The dark side of neutrinos

Aaron Vincent

DESY Theory Meeting
Hamburg Sep. 27 2017

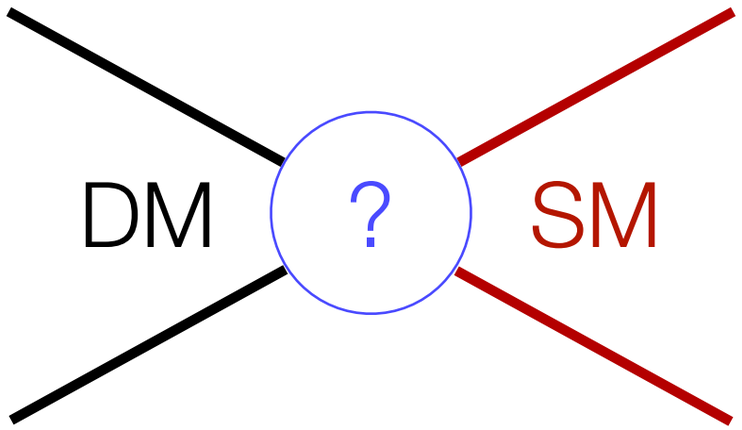
Imperial College London

Based on

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

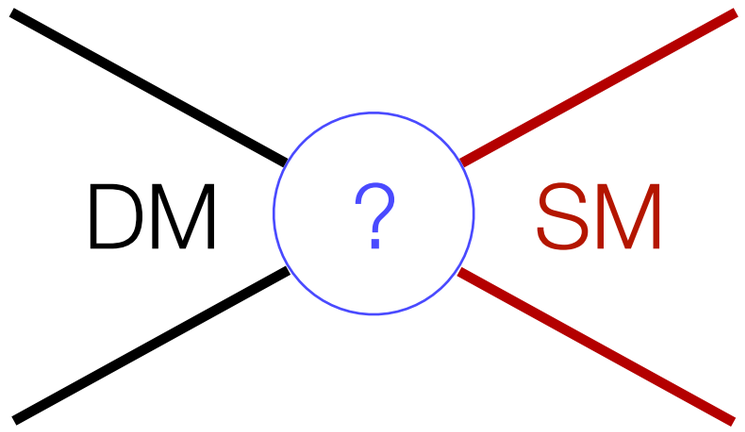
Also *νFATE*: neutrino fast attenuation through earth 1706.09895

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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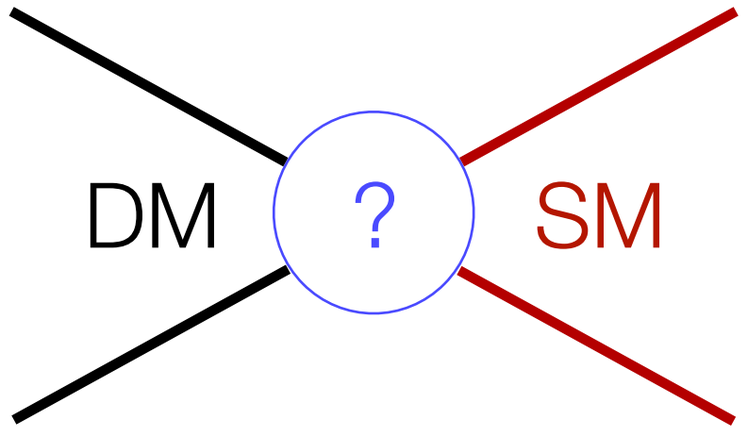

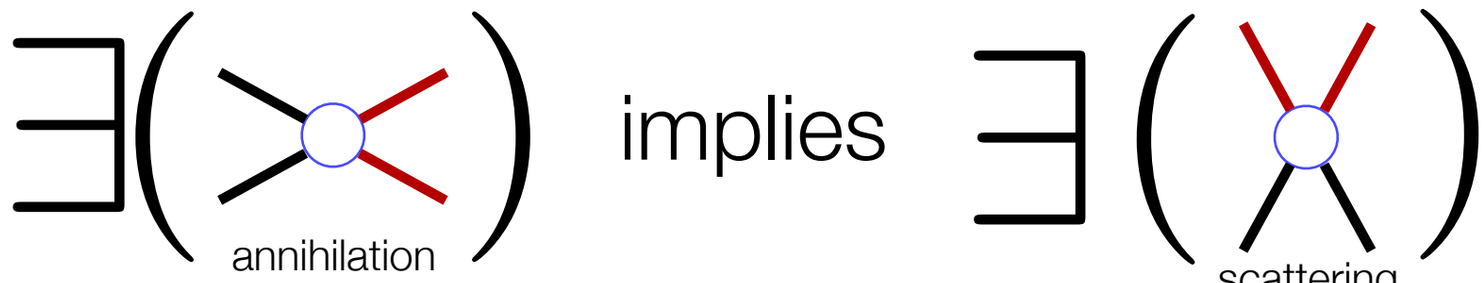

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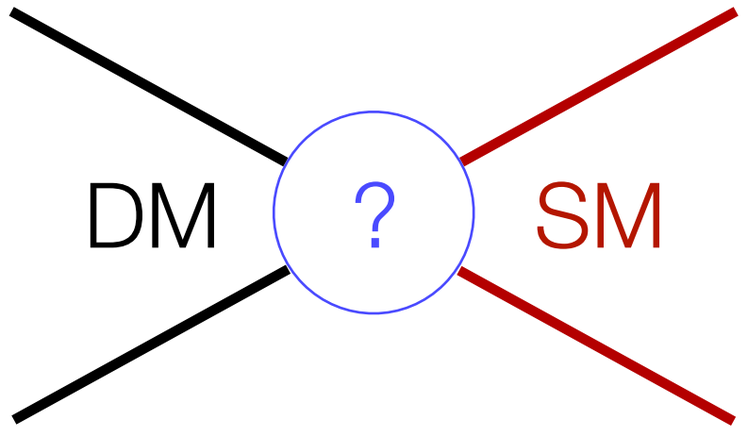
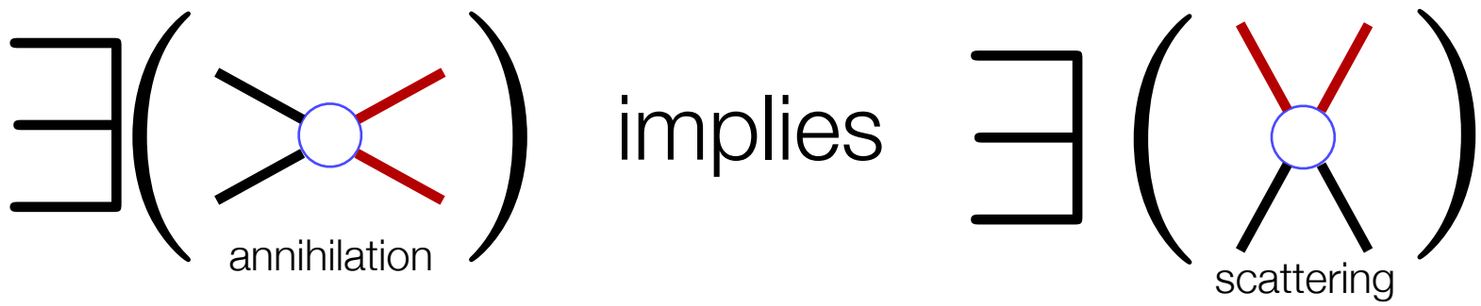
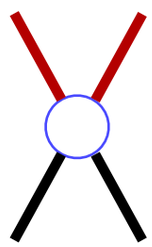




if —— = quarks, then  = direct detection
(LUX, LZ, SuperCDMS, …)

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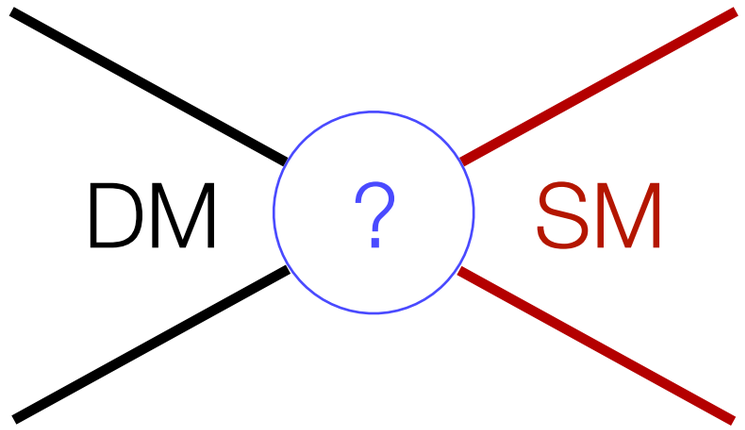
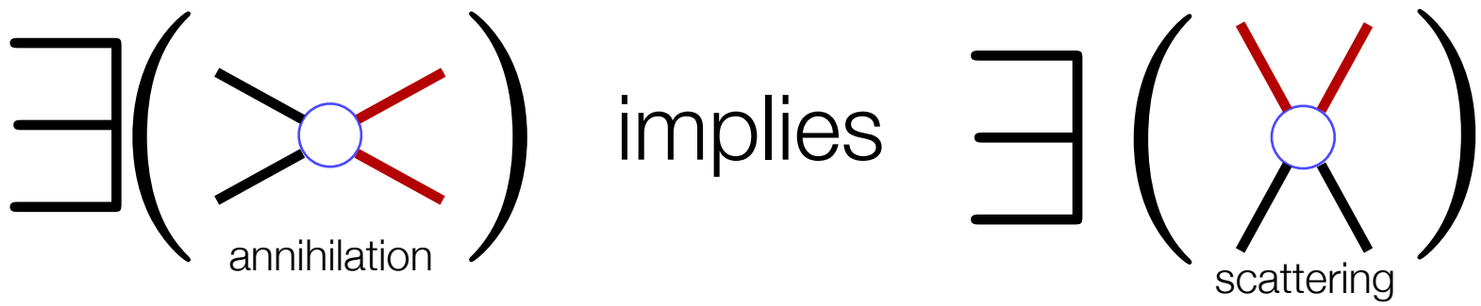
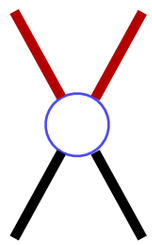




if —— = quarks, then  = direct detection
(LUX, LZ, SuperCDMS, …)

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

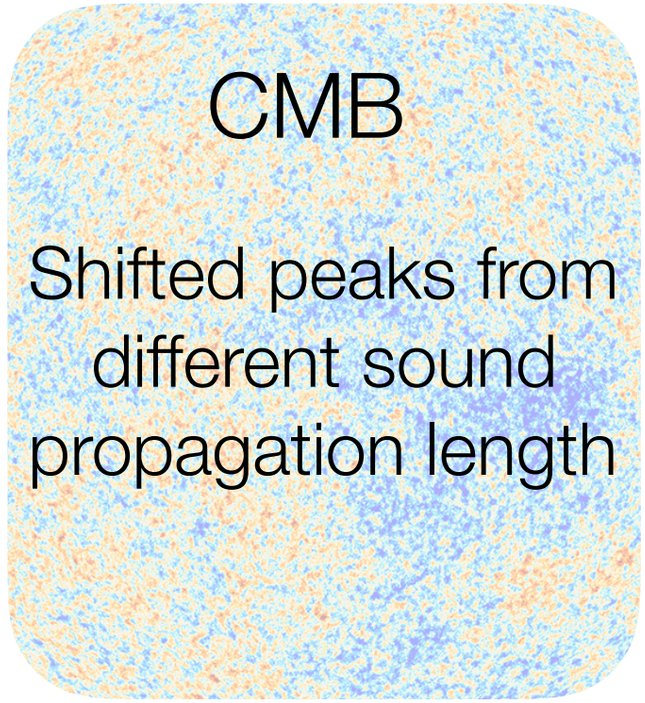
[1] C. Boehm, P. Fayet, and R. Schaeffer, Phys.Lett. **B518**, 8 (2001), arXiv:astro-ph/0012504 [astro-ph].
[2] C. Boehm, A. Riazuelo, S. H. Hansen, and R. Schaeffer, Phys.Rev. **D66**, 083505 (2002), arXiv:astro-ph/0112522 [astro-ph].
[3] C. Boehm and R. Schaeffer, Astron.Astrophys. **438**, 419 (2005), 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

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BBN

neutrons less boltzmann suppressed at FO: more D, He

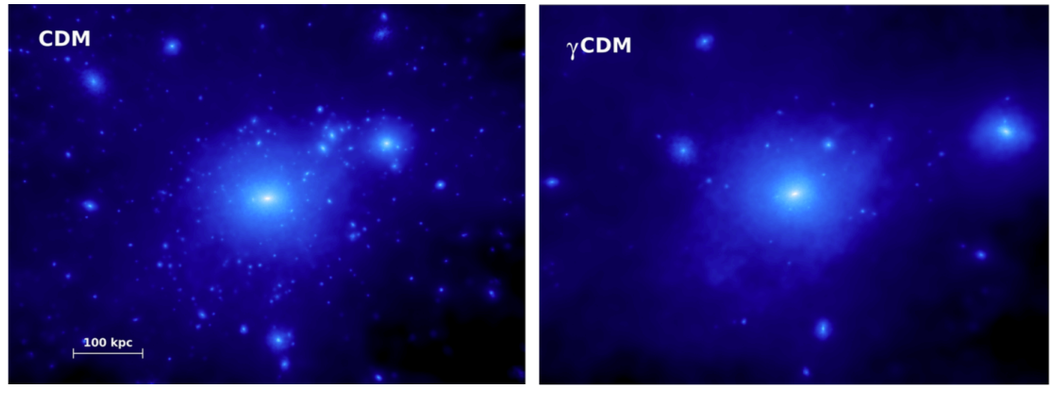
CMB

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

DM-neutrino interactions: cosmology (I)

DM dump E into neutrino sector:

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

faster expansion during and after BBN

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Faster expansion:
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can form more Deuterium, helium
2) During recombination: acoustic peaks are shifted since sound propagation changed

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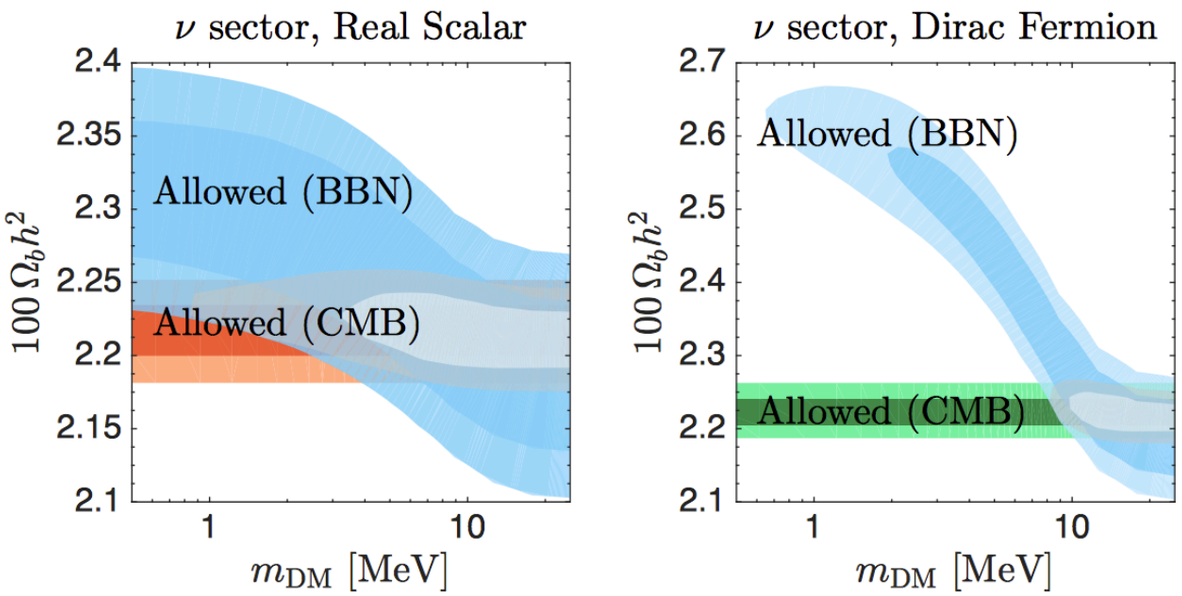
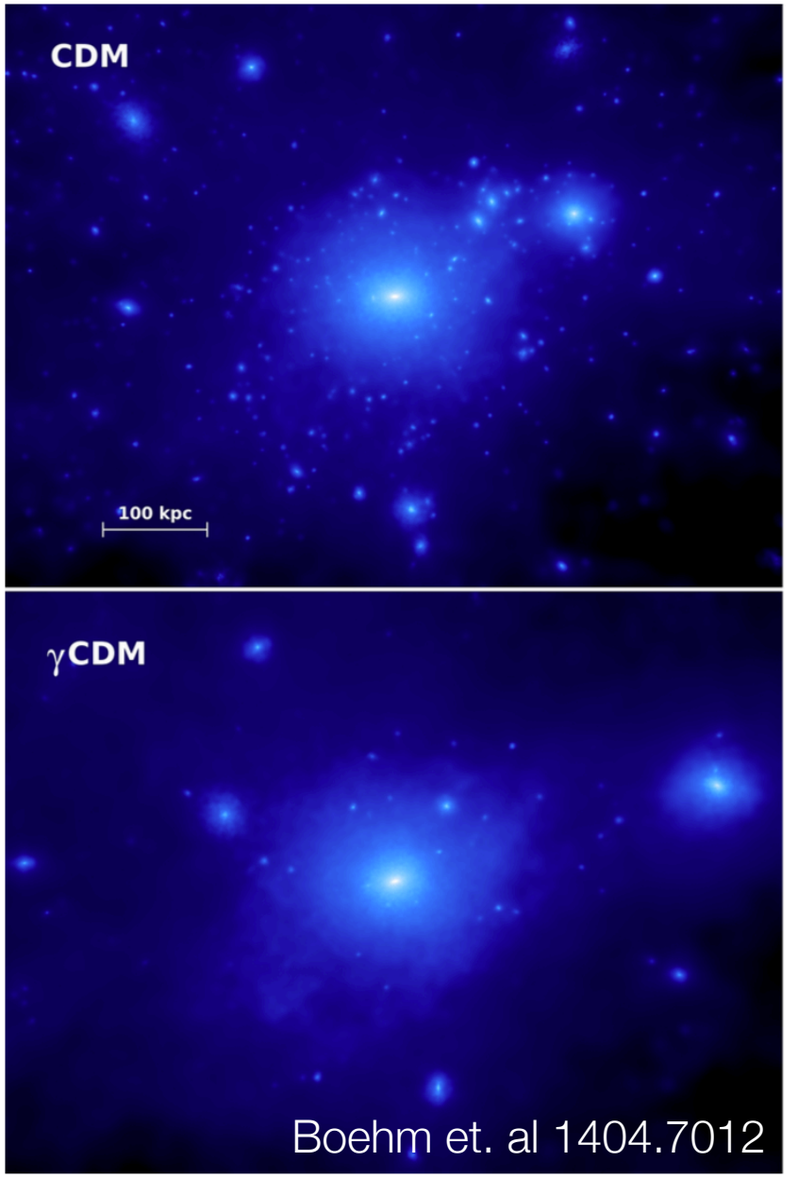


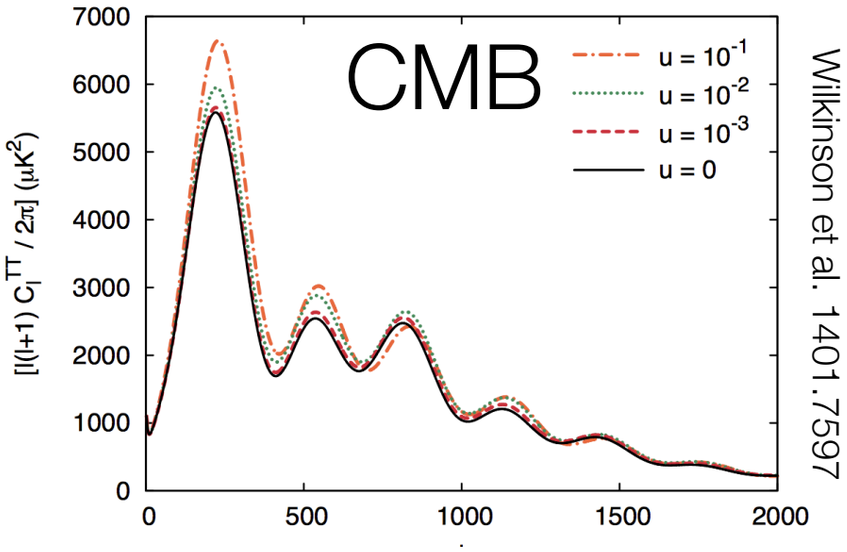
R. Wilkinson, ACV, C. Boehm, C. McCabe 1602.01114

