Exoplanets as Dark Laboratories: New Tests of sub-GeV Dark Matter

Juri Smirnov

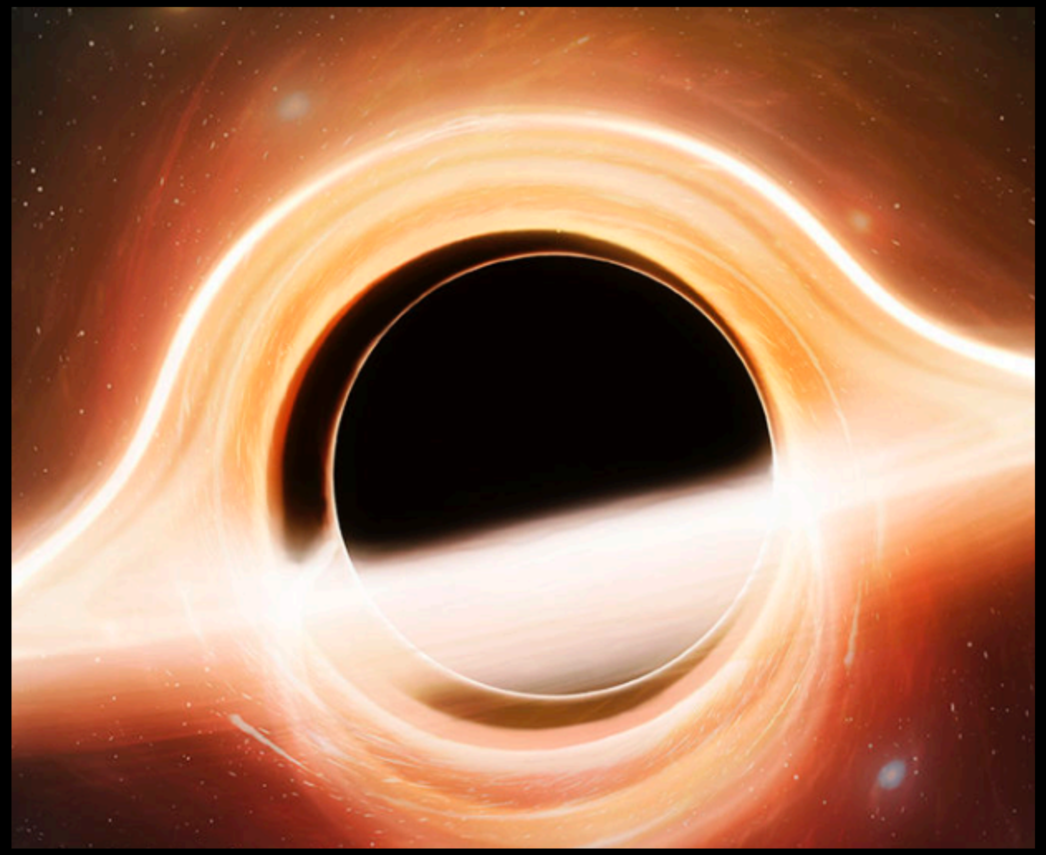
Lecturer: University of Liverpool

Theory Seminar
King's College London: 08/03/23

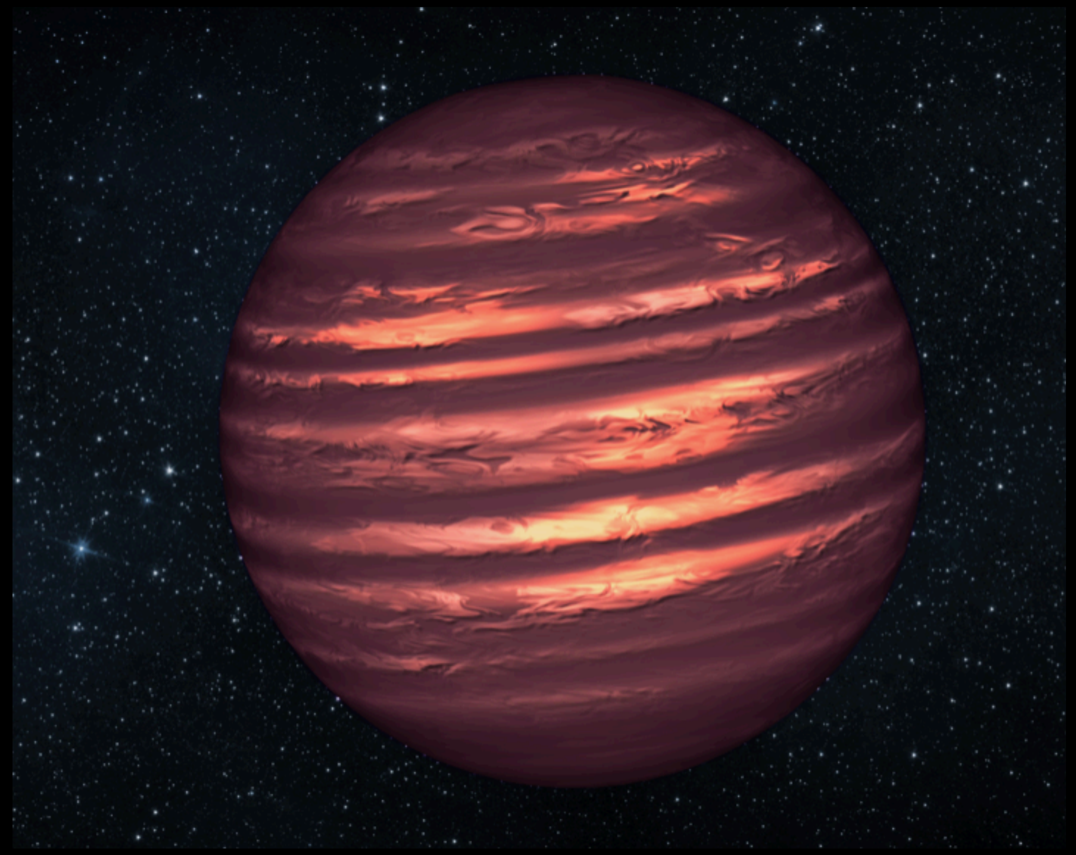
Many thanks to my collaborators: R. K. Leane,
J. Acevedo (SLAC), M. Benito, S. Podar (Tartu Obs.)

A New Dark Laboratory

Stuff in Space



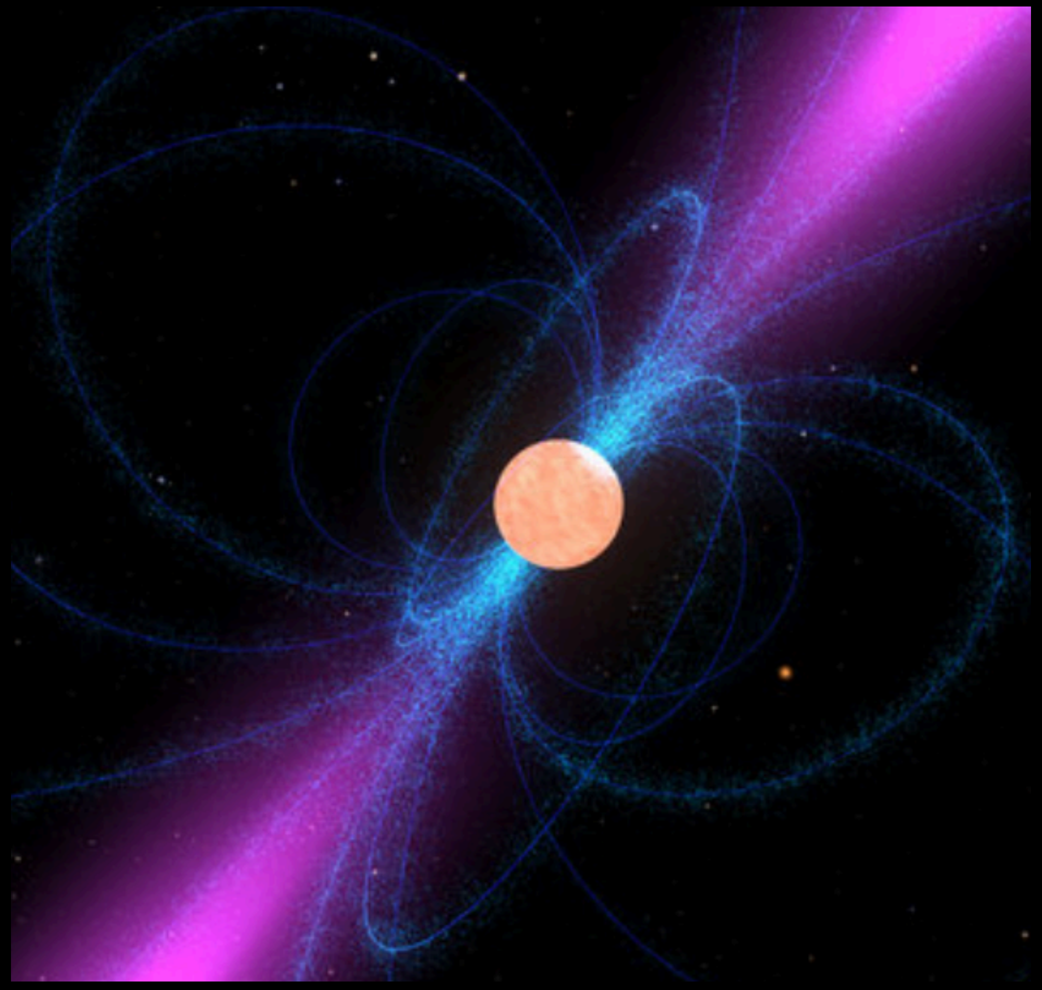
M > few M_{Sol}



$M = 10^{-1} - 10^{-2}\ M_{Sol}$

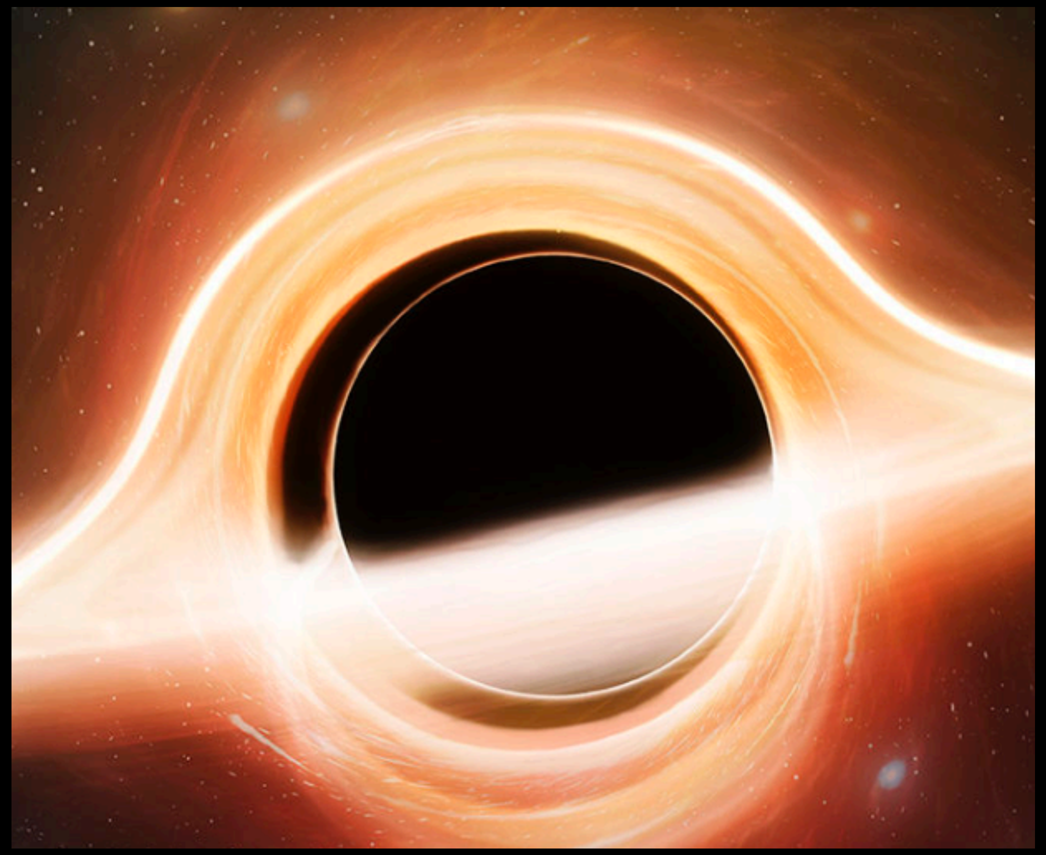
$M = 10^{-3}\ M_{Sol}$

$M = \ M_{Sol}$



$M = 1.4\ M_{Sol}$

Stuff in Space



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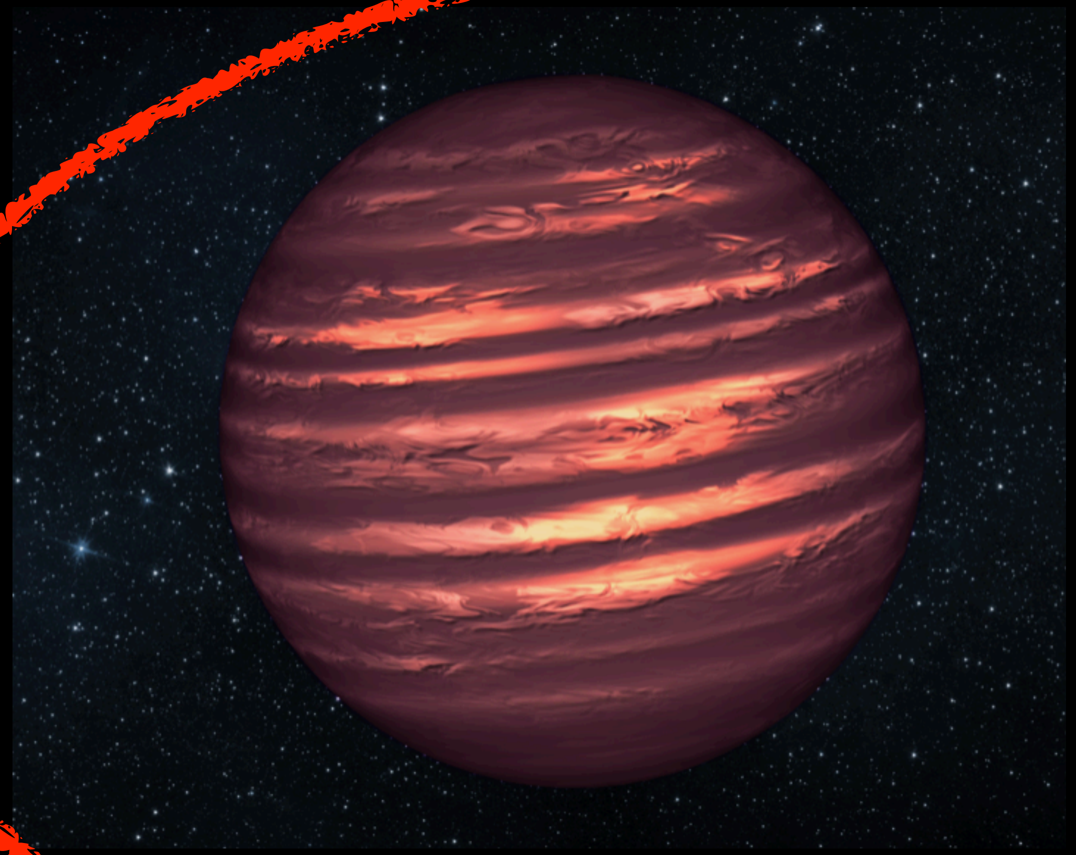

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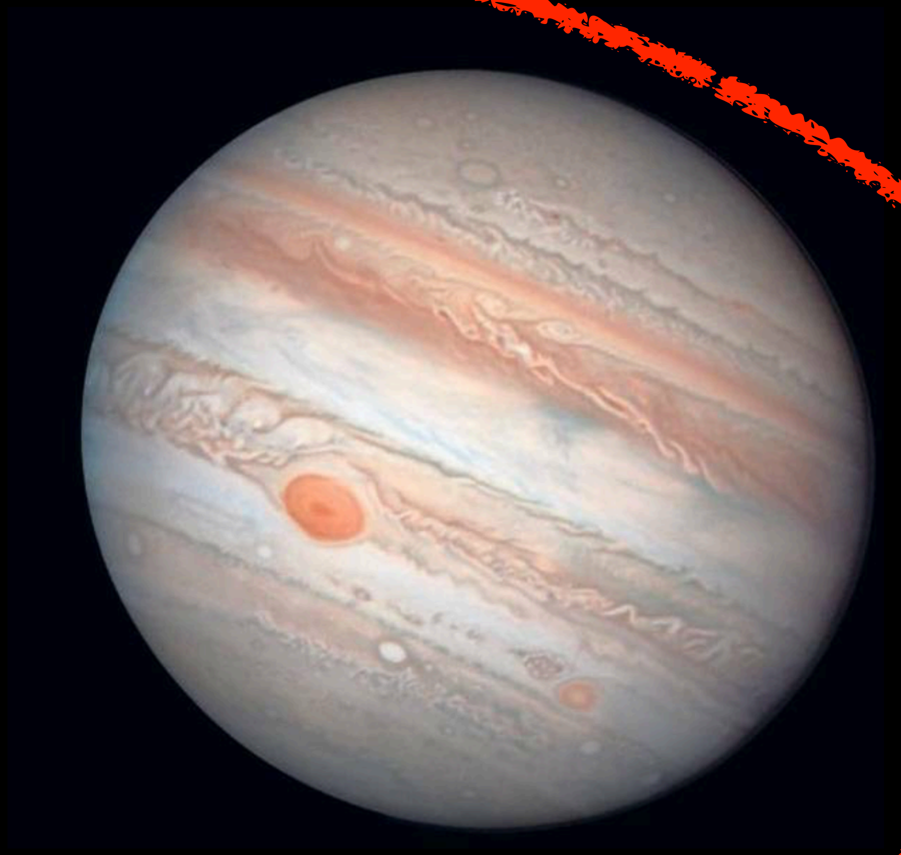
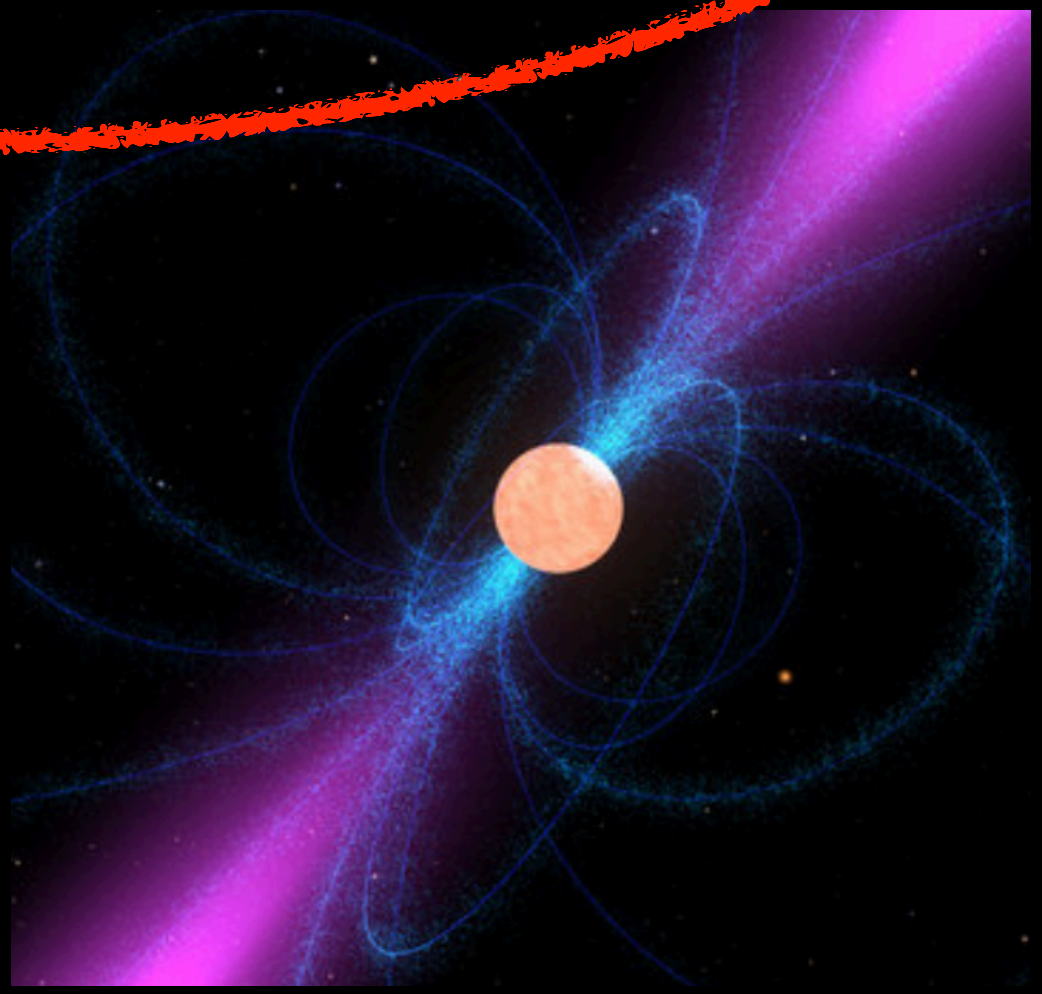


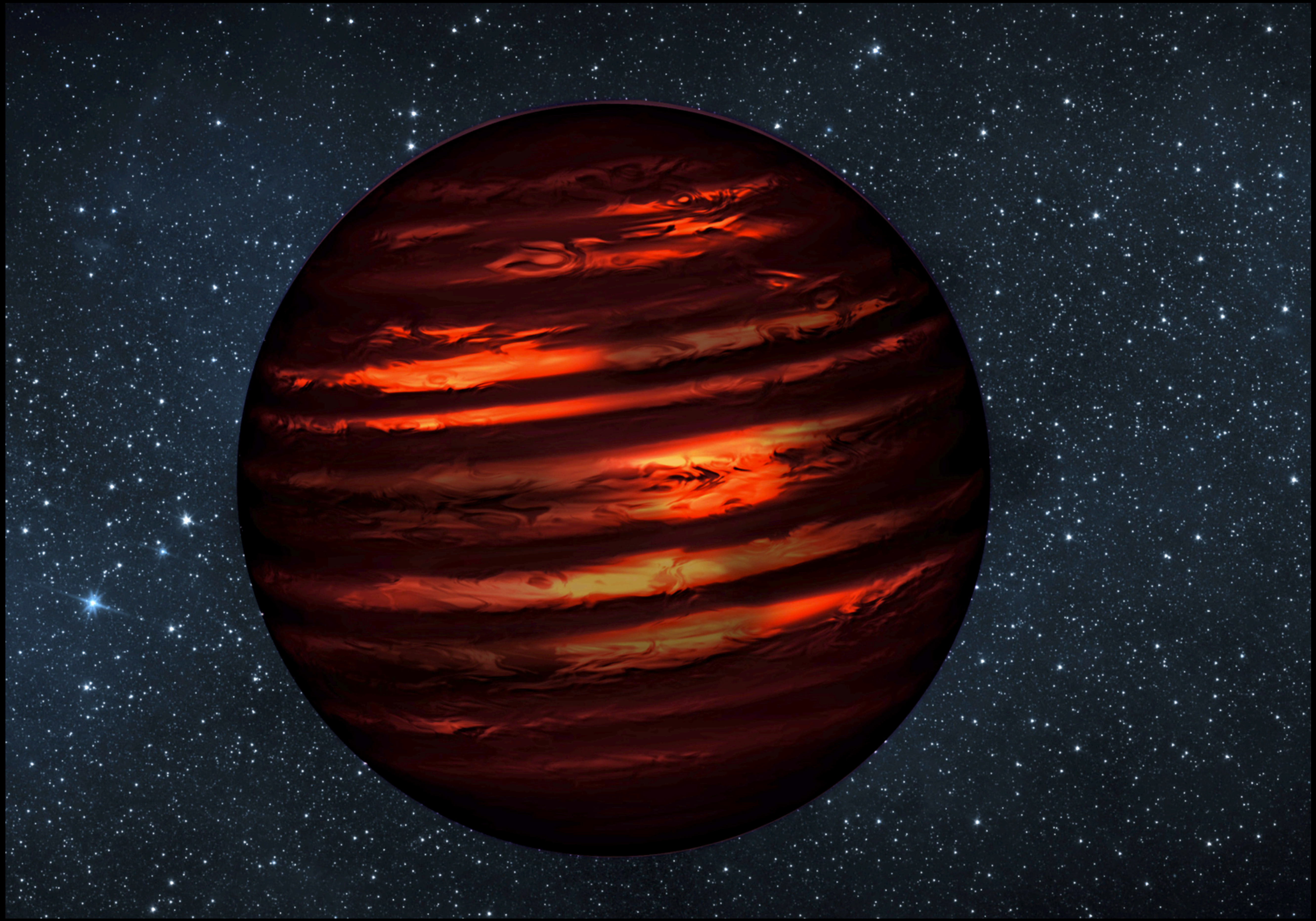
M = 10^{-3} M_{Sol}

M = M_{Sol}



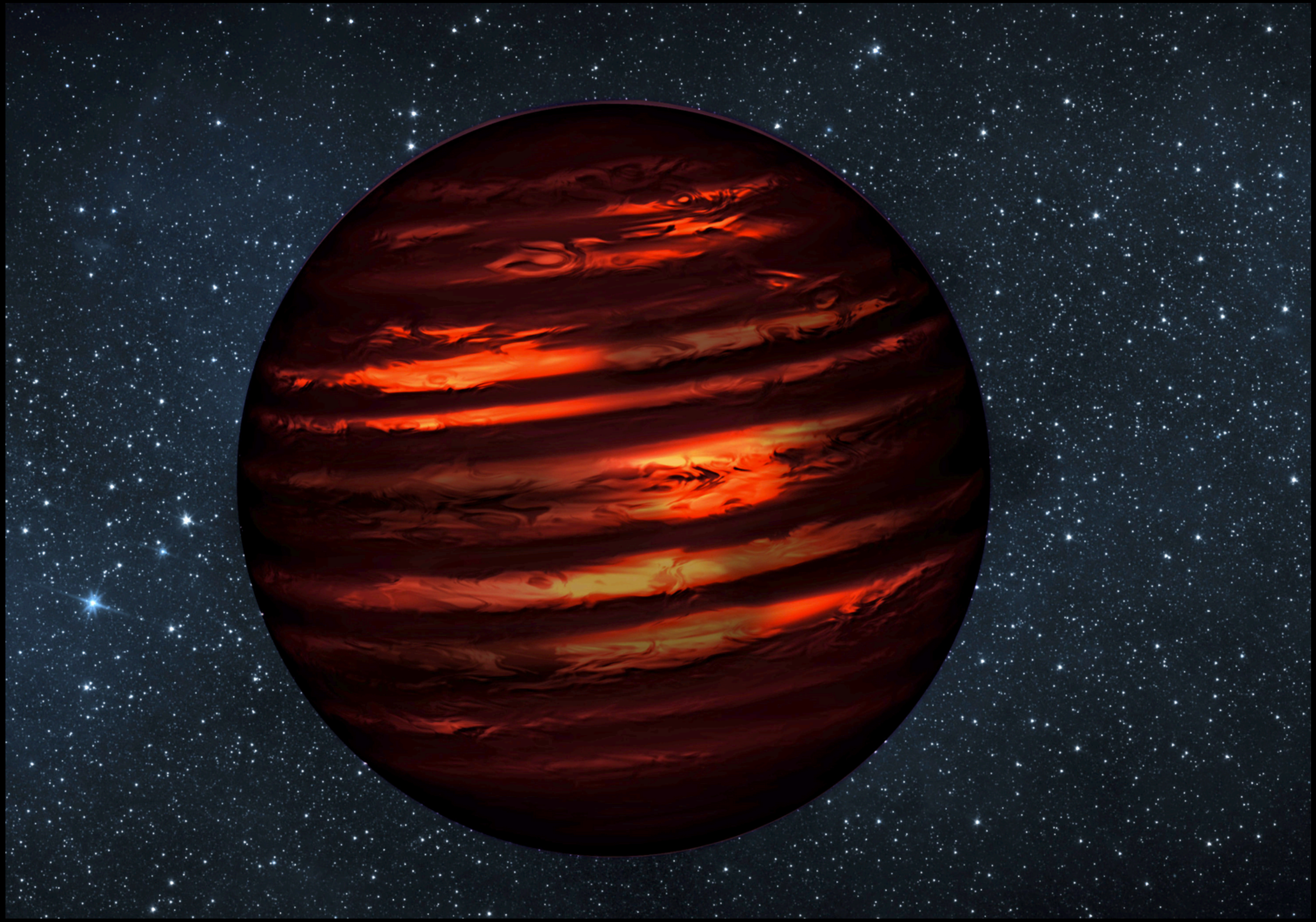
M = 1.4 M_{Sol}

Some Facts



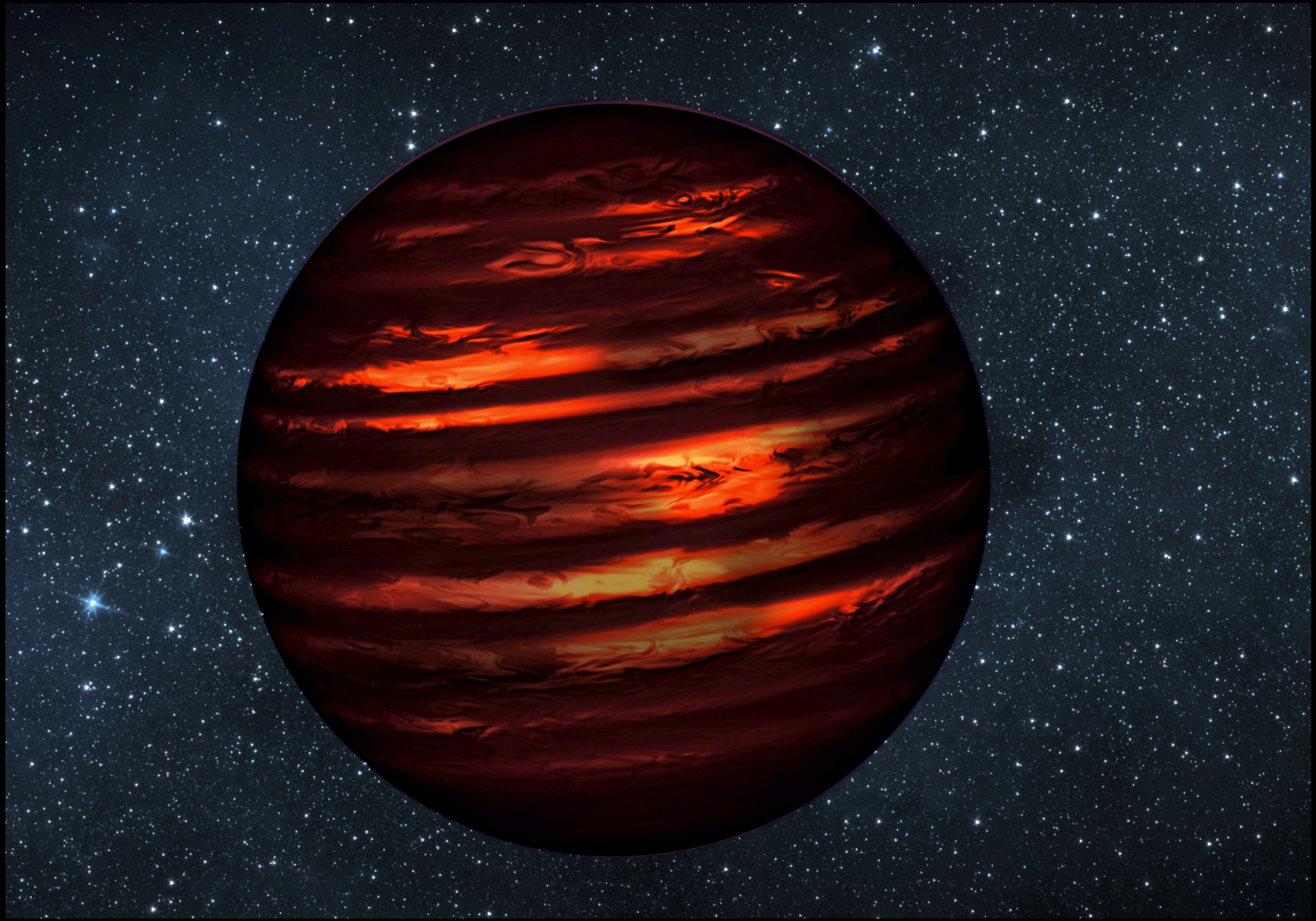
Some Facts

- 300 Billion expected
  Exoplanets in the Galaxy



Some Facts

- 300 Billion expected Exoplanets in the Galaxy
- Estimated 100 Billion rogue planets



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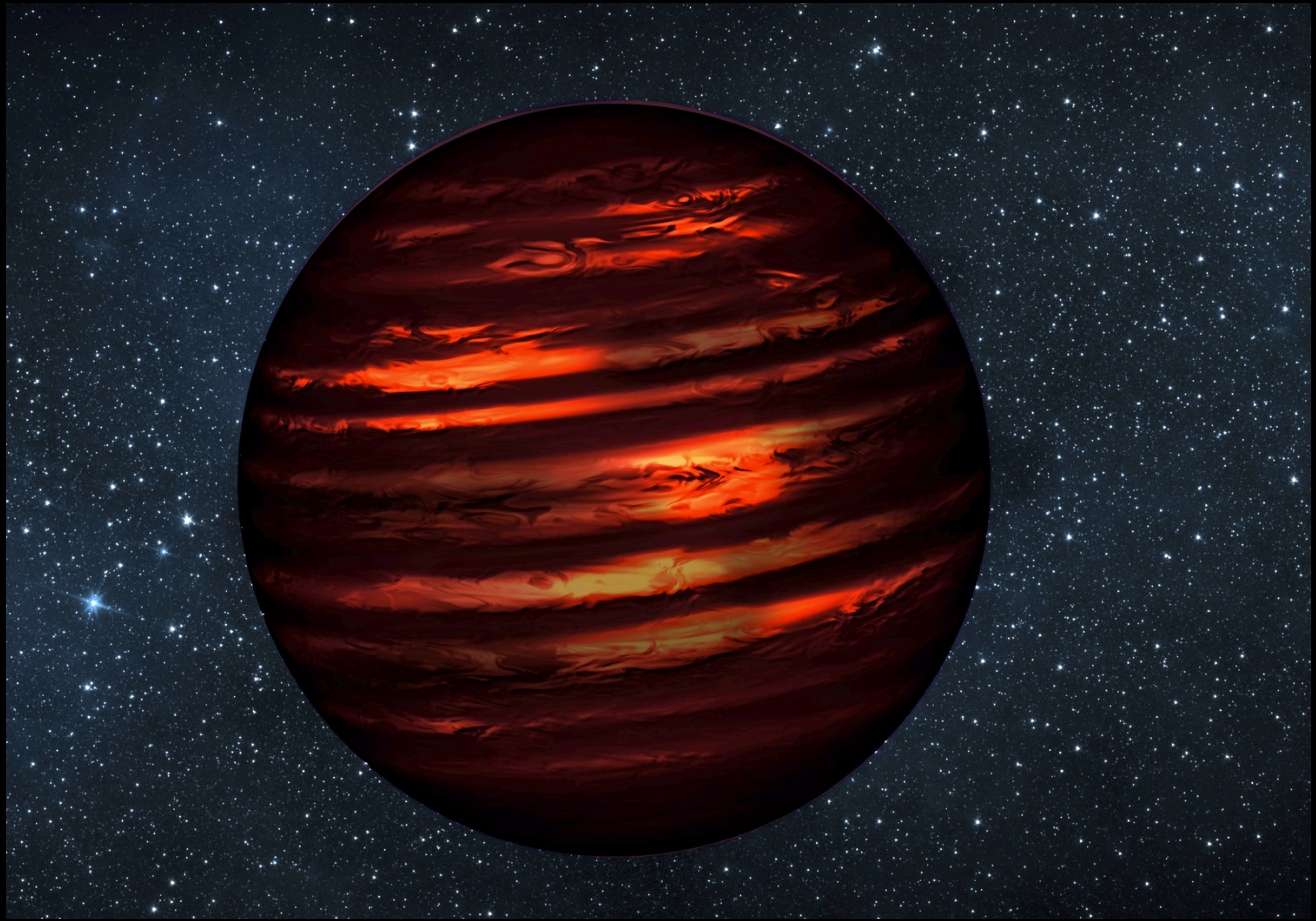
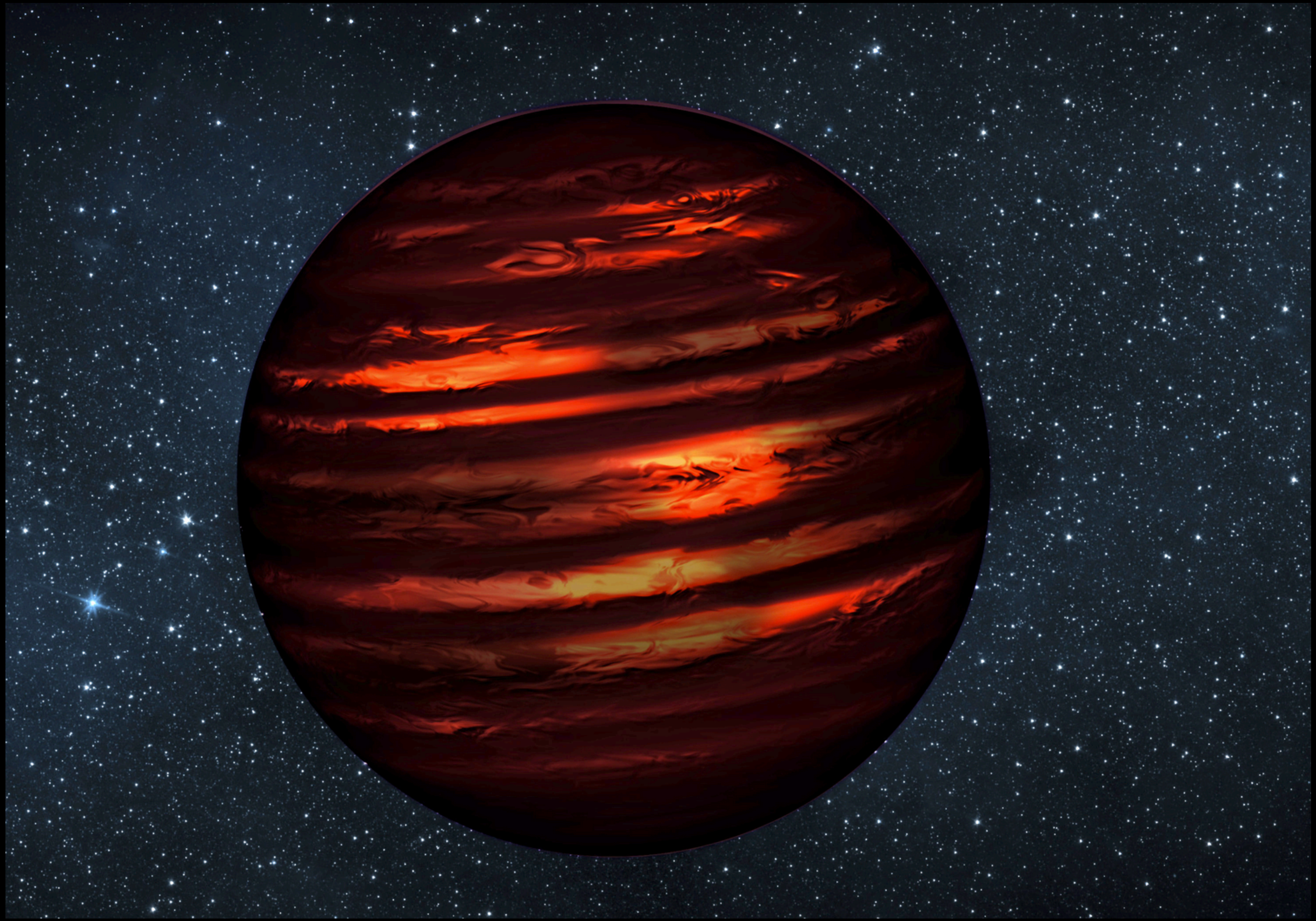
- 4k Confirmed Exoplanets



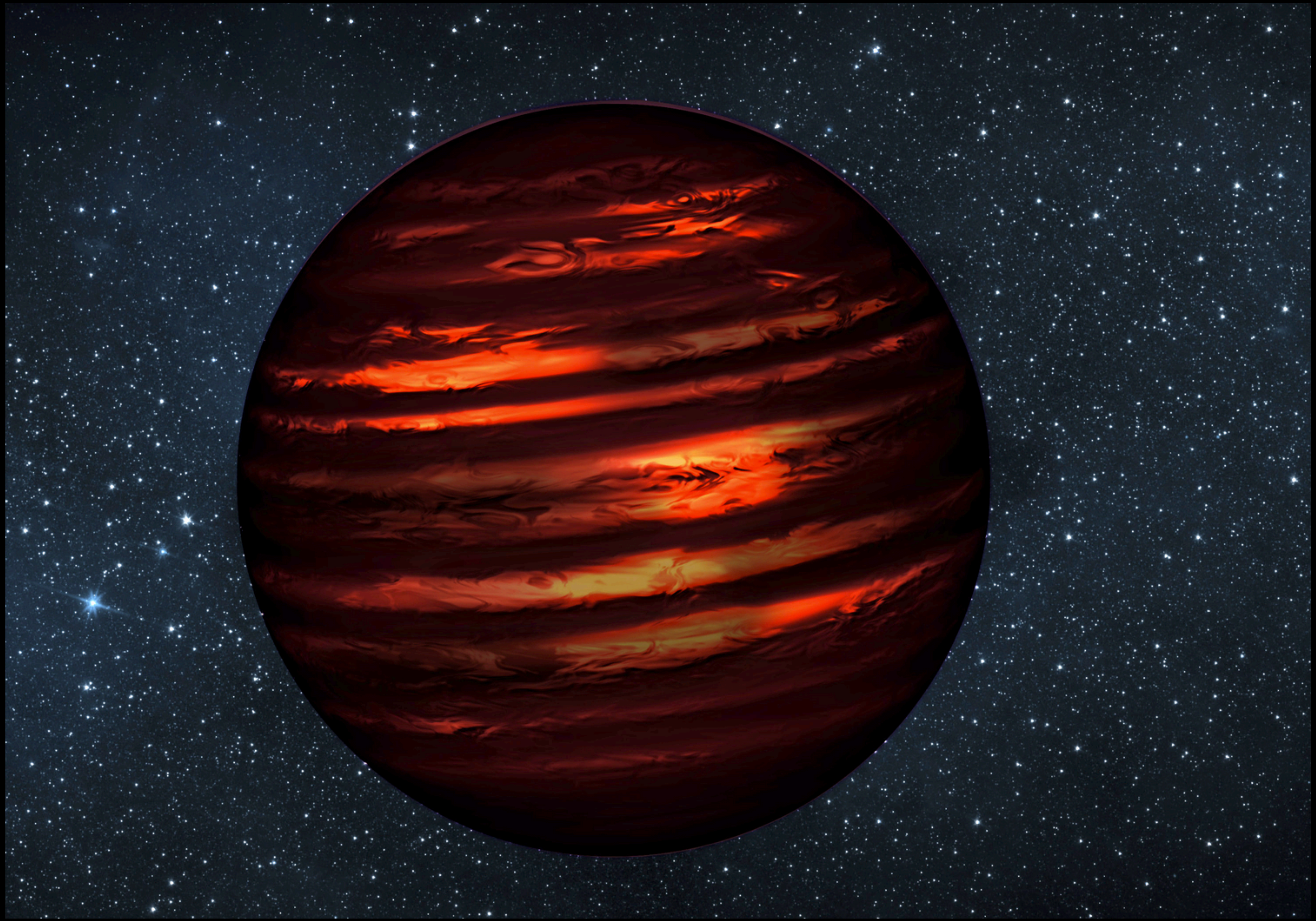
Some Facts

- 300 Billion expected Exoplanets in the Galaxy
- Estimated 100 Billion rogue planets
- 4k Confirmed Exoplanets
- 6k Candidates awaiting confirmation

