Dark Heating of Neutron Stars :
Electron Edition

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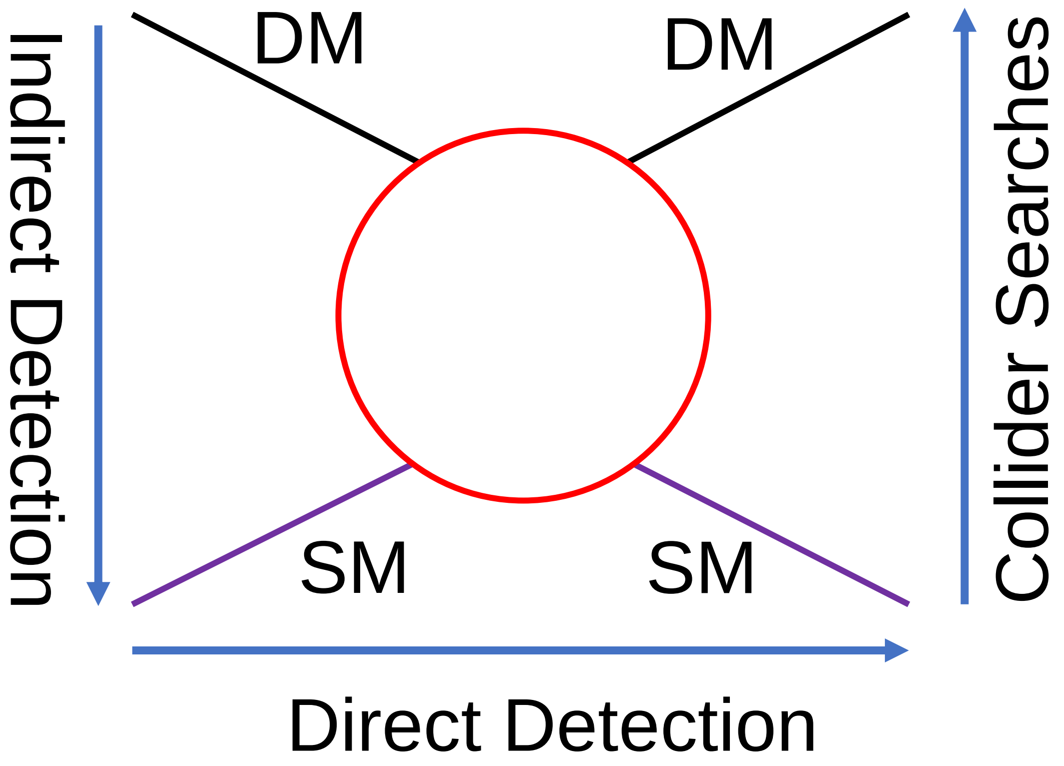
Based On :
Phys.Lett. B(2020)135767 (arXiv: 1911.13293)
Phys.Rev.D 102(2020)12, 123002 (arXiv: 2004.09539)

Work With :
Nirmal Raj (TRIUMF)
Flip Tanedo, Hai-Bo Yu (UC Riverside)

Direct Detection of Dark Matter?

DM scatters and deposits energy in the targets
via DM + SM $\longrightarrow$ DM + SM interactions



