Imaging Galactic Dark Matter with IceCube High-Energy Cosmic Neutrinos

Aaron Vincent

IceCube Particle Astrophysics
Invisibles17, Zurich, 15 June 2017

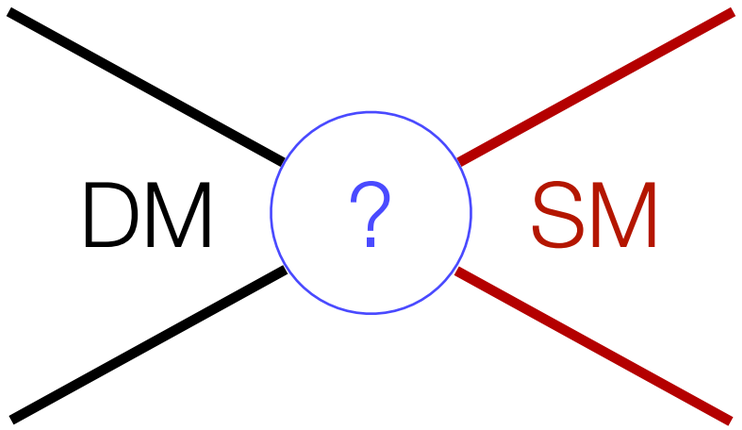
Imperial College London

Based on

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

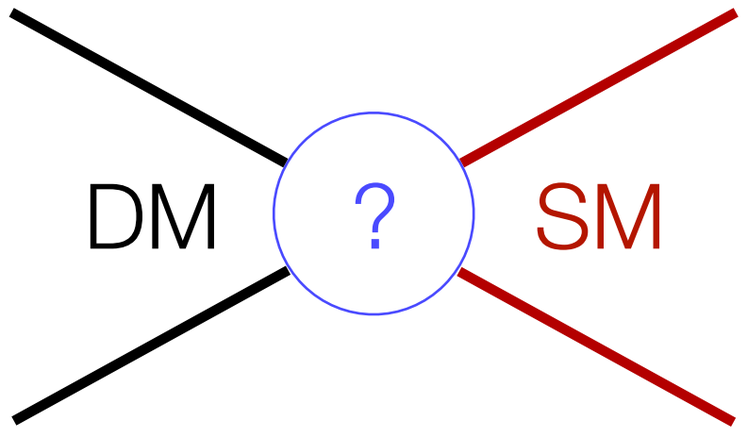
Also *νFATE*: neutrino fast attenuation through earth, coming soon

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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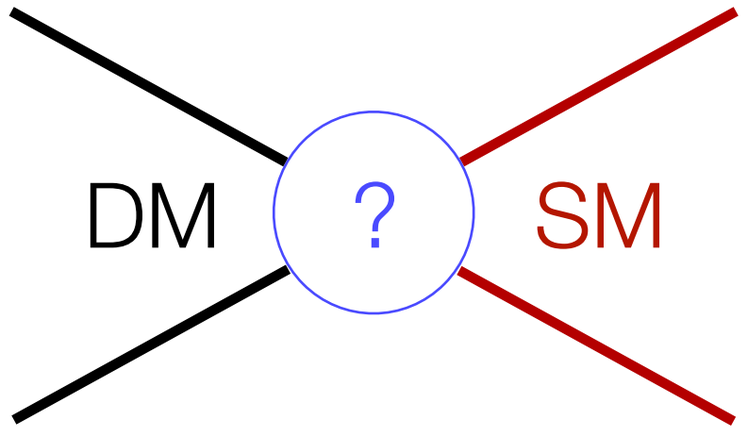

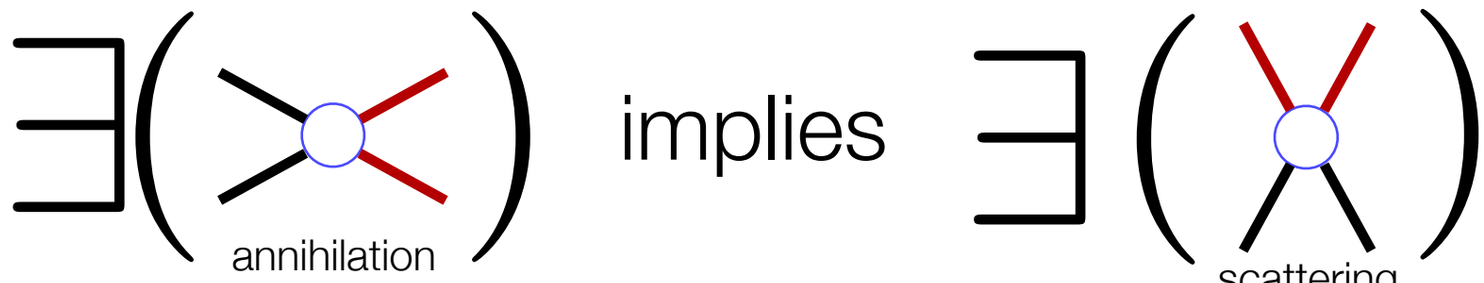

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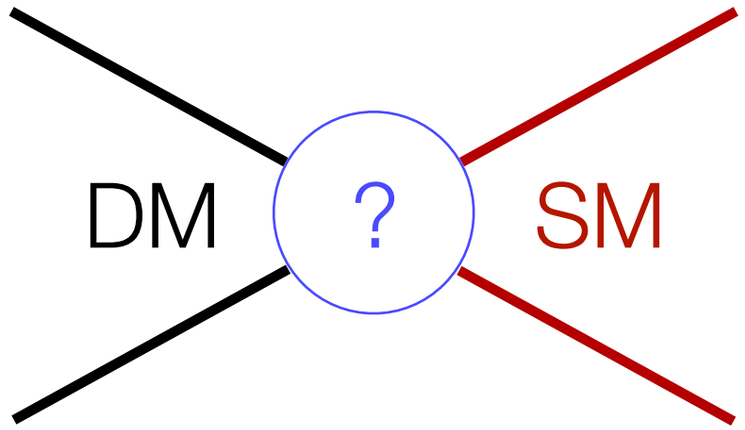
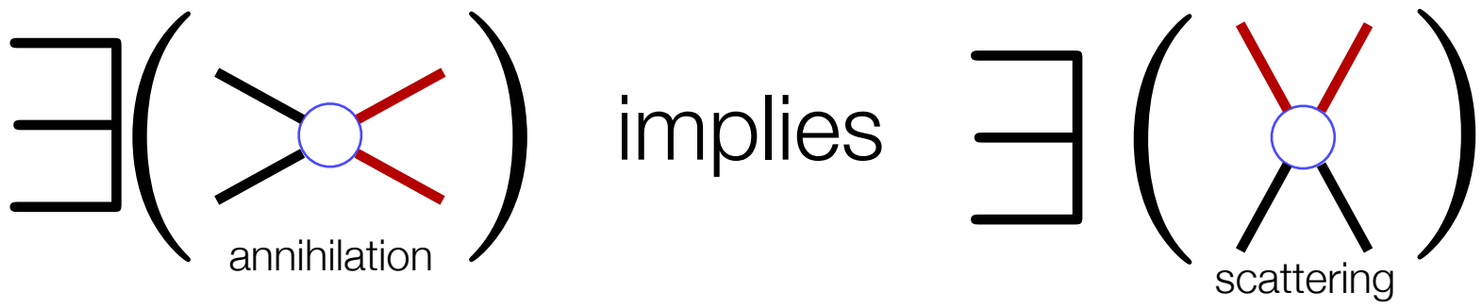
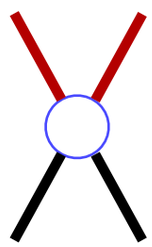




if —— = quarks, then  = direct detection
(LUX, LZ, SuperCDMS, …)

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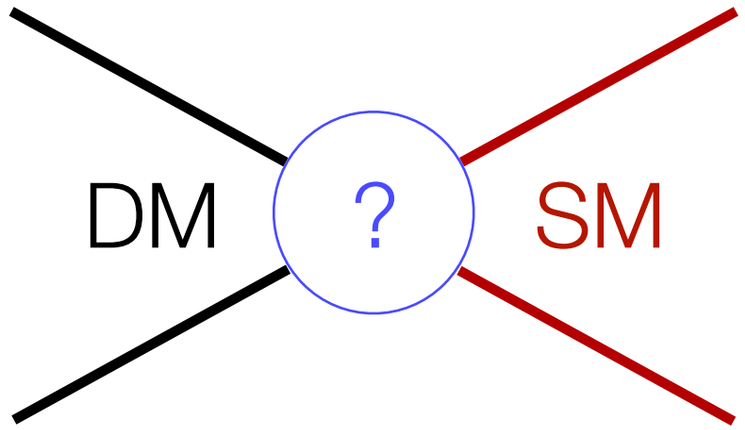
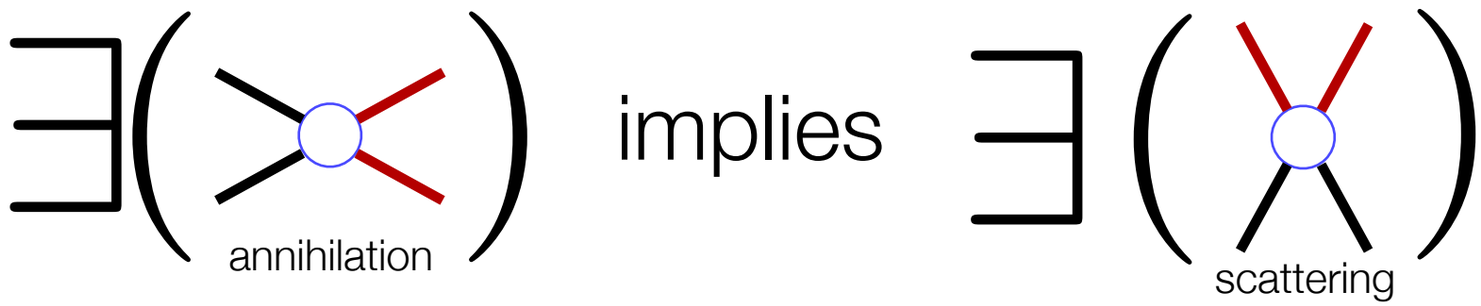
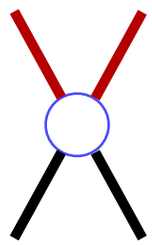




if —— = quarks, then  = direct detection
(LUX, LZ, SuperCDMS, …)

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].
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[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].
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(a few references)

DM-neutrino interactions: cosmology

t s minutes 300kyr 13.5 Gyr

T 2 MeV .5 MeV eV 10^{-4} eV

a = 10^{-10} 10^{-10} 10^{-3} 1

1/(1+z)

D, He formed

Neutrinos decouple, neutron production stops

Recombination CMB formed

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Neutrinos decouple, neutron production stops

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If DM becomes nonrelativistic here:
more entropy in neutrino sector than LCDM predicts

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

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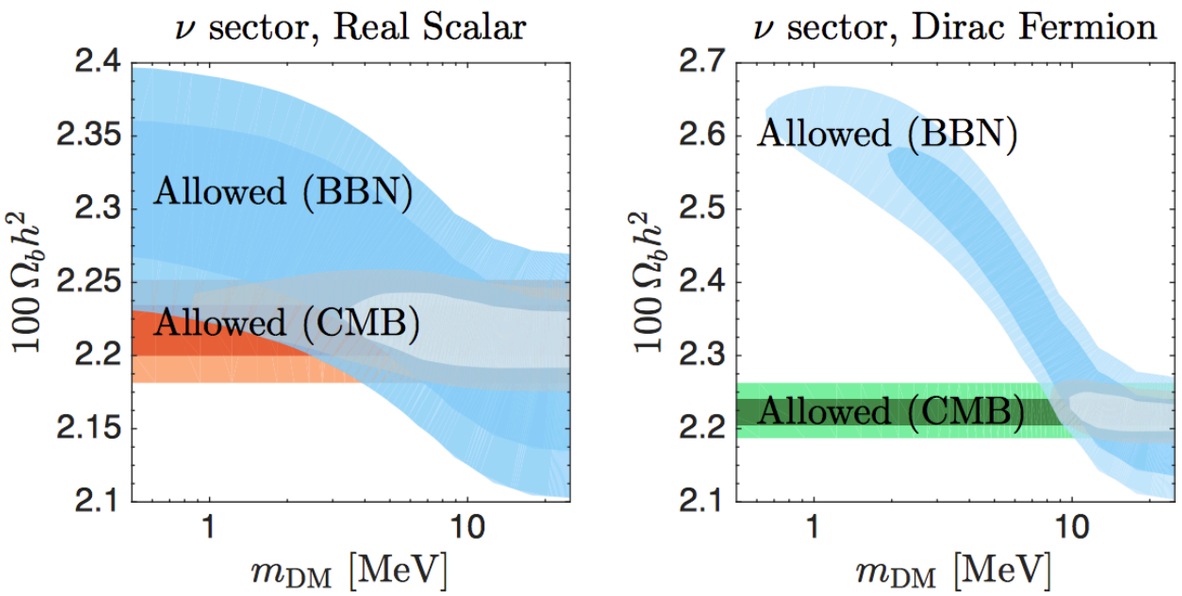
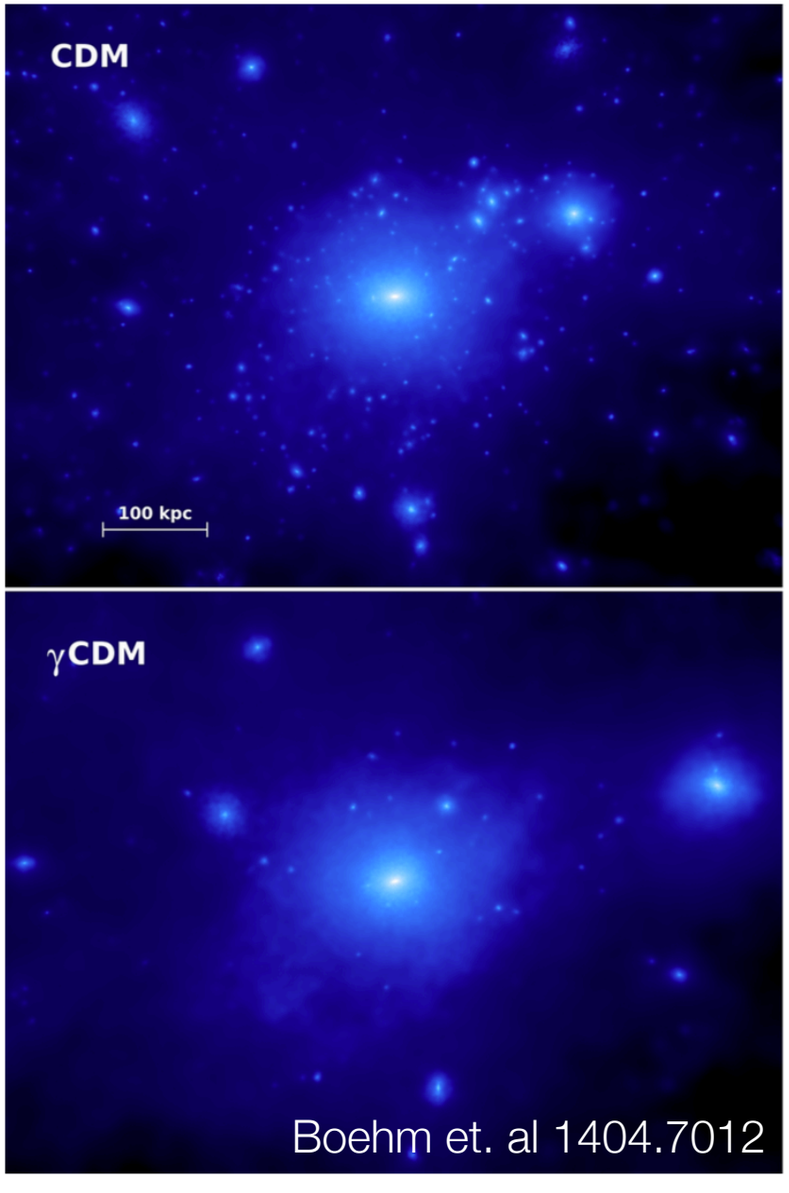


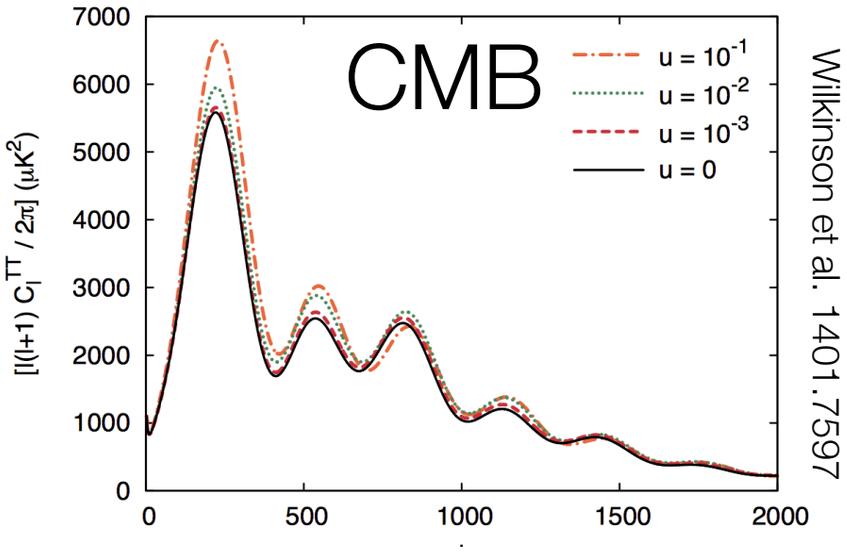
R. Wilkinson, ACV, C. Boehm, C. McCabe 1602.01114

