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

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WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

WIPAC
WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER

Based on

[arXiv:1703.00451]

C. A. Argüelles, A.K, A. C. Vincent

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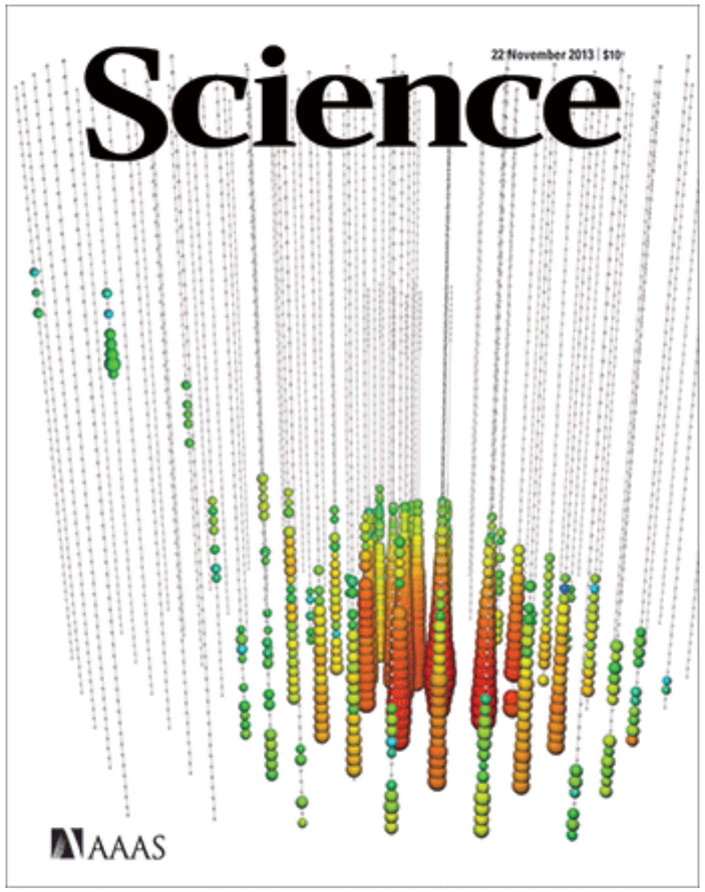
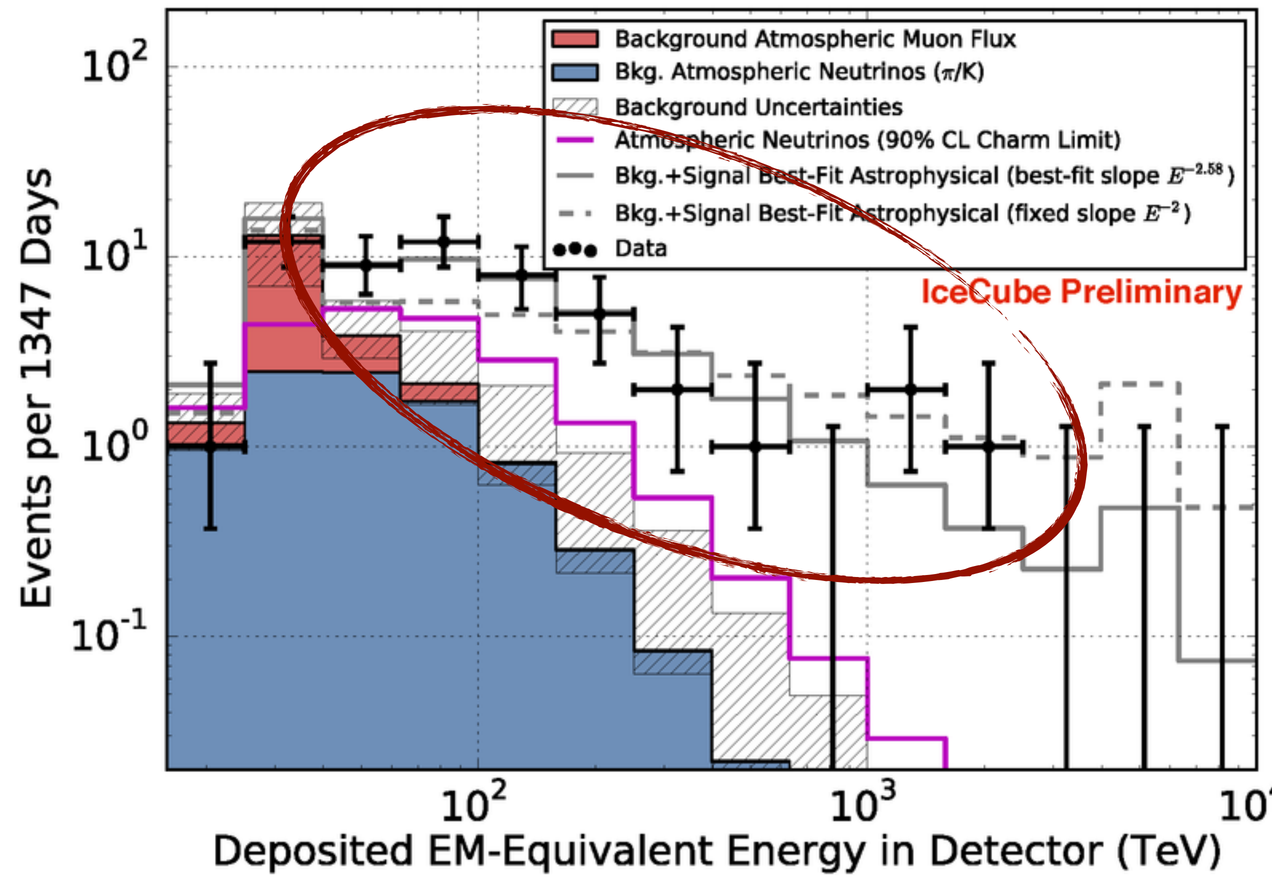
Imperial College London

Also ***νFATE****: Neutrino Fast Attenuation Through Earth,* coming soon!

IceCube & Cosmic Neutrinos

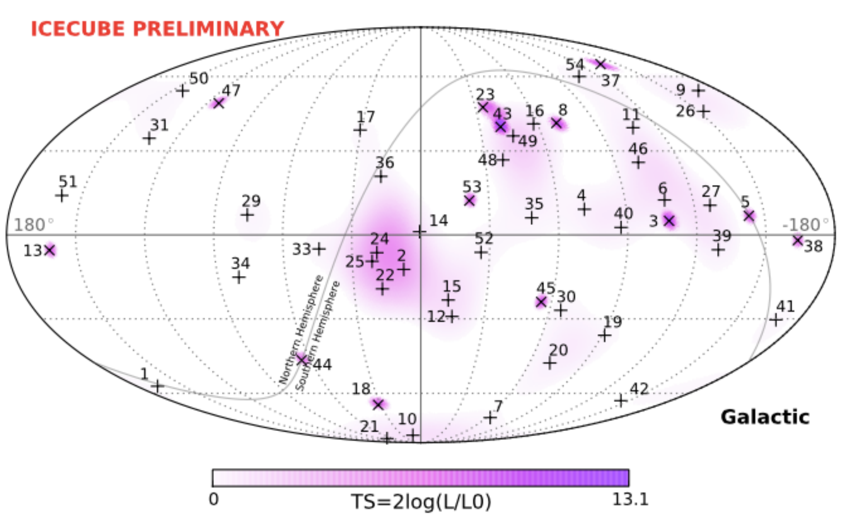




- IceCube Neutrino Observatory discovered neutrinos with extraterrestrial origin in 2013 in a search for High Energy Starting Event (HESE).
- Observation of a clear excess —>6 sigma— of HE neutrino flux above the atmospheric background.
- Observation of astrophysical flux was confirmed in through going tracks analysis.

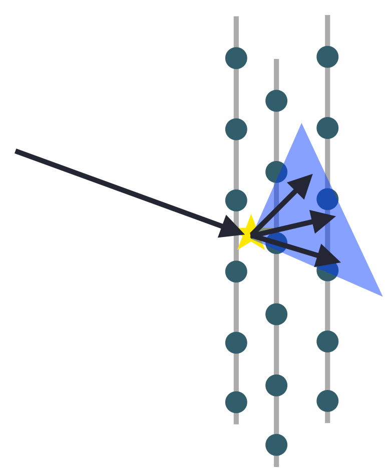
Astrophysical Neutrino Observables

Arrival direction



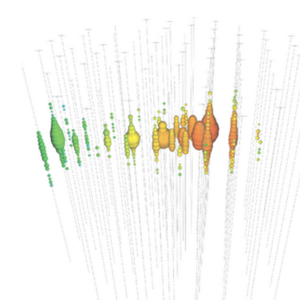
Neutrino energy

Deposited EM-equivalent

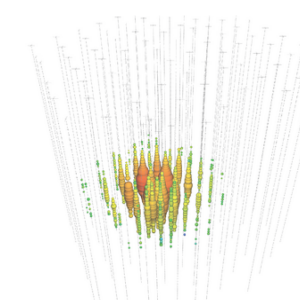


Flavour (e, μ, τ)

