Constraints on Heavy Asymmetric Dark Matter with the Glashow Resonance

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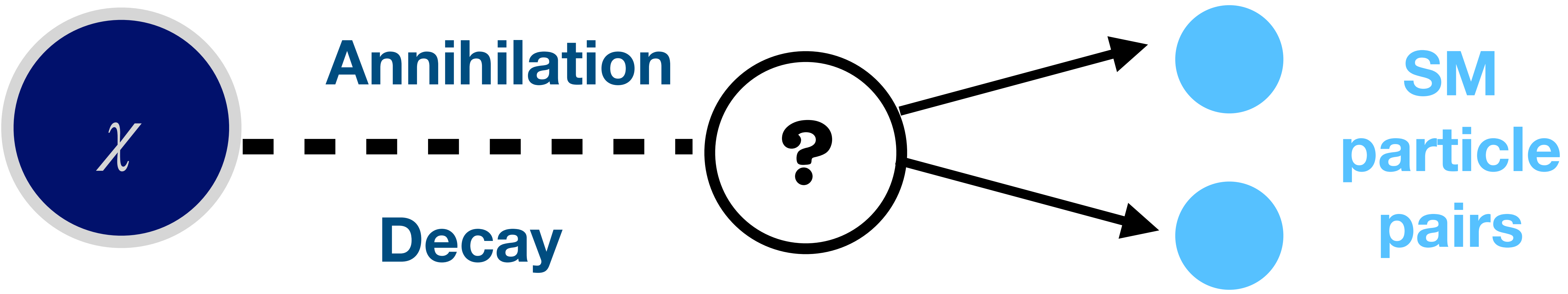
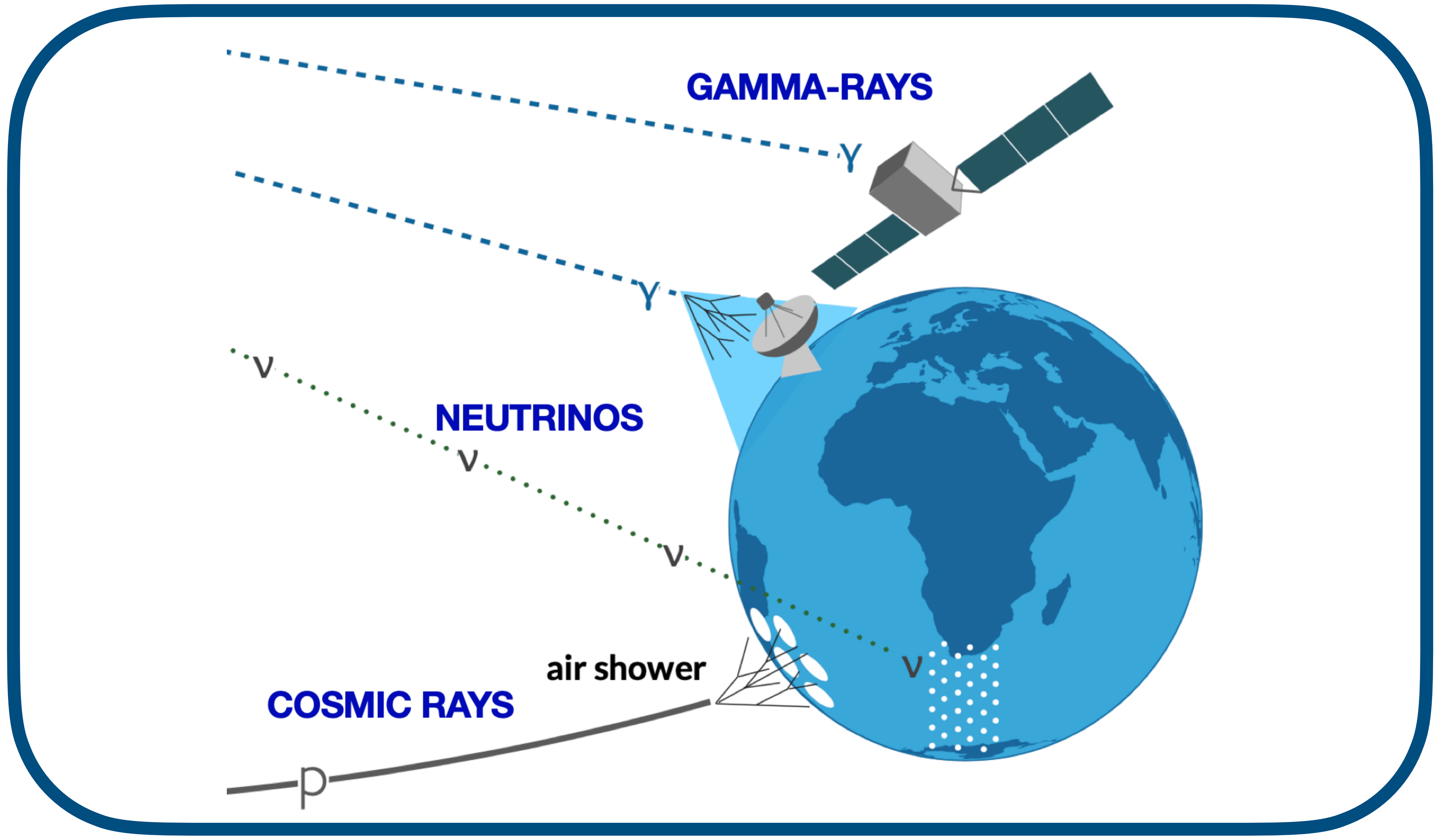
TeVPA 2024

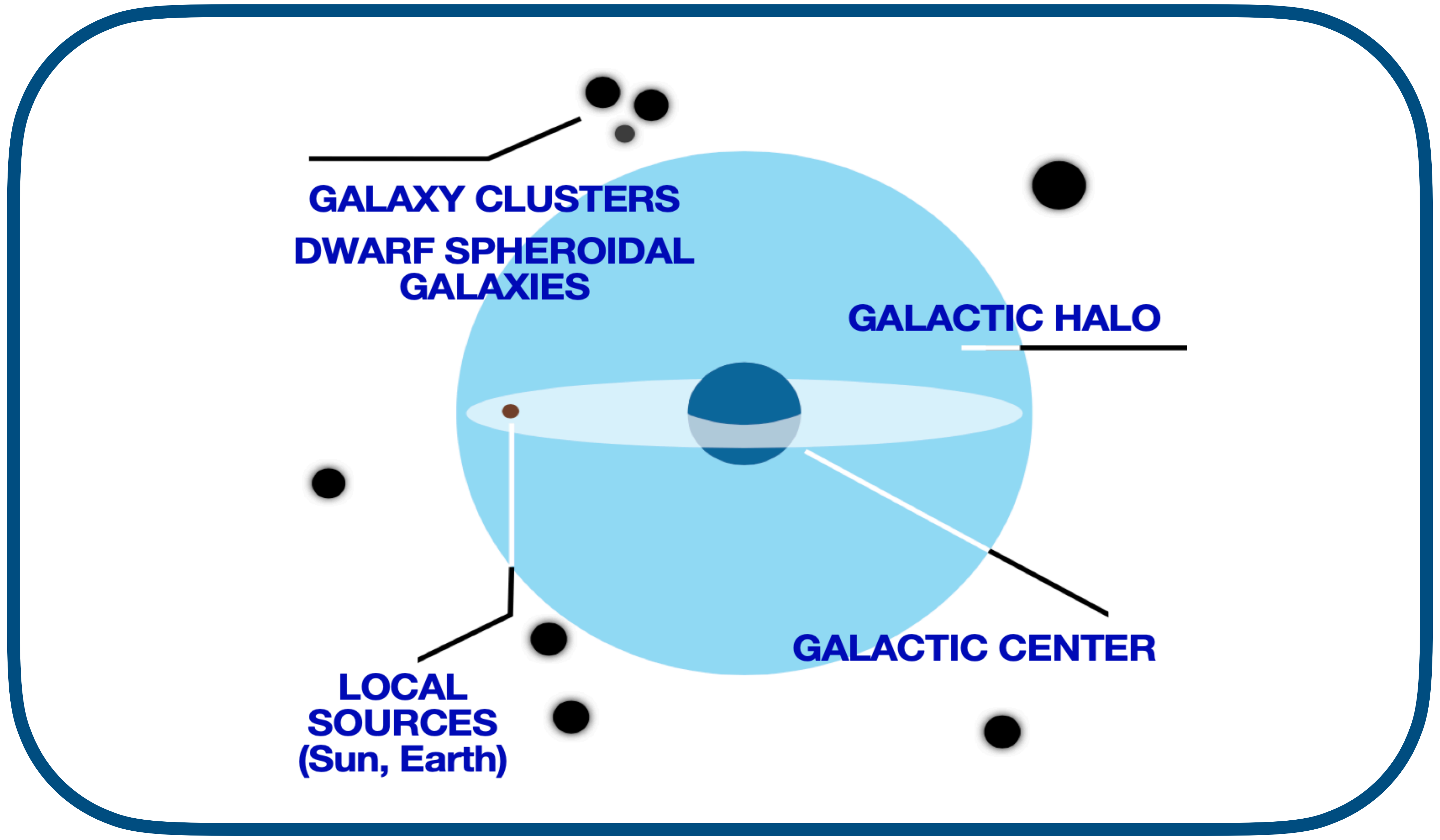
Aug 28th, 2024

Indirect Dark Matter Search





- Neutrino portal: the most invisible and the least studied.
- High-energy cosmic neutrinos observed by IceCube have been used to set constraints.
- Since there are ν and $\bar{\nu}$, can we go beyond pair production?



credit: J. A. Aguilar

Asymmetric Dark Matter (ADM)

- ADM usually carries B-L numbers and transfers an asymmetry between the dark sector and the standard model.
- The decay products have an asymmetry of particle and antiparticle.

$$\mathcal{O}_{\mathrm{ADM}} = \frac{\mathcal{O}_X \mathcal{O}_{\mathrm{B-L}}}{\Lambda^{d-4}}$$

- **Cosmic rays: well…DM is unlikely to be electrically charged**
- **γ rays: same signal for both symmetric & asymmetric DM**
- **Neutrinos: if ν and $\bar{\nu}$ can be identified experimentally, asymmetry can be probed**

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- Th

A neutrino telescope like IceCube detects neutrinos via deep-inelastic scatterings and is blind to ν and $\bar{\nu}$.

Is there a way to differentiate?

$\nu - \bar{\nu}$ **?**

Glashow Resonance

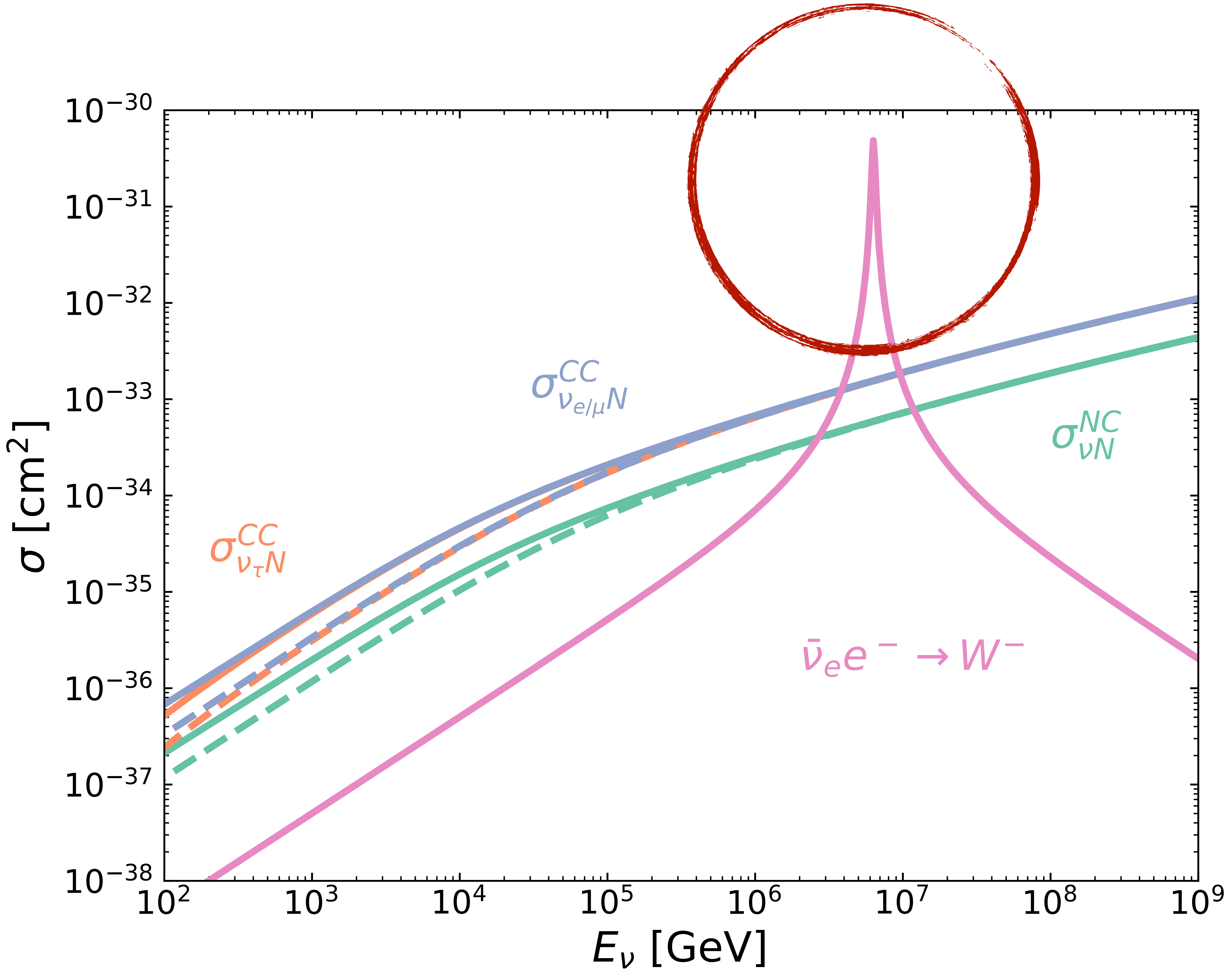
$\bar{\nu}_e$ can be disentangled with resonant interactions