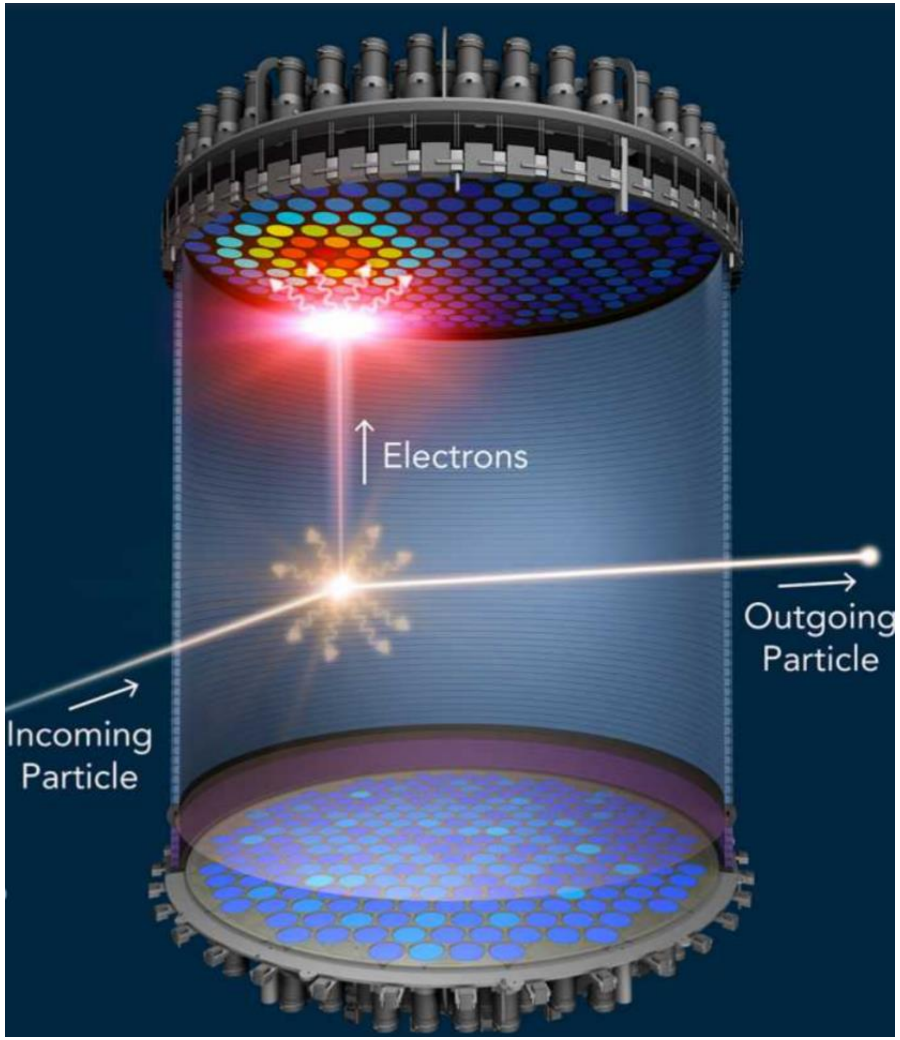


Image: Lux-LZ

Current Status

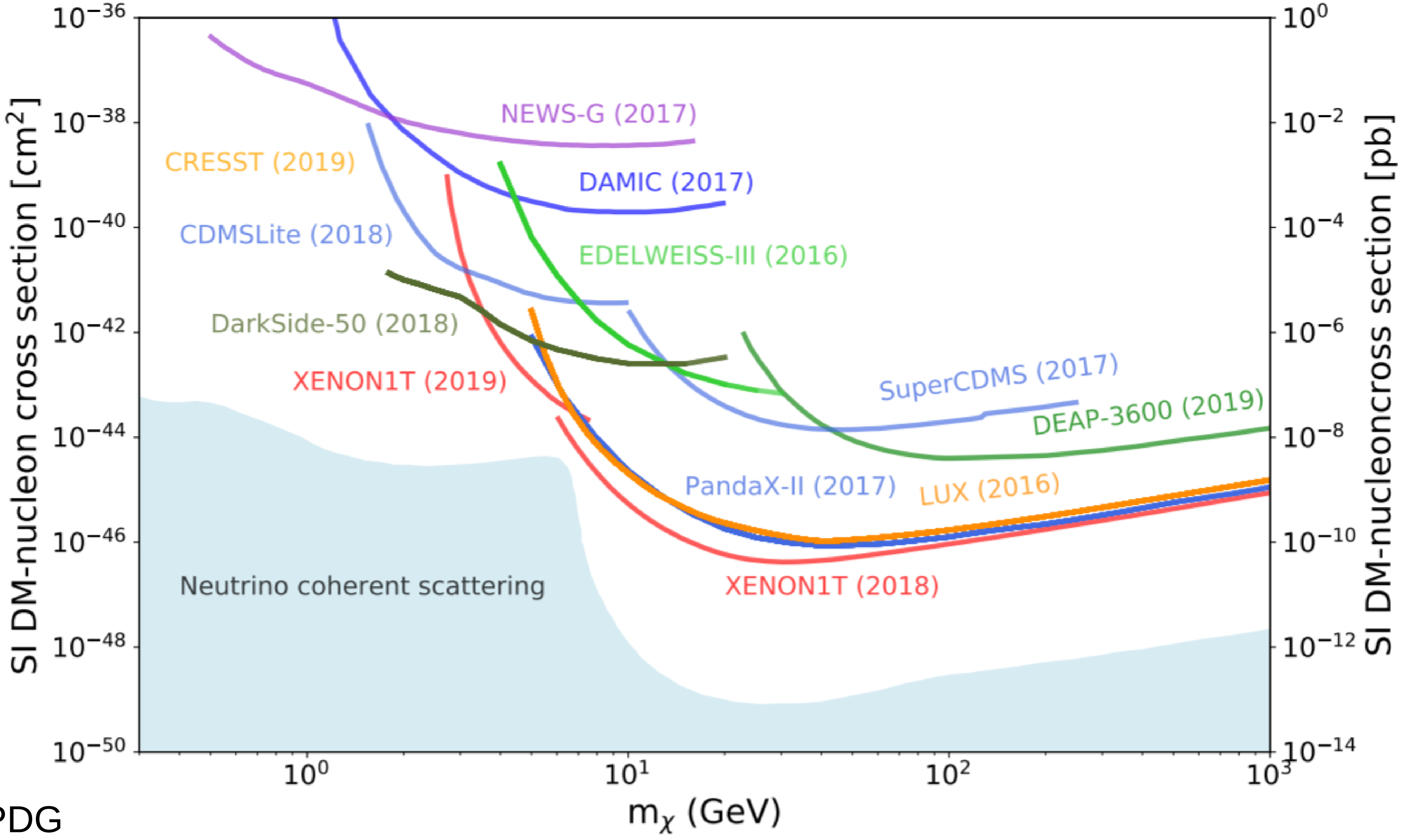
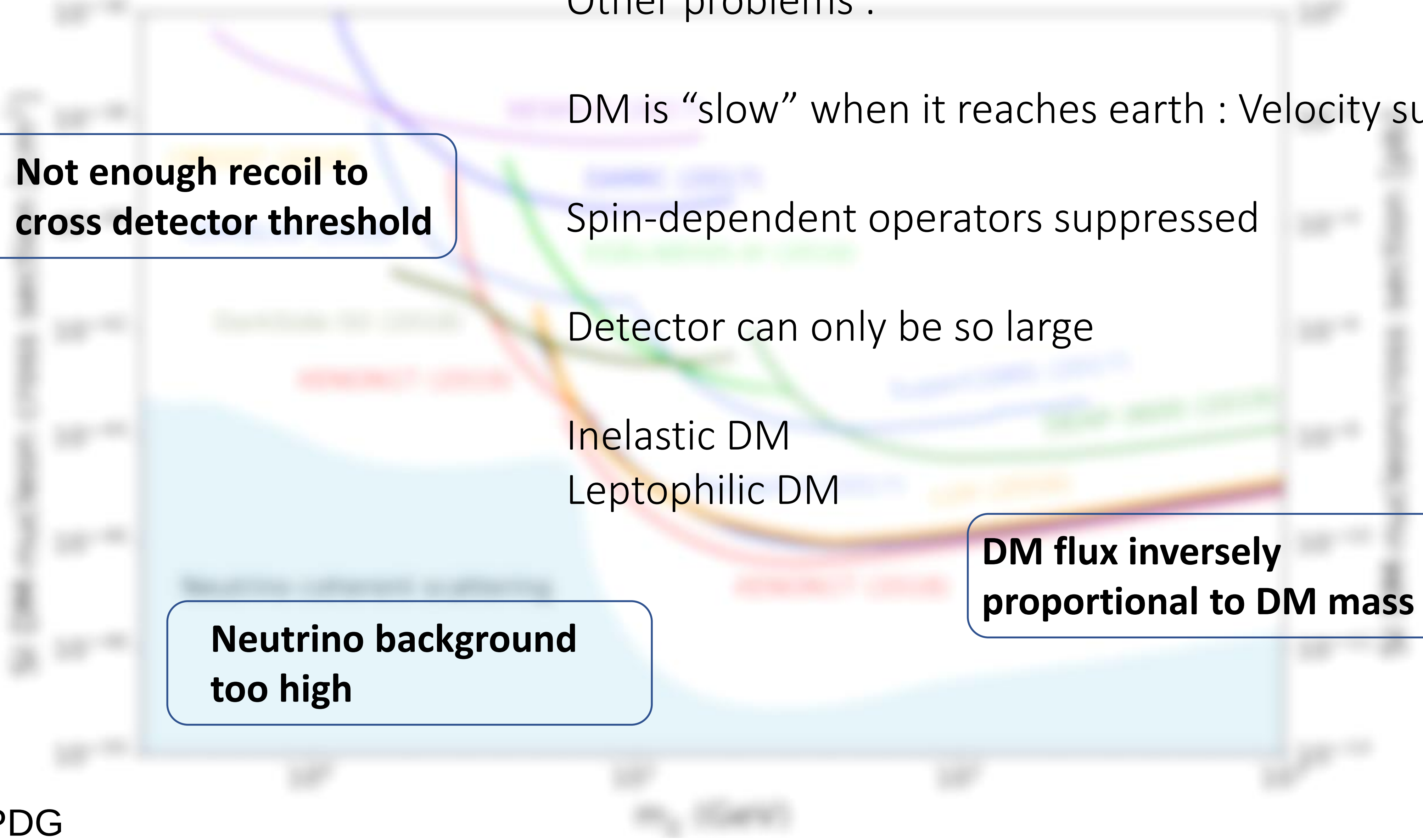


Image: PDG

Current Status



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

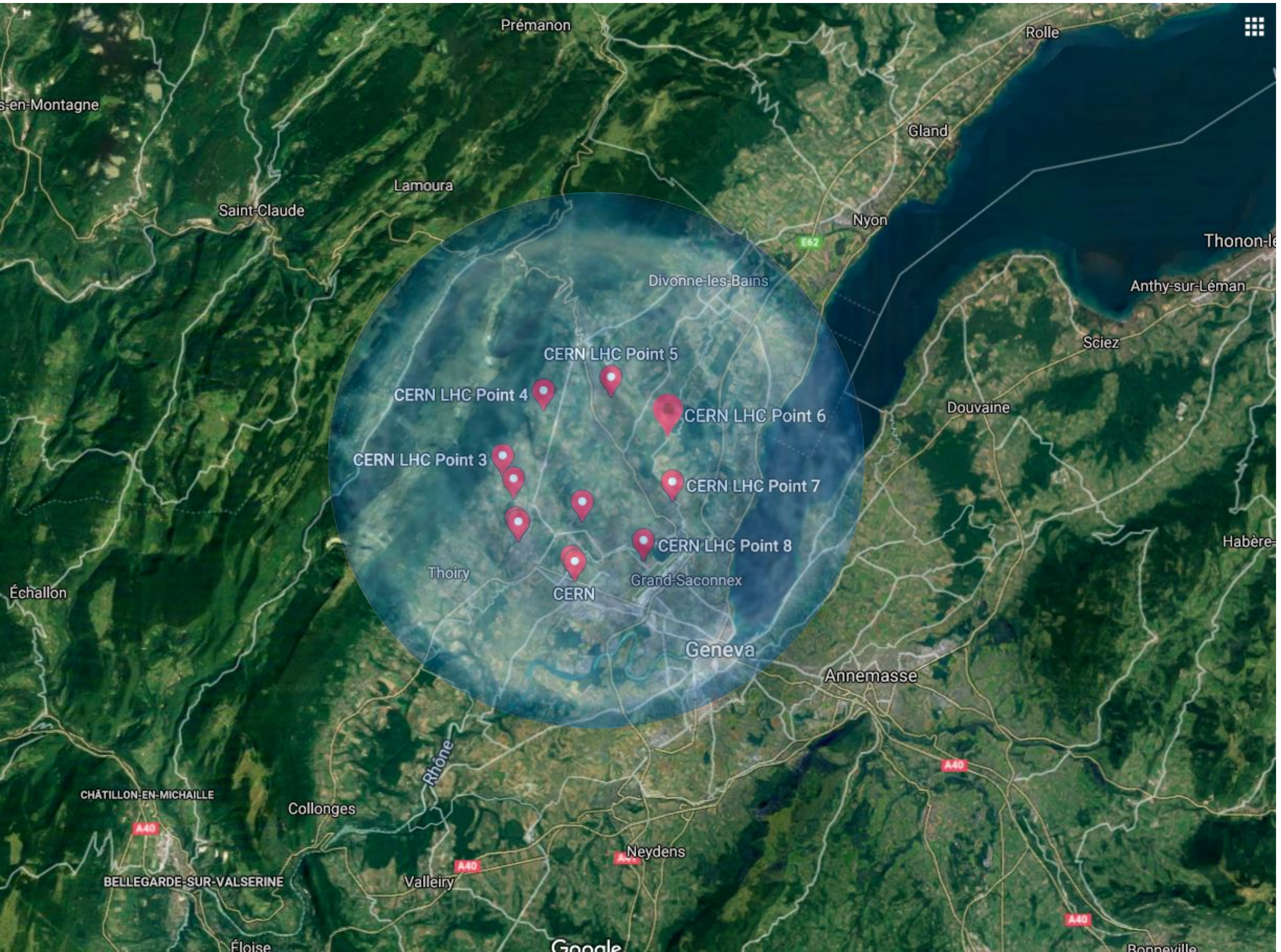
Neutrino background too high

DM flux inversely proportional to DM mass

Image: PDG

Neutron Stars

Neutron star : Dense, strong gravity



Typical Neutron star :

