Neutrinos:
messengers of quantum gravity

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IFIC, CSIC-U. València

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Evidence of physics beyond the Standard Model

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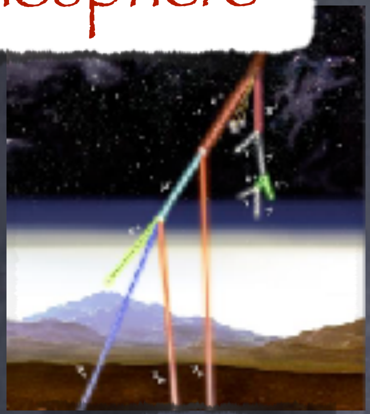
Very sensitive to new physics: eg, QG scenarios

Sources of neutrinos

Natural sources

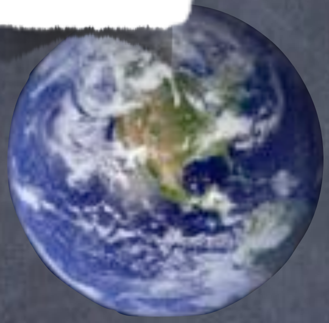
Farther away

Atmosphere



Detected in 1965

Earth

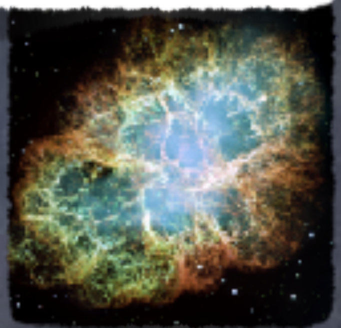


Detected in 2005

Sun

Detected in 1968

Supernova explosions

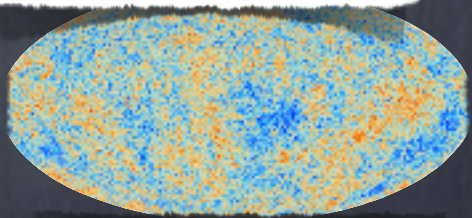


Detected in 1987

Astrophysical sources

Detected in 2013

Cosmic relics



Not yet detected

Man-made sources

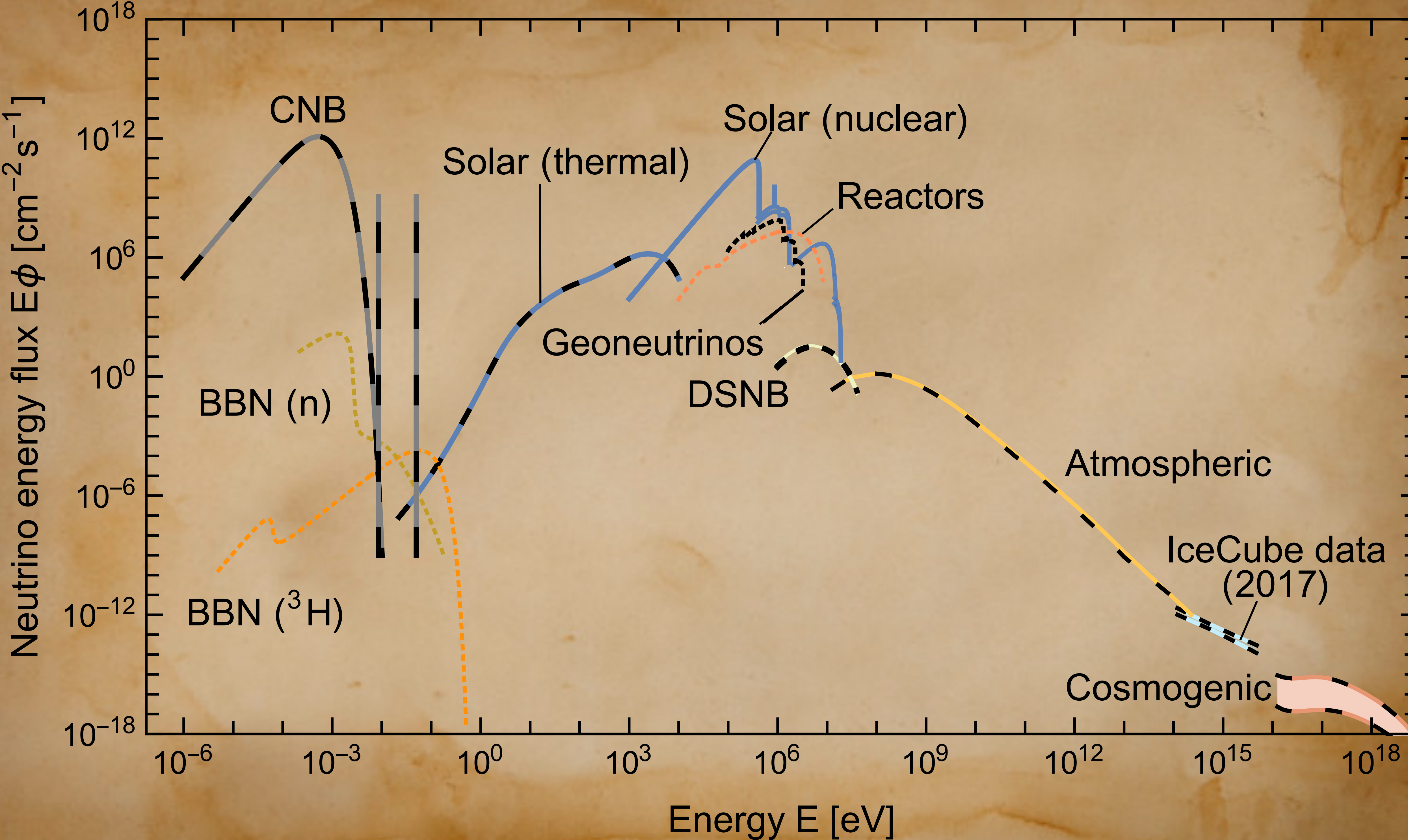
Nuclear reactors

Detected in 1956

Particle accelerators

Detected in 1962

(Standard) Grand Unified Neutrino Spectrum



E. Vitagliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92:45006, 2020

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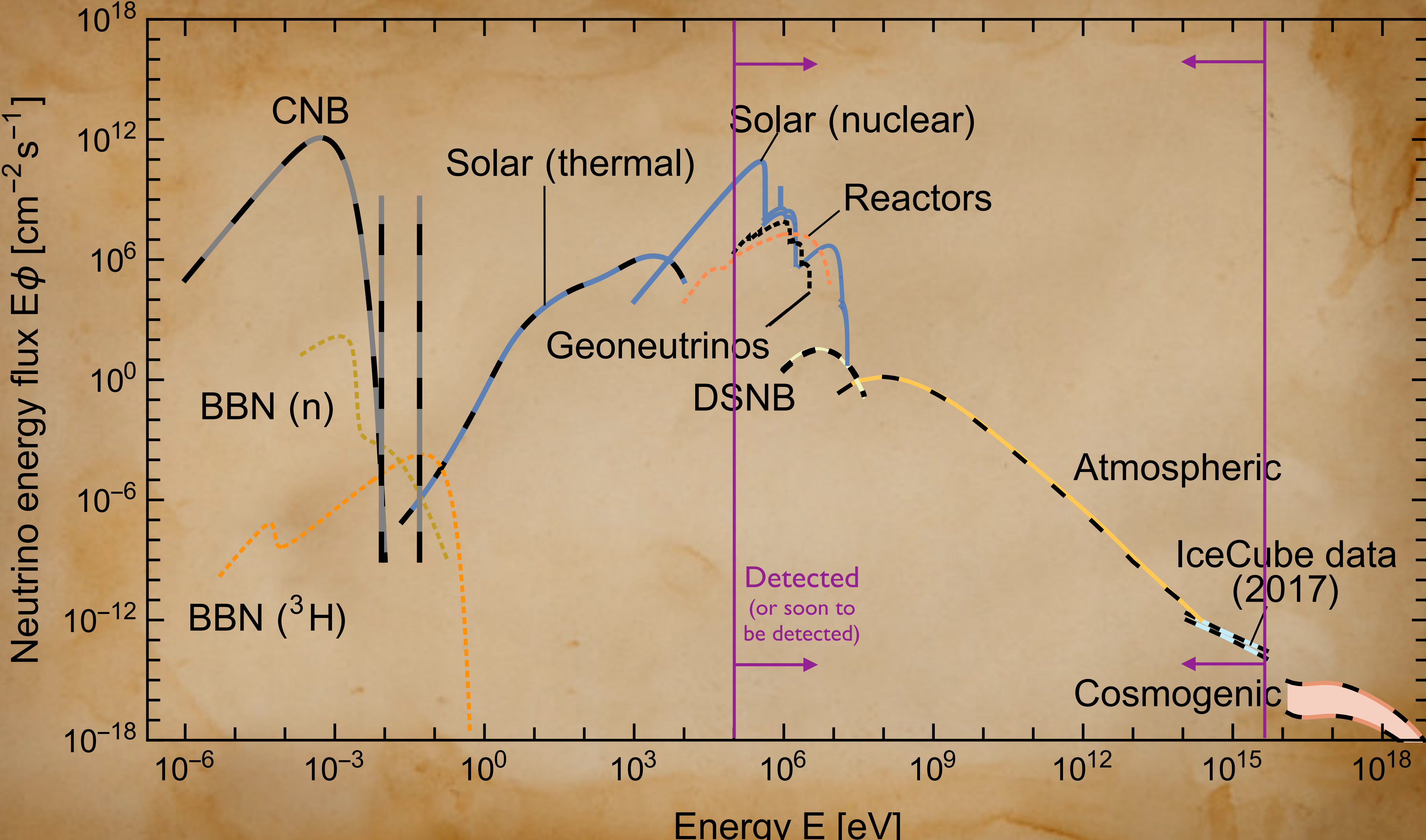

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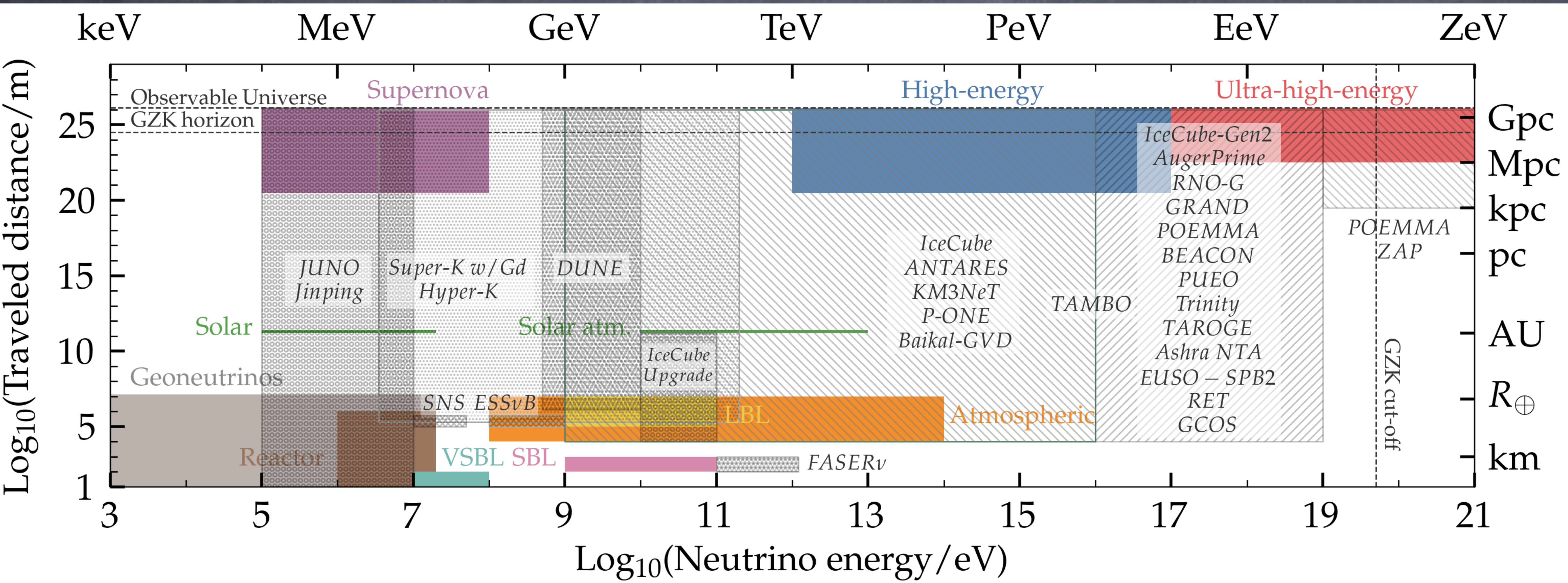
Neutrino sources and detectors

Averaged oscillations



Oscillations

M. Ackermann et al., arXiv:2203.08096

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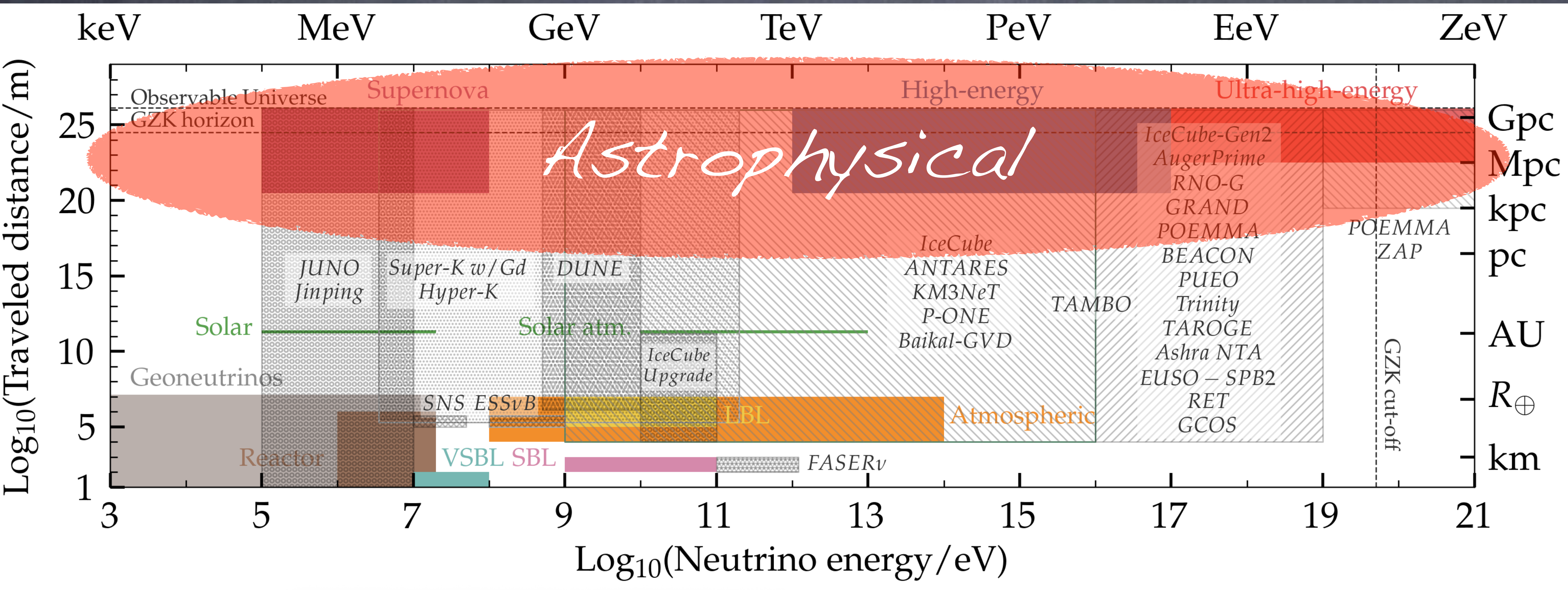

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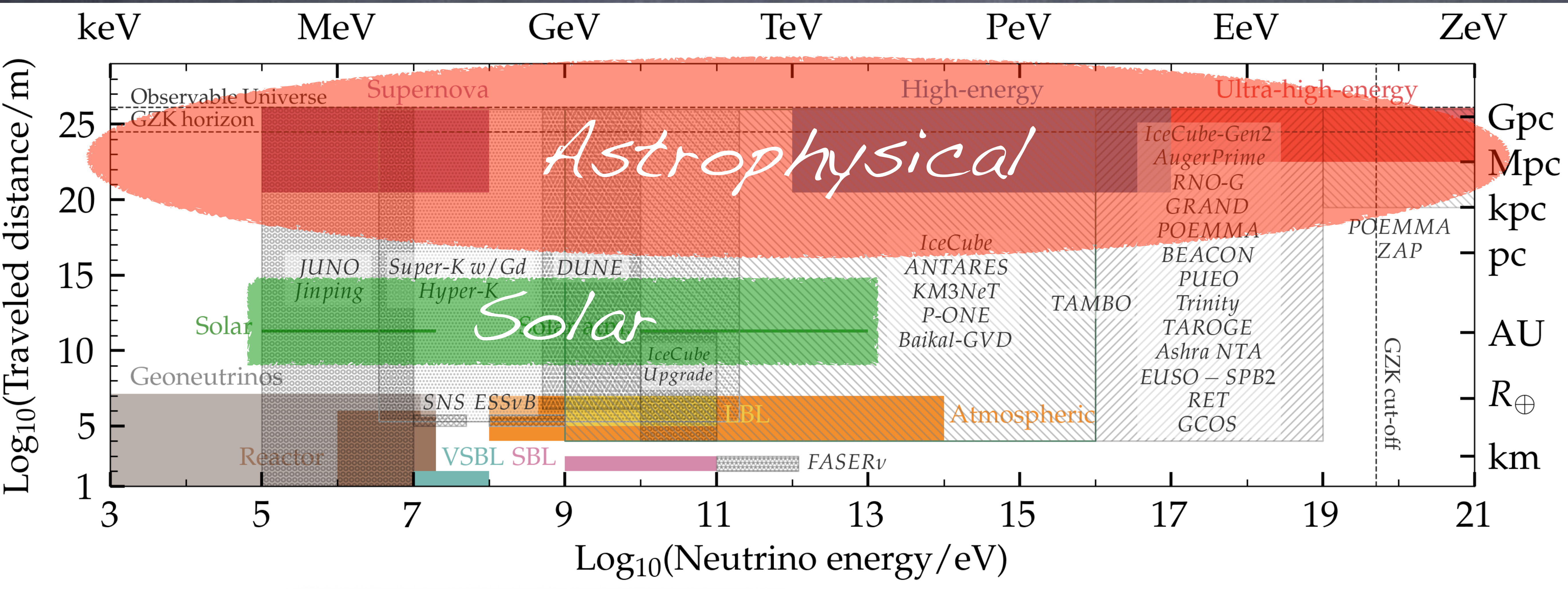

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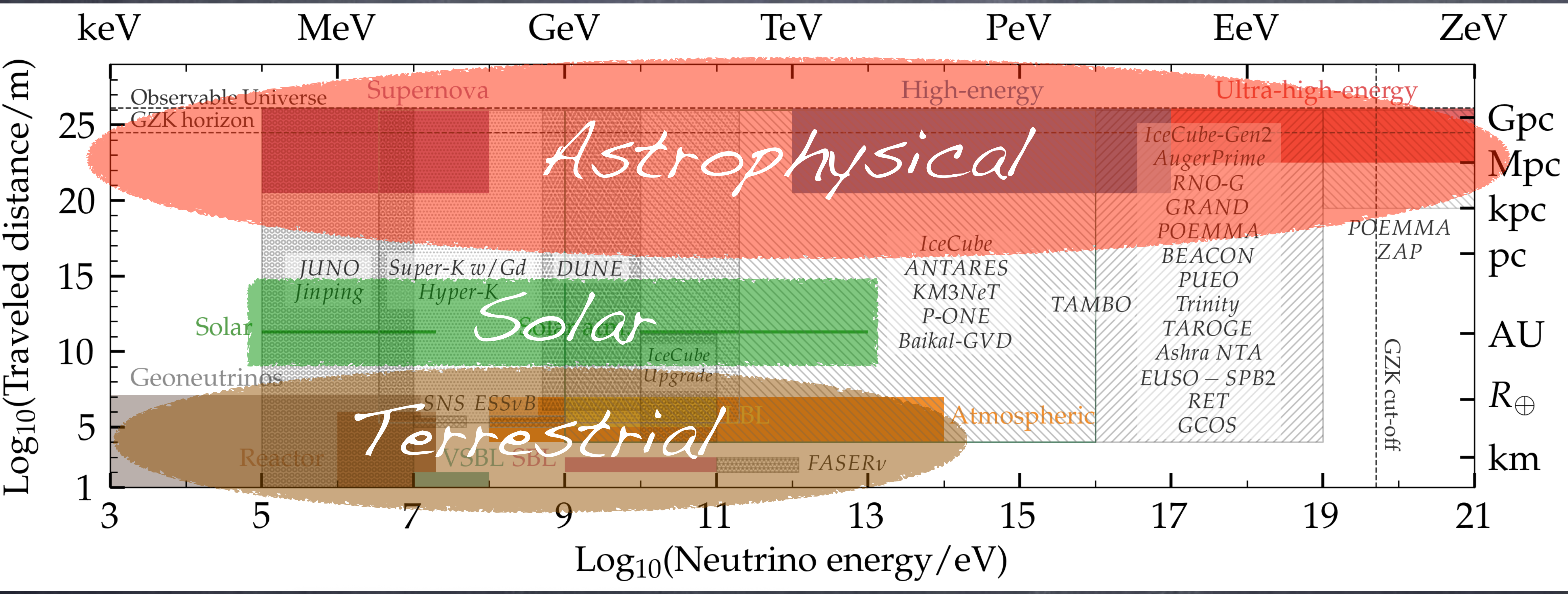

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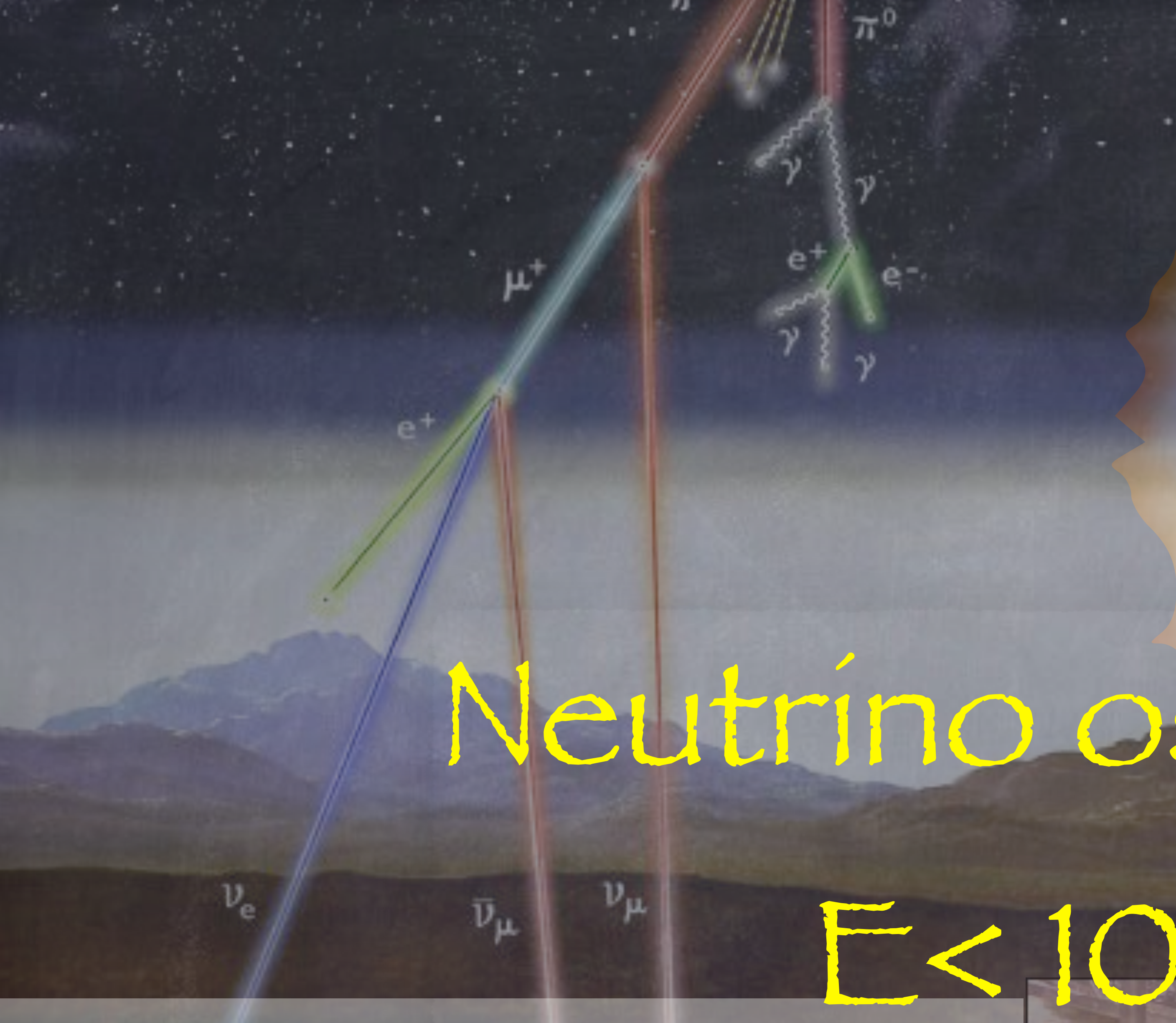


Neutrino oscillations

E< 10 TeV

NEUTRINOS IN THE STANDARD MODEL

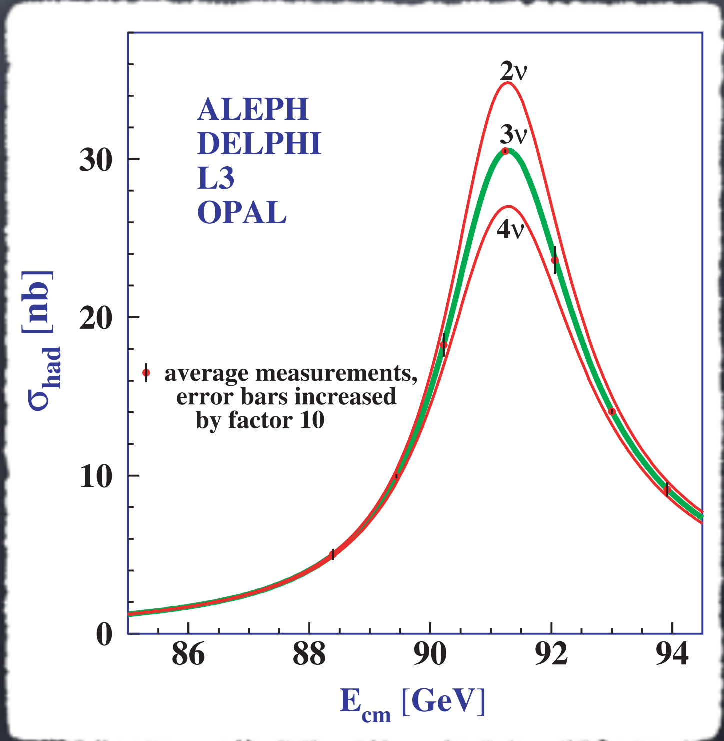
There are no SU(2) singlets (ν_R) →

Accidental global symmetry ($L_e \times L_\mu \times L_\tau$) →

Neutrinos are massless particles: neutrinos are left-handed and antineutrinos are right-handed

Neutrinos have electroweak interactions, belong to SU(2) doublets and, as charged leptons, come in three flavors

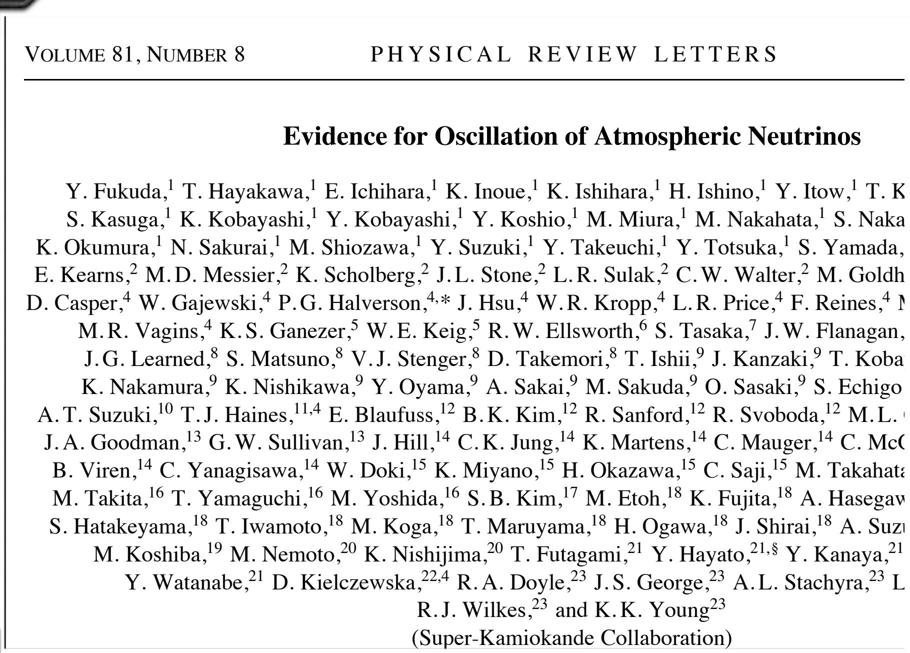
Invisible Z decay



Only 3 (light & active) neutrinos

$N_\nu = 2.9840 \pm 0.0082$

[ALEPH, DELPHI, L3, OPAL, SLD, LEP Collaborations], Phys. Rept. 427:257, 2006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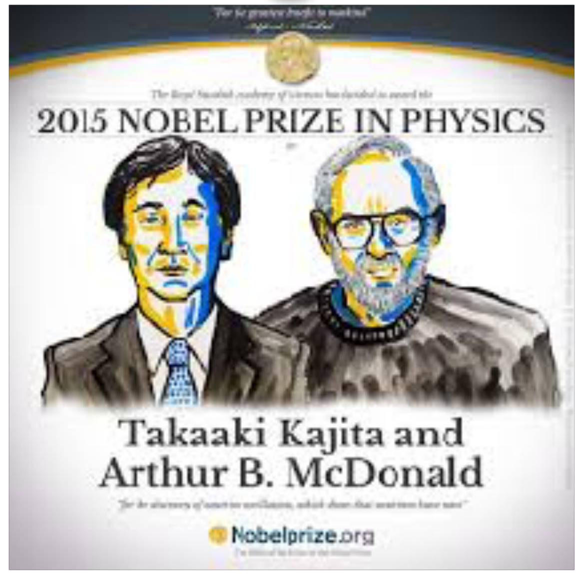

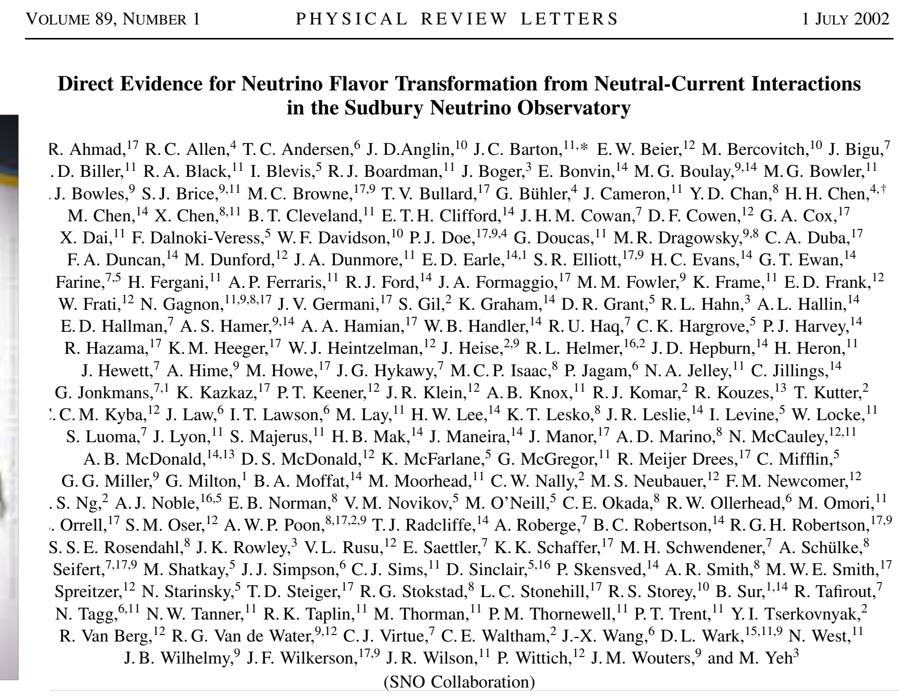
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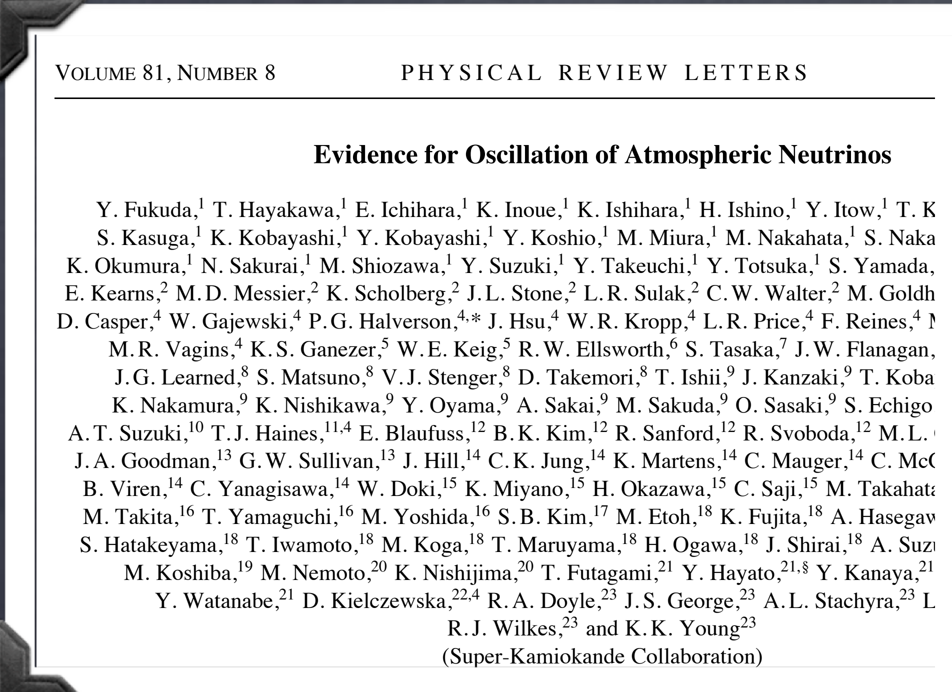
Neutrino oscillations → Lepton Flavor Violation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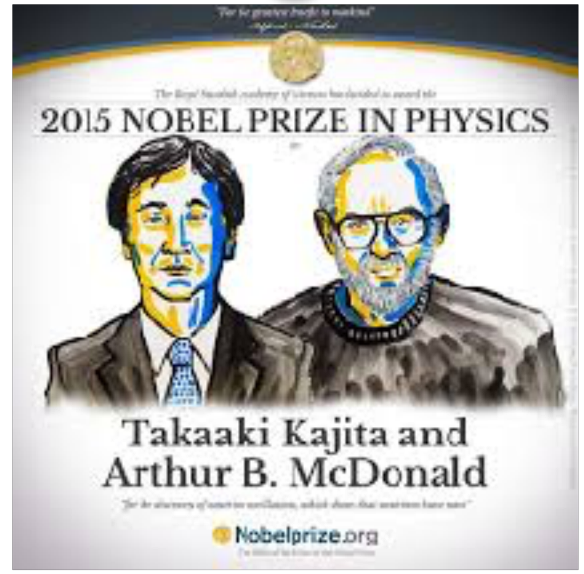

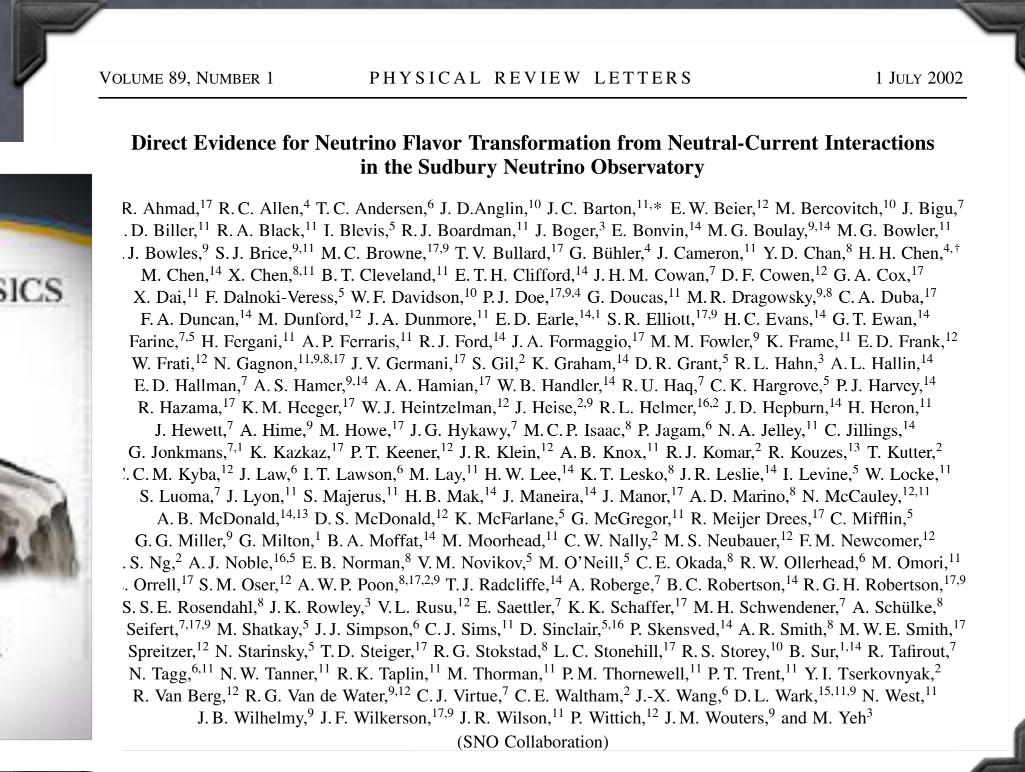
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Minimal extension to allow for LFV → massive neutrinos

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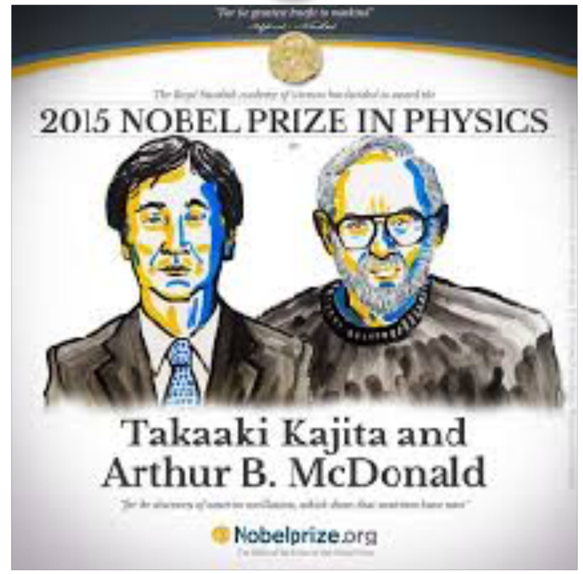
R.J. Wilkes,[23] and K.K. Young[23]
(Super-Kamiokande Collaboration)



VOLUME 89, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 2002

Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory

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(SNO Collaboration)

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Neutrino oscillations → Lepton Flavor Violation

Minimal extension to allow for LFV → massive neutrinos

introduce ν_R and conserve L

violate L (in two units)

Dirac: $\nu \neq \nu^C$

$$M_\nu^D \bar{\nu}_L \nu_R$$

Majorana: $\nu = \nu^C$

$$\frac{1}{2} M_\nu^M \bar{\nu}_L \nu_L^C$$

What are neutrino oscillations?

