

# Constraining the Cosmic Neutrino Background with NGC 1068

Jack Franklin, Ivan Martinez-Soler, Yuber F.Perez-Gonzalez,  
Jessica Turner

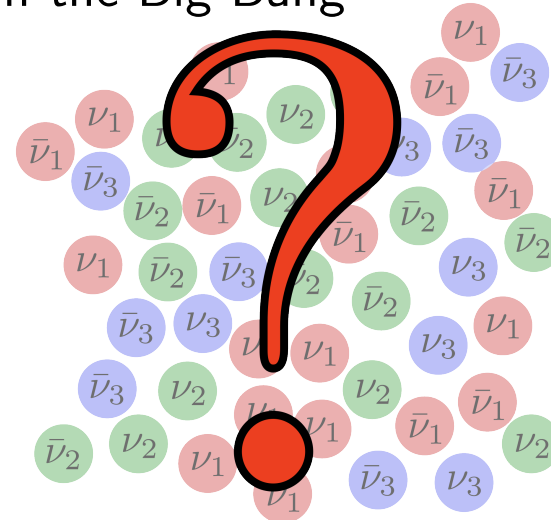
EuCAPT Annual Symposium

14<sup>th</sup> May 2024



# The Cosmic Neutrino Background

- The universe is filled with a sea of neutrinos
- Neutrinos decouple in the early universe
- $\Lambda$ CDM:  $\sim 300$  neutrinos per  $\text{cm}^3$  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?

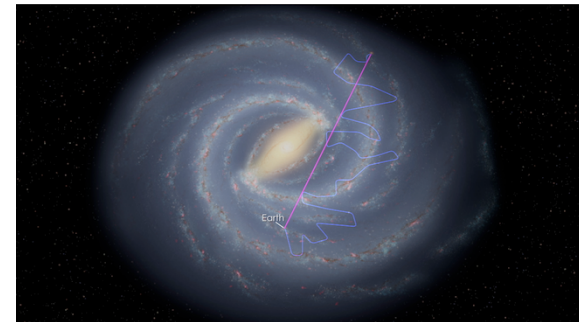
$$\eta = \frac{n}{(56 \text{ cm}^{-3})}$$

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

KATRIN Collaboration,  
[10.1103/PhysRevLett.129.011806](https://arxiv.org/abs/10.1103/PhysRevLett.129.011806)

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

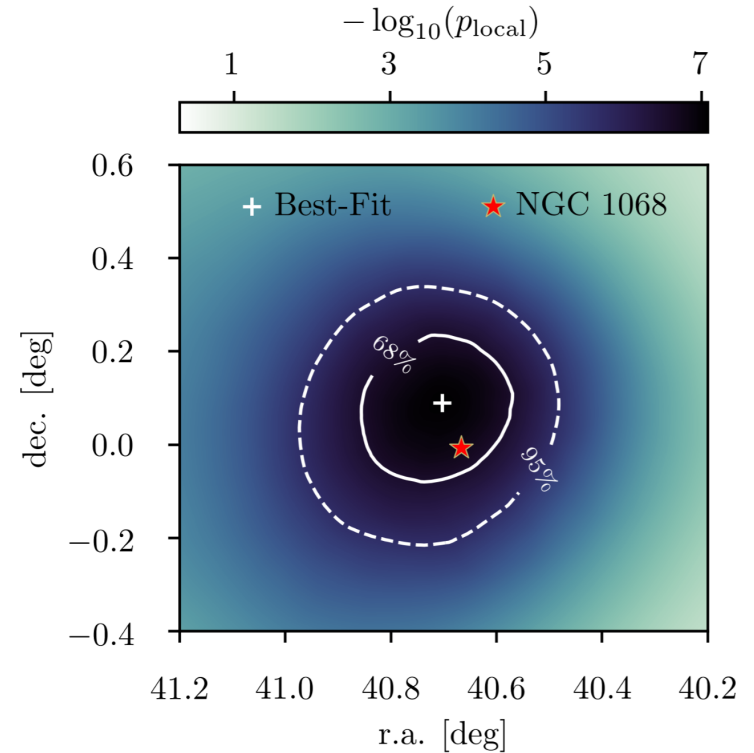
Mar Císcar-Monsalvatje et. al., [2402.00985](https://arxiv.org/abs/2402.00985)



# NGC 1068



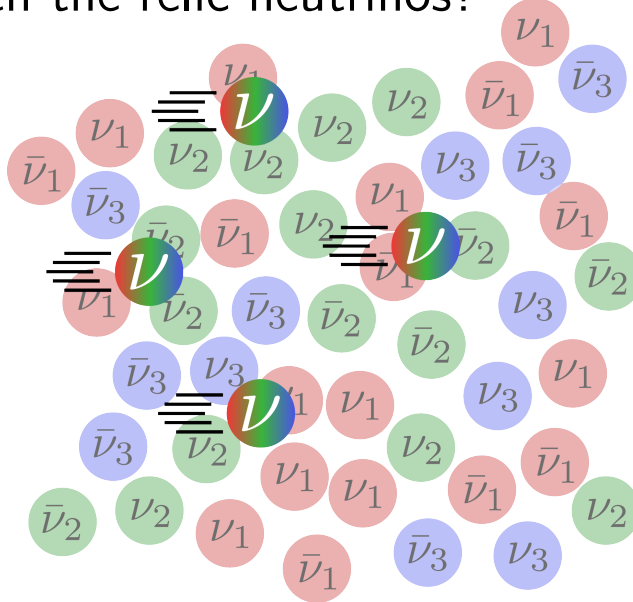
- Galaxy with an active galactic nuclei (AGN)
- Around 14 Mpc from the Milky Way
- Most significant point-source at IceCube



IceCube Collaboration [10.1126/science.abg3395](https://www.icecube.wisc.edu/2015/10/12/10.1126/science.abg3395)

# The Cosmic Neutrino Background

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



# Transport Equation

Need to solve the transport equation for the flux:

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

# Transport Equation

Need to solve the transport equation for the flux:

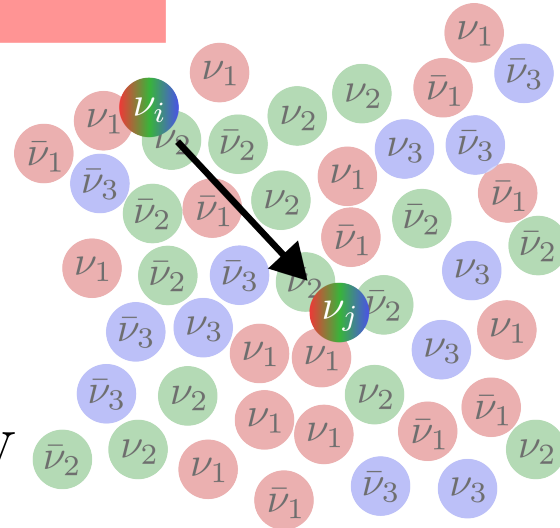
$$\frac{\partial \Phi_i(r, E)}{\partial r} = -\Phi_i(r, E) \sum_j n_j \sigma_{ij}(E)$$

$\Phi$  : Flux  
 $n$  : Num. Density  
 $\sigma$  : SM Cross-Section

Depletion Term

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

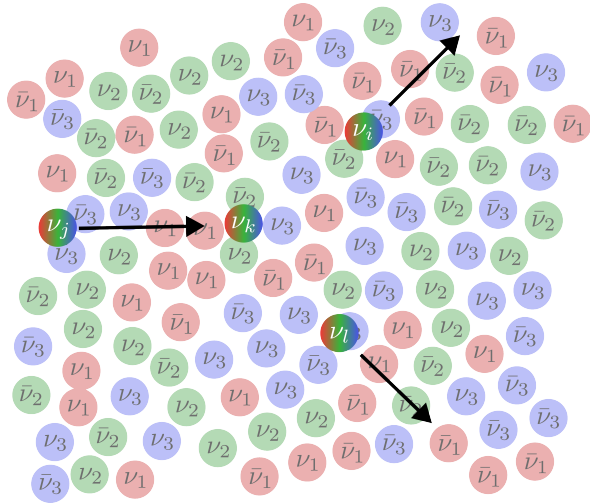
$$\sqrt{s} = \sqrt{2m_j E} \approx \text{keV} - \text{MeV}$$



