Imaging galactic dark matter with high energy Cosmic Neutrinos

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WNPPC, Mont Tremblant
February 17 2018

Queen's University
CPARC
Canadian Particle Astrophysics Research Centre

Based on

- **Carlos Argüelles, Ali Kheirandish, A.C.V**, *Imaging galactic dark matter with high energy cosmic neutrinos 1703.00451* PRL 119.201801

But also

- **A.C.V. C., Argüelles, A Kheirandish**, High-energy neutrino attenuation in the Earth and its associated uncertainties, *1706.09895 (JCAP)*
- **M. Escudero, O. Mena, A.C.V., R.J. Wilkinson & C. Boehm**, *Exploring dark matter microphysics with galaxy surveys, 1505.06735 (JCAP)*
- **R. J. Wilkinson, A.C.V., C. Boehm, C. McCabe**, Ruling out the light WIMP explanation of the galactic 511 keV line 1602.01114 (PRD)
- and many **O. Mena, S. Palomares-Ruiz & ACVincent** papers

The neutrino...is the most ridiculous particle you could imagine. A billion neutrinos went through my nose as we were talking. A trillion, a trillion of them went through my nose just now, and they did nothing to me. They pass through all of the matter around us continually, in a huge, huge blast of particles that does nothing at all.

-Peter Gorham

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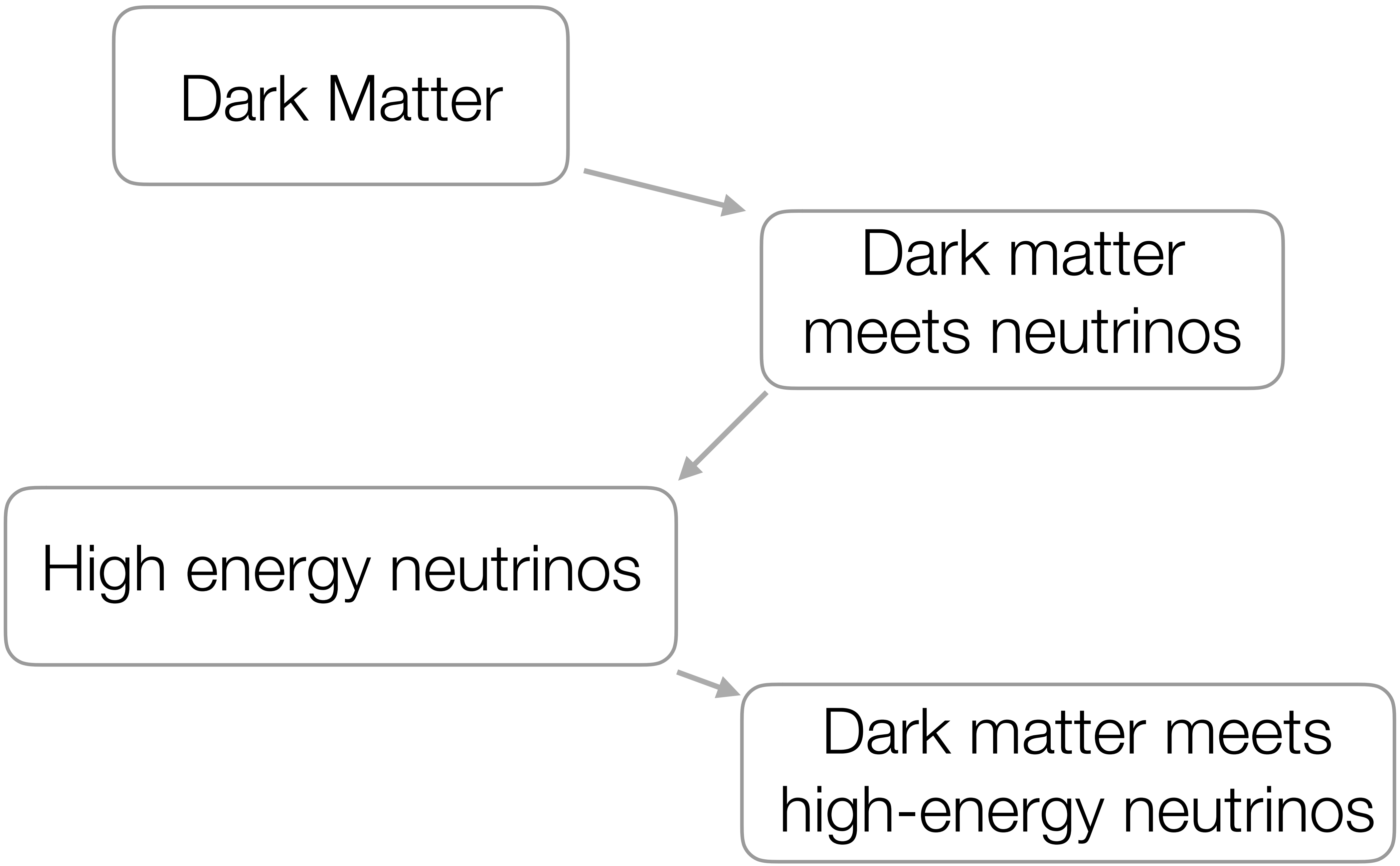
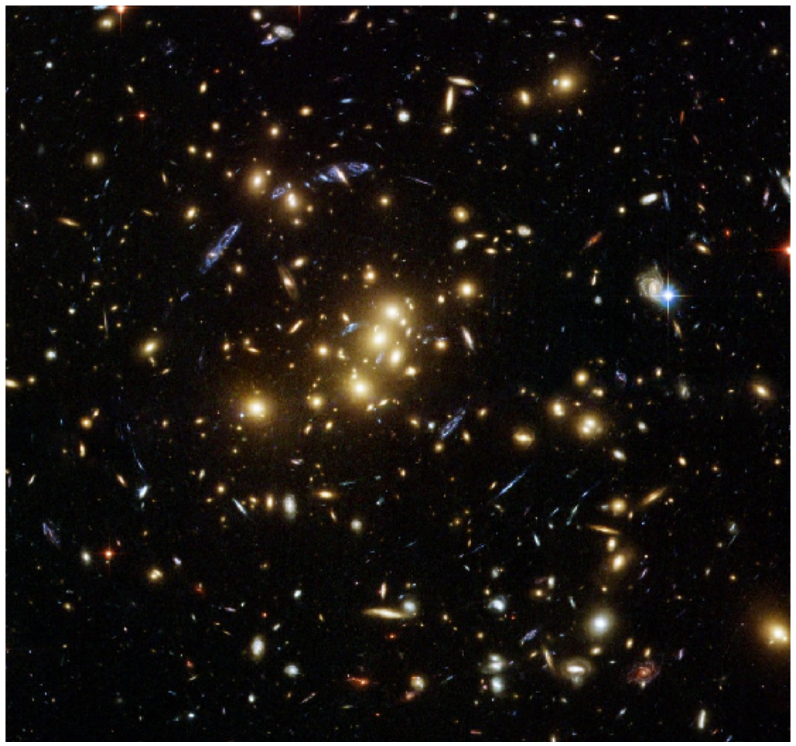
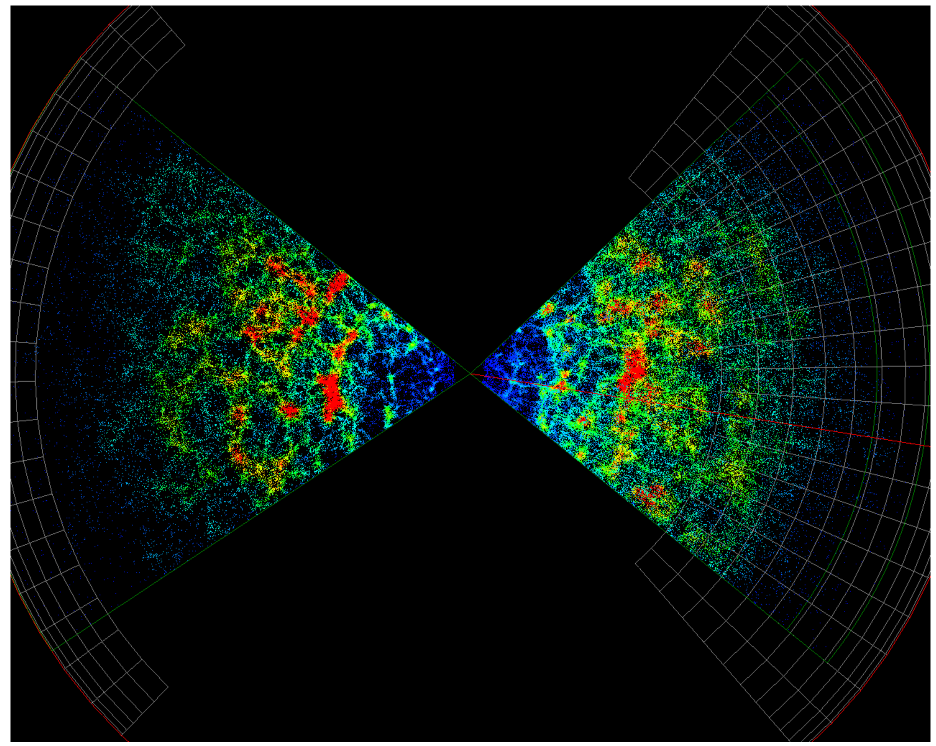
If you think that's mad, wait until
I tell you about using them to detect dark matter

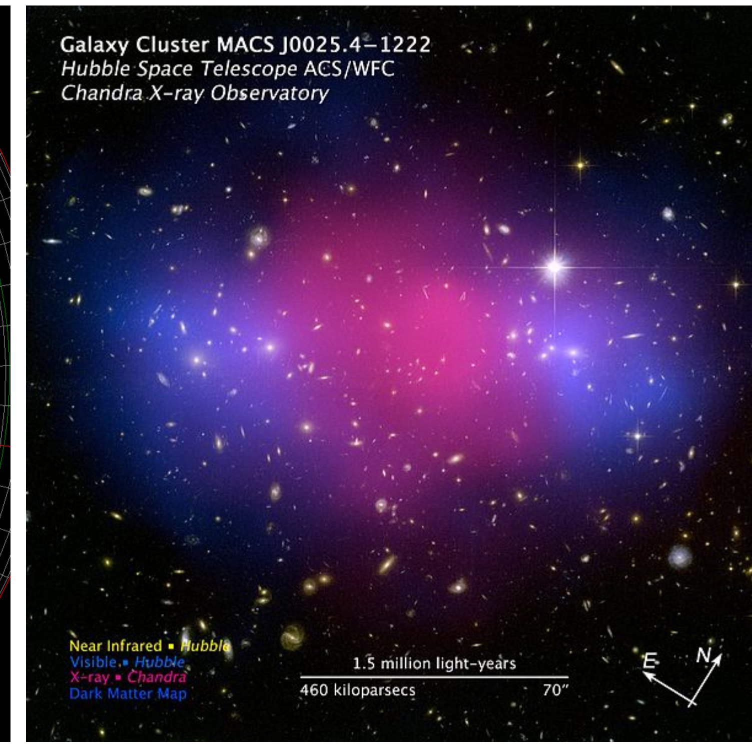
Overview


Dark Matter
Dark matter meets neutrinos
High energy neutrinos
Dark matter meets high-energy neutrinos

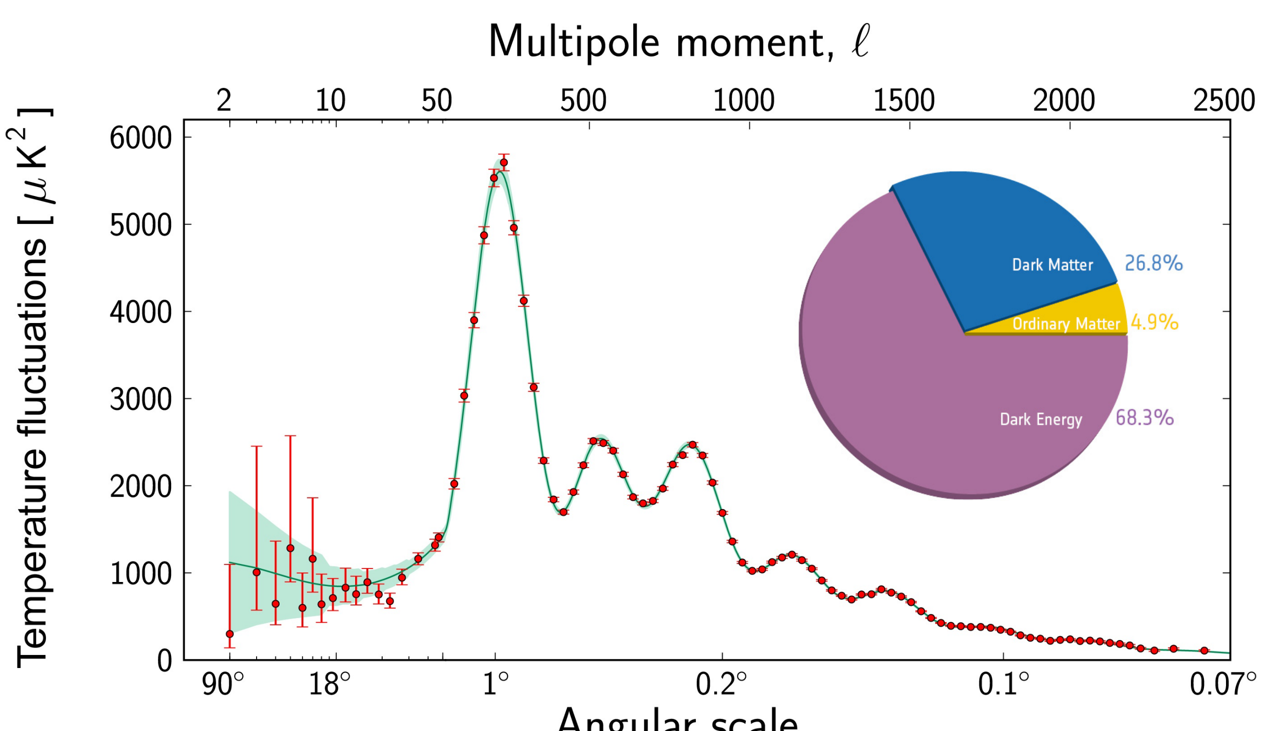
Dark Matter



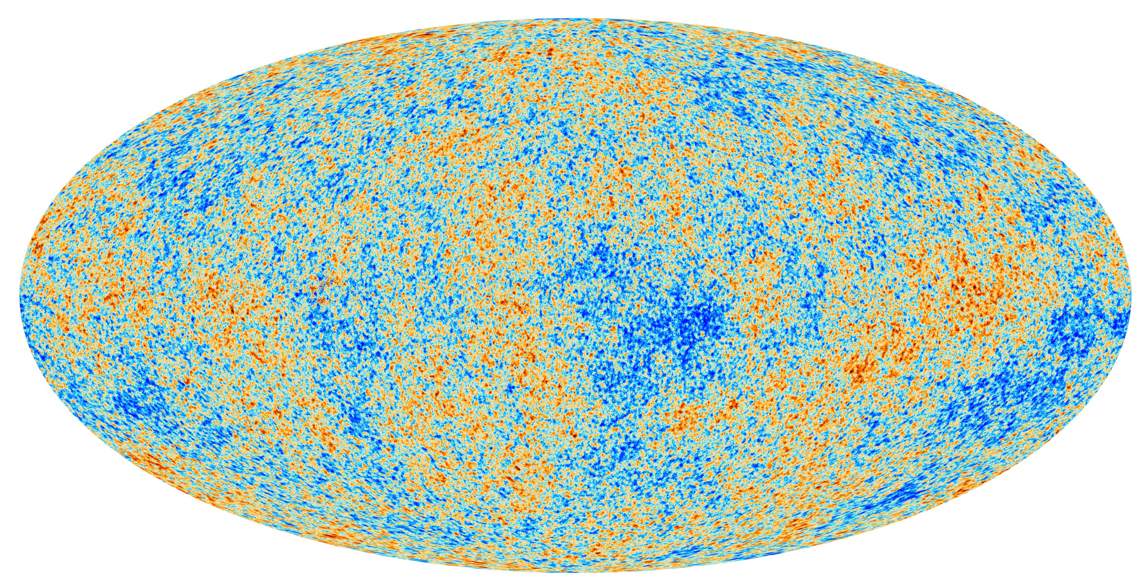




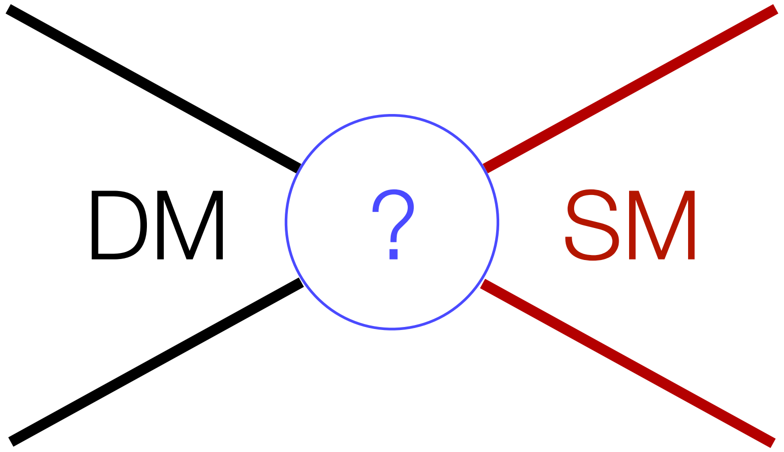
Galaxy Cluster MACS J0025.4−1222
Hubble Space Telescope ACS/WFC
Chandra X-ray Observatory
Near Infrared ▪ Hubble
Visible ▪ Hubble
X-ray ▪ Chandra
Dark Matter Map
1.5 million light-years
460 kiloparsecs
70″
E
N



Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK²]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale
Dark Matter 26.8%
Ordinary Matter 4.9%
Dark Energy 68.3%



All evidence so far is gravitational, but O(1) relationship between DM and SM densities strongly hint at a particle physics relationship



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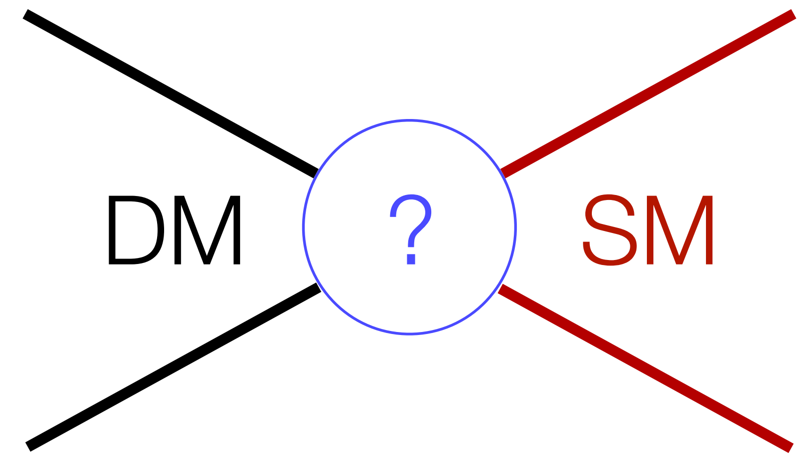
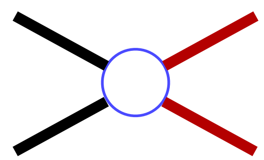
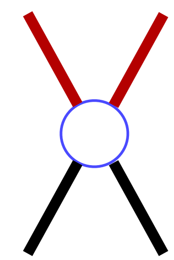


$\exists\big($  $\big)$ implies $\exists\big($  $\big)$

annihilation

scattering

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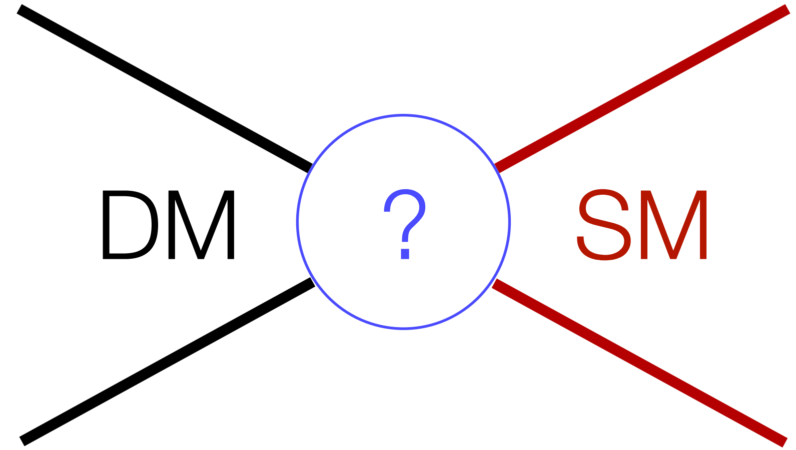
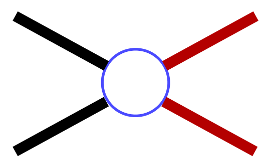
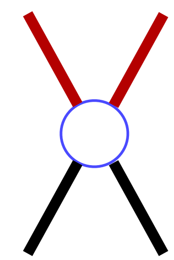
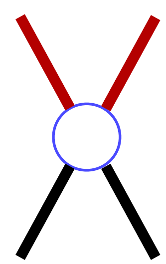


$\exists$() implies $\exists$()

annihilation

scattering

if —— = quarks, then  = direct detection (SuperCDMS, PICO, DEAP …)

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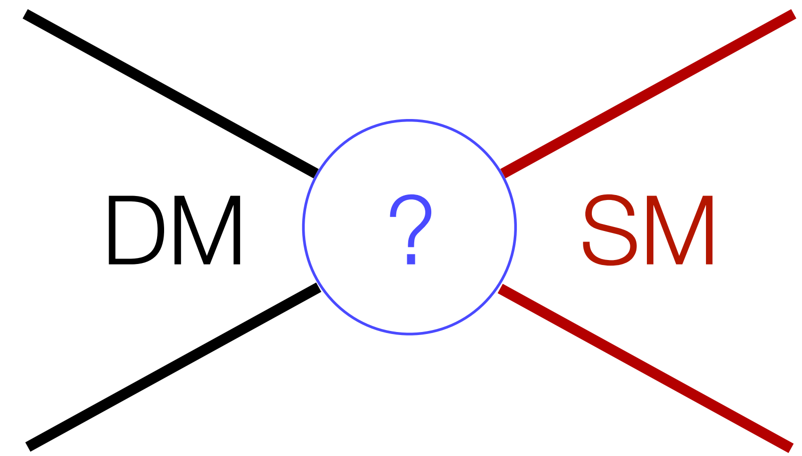
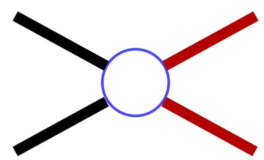
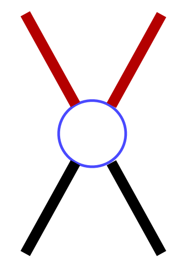
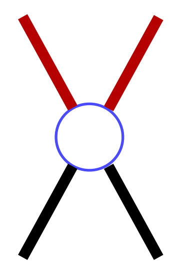
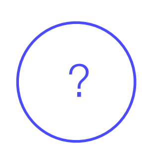


$\exists$ () implies $\exists$ ()

annihilation — scattering

if —— = quarks, then  = direct detection (SuperCDMS, PICO, DEAP ...)

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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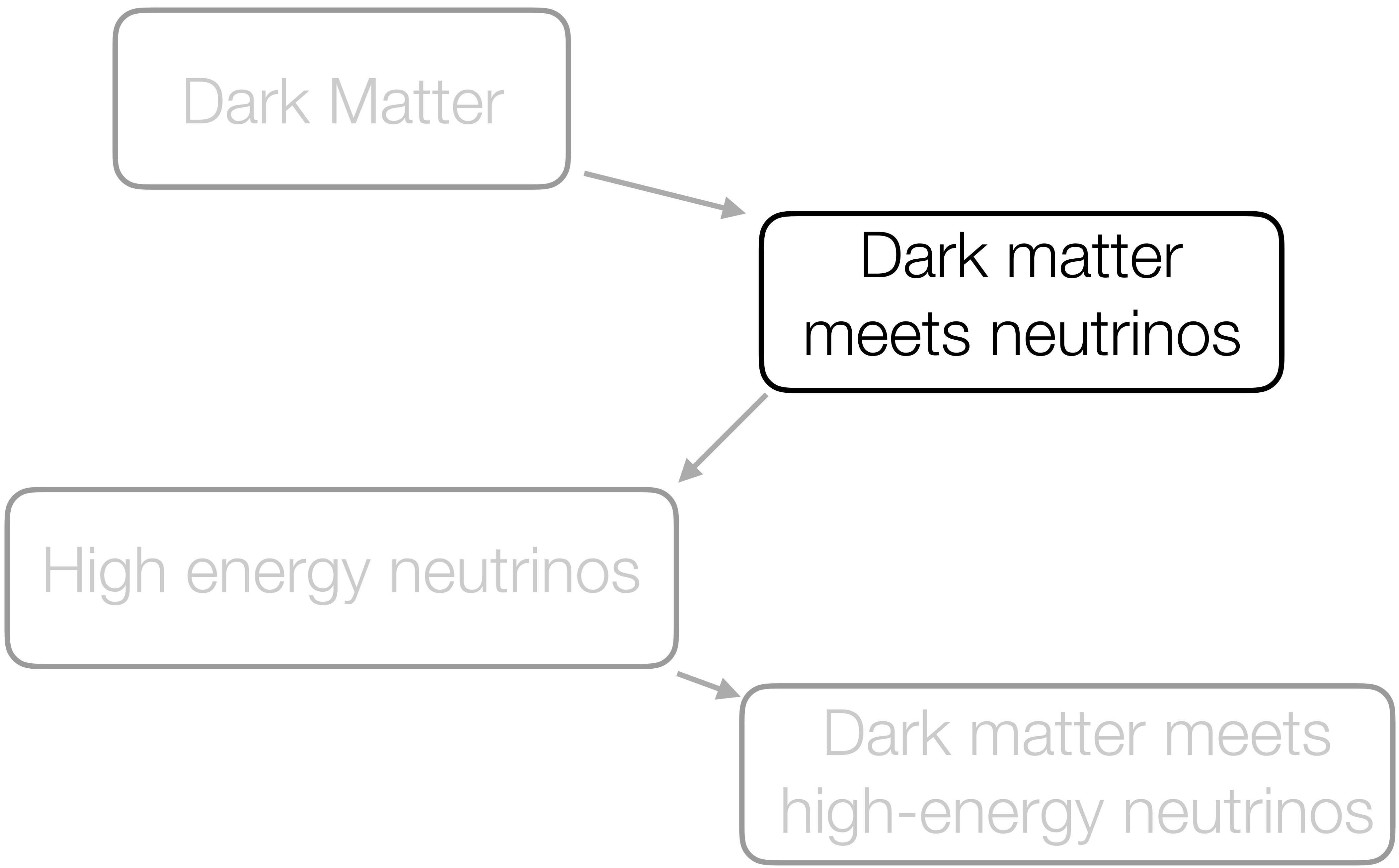
[7] R. J. Wilkinson, C. Boehm, and J. Lesgourgues, JCAP **1405**, 011 (2014), arXiv:1401.7597 [astro-ph.CO].
[8] L. G. van den Aarssen, T. Bringmann, and C. Pfrommer, Phys.Rev.Lett. **109**, 231301 (2012), arXiv:1205.5809 [astro-ph.CO].
[9] Y. Farzan and S. Palomares-Ruiz, JCAP **1406**, 014 (2014), 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)


Dark Matter
Dark matter meets neutrinos
High energy neutrinos
Dark matter meets high-energy neutrinos

Neutrinos & DM are weakly interacting, so we need large number densities

$$n_\nu \propto (1+z)^4$$
$$n_\chi \propto (1+z)^3$$

let's start at high redshift

DM-neutrino interactions: cosmology

t	s	minutes	300kyr	13.5 Gyr
T	2 MeV	.5 MeV	eV	10^{-4} eV
a = 1/(1+z)	10^{-10}	10^{-10}	10^{-3}	1

Neutrinos decouple, neutron production stops

D, He formed

Recombination
CMB formed

gravitational perturbations grow

DM-neutrino interactions: cosmology (I)

Early universe: lots of dark matter, lots of neutrinos

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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 (i.e. $N_{\mathrm{eff}} > 3$)

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

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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

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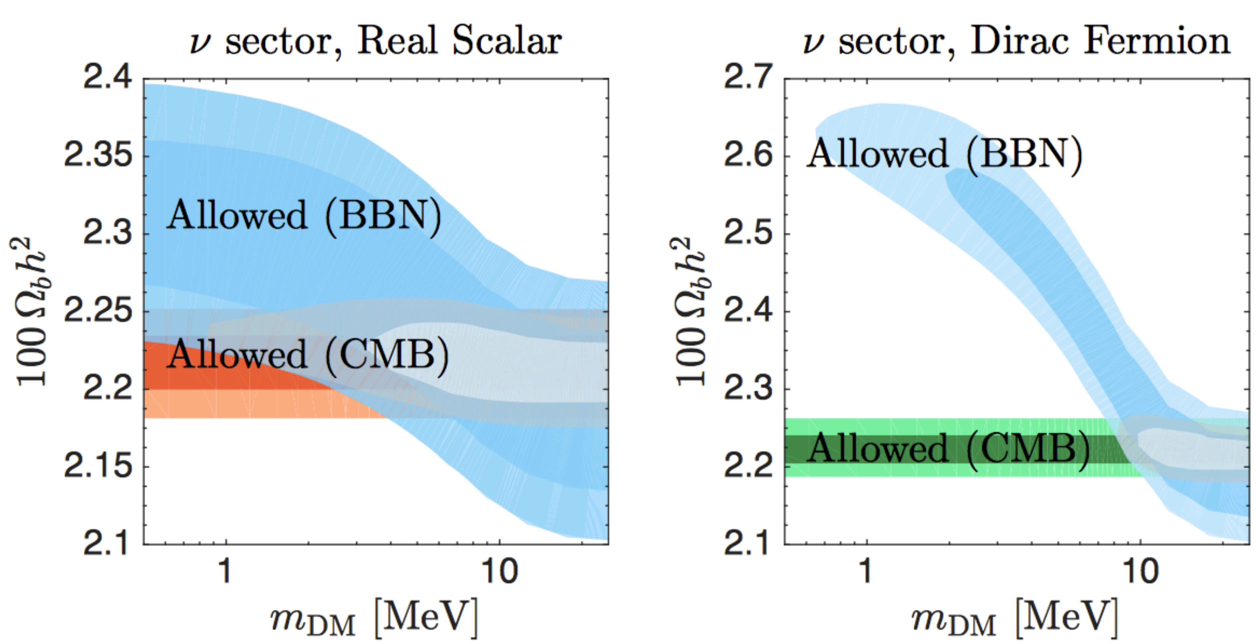


