Dark Matter (h)eats Young Planets

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DC, J Smirnov, arXiv:2309.02495

Your naked eyes

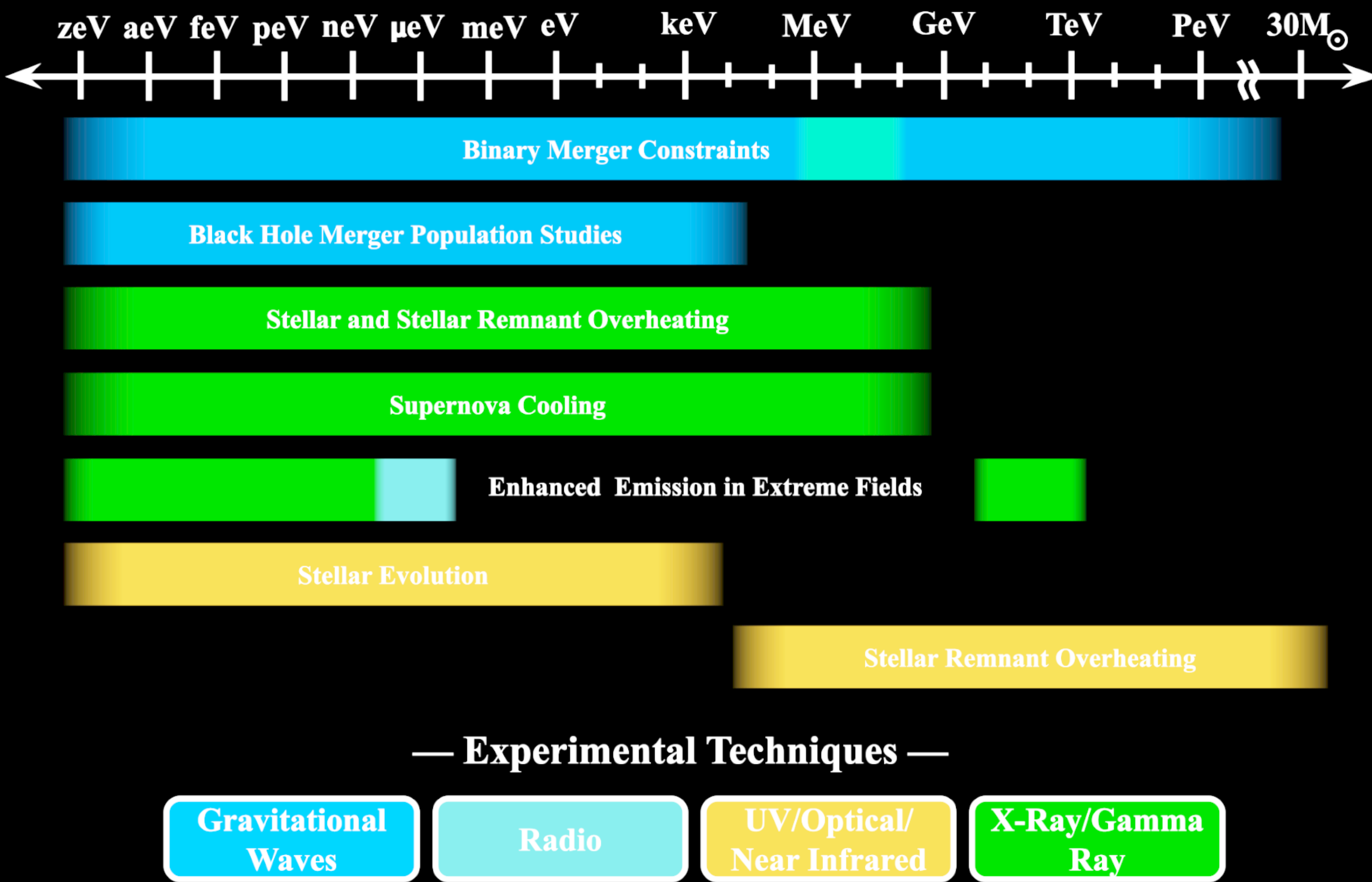
are a dark matter detector

Your naked eyes

are a dark matter detector

Dark matter in extreme astrophysical environments

Baryakhtar, Caputo, DC, Perez et all, SNOWMASS summer study, arXiv:2203.07984 , arXiv:2209.08215



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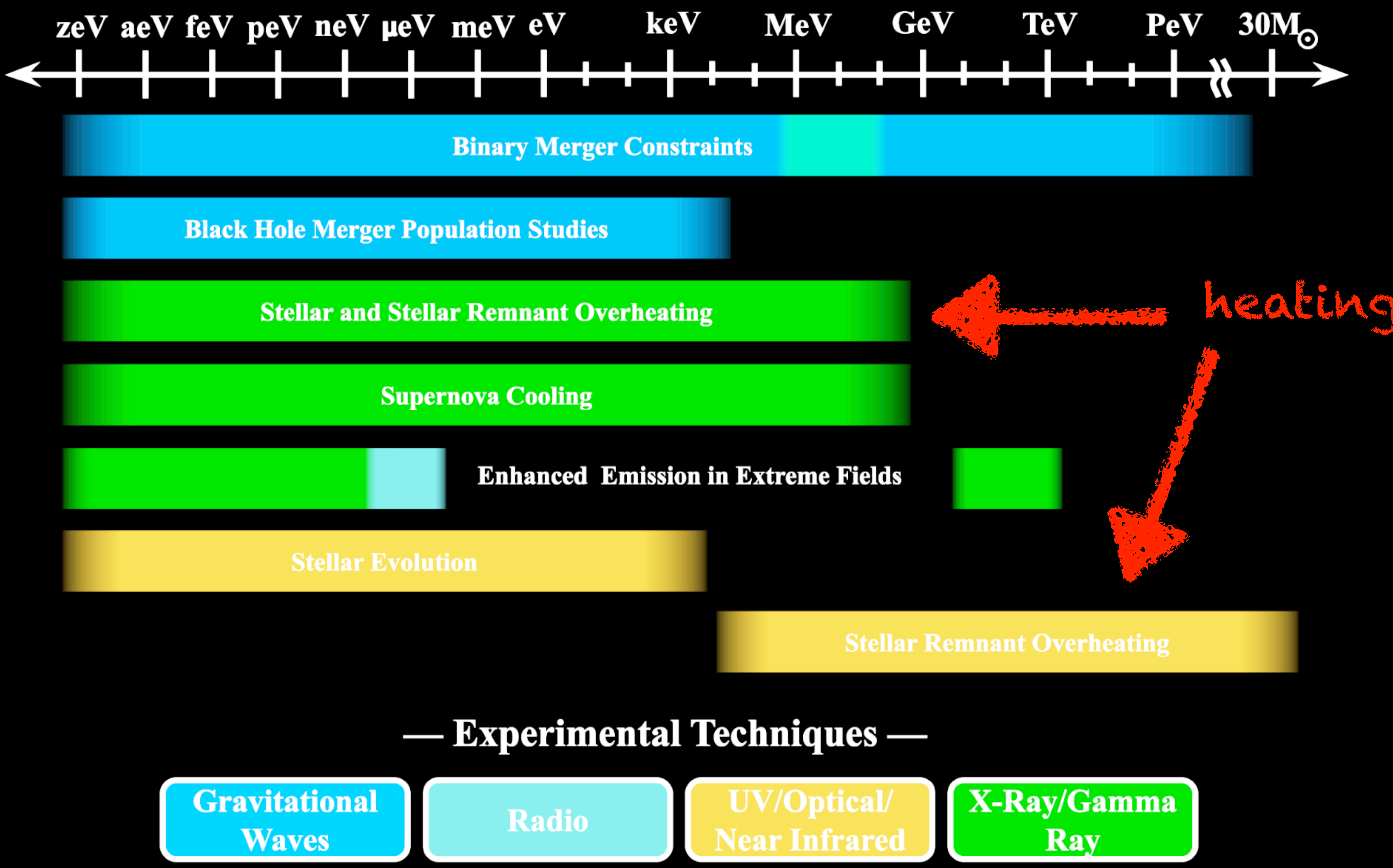

