Constraining the Cosmic Neutrino Background with NGC 1068

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Joint APP, HEPP, NP Conference

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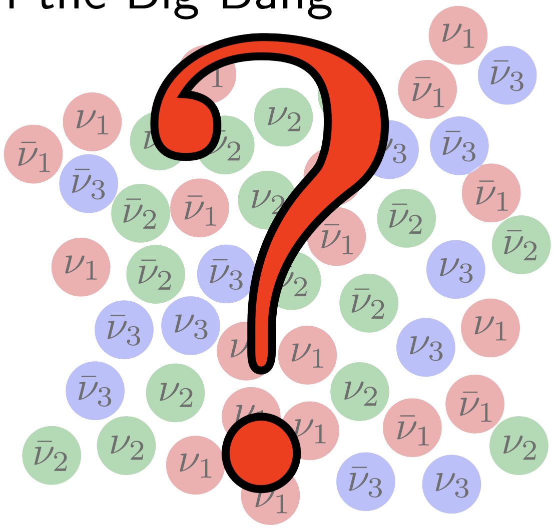
The Cosmic Neutrino Background

- The universe is filled with a sea of neutrinos
- Neutrinos decouple in the early universe
- ΛCDM: ~300 neutrinos per cm^3 left over from the Big Bang
- What we could learn about:
  - Early Universe Physics
  - BSM Neutrino Physics



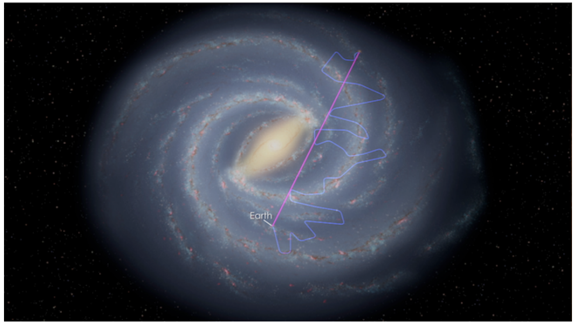
Relic Neutrino Overabundance

What are the experimental bounds on the CνB?

$$\eta = \frac{n}{(56\,\mathrm{cm}^{-3})}$$

- KATRIN Experiment: $\eta < 1.94 \times 10^{11}$

KATRIN Collaboration, 10.1103/PhysRevLett.129.011806



- Cosmic Rays: $\eta \lesssim 10^{11}$

Mar Císcar-Monsalvatje et. al., 2402.00985

Relic Neutrino Overabundance

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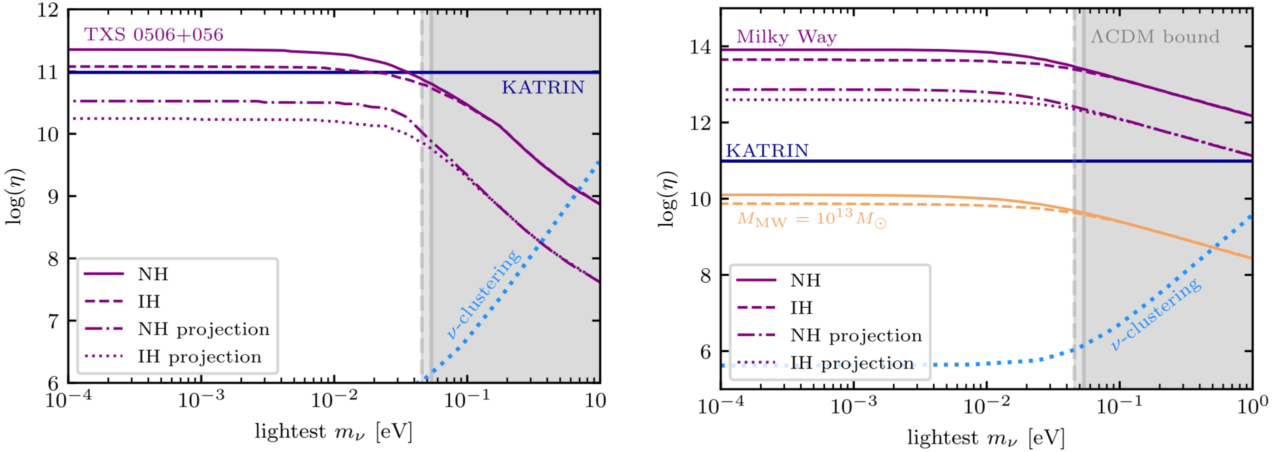

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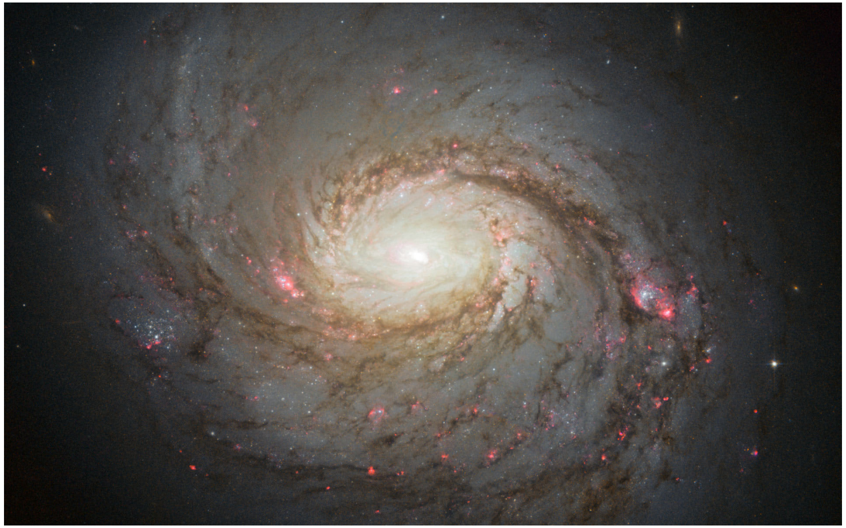
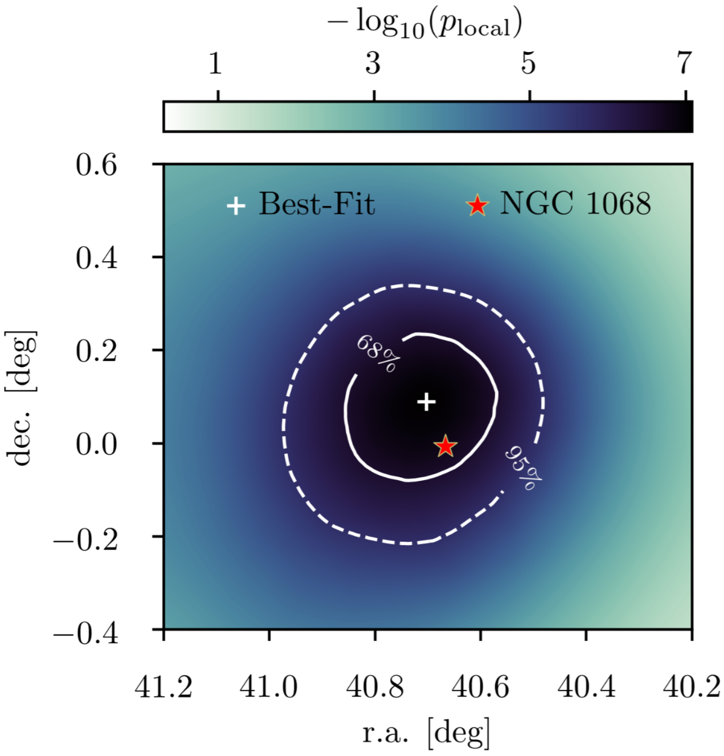
NGC 1068