Mass & Mixing ⇒ Oscillations ($P_{\alpha\beta} \neq 0$)

flavor eigenstates $\nu_e \; \nu_\mu \; \nu_\tau$ ≠ mass eigenstates $\nu_1 \; \nu_2 \; \nu_3$

produced in CC processes | free propagation eigenstates

connected via the (non-diagonal) PMNS mixing matrix: $\nu_\alpha = U_{\alpha i}\nu_i$

$$i\partial_t \left(\nu_{L,R}^{\mp}\right)_i = H_i \left(\nu_{L,R}^{\mp}\right)_i$$

but neutrino masses are very small, so they are (almost) always very relativistic

(assuming Lorentz invariance)

$$E_i \simeq p + \frac{m_i^2}{2p} \simeq E + \frac{m_i^2}{2E}$$

$$P_{\alpha\beta} = \left| \sum_i U_{\alpha i}^* U_{\beta i} \, e^{-i\frac{\Delta m_i^2}{2E}t} \right|^2$$

OSCILLATIONS IN VACUUM

- *Pure quantum mechanical effect:* interference of different components with different phases and amplitudes

- Relative phases depend on *distance*, *mass square differences* and *energy*

- Amplitudes depend on *mixing*

- No information about the absolute mass scale, nor about the Dirac vs Majorana nature

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j\neq i} \mathrm{Re}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{j\neq i} \mathrm{Im}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

At first order, most cases can be reduced to oscillations of a two-neutrino system

For two neutrinos: $$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Appearance $\nu_\alpha \rightarrow \nu_\beta$

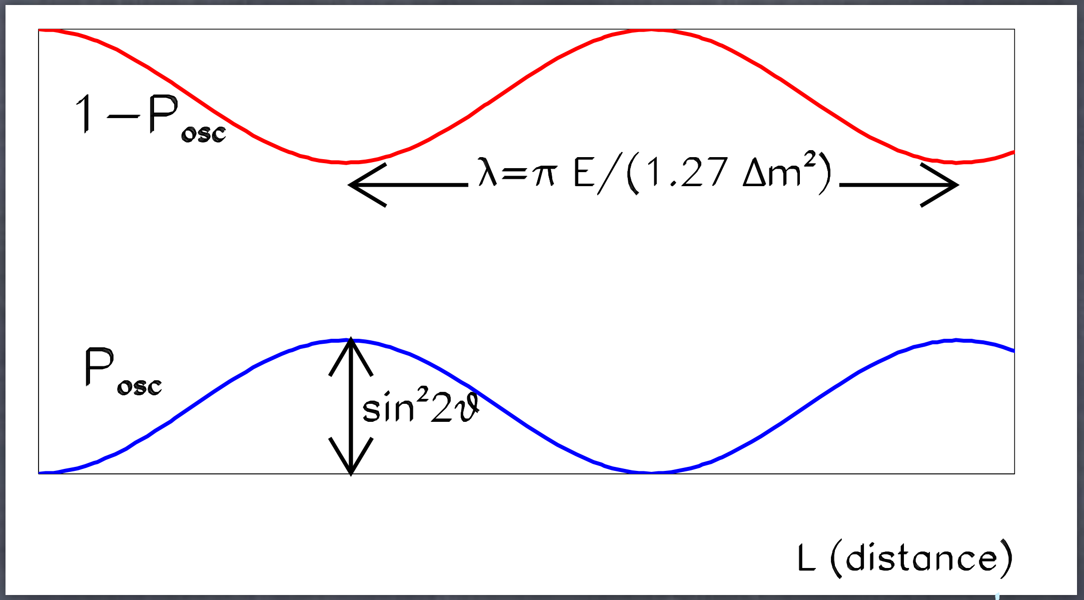
$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L}{\mathrm{km}}\frac{\mathrm{GeV}}{E}\right)$$

Disappearance $\nu_\alpha \rightarrow \nu_\alpha$ $\quad P_{\alpha\alpha} = 1 - P_{\alpha\beta}$

Not sensitive to mass ordering or octant of the mixing angle

OSCILLATIONS IN VACUUM

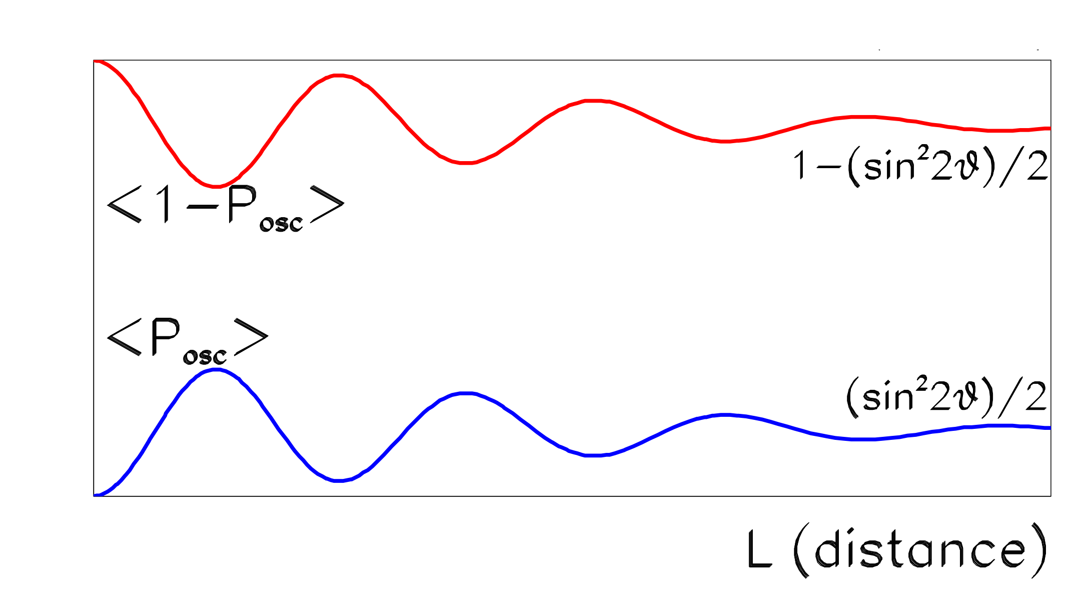
If $L \ll E/\Delta m^2$: No time to oscillate $P_{\alpha\beta} \approx 0$



From M. Maltoni

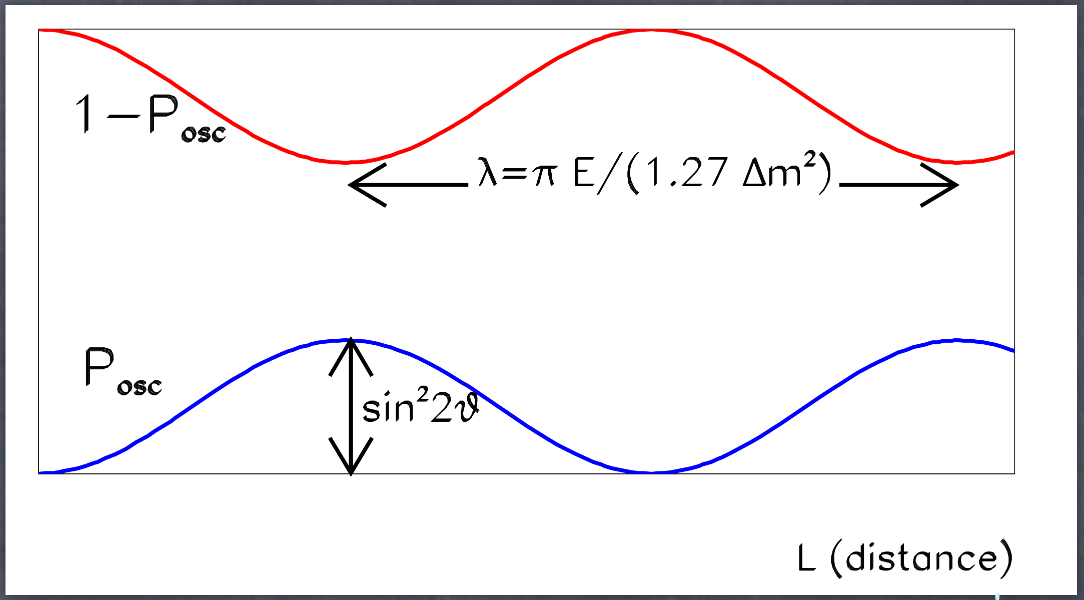
Maximal effect for $L \sim E/\Delta m^2$

If $L \gg E/\Delta m^2$: oscillations are averaged



OSCILLATIONS IN VACUUM

If L << E/Δm² : No time to oscillate $P_{\alpha\beta} \approx 0$



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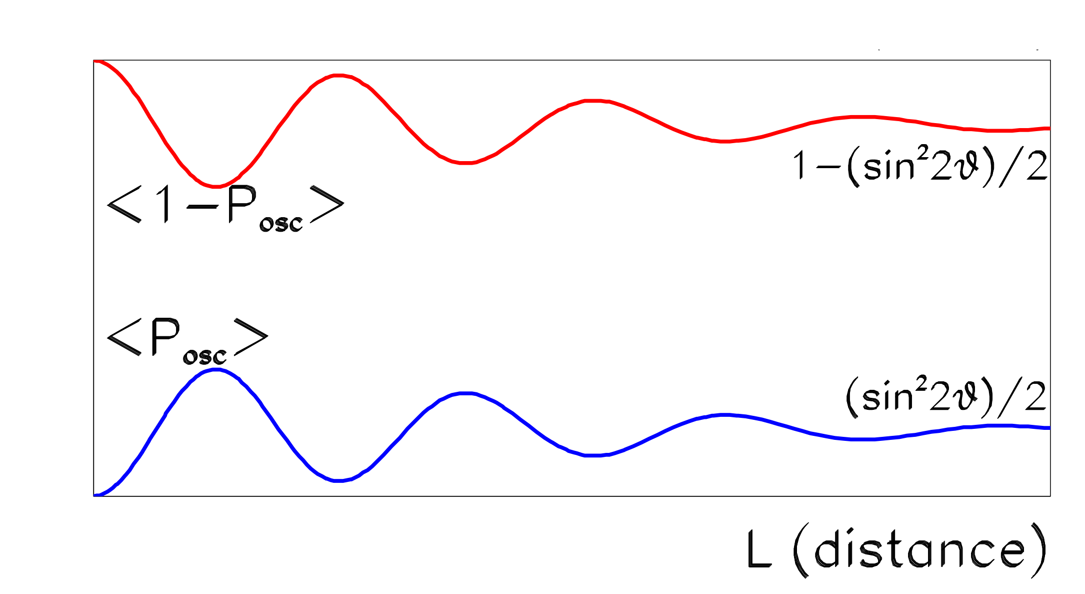
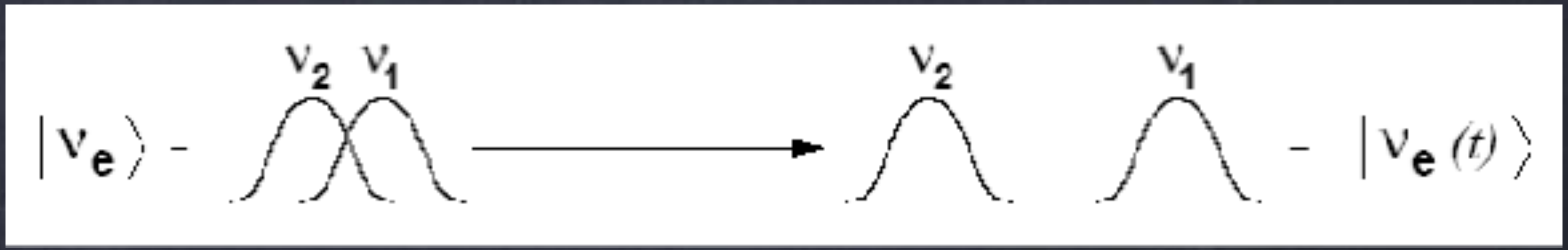
Maximal effect for L~E/Δm²

If L >> E/Δm² : oscillations are averaged



wave packets separate so that they can be differentiated in the detector

$$\langle P_{\alpha\beta} \rangle = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$



Matter effects

L. Wolfenstein, Phys. Rev. D17:2369, 1978

$$\text{Amplitude} = e^{iEnL}$$

index of refraction

$$n = 1 + 2\pi N f(0)/E^2 = 1 + V/E$$

incoherent process

optical theorem $[4\pi \, \mathrm{Im}\, f(0) / E = \sigma]$

Absorption: $E \, \mathrm{Im}(\Delta n) \propto N \sigma$

$$\sigma \propto G_F^2$$

relevant at high energies

coherent forward scattering

$$E \, \mathrm{Re}(\Delta n) \propto N \, \mathrm{Re}\, f(0) / E$$

$$\mathrm{Re}\{f(0)\} \propto G_F$$

relevant at low energies

Matter effects: a matter of scales

different flavors have different interactions

only relative terms matter!

$V_{CC} = \sqrt{2}\, G_F N_e$ $\qquad$ $V_{NC} = -1/\sqrt{2}\, G_F N_n$

solar core

$$V_\odot \sim 10^{-12}\ \mathrm{eV}$$

Earth core

$$V_\oplus \sim 10^{-13}\ \mathrm{eV}$$

coherent scattering
(for GeV energies)

$$\frac{\Delta m^2_{31}}{2E} \sim V_\oplus \sim R_\oplus^{-1}$$

absorption

$$\sigma \sim \frac{G_F\, s}{\pi} \sim 10^{-38} \left(\frac{E}{\mathrm{GeV}}\right) \mathrm{cm}^2$$

$$n\,\sigma \sim \left(\frac{E}{10\ \mathrm{TeV}}\right) R_\oplus^{-1}$$

OSCILLATIONS IN MATTER

S. P. Mikheyev and A. Yu. Smirnov, Sov. J. Nucl. Phys. 42:913, 1985   S. P. Mikheev and A. Yu. Smirnov, Nuovo Cim. C9:17, 1986

$$\mathcal{H} = E + V$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix}$$

amplitude (mixing) and oscillation wavelength are modified

$$\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\Delta m_m^2} \qquad \Delta m_m^2 = \sqrt{\left(\Delta m^2 \cos(2\theta) - 2EV_{CC}\right)^2 + \left(\Delta m^2 \sin(2\theta)\right)^2}$$

oscillations in matter are sensitive to mass ordering and octant

resonant enhancement

adiabatic conversion (MSW effect)

In a medium with varying density θ_m is a dynamical quantity

slowly varying density: $\dfrac{\Delta m_m^2}{4E} >> \dfrac{d\theta_m}{dx}$

$$P_{ee}^{adiabatic} = \sin^2\theta \, \sin^2\theta_m + \cos^2\theta \, \cos^2\theta_m$$

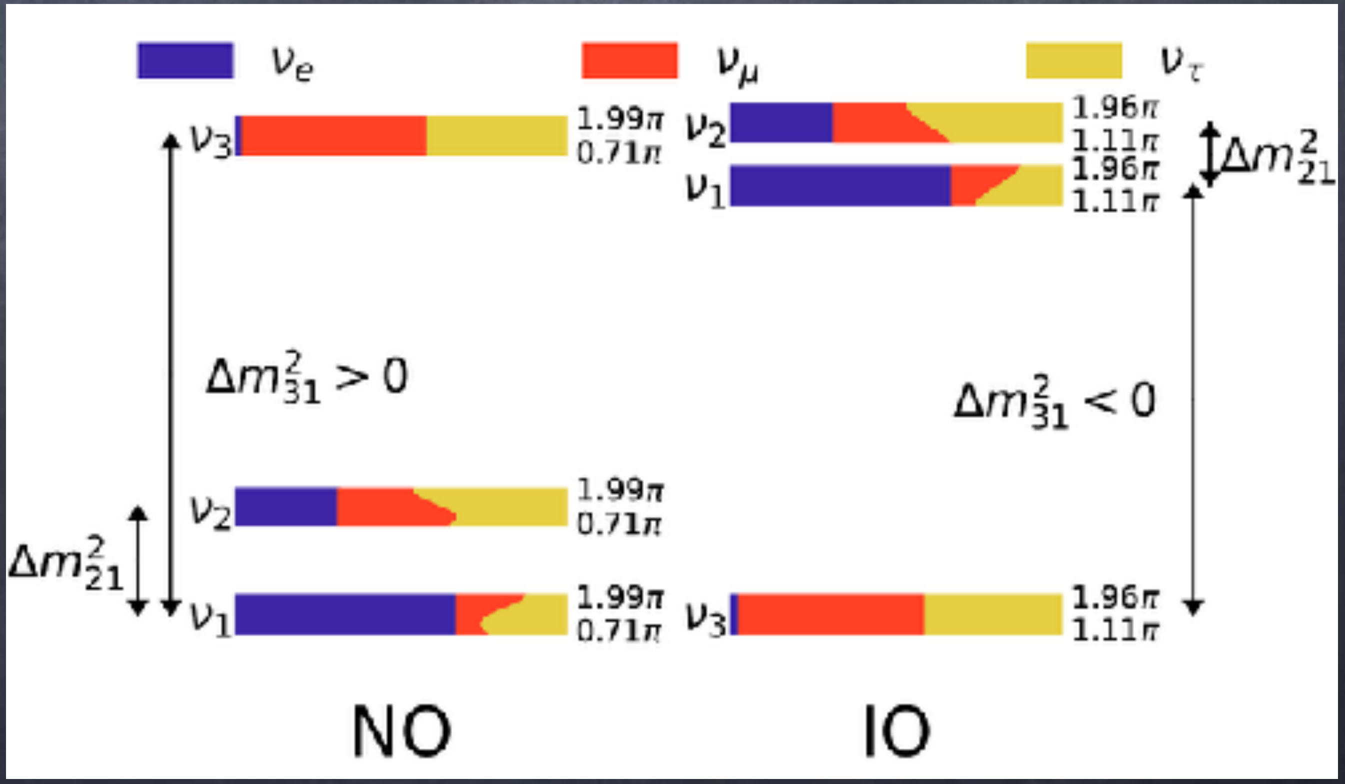
What do we want to know?

3 mixing angles + 1 Dirac phase + 2 Majorana phases

$$U_{PMNS} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

solar angle | reactor angle | atmospheric angle | Majorana phases

2 possible mass orderings



Valencia Neutrino Global Fit

Absolute mass scale?

Majorana vs Dirac nature?

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3 mixing angles + 1 Dirac phase + 2 Majorana phases

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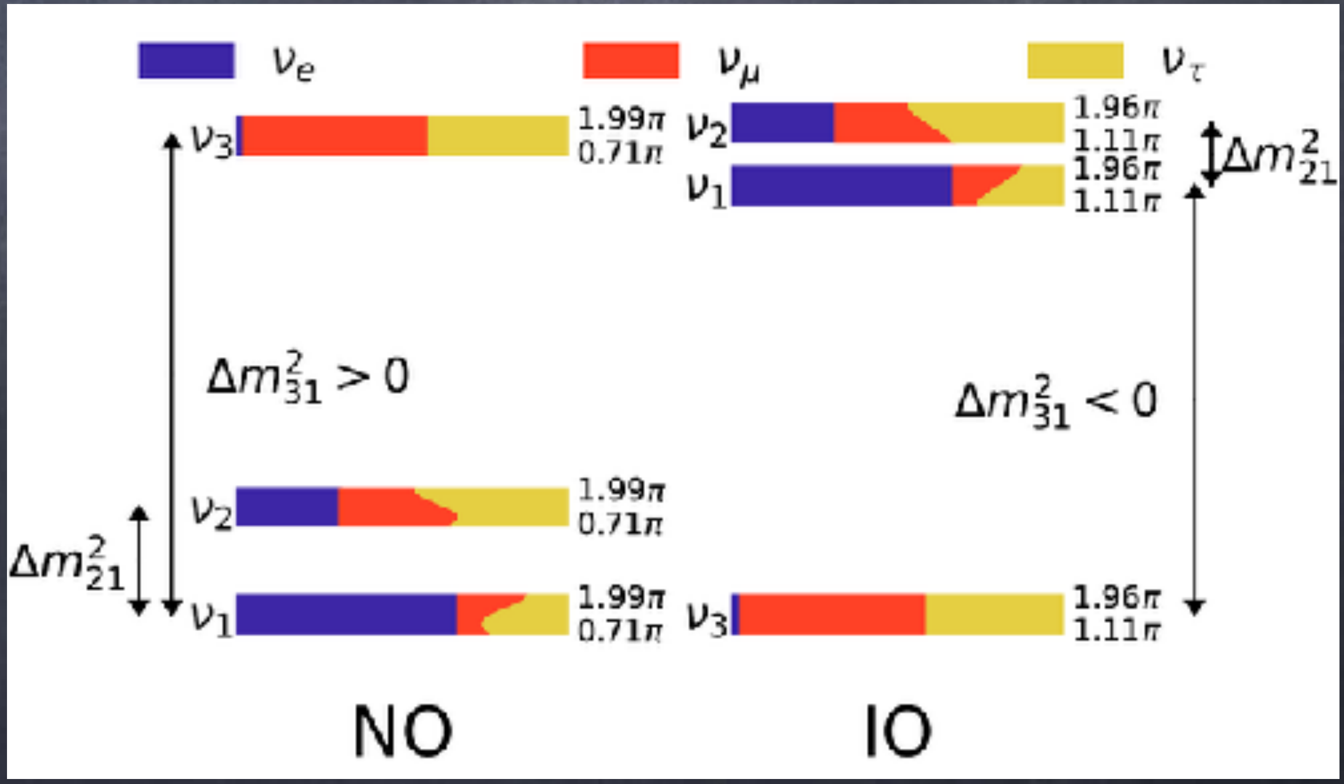
Not from neutrino oscillations

solar angle | reactor angle | atmospheric angle | Majorana phases

2 possible mass orderings



Valencia Neutrino Global Fit

Absolute mass scale?

Majorana vs Dirac nature?

How could we know it?

(mass scale and Dirac vs Majorana)

$$M = \sum_i m_{\nu,i}$$

Cosmological observations

$$\langle m_{\beta\beta}^2 \rangle = \left| \sum_i U_{ei}^2 m_{\nu,i} \right|^2$$

Neutrinoless double beta decay

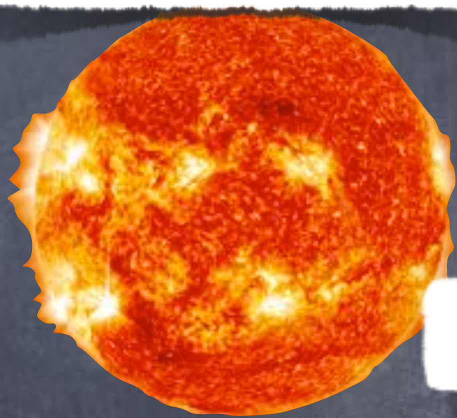
$$\langle m_\beta \rangle^2 = \sum_i |U_{ei}|^2 m_{\nu,i}^2$$

Tritium beta decay

(mixing: OSCILLATIONS)

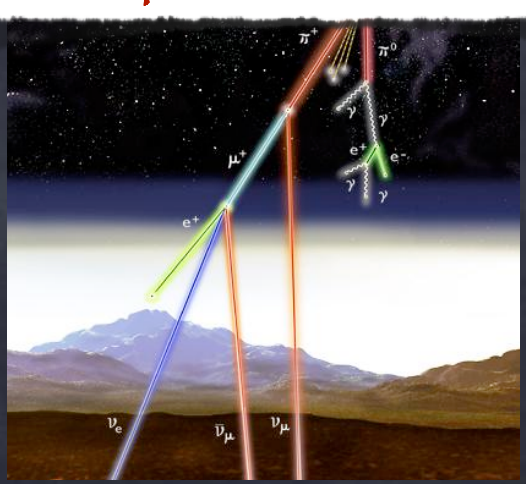
reactor neutrinos

solar neutrinos



accelerator neutrinos

atmospheric neutrinos



Oscillation experiments	dominant dependence	important dependences
solar (SK, SNO, Borexino)	θ_{12}	$\Delta m^2_{21}, \theta_{13}$
reactor LBL (KamLAND)	Δm^2_{21}	θ_{12}, θ_{13}
reactor MBL (DB, Reno, D-C)	θ_{13}	Δm^2_{31}
atmospheric (SK, IC)	$\Delta m^2_{31}, \theta_{23}$	θ_{13}, δ
accelerator LBL disappearance (Minos, T2K, NovA)	Δm^2_{31}	θ_{23}
accelerator LBL appearance (Minos, T2K, NovA)	θ_{13}	$\Delta m^2_{31}, \theta_{23}, \delta$

What do we know?

parameter	best fit $\pm 1\sigma$	2σ range	3σ range
Δm^2_{21}: [10^{-5} eV^2]	$7.50^{+0.22}_{-0.20}$	7.11–7.93	6.94–8.14
$\|\Delta m^2_{31}\|$: [10^{-3} eV^2] (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\|\Delta m^2_{31}\|$: [10^{-3} eV^2] (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
δ_{CP}/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
δ_{CP}/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96

P. F. de Salas et al., JHEP 02 (2021) 071

See also: I. Esteban et al., JHEP 09 (2020) 178 F. Capozzi et al., Phys. Rev. D104:083031, 2021

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Mass hierarchy?

Octant?

CPV?

P. F. de Salas et al., JHEP 02 (2021) 071

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Absolute neutrino mass scale:

(cosmo) $\sum m_i < 0.1$ eV

(ν-less 2β decay) $\left|\sum_i U_{ei}^2 m_i\right| < 0.1$ eV

(β decay – Katrin) $\sqrt{\sum_i \left|U_{ei}\right|^2 m_i^2} < 0.8$ eV

CPV?

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Anomalies at short baselines (LSND, MB, reactors, Gallium):

sterile neutrinos?

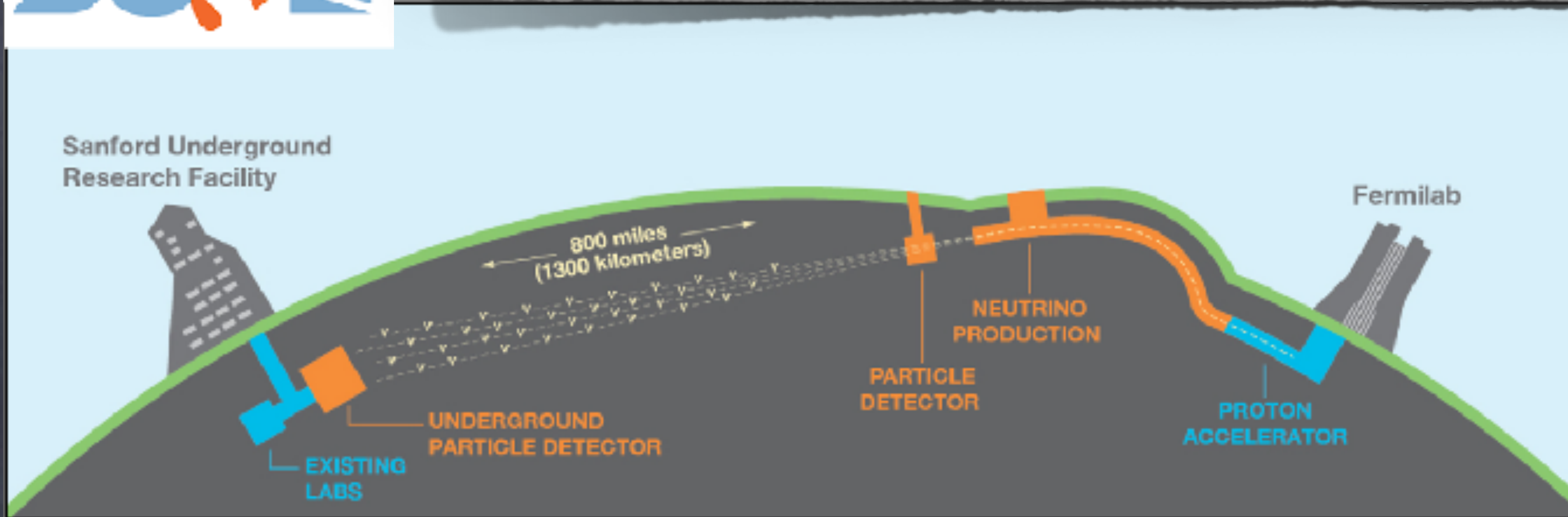
imprecise knowledge of fluxes and systematics?

CPV?

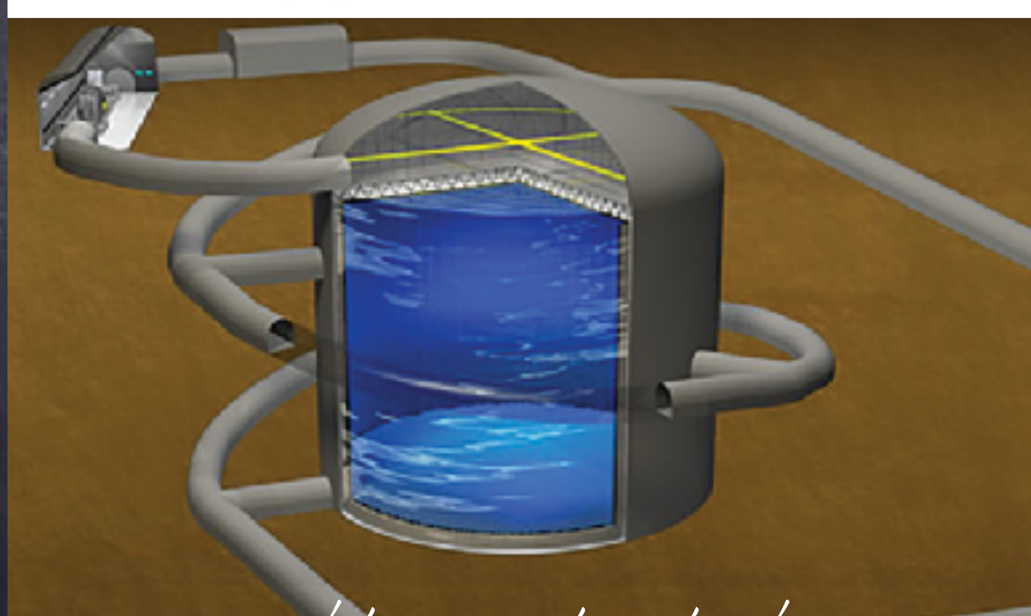
P. F. de Salas et al., JHEP 02 (2021) 071

See also: I. Esteban et al., JHEP 09 (2020) 178 F. Capozzi et al., Phys. Rev. D104:083031, 2021

4 x 10 kton liquid argon time projection chambers + near detector
baseline ~1300 km



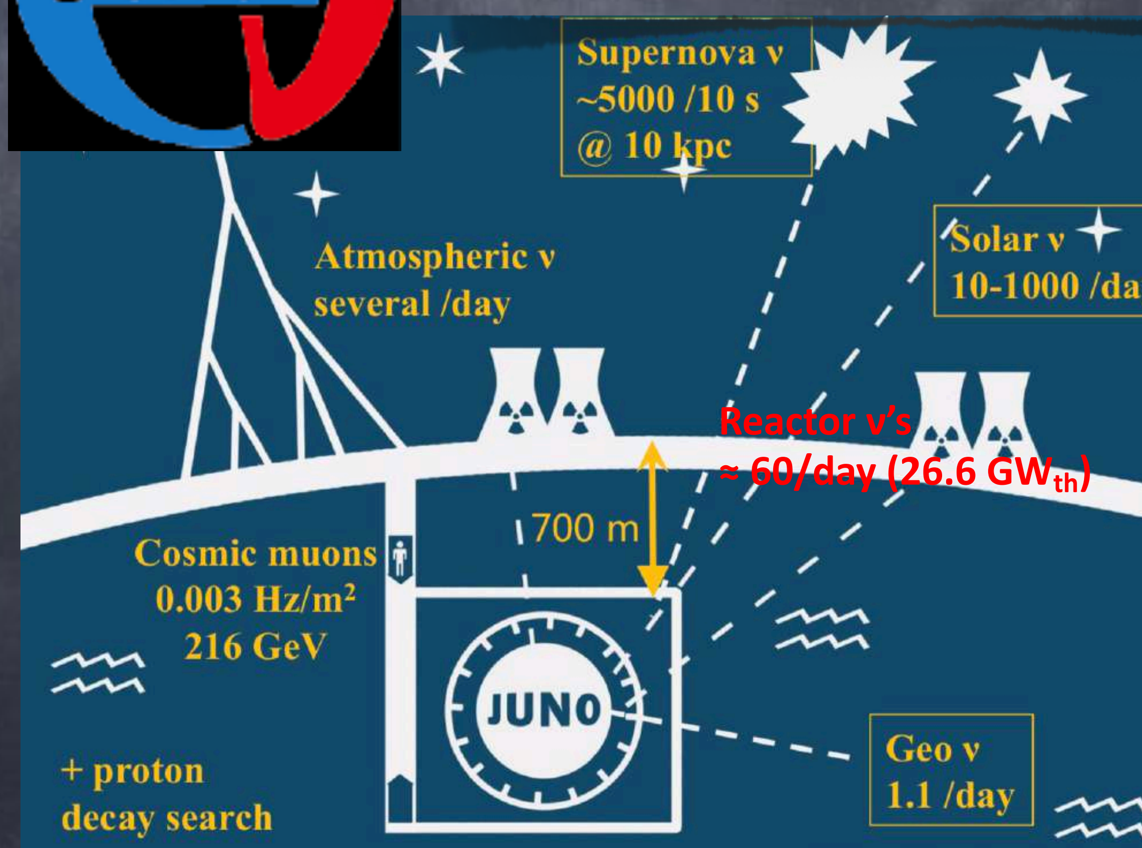
Hyper-Kamiokande



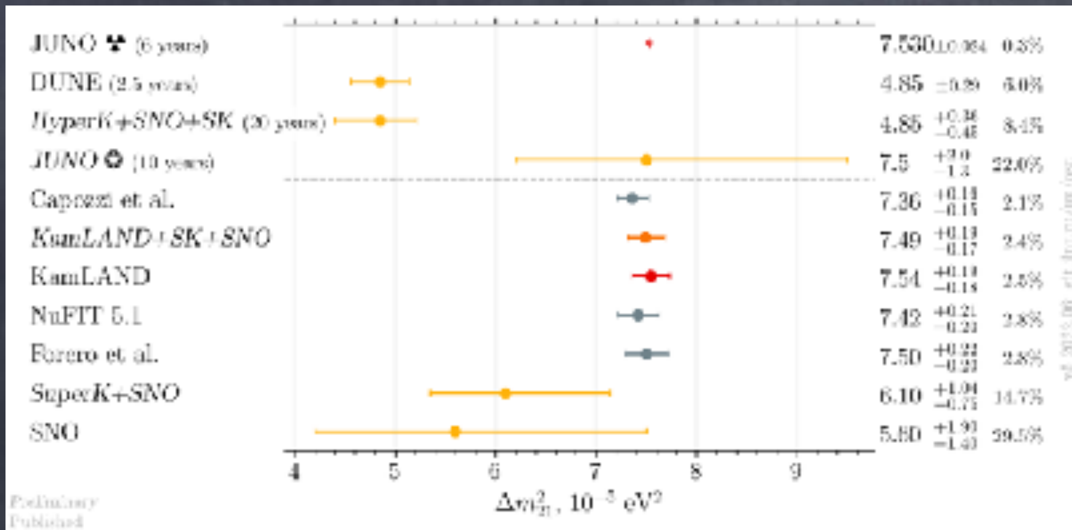
2 x 187 kton water tanks
+0.1 % Gadolinium to improve
inverse beta decay tagging
+ J-PARC neutrino beam

