(High-energy) Astrophysical Neutrinos

Lecture 2

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Some recommended bibliography
(in chronological order)

T. K. Gaisser, *Cosmic rays and particle physics*, 1990, Cambridge University Press

V. S. Berezinskiĭ et al., *Astrophysics of cosmic rays*, 1990, Elsevier

M. Kachelrieß, *Lecture notes on high-energy cosmic rays*, arXiv:0801:4376 [astro-ph]

J. K. Becker, *High-energy neutrinos in the context of multimessenger astrophysics*, Phys. Rept. 458:173, 2008

M. S. Longair, *High energy astrophysics*, 2011, Cambridge University Press

L. A. Anchordoqui et al., *Cosmic neutrino Pevatrons: a brand new pathway to astronomy, astrophysics, and particle physics*, JHEAp 1:1, 2014

M. Ahlers and F. Halzen, *IceCube: neutrinos and multimessenger astronomy*, Prog. Theor. Exp. Phys. 12A105, 2017

M. Spurio, *Probes of multimessenger astrophysics*, 2018, Springer

Plan of lectures

- I Historical remarks and general comments from a multi-messenger perspective
- II Flavor and multi-messenger relations
- III Cosmic acceleration, energetics and sources

Bonus: new physics searches with HE astrophysical neutrinos

Disclaimer

I will only discuss non-thermal emission

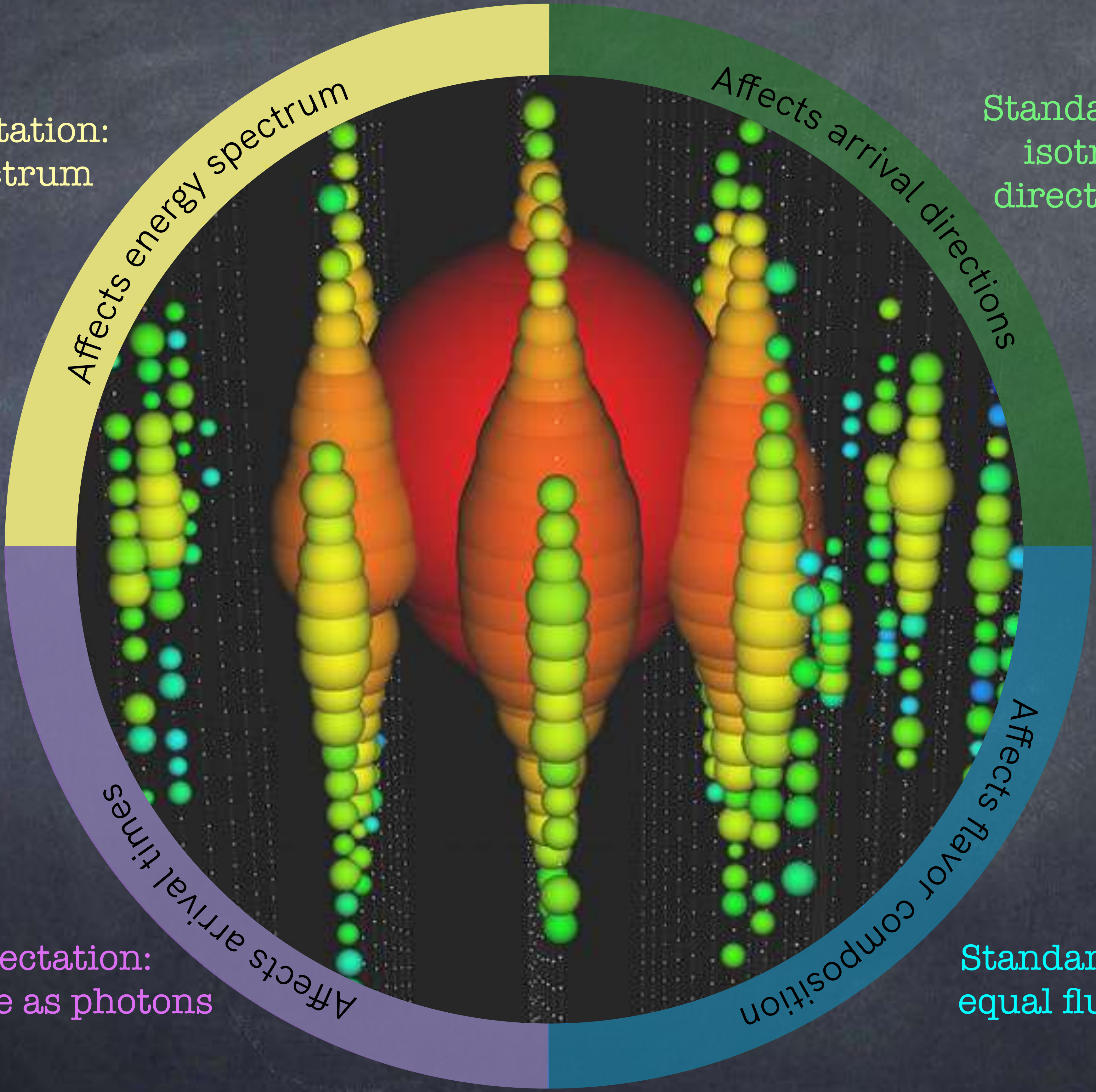
Non-thermal emission

Continuum radiation of a distribution of particles with a non-Maxwellian energy spectrum, which does not depend on the temperature of the source.

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?

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It carries information about the mechanism of production...

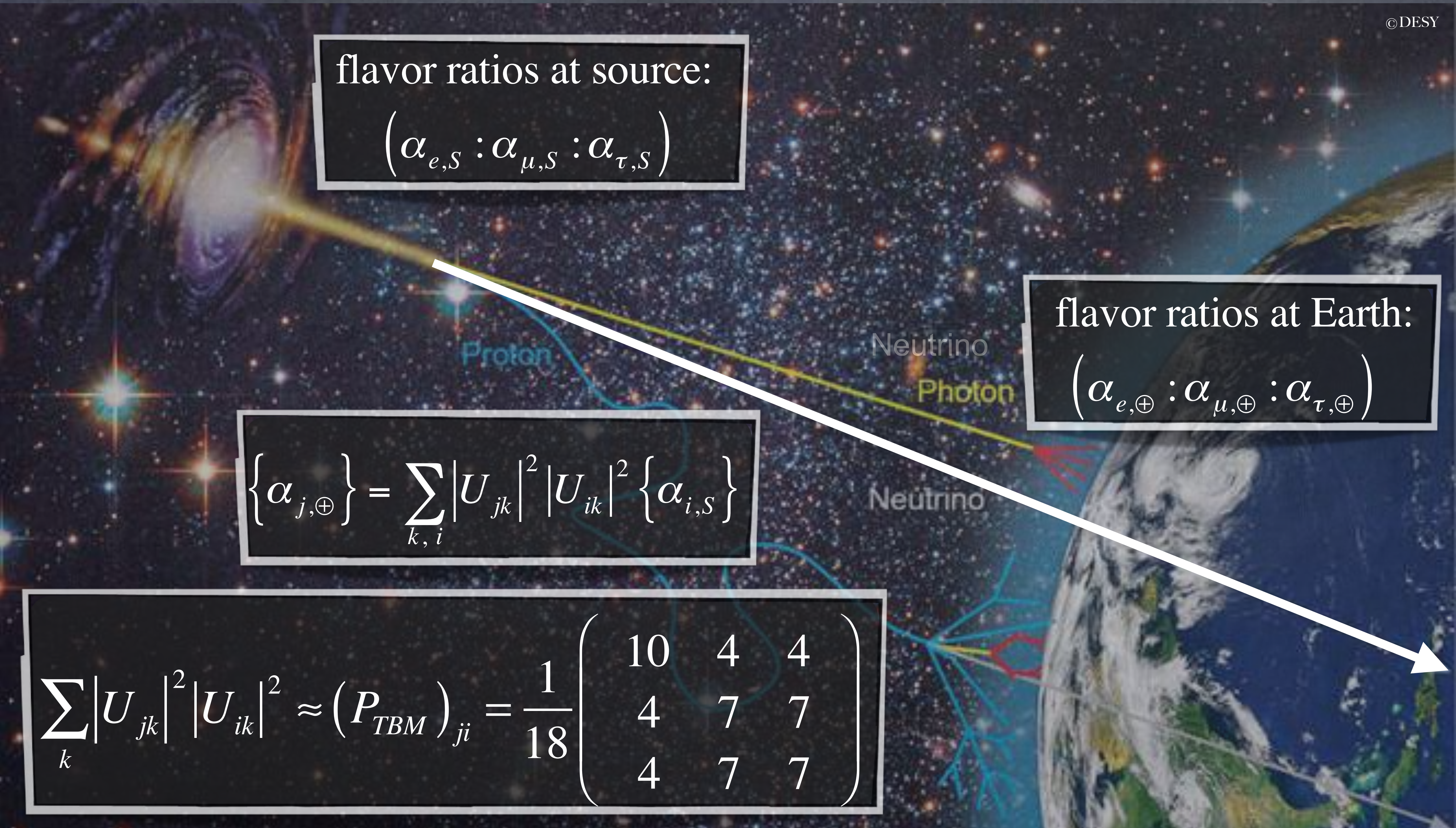
Why do we care about flavor?

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:

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

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

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

But what are neutrino oscillations?

Mass & Mixing ⇒ Oscillations

flavor eigenstates: $\nu_e \quad \nu_\mu \quad \nu_\tau$ $\neq$ mass eigenstates: $\nu_1 \quad \nu_2 \quad \nu_3$

produced in CC processes — free propagation eigenstates

connected via the (non-diagonal) PMNS mixing matrix

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W_\mu^+ \sum_\alpha \left(\bar{\ell}_{L\alpha} \, \gamma^\mu \nu_{L\alpha} \right) + h.c.$$

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W_\mu^+ \sum_{\alpha j} \left(\bar{\ell}_{L\alpha} \, \gamma^\mu \left(U_{PMNS} \right)_{\alpha j} \nu_{Lj} \right) + h.c.$$

$$\left(i\gamma_\mu \partial^\mu - m \right) \nu = 0$$

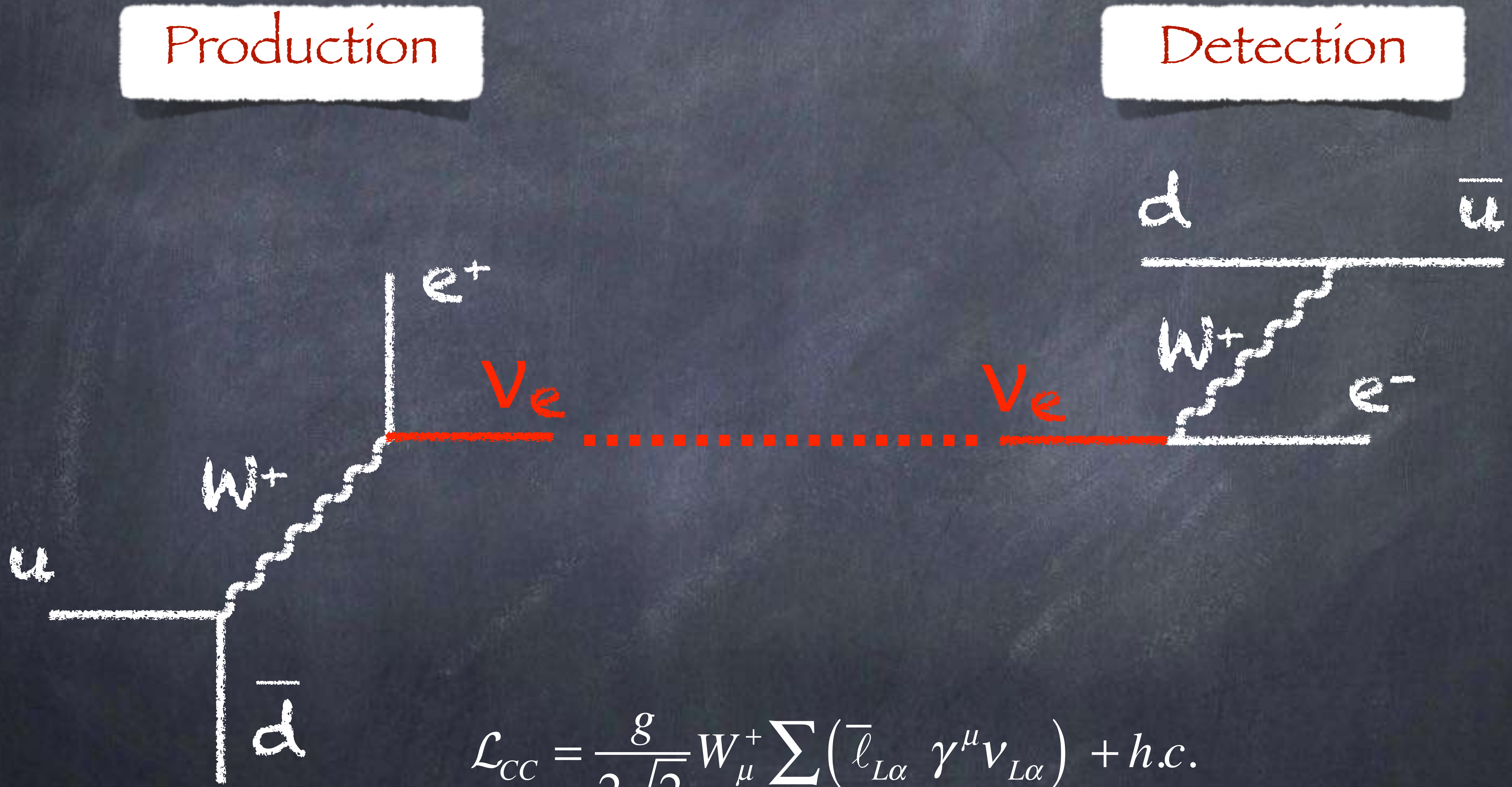
$$i\left(\partial^0 - \vec{\sigma}\,\vec{\nabla} \right) \nu_L = m\nu_R$$