# Transport Equation

Need to solve the transport equation for the flux:

$$\frac{\partial \Phi_i(r, E)}{\partial r} =$$



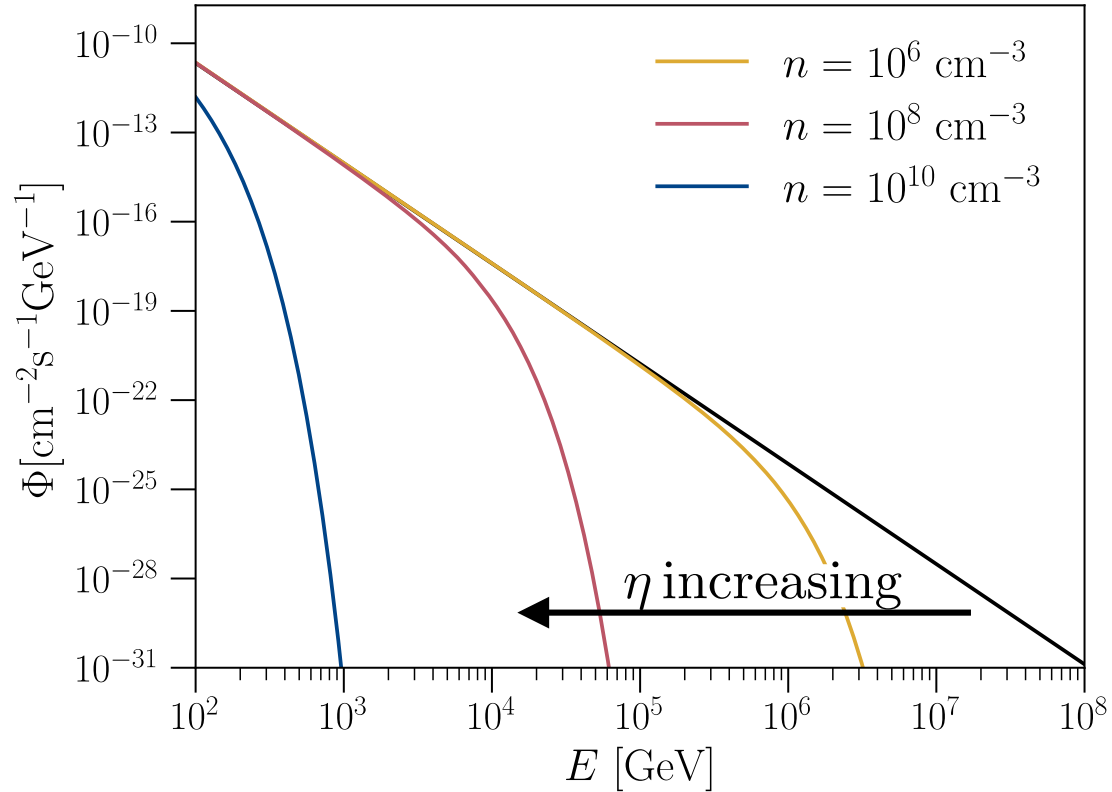
$$+ \sum_{j,k,l} n_k \int_E^\infty dE' \Phi_j(r, E') \frac{d\sigma_{jk \rightarrow il}(E', E)}{dE}$$

Regeneration Term = Upscattering + Downscattering

$$jk \rightarrow il$$



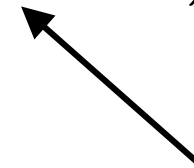
# Fluxes at Earth



# Analysis

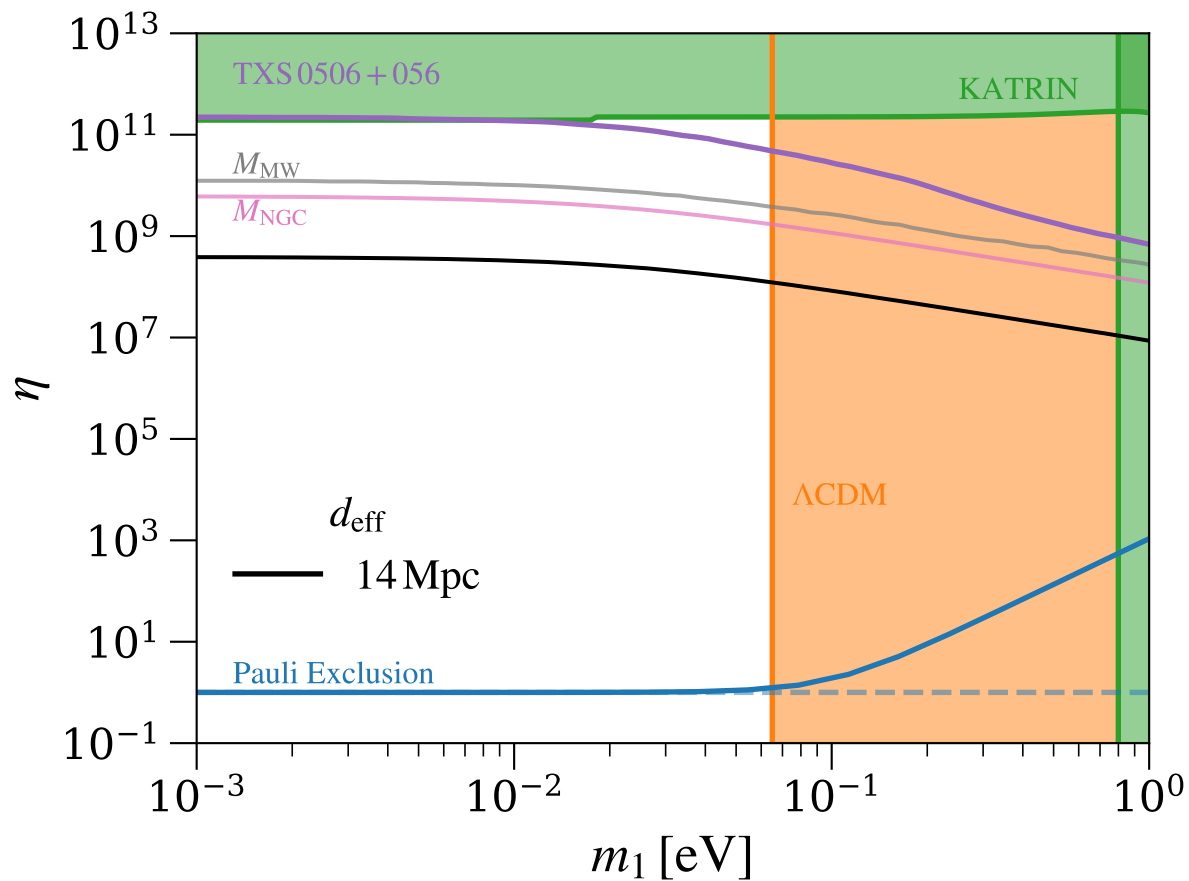
Log-likelihood analysis using IceCube public datasets:

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



Take power law flux as null hypothesis

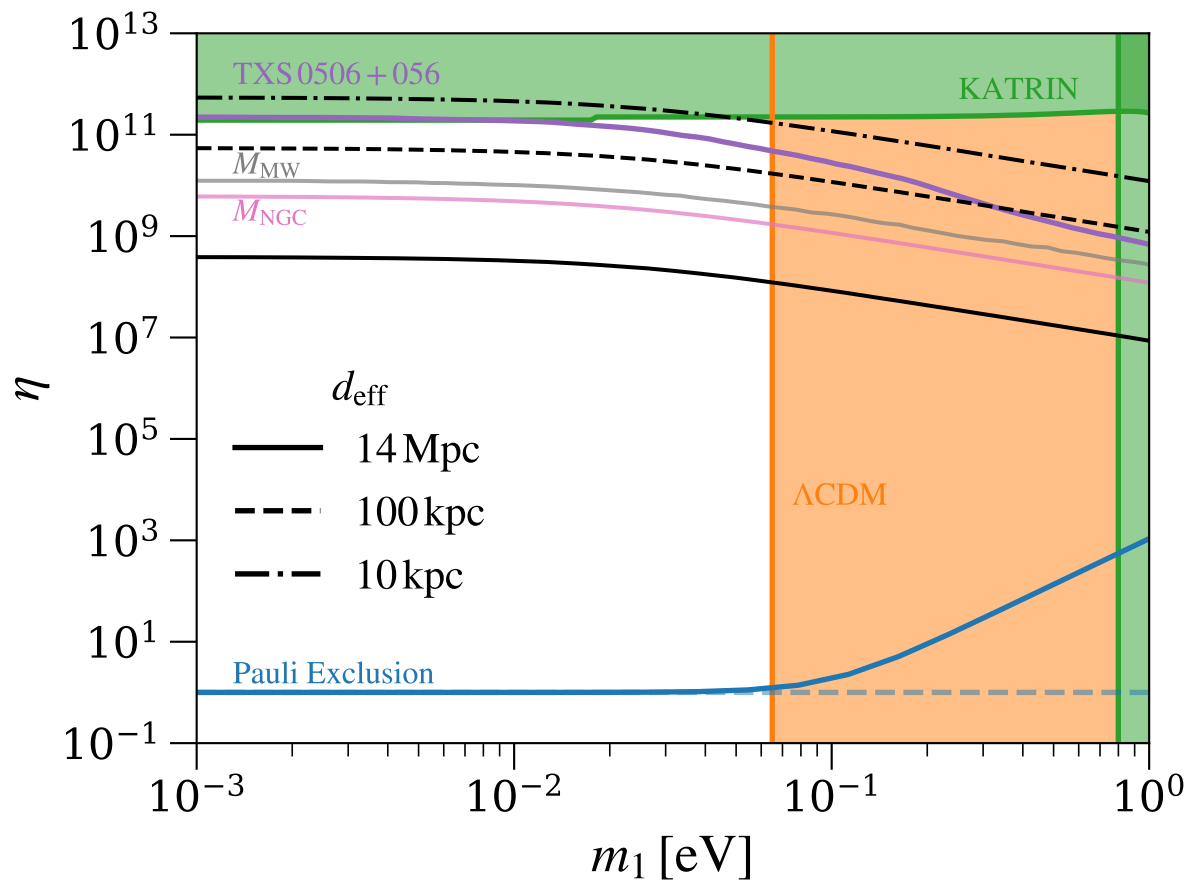
# Results



95% C.L

- CvB Overdensity:  
 $\eta < 3.9 \times 10^8$

# Results



95% C.L

- 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

If you have any more questions,  
please come see me at my poster!

# Constraints on the CνB from NGC 1068



Jack Franklin, Ivan Martinez-Soler,  
Yuber F. Perez-Gonzalez, Jessica Turner  
arxiv: 2404.02202



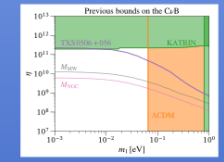
## The Cosmic Neutrino Background

Neutrinos decoupled in the early Universe after electroweak symmetry breaking. This means the Universe is filled with a sea of low energy neutrinos, much like the CMB. Detecting these neutrinos could tell us more about both early Universe physics and neutrinos physics.

## Experimental bounds on the CνB

The ΛCDM model predicts that there should be ~56 neutrinos per cm cubed, for each mass state, and similarly for antineutrinos. Any deviation from this is parametrised by:

$$\eta = \frac{n}{56 \text{ cm}^{-3}}$$



## NGC 1068 and IceCube

NGC 1068 is located 14 Mpc from the Milky Way, and is the most significant source of astrophysical neutrinos at IceCube. These neutrinos typically have energies ~1 TeV.



NASA, ESA & A. van der Horst

The neutrinos from NGC 1068 are travelling through the CνB. By modelling their SM interactions we may be able to put bounds on the relic density of neutrinos...



## Flux Modelling

As the neutrinos from NGC 1068 travel to the Milky Way, the flux changes according to the differential equation:

$$\frac{\partial \Phi_i(r, E)}{\partial r} = -\text{Loss Term} + \text{Gain Term}$$

We take the initial flux to follow a power law:

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

### Loss term

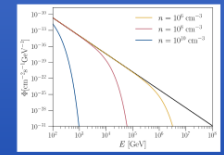
Loss Term =  $\Phi_i(r, E) n \sum_j \sigma_{ij}(E)$   
This term accounts for all of the SM processes which deplete the flux from NGC 1068:

$$\nu\nu \rightarrow \nu\nu \quad \nu\bar{\nu} \rightarrow \nu\bar{\nu} \quad \nu\bar{\nu} \rightarrow e^+e^-$$

### Gain Term

$$\text{Gain Term} = n \sum_{j,k,l} \int_E^\infty dE' \Phi_j(r, E') \frac{d\sigma_{jkl \rightarrow i}}{dE}$$

The gain term determines the change in flux from the upscattering of a relic neutrino, and the downscattering of a higher energy incident neutrino.

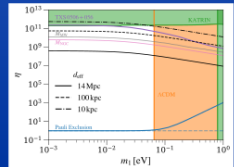


Adding the SM interactions with the CνB produces a shoulder in the neutrino flux from NGC 1068 at high energies. It should be possible to constrain this using data from IceCube.

## Results

We performed a log-likelihood analysis on IceCube public release data to determine the goodness of fit of the flux model taking into account SM interactions between neutrinos.

This model was compared to a power law flux which was found to fit to the data better than a pure background model.



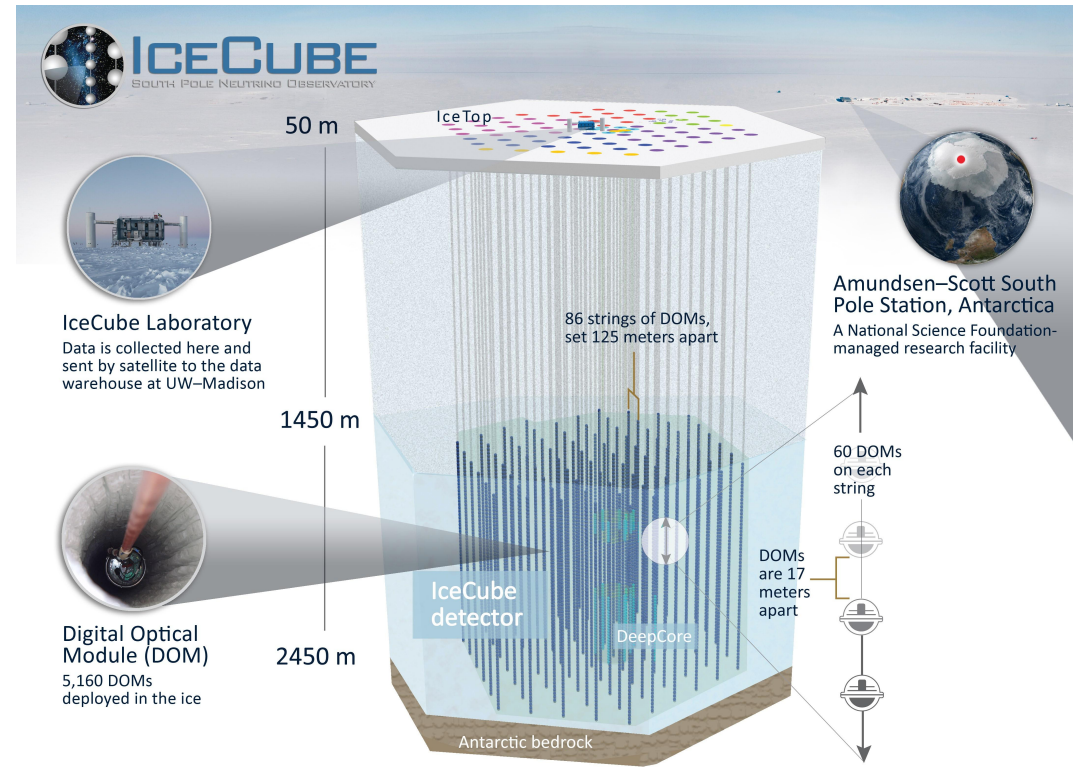
Our analysis was able to improve the bounds on the CνB by over 2 orders of magnitude compared to other direct probes.

