Imaging Galactic Dark Matter with IceCube's High-Energy Cosmic Neutrinos

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Based on

[arXiv:1703.00451]

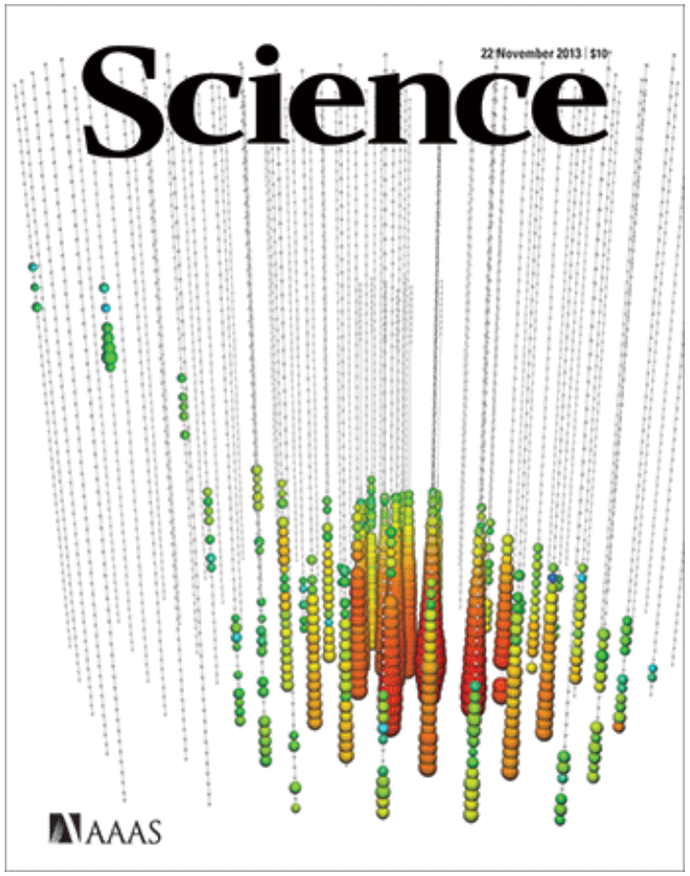
C. A. Argüelles, A.K, A. C. Vincent

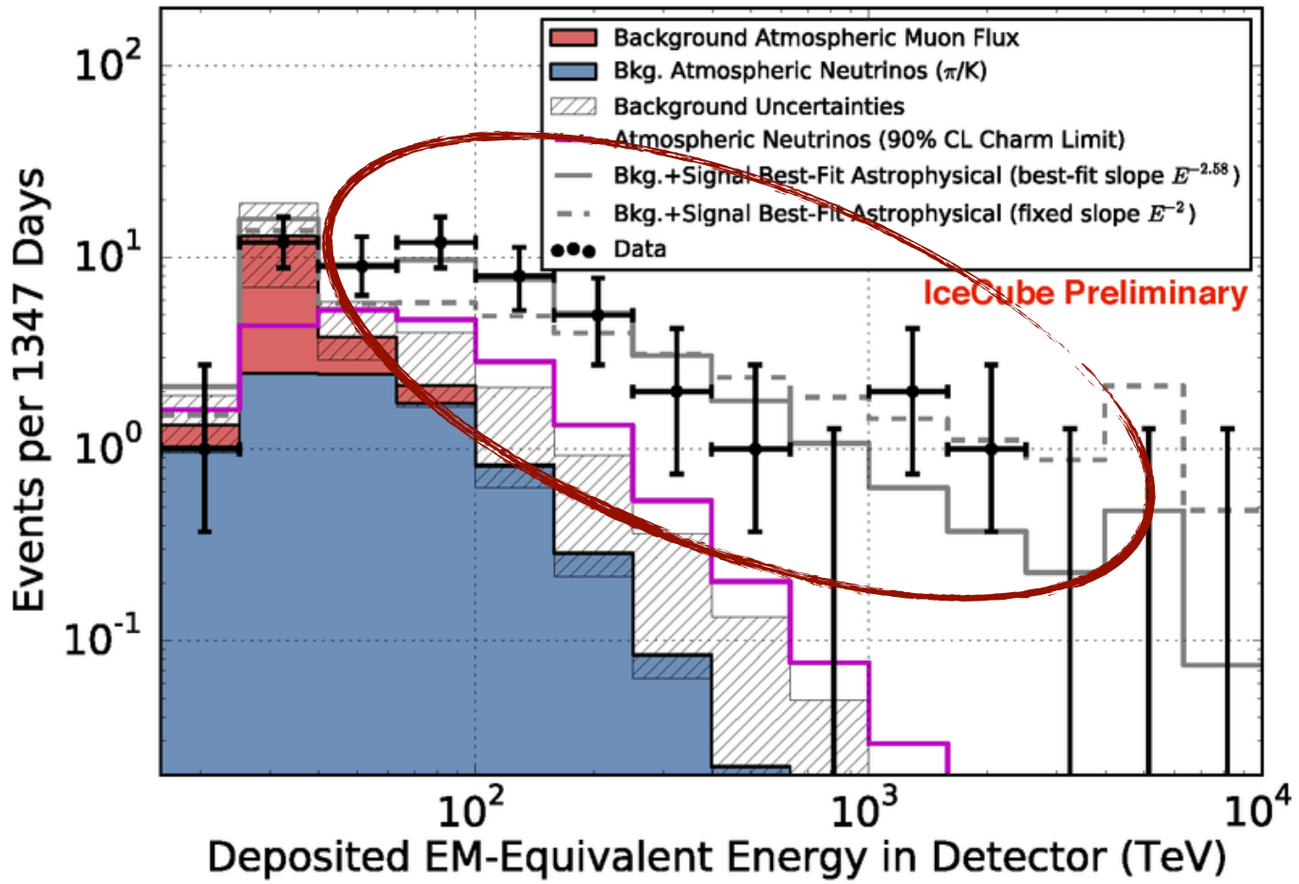
Imaging Galactic Dark Matter with High-Energy Cosmic Neutrinos

Imperial College London

Also νFATE: High-energy neutrino attenuation in the Earth and its associated uncertainties [arXiv:1706.09895]

IceCube & Cosmic Neutrinos

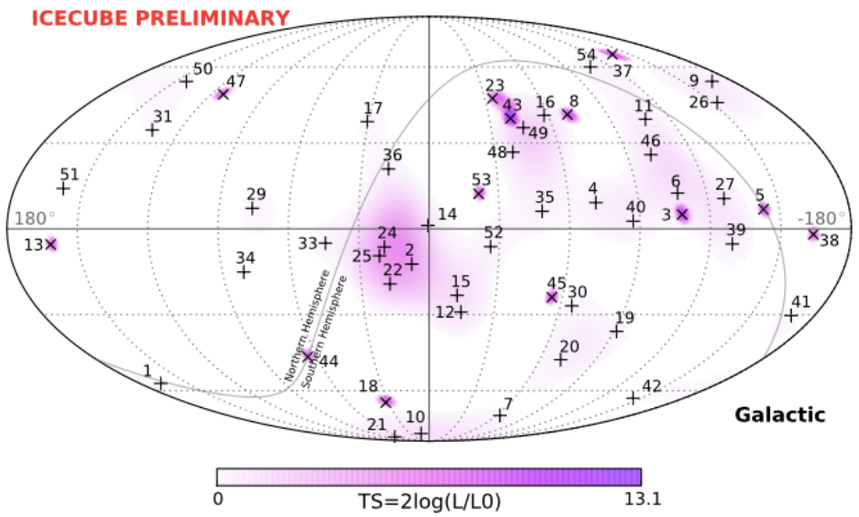




- IceCube Neutrino Observatory discovered neutrinos with extraterrestrial origin in 2013 in a search for High Energy Starting Event (HESE).
- High-energy neutrino flux above the atmospheric background.
- Observation of astrophysical flux was confirmed in through going tracks analysis.
- A new window to the Universe: Neutrinos carry information!

