Imaging Galactic Dark Matter with IceCube High-Energy Cosmic Neutrinos

Aaron Vincent

IceCube Particle Astrophysics
Madison WI, 8 May 2017

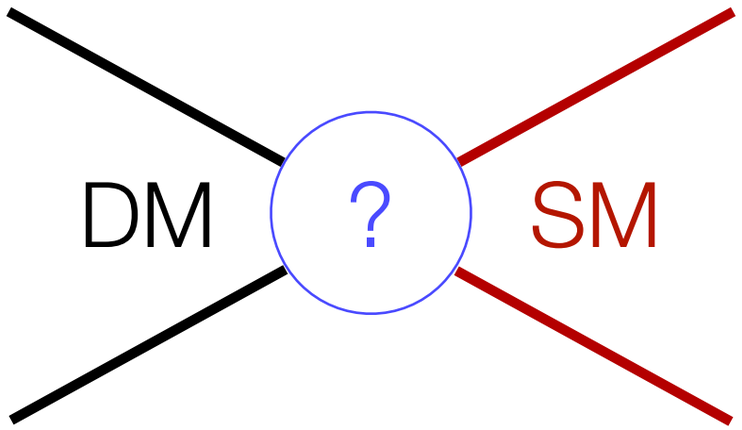
Imperial College London

Based on

C. A. Argüelles, A. Kheirandish, A.C.V, *Imaging galactic dark matter with high energy cosmic neutrinos* 1703.00451

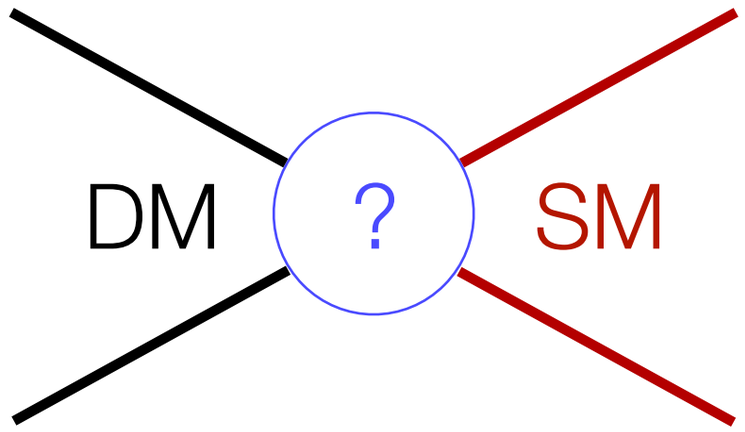
Also *νFATE*: neutrino fast attenuation through earth, coming soon

The 1:5 relationship between Dark Matter and
nuclear (proton, neutron) abundances implies relatively recent creation



…which hints at a stronger connection than just gravity
between our sector and the dark world

What is dark matter?
what particles does it talk to?
how does it talk to it?



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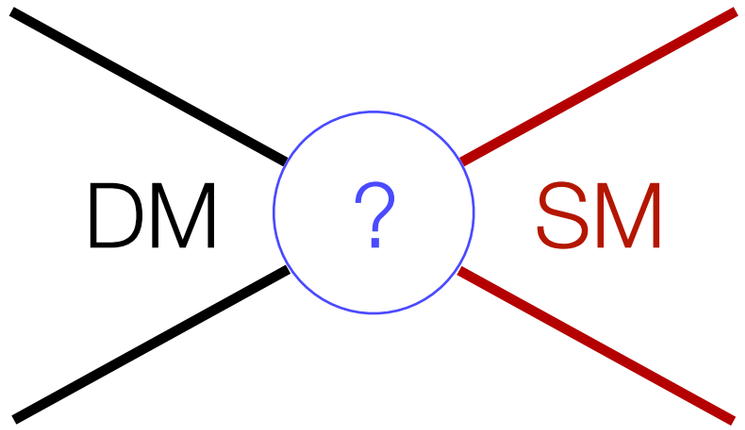

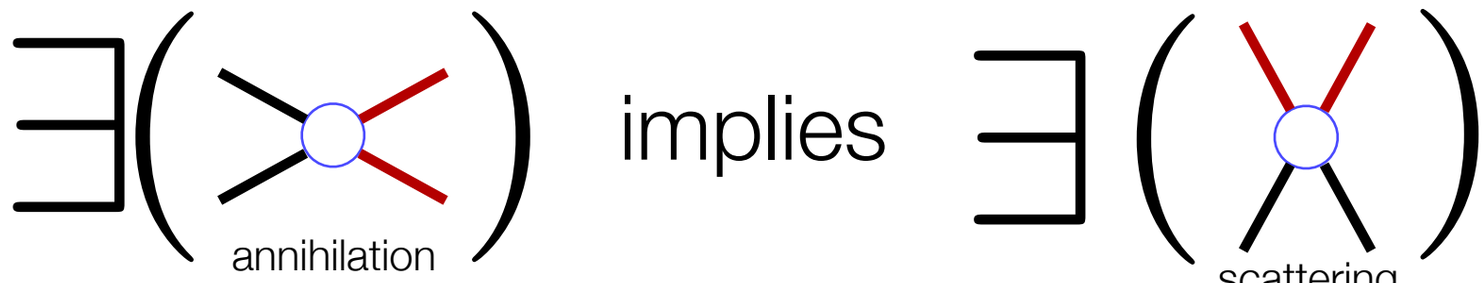

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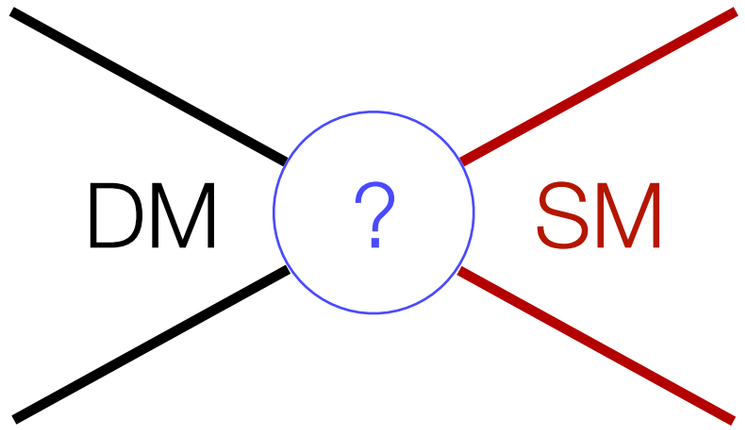
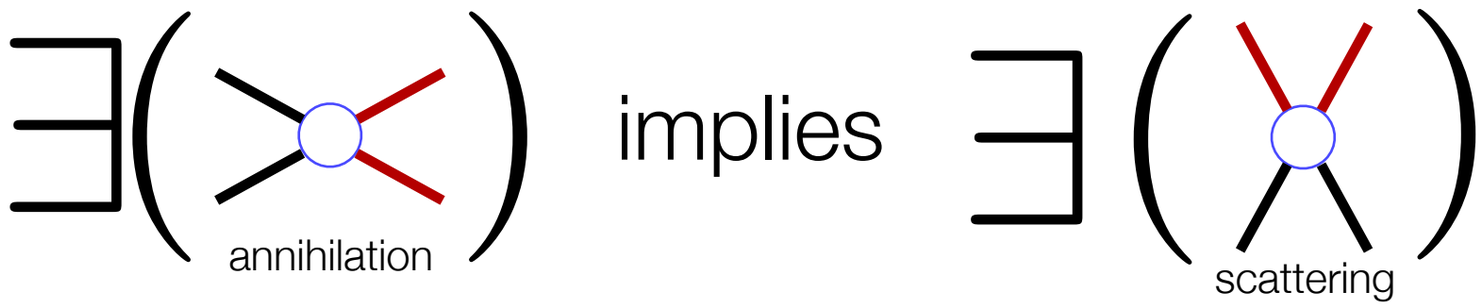
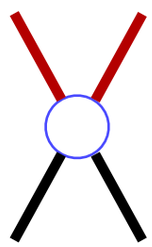




if —— = quarks, then  = direct detection
(LUX, LZ, SuperCDMS, …)

What is dark matter?
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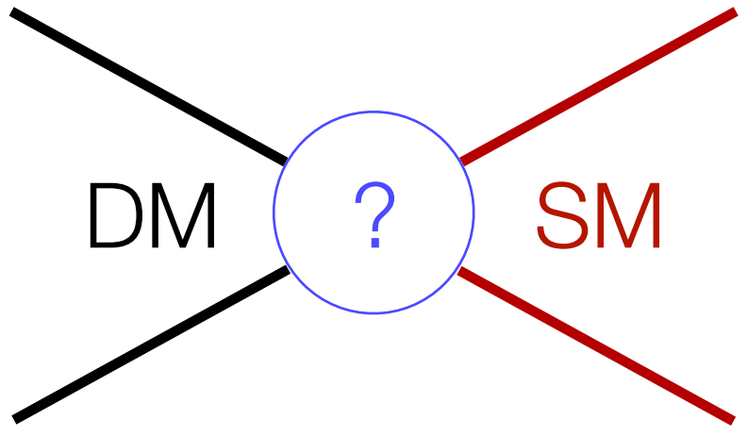
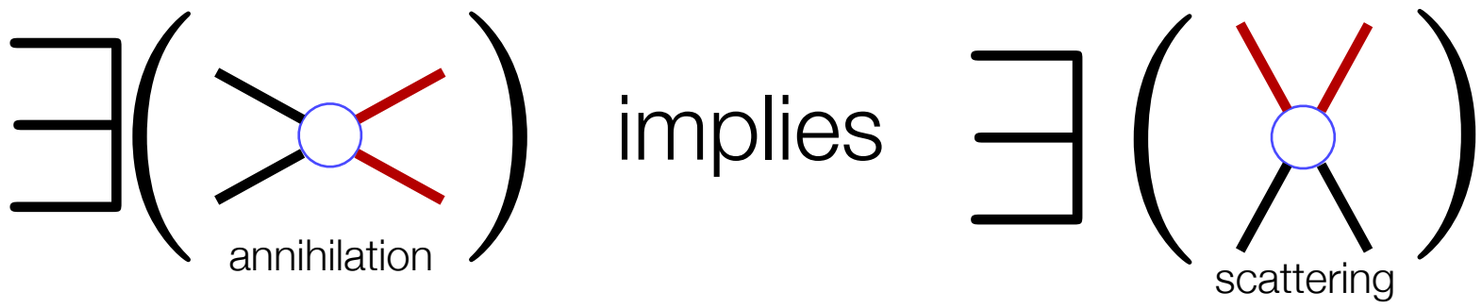
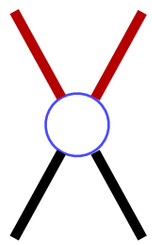




if —— = quarks, then  = direct detection
(LUX, LZ, SuperCDMS, …)