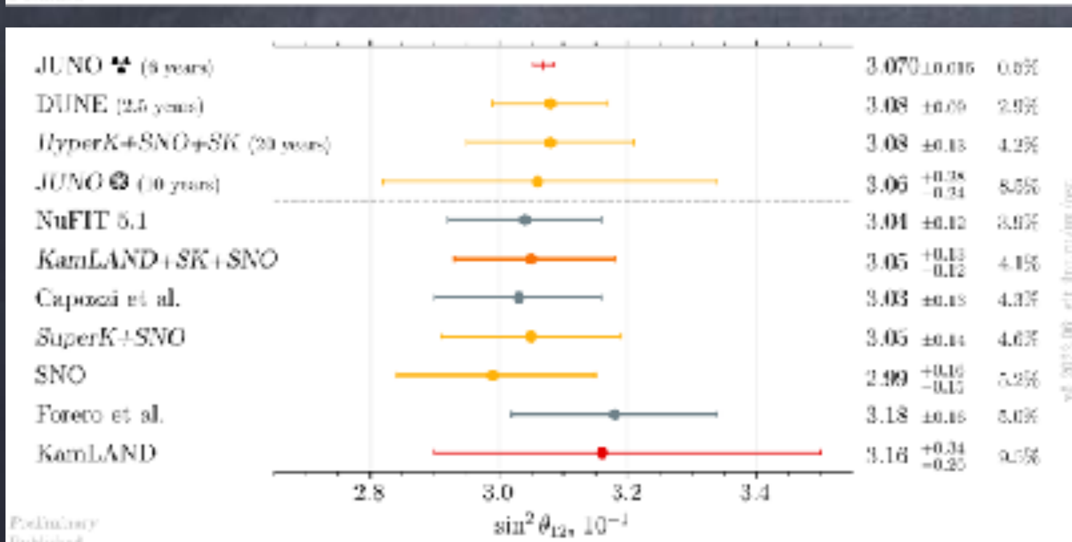
JUNO

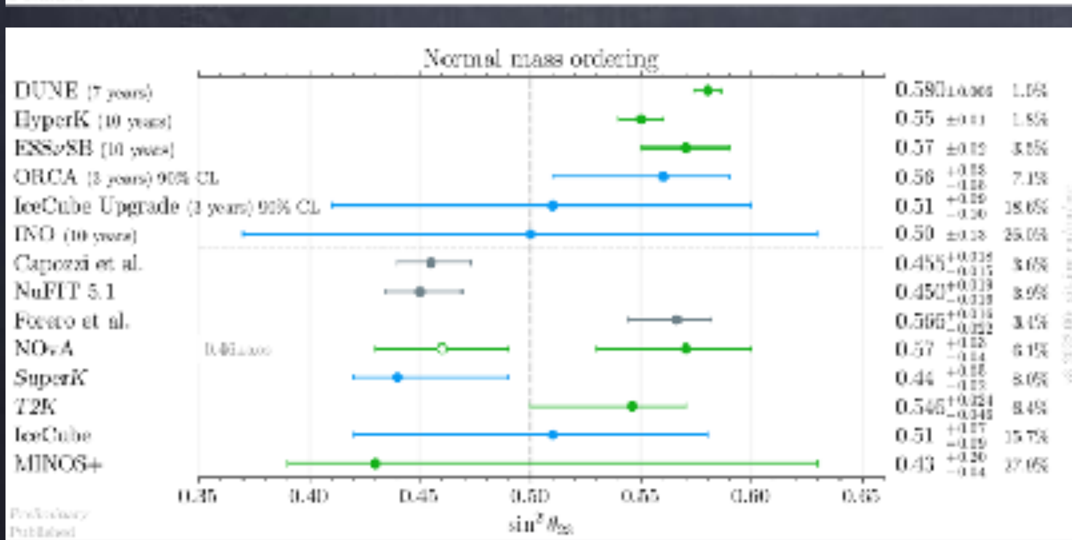
20 kton of liquid scintillator
Thermal power ~ 26.6 GW
baseline ~ 53 km

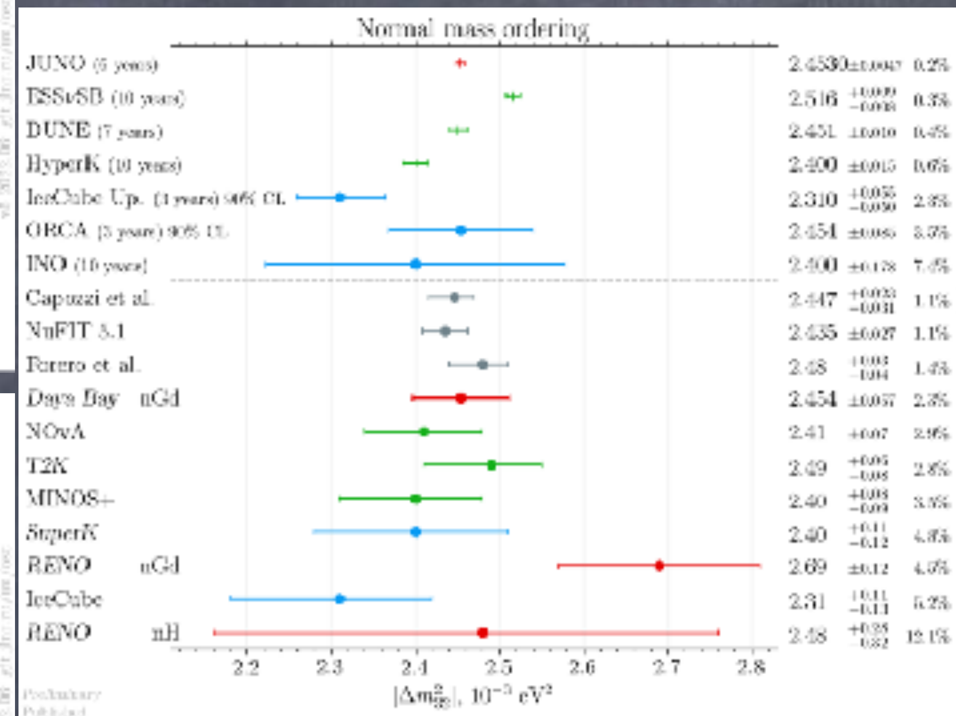


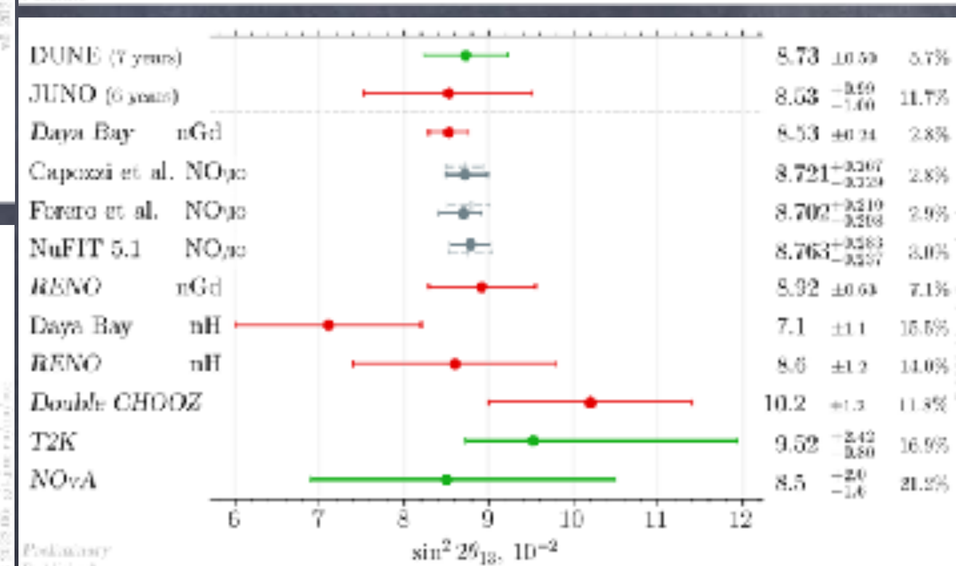
Current results vs Forecasts

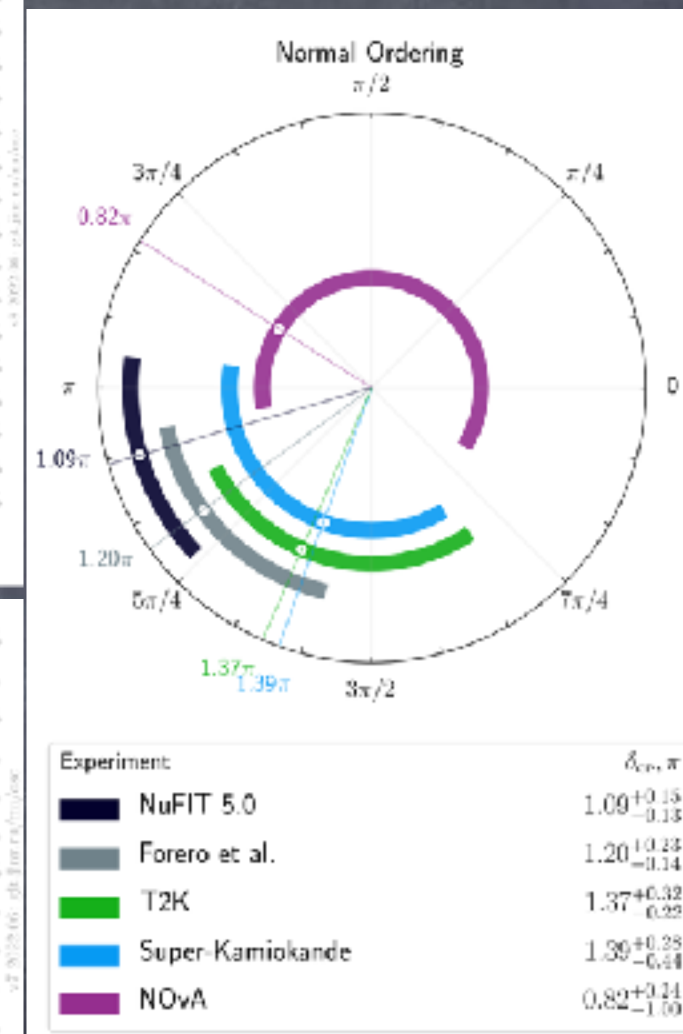






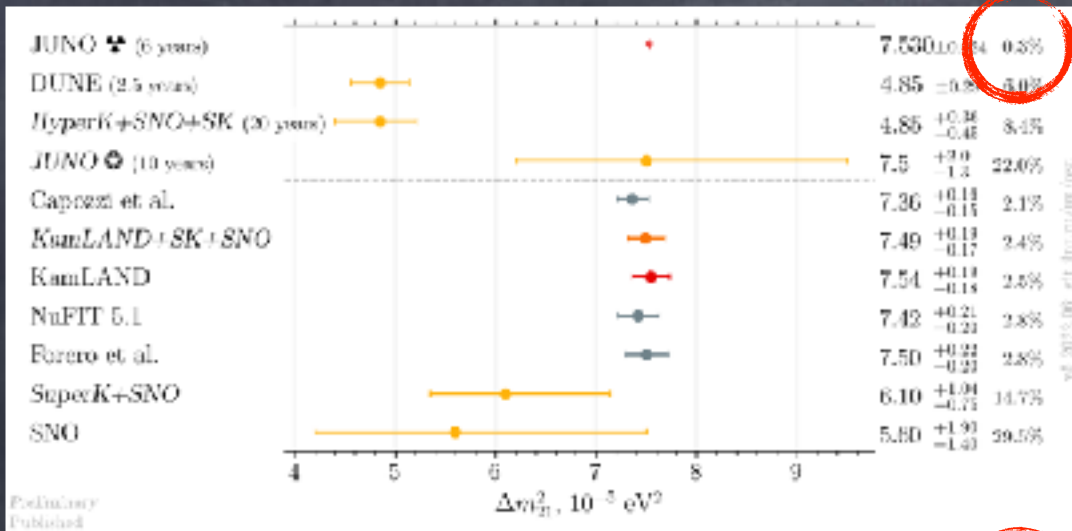


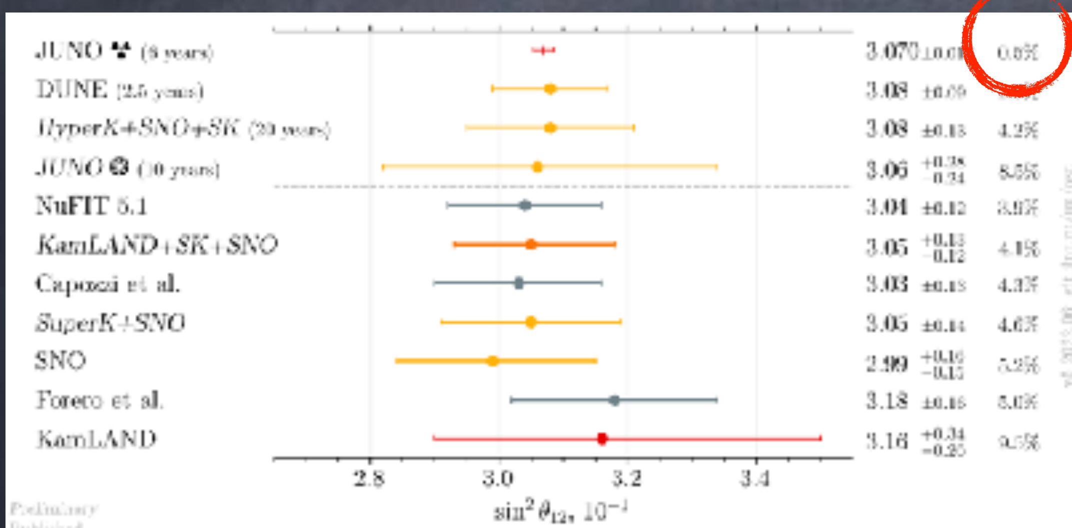


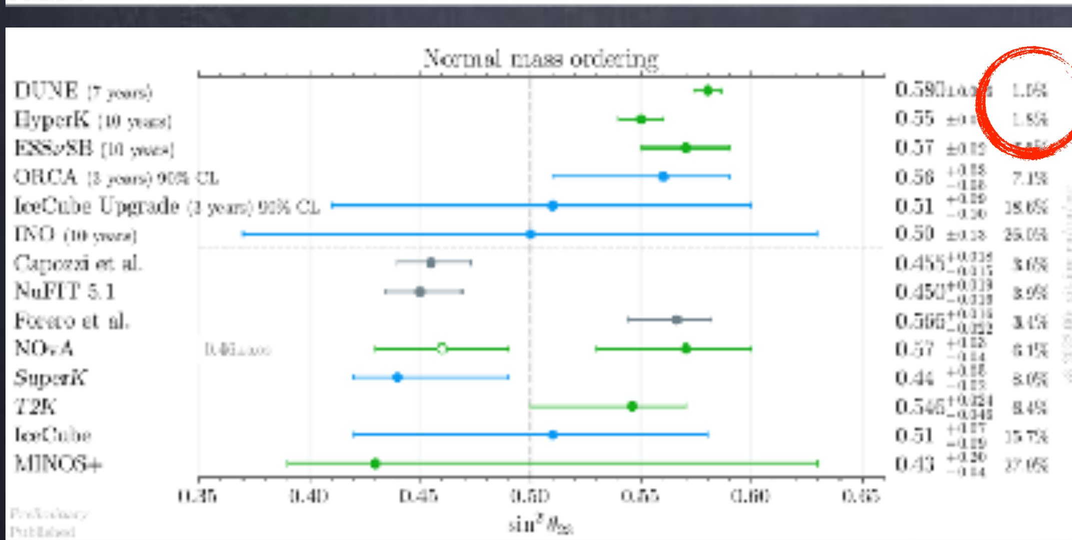


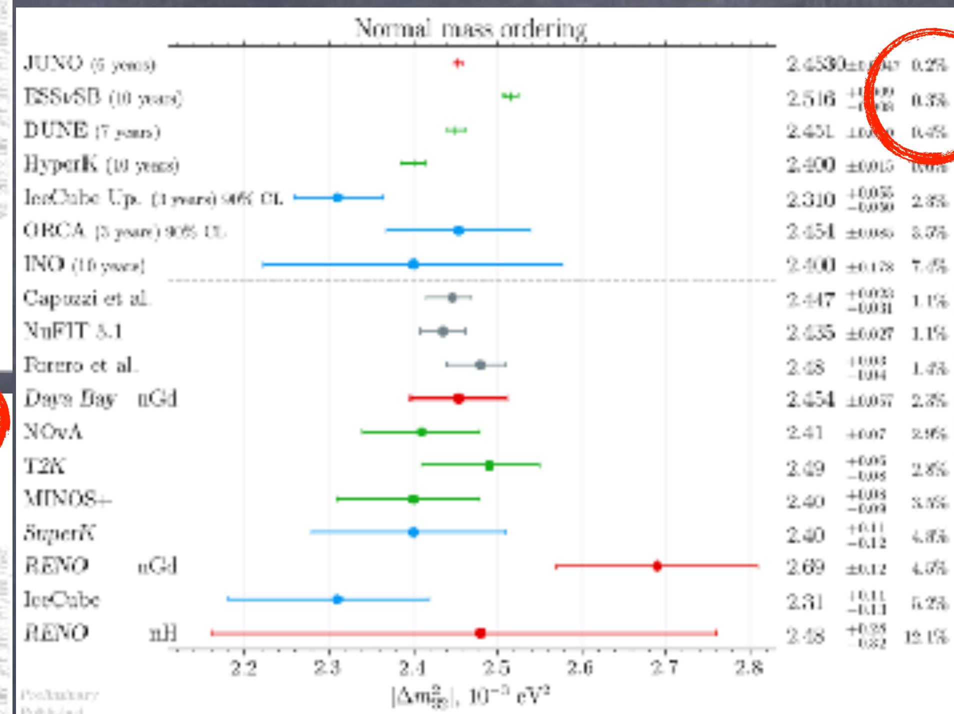
From M. Gonchar GitLab

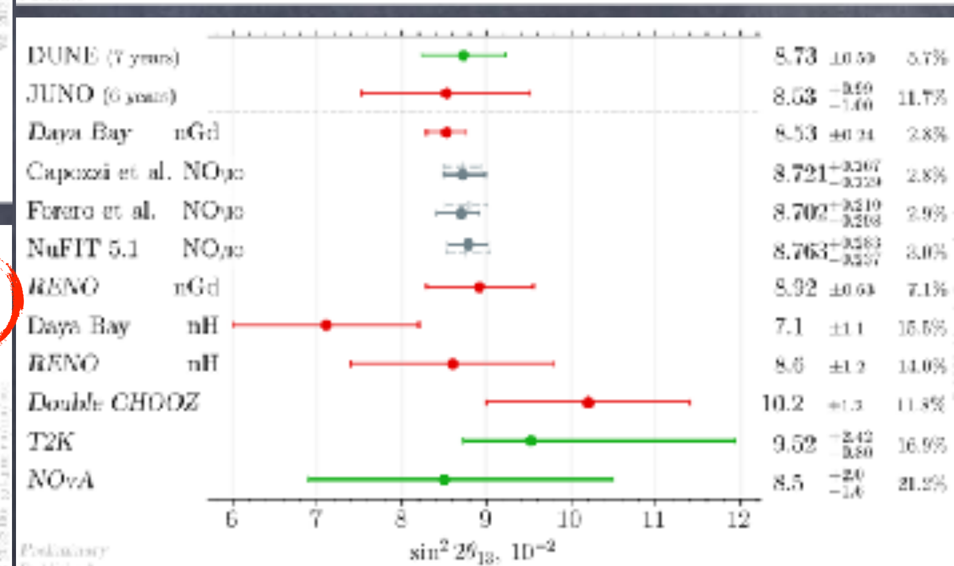
Current results vs Forecasts

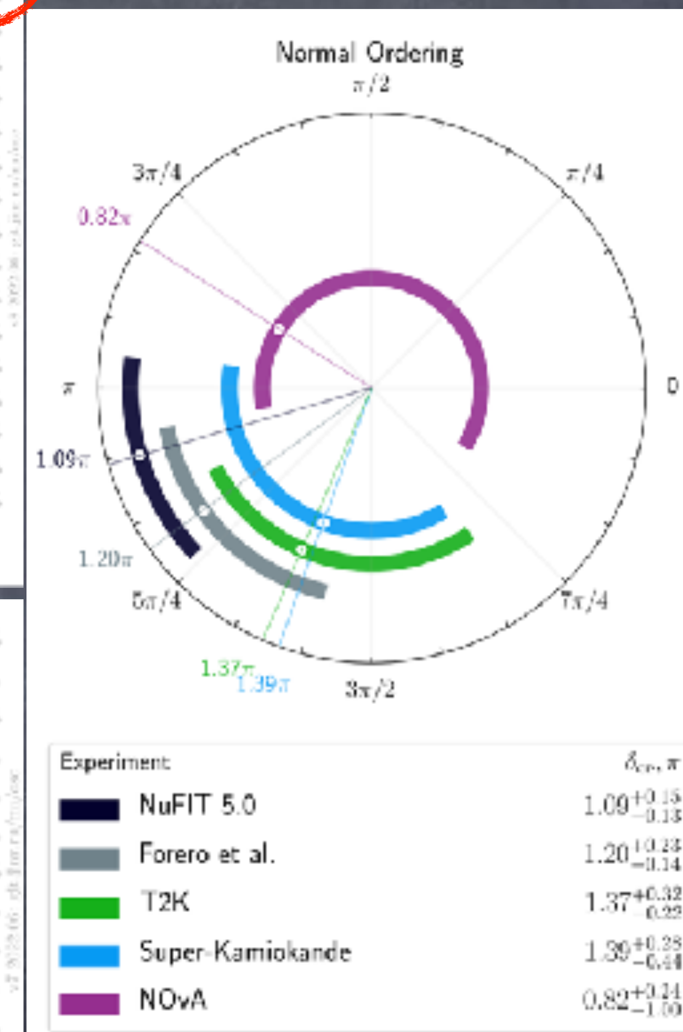












From M. Gonchar GitLab

Neutrinos as QG messengers: CPTV

CPT symmetry is at the foundation of local quantum field theories: The SM and its extensions are based on its validity

CPT symmetry is the combination of Charge Conjugation, Parity and Time reversal. It implies particles and antiparticles have the same mass, lifetime, and mixing angles

It assumes Lorentz invariance, hermiticity of the Hamiltonian and local commutativity

Neutrinos are particularly suited to search for CPT violation

$$\frac{m_{K^0} - m_{\bar{K}_0}}{m_K} < 0.6 \times 10^{-18}$$

the scale is arbitrary

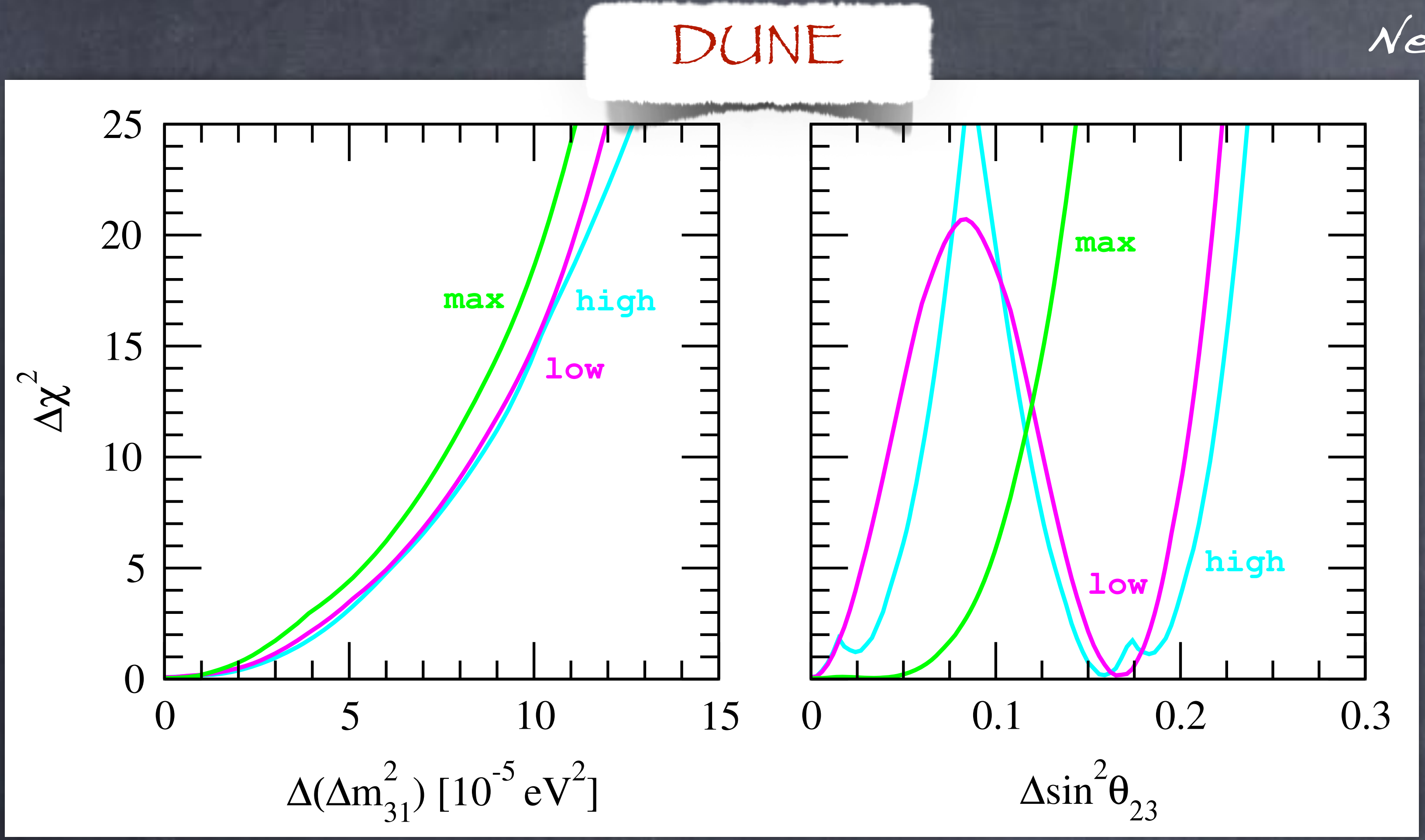
$$|m^2_{K_0} - m^2_{\bar{K}_0}| < 0.25 \text{ eV}^2$$

$$|\Delta m^2_{31} - \Delta \bar{m}^2_{31}| < 3.7 \times 10^{-4} \text{ eV}^2$$

combining neutrino and antineutrino modes at MINOS, T2K and NOvA

G. Barenboim, C. A. Ternes and M. A. Tórtola, Phys. Lett. B780:631, 2018

Tests of CPT violation in neutrino oscillations



G. Barenboim, C. A. Ternes and M. A. Tórtola, Phys. Lett. B780:631, 2018

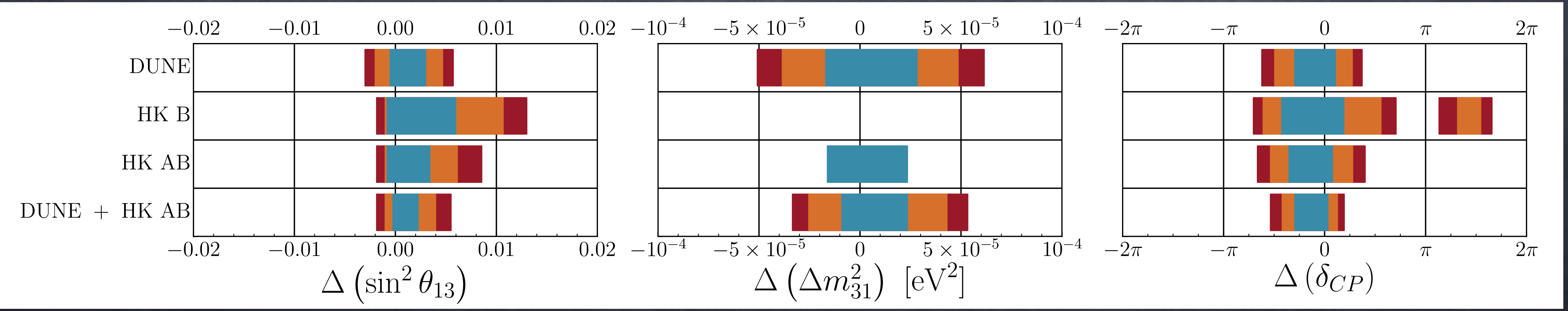
Neutrino and antineutrino parameters assumed to be different

$$\{\Delta m^2_{ij}, \theta_{ij}, \delta\} \quad \{\Delta \bar{m}^2_{ij}, \bar{\theta}_{ij}, \bar{\delta}\}$$

One order of magnitude improvement over current constraints

Establishing CPT conservation is key to determine CP violation

G. Barenboim, C. A. Ternes and M. A. Tórtola, JHEP 07:155, 2020



A. de Gouvêa and K. Kelly, Phys. Rev. D96:095018, 2017

Lorentz invariance violation: SME

The Standard Model Extension (SME) is the effective field theory that incorporates the SM and GR and includes all LIV operators

D. Colladay and V. A. Kostelecky, Phys. Rev. D55:6760, 1997; D. Colladay and V. A. Kostelecky, Phys. Rev. D58:116002, 1998
V. A. Kostelecky, Phys. Rev. D69:105009, 2004

All SME coefficients relevant for neutrinos have been systematically classified for operators of arbitrary dimension

V. A. Kostelecky and M. Mewes, Phys. Rev. D69:016005, 2004; V. A. Kostelecky and M. Mewes, Phys. Rev. D85:096005, 2012

$$\mathscr{L} = \frac{1}{2}\bar{\Psi}_A \left(\gamma^\mu i \partial_\mu \delta_{AB} - m_{AB} + \underbrace{\mathscr{Q}_{AB}}_{\text{LIV operator}} \right) \Psi_B + h.c.$$

It can be decomposed as

$$\mathscr{Q} = \mathscr{S} + i\,\mathscr{P}\,\gamma_5 + \mathscr{V}^\mu \gamma_\mu + \mathscr{A}^\mu \gamma_5 \gamma_\mu + \frac{1}{2}\mathscr{T}^{\mu\nu}\sigma_{\mu\nu}$$

Lorentz invariance violation: SME

It can also be decomposed as

$$\gamma^\nu p_\nu \delta_{AB} - m_{AB} + \mathcal{Q}_{AB} = \Gamma^\nu_{AB} p_\nu - M_{AB}$$

$$\Gamma^\nu_{AB} = \gamma^\nu \delta_{AB} + c^{\mu\nu}_{AB} \gamma_\mu + d^{\mu\nu}_{AB} \gamma_5 \gamma_\mu + e^\nu_{AB} + i f^\nu_{AB} \gamma_5 + \frac{1}{2} g^{\kappa\lambda\nu}_{AB} \sigma_{\kappa\lambda}$$

$$M_{AB} = m_{AB} + \tilde{m}_{AB} + i\tilde{m}_{5AB} \gamma_5 + a^\mu_{AB} \gamma_\mu + b^\mu_{AB} \gamma_5 \gamma_\mu + \frac{1}{2} h^{\mu\nu}_{AB} \sigma_{\mu\nu}$$

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Neutrino oscillations

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu \\ \bar{\nu}\end{pmatrix} = \left(H_0 + H_m + \delta H\right)\begin{pmatrix}\nu \\ \bar{\nu}\end{pmatrix}$$

$$\delta H = \frac{1}{p}\begin{pmatrix} a_{eff} - c_{eff} & -g_{eff} + h_{eff} \\ -g^{\dagger}_{eff} + h^{\dagger}_{eff} & -a^{T}_{eff} - c^{T}_{eff}\end{pmatrix}$$

$$a_{eff} = \sum_d E^{d-2} a_d$$

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neutrino-antineutrino oscillations
not present if rotational invariance

Generic effects of LIV in oscillations

Different dependencies on L and E

Vacuum oscillations: L/E — Matter term: L — LIV terms : LE^n

spectral anomalies

L-E conflicts among experimental results

Time dependence: sidereal and annual variations

Compass asymmetries: direction-dependent effects

neutrino-antineutrino mixing

Tested at short baseline and atmospheric experiments

require violation of rotational invariance

classic CPT test

$$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)$$

see talks by V. Antonelli and P. Martínez-Miravé

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... but time-variations of masses and mixings could be caused by neutrino coupling to ultra-light dark matter

A .Berlin, Phys. Rev. Lett. 117:231801, 2016

G. Krnjaic, P. A. N. Machado and L. Necib, Phys. Rev. D97:075017, 2018

V. Brdar et al., Phys. Rev. D97:043001, 2018

A. Dev, P. A. N. Machado and P. Martínez-Miravé, JHEP 01:094, 2021

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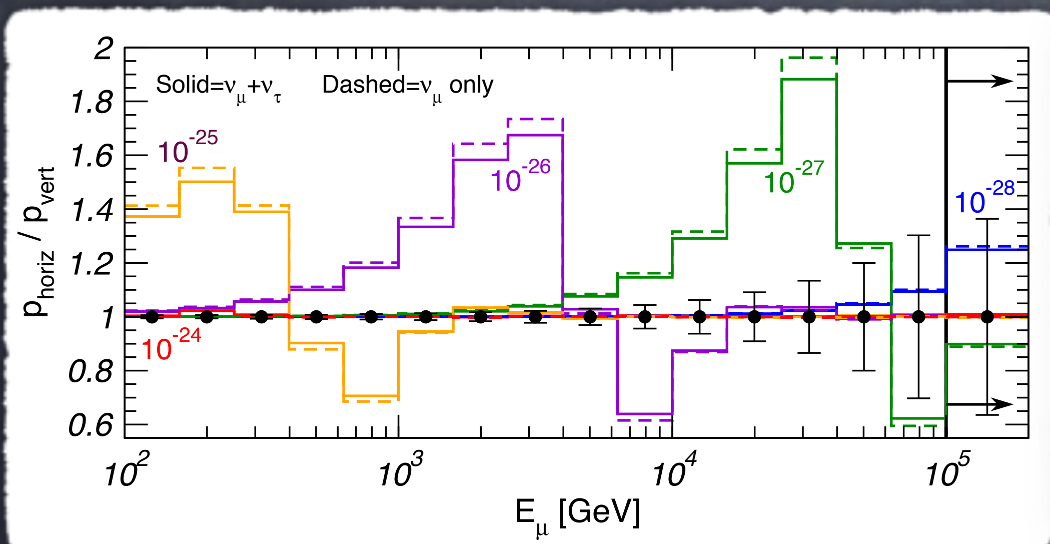
Lorentz invariance violation with atmospheric neutrinos

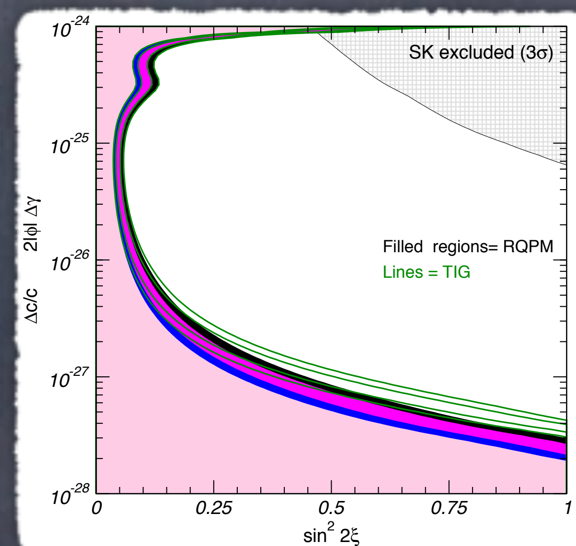
(isotropic case)

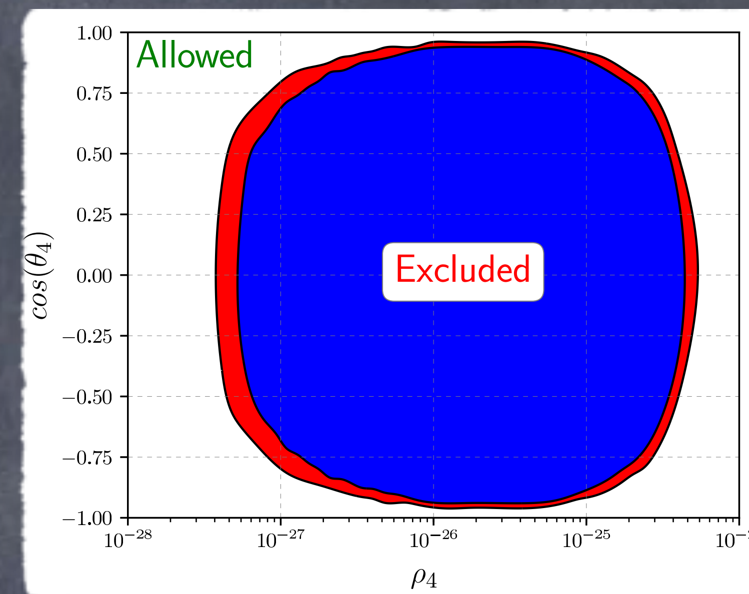
modification of spectral and zenith distribution

$$H = \frac{1}{2E} U M^2 U^\dagger + \sum_{d=3}^{n} (-E)^{d-3} c^d$$

c_4







M. C. González-García, F. Halzen and M. Maltoni, Phys. Rev. D71:093010, 2005

M. G. Aartsen et al. [IceCube Collaboration], Nature Physics 14:961, 2018

See also:

K. Abe et al. [Super-Kamiokande Collaboration], Phys. Rev. D91:052003, 2015

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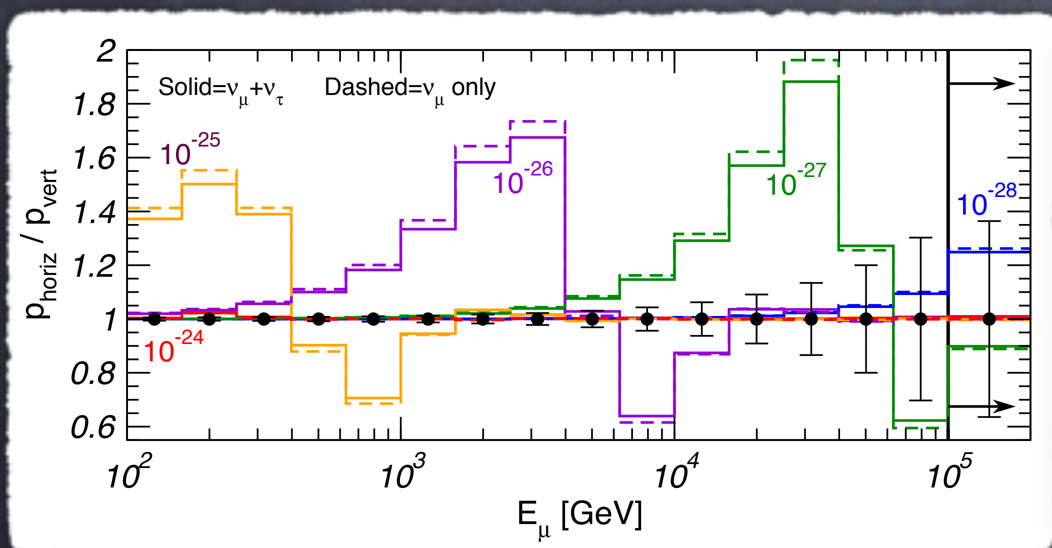

