Multimessenger Astronomy and New Neutrino Physics

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DISCRETE18 -- 28 November, 2018

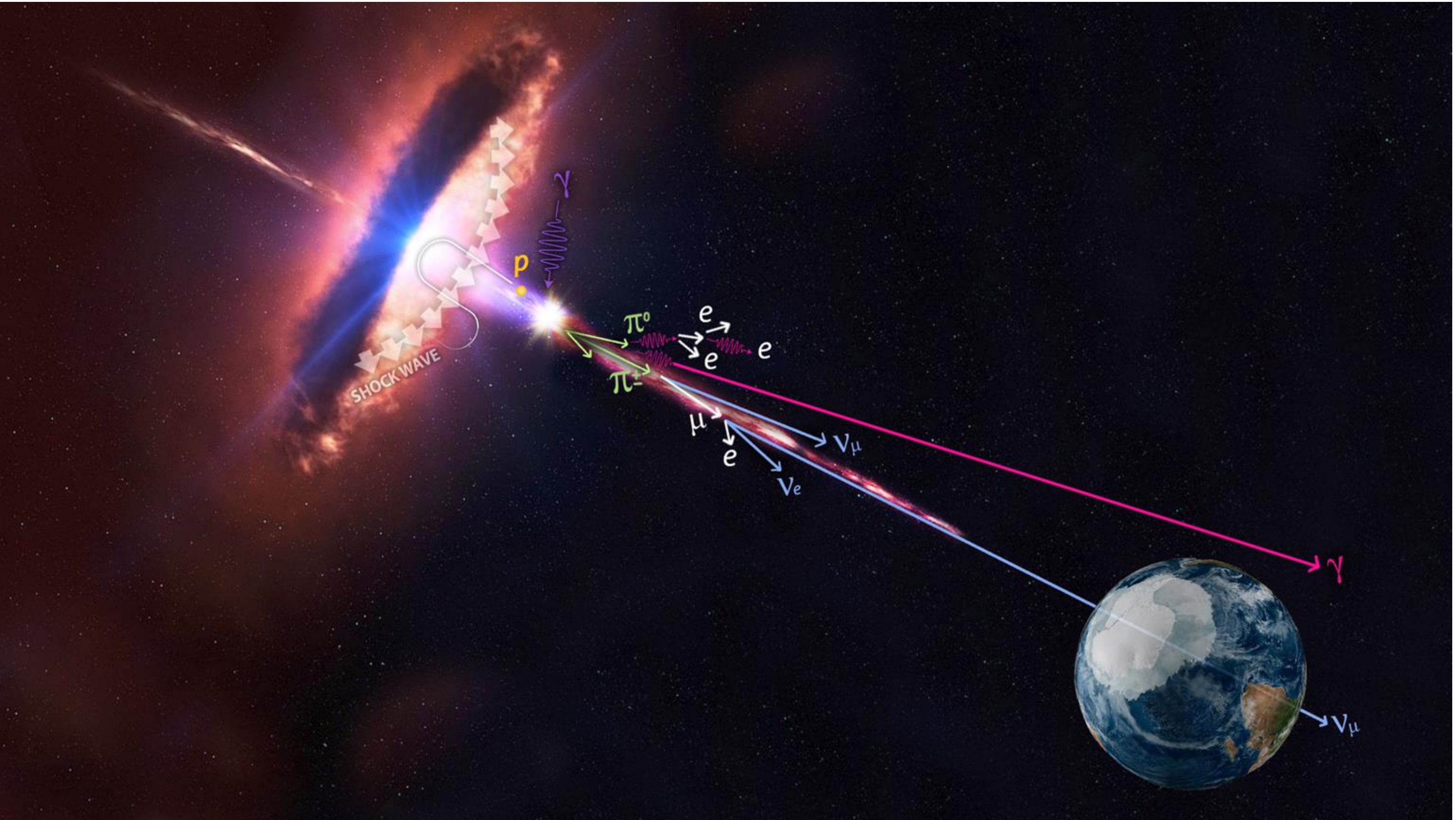
Based on 1808.02889 (**JCAP** 1810 (2018) no. 10, 048) with Pedro A.N. Machado

Outline

- Identifying ultra-high energy neutrino sources
- Probing physics with UHE Neutrinos vs. Supernova Neutrinos
- Models we consider
- Results

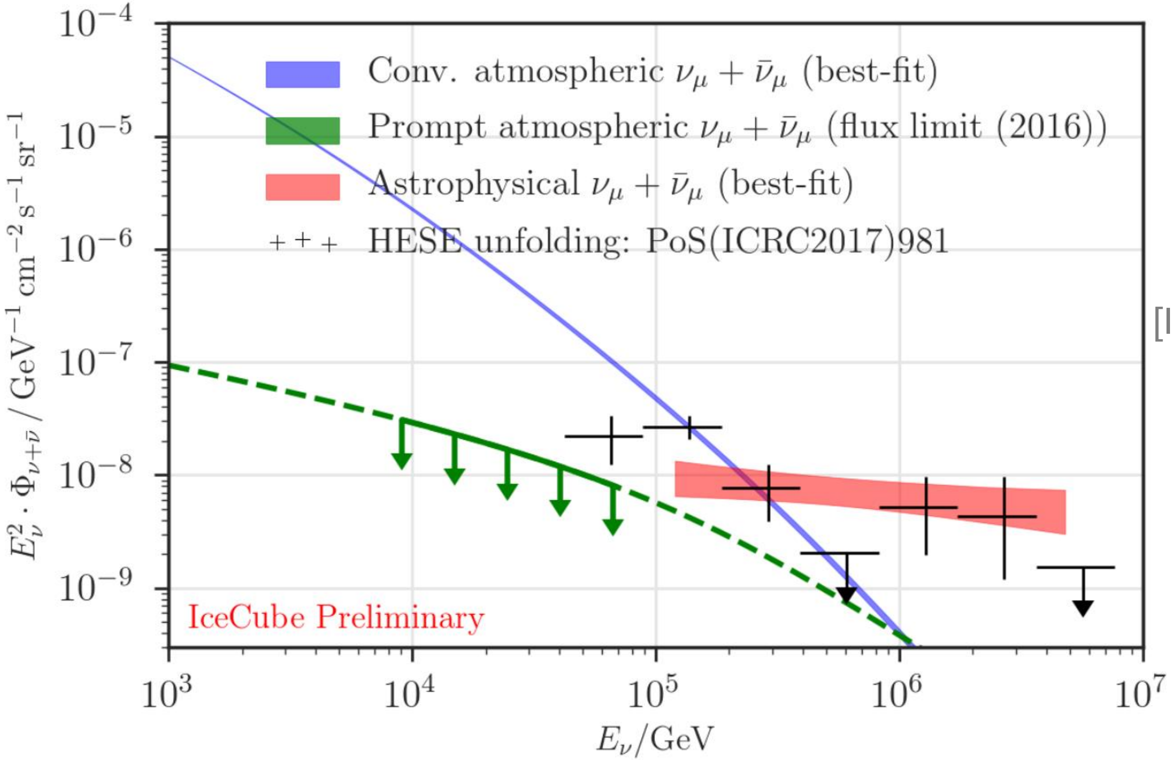
The main idea

Astrophysical environments provide sources of high-energy neutrinos. What types of models can we probe by detecting them?



To date, the only (identified) extragalactic neutrino sources:
SN1987A,
TXS 0506+056

Observing astrophysical neutrinos is great, but...



[IceCube Collaboration, 1710.01191]

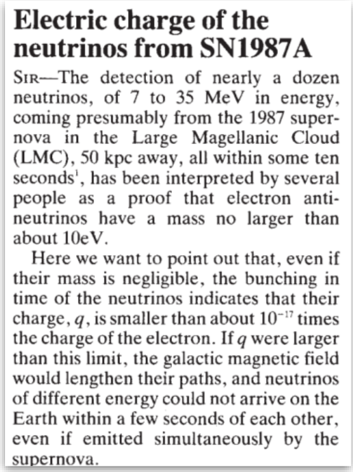
Knowing the origin of a given neutrino provides extra handles: propagation distance, what it traversed (galactic disk, magnetic fields, etc.)

