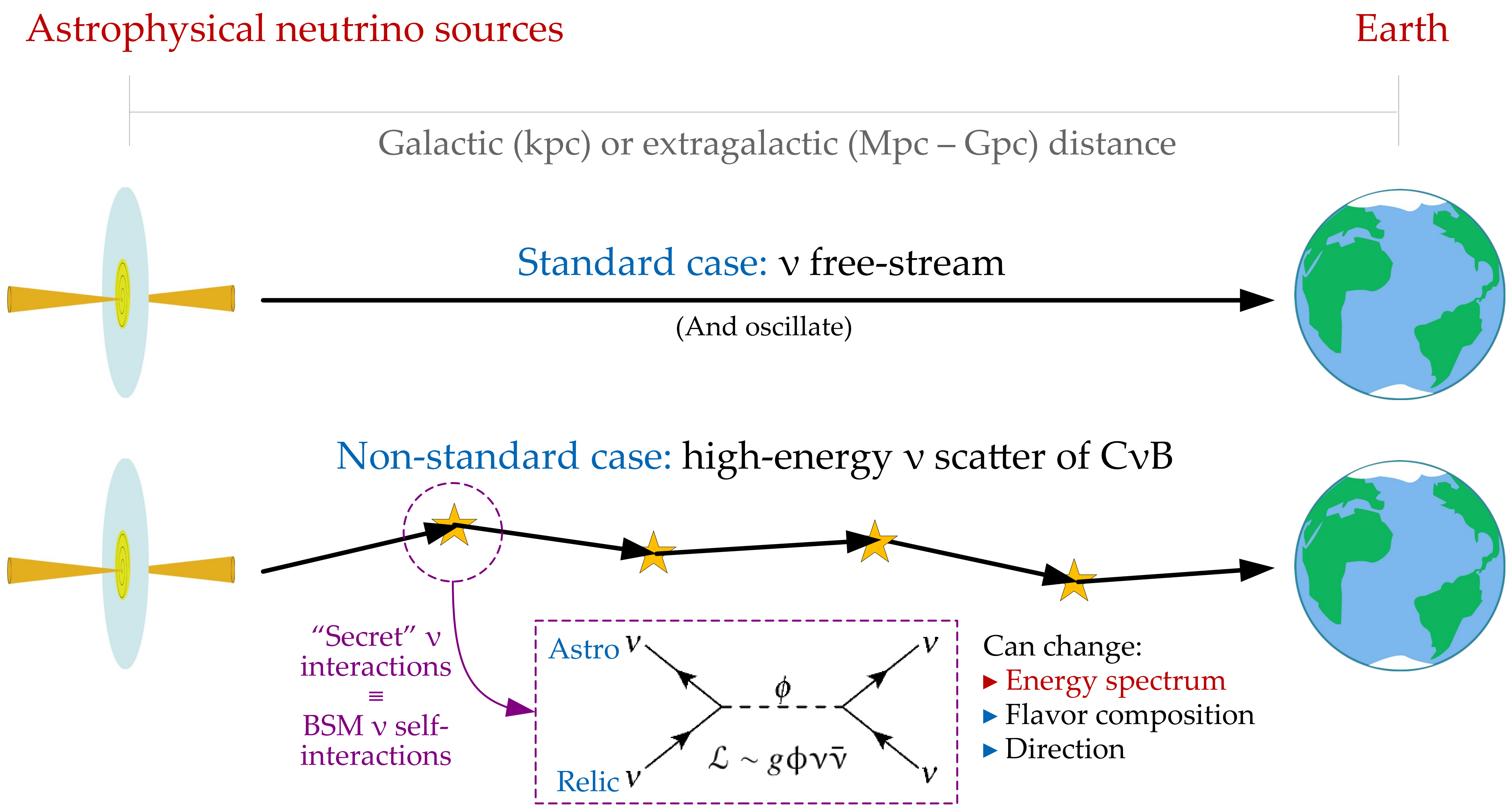
Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
φ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:



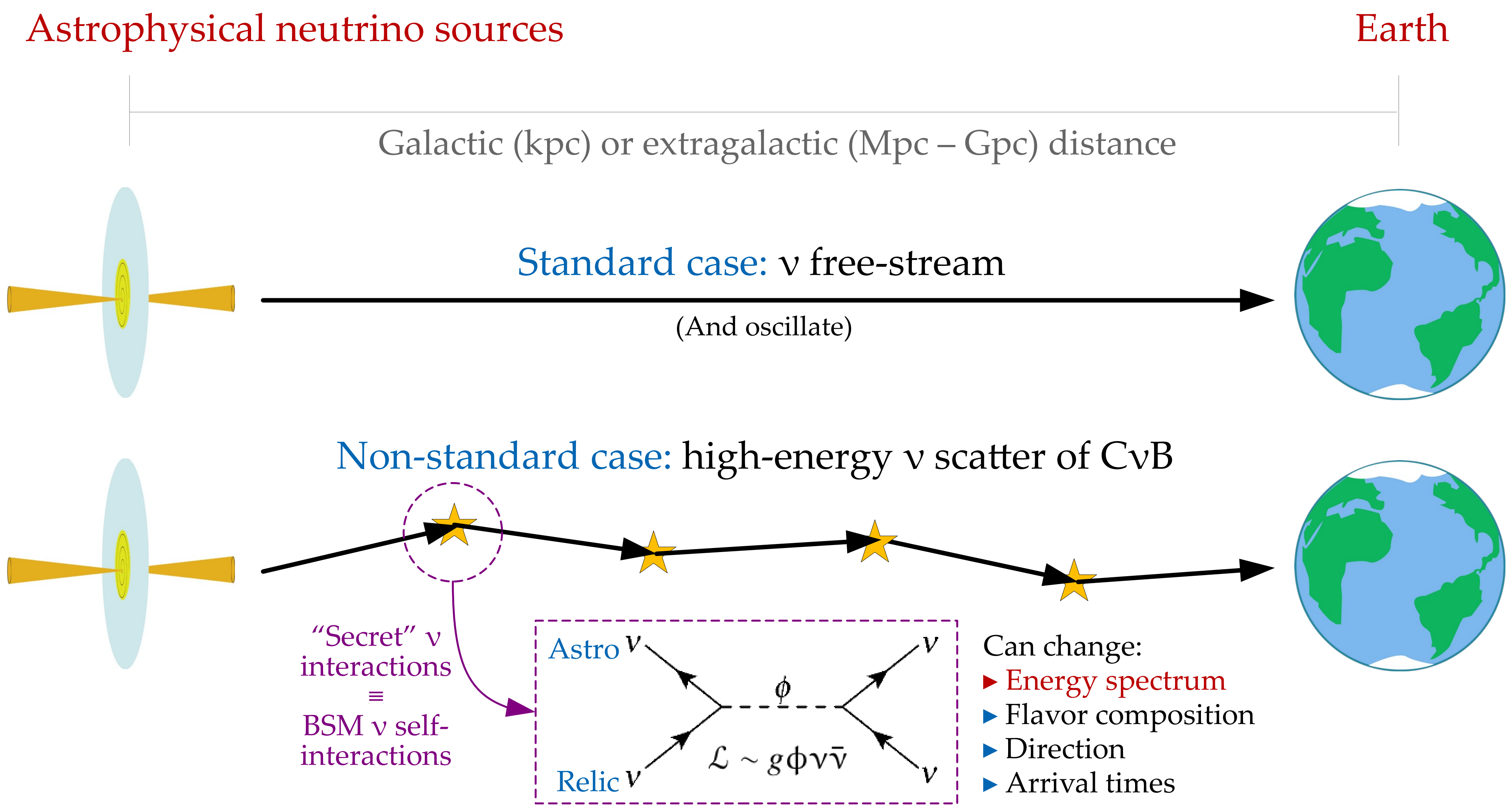
Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
ℒ ~ gϕνν̄
Can change:
▸ Energy spectrum



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



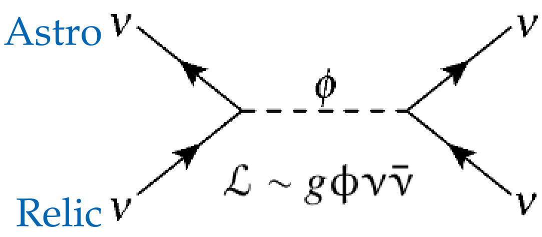
Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change: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