$$\bar{\nu}_e + e^- \rightarrow W^-$$

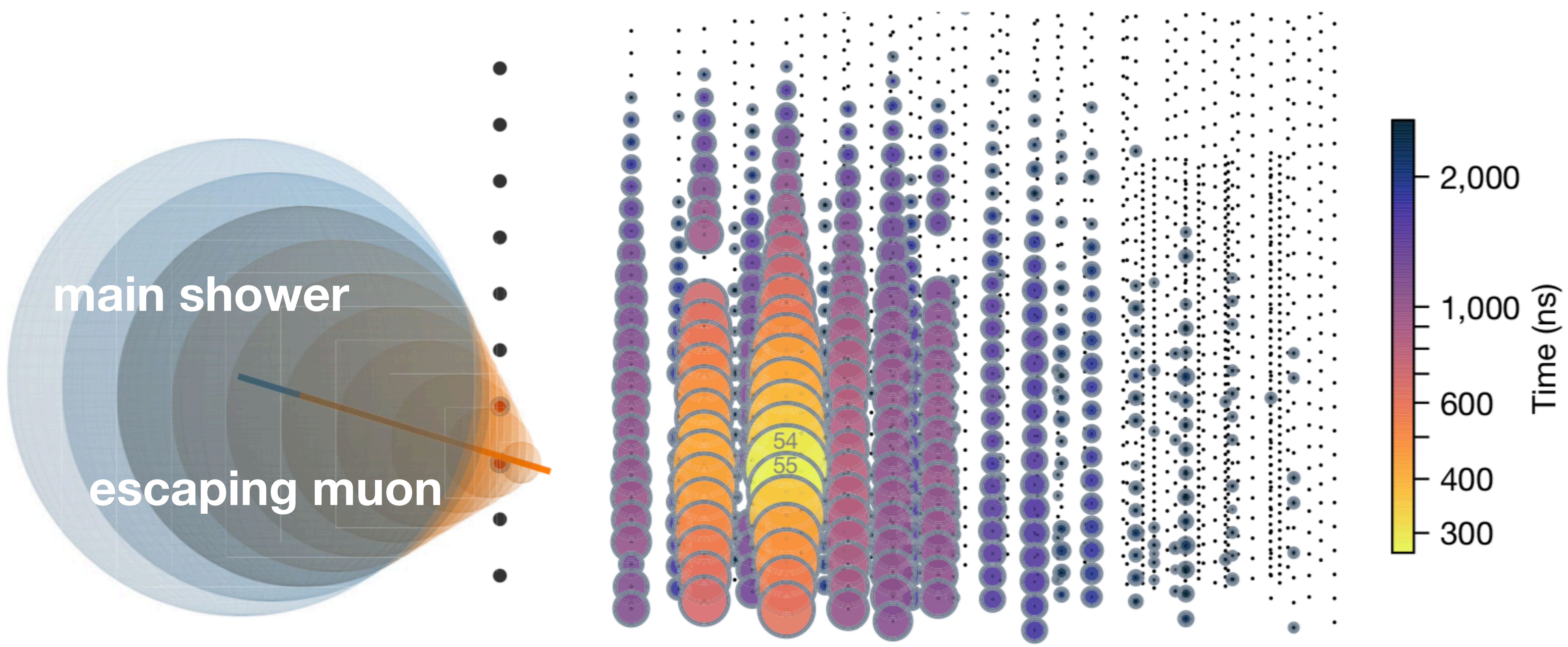
6.3 PeV   511 KeV   80.38 GeV

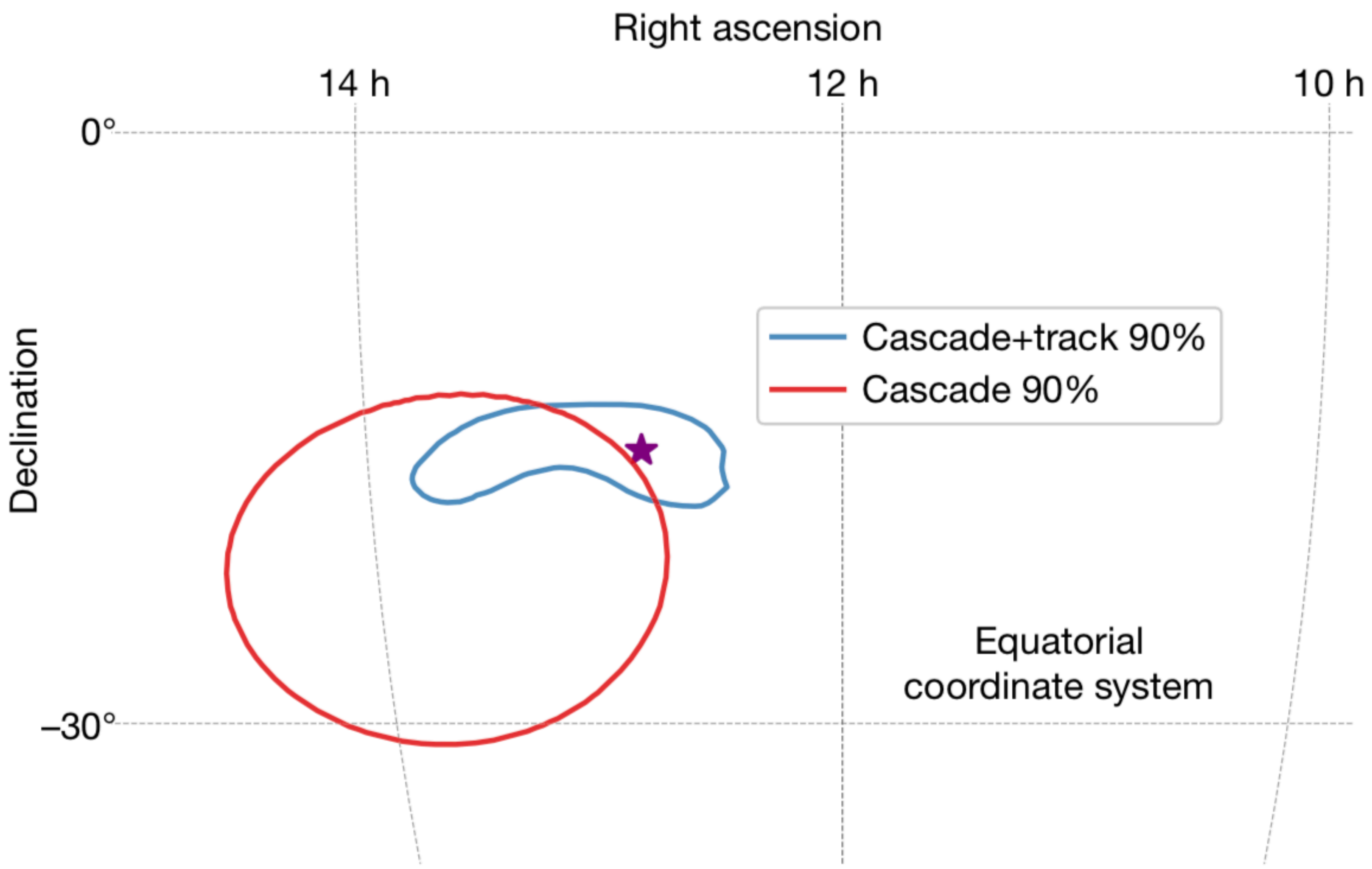
S. Glashow *Phys.Rev.* 118 (1960) 316-317

The only way to differentiate the $\bar{\nu}$ flux in the total flux at high energies.

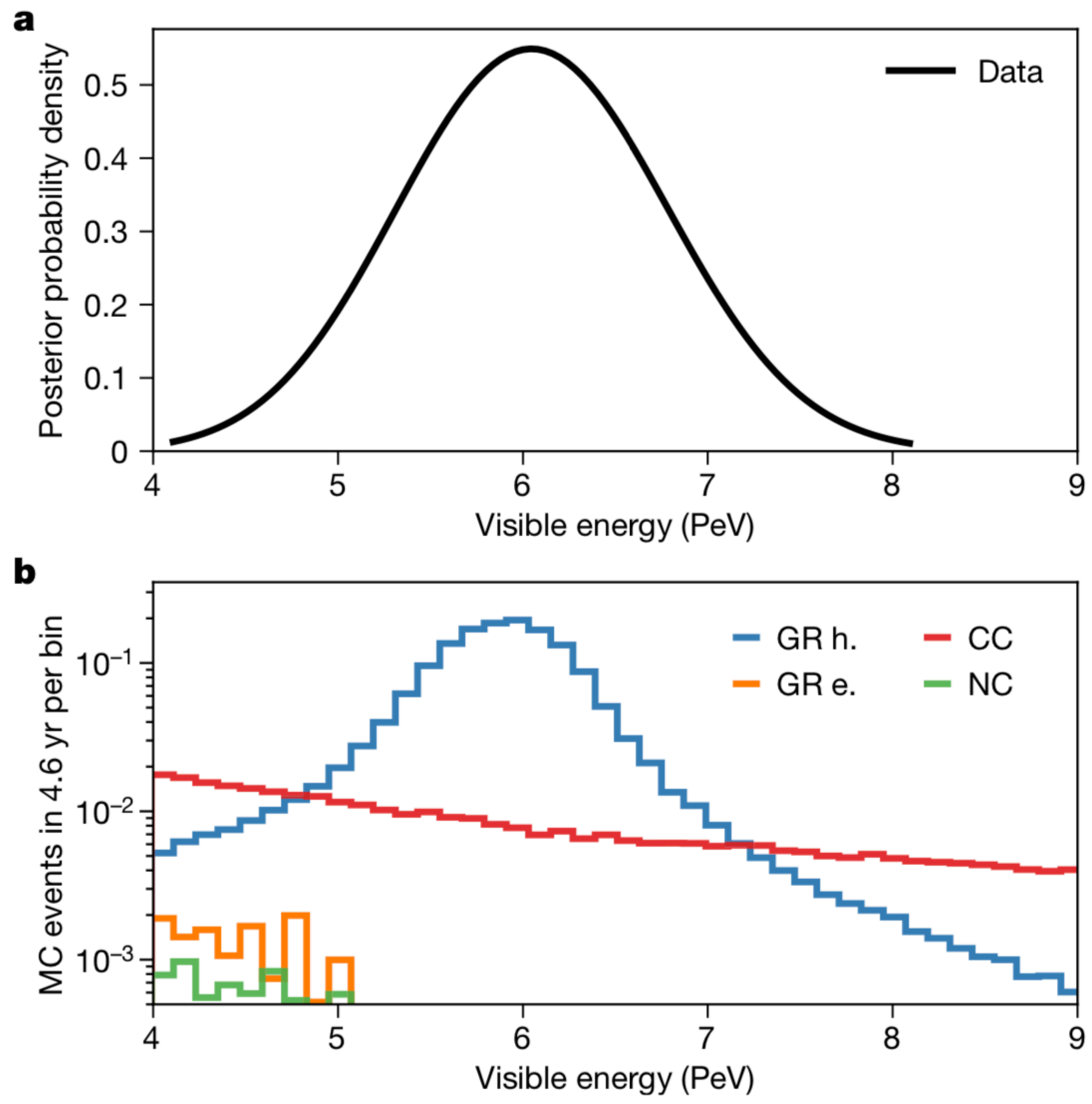


First Detection of Glashow Resonance





PeV energy partially-contained event selection



- Reconstructed energy of 6.05 ± 0.72 PeV.
- The detectable escaping muon suggests it's a hadronic shower.

IceCube Nature 2021

Neutrino Portal of ADM

- We focus on portals where neutrinos are the main signal.
- For distinct signatures, we explore the lowest-dimension operators.
- Depending on the models, the lepton number can be either positive or negative.

Benchmark	Scalar X	Scalar X	Fermion X	Fermion X
$\mathcal{O}_{X\to\nu}$	$\frac{1}{\Lambda}X\psi L\Phi$	$\frac{1}{\Lambda^2}X(L\Phi)^2$	$\frac{1}{\Lambda^2}XL\psi^2$	$\frac{1}{\Lambda^2}XLL\nu^c$
Decay	$X \to \psi\nu/\psi\bar{\nu}$	$X \to \nu\nu/\bar{\nu}\bar{\nu}$	$X \to \nu\psi\bar{\psi}/\bar{\nu}\psi\bar{\psi}$	$X \to \nu\nu\bar{\nu}/\bar{\nu}\nu\bar{\nu}$

$\bar{\nu}$ flux is not 0 even $\bar{\nu}$ is not produced initially

$\bar{\nu}_e$ Flux from ADM

Galactic

$$\frac{d\Phi^{\text{gal.}}_{\bar{\nu}_e}}{dE_\nu} = \frac{1}{4\pi m_X \tau_X} \sum_\alpha^3 \frac{dN^{\text{ch}}_{\bar{\nu}_\alpha}}{dE_\nu} P_{\bar{\nu}_i \to \bar{\nu}_e} \mathscr{D}(\Omega)$$

+ particle physics astrophysics

Extragalactic

$$\frac{d\Phi^{\text{ext. gal.}}_{\bar{\nu}_e}}{dE} = \frac{\Omega_\chi \rho_{\text{crit}}}{4\pi m_X \tau_X} \sum_\alpha^3 \int_0^\infty \frac{dN^{ch}_{\bar{\nu}_\alpha}}{dE'_\nu} \frac{dz}{H(z)} P_{\bar{\nu}_\alpha \to \bar{\nu}_e}$$

Cosmology

τ_X: lifetime

$dN^{\text{ch}}_{\bar{\nu}_i}/dE_\nu$: neutrino production spectrum for a specific channel

$P_{\bar{\nu}_i \to \bar{\nu}_e}$: neutrino oscillation

The integral of Galactic DM distribution

$$\mathscr{D} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{\text{l.o.s}} \rho_\chi ds$$

