Light DM Detection with Neutron Stars

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UC Riverside

with Nirmal Raj, Flip Tanedo and Hai-bo Yu

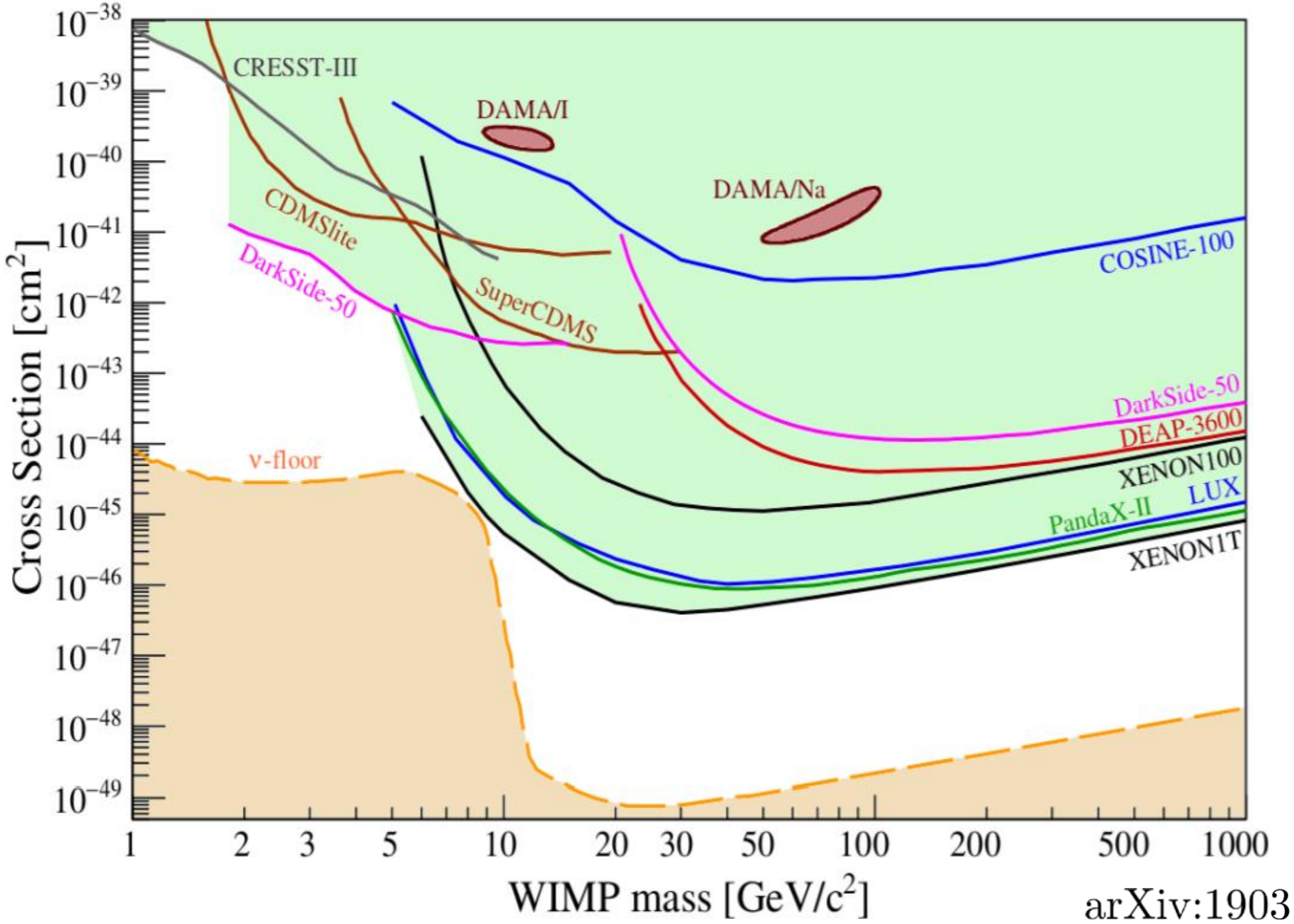
Based on arXiv:1910.XXXX

SoCal BSM 2019

Outline

- Direct detection : status and challenges
- Neutron star kinetic heating
- Lepton heating and relativistic effects
- Results for fermionic DM-lepton VV operator

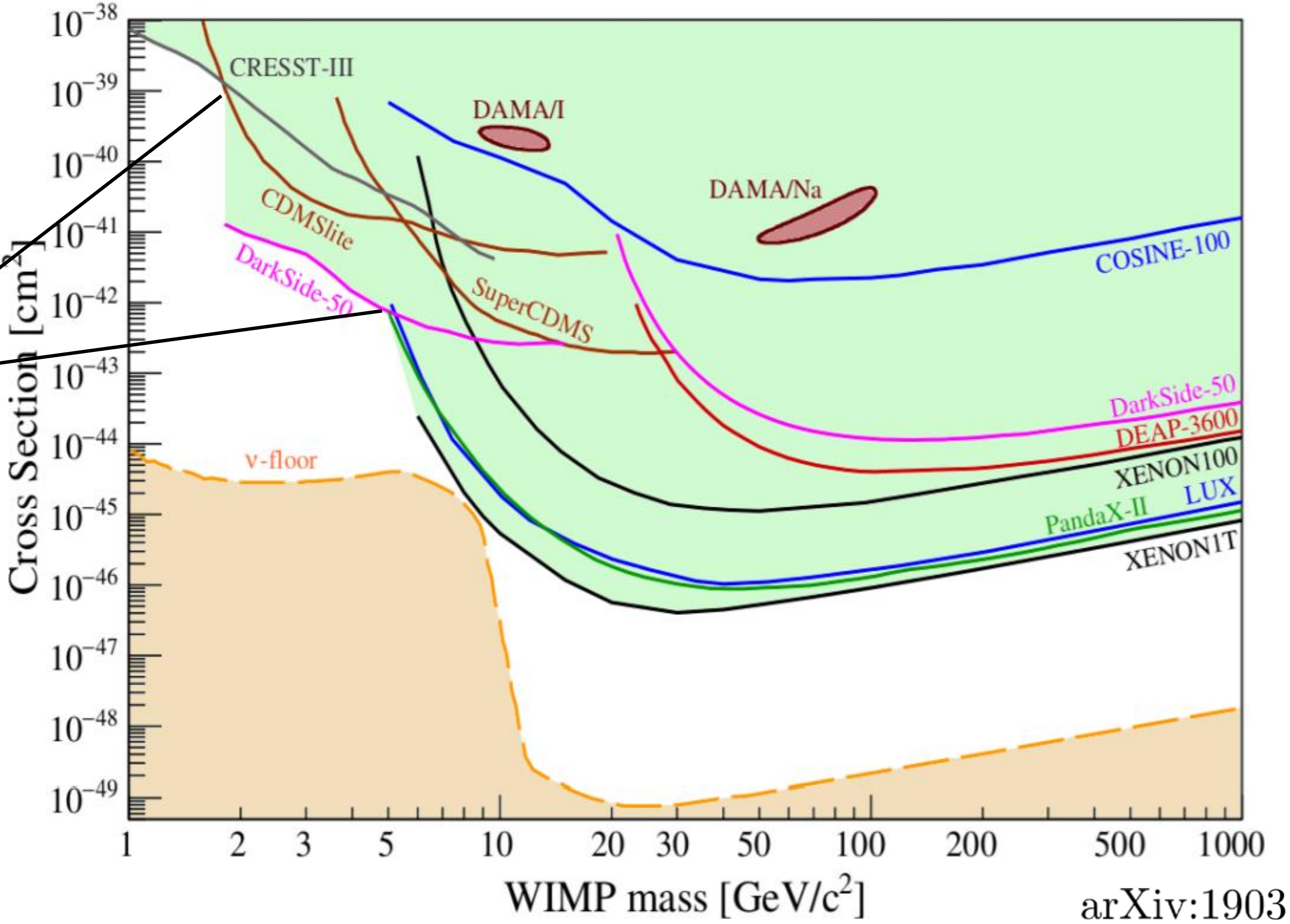
Direct Detection : Status



arXiv:1903.03026

Direct Detection : Challenges

Low Mass: Recoil below detector threshold



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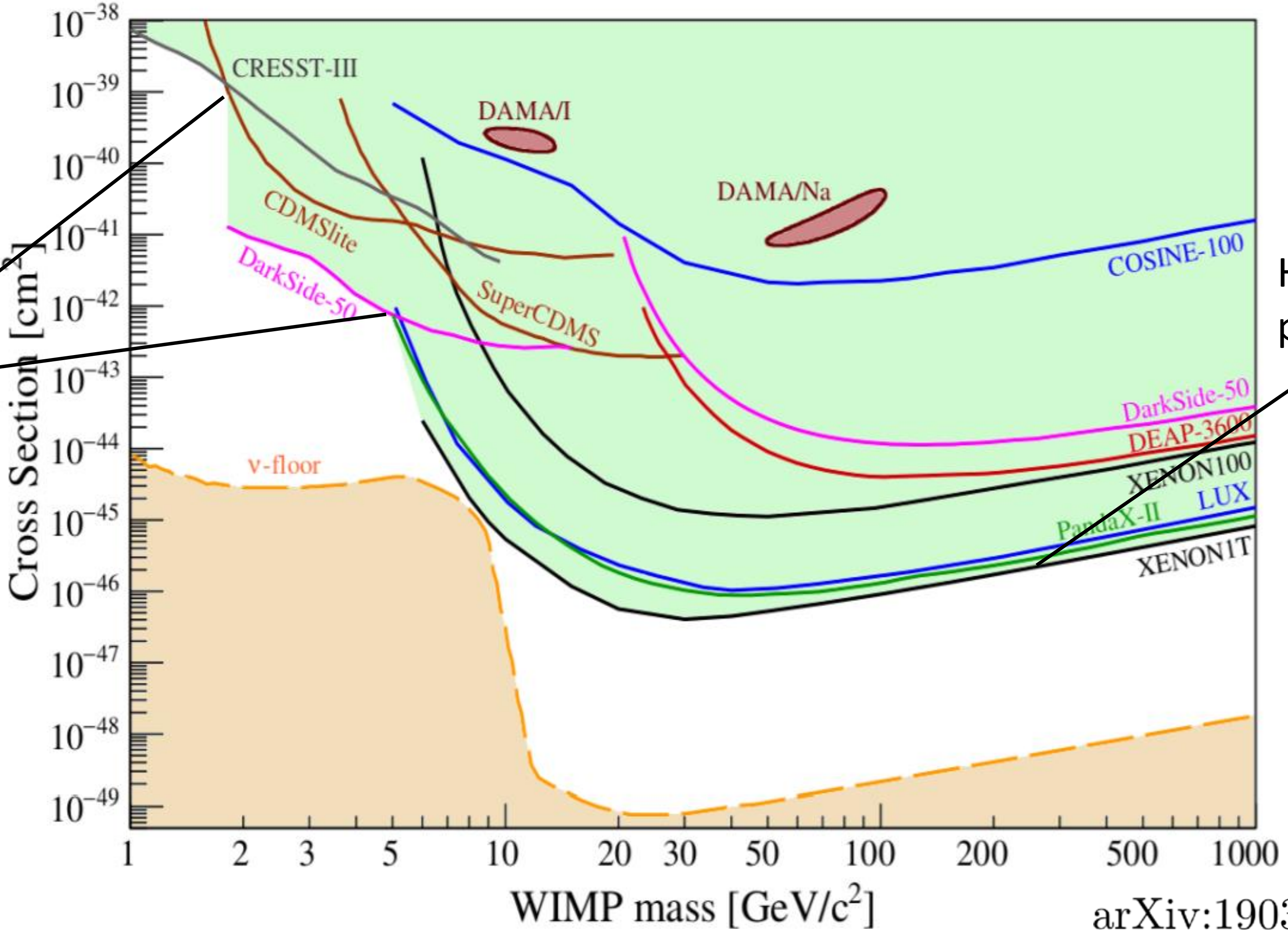
Direct Detection : Challenges



Low Mass: Recoil below detector threshold

High mass: Flux inversely proportional to DM mass

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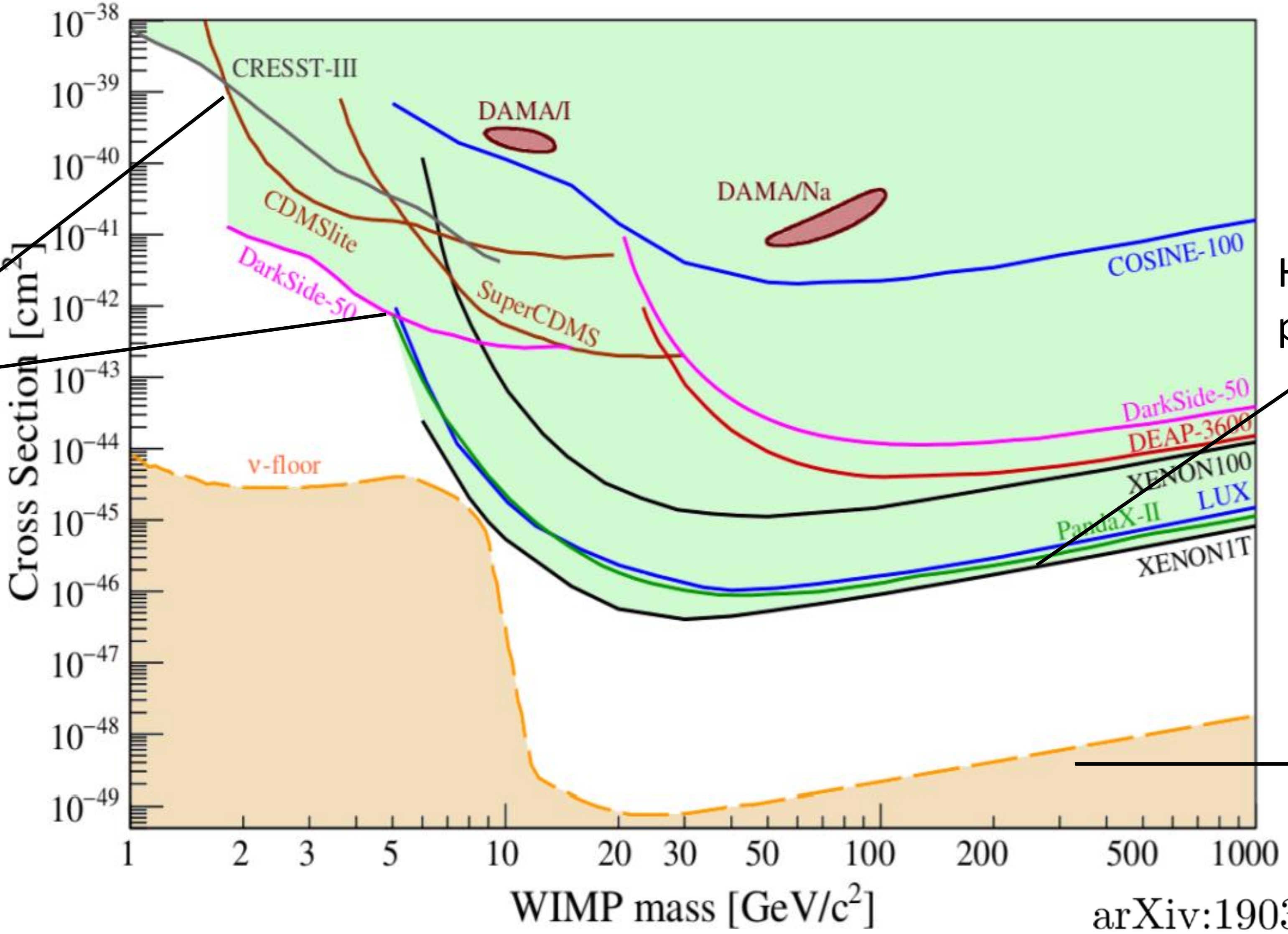
Direct Detection : Challenges