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

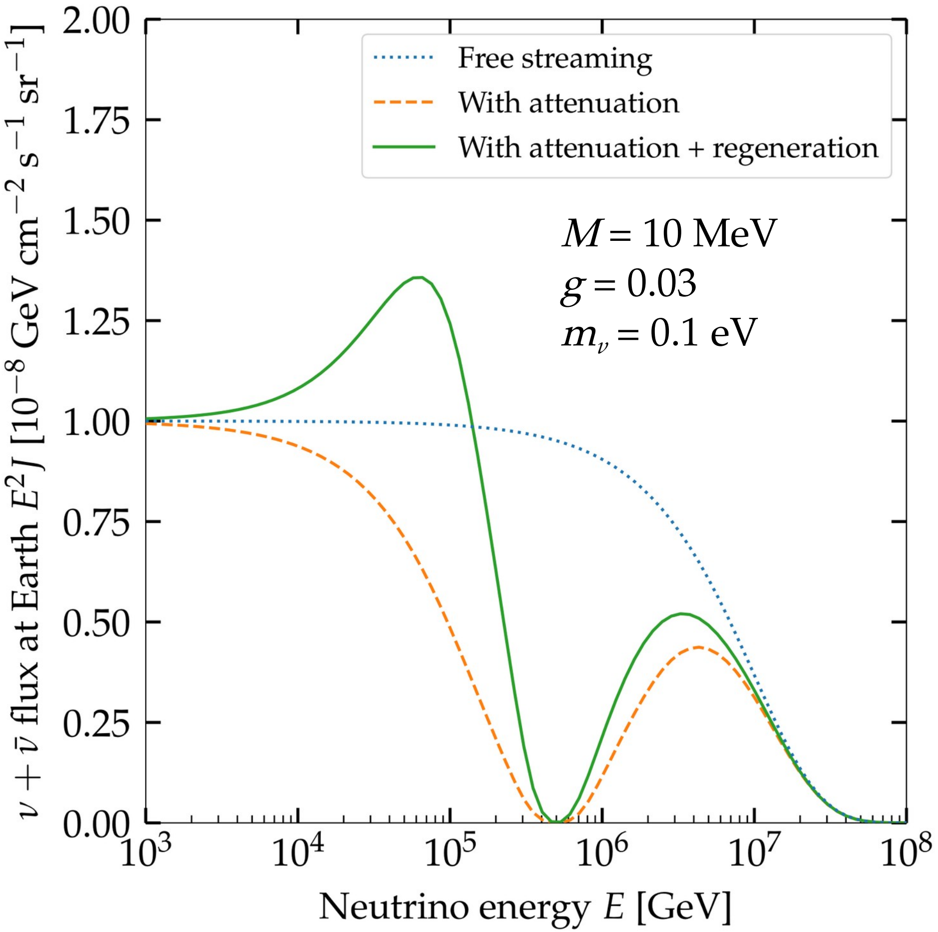
Secret interactions of high-energy astrophysical neutrinos

