Dark Heating of Neutron Stars

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LAPTh Seminar

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Work With :
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1911.13293, 2004.09539

What is Dark Matter?

Overwhelming gravitational evidence

About 5 times the visible matter in the universe

But that’s it…. Not much is known about the nature of its other interactions

Assumption:

A particle beyond SM

Interacts with the ordinary matter

What is Dark Matter?

We want to study these other interactions. We have a robust program.

For this talk, the focus will be on the t-channel

Obvious strategy for direct detection is gravitationally capture DM and make it scatter with something, then study the consequences

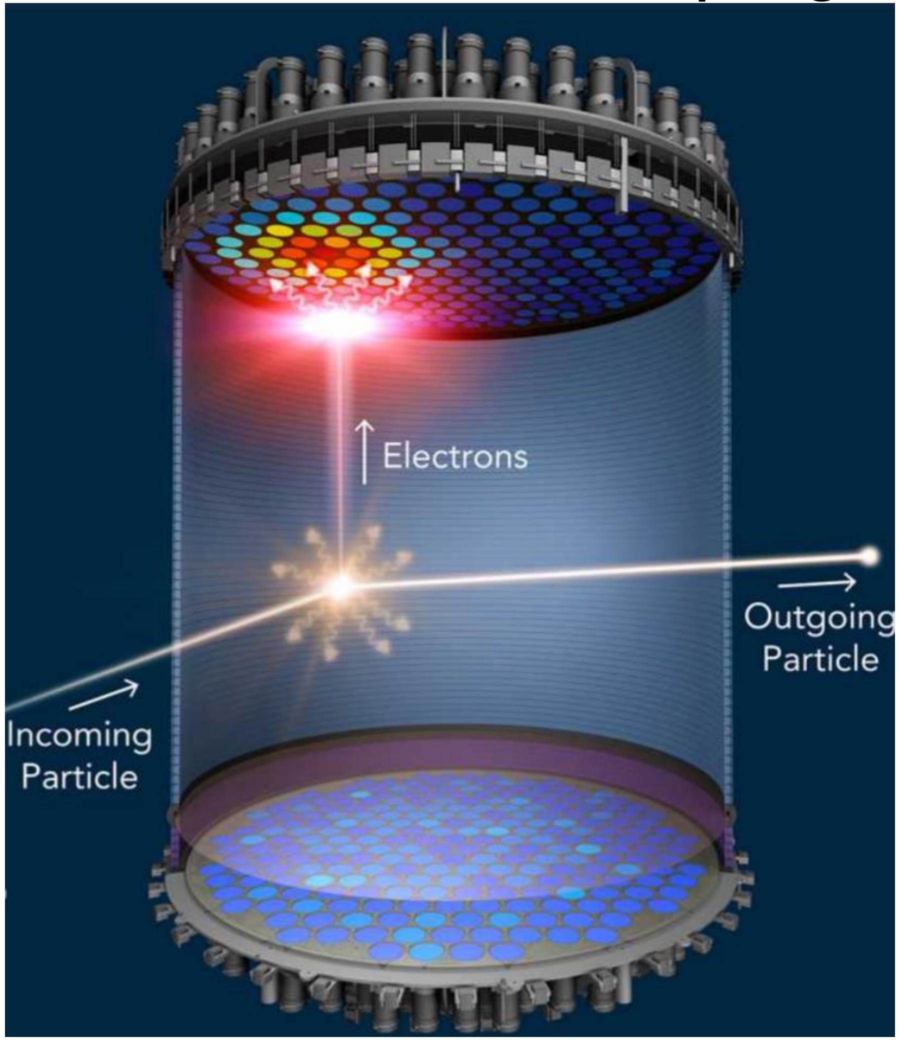


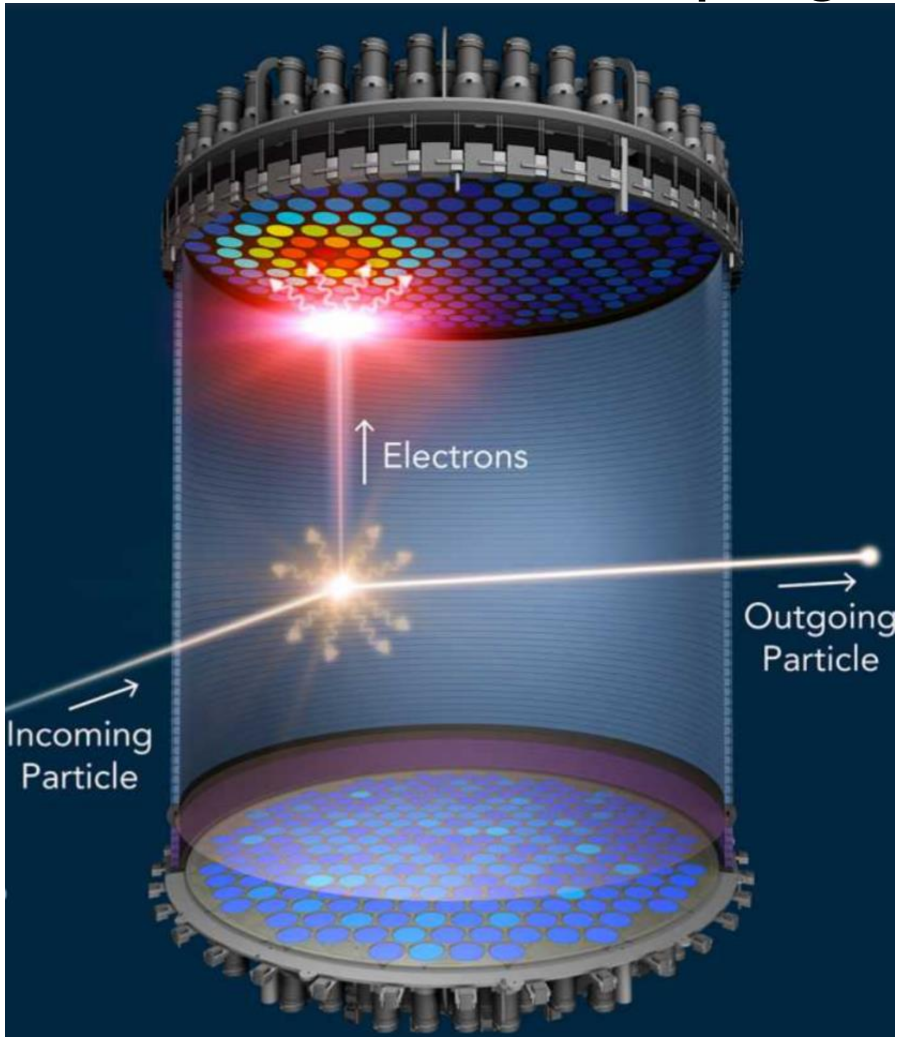
Image: Lux-LZ

Terrestrial Direct Detection

We want to study these other interactions. We have a robust program.

Large detector volume to detect rare events

We look for recoil energy deposited by dark matter in the ordinary matter : Nuclei, electrons..



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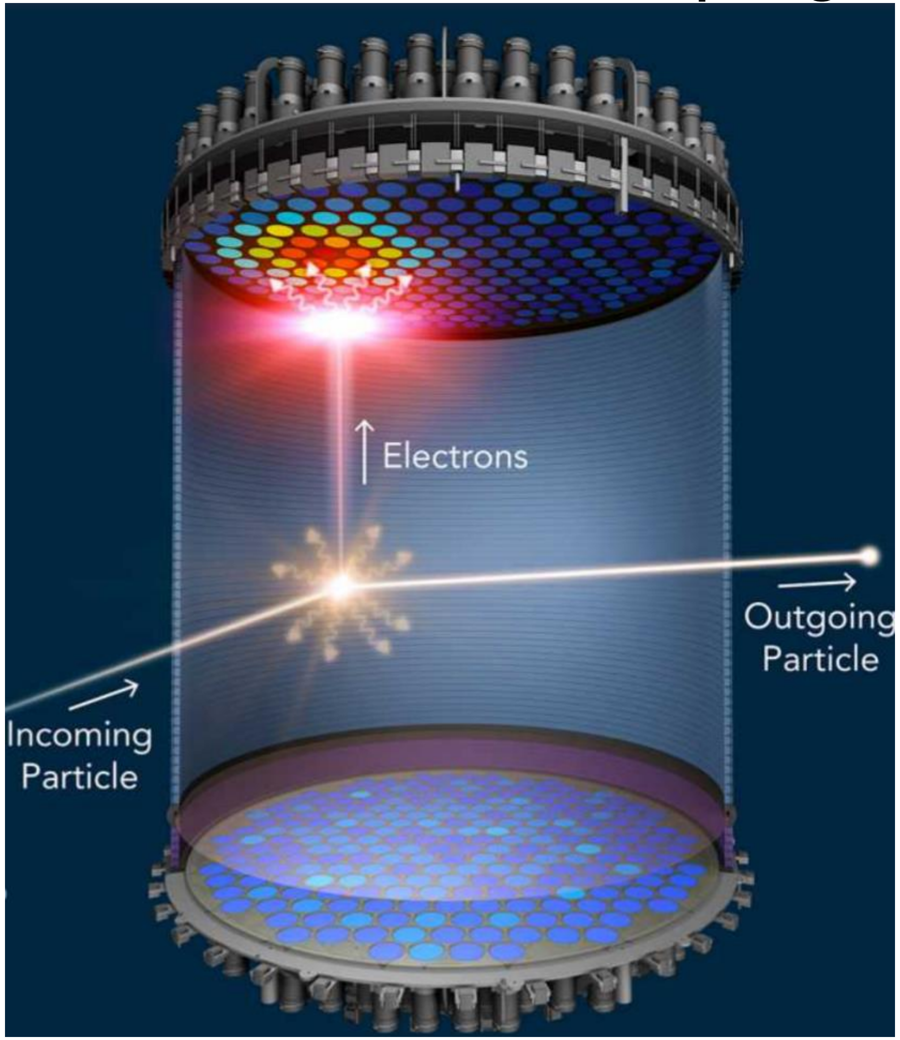

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Current Status

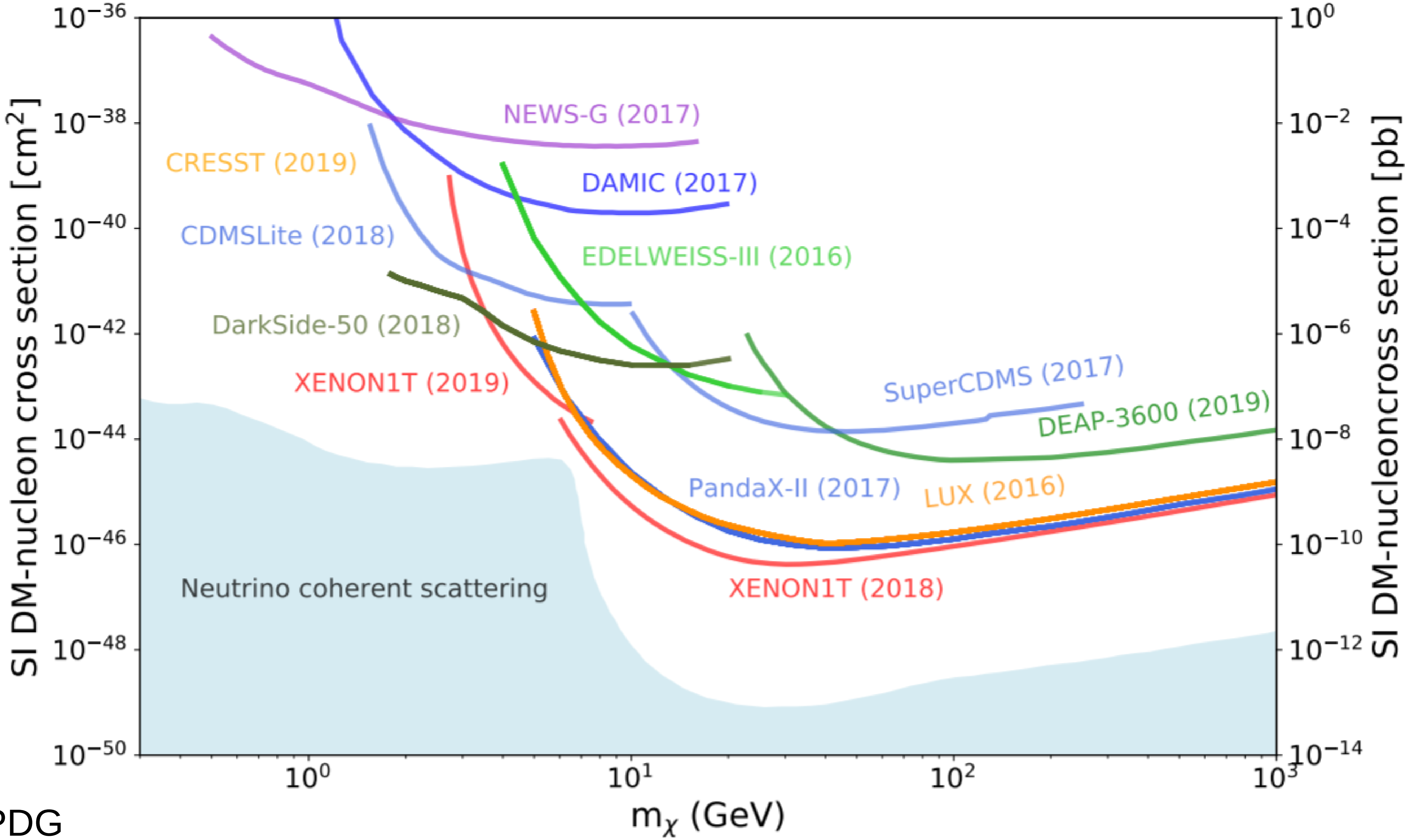

Image: PDG

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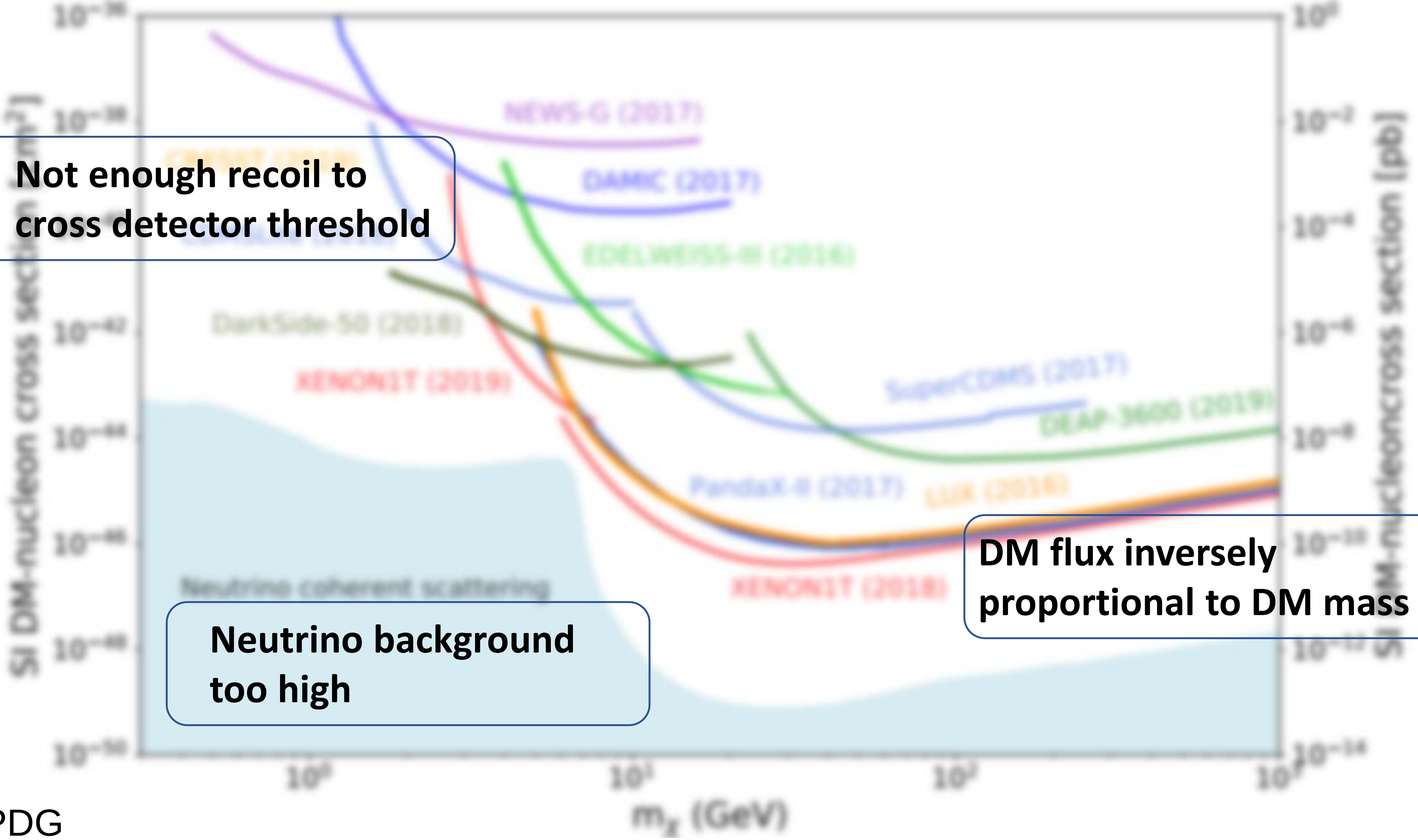

Not enough recoil to cross detector threshold

Neutrino background too high

DM flux inversely proportional to DM mass

Image: PDG

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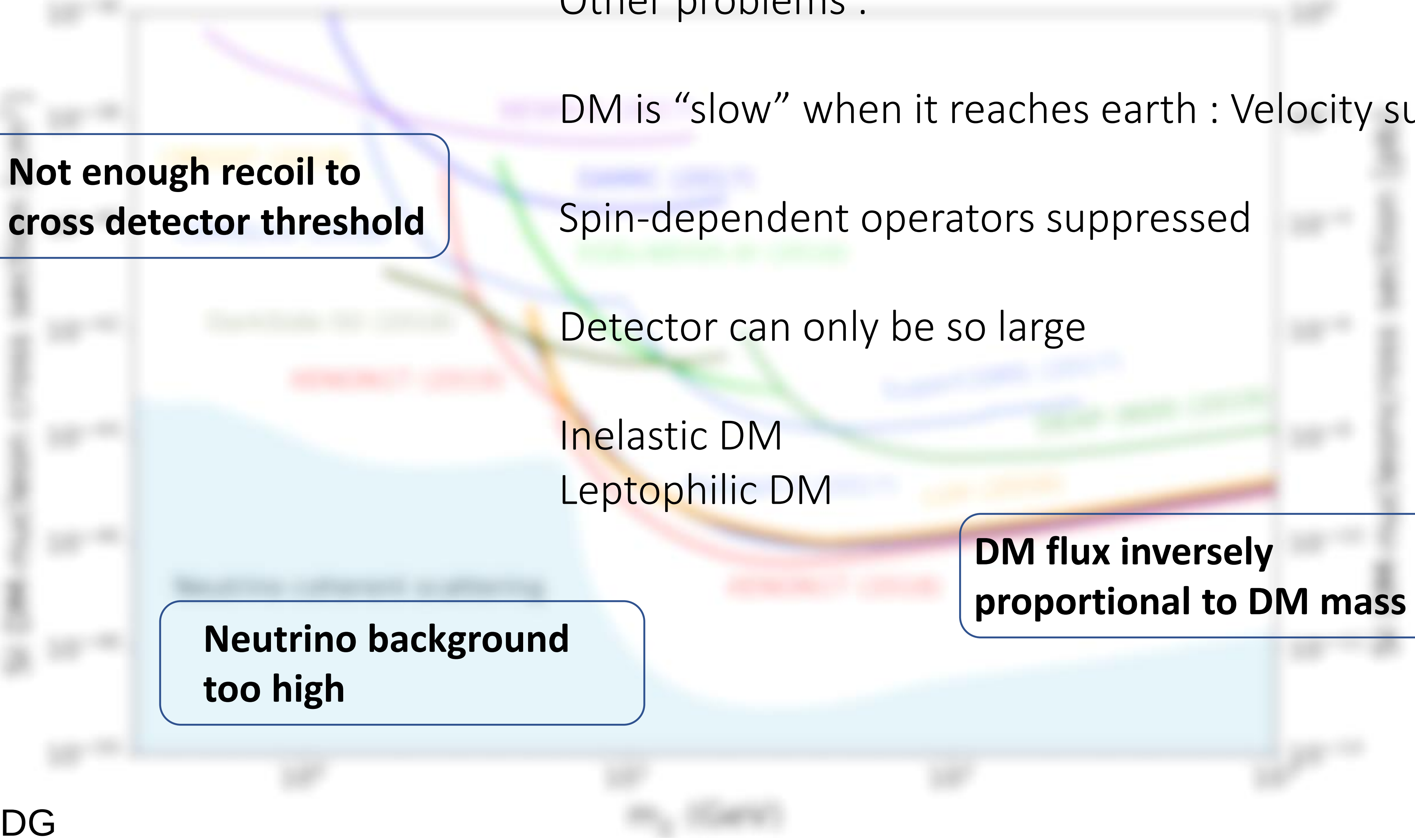

Other problems :

DM is “slow” when it reaches earth : Velocity suppression

Spin-dependent operators suppressed

Detector can only be so large

Inelastic DM
Leptophilic DM

Not enough recoil to cross detector threshold

Neutrino background too high

DM flux inversely proportional to DM mass

Image: PDG

What We Want?