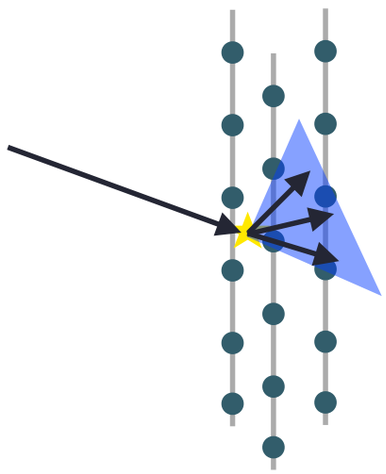
Astrophysical Neutrino Observables

Arrival direction



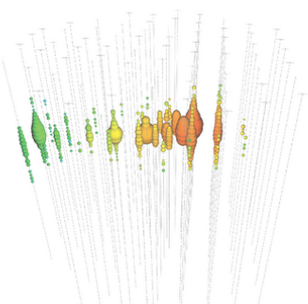
Neutrino energy

Deposited EM-equivalent

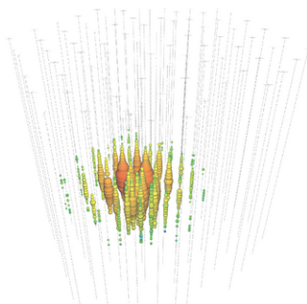


Flavour (e, μ, τ)

Topology

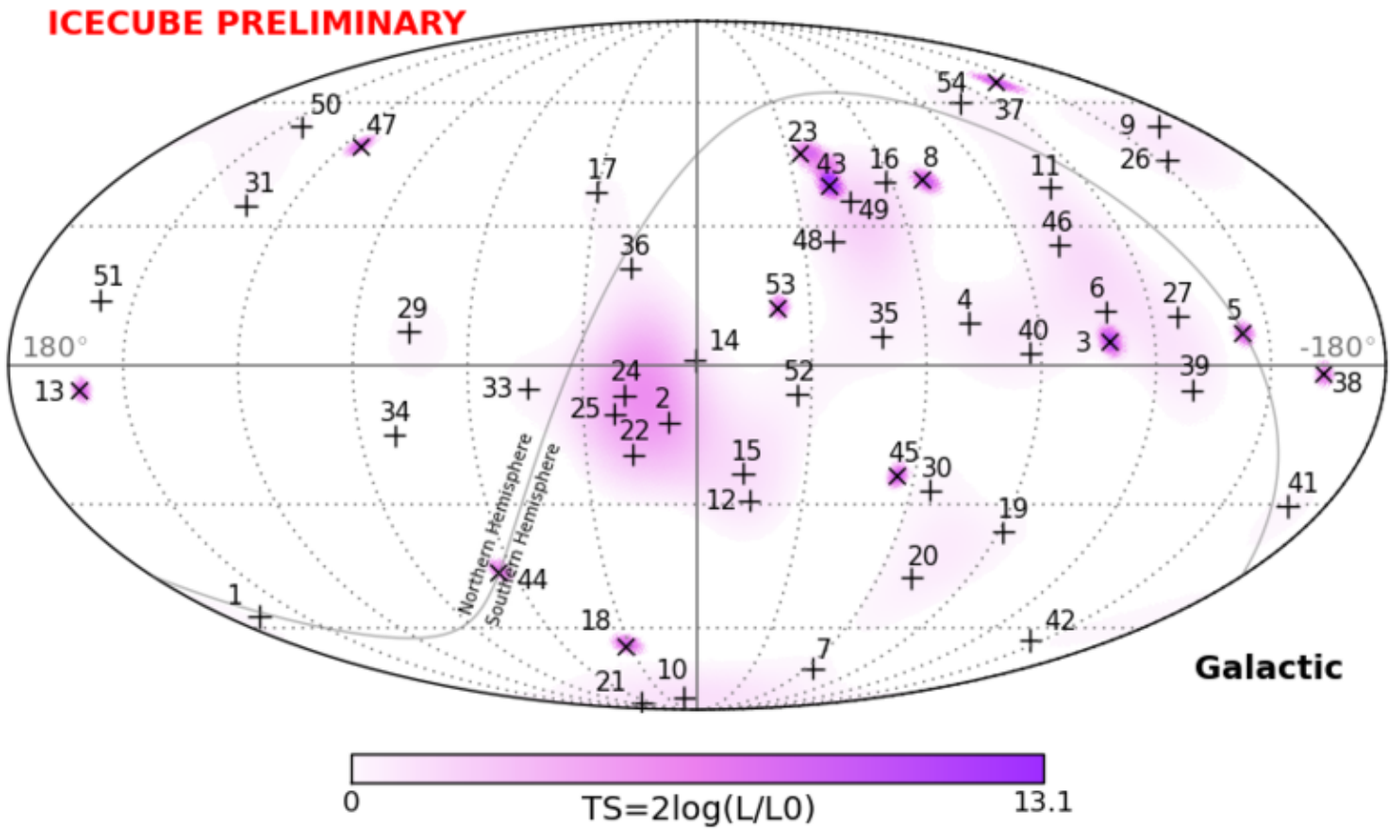


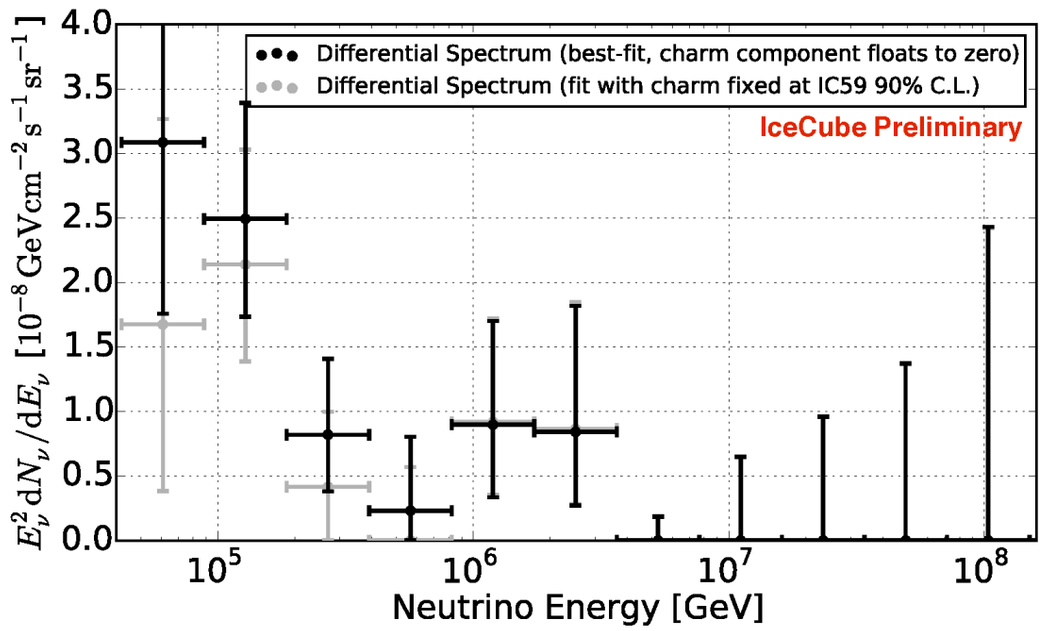
muon track



shower

4 Years of HESE





[IceCube 2015]

- 53 Events in 4 years.
- Events arrival directions is compatible with **isotropic** hypothesis.
- **No correlation** with Galactic plane.
- Event distribution suggests **extragalactic** origin for the majority of the events.
- **Flavor ratio** is consistent with 1:1:1 ratio.