But if—— too light, or (?) does not talk to quarks, then
—— could be $\nu, \bar{\nu}$

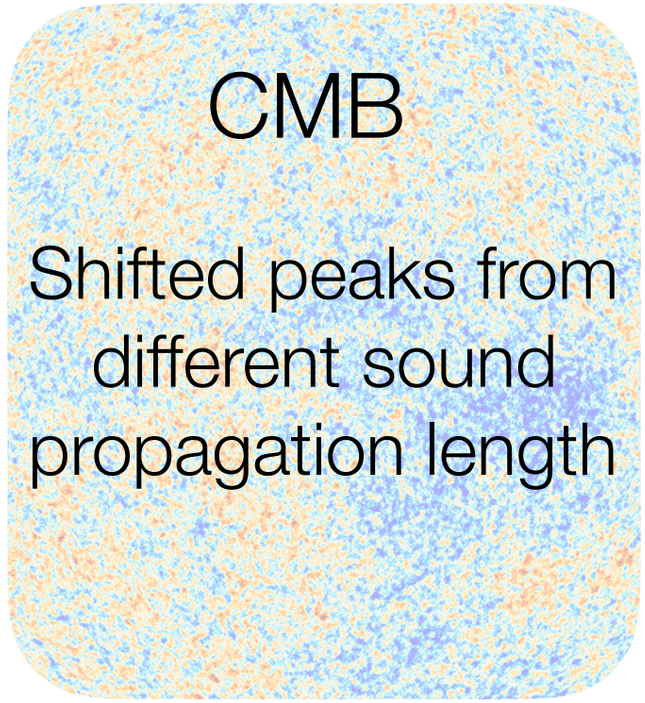
[1] C. Boehm, P. Fayet, and R. Schaeffer, Phys.Lett. **B518**, 8 (2001), arXiv:astro-ph/0012504 [astro-ph].
[2] C. Boehm, A. Riazuelo, S. H. Hansen, and R. Schaeffer, Phys.Rev. **D66**, 083505 (2002), arXiv:astro-ph/0112522 [astro-ph].
[3] C. Boehm and R. Schaeffer, Astron.Astrophys. **438**, 419 (2005), arXiv:astro-ph/0410591 [astro-ph].
[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].
[7] R. J. Wilkinson, C. Boehm, and J. Lesgourgues, JCAP **1405**, 011 (2014), arXiv:1401.7597 [astro-ph.CO].
[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].
[10] C. Boehm, J. Schewtschenko, R. Wilkinson, C. Baugh, and S. Pascoli, Mon.Not.Roy.Astron.Soc. **445**, L31 (2014), arXiv:1404.7012 [astro-ph.CO].
[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].

(a few references)

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

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

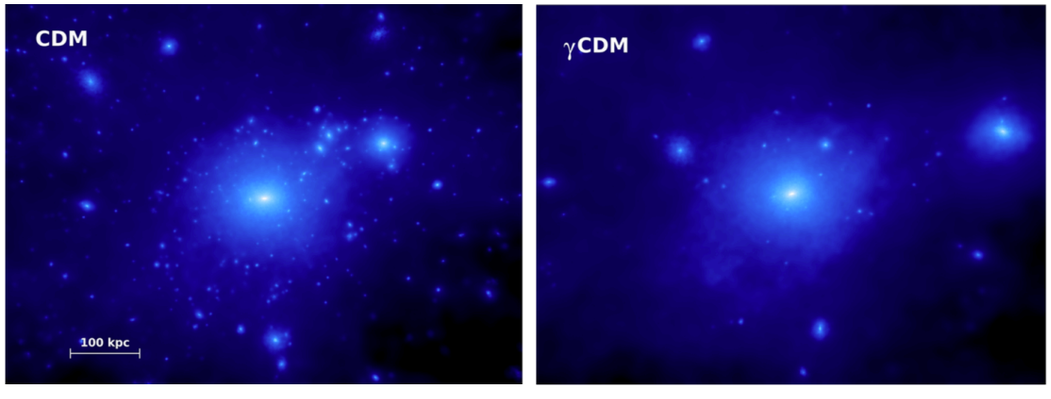
CMB

Shifted peaks from different sound propagation length

upper limit on DM mass

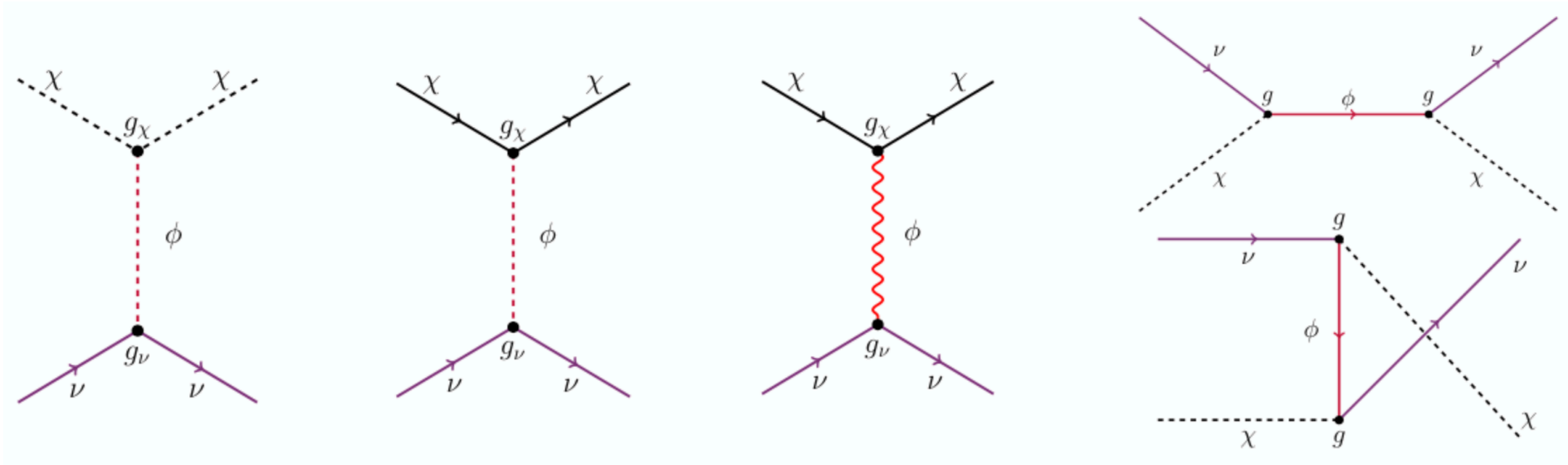
Perturbation damping

Scattering damps power spectrum of primordial fluctuations



Boehm et. al 1404.7012

Upper limit on cross section



Generic scattering cross section:

$$E_\nu \ll m_\chi$$

1) $\sigma \to const.$

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

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

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

Perturbation damping limits:

Escudero+ACV++

$$c.f.\ \sigma_{Thomson} = 10^{-26}\mathrm{cm}^2$$

Mangano 2006 + many others

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

IceCube has seen events above a PeV….

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

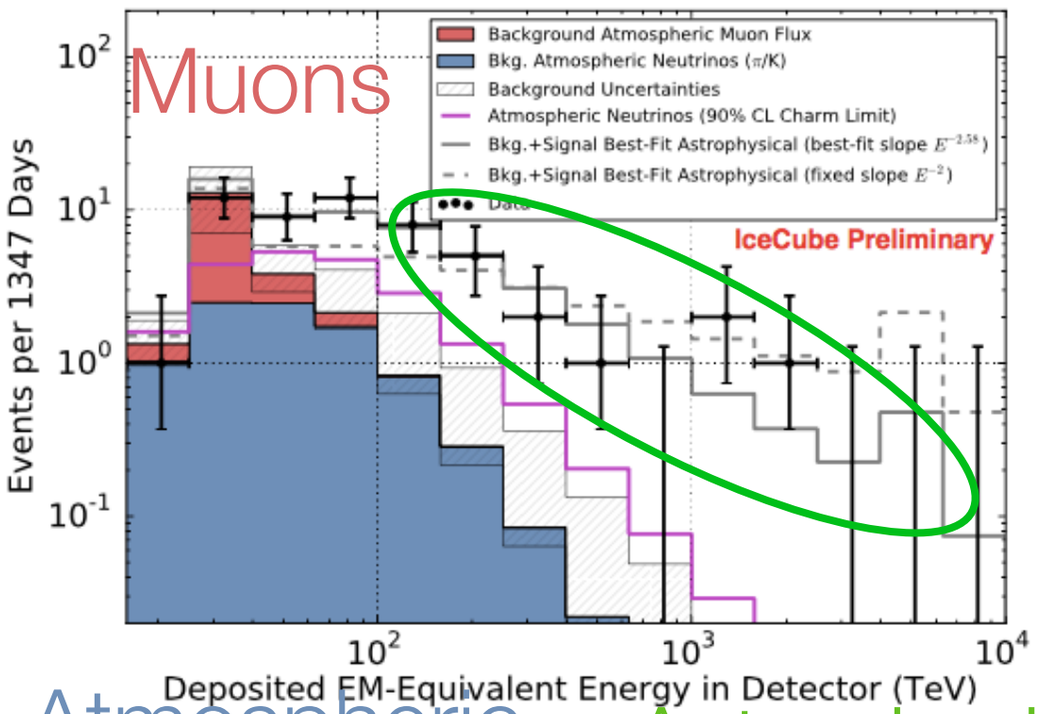
Let’s look there!

