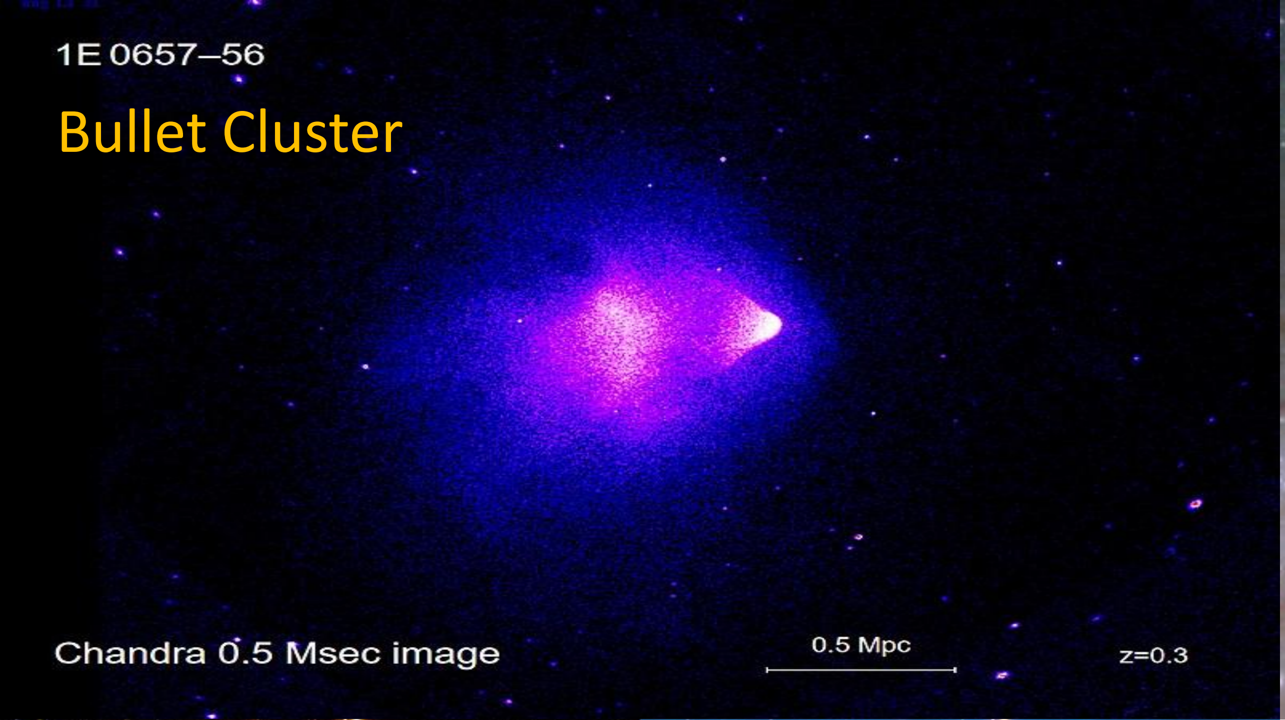
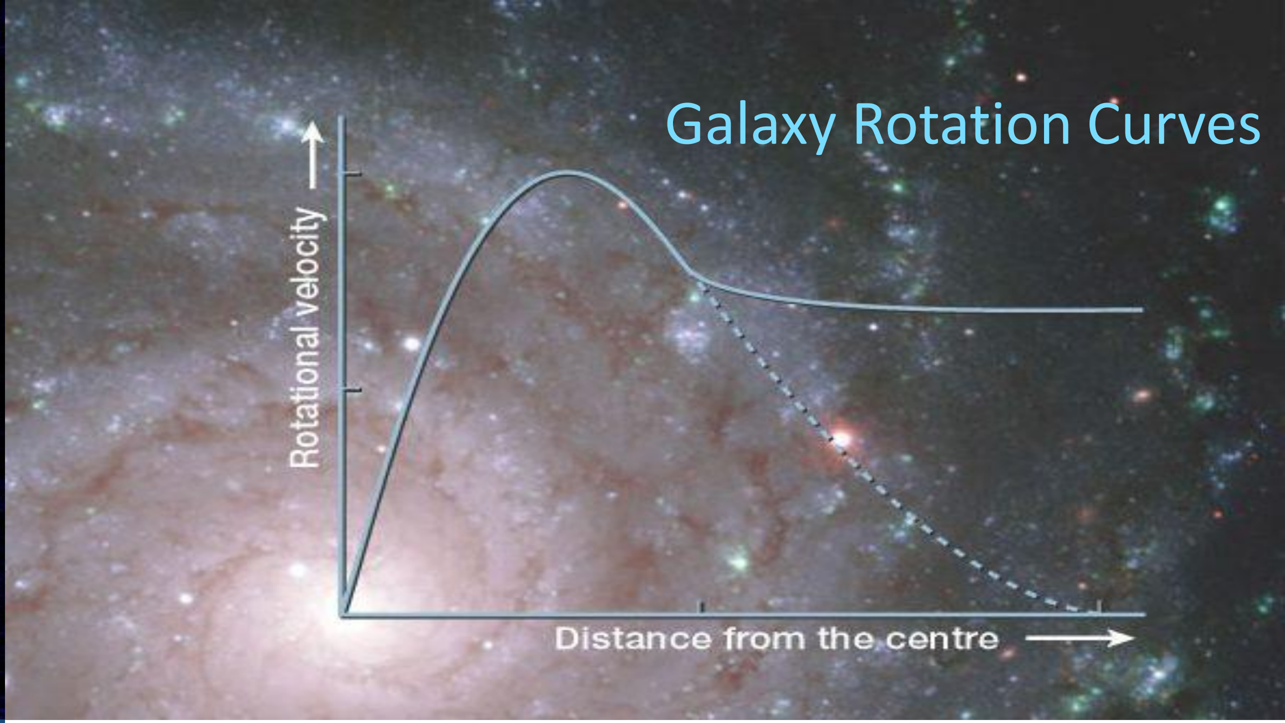
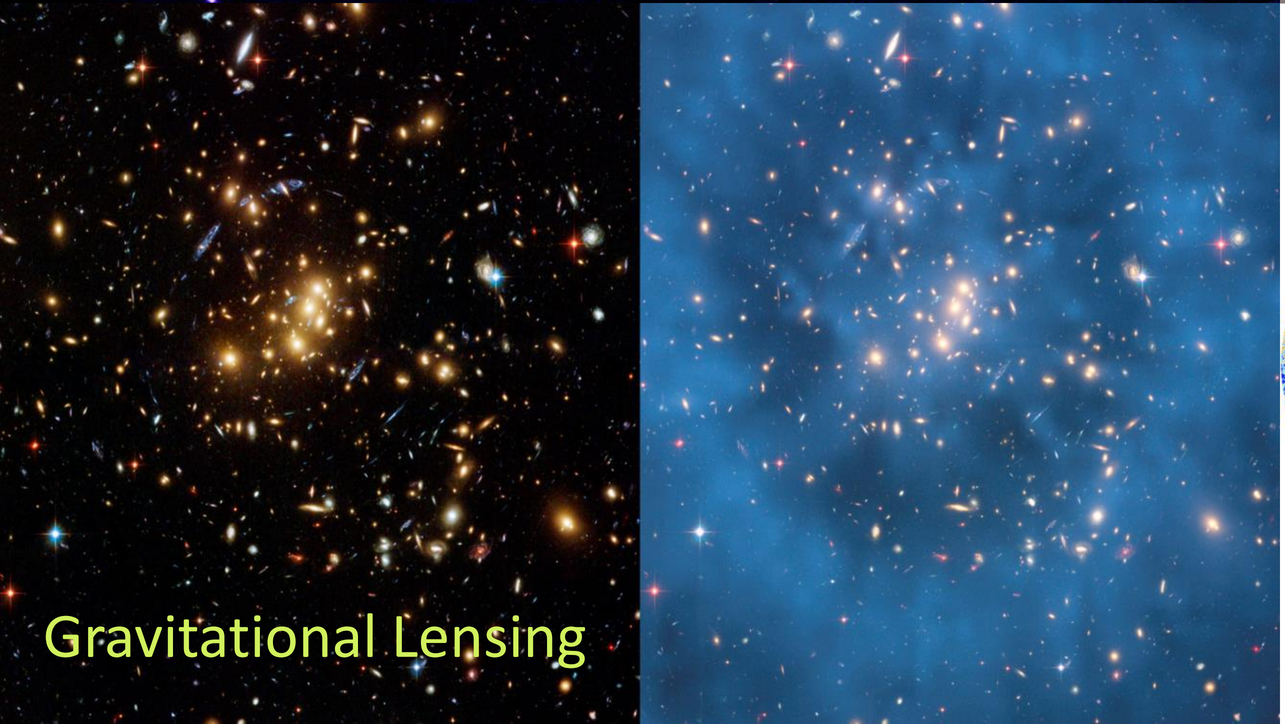
Neutron Stars as Dark Matter Labs

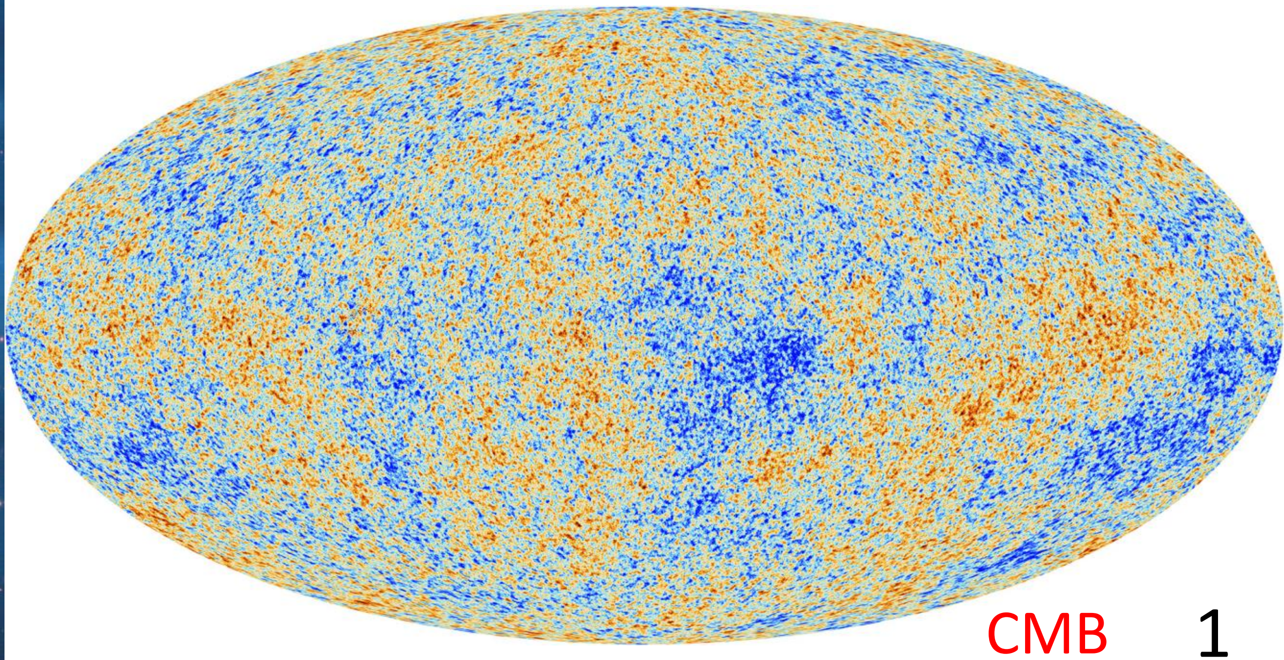
Aniket Joglekar

CPTGA Workshop Annecy
27 September 2021


1E 0657–56
Bullet Cluster
Chandra 0.5 Msec image
0.5 Mpc
z=0.3


Galaxy Rotation Curves
Rotational velocity
Distance from the centre


Gravitational Lensing

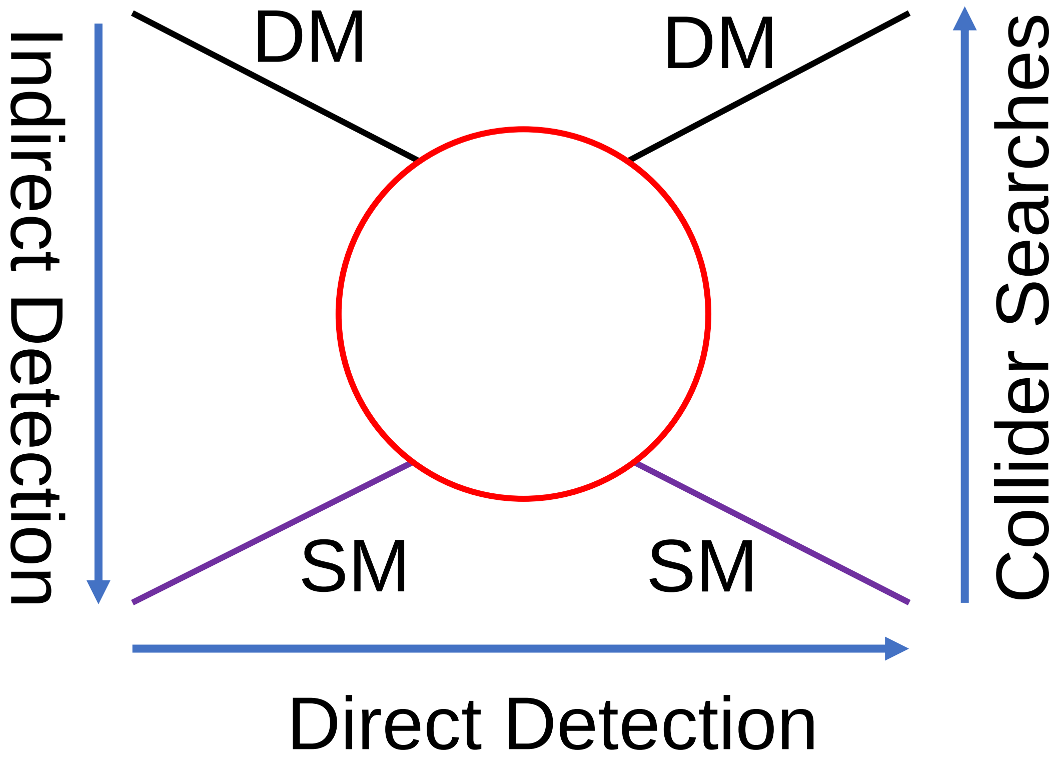

CMB

How to Probe the Nature of Dark Matter?

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

For this talk, the focus will be on the DM + SM ⟶ DM + SM interactions

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



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..