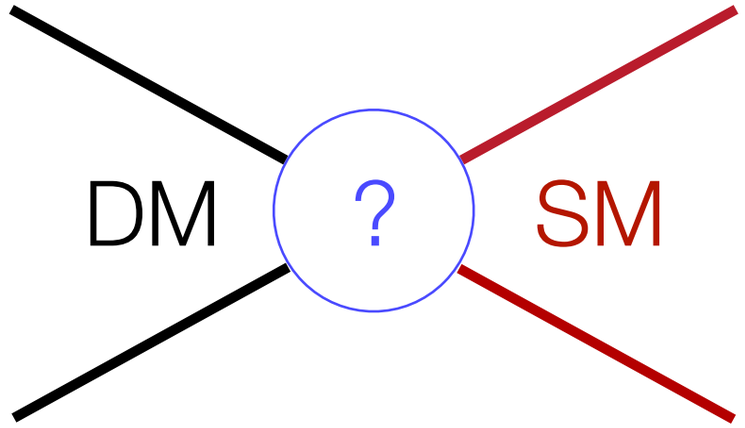
Cosmic Neutrinos & New Physics

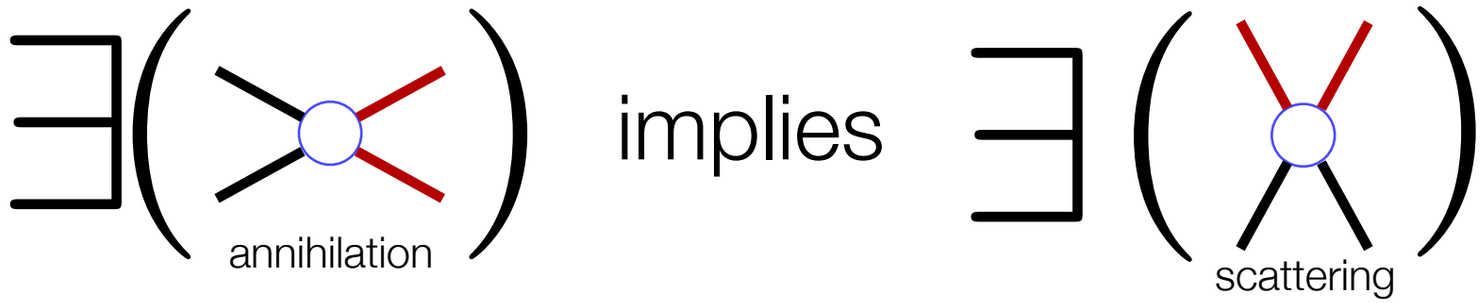
- HE cosmic neutrino flux: new opportunities for new physics studies.*
- A high degree of complementarity exist between astrophysical and cosmological observations.
- What can we understand from DM-neutrinos interaction?

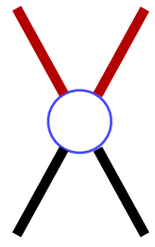
**more on new physics with IceCube:*
C.Argüelles, M. Bustamante, J. Conrad, A.K. , A. C. Vincent, in preparation!

Dark Matter-Neutrino Interaction?

- What is dark matter?
- What SM particles does dark matter interact with?
- How does it interact?





if —— = quarks, then  = direct detection (LUX, LZ, SuperCDMS, …)

But if —— too light, or ? does not talk to quarks, then

—— could be neutrinos

[Boehm+ 01, 02, 05, 14—Bertschinger+ 06— Mangano+ 06—Serra+ 10—Wilkinson+ 14—van den Aarssen+ 12—Farzan+ 14—Cherry+ 14—Bertoni+ 15—Chewtschenko+ 15]

DM-Neutrino Interaction

Generic scattering cross section for $E_\nu \ll m_\chi$

1) $\sigma \to const.$

2) $\sigma \to const. \times E_\nu^2$

Cosmological limits

$$\sigma^{(WiggleZ)}_{\mathrm{DM}-\nu,0} \lesssim 4 \times 10^{-31}\,(m_{\mathrm{DM}}/\mathrm{GeV})\ \ \mathrm{cm}^2$$

$$\sigma^{(WiggleZ)}_{\mathrm{DM}-\nu,2} \lesssim 1 \times 10^{-40}\,(m_{\mathrm{DM}}/\mathrm{GeV})\ \ \mathrm{cm}^2 \times (T_\nu/T_{today})^2$$

[Escudero et.al, 2016]

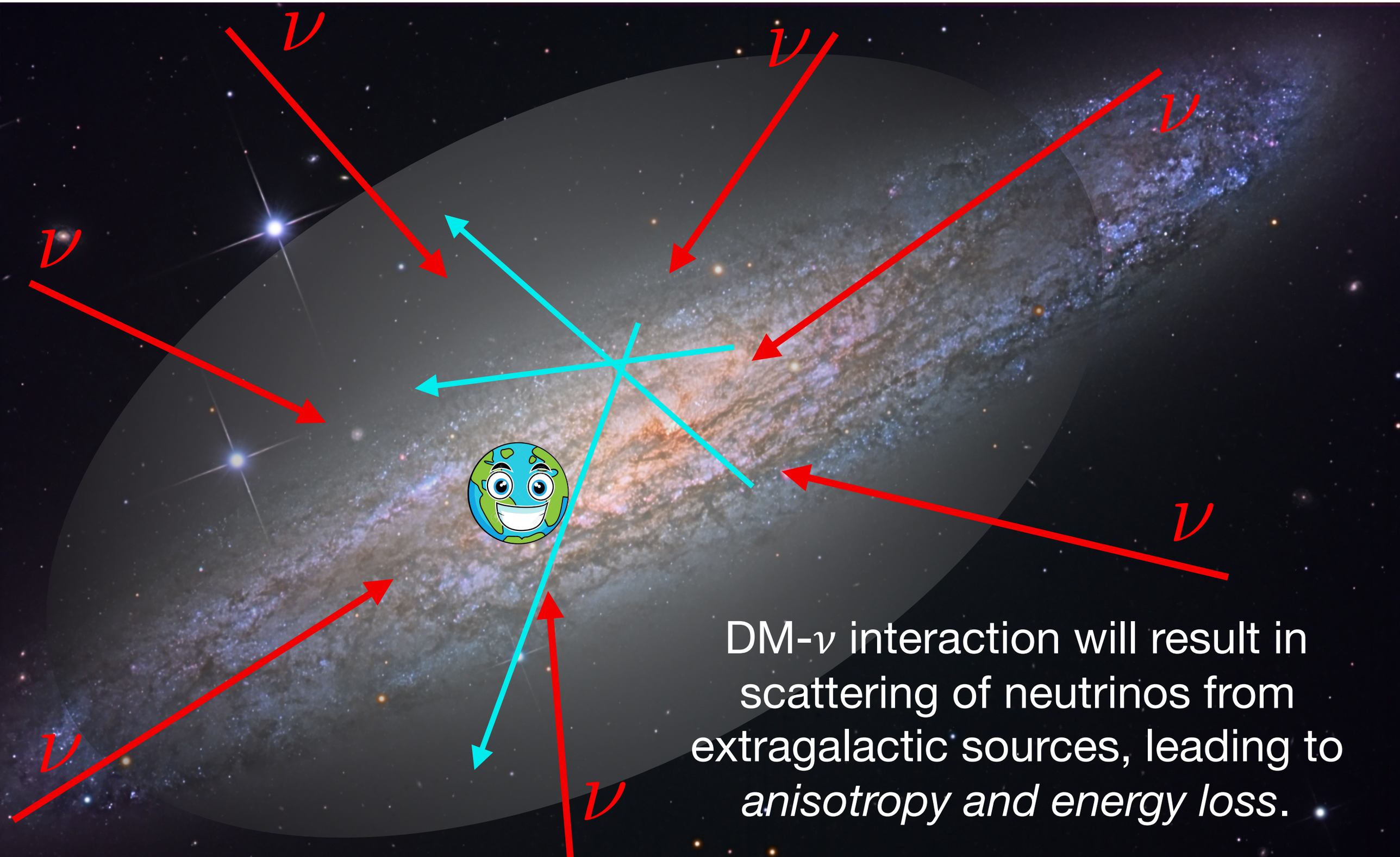
At High-Energy?

$$\sigma_{DM-\nu} \propto E_\nu^2$$

IceCube has seen events above a PeV….

$$\left(\frac{\mathrm{PeV}}{T_{\nu,recomb.}}\right)^2 \sim 10^{30}$$

DM density is largest in center of the galaxy.