R. Wilkinson, ACV, C. Boehm, C. McCabe 1602.01114

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

DM-neutrino interactions: cosmology (II)

t s minutes 300kyr 13.5 Gyr

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

a 10^{-10} 10^{-10} 10^{-3}

Neutrinos decouple, neutrons production stops

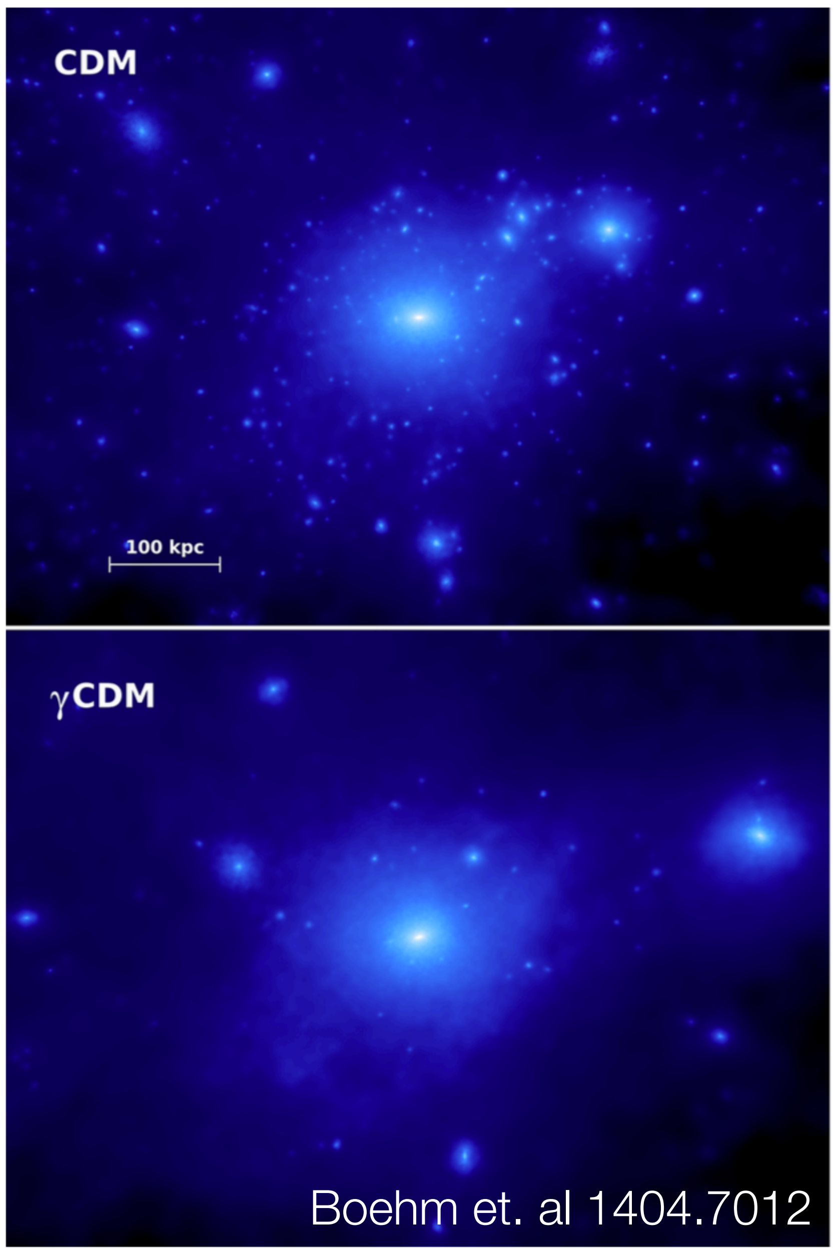
D, He formed

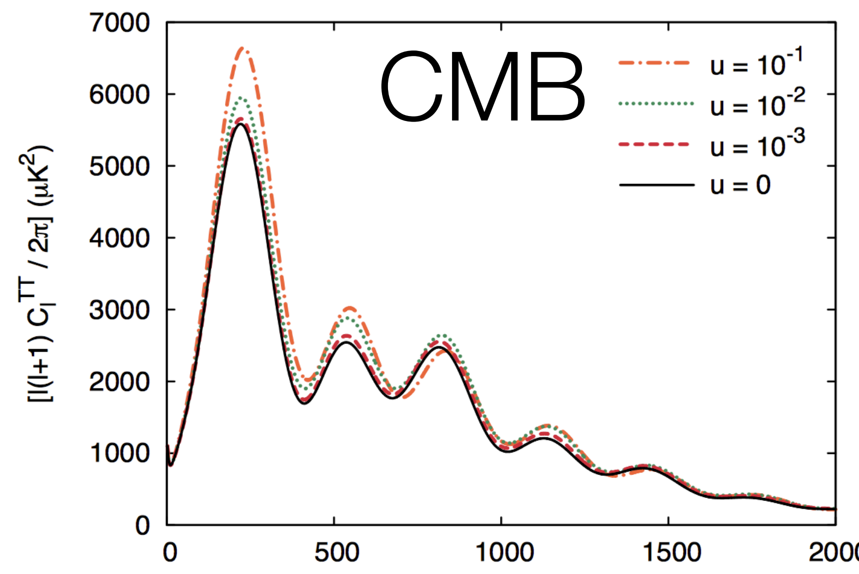
Recombination
CMB formed

gravitational perturbations grow

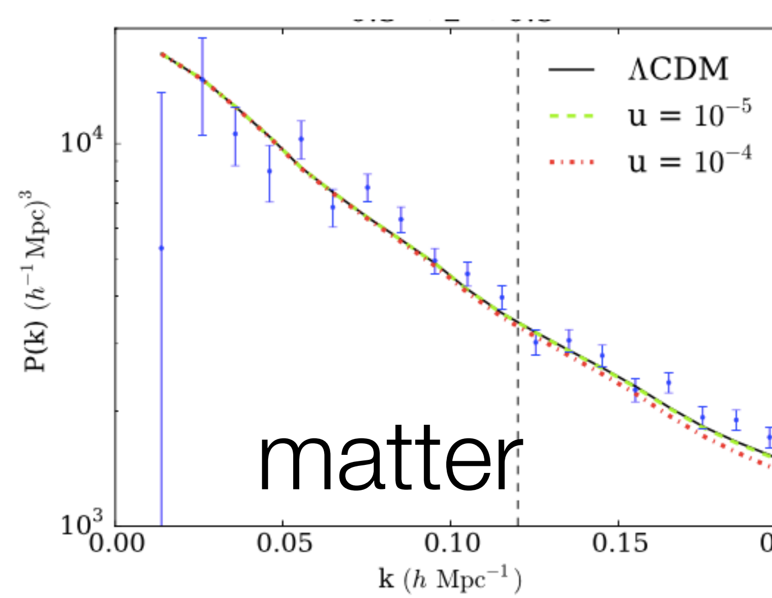
DM-neutrino interactions: cosmology (II)

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

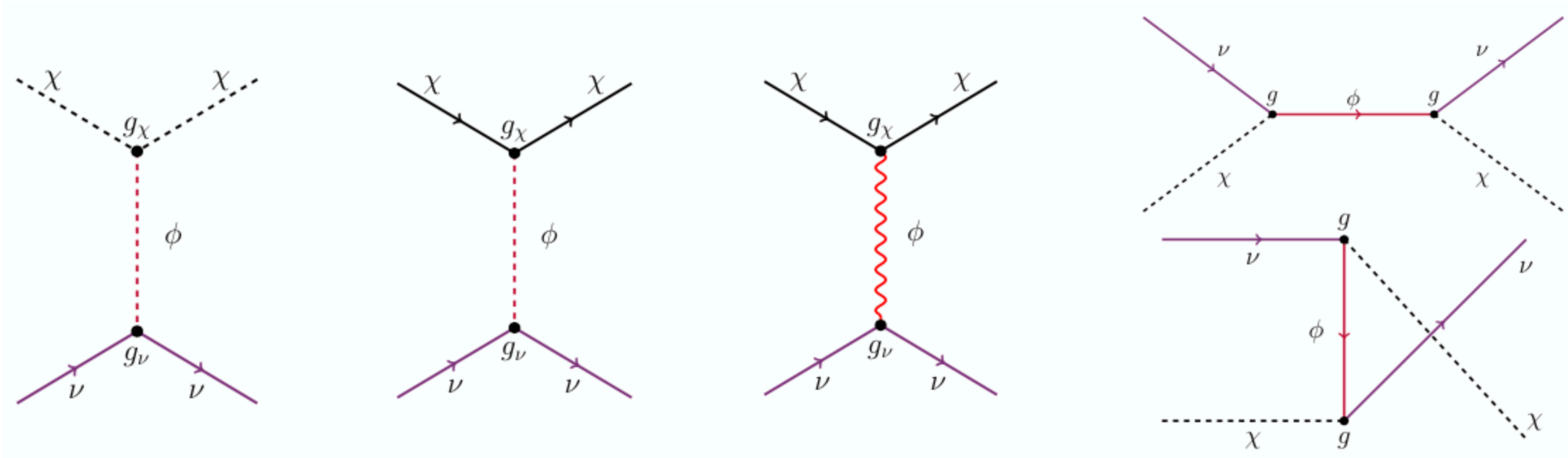




Wilkinson et al. 1401.7597



Escudero ... ACV 1505.06735



Generic scattering cross section:

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

LSS limits:

1) $\sigma \rightarrow const.$

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

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

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

Escudero+ACV++

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

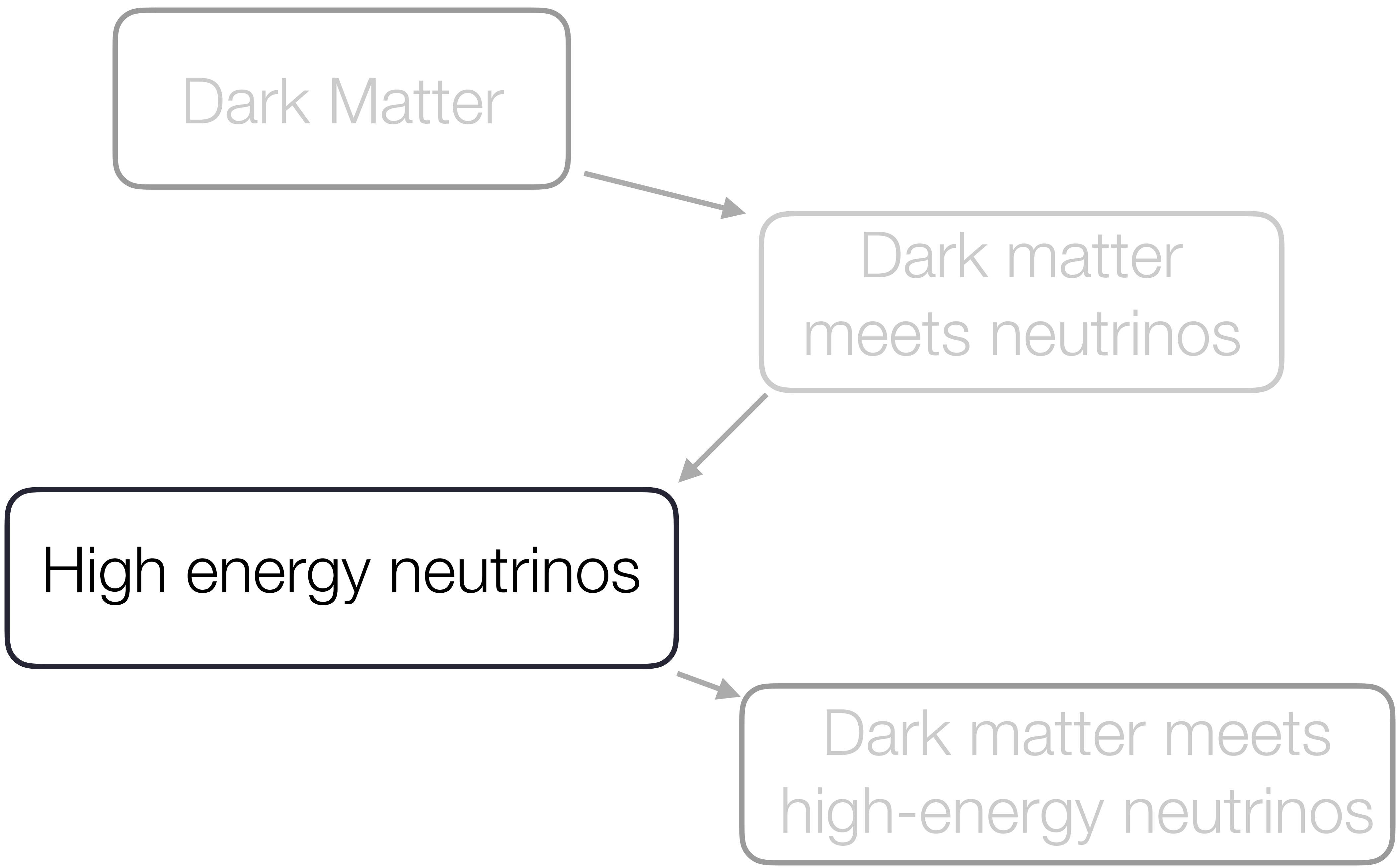
Mangano 2006 + many others

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

IceCube has seen events above a PeV….

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

Let’s look there!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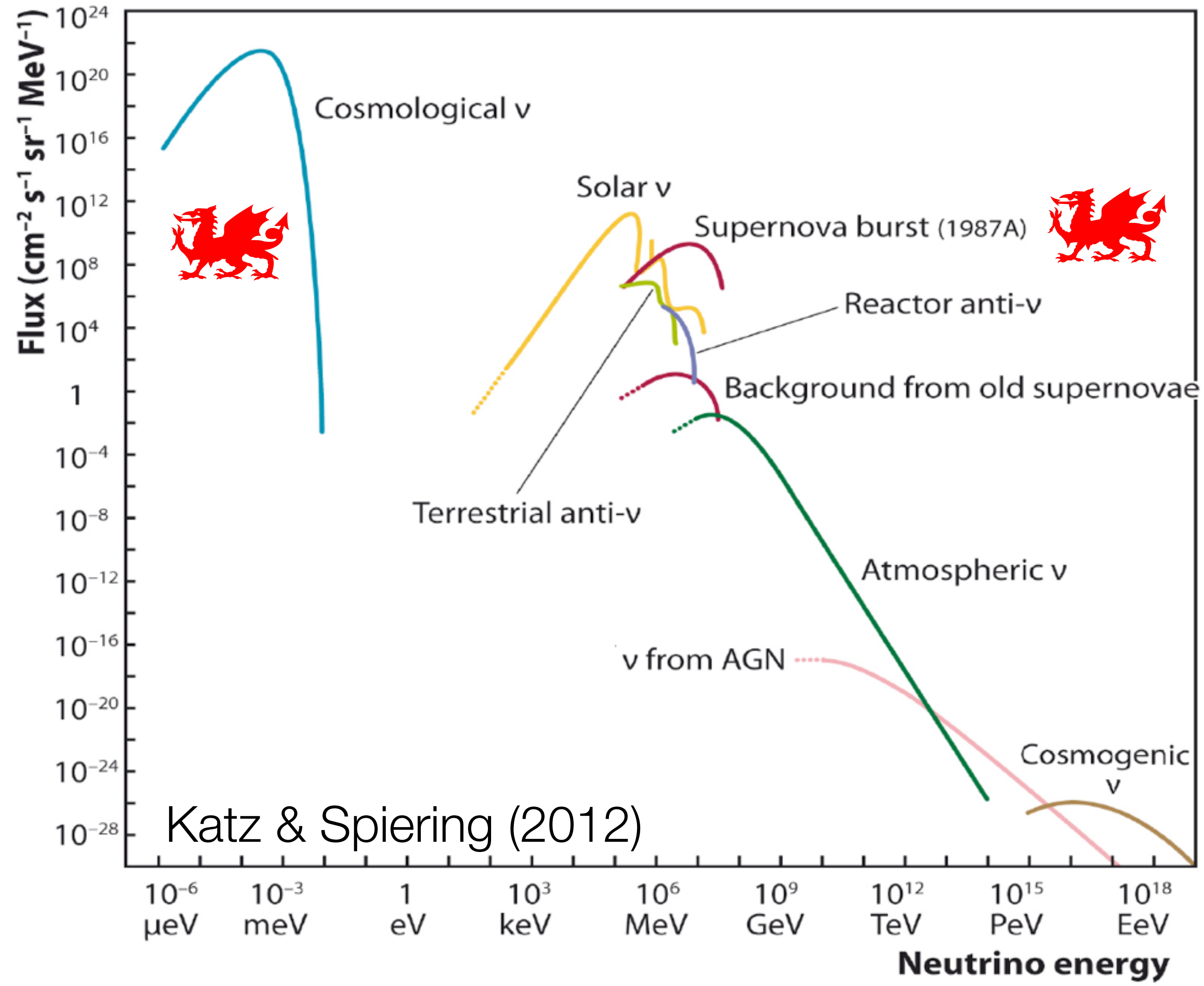
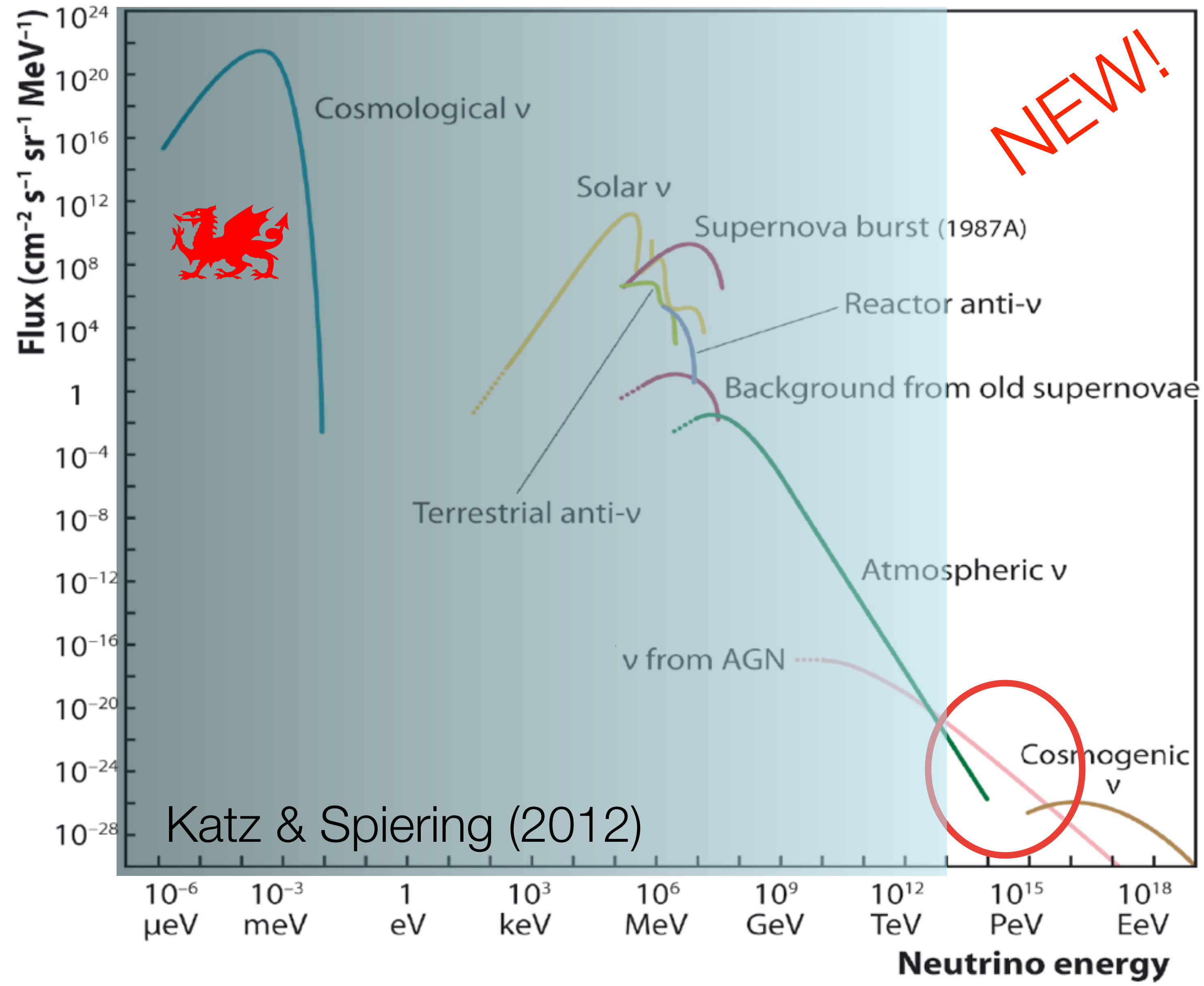
Dark matter meets high-energy neutrinos

Neutrinos



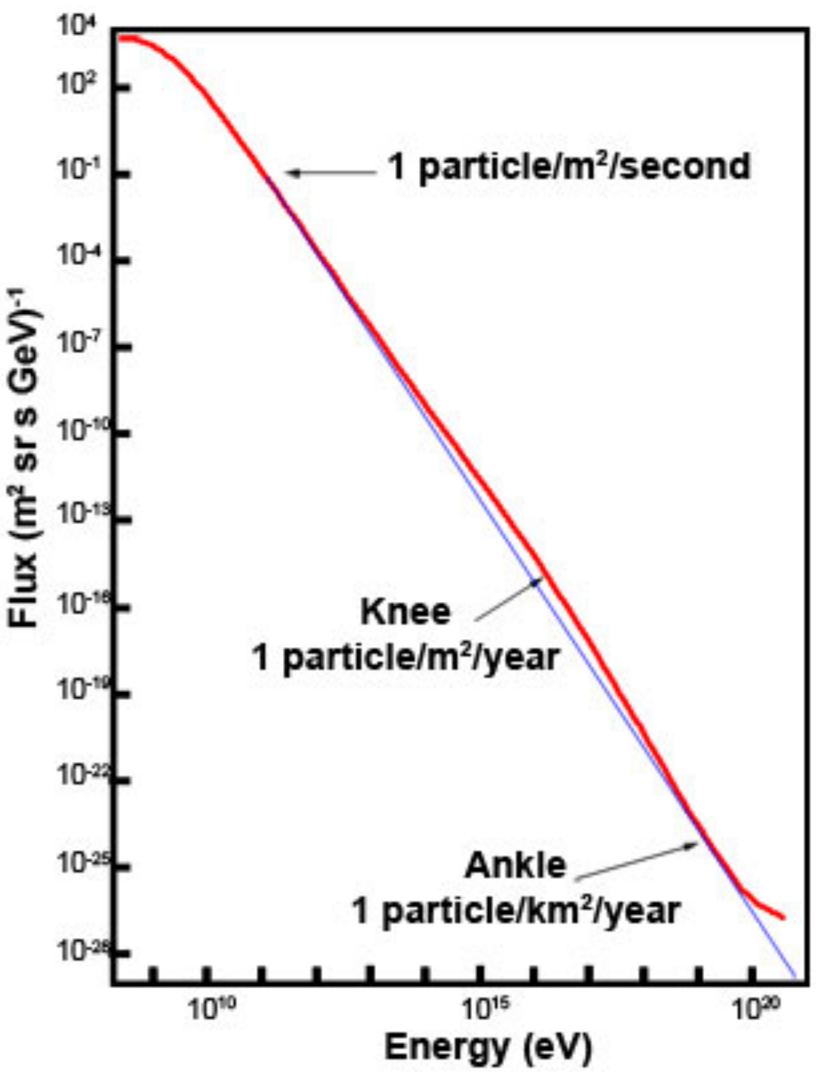
Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Katz & Spiering (2012)
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy

Neutrinos

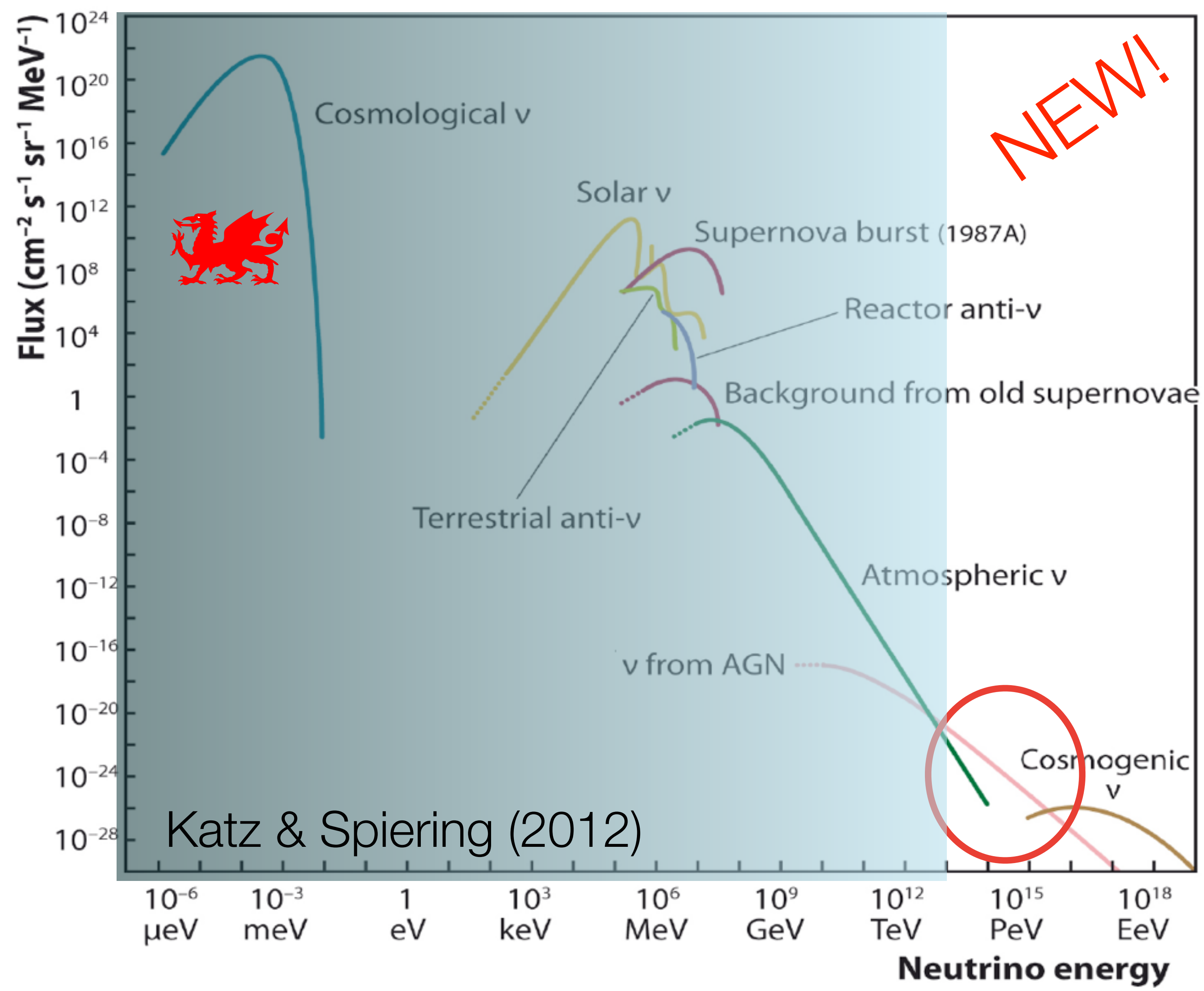


NEW!
Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Katz & Spiering (2012)
Neutrino energy
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
EeV

Cosmic rays

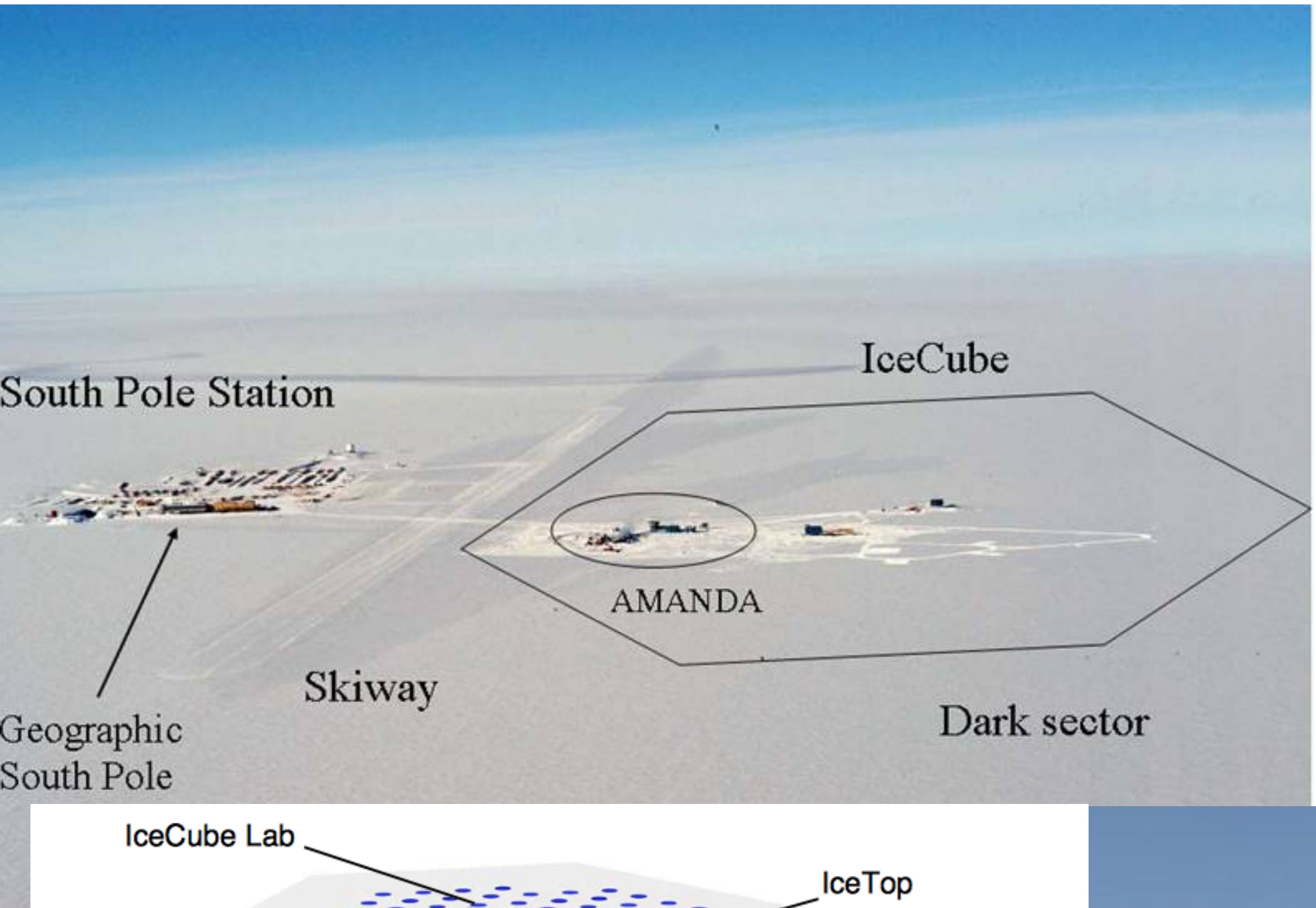


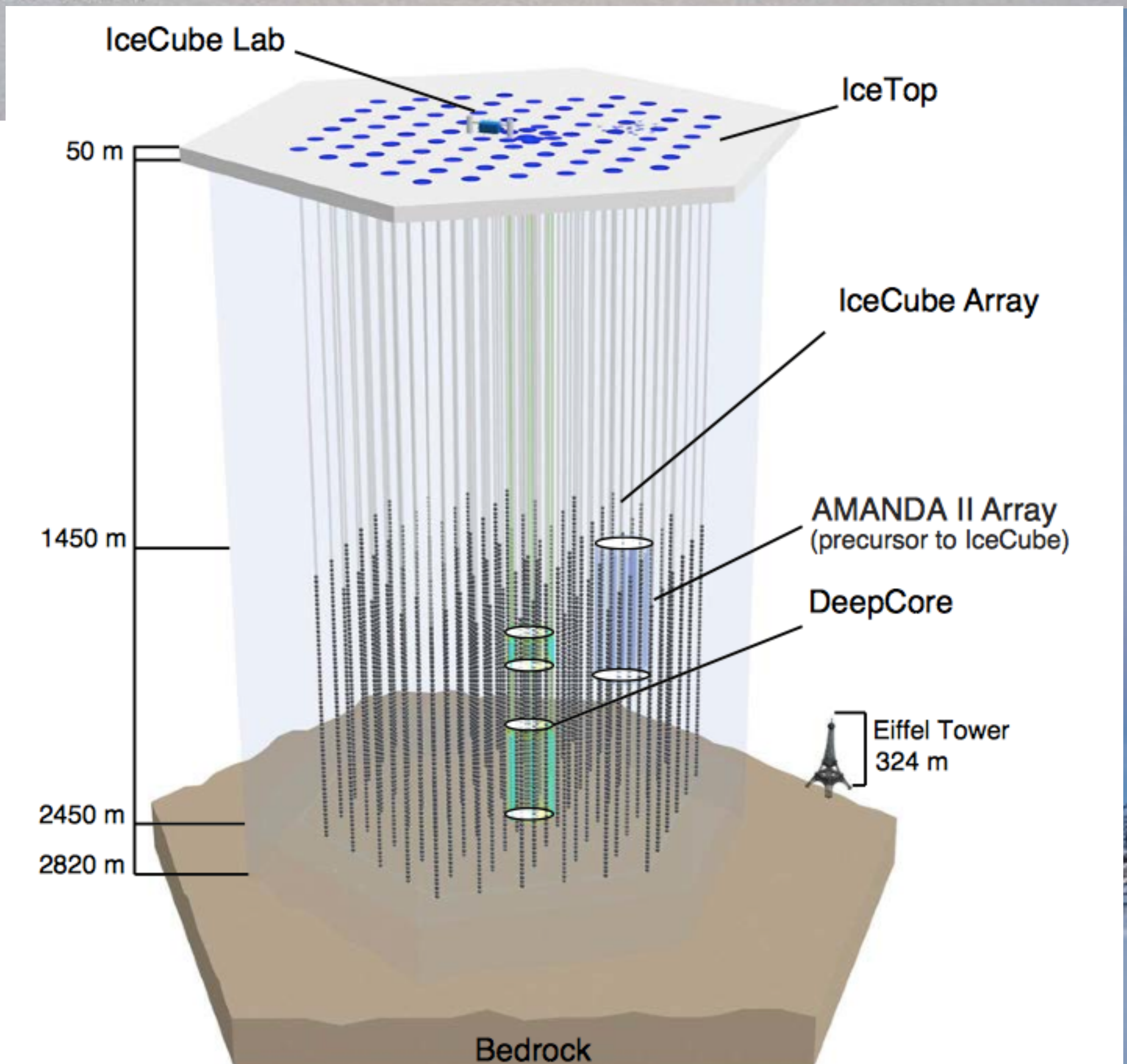
Neutrinos

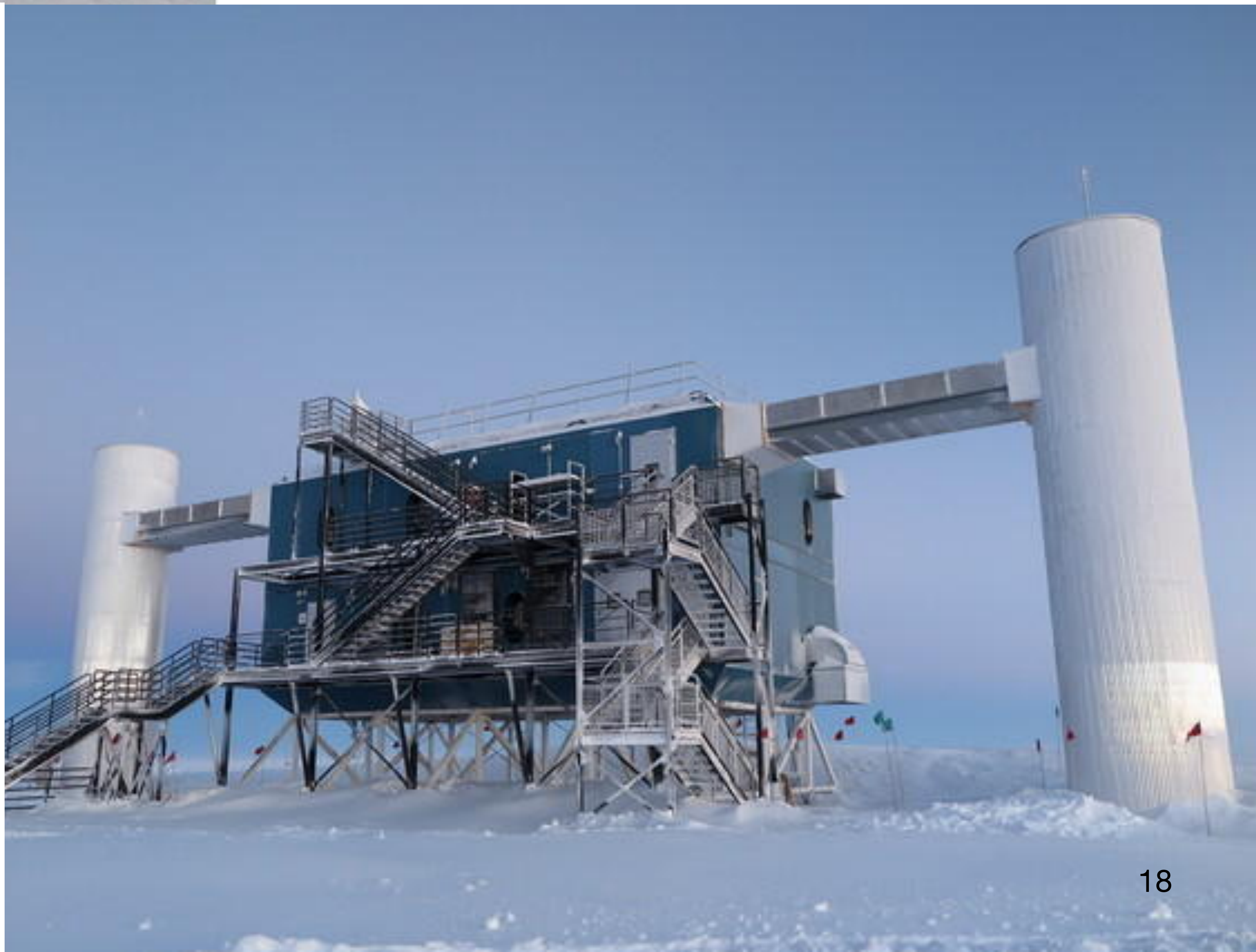


We see high-energy (>> TeV) **cosmic rays** and **gamma rays**, so we know associated **neutrinos** must be produced