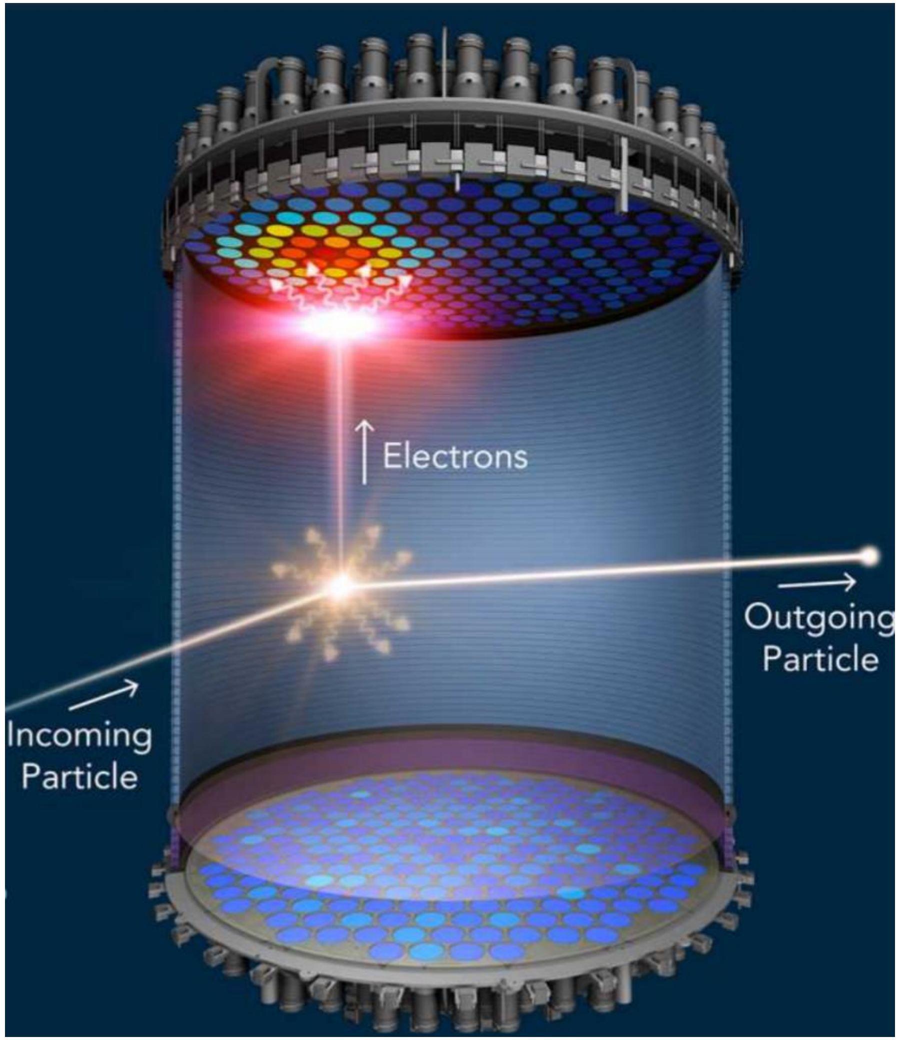


Image: Lux-LZ

Current Status

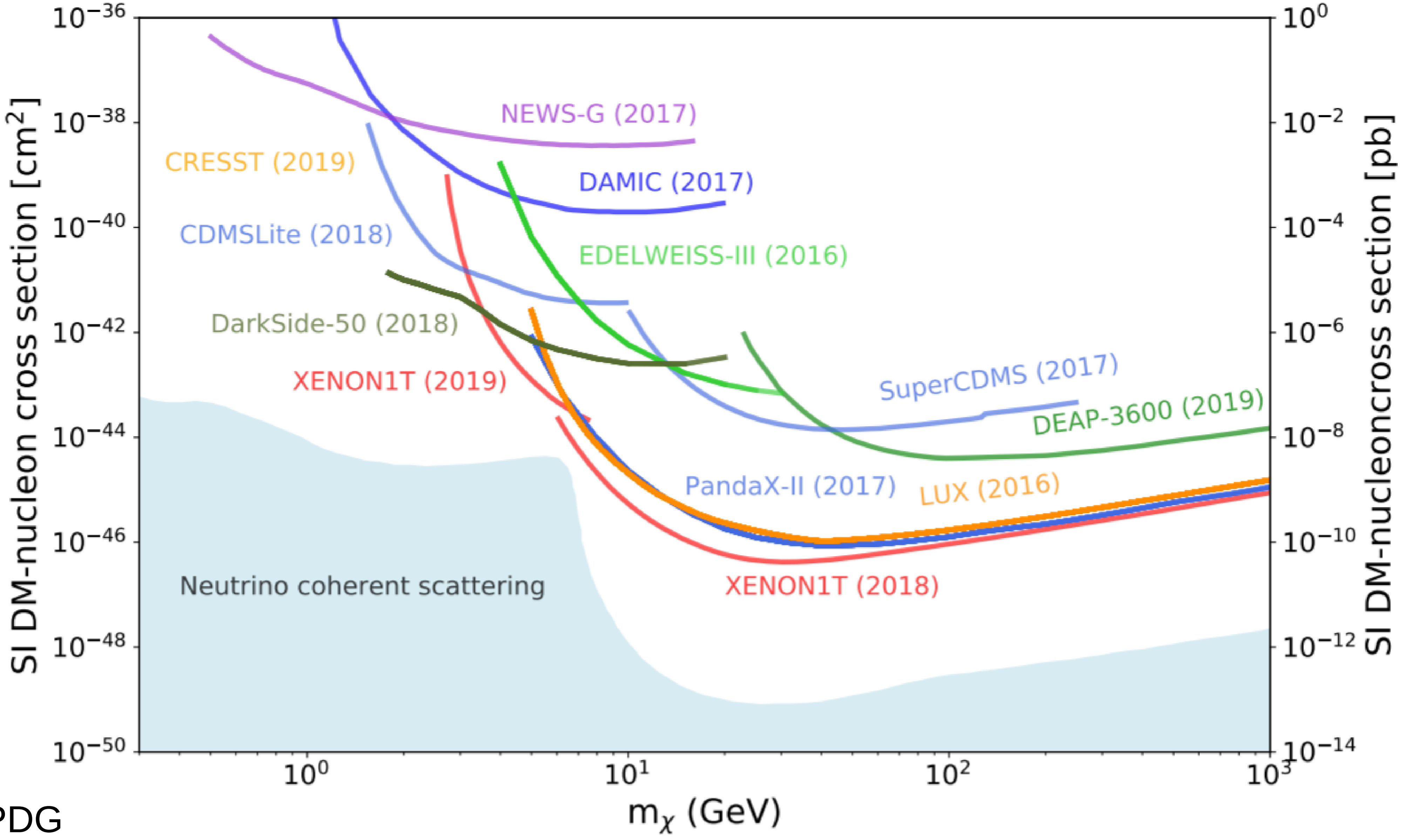
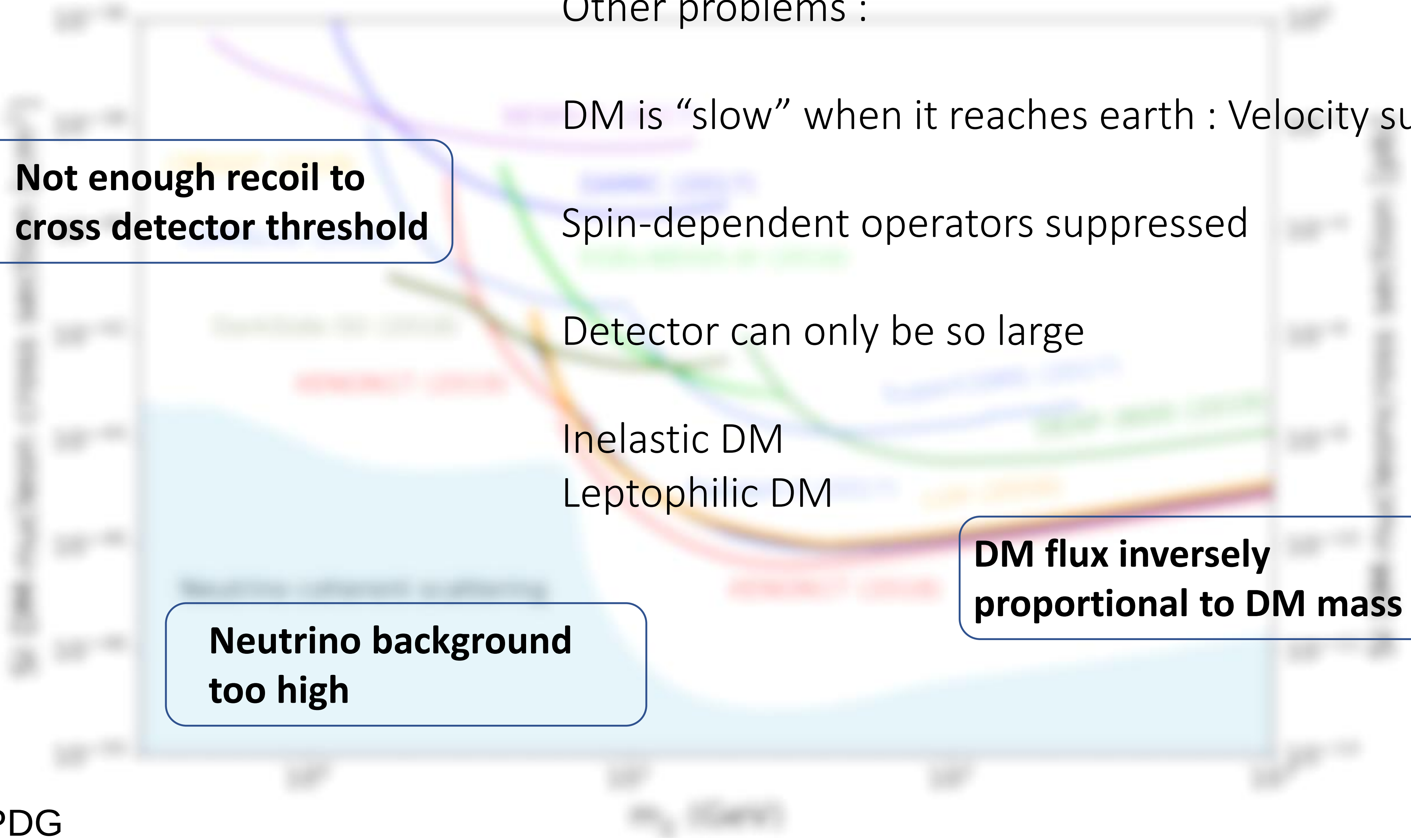


Image: PDG

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

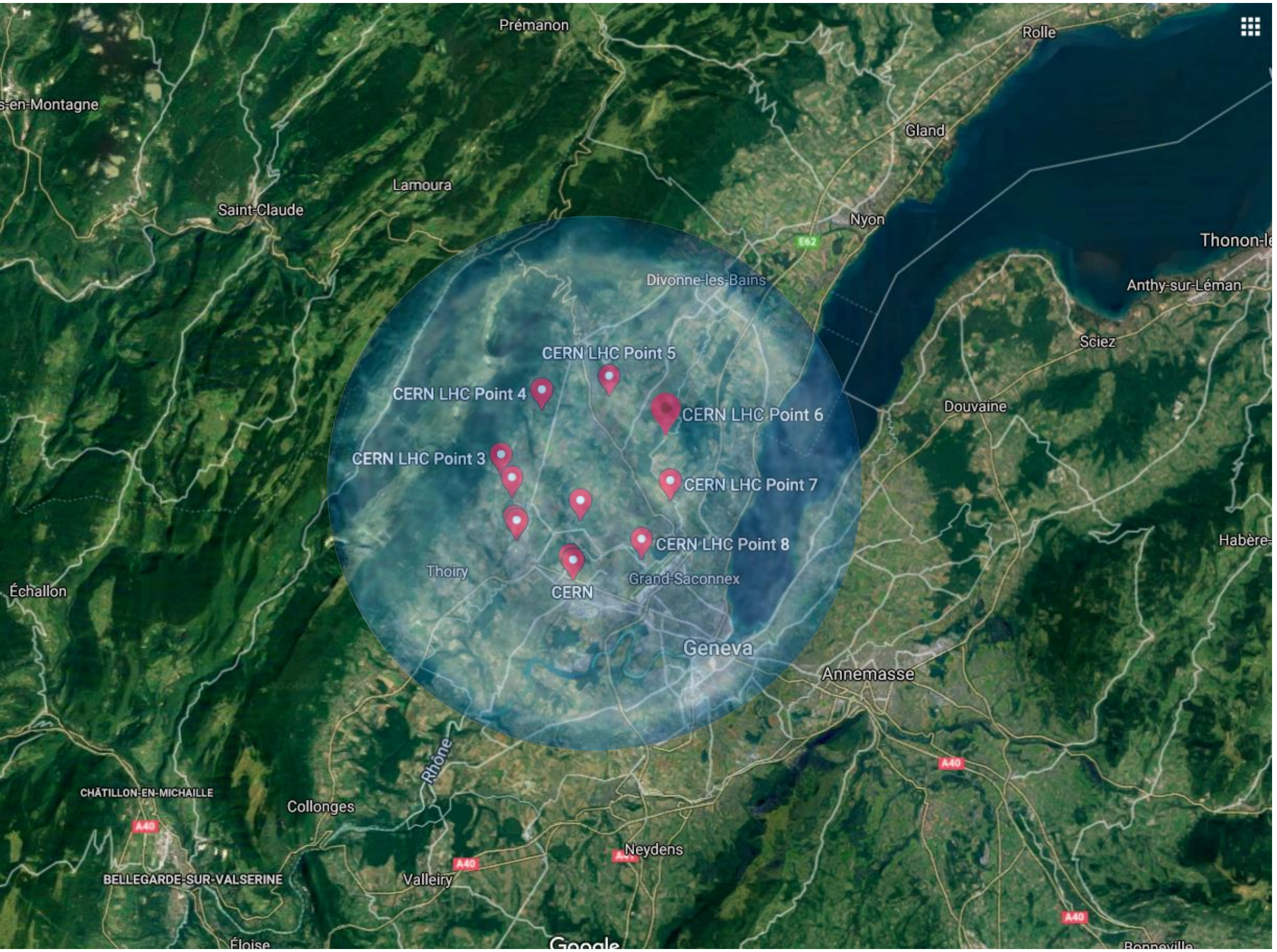
Not enough recoil to cross detector threshold

Neutrino background too high

DM flux inversely proportional to DM mass

Image: PDG

What We Want?



