Neutrino Annihilation Signatures from Inelastic DM in Neutron Stars

Narayani Tyagi (Queen's University)

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Work in preparation with - Javier F. Acevedo, Joseph Bramante and Qinrui Liu [23XX.XXXX]

Queen's UNIVERSITY

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

DM Capture in NS

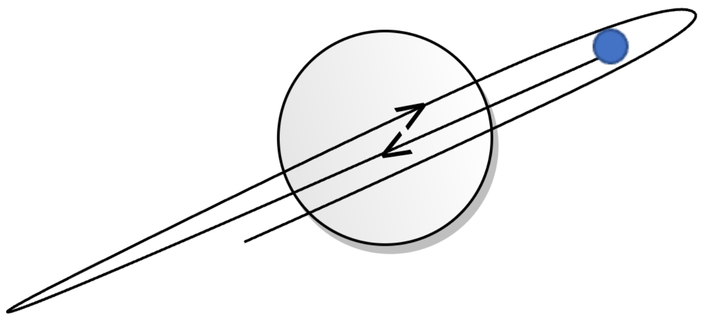
DM can recoil against neutrons in the NS → losing energy

For capture, the dark matter must lose enough of its energy through collisions with scattering sites in the star

For a mass range of GeV < m_χ < PeV

↓

a single scatter is enough for the DM particle to lose enough energy to get completely captured.



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

DM Capture in NS

DM can recoil against neutrons in the NS → losing energy

For capture, the dark matter must lose enough of its energy through collisions with scattering sites in the star

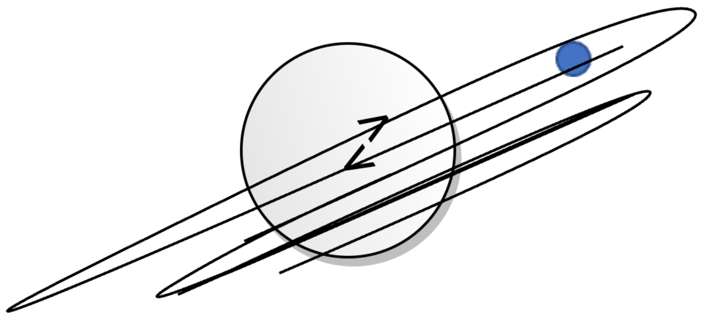
For heavy dark matter, $m_\chi > \text{PeV}$

↓

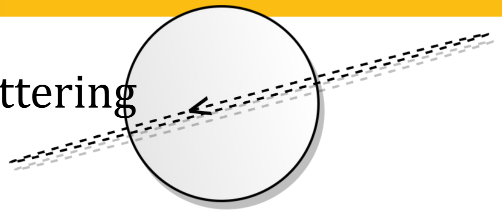
Heavier dark matter has more initial kinetic energy in the halo.

∴ it needs to lose more energy to be captured, i.e., it needs to scatter more.

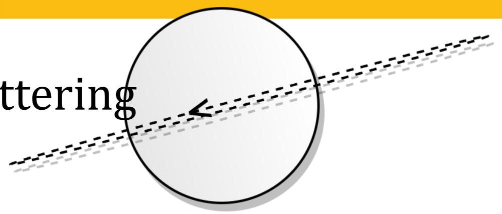
Multiscatter capture becomes more important in this case .



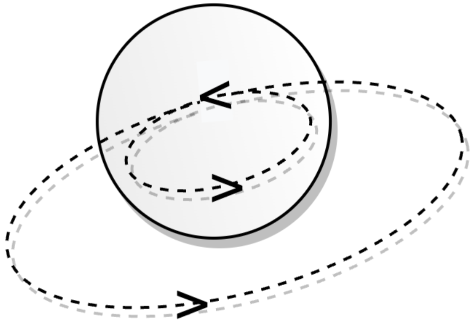
DM is captured as it loses energy by scattering



DM is captured as it loses energy by scattering

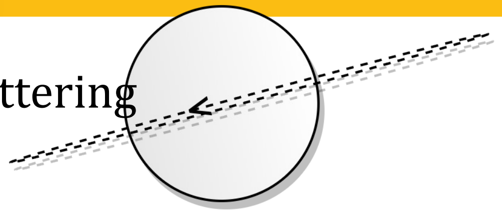


<u>First stage of thermalization:</u>
DM continues in a closed orbit till its orbit is now contained within the NS

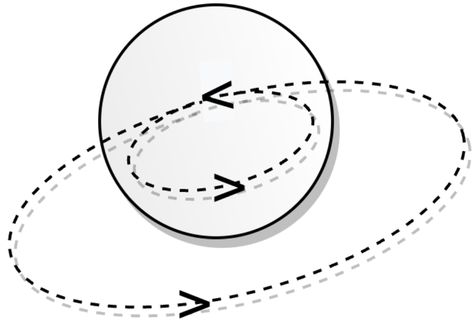


The timescale on which this happens is called $\tau_{1,therm}$

DM is captured as it loses energy by scattering

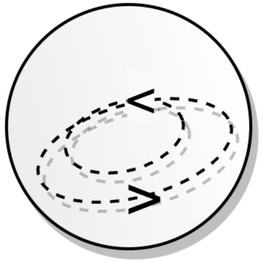


<u>First stage of thermalization:</u>
DM continues in a closed orbit till its orbit is now contained within the NS



The timescale on which this happens is called $\tau_{1,therm}$

<u>Second stage of thermalization:</u>
DM moves completely inside the star on the orbit which shrinks to the thermal radius,
i.e., $T_x = T_{NS}$