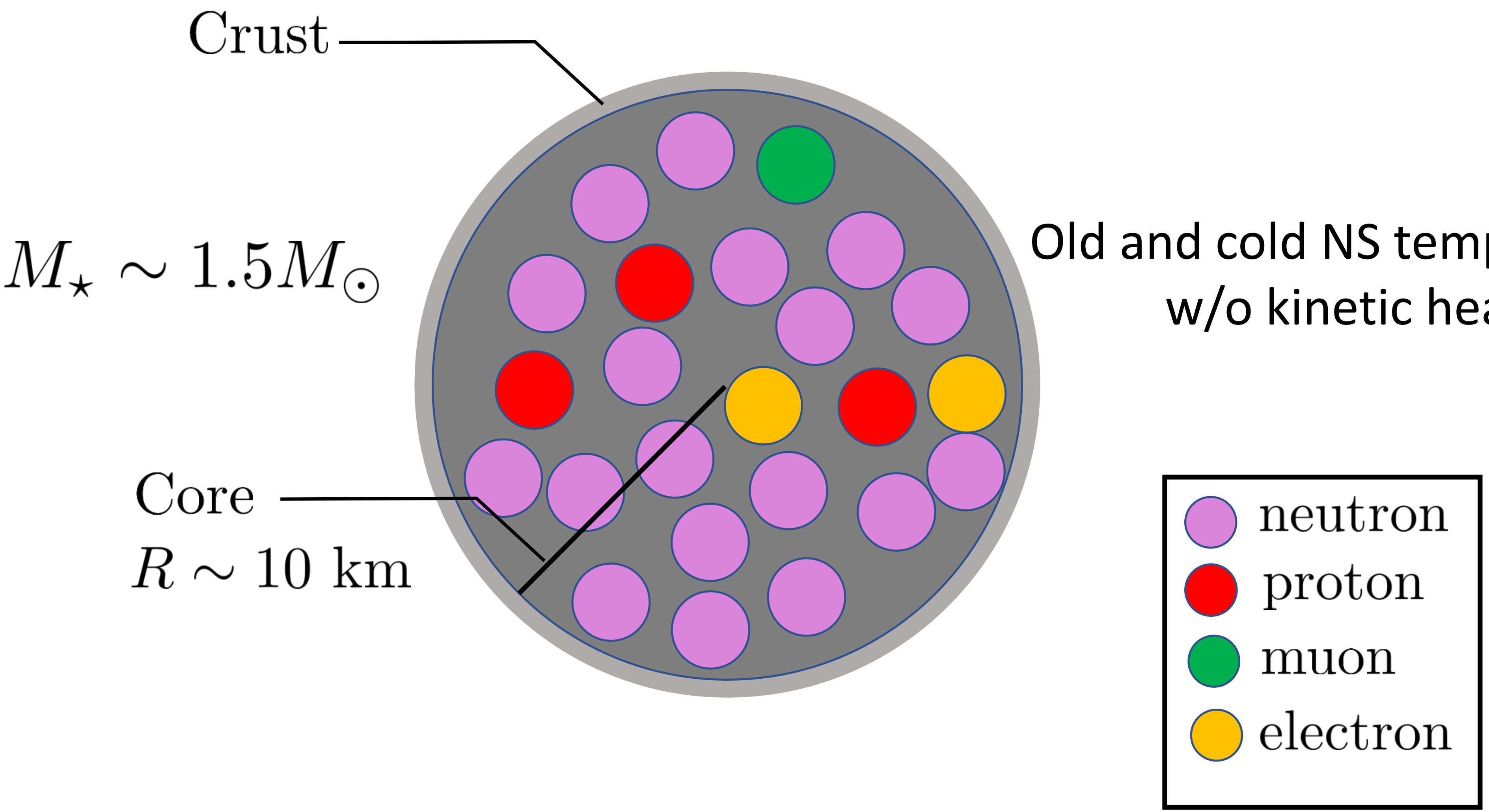
Low Mass: Recoil below detector threshold

High mass: Flux inversely proportional to DM mass

Atmospheric + Solar neutrino bkg

arXiv:1903.03026

Neutron Star Kinetic Heating



Old and cold NS temp ~ O(10) K
w/o kinetic heating

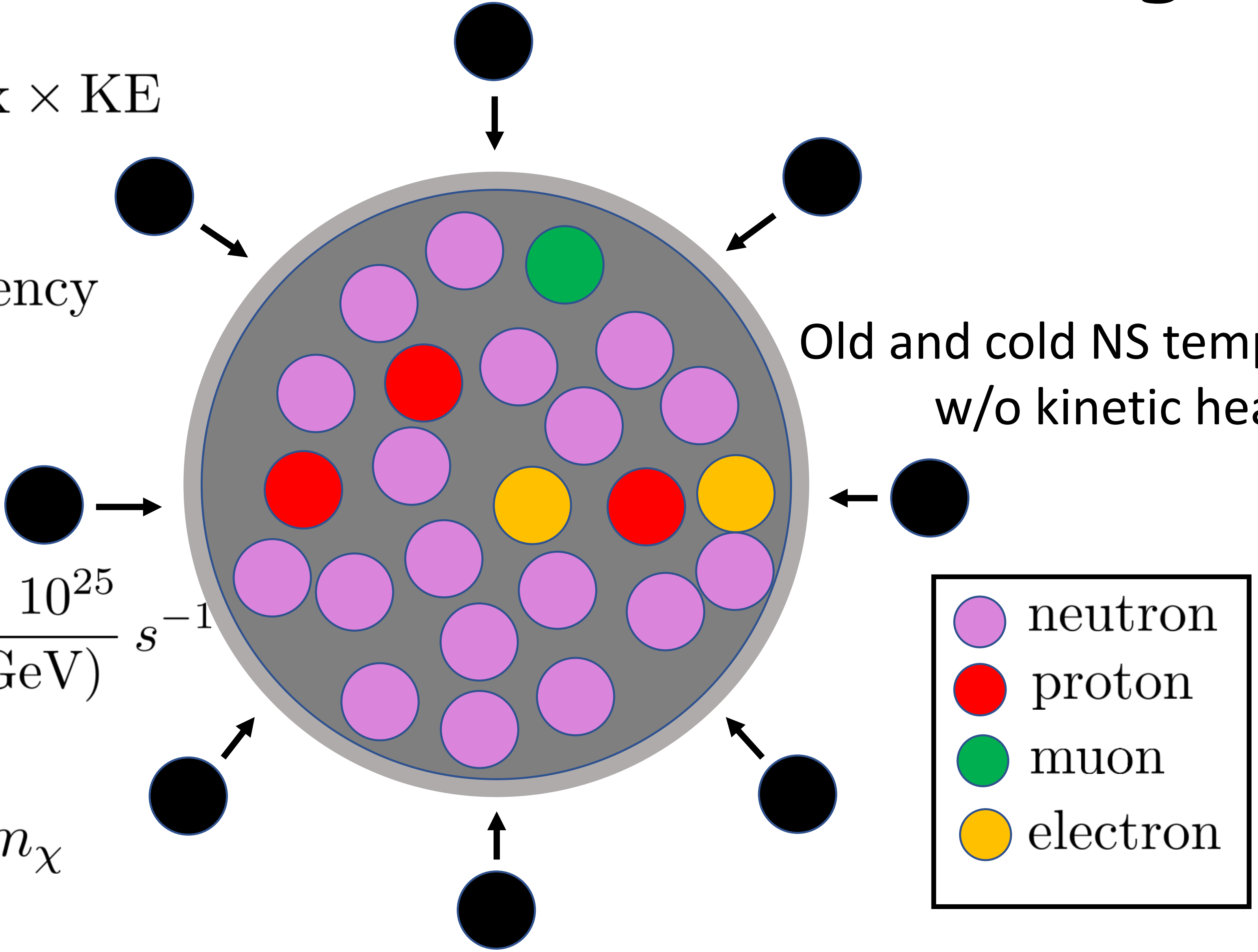
Neutron Star Kinetic Heating

$$\dot{E} = f \times \text{DM flux} \times \text{KE}$$

Capture efficiency

$$\text{DM flux} \sim \frac{3.11 \times 10^{25}}{m_\chi\,(\text{GeV})}\, s^{-1}$$

$$\text{KE} = (\gamma - 1) m_\chi$$



Old and cold NS temp ~ O(10) K
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Neutron Star Kinetic Heating

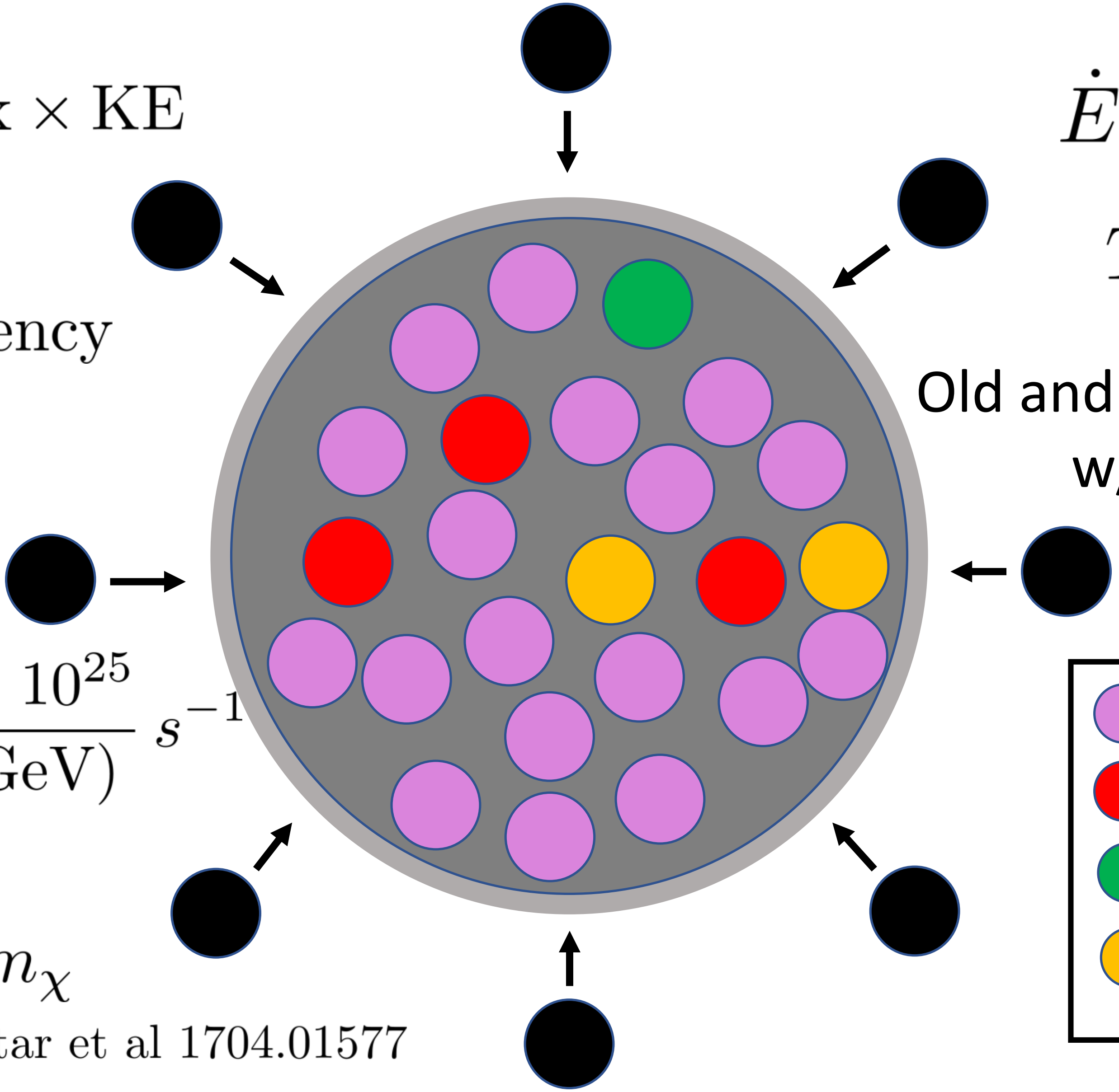
$$\dot{E} = f \times \text{DM flux} \times \text{KE}$$

