Neutron Stars as Dark Matter Detectors

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Direct Detection of Dark Matter

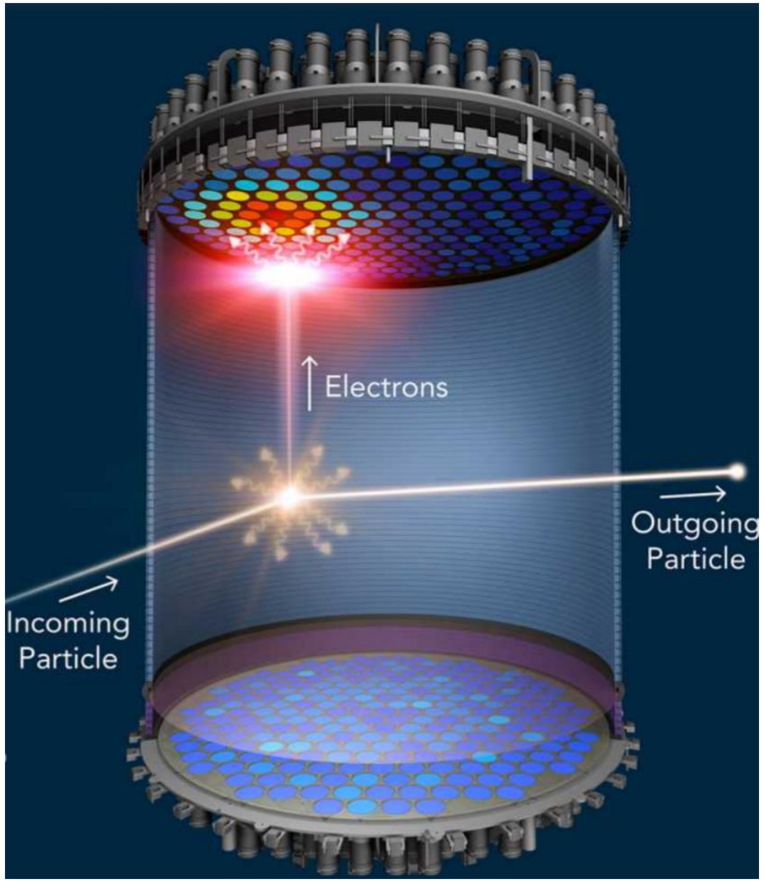
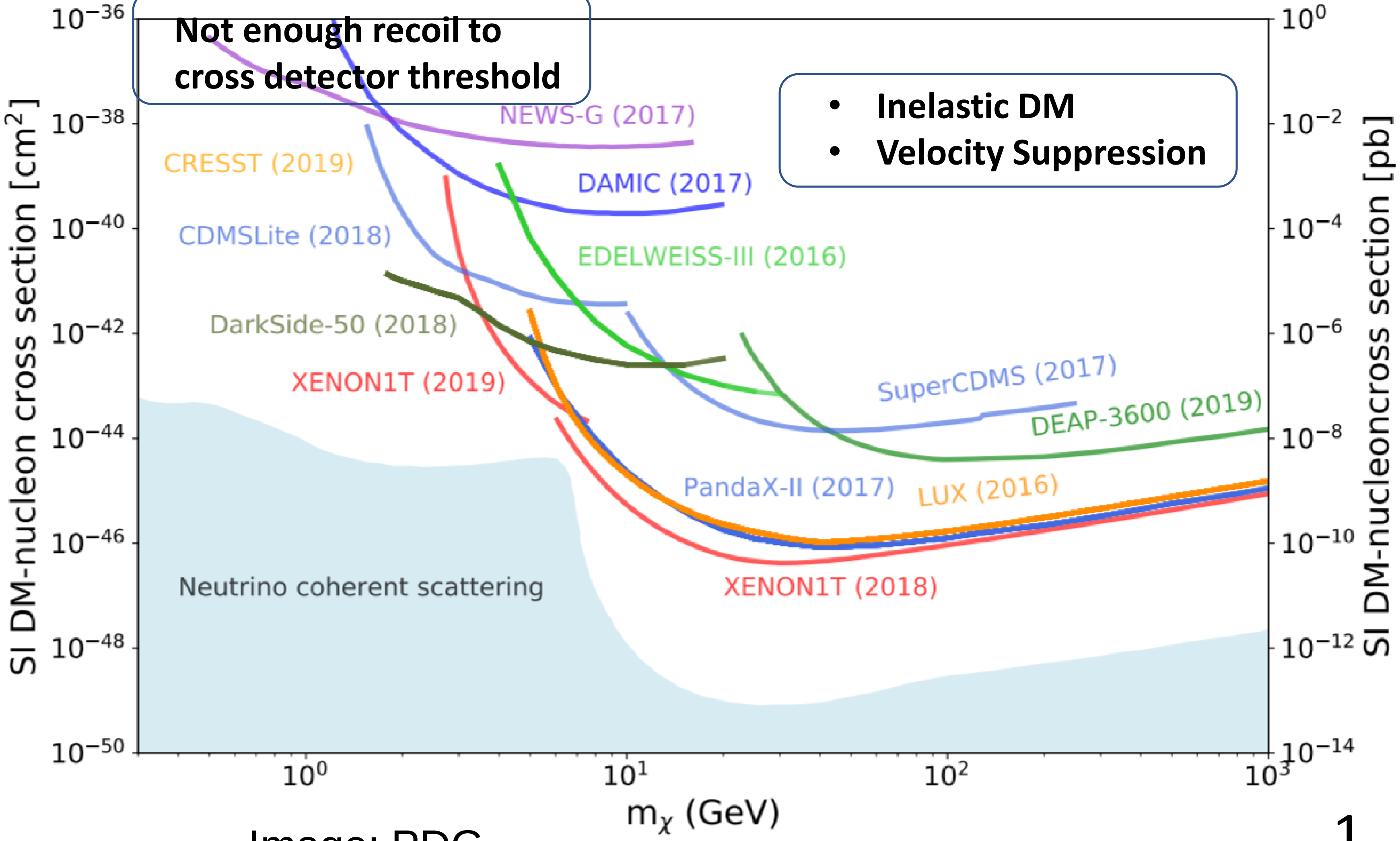


Image: Lux-LZ



Not enough recoil to cross detector threshold

- Inelastic DM
- Velocity Suppression

Image: PDG

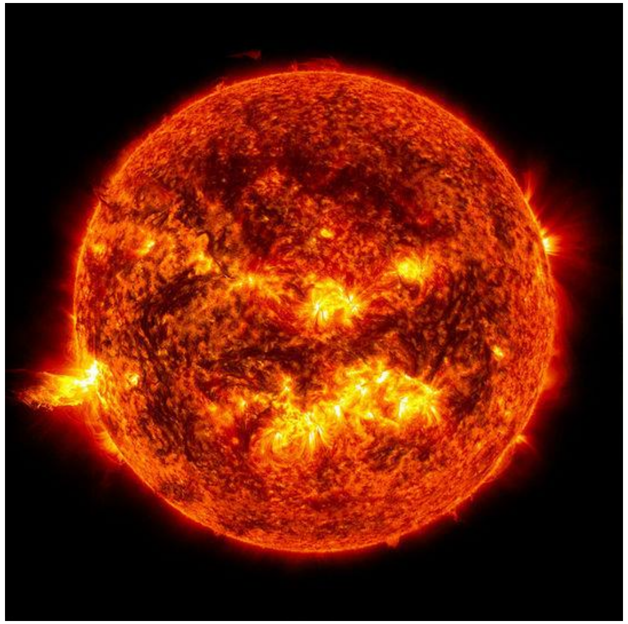
What Celestial Bodies Can Probe Lower $\sigma_{\chi T}$?