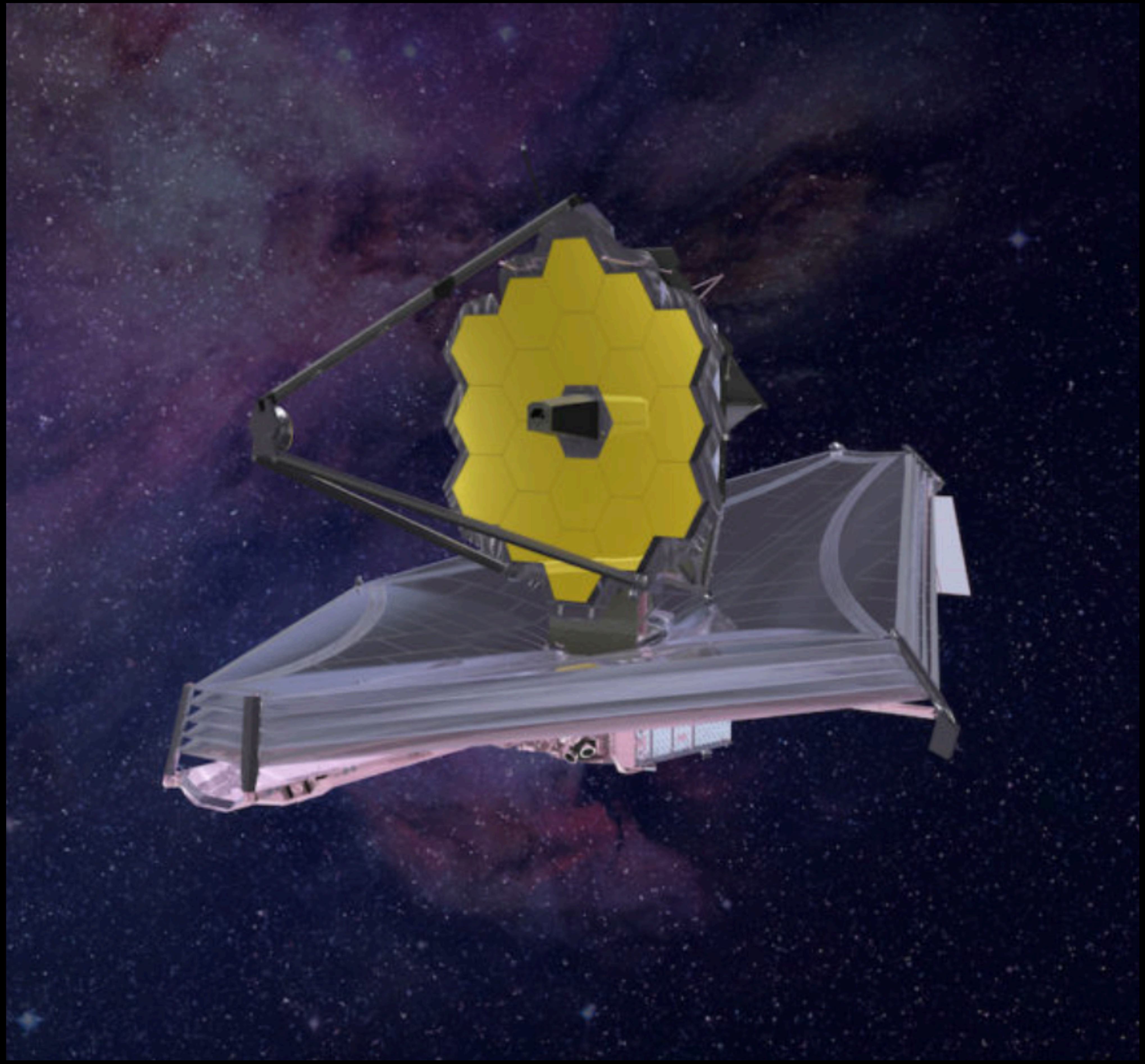


Some Facts

- 300 Billion expected Exoplanets in the Galaxy
- Estimated 100 Billion rogue planets
- 4k Confirmed Exoplanets
- 6k Candidates awaiting confirmation
- New Infrared Telescopes: JWST 2022 and Roman 2026

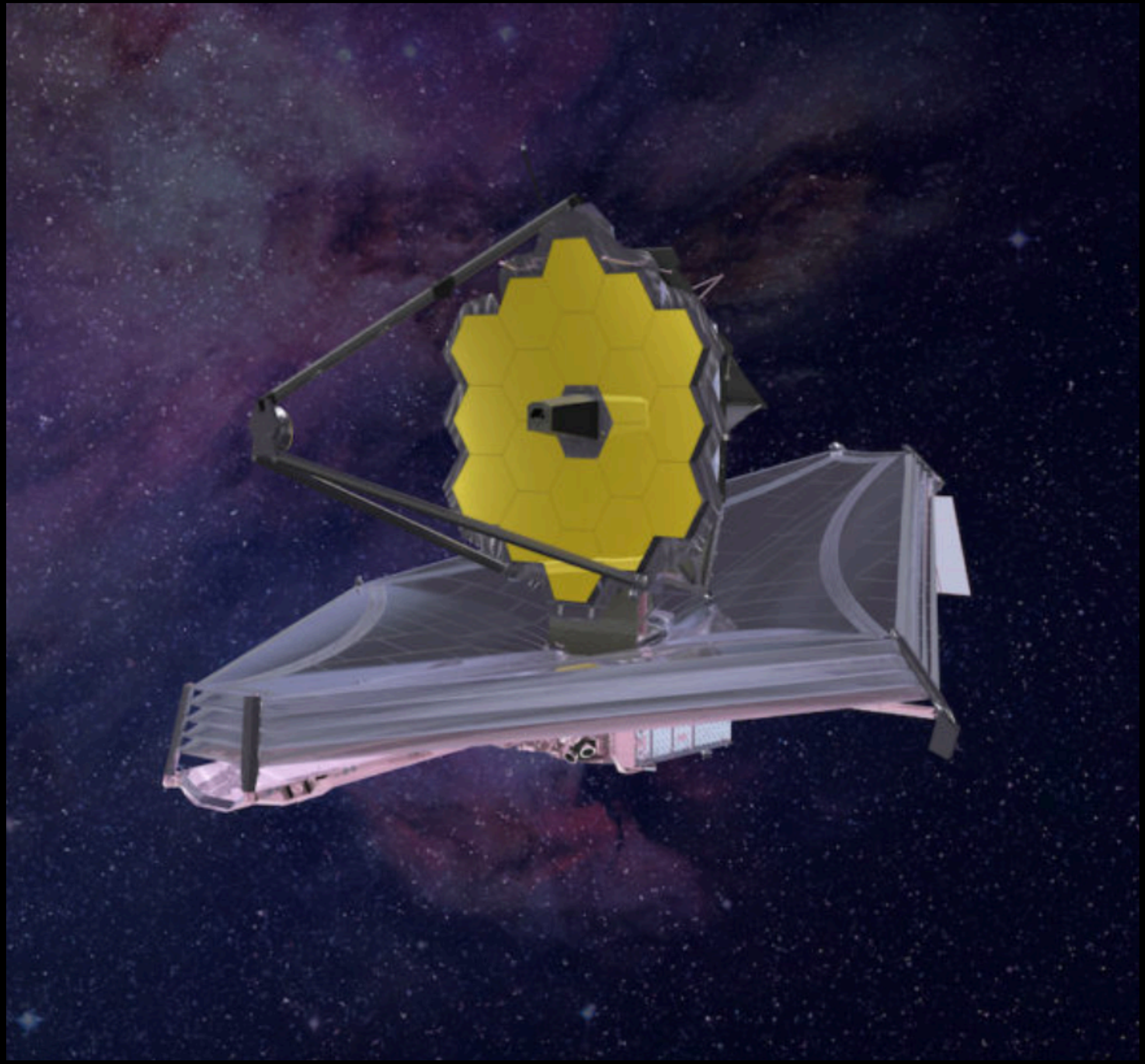


JWST



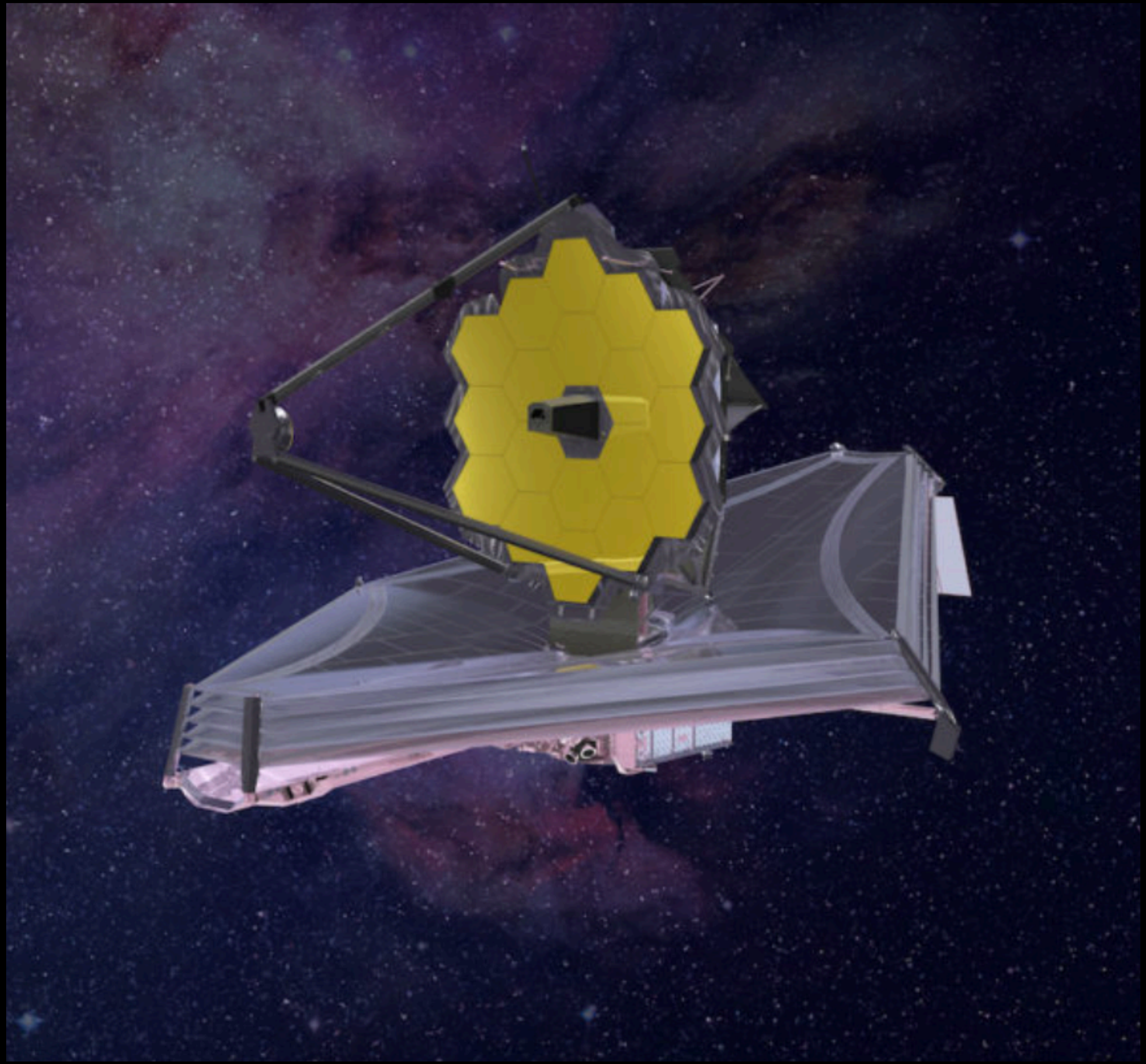
JWST

- 6.5 m Mirror diameter



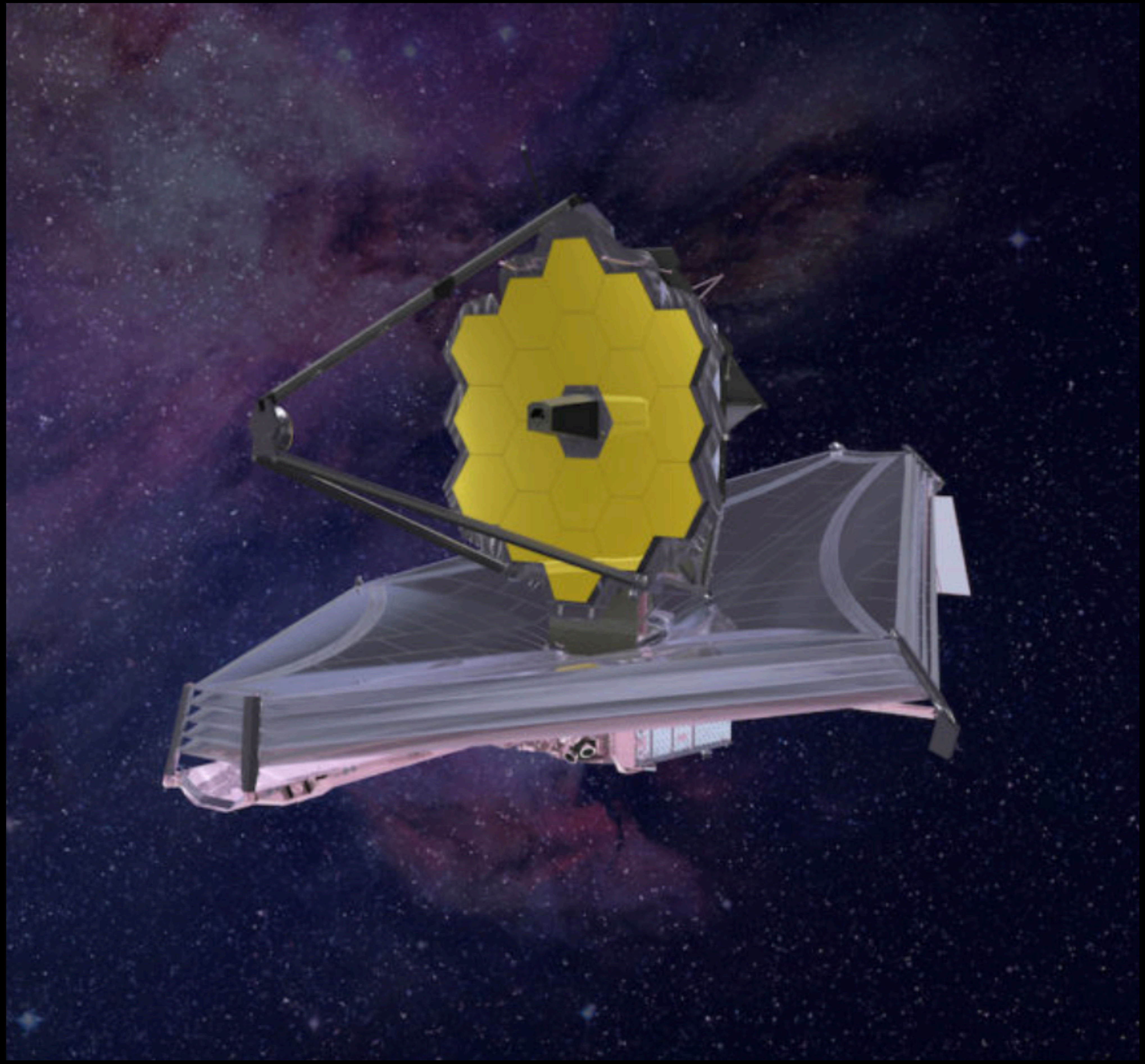
JWST

- 6.5 m Mirror diameter
- 18 Hexagonal Segments



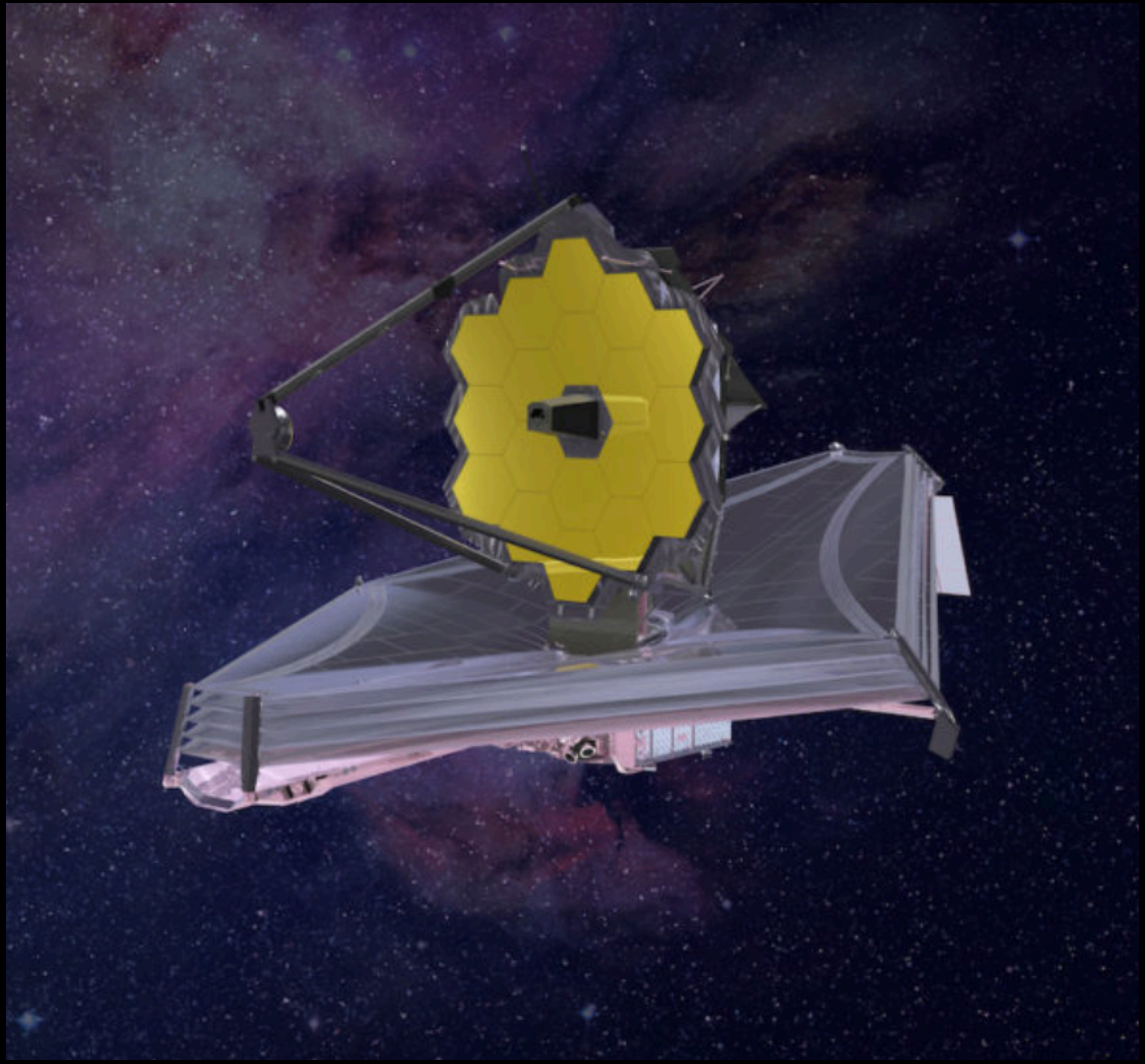
JWST

- 6.5 m Mirror diameter
- 18 Hexagonal Segments
- Near-Infrared Imager and Slitless Spectrometer (NIRISS) for T > 500 K



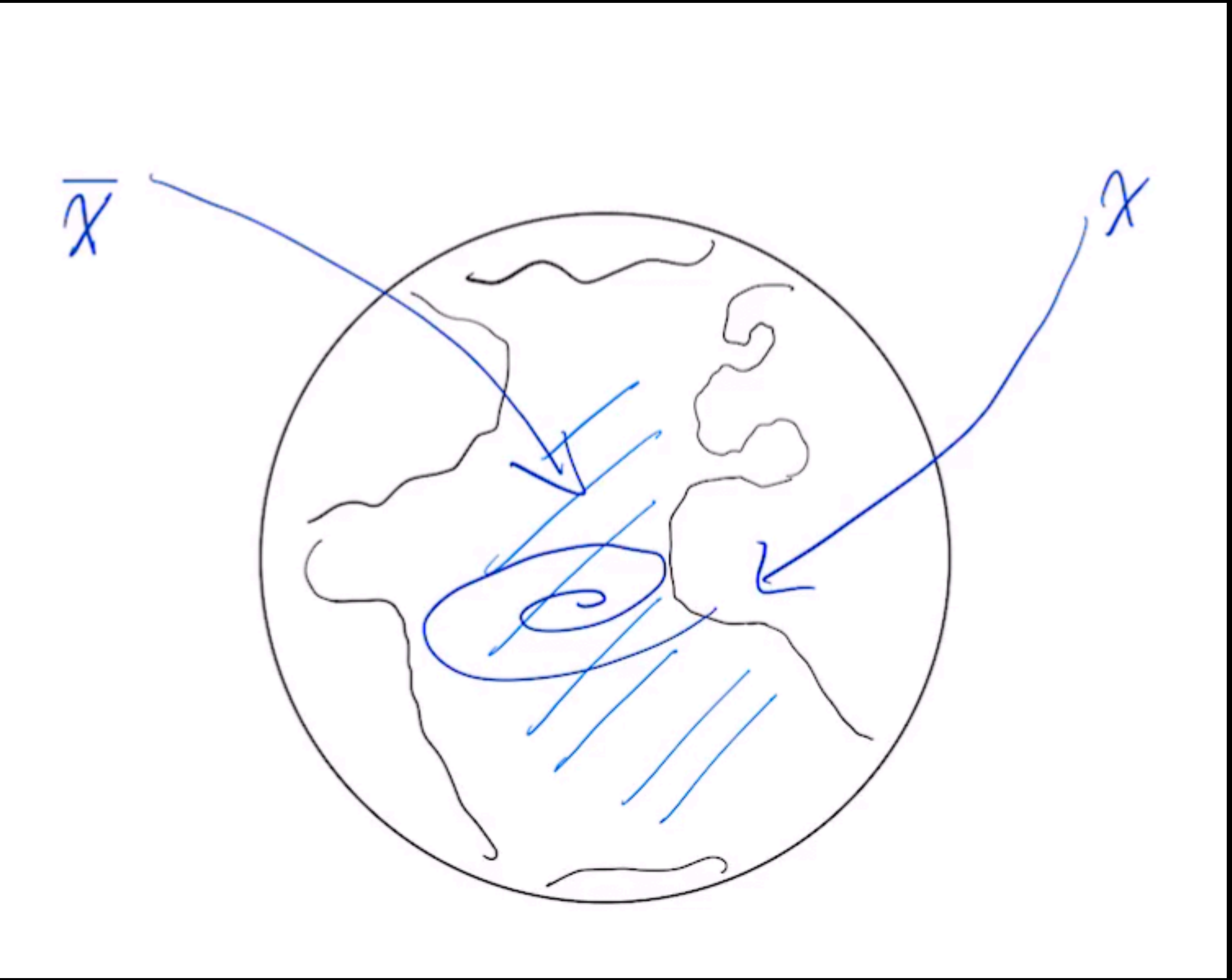
JWST

- 6.5 m Mirror diameter
- 18 Hexagonal Segments
- Near-Infrared Imager and Slitless Spectrometer (NIRISS) for T > 500 K
- Mid-Infrared Instrument (MIRI) for T : 100 - 500 K



Dark Matter Heating

Conditions for Heating: Capture



$$C_{\rm cap} \approx v_{\rm DM} \pi R^2 \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{v_{\rm DM}^2}\right)$$

$$\times \sum_{N=1}^{\infty} f_N(\tau) g_N(v_{\rm DM}, v_{\rm esc})$$

$$= \phi_{\rm DM}\, f_{\rm cap}$$

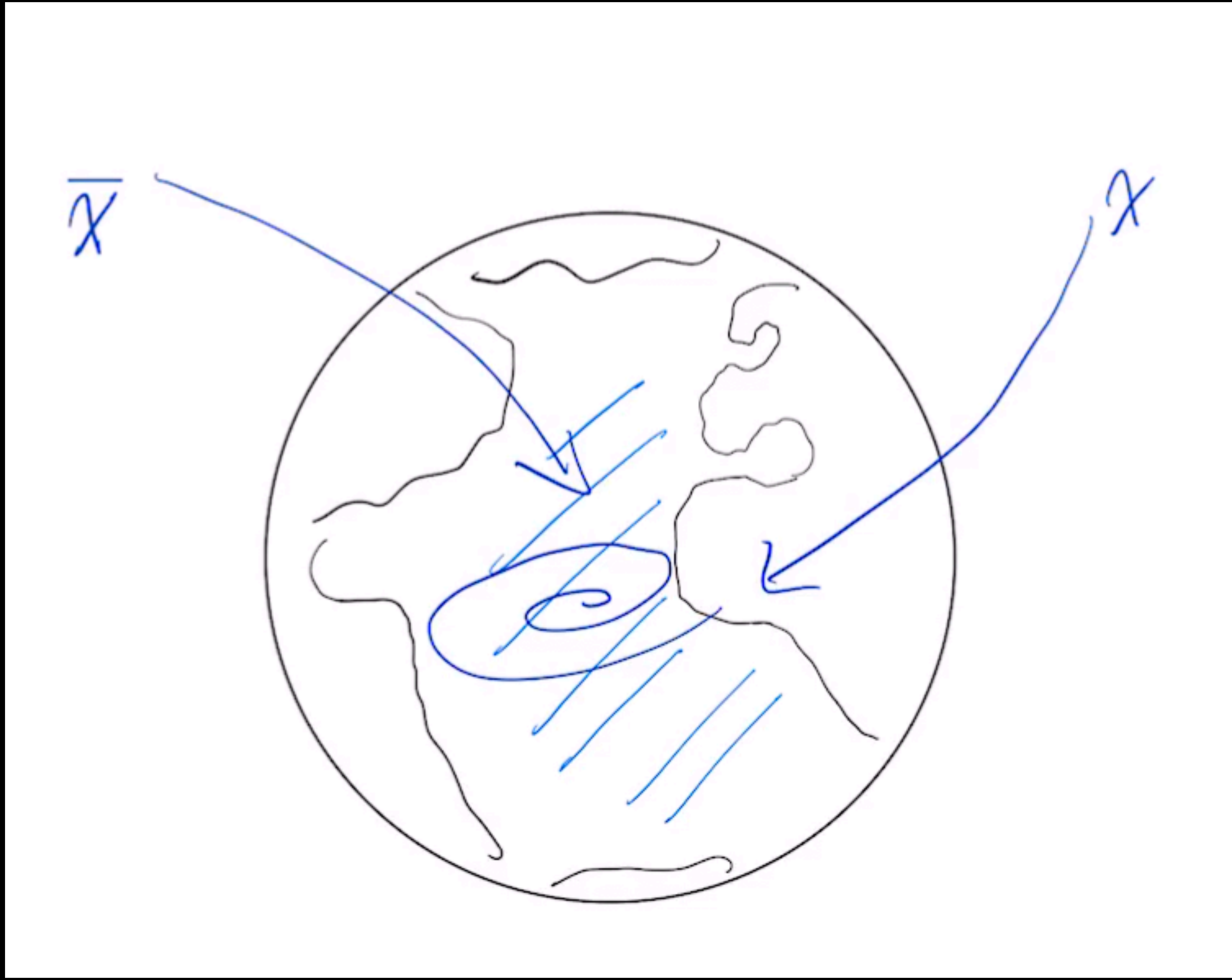
Annihilation Equilibrium

$$\langle \sigma_{\rm ann} v_{\rm rel} \rangle \geq \frac{V_{\rm eff}^{2\to2}}{C_{\rm cap}\tau^2}$$

$$\langle \sigma_{3\to2} v_{\rm rel}^2 \rangle \geq \frac{V_{\rm eff}^{2\to2}}{n_{\rm SM} C_{\rm cap}\tau^2}$$

Co-SIMP process

Phys.Rev.Lett. 125 (2020) 13; J. Smirnov, J. Beacom (OSU)



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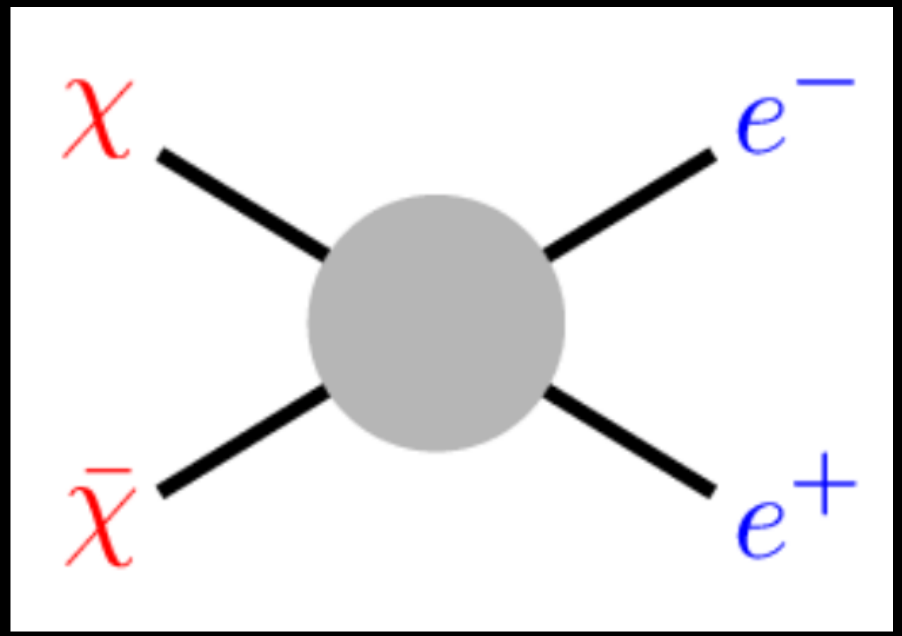

$$\geq \frac{V_{\rm eff}^{2\to 2}}{C_{\rm cap}\tau^2}$$

$$\langle \sigma_{3\to 2} v_{\rm rel}^2 \rangle \geq \frac{V_{\rm eff}^{2\to 2}}{n_{\rm SM} C_{\rm cap}\tau^2}$$

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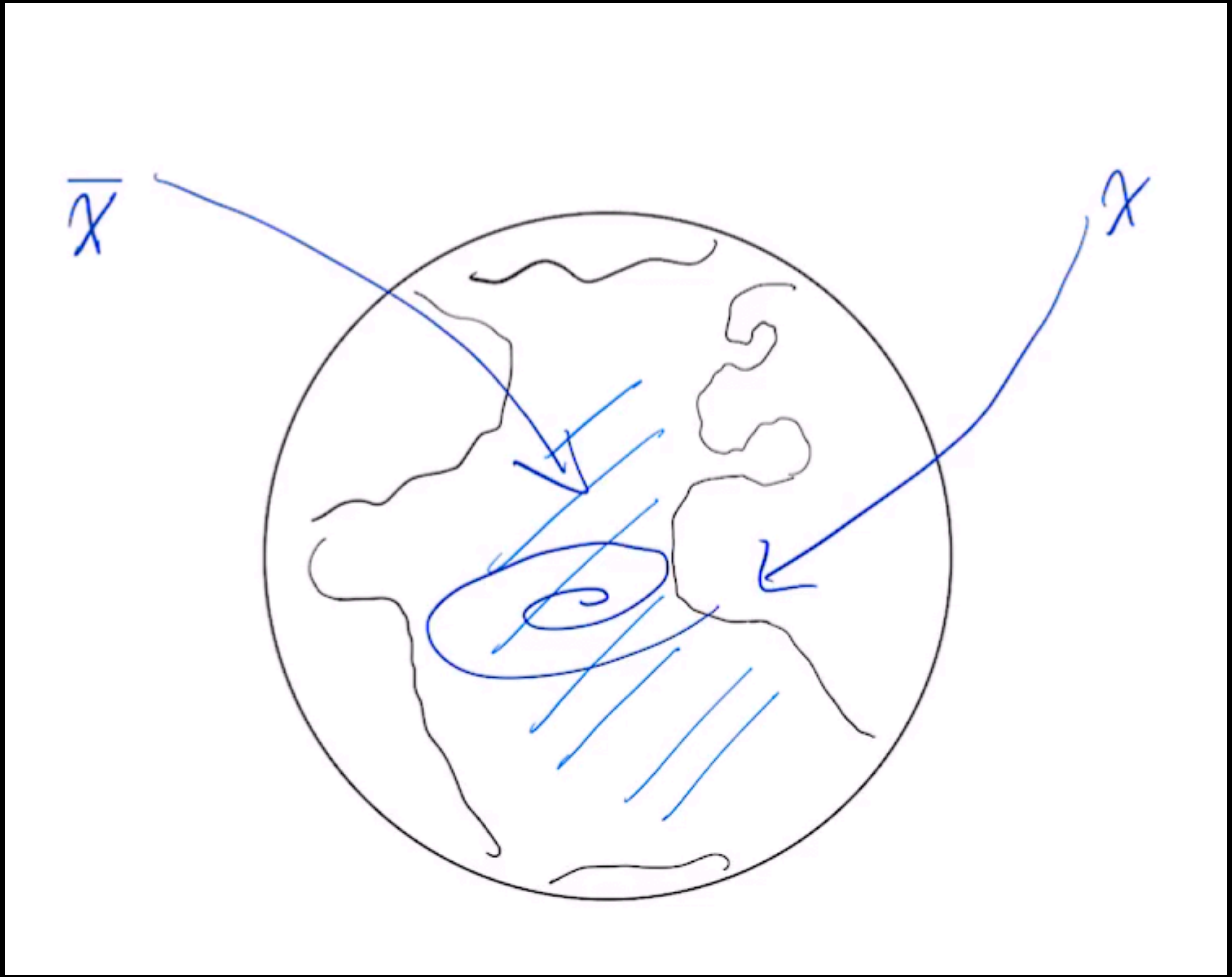

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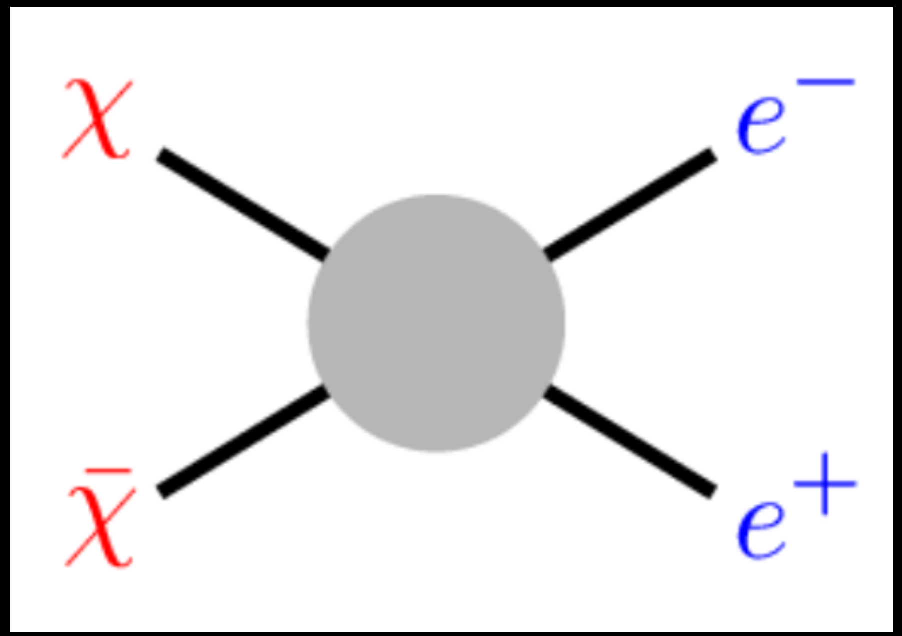

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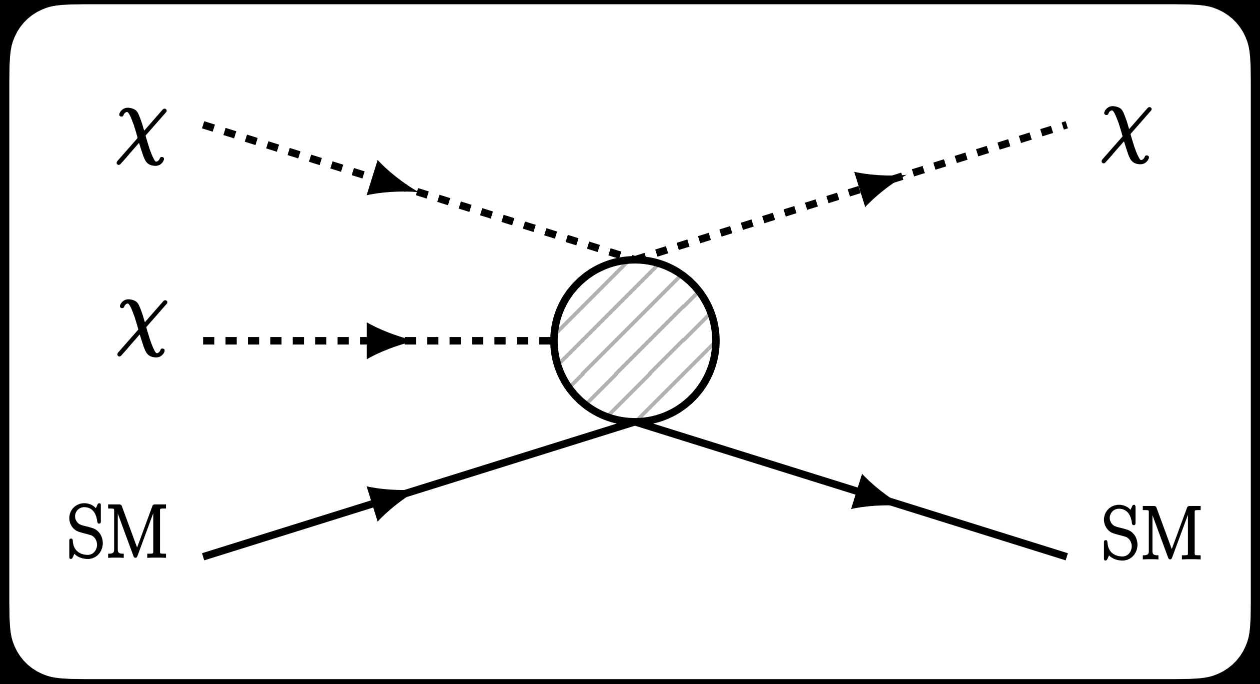