NFW profile

Ω_χ: DM density

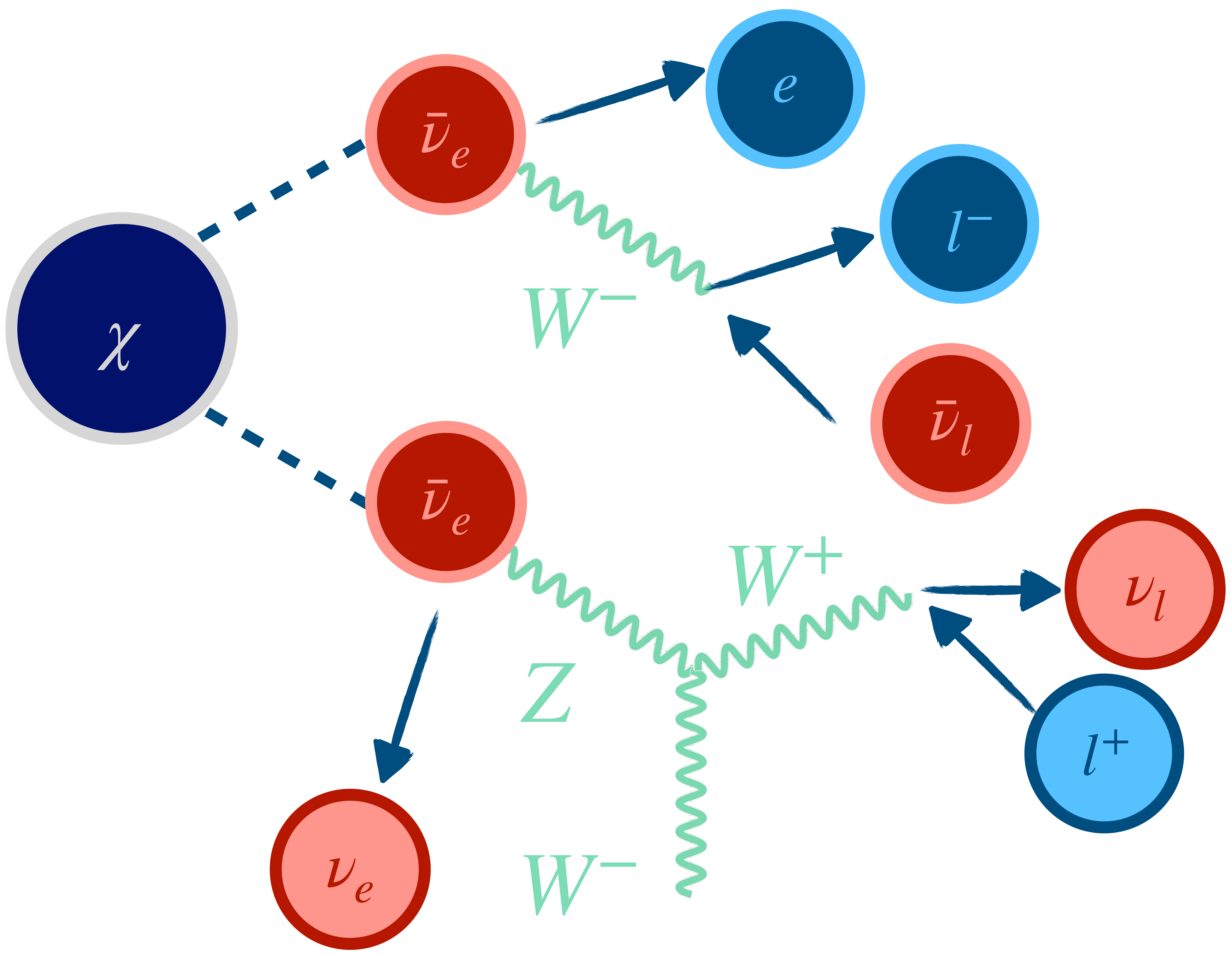
ρ_{crit}: critical density

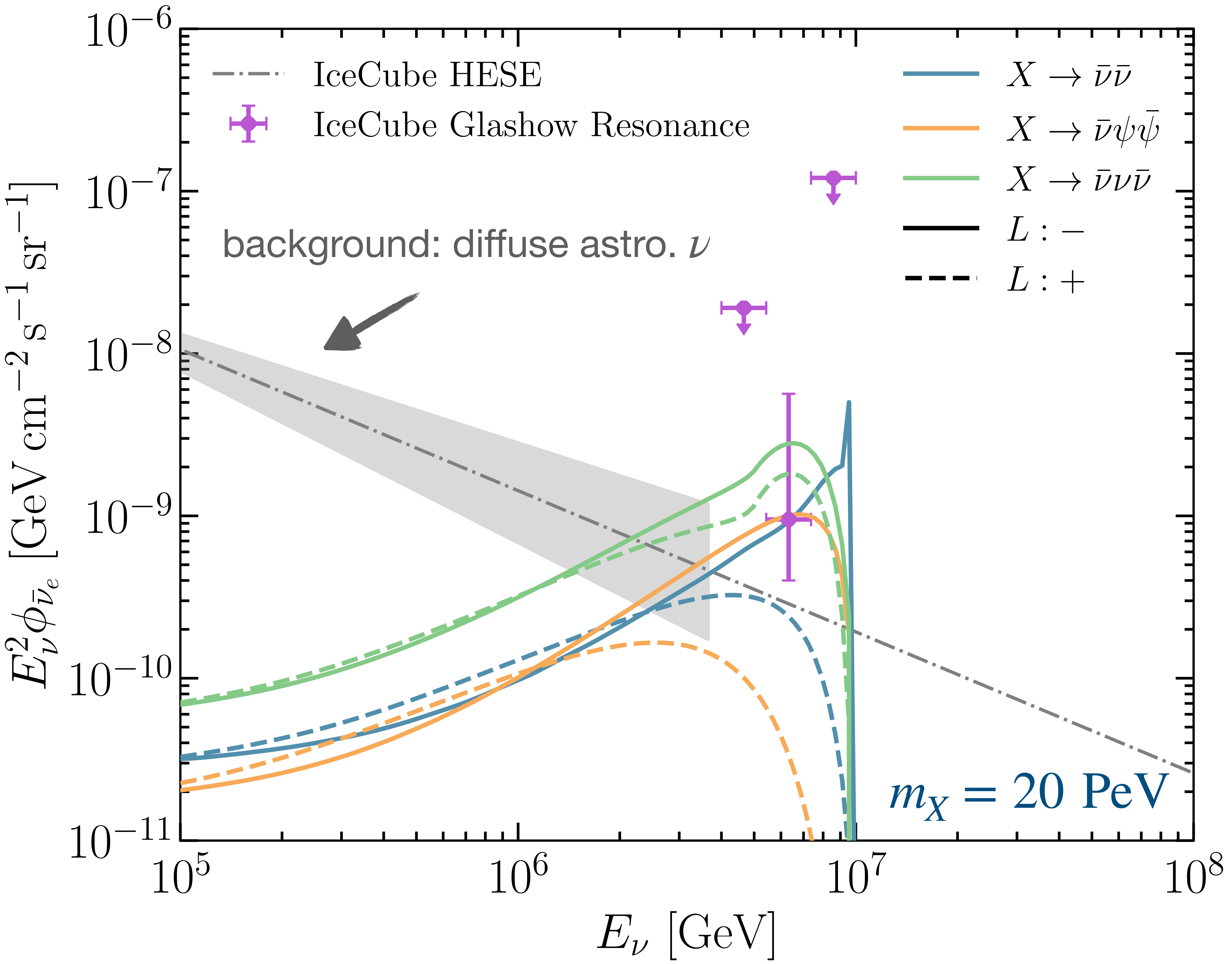
$E'_\nu = (1+z)E_\nu$: redshifted energy

H: Hubble expansion

Electroweak Showering

- **Both ν and $\bar{\nu}$ can be produced no matter whether the lepton number is positive or negative.**
- **The spectrum $dN^{\rm ch}_{\bar{\nu}_i}/dE_\nu$ becomes softer.**