These bounds will improve over time as more events, especially at higher energies, are detected. They will also benefit from new generation experiments such as IceCube Gen 2.

# Backup Slides...

# The IceCube Experiment

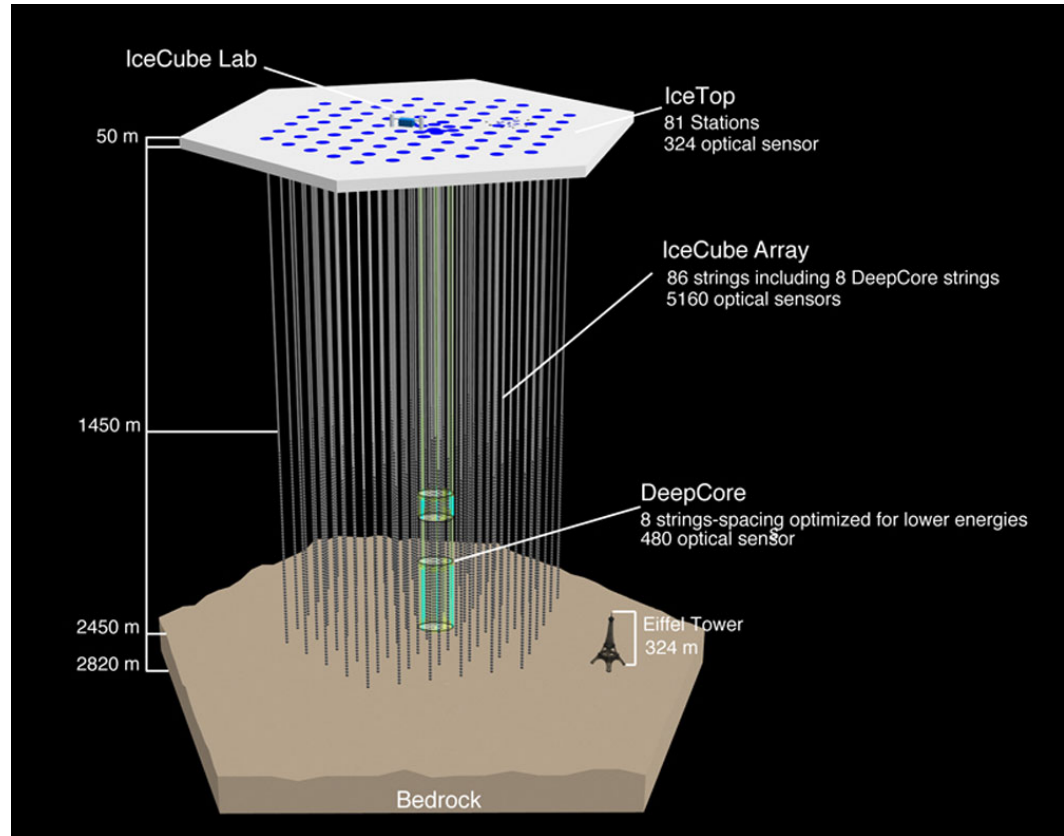
- Neutrino Observatory in Antarctica
- Uses ice as a medium for detecting neutrinos
- Consists of 86 “strings” of light-detecting modules





# The IceCube Experiment

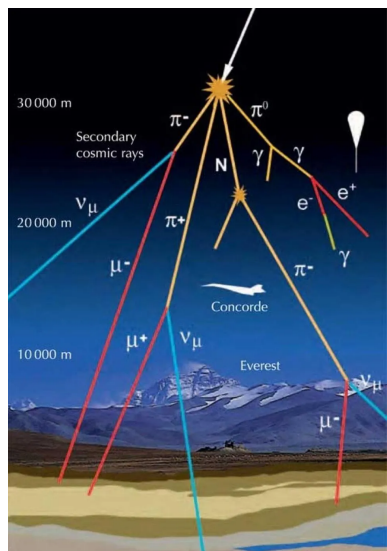
- Neutrino Observatory in Antarctica
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# Neutrino Sources at IceCube

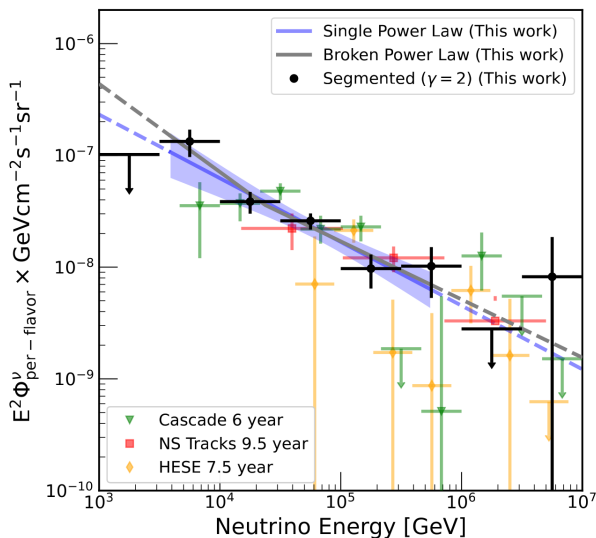
Where do the neutrinos that IceCube observes come from?