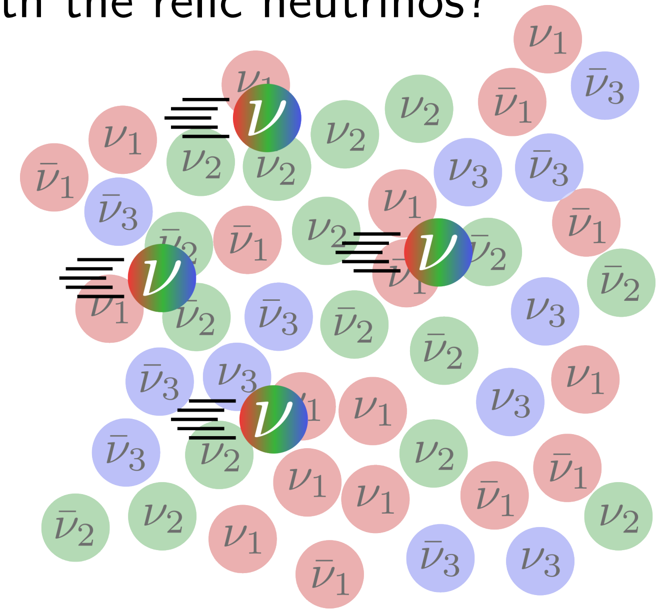


IceCube Collaboration 10.1126/science.abg3395

- Galaxy with an active galactic nuclei (AGN)
- Around 14 Mpc from the Milky Way
- Most significant point-source at IceCube

The Cosmic Neutrino Background

- Neutrinos from NGC 1068 are travelling through the CνB
- What if they interact with the relic neutrinos?



Transport Equation

Need to solve the transport equation for the flux:

$$\frac{\partial \Phi_i(r,E)}{\partial r} = -\Phi_i(r,E) \sum_j n_j \sigma_{ij}(E) + \sum_{j,k,l} n_k \int_E^{\infty} dE' \Phi_j(r,E') \frac{d\sigma_{jk\to il}}{dE}(E',E)$$

Transport Equation

Need to solve the transport equation for the flux:

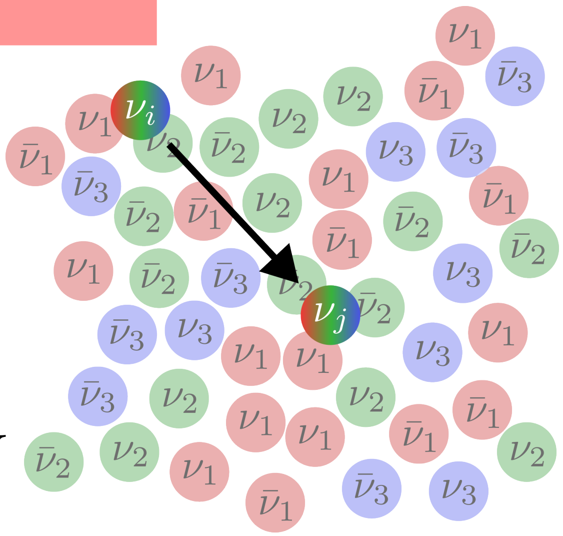
$$\frac{\partial \Phi_i(r,E)}{\partial r} = -\Phi_i(r,E)\sum_j n_j \sigma_{ij}(E)$$

Φ : Flux
n : Num. Density
σ : SM Cross-Section

Depletion Term

- $\nu\nu \to \nu\nu$
- $\bar{\nu}\nu \to \bar{\nu}\nu$
- $\bar{\nu}\nu \to e^+e^-$

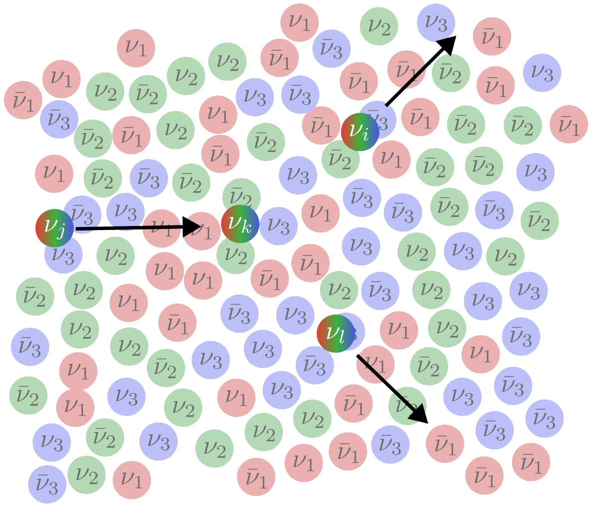
$$\sqrt{s} = \sqrt{2m_j E} \approx \text{keV} - \text{MeV}$$



Transport Equation

Need to solve the transport equation for the flux:

$$\frac{\partial \Phi_i(r,E)}{\partial r} = + \sum_{j,k,l} n_k \int_E^\infty dE' \Phi_j(r,E') \frac{d\sigma_{jk\to il}}{dE}(E',E)$$



