Gamma-ray flux limits from brown dwarfs: Implications for dark matter annihilating into long-lived mediators

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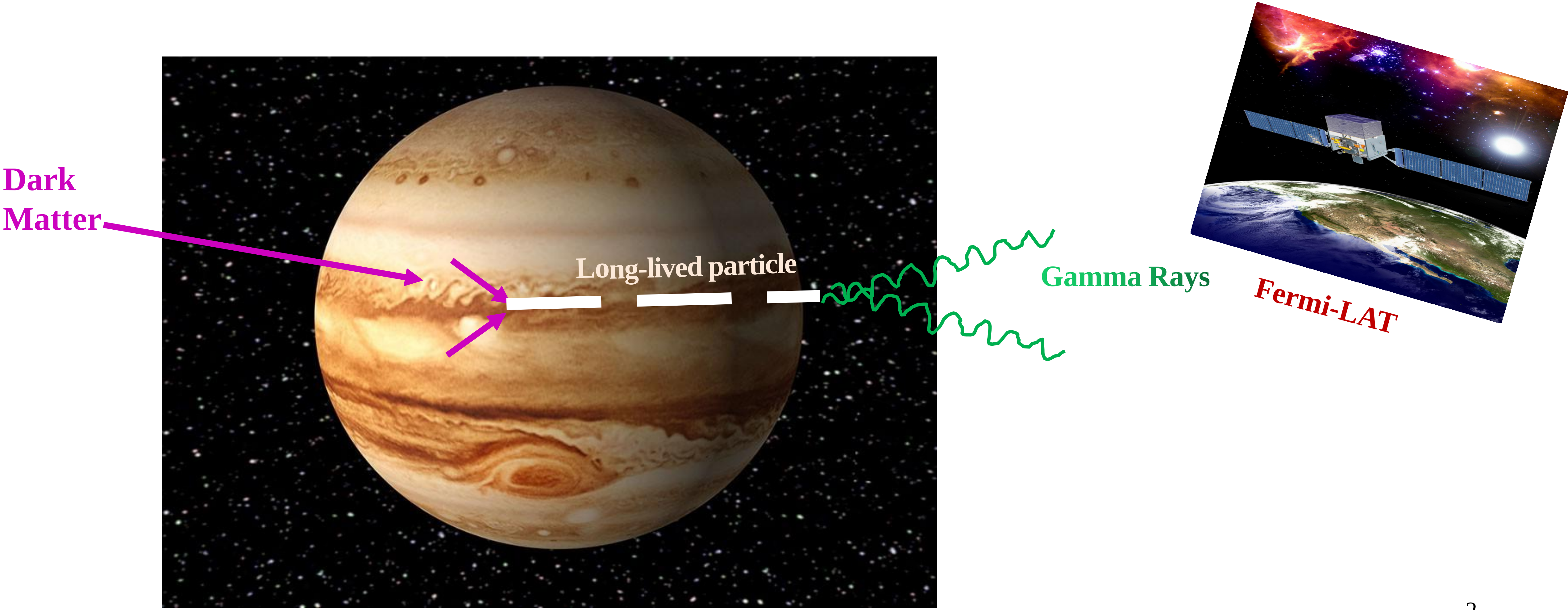
"Dark Matter and Stars: Multi-Messenger Probes of Dark Matter and Modified Gravity"

Center for Astrophysics and Gravitation, Instituto Superior Técnico, University of Lisbon, 3-5 May 2023

Outlook

Indirect detection of Dark Matter captured in Brown Dwarfs

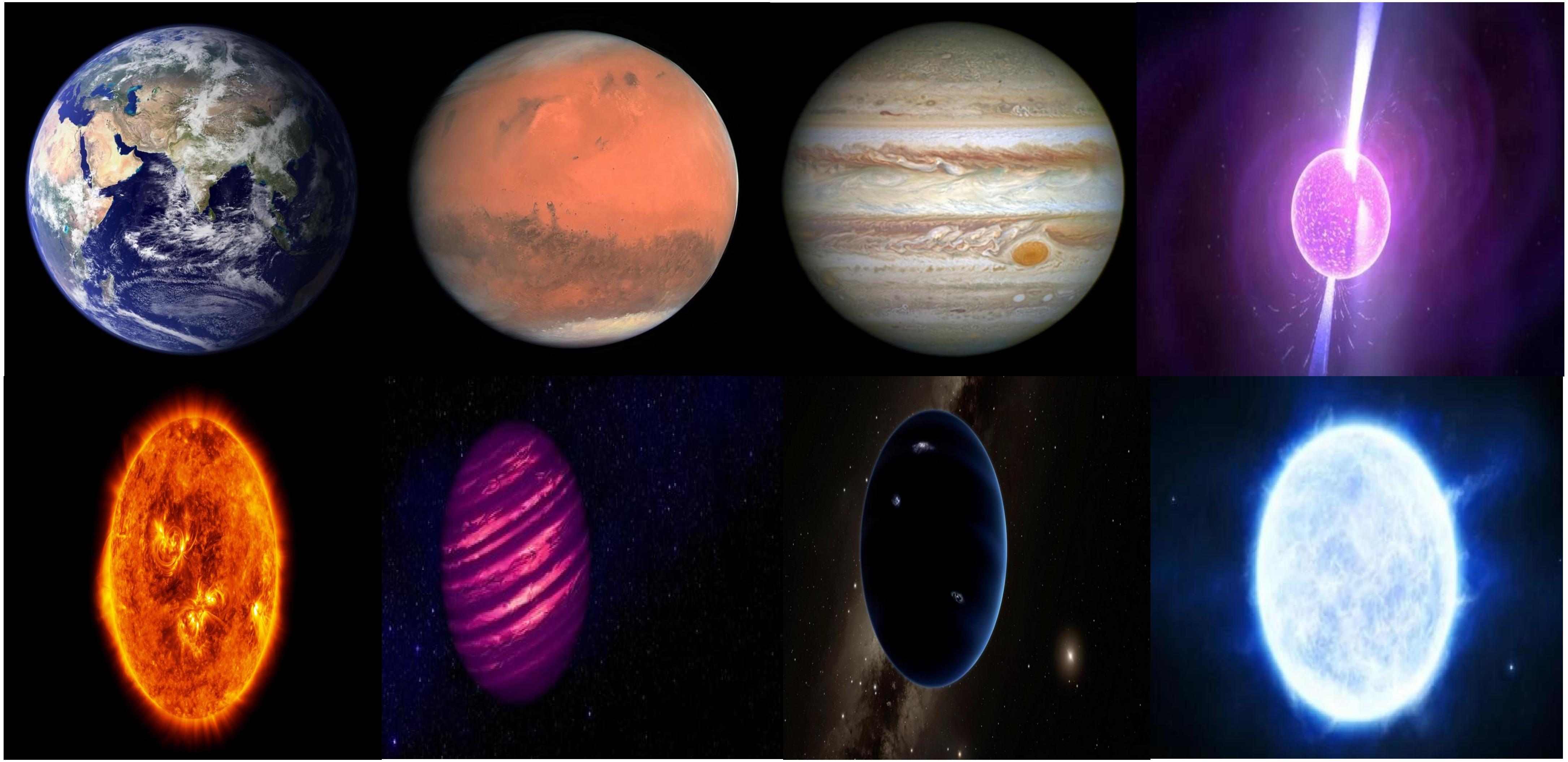


Picture courtesy: R. Leane

Optimal Targets?