White Dwarfs

Density less by factor 10^8 compared to NS

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

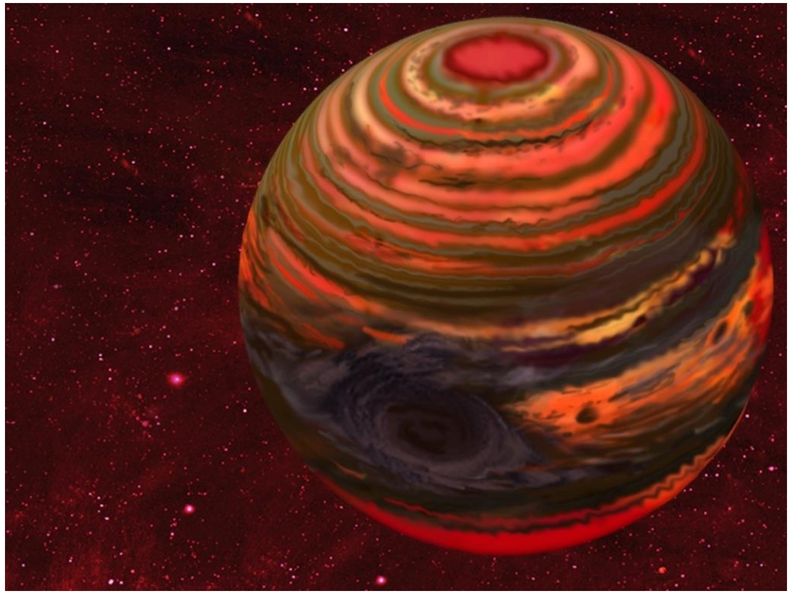
Sun-like Stars



by factor 10^{14}

Capture $\propto$ Density

Brown Dwarfs



by factor 10^{11} - 10^{13}

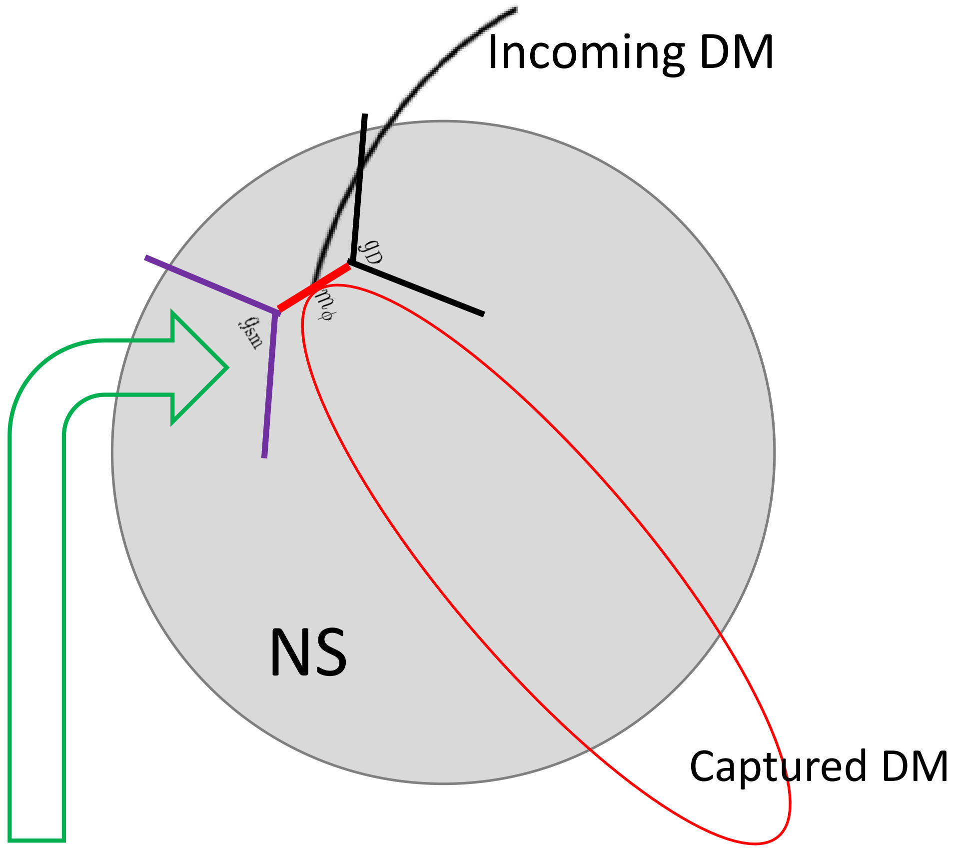
Other stuff $\sim 10^{-35}$ cm^2

Much larger cross-section $\sigma_{\chi T}$ needed to gather enough DM to generate signals in bodies other than NS

10^{-35} cm^2 mostly excluded already! But not 10^{-45} cm^2

How Does the Capture Work?

