Dark Matter Neutrino Scattering in the Galactic Centre

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XIX International Workshop on Neutrino Telescopes

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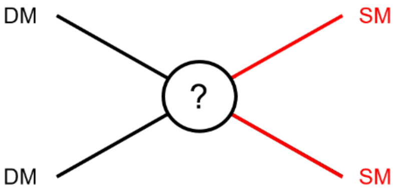
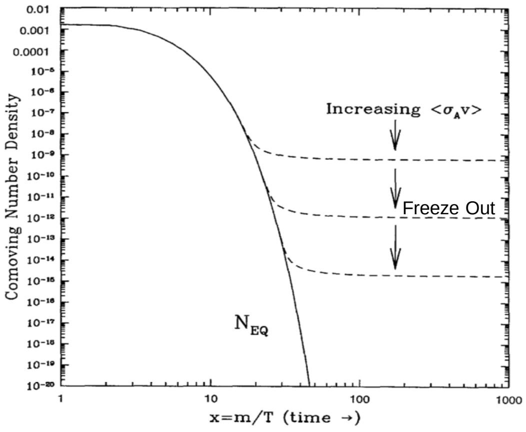
Motivation: DM-neutrino interactions in cosmology

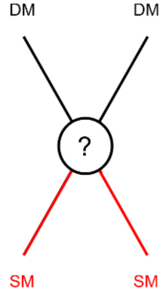


Dark matter annihilation is well motivated (WIMP miracle)

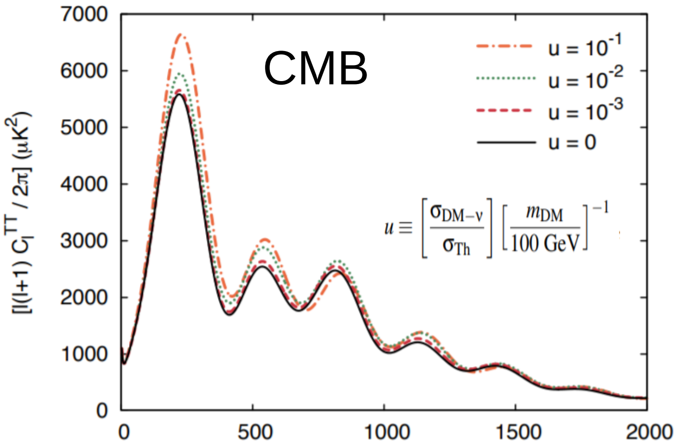


Jungman, et al [Arxiv: 9506380](https://arxiv.org/abs/hep-ph/9506380)