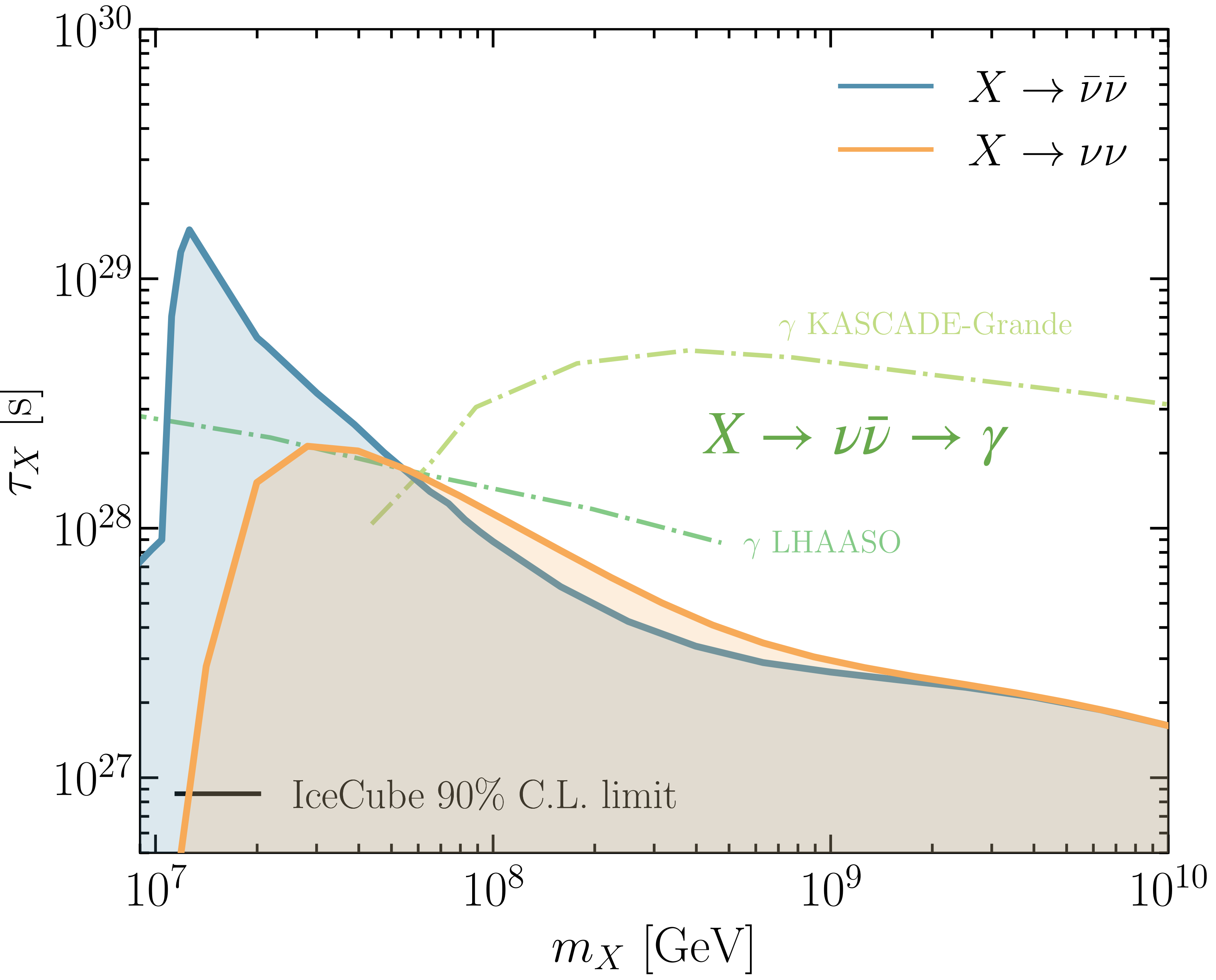


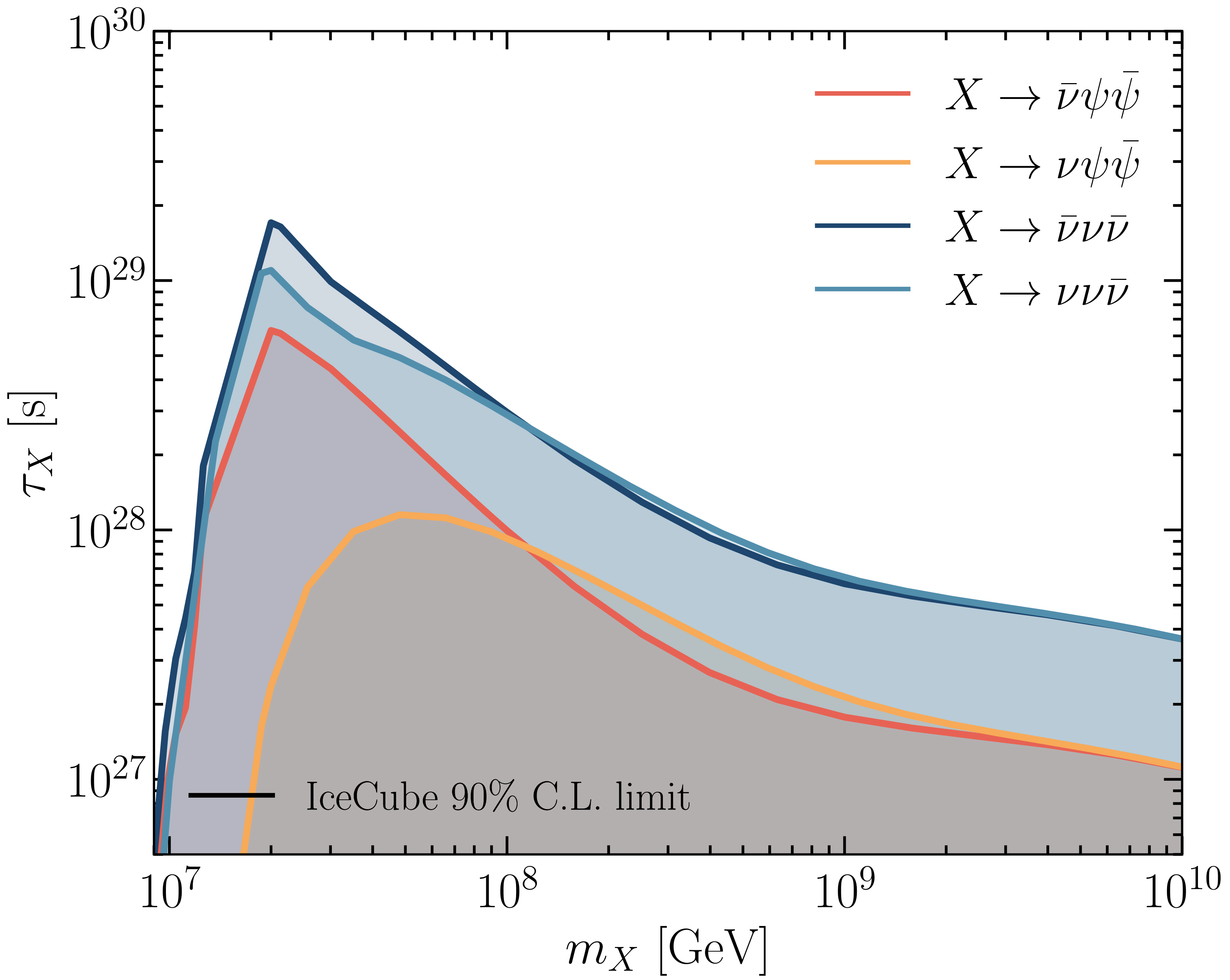


fragmentation functions from HDMSpectra

Bauer, Rodd, Webber 2007.15001

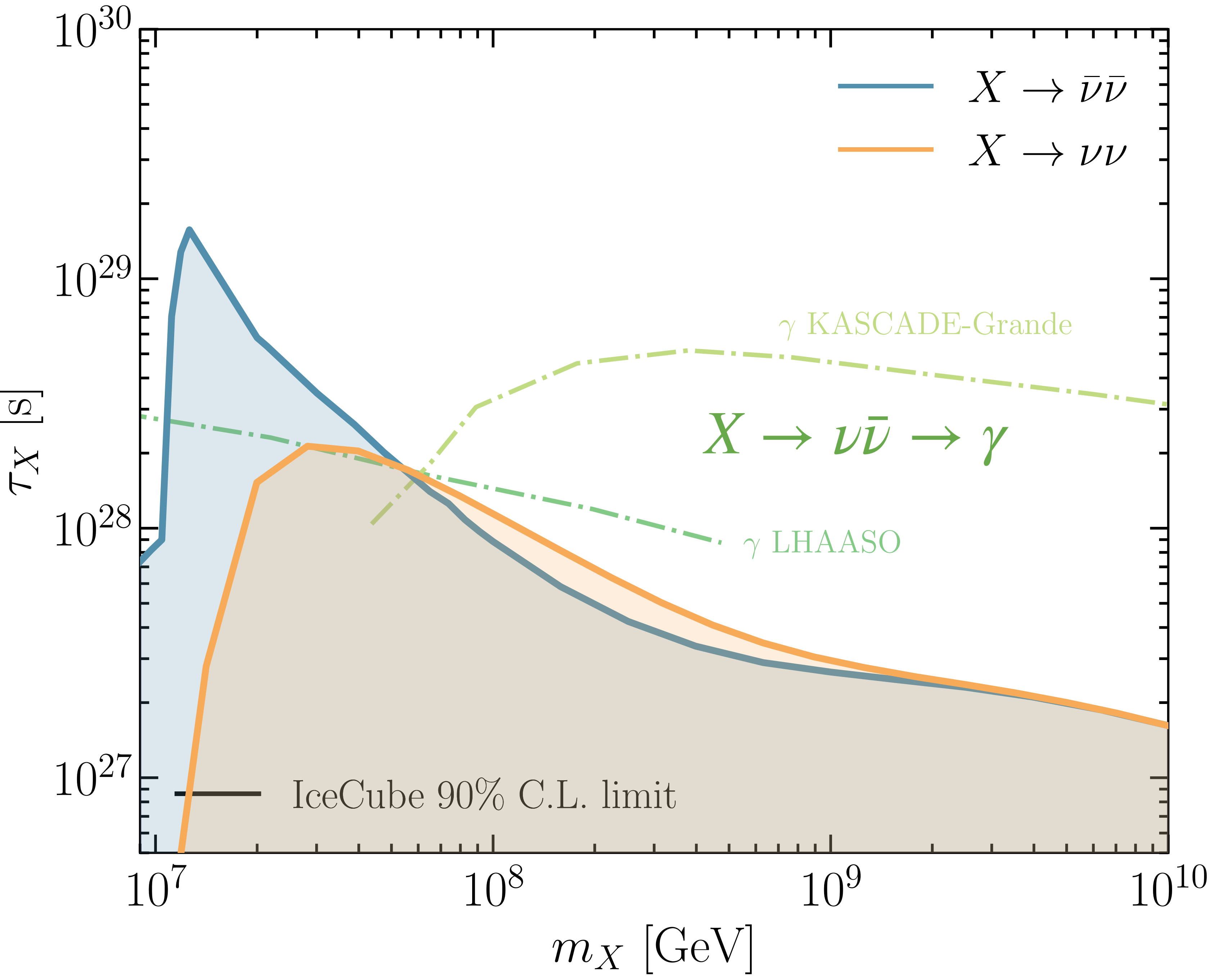
Constraints with Current Observation

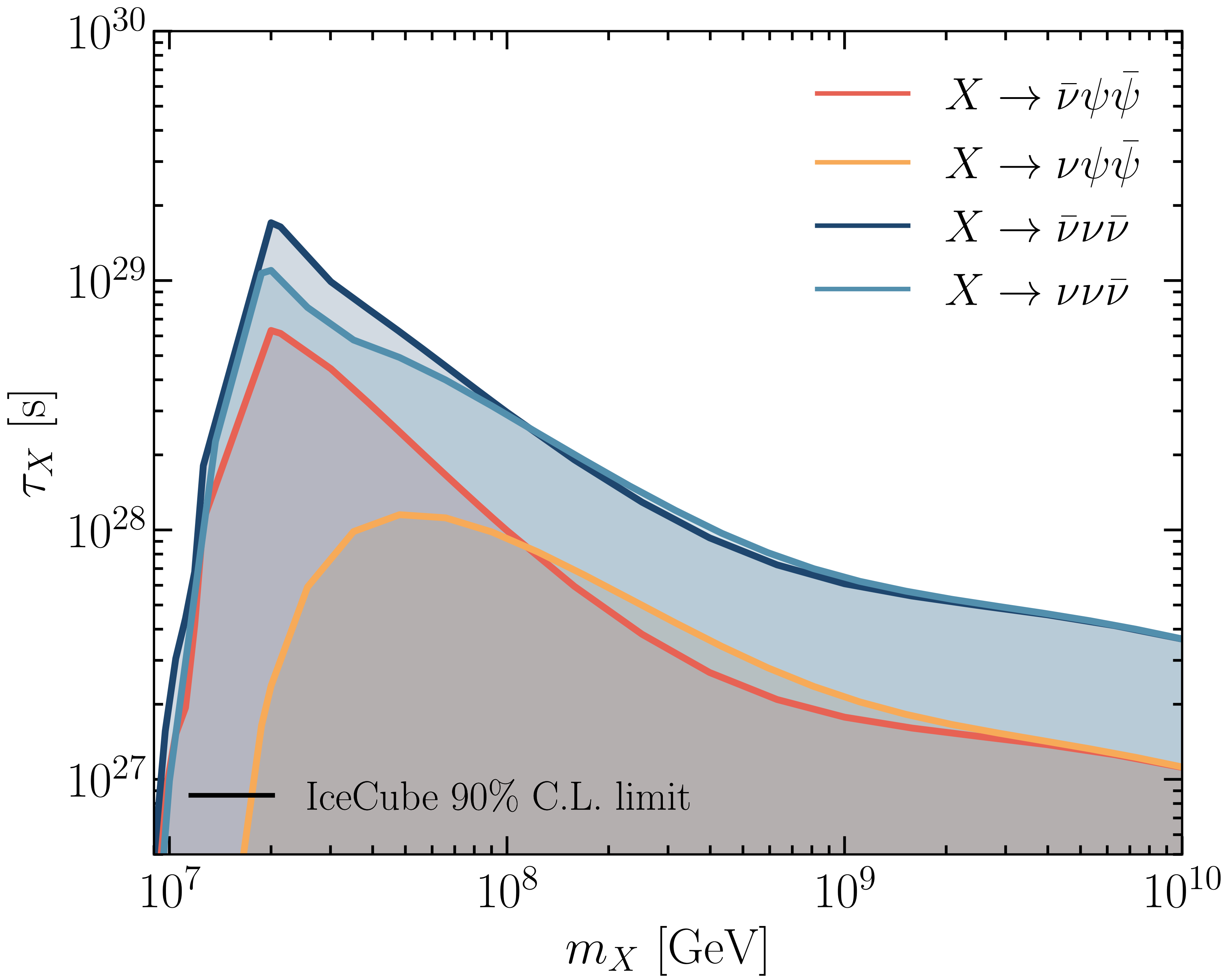


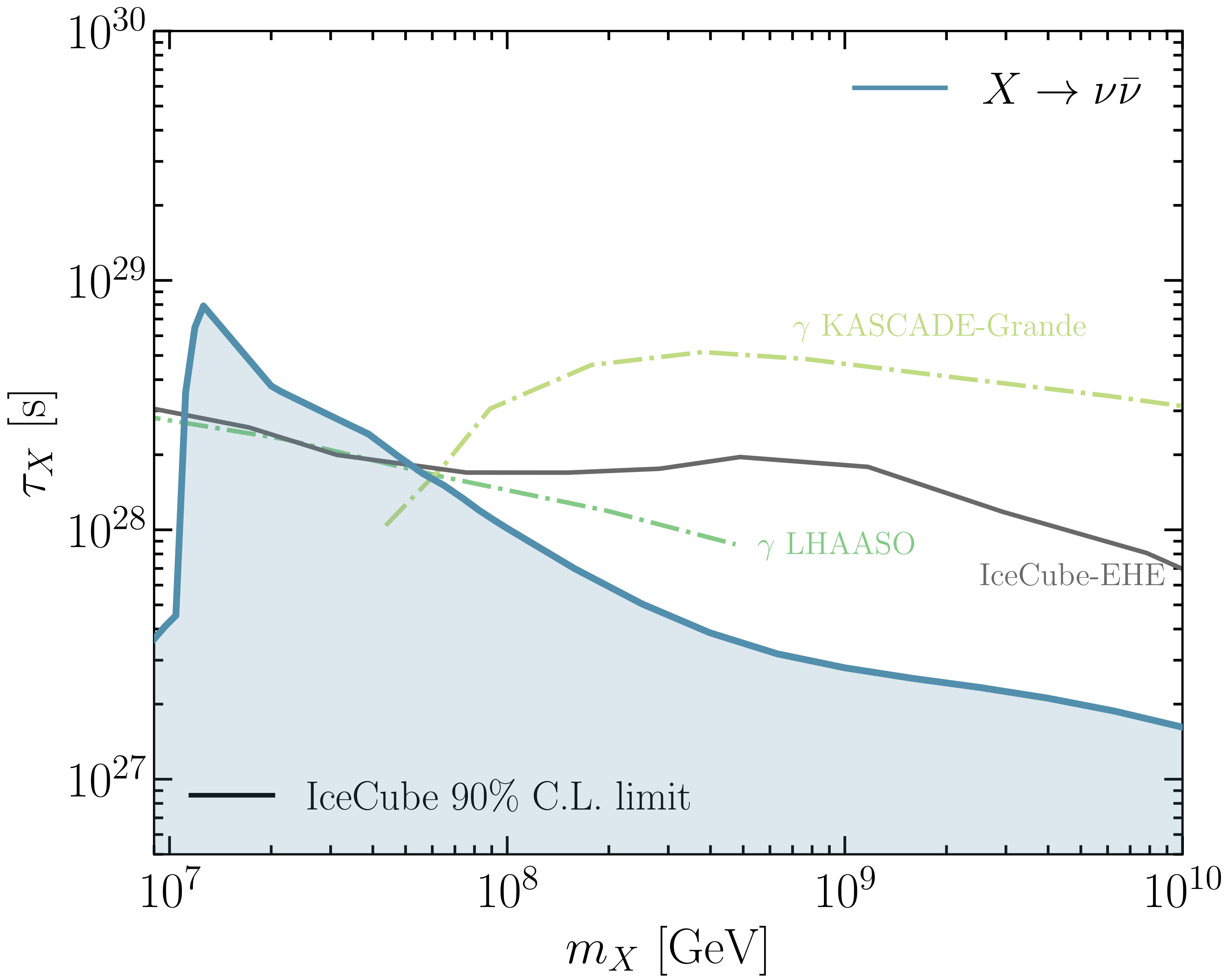


- **Scenarios with positive/negative lepton numbers can be constrained respectively for m_X ~ PeV - EeV.**
- **The sensitivity of Glashow Resonance weakens when the number of decay products increases as $\nu : \bar{\nu} \to 1 : 1$.**