Regeneration Term = Upscattering + Downscattering

$jk \to il$

Transport Equation

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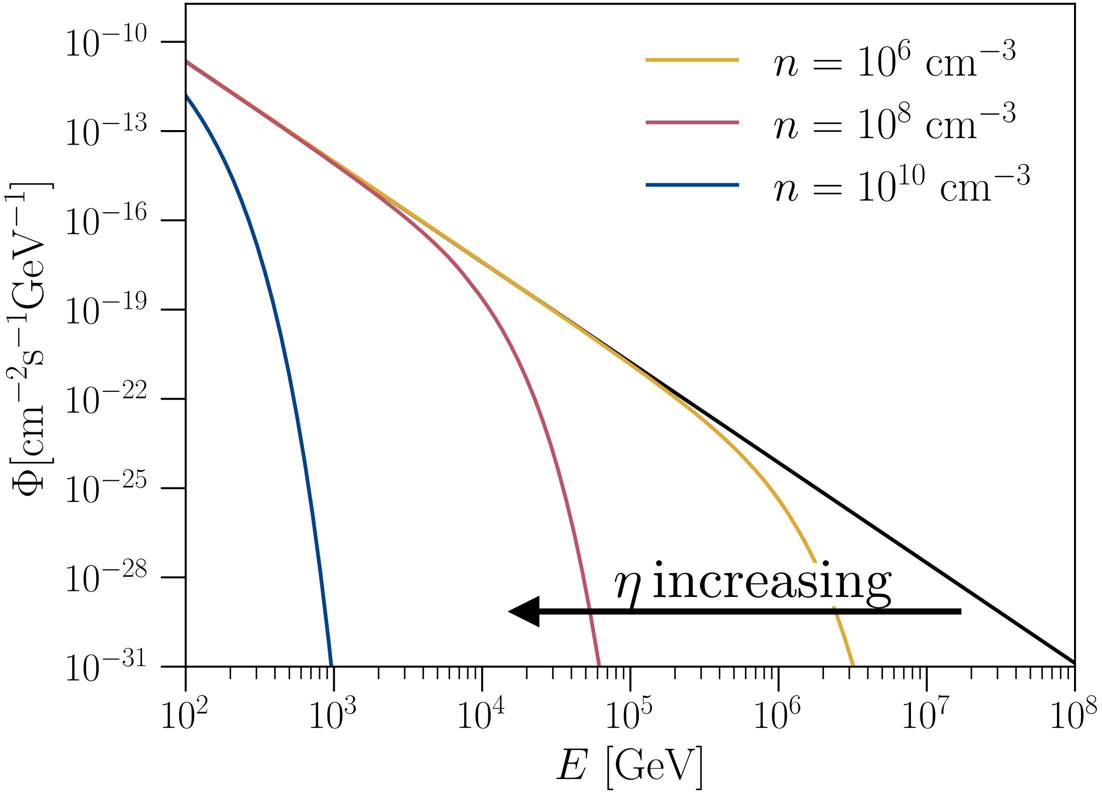
Fluxes at Earth



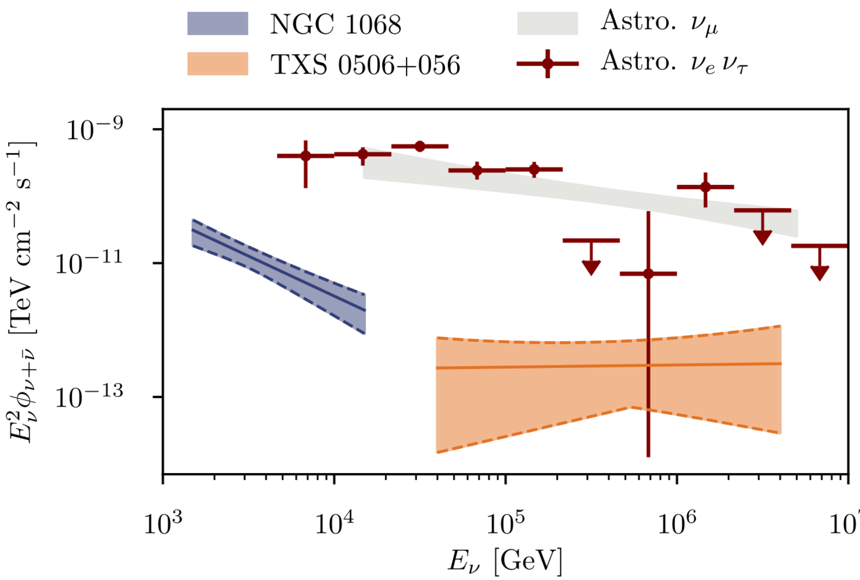
- New shoulder in flux
- $E_{\max} \propto \frac{1}{n}$

Initial Flux

- Parametrise Initial Flux with a Power Law (PL):

$$\Phi = \Phi_0 \left(\frac{E}{E_0} \right)^{-\gamma}$$

Φ_0 : Normalisation at E_0
E_0 : Reference energy (1 TeV)
γ : Spectral index



IceCube Collaboration
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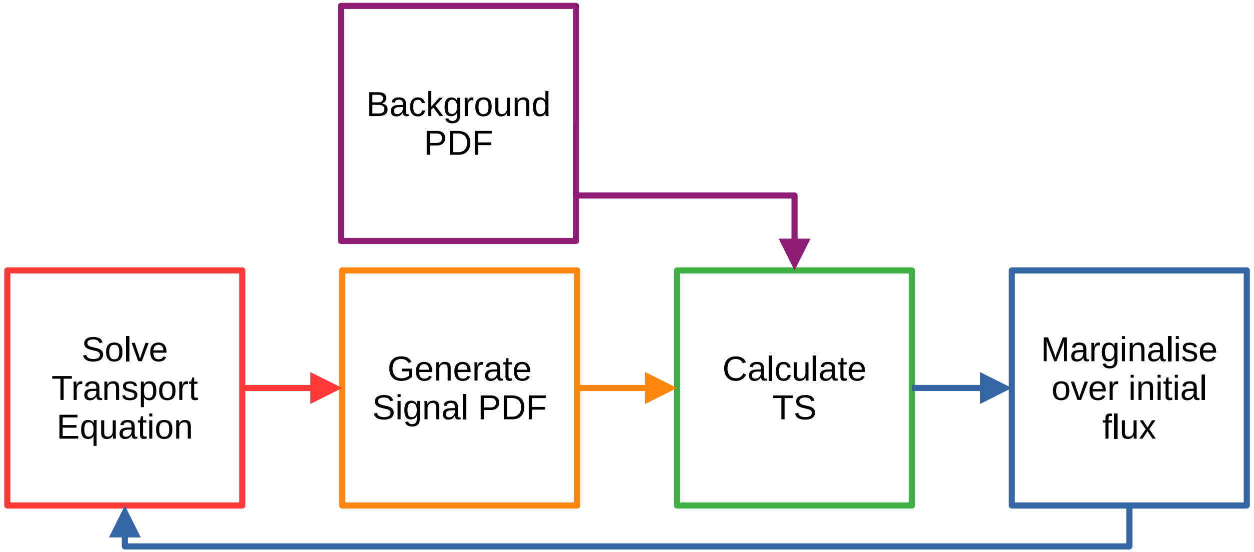
Analysis

$$TS = -2\Delta \log \mathcal{L} = -2 \log \left(\frac{\mathcal{L}(\gamma, \eta, n_s | \mathbf{x}_i, N)}{\mathcal{L}_0} \right)$$