IceCube High Energy Starting Events (HESEs)

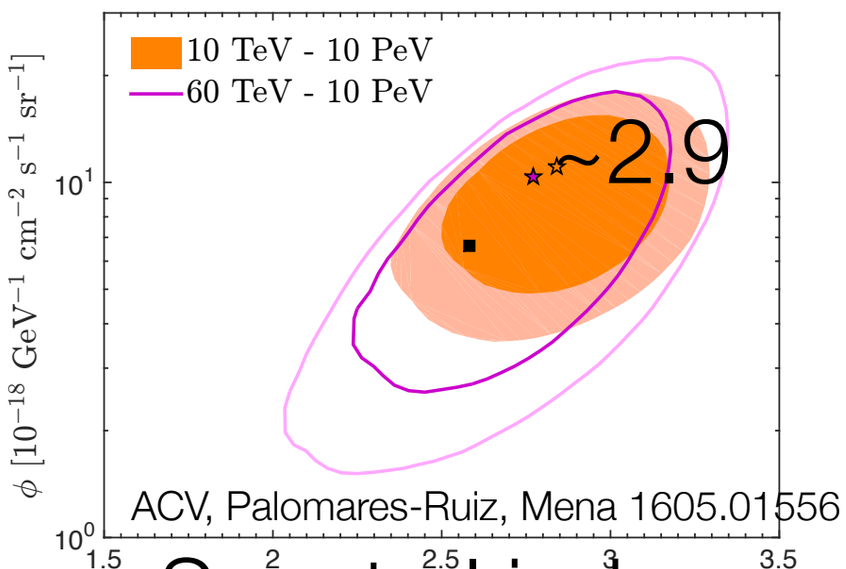
Energy

53 events

IceCube ICRC 1510.05223



Atmospheric Astrophysical



Spectral index

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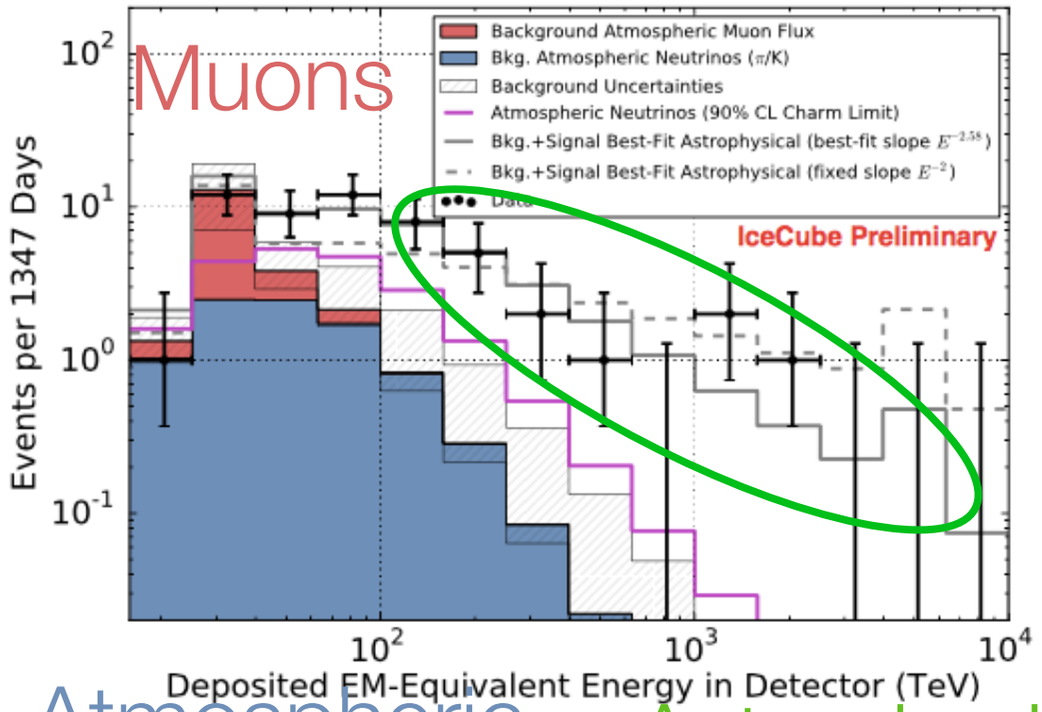
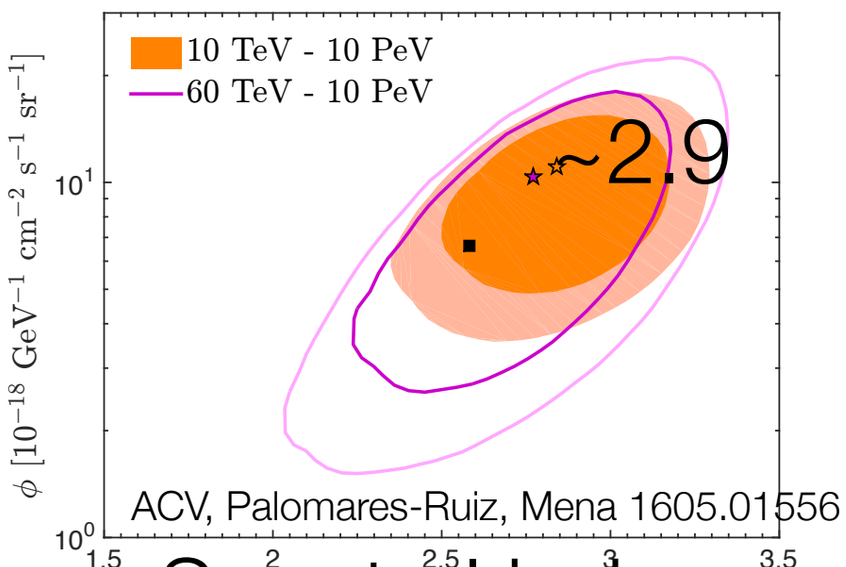


Atmospheric

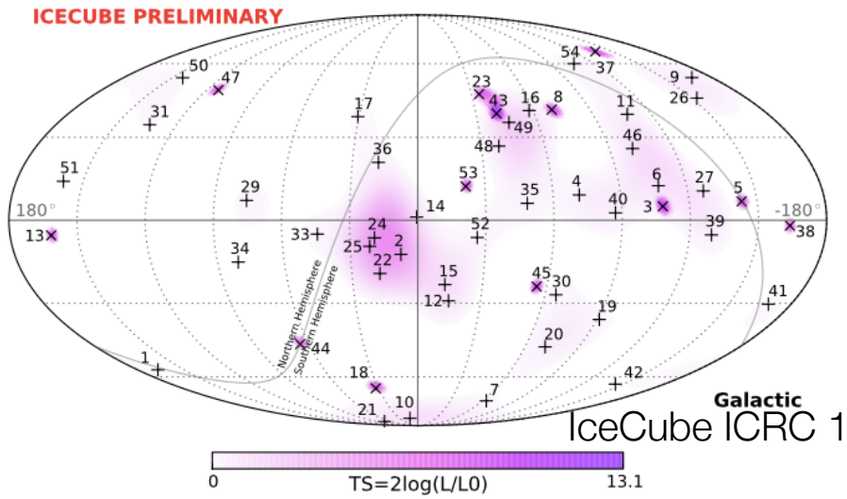
Astrophysical



ACV, Palomares-Ruiz, Mena 1605.01556

Spectral index

Arrival direction



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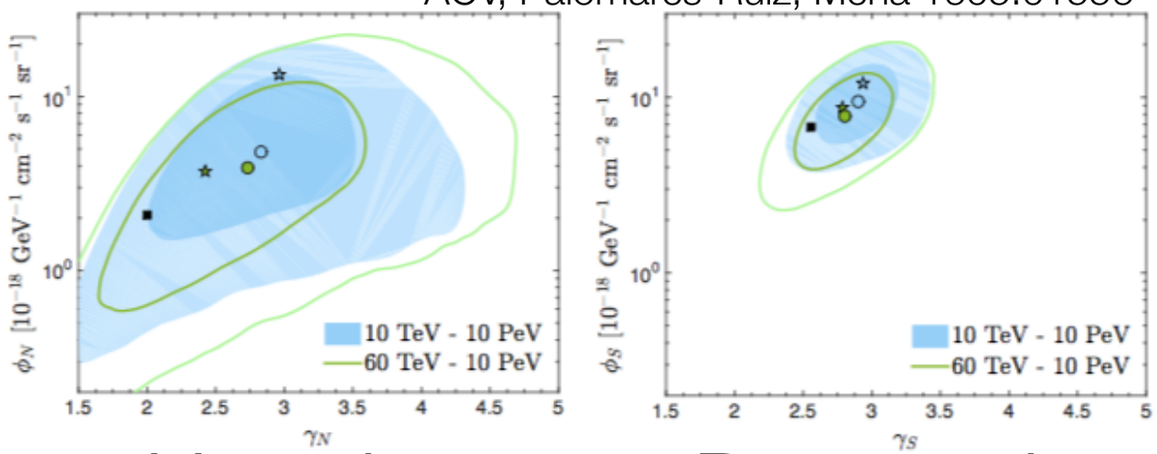


