Neutrino astrophysics as a probe of dark matter

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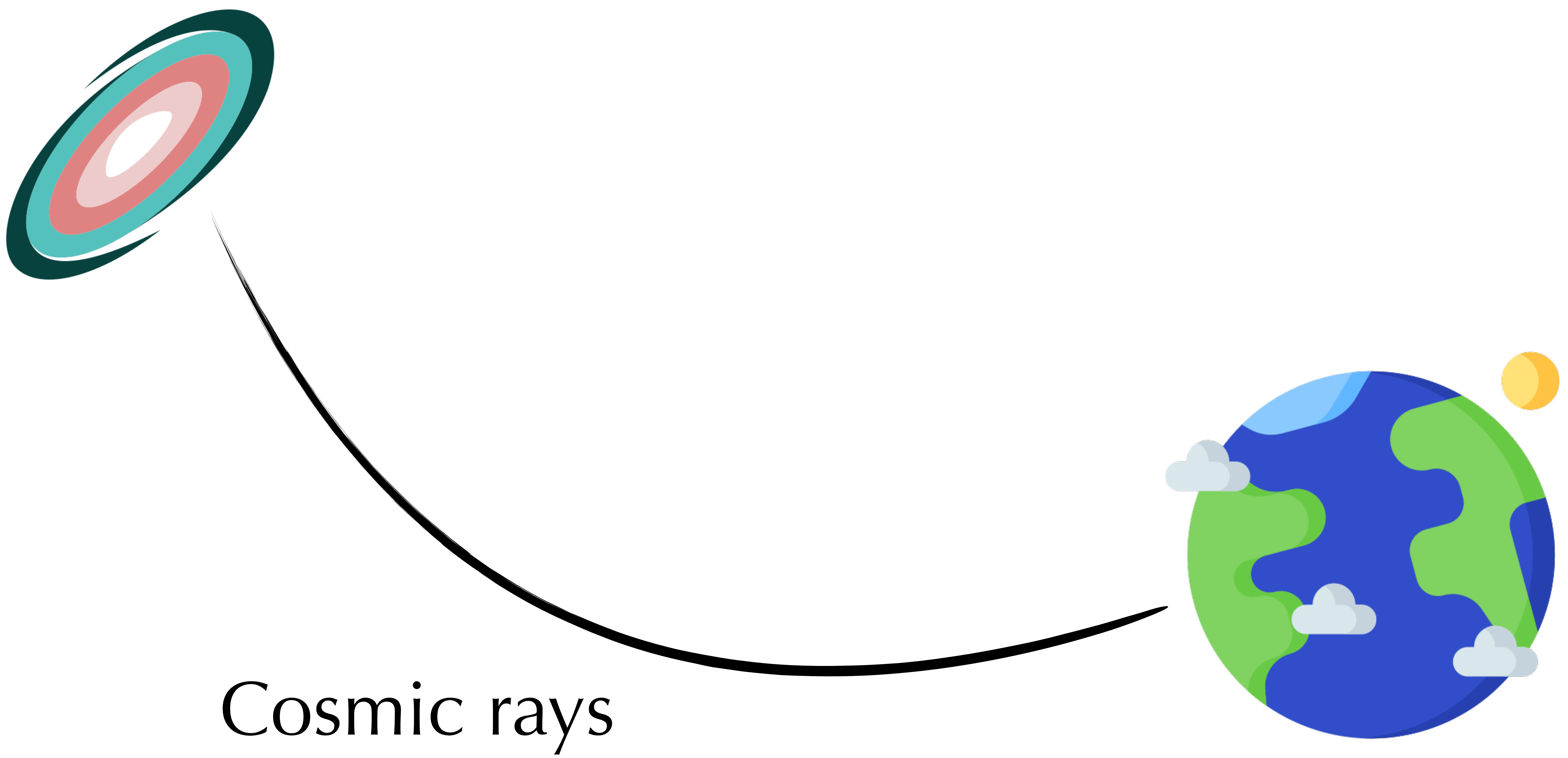
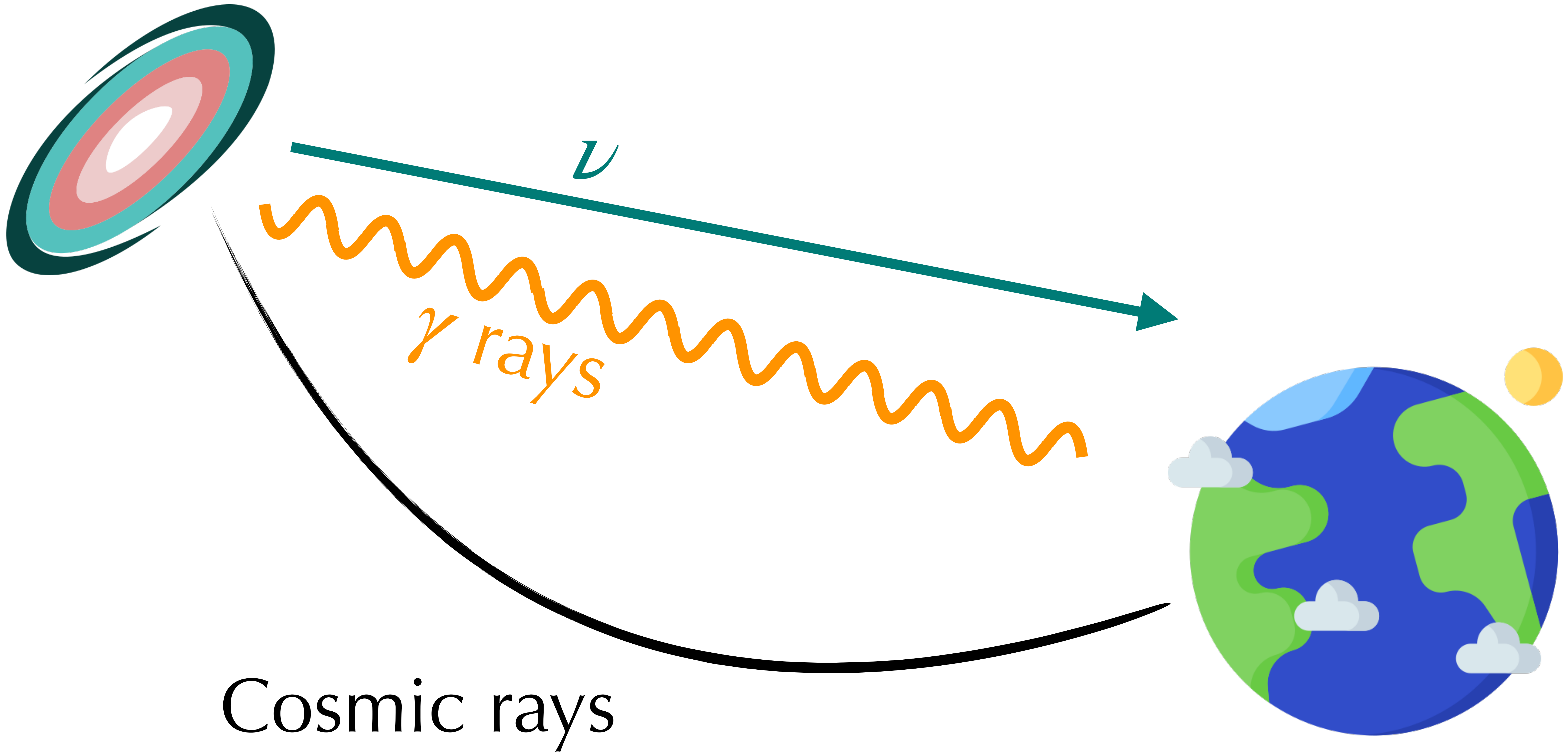
VILLUM FONDEN

Multimessenger astrophysics



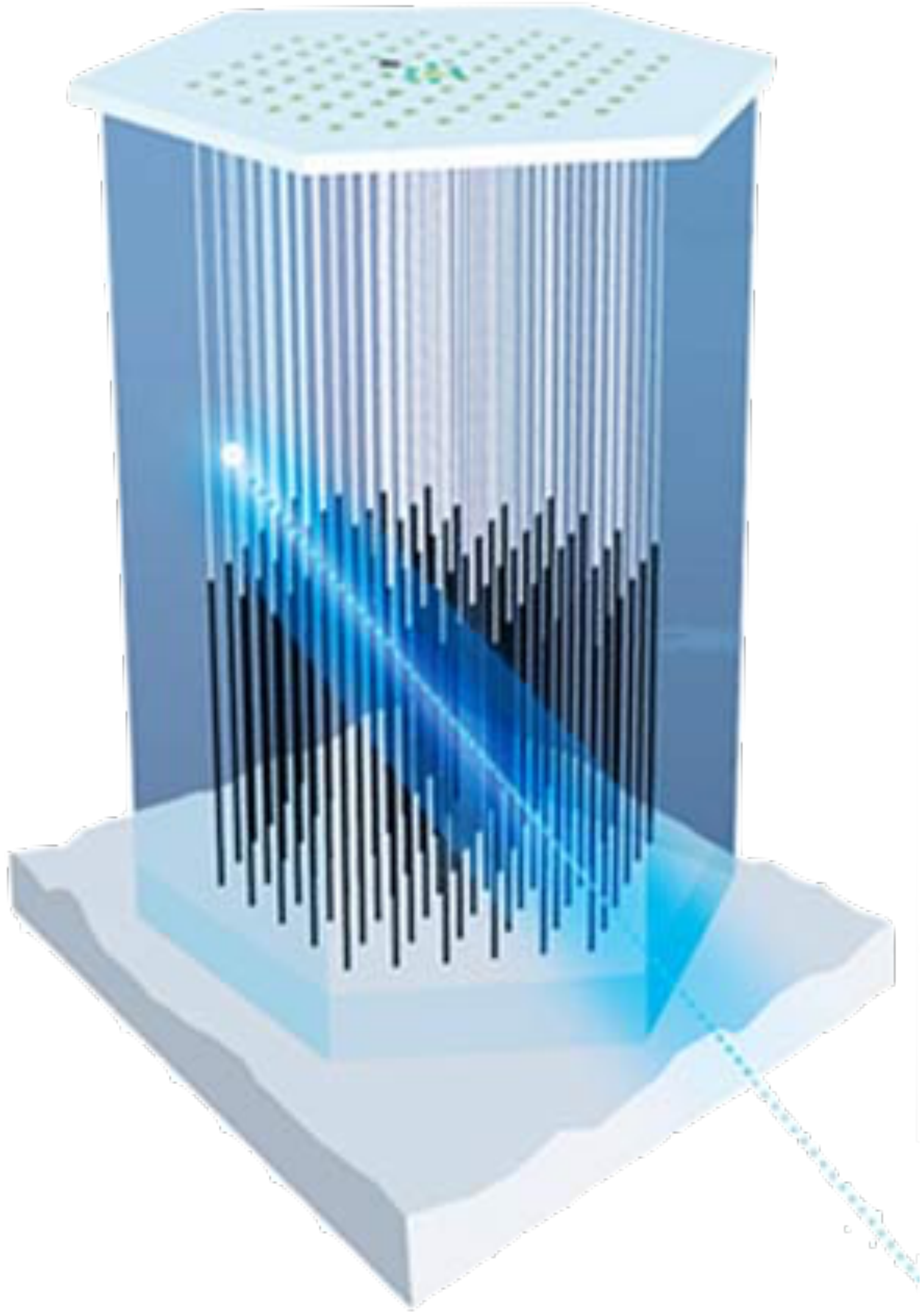
✦ Cosmic rays detected with huge energies, above 100 EeV

Multimessenger astrophysics



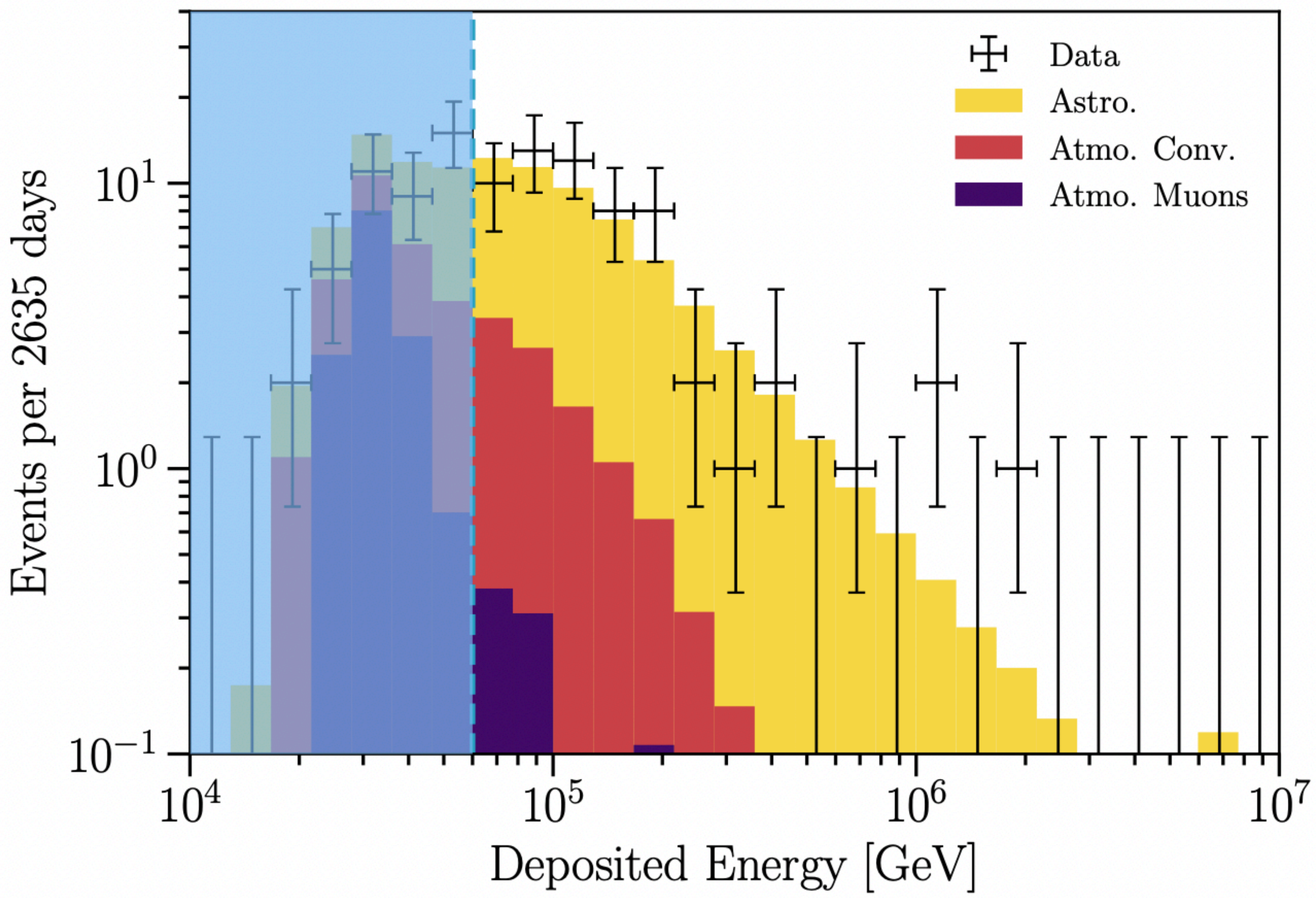
- ✦ Cosmic rays detected with huge energies, above 100 EeV
- ✦ Detectors built for astrophysical gamma-rays ($\sim$ 1960)
- ✦ Final step so far: high-energy neutrino detection (IceCube, $\sim$ 2013)

High-energy neutrino detection



- High-energy neutrinos are **few** and **weakly interacting**
- Detection requires huge volumes, so neutrinos have a chance to interact
- In IceCube, neutrino-nucleon collisions produce charged particles
- Cherenkov light is detectable

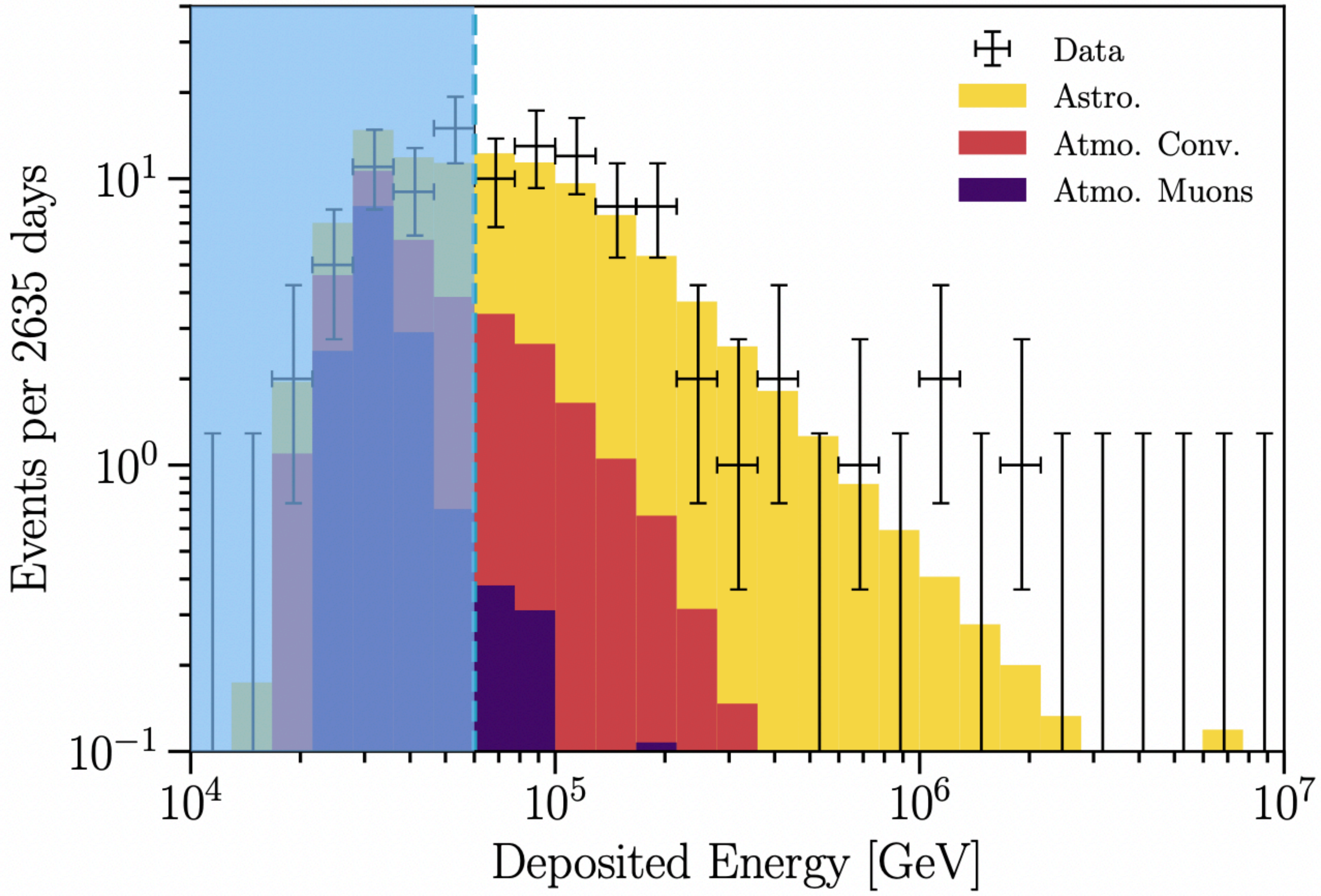
IceCube High-Energy Starting Events (HESE)



