Ultra-high-energy neutrinos as a probe of dark matter

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based on arXiv:2307.02538,
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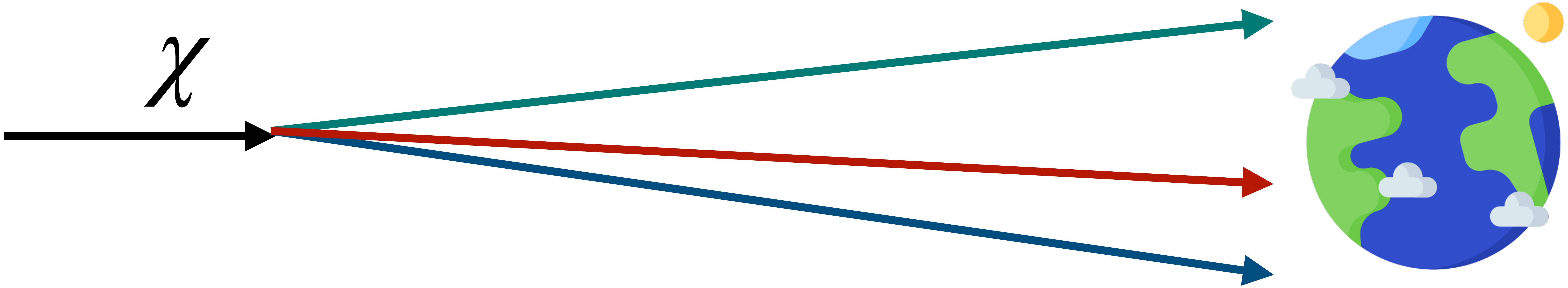
TeVPA 2023

VILLUM FONDEN

Decaying dark matter



- **Gamma-rays**
  - **TeV-PeV range:** e.g. LHAASO (Ando et al., arXiv:2210.15989)
  - **PeV-EeV range:** upper limits from PAO, CASA-MIA, KASCADE-Grande, … (Chianese et al., arXiv:2108.01678; Das et al., 2302.02993, …)

- **Neutrinos**
  - **TeV-PeV range:** IceCube (Abbasi et al., arXiv:2205.12950, …)
  - **PeV-EeV range:** future radio telescopes? (RNO-G, IceCube-Gen2, GRAND, …) (Chianese et al., arXiv:2103.03254; Guèpin et al., arXiv:2106.04446, **DF** et al., arXiv:2307.02538)

Decaying dark matter

How to distinguish dark matter from astrophysical signal?

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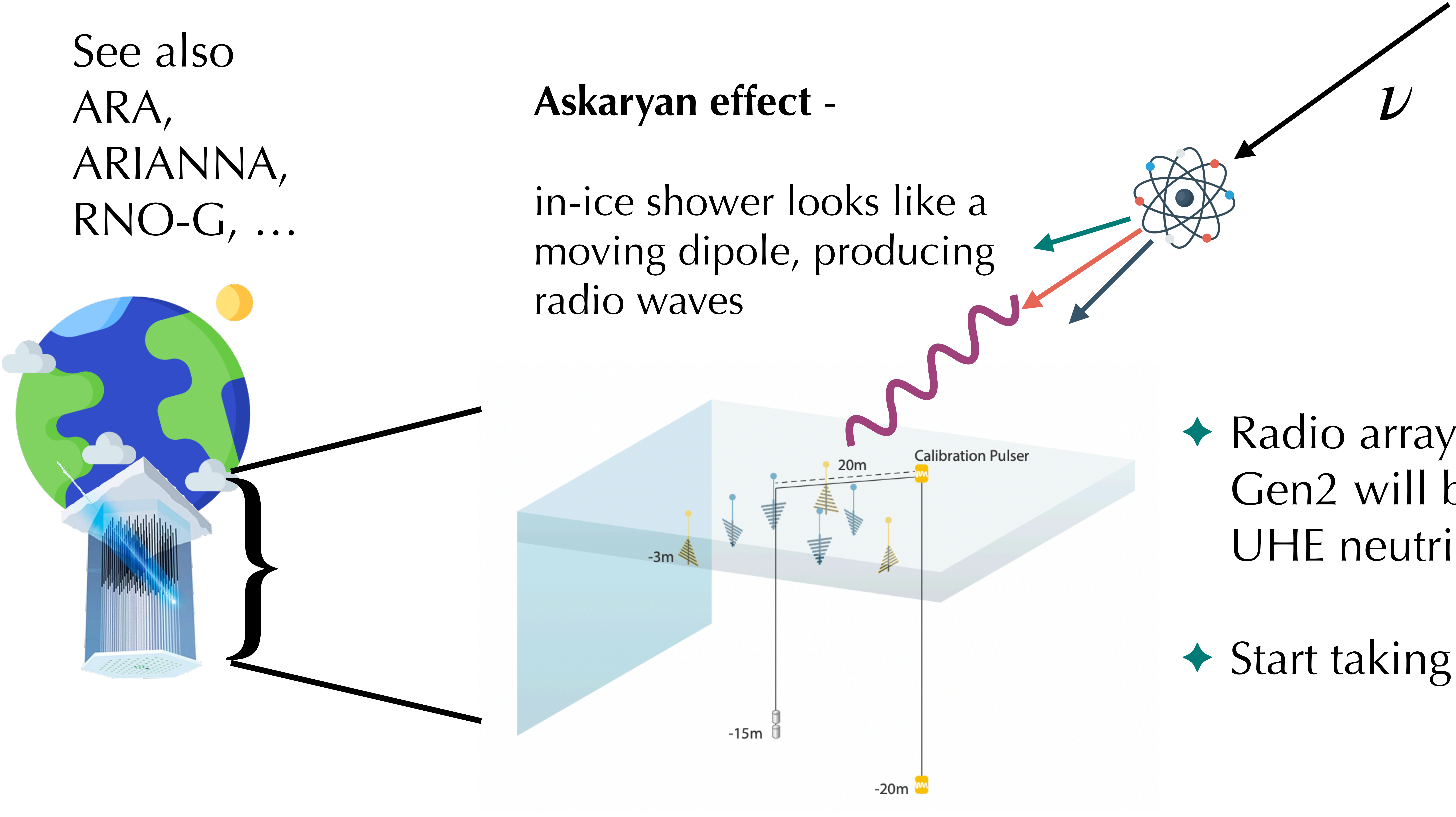
IceCube Gen2 (radio)

See also
ARA,
ARIANNA,
RNO-G, …

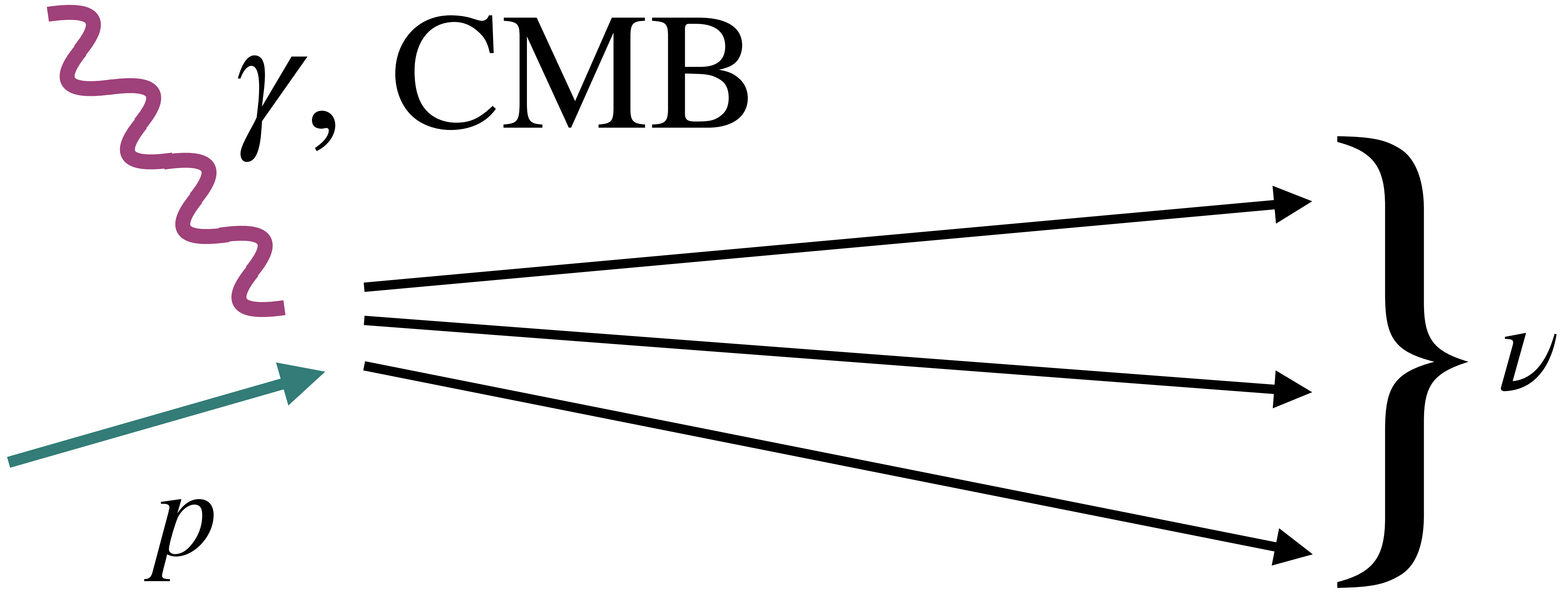


Askaryan effect -

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

- Radio array in IceCube-Gen2 will be sensitive to UHE neutrinos
- Start taking data in 2030

Cosmogenic neutrinos



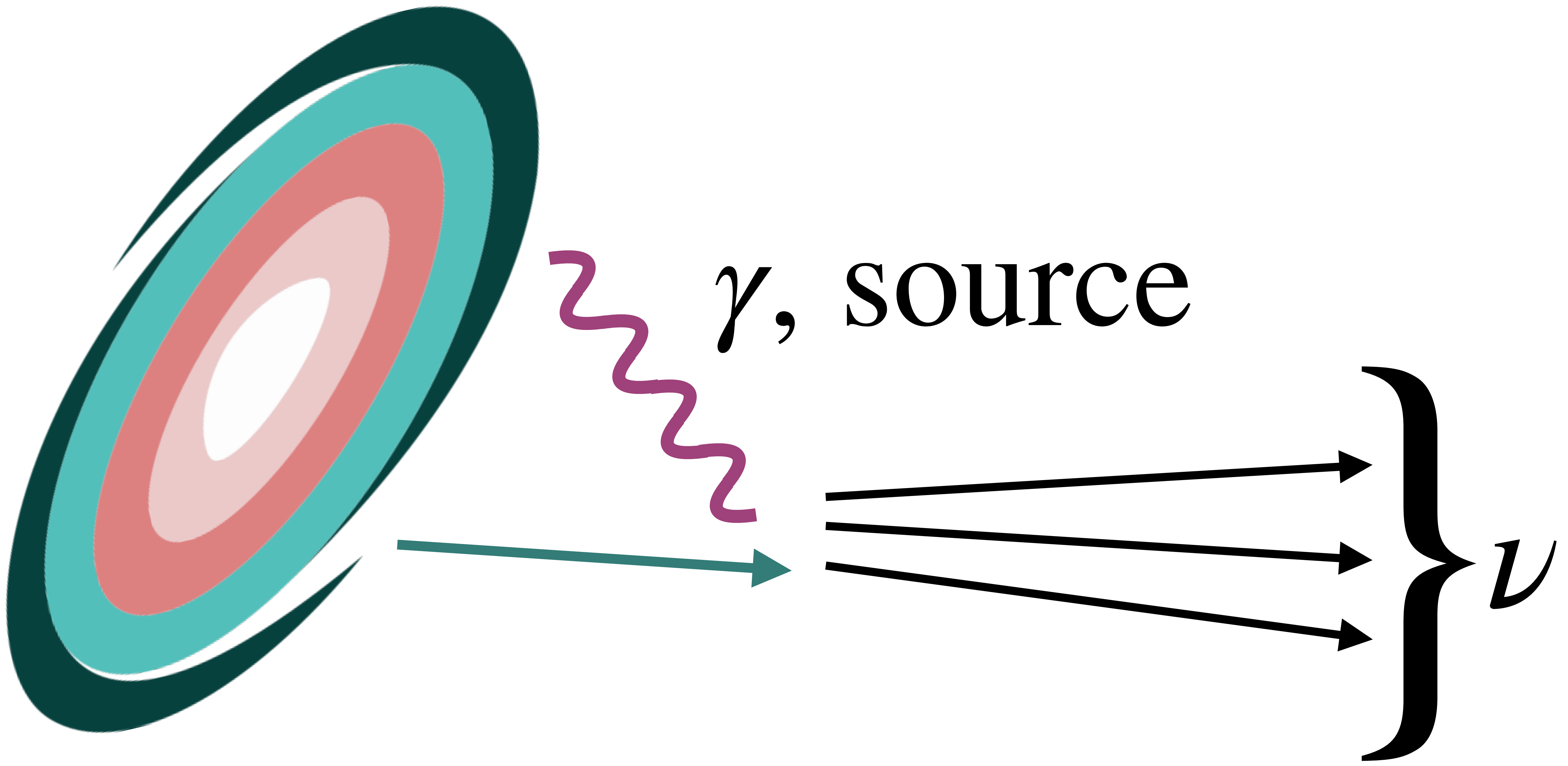
$$p\gamma \to \Delta^+ \to \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