$$M_\star \sim 1.5\, M_\odot$$

$$R_\star \sim 10\,\mathrm{km}$$

Accelerates DM to high velocities

- Overcomes velocity suppression
- Can help to increase energy deposition

NS Kinetic Heating

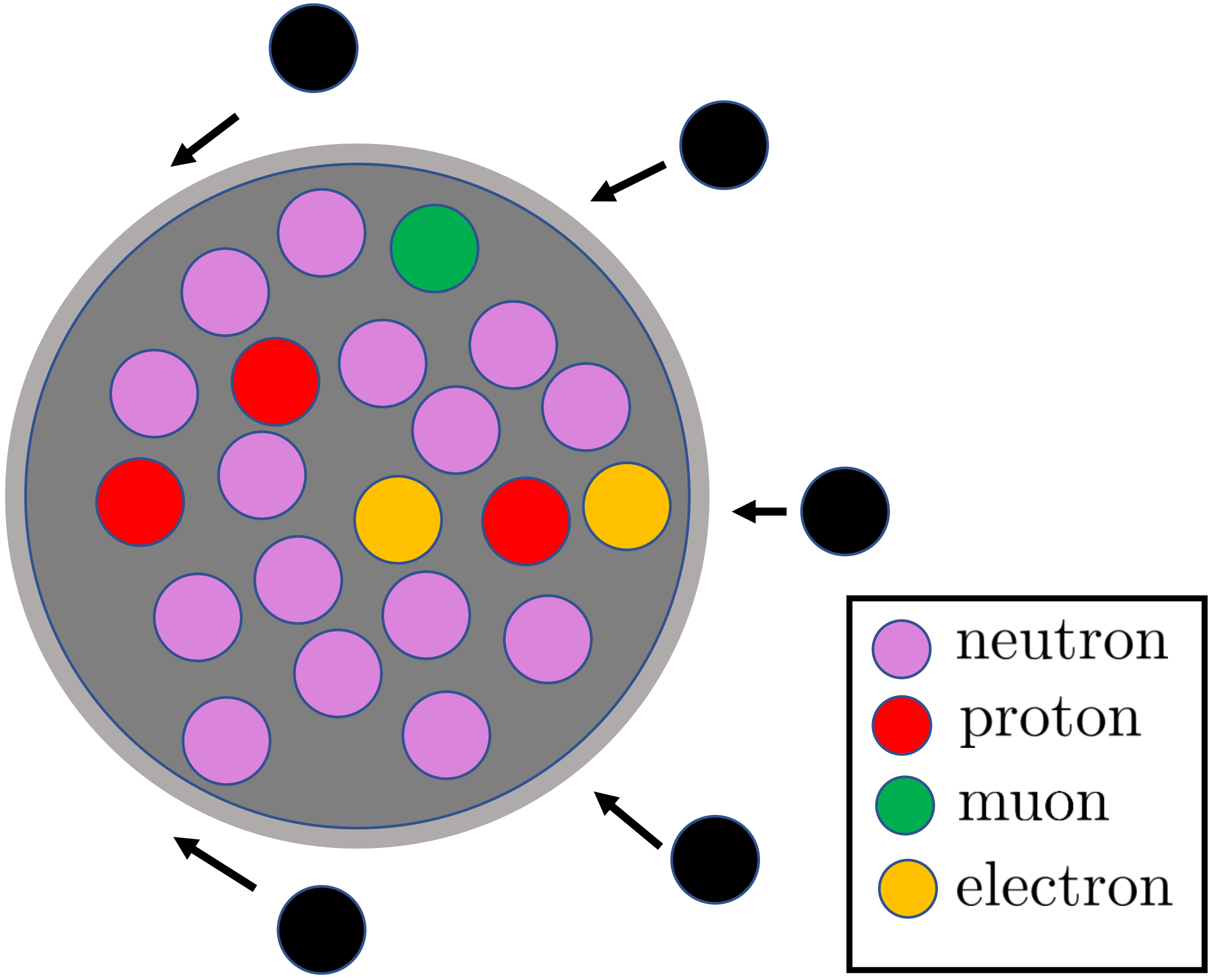
$$\text{Flux} = \pi b_{\text{max}}^2 v_{\text{halo}} \rho$$