IceCube Collaboration, arXiv:2011.03545

- Starting events interact inside the detector
- Astrophysical component detected above 60 TeV

IceCube High-Energy Starting Events (HESE)



IceCube Collaboration, arXiv:2011.03545

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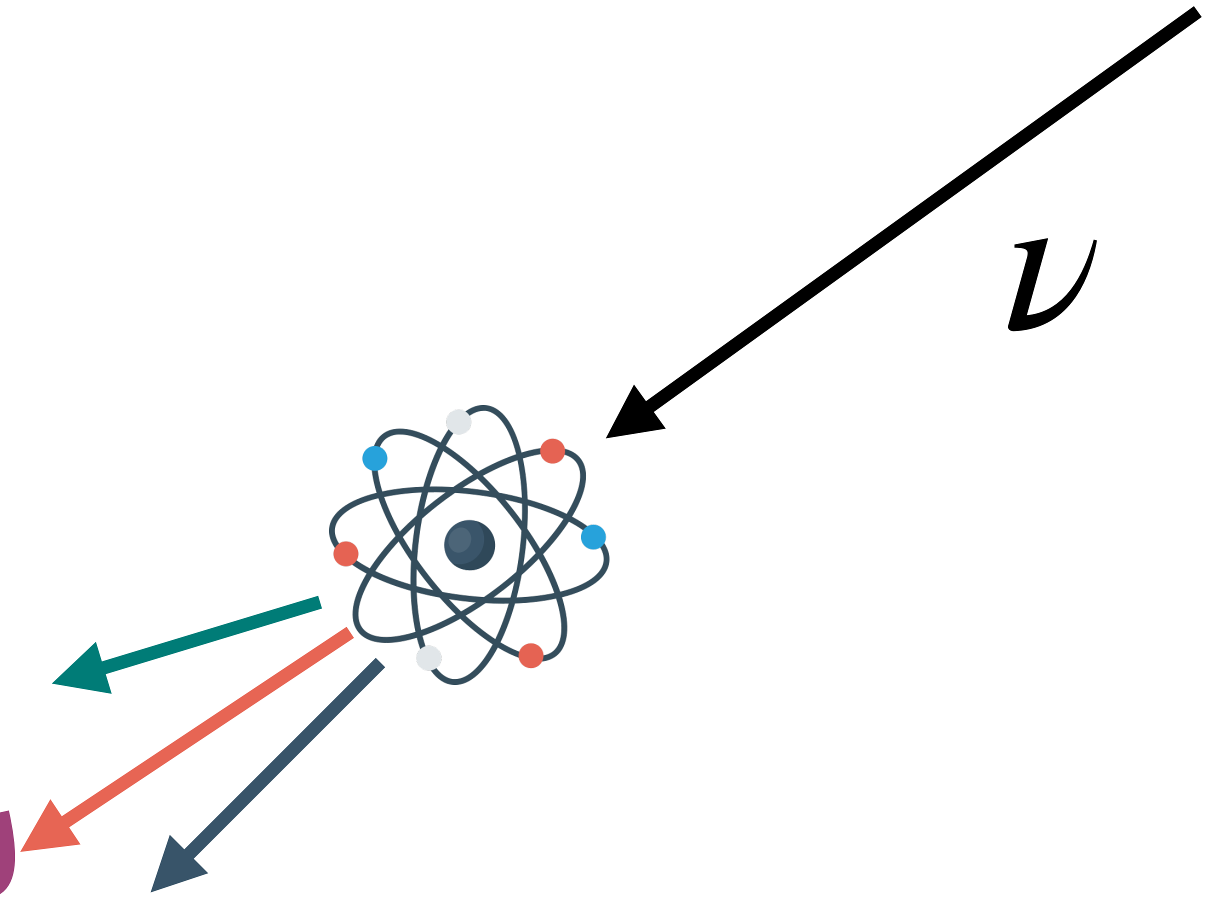
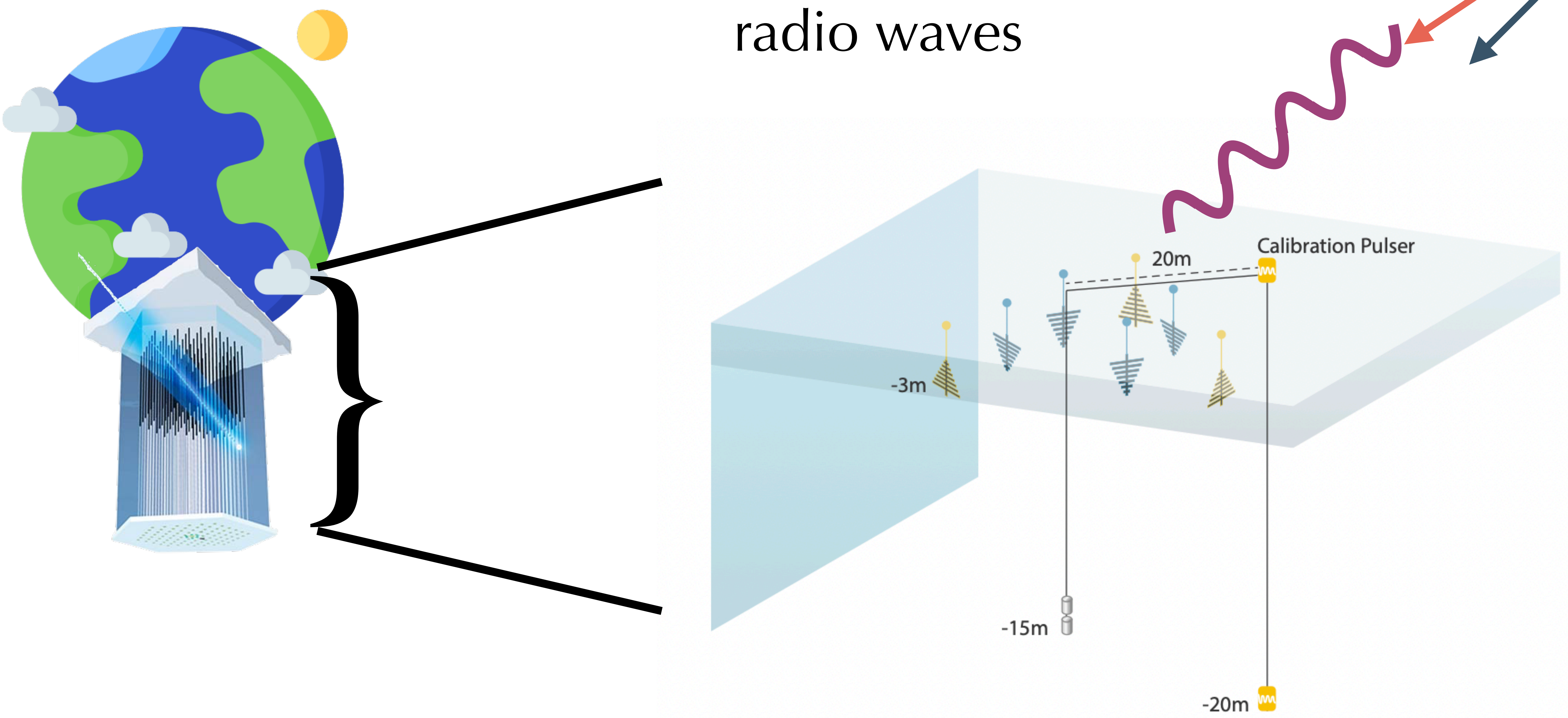
Highest energies?

Ultra-high-energy (UHE) neutrinos

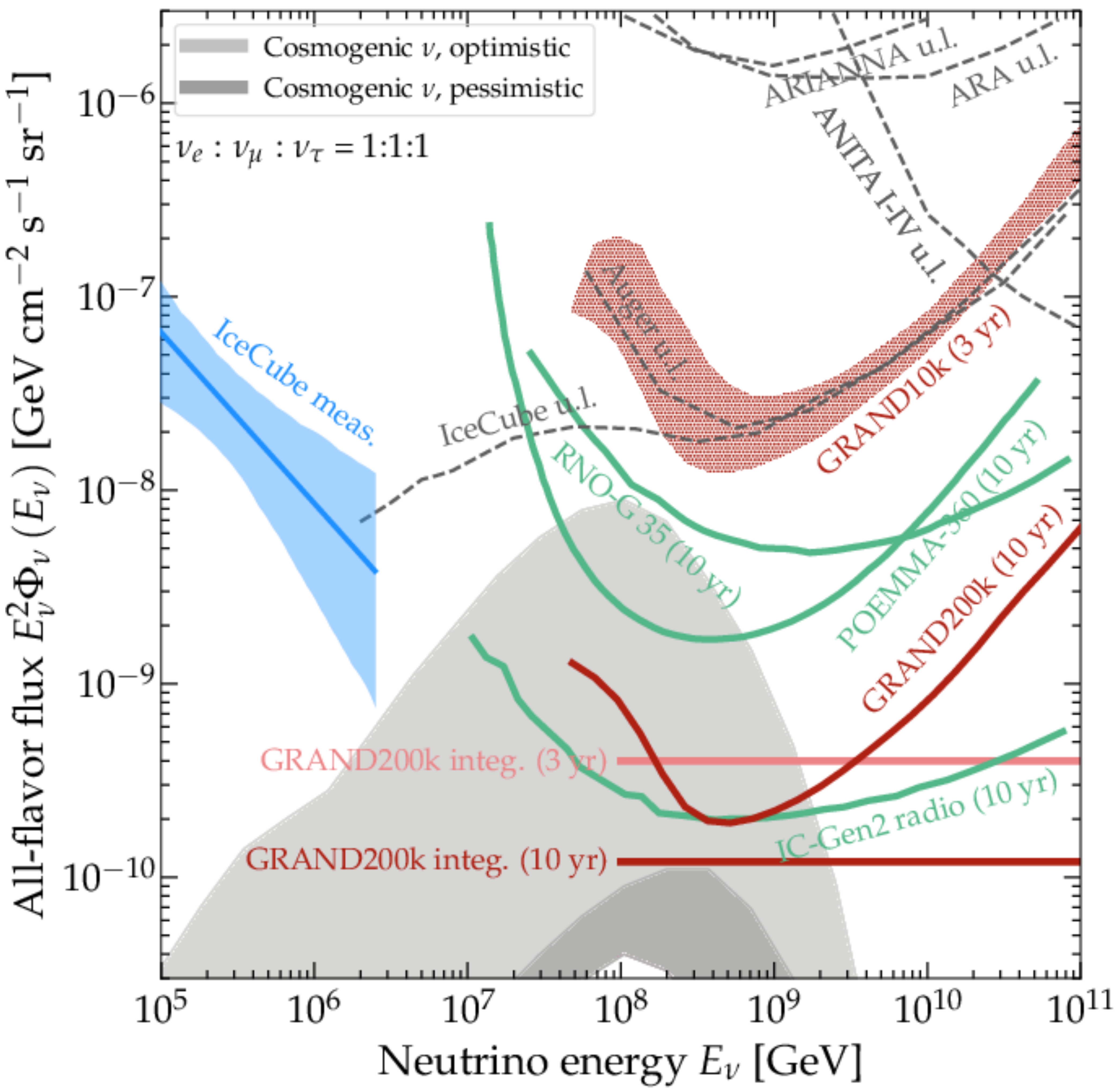
Askaryan effect -

in-ice shower looks like a moving dipole, producing radio waves





Ultra-high-energy (UHE) neutrinos

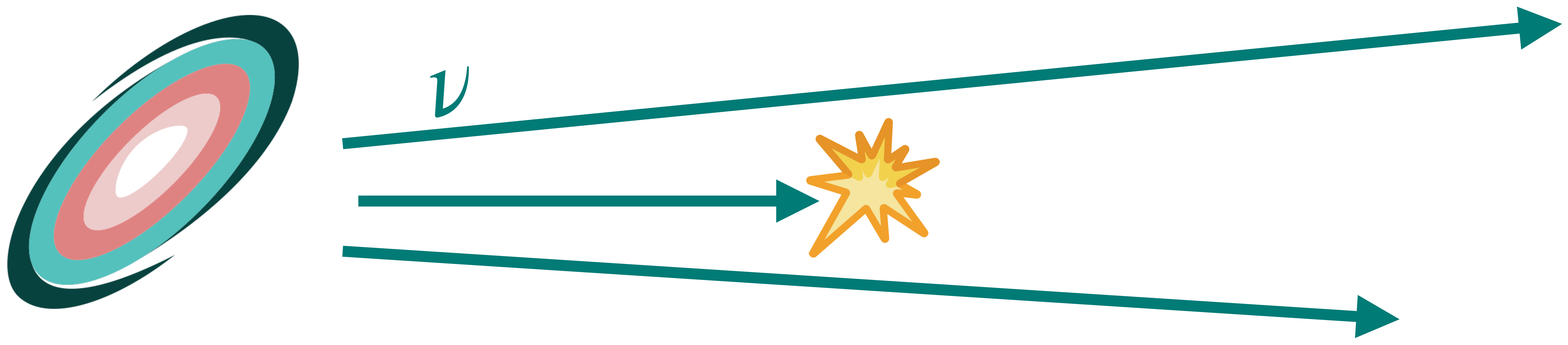


Kotera, arXiv:2108.00032

- Above 10 PeV no detection yet
- Expected cosmogenic neutrinos, from $p\gamma$ collisions
- Possible UHE ν from astrophysical sources
- Highest energy and longest baseline neutrinos

What do these neutrinos tell us about particle physics?

Neutrinos probe (BSM) particle physics



Non-standard interactions ($\nu\nu$ with relic neutrinos, $\nu\chi$ with dark matter, …)