IceCube Neutrino Observatory







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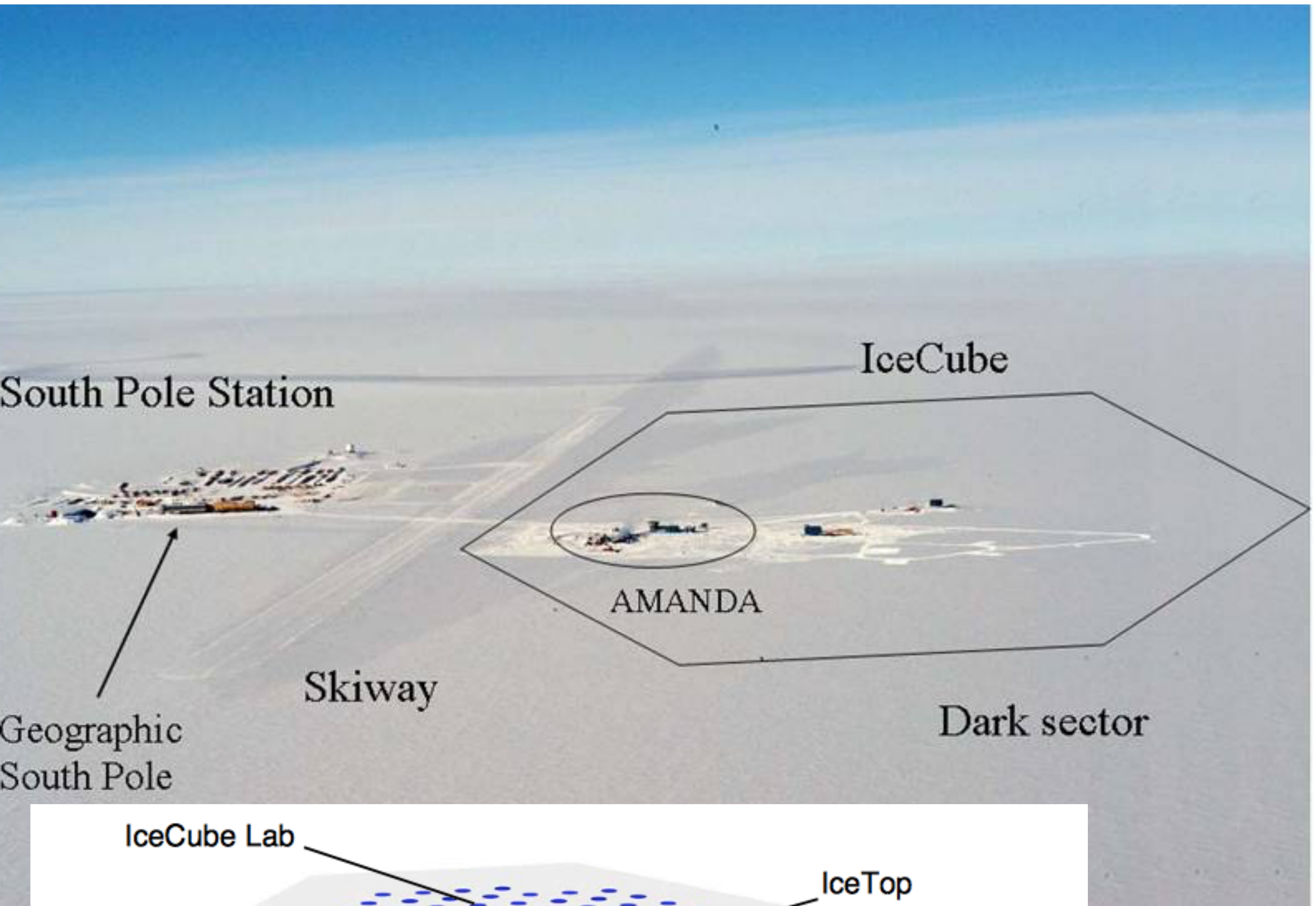
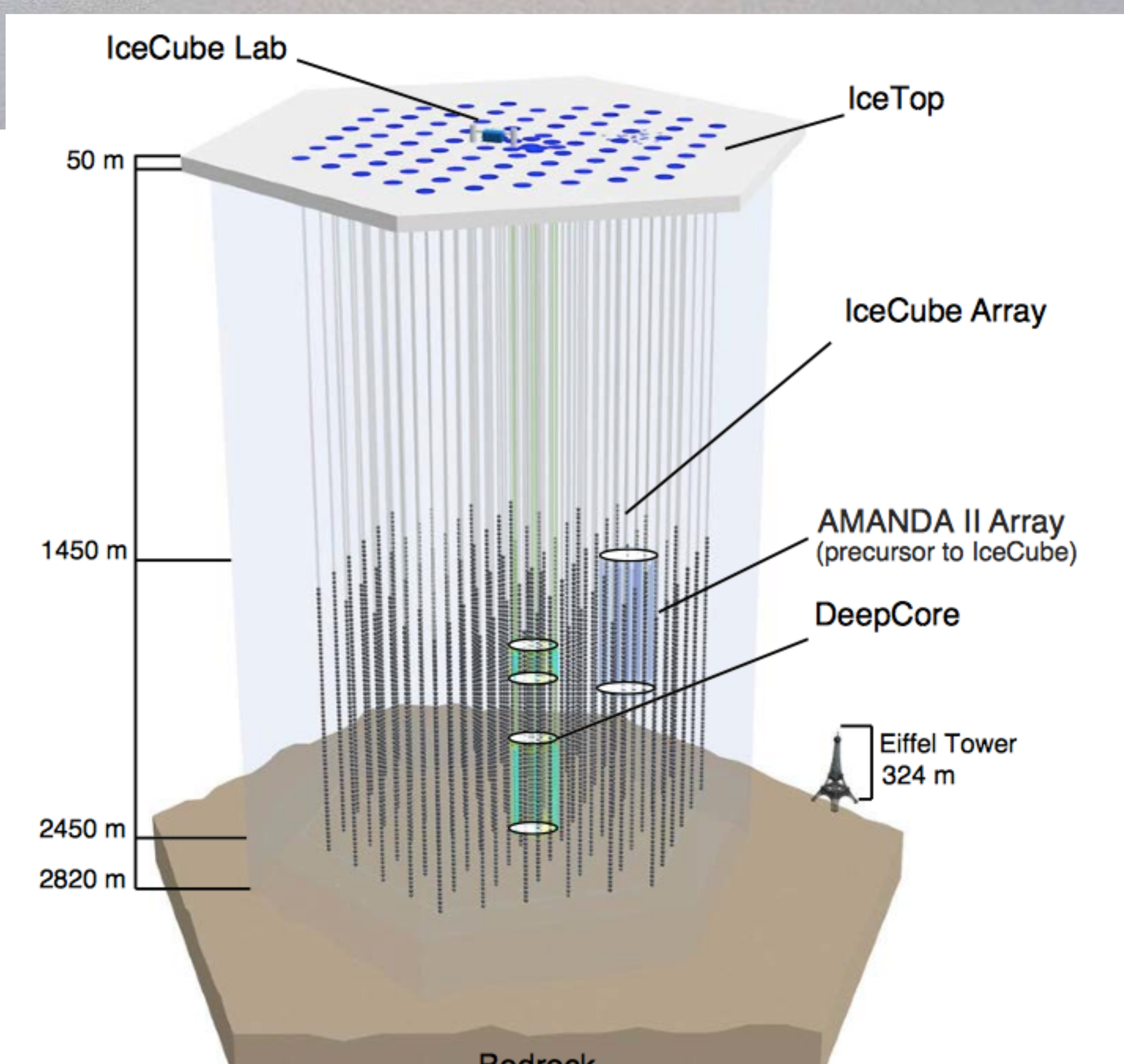
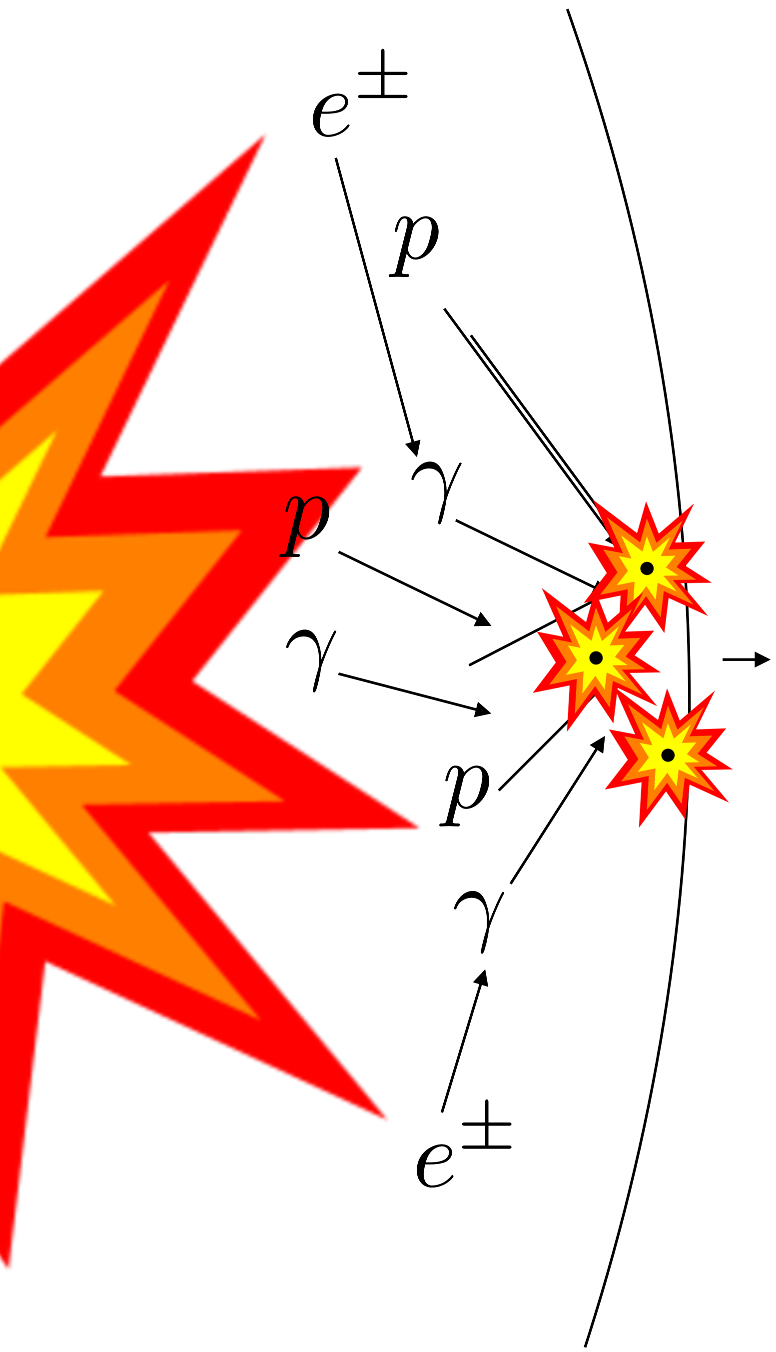
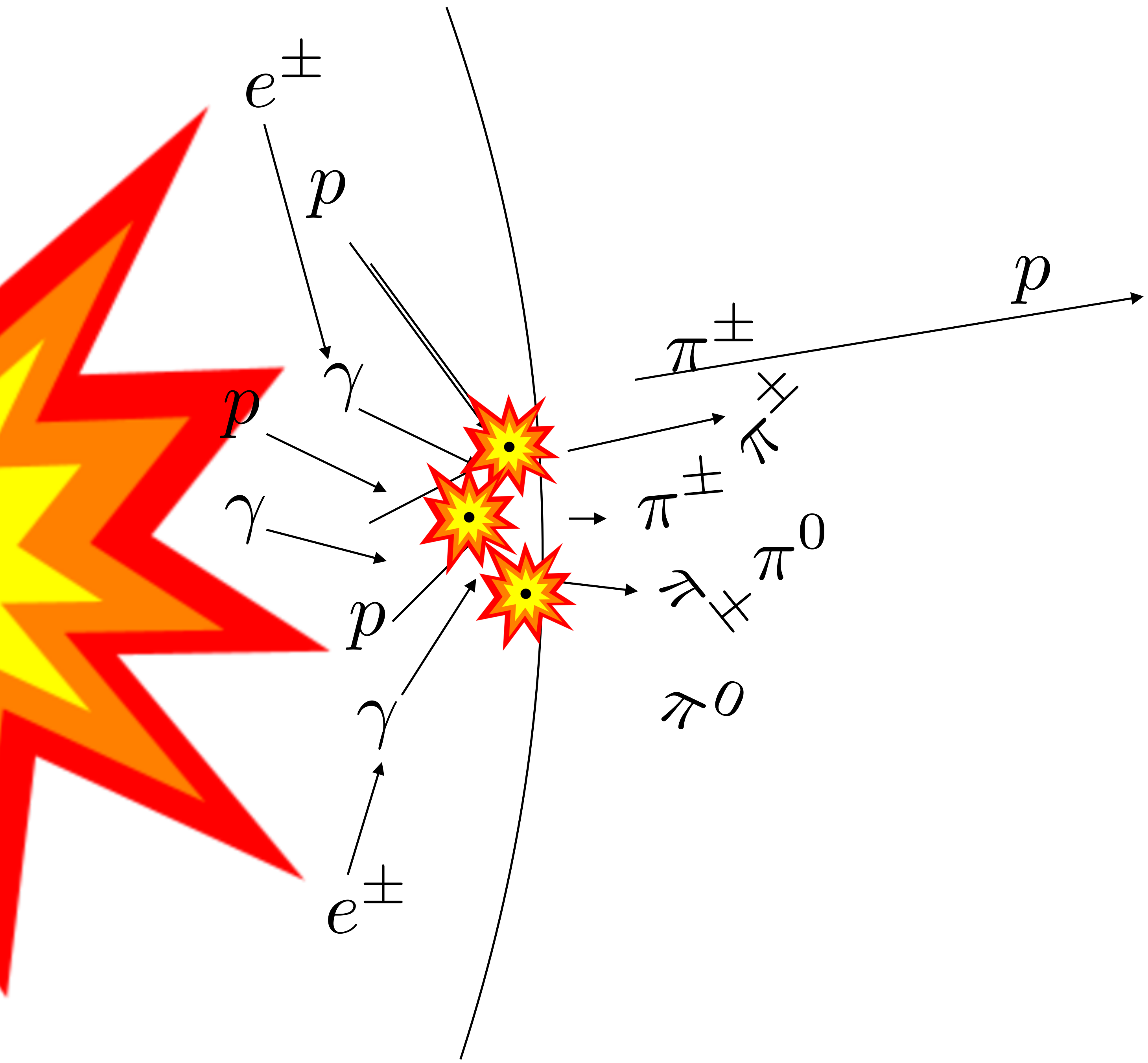
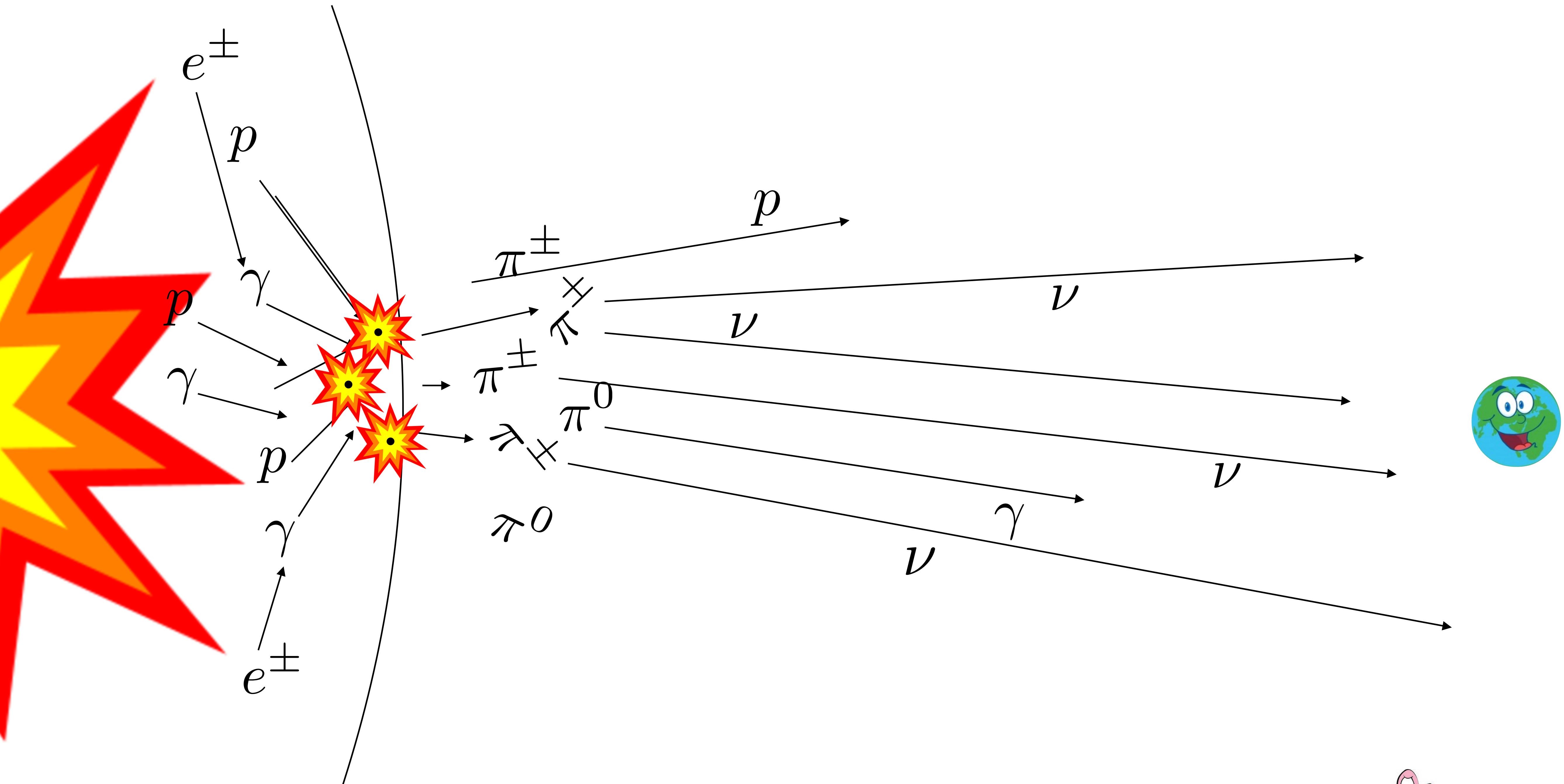





$e^{\pm}$
p
γ
p
γ
p
γ
$e^{\pm}$



$e^{\pm}$
p
γ
p
γ
p
γ
$e^{\pm}$
p
$\pi^{\pm}$
$\pi^{\pm}$
$\pi^{\pm}$
π^0
$\pi^{\pm}$
π^0



Photon, CR
energy limited by
mean free path in CMB

Neutrinos just keep
going….

High energy neutrino observables

High energy neutrino observables

Arrival direction

High energy neutrino observables

Arrival direction

Energy

High energy neutrino observables

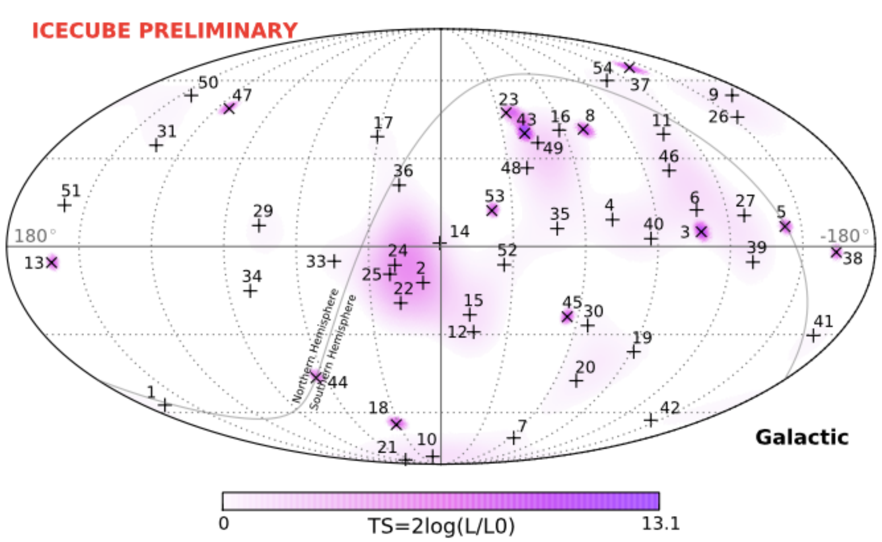
Arrival direction

Energy

Flavour (e, μ, τ)

High energy neutrino observables

Arrival direction

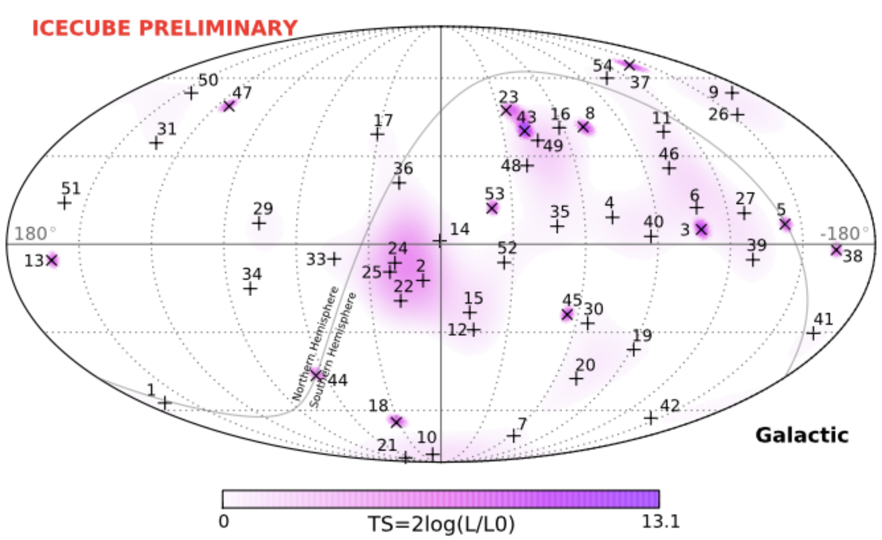


Energy

Flavour (e, μ, τ)

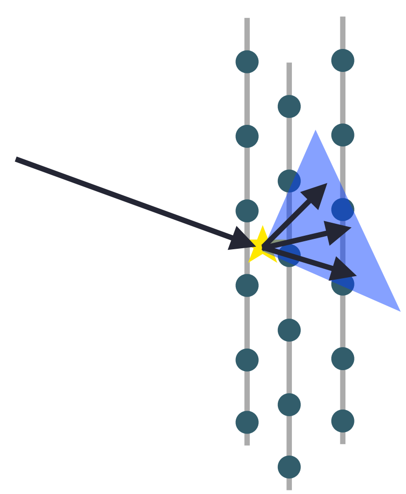
High energy neutrino observables

Arrival direction



Energy

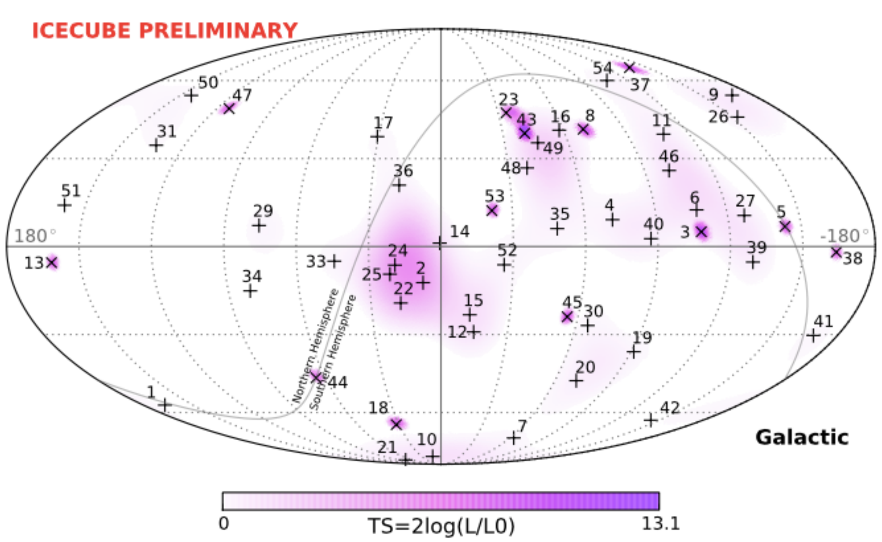
Deposited
EM-equivalent



Flavour (e, μ, τ)

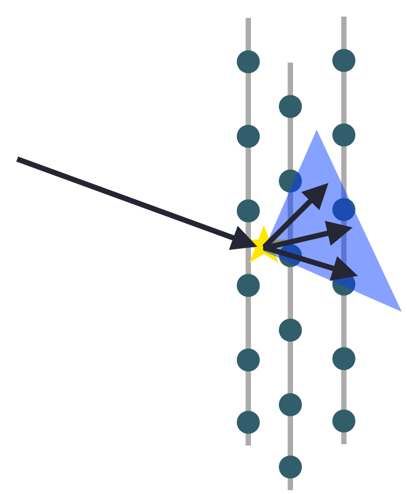
High energy neutrino observables

Arrival direction



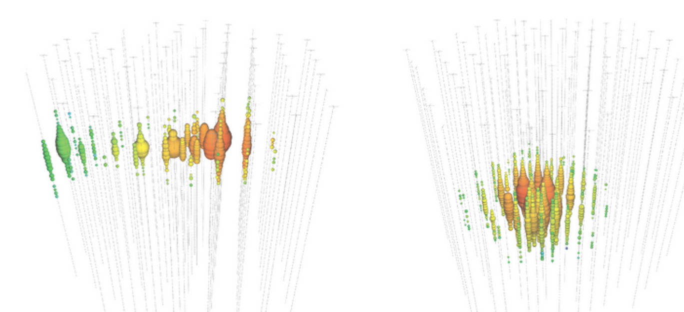
Energy

Deposited EM-equivalent



Flavour (e, μ, τ)

Topology

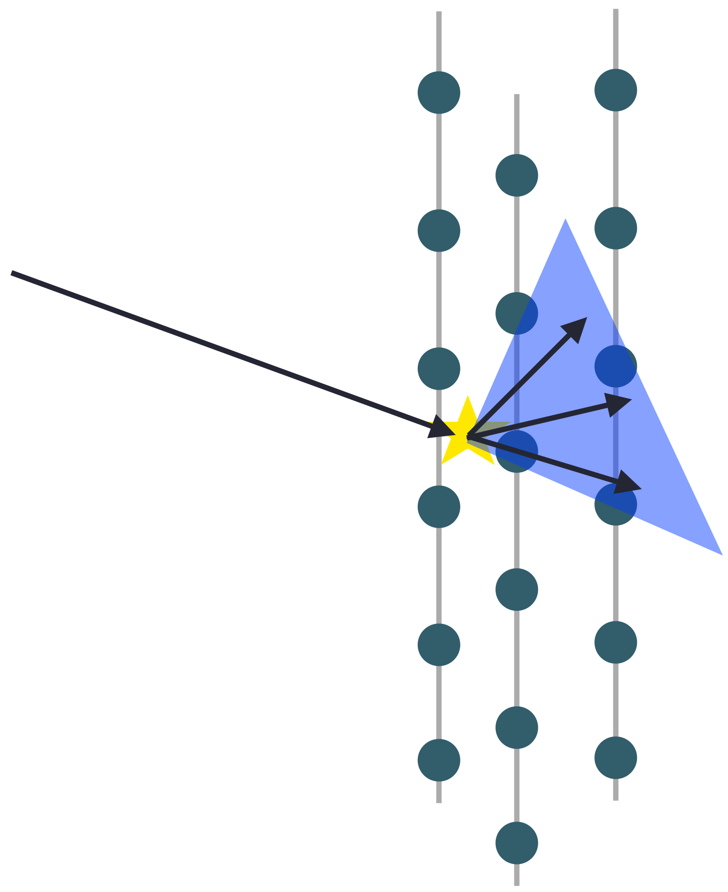


muon track

shower

High energy starting events (HESEs)

1) Neutrino arrives



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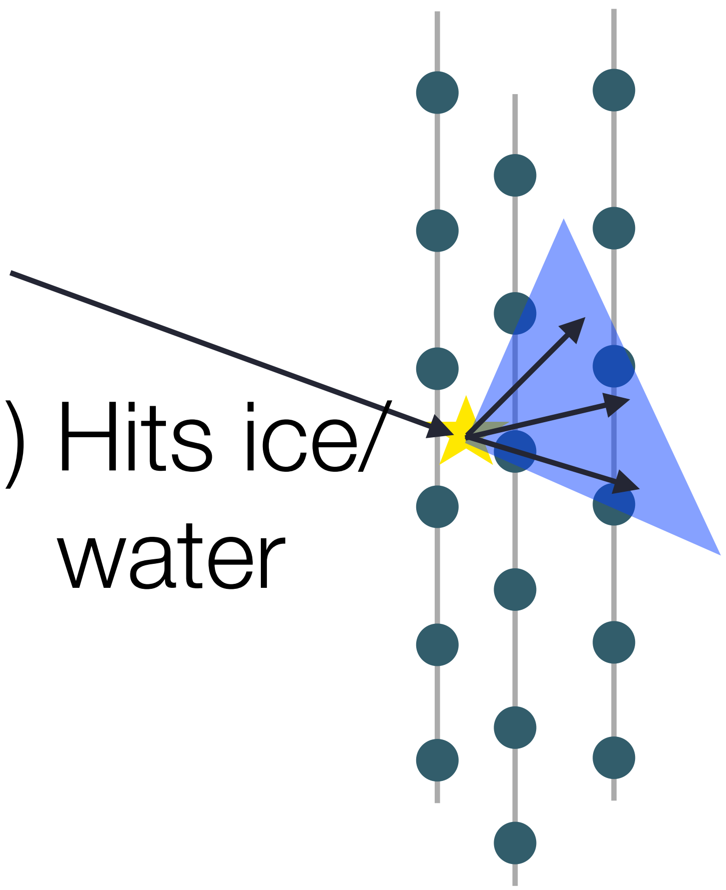