Constraints with Current Observation







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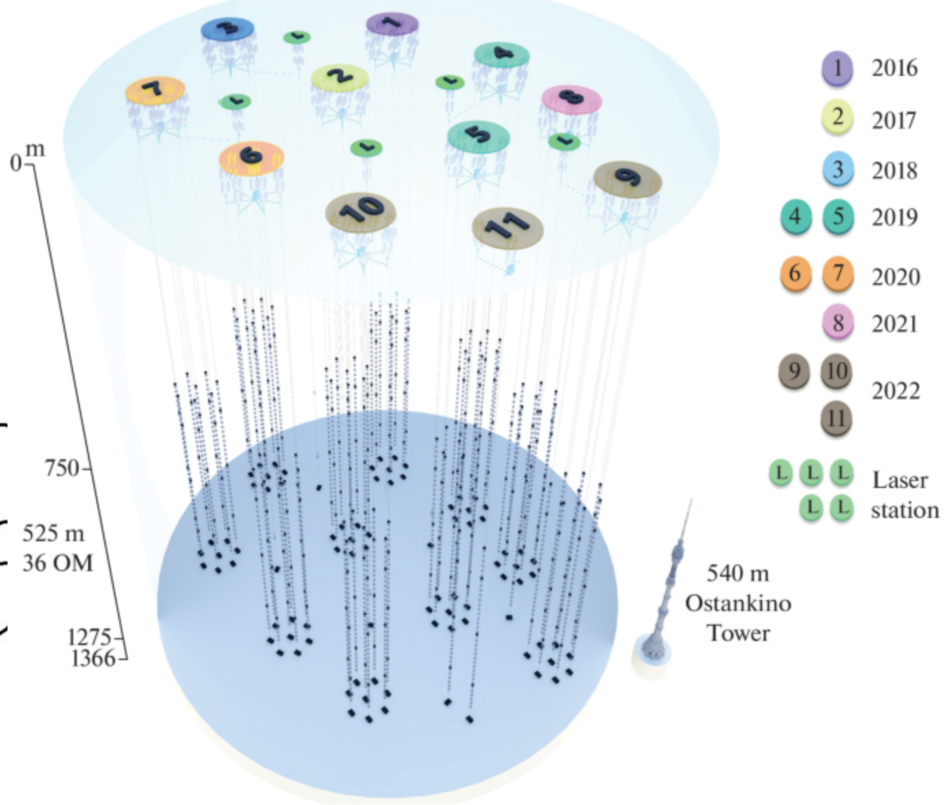
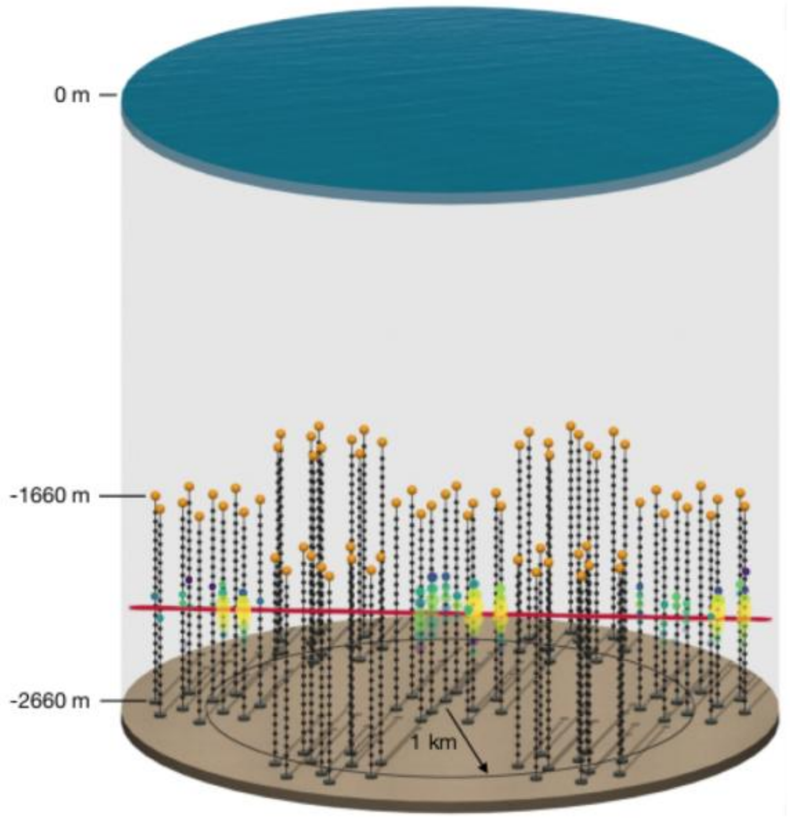
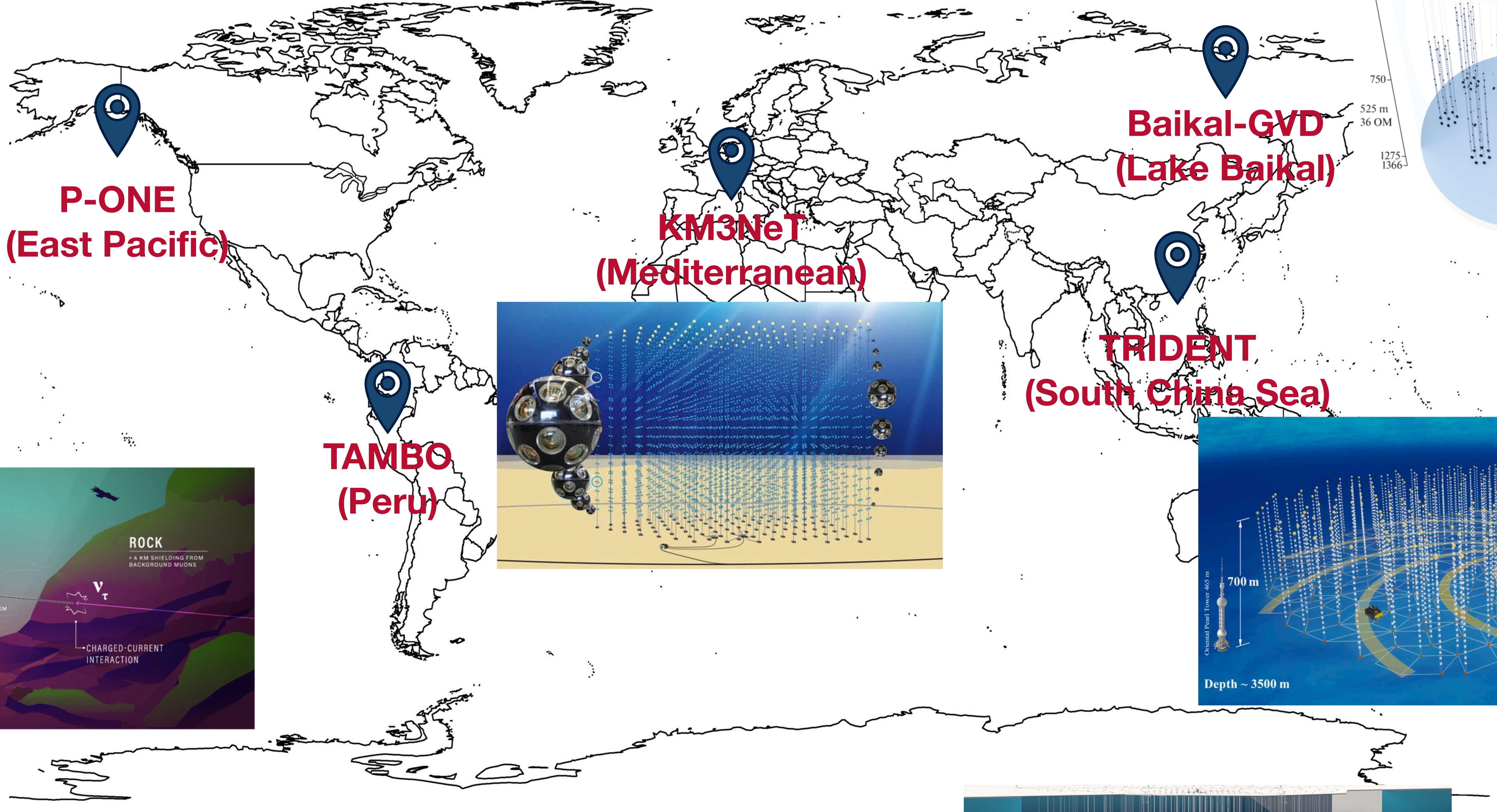
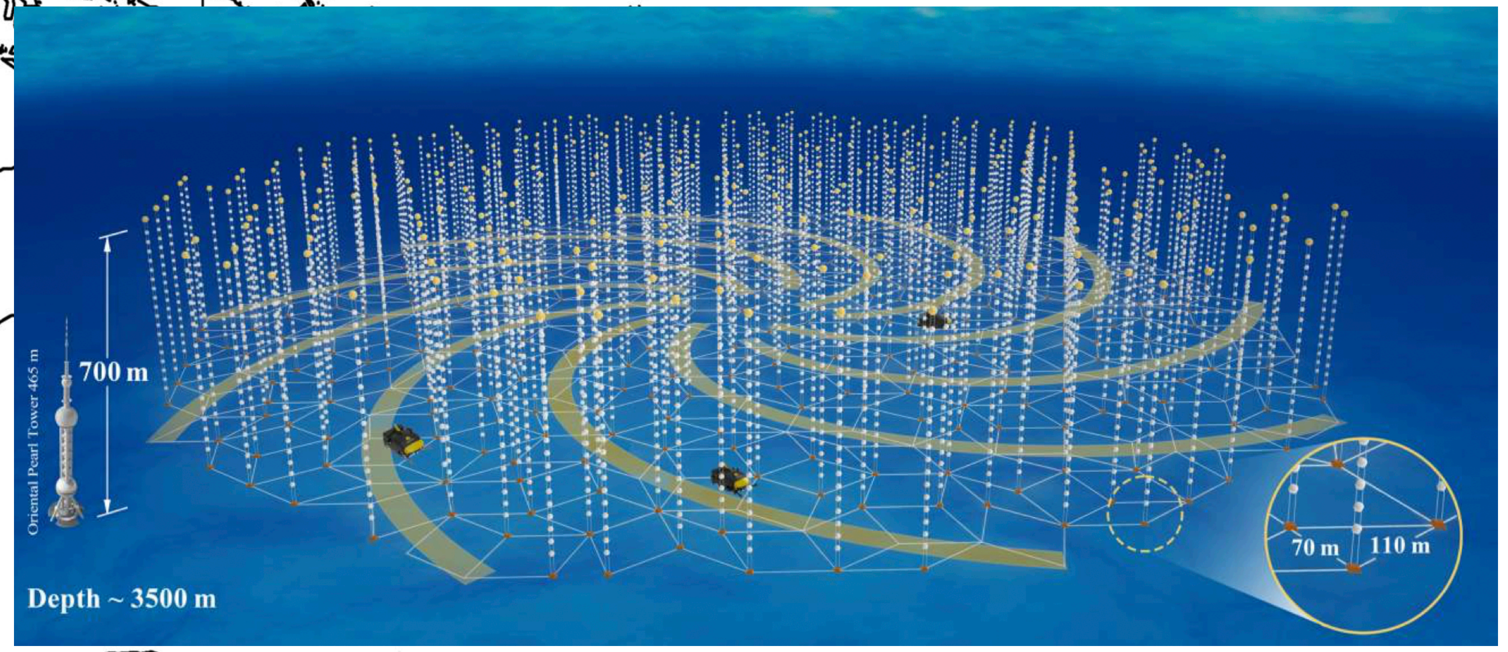
Better constraints on neutrino portal of symmetric DM decay for m_X ~ 10 - 100 PeV

Next-Generation High-Energy Neutrino Telescopes

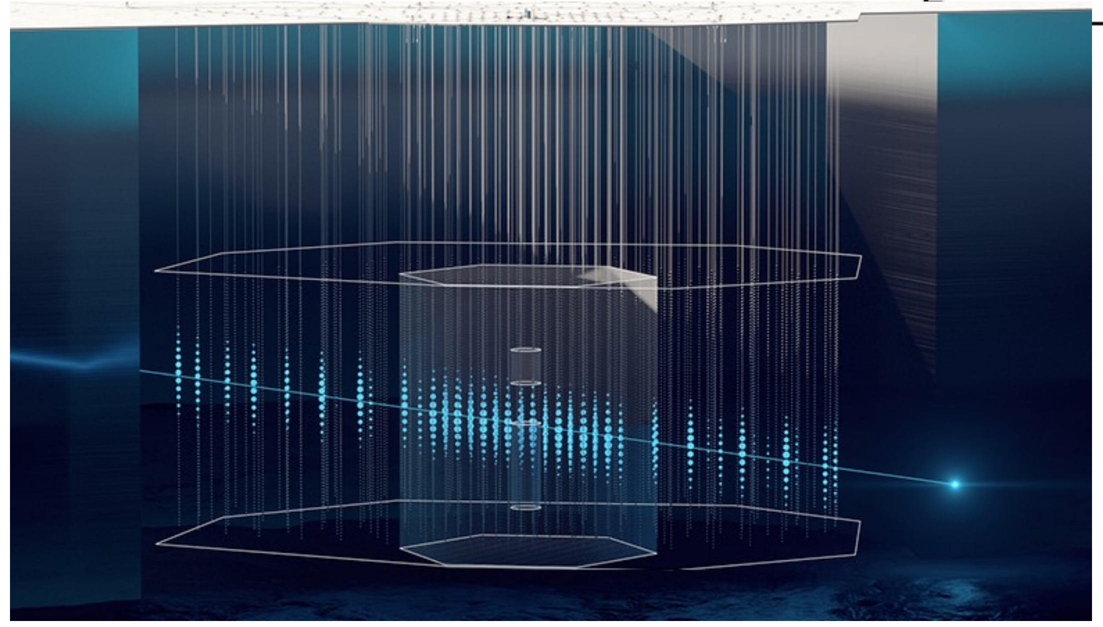








IceCube-Gen2
(South Pole)



More telescopes with larger exposure!

Glashow Resonance Signal

Glashow resonant events can be identified on an event-wise basis in the [4,10] PeV deposited energy window.