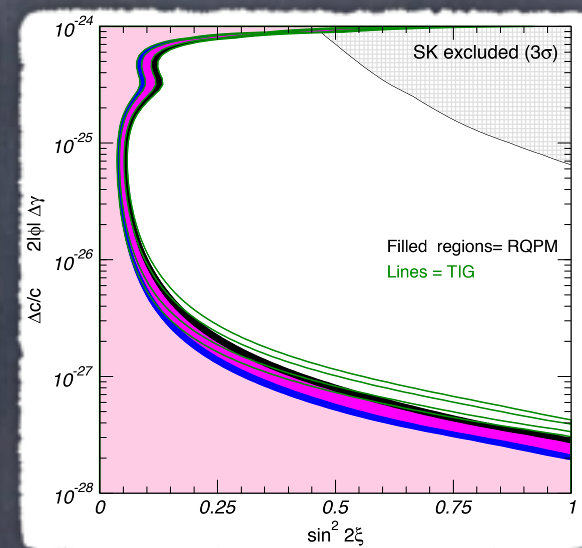

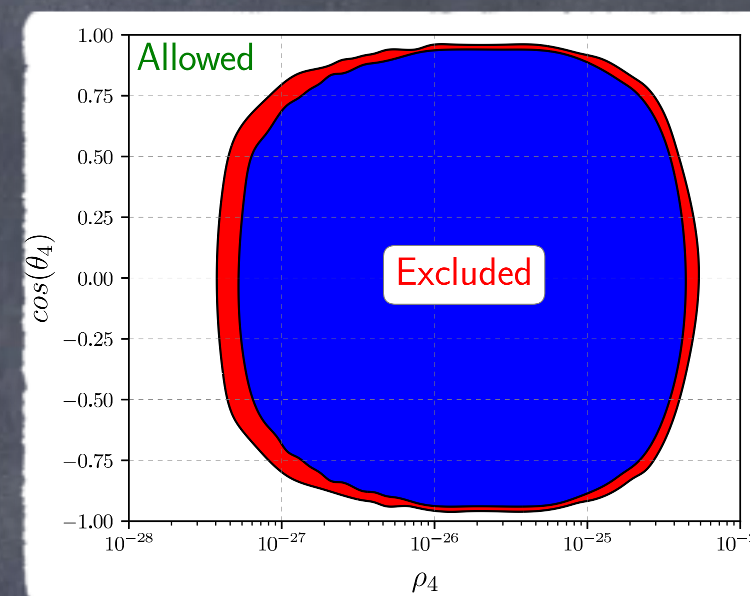

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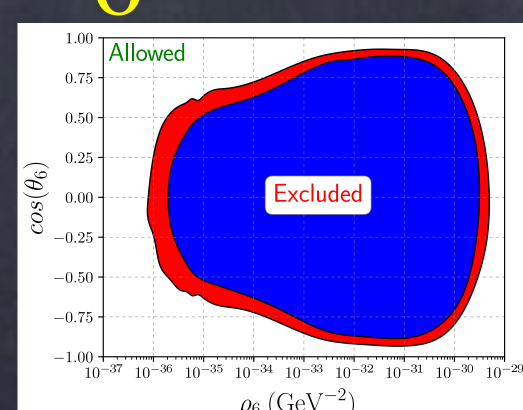
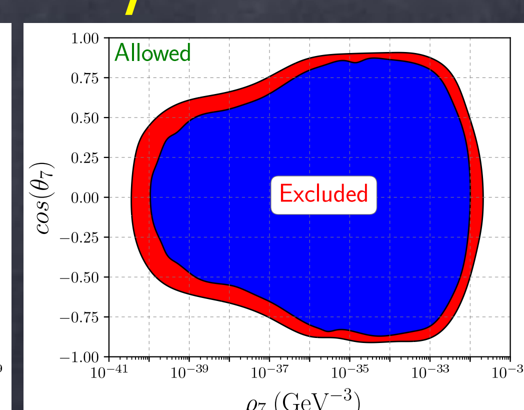
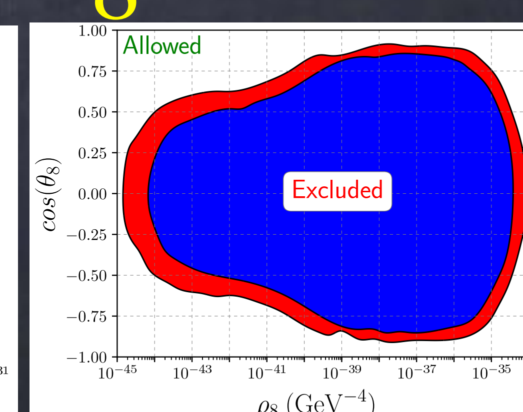
c_6 c_7 c_8

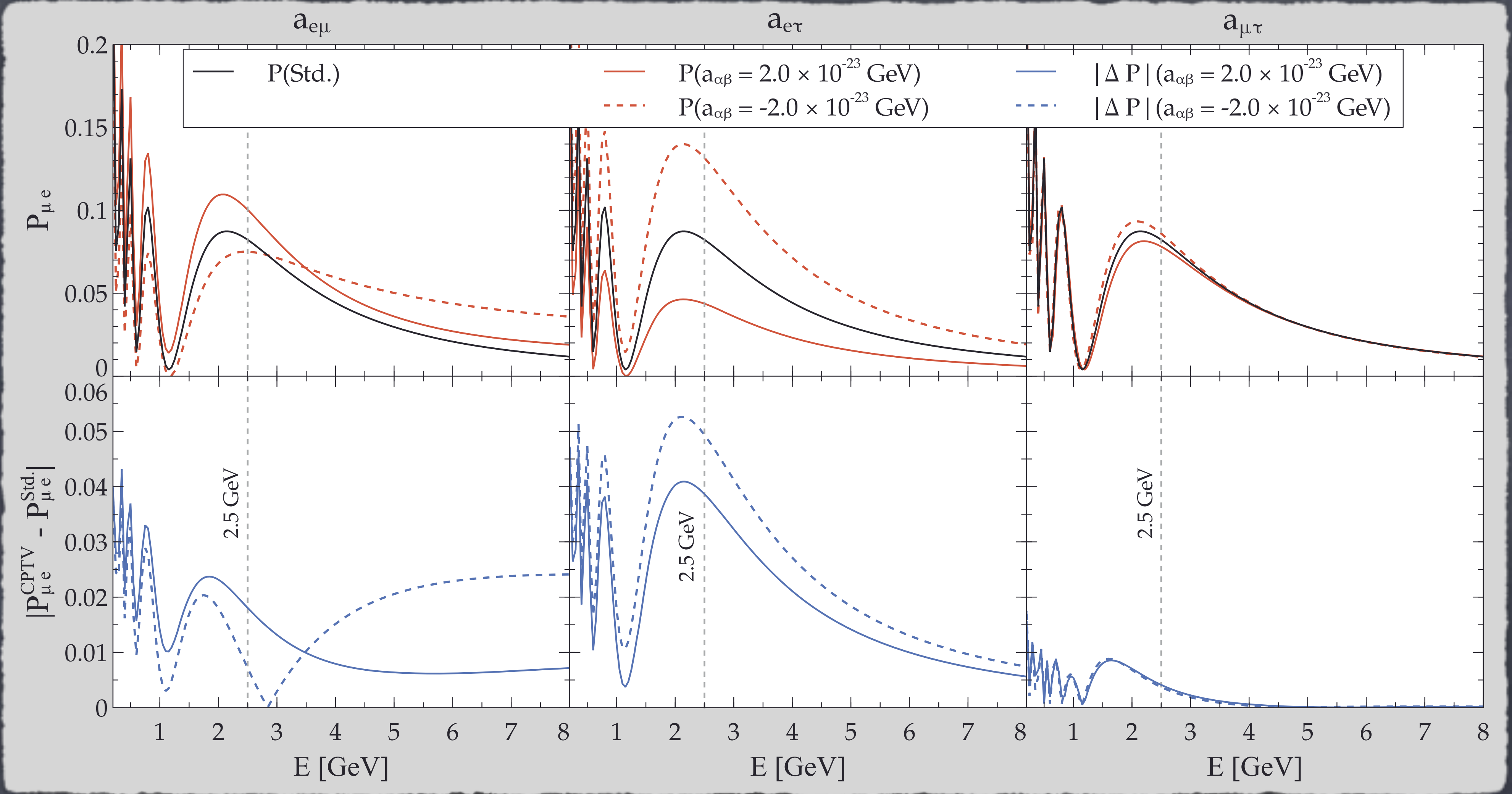






Best limits on these coefficients

Lorentz invariance violation at DUNE



Effect on probabilities of LIV terms

K. Abe et al. [Super-Kamiokande Collaboration], Phys. Rev. D91:052003, 2015

Parameter	Existing bounds	This work
$\lvert a_{e\mu}\rvert$ [GeV]	2.5×10^{-23} [11]	7.0×10^{-24}
$\lvert a_{e\tau}\rvert$ [GeV]	5.0×10^{-23} [11]	1.0×10^{-23}
$\lvert a_{\mu\tau}\rvert$ [GeV]	8.3×10^{-24} [11]	1.7×10^{-23}
a_{ee}[GeV]	–	$-2.5 \times 10^{-22} < a_{ee} < -2.0 \times 10^{-22}$ and $-2.5 \times 10^{-23} < a_{ee} < 3.2 \times 10^{-23}$
$a_{\mu\mu}$[GeV]	–	$-3.7 \times 10^{-23} < a_{\mu\mu} < 4.8 \times 10^{-23}$

Assuming
3.5 yr neutrino +
3.5 yr antineutrino

G. Barenboim, M. Masud, C. A. Ternes and M. A. Tórtola, Phys. Lett. B788:308, 2019

Decoherence

Interactions of neutrinos with the environment could produce decoherence/dissipative effects during neutrino propagation, which could arise in quantum gravity scenarios

Y. Liu, L. Hu and M.-L. Ge, Phys. Rev. D56:6648, 1997
F. Benatti and R. Floreanini, JHEP 02:032, 2000
E. Lisi, A. Marrone and D. Montanino, Phys. Rev. Lett. 85:1166, 2000
F. Benatti and R. Floreanini, Phys. Rev. D64:085015, 2001

$$\frac{d\rho}{dt} = -\, i\,[H, \rho] - D[\rho] \qquad D[\rho] = \sum_m \left[\{\rho, D_m D_m^\dagger\} - 2\, D_m\, \rho\, D_m^\dagger\right]$$

further preserving unitarity and energy conservation

for constant density

eigenvalues of D_m

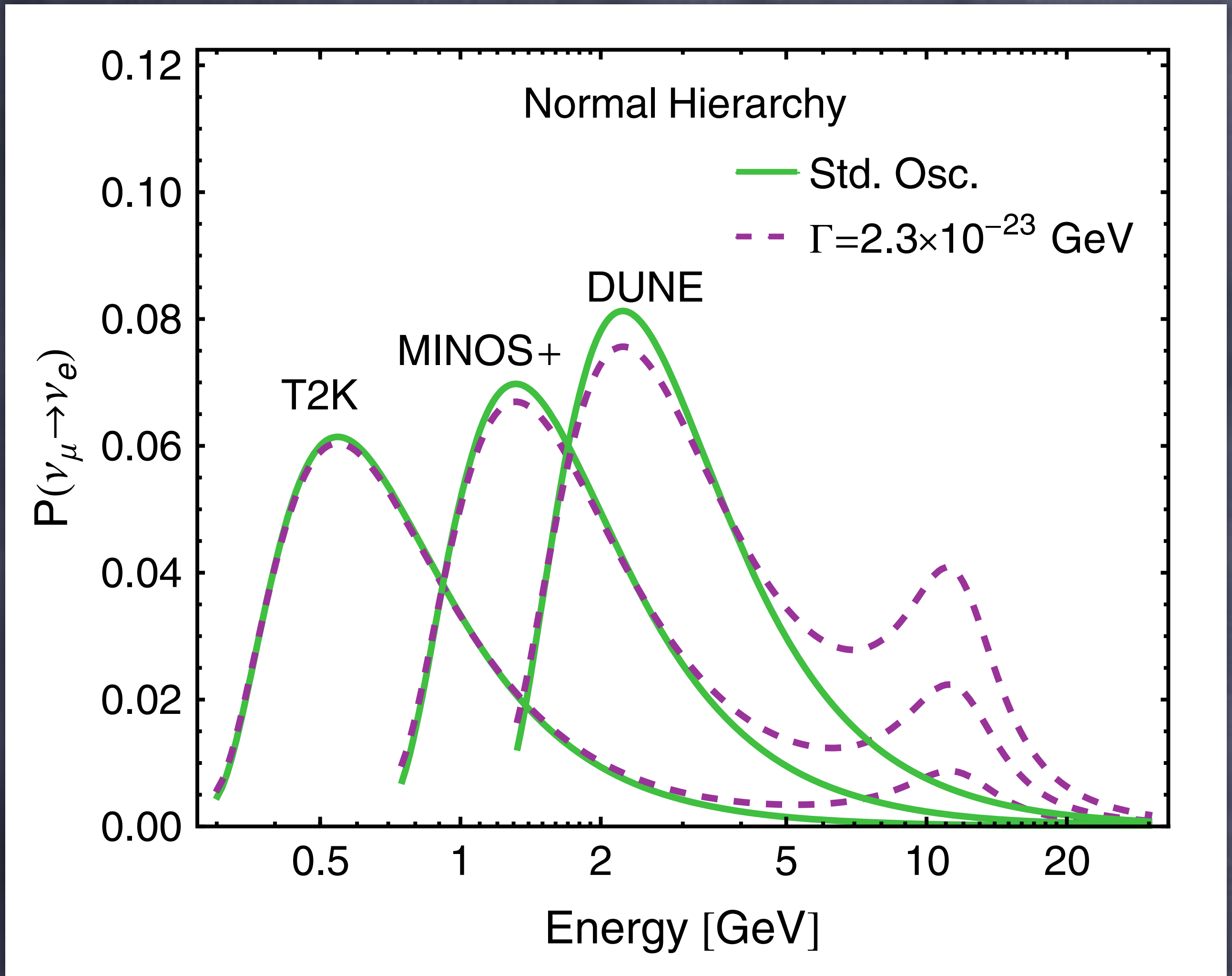
$$\frac{d\rho_{ij}}{dt} = -\left[\gamma_{ij} - i\frac{\Delta m_{ij}^2}{2\,E}\right]\rho_{ij} \qquad \gamma_{ij} \equiv \sum_m \left(d_m^i - d_m^j\right)^2$$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 2\sum_{i<j} Re\left[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right]\left(1 - e^{-\gamma_{ij}L}\cos\left(\frac{\Delta m_{ij}^2}{2\,E}\right)\right) - 2\sum_{i<j} Im\left[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right] e^{-\gamma_{ij}L}\sin\left(\frac{\Delta m_{ij}^2}{2\,E}\right)$$

see talk by J. Coelho

Decoherence at long-baseline accelerator neutrino experiments

Altered MSW due to decoherence



J. A. B. Coelho and W. A. Mann, Phys. Rev. D96:093009, 2017

see also R. L. N. Oliveira, Eur. Phys. J. C76:417, 2016

Decoherence at long-baseline accelerator neutrino experiments

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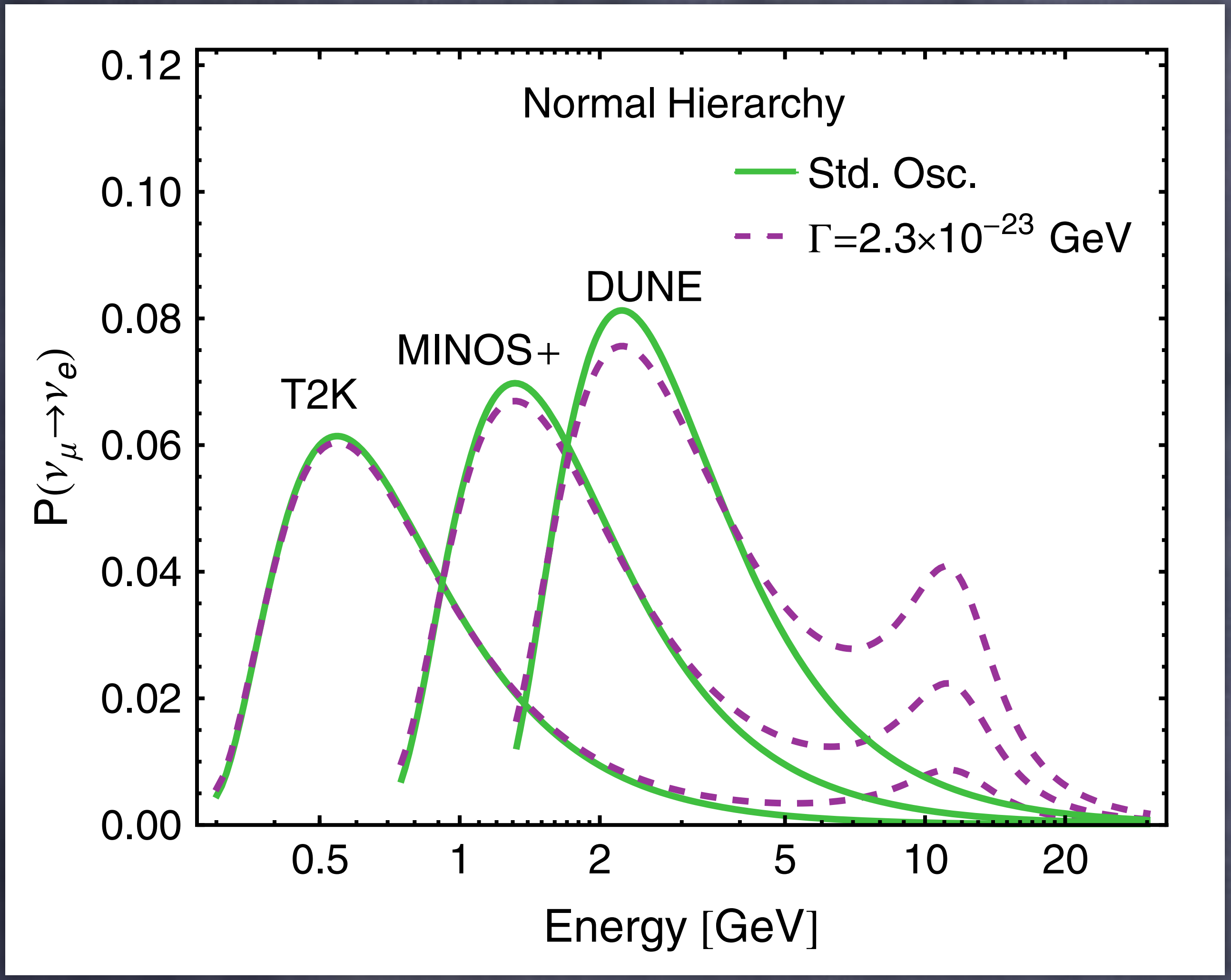

J. A. B. Coelho and W. A. Mann, Phys. Rev. D96:093009, 2017

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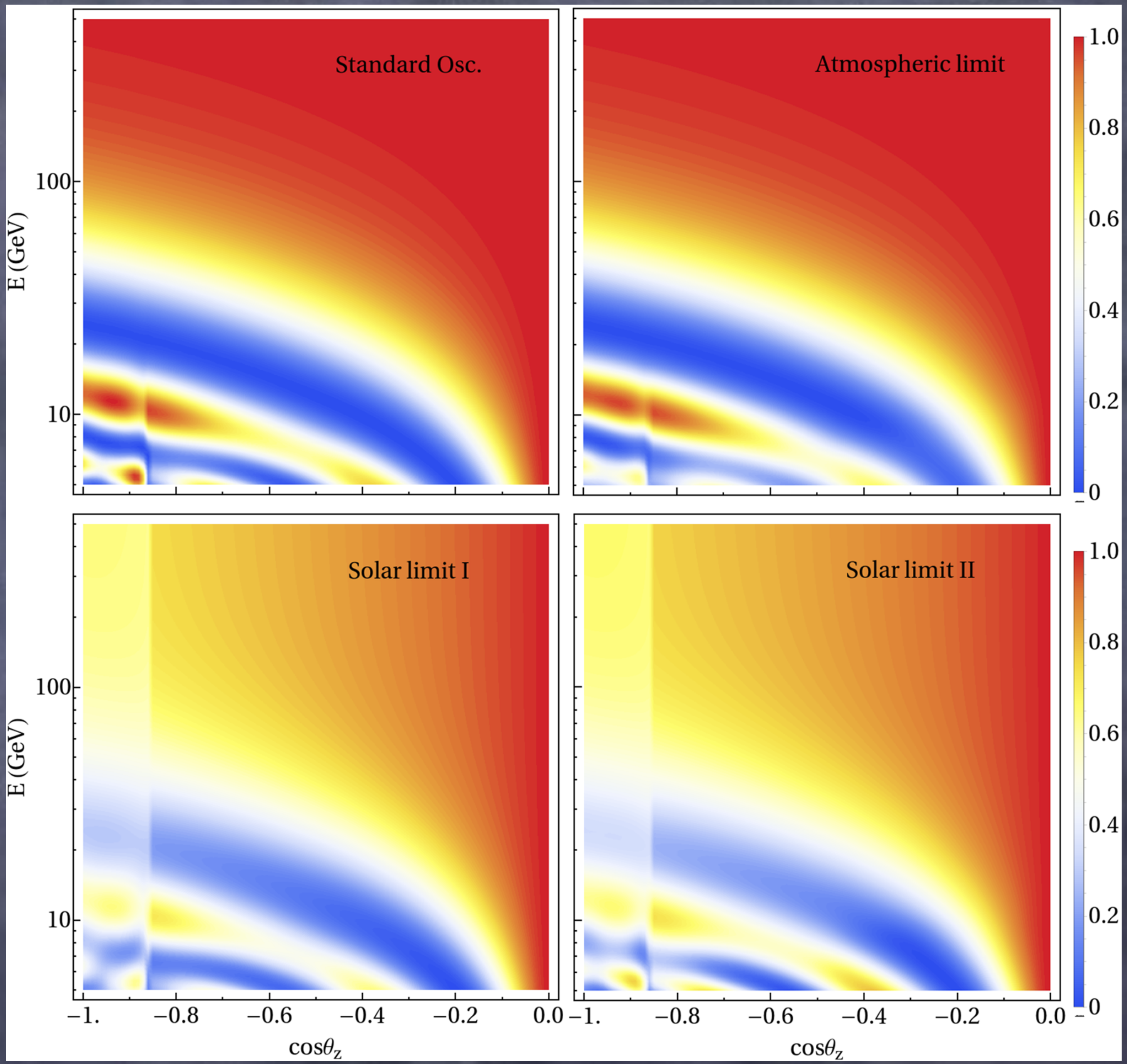
Decoherence with atmospheric neutrinos at IceCube and DeepCore

$P_{\mu\mu}$ $\gamma_{32} = \gamma_{31} = 2.3 \times 10^{-23}$ GeV



$\gamma_{31} = \gamma_{21} = 2.3 \times 10^{-23}$ GeV $\gamma_{32} = \gamma_{21} = 2.3 \times 10^{-23}$ GeV

P. Coloma, J. López-Pavon, I. Martínez-Soler and H. Nunokawa, Eur. Phys. J. C78:614, 2018

High-energy neutrinos
E>10 TeV

Why do we care about high-energy neutrinos?

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Neutrinos point back to their cosmic sources
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Neutrinos carry a quantum number that cosmic rays and photons do not have: flavor

High-energy neutrino production

hadronic

$\pi^{\pm} \to \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$ $\quad \langle E_{\nu} \rangle \simeq E_{\pi}/4$

$\mu^{\pm} \to e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_{\mu}(\nu_{\mu})$ $\quad \langle E_{\nu} \rangle \simeq E_{\pi}/4$

$\pi^0 \to \gamma + \gamma$ $\quad \langle E_{\gamma} \rangle \simeq E_{\pi}/2$

pp interactions

$$e^{-\ell/\tau_{\gamma\gamma}} \frac{d\Phi_{\nu}(E_{\nu} = E_{\gamma}/2)}{dE_{\nu}} \simeq 6\, \frac{d\Phi_{\gamma}(E_{\gamma})}{dE_{\gamma}}$$

connection with gamma-rays

$$E_{\pi} \simeq E_p/5$$

average fraction of energy transferred from the proton to the pion

photohadronic

$$p + \gamma \to \Delta \to \begin{cases} \pi^+ + n \\ \pi^0 + p \end{cases}$$

$$e^{-\ell/\tau_{\gamma\gamma}} \frac{d\Phi_{\nu}(E_{\nu} = E_{\gamma}/2)}{dE_{\nu}} \simeq 3\, \frac{d\Phi_{\gamma}(E_{\gamma})}{dE_{\gamma}}$$

connection with gamma-rays

pγ interactions

comoving frame: $4\, \varepsilon'_{\gamma} E'_p \geq m_{\Delta}^2 - m_p^2$

neutron decay

$$n \to p + e^- + \bar{\nu}_e \qquad \langle E_{\nu} \rangle \simeq 5 \times 10^{-4} E_n$$

High-energy neutrino sources

$$E_{\max} \simeq 3\times 10^{18}\ \mathrm{eV}\ (Z v)\left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{L}{\mathrm{kpc}}\right)$$

Supernova Remnants

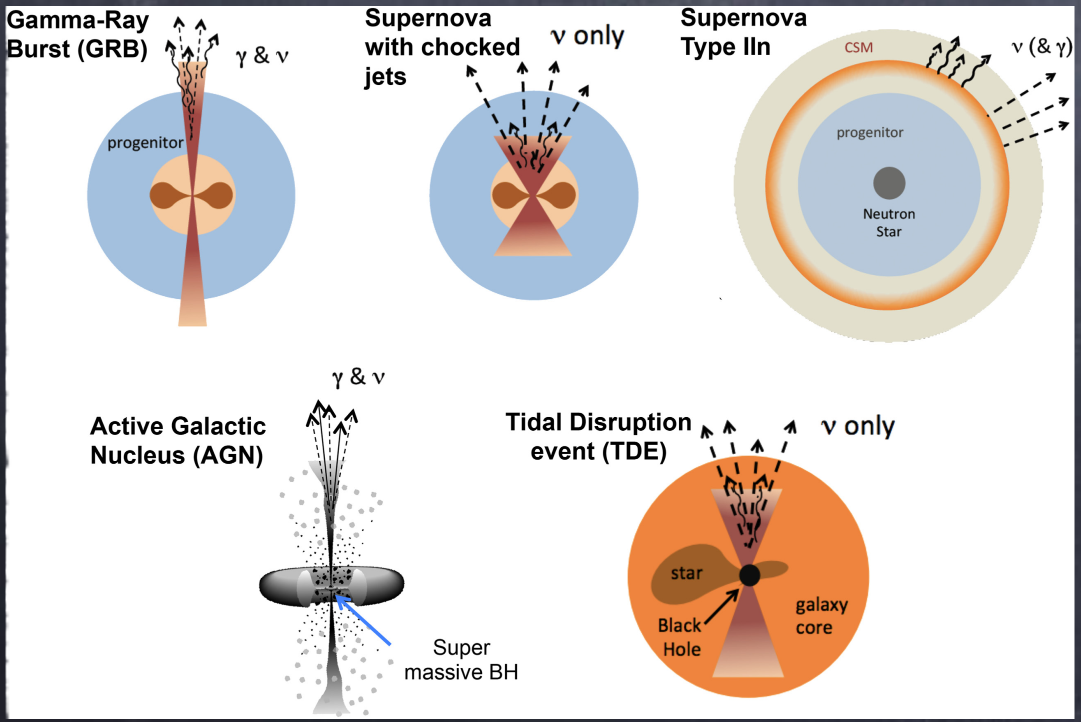
Active Galactic Nuclei

Gamma Ray Bursts

StarBurst Galaxies

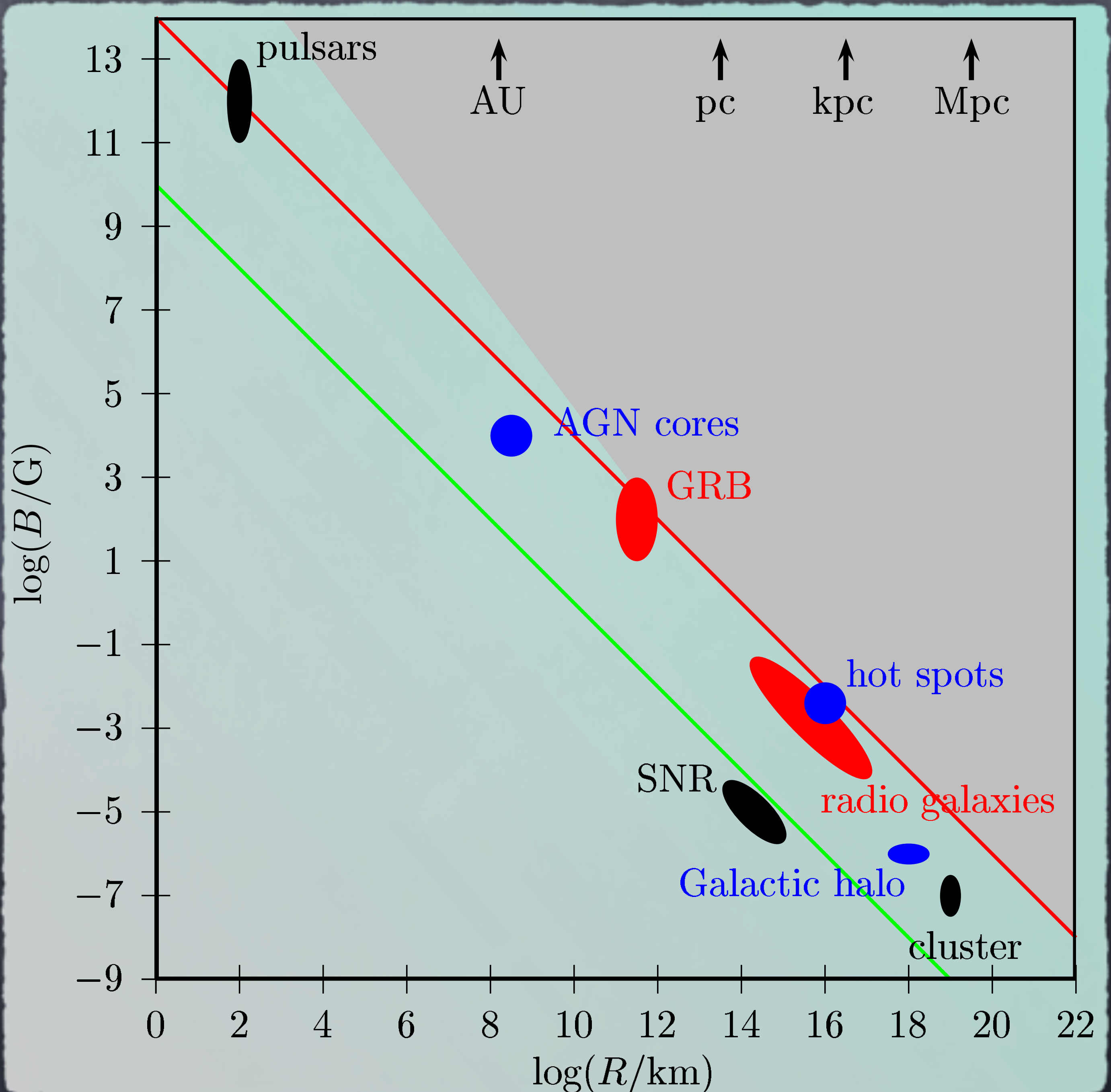
Tidal Disruption Events

Pulsars…



I. Bartos and M. Kowalski, 2017

The Hillas plot



M. Kachelrieß and D. V. Semikoz, Prog. Part. Nucl. Phys. 109:103710, 2019

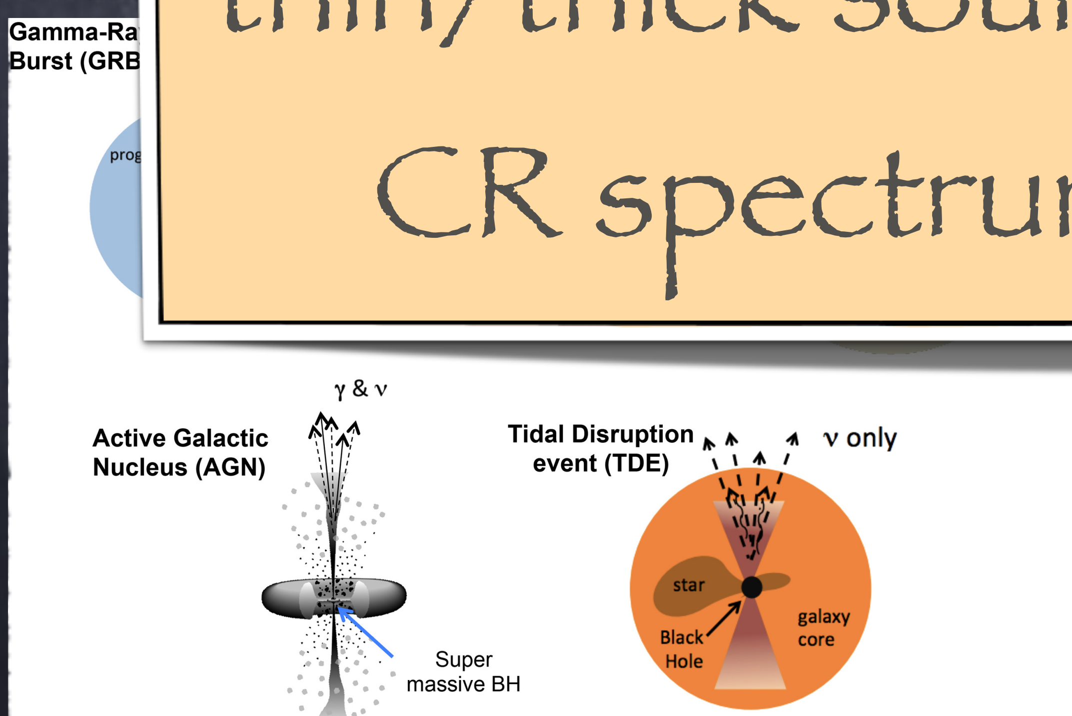
High-energy neutrino sources

$$E_{\max} \simeq 3 \times 10^{18}\ \mathrm{eV}\ (Z v) \left(\frac{B}{\mu\mathrm{G}}\right) \left(\frac{L}{\mathrm{kpc}}\right)$$

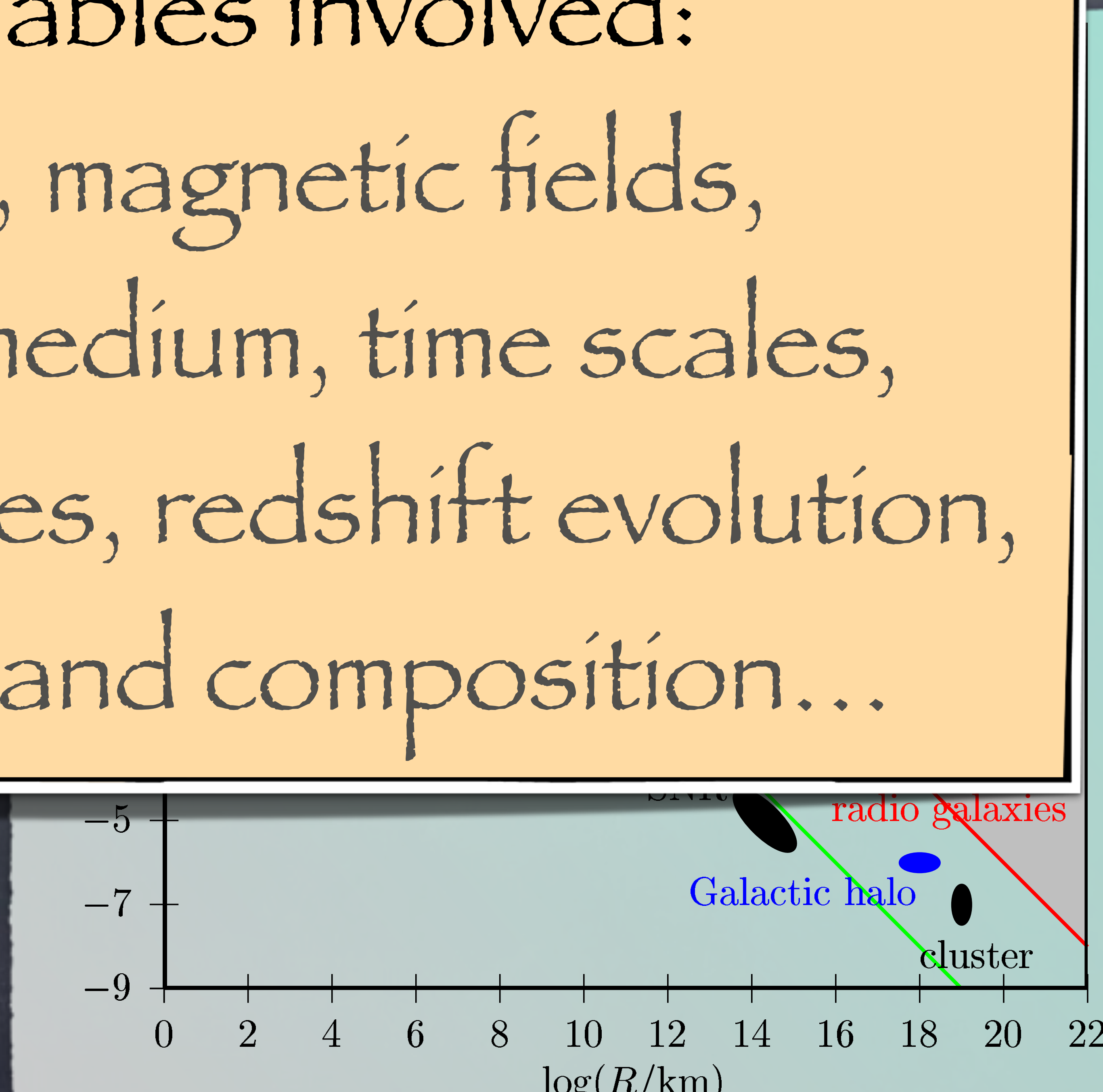
The Hillas plot

Many variables involved:

Energetics, magnetic fields, surrounding medium, time scales, thin/thick sources, redshift evolution, CR spectrum and composition…