Greisen-Zatsepin-Kuzmin limit at 50 EeV

$$E_p \epsilon_\gamma \simeq m_p m_\pi$$

- Chemical composition
- High redshift

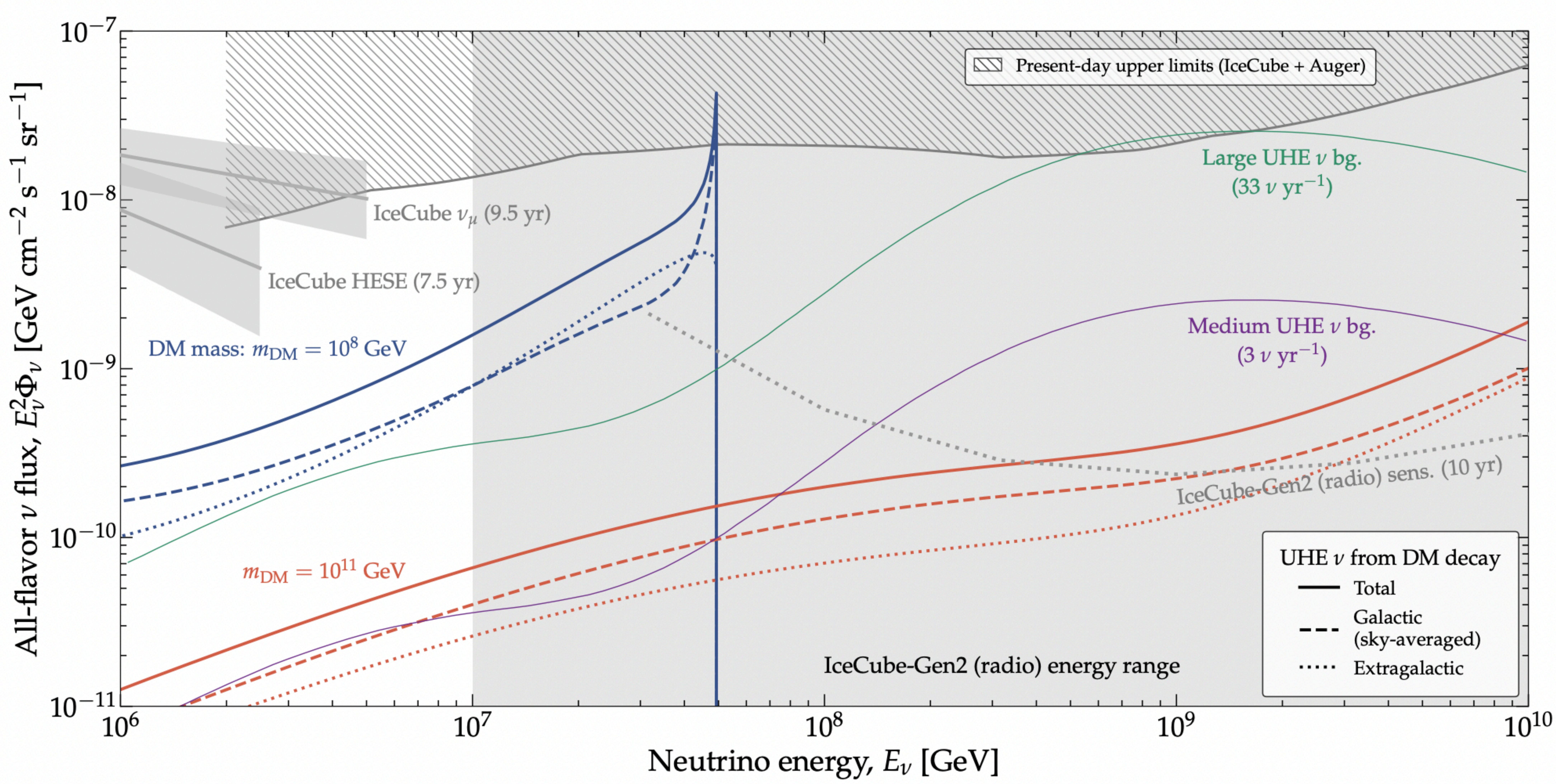
Astrophysical UHE neutrinos



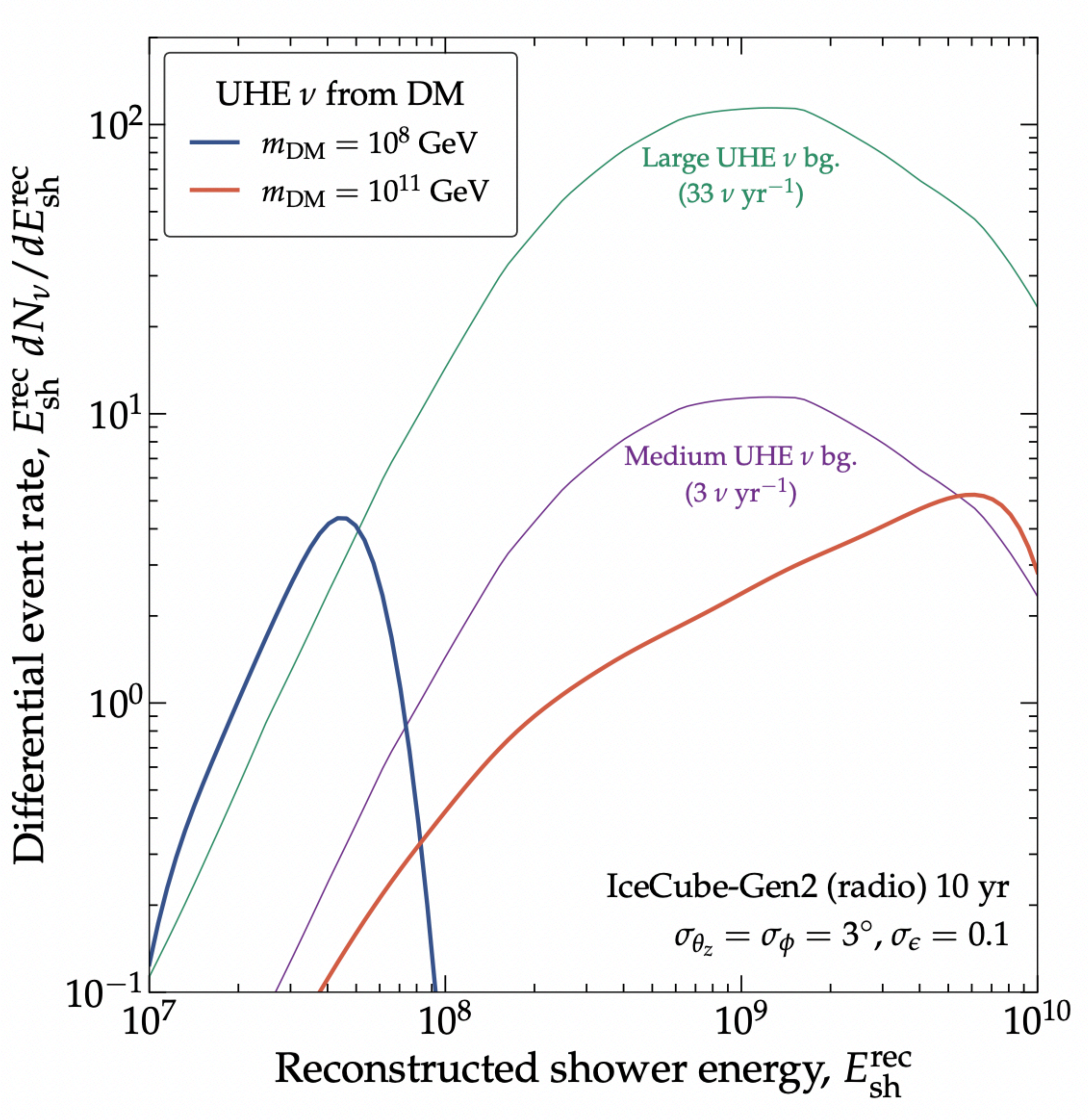
$$E_p \epsilon_\gamma \simeq m_p m_\pi$$

- ✦Requires dense target in source (model dependent)
- ✦UHE neutrino sources need not be sources of observable UHECRs

Energy spectrum



Energy spectrum



- ✦ 10% energy resolution is realistic achievement
- ✦ Lifetimes 10^{29} s lead to order 10 events

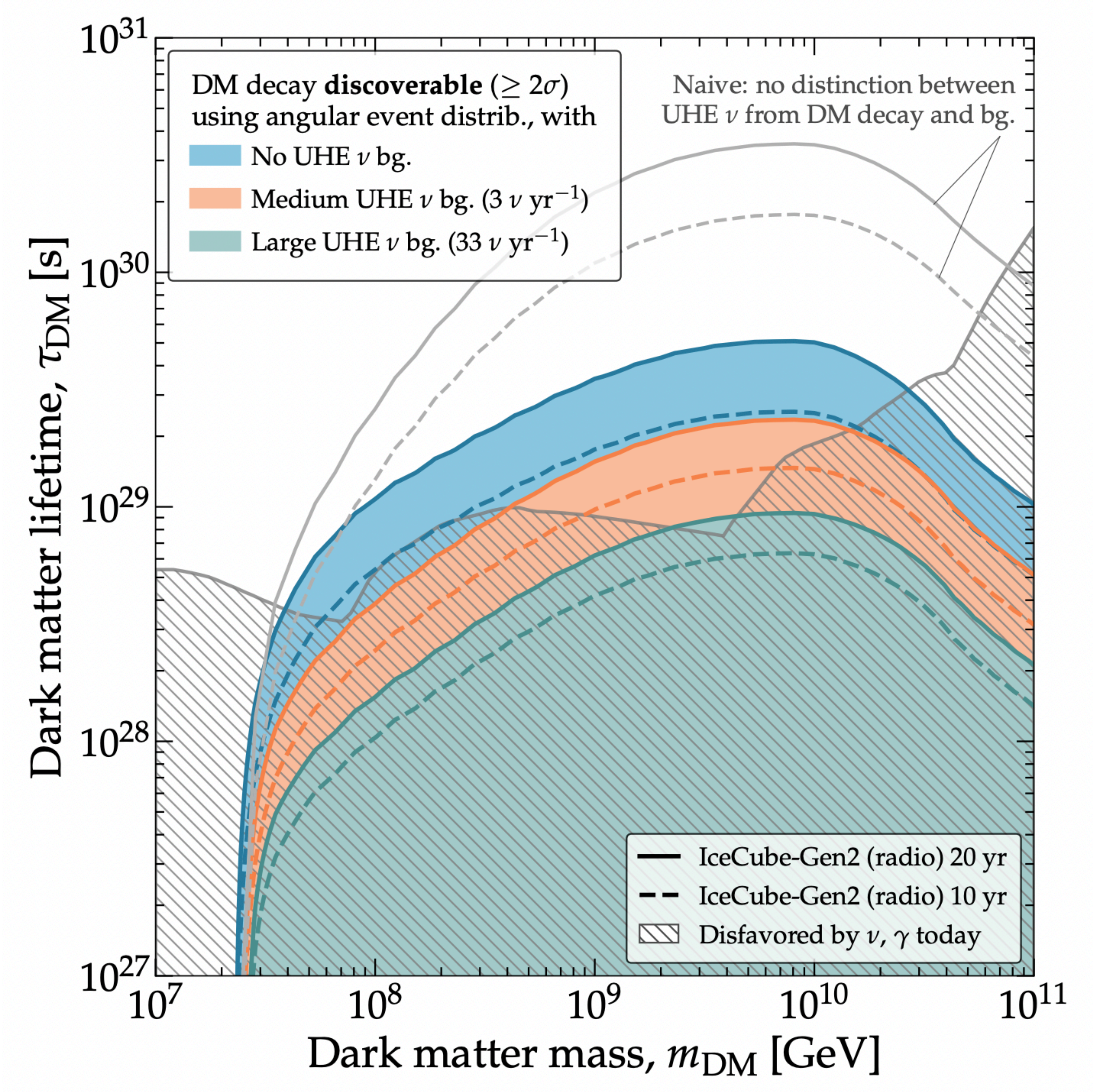
Angular distribution

Angular distribution is a robust probe (all astro sources are extragalactic)

Angular distribution

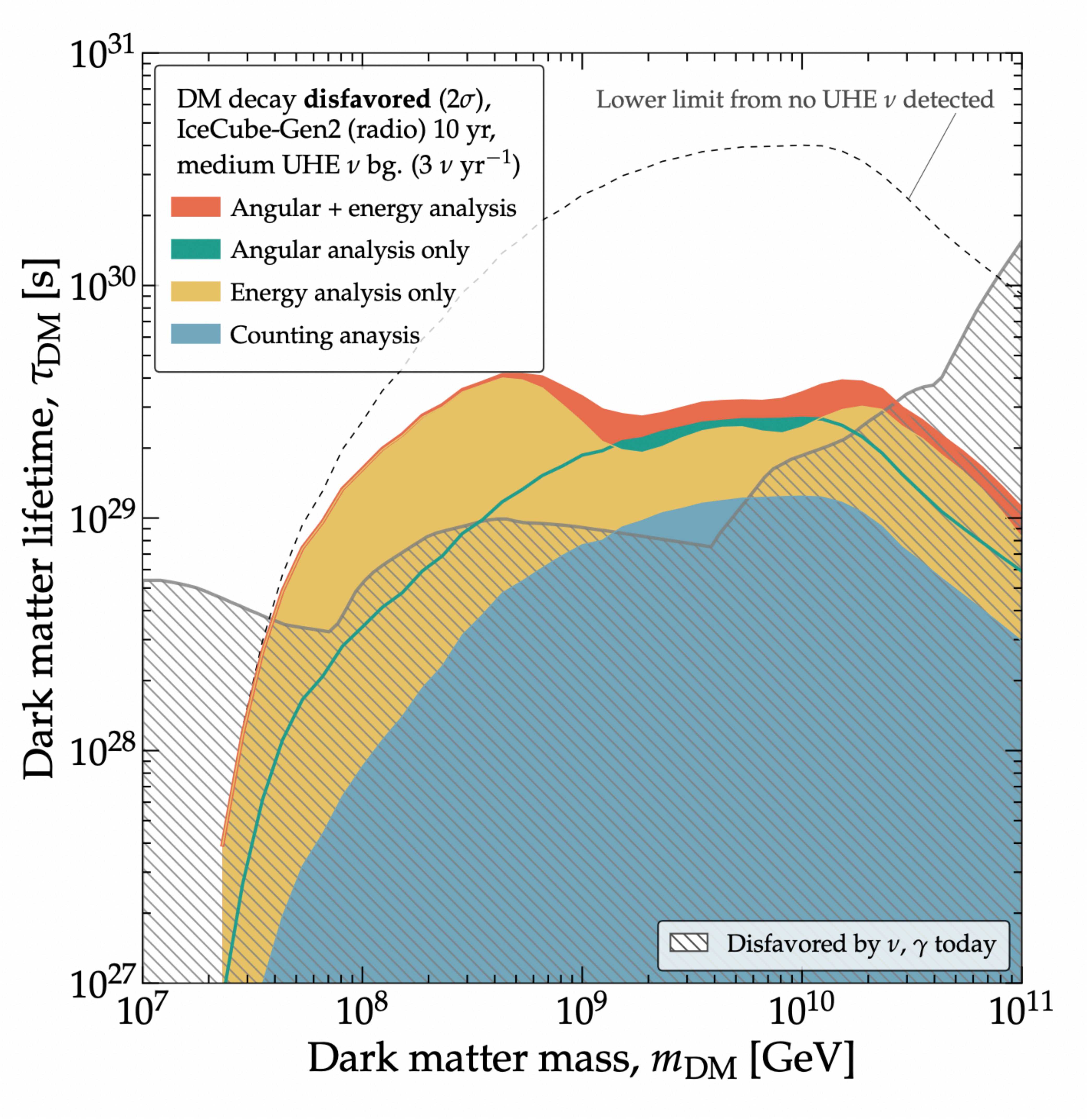
Event rate must account for angular resolution (3°)

Discovering dark matter



- Energy is not an unambiguous signature
- Angle is unambiguous (no galactic UHE sources)
- Large statistics (10-100 events) needed to claim DM origin
- Unbinned all-sky analysis forecast

Constraining dark matter



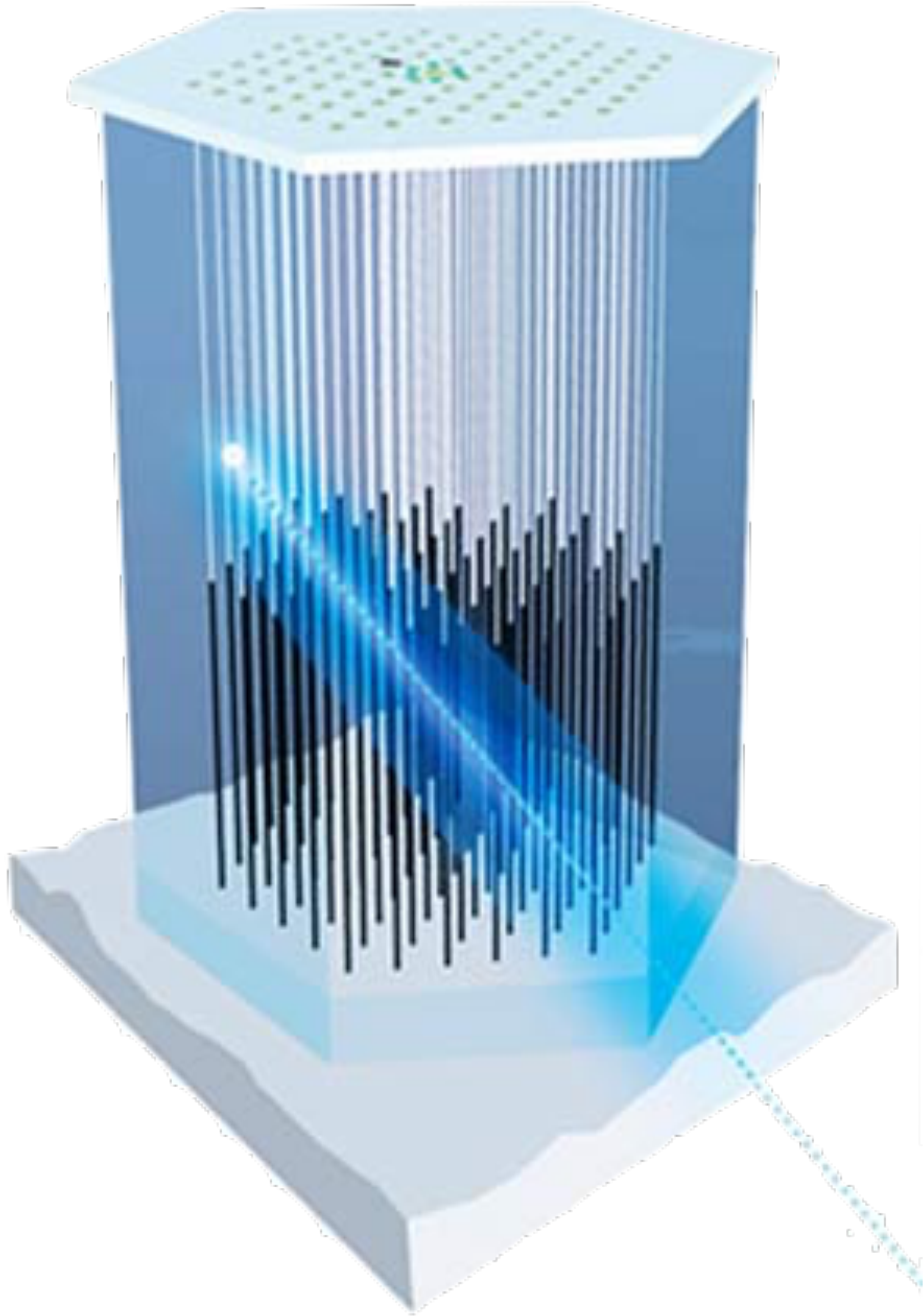
- ✦ Event-counting may provide overly weak limits if diffuse flux is detected
- ✦ Energy and angular information can improve bounds by even one order of magnitude