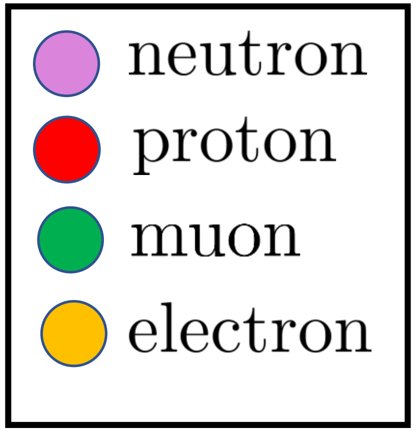
Capture efficiency

$$\dot{E} = 4\pi R_\star^2 \sigma_{\text{SB}} T^4$$

$$T \sim 1750\, f^{1/4}\, \text{K}$$

Old and cold NS temp ~ O(10) K
w/o kinetic heating





$$\text{DM flux} \sim \frac{3.11 \times 10^{25}}{m_\chi\,(\text{GeV})}\, s^{-1}$$

$$\text{KE} = (\gamma - 1) m_\chi$$

See Baryakhtar et al 1704.01577

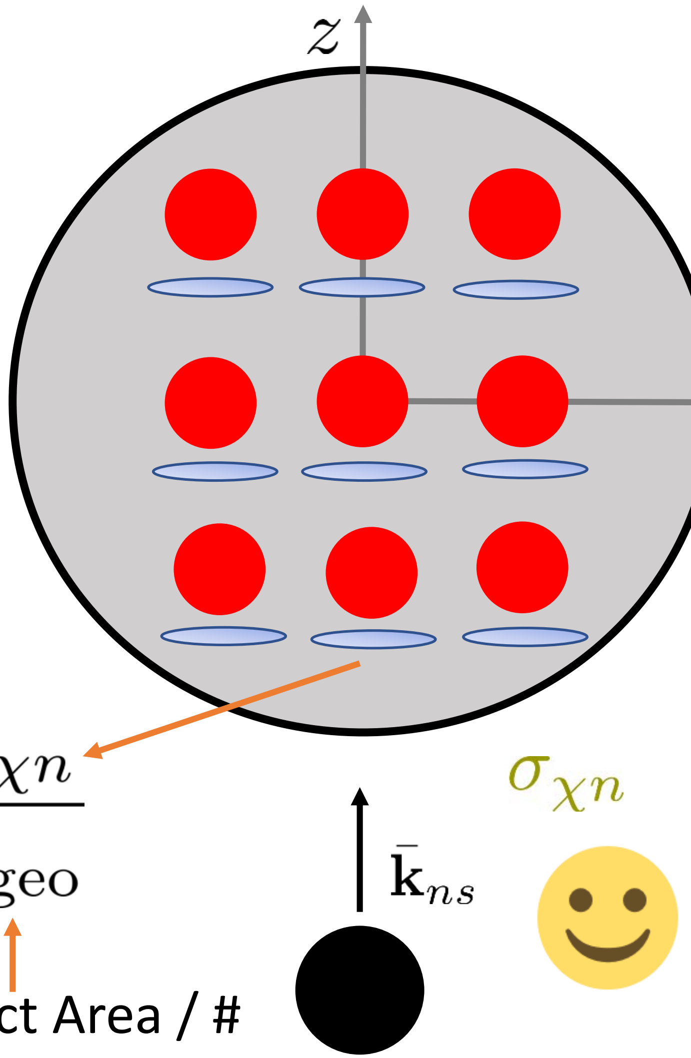
Why Leptons? Challenges?

- About 10-15% of the particles in NS cores could be leptons
- Lighter masses : potentially helpful with light DM detection
- What if DM is leptophilic?

Why Leptons? Challenges?

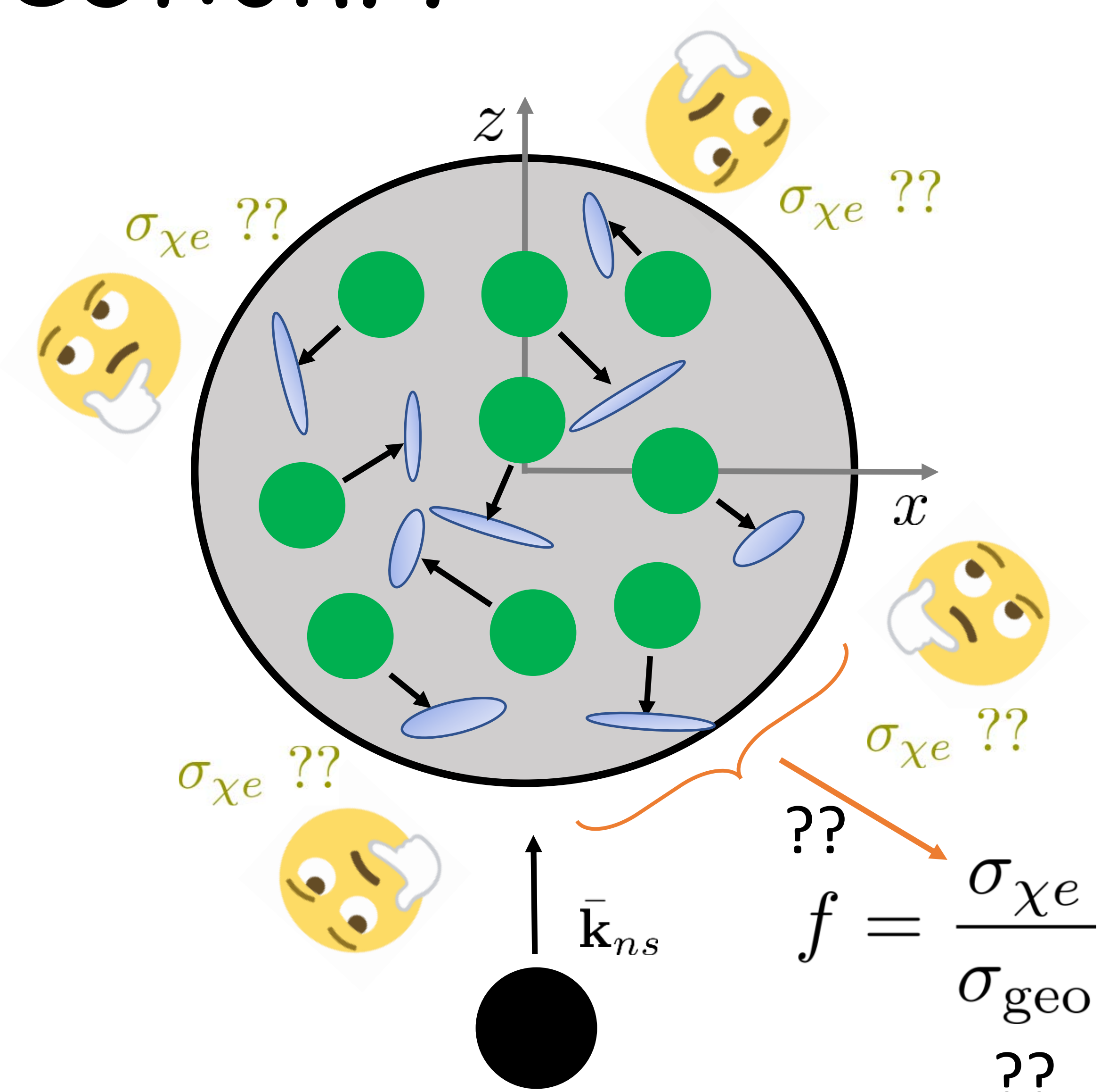
- About 10-15% of the particles in NS cores could be leptons
- Lighter masses : potentially helpful with light DM detection
- What if DM is leptophilic?
- Electrons are highly relativistic Fermi momentum >> mass
- Muons : Fermi momentum ~ mass
- Need careful consideration of relativistic effects

Cross Section??



$$f = \frac{\sigma_{\chi n}}{\sigma_{\rm geo}}$$

const= xsect Area / #



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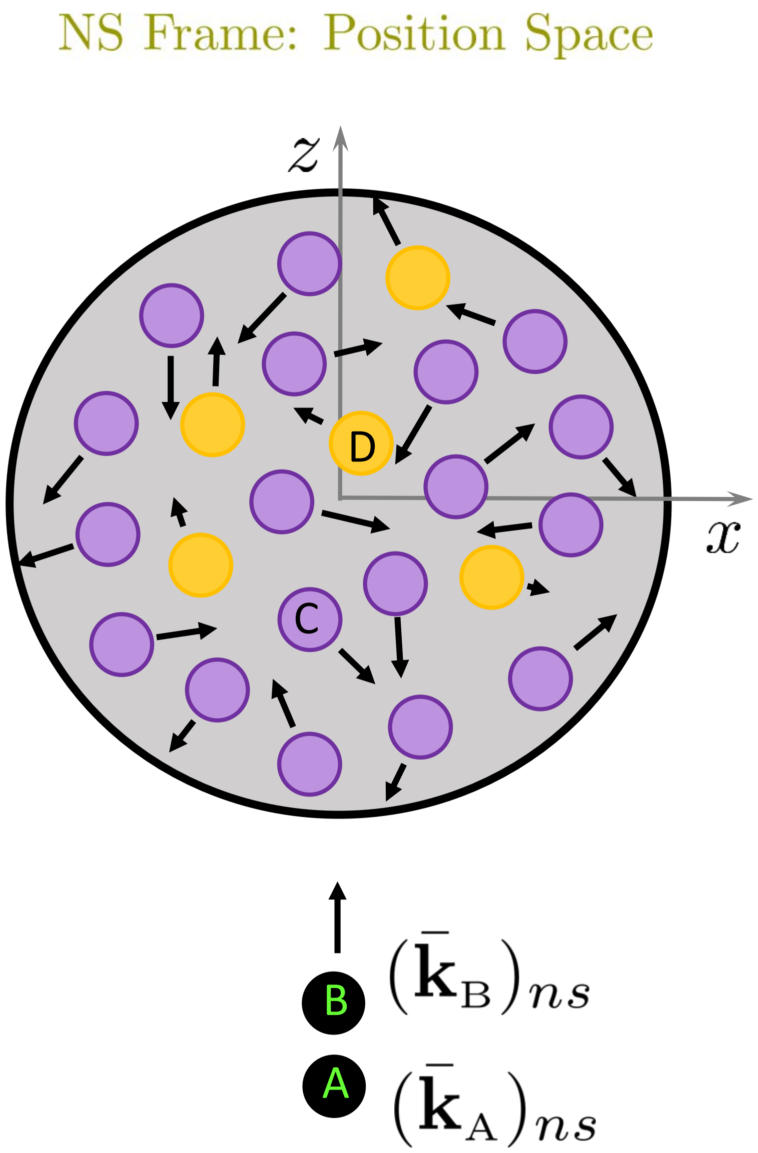
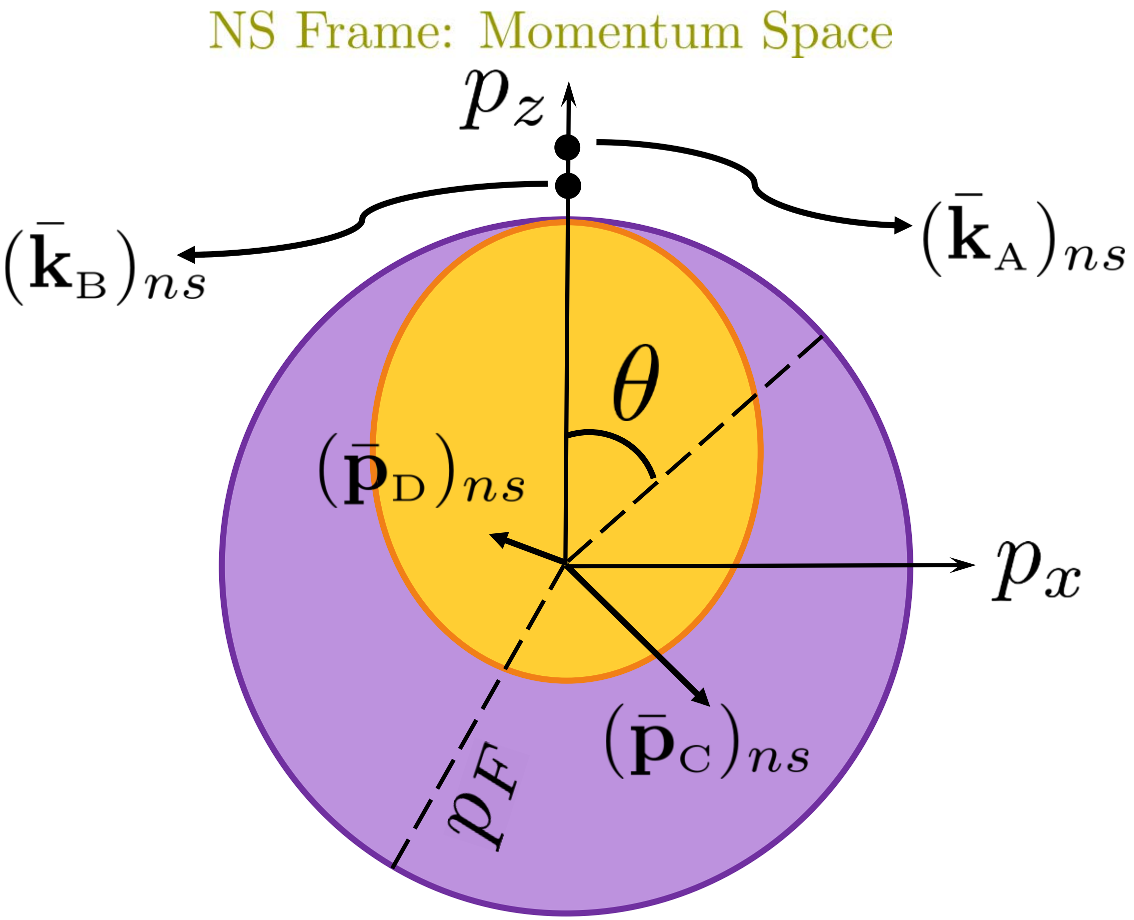
??