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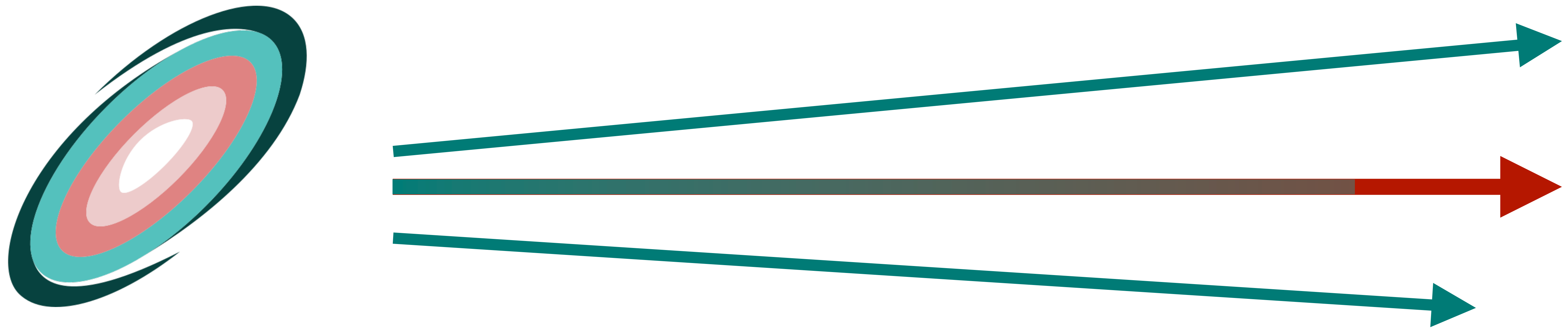
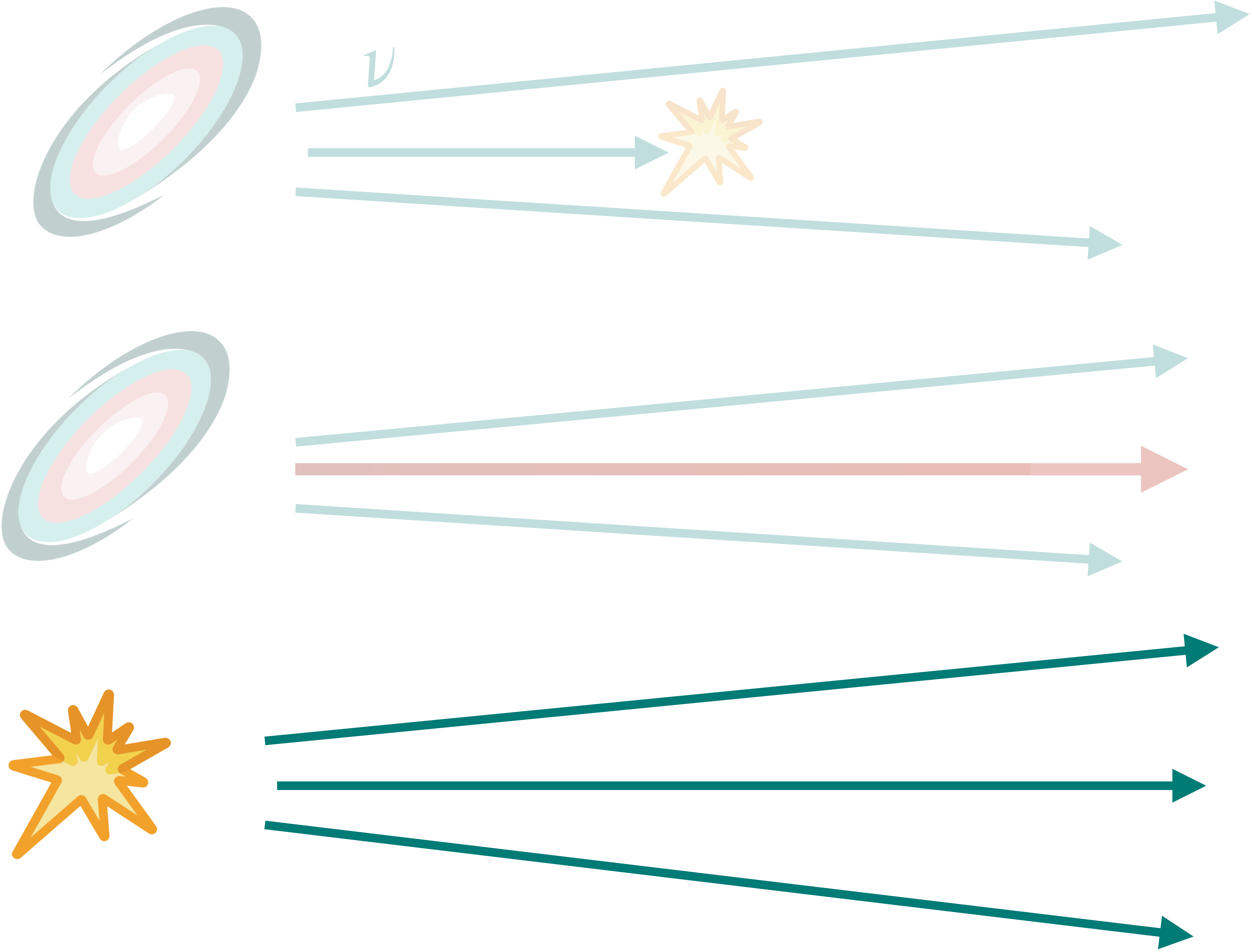


Non-standard oscillations (sterile neutrinos, violation of equivalence principle, Lorentz invariance violation, …)

Neutrinos probe (BSM) particle physics

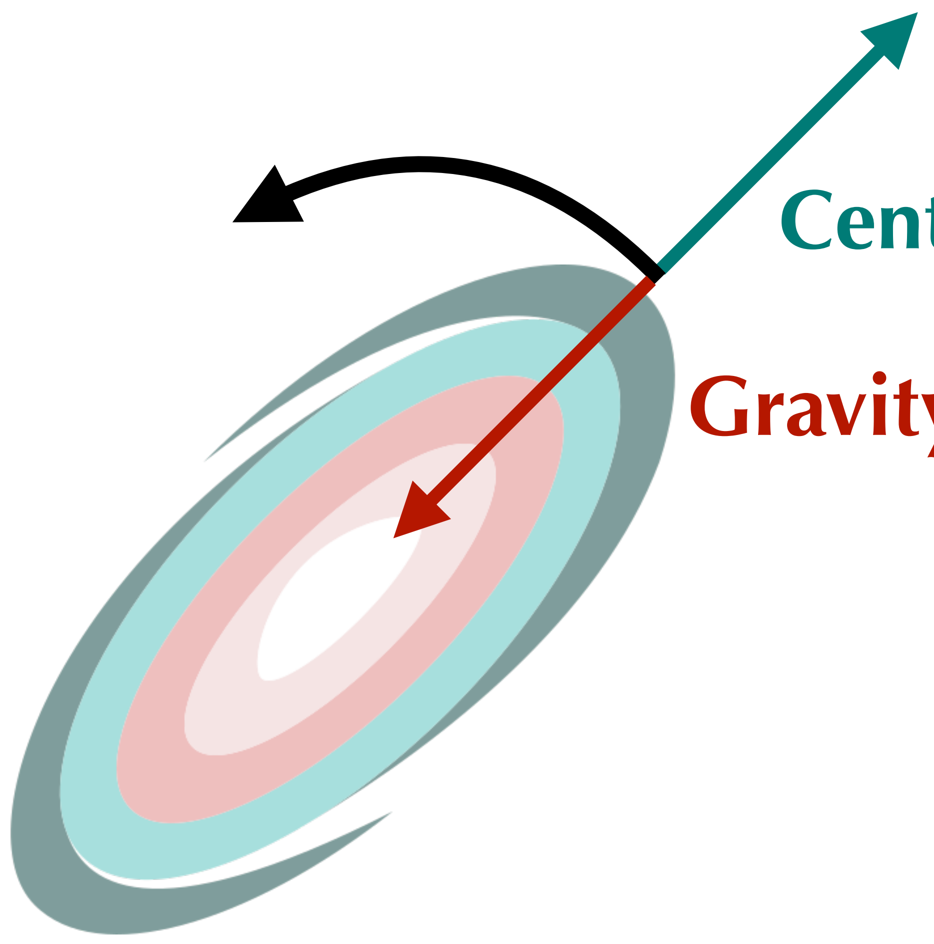


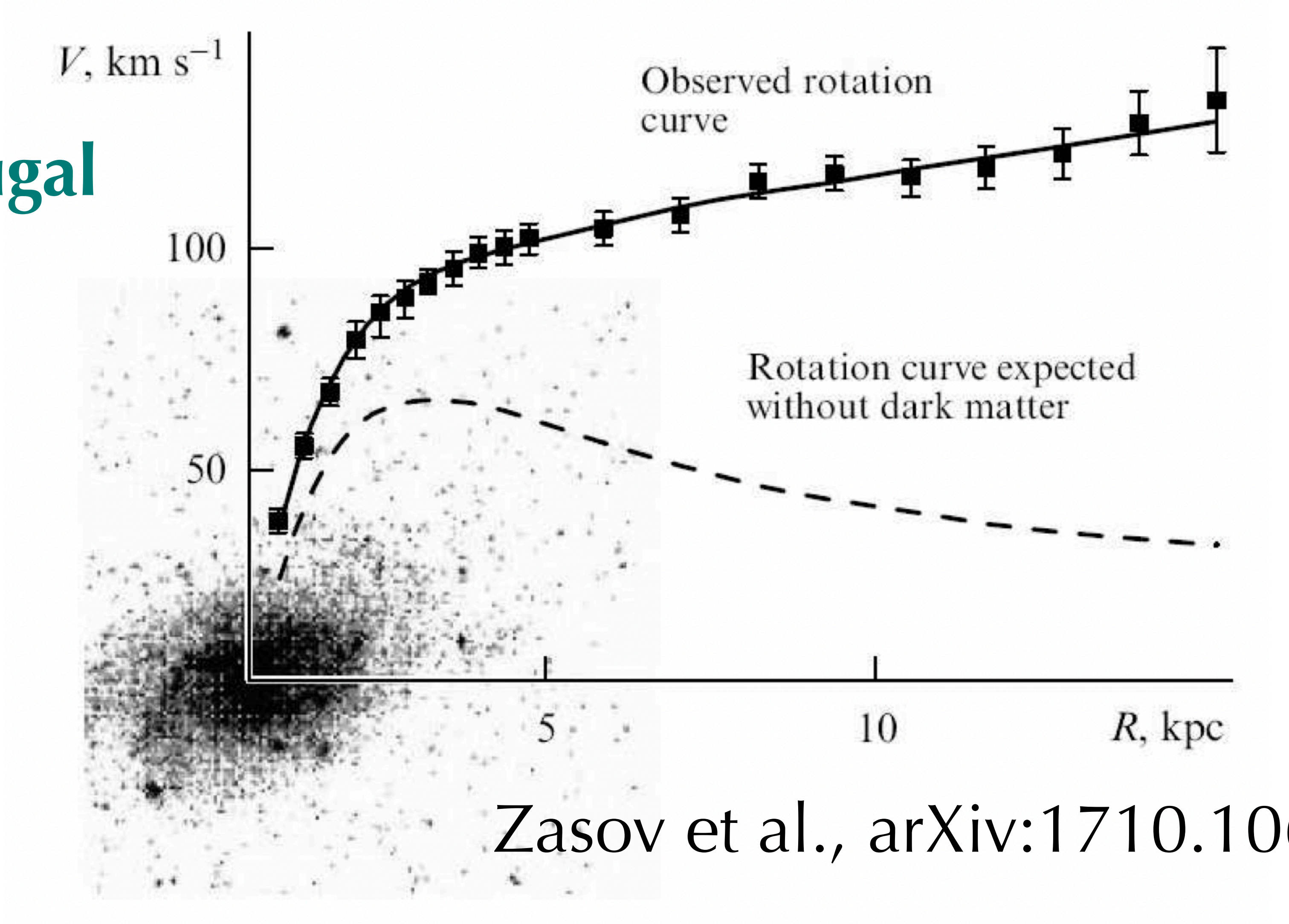
Non-standard interactions ($\nu\nu$ with relic neutrinos, $\nu\chi$ with dark matter, …)

Non-standard oscillations (sterile neutrinos, violation of equivalence principle, Lorentz invariance violation, …)

Non-standard production (dark matter annihilation, **dark matter decay**, …)