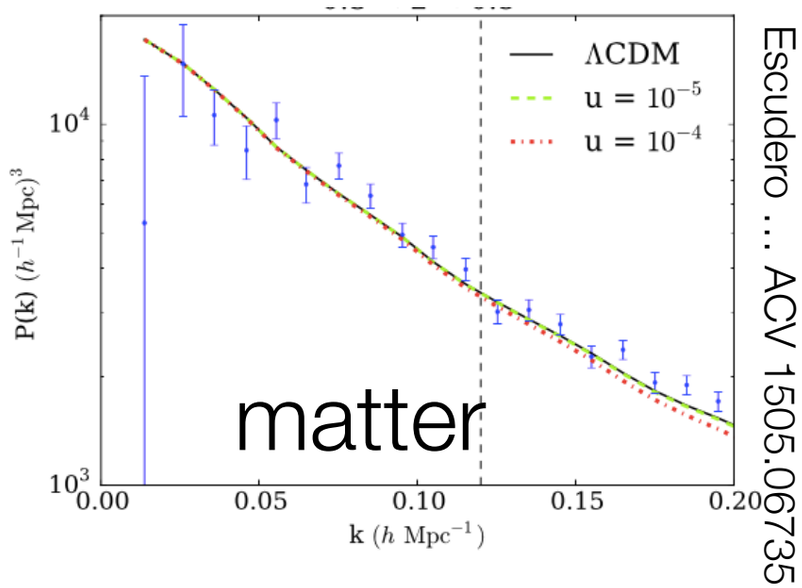
$$m_\chi \gtrsim 5 - 10\text{MeV}$$

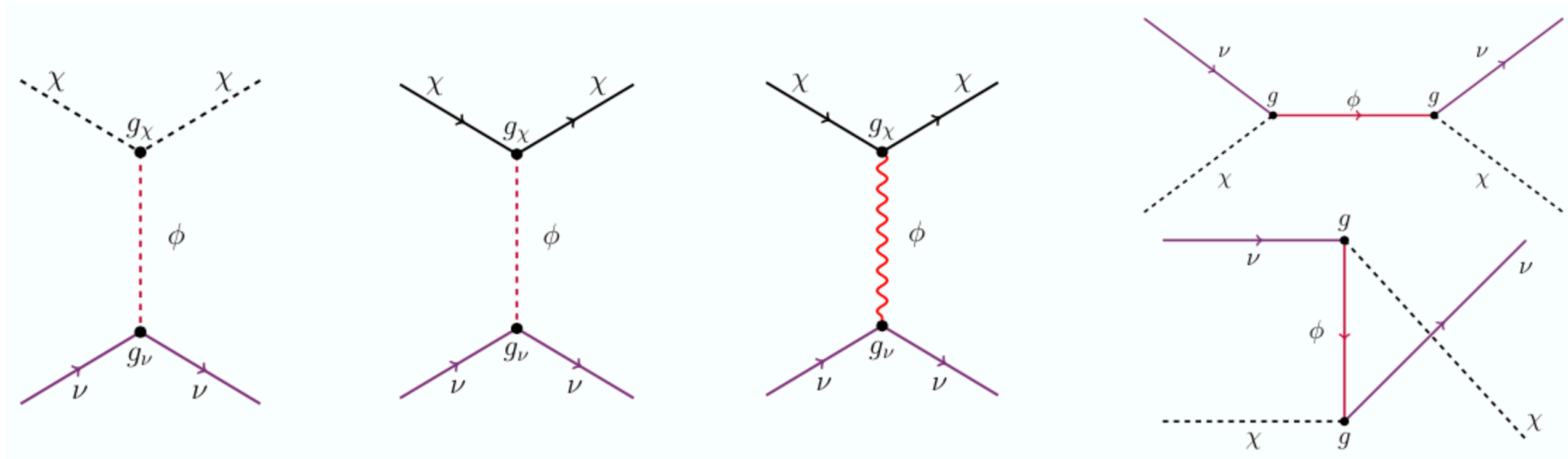
DM-neutrino interactions: cosmology (II)

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









Generic scattering cross section:

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

Perturbation damping limits:

1) $\sigma \to const.$

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

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

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

Escudero+ACV++

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

Mangano 2006 + many others

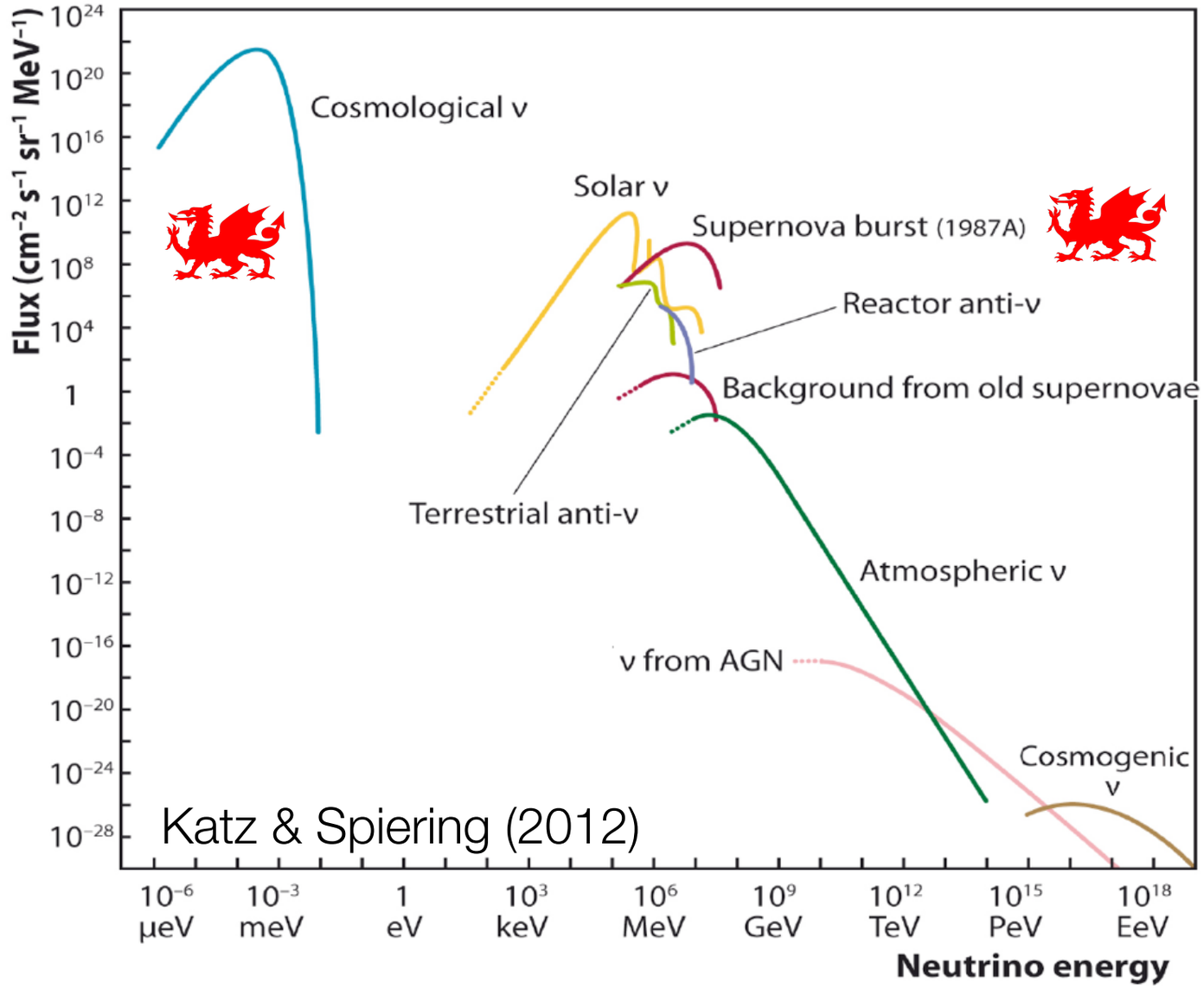
$$\sigma_{DM-\nu} \propto E_\nu^2$$

IceCube has seen events above a PeV….

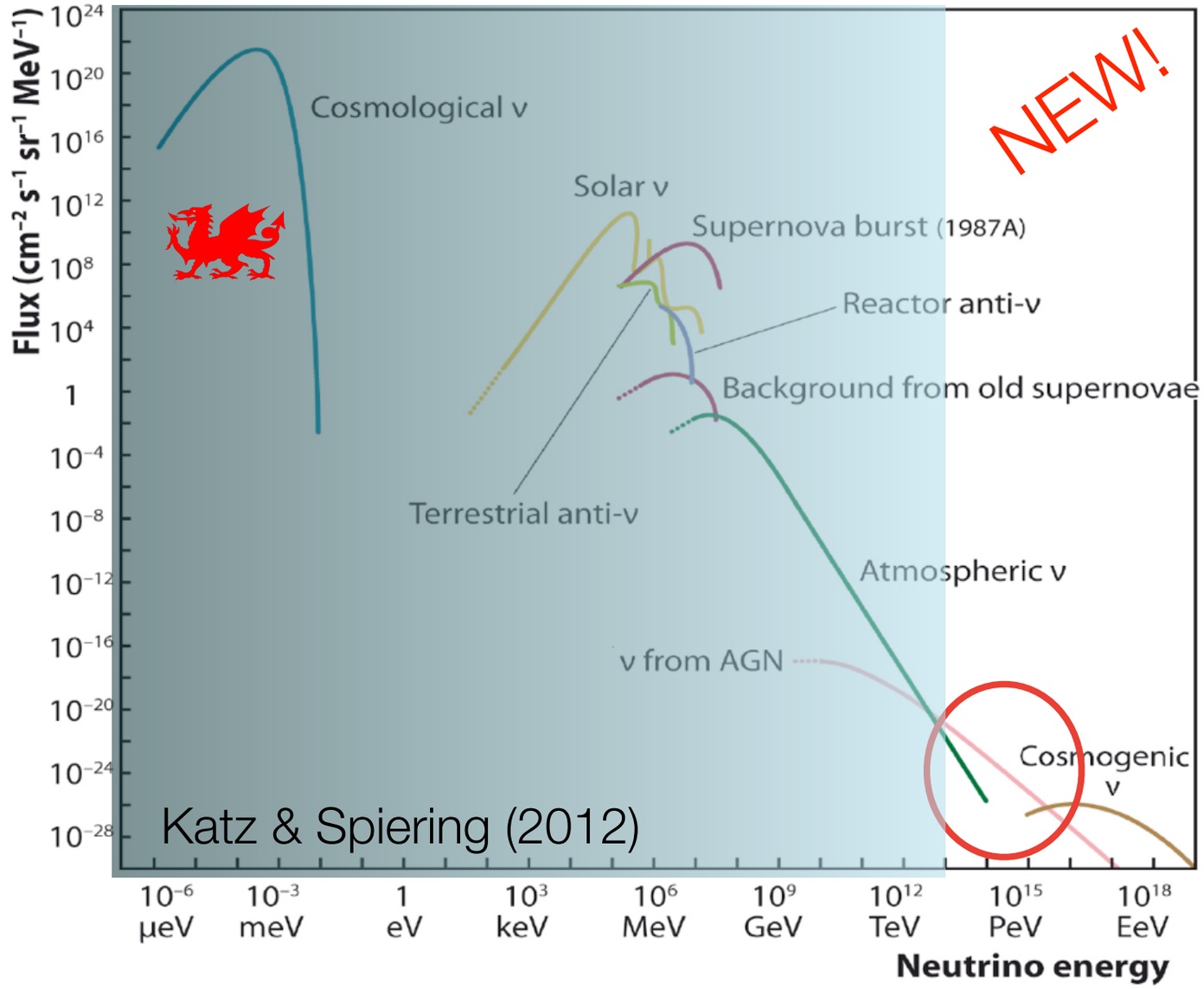
$$\left(\frac{\mathrm{PeV}}{T_{\nu,recomb.}}\right)^2 \sim 10^{30}$$

Let’s look there!

Neutrinos


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Katz & Spiering (2012)
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

Neutrinos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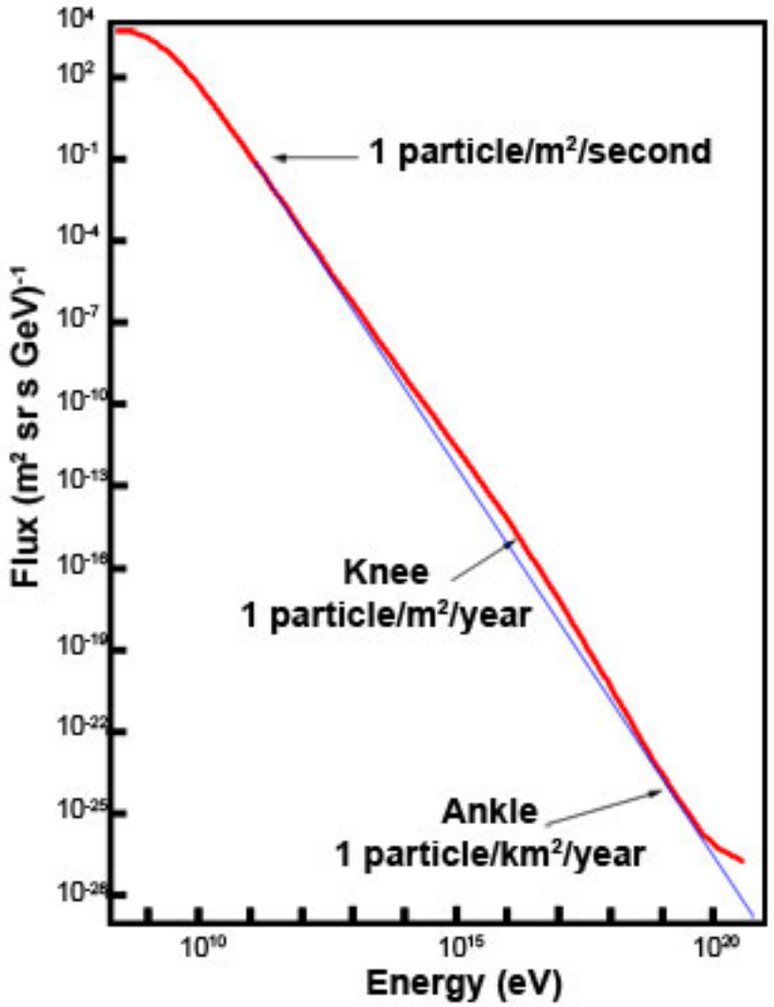
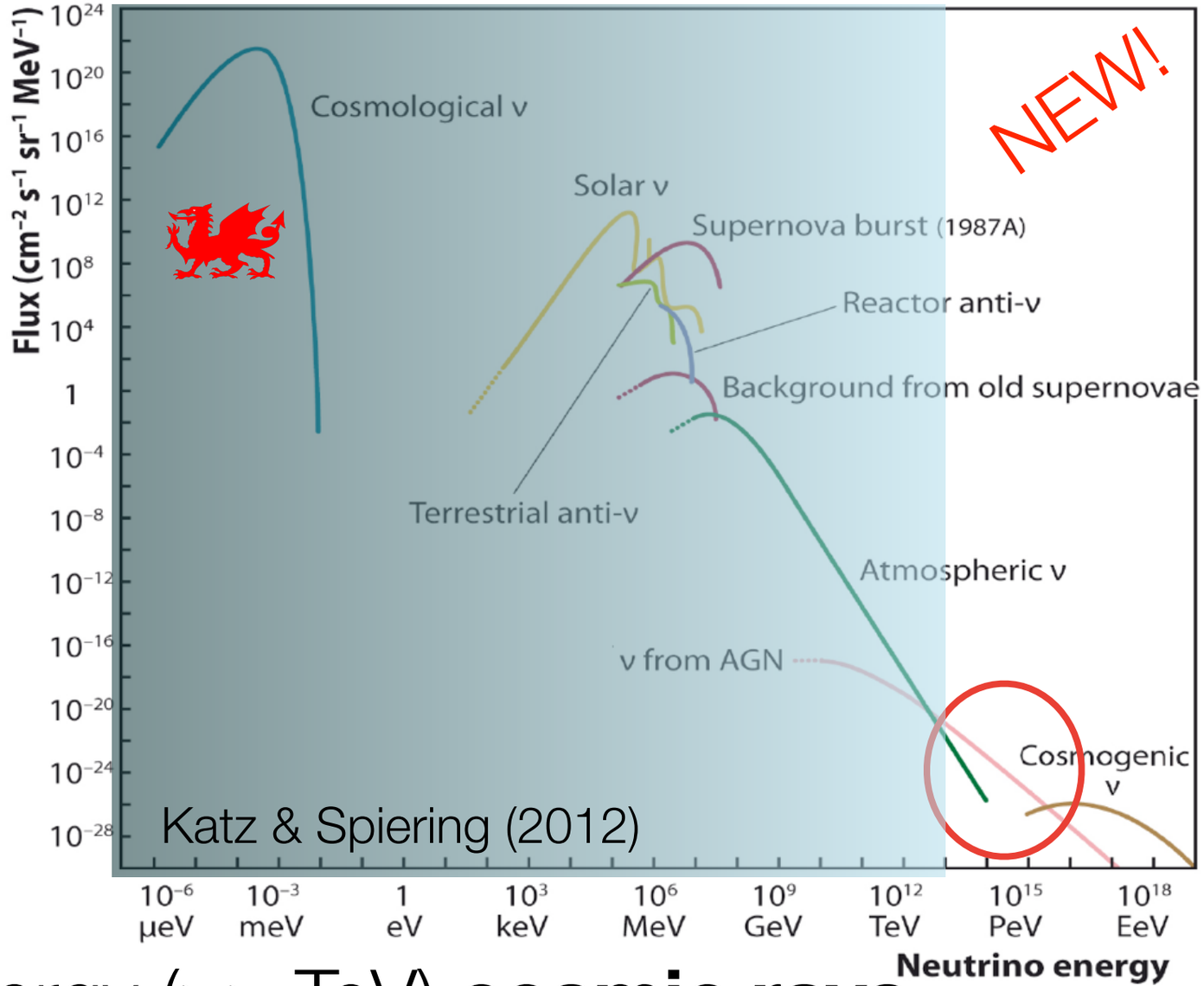
10¹⁸ EeV
Neutrino energy