SN1987A vs. TXS 0506+056

SN1987A: Neutrino energies ~10 MeV
Distance ~50 kpc

TXS 0506+056: Neutrino energy ~290 TeV
Distance ~1.3 Gpc

- 29,000,000 times higher energy, 26,000 times longer distance

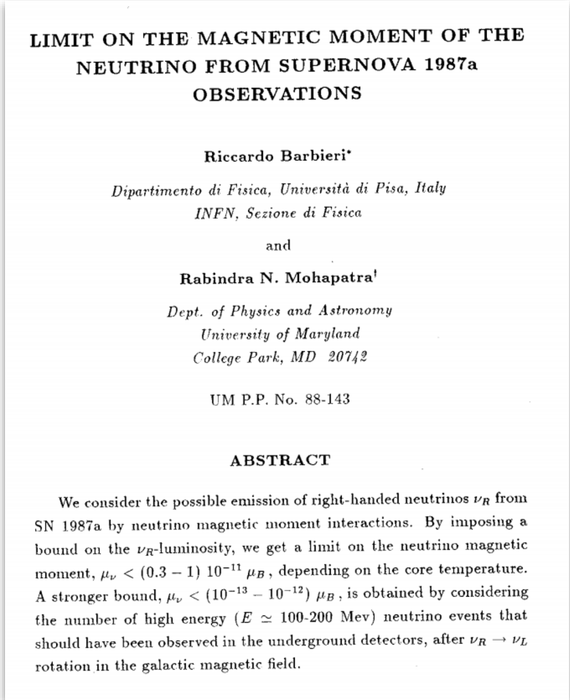


Electric charge of the neutrinos from SN1987A

SIR—The detection of nearly a dozen neutrinos, of 7 to 35 MeV in energy, coming presumably from the 1987 supernova in the Large Magellanic Cloud (LMC), 50 kpc away, all within some ten seconds[1], has been interpreted by several people as a proof that electron antineutrinos have a mass no larger than about 10eV.

Here we want to point out that, even if their mass is negligible, the bunching in time of the neutrinos indicates that their charge, q, is smaller than about 10^{-17} times the charge of the electron. If q were larger than this limit, the galactic magnetic field would lengthen their paths, and neutrinos of different energy could not arrive on the Earth within a few seconds of each other, even if emitted simultaneously by the supernova.

G. Barbiellini, G. Cocconi, 1987



LIMIT ON THE MAGNETIC MOMENT OF THE NEUTRINO FROM SUPERNOVA 1987a OBSERVATIONS

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ABSTRACT

We consider the possible emission of right-handed neutrinos ν_R from SN 1987a by neutrino magnetic moment interactions. By imposing a bound on the ν_R-luminosity, we get a limit on the neutrino magnetic moment, $\mu_\nu < (0.3 - 1)\ 10^{-11}\ \mu_B$, depending on the core temperature. A stronger bound, $\mu_\nu < (10^{-13} - 10^{-12})\ \mu_B$, is obtained by considering the number of high energy ($E \simeq$ 100-200 Mev) neutrino events that should have been observed in the underground detectors, after $\nu_R \rightarrow \nu_L$ rotation in the galactic magnetic field.

R. Barbieri, R. Mohapatra, 1988

While TXS 0506+056 is probing much longer distances, searches for these (and other) new physics models actually suffer from the much larger energy!

Specific (contrasting) example: Neutrino Decay

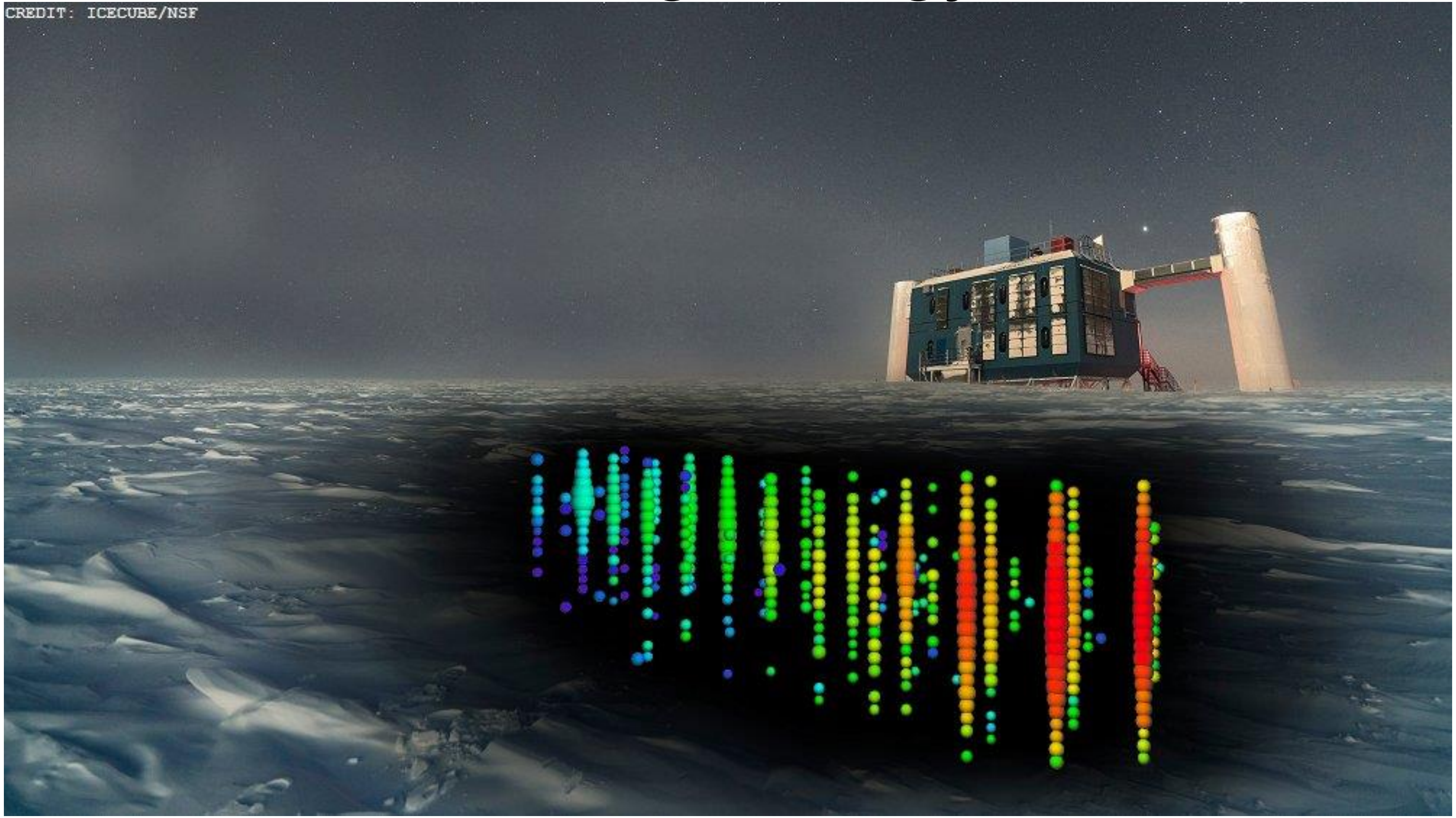
Hypothesis: probe decay of heavier neutrinos during propagation from source to Earth.

Naïve expectation: 26,000 times greater distance means commensurate sensitivity to neutrino decay length.

But,

$$P_{\mathrm{decay}} \propto e^{-\frac{L}{c\tau_0\gamma}} = e^{-\frac{Lm_\nu}{c\tau_0 E_\nu}}$$

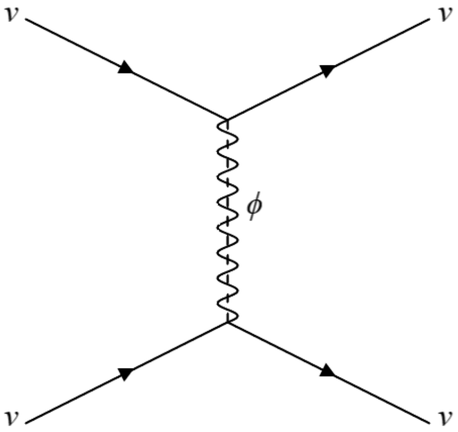
Characteristics of Ultra High Energy Cosmic Neutrinos

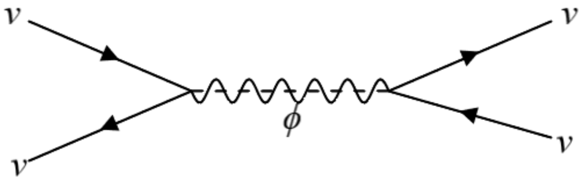


Processes to think about: Blazars, Neutron Star Mergers, ...