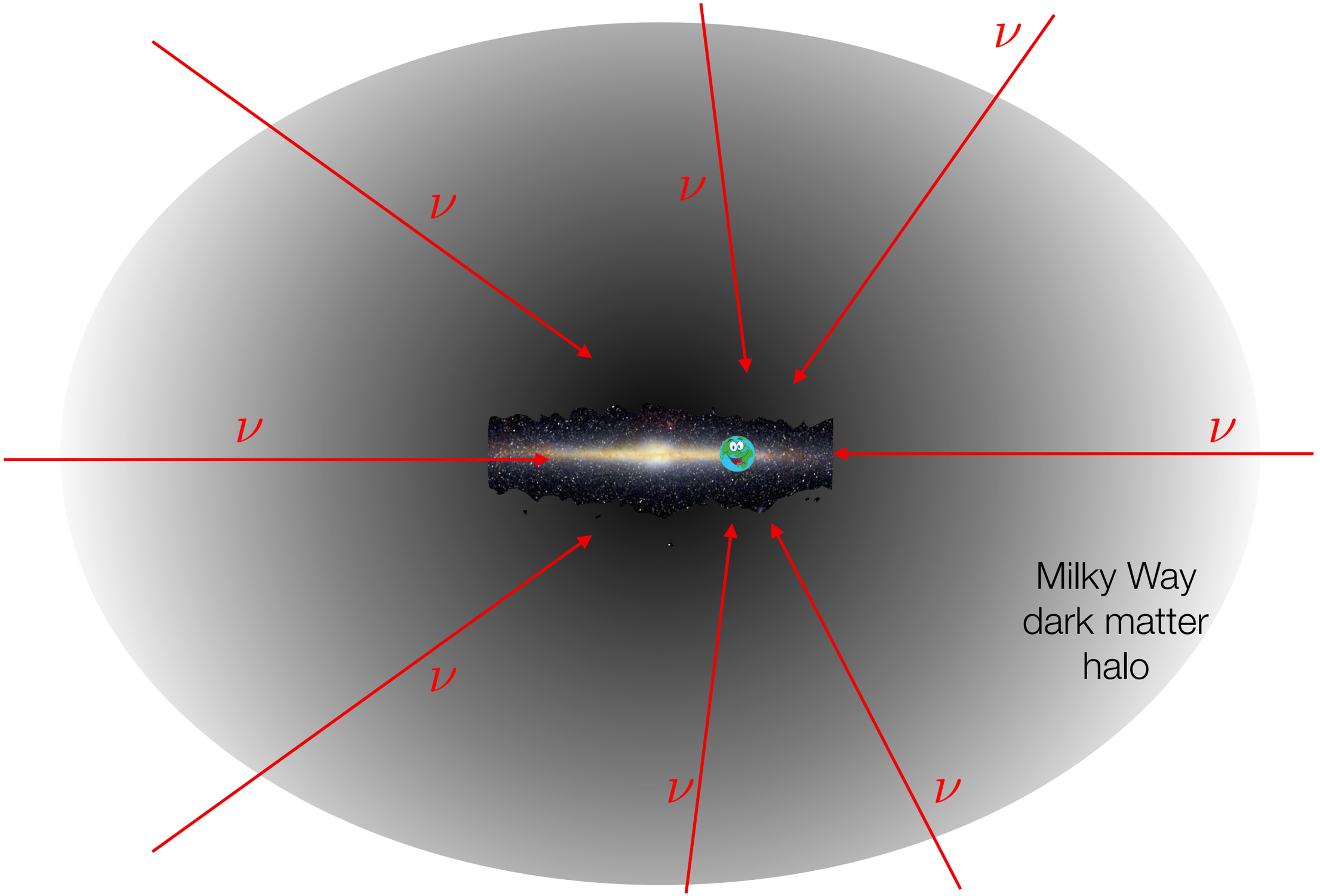
Upgoing

Downgoing

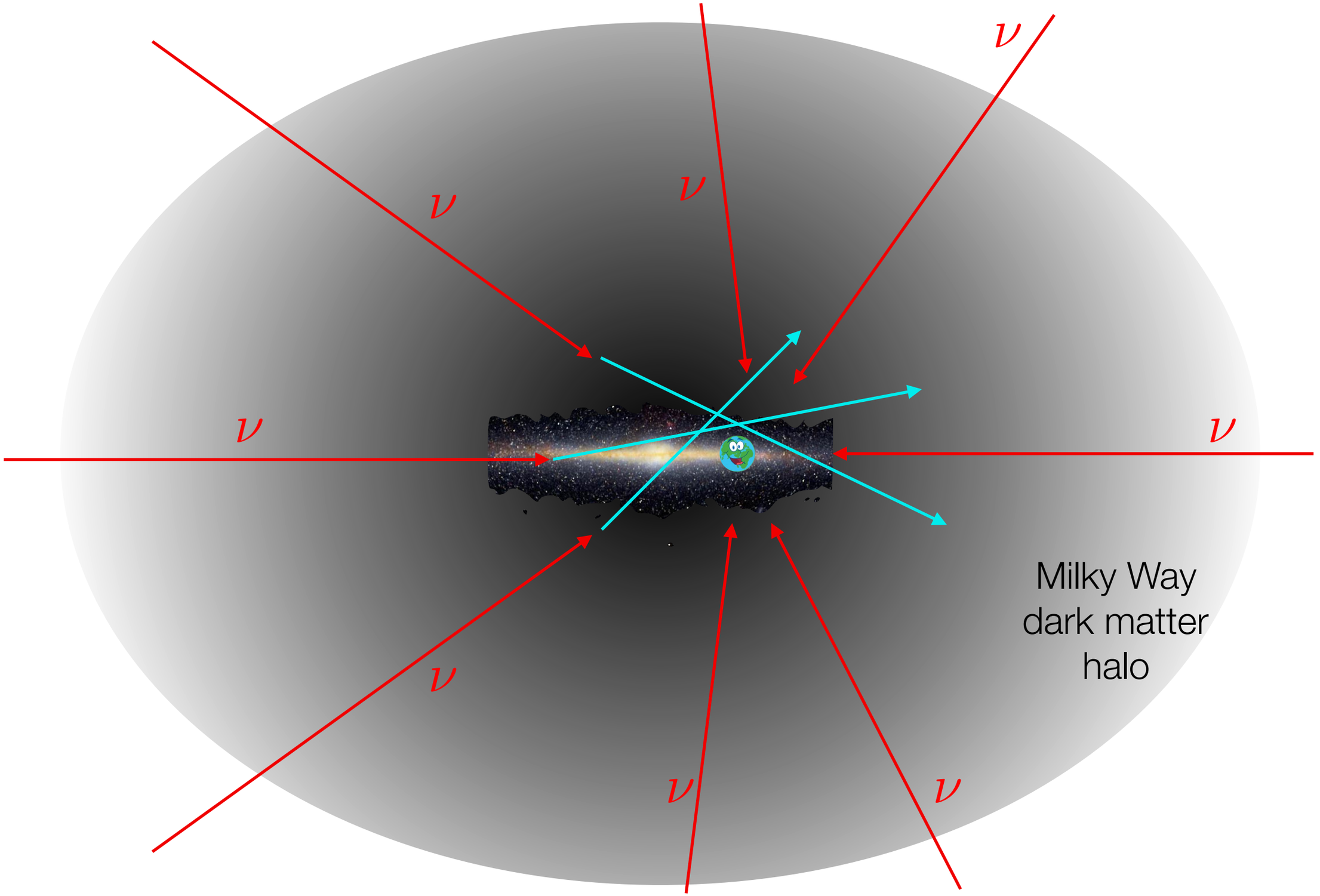
Isotropic arrival

➡ extragalactic

Isotropic extragalactic neutrino flux



Isotropic extragalactic neutrino flux



Anisotropic deflection/energy loss

In practice

b, l: galactic latitude, longitude

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

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

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)

Solve by being clever

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

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

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

λ_i eigenvalues
$\hat{\phi}_i$ eigenvectors

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

Solve by being clever

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λ_i eigenvalues
$\hat{\phi}_i$ eigenvectors

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c_i's determined by initial condition of isotropic power law flux

What about cross section?

$$\sigma_{DM-\nu} \propto E_\nu^2 \xrightarrow[??]{} \left(\frac{\mathrm{PeV}}{T_{\nu,recomb.}}\right)^2 \sim 10^{30}$$

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No!

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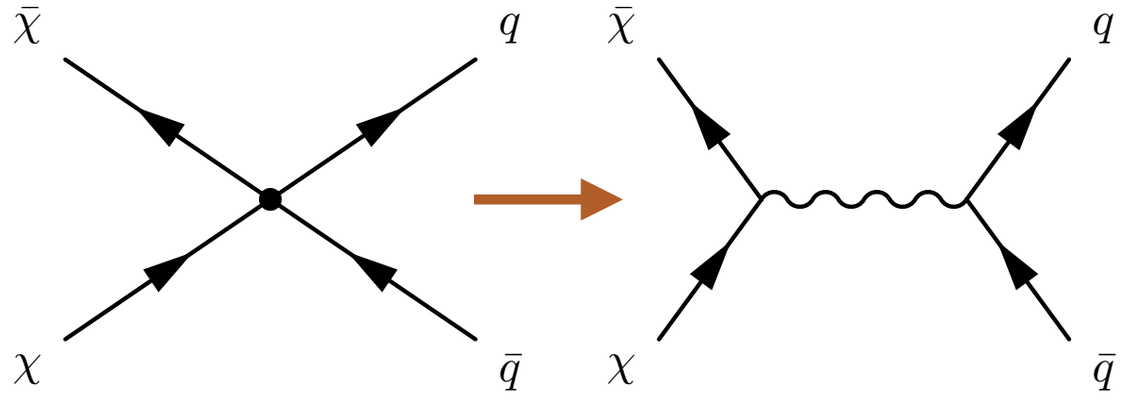
No!

$$E \to \Lambda_{New\,physics}$$

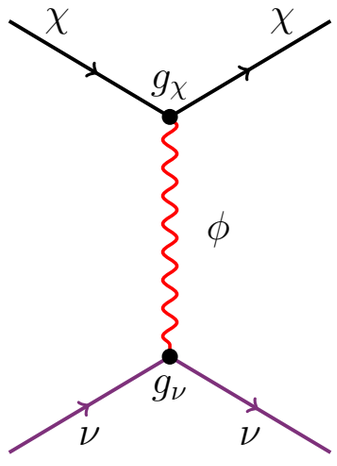


The low energy approximation does not work at a PeV!!

Begin to resolve microphysics: **need more concrete model**

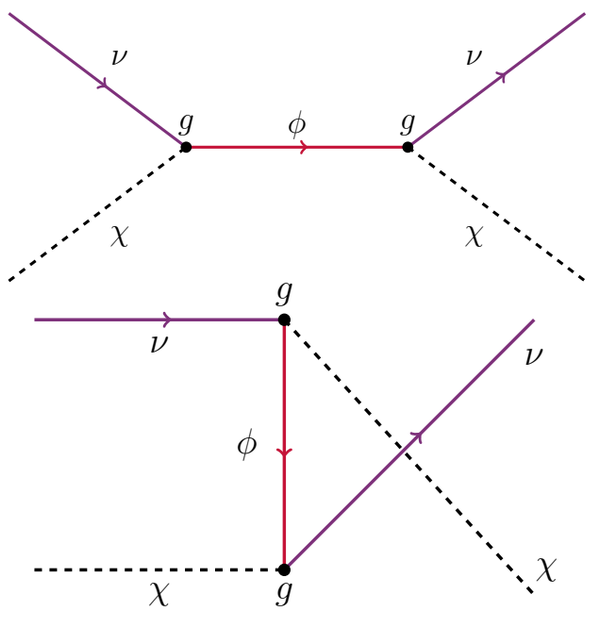
Two fiducial simplified models

1)



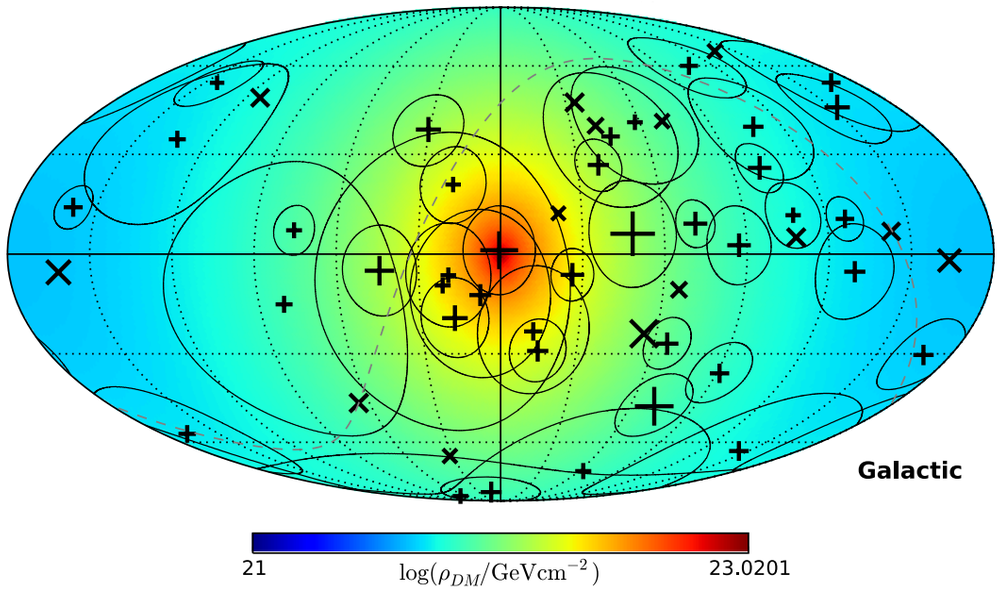
Fermion DM, **vector mediator**: similar to a leptophillic Z' model
Scales strongly with *E*

2)



