Using IceCube Data to Constrain Neutrino Self-Interactions

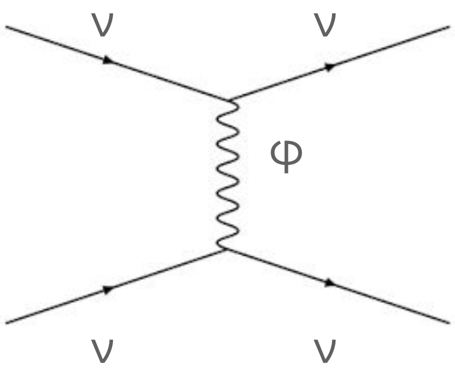
Sabrina Hanning

With Jeffrey Hyde

SWARTHMORE

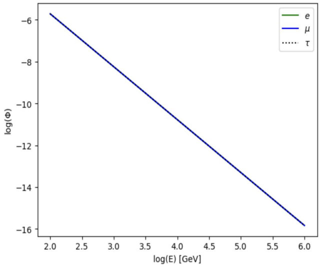
Neutrino Self-Interactions

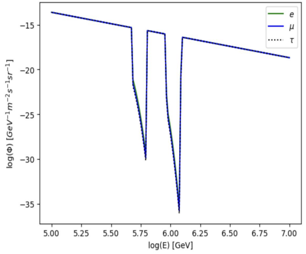
- BSM ν SI
  - Scalar mediator, φ with mass m_{φ}
  - Coupling constant, g
- SM mediated by Z boson, low cross-section

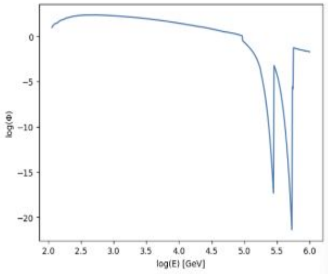


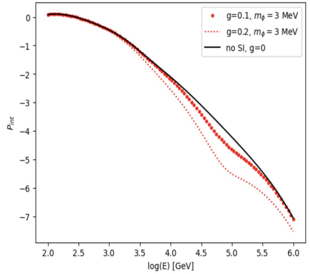
Overview

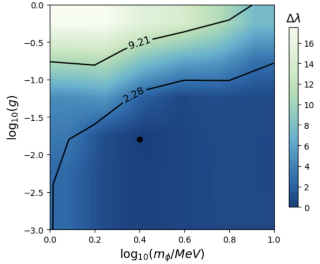
Model Sources + Model Propagation + Model Detection + Analyze Existing Data with Model → Constrain Interactions









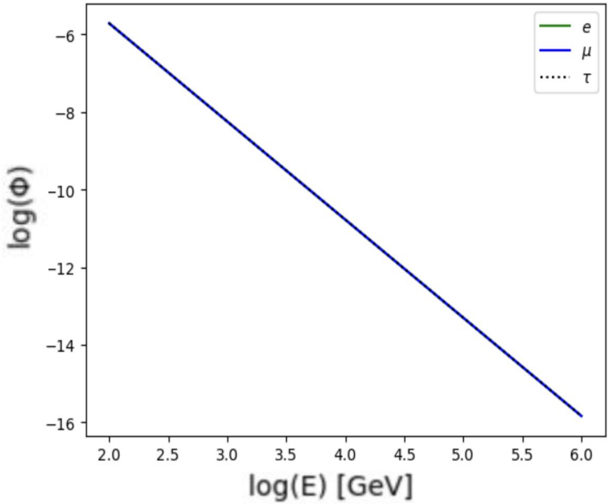


High-Energy Neutrino Sources

- Jets of AGNs, blazars
- In particular:
    - TXS 0506-056 (blazar) (z=0.3365)
    - NGC 1068 (AGN) (z=0.004)
    - Diffuse background flux

Source Modelling

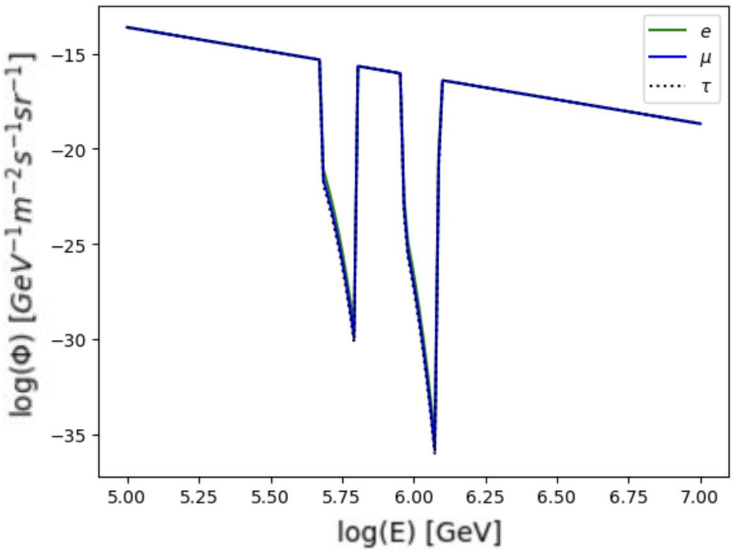
$$\mathcal{L}_0 \propto (E/E_0)^{-\gamma}$$