Everything that is not forbidden is allowed

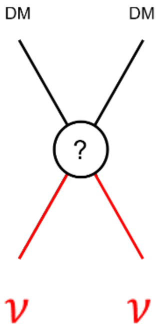


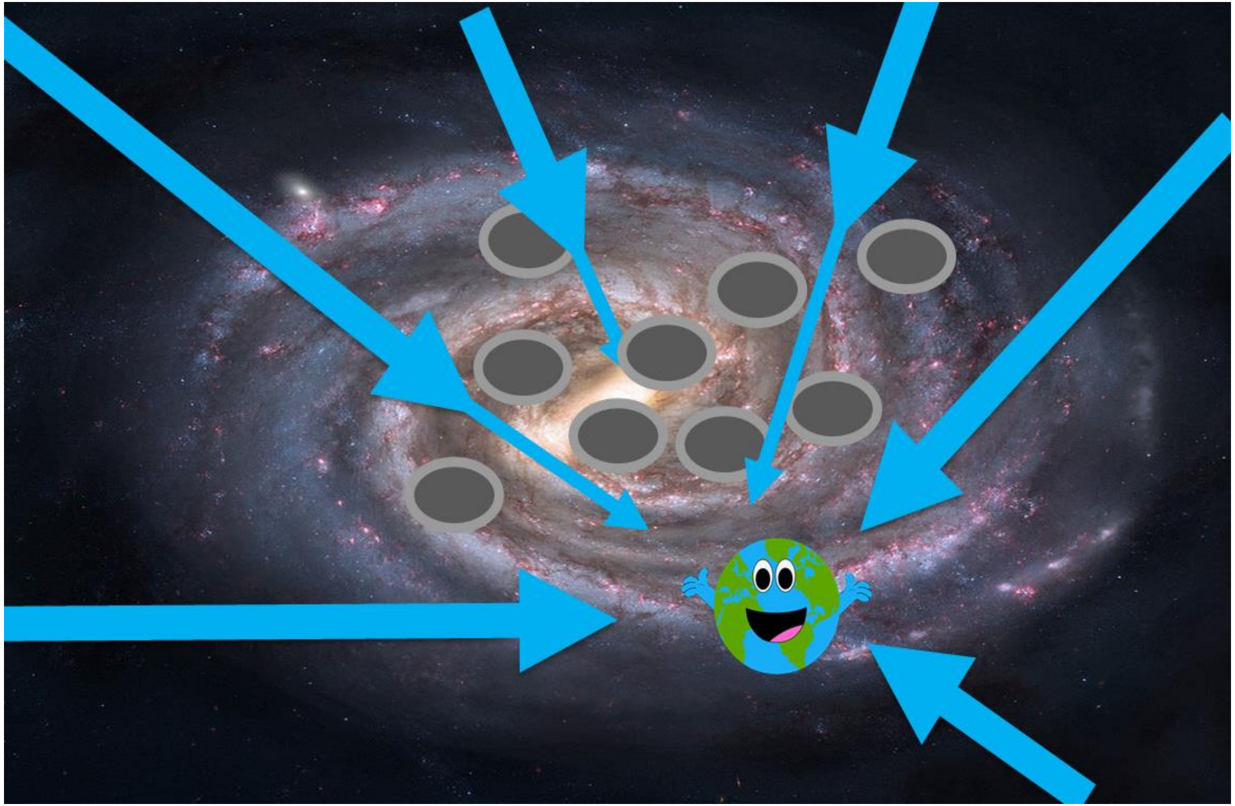
We should also expect to see scattering

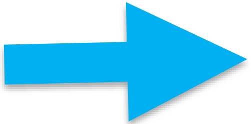


R. Wilkinson, et al [Arxiv: 1401.7597](https://arxiv.org/abs/1401.7597)

General Idea

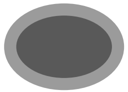






Isotropic Neutrino Flux

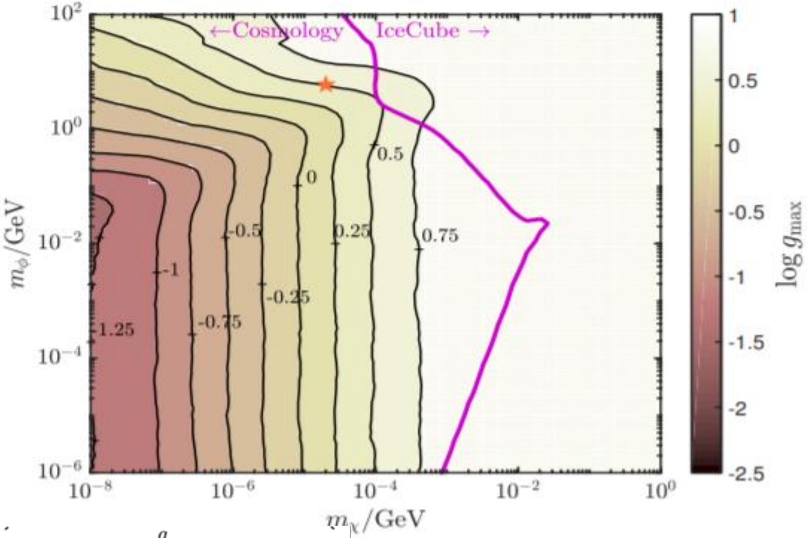
Attenuated Neutrino Flux

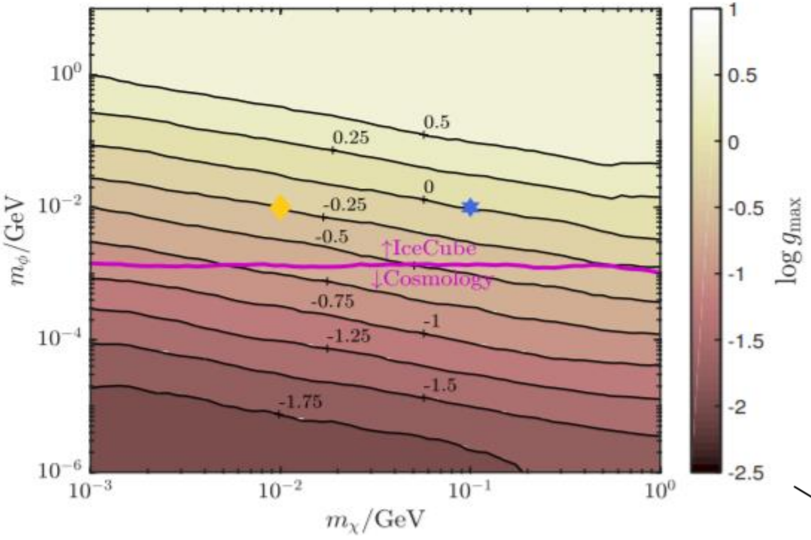


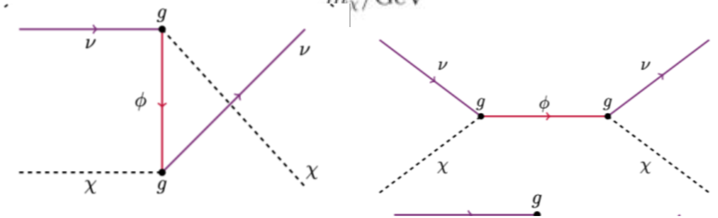
Dark Matter

Earth

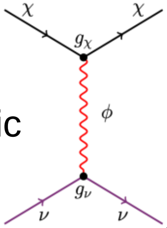
Motivation: Building on Past Work
High Energy Starting Events (HESE)





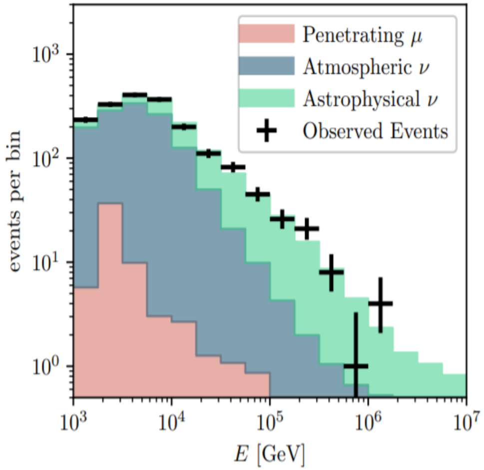


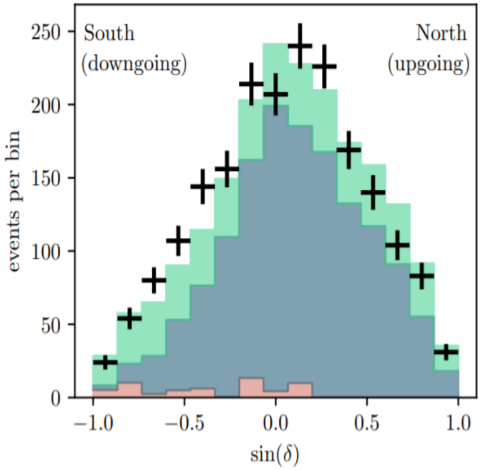
Imaging Galactic Dark Matter with High-Energy Cosmic Neutrinos, Carlos A. Arguelles, Ali Kheirandish, and Aaron C. Vincent [arXiv: 1703.00451](https://arxiv.org/abs/1703.00451)



Different Data Set: Medium Energy Starting Cascades Events (MESC)

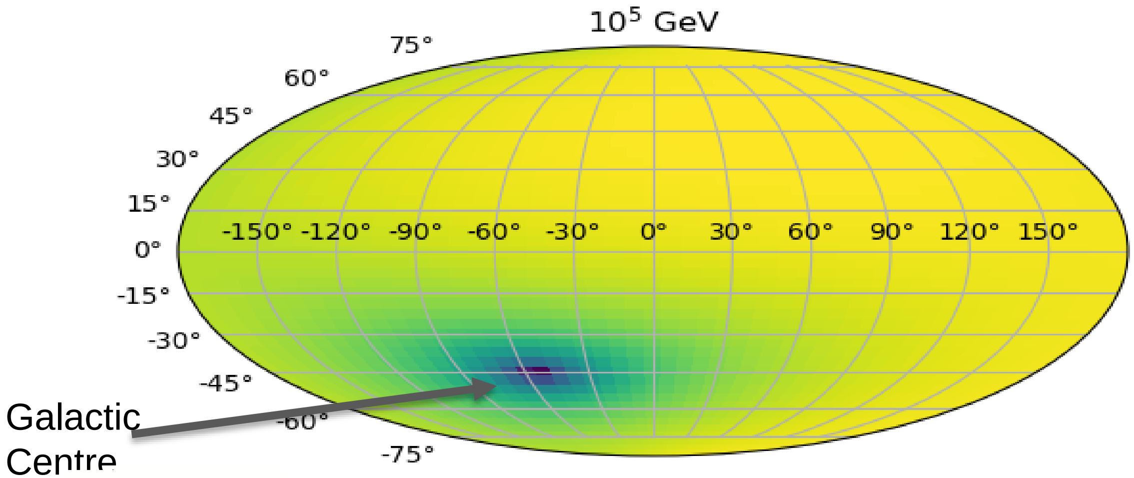
	HESE	MESE
Number of astrophysical type events	~10	~550
Total Number of events	54	1980
Energy Range	30 TeV – 10^4 Tev	1 TeV – 10^4 Tev
Source direction	All sky	All sky

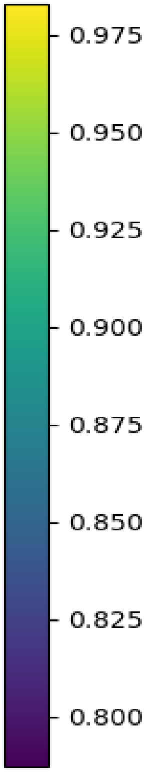




⇒ arXiv:1907.06714

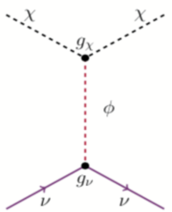
DarkFate: Example





$$SurvivalProbability = \frac{Attenuated\nu Flux}{Isotropic\nu Flux}$$

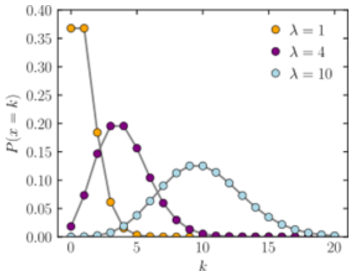
g=1
m_χ=1 GeV
m_ϕ=10 MeV



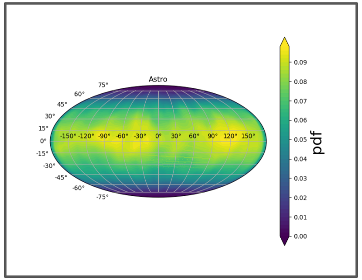
Scalar DM, scalar mediator

Method: Markov Chain Monte Carlo Inference

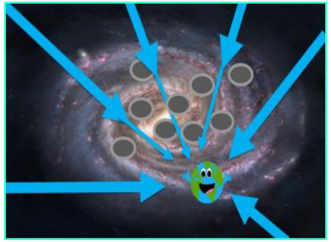
$$\mathcal{L}(\vec{\theta};\{\vec{x}\in\text{dataset}\}) = \frac{e^{-\lambda(\vec{\theta})}\lambda(\vec{\theta})^k}{k!}\prod_i^k \sum_j K(\vec{x}-\vec{x}_j)\frac{d\Phi}{dEd\Omega}(E_j,\alpha_j,\delta_j;\vec{\theta})\frac{L}{g(\vec{\eta}_j)}$$