-For DM capture

Earth **Mars** **Jupiter** **Neutron Stars**



Sun **Brown Dwarf** **Rogue Planets** **White Dwarfs**

*

Condition for the optimal Celestial Targets

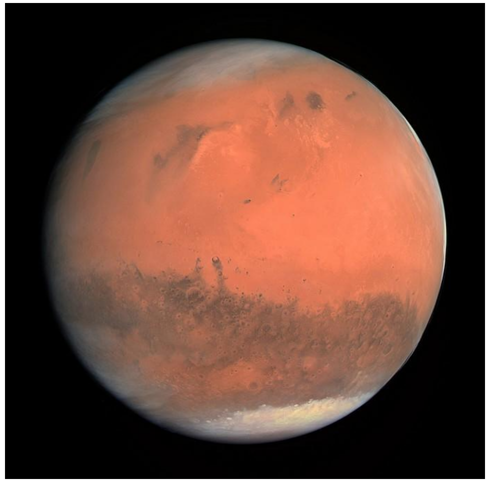
- **Radius: Larger amount of dark matter (DM) captured**, larger annihilation signal.
- **Distance: Nearby objects, since the flux scales as the inverse of the distance squared**. This criterion would be meaningful no matter which emission mechanisms were considered.
- **Density: The denser the region, the larger the capture rate is expected to be**. Easier to trap DM, sensitivity to weaker interactions.
- **Temperature: A cold surface is typically associated with a cold core temperature**; keeping the evaporation mass low; **Can probe the widest parameter space for light DM**.
- **Age: Old objects are more likely to having reached equilibrium between the capture and the annihilation rate**, maximizing the signal strength.

Optimal Targets?

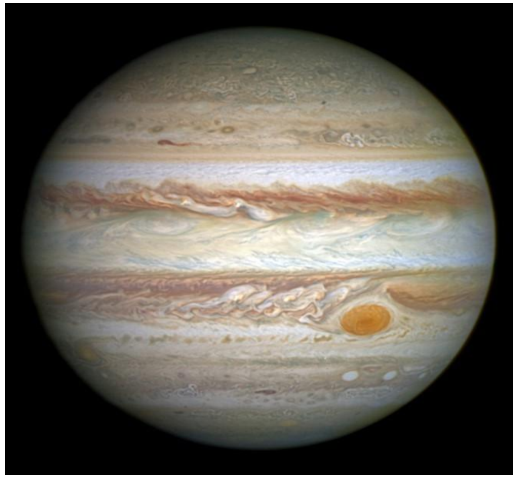
-For DM capture

Earth

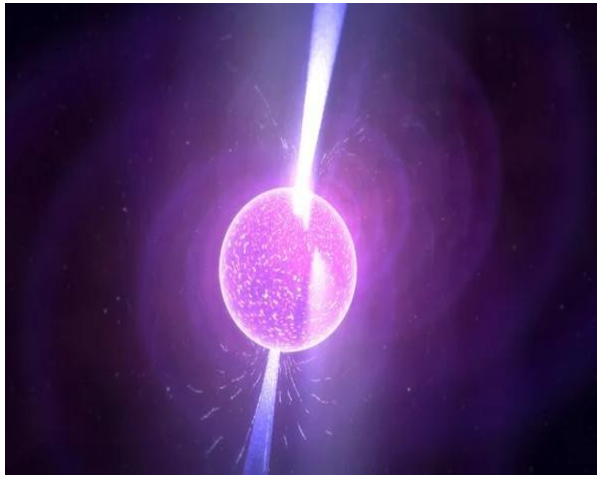
Mars



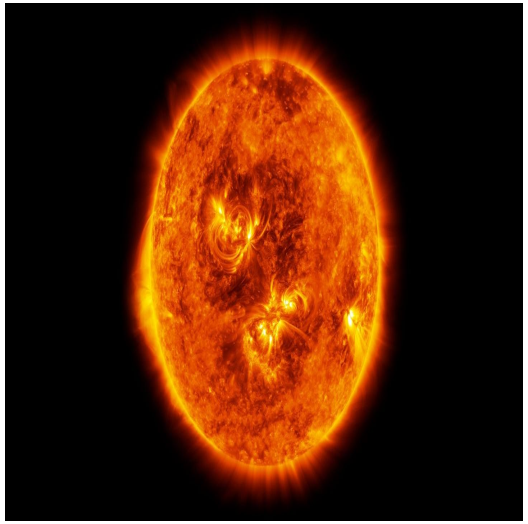
Jupiter



Neutron Stars

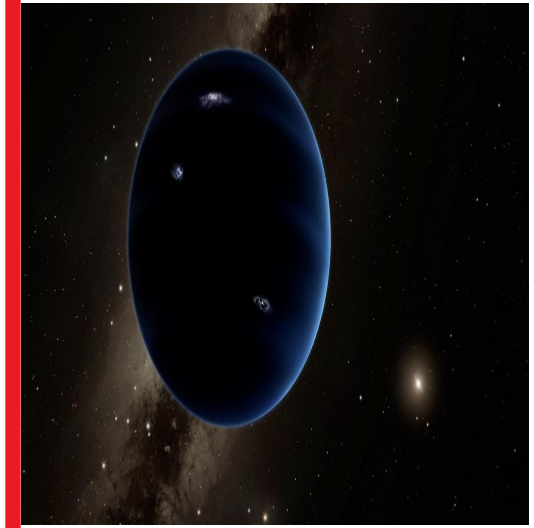


Sun



Brown Dwarf

Rogue Planets



White Dwarfs

Advantages: Brown Dwarf (BD)

Advantage 1: Exploding Research Program & Many upcoming telescopes and searches!