Continuous dark matter flux incident on the NS



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

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

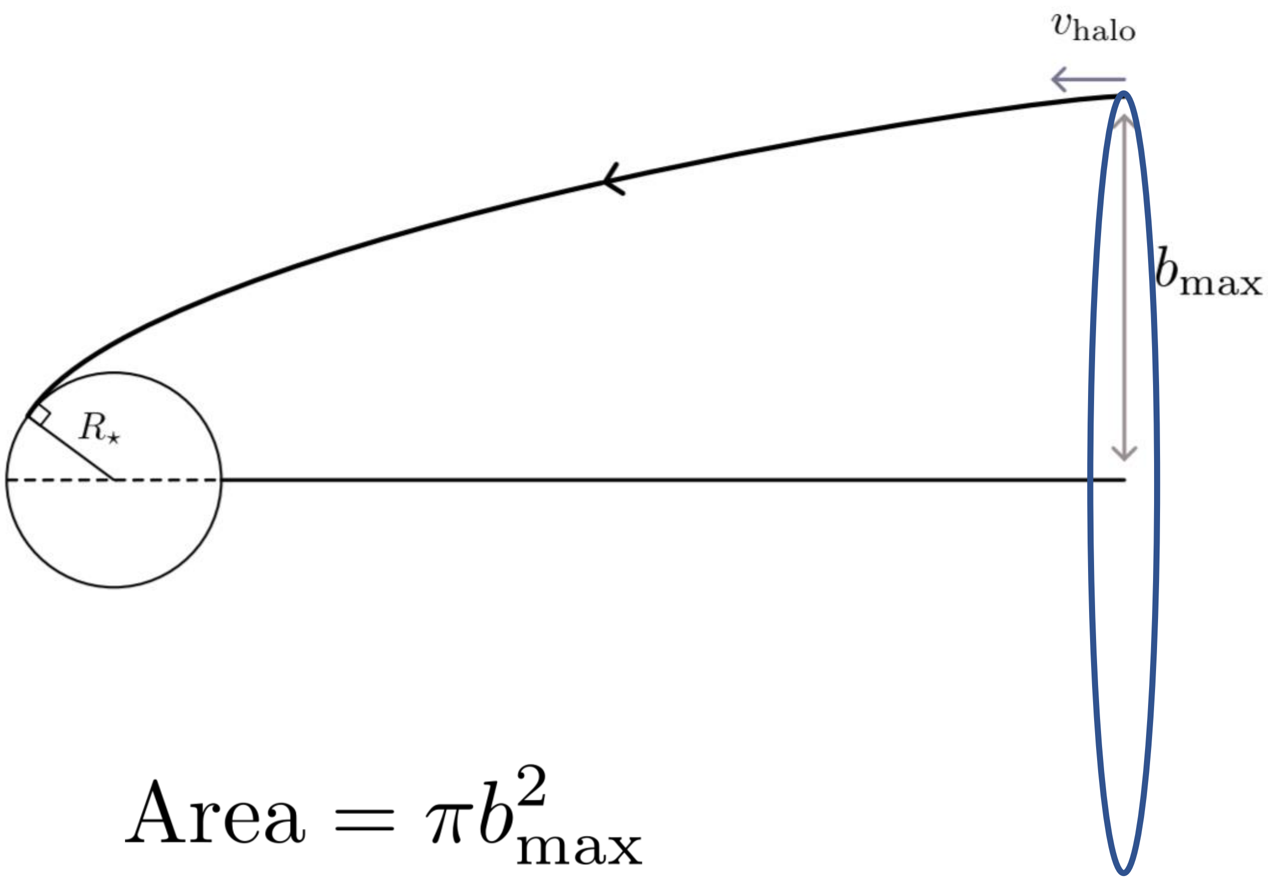
Densely Packed

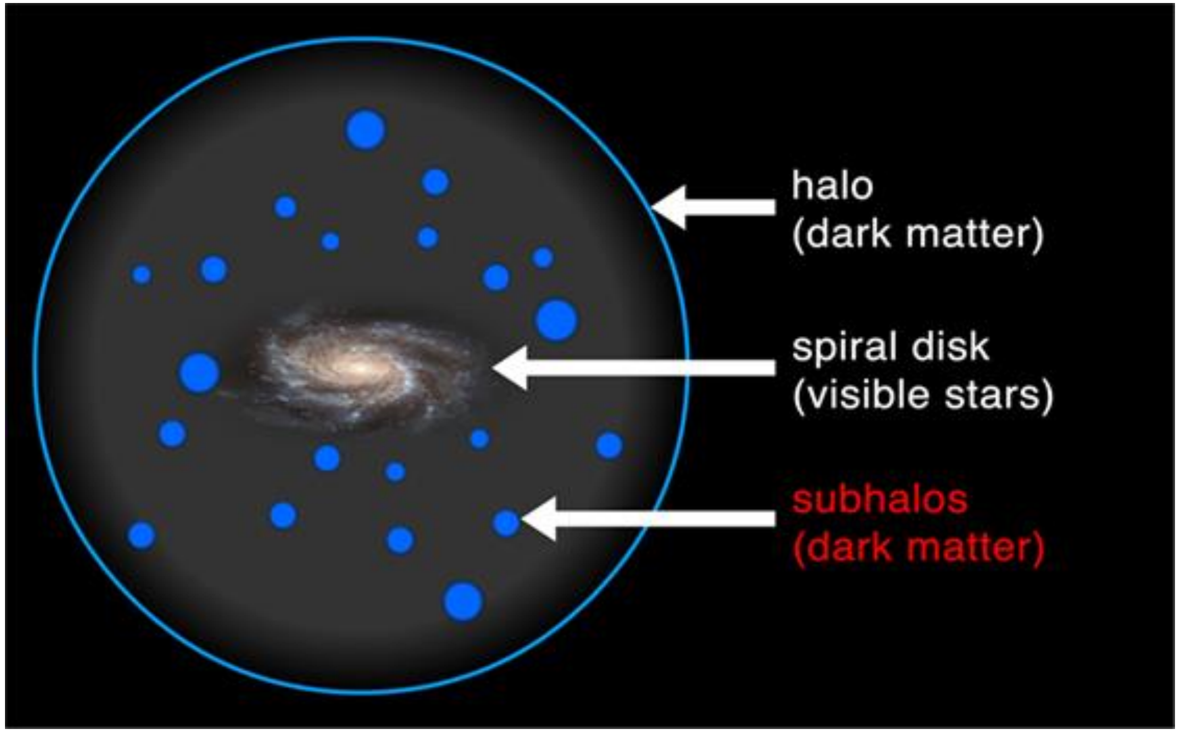
Accelerates DM to $v \sim 0.6\, c$

Interaction where DM loses more energy than its Halo KE

Flux

Continuous dark matter flux incident on the NS





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

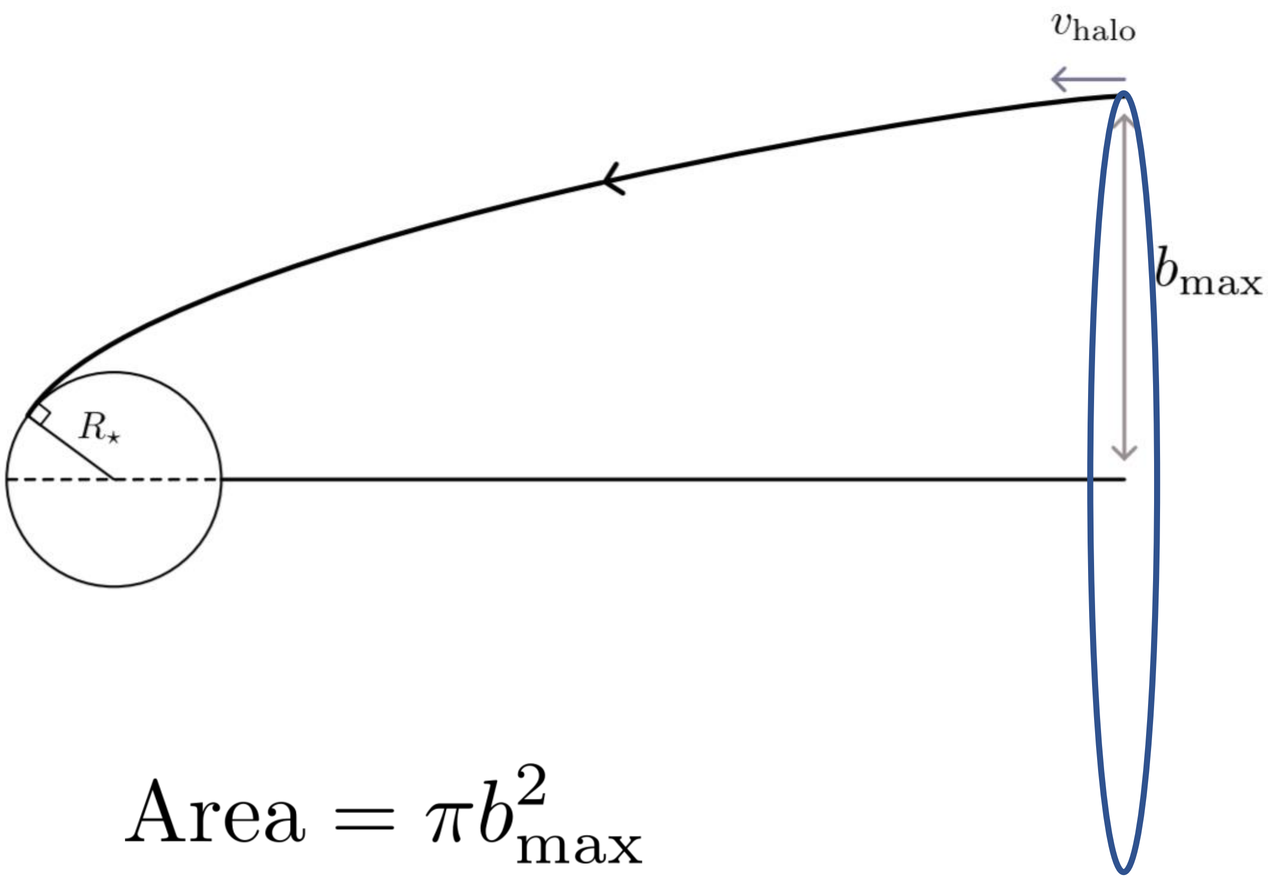
$$v_{\rm halo} = 8 \times 10^{-4},\ \rho_\chi = 0.3\ \text{GeV/cc}$$

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

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

Flux

Continuous dark matter flux incident on the NS



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

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

We take:

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

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

This means :

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

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

Large compared to $R_\star$!

Types of Signals

NS Capture of DM

Kinetic Heating : Infrared emissions

Baryakhtar, Bramant , Li, Linden, Raj Phys.Rev.Lett 119 (2017)13, 131801

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

AJ, Alvarez, Mehr, Yu, *in preparation*

AJ, Serpico, *in preparation*

Axion DM: Primakoff effect, Radio emissions

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

Observation of Old star : Bounds from lack of collapse

Kouvaris, *Phys.Rev.Lett.* 108 (2012) 191301

Bramante, Fukushima, Kumar, Stopnitzky, *Phys.Rev.D* 89 (2014) 1, 015010

AJ, Serpico, *in preparation*

GW signals?