Atmospheric Neutrinos



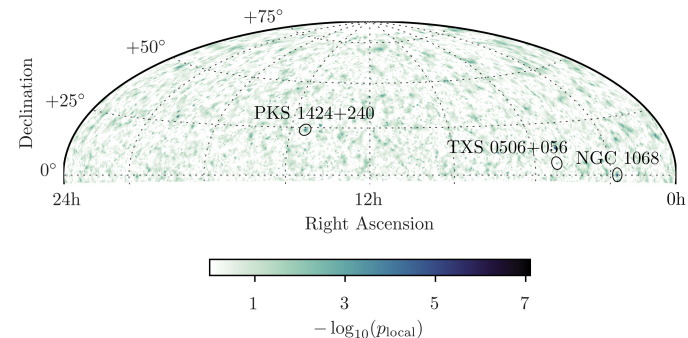
10 MeV ~ PeV  
10/04/24

Diffuse Astrophysical Neutrinos



Jack Franklin

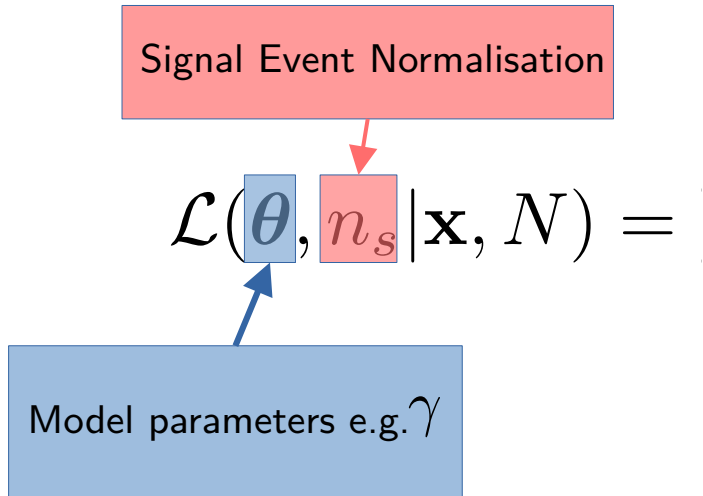
Point-source Neutrinos



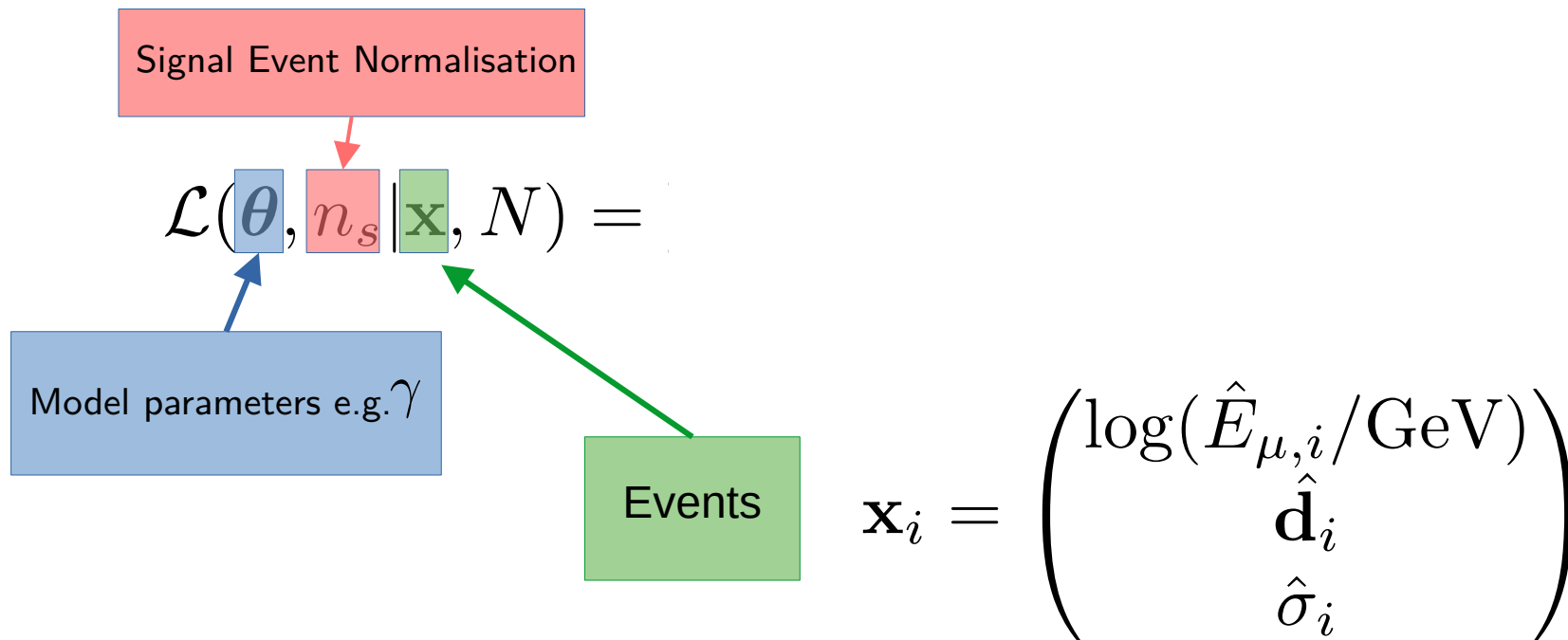
100 GeV ~ PeV

18

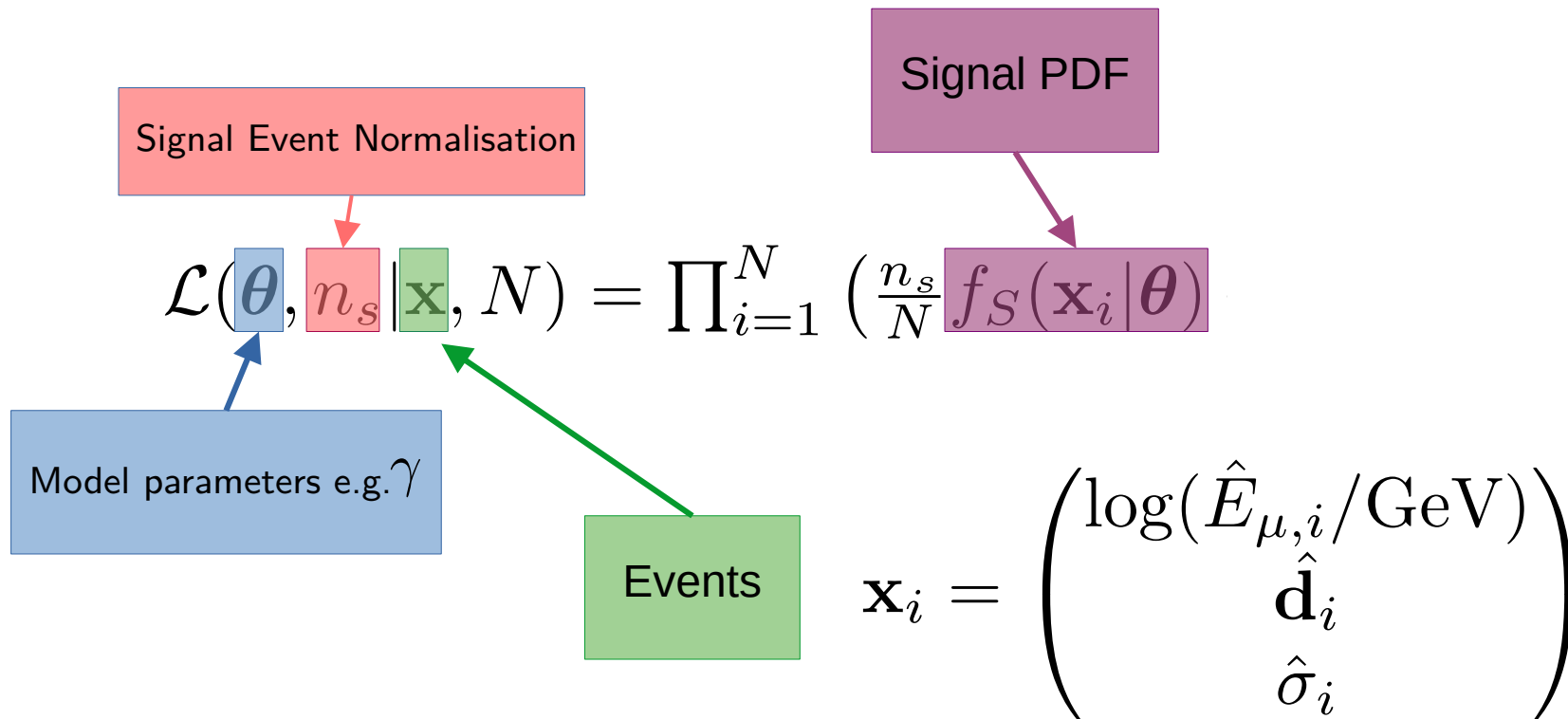
# Finding Point Sources



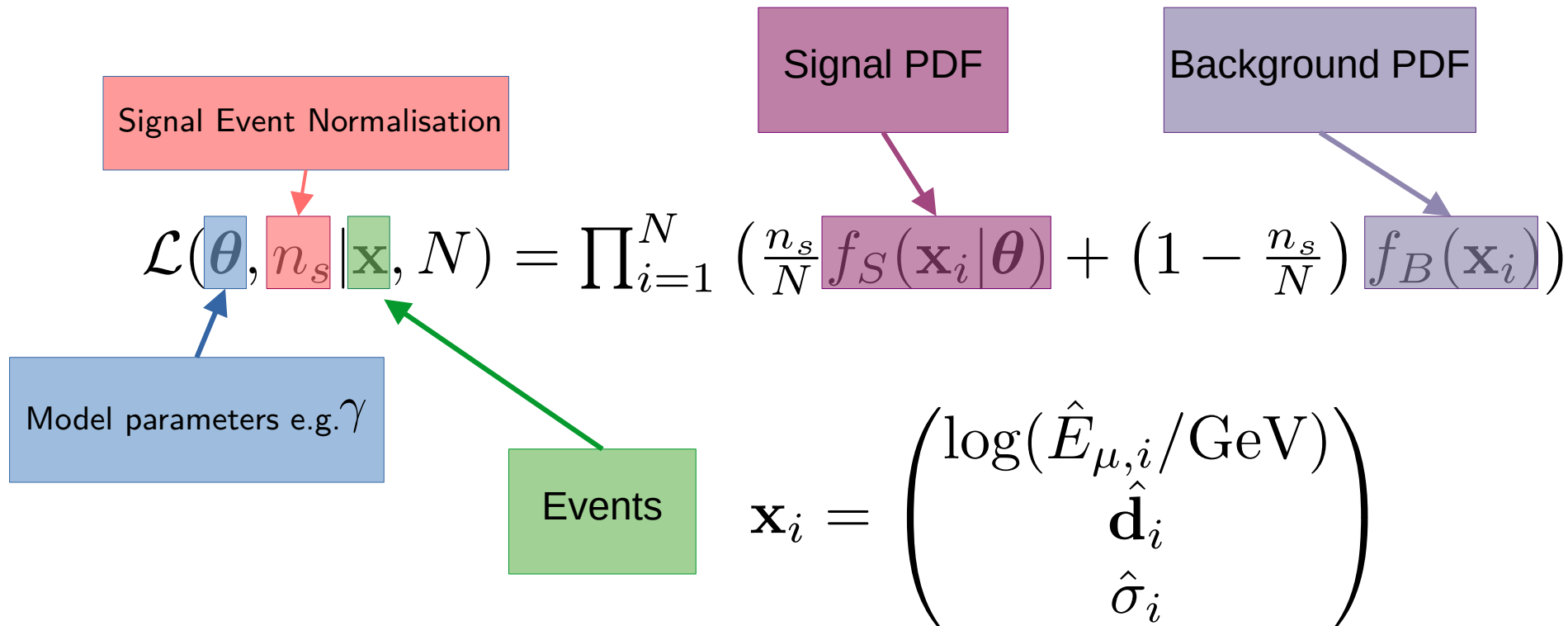
# Finding Point Sources



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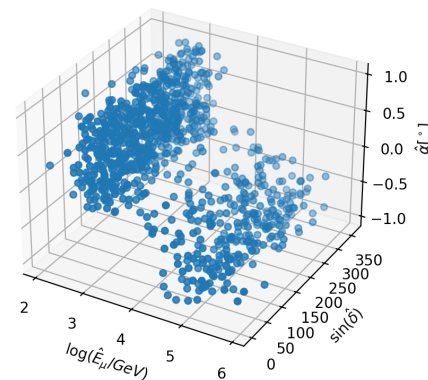


# Finding Point Sources

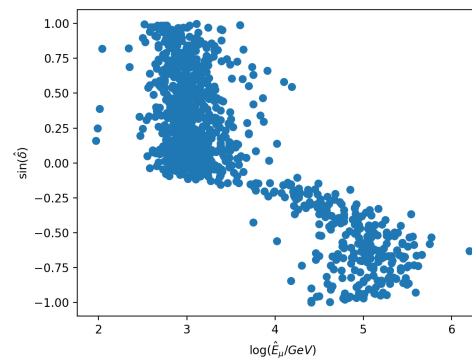
## Probability Density Functions

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

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



“Flatten”



# Finding Point Sources

Probability Density Functions