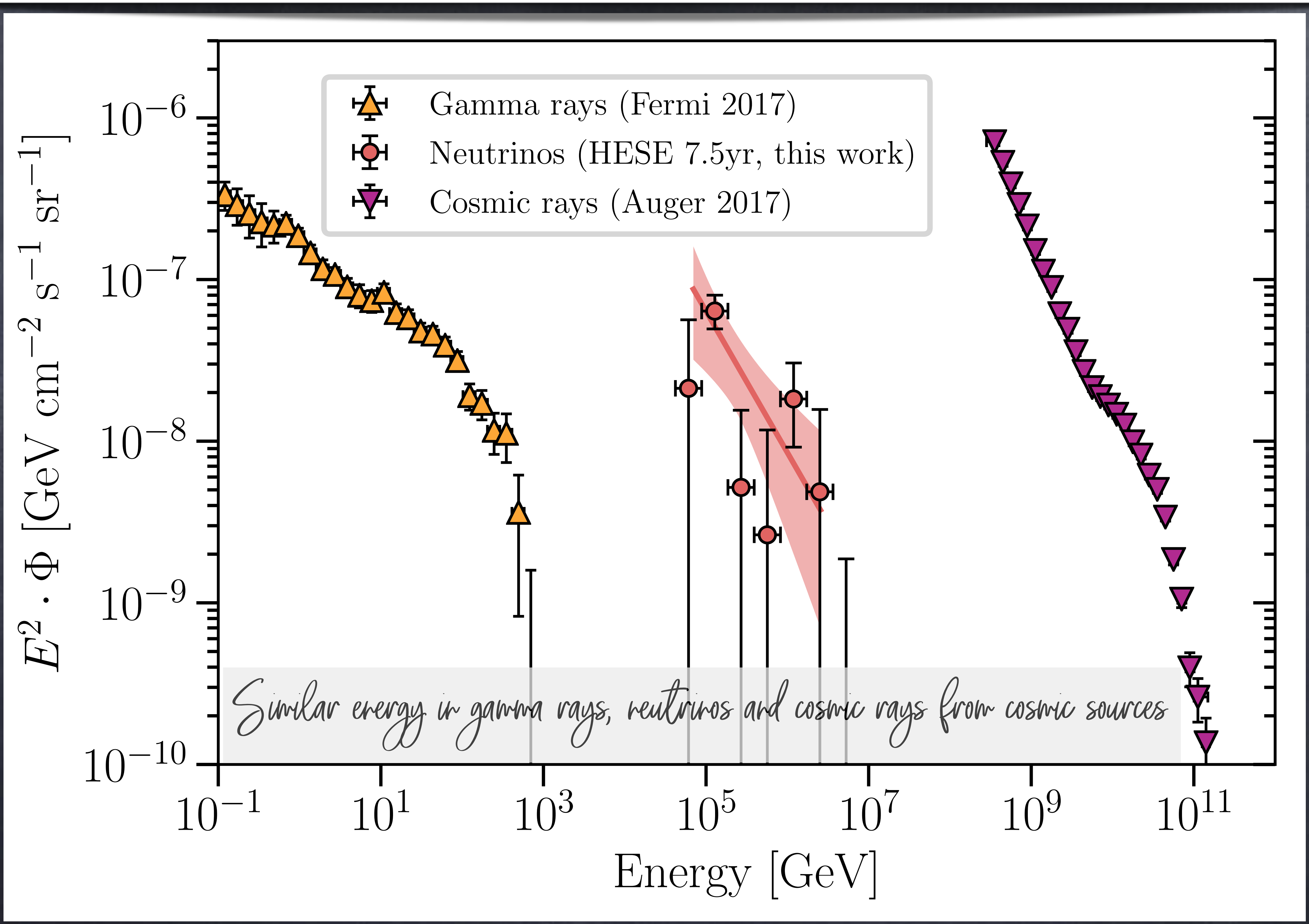
I. Bartos and M. Kowalski, 2017



M. Kachelrieß and D. V. Semikoz, Prog. Part. Nucl. Phys. 109:103710, 2019

The CR/Gamma-ray/Neutrino Connection

Neutrinos and photons are guaranteed byproducts of high-energy cosmic-rays



R. Abbasi et al. [IceCube Collaboration], Phys. Rev. D104:022002, 2021

The CR/Gamma-ray/Neutrino Connection

Neutrinos and photons are guaranteed byproducts of high-energy cosmic-rays

Cosmic-ray interactions in the atmosphere

$$p + X \rightarrow \pi^{\pm} / K^{\pm} + \pi^{0} + Y$$

E < 100 TeV

atmospheric neutrinos

Cosmic-ray interactions at the source

pp or $p\gamma$

E > 100 TeV

astrophysical neutrinos

Cosmic-ray interactions off CMB photons

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow n + \pi^{+}$$

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^{0}$$

E > 100 PeV

cosmogenic neutrinos

Exotics

e.g., heavy dark matter

Methods of detection and detectors

All flavors

Optimal for Earth-skimming ν_τ

optical detection in ice or water

optical Cherenkov light from neutrino-induced showers and tracks

IceCube Antares Baikal NT-200

IceCube-Gen2 KM3NeT Baikal GVD P-ONE

radio detection in ice

Askaryan radiation (radio Cherenkov) from electromagnetic showers

ARA ARIANNA RNO-G RET radio IceCube-Gen2

radio detection from the atmosphere or in space

refracted Askaryan radiation from electromagnetic showers in ice

ANITA PUEO

air-shower particle detection

Cherenkov or scintillation light from air-shower particles passing through the detector

Auger TA TAMBO

air-shower radio detection

Radio emission by air showers from tau decays, via the geomagnetic effect (charge separation in the magnetic field of Earth)

BEACON TAROGE GRAND

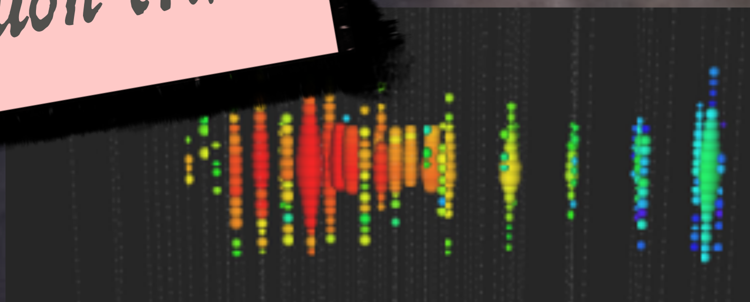
air-shower imaging

Cherenkov and fluorescence light from shower particles

Trinity Ashra NTA POEMMA

TeV-PeV Neutrinos

muon tracks

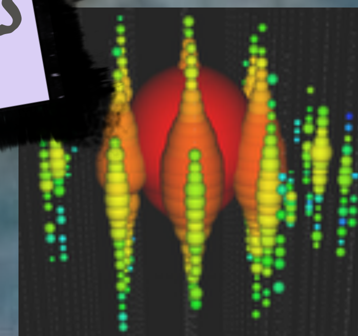


$$\nu_\mu + N \rightarrow \mu + X$$

~15% deposited energy resolution

<1° angular resolution

cascades



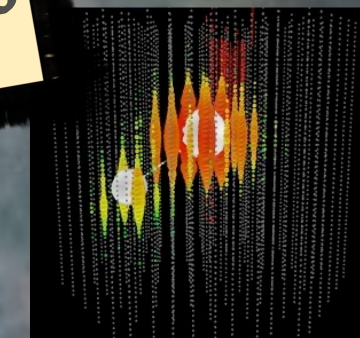
$$\nu_{e,\tau} + N \rightarrow e(\tau) + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

~15% deposited energy resolution

~15° angular resolution

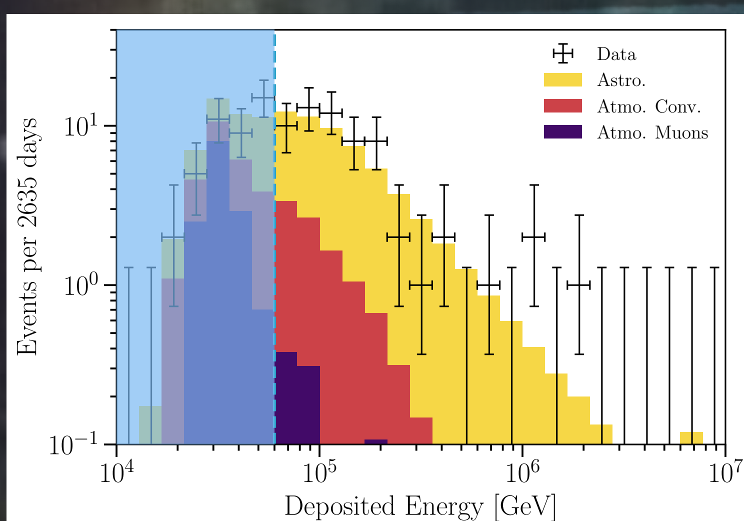
double bangs



$$\nu_\tau + N \rightarrow \tau + X \rightarrow Y + \nu_\tau$$

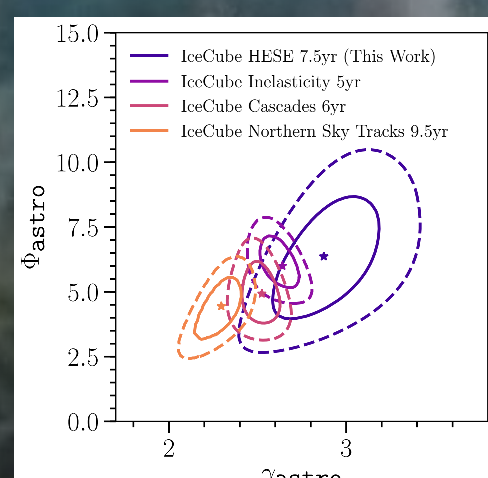
Above ~PeV

Main classes: contained events and through-going muons

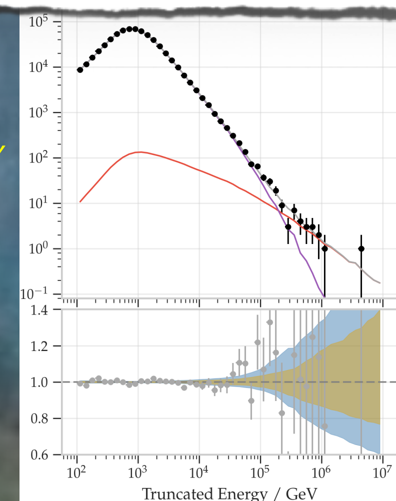


R. Abbasi et al. [IceCube Collaboration], Phys. Rev. D104:022002, 2021

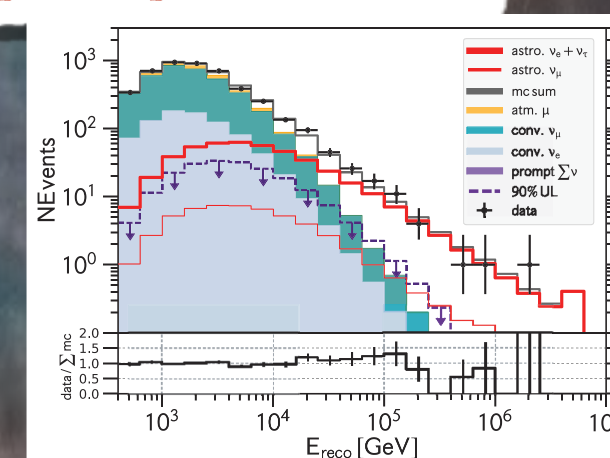
$$\frac{d\Phi}{dE_\nu} = \phi \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma}$$



R. Abbasi et al. [IceCube Collaboration], Phys. Rev. D104:022002, 2021



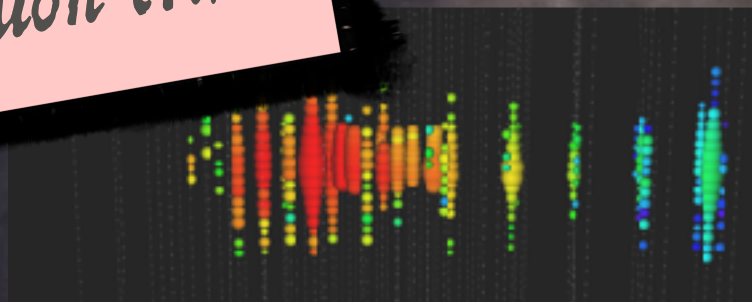
J. Stettner [IceCube Collaboration], PoS (ICRC2019) 1017, 2020



M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 125:121104, 2020

TeV-PeV Neutrinos

muon tracks



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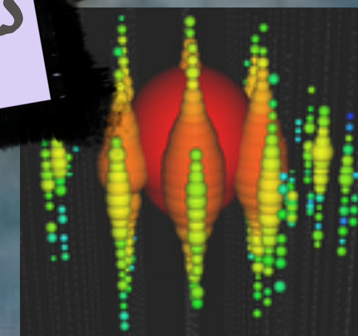

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$$\nu_x + N \rightarrow \nu_x + X$$

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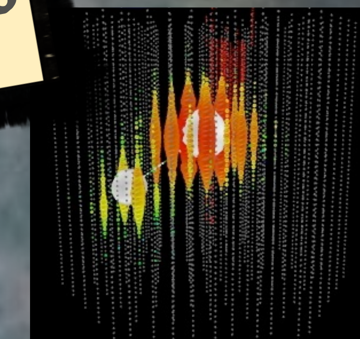
double bangs



$$\nu_\tau + N \rightarrow \tau + X \rightarrow Y + \nu_\tau$$

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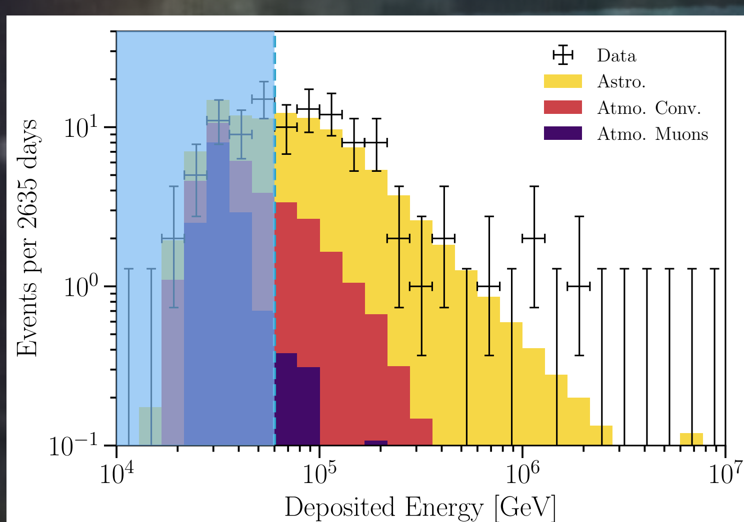

R. Abbasi et al. [IceCube Collaboration], Phys. Rev. D104:022002, 2021

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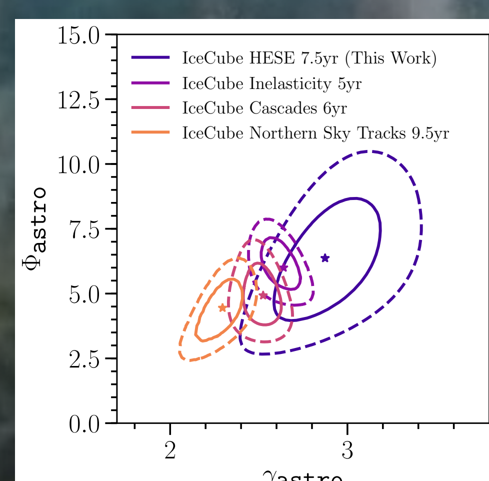
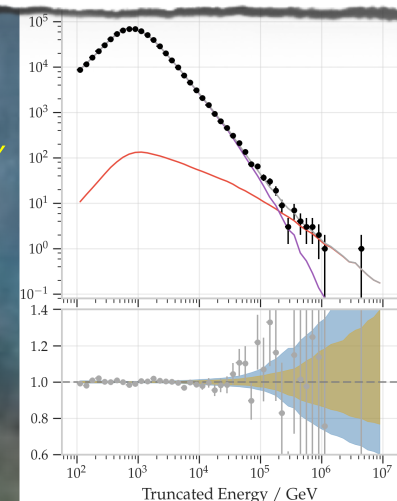
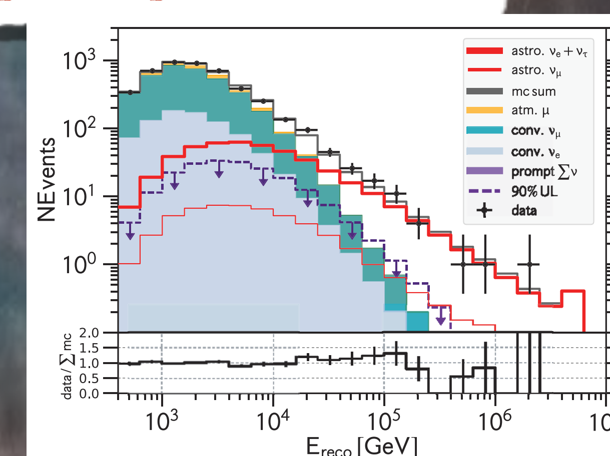


R. Abbasi et al. [IceCube Collaboration], Phys. Rev. D104:022002, 2021



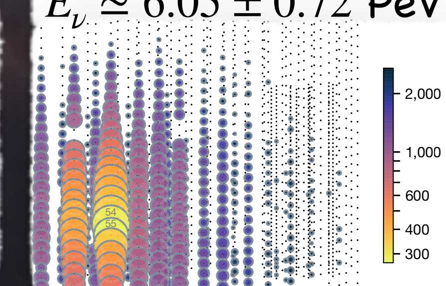
J. Stettner [IceCube Collaboration], PoS (ICRC2019) 1017, 2020



M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 125:121104, 2020

but also partially contained events…
First Glashow resonance event!

$E_\nu \simeq 6.05 \pm 0.72$ PeV



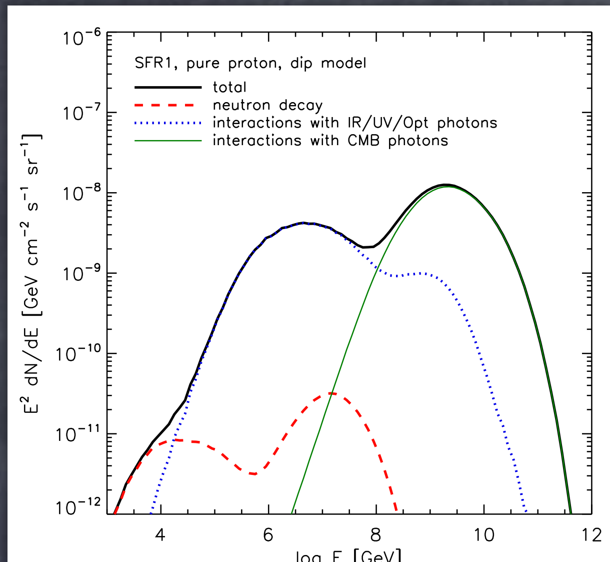
M. G. Aartsen et al. [IceCube Collaboration], Nature 591:220, 2021

Beyond ~10 PeV, only limits... and predictions

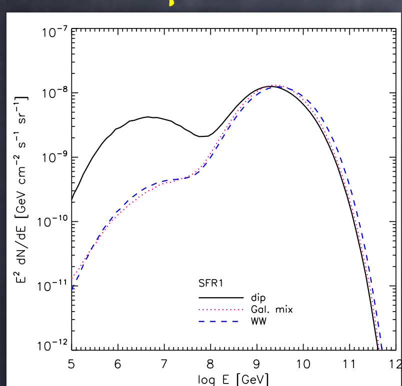
Cosmogenic neutrinos

V. Berezinsky and G. Zatsepin, Yad. Fiz. 11:200, 1970

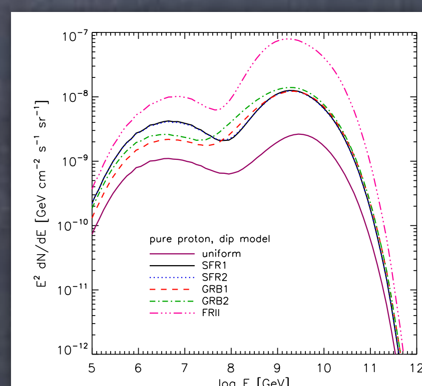
$$p + \gamma_{\mathrm{CMB/EBL}} \to \Delta \to \begin{cases} \pi^+ + n \\ \pi^0 + p \end{cases}$$



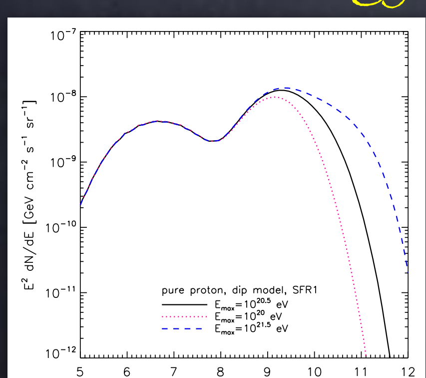
CR spectrum



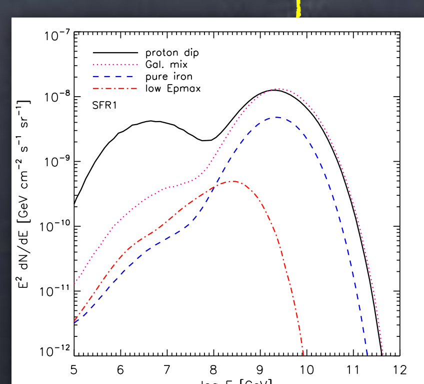
Redshift evolution

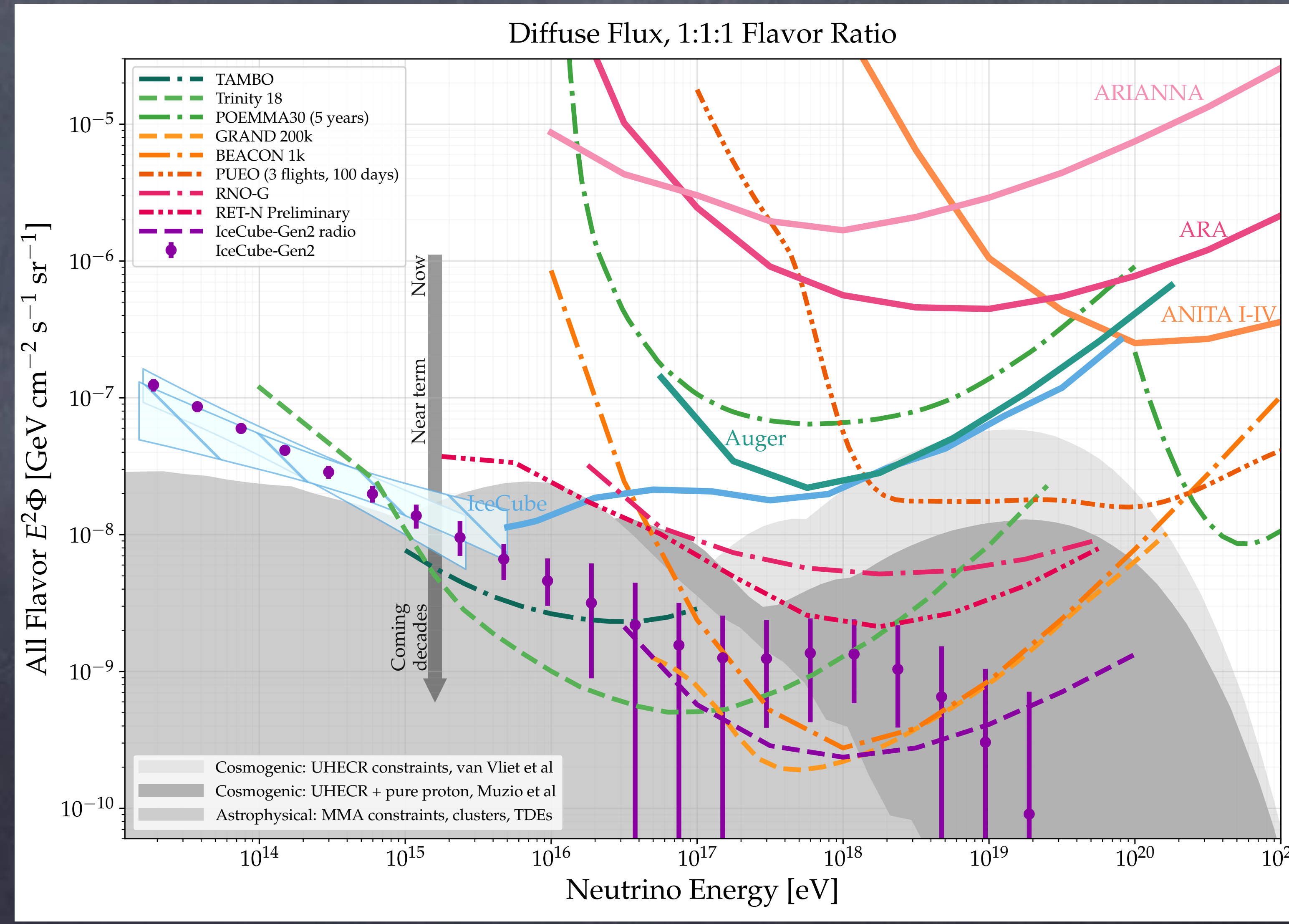


Maximum energy



Spectrum composition





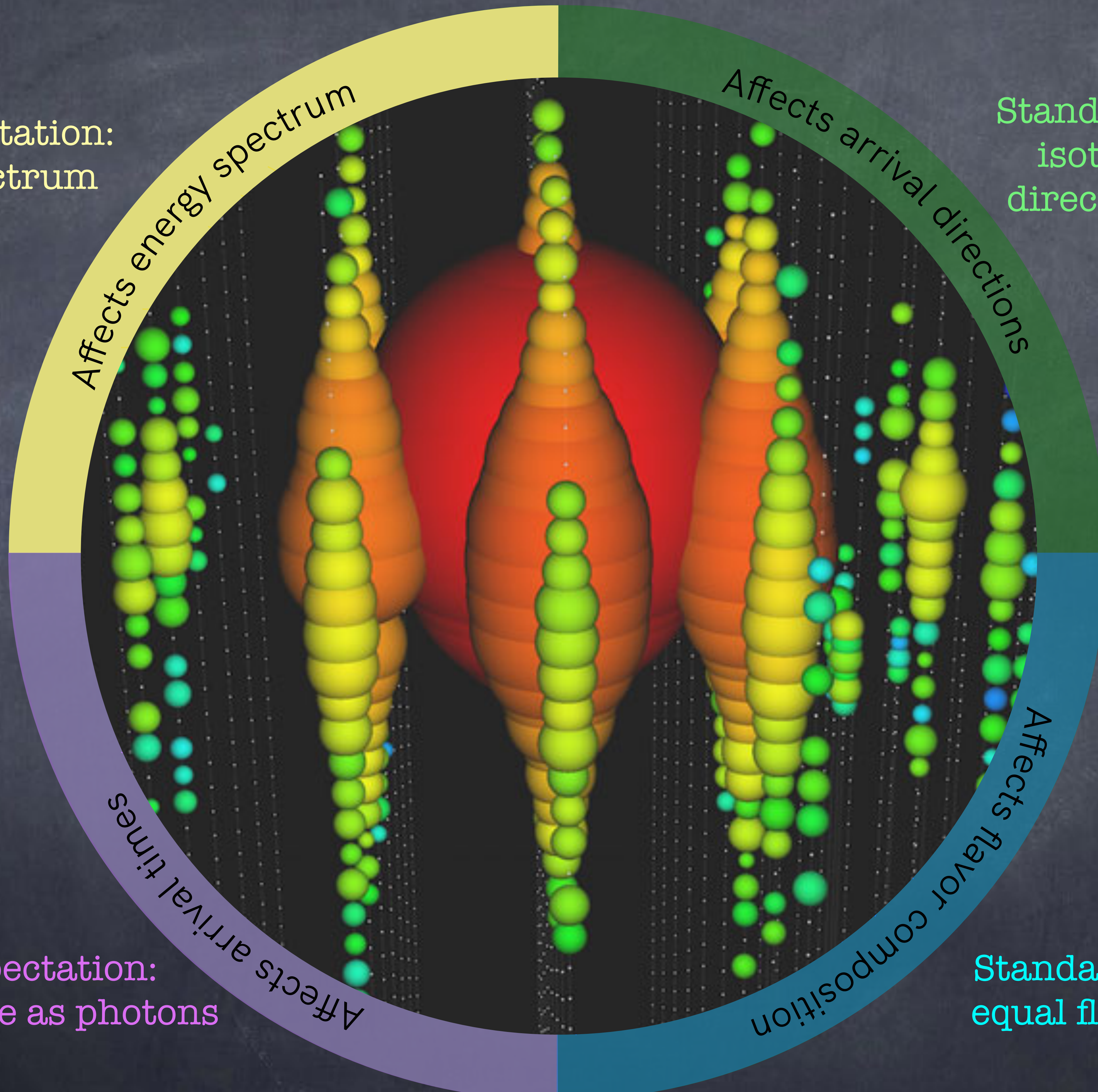
K. Kotera, D. Allard and A. V. Olinto, JCAP 1010:013, 2010

M. Ackermann et al., arXiv:2203.08096

Four main observables

Standard expectation:
power-law spectrum

Standard expectation:
isotropy (diffuse)
directional (sources)



Standard expectation:
same arrival time as photons

Standard expectation:
equal flux of all flavors

C. Argüelles, M. Bustamante, A. Kheirandish, SPR, J. Salvado and A. C. Vincent, PoS(ICRC2019)849, 2020

Why do we care about flavor?

Why do we care about flavor?

It carries information about the mechanism of production...

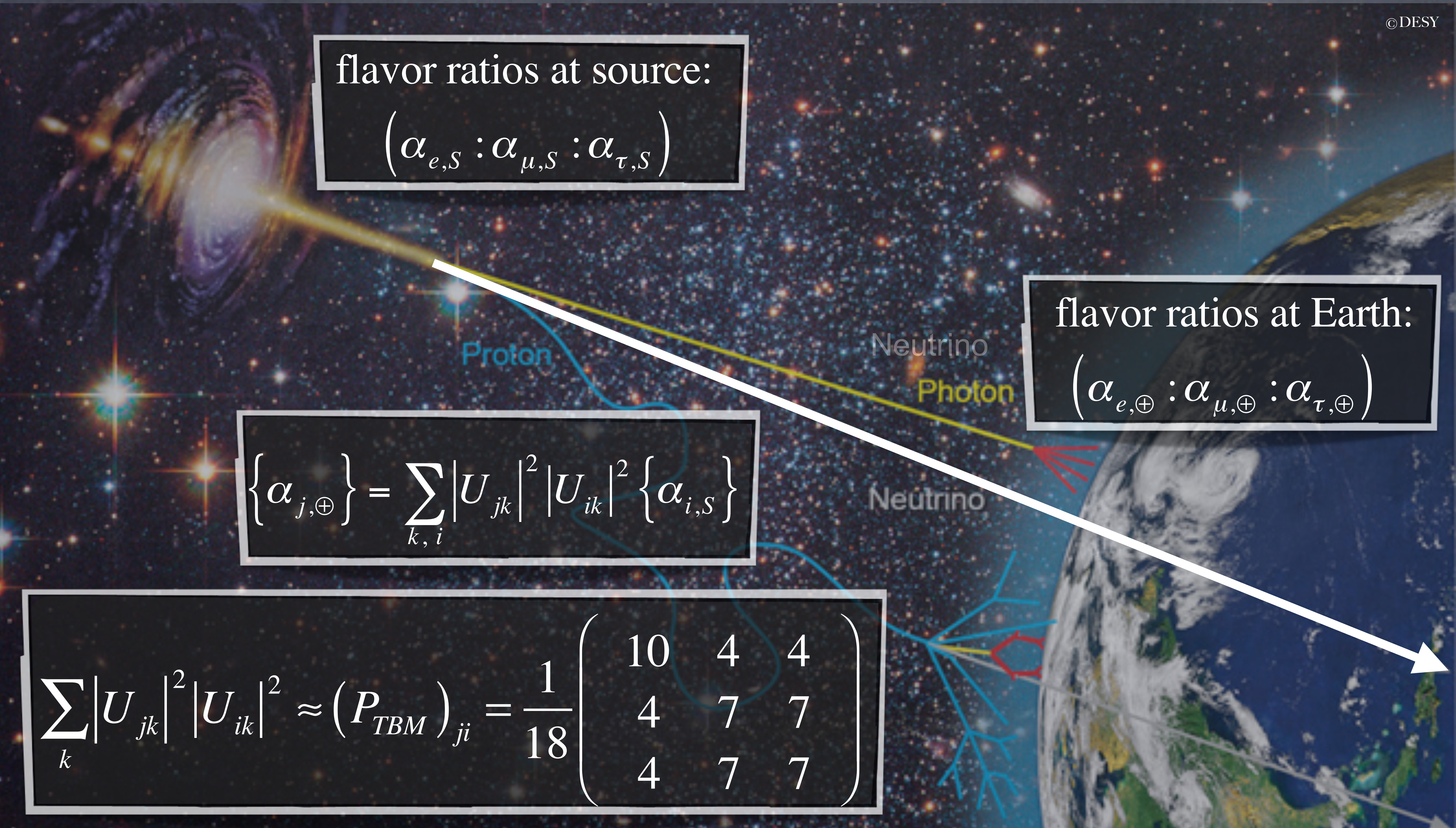
Why do we care about flavor?

It carries information about the mechanism of production...

...but also about the way neutrinos propagate from the sources to the detector

Exotic physics could produce deviations from the standard expectations

Standard cosmic neutrino propagation



flavor ratios at source:

$$\left(\alpha_{e,S} : \alpha_{\mu,S} : \alpha_{\tau,S}\right)$$

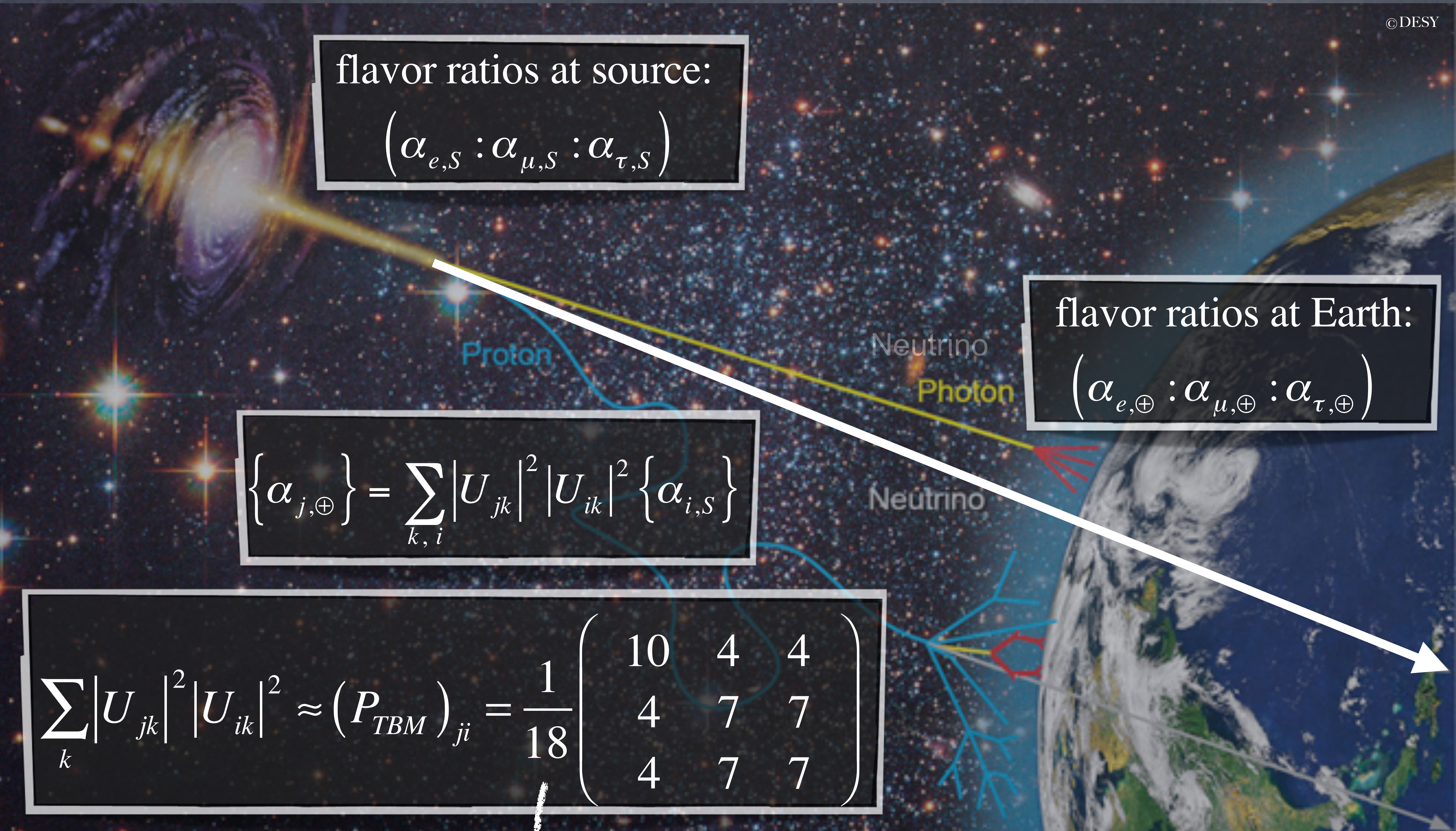
flavor ratios at Earth:

$$\left(\alpha_{e,\oplus} : \alpha_{\mu,\oplus} : \alpha_{\tau,\oplus}\right)$$

$$\left\{\alpha_{j,\oplus}\right\} = \sum_{k,\,i} \left|U_{jk}\right|^2 \left|U_{ik}\right|^2 \left\{\alpha_{i,S}\right\}$$

$$\sum_k \left|U_{jk}\right|^2 \left|U_{ik}\right|^2 \approx \left(P_{TBM}\right)_{ji} = \frac{1}{18}\begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}$$

Standard cosmic neutrino propagation



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$$\sum_k \left|U_{jk}\right|^2 \left|U_{ik}\right|^2 \approx \left(P_{TBM}\right)_{ji} = \frac{1}{18}\begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}$$

standard oscillations... but what if new physics?