2) Hits ice/ water

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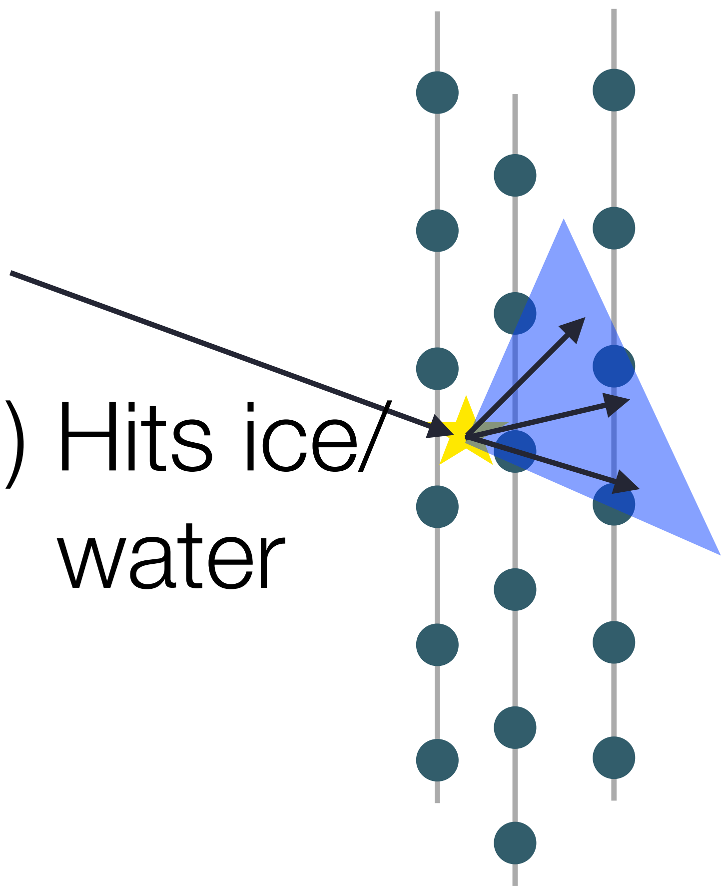

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3) DOMs see Čerenkov light from electrons, muons

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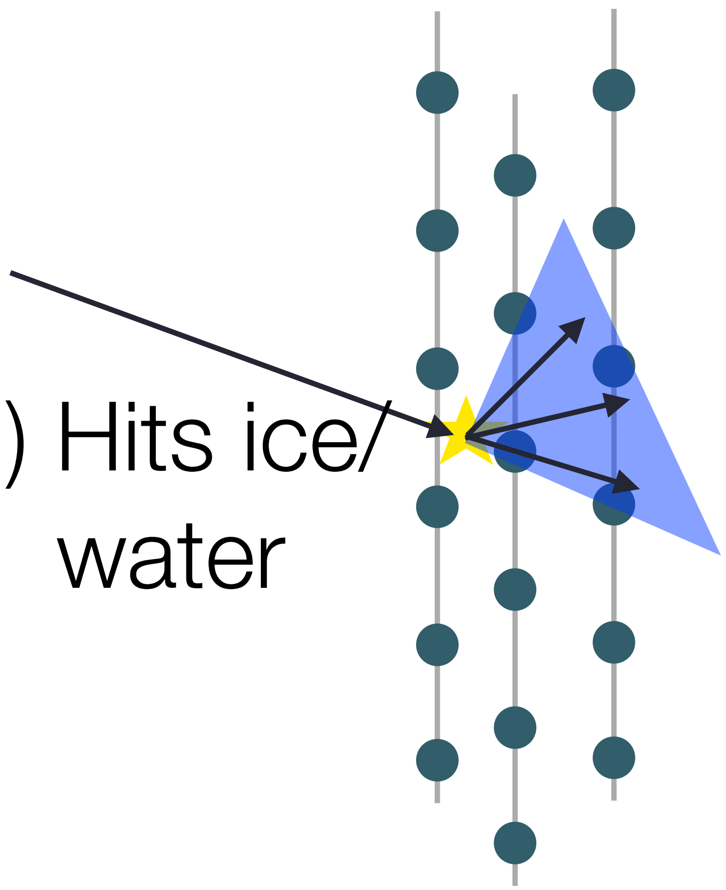

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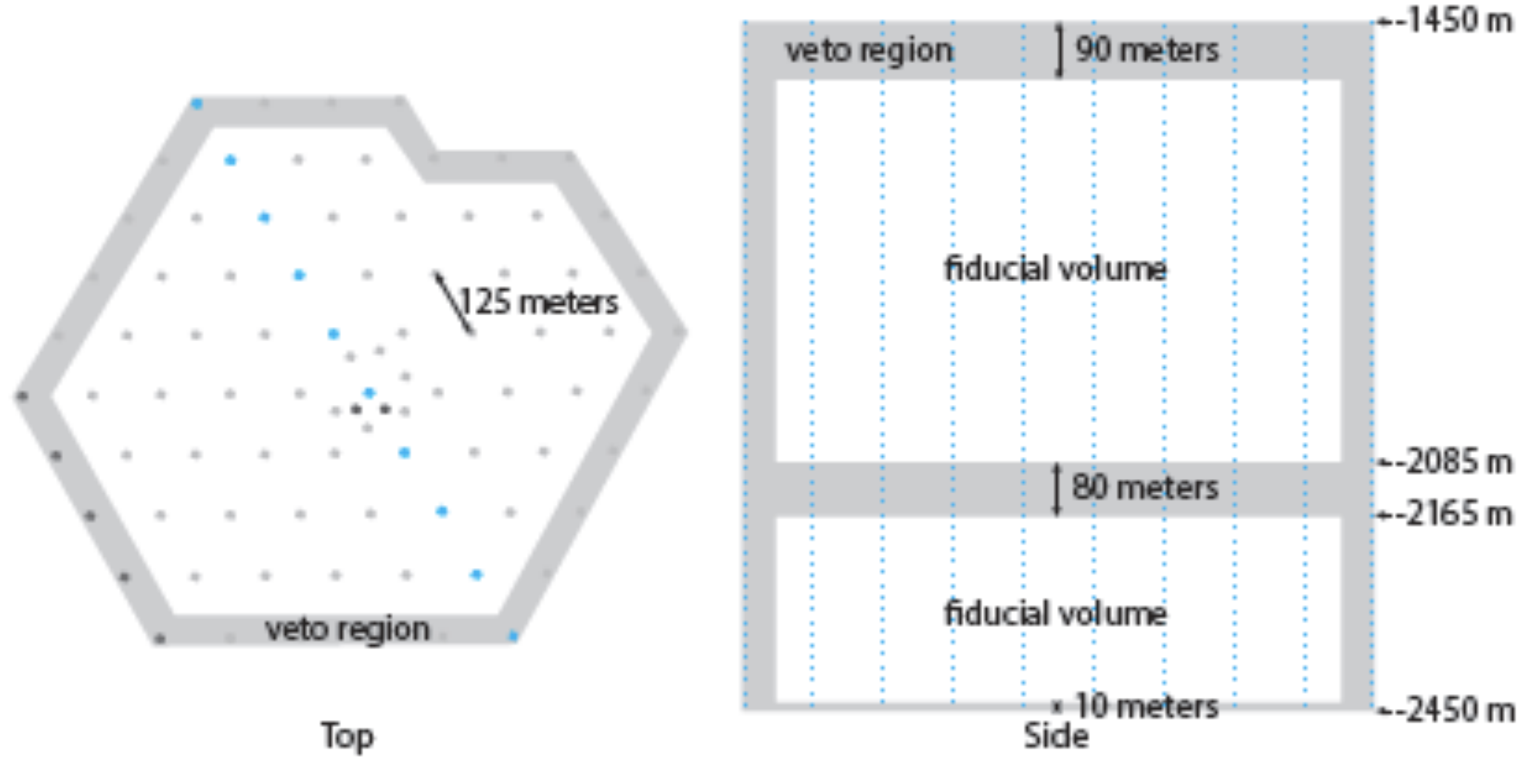

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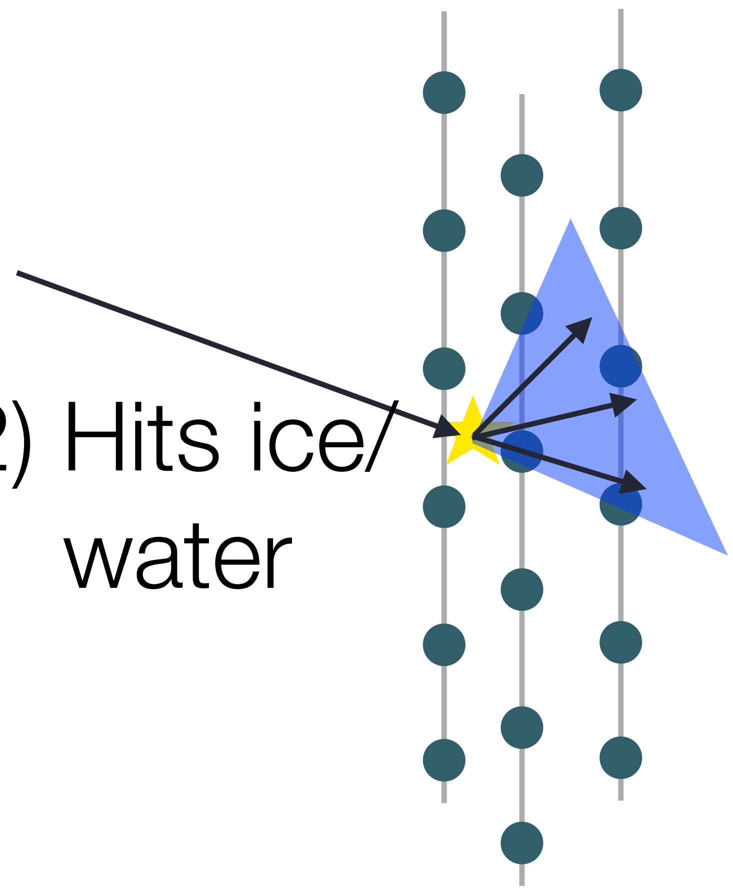

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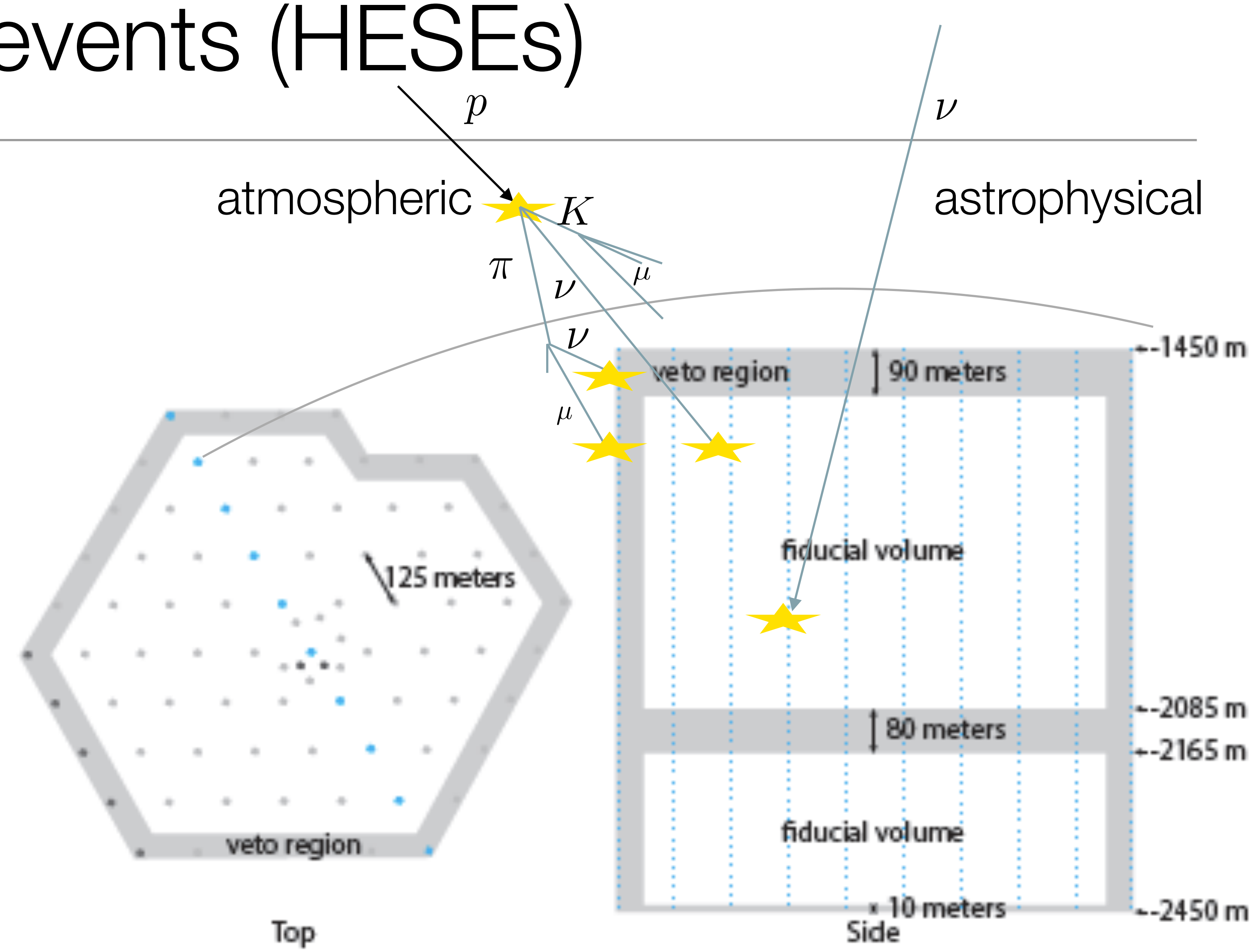

High energy starting events (HESEs)

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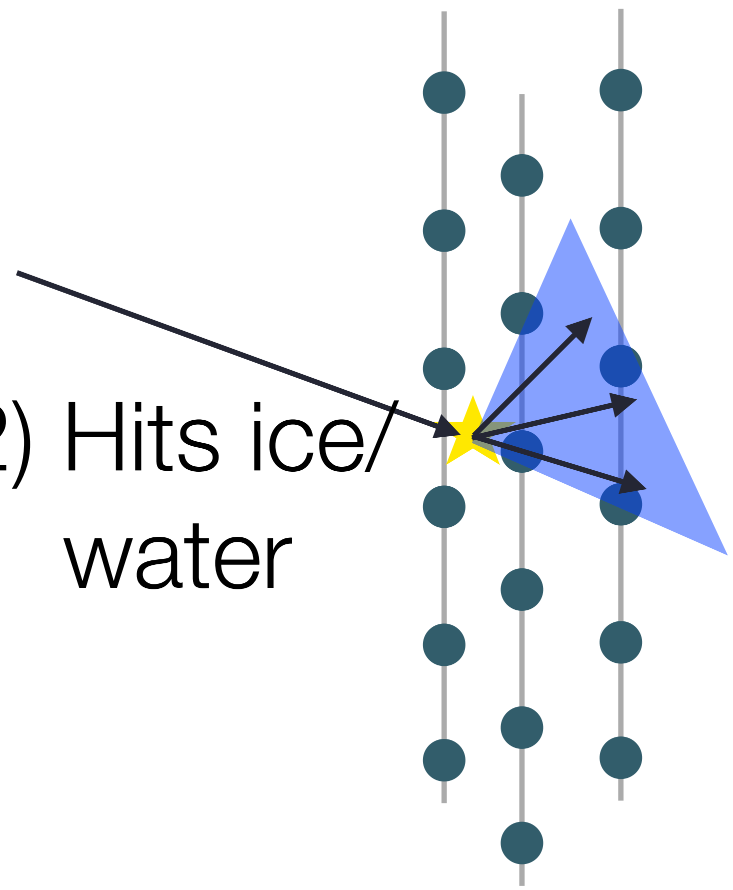

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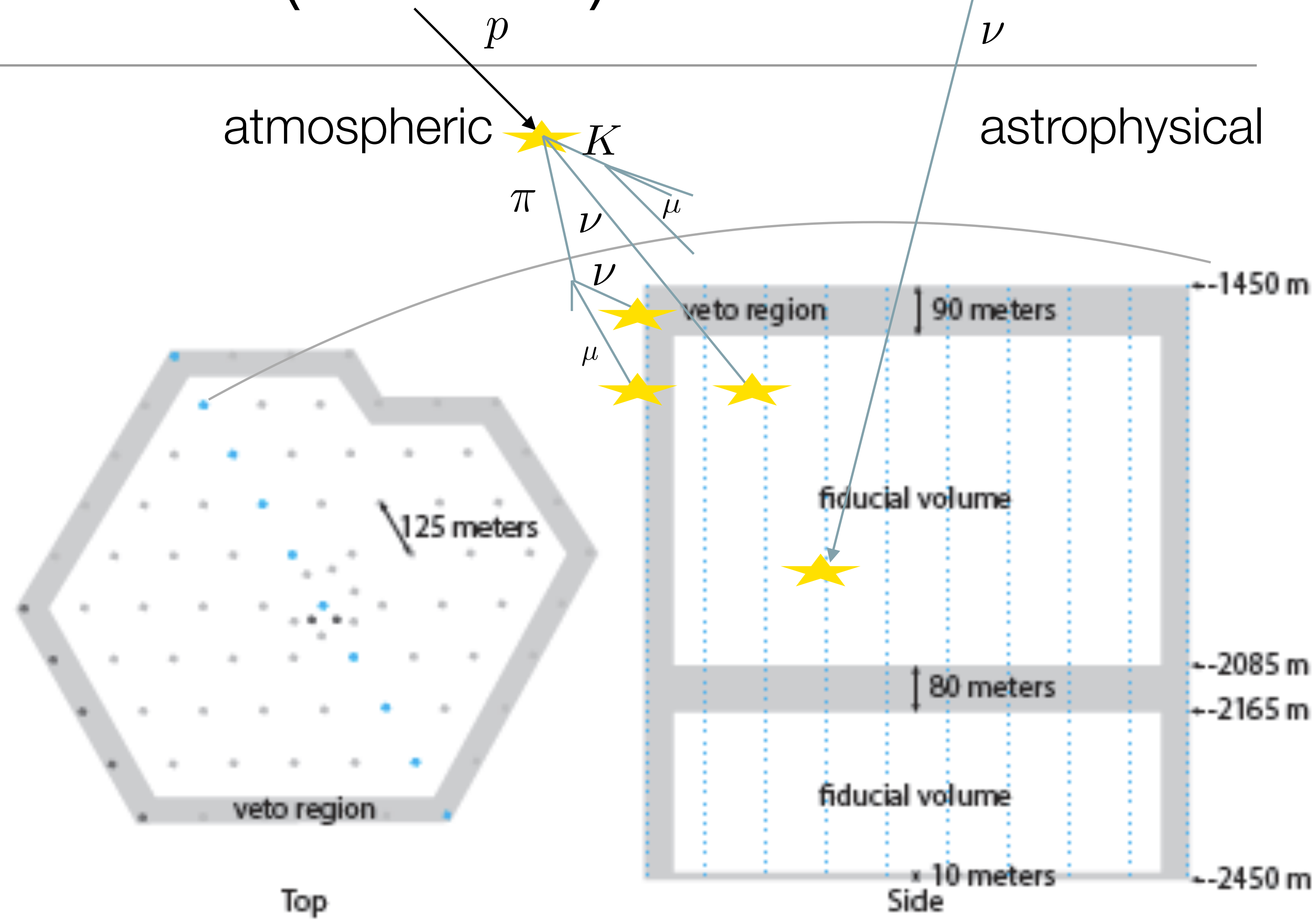
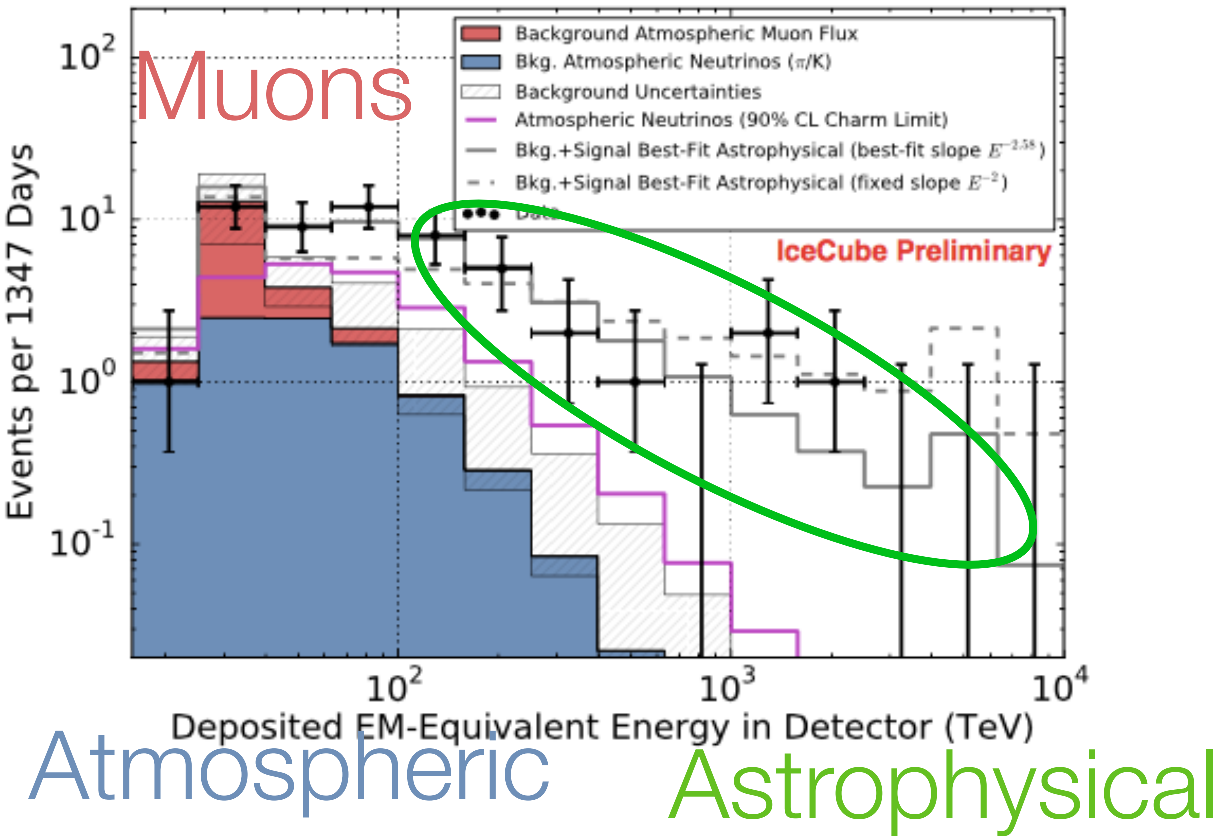


Look at events starting in detector volume: **High Energy Starting Events** (HESEs)

Energy

IceCube ICRC 1510.05223



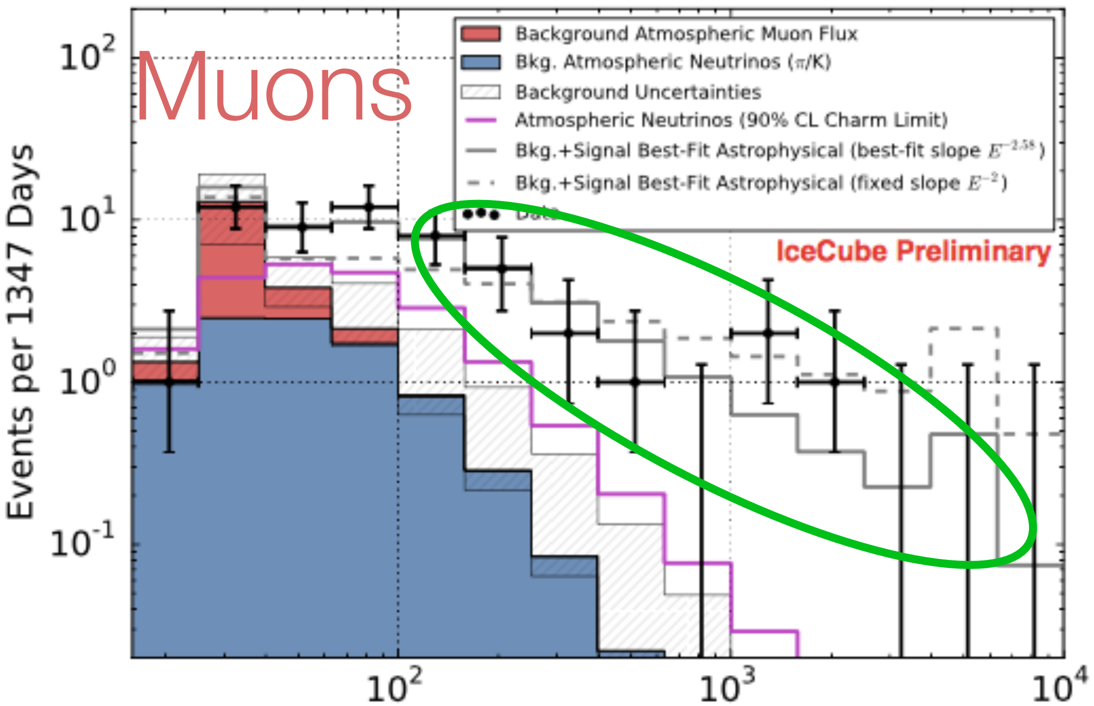
Four-years sample:
54 HESE events

Higher E than
galactic sources

22

Energy

IceCube ICRC 1510.05223

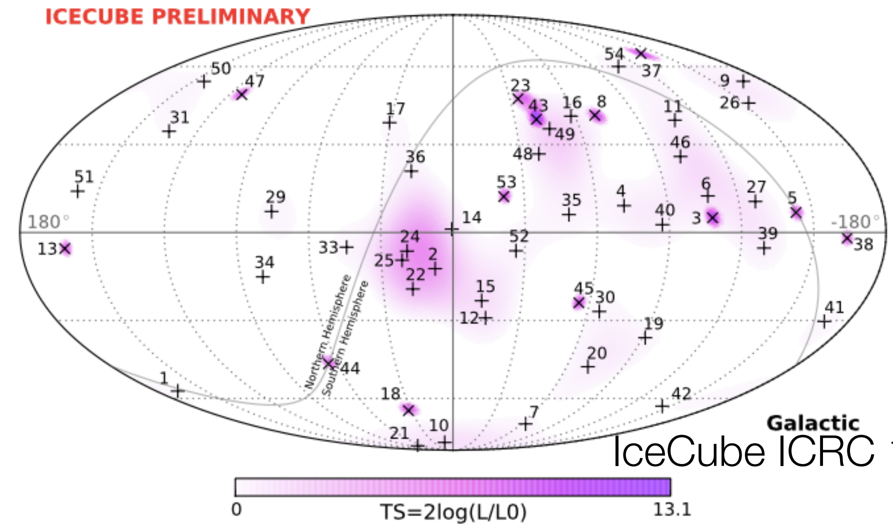


Astrophysical

Four-years sample:
54 HESE events

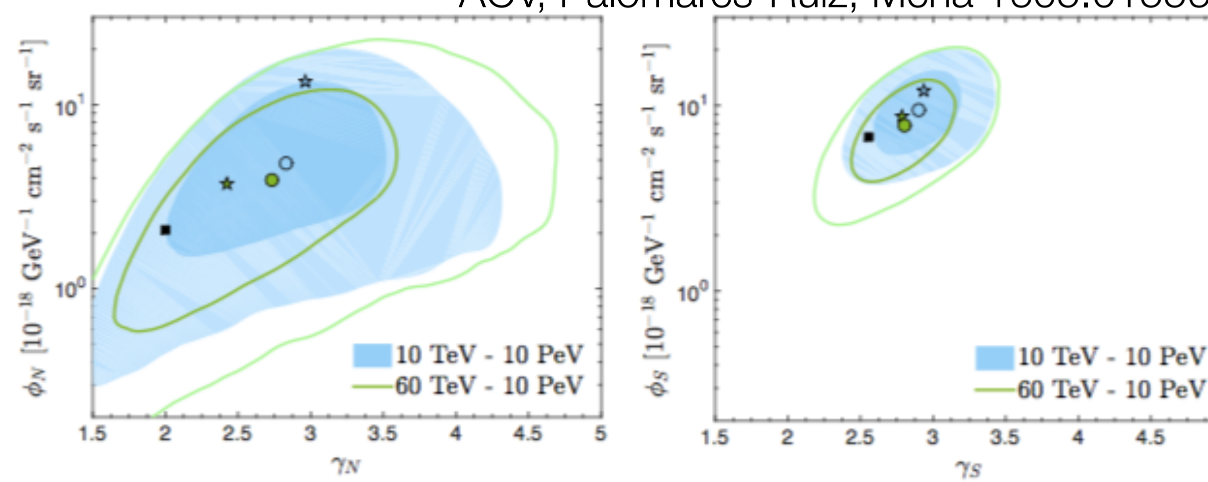
Higher E than galactic sources

Arrival direction



IceCube ICRC 1510.05223

ACV, Palomares-Ruiz, Mena 1605.01556

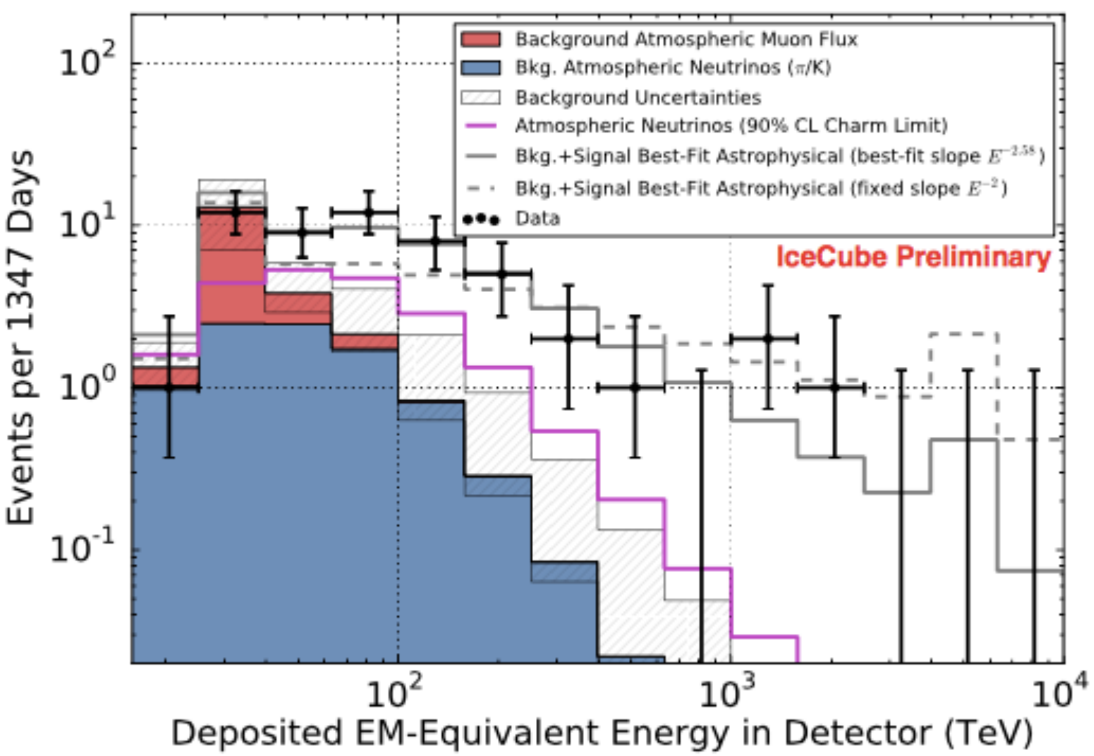


Upgoing Downgoing

Isotropic arrival
➡ extragalactic

Backgrounds

IceCube ICRC 1510.05223

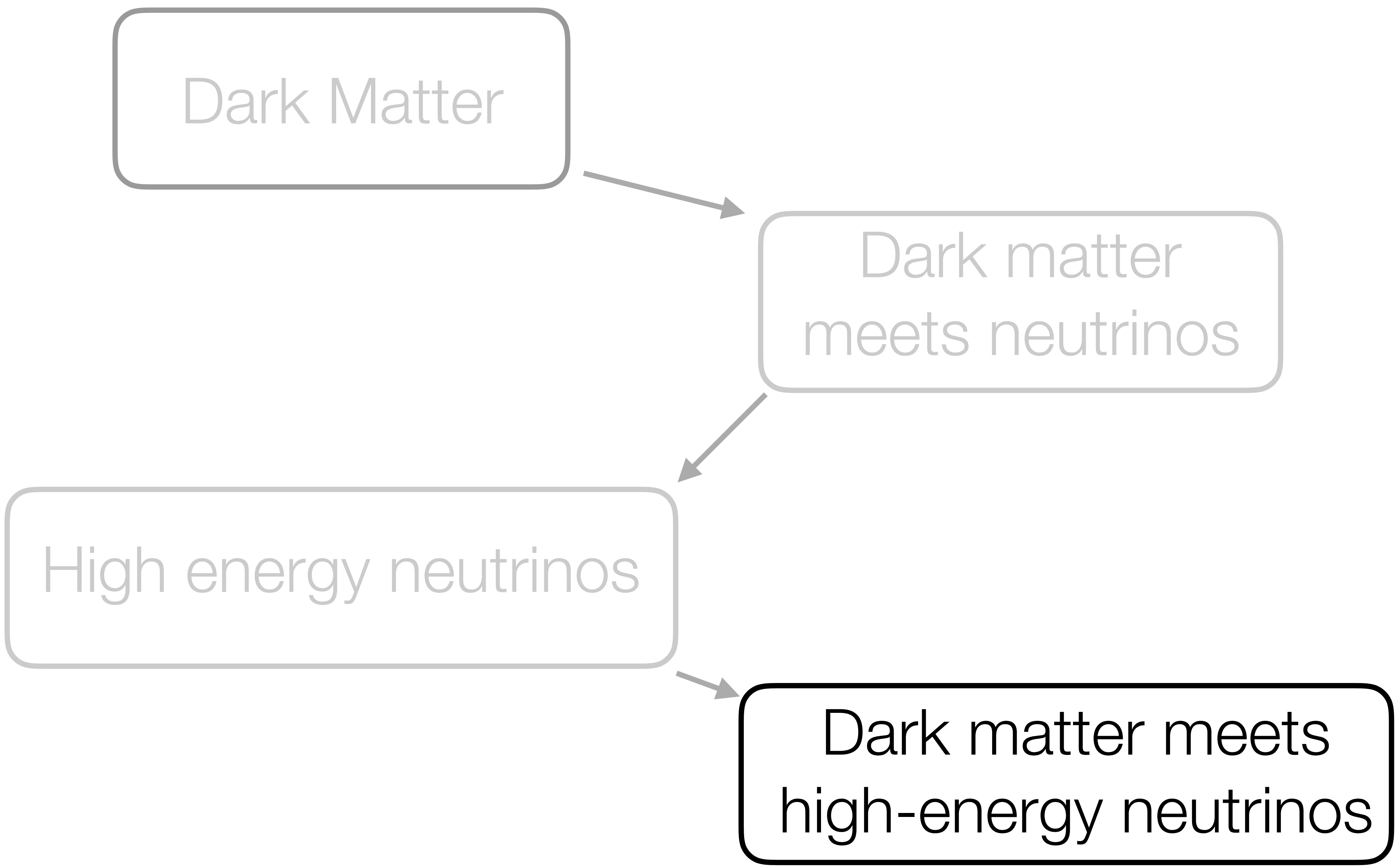


Neutrinos from atmospheric showers can fail to trigger the vetos. These are mostly upgoing (from the north), but concentrated around the horizon.