Power law source ν flux with γ=2.53

Propagation Modelling

- Scattering off of CνB at a rate Γ
  - Γ proportional to σ, n_ν
  - Neutrinos scattered to lower energies
- τ-τ/diagonal interactions
- $\frac{d\Phi}{dt}(t) = -\Gamma(E)\Phi(t)$



Modelled flux of ν_e, ν_μ, ν_τ with γ=2.53, z=0.337, g=0.01, m_φ=0.01 GeV assuming only τ-τ interactions

ν SI Cross-Section

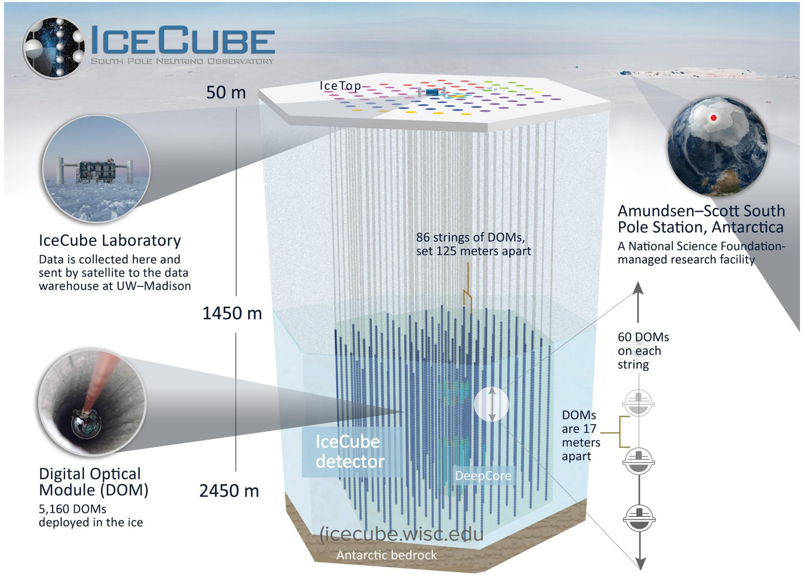
$$\sigma_{ijkl} = \frac{(\hbar c)^2 |g_{ij}|^2 |g_{kl}|^2}{4\pi} \frac{s_j}{[s_j - m_\phi^2]^2 + (m_\phi \Gamma_\phi)^2}$$

- Breit-Wigner form
- Resonant energy: $E_R = \frac{m_\phi^2}{2m_\nu}$
- s_j is the mandelstam parameter
- $\Gamma_\phi = (\sum_{ij} |g_{ij}|^2) \frac{m_\phi}{4\pi}$ is the decay width

Propagation Modelling cont.

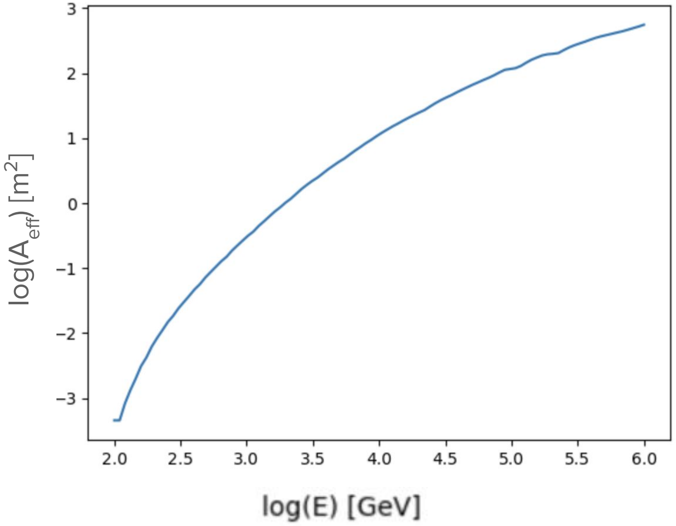
- Other considerations:
  - Mass vs. Flavor basis
  - Neutrino decoherence
    - 2:4:1 (π decay) to 1:1:1
  - Energy redshifting; $E=(1+z_s)E_0$
  - Background density redshifting: $n_{0\nu}=(1+z)^{-3}n_\nu$

