Seeking Neutrino Self-Interactions vs. AGN Source Modeling

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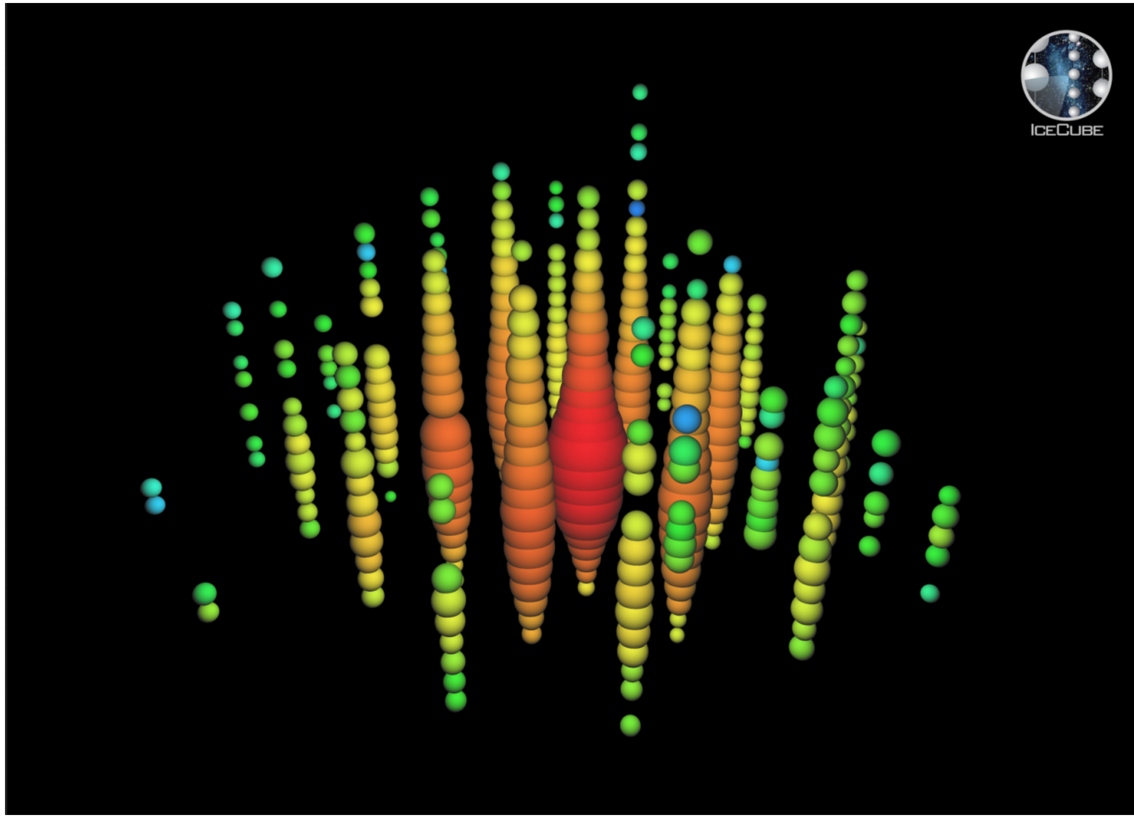
https://apod.nasa.gov/apod/ap130510.html

Motivation: Can use high-energy astrophysical neutrinos for….

- Particle Phenomenology – accesses neutrino interactions at very high energies

- High-Energy Astrophysics – provides insight into energetic / hidden phenomena

However, these can overlap (or interfere)!



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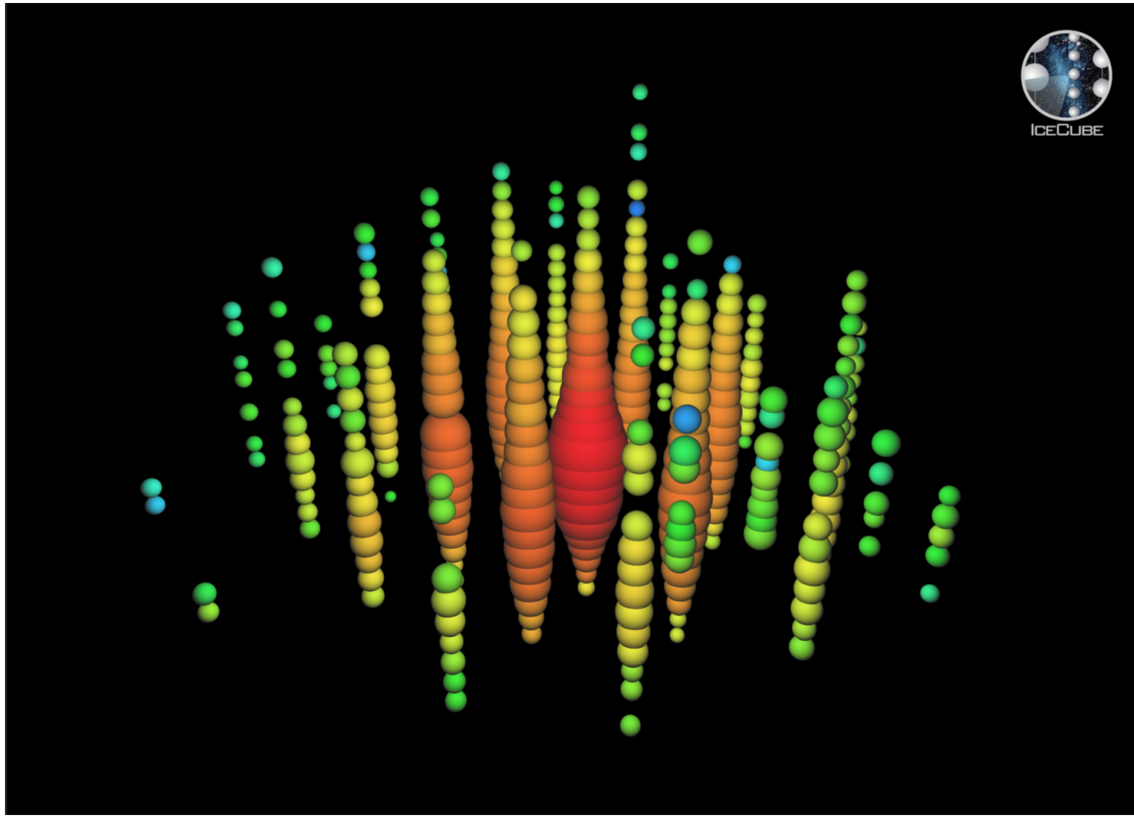
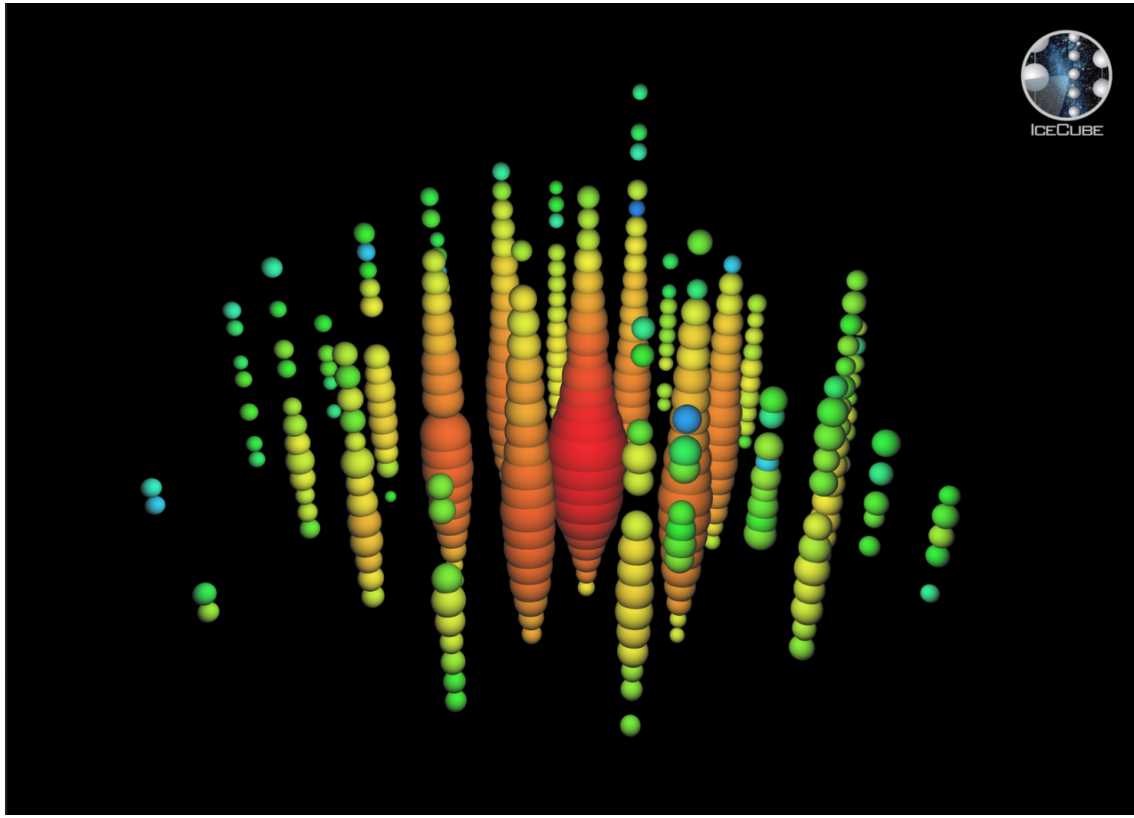


I'll show an explicit example soon, after providing some background.

