Searching for Dark Matter-Neutrino Scattering in the Galactic Centre with IceCube

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Adam McMullen
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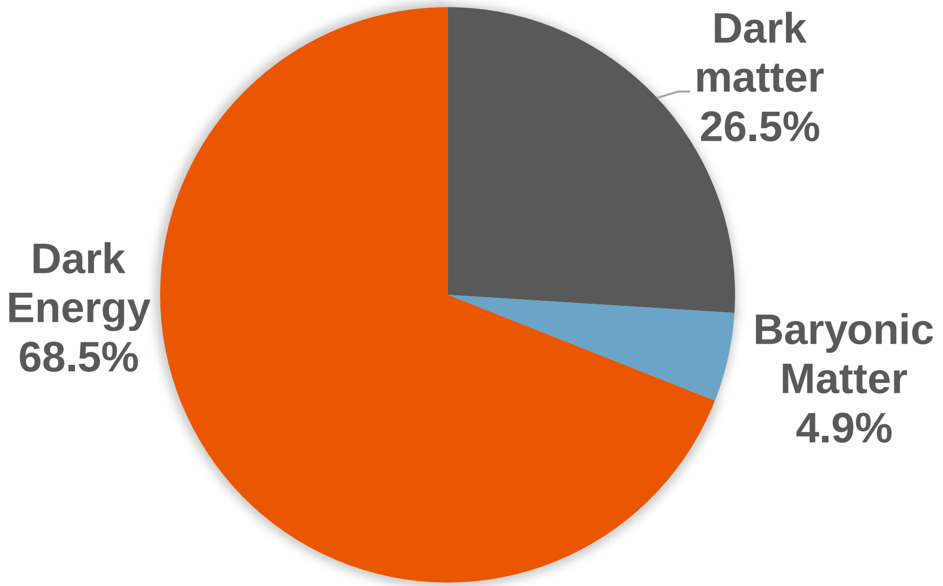
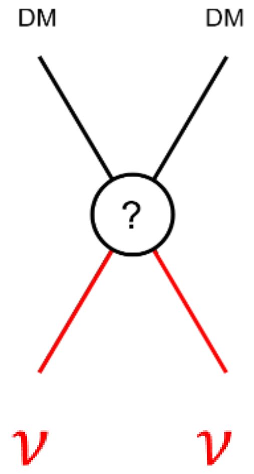
Motivation: Dark Matter

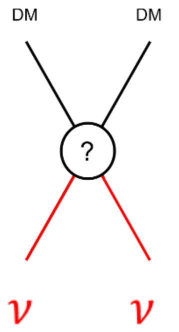


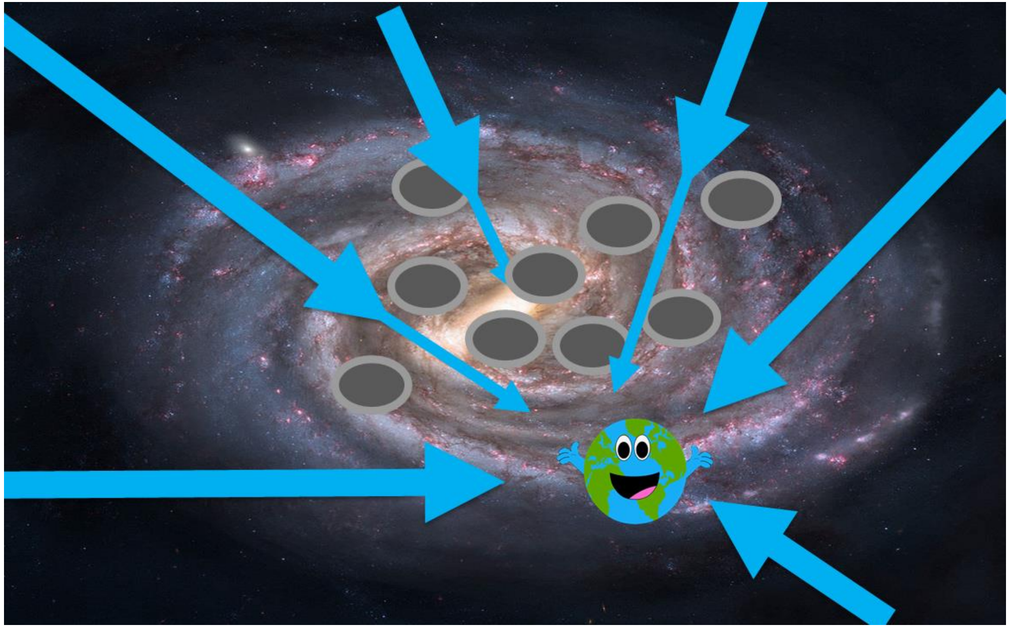
COMPOSITION OF THE UNIVERSE TODAY

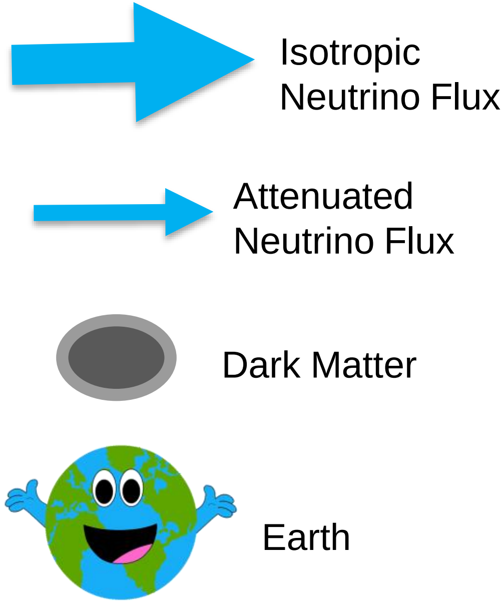


General Idea

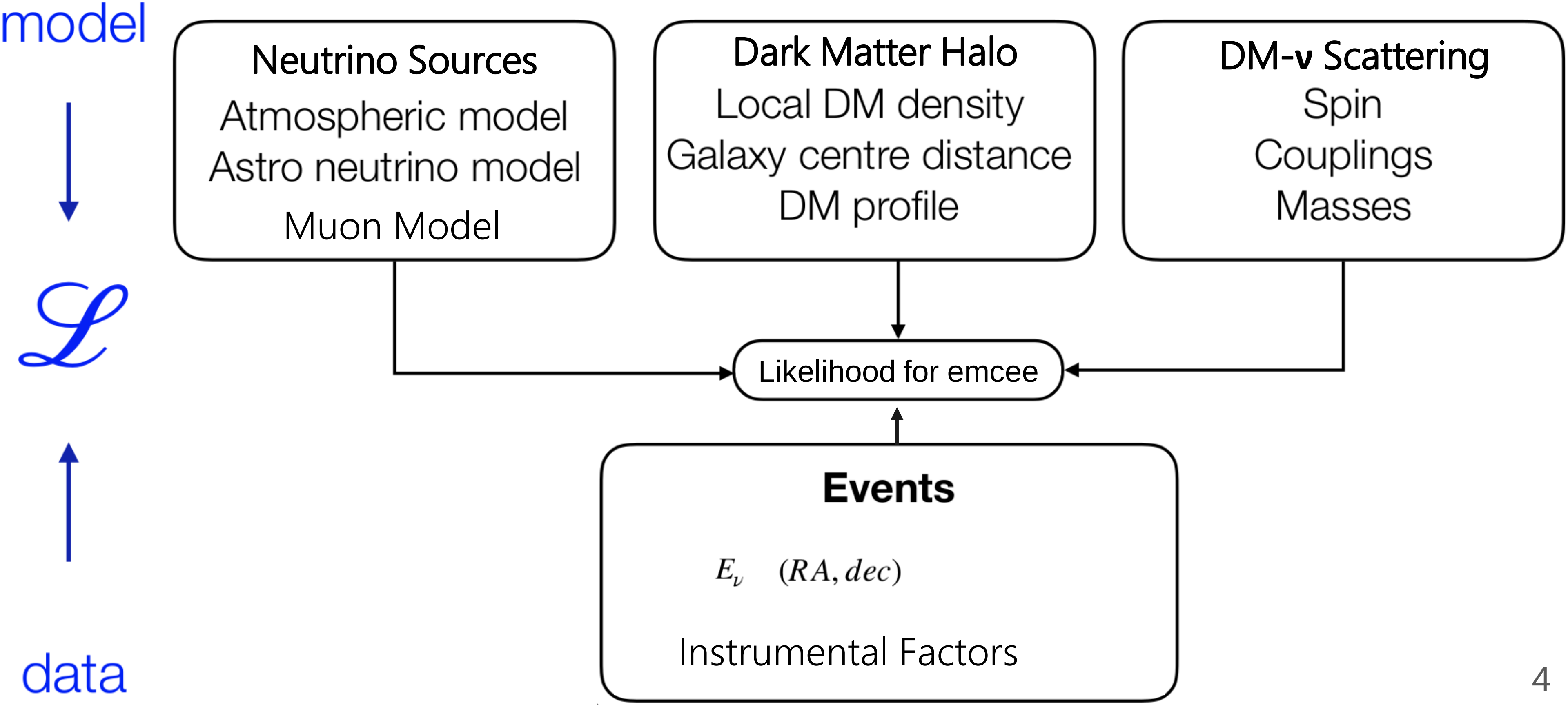
- An isotropic extragalactic neutrino flux is preferentially attenuated at the galactic centre from dark matter-neutrino scattering





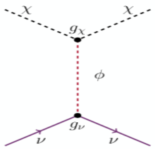


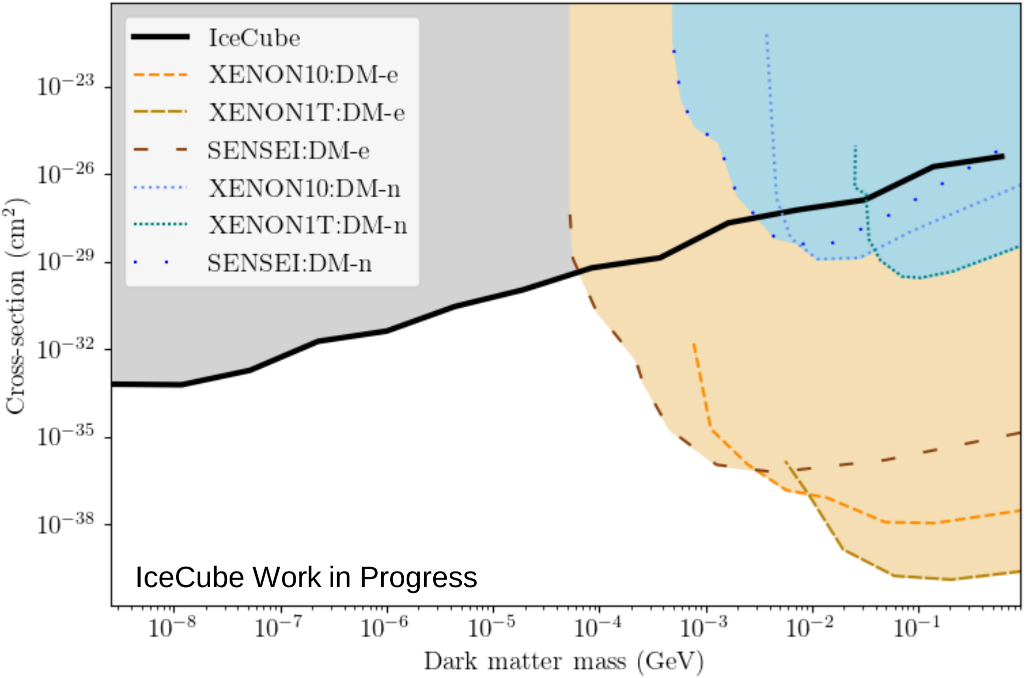
The Process

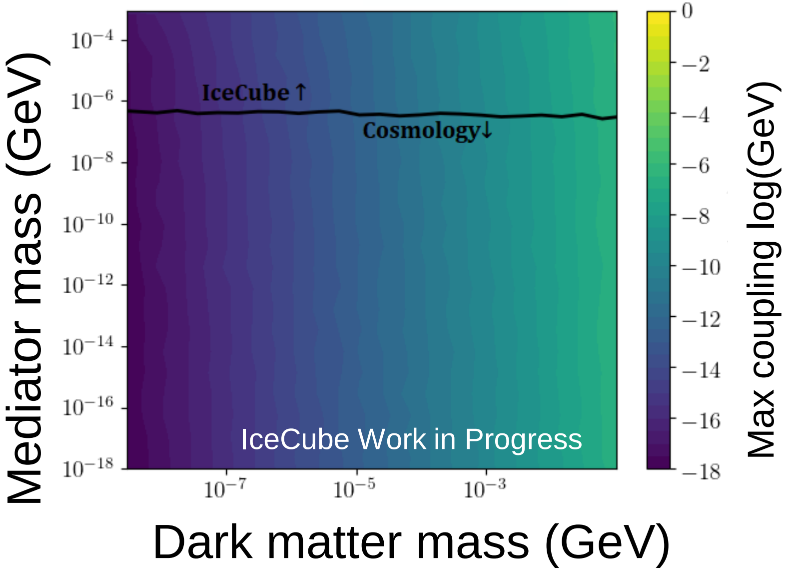

model
data
Neutrino Sources
Atmospheric model
Astro neutrino model
Muon Model
Dark Matter Halo
Local DM density
Galaxy centre distance
DM profile
DM-ν Scattering
Spin
Couplings
Masses
Likelihood for emcee
Events
E_ν (RA, dec)
Instrumental Factors