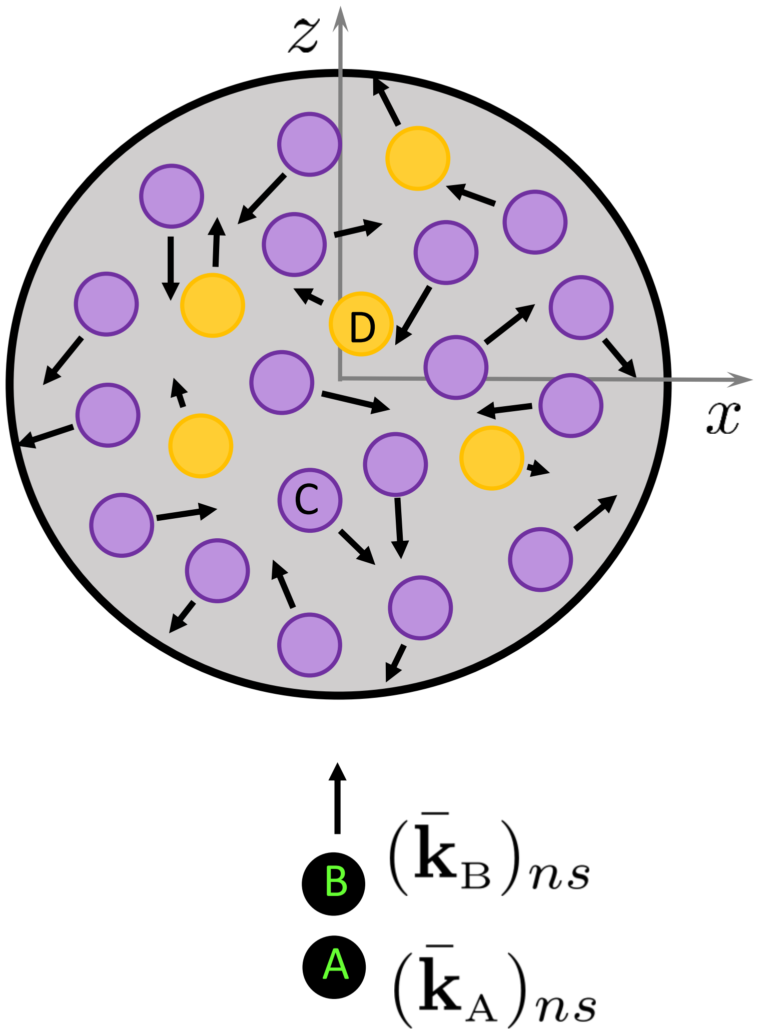
Pauli Blocking



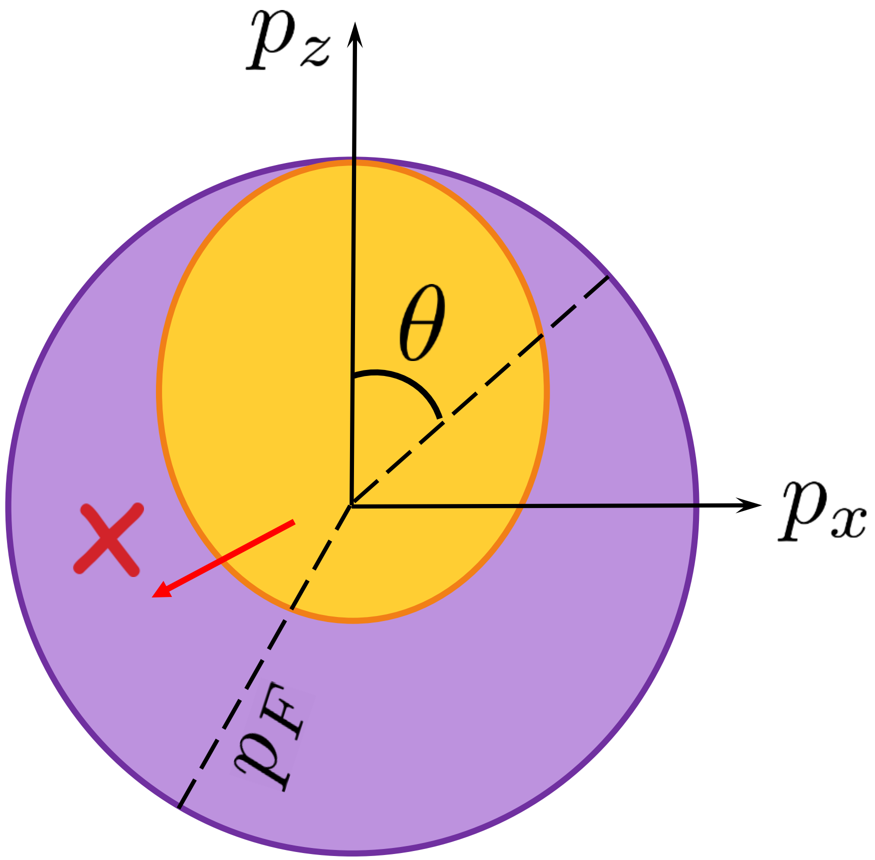


Pauli Blocking

NS Frame: Position Space



NS Frame: Momentum Space



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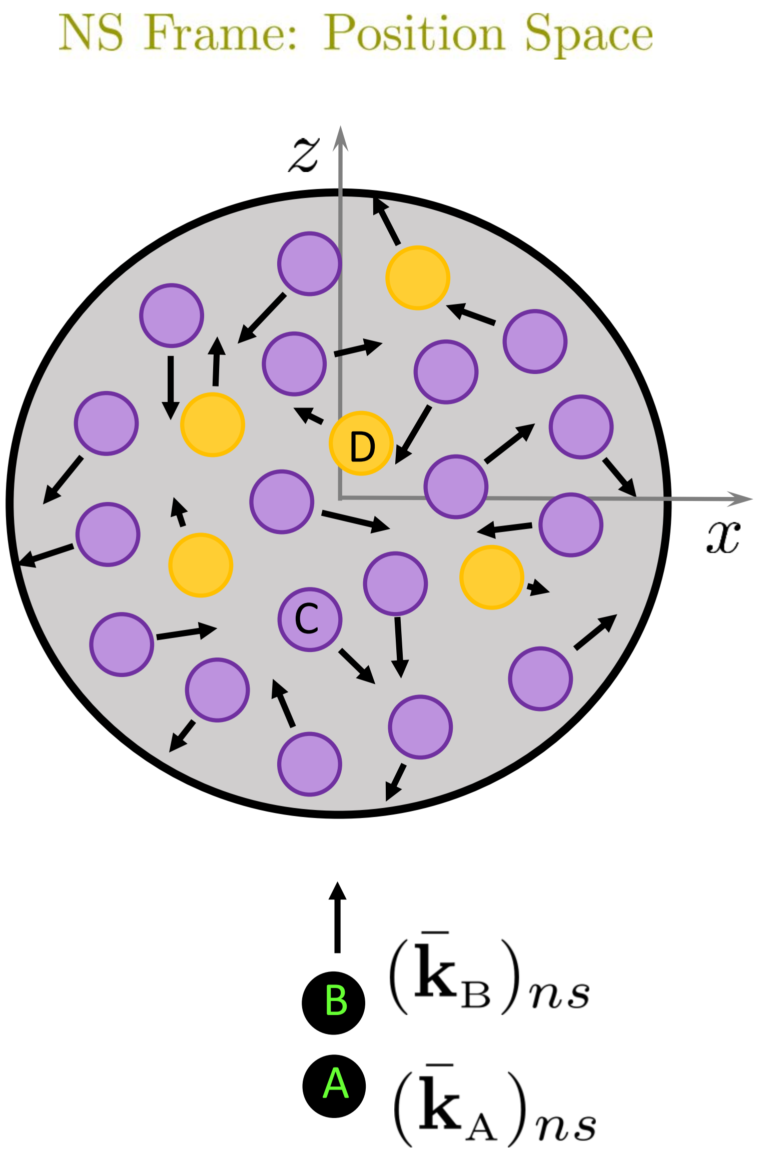

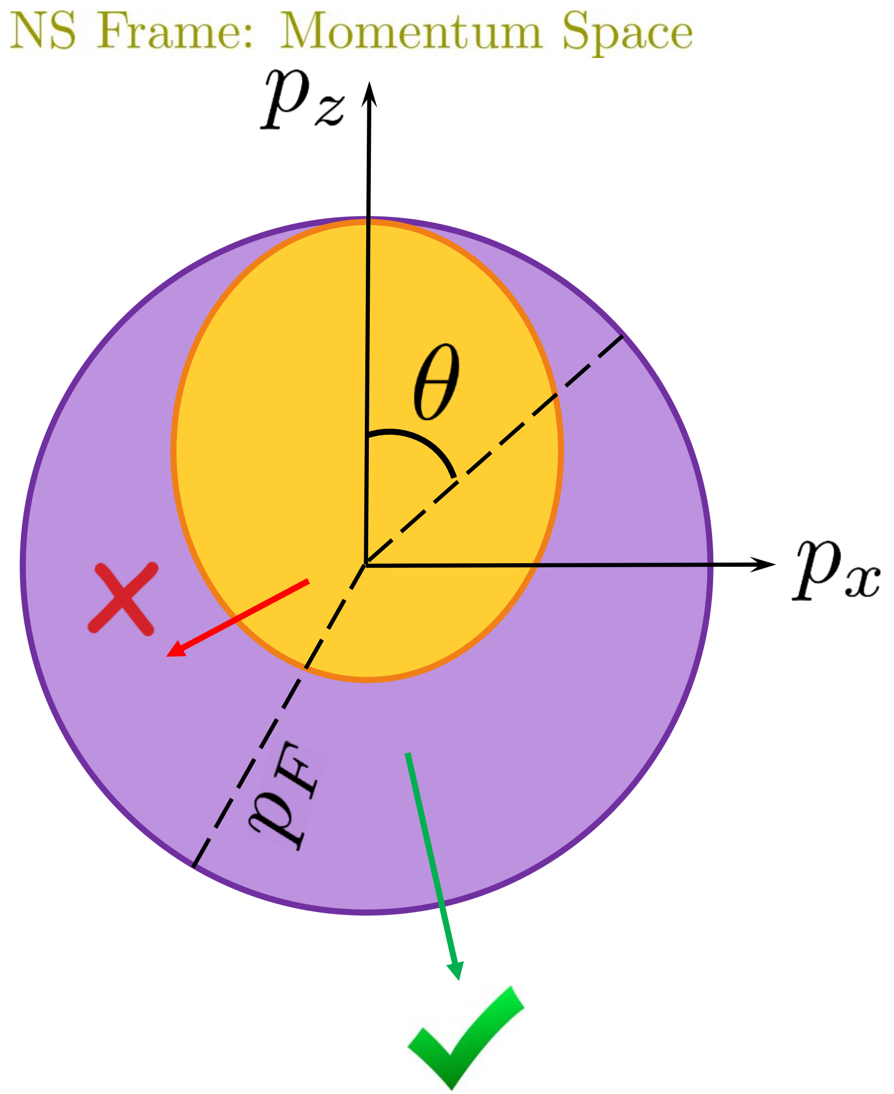

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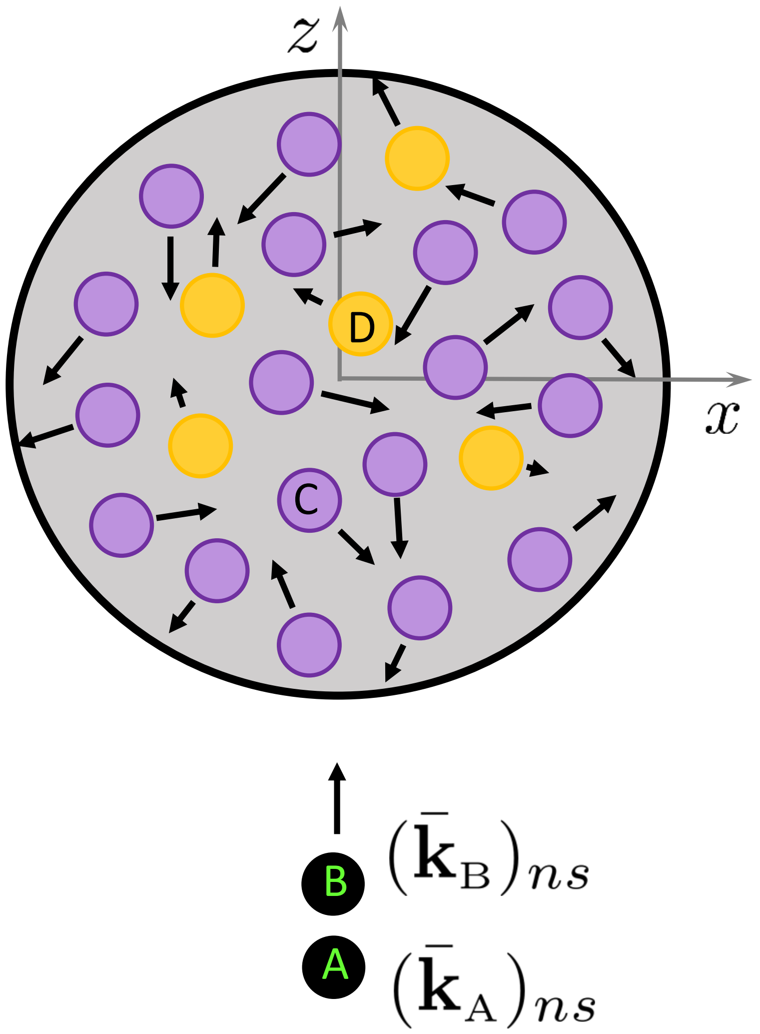