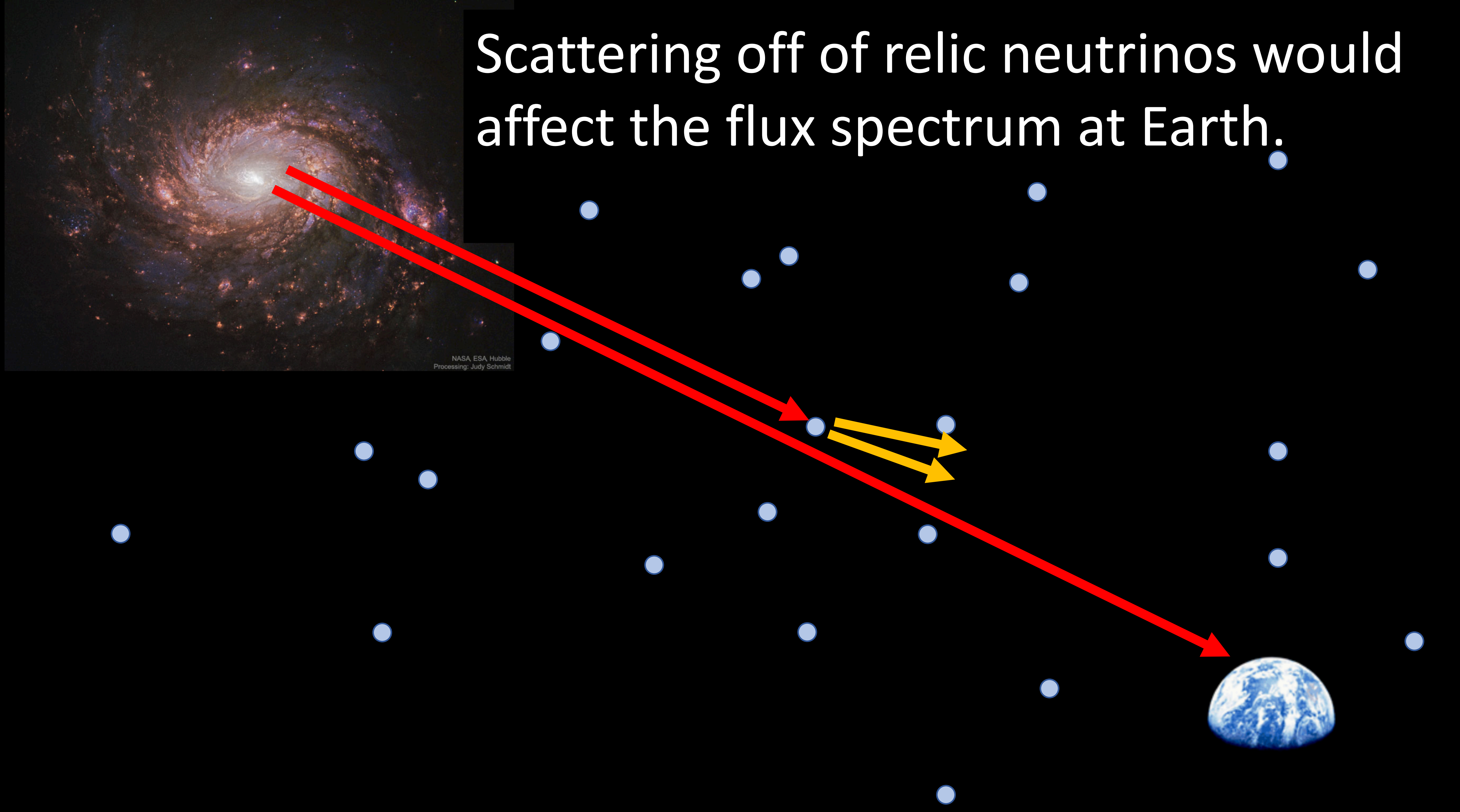
Outline of Talk

- Neutrino Self-interactions, high-energy neutrino constraints
  - arXiv:2307.02361 & upcoming paper

- Degeneracies between broken-power law models of AGN neutrino flux, and neutrino self-interactions
  - Work in progress



Scattering off of relic neutrinos would affect the flux spectrum at Earth.



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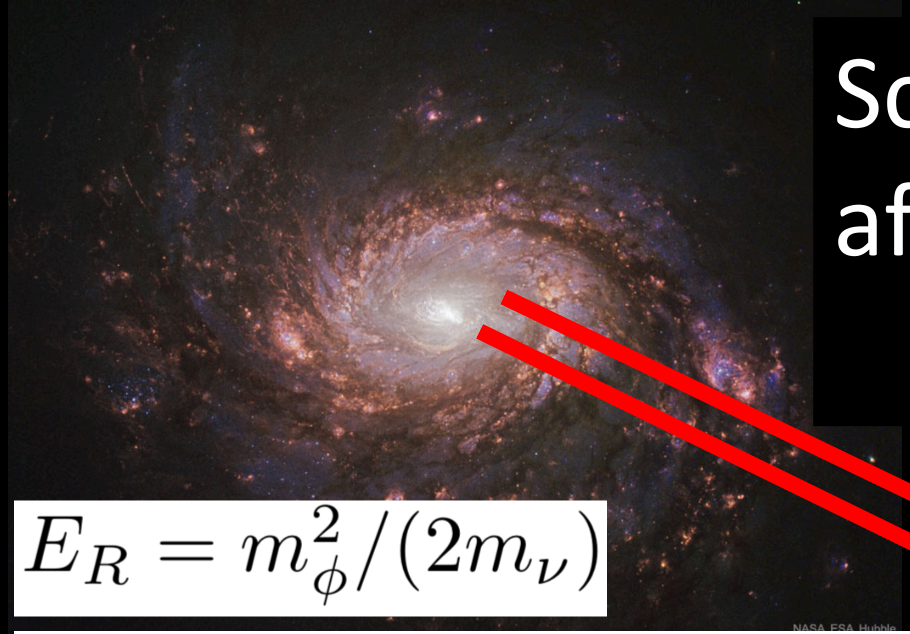
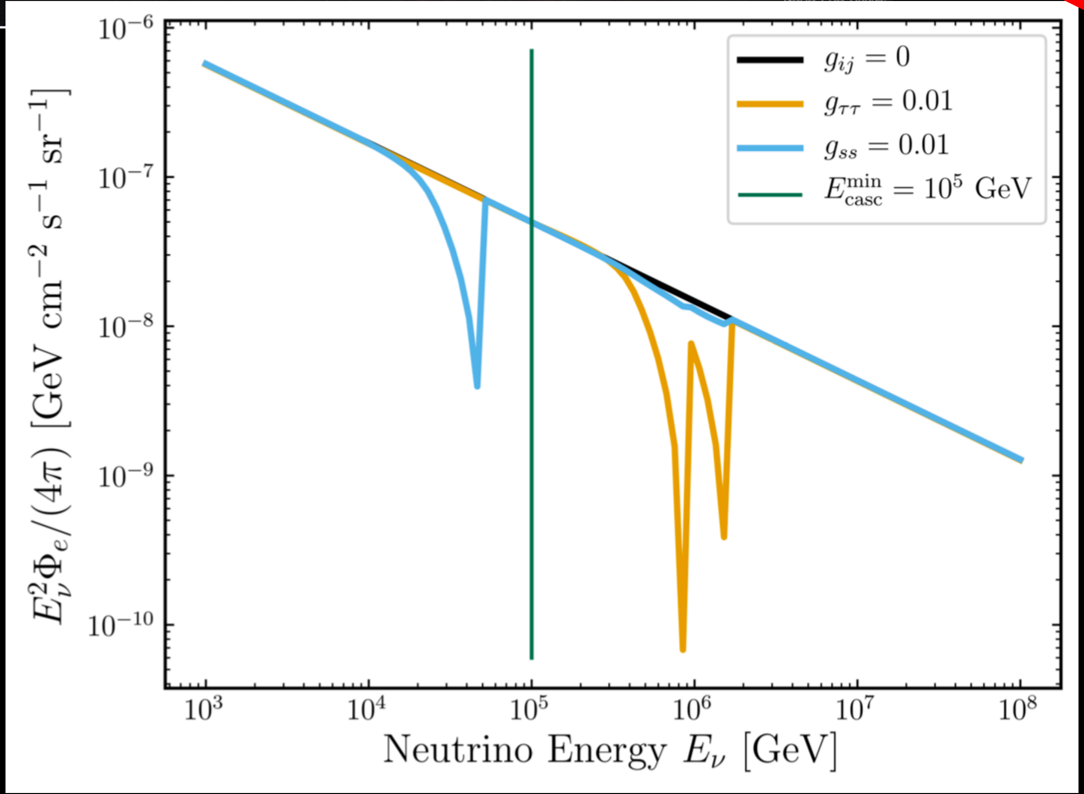
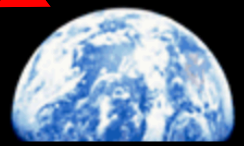


$$E_R = m_\phi^2/(2m_\nu)$$





Lots of people have thought about this;
Starting w/ Kolb & Turner re: SN 1987a

← From work w/ Cyril Creque-Sarbinowski & Marc Kamionkowski
CCS, JH, MK, Phys. Rev. D 103, 023527, arXiv:2005.05332

Catalogue of extragalactic neutrino point sources:

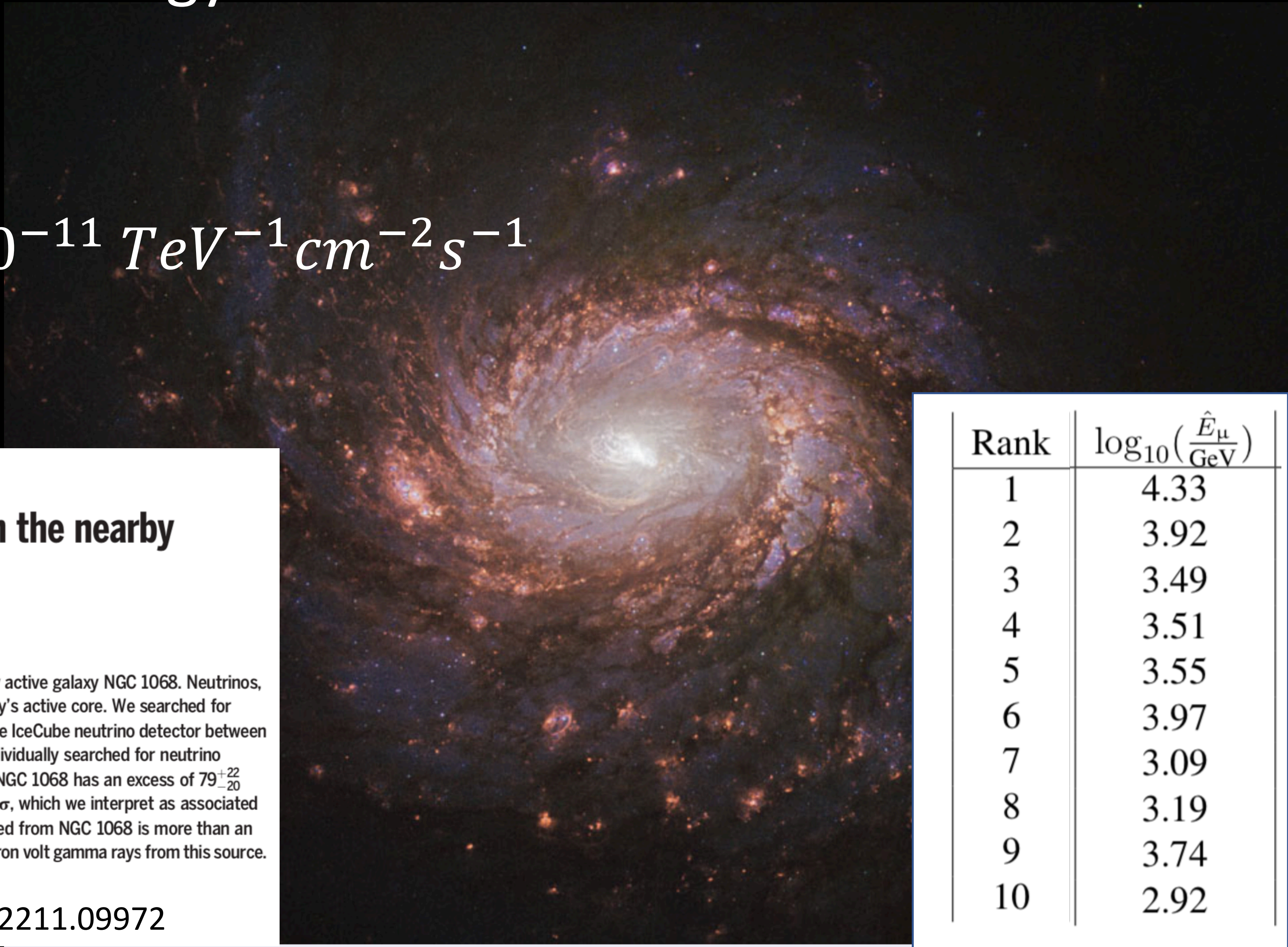
- SN 1987a: nearby, MeV neutrinos, ~20 detected
- TXS 0506+056: far away, high energy… and just a few detected