First Scenario Considered

New particle (can be scalar, pseudoscalar, vector, or axial-vector) that couples exclusively to neutrinos.

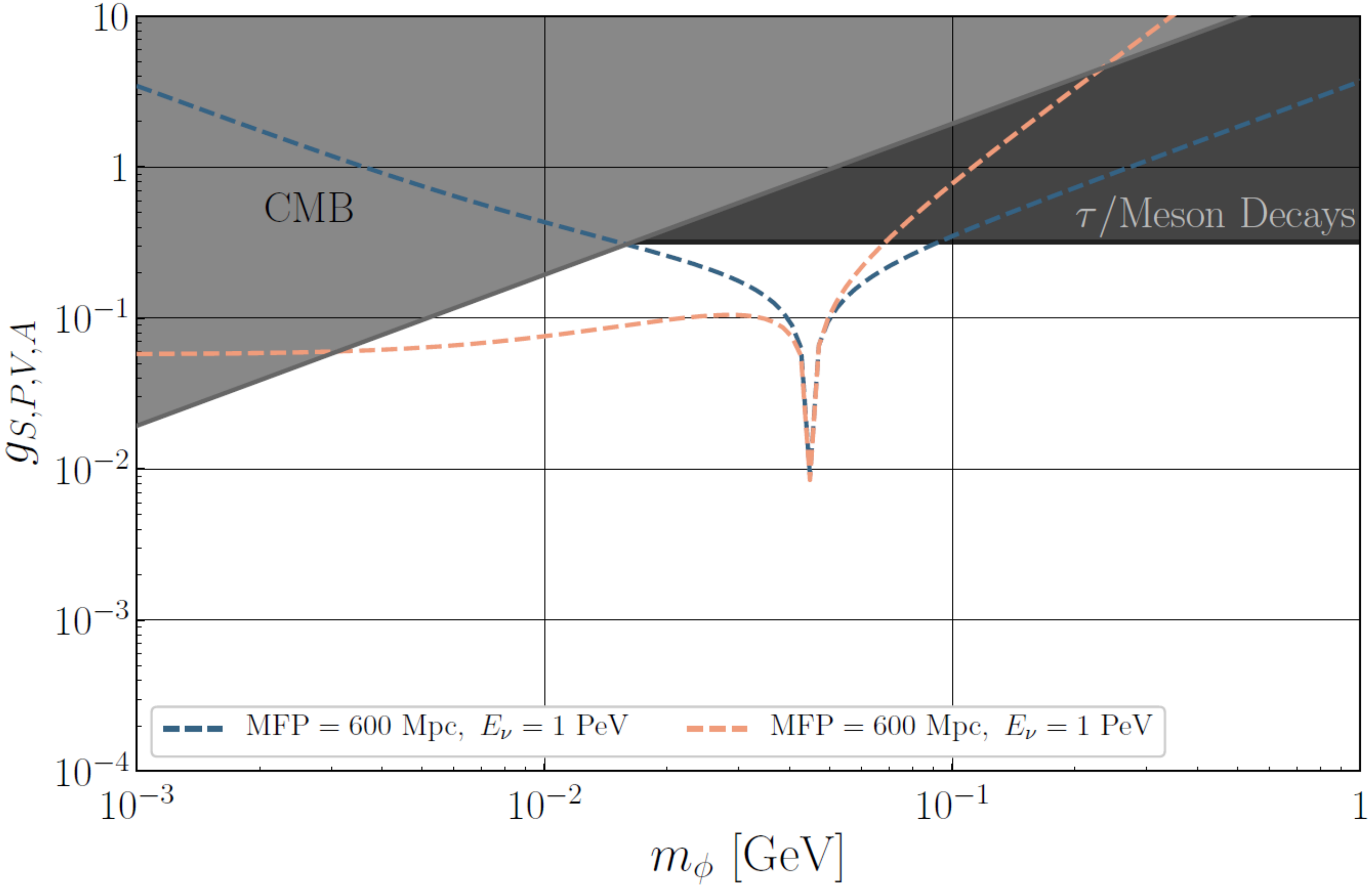




$$\lambda_{\mathrm{MFP}} = \frac{1}{n_X \sigma(\nu X \to Y)}$$

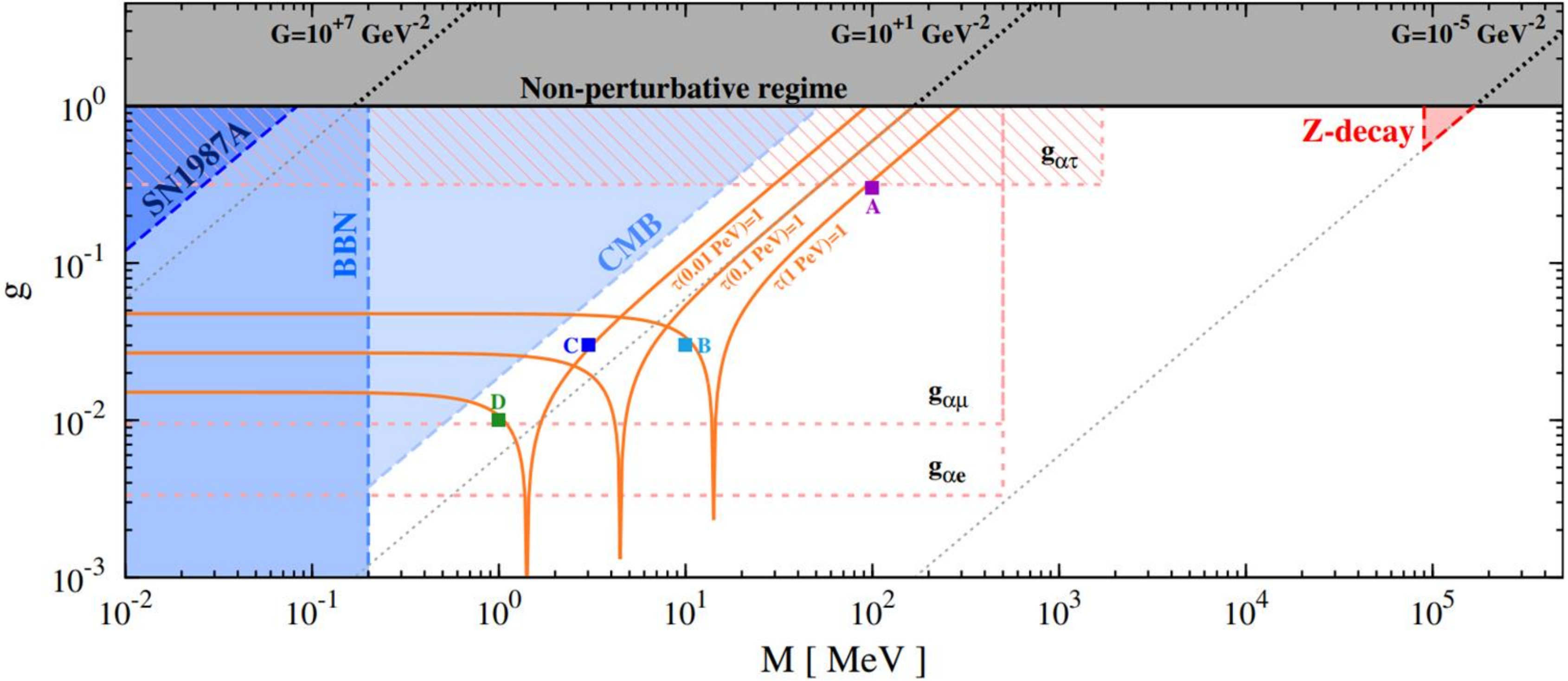
High-energy neutrinos can scatter with relic Cosmic Neutrino Background neutrinos while travelling to Earth.