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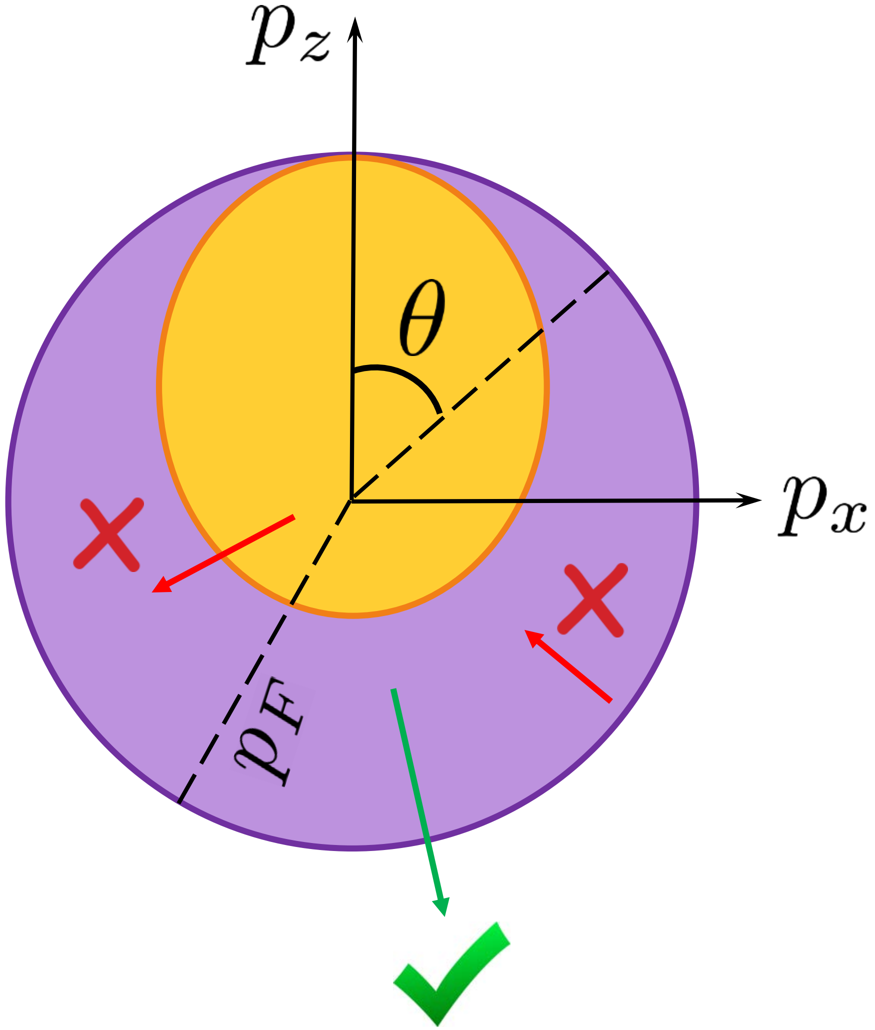
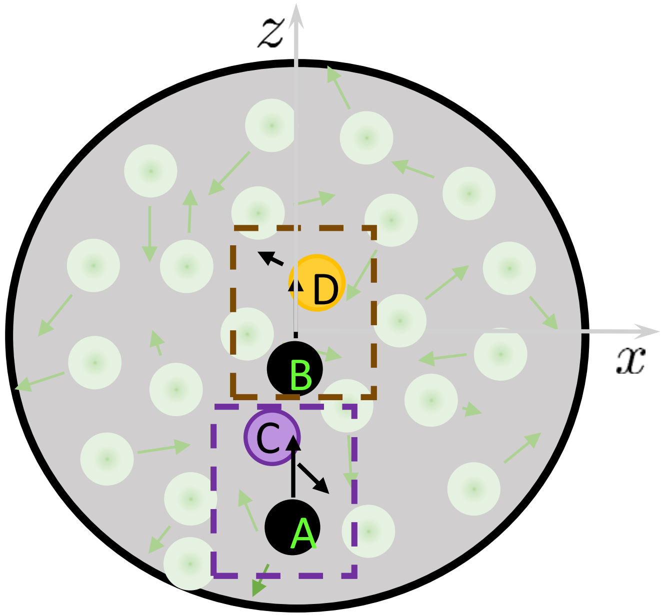


Interactions in NS and CM frames



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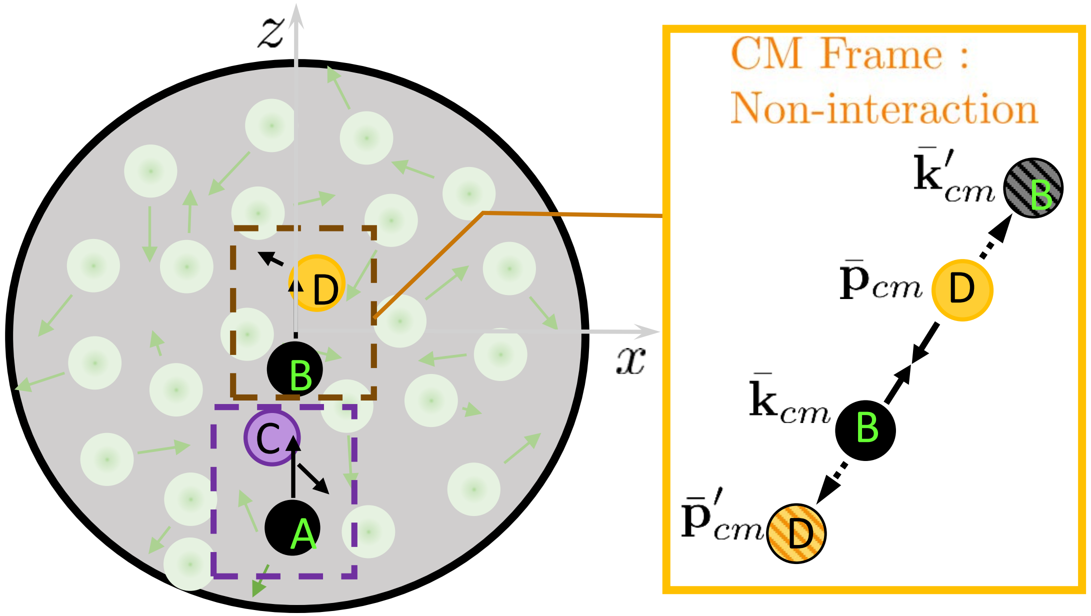

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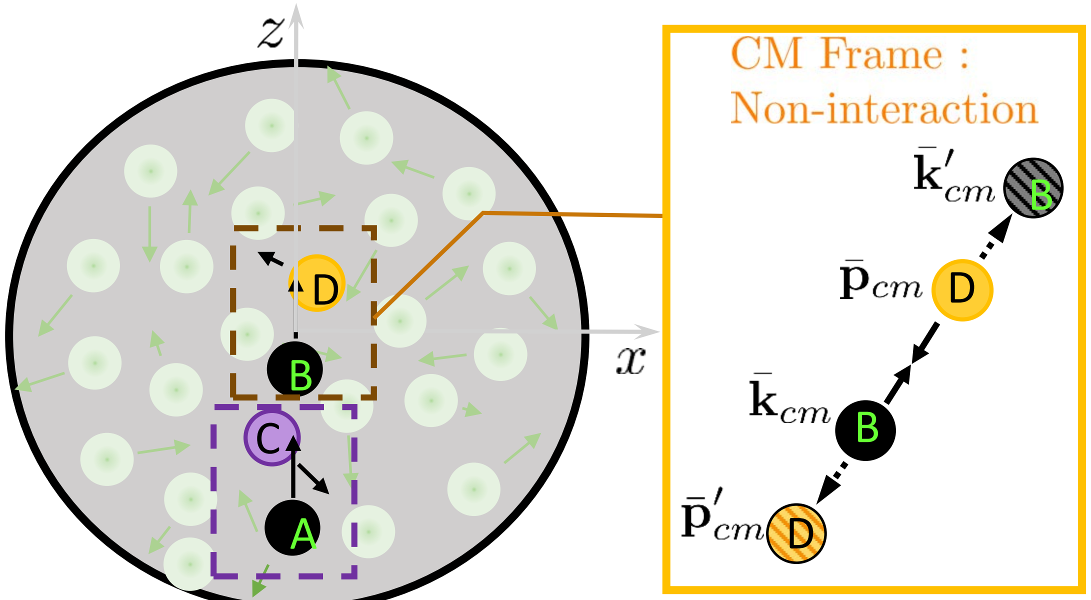
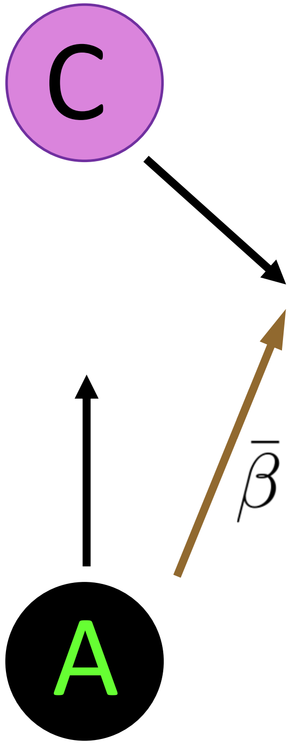