Sensitivities

Scalar scalar model





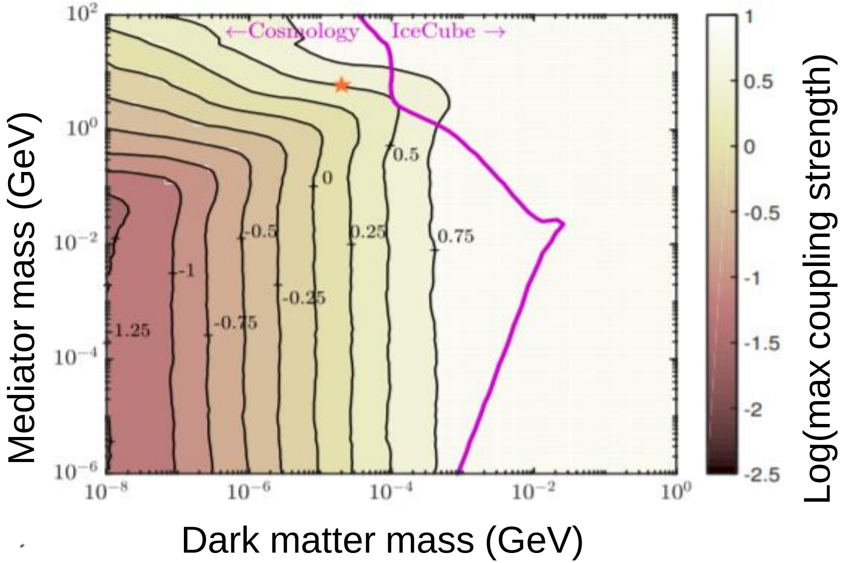


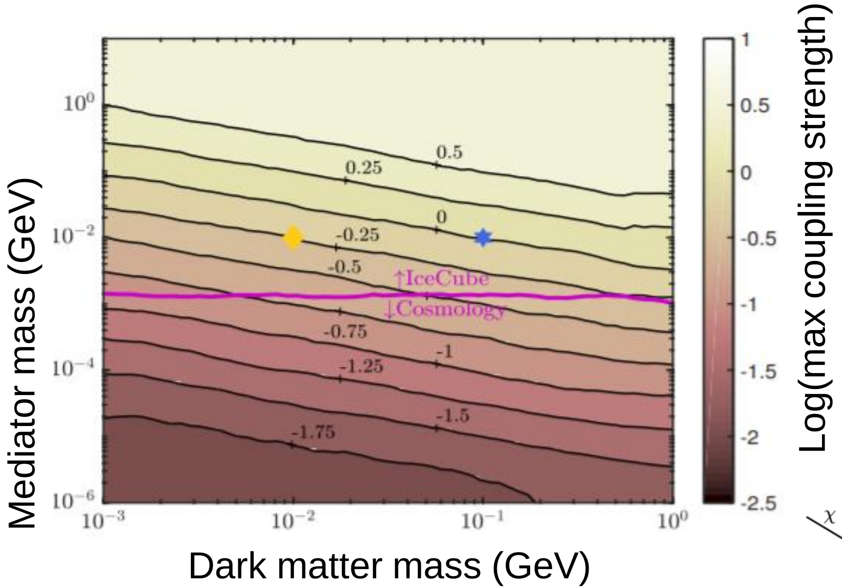
$$\sigma_{\nu-DM} \lesssim 10^{-27}\left(\frac{m_\chi}{\text{GeV}}\right)\left(\frac{E_\nu}{\text{PeV}}\right)^{-2}\ \text{cm}^2$$

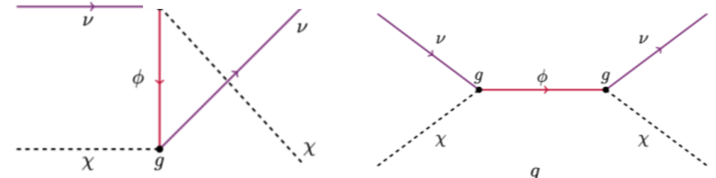
Thank You

Extra Slides

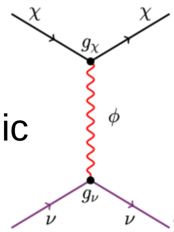
Motivation: Building on Past Work
High Energy Starting Events (HESE)







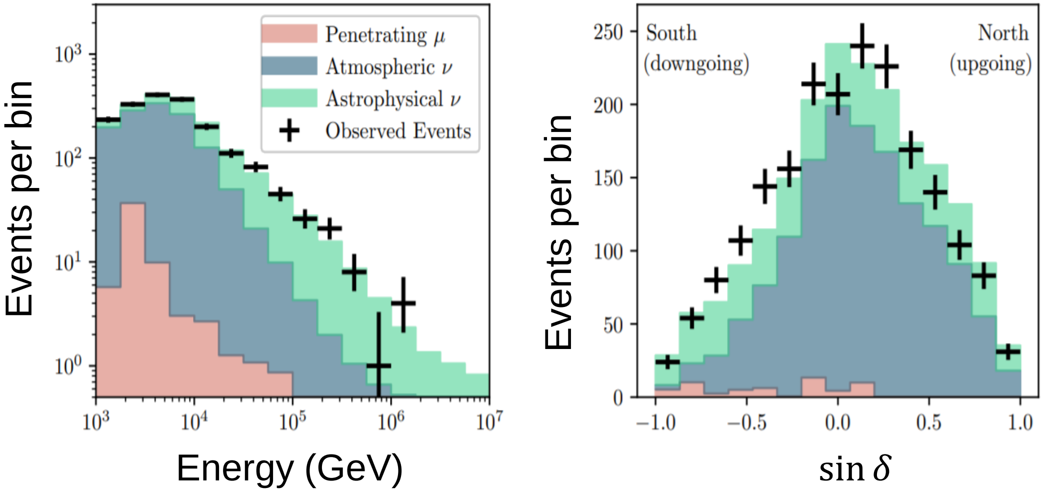
Imaging Galactic Dark Matter with High-Energy Cosmic Neutrinos, Carlos A. Arguelles, Ali Kheirandish, and Aaron C. Vincent arXiv: 1703.00451



Different Data Set: Medium Energy Starting Events- Cascades (MESE-C)

- We will use the 7 year MESE cascade dataset

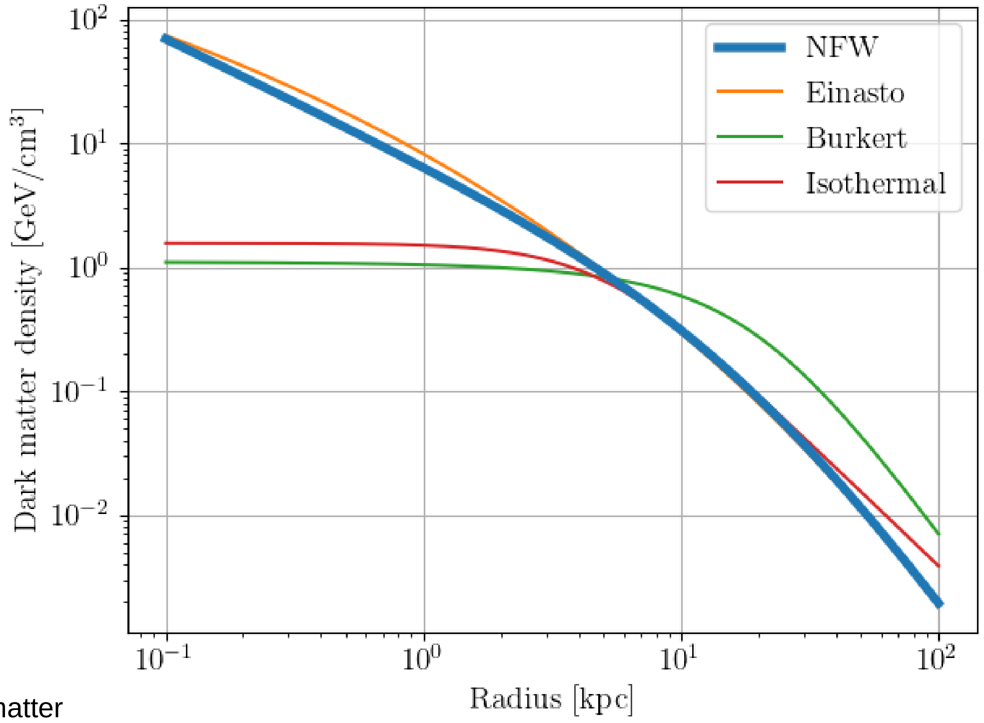
	HESE	MESE-C
Energy range	30 TeV – 10^4 Tev	1 TeV – 10^4 Tev
Number of astrophysical type events	~30	~550
Total number of events	54	1980
Source direction	All sky	All sky



M. G. Aartsen, et al., Search for sources of astrophysical neutrinos using seven years of icecube cascade events (2019)

Dark Matter Density Profiles

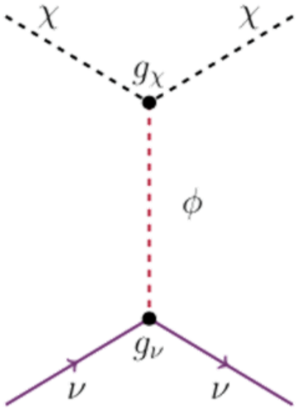
- In this analysis the NFW profile was used
- $\rho_{NFW}(r) = \frac{\rho_0}{\left(\frac{r}{r_S}\right)\left[1+\frac{r}{r_S}\right]^2}$
- $\rho_0 = 0.4 \text{ GeV/cm}^3$
- $r_s = 26 \text{ kpc}$



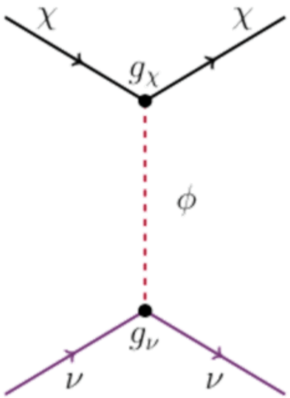
M. Benito, F. Iocco and A. Cuoco, Uncertainties in the galactic dark matter distribution: an update, 2009.13523.