Something with large number of targets and dense
– Overcomes detector volume issue

Accelerates DM to very high velocities, so something with large gravitational field
- Overcomes velocity suppression
- can help to increase energy deposition

Something “cheap” to detect
- meaning someone already paying for it

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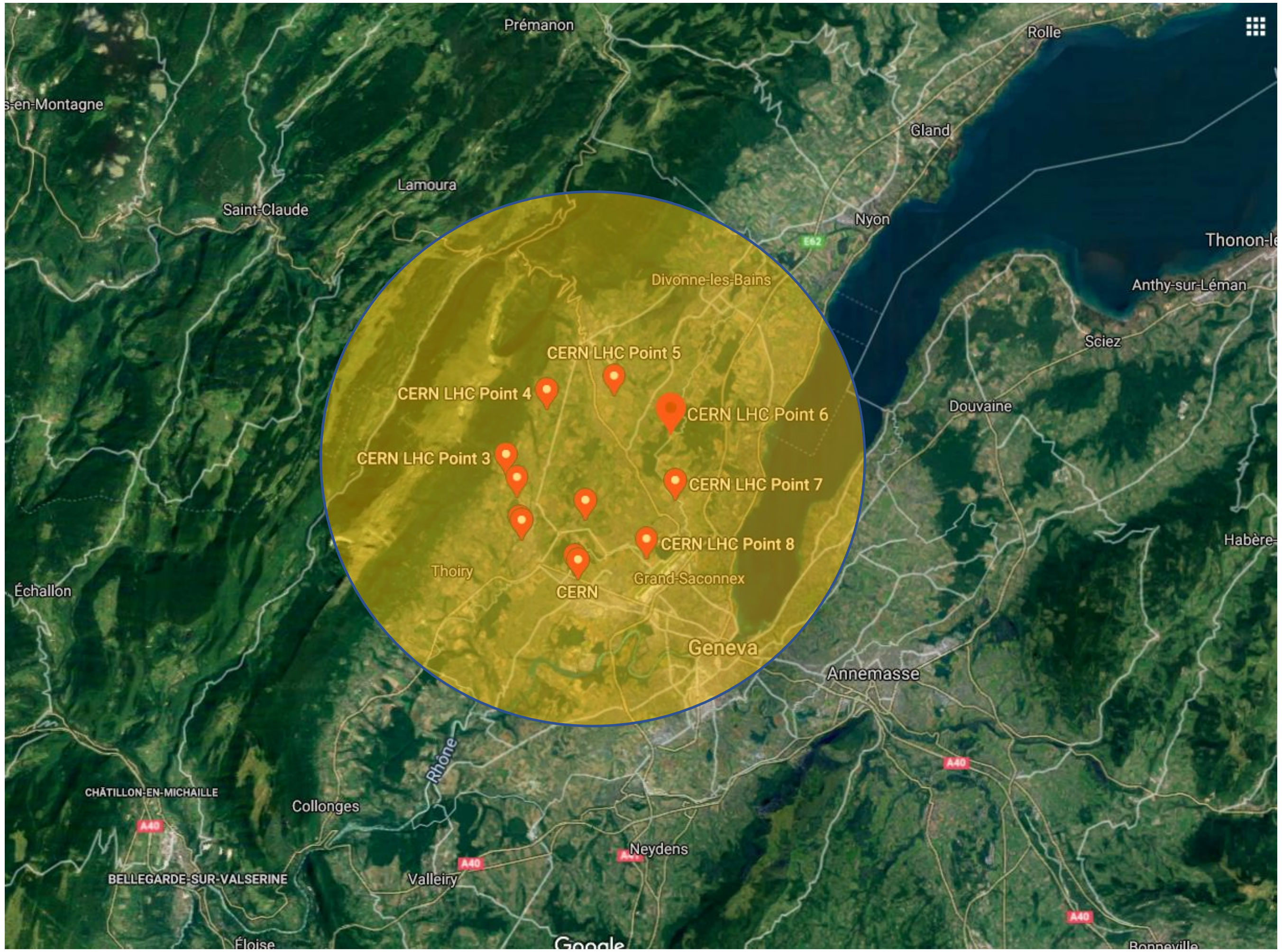
What We Want?

Neutron star : Dense, strong gravity



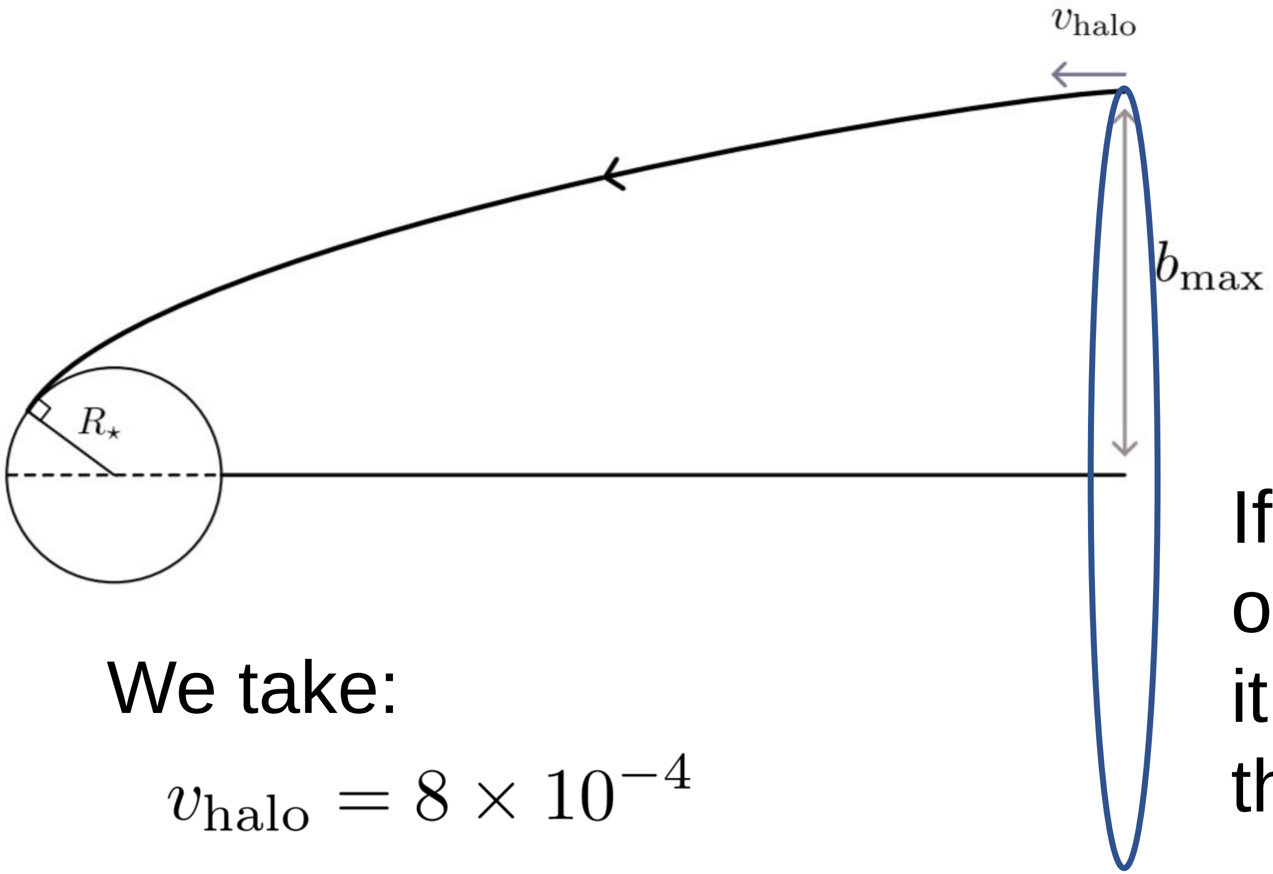
Typical Neutron star :

$$M_\star = 1.5\, M_\odot$$

$$R_\star = 12.6\, \mathrm{km}$$

How Does it Work?

Continuous dark matter flux incident on the NS



Dark matter scatters with the NS constituents; loses energy by transferring the momentum

If it loses more KE than it originally had in the halo, then it gets gravitationally bound to the star - Captured

We take:

$$v_{\text{halo}} = 8 \times 10^{-4}$$

$$\rho_\chi = 0.3 \text{ GeV/cc}$$

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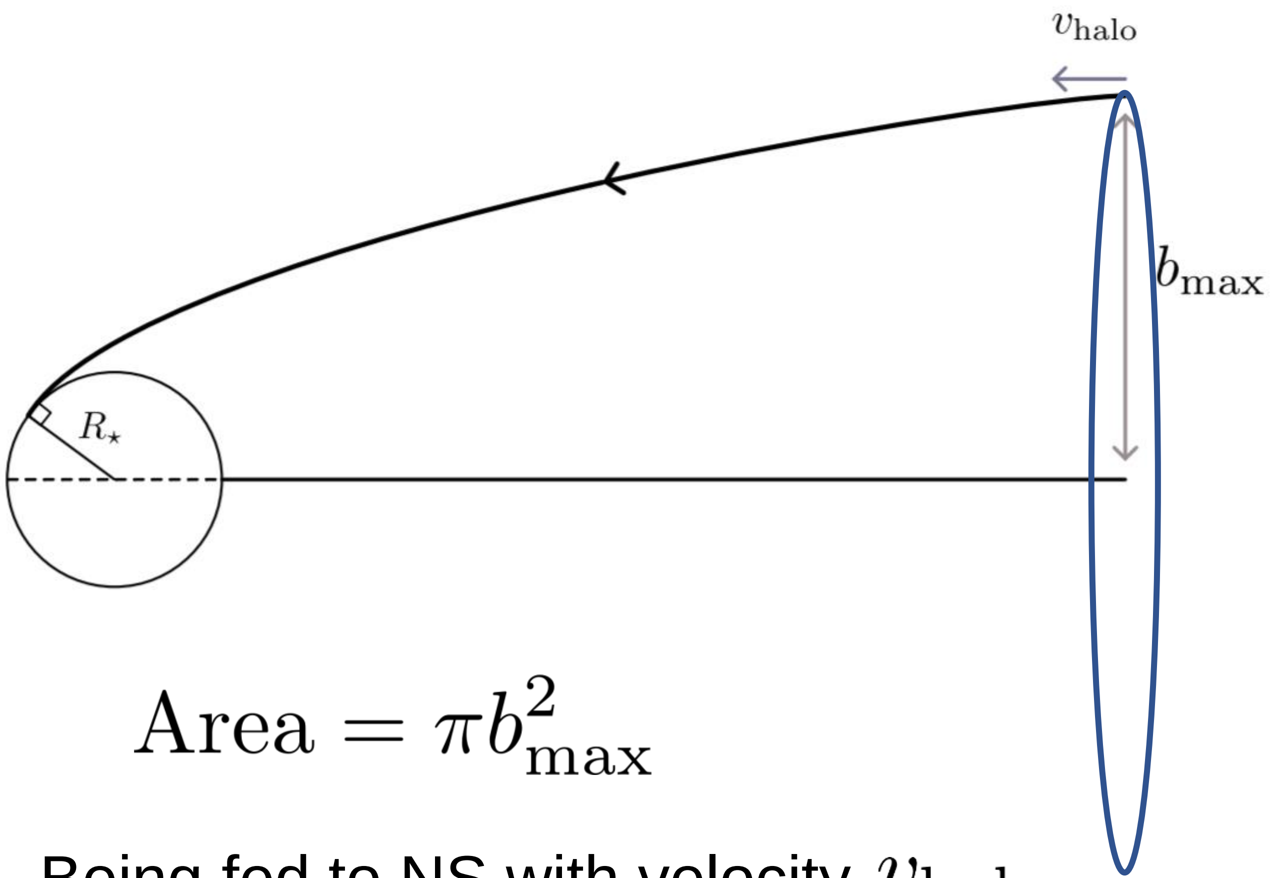


$$\text{Area} = \pi b_{\rm max}^2$$

Being fed to NS with velocity $v_{\rm halo}$

We take:

$$v_{\rm halo} = 8 \times 10^{-4}$$
$$\rho_\chi = 0.3 \ \text{GeV/cc}$$
$$M_\star = 1.5 \, M_\odot$$
$$R_\star = 12.6 \, \text{km}$$

This means :

$$b_{\rm max} = \frac{R_\star}{v_{\rm halo}} \sqrt{\frac{2GM}{R}} \left(1 - \frac{2GM}{R}\right)^{-1/2}$$

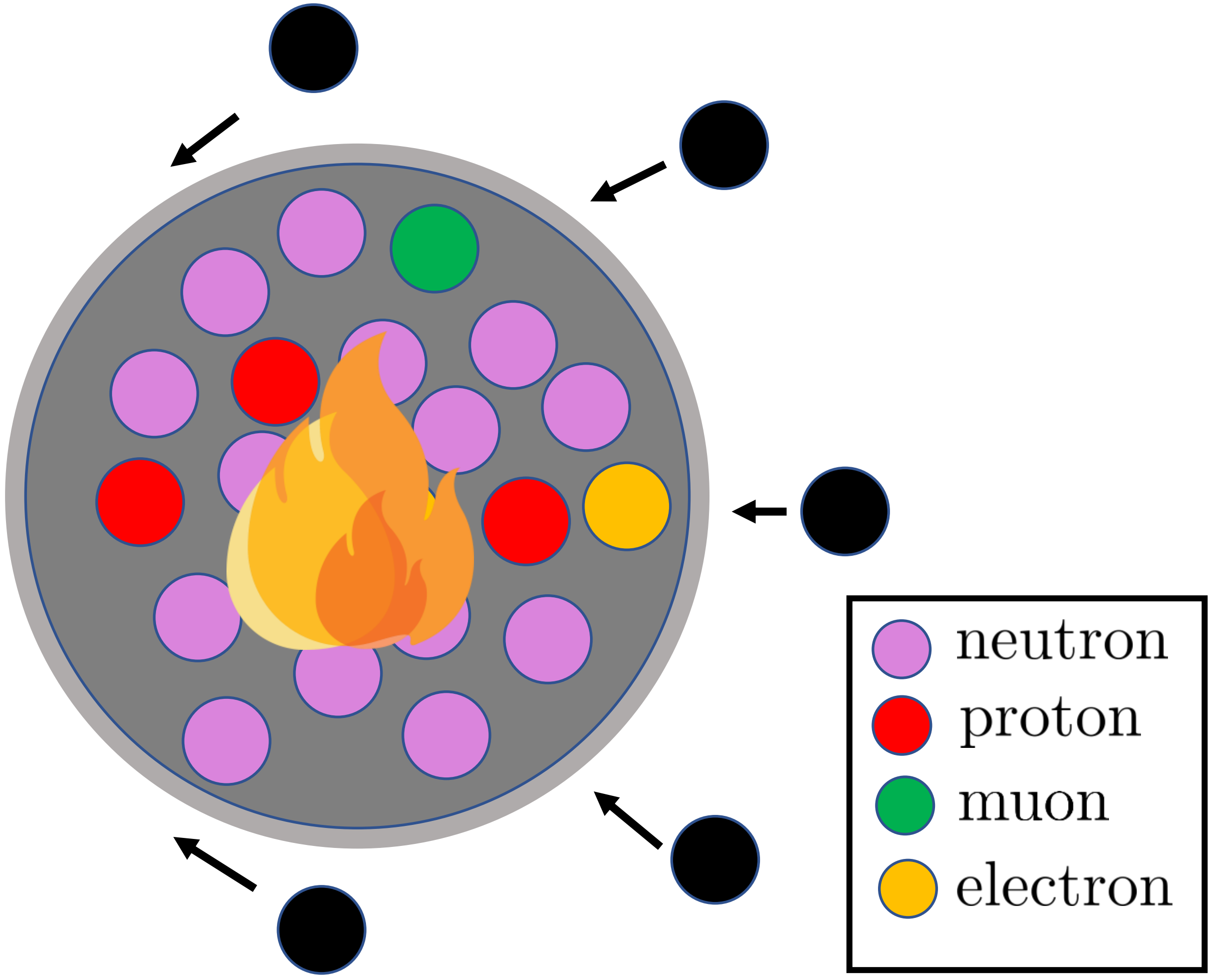
DM Flux is :

$$\pi b_{\rm max}^2 \rho_\chi v_{\rm halo}$$

NS Kinetic Heating : Dark Fires

$$\text{Flux} = \pi b_{\text{max}}^2 v_{\text{halo}} \rho$$

$$\sim \frac{4 \times 10^{25}}{m_\chi \, (\text{GeV})} \, s^{-1}$$



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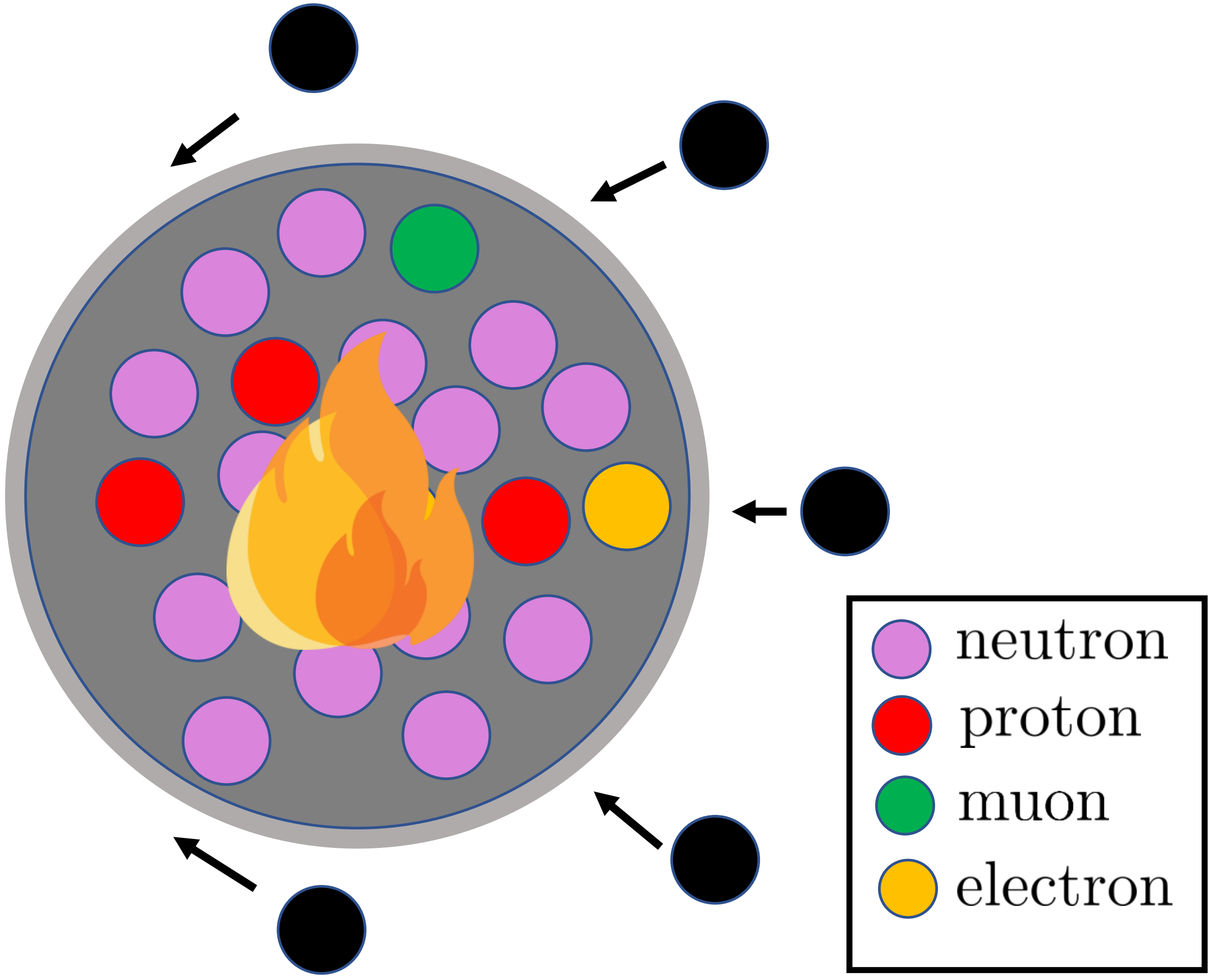