$$i\left(\partial^0 + \vec{\sigma}\,\vec{\nabla} \right) \nu_R = m\nu_L$$

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

MASS & MIXING ⇒ OSCILLATIONS

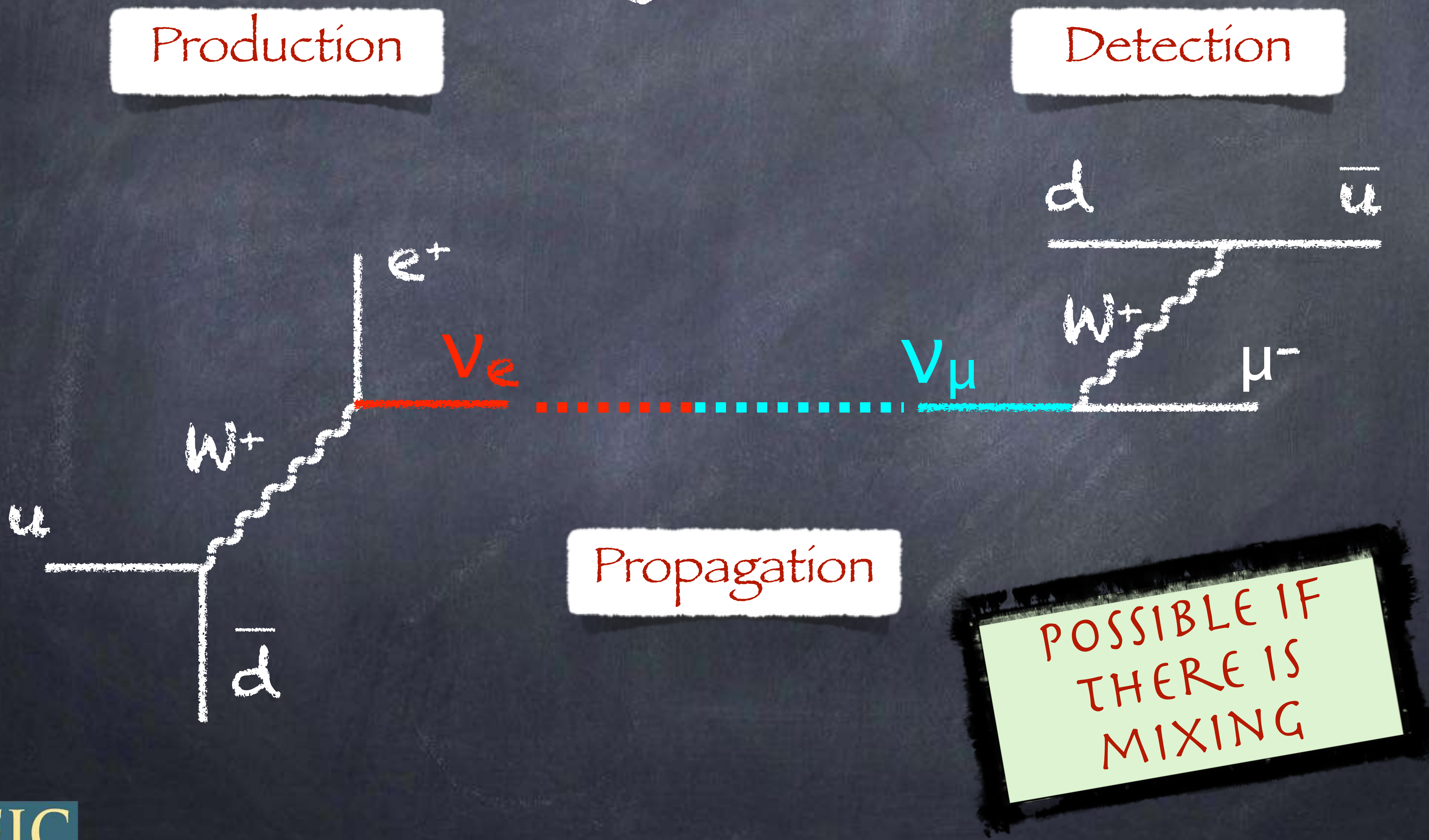
at short distances



$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W_\mu^+ \sum_\alpha \left(\bar{\ell}_{L\alpha} \, \gamma^\mu \nu_{L\alpha} \right) + h.c.$$

MASS & MIXING ⇒ OSCILLATIONS

at longer distances



Basics: oscillations in vacuum

In principle, one should use wave packets, but using plane waves provides the correct result.

$$i\frac{\partial \nu_i}{\partial t} = E_i \ \nu_i$$

Each mass eigenstate evolves as a plane wave:

$$\left|\nu_i(t)\right\rangle = e^{-iE_i t}\left|\nu_i(t=0)\right\rangle$$

and acquires a different phase $E_i t$

but flavor eigenstates are a combination of mass eigenstates

$$\left|\nu_\alpha(t)\right\rangle = \sum_i U^*_{\alpha i}\left|\nu_i(t)\right\rangle = \sum_i U^*_{\alpha i}\ e^{-iE_i t}\left|\nu_i(t=0)\right\rangle$$

Basics: oscillations in vacuum

Probability of detecting ν_β at a time t after having produced ν_α

$$P_{\alpha\beta} = \left| \langle \nu_\beta | \nu_\alpha(t) \rangle \right|^2 = \left| \sum_{ij} U^*_{\alpha i} U_{\beta j} \langle \nu_j | \nu_i(t) \rangle \right|^2 = \left| \sum_i U^*_{\alpha i} U_{\beta i} \; e^{-iE_i t} \right|^2$$

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

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

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

if non-degenerate states and if sufficient time of travel

mass and mixing ⇒ oscillations ($P_{\alpha\beta} \neq 0$)

Basics: 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

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

Basics: oscillations in vacuum

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

Appearance $\nu_\alpha \to \nu_\beta$

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

Disappearance $\nu_\alpha \to \nu_\alpha$ $\qquad P_{\alpha\alpha} = 1 - P_{\alpha\beta}$

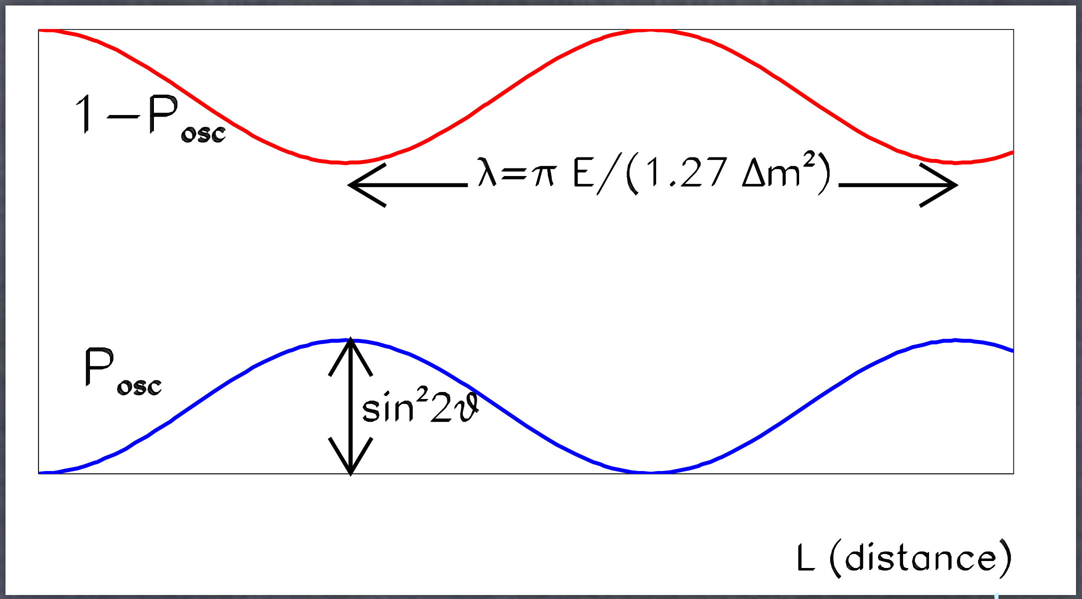
Maximal effect for L ~ E/Δm²

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

If L >> E/Δm² : oscillations are averaged $\quad \langle P_{\alpha\beta} \rangle = \frac{1}{2}\sin^2(2\theta)$

Basics: oscillations in vacuum

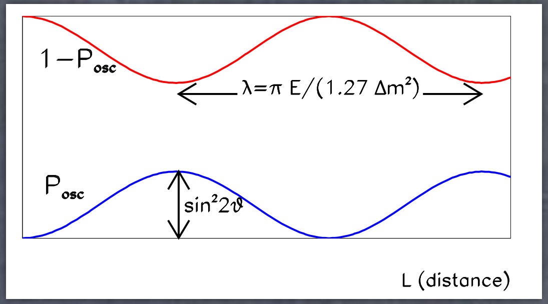
Maximal effect for L ~ $E/\Delta m^2$



From M. Maltoni

Basics: oscillations in vacuum

Maximal effect for L ~ E/Δm²



astrophysical neutrinos

Very long distances

L >> E/Δm²

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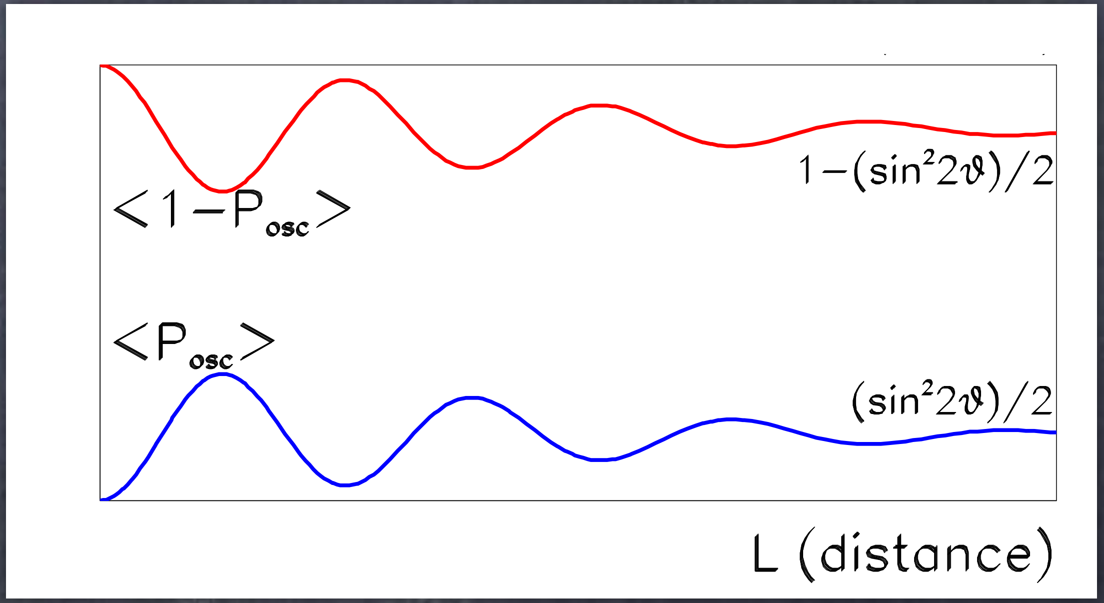
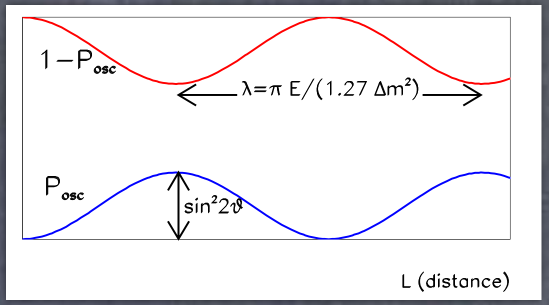


Basics: oscillations in vacuum

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



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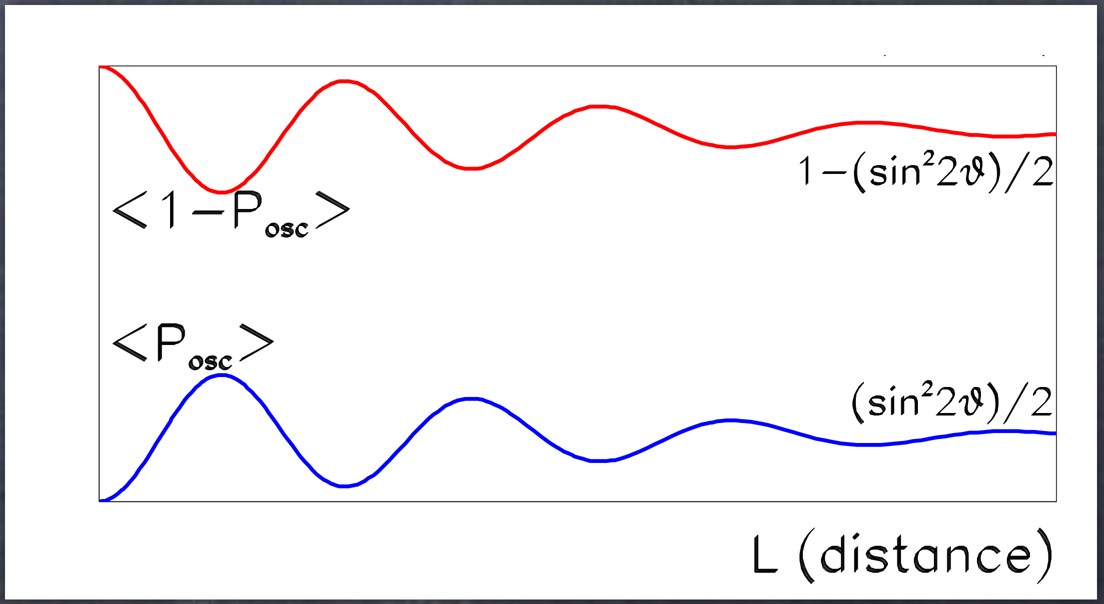

astrophysical neutrinos

Very long distances

$L \gg E/\Delta m^2$

wave packets separate so that they cannot be differentiated in the detector

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

Current status

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

NuFIT 5.0 (2020)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$
		Normal Ordering (best fit)		**Inverted Ordering ($\Delta\chi^2 = 7.1$)**	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.029}$	$-2.581 \to -2.414$

See also:

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

F. Capozzi et al., arXiv:2107.00532

I. Esteban et al., JHEP 09:178, 2020

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

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

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

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

Flavor ratios at source and at Earth

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

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

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

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

Flavor ratios at source and at Earth

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

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$\pi^{\pm} \rightarrow \mu^{\pm} + $ ✖ $\nu_{\mu}(\bar{\nu}_{\mu})$, $\mu^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_{\mu}(\nu_{\mu})$