New Physics Models

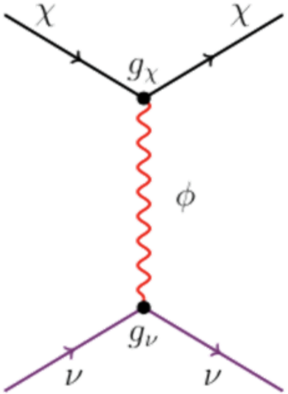
We look for four effective DM-neutrino interaction processes:



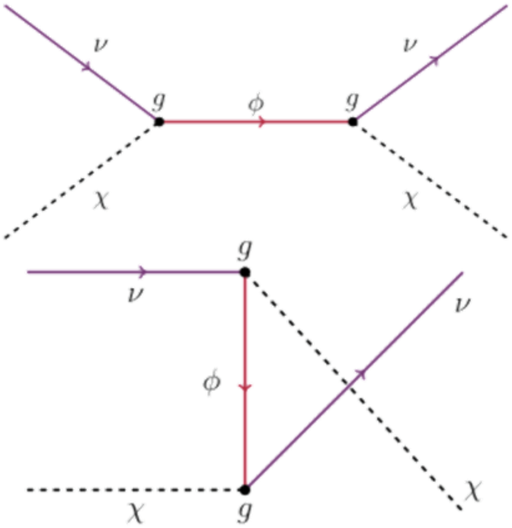
Scalar mediator, scalar DM



Scalar mediator, fermion DM

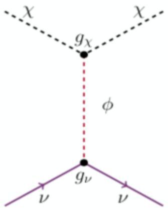


Vector mediator, fermion DM

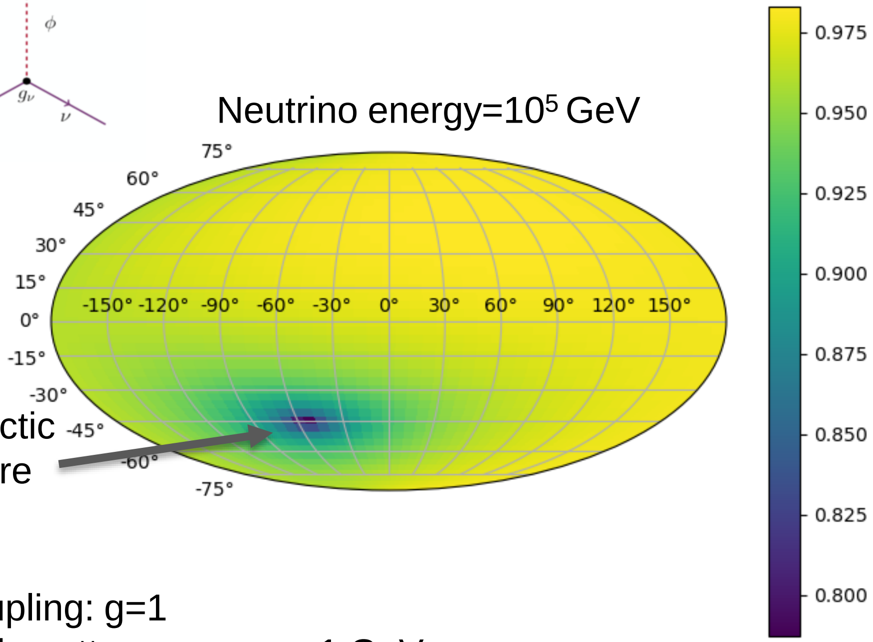


Fermion mediator, scalar DM

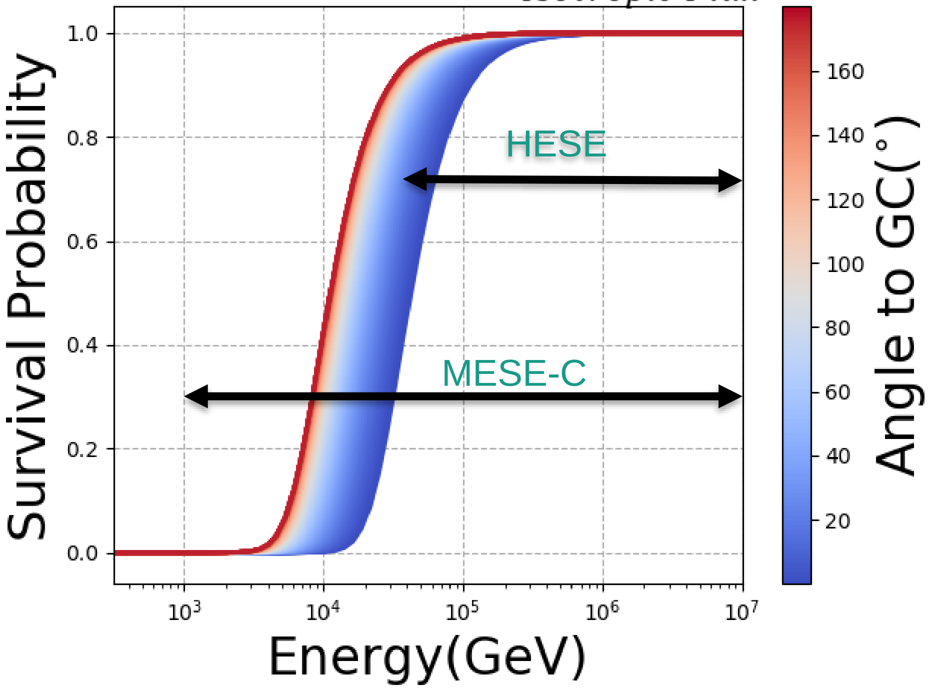
DM-neutrino scattering signal



Neutrino energy=10^5 GeV



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

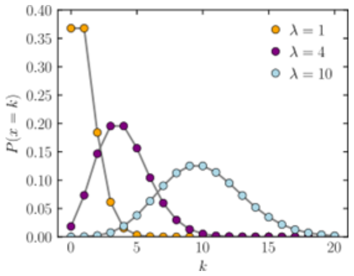


Coupling: g=1
Dark matter mass: m_χ=1 GeV
Mediator mass: m_ϕ=10 MeV

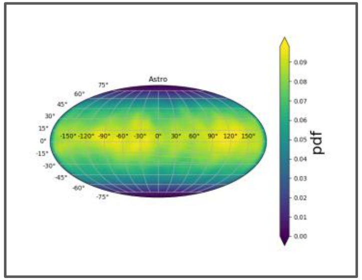
Scalar DM, scalar mediator

Method: Markov Chain Monte Carlo Sampler

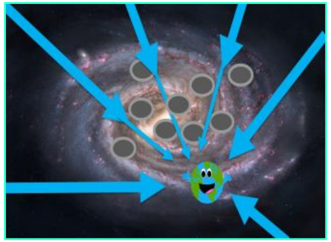
$$\mathcal{L}(\vec{\theta}; \{\vec{x} \in \text{dataset}\}) = \frac{e^{-\lambda(\vec{\theta})}\lambda(\vec{\theta})^k}{k!} \prod_i^k \sum_j K(\vec{x} - \vec{x}_j) \frac{d\Phi}{dE d\Omega}(E_j, \alpha_j, \delta_j; \vec{\theta}) \frac{L}{g(\vec{\eta}_j)}$$



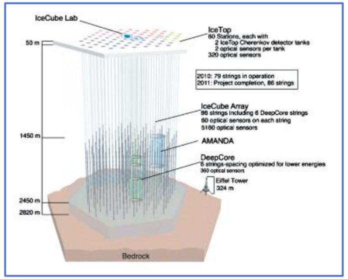
Poisson Normalization



Energy and Direction Probability Density Functions



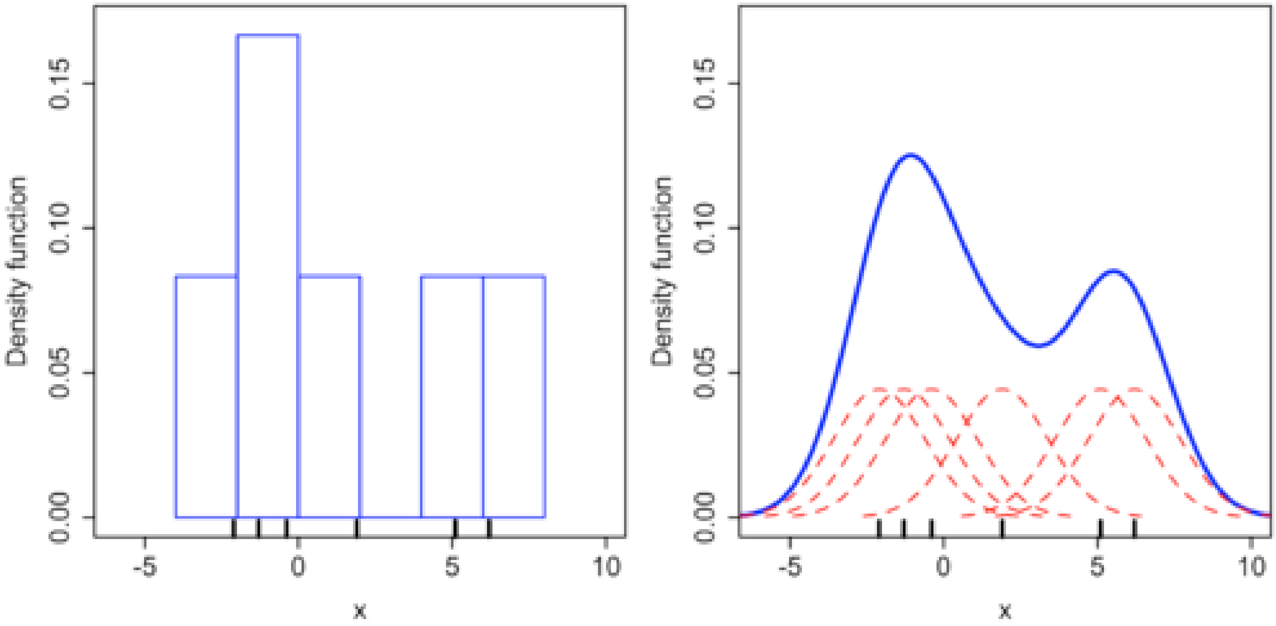
Dark Matter Hypothesis in Neutrino Flux



Instrumental Factors

Kernel Density Estimation

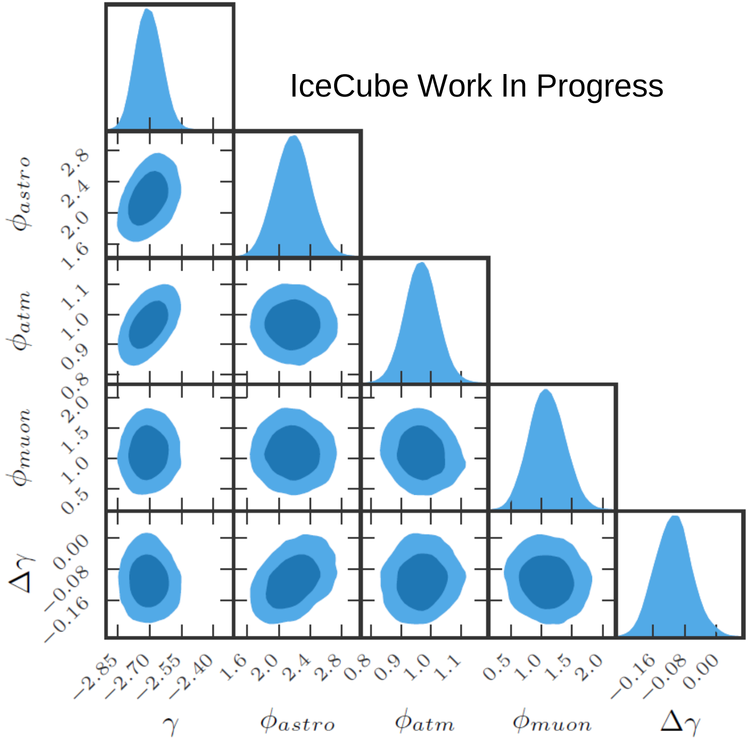
Sample	1	2	3	4	5	6
Value	-2.1	-1.3	-0.4	1.9	5.1	6.2