Topology



muon track



shower

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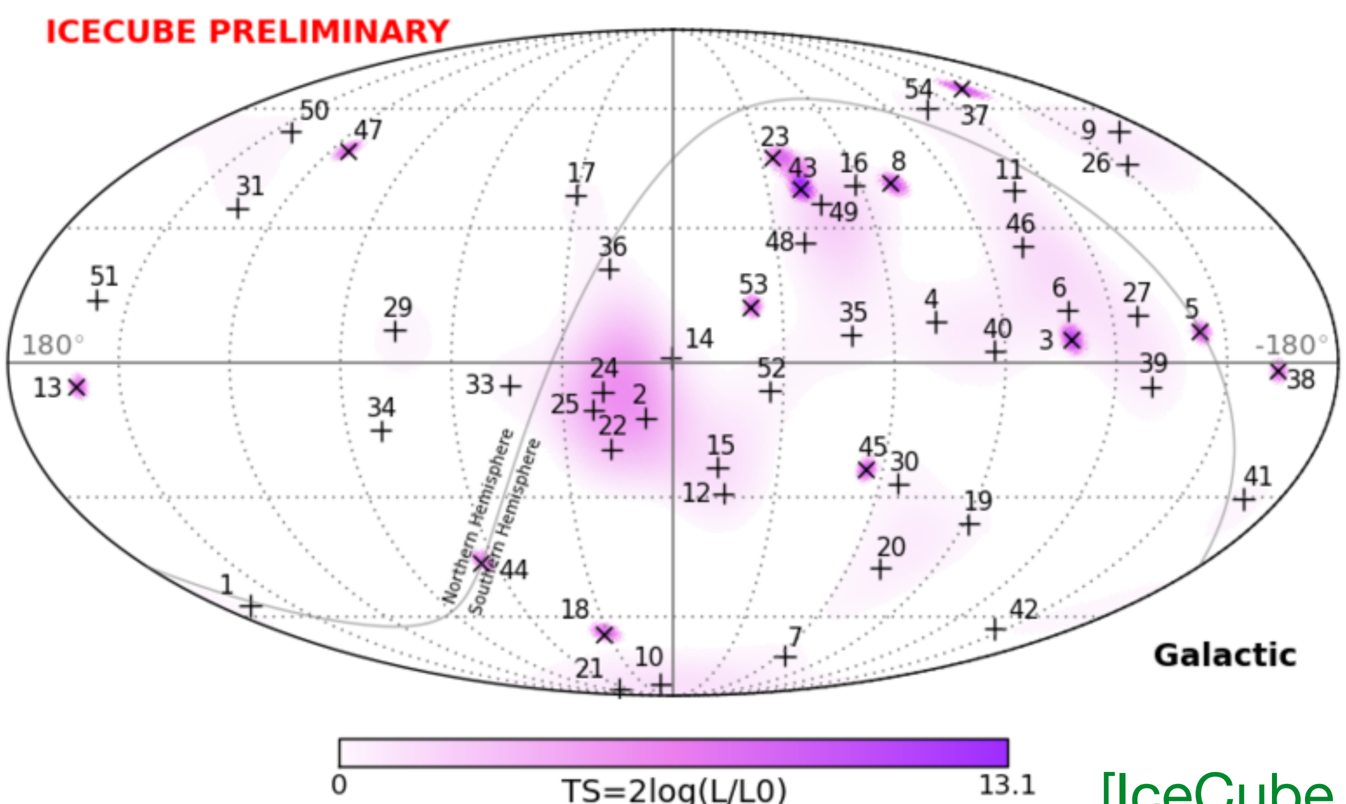
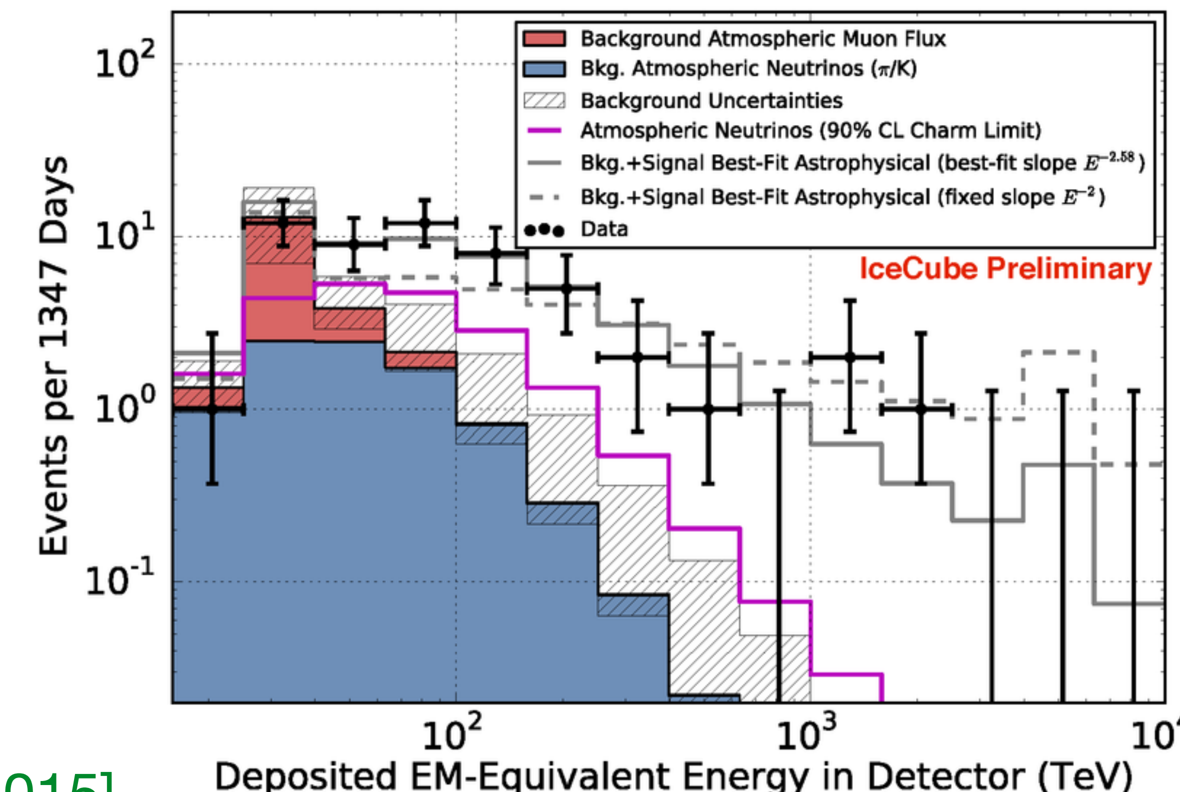
4 Years of HESE



[IceCube 2015]



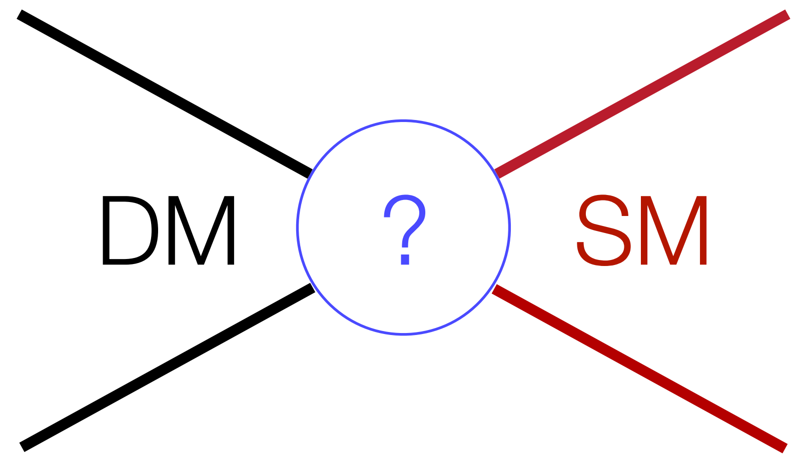
- 53 Events in 4 years.
- Events arrival directions is compatible with **isotropic** hypothesis.
- **No correlation** with Galactic plane.
- Event distribution suggests **extragalactic** origin for the majority of the events.
- **Flavor ratio** is consistent with 1:1:1 ratio.

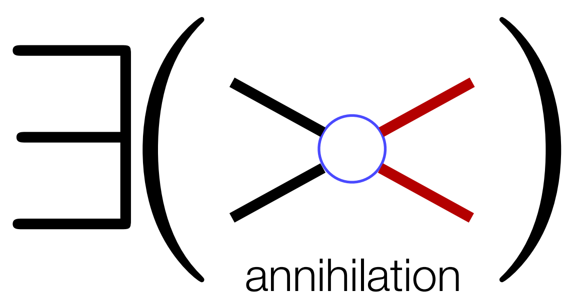
Cosmic Neutrinos: Internal Complementarity

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

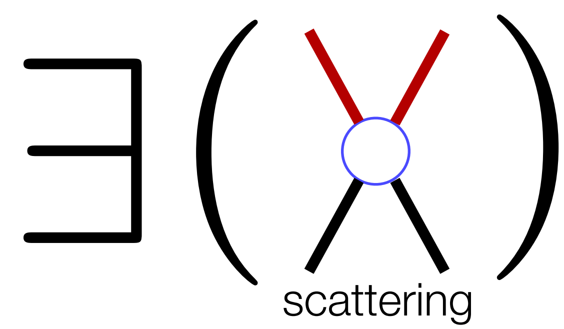
Dark matter-neutrino interaction?

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

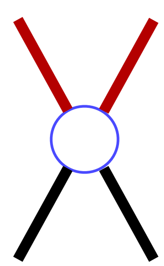




implies



if —— = quarks, then



= direct detection (LUX, LZ, SuperCDMS, …)

But if —— too light, or (?) does not talk to quarks, then —— could be neutrinos

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DM-Neutrino Interaction in Literature

[1] C. Boehm, P. Fayet, and R. Schaeffer, Phys.Lett. **B518**, 8 (2001), arXiv:astro-ph/0012504 [astro-ph].