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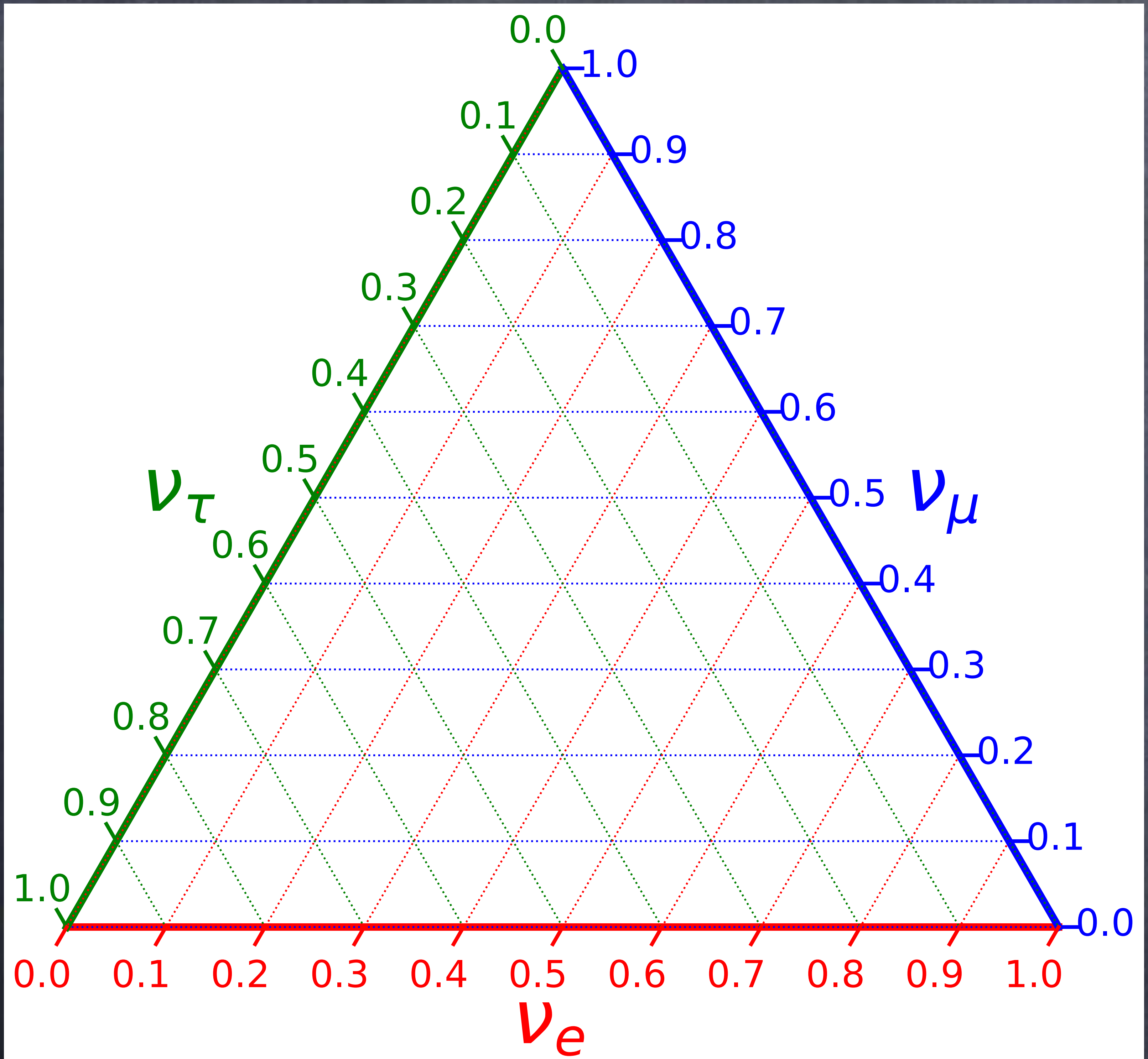
Neutron sources $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (1:0:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (5:2:2)$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Flavor triangles

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



Assumes unitarity: sum equal to 1

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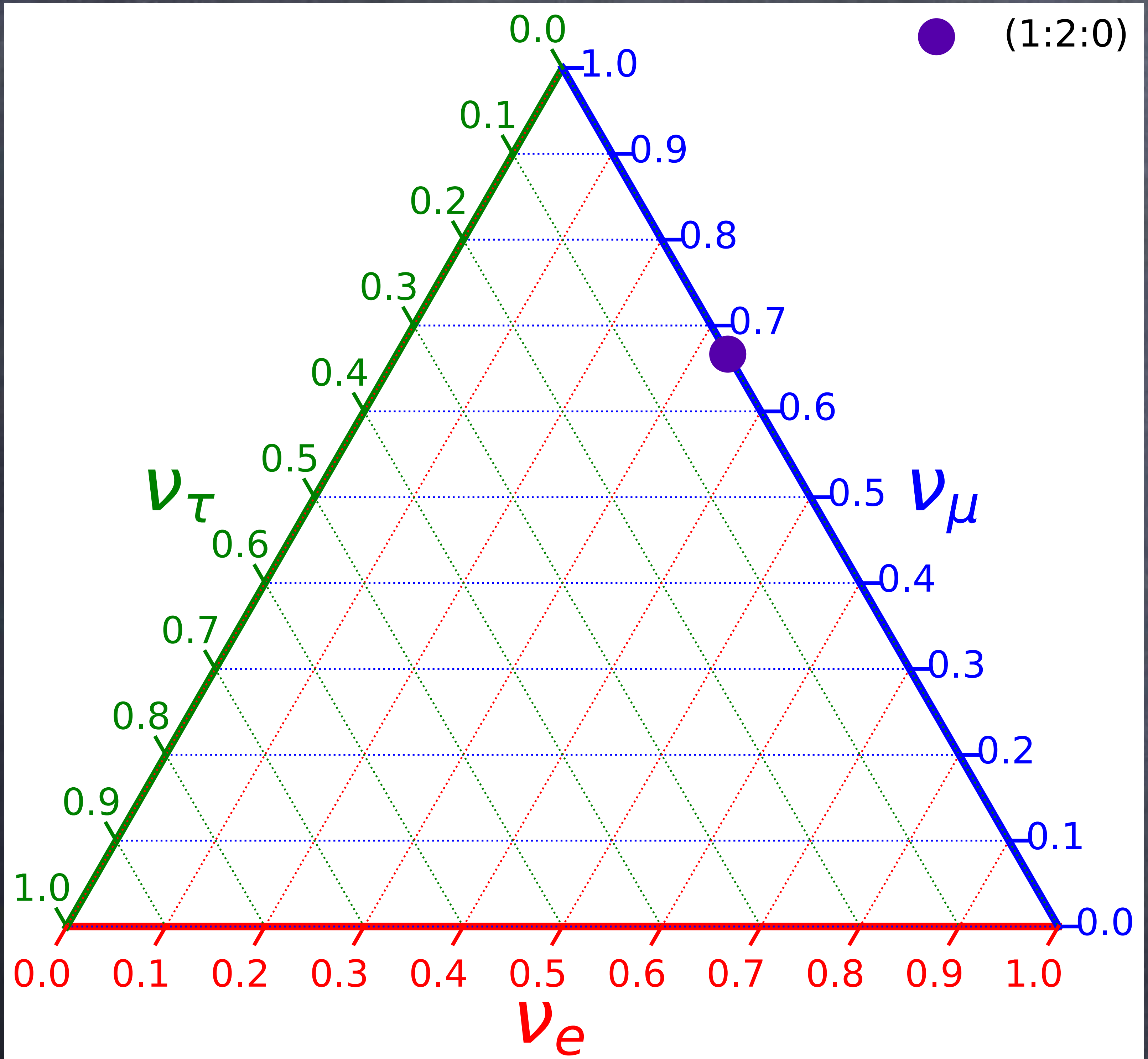

Pion decay

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

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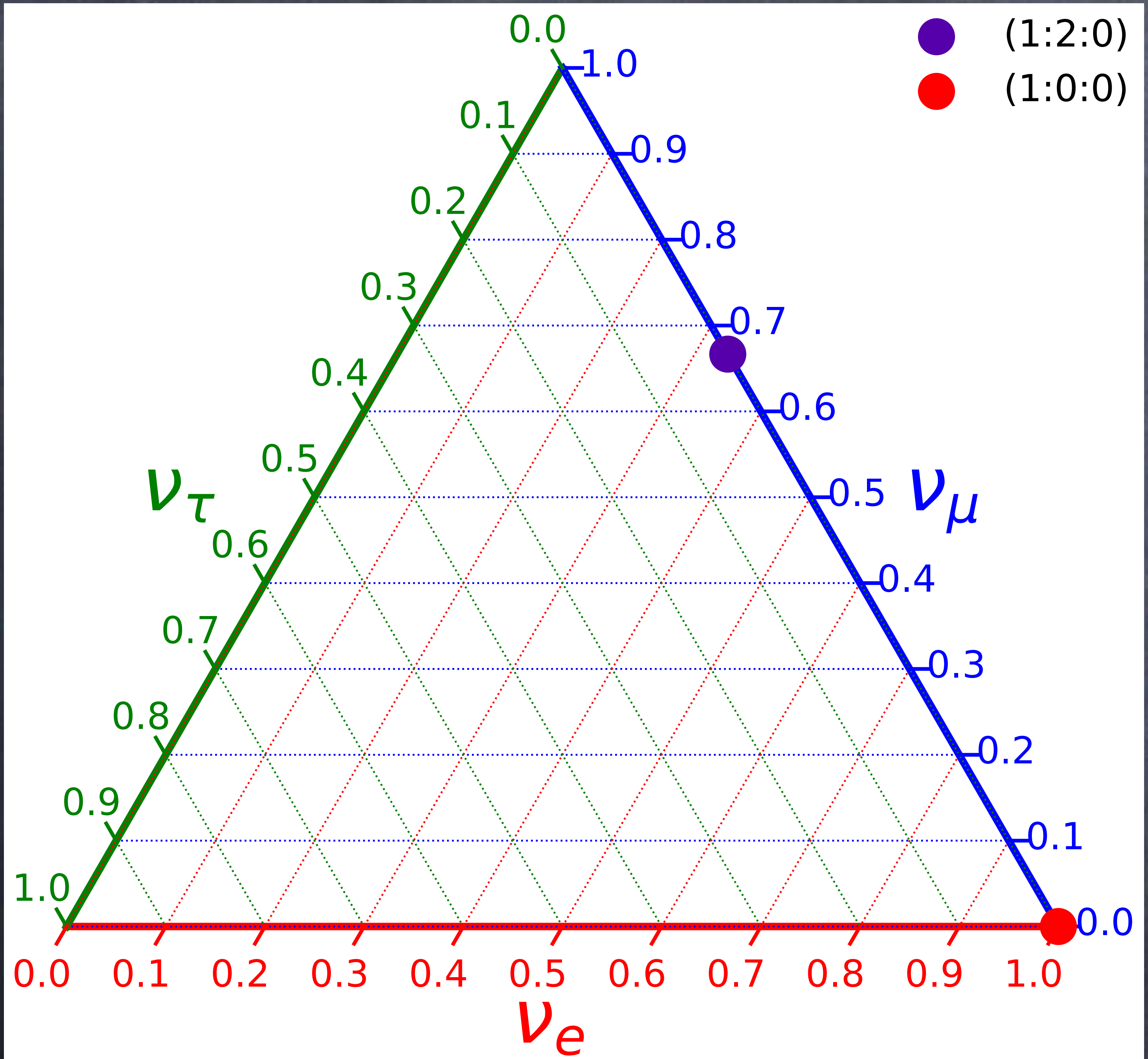

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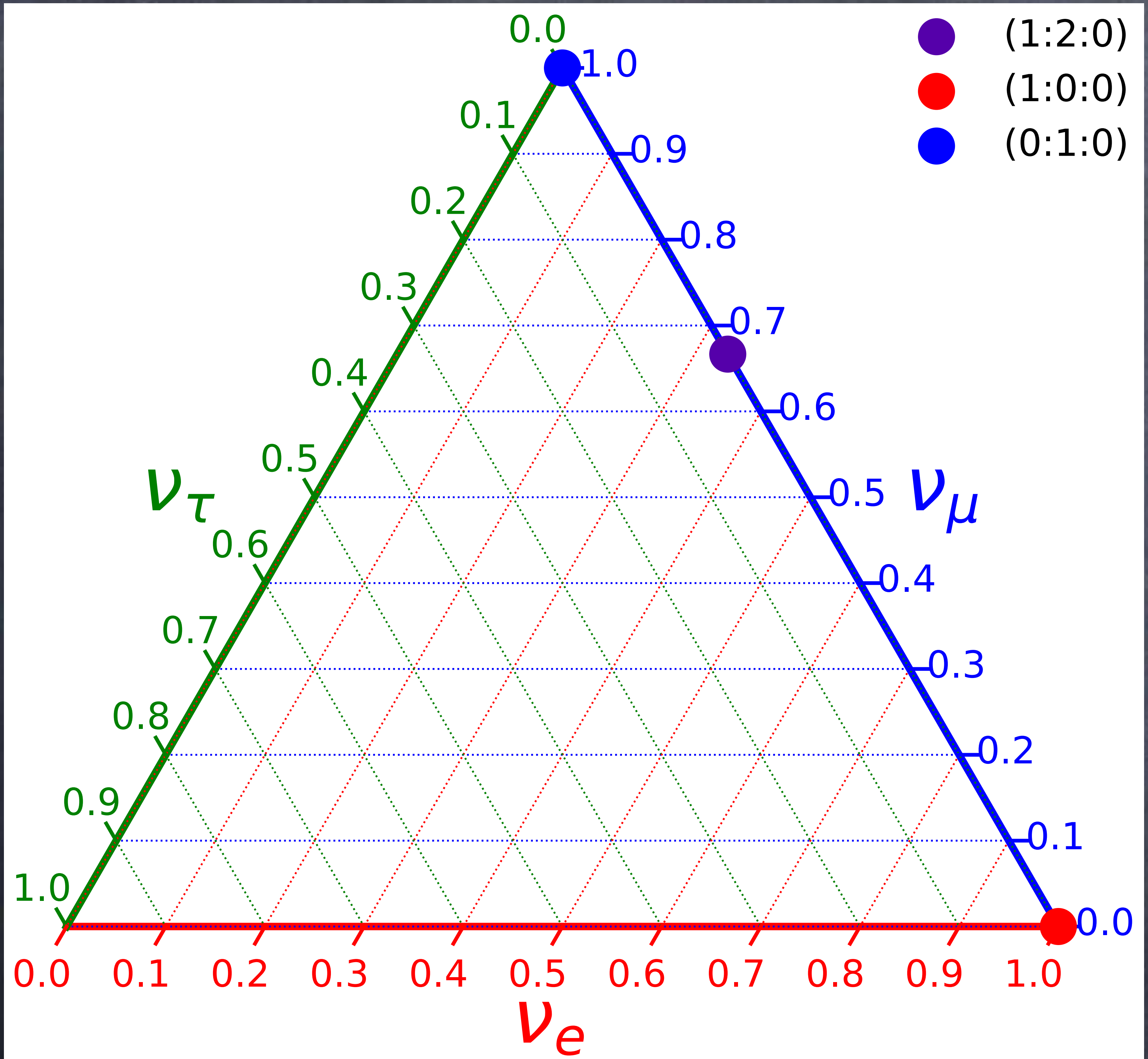