Something very dense

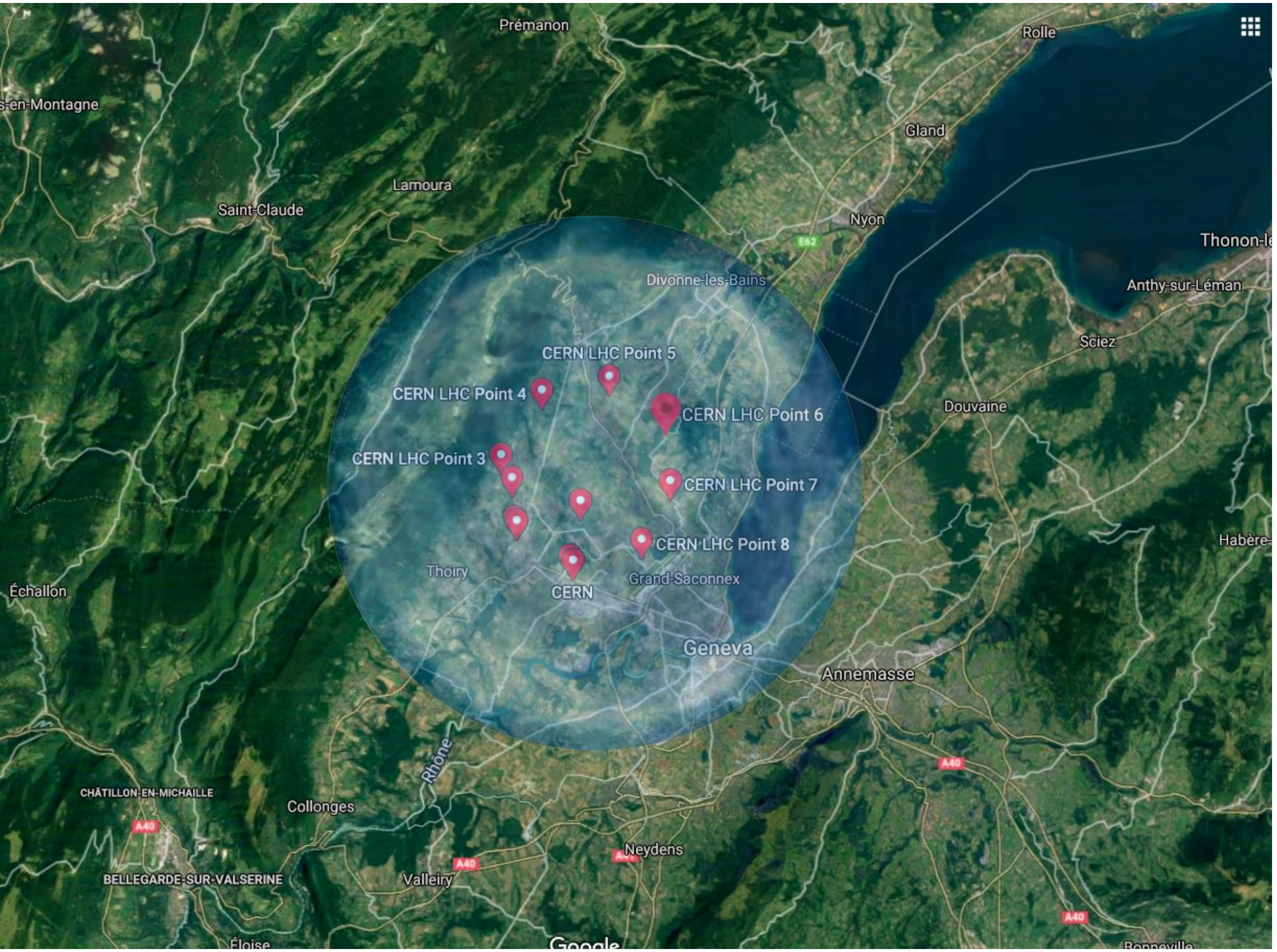
With lots of targets

Accelerates DM to relativistic speeds

Has large surface/ catchment area

Celestial Bodies??

What We Want?



Typical Neutron star :

$$M_\star = 1.5\, M_\odot$$
$$R_\star = 12.6\, \mathrm{km}$$

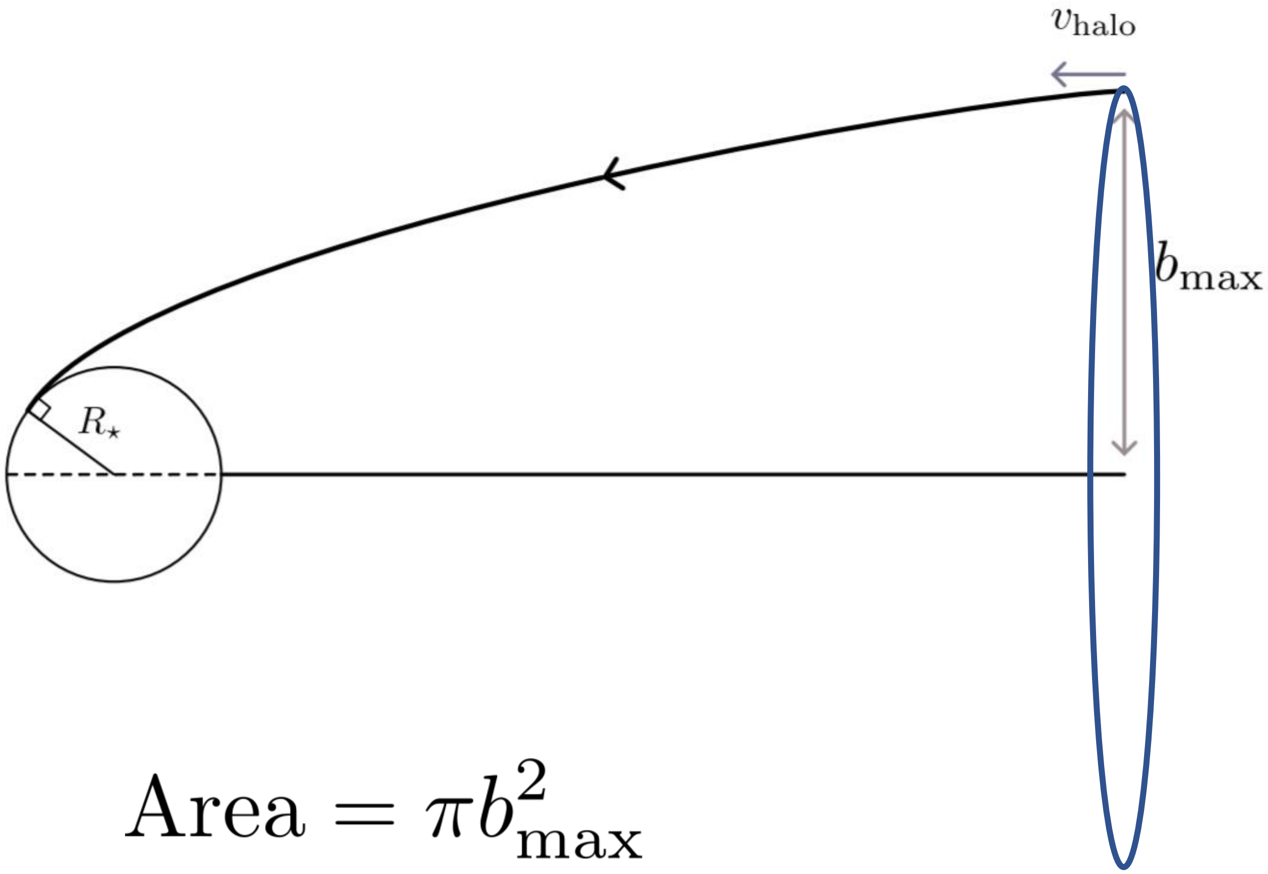
$\sim 5 \times 10^{57}$ Targets

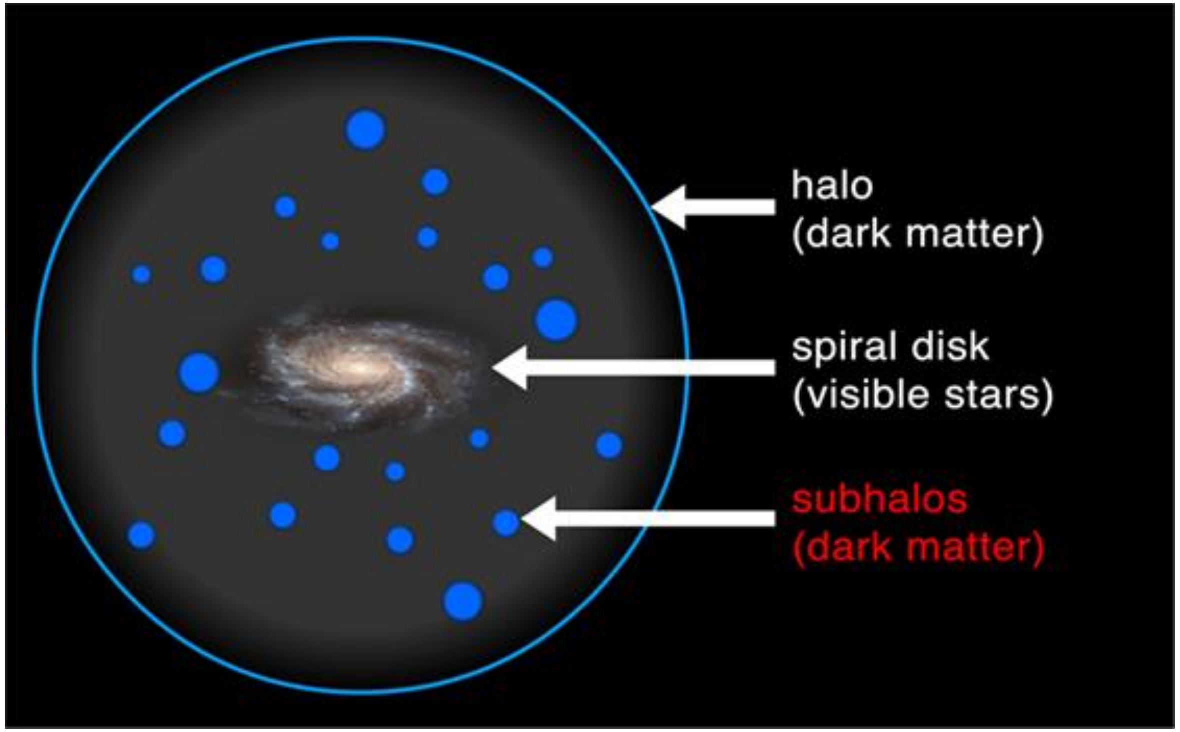
Densely Packed

Accelerates DM to $v \sim 0.6\, c$

Flux

Continuous dark matter flux incident on the NS





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

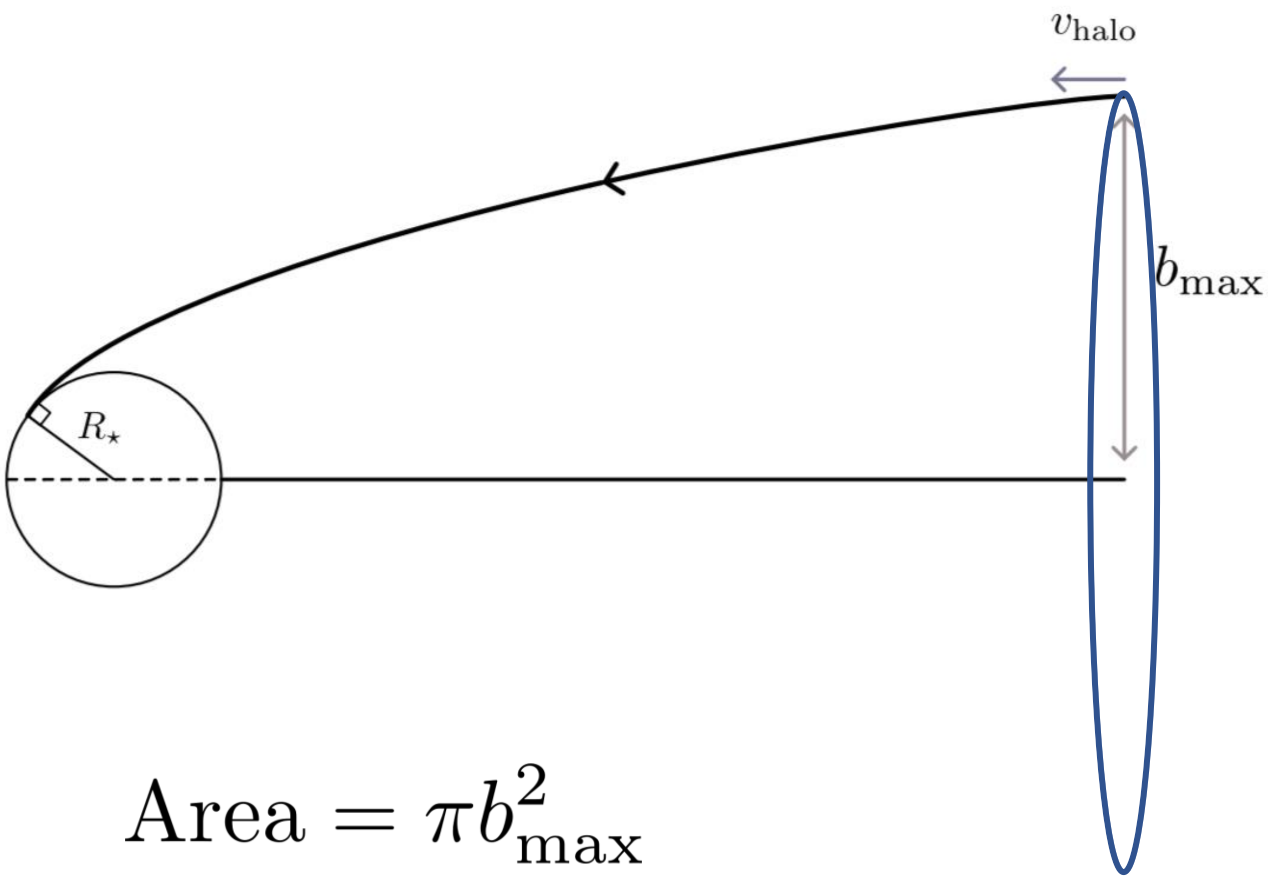
$$v_{\rm halo} = 8 \times 10^{-4},\ \rho_\chi = 0.3\ \text{GeV/cc}$$

$$M_\star = 1.5\, M_\odot,\ R_\star = 12.6\,\text{km}$$

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

Flux

Continuous dark matter flux incident on the NS



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

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 :

