Neutrinos from heavy quarks, astrophysical sources, and energy dependent flavor ratios

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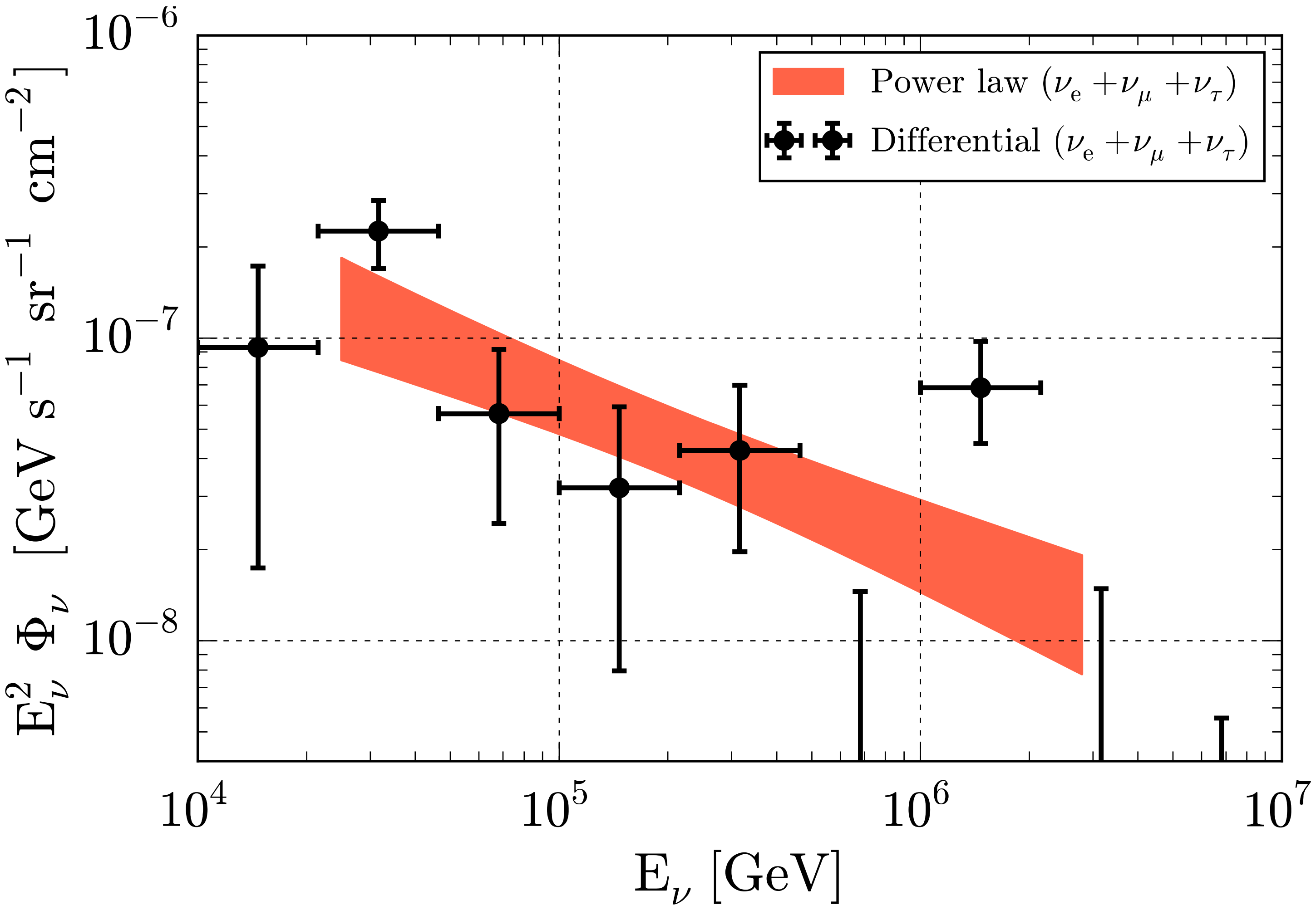
Astrophysical neutrinos