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

Exotic long range forces,

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

AJ, Serpico, *in preparation*

PBH capture etc.

Next talk ⇨ Genolini, Serpico, Tinyakov Phys.Rev.D 102 (2020) 8, 083004

Dark Kinetic Heating

NS Kinetic Heating : Dark Fires

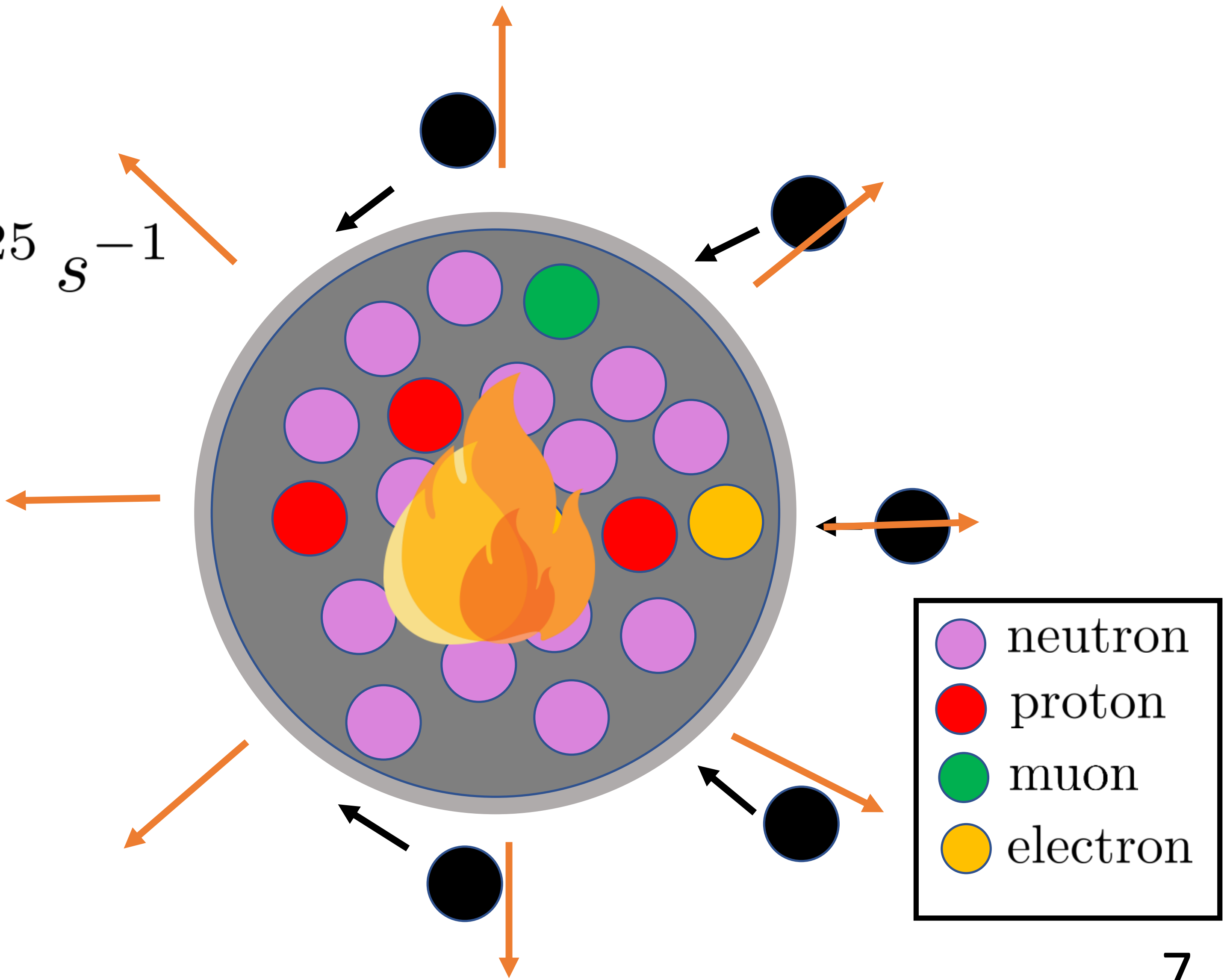
$$\gamma_{\rm esc} \sim 1.35$$

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

Stephan-Boltzmann Law

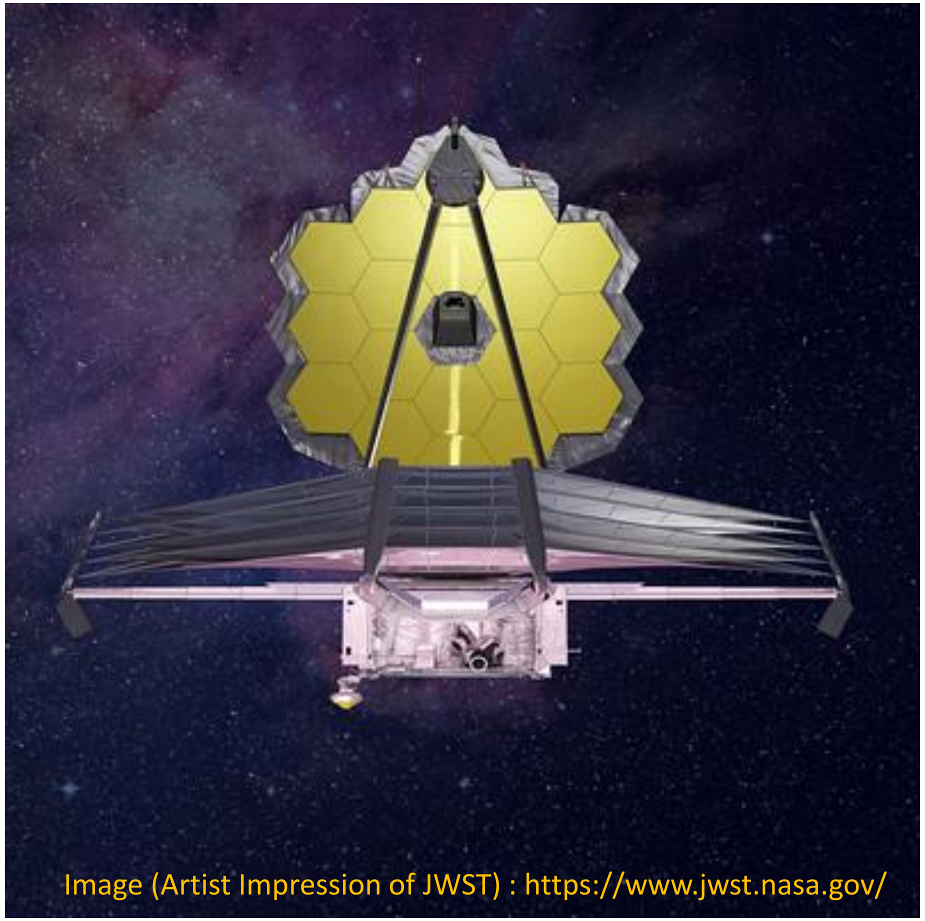
$$\dot{E} = 4\pi R_\star^2 \sigma_{\rm SB} T^4$$

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

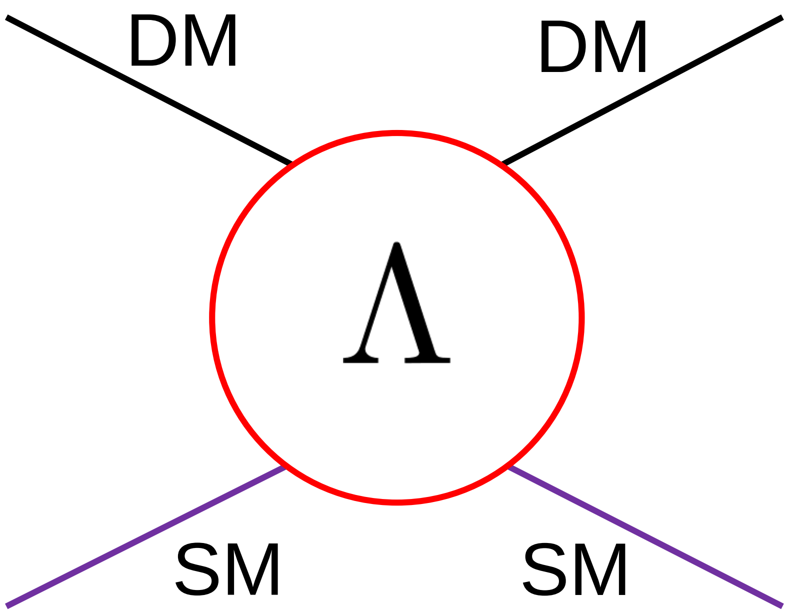


How to Detect Excess Heating?