2011-2020: 79 high-energy neutrinos from NGC 1068

$$\Phi_\nu = \Phi_0 (E/E_0)^{-\gamma}$$

$$\Phi_0 = (5.0 \pm 2.1)\times 10^{-11}\, TeV^{-1} cm^{-2} s^{-1}$$

$$\gamma = 3.2 \pm 0.2$$



NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

A supermassive black hole, obscured by cosmic dust, powers the nearby active galaxy NGC 1068. Neutrinos, which rarely interact with matter, could provide information on the galaxy's active core. We searched for neutrino emission from astrophysical objects using data recorded with the IceCube neutrino detector between 2011 and 2020. The positions of 110 known gamma-ray sources were individually searched for neutrino detections above atmospheric and cosmic backgrounds. We found that NGC 1068 has an excess of 79^{+22}_{-20} neutrinos at tera–electron volt energies, with a global significance of 4.2σ, which we interpret as associated with the active galaxy. The flux of high-energy neutrinos that we measured from NGC 1068 is more than an order of magnitude higher than the upper limit on emissions of tera–electron volt gamma rays from this source.

Science 378, 6619, 538 (2022), arXiv: 2211.09972

Rank	$\log_{10}(\frac{\hat{E}_\mu}{\text{GeV}})$
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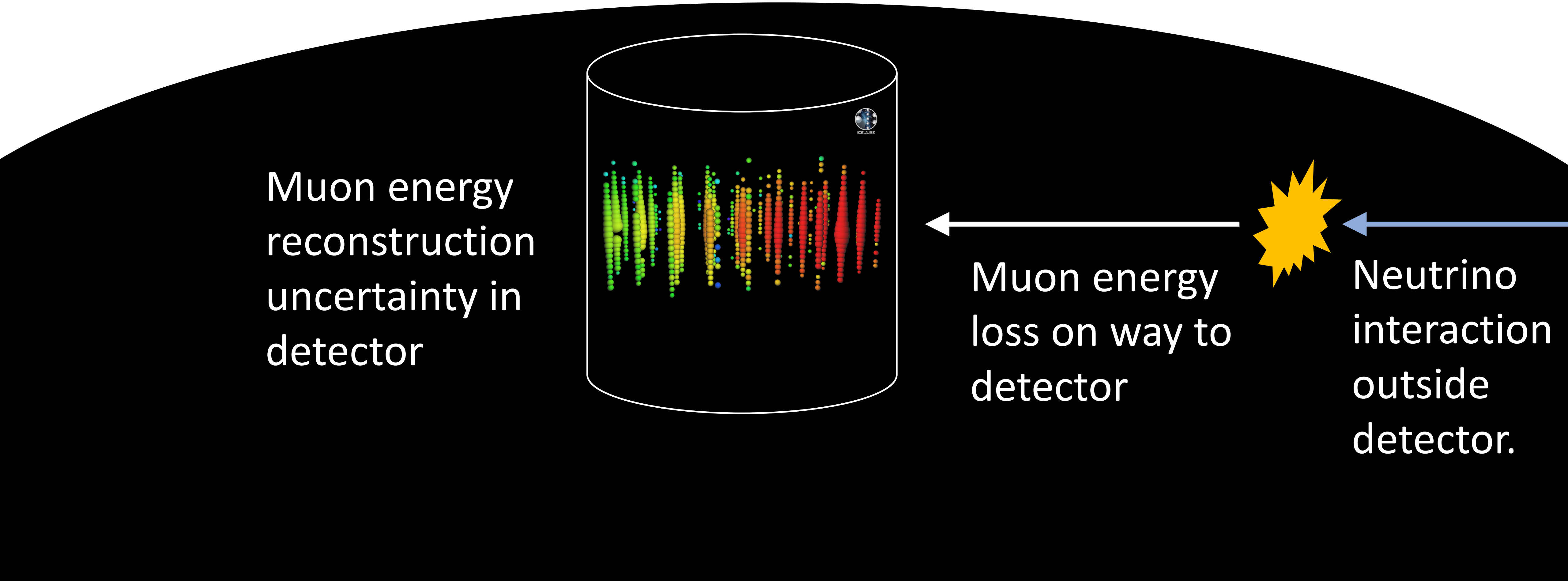
To analyze effect of nonstandard neutrino physics:

- What effect does the model in question have on the signal arriving at Earth?
- How well does the detector let us “see” this signal?

For this event: “The most probable muon energy is 604 TeV, and the most probable neutrino energy is 880 TeV.”



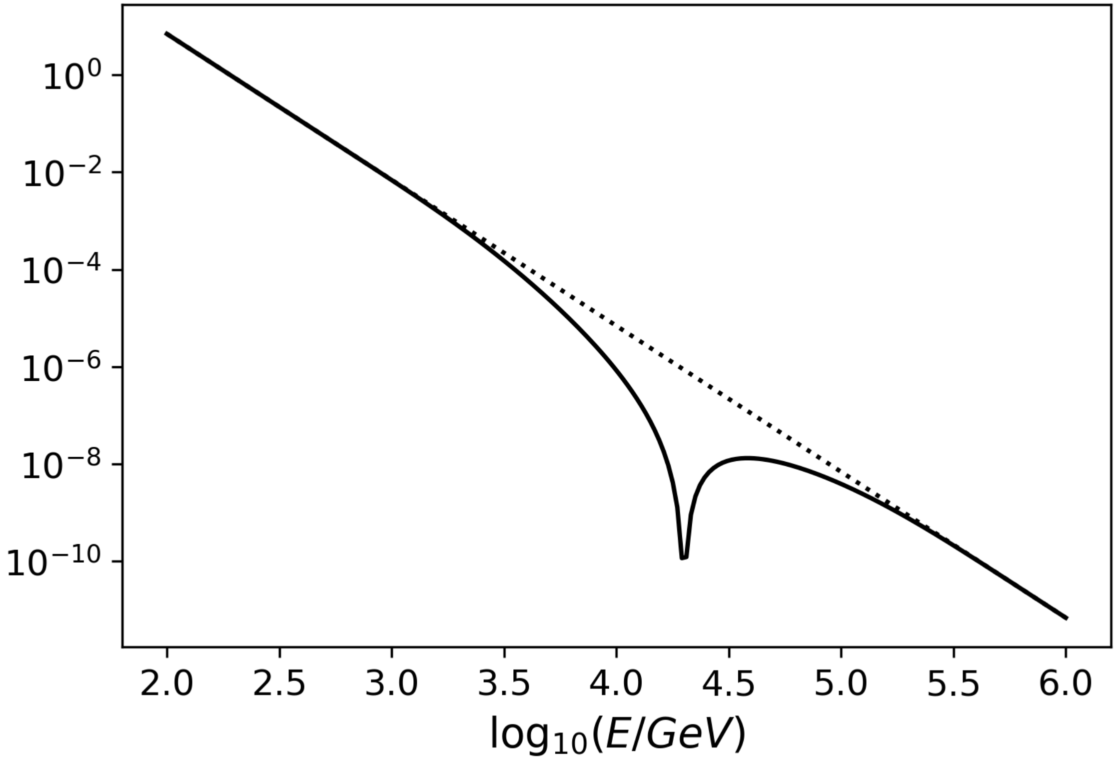
Energy PDF modeling

$$\sigma = \frac{g^4}{4\pi} \frac{s}{((s - m_\phi^2)^2 + m_\phi^2 \Gamma^2}$$

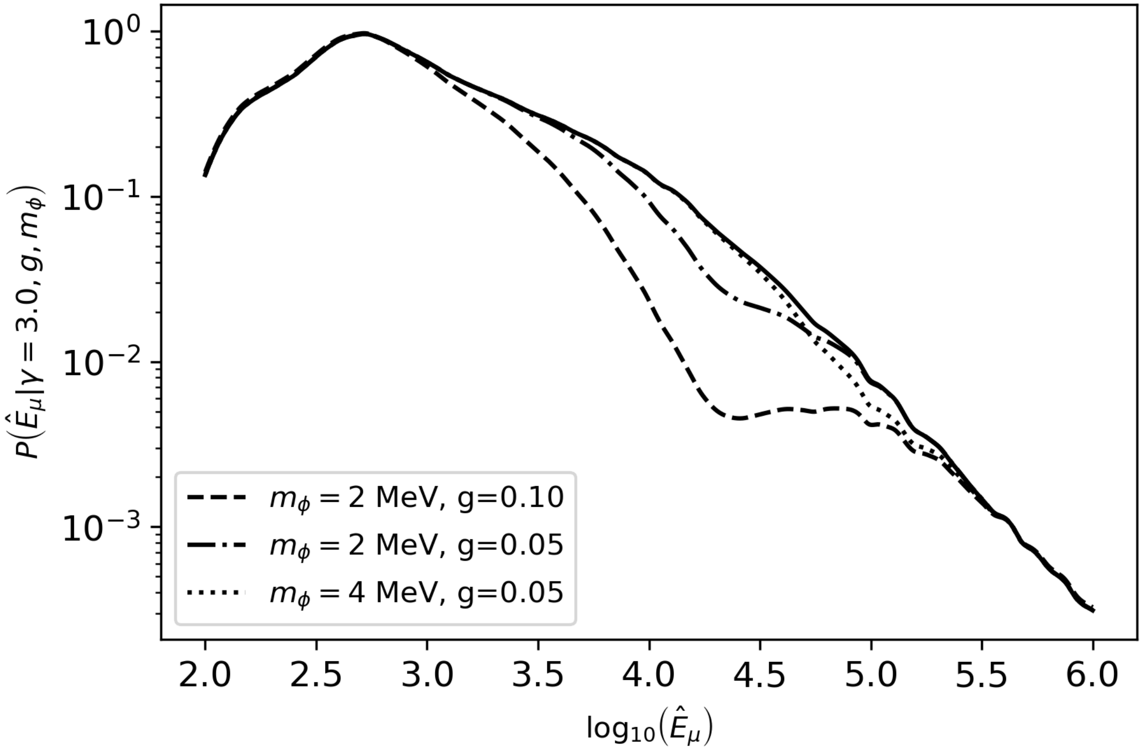
$$s = 2 E m_\nu \qquad \Gamma = g^2 m_\phi / (4\pi)$$