★ $W^- \rightarrow \text{hadrons}$ **BR ~67 %**

✔ escaping muons, the only irreducible background is from neutral-current events

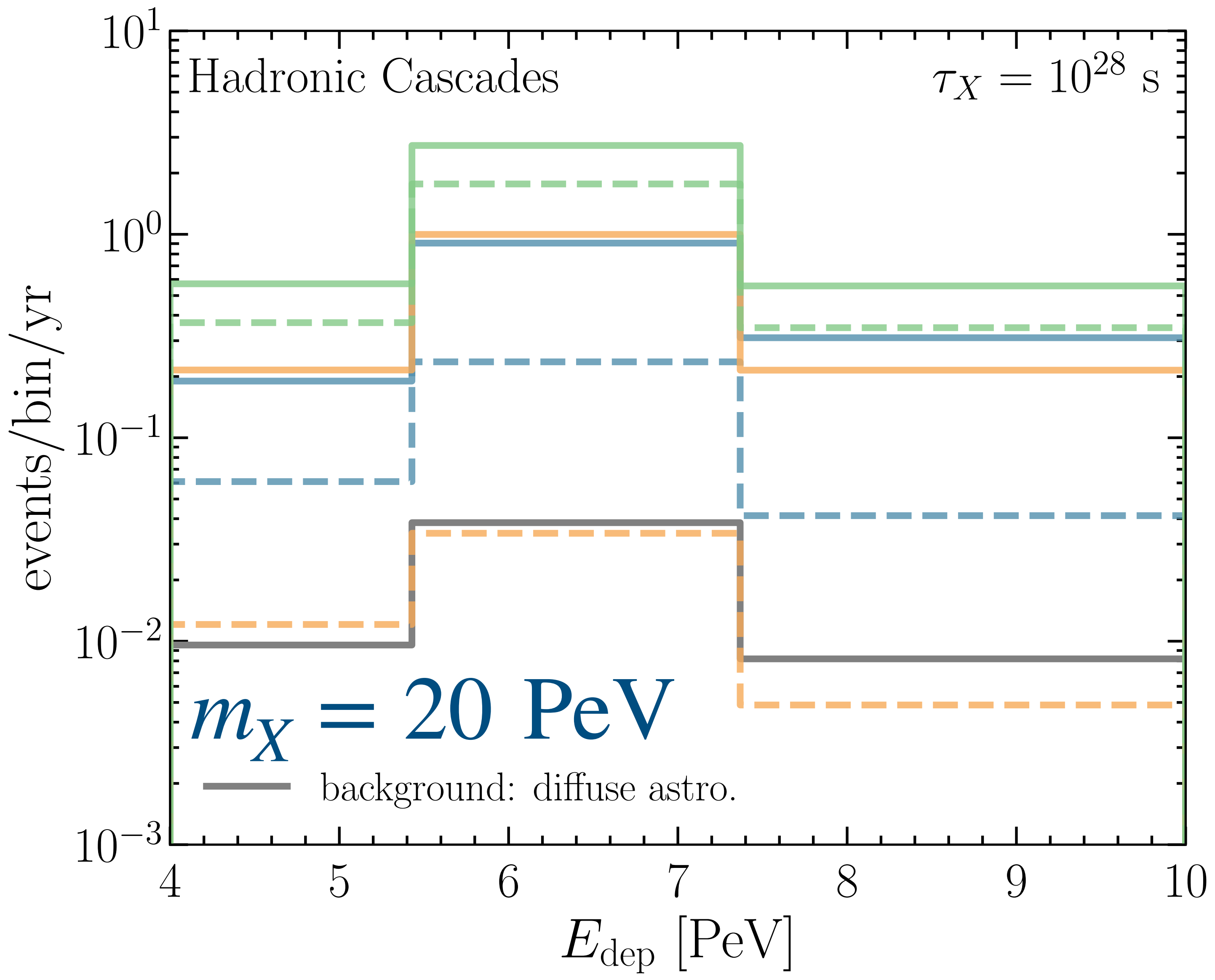
★ $W^- \rightarrow e^-\bar{\nu}_e/\tau^-\bar{\nu}_\tau$ **BR ~11 %**

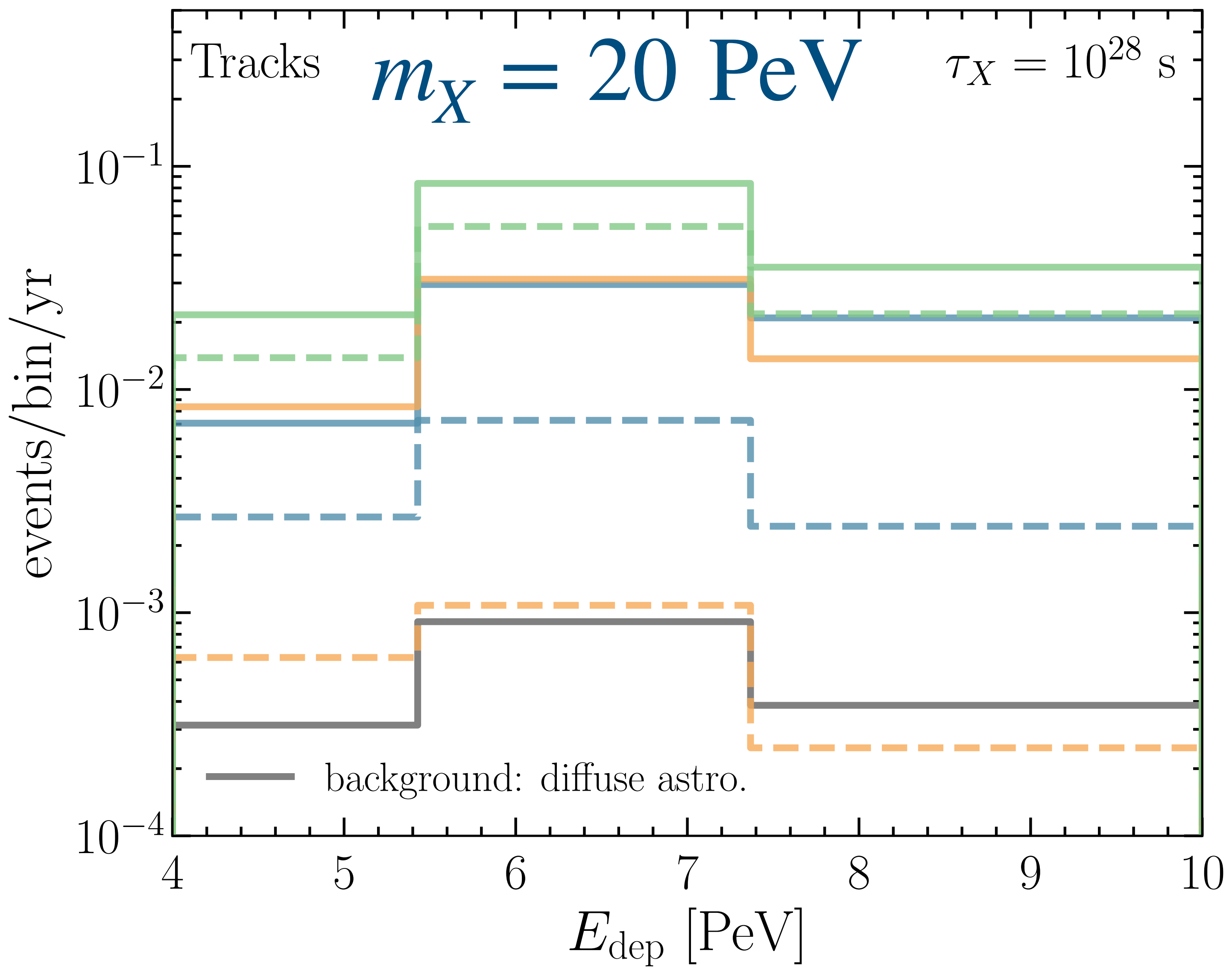
✘ Undistinguishable to a deep-inelastic-scattering cascade

★ $W^- \rightarrow \mu^-\bar{\nu}_\mu$ **BR ~11 %**

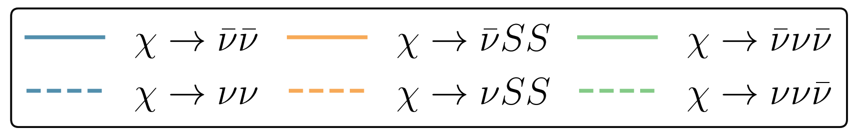
✔ track without the initial cascade compared to ν_μ charged-current events

QL, Song, Vincent, 2304.06068





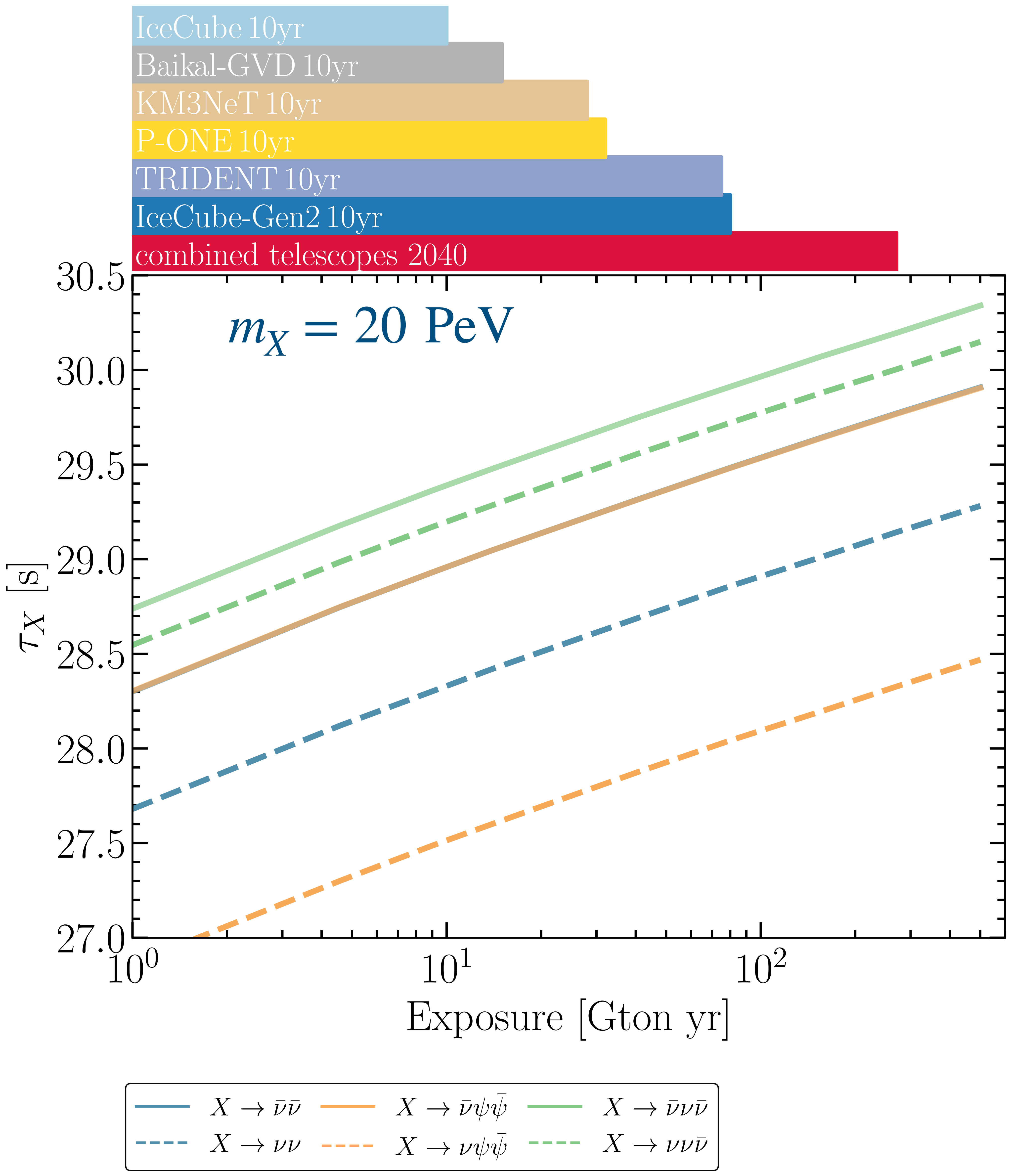
Event rates of Glashow resonance at IceCube as partially contained events

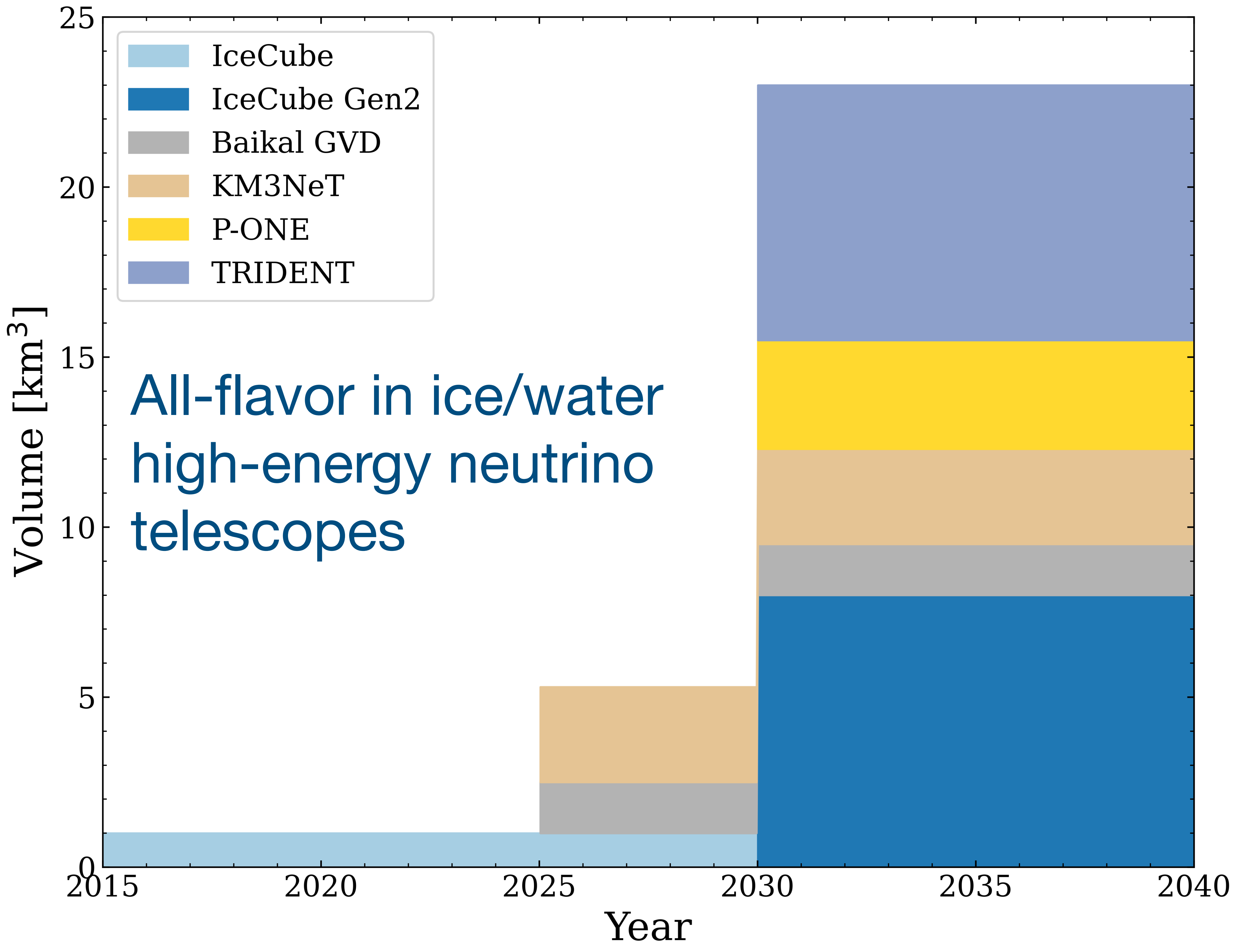


Projected Sensitivities in the Future

- 90% C.L. sensitivities are estimated.
- Projected 10yr IceCube-Gen2 (8 × IceCube) sensitivities have lifetimes ~5 of current constraints.