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

Dark matter column density seen from Earth



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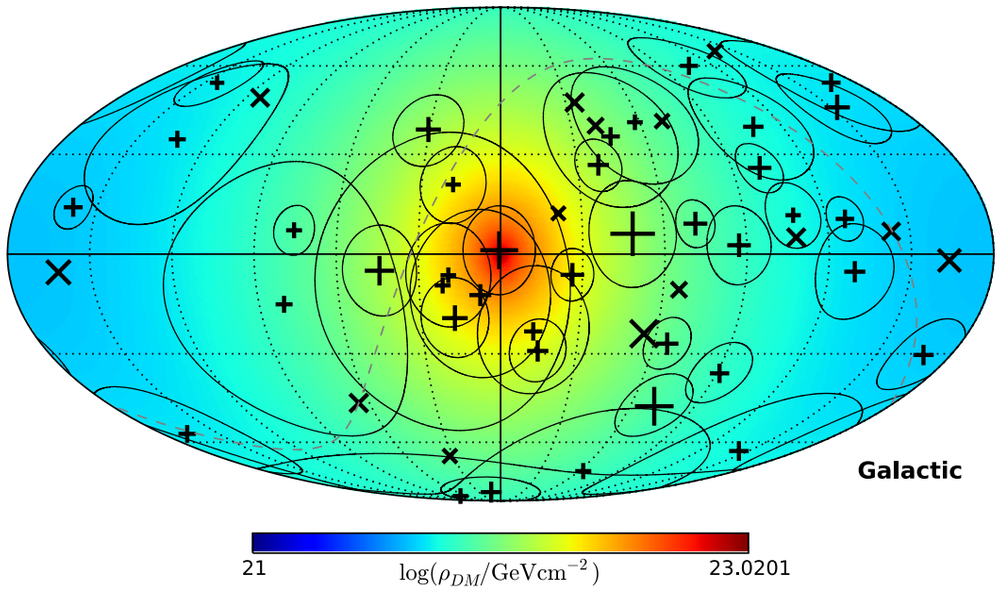
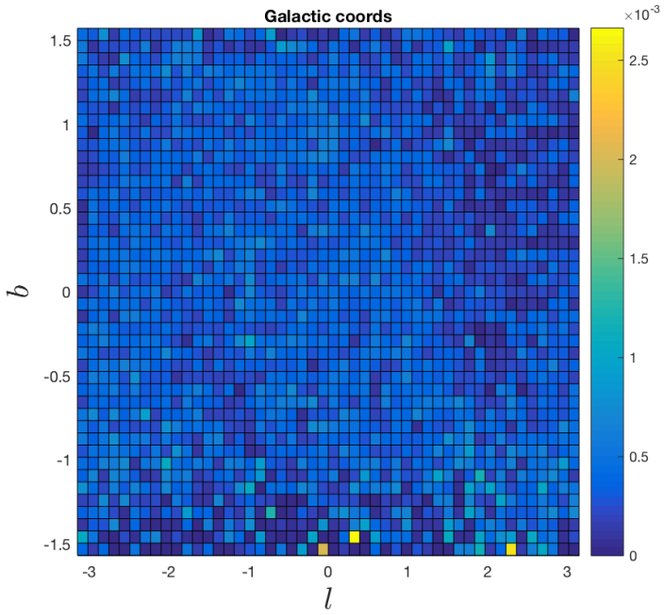
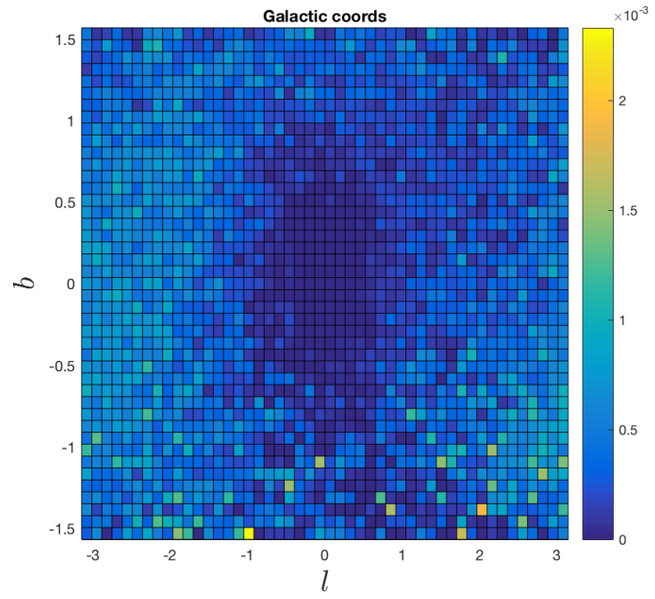