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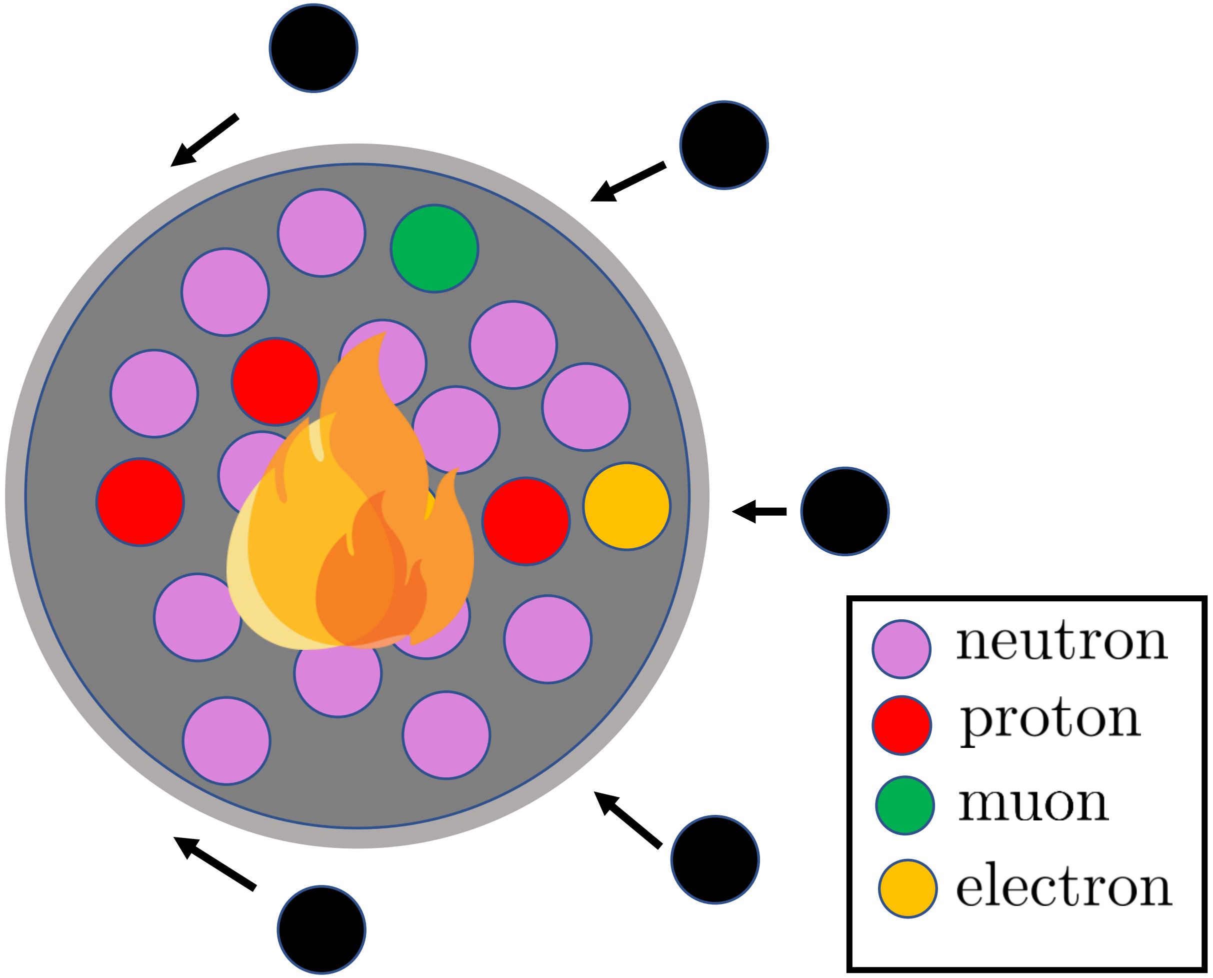

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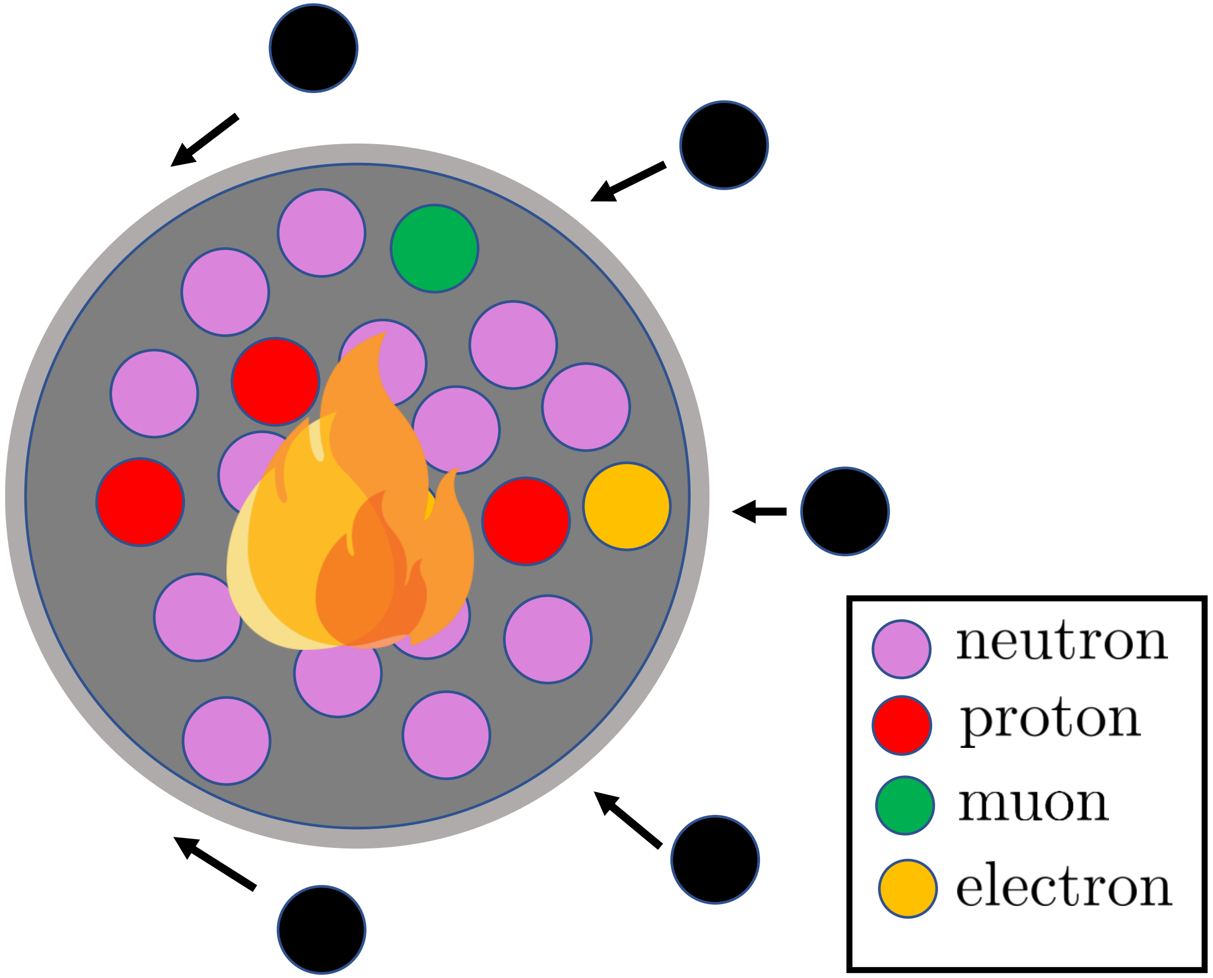
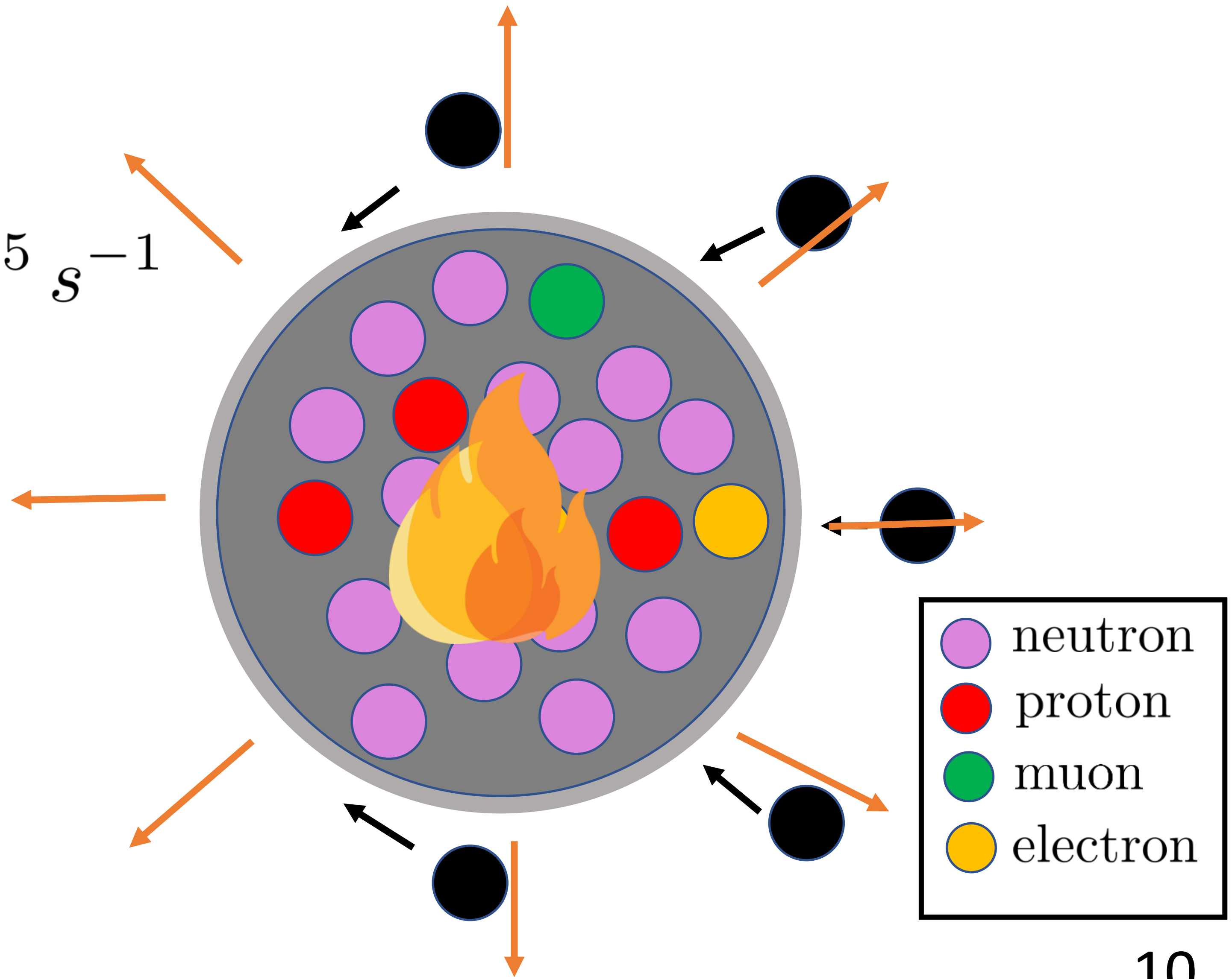
Capture efficiency



NS Kinetic Heating : Dark Fires

$$\gamma \sim 1.24$$

$$\dot{E} = f \times (\gamma - 1) \times 4 \times 10^{25}\, s^{-1}$$



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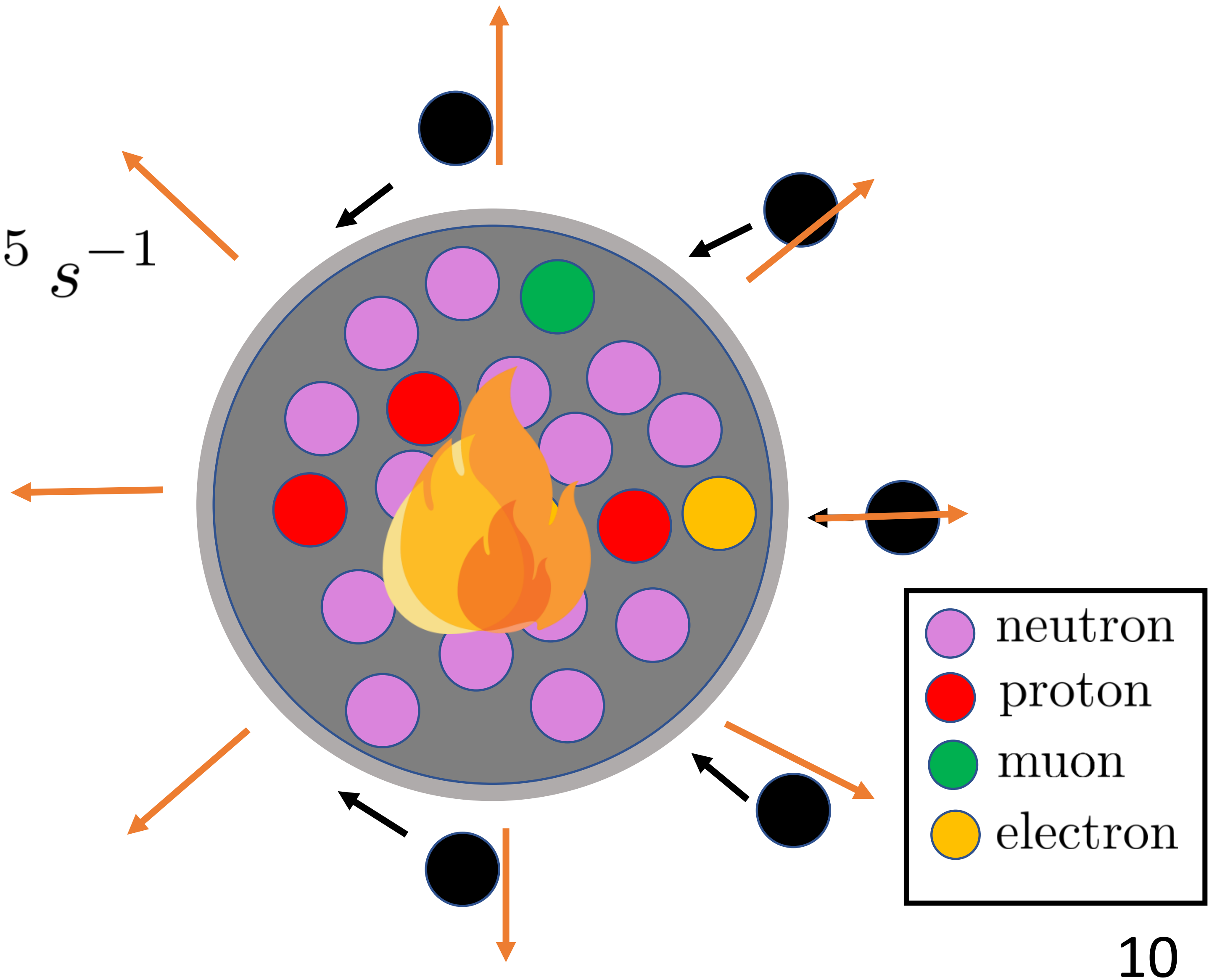
Stephan-Boltzmann Law

