Searching for sub-GeV dark matter in celestial objects

Javier Acevedo

November 7th 2023

Based on: **JA**, Leane & Santos-Olmsted, **2309.10843**
JA, Leane & Smirnov, **2303.01516**

SLAC NATIONAL ACCELERATOR LABORATORY

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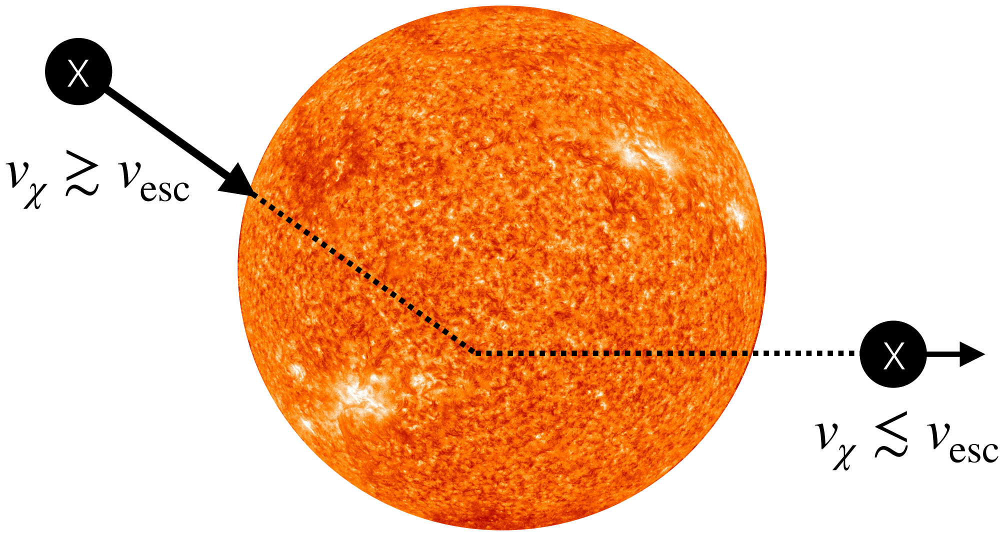
Celestial bodies as dark matter probes

$\sigma_{\chi-\mathrm{SM}} \neq 0$



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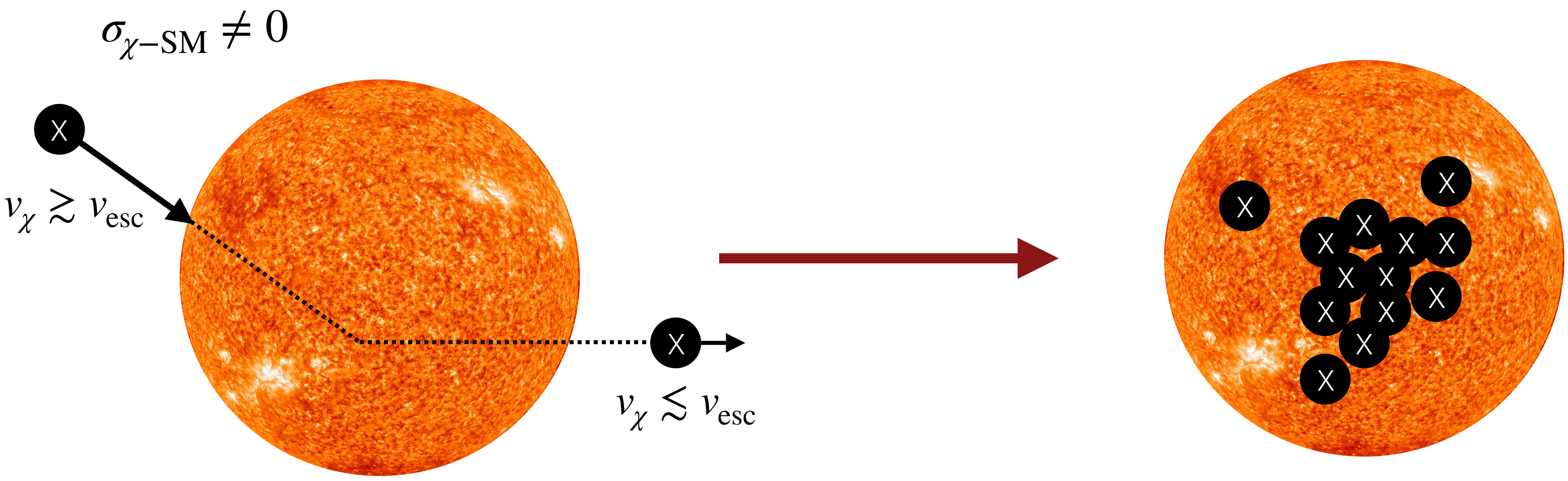
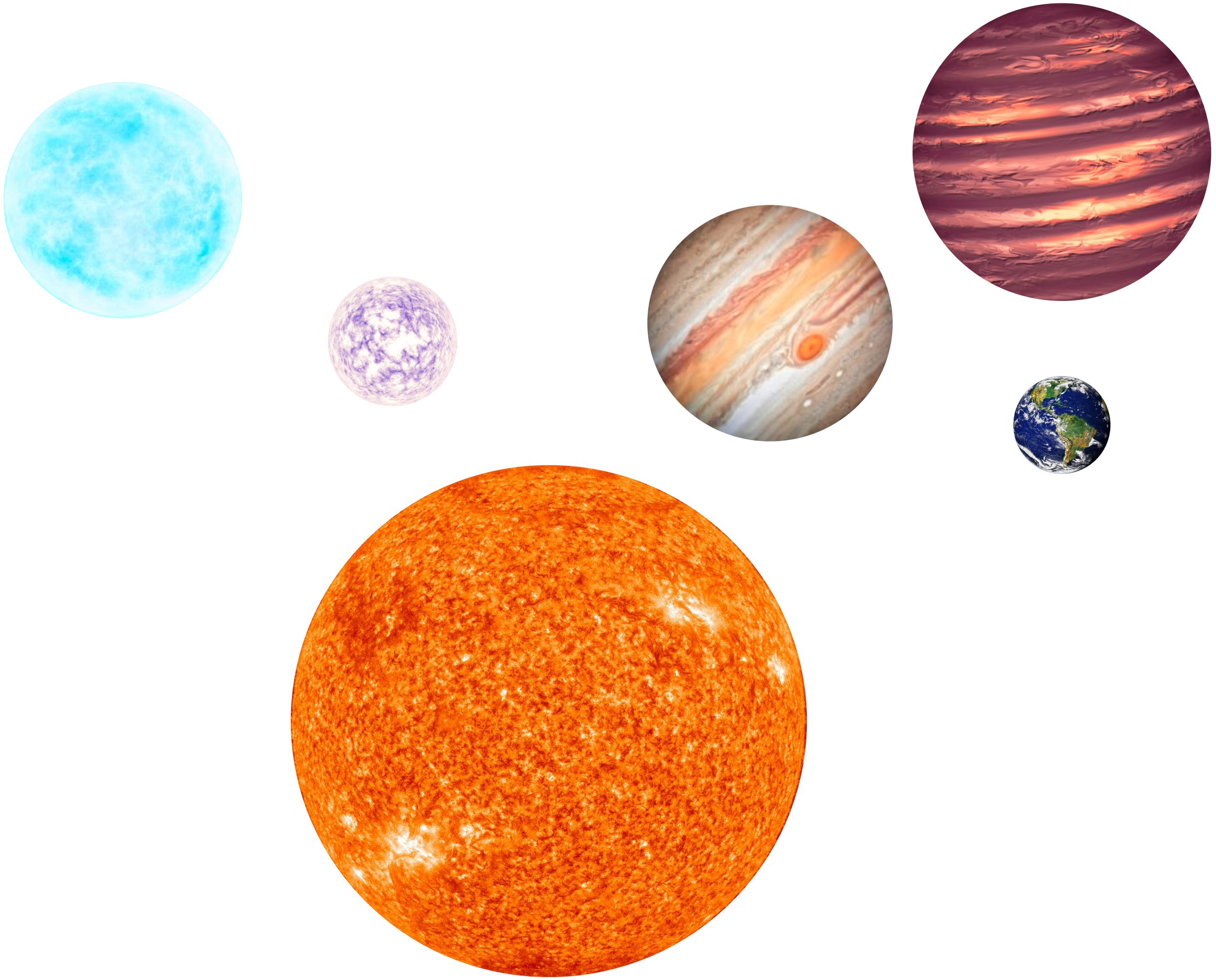


potential DM signal

Celestial bodies as dark matter probes



- Kinetic heating
- Stellar transients
- Type-Ia supernovae
- Annihilation to various states
- Transport processes
- Gravitational waves

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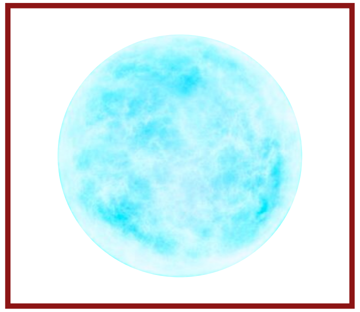
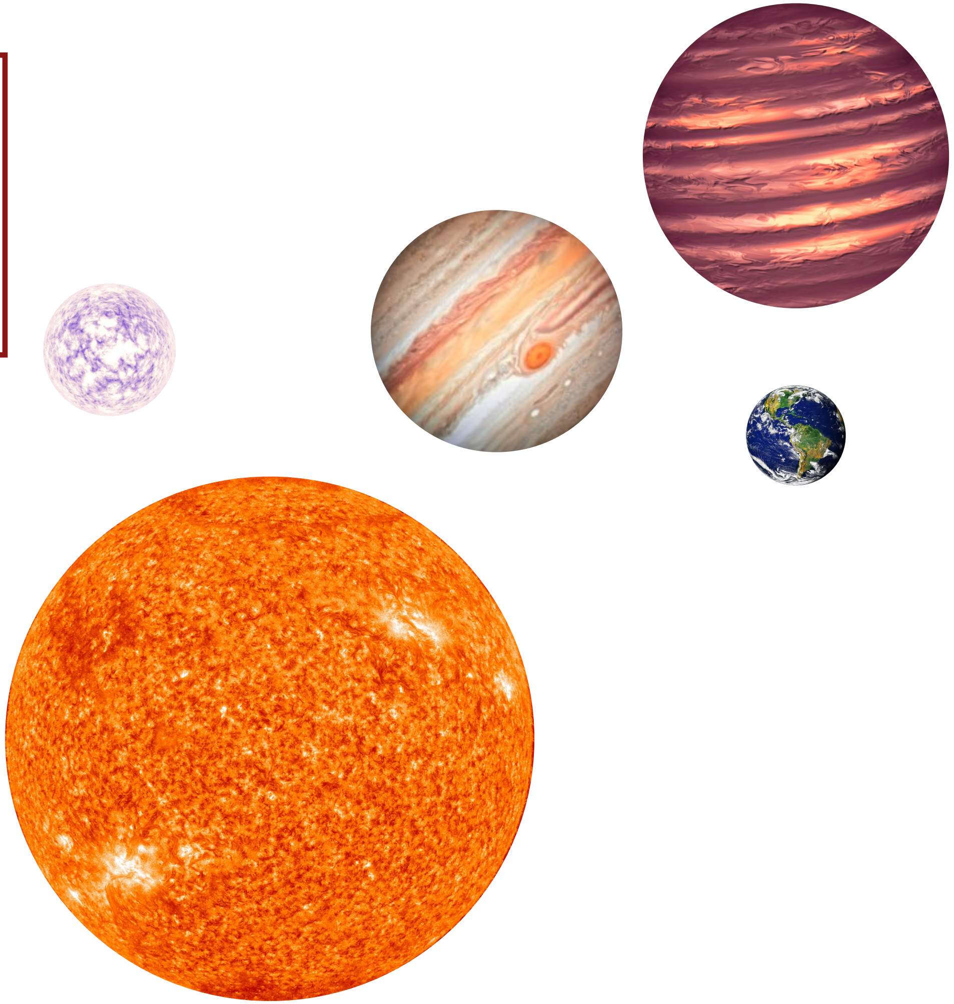
Celestial bodies as dark matter probes

white dwarfs



1st half of talk



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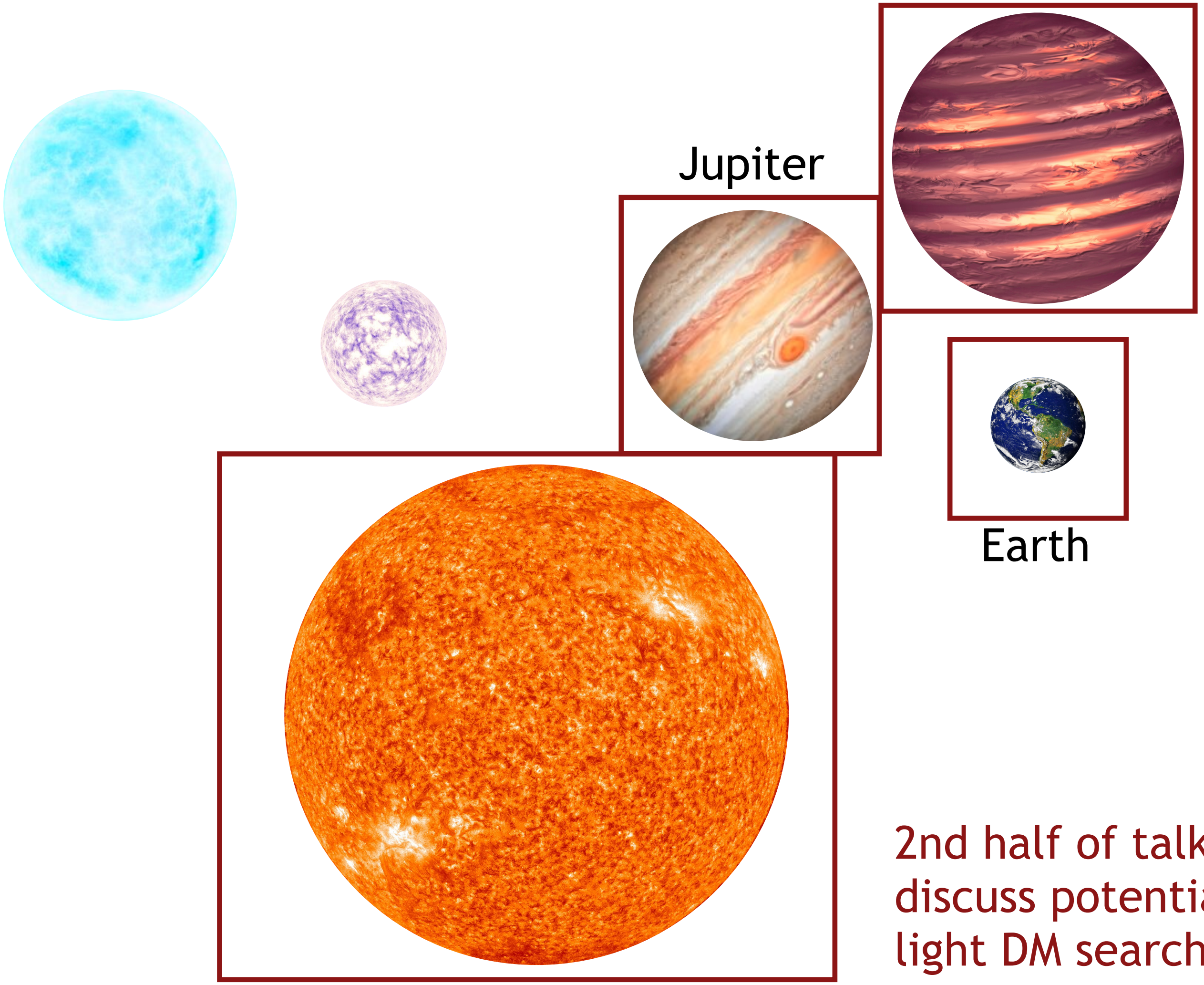

