Neutrino and Gamma Ray Annihilation Signatures from Inelastic Dark Matter Around Neutron Stars

Qinrui Liu

Queen's University

with Javier F. Acevedo, Joseph Bramante and Narayani Tyagi

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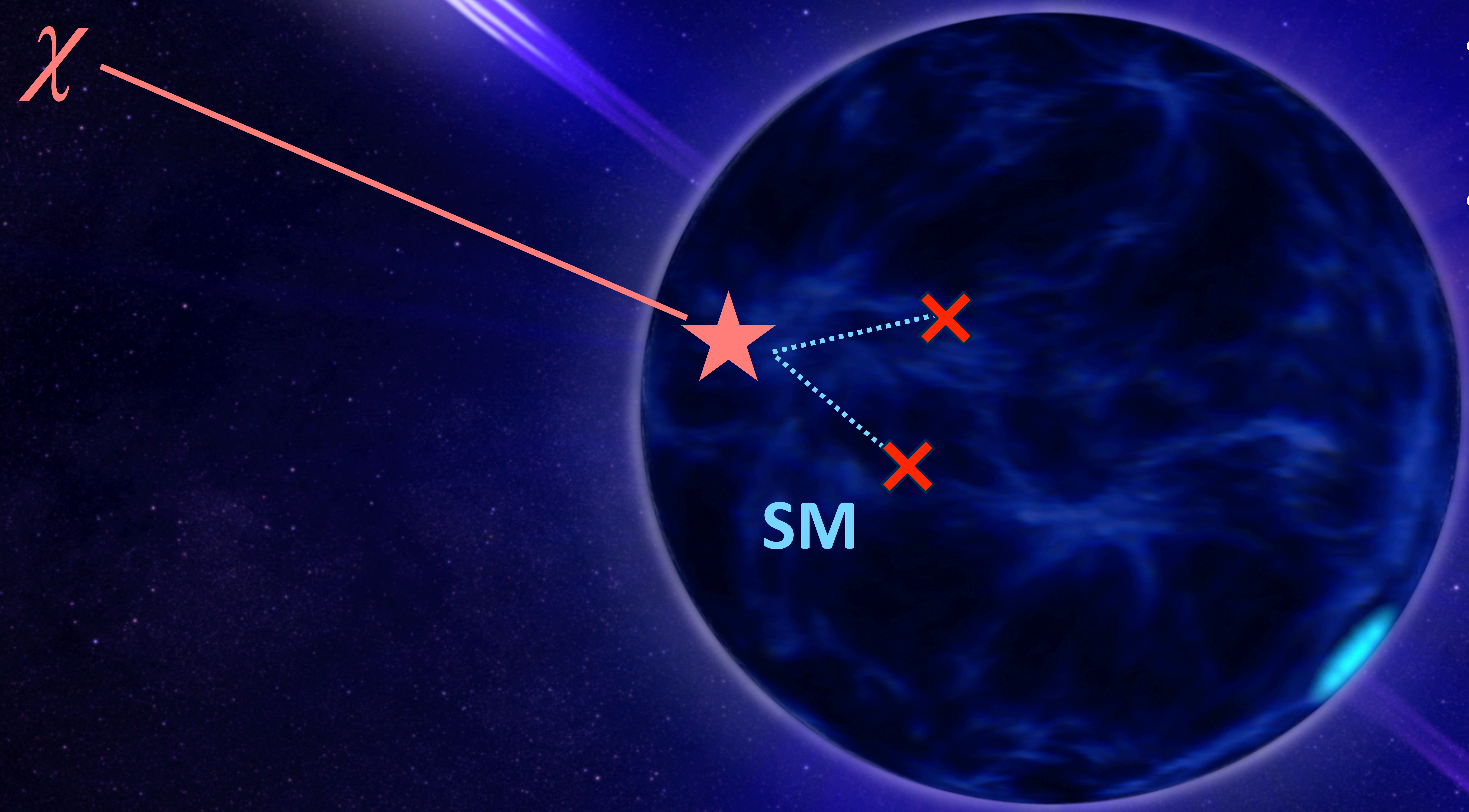
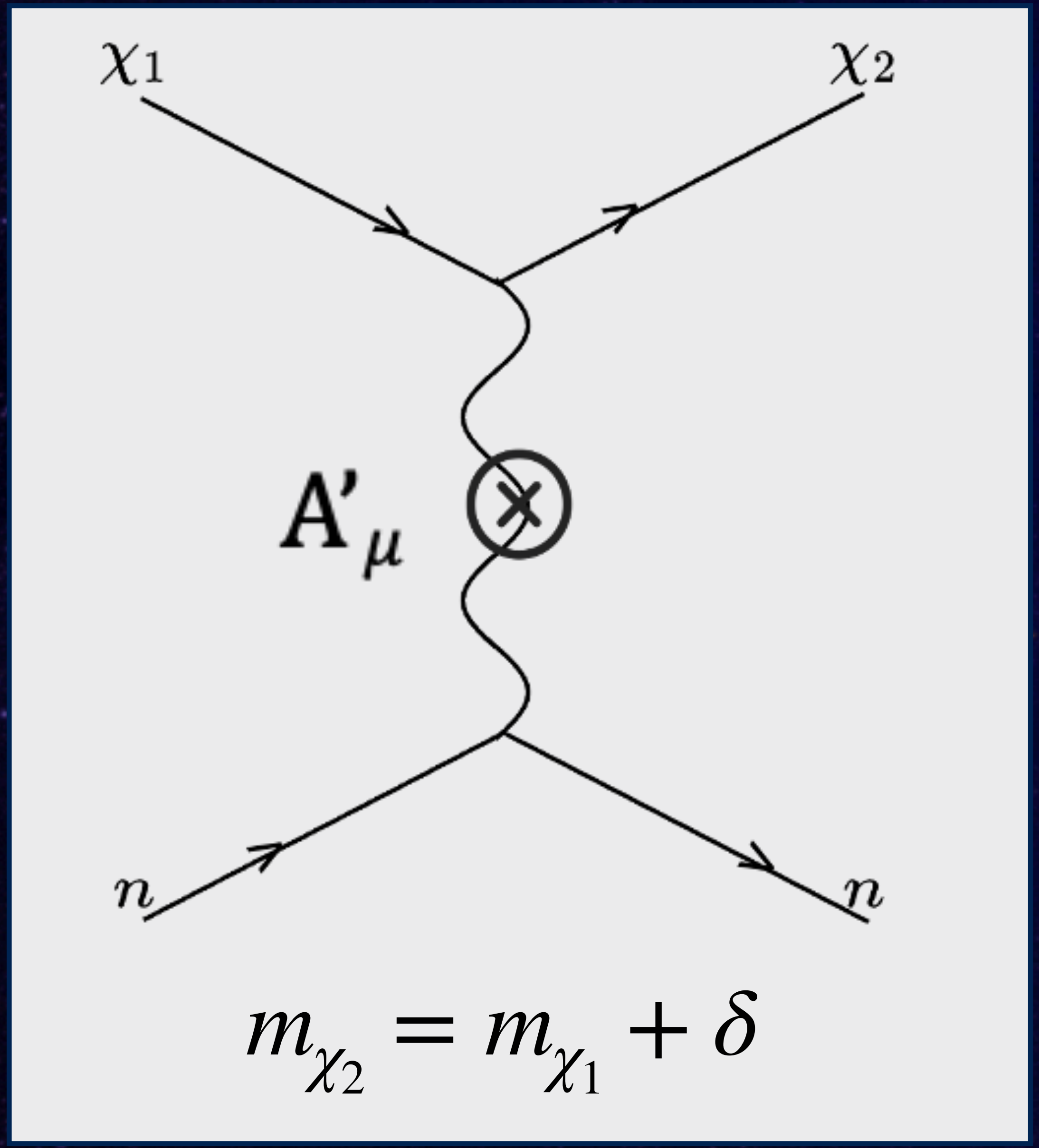
DM Capture & Annihilation in NS



- DM can be gravitationally captured by celestial bodies.
- DM sinks toward the center fast.
- An NS efficiently captures and accumulates DM due to the dense environment. However, annihilation products cannot escape, even for neutrinos.

DM Capture & Annihilation in NS



- For inelastic DM, the process for DM to settle down completely inside the NS is much slower.
- If DM is outside the NS for a time long enough, the annihilation products can be detected.

Fate of DM at NS - the Thermalization Processes

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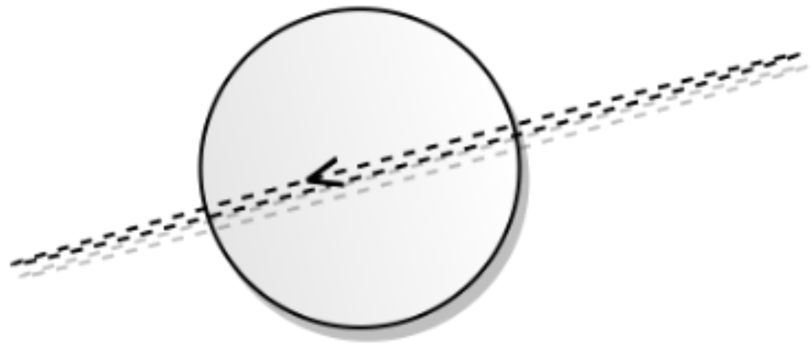
- Stage 1:

$R > R_{NS}$



DM is captured by NS.

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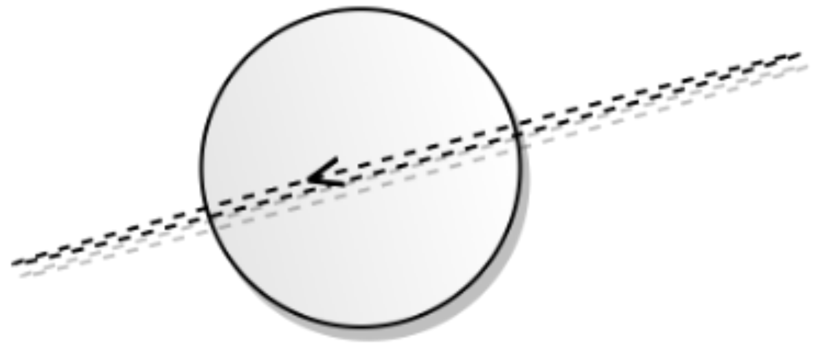
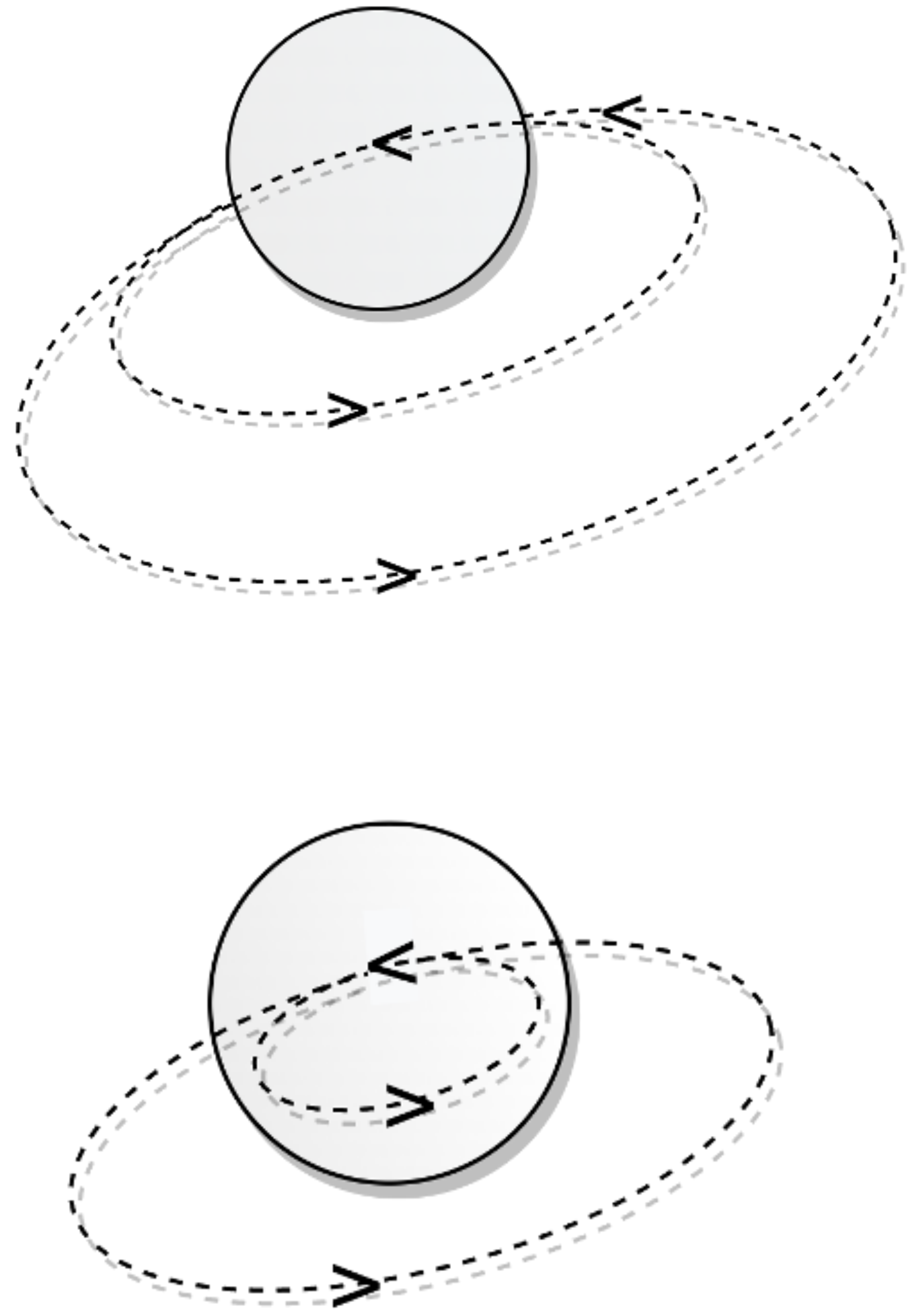


DM is captured by NS.