Discovered by IceCube in 2013



IceCube, M. G. Aartsen et al 2015 ApJ 809 98

Astrophysical sources

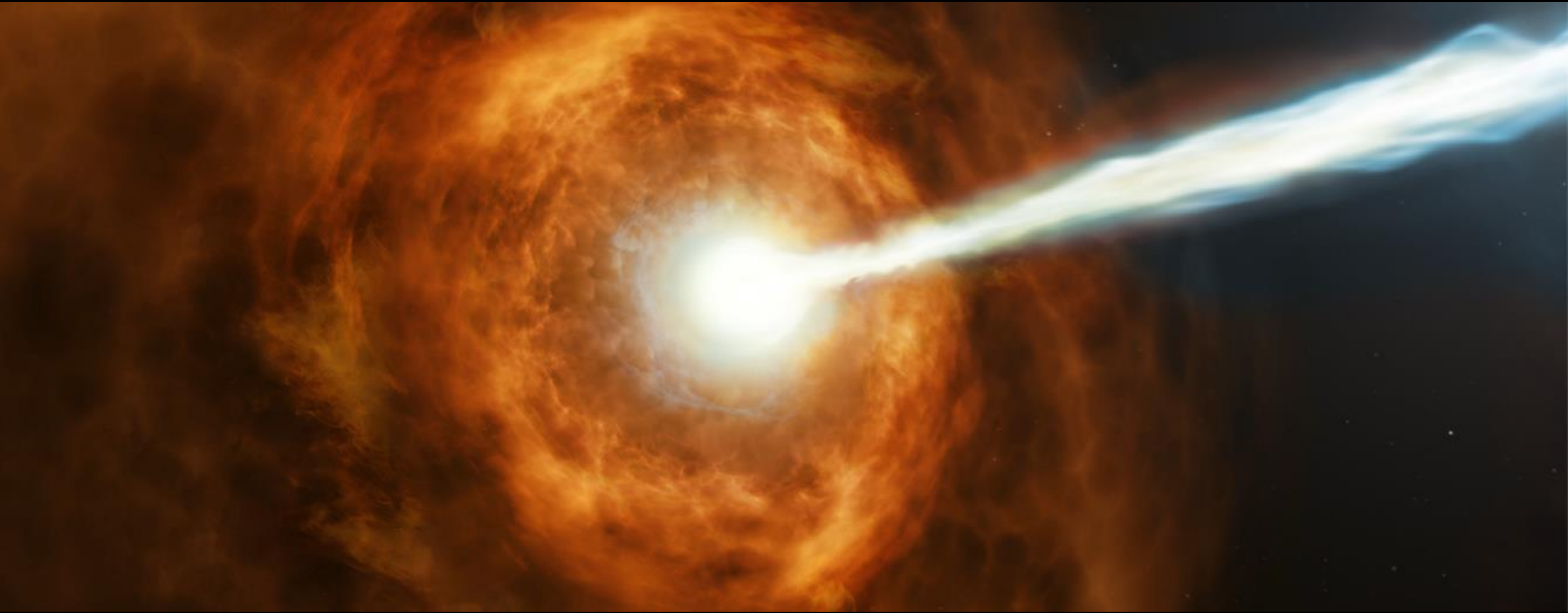
General name for cosmic objects or events that **accelerate** charged particles to high energies and **emit** high-energy photons, hadrons and/or neutrinos.

Typically $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$ and $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\bar{\nu}_\mu\nu_\mu$

Examples:

Active galactic nuclei (AGN)
Gamma ray bursts (GRB)
Starburst galaxies
Microquasars (black hole binaries)
Supernovae with jets (choked jets, slow jets — *meeker cousins of GRBs*)
Magnetars (magnetized neutron stars)

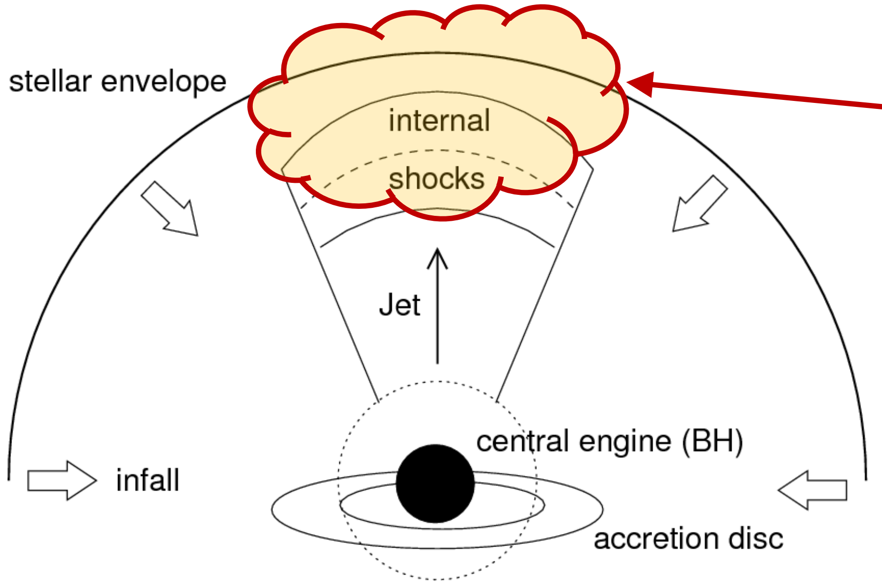
Gamma Ray Bursts emit most of their energy in two narrow relativistic outflows along their rotation axes – relativistic jets (Lorentz gamma of 100–1000)



One type of GRBs are core-collapse supernovae (hypernovae)
So maybe there are "normal" supernovae with similar jets?