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



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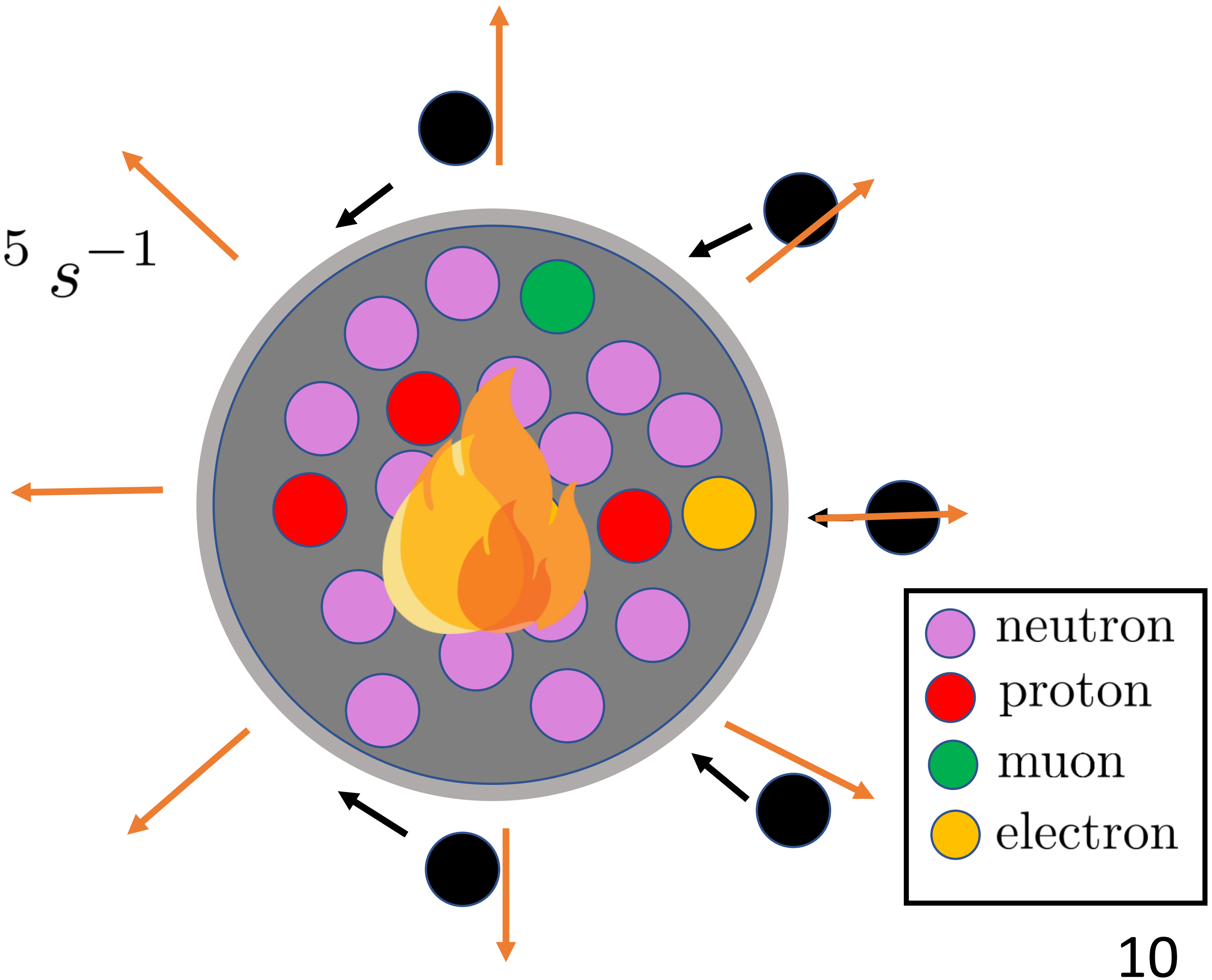
$$T \sim 1600 f^{1/4}\, K$$



NS Kinetic Heating : Dark Fires

$$T \sim 1600\, f^{1/4}\, K$$

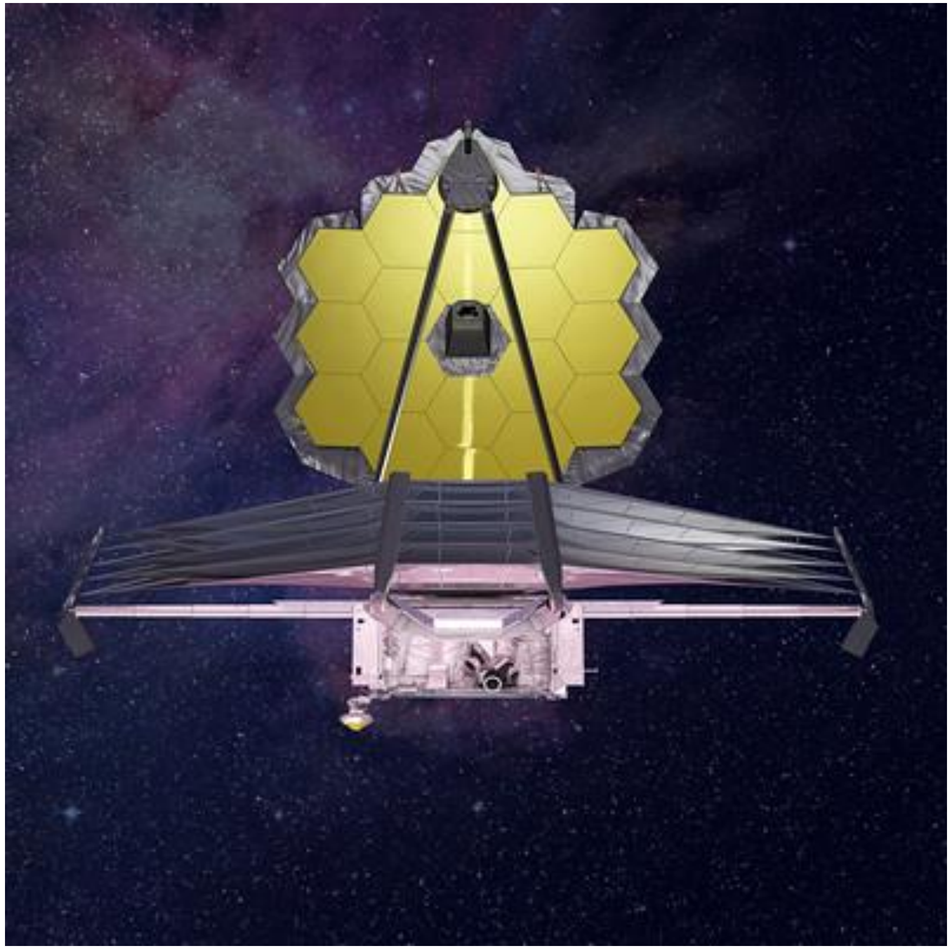
Cooling models predict 10s of K temperatures for Billion year old NS

For efficient capture

Without DM

With DM

How to Detect Heated NS?



IR telescope JWST is sensitive to wavelengths range from 0.7 μm to 30 μm

Image (Artist Impression of JWST) : https://www.jwst.nasa.gov/

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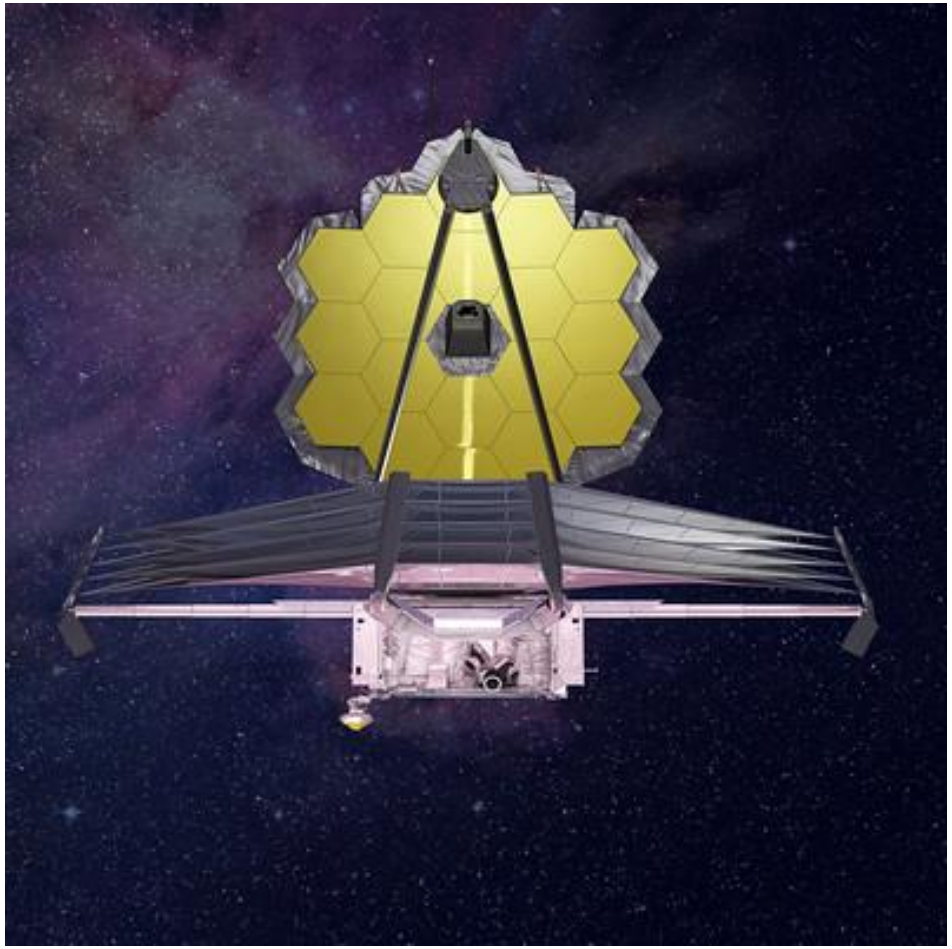

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Not sensitive below few 100 K and very good sensitivity around 1000 K to 2000 K

More infrared telescopes coming : TMT, ELT

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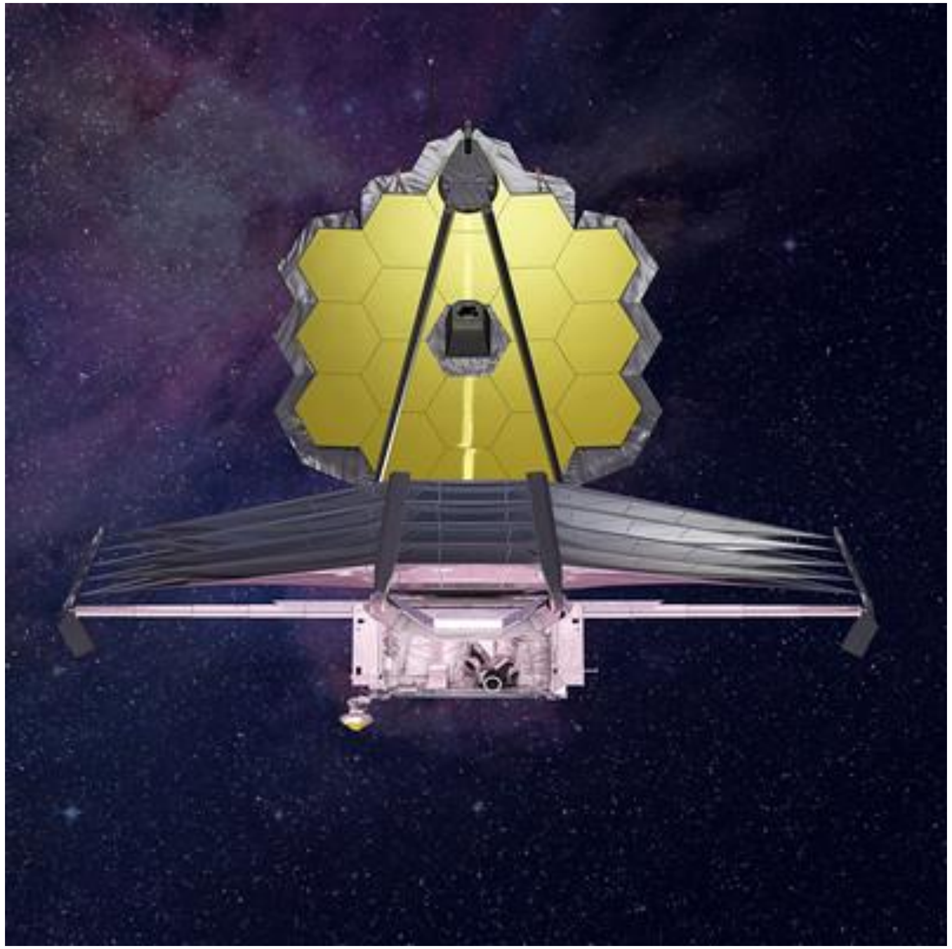

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Not sensitive below few 100 K and very good sensitivity around 1000 K to 2000 K

More infrared telescopes coming : TMT, ELT

Exposure time for 2σ : $10^5 \left(\frac{d}{10\,\mathrm{pc}}\right)^4$ s

For efficient capture : We go from blind to observation of a "nearby" NS

Image (Artist Impression of JWST) : https://www.jwst.nasa.gov/

Do We Know its Age?

But how do we know if the star our telescope is seeing should have been cold?

What if it is a younger one, which is supposed to have 1000 K-ish temperatures?

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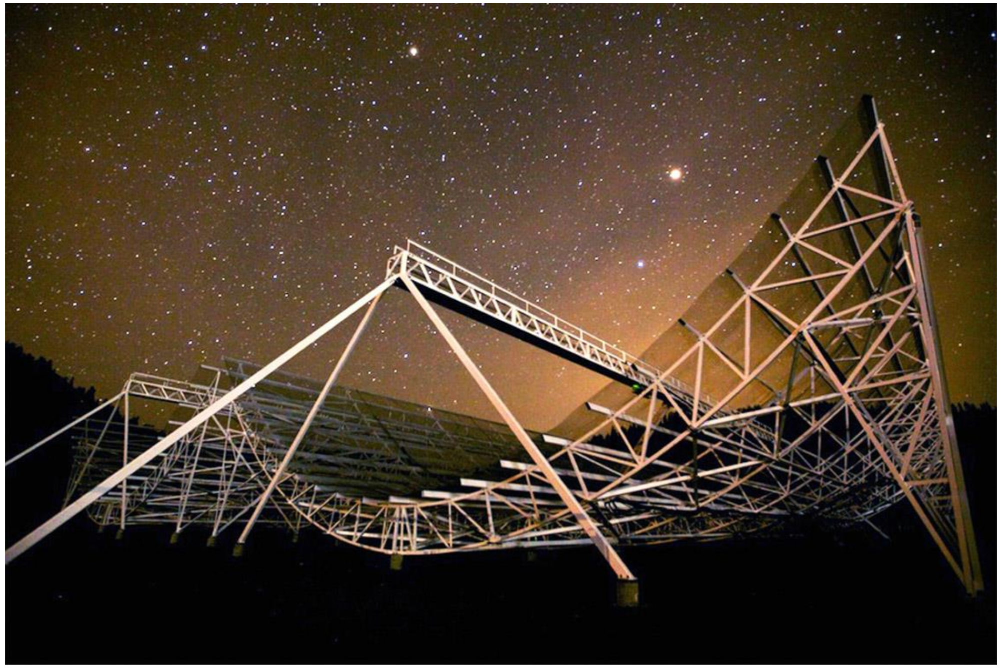


Photo : CHIME

Credit: Ou Dongqu/Xinhua/ZUMA

What if it is a younger one, which is supposed to have 1000 K-ish temperatures?

Radio Telescopes!!

What We Want?

So that’s it? They seems to have every advantage over terrestrial detection. So we done here?

Also they are far away so far more dumping of recoil energy compared to terrestrial experiements is needed for successful detection

Not quite….

Fermions in them are tightly packed This means Pauli exclusion principle will deny a lot of phase under certain conditions.

What We Want?

So that’s it? They seems to have every advantage over terrestrial detection. So we done here?

Not quite….

That’s what this talk is about …

New formalism for relativistic capture

Resulting NS projected bounds for DM-SM contact operators

Comparison to terrestrial direct detection

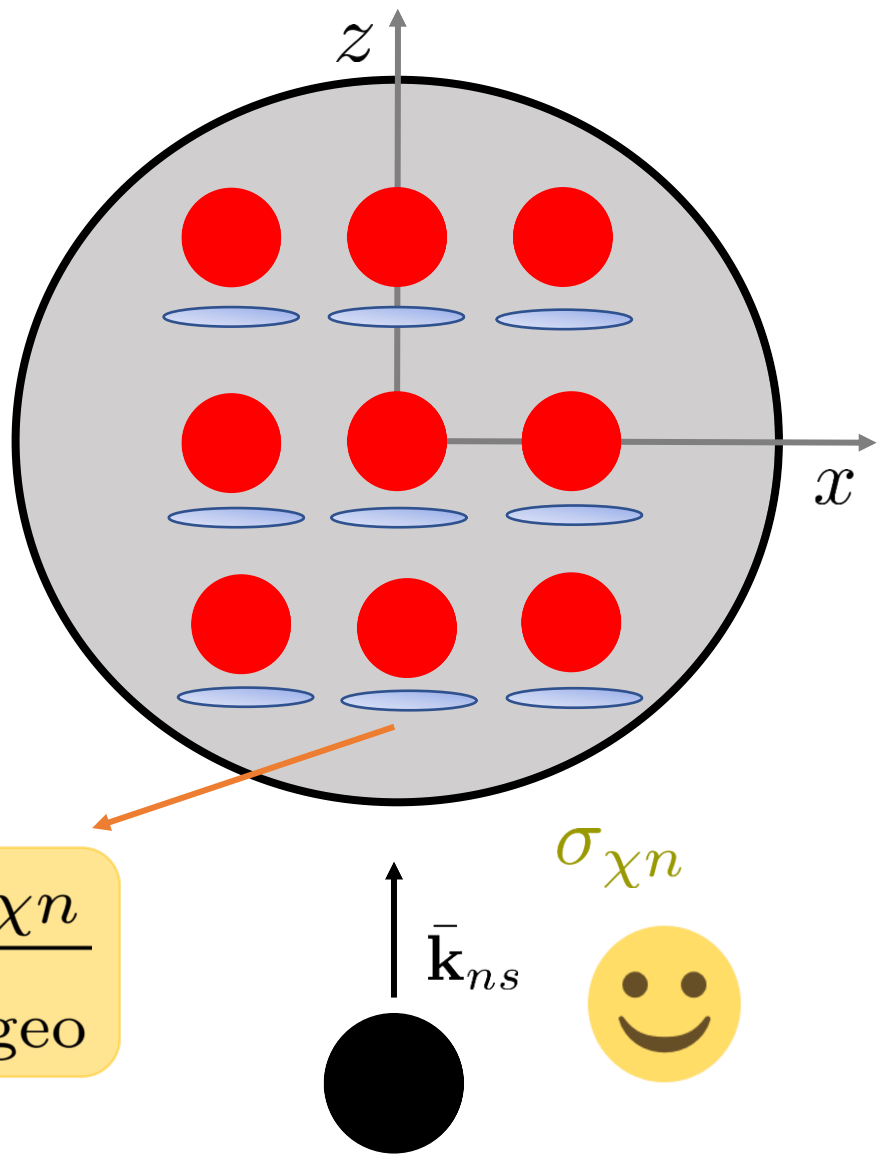
How Efficient is the Capture?

$$T \sim 1600\, f^{1/4}\, \mathrm{K}$$

For non relativistic targets

$$\sigma_{\mathrm{geo}} = \frac{\text{Cross section of star}}{\text{Number of targets}}$$

$$\approx \frac{\pi R_\star^2 m_n}{M_\star}$$



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

What Could Make It Less Efficient?

Fully efficient capture for cross section above the geometric cross section works for large range of DM masses.