Cosmic rays

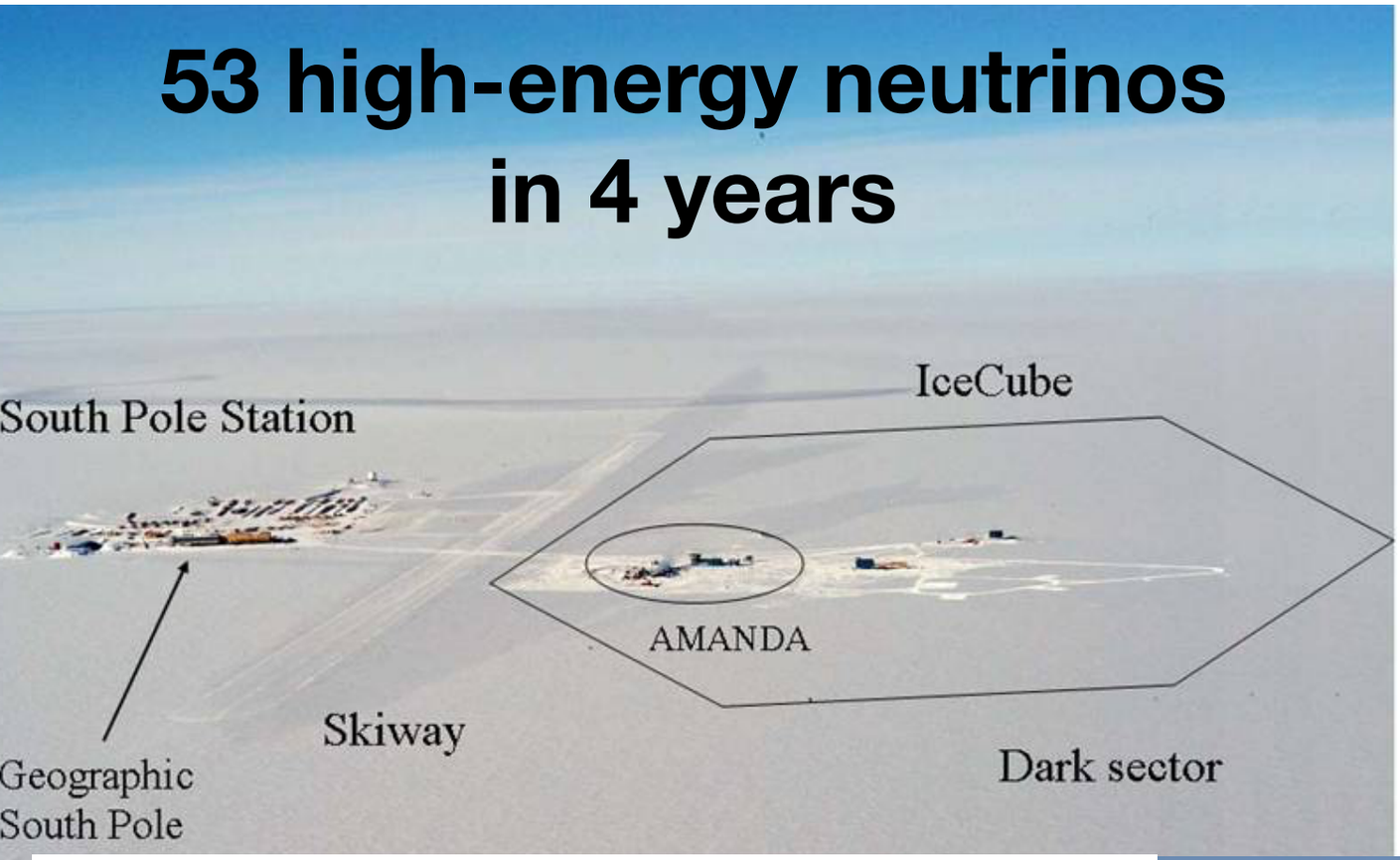


Neutrinos

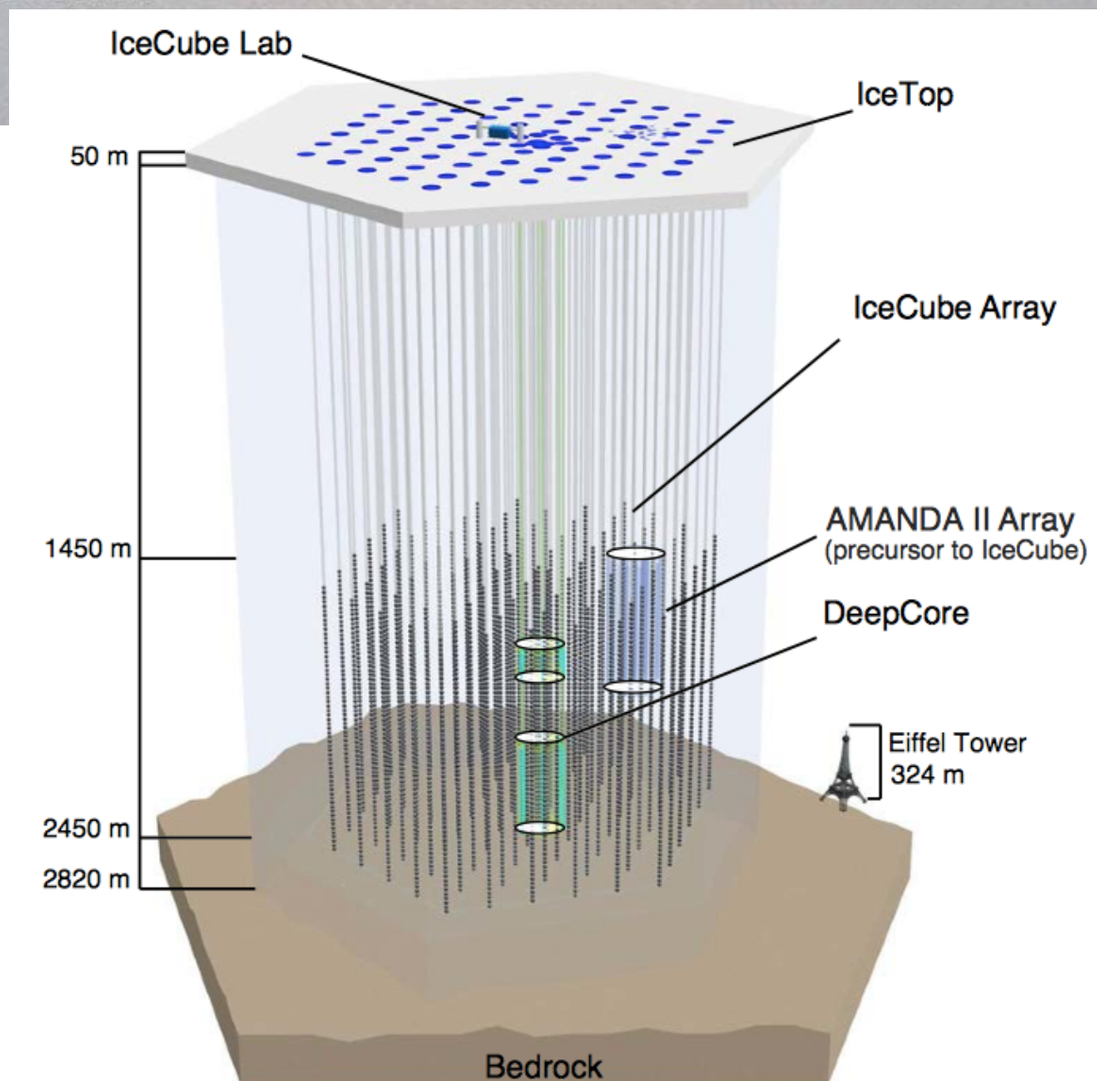


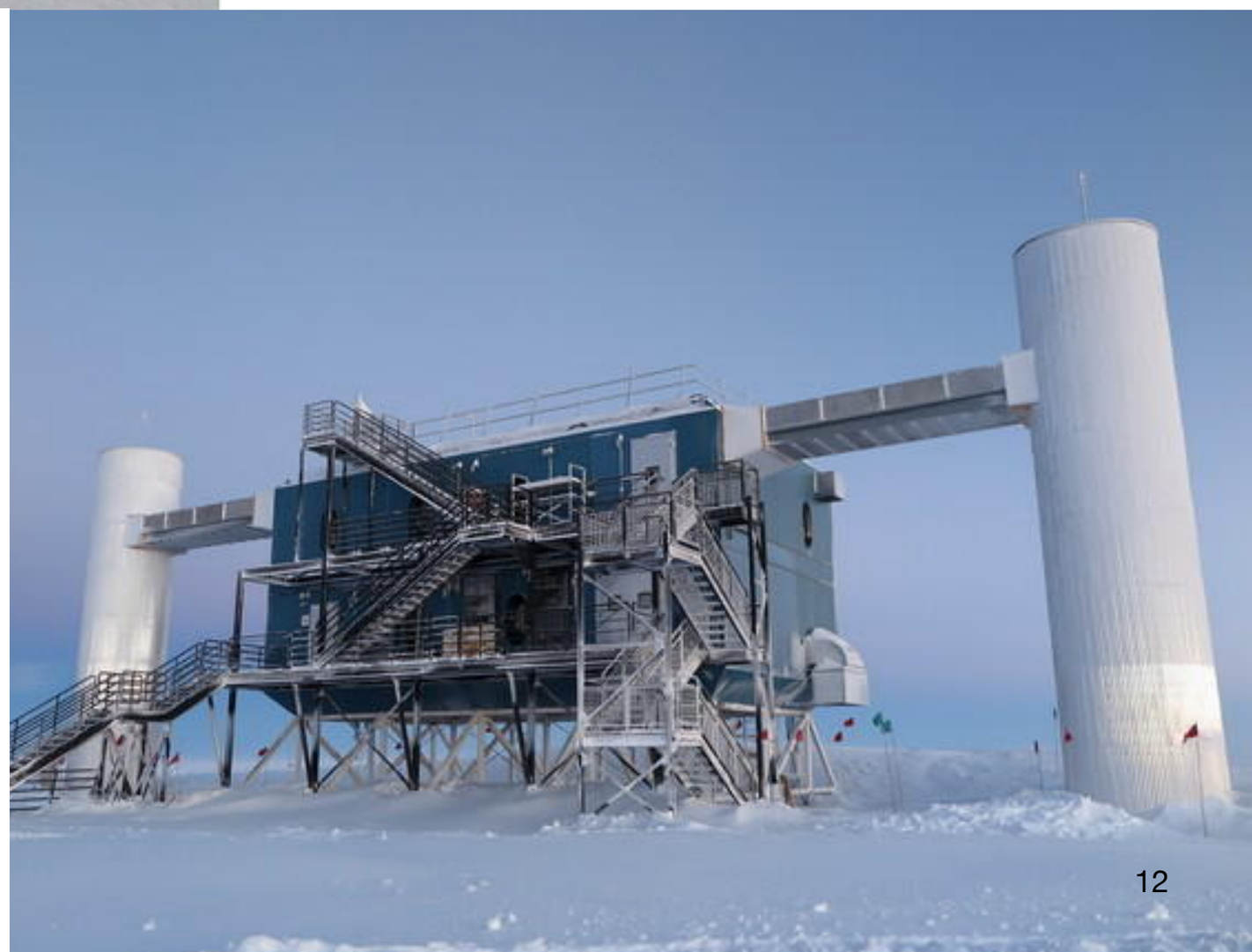
We see high-energy (>> TeV) **cosmic rays** and **gamma rays**, and evidence suggests these are extragalactic.. We know associated **neutrinos** must be produced

53 high-energy neutrinos in 4 years



IceCube Neutrino Observatory





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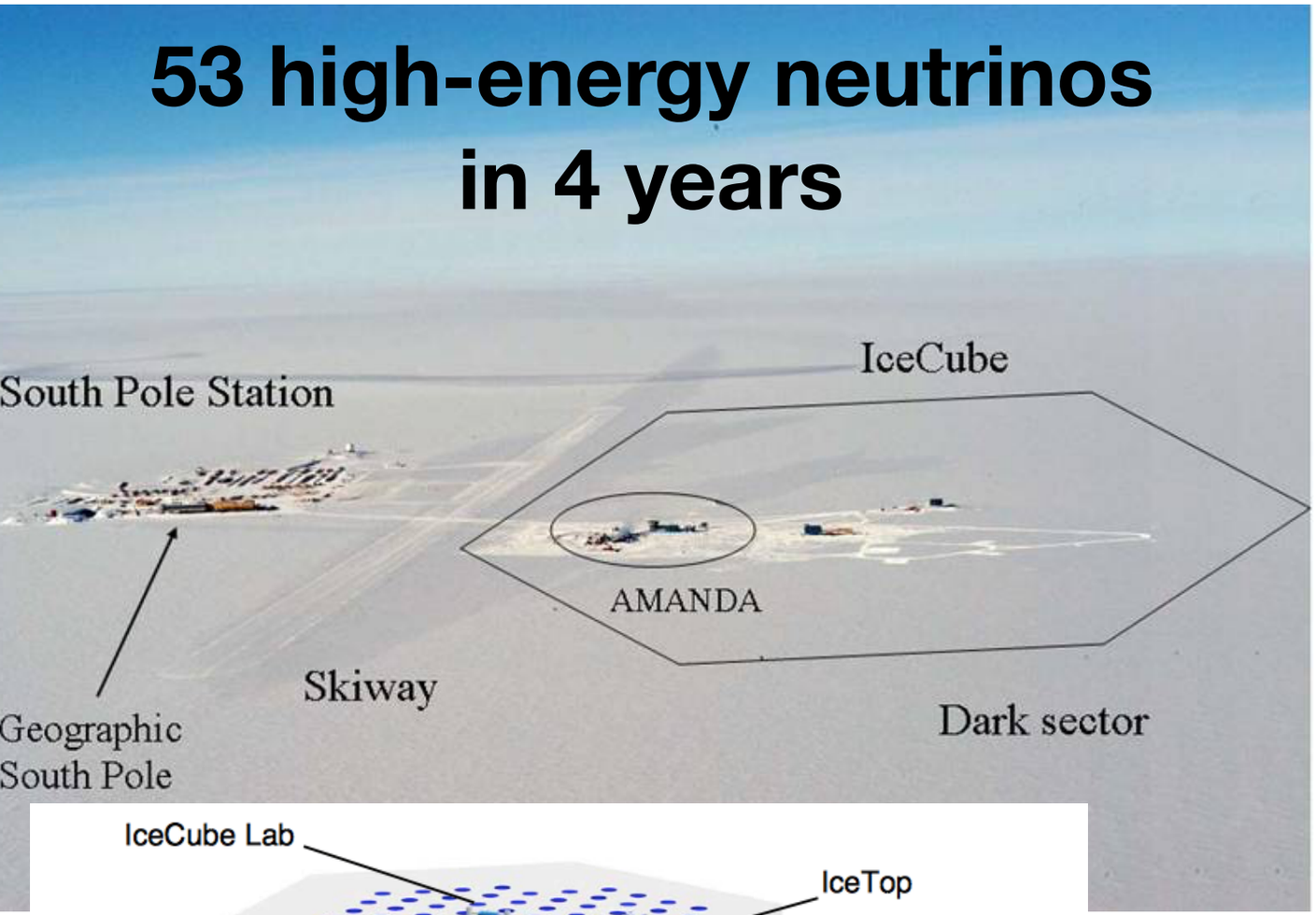
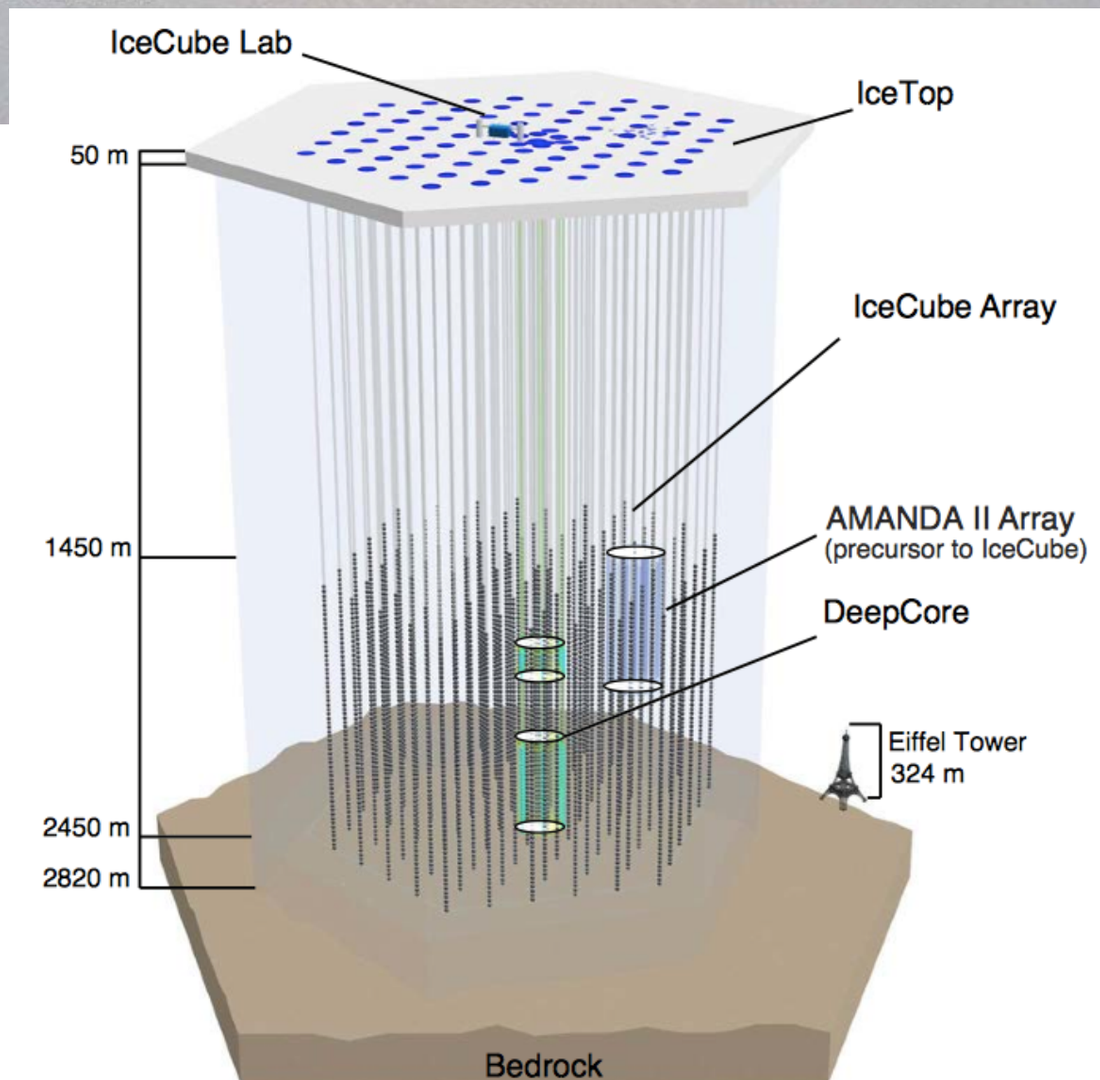
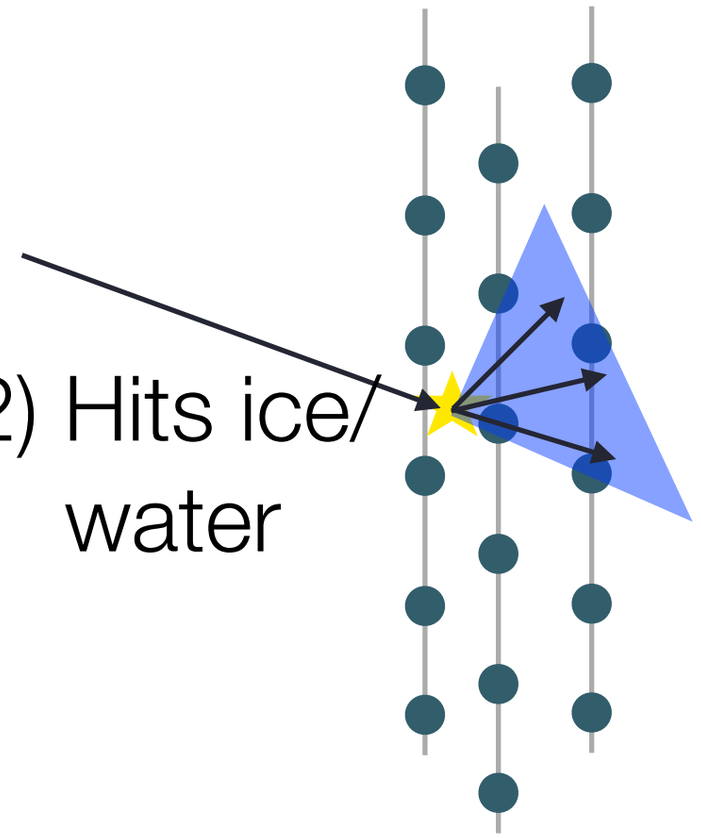