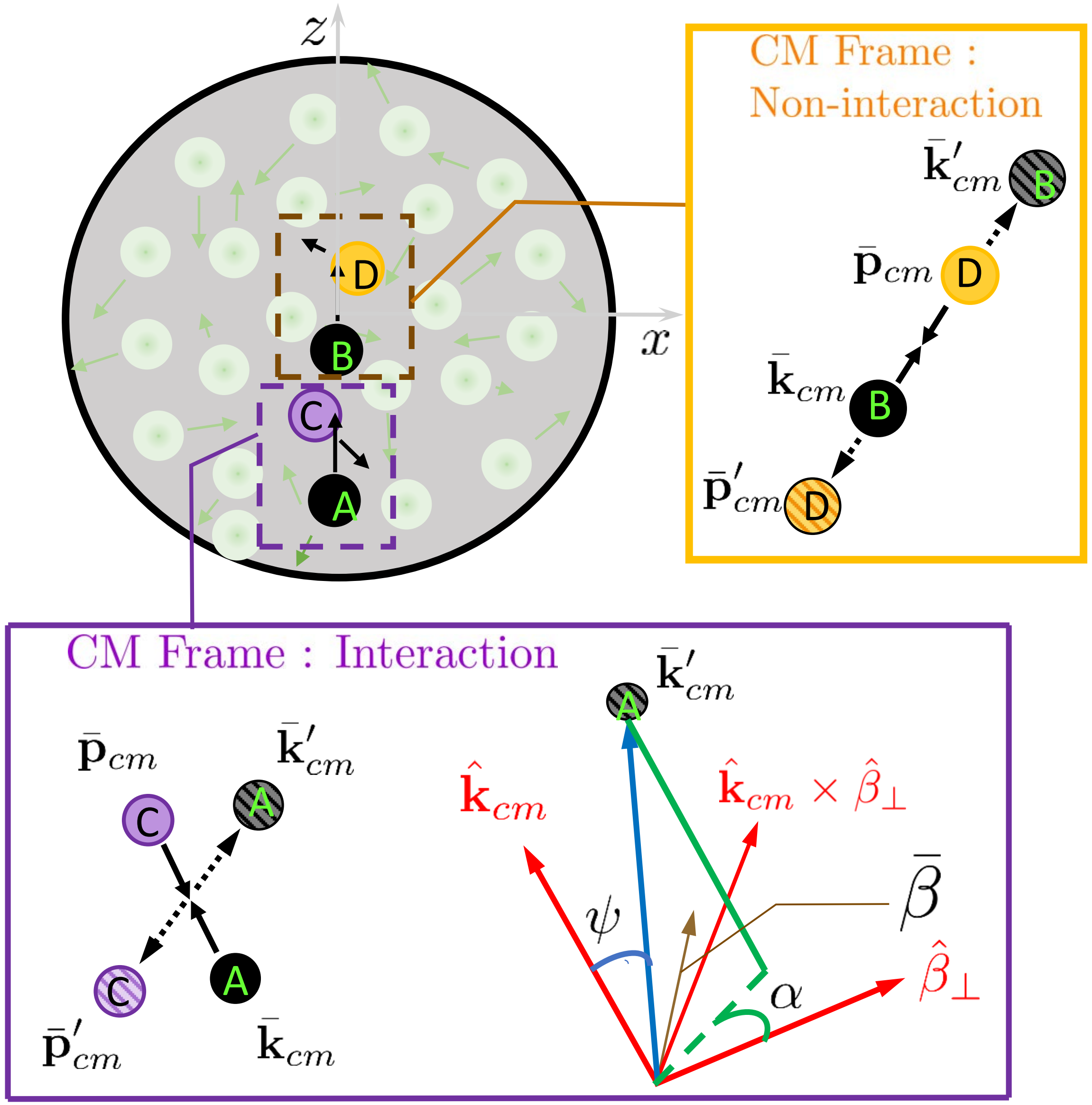
NS Frame : Interaction

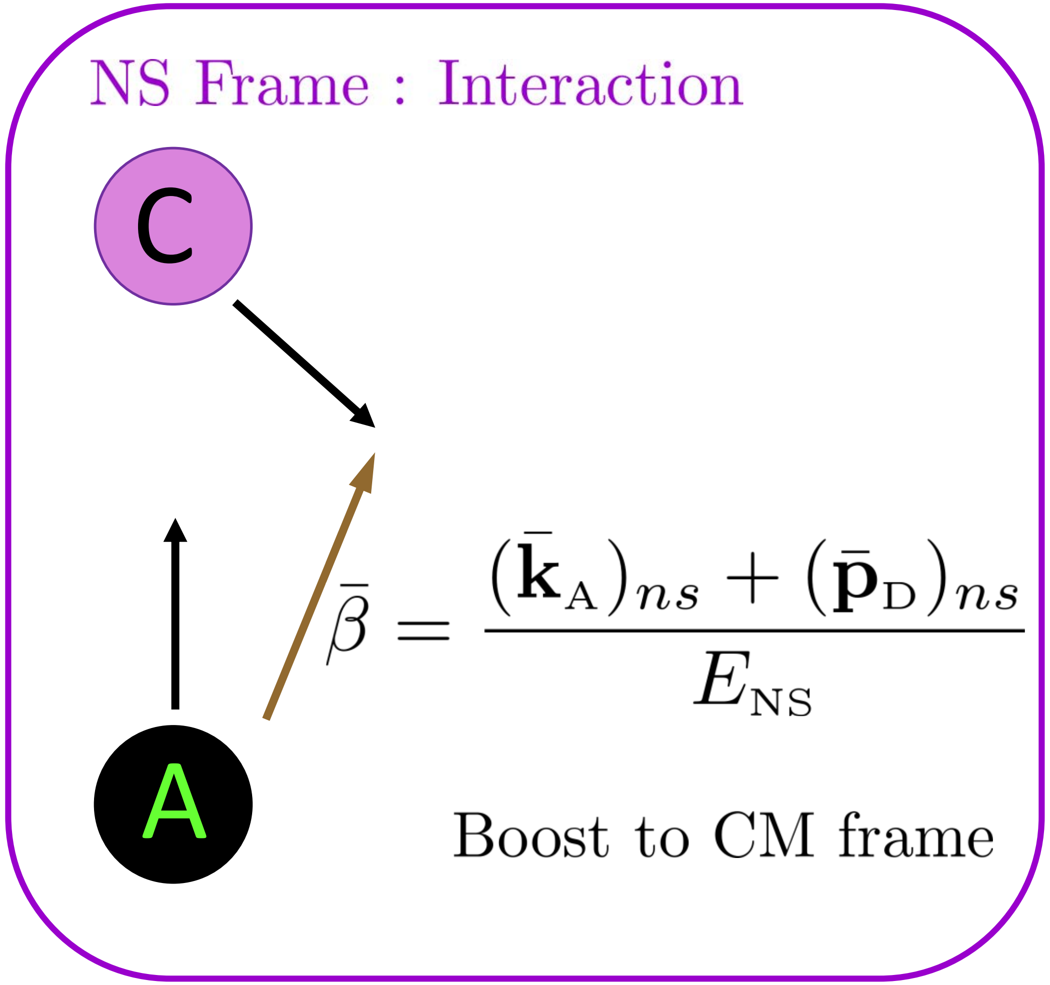


$$\bar{\beta} = \frac{(\bar{\mathbf{k}}_{\rm A})_{ns} + (\bar{\mathbf{p}}_{\rm D})_{ns}}{E_{\rm NS}}$$

Boost to CM frame

Interactions in NS and CM frames





Lorentz Invariant Capture Efficiency

Total interactions in DM rest frame

$$d\nu = (d\sigma) v_{\mathrm{T}} (dn_{\mathrm{T}})\, n_\chi \Delta V \Delta t$$

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Lorentz Invariant

$$\frac{d\nu}{n_\chi \Delta V} = (d\sigma) v_{\mathrm{T}} \, (dn_{\mathrm{T}}) \Delta t$$

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$$df = \frac{d\nu}{n_\chi \Delta V} = \underbrace{(d\sigma) v_{\mathrm{T}}}_{\text{known in CM frame}} (dn_{\mathrm{T}}) \Delta t$$

Lorentz Invariant Capture Efficiency

Total interactions in DM rest frame

$$d\nu = (d\sigma)v_{\rm T}(dn_{\rm T})\,n_\chi \Delta V \Delta t$$

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known in NS frame

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known in NS frame

$\sim R_\star$

Lorentz Invariant Capture Efficiency

Total interactions in DM rest frame

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Lorentz Invariant

$$df = \frac{d\nu}{n_\chi \Delta V} = \underbrace{(d\sigma) v_{\mathrm{T}}}_{\text{known in CM frame}} (dn_{\mathrm{T}}) \Delta t$$

$\Delta t \sim R_\star$

dn_{T}: known in NS frame

Lorentz Invariant Capture Efficiency

Total interactions in DM rest frame

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Lorentz Invariant

$$df = \frac{d\nu}{n_\chi \Delta V} = (d\sigma) v_{\mathrm{T}}\, (dn_{\mathrm{T}}) \Delta t$$

$$(d\sigma)_{\mathrm{CM}} \frac{\sqrt{(p^\mu k_\mu)^2 - m_{\mathrm{T}}^2 m_\chi^2}}{(E_{\mathrm{T}})_{\mathrm{NS}} (E_\chi)_{\mathrm{NS}}}$$

$$\langle n_{\mathrm{T}} \rangle \frac{3(|\bar{p}|)^2_{\mathrm{NS}}}{2p_{\mathrm{F}}^3} \Theta((|\bar{p}|'_{\mathrm{T}})_{\mathrm{NS}} - p_{\mathrm{F}})\, d(|\bar{p}|)_{\mathrm{NS}}\, d\cos\theta$$

Lorentz Invariant Capture Efficiency

$$f = \frac{3Y_{\mathrm{T}} M_\star}{\frac{4}{3}\pi R_\star^2 m_n} \int_0^{2\pi}\int_{-1}^{1}\int_{-1}^{1}\int_0^{p_{\mathrm{F}}} \frac{|\mathcal{M}|^2}{64\pi^2 (E)_{\mathrm{CM}}^2} \frac{\sqrt{(p^\mu k_\mu)^2 - m_{\mathrm{T}}^2 m_\chi^2}}{(E_{\mathrm{T}})_{\mathrm{NS}} (E_\chi)_{\mathrm{NS}}}$$

Interaction time, Av. density

Differential Cross section in CM frame

Transformation factor to account boosts

$$\times \frac{3(|\bar{p}|)_{\mathrm{NS}}^2}{2p_{\mathrm{F}}^3} \Theta((|\bar{p}|'_{\mathrm{T}})_{\mathrm{NS}} - p_{\mathrm{F}}) \; d(|\bar{p}|)_{\mathrm{NS}}\, d\cos\theta \;\; d\cos\psi\, d\alpha$$

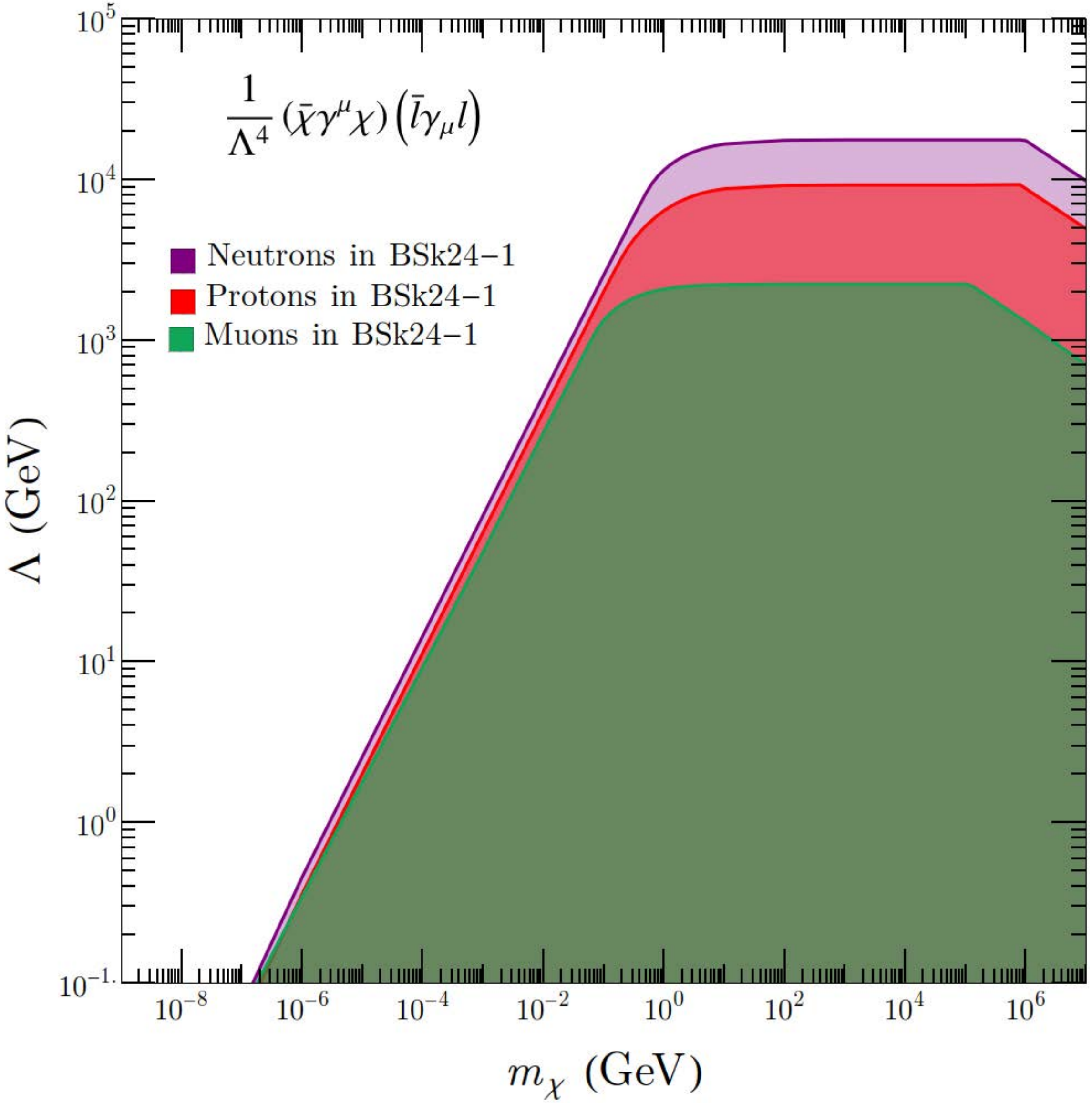
Volume fraction of Fermi sphere

Pauli Blocking

In-state variables

Out state variables

Cut-off reach for VV operator



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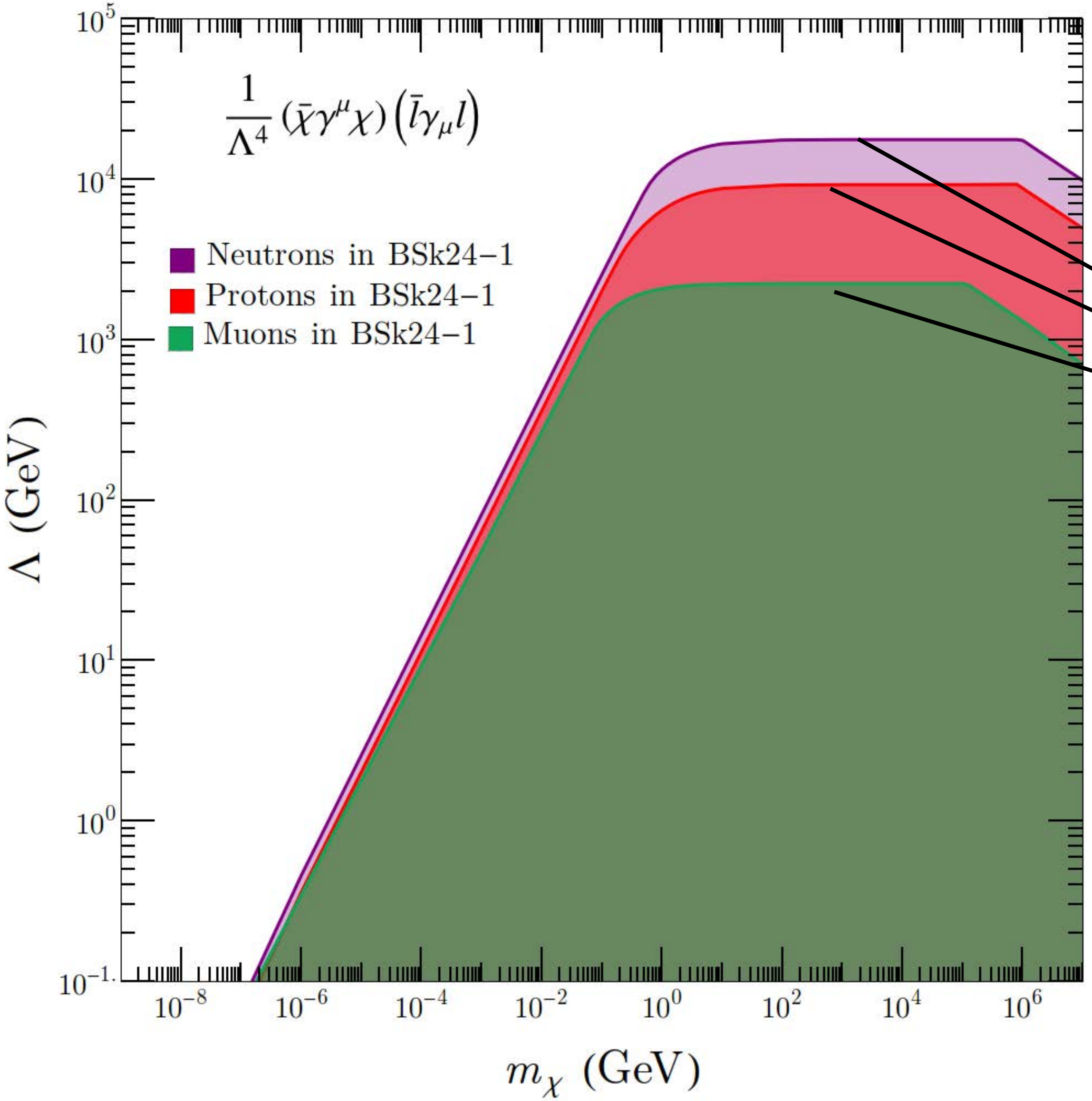
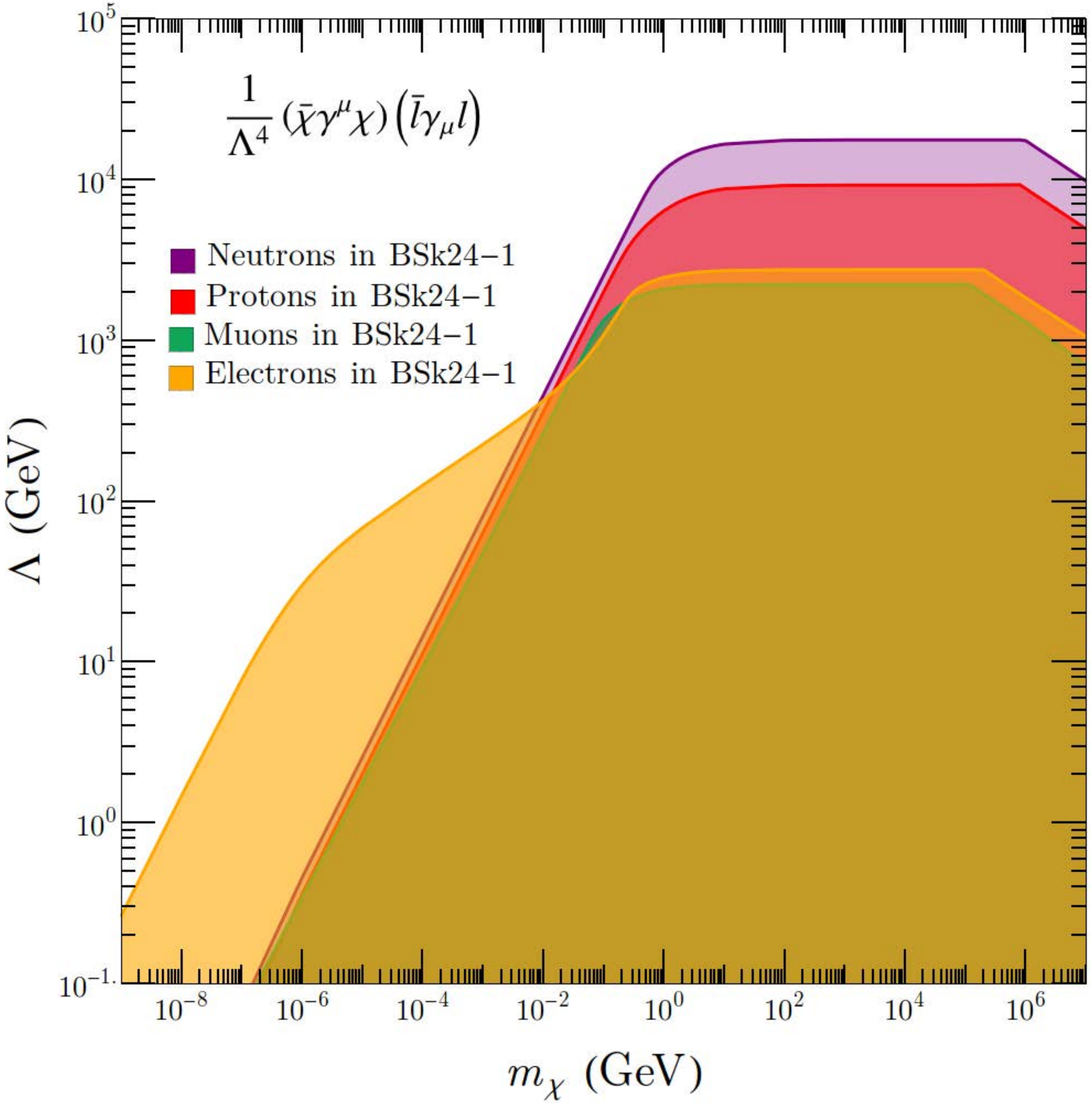