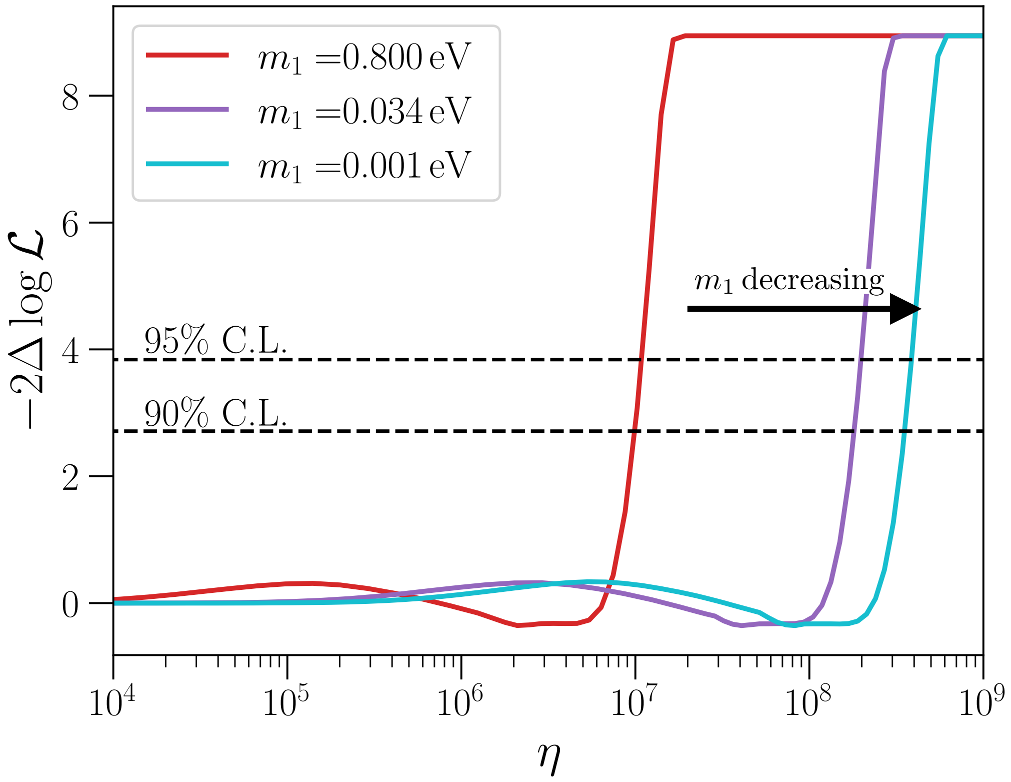
Null hypothesis = best-fit PL

Analysis

$$TS = -2\Delta \log \mathcal{L} = -2 \log \left(\frac{\mathcal{L}(\gamma, \eta, n_s | \mathbf{x}_i, N)}{\mathcal{L}_0} \right)$$