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

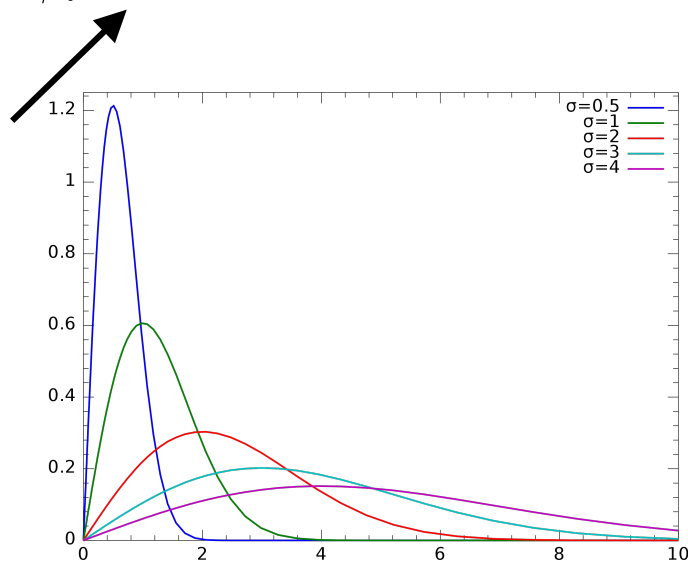


# Finding Point Sources

## Probability Density Functions

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

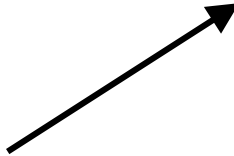
Rayleigh Distribution



# Finding Point Sources

Probability Density Functions

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

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


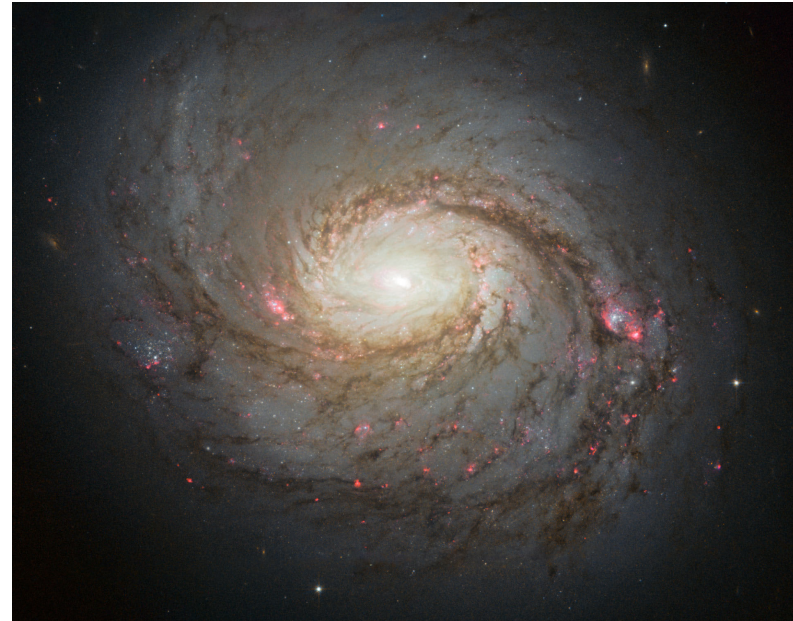
# NGC1068

- Our best fit values ( $2.9\sigma$ ):

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

- New IC method results ( $5\sigma$ ):

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



# The Cosmic Neutrino Background

Could they interact?