$$E_R = m_\phi^2 / (2 m_\nu)$$

Effect on incident flux…



…and energy pdf



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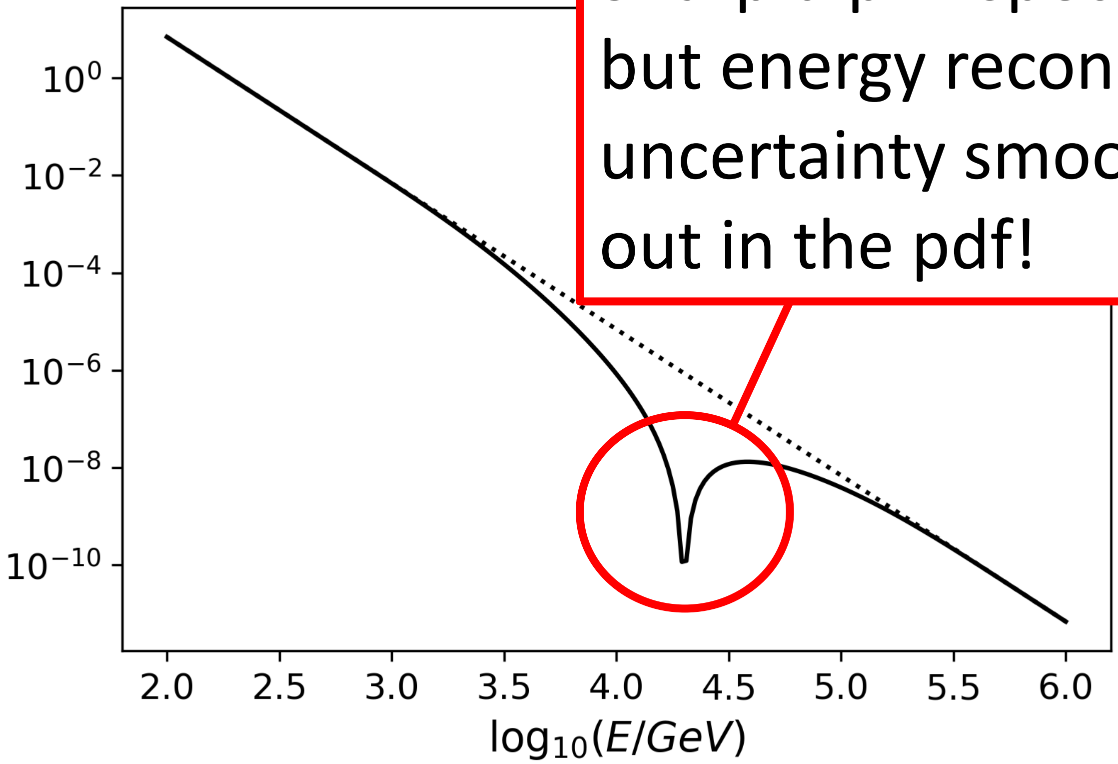
Effect on inci

Sharp dip in spectrum… but energy reconstruction uncertainty smooths this out in the pdf!



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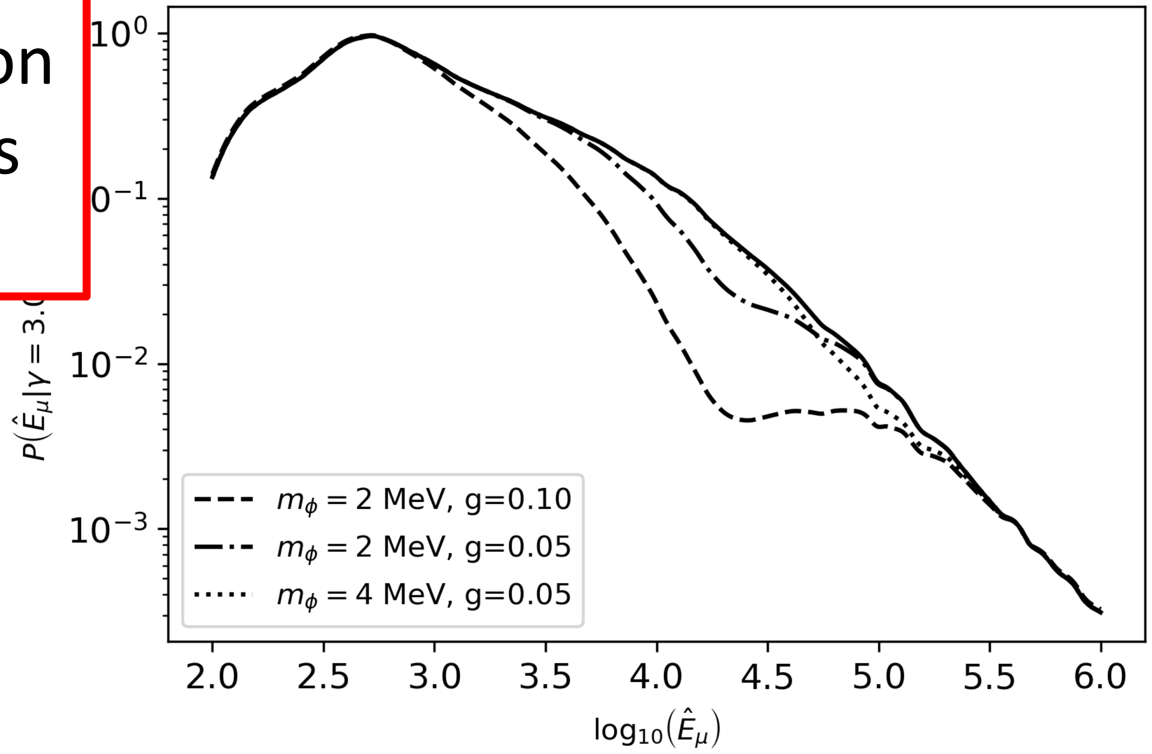
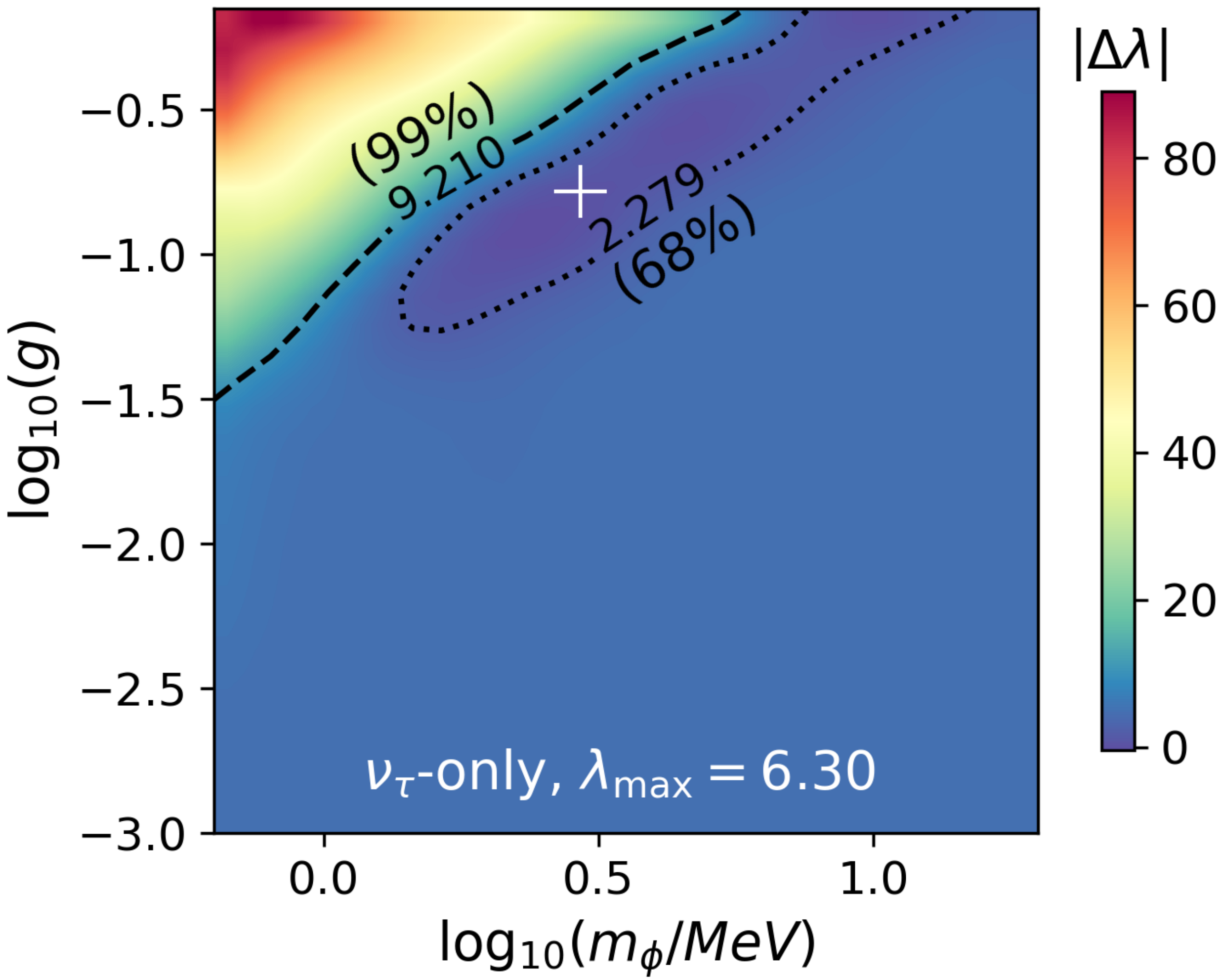