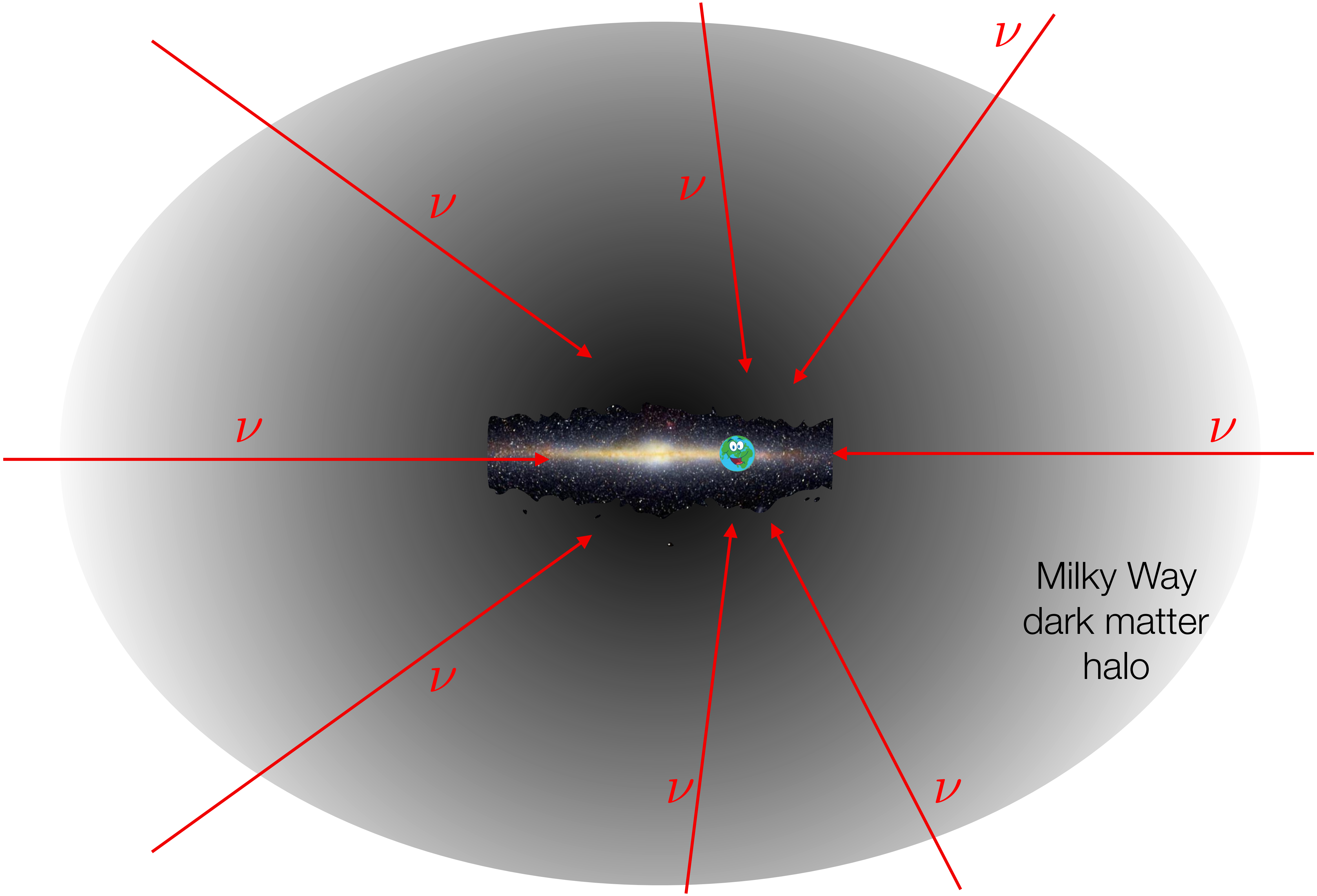
HESE: ~ 12/53 atmospheric neutrinos

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

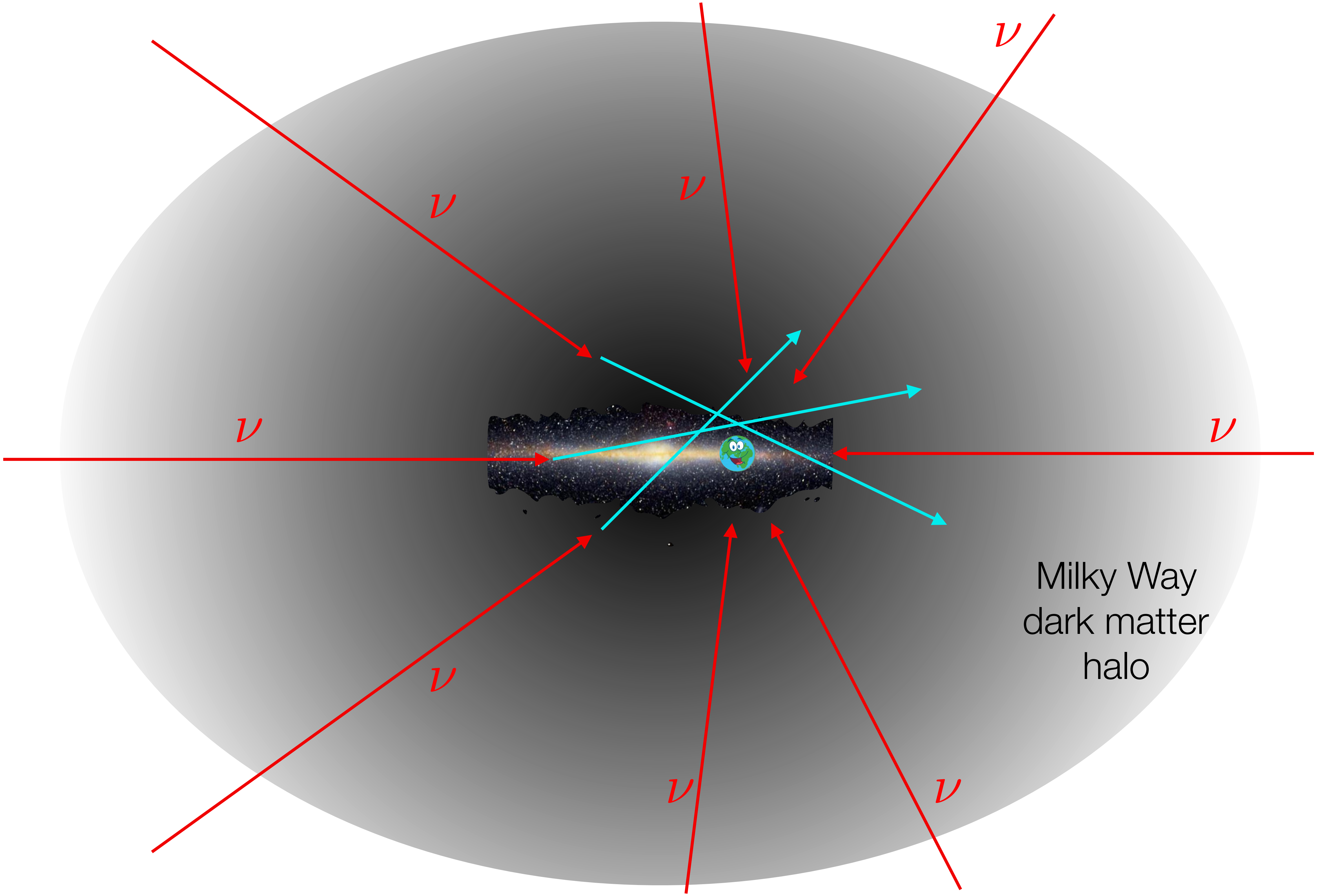
HESE: ~ 10/53 atmospheric muons


Dark Matter
Dark matter meets neutrinos
High energy neutrinos
Dark matter meets high-energy neutrinos

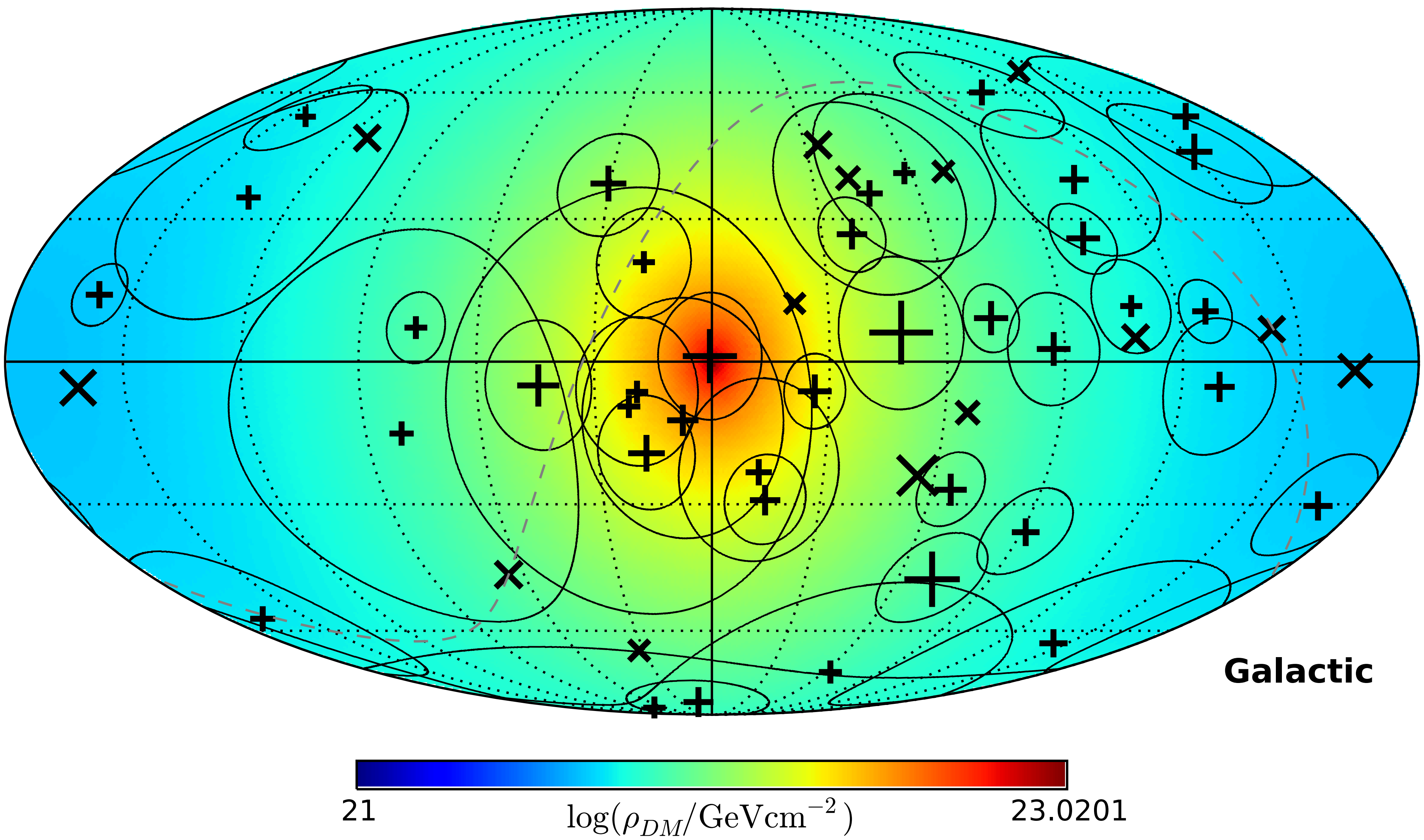
Isotropic extragalactic neutrino flux



Isotropic extragalactic neutrino flux

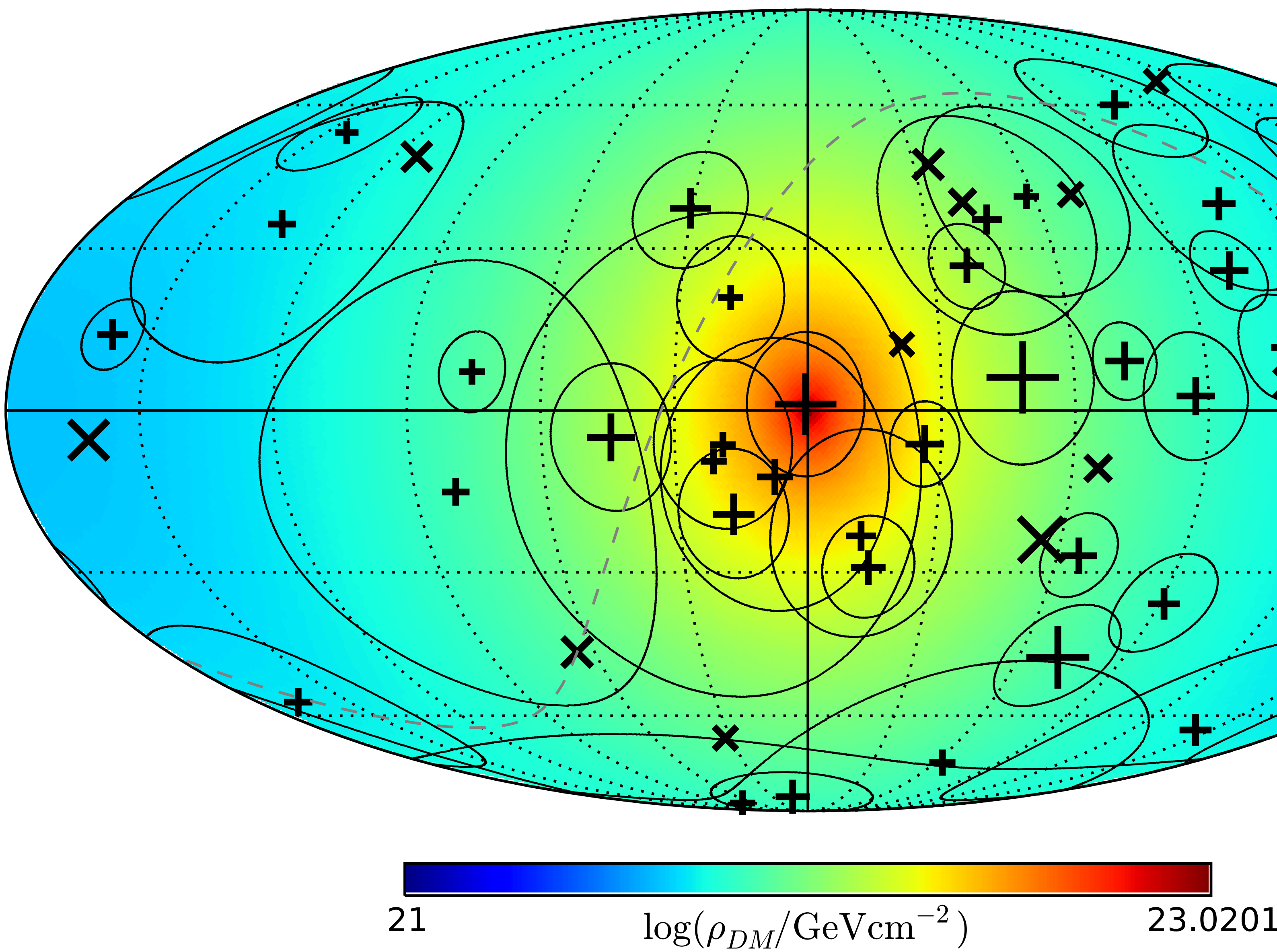


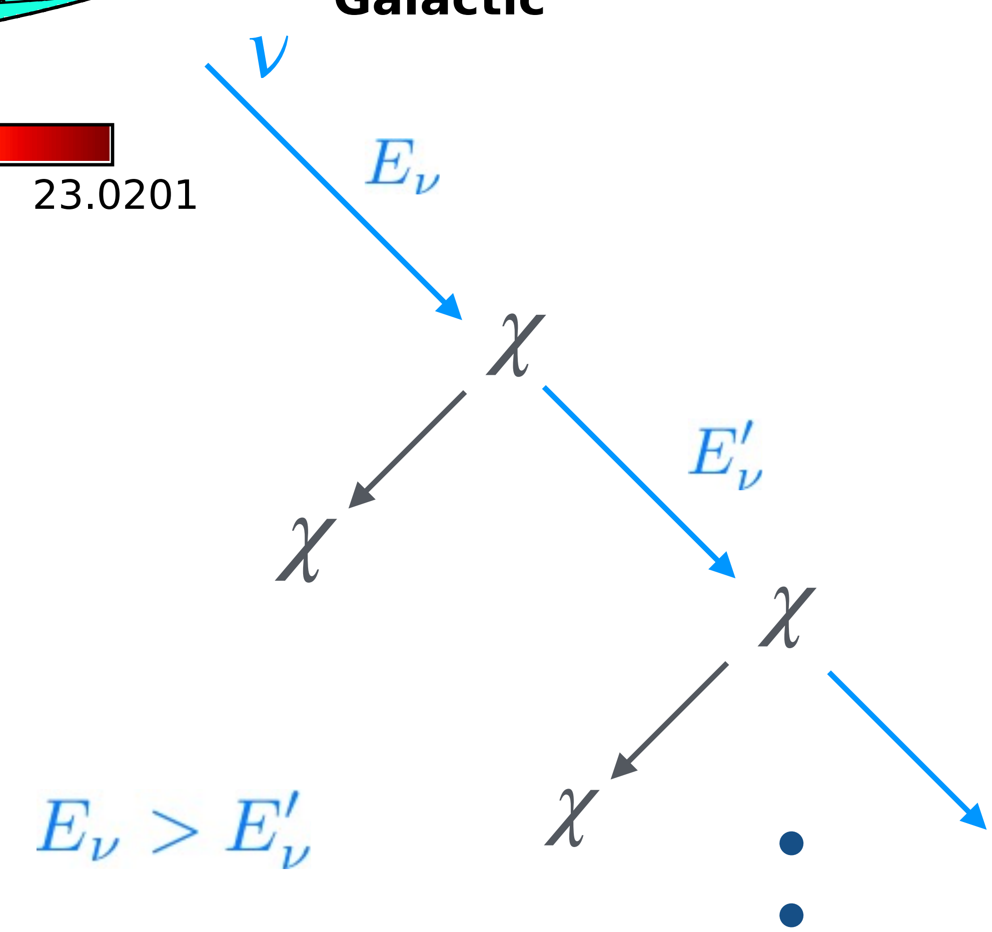
Anisotropic deflection/energy loss



Points: IceCube observations

Colour: DM column density





Points: IceCube observations

Colour: DM column density

In practice

b, l: galactic latitude, longitude

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

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

↓ 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)

What about cross section?

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

What about cross section?

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

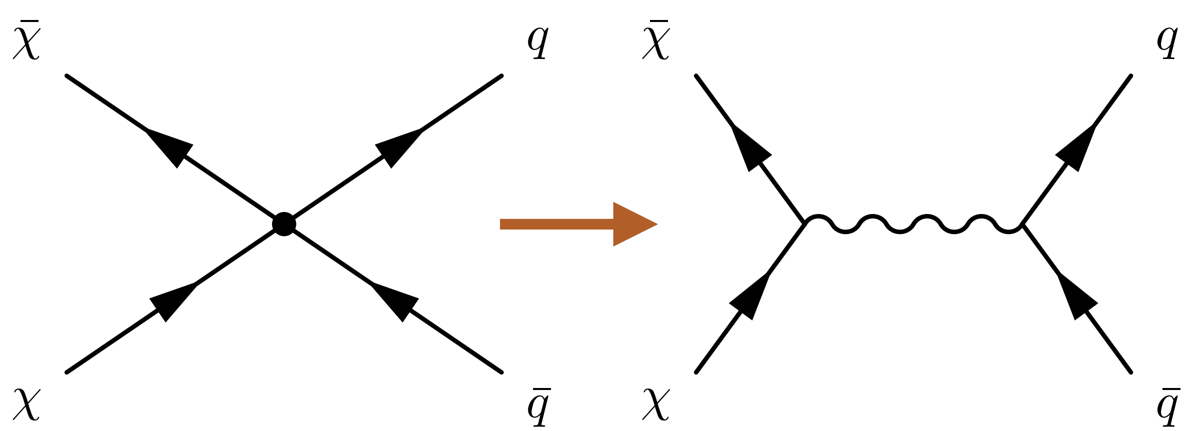
No!

What about cross section?

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

No!

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

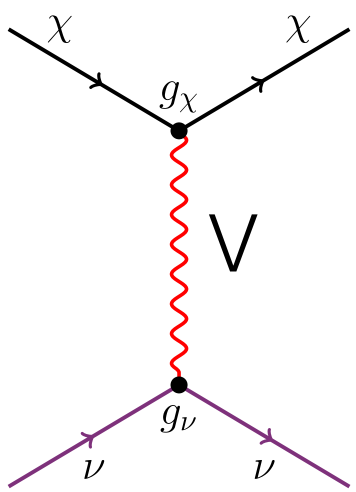


The low energy approximation does not work at a PeV!!

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

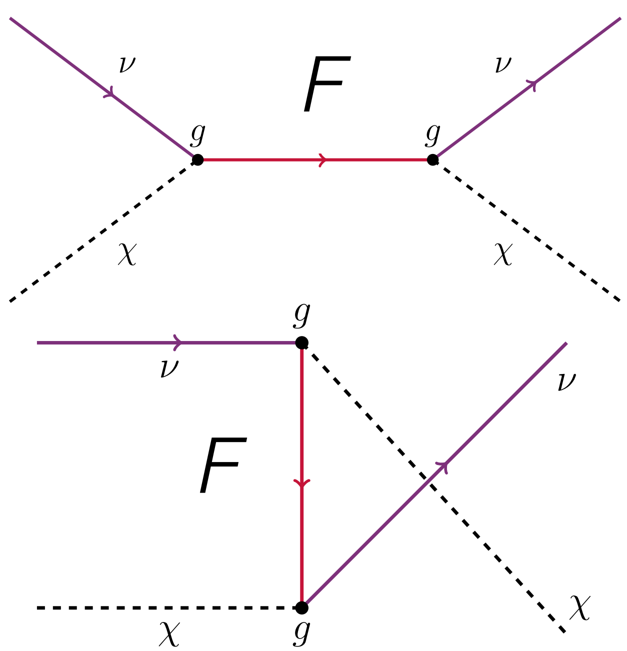
Two fiducial simplified models

1)



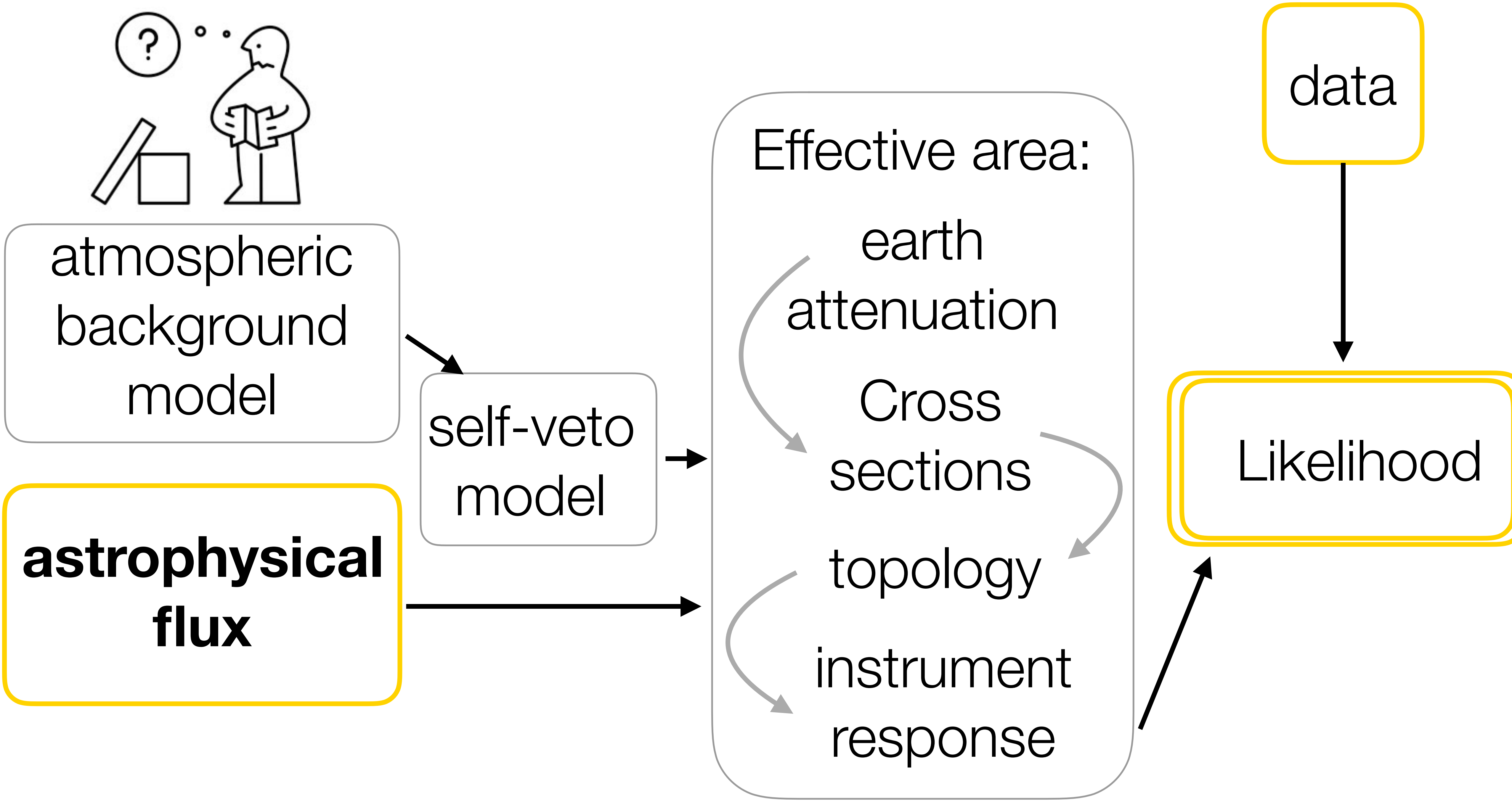
Fermion DM, **vector mediator**:
Scales strongly with *E*

2)



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

IceCube HESE analysis



$$P_a(t_i, E_i, \vec{x}_i) \propto \sum_{f=e,\mu,\tau} \int dE_t d^2\vec{x}_t \; R_E(E_i, E_t) A_{eff}(f, E_t, t_i, \vec{x}_t) P_{veto}(f, E_t, t, \vec{x}) \boxed{\phi_a(E_t, \vec{x}_t).}$$

flavour

"true" EM energy

Resolution

Effective area $\propto \sigma_{\nu,nuc.} V_{IceCube}$

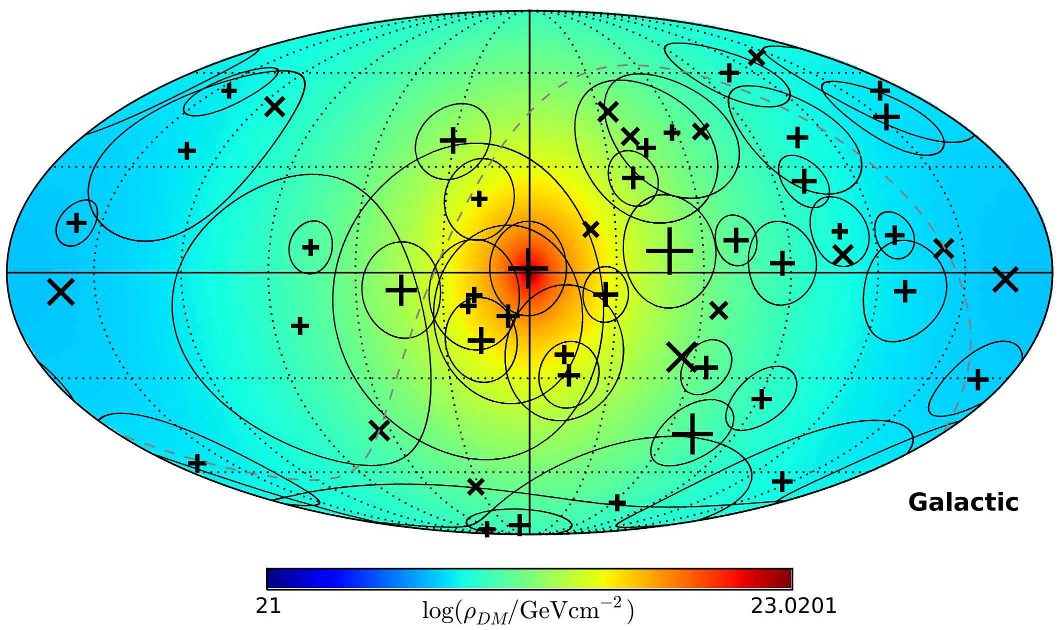
Veto likelihood (atmospheric case)

$$\phi_a(E_t, \vec{x}_t)$$

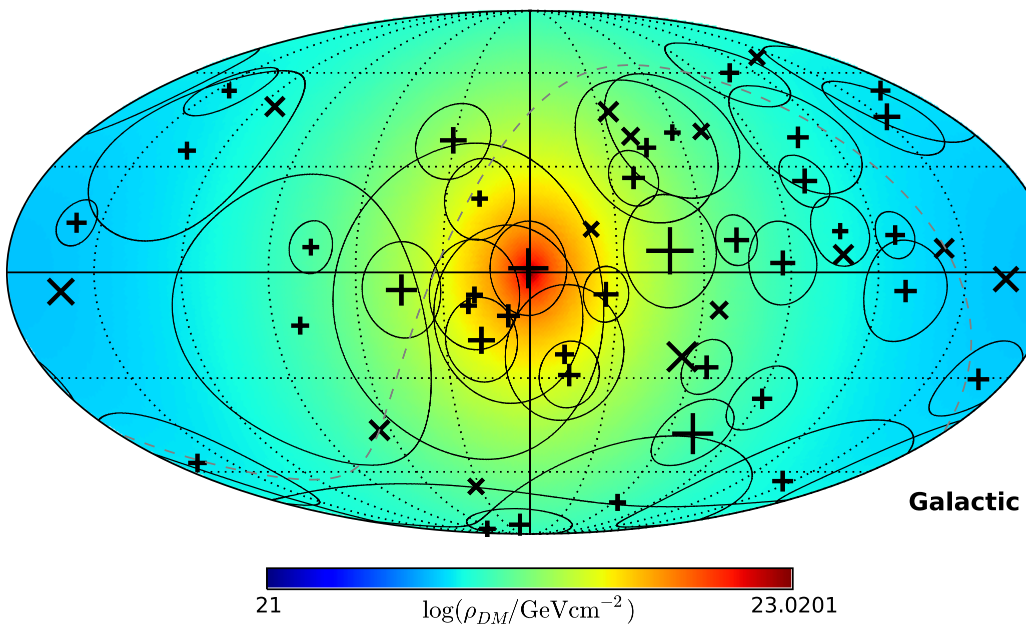
Atmospheric component:
Honda Gaisser model