- Stage 2:

$R > R_{NS} \to R < R_{NS}$



DM undergoes energy loss via subsequent scatterings following a shrinking closed orbit.

Fate of DM at NS - the Thermalization Processes

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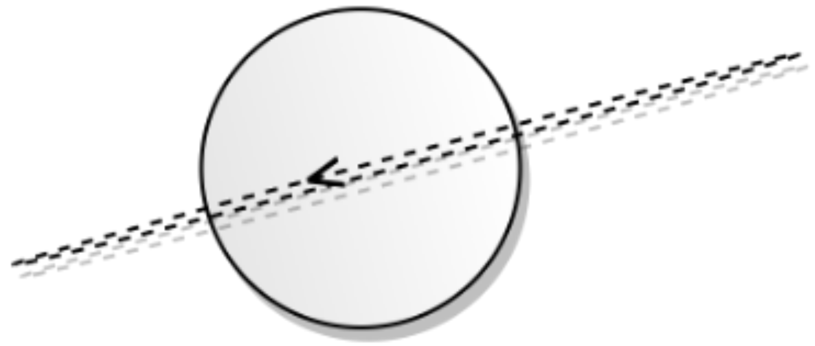

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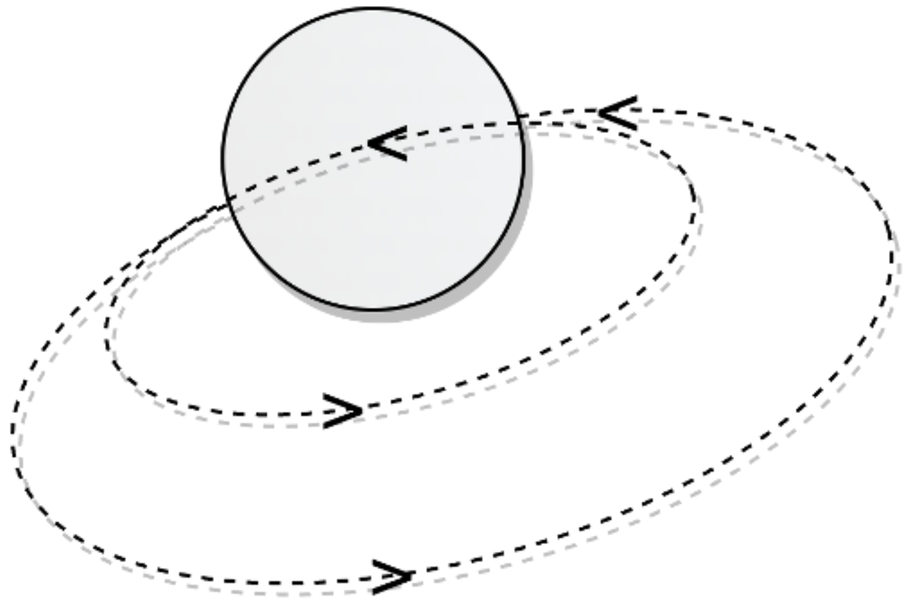

- Stage 2:
  $R > R_{NS} \rightarrow R < R_{NS}$

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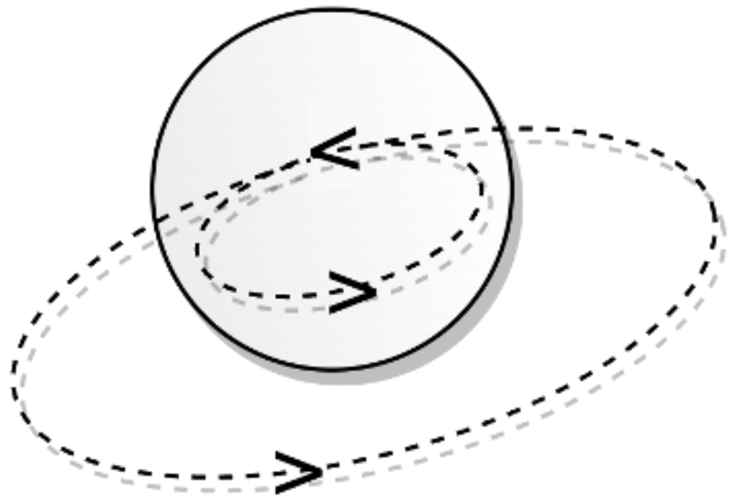
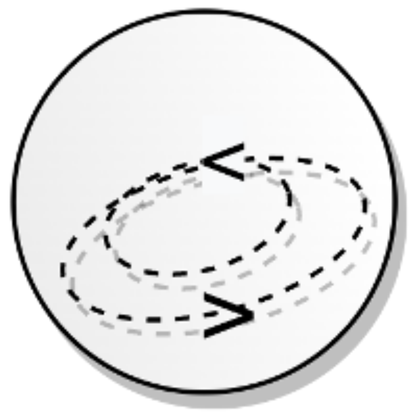


- Stage 3:
  $R < R_{NS}$



The contained orbit shrinks to the thermal radius, i.e. $T_\chi = T_{NS}$

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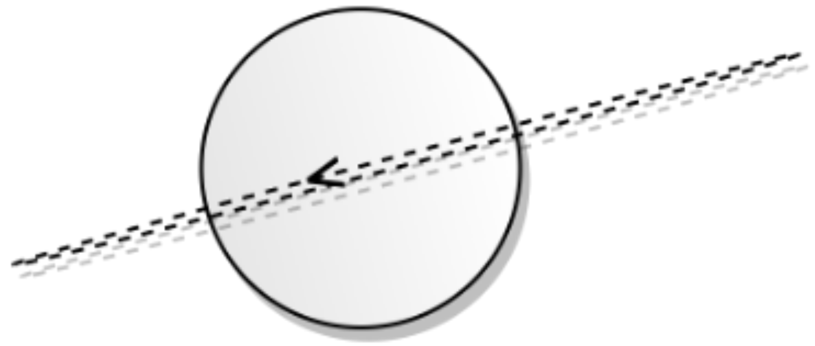

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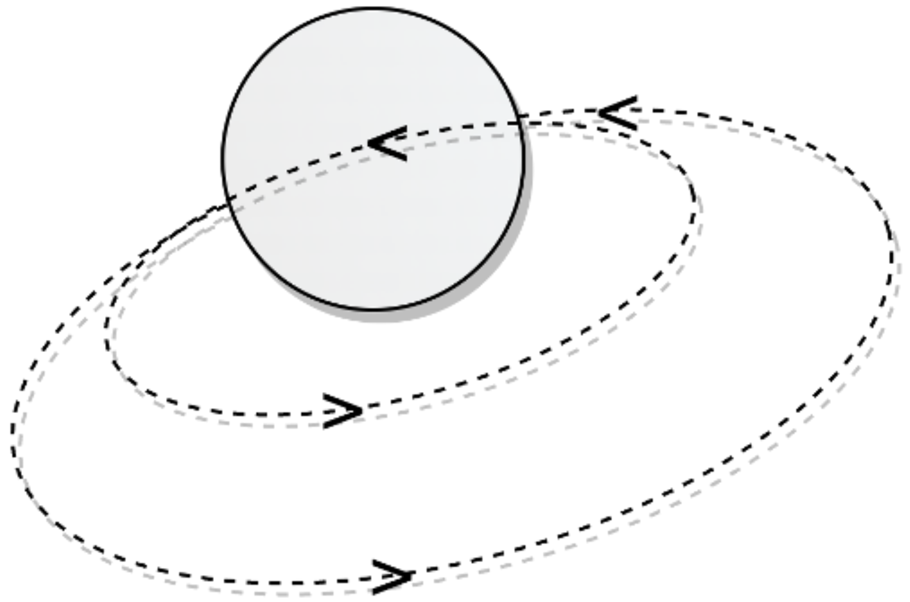
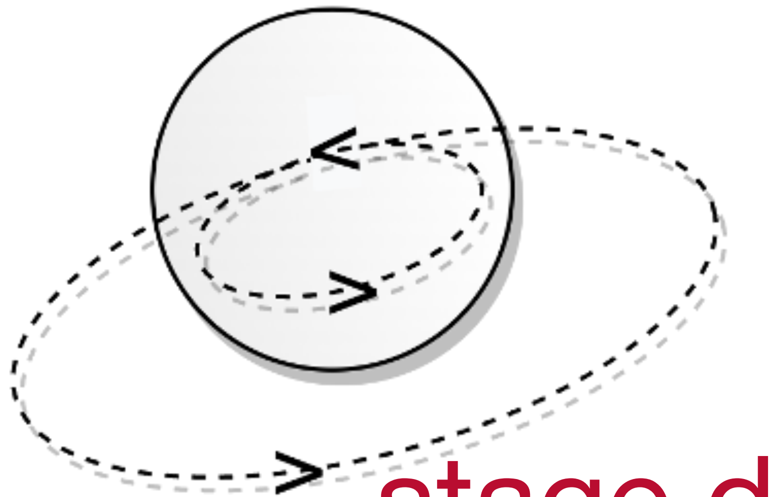
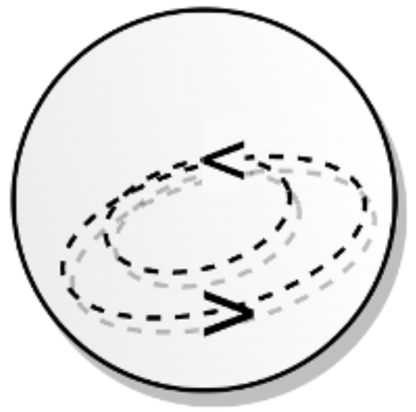




DM undergoes energy loss via subsequent scatterings following a shrinking closed orbit.