Results

Tau-neutrino specific self-interaction

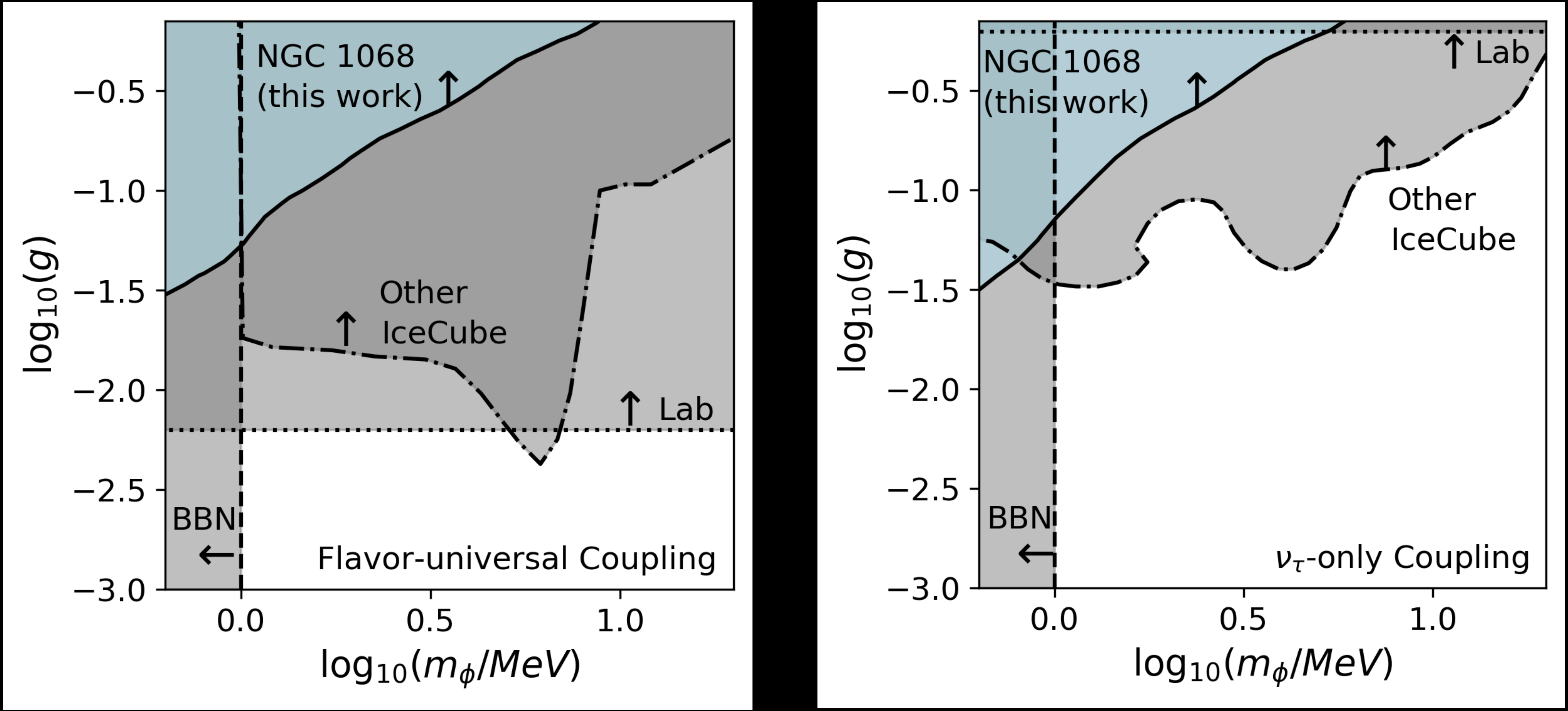


This LLH or higher in 4.3% of trials if null hypothesis is true… a.k.a. not significant!

Test statistic $\lambda = 2\log\left(\frac{\mathcal{L}(H_1)}{\mathcal{L}(H_0)}\right)$,

max. value $\lambda = 6.30$ indicated by "+".

Constraints from NGC 1068 (see 2307.02361)



More Comprehensive Constraints?

- Different analyses have considered point source constraints, or diffuse constraints. (And methodology/assumptions not always the same!)

- Each source has its own strengths and weaknesses (e.g. diffuse flux requires assumptions about where neutrinos sourced) – a joint analysis among available sources will be valuable.

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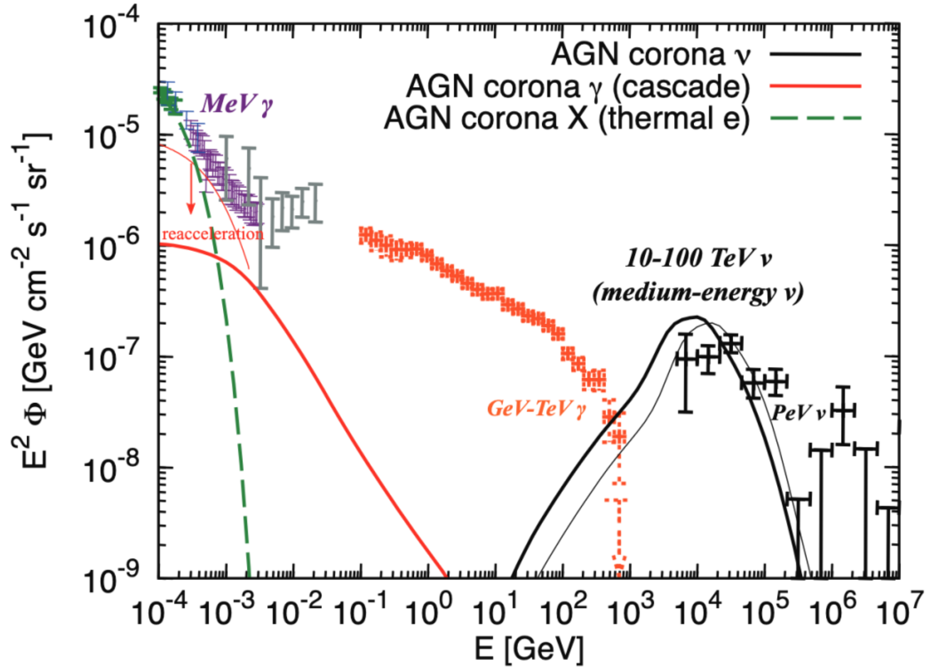
- Ongoing work (paper out soon) with Swarthmore student Sabrina Hanning:
  - Combined analysis of NGC 1068, TXS 0506+056, and diffuse HE flux data.

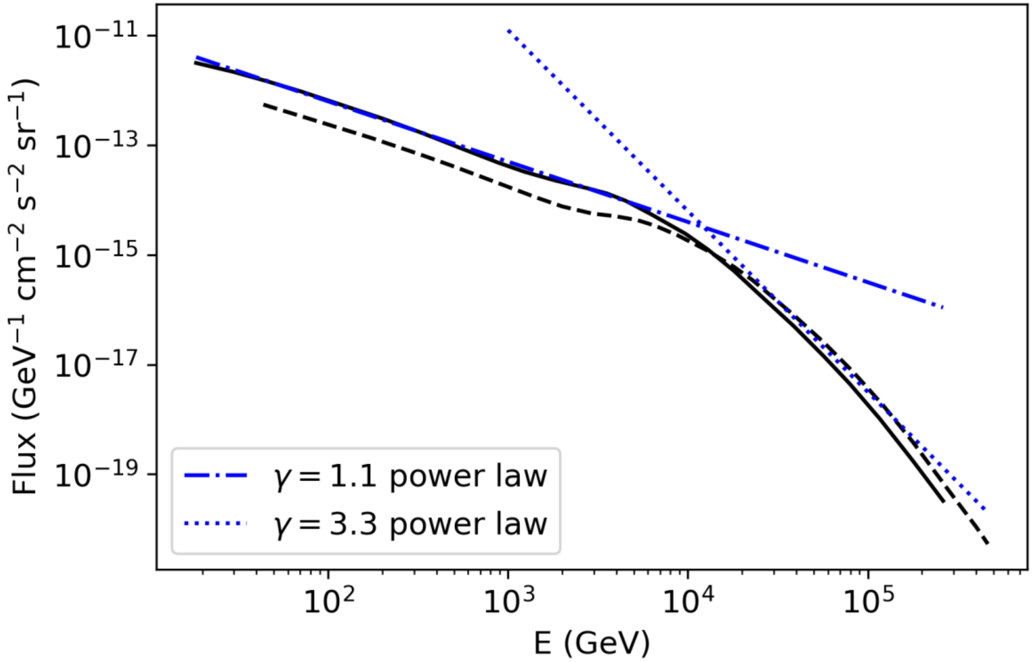
But…

What about source modeling?

- AGN spectra not expected to be strict power law over all energies (see e.g. 1904.04226).

- A broken power law looks “similar” to some neutrino self-interaction effects.