Lower Limit on Mean Free Path



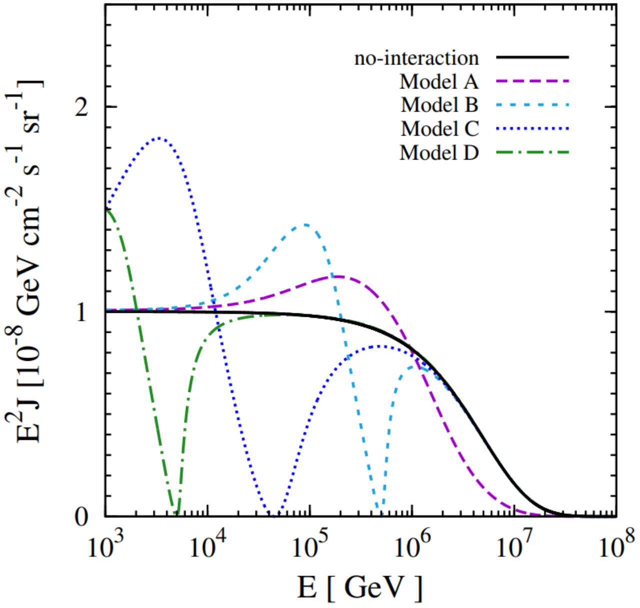
Previously Explored as “Secret Neutrino Interactions”

[Ng, Beacom 1404.2288]

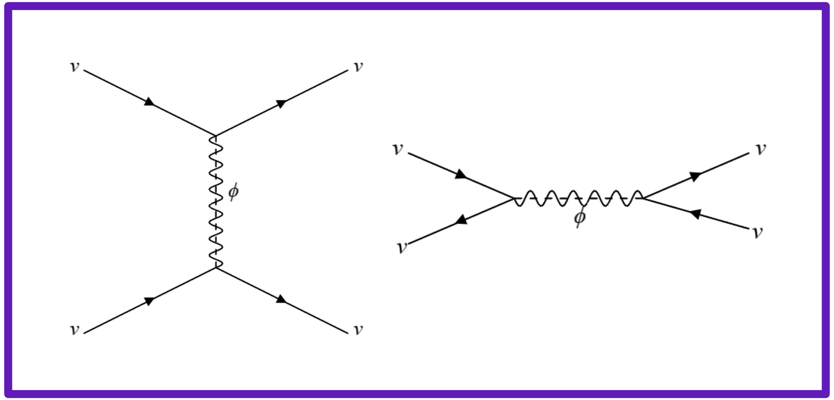


When mass is large, you probe a new four-fermion interaction. Current limits are probing *much* stronger interactions than G_F. Orange lines correspond to an optical depth of 1 for a propagation length of one Hubble length.

Pileup of events



[Ng, Beacom 1404.2288]

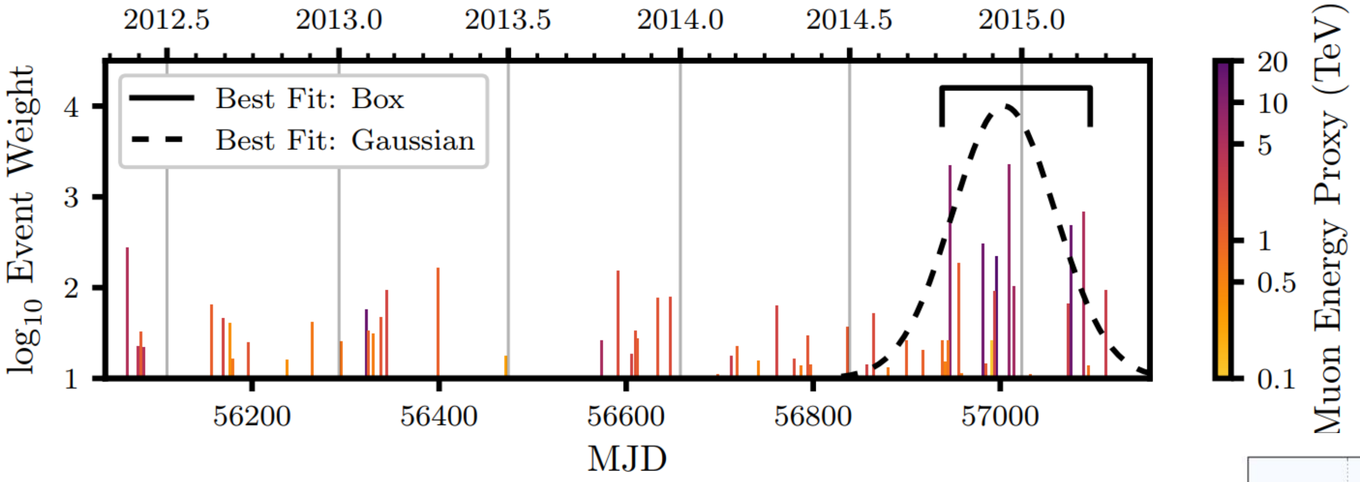


For a continuous (over time) flux of neutrinos, this type of absorption would lead to a re-emission of neutrinos at lower energies.

However, we are interested in specific neutrino-producing events. A typical scattering will give large enough deflections that the neutrino will not appear to arrive coincident in time/direction with its source.

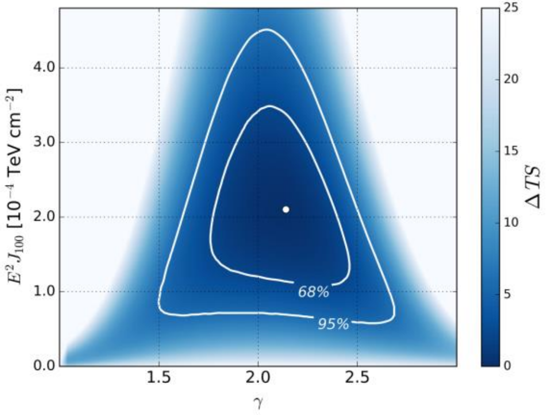
Enter TXS 0506+056

[IceCube Collaboration, 1807.08794]

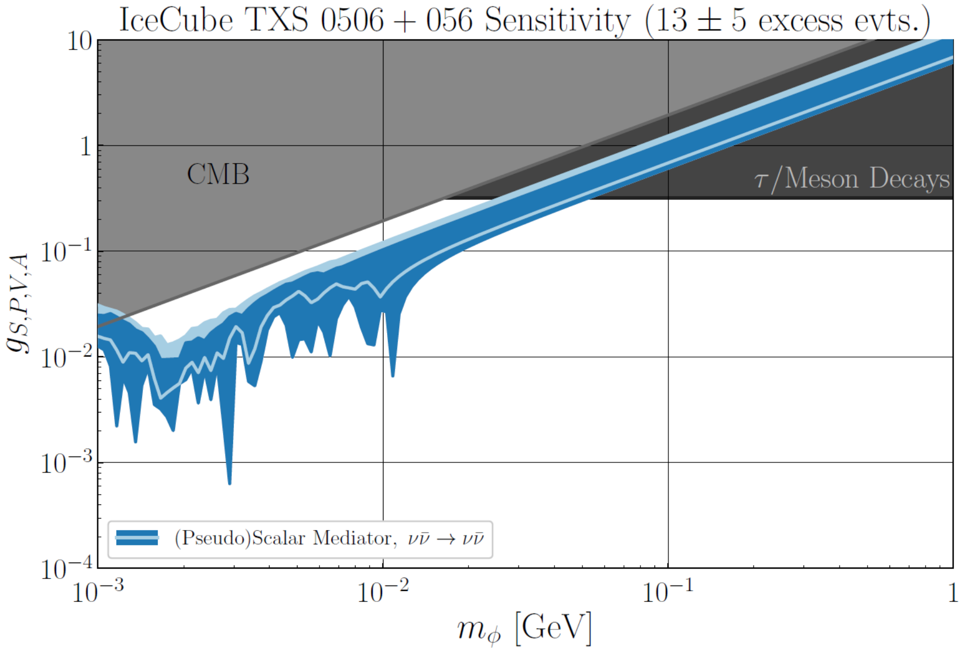


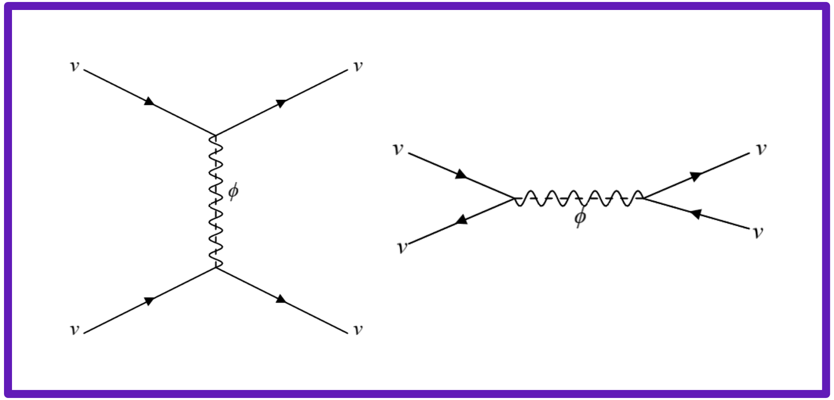
After the first neutrino event detection (coincident with the location of TXS 0506+056 and in time with a gamma ray burst flare), the IceCube collaboration performed a historical analysis of their data and found a time window with 13 ± 5 excess signal events.