Simulation including effects of detector, Earth

no interaction

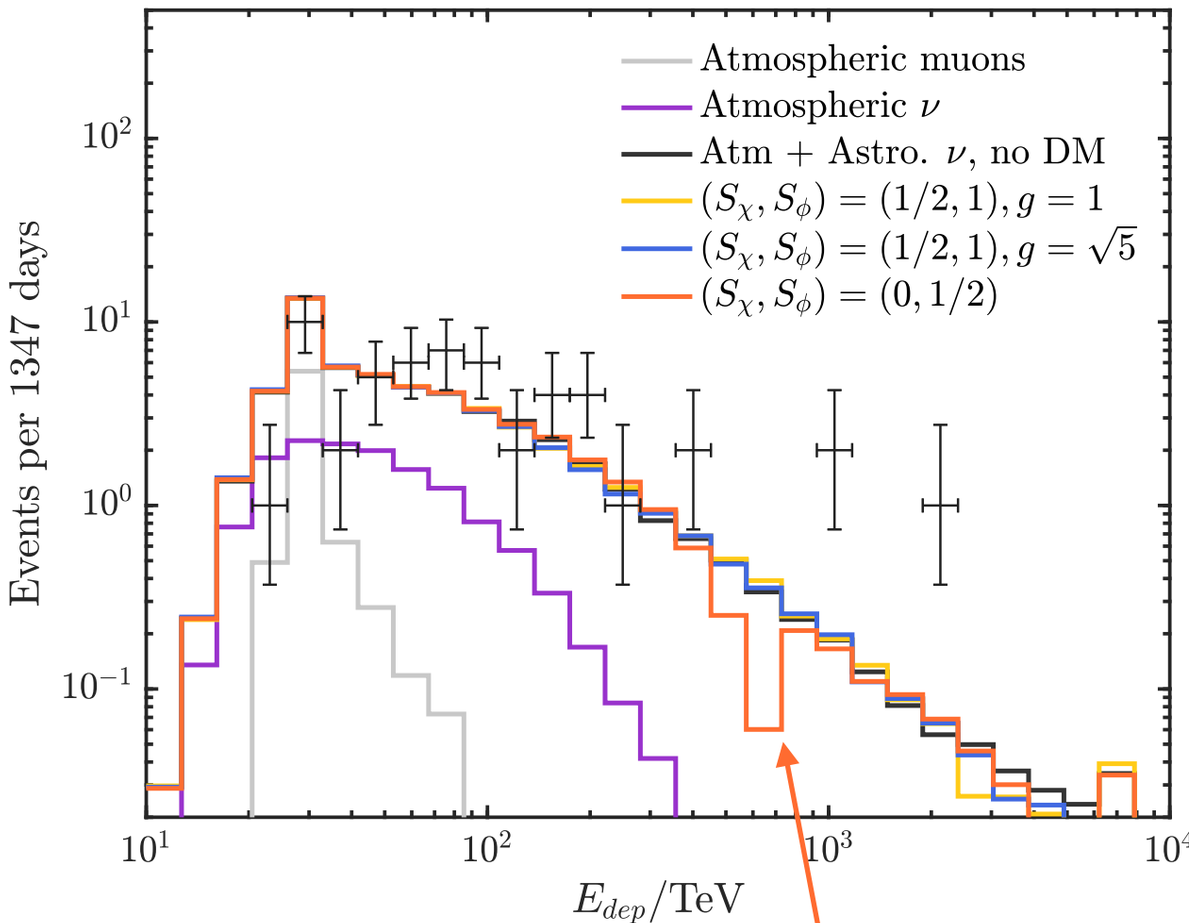


strong interaction



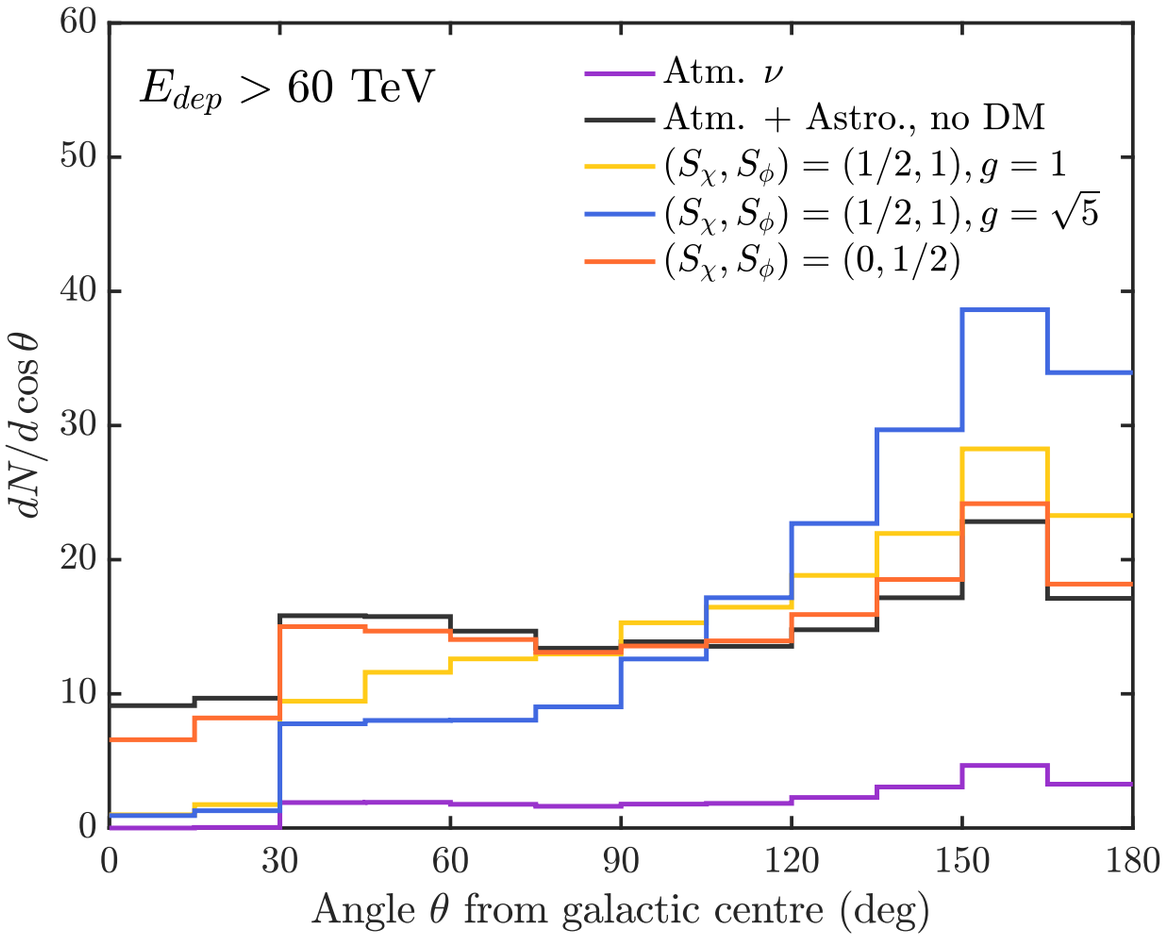
Energy & morphology

Energy



Resonance @ 810 TeV

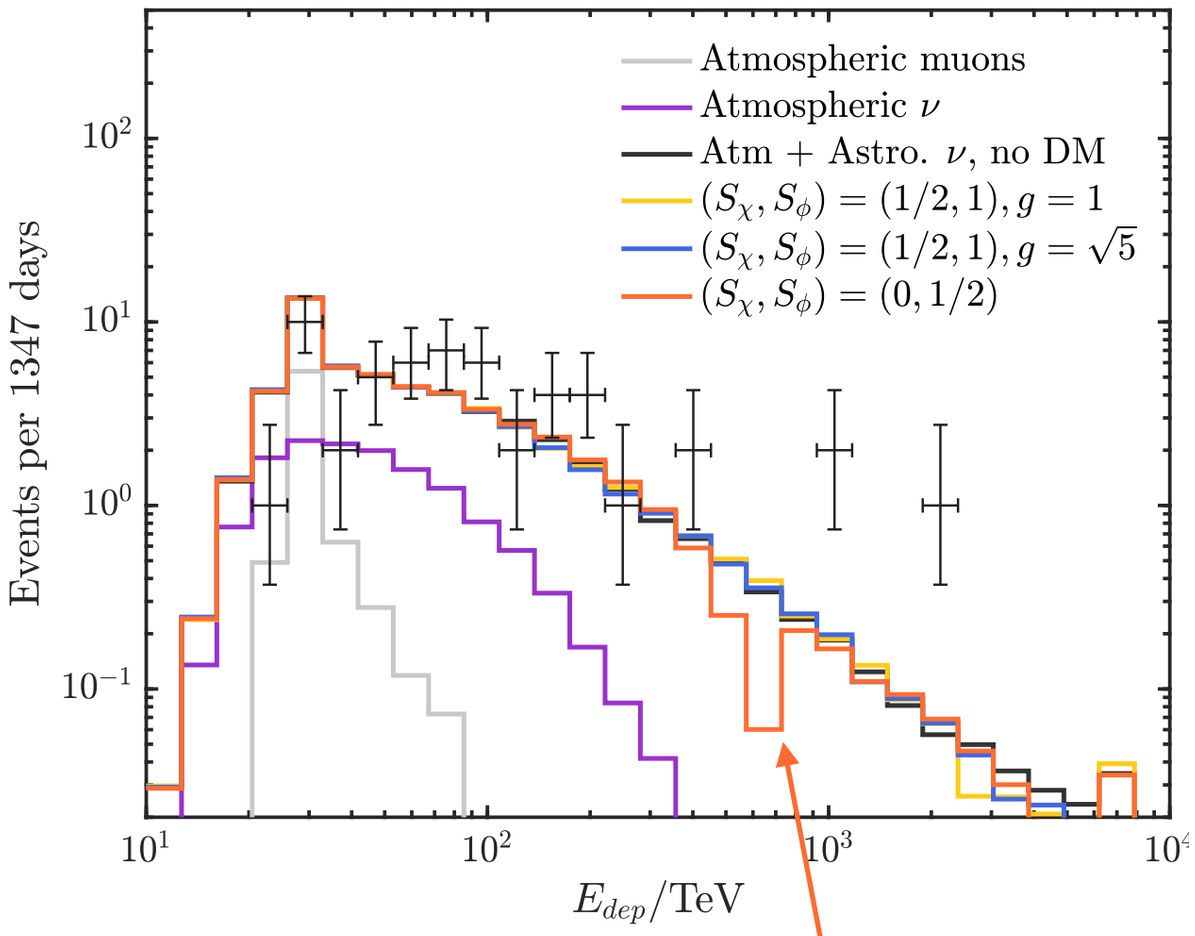
Angle from galactic centre



IceCube HESE events

Energy & morphology

Energy



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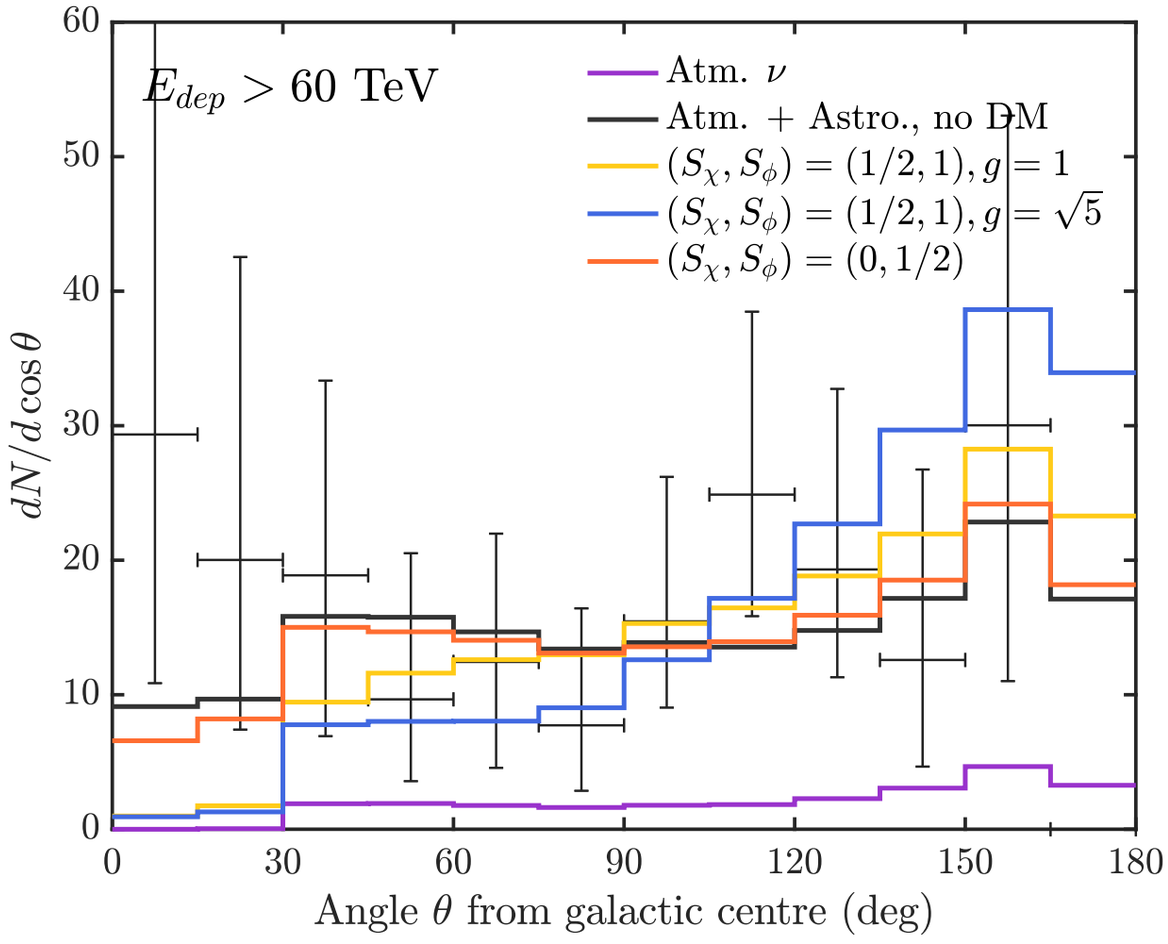
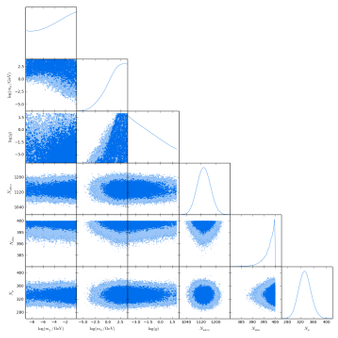


IceCube HESE events

Compare Likelihood to real events

$\ln \mathcal{L}$
$+$

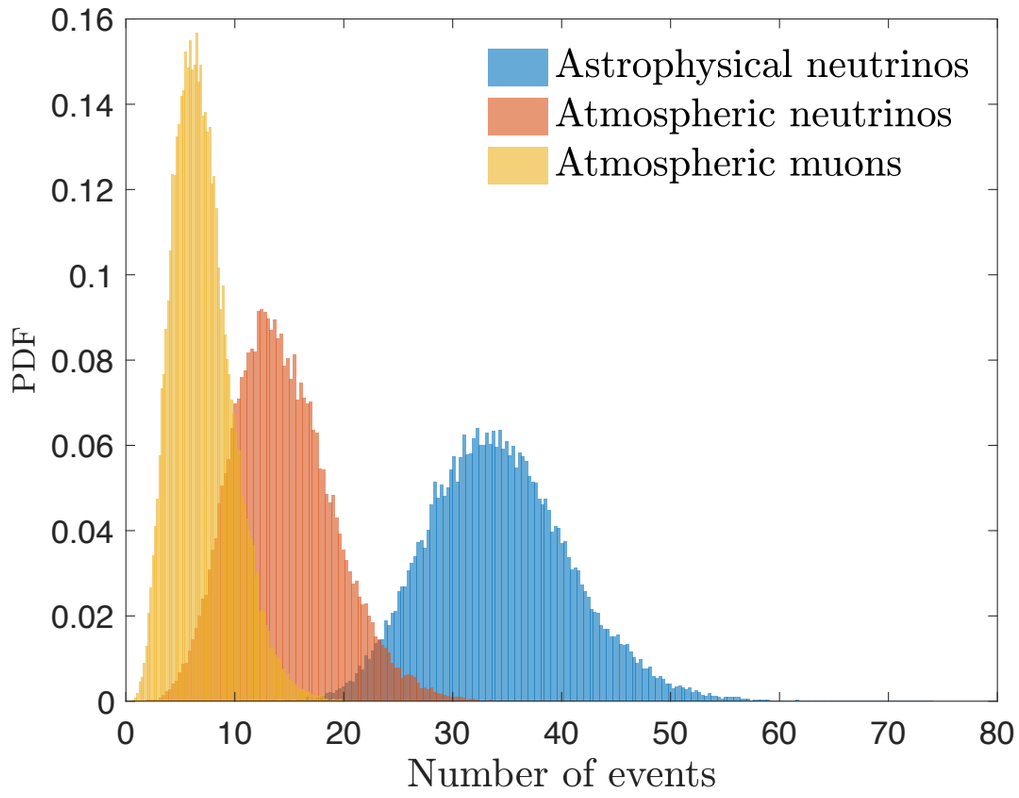
$*$



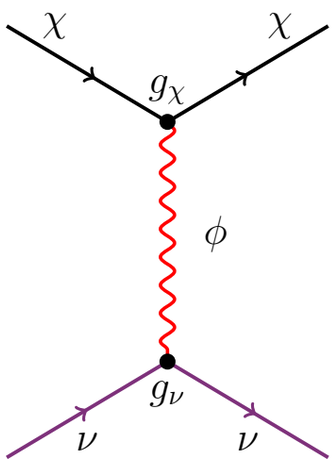
$$\mathcal{L}(\{t, E, \vec{x}\}|\vartheta) = e^{-\sum_b N_b} \prod_{i=1}^{N_{obs}} \sum_a N_a P_a(t_i, E_i, \vec{x}_i|\vartheta).$$