Conclusions

- Disentangling DM from astro origin in UHE neutrinos leads to:
    - **Discovery power:** angular signature is only unambiguous signal of discovery
    - **Constraint power:** energy and angle can improve constraints by factor 30

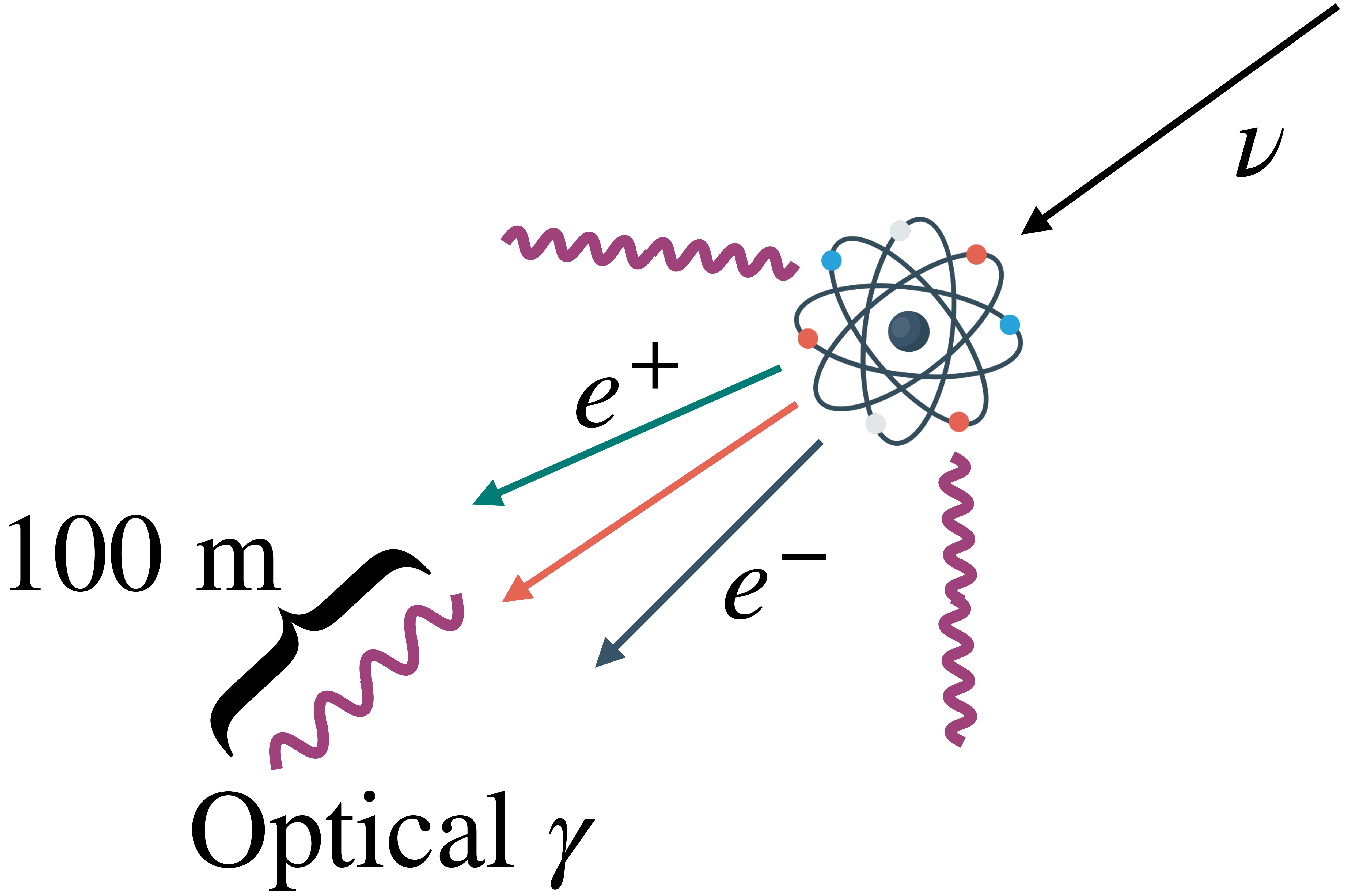
Backup slides

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

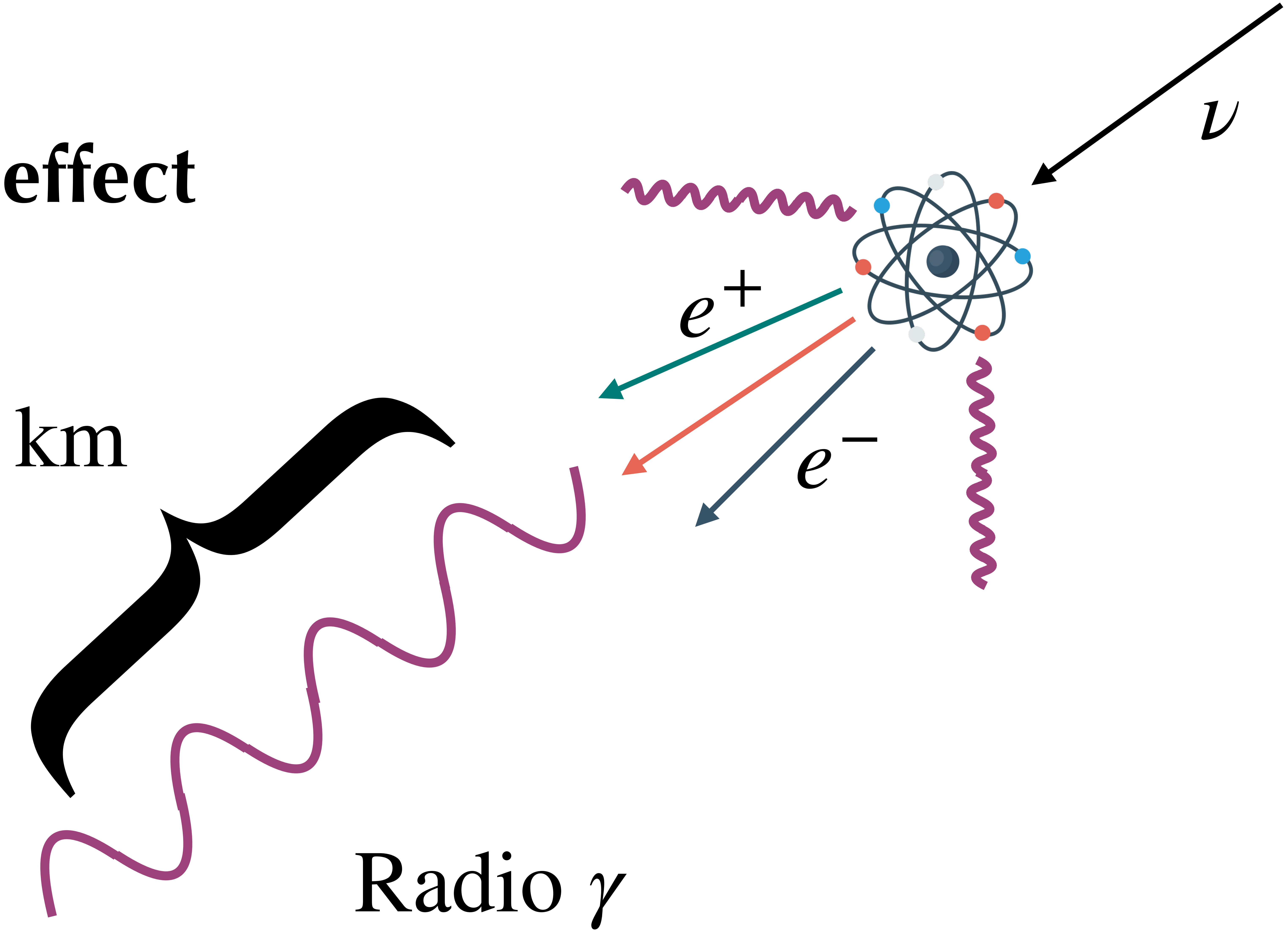
In-ice radio detection



Requires densely instrumented, huge detectors

In-ice radio detection

Askaryan effect



Angular distribution

Uncertainty is dominated by DM density profile

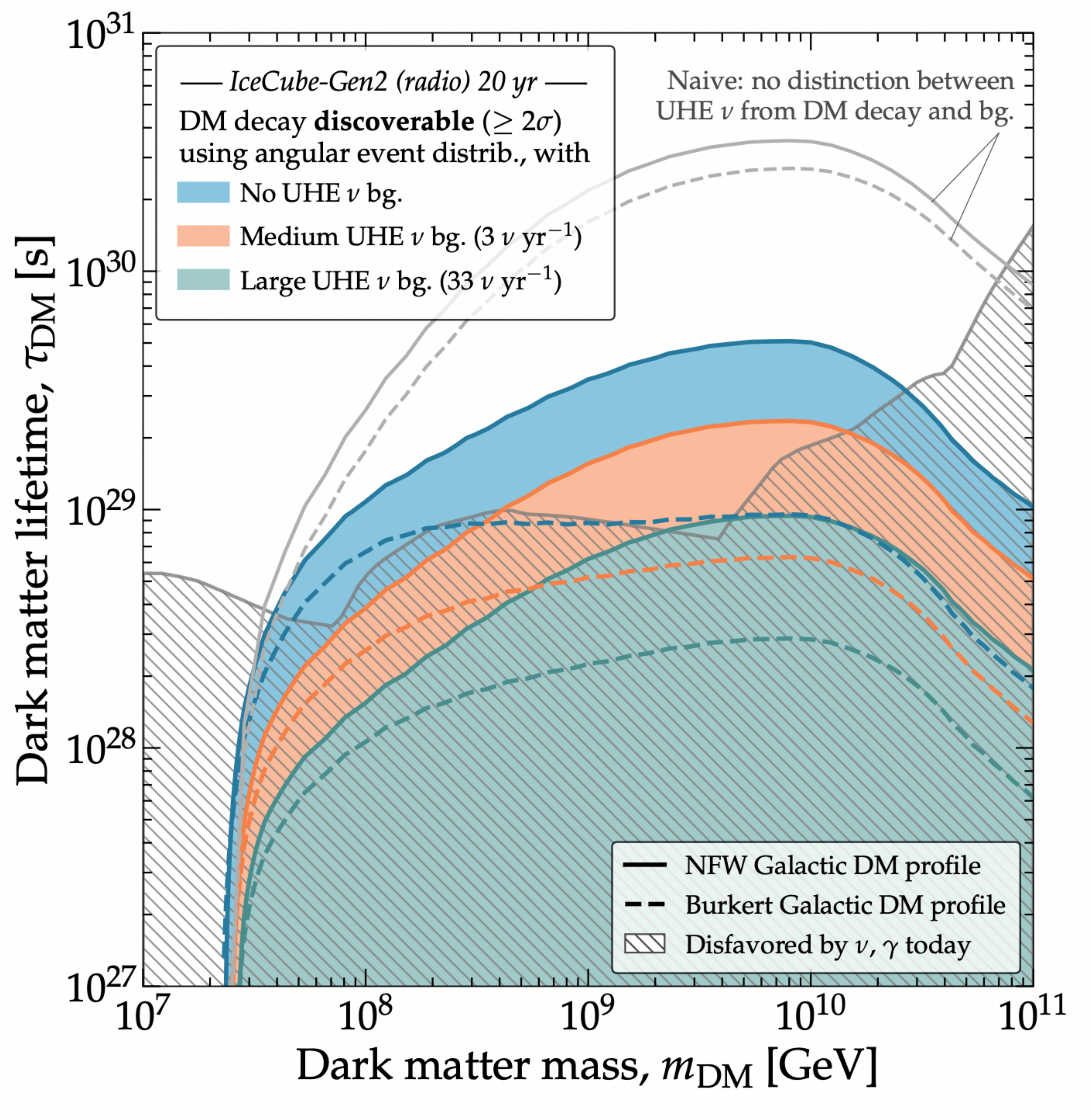
Angular distribution

UHE ν from DM decay
Galactic+extragalactic
Burkert

Non-DM UHE ν:
Large UHE ν bg.
(33 ν yr^{-1})

Event rate must account for angular resolution (3°)

Discovering dark matter



- ✦ Energy is not an unambiguous signature
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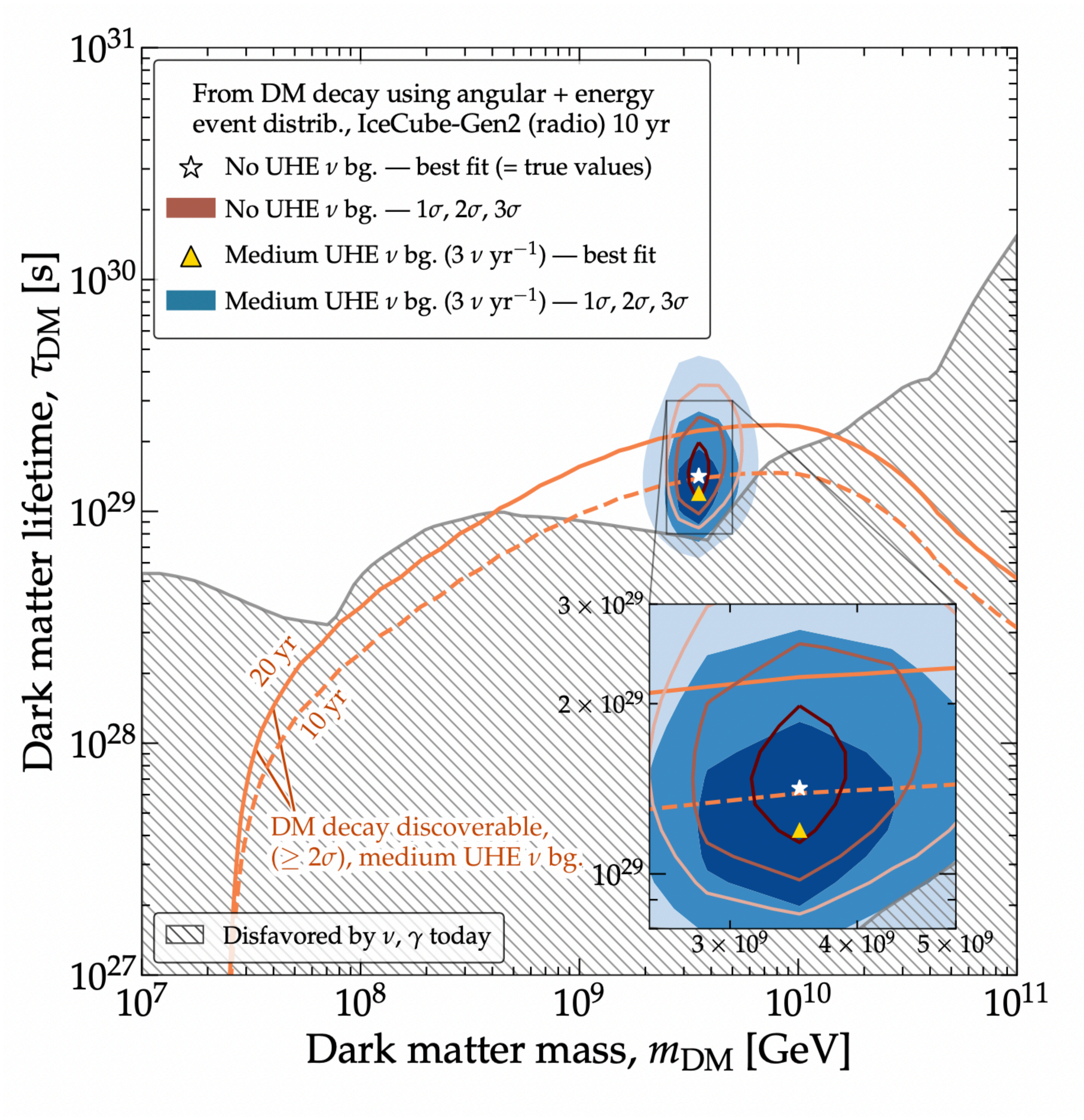
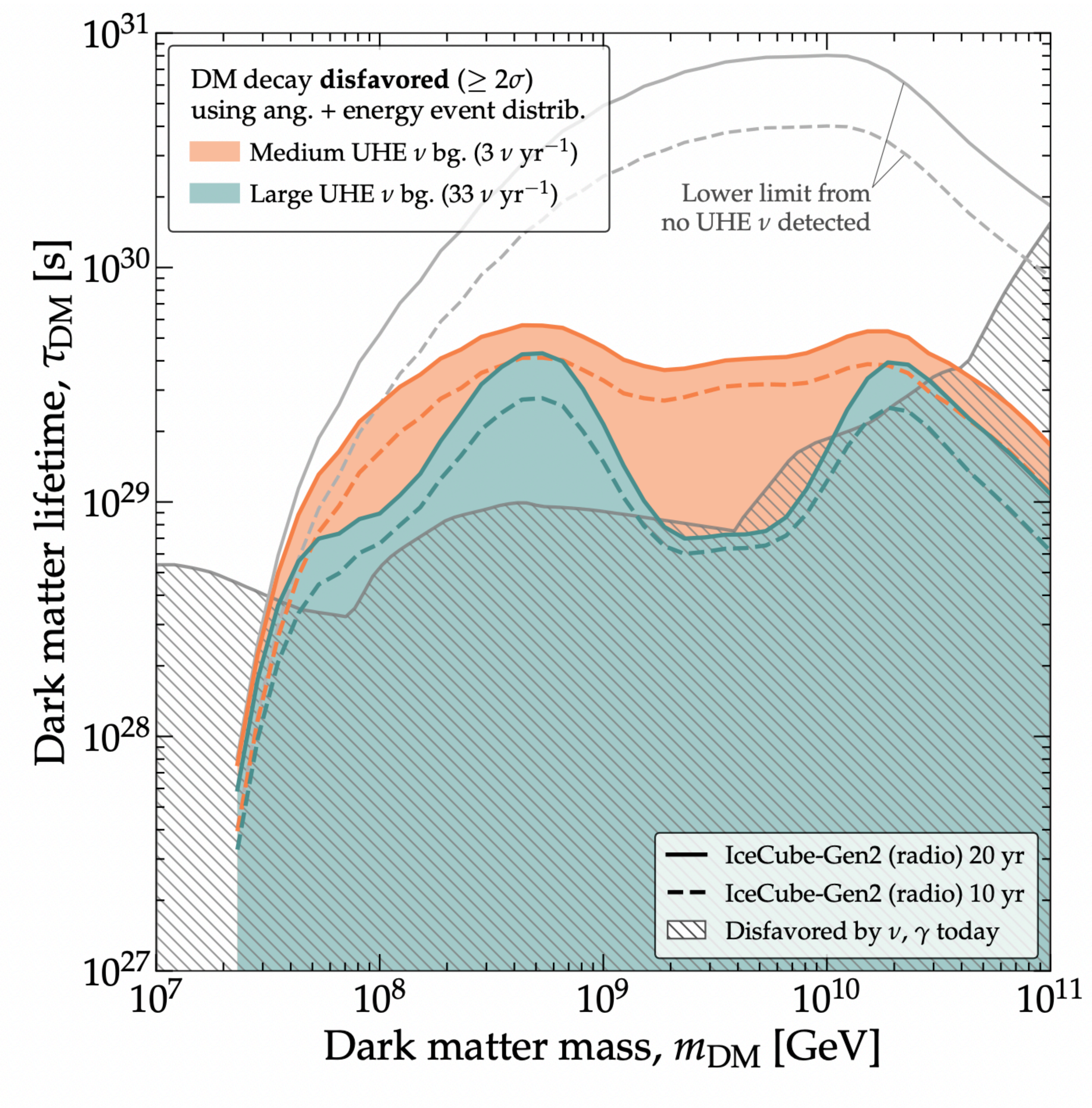
Discovering dark matter