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



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

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



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

See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021

Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021

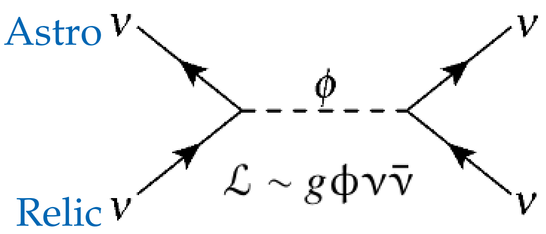
Ng & Beacom, *PRD* 2014

Cherry, Friedland, Shoemaker, 1411.1071

Blum, Hook, Murase, 1408.3799

Secret interactions of high-energy astrophysical neutrinos

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

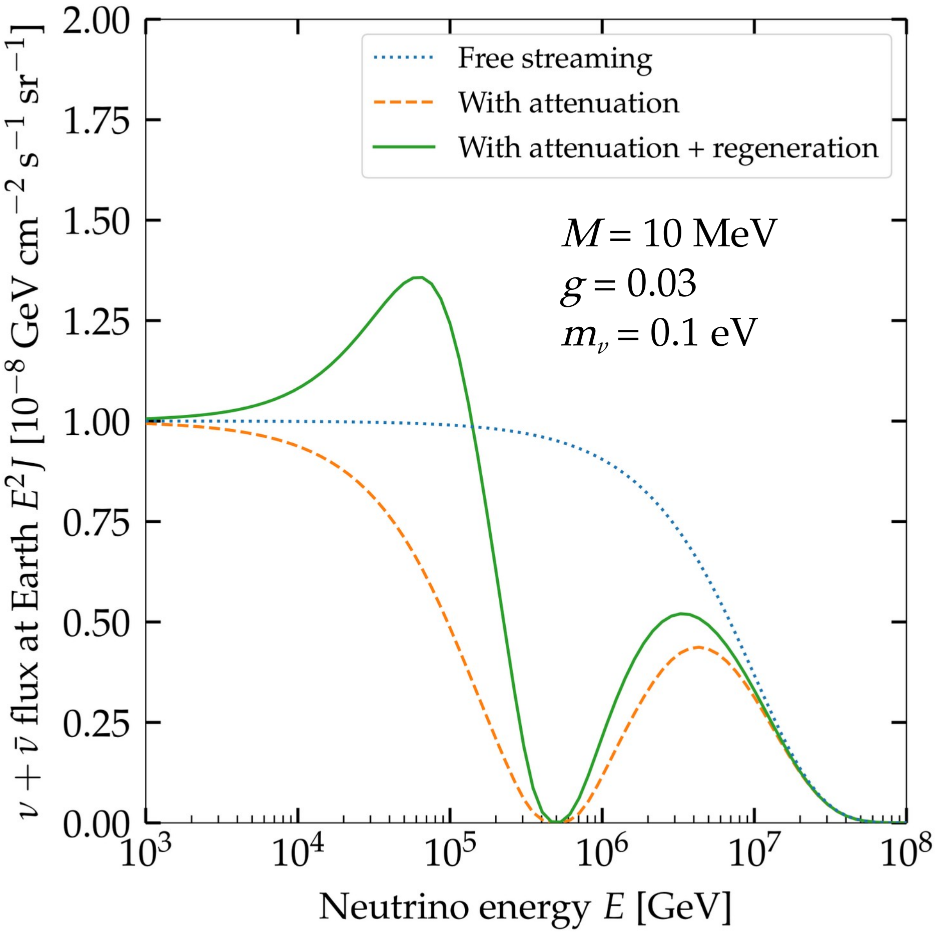


New coupling

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

Mediator mass

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



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

See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021

Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021

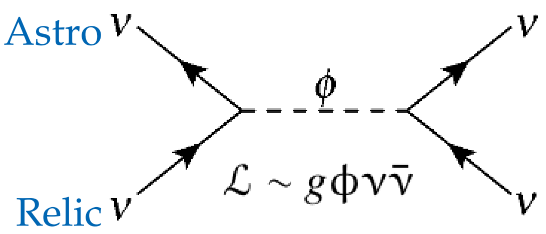