[2] C. Boehm, A. Riazuelo, S. H. Hansen, and R. Schaeffer, Phys.Rev. **D66**, 083505 (2002), arXiv:astro-ph/0112522 [astro-ph].

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[4] E. Bertschinger, Phys.Rev. **D74**, 063509 (2006), arXiv:astro-ph/0607319 [astro-ph].

[5] G. Mangano, A. Melchiorri, P. Serra, A. Cooray, and M. Kamionkowski, Phys.Rev. **D74**, 043517 (2006), arXiv:astro-ph/0606190 [astro-ph].

[6] P. Serra, F. Zalamea, A. Cooray, G. Mangano, and A. Melchiorri, Phys.Rev. **D81**, 043507 (2010), arXiv:0911.4411 [astro-ph.CO].

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[8] L. G. van den Aarssen, T. Bringmann, and C. Pfrommer, Phys.Rev.Lett. **109**, 231301 (2012), arXiv:1205.5809 [astro-ph.CO].

[9] Y. Farzan and S. Palomares-Ruiz, JCAP **1406**, 014 (2014), arXiv:1401.7019 [hep-ph].

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[11] J. F. Cherry, A. Friedland, and I. M. Shoemaker, (2014), arXiv:1411.1071 [hep-ph].

[12] B. Bertoni, S. Ipek, D. McKeen, and A. E. Nelson, JHEP **1504**, 170 (2015), arXiv:1412.3113 [hep-ph].

[13] J. Schewtschenko, R. Wilkinson, C. Baugh, C. Boehm, and S. Pascoli, Mon.Not.Roy.Astron.Soc. **449**, 3587 (2015), arXiv:1412.4905 [astro-ph.CO].

DM-Neutrino Interaction

Low-Energy Limit & Cosmology

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

1) $\sigma \rightarrow const.$

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

Perturbation damping limits

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

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

[Escudero et.al, 2016]

DM-Neutrino Interaction

At High-Energy?

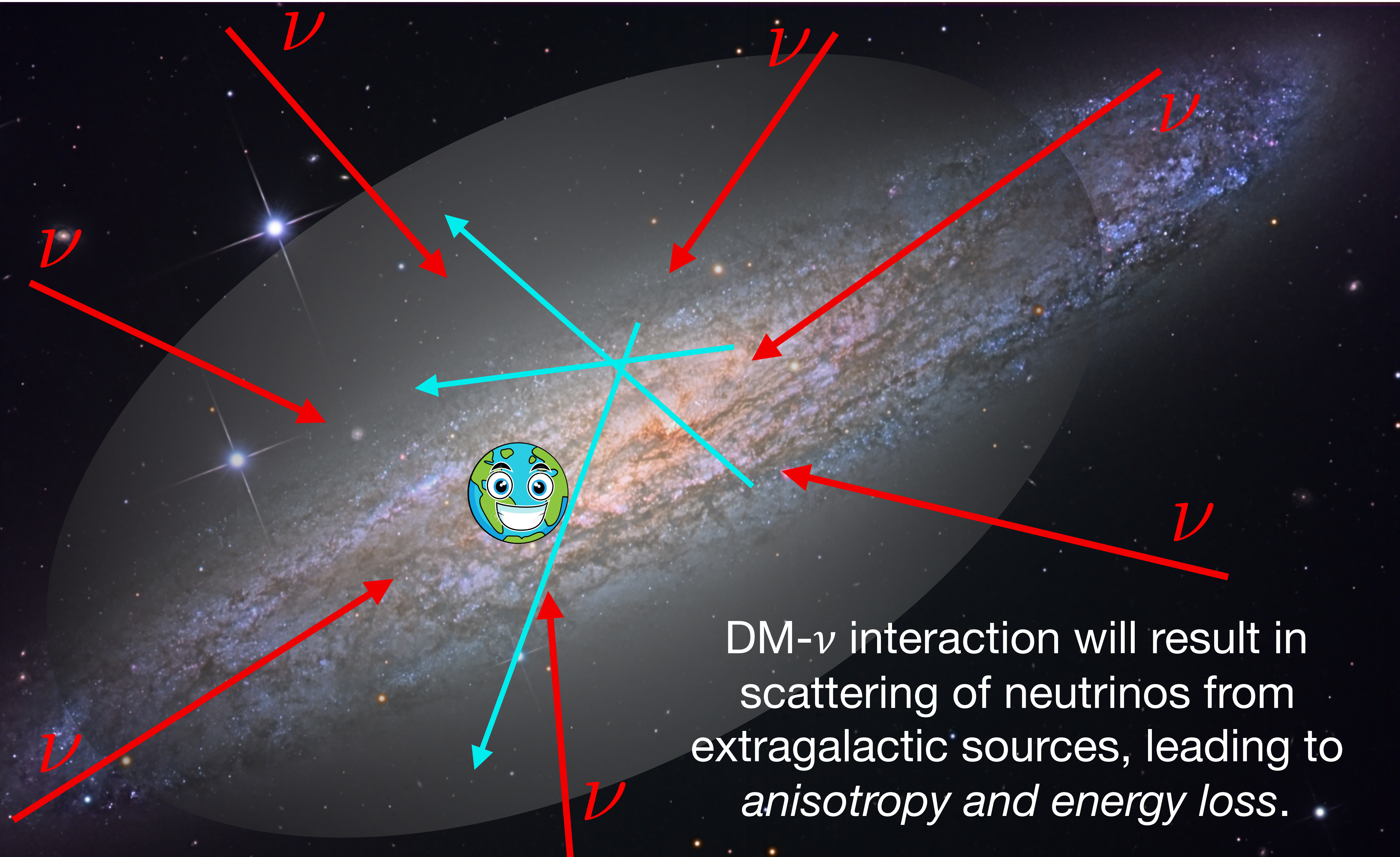
$$\sigma_{DM-\nu} \propto E_\nu^2$$

IceCube has seen events above a PeV….

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

Let's look there!

DM density is largest in center of the galaxy.



In Practice

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

b, l: galactic latitude, longitude

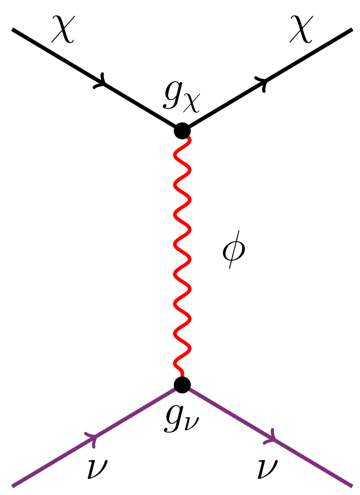
$$\frac{d\Phi(E,\tau)}{d\tau} = -\sigma(E)\Phi(E,\tau) + \int_E^\infty d\tilde{E}\,\frac{d\sigma(\tilde{E},E)}{dE}\Phi(\tilde{E},\tau)$$

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

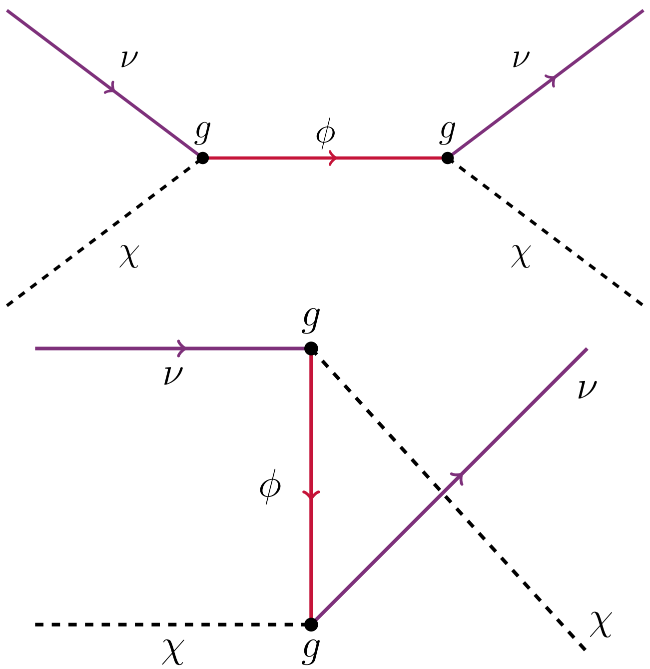
↓ scattering **to** *E* from any energy $\tilde{E}$