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

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

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

Capture efficiency



NS Kinetic Heating

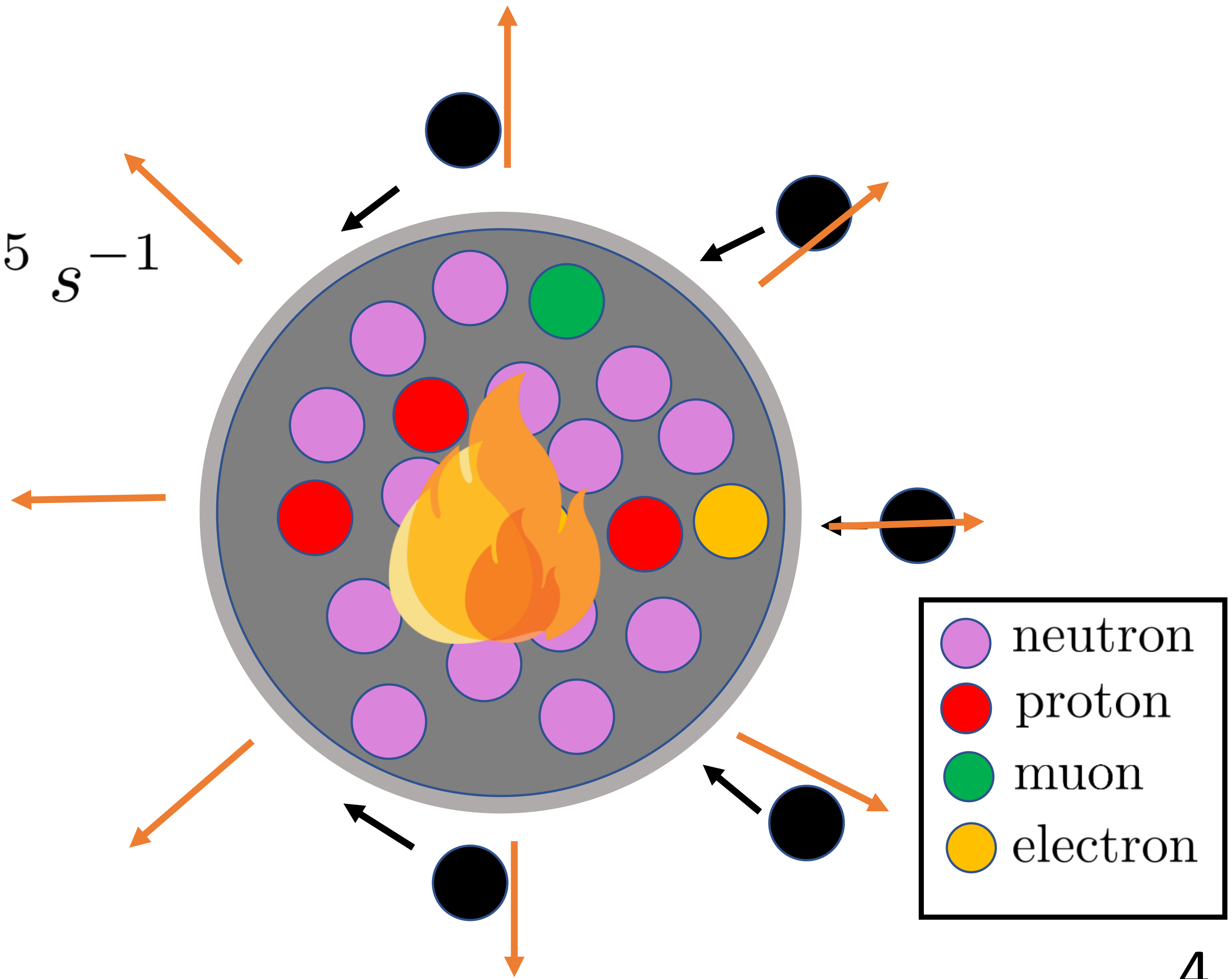
$$\gamma_{\text{esc}} \sim 1.35$$

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

Stephan-Boltzmann Law

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

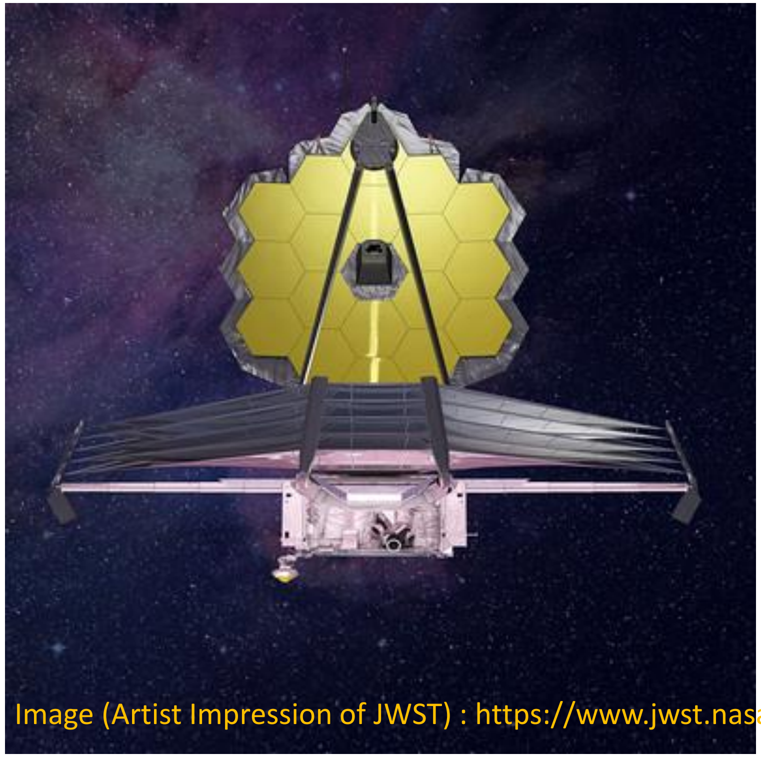
$$T \sim 1600 f^{1/4}\, K$$



How to Detect Heated NS?

FAST

New generation of radio telescopes can see an old neutron star with expected temperatures of O(10-100) K without DM



JWST

Upcoming infrared telescopes like JWST, TMT, ELT can see if it is heated to O(1000) K

Baryakhter, Bramante, Li, Linden, Raj 1704.01577 *Phys.Rev.Lett.* 119 (2017) 13, 131801

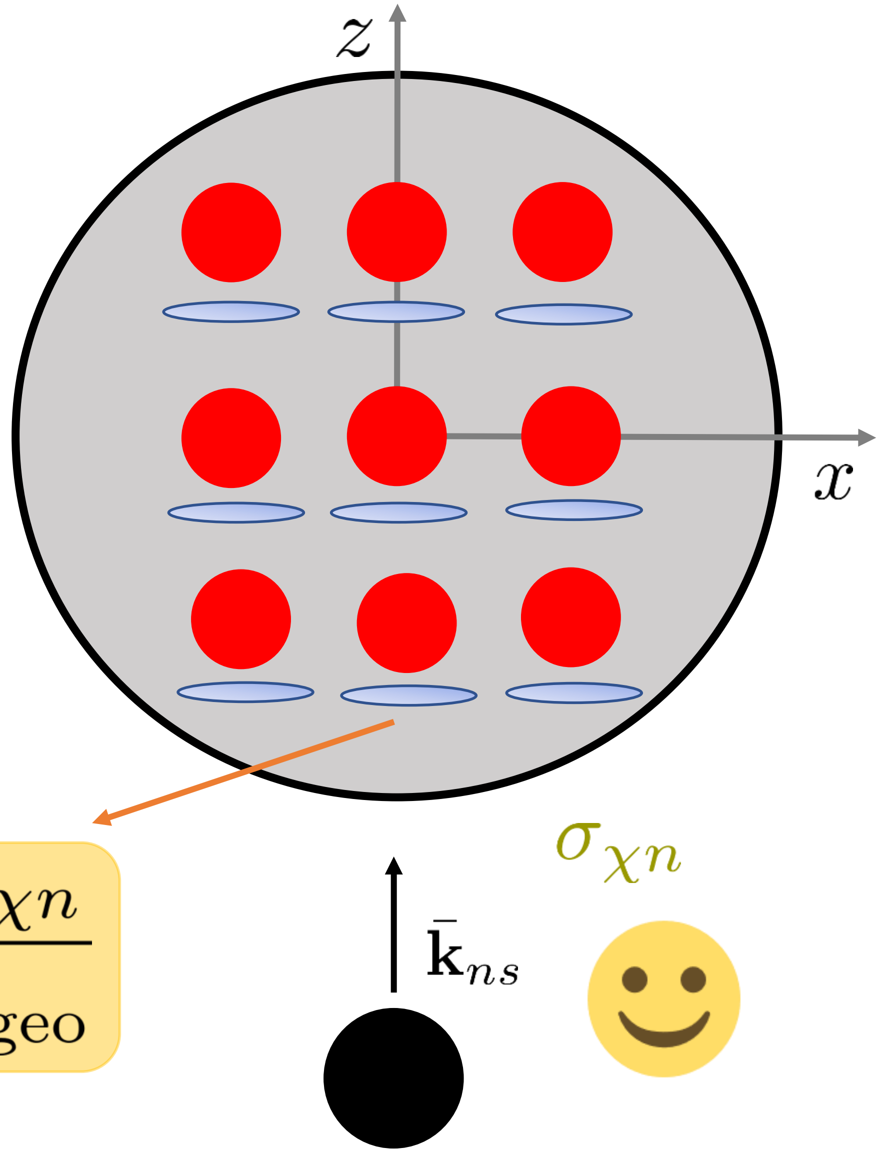
How Efficient is the Capture?

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

For non relativistic targets

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

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



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

Baryakhter, Bramante, Li, Linden, Raj *Phys.Rev.Lett.* 119 (2017) 13, 131801
Raj, Tanedo, Yu *Phys.Rev.D* 97 (2018) 4, 043006

Electrons in Neutron Stars

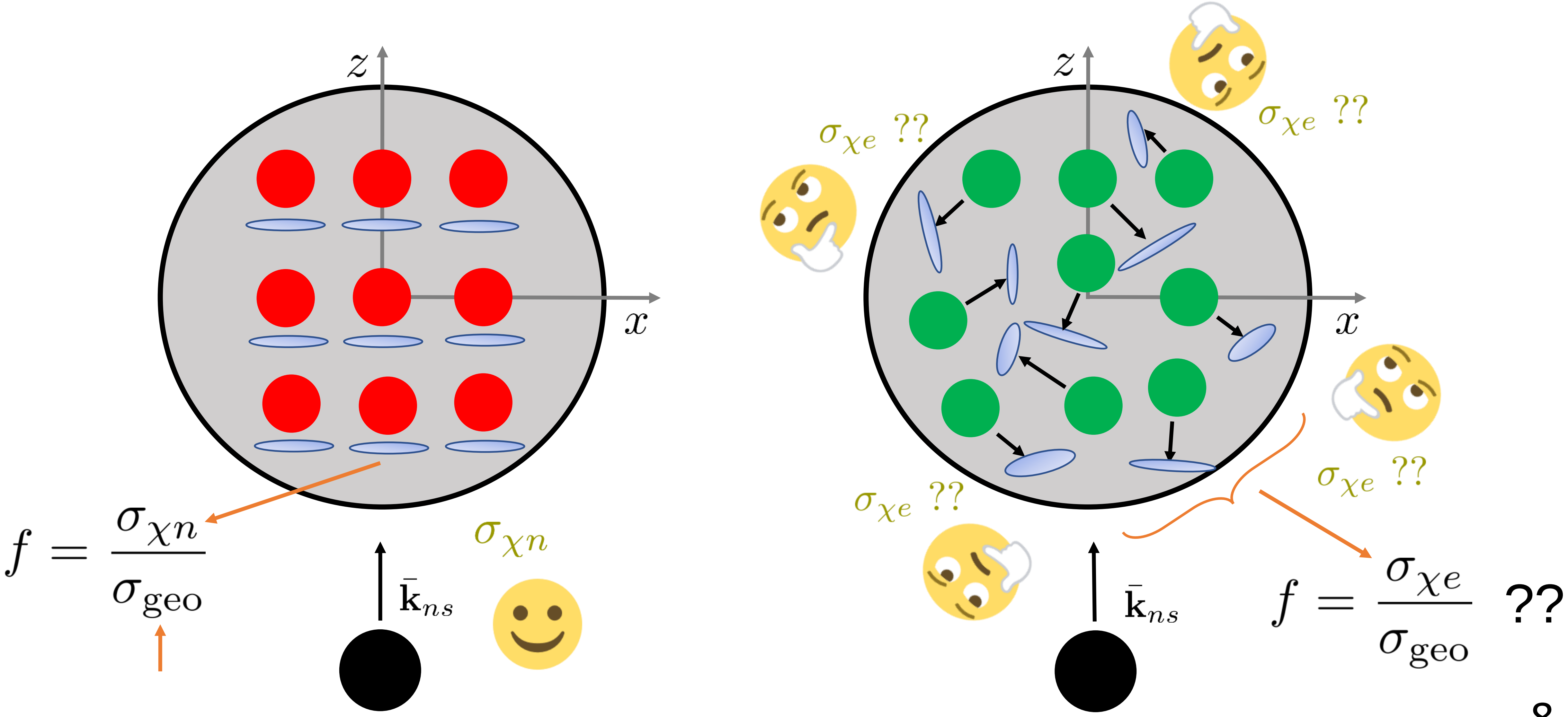
Leptons are present in a neutron star (mainly electrons)