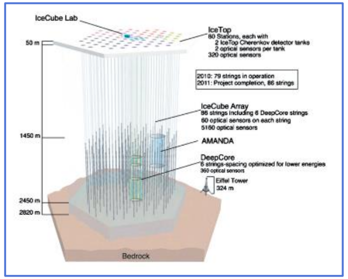
Poisson Normalization



Energy and Direction Probability Density Functions



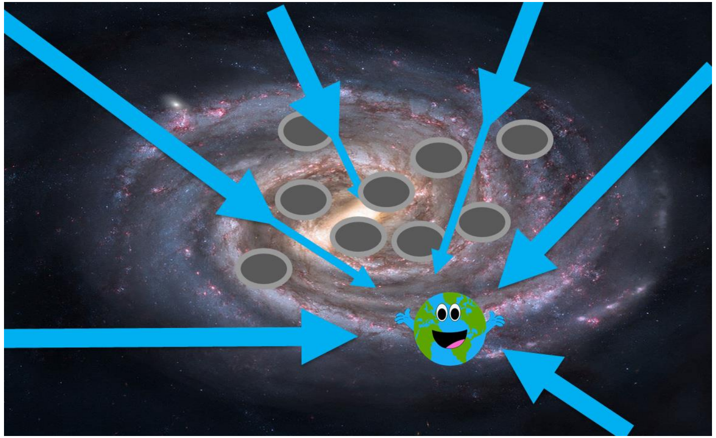
Dark Matter Hypothesis



Instrumental Factors

Conclusions

- Neutrino-DM scattering is motivated by cosmology
- We are searching for a 'neutrino shadow' at the Galactic Centre
- We are in the process of doing MCMC scans of dark matter parameters

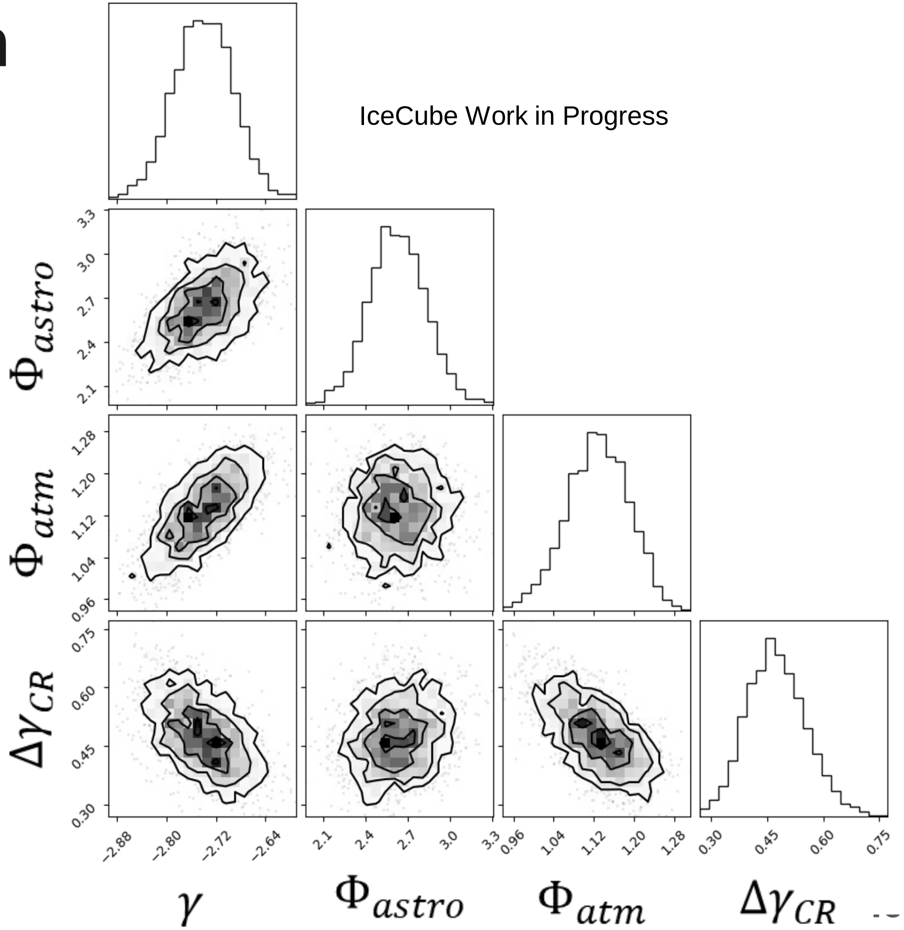


Extra Slides

Spectral Index Validation

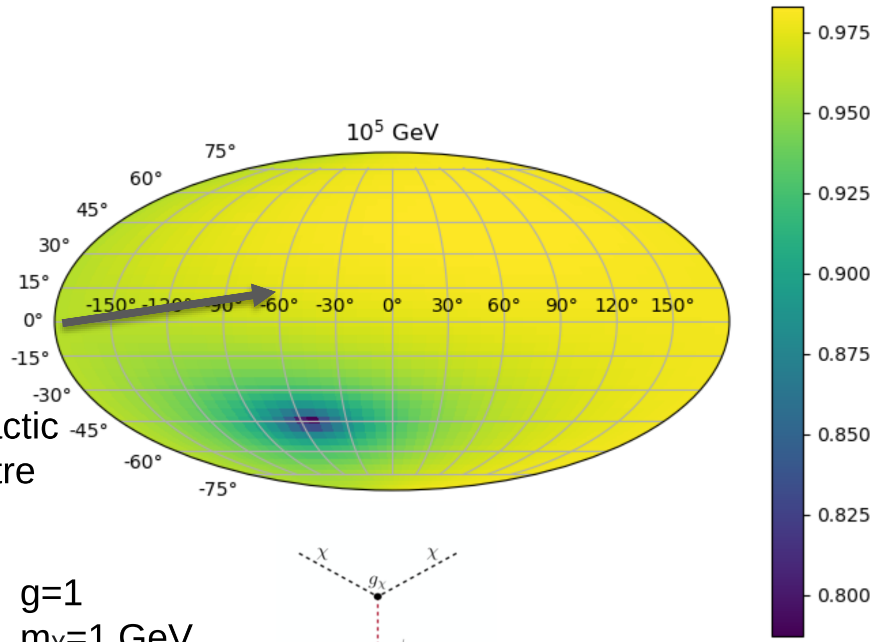
- Here we use Emcee confirm that the likelihood function settles to the expected spectral index and normalization
- Still investigating

- $\gamma = -2.73^{+0.05}_{-0.05}$
- $\Delta\gamma^{CR} = 0.47^{+0.08}_{-0.07}$
- $\Phi_{astro} = 2.623^{+0.06}_{-0.06}$
- $\Phi_{atm} = 1.13^{+0.08}_{-0.07}$