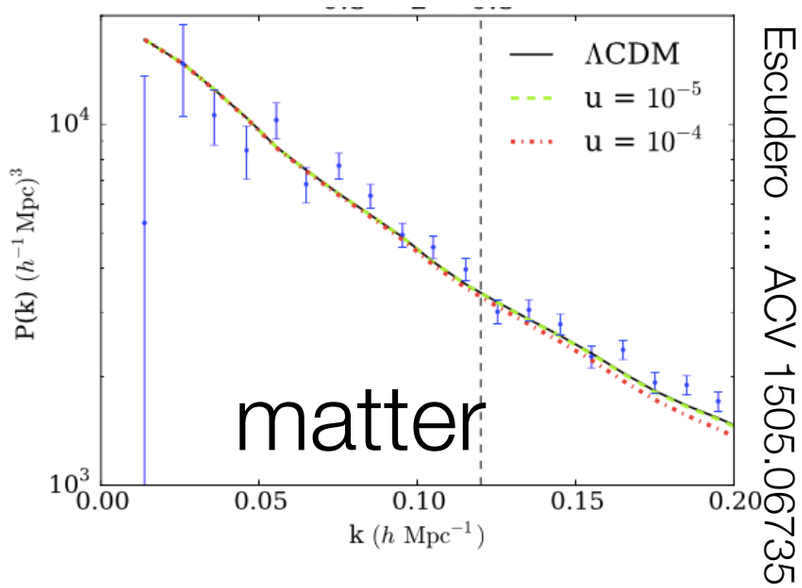
$$m_\chi \gtrsim 5 - 10\text{MeV}$$

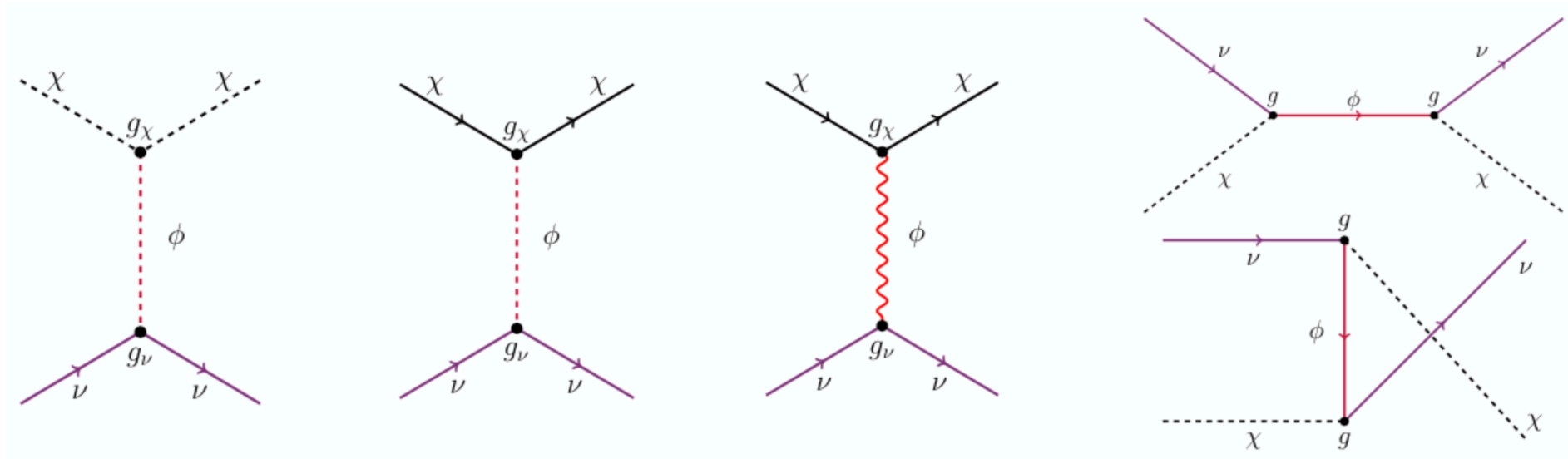
DM-neutrino interactions: cosmology (II)

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

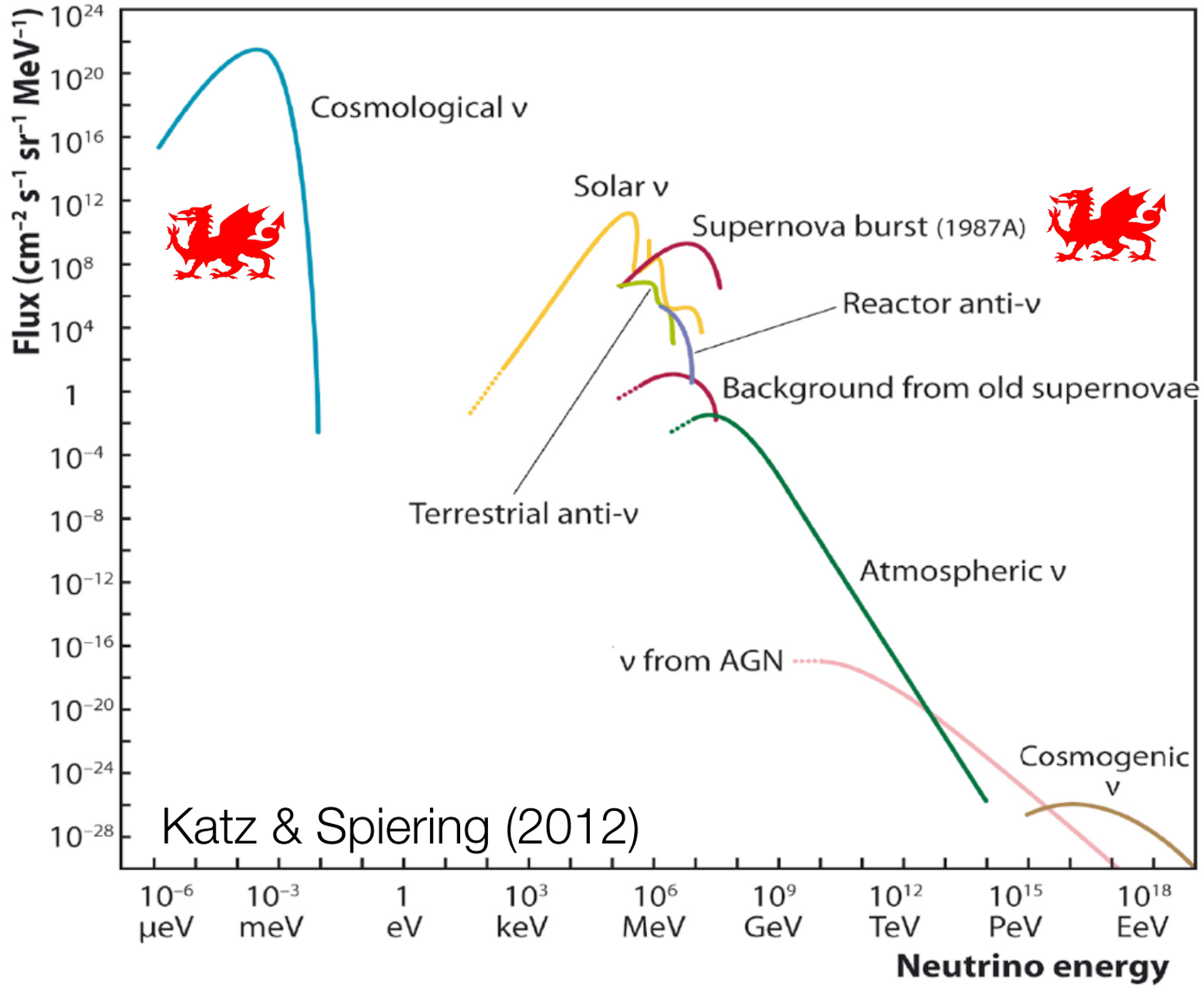
$$\sigma_{DM-\nu} \propto E_\nu^2$$

IceCube has seen events above a PeV….

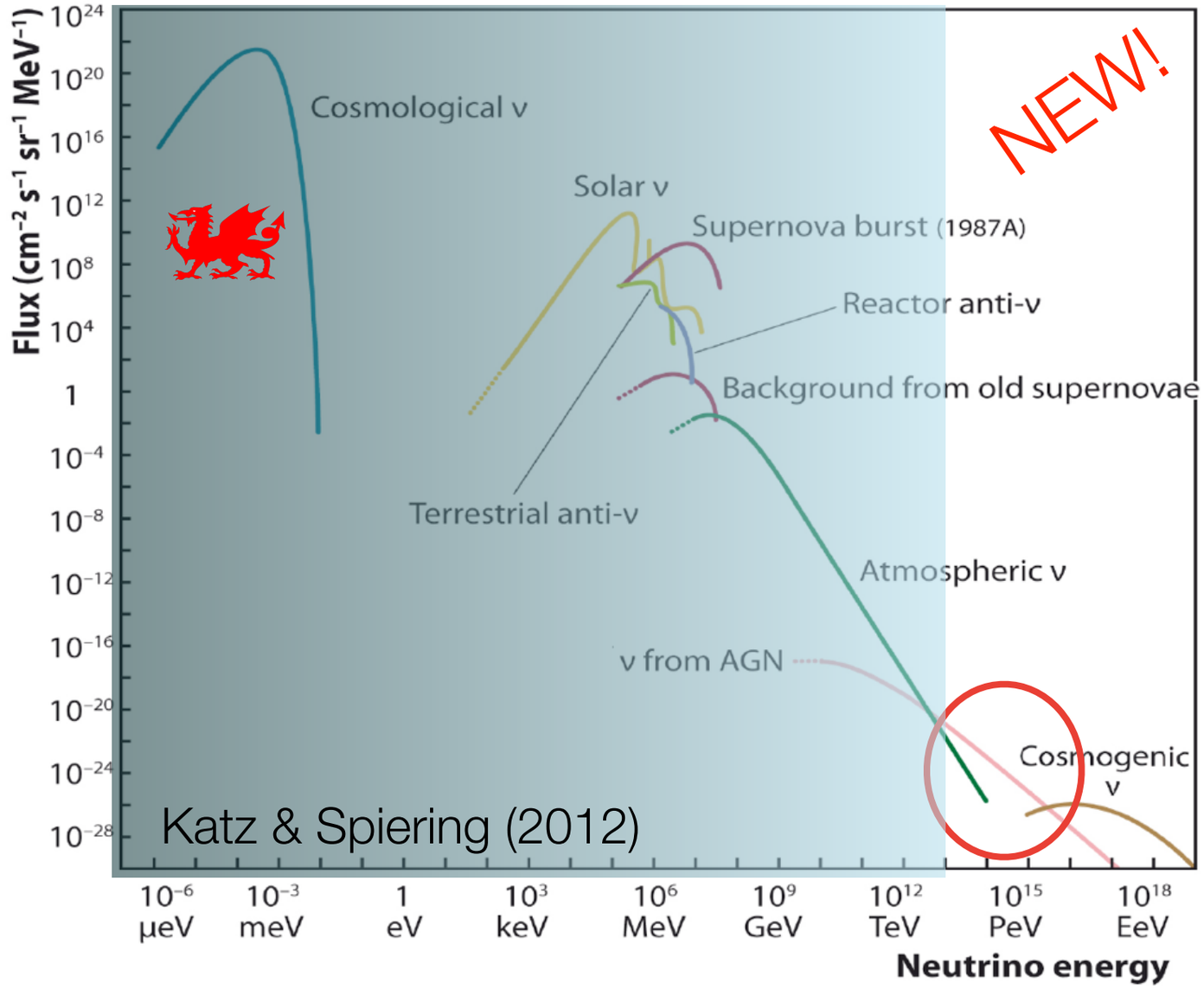
$$\left(\frac{\mathrm{PeV}}{T_{\nu,recomb.}}\right)^2 \sim 10^{30}$$

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


NEW!
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10⁻¹⁶
10⁻²⁰
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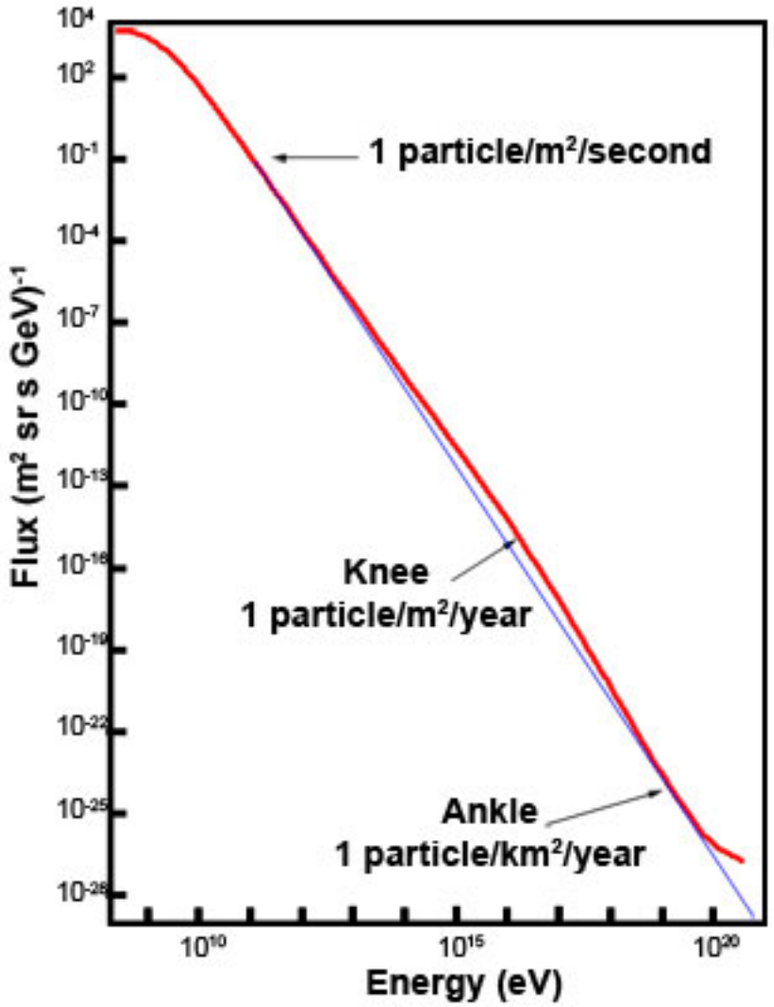
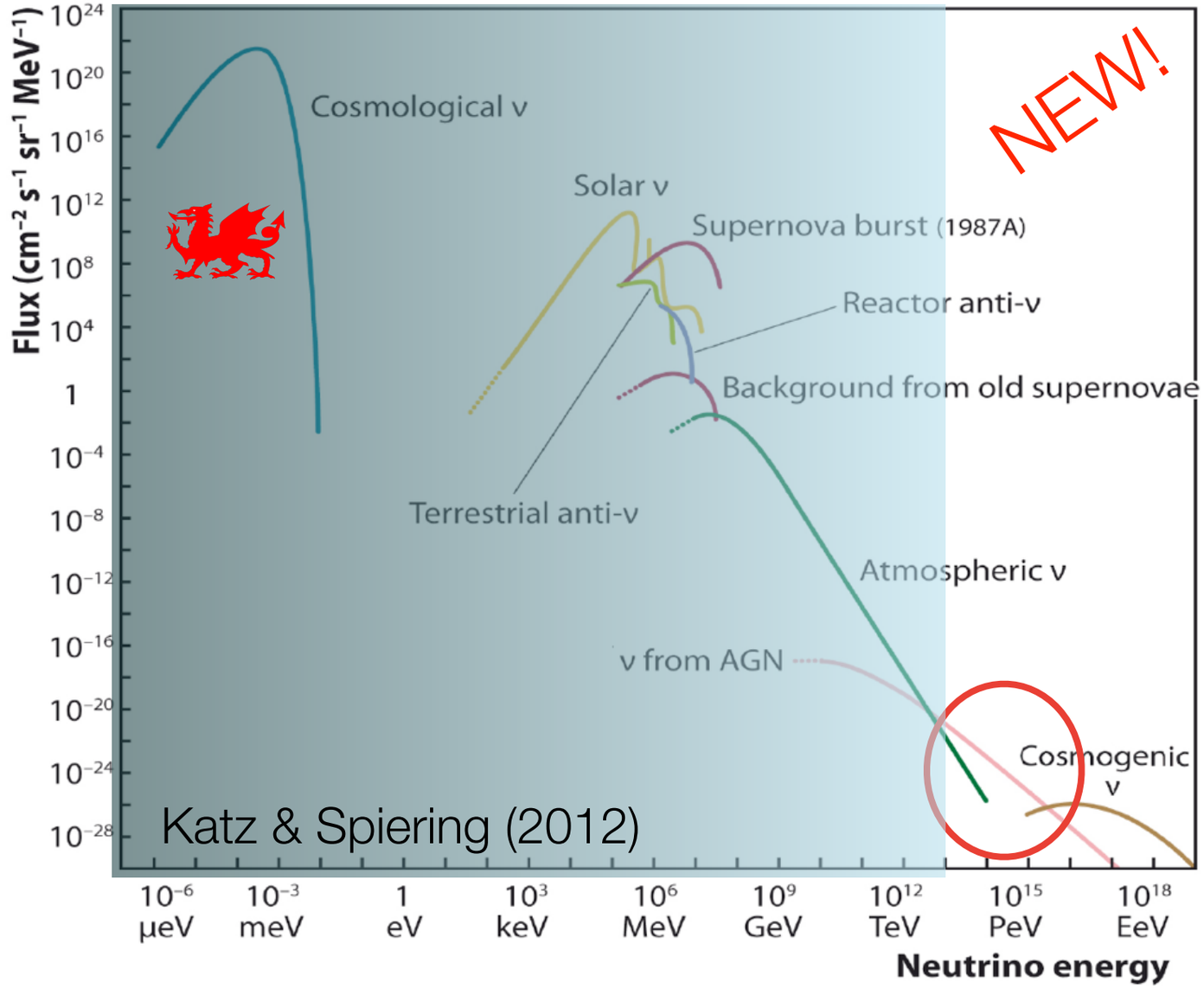
10¹⁸ EeV
Neutrino energy