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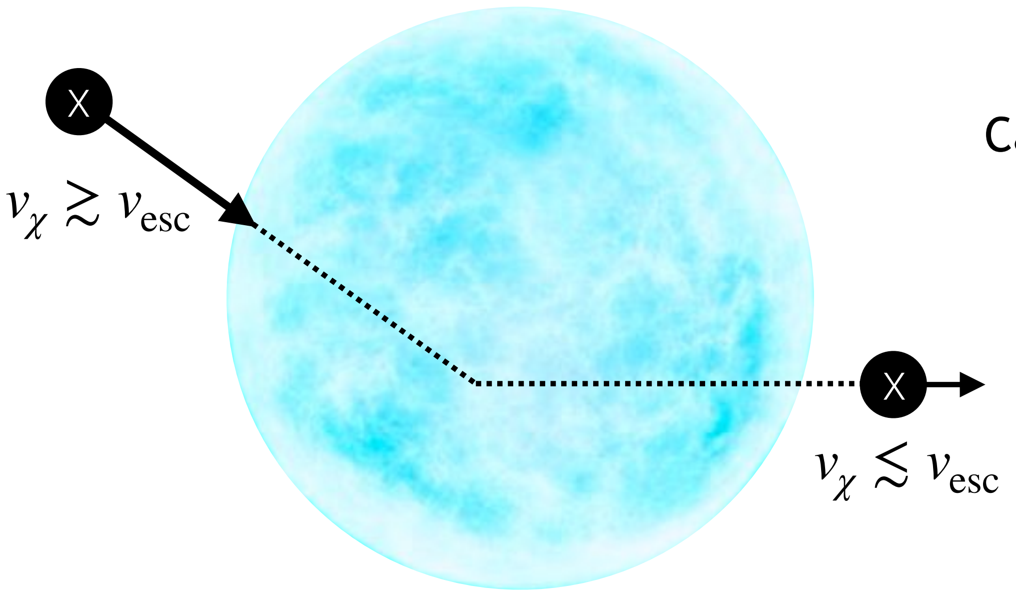
2nd half of talk:
discuss potential for
light DM searches in these

Dark Matter Capture in White Dwarfs



Capture rate in the optically thin limit:

$$C_{\rm WD} \sim \rho_\chi \times \left(\frac{\sigma_{n\chi}}{\sigma_{n\chi}^{\rm geom}}\right) \times F\left(m_\chi, m_N, v_\chi, v_N, R_{\rm WD} \ldots\right)$$

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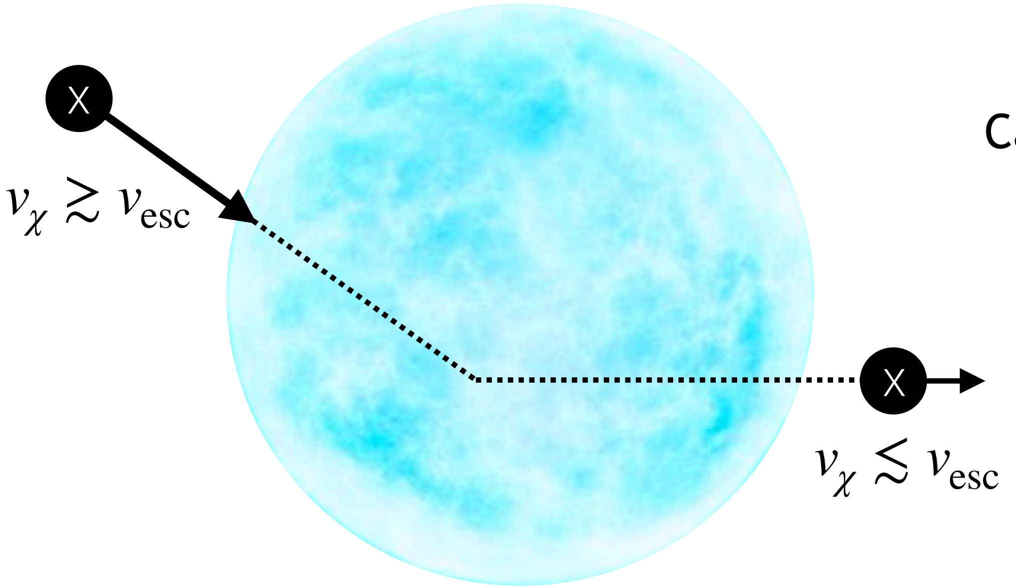

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density

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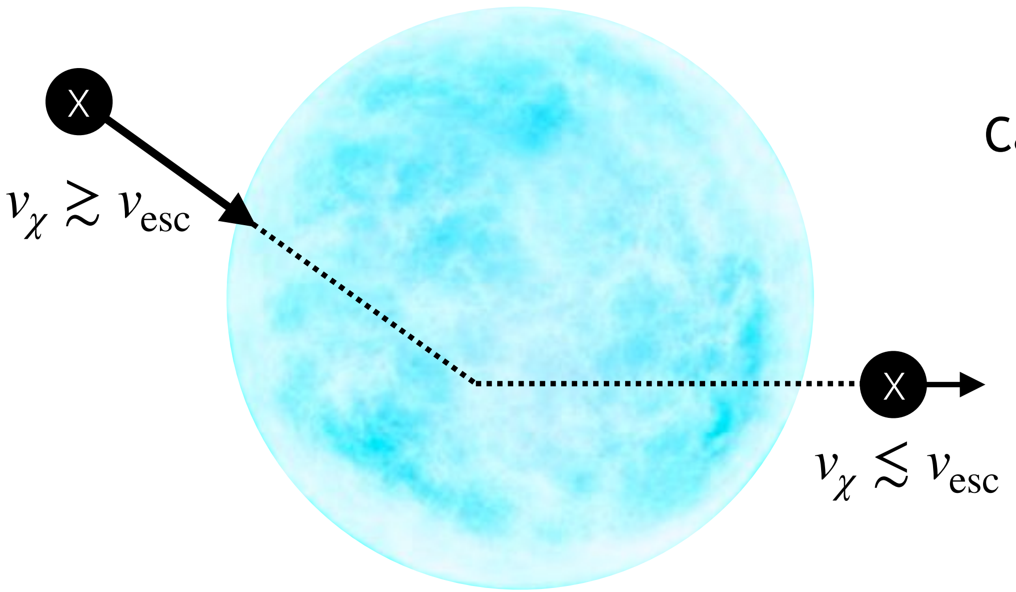

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density fraction

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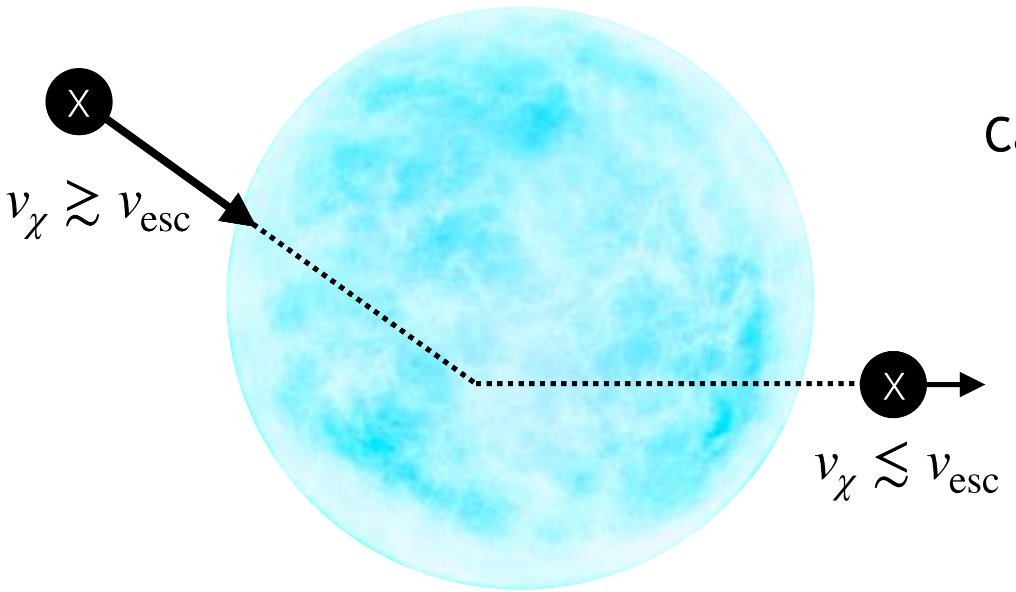

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density — fraction — some complicated function of kinematics

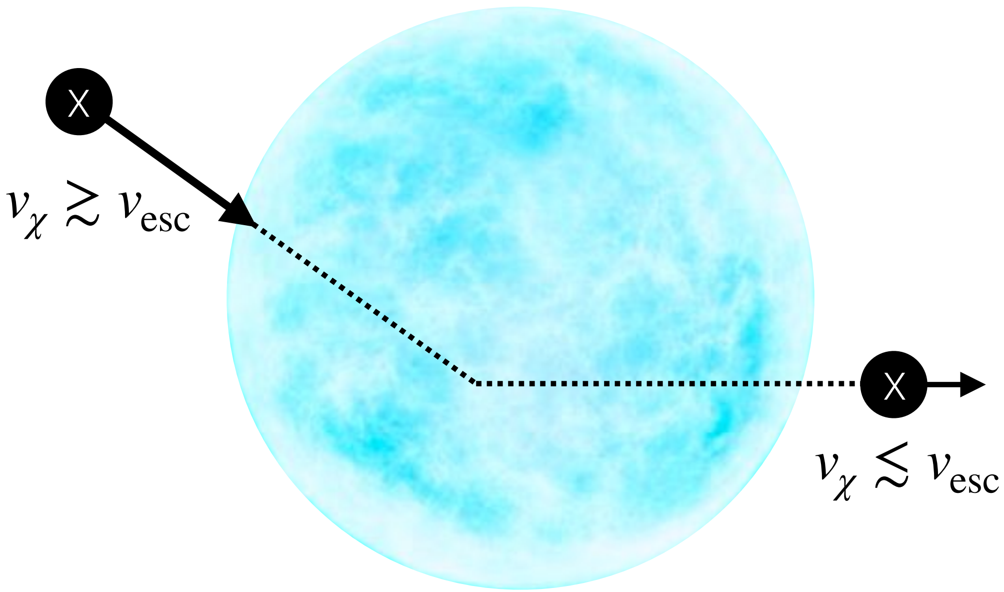
(ion velocity, WD motion, etc.)

for more details:

JA, Leane & Santos-Olmsted, 2309.10843

Dark Matter Capture in White Dwarfs

* will revisit later



Compared to other objects:

- High density
- Relatively large radius
- Low evaporation mass*
- Distances O(pc)
- High internal temperature

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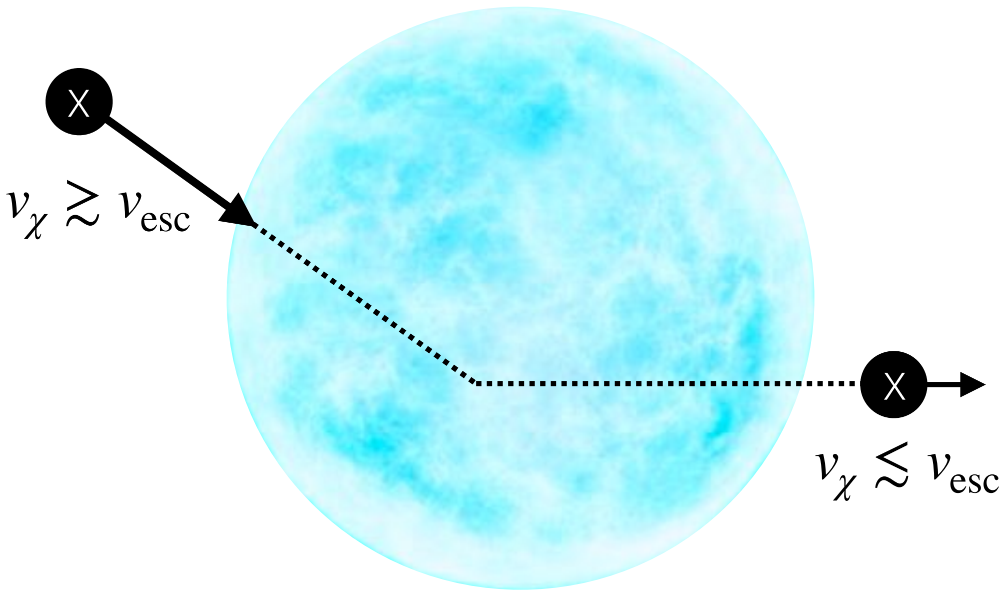