Dark matter

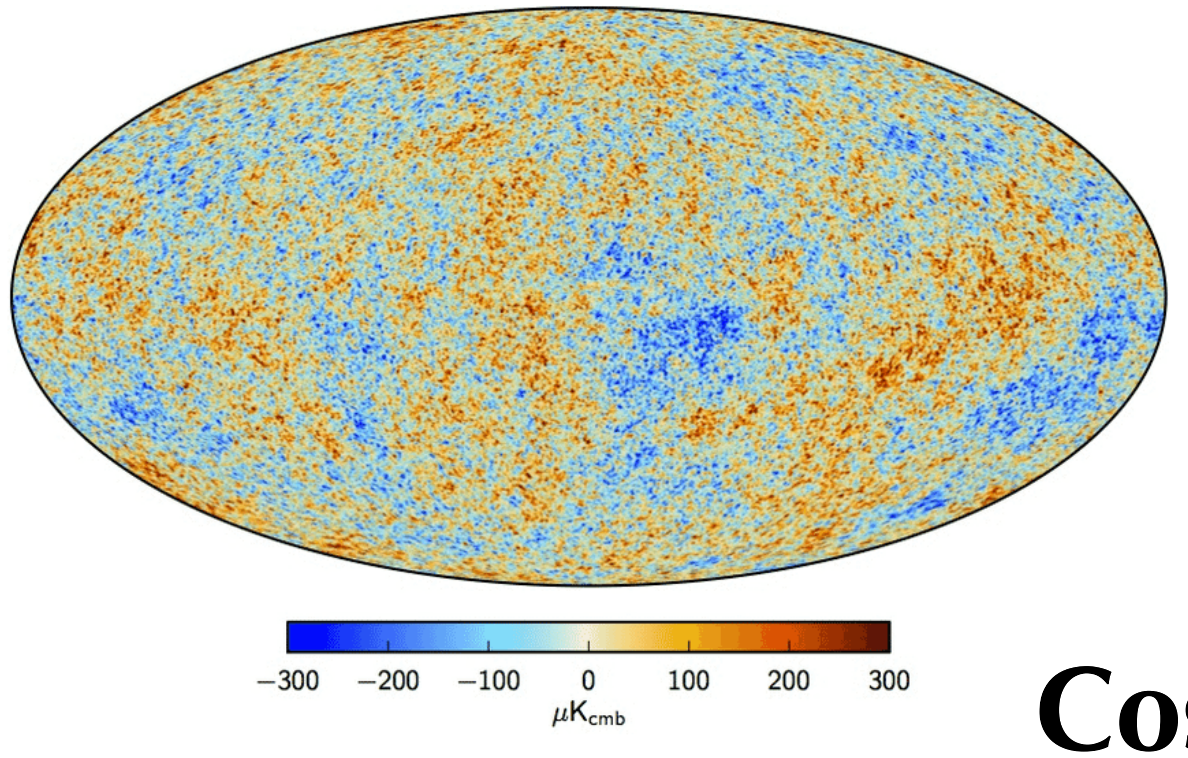




Zasov et al., arXiv:1710.10630

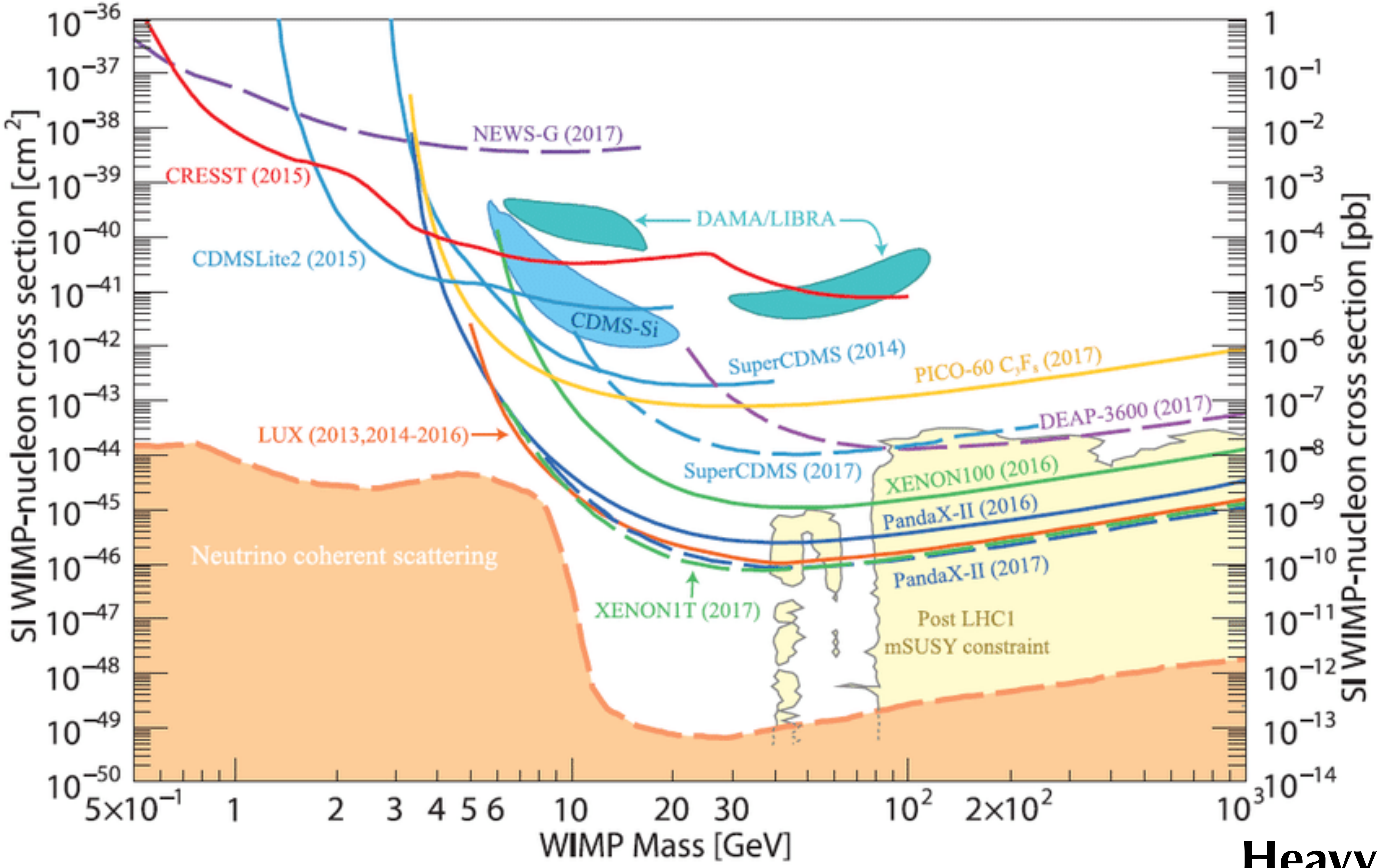
Gravitational motion

Gravitational lensing



Cosmology

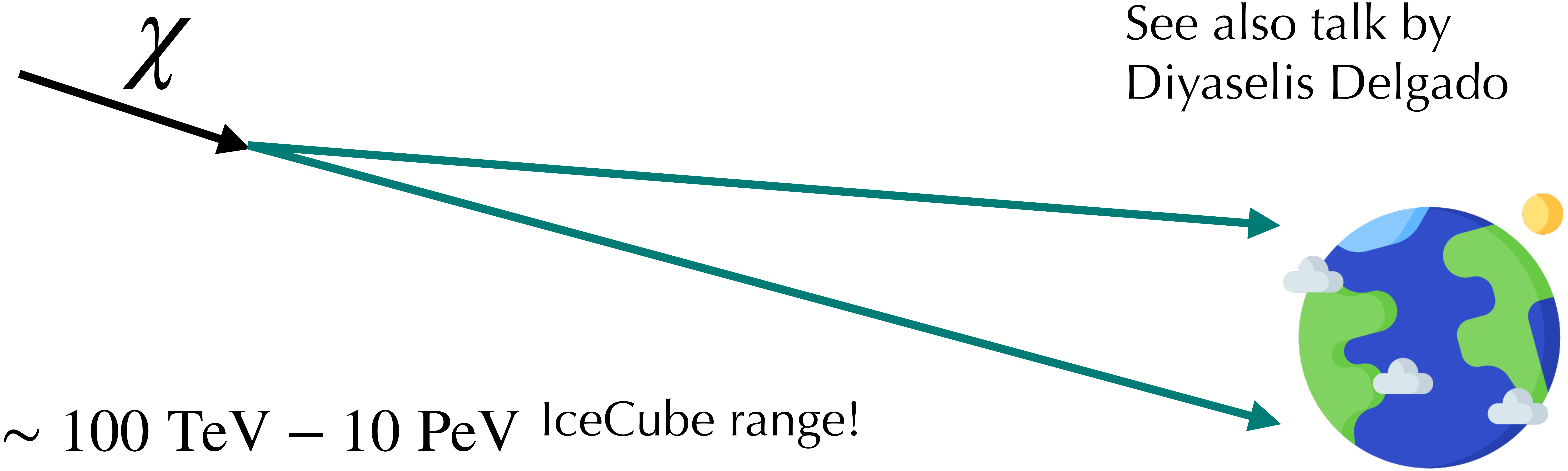
Dark matter



PDG 2018

Heavy dark matter

Decaying dark matter



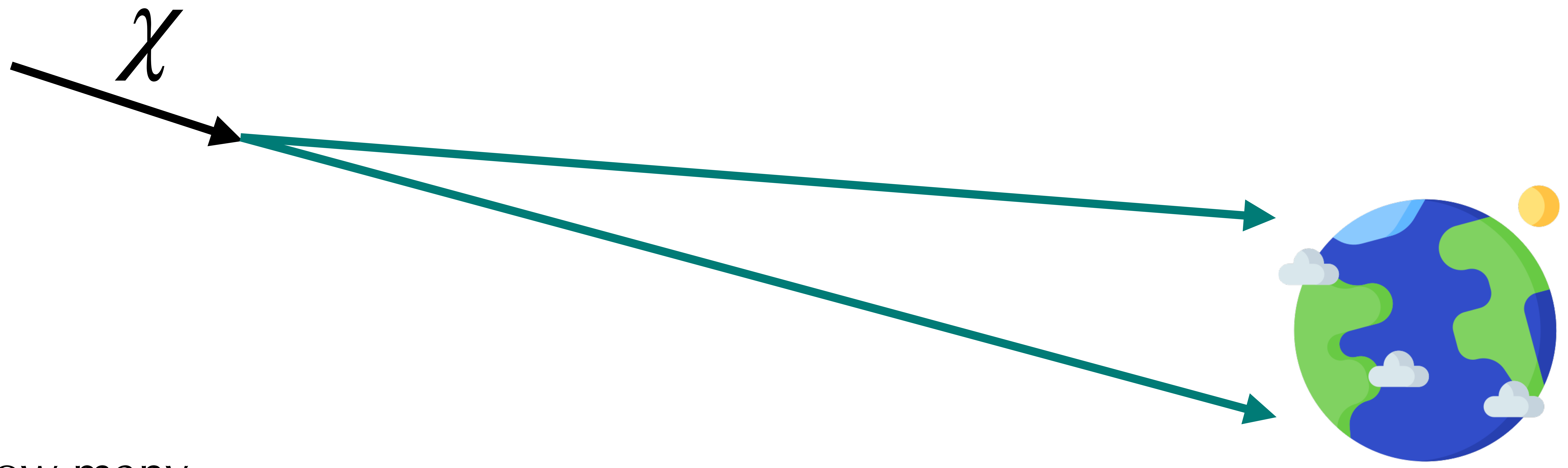
See also talk by Diyaselis Delgado

$m_{\rm DM} \sim 100$ TeV – 10 PeV IceCube range!

$m_{\rm DM} \sim 1$ EeV – 100 ZeV UHE range!

Produce gamma-rays and cosmic rays as well!

Decaying dark matter

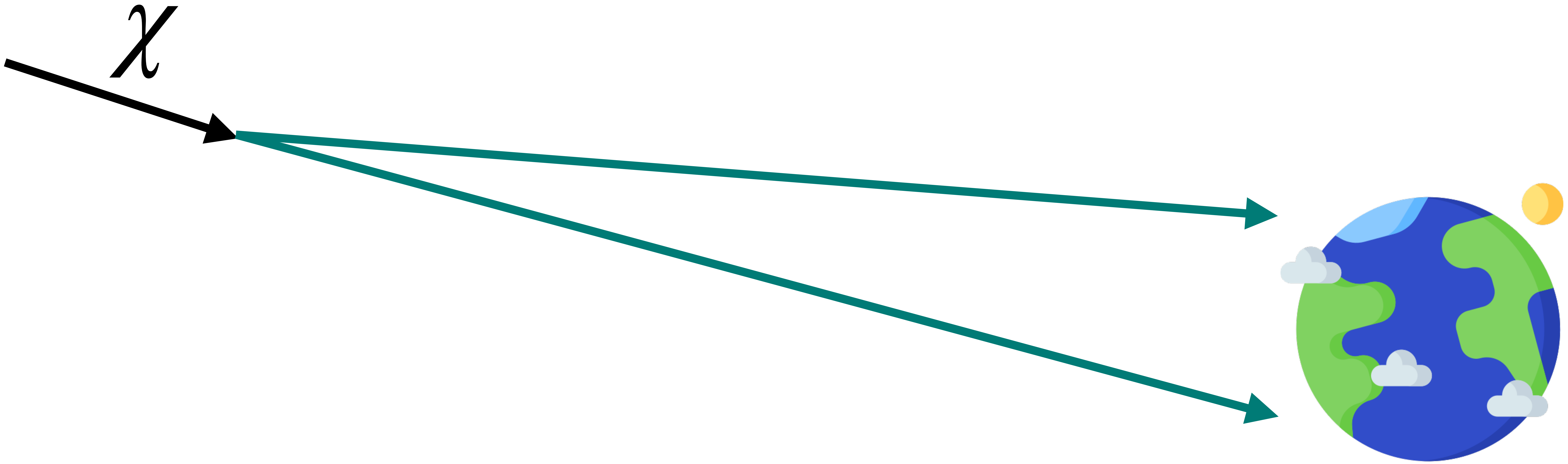


1. How many neutrinos in a decay?

2. Where are they produced? How do they propagate?

3. Can we detect them?

Decaying dark matter



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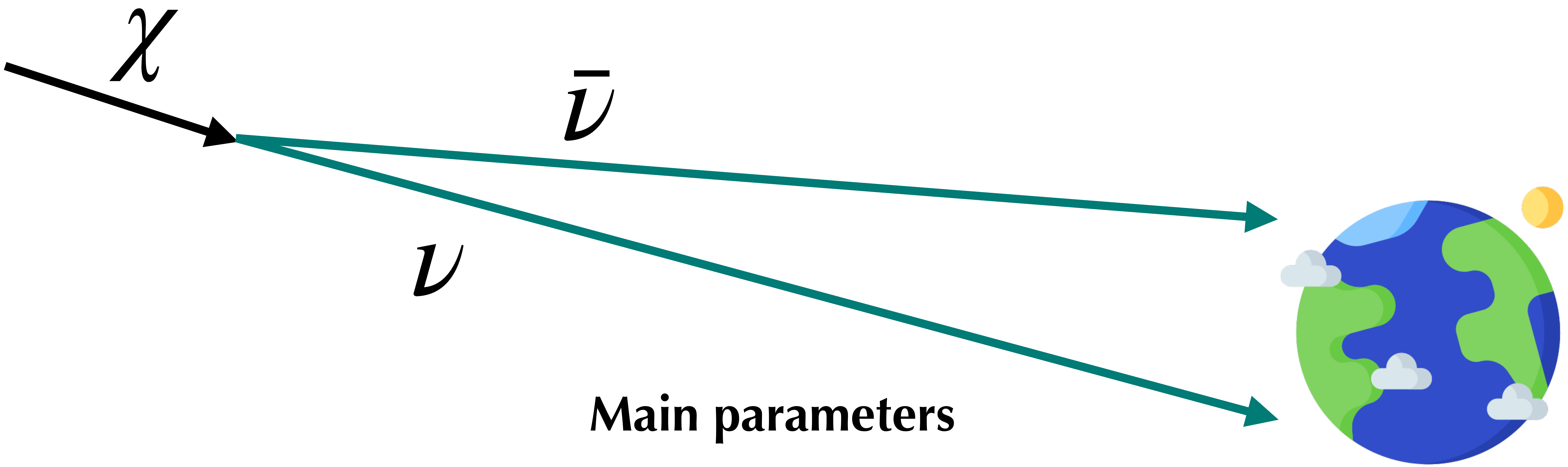
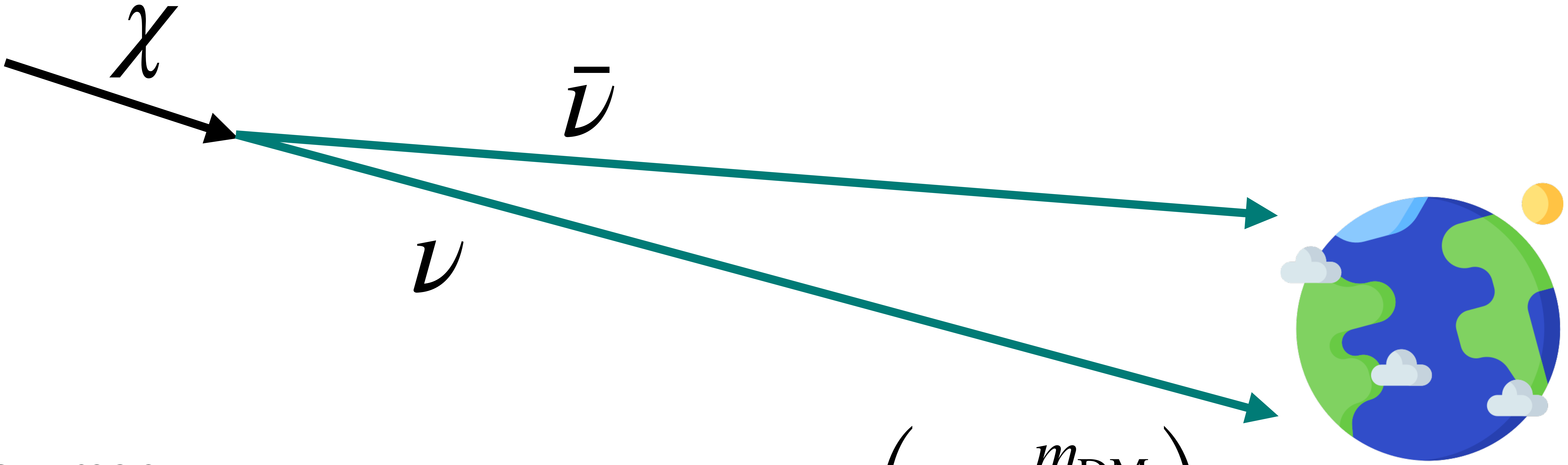


Main parameters

1. How many neutrinos in a decay?

$m_{\rm DM}$	sets the energy scale
$\tau_{\rm DM}$	sets the normalization
$\chi \to \bar{f}f$	sets the energy spectrum

Decaying dark matter



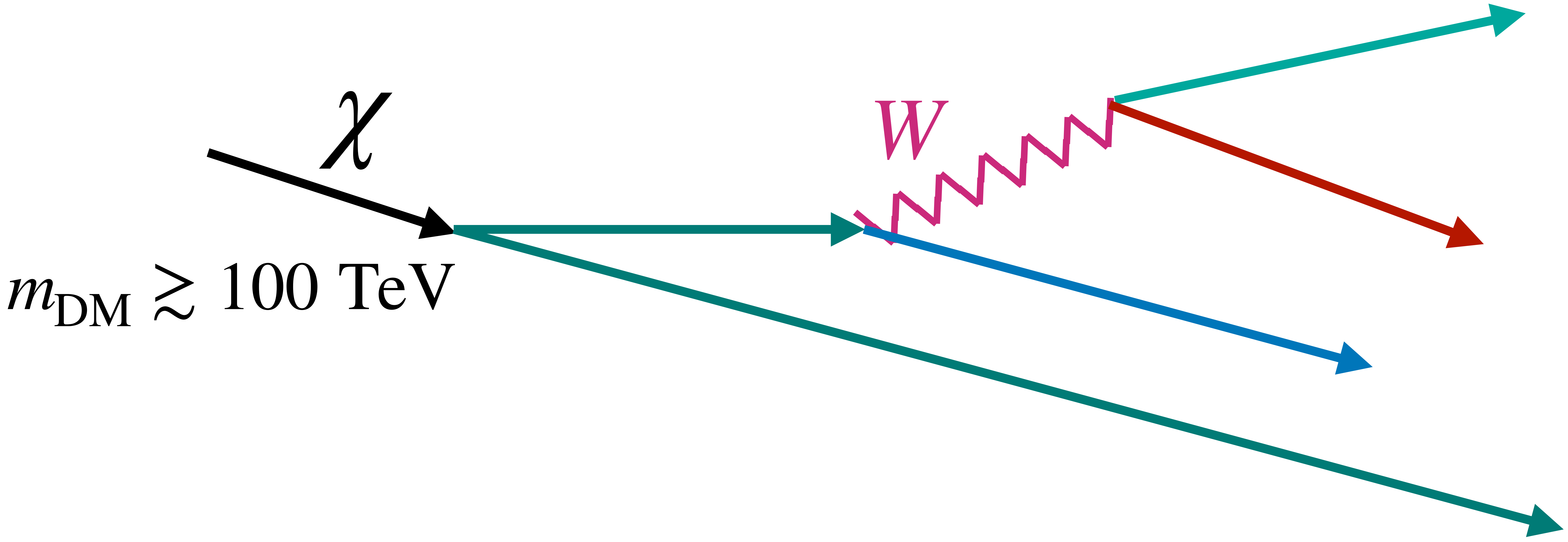
1. How many neutrinos in a decay?

$$\chi \to \bar{\nu}\nu \qquad \delta\left(E - \frac{m_{\rm DM}}{2}\right) \,?$$

$$\chi \to \bar{f}f$$

No neutrino produced?