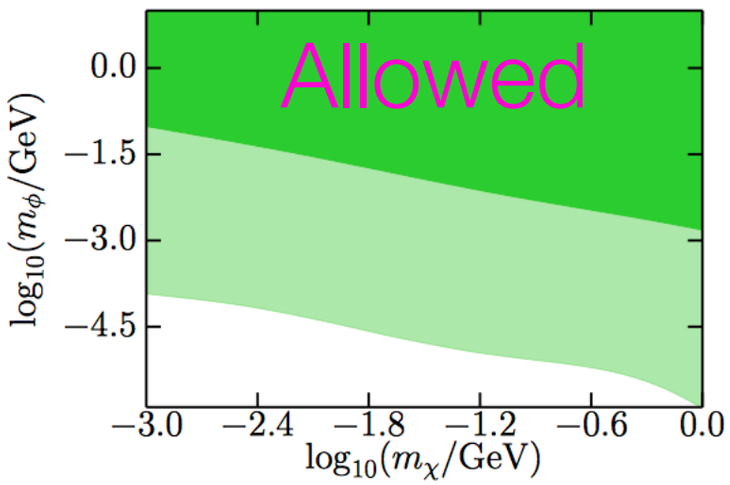
Parameters:

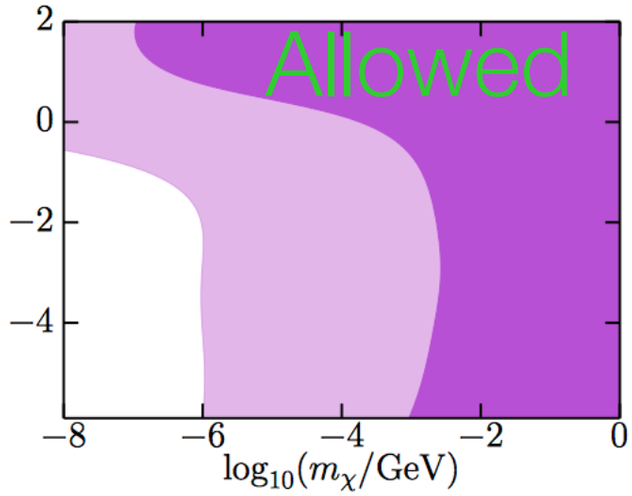
$$m_\chi \; m_\phi \; g \; N_{astro} \; N_{atmo} \; N_{\mu\pm}$$

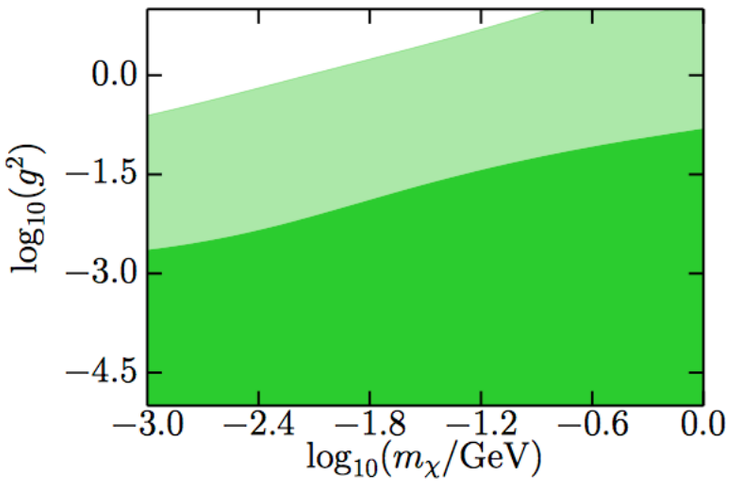


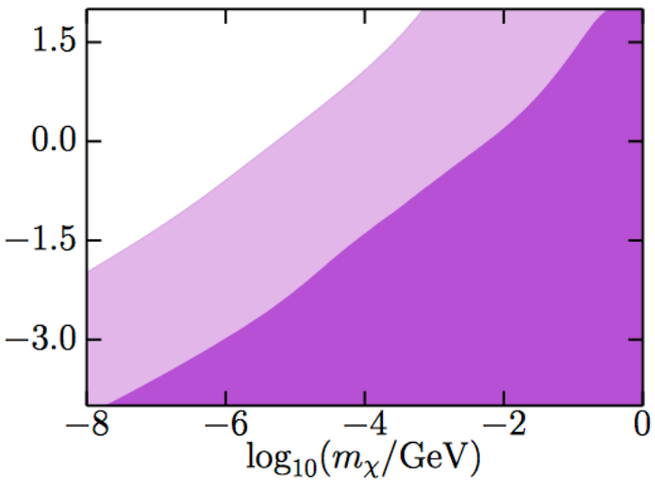
*IceCube data

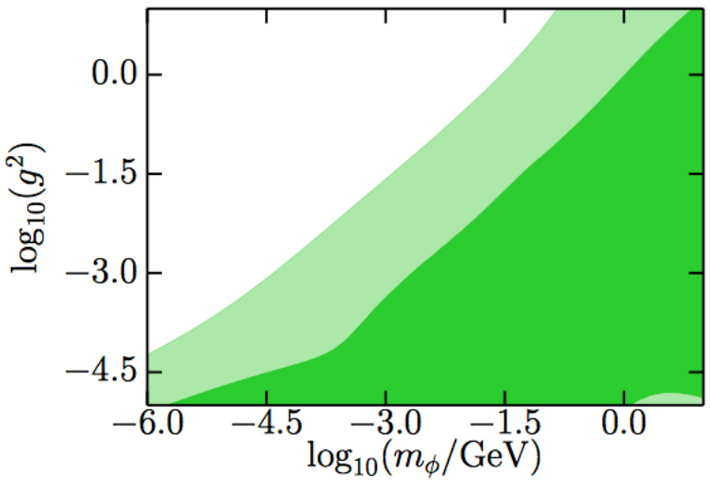

χ
χ
g_χ
ϕ
g_ν
ν
ν

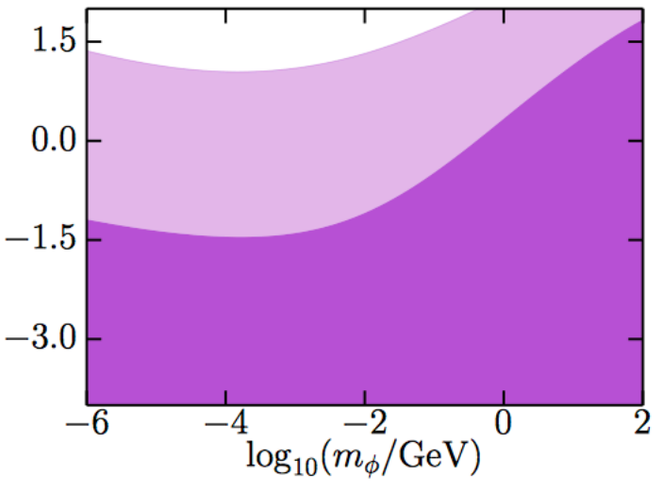

Allowed
$\log_{10}(m_\phi/\mathrm{GeV})$
0.0
−1.5
−3.0
−4.5
−3.0
−2.4
−1.8
−1.2
−0.6
0.0
$\log_{10}(m_\chi/\mathrm{GeV})$

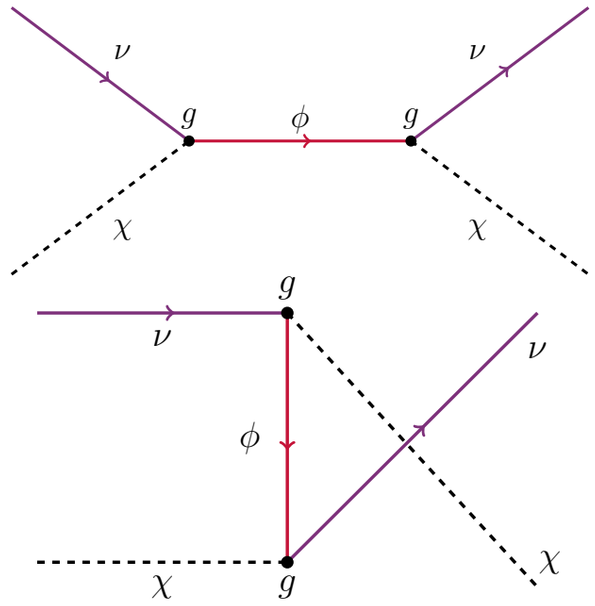

Allowed
2
0
−2
−4
−8
−6
−4
−2
0
$\log_{10}(m_\chi/\mathrm{GeV})$


0.0
−1.5
−3.0
−4.5
$\log_{10}(g^2)$
−3.0
−2.4
−1.8
−1.2
−0.6
0.0
$\log_{10}(m_\chi/\mathrm{GeV})$