Flavor ratios at source and at Earth

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\downarrow$$
$$e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

Pion sources $\left(\nu_{\mathrm{e}} : \nu_{\mu} : \nu_{\tau}\right)_{S} = (1:2:0) \Rightarrow \left(\nu_{\mathrm{e}} : \nu_{\mu} : \nu_{\tau}\right)_{\oplus} = (1:1:1)$

Flavor ratios at source and at Earth

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\downarrow$$
$$e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\cancel{\downarrow}$$
$$e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

Pion sources $\left(\nu_{\mathrm{e}} : \nu_{\mu} : \nu_{\tau}\right)_{S} = (1:2:0) \Rightarrow \left(\nu_{\mathrm{e}} : \nu_{\mu} : \nu_{\tau}\right)_{\oplus} = (1:1:1)$

Muon damped sources $\left(\nu_{\mathrm{e}} : \nu_{\mu} : \nu_{\tau}\right)_{S} = (0:1:0) \Rightarrow \left(\nu_{\mathrm{e}} : \nu_{\mu} : \nu_{\tau}\right)_{\oplus} = (4:7:7)$

Flavor ratios at source and at Earth

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\downarrow$$
$$e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\downarrow$$
$$e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$

$$\pi^{\pm} \to \mu^{\pm} + \cancel{\nu_{\mu}(\bar{\nu}_{\mu})}$$
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Muon sources $\left(\nu_e : \nu_{\mu} : \nu_{\tau}\right)_S = (1:1:0) \Rightarrow \left(\nu_e : \nu_{\mu} : \nu_{\tau}\right)_{\oplus} = (14:11:11)$

Flavor ratios at source and at Earth

$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar\nu_\mu) \qquad \pi^\pm \to \mu^\pm + \nu_\mu(\bar\nu_\mu) \qquad \pi^\pm \to \mu^\pm + \cancel{\nu_\mu(\bar\nu_\mu)}$$

$$e^\pm + \nu_e(\bar\nu_e) + \bar\nu_\mu(\nu_\mu) \qquad e^\pm + \nu_e(\bar\nu_e) + \bar\nu_\mu(\nu_\mu) \qquad e^\pm + \nu_e(\bar\nu_e) + \bar\nu_\mu(\nu_\mu)$$

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Muon damped sources $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (0:1:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (4:7:7)$

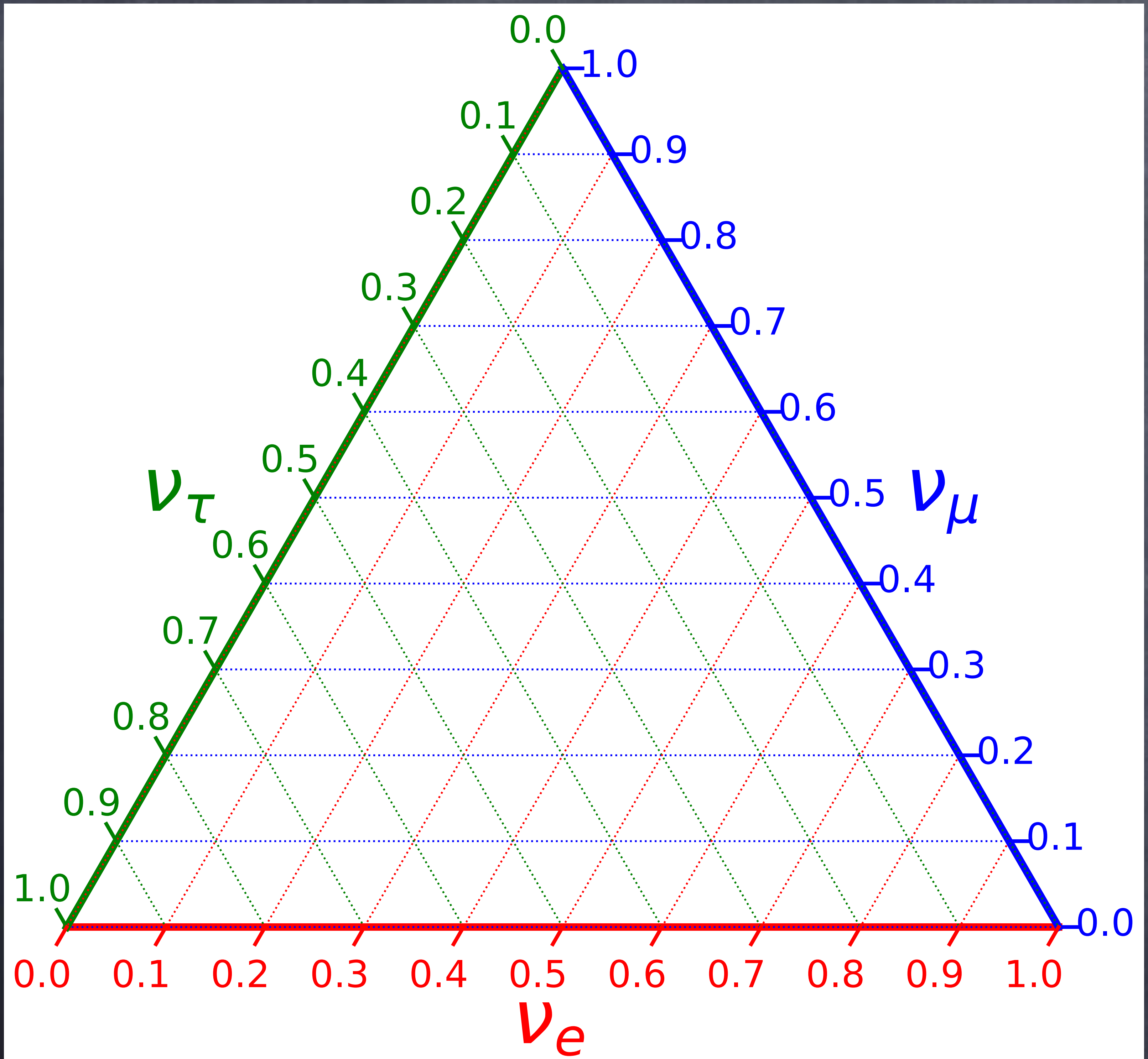
Muon sources $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (1:1:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (14:11:11)$

Neutron sources $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (1:0:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (5:2:2)$

$$n \to p + e^- + \bar\nu_e$$

Flavor triangles

First flavor analysis of IceCube data: O. Mena, SPR and A. C. Vincent, Phys. Rev. Lett. 113:091103, 2014



assuming unitarity: sum equal to 1

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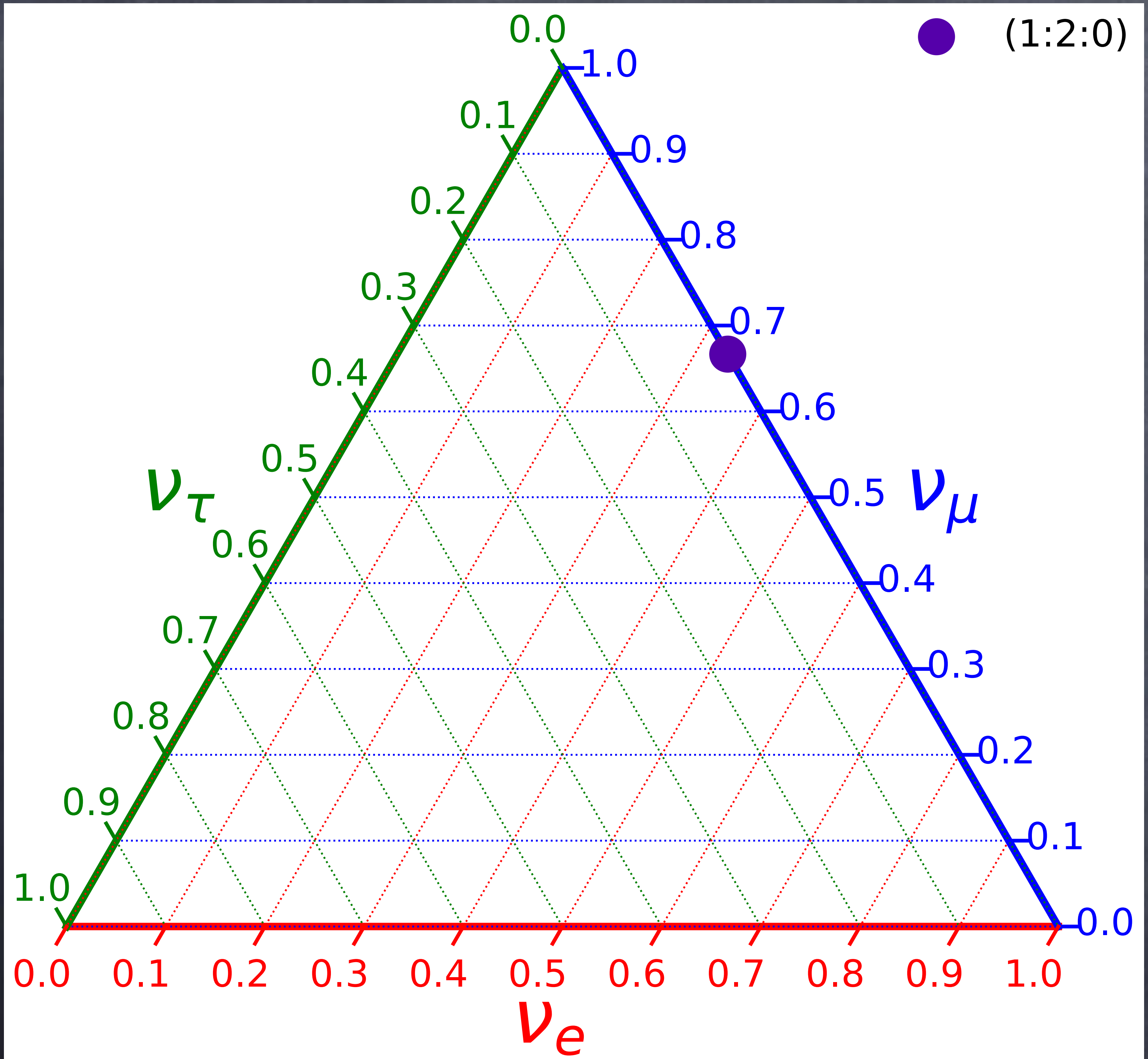

Pion decay

$$\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = \left(1 : 2 : 0\right)_S$$

assuming unitarity: sum equal to 1

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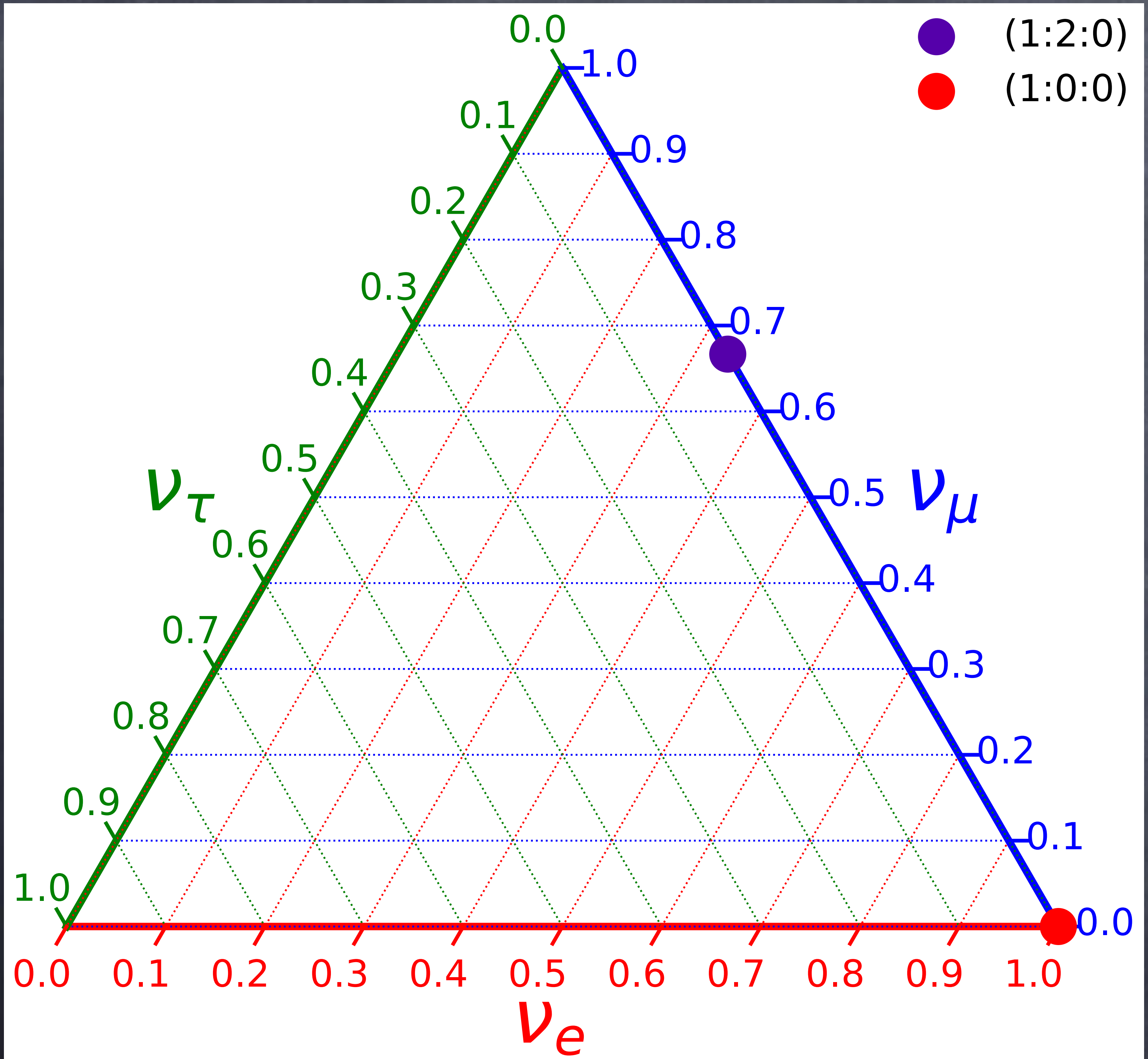

Pion decay

$$(\nu_e : \nu_\mu : \nu_\tau)_S = (1 : 2 : 0)_S$$

Neutron decay

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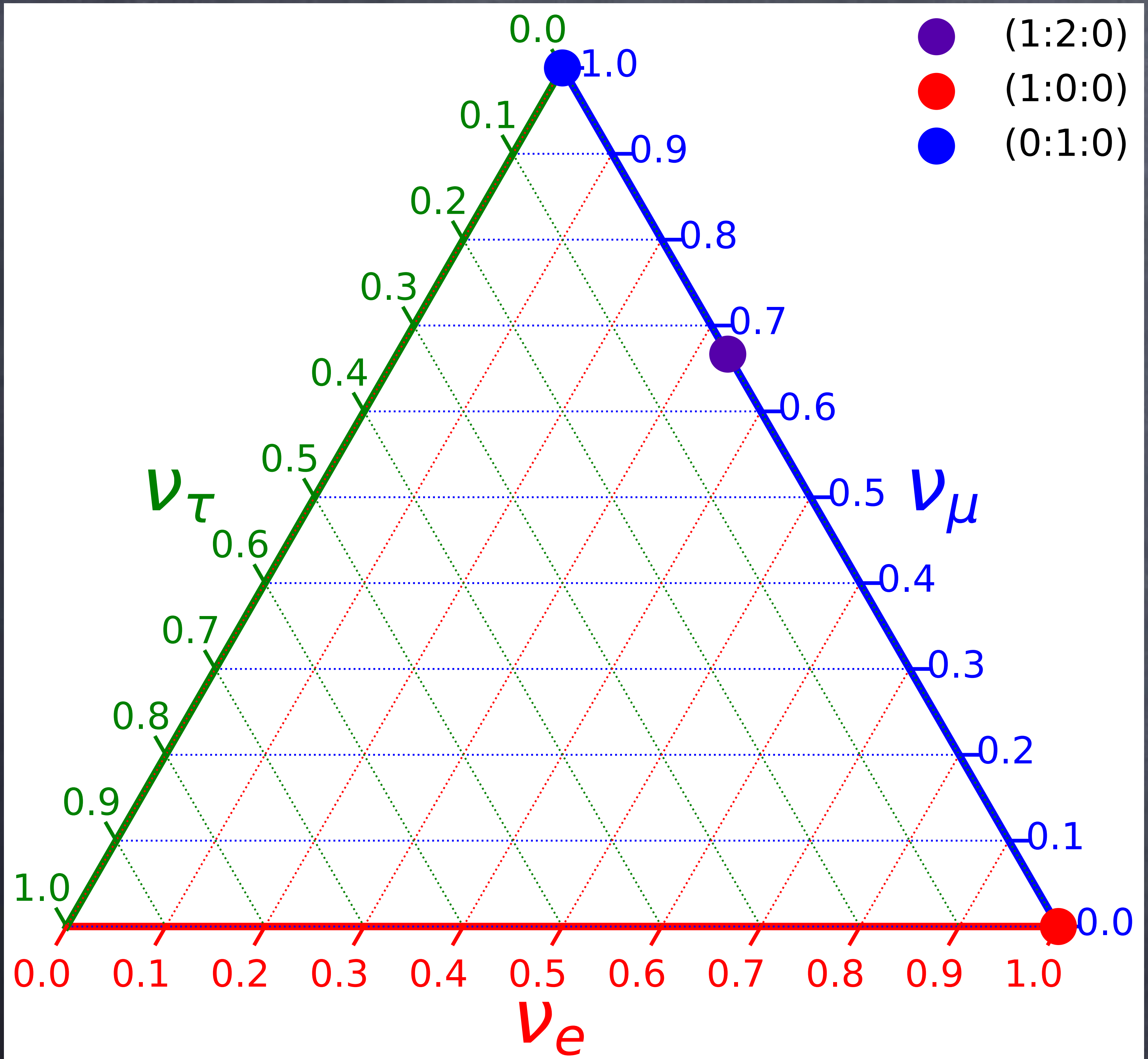

Pion decay

$$(\nu_e : \nu_\mu : \nu_\tau)_S = (1 : 2 : 0)_S$$

Neutron decay

$$(\nu_e : \nu_\mu : \nu_\tau)_S = (1 : 0 : 0)_S$$

Muon damped

$$(\nu_e : \nu_\mu : \nu_\tau)_S = (0 : 1 : 0)_S$$

assuming unitarity: sum equal to 1

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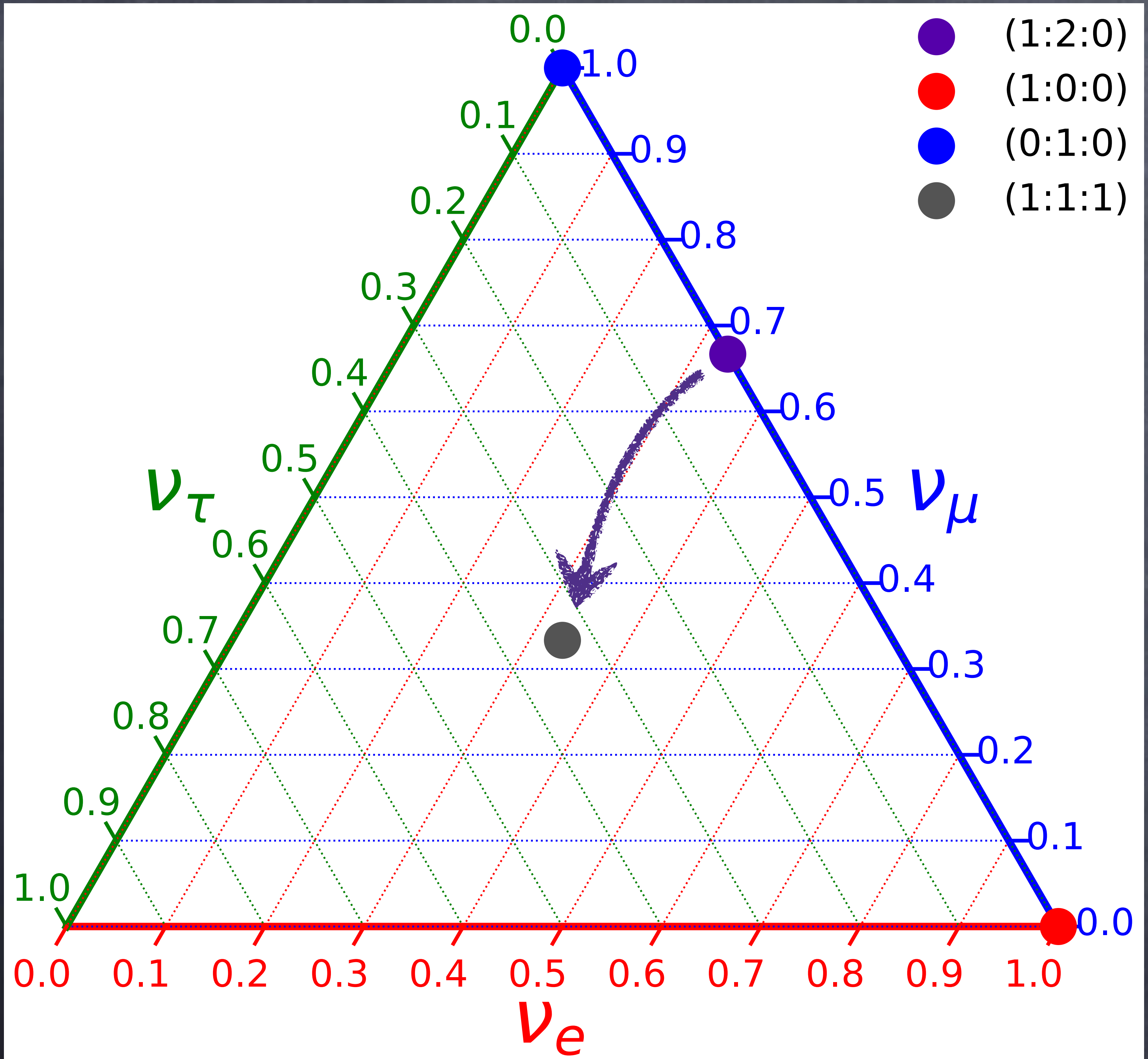

Pion decay

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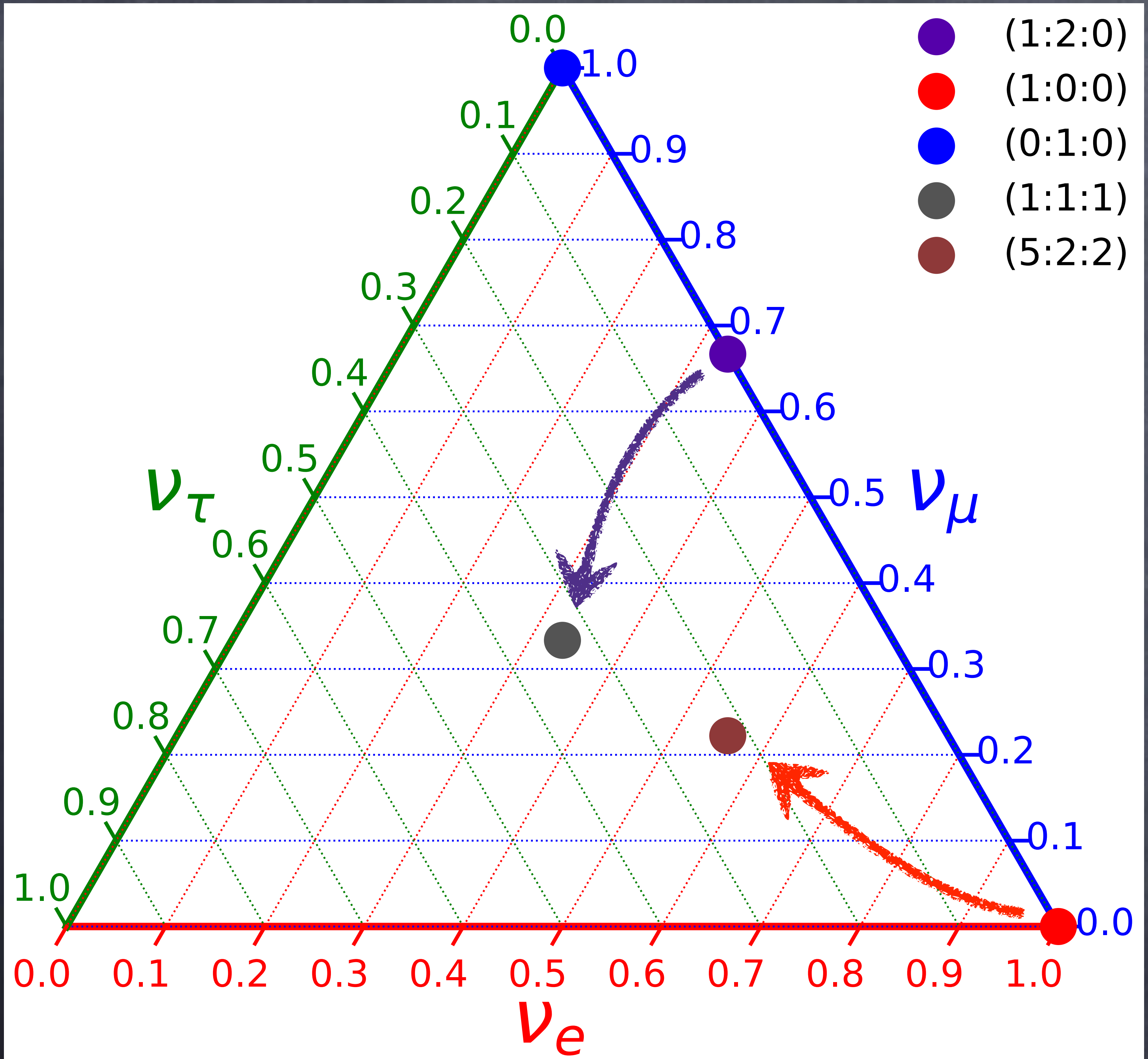

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Neutron decay

$$(\nu_e : \nu_\mu : \nu_\tau)_S = (1:0:0)_S$$

$$(\nu_e : \nu_\mu : \nu_\tau)_\oplus = (5:2:2)_\oplus$$

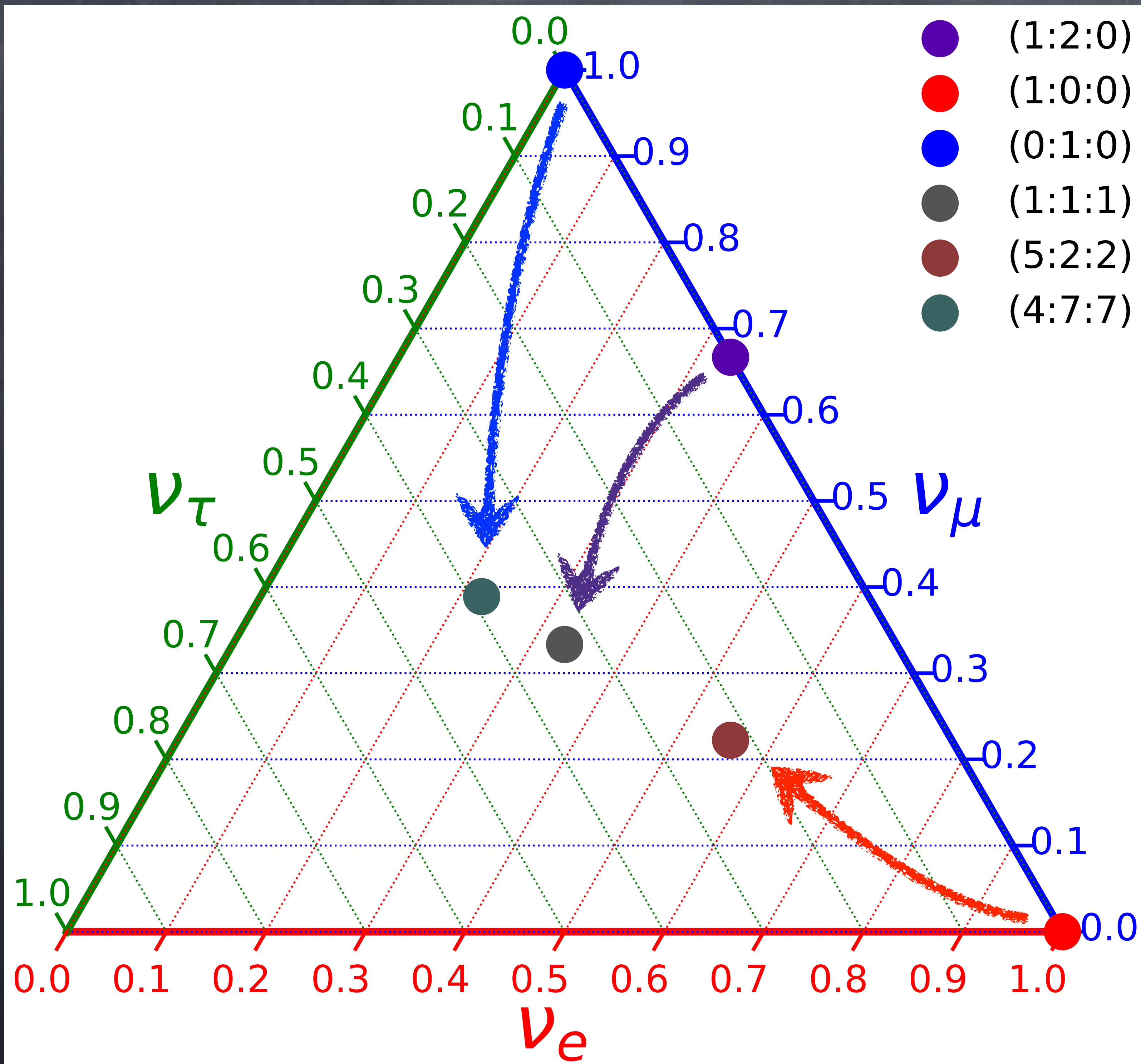
Muon damped

$$(\nu_e : \nu_\mu : \nu_\tau)_S = (0:1:0)_S$$

assuming unitarity: sum equal to 1

Flavor triangles

First flavor analysis of IceCube data: O. Mena, SPR and A. C. Vincent, Phys. Rev. Lett. 113:091103, 2014



Pion decay

$$(\nu_e:\nu_\mu:\nu_\tau)_S = (1:2:0)_S$$

$$(\nu_e:\nu_\mu:\nu_\tau)_\oplus = (1:1:1)_\oplus$$

Neutron decay

$$(\nu_e:\nu_\mu:\nu_\tau)_S = (1:0:0)_S$$

$$(\nu_e:\nu_\mu:\nu_\tau)_\oplus = (5:2:2)_\oplus$$

Muon damped

$$(\nu_e:\nu_\mu:\nu_\tau)_S = (0:1:0)_S$$

$$(\nu_e:\nu_\mu:\nu_\tau)_\oplus = (4:7:7)_\oplus$$

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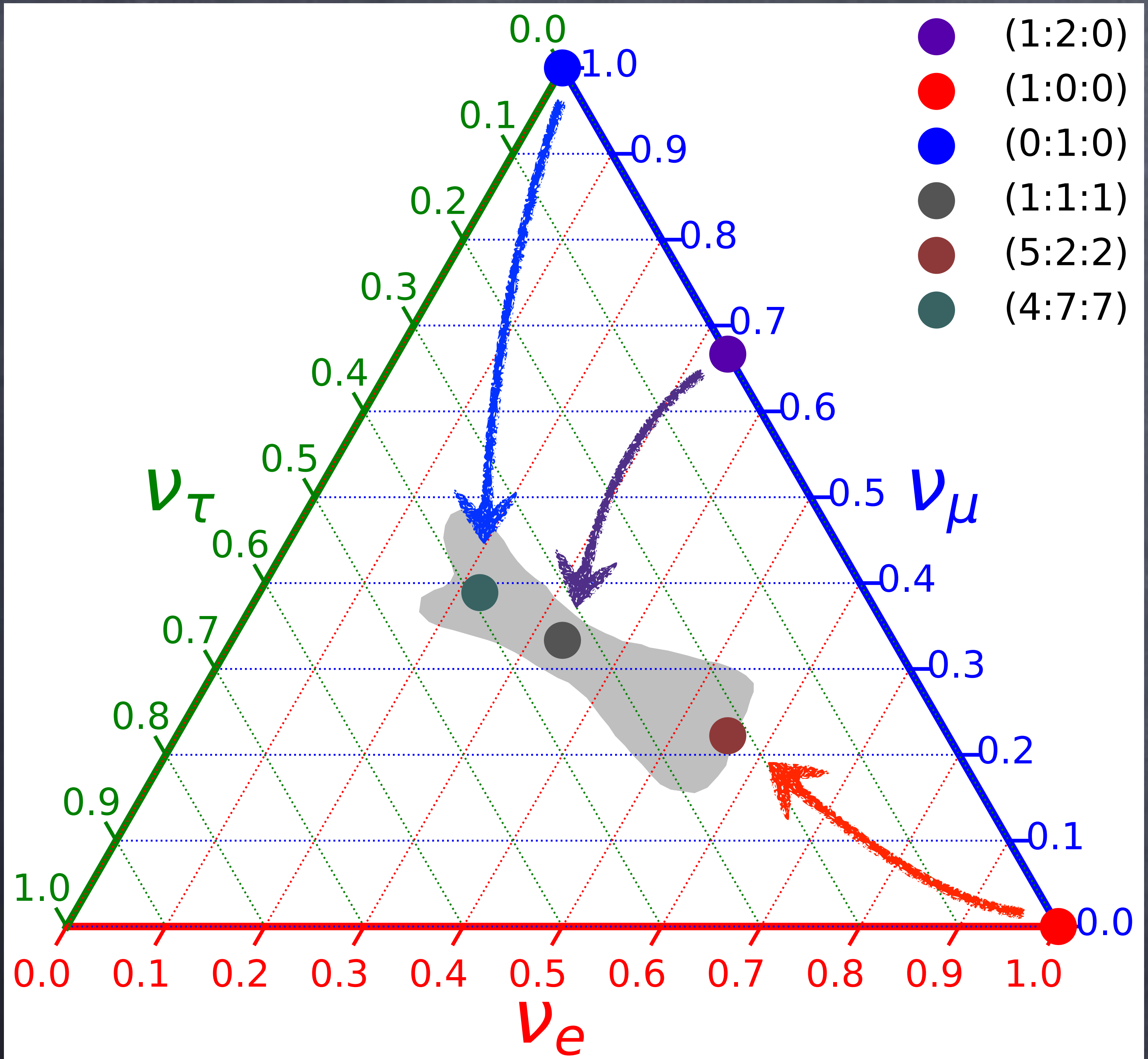

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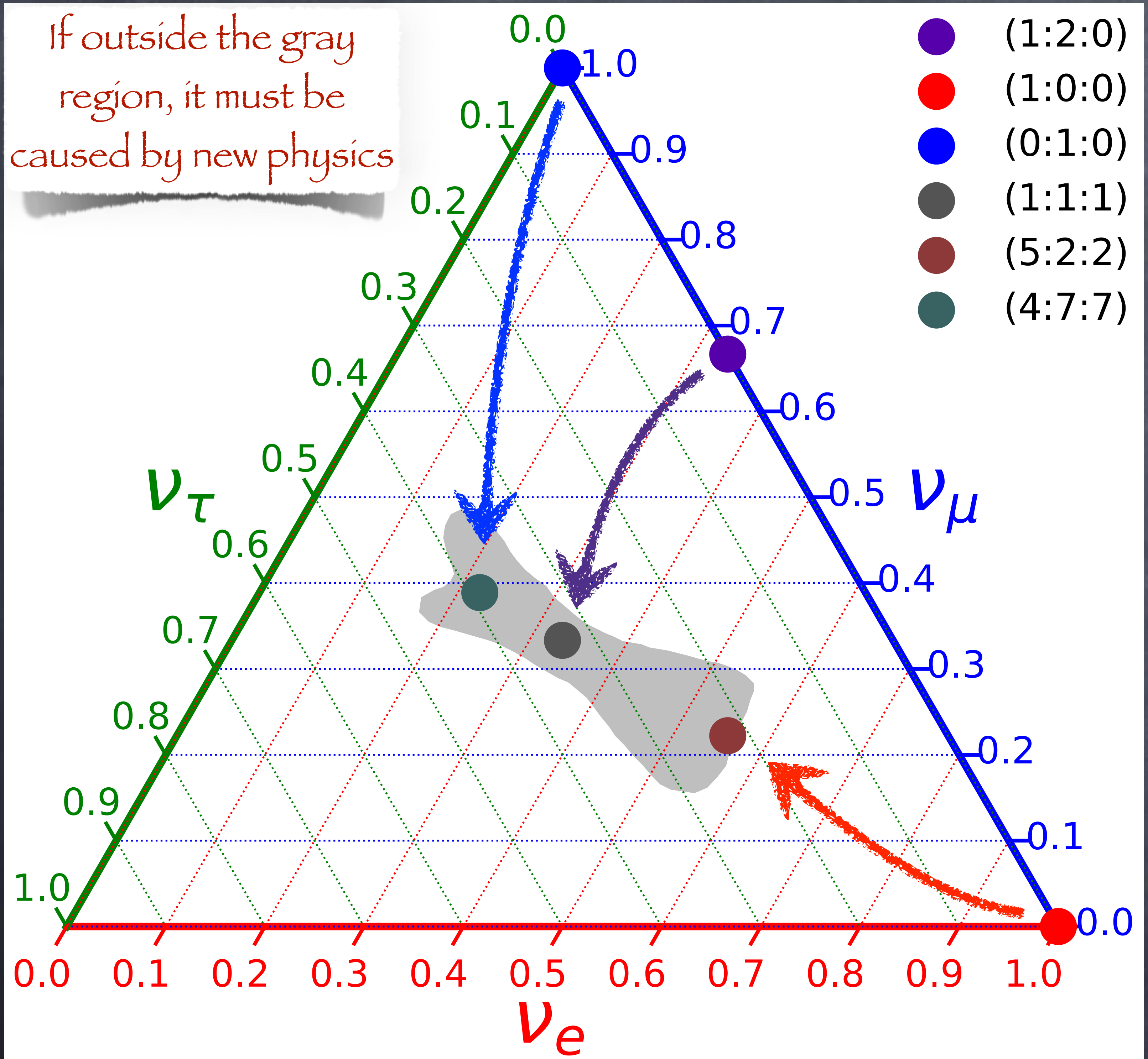