IceCube Neutrino Observatory

1) Neutrino arrives



2) Hits ice/ water

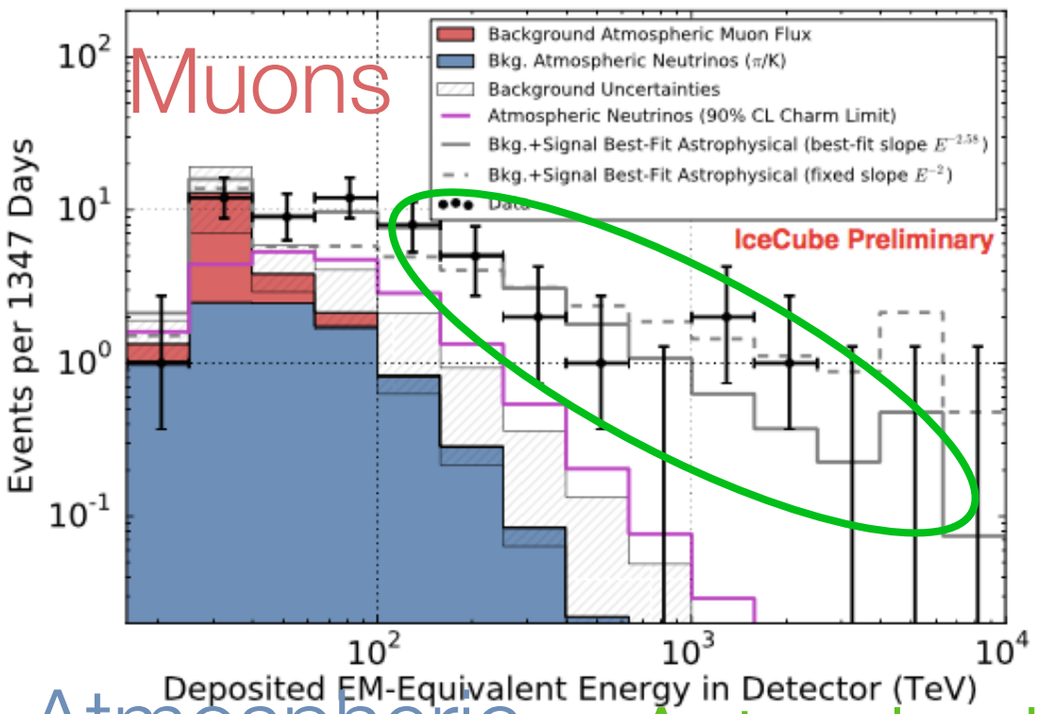
3) DOMs see Čerenkov light from electrons, muons

IceCube High Energy Starting Events (HESEs)

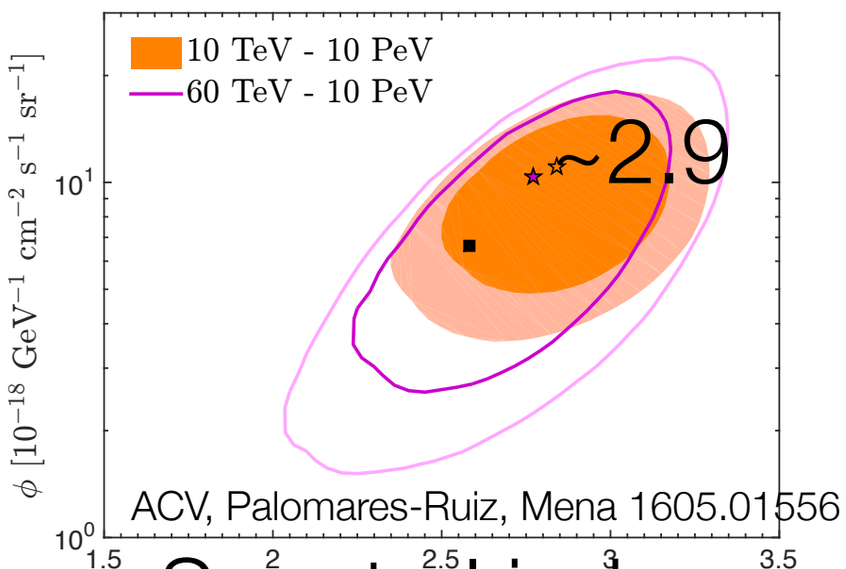
Energy

53 events

IceCube ICRC 1510.05223



Atmospheric Astrophysical



Spectral index

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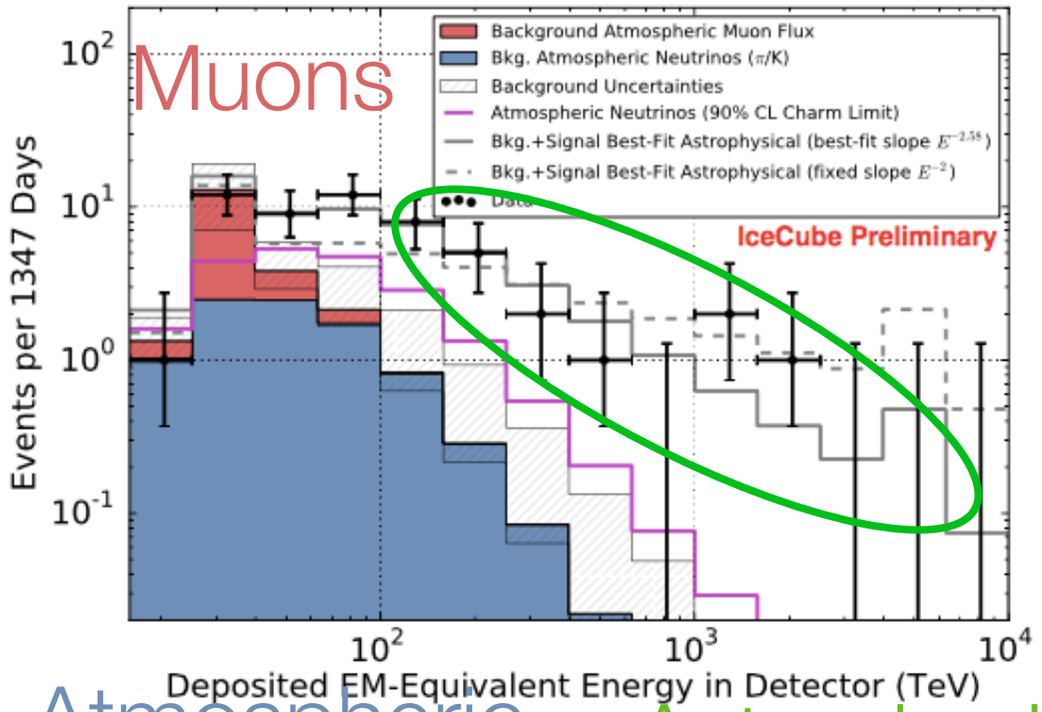
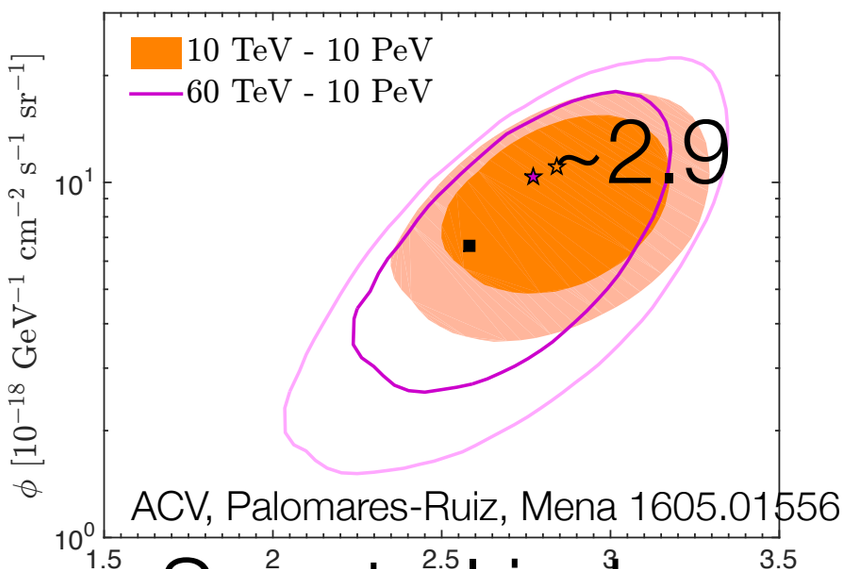


Atmospheric

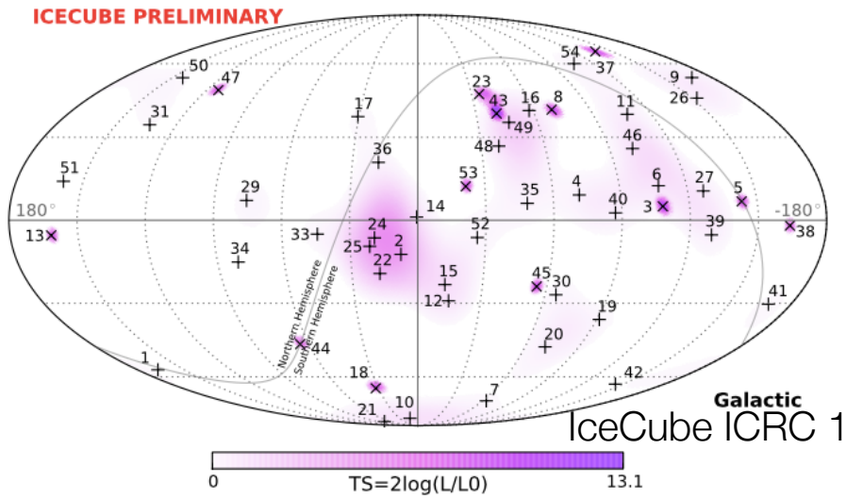
Astrophysical



ACV, Palomares-Ruiz, Mena 1605.01556

Spectral index

Arrival direction



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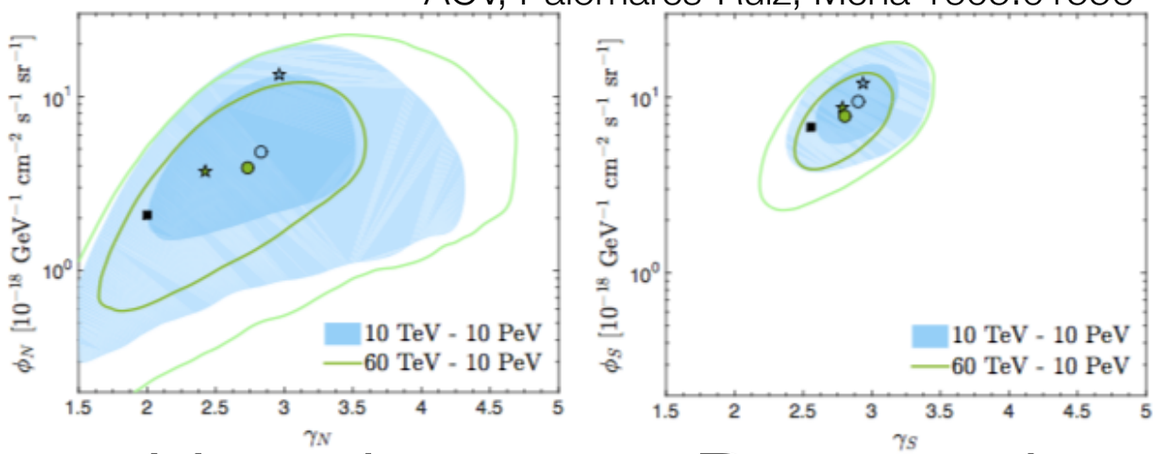


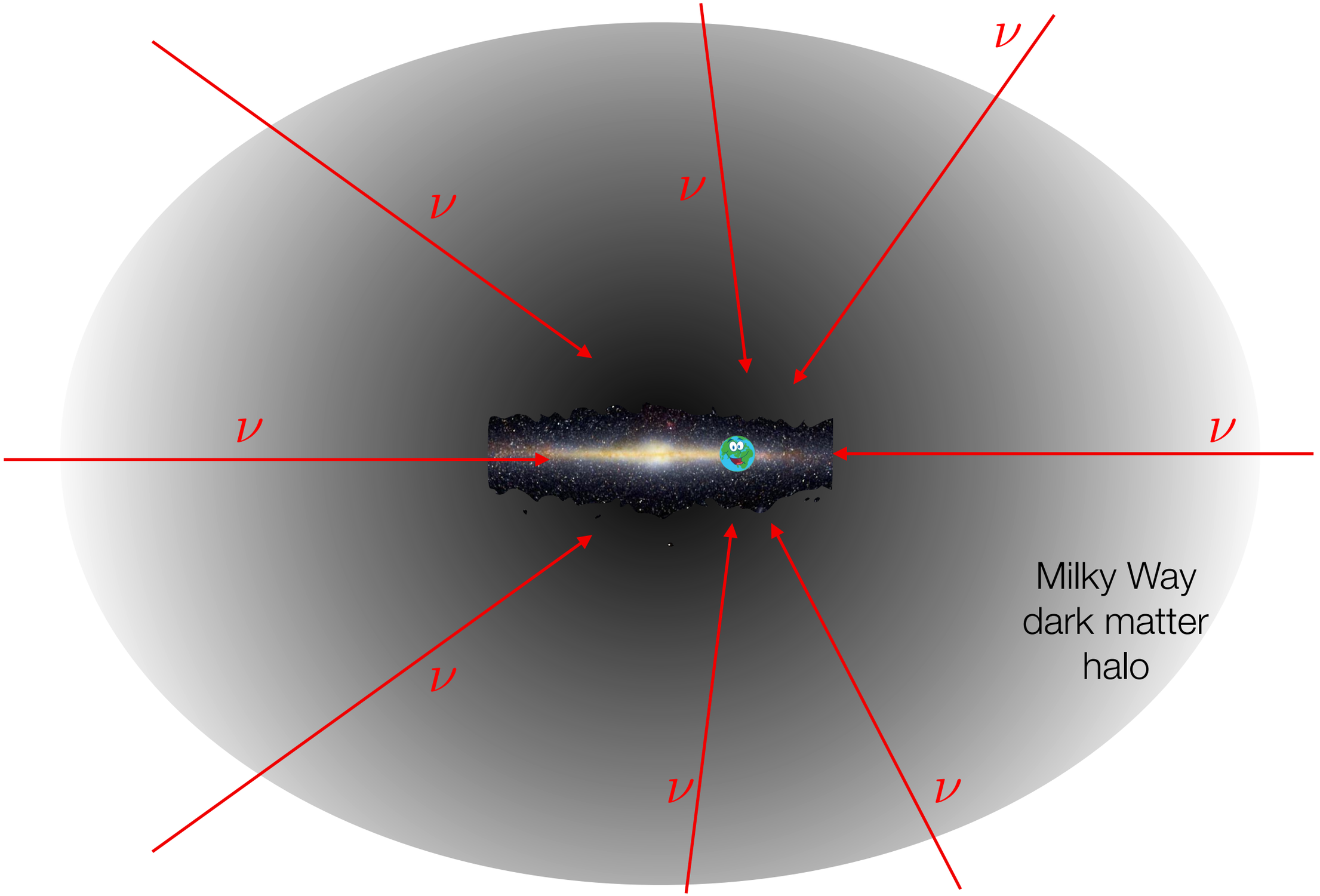
Upgoing

Downgoing

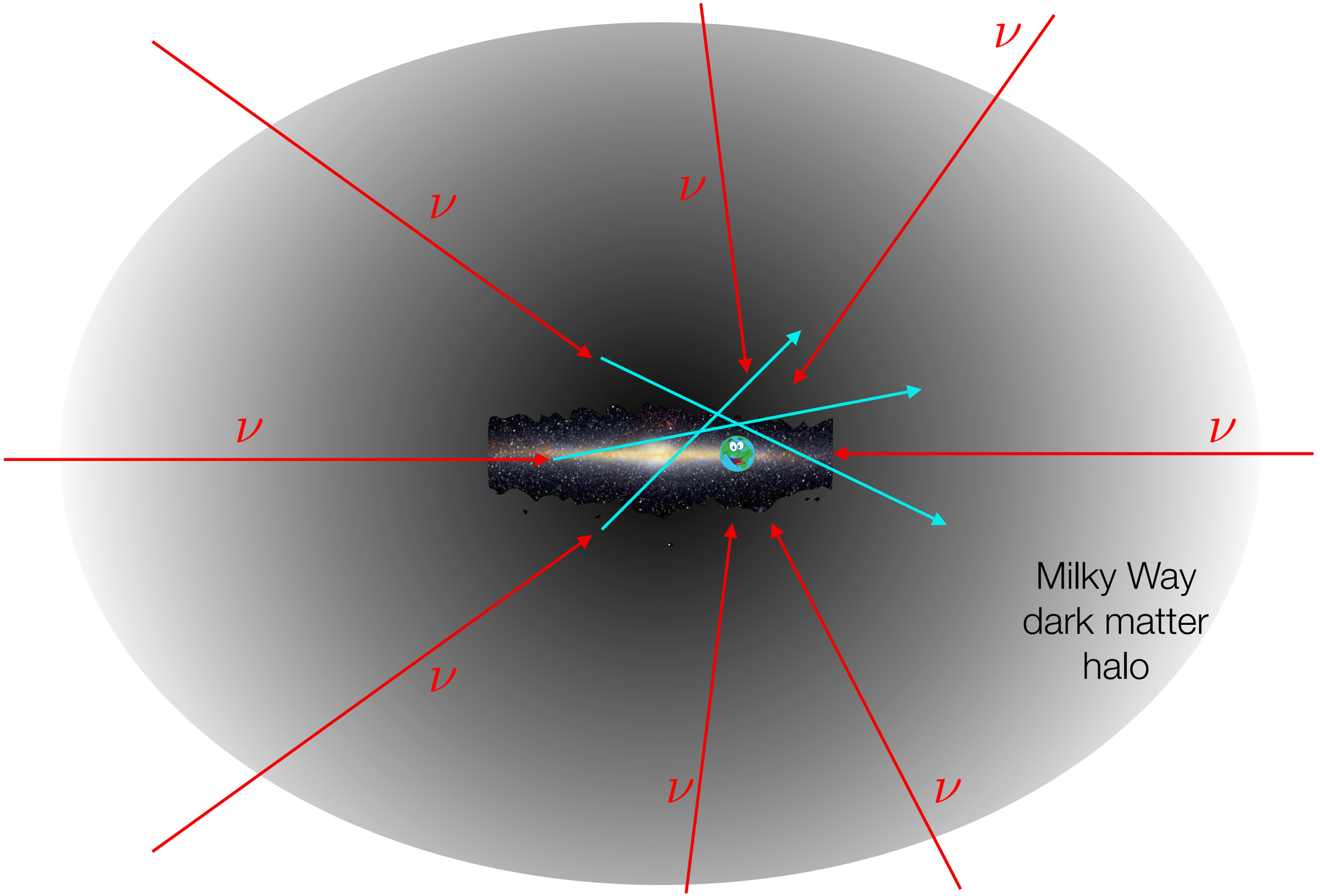
Isotropic arrival

➡ 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)

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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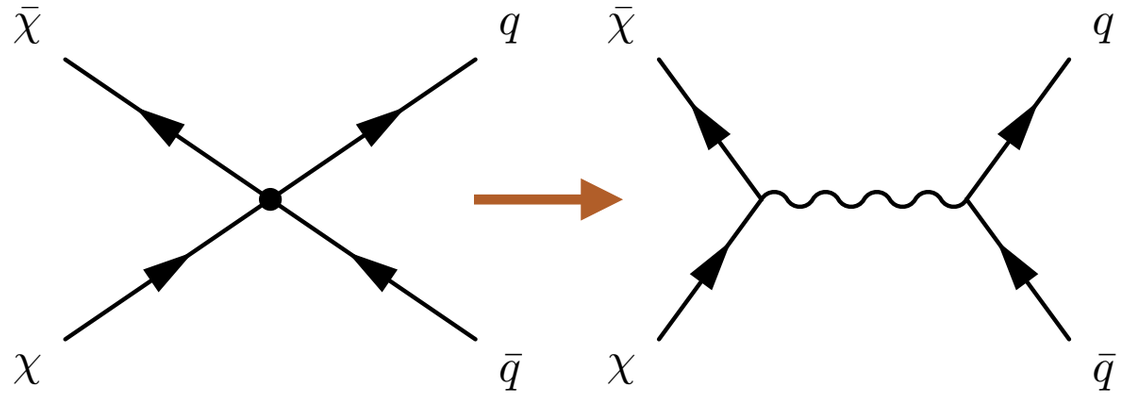
No!