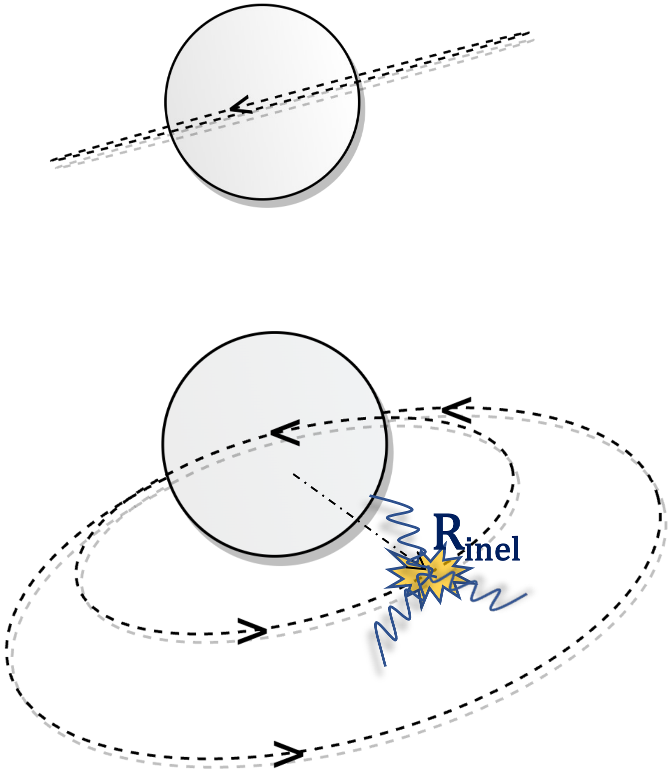


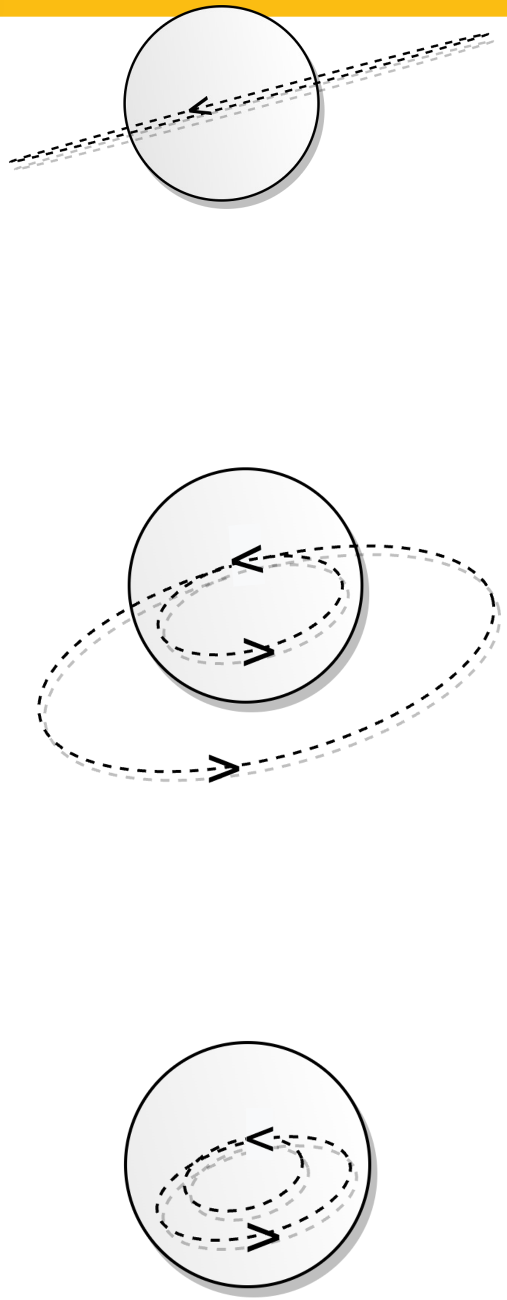
The timescale on which this happens is called $\tau_{2,therm}$

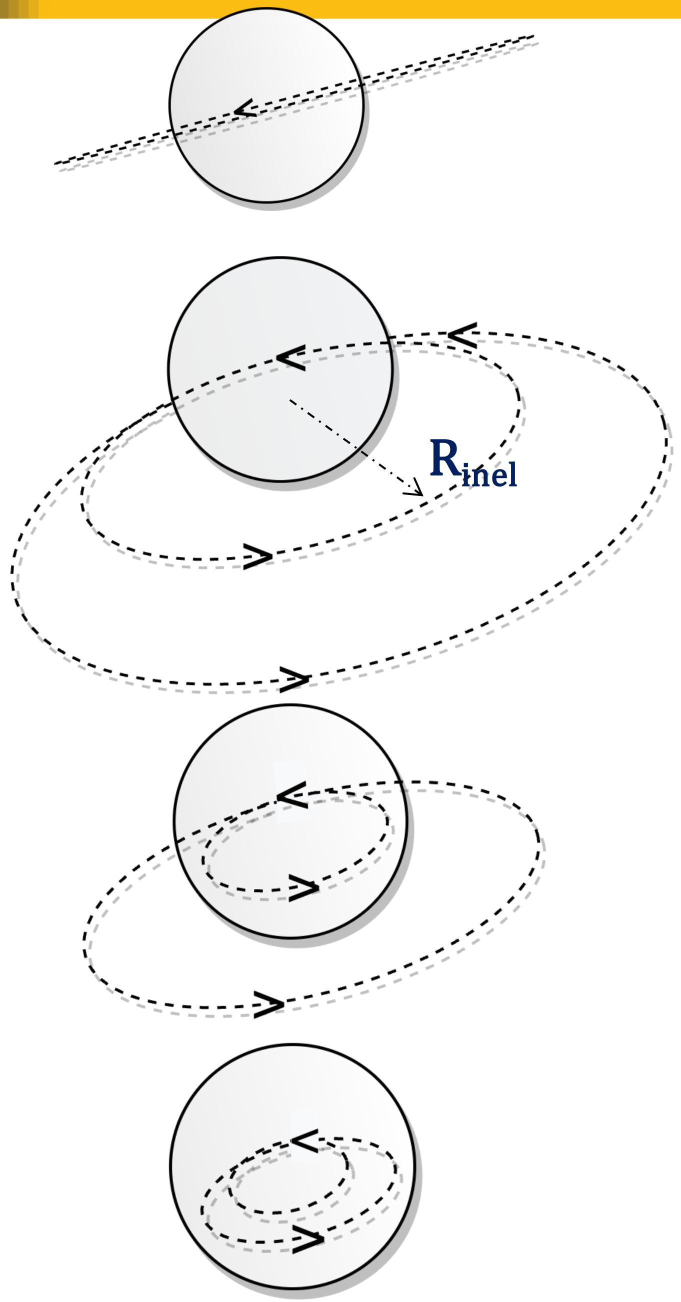
Inelastic DM

- We investigate the possibility of Inelastic DM thermalizing outside NS before it eventually settles in the NS.