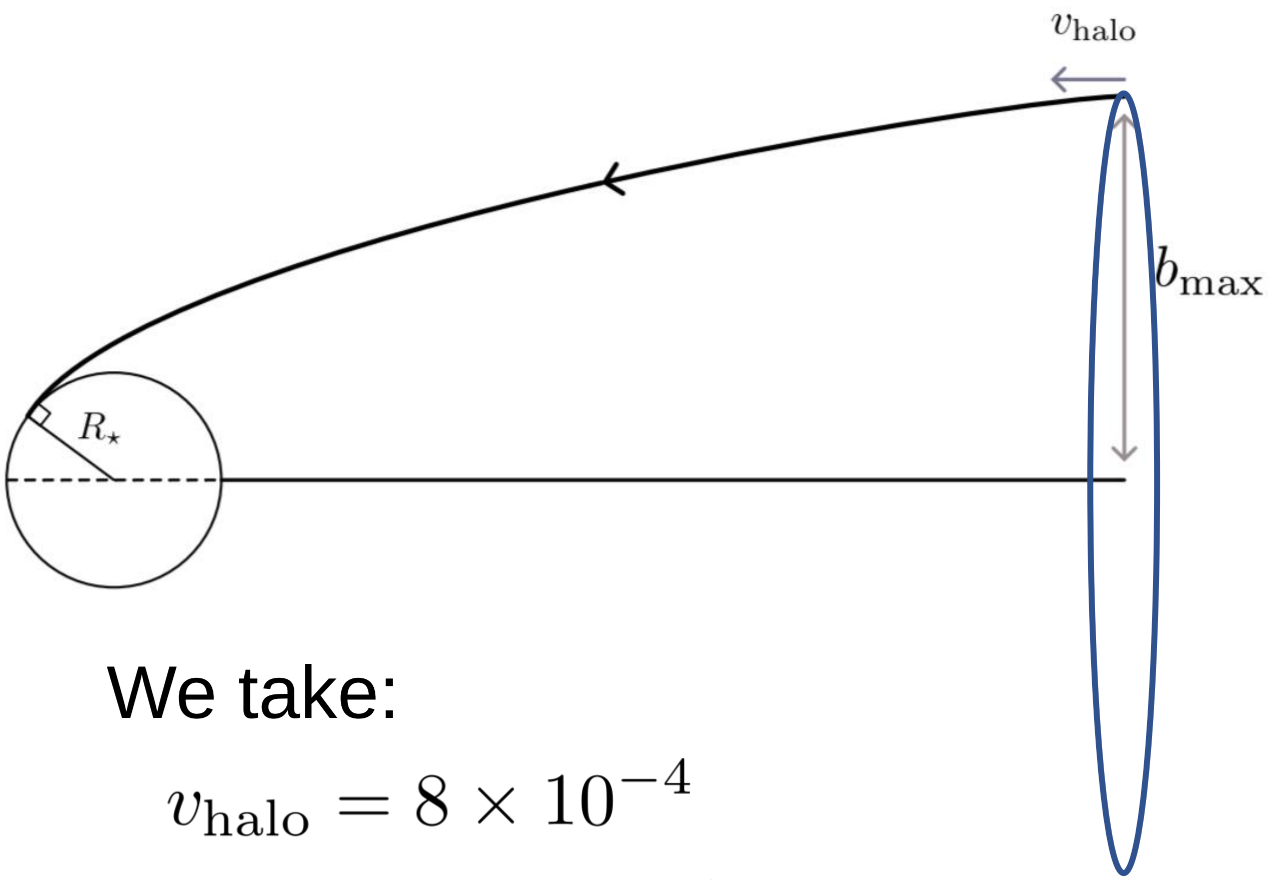
$$b_{\rm max} = \frac{R_\star}{v_{\rm halo}} \sqrt{\frac{2GM}{R}} \left(1 - \frac{2GM}{R}\right)^{-1/2}$$

$$\frac{2GM_\star}{R_\star} \sim 0.35 \qquad b_{\rm max} \sim 10^3\, R_\star$$

DM Flux is : $\pi b_{\rm max}^2 \rho_\chi v_{\rm halo}$

How Does the Capture 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:

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

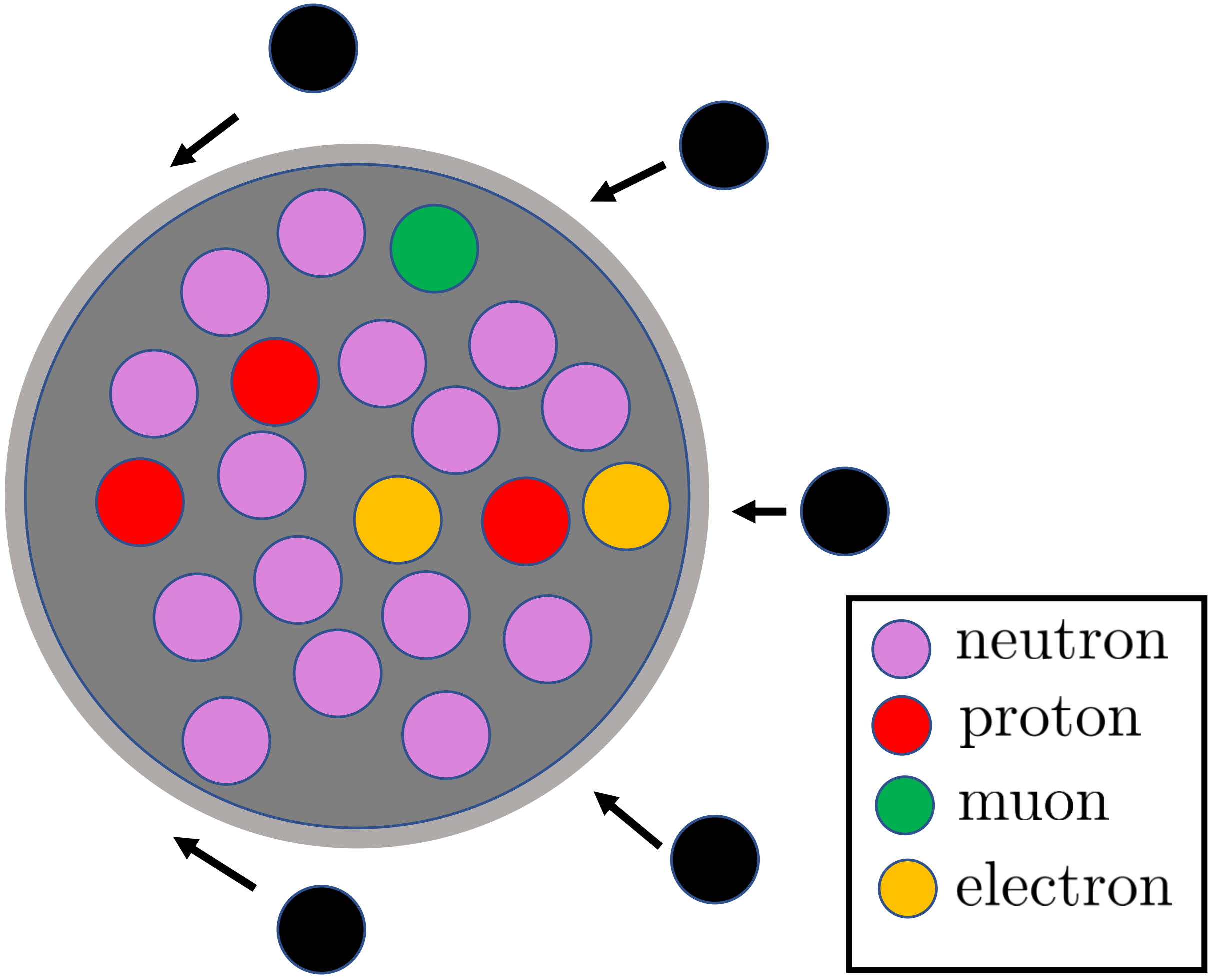
$$\rho_\chi = 0.3\ \text{GeV}/\text{cc}$$

Thermalizes after multiple collisions

NS Kinetic Heating : Dark Fires

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

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



Types of Signals

EM Radiation

Infrared

Dark Kinetic Heating

Baryakhtar, Bramant, Li, Linden, Raj *Phys.Rev.Lett.* 127 (2021) 6, 061805

Joglekar, Raj, Tanedo, Yu *Phys.Lett.* B (2020) 135767, *Phys.Rev.D* 102 (2020) 12, 123002

Internal Dark Heating

McKeen, Pospelov, Raj *Phys.Rev.Lett.* 127 (2021) 6, 061805

Radio

Primakov Effect

Hook, Kahn, Safdi, Sun *Phys.Rev.Lett.* 121 (2018) 24, 241102

GW Radiation

Binary Dynamics

Dark Cores

Exotic Dark Forces

Dror, Laha, Opferkuch *Phys.Rev.D* 102 (2020) 2, 023005

Transmutation

PBH Capture

Genolini, Serpico, Tinyakov *Phys.Rev.D* 102 (2020) 8, 083004

Particle DM capture

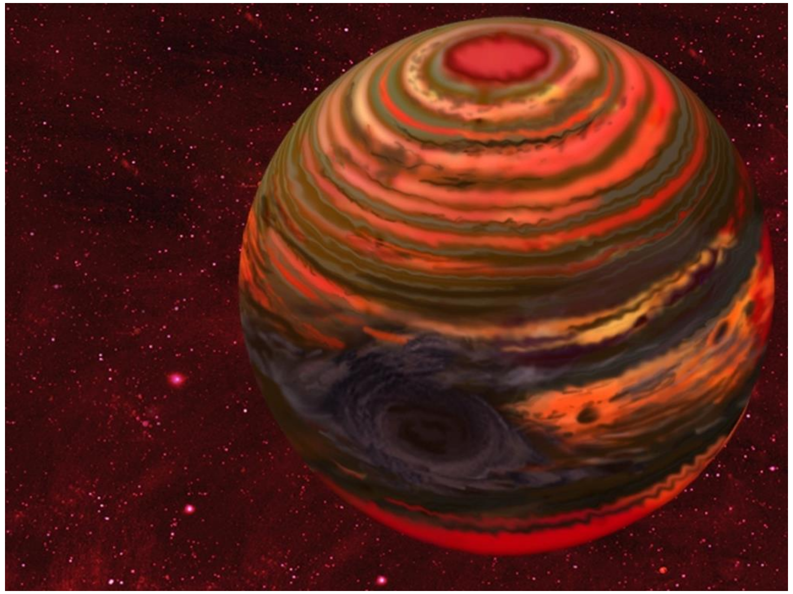
Dasgupta, Laha, Ray *Phys.Rev.Lett.* 126 (2021) 14, 141105

Lack of any collapse can put exclusion bounds on dark sectors

Capture in Other Celestial Bodies?

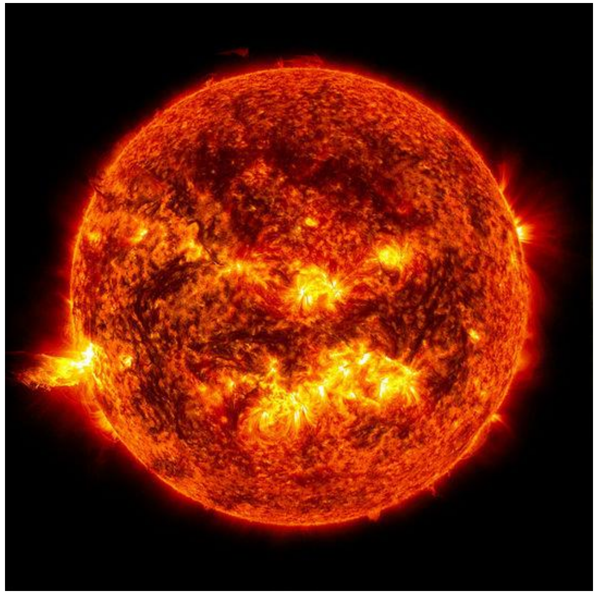
Density less by factor 10^8

Neutron Stars $\sim 10^{-45}\,\mathrm{cm}^2$



by factor 10^{12}-10^{14}

Capture $\propto$ Density



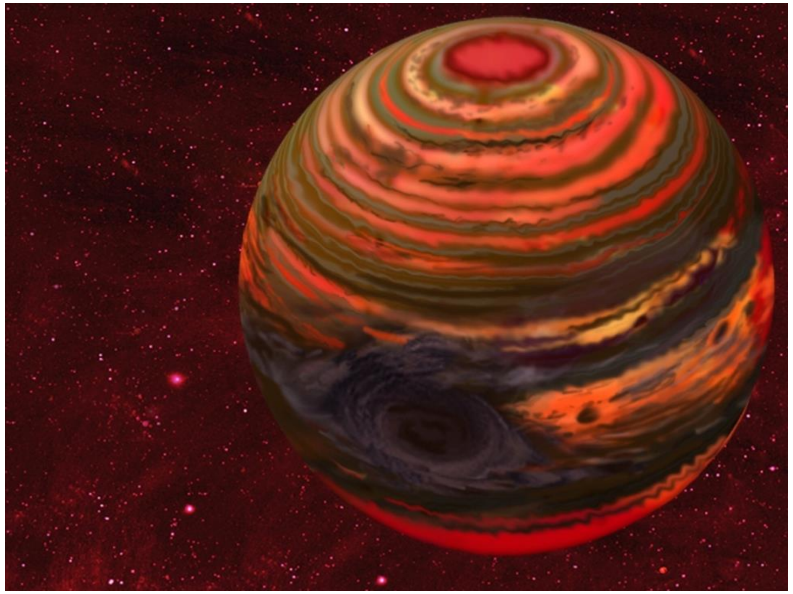
by factor 10^{14}

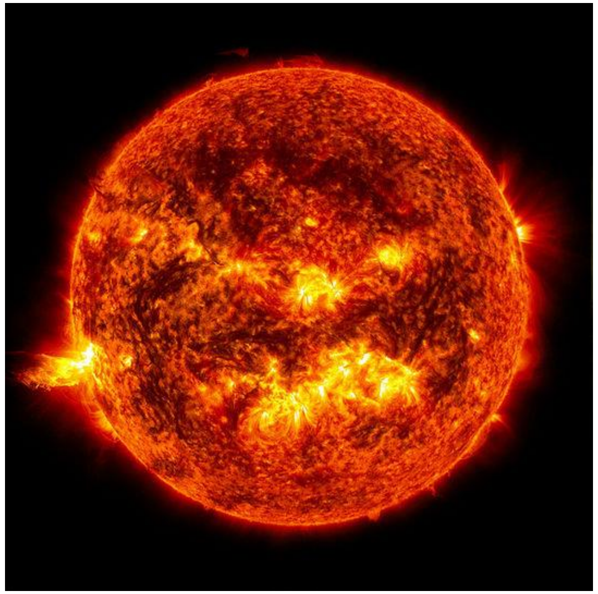
Other stuff $\sim 10^{-35}\,\mathrm{cm}^2$

Large cross-section $\sigma_{\chi T}$ needed for gathering enough DM for collapse

Mostly excluded already!