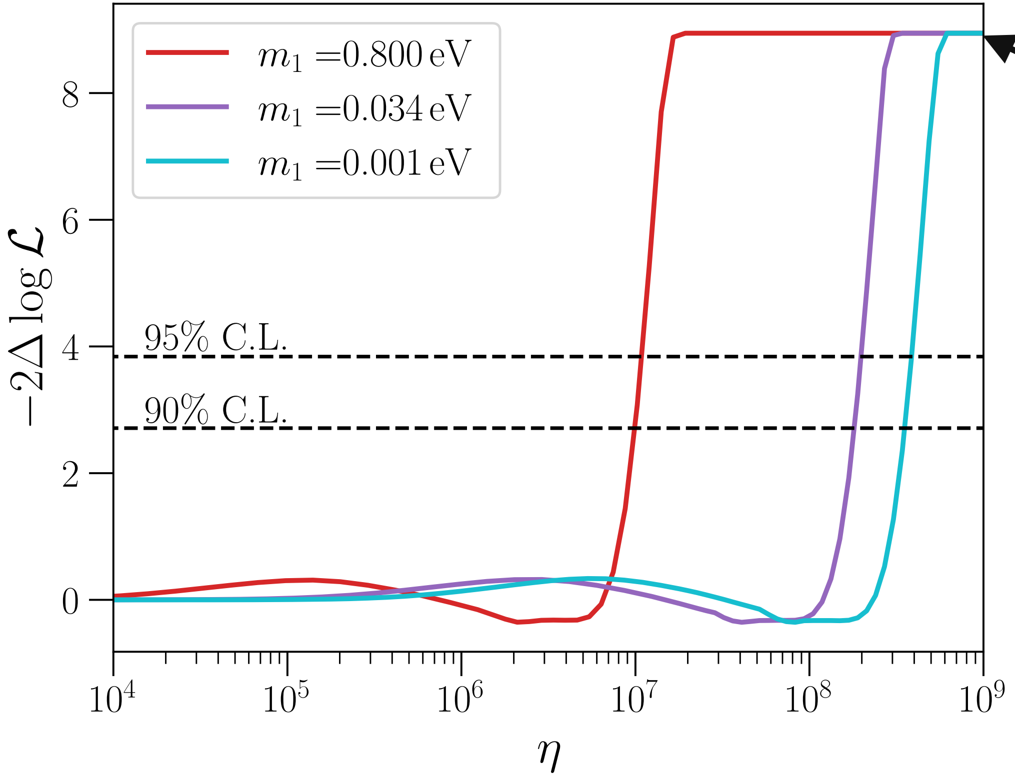


Results



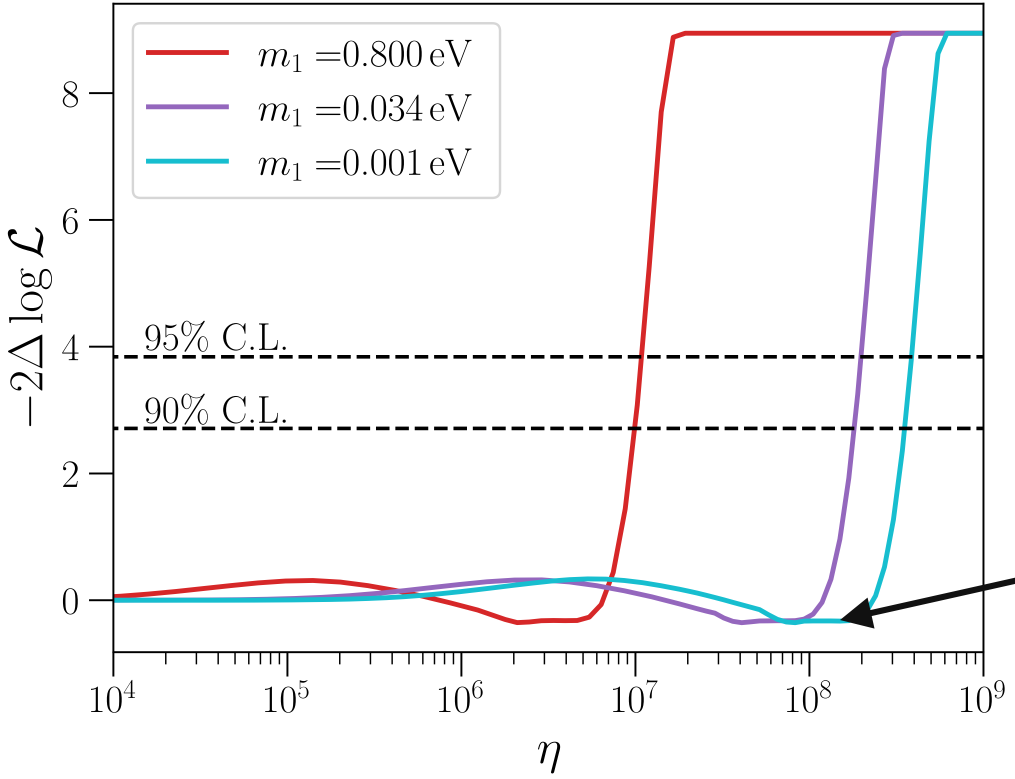
m_1 =0.800 eV
m_1 =0.034 eV
m_1 =0.001 eV
m_1 decreasing
95% C.L.
90% C.L.
$-2\Delta \log \mathcal{L}$
8
6
4
2
0
10^4
10^5
10^6
10^7
10^8
10^9
η

Results



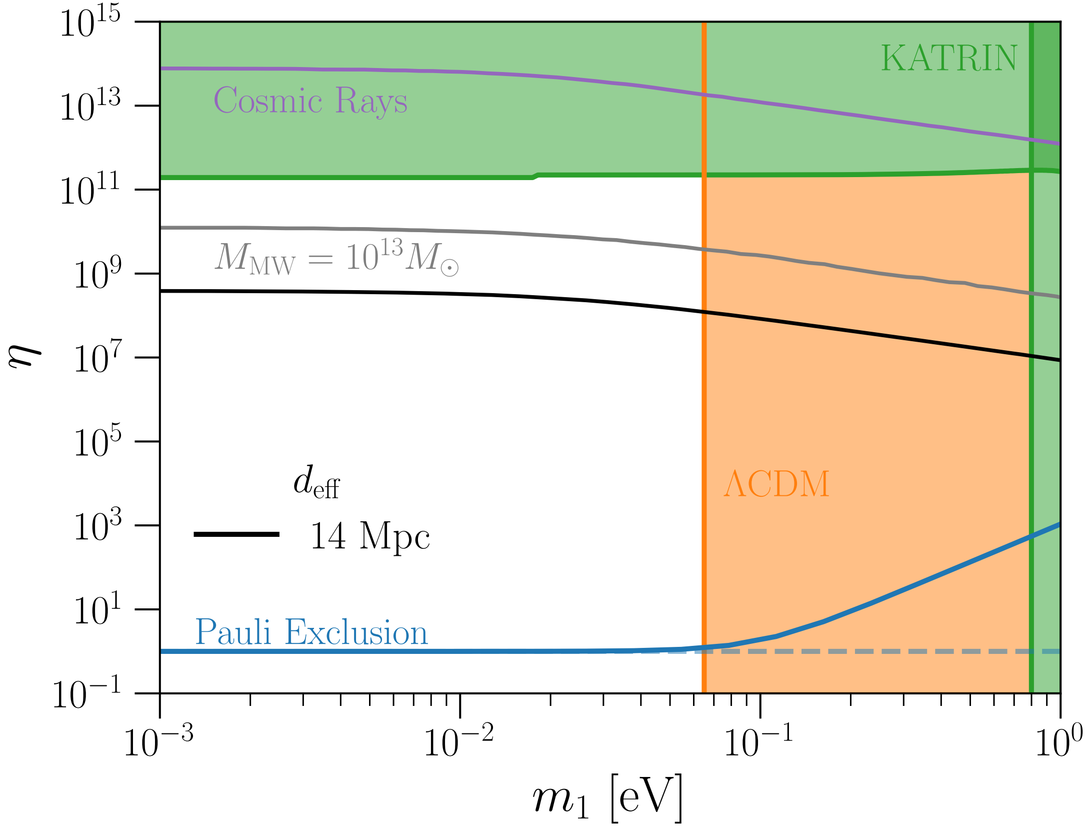
Limited by statistics and methods in public data

Results



Slight preference due to lack of higher energy events. Well below 1 sigma.