- Depending on the DM model, it might be possible to detect this partial DM annihilation outside the NS, in the form of neutrinos or gamma ray signatures.

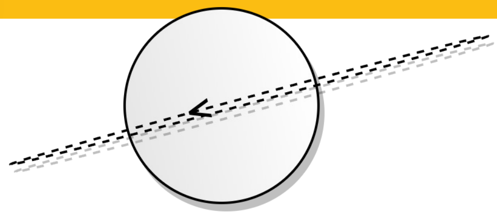






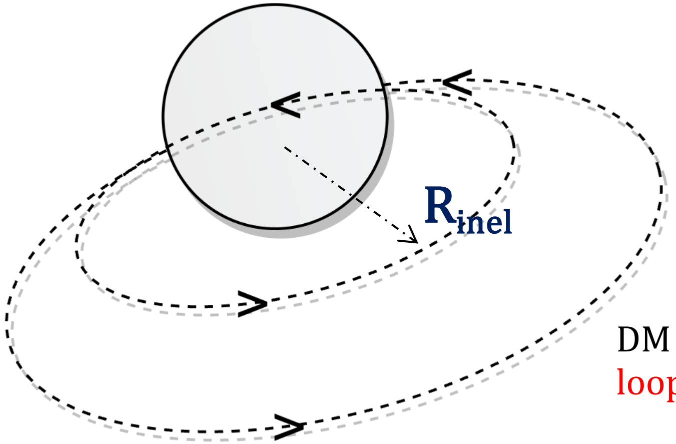
R_inel

τ_{eq}
Rate of Capture = Rate of Annihilation



In the case of inelastic, $\tau_{eq} << \tau_{1,therm}$

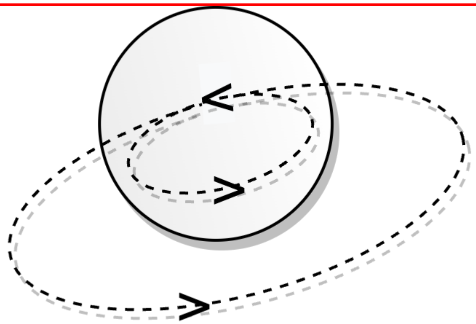
$\tau_{inel,therm}$
Time to thermalize to $R_{inel} > R_{NS}$



In the case of $\sigma_{inelastic}$, this is stage 2
&
$\tau_{inel,therm} << \tau_{1,therm}$

DM predominantly scatters inelastically off nuclei with negligible loop level elastic scattering

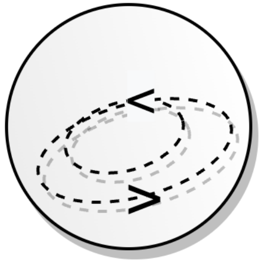
$\tau_{1,therm}$
Time to thermalize to $R < R_{NS}$



In the case of $\sigma_{elastic}/\sigma_{inelastic}$,

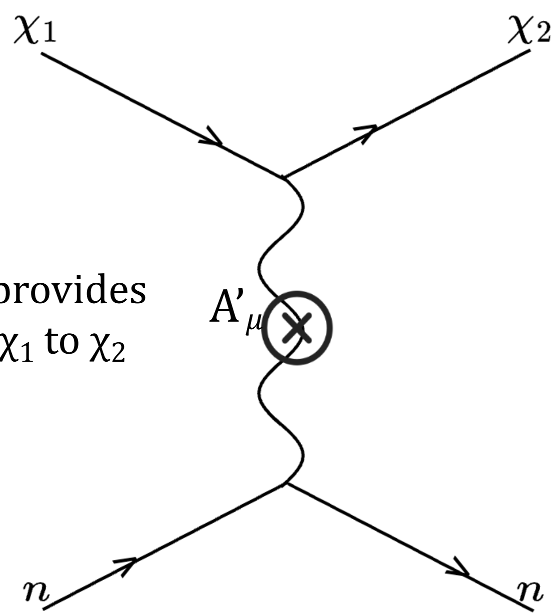
this is stage 2/stage 3

$\tau_{2,therm}$
Time to thermalize to $T_{\chi} = T_{NS}$



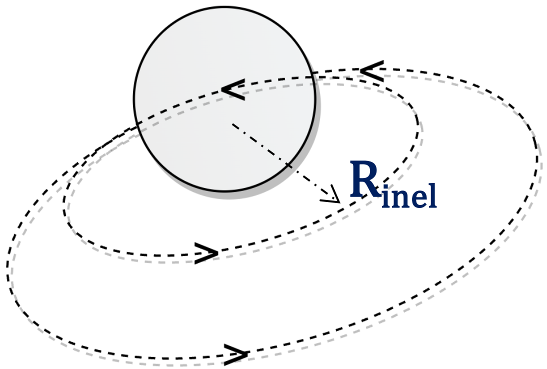
Inelastic Dark Matter

Inelastic dark matter models feature a DM particle χ_1 with mass m_χ



and a slightly heavier state χ_2 with mass $m_\chi + \delta m$, where $\delta m \ll m_\chi$

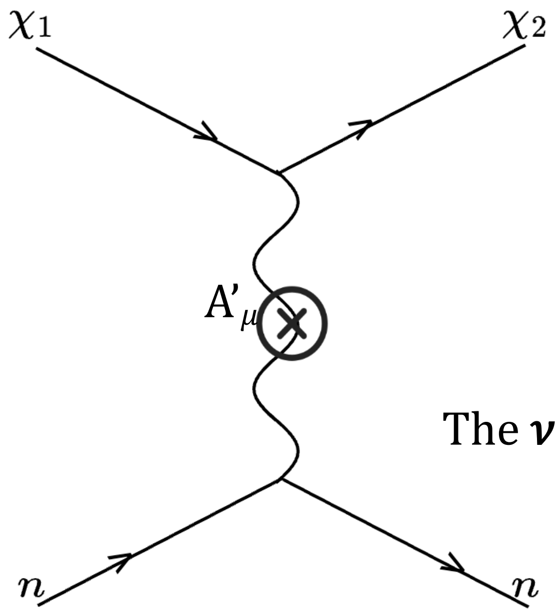
NS can accelerate DM to ~0.7c during infall. This provides sufficient kinetic energy to allow <u>up-scattering</u> of χ_1 to χ_2