Neutrino fluence measured to be commensurate with gamma ray flux (measured by Fermi-LAT).



Perform Pseudoexperiments with IceCube Data

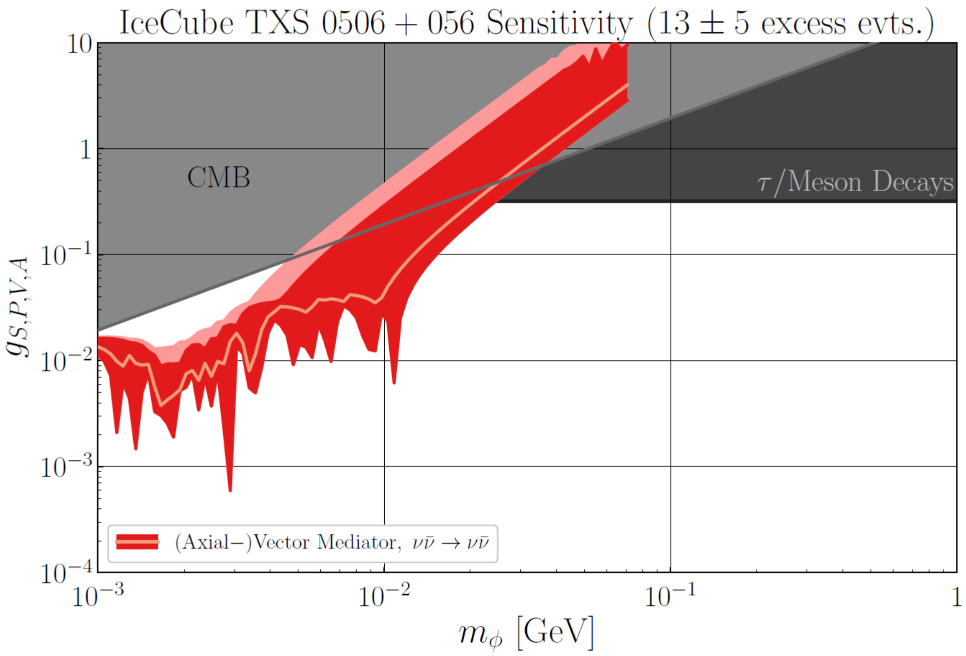


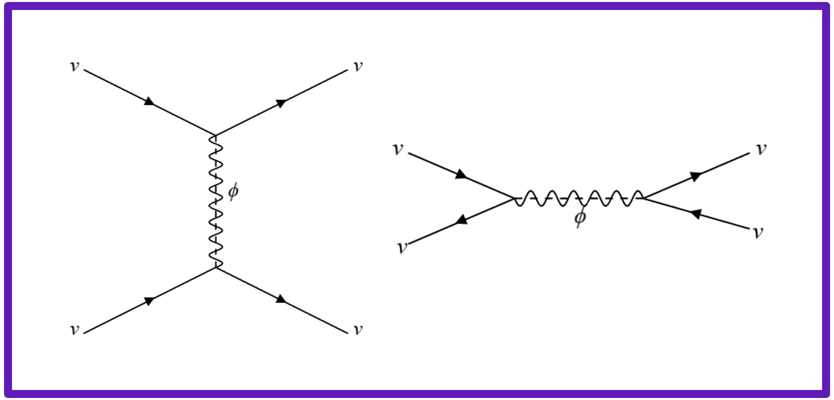


$$\sigma(\nu\bar{\nu} \to S \to \nu\bar{\nu}) \simeq \frac{g^4 m_\phi^4 (1-\epsilon)}{64\pi s (s - m_\phi^2)^2} \frac{s^2((2-\epsilon)\epsilon + 4) - 4 s m_\phi^2 + 8 m_\phi^4}{(2(s+m_\phi^2) - \epsilon s)(\epsilon s + 2 m_\phi^2)} + \frac{g^4 m_\phi^4}{16\pi s^2 (s - m_\phi^2)} \tanh^{-1}\left(\frac{s(1-\epsilon)}{s + 2m_\phi^2}\right), \tag{II.3}$$

$$\sigma(\nu\bar{\nu} \to P \to \nu\bar{\nu}) \simeq \sigma(\nu\bar{\nu} \to S \to \nu\bar{\nu}). \tag{II.4}$$

Perform Pseudoexperiments with IceCube Data



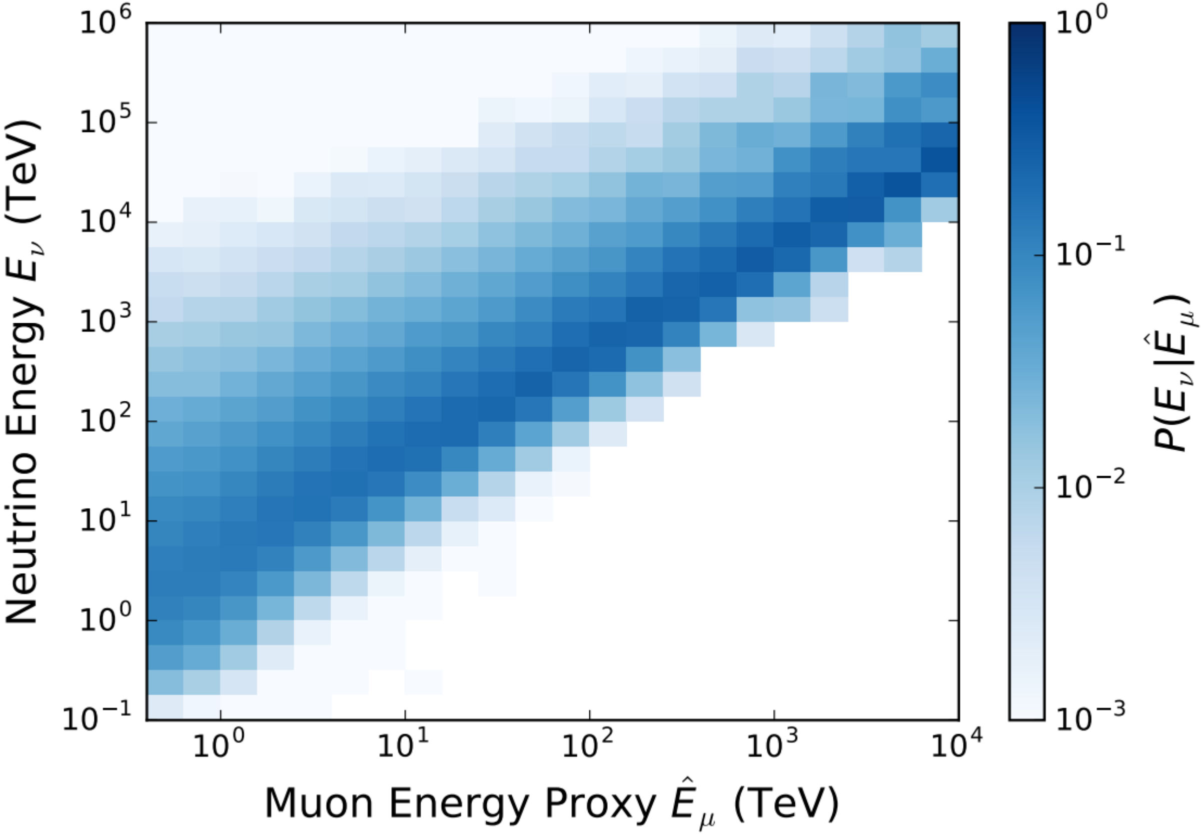


$$\sigma(\nu\bar{\nu} \to V \to \nu\bar{\nu}) \simeq \frac{g^4 m_\phi^2 (s + m_\phi^2)}{4\pi s^2 (s - m_\phi^2)} \log\left[\frac{(2-\epsilon)s + 2m_\phi^2}{\epsilon s + 2m_\phi^2}\right] + \frac{g^4(\epsilon - 1)P^{(8)}(s, m_\phi, \epsilon)}{192\pi s(s - m_\phi^2)^2(\epsilon s + 2m_\phi^2)((\epsilon - 2)s - 2m_\phi^2)}, \quad \text{(II.5)}$$

$$\sigma(\nu\bar{\nu} \to A \to \nu\bar{\nu}) \simeq \sigma(\nu\bar{\nu} \to V \to \nu\bar{\nu}), \quad \text{(II.6)}$$

$$\begin{aligned} P^{(8)}(s, m_\phi, \epsilon) \simeq\; & s^4(48 + \epsilon(2-\epsilon)(\epsilon(\epsilon - 2) - 20)) + 16 s^3 m_\phi^2(\epsilon(\epsilon - 2) - 5) \\ & - 32 s^2 m_\phi^4(\epsilon(\epsilon - 2) + 7) + 96 s m_\phi^6 + 192 m_\phi^8. \quad \text{(II.7)} \end{aligned}$$