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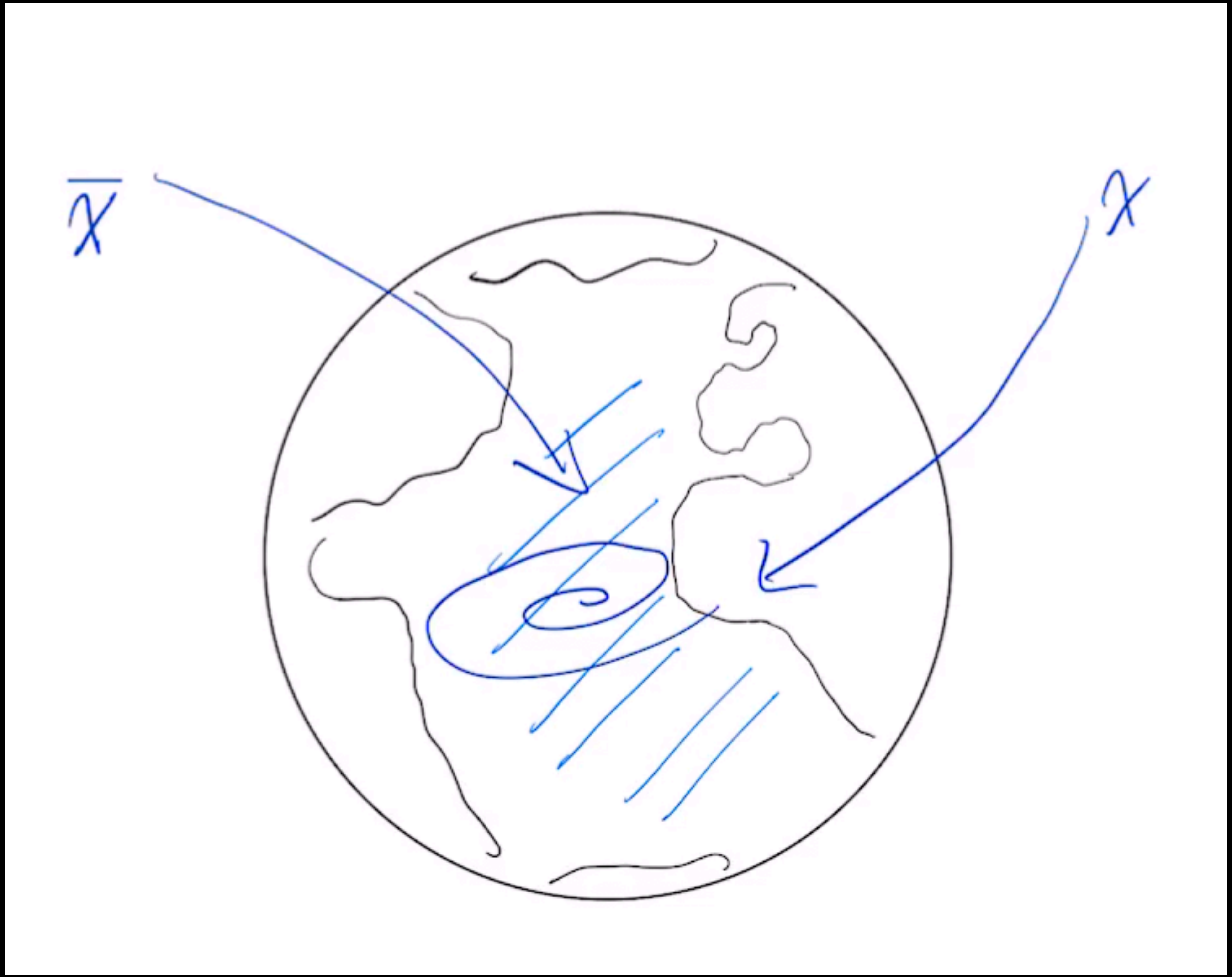
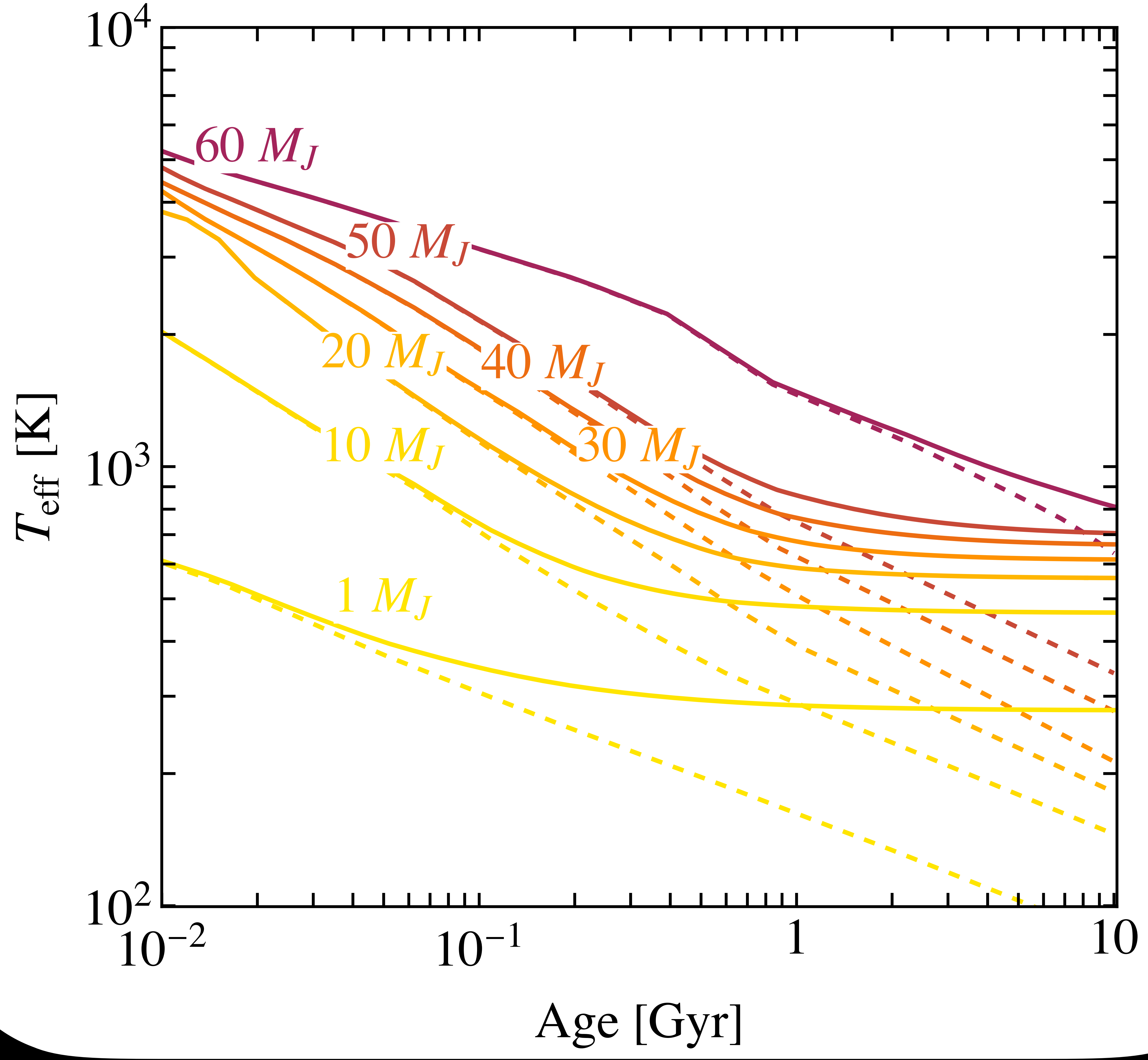


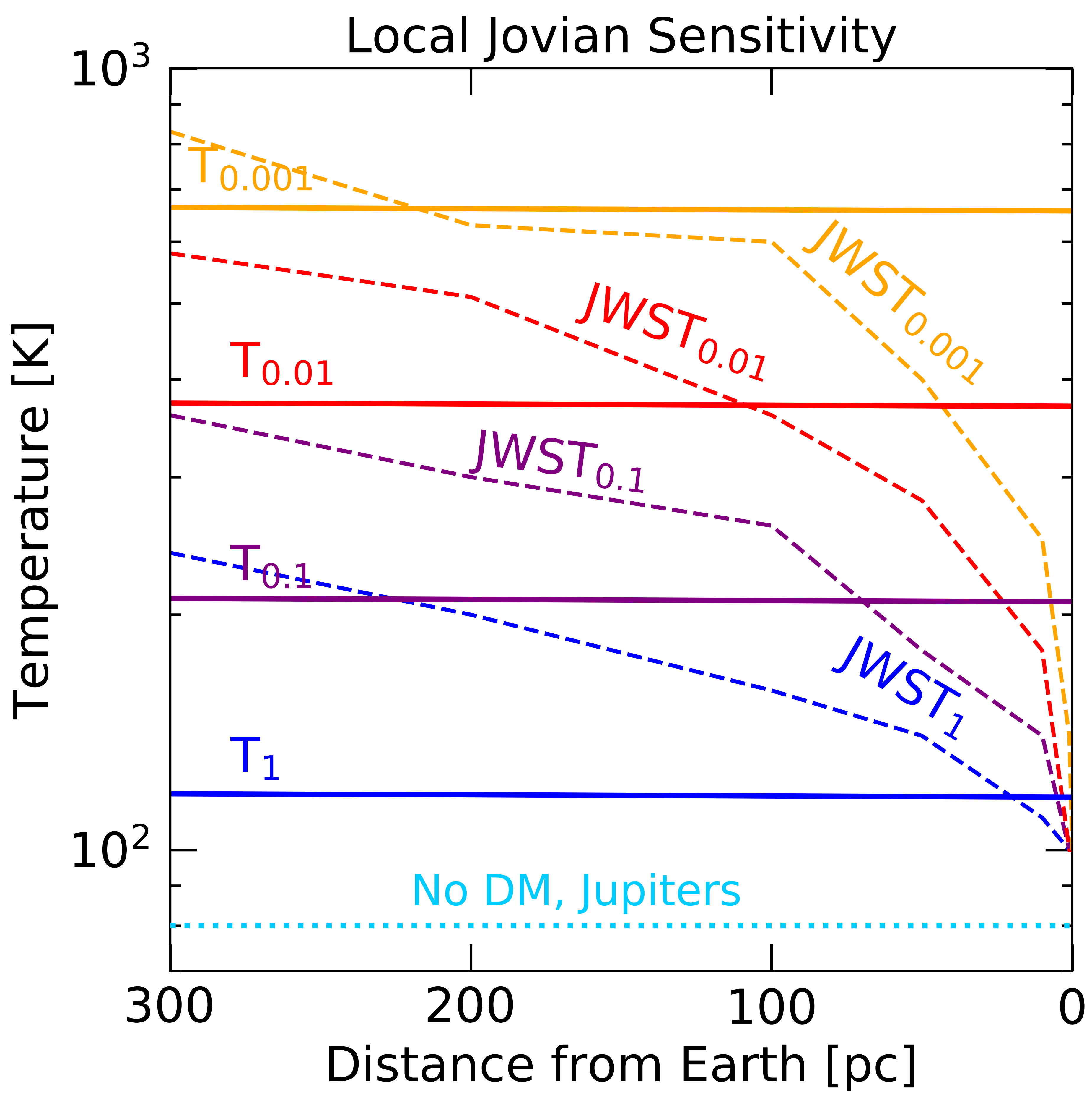
Temperature Evolution



Search Strategies

1: In our Neighborhood

Local Search



arXiv: 2010.00015; R. K. Leane (Stanford), **J. Smirnov**

What about Jupiter?

What about Jupiter?

Article | Open Access | Published: 13 September 2018

Less absorbed solar energy and more internal heat for Jupiter

Liming Li, X. Jiang, R. A. West, P. J. Gierasch, S. Perez-Hoyos, A. Sanchez-Lavega, L. N. Fletcher, J. J. Fortney, B. Knowles, C. C. Porco, K. H. Baines, P. M. Fry, A. Mallama, R. K. Achterberg, A. A. Simon, C. A. Nixon, G. S. Orton, U. A. Dyudina, S. P. Ewald & R. W. Schmude Jr.

Previous: $F = 5.4 \pm 0.4 \text{ Watt}/m^2$

New: $F = 7.5 \pm 0.2 \text{ Watt}/m^2$

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Previous: $F = 5.4 \pm 0.4$ Watt$/m^2$

New: $F = 7.5 \pm 0.2$ Watt$/m^2$

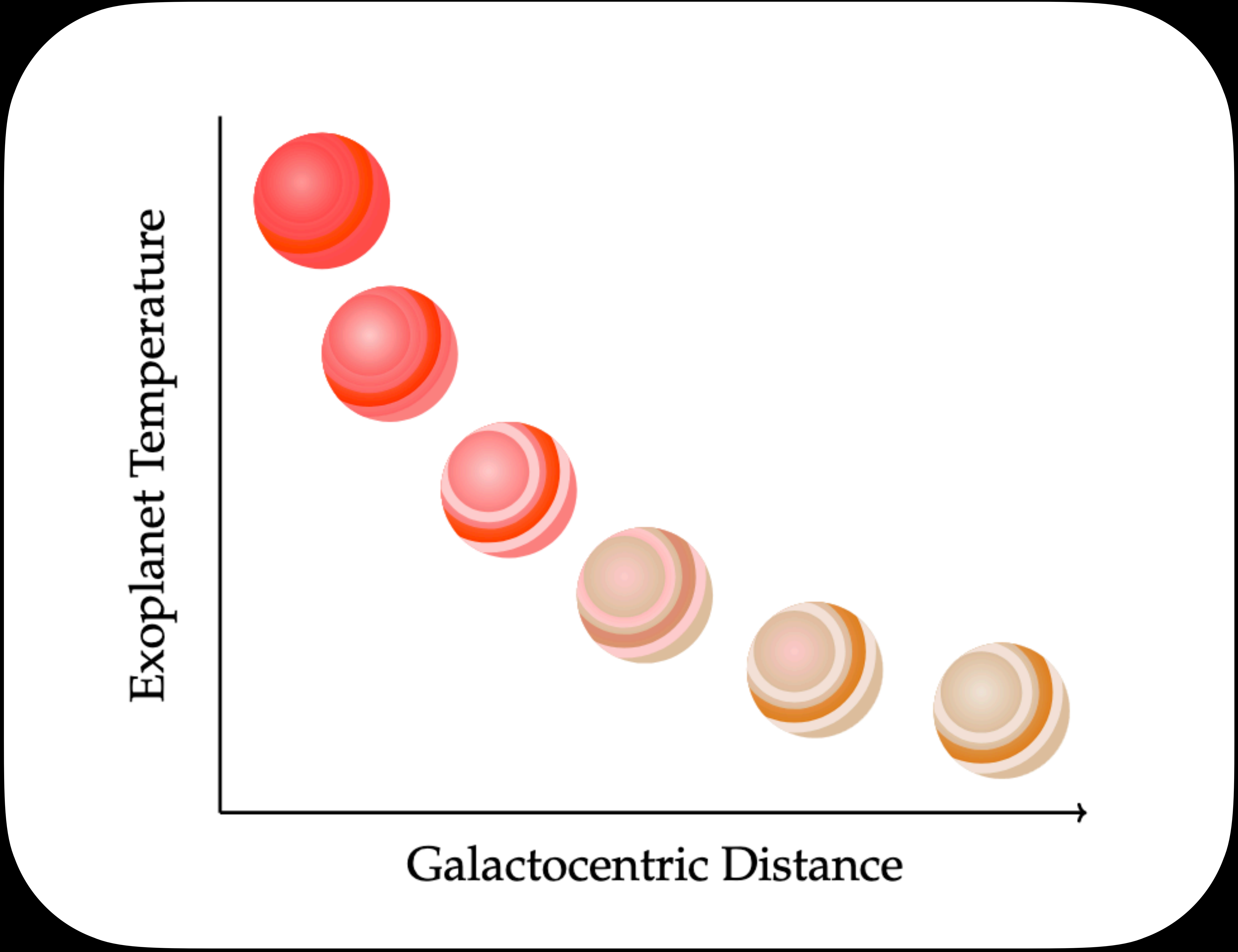
Expected w/o heating: $F \approx 4$ Watt$/m^2$

Expected with heating: $F \approx 8$ Watt$/m^2$

$\Delta F \approx 1 - 1.5$ Watt$/m^2$

2: In our Galaxy, but far, far away

A Position Dependent Signal



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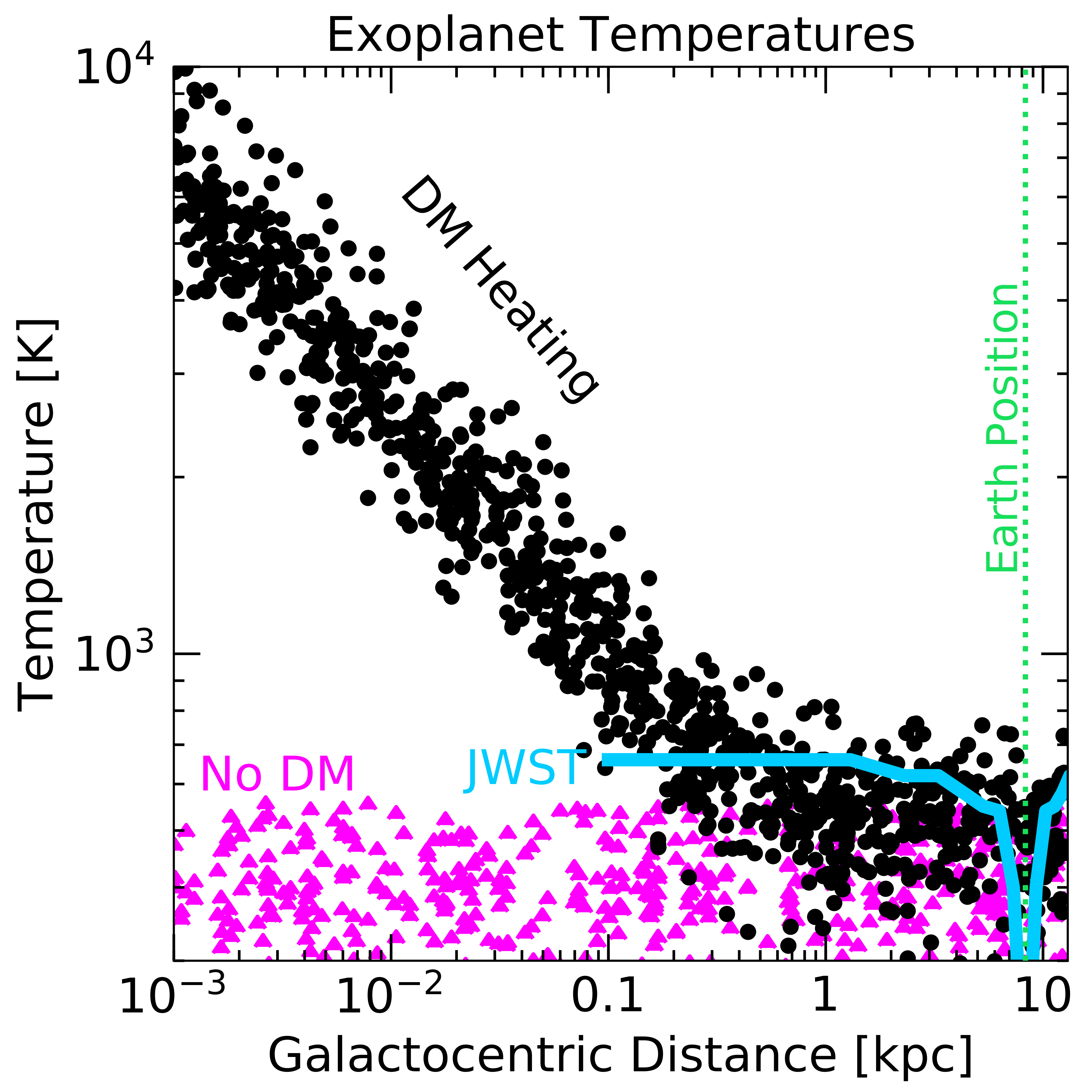
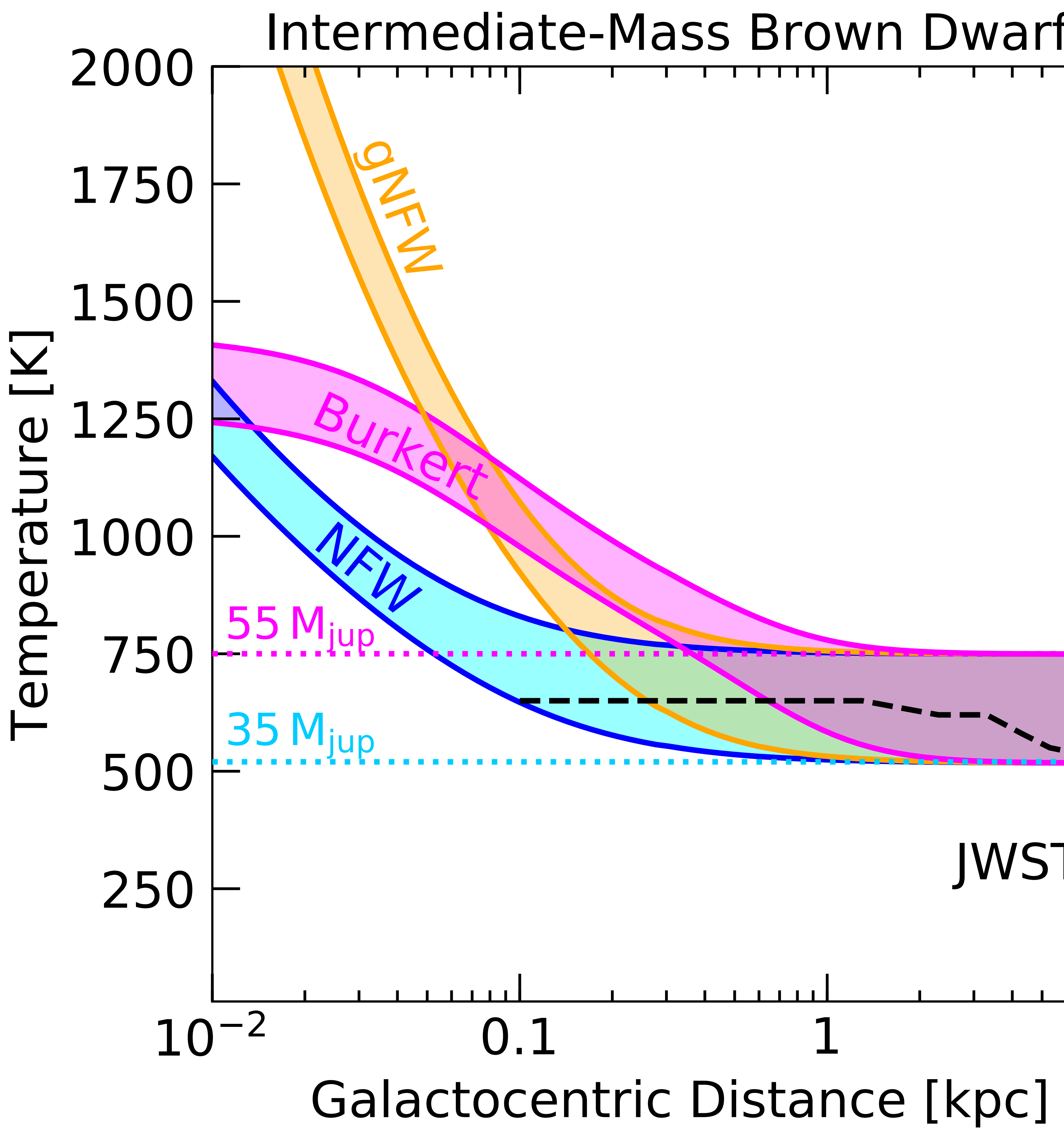


arXiv: 2010.00015; R. K. Leane (SLAC), **J. Smirnov**

DM Profile Dependence



arXiv: 2010.00015; R. K. Leane (SLAC), **J. Smirnov**

Search Limitations

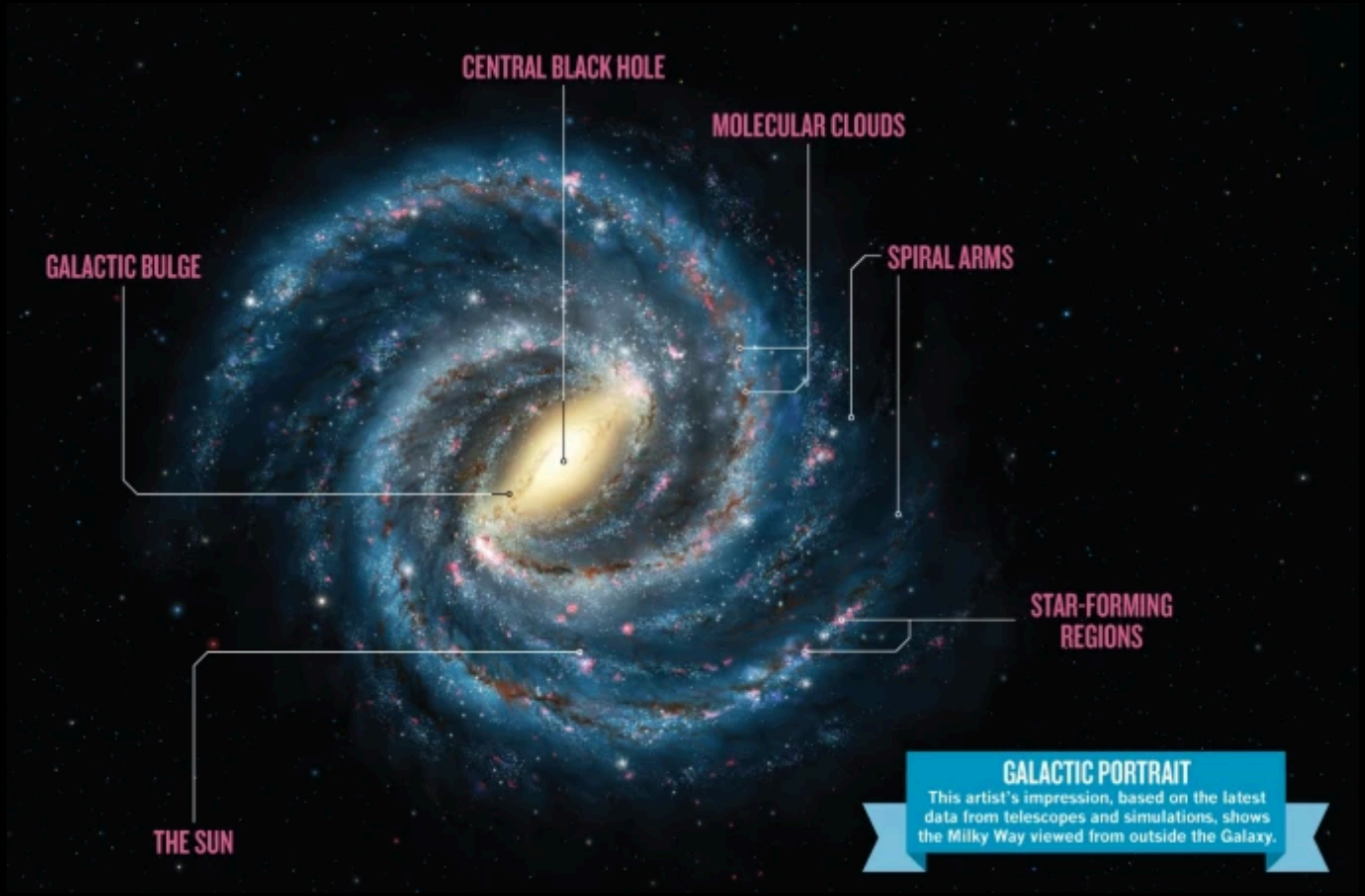
Interstellar Dust

Stars per Pixel

at 1° off the Galactic Plane i.e. 0.1 kpc form GC:
JWST: 20% populated pixels

Extracting DM Halo Parameters

Modeling Our Galaxy



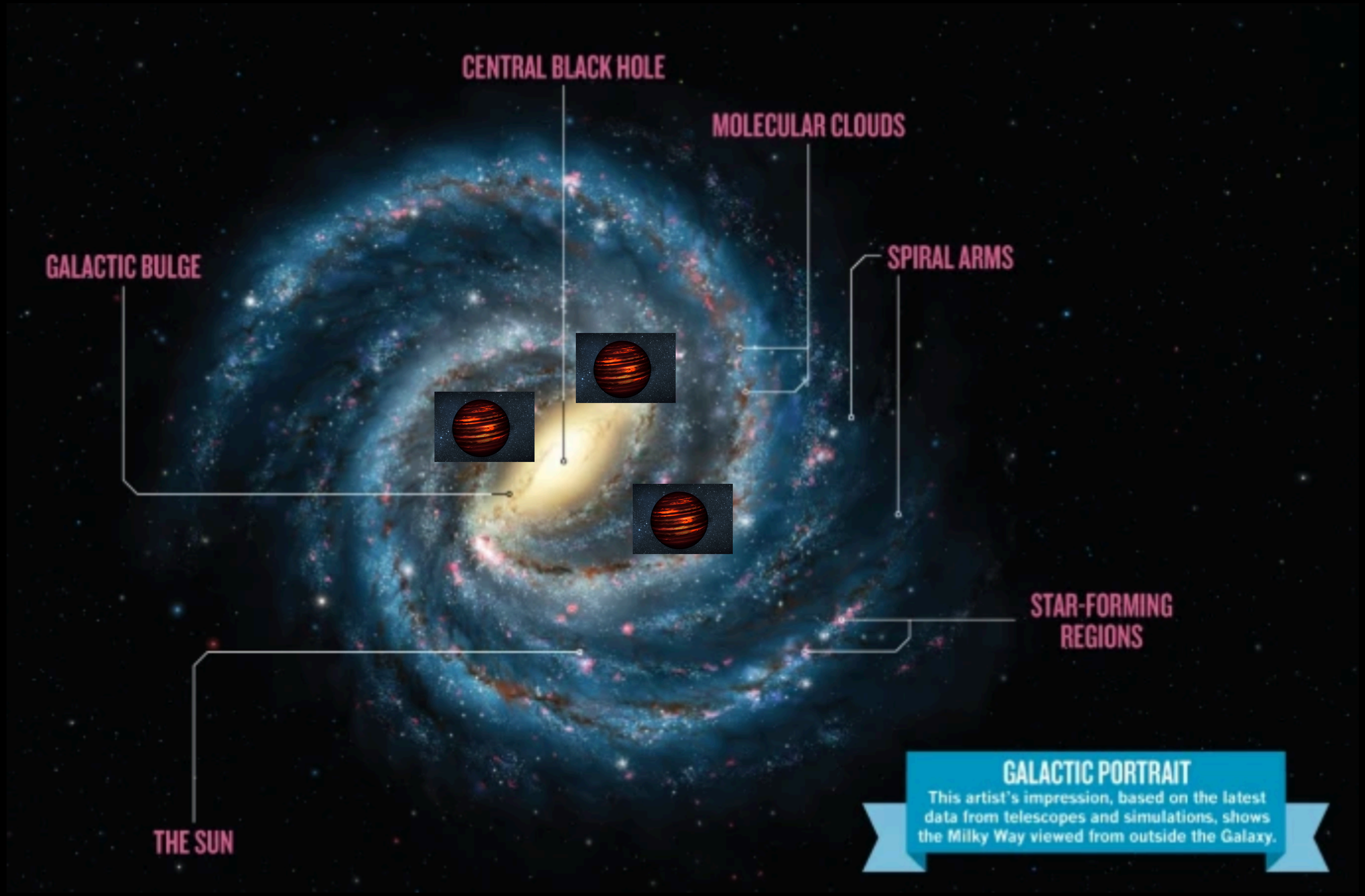
- Old population in the Bulge: t > few Gyr
- E2 Bulge Profile (astro-ph/9605162)
- Power law Mass function

$$\frac{dN_{\rm BD}}{dM} = \frac{1}{M^{\alpha}}$$

$$\alpha \approx 0.6$$

Work in progress: M. Benito, R. K. Leane, S. Podar, J. Smirnov

Modeling Our Galaxy



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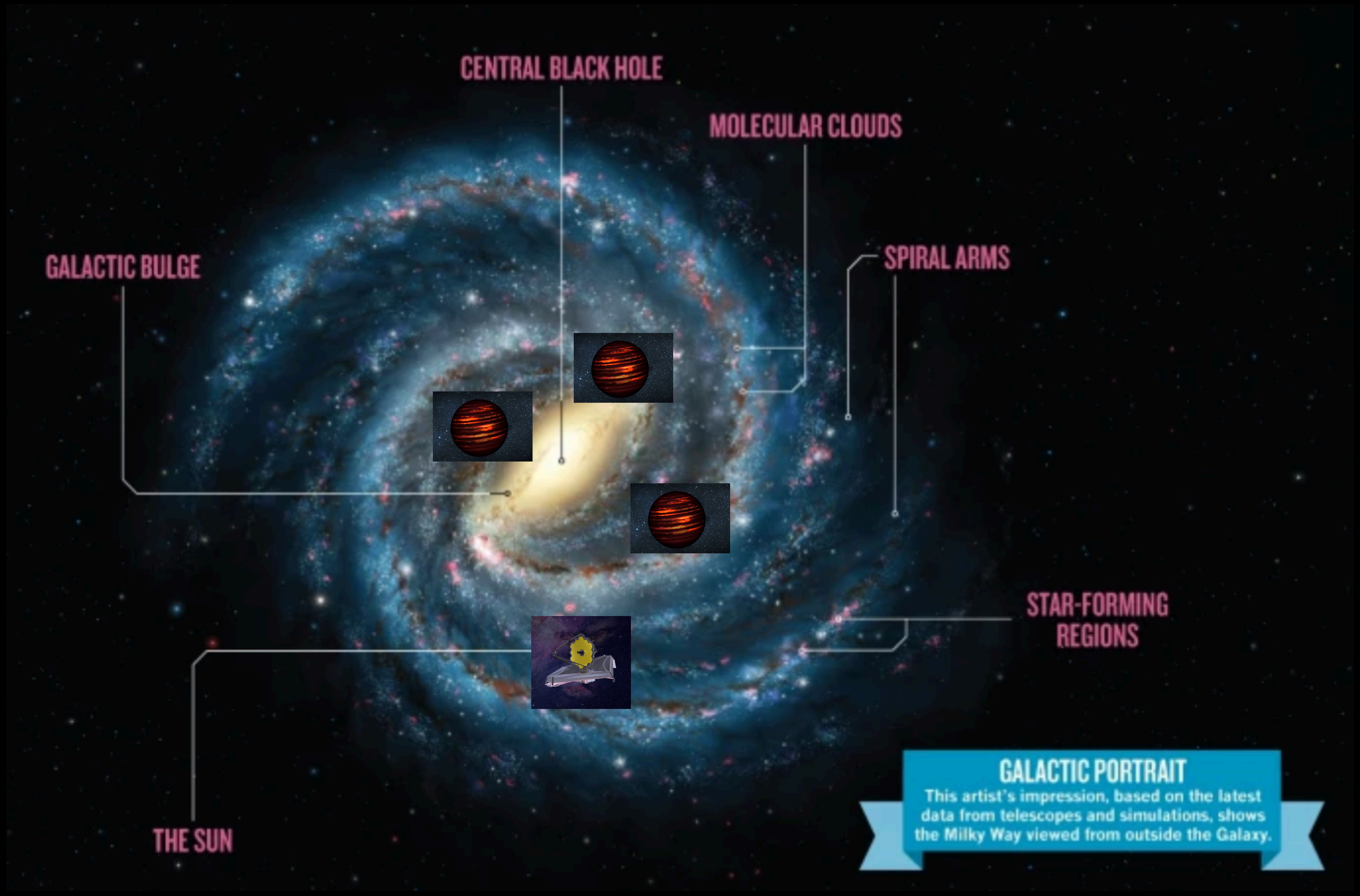

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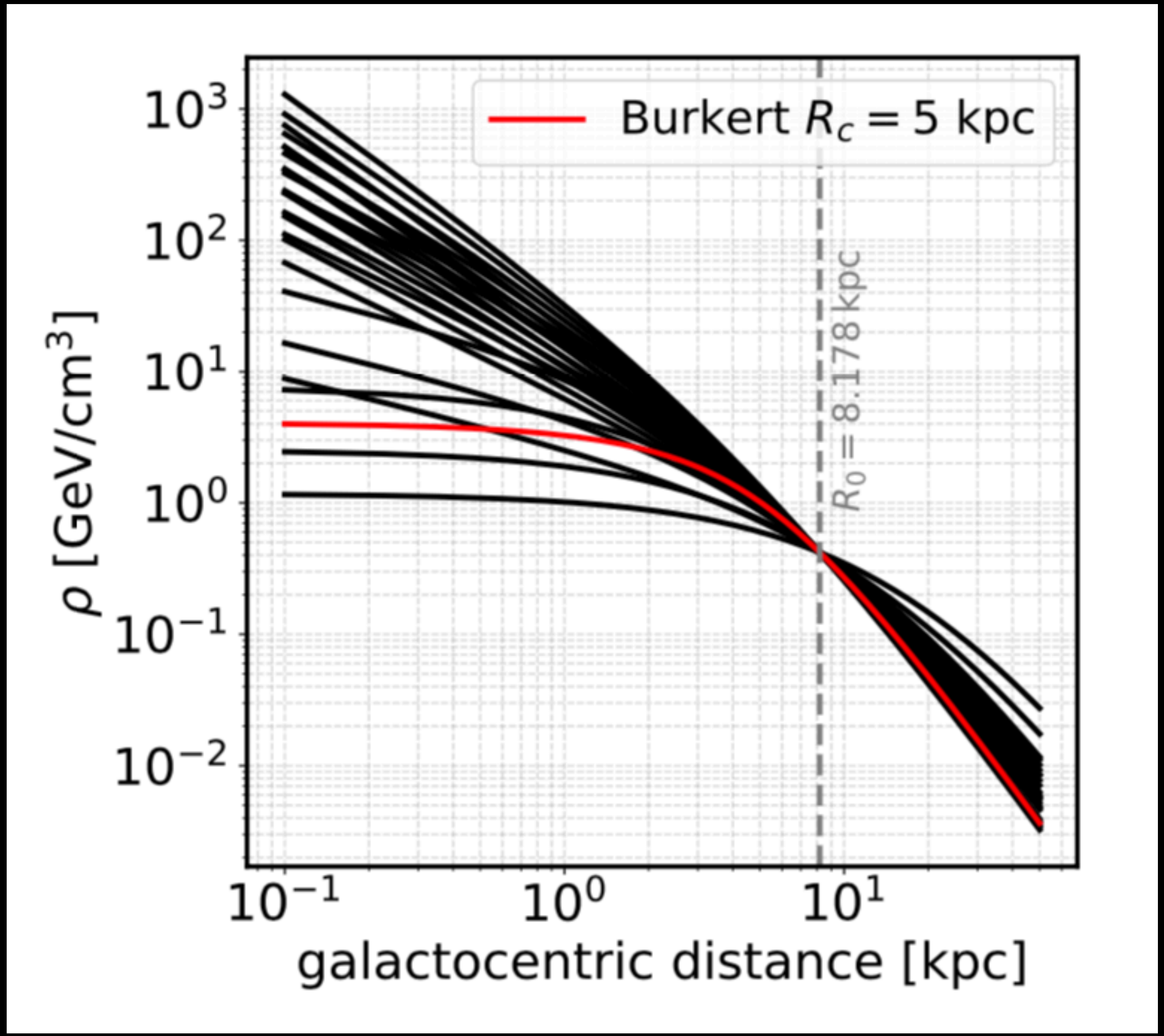
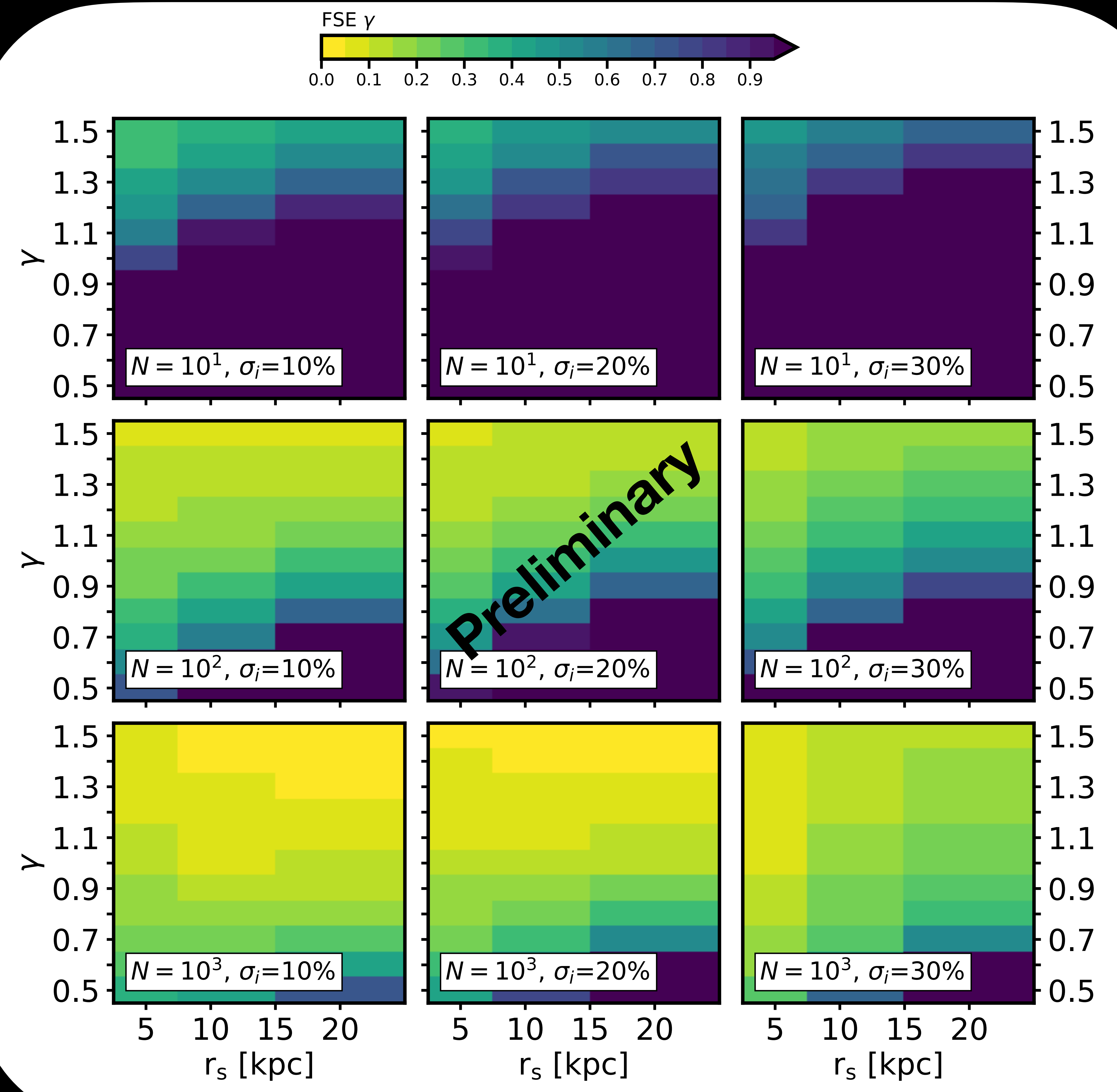
Add DM Profile

$$\rho_{\mathrm{DM}}(r;\gamma,r_s,\rho_0) =$$
$$\rho_0\left(\frac{R_0}{r}\right)^{\gamma}\left(\frac{r_s+R_0}{r_s+r}\right)^{3-\gamma}$$