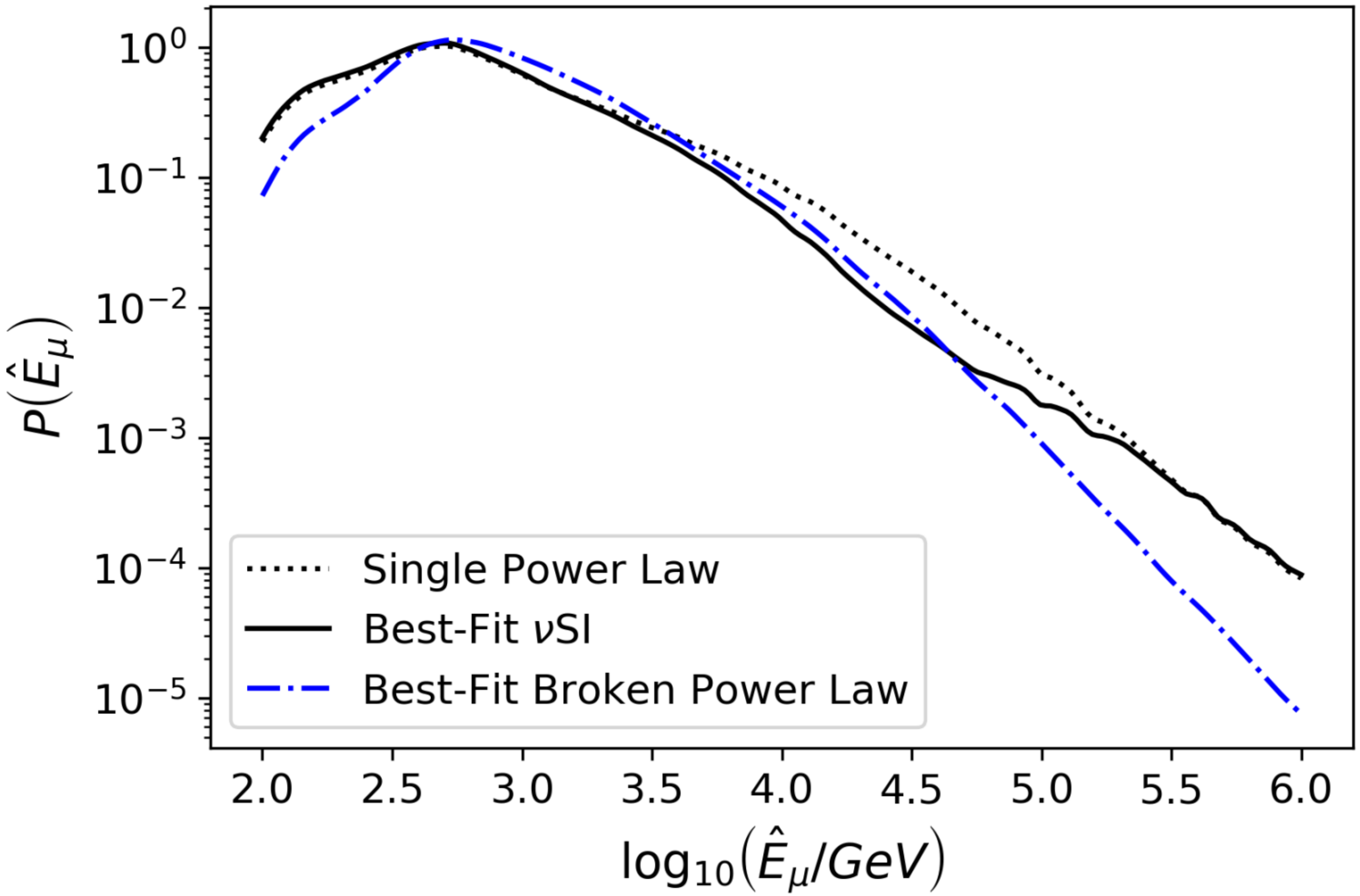




Two Fits to NGC 1068 Data

The energy pdf corresponding to best-fit parameters for broken power law, versus neutrino self-interactions.

Unsurprisingly, energy pdfs for best-fit values of the parameters look very similar!

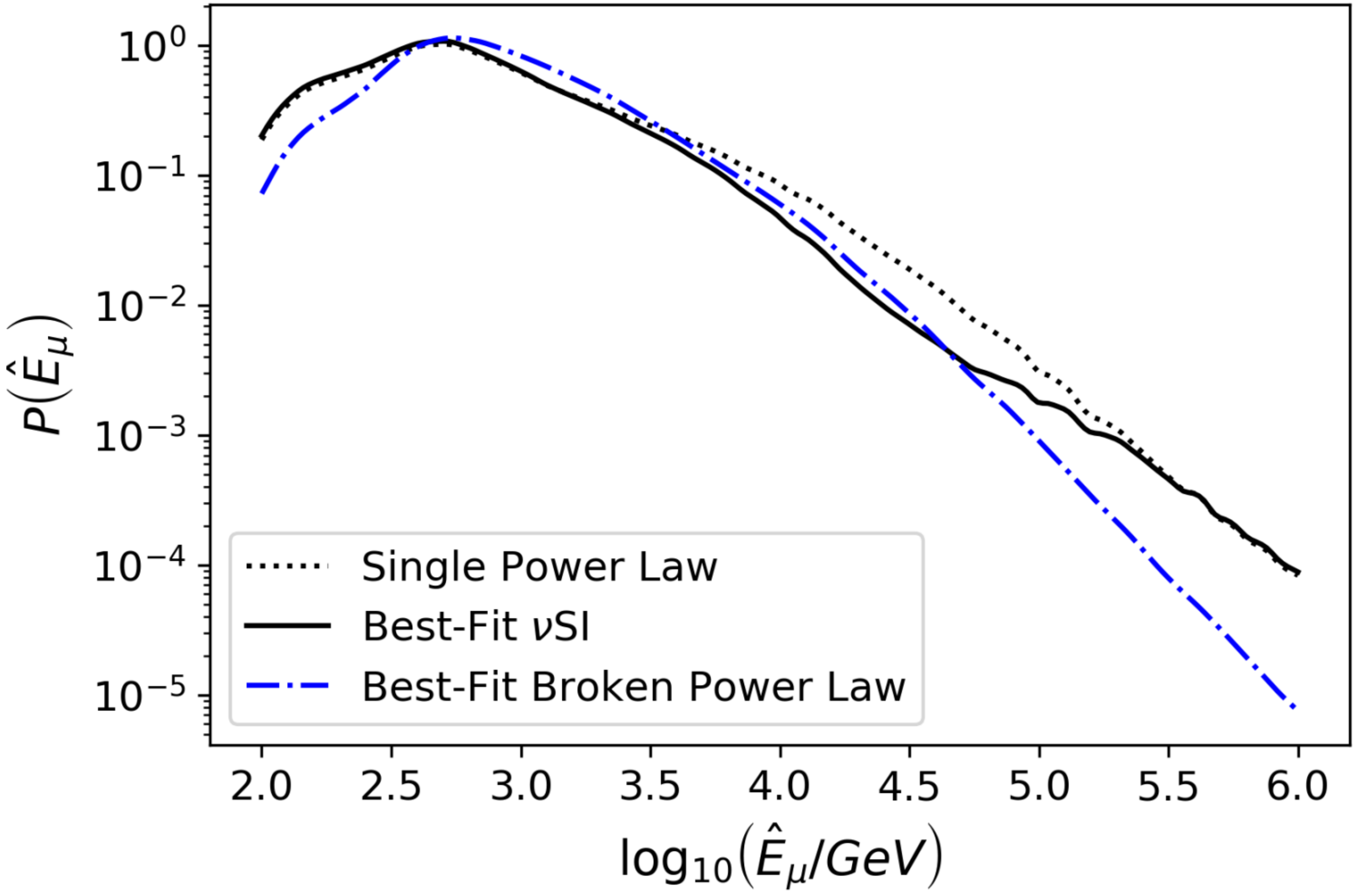


How can this degeneracy be resolved with future data?

Two initial thoughts:

- Effect of neutrino self-interactions should grow with distance, while BPL shouldn't.

- The likelihood ratio Log(L_{BPL} / L_{nuSI}) is a reasonable statistic to look at first…



How can this degeneracy be resolved with future data?

Our approach: Try this out by running the analysis on mock data.

→ But we need to pick a plausible set of future observations! How?

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Assumptions:

- Take Seyfert galaxies to all have same ratio of neutrino to x-ray luminosity. (see e.g. 2404.05690, 2406.06684, 2406.07601)
- Use this & (current) effective area to estimate 20-year event number.
- Use a cutoff for which would have been “discovered” in that time.
- This oversimplifies the discovery process, but is (I think) reasonable for understanding how results scale.

Back to

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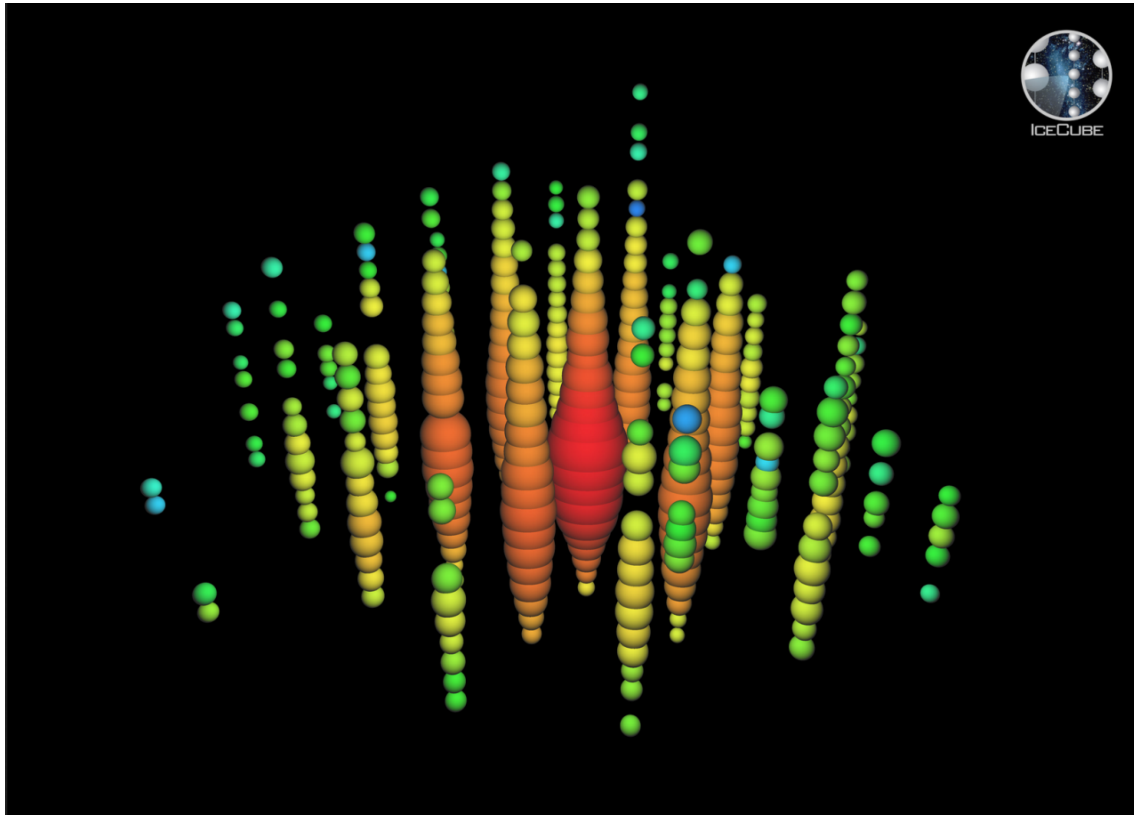