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

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

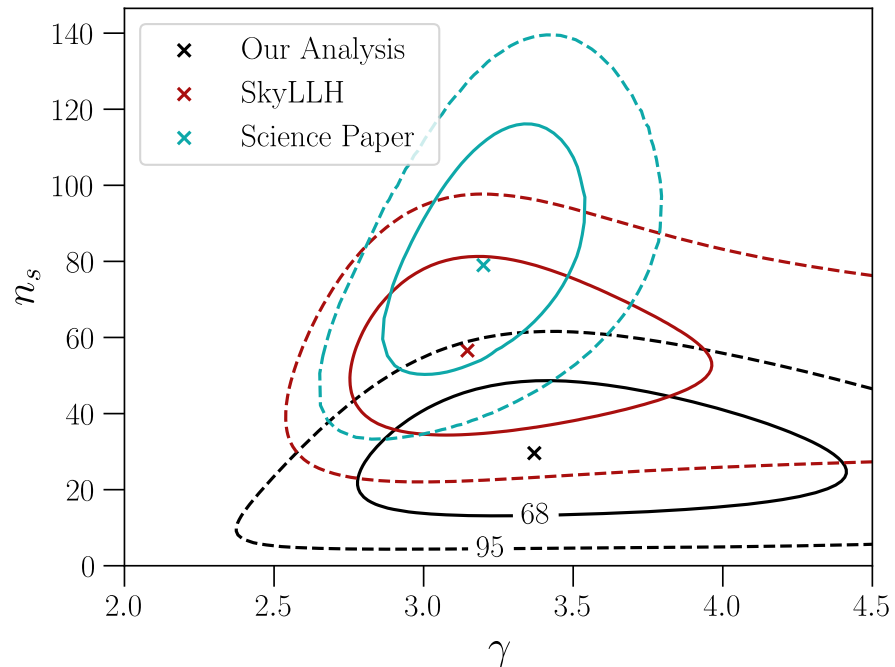
# Point Source Analysis Results

Science Paper:

- New data
- Better energy reconstruction
- More accurate pdfs

SkyLLH:

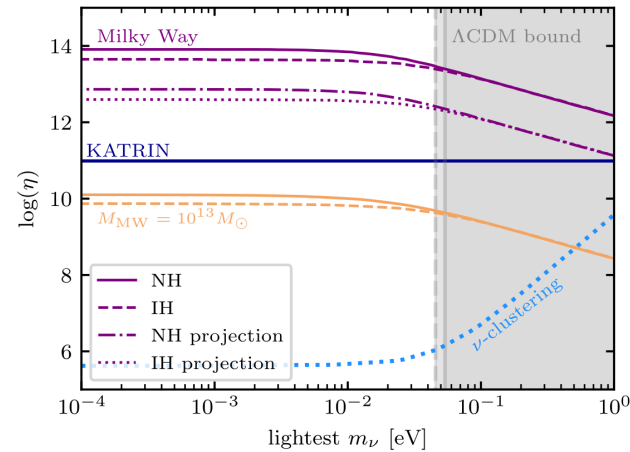
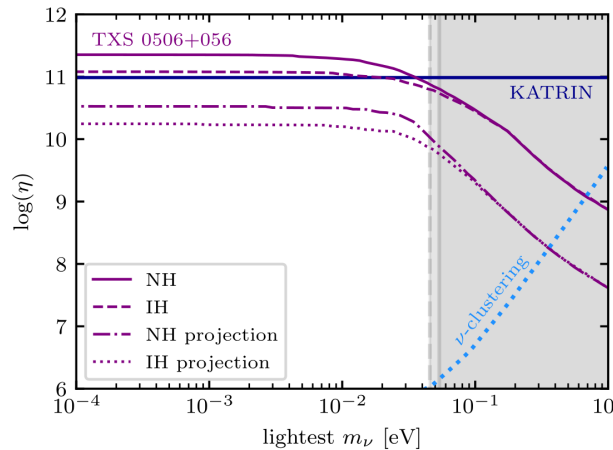
- Includes data pre IC86II



# Relic Neutrino Overabundance

What are the experimental bounds on the CvB?

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



Mar Císcar-Monsalvatje et. al., [2402.00985](#)

# Initial Flux

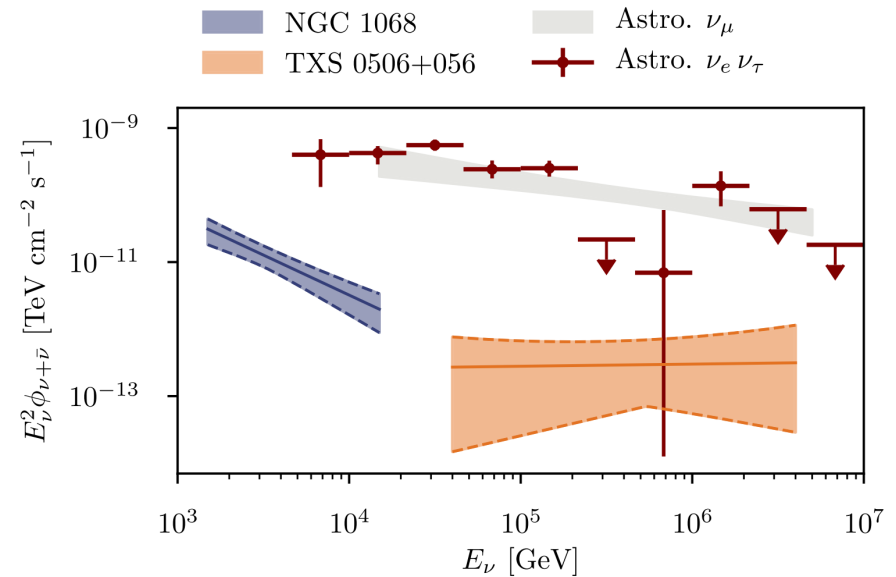
- Parametrise Initial Flux with a Power Law (PL):

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

$\Phi_0$  : Normalisation at  $E_0$

$E_0$  : Reference energy (1 TeV)

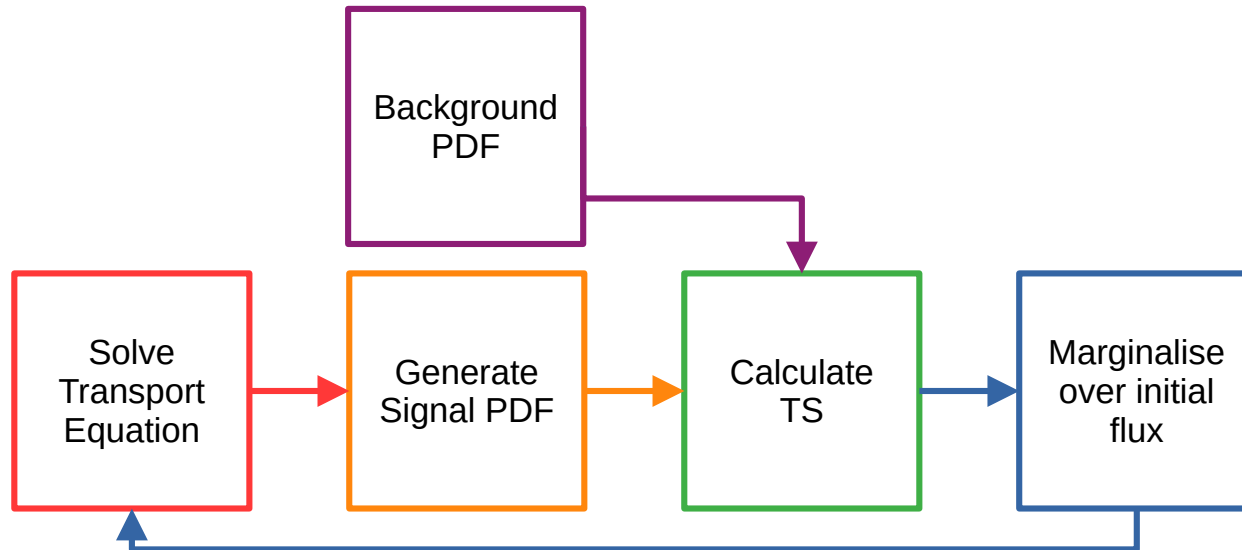
$\gamma$  : Spectral index



IceCube Collaboration  
[10.1126/science.abg3395](https://doi.org/10.1126/science.abg3395)