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Neutron decay

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

Muon damped

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

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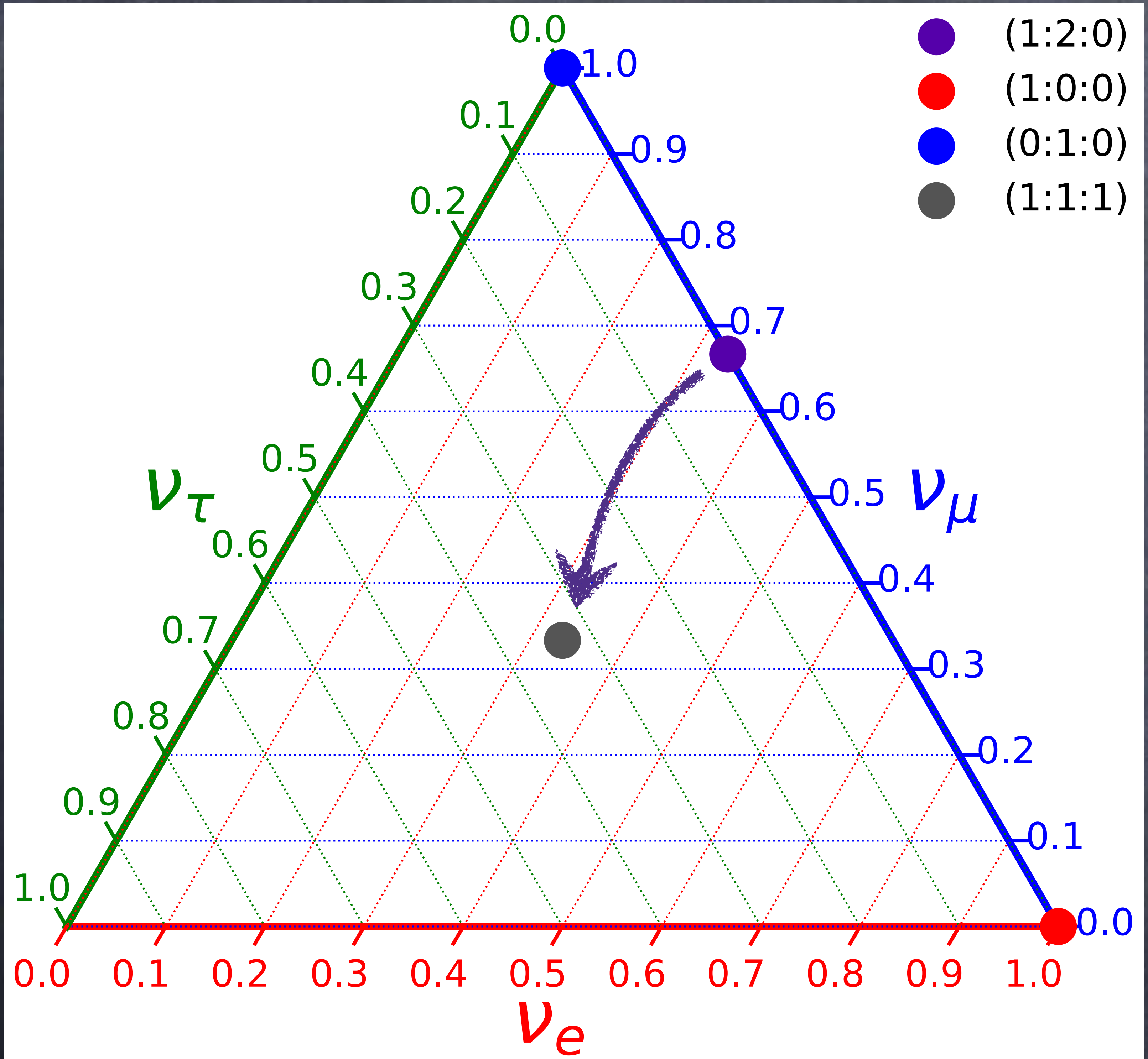

Pion decay

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

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

Neutron decay

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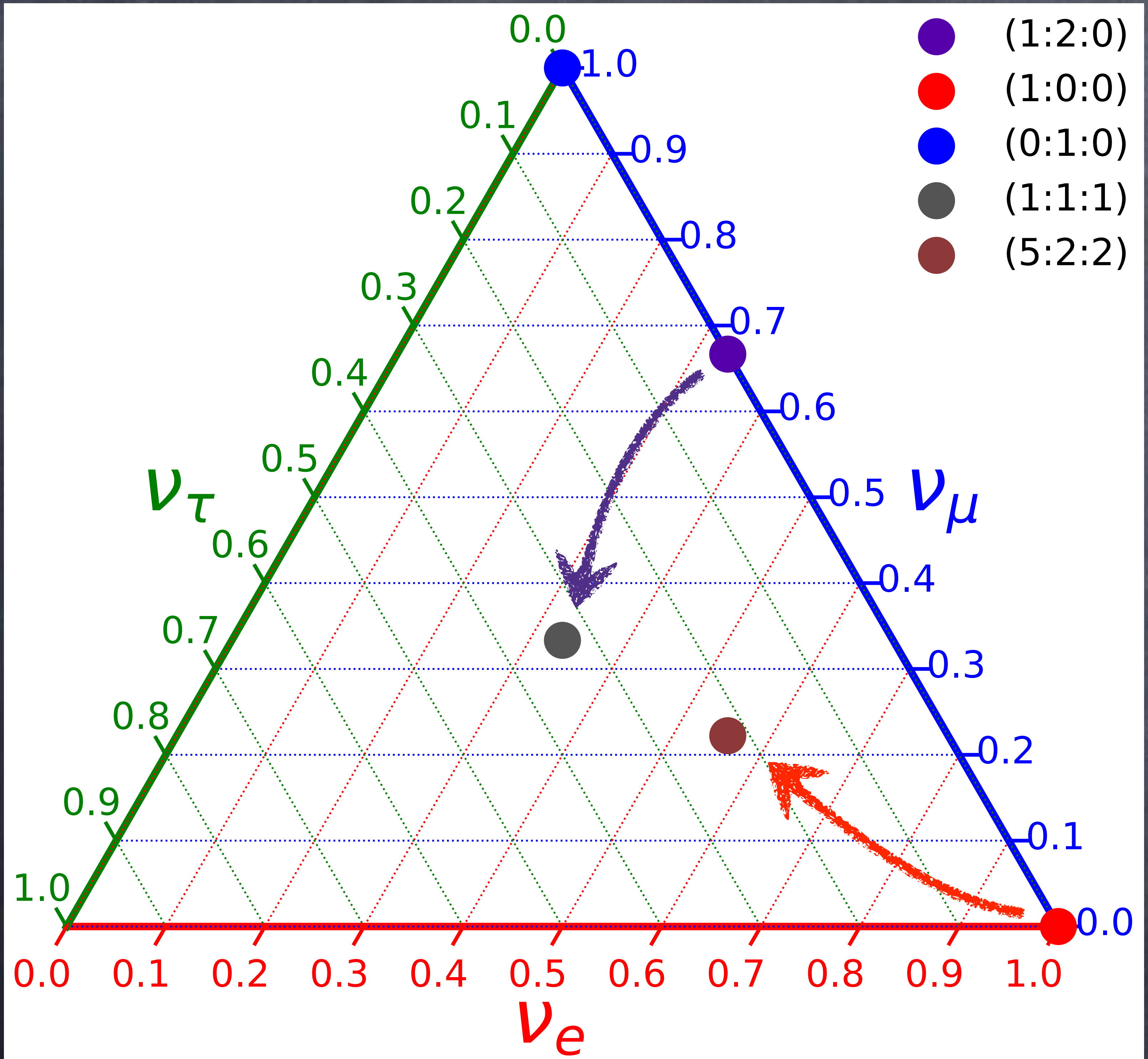

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Neutron decay

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

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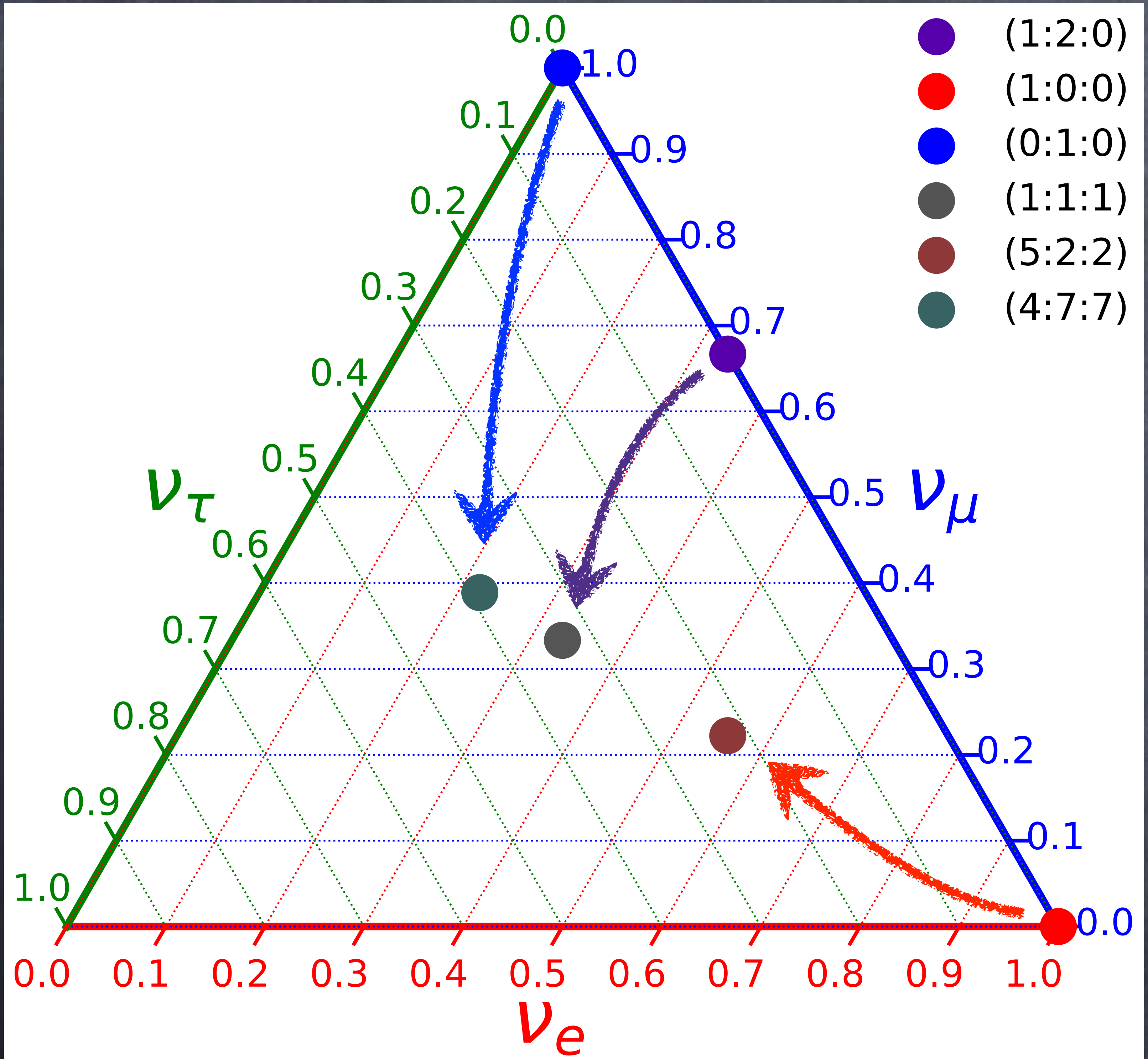

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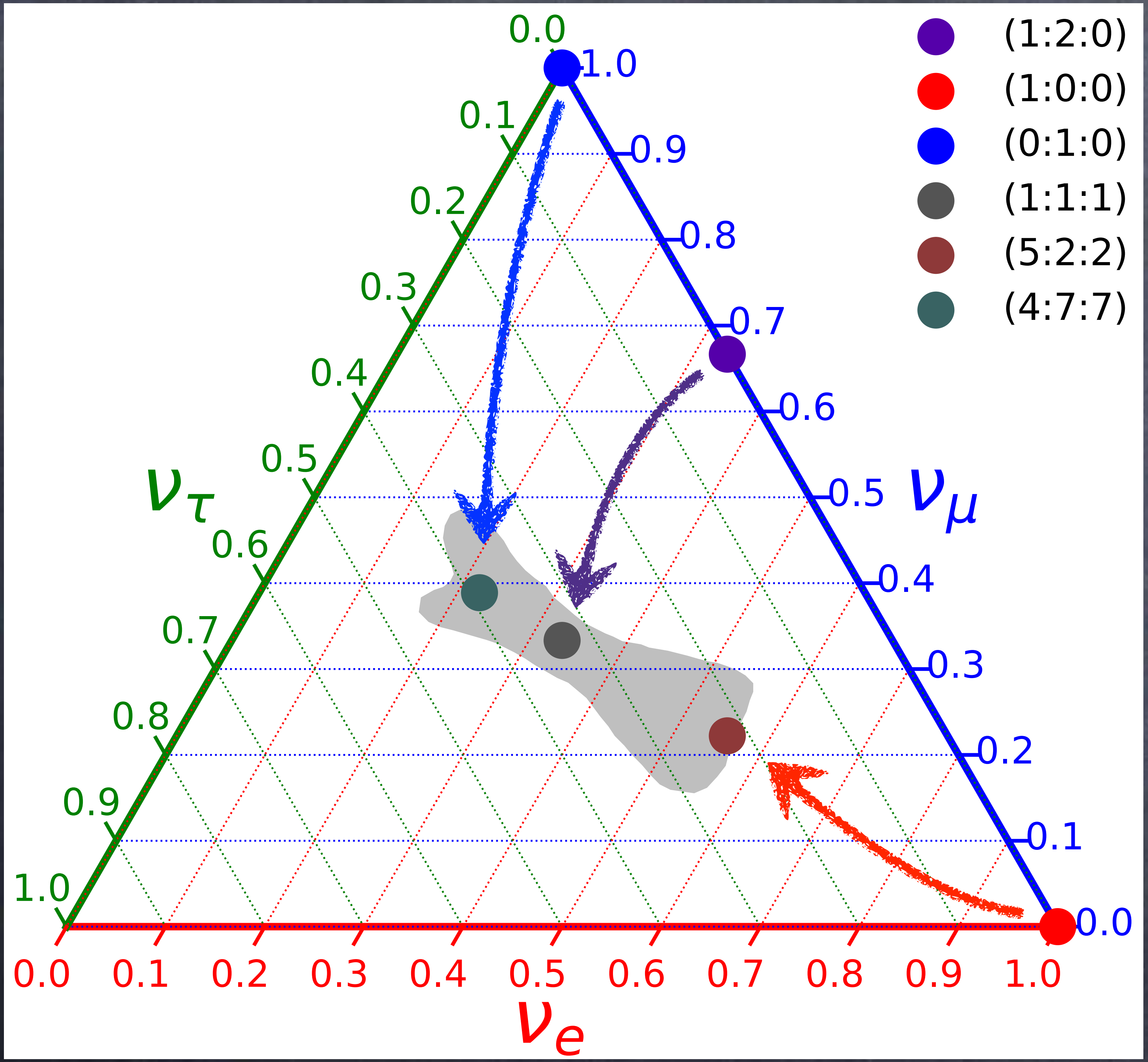