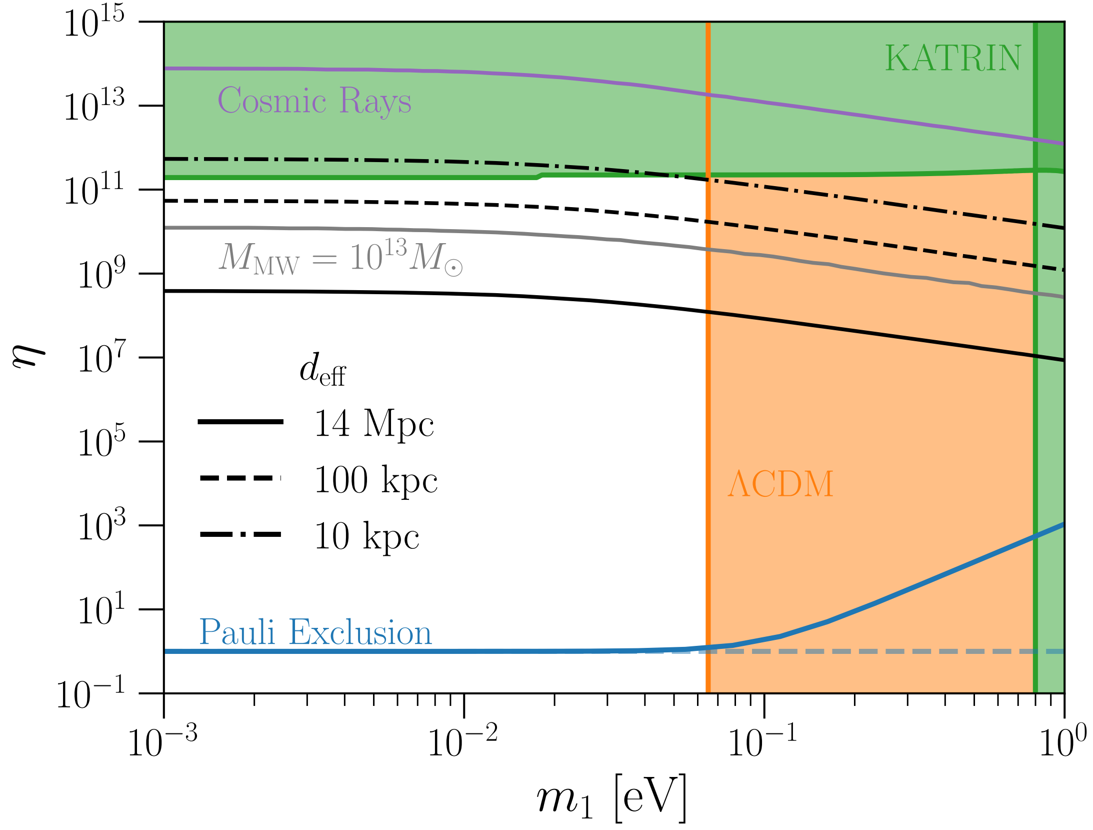
Results



- CνB Overdensity:

$$\eta < 3.9 \times 10^8$$

Results



- CνB Overdensity:

$$\eta < 3.9 \times 10^8$$

- Local Overdensity:

$$\eta \lesssim 5 \times 10^{11}$$

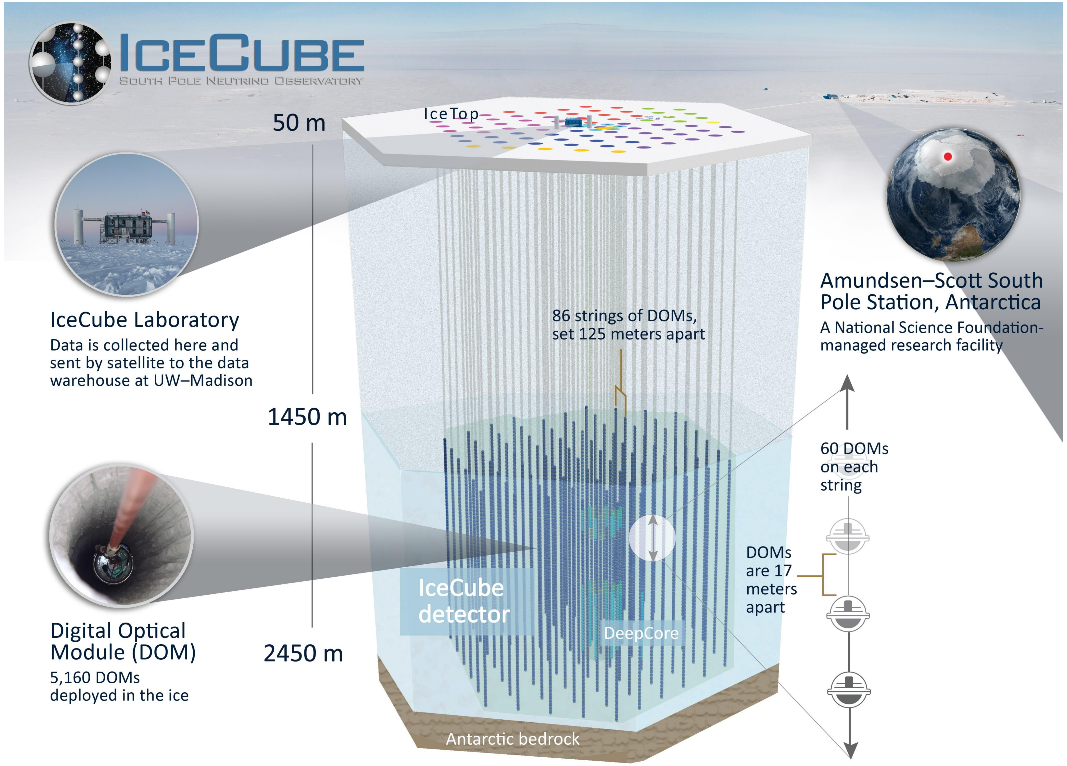
Conclusion

- Direct observation constraints improved by over 2 orders of magnitude!
- A lot of constraining power still available right now with IceCube's improved analysis techniques
- Future improvements from:
  - More events
  - Higher energy neutrinos
- Extension to this work could also constrain neutrino NSIs

Backup Slides...

The IceCube Experiment

- Neutrino Observatory in Antarctica
- Uses ice as a medium for detecting neutrinos
- Consists of 86 “strings” of light-detecting modules