Inelastic Dark Matter

δ imposes an energy threshold below which interactions are suppressed. (i.e. R_{inel} depends on δ)

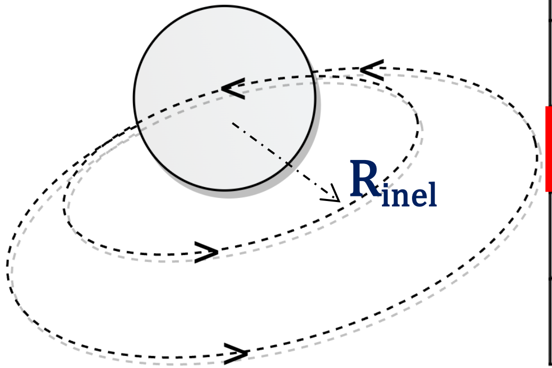
For $m_\chi >$ GeV → $\delta \in$ [50-300 MeV]



DM can partly thermalize and annihilate outside NS, and can produce SM particles

The $\boldsymbol{\nu}$ (or $\boldsymbol{\gamma}$) flux can be detected by $\boldsymbol{\nu}$ (or $\boldsymbol{\gamma}$) detectors

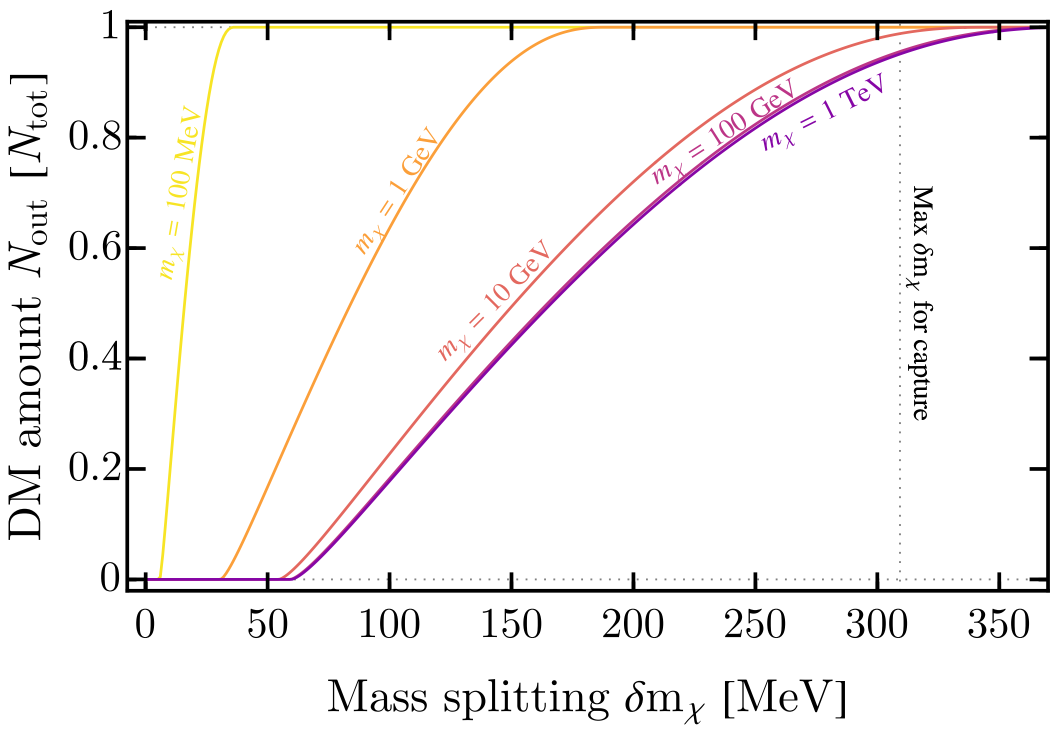
Timescales for DM thermalization

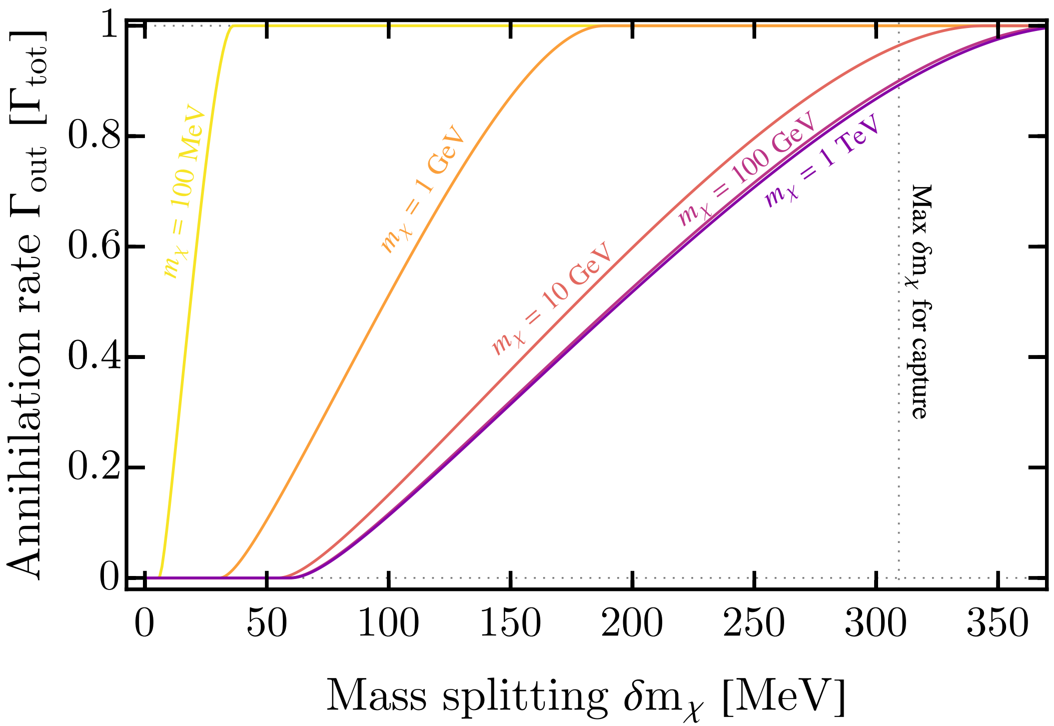


Timescale		
τ_{eq}	Time for capture-annihilation equilibrium	$\sim 9 \ \ hours$
$\tau_{1,inel}$	Time to thermalize to R_{inel}	$\sim 12 \ \ hours$
$\tau_{1,el}$	Time to thermalize to $R \leq R_{NS}$	$\sim 100 \ \ years$
τ_2	Time to thermalize to $T_{NS} = T_\chi$	$\sim 10^5 \ \ years$