stage during which we expect the signal to happen

- Stage 3:
  $R < R_{NS}$



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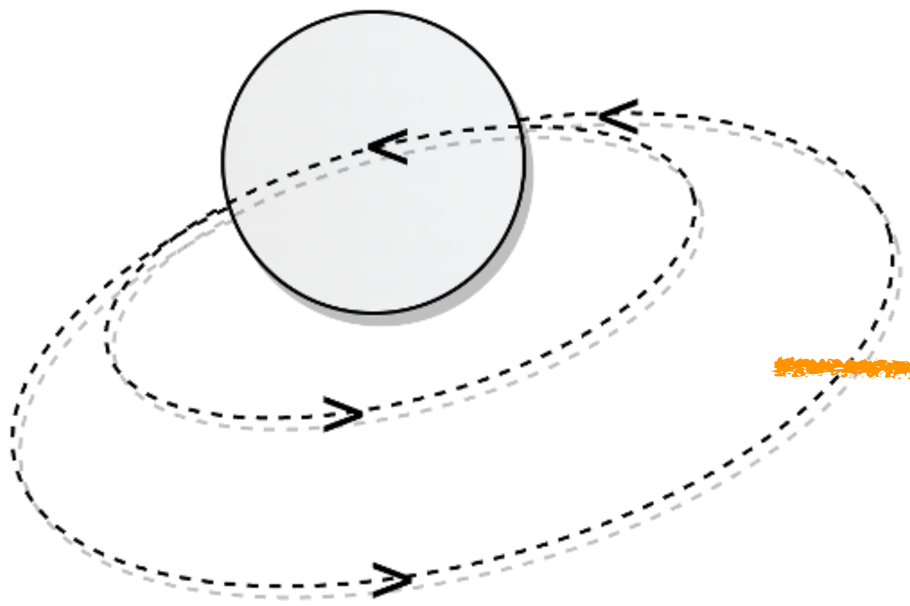
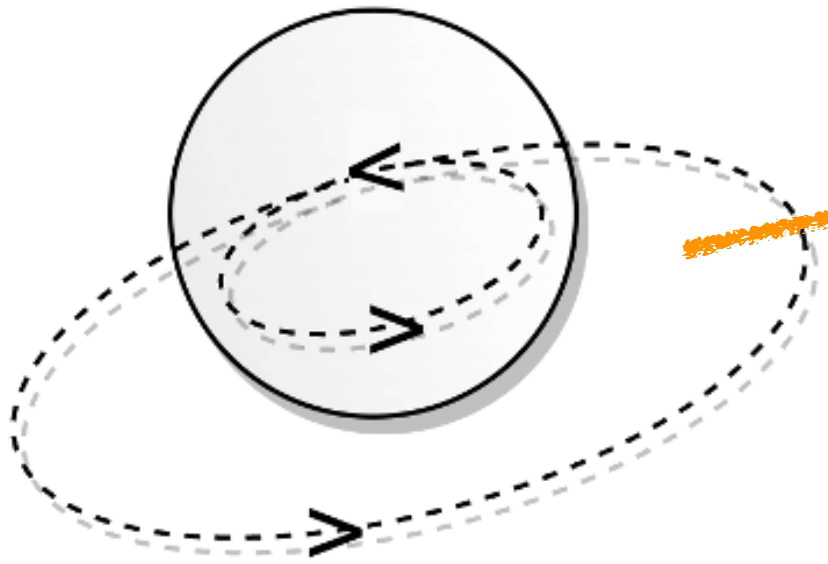
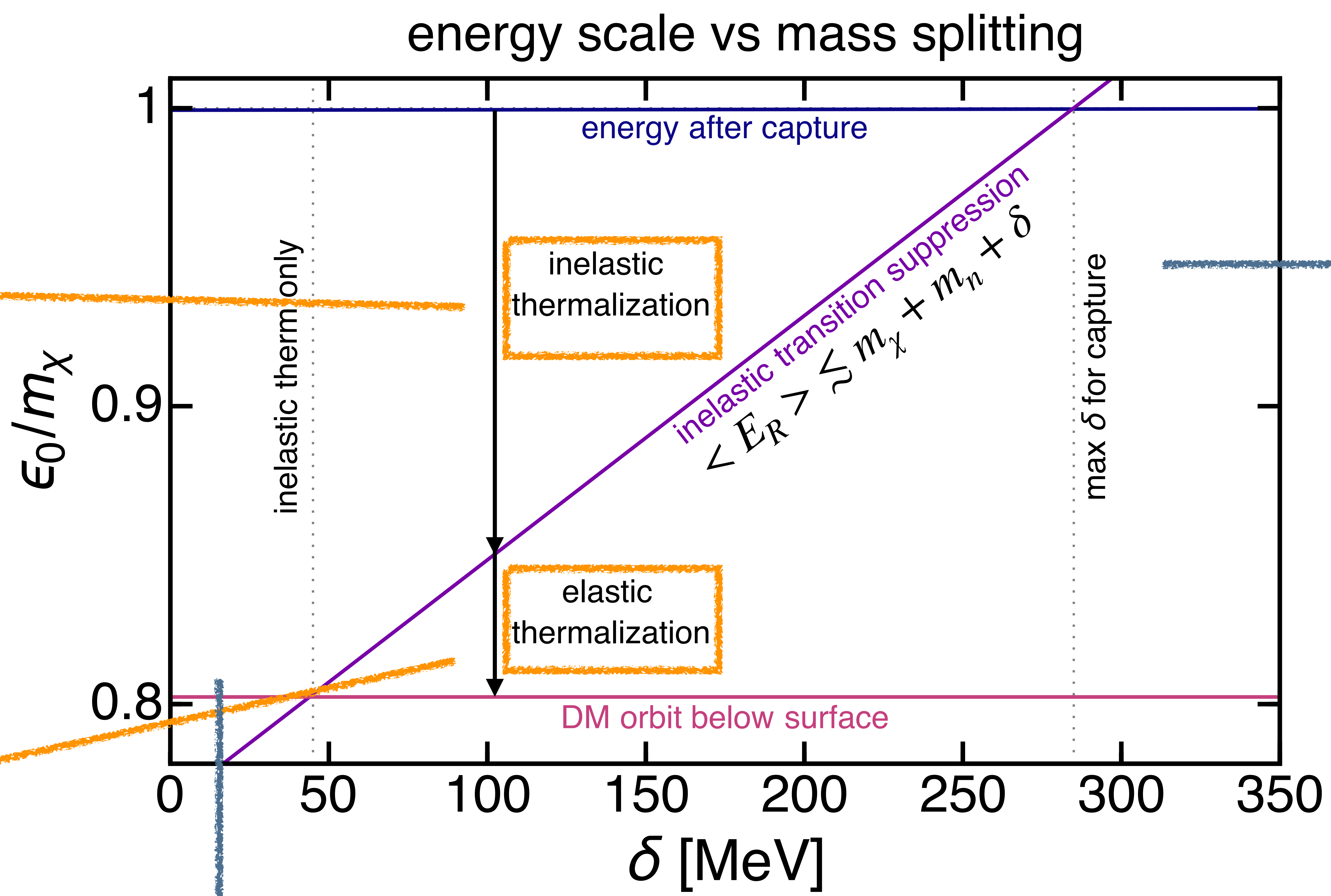


τ_{inel}



τ_{elas}

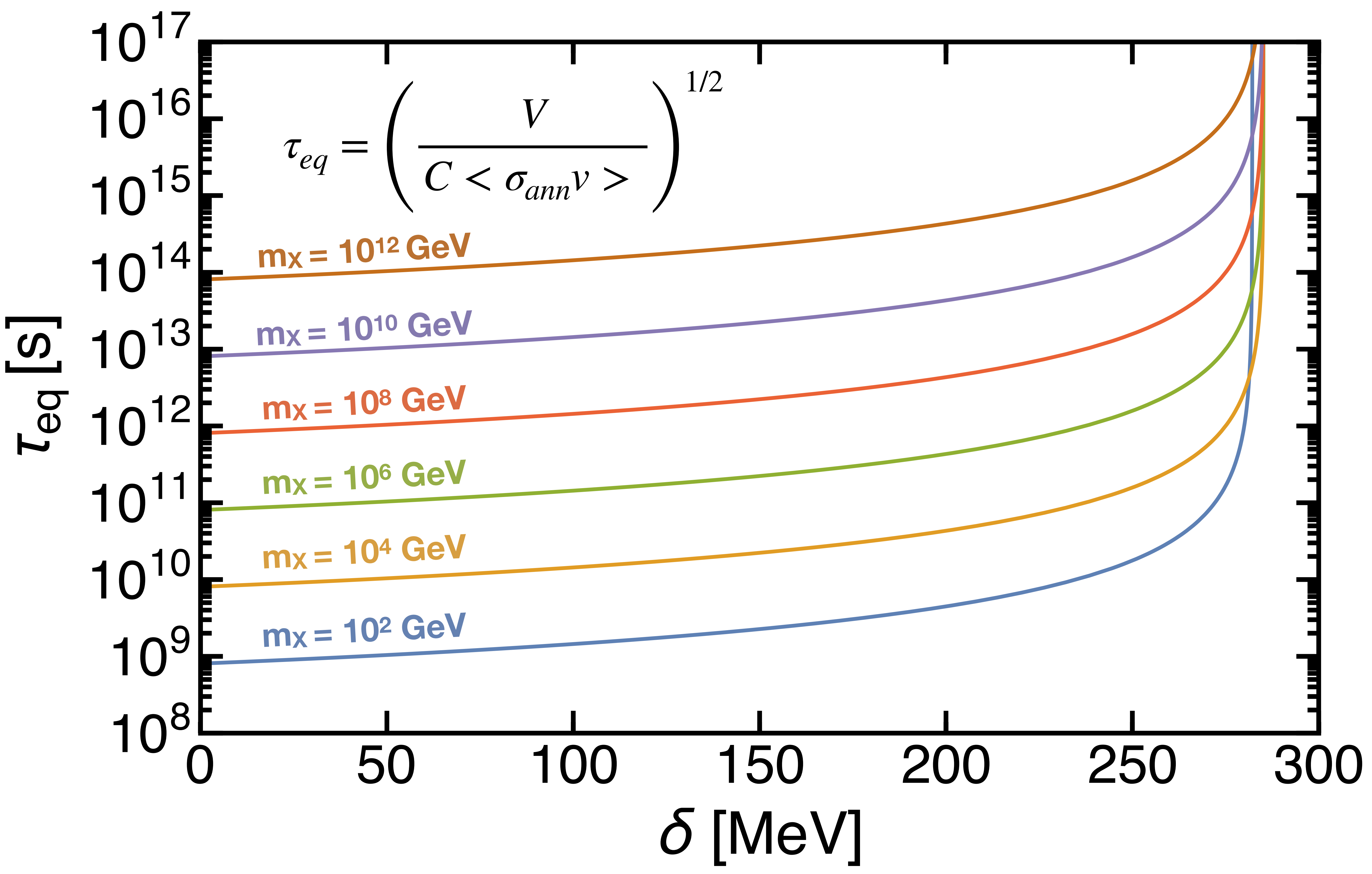


The inelastic transition cannot be excited, so DM cannot be captured.

Inelastic DM can rapidly be thermalized to be contained in the NS.

Timescales

To allow annihilation to happen outside NS, thermalization timescales need to be compared with the timescale to reach the capture and annihilation equilibrium τ_{eq}.