Ng & Beacom, *PRD* 2014

Cherry, Friedland, Shoemaker, 1411.1071

Blum, Hook, Murase, 1408.3799

Secret interactions of high-energy astrophysical neutrinos

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

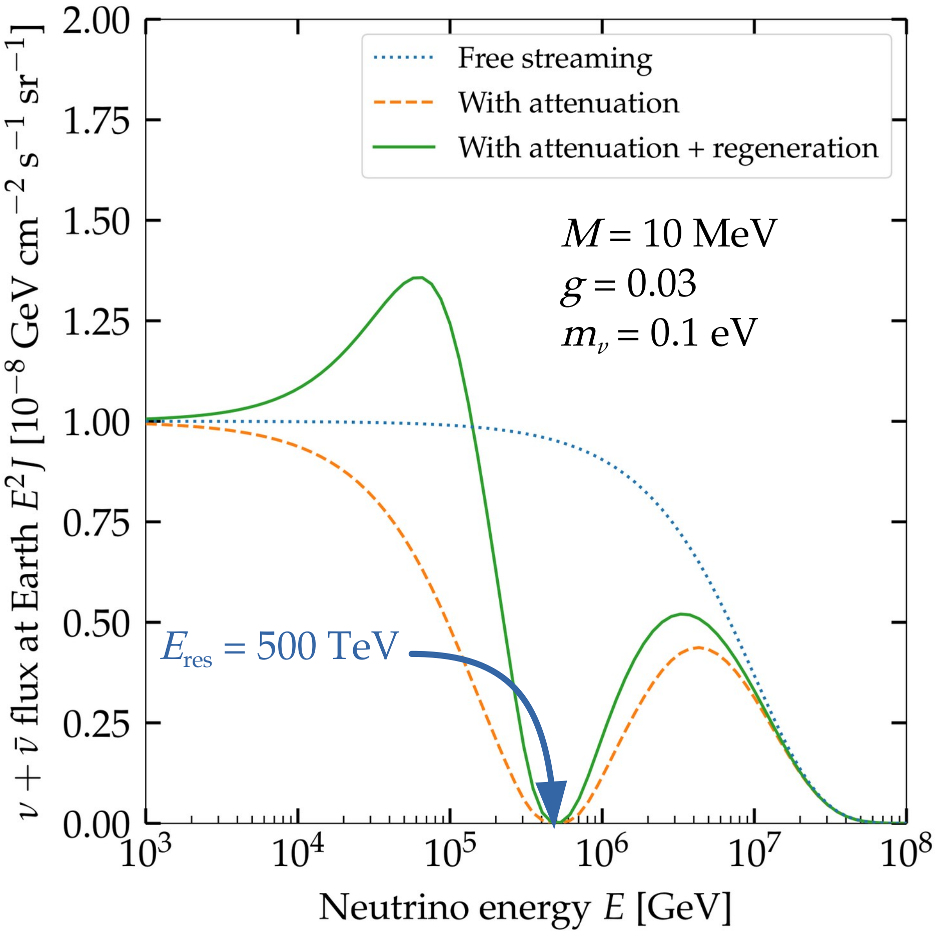


New coupling

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

Mediator mass

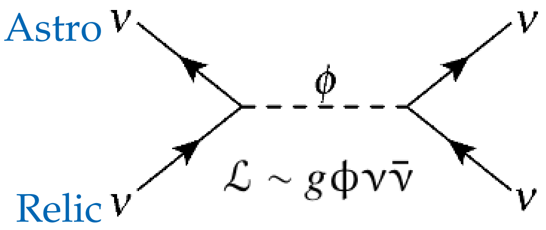
Resonance energy: $E_{\rm res} = \frac{M^2}{2m_\nu}$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Secret interactions of high-energy astrophysical neutrinos

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

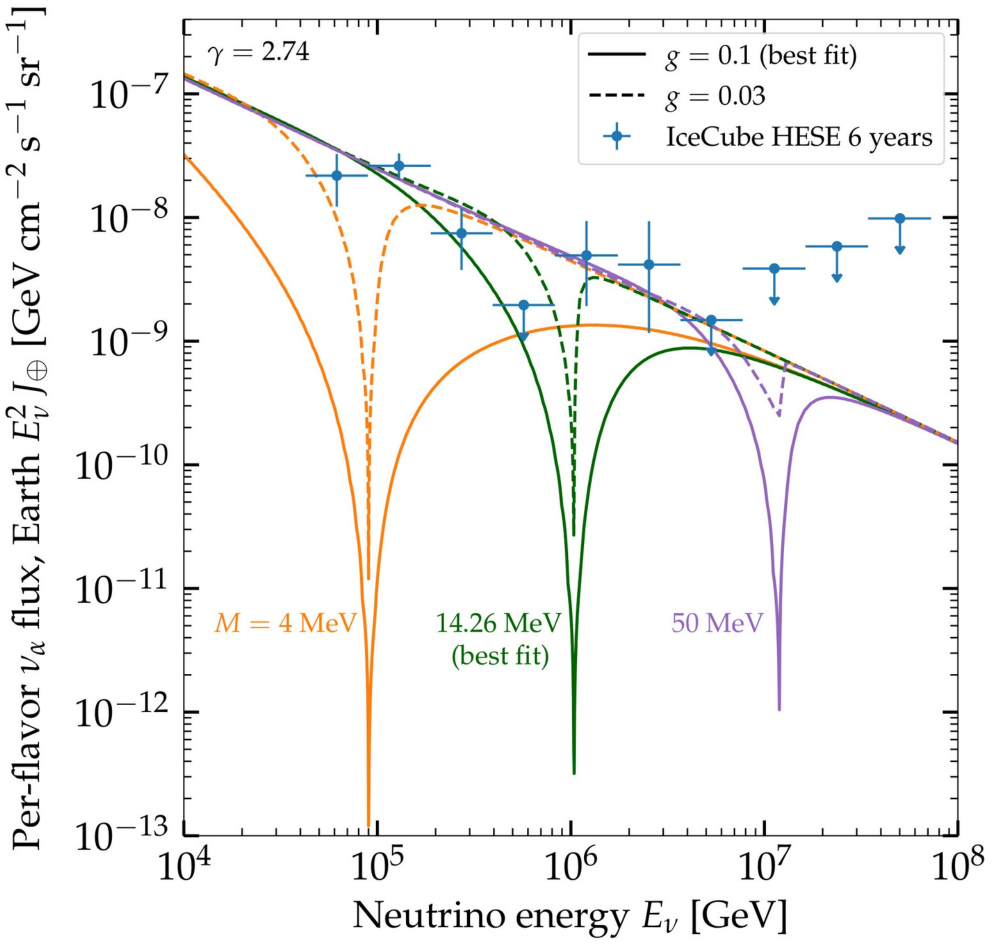


New coupling

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

Mediator mass

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

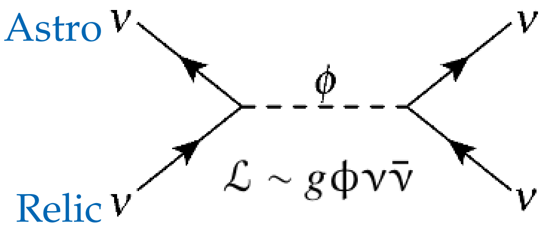


MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020

See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Secret interactions of high-energy astrophysical neutrinos