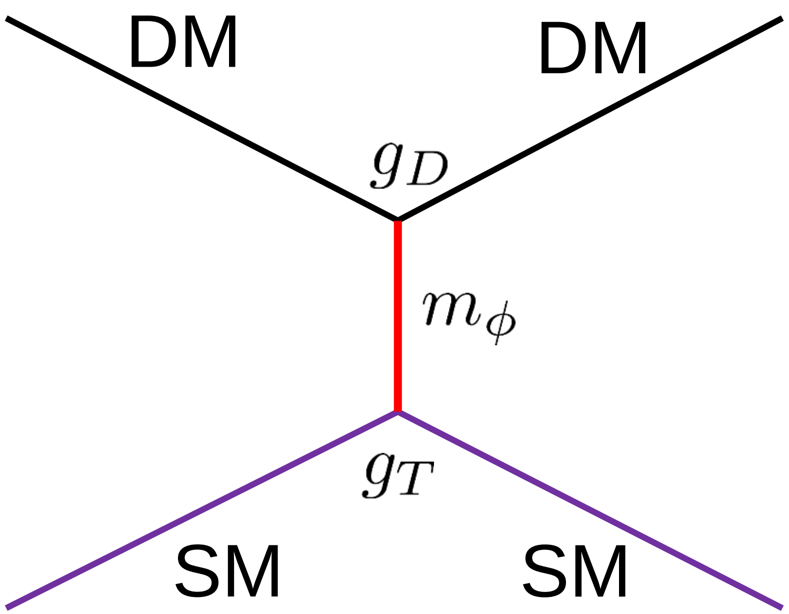
Find an old “nearby” NS with radio telescope with expected temp $\mathcal{O}(10-100)\,\mathrm{K}$



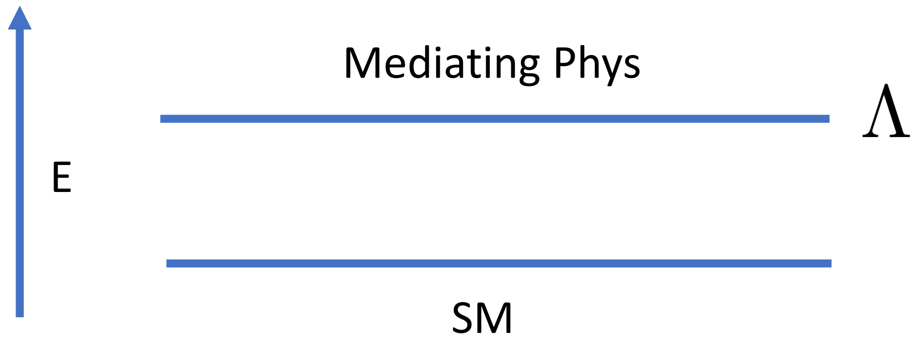
Point JWST towards it to see if it has infrared temperatures of $\mathcal{O}(1000)\,\mathrm{K}$