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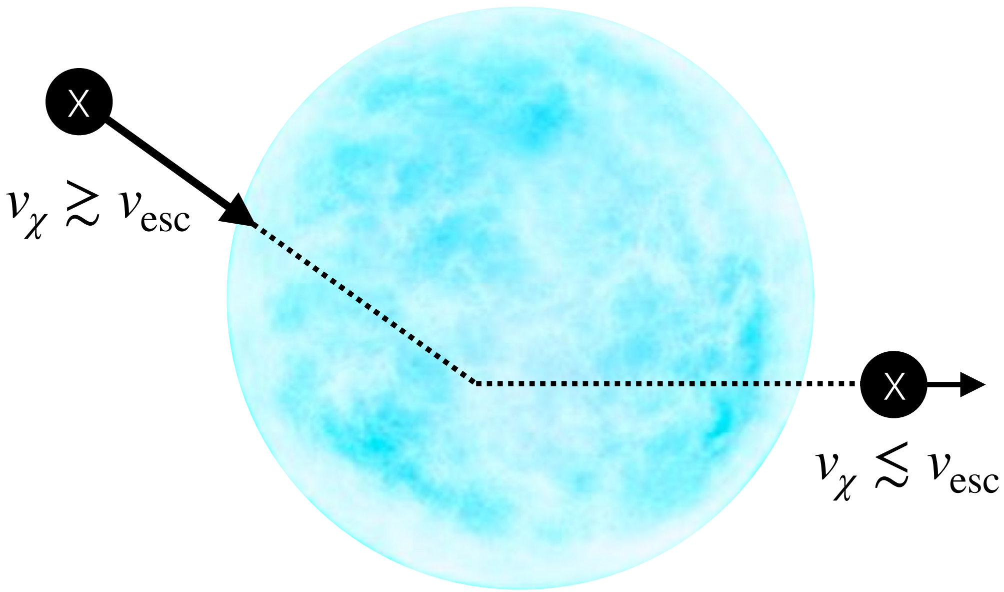

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some works circumvent this by considering Globular Cluster M4

DM content is uncertain there

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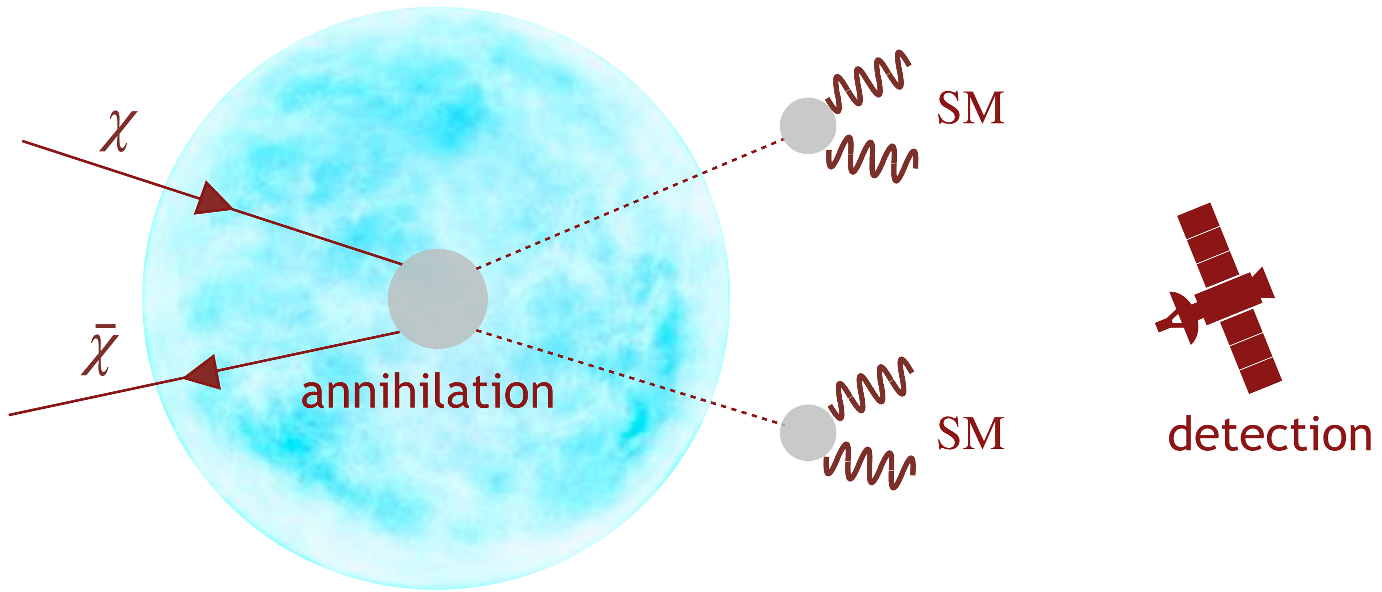
Annihilation to long-lived mediators

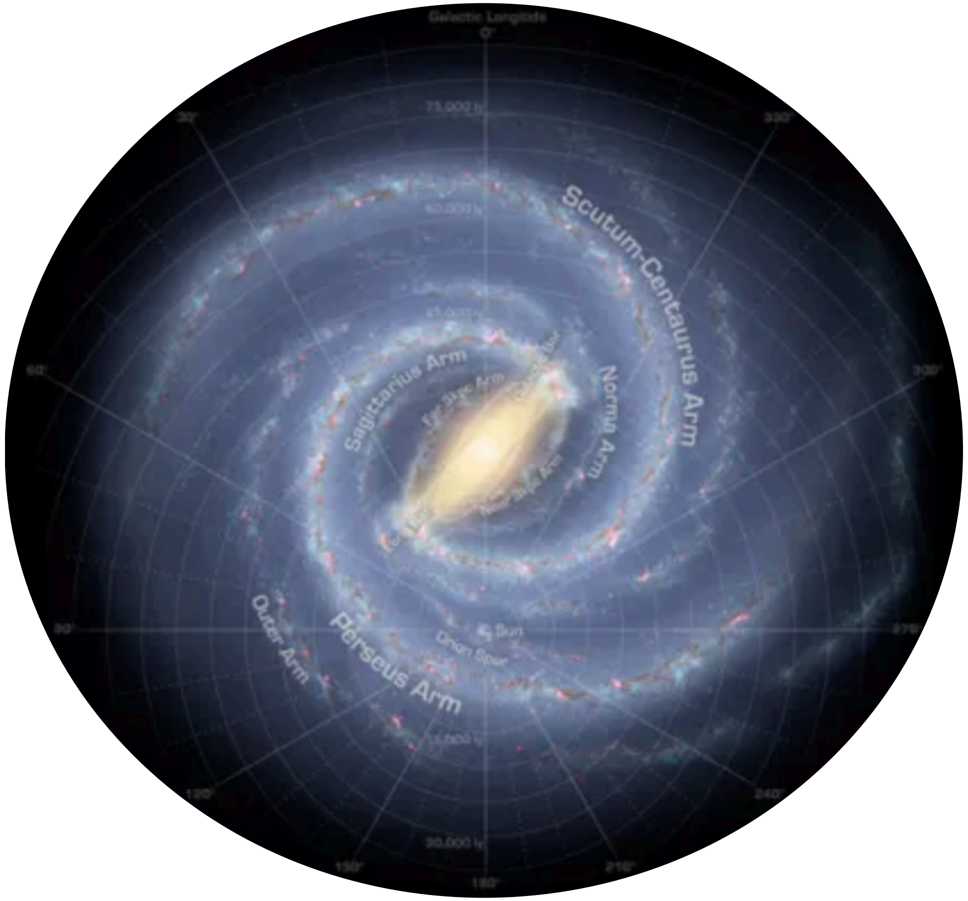


See e.g.

Schuster, Toro, Weiner & Yavin, 0910.1839
Feng, Smolinsky & Tanedo, 1602.01465
Leane, Ng & Beacom, 1703.05629
Leane, Linden, Mukhopadhyay, & Toro, 2101.12213
Bell, Dent & Sanderson, 2103.16794
Bose, Maity & Ray, 2108.12420
Nguyen & Tait, 2212.12547

Goal: target the Galactic Center where DM content is known to be high and WDs are abundant

Galactic Signal of DM annihilation in WDs



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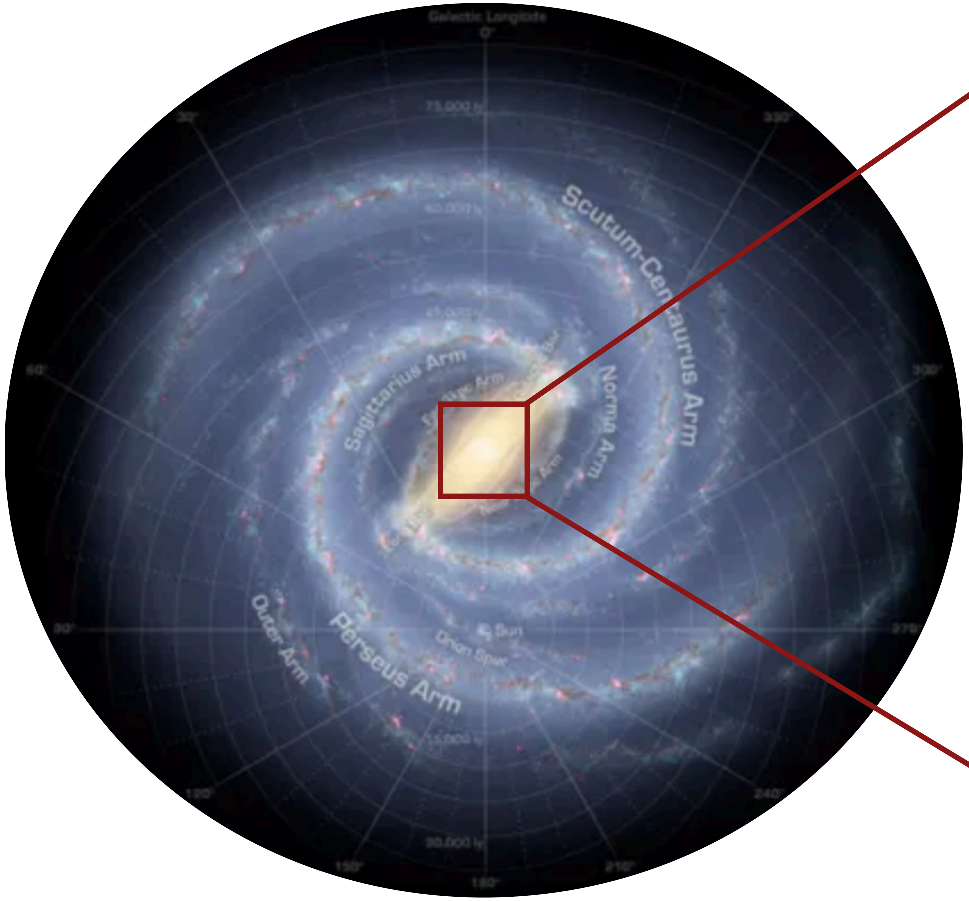
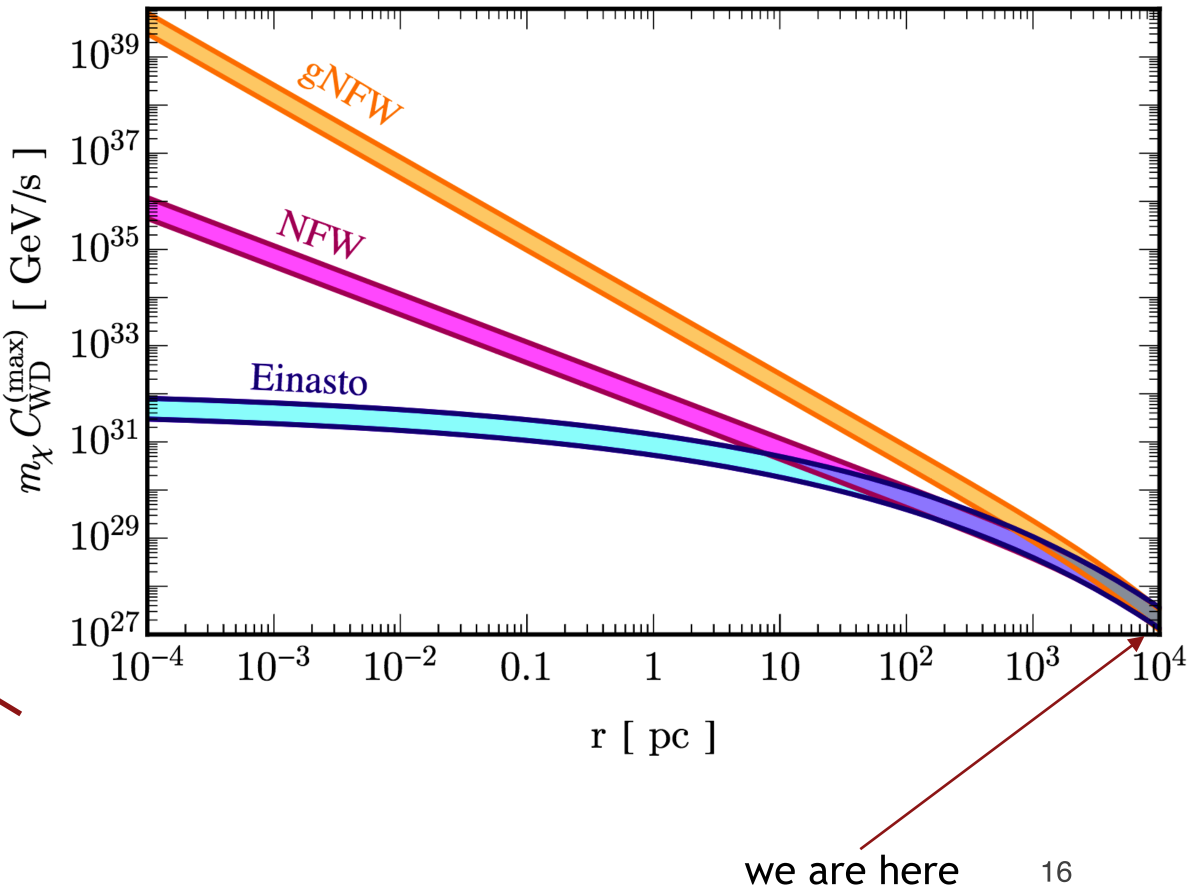