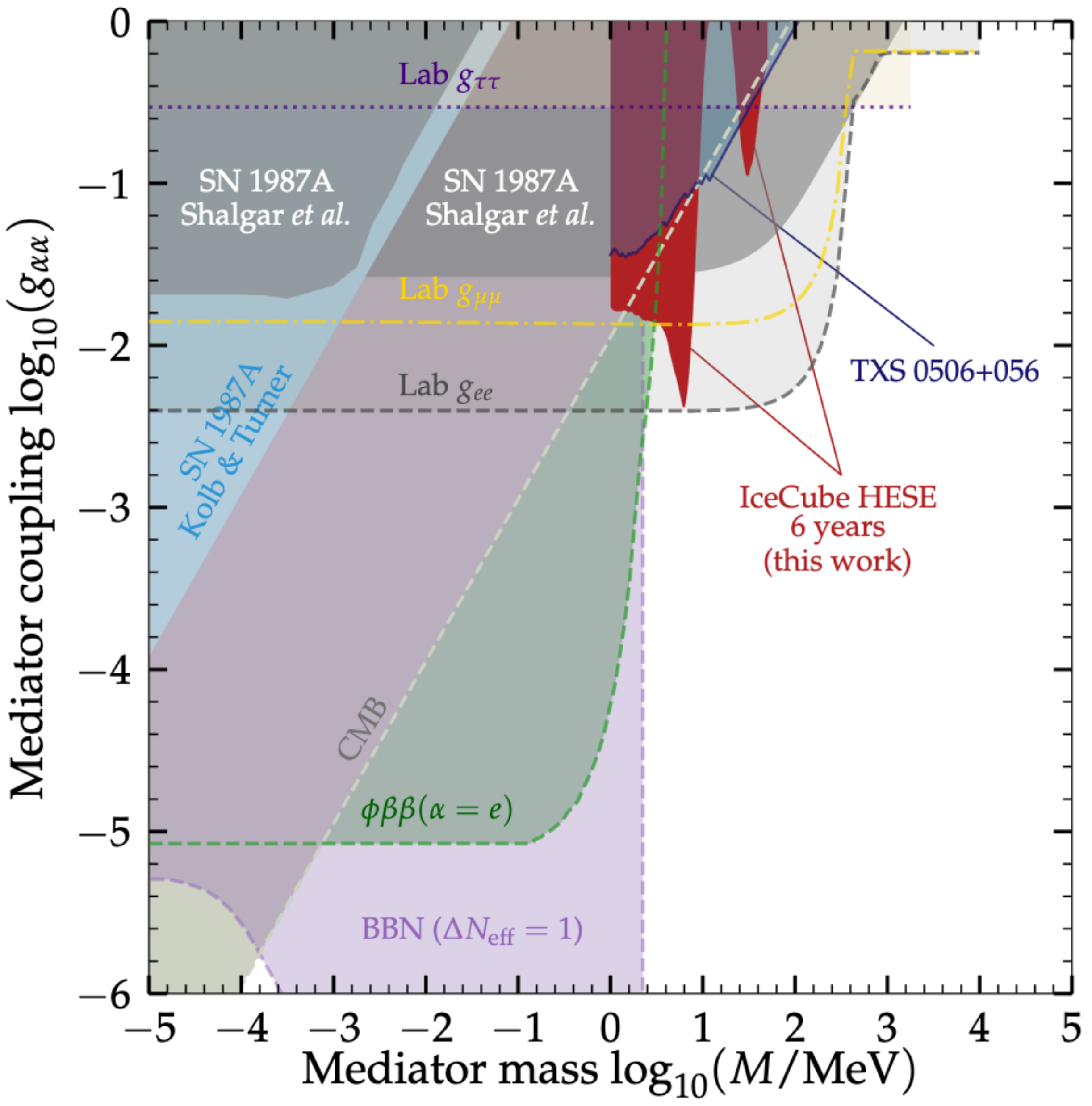
However, these can overlap (or interfere)!

As more data accumulates, it will be increasingly probed for both of these aspects.
It's worth thinking now about the limitations and opportunities!

Thank you!

Existing constraints from…

- Other sources of astrophysical neutrinos (SN 1987A, diffuse high-energy flux, TXS 0506+056)
- Cosmology (relativistic degrees of freedom from CMB, BBN)
- Lab experiments (decays w/ final-state neutrinos)



Bustamante et al, 2001.04994

What mediator masses do the highest-energy events probe?

Order of magnitude estimate…

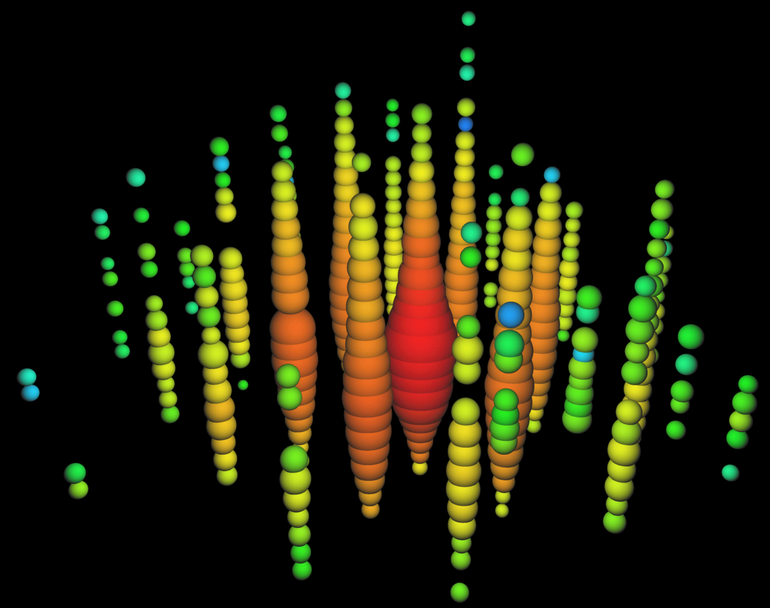
$$E_R = \frac{m_\phi^2}{2m_v}, \quad \text{so} \quad m_\phi \sim \sqrt{2\, E_{signal} m_{nu}} \sim \sqrt{10^5 10^{-10}}\ \text{GeV}$$

∼ up to several MeV…

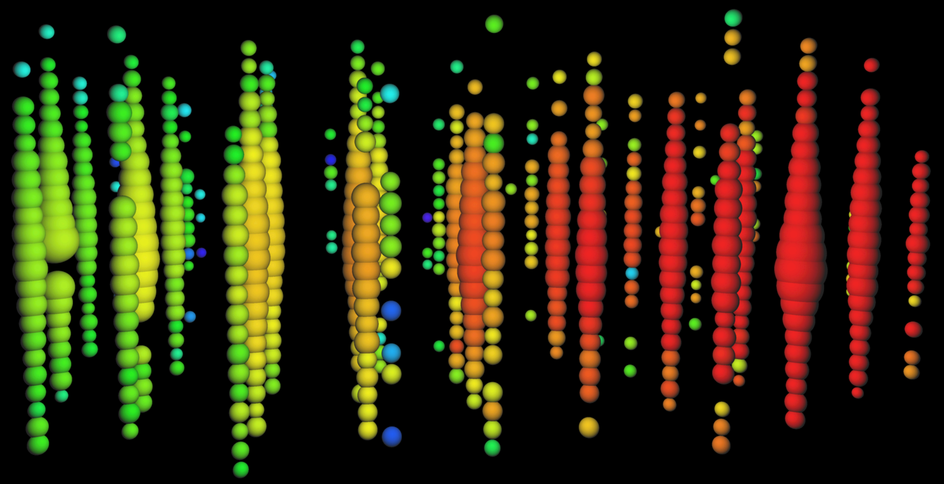
(above BBN bound)

<u>But</u> note that this is the reconstructed muon energy, an underestimate of neutrino energy.

IceCube Event Types



- Cascades: good energy estimation, less accurate direction.



- Tracks: Good pointing, energy not as well-measured.
- Point source search uses muon tracks. Sample consists of signal + atmospheric background.

Evidence for / constraints on neutrino self-interactions?

- Want to know if test hypothesis (presence of neutrino SI) is favored over the null hypothesis (spectrum is background + power-law signal).

- Likelihood ratio test statistic: $\lambda = 2\log\left(\frac{\mathcal{L}(H_1)}{\mathcal{L}(H_0)}\right)$.

- Likelihood function is

$$\mathcal{L}(\{x_i\}|\{\theta_i\}) = \prod_{i=1}^{N}\left[\frac{n_s}{N}f_{\text{signal}}(x_i|\theta_i) + \left(1-\frac{n_s}{N}\right)f_{\text{background}}(x_i)\right]$$

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Parameters that maximize λ → best fit.

Value of max λ tells us merit of H1 rel. to H0.

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Spatial pdf x energy pdf

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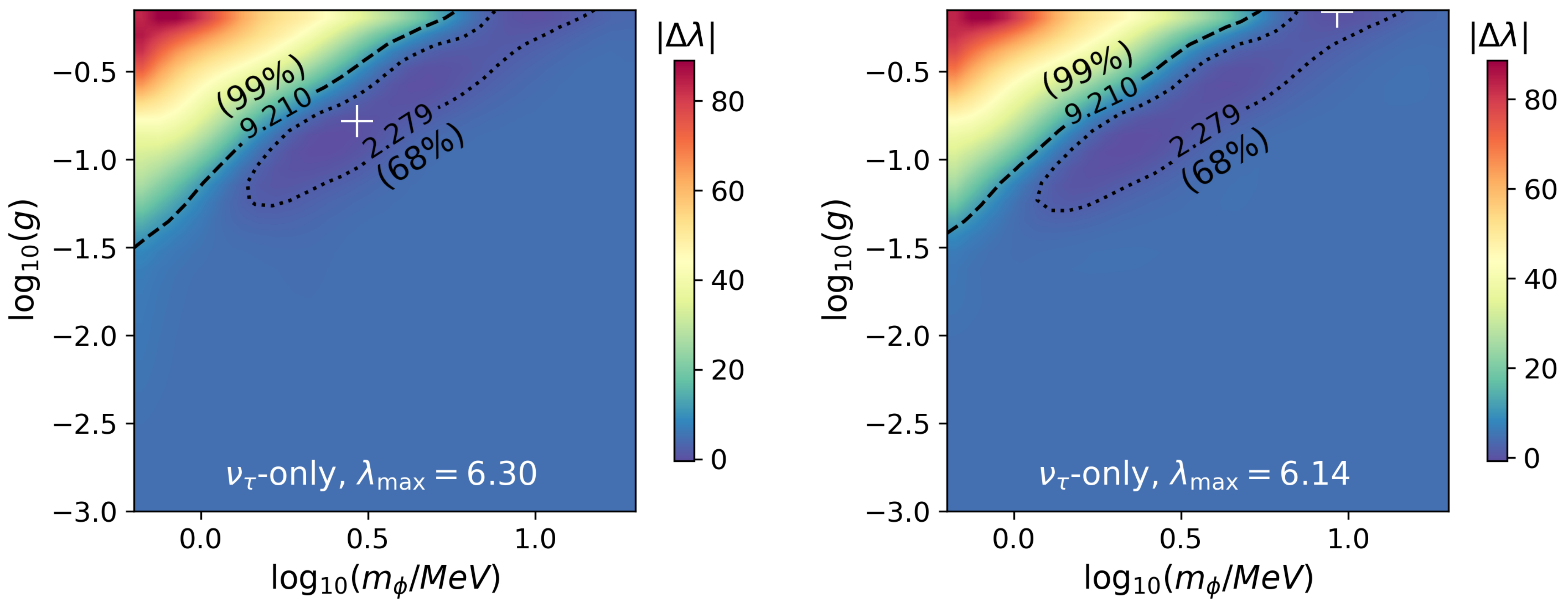
Spatial pdf x energy pdf

Depends on neutrino self-interactions

Effect of neutrino mass scale



Highest allowed mass scale vs. Lowest mass reduced by half

IceCube Point Source Search

- Point source search: 665,293 all-sky track events over ~10 years, 19,452 w/in 15 degrees of NGC 1068.