Image credit: NASA, ESA, and M. Kornmesser CC BY 2.0 DEED

Schematic picture of black hole-driven source



pp and **pγ** collisions

[Fig adapted from Razzaque et al astro-ph/0509729]

Relativistic jet inside a collapsing star — may or may not punch through the envelope

Protons and electrons are **shock accelerated** in jet → collide with protons or photons

Charm production?

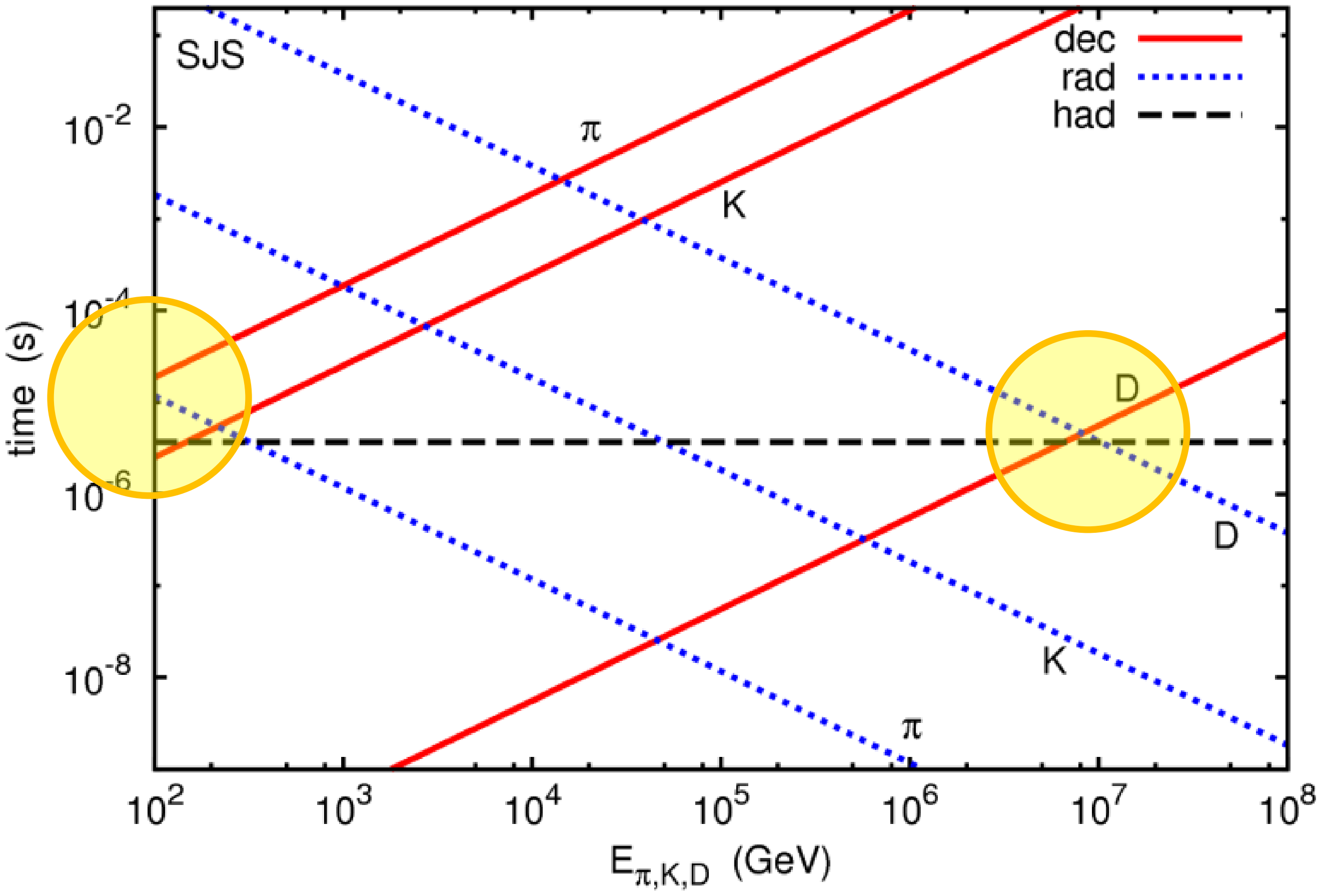
- Often assumed that neutrinos come from **pγ** collisions
  (protons of relativistic jet collide with the immense amount of photons)
- If there are baryons in the surrounding envelope there may be **pp** collisions giving **ccbar** production
  [RE, M.H. Reno, I. Sarcevic, arXiv:0808.2807 and Bhattacharya+ERS, arXiv:1407.2985]
- Then there would be prompt neutrinos in astrophysical sources, with **less cooling** (energy loss) than those from pions
- **pγ** gives pions, kaons: $(\nu_e : \nu_\mu : \nu_\tau) =$ (1 : 2 : 0) at the source
- **pp** gives D mesons: $(\nu_e : \nu_\mu : \nu_\tau) =$ (1 : 1 : 0) at the source
- **Charm dominates at higher energy → you get different flavor ratios**

But how can charm dominate? Impossible!