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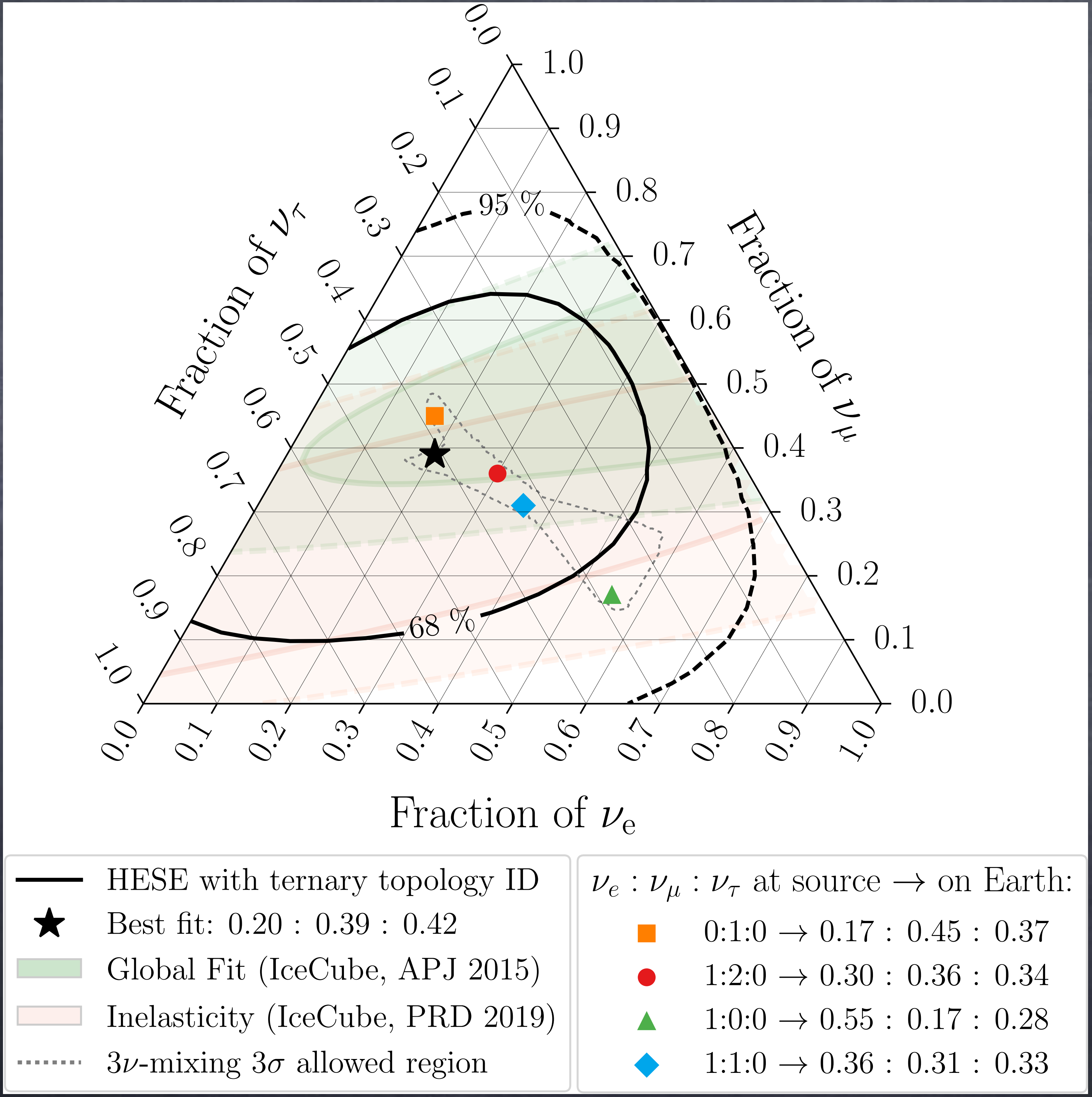
Current status of flavor triangle

R. Abbasi et al. [IceCube Collaboration], arXiv:2011.03561



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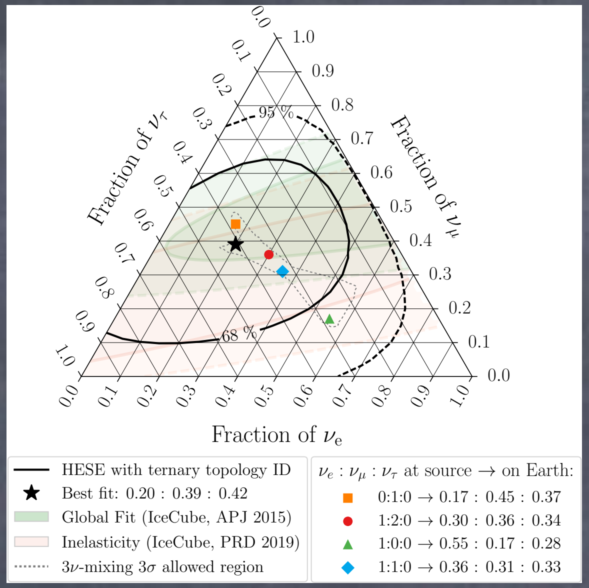
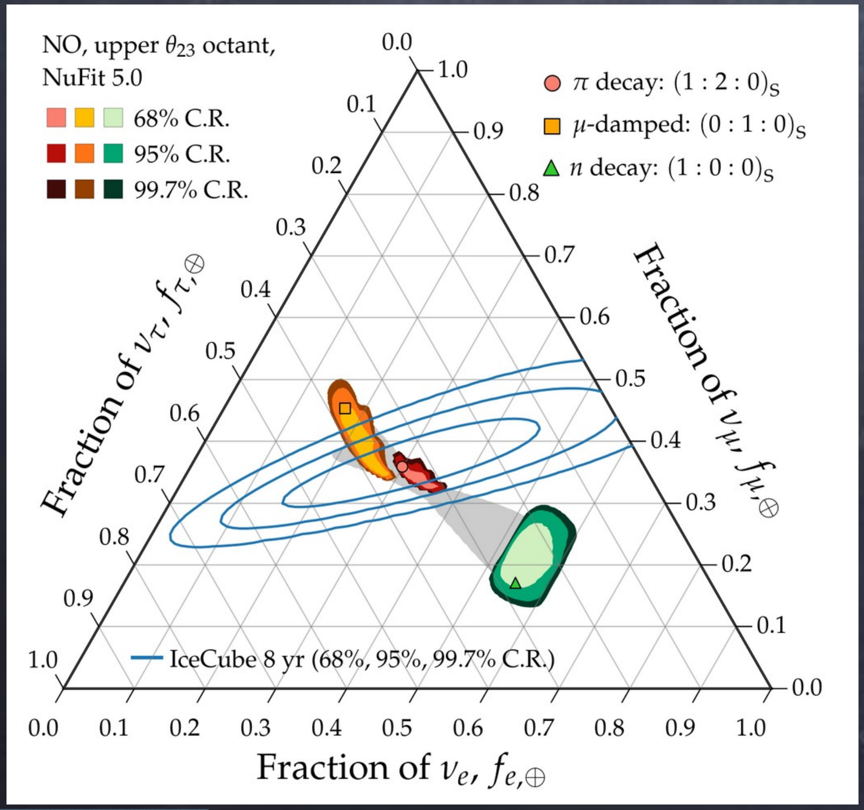


(expected) Future evolution

2020



N. Song, S. W. Li, C. Argüelles, M. Bustamante and A. C. Vincent, JCAP 04:054, 2021

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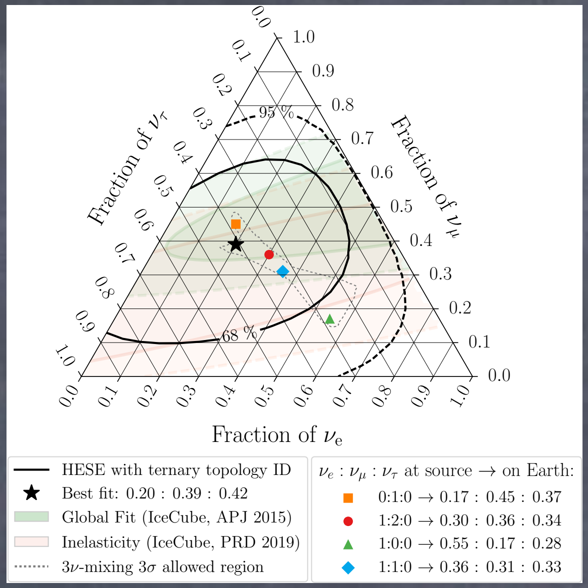

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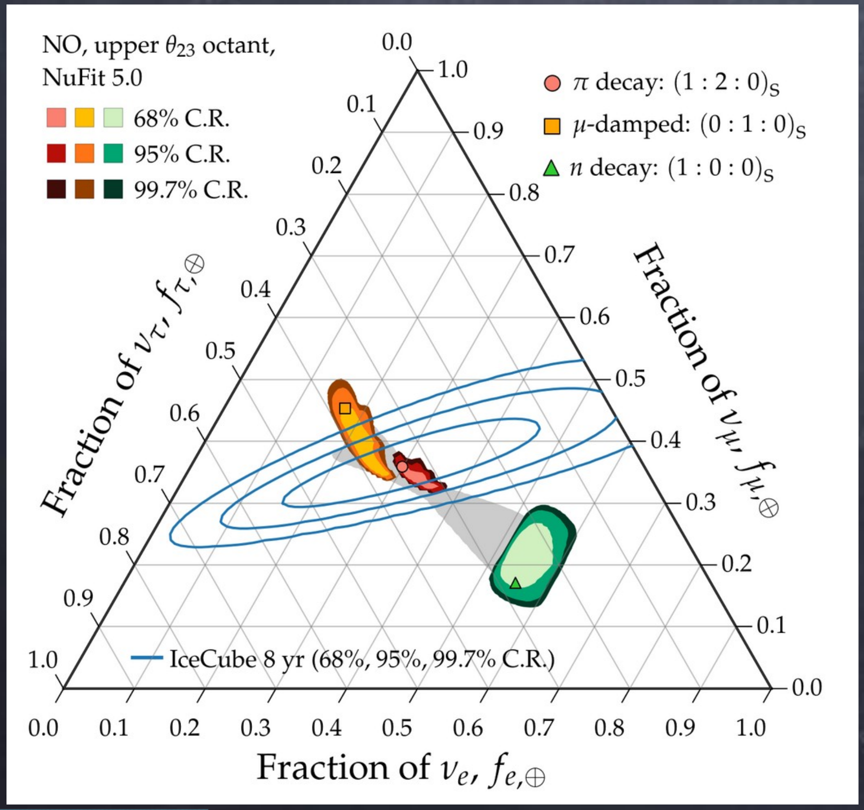
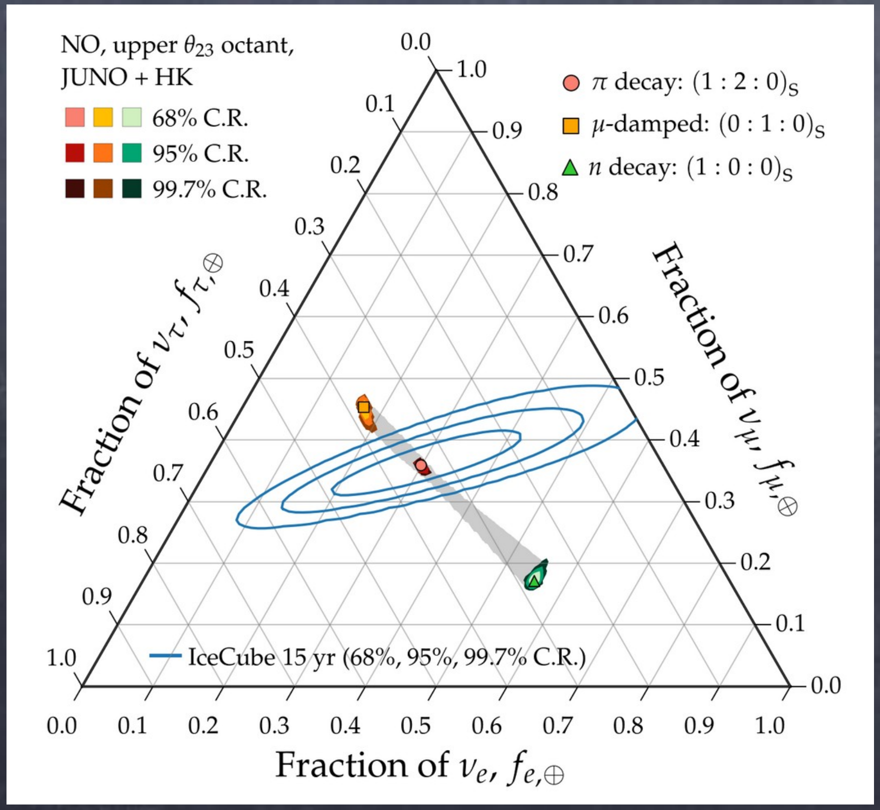


2030



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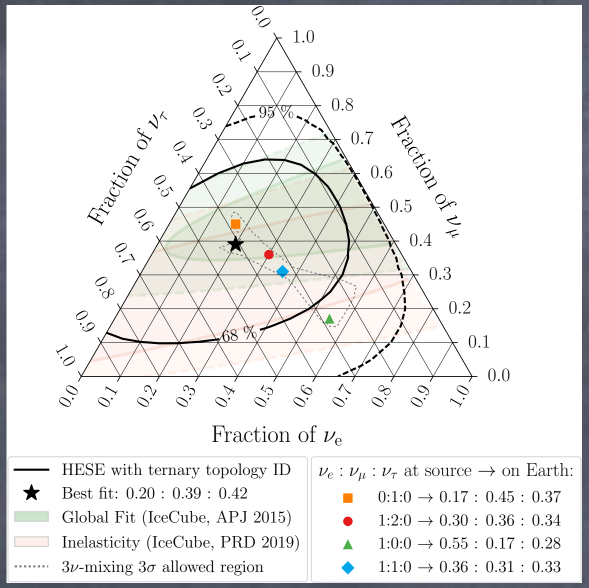

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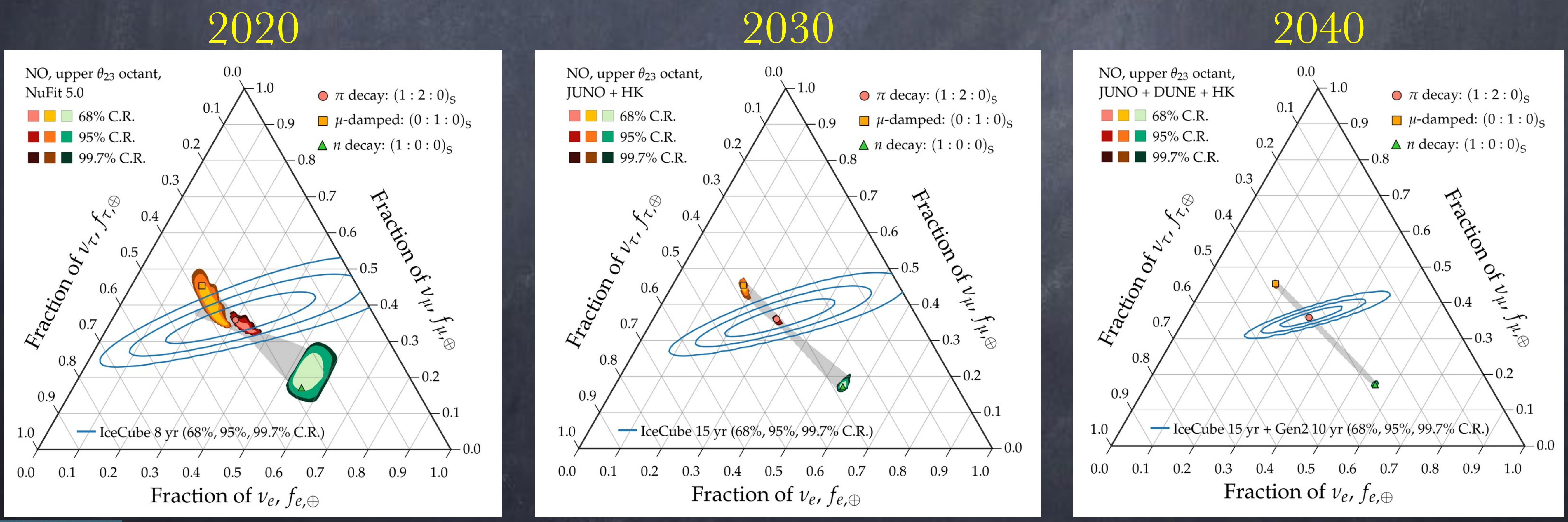

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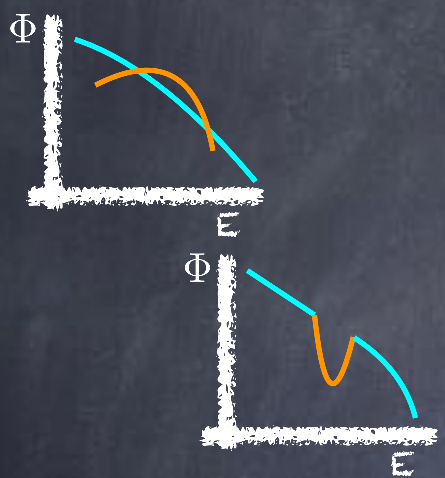
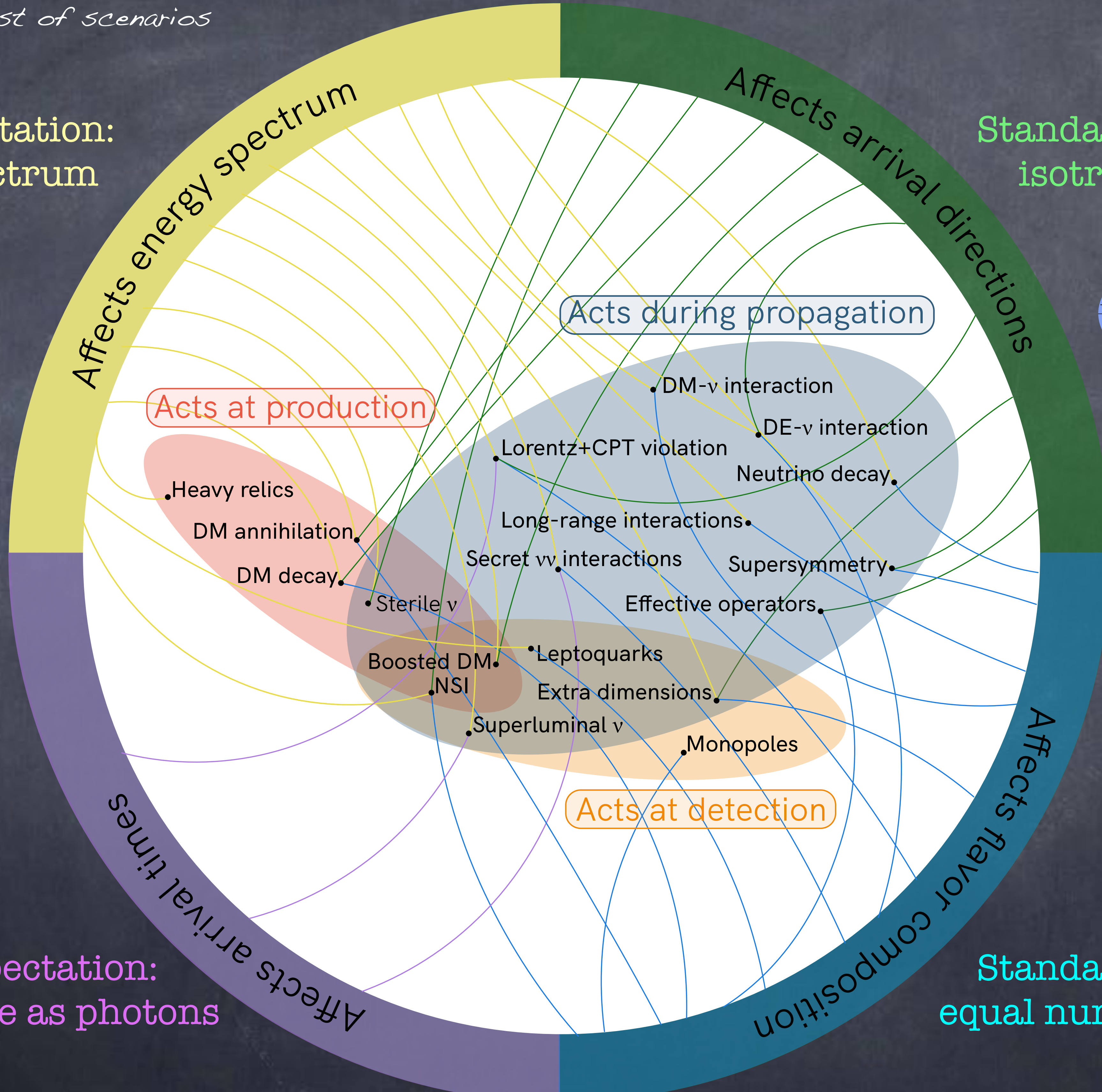
Searching for new physics

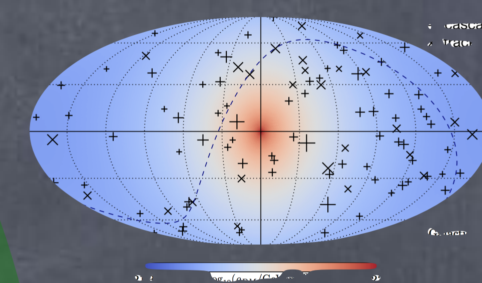
Note: representative list of scenarios

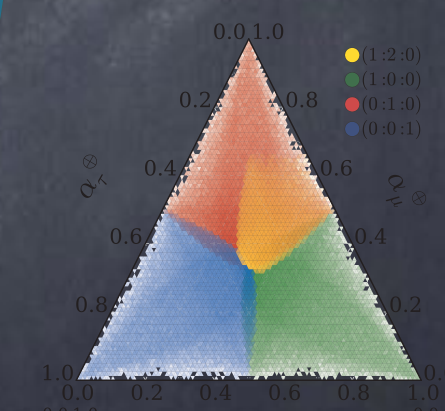
Standard expectation:
power-law spectrum





Standard expectation:
isotropy (diffuse)





Standard expectation:
same arrival time as photons

Standard expectation:
equal number of all flavors

C. Argüelles, M. Bustamante, A. Kheirandish, SPR, J. Salvado and A. C. Vincent, PoS(ICRC2019)849, 2020

Searching for new physics

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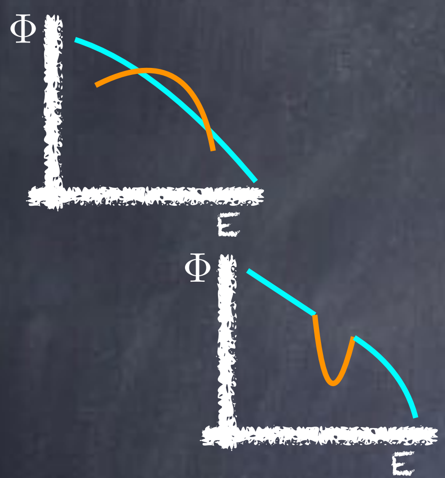

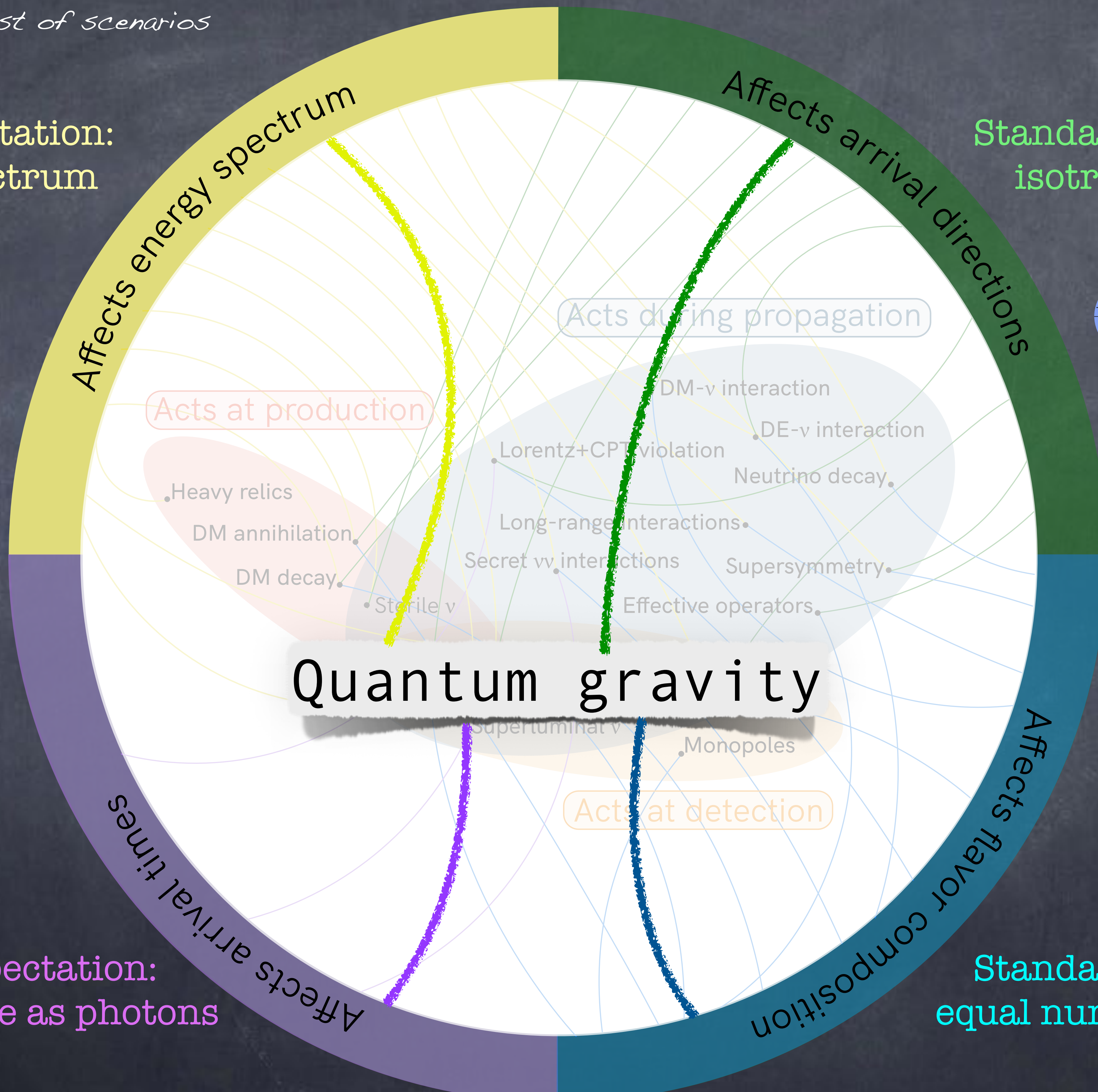

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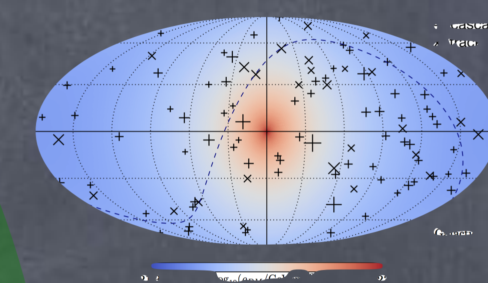

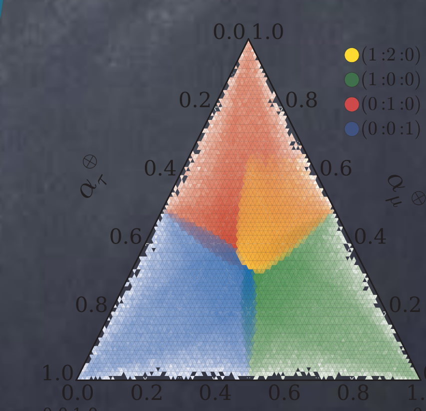

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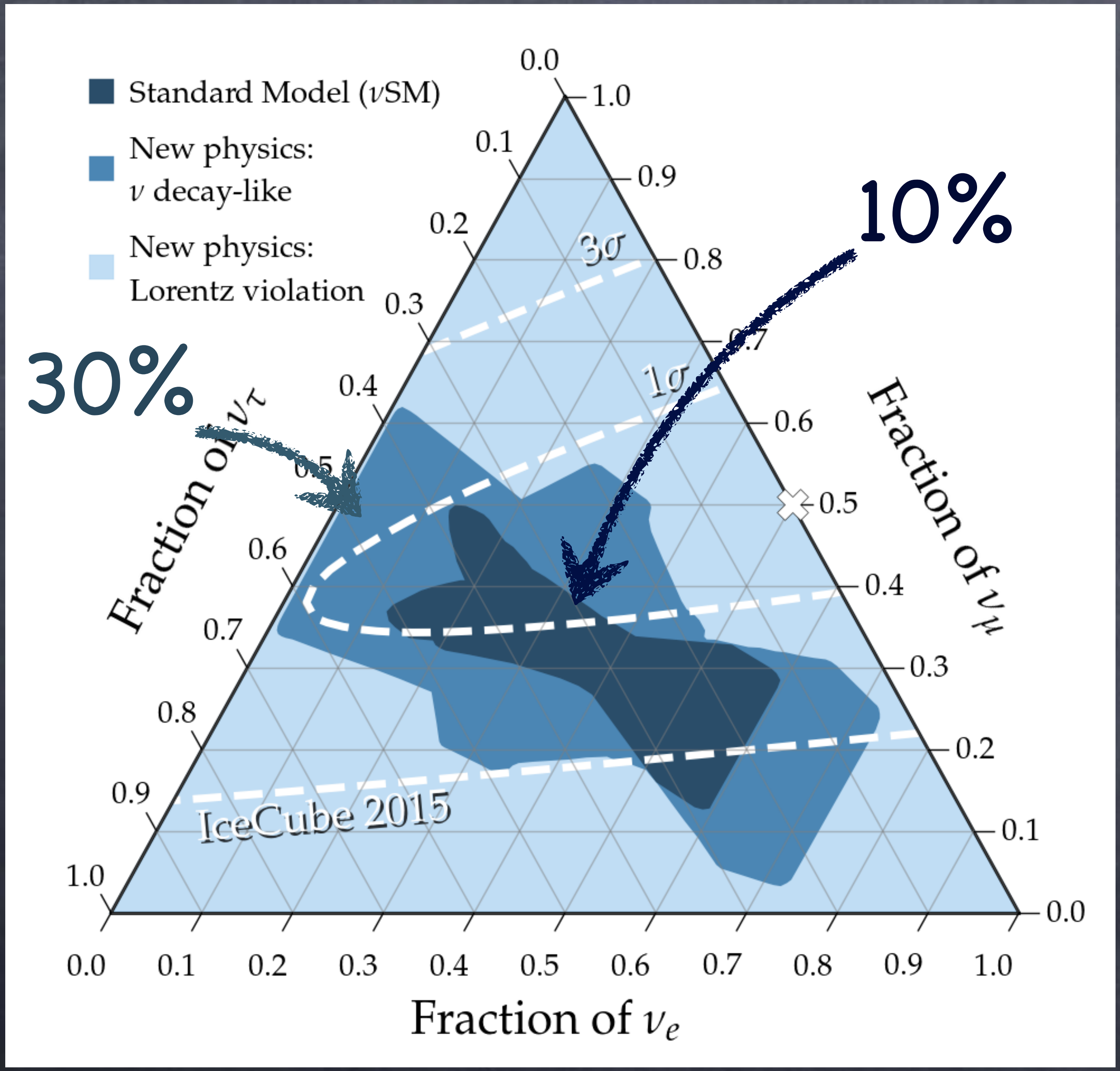
Using flavor ratios in IceCube

What if any incoherent mixture of mass eigenstates is possible?

neutrino decays, pseudo-Dirac neutrinos… or neutrino secret interactions, Planck-scale decoherence



Yet, flavor triangle not fully covered!

More extreme scenarios are required!

M. Ackermann et al., Bull. Am. Astron. Soc. 51:215, 2019

MORE EXTREME SCENARIOS

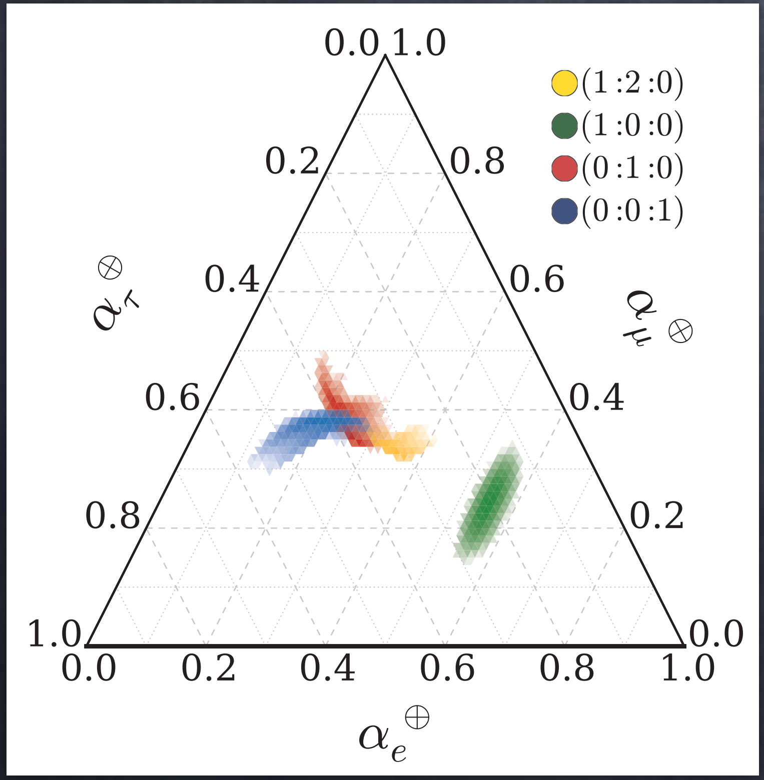
Using effective operators:
general evolution hamiltonian

flavor structure of new physics

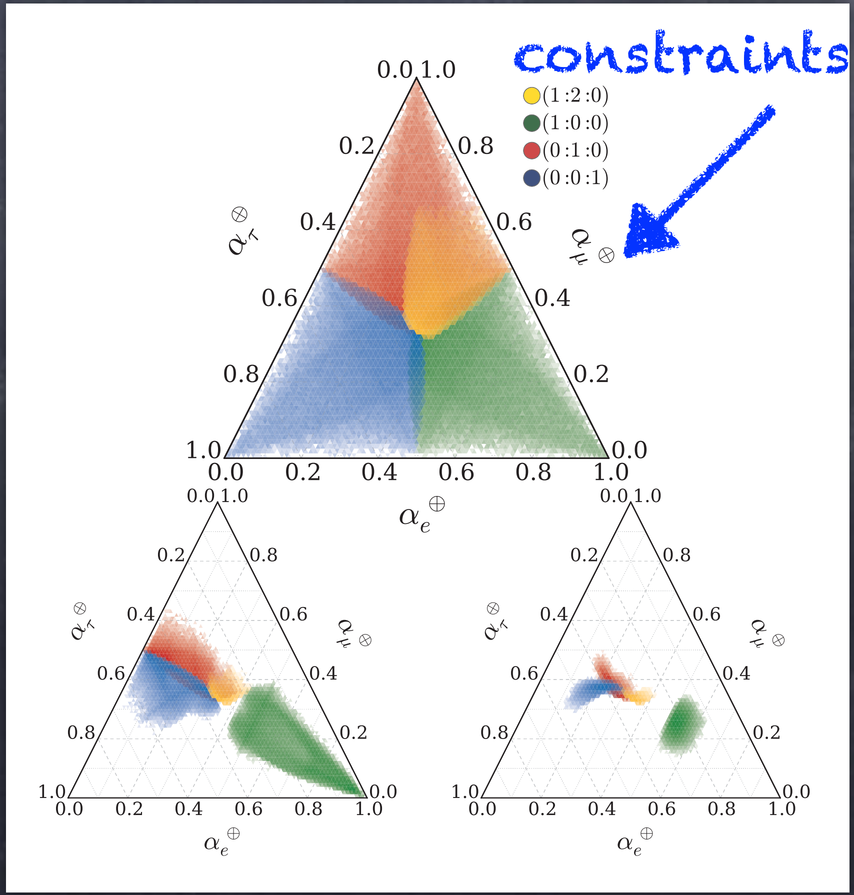
$$H = \frac{1}{2E} U M^2 U^\dagger + \sum_n \left(\frac{E}{\Lambda_n} \right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger$$