Thermalization timescales for $m_\chi \sim \mathcal{O}(TeV)$, $\delta = 100\ MeV, \sigma_{inel} = 2 \times 10^{-45}\ cm^2, \sigma_{el} \simeq 10^{-50}\ cm^2$

Amount of DM annihilating outside NS





Fraction of the total captured and thermalized DM outside the neutron star comes from the condition

$$E_{CM} \gtrsim m_n + m_\chi + \delta m_\chi$$

Where E_{CM} is the center-of-mass energy of a dark matter particle transiting a neutron star

n_{NS} & ρ_{DM} Models

- ν flux produced by a single NS is too faint to be detected.
- $\sim 10^9$ NS predicted in the Milky Way with densest population in galactic center

$\therefore$ Adopting NS distribution models

- Surface density of disk :
  arXiv: 0908.3182v1

$$log\Sigma(R) = a_0 + a_1 R + a_2 R^2 + a_3 R^3 + a_4 R^4$$

- Number density distribution :
  arXiv: 2101.12213

$$n_{NS} = 5.98 \times 10^3 \left(\frac{r}{1pc}\right)^{-1.7} pc^{-3}; \quad 0.1\text{pc} < \text{r} < 2 \text{ pc},$$

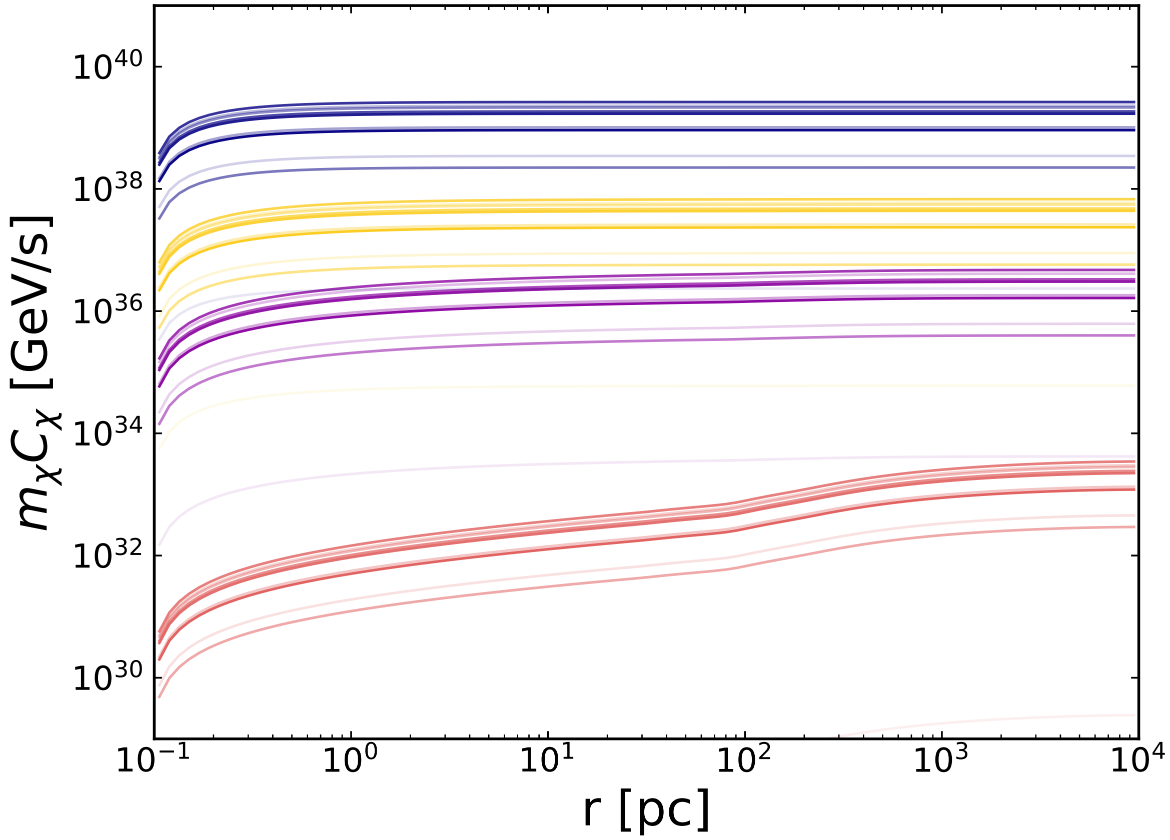
$$= 2.08 \times 10^4 \left(\frac{r}{1pc}\right)^{-3.5} pc^{-3}; \qquad \text{r} > 2 \text{ pc}$$