Advantage 2: Statistics

First exoplanet discovery: 1992

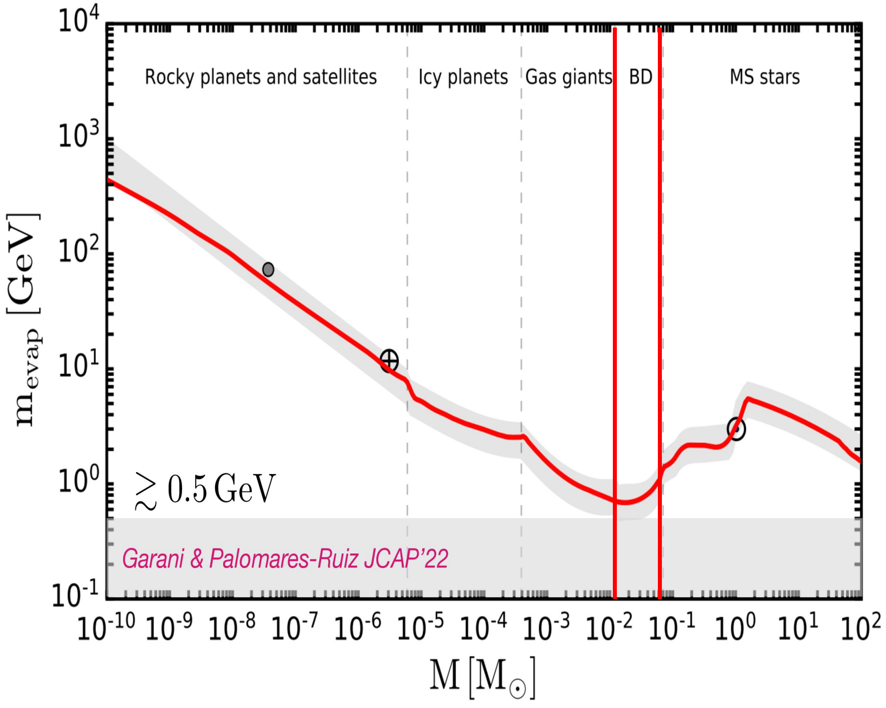
Estimates predict **around 300 billion exoplanets** in our galaxy!

Advantage 3: Low temperatures

Brown Dwarf can be very cold, as they do not undergo nuclear fusion

-- Low temperatures allow for a **clearer signal over background for DM heating**

-- Low core temperatures in part **prevent DM evaporation, providing new sensitivity to lighter (sub-GeV) DM.**



Evaporation sets a **lower limit of DM mass** for which these **bounds are valid**!!

Brown Dwarfs (BDs) are new, exciting, and powerful detectors of dark matter (DM).

Our Selection Criteria

- **Radius: The radius of BDs being around R_J**
- **Distance: Select BDs within 11 pc from us.**
- **Mass: Consider BDs with large masses ($M > 20\ M_J$)**
- **Temperature & Age: BDs are spectrally classified in L, T, and Y types, from warmer to colder.**

Y-type BDs are the older but their masses are below 20 M_J.

Thus we select nine T-type BDs with typical estimated ages are greater than 2 Gyr.

Source Name (ID number)	ℓ (degree)	b (degree)	Distance (pc)	Mass ($M_{♃}$)	Radius ($R_{♃}$)	Temperature (K)	Estimated age (Gyr)	Spectral Type
2MASS J02431371-2453298 (Source 1)	40.81	−24.89	10.68	34	0.97	1070	1.7 [38]	T6
WISEPA J031325.96 + 780744.2 (Source 2)	48.36	78.13	6.54	26	0.88	651	10 [39]	T8.5
Epsilon Indi Ba (Source 3)	−28.96	−56.78	3.63	47	0.89	1276	3.5 [40]	T1
SCR 1845-6357 B (Source 4)	−78.73	−63.96	3.85	45	0.88	950	3.1 [41]	T6
2MASS J12171110–0311131 (Source 5)	−175.71	−3.19	10.73	31	0.95	870	10 [42]	T7.5
WISEPC J121756.91 + 162640.2 A (Source 6)	−175.53	16.44	10.10	30	0.89	575	8 [43]	T9
2MASS J04151954-0935066 (Source 7)	63.83	−9.59	5.64	35	0.91	750	10 [42]	T8
2MASS J09373487 + 2931409 (Source 8)	144.39	29.53	6.12	58	0.79	810	10 [38]	T7
WISE J104915.57-531906.1 (Source 9)	162.33	−53.32	2	33.5	0.85	1350	4.5 [44]	T0.5

How to detect the impact of DM capture in BDs?

There are two possible strategies!!

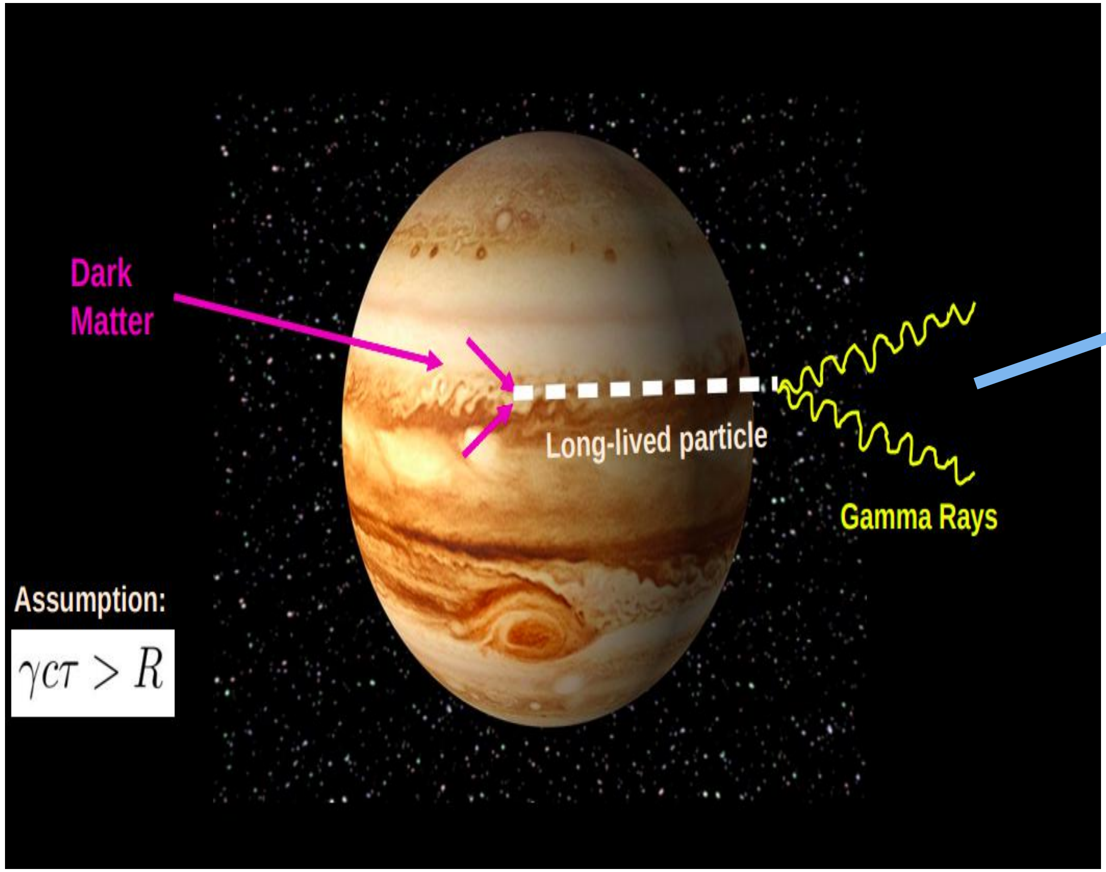
1) One possibility is to look for the anomalous heating due to the deposited kinetic energy associated to DM capture and annihilation. It could have been detected by deep and sensitive optical and infrared sky surveys, such as JWST.