Astro component: solution to cascade eq.
Assume
- Isotropic extragalactic flux
- E-2 power spectrum
- (1:1:1) flavour composition

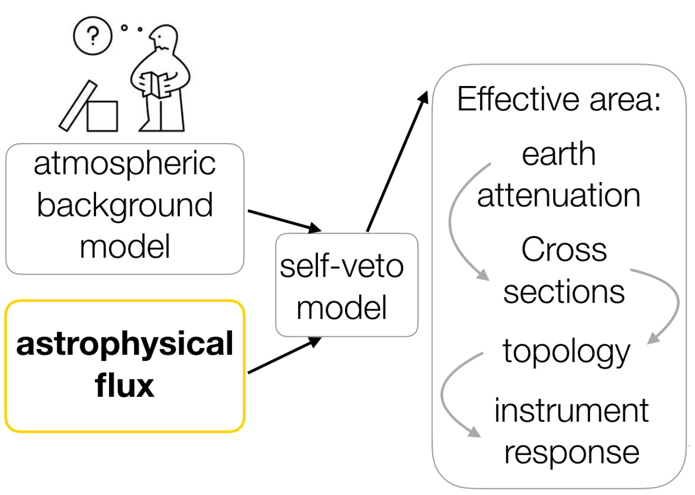
Dark matter column density seen from Earth



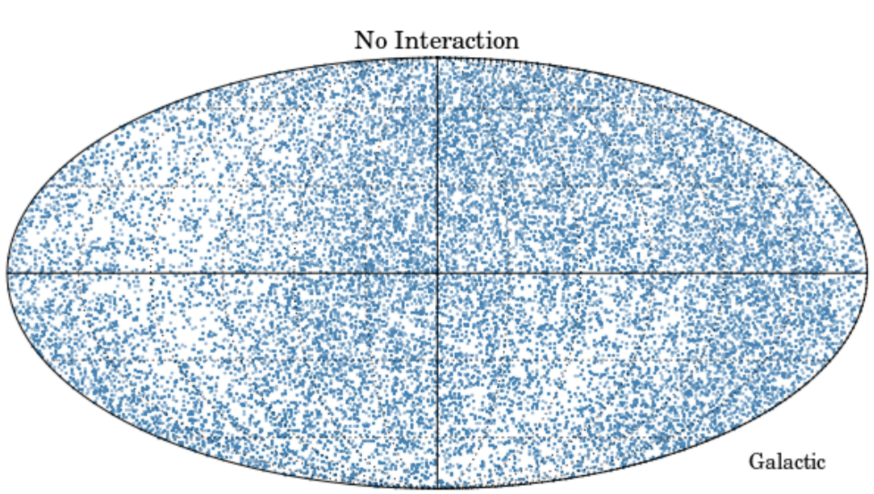
Dark matter column density seen from Earth



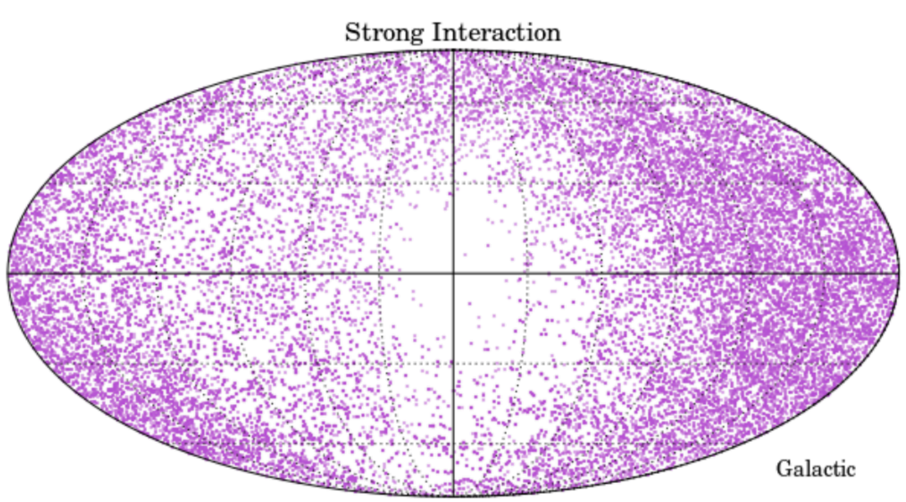
Simulation including effects of detector, Earth



no interaction

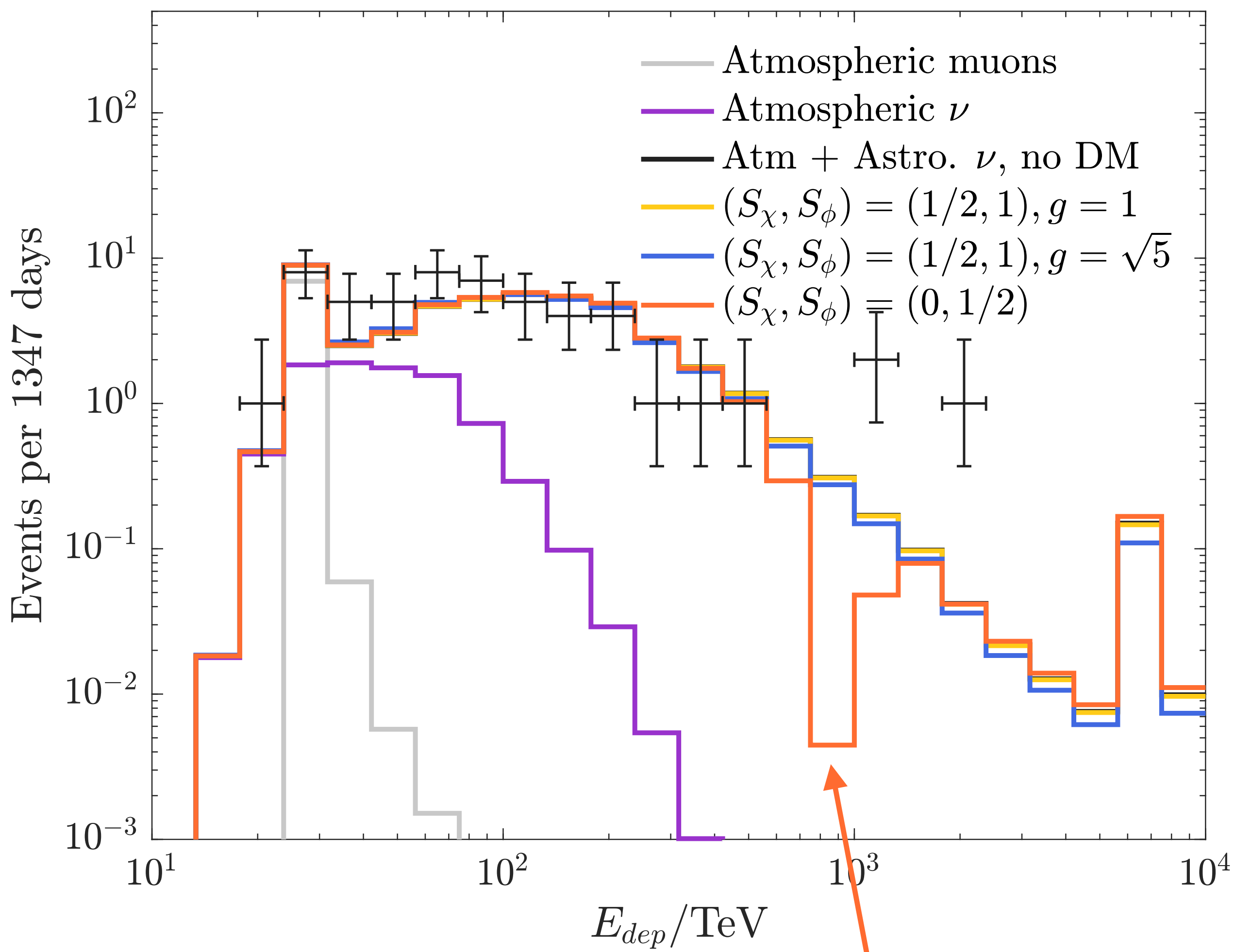


strong interaction



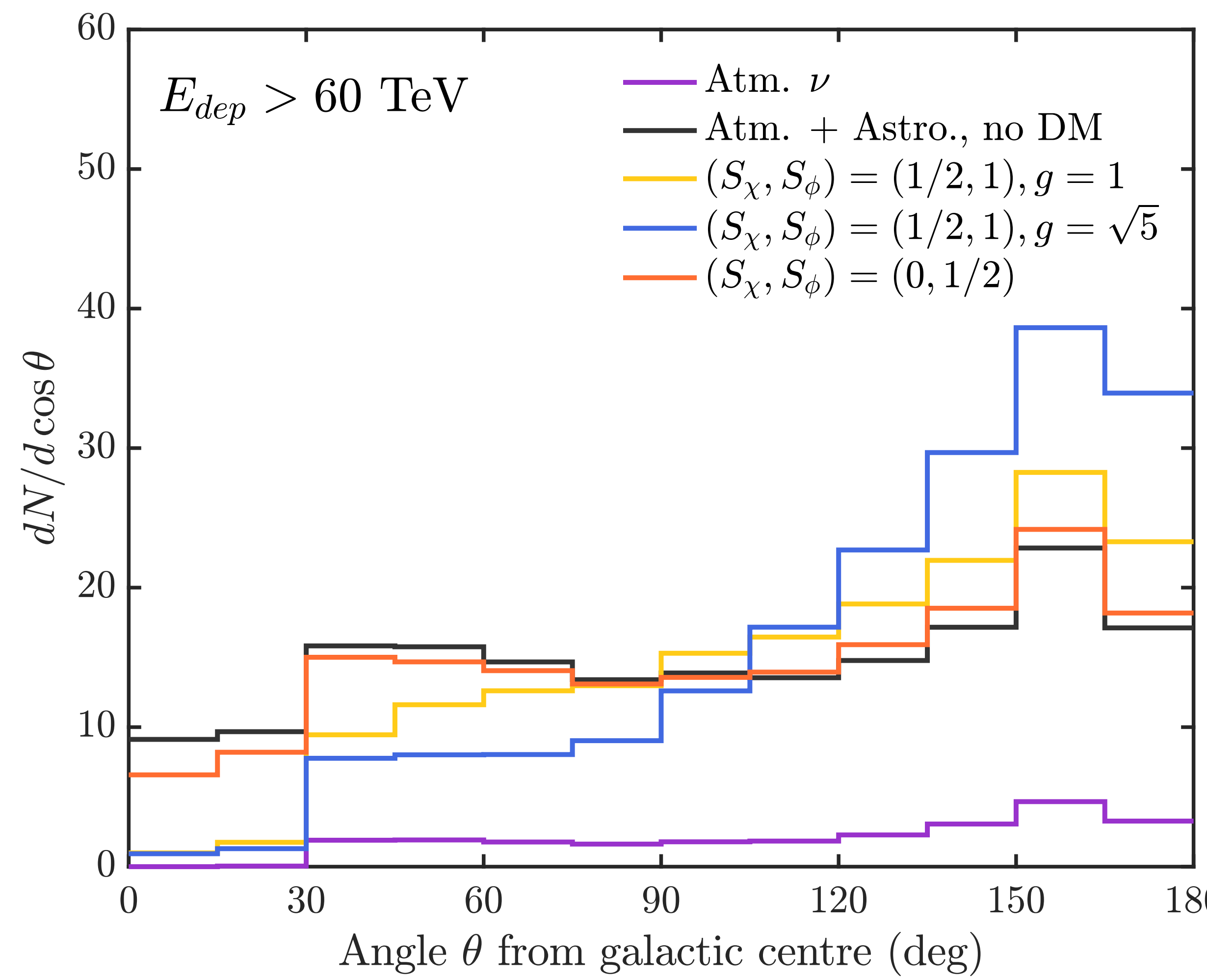
Energy & morphology

Energy



Resonance @ 810 TeV

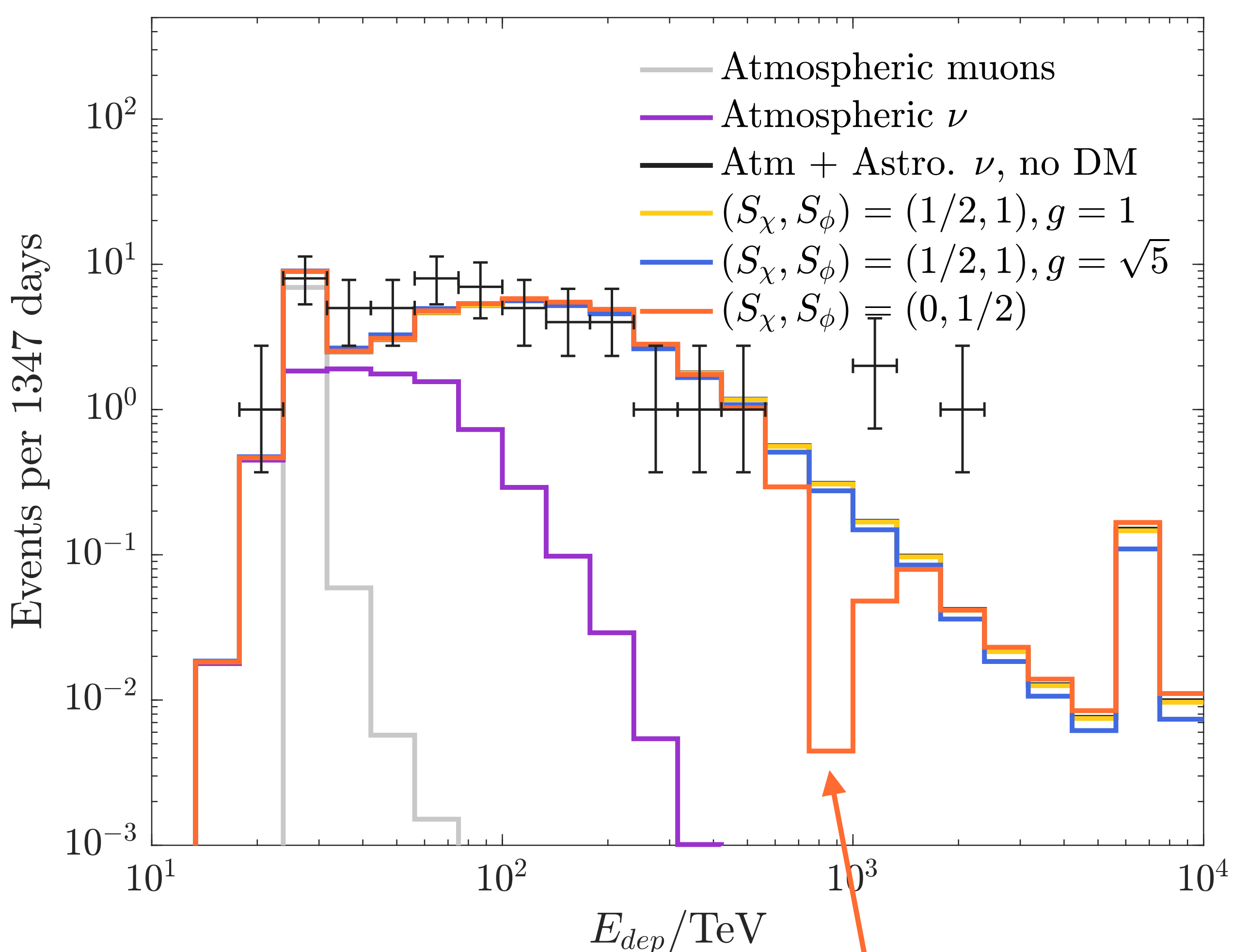
Angle from galactic centre



IceCube HESE events

Energy & morphology

Energy



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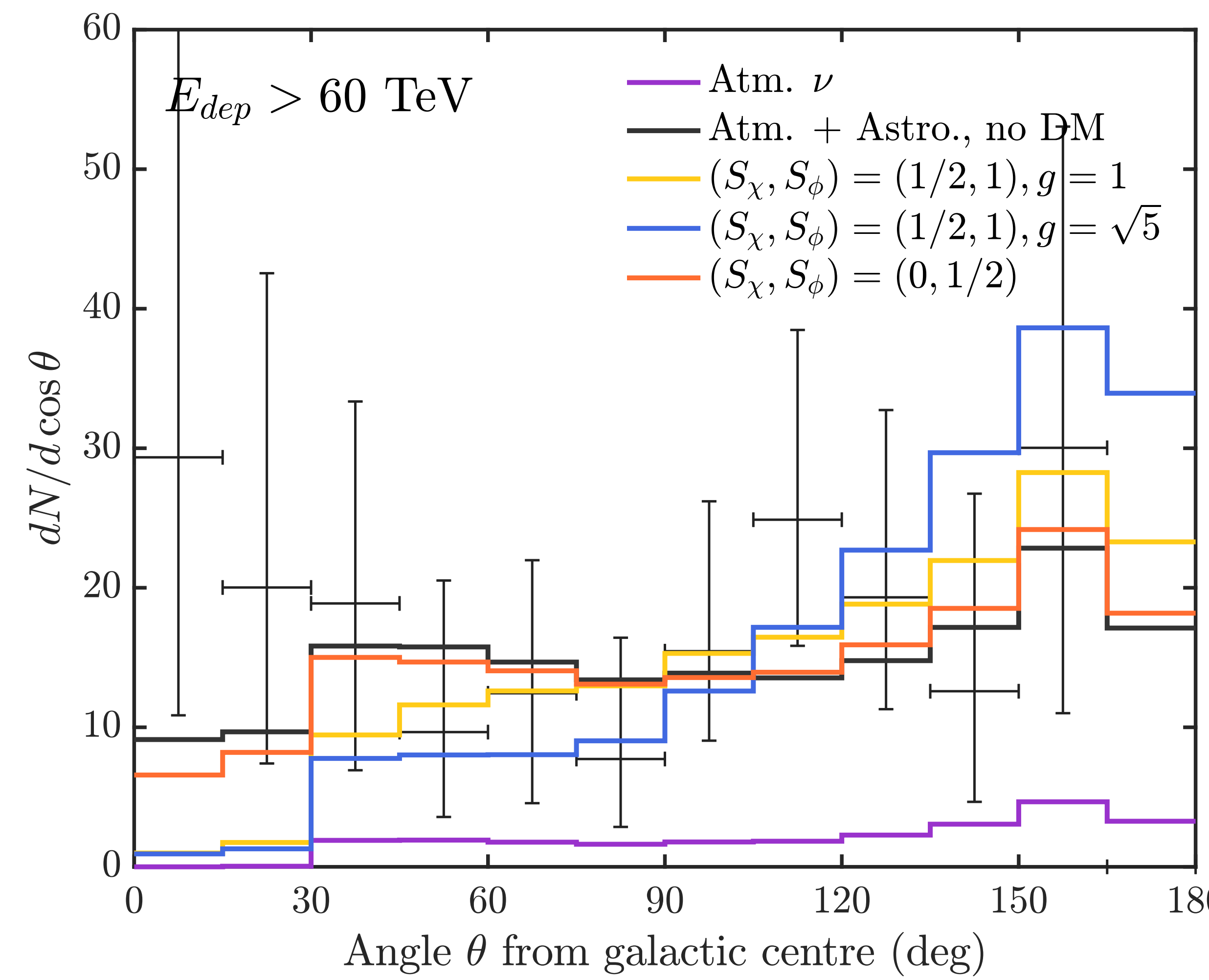
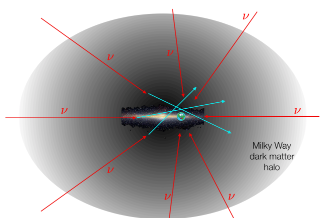
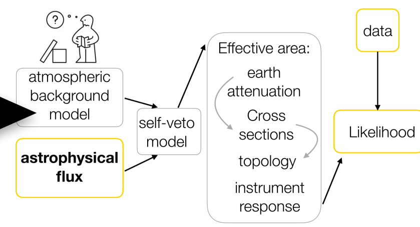


IceCube HESE events

Compare Likelihood to real events



model

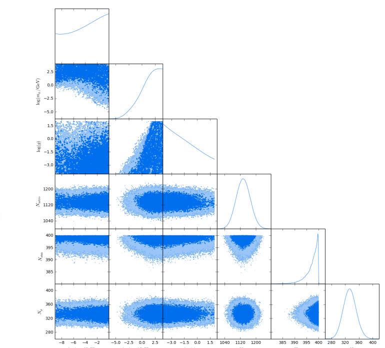


likelihood

IceCube data

emcee
The MCMC Hammer

MCMC



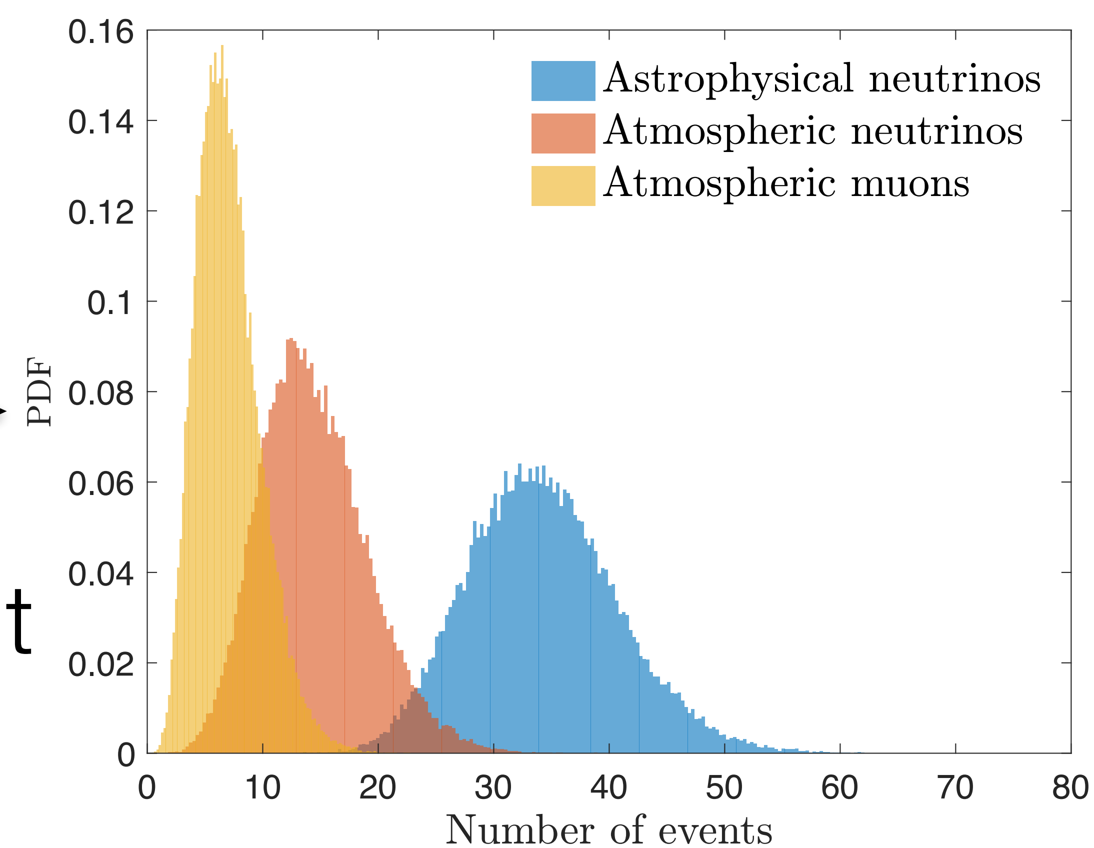
posterior

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

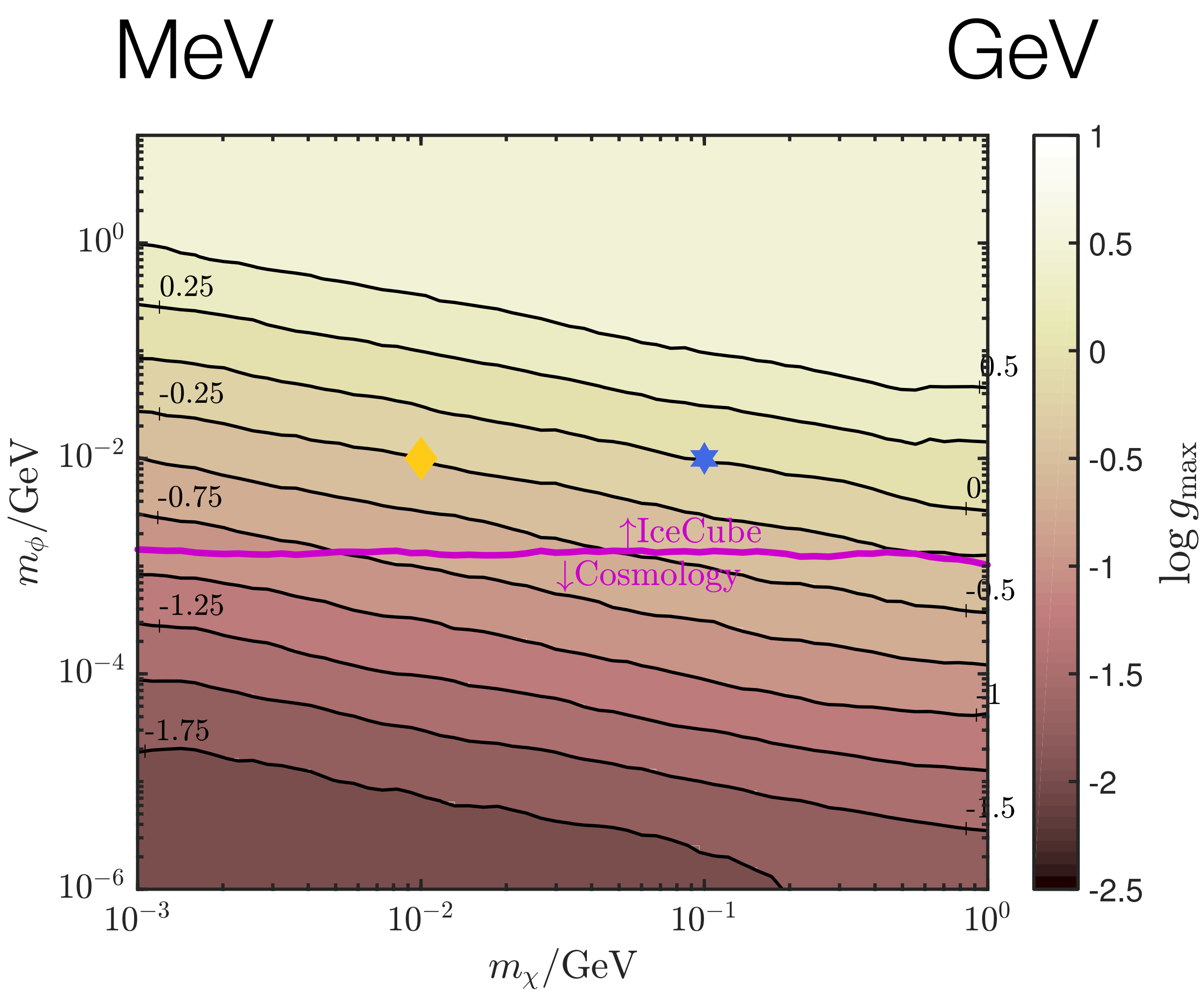
Parameters:

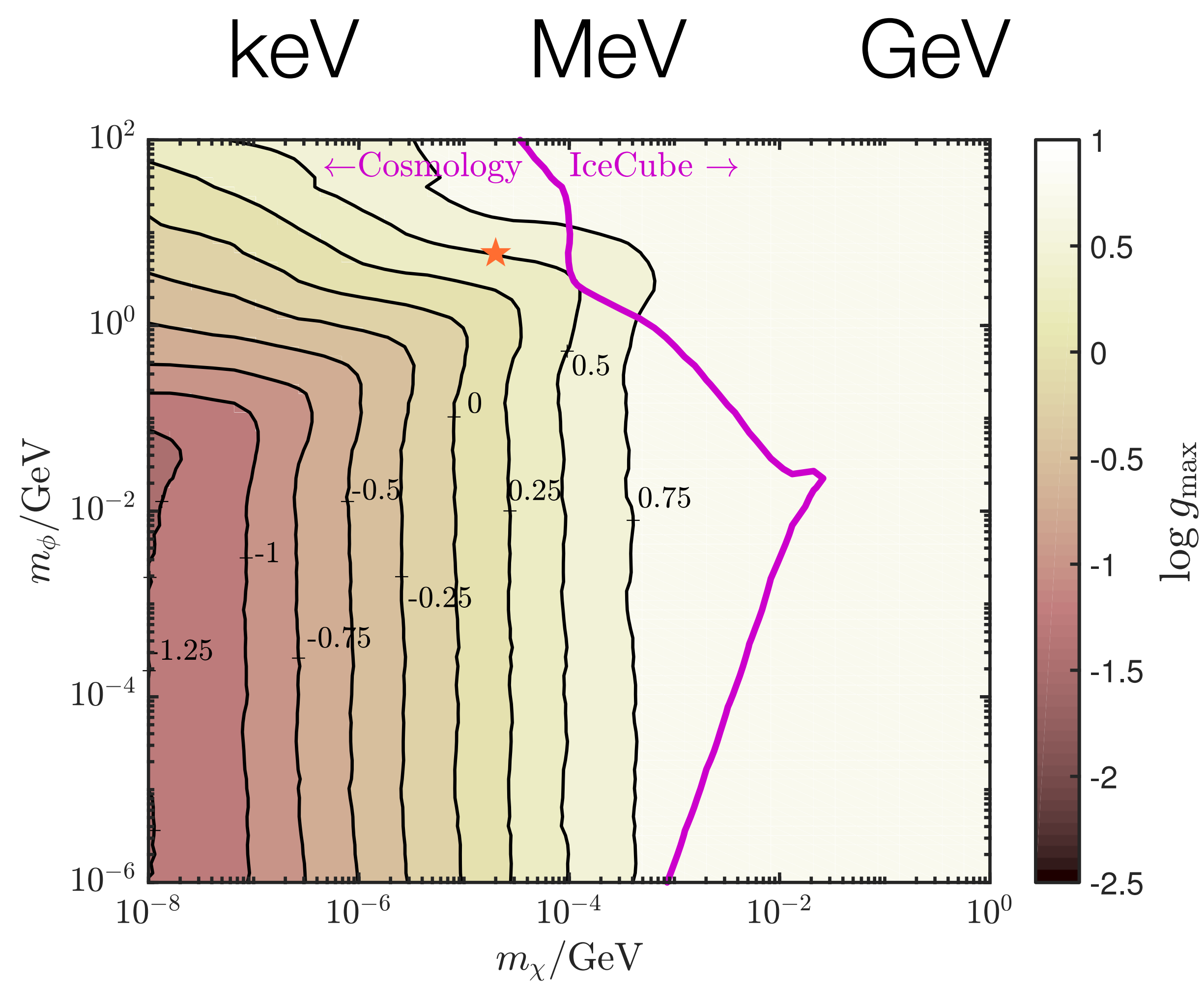
$$m_\chi \; m_\phi \; g \; N_{astro} \; N_{atmo} \; N_{\mu^\pm} \; \gamma$$

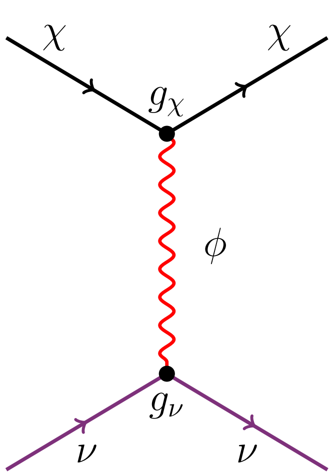
- DM+mediator masses
- coupling
- Normalization of each component
- Astro spectral index