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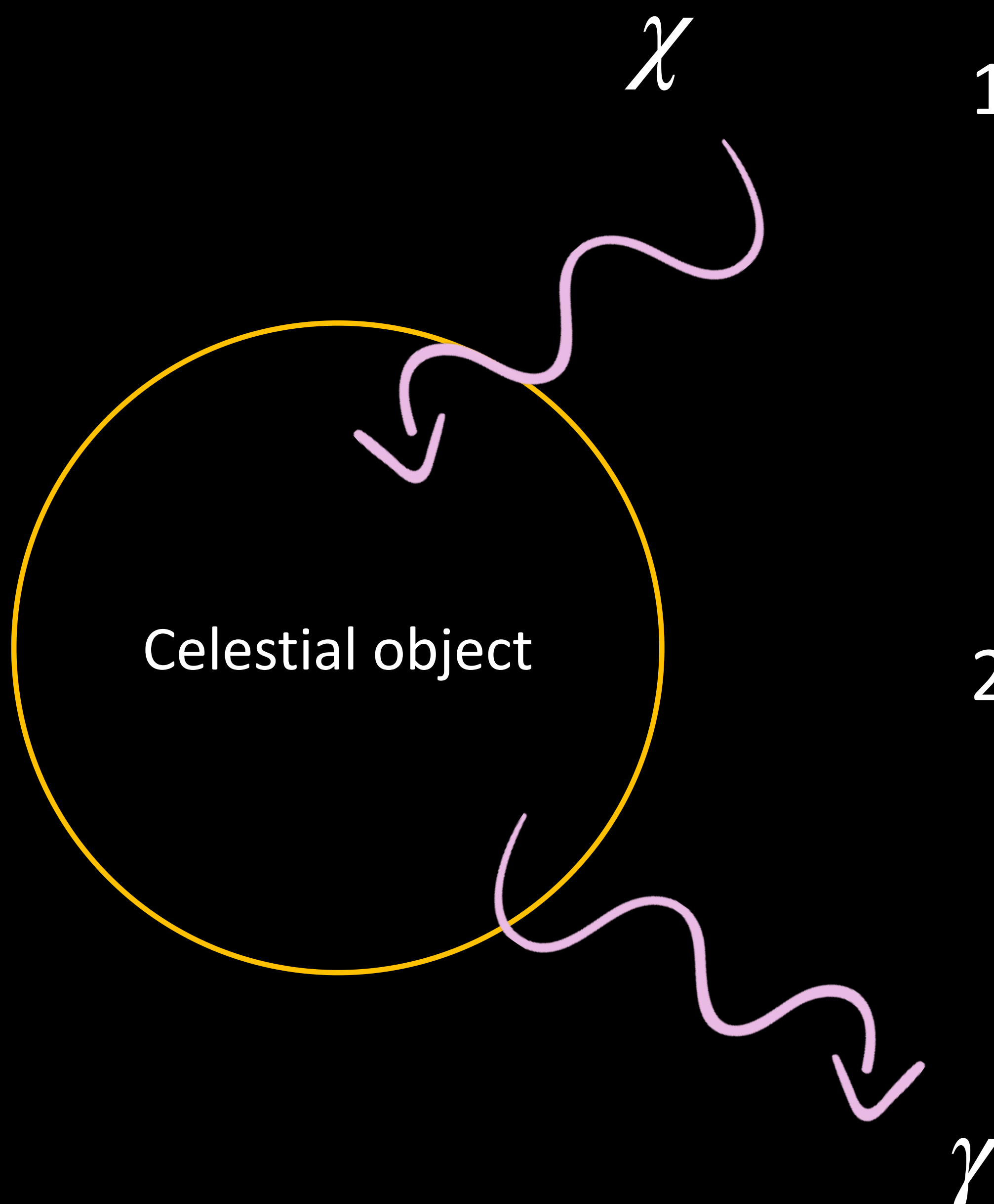
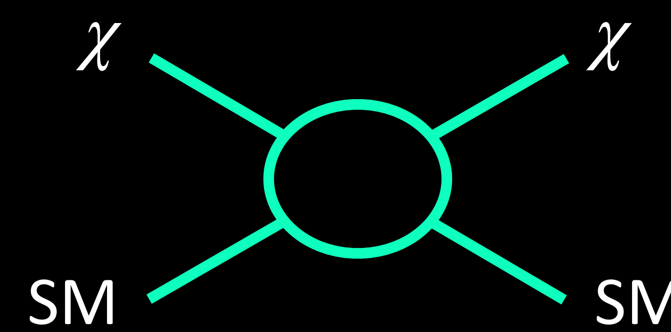
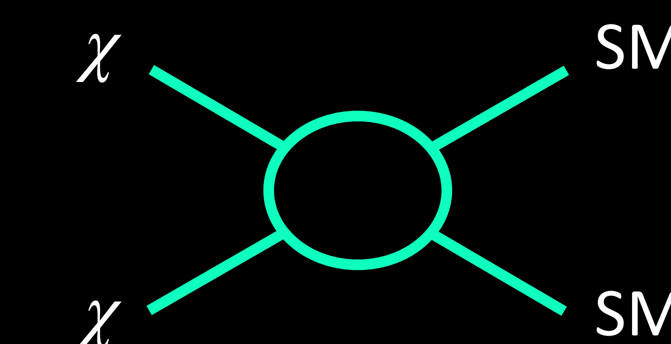
Dark matter heating



1. Capture



2. Annihilation



Sensitive to DM abundance ✓

Maximum injection for a non-depleting abundance: annihilation equilibrium

Dark matter heating

- Typically relevant for celestial objects without nuclear burning

- Sensitive to DM abundance ✓

Type of DM	signal	mass range	coupling range
DM with scattering and annihilation processes	Stars and planets overheating, or producing gamma rays/neutrinos	$\gtrsim \mathcal{O}(\text{keV})$ (depending on object and particle model)	$\sigma_{n\chi} \gtrsim 10^{-47}\ \text{cm}^2$ (depending on object and particle model)
DM mixing with neutrons	NS overheating	$\lesssim 1.5$ GeV	$10^{-17} \leq \epsilon_{nn'}/\text{eV} \leq 10^{-9}$