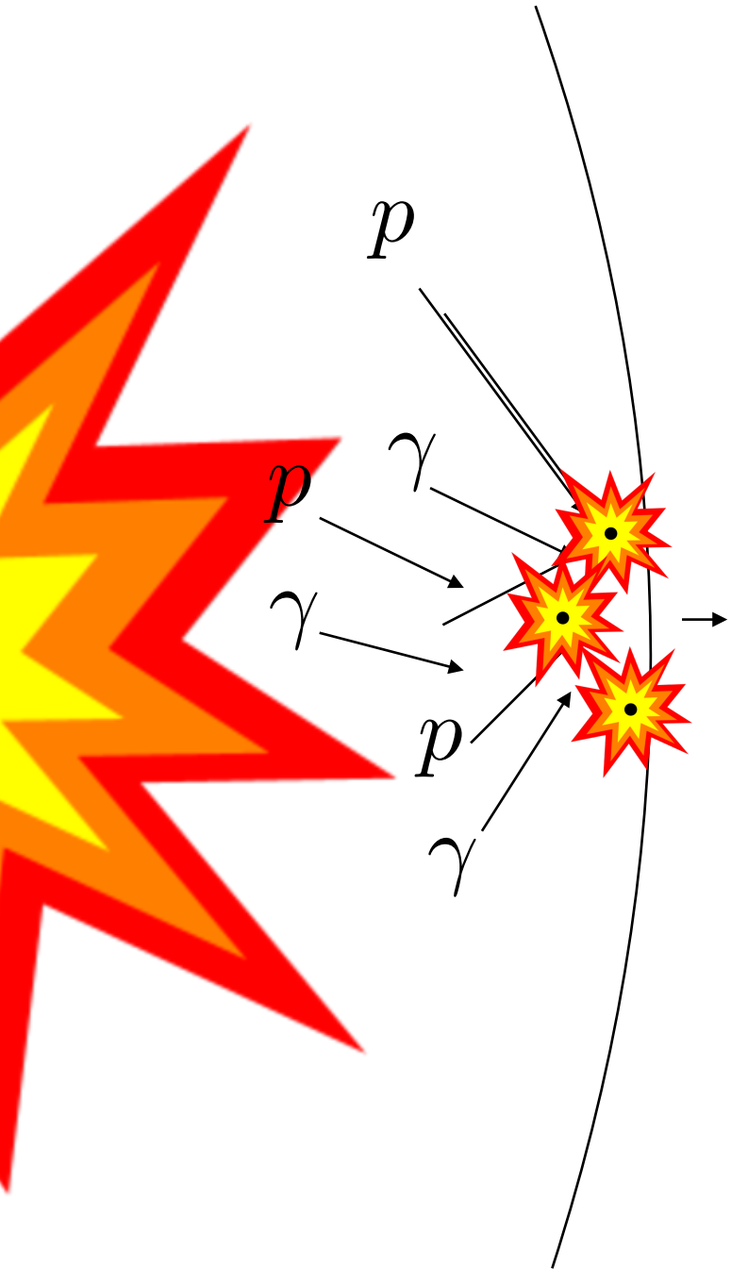
Cosmic rays

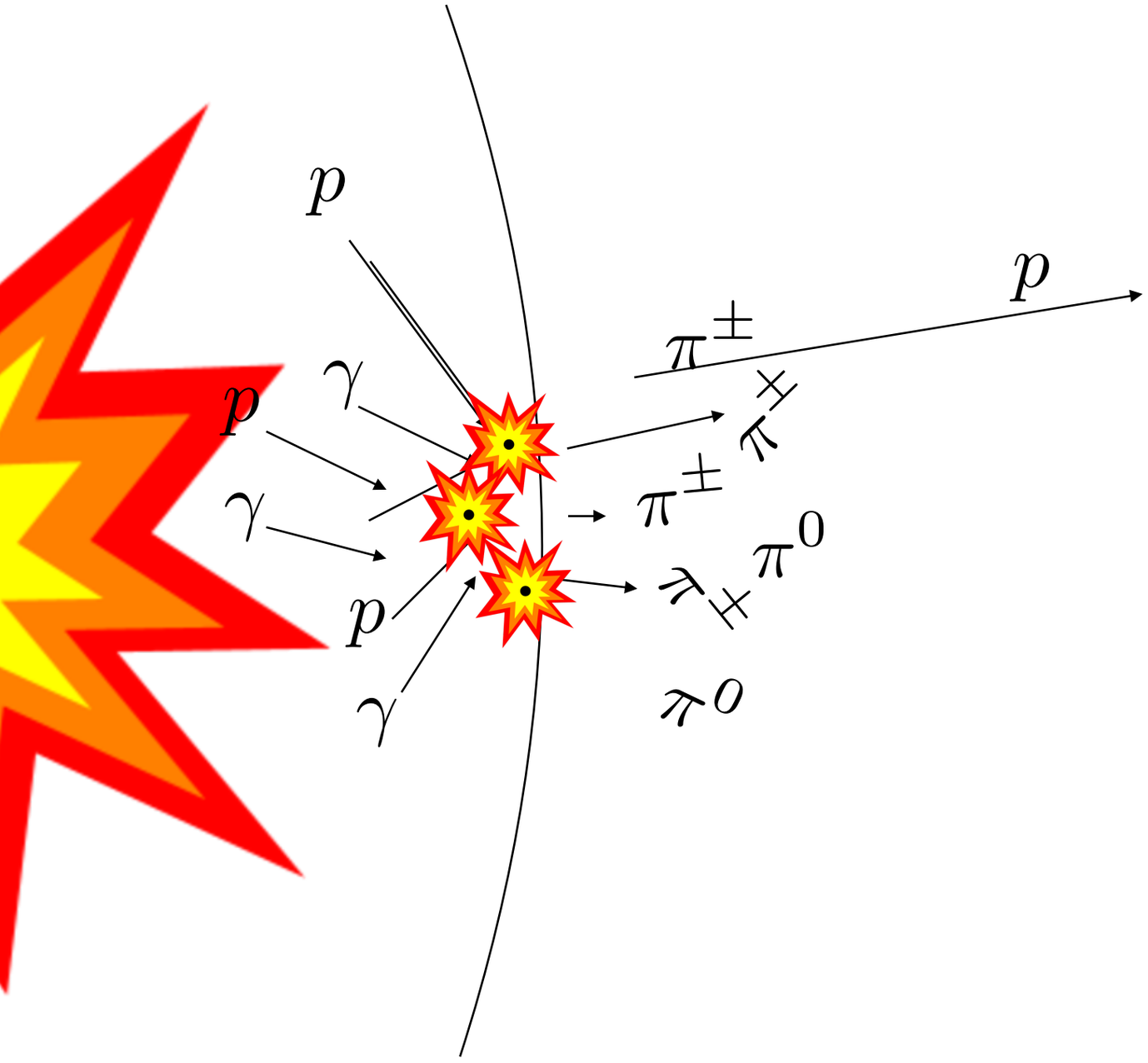


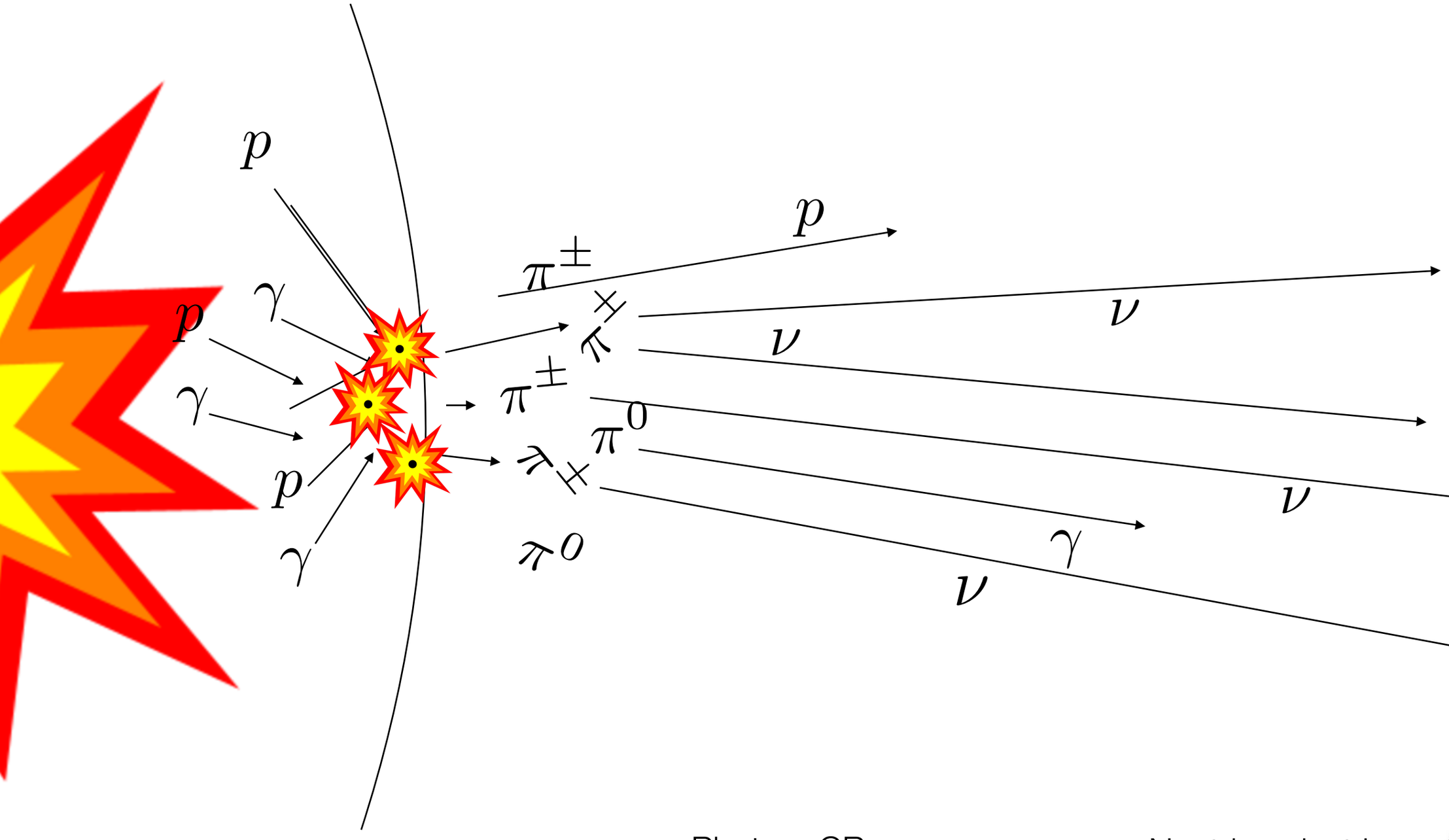
Neutrinos



We see high-energy (>> TeV) **cosmic rays** and **gamma rays**, so we know associated **neutrinos** must be produced

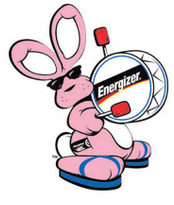

p
γ
p
γ
p
γ


p
γ
p
γ
p
γ
p
π±
π±
π±
π0
π0



Photon, CR
energy limited by
mean free path in CMB

Neutrinos just keep
going….



Astrophysical neutrino flux ~ PeV (Bahcall)

$$\Phi \sim 10^{-13} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

Cross section

$$\sigma(E \sim \mathrm{PeV}) \sim 10^{-33} \mathrm{cm}^2$$

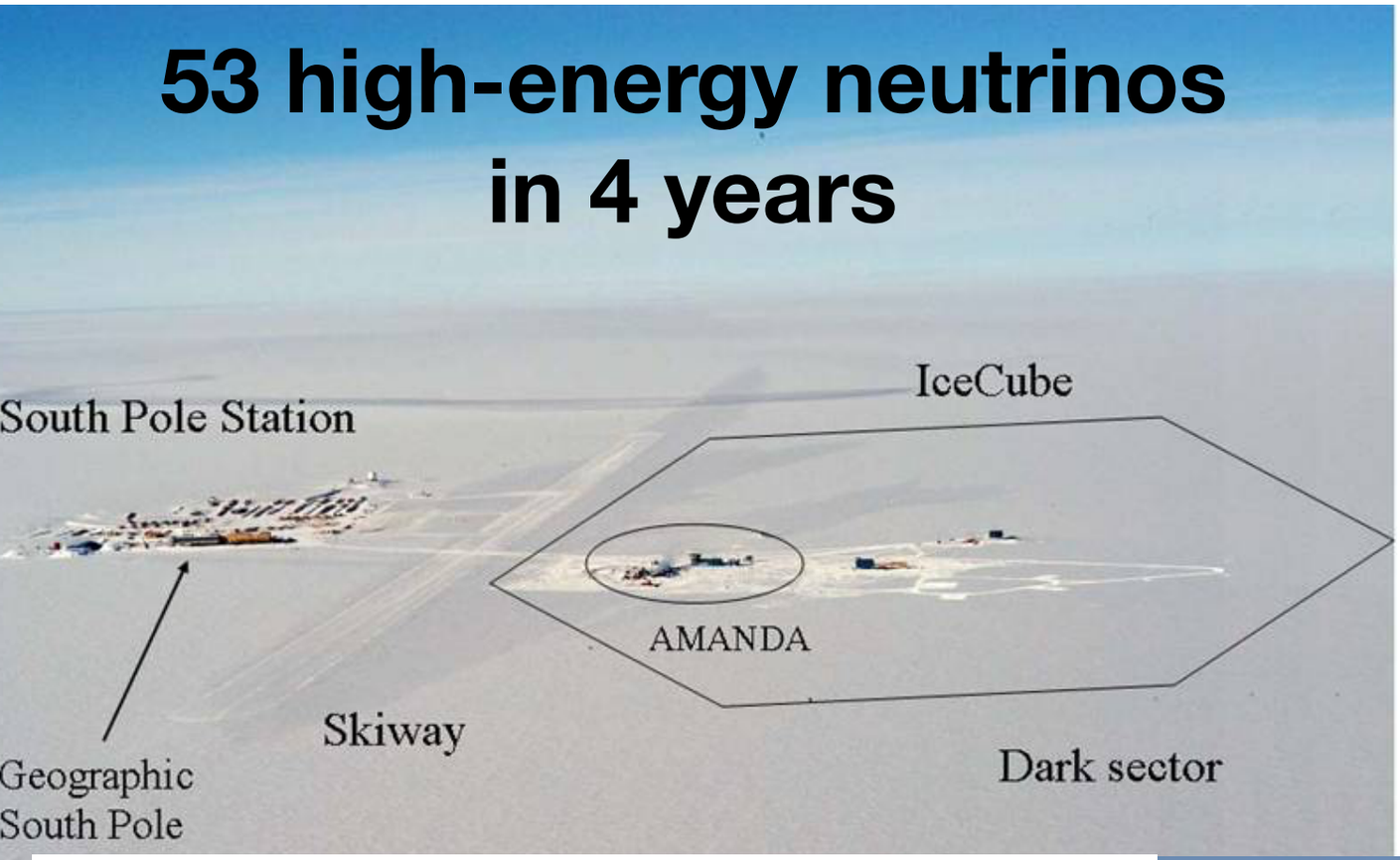
To see a few events per T = year for target density