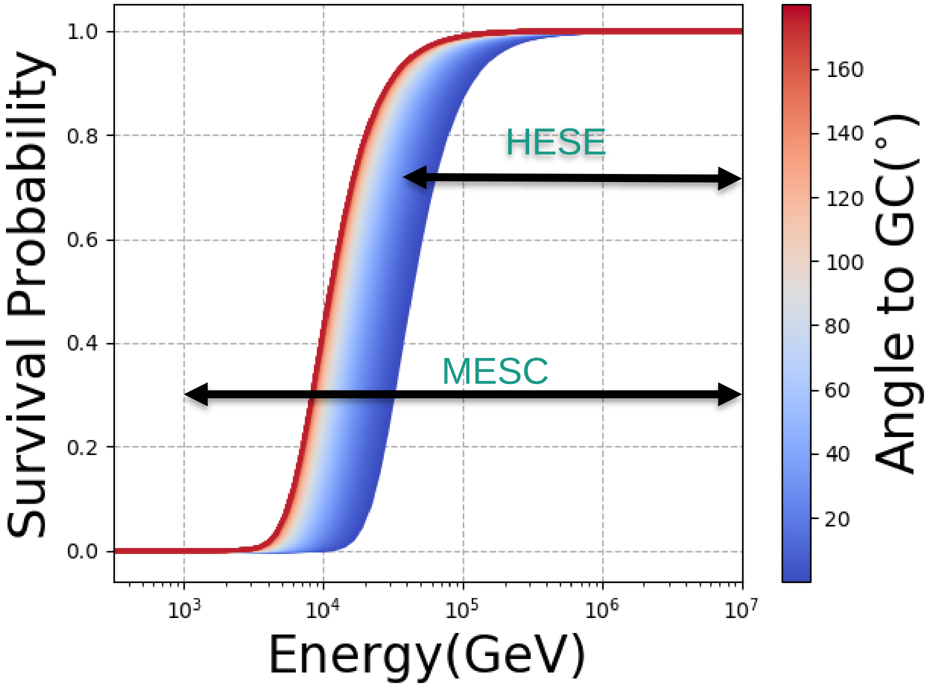


DarkFate: Example

$$Survival\ Probablity = \frac{Attenuated\ Flux}{Isotropic\ Flux}$$



Galactic Centre



g=1
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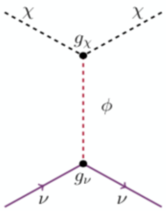
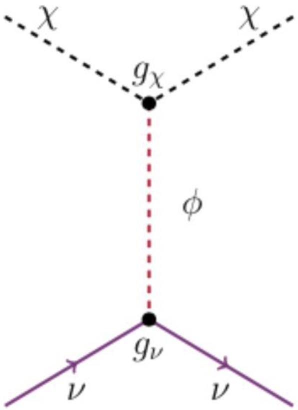


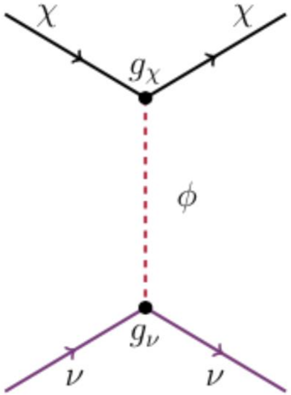
Scalar DM, scalar mediator

Models

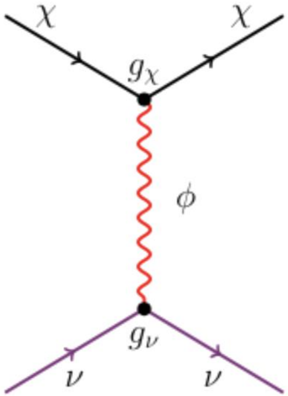
We look for four effective DM-neutrino interaction