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

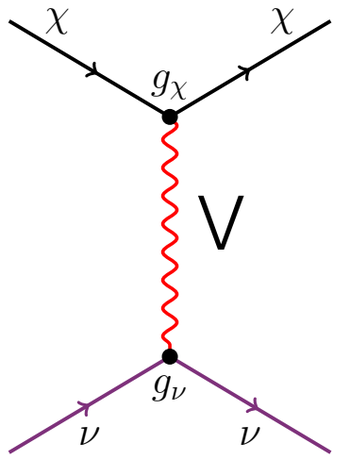


The low energy approximation does not work at a PeV!!

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

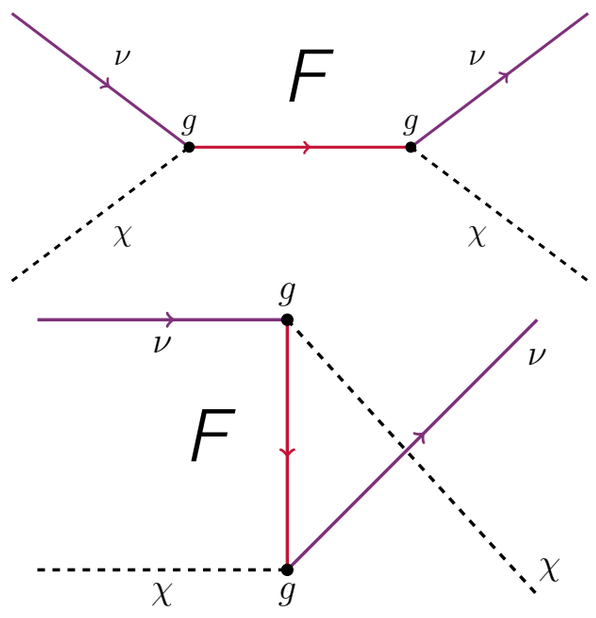
Two fiducial simplified models

1)



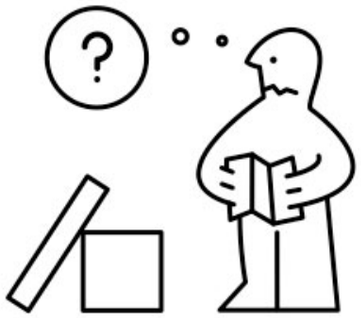
Fermion DM, **vector mediator**:
Scales strongly with *E*

2)



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

IceCube HESE analysis



atmospheric background model

self-veto model

astrophysical flux

Effective area:

earth attenuation

Cross sections

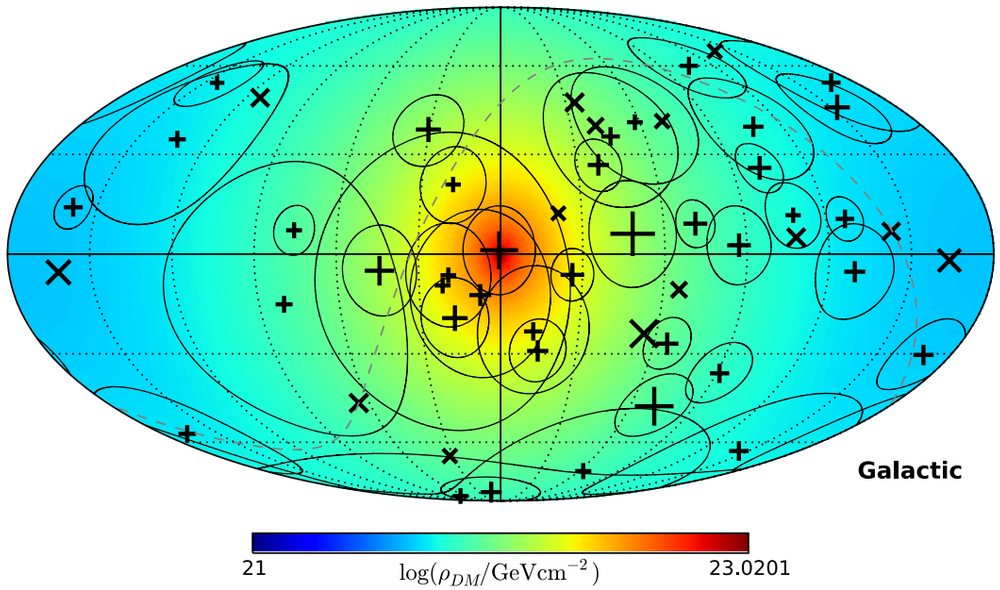
topology

instrument response

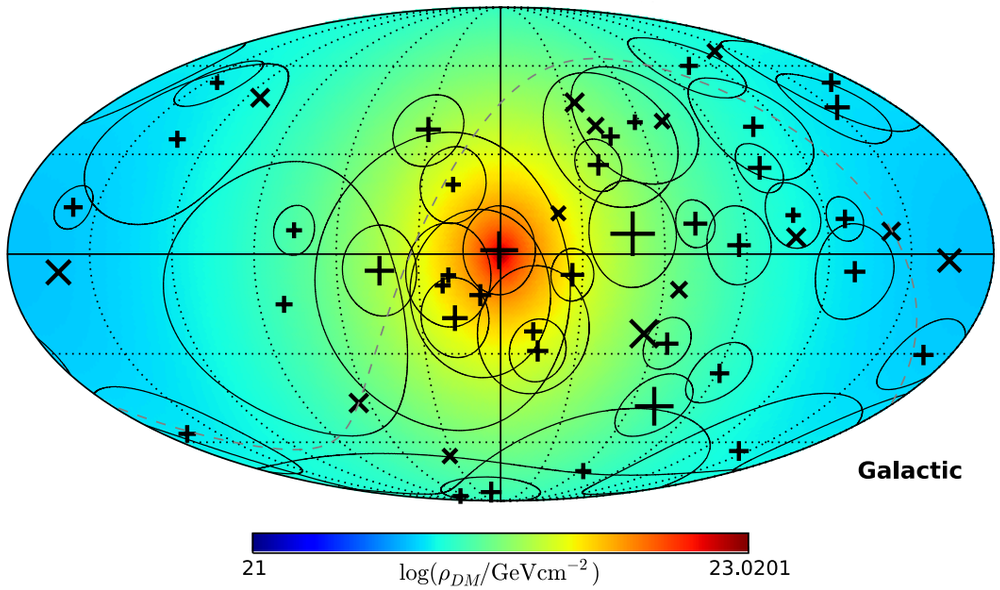
data

Likelihood

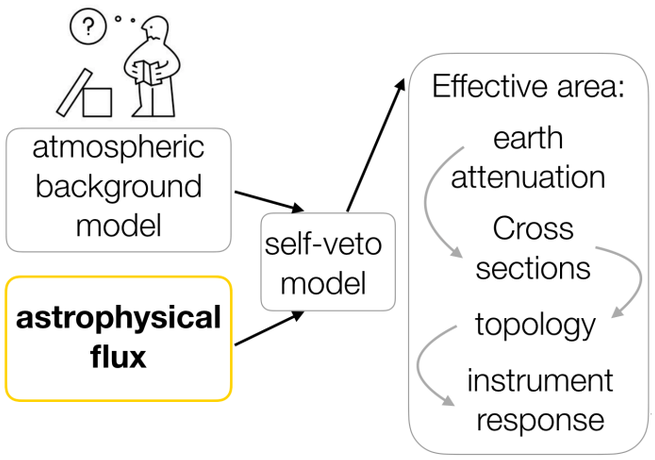
Dark matter column density seen from Earth



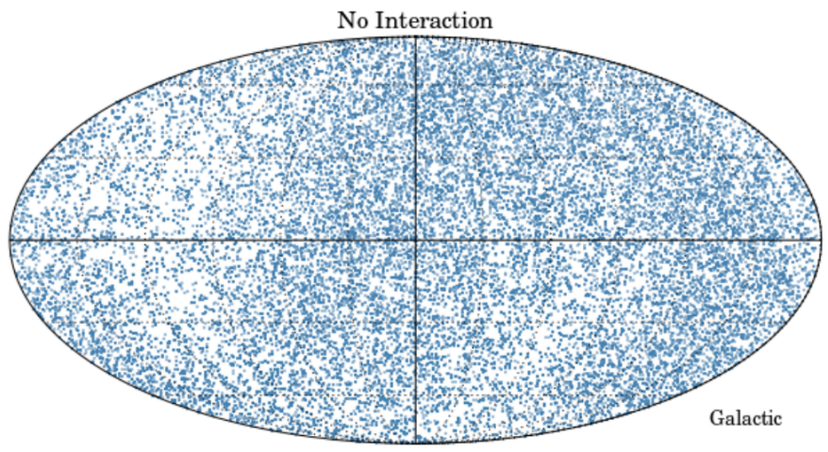
Dark matter column density seen from Earth



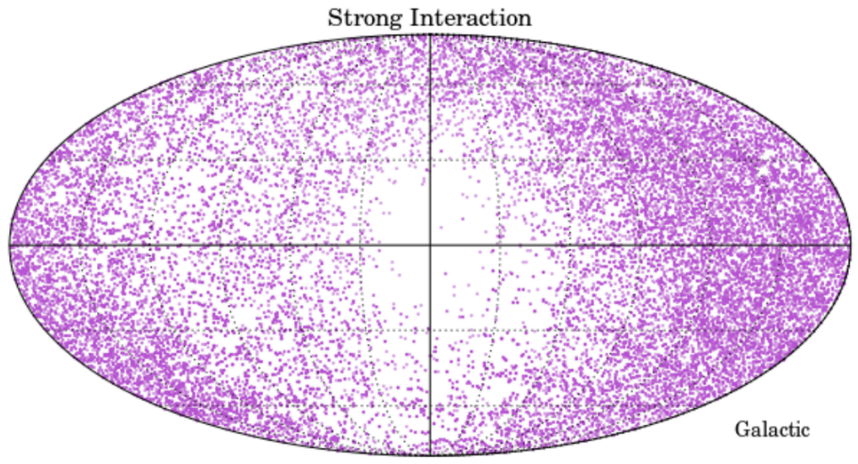
Simulation including effects of detector, Earth