2) Second is to focus on a scenario where DM annihilation proceeds into the long-lived mediator final states (Provided mass of mediator,ϕ, is lighter than the DM) and ϕ eventually decays into light SM particles outside the BD.

We followed the second one!!!

Detecting gamma-ray signals from BDs
-with Fermi Large Area Telescope (LAT) data

DM annihilates to long-lived mediators → escapes BDs!



R. Leane , 2021

The Fermi-LAT is a gamma-ray space-based detector that scans the whole sky every 3 hours for an collecting photons from about 20 MeV to almost 1 TeV.

Search for gamma-ray emission in Fermi-LAT data

1. Analyze 13 years of data with energy range between 100 MeV to 500 GeV.

2. Use fermipy version 1.0.1, and Fermi Science Tools version 2.0.8.

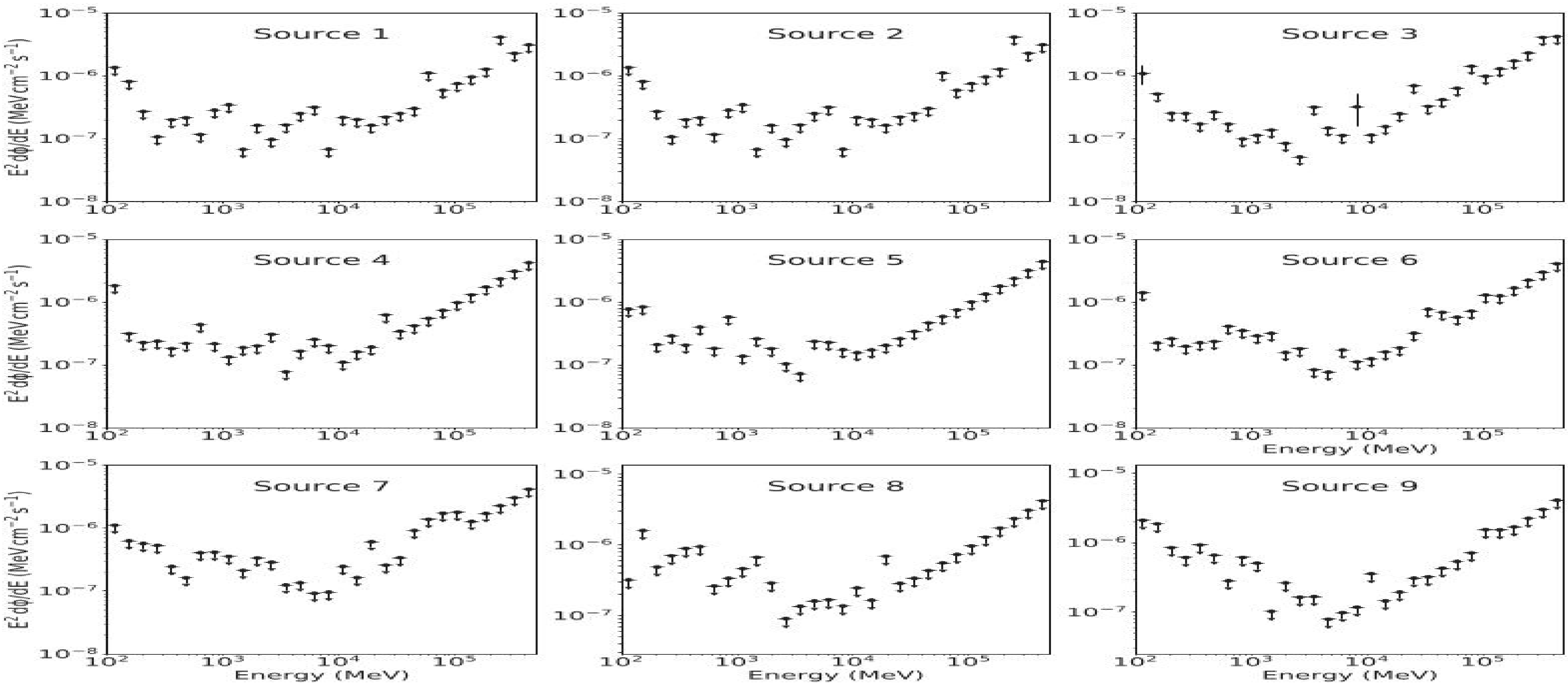
3. Perform the binned likelihood analysis and no significant excess emission is found.

   I. Next, derive the gamma-ray flux upper limits at 95% confidence level (C.L.)

   II. Also perform the stacked analysis via a conventional joint likelihood method.

We follow the main recommendations for pointlike source analysis provided by the Fermi-LAT Collaboration.

Gamma-ray flux upper limits from BDs

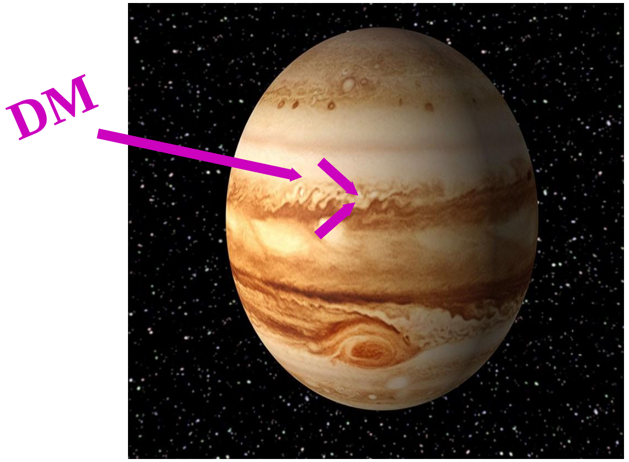


bin-by-bin differential flux upper limits at 95% C.L. for all nine BDs

We use the model independent approach. Do not use any DM model here.

DM capture rate and annihilation in BDs

When DM particles transit through the BDs, if colliding one or multiple times, they lose sufficient energy and eventually get captured.



If all the passing DM are getting captured:

Maximum capture rate: $C_{\max}(r) = \pi R_\star^2 n_\chi(r) v_0 \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{\bar{v}(r)^2}\right)$

But this is far from being the real scenario!!!