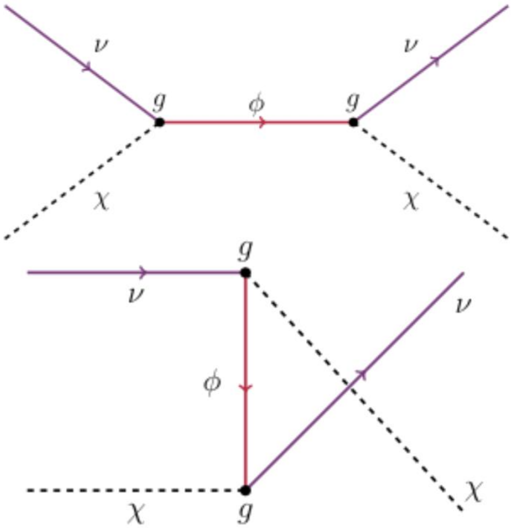
Scalar mediator, scalar DM



Scalar mediator, fermion DM

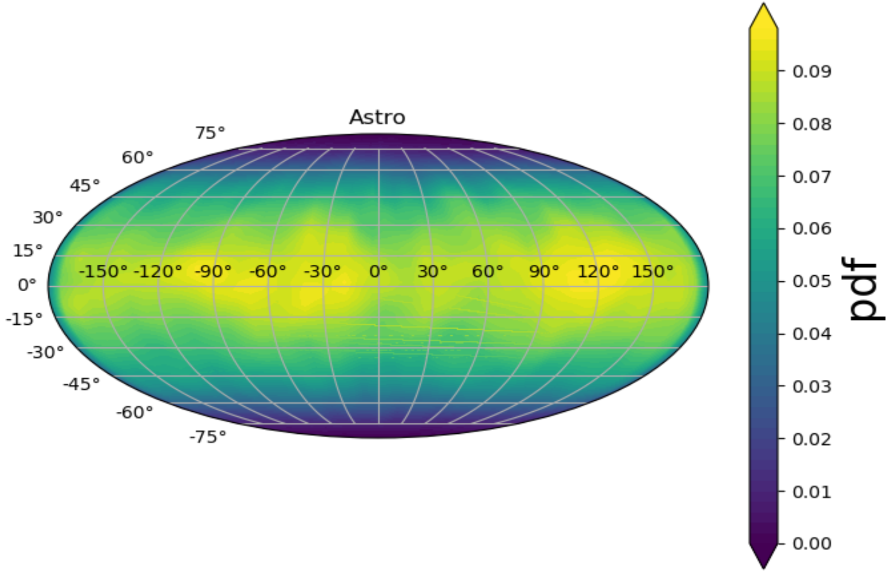


Vector mediator, fermion DM

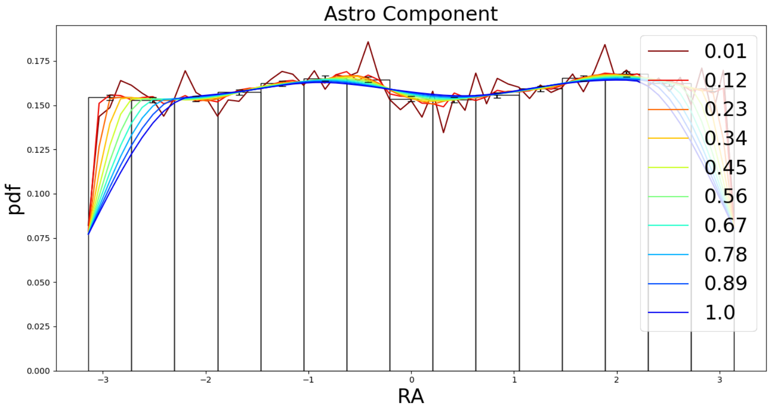


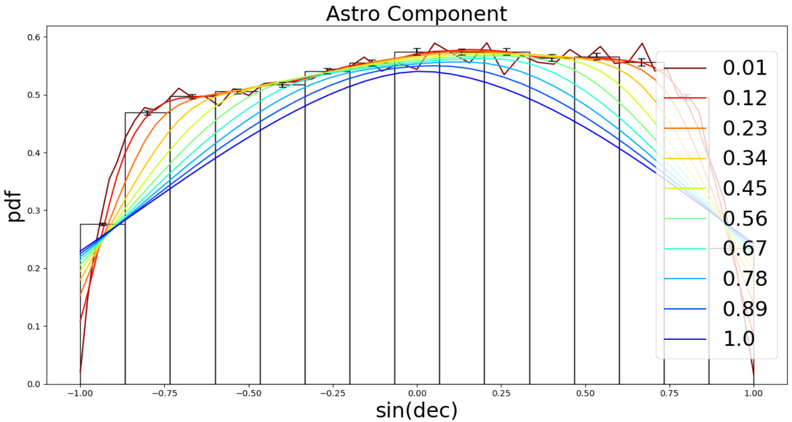
Fermion mediator, scalar DM

Method 1: Forward / KDE



Bandwidth=0.2





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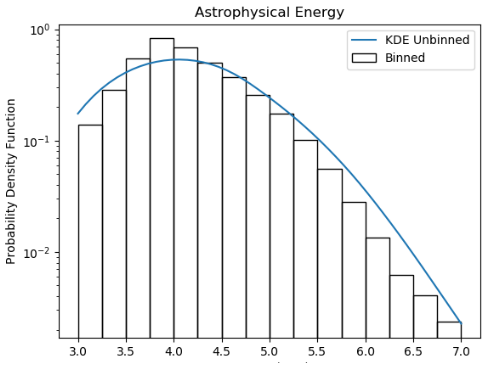
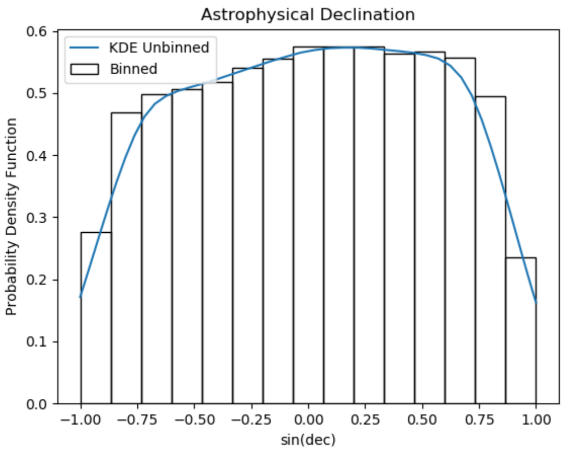
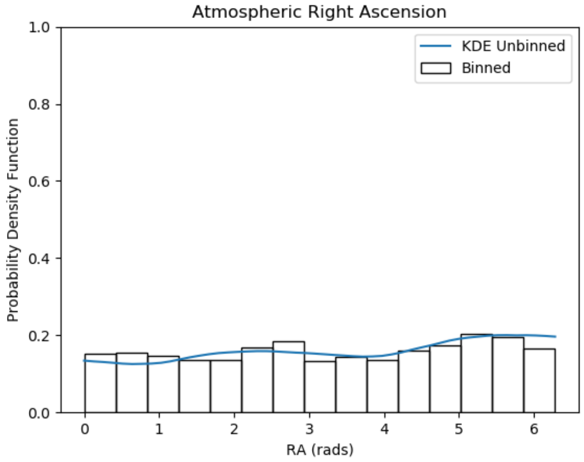
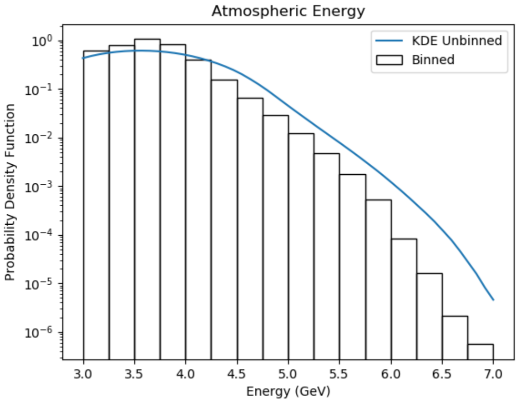
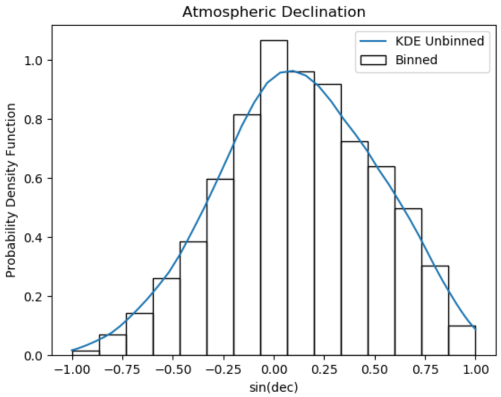










Generation Weight

$$p_{\mathrm{MC}} = N_{\mathrm{gen}} \frac{1}{\Omega_{\mathrm{gen}} A_{\mathrm{gen}}} \times \frac{\rho_{\mathrm{gen}}(\ell)}{X^{\mathrm{col}}_{\mathrm{gen}}} \times \frac{1}{\sigma_{\mathrm{tot}}} \frac{\partial^2 \sigma}{\partial x \partial y} \times \frac{\Phi(E)}{\int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \Phi(E) dE}$$

Theory

b, *l*: galactic latitude, longitude

column density: $$\tau(b,l) = \int_{l.o.s} n_\chi(x;b,l)\ dx.$$

$$\frac{d\Phi(E,\tau)}{d\tau} = -\sigma(E)\Phi(E,\tau) + \int_E^\infty d\tilde{E}\frac{d\sigma(\tilde{E},E)}{dE}\Phi(\tilde{E},\tau)$$

scattering **from** *E* to any energy

scattering **to** *E* from any energy $\tilde{E}$

DarkFate Development

Based on νFATE: Neutrino Fast Attenuation Through Earth

$$\frac{d\Phi(E,\tau)}{d\tau} = -\sigma(E)\Phi(E,\tau) + \int_E^\infty d\tilde{E}\frac{d\sigma(\tilde{E},E)}{dE}\Phi(\tilde{E},\tau)$$

$$E \to \vec{E} \qquad \Phi \to \vec{\Phi} \qquad C_{ij} = d\tilde{E}_i\frac{d\sigma}{dE}(\tilde{E}_i, E_j)$$