no interaction

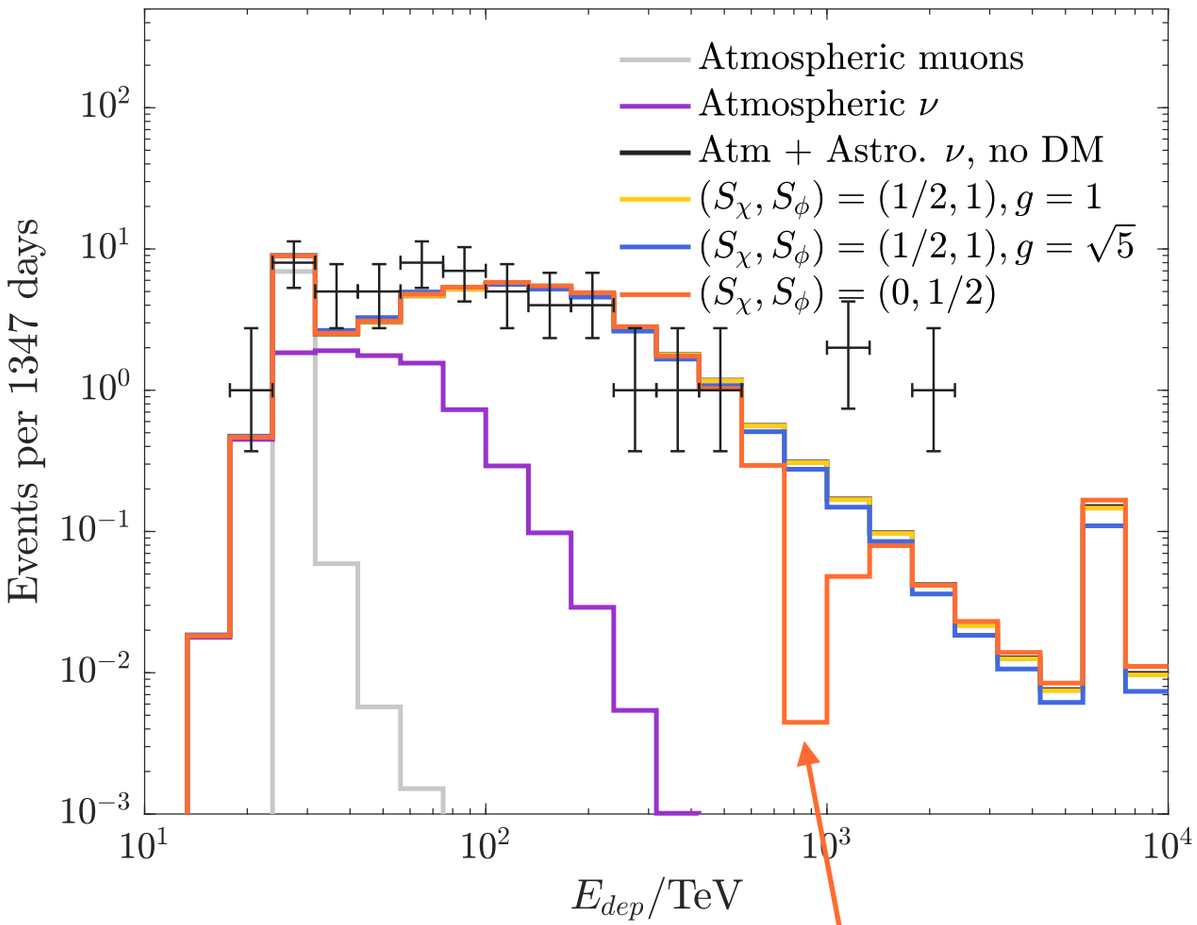


strong interaction



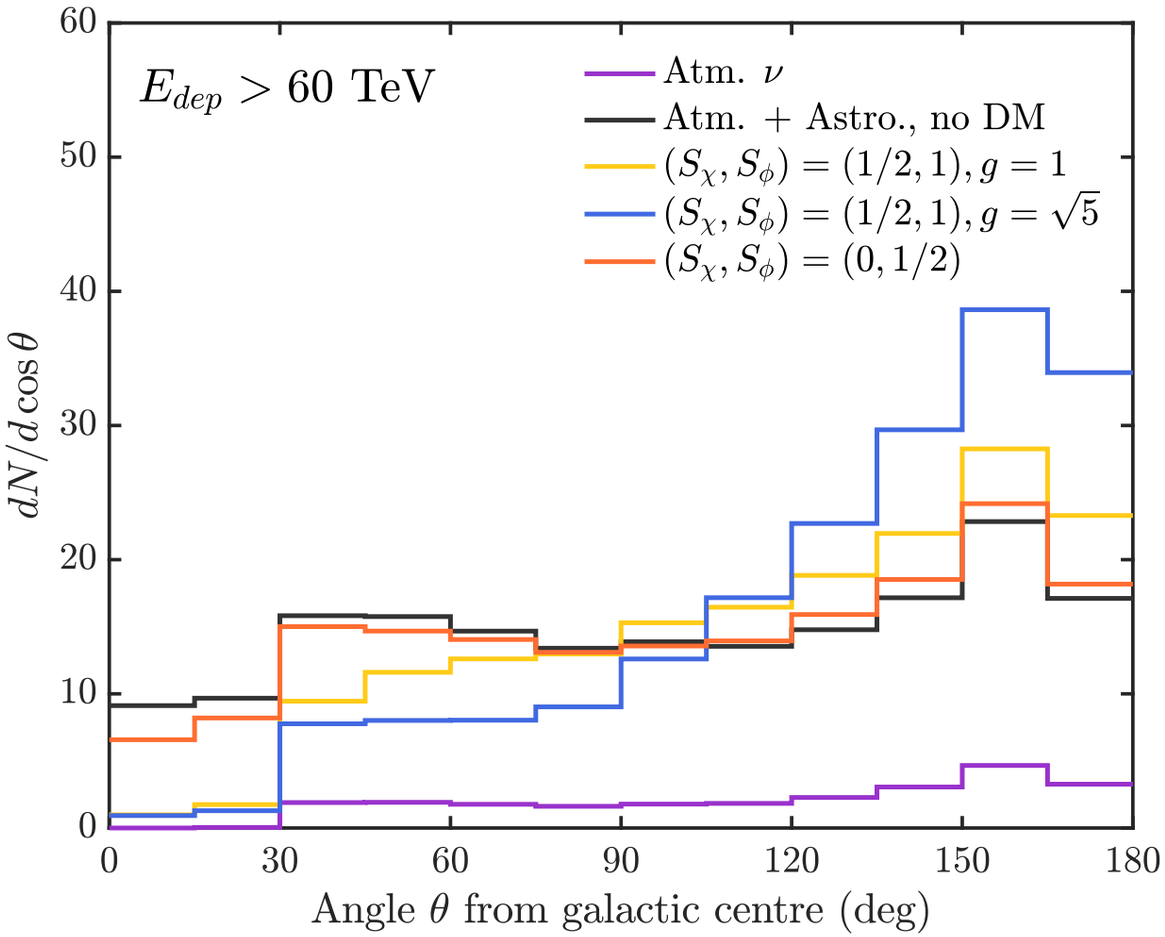
Energy & morphology

Energy



Resonance @ 810 TeV

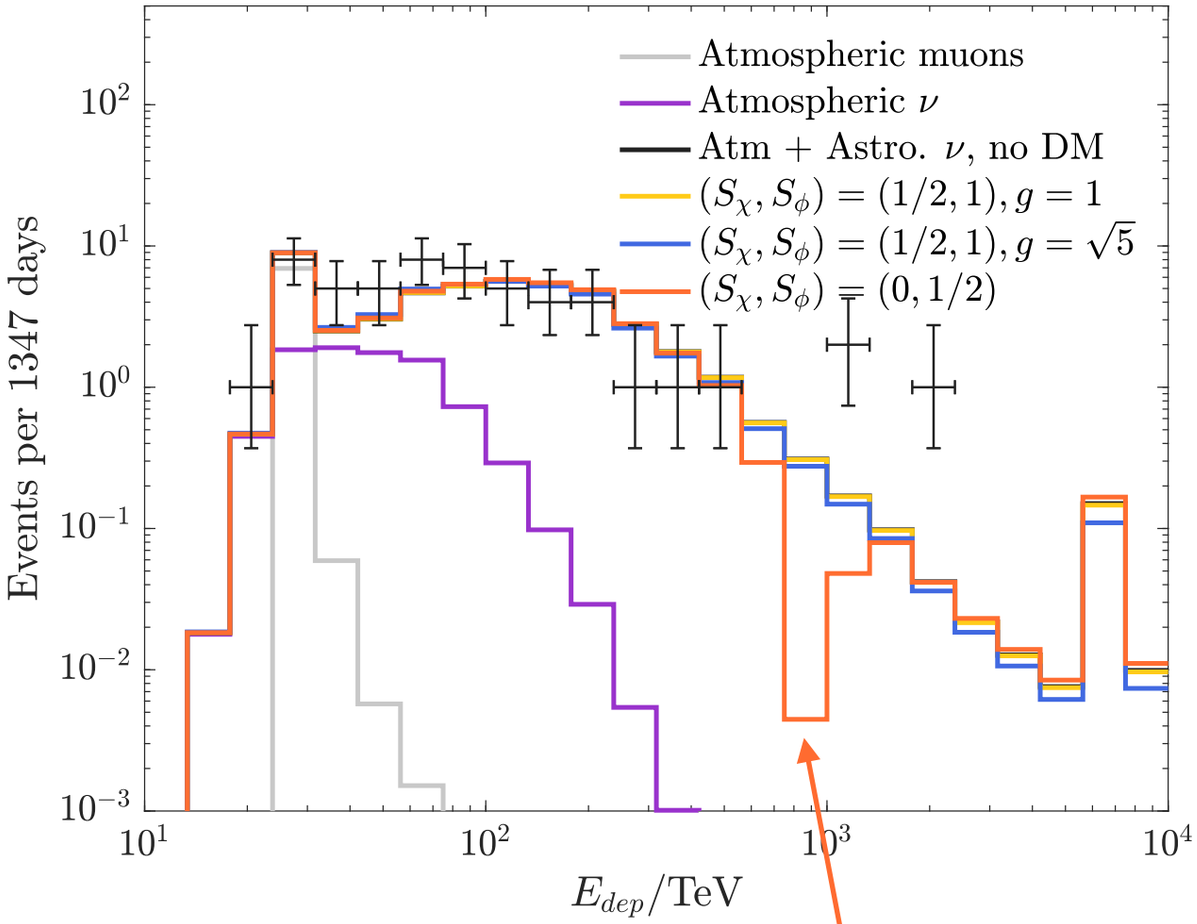
Angle from galactic centre



IceCube HESE events

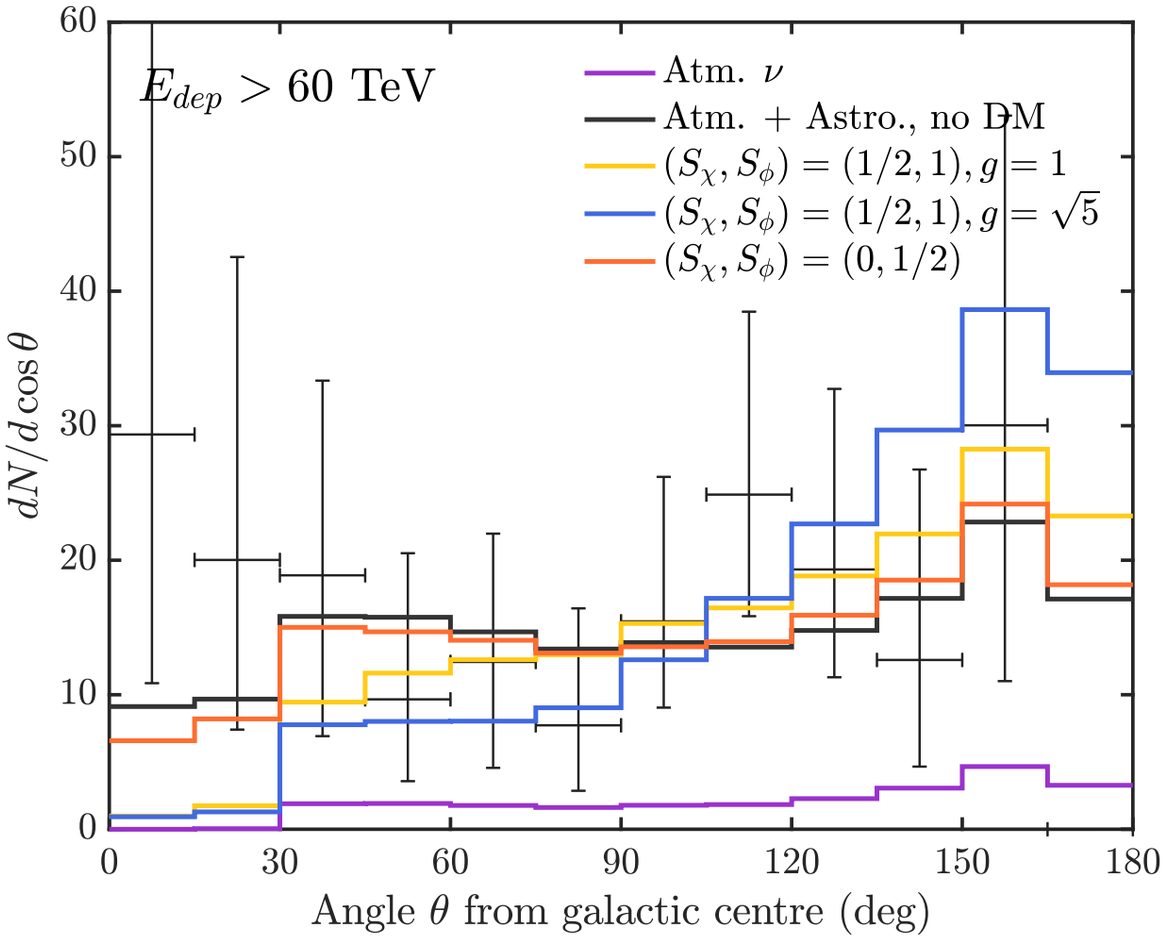
Energy & morphology

Energy



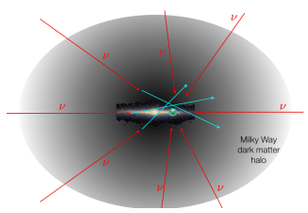
Resonance @ 810 TeV

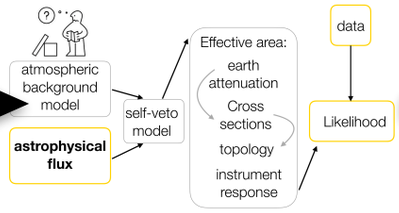
Angle from galactic centre

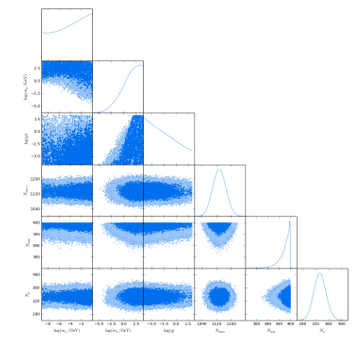


IceCube HESE events

Compare Likelihood to real events





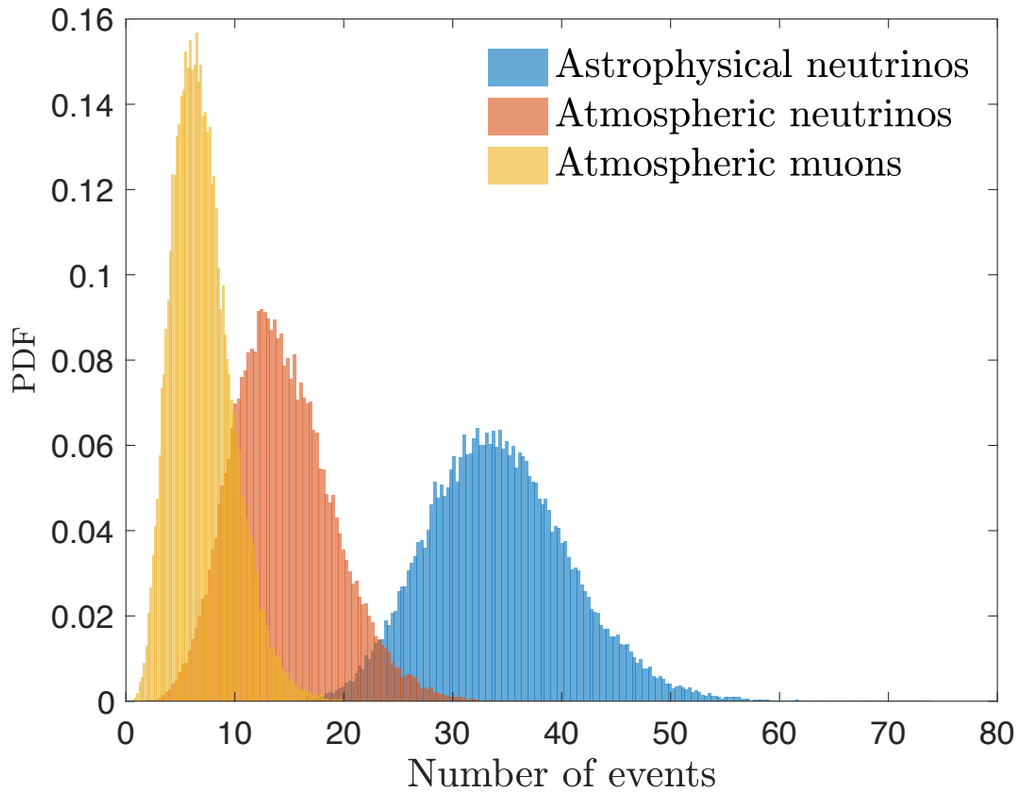


model likelihood IceCube data MCMC posterior

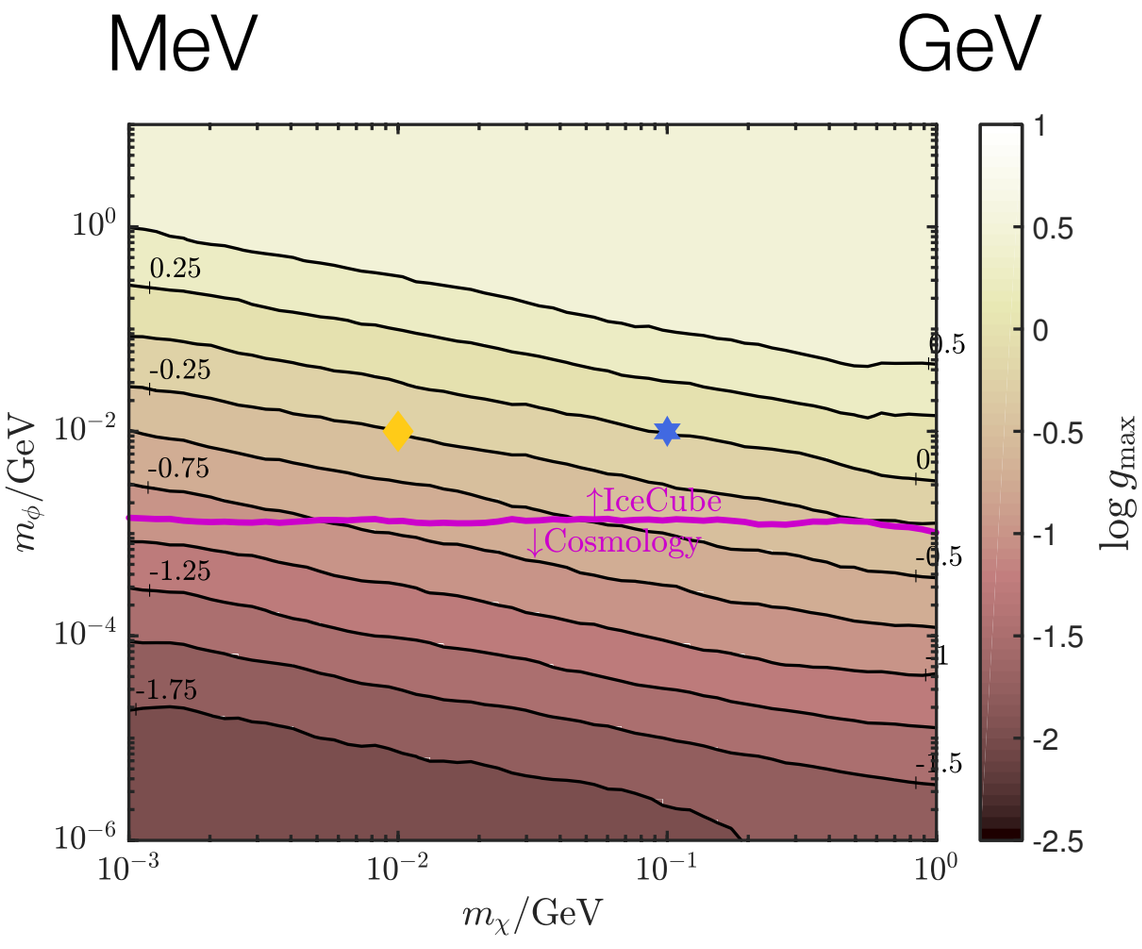
$$\mathcal{L}(\{t, E, \vec{x}\}|\vartheta) = e^{-\sum_b N_b} \prod_{i=1}^{N_{obs}} \sum_a N_a P_a(t_i, E_i, \vec{x}_i|\vartheta).$$

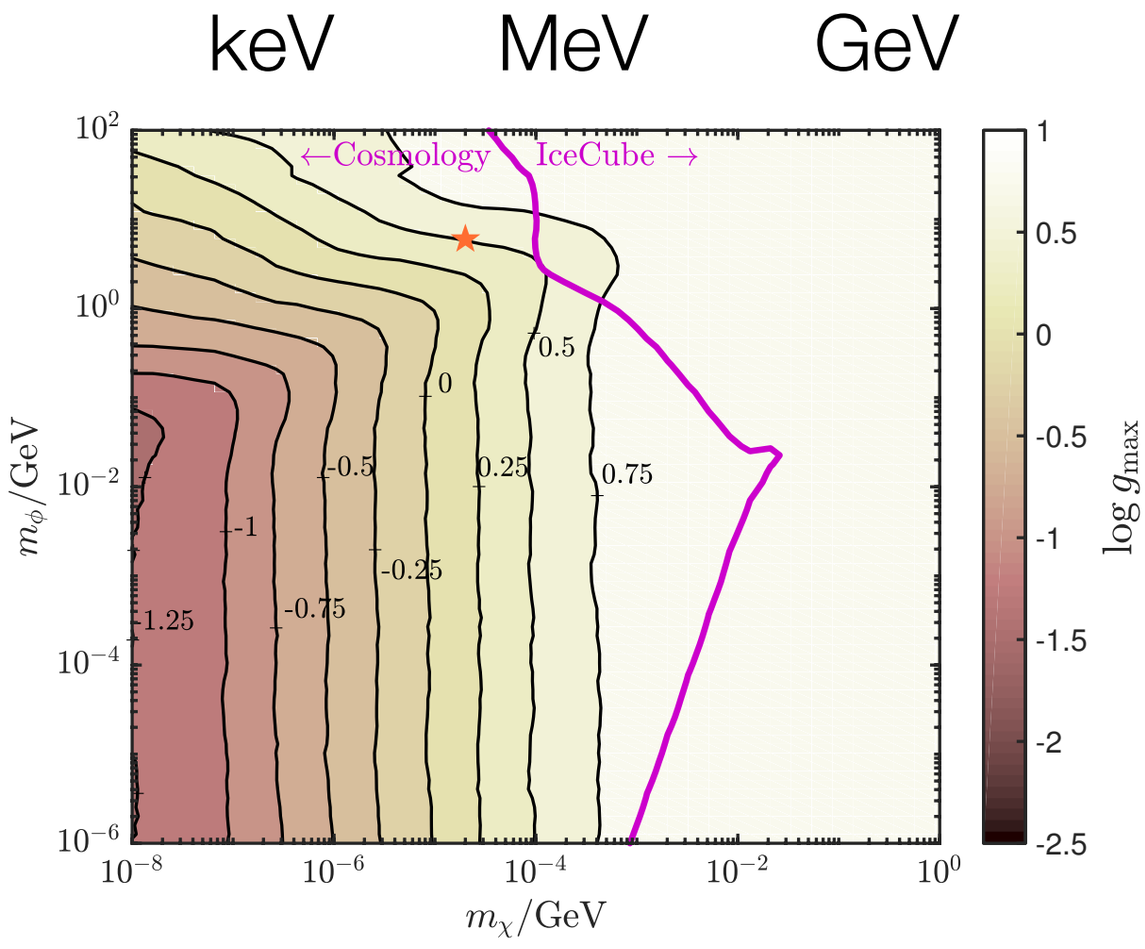
Parameters:

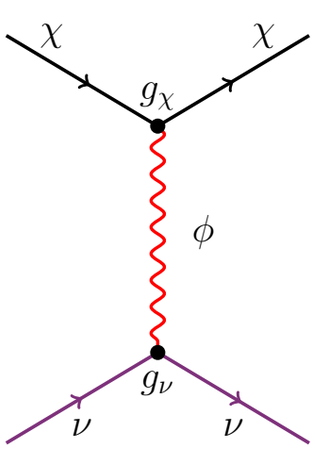
$$m_\chi \; m_\phi \; g \; N_{astro} \; N_{atmo} \; N_{\mu^\pm} \; \gamma$$



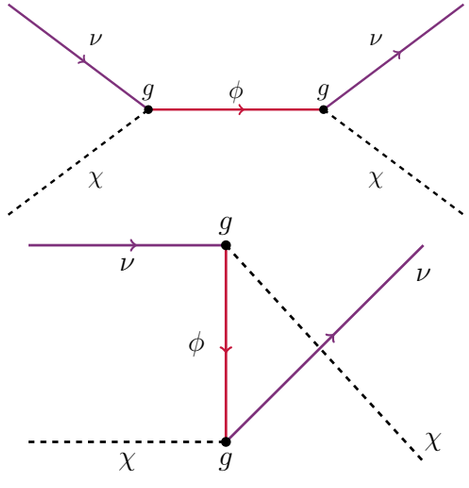
Limits from IceCube





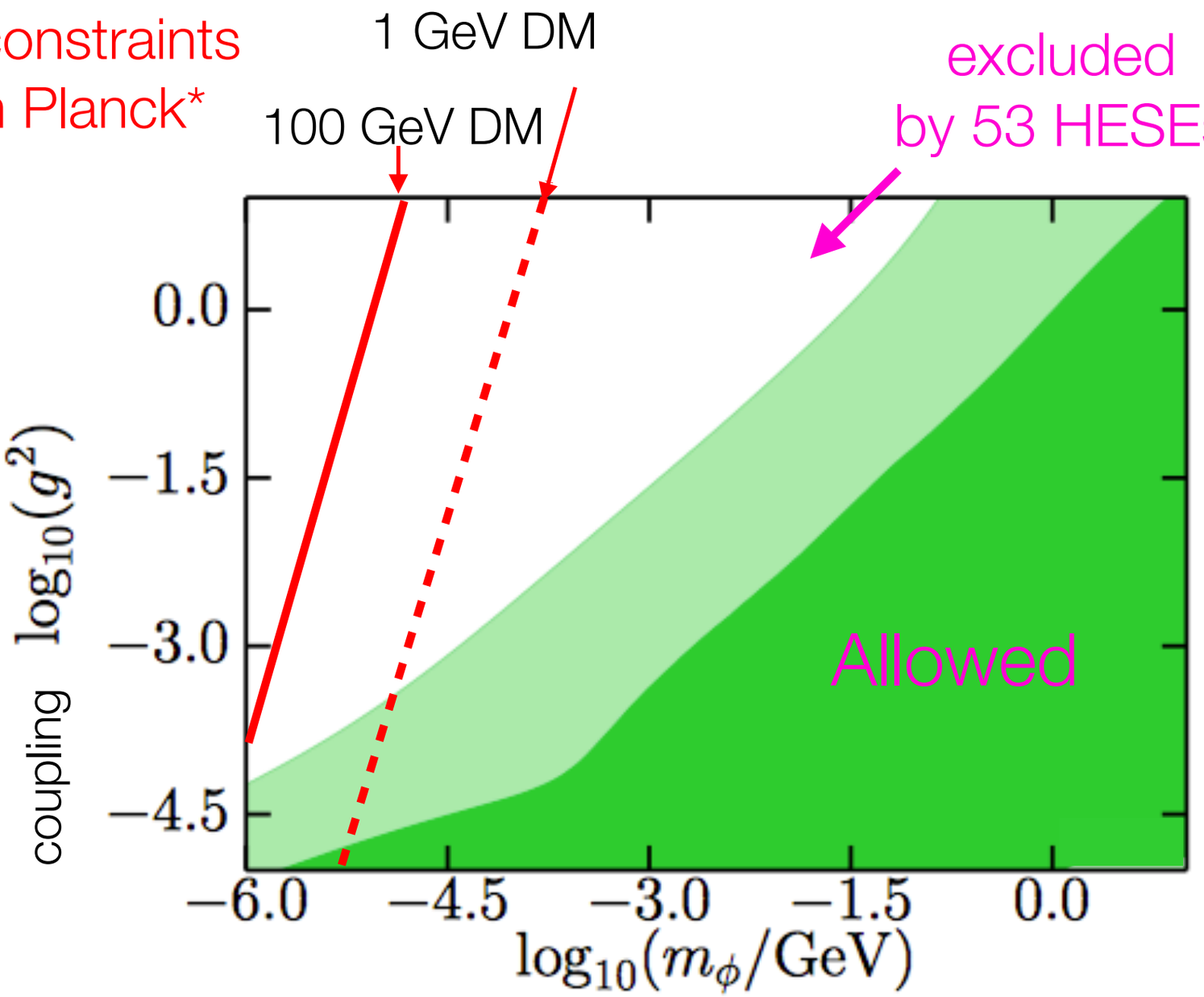


Only 53 events:
already eating into
cosmology parameter
space

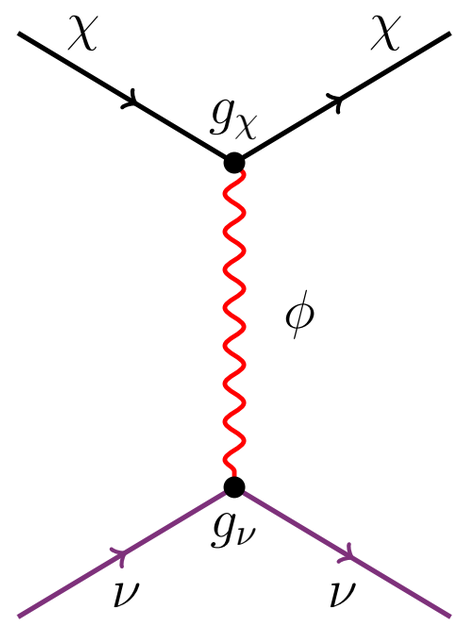


New limits on dark force carriers

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

- Need more stats —> more data next year + forecasts for Gen2 & much more to come