For both single and multiple scatterings of DM particles

The total capture rate: $C_{\rm tot}(r) = \sum_{N=1}^{\infty} C_N(r)$

The capture rate associated with N scatterings

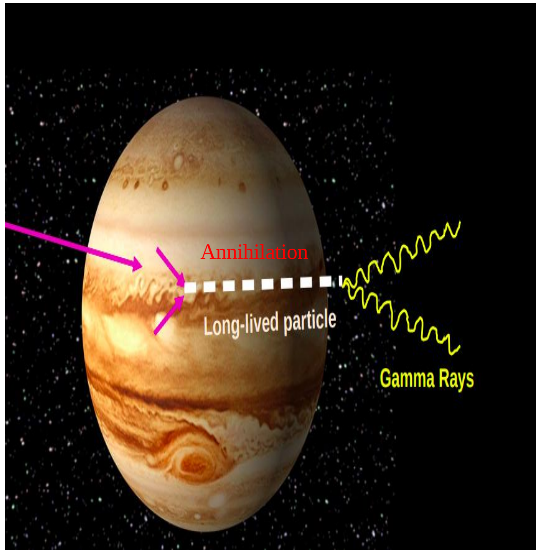
$$C_N(r) = \pi R_\star^2 p_N(\tau) \frac{\sqrt{6} n_\chi(r)}{3\sqrt{\pi}\bar{v}(r)} \left[(2\bar{v}(r)^2 + 3v_{\rm esc}^2) - (2\bar{v}(r)^2 + 3v_N^2) \exp\left(-\frac{3(v_N^2 - v_{\rm esc}^2)}{2\bar{v}(r)^2}\right) \right]$$

The perturbative estimate is applicable for our study, we impose the condition C= min[Ctot, Cmax]

Dark matter annihilation inside BDs

$\chi\chi \to \phi\phi$ $\quad m_\phi \ll m_\chi \quad \Longrightarrow \quad \phi \to \gamma\gamma$

DM



DM particles accumulated in the core with time, t:

$$\frac{dN(t)}{dt} = C - C_{\rm ann} N^2(t)$$

In the absence of evaporation, the annihilation rate:

$$C_{\rm ann} = \langle \sigma_{\rm ann} v \rangle / V_{\rm ann}$$

The total DM annihilation rate:

$$\Gamma_{\rm ann}(t) \equiv \frac{C_{\rm ann} N^2(t)}{2} = \frac{C}{2}\left(\tanh \frac{t}{t_{\rm eq}}\right)^2$$

If equilibrium is reached today, i.e., t★ ≫ teq , then $\Gamma_{\rm ann} \to \frac{C}{2}$

The DM gamma-ray flux expected from long-lived mediators decay:

$$E^2 \frac{d\Phi}{dE} = \frac{\Gamma_{\rm ann}}{4\pi d_\star^2} \times E^2 \frac{dN}{dE} \times P_{surv}$$

New dark matter limits on scattering cross-section

For long-lived mediators

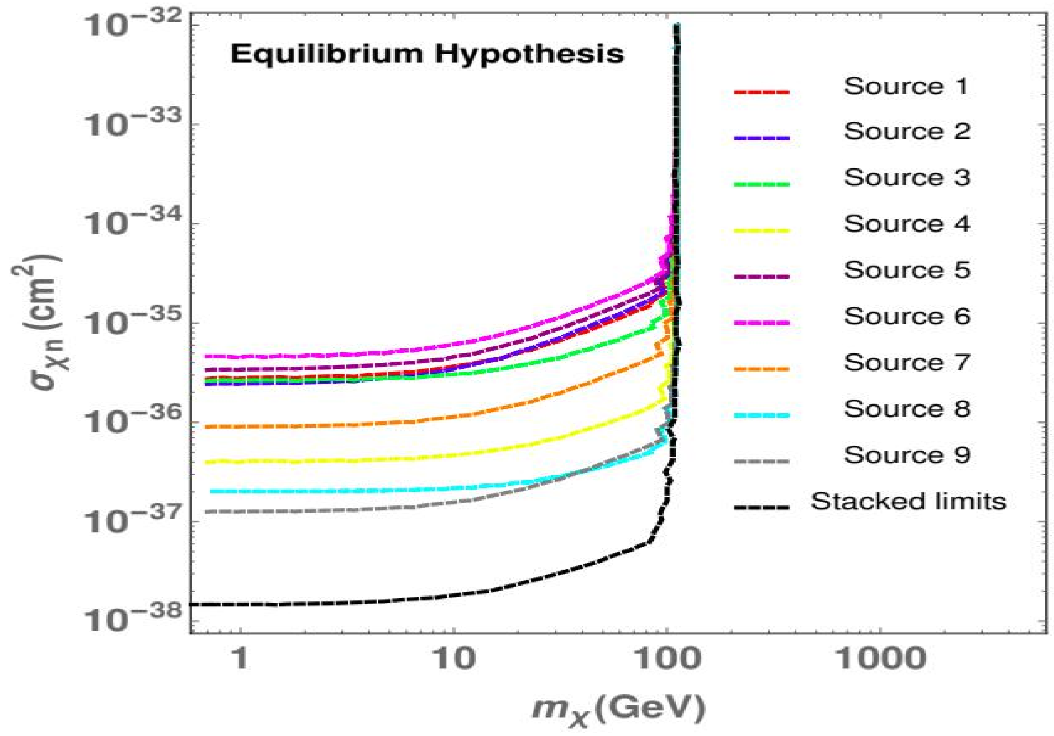
1) Equilibrium Hypothesis

2) From Real Age

For Equilibrium Hypothesis: $\Gamma_{\text{ann}} \rightarrow \frac{C}{2}$

We translate the Fermi-LAT gamma-ray flux upper limits into constraints on the DM particle parameter space

------- set bounds on the scattering cross section, σχn as a function of the DM mass, mχ .



The decay length of the mediators should satisfy this range:

$$10^8 \text{ m} \simeq R_\star \lesssim L \lesssim d_\star \theta_{68\%} \simeq 10^{14} \text{ m}$$

From Real Age:

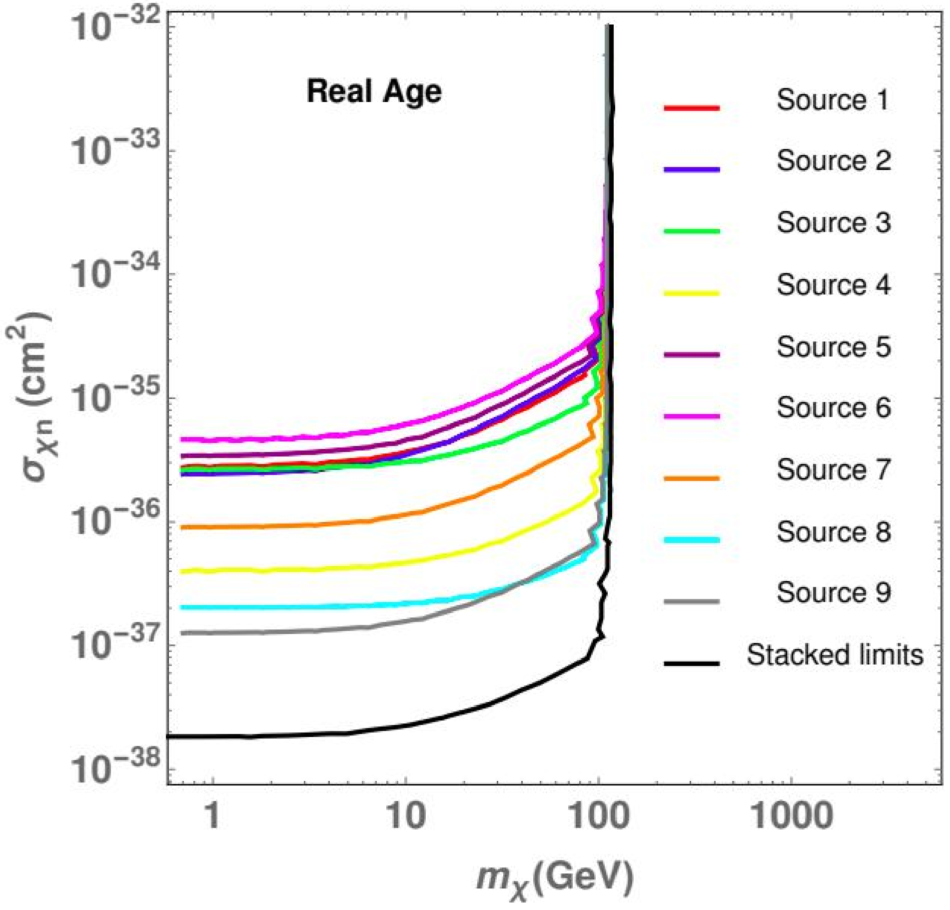
$$C_{\rm ann} = \langle \sigma_{\rm ann} v \rangle / V_{\rm ann}$$ ← $\langle \sigma v \rangle \lesssim 5.1 \times 10^{-27}\ \mathrm{cm^3\ sec^{-1}}$

V_{ann} is the containment volume where annihilation takes place

$$V_{\rm ann} = \frac{4}{3}\pi r_{\rm ann}^3 = \frac{9}{\sqrt{4\pi}}\left(\frac{T_{\star,c}}{G\rho_{\star,c} m_\chi}\right)^{3/2}$$

Source	$T_{\star,c}$ [$\times 10^5$ K]	$\rho_{\star,c}$ [g/cm^3]
1	3.35	248.94
2	1.40	145.57
3	4.19	475.70
4	4.53	436.10
5	2.22	206.95
6	1.87	193.82
7	2.27	263.80
8	5.11	724.42
9	2.58	241.67

Bounds →



$T_{\star,c}$ and $\rho_{\star,c}$ are the temperature and density in the core of BD

What is the impact of equilibrium hypothesis

The equilibrium time for a 1 GeV DM mass:

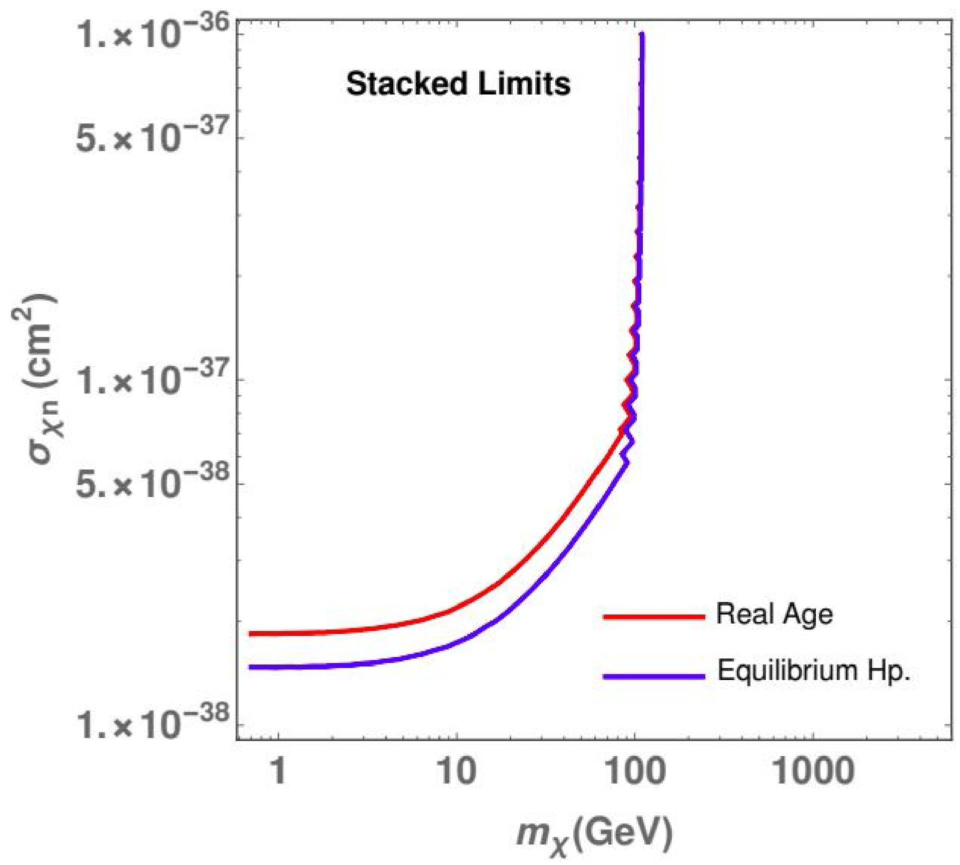
$$t_{\rm eq} = 1.24 t_{\rm eq}^{2+} \times \left(\frac{T_{\star,c}}{2\times10^5\ {\rm K}} \frac{200\ {\rm g/cm^3}}{\rho_{\star,c}} \right)^{3/4} \times \sqrt{\frac{5\times10^{-27}\ {\rm cm^3/s}}{\langle\sigma v\rangle}} \sqrt{\frac{10^{-38}\ {\rm cm^2}}{\sigma_{\chi n}}}.$$

m_χ = 1 GeV and $\sigma_{\chi n} = 10^{-38}$ cm^2

Source	$t_{\rm eq}$ [Gyr]
1	0.46
2	0.36
3	0.33
4	0.38
5	0.39
6	0.36
7	0.33
8	0.28
9	0.39