- Neutrino-Nucleon CC Interactions
- Track vs. Cascade events
  - Track have better angular resolution
  - Cascade have better energy resolution

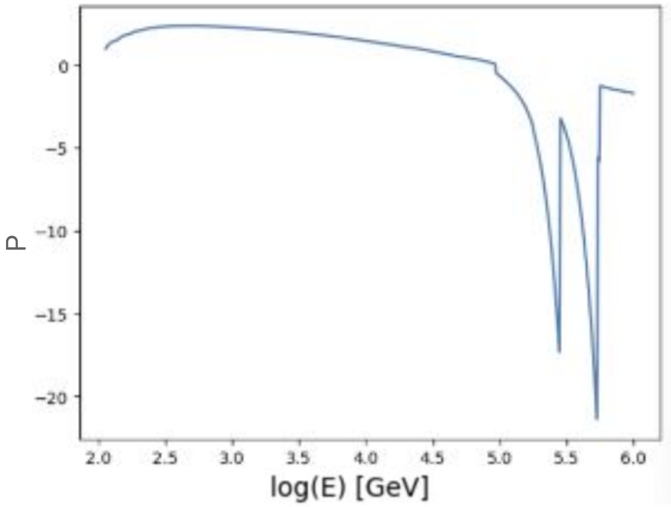


IceCube Detection Modelling

- $$\frac{dN}{dE} = \Phi(E)A_{eff}(E)t$$
  - Track events detect ν_μ
  - A_{eff} from IceCube



IceCube effective area from IC86c data release



Probability of ν_μ detection with γ=2.53, z=0.337, g=0.01, m_φ=0.01 GeV assuming only τ-τ interactions

Statistical Analysis

- Look for dips in detected energy spectrum
- Likelihood ratio test: $\lambda = 2\log\left(\frac{\mathcal{L}_{H1}}{\mathcal{L}_{H0}}\right)$
  - H_0 with g=0 and n_s and γ maximized for likelihood
  - H_1 with SI, fit g, m_φ, n_s, γ
  - $\lambda \sim \chi^2$

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

Statistical Analysis cont.

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

Probability that an event is signal vs. background

$$f_{\text{signal}} = \frac{1}{2\pi \sin(\hat{\psi})} f_{\text{energy}}(E_\mu|sin\delta, \gamma, \mu_{ns}, m_\phi, g) f_{\text{spatial}}(\psi_i|E, \sigma, sin\delta, \gamma)$$

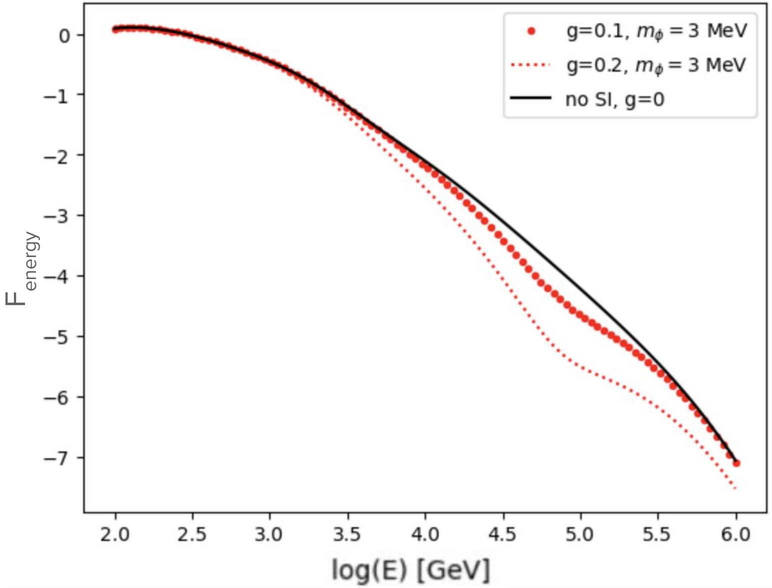
Spatial and energy components

$$f_{\text{energy}}(\hat{\epsilon}_\mu|\gamma, g, m_\phi) = N^{-1} \int d\epsilon_\nu P_{\text{prop.}}(\hat{\epsilon_\mu}|\epsilon_\nu) P_{\text{int.}}(\epsilon_\nu|\gamma, g, m_\phi)$$