About 5-10% by number as per EoS studies

Can help with detecting leptophilic, electrophilic DM that are elusive for terrestrial direct detection

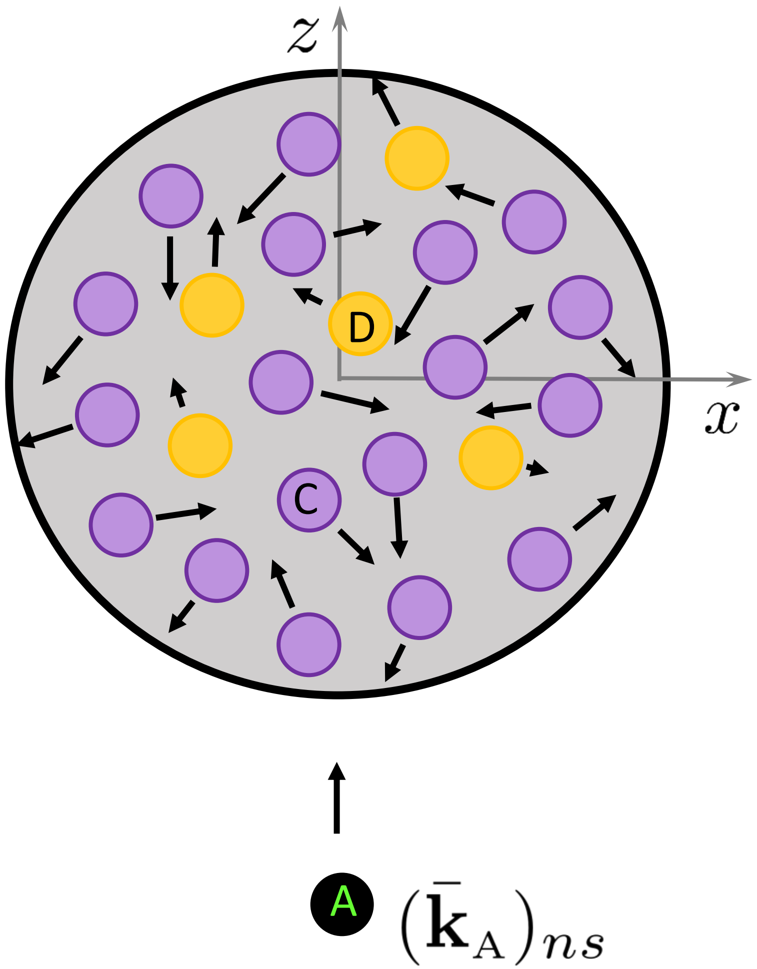
Ultra-relativistic as Fermi energy ~ 150 MeV. Makes efficiency computation challenging