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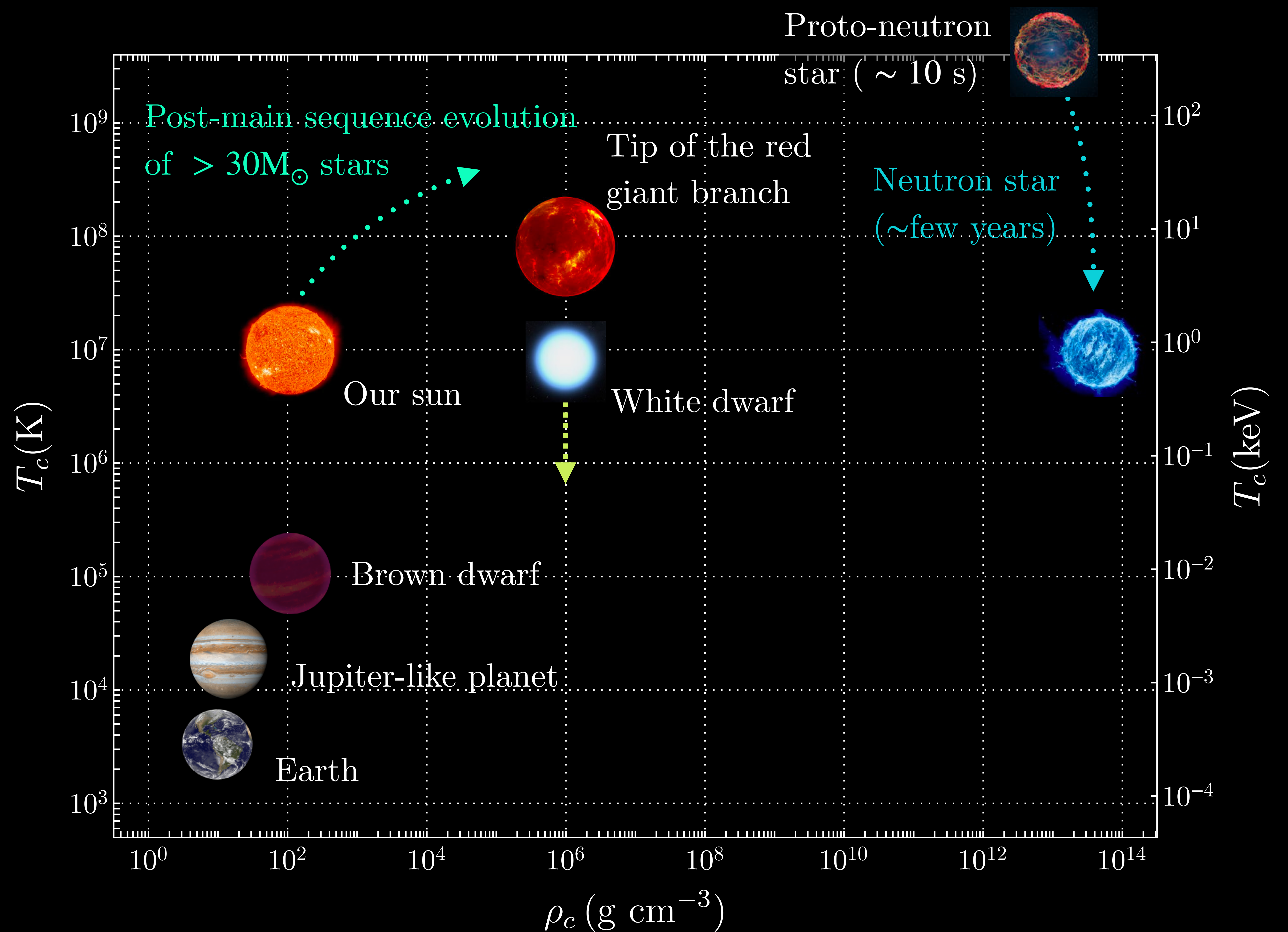
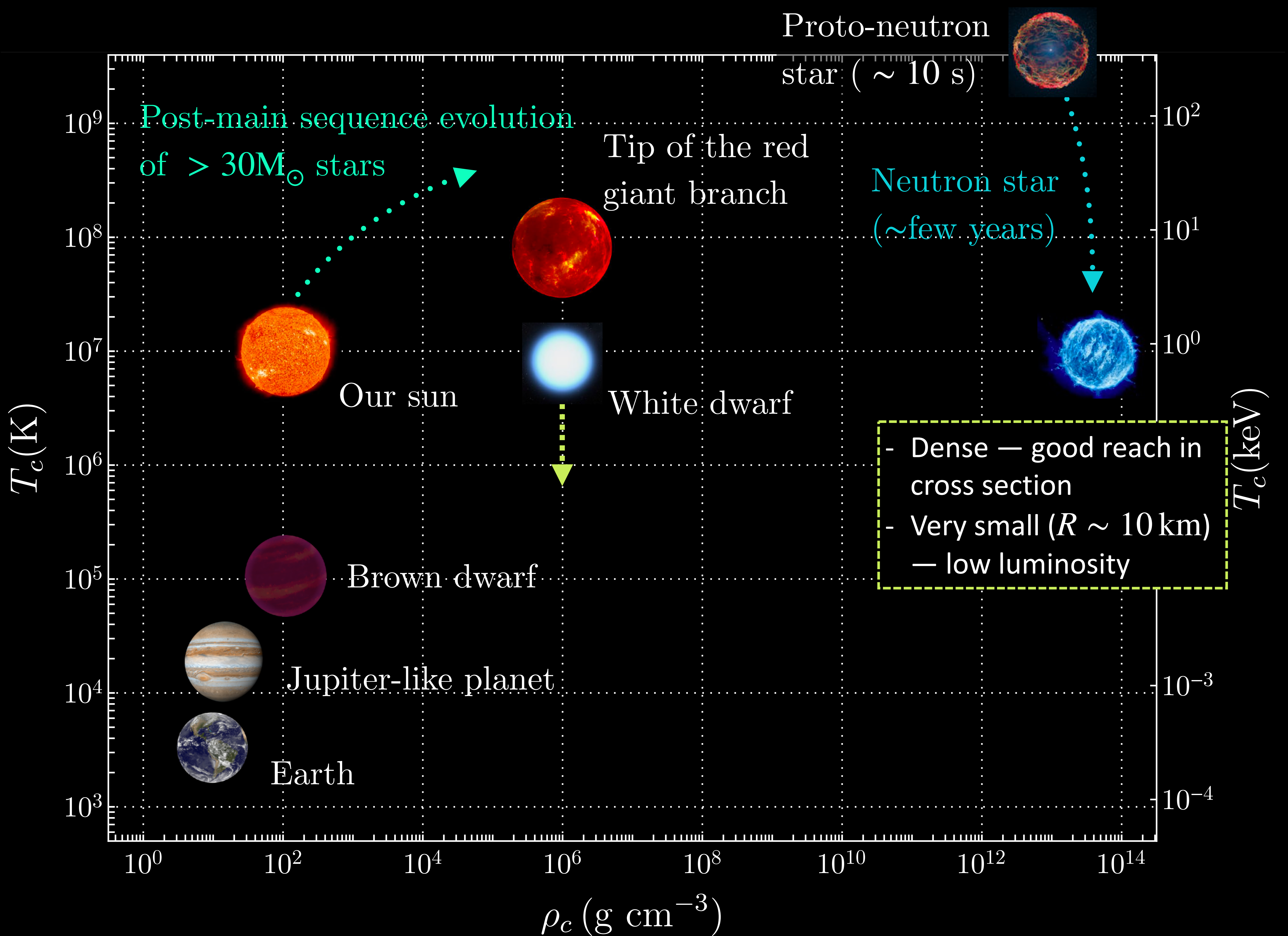
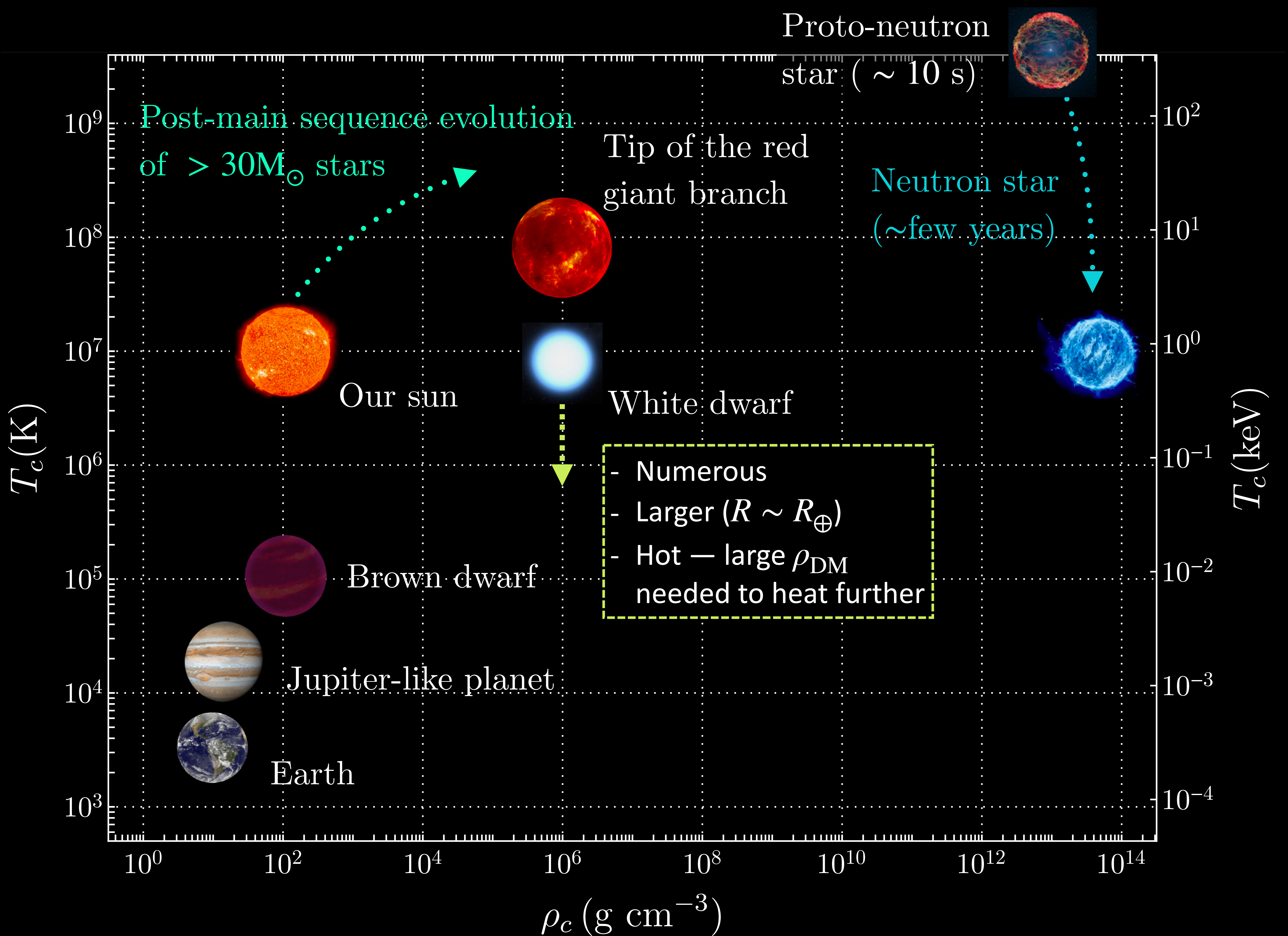