DM-ν interaction will result in scattering of neutrinos from extragalactic sources, leading to *anisotropy and energy loss*.

In Practice

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

b, l: galactic latitude, longitude

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

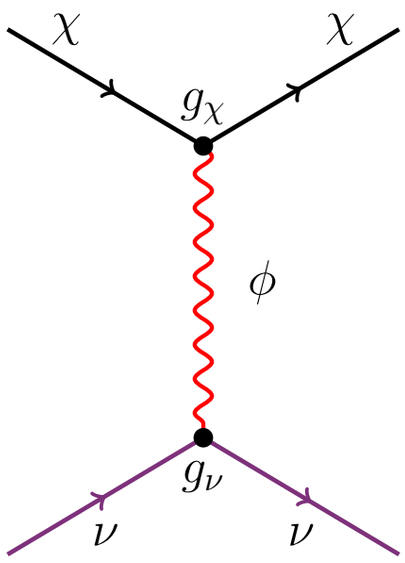
scattering **from** E to any energy

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

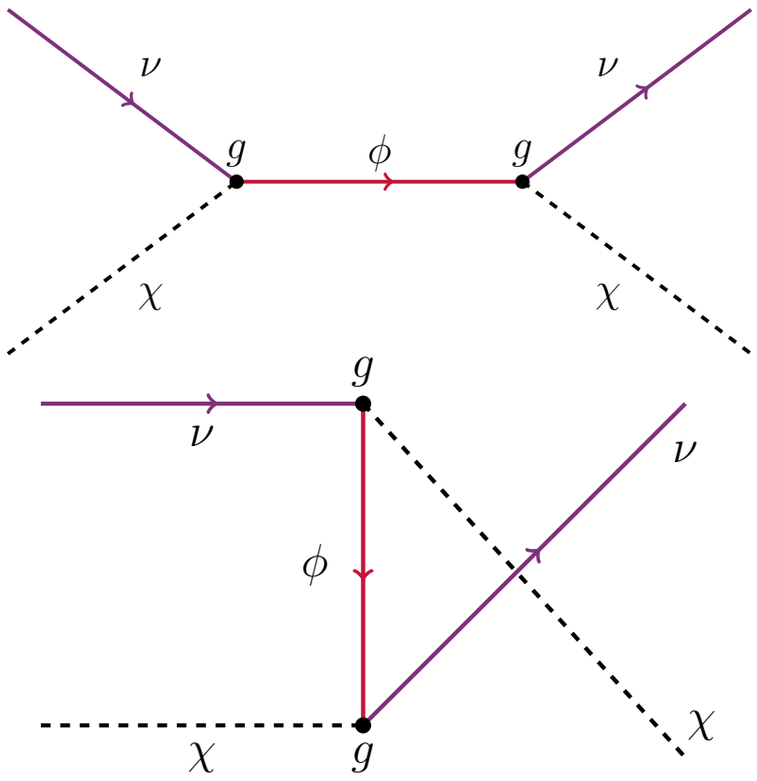
solve to find flux at Earth at energy E and direction *(b,l)*

NUFATE github.com/aaronvincent/nuFATE

Two fiducial simplified models

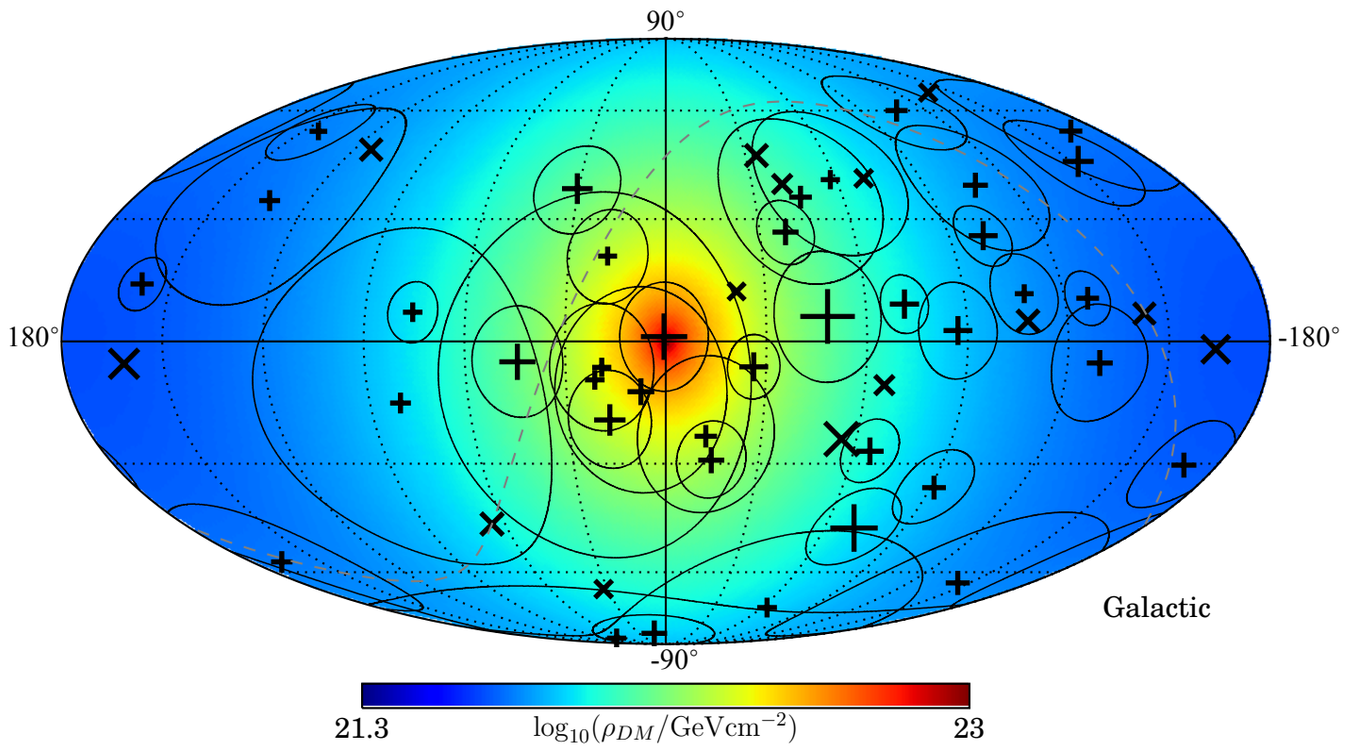


Fermion DM, **vector mediator**:
similar to a leptophillic Z' model
Scales strongly with *E*