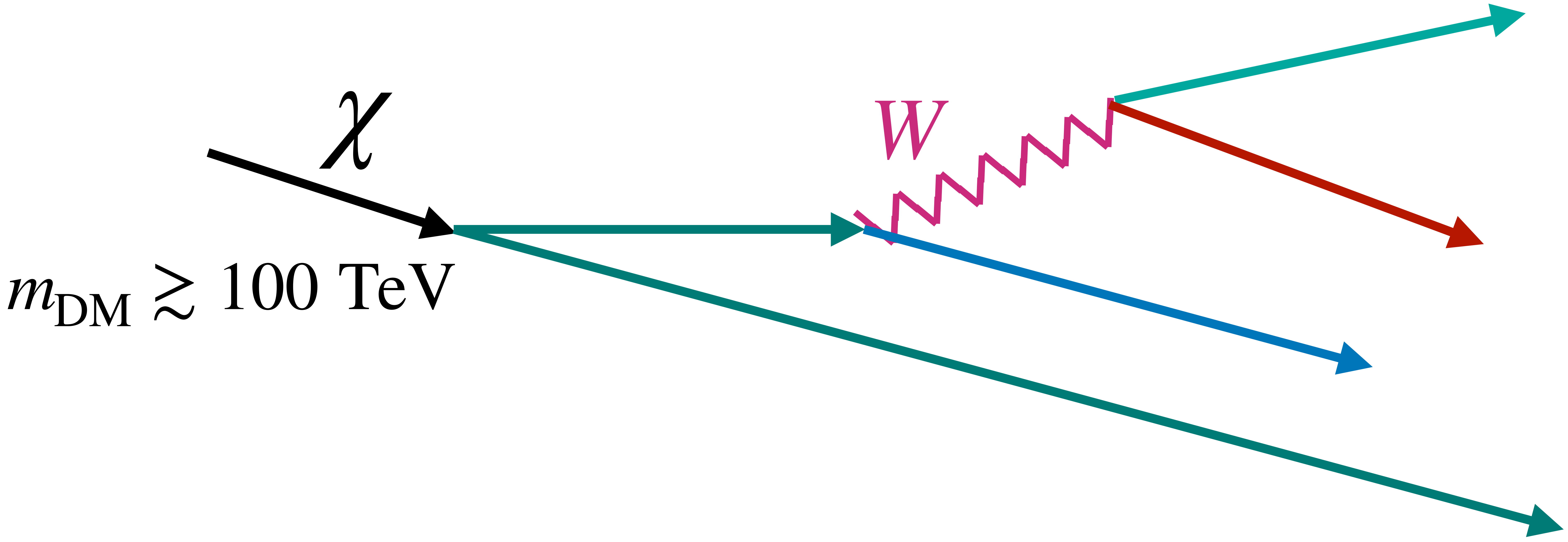
Electroweak corrections



1. How many neutrinos in a decay?

$$P \sim \alpha_W ?$$

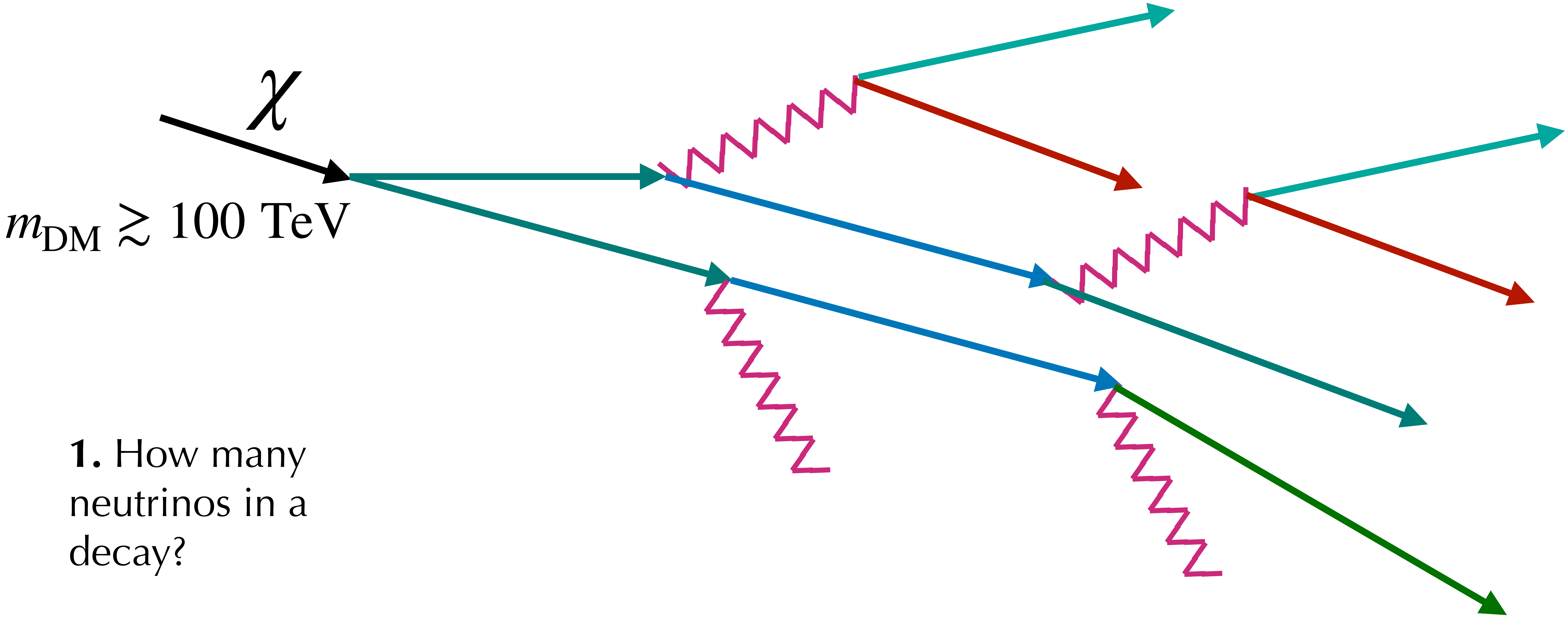
Electroweak corrections



1. How many neutrinos in a decay?

$$P \sim \alpha_W \log^2\left(\frac{m_{\rm DM}}{m_W}\right)$$

Electroweak corrections

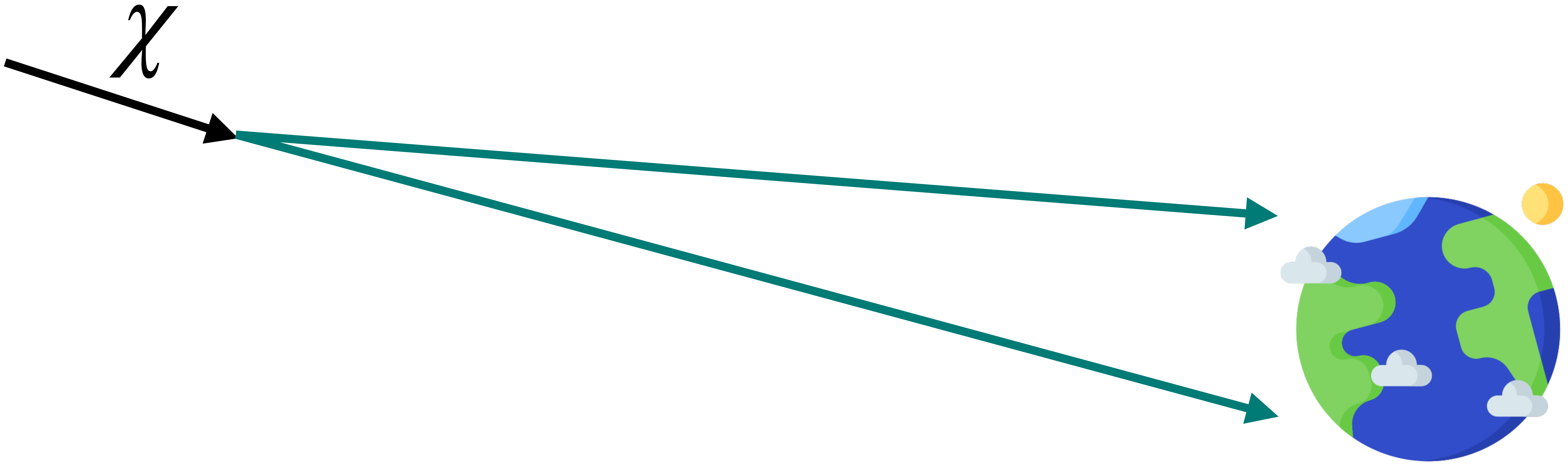


1. How many neutrinos in a decay?

Energy cascade, treated by DGLAP equations

HDMSpectra (arXiv:2007.15001)

Decaying dark matter



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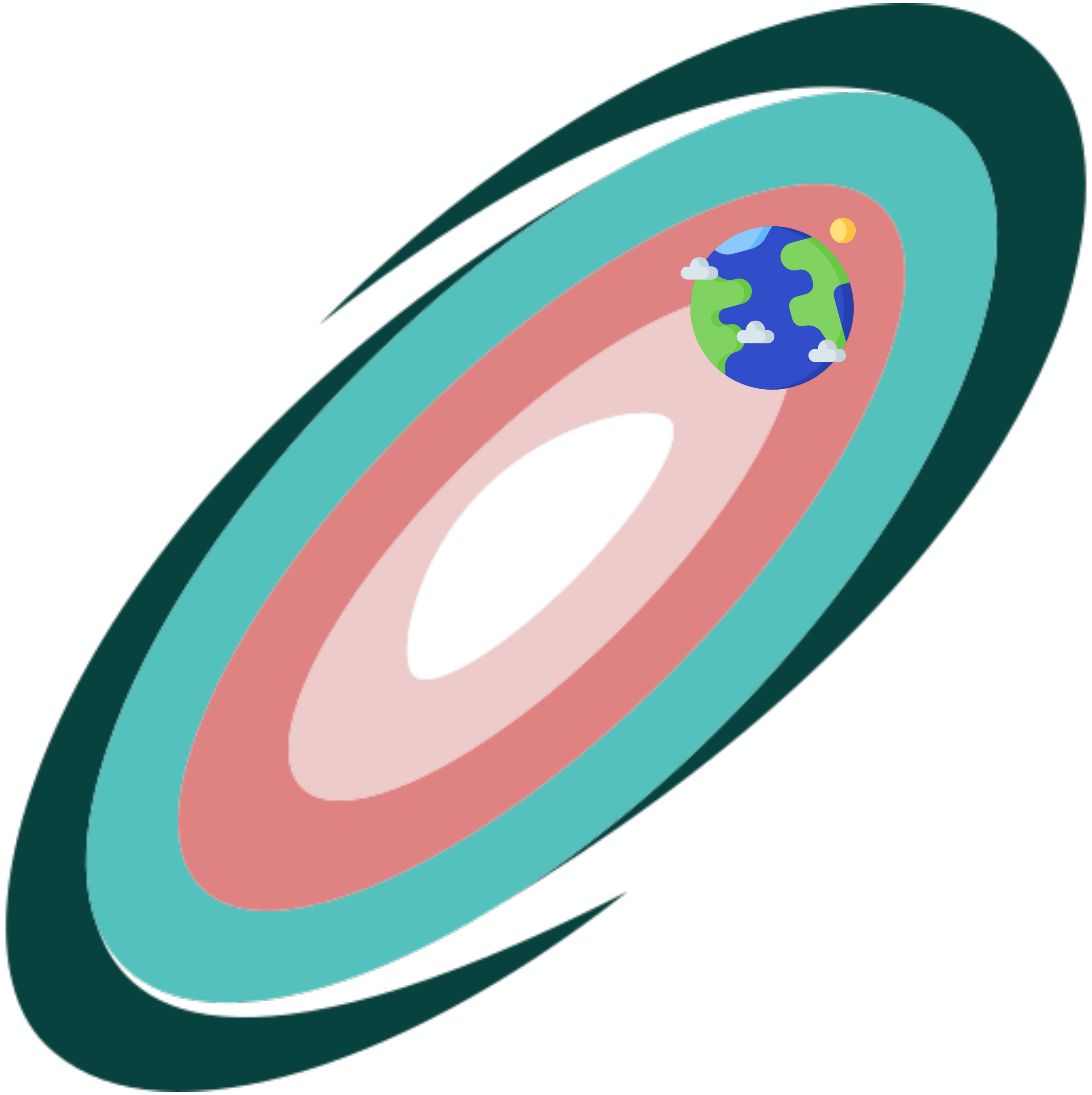
Diffuse DM production



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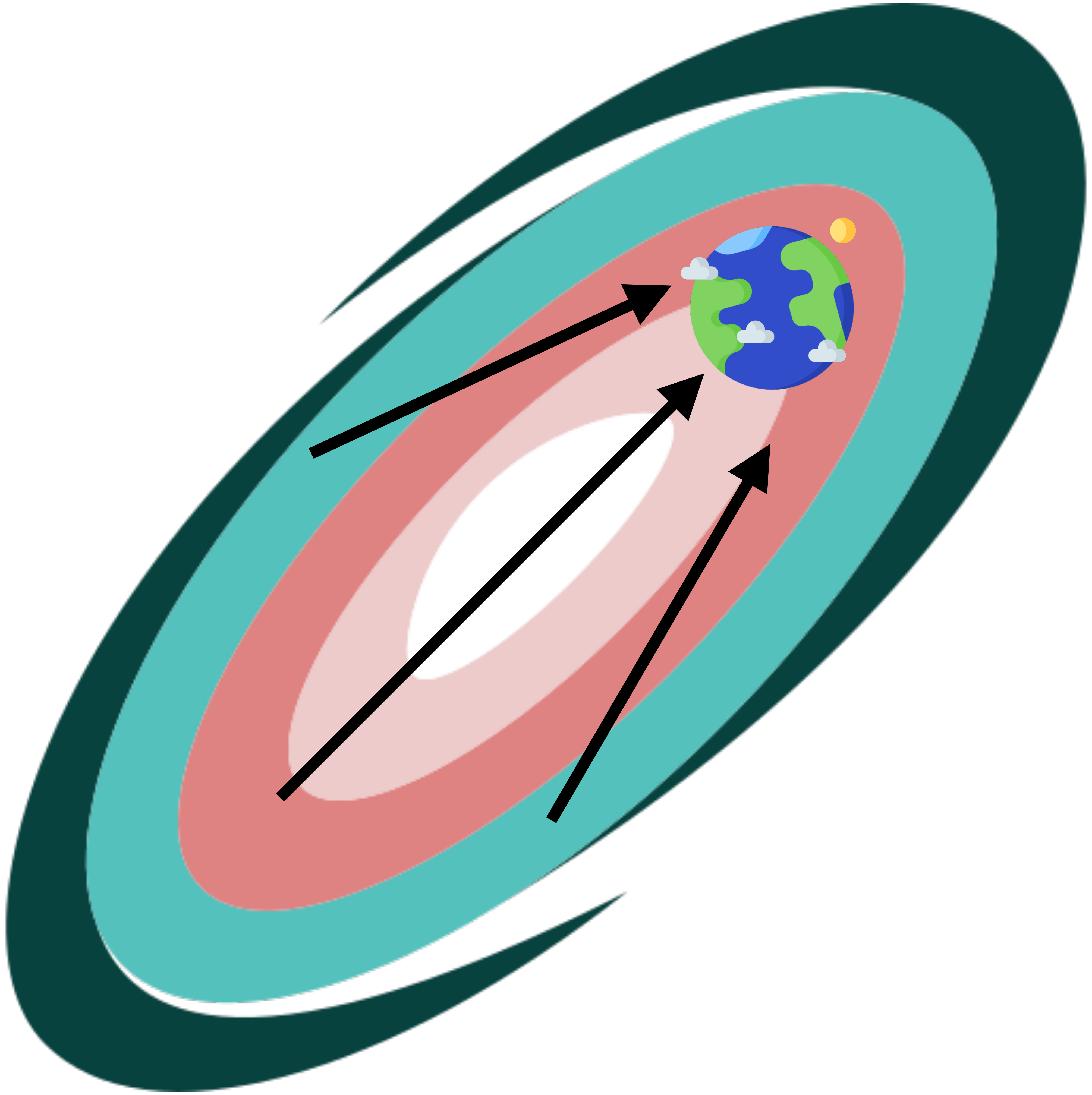

Galactic production

- ✦ Depends on DM distribution
- ✦ Slightly anisotropic

Diffuse DM production

$$\frac{d\phi_{G,\beta}}{dEd\Omega} = \frac{1}{4\pi}\frac{1}{\tau_{\rm DM}}\sum_\alpha \frac{dN_\alpha}{dE}P_{\alpha\to\beta}\int ds \frac{\rho(s,l,b)}{m_{\rm DM}}$$

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How fast does it decay?

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Neutrino mixing

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- $\frac{1}{\tau_{DM}}$: How fast does it decay?
- $\frac{dN_\alpha}{dE}$: How many are produced?
- $P_{\alpha\to\beta}$: Neutrino mixing
- $\frac{\rho(s,l,b)}{m_{DM}}$: How many DM particles?

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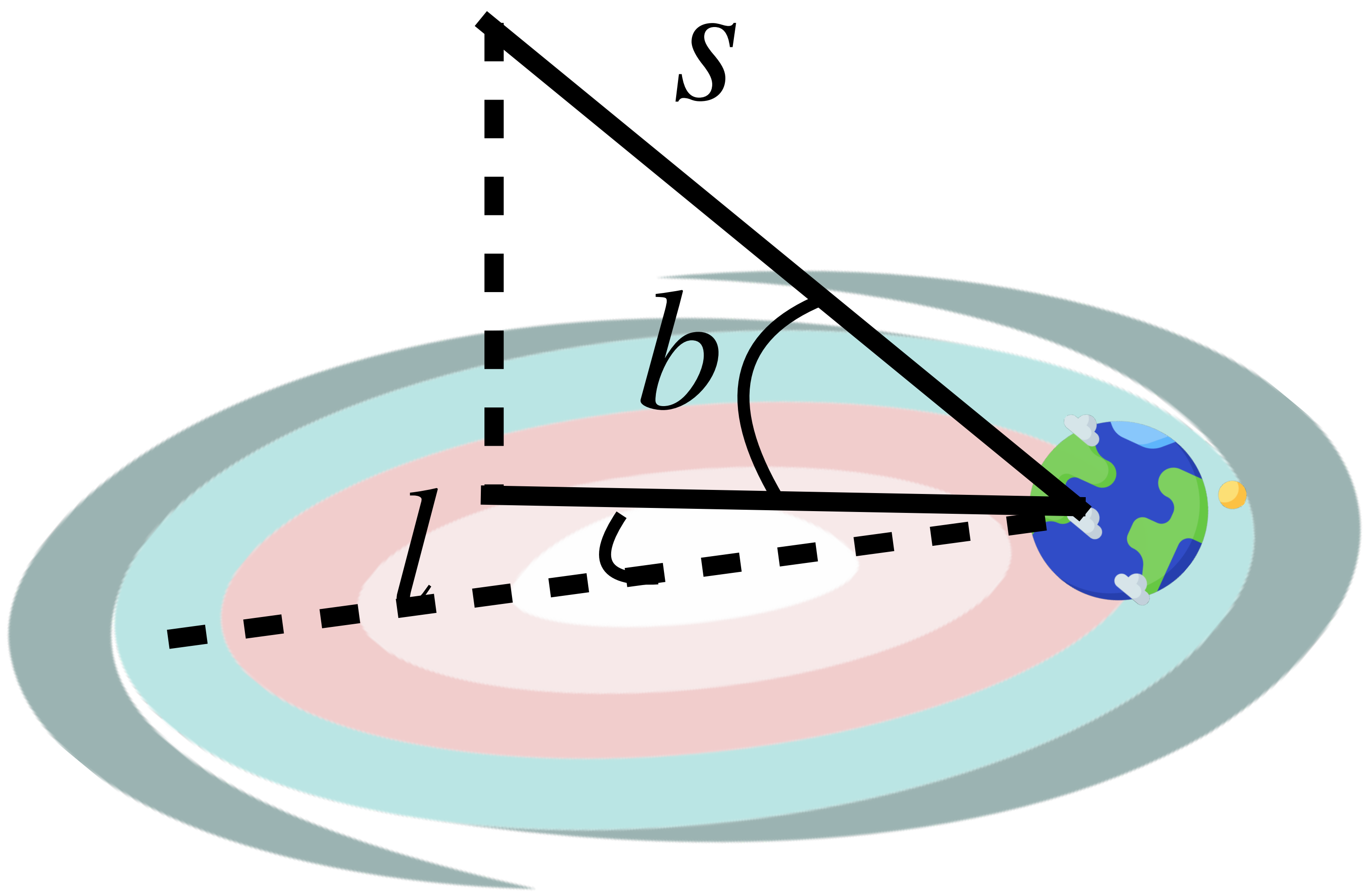