Relativistic Capture Efficiency

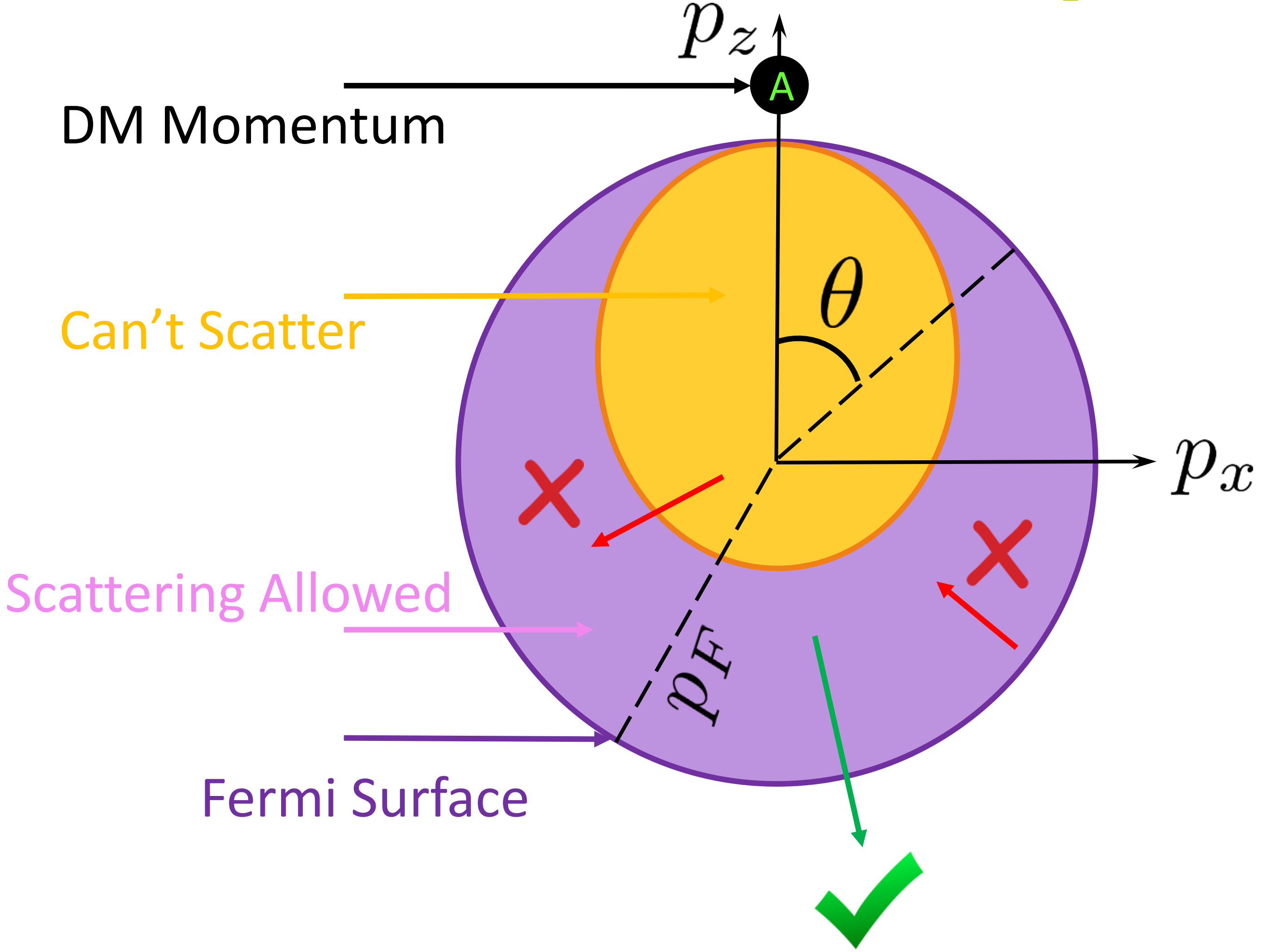


Pauli Blocking

NS Frame: Position Space



NS Frame: Momentum Space

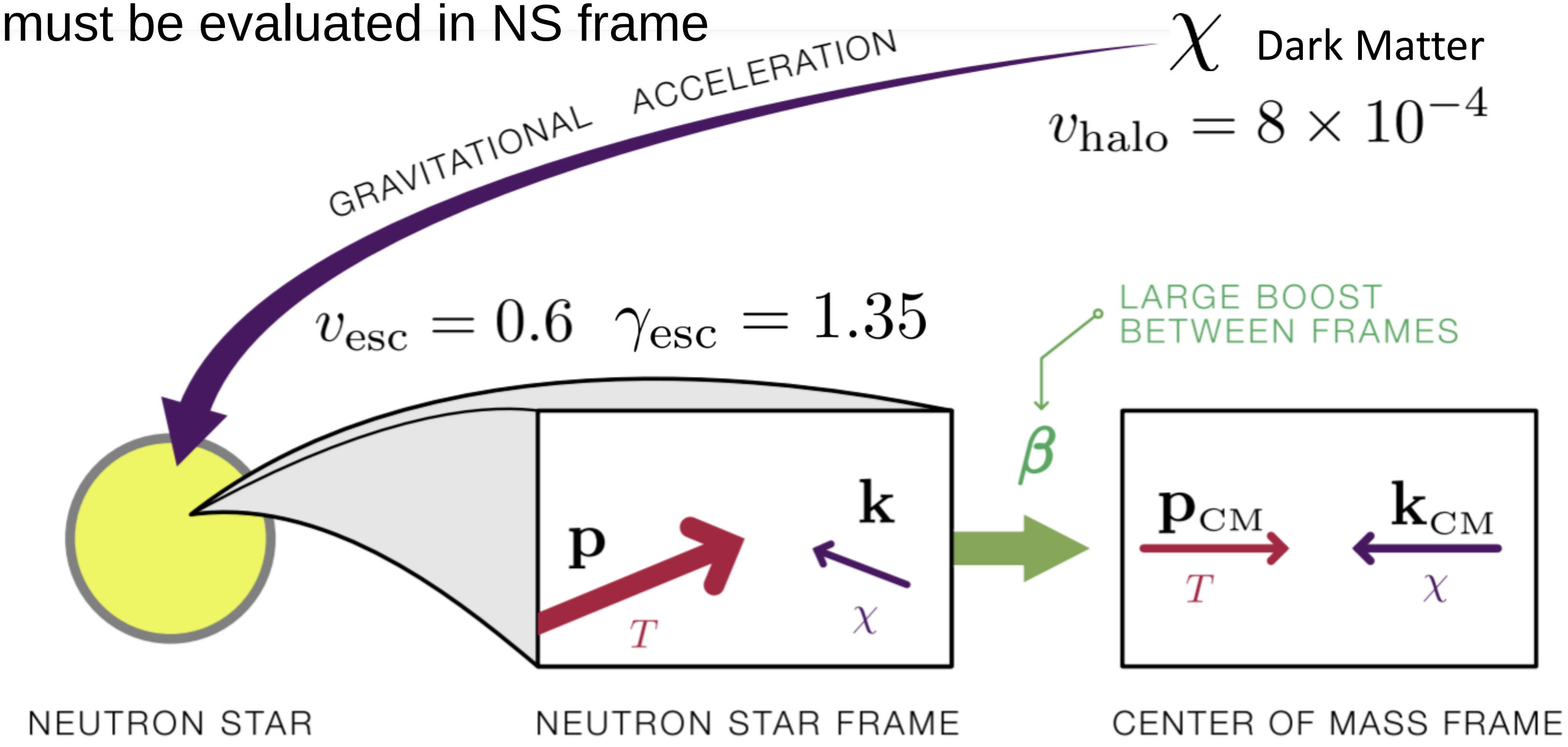


Frames, Moving Parts

Momentum distribution of particles best given in NS frame

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

Total KE deposited must be evaluated in NS frame



f needs to be frame invariant

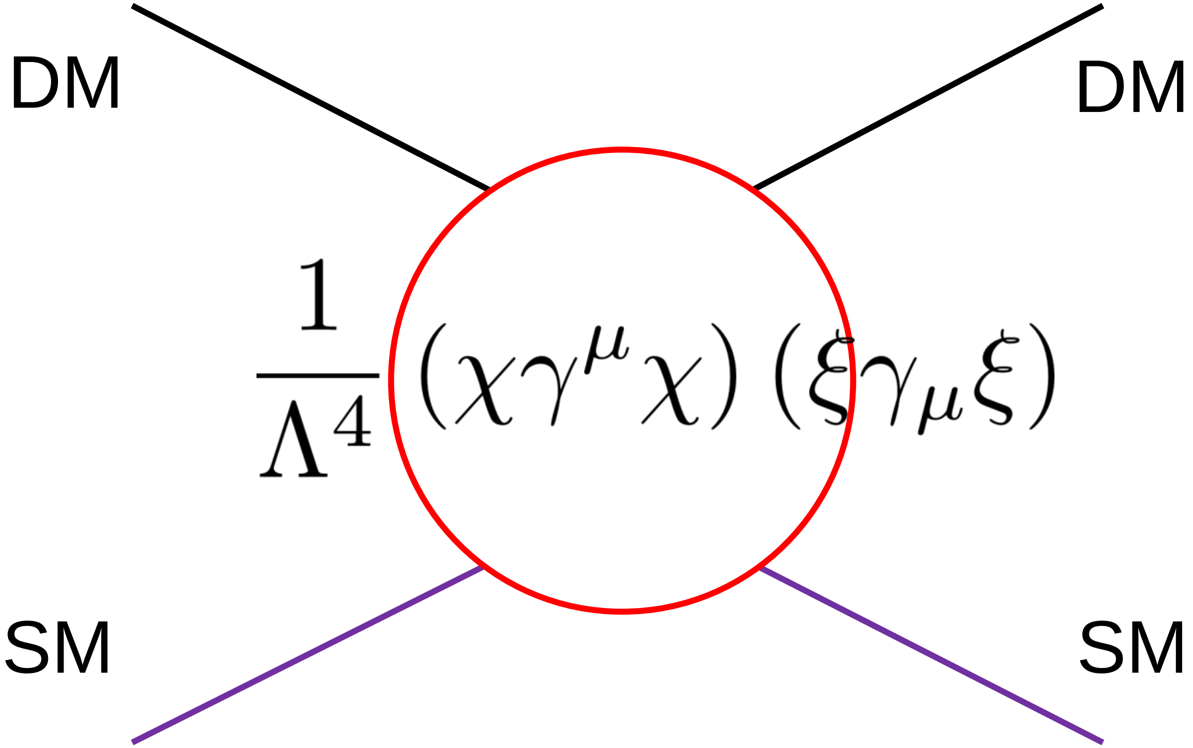
Formalism

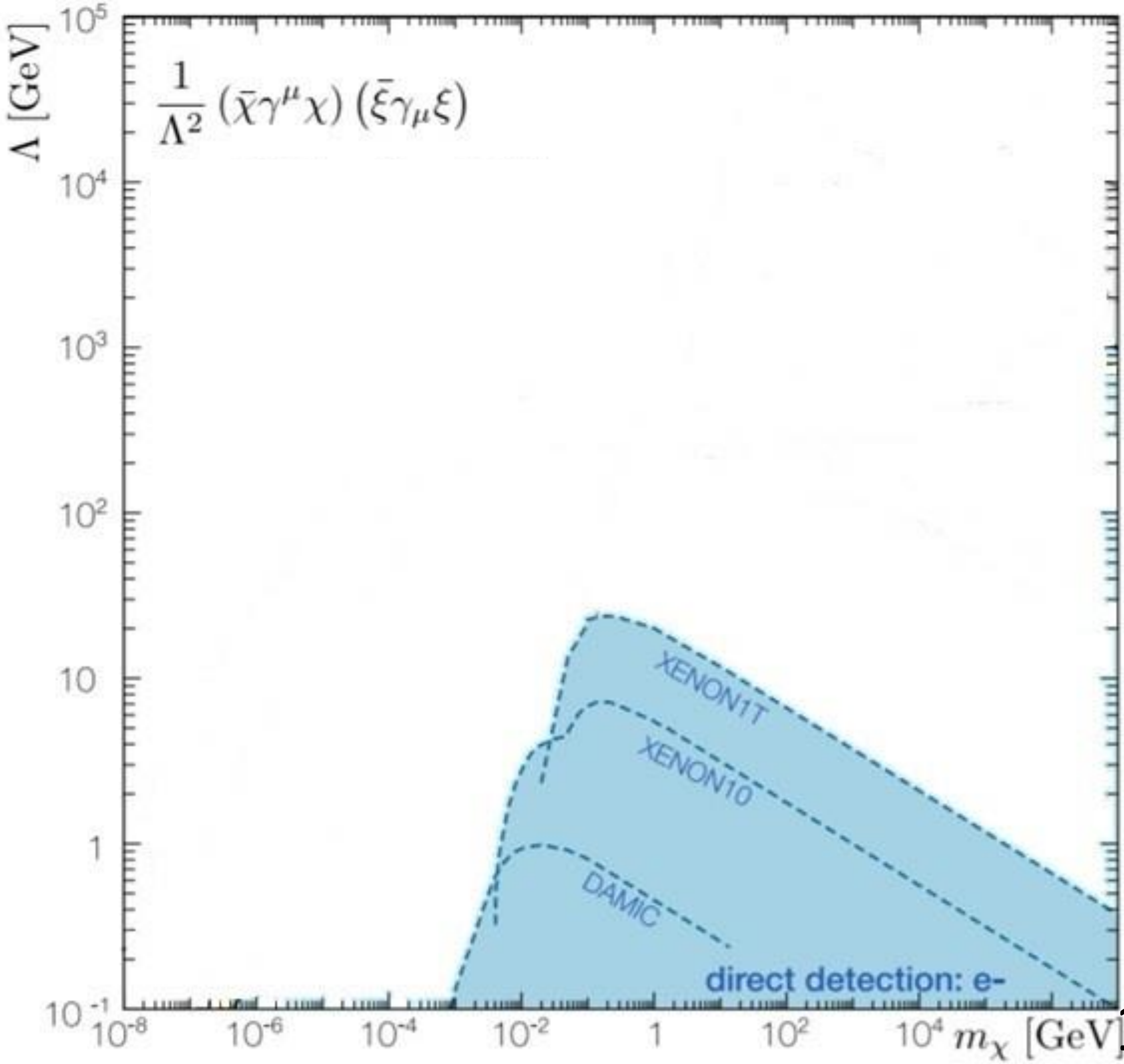
$$df = \sum_{\mathrm{N_{hit}}} \frac{1}{N_{\rm hit}} d\Omega_{\rm CM} \left(\frac{d\sigma}{d\Omega}\right)_{\rm CM} (v_{\rm mol}\, dn_{\rm T} \Delta t)_{\rm NS}$$