Caveat: Energy reconstruction is (far from) perfect



[IceCube Collaboration, 1807.08794]

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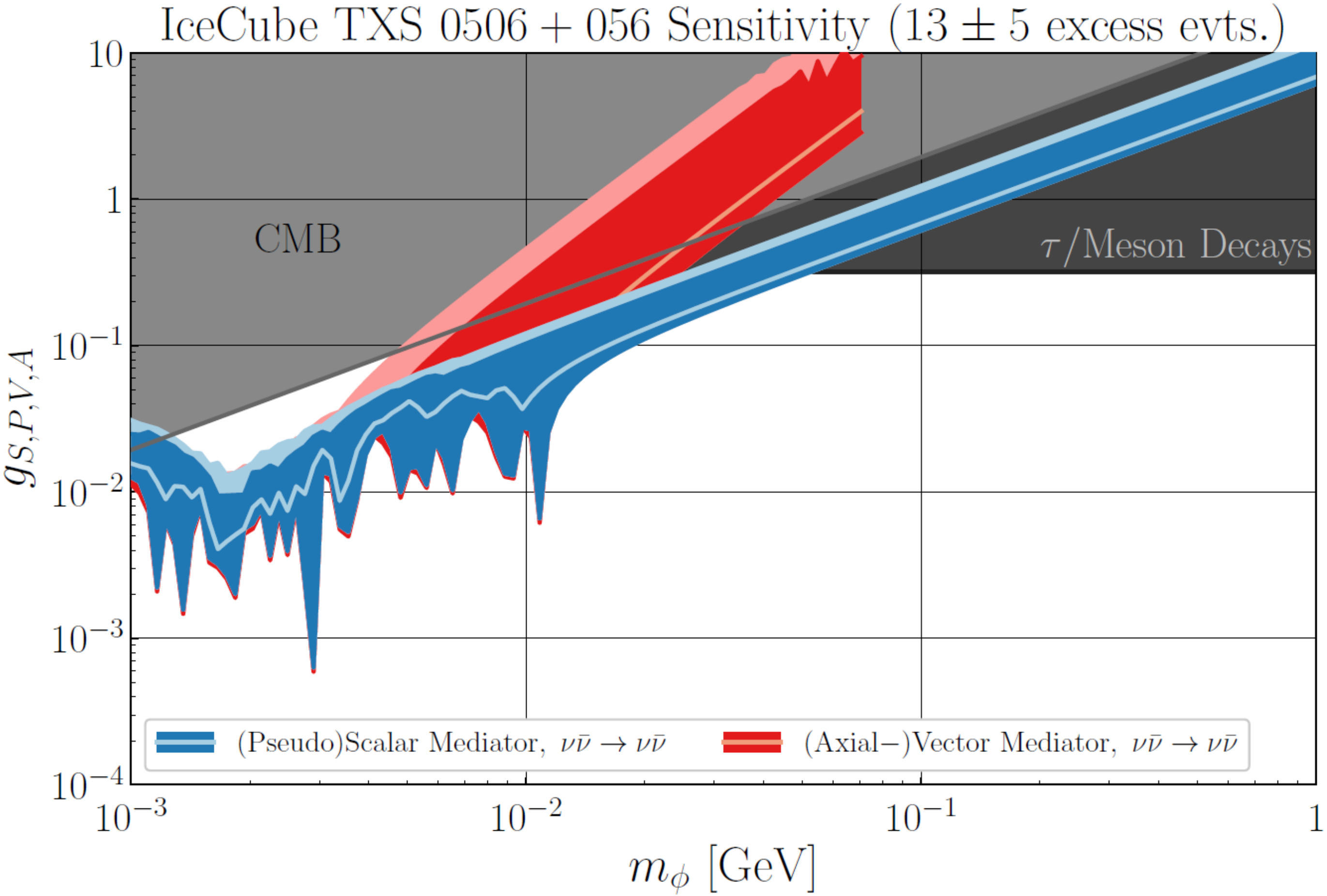