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

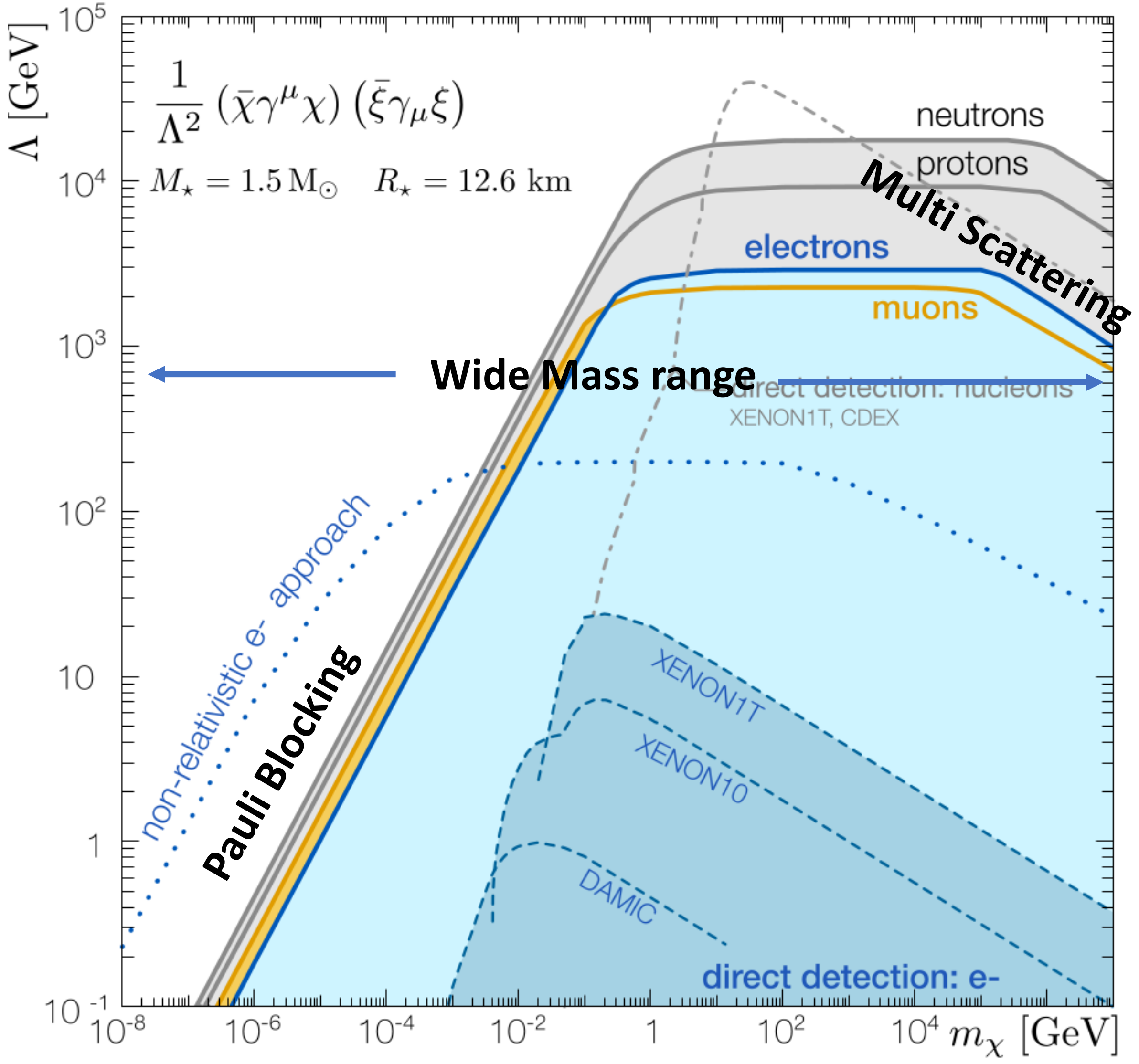


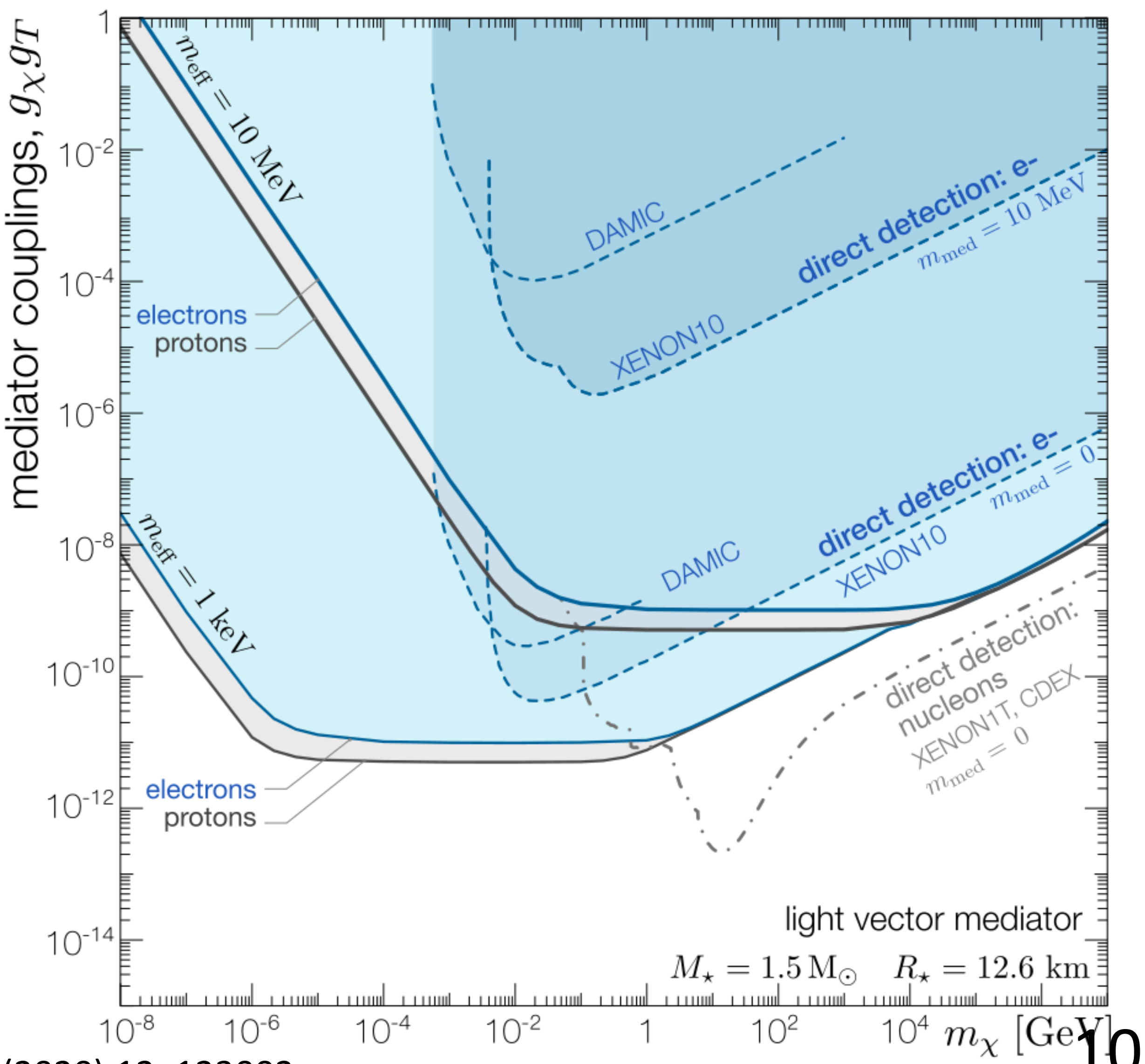
Light mediator



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