Spectral Index Validation

- Emcee was used to confirm the likelihood recovers the expected background parameters for no dark matter

γ	$-2.70^{+0.06}_{-0.05}$
Φ_{astro}	$2.18^{+0.20}_{-0.21}$
Φ_{atm}	$0.96^{+0.05}_{-0.04}$
$\Delta\gamma$	$0.11^{+0.04}_{-0.04}$

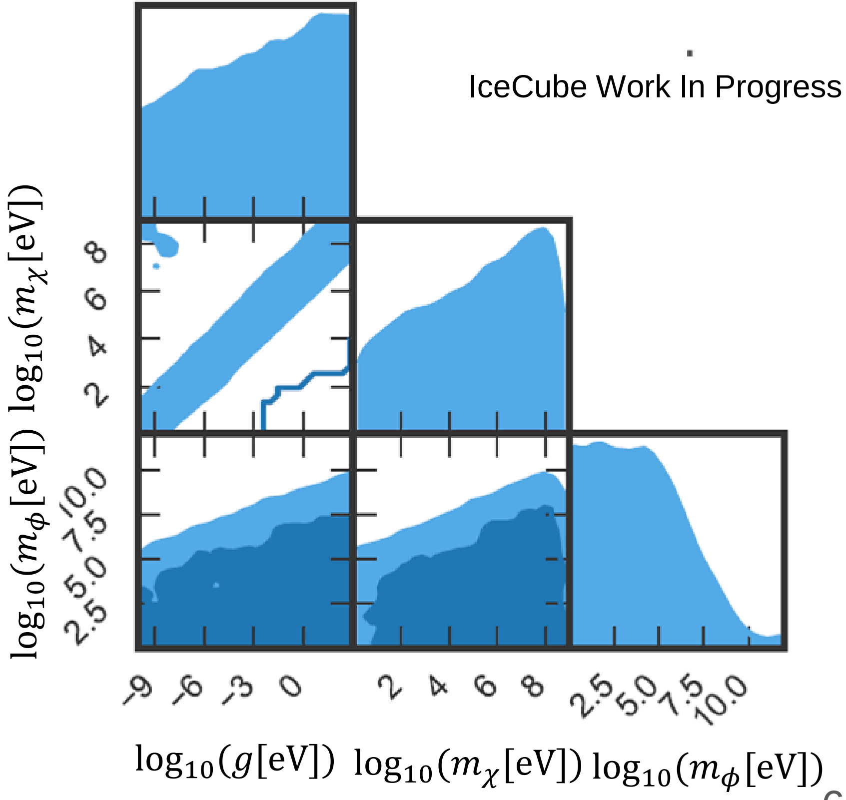


$$\frac{d\Phi_\nu^{atm}}{dE} = \Phi_{atm}\left(\frac{E_\nu}{E_0^p}\right)^{-\Delta\gamma}$$

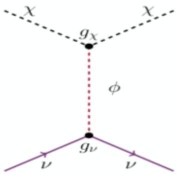
$$\frac{d\Phi^{astro}}{dE} = \Phi_{astro}\left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma}$$

Posteriors on DM Parameters

- Sensitivities can be set with the posterior probabilities on the dark matter mass m_χ, mediator mass m_ϕ and coupling strength g

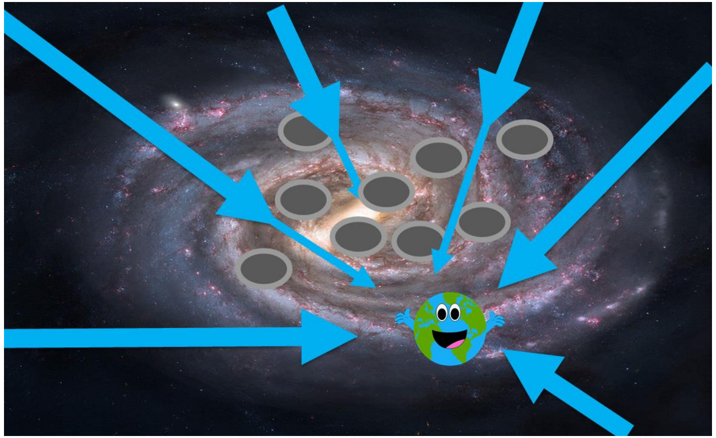


Scalar scalar model



Conclusions

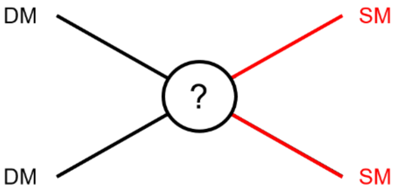
- Neutrino-DM scattering is motivated by cosmology
- The neutrino flux would be preferentially attenuated in the direction of the galactic centre
- Sensitivities at IceCube can beat cosmology



Next Steps

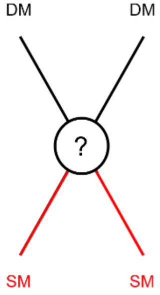
- Will explore other models
- Will determine constraints with unblinded IceCube data

Motivation: Particle dark matter and DM-neutrino interactions in cosmology

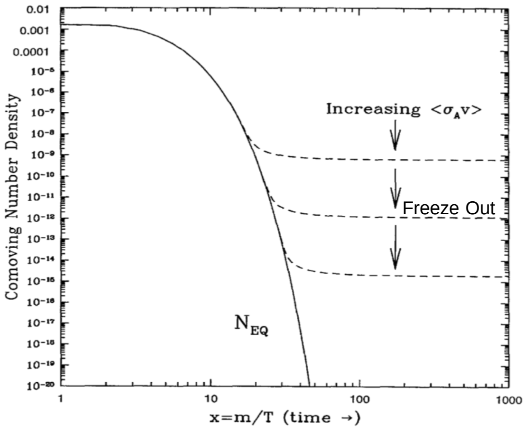


Dark matter annihilation is motivated by the WIMP miracle

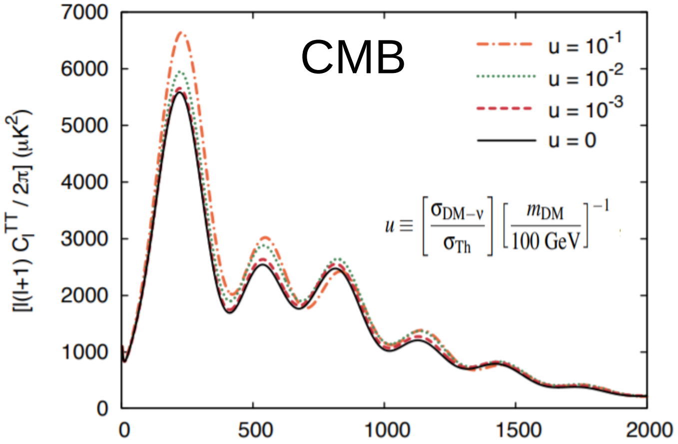
Crossing symmetry implies the existence of a scattering interaction