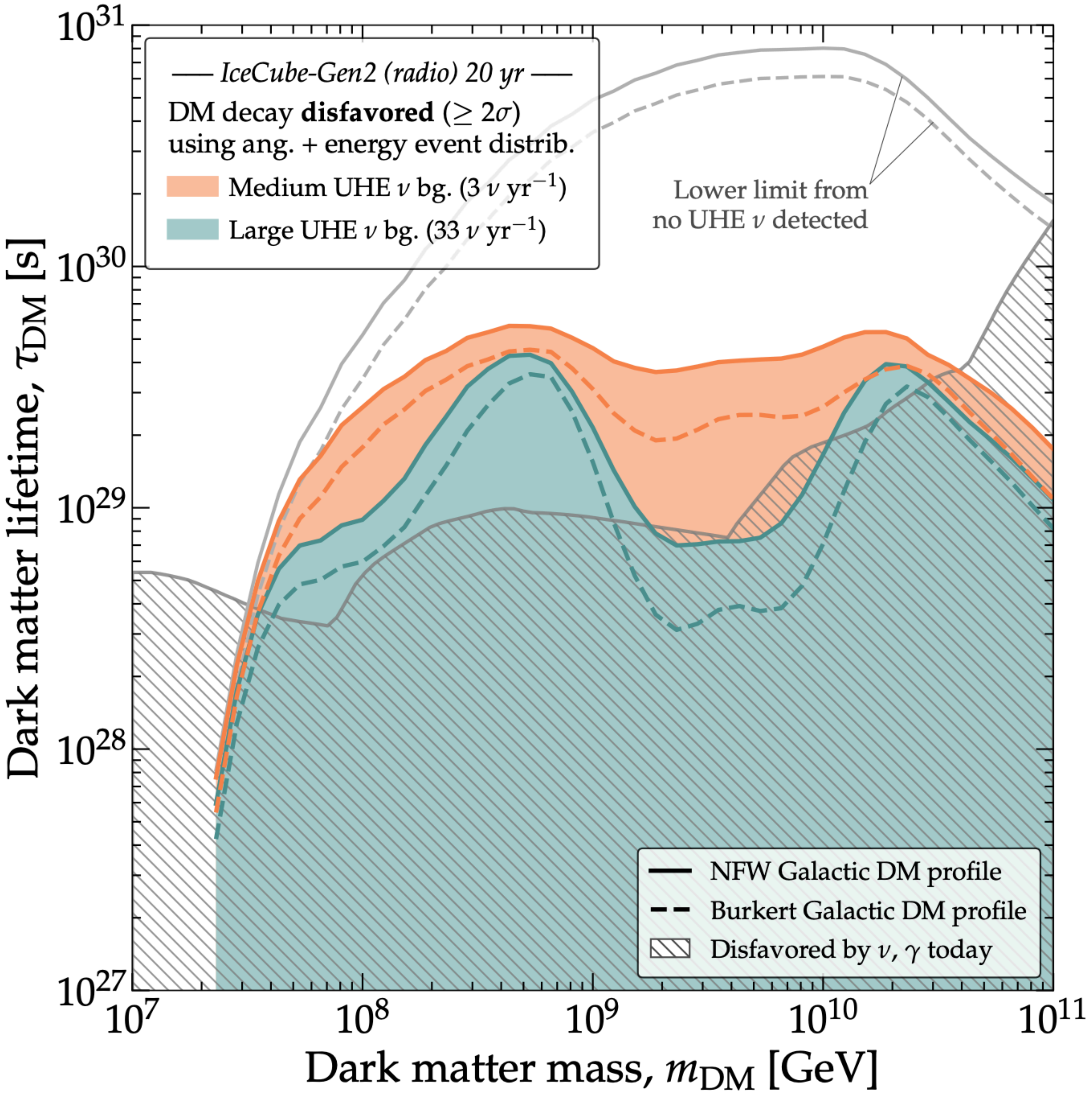
- If angular excess is discovered, parameter reconstruction to less than factor 2

Constraining dark matter



- Event-counting may provide overly weak limits if diffuse flux is detected
- Energy and angular information can improve bounds by even one order of magnitude

Constraining dark matter



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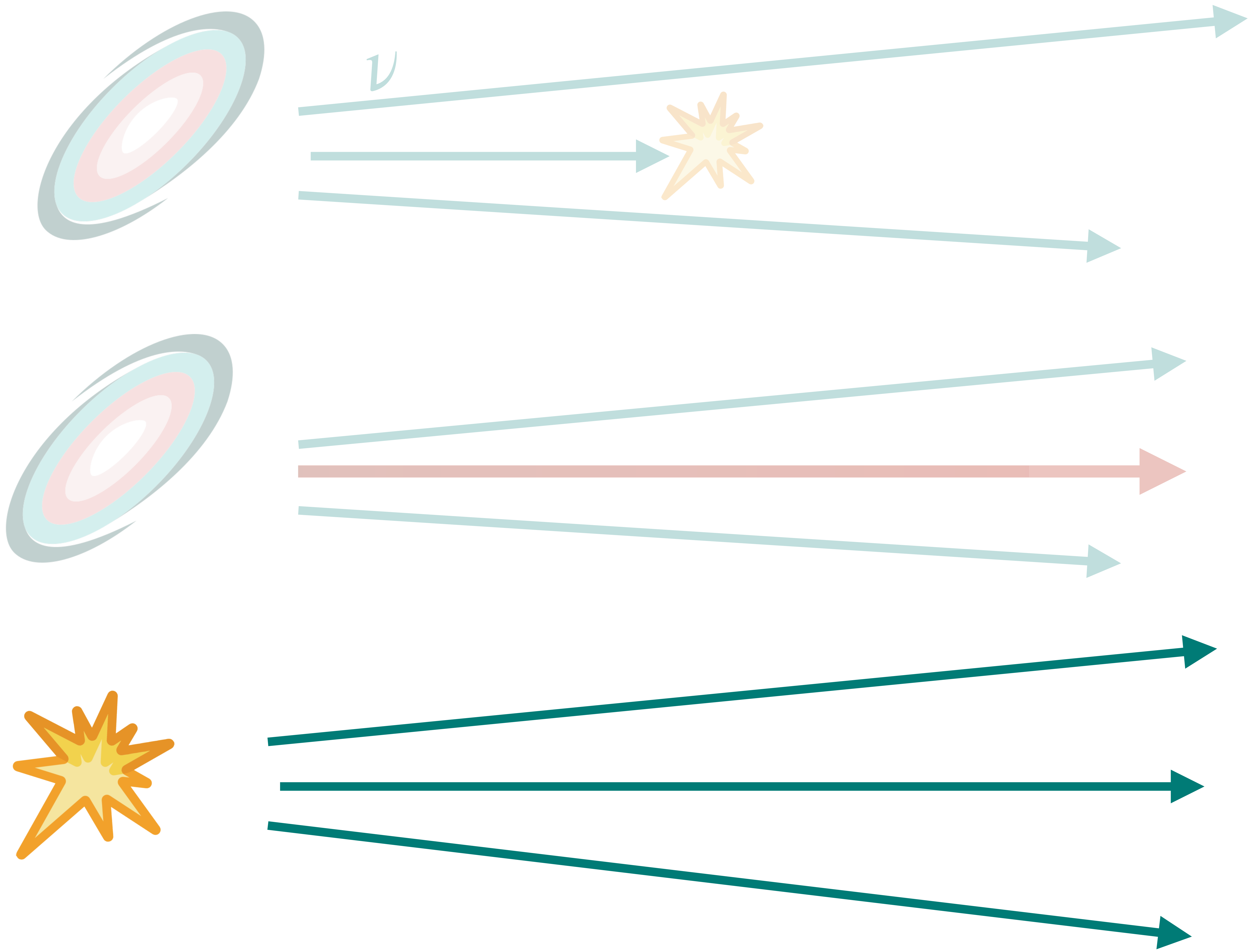
Neutrinos probe (BSM) particle physics

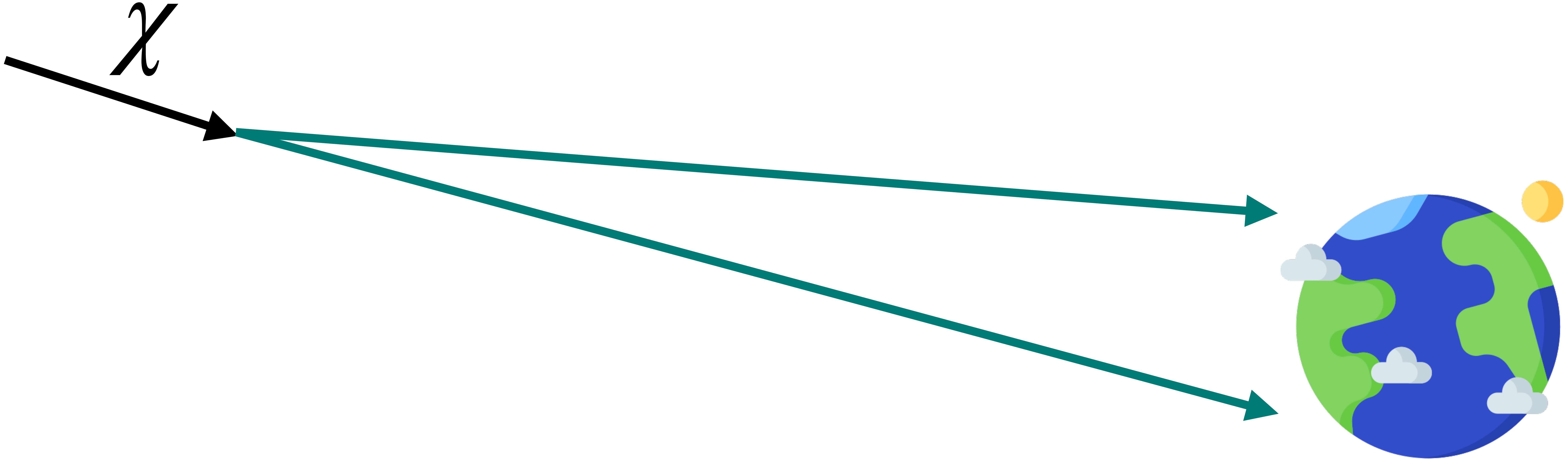


Non-standard interactions ($\nu\nu$ with relic neutrinos, $\nu\chi$ with dark matter, …)