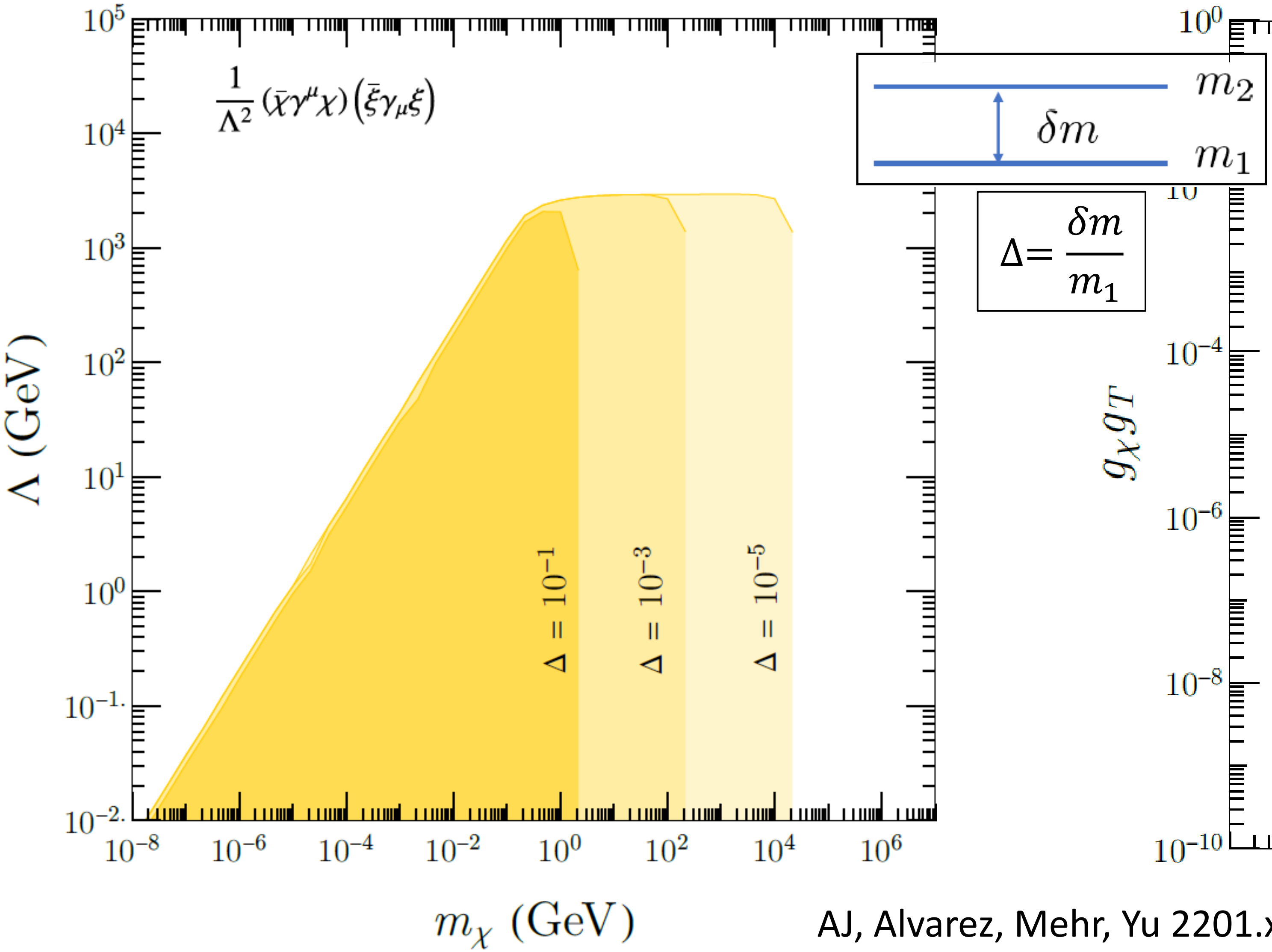
Reach

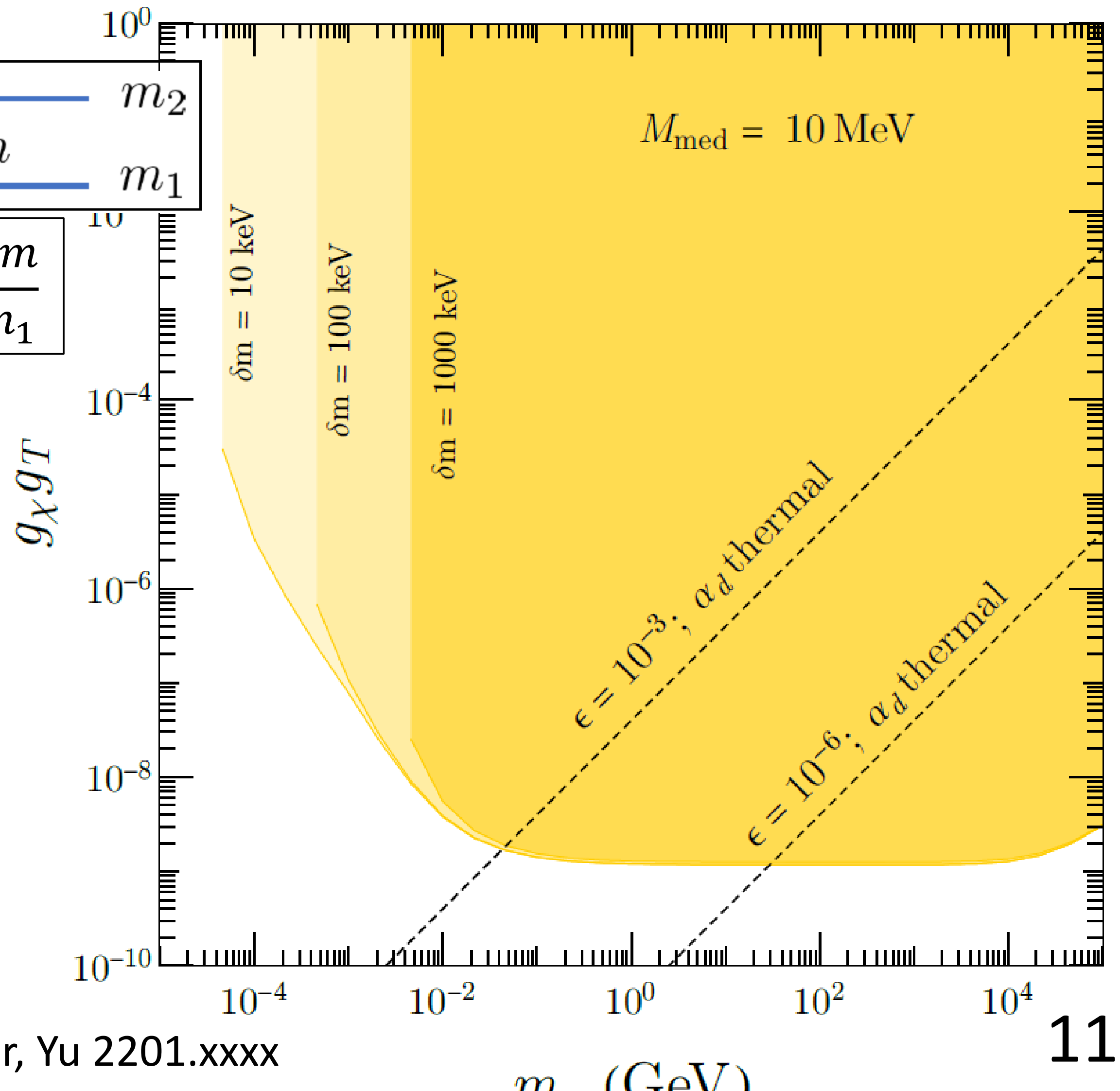




Joglekar, Raj, Tanedo, Yu *Phys.Lett.* B (2020) 135767, *Phys.Rev.D* 102 (2020) 12, 123002