Work in progress: M. Benito, R. K. Leane, S. Podar, J. Smirnov

DM Profile Reconstruction



Work in progress:
R. K. Leane (SLAC),
M. Benito, S. Podar (Tartu),
J. Smirnov

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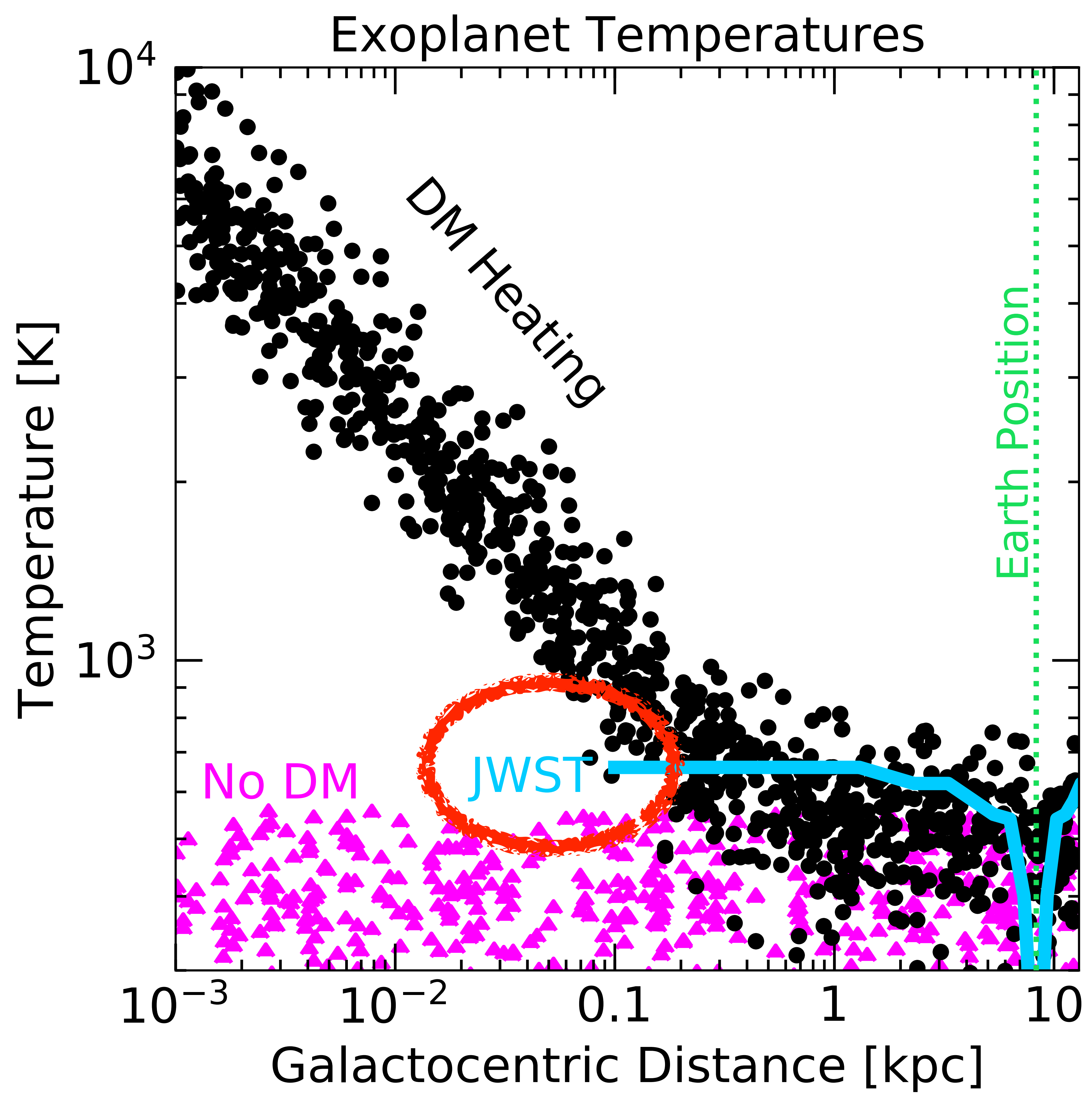
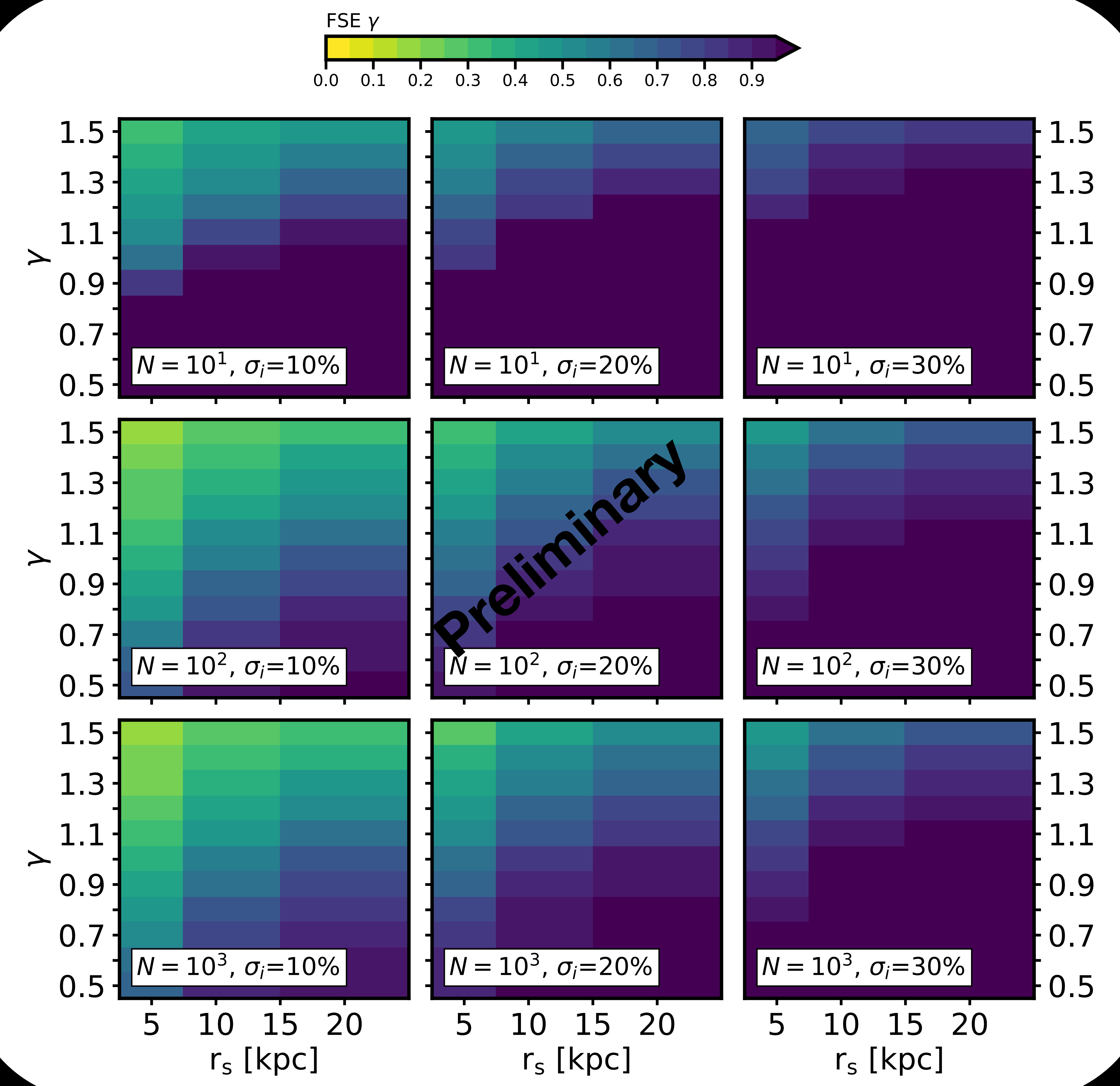


arXiv: 2010.00015; R. K. Leane (SLAC), **J. Smirnov**

DM Profile Reconstruction (T>650 K)



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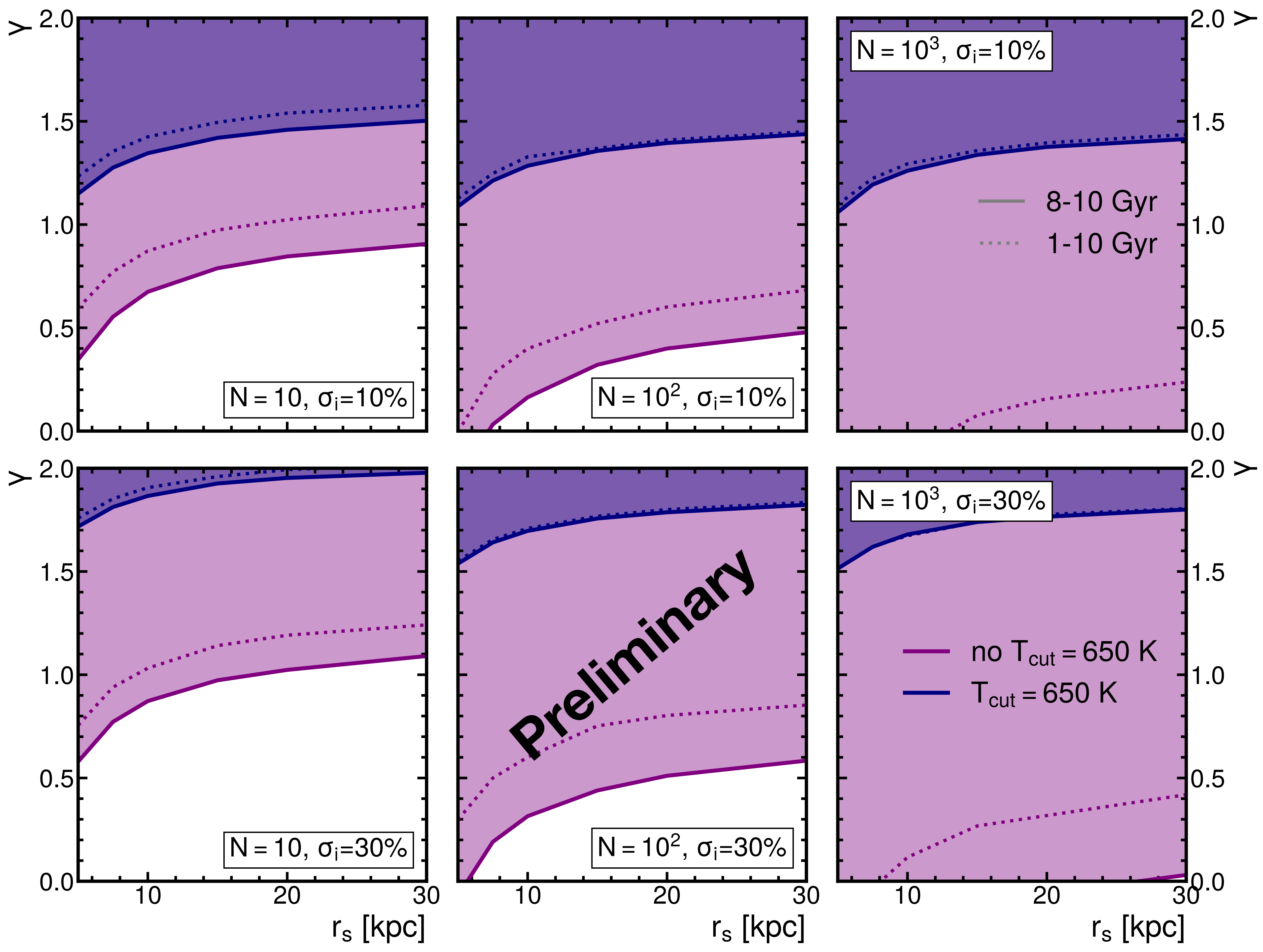
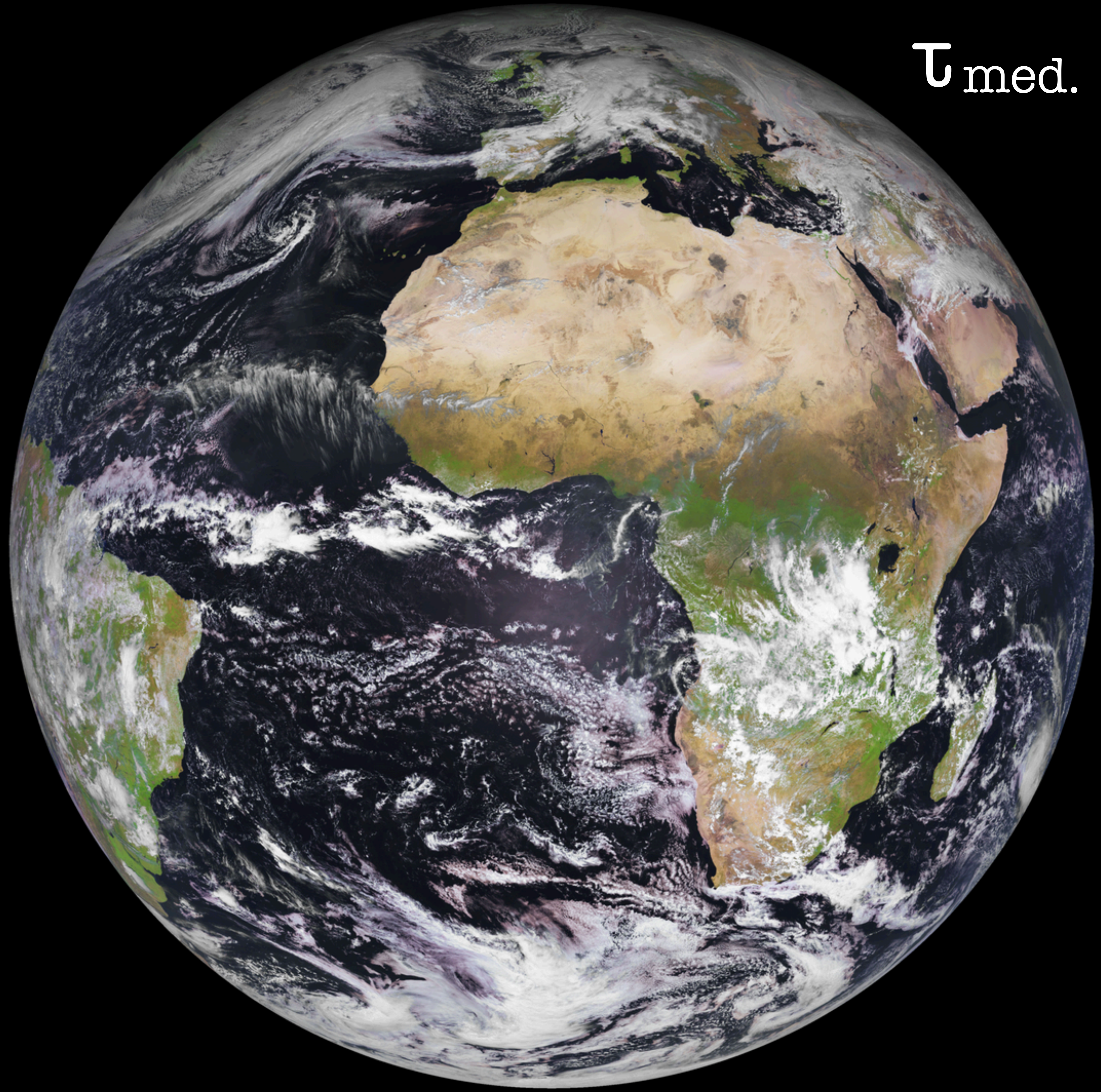
Constraining Power



What do we Test?

Limits from the Earth Heat Flow

$\tau_{\text{med.}} < 0.01$ s



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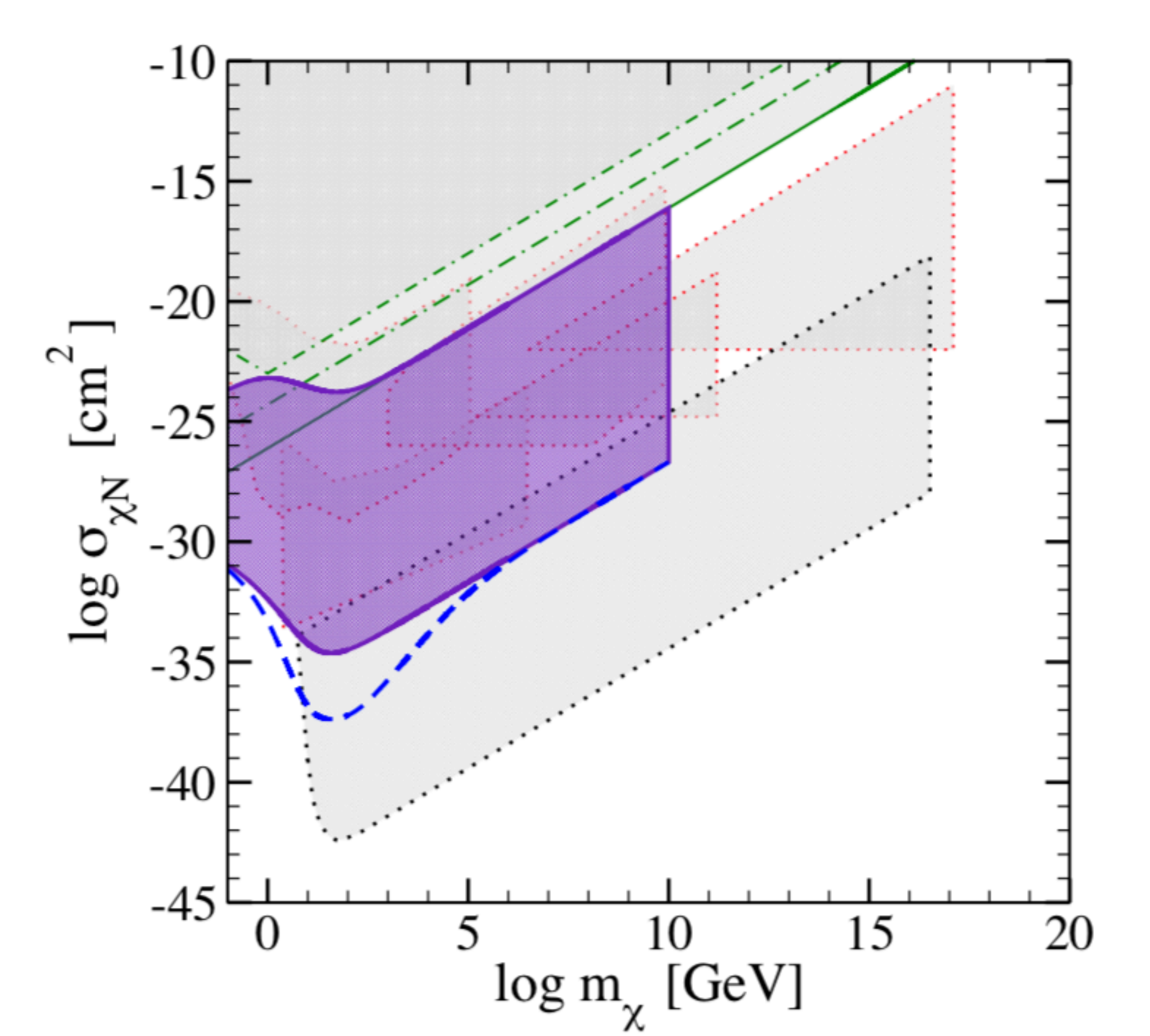

J. Beacom (OSU) et al. 2007

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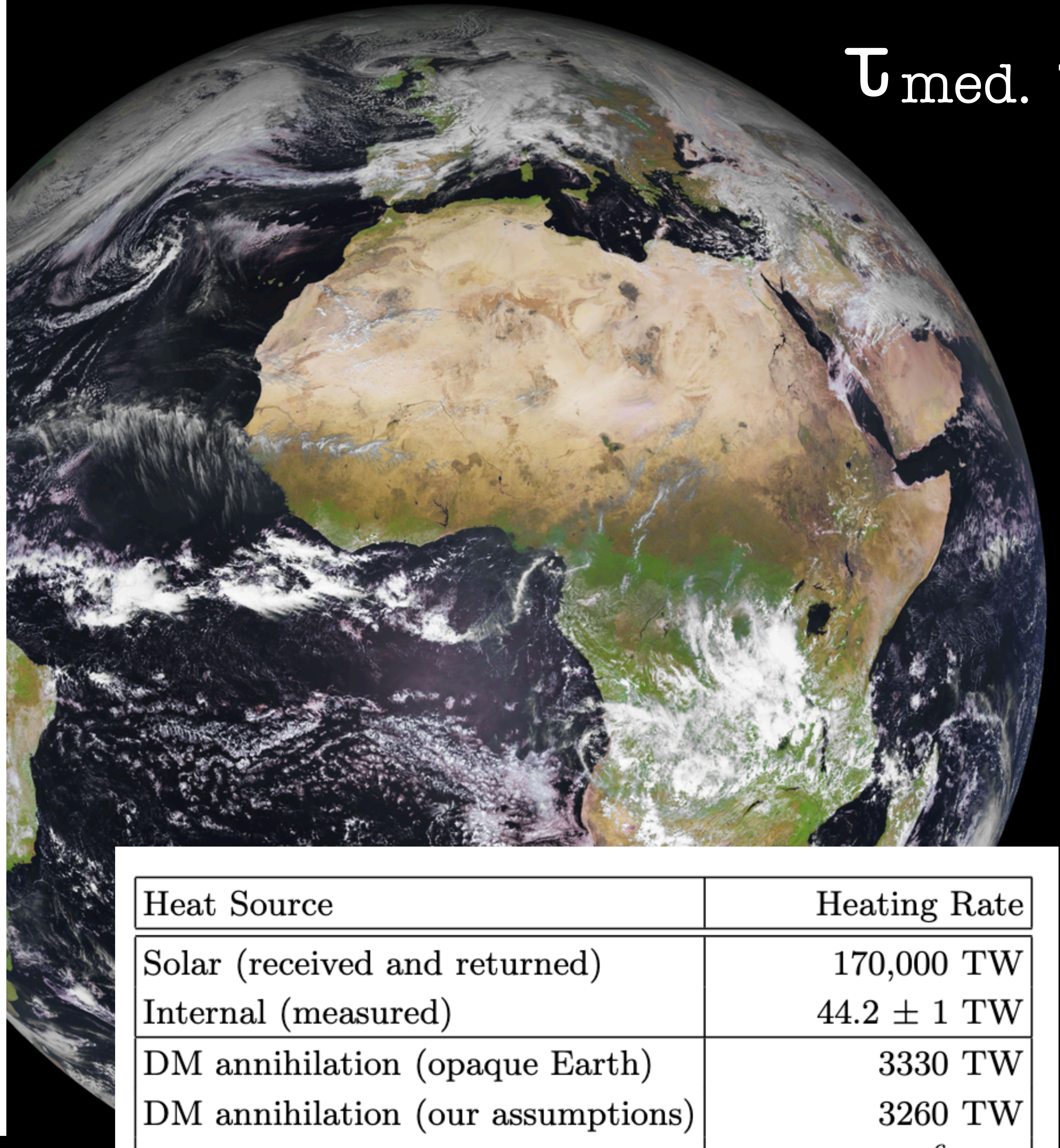
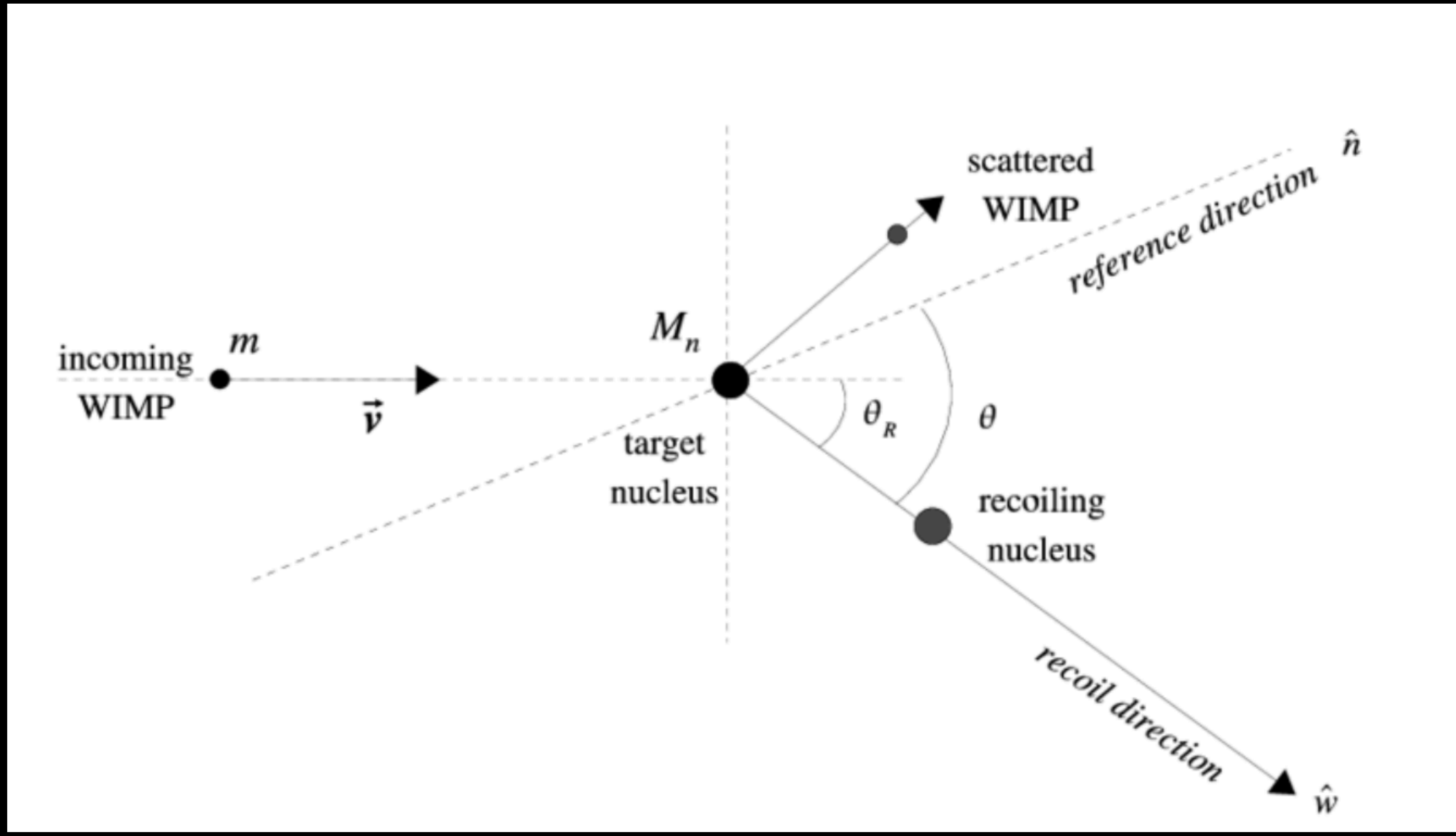


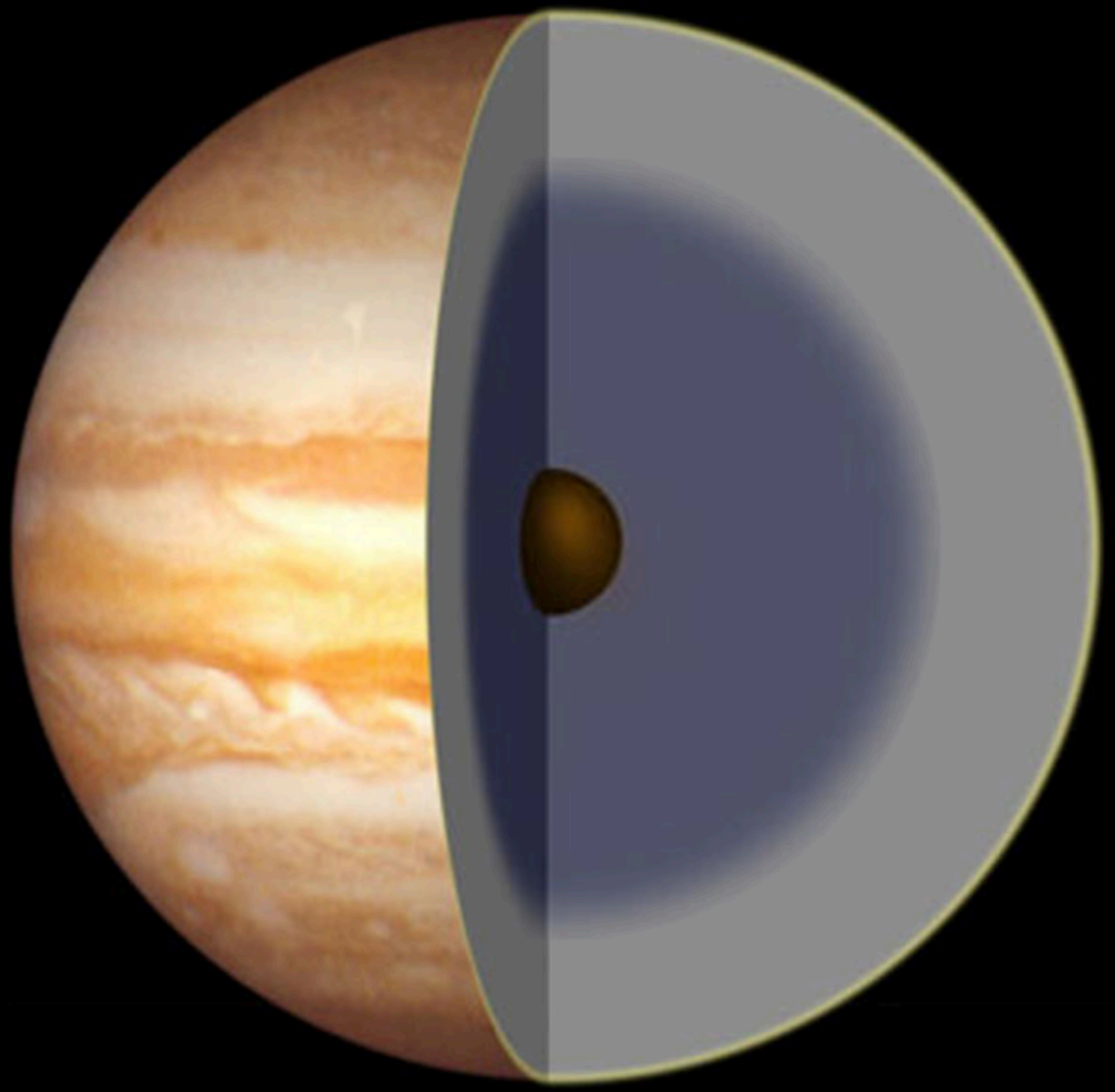
Heat Source	Heating Rate
Solar (received and returned)	170,000 TW
Internal (measured)	44.2 ± 1 TW
DM annihilation (opaque Earth)	3330 TW
DM annihilation (our assumptions)	3260 TW
DM kinetic heating	$\sim 3000 \times 10^{-6}$ TW

Lower Masses

Capture and Evaporation



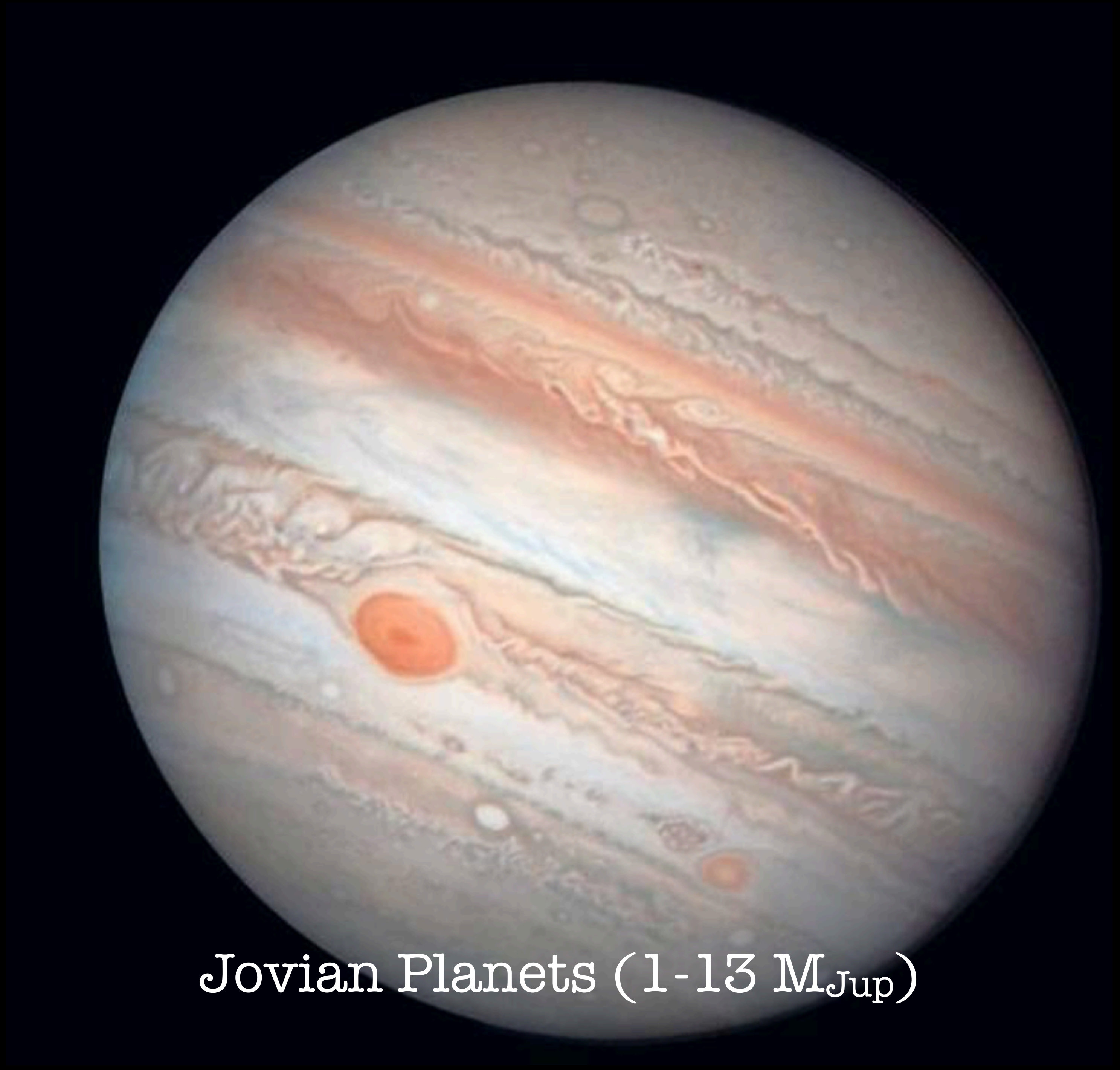
a) Target kinematics



b) Ratio between Potential and Temperature

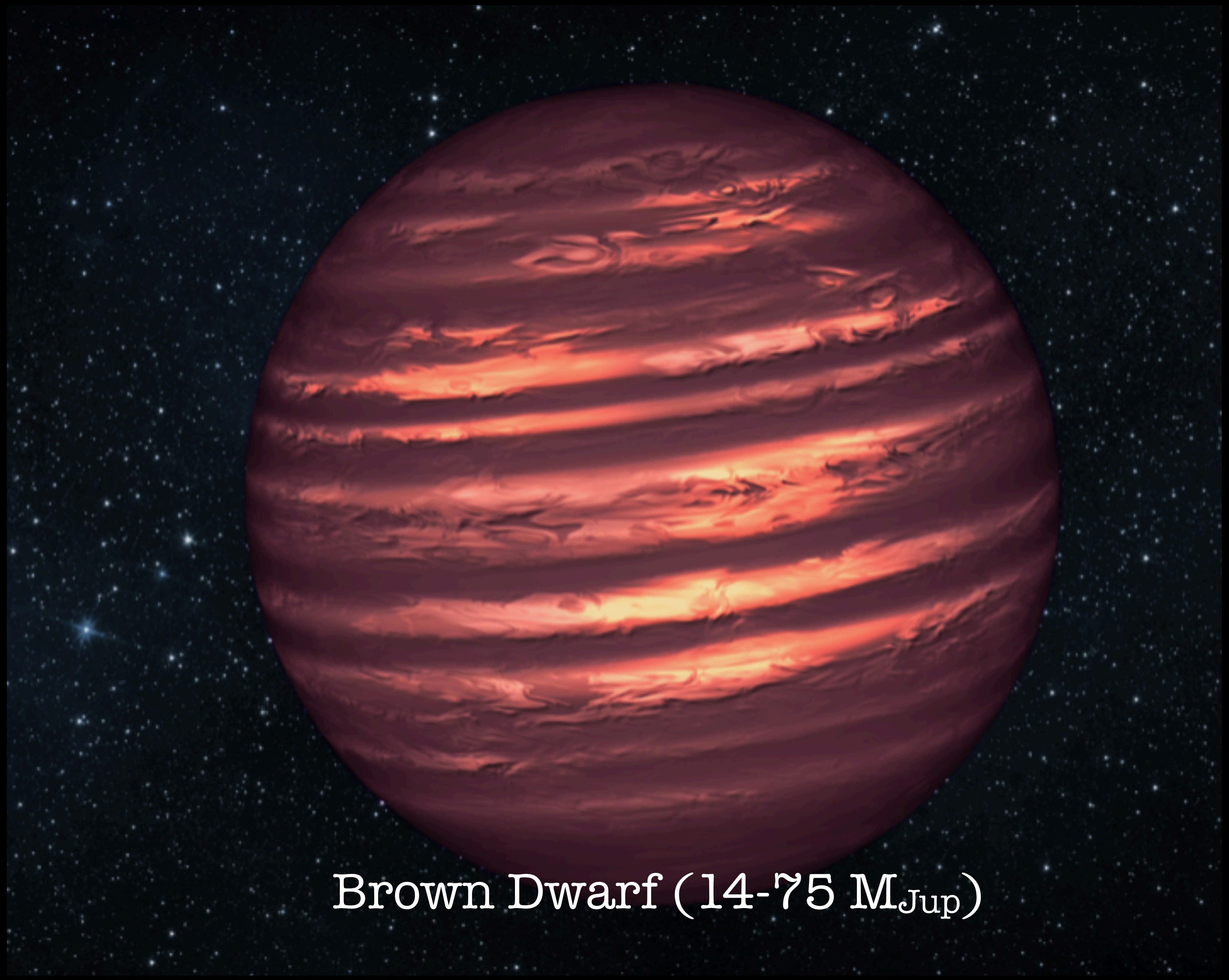
Longer Mediator Lifetime

Long Lived Mediators: Jovians/BDs

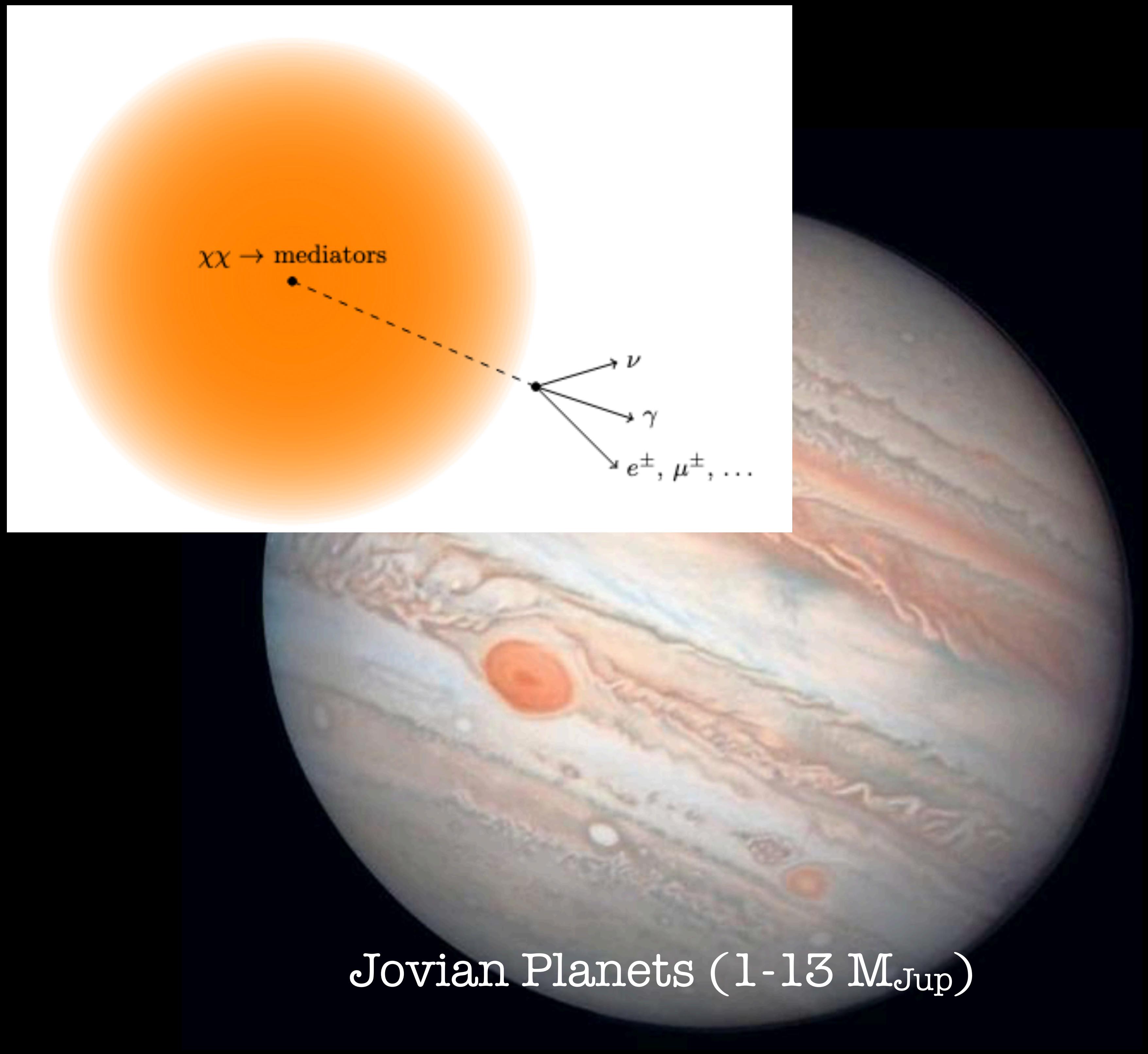


$\tau_{med} < 0.2$ s
heating

$\tau_{med} > 0.2$ s
indirect
signals



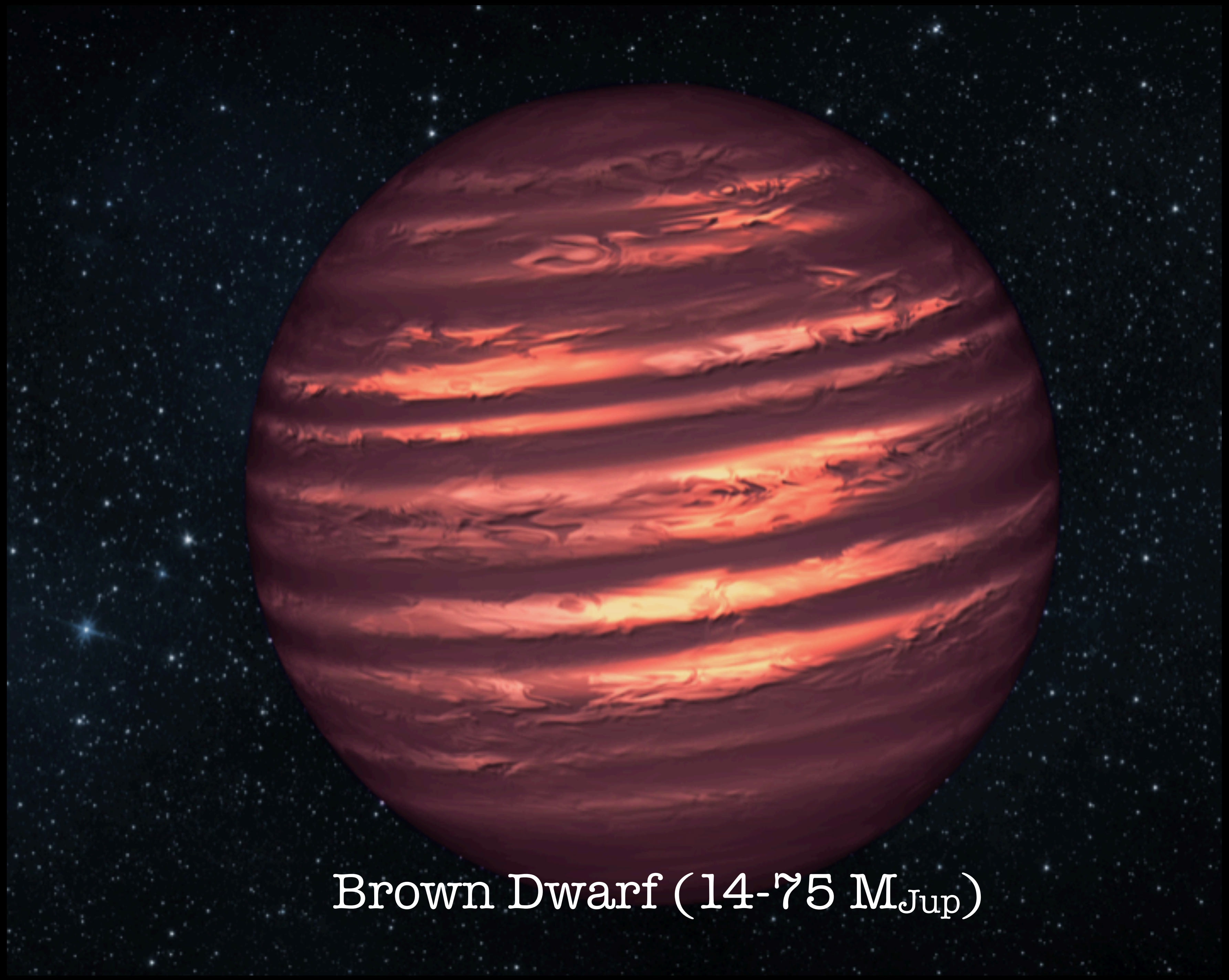
Long Lived Mediators: Jovians/BDs



Jovian Planets (1-13 M_{Jup})