In case of most dim-6 contact operator Interactions between DM-SM, this range could be as large as 1 GeV to 1 PeV

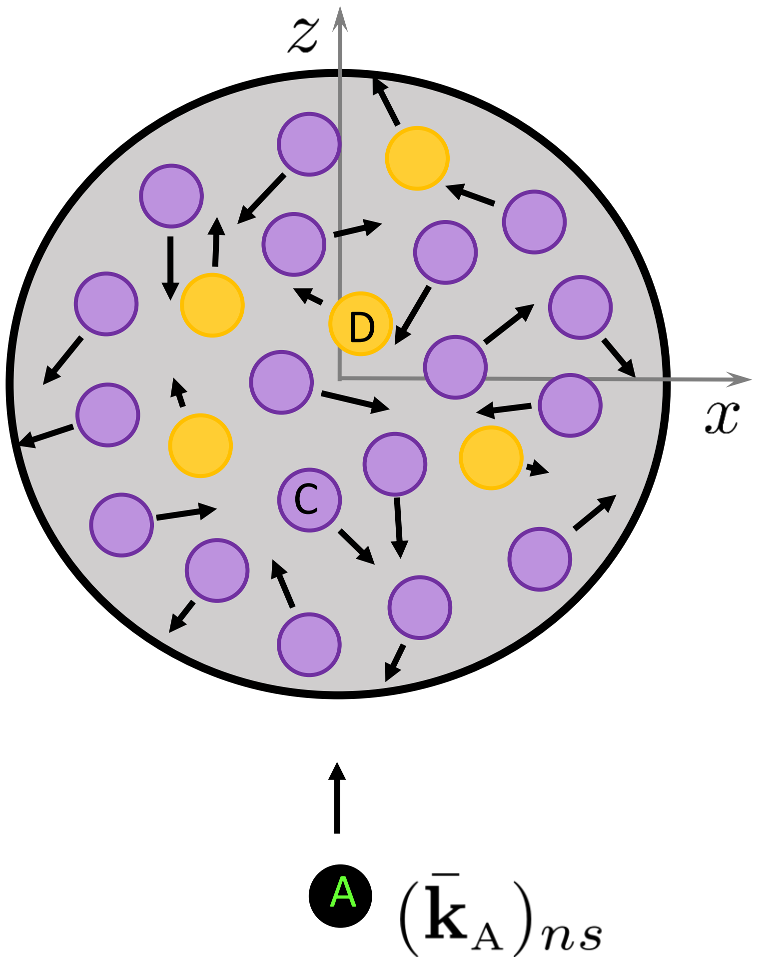
Efficiency can get killed in two ways:

1) Pauli Blocking in the case of light DM

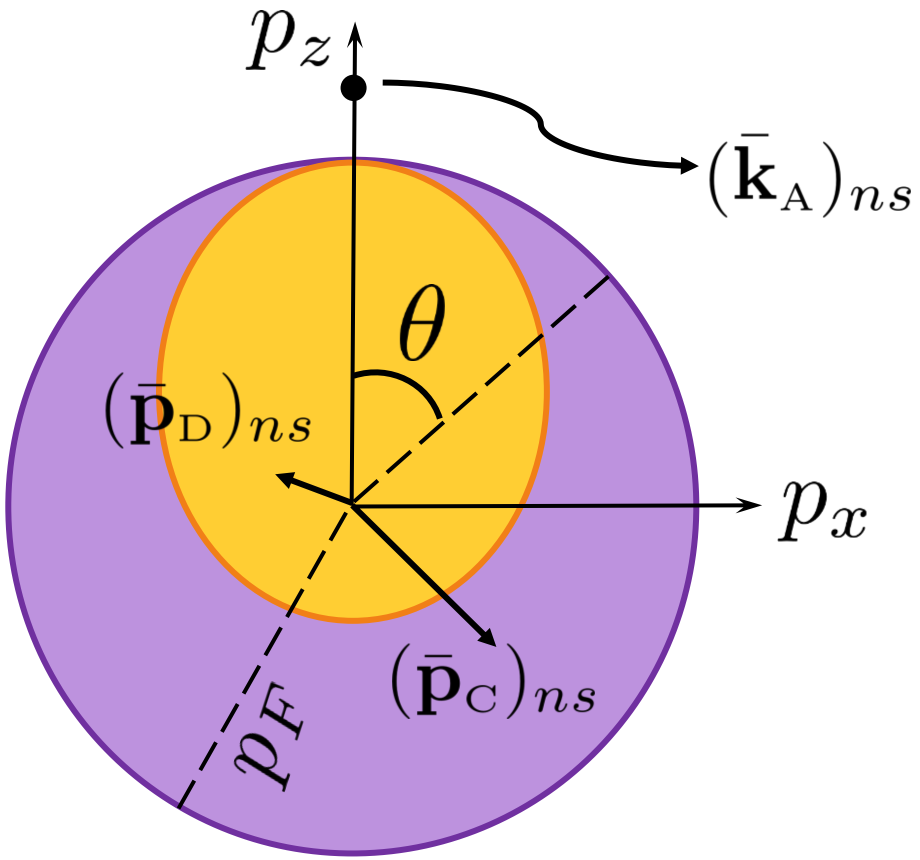
2) Multi-scattering in the case of very heavy DM
- DM can't lose its halo KE in 1 scatter

Pauli Blocking

NS Frame: Position Space



NS Frame: Momentum Space



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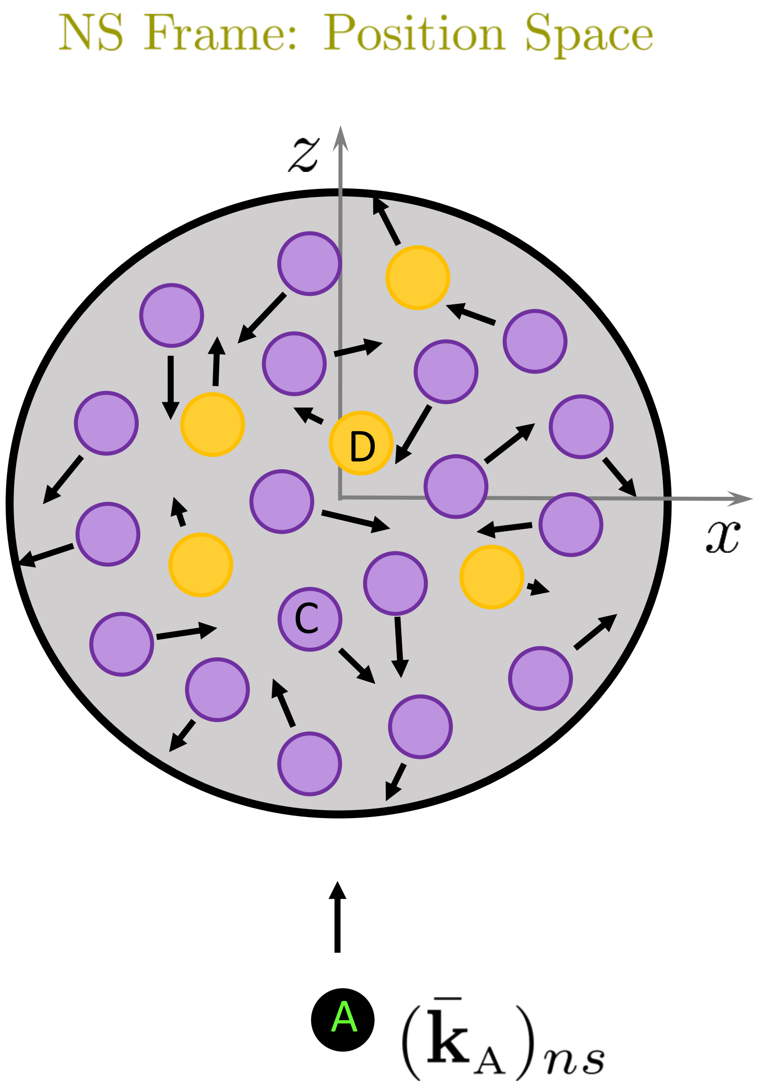

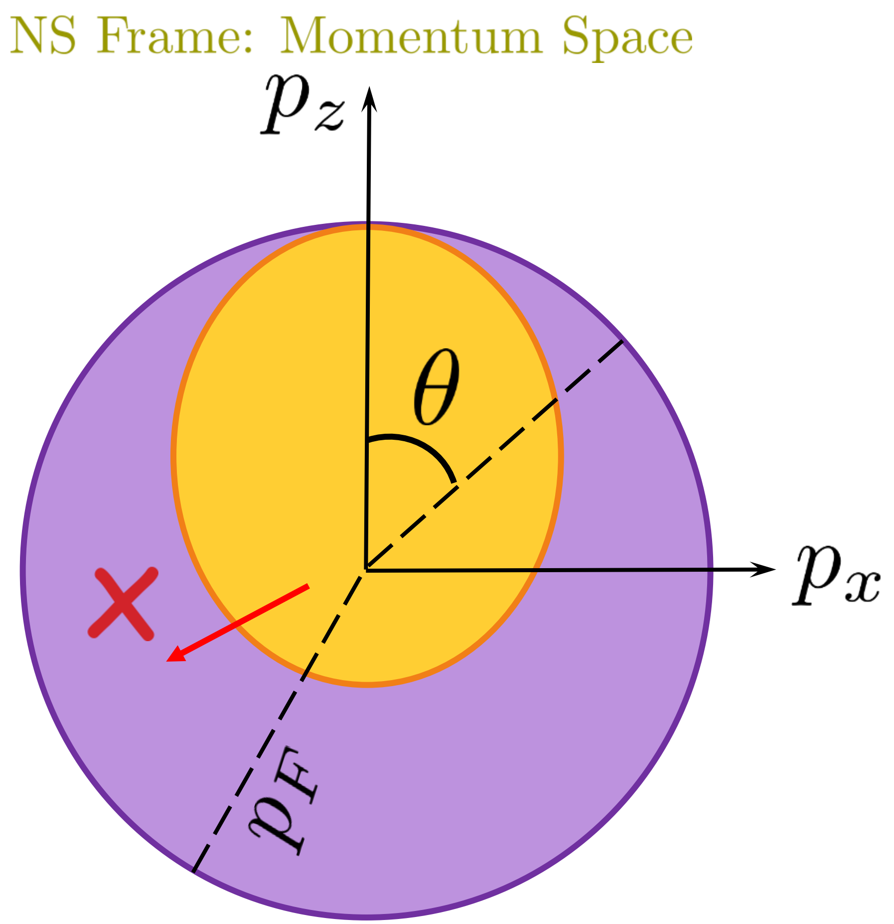

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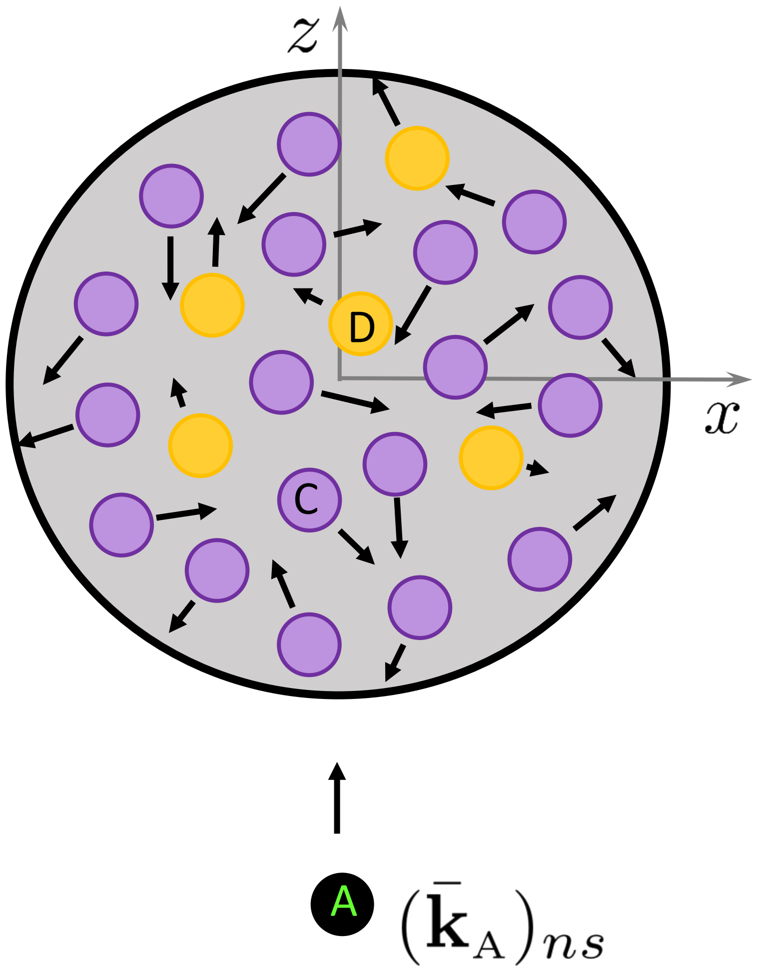

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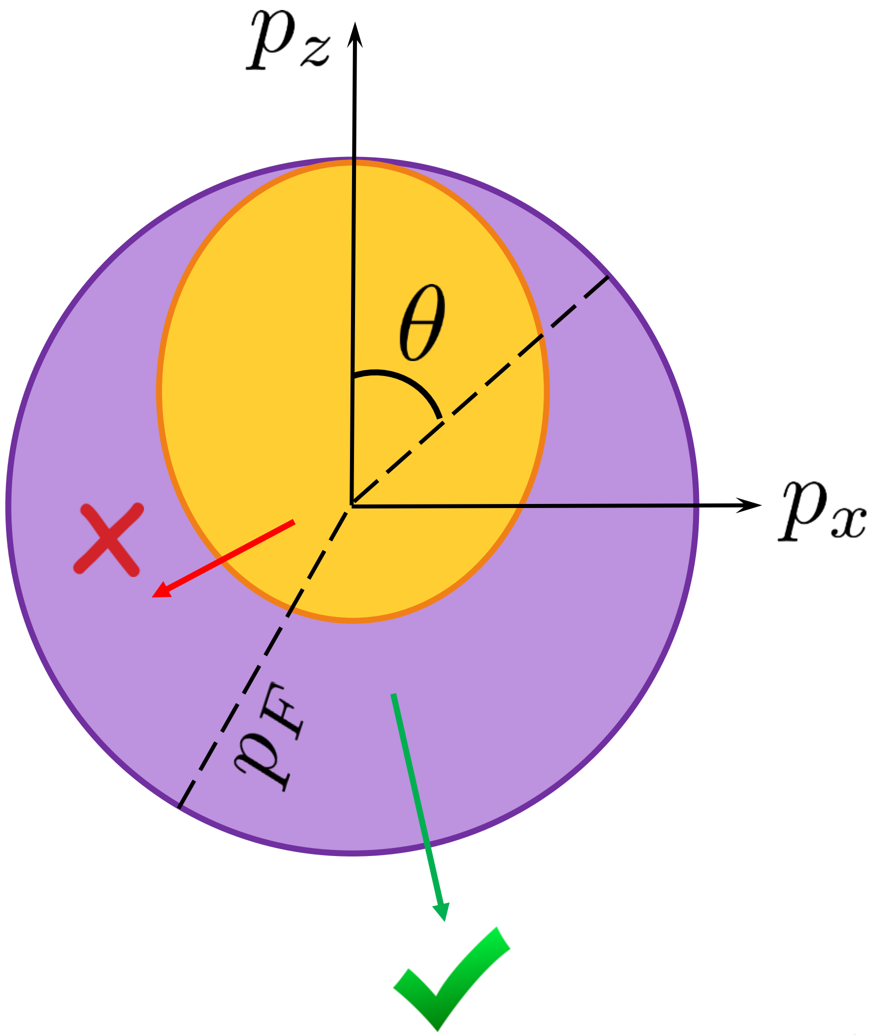

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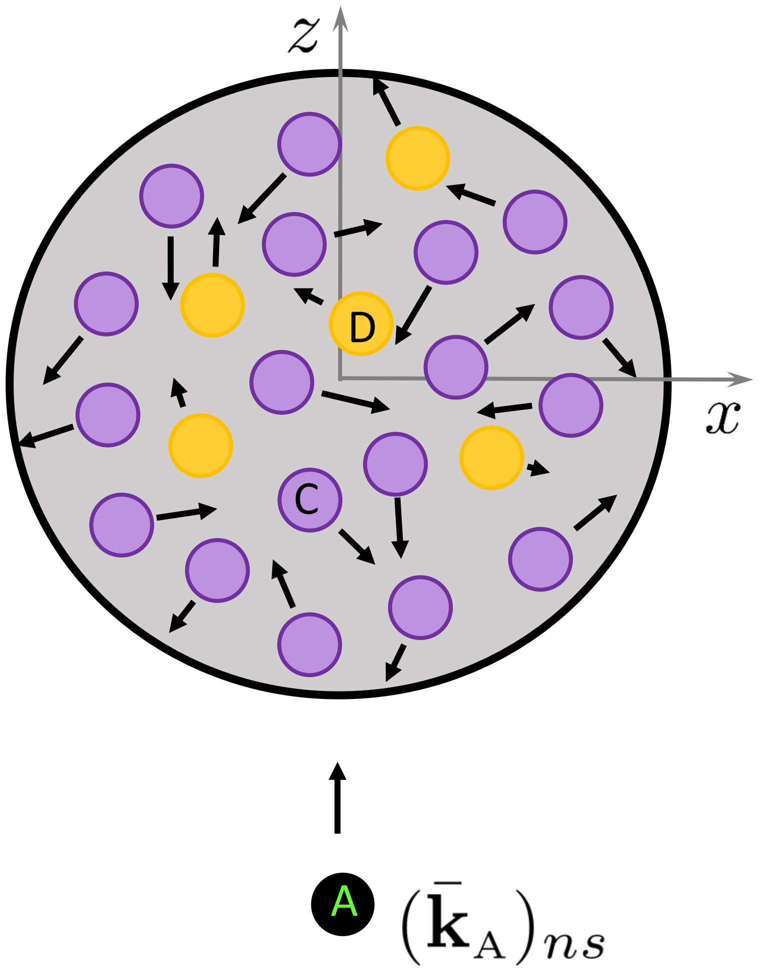

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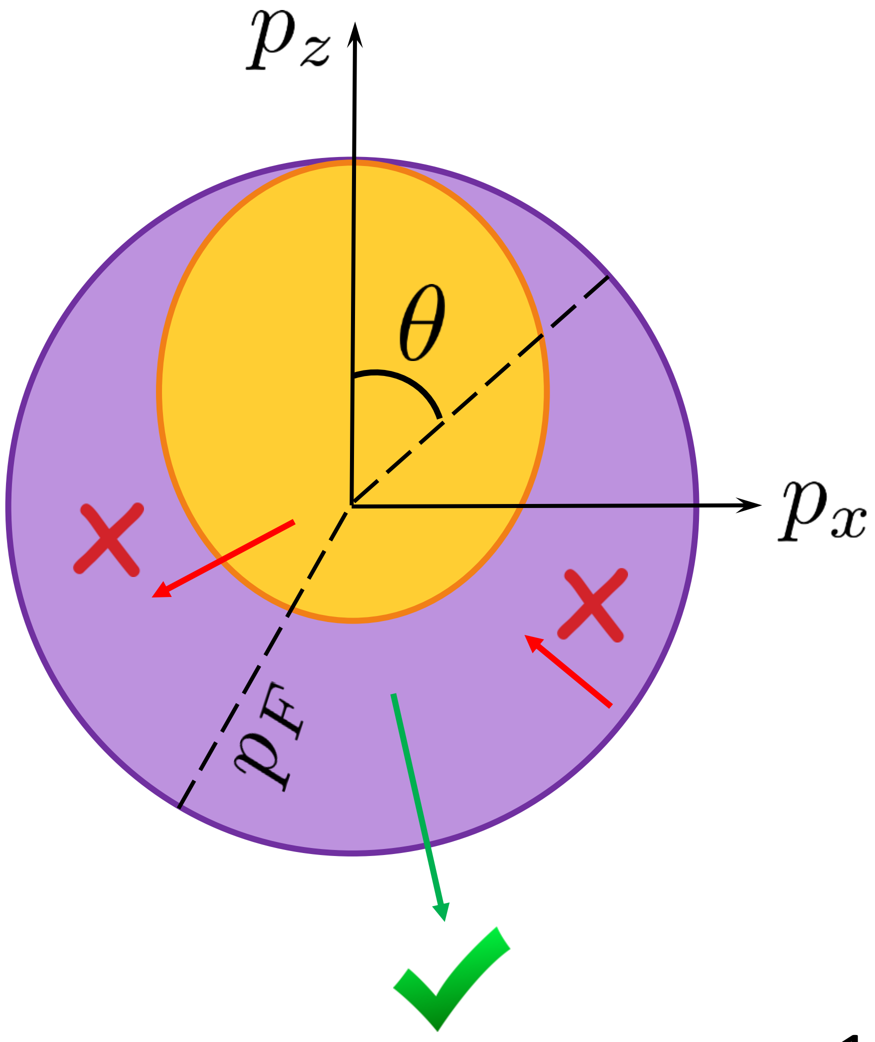