$$n_{nuc} \sim N_A \mathrm{cm}^{-3}$$

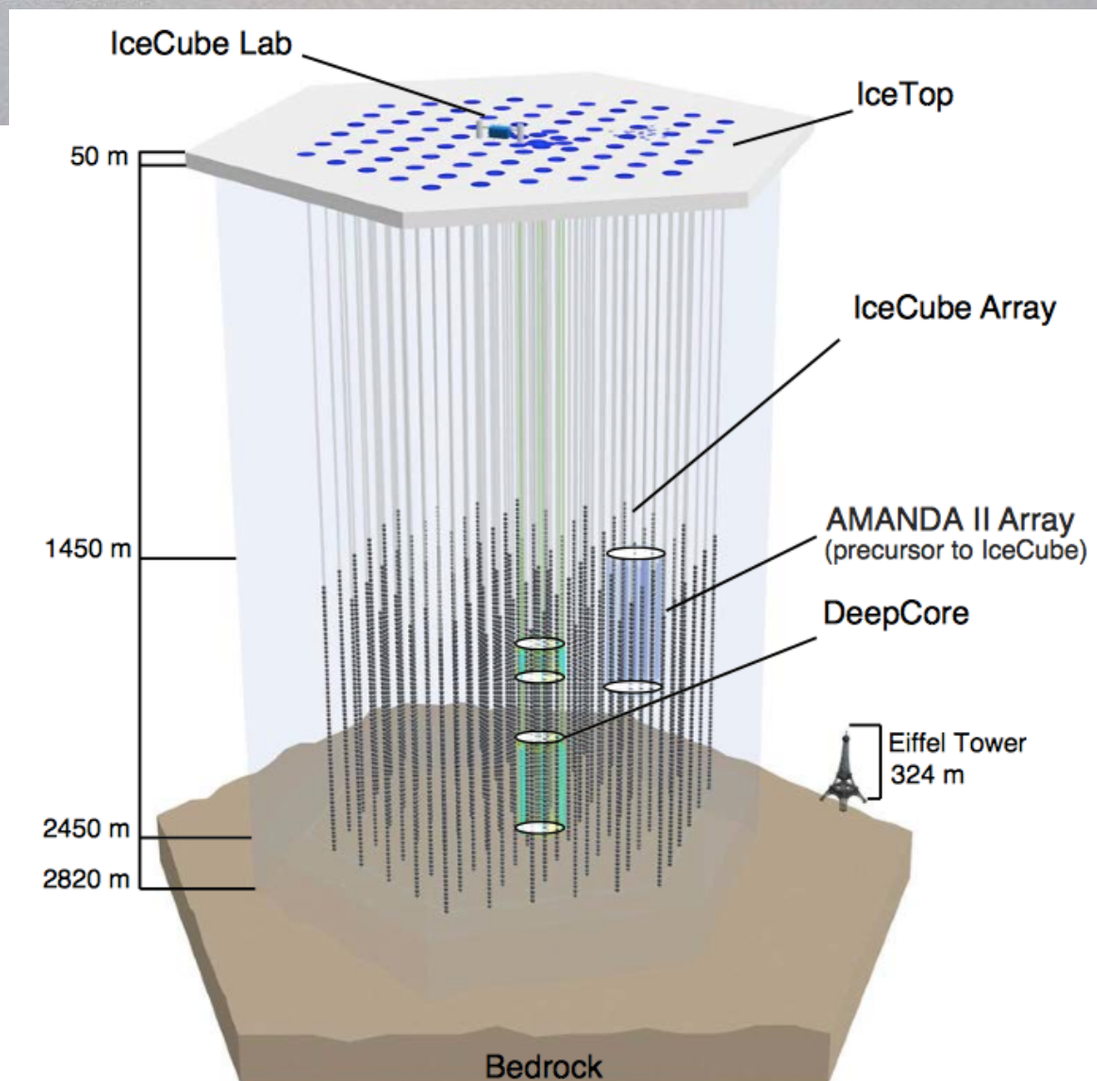
Require detector volume

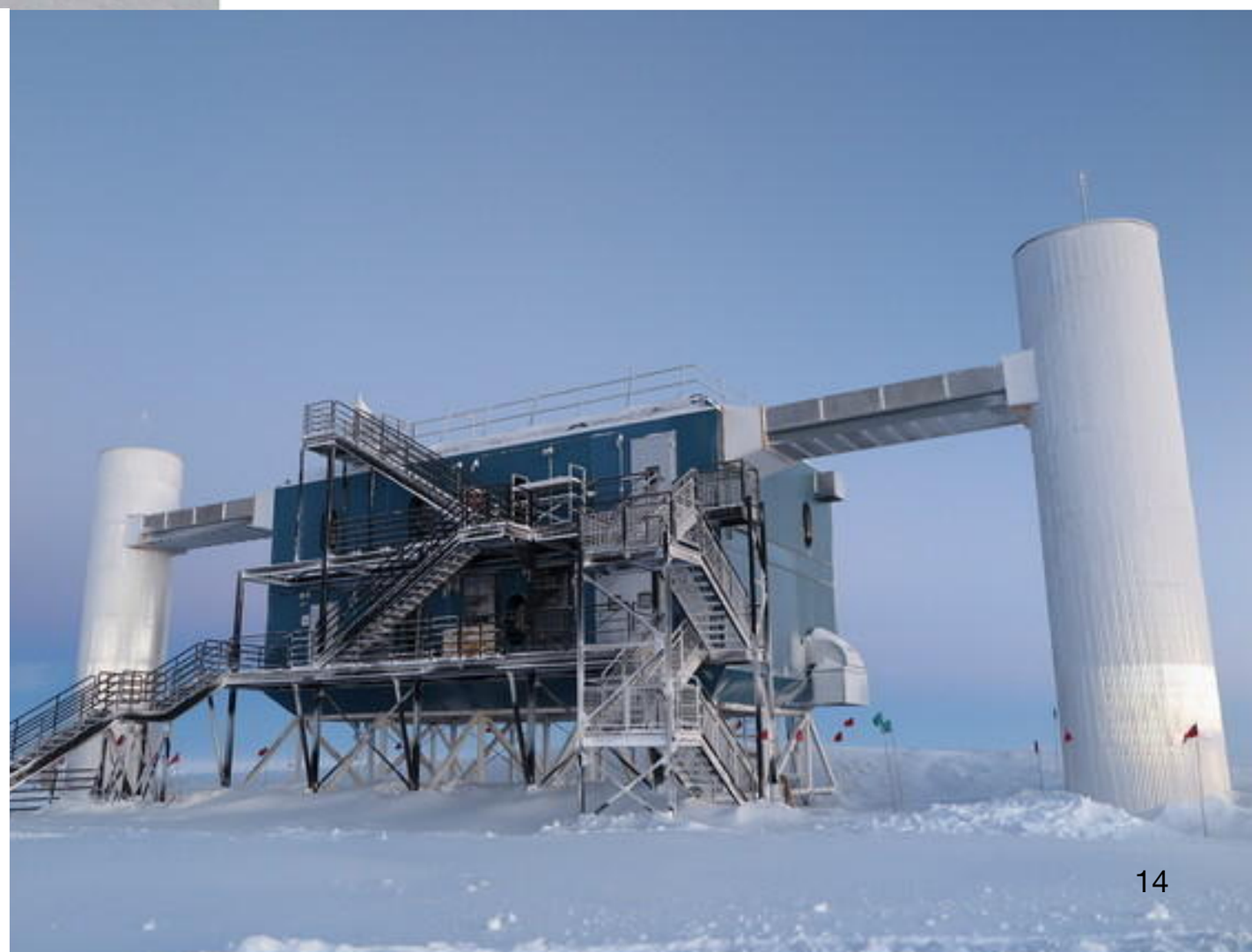
$$V = \frac{1}{T N_A \sigma \Phi} \sim \mathrm{km}^3$$

53 high-energy neutrinos in 4 years



IceCube Neutrino Observatory





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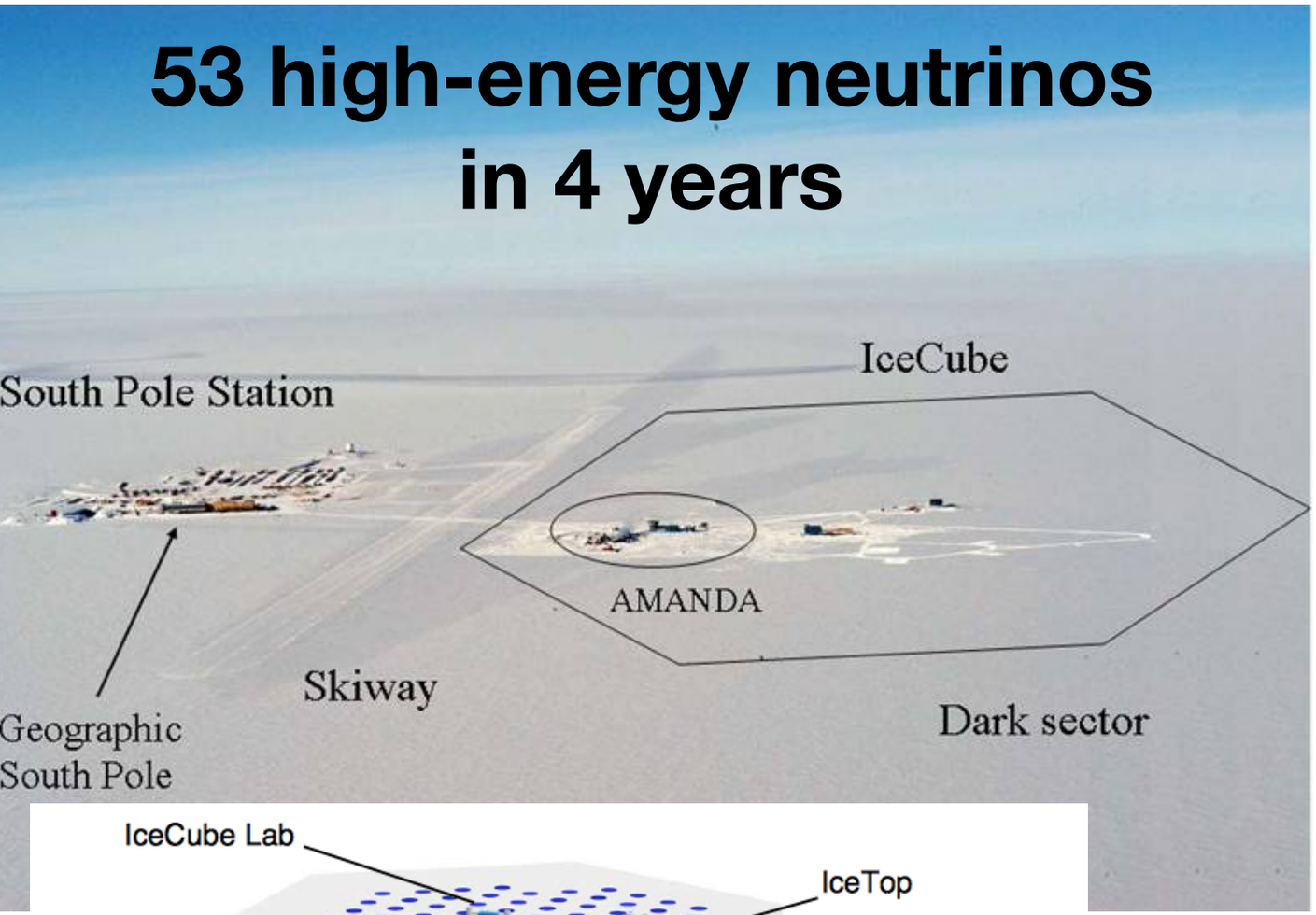
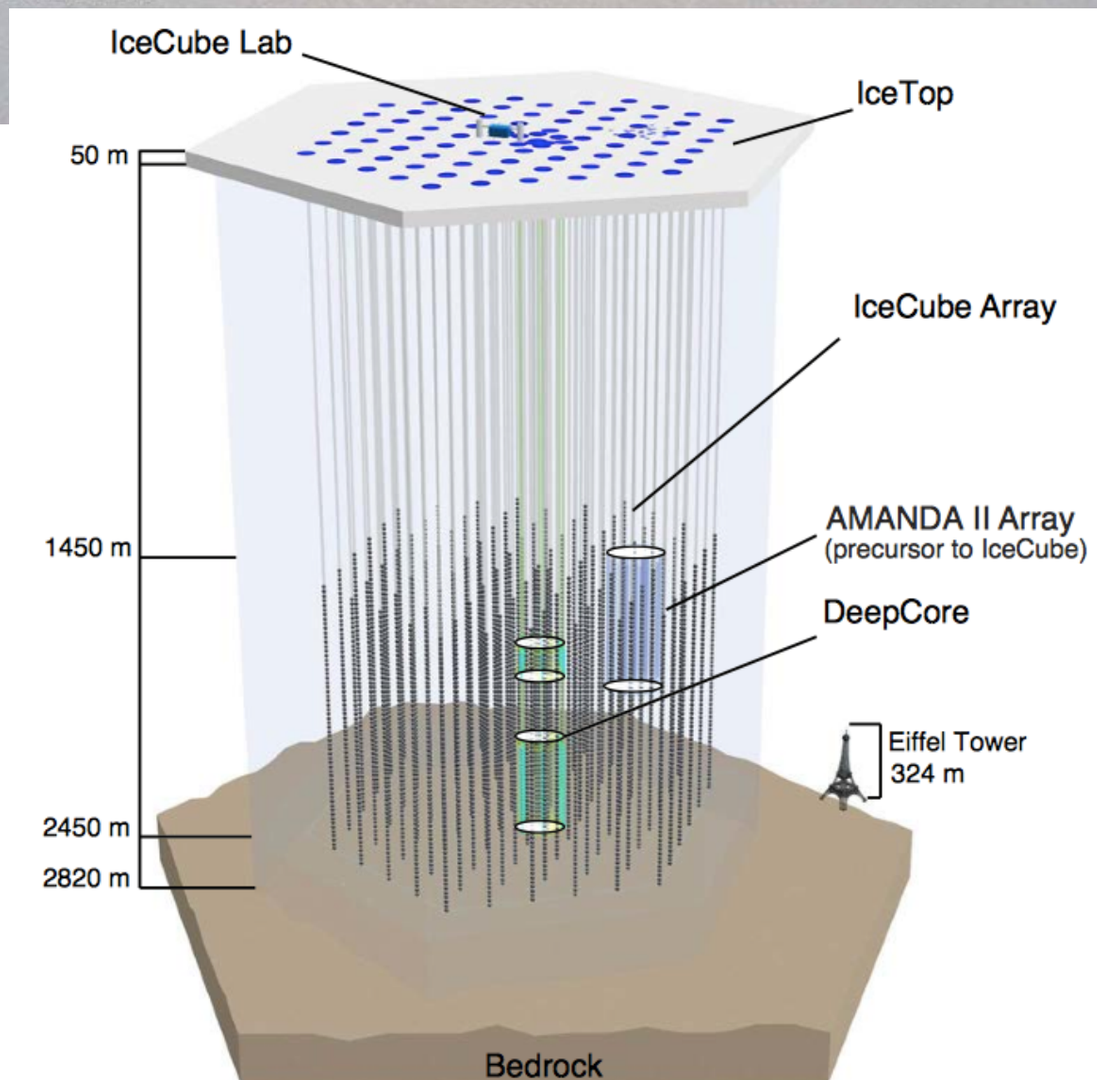
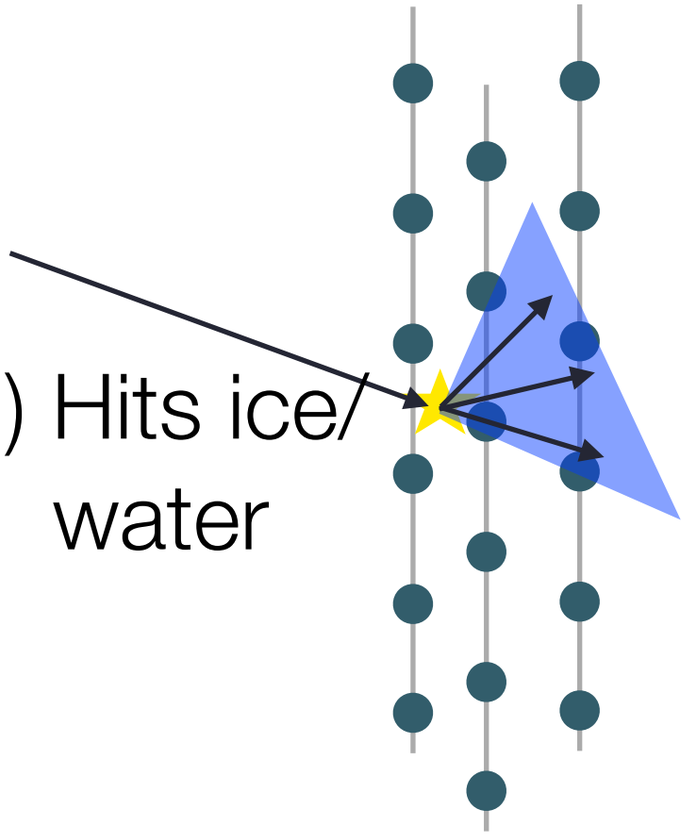




IceCube Neutrino Observatory

1) Neutrino arrives



2) Hits ice/ water

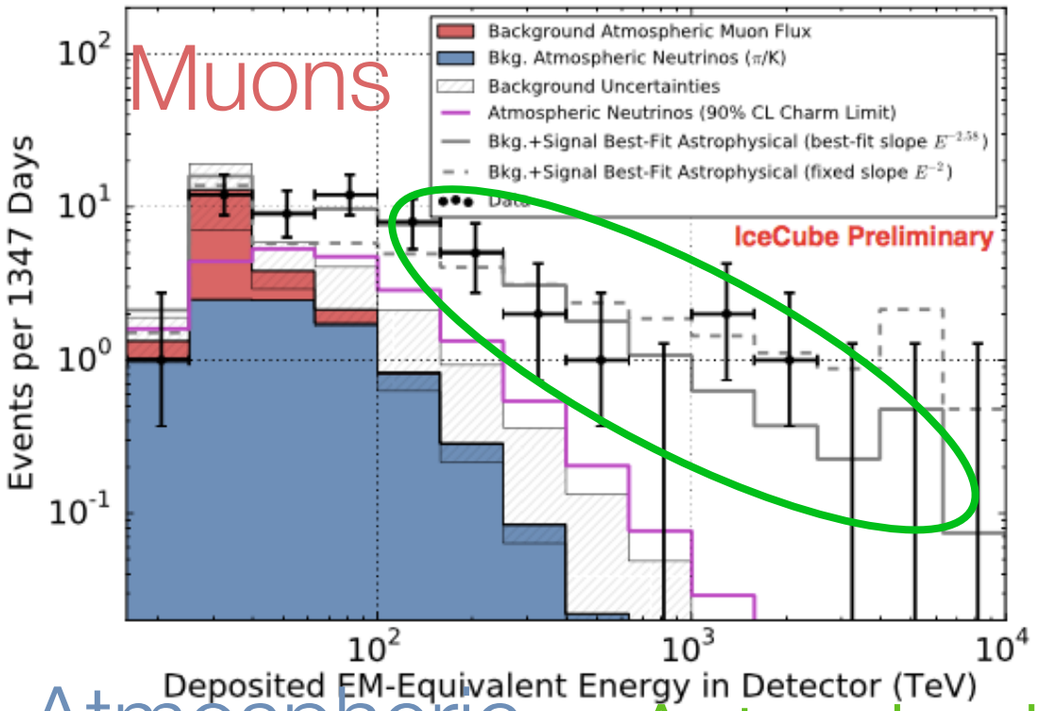
3) DOMs see Čerenkov light from electrons, muons

IceCube High Energy Starting Events (HESEs)

Energy

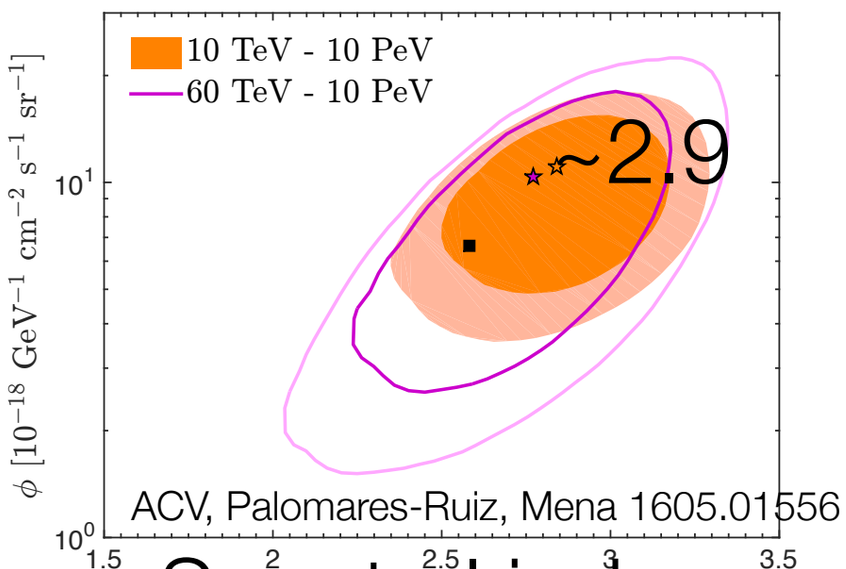
53 events

IceCube ICRC 1510.05223



Atmospheric

Astrophysical



Spectral index

IceCube High Energy Starting Events (HESEs)

Energy

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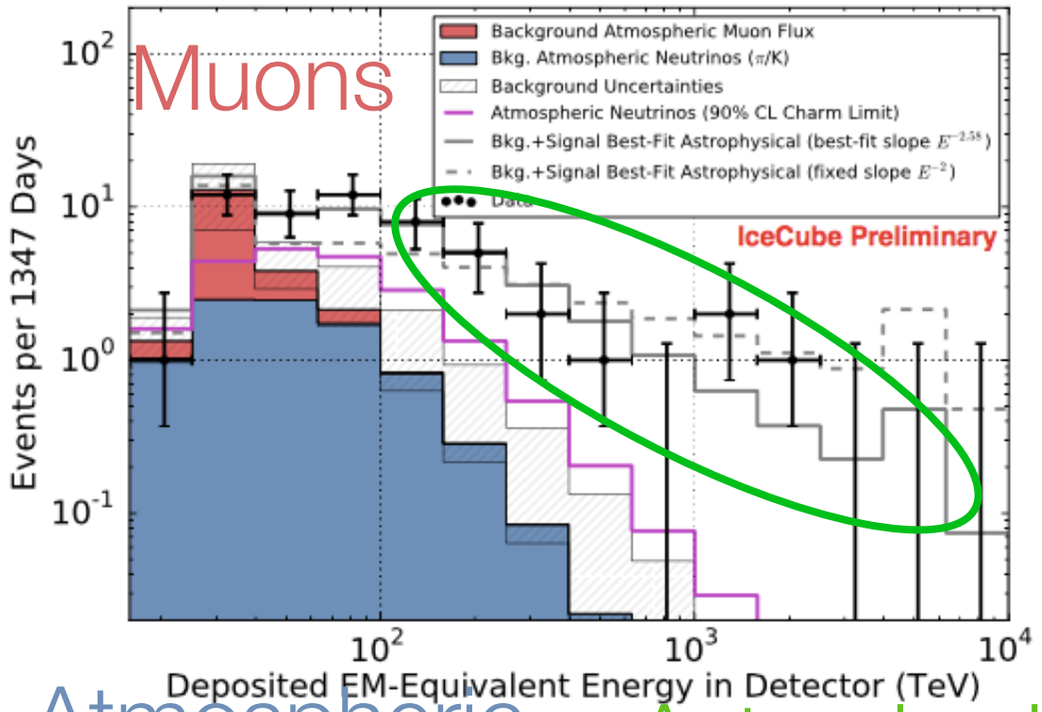
IceCube ICRC 1510.05223