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

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

Decaying dark matter

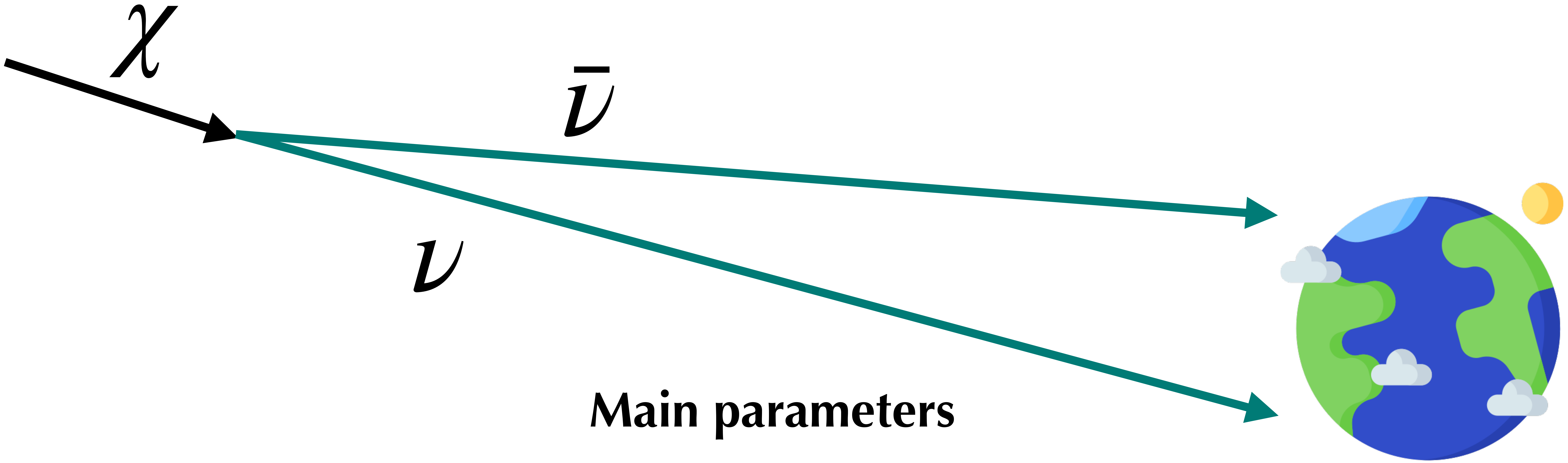


1. How many neutrinos in a decay?

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

3. Can we detect them?

Decaying dark matter

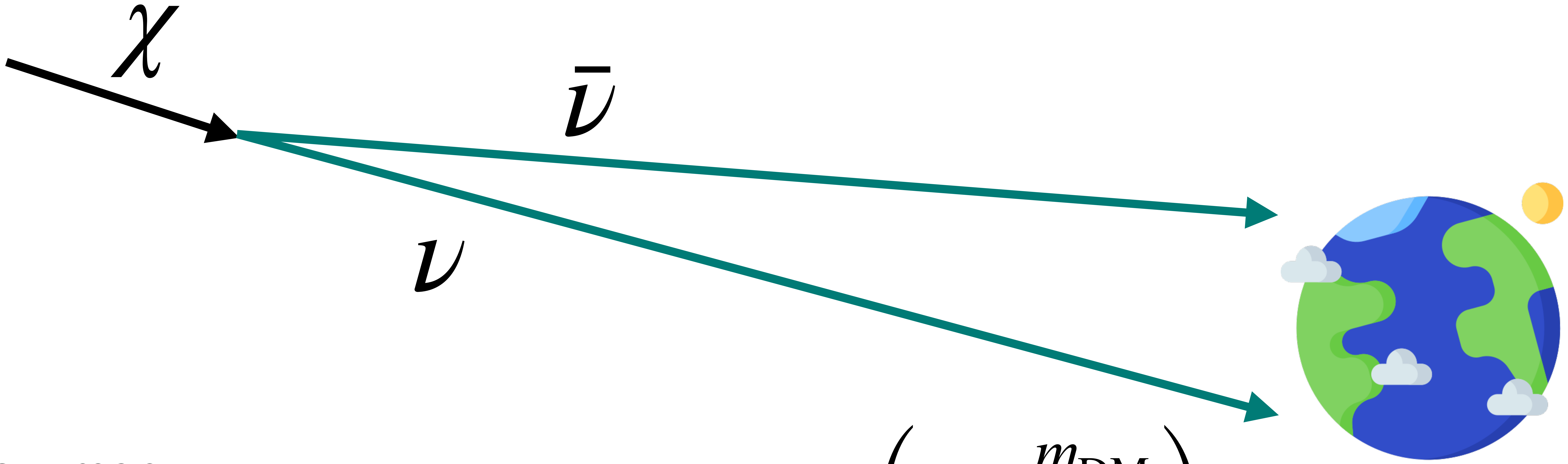


1. How many neutrinos in a decay?

Main parameters

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

Decaying dark matter

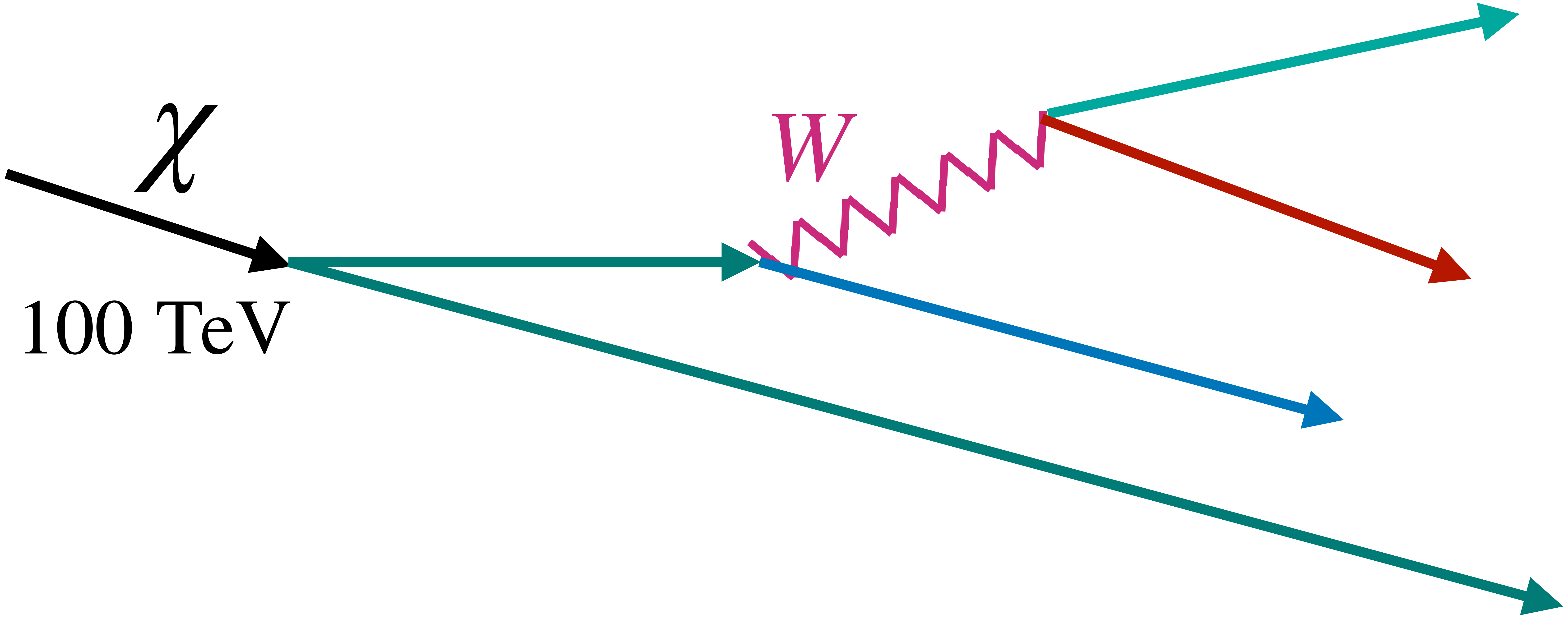


1. How many neutrinos in a decay?

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

$\chi \to \bar{f}f$ No neutrino produced?

Electroweak corrections

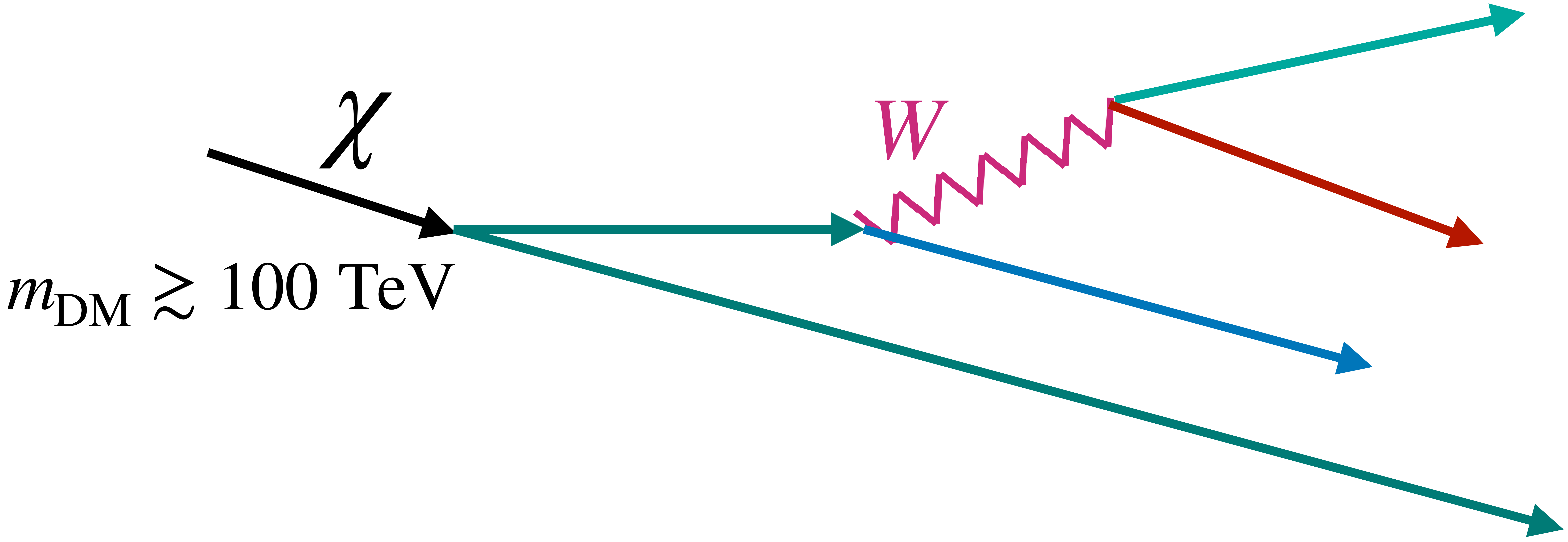


$m_{\mathrm{DM}} \gtrsim 100\ \mathrm{TeV}$

1. How many neutrinos in a decay?

$$P \sim \alpha_W ?$$

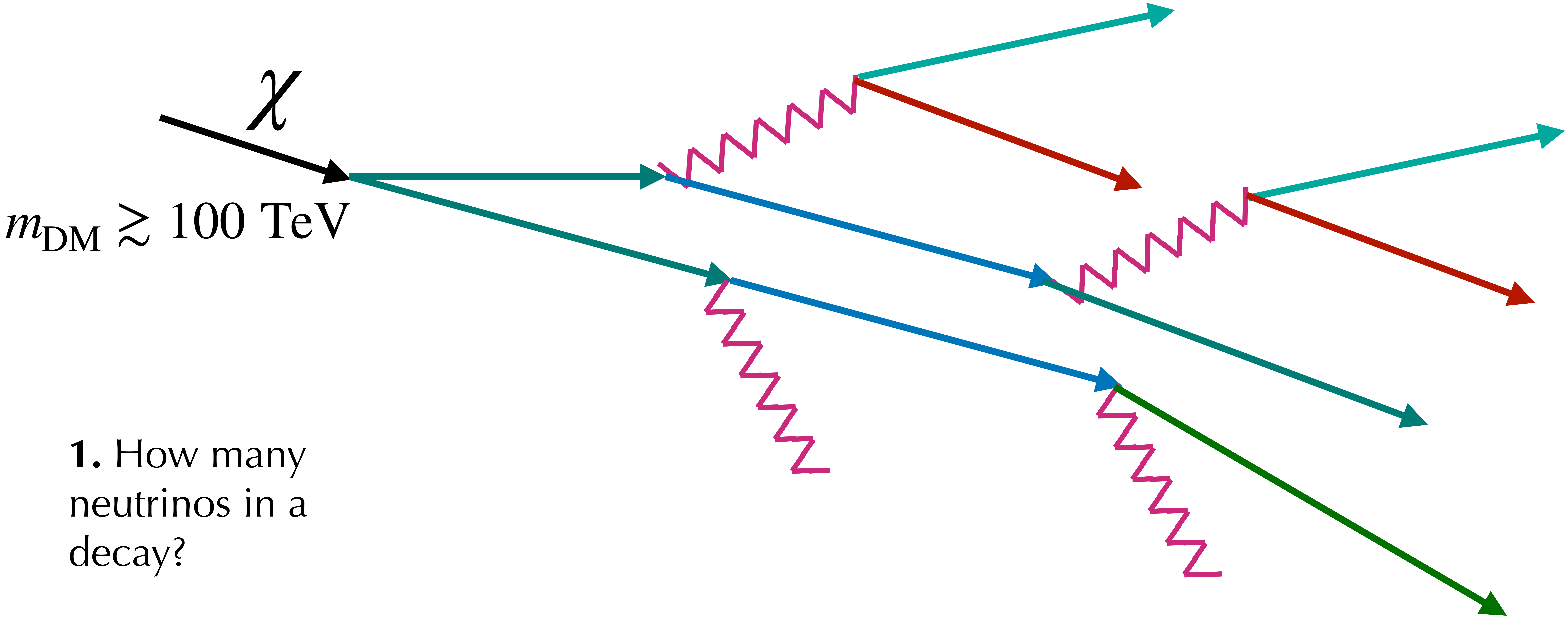
Electroweak corrections



1. How many neutrinos in a decay?

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

Electroweak corrections

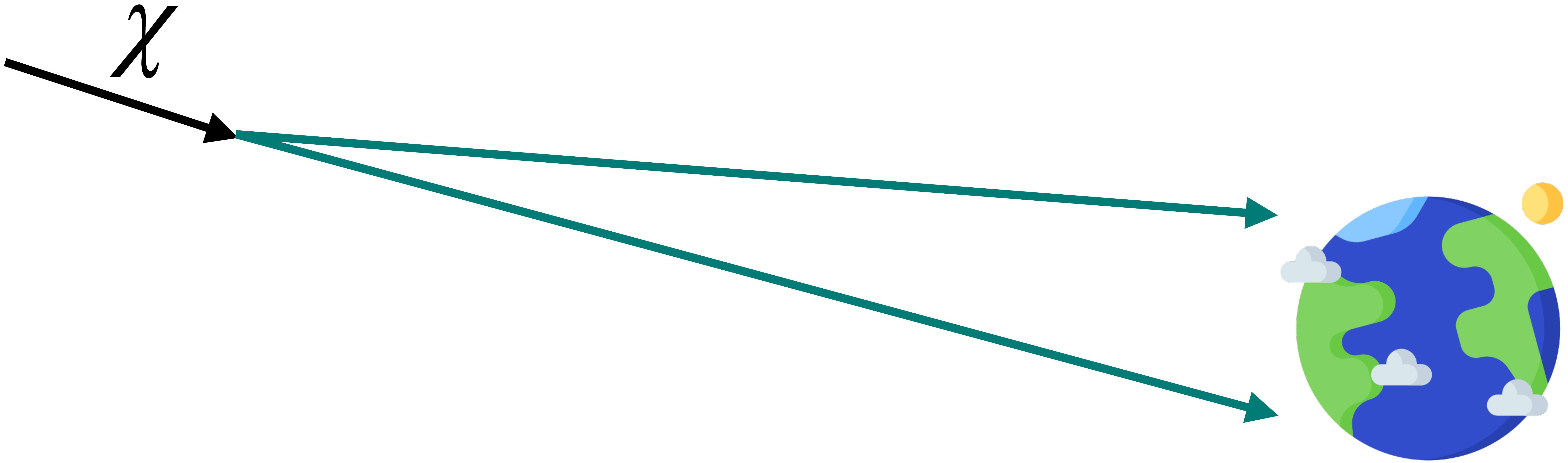


1. How many neutrinos in a decay?

Energy cascade, treated by DGLAP equations

HDMSpectra (arXiv:2007.15001)

Decaying dark matter



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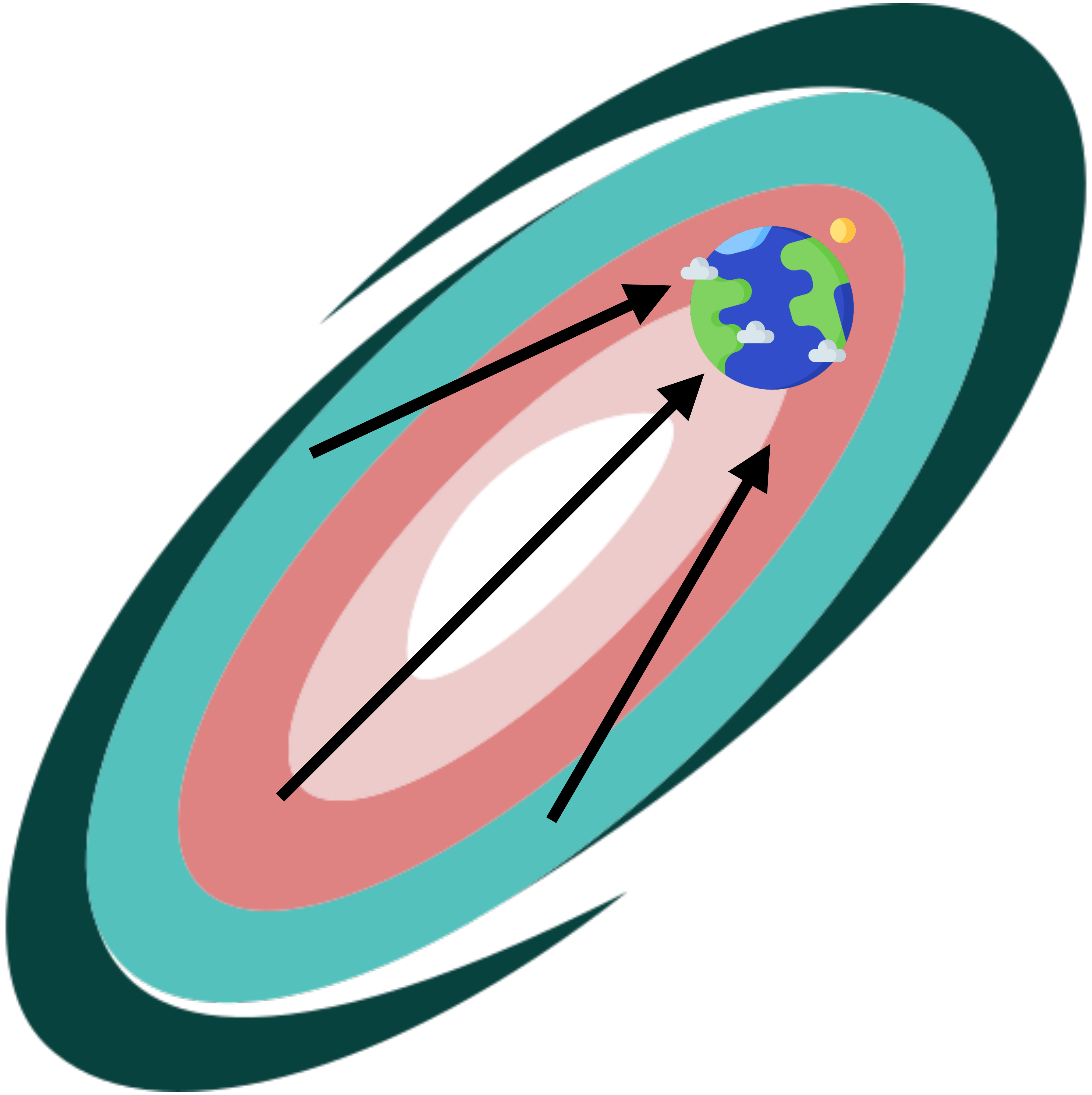
Diffuse DM production



Galactic production

- ✦ Depends on DM distribution
- ✦ Slightly anisotropic

Diffuse DM production

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

How fast does it decay?