$f = 1$

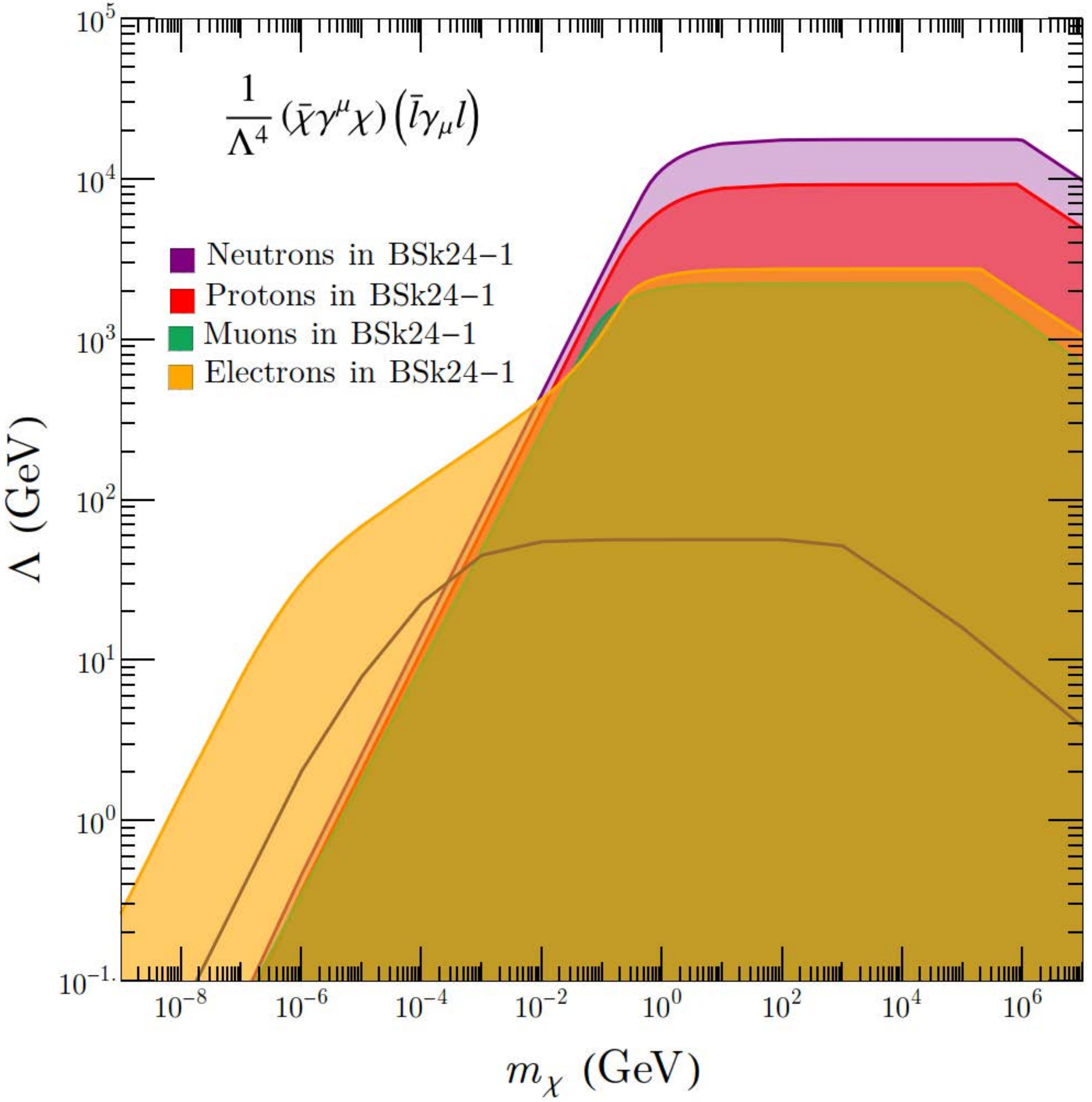
Recall,
$T \sim 1750\, f^{1/4}\,\mathrm{K}$