Max capture rate:

JA, Leane & Santos-Olmsted, 2309.10843



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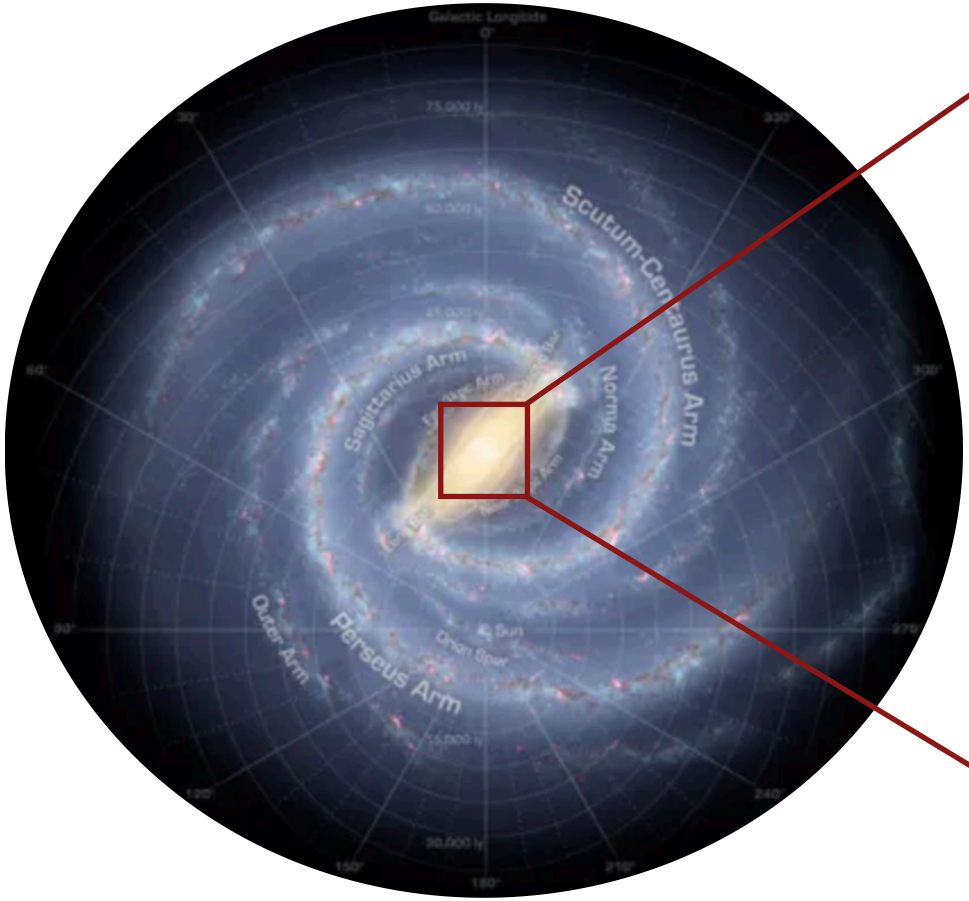
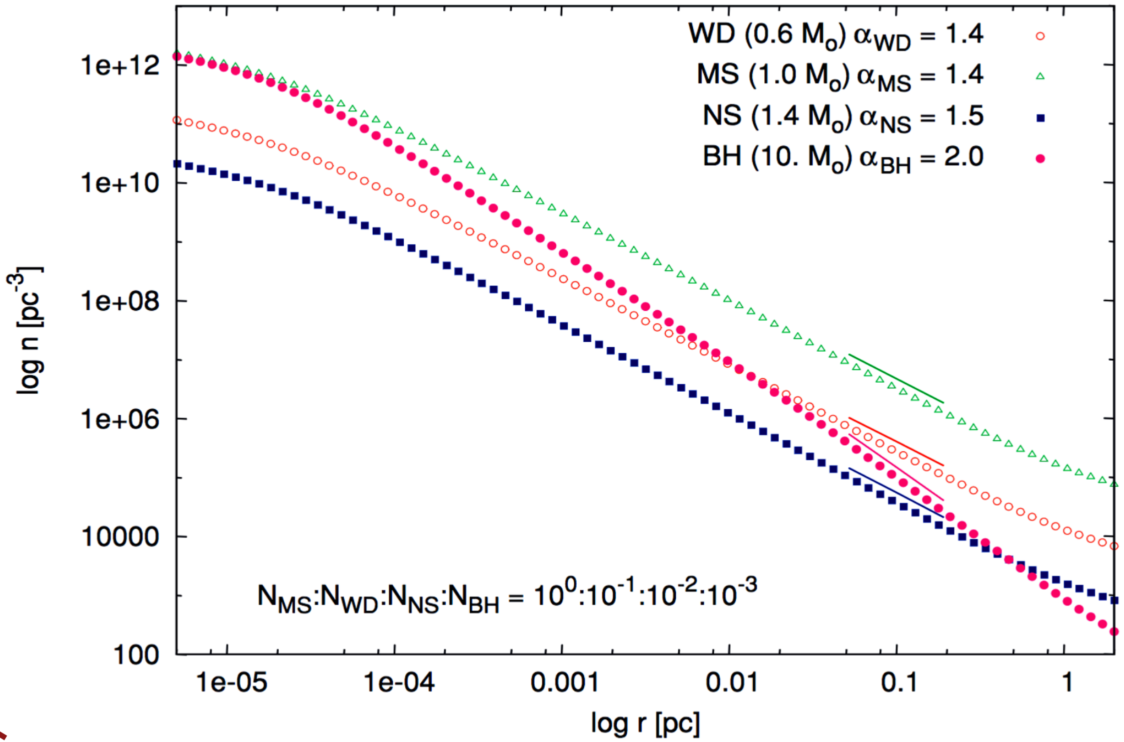


WD density:

Hopman & Alexander, 0808.3150



see also e.g.:
Panamarev et. al., 1805.02153
Baumgardt et. al., 1701.03818
Habibi et. al., 1902.07219
Schödel et. al., 1701.03817
Chen et. al., 2212.01397

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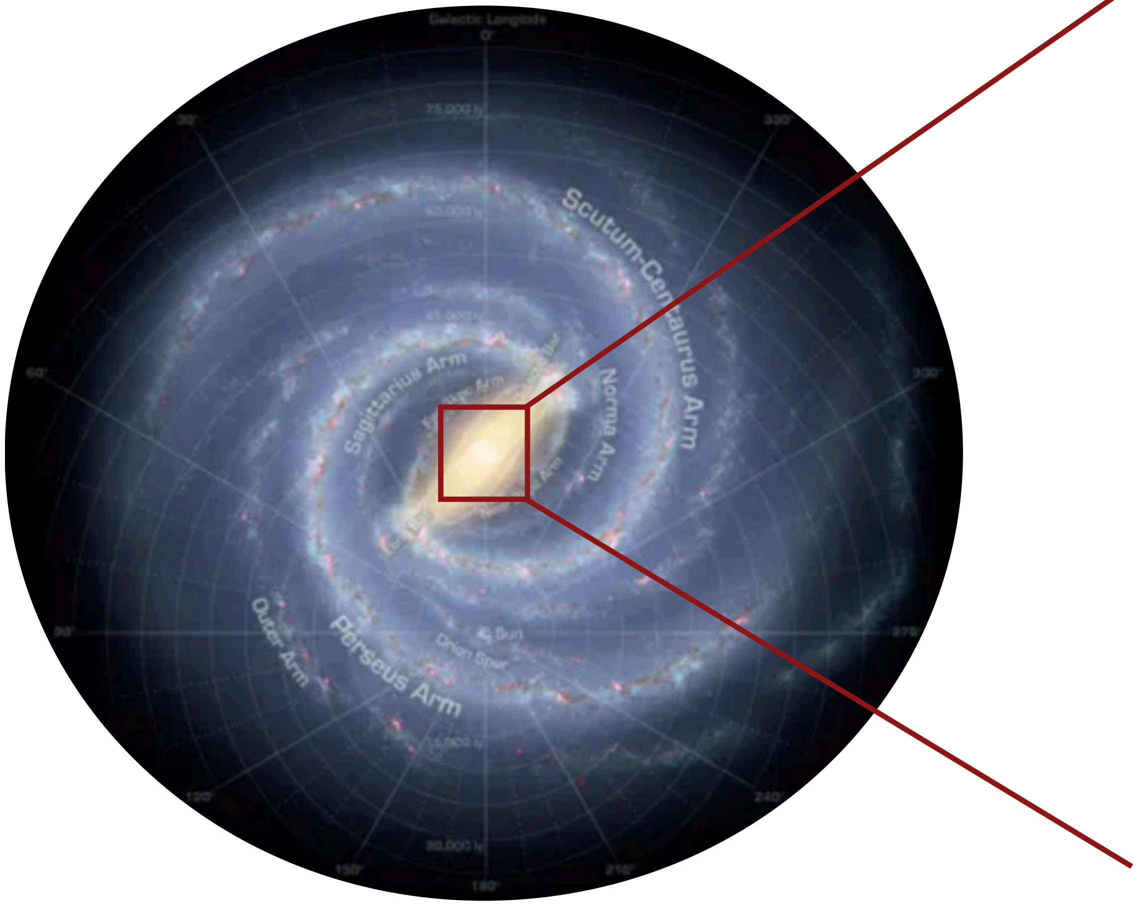
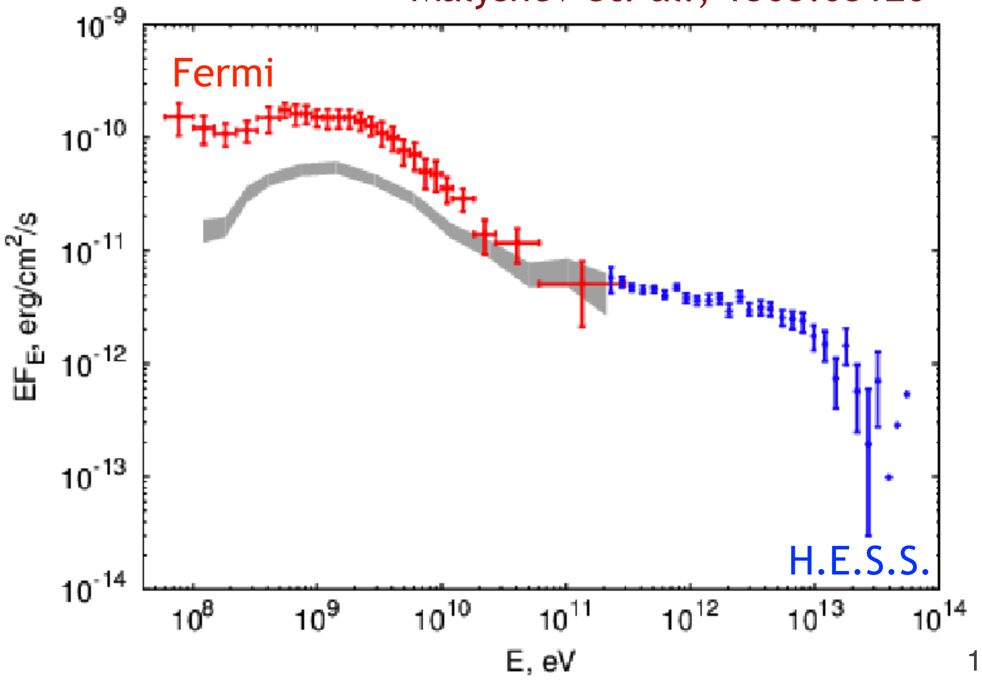


Integrated signal:

$$E_\gamma^2 \frac{d\Phi_\gamma}{dE_\gamma} = \int_{r_{min}}^{r_{\max}} \frac{\Gamma_{\text{ann}}}{4\pi D^2} \times E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \times n_{\text{WD}}(r) \times 4\pi r^2 dr$$

Malyshev et. al., 1503.05120



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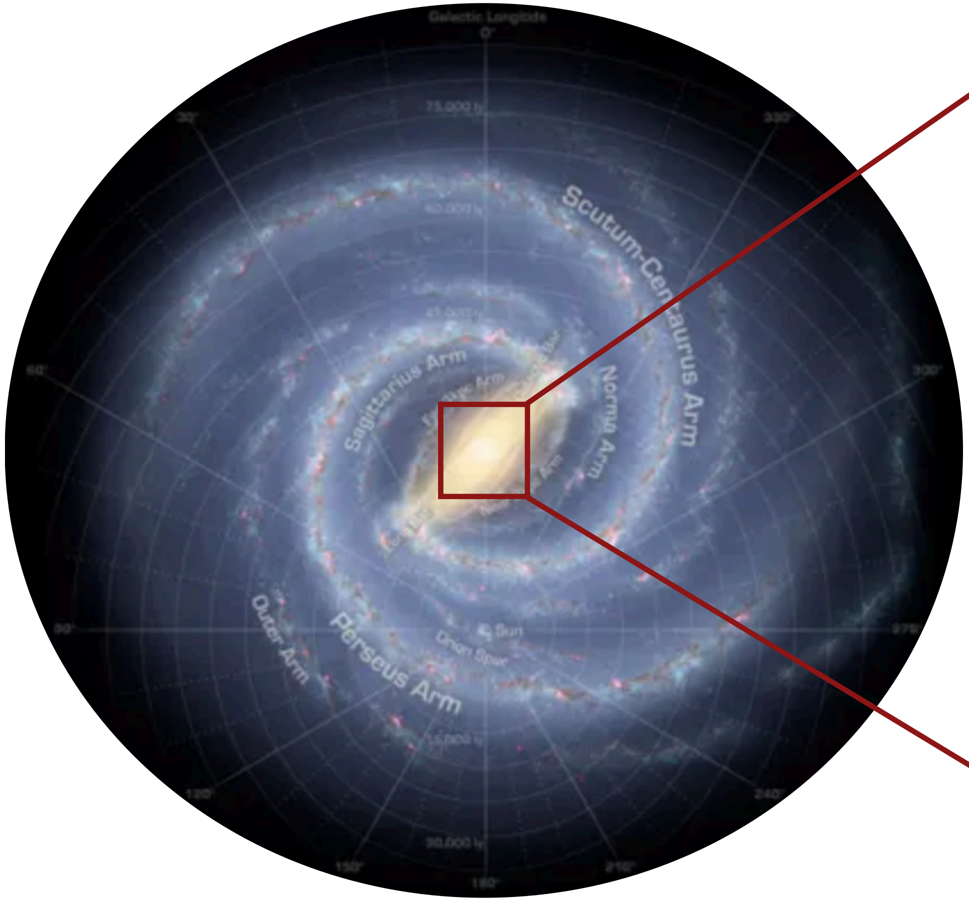