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

Two fiducial simplified models

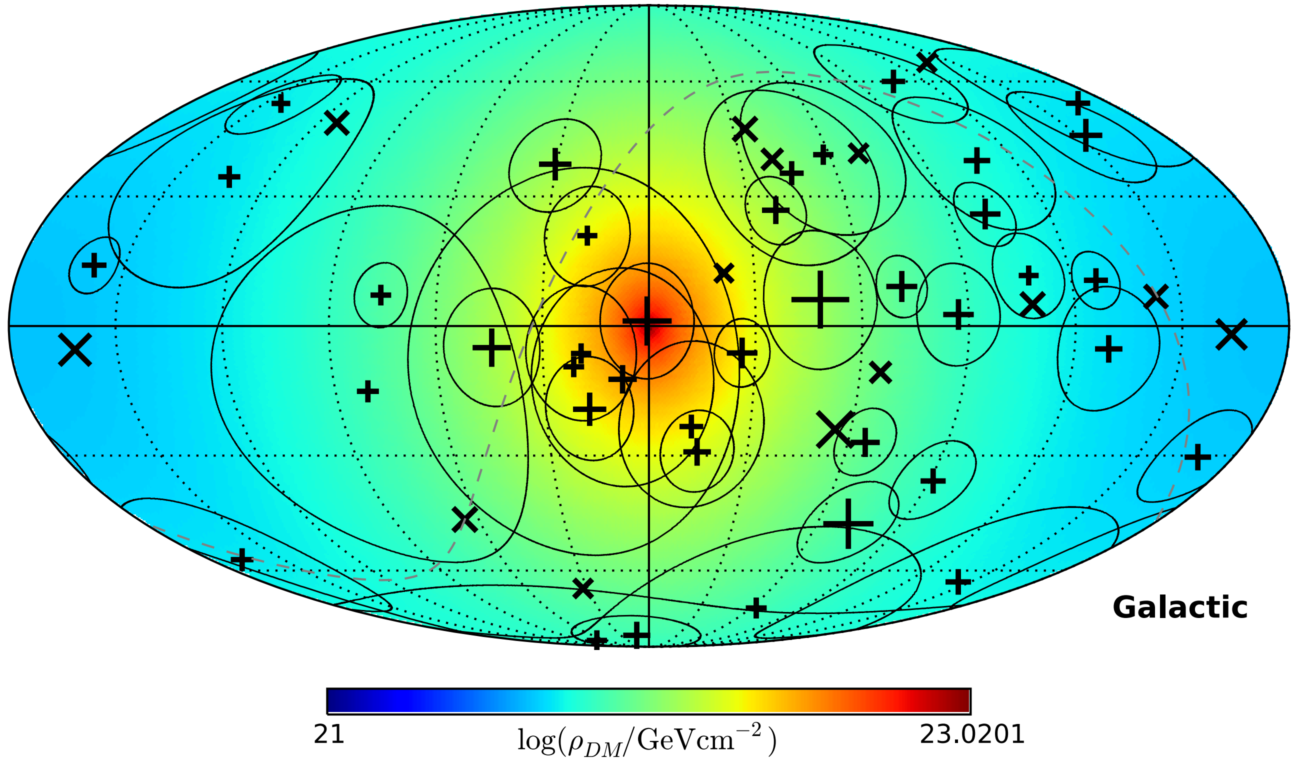


Fermion DM, **vector mediator**:
similar to a leptophillic Z' model
Scales strongly with *E*

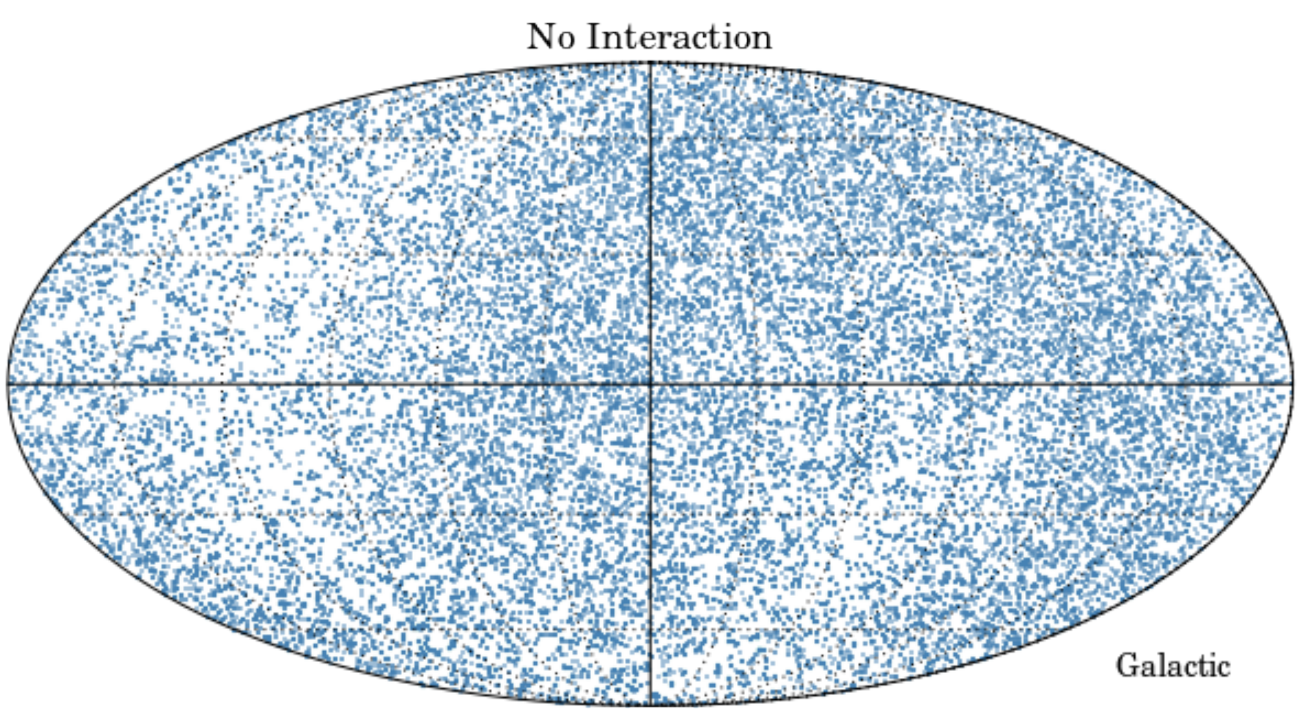


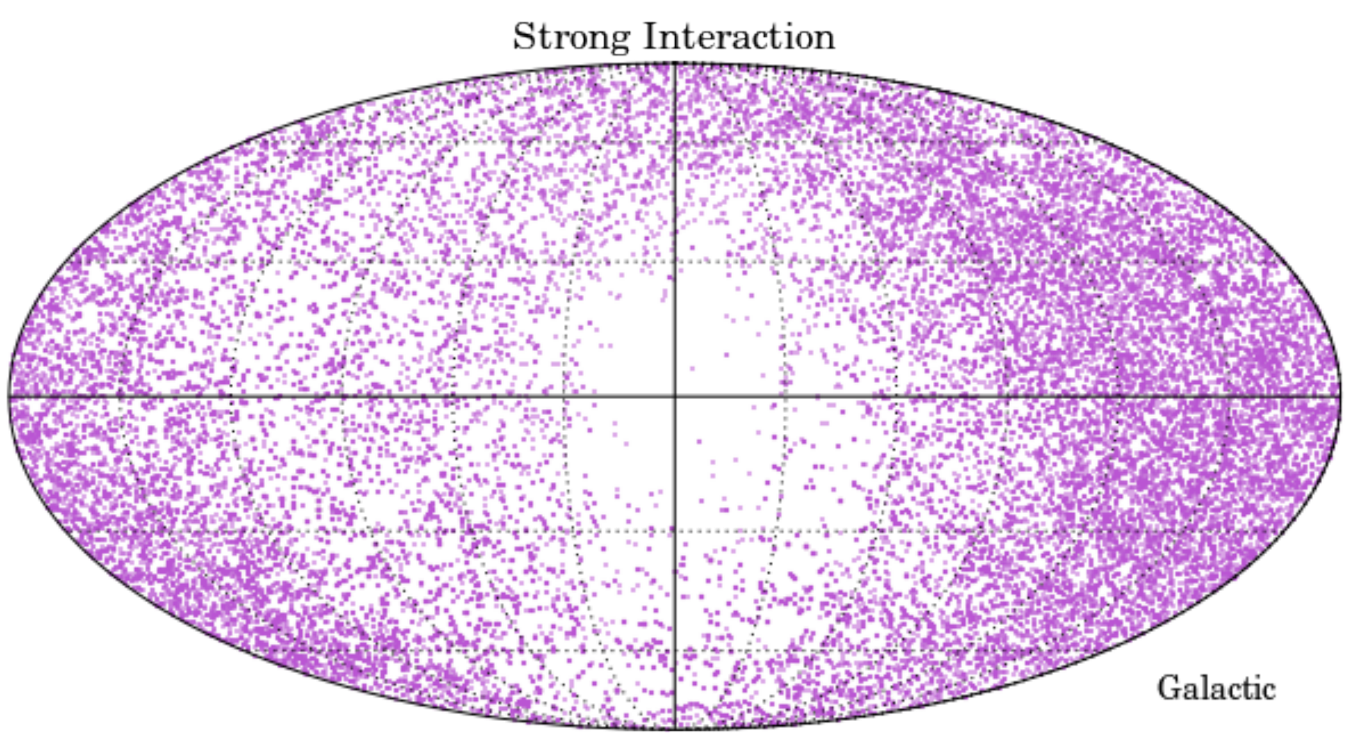
Scalar DM, **fermionic mediator**:
e.g. sneutrino dark matter, neutralino mediator. Resonant behaviour (s-channel)