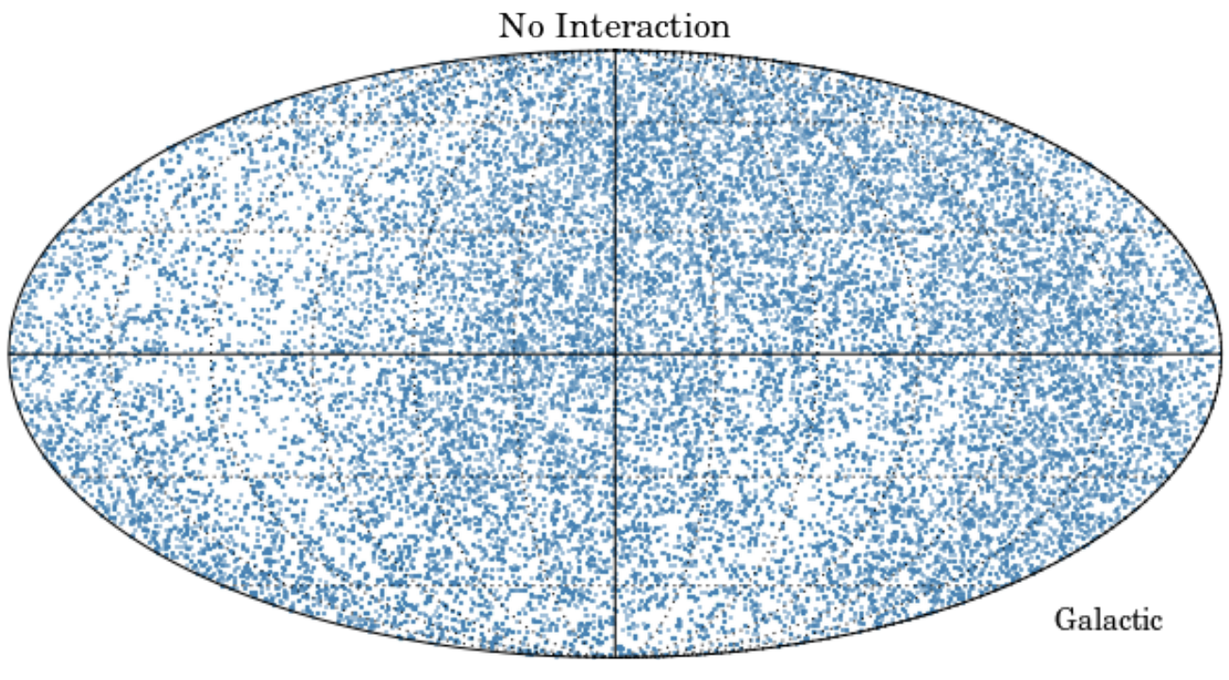


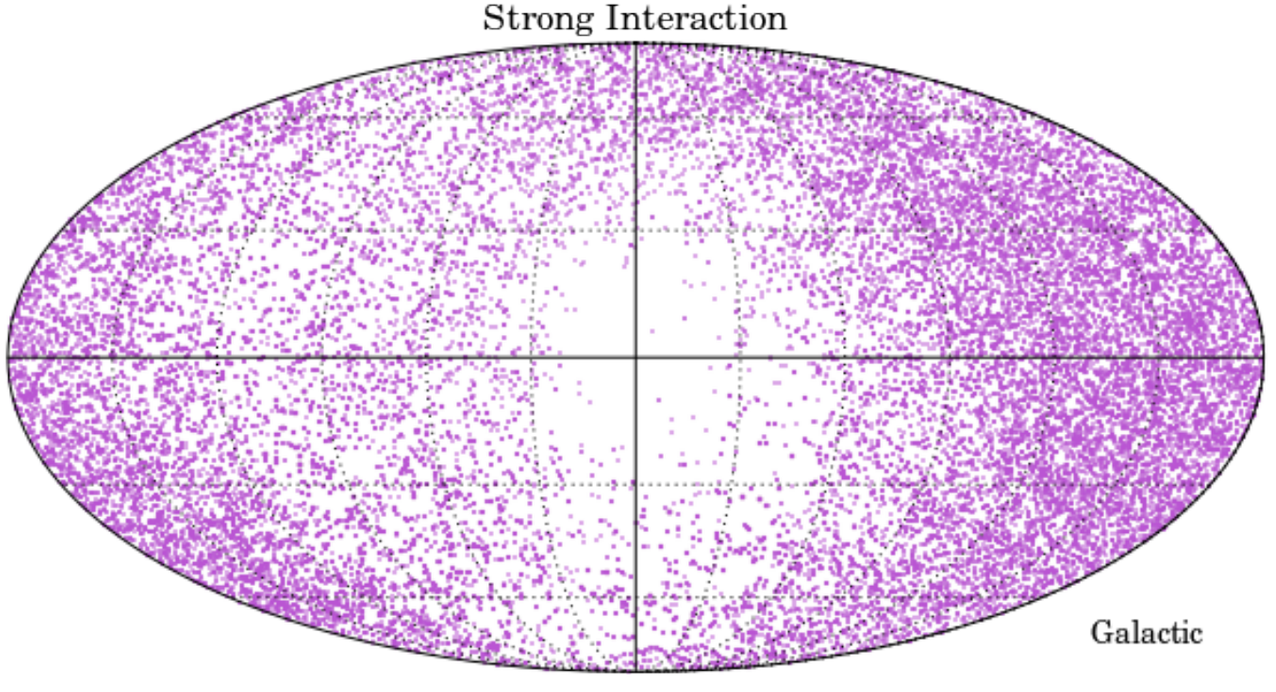
Scalar DM, **fermionic mediator**:
e.g. sneutrino dark matter,
neutralino mediator.
Resonant behaviour (s-channel)