1.5
0.0
−1.5
−3.0
−8
−6
−4
−2
0
$\log_{10}(m_\chi/\mathrm{GeV})$

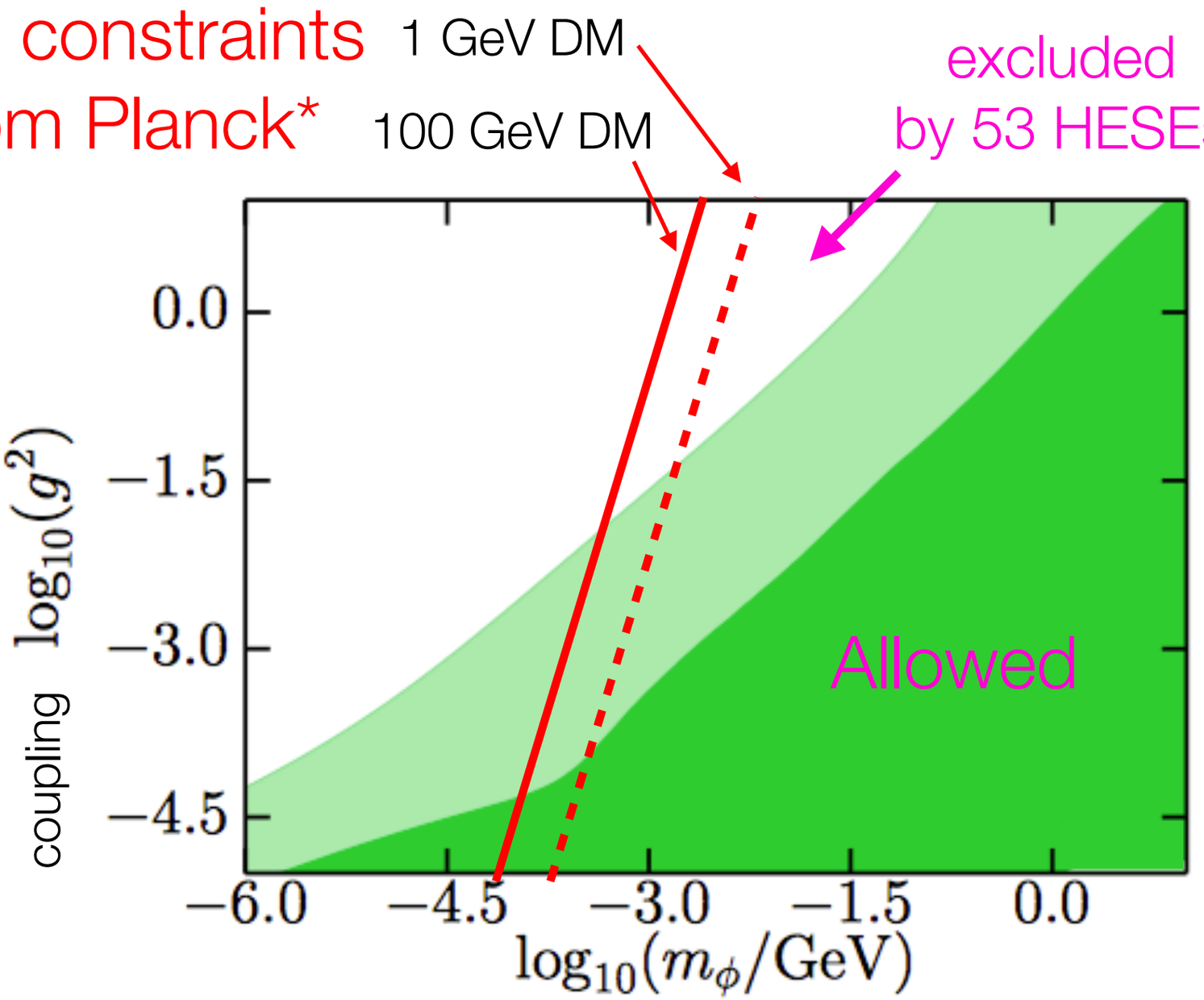

0.0
−1.5
−3.0
−4.5
$\log_{10}(g^2)$
−6.0
−4.5
−3.0
−1.5
0.0
$\log_{10}(m_\phi/\mathrm{GeV})$


1.5
0.0
−1.5
−3.0
−6
−4
−2
0
2
$\log_{10}(m_\phi/\mathrm{GeV})$

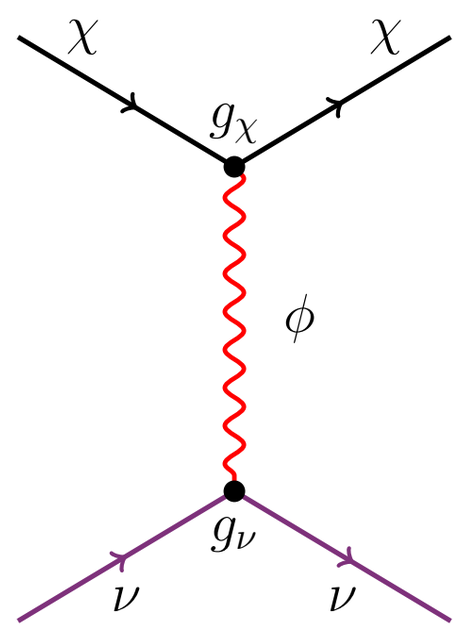

ν
g
ϕ
g
ν
χ
χ
g
ν
ν
ϕ
χ
g
χ

New limits on dark force carriers

Best constraints from Planck*



log mediator mass



* + LSS, see Escudero, … Vincent 2016

Summary

- No reason to believe DM-neutrino interactions aren't there

- Isotropy of the signal can be used to constrain such interactions

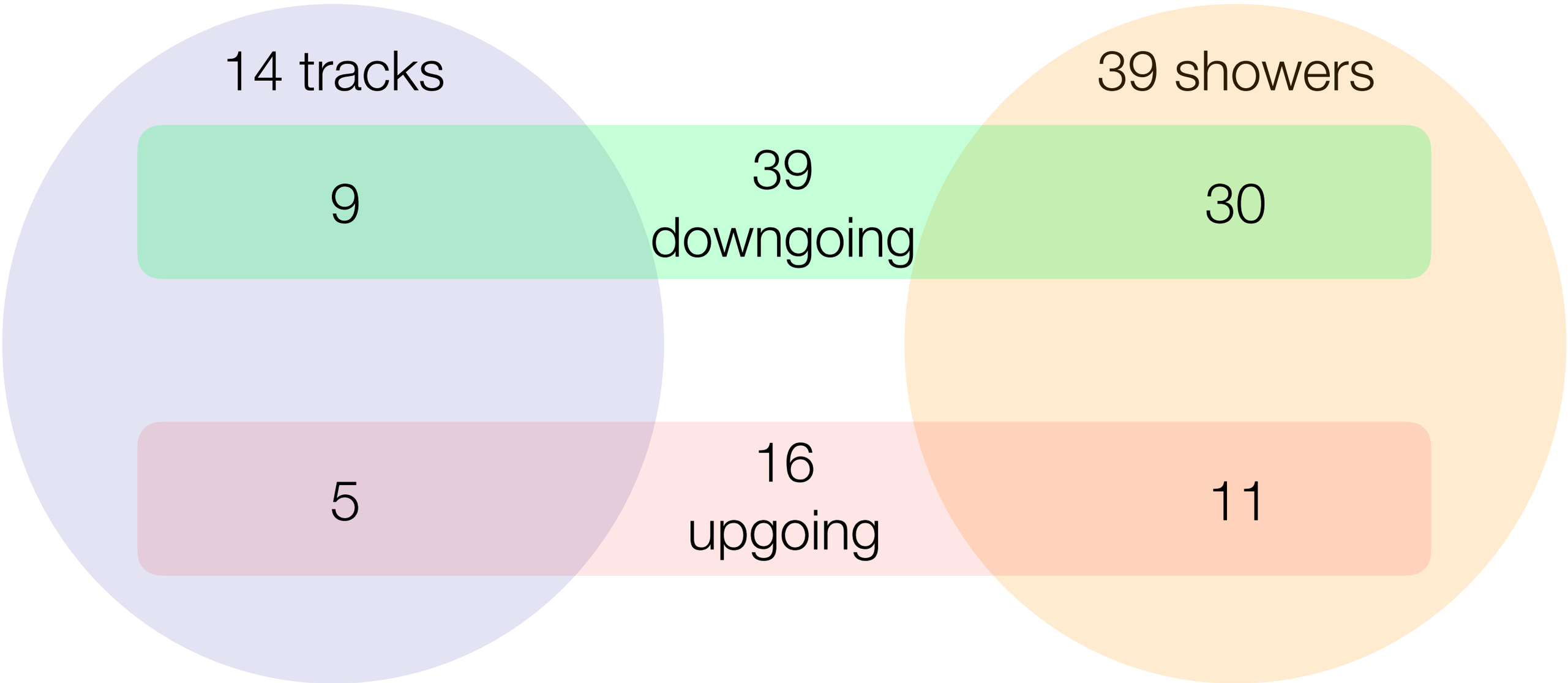
- Can even do better than cosmology in some ranges, mainly 1-100 MeV

- Need more stats —> forecasts for Gen2 & more to come

Thank you

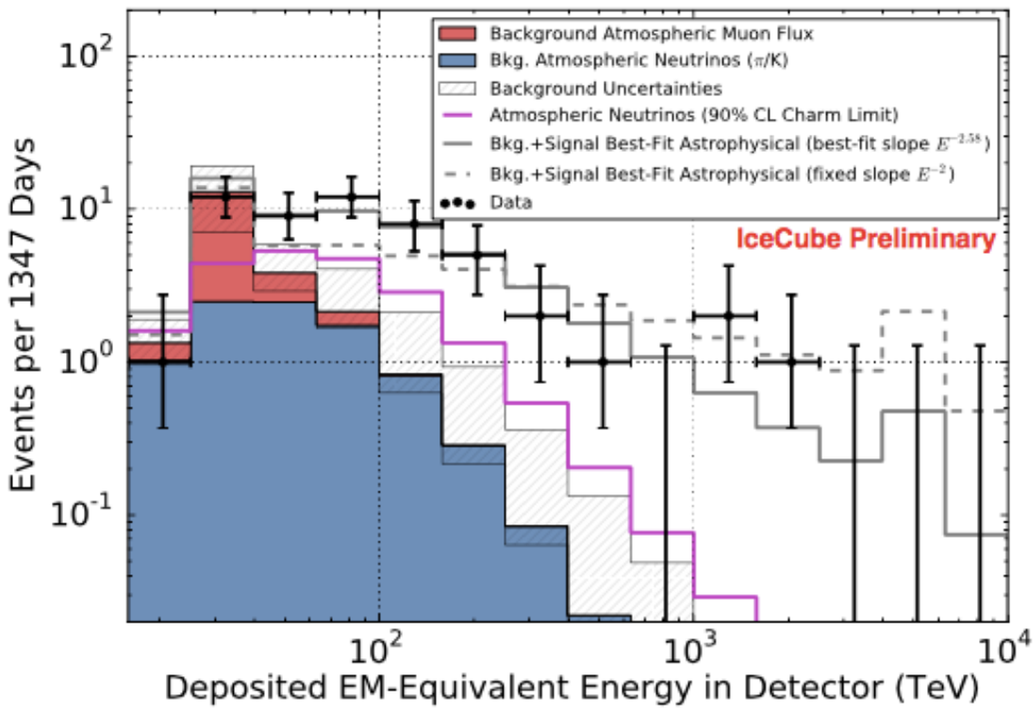
Four-year HESE sample

53 events



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