$$\vec{\Phi}'(\tau) = -(\mathrm{diag}(\vec{\sigma}) + C)\vec{\Phi}(\tau)$$

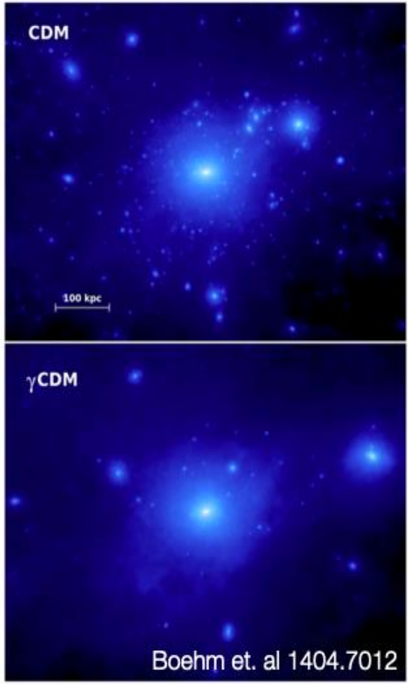
λ_i eigenvalues

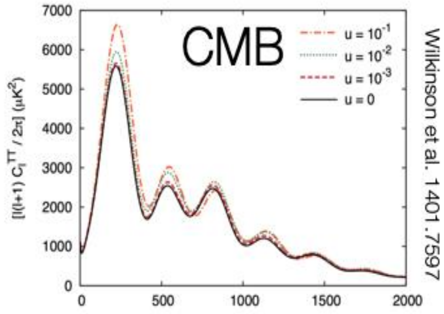
$\hat{\phi}_i$ eigenvectors

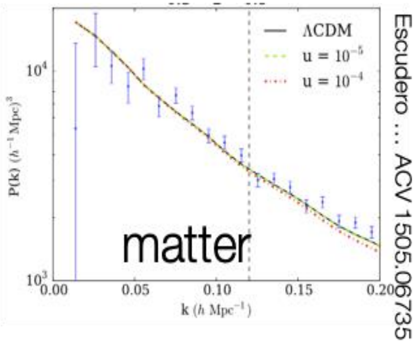
$$\vec{\Phi} = \sum c_i\hat{\phi}_i e^{\lambda_i\tau}$$

Motivation: DM-neutrino scattering in cosmology

Power "bled away" on small scales
by neutrinos streaming away; increased correlations on large scales



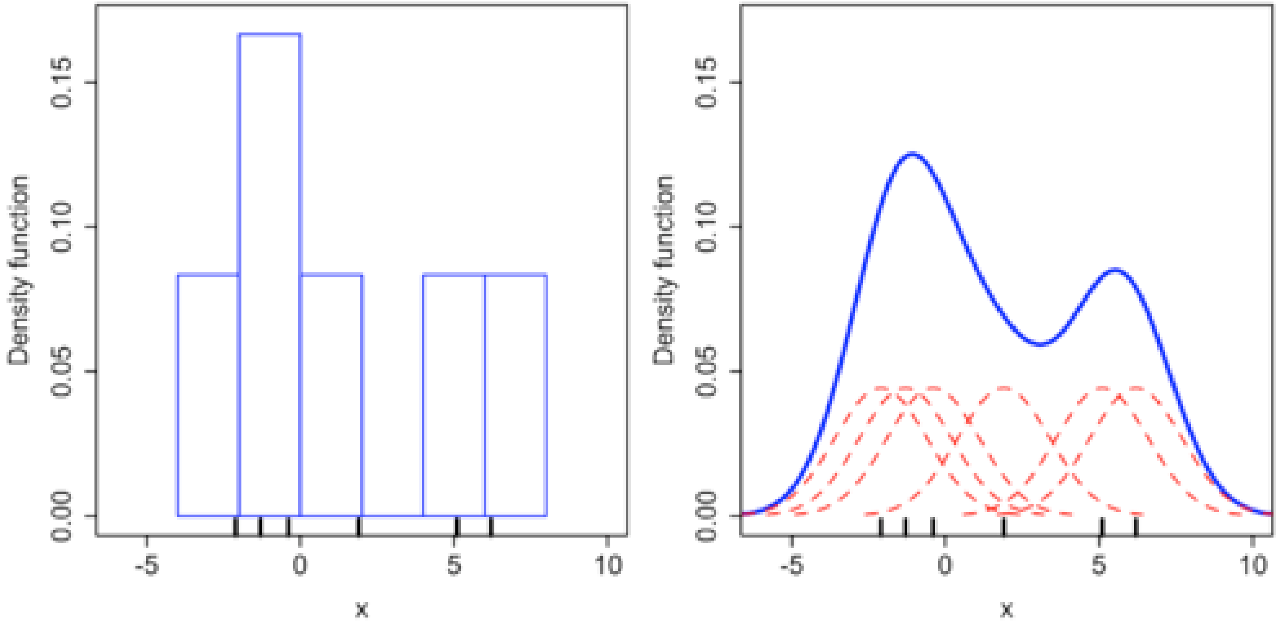




$$u \equiv \left[\frac{\sigma_{DM-\nu}}{\sigma_{Th}}\right]\left[\frac{m_{DM}}{100\ \mathrm{GeV}}\right]^{-1}$$

Method 1: Forward / KDE

Sample	1	2	3	4	5	6
Value	-2.1	-1.3	-0.4	1.9	5.1	6.2



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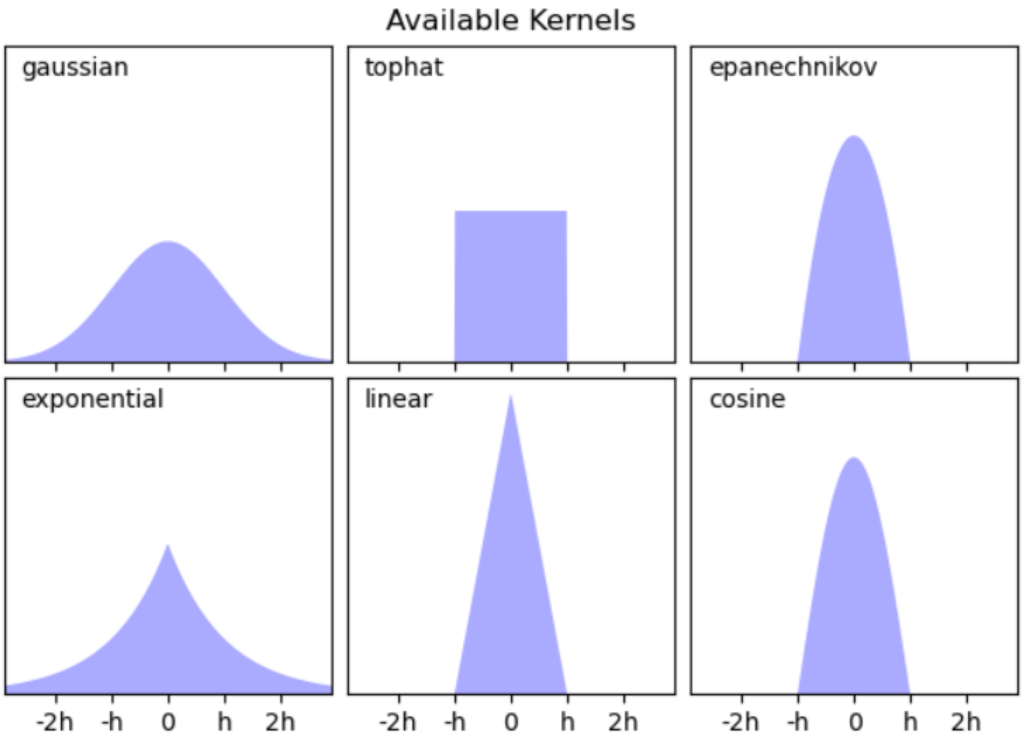