- Yes, there are enormous amounts of pions produced
- Yes, **pγ** only gives pions, no charm
- Yes, **σ**(cc) ≪ **σ**(pions, kaons)

But! Pions lose energy much faster and more efficiently than charm mesons!

- Pions long-lived, charm short-lived
- Synchrotron, IC energy losses ∝ m^{-4}
- When cooling time gets shorter than decay time the meson flux becomes suppressed



[RE, M.H. Reno, I. Sarcevic, arXiv:0808.2807]

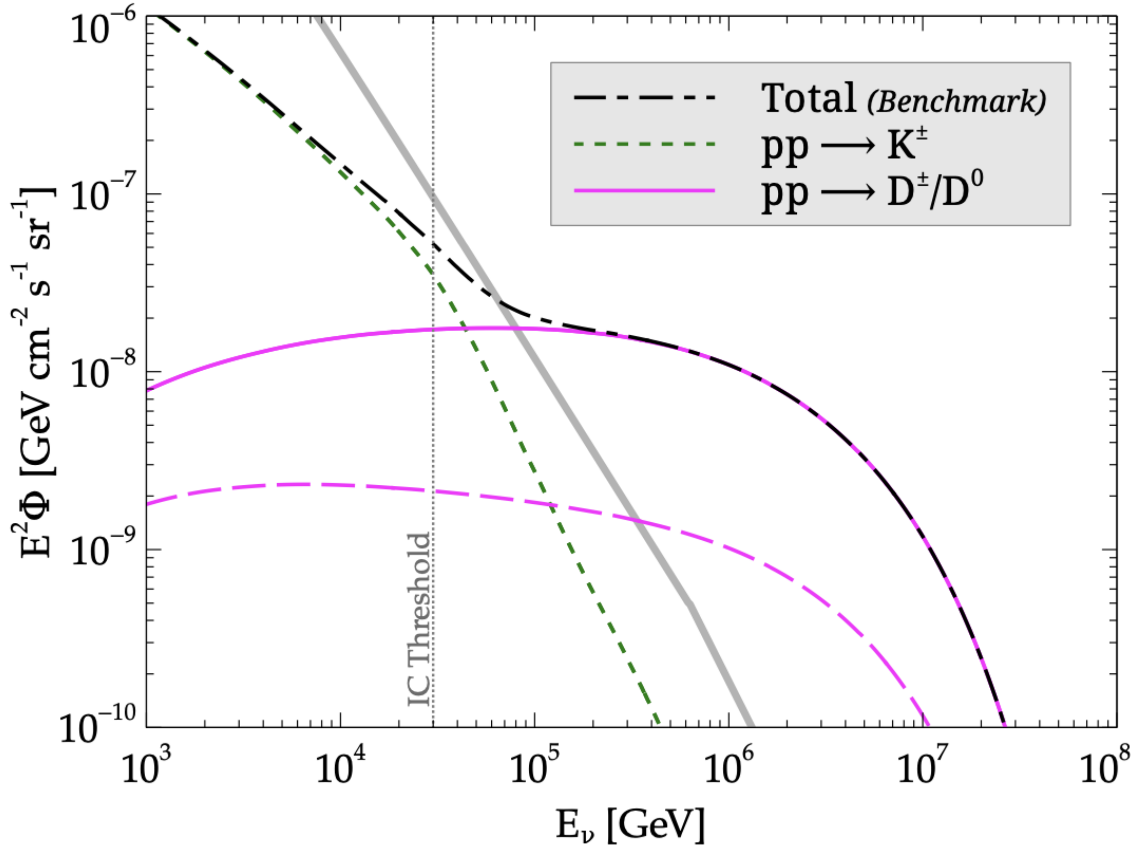
This is qualitatively similar to prompt atmospheric neutrinos…