Projected Sensitivities in the Future





Summary

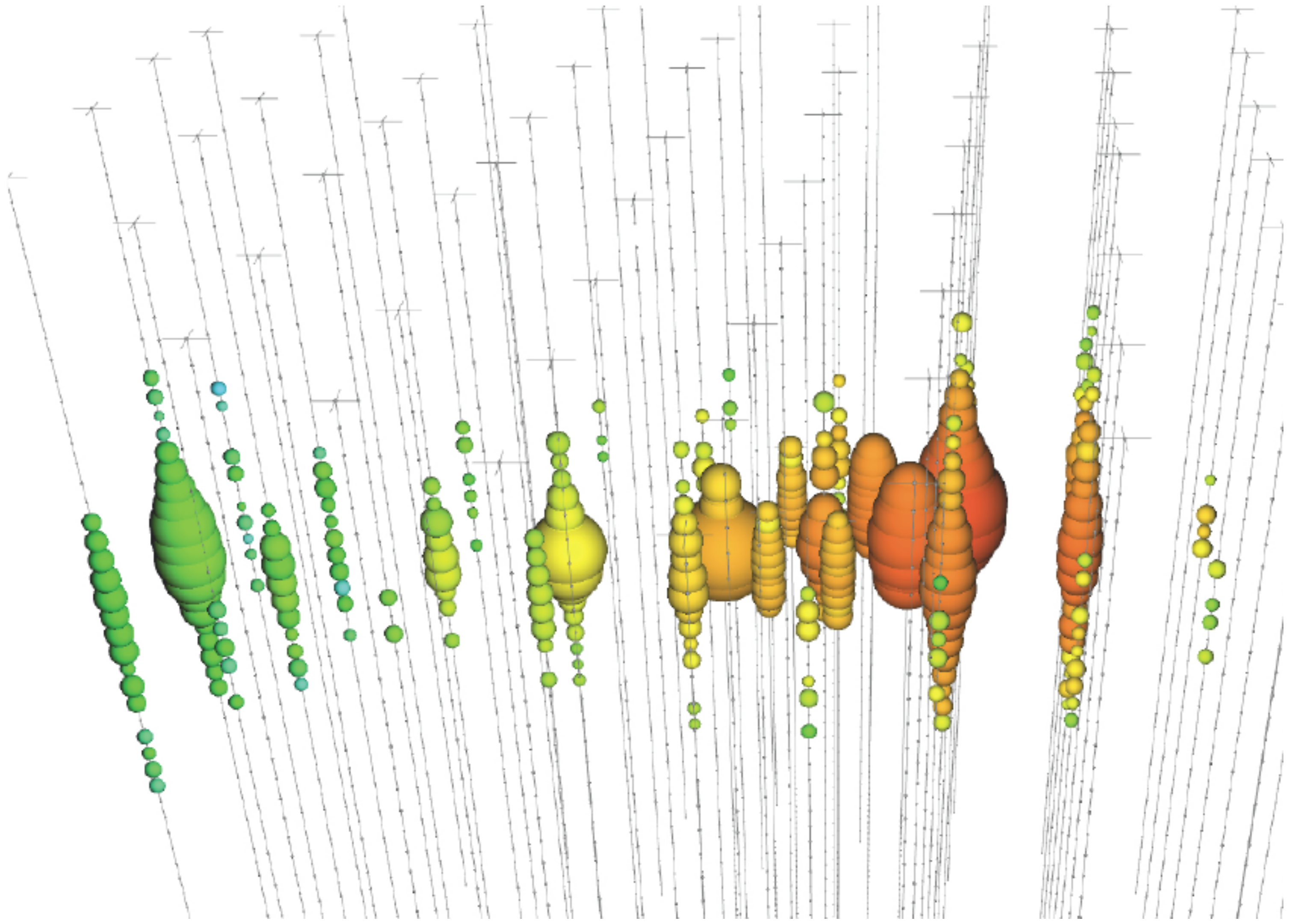
- ADM models predict DM carrying B-L numbers, resulting in asymmetry of particle/antiparticle signals in indirect DM searches.
- The Glashow Resonance provides a way to differentiate neutrinos and antineutrinos in detection at high energies.
- IceCube observed the first candidate of such events, which can be used to constrain the lifetime of ADM.
- The sensitivities to the lifetime with the next-generation neutrino telescopes are estimated.

Thank you!

Bonus Slides

Event Morphologies

Charged Current ν_μ



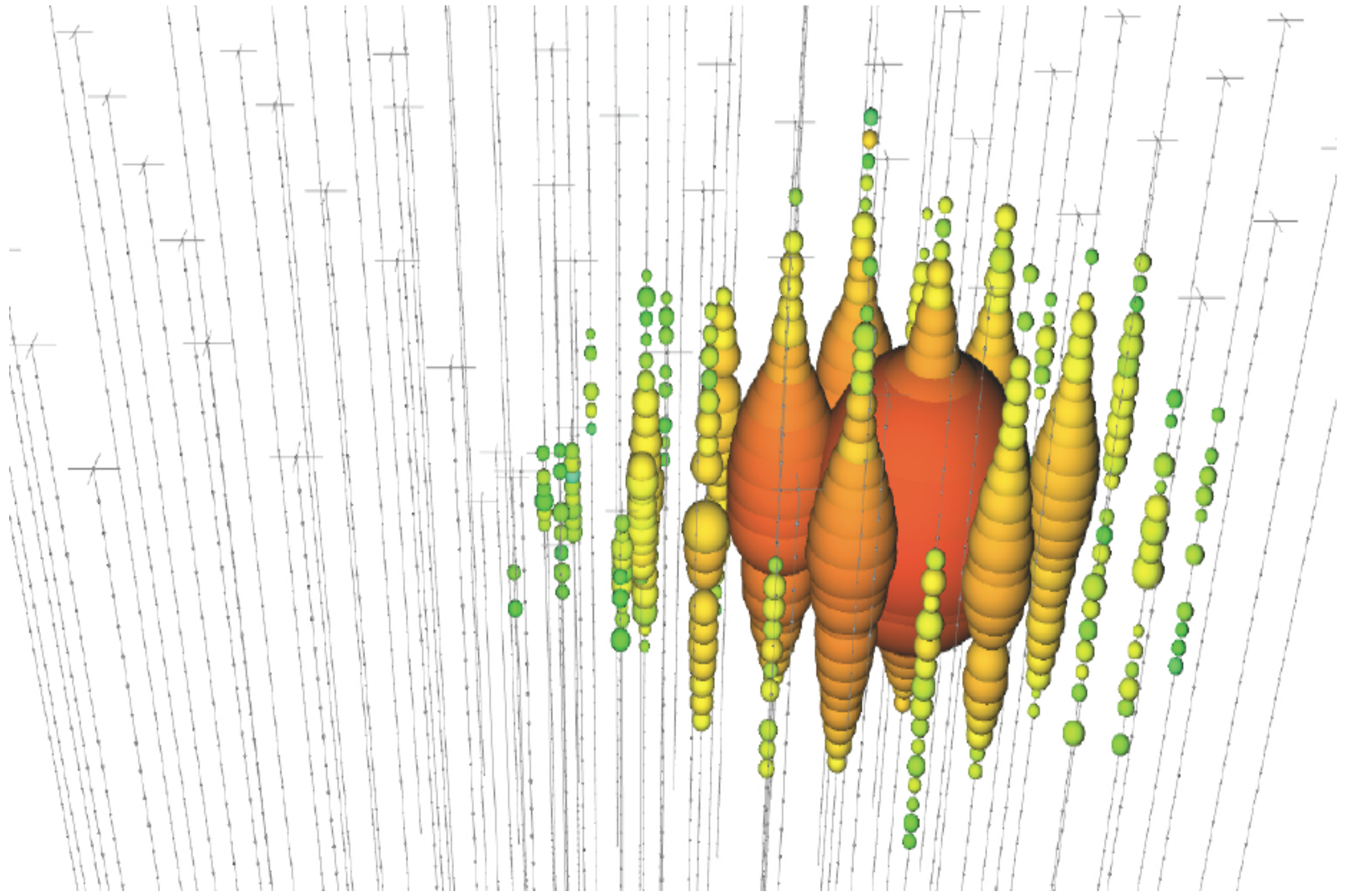
$$\nu_\mu + N \rightarrow \mu + X$$

Track (data)

Angular resolution $0.2^\circ \sim 1^\circ$

Energy resolution ~ $2E$

Neutral Current ν / Charged Current ν_e



$$\nu_e + N \rightarrow e + X$$

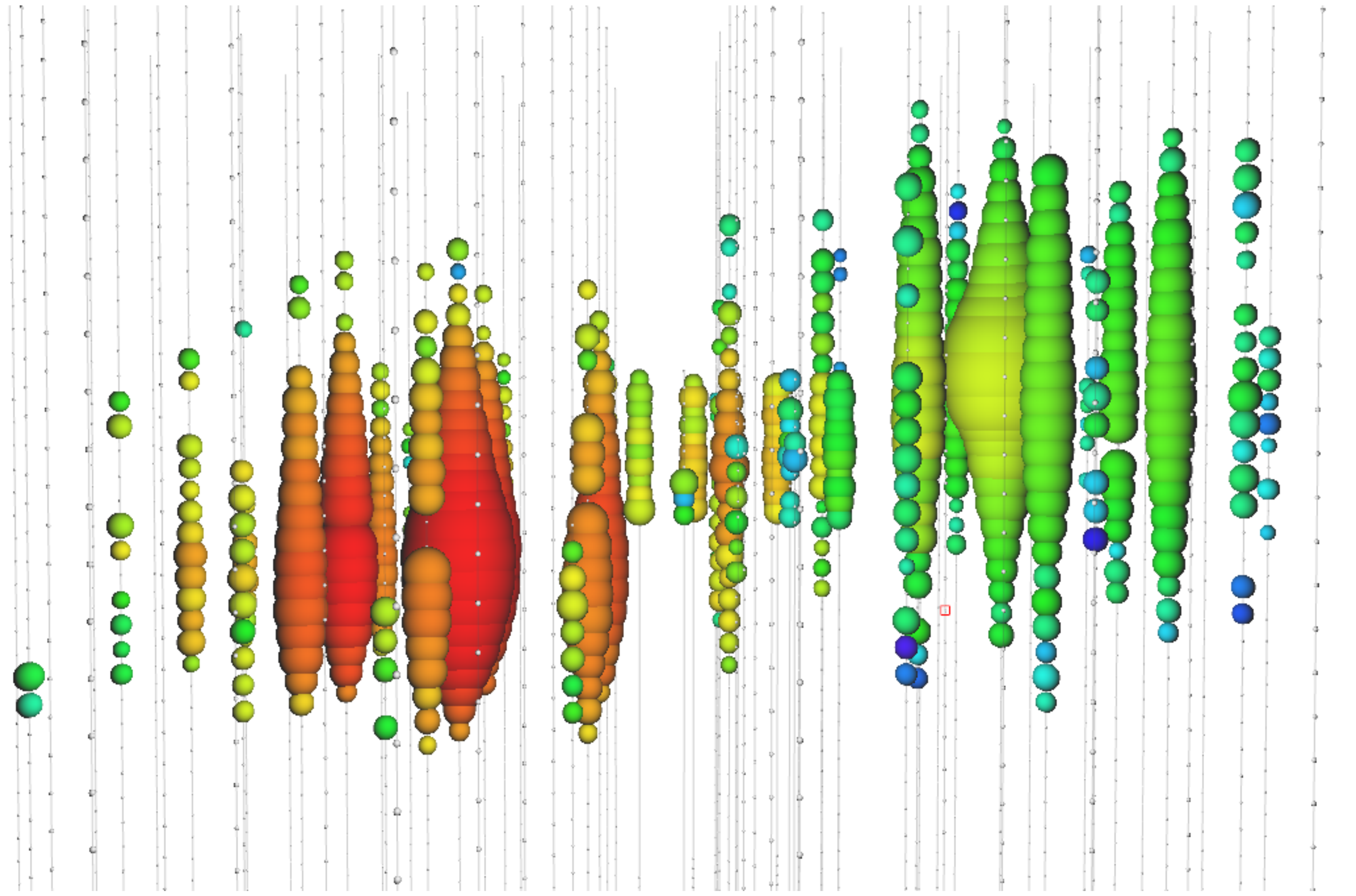
$$\nu_x + N \rightarrow \nu_x + N$$

Cascade (data)