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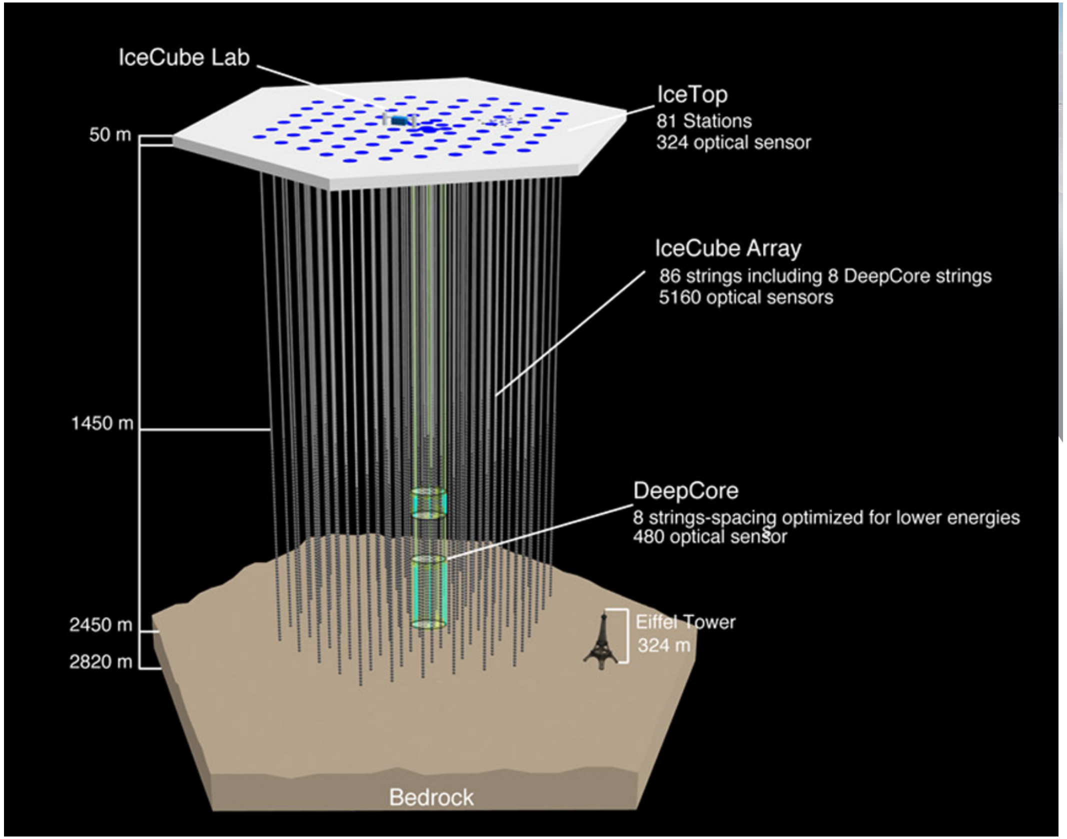
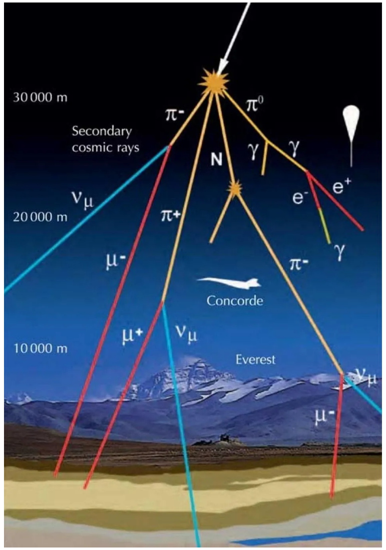
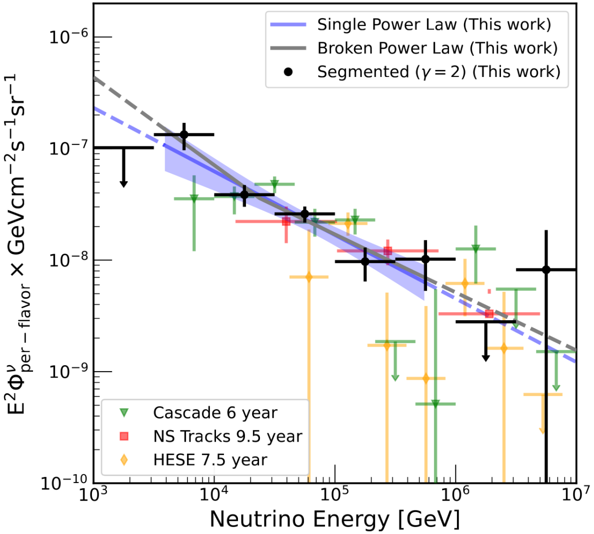


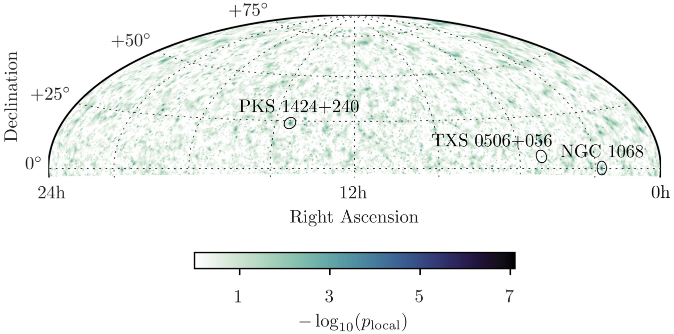
Neutrino Sources at IceCube

Where do the neutrinos that IceCube observes come from?

Atmospheric Neutrinos	Diffuse Astrophysical Neutrinos	Point-source Neutrinos







10 MeV ~ PeV

100 GeV ~ PeV

Finding Point Sources

Signal Event Normalisation

$$\mathcal{L}(\boldsymbol{\theta}, n_s | \mathbf{x}, N) =$$

Model parameters e.g. γ

Finding Point Sources

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Model parameters e.g. γ

Events

$$\mathbf{x}_i = \begin{pmatrix} \log(\hat{E}_{\mu,i}/\mathrm{GeV}) \\ \hat{\mathbf{d}}_i \\ \hat{\sigma}_i \end{pmatrix}$$

Finding Point Sources

Signal Event Normalisation

Signal PDF

$$\mathcal{L}(\boldsymbol{\theta}, n_s | \mathbf{x}, N) = \prod_{i=1}^{N} \left(\frac{n_s}{N} f_S(\mathbf{x}_i | \boldsymbol{\theta}) \right.$$

Model parameters e.g. γ

Events

$$\mathbf{x}_i = \begin{pmatrix} \log(\hat{E}_{\mu,i}/\mathrm{GeV}) \\ \hat{\mathbf{d}}_i \\ \hat{\sigma}_i \end{pmatrix}$$

Finding Point Sources

- Signal Event Normalisation
- Signal PDF
- Background PDF
- Model parameters e.g. γ
- Events

$$\mathcal{L}(\boldsymbol{\theta}, n_s | \mathbf{x}, N) = \prod_{i=1}^{N} \left(\frac{n_s}{N} f_S(\mathbf{x}_i | \boldsymbol{\theta}) + \left(1 - \frac{n_s}{N}\right) f_B(\mathbf{x}_i) \right)$$