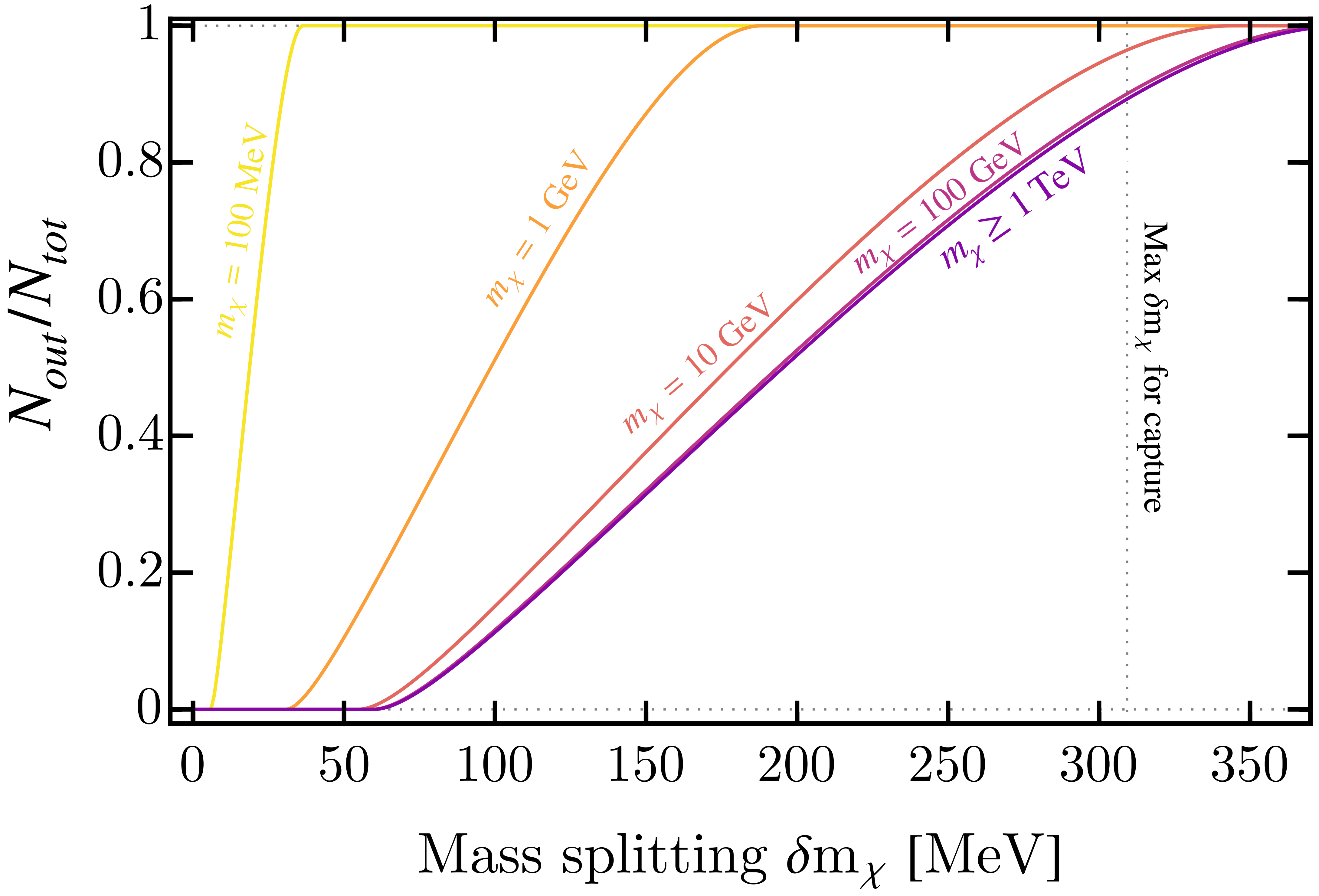


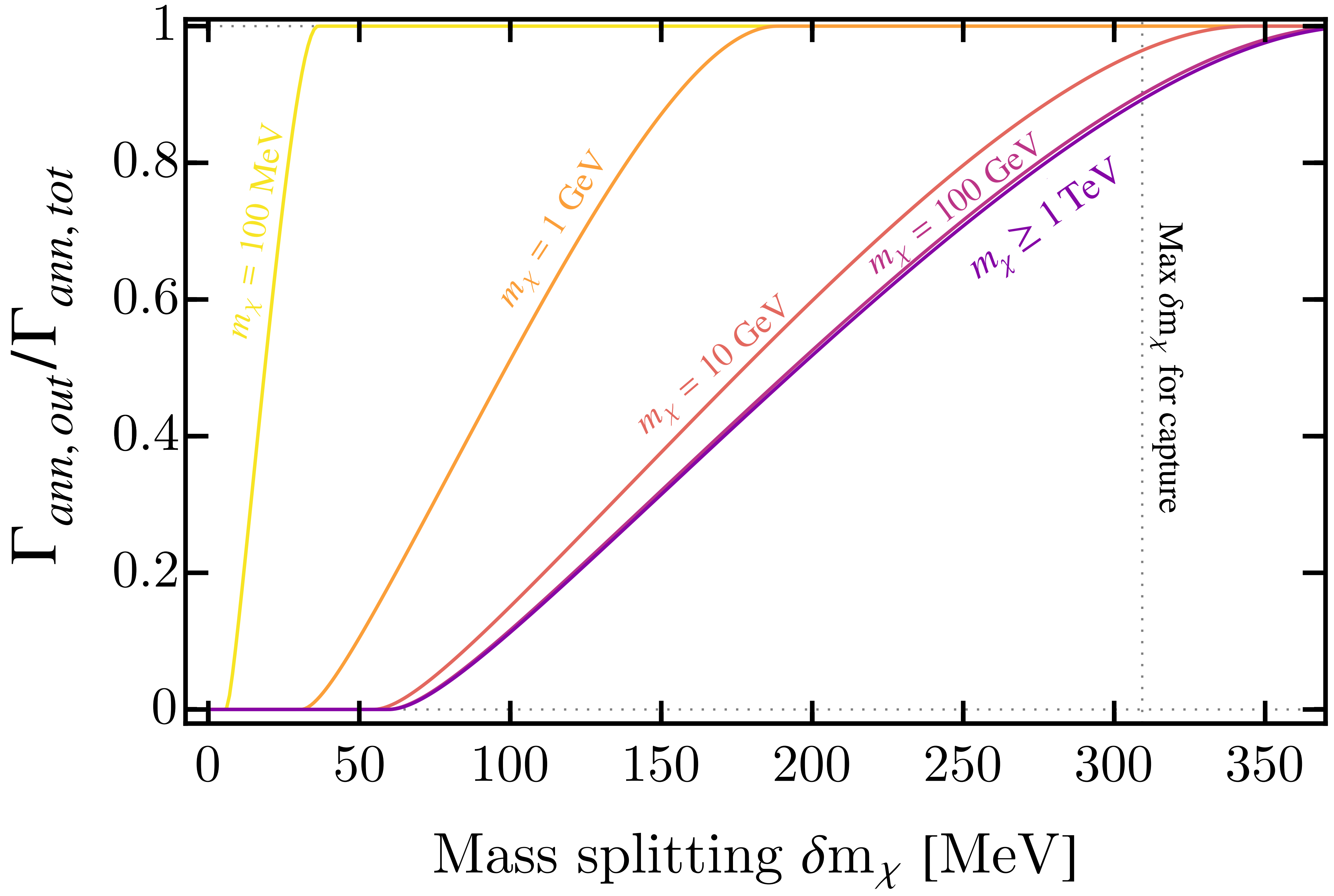
$$\frac{dE}{dt} = -\frac{\langle \Delta E \rangle_{\rm NS}}{t_{orb}} \quad \langle \Delta E \rangle_{\rm NS} = \frac{2}{R_{NS}} \int_0^{R_{NS}} n_n(r) \sigma_{\chi n} E_R(z) dz$$

$$\tau_{elas} \simeq 5 \times 10^{12} \mathrm{s} \left(\frac{10^{-50} \mathrm{cm}^2}{\sigma_{\chi_n}^{elas}} \right) \left(\frac{m_\chi}{10^6 \, \mathrm{GeV}} \right)$$

- $\sigma_{\chi_n}^{inel} \lesssim 10^{-45} \mathrm{cm}^2$, τ_{inel} can be small comparing to τ_{eq}.
- Due to the loop-level suppression for inelastic DM, $\sigma_{\chi_n}^{elas} \lesssim 10^{-50} \mathrm{cm}^2$, τ_{elas} is long.
- so $\tau_{inel} + \tau_{elas} \gtrsim \tau_{eq}$ can be obtained where an equilibrium condition can be reached for NS.

Fraction of DM annihilating outside NS





Depending on the mass splitting, a large fraction of annihilation can happen outside the NS.

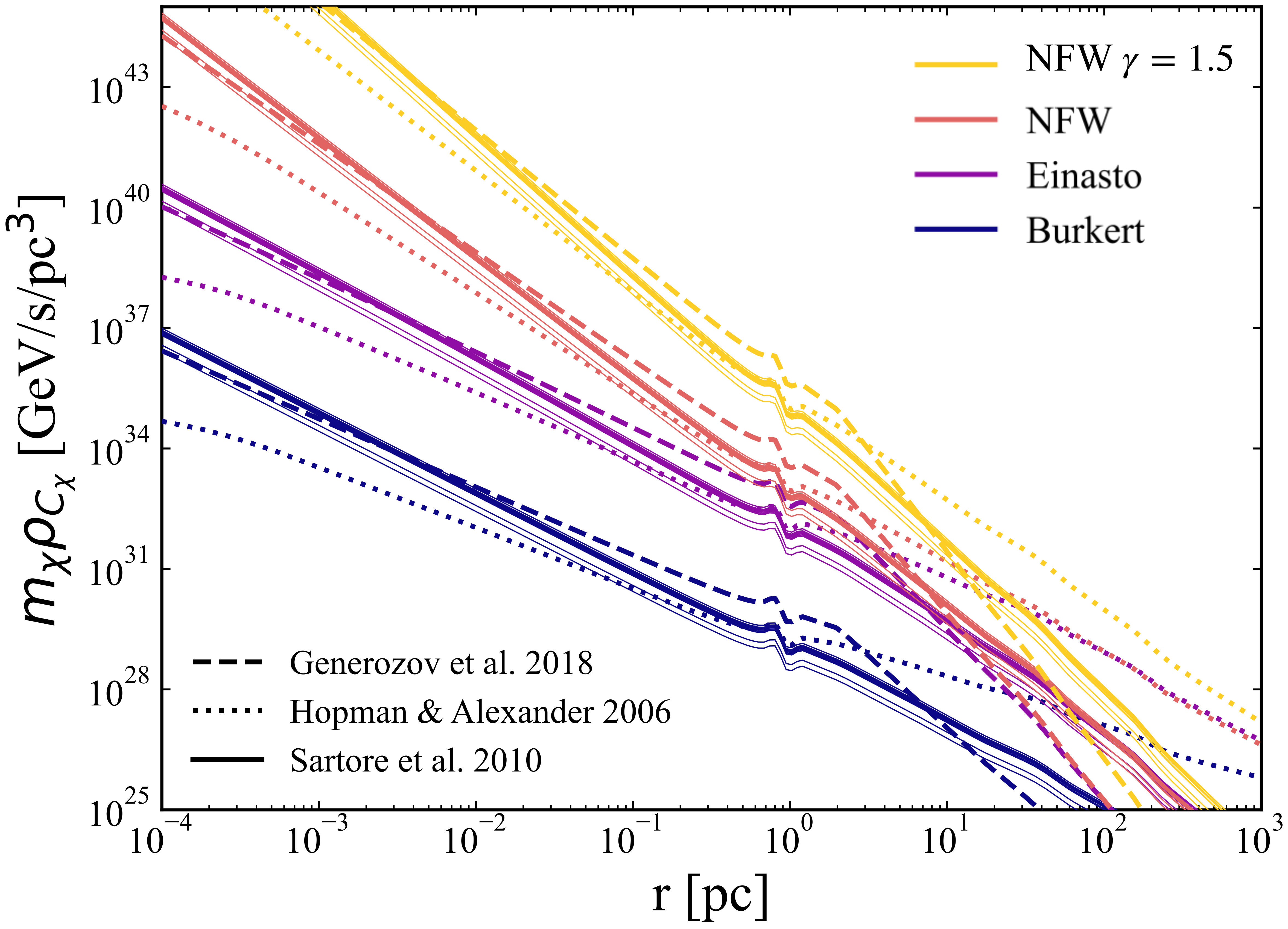
Annihilation Rate

- One single NS produces a signal too faint to be detected.
- In this work, we study the signal from the vicinity of the Galactic Center where DM and NS accumulate.

$$\Gamma_{tot} = C_{tot}/2 = \frac{1}{2}\int_{r_{min}}^{r_{max}} \rho_{C_\chi} 4\pi r^2 dr$$

$$\rho_{C_\chi} = \rho_\chi(r) \cdot \rho_{NS}(r) \cdot C_\chi$$

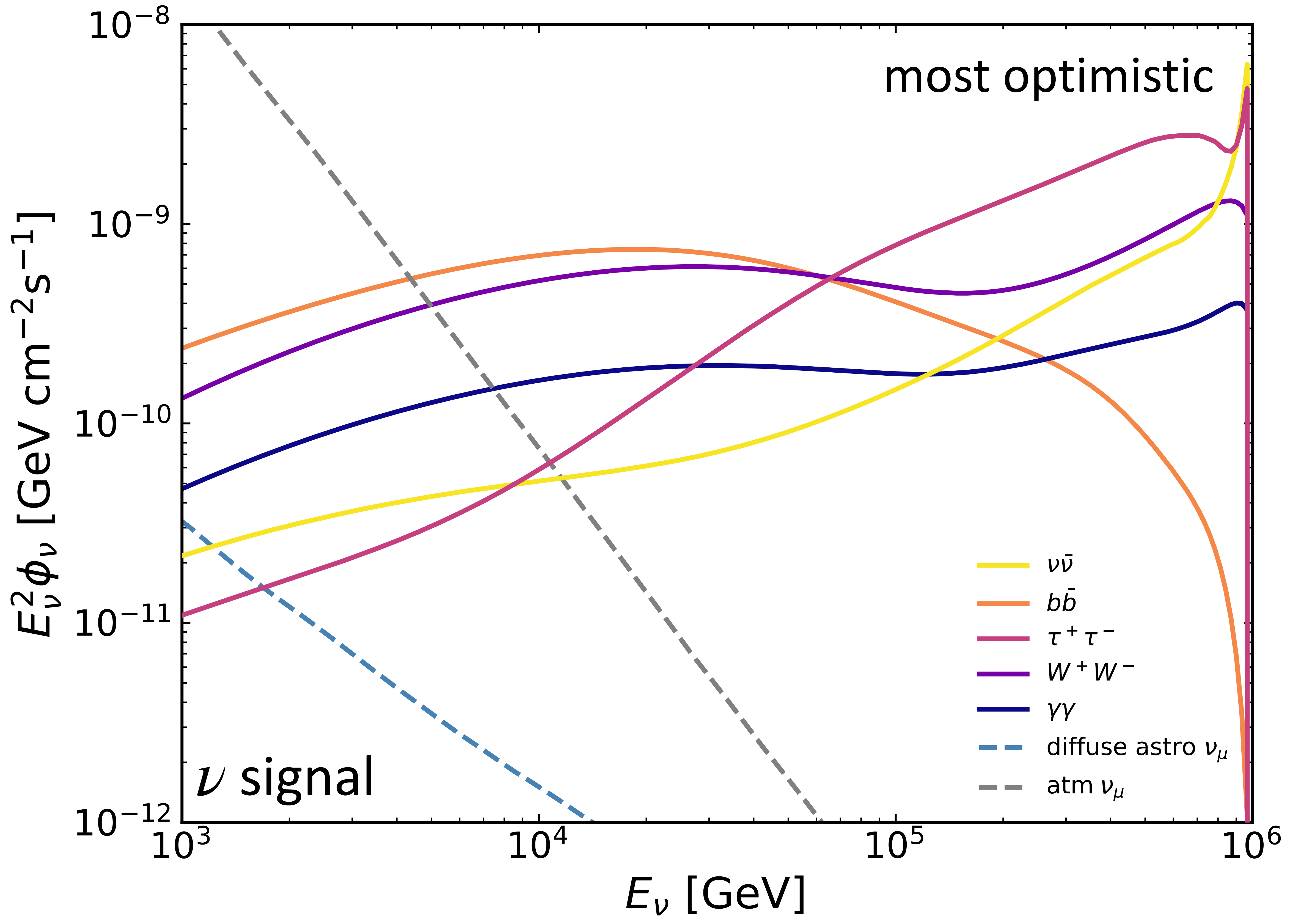
DM profile — NS density — single NS capture rate