Dark matter column density* seen from Earth



Simulation including effects of detector, Earth

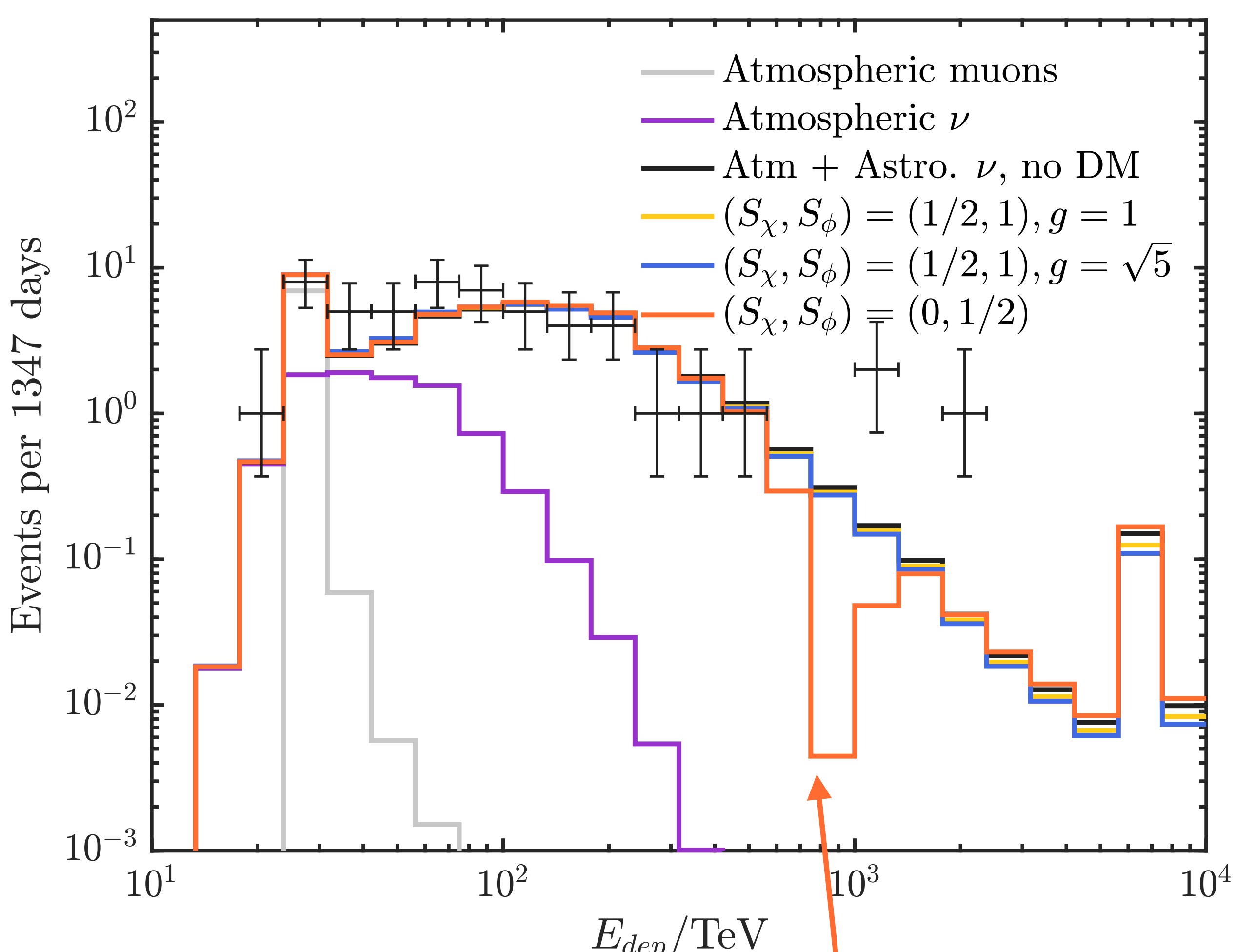




* *Einasto*

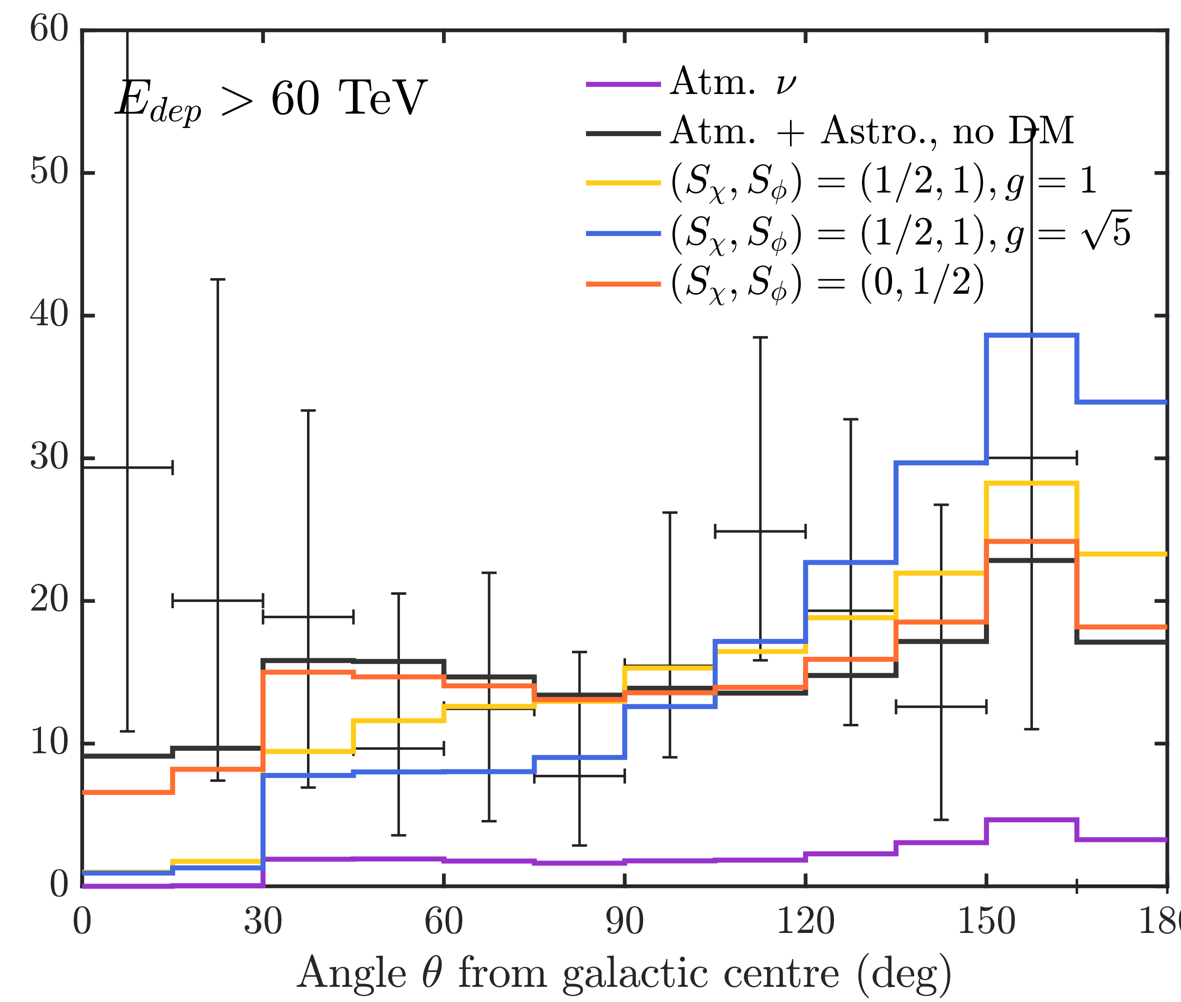
Energy & morphology

Energy



Resonance @ 810 TeV

Direction



IceCube HESE events

Likelihood Test

We test the likelihood of events originating from 3 components:

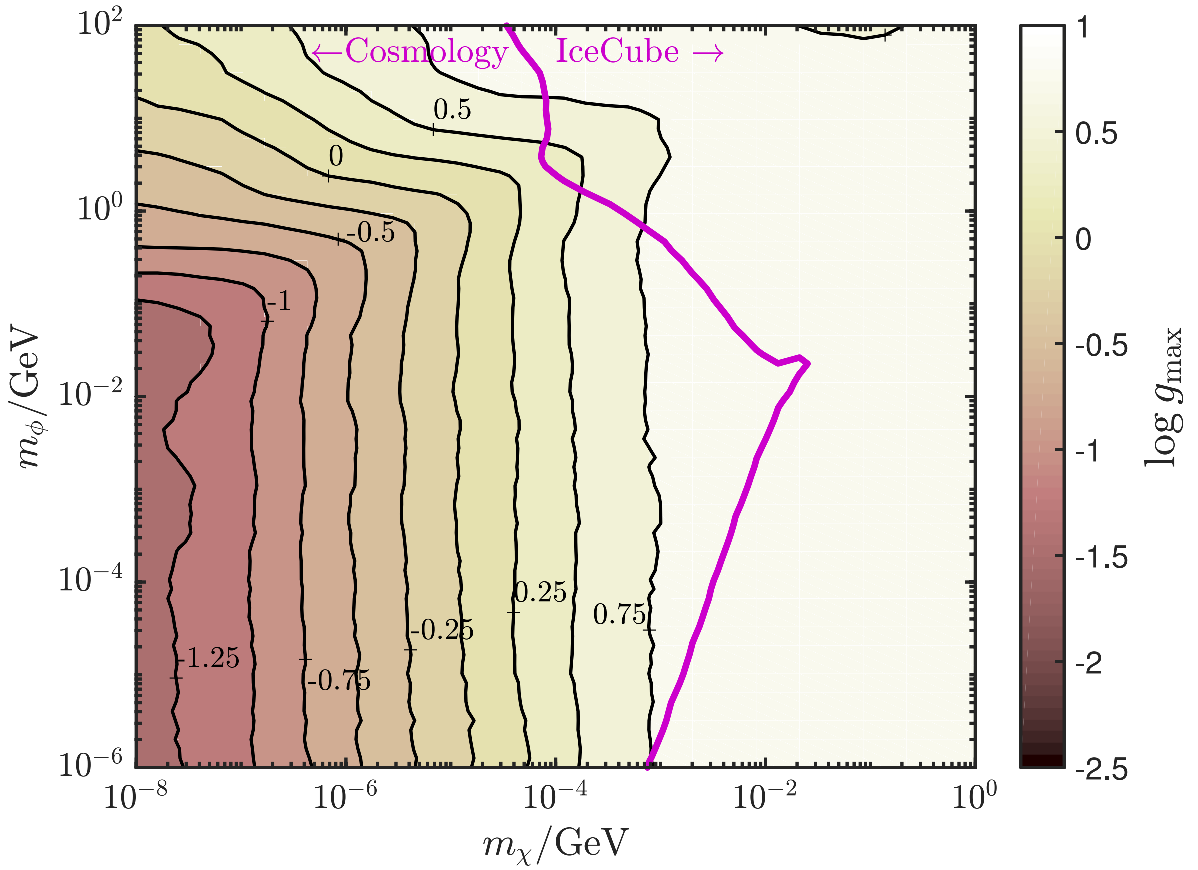
- Astrophysical neutrino component modified by DM-neutrino interaction, originating from E^{-2} spectrum
- Atmospheric neutrinos
- Atmospheric muons