Angular resolution $5^\circ \sim 10^\circ$

Energy resolution $\sim 15\,\%\,E$

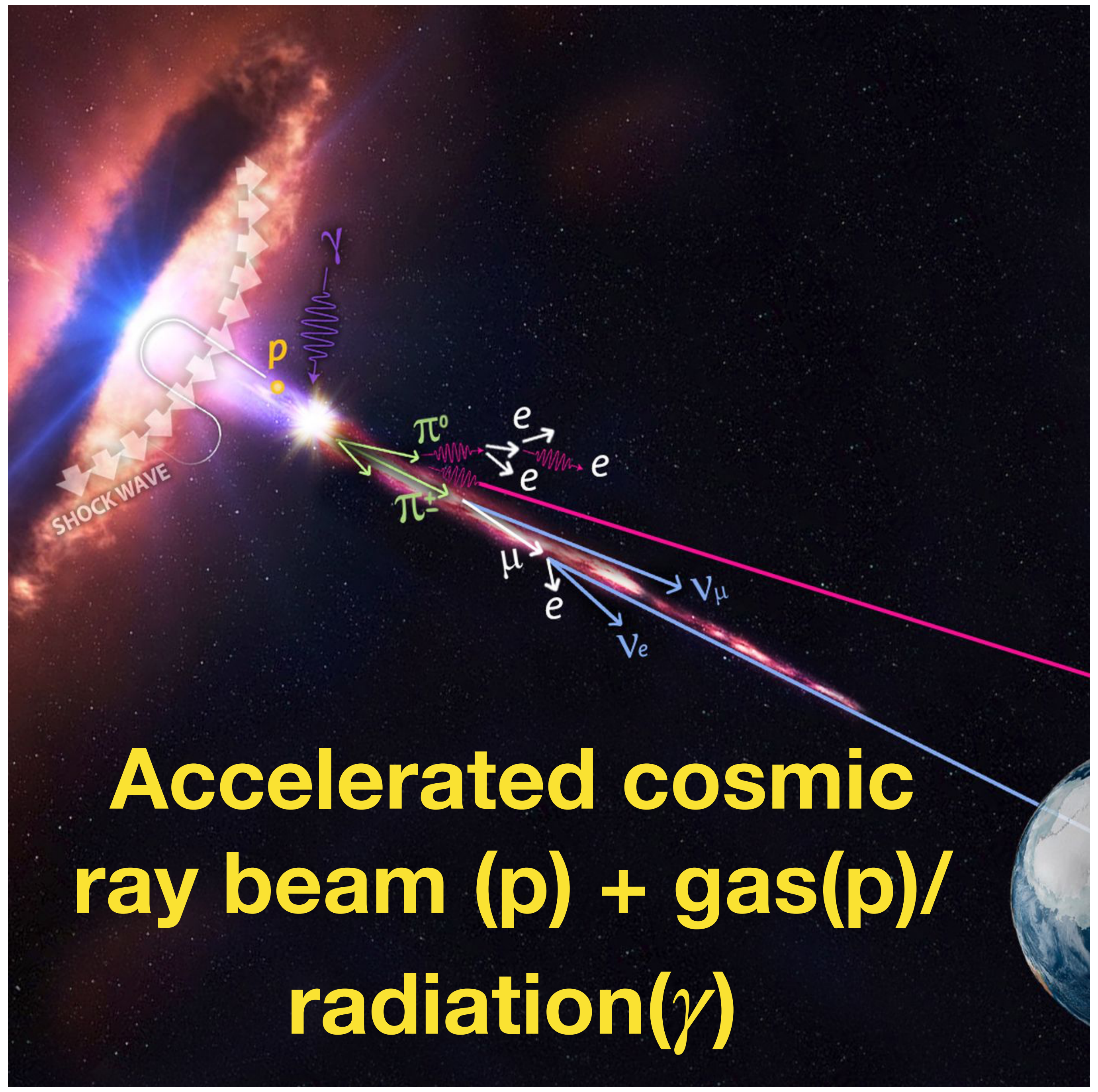
Charged Current ν_τ



$$\nu_\tau + N \rightarrow \tau + X$$

"Double-Cascade" (simulation)

Astrophysical Processes



Hadronuclear $p + p \to n_\pi \left[\pi^0 + \pi^+ + \pi^-\right]$

Photohadronic $p + \gamma \to \Delta^+ \to \pi^+ + n$

Uniform distribution of all charges

Dominating π^+

$$\begin{cases} \pi^+ \to \nu_\mu + \mu^+ \to \nu_\mu + \left(e^+ + \nu_e + \bar{\nu}_\mu\right) \\ \pi^- \to \bar{\nu}_\mu + \mu^- \to \bar{\nu}_\mu + \left(e^- + \bar{\nu}_e + \nu_\mu\right) \end{cases}$$

Asymmetry of pion charges can be seen in the ν vs $\bar{\nu}$ ratio

Differentiating ν and $\bar{\nu}$

standard mixing

	$\{f_{\nu_e,s}, f_{\bar{\nu}_e,s}\} : \{f_{\nu_\mu,s}, f_{\bar{\nu}_\mu,s}\} : \{f_{\nu_\tau,s}, f_{\bar{\nu}_\tau,s}\}$	$\longrightarrow$	$\{f_{\nu_e,\oplus}, f_{\bar{\nu}_e,\oplus}\} : \{f_{\nu_\mu,\oplus}, f_{\bar{\nu}_\mu,\oplus}\} : \{f_{\nu_\tau,\oplus}, f_{\bar{\nu}_\tau,\oplus}\}$
pp	$\{1,1\} : \{2,2\} : \{0,0\}$		$\{0.17,0.17\} : \{0.17,0.17\} : \{0.16,0.16\}$
$p\gamma$	$\{1,0\} : \{1,1\} : \{0,0\}$		$\{0.26,0.08\} : \{0.21,0.13\} : \{0.20,0.13\}$
pp μ damped	$\{0,0\} : \{1,1\} : \{0,0\}$		$\{0.11,0.11\} : \{0.20,0.20\} : \{0.19,0.19\}$
$p\gamma$ μ damped	$\{0,0\} : \{1,0\} : \{0,0\}$		$\{0.23,0.00\} : \{0.39,0.00\} : \{0.38,0.00\}$

Spectrum Generation with Electroweak Corrections

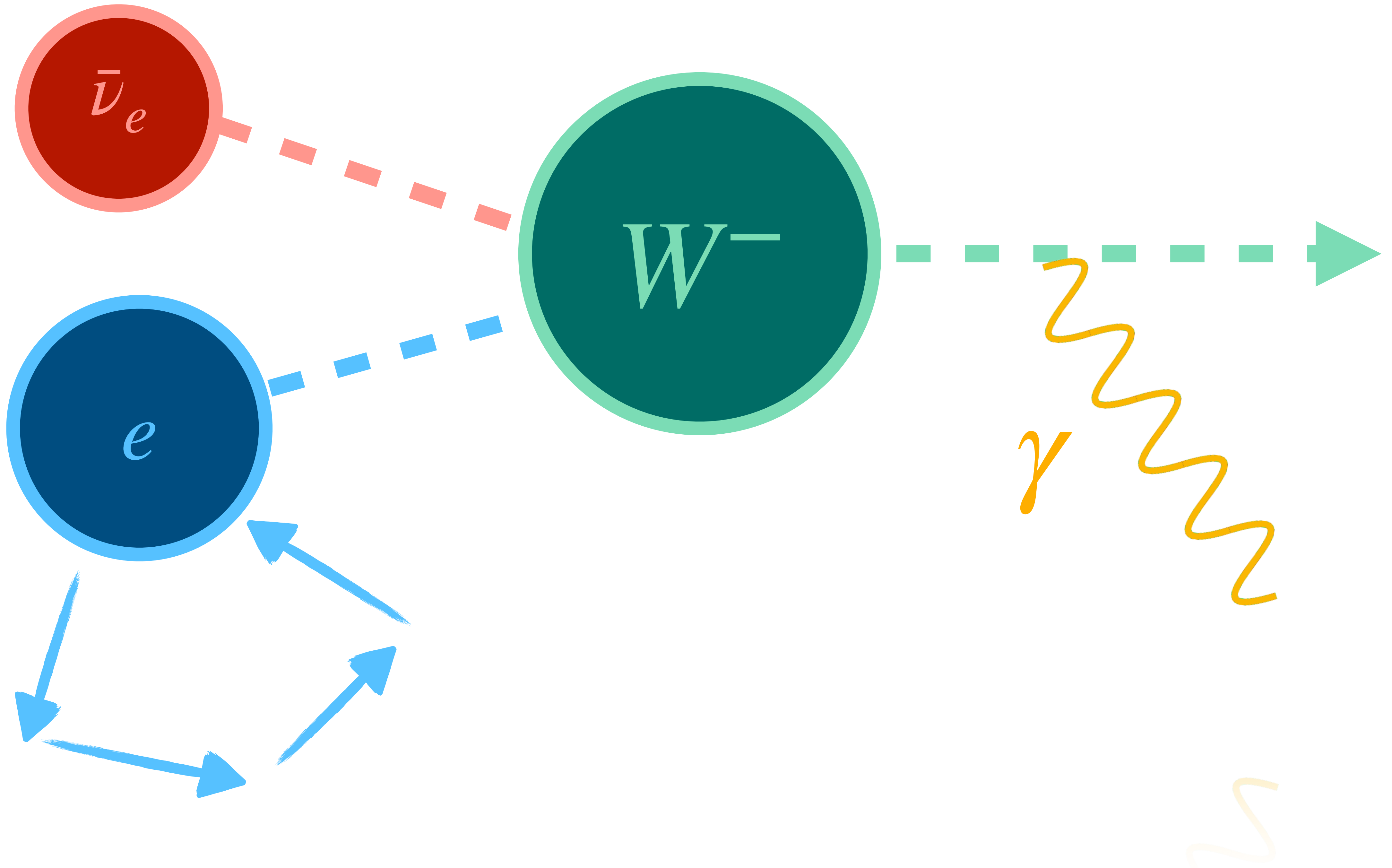
$$\frac{dN^{\mathrm{ch}}_{\bar{\nu}_i}}{dE_\nu}(E_\nu) = \sum_j \int_{E_\nu/m_\chi}^{1} \frac{1}{ym_\chi} \frac{df_j}{dy} D_j^{\bar{\nu}_i}\left(\frac{E_\nu}{ym_\chi}; ym_\chi\right) dy$$

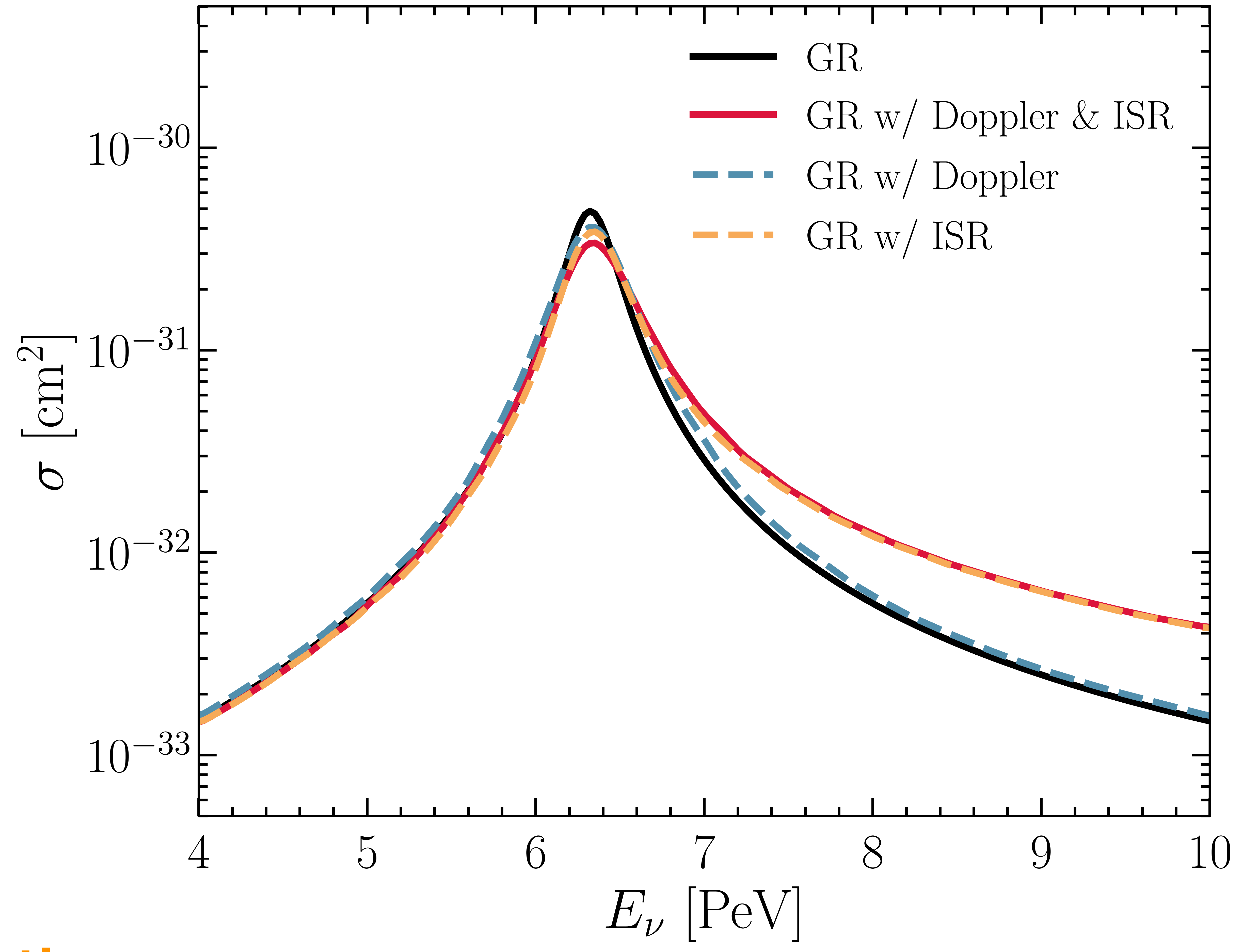
Initial energy distribution of the decay product i with $E_i = ym_\chi$

Fragmentation function from i to $\bar{\nu}_e$, including electroweak showering and sequent evolution

Corrected Cross Section

subleading effects that affect the cross section





Atomic e motion:
Doppler Broadening

Initial State Radiation