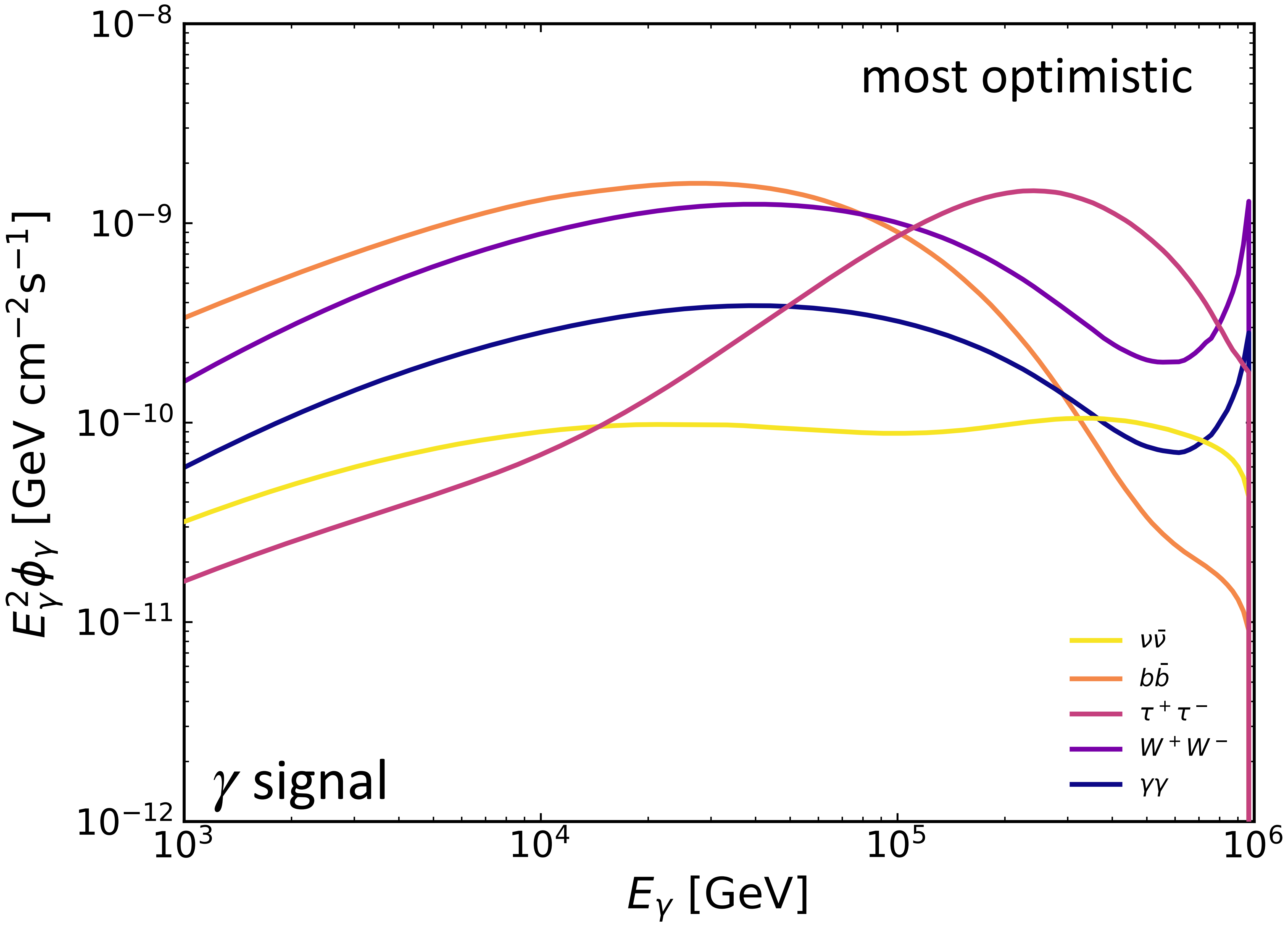


Different NS distribution models give a factor of ~5 difference within $\mathcal{O}(10\,\mathrm{pc})$ to the Galactic Center.

Neutrino & Gamma-ray Flux

Only the Galactic Center region is studied here (up to 50pc to the Galactic Center), so the point-source assumption is followed.





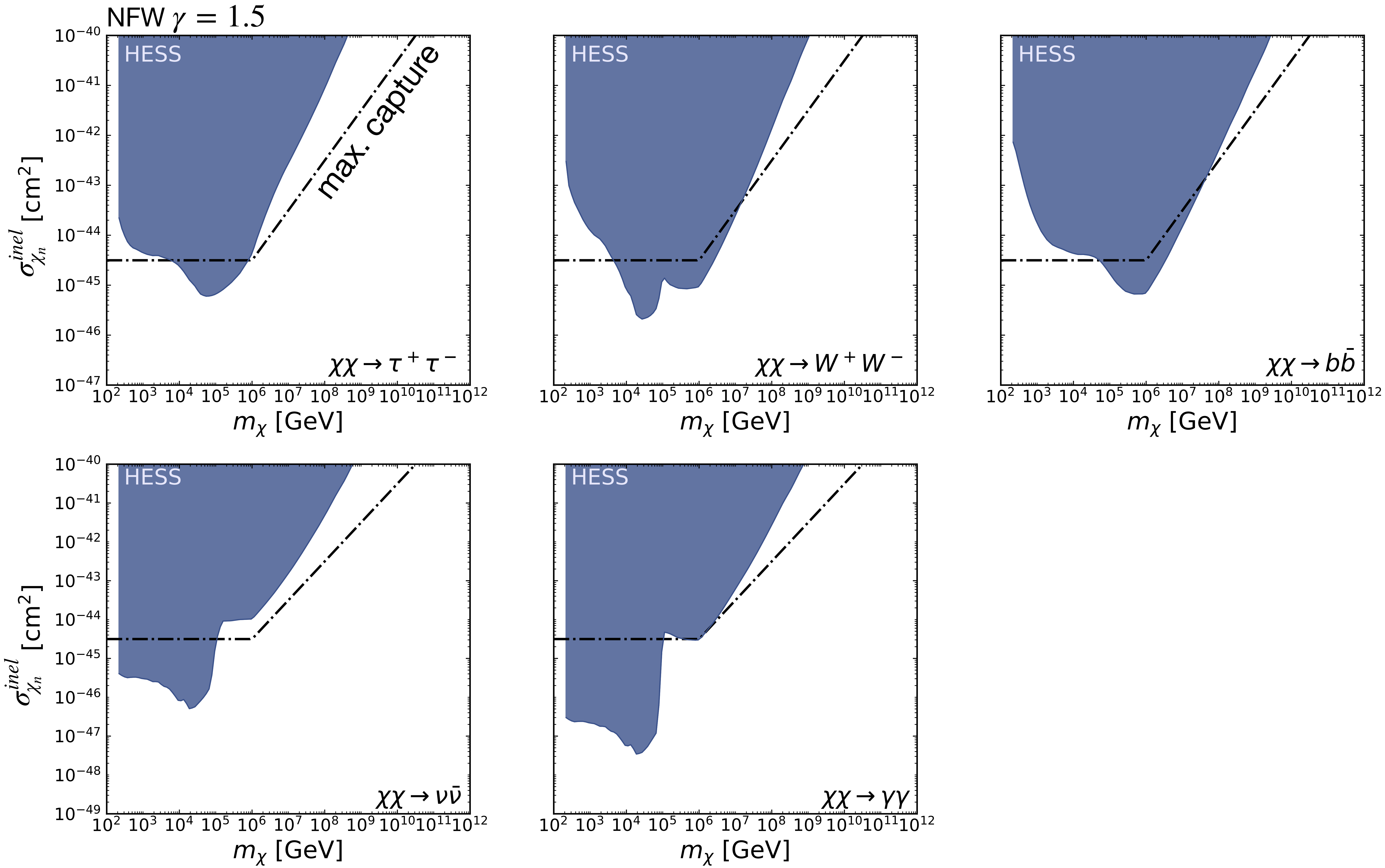
$$\phi_\nu(E_\nu) = \frac{\Gamma_{out}}{4\pi D^2}\frac{dN_{\nu,ch}}{dE_\nu}(E_\nu)$$

$$\phi_\gamma(E_\gamma) = \frac{\Gamma_{out}}{4\pi D^2}\frac{dN_{\gamma,ch}}{dE_\gamma}(E_\gamma)e^{-\tau_{\gamma\gamma}(E_\gamma,D)}$$

Non-negligible absorption for $E_\gamma \gtrsim 100\,\mathrm{TeV}$

✴ Annihilation spectra from PPPC4DMID (< 100 TeV) and HDMSpectrum (>100 TeV).

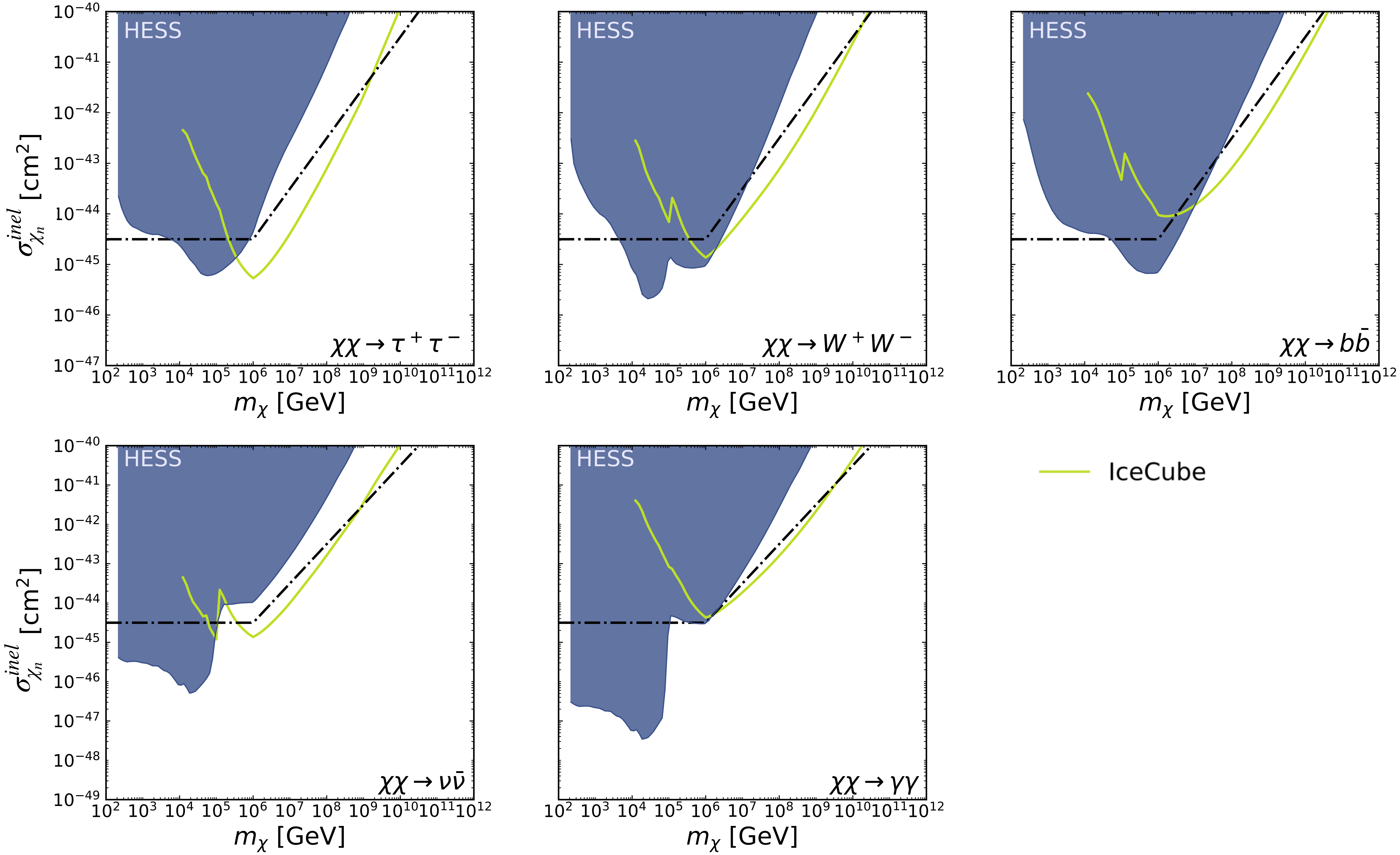
Constraints & Sensitivities



Very-high-energy Gamma-Ray Signal

- Constraints from H.E.S.S. Galactic Center observation
- 90% 10yr sensitivity of IceCube, next-generation neutrino observatories, IceCube-Gen2 Radio
- 5σ sigma sensitivity of CTA (50hr) and SWGO (5yr)

Constraints & Sensitivities



High-Energy Neutrino Signal

- IceCube ν_μ flux for the good pointing power.
- The point-source sensitivity of IceCube to the Southern Sky is limited by the atmospheric background.