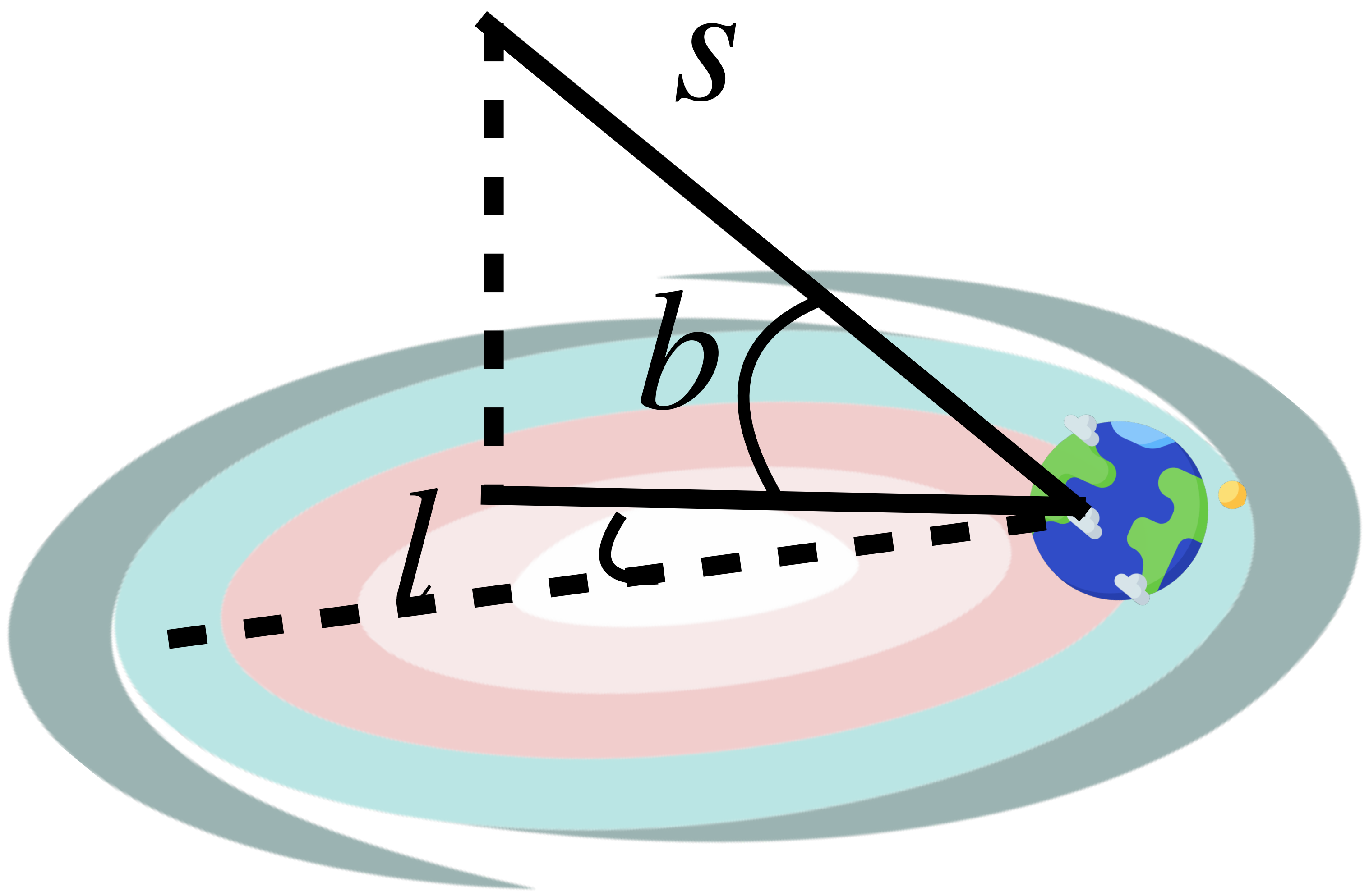
How many are produced?

Neutrino mixing

How many DM particles?

Galactic production

- Depends on DM distribution
- Slightly anisotropic



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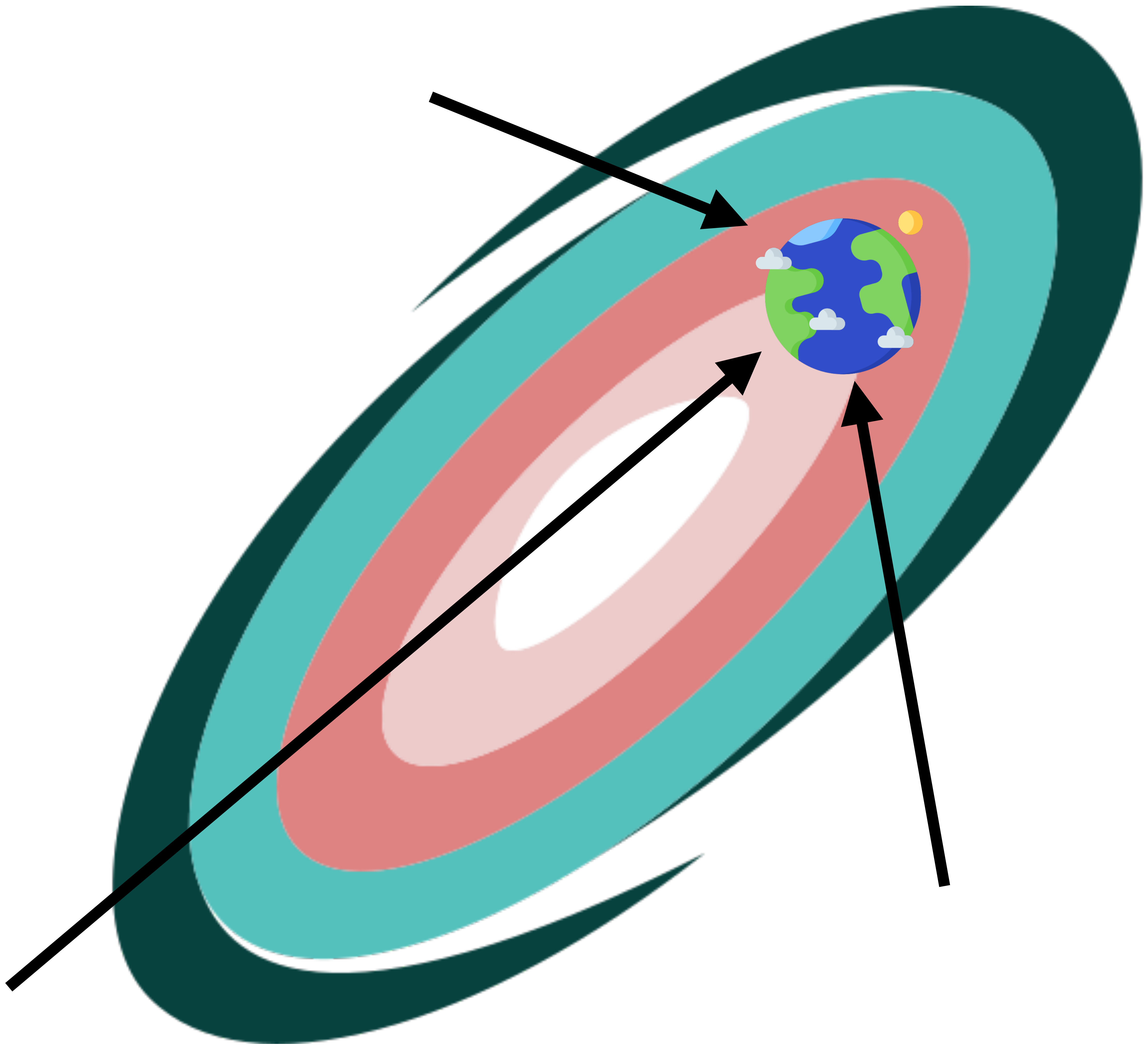

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Extragalactic production

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

Diffuse DM production

$$\frac{d\phi_{EG,\beta}}{dEd\Omega} = \frac{1}{4\pi}\underbrace{\frac{1}{\tau_{\rm DM}}}_{\text{How fast does it decay?}}\sum_\alpha \underbrace{P_{\alpha\to\beta}}_{\text{Neutrino mixing}}\int \frac{dz}{H(z)}\underbrace{\frac{dN_\alpha}{dE}[E(1+z)]}_{\text{Redshifted neutrino spectrum}}\underbrace{\frac{\Omega_\chi \rho_c}{m_{\rm DM}}}_{\text{Dark matter density}}$$

Galactic production

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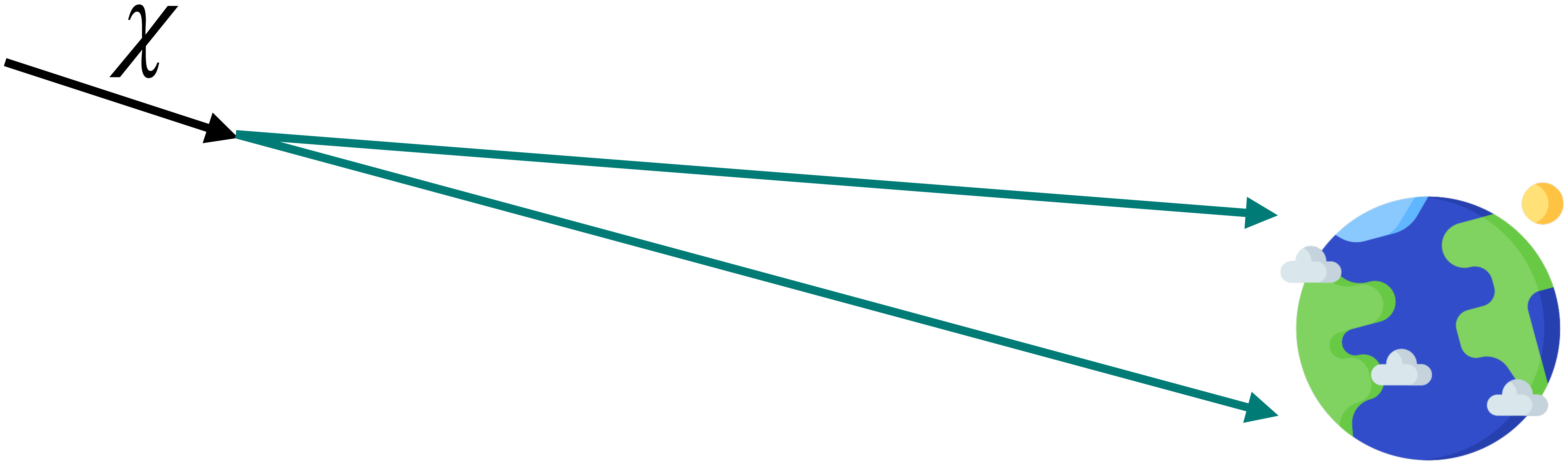
Decaying dark matter



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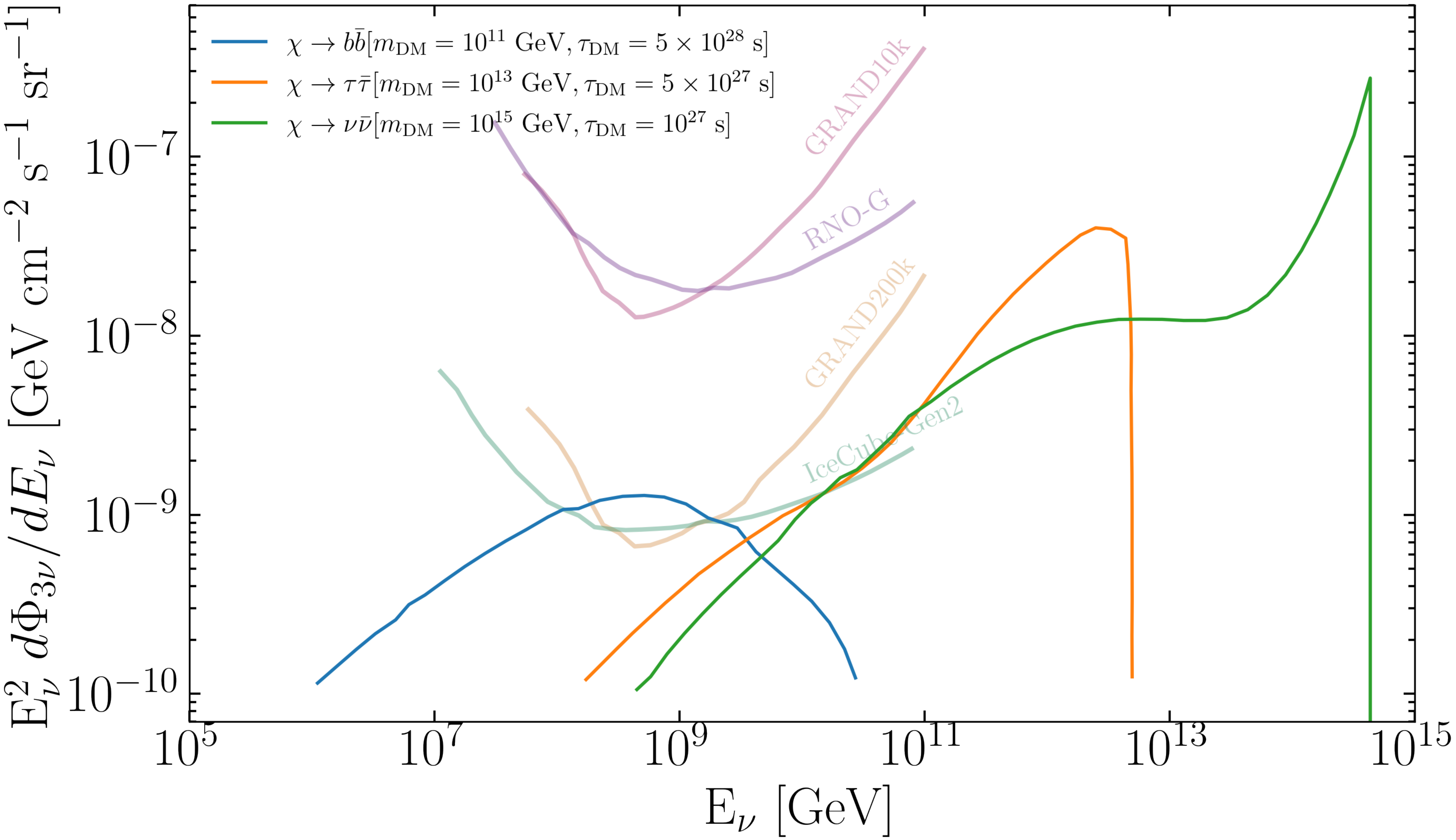
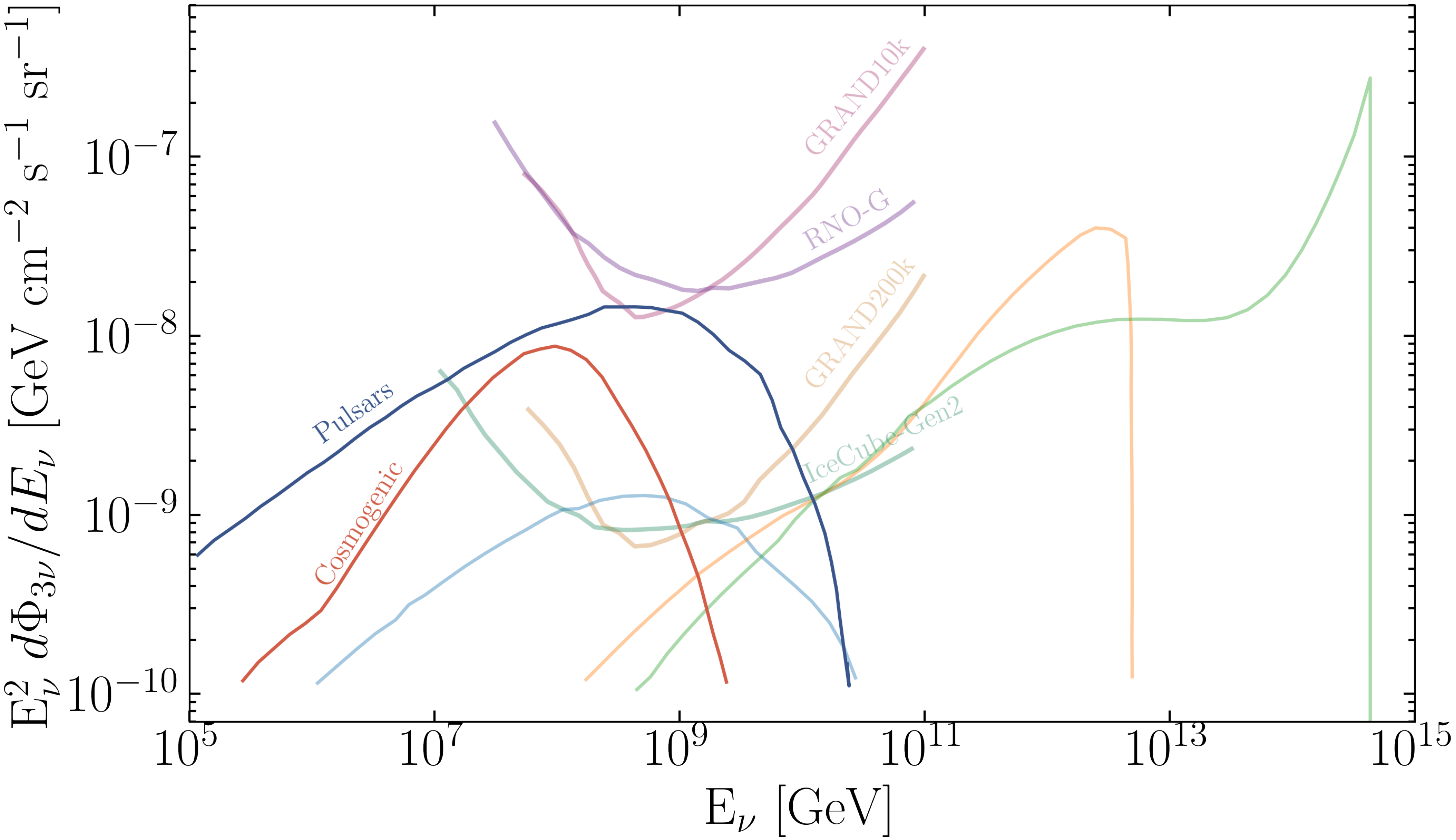
UHE neutrinos