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Neutron decay

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

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

Muon damped

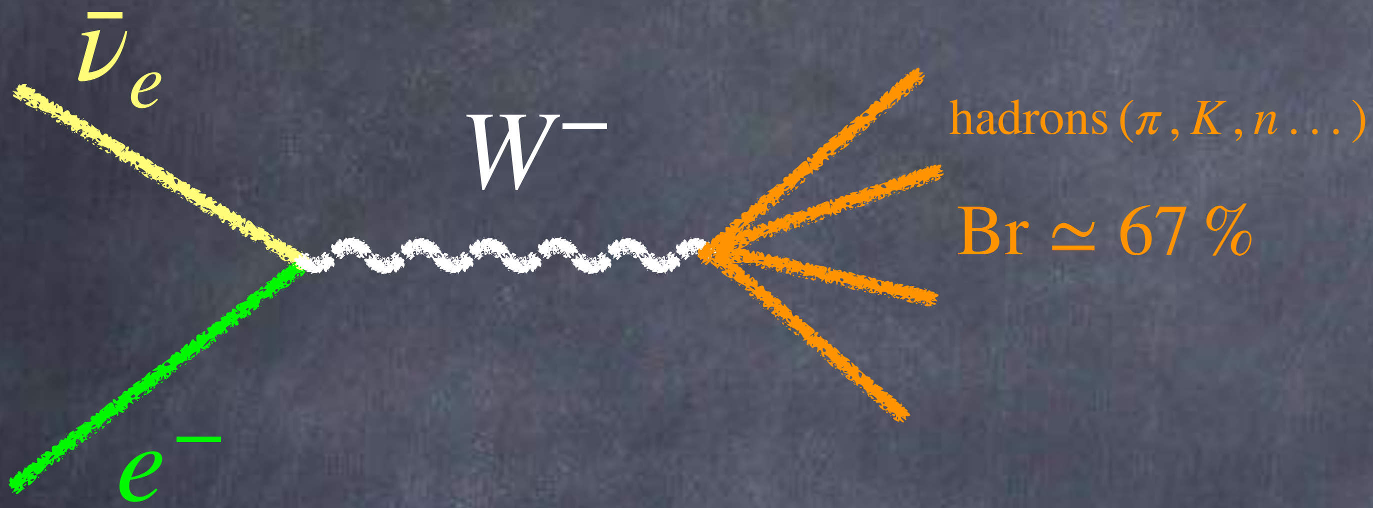
$$(\nu_e : \nu_\mu : \nu_\tau)_S = (0:1:0)_S$$

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

Assumes unitarity: sum equal to 1

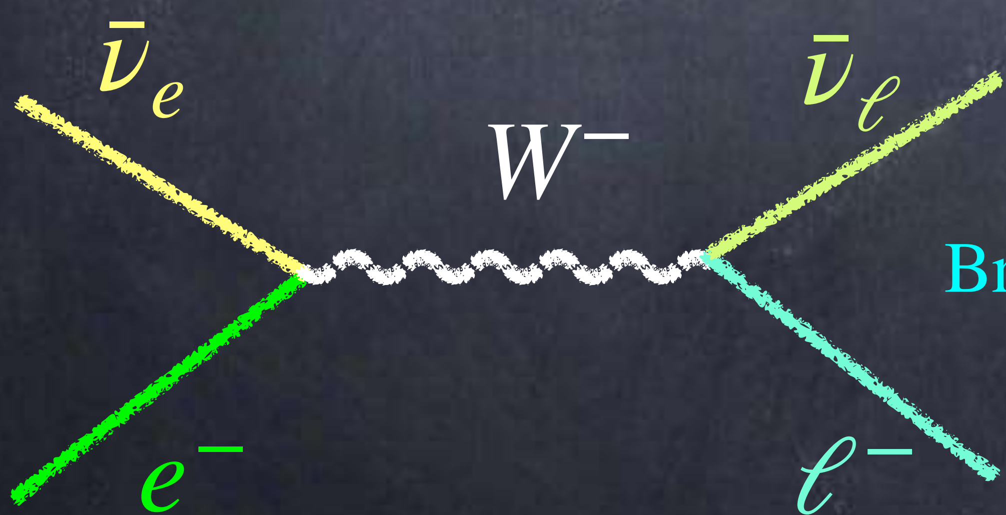
Glashow resonance as production mechanism diagnostic

S. L. Glashow, Phys. Rev. 118:316, 1960

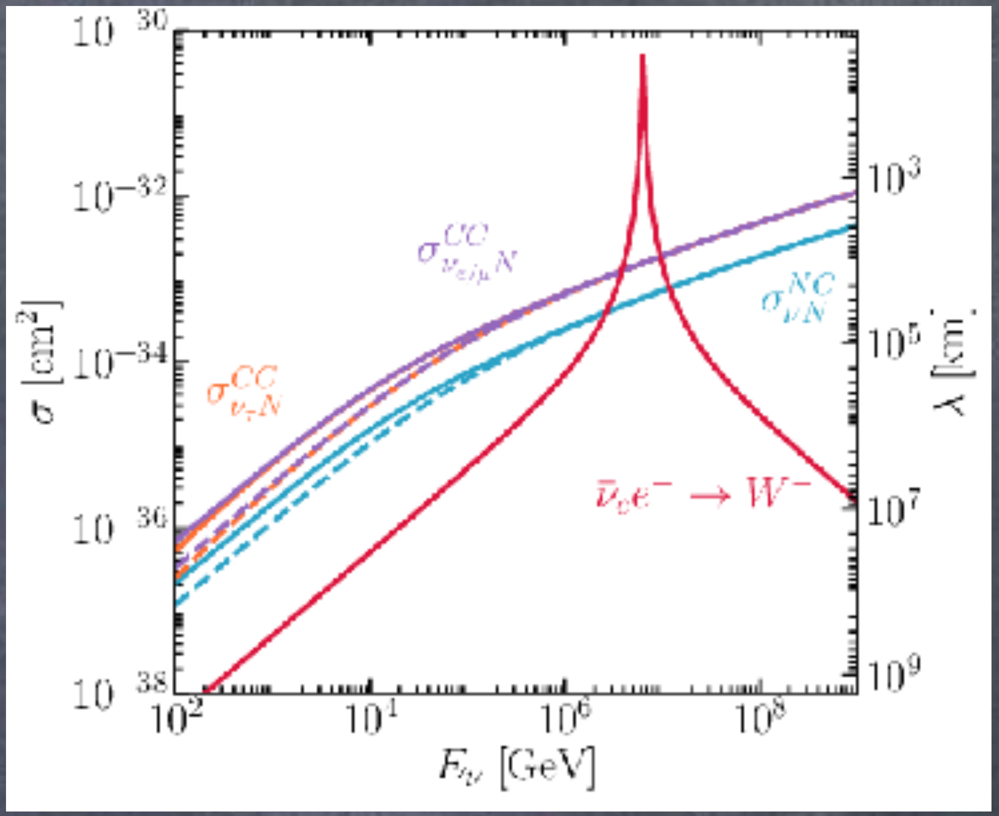


Br ≃ 67 %

$$E_\nu \simeq \frac{M_W^2}{2\,m_e} \simeq 6.4 \text{ PeV}$$



Br ≃ 33 %



G-Y. Huang and Q. Liu, JCAP 03:005, 2020

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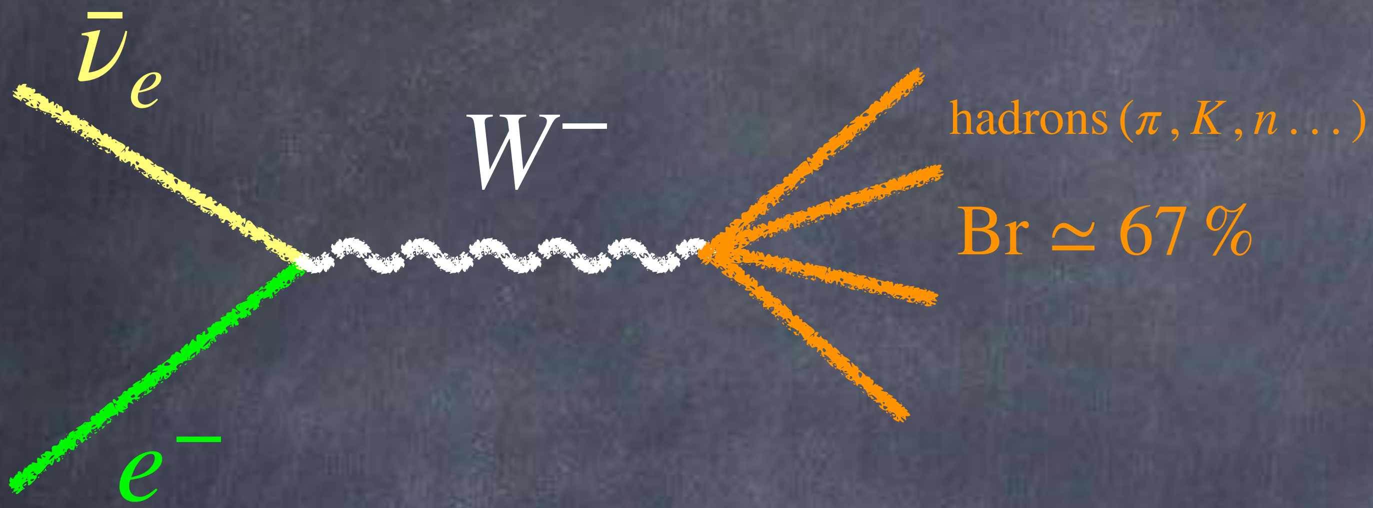

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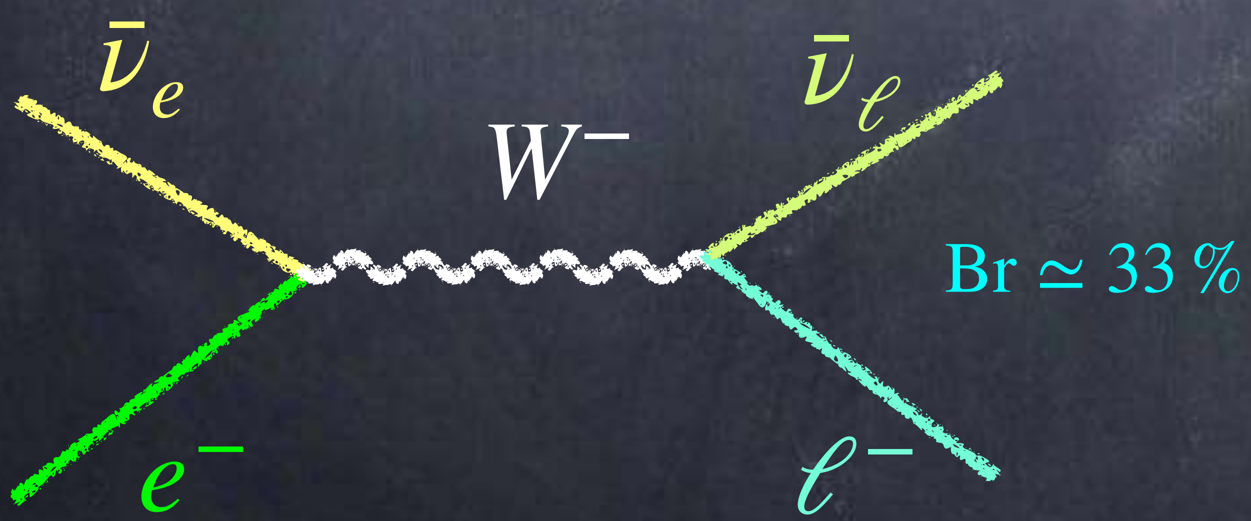
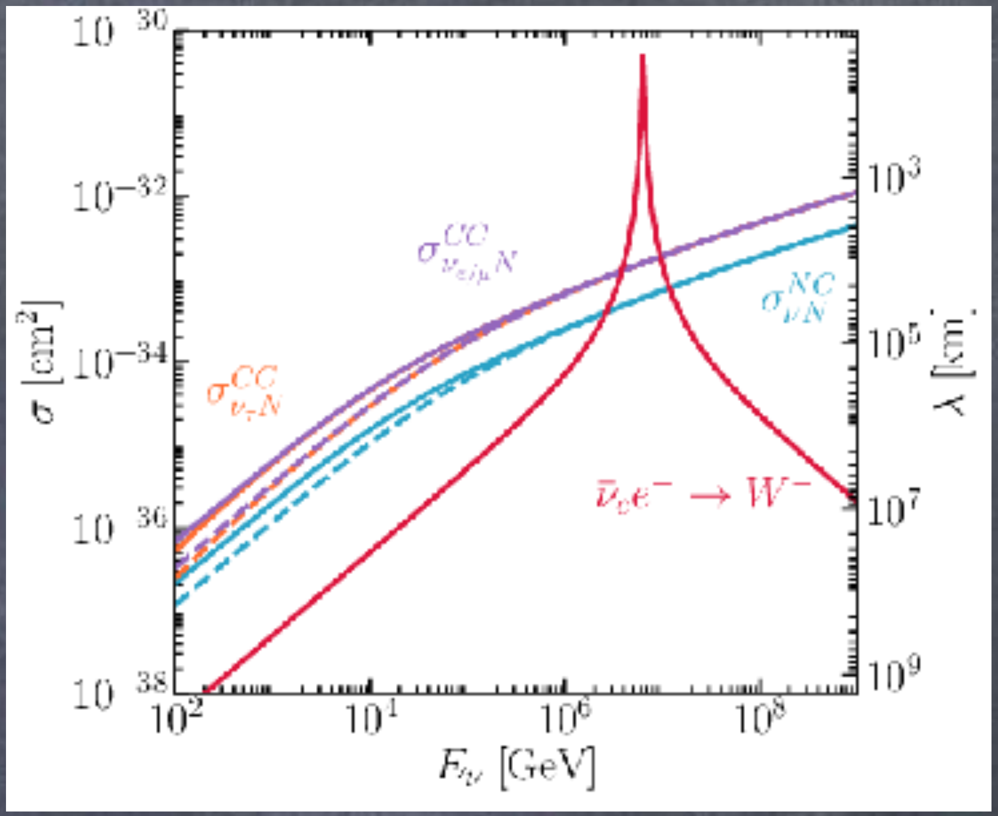
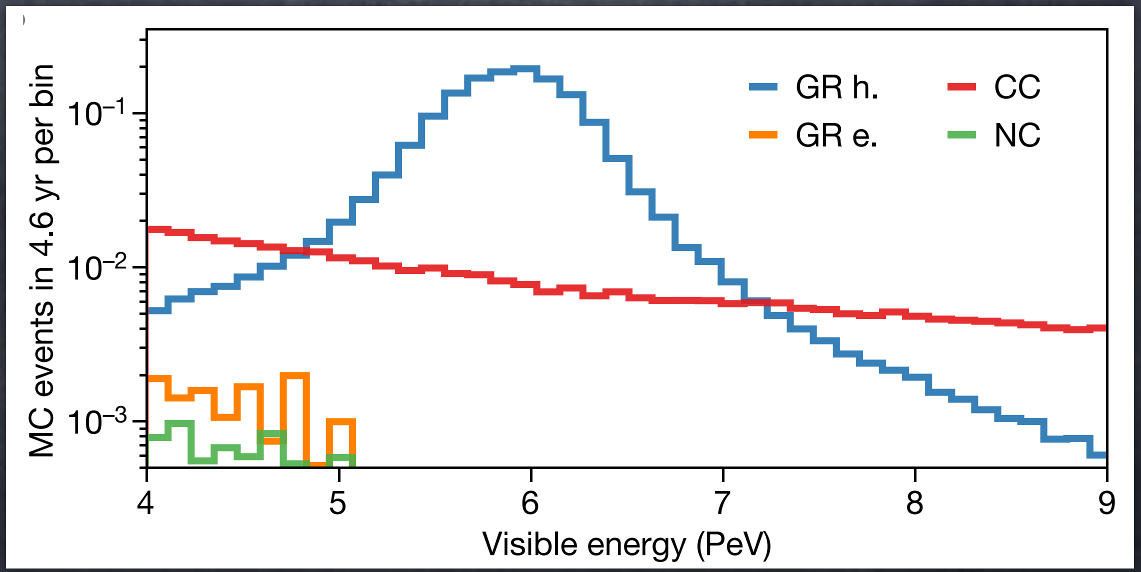