We should also expect to see scattering

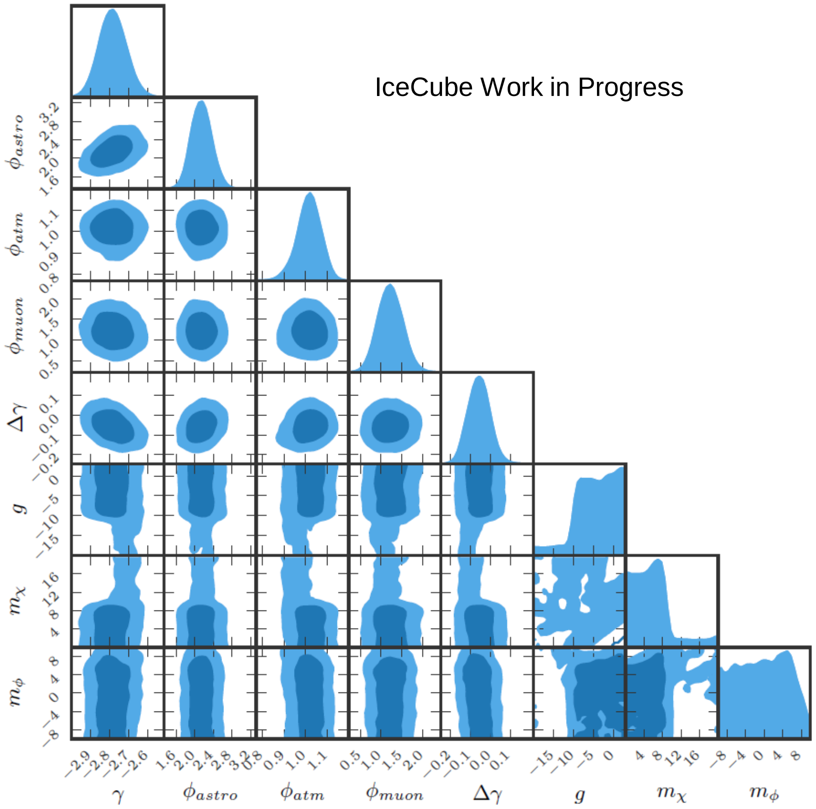


Jungman, et al Arxiv: 9506380



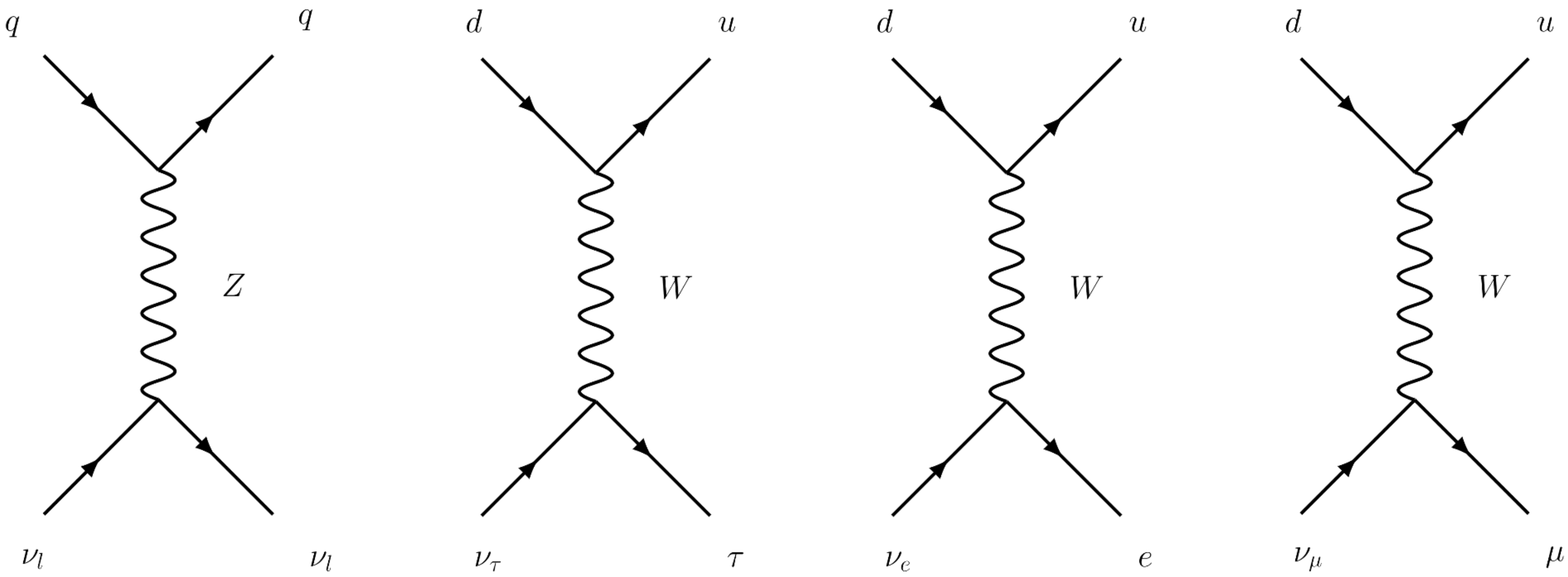
R. Wilkinson, et al Arxiv: 1401.7597

Full Posterior

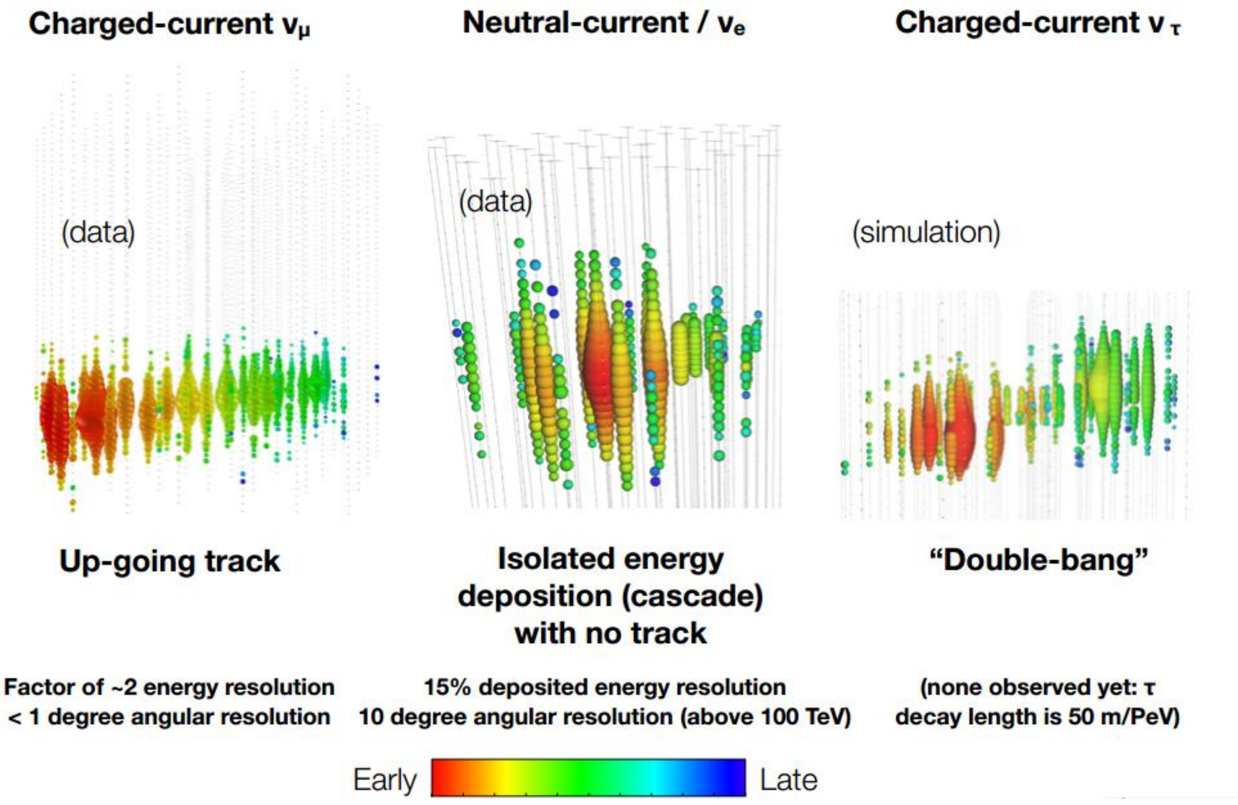


scalar dark matter
Scalar mediator

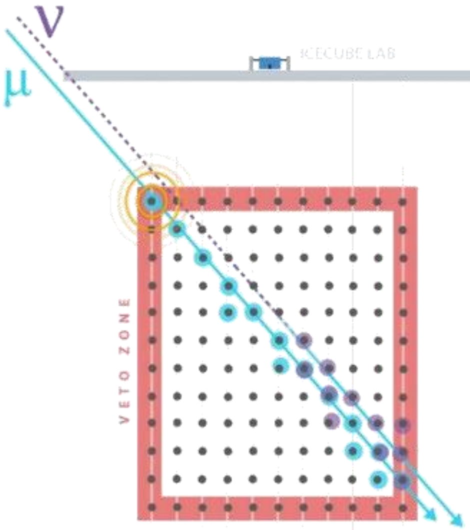
Neutrino Interactions at IceCube

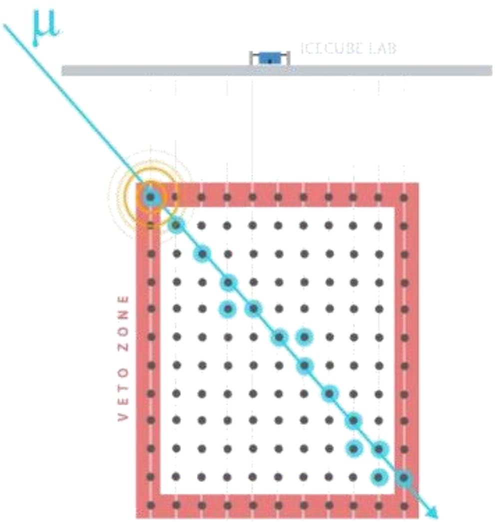


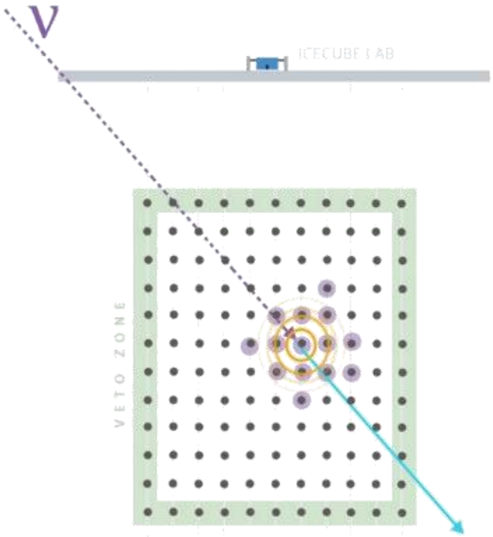
Event Morphologies



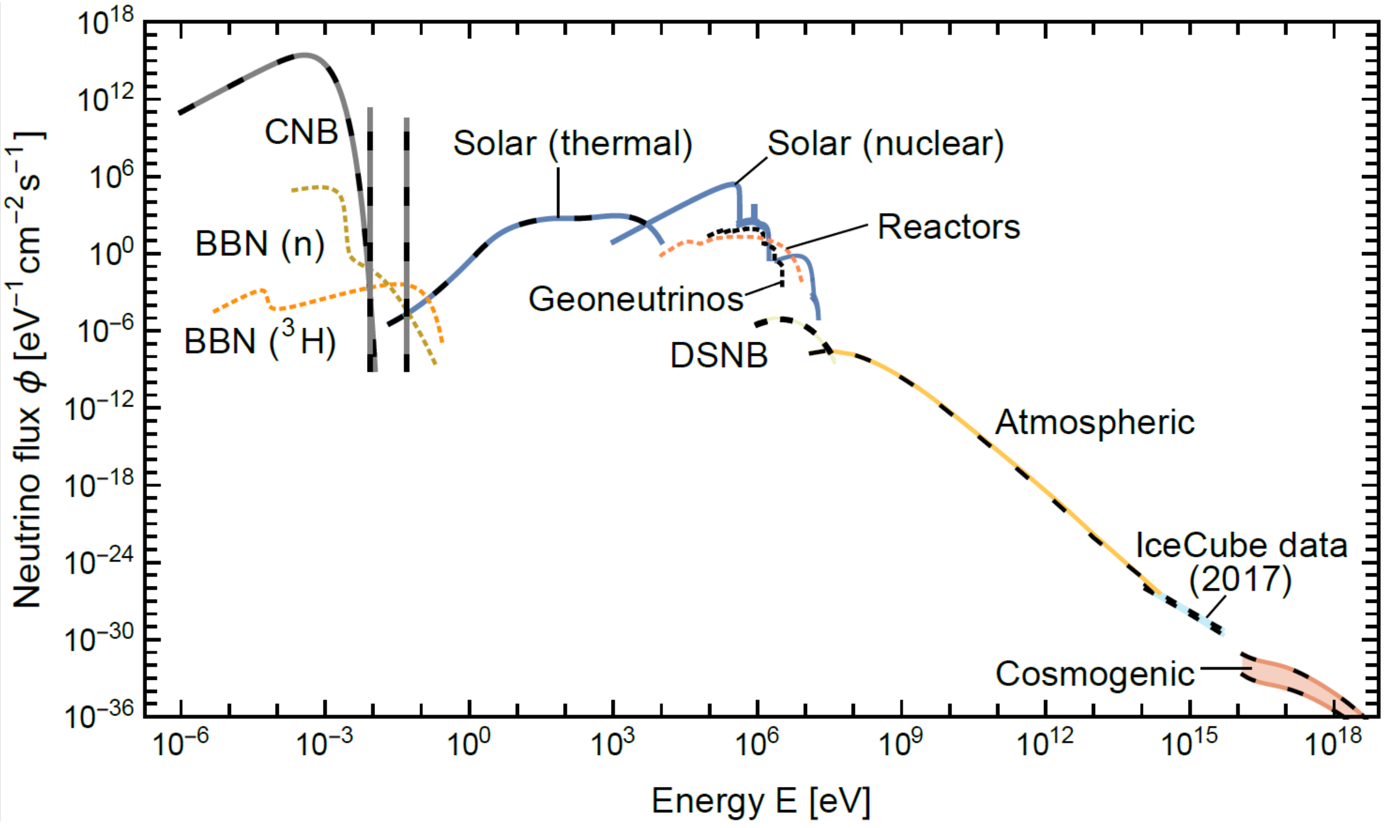
The IceCube Detector



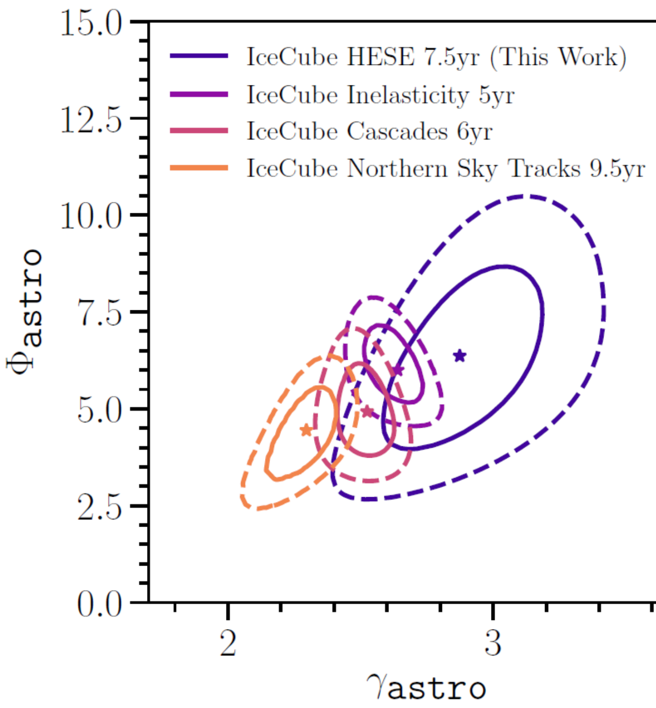




Grand Unified Neutrino Spectrum