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

$$\times \Theta\left(\Delta E + E_p - E_{\rm F}\right)$$ Pauli Blocking Condition

Terrestrial DD Reach for Leptophilic DM





NS Reach for Leptophilic DM

$f \propto |\mathcal{M}|^2 \propto \frac{1}{\Lambda^4}$; Recall : $T \sim 1600\, f^{1/4}\, \mathrm{K}$ $T \propto \Lambda^{-1}$

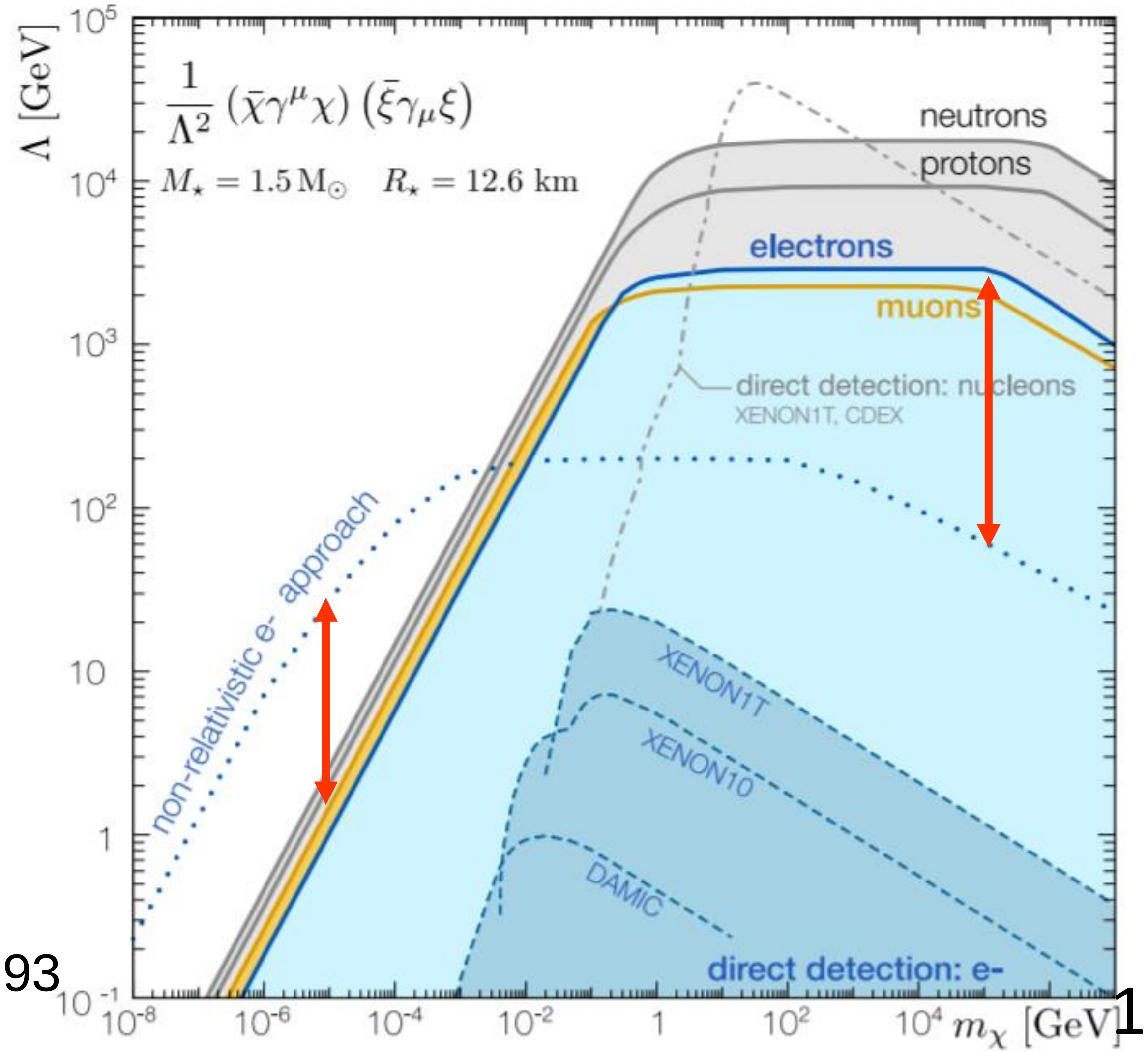
Electron reach ~ 1-2 orders powerful wrt non-rel. for DM mass > 1 GeV

~ 5- 8 orders in capture rate !!

Suppression in reach wrt non-rel. for light DM by an order ~ 4 orders in capture rate