Proto-neutron star (~ 10 s)
Post-main sequence evolution of > 30M$_\odot$ stars
Tip of the red giant branch
Neutron star (~few years)
Our sun
White dwarf
Brown dwarf
Jupiter-like planet
Earth
T_c(K)
T_c(keV)
ρ_c (g cm^{-3})
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}



Proto-neutron star (~ 10 s)
Post-main sequence evolution of > 30M⊙ stars
Tip of the red giant branch
Neutron star (~few years)
Our sun
White dwarf
- Dense — good reach in cross section
- Very small (R ~ 10 km) — low luminosity
Brown dwarf
Jupiter-like planet
Earth
T_c(K)
T_c(keV)
ρ_c (g cm^{-3})
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-3}
10^{-4}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}



Proto-neutron star (~ 10 s)
Post-main sequence evolution of > 30$M_\odot$ stars
Tip of the red giant branch
Neutron star (~few years)
Our sun
White dwarf
- Numerous
- Larger ($R \sim R_\oplus$)
- Hot — large ρ_{DM} needed to heat further
Brown dwarf
Jupiter-like planet
Earth
T_c(K)
T_c(keV)
ρ_c (g cm^{-3})
10^3 10^4 10^5 10^6 10^7 10^8 10^9
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2
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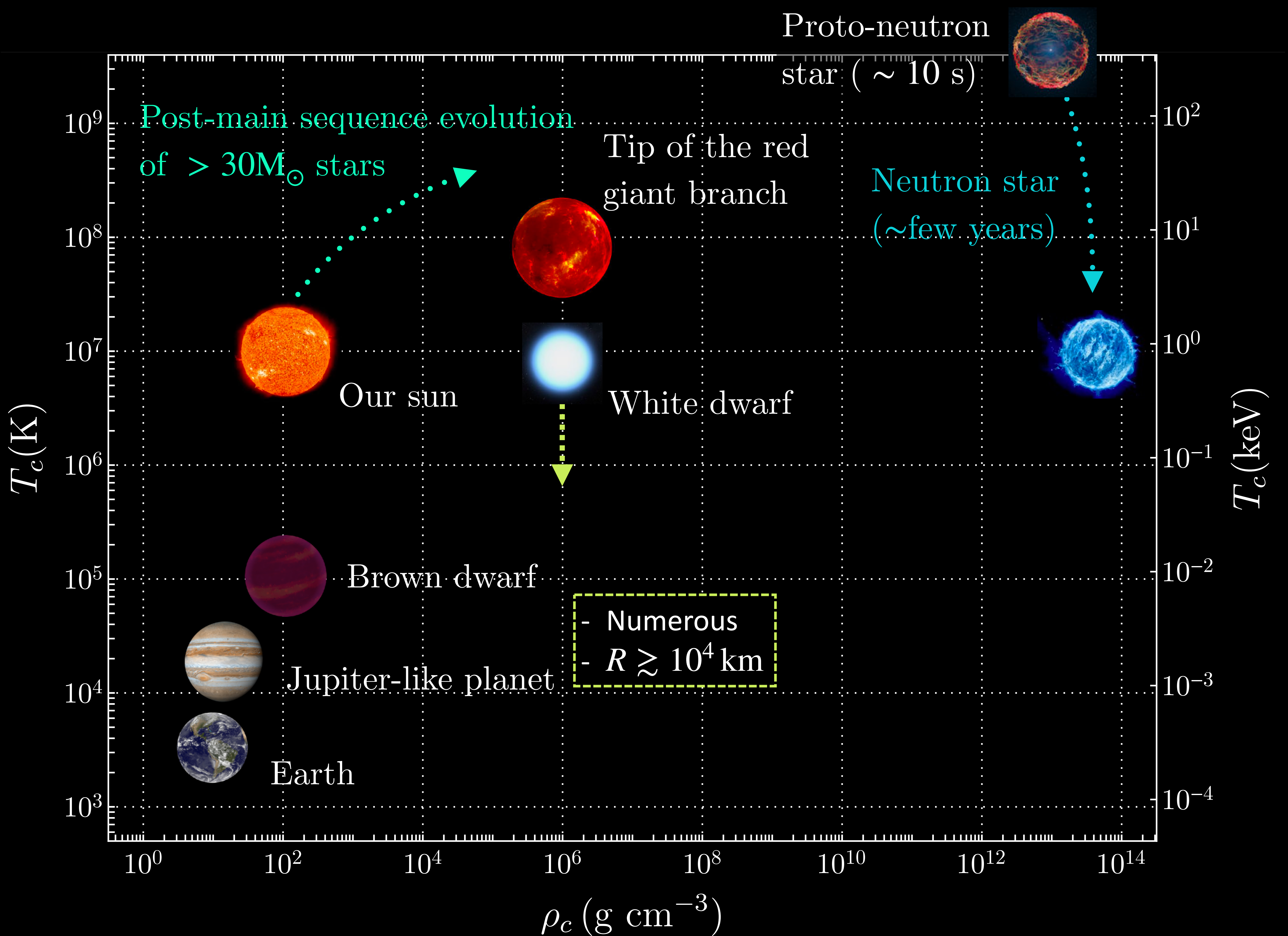