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



New coupling

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

Mediator mass

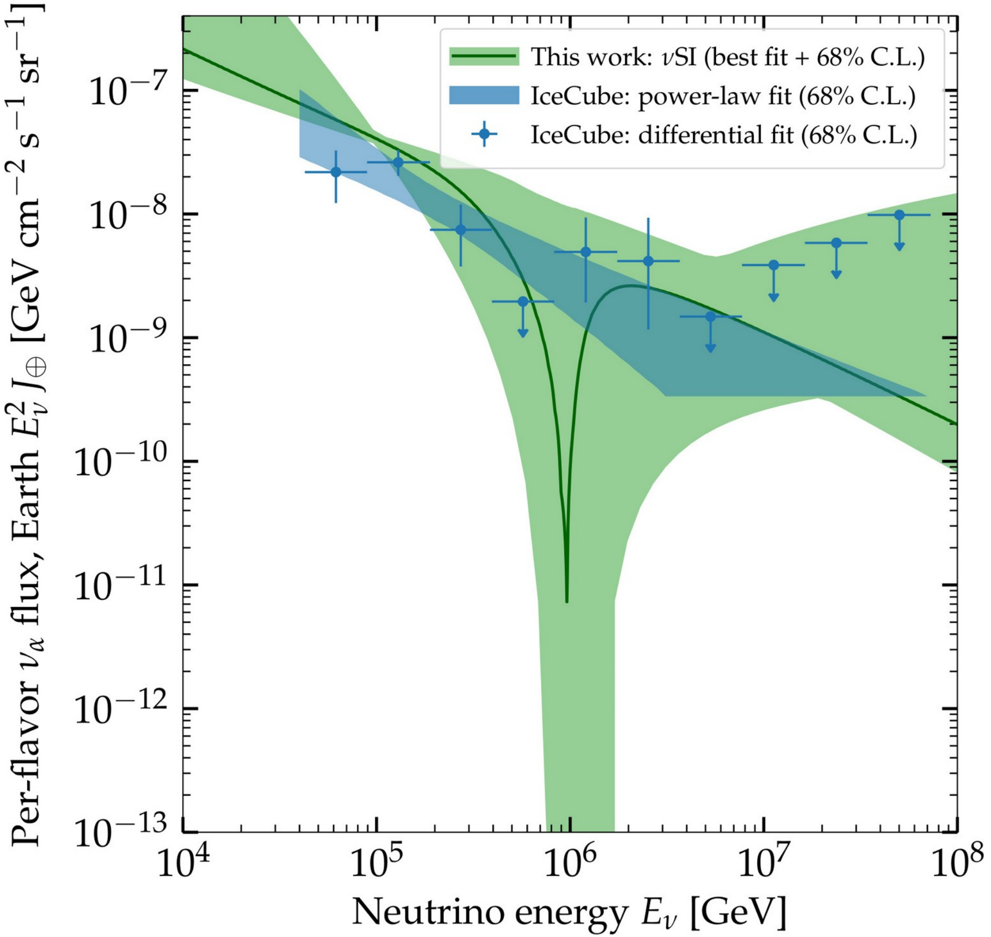
Resonance energy: $$E_{\rm res} = \frac{M^2}{2m_\nu}$$