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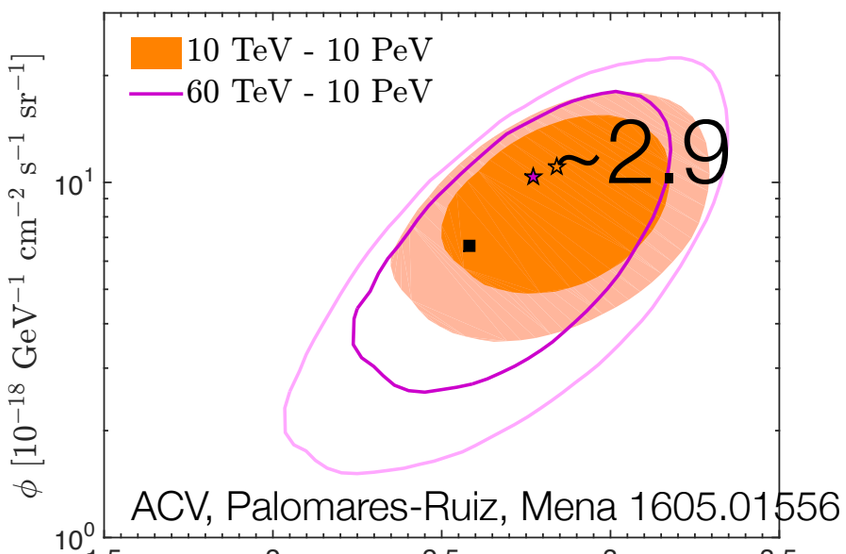
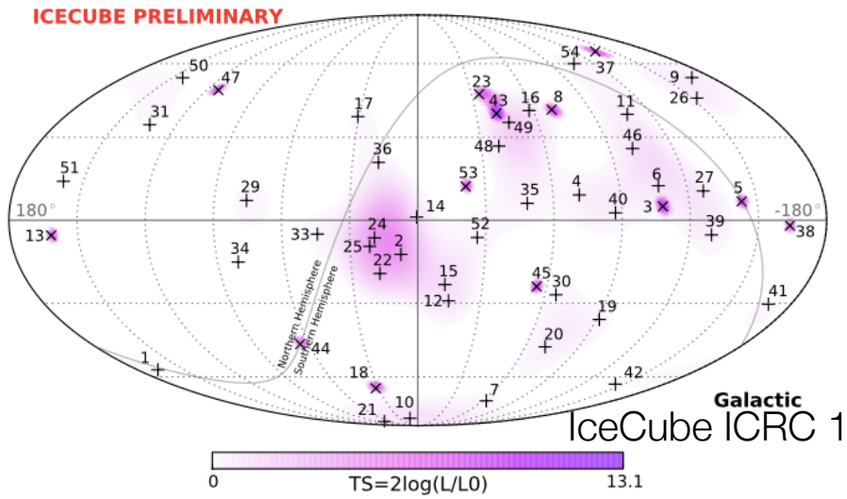
Astrophysical



ACV, Palomares-Ruiz, Mena 1605.01556

Spectral index

Arrival direction



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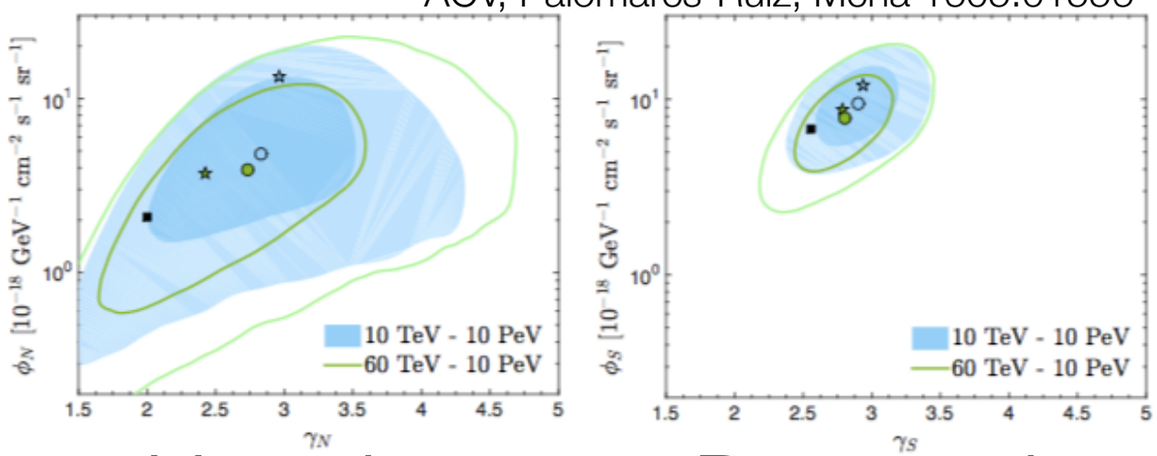


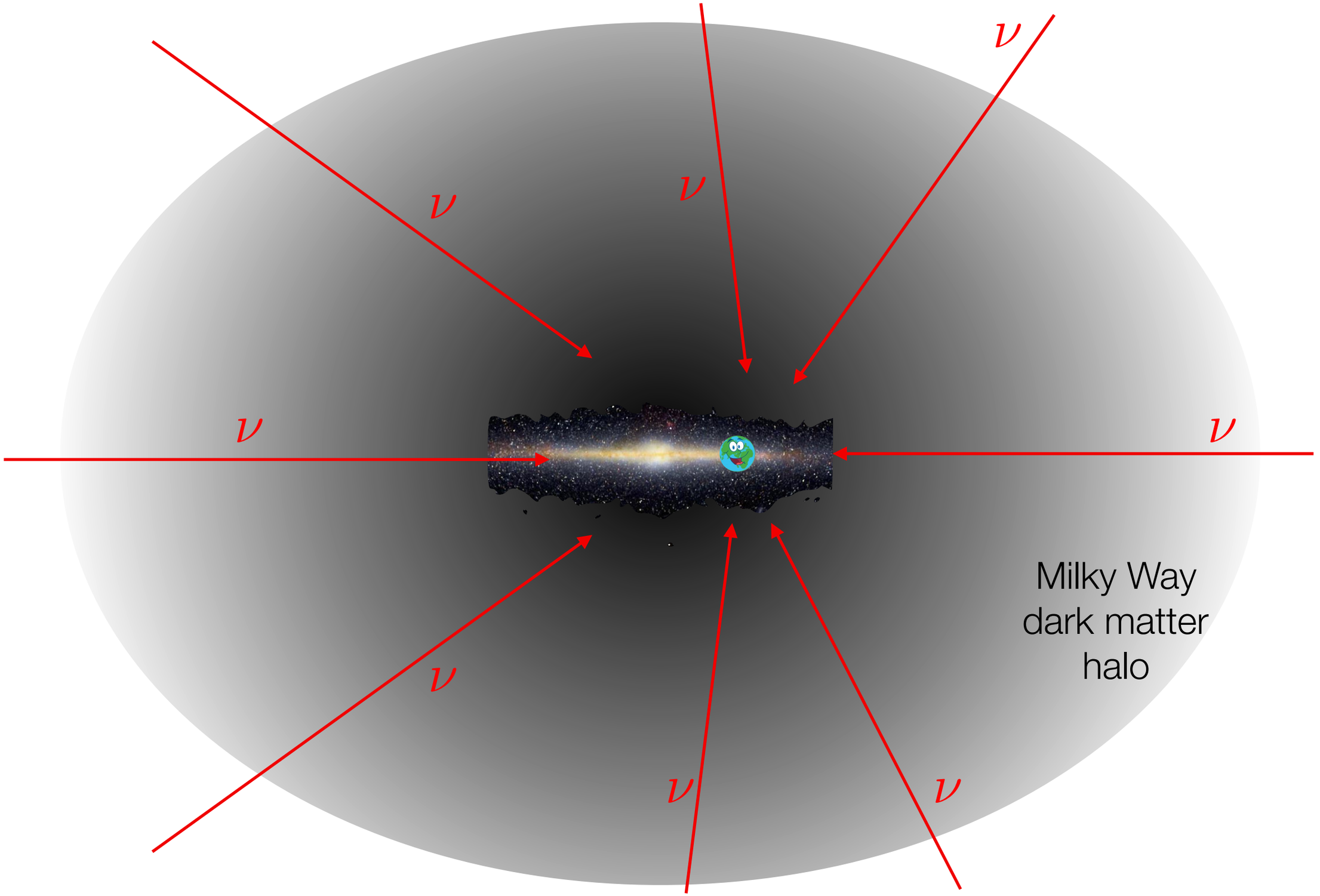
Upgoing

Downgoing

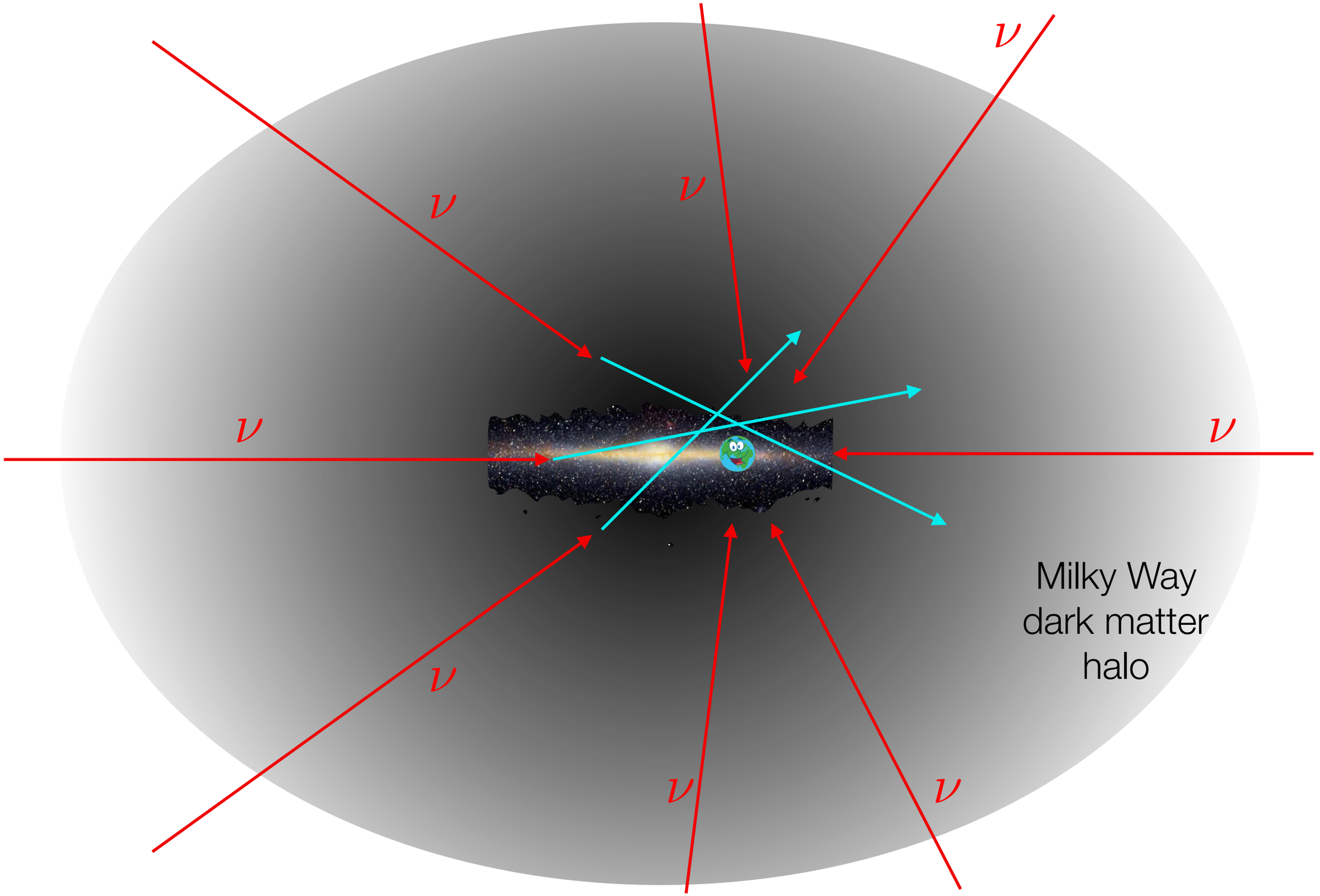
Isotropic arrival

➡ 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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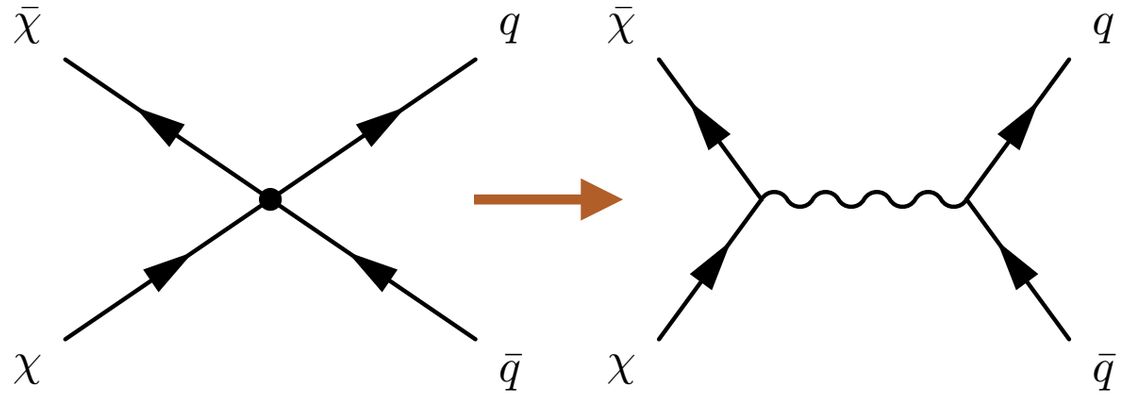
No!

What about cross section?

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

No!

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

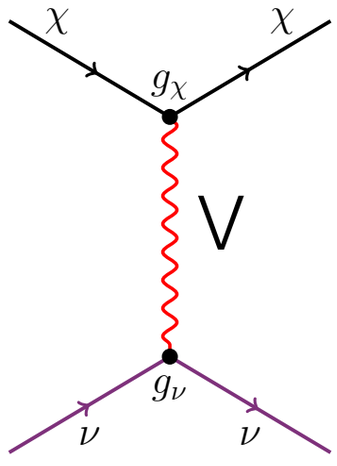


The low energy approximation does not work at a PeV!!

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

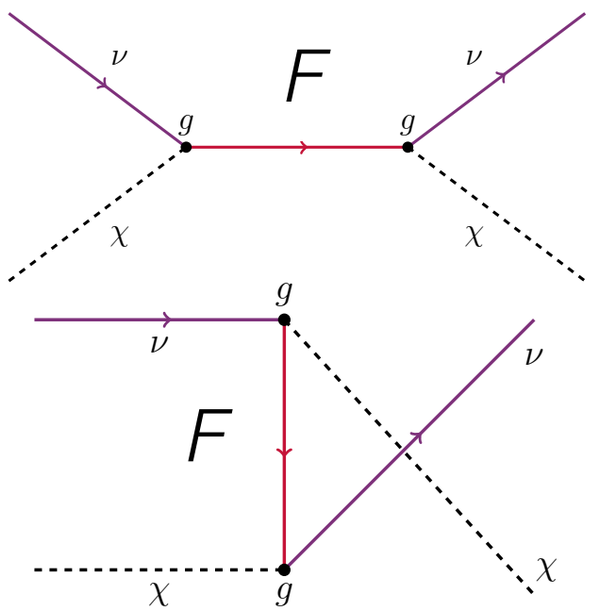
Two fiducial simplified models

1)



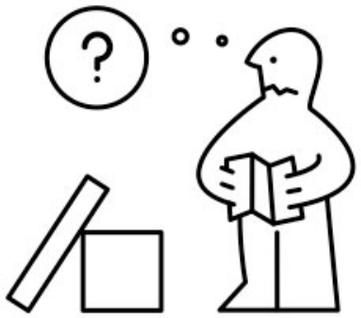
Fermion DM, **vector mediator**:
Scales strongly with *E*