Thank you

Four-year HESE sample

53 events

14 tracks

39 showers

9

39 downgoing

30

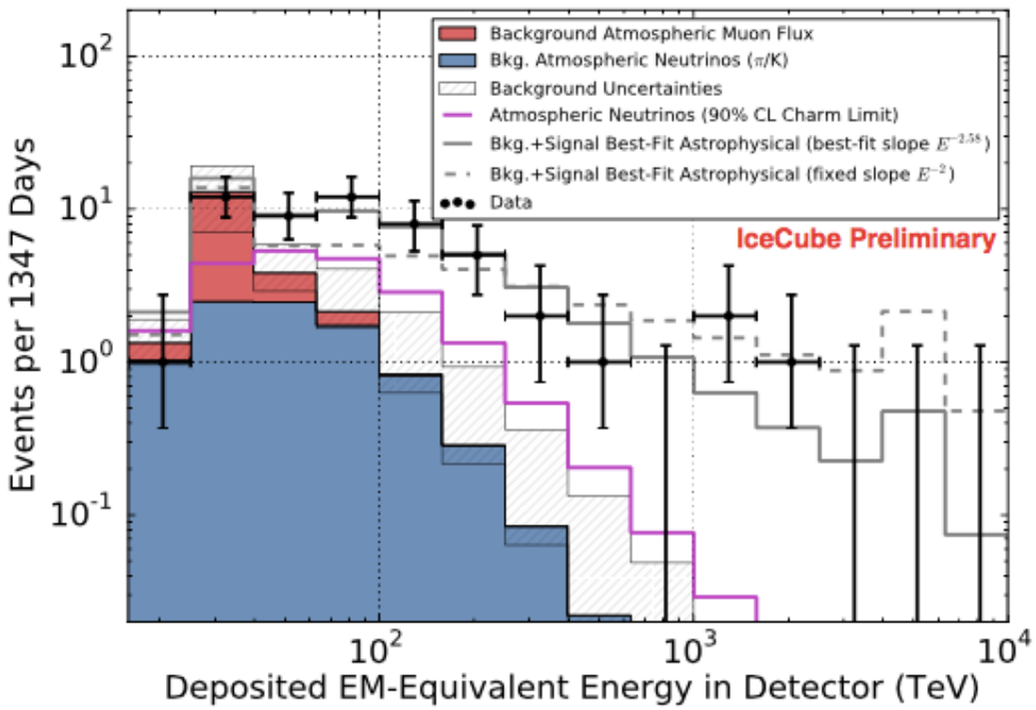
5

16 upgoing

11

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.

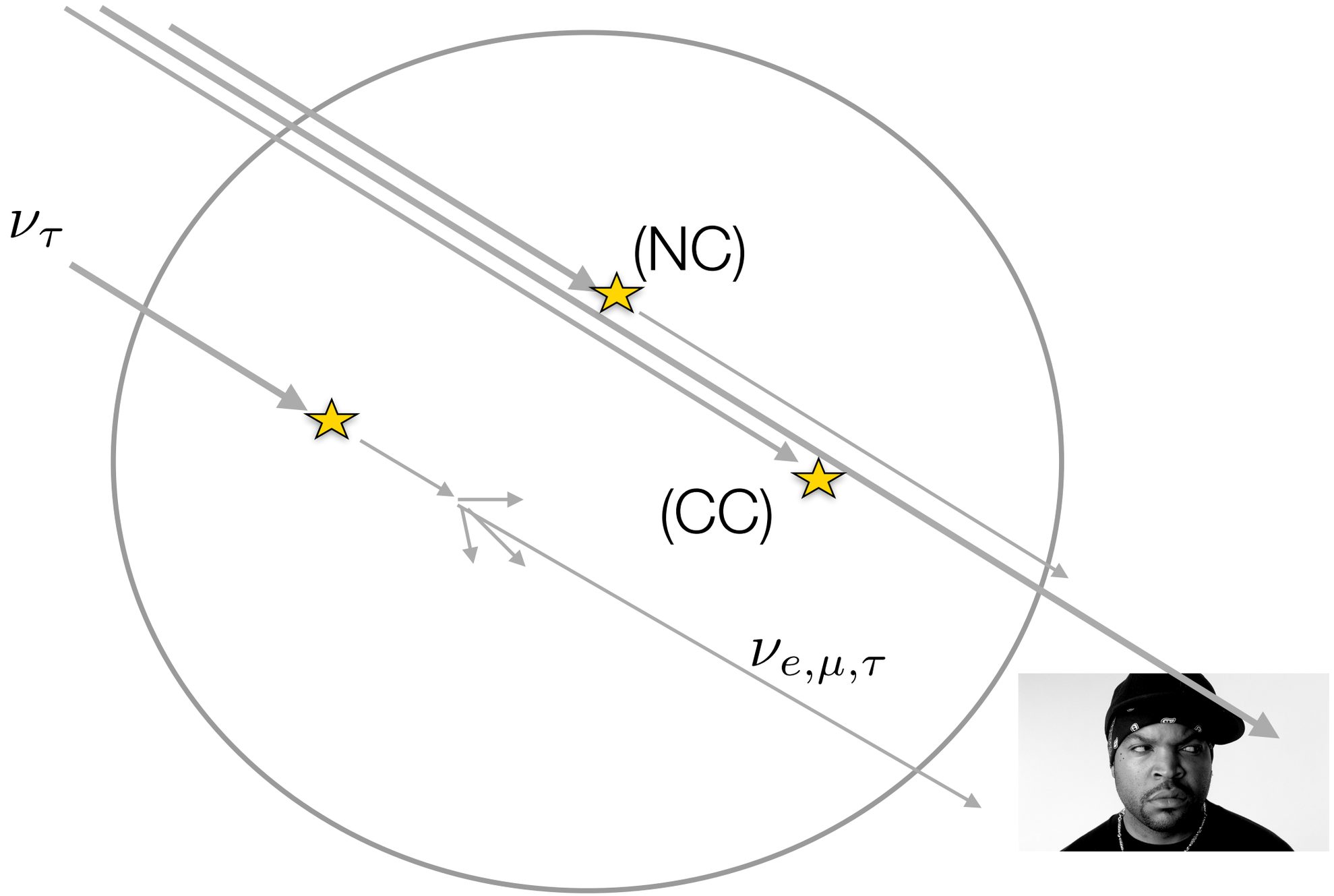
HESE: ~ 12/53 atmospheric neutrinos

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

Attenuation by Earth

$$\frac{dN^c}{dE_{\rm true}} = T\,N_A \int_0^\infty \boxed{Att^f_{\nu_\ell}(E_\nu)}\, M_{\rm eff}(E_{\rm true})\, \frac{d\phi^f_{\nu_\ell}(E_\nu)}{dE_\nu}\, \frac{d\sigma^c_{\nu_\ell}(E_\nu, E_{\rm true})}{dE_{\rm true}}\, dE_\nu$$



νFATE: neutrino fast attenuation through earth

$$\frac{\partial}{\partial x}\left(\frac{d\phi_{\nu_\ell}(E_\nu,x)}{dE_\nu}\right) = -\left(\sigma^{\rm NC}_{\nu_\ell}(E_\nu)+\sigma^{\rm CC}_{\nu_\ell}(E_\nu)\right)\frac{d\phi_{\nu_\ell}(E_\nu,x)}{dE_\nu} + \int_E^\infty d\tilde{E}\,\frac{d\sigma^{\rm NC}_{\nu_\ell}(E_\nu,\tilde{E}_\nu)}{dE_\nu}\,\frac{d\phi_{\nu_\ell}(\tilde{E}_\nu,x)}{d\tilde{E}_\nu}$$

d flux at E = — Scattering from E + Scattering to E

https://github.com/aaronvincent/nuFATE

ACV, Argüelles, Kheirandish 1706.09895

νFATE: neutrino fast attenuation through earth

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$$E_\nu \to \vec{E}_\nu \qquad \phi \to \vec{\phi}$$

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d flux at E = — Scattering from E + Scattering to E

$$E_\nu \to \vec{E}_\nu \qquad \phi \to \vec{\phi}$$

$$\frac{d\vec{\phi}}{dx} = (-\mathrm{diag}(\vec{\sigma}) + C)\vec{\phi} = M\vec{\phi}$$

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ACV, Argüelles, Kheirandish 1706.09895

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λ_i Eigenvalues of *M*

$\hat{\phi}_i$ Eigenvectors of *M*

c_i Initial conditions

https://github.com/aaronvincent/nuFATE

ACV, Argüelles, Kheirandish 1706.09895

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λ_i Eigenvalues of *M*

$\hat{\phi}_i$ Eigenvectors of *M*

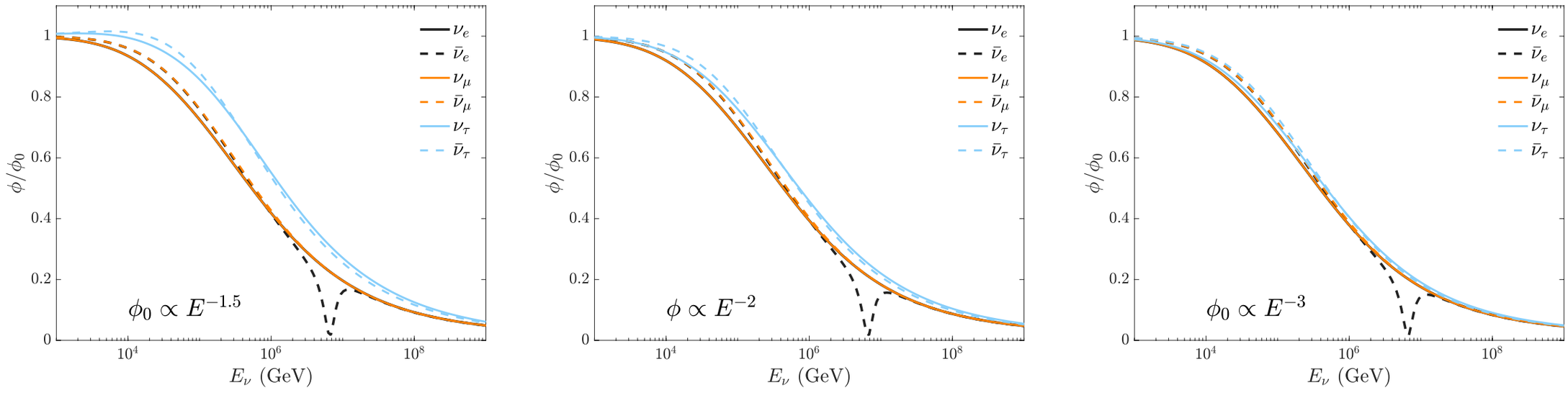
c_i Initial conditions

Small modifications allow tau regen + secondaries

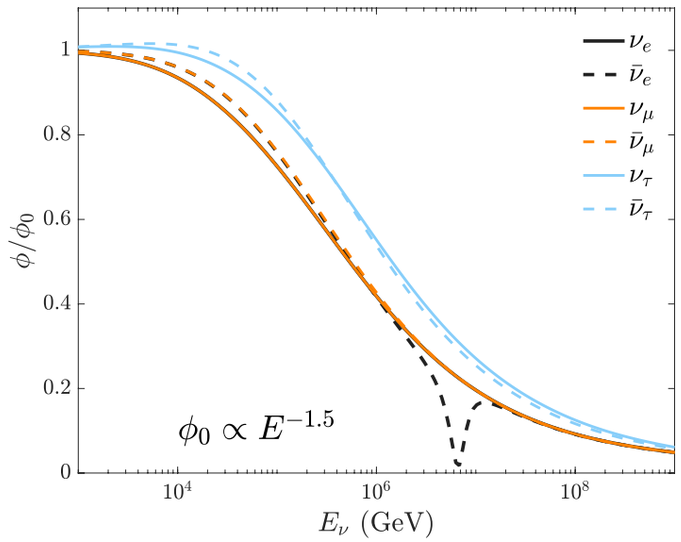
https://github.com/aaronvincent/nuFATE

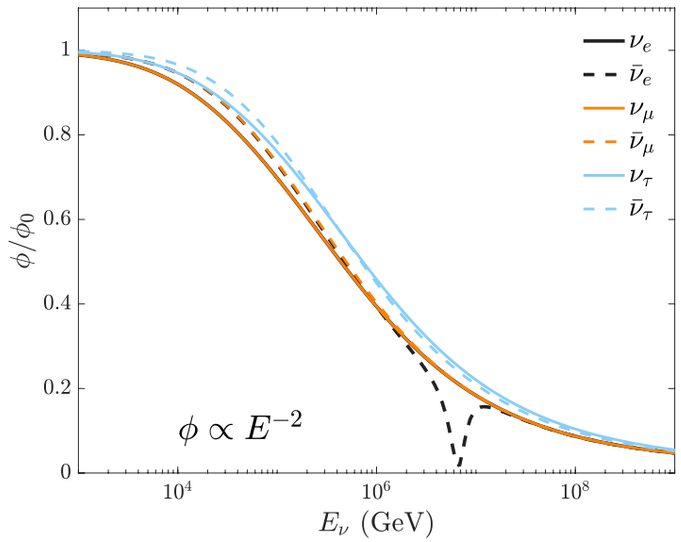
ACV, Argüelles, Kheirandish 1706.09895

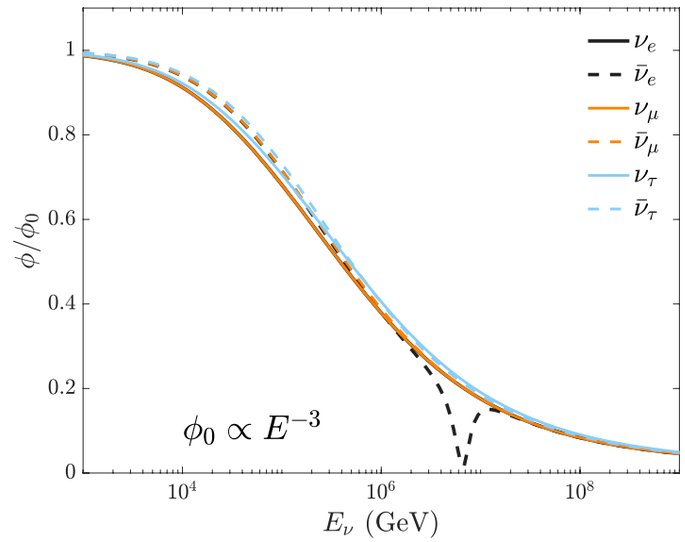
νFATE: average attenuation of upgoing flux



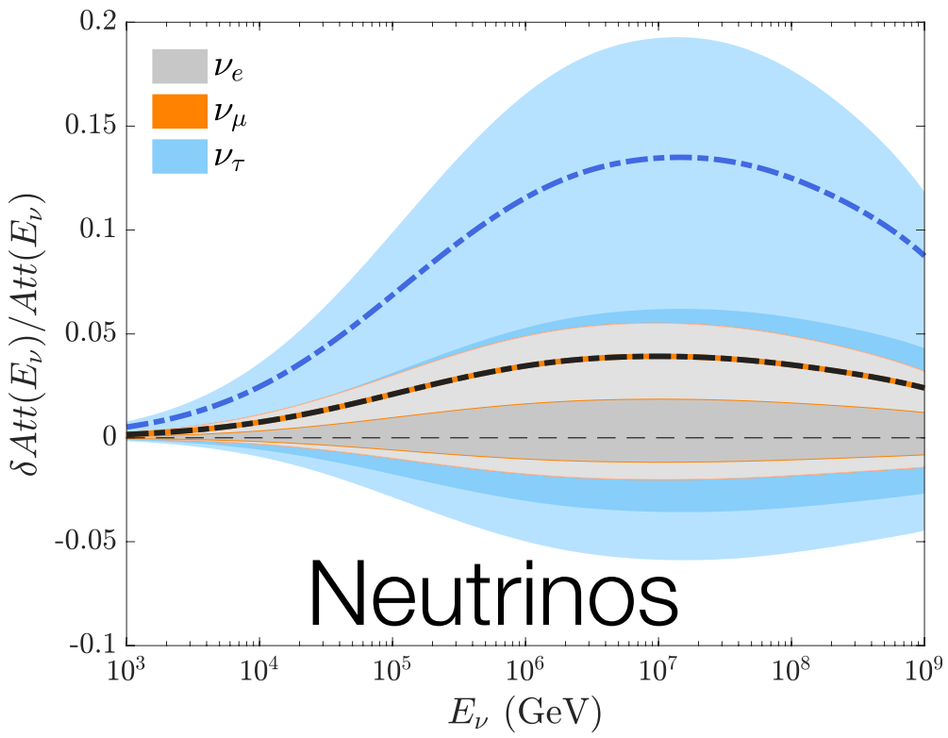
νFATE: average attenuation of upgoing flux