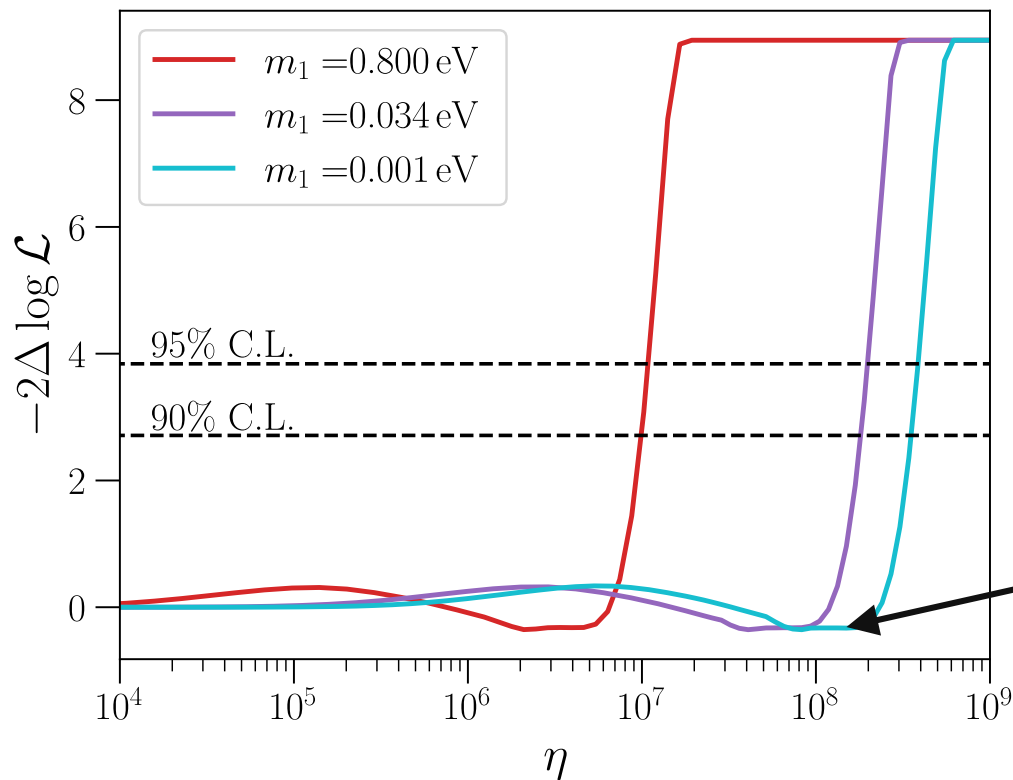
# Analysis

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



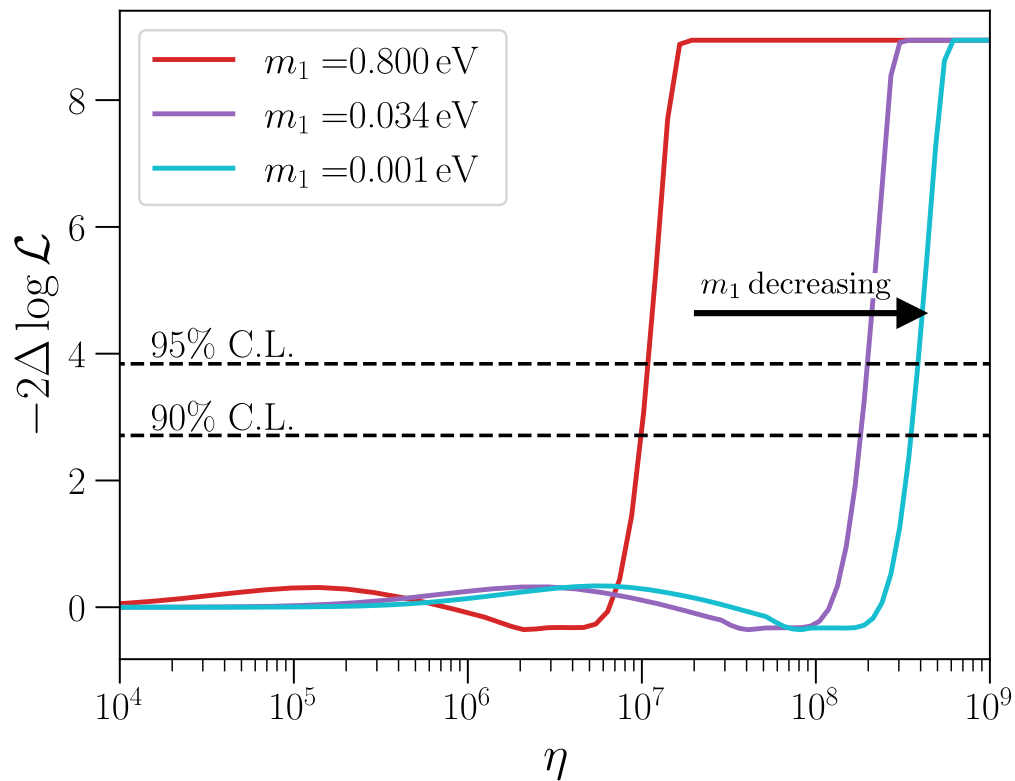


# Results

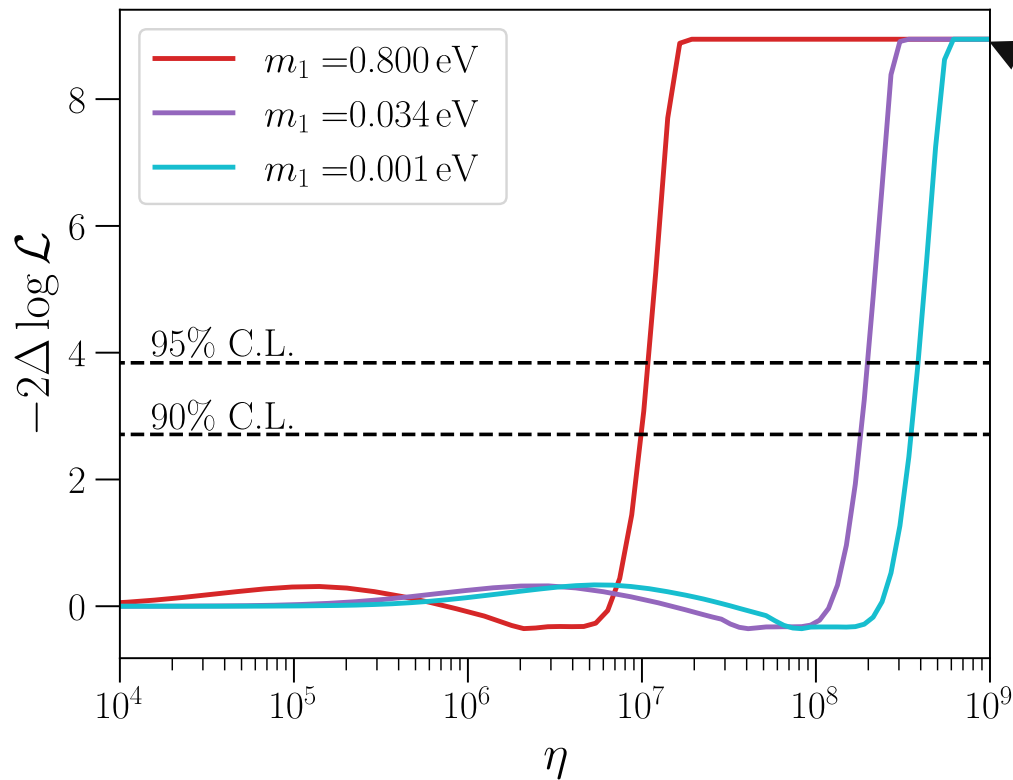


Slight preference due to lack of higher energy events. Well below 1 sigma.

# Results



# Results



Limited by statistics and methods in public data