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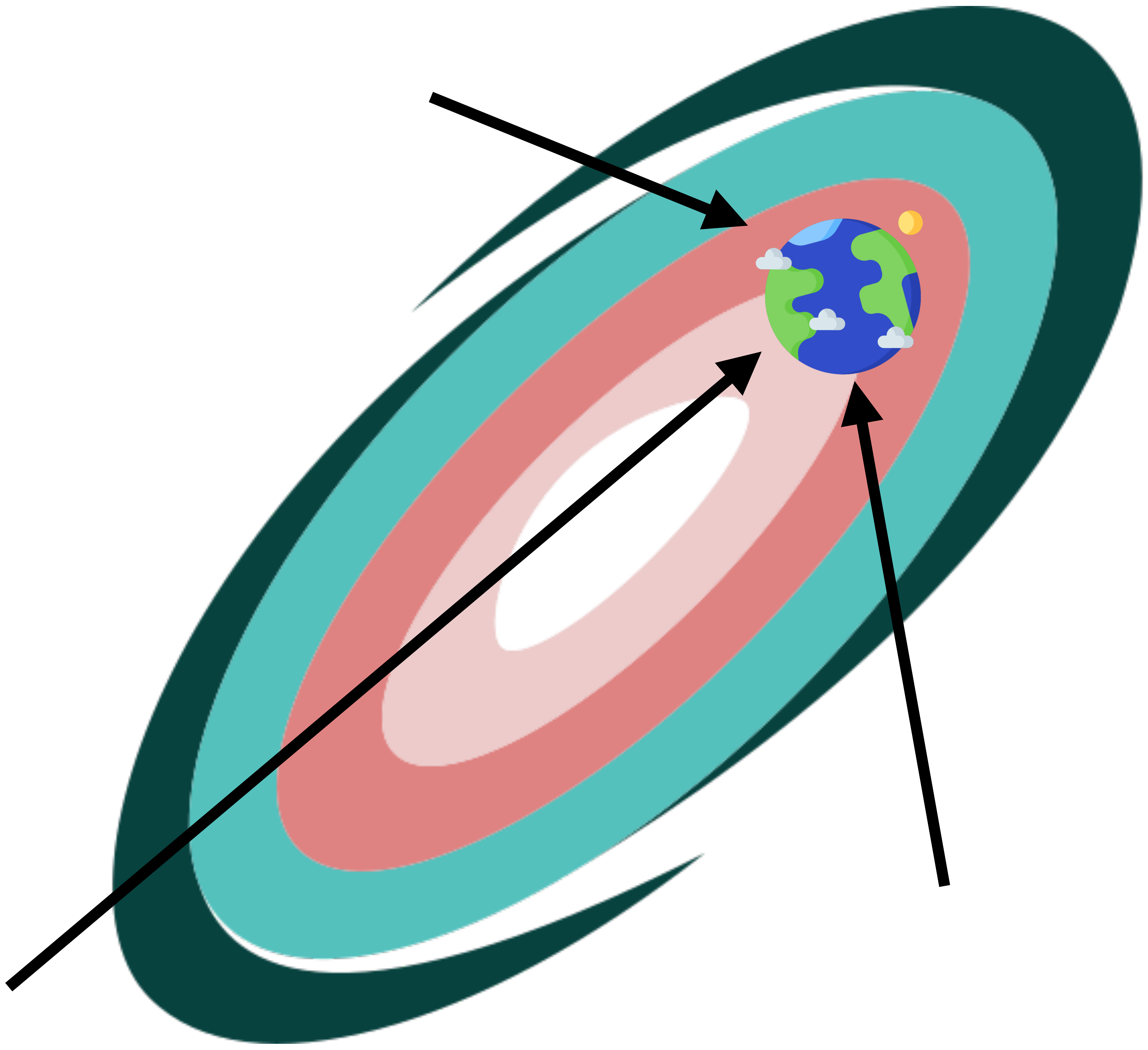

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Extragalactic production

- (Mostly) isotropic
- Redshifted, dominates at low energies

Diffuse DM production

$$\frac{d\phi_{EG,\beta}}{dEd\Omega} = \frac{1}{4\pi}\frac{1}{\tau_{\rm DM}}\sum_\alpha P_{\alpha\to\beta}\int\frac{dz}{H(z)}\frac{dN_\alpha}{dE}[E(1+z)]\frac{\Omega_\chi\rho_c}{m_{\rm DM}}$$

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How fast does it decay?

Neutrino mixing

Redshifted neutrino spectrum

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How fast does it decay?

Neutrino mixing

Redshifted neutrino spectrum

Dark matter density

Galactic production

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Extragalactic production

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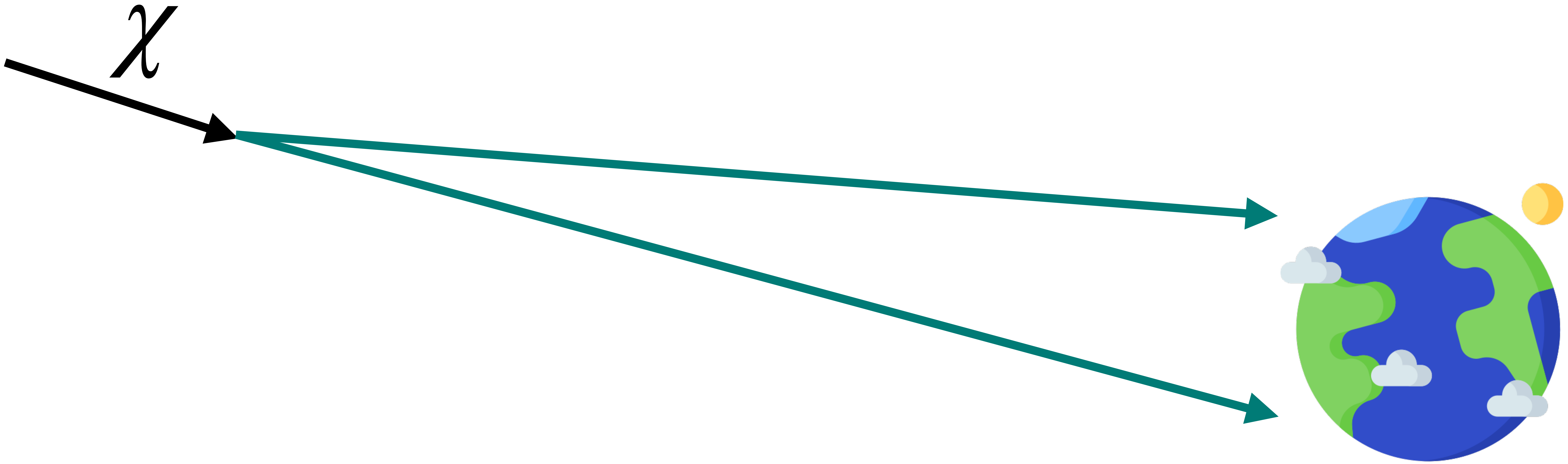
- Redshifted, dominates at low energies

Decaying dark matter



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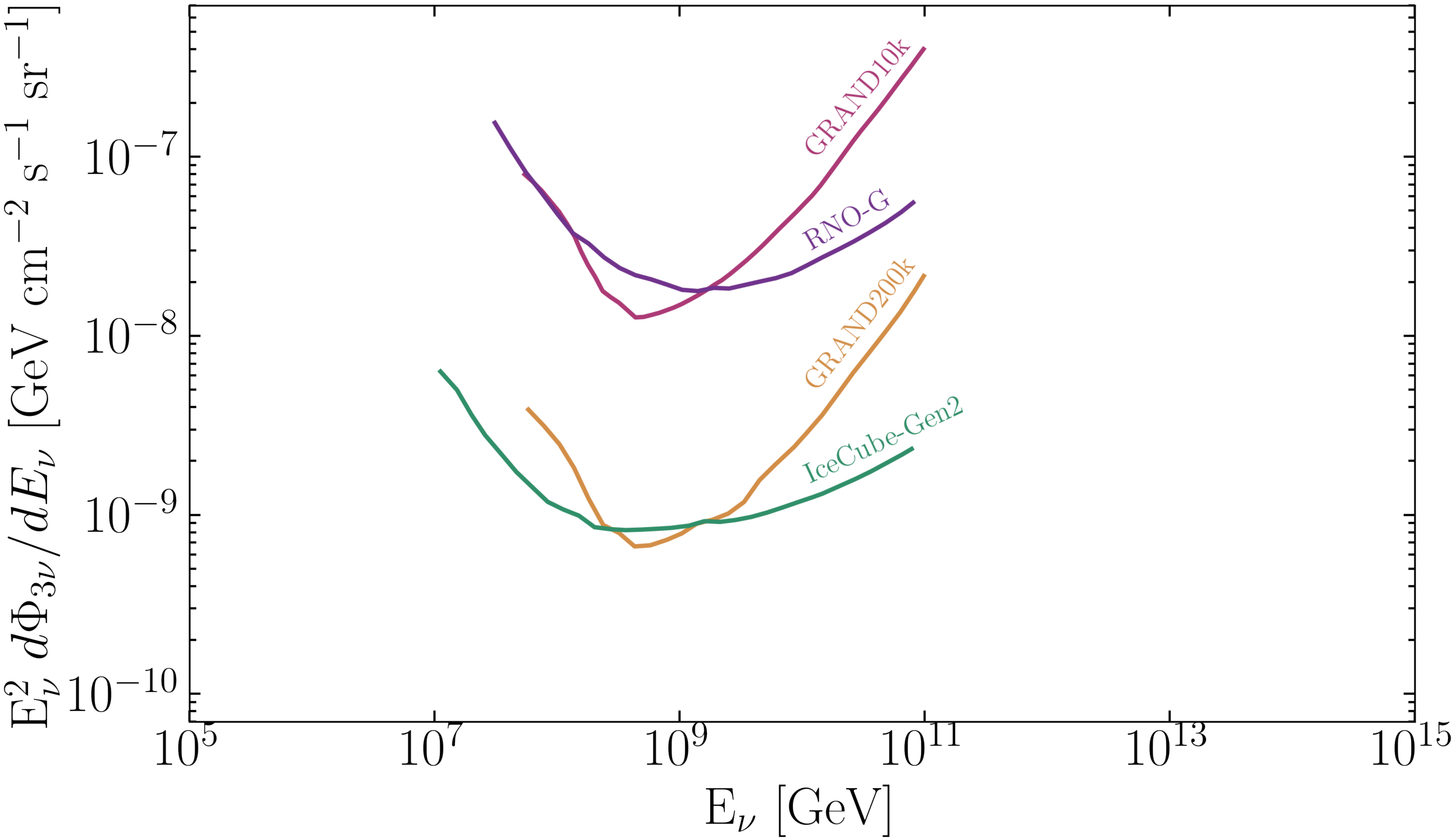
UHE neutrinos



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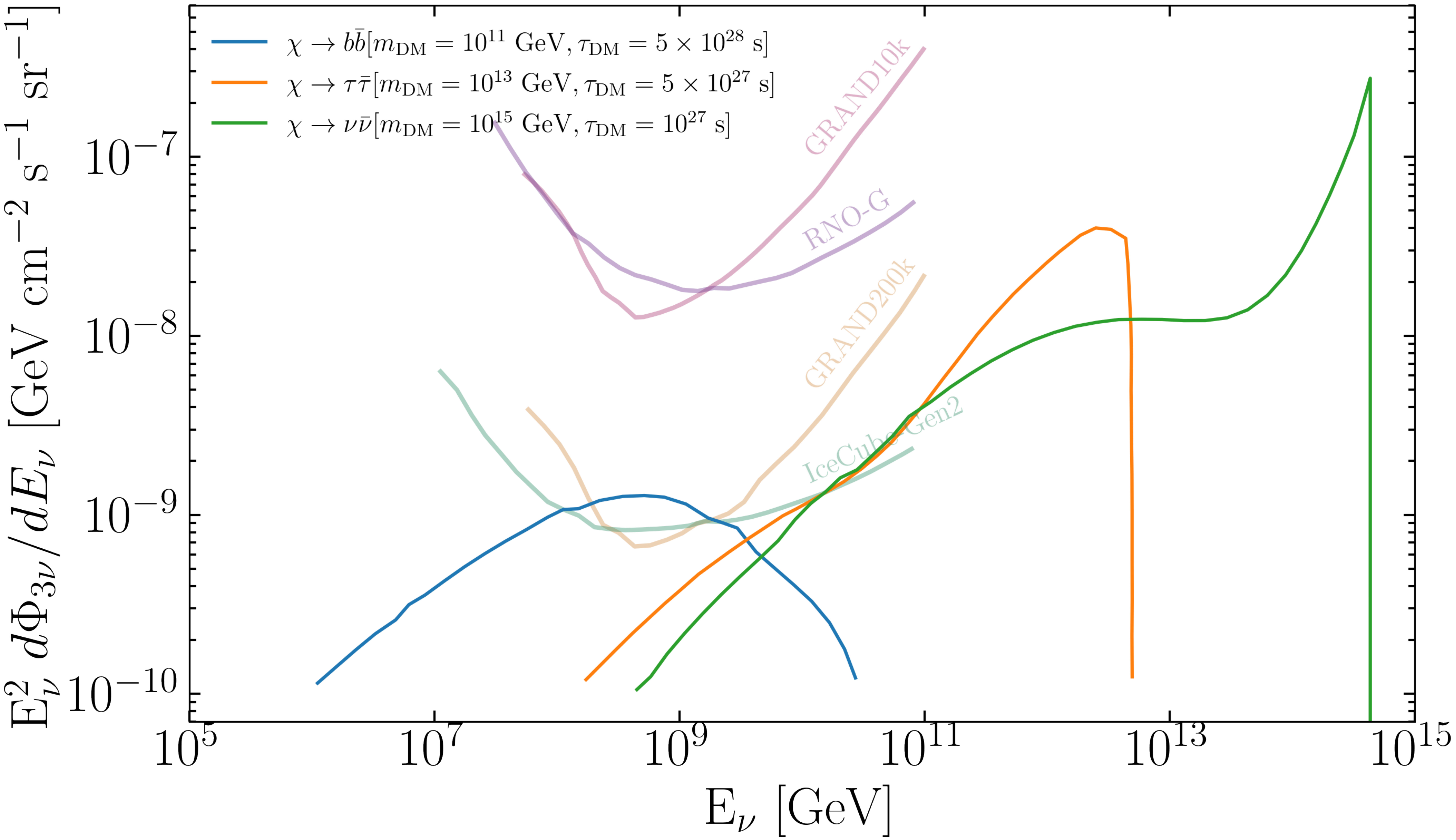

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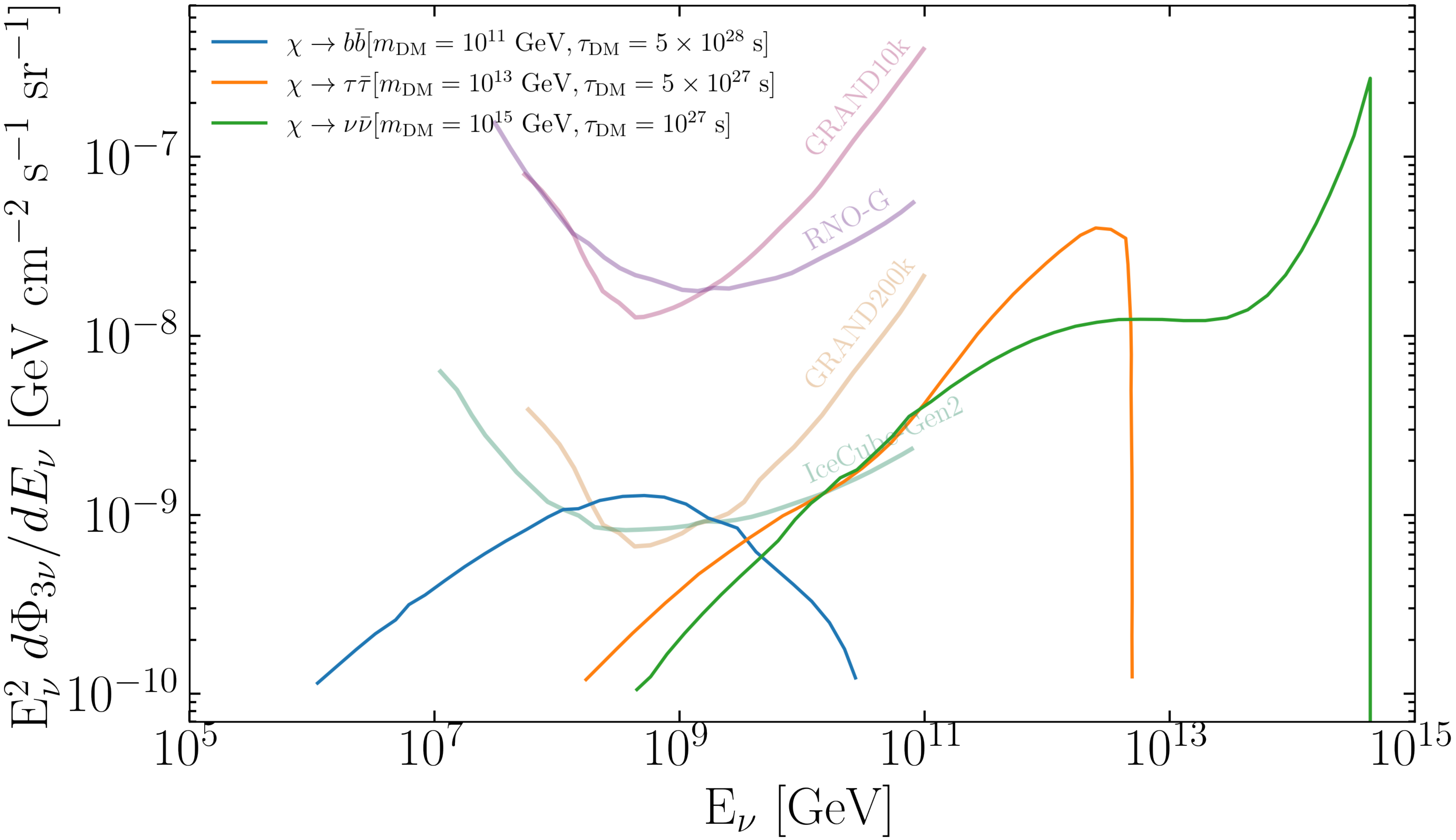
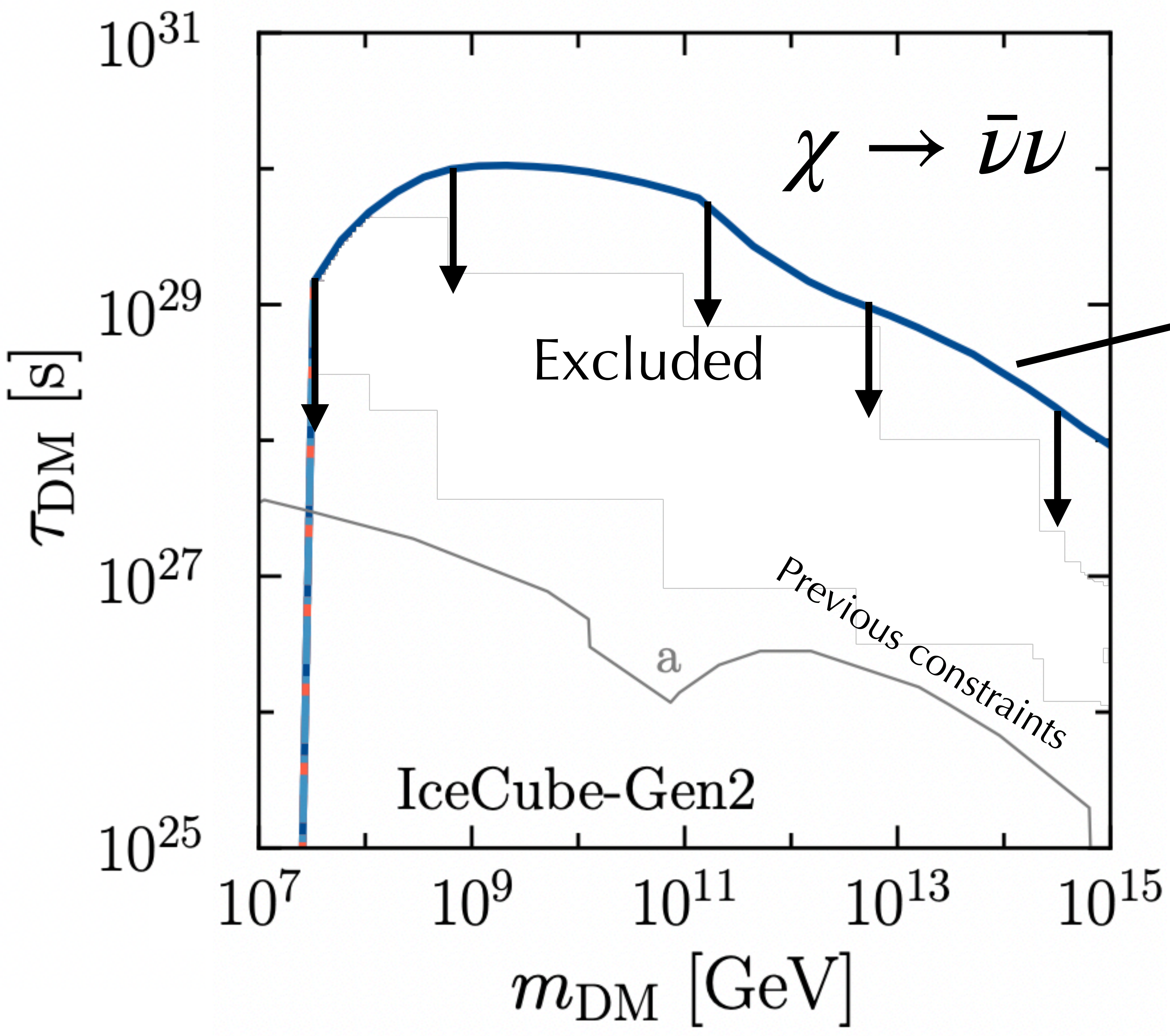