Capture in Other Celestial Bodies?





Leane, Smirnov *Phys.Rev.Lett.* 126 (2021) 16, 161101

Too hot !

Too hot !

Flux not much larger than NS + low density

Usually can’t deposit enough energy to distinguish signal from background temp

Dark Kinetic Heating

NS Kinetic Heating : Dark Fires

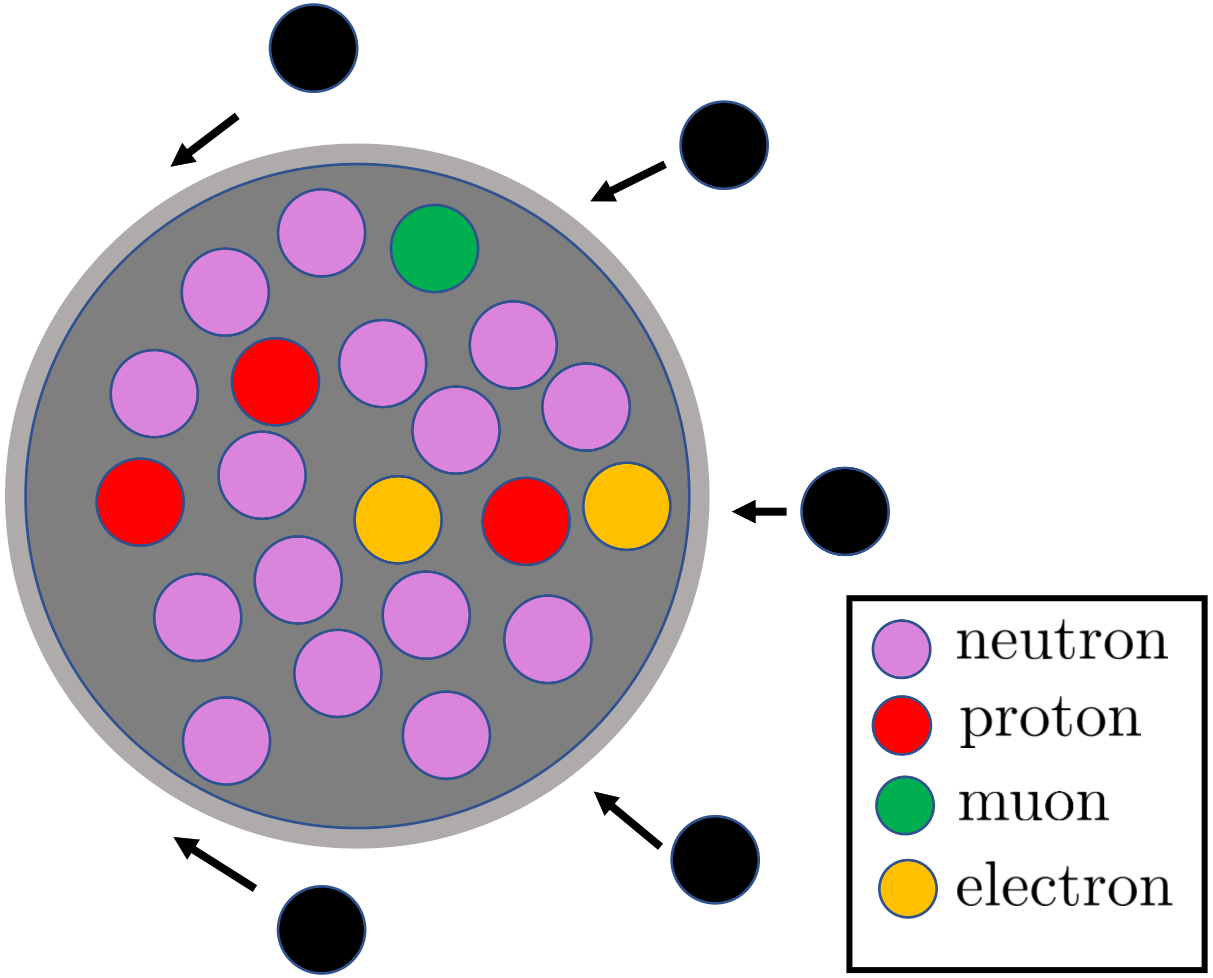
$$\text{Flux} = \pi b_{\text{max}}^2 v_{\text{halo}} \rho$$

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

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

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

Capture efficiency



NS Kinetic Heating : Dark Fires

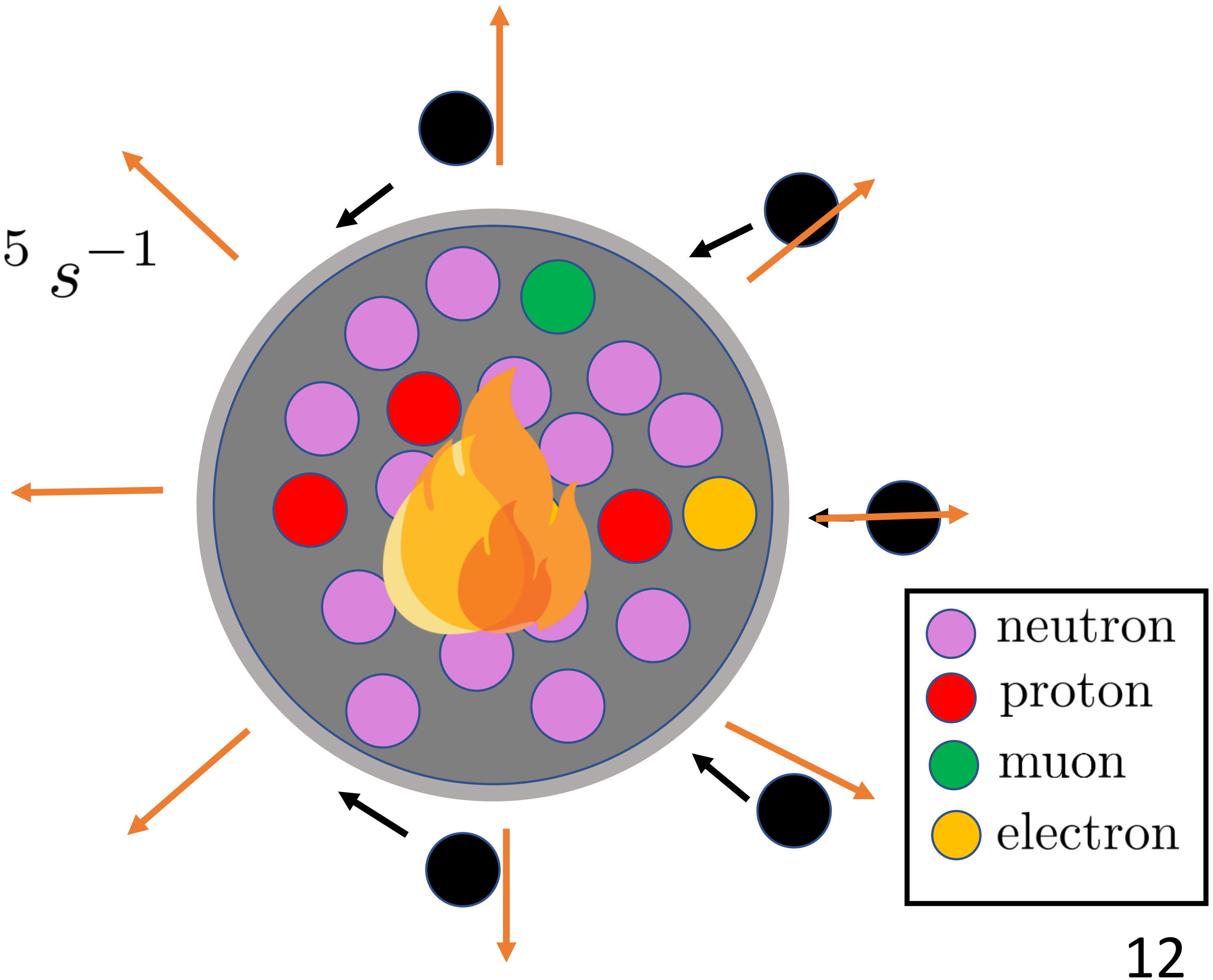
$$\gamma_{\rm esc} \sim 1.35$$

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

Stephan-Boltzmann Law

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

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



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

Do We Know its Age?

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

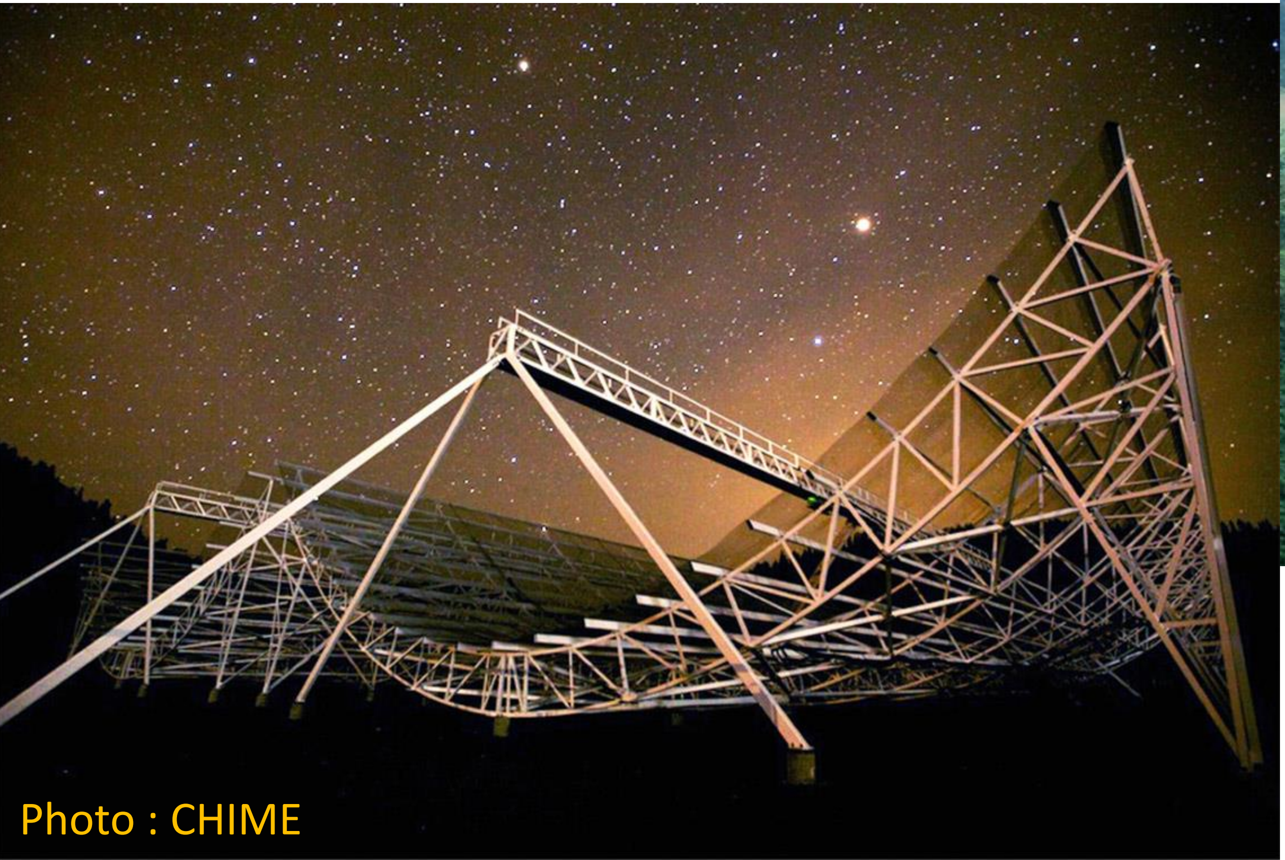


Photo : CHIME


Credit: Ou Dongqu/Xinhua/ZUMA

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

Do We Know its Age?

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

Radio Telescopes!!

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

How to Detect Heated NS?

IR telescope JWST is sensitive to wavelengths range from 0.7 μm to 10 μm

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

More infrared telescopes coming : TMT, ELT

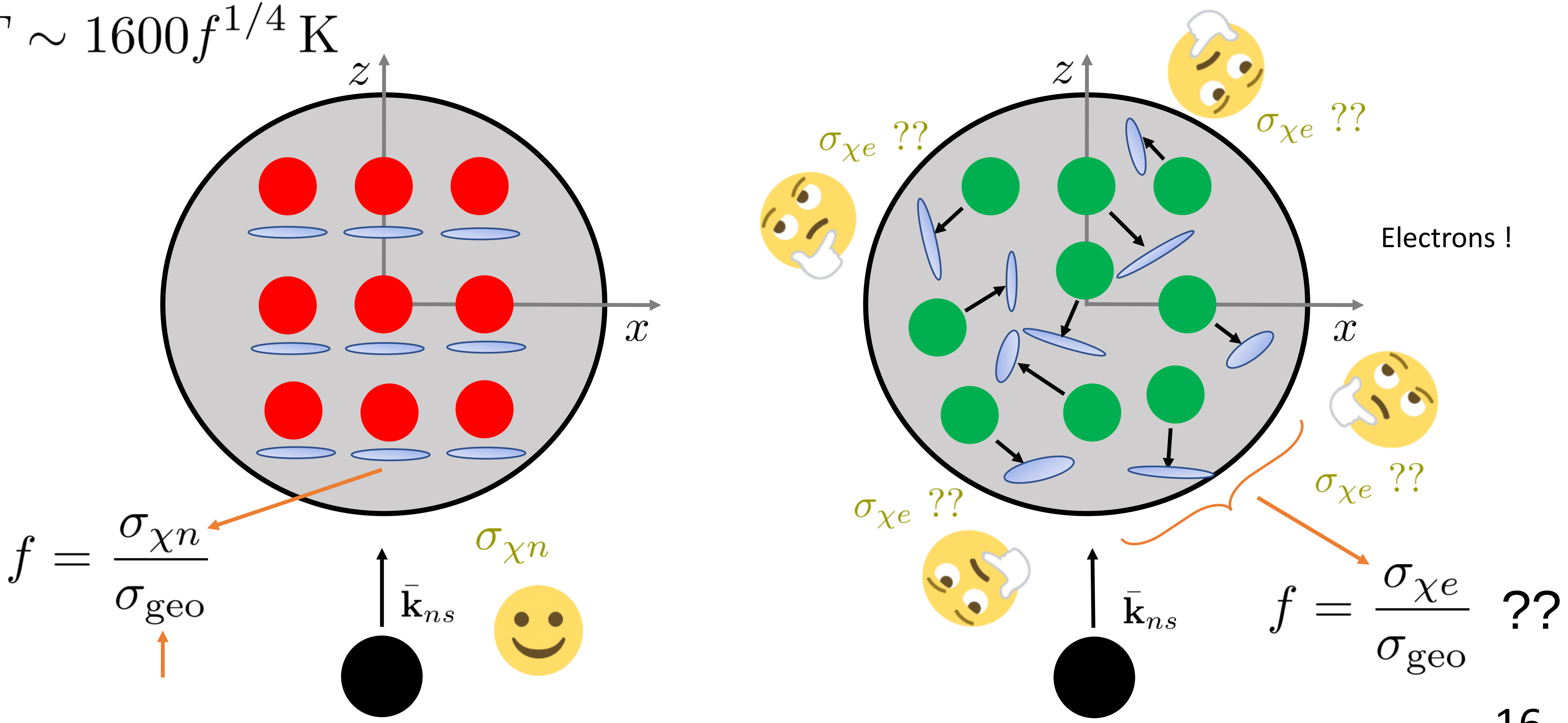
Exposure time for 2σ : $10^5 \left(\frac{d}{10\,\mathrm{pc}}\right)^4$ s