$\tau_{med} < 0.2$ s
heating

$\tau_{med} > 0.2$ s
indirect
signals


Brown Dwarf (14-75 M_{Jup})

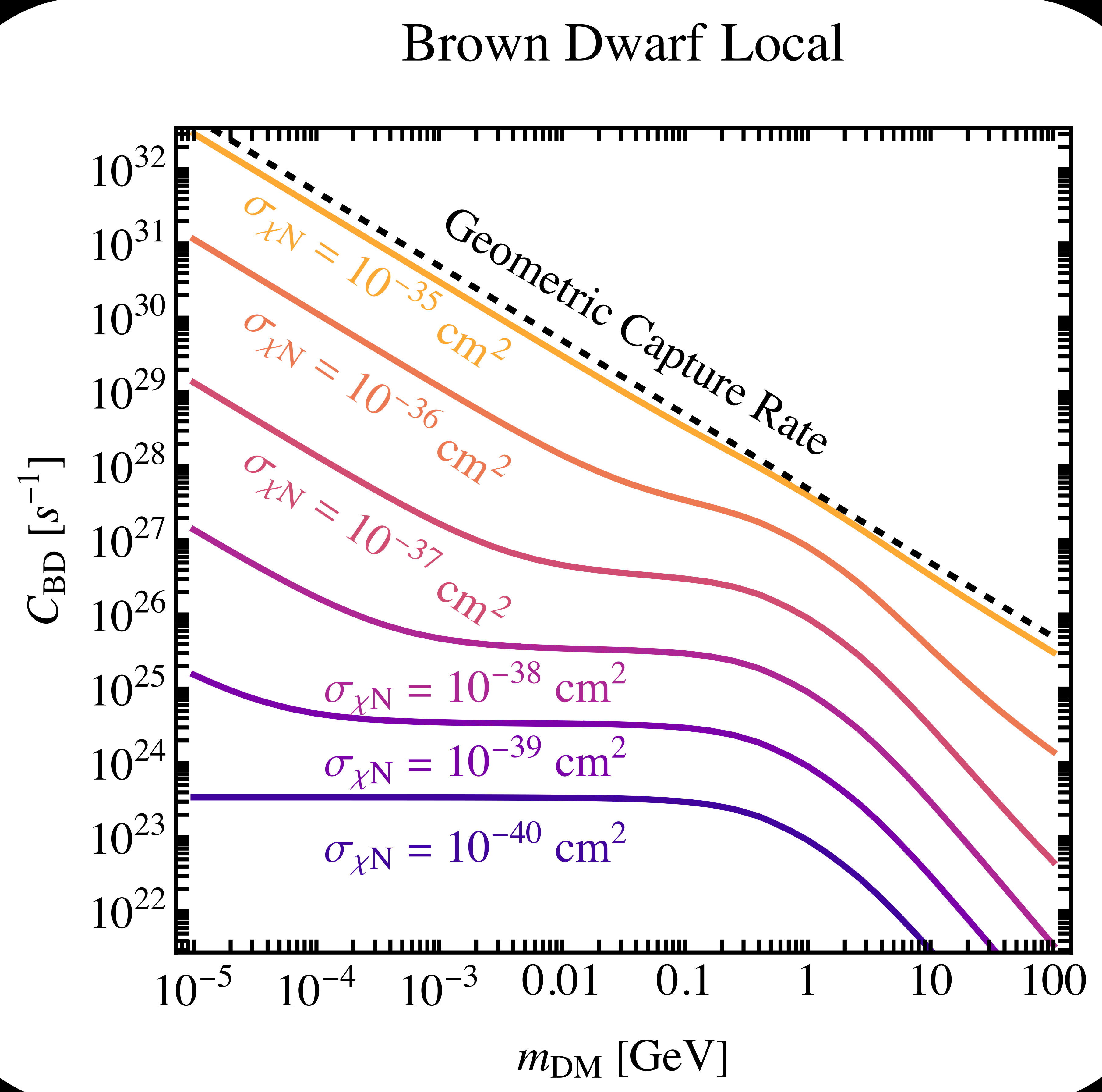
Dark Matter Distribution

1) Capture Rates

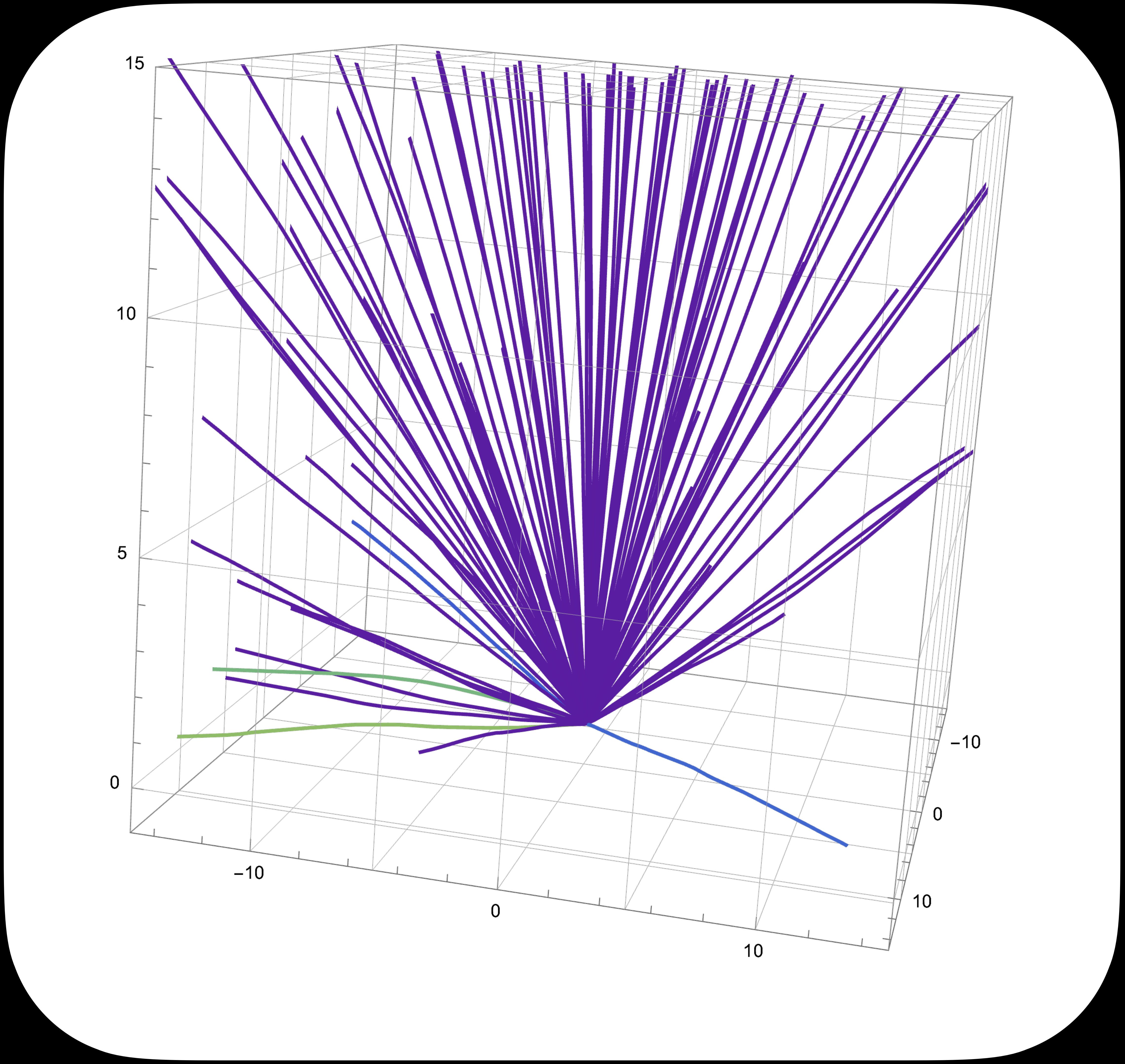
$$C_{\rm cap} \approx v_{\rm DM} \pi R^2 \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{v_{\rm DM}^2}\right)$$

$$\times \sum_{N=1}^{\infty} f_N(\tau) g_N(v_{\rm DM}, v_{\rm esc})$$

$$= \phi_{\rm DM}\, f_{\rm cap}$$



Reflection Correction Possible



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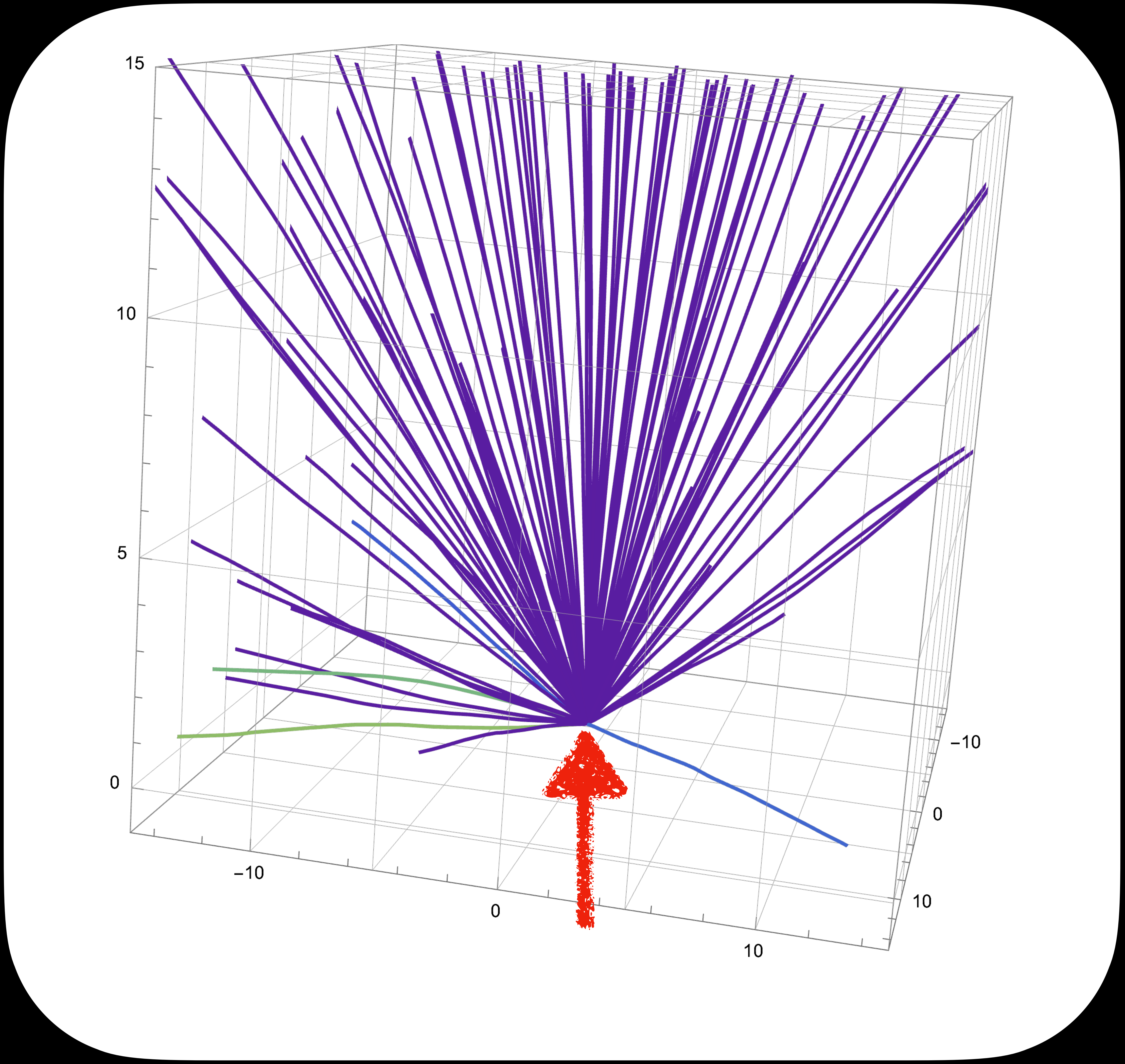

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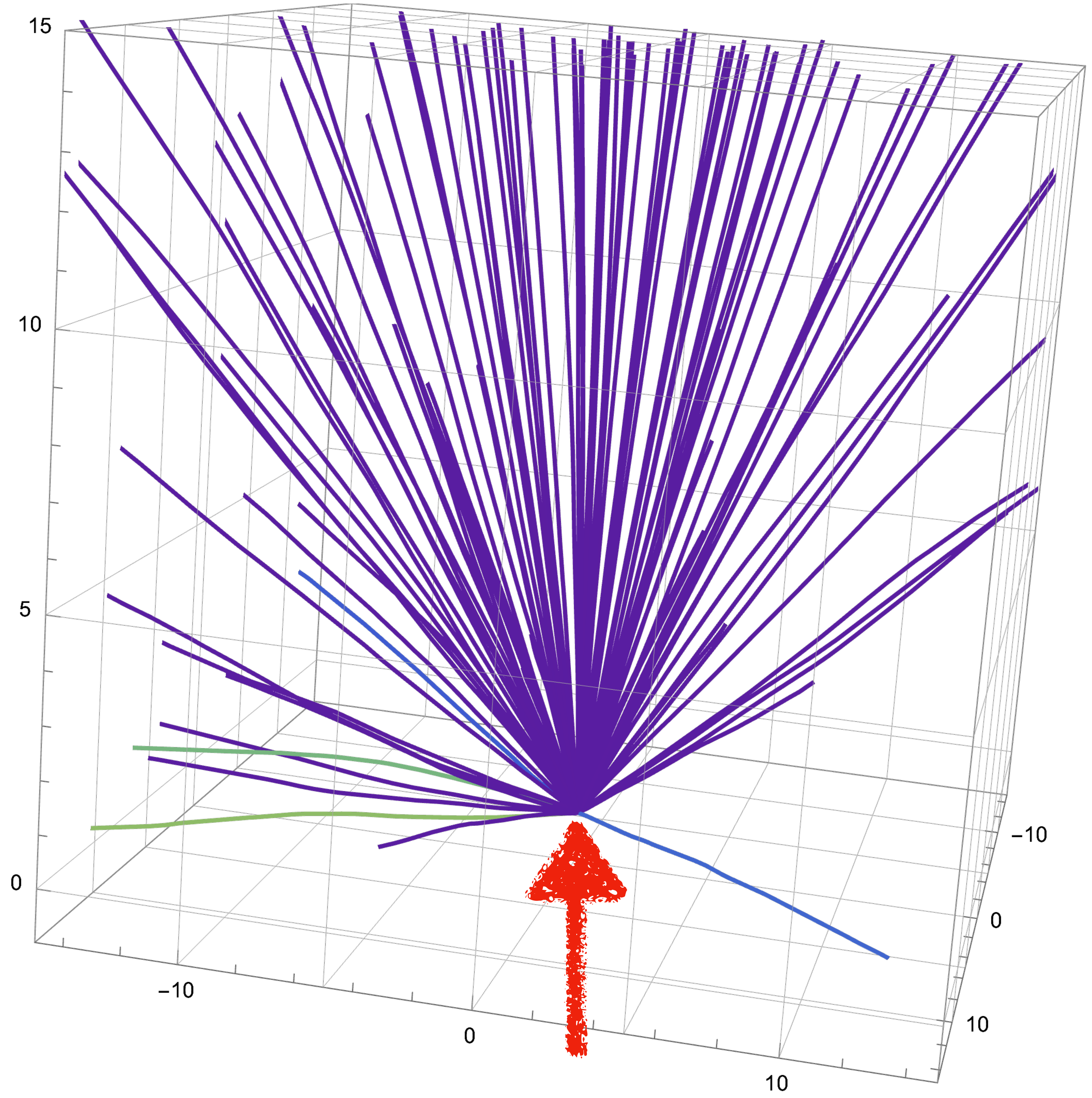
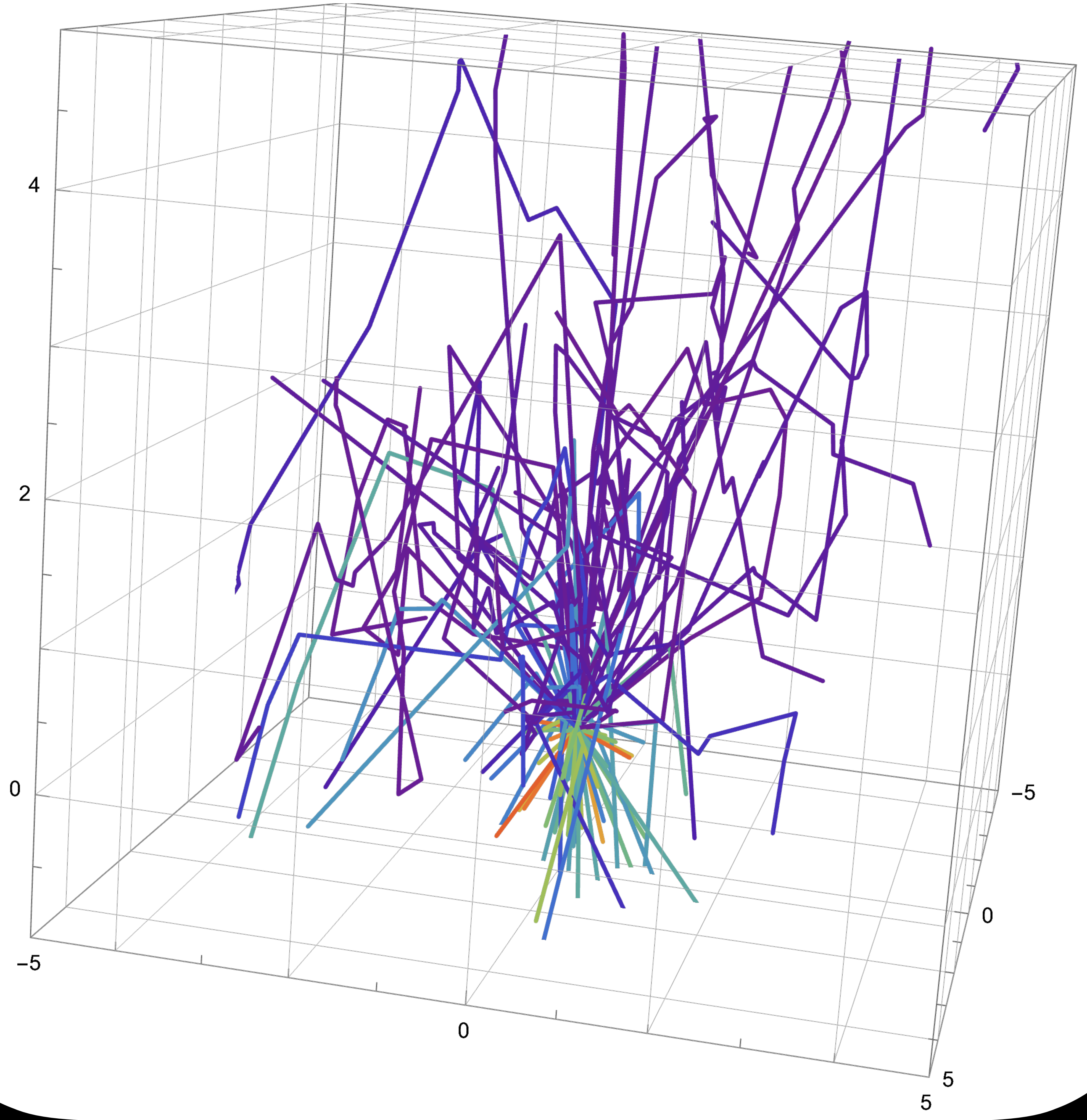
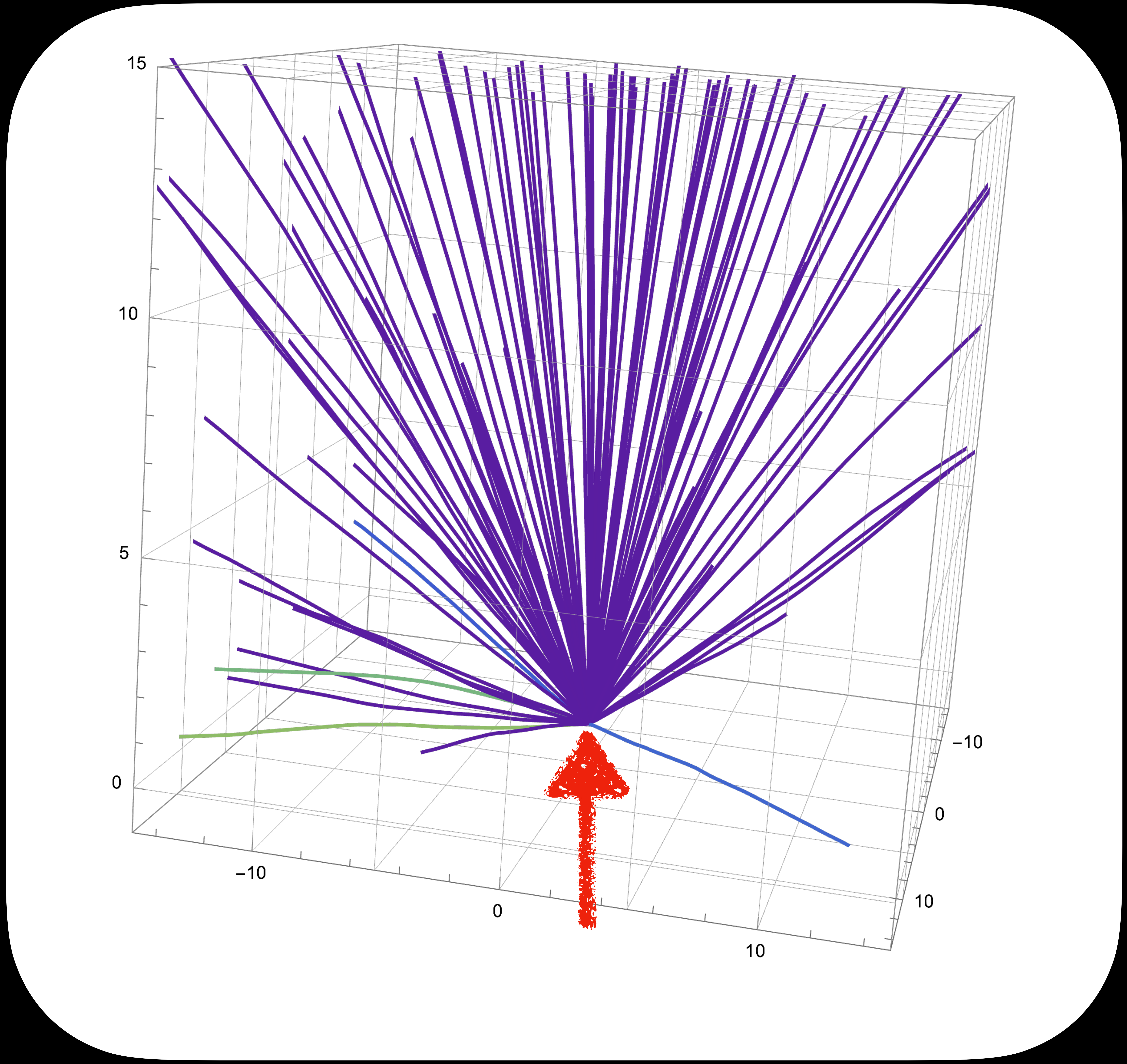
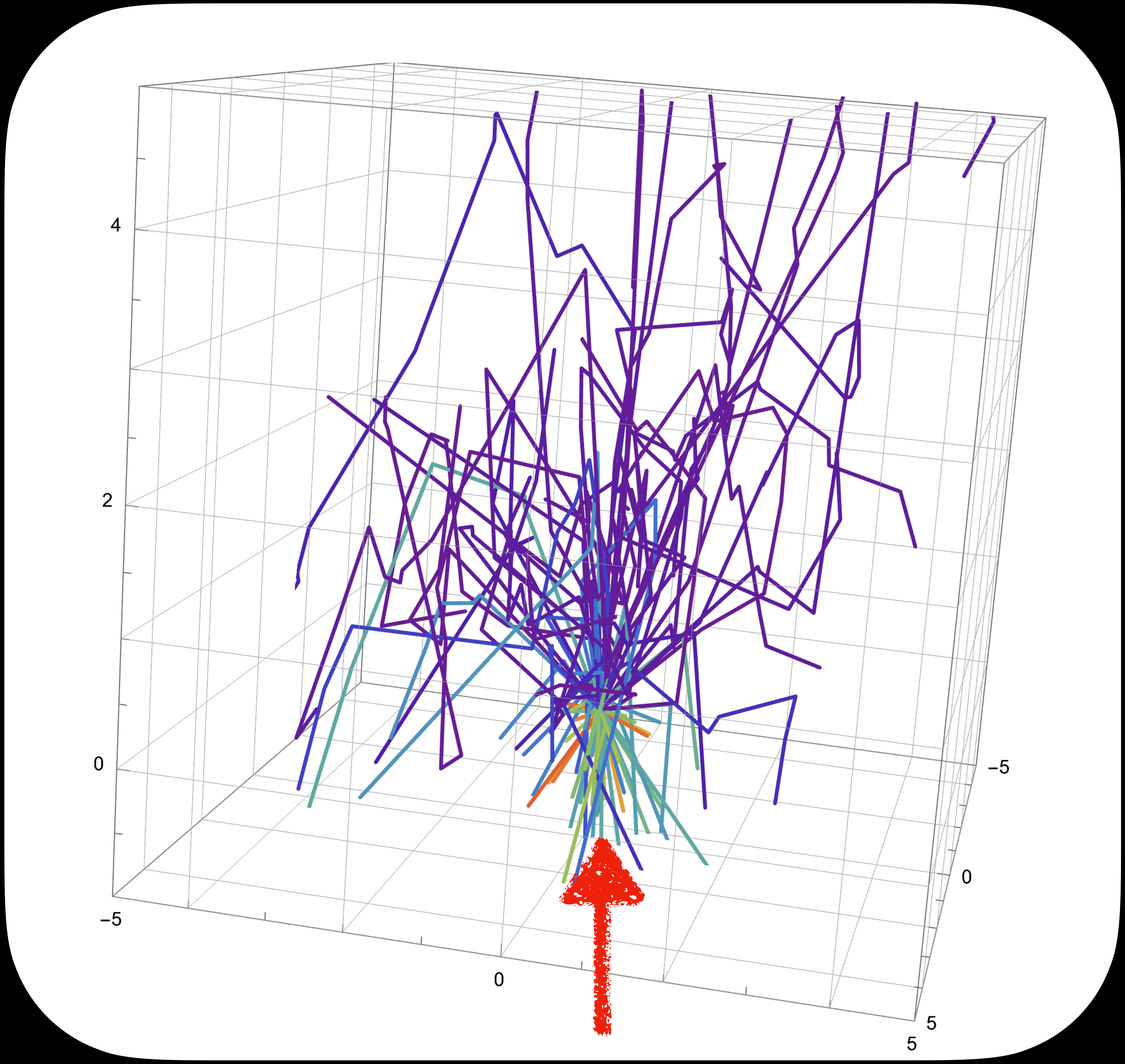




Reflection Correction Possible



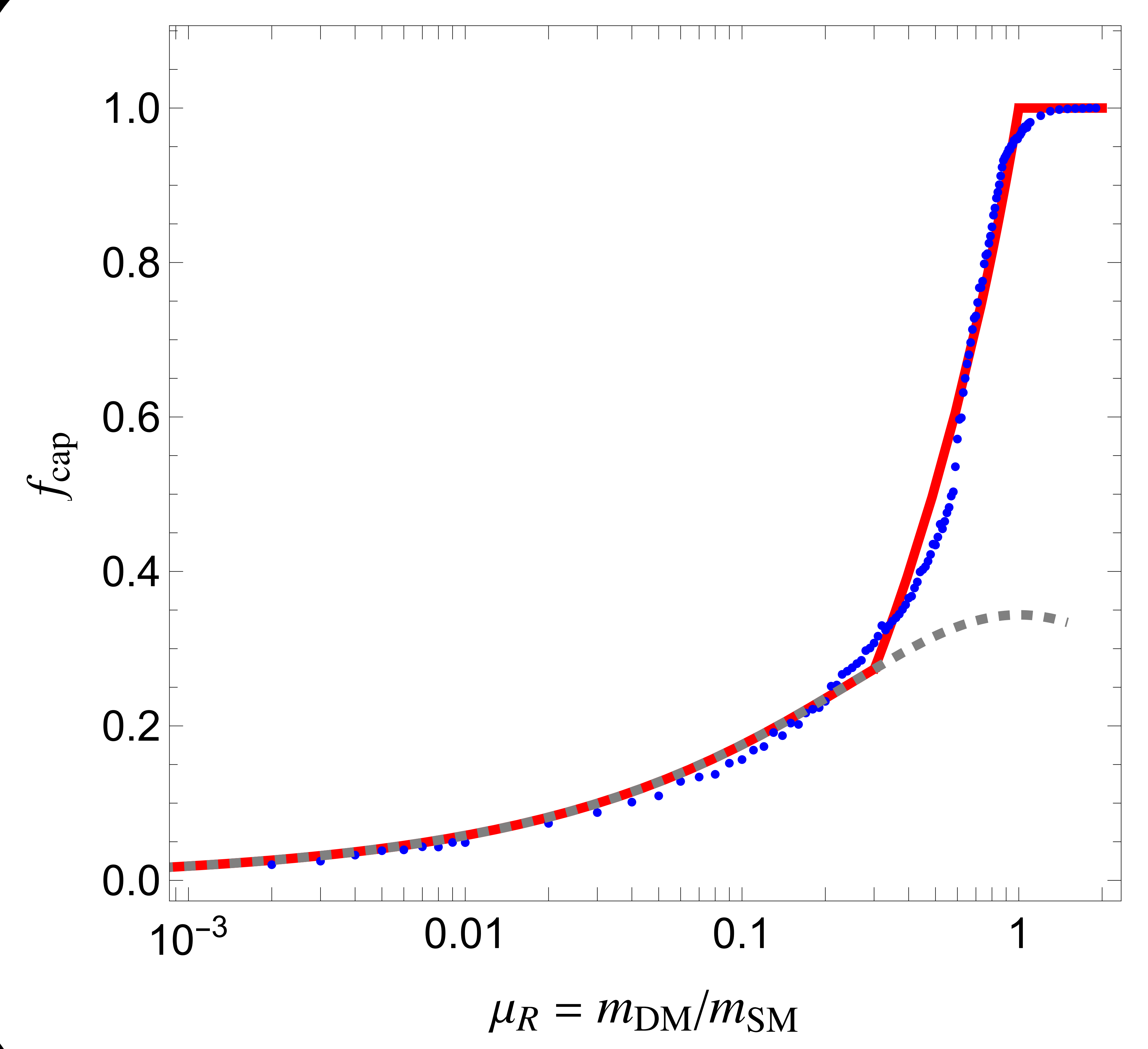


Simulation and Analytic Result

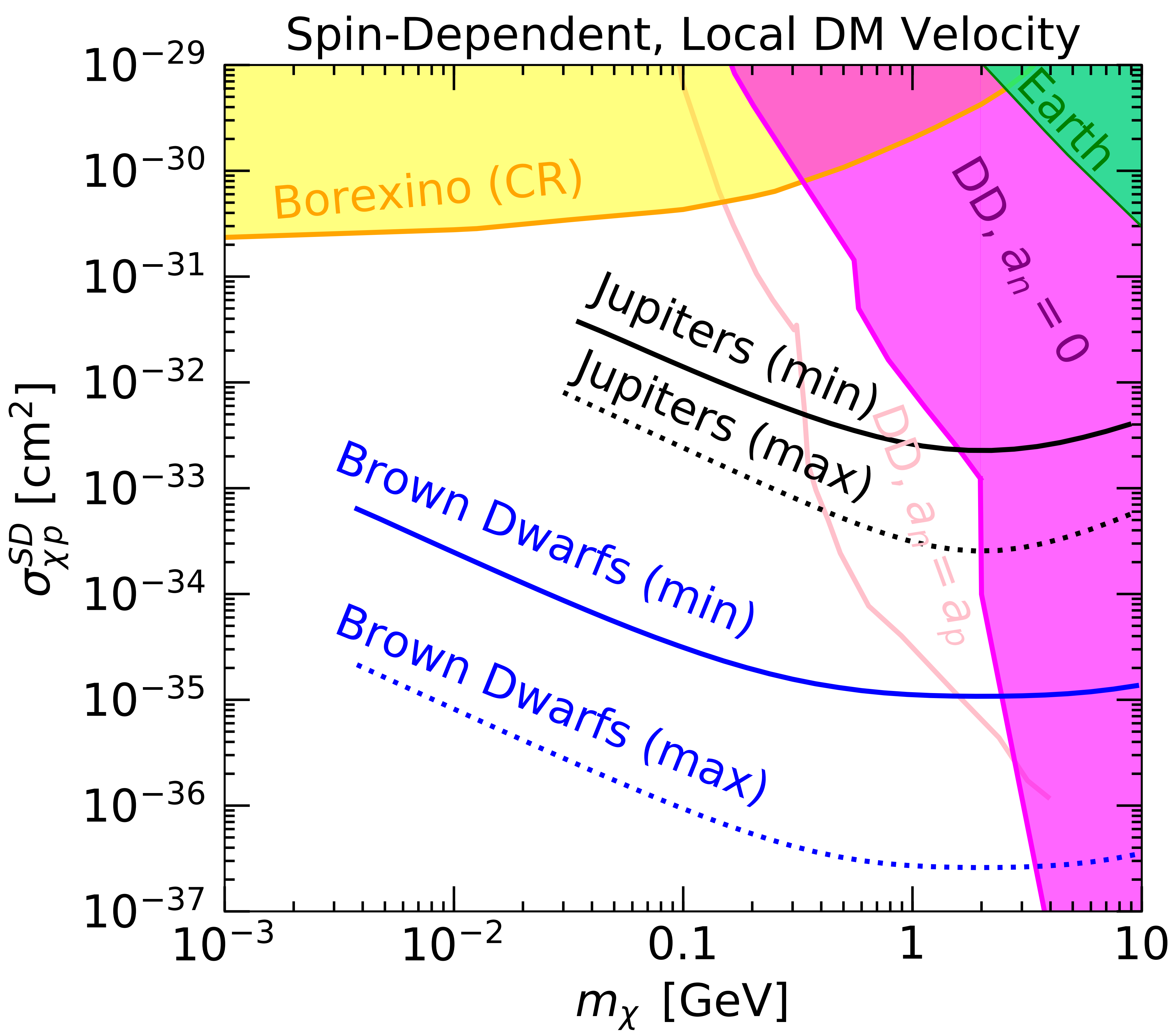
$$f_{\rm ref} \approx 1 - \frac{2}{\sqrt{\pi}}\frac{1}{\sqrt{N_{\rm cap}}}$$

$$N_{\rm cap} \approx \frac{\log\left(\frac{v_{\rm DM}^2}{v_{\rm esc}^2}\right)}{\log\left(1-\langle z\rangle\beta\right)}$$

$$\langle z\rangle \sim \frac{1}{2} \text{ and } \beta = \frac{4 m_{\rm DM} m_{\rm SM}}{\left(m_{\rm DM}+m_{\rm SM}\right)^2}$$



Resulting Capture Fractions



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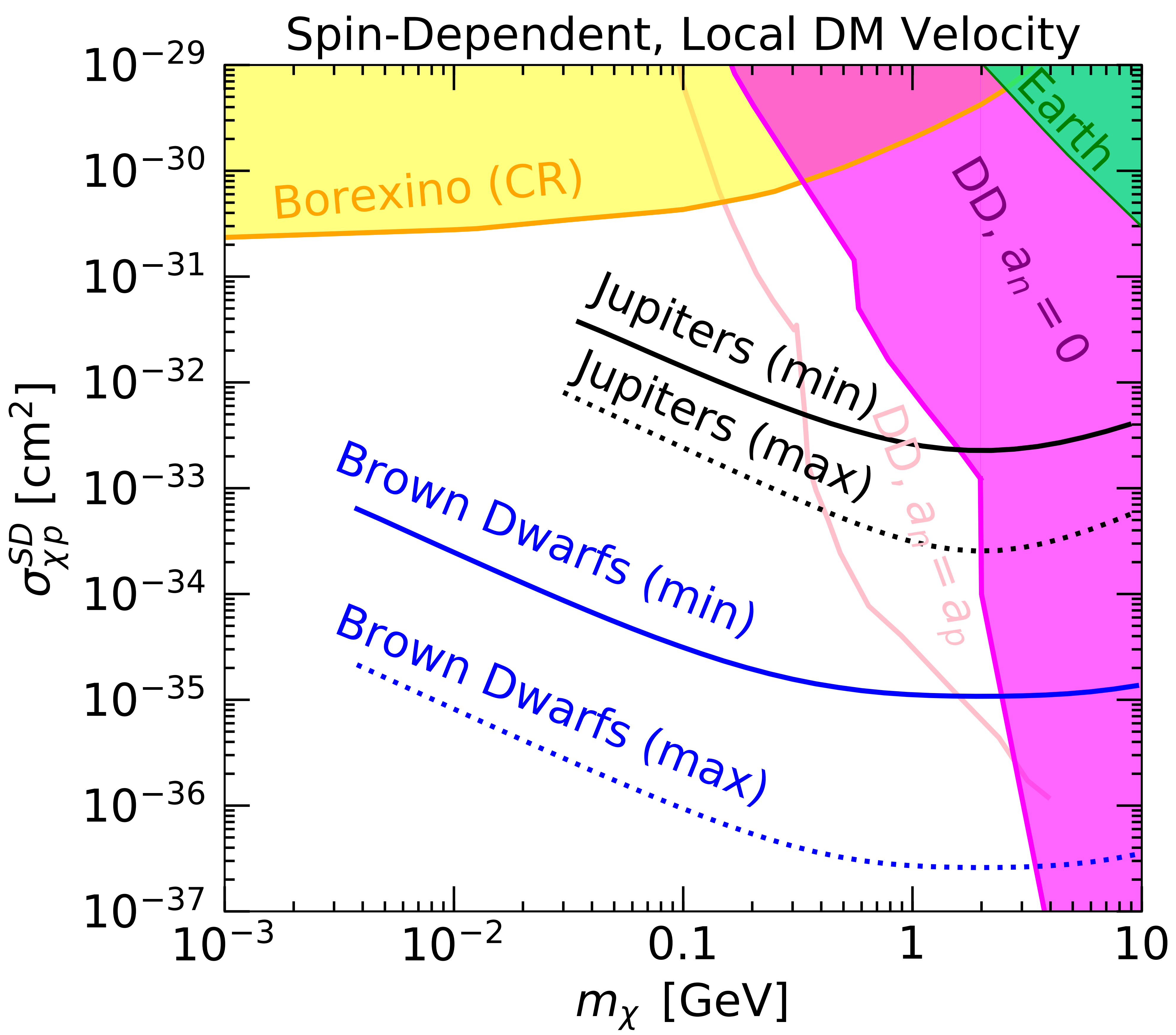

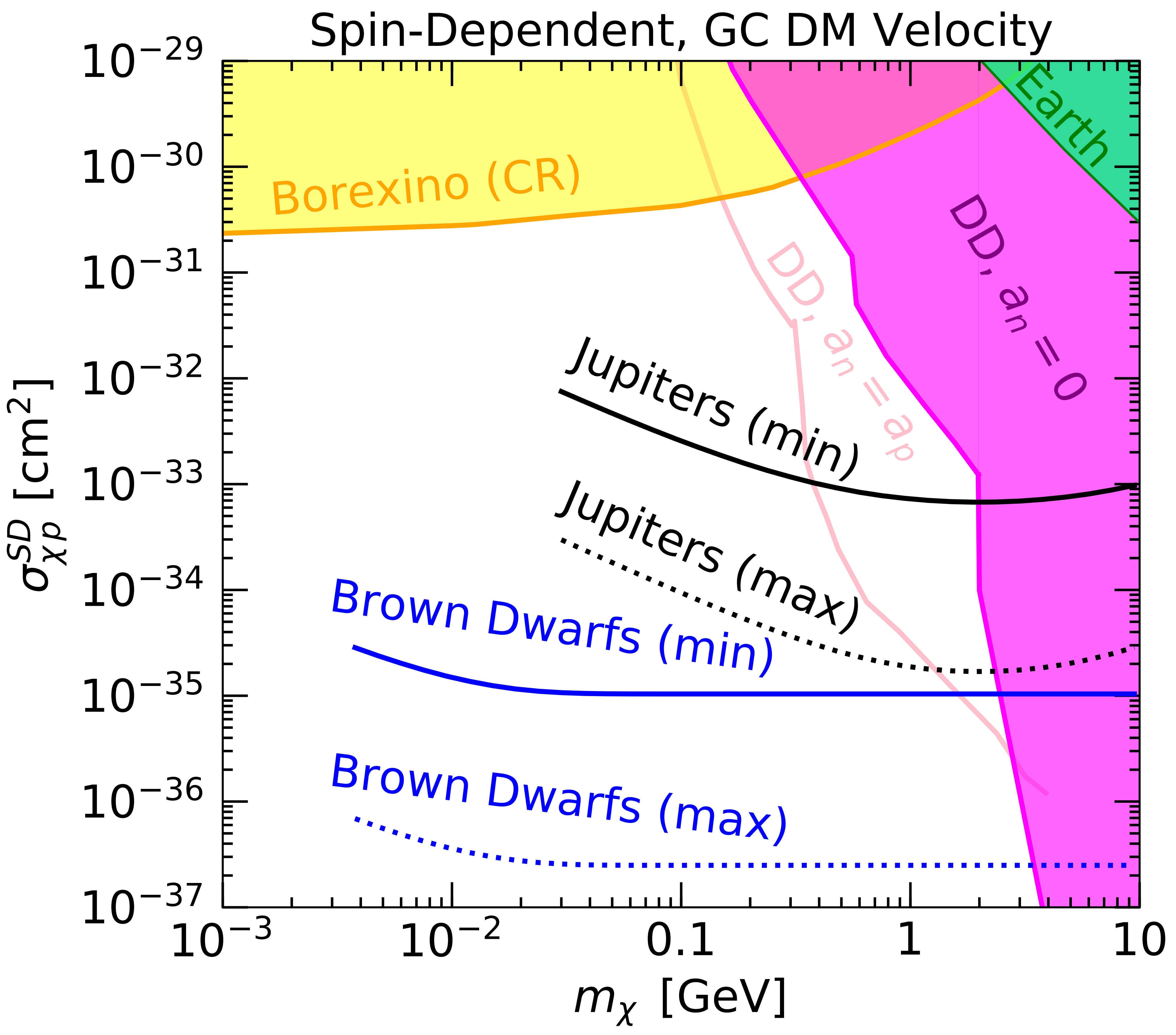

2) Captured Dark Matter Profile

$$\frac{\nabla(n_\chi T)}{n_\chi T} + \frac{f_{\rm grav}(r)}{T} + \kappa \frac{\nabla T}{T} - \frac{n_\chi^0 v_\chi^0}{n_\chi D_{12}} \left(\frac{R}{r}\right)^2 = 0$$