Charm production in astrophysical sources

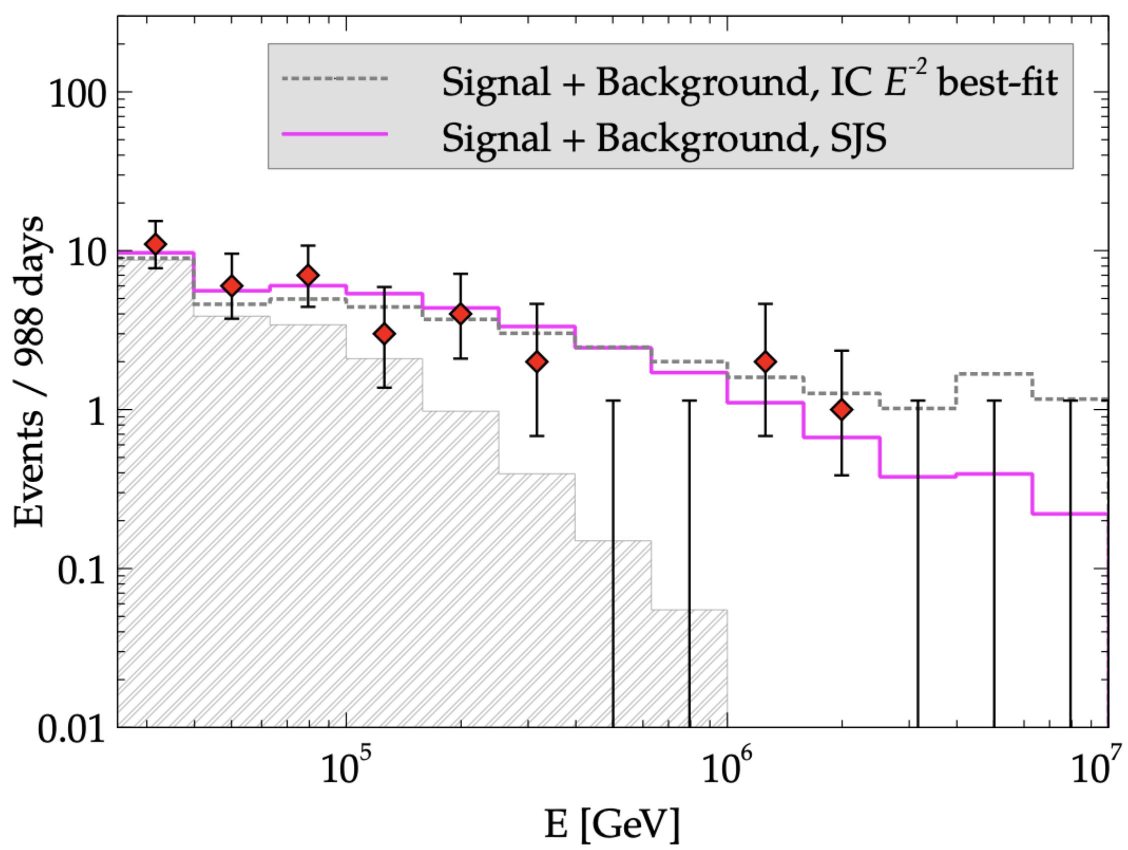
- We proposed this in 2008 [RE, Reno, Sarcevic, arXiv:0808.2807]
- Showed in 2014 that it could explain the observed diffuse flux with some choice of parameters [Bhattacharya, RE, Reno, Sarcevic, arXiv:1407.2985]
- But the flux can be explained by many different sources
- Here: new idea for testing charm: *It would give a different flavor composition of the observed neutrino flux*
  [Bhattacharya, RE, Reno, Sarcevic, arXiv:2309.09139]
- We illustrate this with two types of astrophysical sources as examples:
  - *Slow-jet supernovas*
  - *Magnetars*