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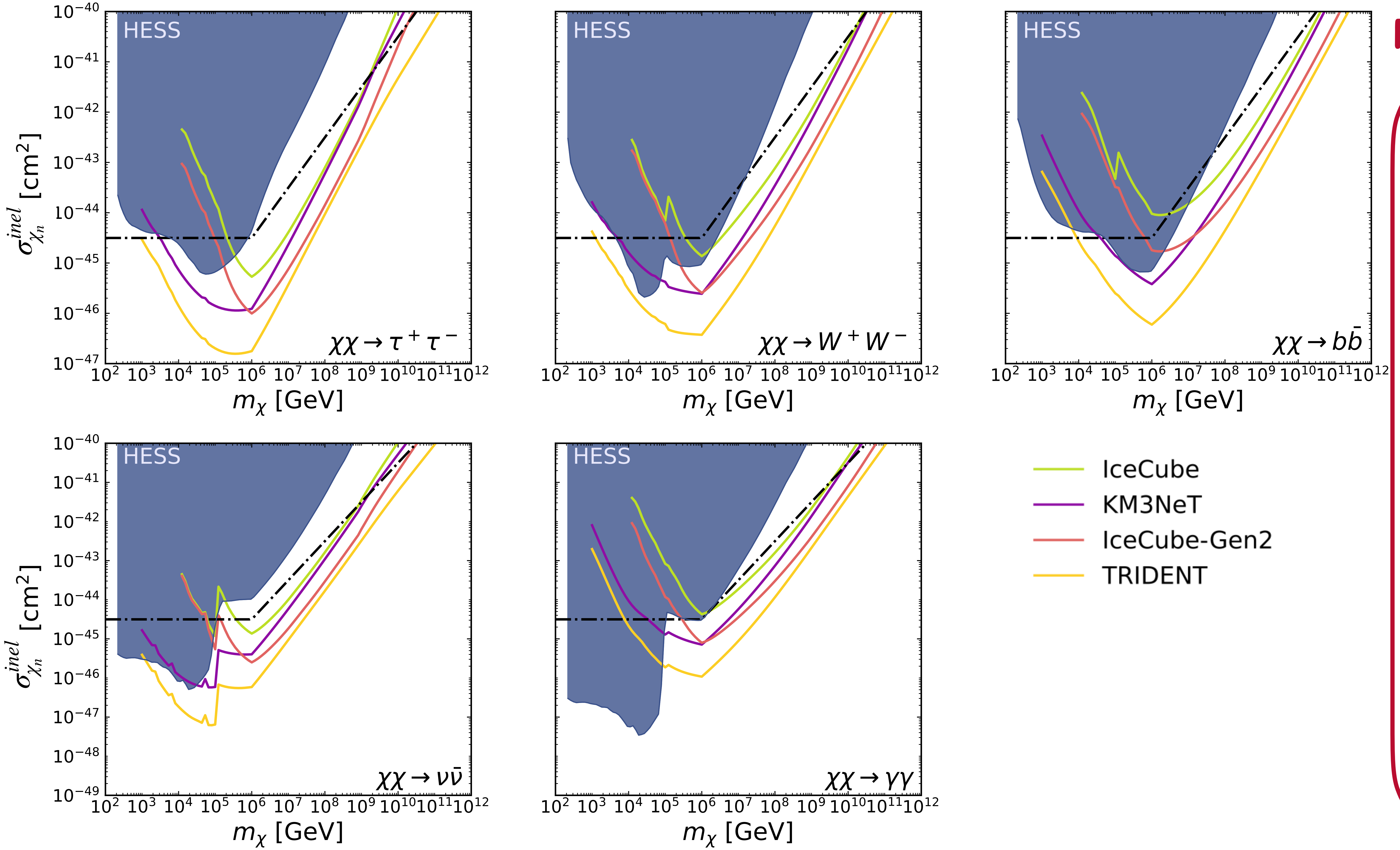
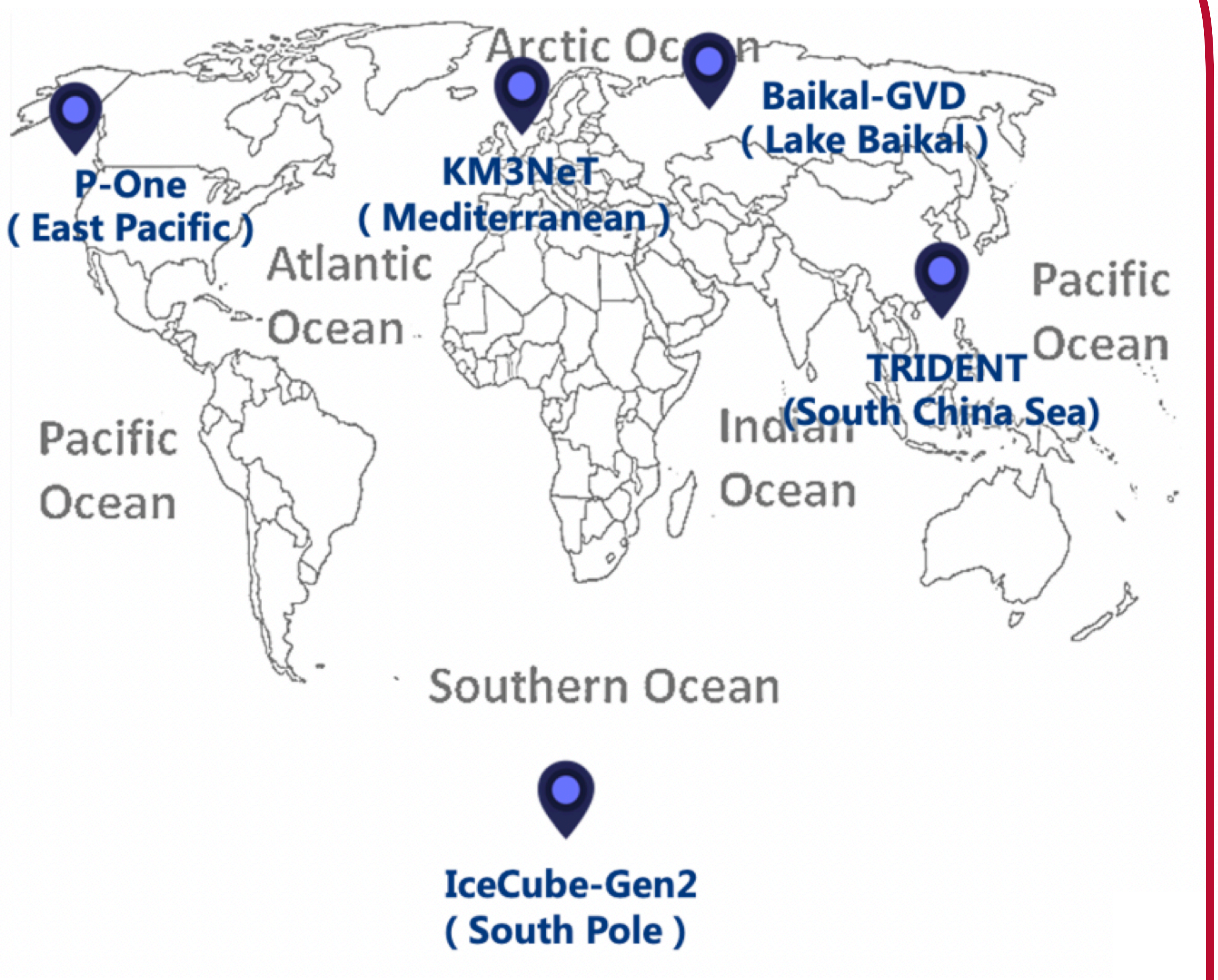


Future Global Neutrino Telescopes



Neutrino telescopes in the Northern Hemisphere can have better view to the Galactic Center

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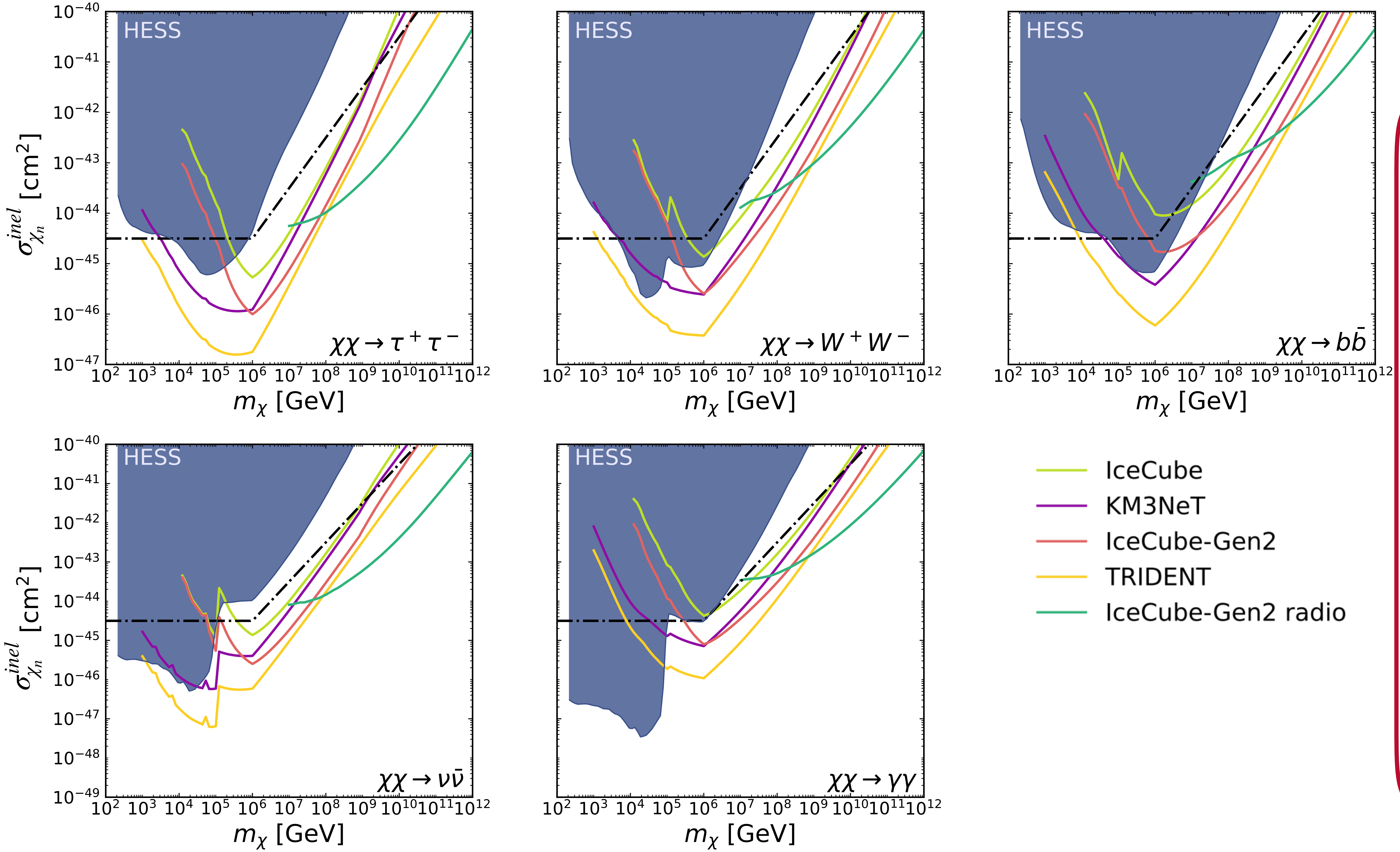
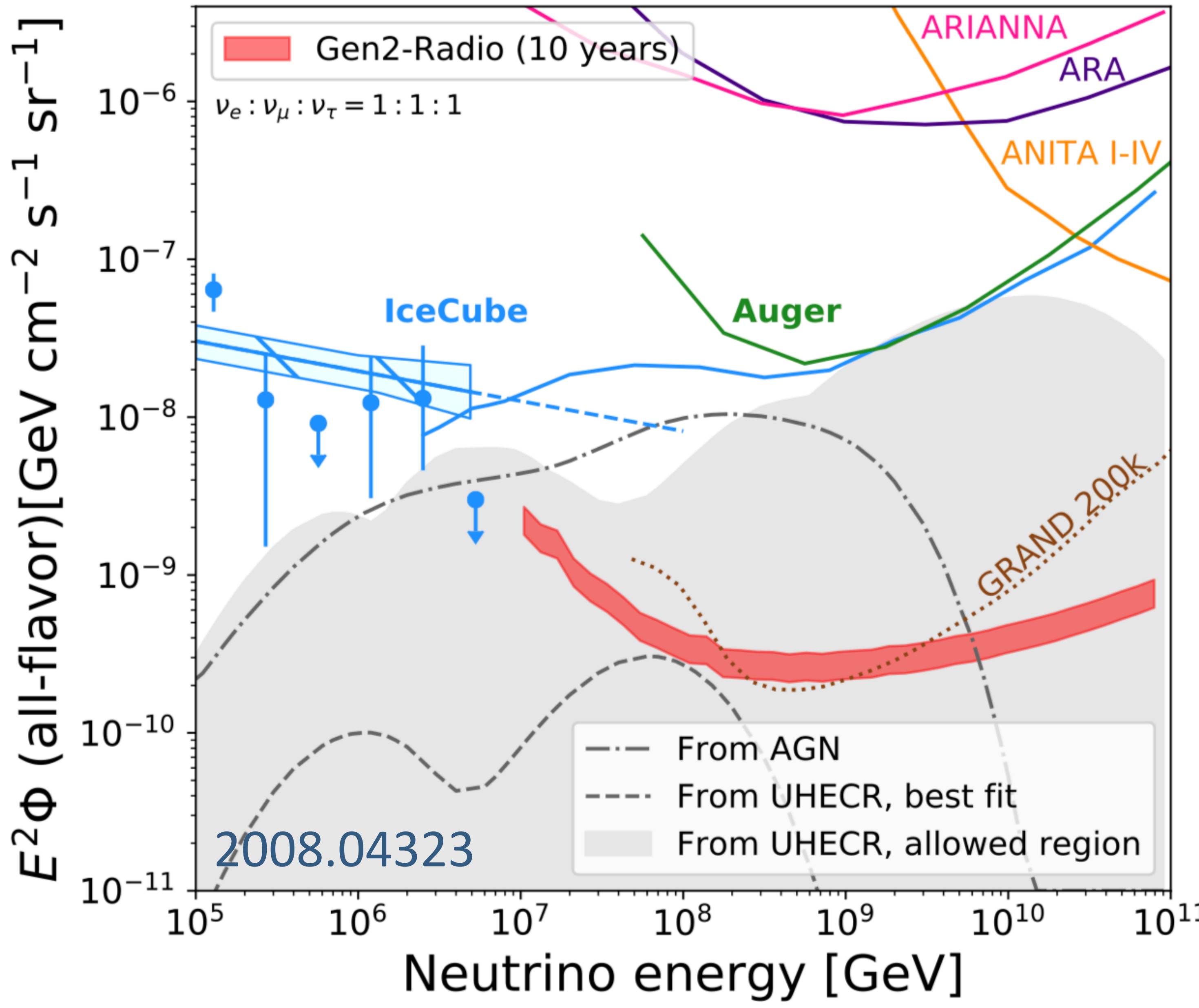