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Hydrostatic equilibrium:
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Ref: Effect of hypothetical, weakly interacting, massive particles on energy transport in the solar interior
D.N. Spergel and W.H. Press in 1984

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DM influx & diffusion:
Dynamical equilibrium

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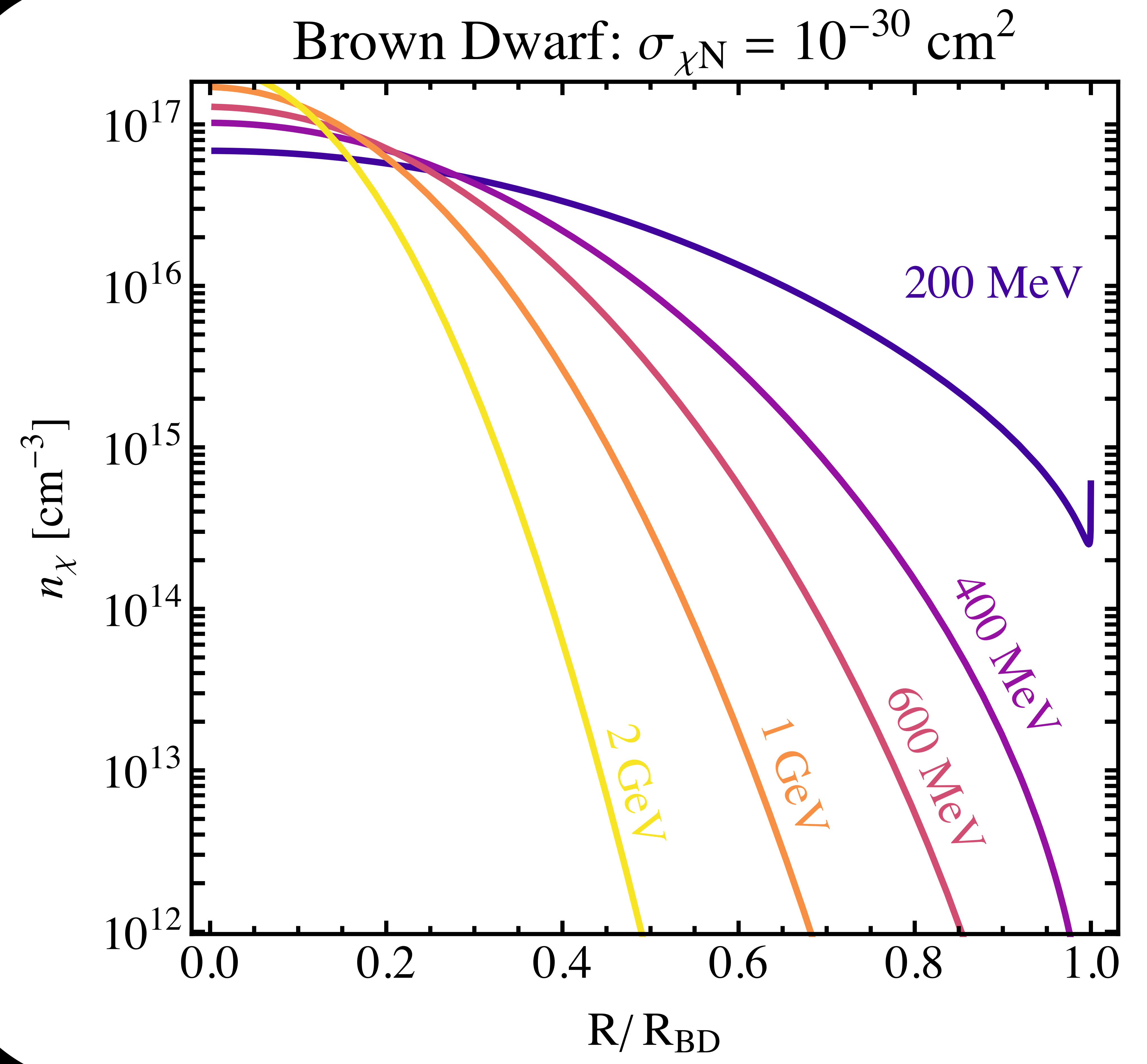
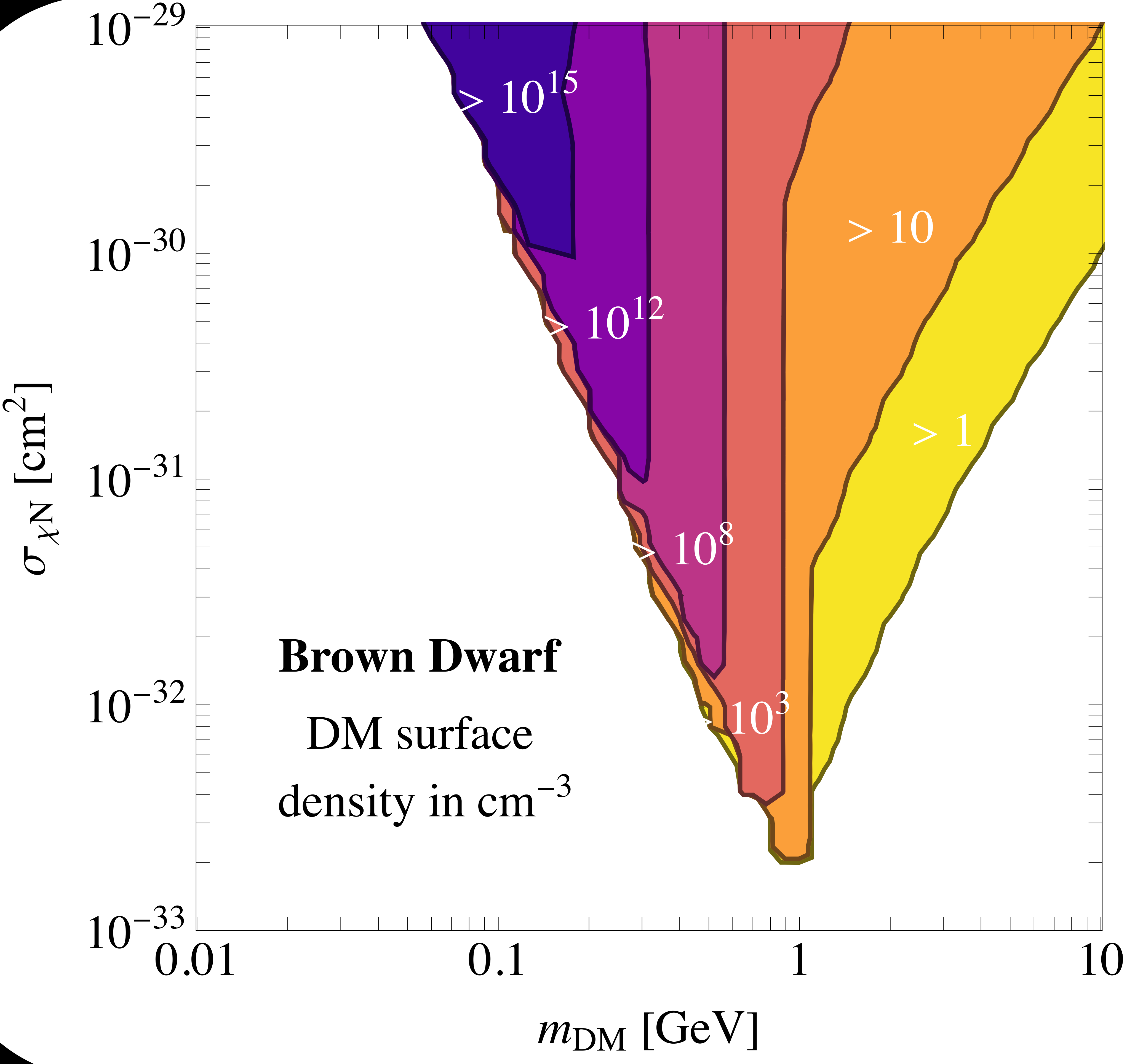
Ref: Floating Dark Matter in Celestial Bodies: 2209.09834
R.K. Leane and J. Smirnov

DM Diffusion in a Brown Dwarf

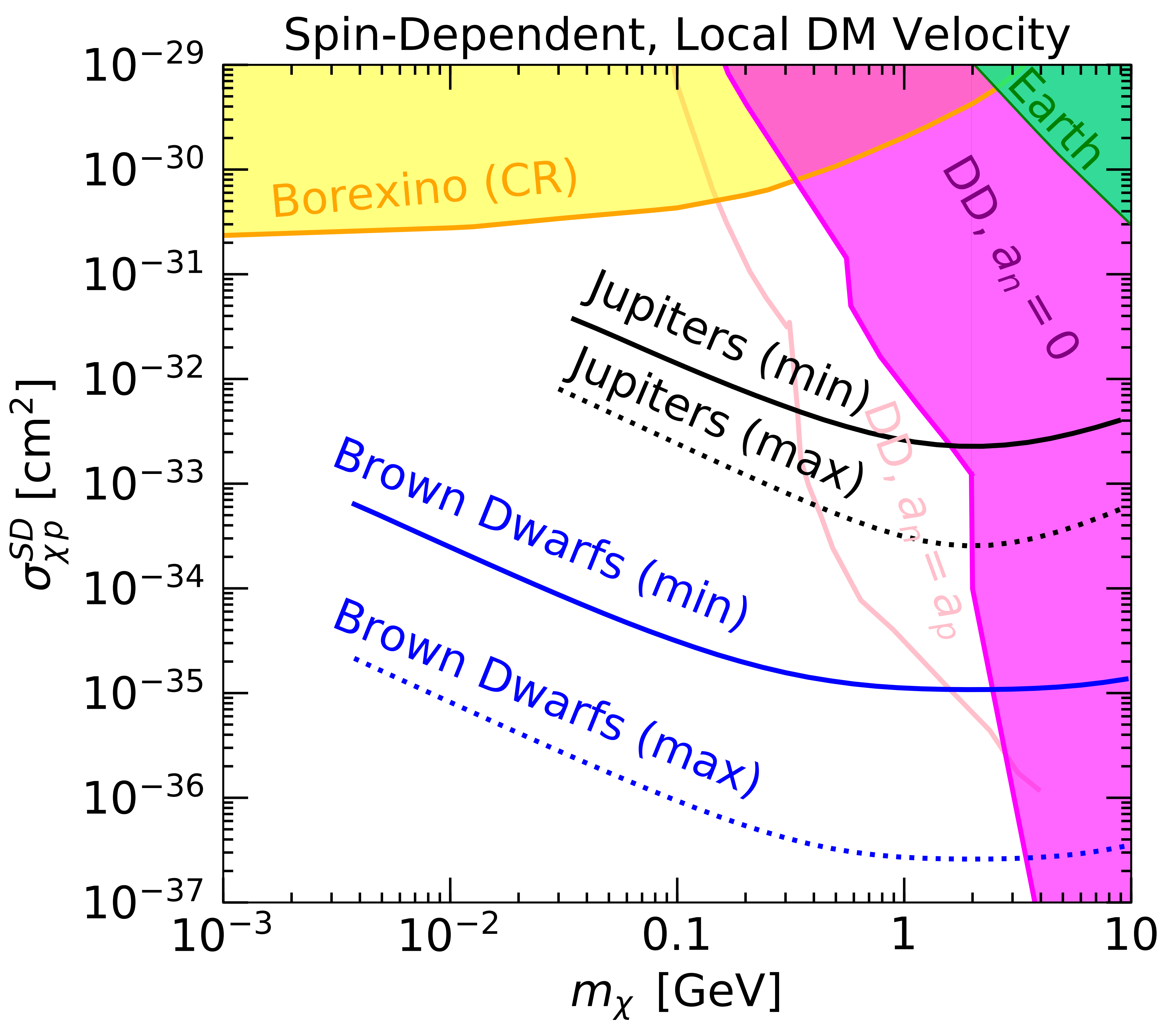


3) Surface Accumulation in Diffusive Regime

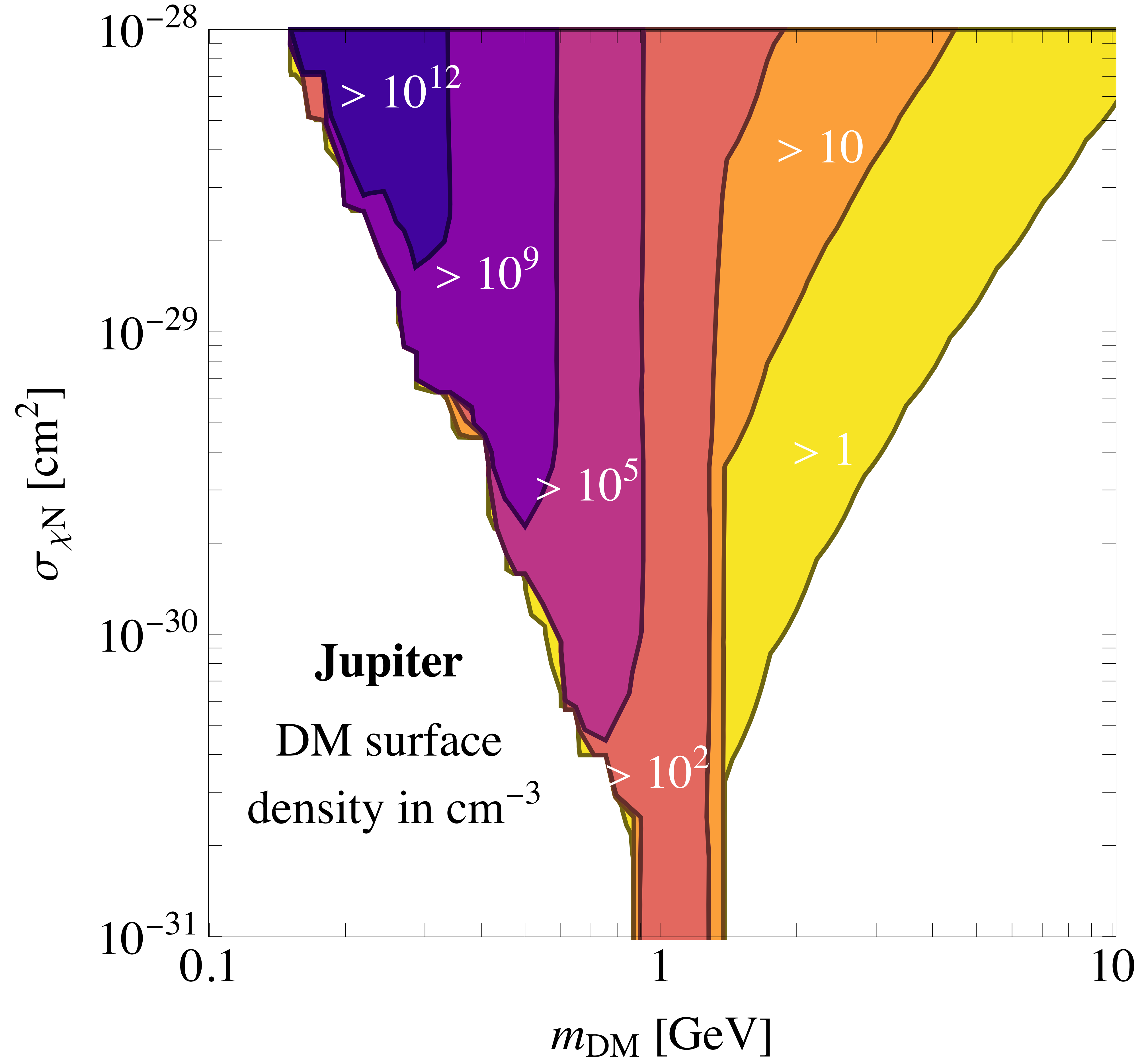


What about evaporation?

Evaporation from Jupiter



arXiv: 2010.00015; R. K. Leane, **J. Smirnov**



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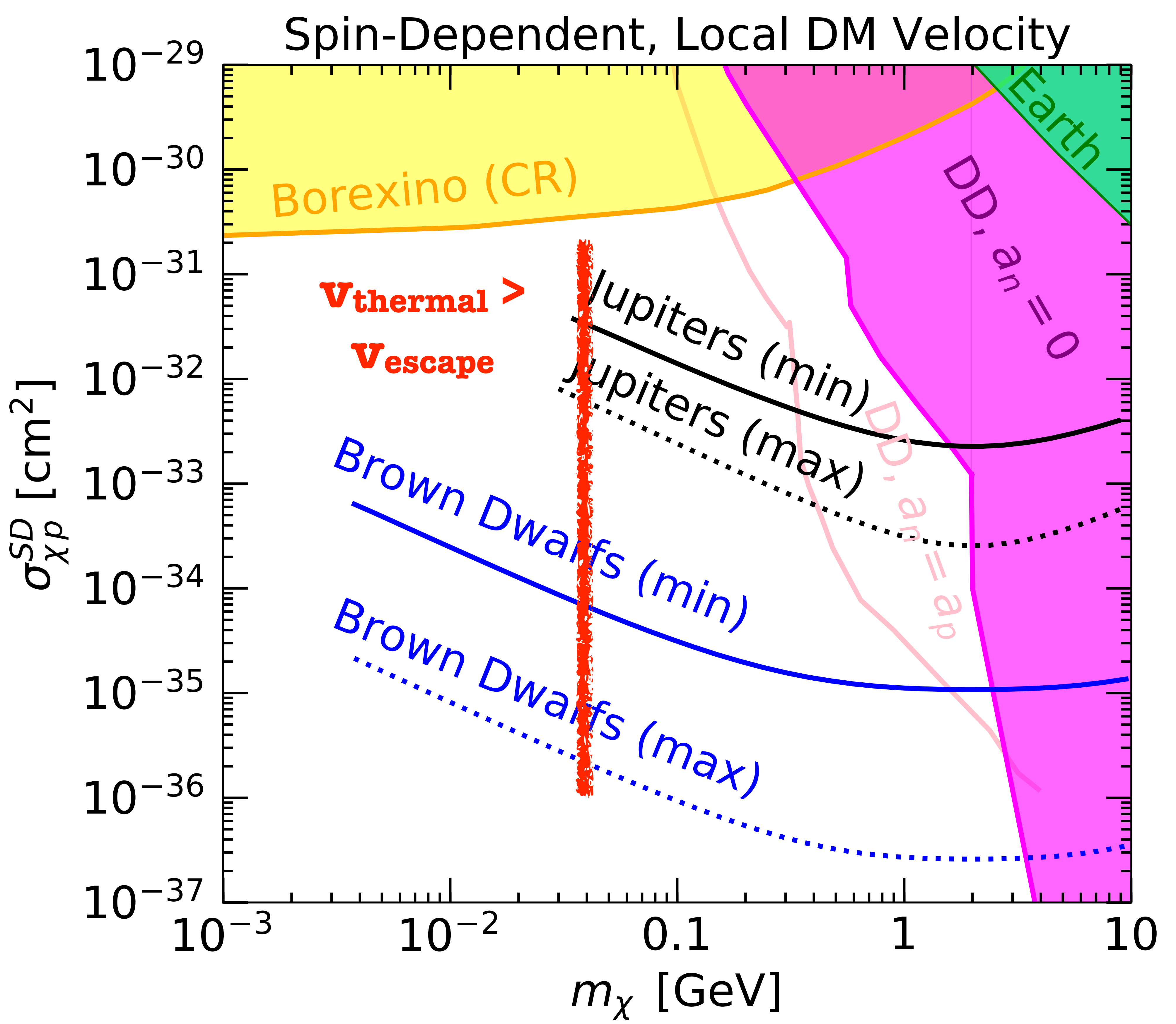
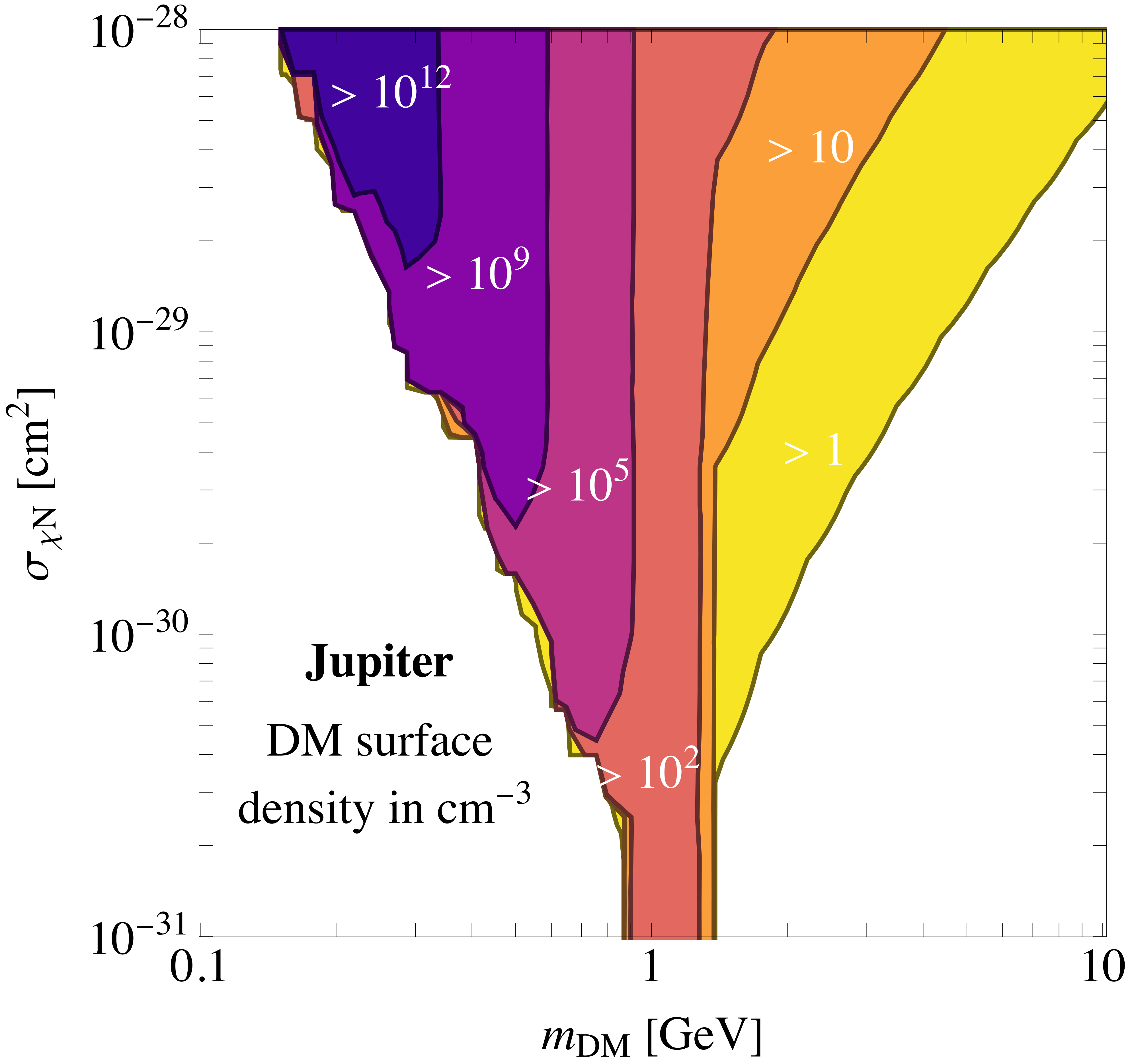
Evaporation from Jupiter



arXiv: 2010.00015; R. K. Leane, **J. Smirnov**



arXiv: 2209.09834; R. K. Leane, **J. Smirnov**

Model Dependence of Evaporation

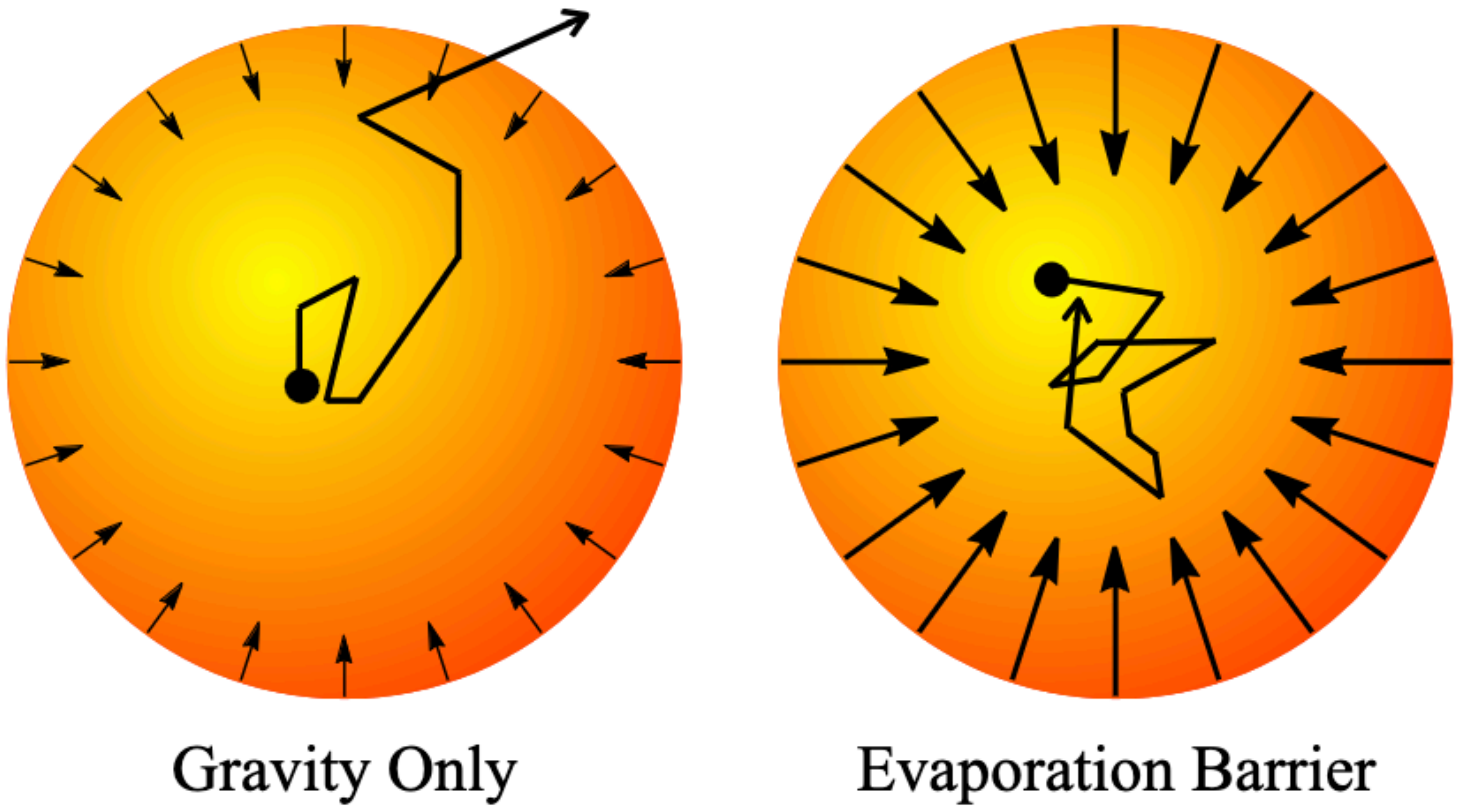
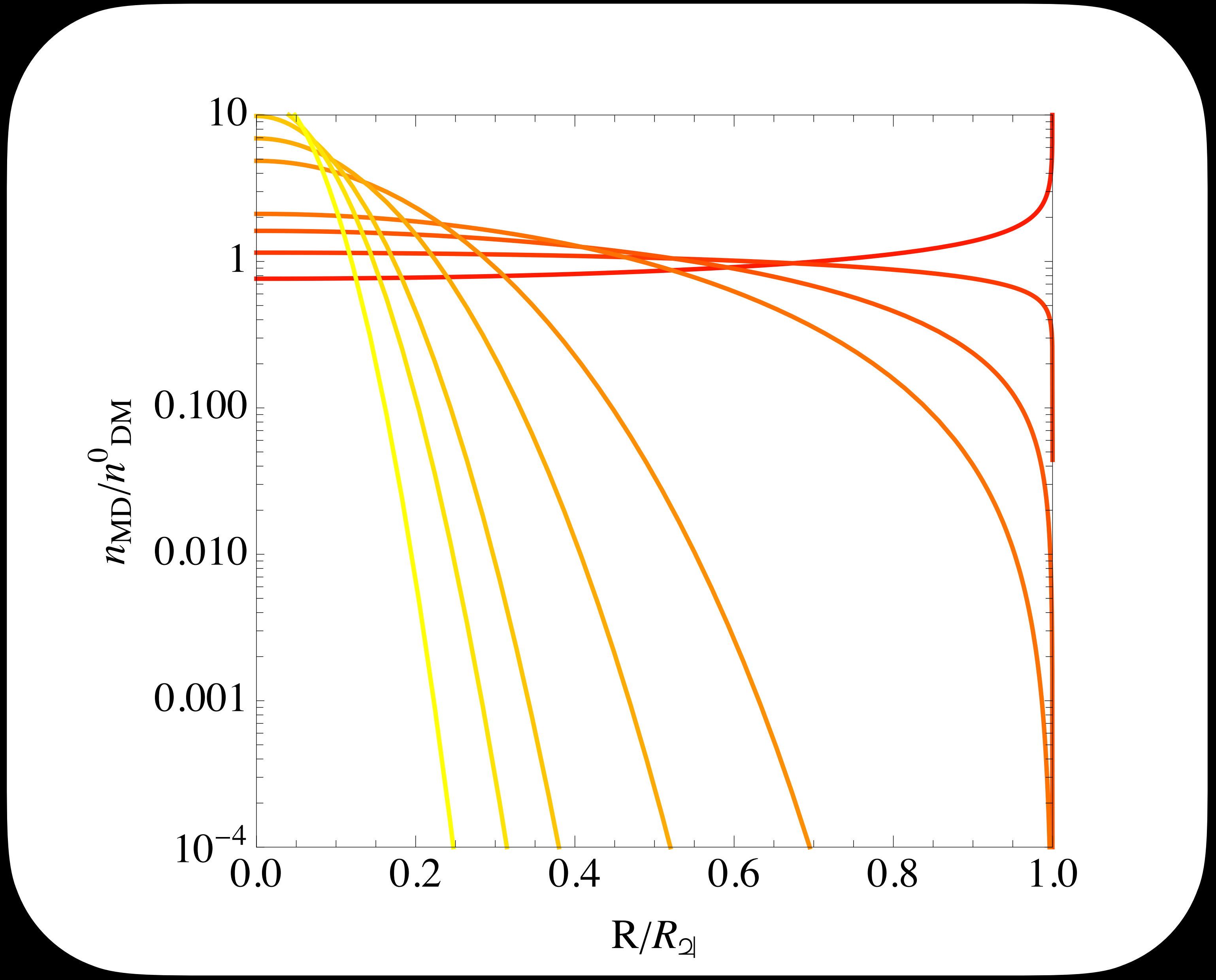


FIG. 1. Schematic representation of the evaporation barrier. **Left:** Gravity only (previous assumption). Evaporation of upscattered light DM particles is not suppressed. **Right:** The evaporation barrier blocks evaporation (this work).

arXiv: 2303:01516 ; J. Acevedo, R. K. Leane, **J. Smirnov**

Dark Long Range Forces

$$\phi_{\text{barrier}}(\vec{r}) = -g_{\text{SM}} g_\chi \int_V d^3\vec{r}' \, \frac{n_{\text{SM}}(\vec{r}')\, e^{-m_\phi|\vec{r}-\vec{r}'|}}{4\pi|\vec{r}-\vec{r}'|}$$



$$\phi_{\text{barrier}}(r) \simeq -\frac{g_{\text{SM}}\, g_\chi N_{\text{eff}}}{r_Y} \simeq -\frac{g_{\text{SM}}\, g_\chi n_{\text{SM}}(r)}{m_\phi^2}$$

$$f_{\text{barrier}} \propto \nabla n_{\text{SM}}(r)$$

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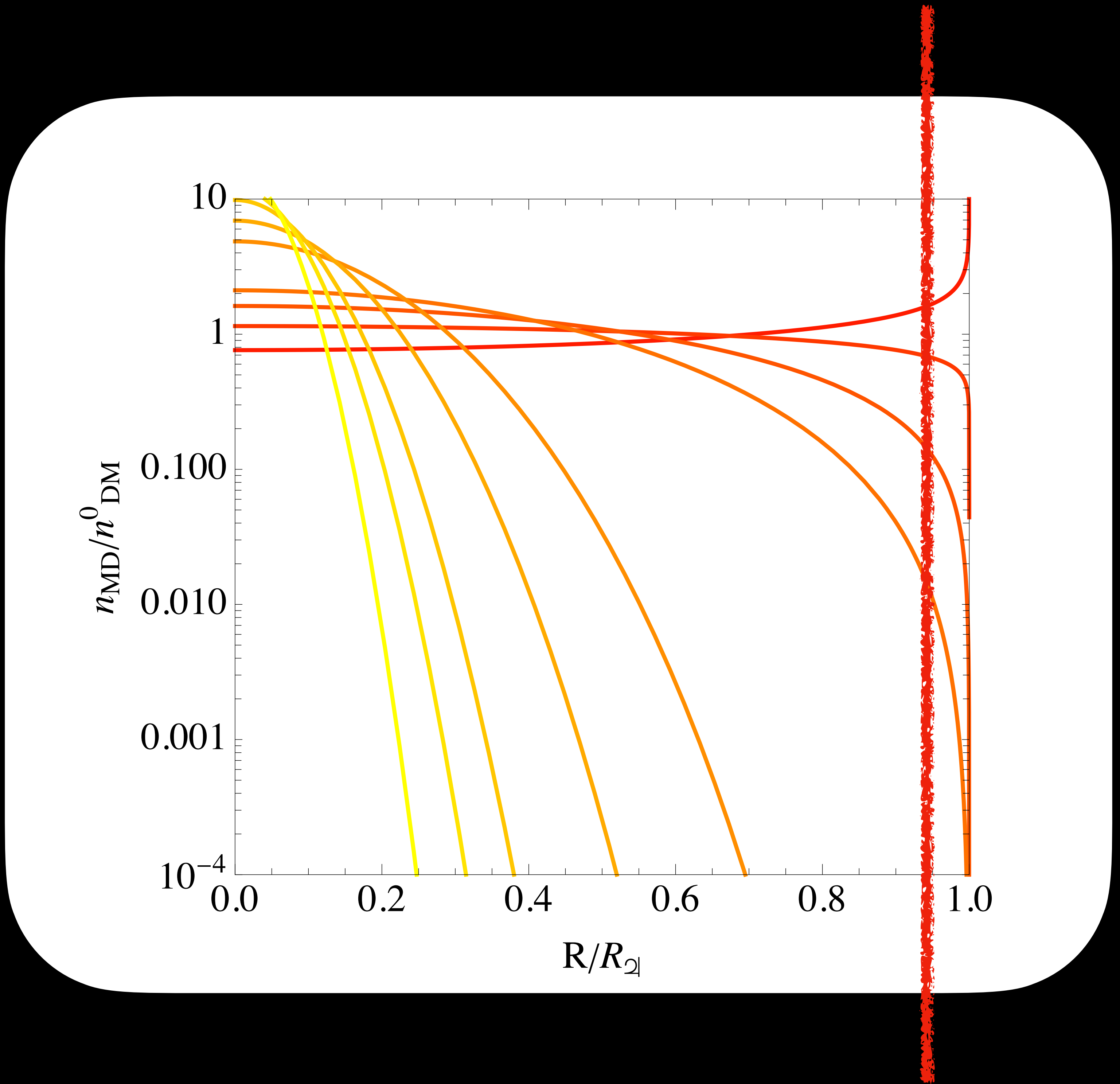
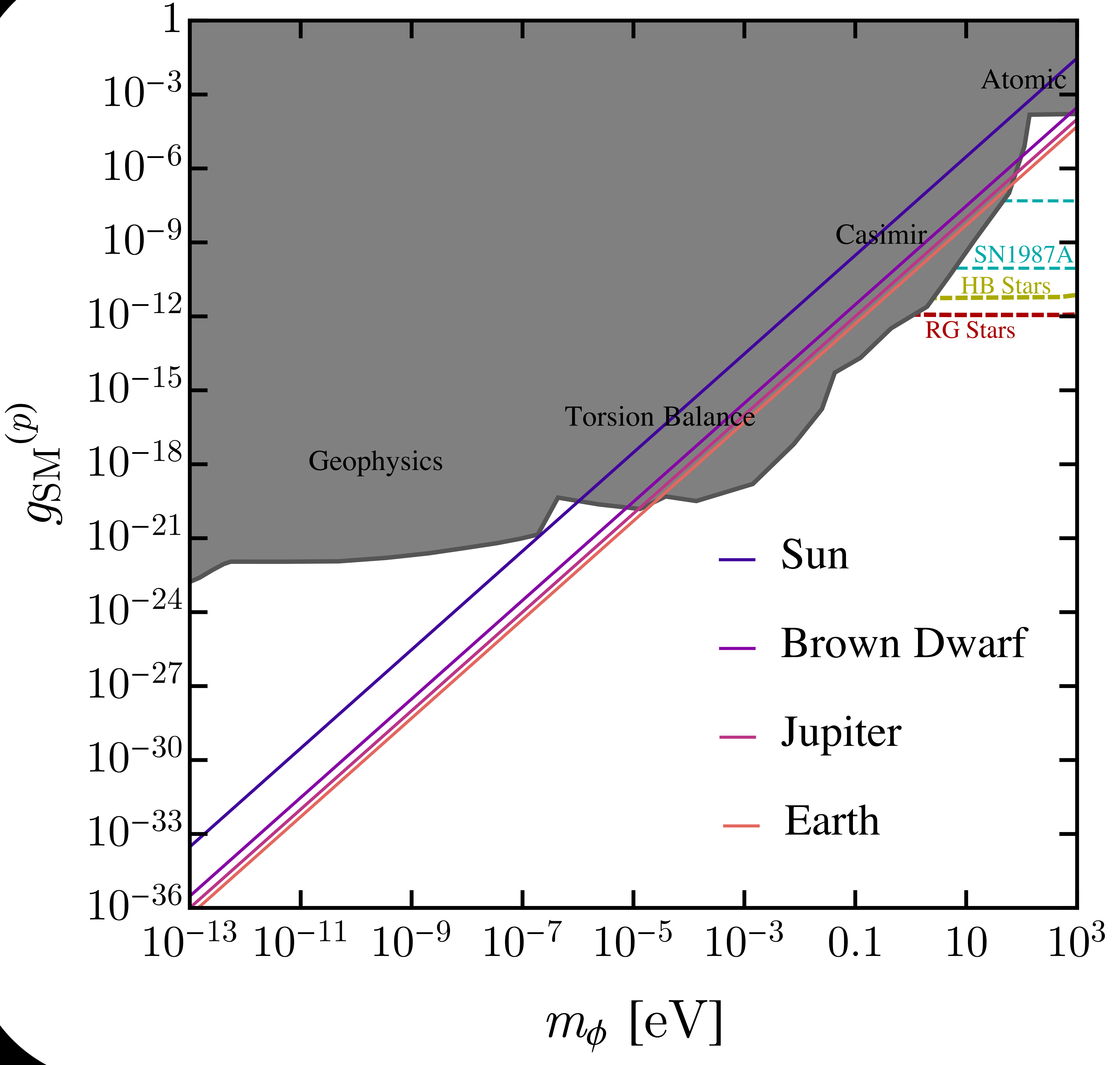
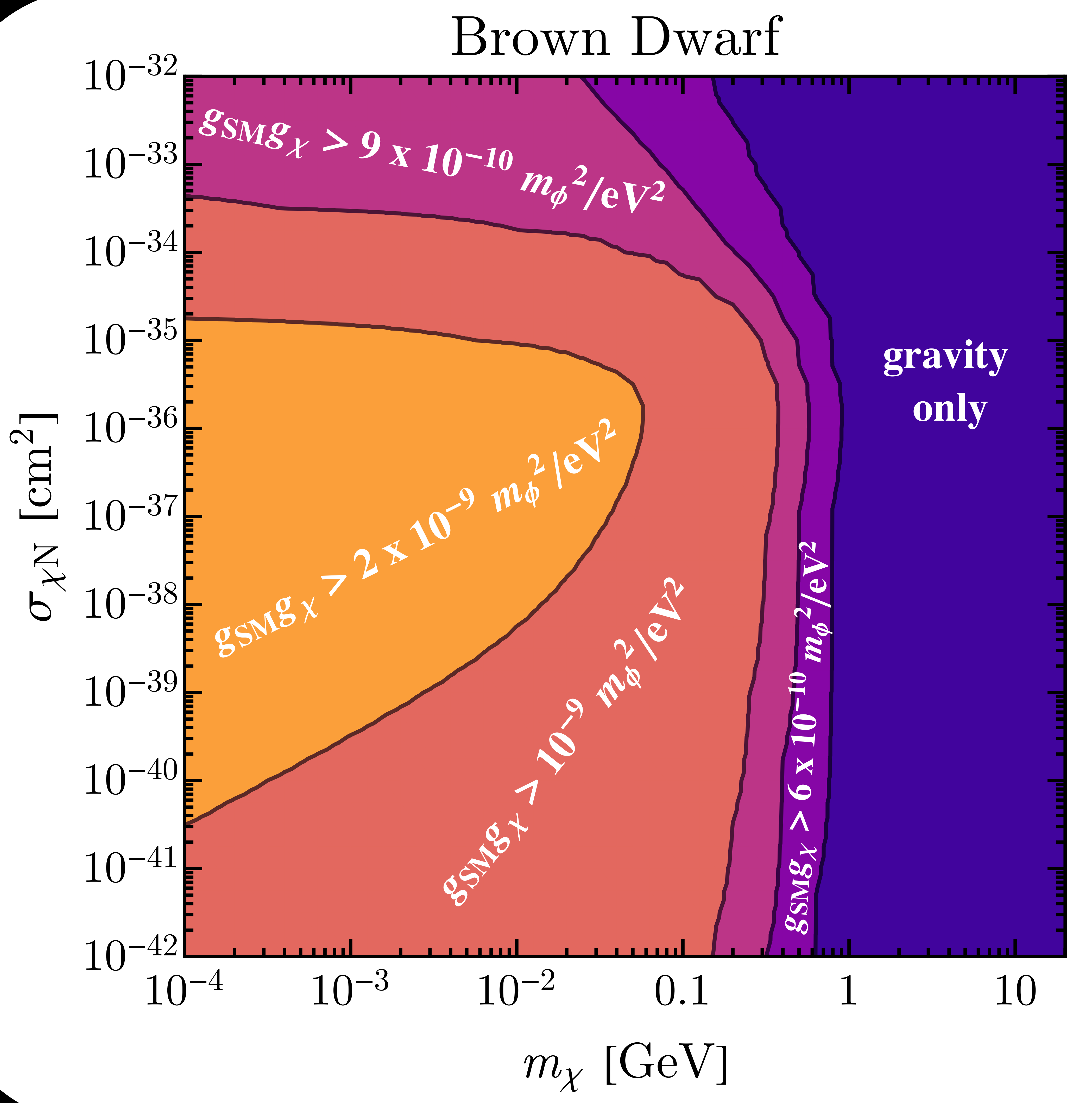