Slow-jet supernovae

Flux from single source



Diffuse flux and observed

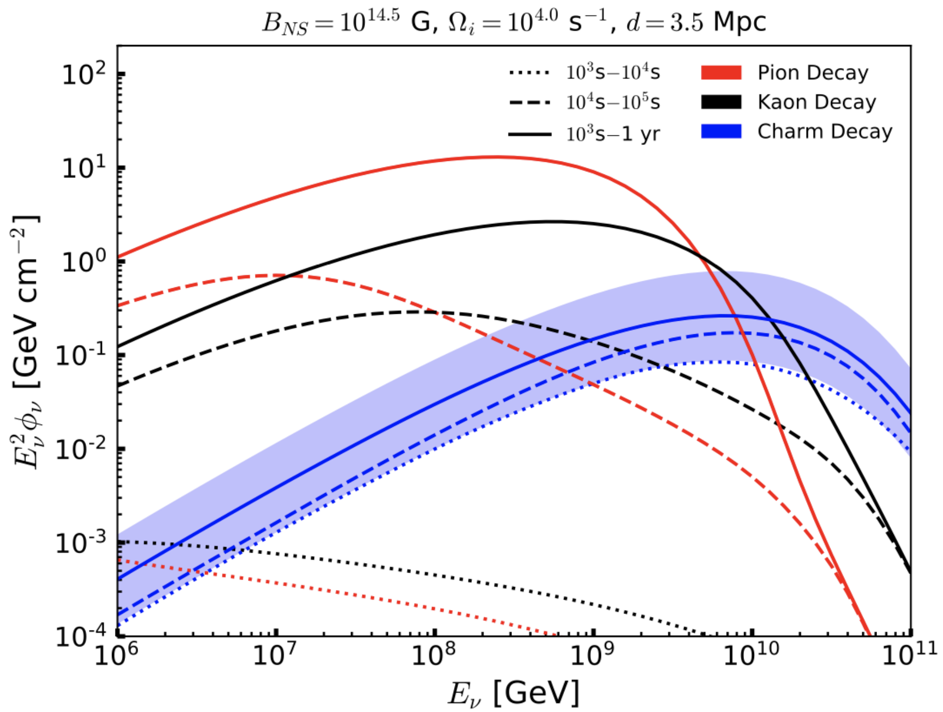


[Bhattacharya, RE, Reno, Sarcevic, arXiv:1407.2985, in JCAP]

Newborn magnetars

Magnetars: neutron stars with extreme magnetic field (10^{10}–10^{12} T)
(1000 times more than normal neutron star)

Similar calculation to SJS, with charm production in addition to pions – we use this as another benchmark



Carpio, Murase, Reno, Sarcevic, Stasto [arXiv:2007.07945]

Propagation of neutrino flavors

Using best fit neutrino parameters we get central values for averaged out oscillation probabilities

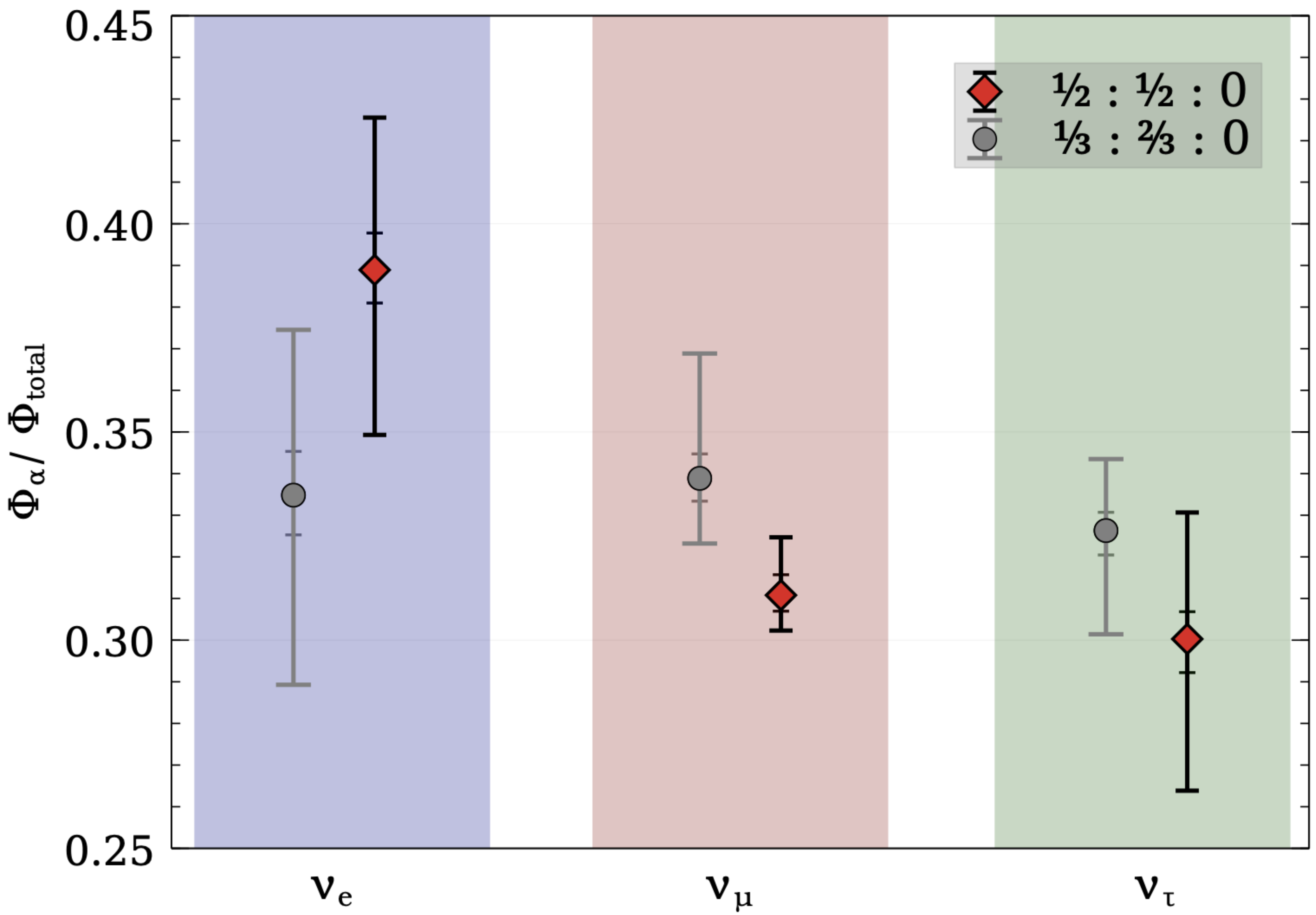
$$\langle P_{\nu_\alpha \to \nu_\beta} \rangle = \sum_{j=1}^{3} |U_{\beta j}|^2 |U_{\alpha j}|^2$$