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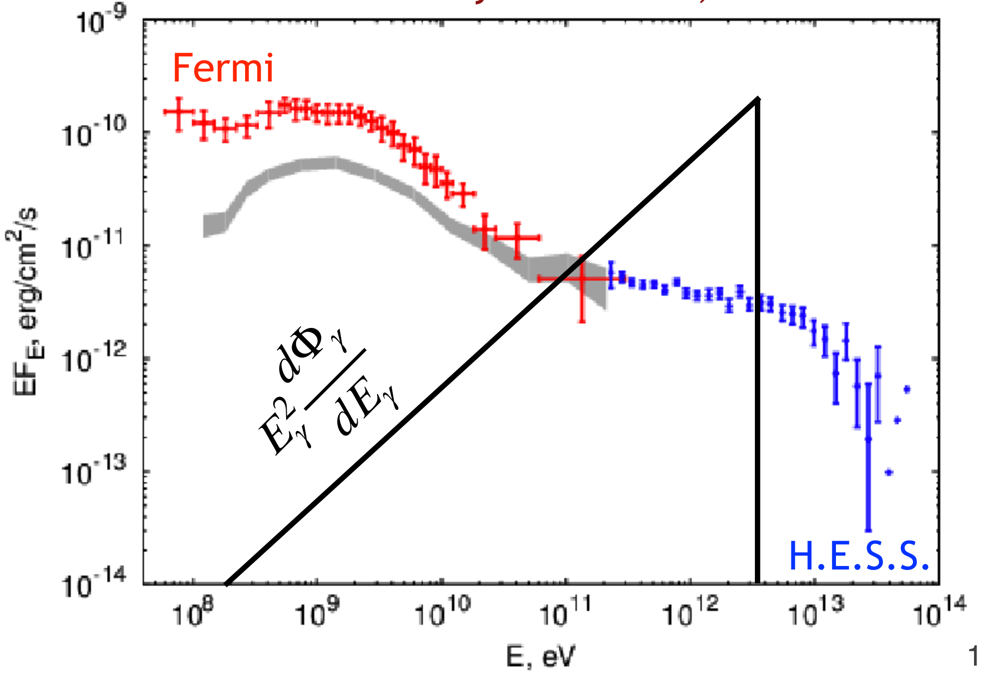

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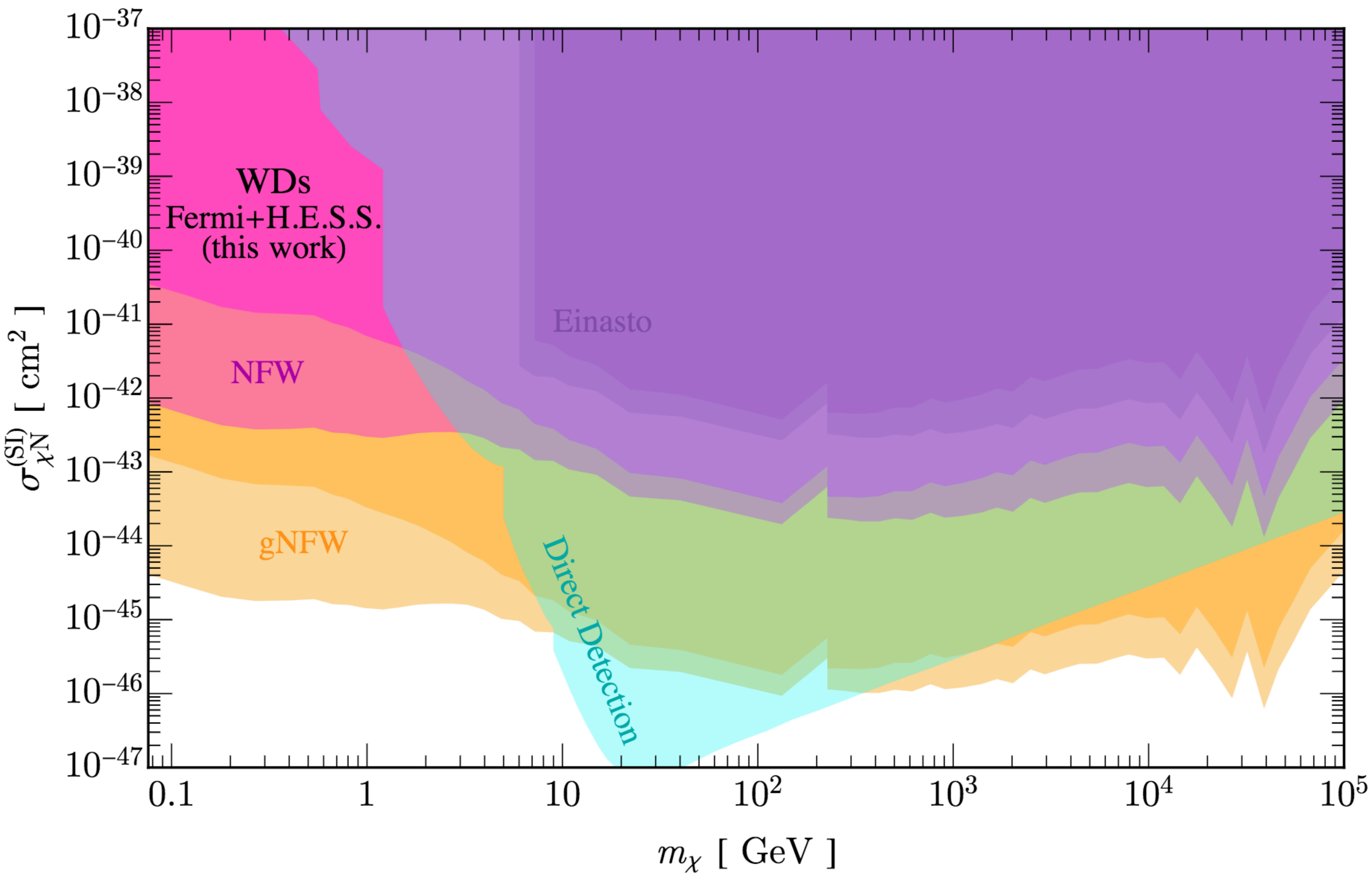
Sub-GeV (and TeV) DM Limits



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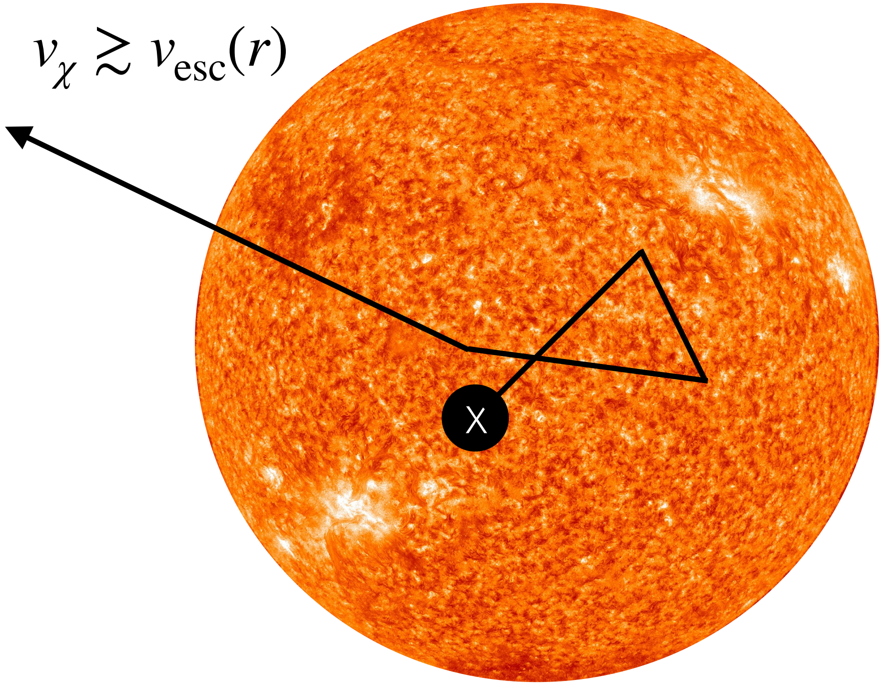
Dark matter evaporation

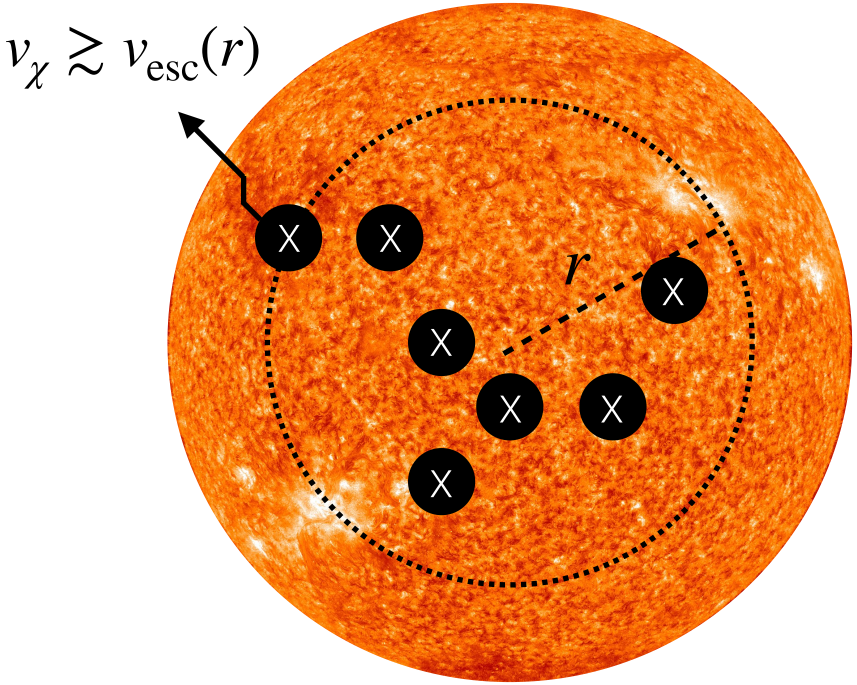


Evaporation: thermal upscattering of the DM to the escape velocity

e.g. for the Sun:

$$\frac{3}{2}T_{\rm central} \sim \frac{GM_* m_\chi}{R_*} \longrightarrow m_\chi \gtrsim 0.91 \ {\rm GeV}$$

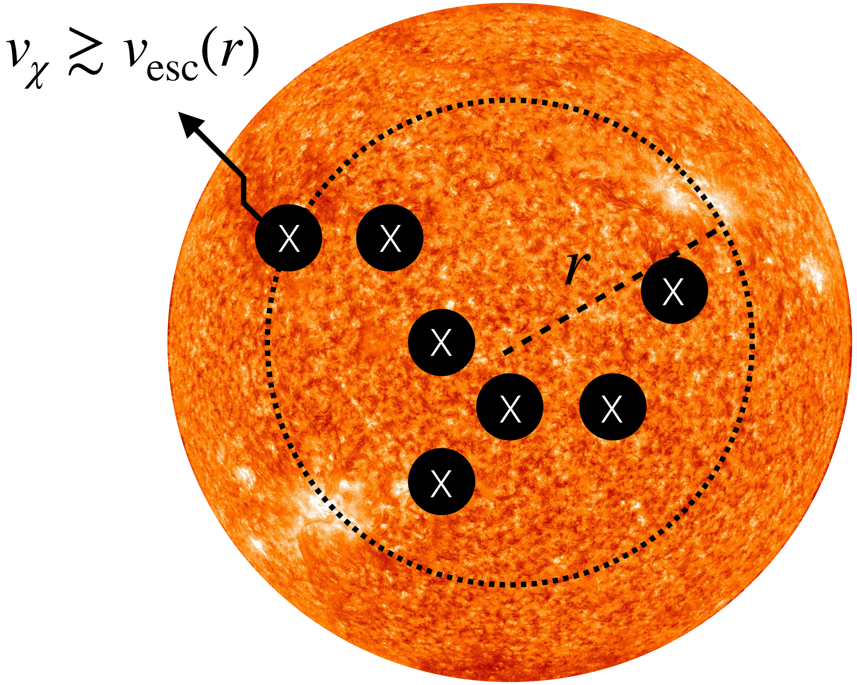
Dark matter evaporation



Accurate evaporation rate:

$$\Gamma_{\rm evap} \propto \exp\left(-\frac{\phi_{\rm grav}(r)}{T(r)}\right)\exp\left(-\tau(r)\right)$$

Dark matter evaporation



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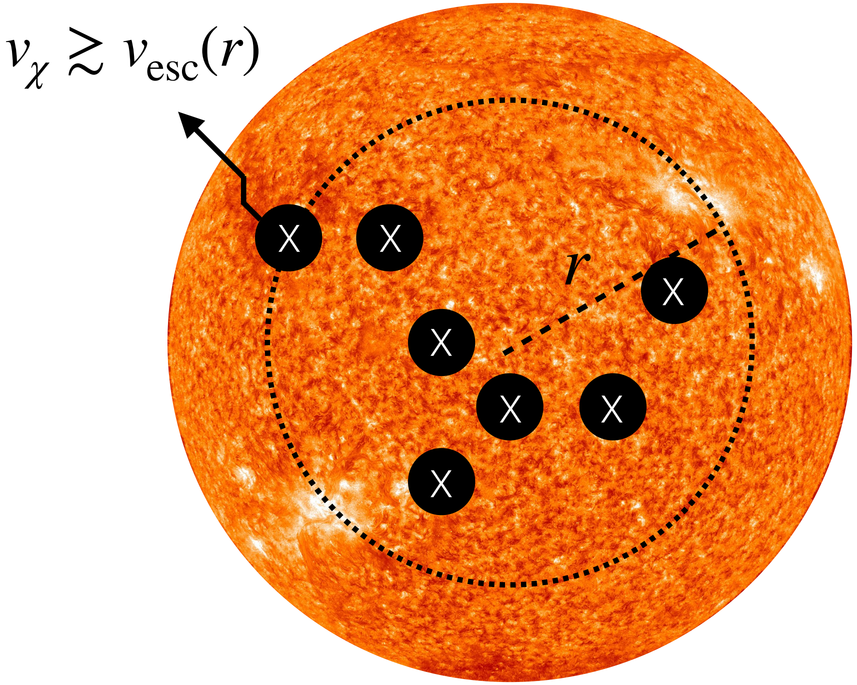
escape energy vs. temperature