Dark Long Range Force Space



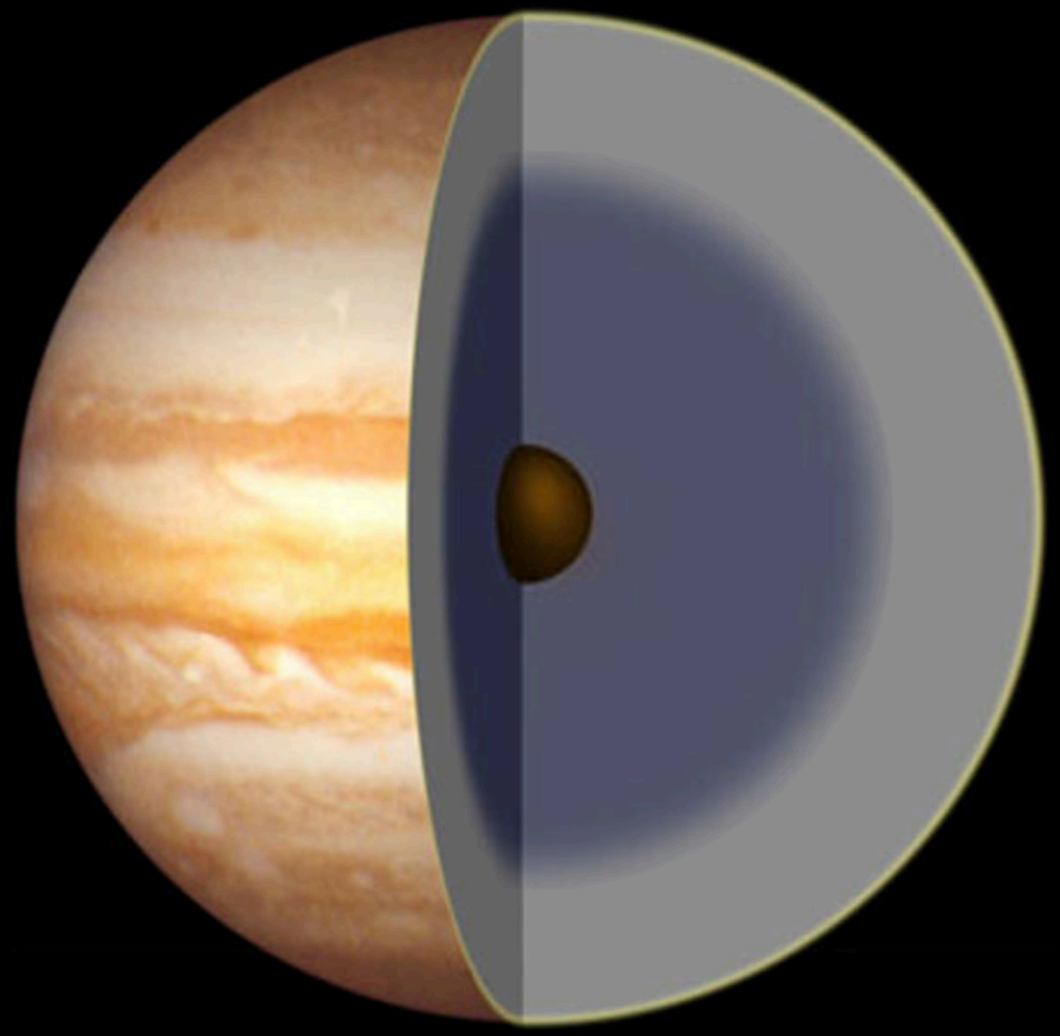
arXiv: 2303: 2303:01516;
J. Acevedo, R. K. Leane, **J. Smirnov**

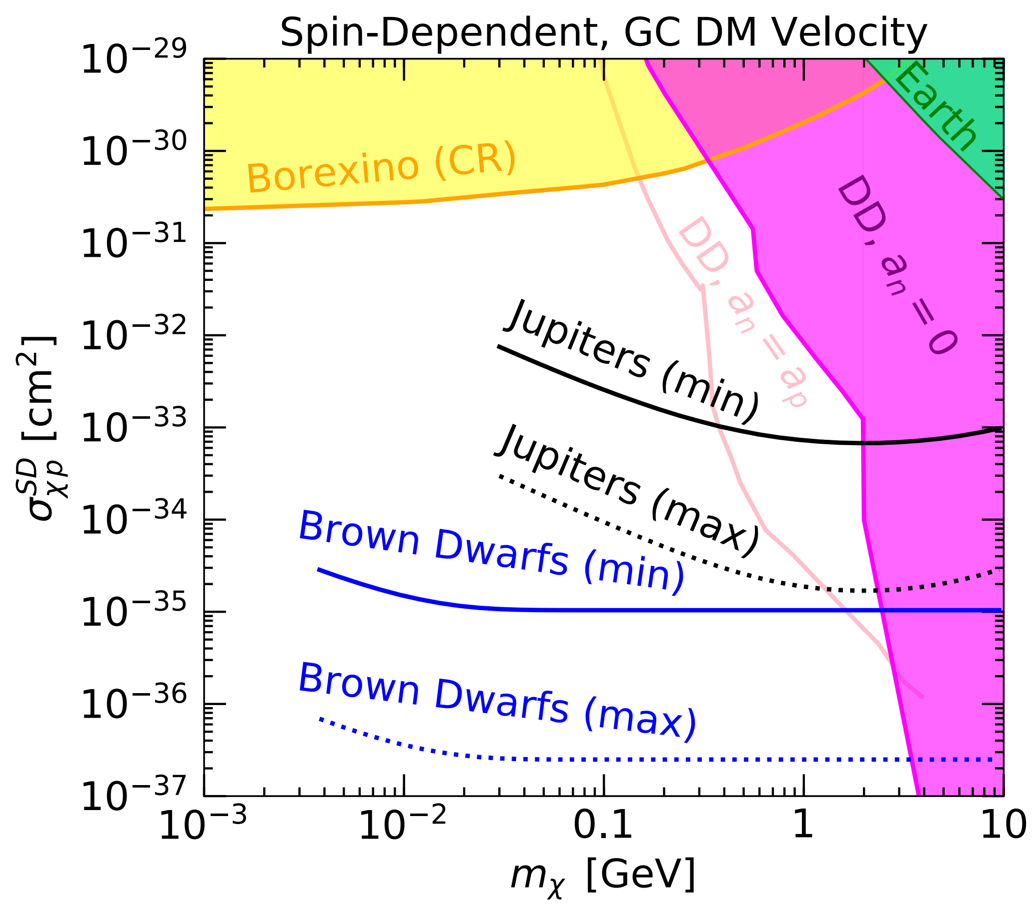
Model Dependence of Evaporation



arXiv: 2303: 2303:01516;
J. Acevedo, R. K. Leane, **J. Smirnov**

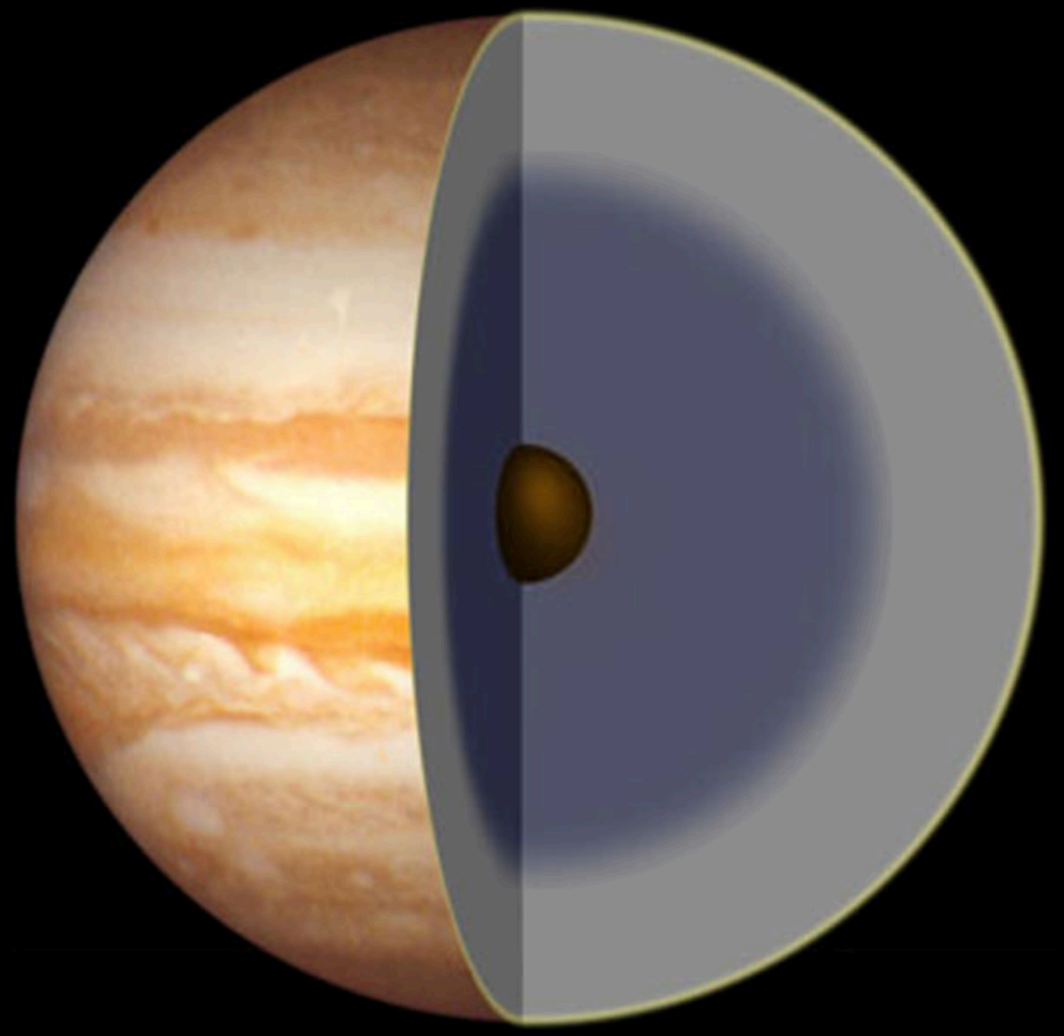
Further Implications

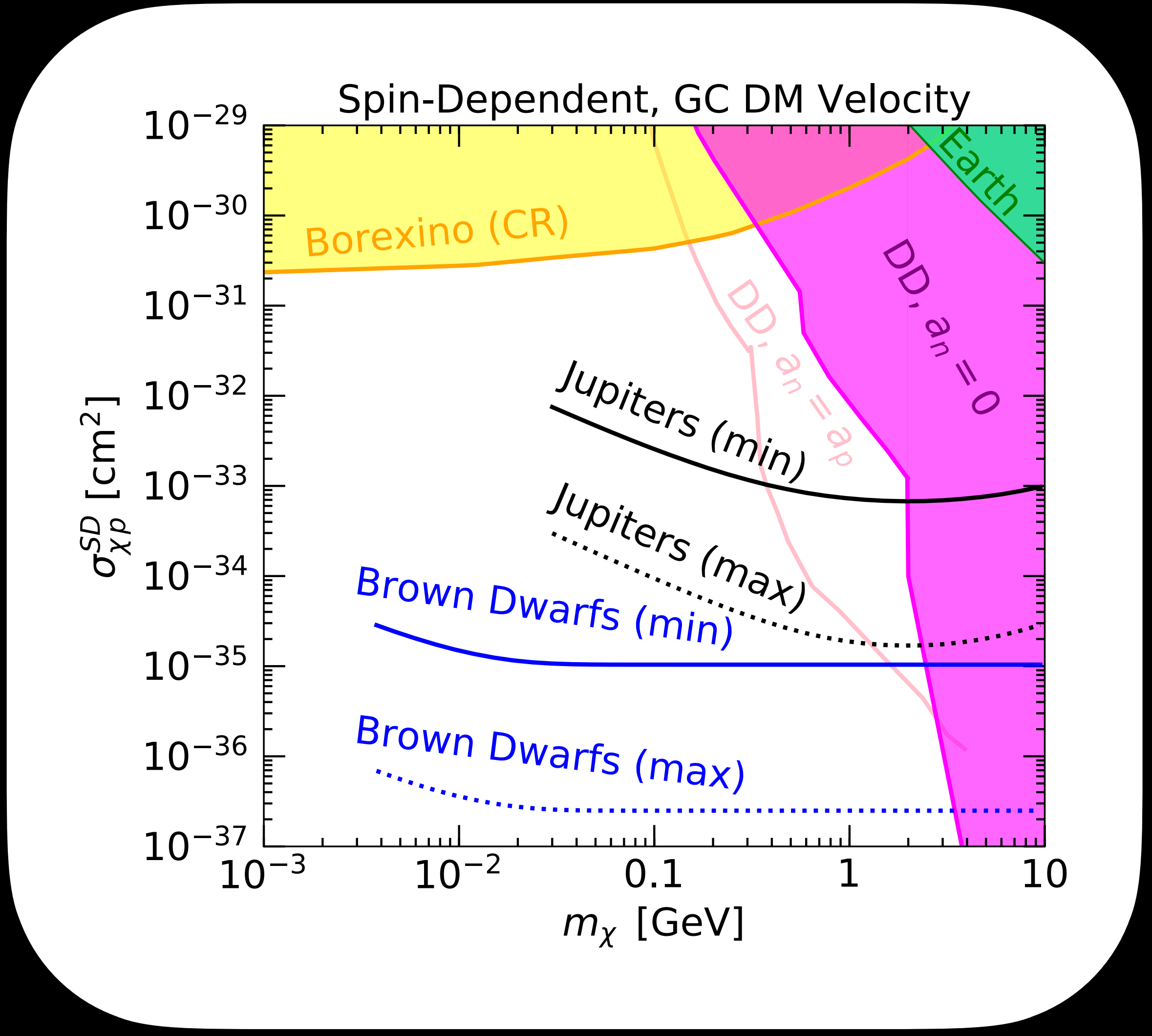




Further Implications

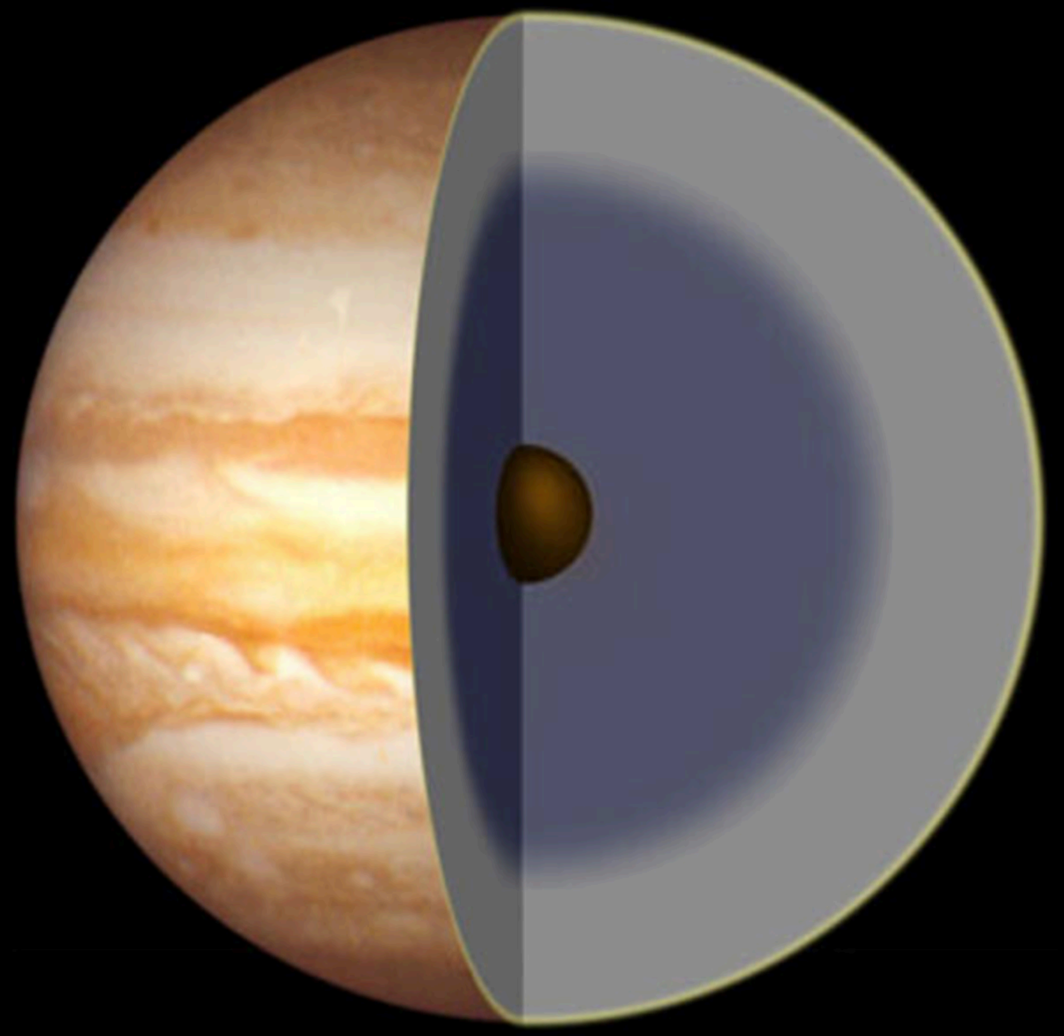
- Accumulated high surface density of DM particles

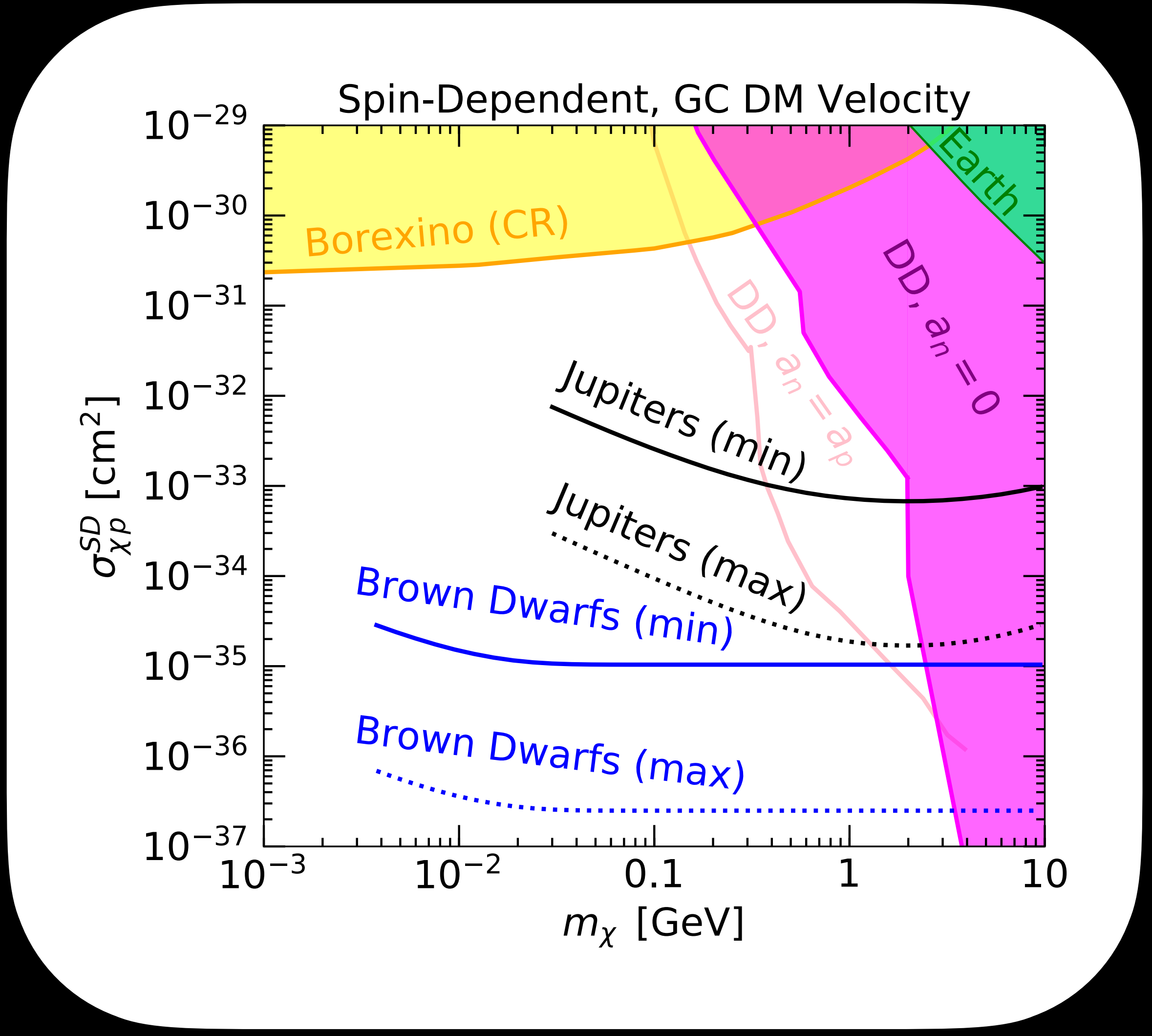




Further Implications

- Accumulated high surface density of DM particles
- Earth: boosted Sensitivity of Direct Detection, once threshold is reached





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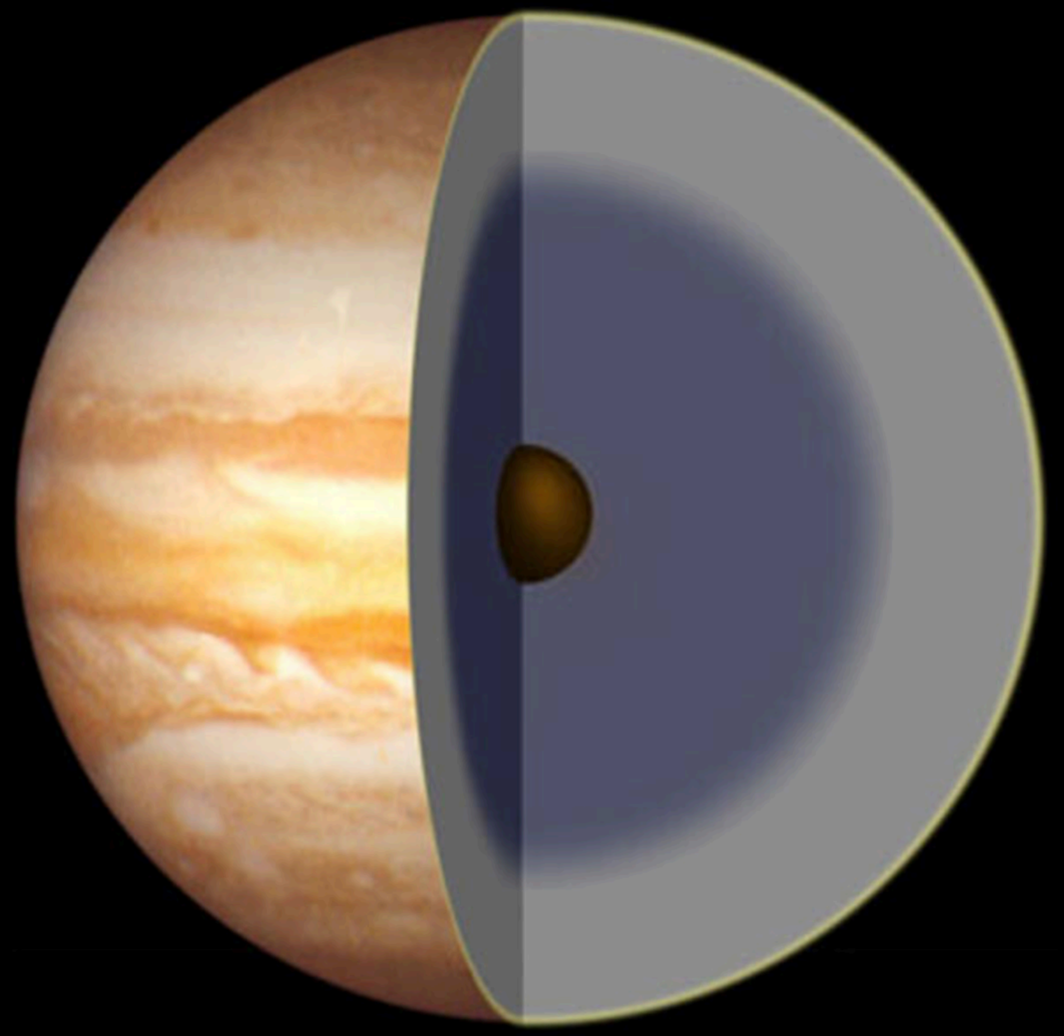
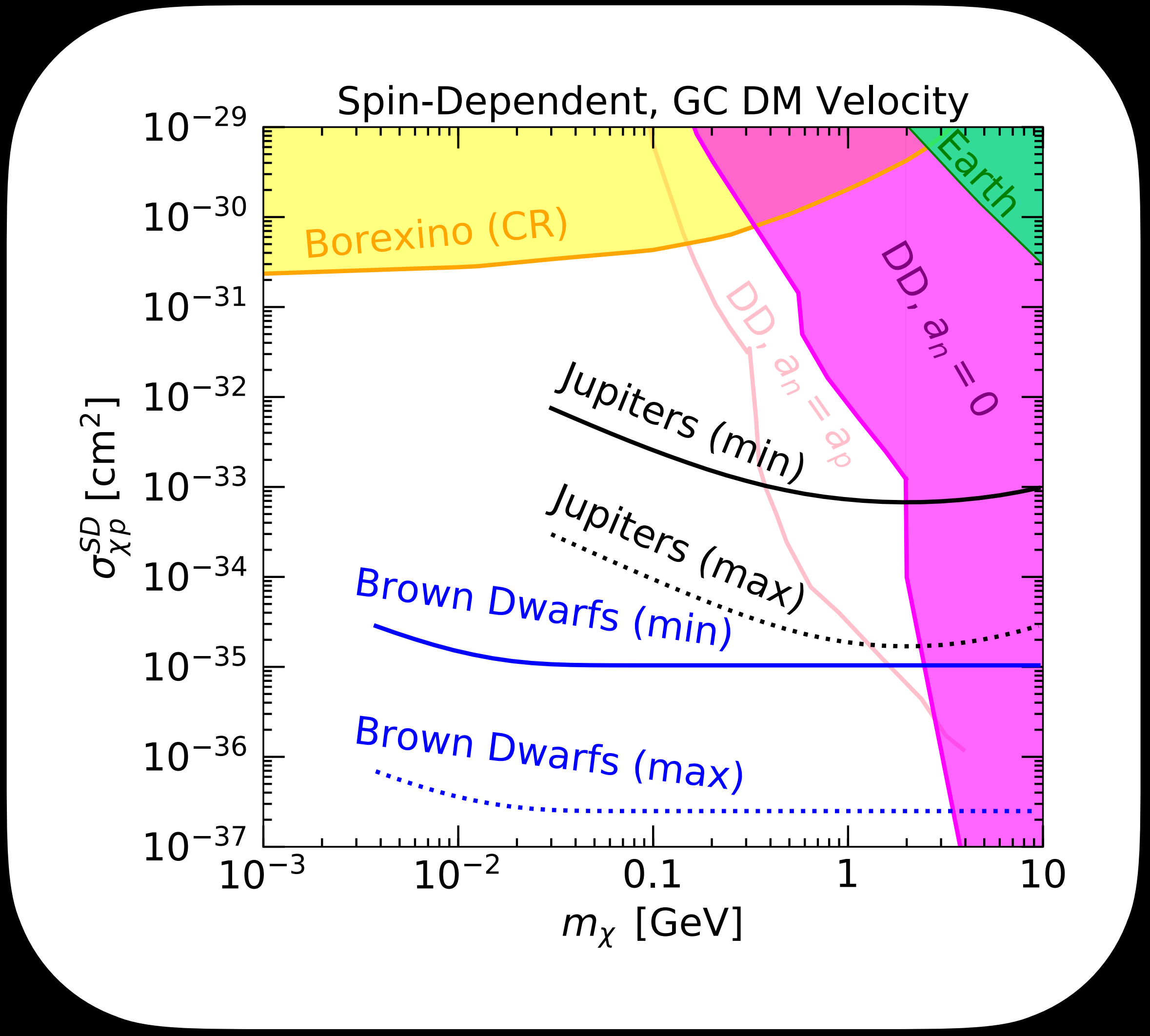
- Distribution can affect stellar heat transport and Solar abundance





Further Implications

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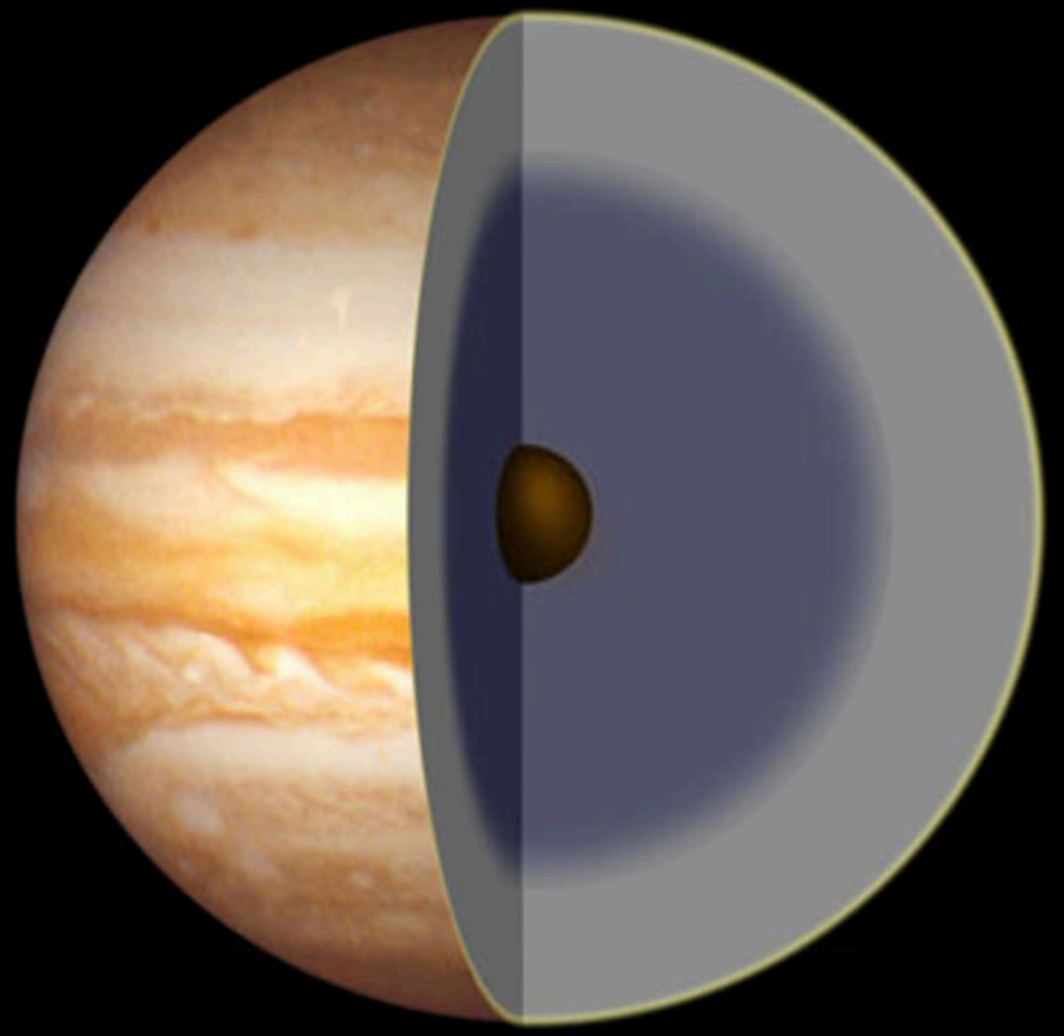
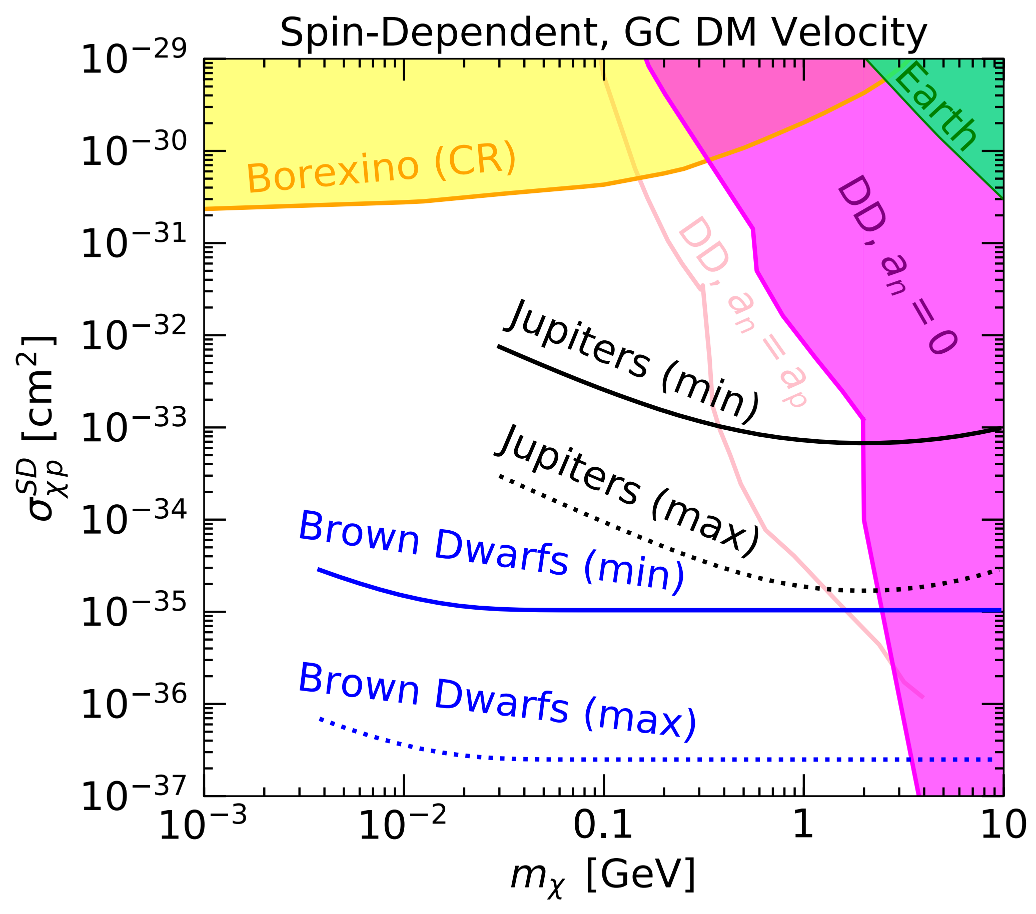
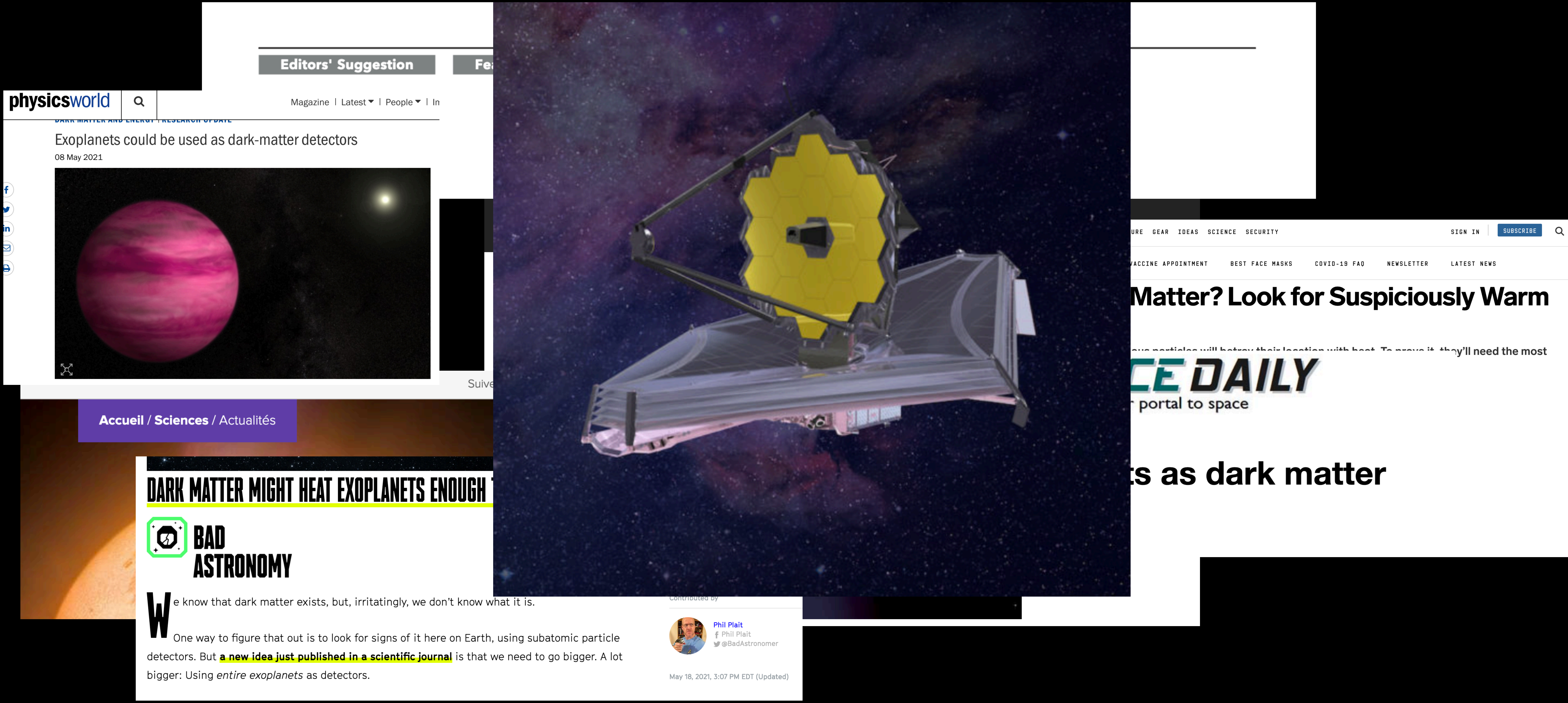
- Distribution can affect stellar heat transport and Solar abundance
- Distribution affects the long-lived mediator signals



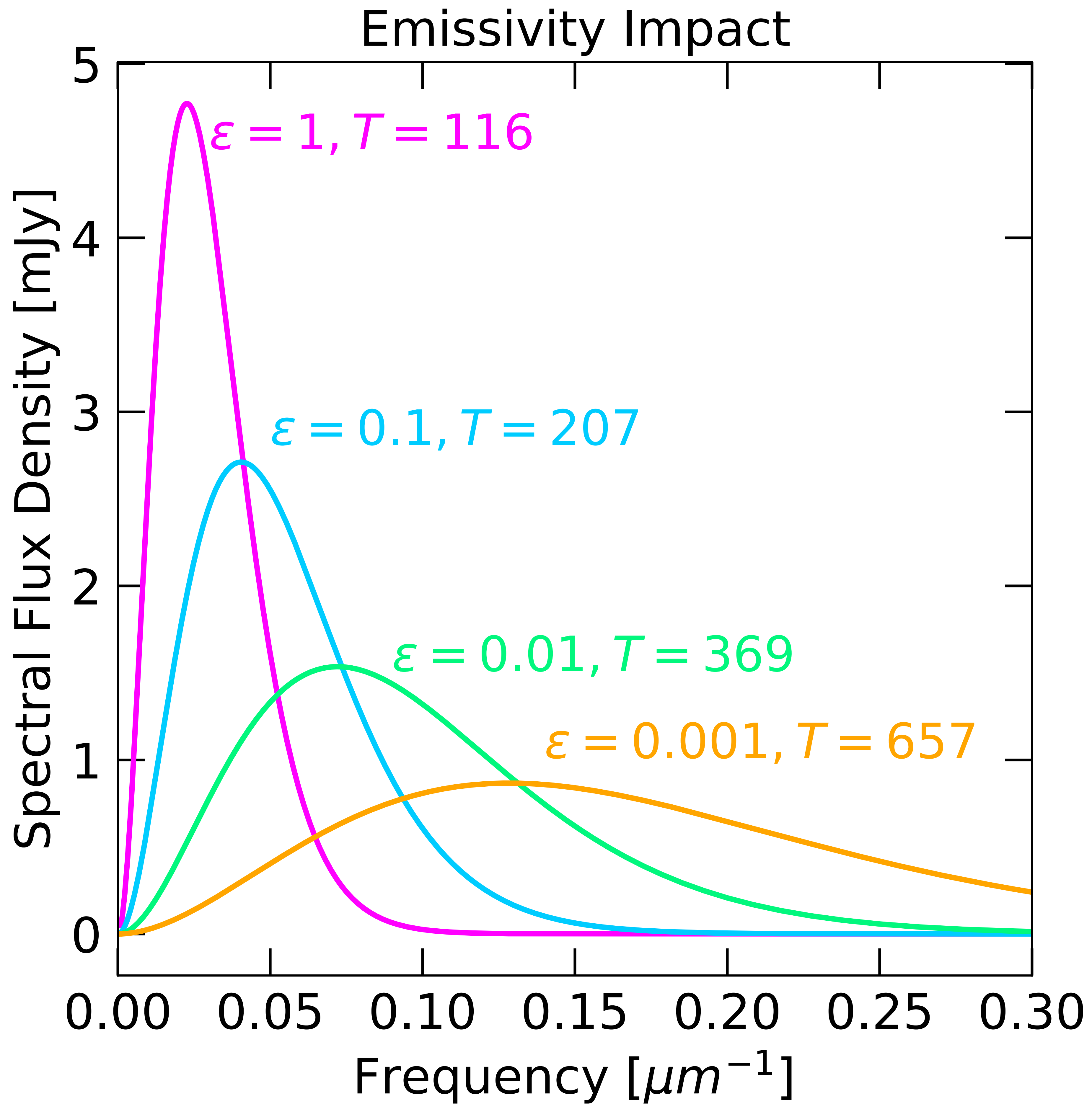


New Worlds Ahead



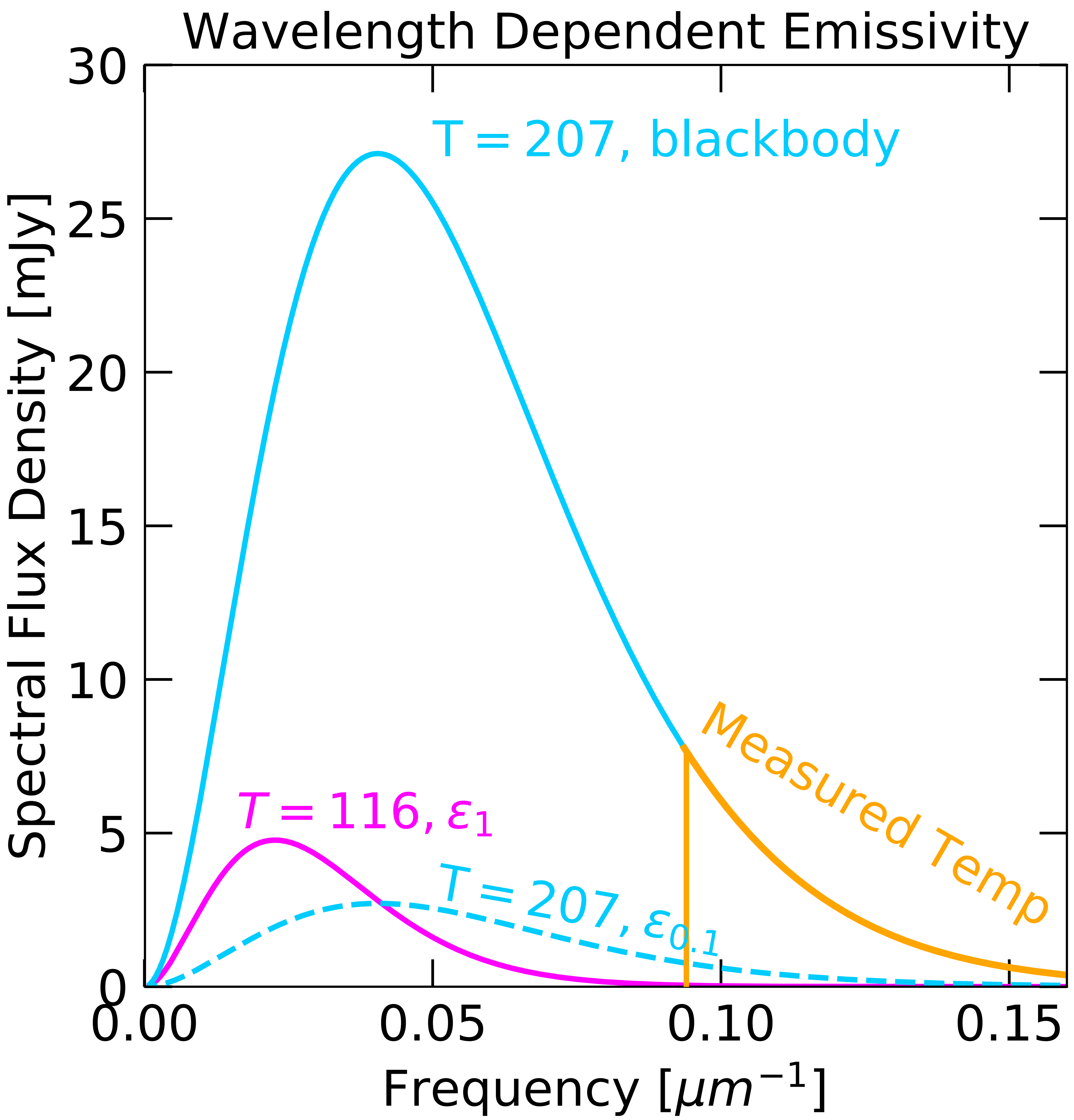
Thanks!