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

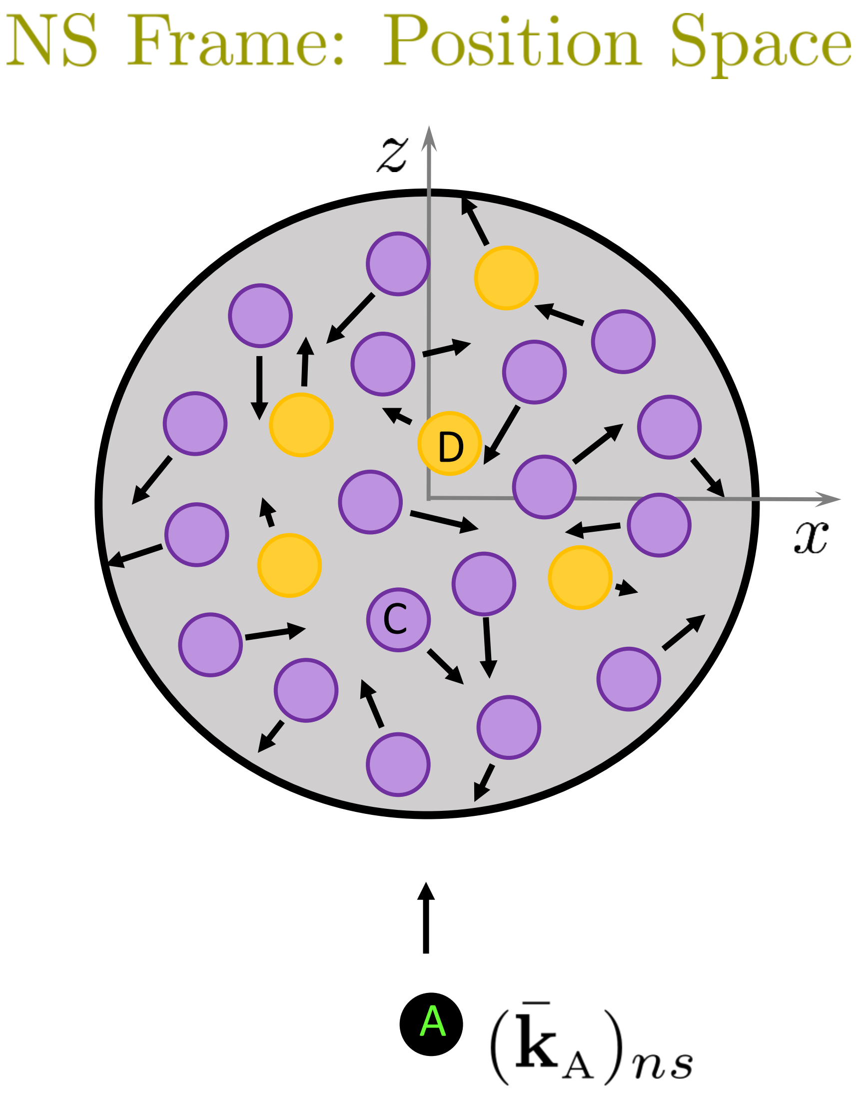
Image (Artist Impression of JWST) : https://www.jwst.nasa.gov/