Probability of observing nothing

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

UHE neutrinos

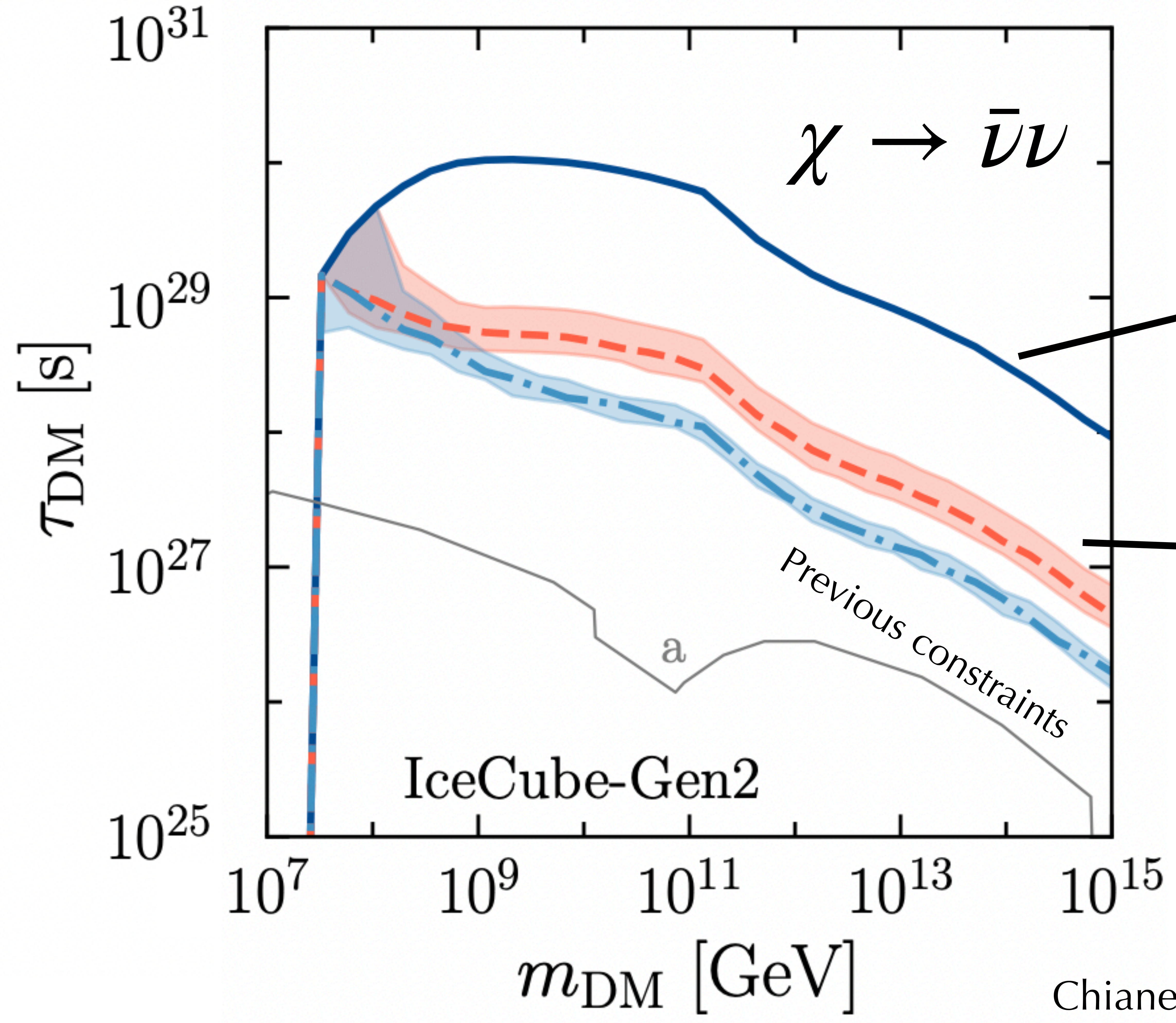


We may observe some events of astrophysical origin

⬇

Weaker constraints!

Constraints from UHE neutrinos

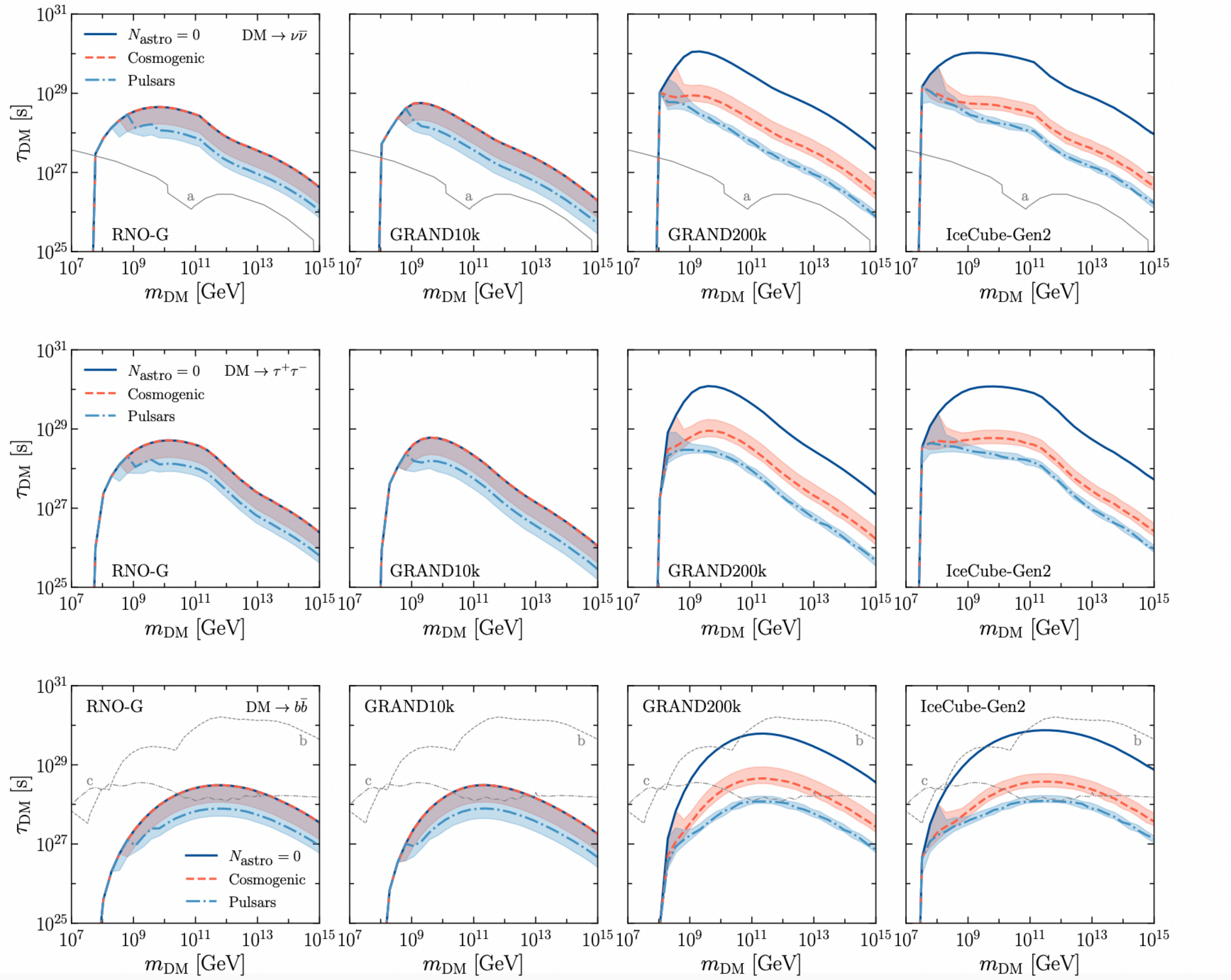


If no event is detected, DM should produce less than 2.71 expected events (95% CL)

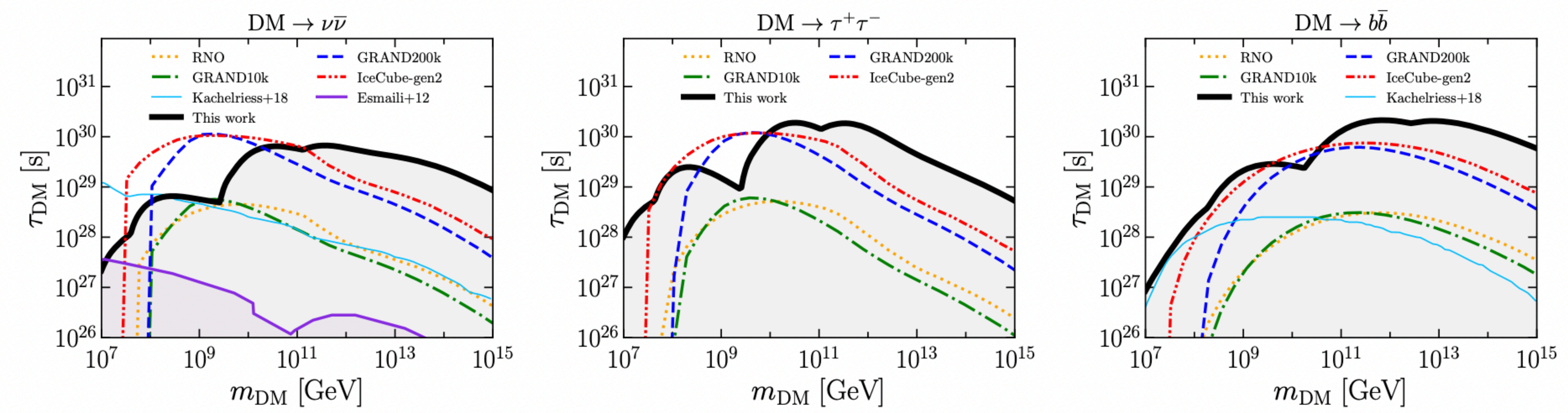
If astro events are detected, constraints are weaker

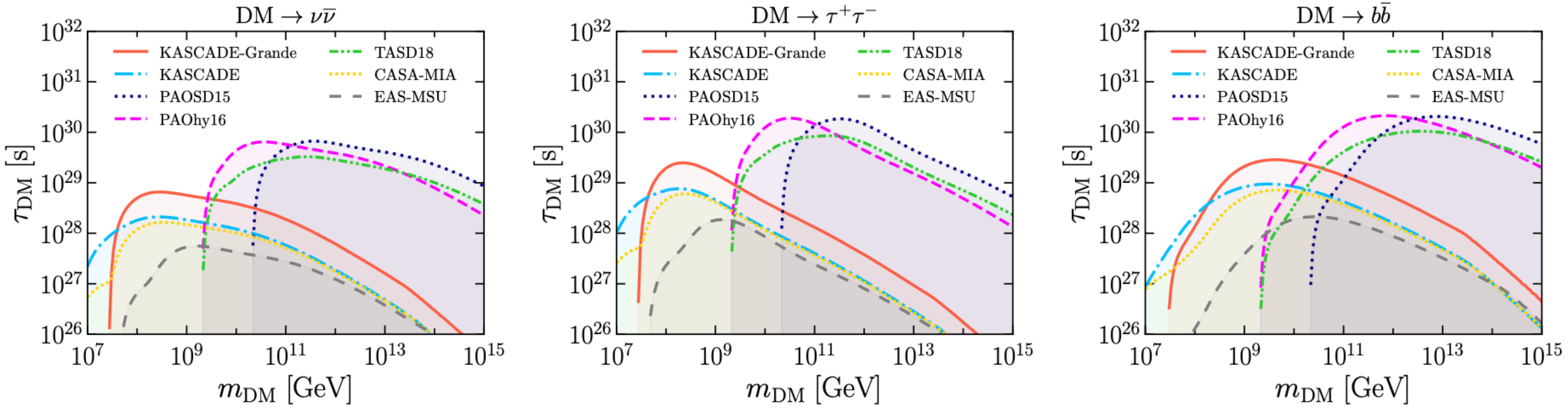
Chianese, **DF**, Hajjar, Miele, Morisi, Saviano 2103.03254