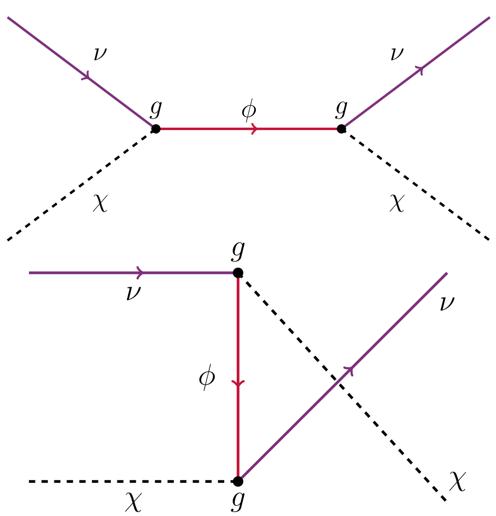
Limits from IceCube



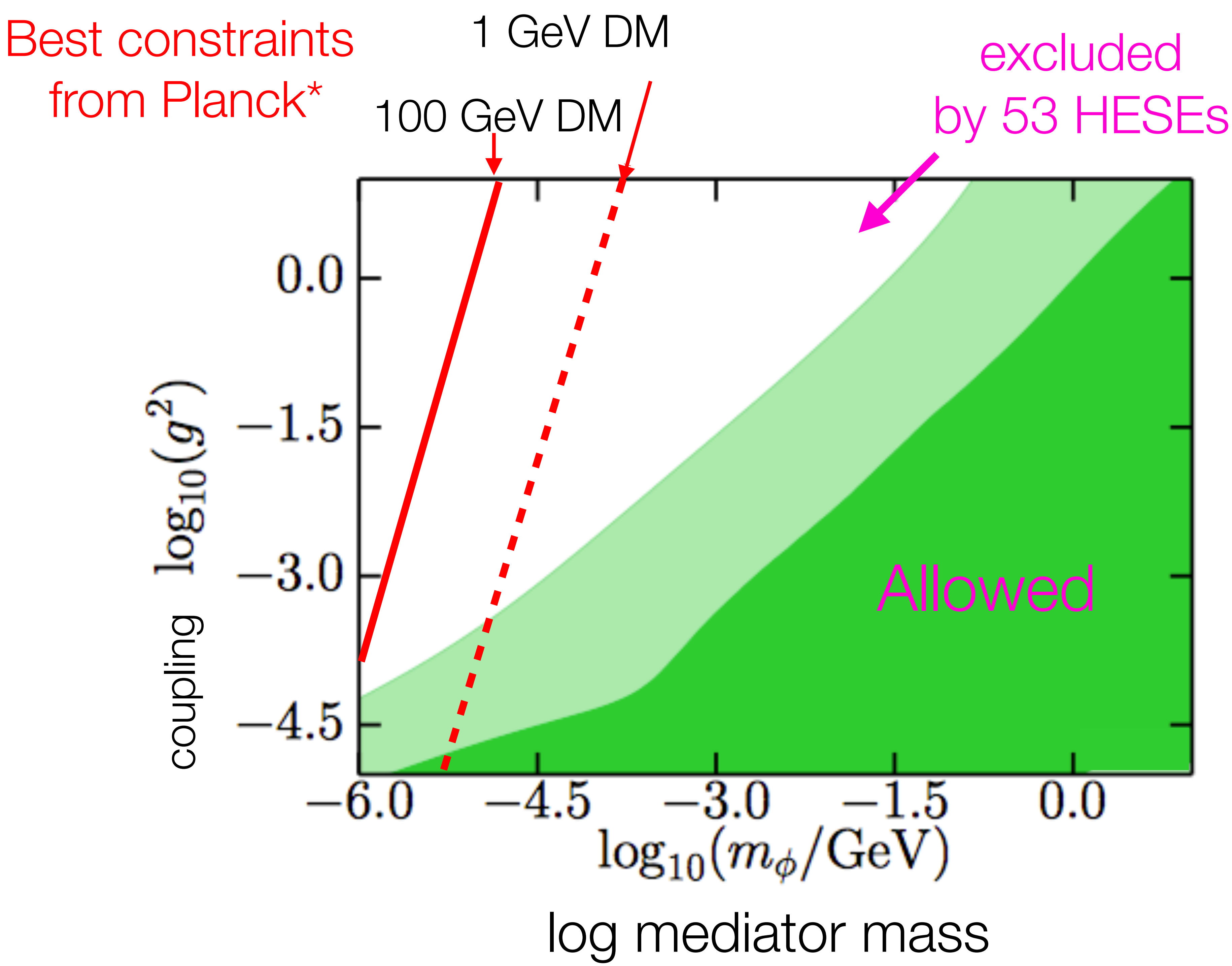


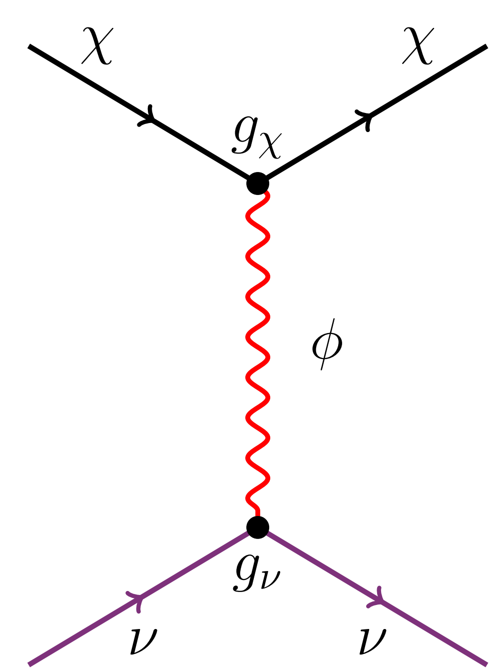


Only 53 events: already eating into cosmology parameter space



New limits on dark force carriers





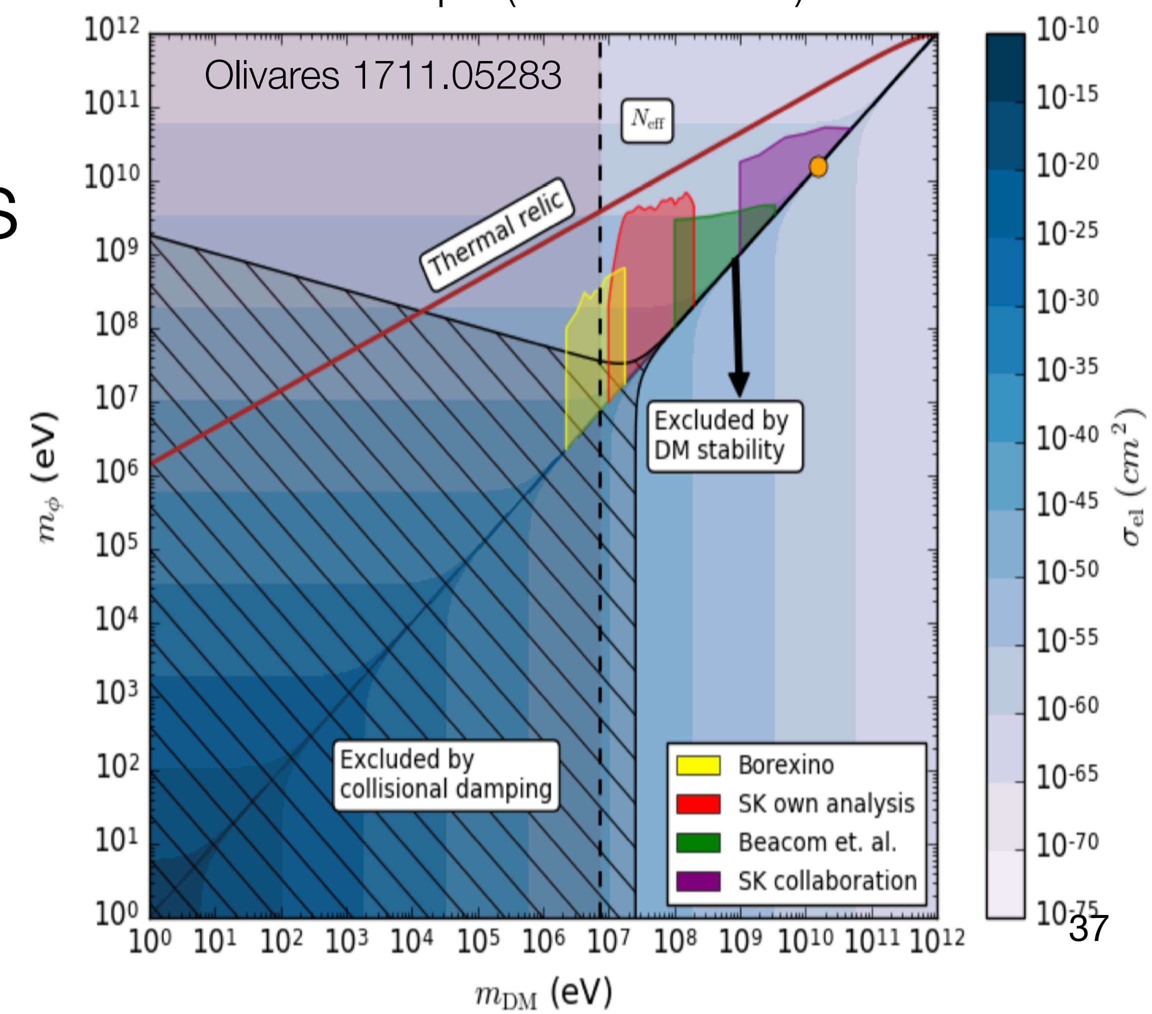
* + LSS, see Escudero, … Vincent 2016

Future considerations

- SU(2) implies coupling to the electron in some of these models (there are clunky ways around that, e.g. only coupling to 3rd gen neutrinos)
- Gauge anomaly cancellation?
- Constraints from meson decays
- Relic density

$$DM + DM \to \nu + \nu$$

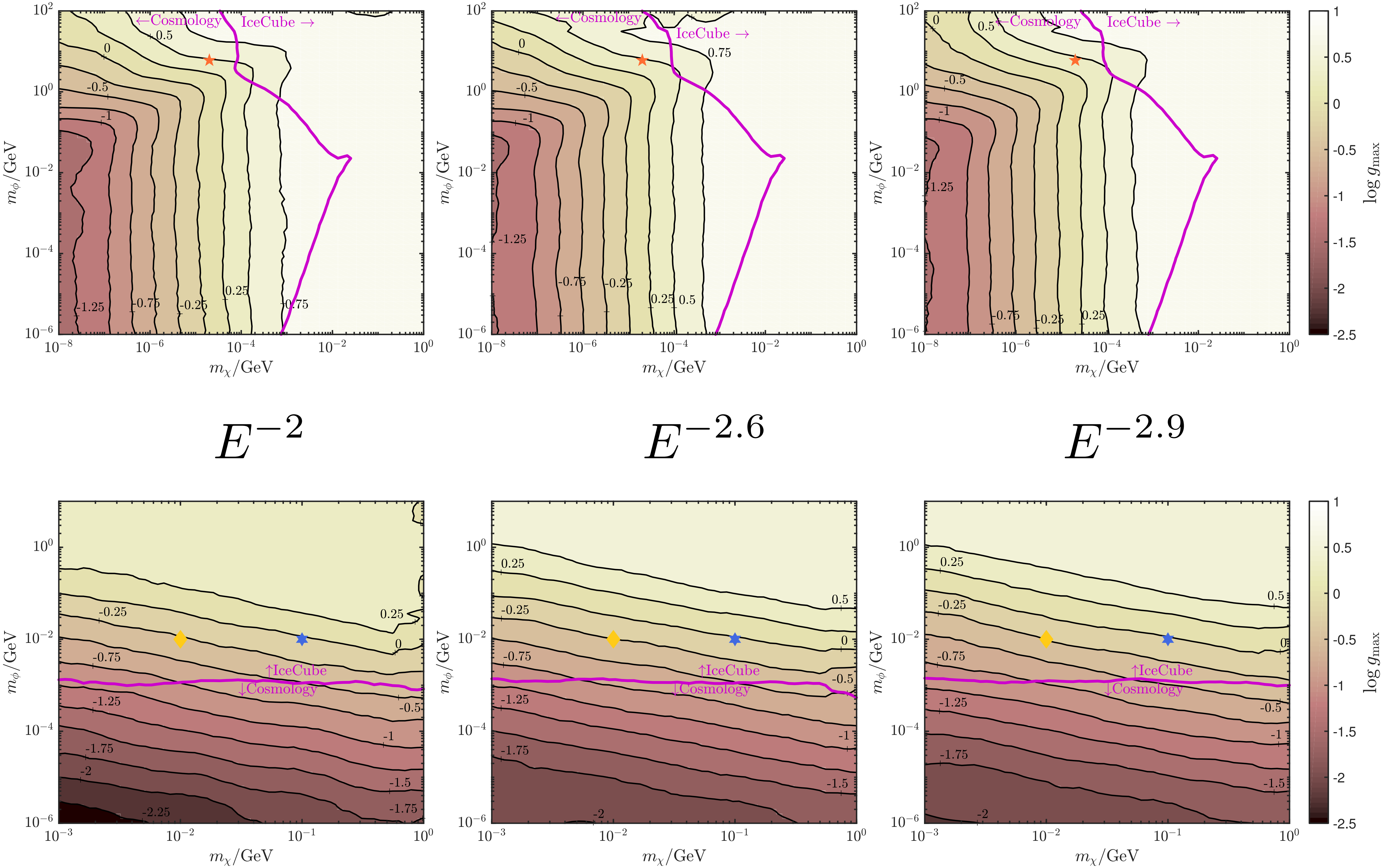
Ongoing work with Andrés Olivares del Campo (IPPP Durham)



Summary

- Neutrino astronomy can tell us about dark matter!
- No reason to believe DM-neutrino interactions aren’t there
- Isotropy of the signal can be used to constrain such interactions
- Can do better than cosmology in some ranges
- Need more stats —> 7yr data? + forecasts for Gen2 & much more (incl. more models to come)

Fixed astro spectral indices



Flavour composition in astrophysical sources

(GRBs, AGNs, blazars, pulsars…) $(\alpha_e : \alpha_\mu : \alpha_\tau)$

Pion sources $\pi^+ \to \mu^+ + \nu_\mu$

(c.c. for π^-) $\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$

(1 : 2 : 0)

“muon-damped” $\pi^+ \to \mu^+ + \nu_\mu$ (with μ^+ crossed out)

(c.c. for π^-)

(0 : 1 : 0)

“muon source” $\pi^+ \to \mu^+ + \nu_\mu$ (with ν_μ crossed out)

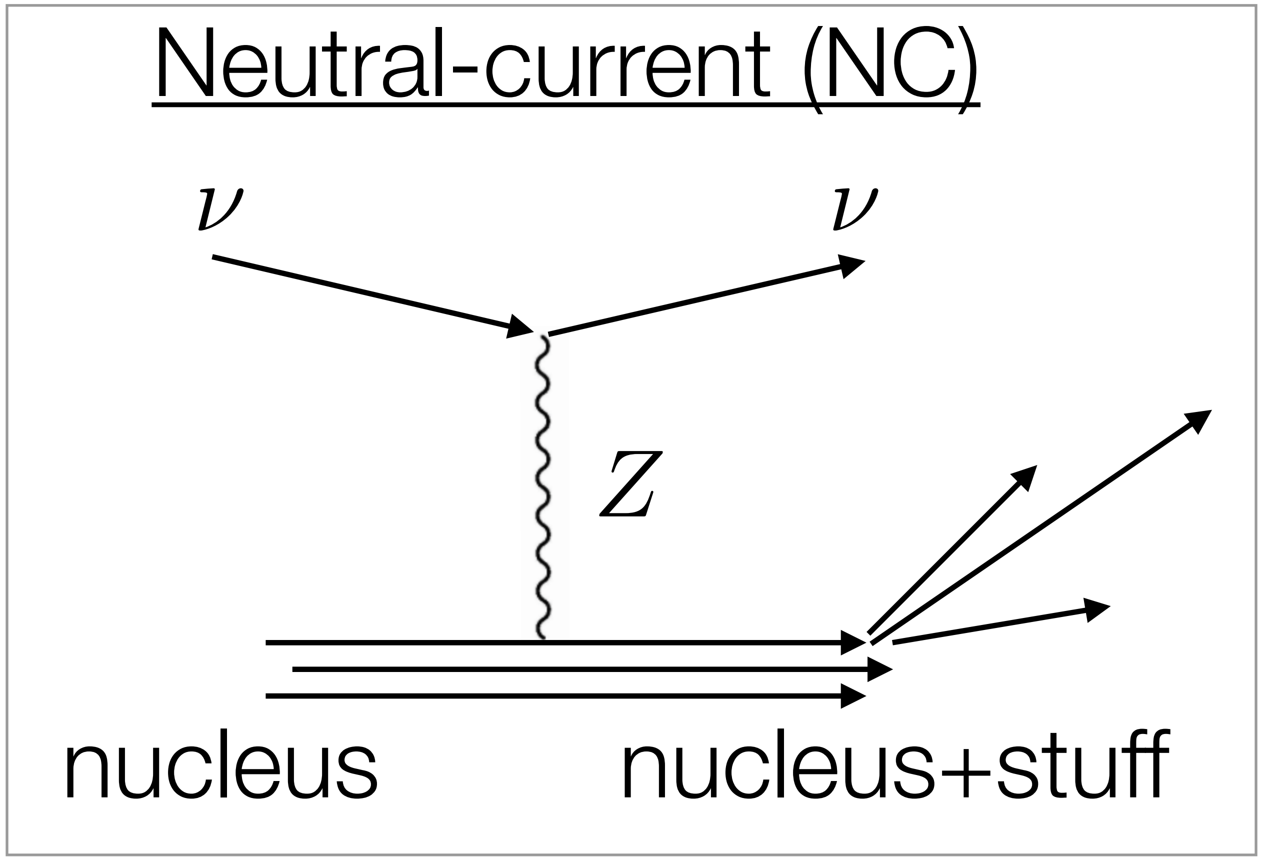
(c.c. for π^-) $\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$

(1 : 1 : 0)

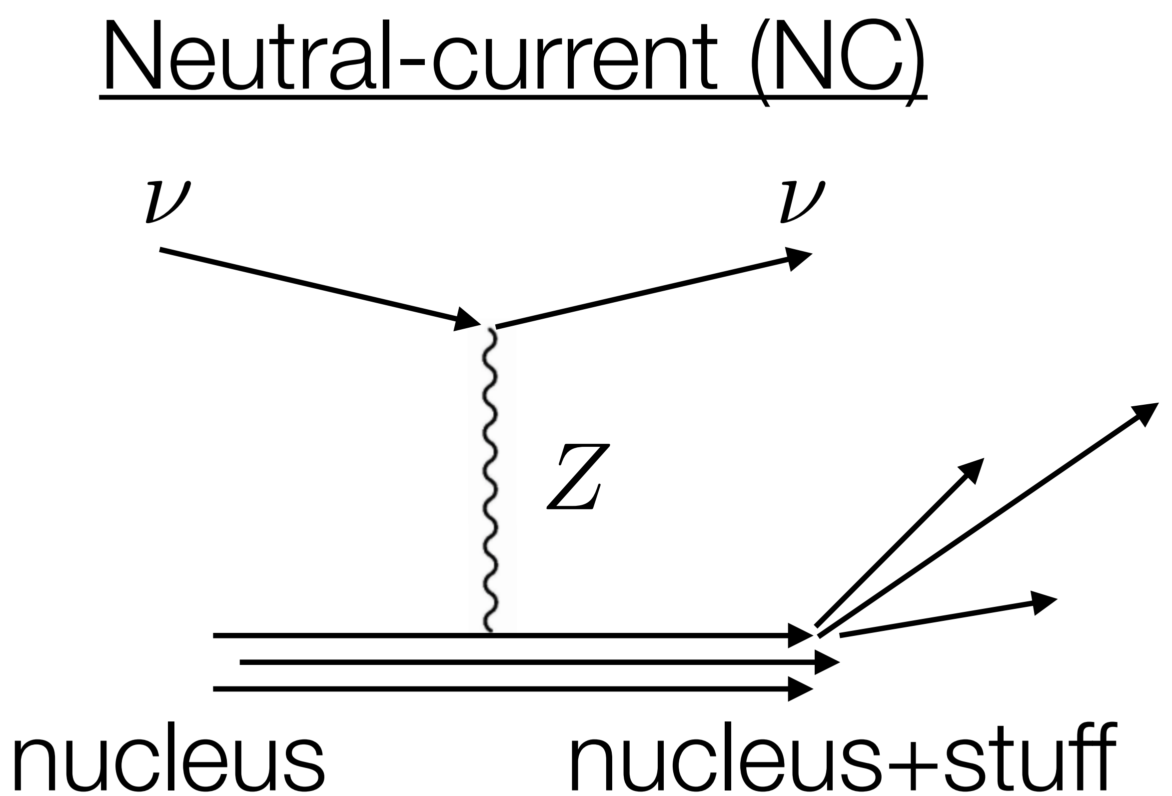
Neutron source $n \to p + e^- + \bar{\nu}_e$

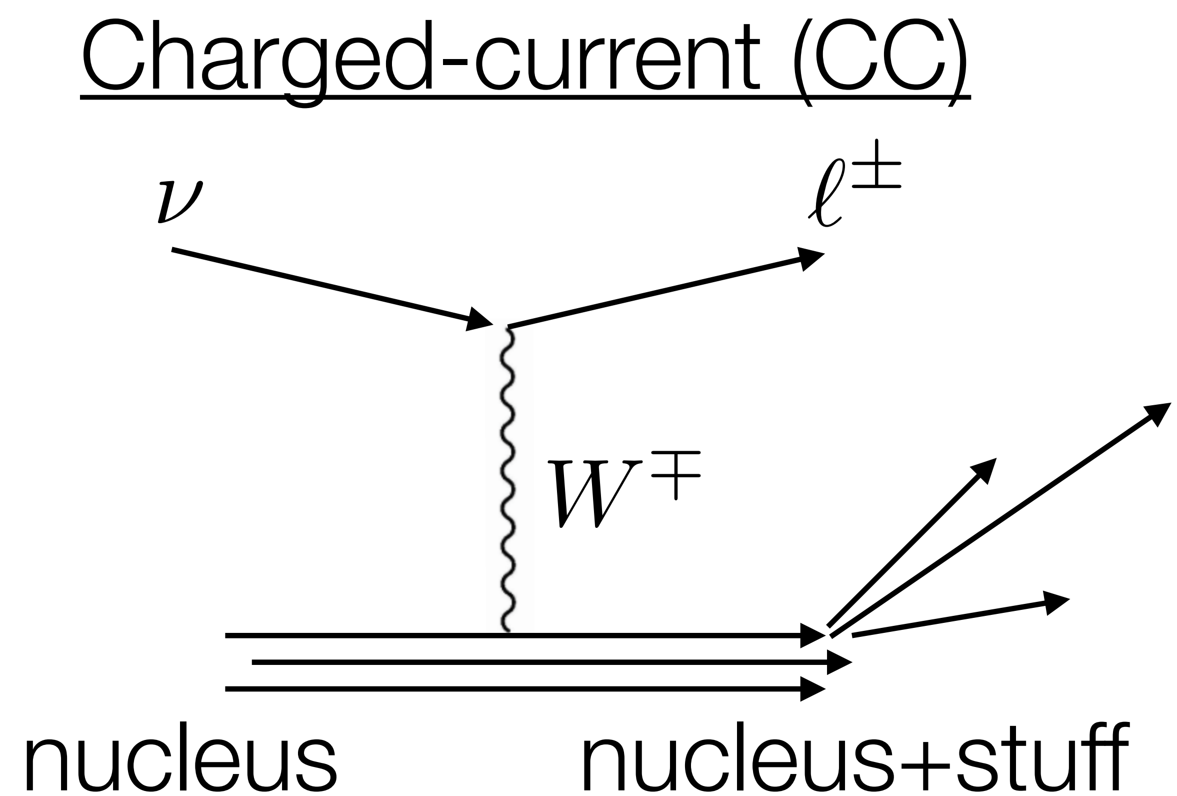
(1 : 0 : 0)

Interactions with the charged sector: detection



Interactions with the charged sector: detection





Final-state lepton:

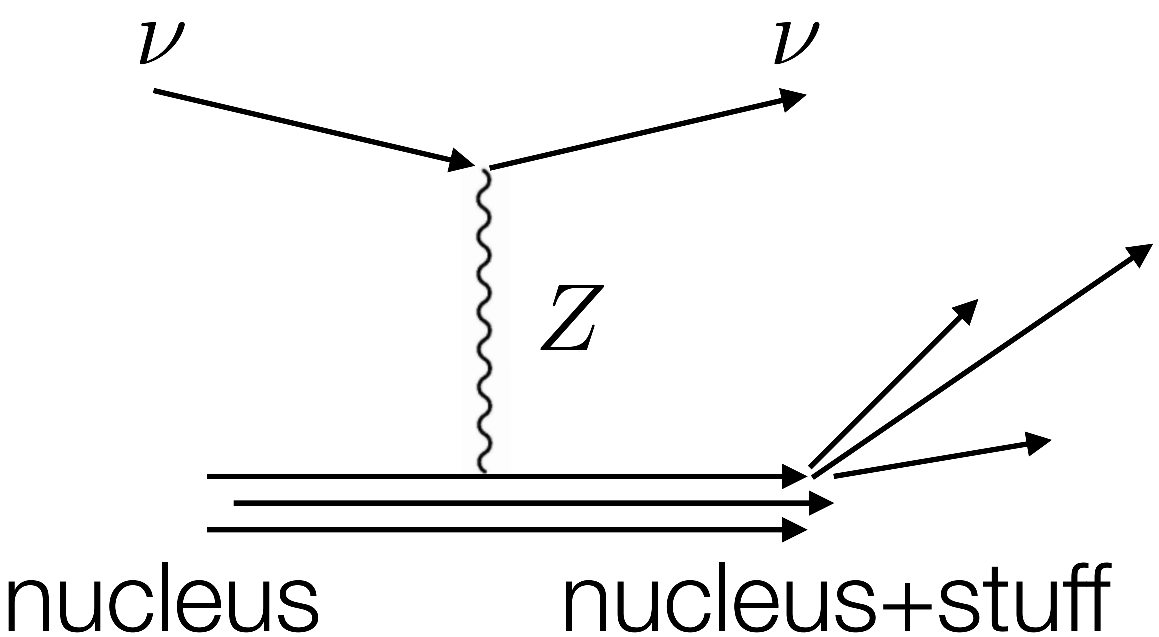
electron: deposits E

muon: can travel ~ km

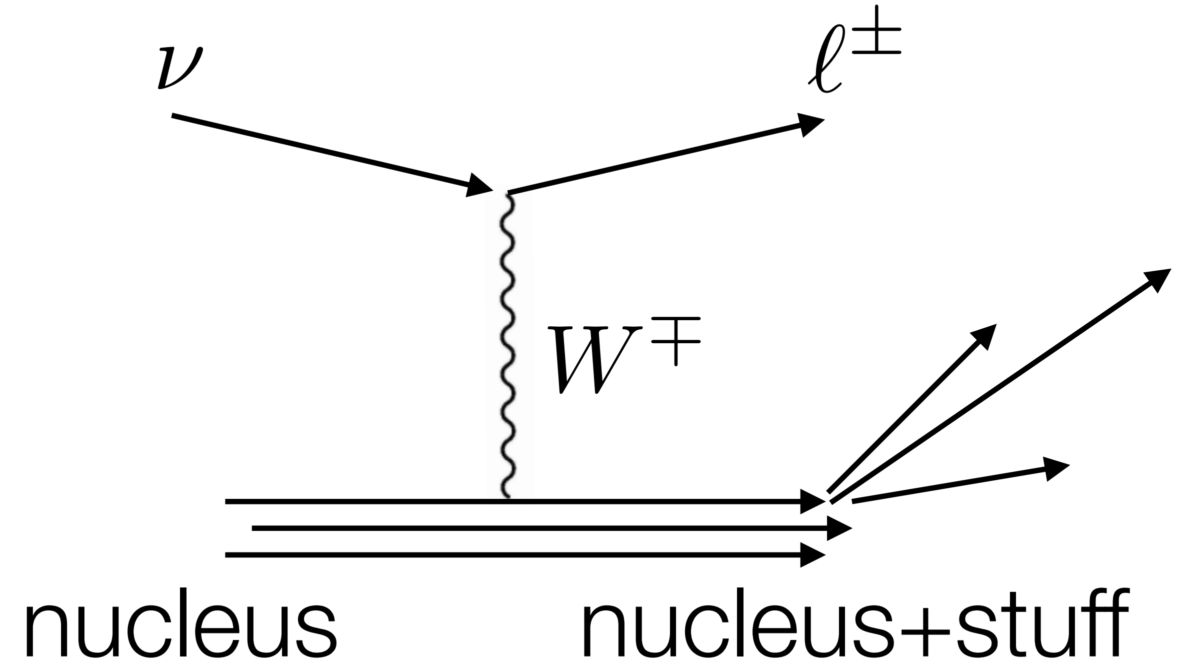
tau : decays to stuff

Interactions with the charged sector: detection

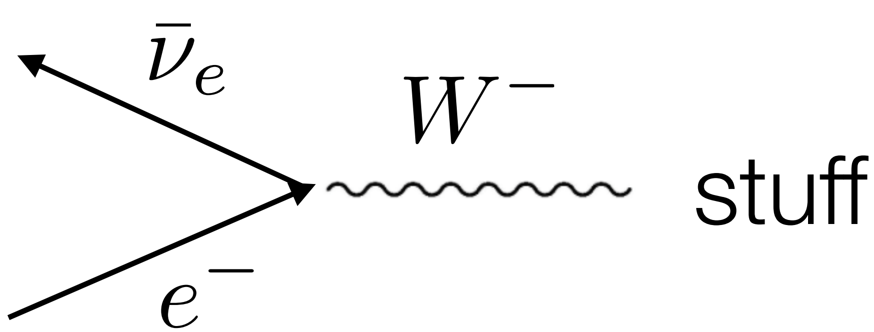
<u>Neutral-current (NC)</u>



<u>Charged-current (CC)</u>



<u>electron</u>



<u>Final-state lepton:</u>

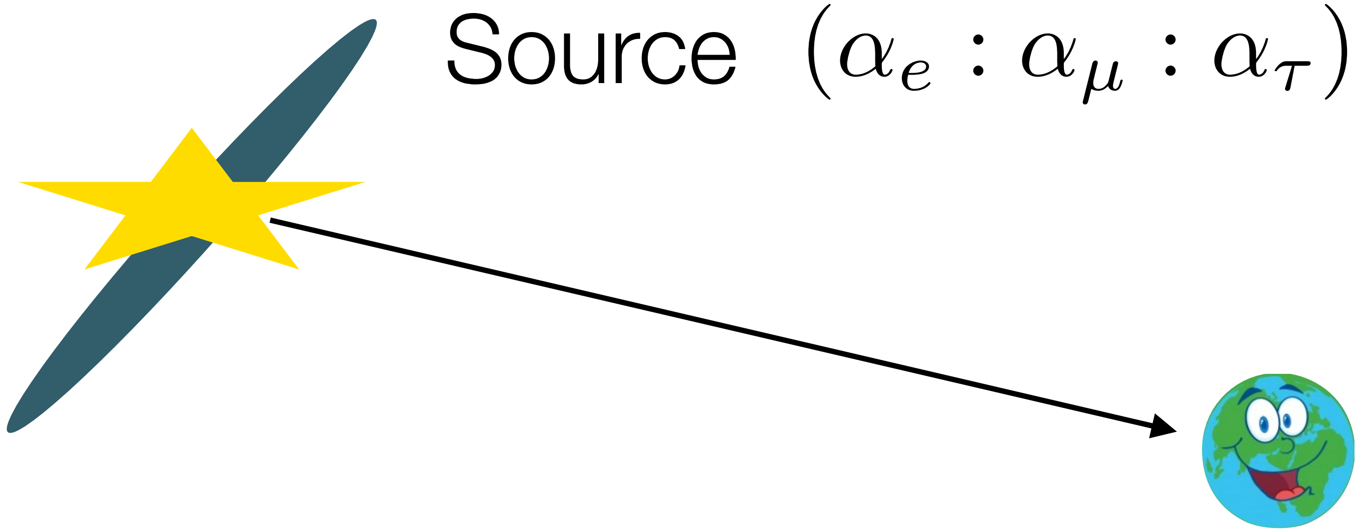
electron: deposits E

muon: can travel ~ km

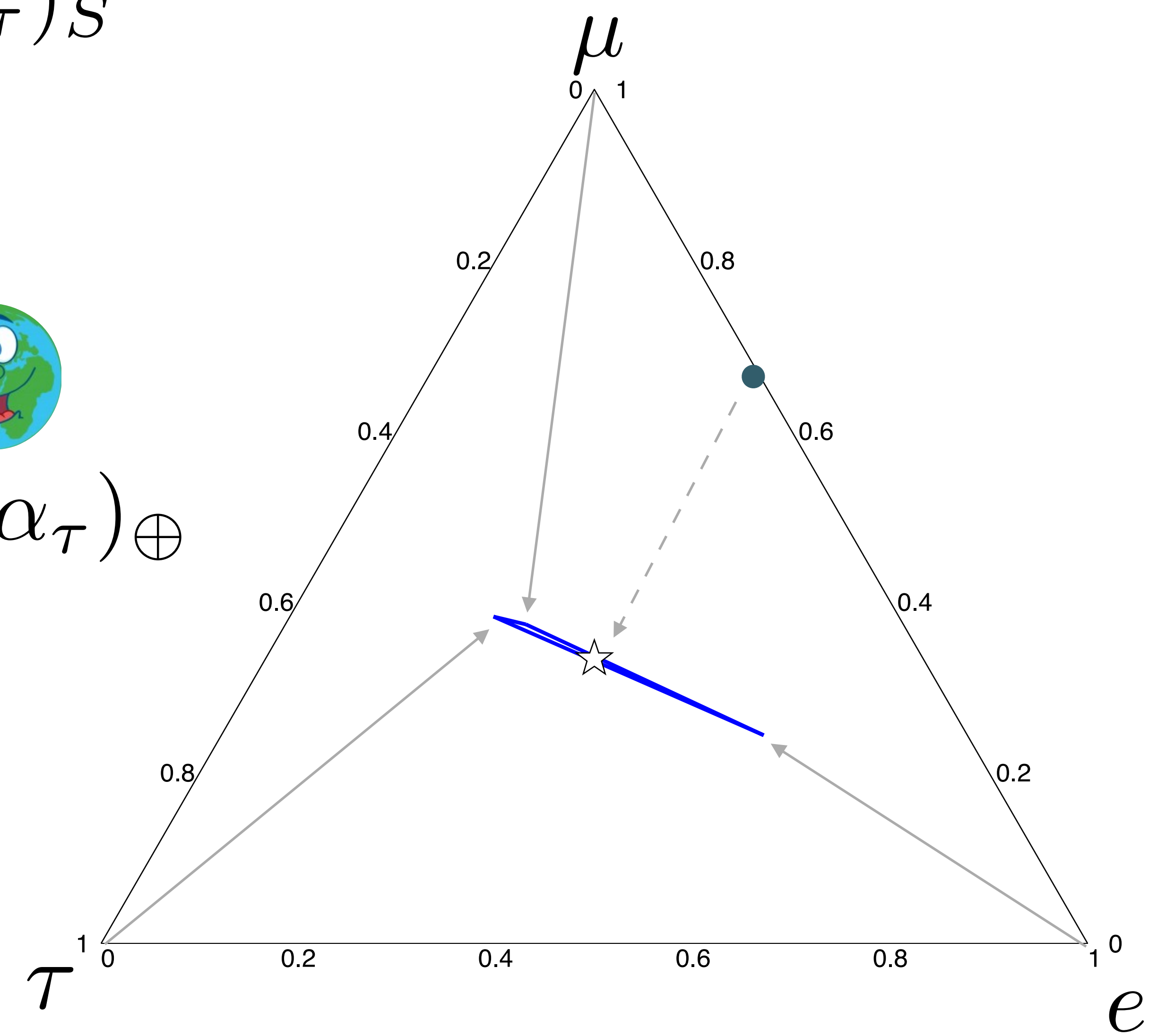
tau : decays to stuff

Travel to earth

Source $(\alpha_e : \alpha_\mu : \alpha_\tau)_S$



$(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$



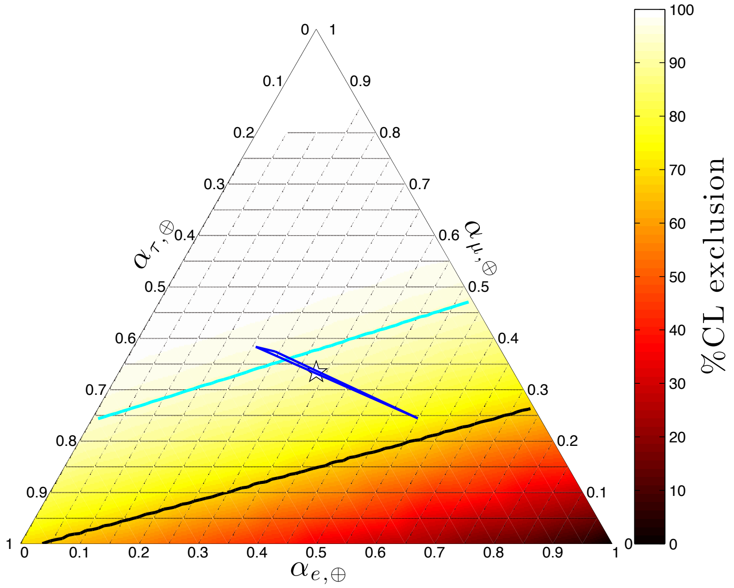
$$\{\alpha_j\}_\oplus = \sum_{k,i} |U_{jk}|^2 |U_{ik}|^2 \{\alpha_j\}_S$$