Looking for evidence of νSI

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

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

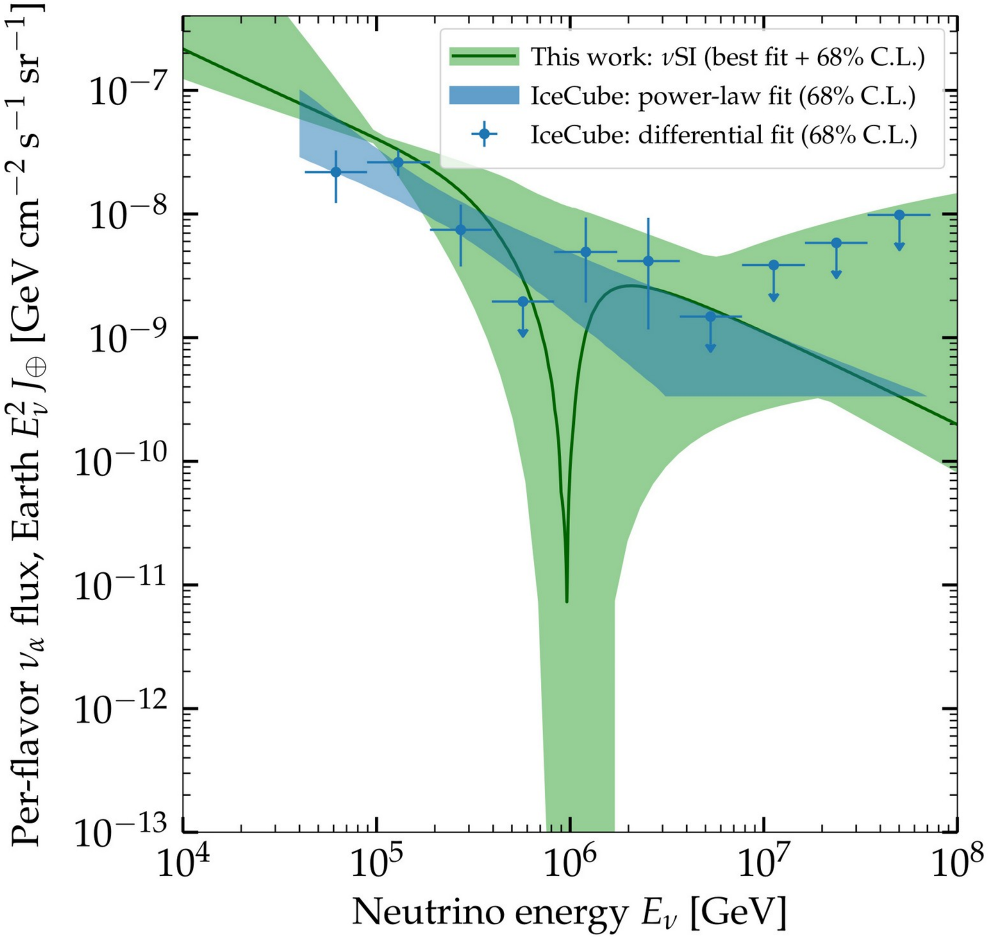
No significant (> 3σ) evidence for a spectral dip …