Probability of observing nothing

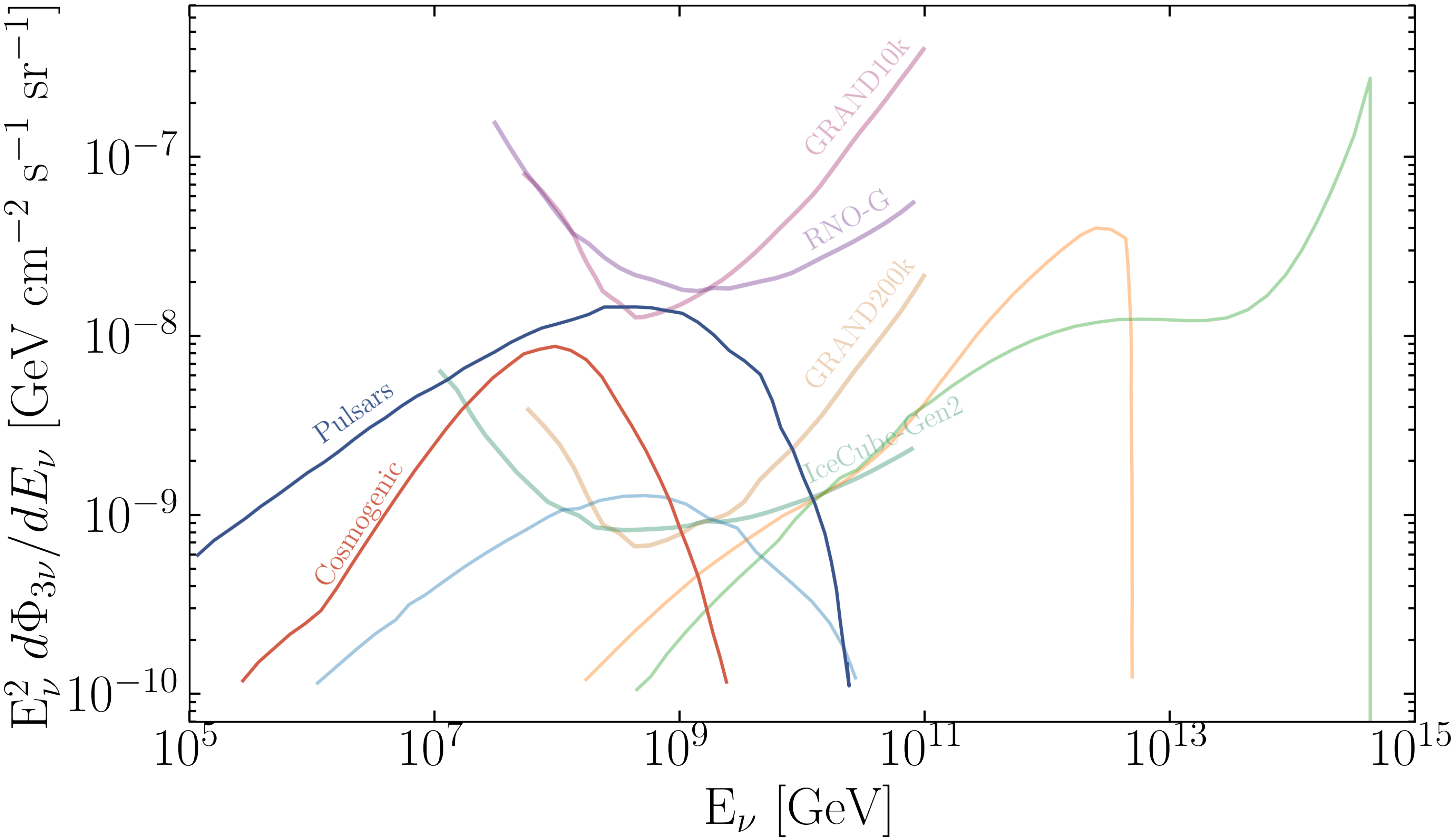
$\exp[-\mu(m_{\rm DM}, \tau_{\rm DM})]$

Constraints from UHE neutrinos



If no event is detected, DM should produce less than 2.71 expected events (95% CL)

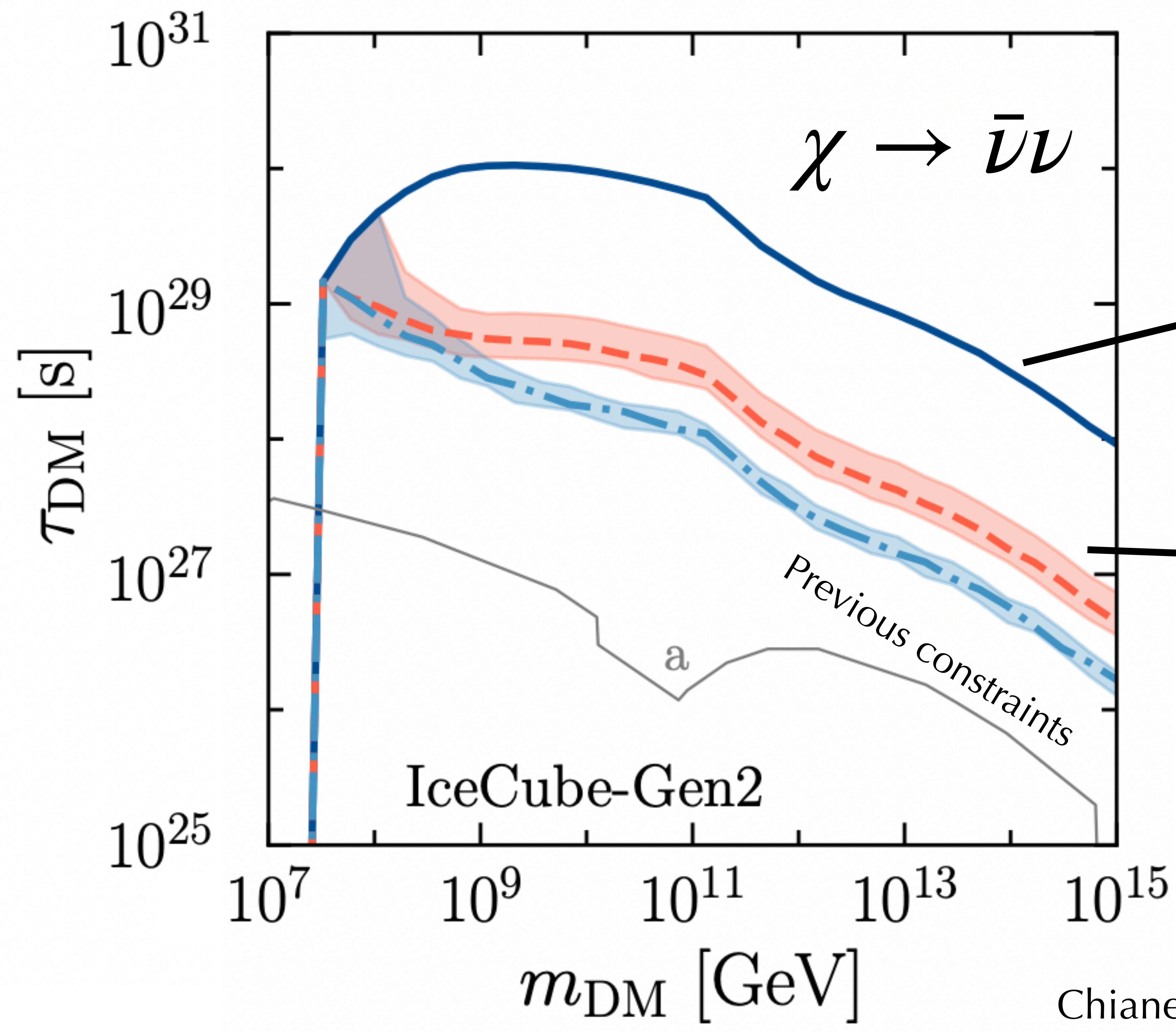
UHE neutrinos



We may observe some events of astrophysical origin

Weaker constraints!

Constraints from UHE neutrinos



If no event is detected, DM should produce less than 2.71 expected events (95% CL)

If astro events are detected, constraints are weaker

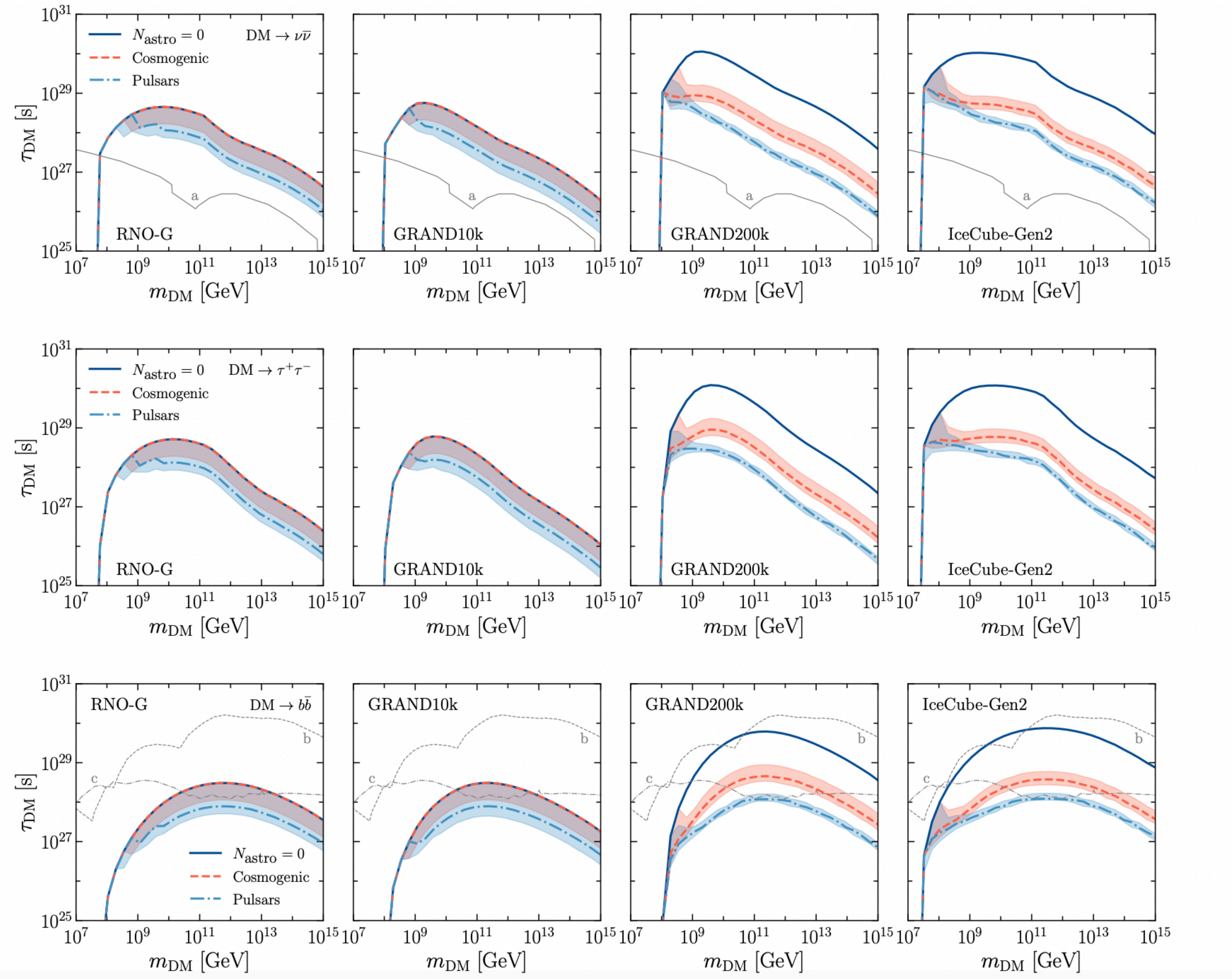
Chianese, **DF**, Hajjar, Miele, Morisi, Saviano 2103.03254

Conclusions

- Astrophysical neutrinos are ideal probe for particle physics
- IceCube is already most competitive probe of neutrinophilic DM ($m_{\rm DM} \sim 100$ TeV – 1 PeV)
- Radio telescopes will probe heavier DM ($m_{\rm DM} \sim 1$ EeV – 100 ZeV)
- Neutrinos are just one side, multimessenger approach coming to the front for strong constraints