Spectral Index Expectation



Astrophysical Neutrinos

$$p + p \rightarrow N[\pi^0 + \pi^+ + \pi^-] + X$$

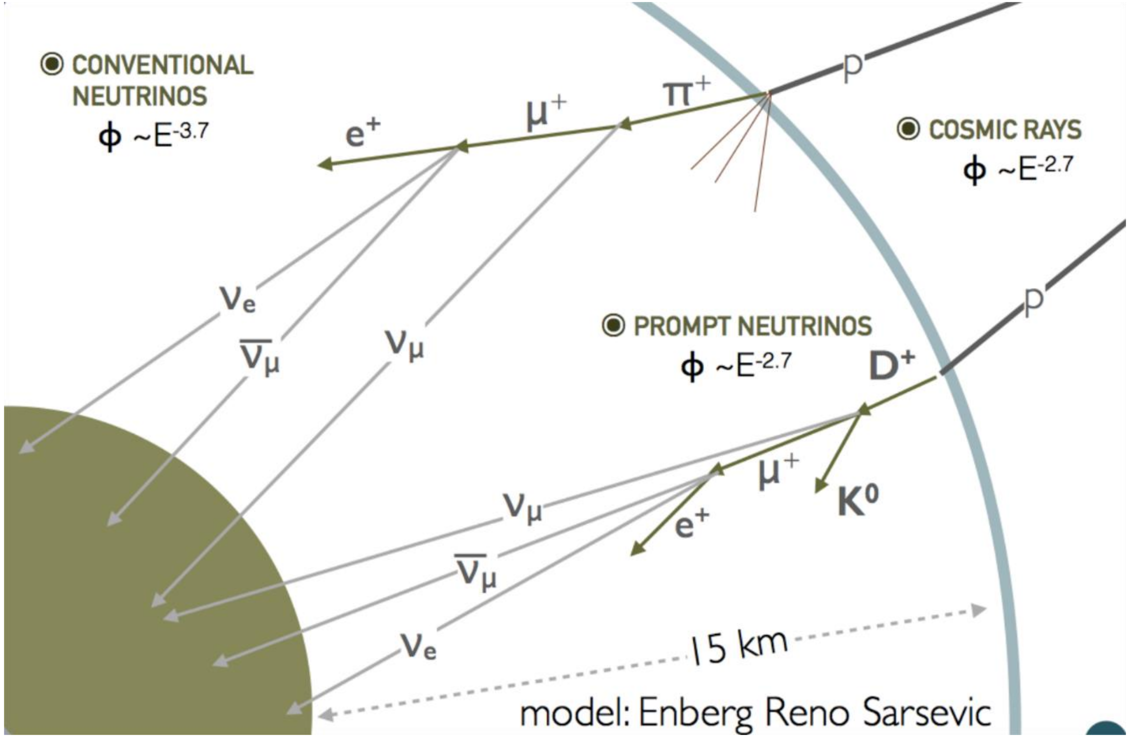
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

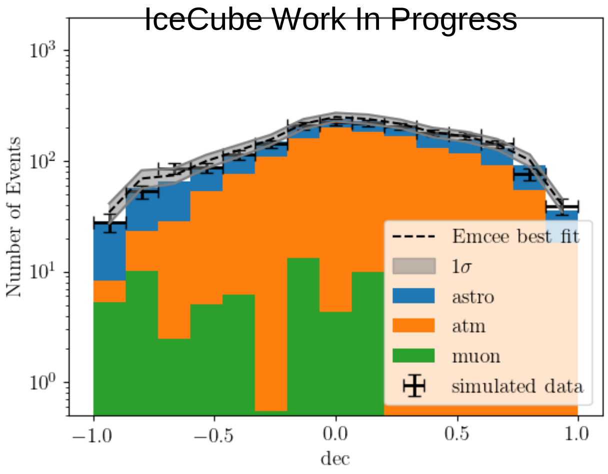
$$\frac{d\Phi^{astro}}{dE} = \Phi_{astro} \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma} \cdot 1 \times 10^{-18} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

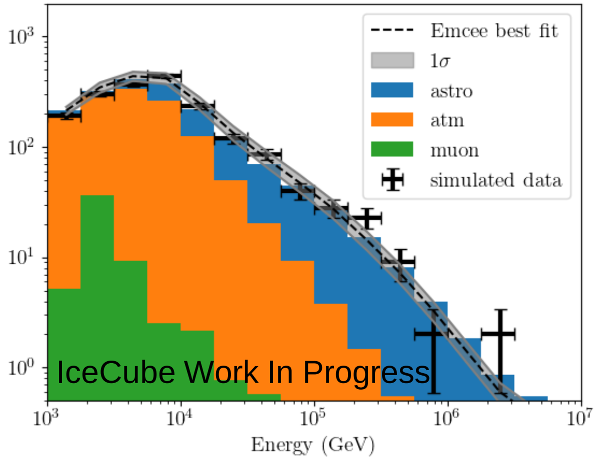
Atmospheric Neutrinos

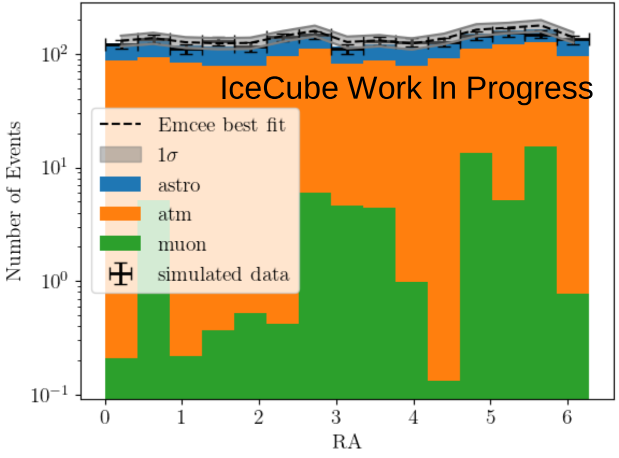
$$\frac{d\Phi_{\nu}^{atm}}{dE} = \Phi_{conv}\left(\frac{E_{\nu}}{E_0^p}\right)^{-\Delta\gamma_{CR}}$$