$$\begin{pmatrix} \Phi_{\nu_e} \\ \Phi_{\nu_\mu} \\ \Phi_{\nu_\tau} \end{pmatrix}_{\text{Earth}} = \begin{pmatrix} 0.553 & 0.226 & 0.221 \\ 0.226 & 0.395 & 0.379 \\ 0.221 & 0.379 & 0.399 \end{pmatrix} \begin{pmatrix} \Phi_{\nu_e} \\ \Phi_{\nu_\mu} \\ \Phi_{\nu_\tau} \end{pmatrix}_{\text{source}}$$

Pion composition at source: (1 : 2 : 0) → (1.05 : 0.99 : 0.96) at Earth

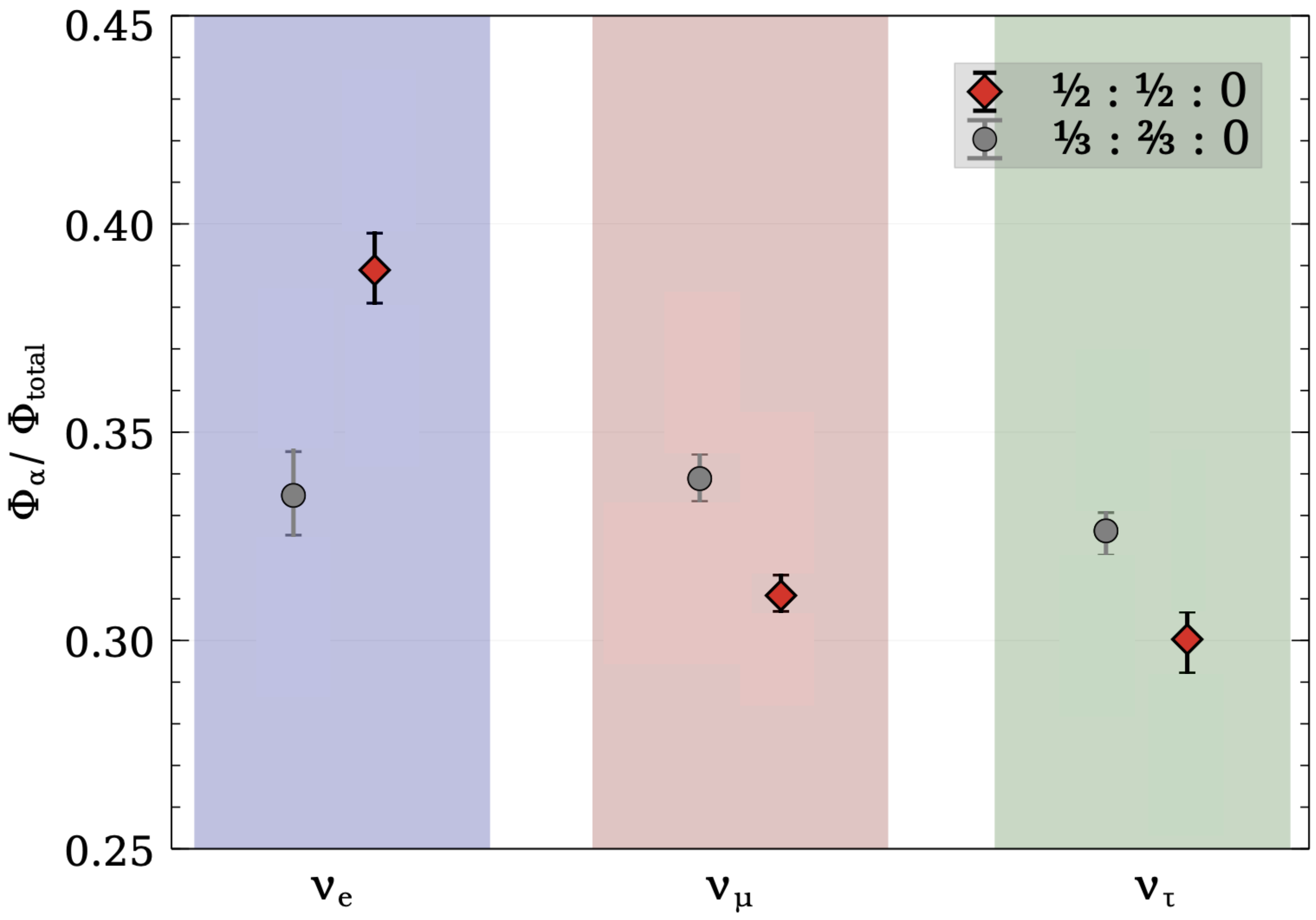
Charm composition at source: (1 : 1 : 0) → (0.8 : 0.62 : 0.58) at Earth