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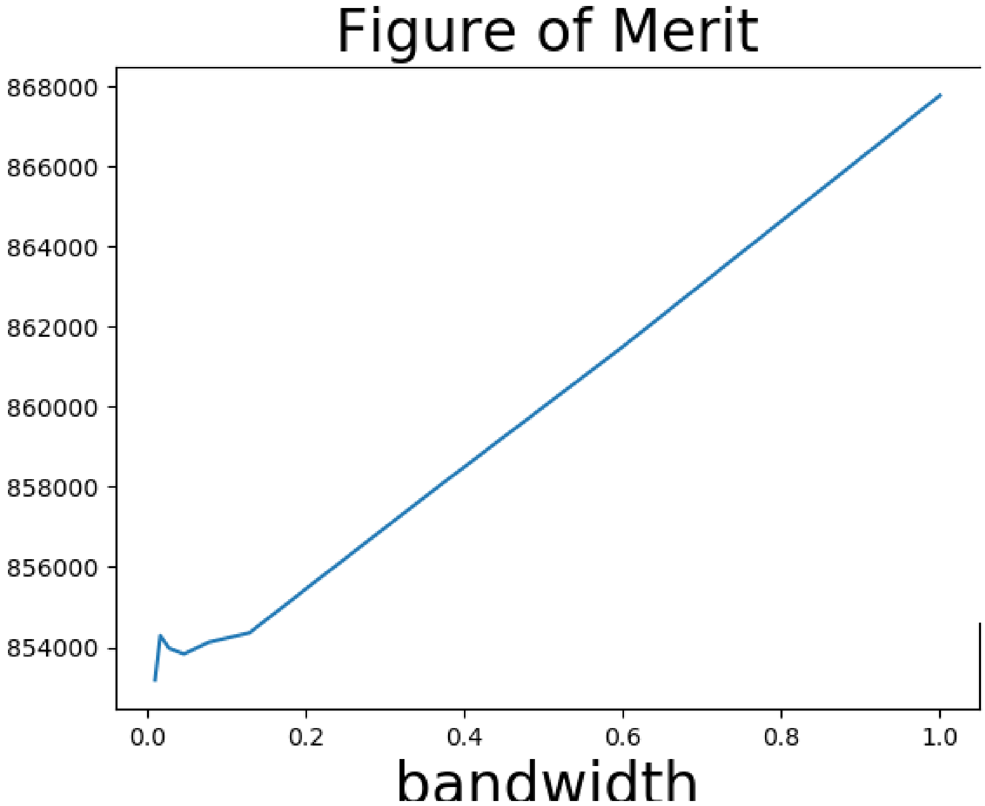
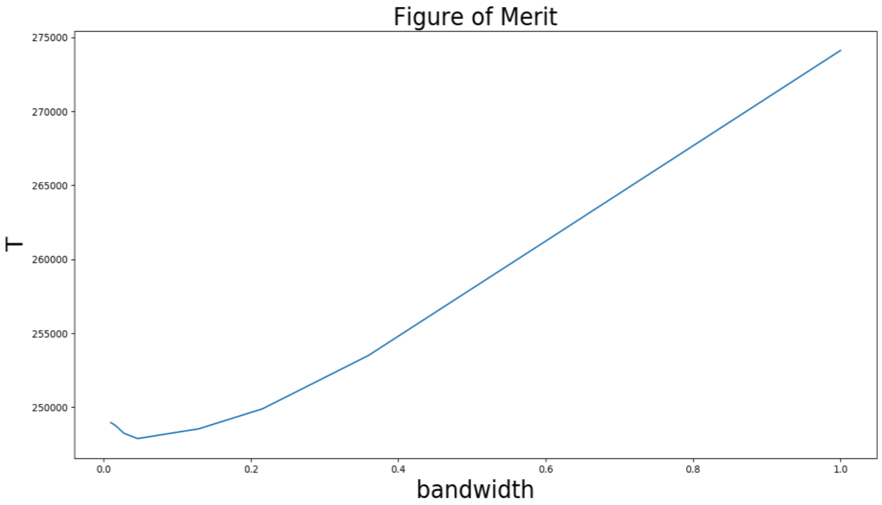




Two Approaches to uncertainties

Event properties:

- Direction
- Energy

1. Use MC to map reconstruction observables to real parameters

OR

2. Use Bayesian methods to derive uncertainties on these properties

Dark matter related:

- DM distribution uncertainties

Add DM model parameters

Method 2: Bayesian hierarchical model

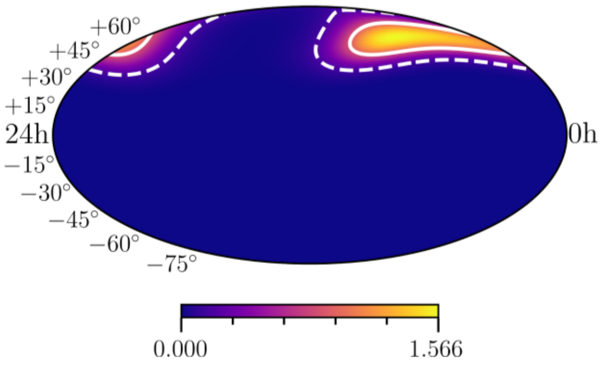
Instead of dealing with the nuisance parameters and physics parameters separately. We can throw everything into a giant Markov Chain Monte Carlo.

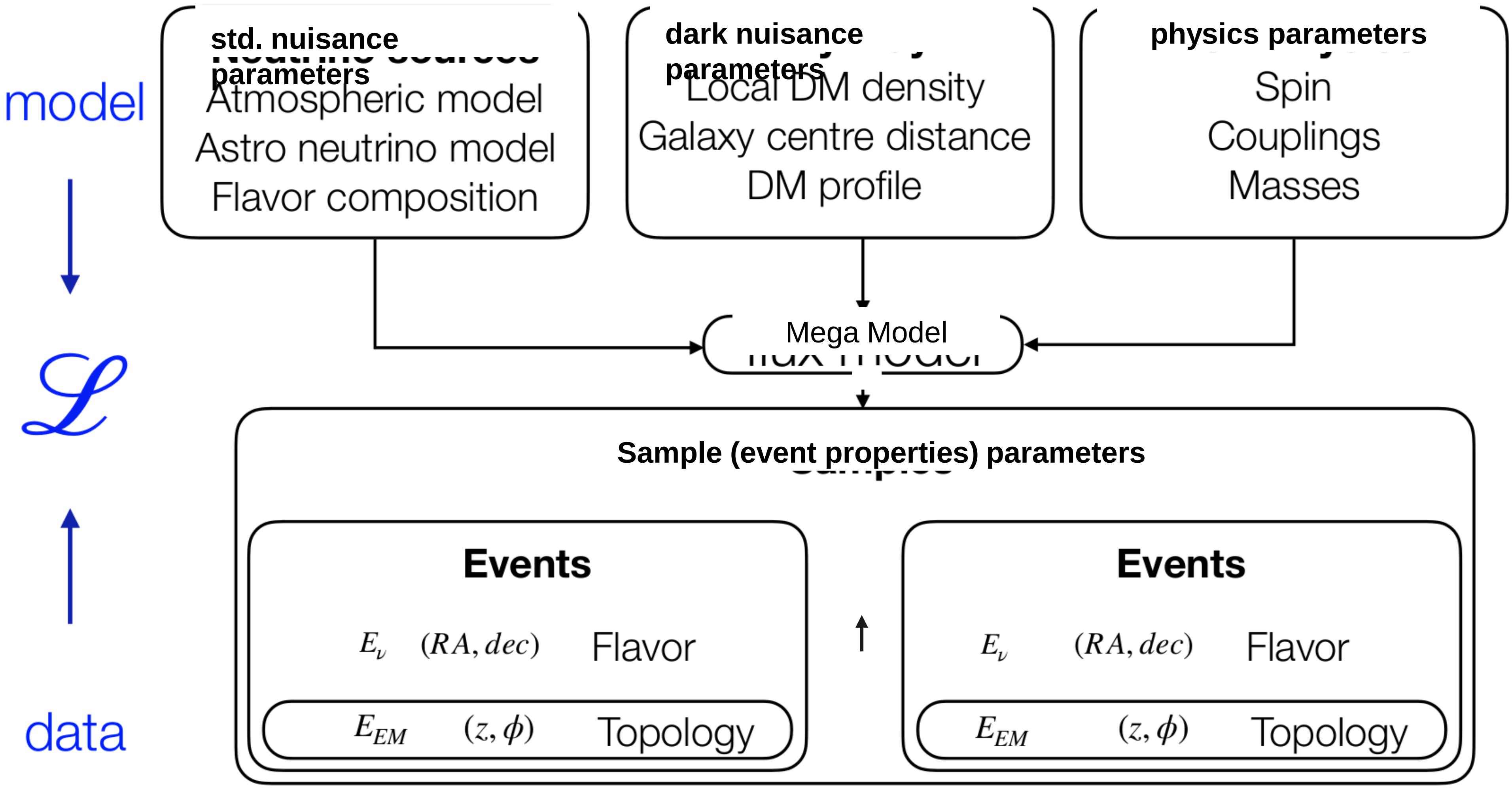
Instead of using the best-fit properties of each event we can use, in this scope, the full reconstructed likelihood of the event.

$$\mathcal{P}(Q_k) = \mathcal{P}(\{O_{i,j}|Q_k\})\Pi(Q_k)$$

where here O_i,j are the set of observables from the ensemble of events and Q_k its true underlying properties.