Proto-neutron star (~ 10 s)
Post-main sequence evolution of > 30M⊙ stars
Tip of the red giant branch
Neutron star (~few years)
Our sun
White dwarf
Brown dwarf
- Numerous
- $R \gtrsim 10^4$ km
Jupiter-like planet
Earth
T_c(K)
T_c(keV)
ρ_c (g cm^{-3})
10^3 10^4 10^5 10^6 10^7 10^8 10^9
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2
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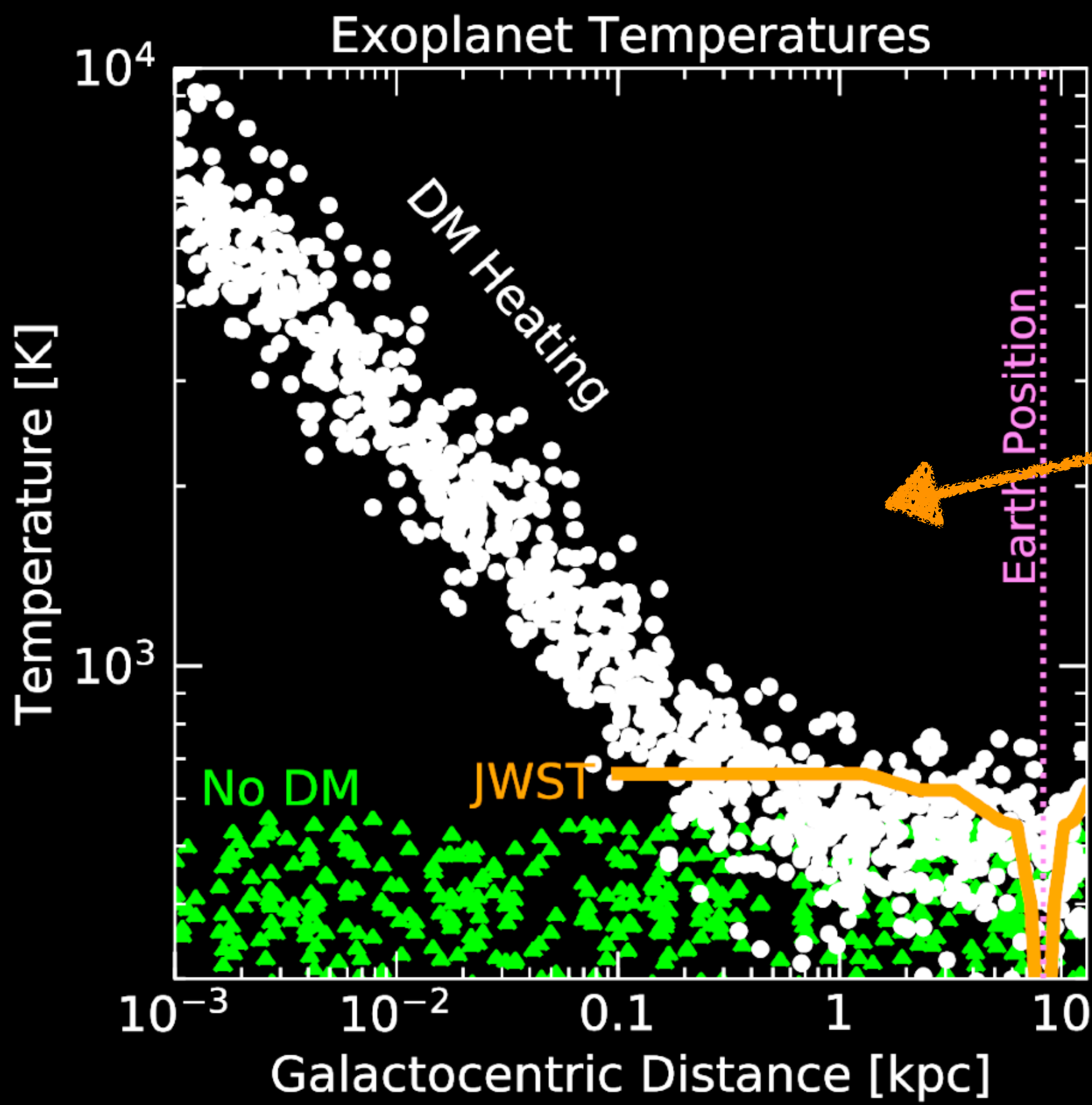
Exoplanet heating



- First be identified by e.g. Doppler spectroscopy or gravitational lensing
- Infrared telescopes (such as JWST) may be able to measure their temperature

Assumption: annihilation equilibrium

Leane and Smirnov, PRD, arXiv:2010.00015

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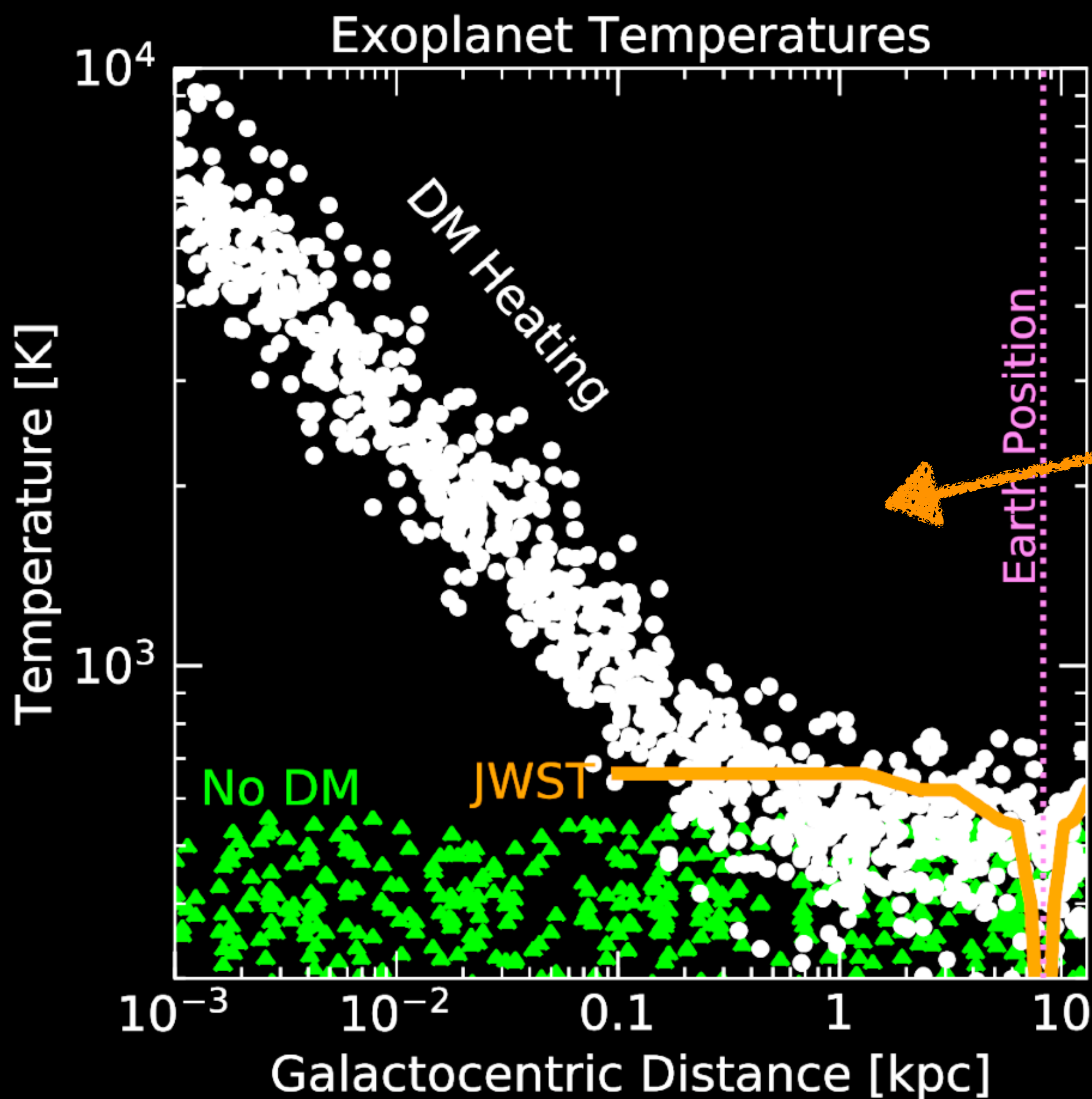