Earth composition (current values 3σ uncert)



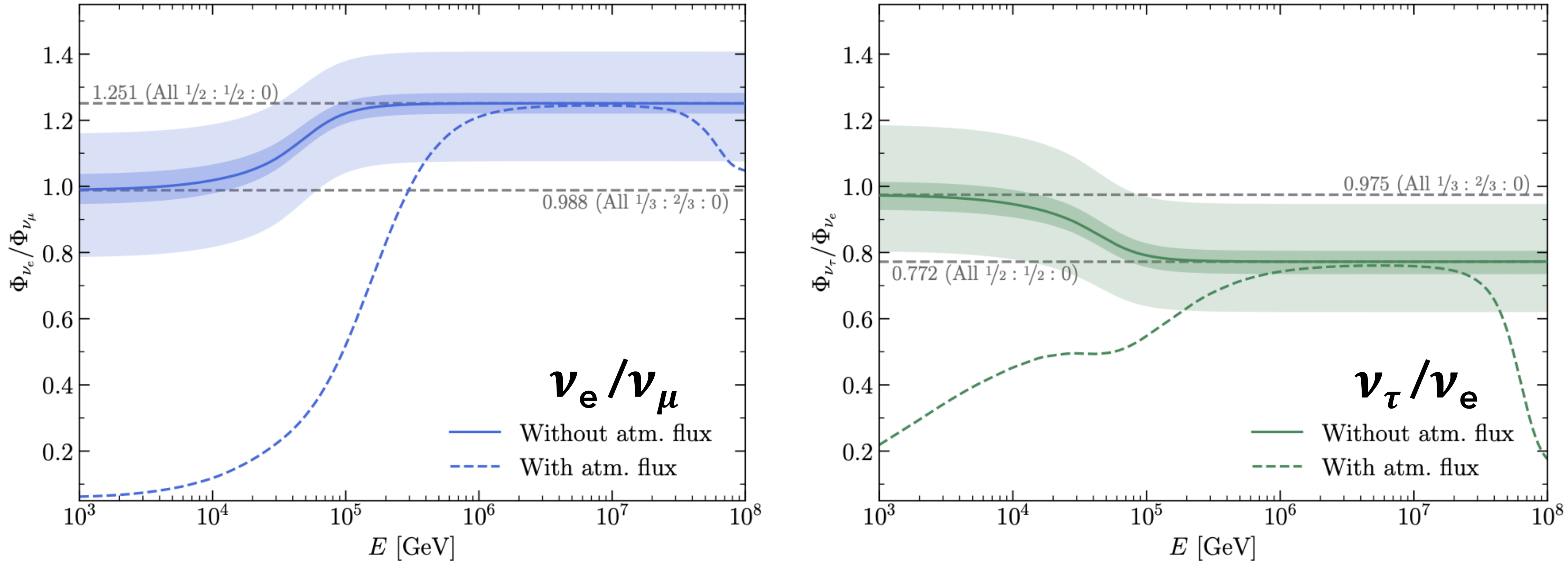
[Bhattacharya, RE, Reno, Sarcevic, arXiv:2309.09139, JCAP]

Earth composition (2040 proj 3σ uncert)



[Bhattacharya, RE, Reno, Sarcevic, arXiv:2309.09139, JCAP]

Energy dependence for slow-jet supernovas



Light band: current uncertainties on neutrino parameters
Dark band: 2040 projected uncertainties
Dashed curve: if atmospheric neutrinos are added

[Bhattacharya, RE, Reno, Sarcevic, arXiv:2309.09139, JCAP]

Conclusions

- Sources of astrophysical neutrino flux not known
- Flavor ratios may give insight into its sources
- We propose a new source of energy dependence of the flavor ratios
- It’s hard to detect, but may be doable by 2040