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

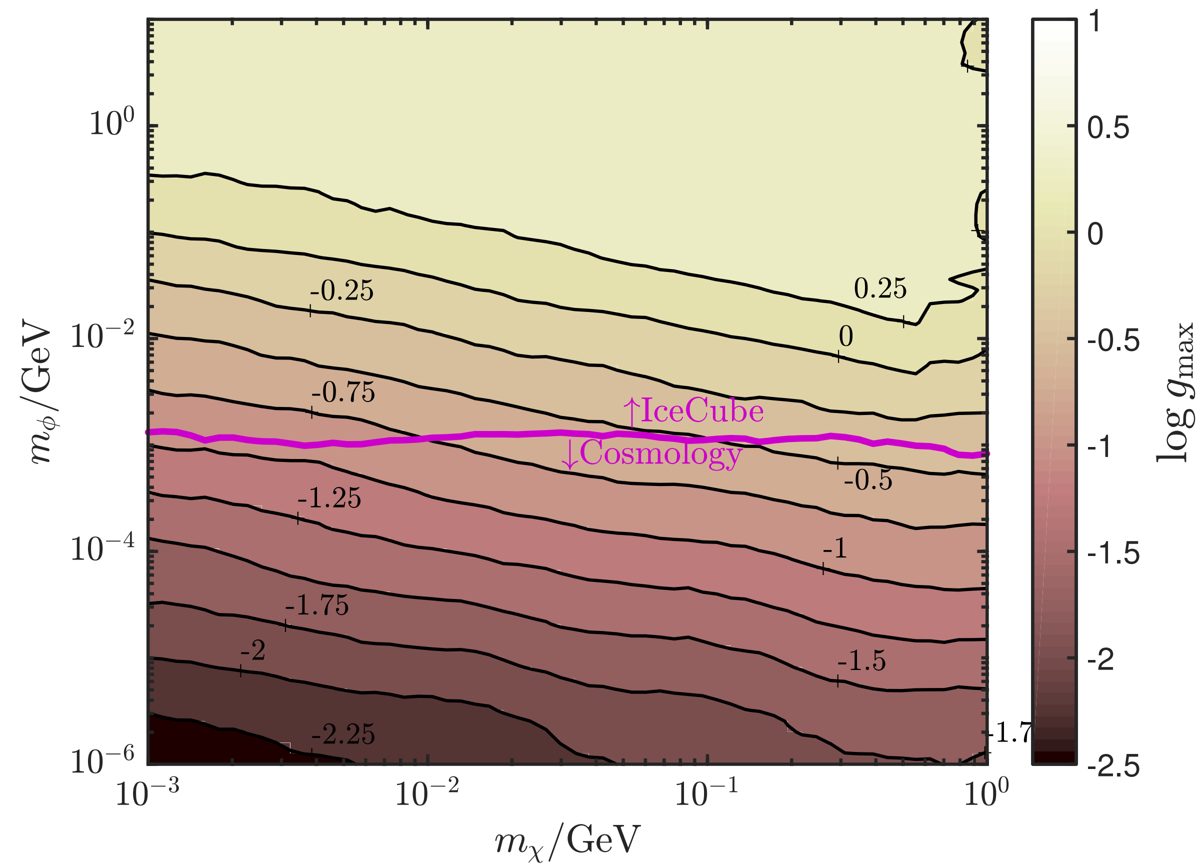
We establish a limit based on MCMC scan of the parameter space of each interaction model.

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

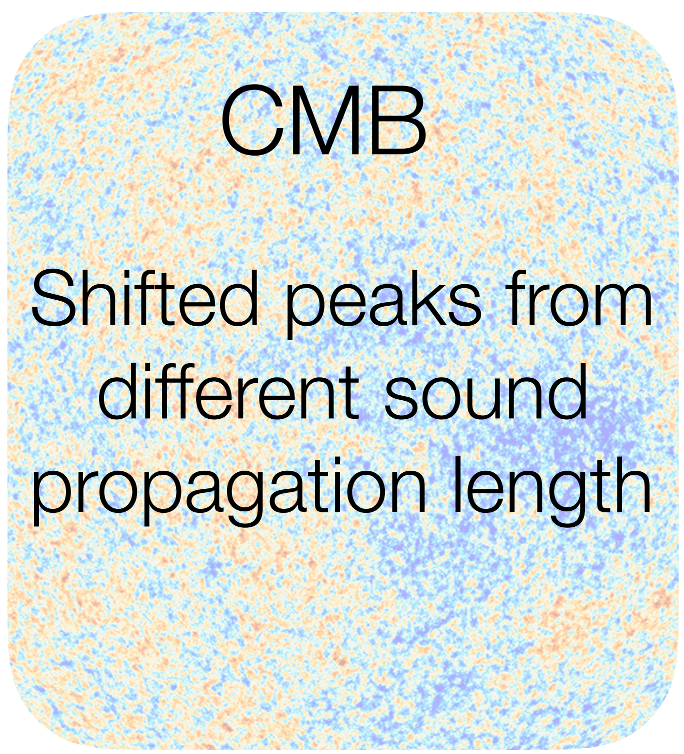
- No reason to believe DM-neutrino interactions aren't there.
- Isotropy of the signal can be used to constrain such interactions.
- Can even do better than cosmology in some ranges, mainly 1-100 MeV.
- Need more statistics: forecasts for *IceCube-Gen2* & more studies to come.

APPENDIX

DM-neutrino interactions: two constraints from cosmology

Extra radiation N_{eff}

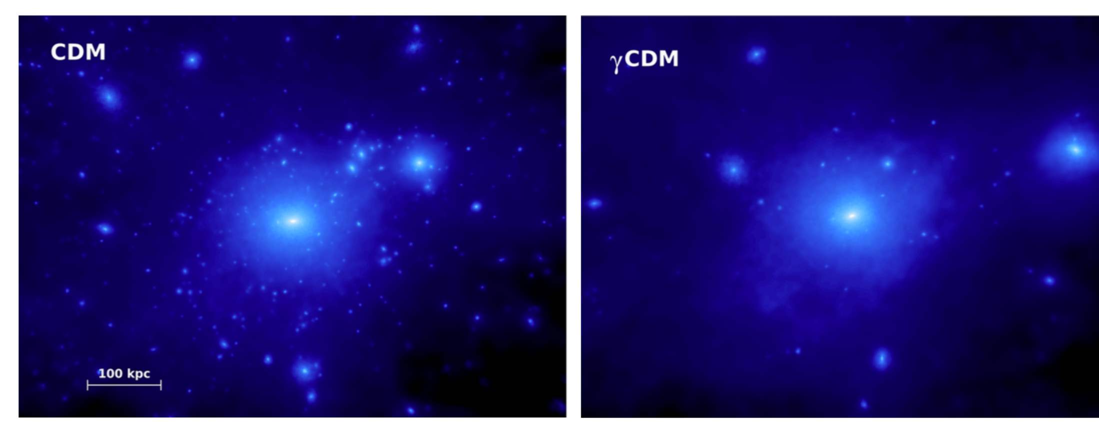
If DM is light (< 10 MeV) it can dump entropy into neutrino sector as it becomes non-relativistic



upper limit on DM mass

Perturbation damping

Scattering damps power spectrum of primordial fluctuations



Boehm et. al 1404.7012

Upper limit on cross section

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DM-neutrino interactions: cosmology (I)

Early universe: lots of dark matter, lots of neutrinos

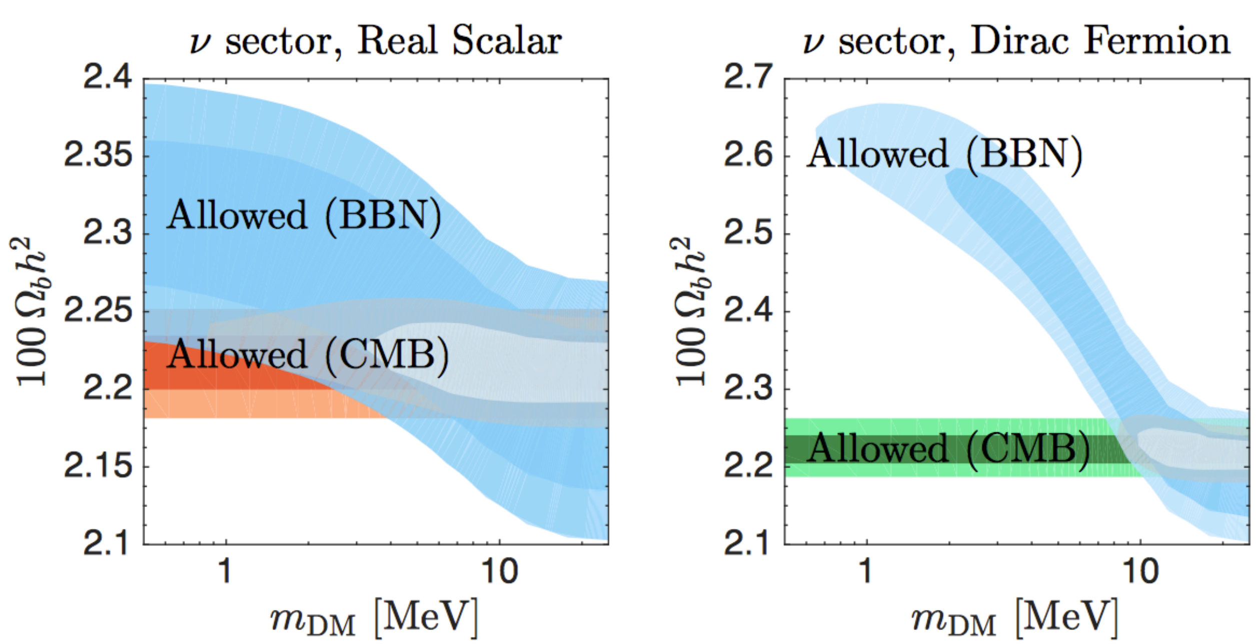
Thermal: if $m \sim T_{\nu,\mathrm{decoupling}}$, then DM dumps energy into neutrino sector as it becomes nonrelativistic. This means that there is more energy density in the neutrino sector, accelerating the expansion of the Universe

$$H^2 = \frac{8\pi}{3}\rho$$

Faster expansion:

1) During BBN: neutrons less boltzmann-suppressed at freeze-out: can form more Deuterium, helium

2) During recombination: acoustic peaks are shifted since sound propagation changed

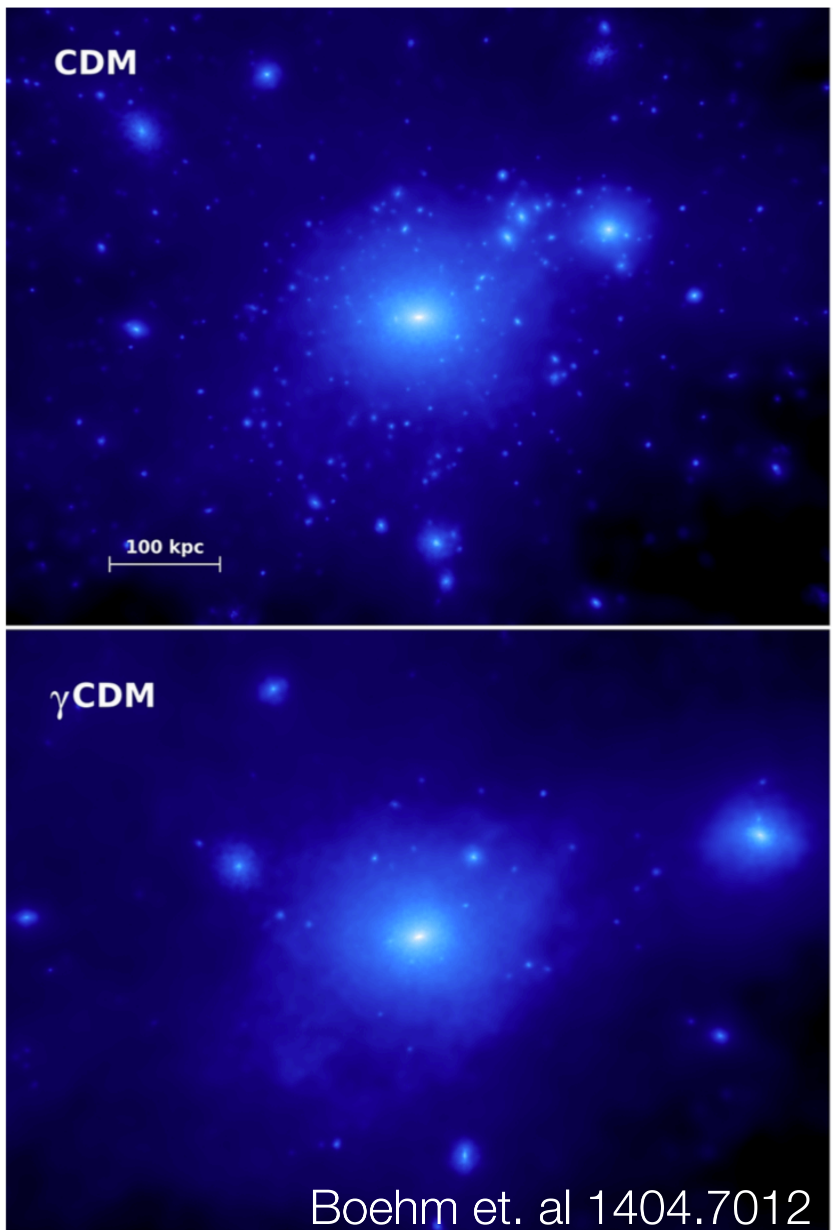


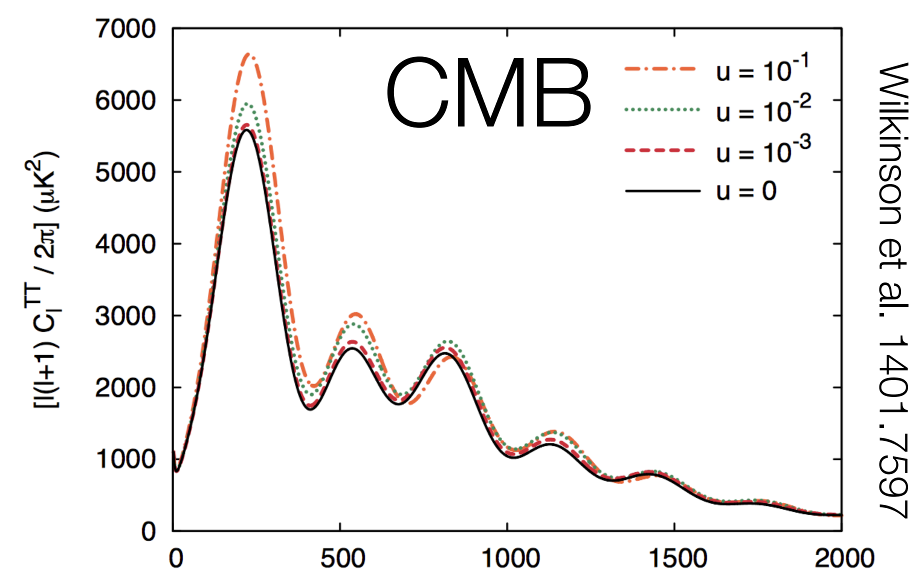
R. Wilkinson, ACV, C. Boehm, C. McCabe 1602.01114

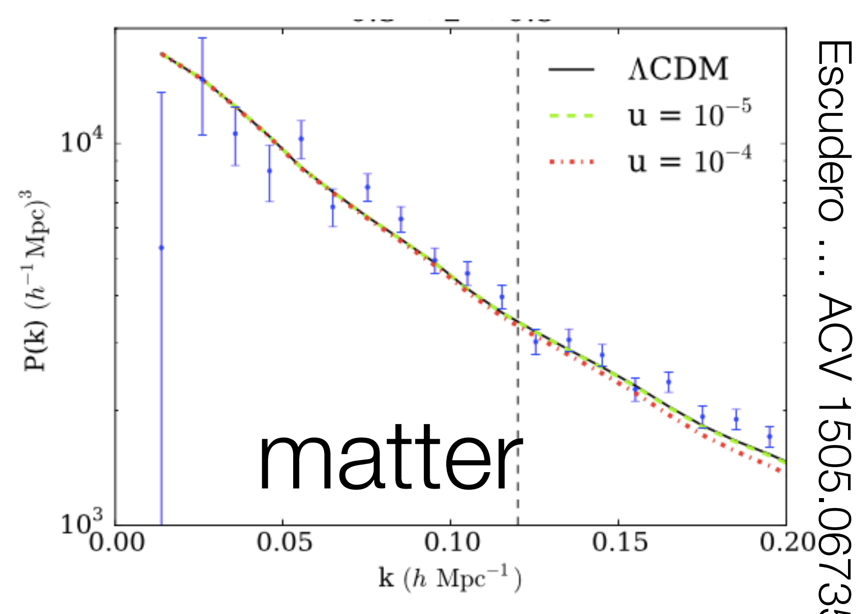
$$m_\chi \gtrsim 5 - 10\mathrm{MeV}$$

DM-neutrino interactions: cosmology (II)