UHE neutrinos: constraints



UHE neutrinos: constraints

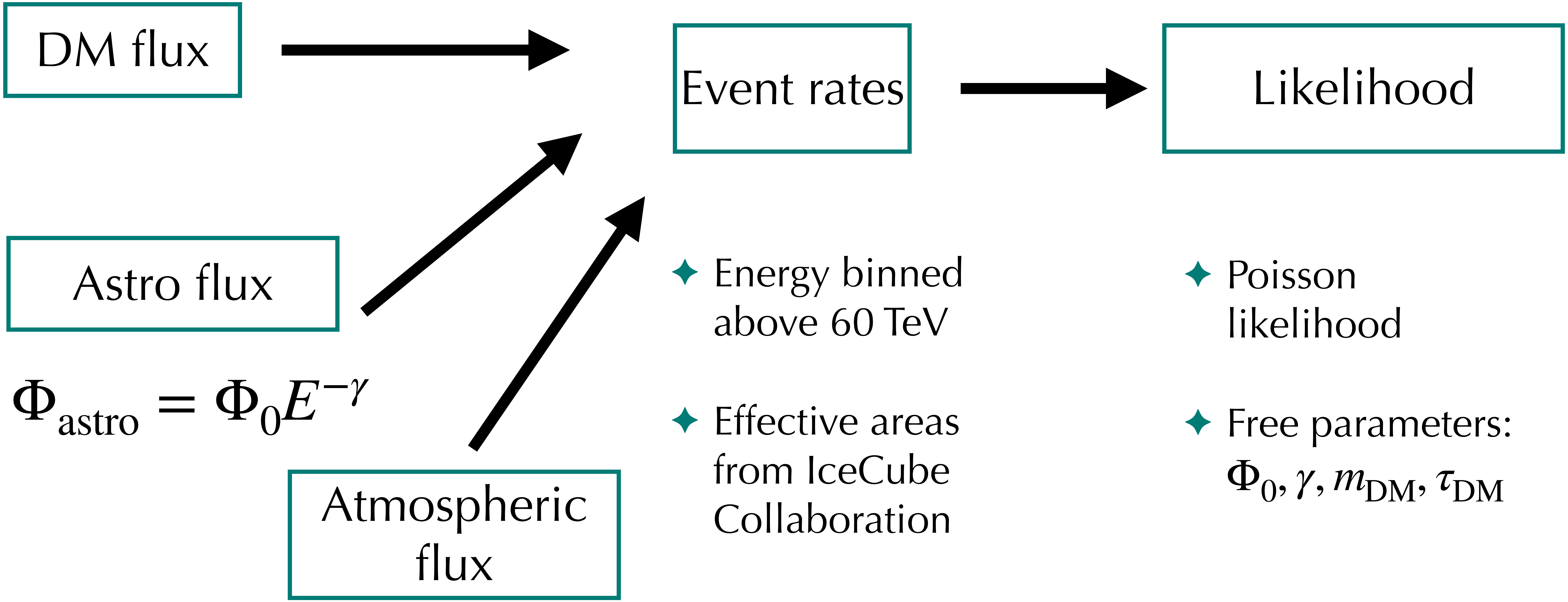




Electroweak corrections

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

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

Atmospheric flux

Schneider, 1907.11266

Event rates

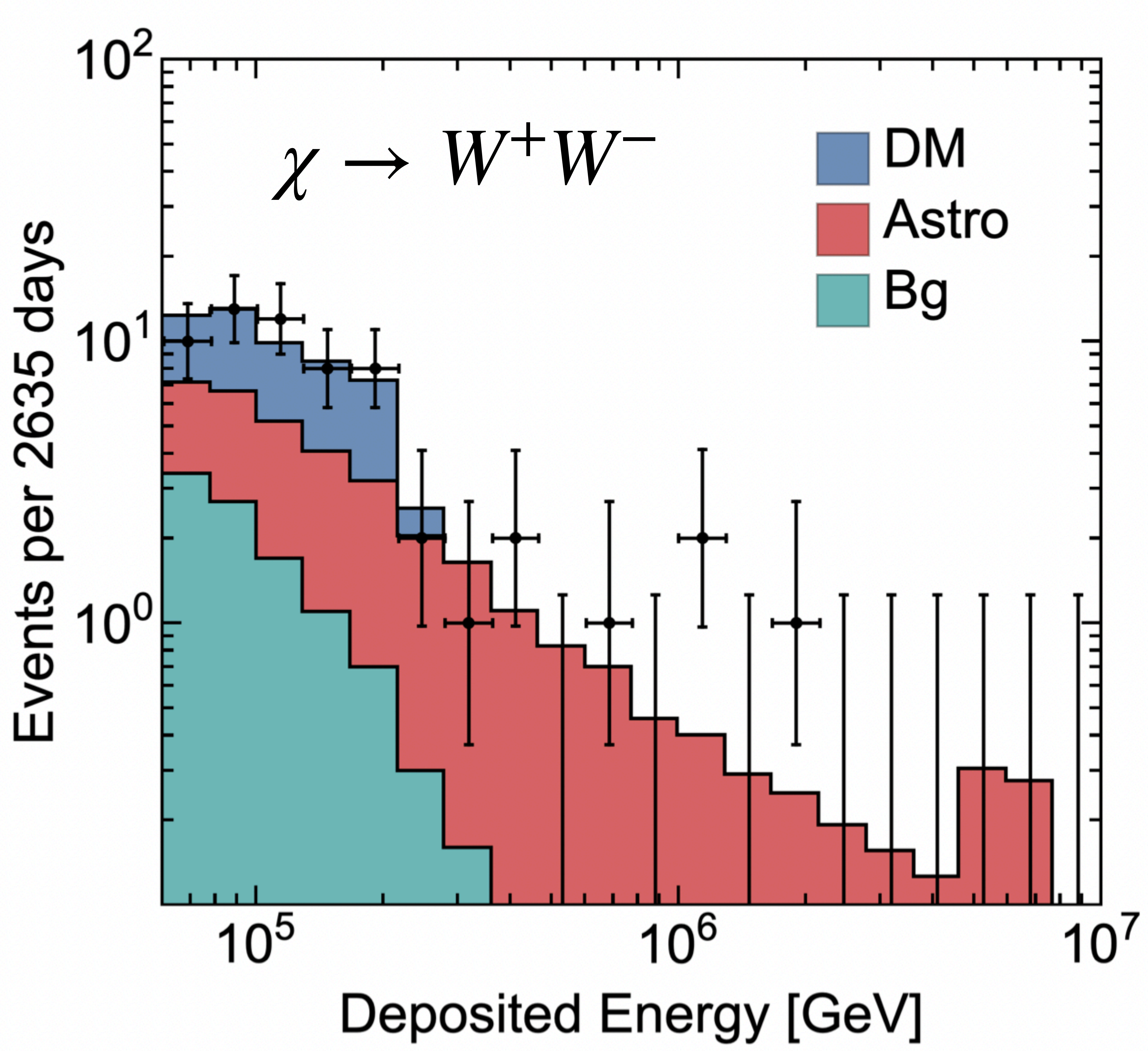
- Energy binned above 60 TeV
- Effective areas from IceCube Collaboration

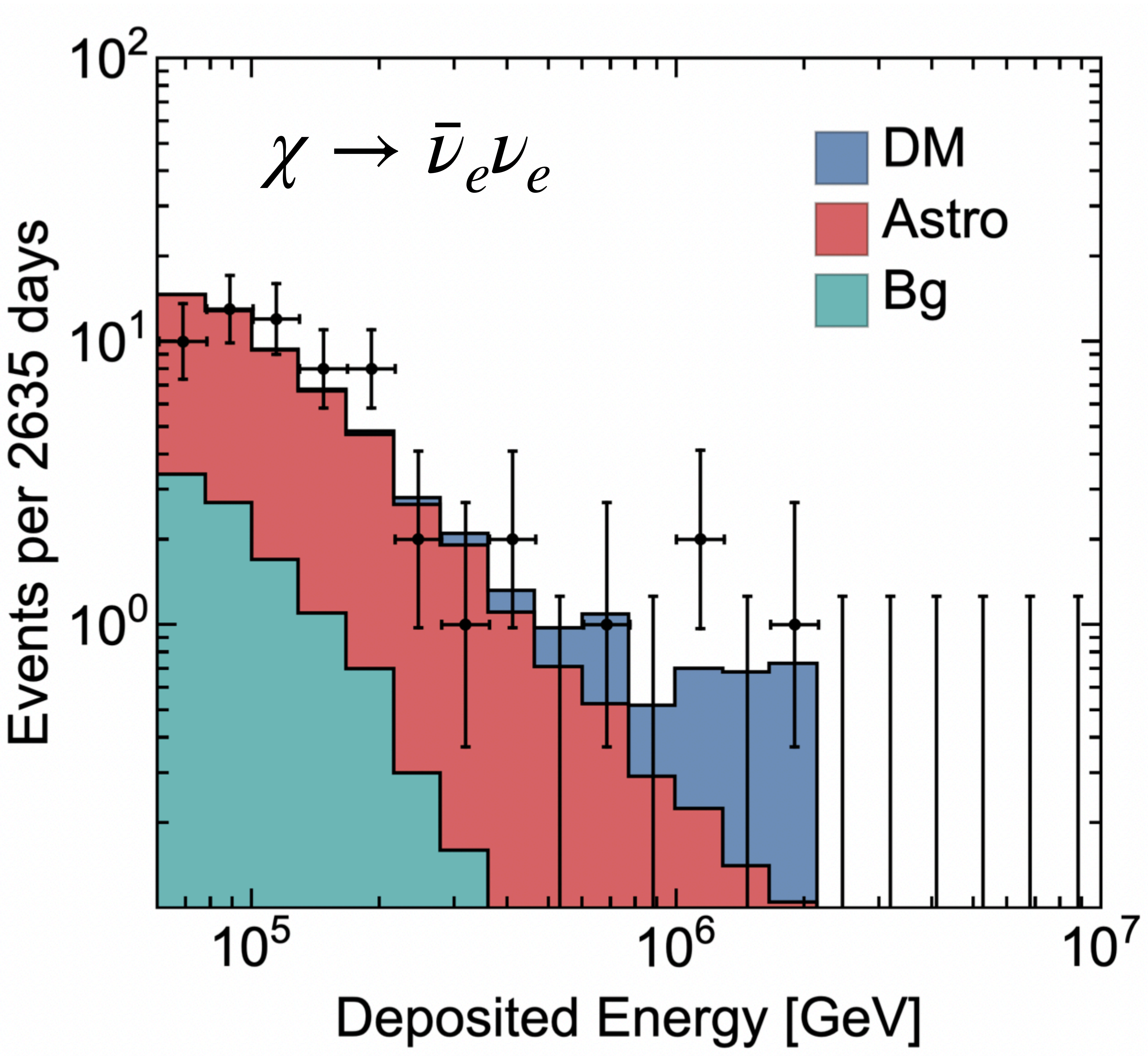
Likelihood

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

High-energy range: IceCube

DM can improve fit to data in two ways





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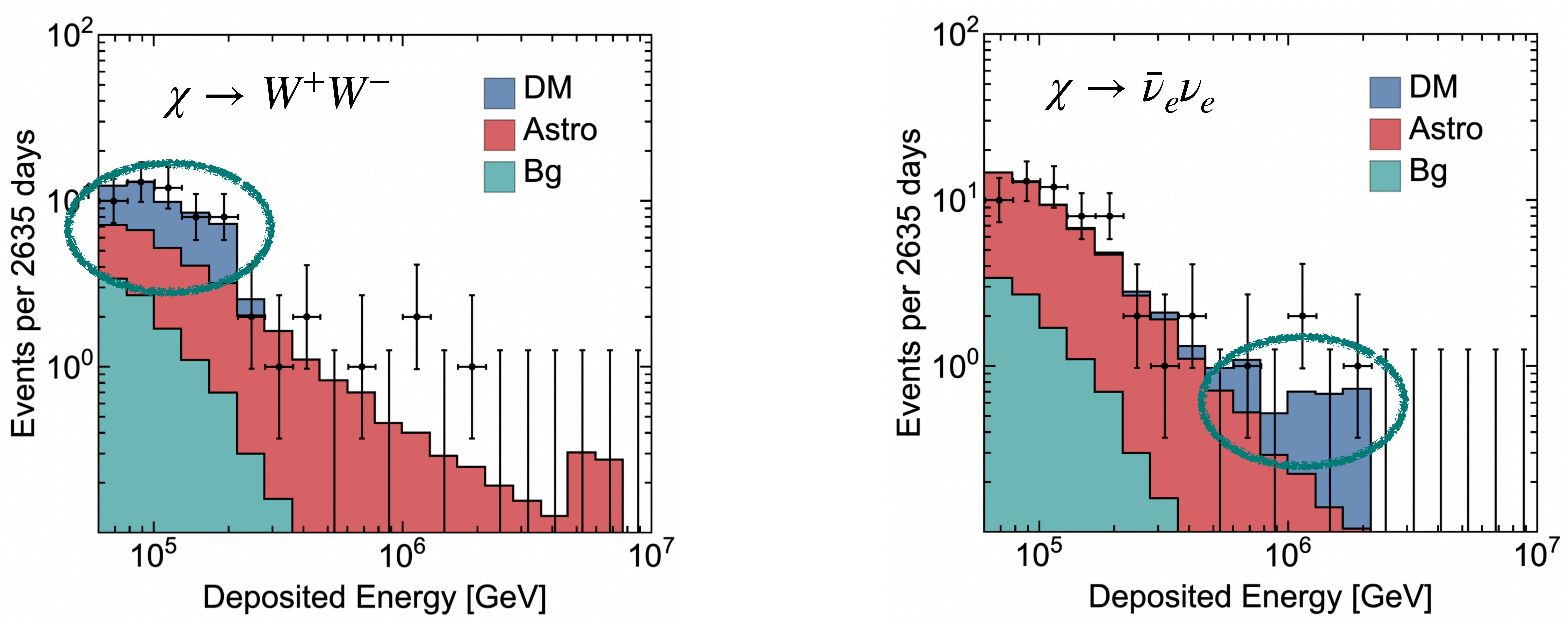
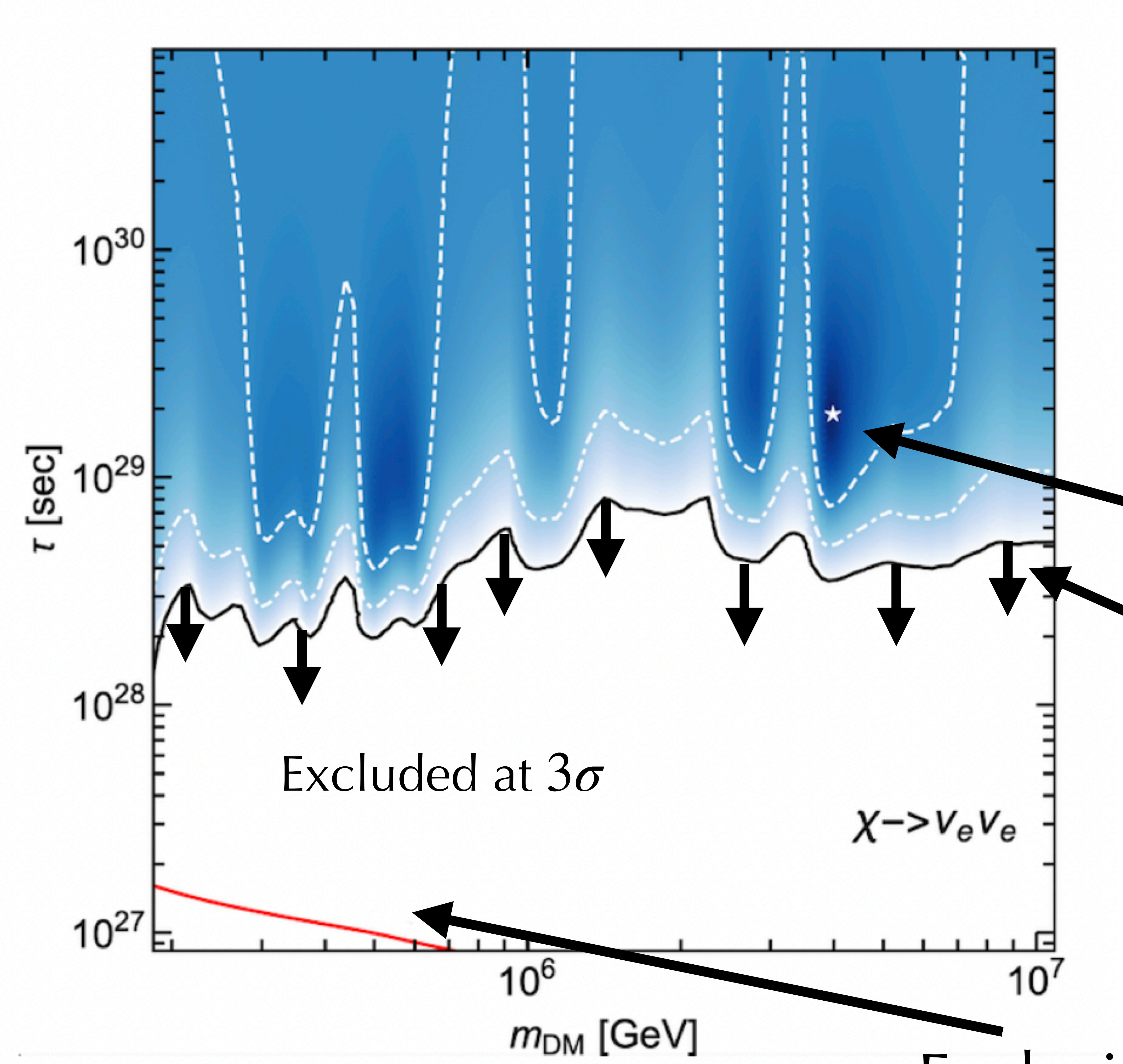


High-energy range: IceCube



Best fit solution

Neutrinos exclude too rapid decays

Exclusion from gamma-rays

(Cohen et al., arXiv:1612.05638)

High-energy range: IceCube