Future Ultra-High-Energy Neutrino Detection

Detection of Earth-skimming neutrinos at $E_\nu \gtrsim 10\,\mathrm{PeV}$



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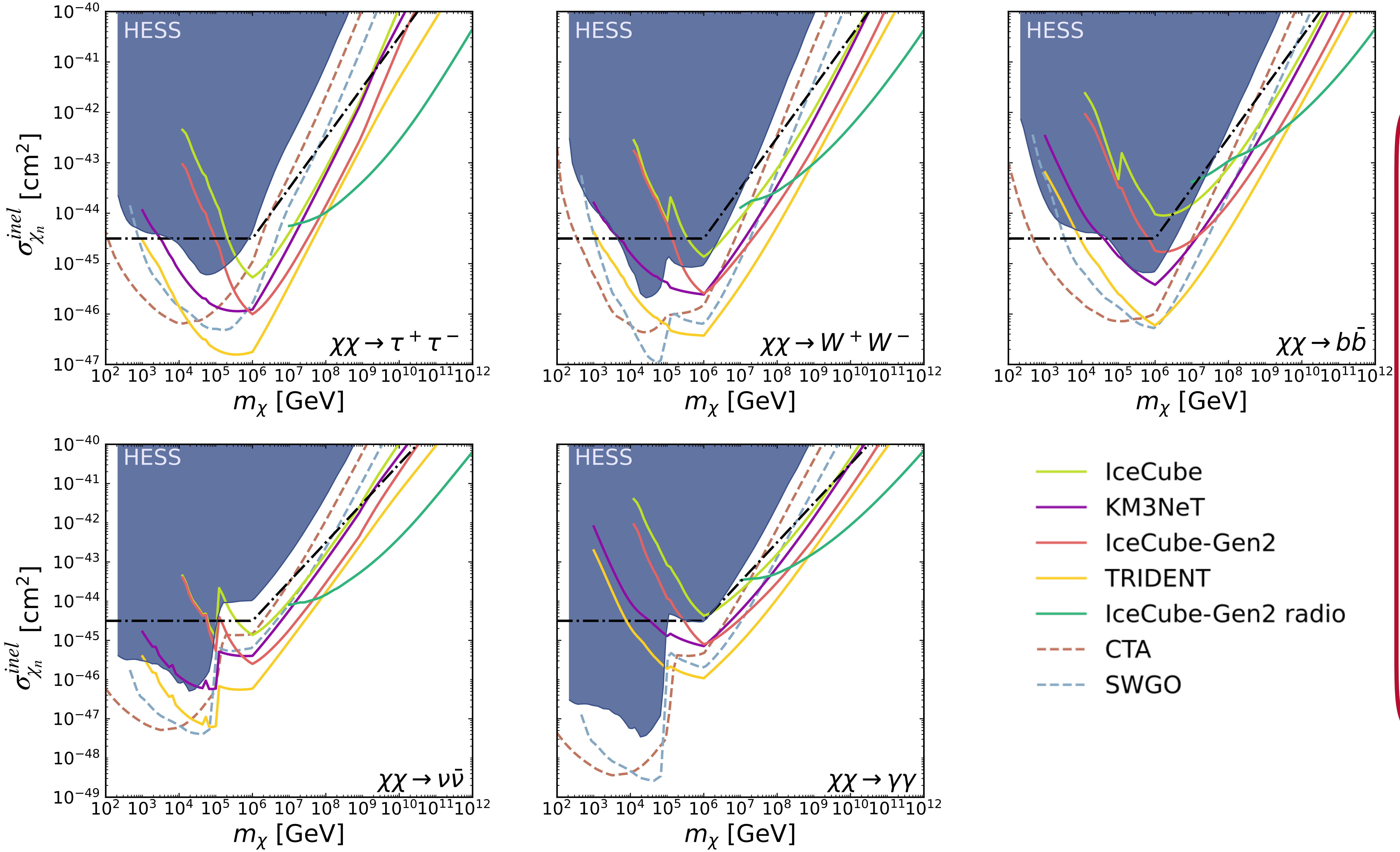
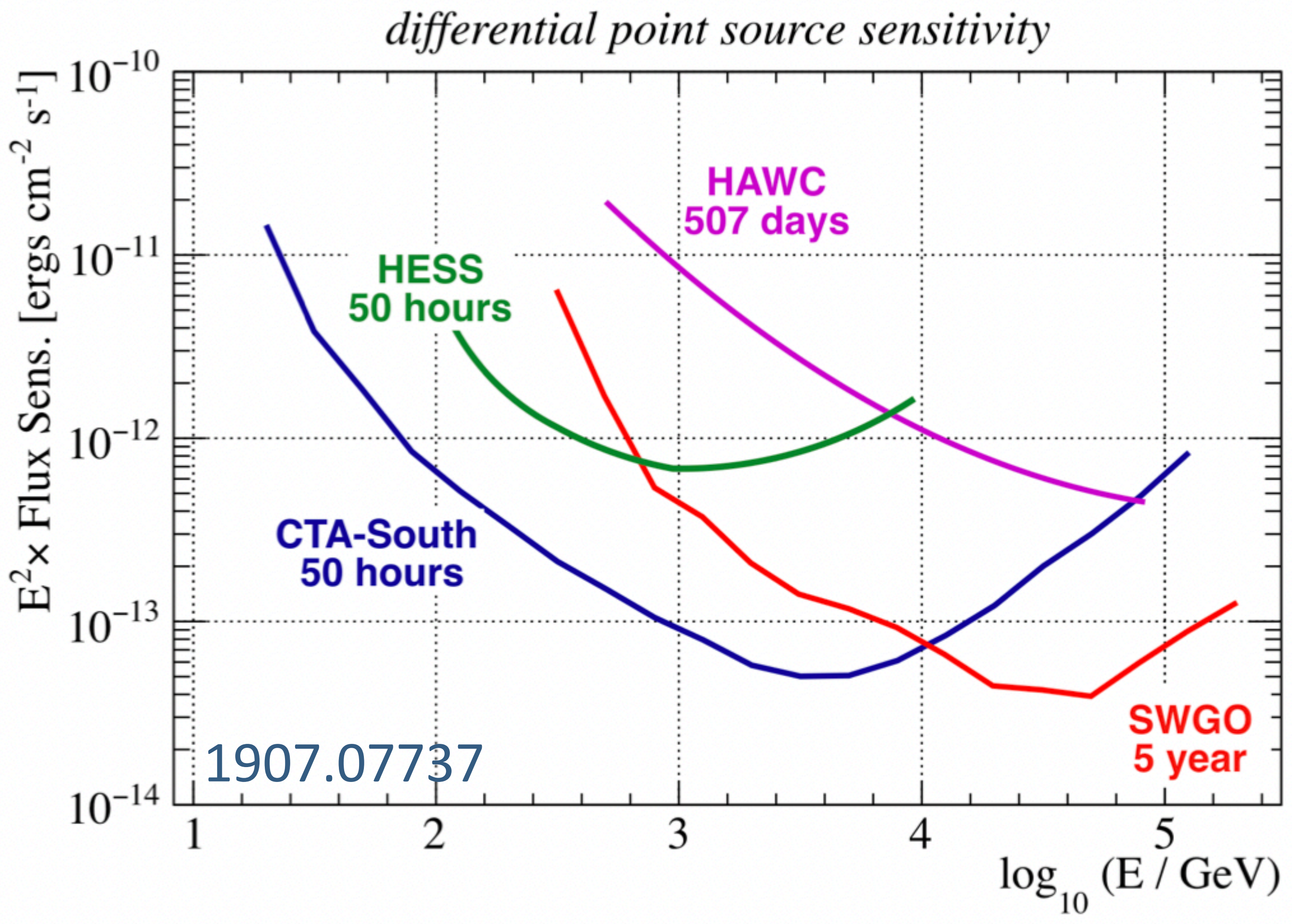


Future Very-High-Energy Gamma-Ray Observation



CTA and SWGO located in the Southern Hemisphere will reach optimal sensitivity to the Southern Sky

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- 5σ sigma sensitivity of CTA (50hr) and SWGO (5yr)

Summary

- After capture, inelastic DM can stay around the NS long enough before being completely contained inside the NS.
- The SM particles produced in annihilation happening outside the NS can reach the Earth and be detected.
- The cross sections of DM-nucleon scattering can be constrained with the current gamma-ray and neutrino experiments.
- We show the sensitivities to the cross sections with future gamma-ray and neutrino experiments.

Thank you!