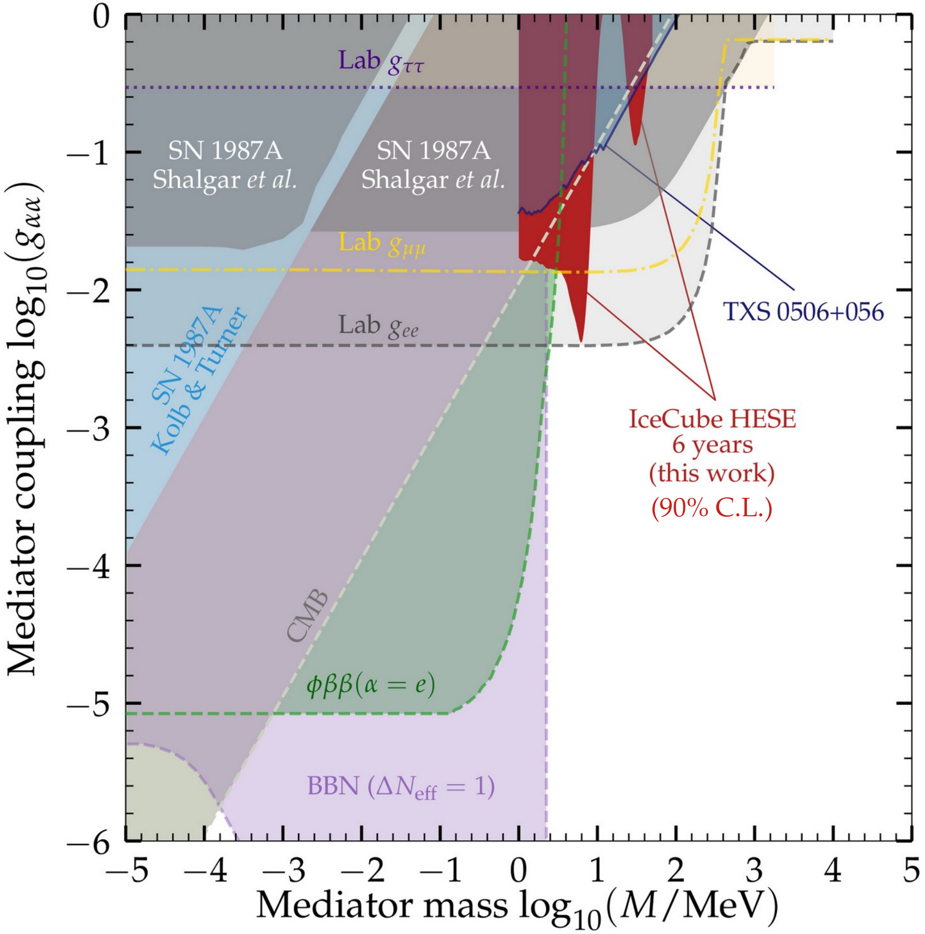


MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020

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

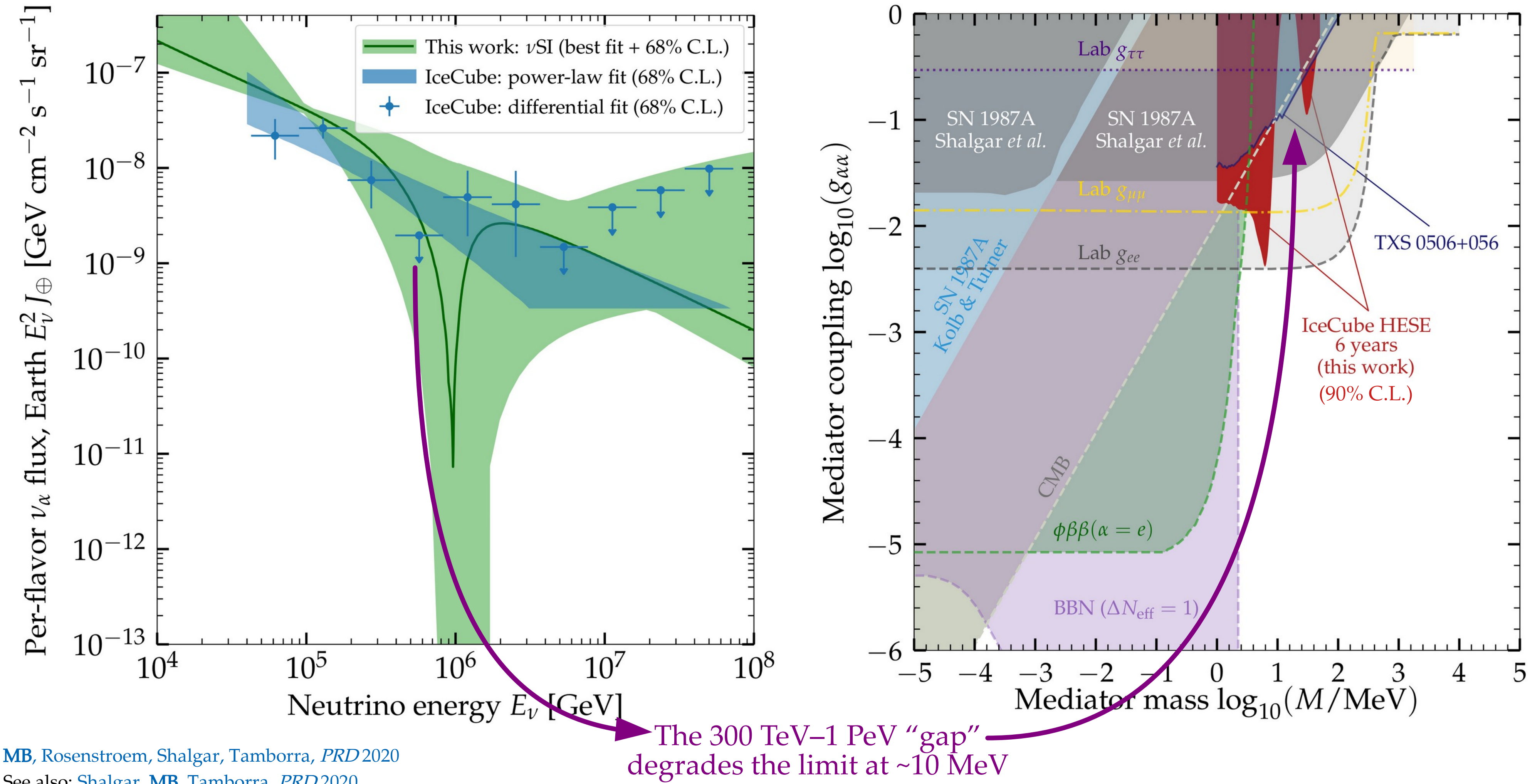
No significant (> 3σ) evidence for a spectral dip … … so we set upper limits on the coupling g





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

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



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