G-Y. Huang and Q. Liu, JCAP 03:005, 2020



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

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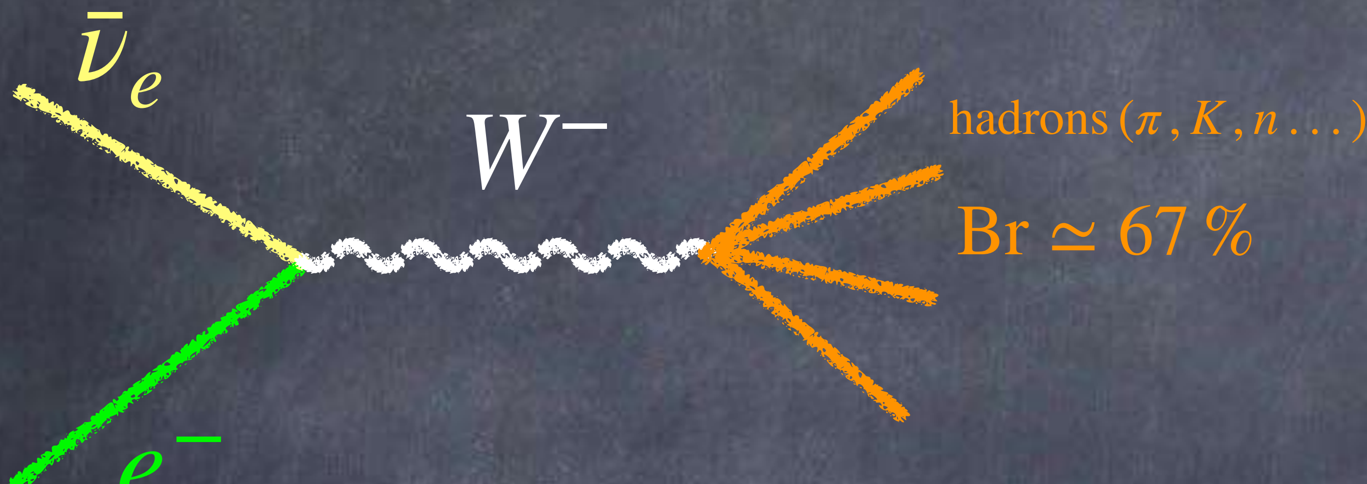

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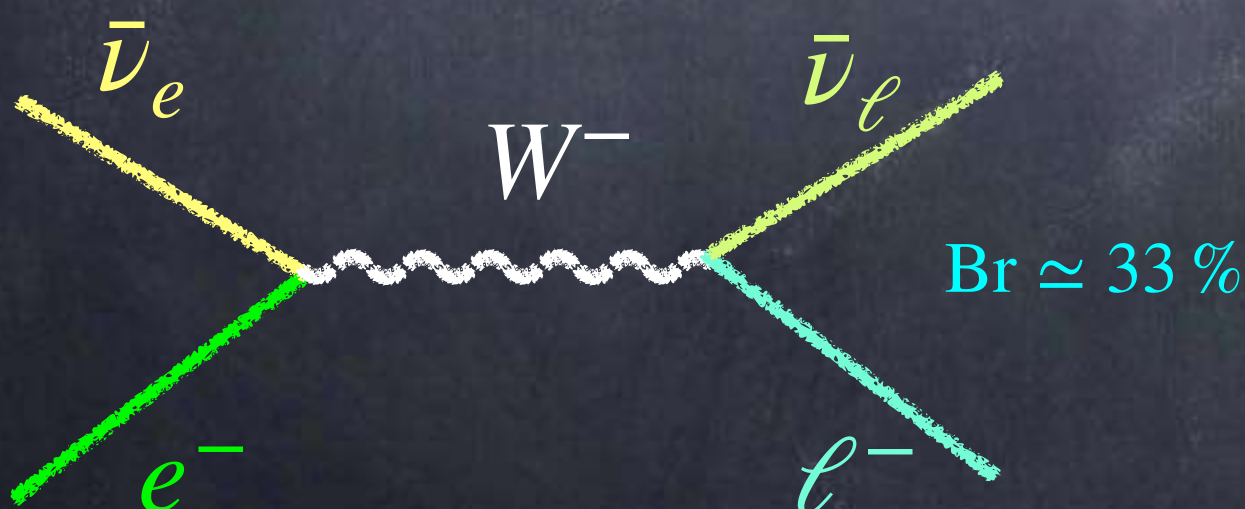
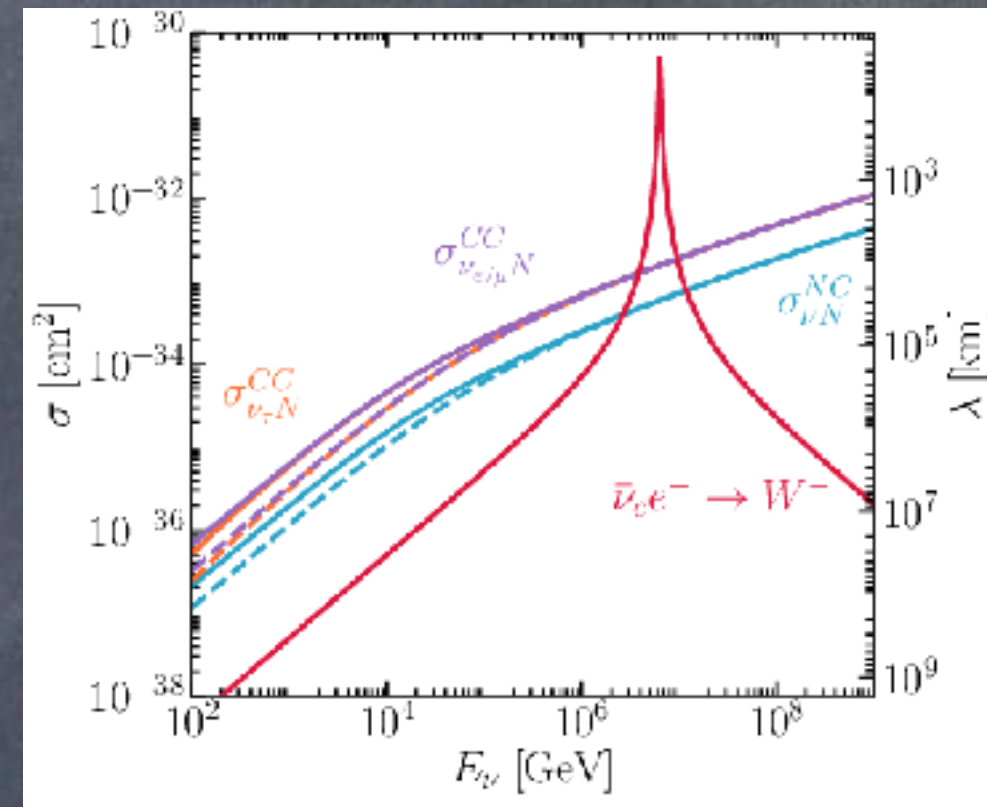
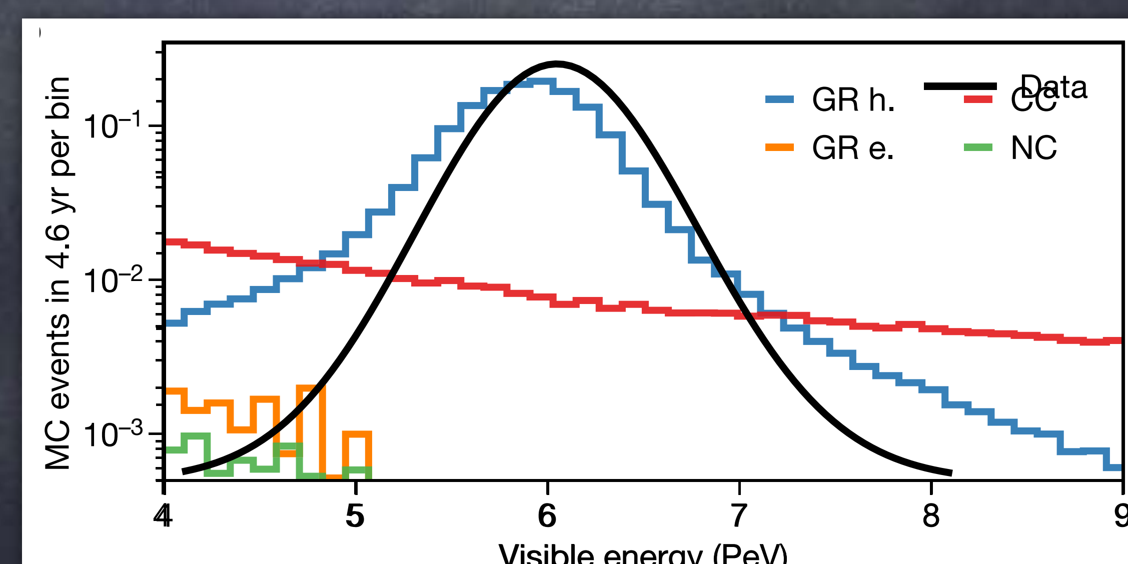




G-Y. Huang and Q. Liu, JCAP 03:005, 2020



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

Glashow resonance as production mechanism diagnostic

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

$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$
$$\not\downarrow$$
$$e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

Pion sources

pp

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

pγ

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

$$\left(\bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau\right)_S = (0 : 1 : 0) \to \left(\bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau\right)_\oplus = (4 : 7 : 7)$$

Muon damped sources

pp

$$\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (0 : 1 : 0) \to \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (4 : 7 : 7)$$

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Glashow resonance as production mechanism diagnostic

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

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
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Pion sources

pp

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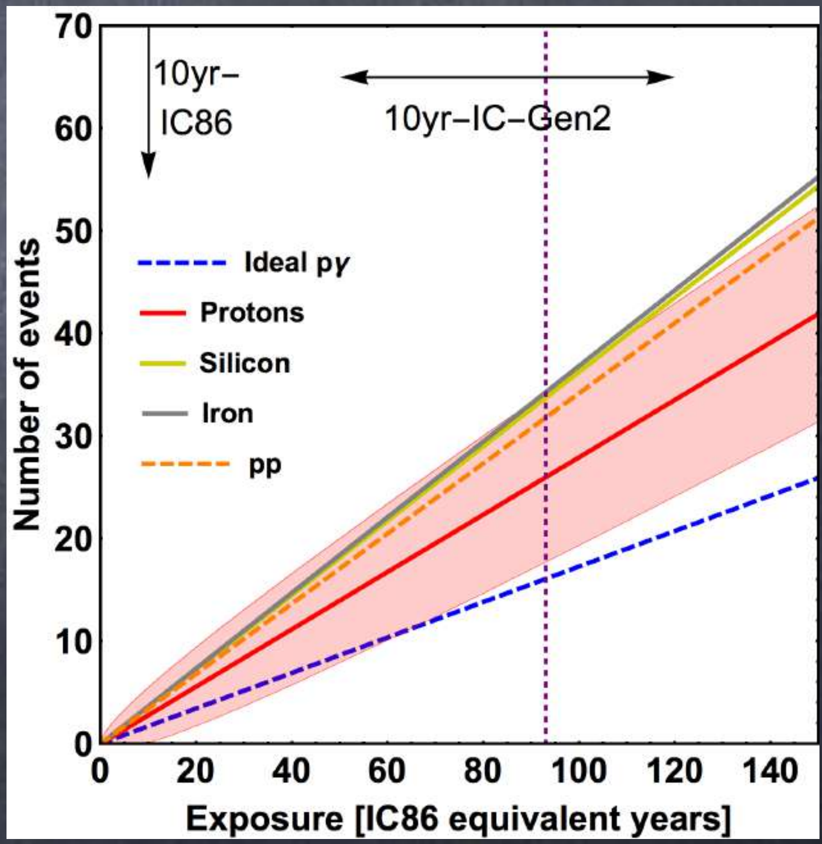
Not really the ideal scenario

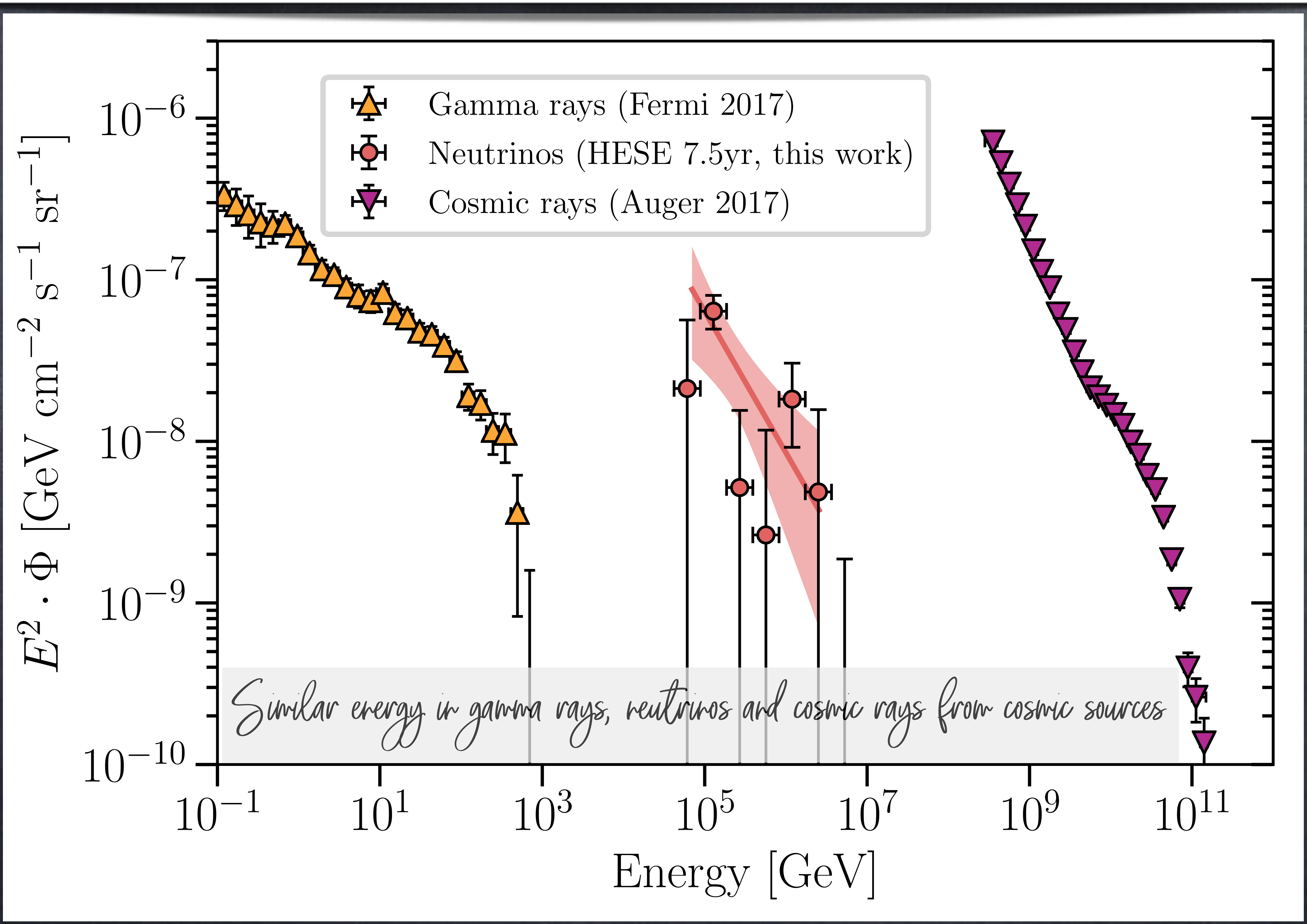
Next generation?