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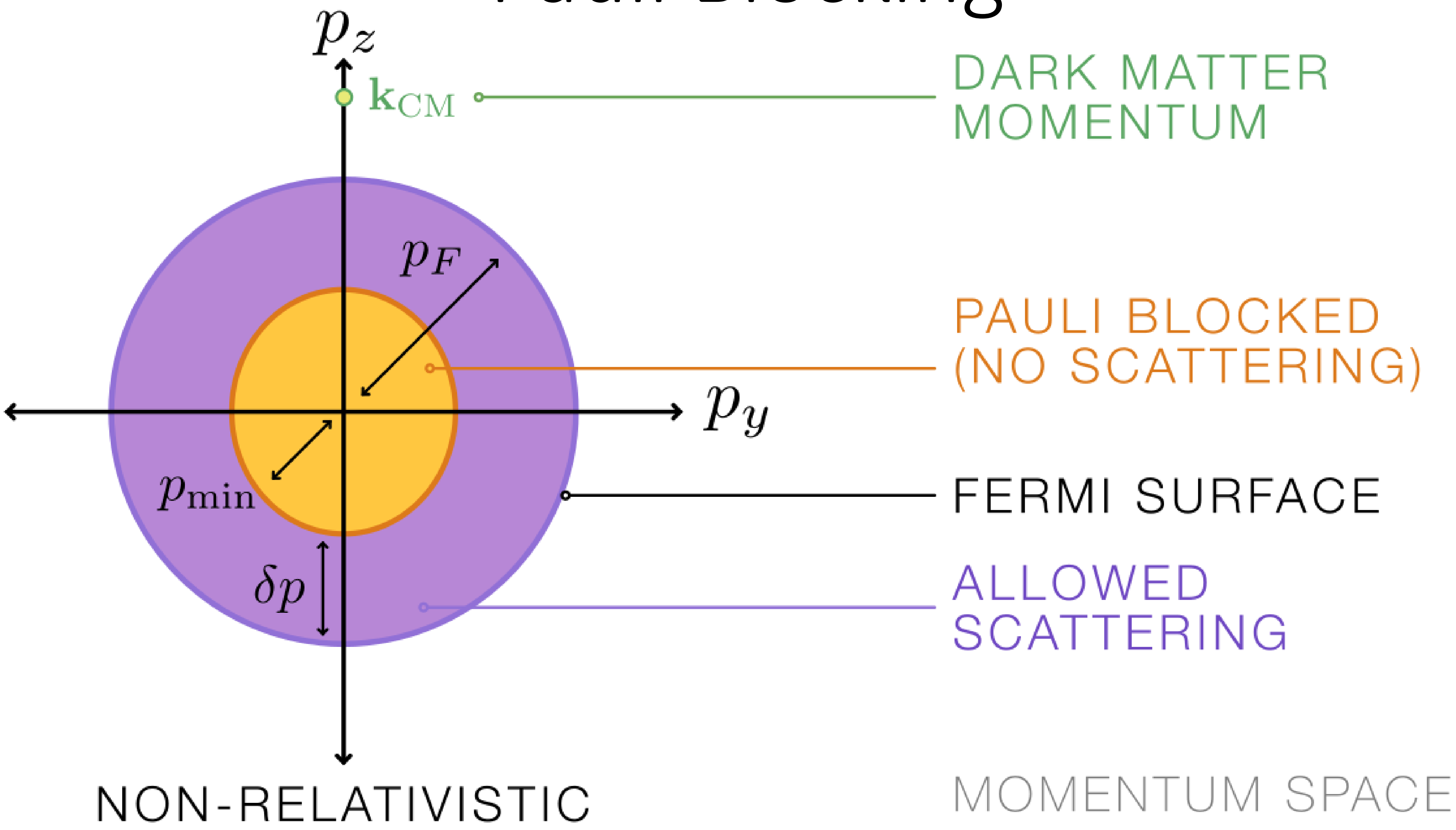
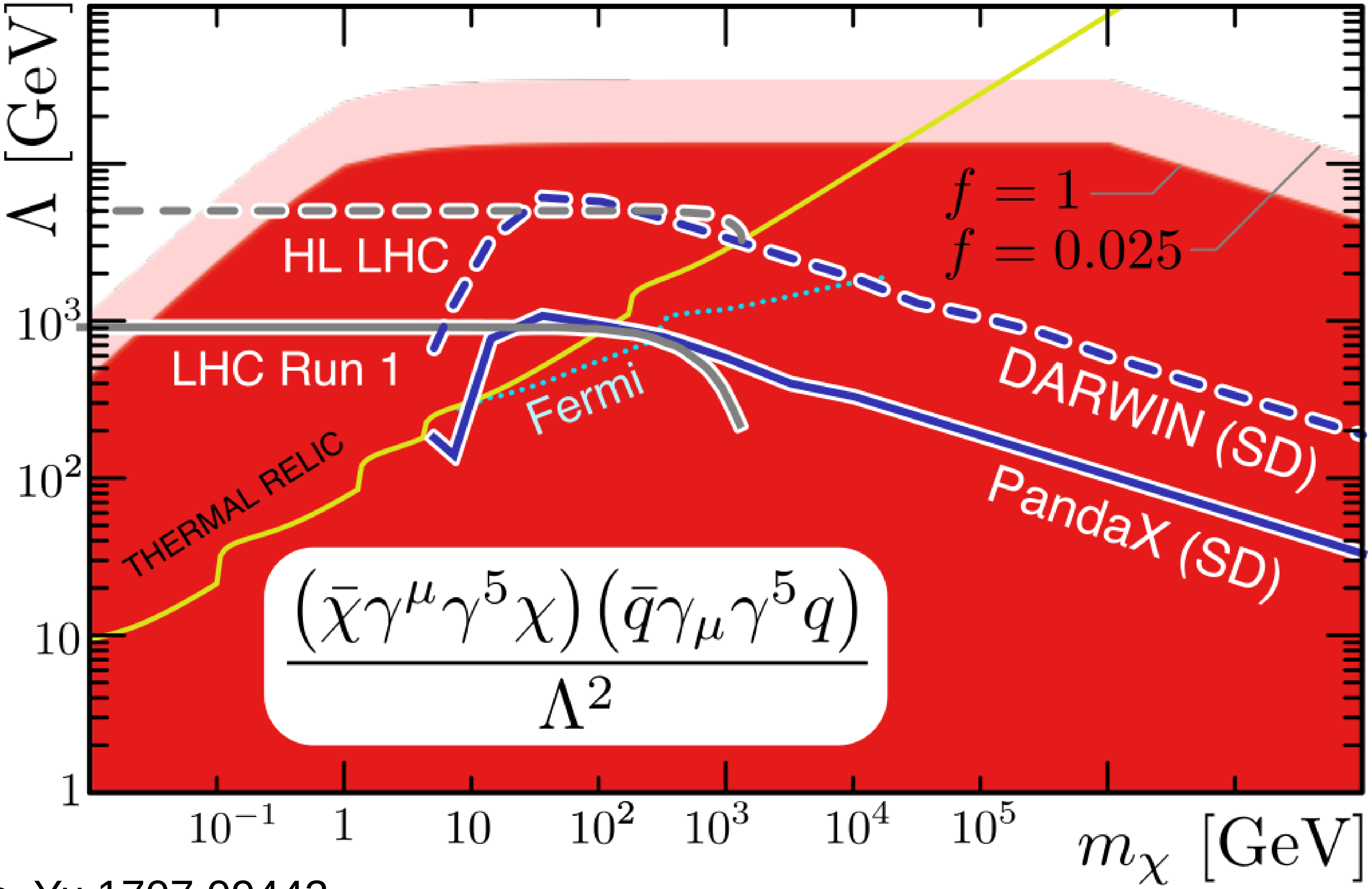


NS Reach for Cut-off energy

Nonrelativistic Targets



Raj, Tanedo, Yu 1707.09442

Is There Anything Left?

Yes. NS also has protons and electrons – because beta equilibrium

Could be useful to detect leptophilic DM if capture by electrons is significant

Can't we just replace neutron mass and number density with those for the electrons and get done with it?

No. Because electrons are ultrarelativistic. Most EoS give their abundance to be up to 10% of the number of neutrons. So the Fermi energy is in the ballpark of neutron Fermi energy ~ O(100) MeV

This alters the kinematics of the capture

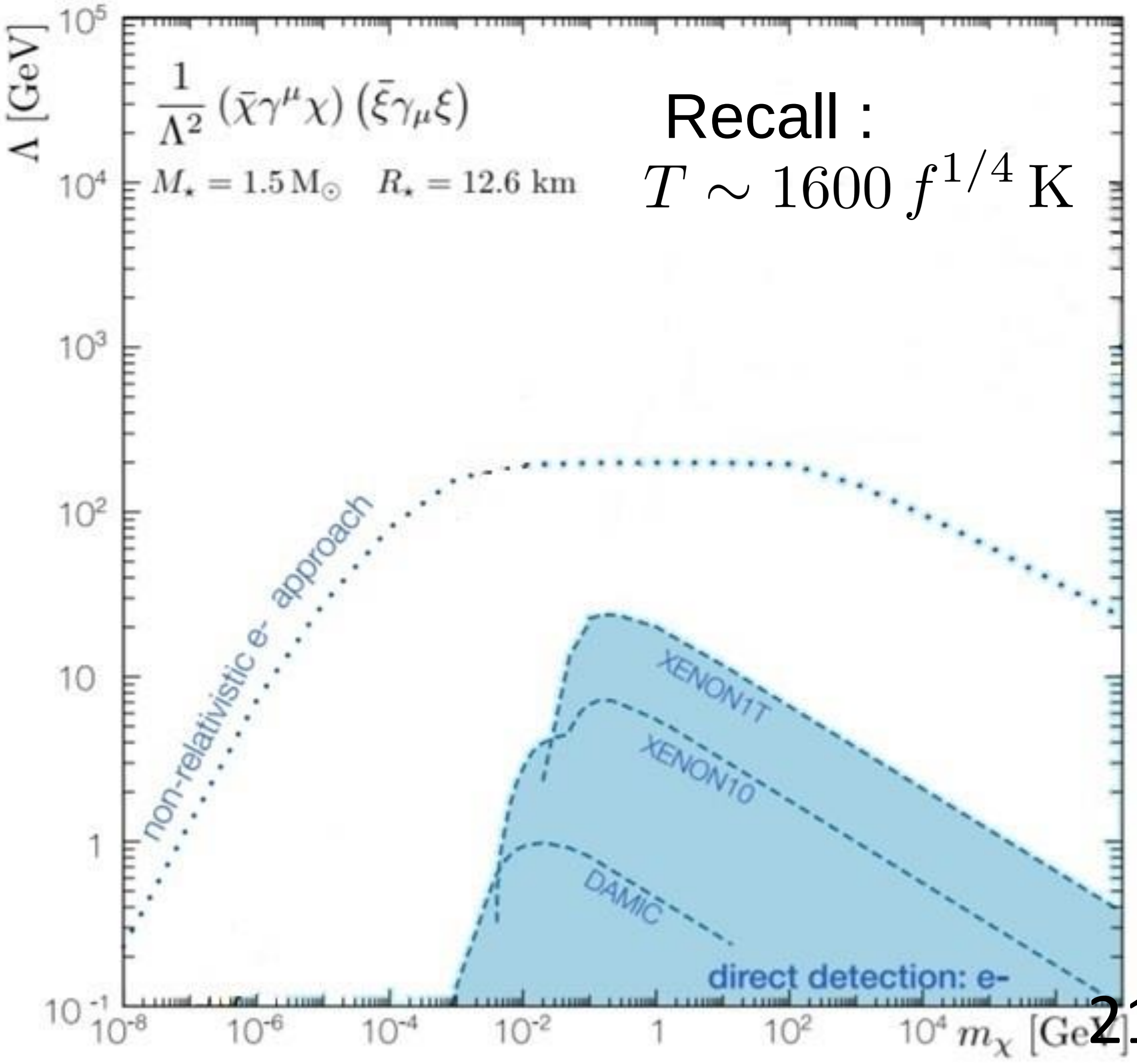
Terrestrial DD Reach for Leptophilic DM

We look at the effective interactions between DM and SM

Consider bounds on vector-vector operator cut-off scale

$$f \propto |\mathcal{M}|^2 \propto \frac{1}{\Lambda^4};\ T \propto \Lambda^{-1}$$

Shaded area corresponds to f = 1 or star temperature of 1600 K



Recall :
$$T \sim 1600\, f^{1/4}\, \mathrm{K}$$

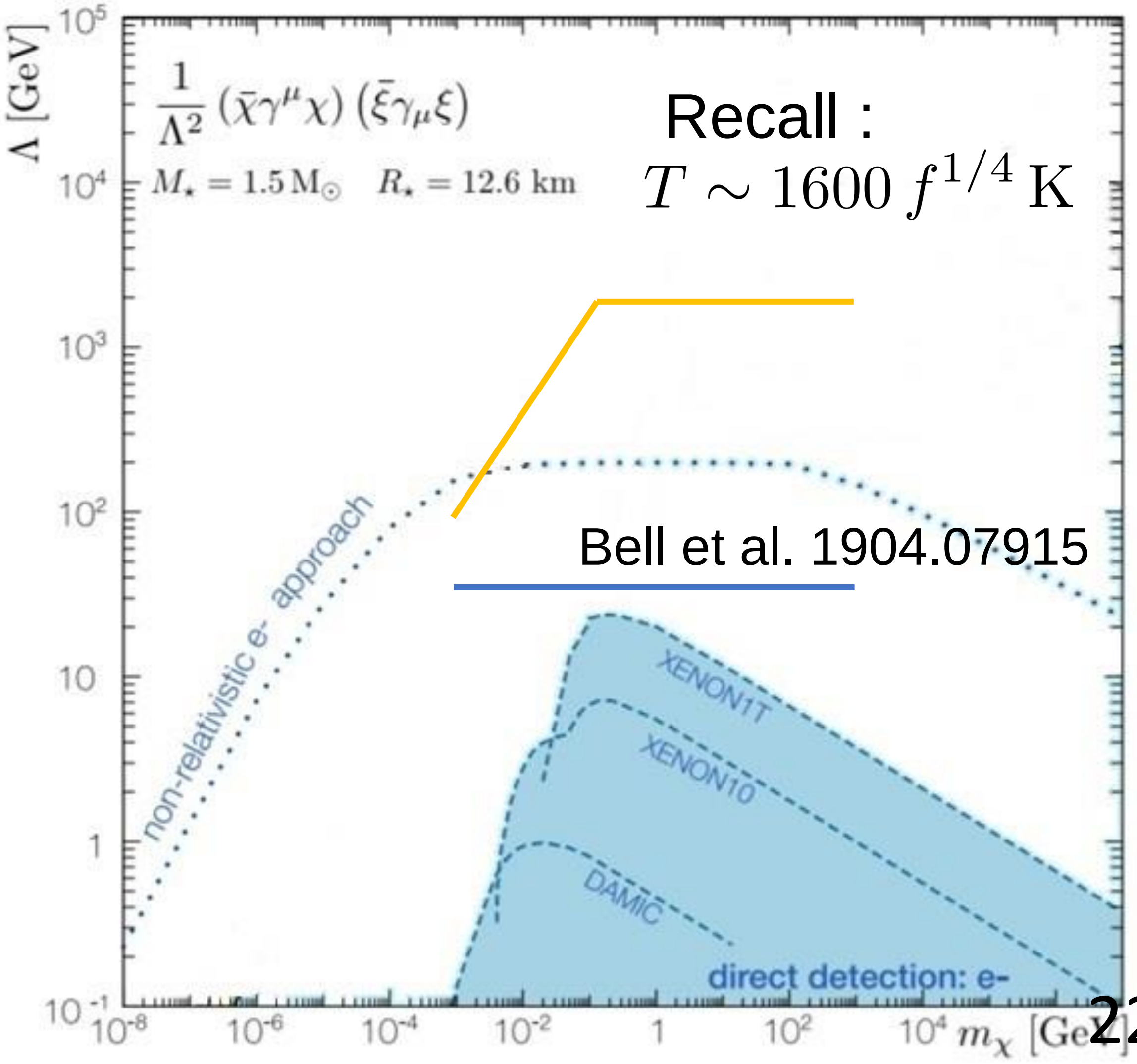
NS Reach for Leptophilic DM

Previous results in the literature concluded

1) Capture by electrons is kind of competitive with existing DD bounds on Leptophilic DM

2) Will be closely beaten by DD in near future

3) While muons bounds are way more powerful



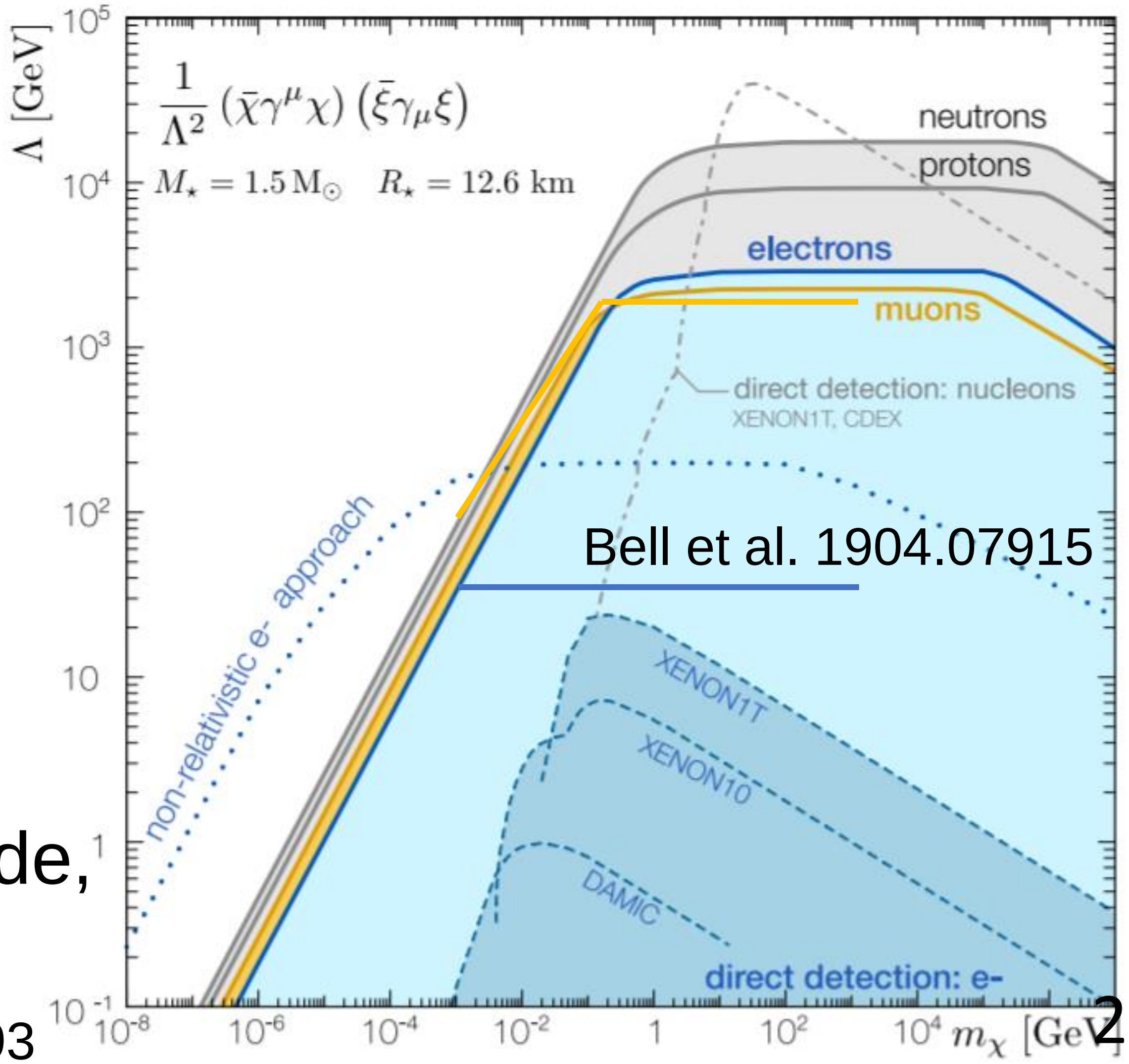
NS Reach for Leptophilic DM

We obtain electron reach on cut-off to be about 2 orders of magnitude powerful for DM mass > 1 GeV

That's about 8 orders of magnitude different in capture rate !!