Dark matter evaporation

for full details see e.g.
Gould, Astrophys. J. 356 (1990)



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escape energy vs. temperature (first factor); optical depth to surface (second factor)

Dark matter evaporation

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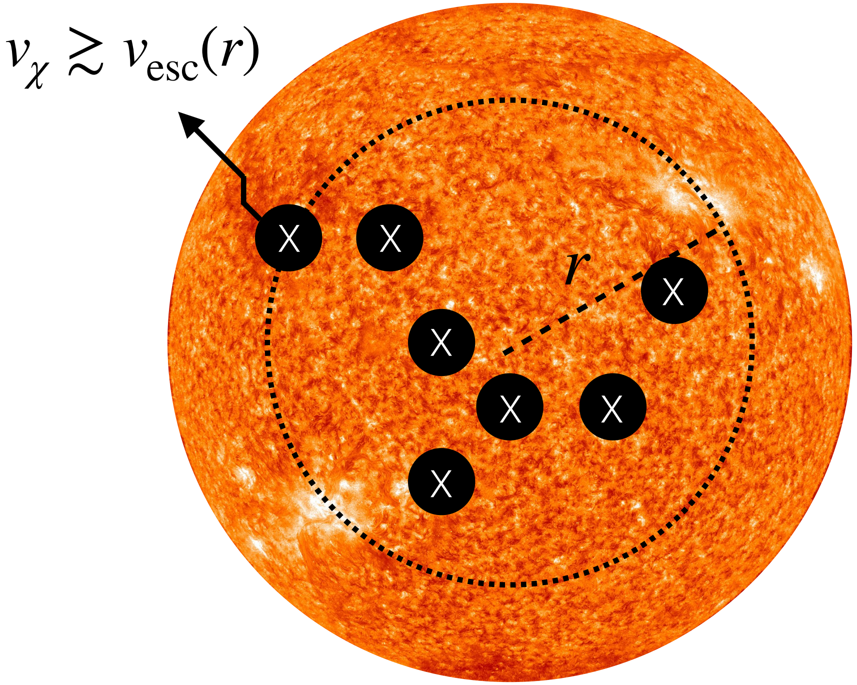

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escape energy vs. temperature

optical depth to surface

Usual assumptions:
- DM-SM contact interactions
- Only gravity and temperature matters

Computing the evaporation mass

Net DM number given by: $\dot{N}_\chi = \Gamma_{\rm cap} - \Gamma_{\rm evap} N_\chi - \Gamma_{\rm ann} N_\chi^2$

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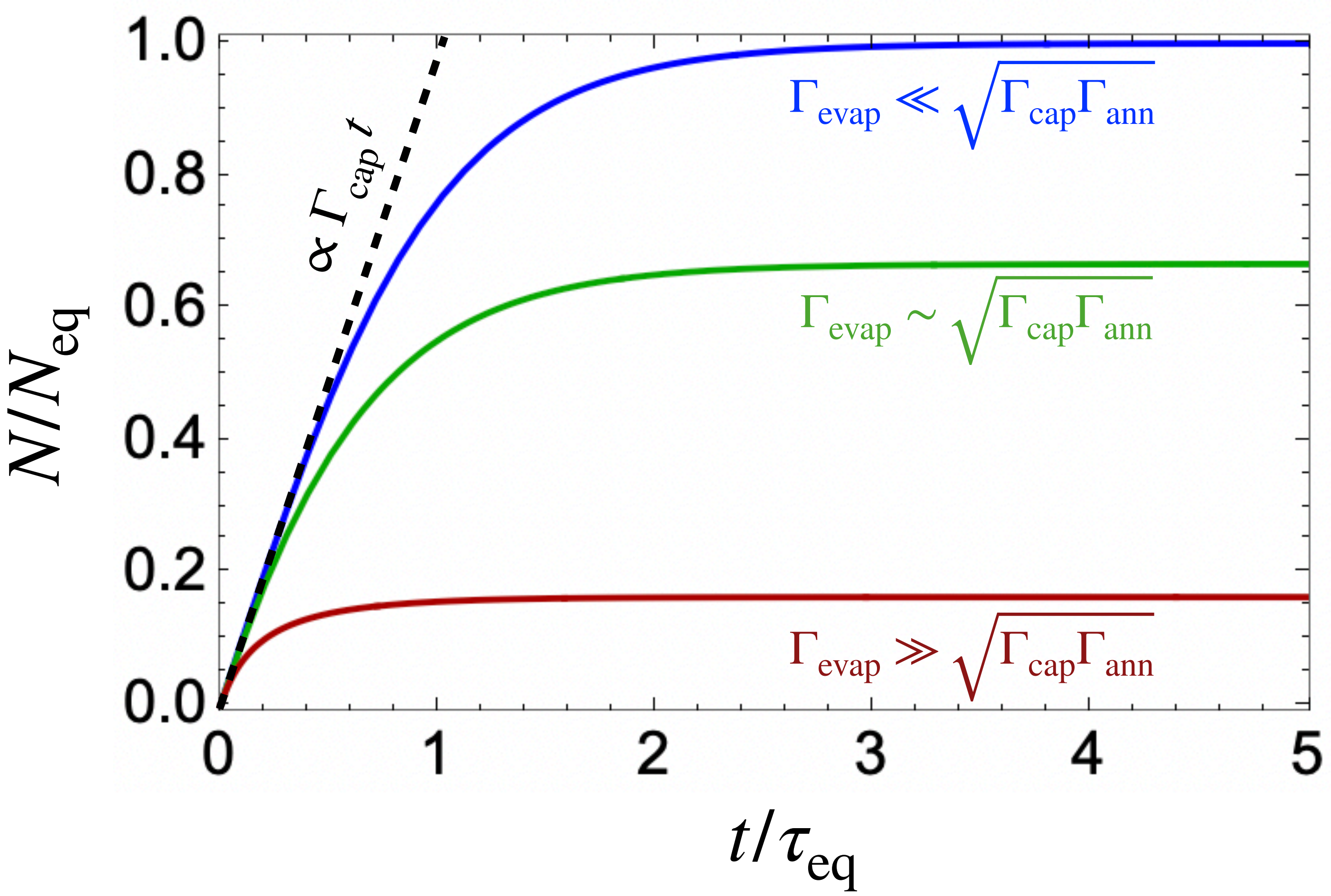

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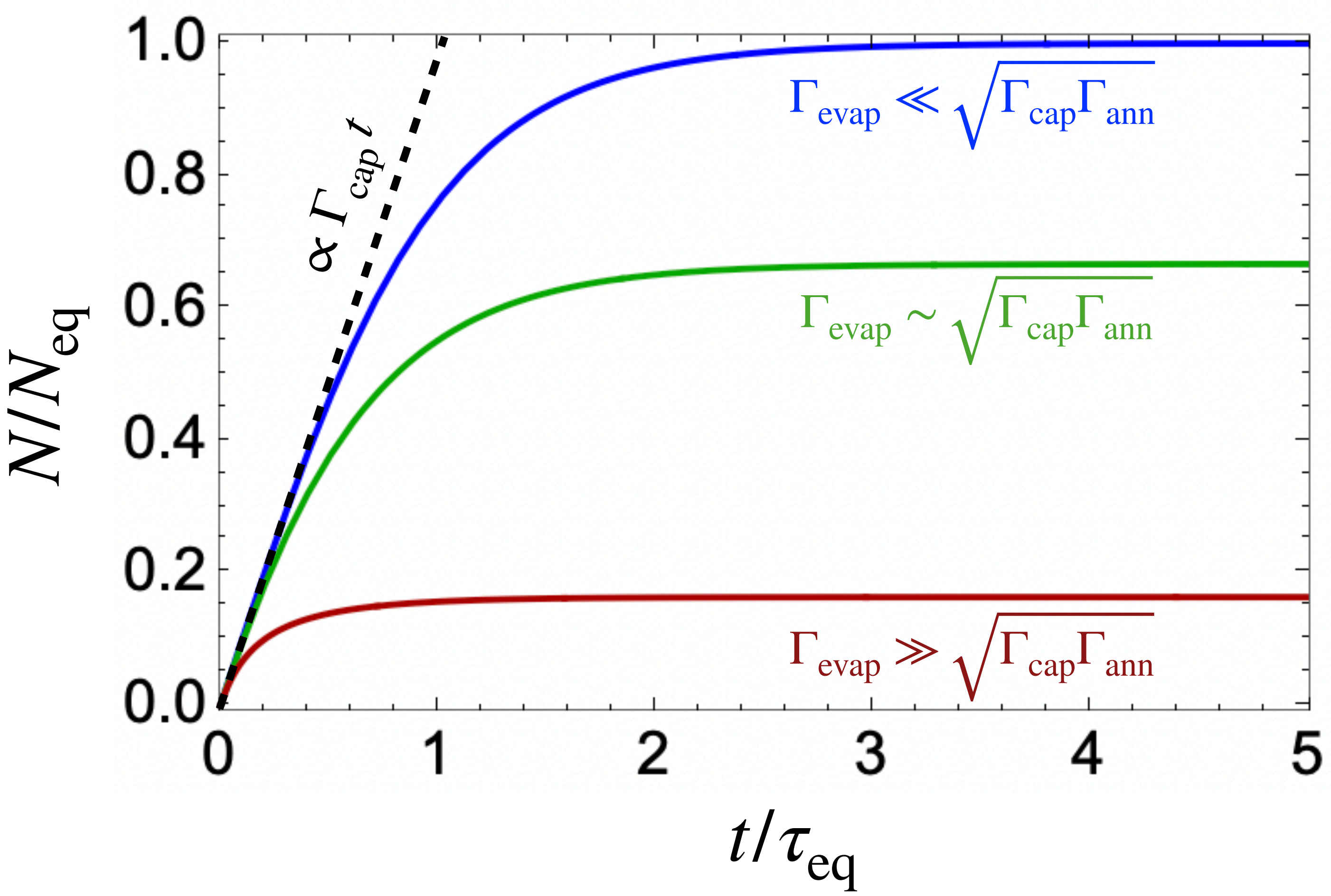
for the Sun:



$m_\chi \simeq 3.21$ GeV

$m_\chi \simeq 3.20$ GeV

$m_\chi \simeq 3.19$ GeV

(at cross-section ~10^{-35} cm^2)

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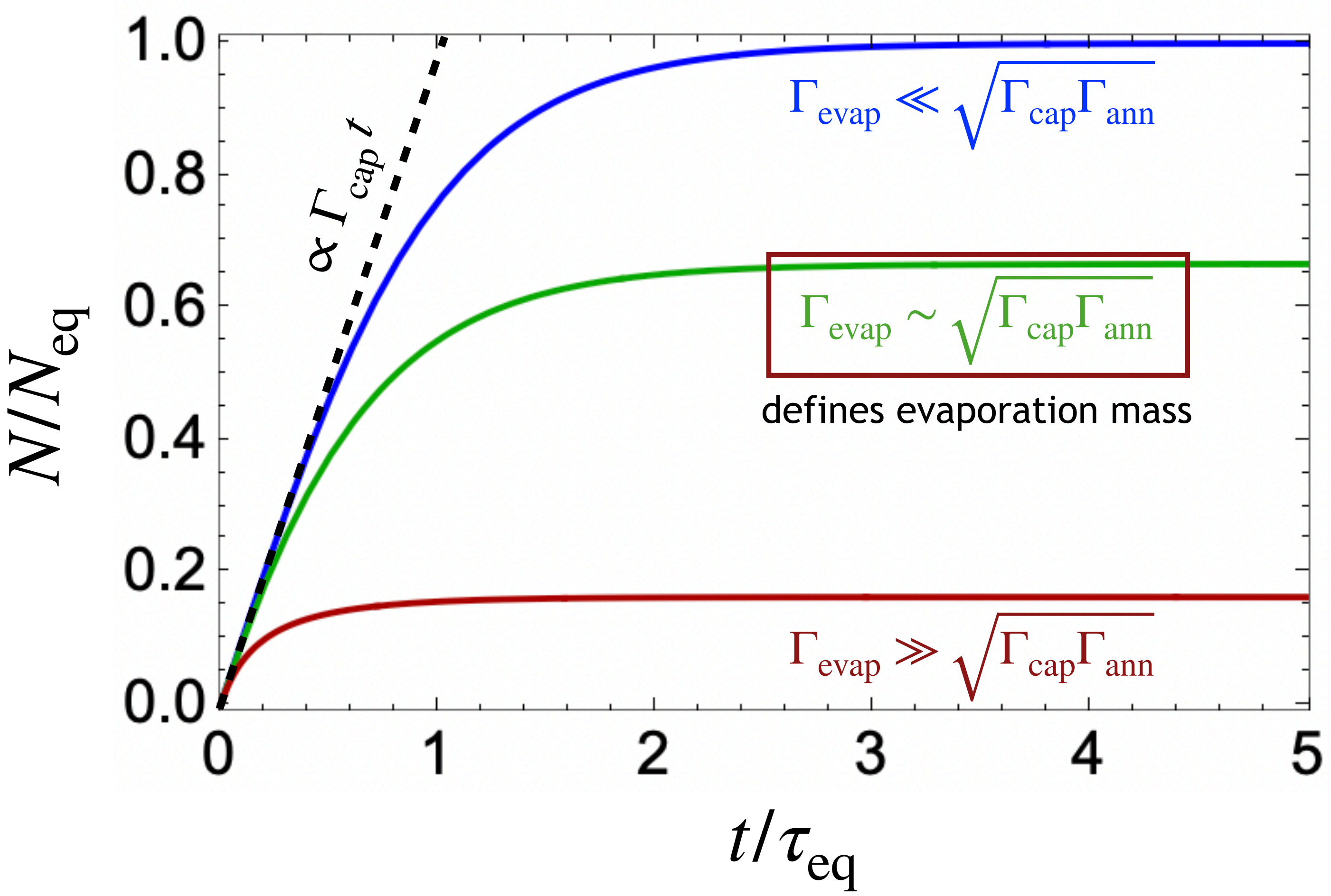

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- Light scalars, or vectors w/ correct charge assignment mediate long-range DM-SM attractive forces.