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

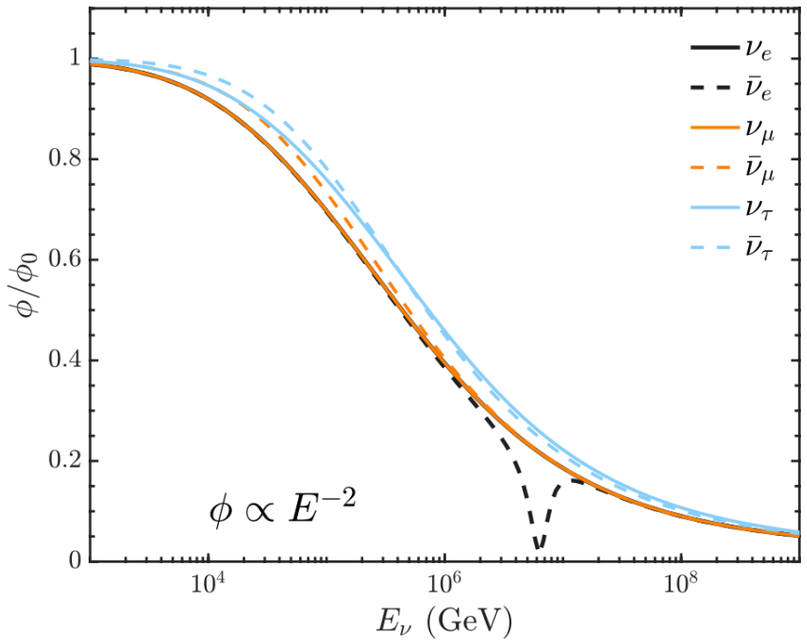
instrument response

data

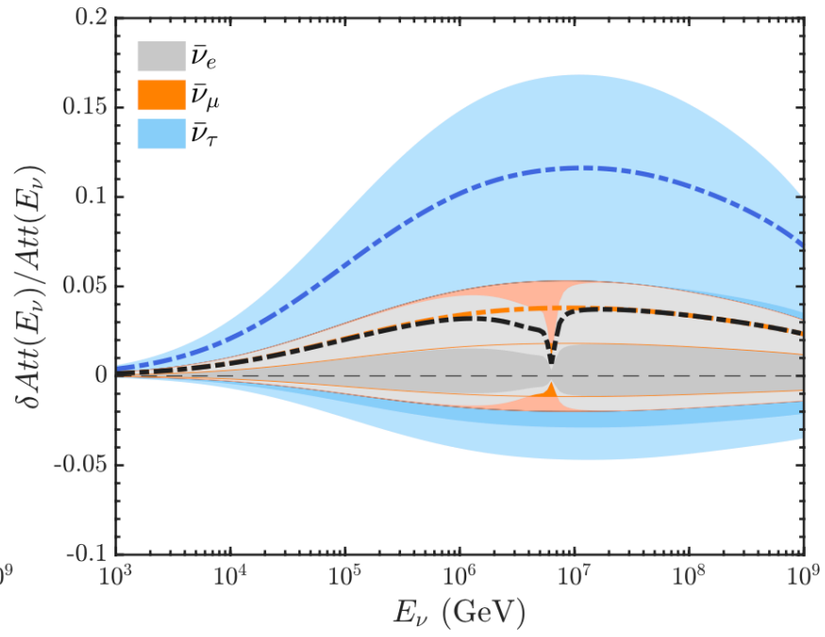
Likelihood

Aside: attenuation by earth

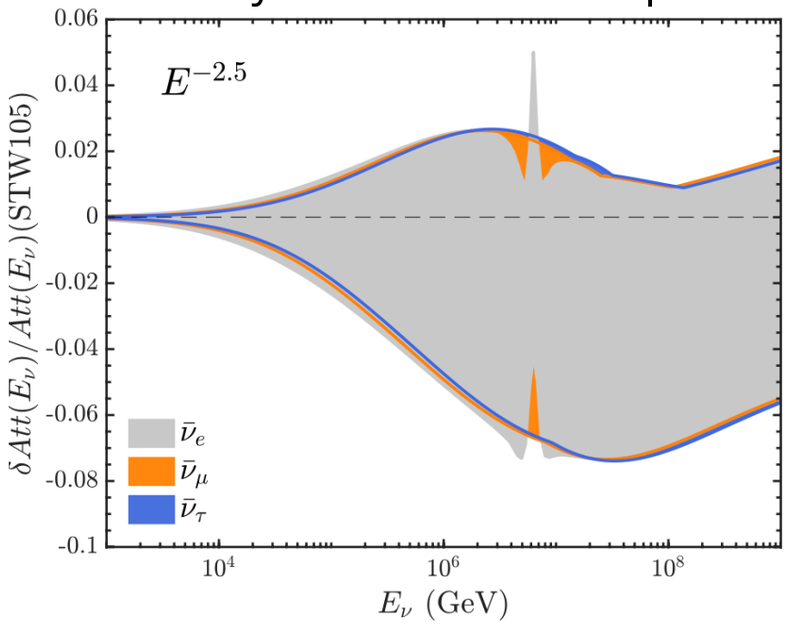
average upgoing flux



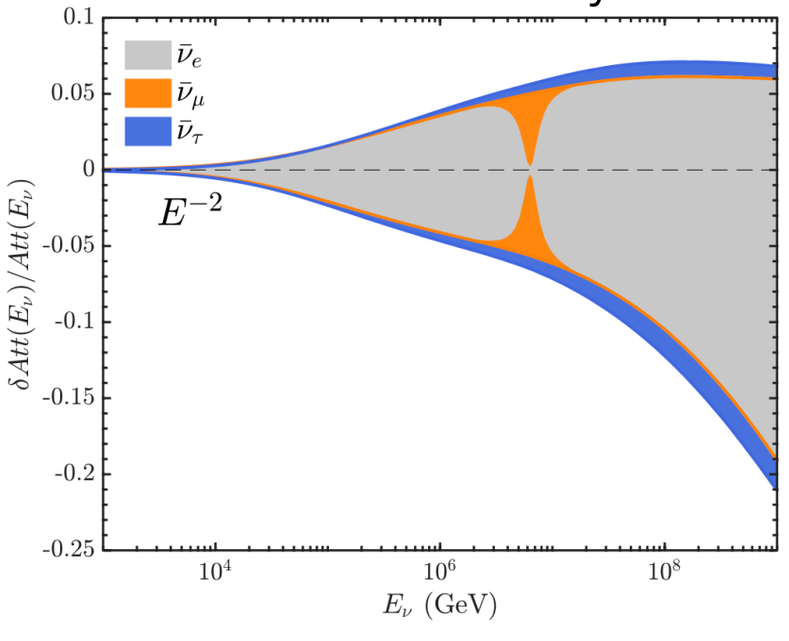
uncertainty on astro spectral index



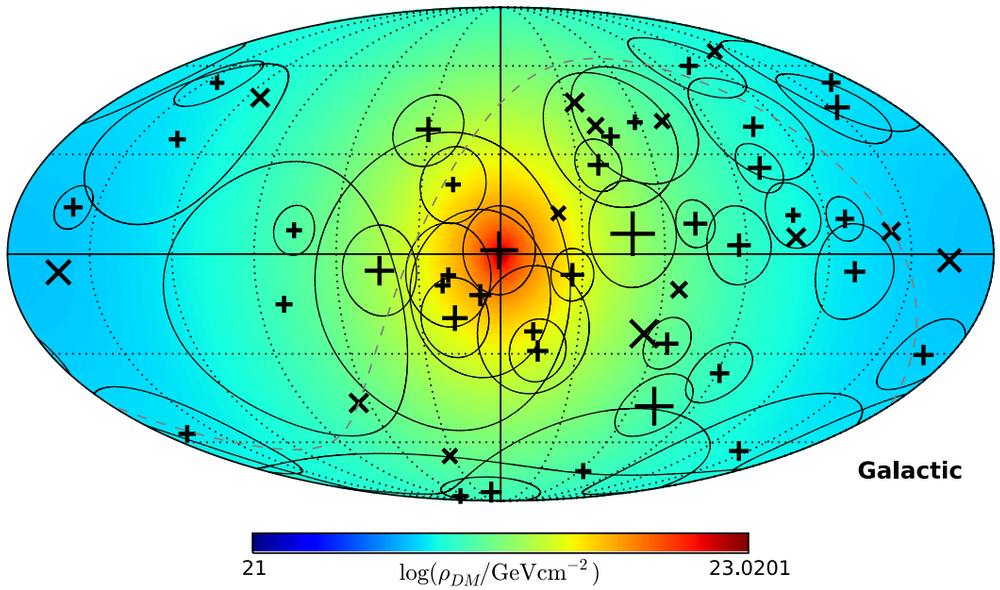
uncertainty on Earth composition

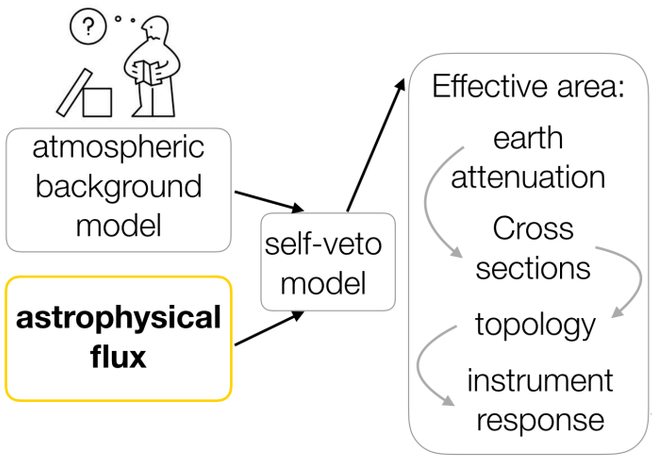


PDF uncertainty

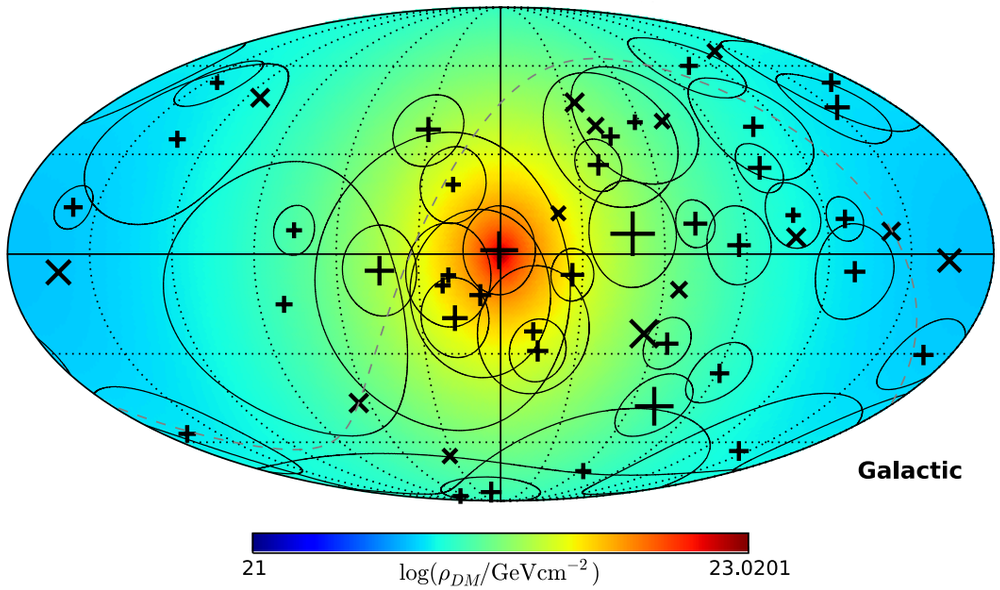


Dark matter column density seen from Earth

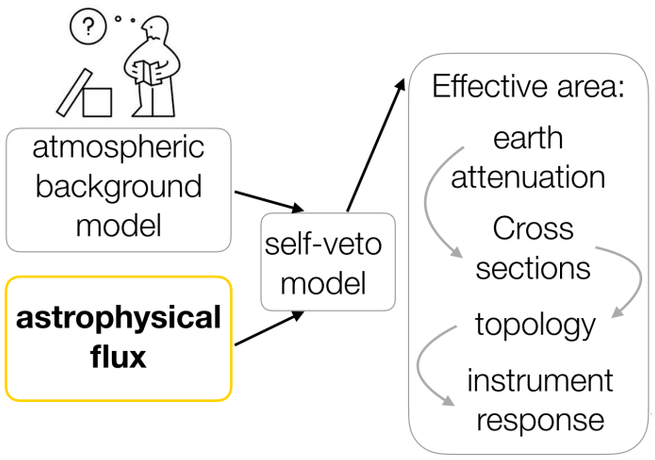




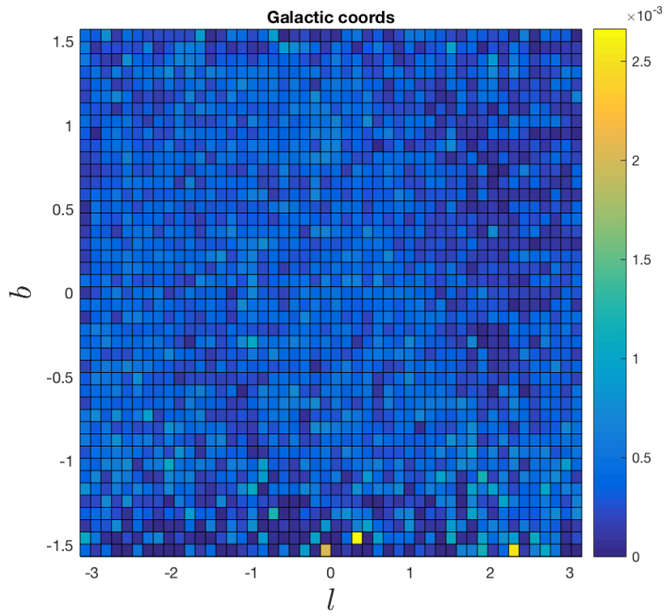
Dark matter column density seen from Earth



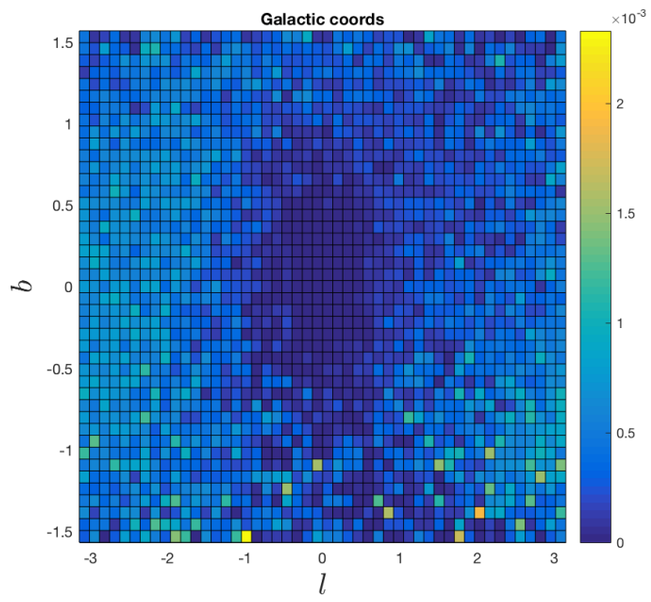
Simulation including effects of detector, Earth