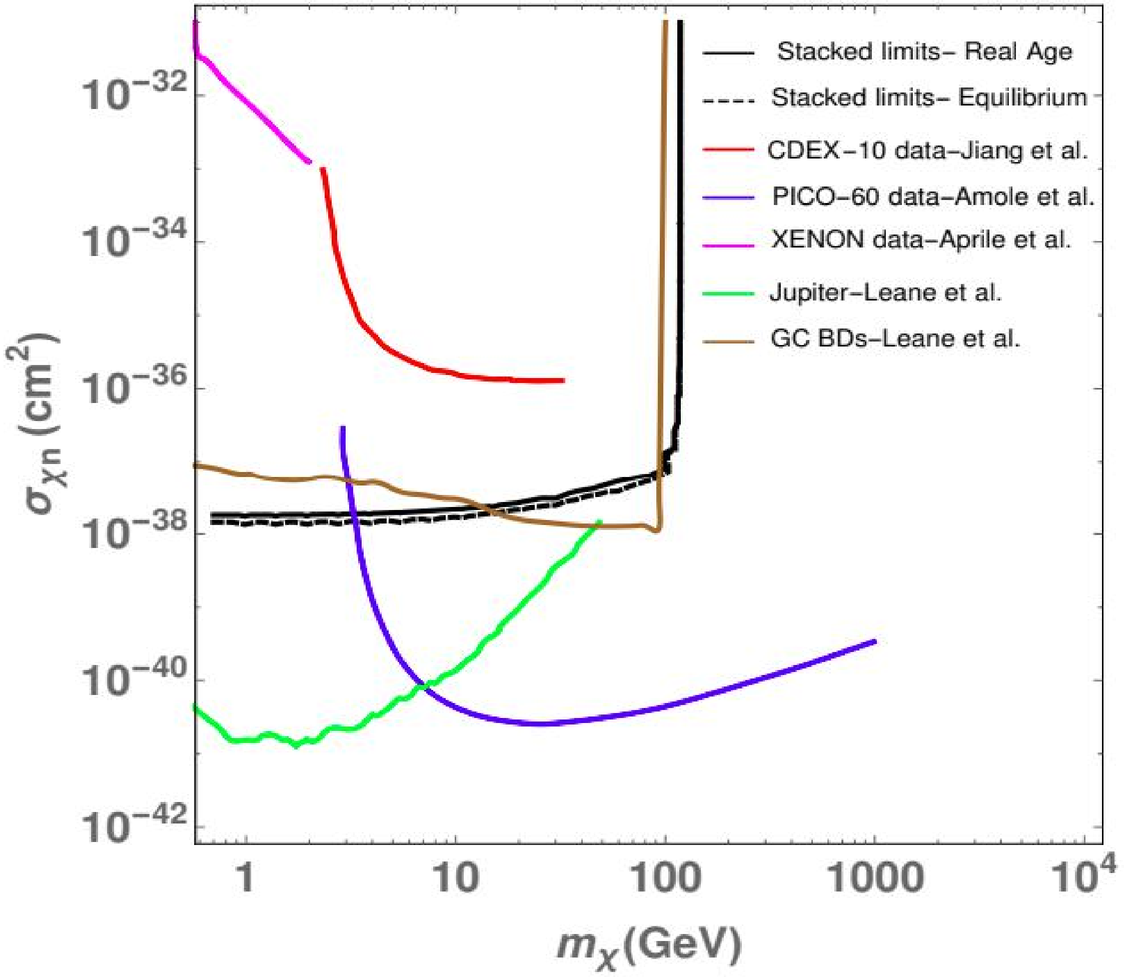
teq is comparable or shorter than the age of our BDs

The bounds are mildly weaker but more realistic one!!!



Hence, the equilibrium hypothesis justifies well!!!

Comparison with other literature studies



1. **For low DM masses, the evaporation of DM particle becomes important. We limit ourselves to masses above 0.7 GeV.**

2. **BDs limits have the unique advantage to extend to masses lower than a few GeV with sensitivity reaching cross section values of at least 10 $^{-38}$ cm^2 .**

3. **Limits obtained from Jupiter is five order of magnitude more stringent but the distance is ~5 AU. Thus, our bounds apply to much wider parameter space.**

4. **Bounds from GC population rely both on the assumed DM density profile and the model of the BD population toward the Galactic center region.**

5. **Besides astrophysical bounds, we compare our results with DM direct detection experiments**

Code is publicly available on GitLab and ESCAPE OSSR

The code and data to reproduce the results of this study are available on GitLab, https://gitlab.in2p3.fr/francesca.calore/brown-dwarfs-gamma, 10.5281/zenodo.7596302

The code is also onboarded in the ESCAPE OSSR as a part of Dark Matter Test Science Project (TSP) and is in full agreement with the Open Science Uptake of EOSC-Future.

Outlook

1) **We perform (for the first time, to the best of our knowledge) a model-independent search of a gamma-ray signal from the direction of known BDs in Fermi-LAT data.**

2) **This study does not rely on extrapolations or statistical arguments on the BD population, especially toward the Galactic center (GC).**

3) **No excess gamma-ray signal being found**, we interpret the resulting **upper limits on the BDs' gamma-ray flux in a DM model annihilating into gamma rays via light, long-lived mediators.**

4) **Our constraints apply to a much broader range of lifetime for the mediators.**

5) **We explicitly test that equilibrium between capture and annihilation holds for known BDs.**

- Motivates follow up cumulative emission of local BD population.

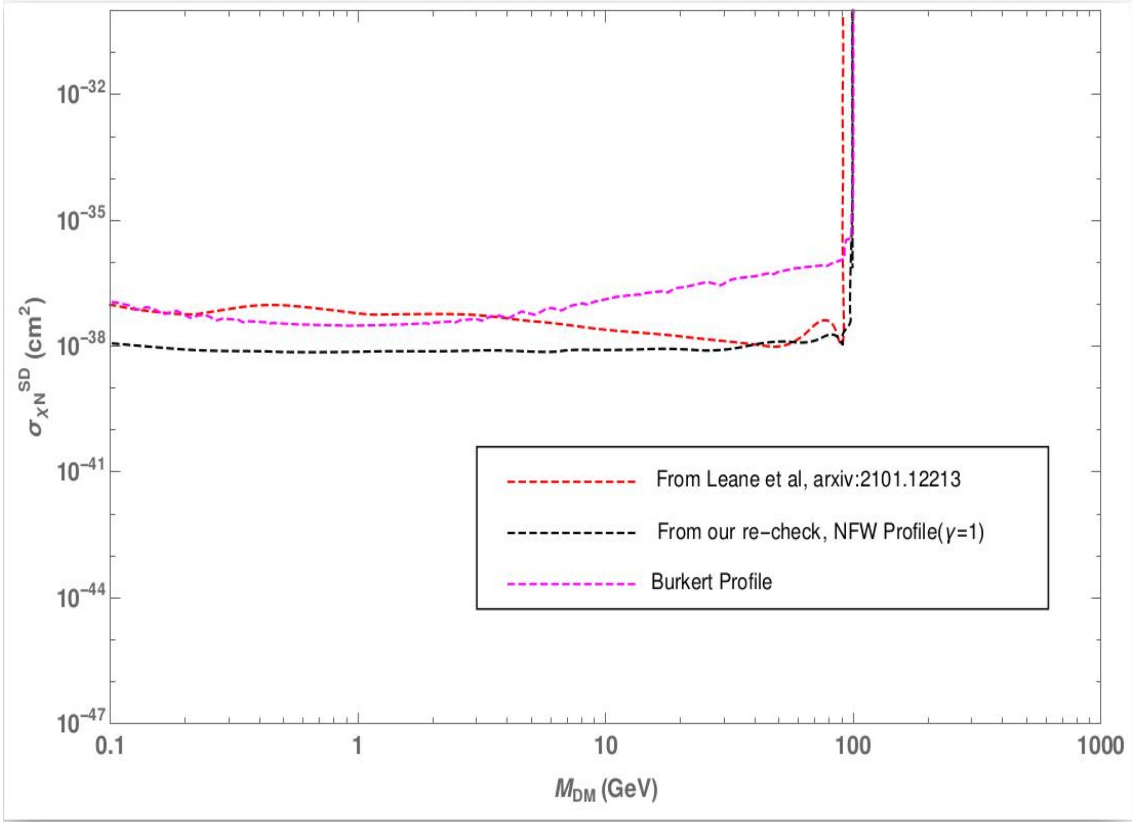
-Strong constraints with long-lived particles.