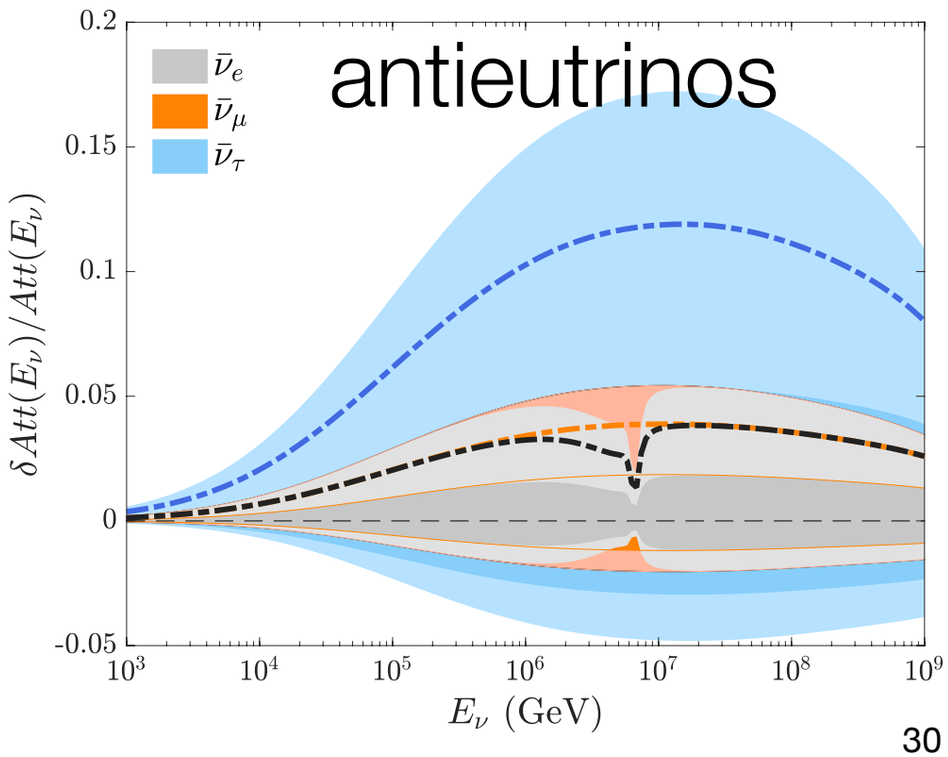






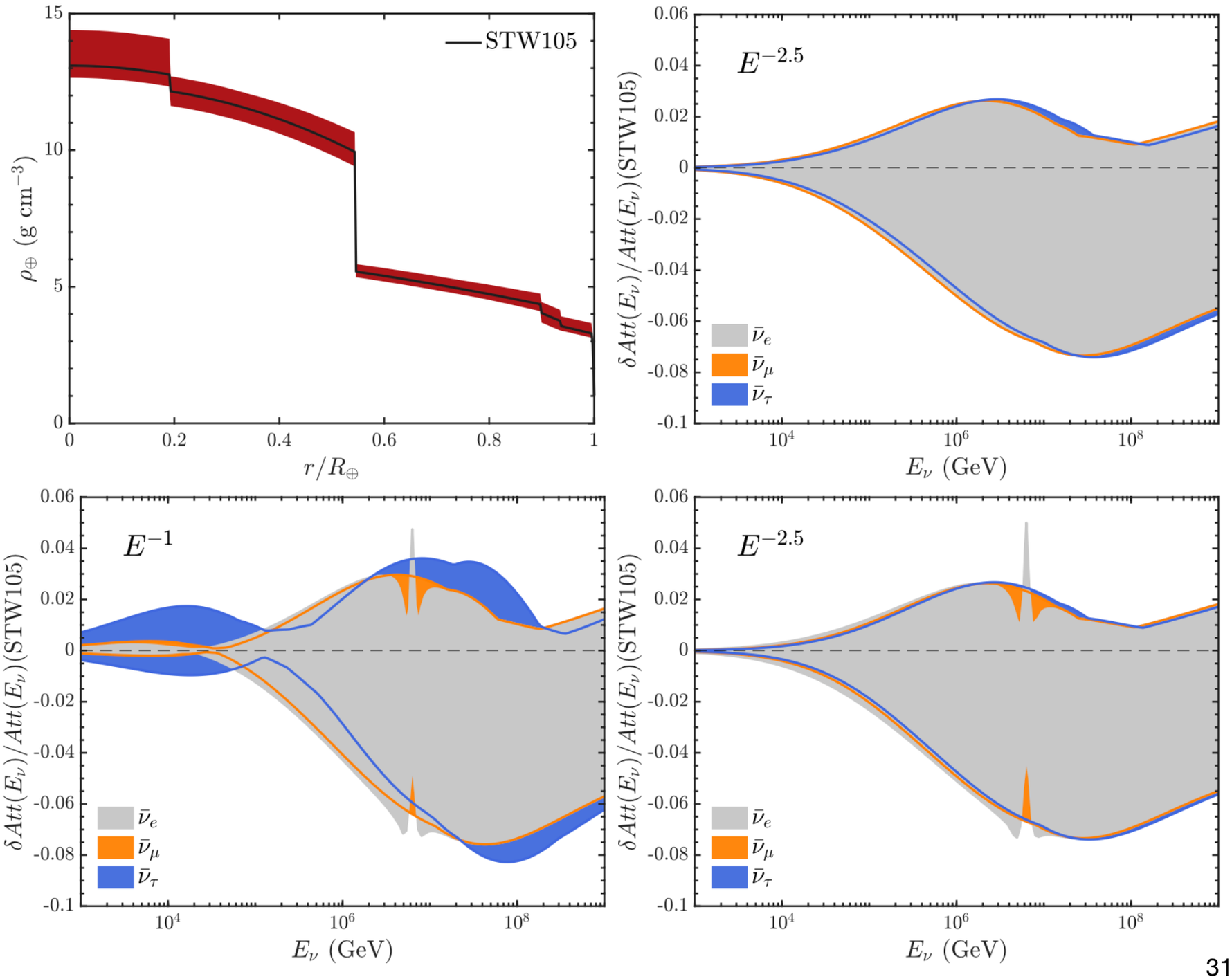
propagation of uncertainty on astro spectral index





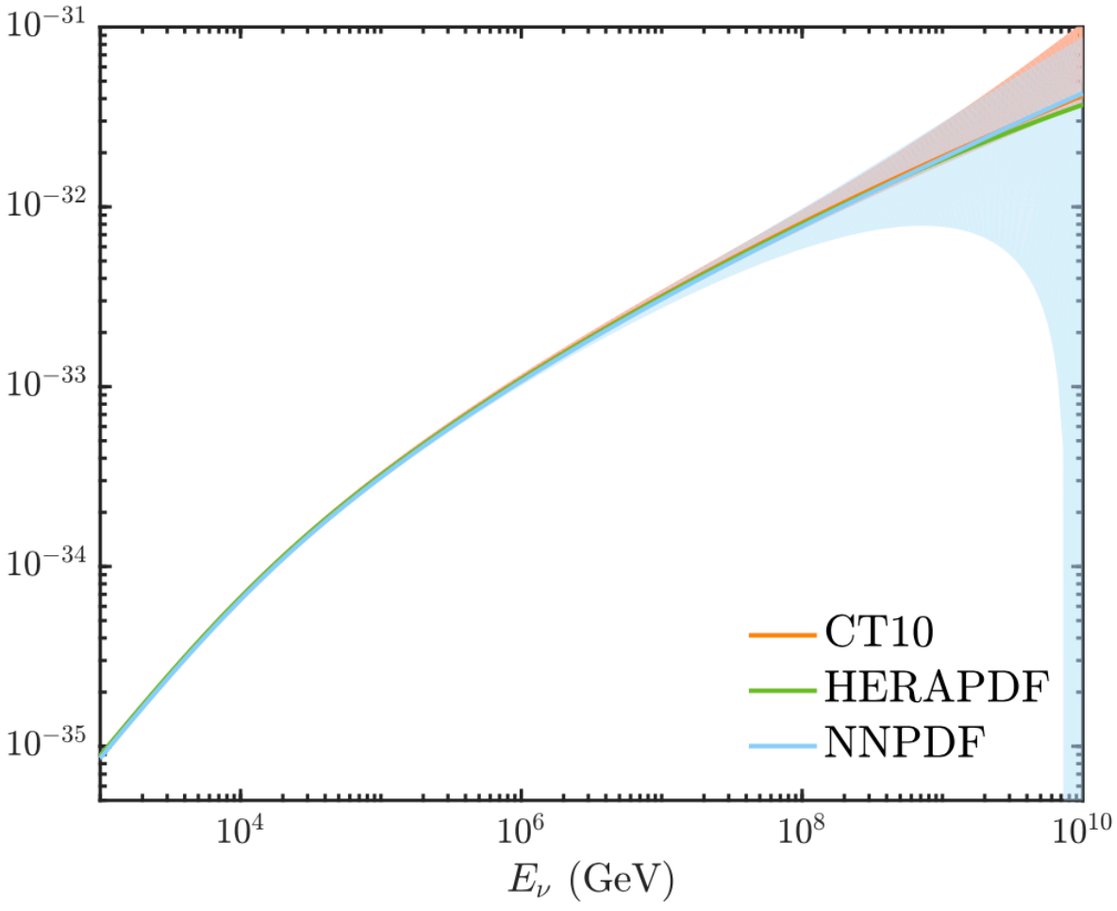
Earth composition uncertainty

10% uncertainty constrained by total mass & moment of inertia

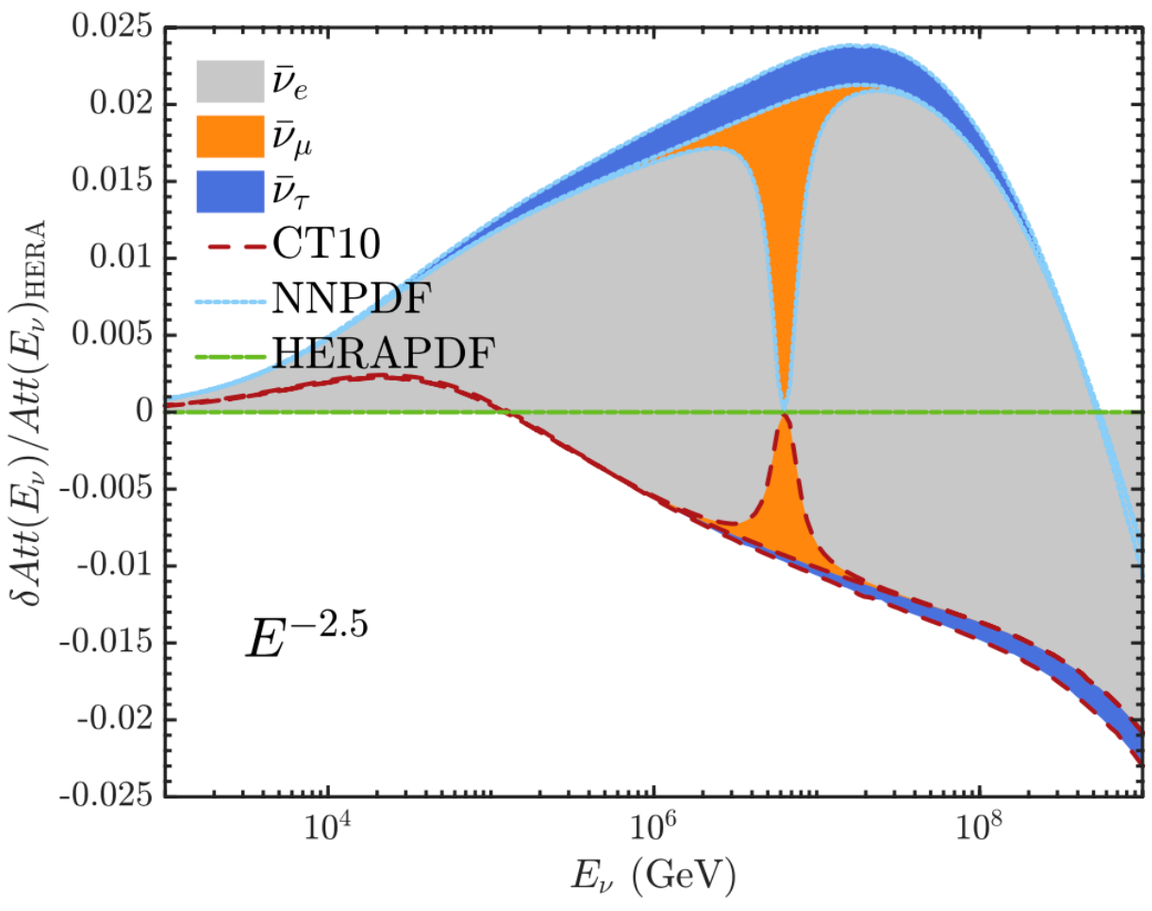


Parton distribution functions (PDFs)

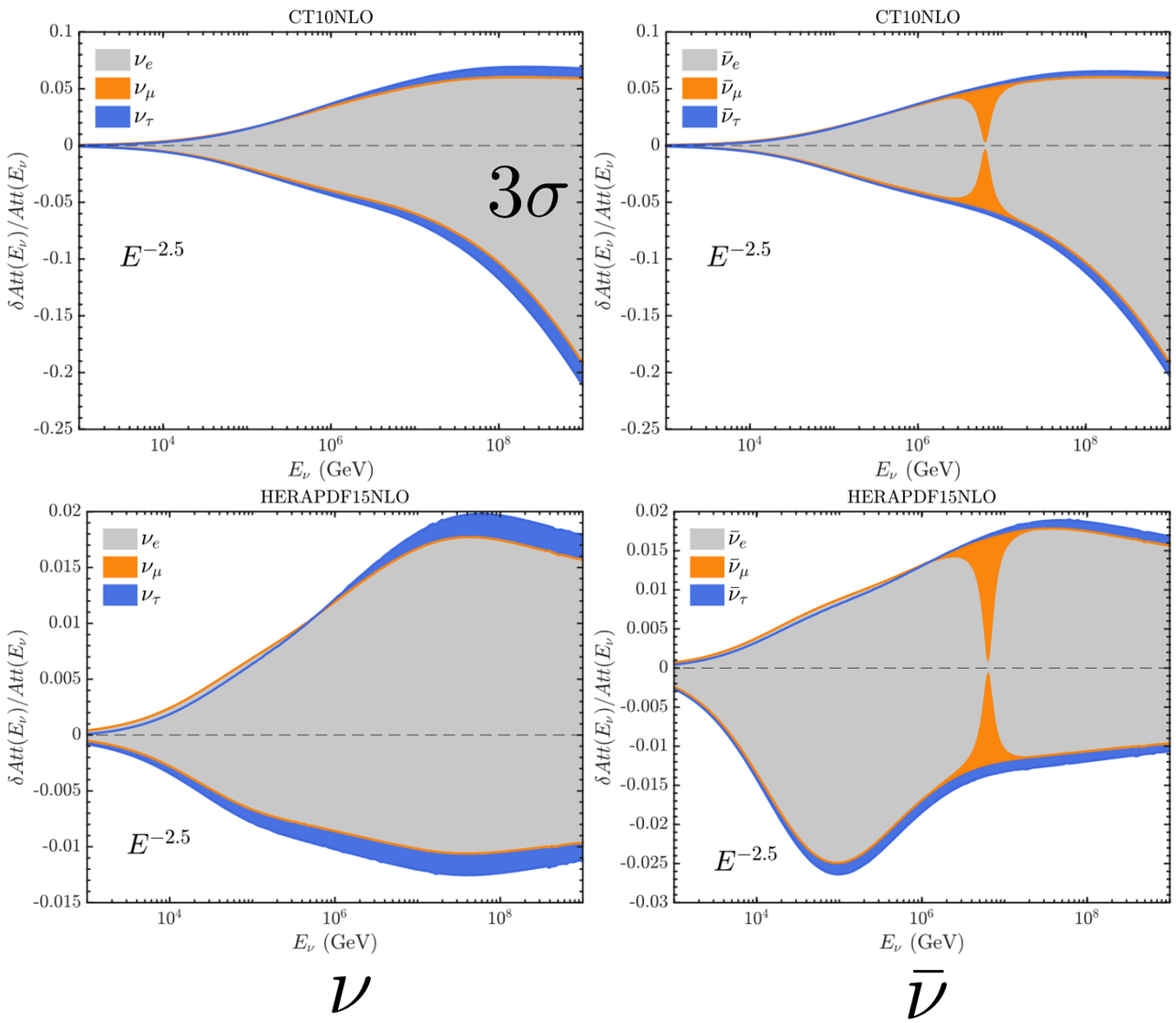
Cross section



Attenuation

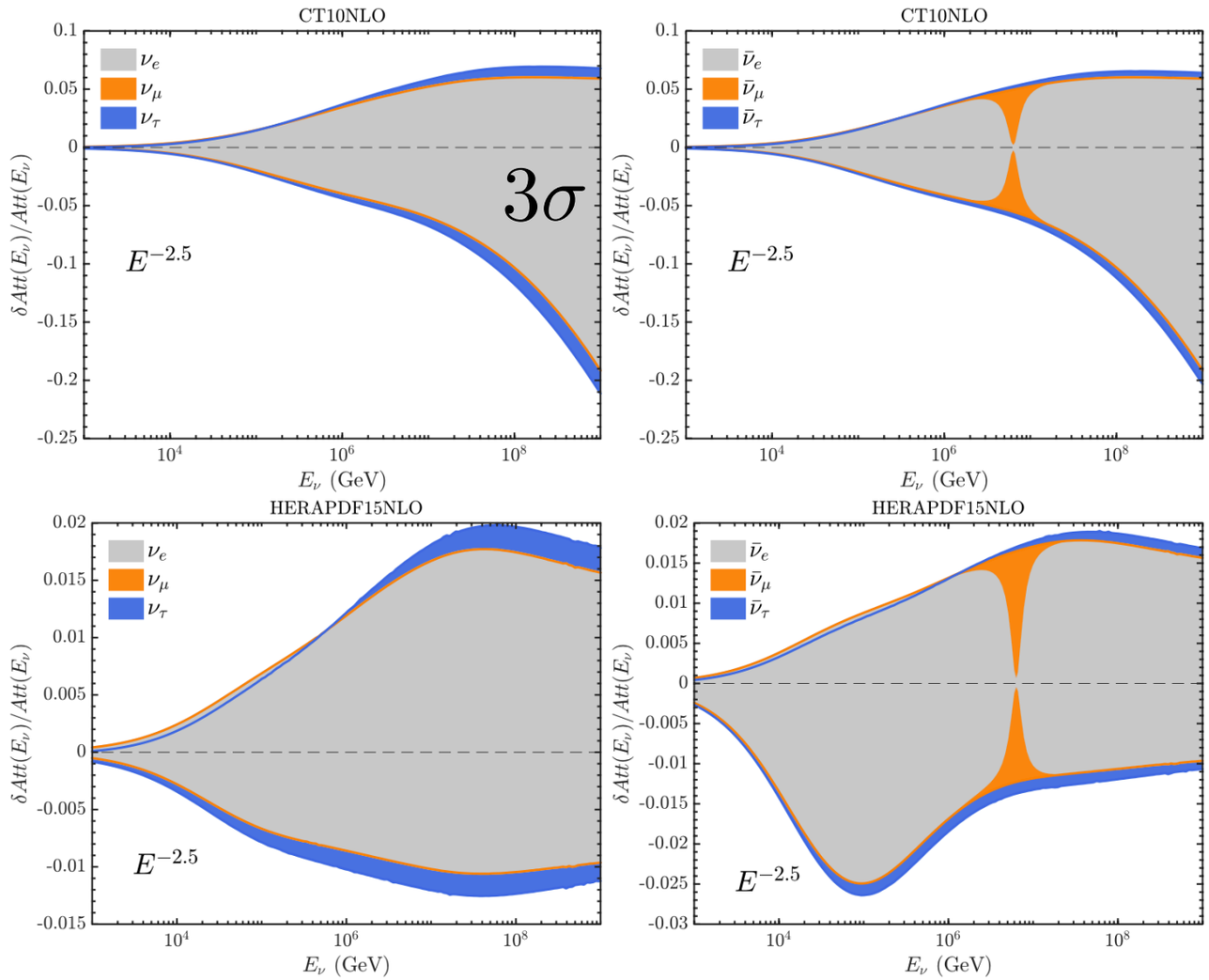


PDFs: errors

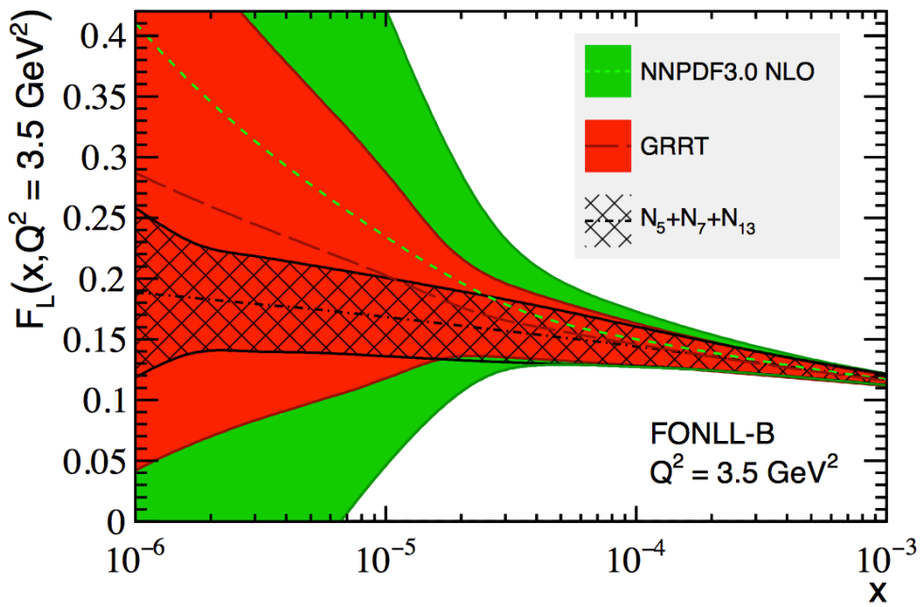

CT10NLO
ν_e
ν_μ
ν_τ
3σ
$E^{-2.5}$
$\delta Att(E_\nu)/Att(E_\nu)$
E_ν (GeV)
CT10NLO
$\bar{\nu}_e$
$\bar{\nu}_\mu$
$\bar{\nu}_\tau$
$E^{-2.5}$
$\delta Att(E_\nu)/Att(E_\nu)$
E_ν (GeV)
HERAPDF15NLO
ν_e
ν_μ
ν_τ
$E^{-2.5}$
$\delta Att(E_\nu)/Att(E_\nu)$
E_ν (GeV)
HERAPDF15NLO
$\bar{\nu}_e$
$\bar{\nu}_\mu$
$\bar{\nu}_\tau$
$E^{-2.5}$
$\delta Att(E_\nu)/Att(E_\nu)$
E_ν (GeV)
ν
$\bar{\nu}$

PDFs: errors

Probably underestimated:
most PDF sets don't go to very low *x*



ν $\bar{\nu}$



Gauld,Rojo 1610.09373