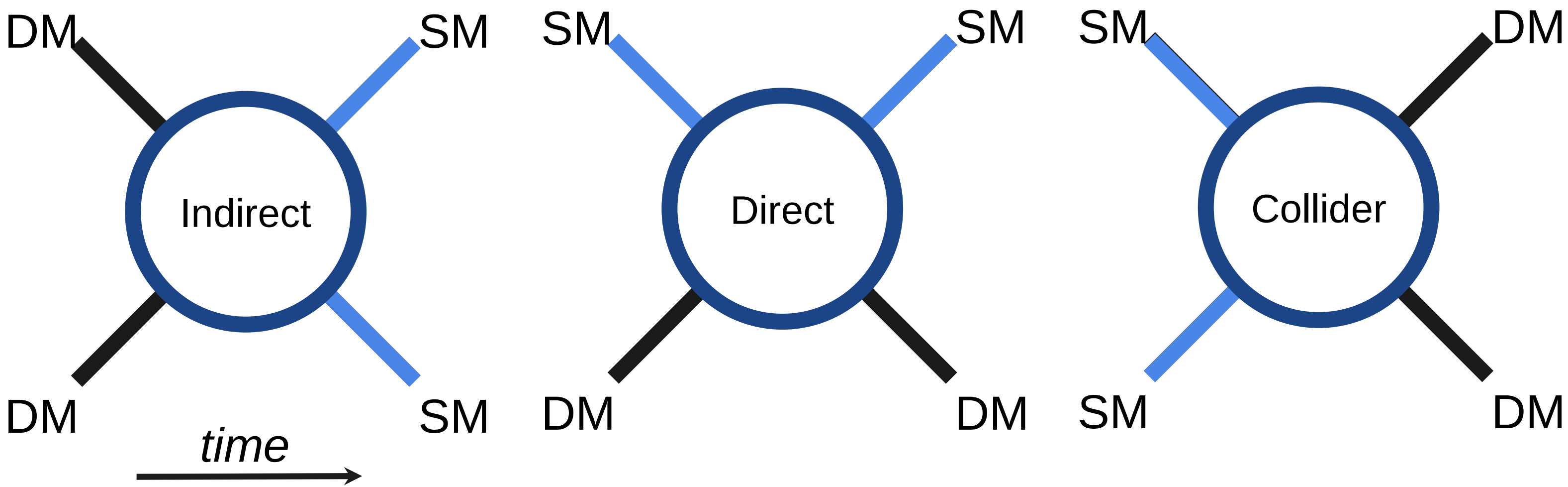
Spectral Index Best Fits





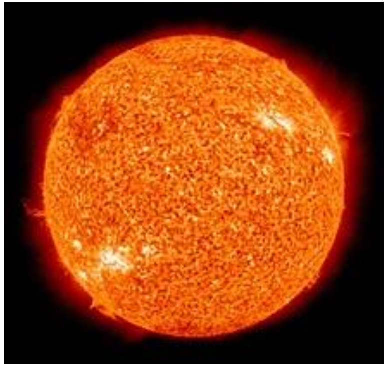


Dark Matter Detection Methods

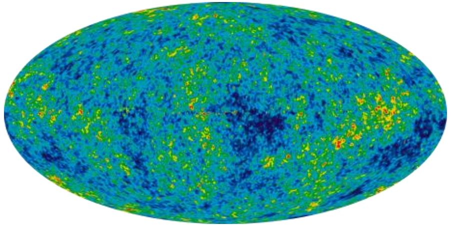


Motivation: Dark Matter Sources

Cosmic rays



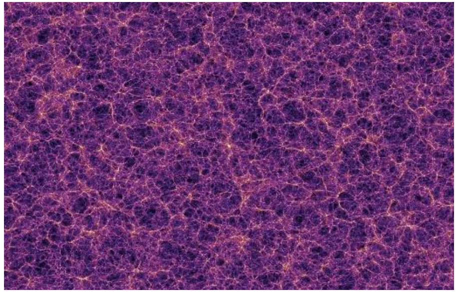
Sun



Cosmic Microwave Background

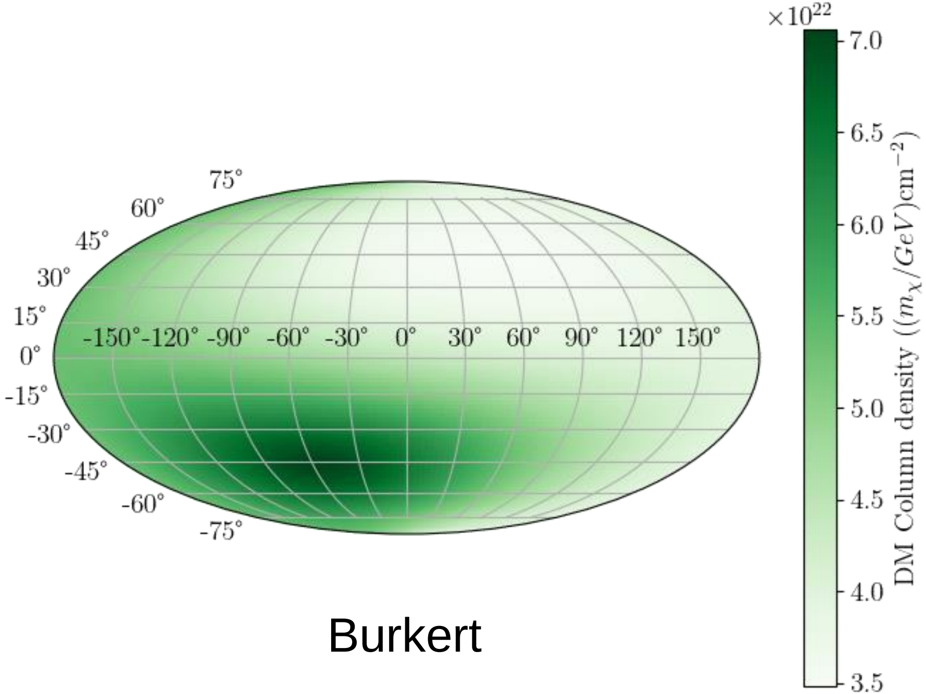
Dwarf Galaxies

Galactic Centre

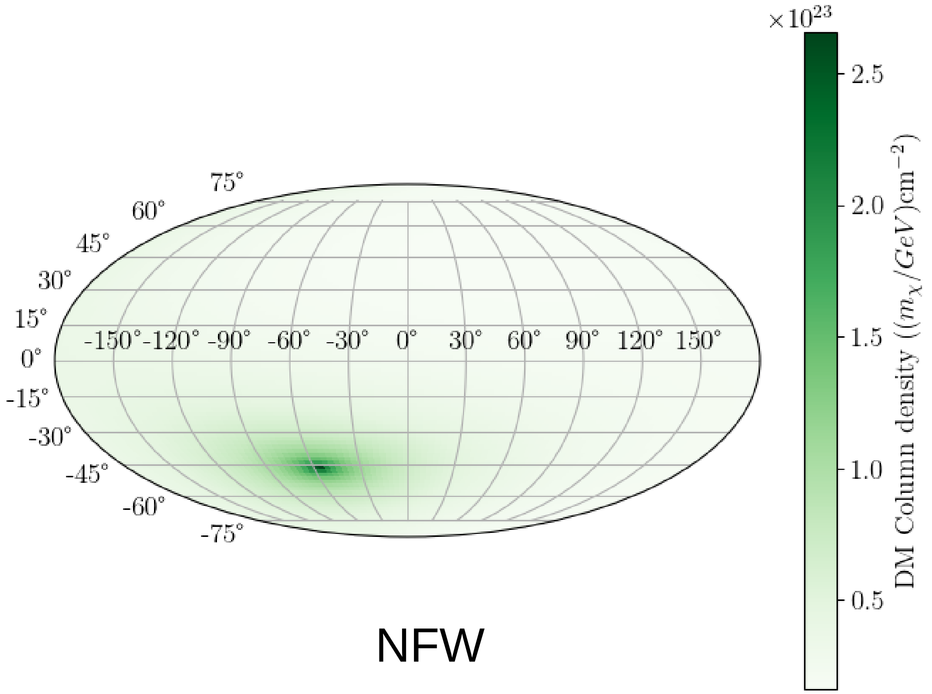


Large Scale Structure

Dark Matter Column Density

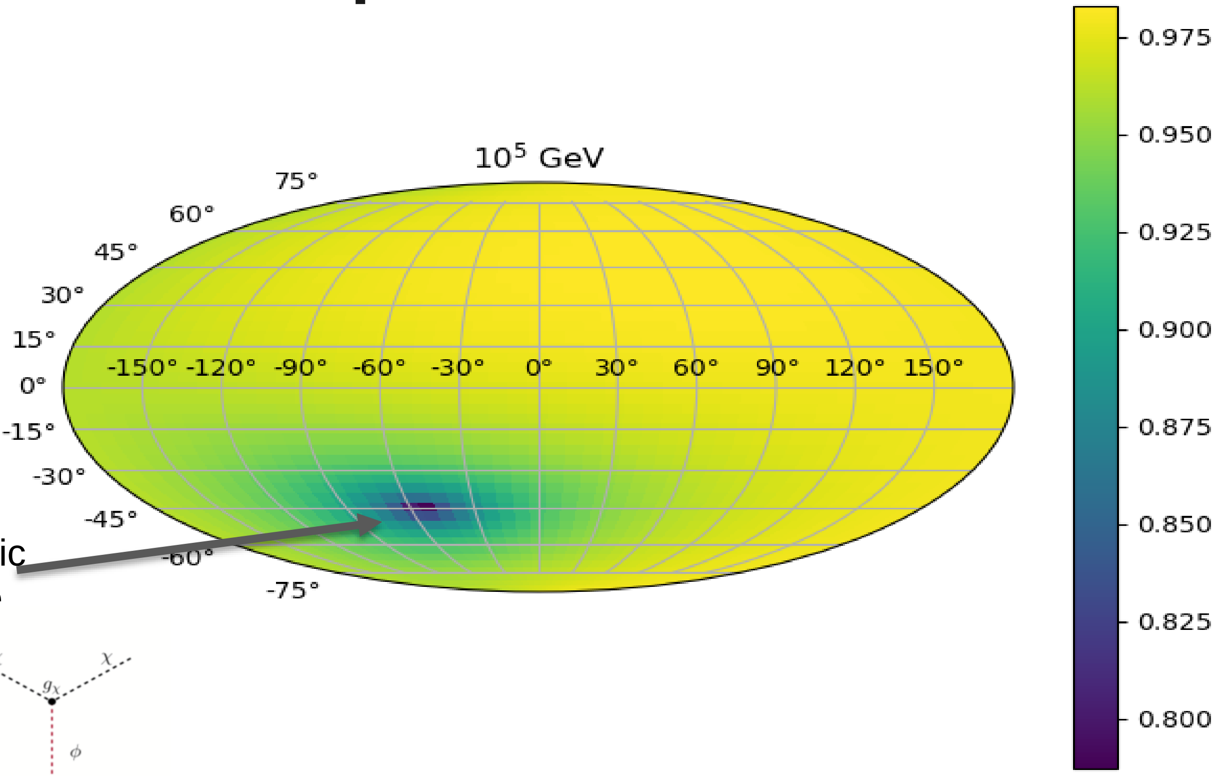


Burkert



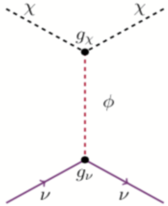
NFW

DarkFate: Example



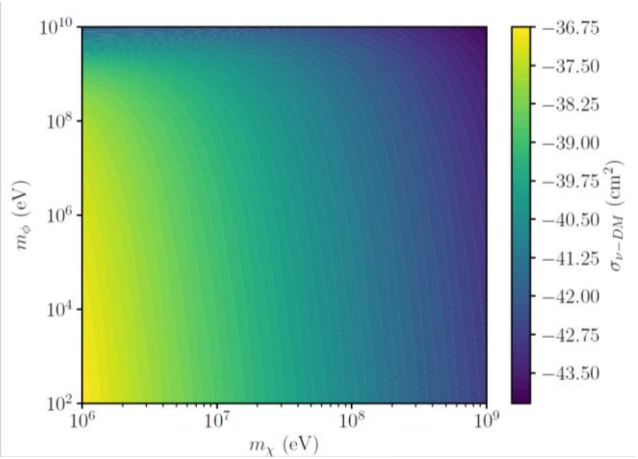
$$SurvivalProbability = \frac{Attenuated \nu Flux}{Isotropic \nu Flux}$$