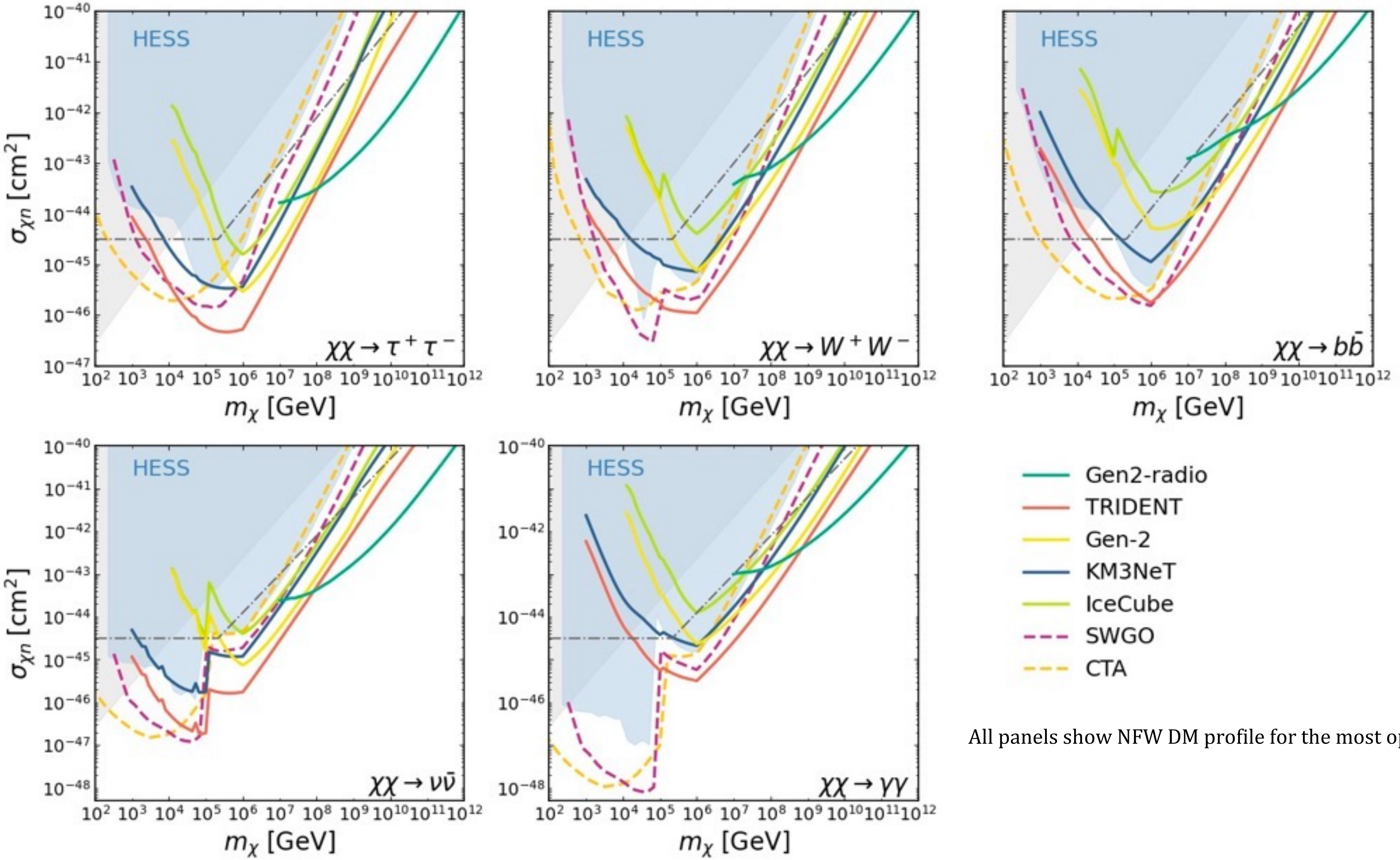
ν flux signal

Then ν flux for a distribution of NS models + DM halo density profiles –

$$\Gamma_{tot} = \int_{r_{min}}^{r_{max}} \Gamma_{ann}(r)\rho_{NS}(r)4\pi r^2 dr,$$

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





All panels show NFW DM profile for the most optimistic NS distribution

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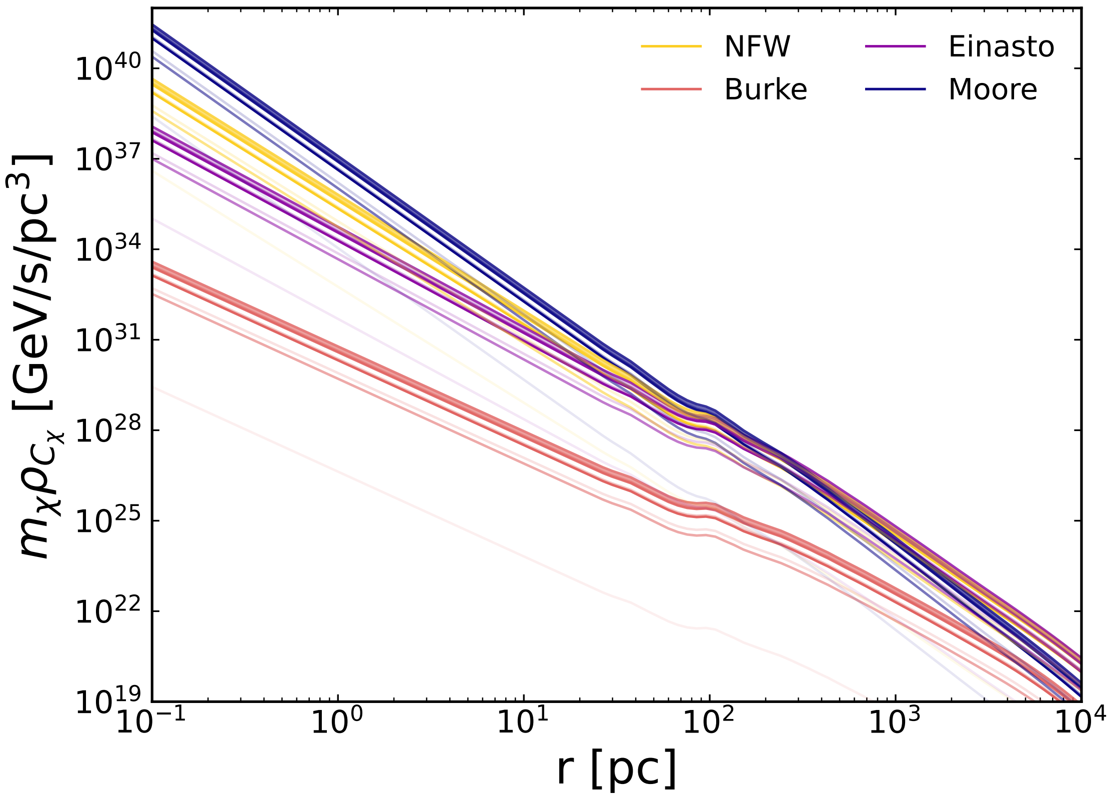
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Queen's University