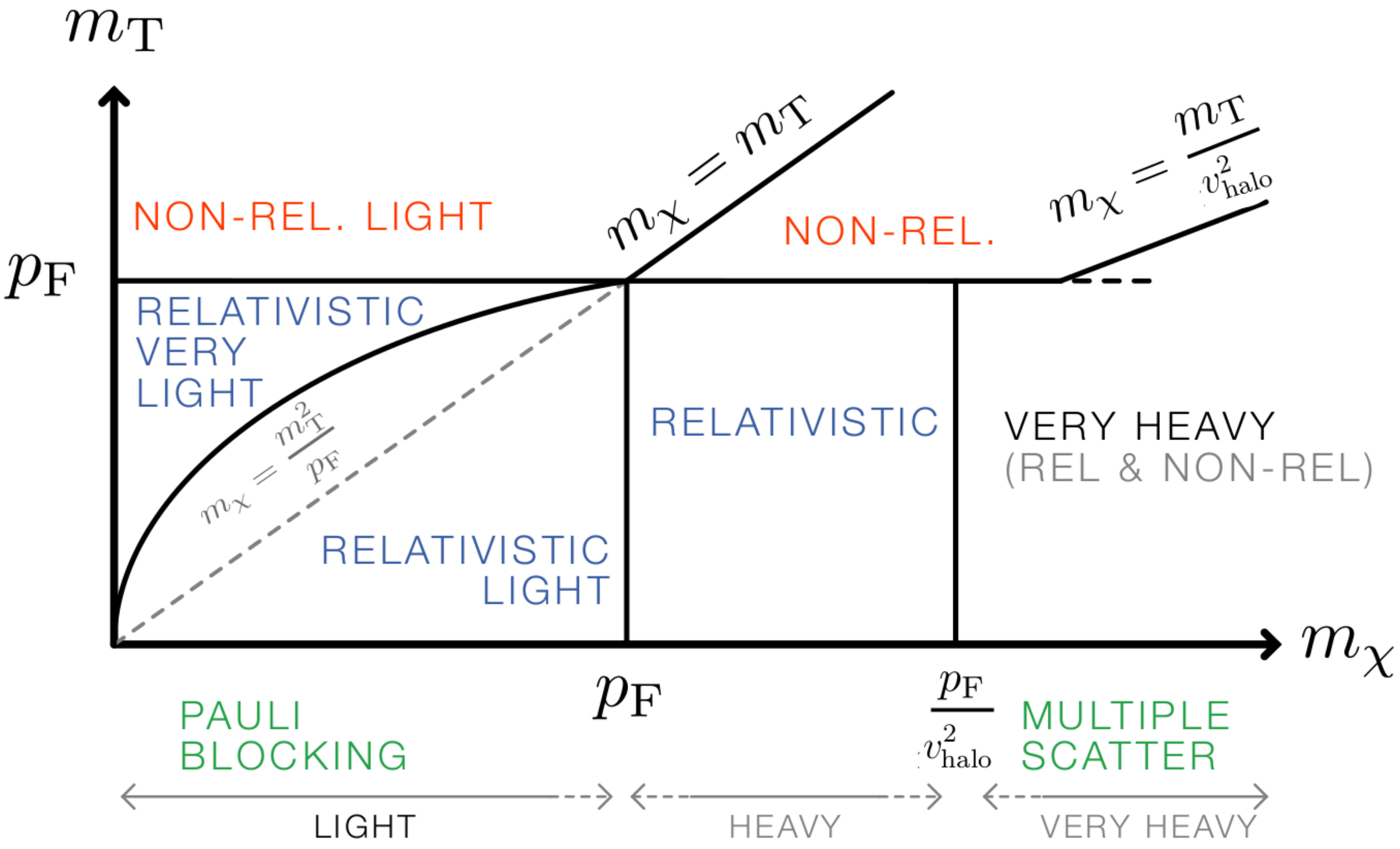
Beats DD bounds by many orders

Close to neutron bounds



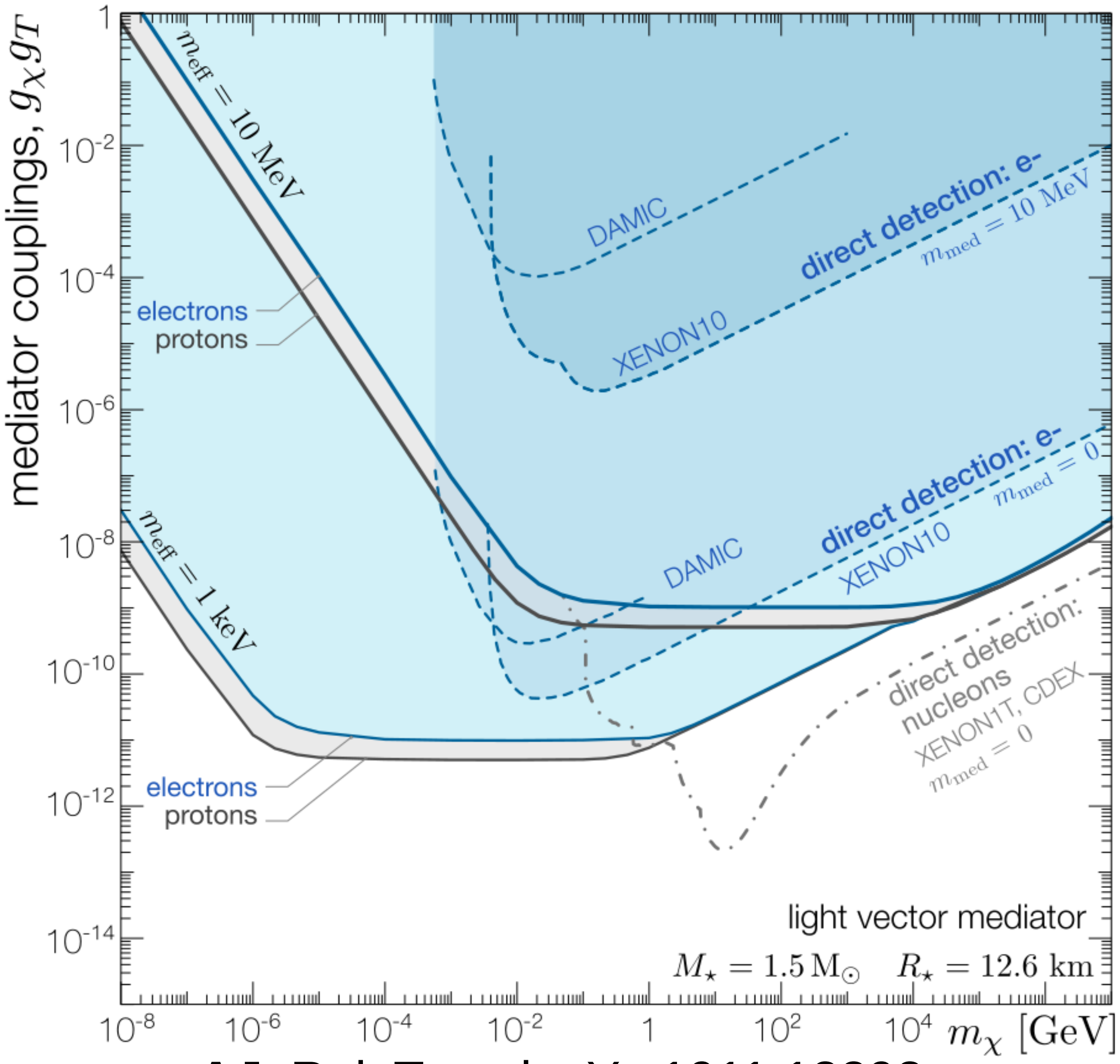
AJ, Raj, Tanedo, Yu 1911.13293
Phys.Lett. B (2020) 135767

Phase Space of Scattering



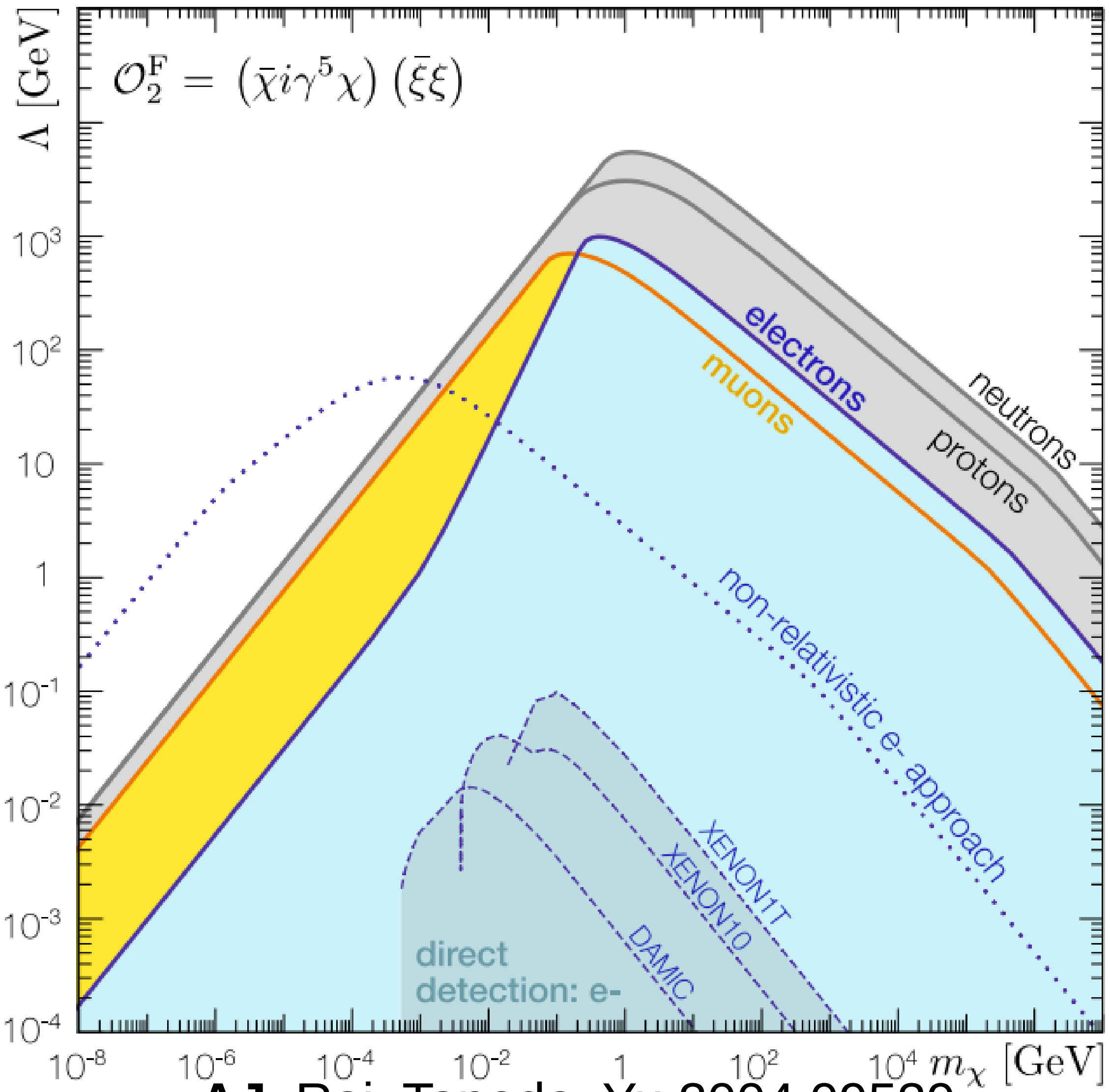
AJ, Raj, Tanedo, Yu 2004.09539 *Phys.Rev.D* 102 (2020) 12, 123002

Light Mediator



AJ, Raj, Tanedo, Yu 1911.13293
Phys.Lett. B (2020) 135767

P-S Operator



AJ, Raj, Tanedo, Yu 2004.09539
Phys.Rev.D 102 (2020) 12, 123002

Summary

Search for NS kinetic heating can nicely complement existing terrestrial direct detection program. Advantages in various mass ranges especially for leptophilic DM are large.

Electrons in NS can be a powerful probe. New relativistic formalism is needed.

Bounds almost as strong as neutrons!

Fermi energy for relativistic targets serves the role of target mass in non-relativistic case.