no interaction

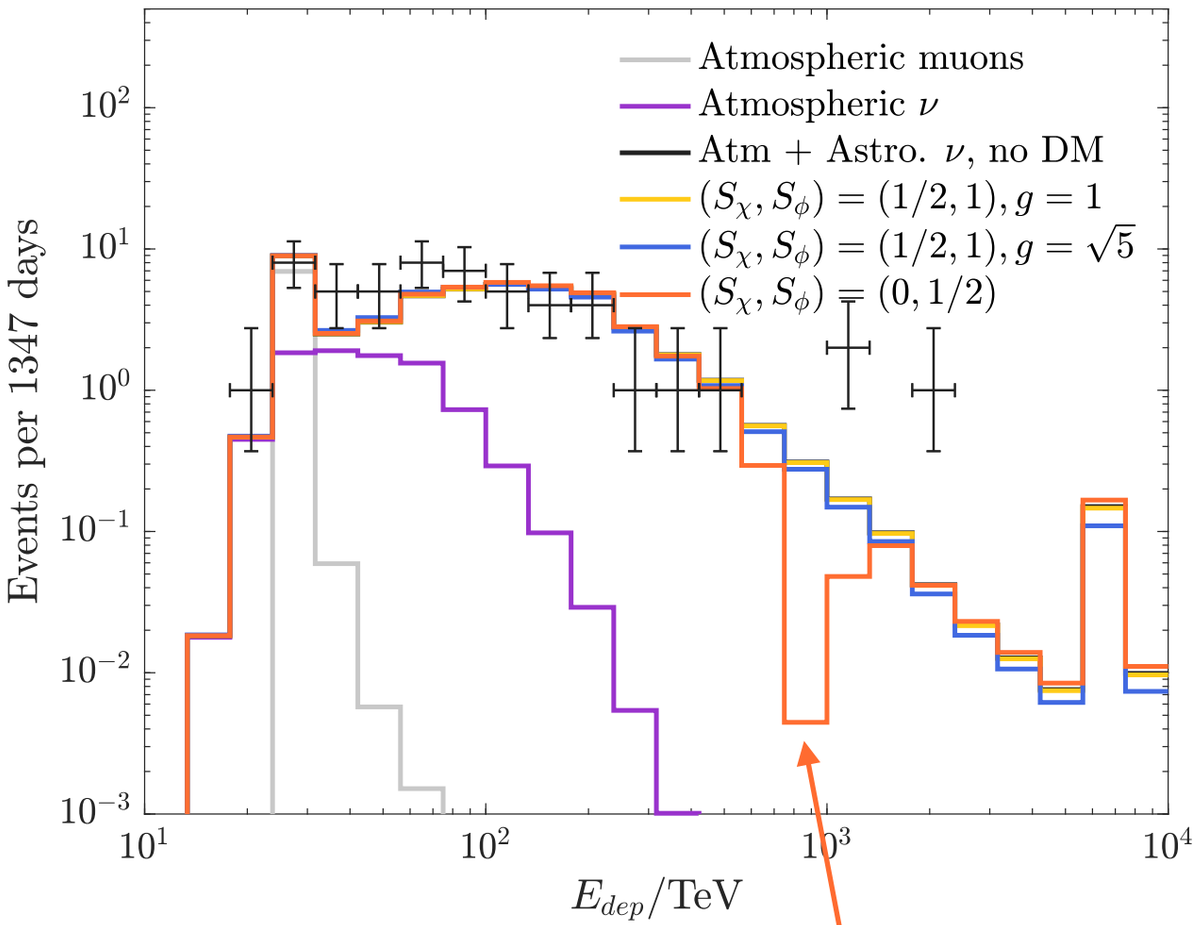


strong interaction



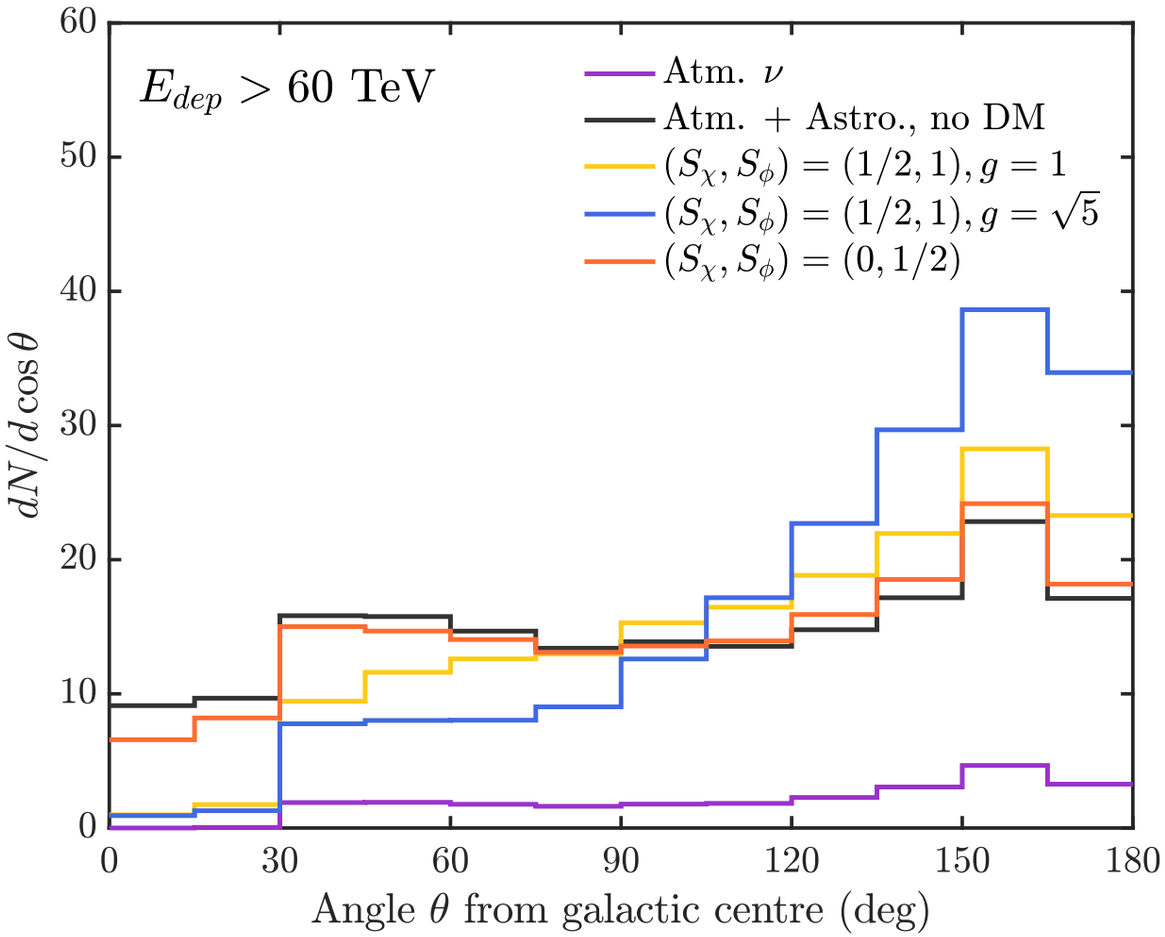
Energy & morphology

Energy



Resonance @ 810 TeV

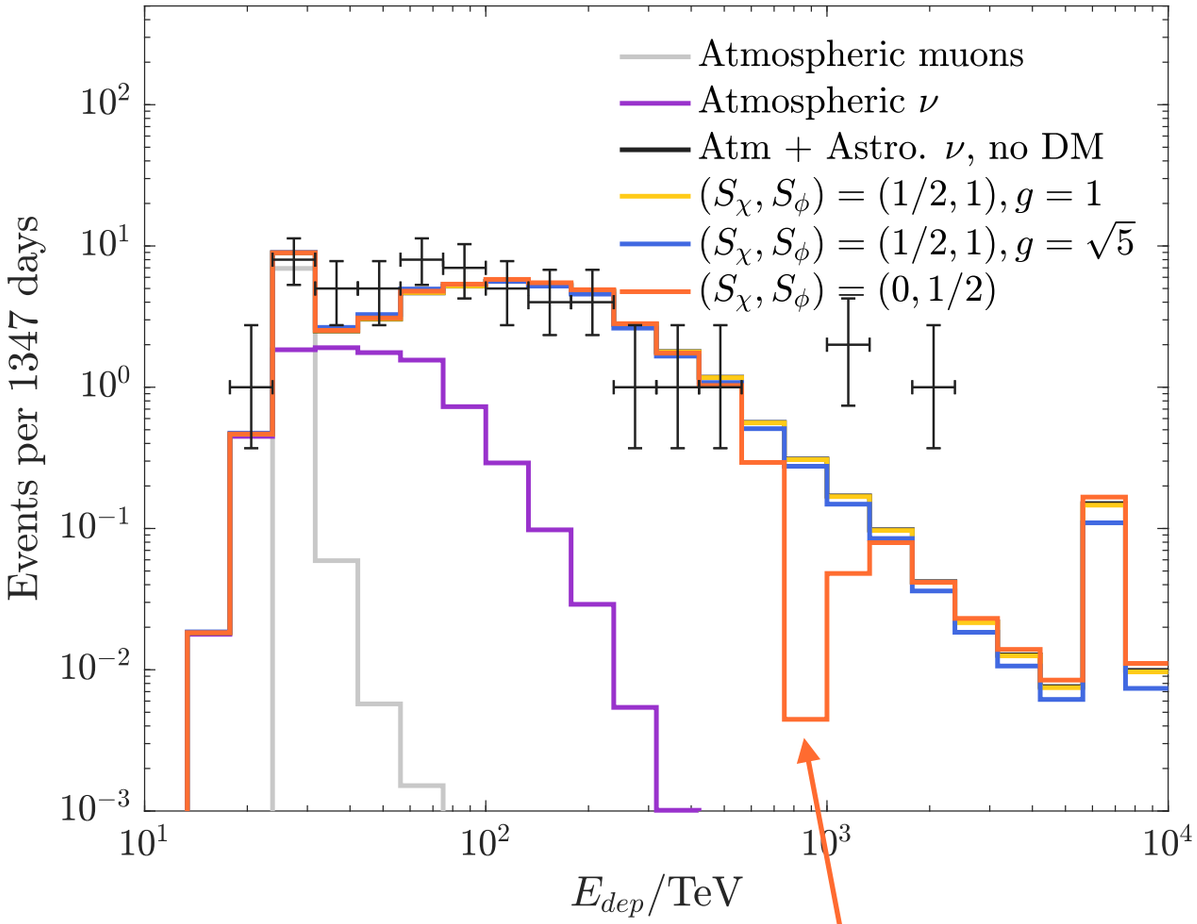
Angle from galactic centre



IceCube HESE events

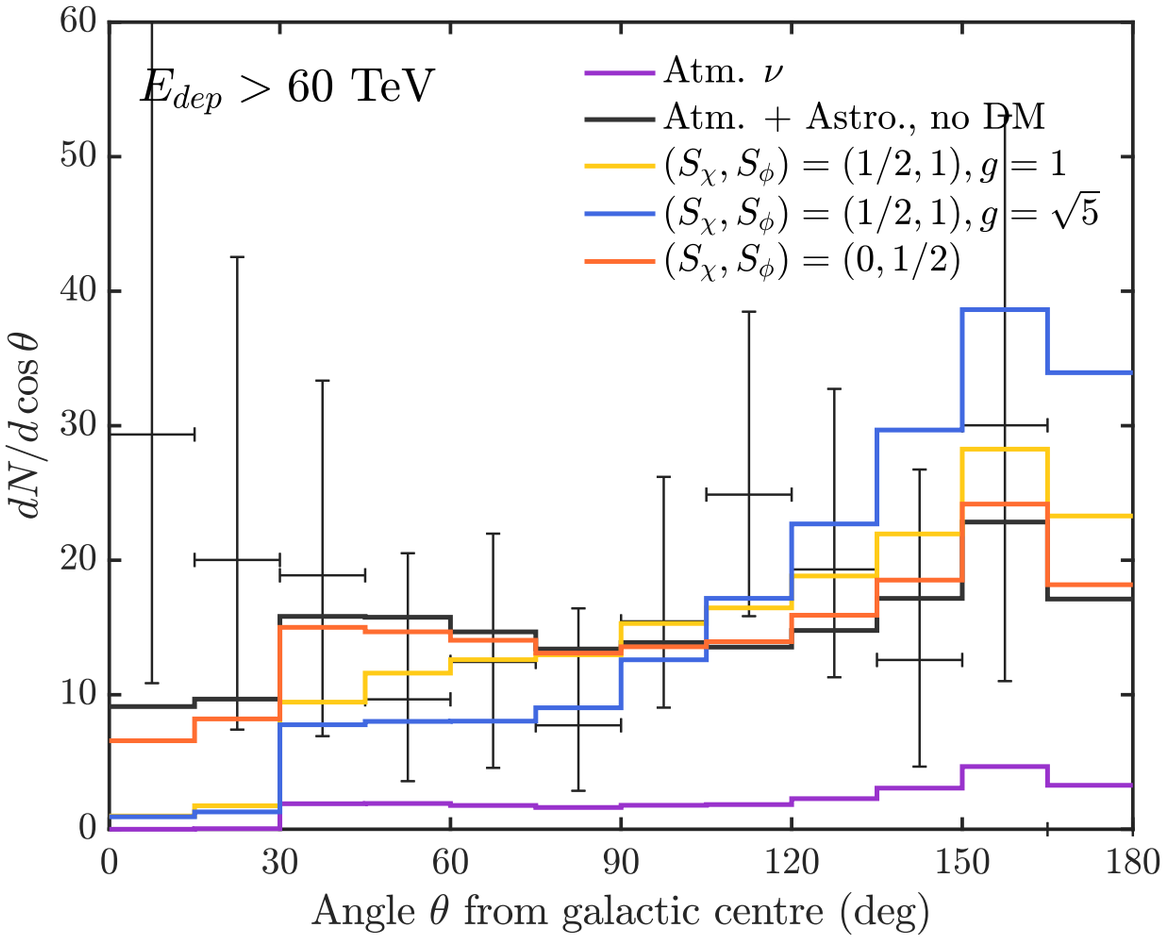
Energy & morphology

Energy



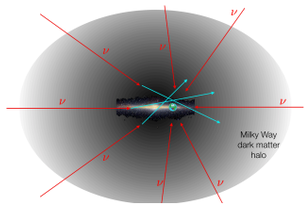
Resonance @ 810 TeV

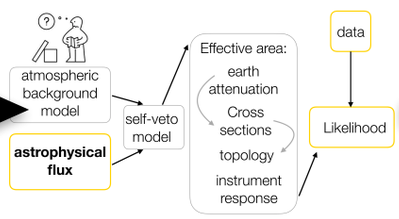
Angle from galactic centre



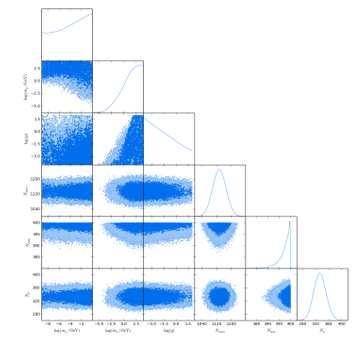
IceCube HESE events

Compare Likelihood to real events





*

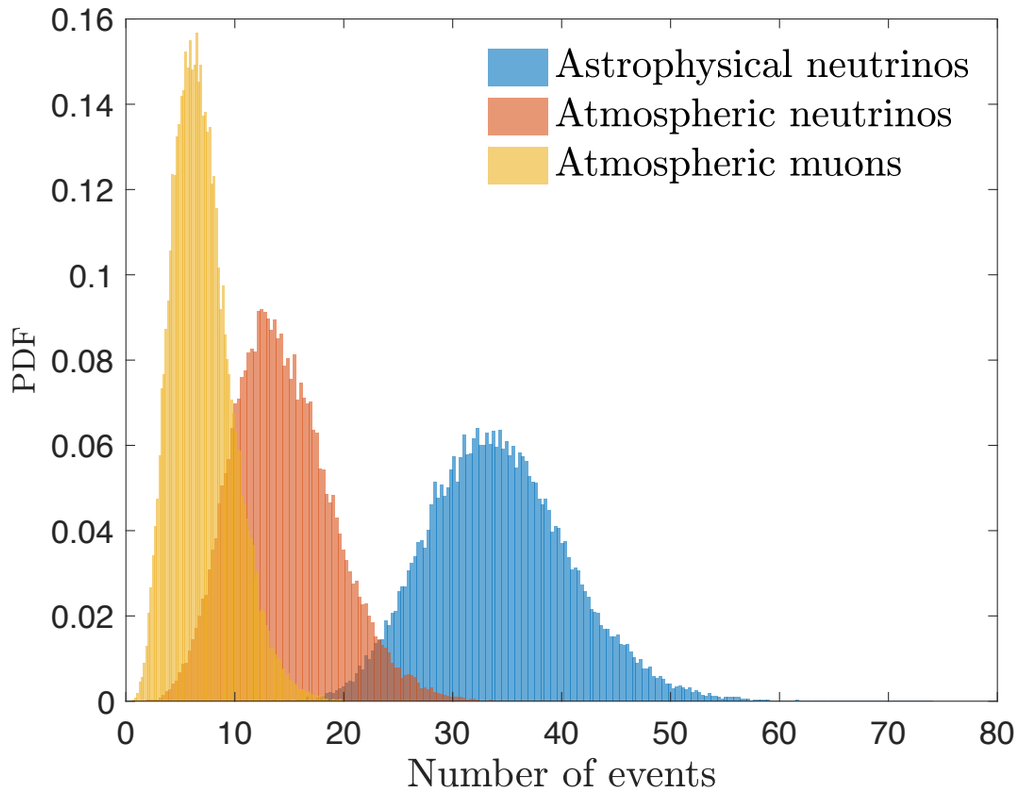


model likelihood IceCube data MCMC posterior

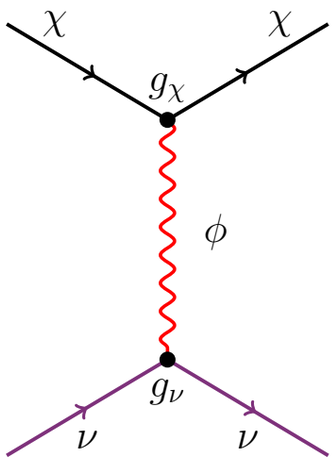
$$\mathcal{L}(\{t, E, \vec{x}\}|\vartheta) = e^{-\sum_b N_b} \prod_{i=1}^{N_{obs}} \sum_a N_a P_a(t_i, E_i, \vec{x}_i|\vartheta).$$

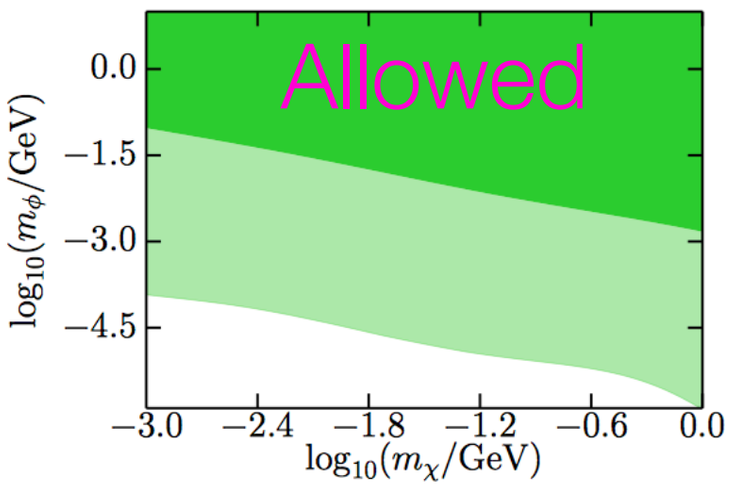
Parameters:

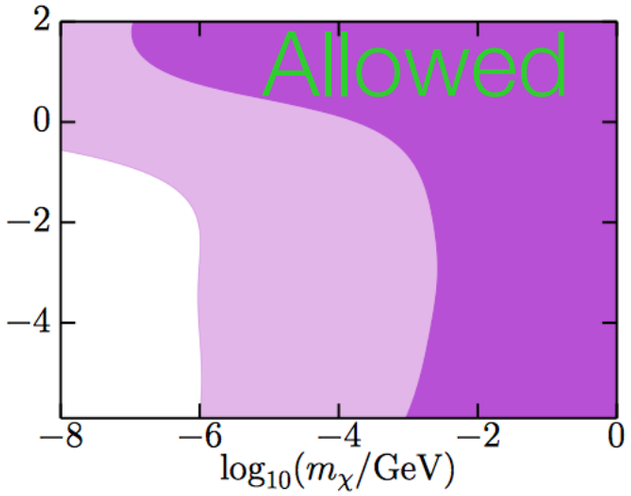
$$m_\chi \; m_\phi \; g \; N_{astro} \; N_{atmo} \; N_{\mu^\pm}$$