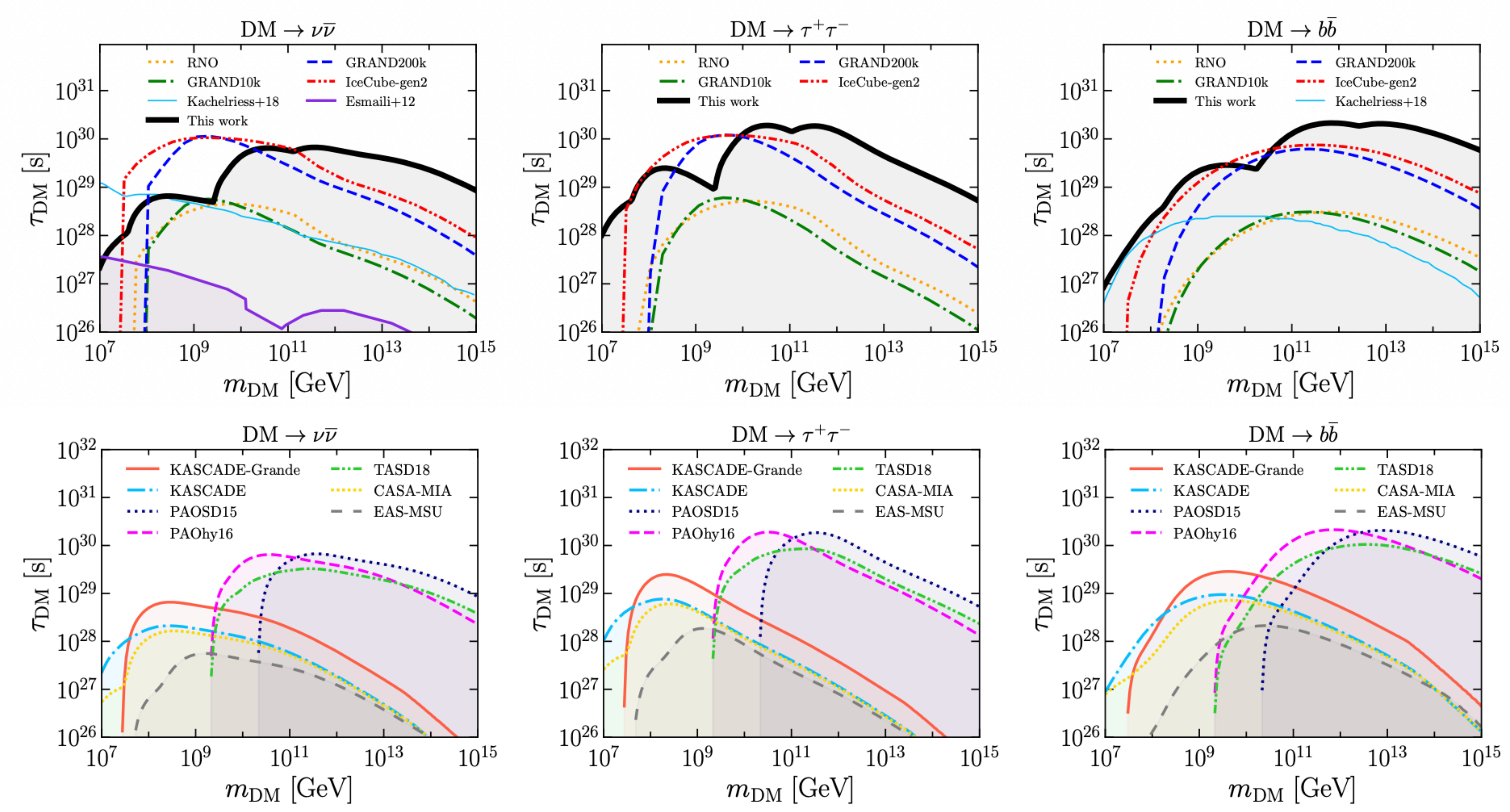
Backup slides

UHE neutrinos: constraints



Damiano Fiorillo

UHE neutrinos: constraints



Electroweak corrections

For $m_{\rm DM} \lesssim 100$ TeV perturbative approach

PPPC 4 DM ID (arXiv:1012.4515)

MonteCarlo simulating shower (with some limitations)

Pythia (arXiv:1401.5238)

Full solution of DGLAP equations

HDMSpectra (arXiv:2007.15001)

High-energy range: IceCube

DM flux

Astro flux

$$\Phi_{\text{astro}} = \Phi_0 E^{-\gamma}$$

Atmospheric flux

Schneider, 1907.11266

High-energy range: IceCube

DM flux → Event rates

Astro flux → Event rates

$$\Phi_{\rm astro} = \Phi_0 E^{-\gamma}$$

Atmospheric flux → Event rates

Schneider, 1907.11266

- Energy binned above 60 TeV
- Effective areas from IceCube Collaboration

High-energy range: IceCube

DM flux → Event rates → Likelihood

Astro flux → Event rates

$$\Phi_{\rm astro} = \Phi_0 E^{-\gamma}$$

Atmospheric flux → Event rates

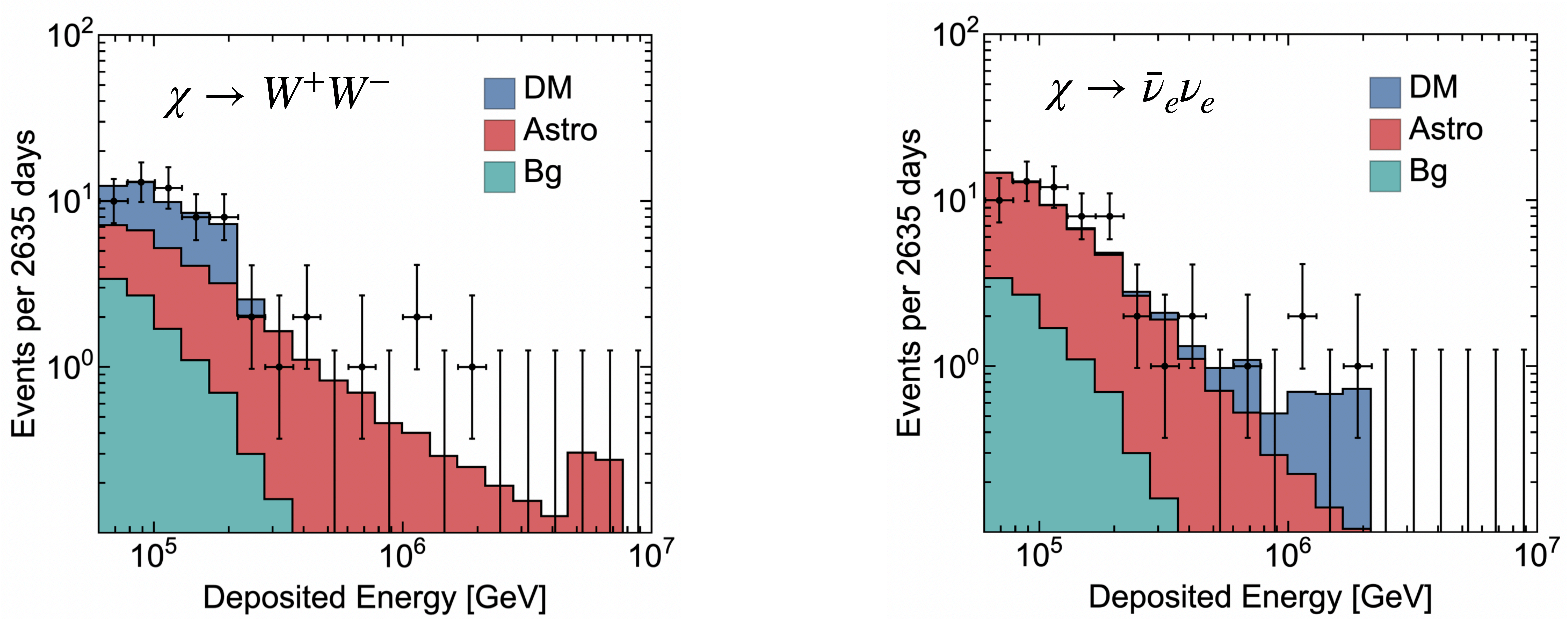
Schneider, 1907.11266

- Energy binned above 60 TeV
- Effective areas from IceCube Collaboration

- Poisson likelihood
- Free parameters: $\Phi_0, \gamma, m_{\rm DM}, \tau_{\rm DM}$

High-energy range: IceCube

DM can improve fit to data in two ways



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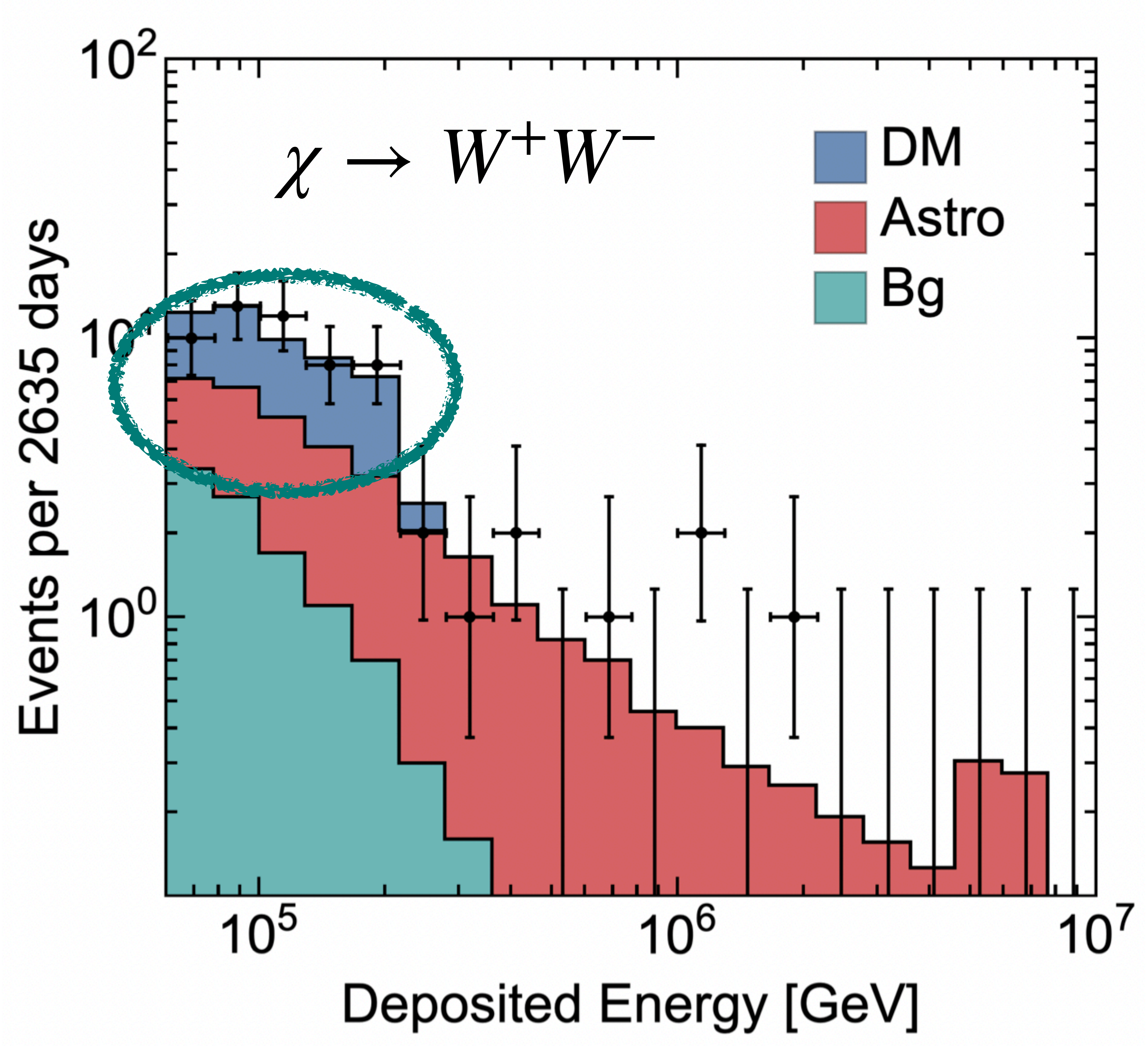
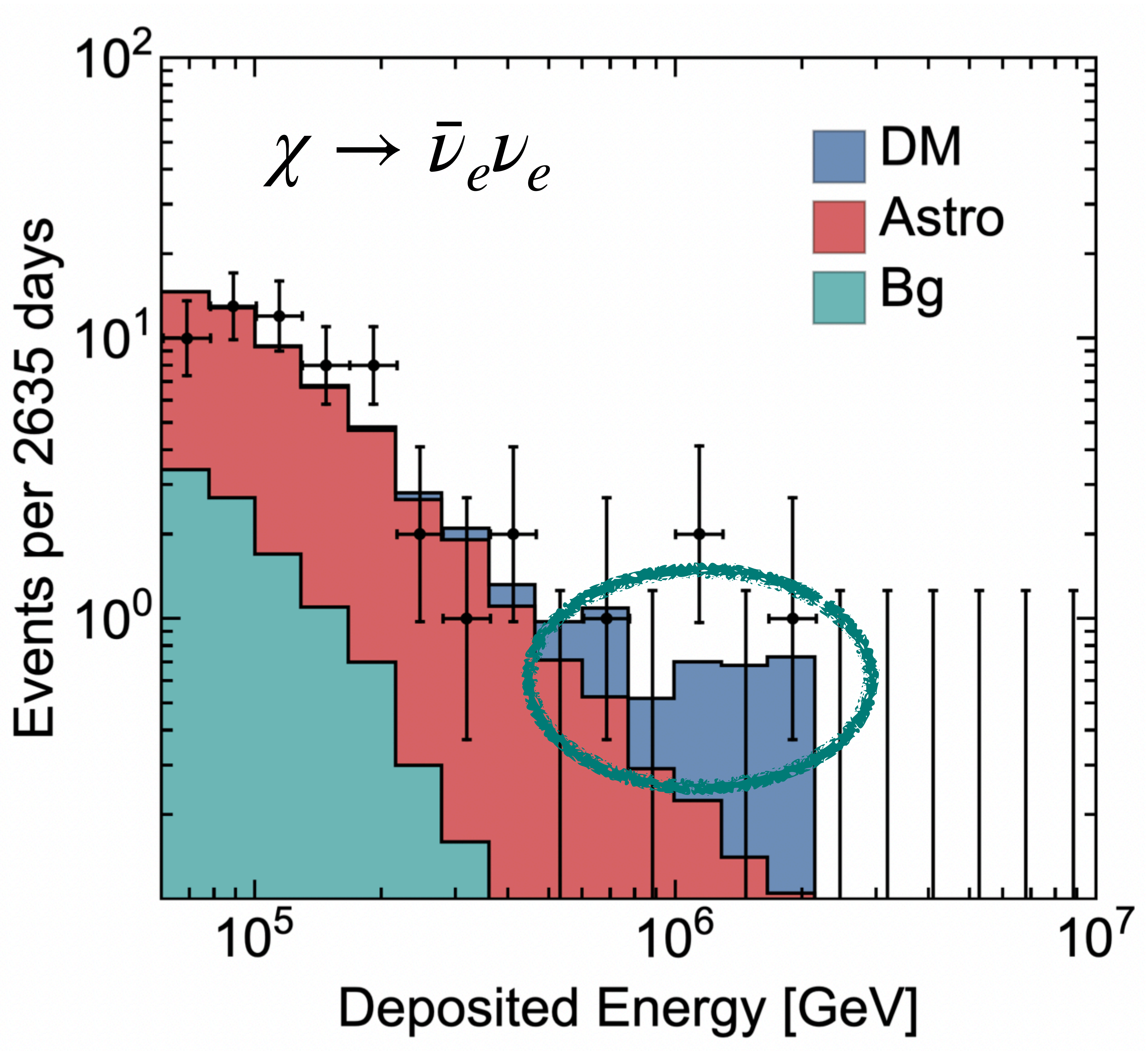
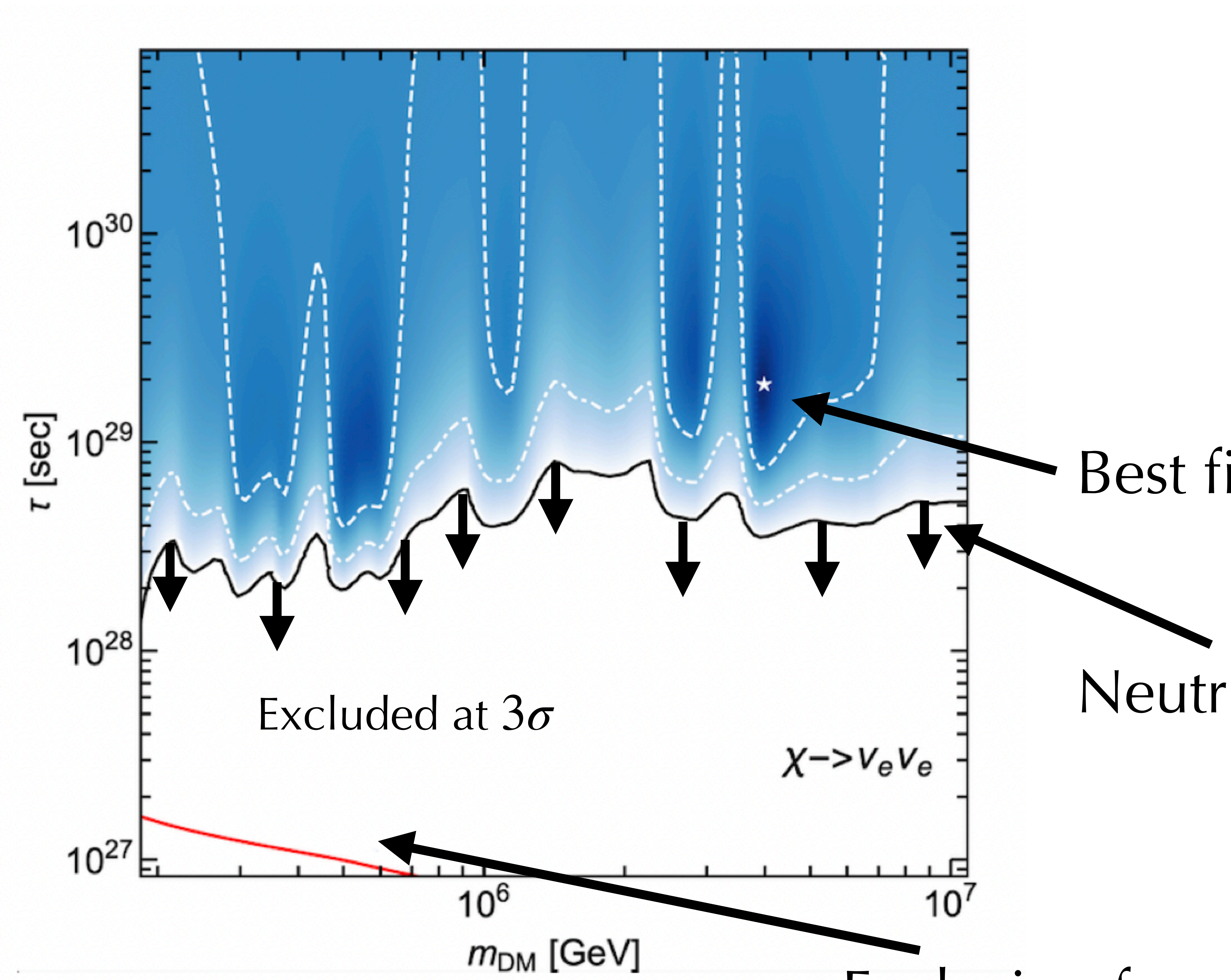




High-energy range: IceCube



(Cohen et al., arXiv:1612.05638)

High-energy range: IceCube