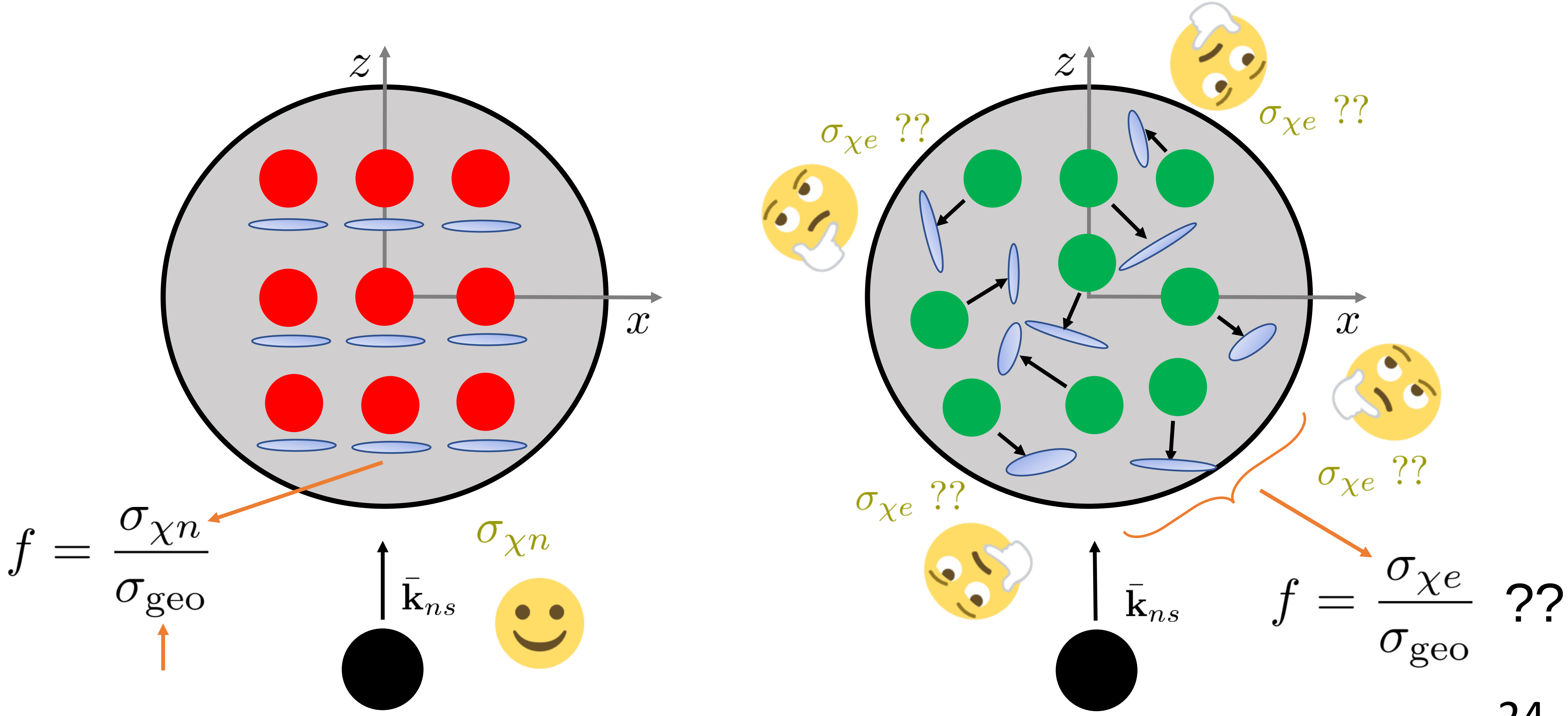
For lower masses we obtain qualitatively different behavior

Beats DD bounds by orders of magnitude, curiously close to neutron bounds



AJ, Raj, Tanedo, Yu 1911.13293

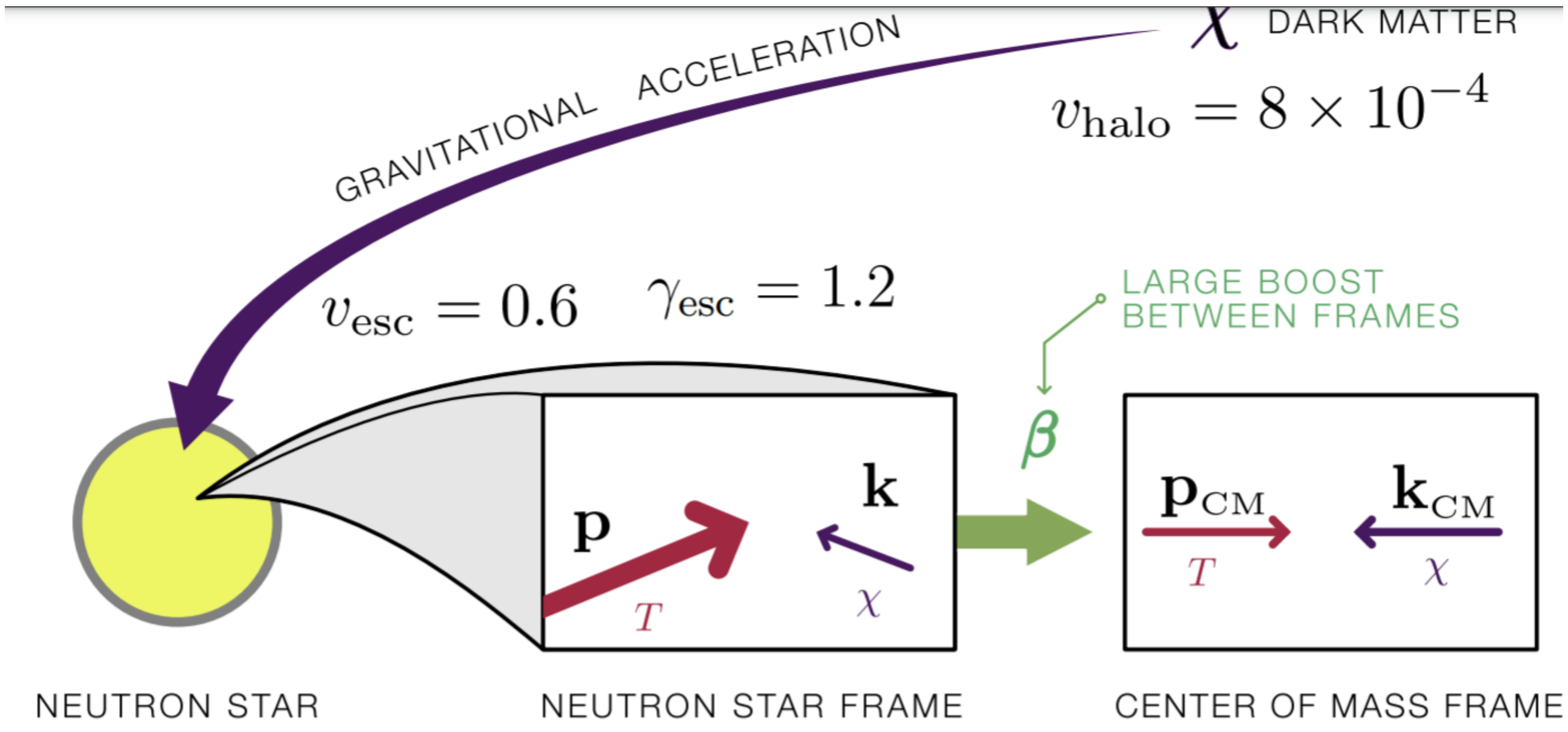
Relativistic Capture Efficiency



Frames, Moving Parts

Momentum distribution of particles best given in NS frame

Differential cross section and scattering angles are best described in the CM frame



f needs to be frame invariant

Total KE deposited must be evaluated in NS frame

Formalism

$$d\nu = (d\sigma\, v_{\rm rel}\, dn_{\rm T}\, dn_\chi \Delta V\, \Delta t)_{\rm DM} = (d\sigma\, v_{\rm rel}\, dn_{\rm T}\, dn_\chi \Delta V\, \Delta t)_{\rm NS}$$

$$df = \frac{d\nu}{dN_\chi}$$

$$dN_\chi = (dn_\chi \Delta V)_{\rm DM} = (dn_\chi \Delta V)_{\rm NS}$$

$$df = (d\sigma\, v_{\rm rel}\, dn_{\rm T} \Delta t)_{\rm NS}$$

Formalism

$$(d\sigma\, v_{\rm rel})_{\rm frame} = d\sigma_{\rm CM}\, (v_{\rm mol})_{\rm frame}$$

$$v_{\rm mol} = \frac{\sqrt{(p.k)^2 - m_{\rm T}^2 m_\chi^2}}{E_p E_k}$$

$$(d\sigma\, v_{\rm rel})_{\rm NS} = d\sigma_{\rm CM}\, (v_{\rm mol})_{\rm NS}$$

Formalism

$$df = (d\sigma\, v_{\rm rel})_{\rm NS}\, (dn_{\rm T} \Delta t)_{\rm NS}$$

$$df = d\Omega_{\rm CM} \left(\frac{d\sigma}{d\Omega}\right)_{\rm CM} (v_{\rm mol}\, dn_{\rm T} \Delta t)_{\rm NS}$$

Formalism

$$df = \sum_{\mathrm{N_{hit}}} \frac{1}{N_{\mathrm{hit}}} \, d\Omega_{\mathrm{CM}} \left(\frac{d\sigma}{d\Omega} \right)_{\mathrm{CM}} \left(v_{\mathrm{mol}} \, dn_{\mathrm{T}} \Delta t \right)_{\mathrm{NS}}$$

$$\times \Theta \left(\Delta E - \frac{E_{\mathrm{halo}}}{N_{\mathrm{hit}}} \right) \Theta \left(\frac{E_{\mathrm{halo}}}{N_{\mathrm{hit}} + 1} - \Delta E \right)$$

$$\times \Theta \left(\Delta E + E_p - E_{\mathrm{F}} \right)$$

Formalism

$$df = \sum_{\mathrm{N_{hit}}} \frac{\langle n_{\mathrm{T}} \rangle \Delta t}{N_{\mathrm{hit}}} \int \Omega_{\mathrm{F}} \int \frac{p^2 dp}{V_{\mathrm{F}}} \int d\Omega_{\mathrm{CM}} \left(\frac{d\sigma}{d\Omega} \right)_{\mathrm{CM}} v_{\mathrm{mol}} \Theta^3 (\Delta E)$$

$$d\Omega = d\alpha \, d(\cos\psi)$$

$$\Omega_{\mathrm{F}} = d\phi \, d(\cos\theta)$$

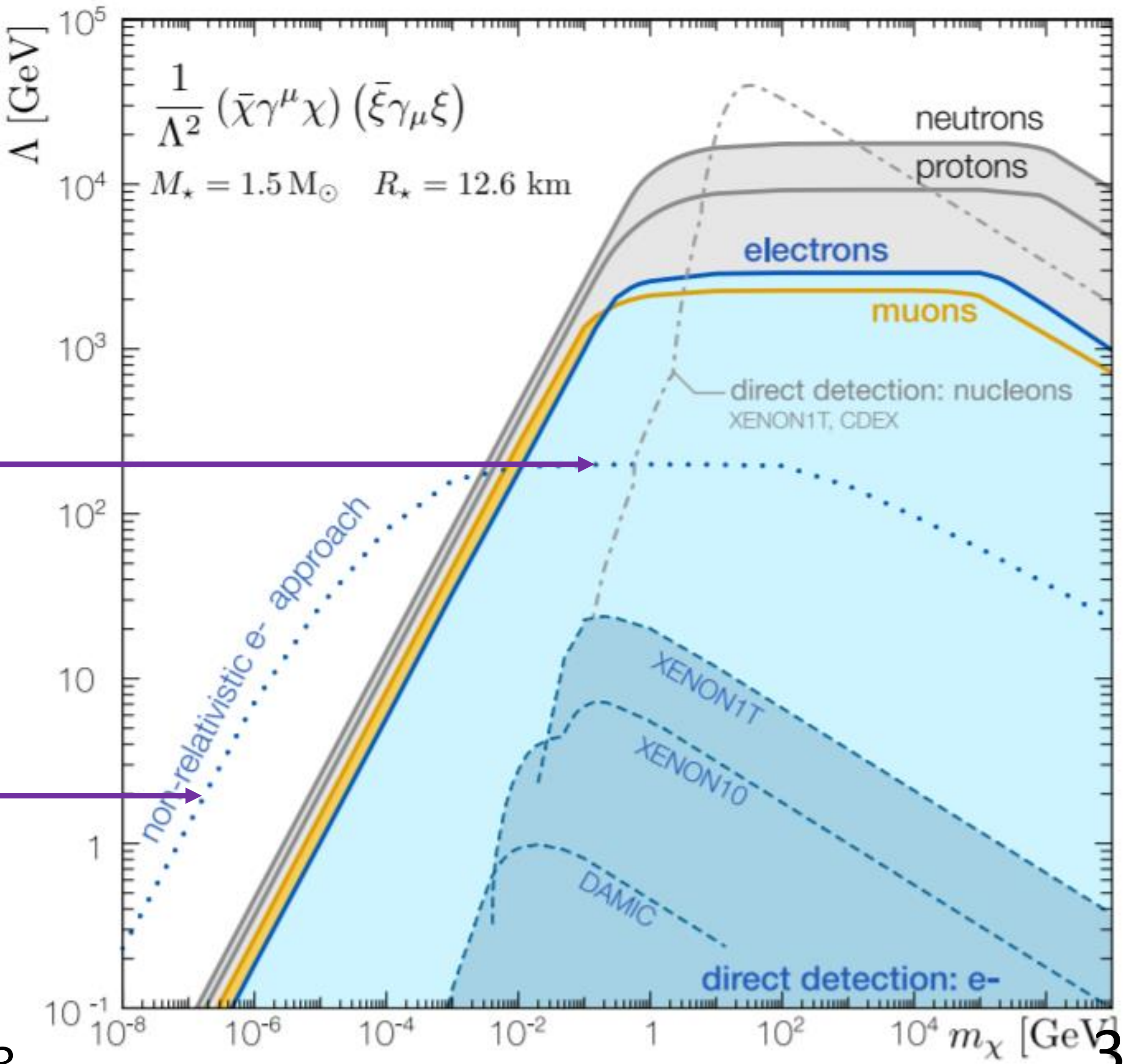
$$dn_{\mathrm{T}} = \langle n_{\mathrm{T}} \rangle \Omega_{\mathrm{F}} \frac{p^2 dp}{V_{\mathrm{F}}}$$

$$V_{\mathrm{F}} = \frac{4}{3} \pi p_{\mathrm{F}}^3$$

Result

Non relativistic approach will underestimate for heavy DM

Non relativistic approach will overestimate for light DM



AJ, Raj, Tanedo, Yu 1911.13293

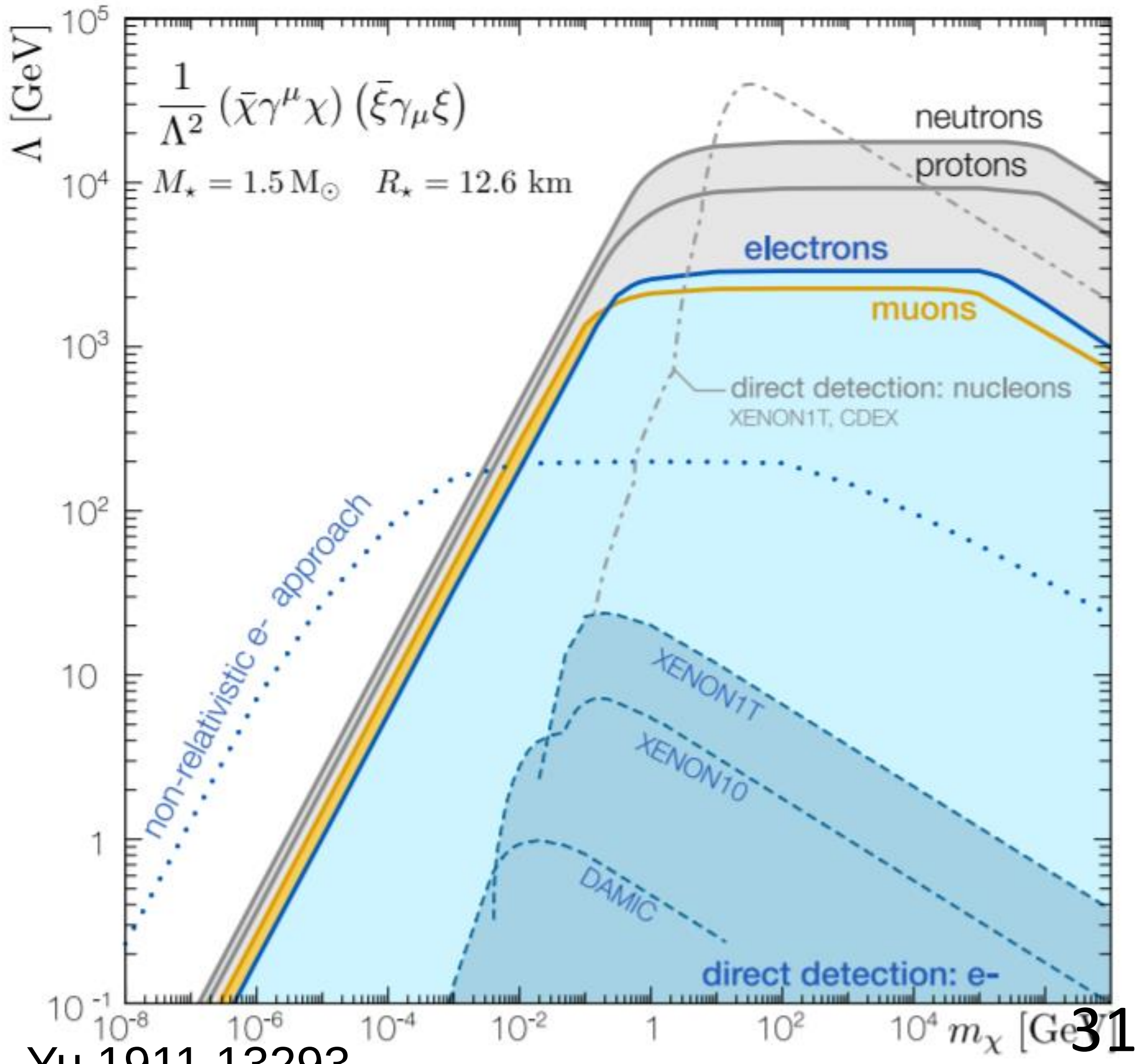
Generalizing the Results

How will things look for other fermionic operators?