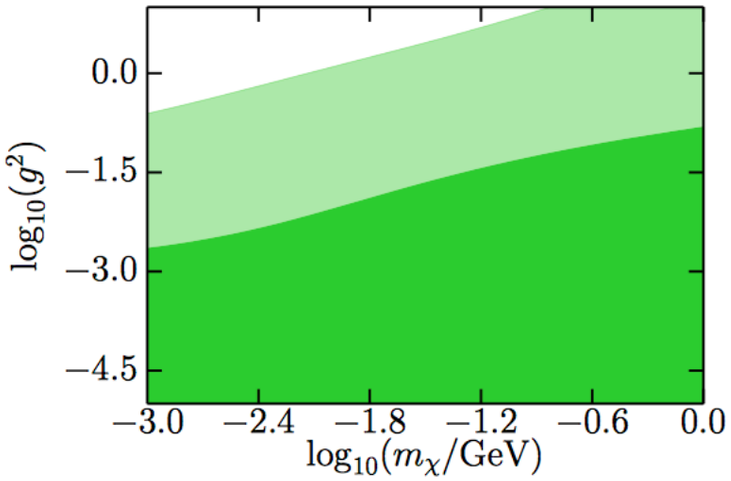


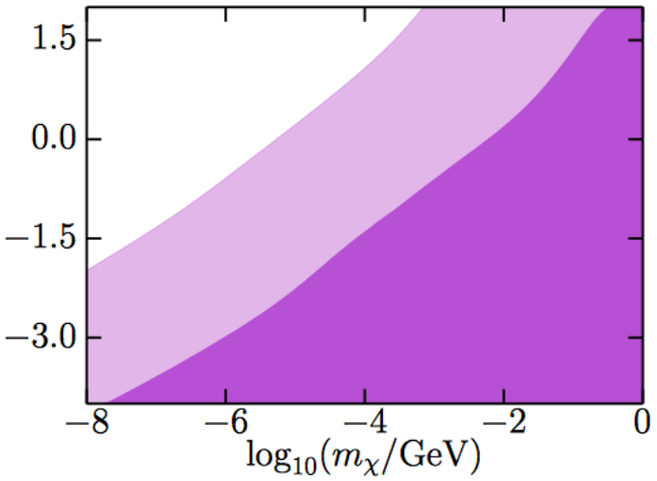
*IceCube data

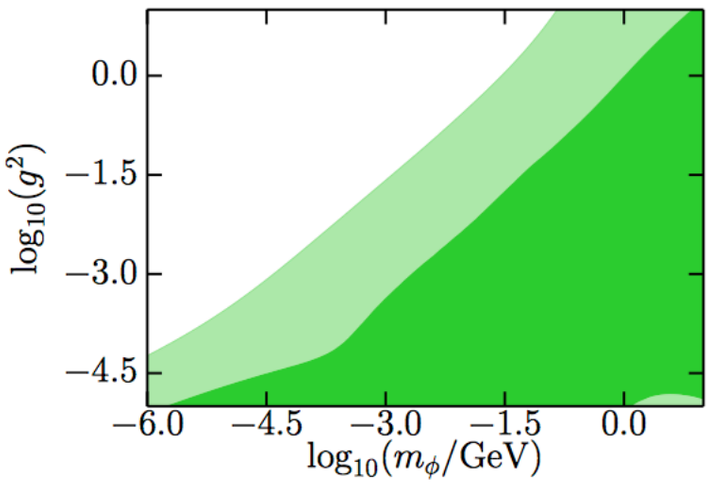

χ
χ
g_χ
ϕ
g_ν
ν
ν

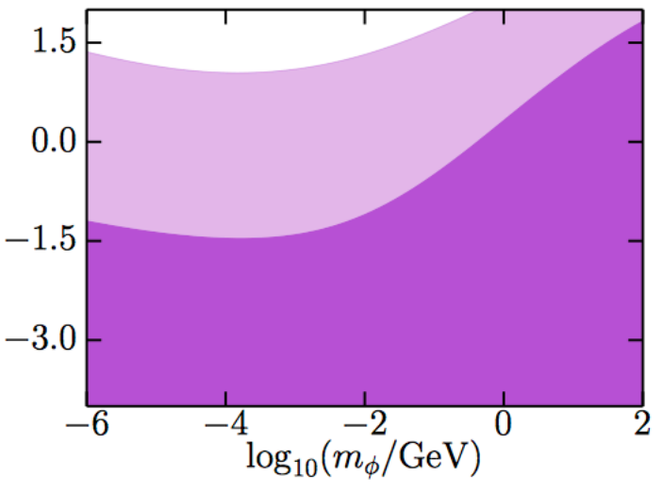

Allowed
$\log_{10}(m_\phi/\mathrm{GeV})$
$\log_{10}(m_\chi/\mathrm{GeV})$

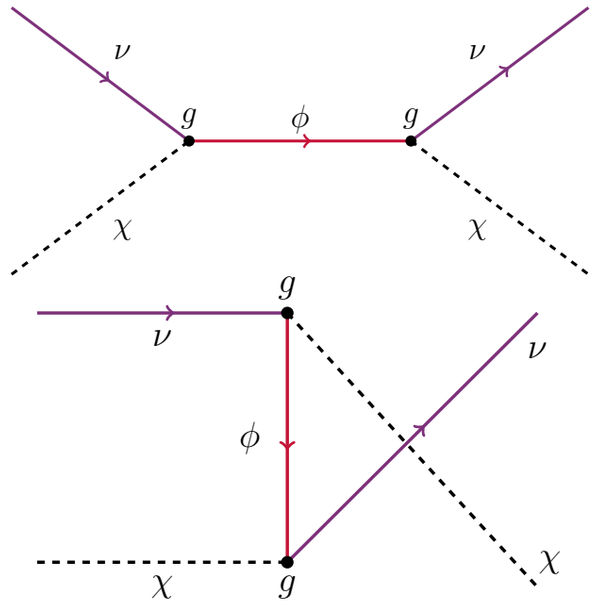

Allowed
$\log_{10}(m_\chi/\mathrm{GeV})$


$\log_{10}(g^2)$
$\log_{10}(m_\chi/\mathrm{GeV})$


$\log_{10}(m_\chi/\mathrm{GeV})$

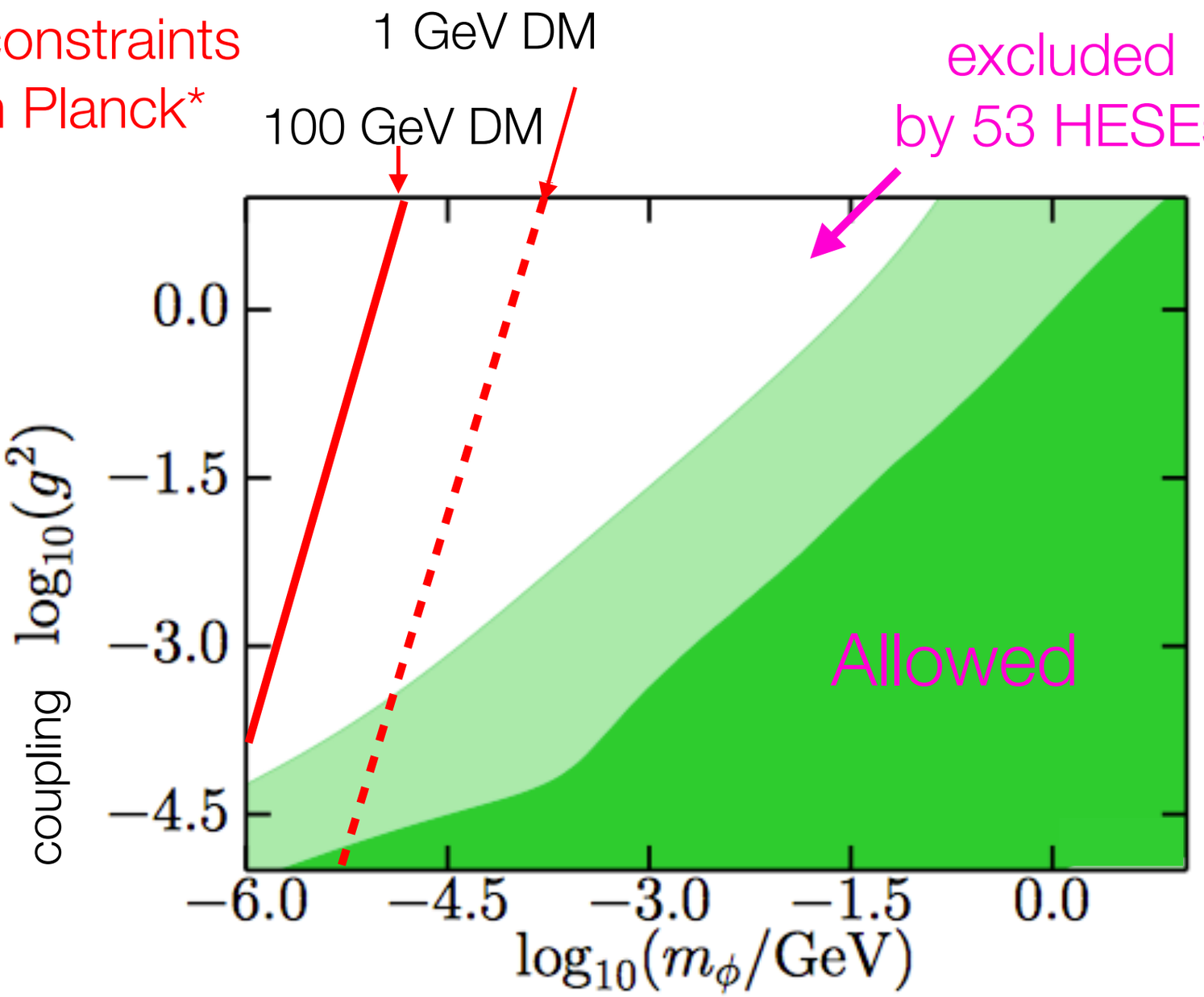

$\log_{10}(g^2)$
$\log_{10}(m_\phi/\mathrm{GeV})$


$\log_{10}(m_\phi/\mathrm{GeV})$

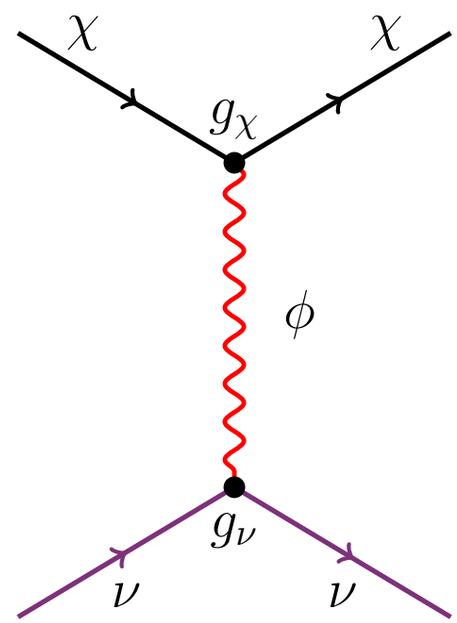

ν
g
ϕ
g
ν
χ
χ
g
ν
ν
ϕ
χ
g
χ

New limits on dark force carriers

Best constraints from Planck*

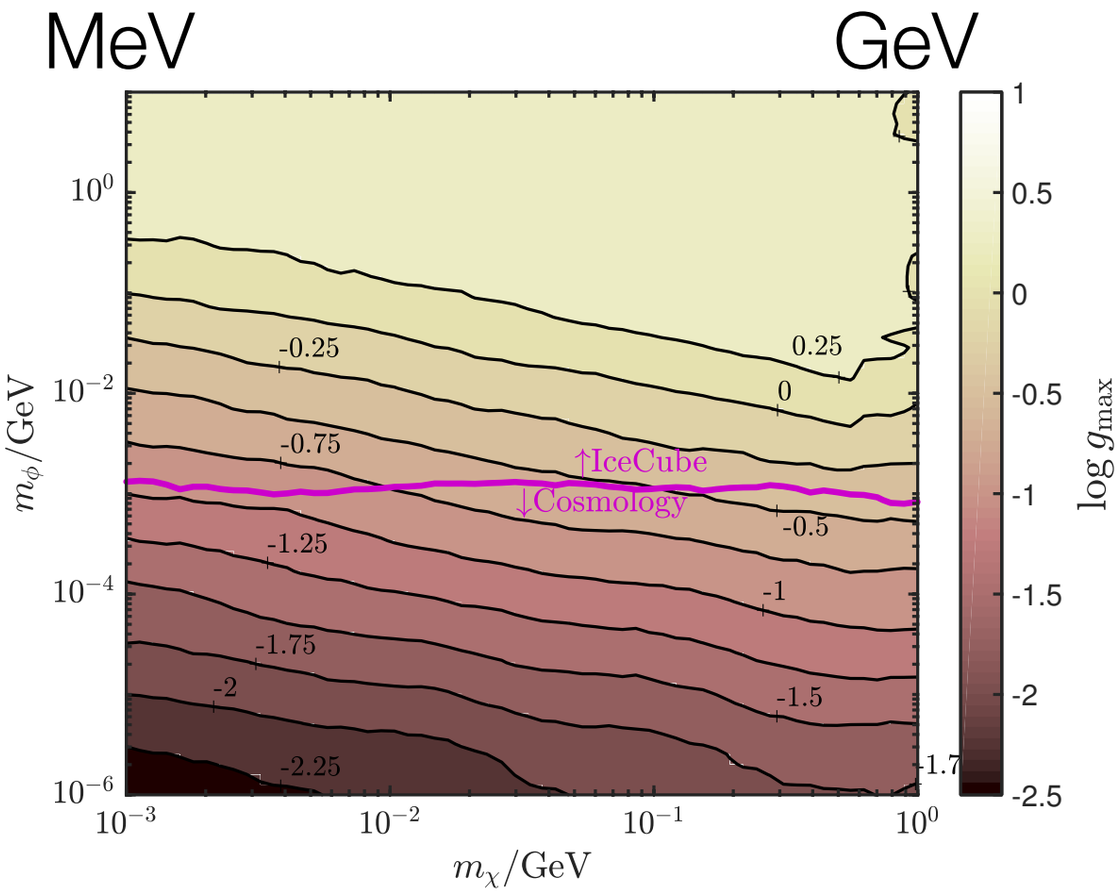


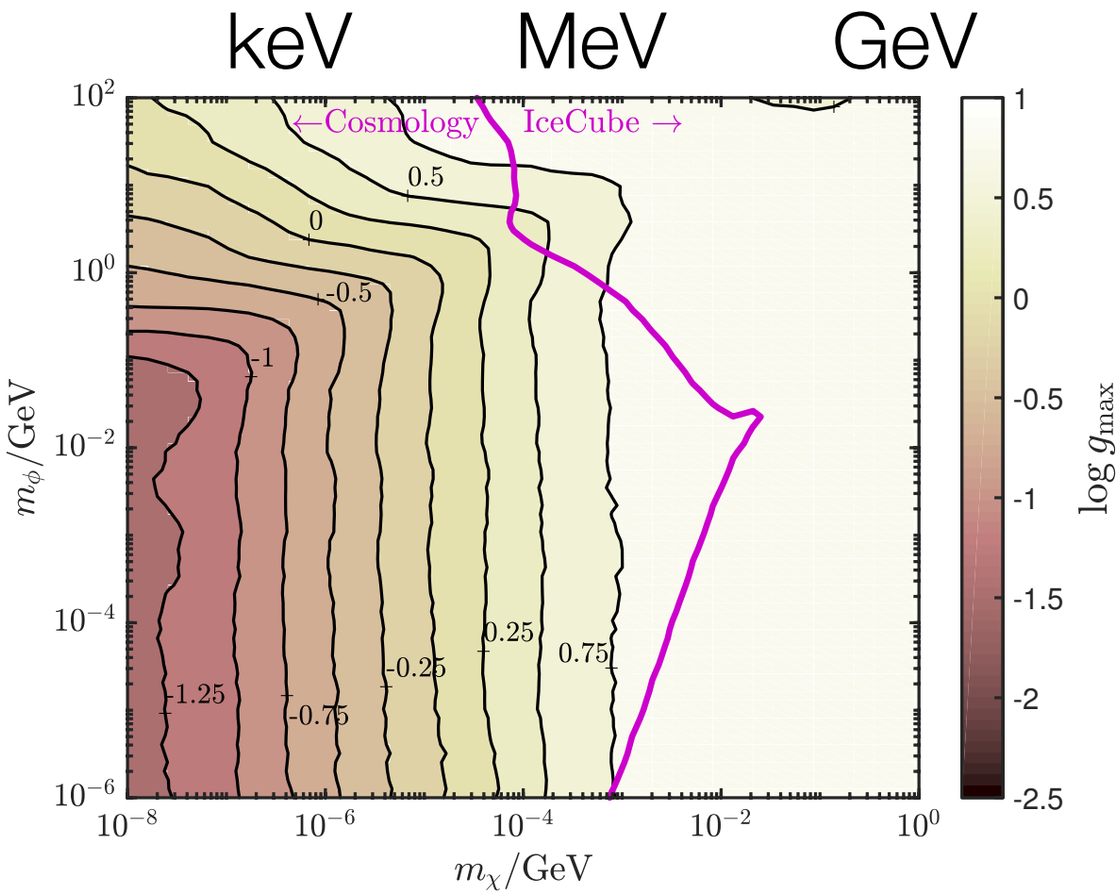
log mediator mass

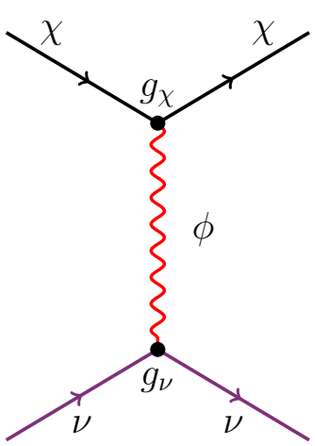


* + LSS, see Escudero, … Vincent 2016

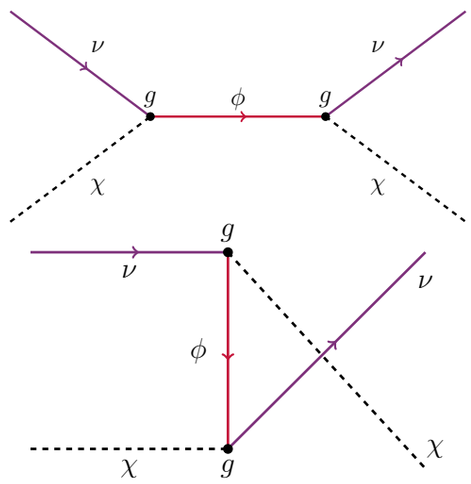
Limits from IceCube







Only 53 events:
already eating into
cosmology parameter
space



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 —> forecasts for Gen2 & more to come

- Annihilation/relic density? See talk by Andrés yesterday

Thank you

Four-year HESE sample

53 events

14 tracks

39 showers

9

39 downgoing

30

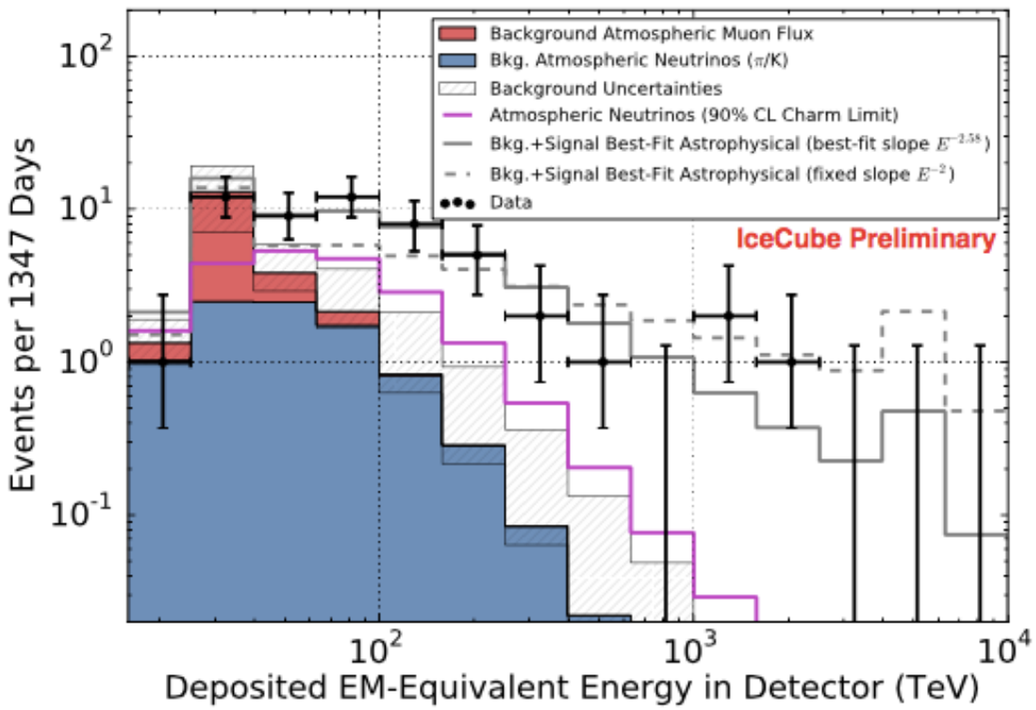
5

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