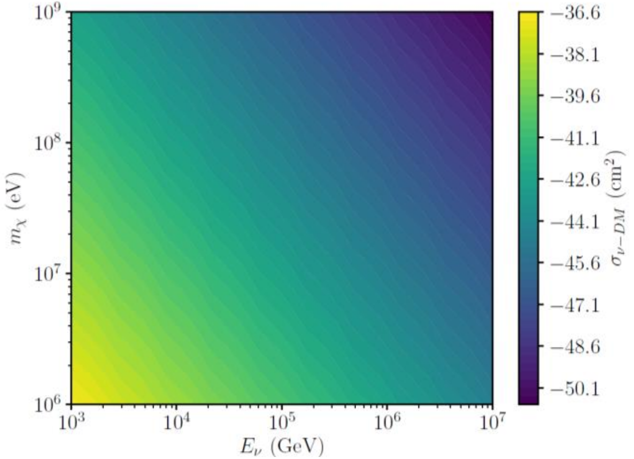
g=1
m_χ=1 GeV
m_Φ=10 MeV

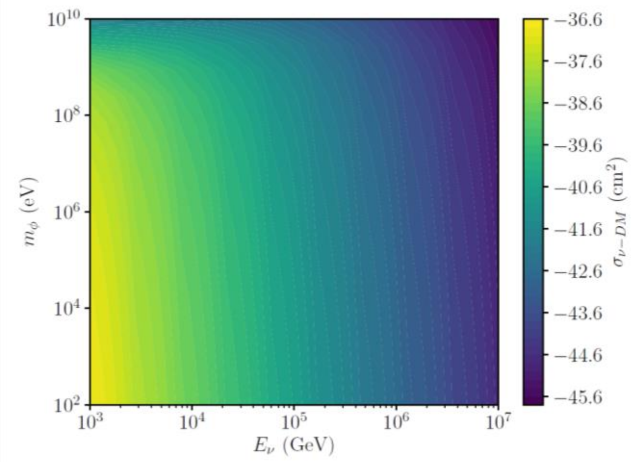


Scalar DM, scalar mediator

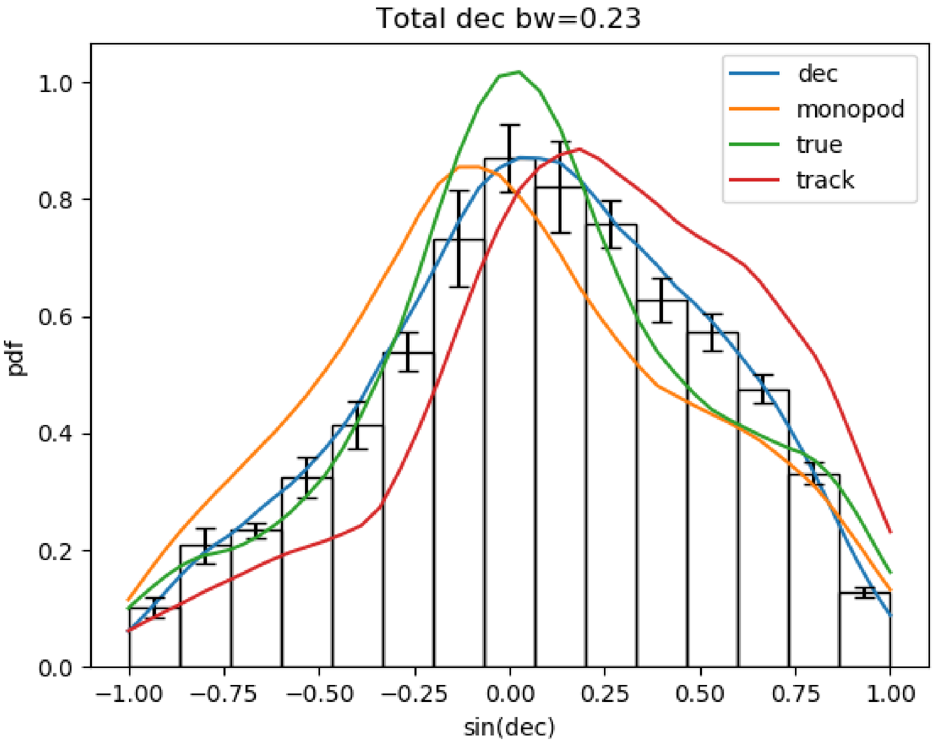
Cross Sections: scalar-scalar



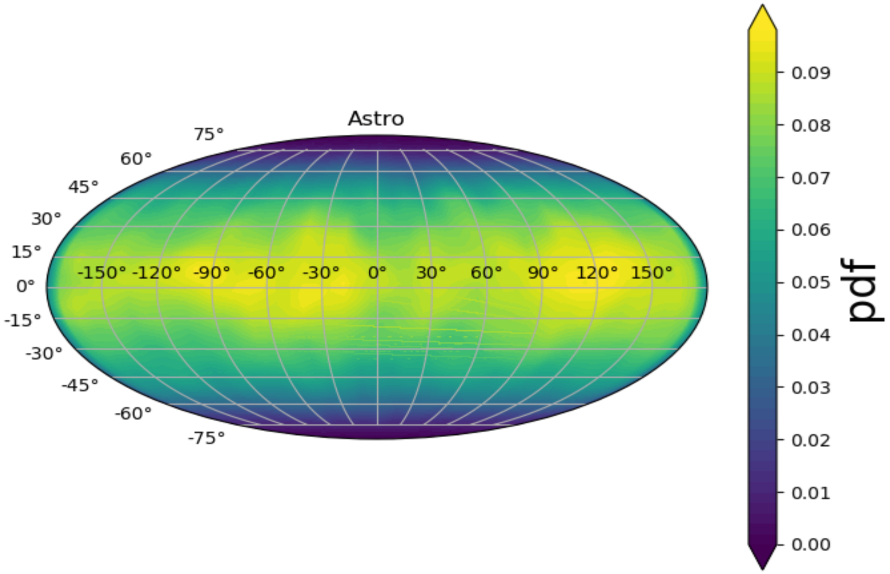




Reconstruction Techniques



Probability Density Functions KDE



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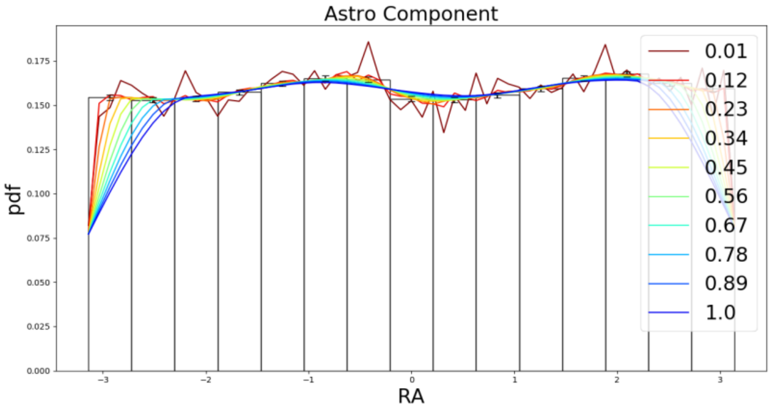
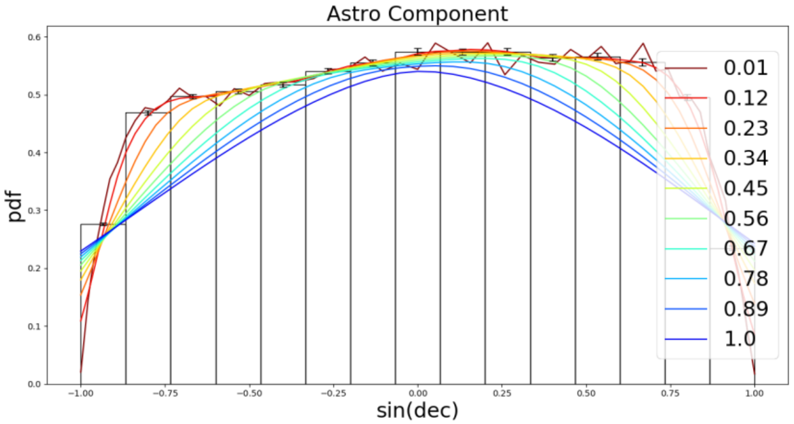
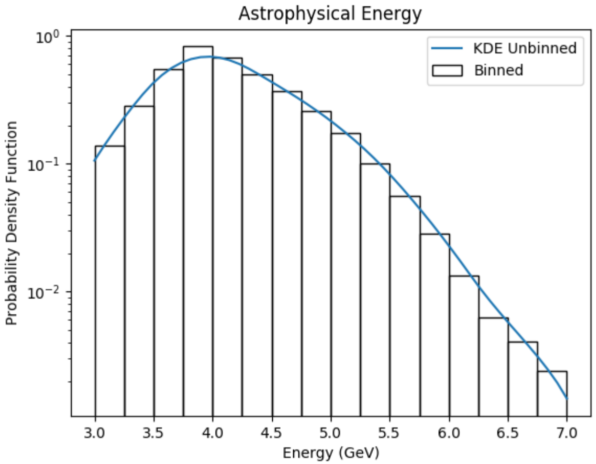
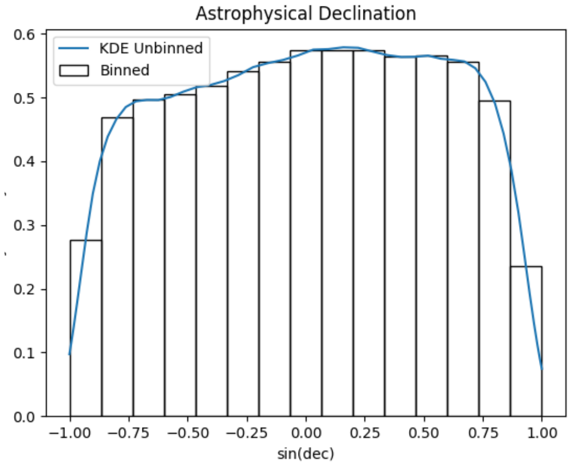
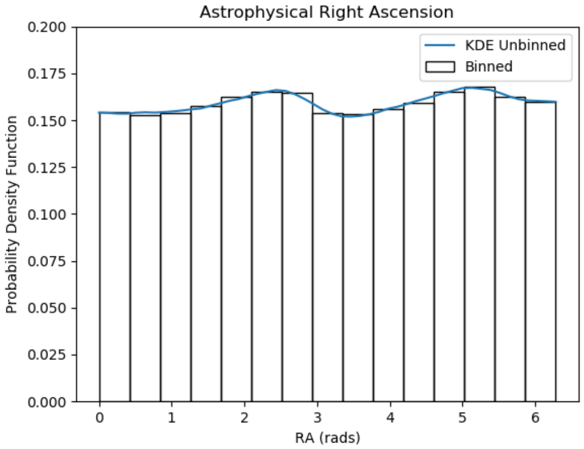




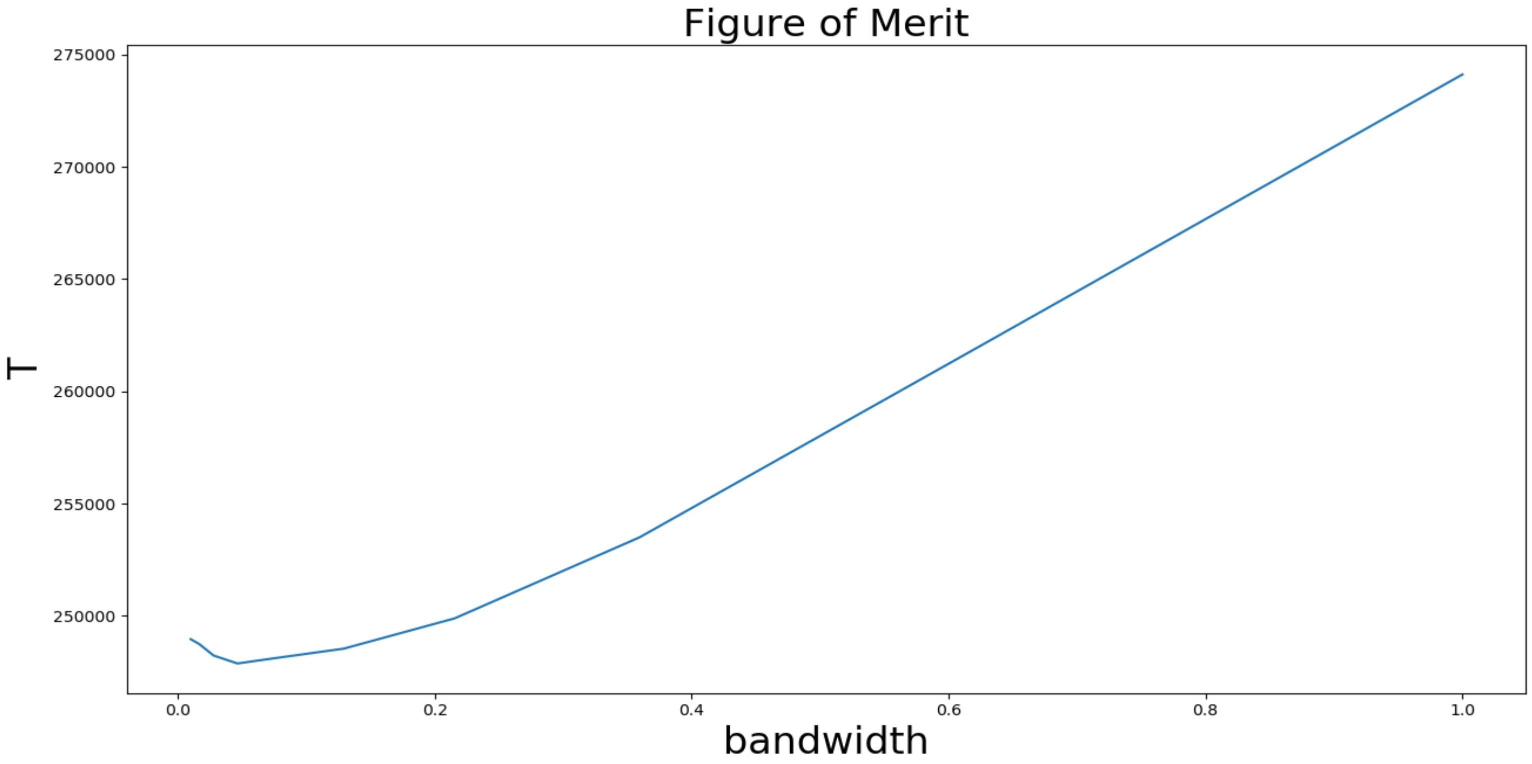
PDFs: Kernel Density Estimation



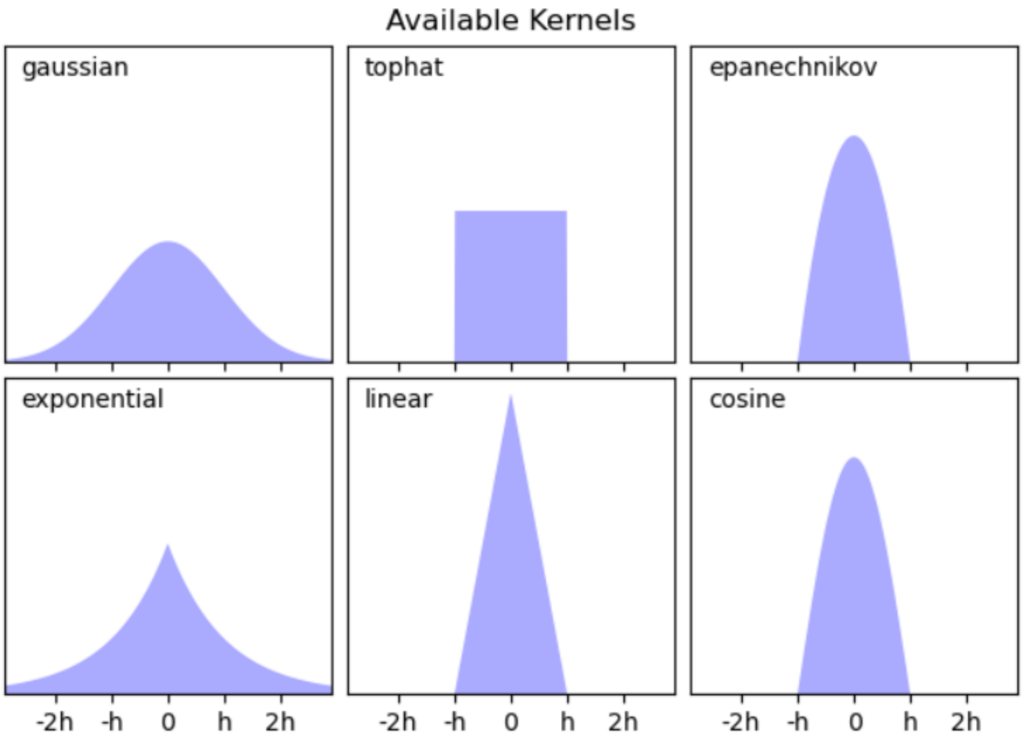




KDE Figure Of Merit



Method 1: Forward / KDE



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 vFATE: Neutrino Fast Attenuation Through Earth

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

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

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

λ_i eigenvalues

$\hat{\phi}_i$ eigenvectors

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

The IceCube Detector

- Cherenkov light detector
- Located at the South Pole
- Detects light from secondary charged particles