What about bosonic DM operators?

Can we just guess shapes given an operator?

What if we change target mass or Fermi energy? How do shapes and magnitudes vary?



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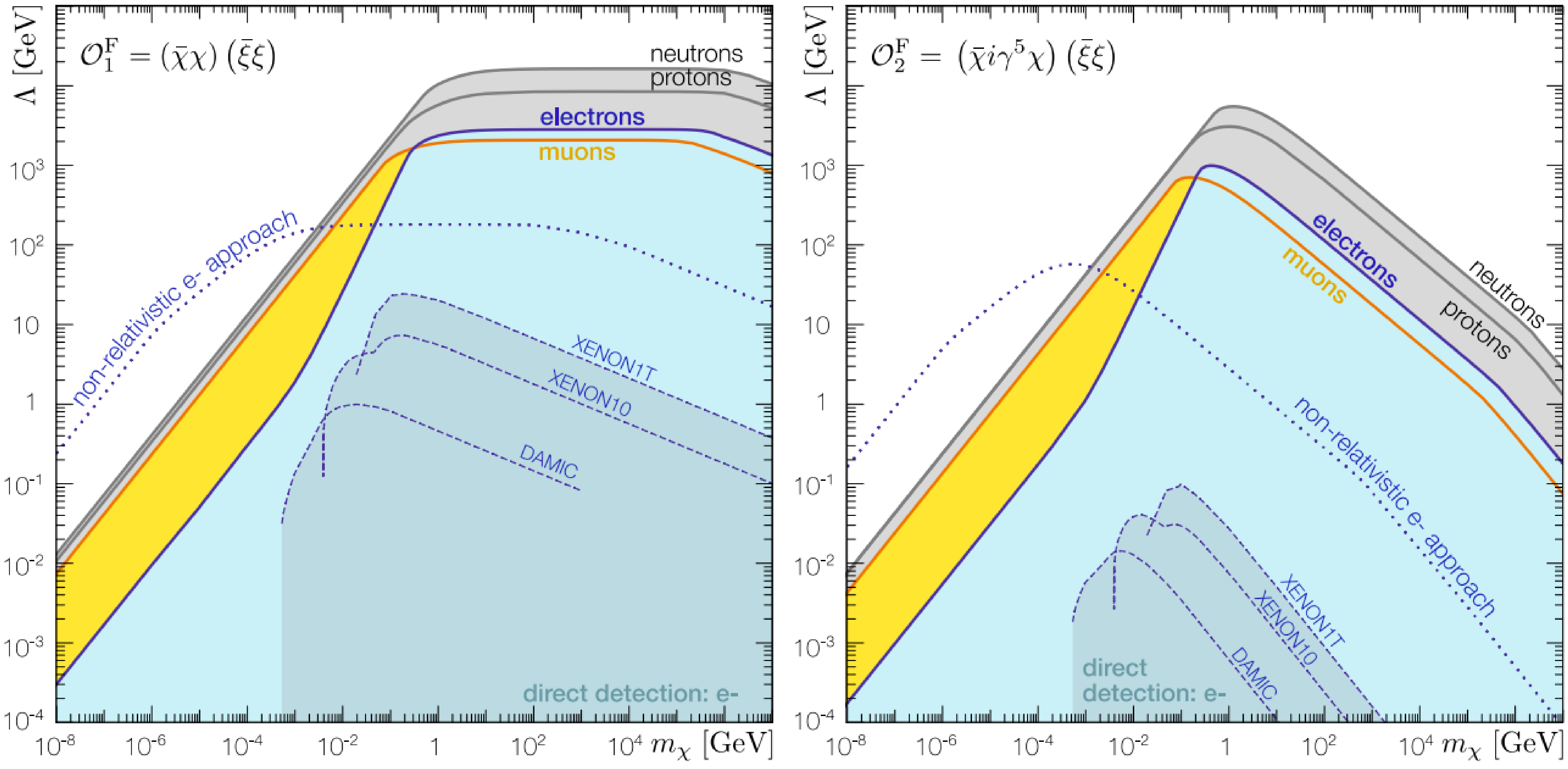
Sample Results for Other Operators



AJ, Raj, Tanedo, Yu 2004.09539

Scaling of Cut-off with DM Mass

Based on what we did so far there are 4 obvious regions of available $m_\chi - m_\mathrm{T}$ space

Nonrelativistic target light DM

$$m_\chi < m_\mathrm{T}$$

Nonrelativistic target heavy DM

$$m_\chi < p_\mathrm{F}$$

Relativistic target light DM

$$m_\chi < p_\mathrm{F}$$

Relativistic target heavy DM

$$m_\chi > p_\mathrm{F}$$

Scaling of Cut-off with DM Mass

$$df = \sum_{\mathrm{N_{hit}}} \frac{\langle n_{\mathrm{T}} \rangle \Delta t}{N_{\mathrm{hit}}} \int \Omega_{\mathrm{F}} \int \frac{p^2 dp}{V_{\mathrm{F}}} \int d\Omega_{\mathrm{CM}} \left(\frac{d\sigma}{d\Omega} \right)_{\mathrm{CM}} v_{\mathrm{mol}} \Theta^3(\Delta E)$$

Various components of this scale differently wrt DM mass in these regimes

Are there further sub-divisions inside these categories that would lead to different scaling of cut-off bounds wrt DM mass??

Scaling of Cut-off with DM Mass

Scaling of 4 main components affects scaling of f and subsequently T

Phase Space : 4 variables α, θ, ψ, p

$\Theta^3(\Delta E)$ Is what shrinks the phase space

Phase space for first 2 doesn't scale with DM mass

Easy to see in the case of α. In energy transfer formula it only appears as a cos α factor in one of the terms

$$f \sim \frac{1}{N_{\rm hit}} \int_{\cos\psi_0}^{1} d(\cos\psi) \int_{p_{\rm min}}^{p_{\rm F}} \frac{p^2 dp}{p_{\rm F}^3} \frac{|\mathcal{M}|^2}{s}$$

Scaling of Cut-off with DM Mass

Scaling of 4 main components affects scaling of f and subsequently T

Phase Space : 4 variables α, θ, ψ, p

$\Theta^3(\Delta E)$ Is what shrinks the phase space

Same is true for θ in 3 out of 4 regimes except relativistic target light DM

In rel. target light DM case also it could be true provided $(1 - \cos\psi)$ scales as m_χ

$$f \sim \frac{1}{N_{\rm hit}} \int_{\cos\psi_0}^{1} d(\cos\psi) \int_{p_{\rm min}}^{p_{\rm F}} \frac{p^2 dp}{p_{\rm F}^3} \frac{|\mathcal{M}|^2}{s}$$

Scaling of Cut-off with DM Mass

Scaling of 4 main components affects that of f and subsequently the T

Other 3 components are $|\mathcal{M}|^2,\ s$ and $N_{\rm hit}$

$N_{\rm hit}$ always scales as inverse of DM mass for DM masses greater than target energy / (halo velocity)^2

This creates a sub-regime of “very heavy” DM in which the cut-off scales one less power compared to heavy DM regime

Now focus on :
$$f \sim \int_{\cos\psi_0}^{1} d(\cos\psi) \int_{p_{\rm min}}^{p_{\rm F}} \frac{p^2 dp}{p_{\rm F}^3} \frac{|\mathcal{M}|^2}{s}$$

Scaling of Cut-off with DM Mass

Now focus on : $$f \sim \int_{\cos\psi_0}^{1} d(\cos\psi) \int_{p_{\min}}^{p_{\mathrm{F}}} \frac{p^2 dp}{p_{\mathrm{F}}^3} \frac{|\mathcal{M}|^2}{s}$$

$$\sim (1-\cos\psi_0)\frac{\Delta p}{p_{\mathrm{F}}} \frac{|\mathcal{M}|^2}{s}$$

$\frac{\Delta p}{p_{\mathrm{F}}}$ scales proportional to DM mass only in both the light DM regimes
but it does so in the exact same way
doesn’t create sub-regimes

$(1-\cos\psi_0)$ scales with DM mass only in relativistic target light DM regime but scales differently for “very light” DM

Scaling of Cut-off with DM Mass

Now focus on : $f \sim (1 - \cos\psi_0)\,\frac{\Delta p}{p_{\rm F}}\,\frac{|\mathcal{M}|^2}{s}$

$\frac{|\mathcal{M}|^2}{s}$ scales with DM mass only in all regimes and divides relativistic target light DM regime into 3 regions owing to behavior of s. "Very light" regime here is same.

$$s \approx \begin{cases} m_{\rm T}^2 & m_\chi \ll m_{\rm T}^2/p_{\rm F} \\ m_\chi E_p & m_{\rm T}^2/E_{\rm F} \ll m_\chi \ll p_{\rm F} \\ m_\chi^2 & p_{\rm F} \ll m_\chi \end{cases}$$

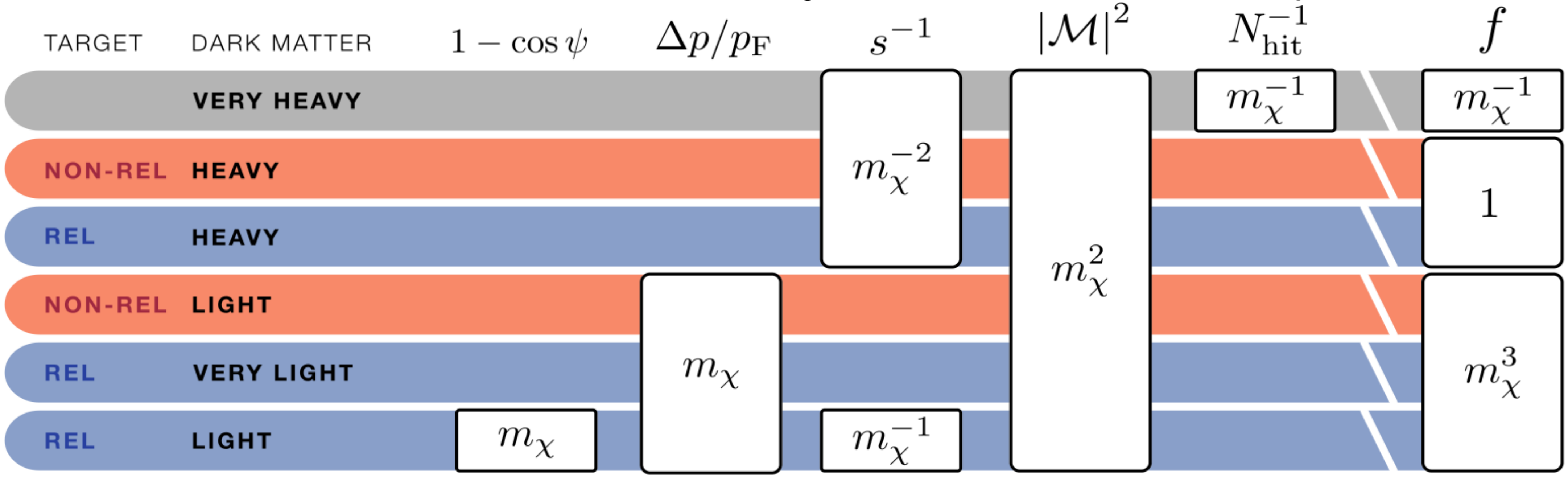
$(1 - \cos\psi_0)$ scales with DM mass only in relativistic target light DM regime but scales differently for "very light" DM

Scaling of Cut-off with DM Mass

For 8 out of 14 operators : $\frac{|\mathcal{M}|^2}{s} \approx \frac{m_\chi^2 E_p^2}{s\Lambda^4} \approx \frac{m_\chi^2 m_{\rm T}^2}{s\Lambda^4}\left(1 + \frac{E_{\rm F}^2}{m_{\rm T}^2}\right)$

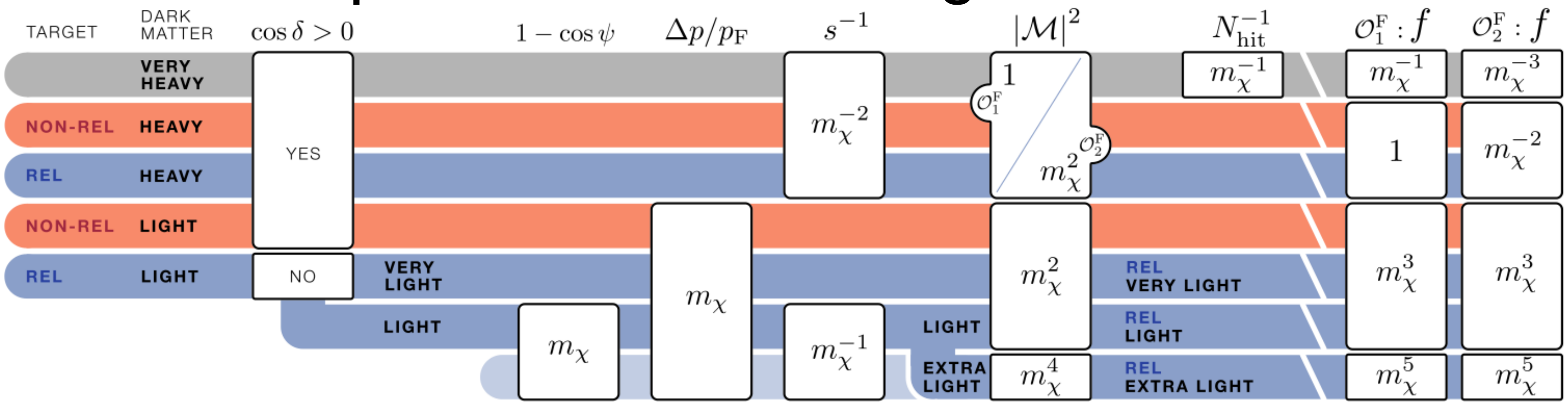
Reminiscent of cross section being proportional to reduced mass squared

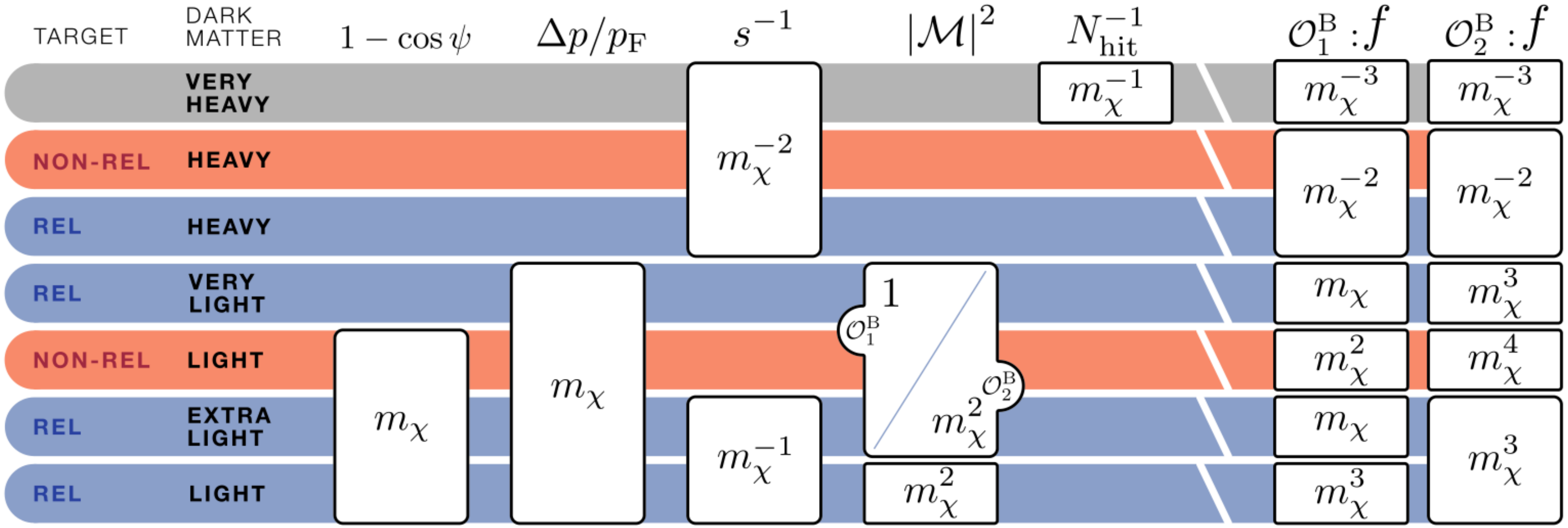
Leads to “baseline” behavior for scaling wrt DM mass or any other mass scale



Scaling of Cut-off with DM Mass

For some other operators, the scaling could be more complex





Scaling of Cut-off with All Mass Scales

Use the same recipe but now write down dependence on all the mass/ distance scales in the problem. Additionally write down such a dependence in the prefactor $\frac{\langle n_T \rangle \Delta t}{N_{hit}}$ as well

m_T	Non-Relativistic		Relativistic			
m_χ	Heavy	Light	Heavy	Light-ish	Med. Light	Very Light
Baseline	$p_F^{1/4} m_T$	$p_F^{1/2} m_\chi^{3/4}$	$p_F^{5/4}$	$p_F^{1/2} m_\chi^{3/4}$	$p_F^{1/2} m_\chi^{3/4}$	$p_F^{1/2} m_\chi^{3/4}$
$\mathcal{O}_1^F$				$m_\chi^{5/4}$		
$\mathcal{O}_2^F$	$p_F^{1/4} m_\chi^{-1/2} m_T^{3/2}$		$p_F^{7/4} m_\chi^{-1/2}$	$m_\chi^{5/4}$		
$\mathcal{O}_3^F$		$p_F^{1/2} m_\chi^{5/4} m_T^{-1/2}$		$m_\chi^{5/4}$	$m_\chi^{5/4}$	$m_\chi^{5/4}$
$\mathcal{O}_4^F$	$p_F^{1/4} m_\chi^{-1/2} m_T^{3/2}$	$p_F^{1/2} m_\chi^{5/4} m_T^{-1/2}$	$p_F^{7/4} m_\chi^{-1/2}$	$m_\chi^{5/4}$	$m_\chi^{5/4}$	$m_\chi^{5/4}$
$\mathcal{O}_1^S$	$p_F^{1/2} m_\chi^{-1} m_T^2$	$p_F\, m_\chi^{1/2}$	$p_F^{5/2} m_\chi^{-1}$	$m_\chi^{3/2}$	$m_\chi^{1/2} m_T$	$m_\chi^{1/2} m_T$
$\mathcal{O}_2^S$	$p_F^{1/2} m_\chi^{-1} m_T^2$	$p_F\, m_\chi^{3/2} m_T^{-1}$	$p_F^{5/2} m_\chi^{-1}$	$m_\chi^{3/2}$	$m_\chi^{3/2}$	$m_\chi^{3/2}$

AJ, Raj, Tanedo, Yu
2004.09539

Results for Scaling

For 8 out of 14 operators, show identical behavior

Of the remaining 6, three fermionic DM operators show baseline behavior in 2 or 3 regimes.

Fermionic DM PP operator and scalar DM SS and PP operators differ in all regimes.

Magnitudes of their reaches are far-off from baseline. No plateaus.

Curious closeness of electron and neutron bounds in light DM regimes can be explained by closeness of Fermi energies of both the species

Summary

Search for NS kinetic heating can nicely complement existing terrestrial direct detection program

Electrons in NS can be a powerful probe too. Almost as strong as neutrons!

Some surprises on the way. New formalism is needed.

This approach can also give nice recipe for predicting various mass scale dependences of cut-off scale bounds