Dark matter column density* seen from Earth



Simulation including effects of detector, Earth

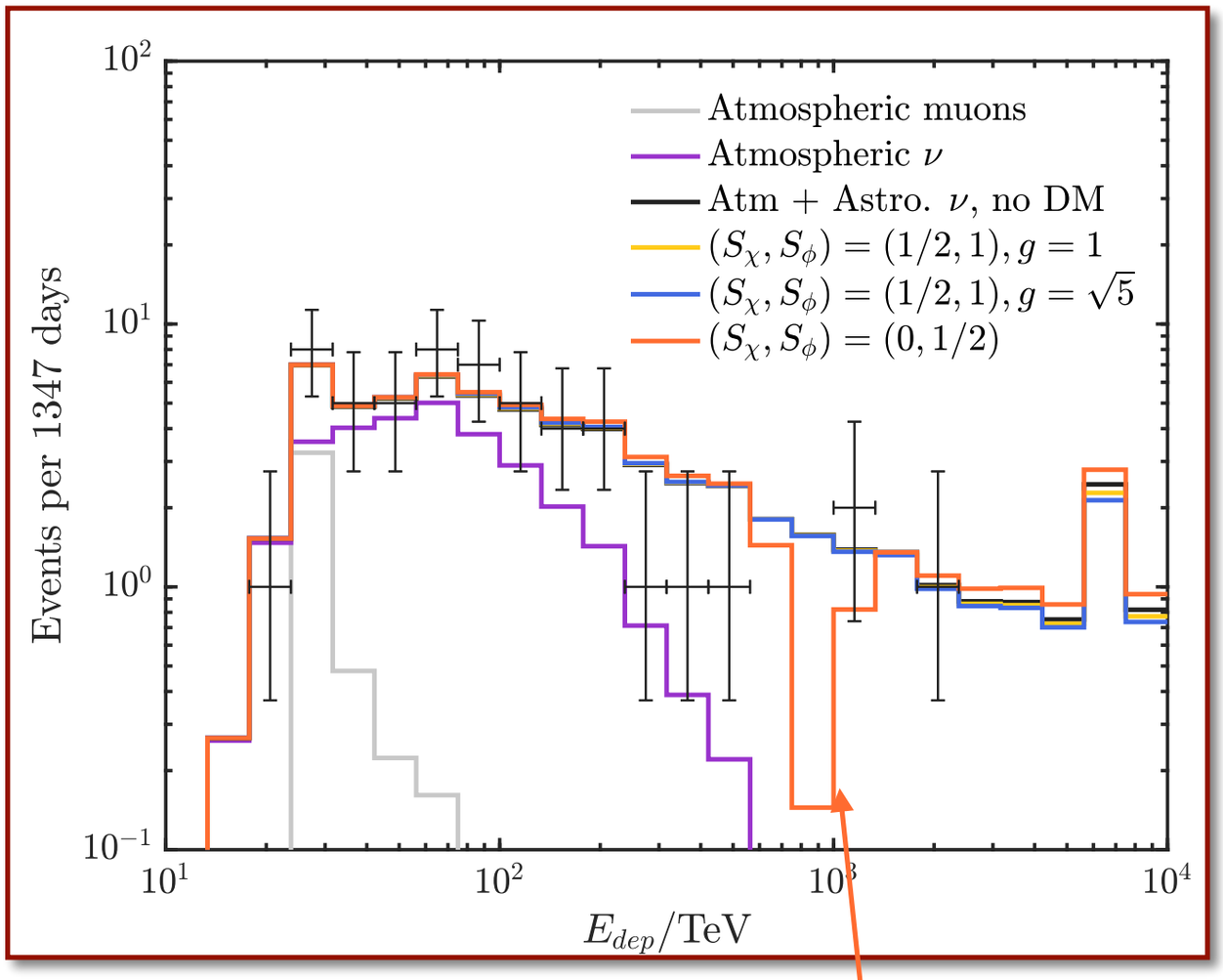




* *Einasto*

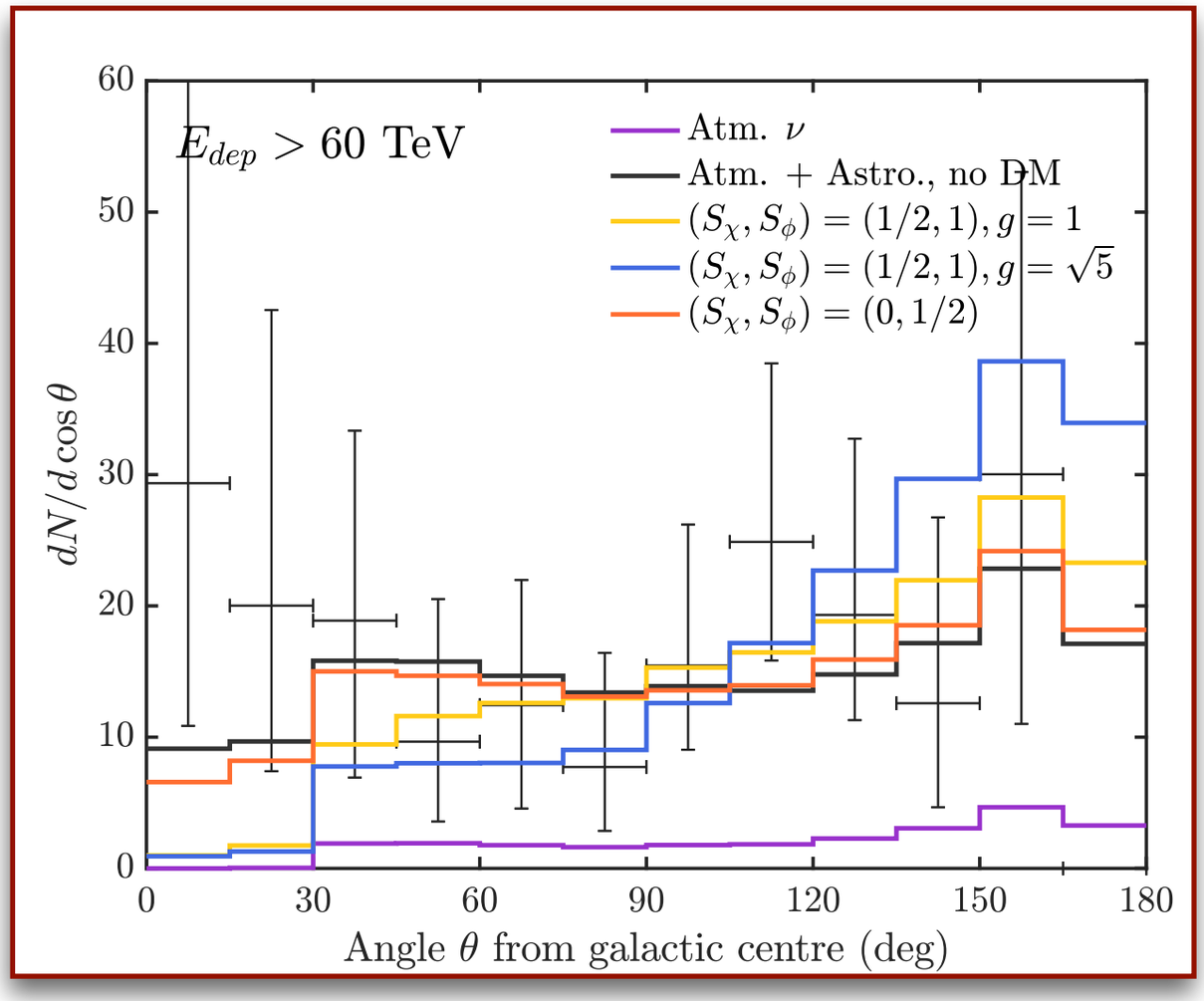
Energy & morphology

Energy



Resonance @ 810 TeV

Direction



IceCube HESE events

Likelihood Test

We test the likelihood of events originating from 3 components:

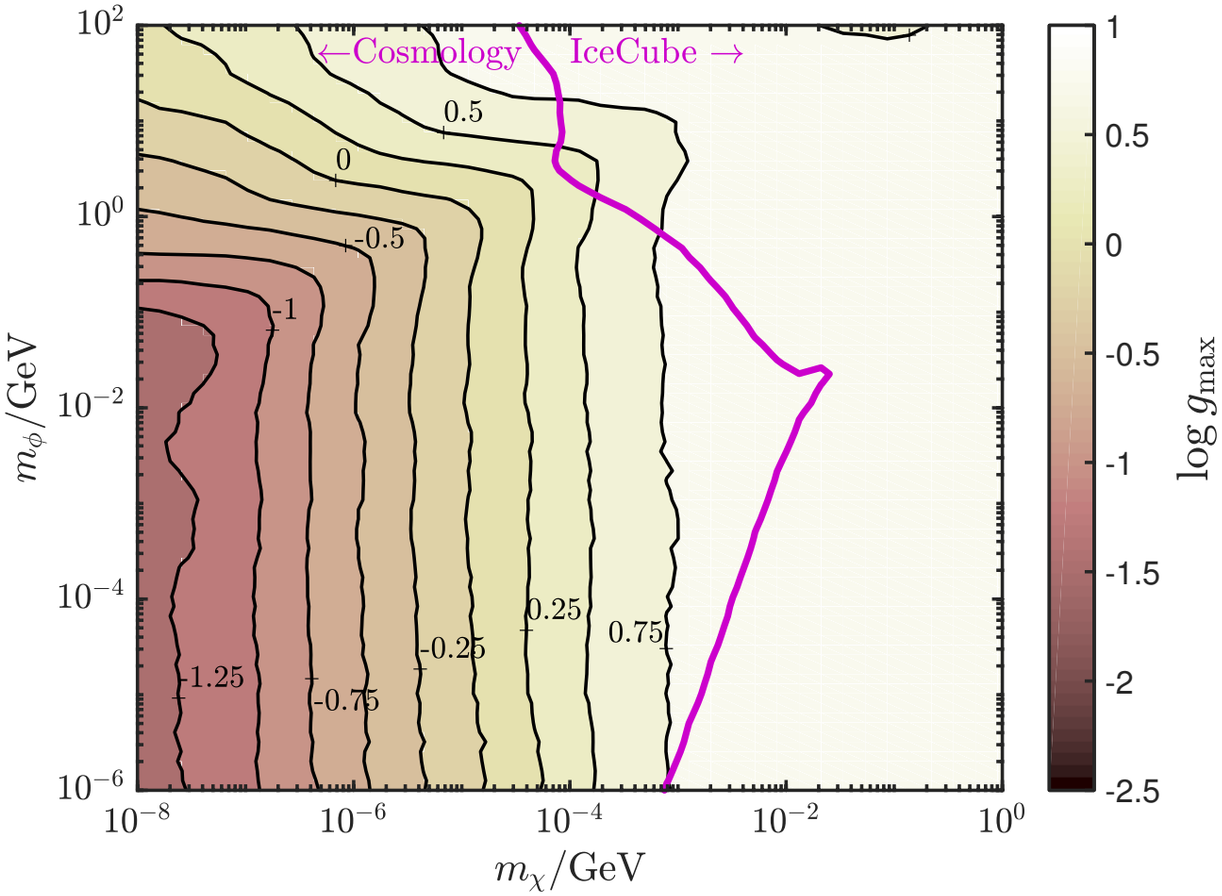
- Astrophysical neutrino component modified by DM-neutrino interaction, originating from E^{-2} spectrum
- Atmospheric neutrinos
- Atmospheric muons

$$\mathcal{L}(\{t, E, \vec{x}\}|\vartheta) = e^{-\sum_b N_b} \prod_{i=1}^{N_{obs}} \sum_a N_a P_a(t_i, E_i, \vec{x}_i|\vartheta)$$