Detection and propagation components

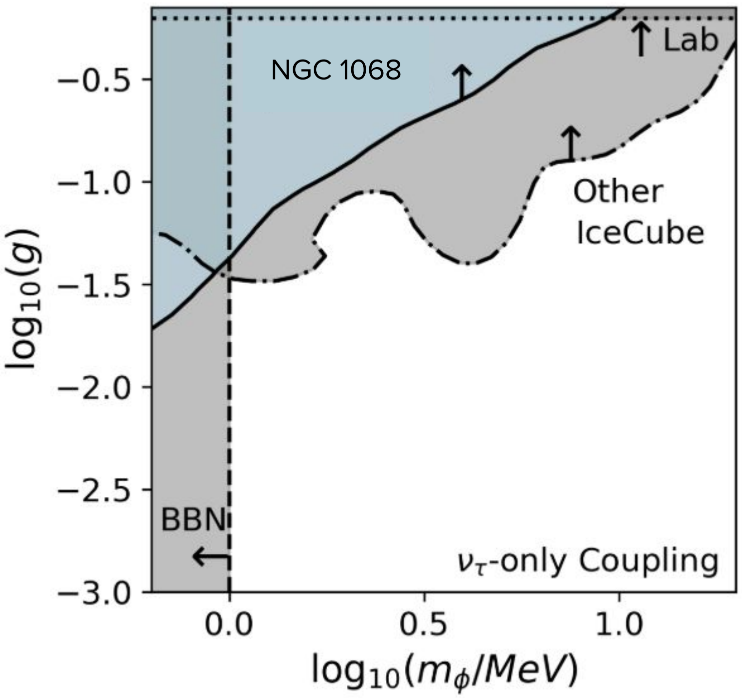
Statistical Analysis cont.

- We modify the energy pdf to account for ν self-interactions
- Compare red line to black line



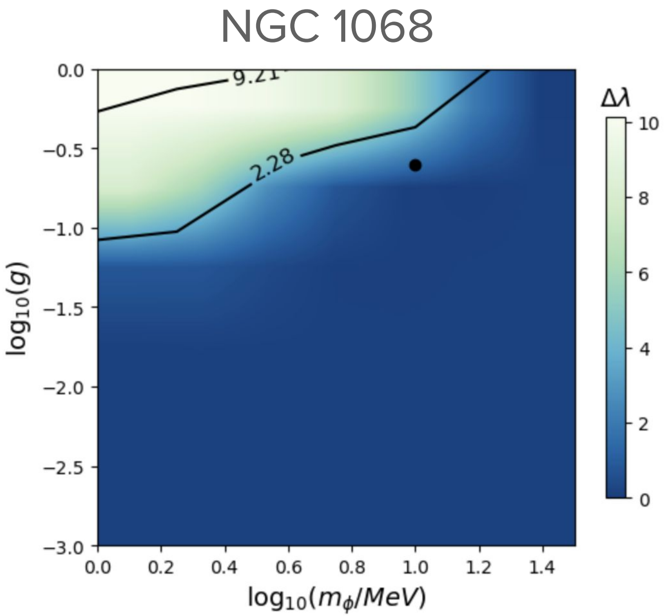
Normalized modeled Energy pdf for NGC 1068 with γ=2.8, z=0.004, assuming only τ-τ interactions

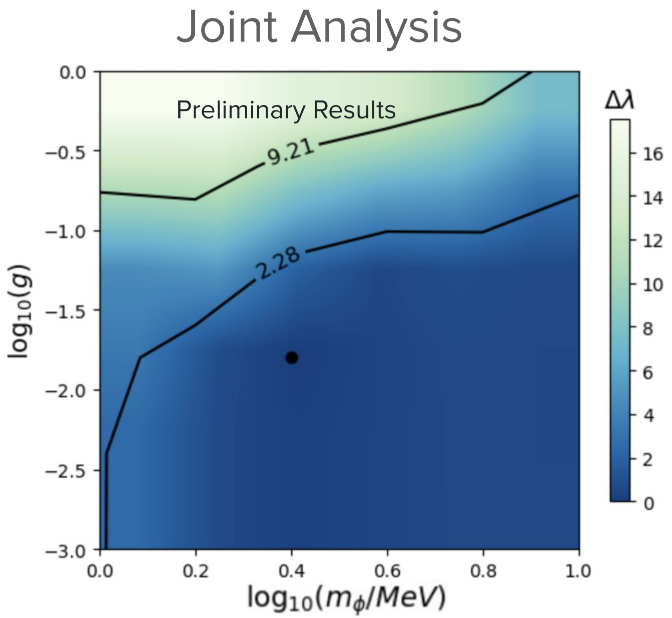
Current Constraints



(Hyde '23)

Preliminary constraints from this analysis





- Maximized with low significance at log(g)=-1.8, log(m_φ)= 0.4 (2.5 MeV)

Summary

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