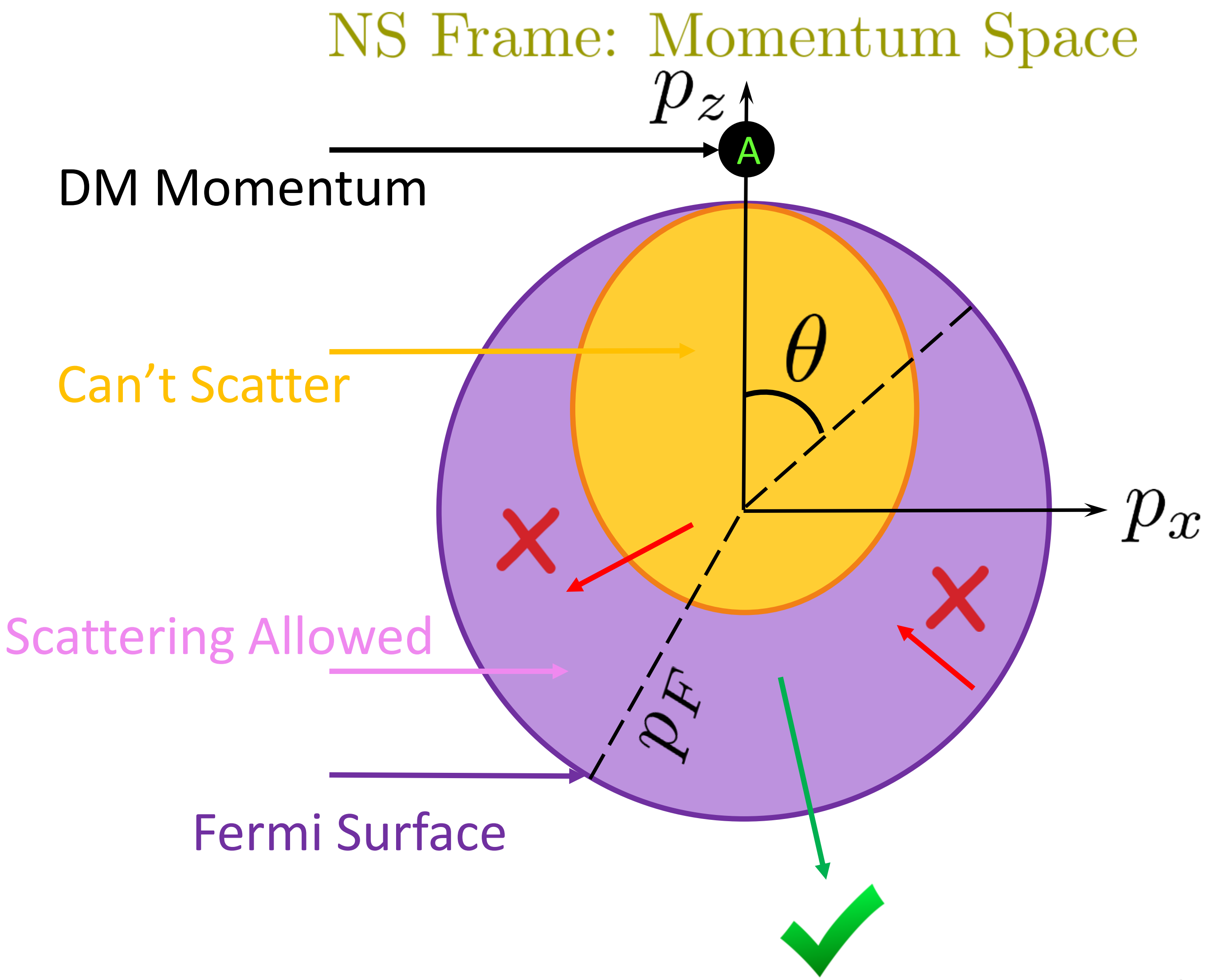
Relativistic Capture Efficiency

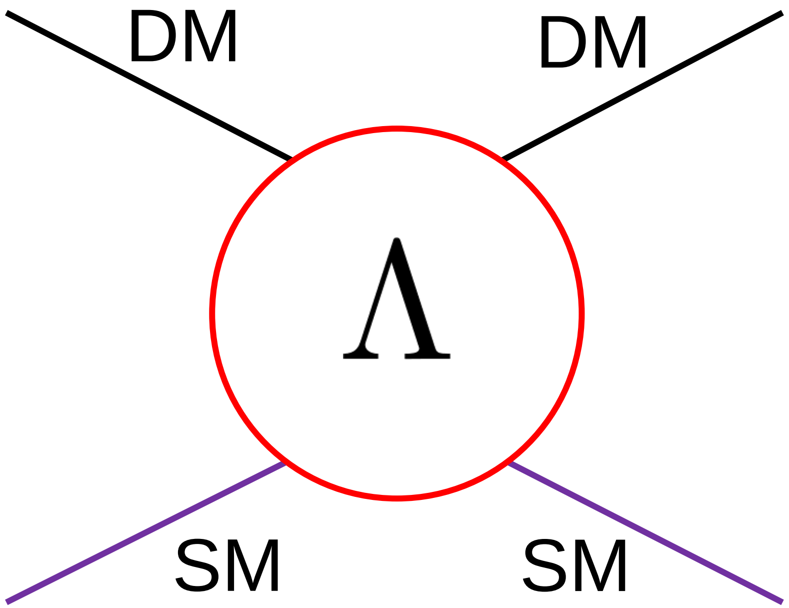
$T \sim 1600 f^{1/4}\,\mathrm{K}$

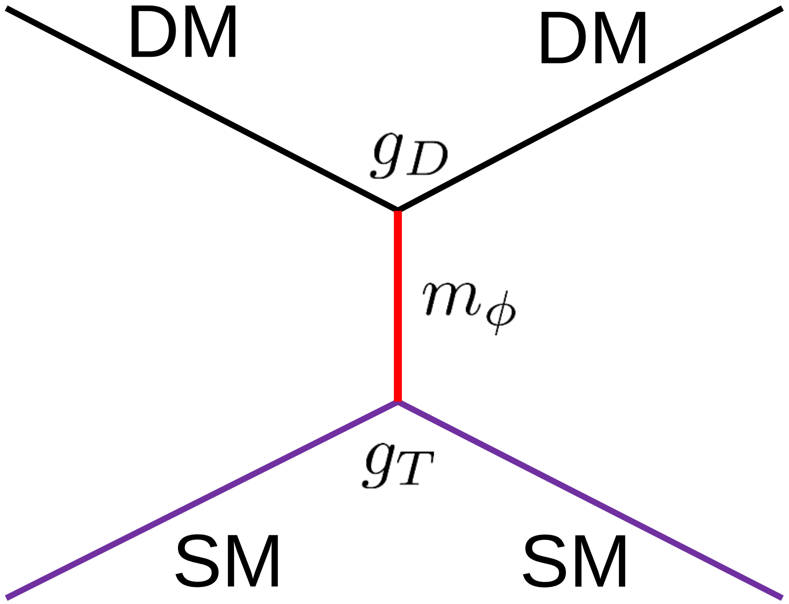


Pauli Blocking



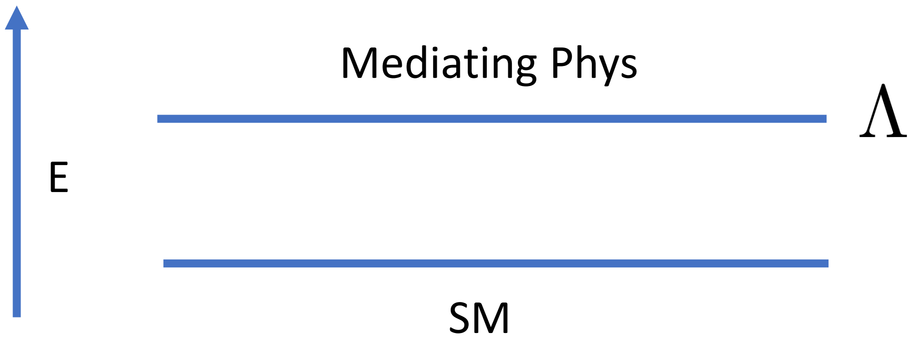






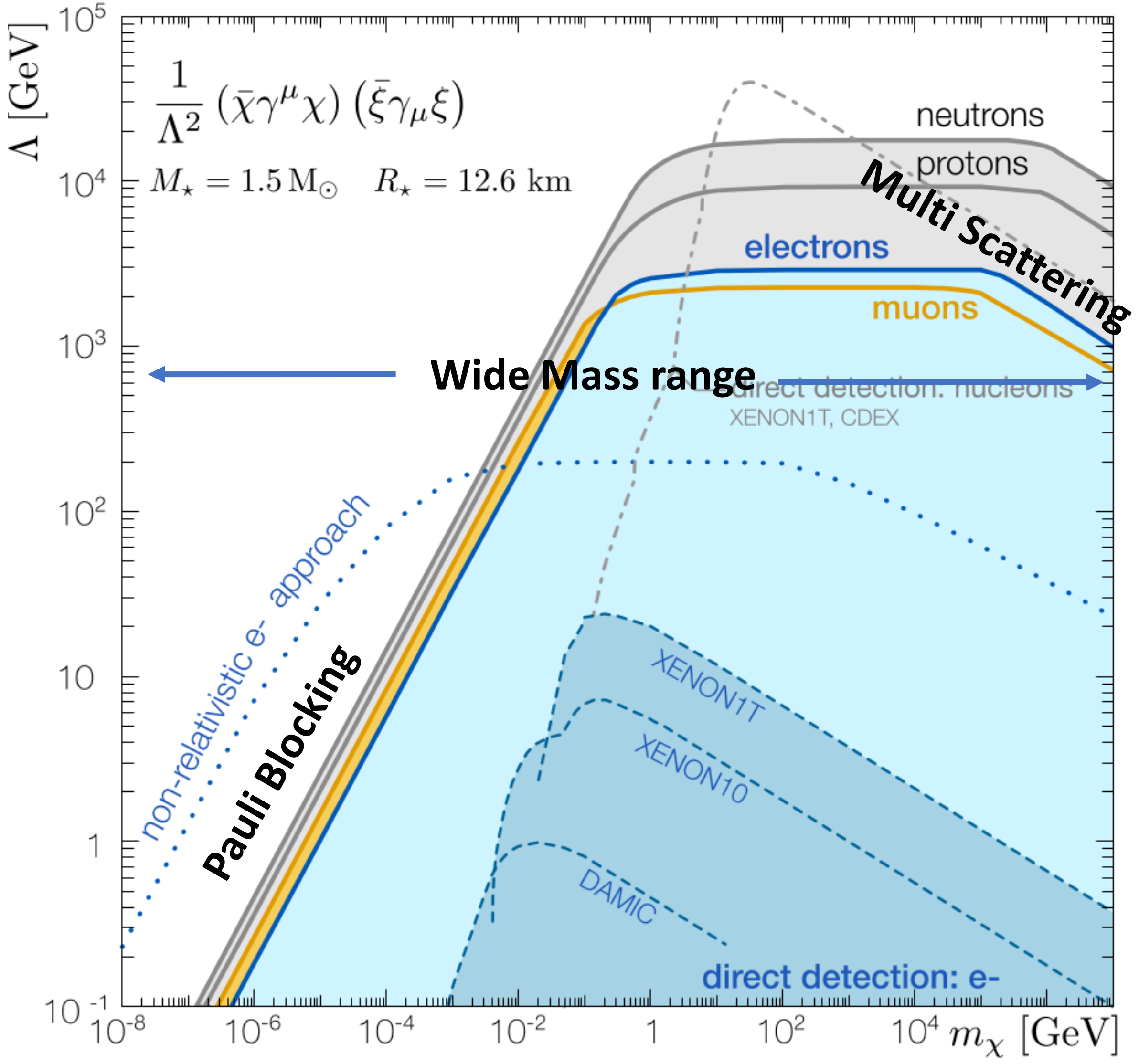
$$\Lambda >> \text{momentum transfer}$$

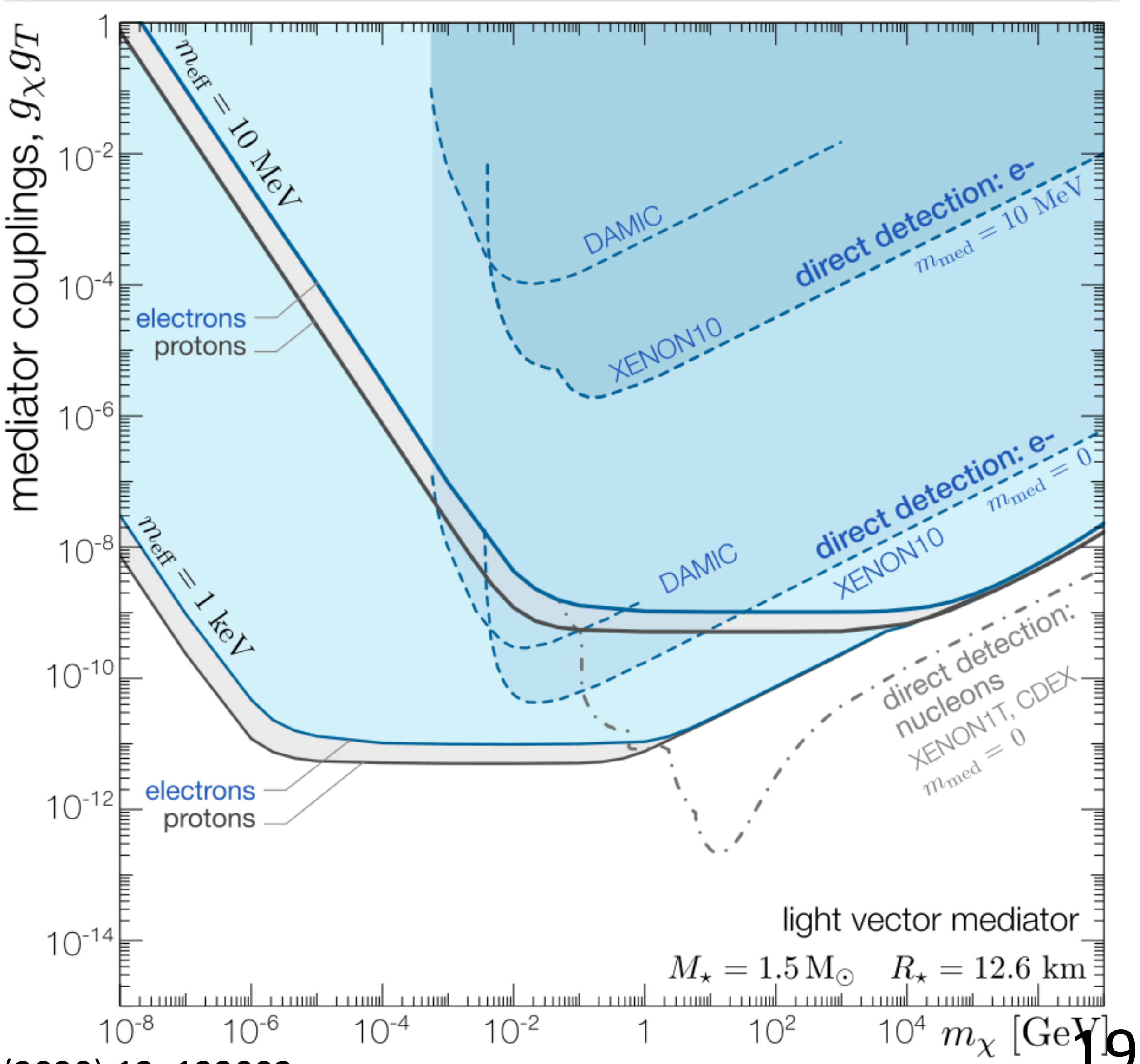
Light mediator



$$m_\phi < \text{momenetum transfer}$$

Reach

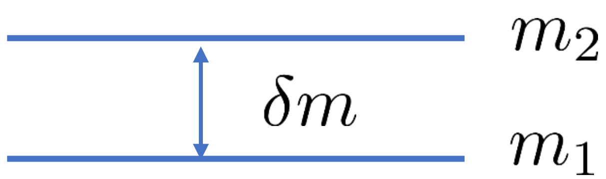


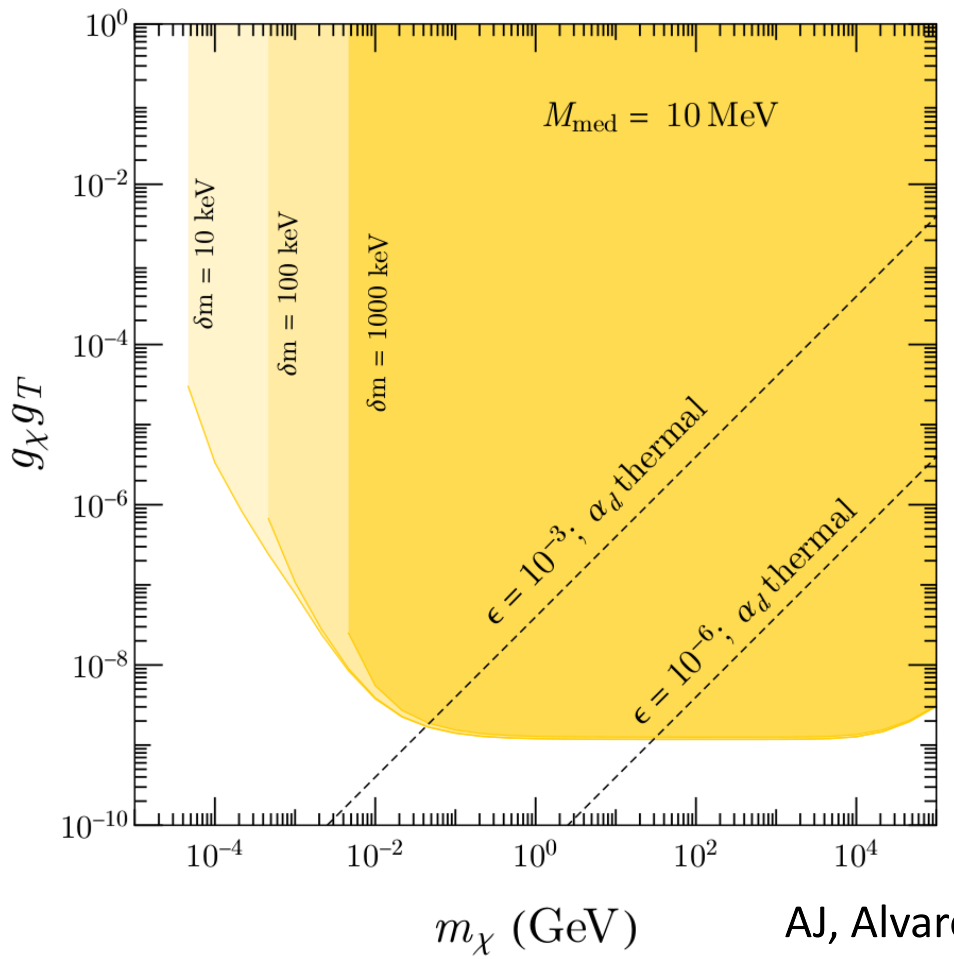


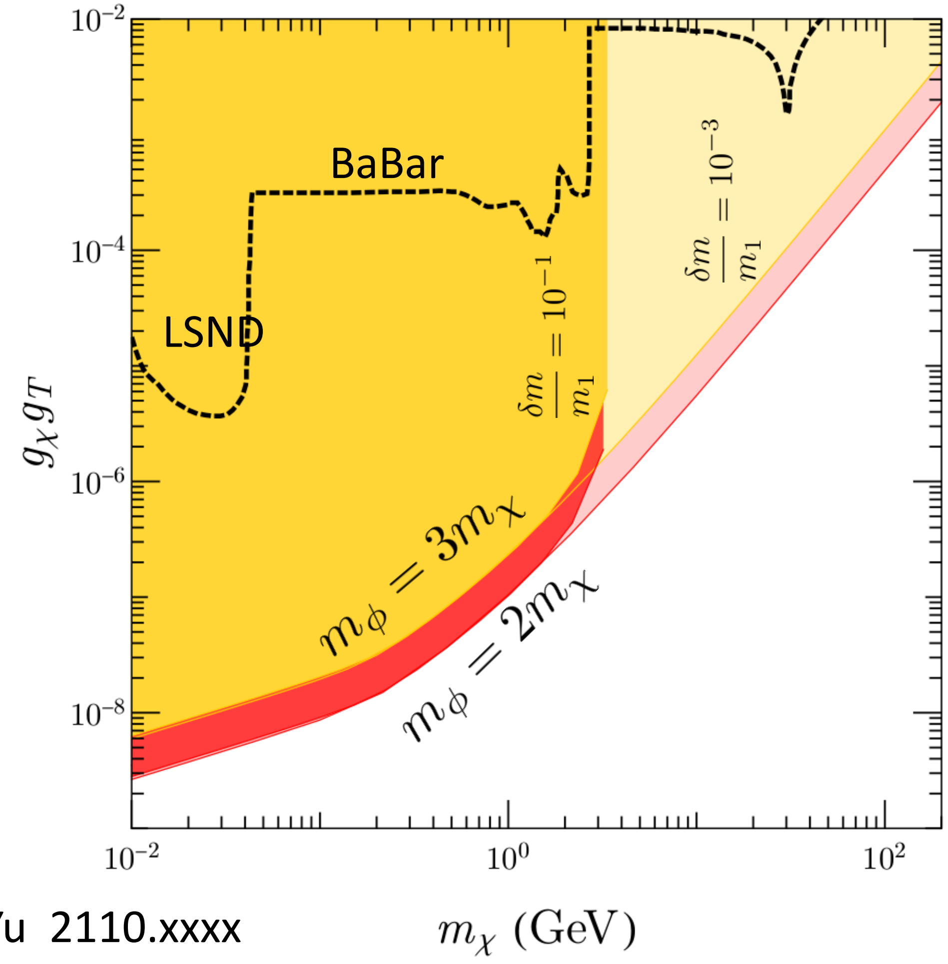
Joglekar, Raj, Tanedo, Yu *Phys.Lett.* B (2020) 135767, *Phys.Rev.D* 102 (2020) 12, 123002

Reach

Inelastic DM



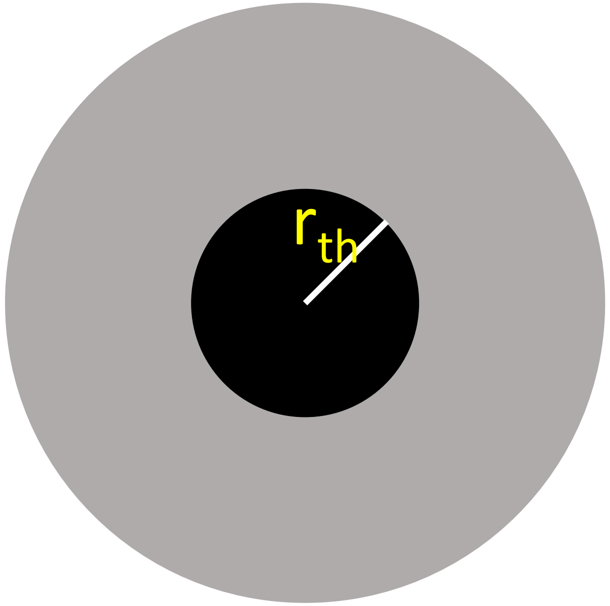




AJ, Alvarez, Mehr, Yu 2110.xxxx

Collapse to Black Hole

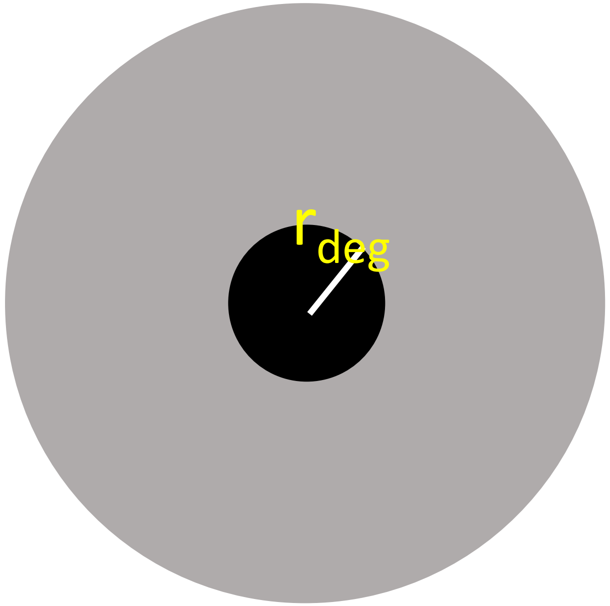
Dark Cores



Thermal radius is decided by virial balance between the temperature and gravitational pull

$$r_{th} \sim \left(\frac{T}{T_\odot}\right)^{1/2} \left(\frac{1\,\mathrm{GeV}}{m_\chi}\right)^{1/2} \mathrm{m}$$