$$\simeq \frac{1}{18} \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}$$

$$(1:2:0) \to (1:1:1)$$
$$(0:1:0) \to (4:7:7)$$
$$(1:0:0) \to (5:2:2)$$

Flavour Composition of IceCube's HESEs

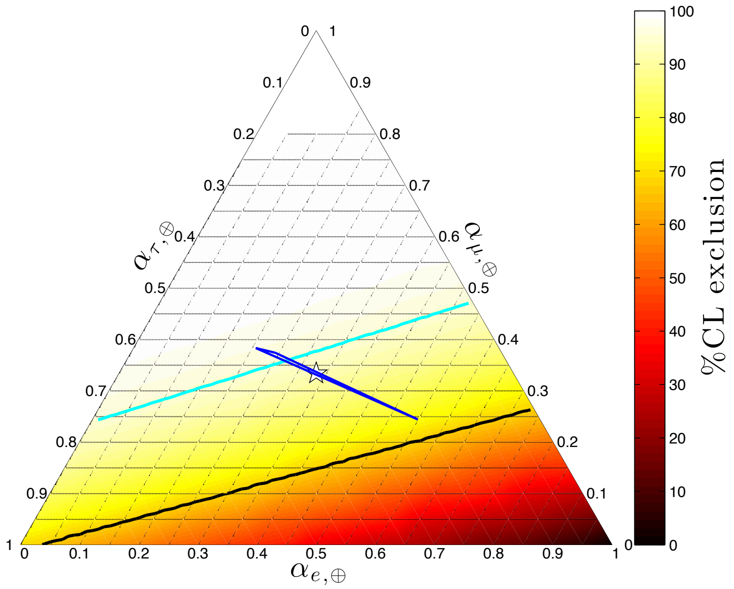
Topologies



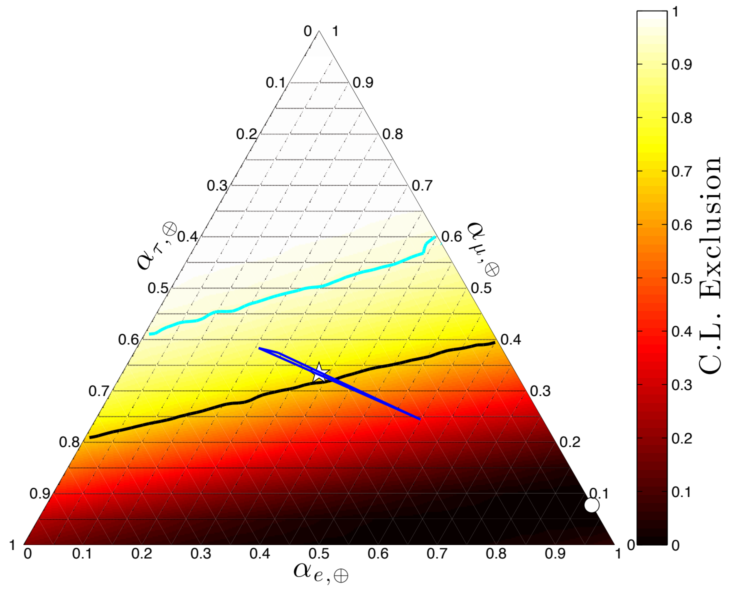
{Mena, Palomares-Ruiz, ACV}
1411.2998
1502.02649
1505.03355
1605.01556

Flavour Composition of IceCube's HESEs

Topologies



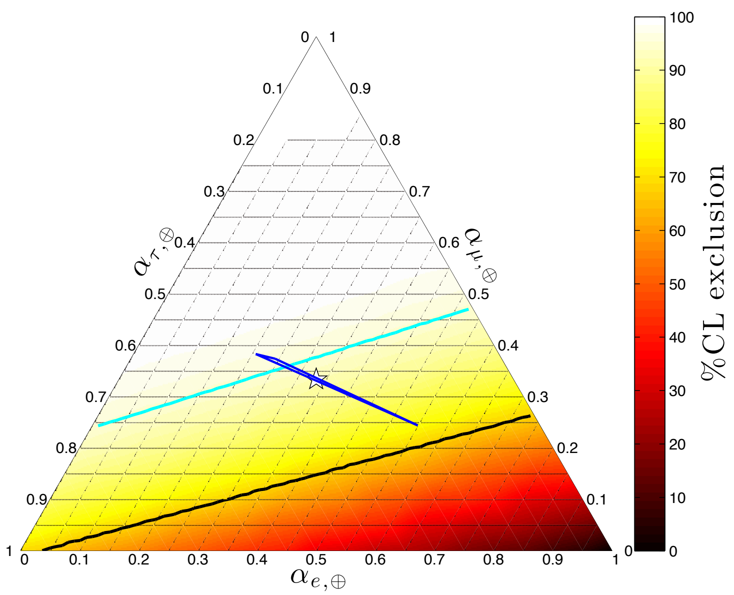
+ spectrum



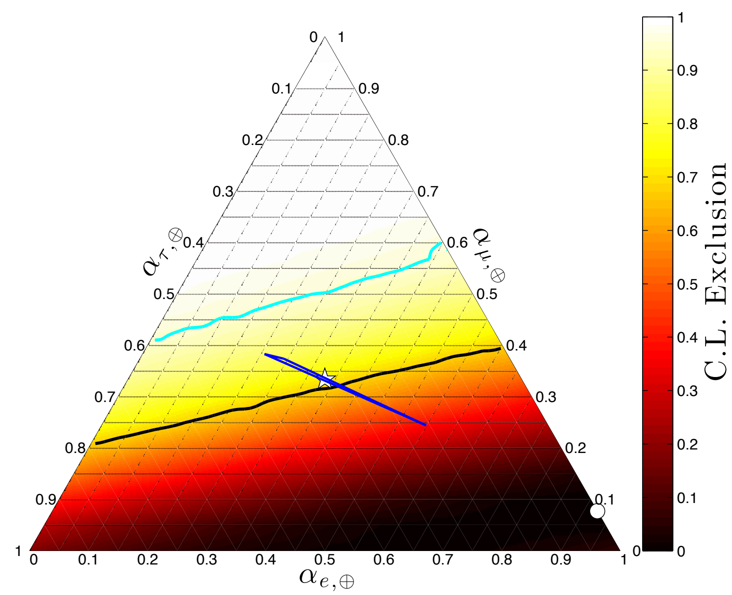
{Mena, Palomares-Ruiz, ACV}
1411.2998
1502.02649
1505.03355
1605.01556

Flavour Composition of IceCube’s HESEs

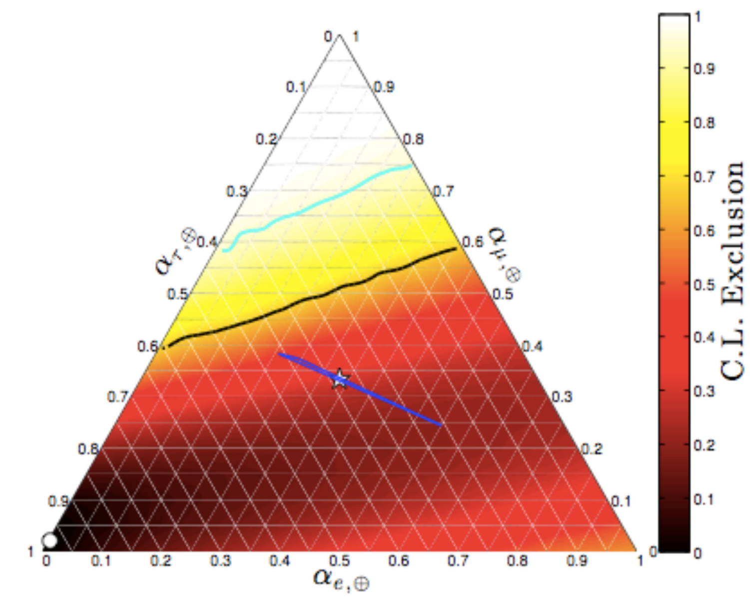
Topologies



+ spectrum



+ extend E range



{Mena, Palomares-Ruiz, ACV}
1411.2998
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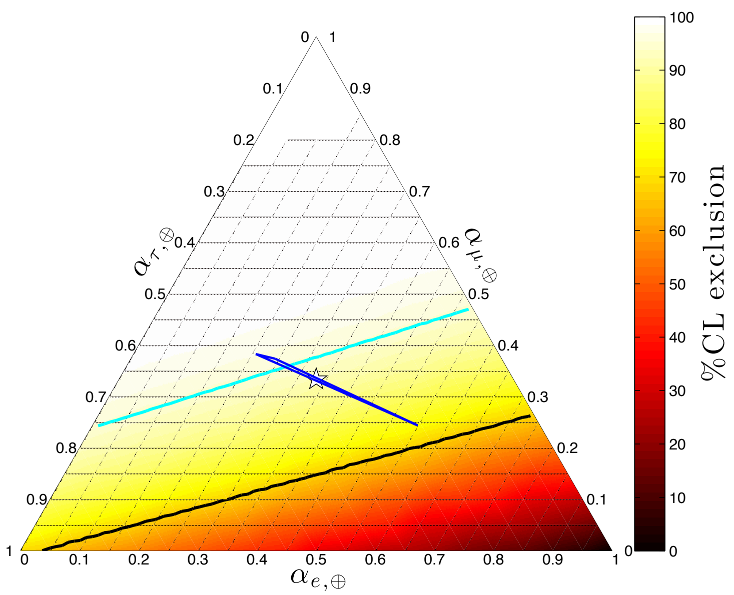
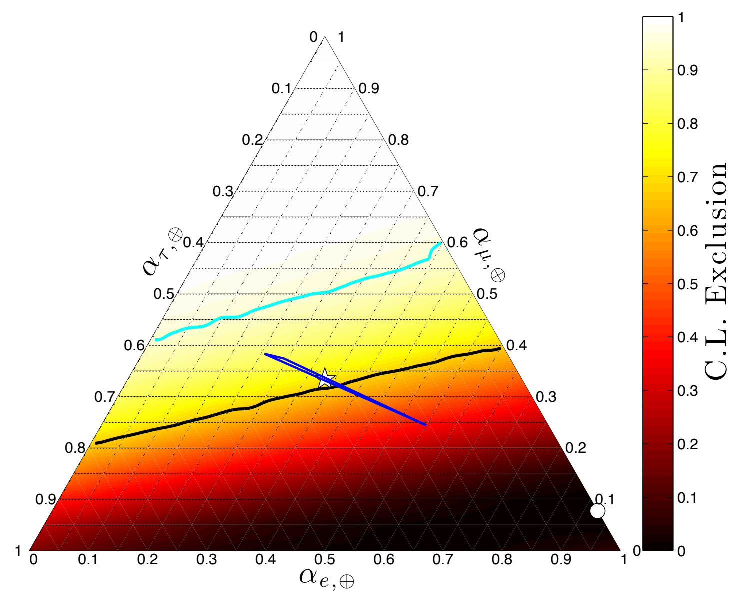
Flavour Composition of IceCube's HESEs

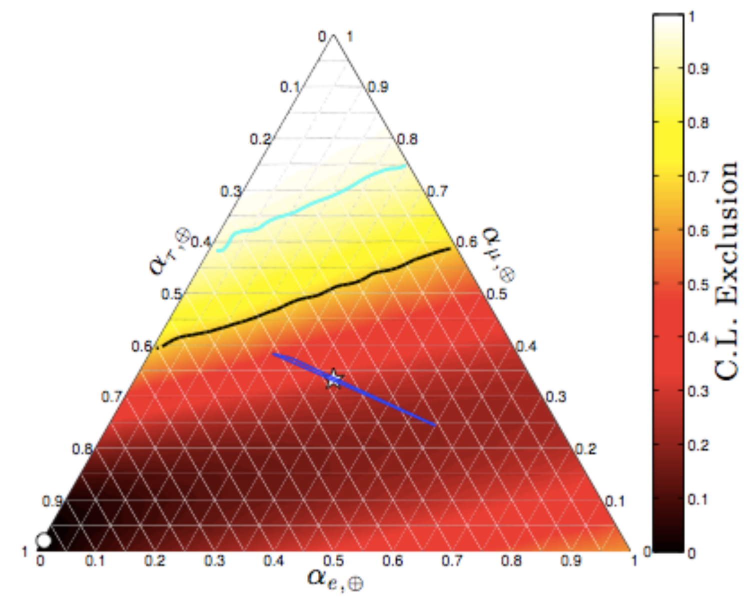
Topologies



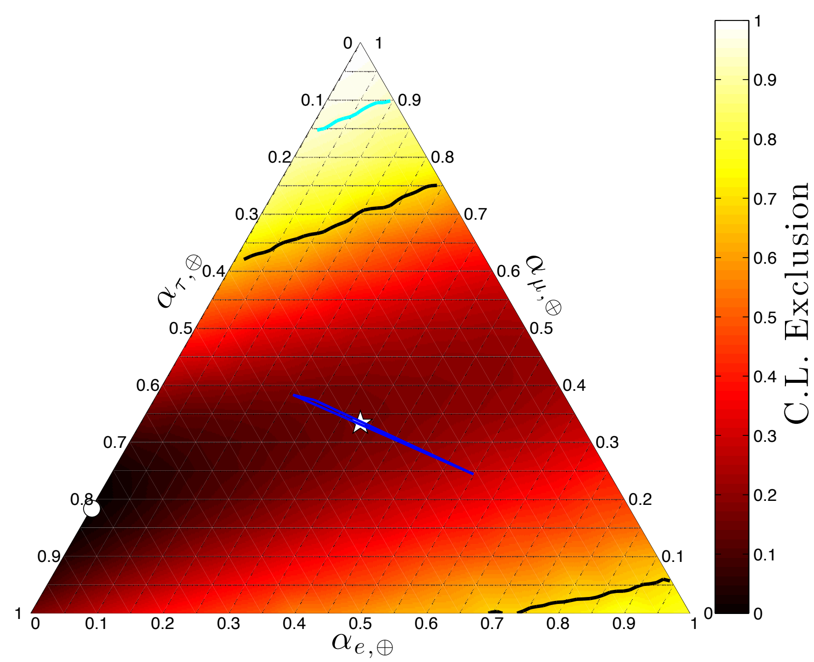
+ spectrum



+ extend E range

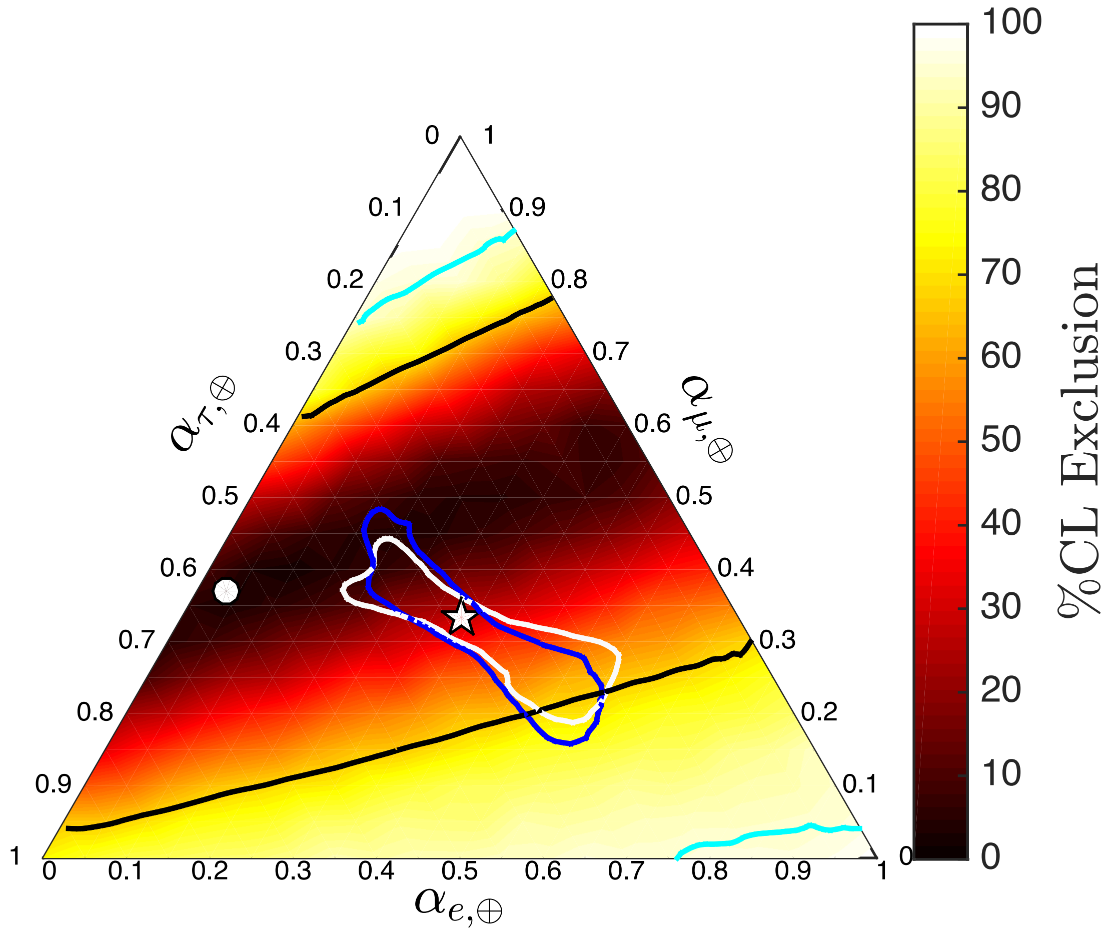


+ Mis-ID of tracks as showers:

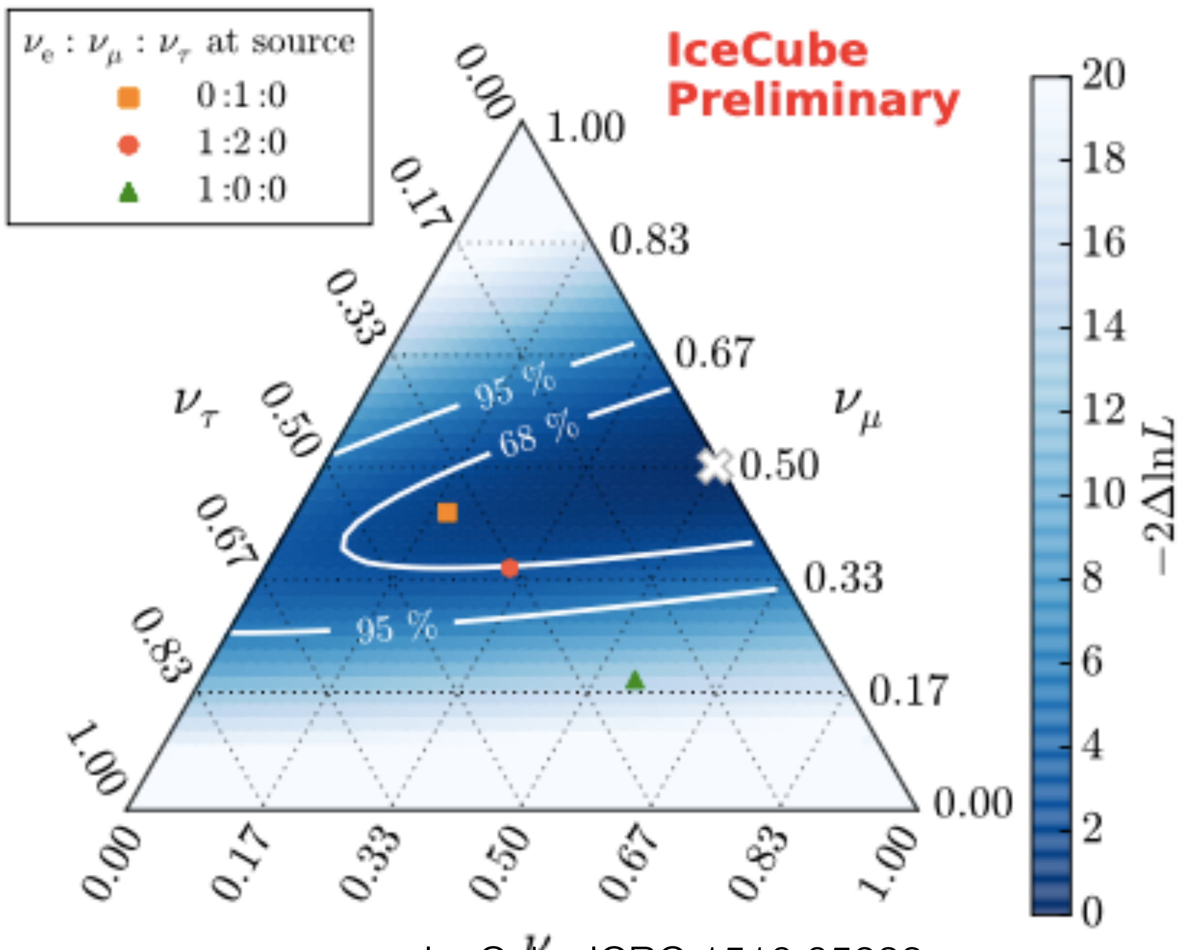


{Mena, Palomares-Ruiz, ACV}
1411.2998
1502.02649
1505.03355
1605.01556

Four years, including spectral information + mis-ID



ACV, Palomares-Ruiz, Mena 1605.01556



IceCube ICRC 1510.05223

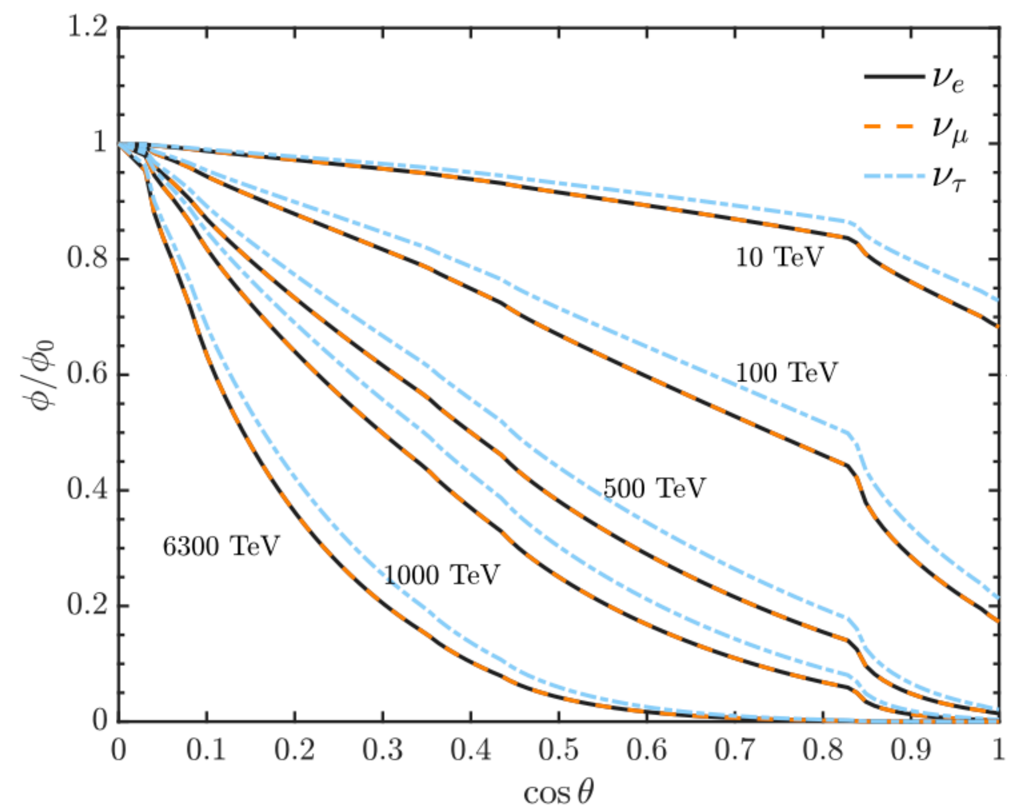
νFATE 1706.09895

http://github.com/aaronvincent/nuFATE
available for python & matlab
coming soon C++ & home video

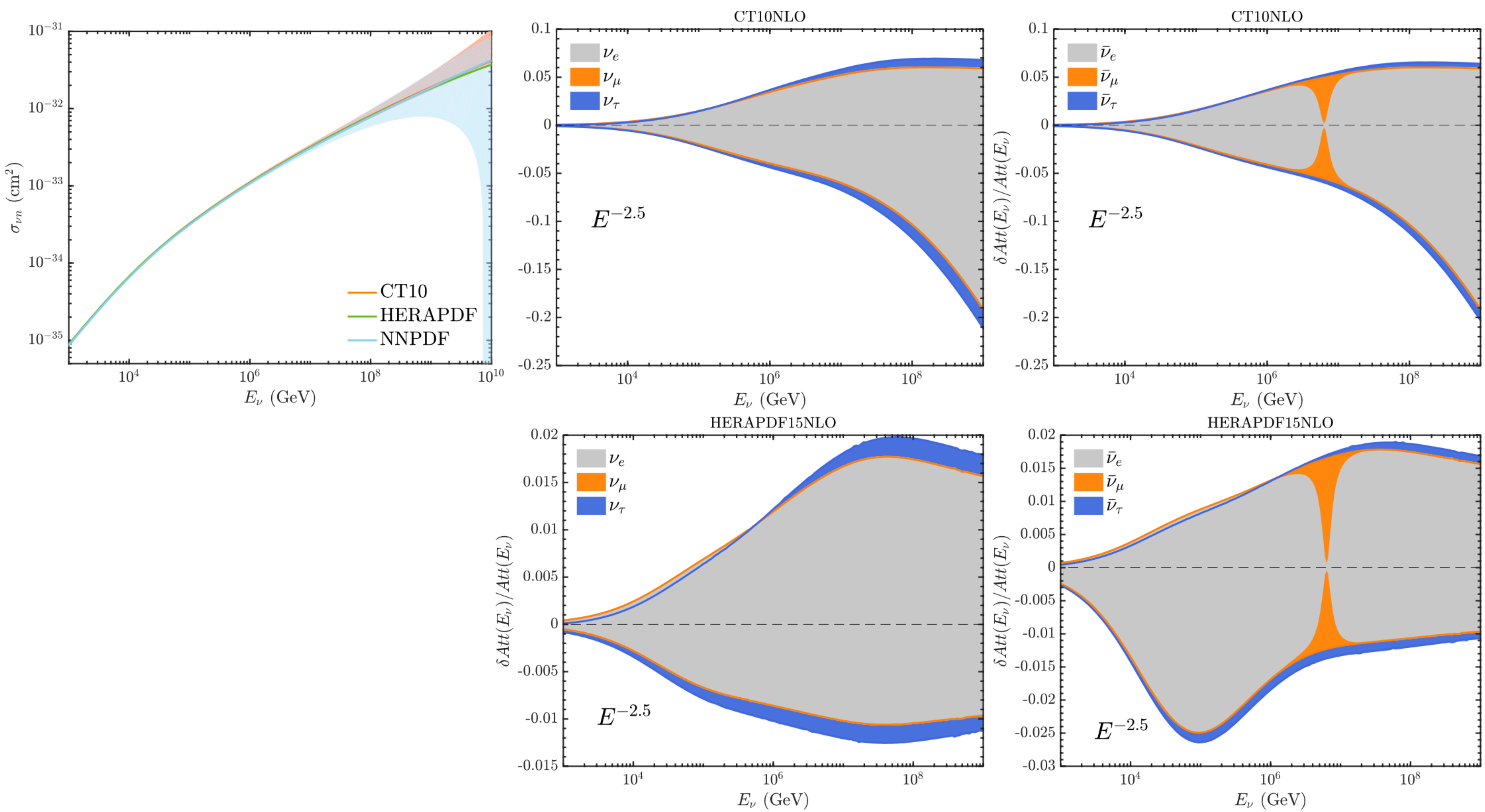
$$\frac{\partial}{\partial x}\left(\frac{d\phi_{\nu_\ell}(E_\nu,x)}{dE_\nu}\right) = -\left(\sigma^{\rm NC}_{\nu_\ell}(E_\nu)+\sigma^{\rm CC}_{\nu_\ell}(E_\nu)\right)\frac{d\phi_{\nu_\ell}(E_\nu,x)}{dE_\nu} + \int_E^\infty d\tilde{E}\,\frac{d\sigma^{\rm NC}_{\nu_\ell}(E_\nu,\tilde{E}_\nu)}{dE_\nu}\,\frac{d\phi_{\nu_\ell}(\tilde{E}_\nu,x)}{d\tilde{E}_\nu}$$

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

$$\vec{\phi} = \sum c_i \hat{\phi}_i e^{\lambda_i x}.$$



PDF errors



CT10
HERAPDF
NNPDF
$\sigma_{\nu n}$ (cm^2)
E_ν (GeV)
CT10NLO
CT10NLO
HERAPDF15NLO
HERAPDF15NLO
ν_e
ν_μ
ν_τ
$\bar{\nu}_e$
$\bar{\nu}_\mu$
$\bar{\nu}_\tau$
$E^{-2.5}$
$\delta Att(E_\nu)/Att(E_\nu)$


ν_τ
$\bar{\nu}_\tau$
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$