D. Biehl et al., JCAP 01:033, 2017

The CR/Gamma-ray/Neutrino Connection

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



R. Abbasi et al. [IceCube Collaboration], arXiv:2011.03545

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

Cosmic Neutrino production

hadronic

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

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

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

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

pp interactions

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

average fraction of energy transferred from the proton to the pion

photohadronic

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

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

pγ interactions

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

neutron decay

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\langle E_{\nu} \rangle \simeq 5 \times 10^{-4} E_n$$

Exercise:

What is the minimum neutrino energy from photohadronic (resonant) production off stellar light?

Consider a background photon field with a wavelength of 200 nm.

To reach PeV neutrino energies, what is the minimum energy of the photon background needed in highly boosted sources ($\gamma \sim 300$)?

CR/Gamma-ray/Neutrino Connection

Some definitions:

$\tilde{\kappa}_\pi$: inelasticity of the hadronic interaction
κ_π : inelasticity (per pion) of the interaction
N_π: number of produced pions
f_π: probability of pion production in the source

For pp, $\tilde{\kappa}_\pi = 0.5,\ K_\pi = \dfrac{N_{\pi^\pm}}{N_{\pi^0}} = 2$

For pγ, $\tilde{\kappa}_\pi = 0.2,\ K_\pi = \dfrac{N_{\pi^+}}{N_{\pi^0}} = 1$

$$\kappa_\pi = \frac{\tilde{\kappa}_\pi}{N_\pi} \simeq 0.2 \qquad f_\pi = 1 - e^{-\kappa_\nu \ell \sigma n}$$

Average energies of neutrinos and photons:

$$\langle E_\nu \rangle = \kappa_\nu E_\pi \simeq \frac{E_\pi}{4} \qquad \frac{\langle E_\nu \rangle}{E_N} = \frac{\kappa_\pi}{4} \simeq 0.05$$

$$\langle E_\gamma \rangle = \kappa_\gamma E_\pi \simeq \frac{E_\pi}{2} \qquad \frac{\langle E_\gamma \rangle}{E_N} = \frac{\kappa_\pi}{2} \simeq 0.1$$

Relating number of pions to number of neutrinos and photons

$$N_{\pi^\pm} = \frac{1}{2}\int_{\kappa_\nu E_1}^{\kappa_\nu E_2} \frac{dN_{\nu_\mu}}{dE_\nu}\, dE_\nu \qquad N_{\pi^0} = \frac{1}{2}\int_{\kappa_\gamma E_1}^{\kappa_\gamma E_2} \frac{dN_\gamma}{dE_\gamma}\, dE_\gamma$$

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Differentiating with respect to E_2

$$\frac{\kappa_\nu}{2}\left.\frac{dN_{\nu_\mu}}{dE_\nu}\right|_{E_\nu=\kappa_\nu E} = \left.\frac{dN_{\pi^\pm}}{dE_\pi}\right|_E \qquad \frac{\kappa_\gamma}{2}\left.\frac{dN_\gamma}{dE_\gamma}\right|_{E_\gamma=\kappa_\gamma E} = \left.\frac{dN_{\pi^0}}{dE_\pi}\right|_E$$

Q: number of particles per unit time and energy

$$\frac{N_{\nu_\mu}}{N_{\nu_e}} = 2$$

$$Q_{\nu_\mu}\left(E_\nu\right) = \frac{2}{\kappa_\nu} Q_{\pi^\pm}\left(\frac{E_\nu}{\kappa_\nu}\right) \simeq 8\, Q_{\pi^\pm}\left(4\, E_\nu\right)$$

$$Q_\gamma\left(E_\gamma\right) = \frac{2}{\kappa_\gamma} Q_{\pi^0}\left(\frac{E_\gamma}{\kappa_\gamma}\right) \simeq 4\, Q_{\pi^0}\left(2\, E_\gamma\right)$$

$$Q_{\nu_e}\left(E_\nu\right) = \frac{1}{\kappa_\nu} Q_{\pi^\pm}\left(\frac{E_\nu}{\kappa_\nu}\right) \simeq 4\, Q_{\pi^\pm}\left(4\, E_\nu\right)$$

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$$\frac{1}{3}\sum_\alpha Q_{\nu_\alpha}\left(E_\nu\right) \simeq \frac{1}{3}\left(Q_{\nu_\mu}\left(E_\nu\right) + Q_{\nu_e}\left(E_\nu\right)\right) \simeq 4\, Q_{\pi^\pm}\left(4\, E_\nu\right)$$

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$$\frac{1}{3}\sum_\alpha E_\nu\, Q_{\nu_\alpha}\left(E_\nu\right) \simeq 4\, E_\nu\, Q_{\pi^\pm}\left(4\, E_\nu\right) = \left[E_\pi\, Q_{\pi^\pm}\left(E_\pi\right)\right]_{E_\pi = E_\nu/\kappa_\nu}$$

Recalling that $Q_{\pi^\pm}(E_\pi) = K_\pi \, Q_{\pi^0}(E_\pi)$

$$Q_{\nu_\mu}(E_\nu) = \frac{2\,K_\pi}{\kappa_\nu} Q_{\pi^0}\left(\frac{E_\nu}{\kappa_\nu}\right) \qquad Q_{\nu_e}(E_\nu) = \frac{K_\pi}{\kappa_\nu} Q_{\pi^0}\left(\frac{E_\nu}{\kappa_\nu}\right)$$

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Assuming a fraction f_π of the energy goes into pions (calorimeter)

$$E_\pi^2\, Q_{\pi^\pm}\left(E_{\pi^\pm}\right) \simeq f_\pi\, \frac{K_\pi}{1+K_\pi}\left[E_N^2\, Q_N\left(E_N\right)\right]_{E_N=E_\pi/\kappa_\pi}$$

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The Waxman-Bahcall bound
(on the diffuse neutrino flux)

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(on the diffuse neutrino flux)

$$\frac{d\Phi_{\nu_\alpha}\left(E_\nu\right)}{dE_\nu} = \int \frac{d\Phi^{\rm PS}_{\nu_\alpha}\left(E_\nu\right)}{dE_\nu}\, n(z)\, dV_c = \int \frac{(1+z)^2}{4\pi\, d_L^2(z)} Q_{\nu_\alpha}\left((1+z)\, E_\nu\right)\, n(z)\, dV_c$$

$$dV_c = r^2\, d\Omega\, \frac{dz}{H(z)} \qquad d_L = (1+z)\, r$$

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$$\frac{d\Phi_{\nu_\alpha}\left(E_\nu\right)}{dE_\nu} = \int \frac{d\Phi^{\rm PS}_{\nu_\alpha}\left(E_\nu\right)}{dE_\nu}\, n(z)\, dV_c = \int \frac{(1+z)^2}{4\pi\, d_L^2(z)} Q_{\nu_\alpha}\left((1+z)\,E_\nu\right)\, n(z)\, dV_c$$

$$dV_c = r^2\, d\Omega\, \frac{dz}{H(z)} \qquad d_L = (1+z)\, r$$

$$\frac{d\Phi_{\nu_\alpha}\left(E_\nu\right)}{dE_\nu} = \frac{1}{4\pi}\int_0^\infty \frac{dz}{H(z)}\, n(z)\, Q_{\nu_\alpha}\left((1+z)\,E_\nu\right) = \frac{1}{4\pi}\,\frac{\zeta_z(E_\nu)}{H_0}\,\mathscr{L}_{\nu_\alpha}\left(0, E_\nu\right) = \frac{1}{4\pi}\,\frac{\zeta_z(E_\nu)}{H_0}\, n_0\, Q_{\nu_\alpha}\left(E_\nu\right)$$

$$\frac{1}{3}\sum_\alpha E_\nu^2\, \frac{d\Phi_{\nu_\alpha}(E_\nu)}{dE_\nu} = \frac{1}{4\pi}\,\frac{\zeta_z(E_\nu)}{H_0}\, n_0\, \frac{1}{3}\sum_\alpha E_\nu^2\, Q_{\nu_\alpha}\left(E_\nu\right)$$

$$\frac{1}{3}\sum_\alpha E_\nu^2\, \frac{d\Phi_{\nu_\alpha}(E_\nu)}{dE_\nu} = \frac{1}{4\pi}\,\frac{\zeta_z(E_\nu)}{H_0}\,\frac{\kappa_\nu\, f_\pi\, K_\pi}{1+K_\pi}\, n_0\, \left[E_N^2\, Q_N\left(E_N\right)\right]_{E_N = E_\nu/(\kappa_\pi\,\kappa_\nu)}$$

The Waxman-Bahcall bound
(on the diffuse neutrino flux)

$$\frac{d\Phi_{\nu_\alpha}\left(E_\nu\right)}{dE_\nu} = \int \frac{d\Phi^{\rm PS}_{\nu_\alpha}\left(E_\nu\right)}{dE_\nu}\, n(z)\, dV_c = \int \frac{(1+z)^2}{4\pi\, d_L^2(z)} Q_{\nu_\alpha}\left((1+z)\,E_\nu\right)\, n(z)\, dV_c$$

$$dV_c = r^2\, d\Omega\, \frac{dz}{H(z)} \qquad d_L = (1+z)\, r$$

$$\frac{d\Phi_{\nu_\alpha}\left(E_\nu\right)}{dE_\nu} = \frac{1}{4\pi}\int_0^\infty \frac{dz}{H(z)}\, n(z)\, Q_{\nu_\alpha}\left((1+z)\,E_\nu\right) = \frac{1}{4\pi}\,\frac{\zeta_z(E_\nu)}{H_0}\,\mathscr{L}_{\nu_\alpha}\left(0, E_\nu\right) = \frac{1}{4\pi}\,\frac{\zeta_z(E_\nu)}{H_0}\, n_0\, Q_{\nu_\alpha}\left(E_\nu\right)$$

$$\frac{1}{3}\sum_\alpha E_\nu^2\, \frac{d\Phi_{\nu_\alpha}(E_\nu)}{dE_\nu} = \frac{1}{4\pi}\,\frac{\zeta_z(E_\nu)}{H_0}\, n_0\, \frac{1}{3}\sum_\alpha E_\nu^2\, Q_{\nu_\alpha}\left(E_\nu\right)$$

$$\frac{1}{3}\sum_\alpha E_\nu^2\, \frac{d\Phi_{\nu_\alpha}(E_\nu)}{dE_\nu} = \frac{1}{4\pi}\,\frac{\zeta_z(E_\nu)}{H_0}\,\frac{\kappa_\nu\, f_\pi\, K_\pi}{1+K_\pi}\, n_0\, \left[E_N^2\, Q_N\left(E_N\right)\right]_{E_N = E_\nu/(\kappa_\pi\,\kappa_\nu)}$$

Using the measured luminosity: $\mathscr{L}_N(E_N) \equiv n_0\, E_N^2\, Q_N\left(E_N\right) \sim 10^{44}\,{\rm erg\,Mpc^{-3}\,yr^{-1}}$

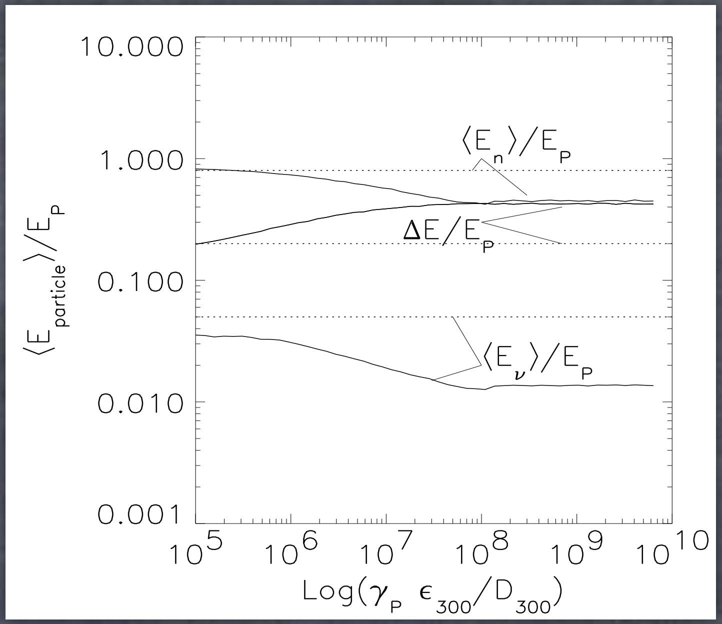
$$E_\nu^2\, \frac{d\Phi_{\nu_\alpha}\left(E_\nu\right)}{dE_\nu} \simeq 10^{-8}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

E. Waxman and J. N. Bahcall, Phys. Rev. D59:023002, 1999

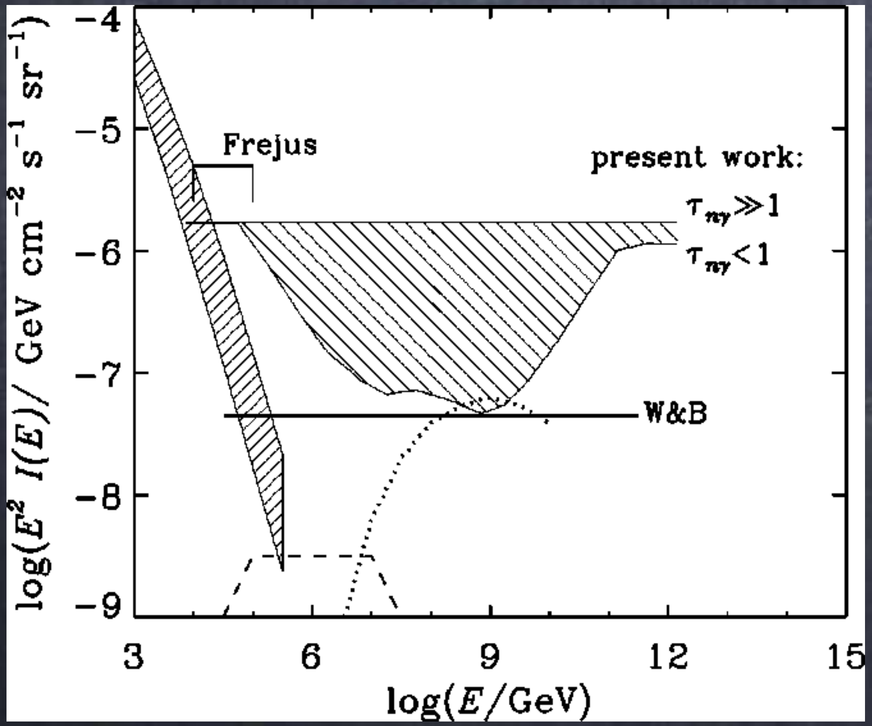
Is this a robust bound?