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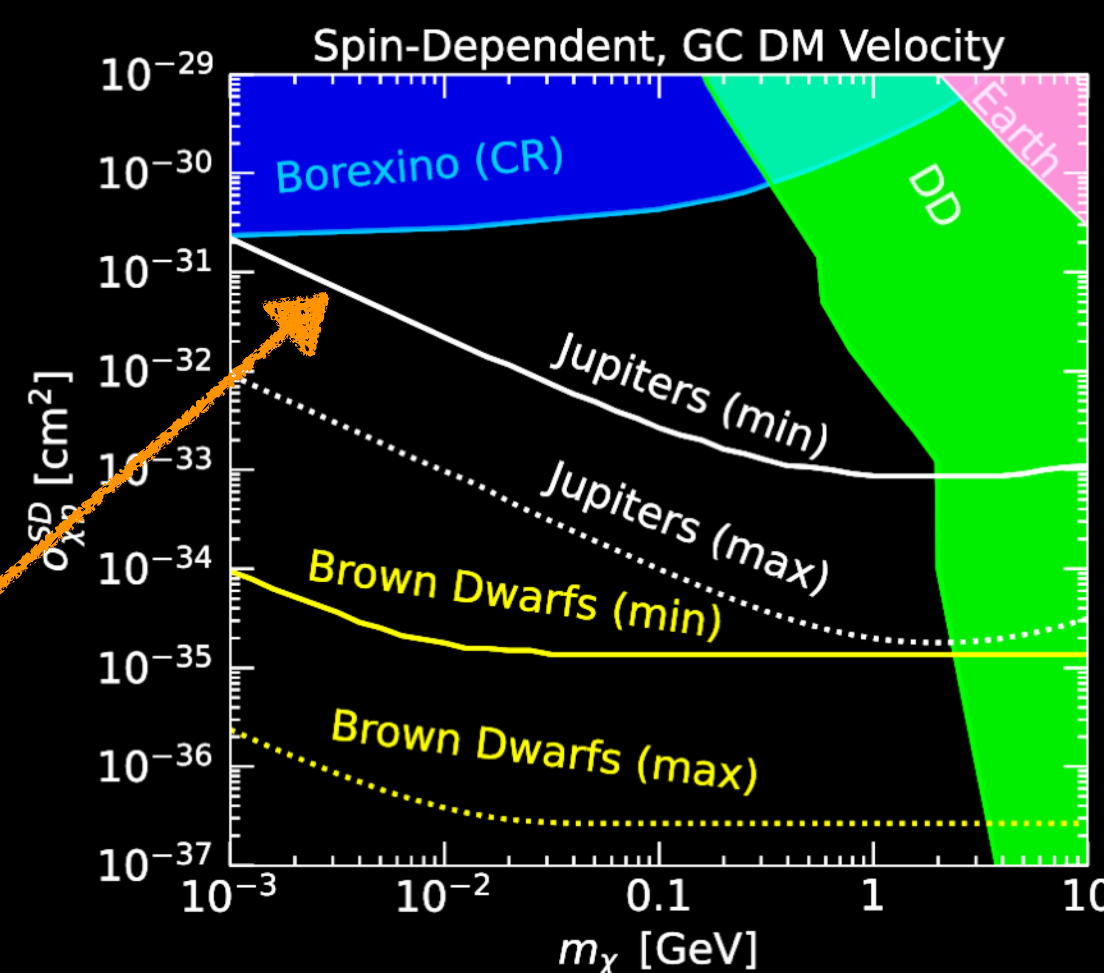

all DM captured

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Formation of Jovian planets

... a sensitive process

"If we could not see Jupiter with our own eyes, we might not believe that such a planet could exist anywhere."

Rob Field, lecture on the formation of Jupiter

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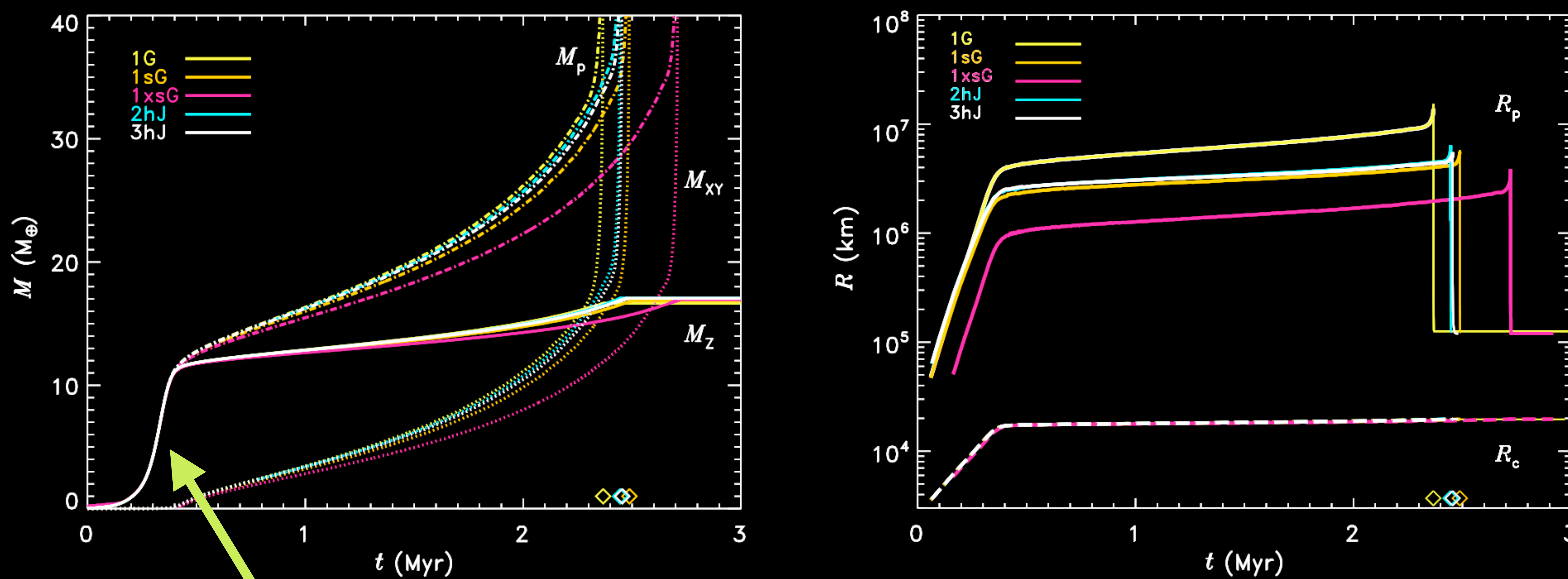
(Jupiter had less than ten million years to capture all of its gas because the Sun expelled most of the gas in the solar system shortly after thermonuclear fusion was initiated in its core)