- Most significant events around $log_{10}(\hat{E}_\mu/GeV) \sim 3-4$, but there are contributions from across the energy range $log_{10}(\hat{E}_\mu/GeV) \sim 2-5$.

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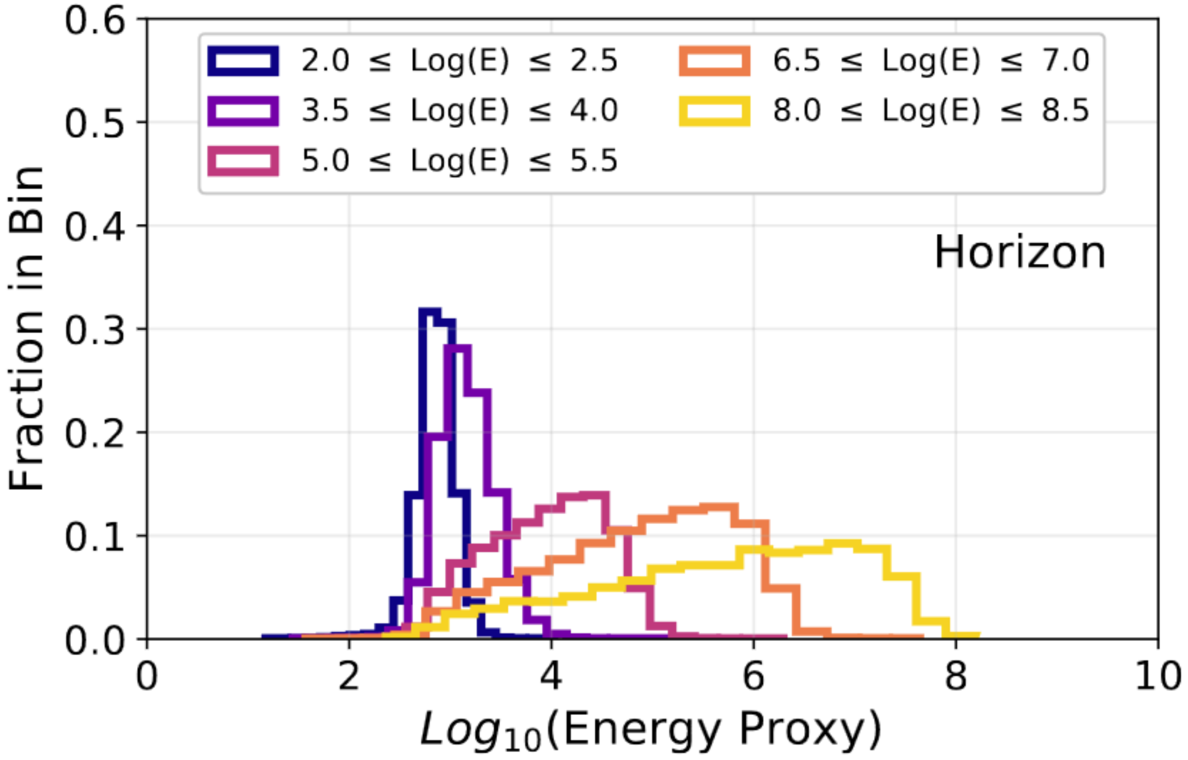
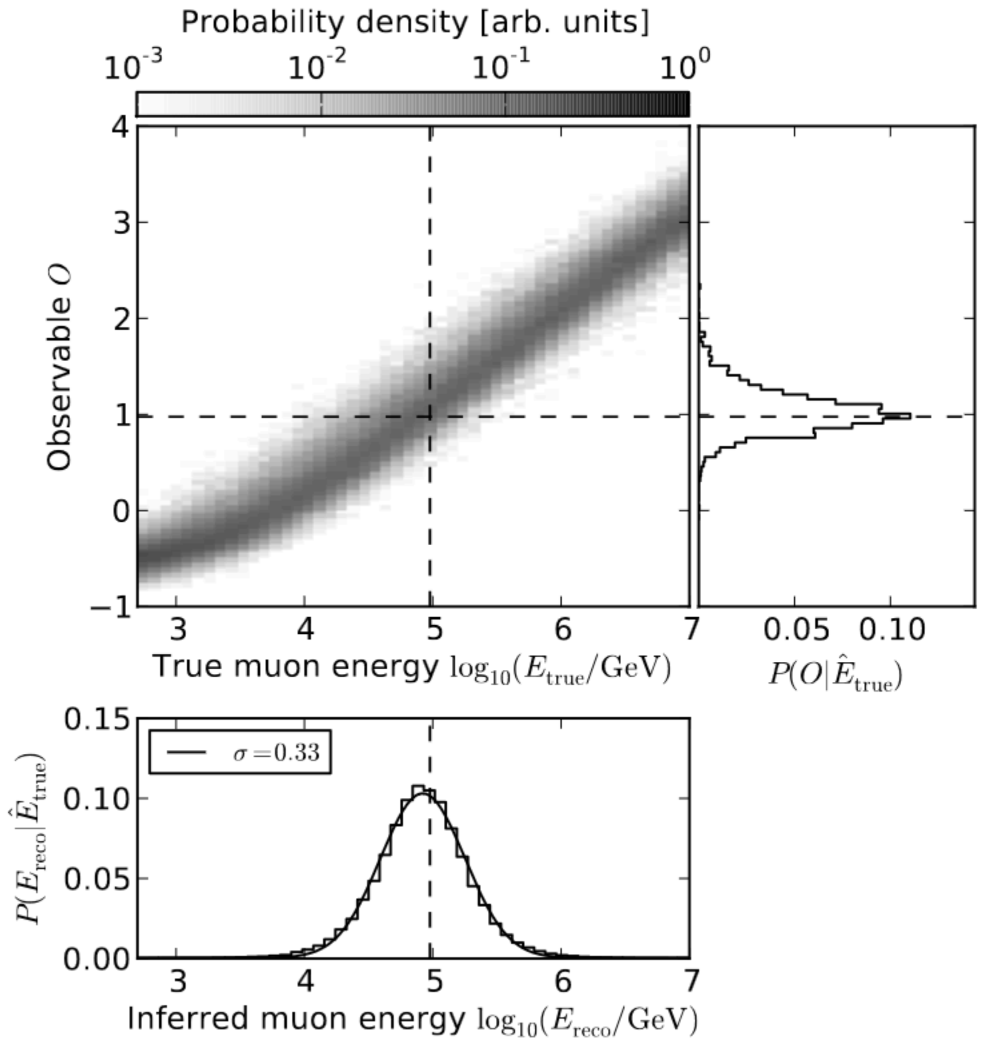
Table S4: **The ten events which contribute most to the test statistic at the position of NGC 1068.** Ranking and characteristic of the top 10 events contributing to the neutrino ex-

Muon and Neutrino Energy Reconstruction

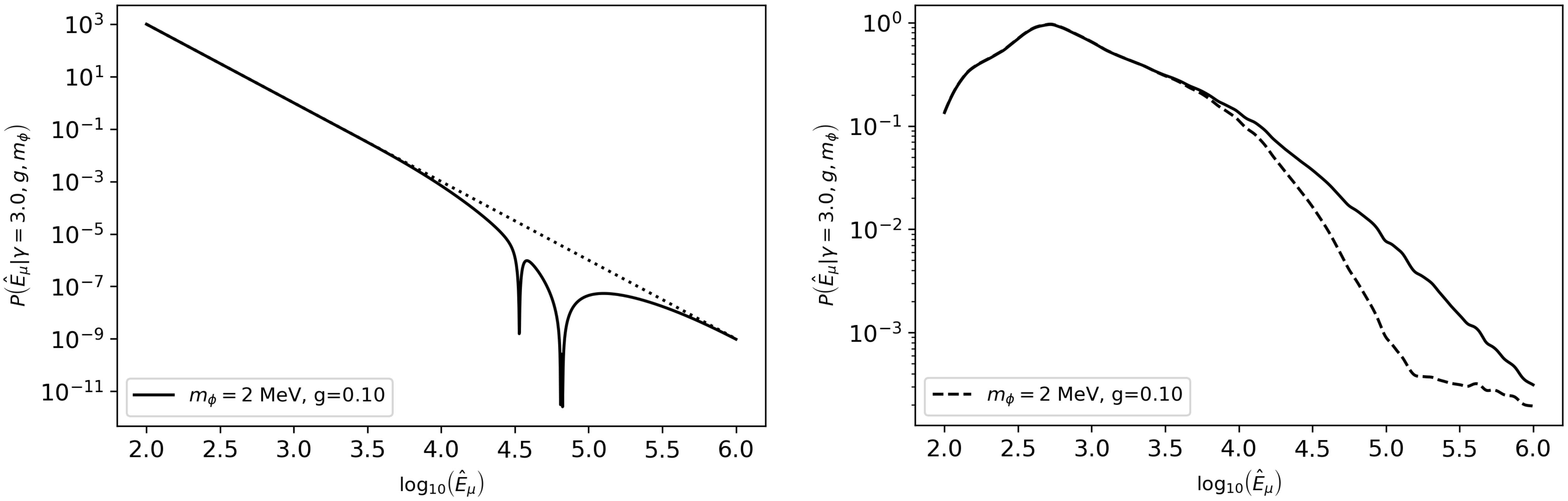


arXiv:2101.09836



arXiv:1311.4767

With three neutrino flavors and mixing during propagation:



Cartoon* Example: Several AGN w/ same unknown neutrino spectrum

Look at likelihood ratio for two opposing test hypotheses:

$\mathrm{Log}(L_{BPL} / L_{nuSI})$