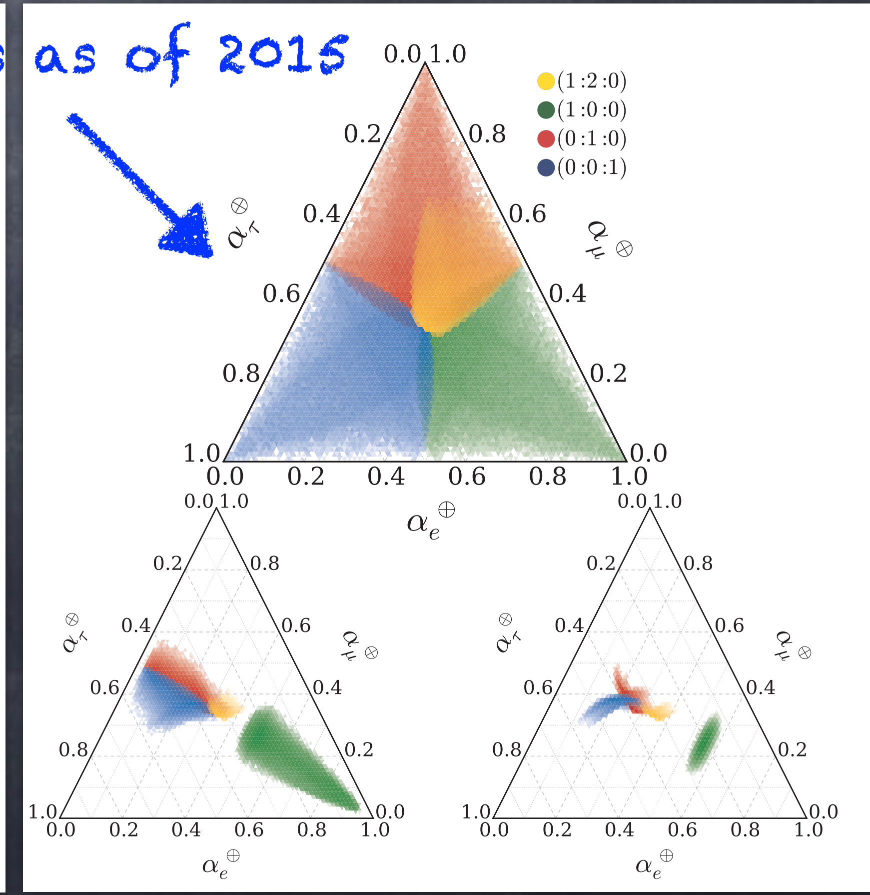
n=0 : neutrino couplings to spacetime torsion, CPT-odd Lorentz violation, NSI

n=1 : CPT-even Lorentz violation, equivalence principle violation



constraints as of 2015

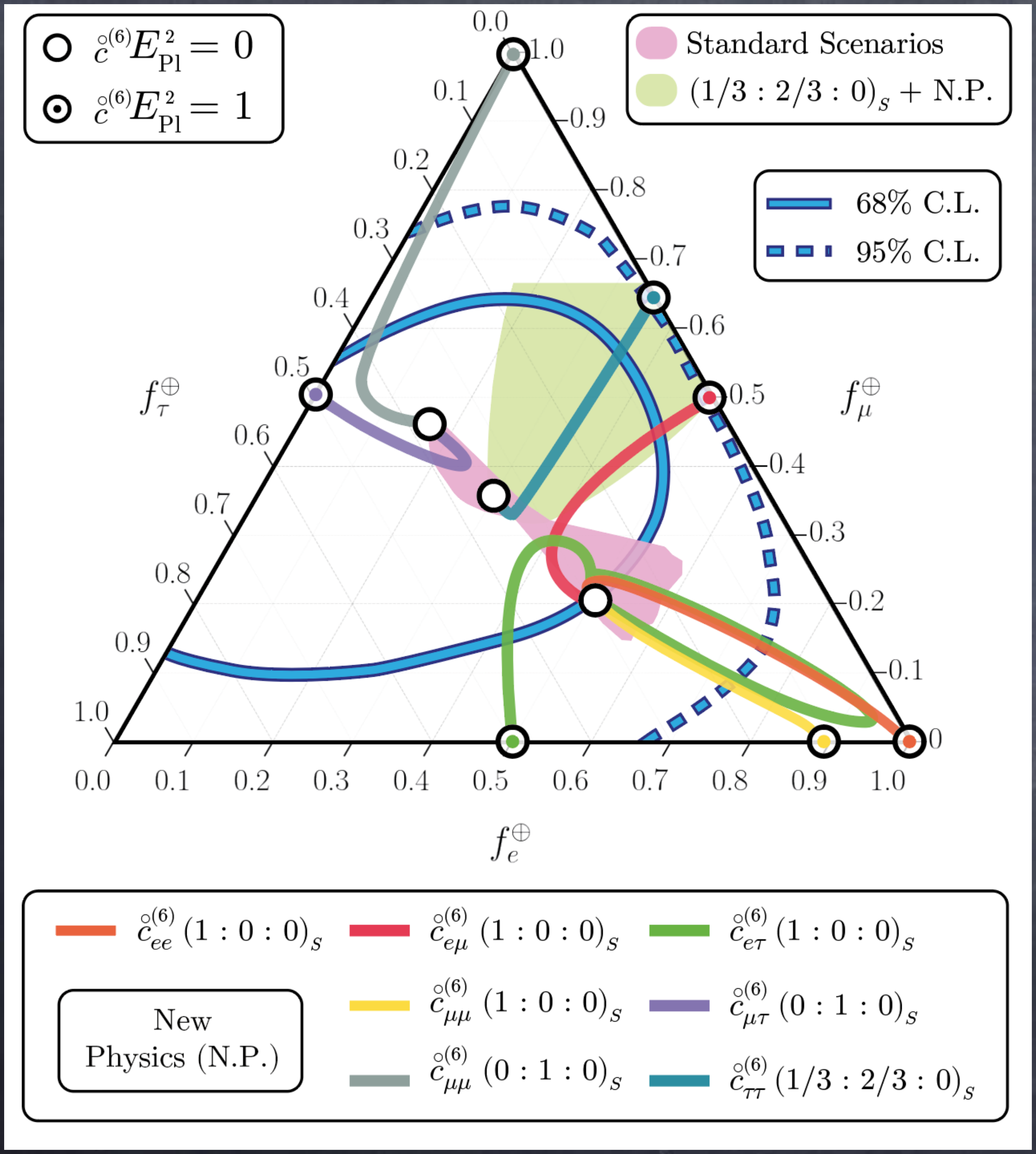




C. A. Argüelles, T. Katori and J. Salvadó, Phys. Rev. Lett. 115:161303, 2015

Current LIV constraints from flavor

isotropic case



$$H = \frac{1}{2E} U M^2 U^\dagger + \sum_{d=3}^{n} (-E)^{d-3} c^d$$

Using 7.5 yr HESE IC data

$$\odot : c^6 \sim M_{\rm Pl}^{-2}$$

R. Abbasi et al. [IceCube Collaboration], arXiv:2111.04654

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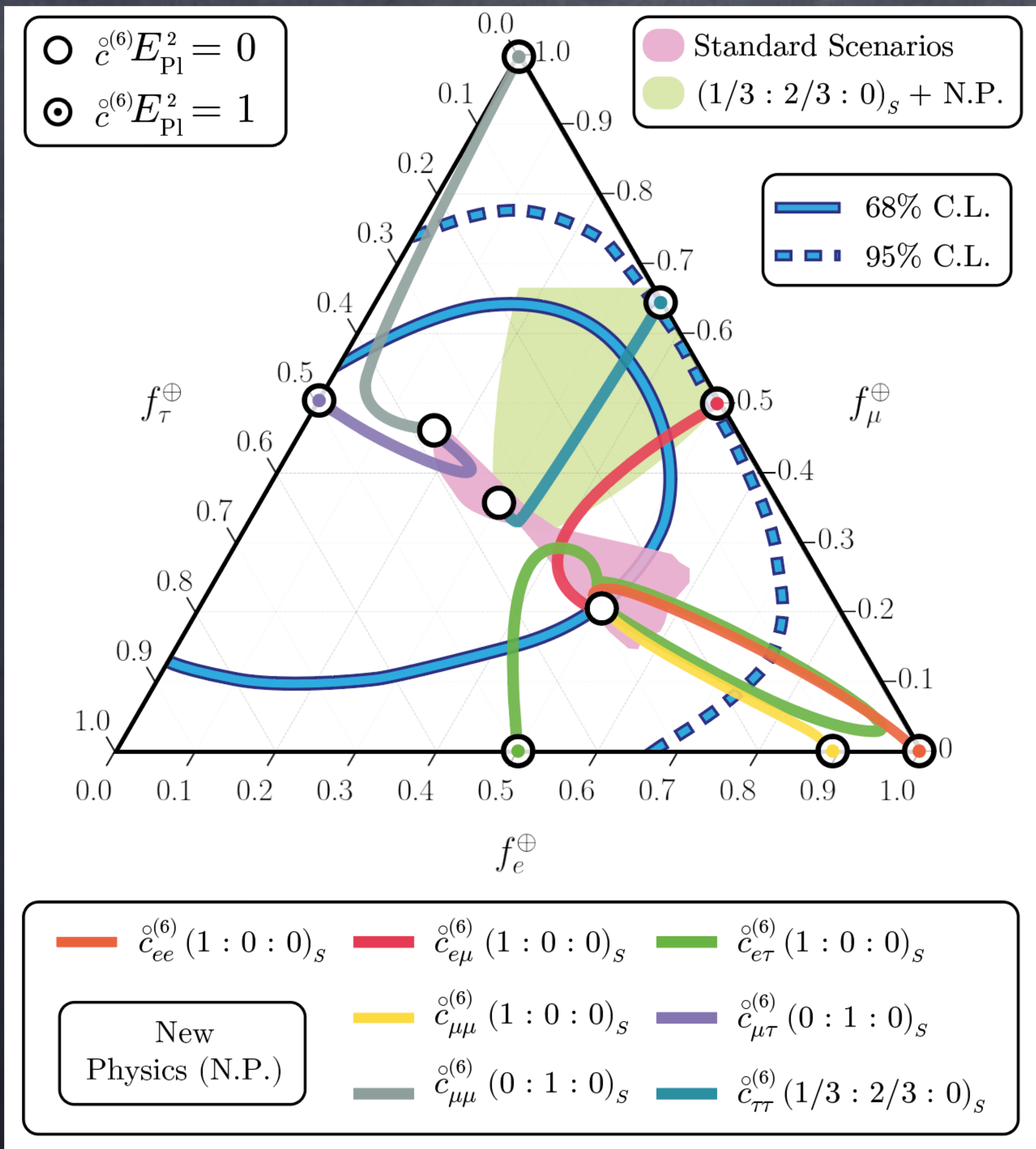

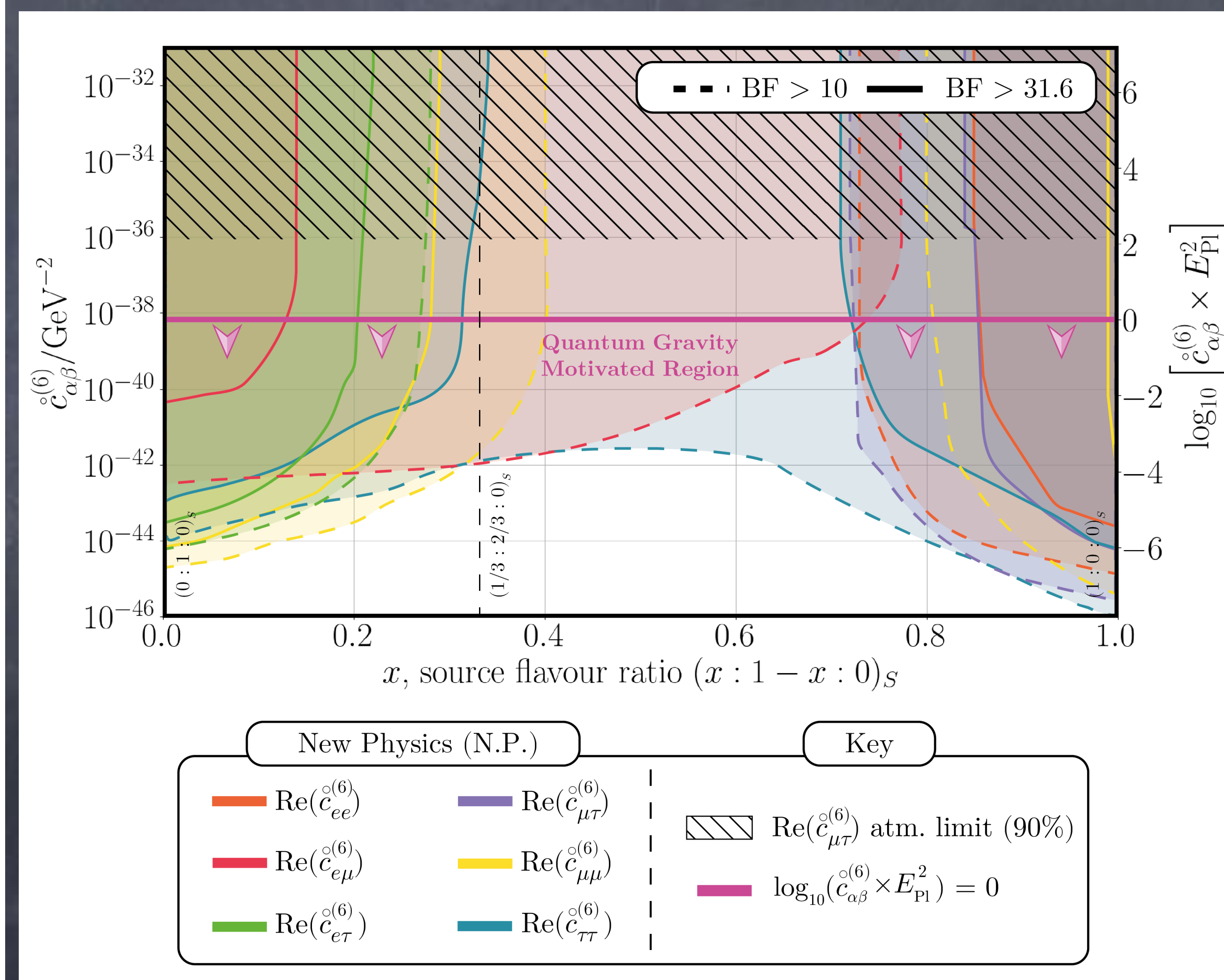

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Other effects of LIV

(all expressions for the isotropic case)

Modified dispersion relations:
$$E = p + \frac{m^2}{2p} + \sum_d p^{d-3}\left(\pm a_d - c_d\right)$$

Group velocity:
$$v = 1 - \frac{m^2}{2p^2} + \sum_d (d-3)\, p^{d-4}\left(\pm a_d - c_d\right)$$

time-of-flight measurements

Comparison of arrival times with other messengers

Cherenkov processes

neutrino splitting $\nu_2 \to \nu_2 \nu_1 \bar{\nu}_1$

pair production $\nu_2 \to \nu_2 e^- e^+$

photon radiation $\nu_2 \to \nu_2 \gamma$

Anomalous threshold effects

Decay modes that produce neutrinos might be forbidden

eg, pion decay: $\delta E \leq \frac{(m_\pi - m_\mu)^2}{2p}$

eg, relaxing the GZK suppression

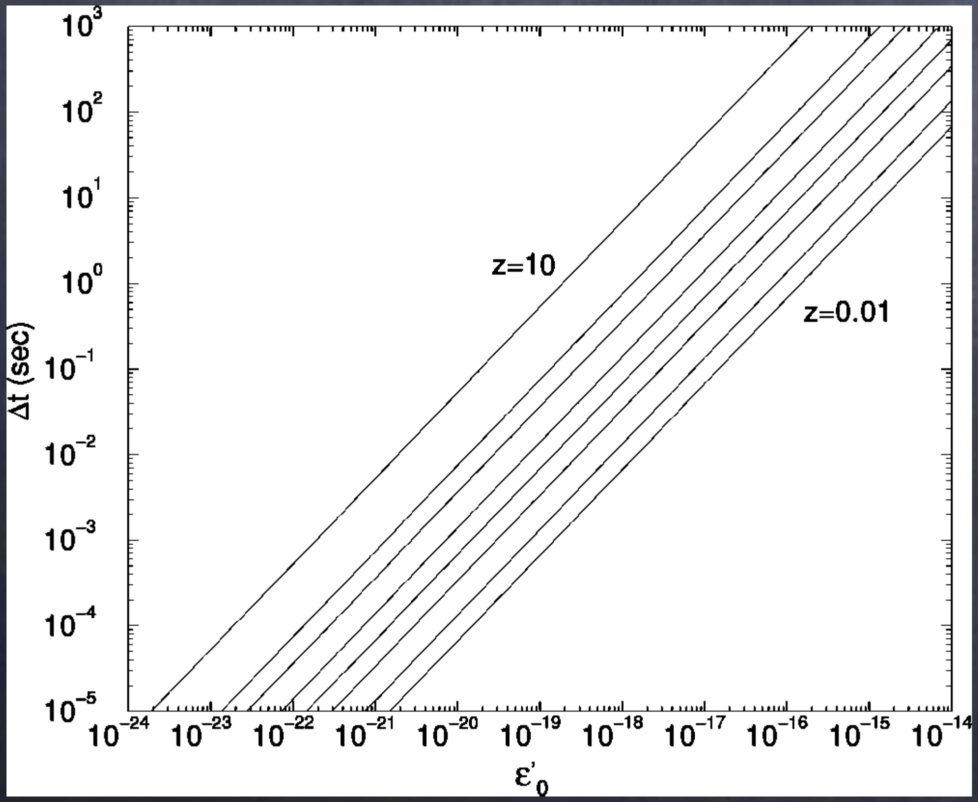
This can cause a cutoff in the high-energy spectrum

time-of-flight measurements

$$v = 1 - \frac{m^2}{2p^2} + \sum_d (d-3)\, p^{d-4} \left(\pm a_d - c_d\right) \rightarrow 1 - \frac{m^2}{2p^2} + \xi_d (d-3) \left(\frac{p}{M_{\rm Pl}}\right)^{d-4}$$

time delay with respect to photons from the same source

$$\Delta T = (1-v)\, L = \left(\frac{m^2}{2p^2} - \xi_d (d-3) \left(\frac{p}{M_{\rm Pl}}\right)^{d-4} \right) L$$



S. Choubey and S. F. King, Phys. Rev. D67:073005, 2003

$$L \rightarrow \frac{1}{H_0} \int_0^z \frac{(1+z)^{d-4}}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}$$

Using neutrinos and photons from SN 1987A, E~10 MeV

$$\Delta v \lesssim 10^{-9} - 10^{-8}$$

M. J. Longo, Phys. Rev. D36:3276, 1987

L. Stodolsky, Phys. Lett. B201:303, 1988

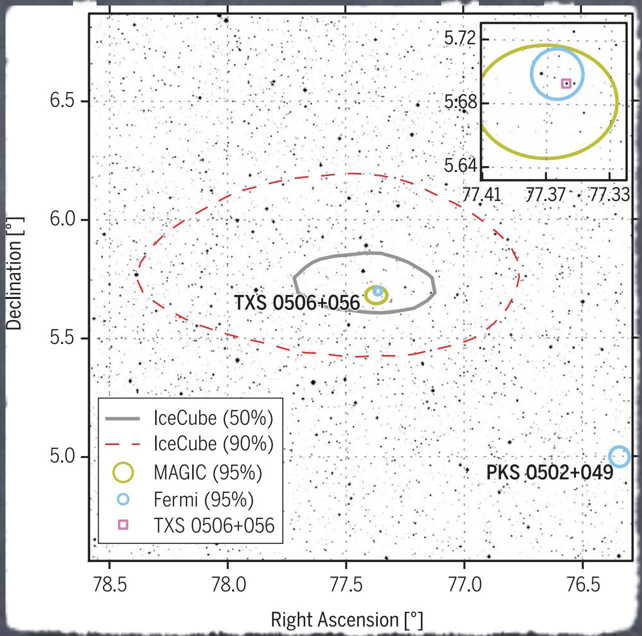
J. Ellis et al., Phys. Rev. D78:033013, 2008

time-of-flight measurements

First identified neutrino source:
blazar TXS 0506+056, at z=0.3365

M. Aartsen et al., Science 361:eaat1378, 2018

M. Aartsen et al. [IceCube Collaboration], Science 361:147, 2018



Using the time of arrivals of neutrinos and photons, E > 100 TeV

$$\Delta v \lesssim 4.2 \times 10^{-12} \left(\frac{\Delta T}{7 \text{ days}} \right) \rightarrow \xi_5 \lesssim 300 \; ; \; \xi_6 \lesssim 10^{16}$$

J. Ellis, N. Mavromatos, A. S. Sakharov and E. K. Sarkisyan-Grinbaum, Phys. Lett. B789:352, 2019
R. Laha, Phys. Rev. D100:103002, 2019 J.-J. Wei et al., JHEAp 22:1, 2019

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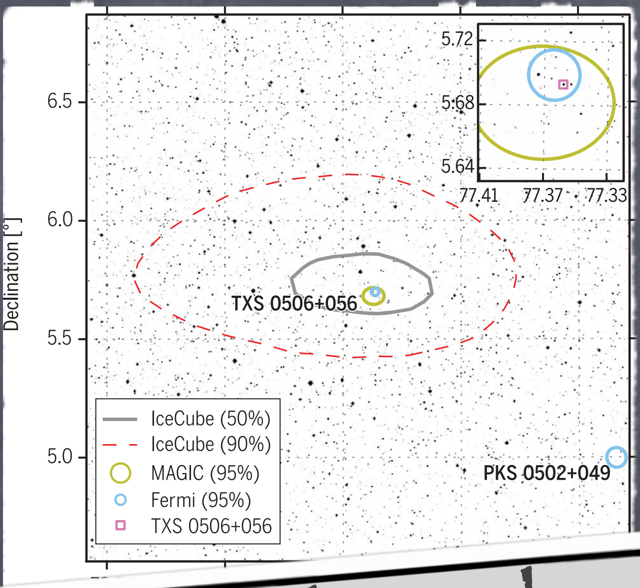

Usi… TeV

Δv … $\xi_6 \sim 10^{16}$

… days …

Other correlations can be considered:
IC-160731, potential GRB neutrinos…

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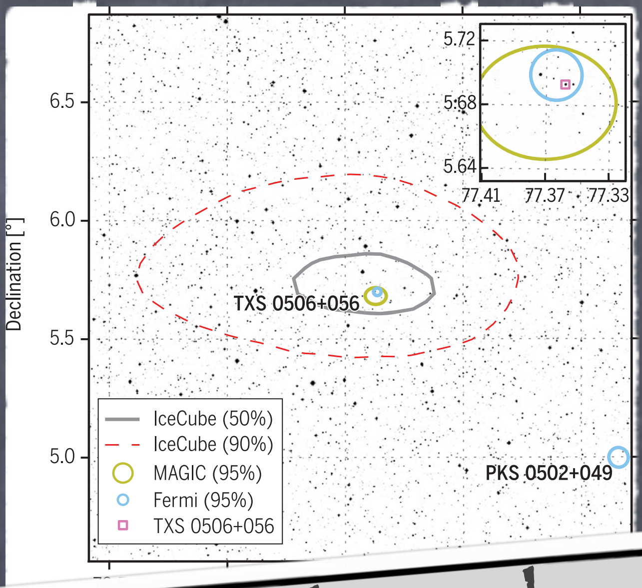

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M. J. Longo, Phys. Rev. Lett. 60:173, 1988

L. M. Krauss and S. Tremaine, Phys. Rev. Lett. 60:176, 1988

S. Pakvasa, W. A. Simmons and T. J. Weiler, Phys. Rev. D39:1761, 1989

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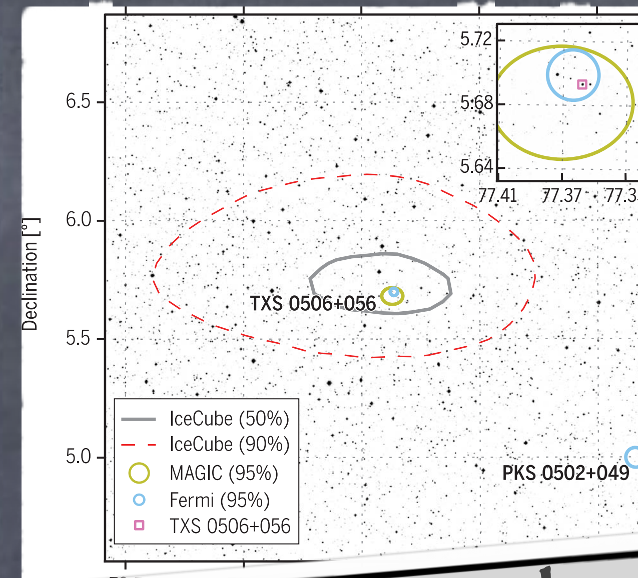

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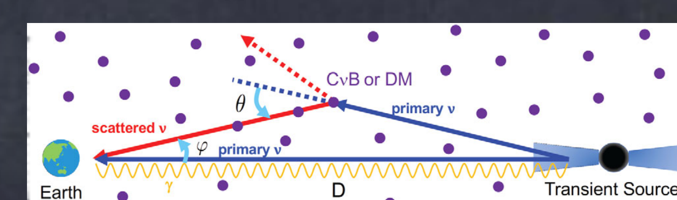
…and neutrino-dark matter scattering could also produce time delays



S. Koren, JCAP 09:013, 2019

K. Murase and I. M. Shoemaker, Phys. Rev. Lett. 123:24, 2019

Cherenkov processes

neutrino Cherenkov emission: $\nu \to \nu\gamma$

S. Coleman and S. L. Glashow, Phys. Rev. D59:116008, 1999

$$\tau_{\nu\gamma} \simeq \xi_d^{-2} \left(\frac{E}{1\ \mathrm{PeV}} \right)^{-2d-1} 10^{26d-86}\ \mathrm{s}$$

neutrino splitting: $\nu \to \nu\nu\bar{\nu}$

D. M. Mattingly et al., JCAP 02:007, 2010

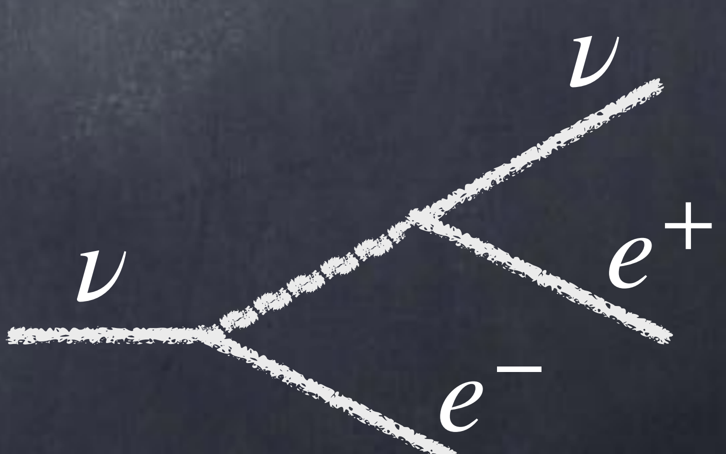
$$\tau_{\nu-\mathrm{splitting}} \simeq \frac{64\pi^3}{3\, G_F^2\, E^5}\, \xi_d^{-3} \left(\frac{M_{\mathrm{Pl}}}{E} \right)^{3d-6}$$

neutrino pair emission: $\nu \to \nu e^+ e^-$

D. M. Mattingly et al., JCAP 02:007, 2010

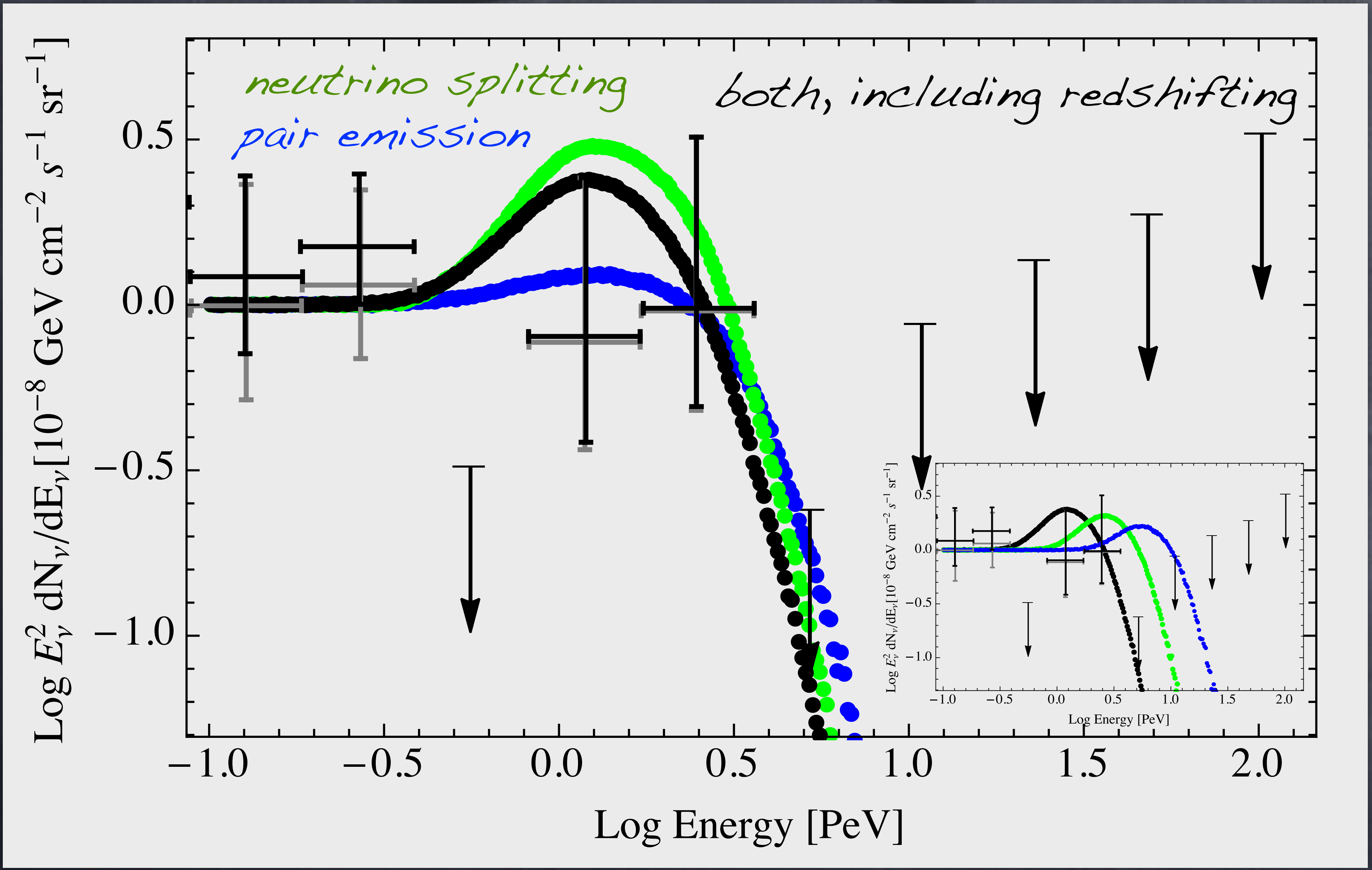
$$\tau_{\nu-pair} \simeq G_F^{-2}\, E^{-5}\, \xi_d^{-3} \left(\frac{\mathrm{Mpl}}{E} \right)^{3d-6}$$

$$E_{\mathrm{th}}^2 = \frac{4\, m_e^2}{\xi_d\, (E_{\mathrm{th}}/M_{\mathrm{Pl}})^{d-4}}$$



LIV for d=6 (CPT conserving)

IceCube 3-year data



F. W. Stecker, S. T. Scully, S. Liberati and D. Mattingly, Phys. Rev. D91:045009, 2015

see also F. W. Stecker and S. T. Scully, Phys. Rev. D90:043012, 2014

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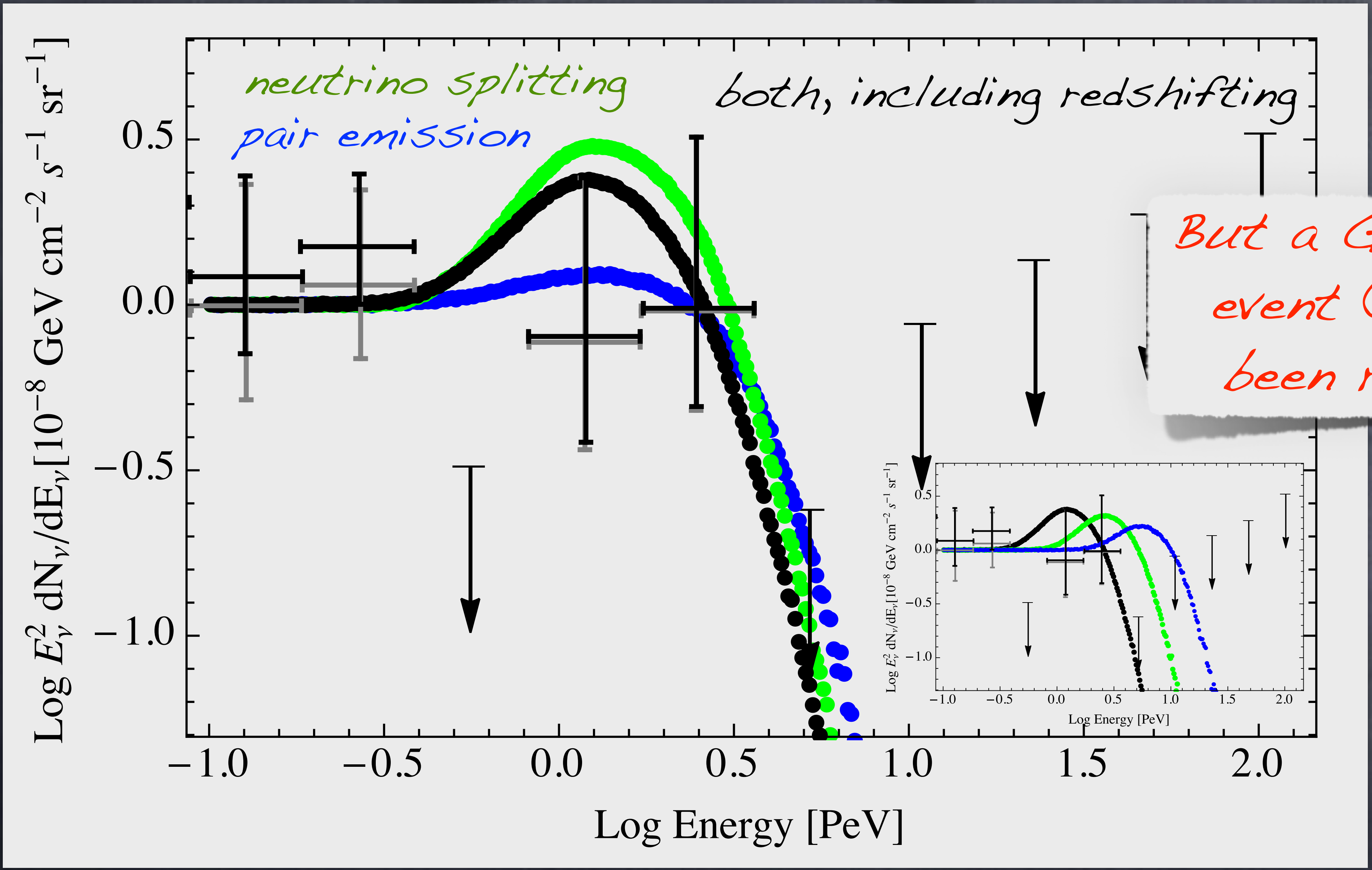

But a Glashow resonance event ($E \sim 6.3$ PeV) has been recently detected

F. W. Stecker, S. T. Scully, S. Liberati and D. Mattingly, Phys. Rev. D91:045009, 2015

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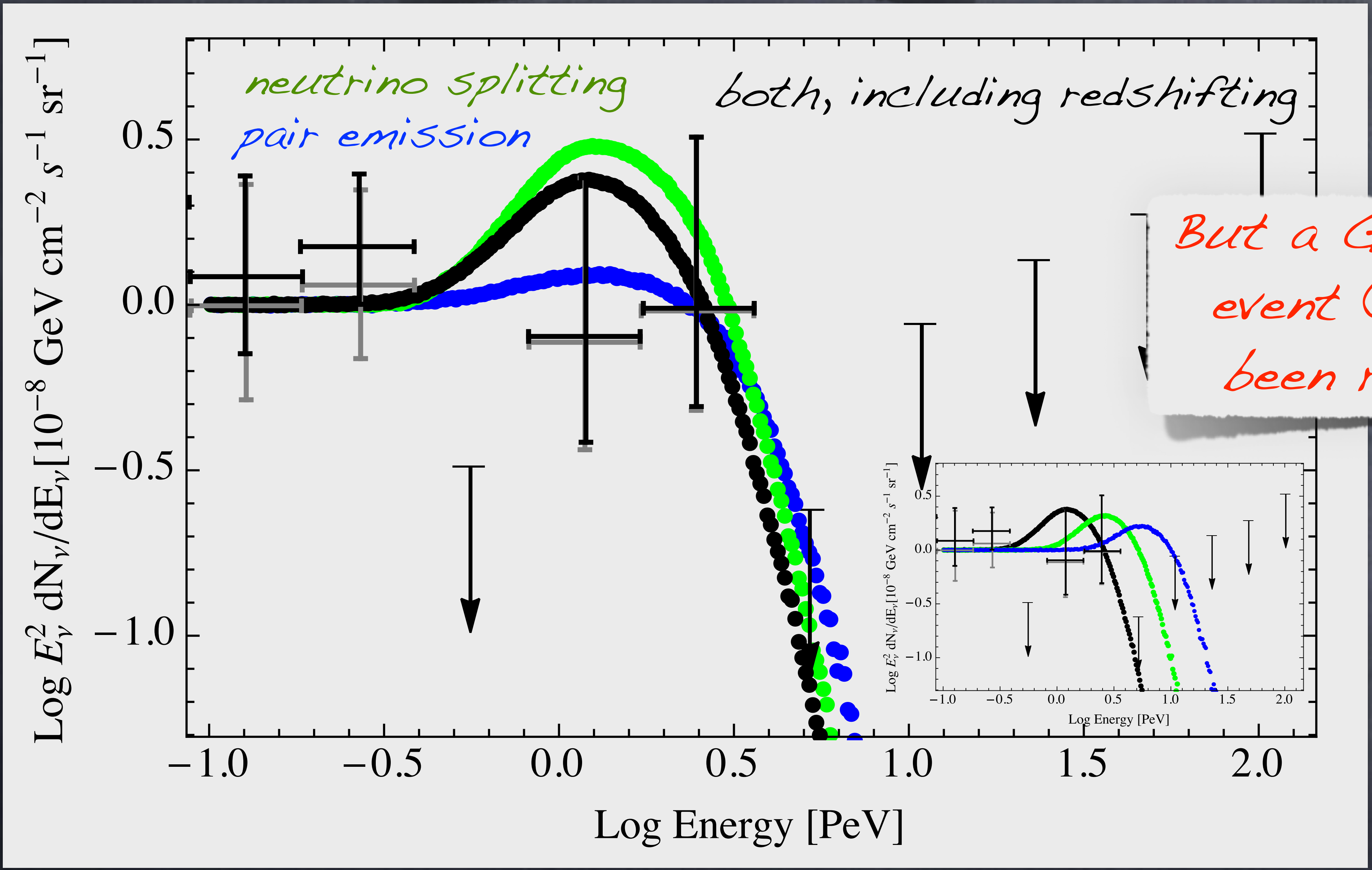

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...and neutrino-dark matter scattering could also produce a cutoff in the spectrum

K. J. Kelly and P. A. N. Machado, JCAP 10:048, 2018

J. B. G. Alvey and M. Fairbairn, JCAP 07:041, 2019

K. Choi, J. Kim and C. Rott, Phys. Rev. D99:8, 2019

Conclusions

Neutrino oscillations, albeit some anomalies, are well established: neutrinos have mass → evidence of physics beyond the SM

The weakness of their interactions is the strength of their sensitivity to search for new physics signatures

A very broad energy and baseline range explored by numerous experiments

In particular, neutrinos of different energies set very competitive limits on QG scenarios