Rob Field, lecture on the formation of Jupiter

Formation of Jovian planets

Core accretion gas capture theory

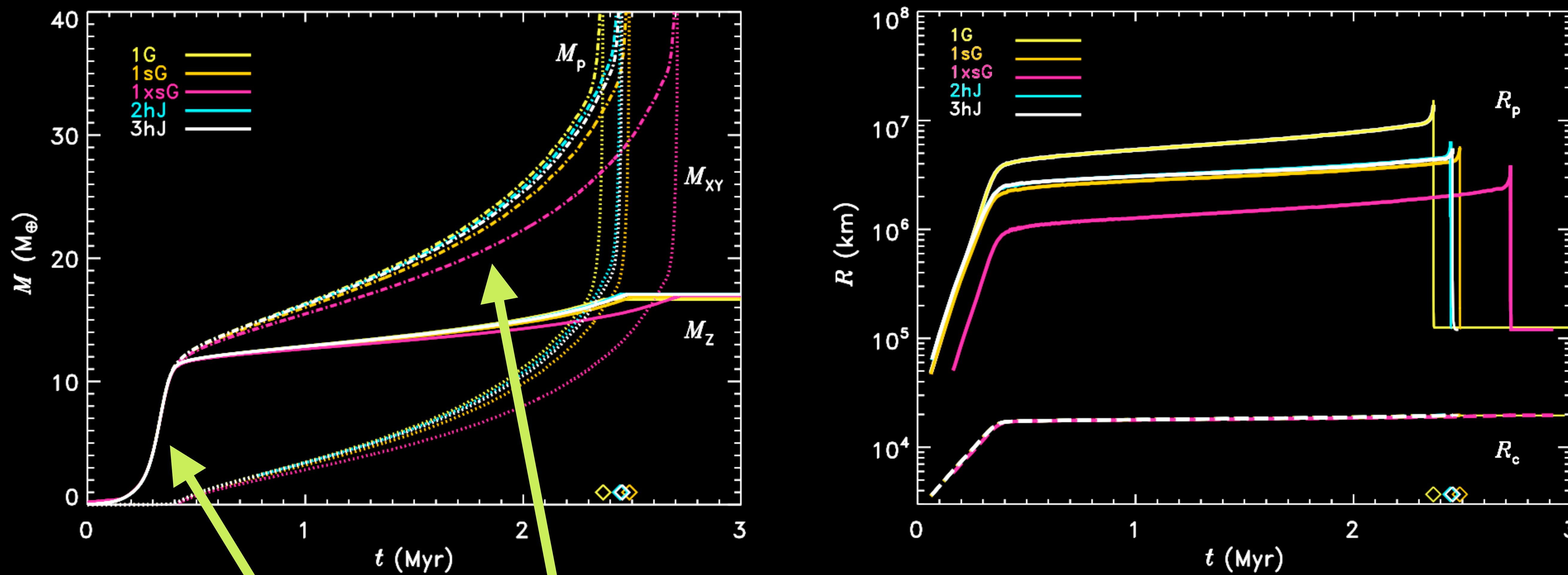


1. Core accretion

Lissauer et al, Icarus 199, arXiv:0810.5186

Formation of Jovian planets

Core accretion gas capture theory



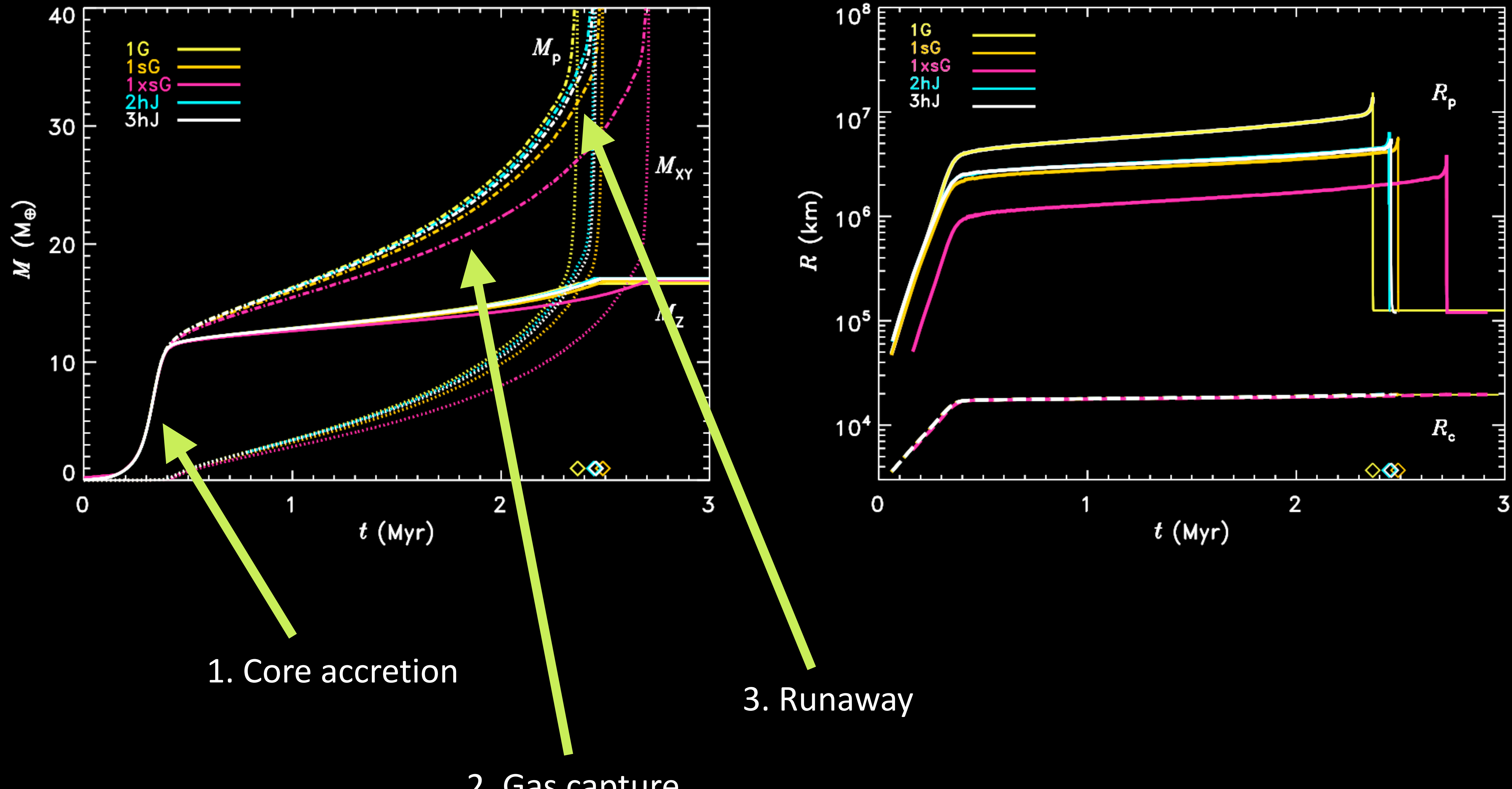
1. Core accretion

2. Gas capture

Lissauer et al, Icarus 199, arXiv:0810.5186

Formation of Jovian planets

Core accretion gas capture theory



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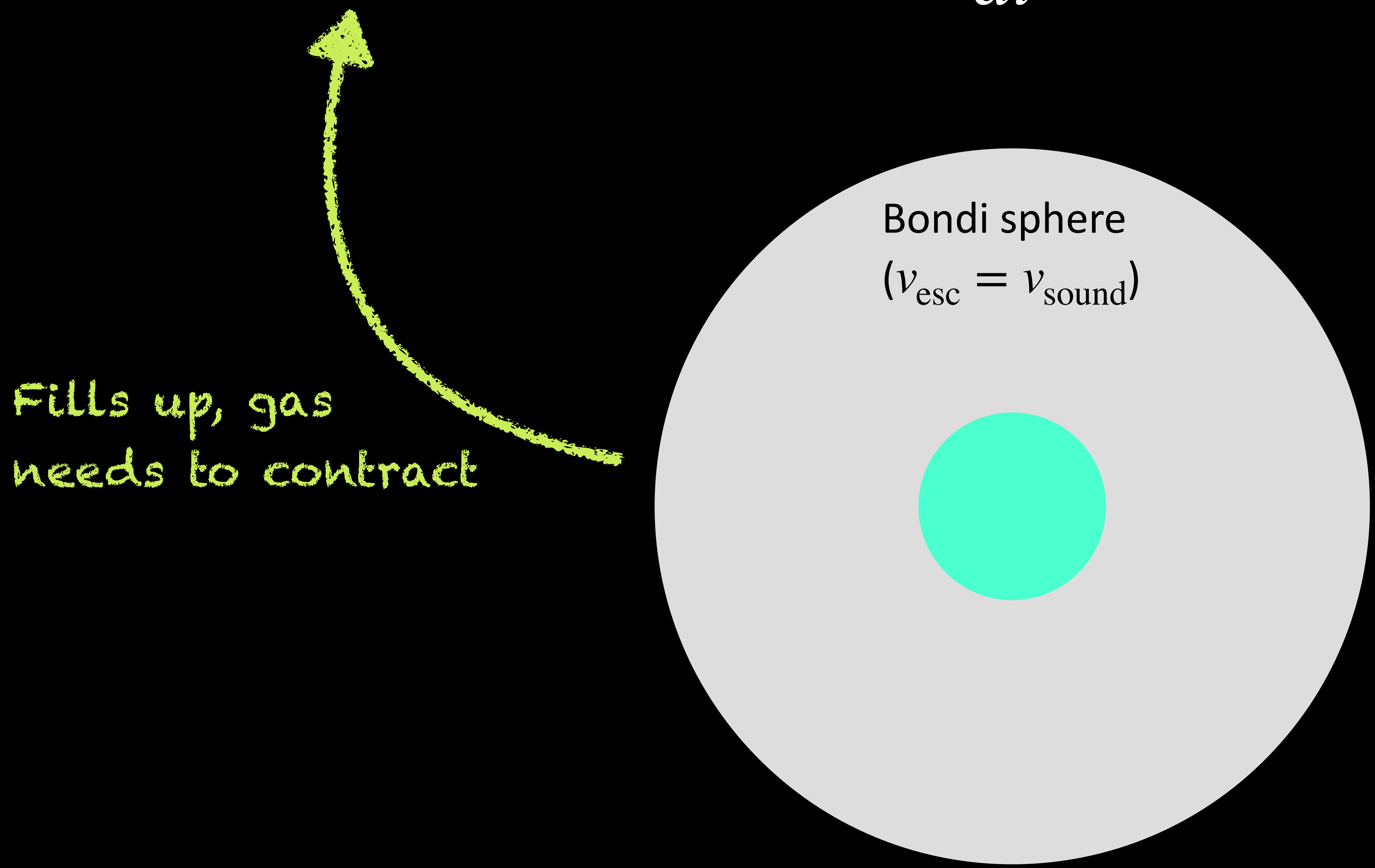
Formation of Jovian planets