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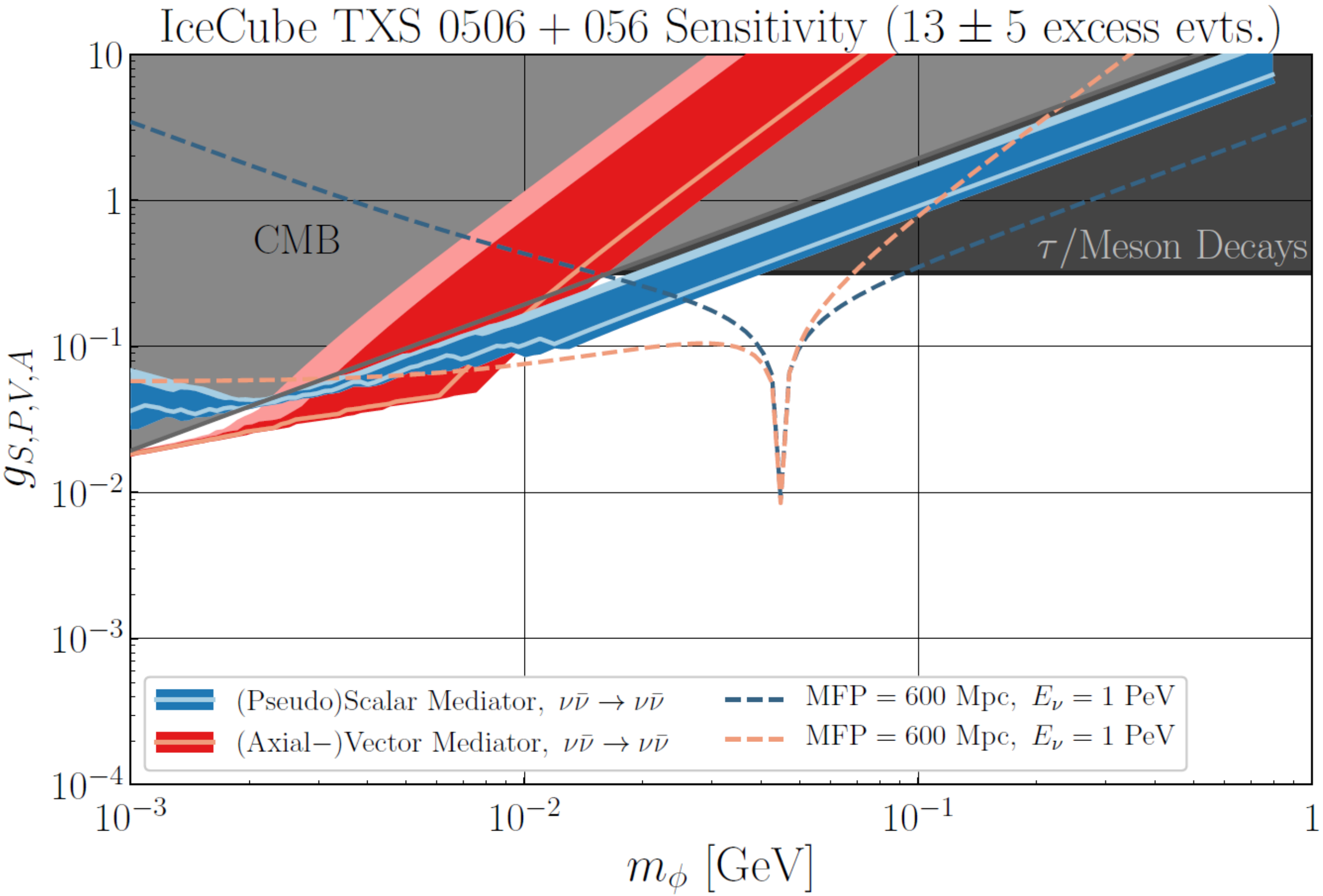
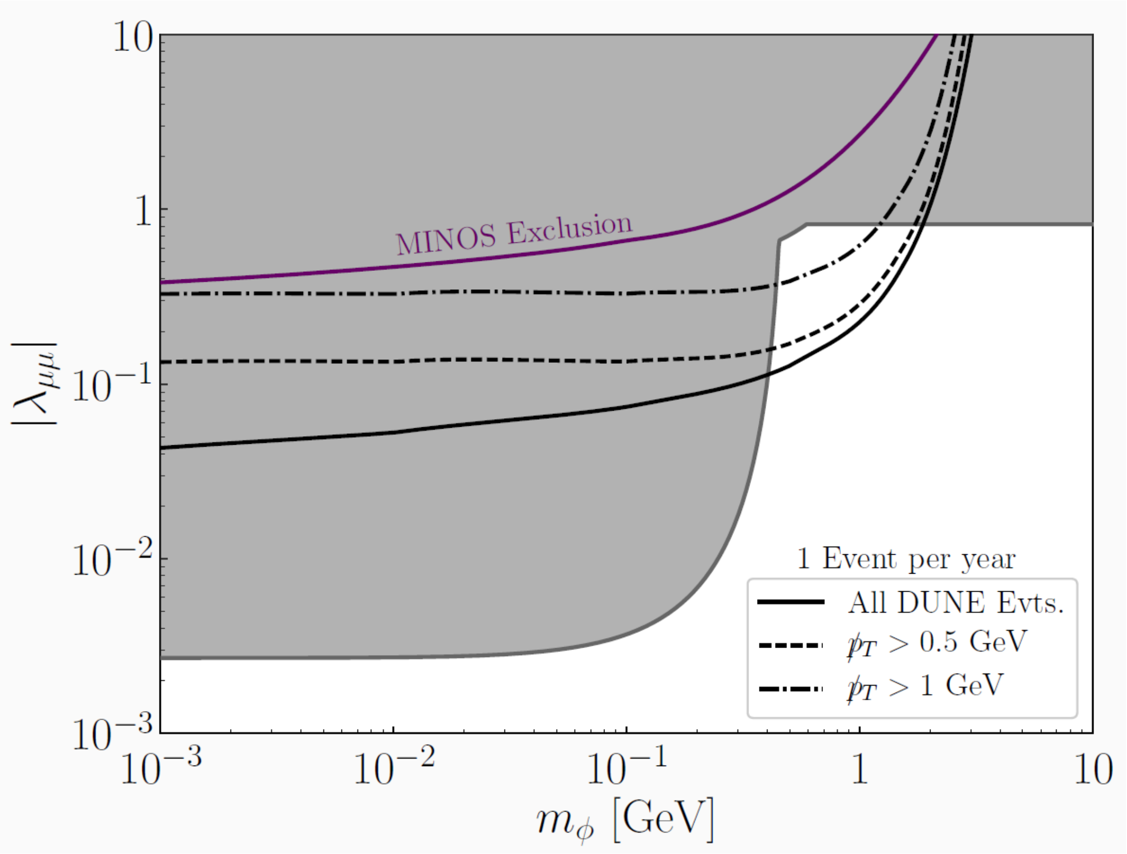
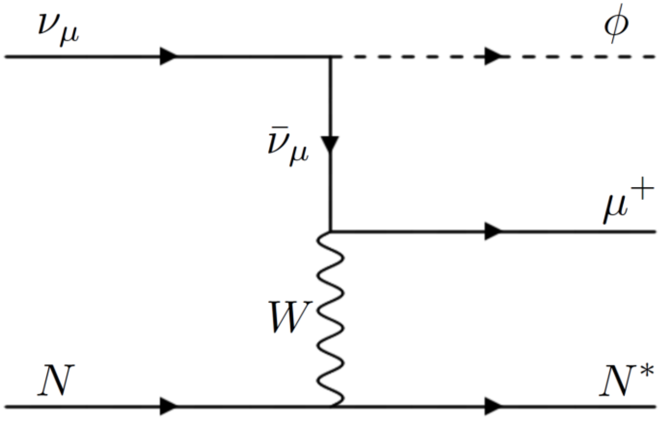


Brief aside: Terrestrial Sensitivity to νSI

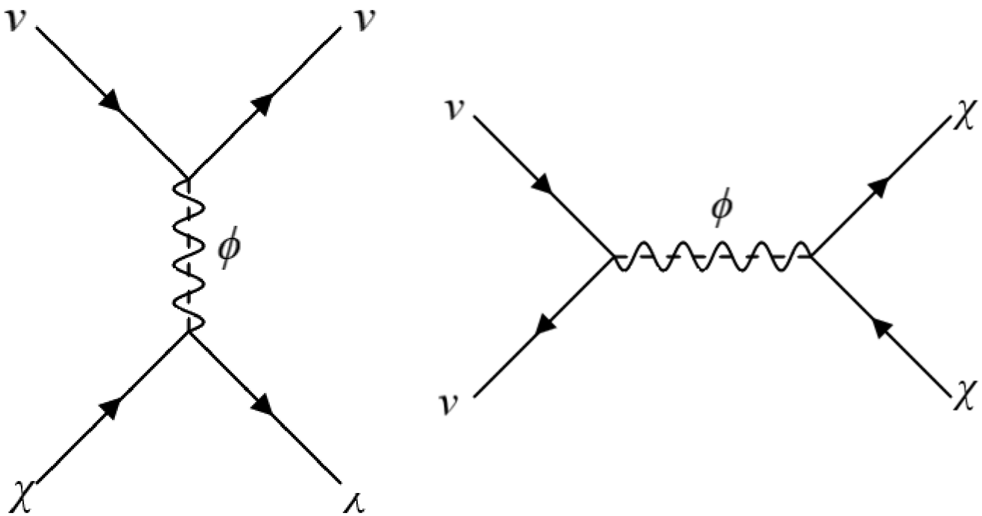




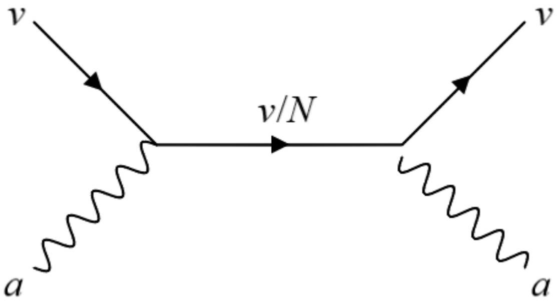
Slightly different setup: scalar carries lepton number 2, can search for in DUNE near detector by looking for events with large (visible) transverse momentum.