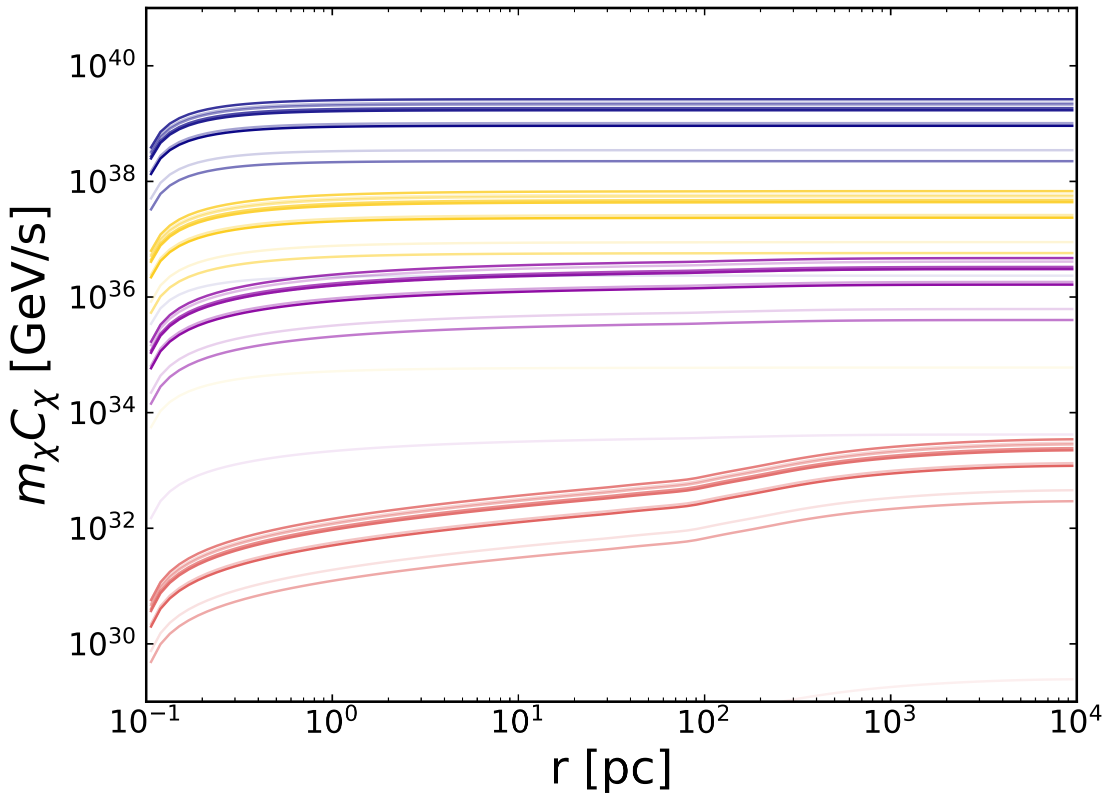
Thank you !　　Questions?

Backup Slides

Mass capture rate densities



Mass capture rates



η_{NS} & ρ_{DM} Models

DM density profiles : $$\rho_{NFW}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)\right]^2}$$

$$\rho_{Moore}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)\right]^{3-\gamma}}$$

$$\rho_{Bur}(r) = \frac{\rho_0}{\left(1+\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)^2\right]}$$

$$\rho_{Einasto}(r) = \rho_0 \exp\left[-\left(\frac{2}{\alpha}\right)\left\{\left(\frac{r}{r_s}\right)^{\alpha}-1\right\}\right]$$

Then ν flux for a distribution of NS models + DM halo density profiles –

$$\phi = \int_r d^3r\, \eta_{NS}(r)\dot{m}\left(\frac{\rho_\chi(r)}{0.42\, GeV cm^{-3}}\right)\left(\frac{230\, km\, s^{-1}}{v_{\chi(r)}}\right)$$

Note: halo velocities have been adopted from MW RC [*Sofue Y. 2020*]