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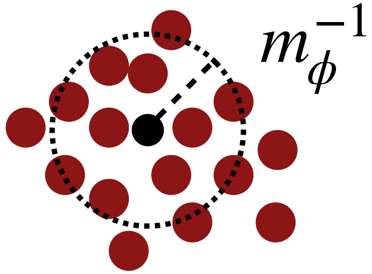
- DM particles "see" the large density of particles in celestial objects.



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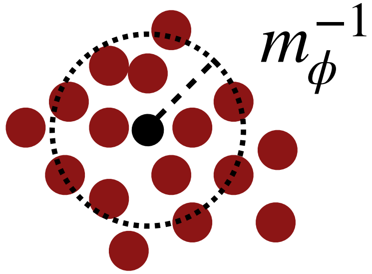

- Celestial objects source a potential for the DM:

$$\phi_{\rm barrier}(r) \sim \frac{n_{\rm SM}(r)}{m_\phi^2}$$

JA, Leane & Smirnov, 2303.01516

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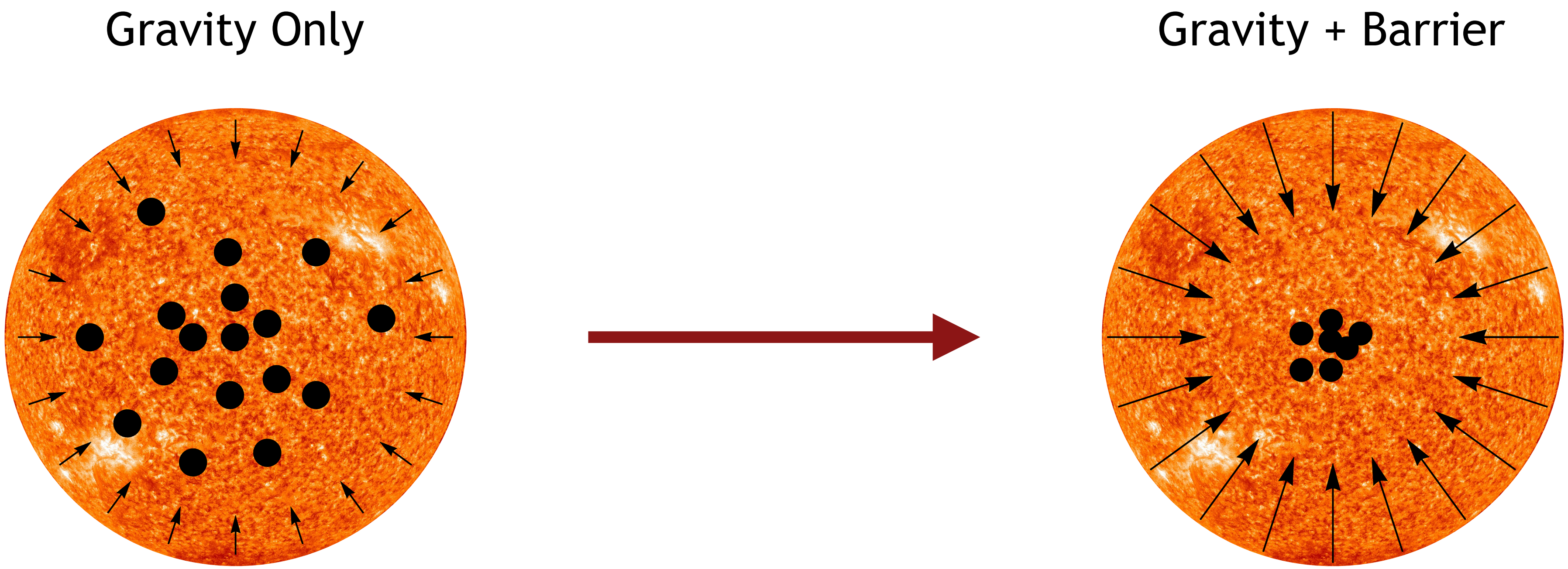
Evaporation Barrier



- Enhanced annihilation rate
- Increased overburden for evaporation
- Increased escape energy

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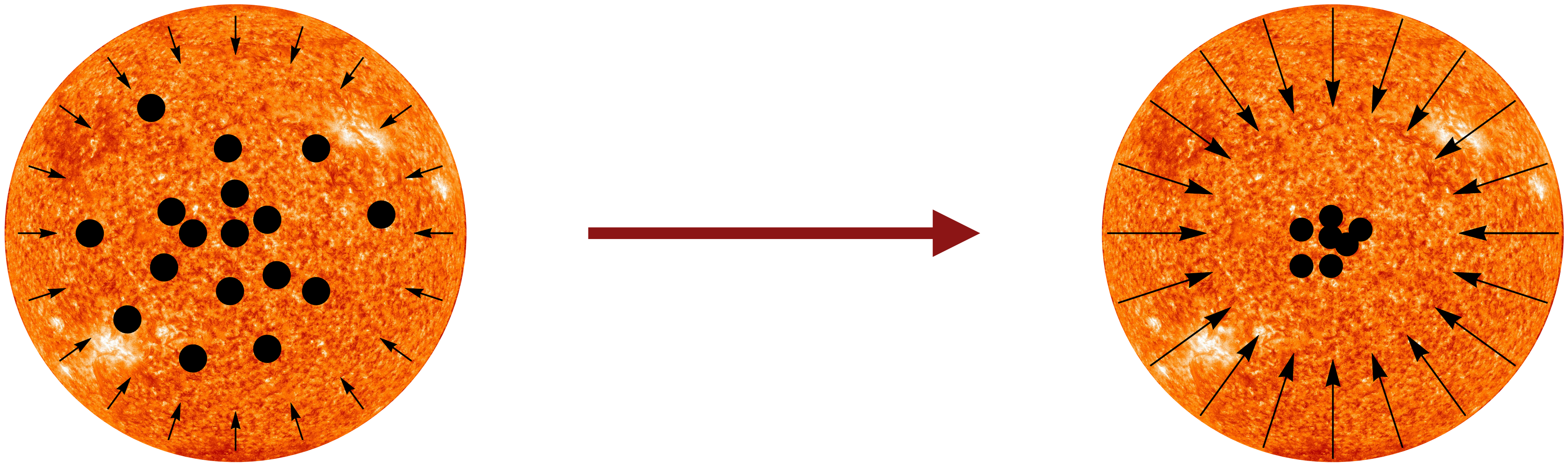
Evaporation Barrier

Gravity Only

Gravity + Barrier



- Enhanced annihilation rate

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exponential suppression to evaporation rate

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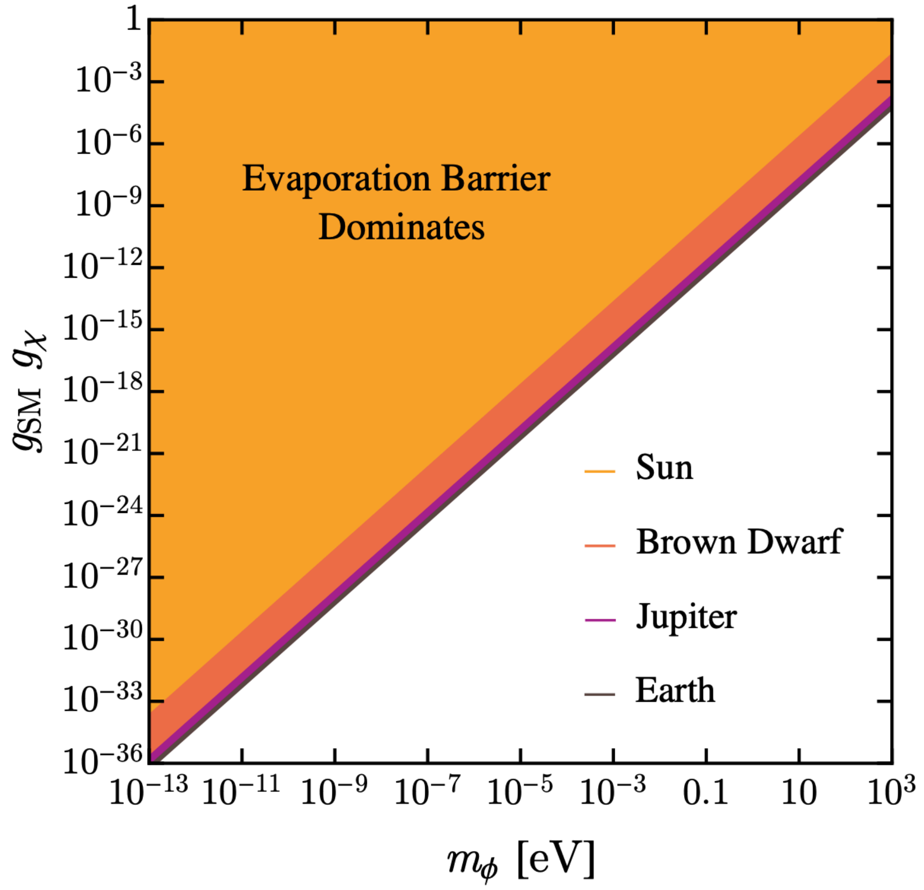
Evaporation Barrier

Evaporation mass changes when: $\phi_{\rm barrier}(r) \gtrsim \phi_{\rm grav}(r)\Big|_{m_\chi^{\rm evap}}$



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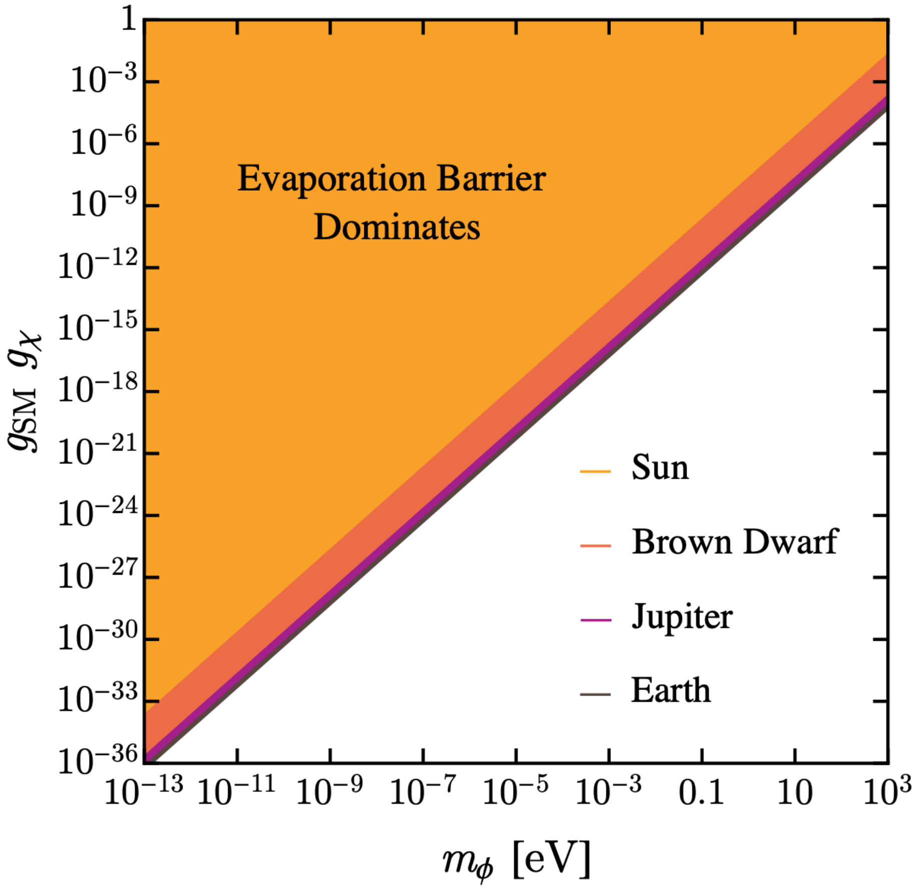
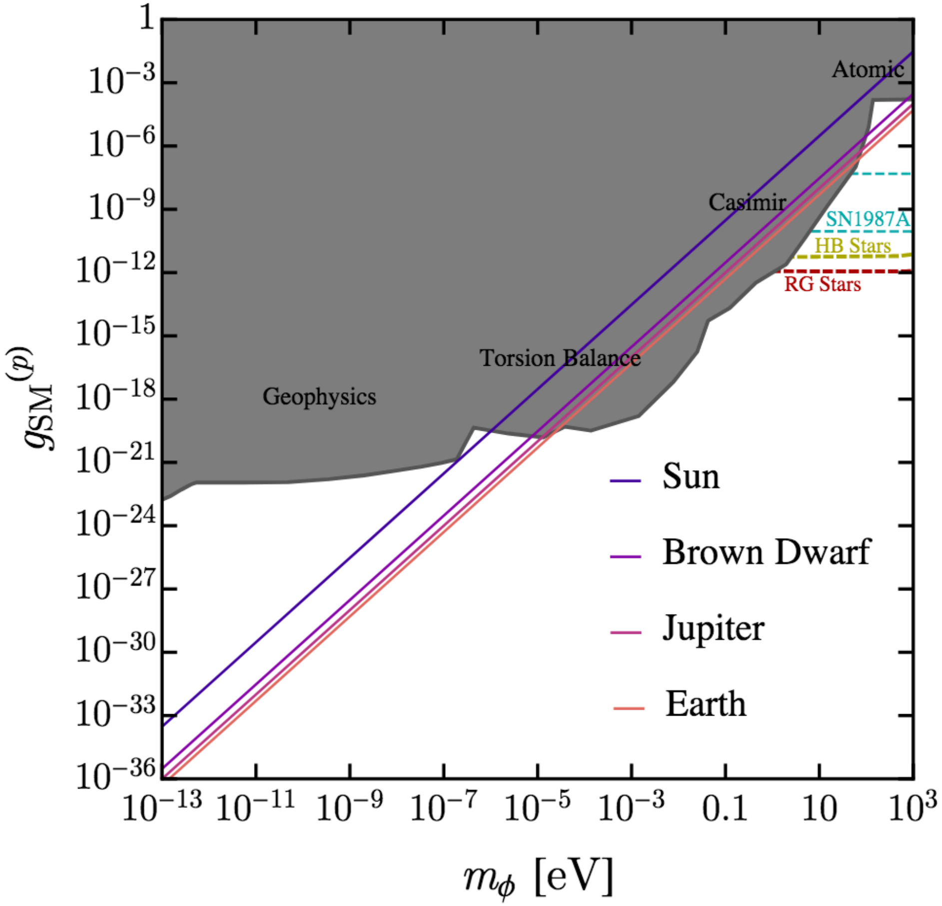