For example, the direct-fit direction posterior when assuming a flat prior




model
data
std. nuisance parameters
Atmospheric model
Astro neutrino model
Flavor composition
dark nuisance parameters
Local DM density
Galaxy centre distance
DM profile
physics parameters
Spin
Couplings
Masses
Mega Model
Sample (event properties) parameters
Events
E_ν (RA, dec) Flavor
E_{EM} (z, ϕ) Topology
Events
E_ν (RA, dec) Flavor
E_{EM} (z, ϕ) Topology

Method: Hierarchical model

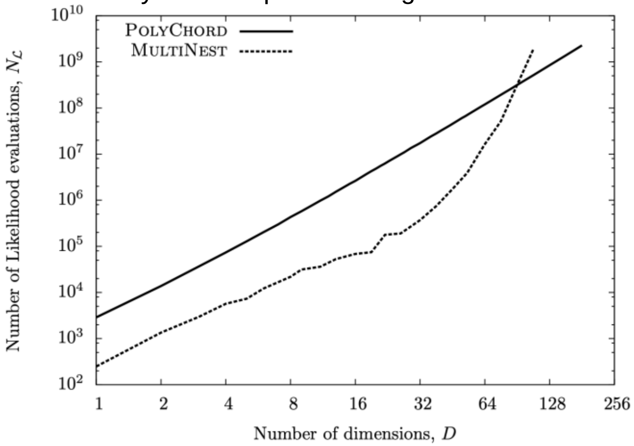
So now to construct the model evidence we need to compute the integral of the following likelihood:

$$\mathcal{L}(\theta) = \frac{e^{-\lambda(\vec{\theta})}\lambda(\vec{\theta})^n}{n!}\prod_i^n \int d\vec{Q}\rho(\theta)\mathcal{P}(\vec{Q})$$

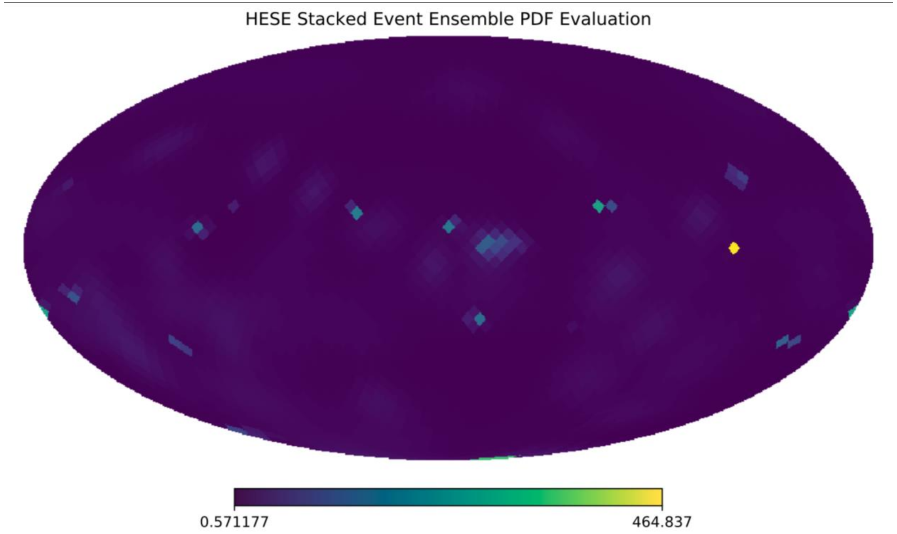
The most efficient way of doing this is to compute the integral over the physics parameters, nuisance parameters, and event properties simultaneously.

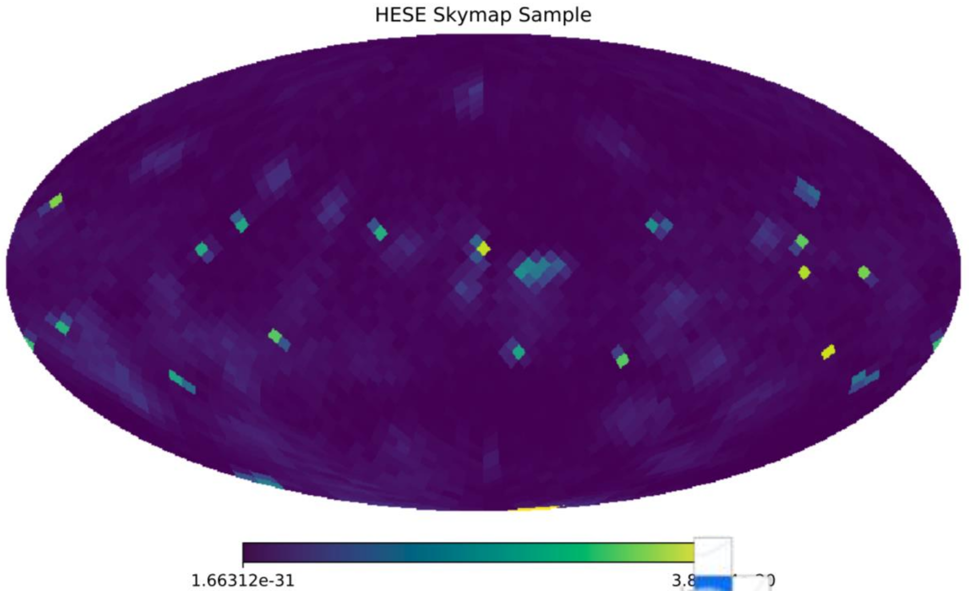
This is not an entirely trivial problem as there are O(10) nuisance and physics parameters, but O(100) event properties to take into account in the sample. Thus the integral is not small dimensional.

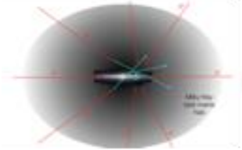
PolyChord https://arxiv.org/abs/1506.00171



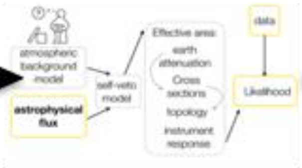
Method: Hierarchical model: Example





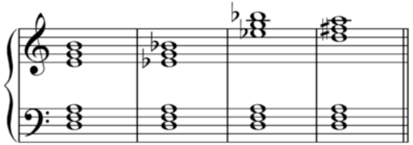


model

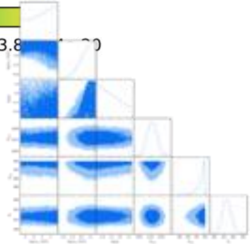


likelihood

IceCube data



MCMC



posterior