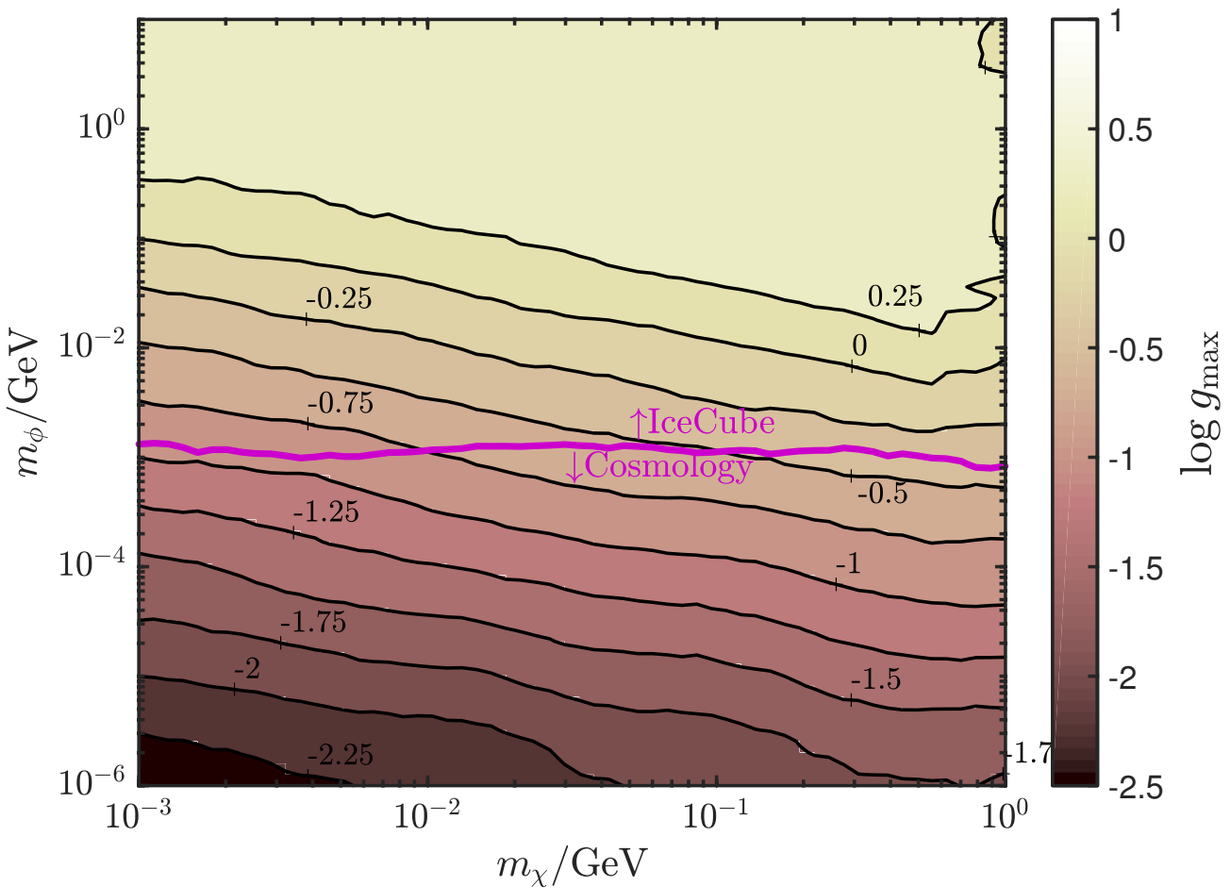
We establish a limit based on MCMC scan of the parameter space of each interaction model.

Parameters: $(m_\chi, m_\phi, g, N_{astro}, N_{atmo}, N_\mu)$

Constraints



Scalar DM
Fermionic Mediator



Fermionic DM
Vector Mediator

With only 53 events, can do better than cosmology in some ranges.

Summary & Outlook

- No reason to believe DM-neutrino interactions aren't there.
- Isotropy of the cosmic neutrino signal can be used to constrain such interactions.
- This study does better than cosmology in some ranges, mainly 1-100 MeV DM mass.
- Need more statistics: forecasts for *IceCube-Gen2* & more studies to come.
- Updates with 6 years of observation to come soon.

Thank you!

APPENDIX

DM-neutrino interactions: two constraints from cosmology

Extra radiation N_{eff}

If DM is light (< 10 MeV) it can dump entropy into neutrino sector as it becomes non-relativistic

BBN

neutrons less boltzmann suppressed at FO: more D, He

CMB

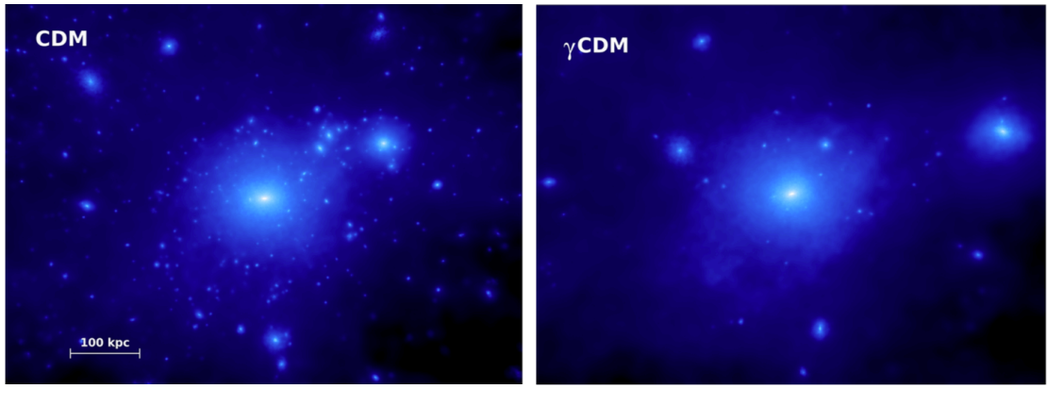
Shifted peaks from different sound propagation length