Bonus Slides

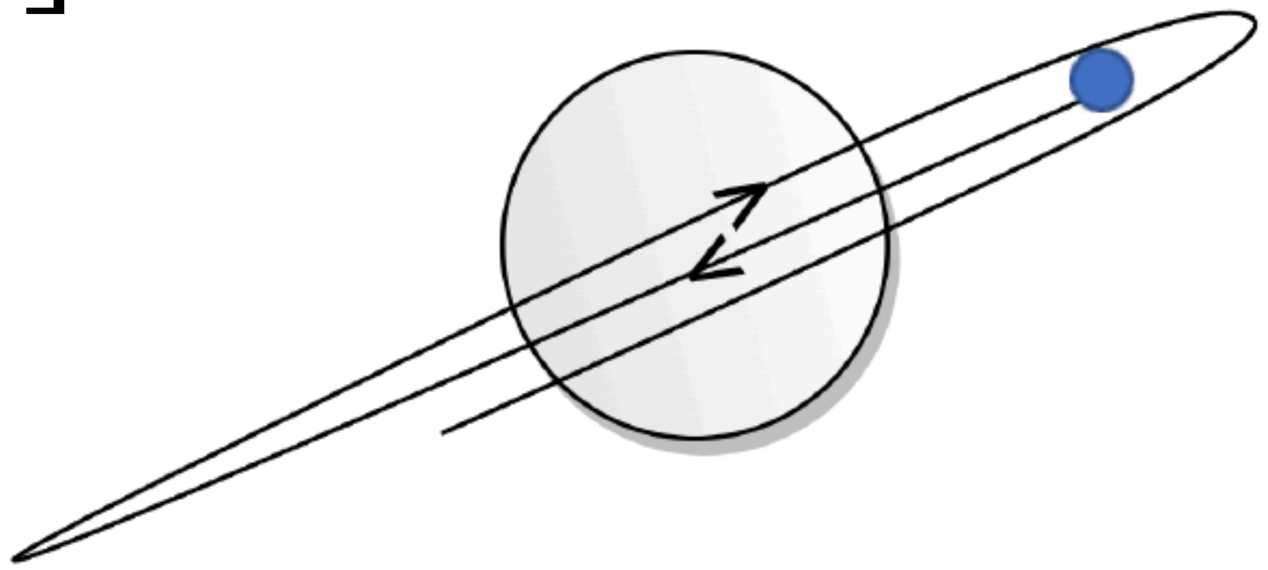
DM capture in NS

$$m_\chi C_\chi \propto \pi R^2 M_{NS}\,\mathrm{Min}\left[1, \frac{\sigma}{\sigma_{sat}}\right]$$

- $\mathrm{GeV} < m_\chi < \mathrm{PeV}$

  A single scattering is enough for DM capture.

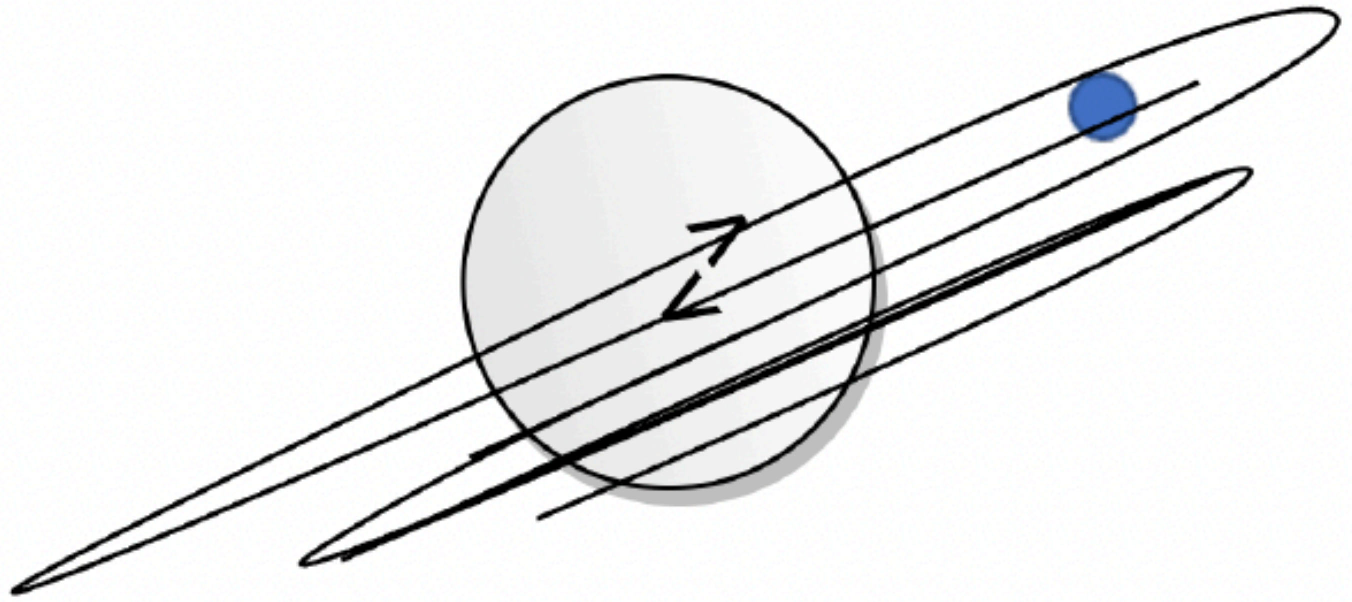
  $$\sigma_{sat}^{single} \simeq 2\times 10^{-45}\mathrm{cm}^2 \left(\frac{1.5\mathrm{M}_\odot}{\mathrm{M}_{\mathrm{NS}}}\right)\left(\frac{\mathrm{R}_{\mathrm{NS}}}{10\,\mathrm{km}}\right)^2$$



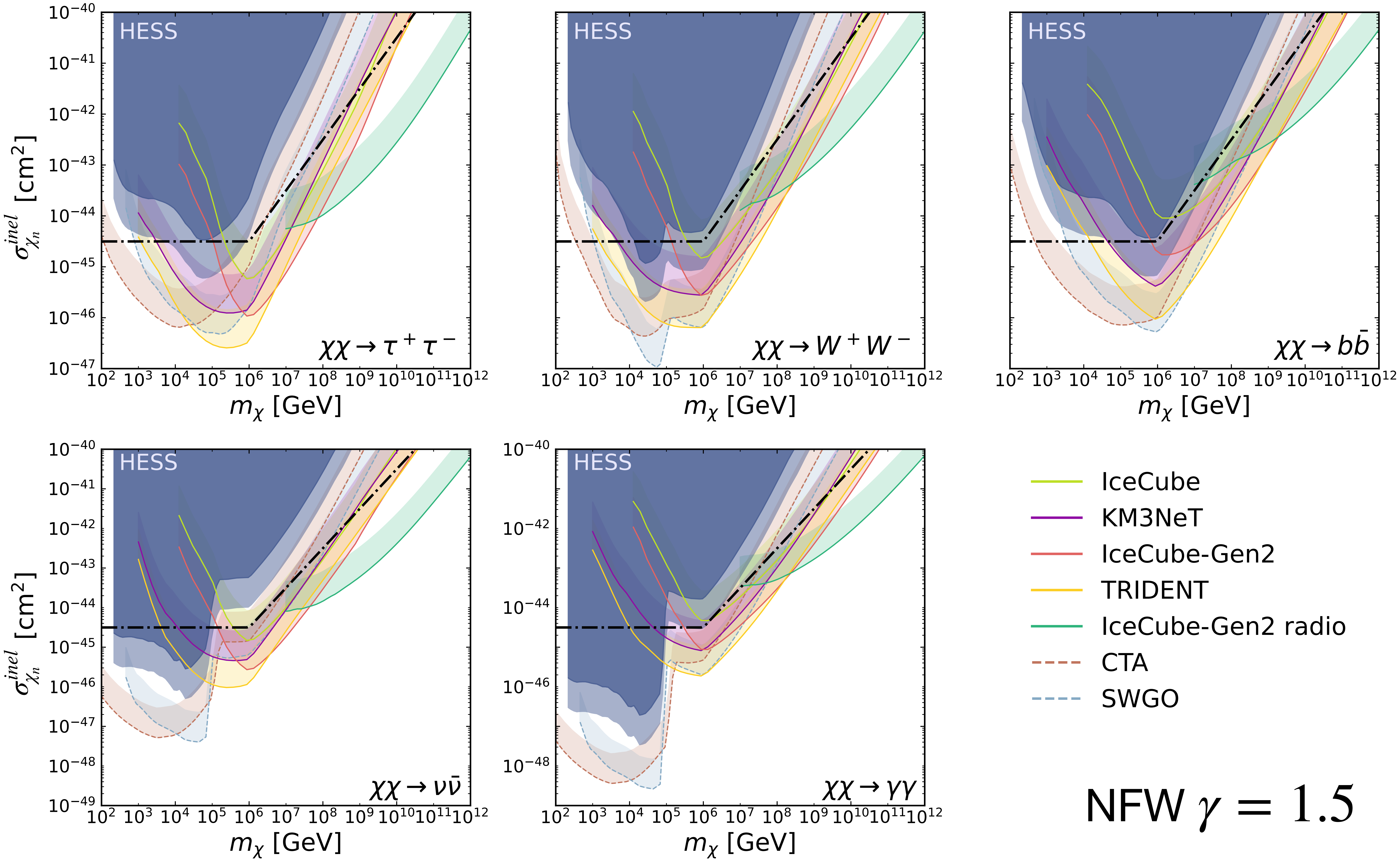
- $m_\chi > \mathrm{PeV}$

  Multiple scatterings are needed due to the higher initial kinetic energy in the halo

  $$\sigma_{sat}^{single} \simeq 2\times 10^{-45}\mathrm{cm}^2 \left(\frac{\mathrm{m}_\chi}{\mathrm{PeV}}\right)\left(\frac{1.5\mathrm{M}_\odot}{\mathrm{M}_{\mathrm{NS}}}\right)\left(\frac{\mathrm{R}_{\mathrm{NS}}}{10\,\mathrm{km}}\right)^2$$

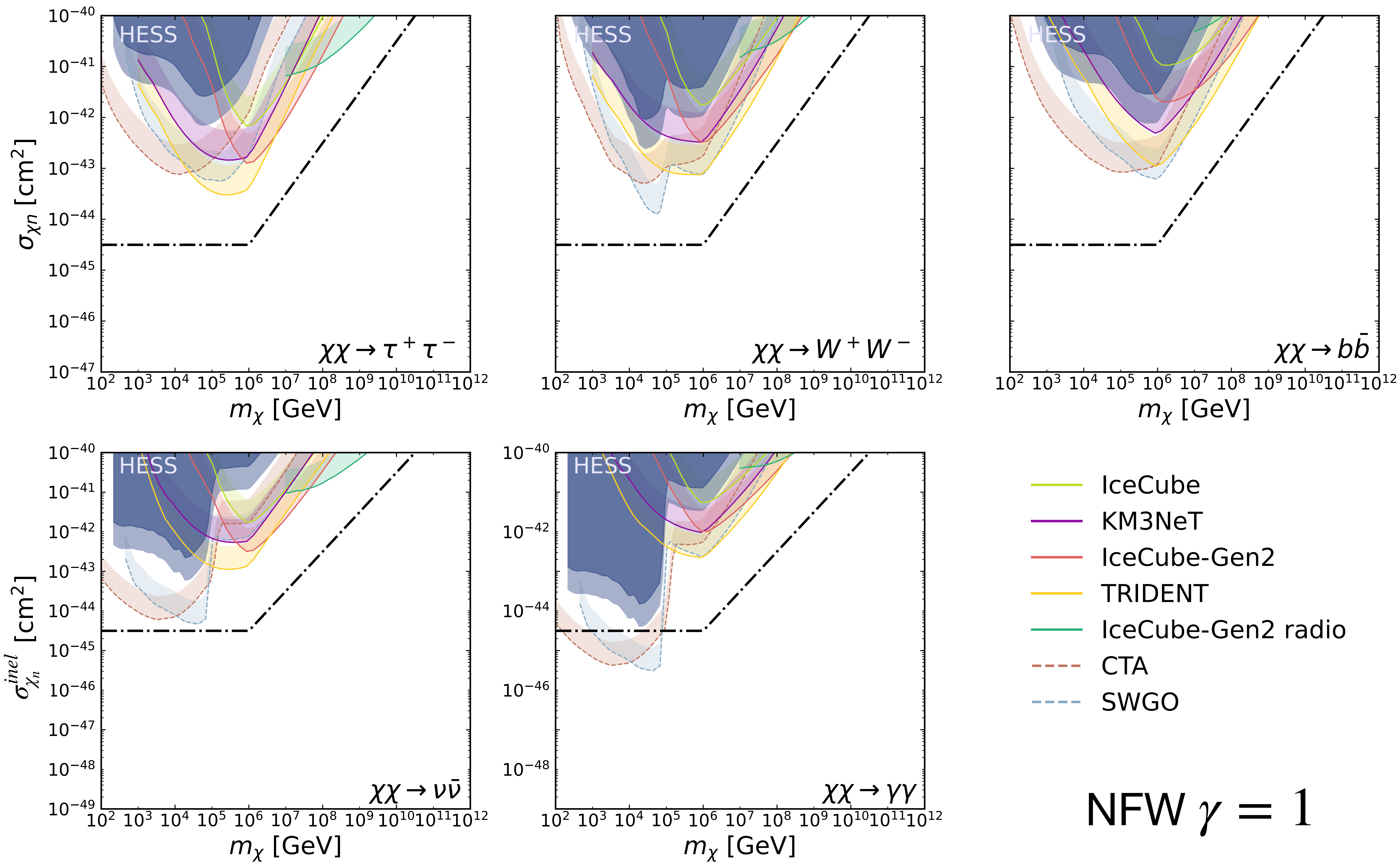


Constraints & Sensitivity



NFW $\gamma = 1.5$

Constraints & Sensitivity



NFW $\gamma = 1$