[Jeffrey Berryman, André de Gouvêa, KJK, Yue Zhang, 1802.00009]
[KJK, Yue Zhang, Forthcoming]

Other models to consider

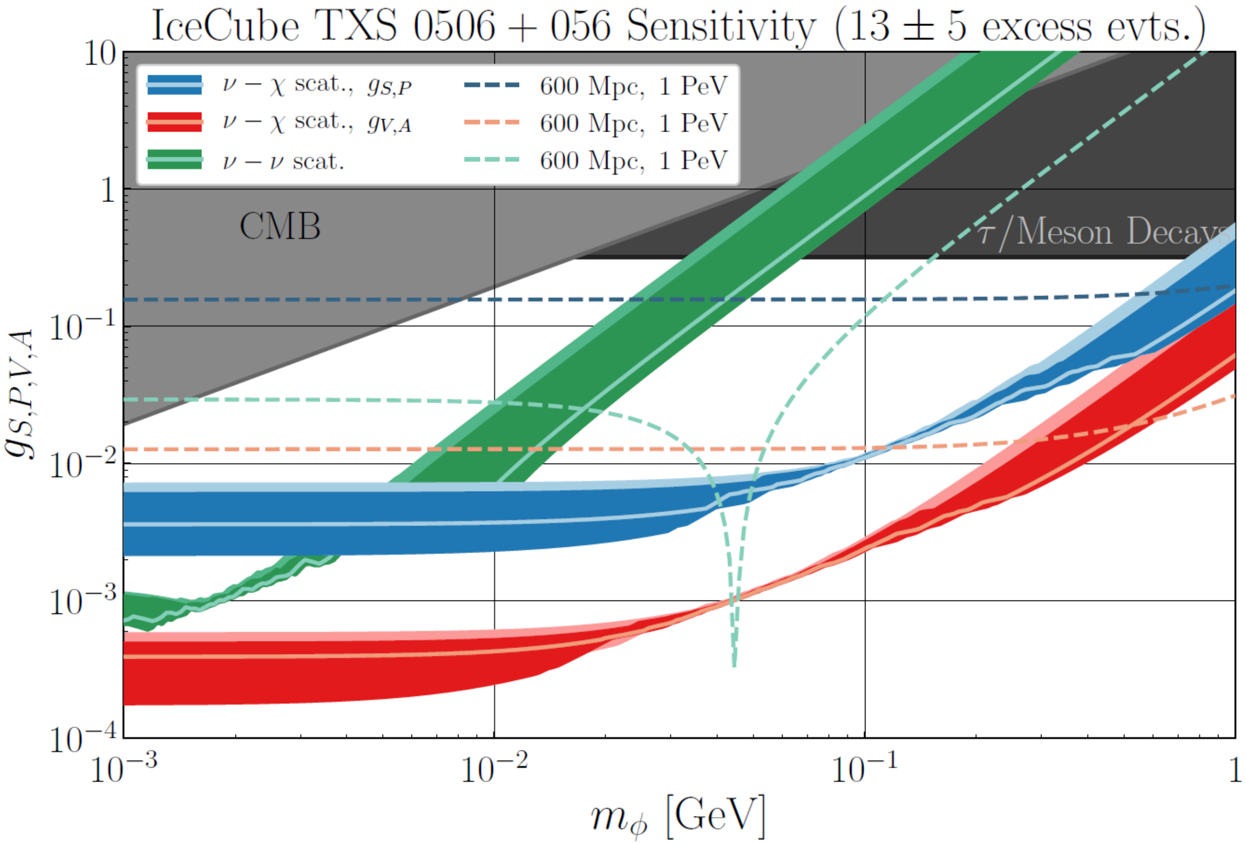


Neutrinophilic Dark Matter
(m_χ~ keV)



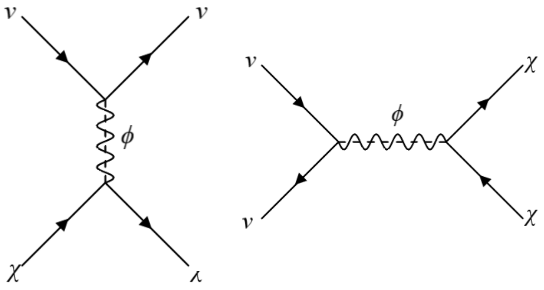
Lepton-Number-Charged Axions

Neutrinophilic DM

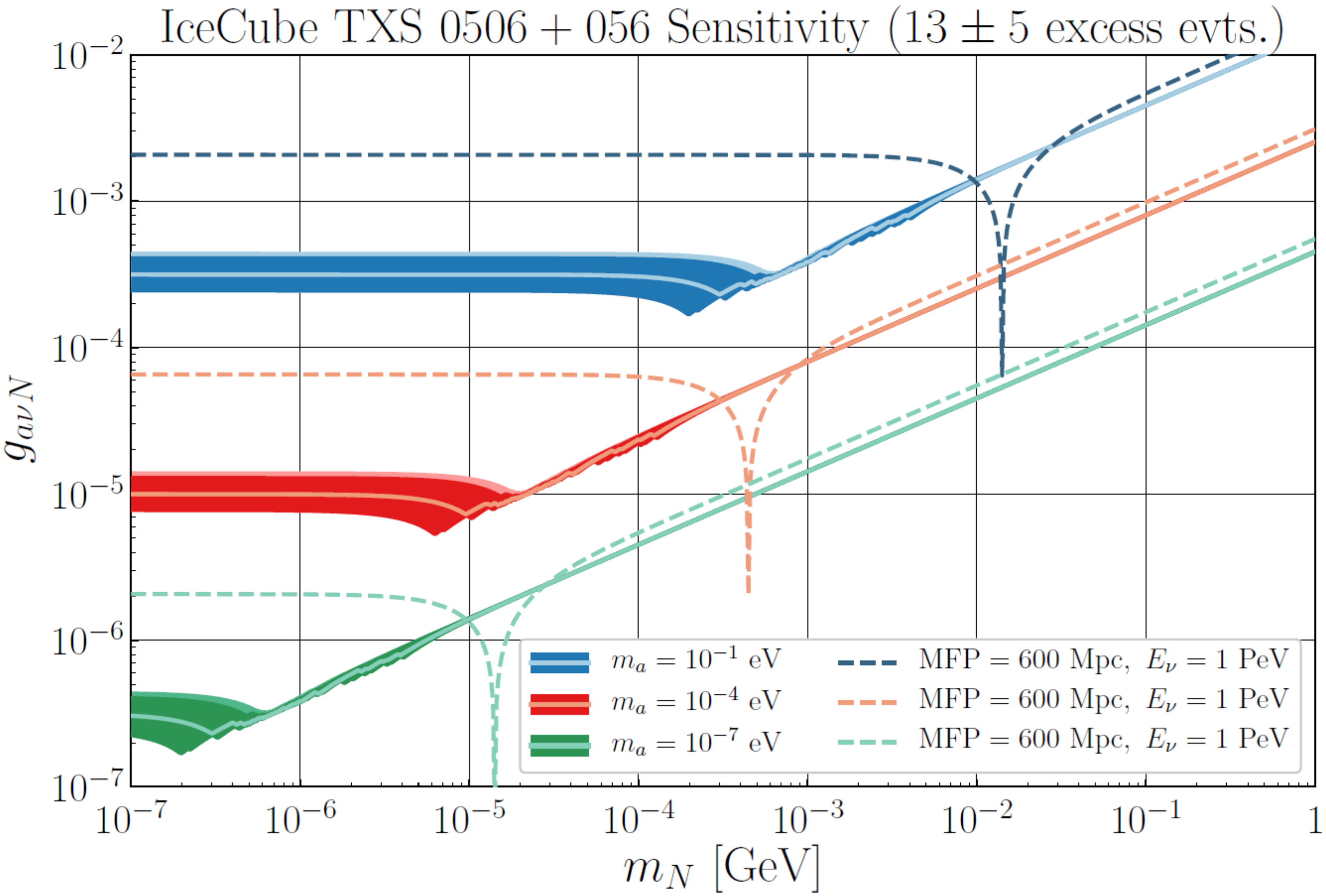


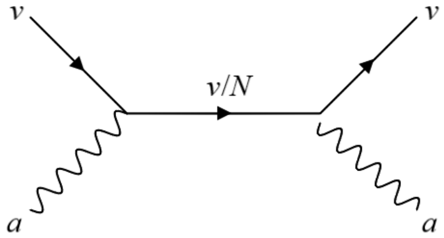
Fermionic χ can serve as thermal relic dark matter for masses near MeV
[KJK, Yue Zhang, Forthcoming]

Astrophysical probes provide an alternative basis (flavor vs. mass vs. combination) to probe new couplings



Lepton-number-charged Axions





Enough limits, how do we make a discovery?

This search strategy relies on observing events, recognizing that the neutrino flux matches expectations, and setting limits on the mean free path.

Non-observation of neutrinos is more challenging: which interpretation is more sensible, that the neutrino flux for a given astrophysical event is just lower, or that new physics caused neutrinos to be absorbed?

To make a discovery, we need many observations across different progenitor distances and neutrino energies -- then, the absence of events above some distance can point to this type of effect.

Conclusions

- Identifying sources of astrophysical neutrinos gives us additional handles.
    - Specifically, the distance that the neutrinos travelled allows us to make statements regarding their mean free path.
- Certain classes of new physics models can be probed better than ever by high energy neutrinos travelling great distances.
- Detection of such new physics is a greater challenge, but with existing and upcoming experiments, it could be possible.

Thank you!

Questions?