map to specific model

proton coupling



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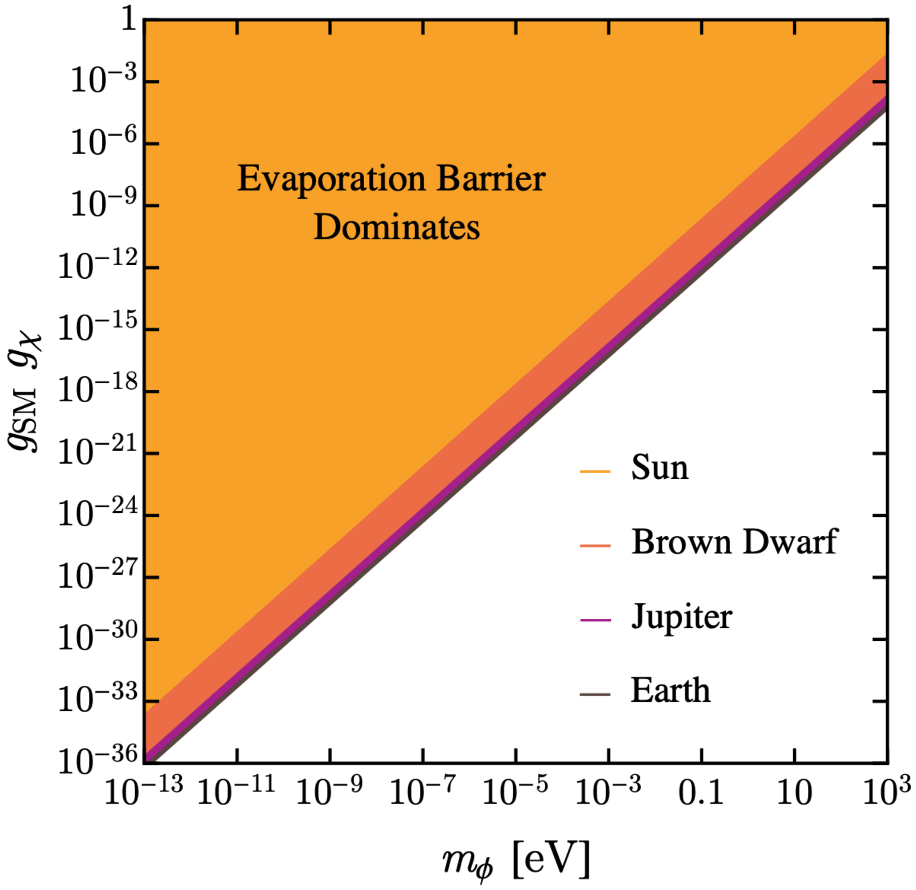

map to
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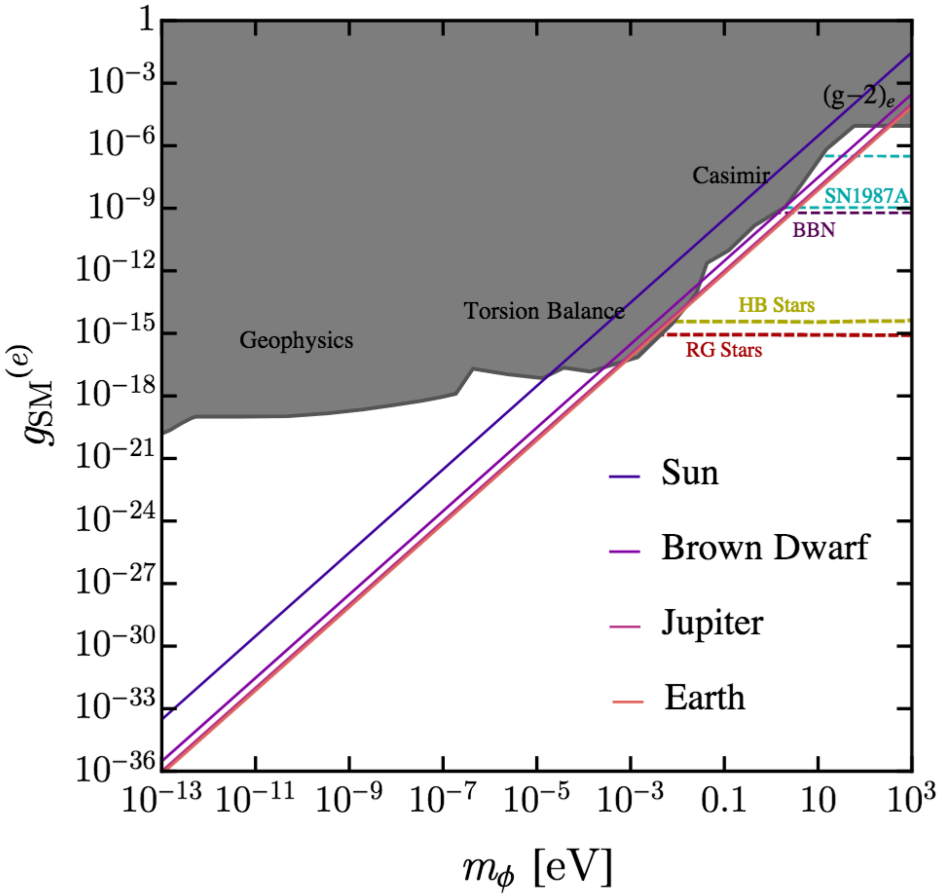
electron coupling



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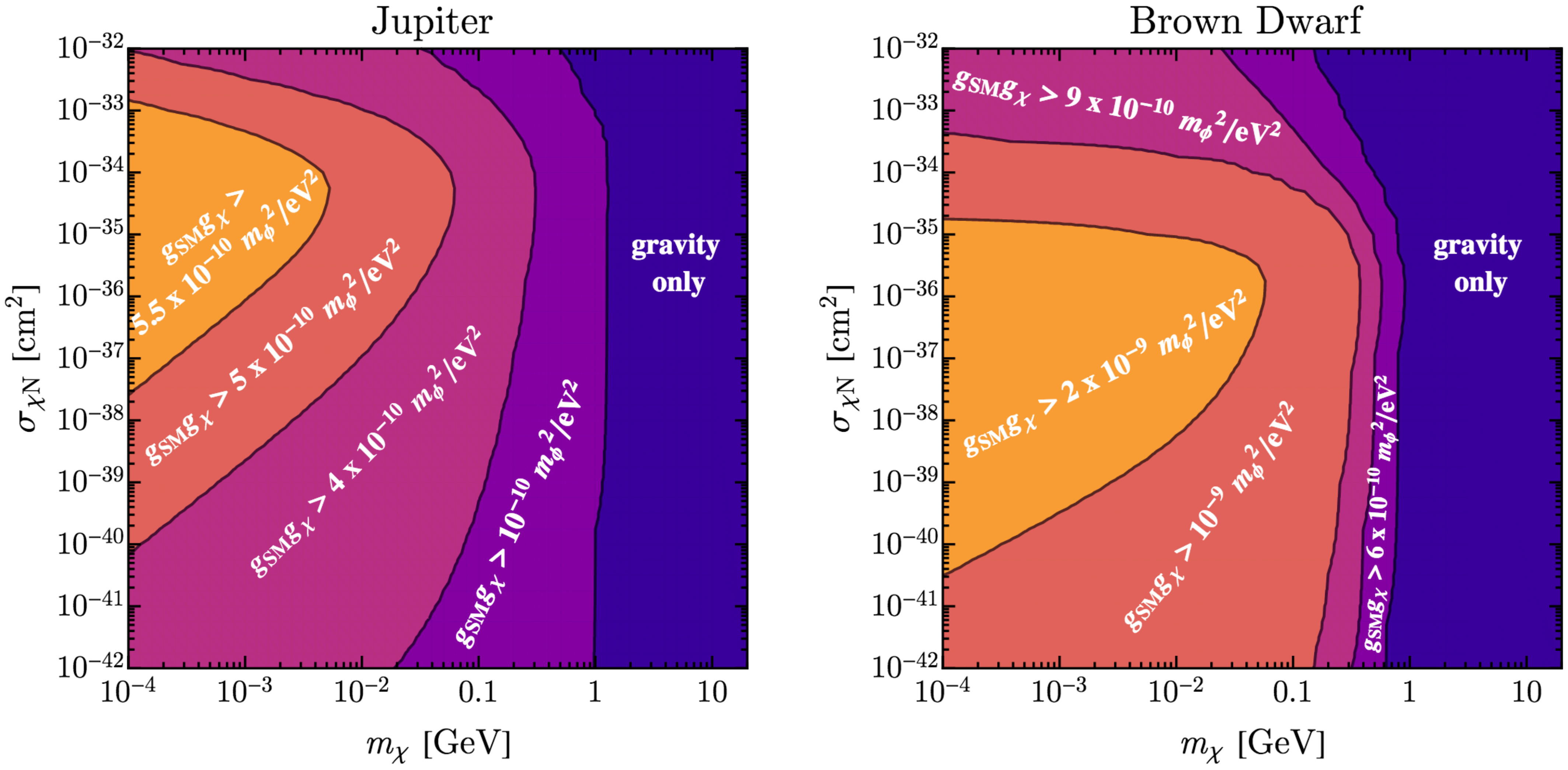
New Parameter Space - Jupiter & Brown Dwarfs



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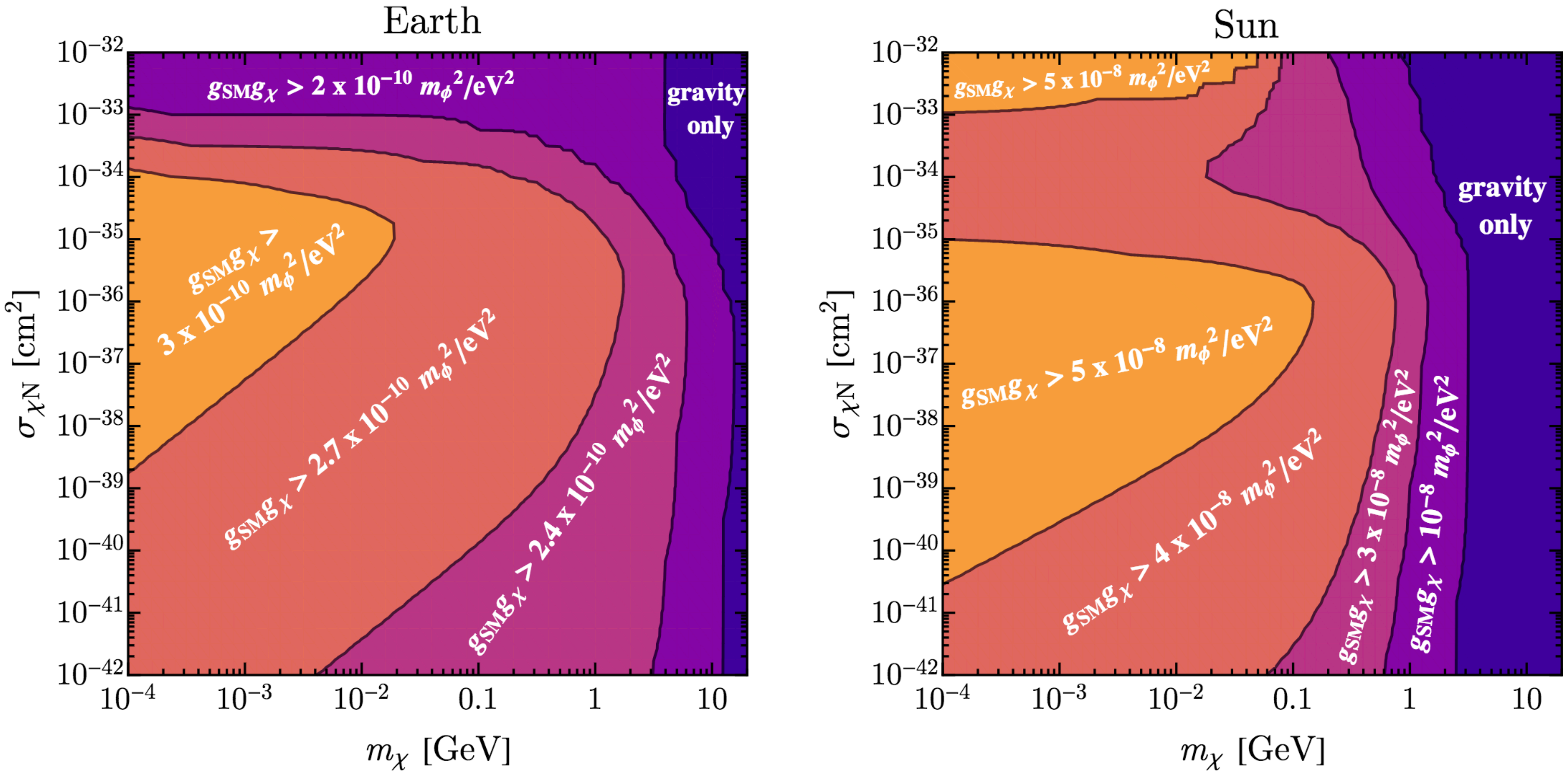
New Parameter Space - Earth & Sun



JA, Leane & Smirnov, 2303.01516

Final Remarks

Part I

- Galactic Center WDs can be very sensitive sub-GeV DM detectors.

- Depending on the halo profile, they outperform direct detection by up to 9 orders of magnitude.

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Part II

- Other non-compact objects can also serve as light DM detectors if attractive long-range forces exist in the dark sector.

- Data from celestial objects should be analyzed to the fullest extent that experimental thresholds allow (i.e. no cutoffs at the usually quoted evaporation mass).