Atmospheric Emissivity



Ongoing work: R. K. Leane (SLAC), B. Macintosh (Stanford), **J. Smirnov**

Realistic Atmospheres



Ongoing work: R. K. Leane (SLAC), B. Macintosh (Stanford), **J. Smirnov**

Model dependent Evaporation

An Analytic Example

$$P = \kappa\, \rho^{\frac{n+1}{n}}$$

$$\alpha^2 \frac{1}{x^2} \frac{d}{dx} \left(x^2 \frac{d\theta(x)}{dx} \right) = -\theta(x)^n$$

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$$\alpha^2 \frac{1}{x^2}\frac{d}{dx}\left(x^2 \frac{d\theta(x)}{dx}\right) = -\theta(x)^n$$

$$n = 1 \Rightarrow \theta = \frac{\sin(x)}{x}$$

$$\rho = \rho_c\,\theta(r)$$

$$P = P_c\,\theta(r)^2$$

$$T = T_c\,\theta(r)$$

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$$T = T_c\, \theta(r)$$

$$\frac{n^{\rm LTE}(R)}{n(0)} = \left[\frac{T(R)}{T_c}\right]^{-(\alpha-3/2)} \times \exp\left[-\int_0^R \frac{f(r)}{T(r)} dr\right] = \left[\frac{T(R)}{T_c}\right]^{-(\alpha-3/2)+\frac{G_N M_0 m_\chi}{R_0 T c}} \approx \left[\frac{T(R)}{T_c}\right]^{-1/2+\frac{v_{\rm esc}^2}{v_{\rm th}^2}}$$

An Analytic Example

$$P = \kappa \rho$$

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$$= P_c\, \theta(r)^2$$

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$$\alpha^2 \frac{1}{x^2}\frac{d}{dx}\left(x^2 \frac{d\theta(x}{dx}\right.$$

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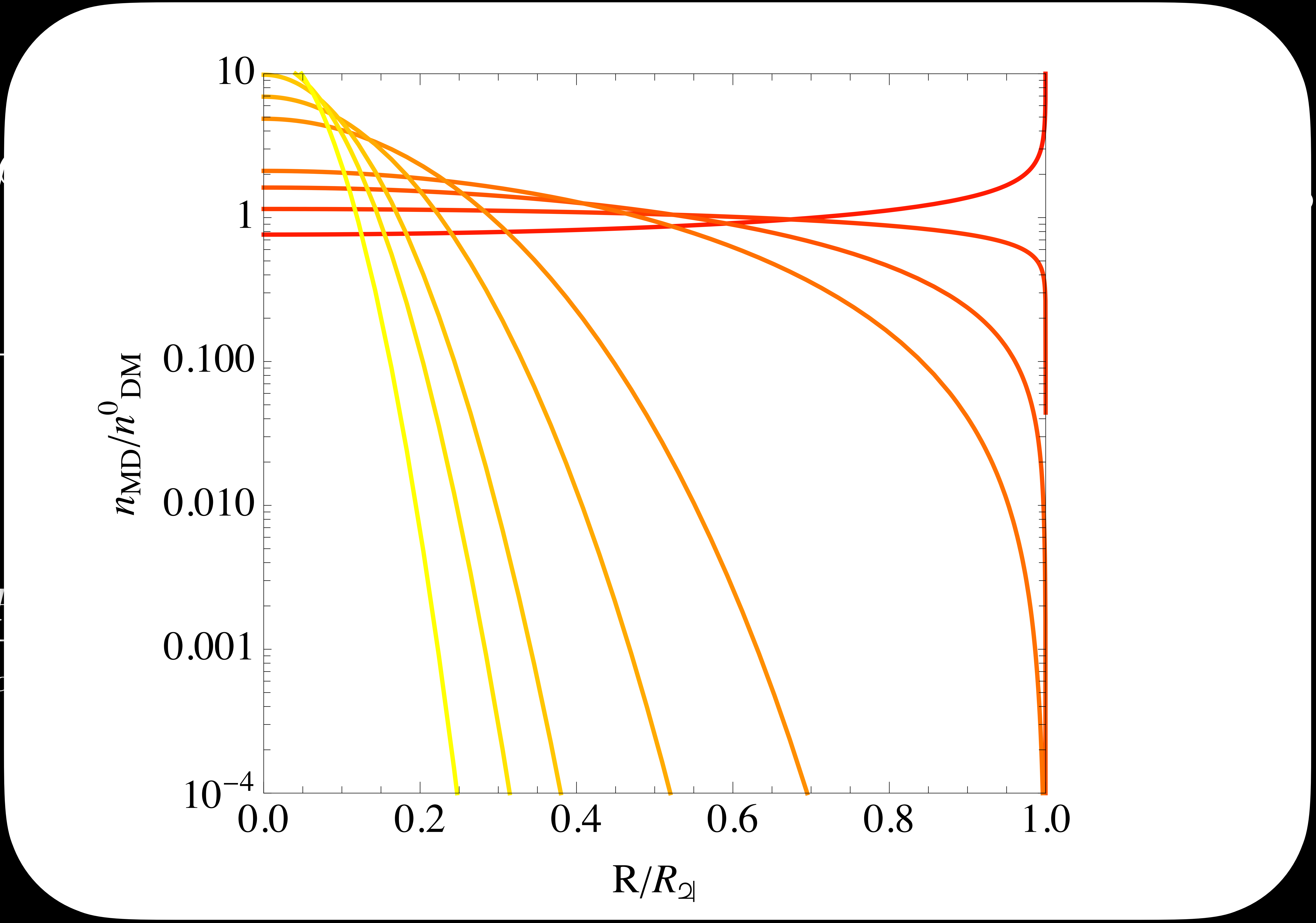
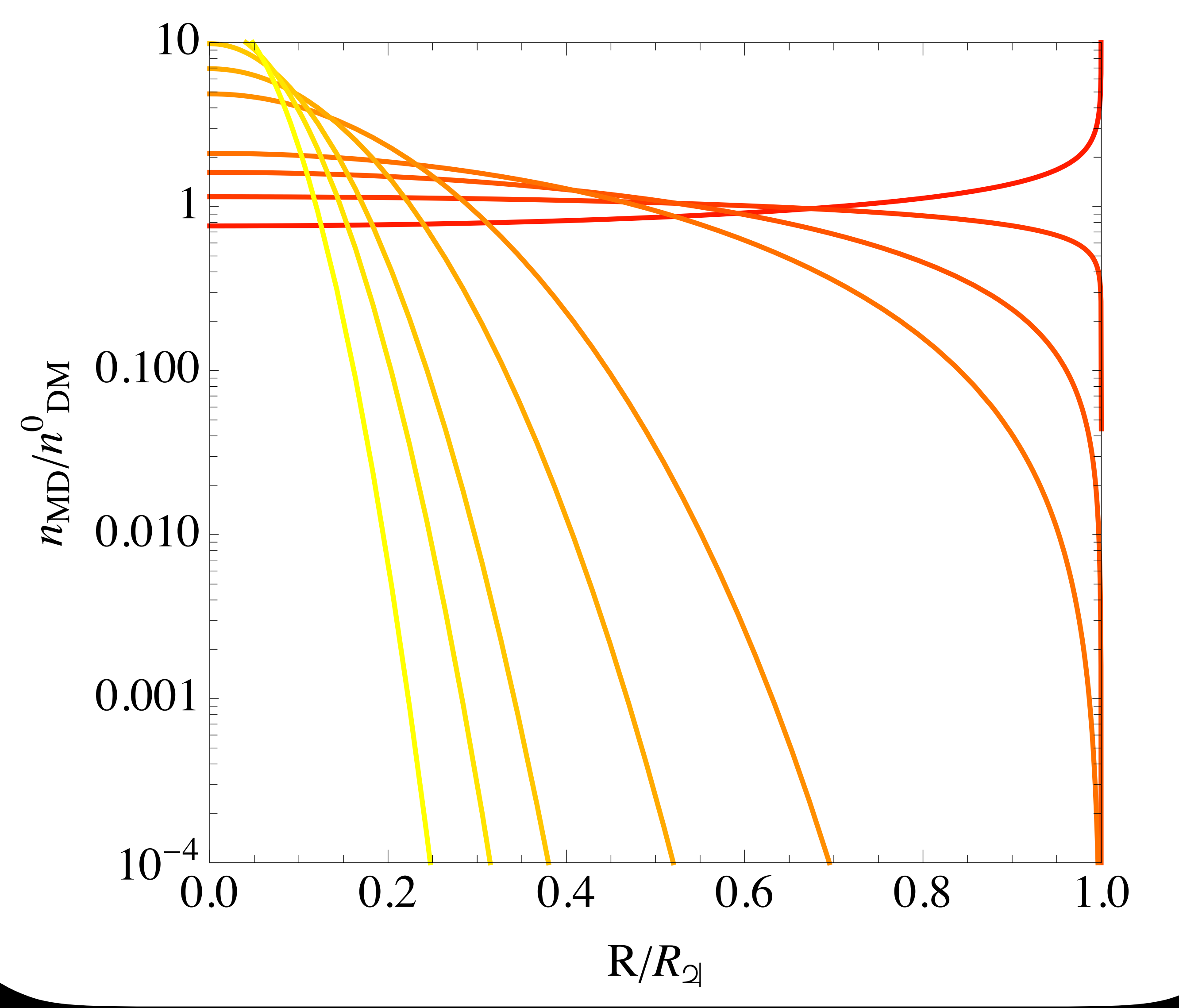


Model Dependence

$$V_{\text{long}} = \frac{\alpha}{r}\, e^{-m_V\, r}$$

$$E_{\text{barrier}} \approx \frac{\alpha n_{\text{SM}}}{m_V^2} \approx \alpha\, 10^9 \left(\frac{\text{eV}}{m_V}\right)^2 \text{eV}$$



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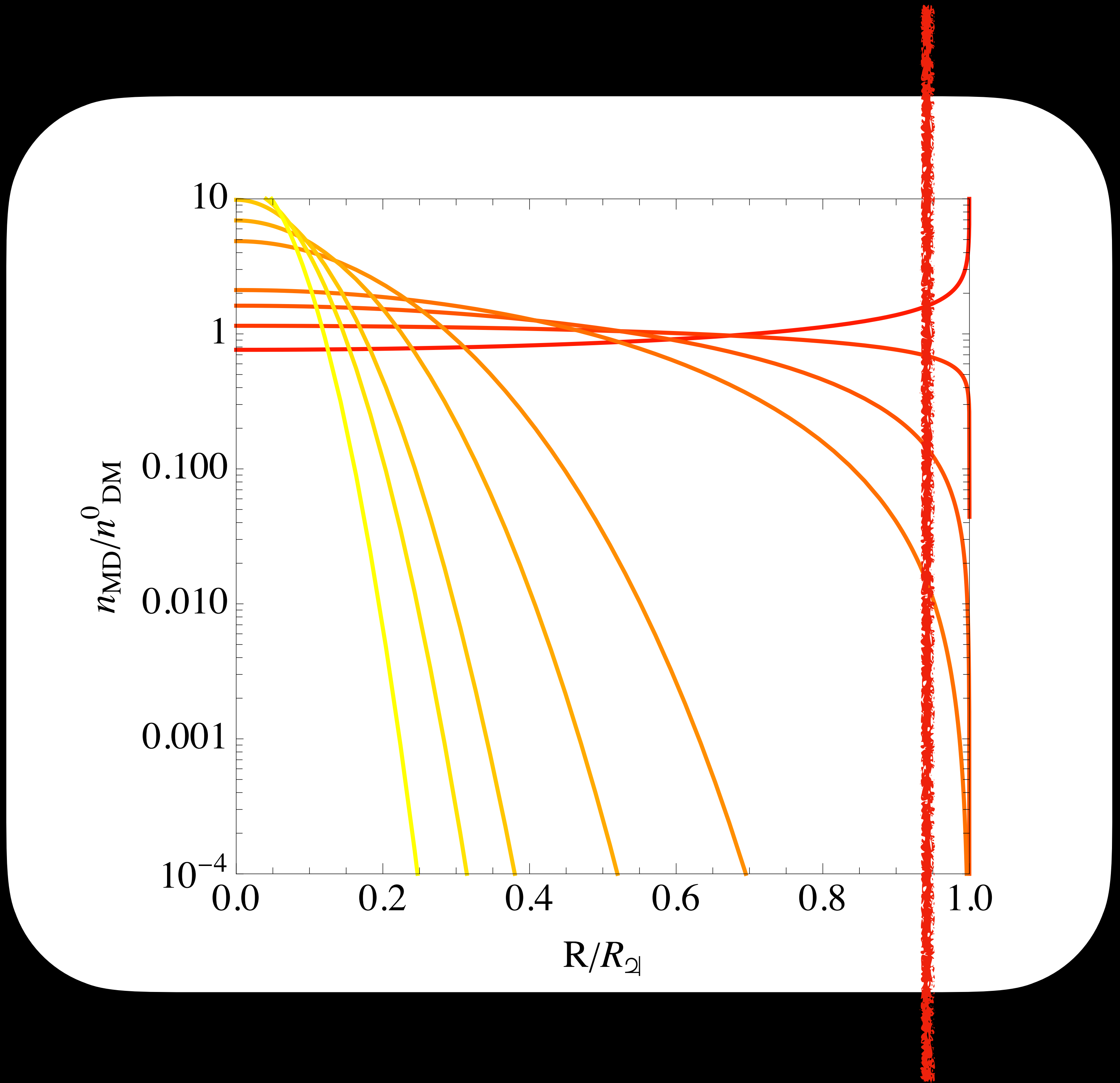

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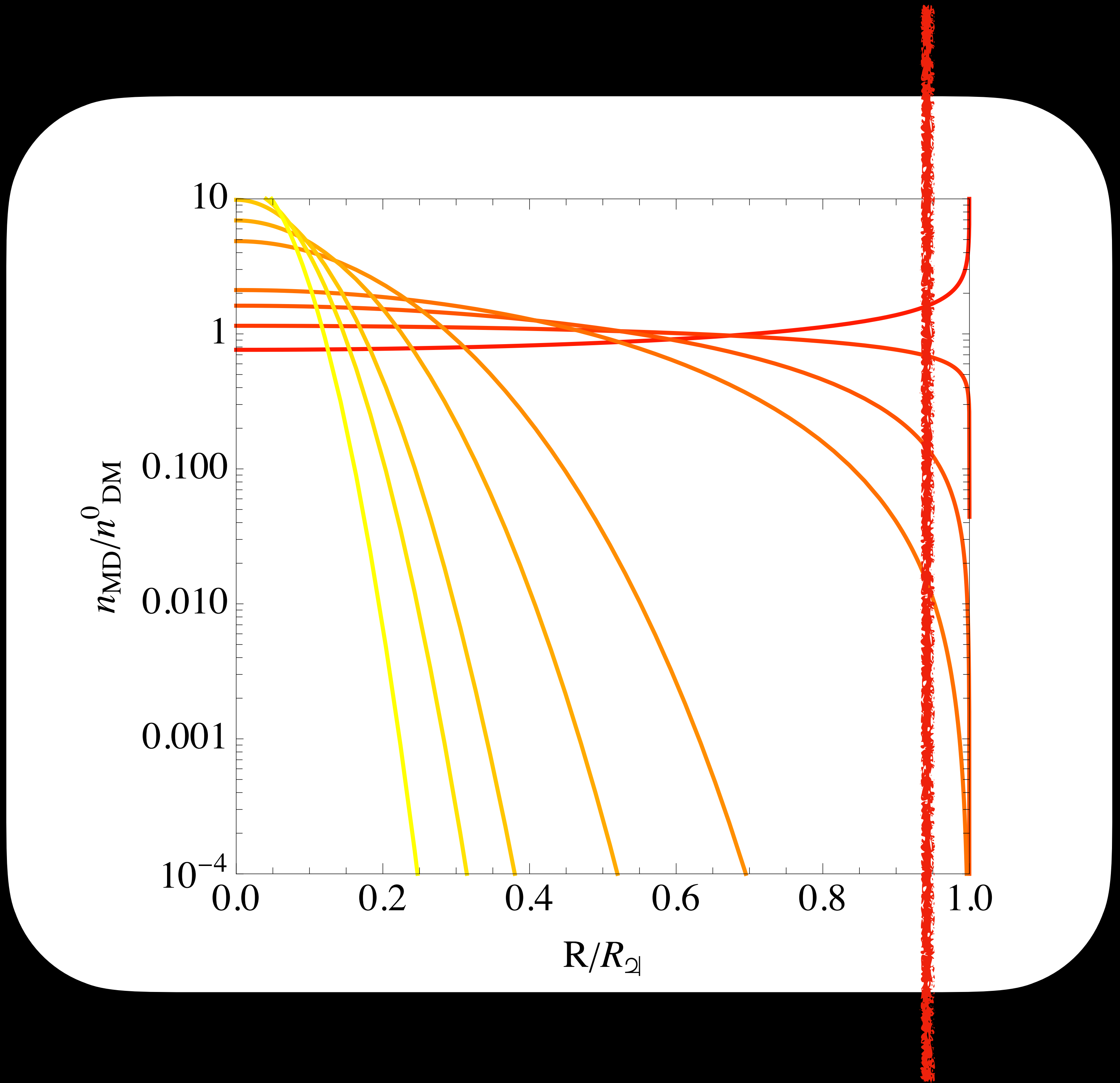
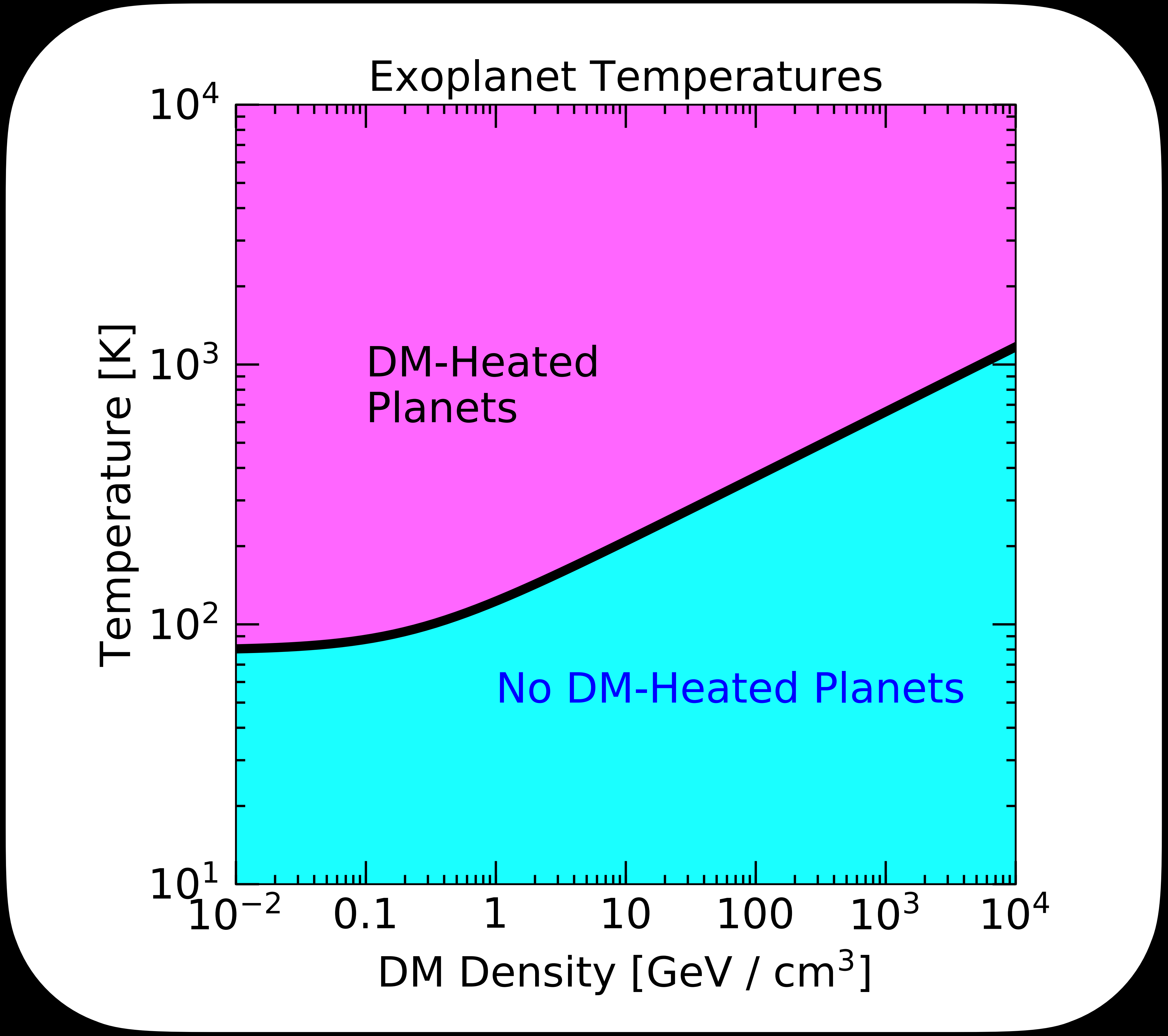
Dominates:

$$m_V \sim 10^{-7}\text{eV} \Rightarrow \alpha > 10^{-24}$$



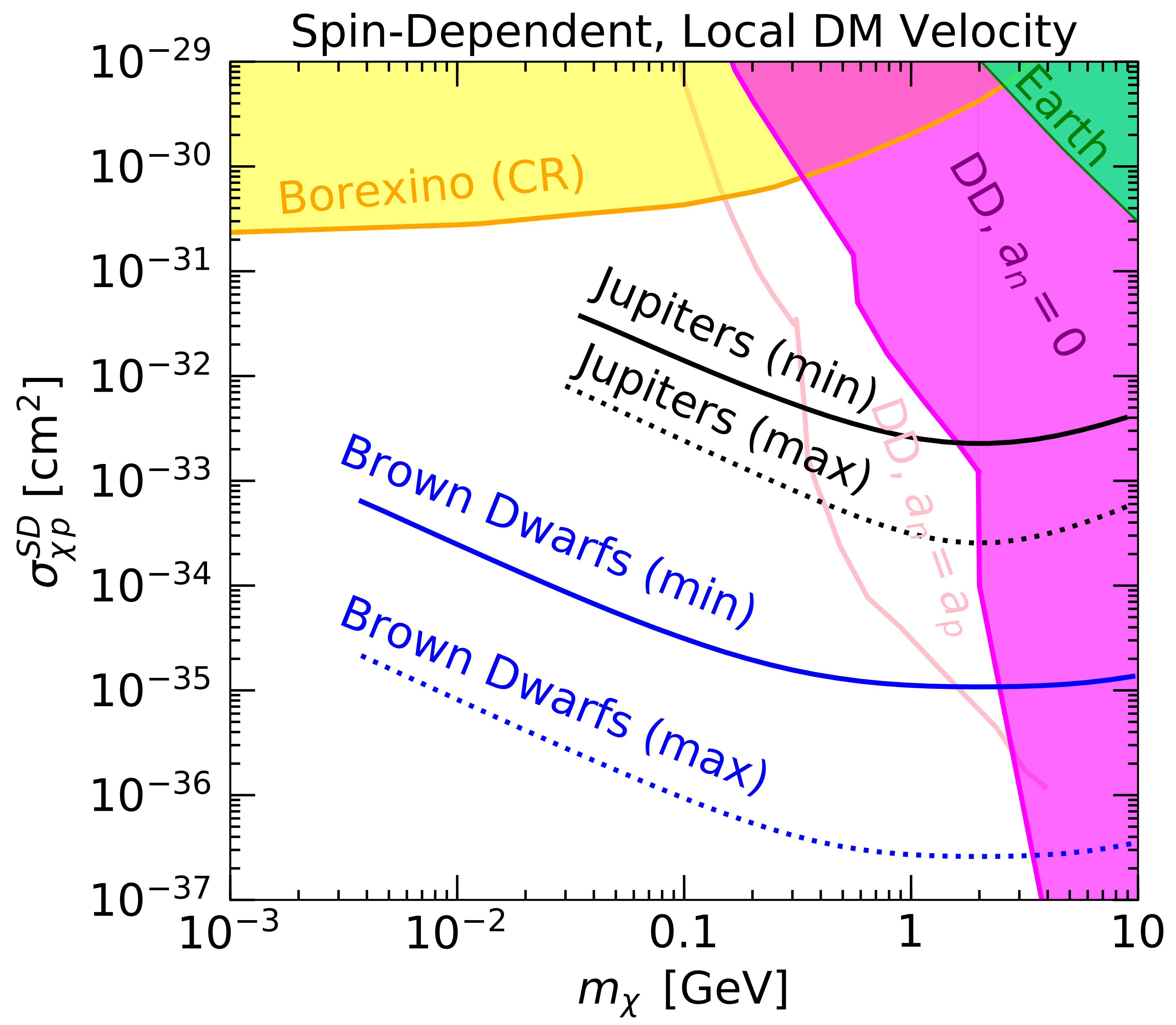
3: Localized DM Overdensities

How Dense is too Dense?



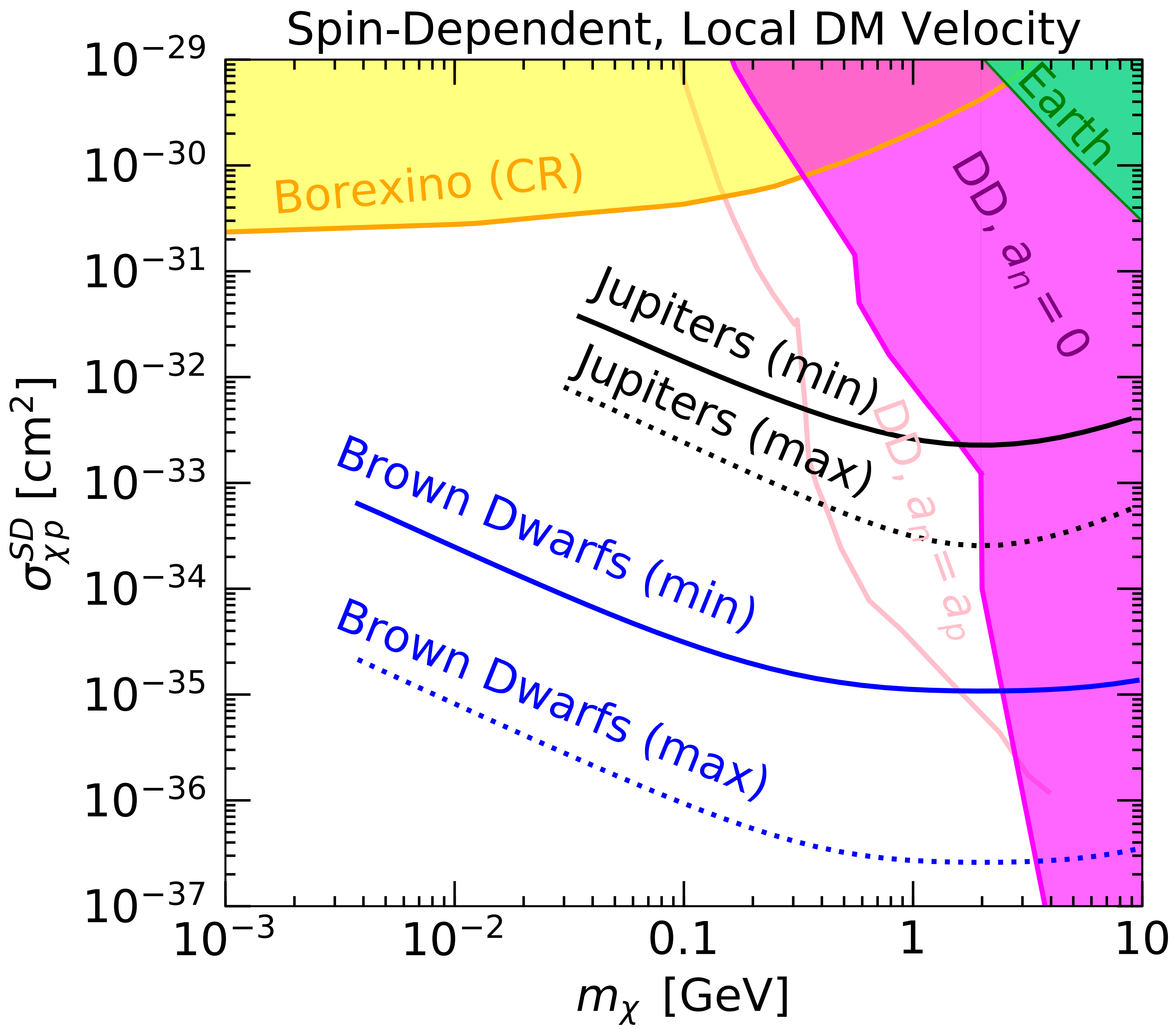
arXiv: 2010.00015; R. K. Leane (SLAC), J. Smirnov

DM-Proton Scattering (local)



arXiv: 2010.00015; R. K. Leane, **J. Smirnov**

Evaporation from Brown Dwarfs



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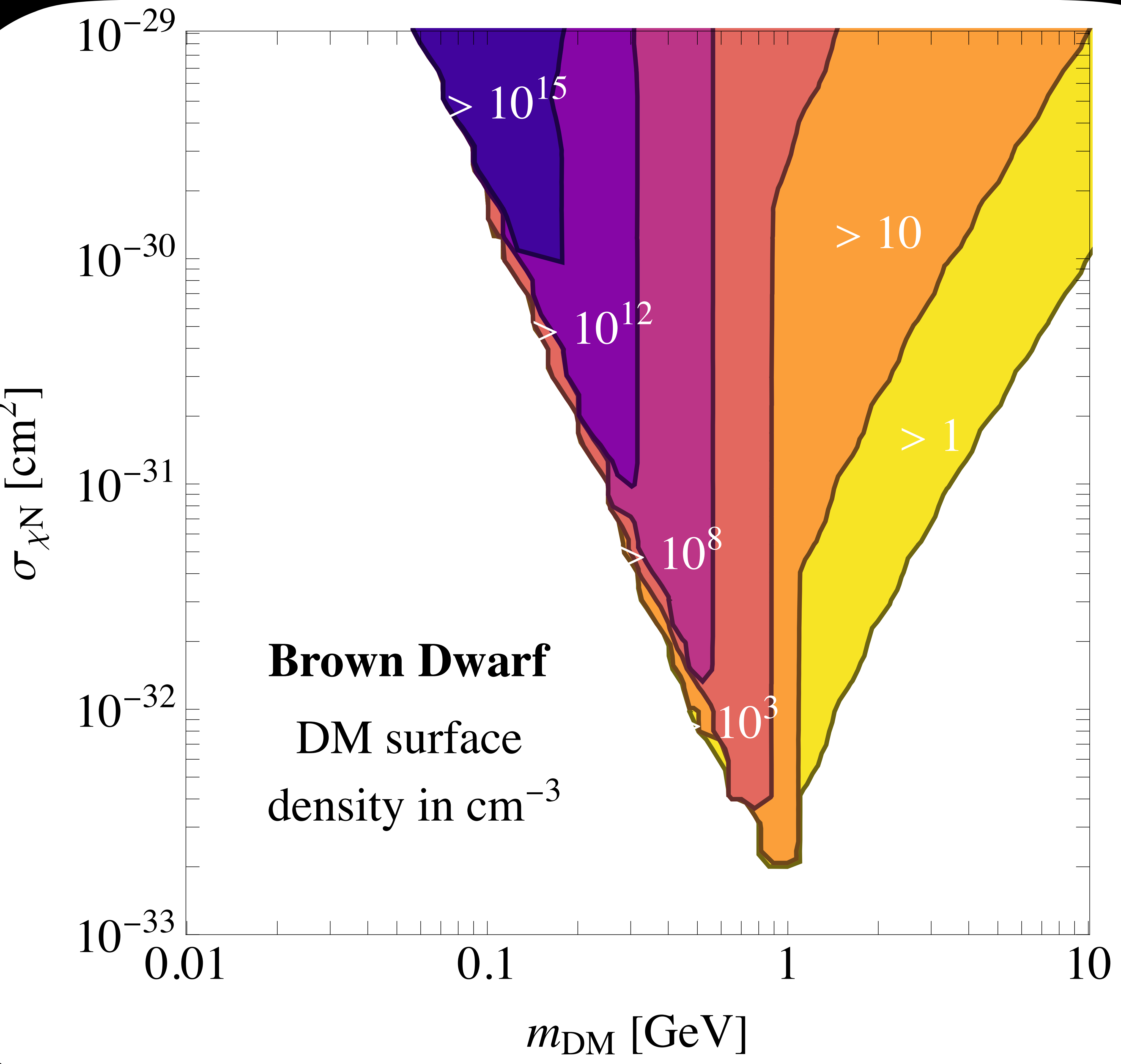

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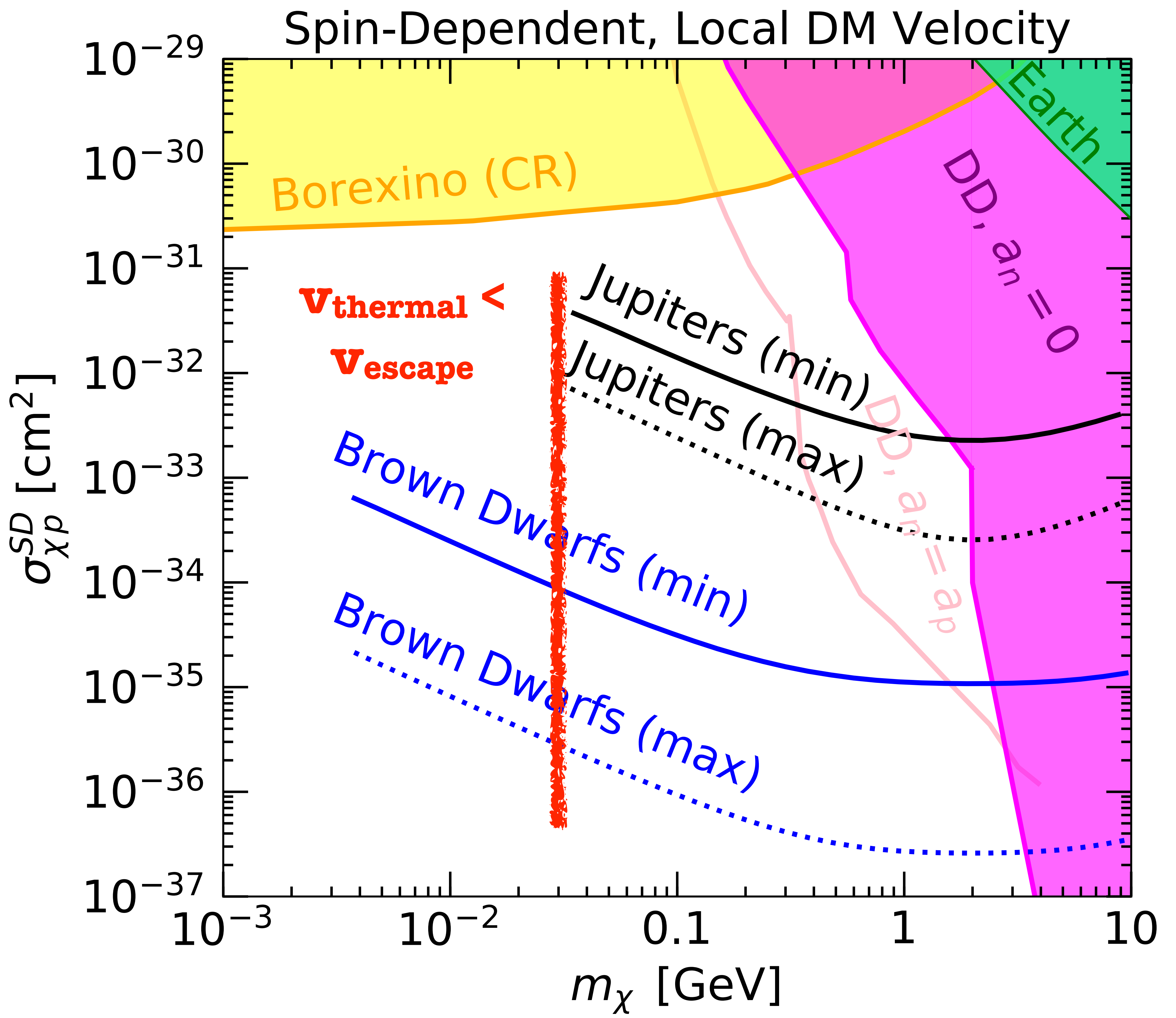
Evaporation from Brown Dwarfs



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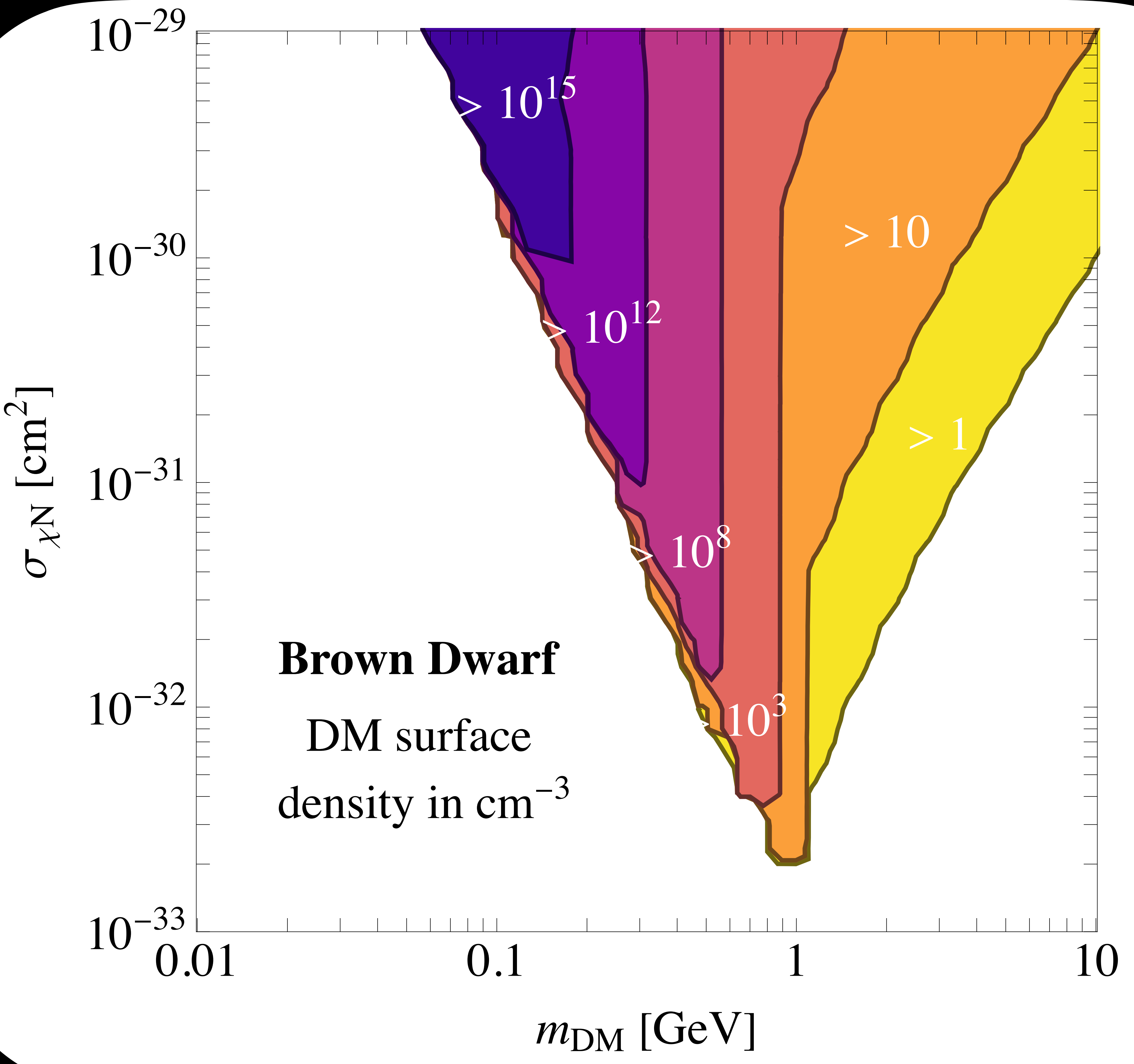

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