Inelastic DM`



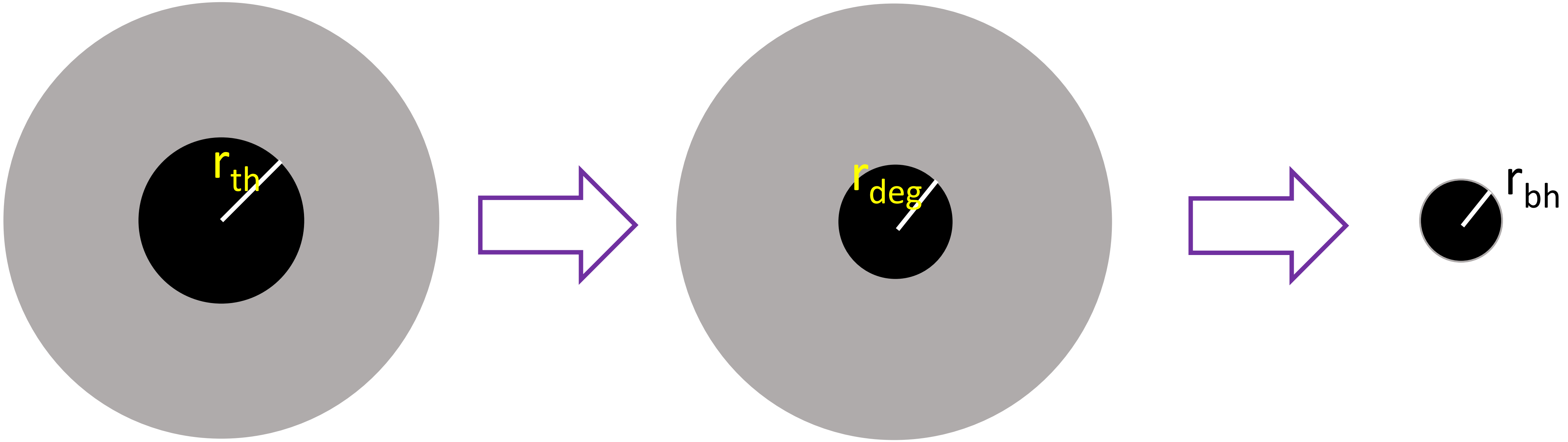


AJ, Alvarez, Mehr, Yu 2201.xxxx

Collapse to Black Hole

Probing ‘invisible’ forces in the dark sector

Dark Cores



Thermal radius :
Virial balance between temperature & gravity

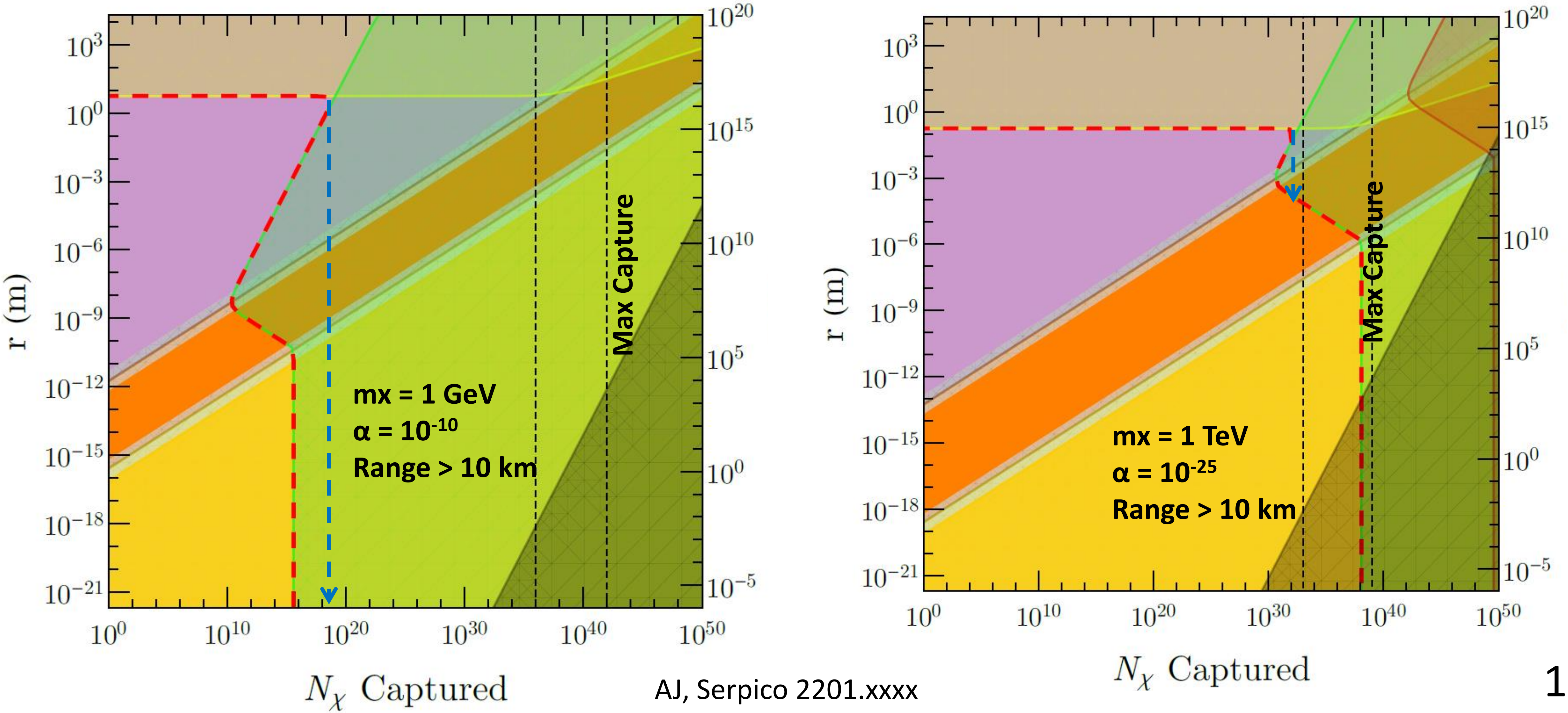
Nudge due to an additional attractive force can trigger collapse

Resultant BH can eat up the star

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

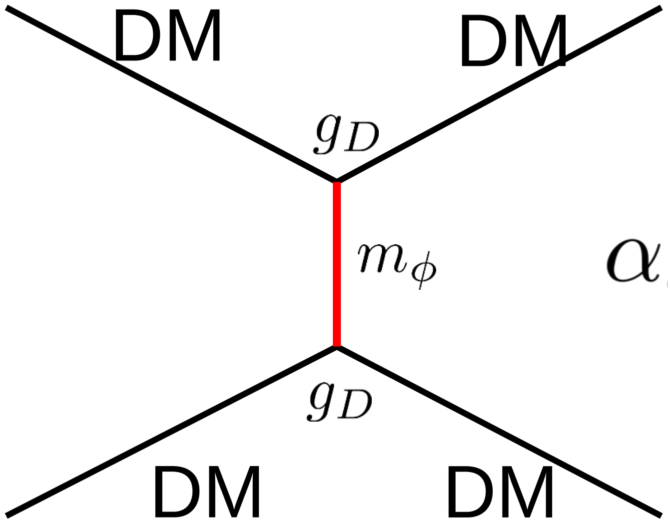
Old star observation ⇒ Constraint on attraction strength

Dark Cores

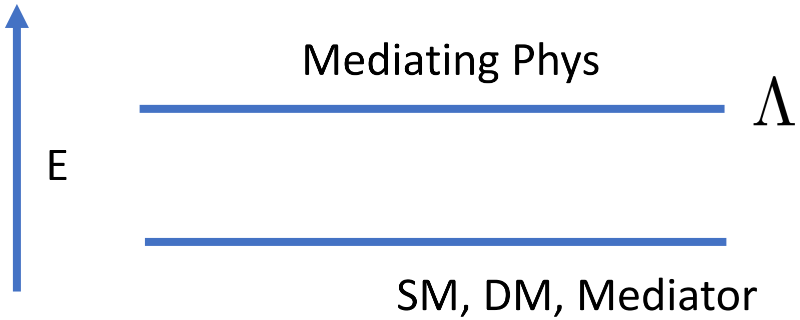


AJ, Serpico 2201.xxxx

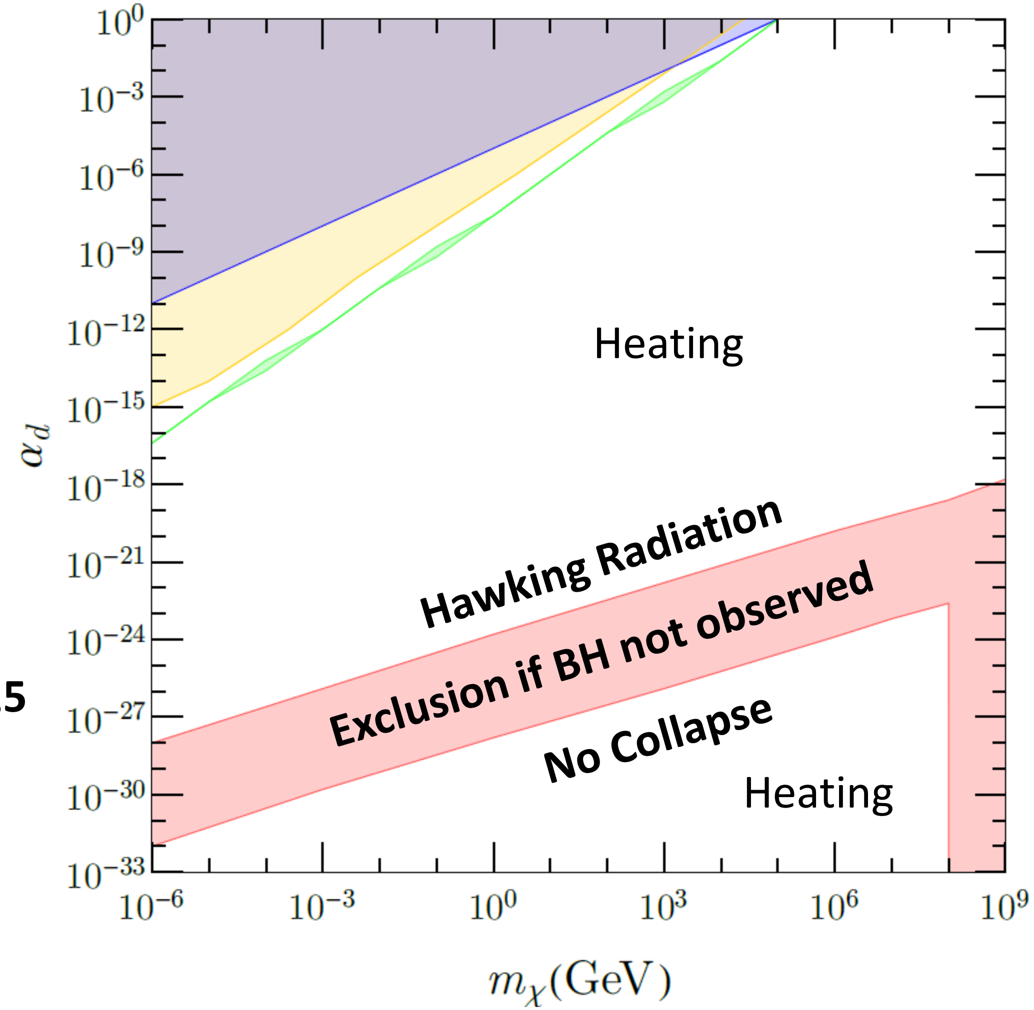
Exclusion Bounds from Non-observation of Collapse



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



PSR J0437–4715



Remarkable that huge parameter space prev. ignored, very tiny couplings for self-interactions can be probed

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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
- Thermal emission of old NS is an intriguing frontier. JWST launches very soon, so may be more data soon …

Thank You!