upper limit on DM mass

Aaron Vincent

Perturbation damping

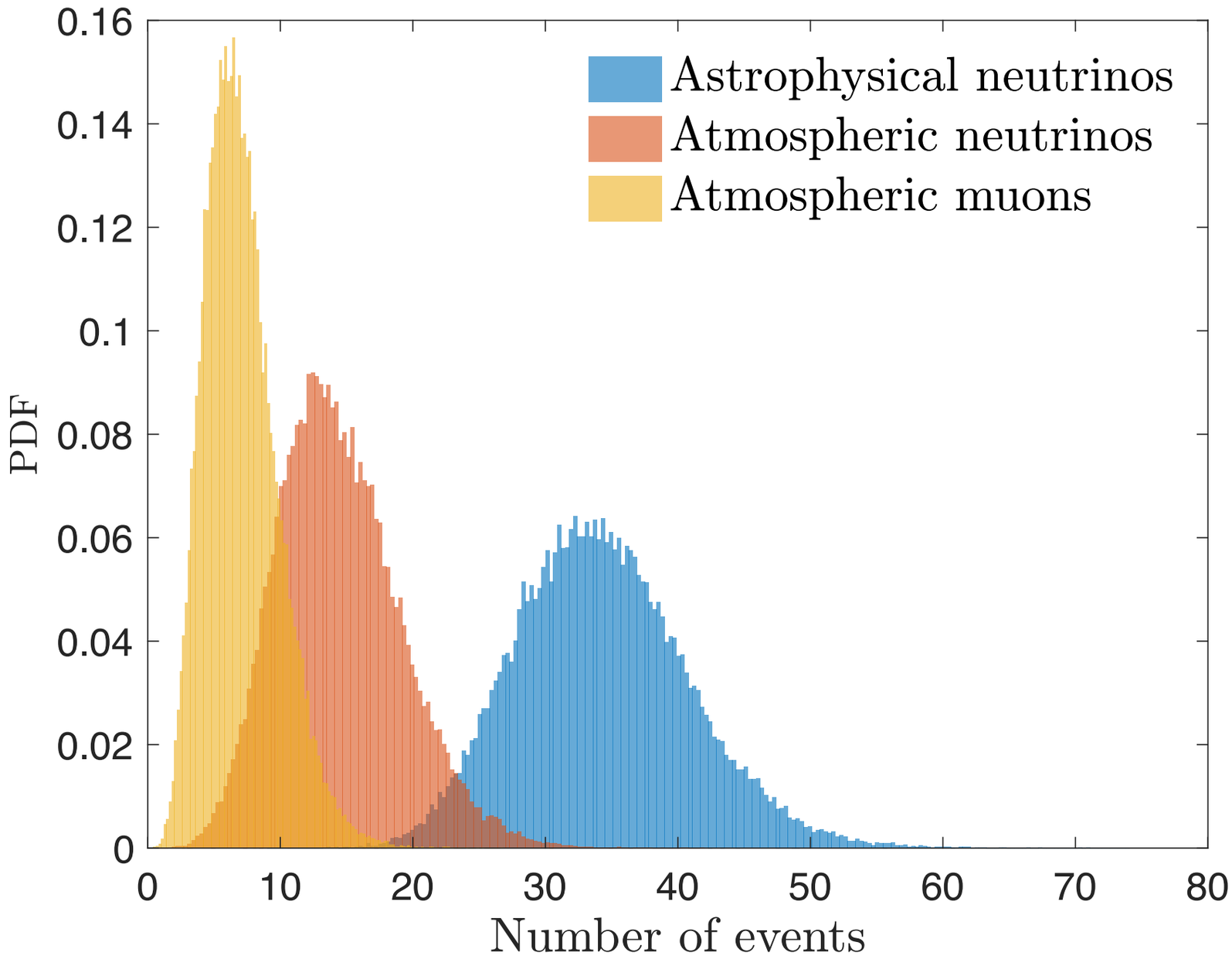
Scattering damps power spectrum of primordial fluctuations



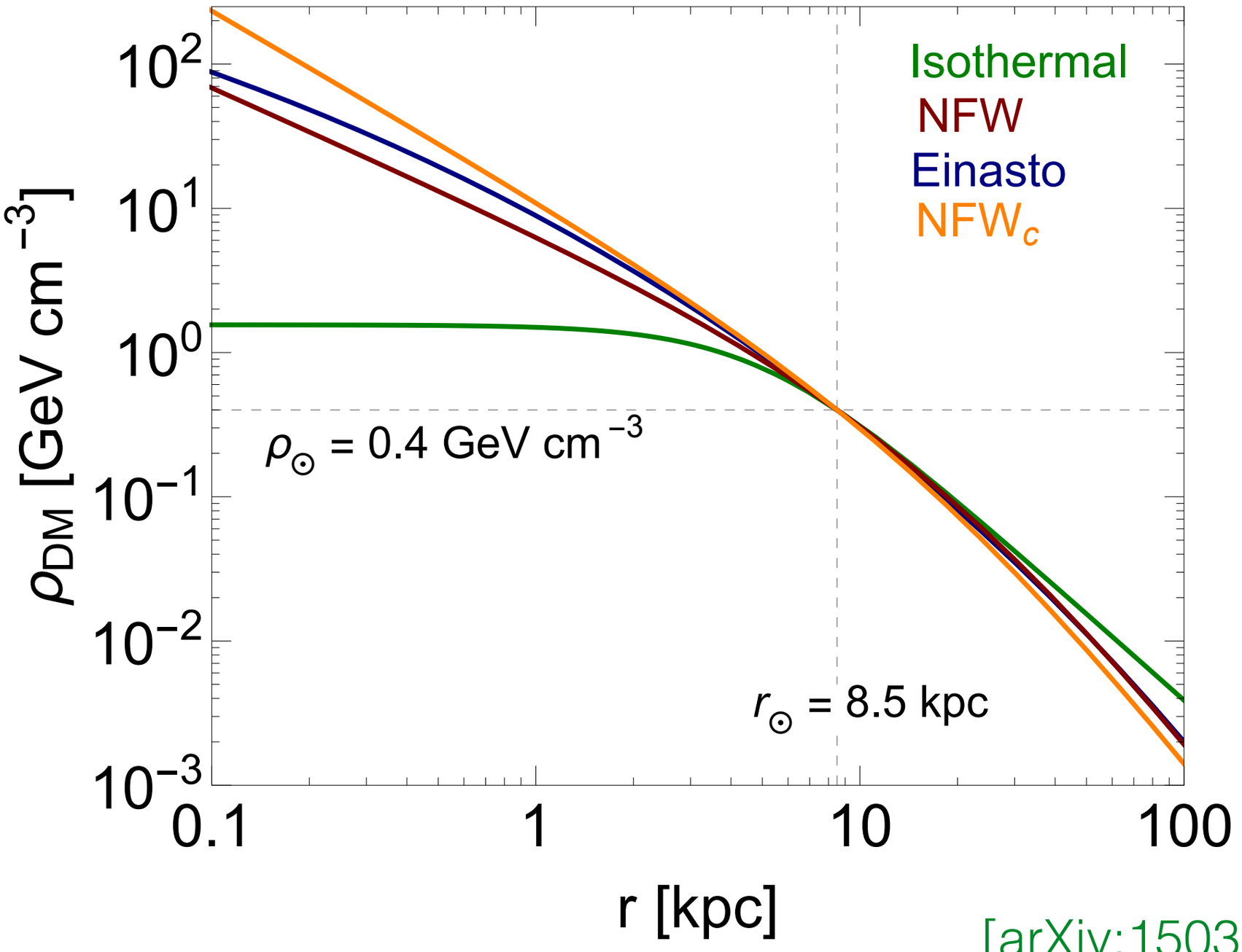
Boehm et. al 1404.7012

Upper limit on cross section

Distribution of flux components



DM profiles



[arXiv:1503.07169]

Cross Sections

Fermion DM—Vector Mediator

$$\frac{d\sigma}{d\cos\theta} = \frac{g^2 \left(g'\right)^2 E_\nu^2 m_\chi^2 \left(2(1-x)E_\nu + (1+x)m_\chi\right)}{4\pi \left((1-x)E_\nu + m_\chi\right)\left((1-x)E_\nu m_\phi^2 + m_\chi\left(m_\phi^2 - 2(x-1)E_\nu^2\right)\right)^2}$$

$$\sigma = \frac{g^2 g'^2}{16\pi E_\nu^2 m_\phi^2}\left(m_\phi^2 \log\left(\frac{m_\phi^2(2E_\nu + m_\chi)}{m_\chi(4E_\nu^2 + m_\chi^2) + 2E_\nu m_\phi^2}\right) + \frac{4m_\chi E_\nu^2}{m_\chi + \frac{2E_\nu m_\phi^2}{4E_\nu^2 + m_\phi^2}}\right)$$

Scalar DM—Fermion Mediator

$$\frac{d\sigma}{d\cos\theta} = \frac{g^4 E_\nu^2 m_\chi((x-1)m_\phi^6 - 2(x-1)m_\phi^4 m_\chi^2 + 8E_\nu^2((x-1)E_\nu - m_\chi)m_\chi^3 + (x-1)m_\phi^2 m_\chi^4)}{4\pi((x-1)E_\nu - m_\chi)^3((m_\phi^2 - m_\chi^2)^2 - 4E_\nu^2 m_\chi^2)^2}$$

$$\sigma = \frac{g^4 E_\nu^2 (m_\phi^6 - 2m_\phi^4 m_\chi^2 + m_\phi^2 m_\chi^4 + 8E_\nu^2 m_\chi^3(2E_\nu + m_\chi))}{2\pi(2E_\nu + m_\chi)^2((m_\chi^2 - m_\phi^2)^2 - 4E_\nu^2 m_\chi^2)^2}$$