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







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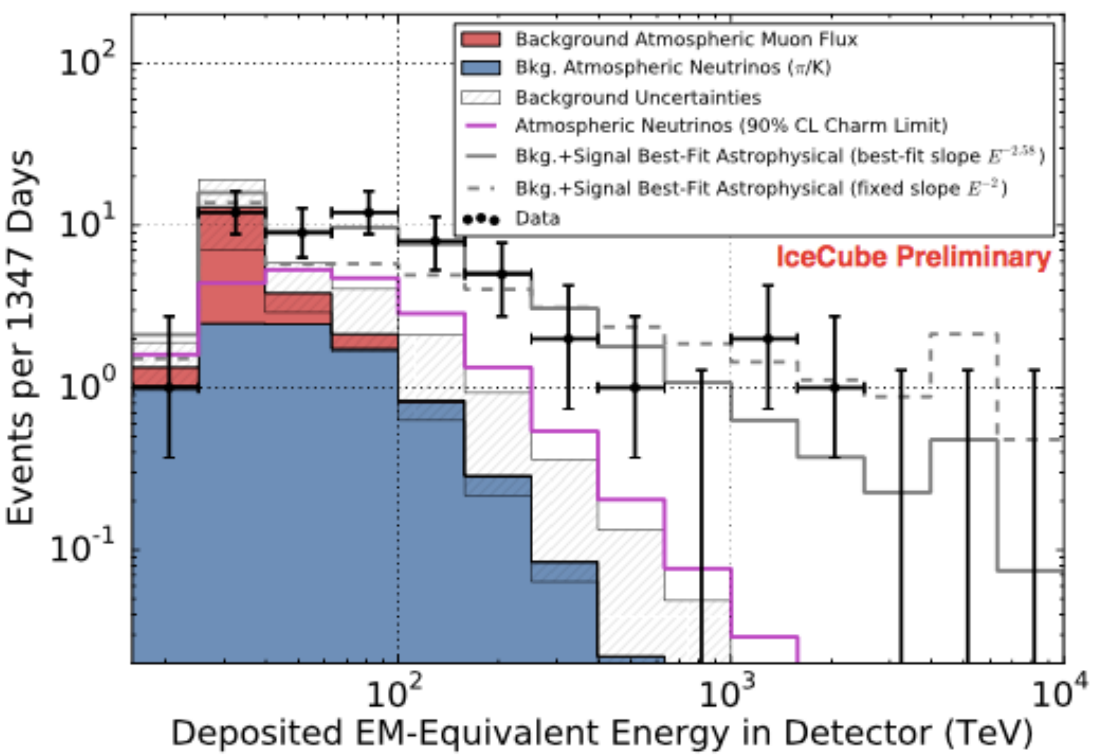
Backgrounds

IceCube ICRC 1510.05223



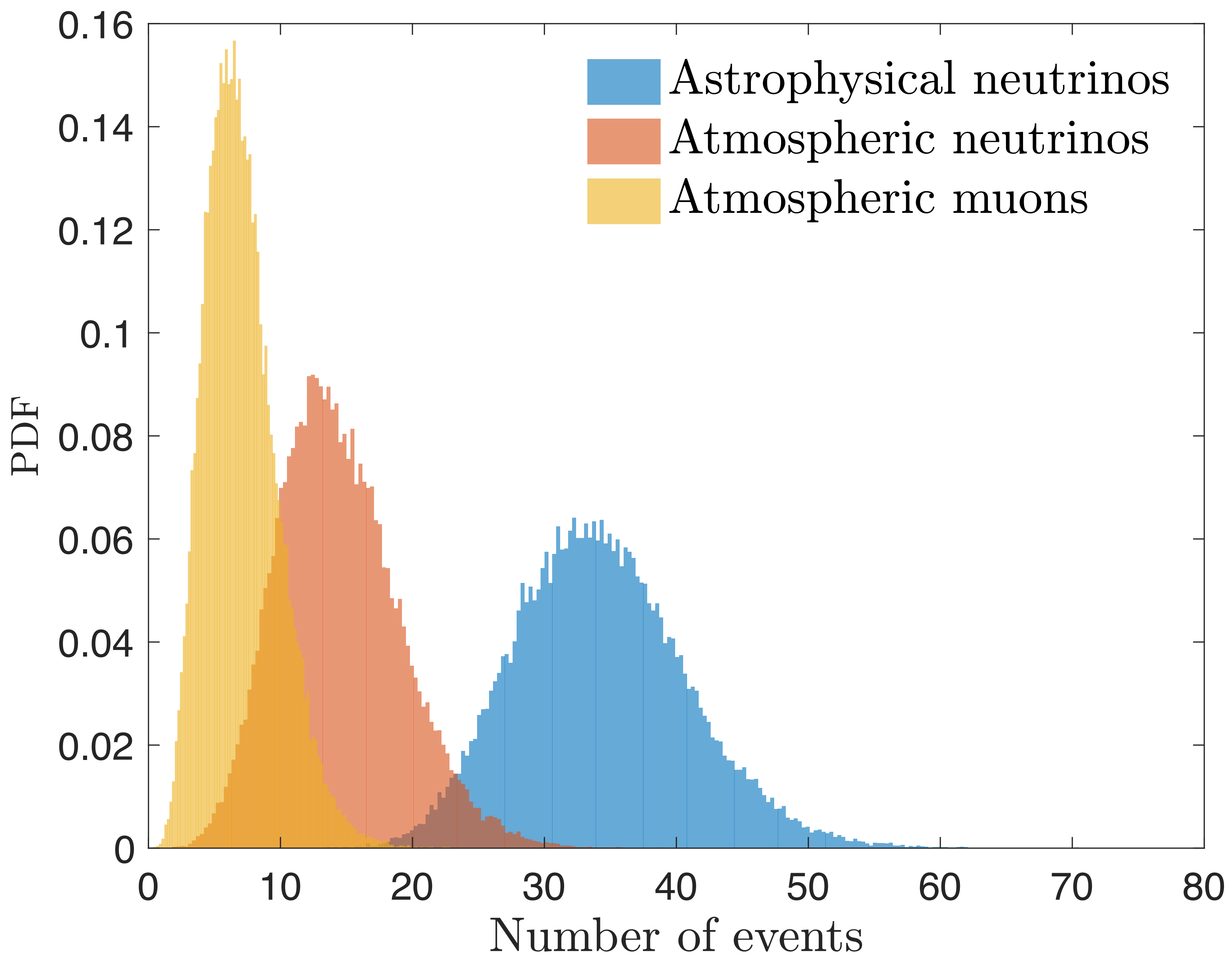
Neutrinos from atmospheric showers can fail to trigger the vetos. These are mostly upgoing (from the north), but concentrated around the horizon.

HESE: ~ 12/53 atmospheric neutrinos

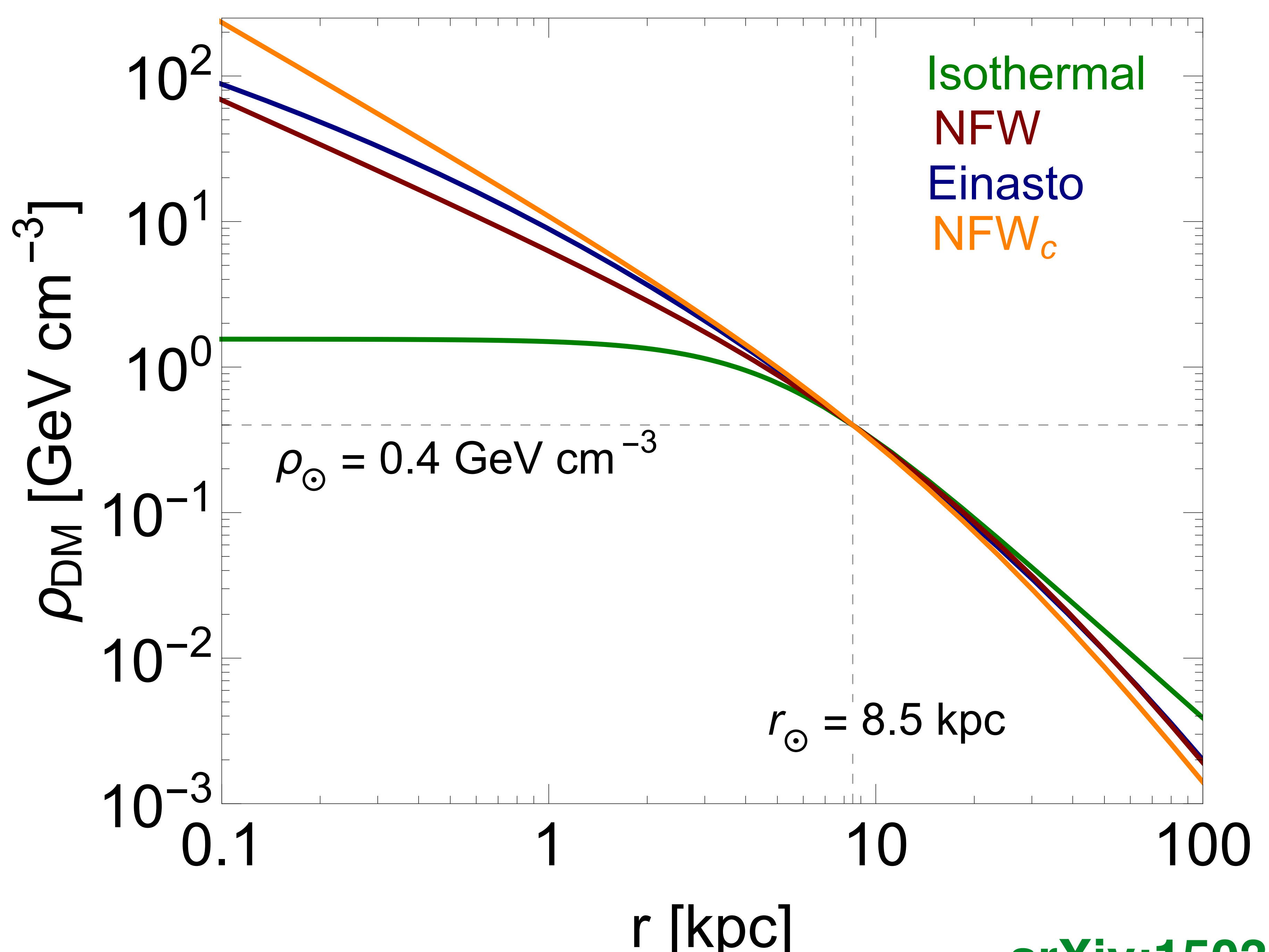
Muons from atmospheric showers can slip through the veto region. These occur at low energies, and only from the southern (downgoing) direction

HESE: ~ 10/53 atmospheric muons

Distribution of flux components



DM profiles



arXiv:1503.07169