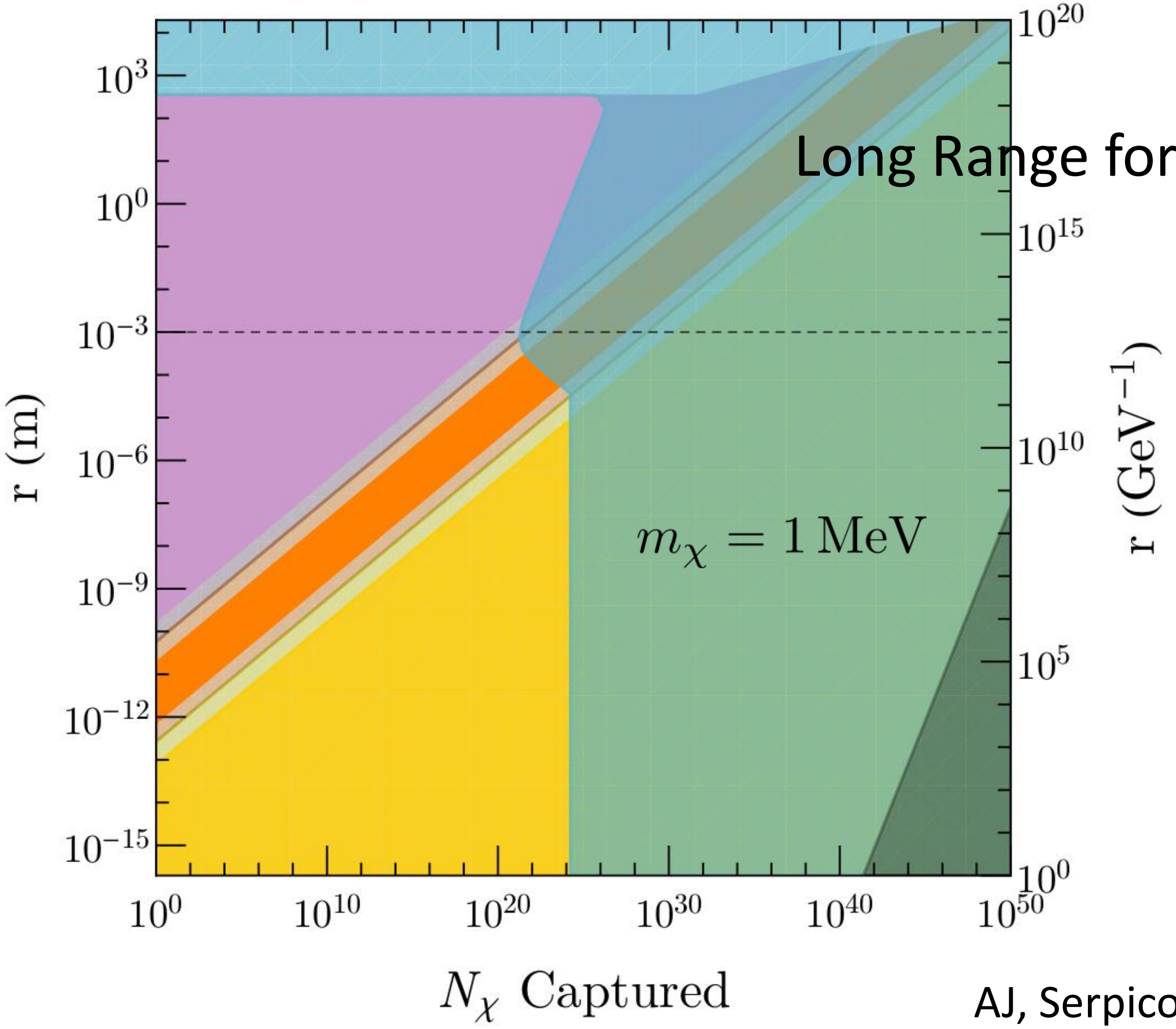
Nudge due to an additional attractive force can trigger collapse



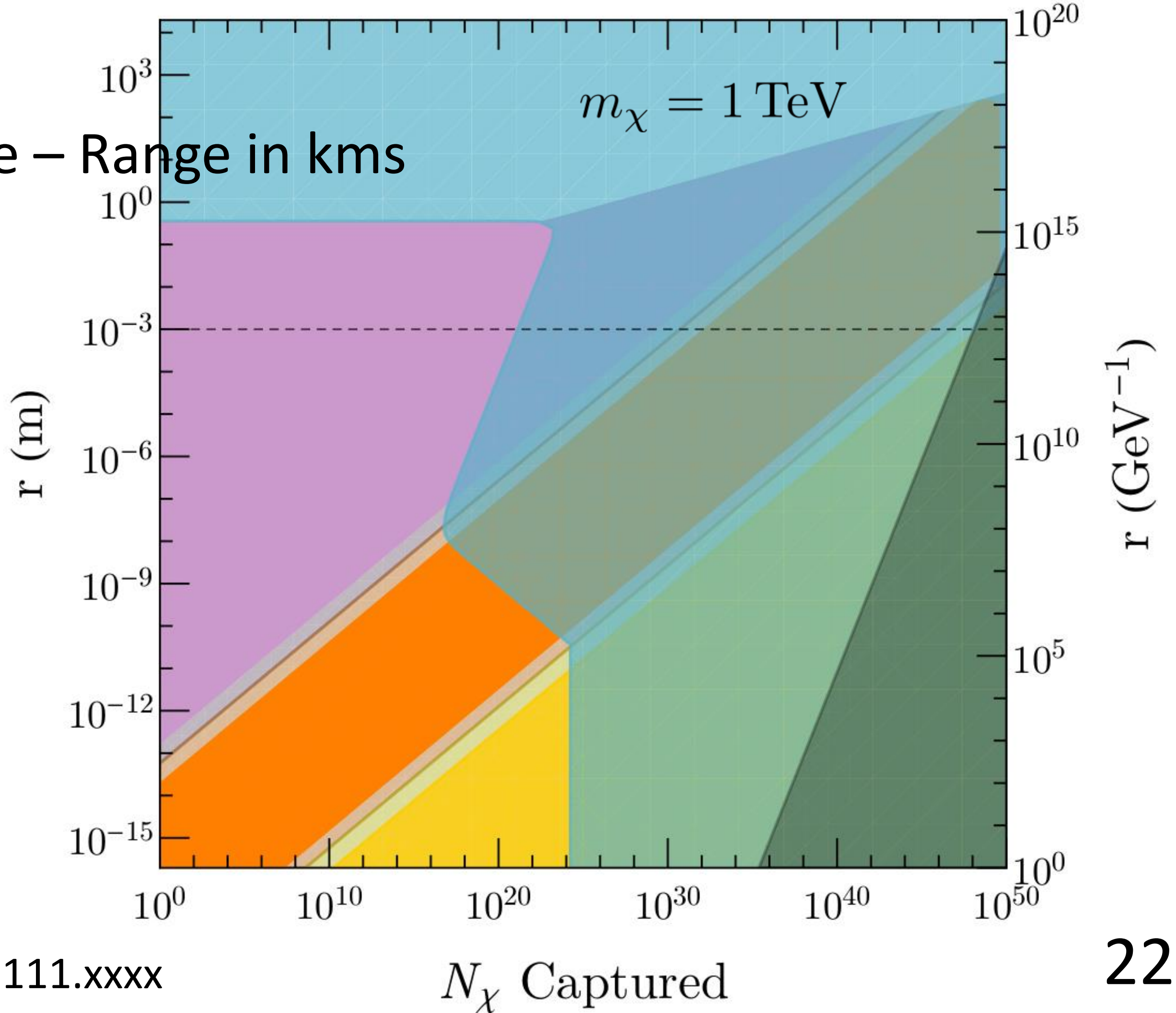
Collapse from thermal balance with eventually find support due to Fermi degeneracy. Even more DM particles needed, but not always!

Collapse due to Long-range Force

Evolution path matters to correctly predict the number of DM required for collapse!



Long Range force – Range in kms

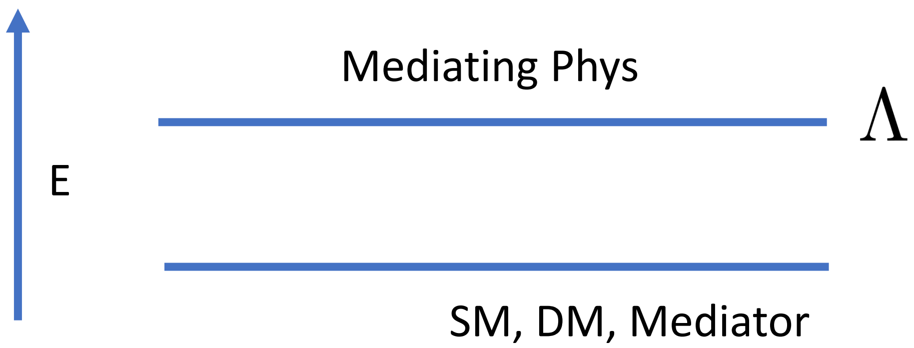


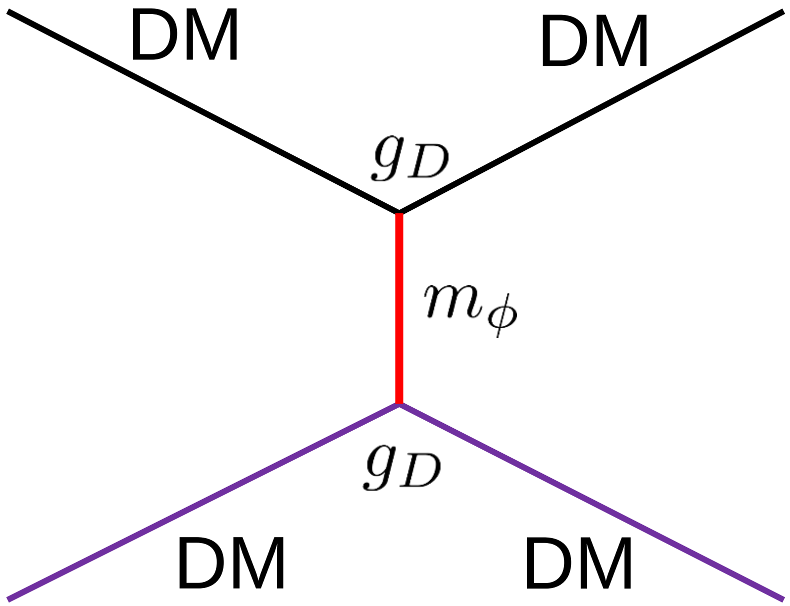
AJ, Serpico 2111.xxxx

Exclusion Bounds from Non-observation of Collapse

Interaction strengths that can be excluded by observation of old neutron star crucially depend on it

Remarkable that very tiny coupling for self-interactions can be excluded





$$\alpha_d = \frac{g_D^2}{4\pi}$$

AJ, Serpico 2111.xxxx

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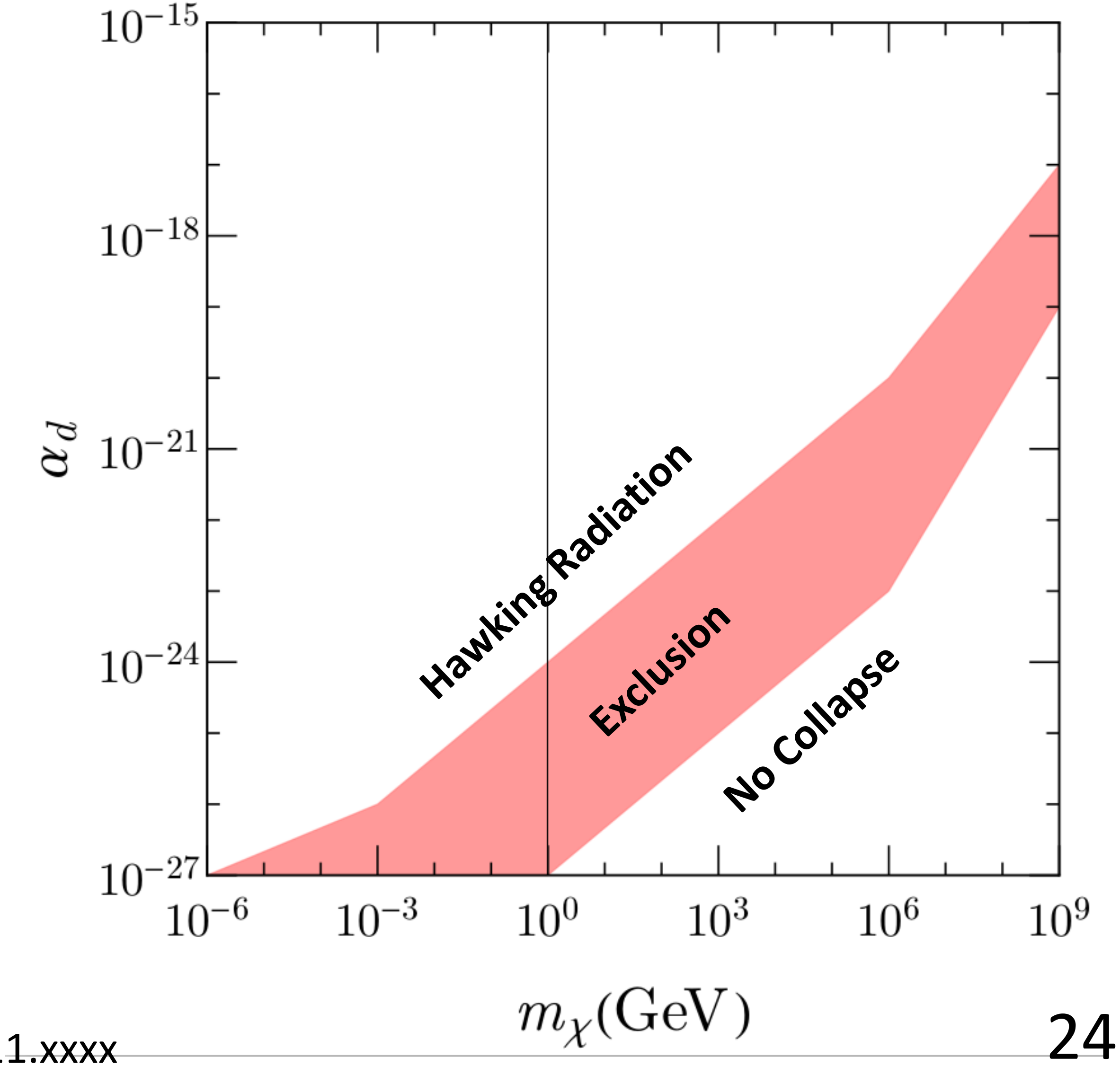
PSR J0437−4715



AJ, Serpico 2111.xxxx

Summary

- Neutron stars are great for learning more about the nature of DM
- Can complement or exceed terrestrial searches
- Collapse or its non-observation can put strong bounds on dark sector parameters
- JWST launches very soon, so many be more data soon …