Many assumptions

- thin sources
- proton composition
- E_p^{-2} spectrum
- normalization at $E_{p,\min} = 10^{10}$ GeV
- inelasticities and average energies taken as independent of the scenario
- energy losses are not included

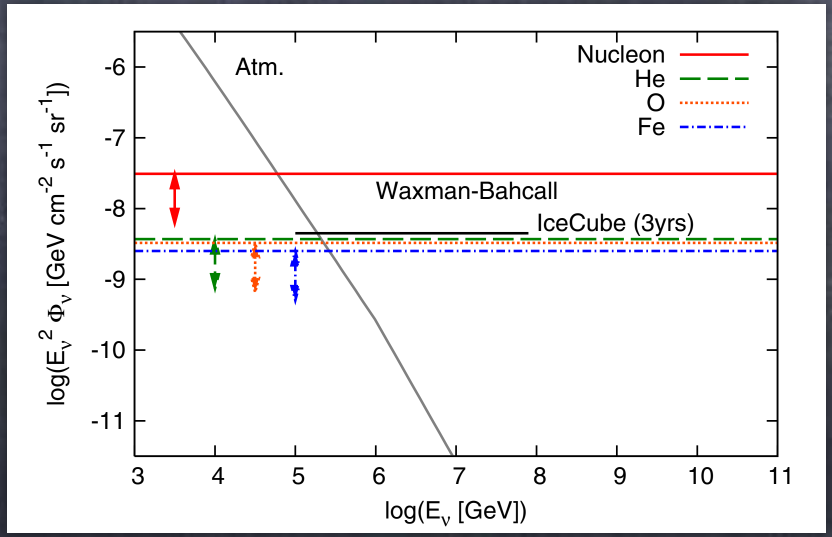


A. Mücke et al., astro-ph/9905153

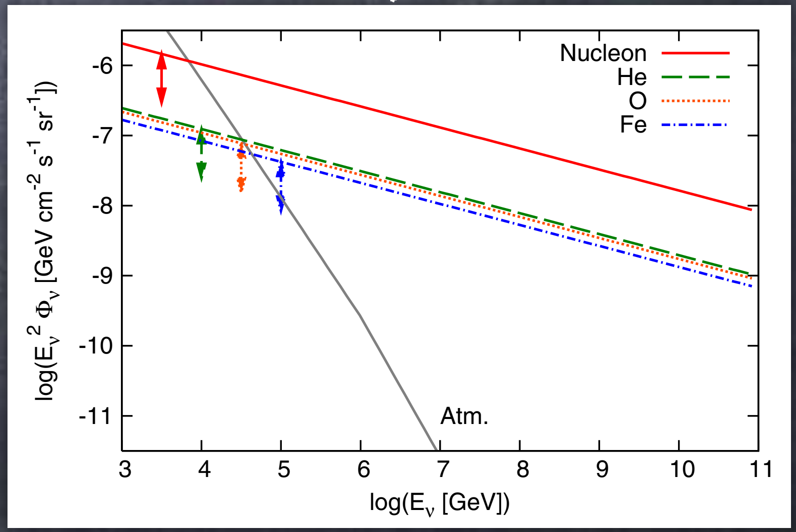


K. Mannheim, R. J. Protheroe and J. P. Rachen, Phys. Rev. D63:023003, 2001

nuclei?



softer spectrum?



K. Murase and J. F. Beacom, Phys. Rev. D81:123001, 2010

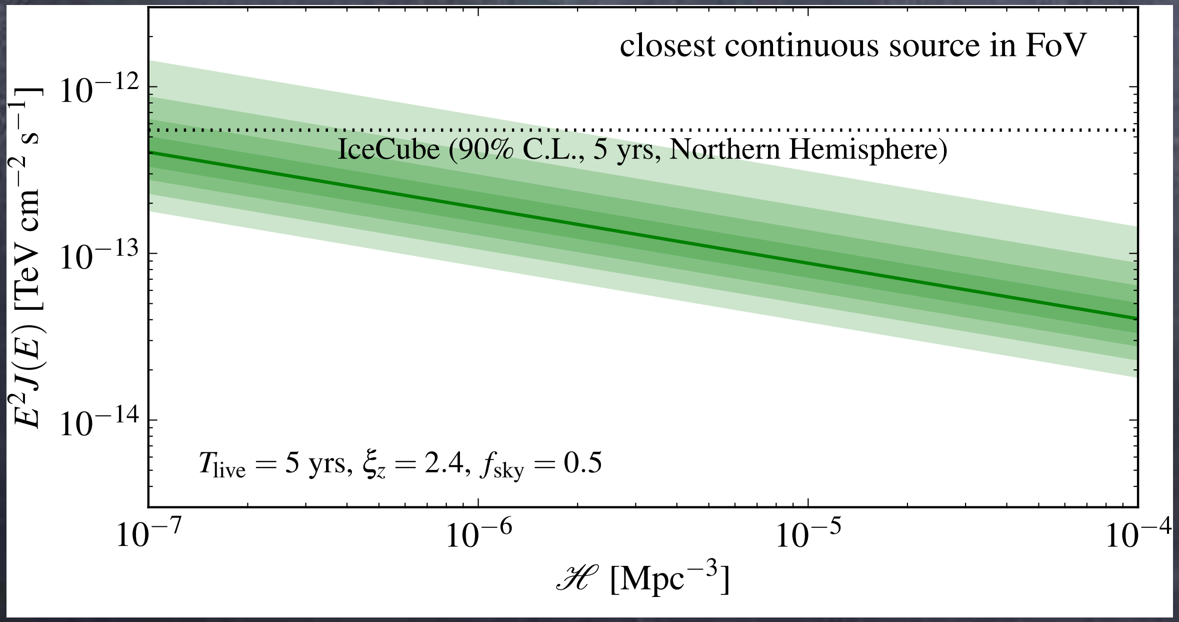
FLUX ESTIMATE FOR A STEADY SOURCE

Using the IceCube measurement of the diffuse flux

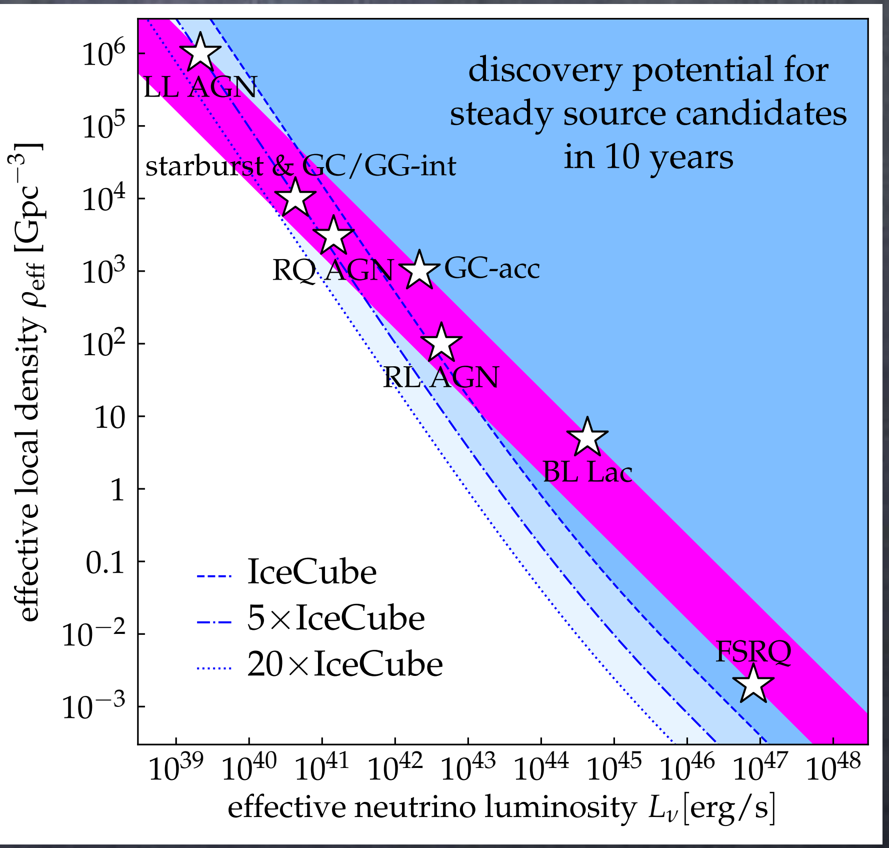
$$E_\nu^2 \frac{d\Phi_{\nu_\alpha}(E_\nu)}{dE_\nu} \simeq 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

For an individual continuously emitting source at 10 Mpc

$$E_\nu^2 \frac{d\Phi^{\mathrm{PS}}_{\nu_\alpha}(E_\nu)}{dE_\nu} \simeq 10^{-12}\,\mathrm{TeV\,cm^{-2}\,s^{-1}} \left(\frac{2.4}{\zeta_z}\right)\left(\frac{10^{-5}\,\mathrm{Mpc^{-3}}}{\rho_0}\right)\left(\frac{10\,\mathrm{Mpc}}{d}\right)^2$$



M. Ahlers and F. Halzen, Phys. Rev. D90:043005, 2014



M. Ackerman et al., Bull. Am. Astron. Soc. 51:185, 2019

FLUX ESTIMATE FOR A TRANSIENT SOURCE

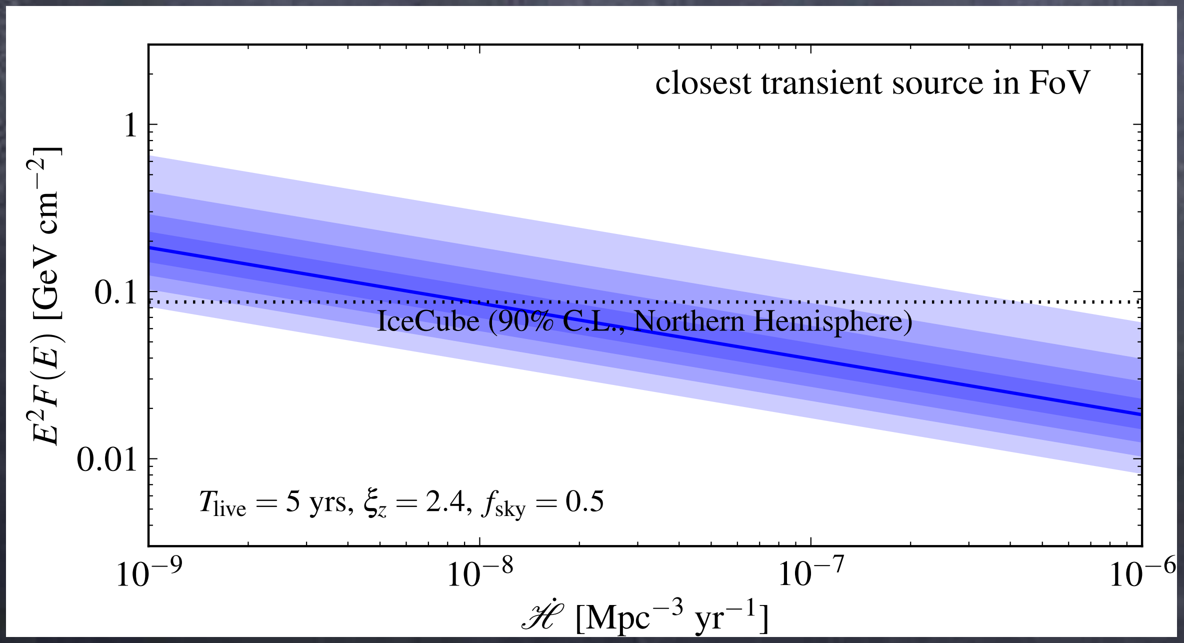
Using the IceCube measurement of the diffuse flux

$$E_\nu^2 \frac{d\Phi_{\nu_\alpha}(E_\nu)}{dE_\nu} \simeq 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

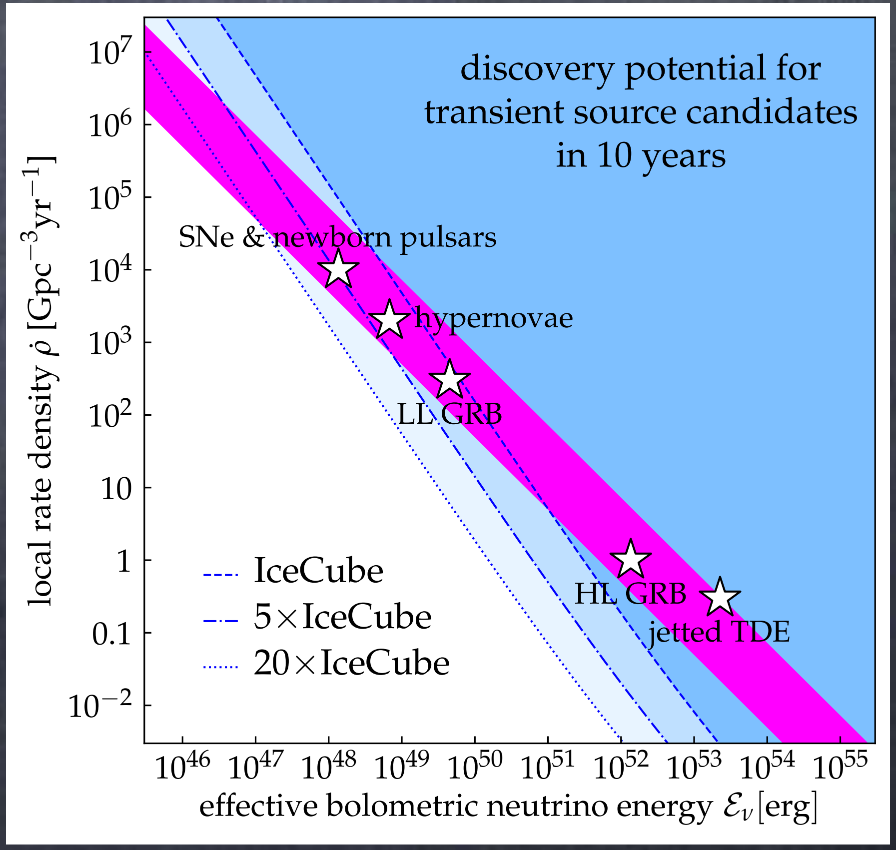
For a transient source at 10 Mpc

$$\mathscr{L}(z, E_\nu) = \dot{\rho}(z)\frac{dN}{dE_\nu}$$

$$E_\nu^2 \frac{dN}{dE_\nu} \simeq 0.3\,\mathrm{GeV\,cm^{-2}} \left(\frac{2.4}{\zeta_z}\right)\left(\frac{10^{-6}\,\mathrm{Mpc^{-3}\,yr^{-1}}}{\dot{\rho}_0}\right)\left(\frac{10\,\mathrm{Mpc}}{d}\right)^2$$



M. Ahlers and F. Halzen, Phys. Rev. D90:043005, 2014



M. Ackerman et al., Bull. Am. Astron. Soc. 51:185, 2019