Colored region
$T \sim 1750\,\mathrm{K}$

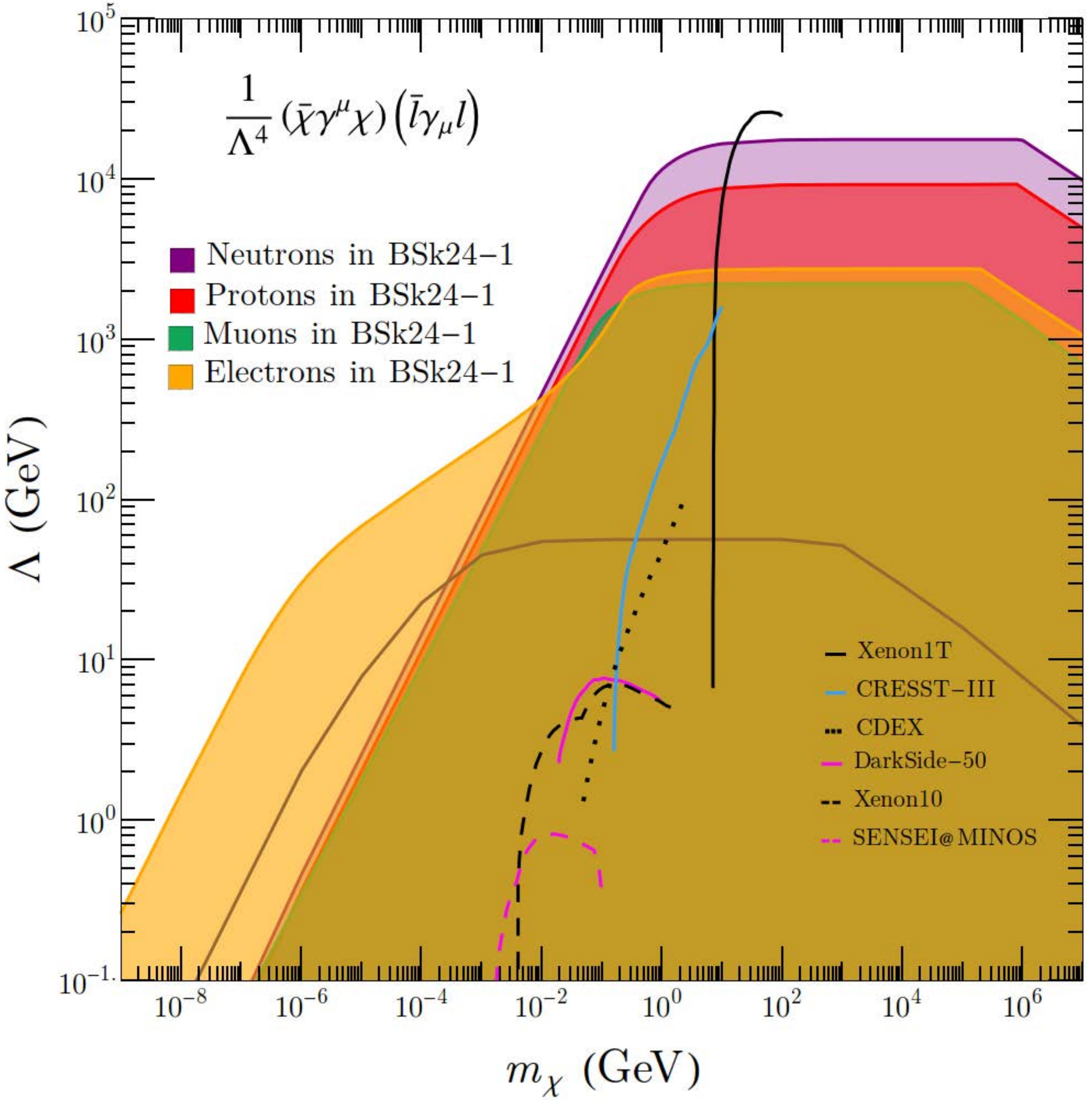
Cut-off reach for VV operator



Cut-off reach for VV operator



Comparison with Earth based DD



Cut-off reach for VV operator

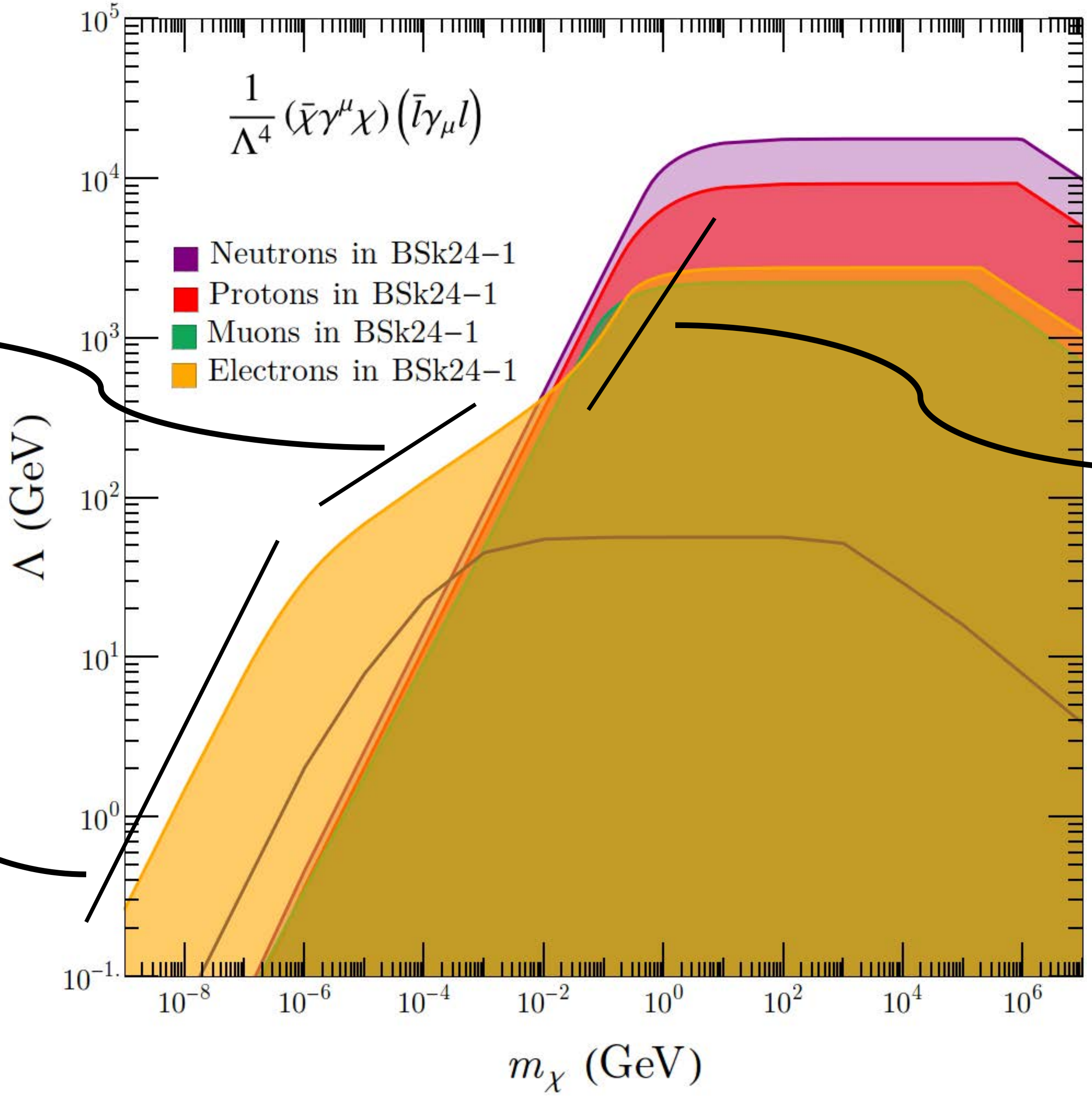
slope $\sim \frac{1}{4}$

$|\mathcal{M}|^2 \propto m_\chi$

slope $\sim \frac{3}{4}$

$|\mathcal{M}|^2 \propto m_\chi^2$

Pauli blocking $\propto m_\chi$

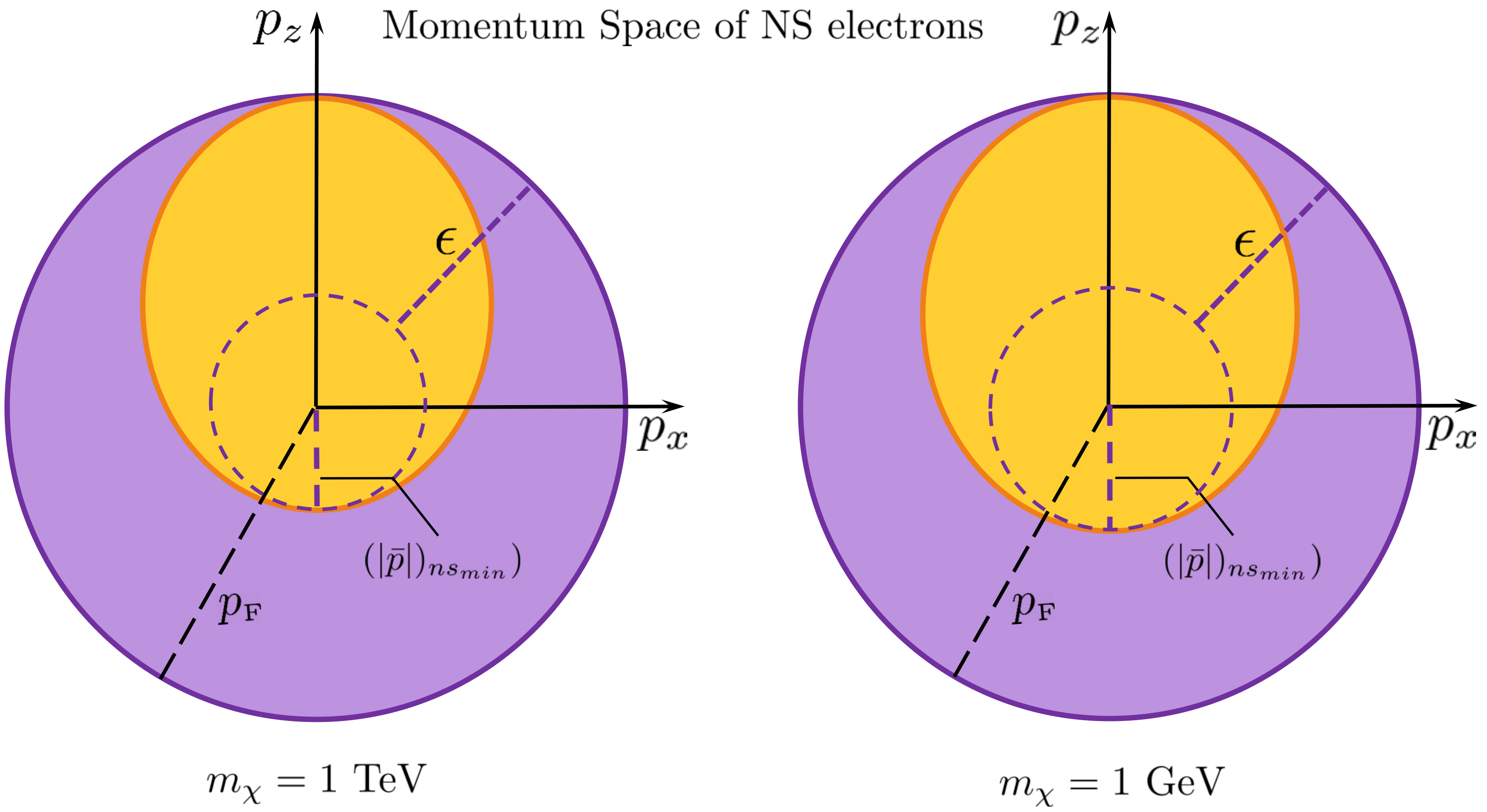


slope $\sim \frac{3}{4}$

$|\mathcal{M}|^2 \propto m_\chi^2$

Pauli blocking $\propto m_\chi$

Pauli Blocking



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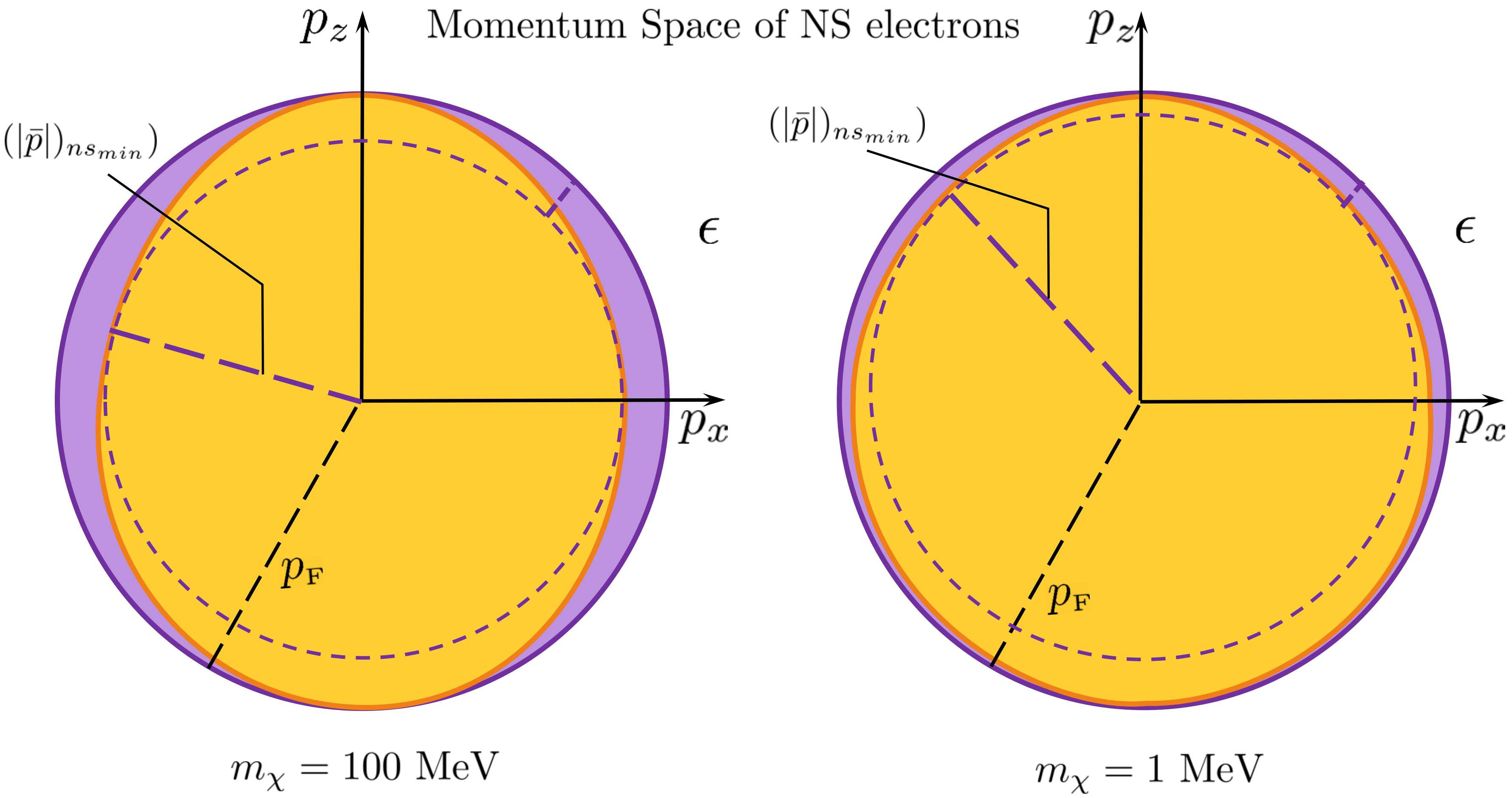
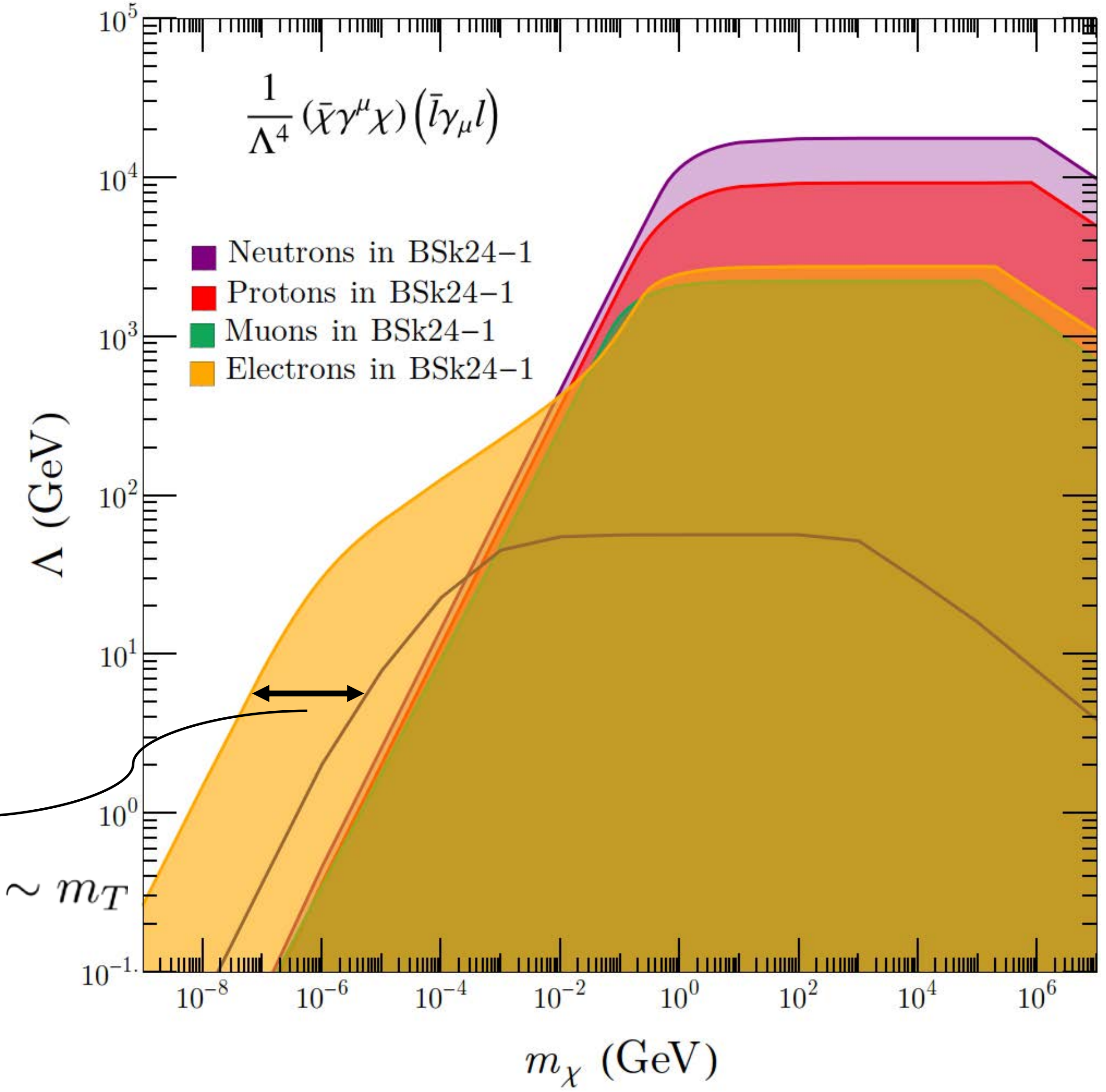


Cut-off reach for VV operator



Turns at m_T^2/p_F

For non-relativistic $m_T^2/p_F \sim m_T$

Summary

- NS kinetic heating has advantage over earth based DD probes for low and high mass regimes compared to standard WIMP mass range
- Formulated Lorentz invariant capture efficiency for relativistic target species
- Lepton (esp. electron) aided DM capture greatly enhances sensitivity for light DM
- Relativistic effects play crucial role in this and also making electrons strongest probe for leptophilic DM in high mass range as well

Thank you!