6) **BDs limits have the unique advantage to extend to masses lower than a few GeV and provides comparable bounds to DM direct detection in sub-GeV mass range.**

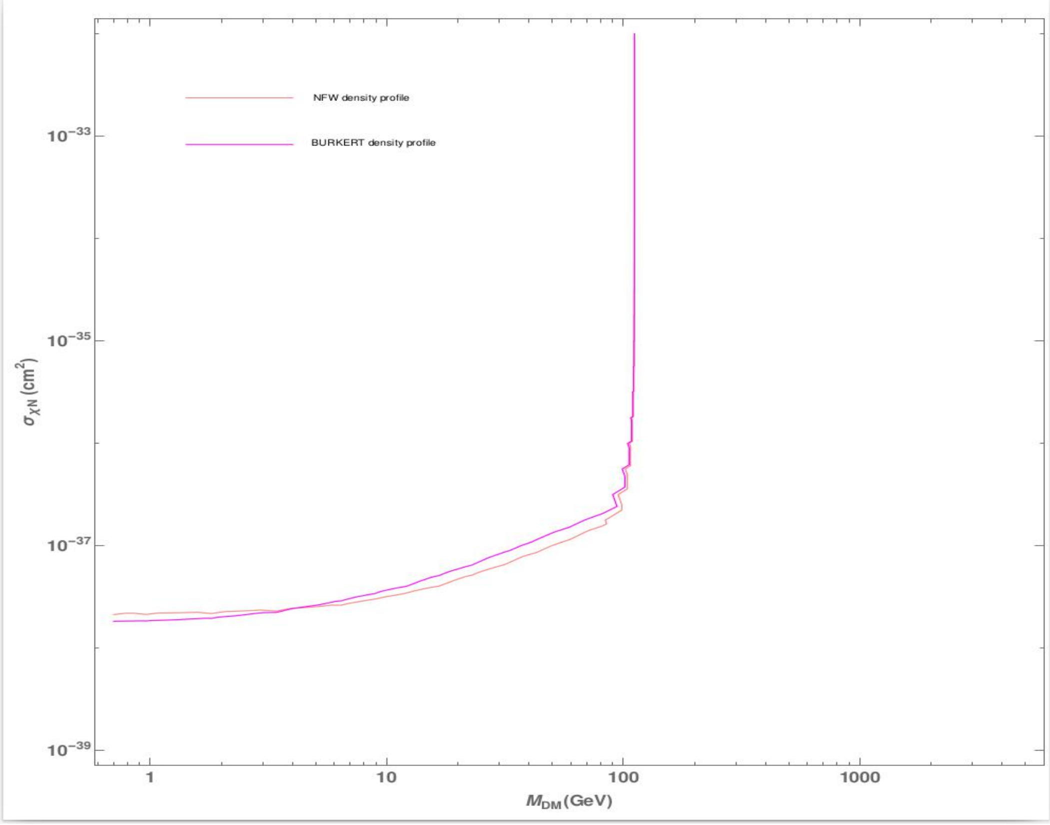
7) With **deeper optical and infrared sky surveys, such as JWST**, the **detection of ultracool BDs would be increased.**


THANK YOU
FOR YOUR
ATTENTION

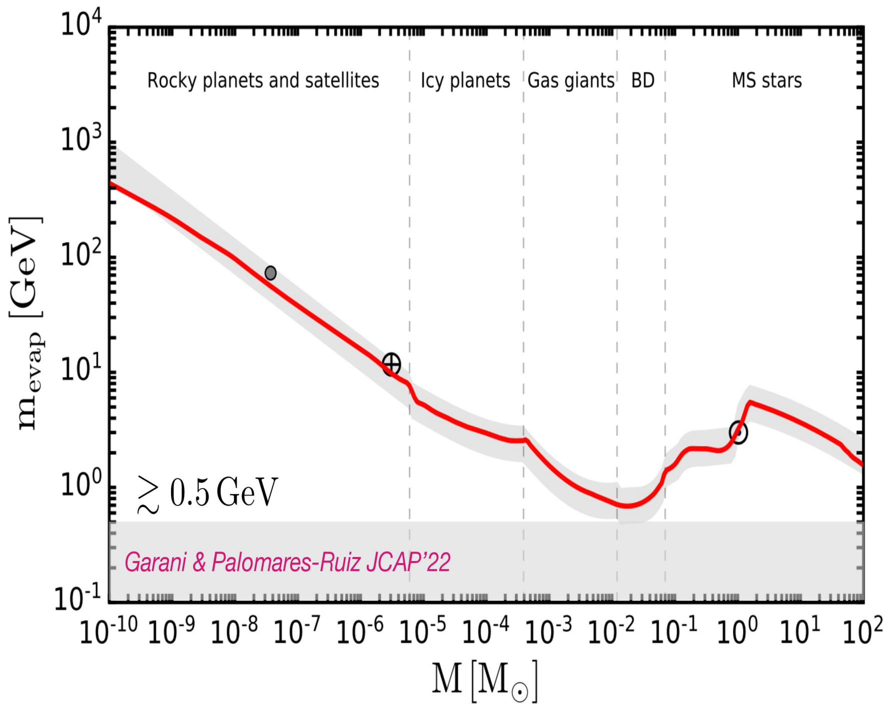
Backup Slides



For GC population



For local BDs



Evaporation sets a **lower limit of DM mass** for which these **bounds are valid**!!

box-shaped spectrum with Heaviside function

$$\frac{dN}{dE} \simeq \frac{2\Theta(m_\chi - E)}{m_\chi}.$$

Photon survival probability

$$P_{surv} = e^{-\frac{R}{L}} - e^{-\frac{D}{L}}$$