Telescope Sensitivities & Detection Prospects

SWGO
The Southern Wide-field Gamma-ray Observatory

cta
cherenkov telescope array

TRIDENT
海 | 铃 | 计 | 划

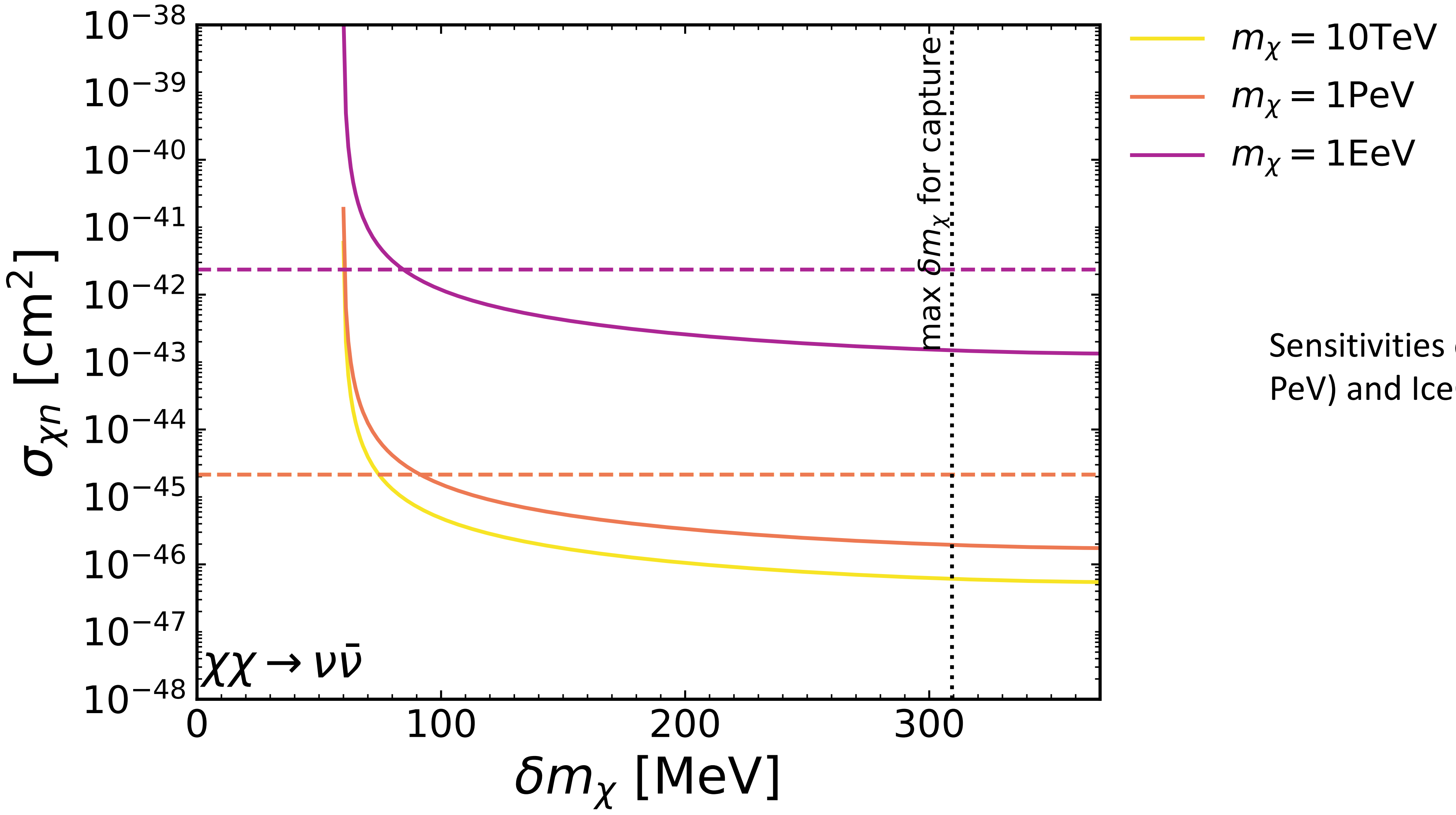
IceCube Gen2

IceCube

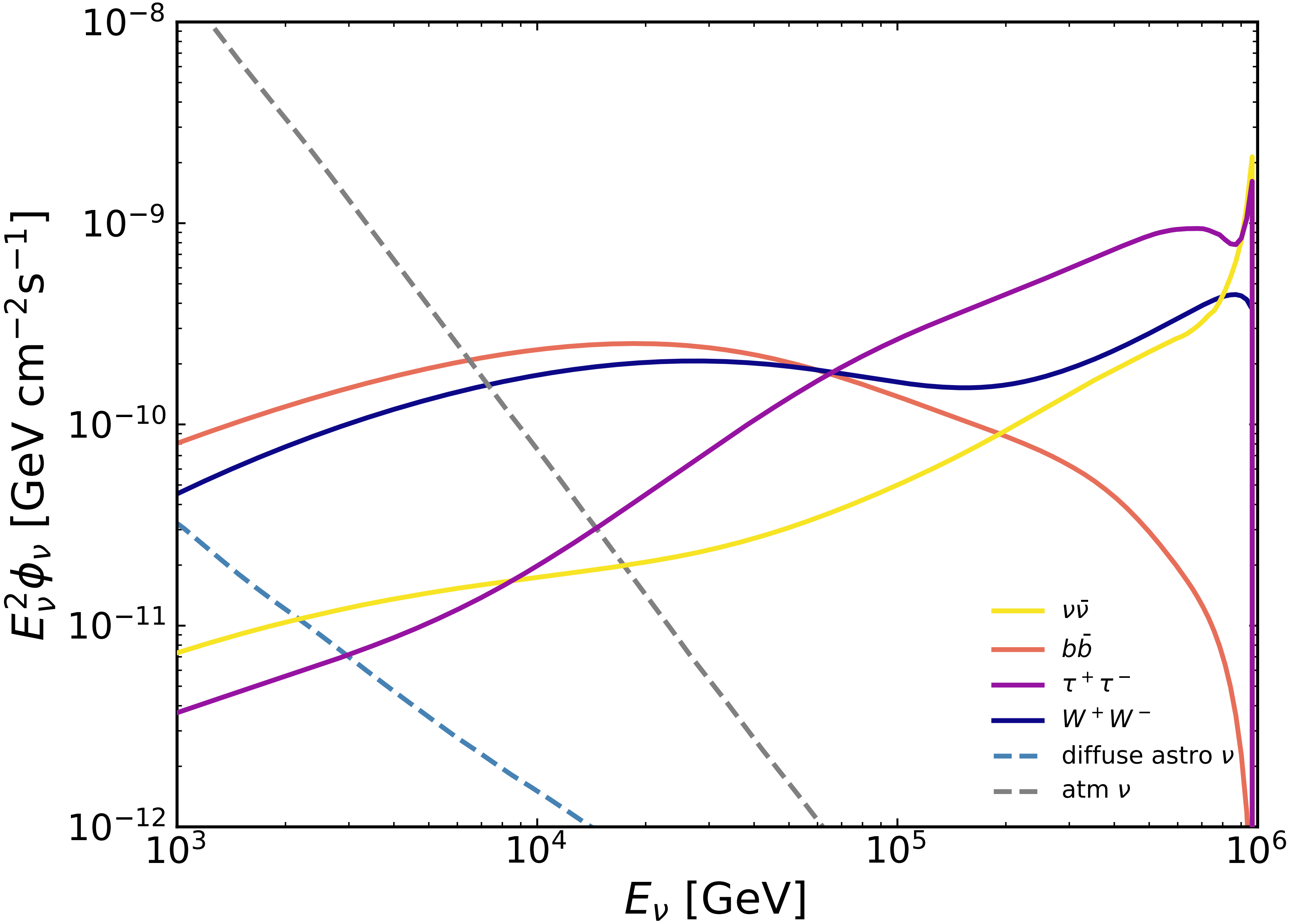
KM3NeT

BAIKAL-GVD

P-ONE



Sensitivities of TRIDENT (10 TeV and 1 PeV) and IceCube-Gen2 radio (1EeV).



DM=1 PeV with the background fluxes , the capture rate used is the maximum.