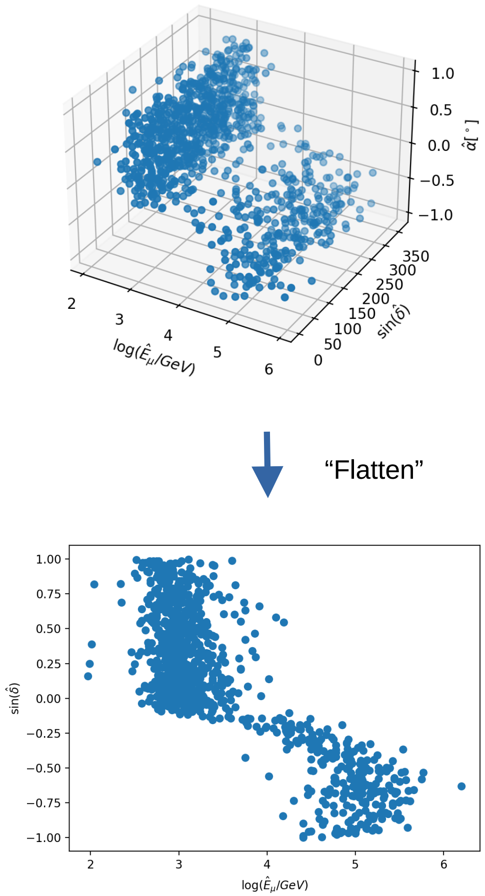
$$\mathbf{x}_i = \begin{pmatrix} \log(\hat{E}_{\mu,i}/\mathrm{GeV}) \\ \hat{\mathbf{d}}_i \\ \hat{\sigma}_i \end{pmatrix}$$

Finding Point Sources

Probability Density Functions

- Background events have no dependence on right ascension
- There are ~100,000 events, of which <100 are signal
- The background pdf ~ pdf of **all** events

$$f_B(\hat{E}_{\mu,i}, \hat{\mathbf{d}}_\mathbf{i}, \hat{\sigma}_i) = \frac{1}{2\pi} f_B(\hat{E}_{\mu,i}, \sin\hat{\delta}_i)$$



Finding Point Sources

Probability Density Functions

$$f_S(\hat{E}_{\mu,i}, \hat{d}_i, \hat{\sigma}_i | \sin\delta_{\rm src}, \theta) \approx \frac{1}{2\pi\hat{\psi}_i} f_S(\hat{\psi}_i | \hat{E}_{\mu,i}, \sigma_i, \theta) \times f_S(\hat{E}_{\mu,i} | \sin\delta_{\rm src}, \theta)$$

Finding Point Sources

Probability Density Functions

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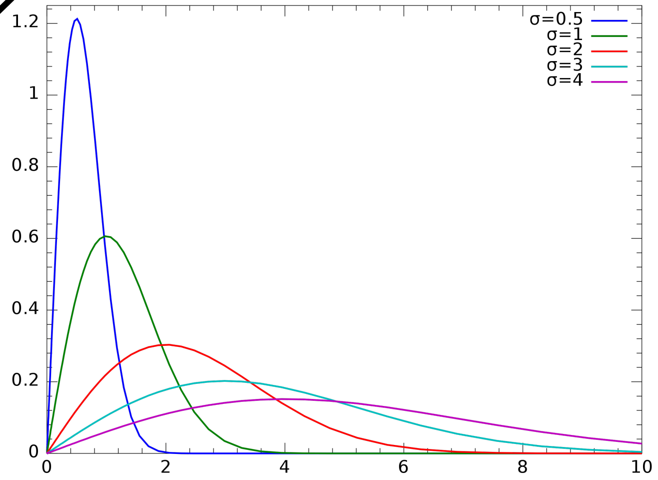
Rayleigh Distribution



Finding Point Sources

Probability Density Functions

$$f_S(\hat{E}_{\mu,i}, \hat{d}_i, \hat{\sigma}_i | \sin\delta_{\rm src}, \theta) \approx \frac{1}{2\pi\hat{\psi}_i} f_S(\hat{\psi}_i | \hat{E}_{\mu,i}, \sigma_i, \theta) \times f_S(\hat{E}_{\mu,i} | \sin\delta_{\rm src}, \theta)$$

$$f_S(\hat{E}_{\mu,i} | \sin\delta_{\rm src}, \theta) = \int dE_\nu \, f(E_\nu | \sin\delta_{\rm src}, \theta) f(\hat{E}_{\mu,i} | E_\nu, \sin\delta_{\rm src})$$

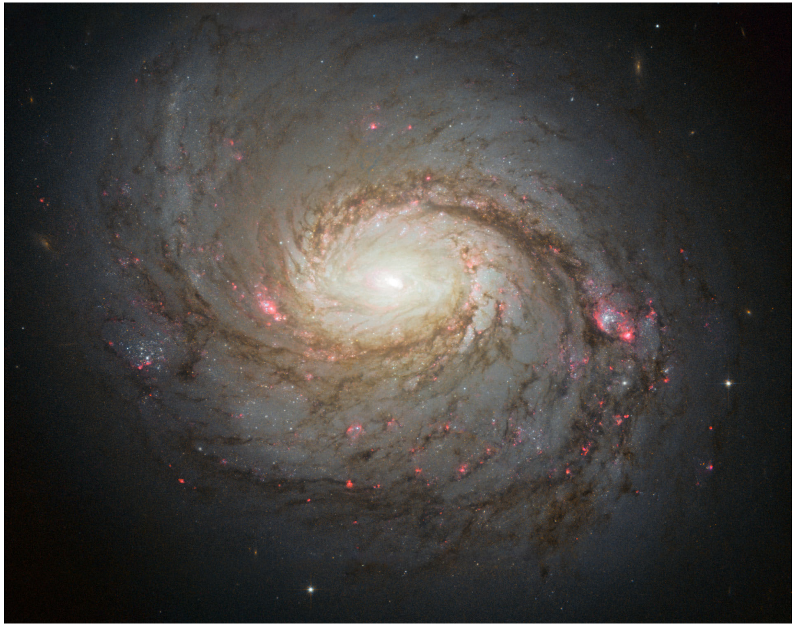
NGC1068

- Our best fit values (2.9σ):

$$n_s = 29.6\,,\gamma = 3.37$$

- New IC method results (5σ):

$$n_s = 79\,,\gamma = 3.2$$



The Cosmic Neutrino Background

Could they interact?

Mean free path: $\lambda = \frac{1}{n\sigma}$, $\sigma \approx G_F^2 s = 2G_F^2 E_\nu m_\nu$

$$\frac{L}{\lambda} \approx 1.5 \times 10^{-8} \left(\frac{L}{14.4\,\mathrm{Mpc}}\right) \left(\frac{n}{56\,\mathrm{cm}^{-3}}\right) \left(\frac{E_\nu}{1\,\mathrm{TeV}}\right) \left(\frac{m_\nu}{1\,\mathrm{meV}}\right)$$

Point Source Analysis Results

Science Paper:

- New data
- Better energy reconstruction
- More accurate pdfs

SkyLLH:

- Includes data pre IC86II