- Kelvin-Helmholtz contraction: $\dot{Q} = -\frac{dU}{dt}$



Formation of Jovian planets with DM

- Kelvin-Helmholtz contraction: $\dot{Q} - L_{\mathrm{DM}}(R) = -\frac{dU}{dt}$

$$4\pi R^2 \times \sigma_{\mathrm{SB}} T^4 - L_{\mathrm{DM}}(R) = c_1 \frac{GM^2}{R^2} \frac{dR}{dt}$$

Proto-planet will have to heat up more to radiate enough energy to contract

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Proto-planet will have to heat up more to radiate enough energy to contract

- But… the envelope is made up of light elements which can evaporate

A maximum temperature

Flux of escaping particles:

$$\Gamma_J(T) = \frac{nv}{2\sqrt{\pi}}\left(1 + \frac{v_{\rm esc}^2}{v^2}\right)\exp\left(-\frac{v_{\rm esc}^2}{v^2}\right)\Bigg|_T$$

$$v = \sqrt{2T/m}$$

Jeans, the dynamical theory of gases

A maximum temperature

Flux of escaping particles:

Conservative assumption: $C = 10$

$$\Gamma_\mathrm{J}(T) = \frac{nv}{2\sqrt{\pi}}\left(1 + \frac{v_\mathrm{esc}^2}{v^2}\right)\exp\left(-\frac{v_\mathrm{esc}^2}{v^2}\right)\Bigg|_{T=T_\mathrm{max}} = C\dot{M}$$

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Growth of the planet
in the absence of DM heat

e.g. Lissauer et al, Icarus 199, arXiv:0810.5186
d'Angelo et al, Icarus 355, arXiv:2009.05575

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→ for $^1\mathrm{H}$,

- In the core $T_{\max} \sim 10^3\,\mathrm{K}$
- In the envelope, $T_{\max} \sim 8\,\mathrm{K}$

Dark matter halts accretion

- Then, DM can halt accretion for injections with

$$L_{\mathrm{DM}} \geq 4\pi R^2 \sigma T_{\mathrm{max}}^4$$

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$$\geq 4 \times 10^{-8} \times \left(\frac{R}{10^3 R_p}\right)^2 \left(\frac{T_{\rm max}}{8{\rm K}}\right)^4 {\rm L}_\odot$$

Can we expect such injections to be reached?

Dark matter halts accretion

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- In capture-annihilation equilibrium,

$$L_{\rm DM} = m_{\rm DM} C_{\rm cap}$$

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- In capture-annihilation equilibrium,

$$L_{\rm DM} = m_{\rm DM} C_{\rm cap} = m_{\rm DM} f_{\rm cap} \Phi$$

$$\Phi = v_{\rm DM}\sqrt{\frac{8}{3\pi}}\frac{\rho_{\rm DM}}{m_{\rm DM}}\left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{v_{\rm DM}^2}\right)$$

$$\sim 2 \times 10^{-9} f_{\rm cap} \left(\frac{R}{10^3 R_p}\right)\left(\frac{M}{10 M_\oplus}\right)\left(\frac{v_{\rm DM}}{270{\rm km\,s^{-1}}}\right)^{-1}\left(\frac{\rho_{\rm DM}}{0.42\,{\rm GeV\,cm^{-3}}}\right) L_\odot$$

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Capture-annihilation equilibrium

- Boltzmann equation: $\frac{dN}{dt} = C_{\rm cap} - C_{\rm ann} N_\chi^2$

$$C_{\rm ann} = \langle \sigma_{\rm ann} v \rangle / V_{\rm eff} = \langle \sigma_{\rm ann} v \rangle \frac{\int_V n_\chi^2}{\int_V n_\chi}$$

Capture-annihilation equilibrium

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$$C_{\text{ann}} = \langle \sigma_{\text{ann}} v \rangle / V_{\text{eff}} = \langle \sigma_{\text{ann}} v \rangle \frac{\int_V n_\chi^2}{\int_V n_\chi}$$

- In capture-annihilation equilibrium, $N_\chi \sim \sqrt{C_{\text{cap}}/C_{\text{ann}}}$, reached after

$$\tau \sim (C_{\text{cap}} C_{\text{ann}})^{-1/2} \approx \sqrt{\frac{m_\chi}{\text{GeV}} \frac{10^{-30}\text{cm}^3/\text{s}}{\langle \sigma_{\text{ann}} v \rangle}} \text{Myr}$$

The capture fraction

- Spin-independent: $\sigma_{\mathrm{SI}} = \sigma_{\chi N}^{\mathrm{SI}} A^2 \left(\frac{\mu(m_\chi, m_A)}{\mu(m_\chi, m_N)} \right)^2$

Reduced mass

Atomic number

The capture fraction

- Spin-independent: $\sigma_{\mathrm{SI}} = \sigma_{\chi N}^{\mathrm{SI}} A^2 \left(\frac{\mu(m_\chi, m_A)}{\mu(m_\chi, m_N)} \right)^2$
- Spin-dependent:

$$\sigma_{SD} = \sigma_{\chi N}^{\mathrm{SD}} \frac{4\left(J_A + 1\right)}{3J_A} \left[a_p \langle S_p \rangle + a_n \langle S_n \rangle \right]^2 \left(\frac{\mu(m_\chi, m_A)}{\mu(m_\chi, m_N)} \right)^2$$

Nuclear spin

Average proton, neutron spin

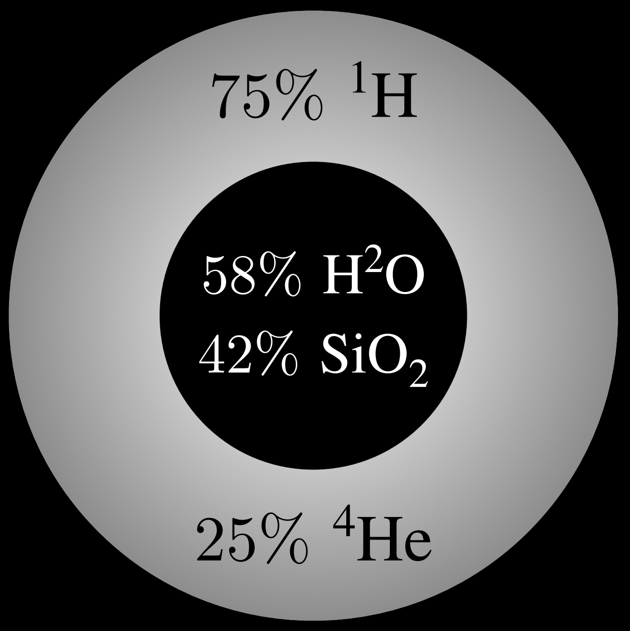
The capture fraction

- Spin-independent: $\sigma_{\rm SI} = \sigma_{\chi N}^{\rm SI} A^2 \left(\frac{\mu(m_\chi, m_A)}{\mu(m_\chi, m_N)} \right)^2$
- Spin-dependent:

$$\sigma_{SD} = \sigma_{\chi N}^{\rm SD} \frac{4\left(J_A+1\right)}{3J_A} \left[a_p \langle S_p \rangle + a_n \langle S_n \rangle \right]^2 \left(\frac{\mu(m_\chi, m_A)}{\mu(m_\chi, m_N)} \right)^2$$

$a_p = 1, a_n = 0$

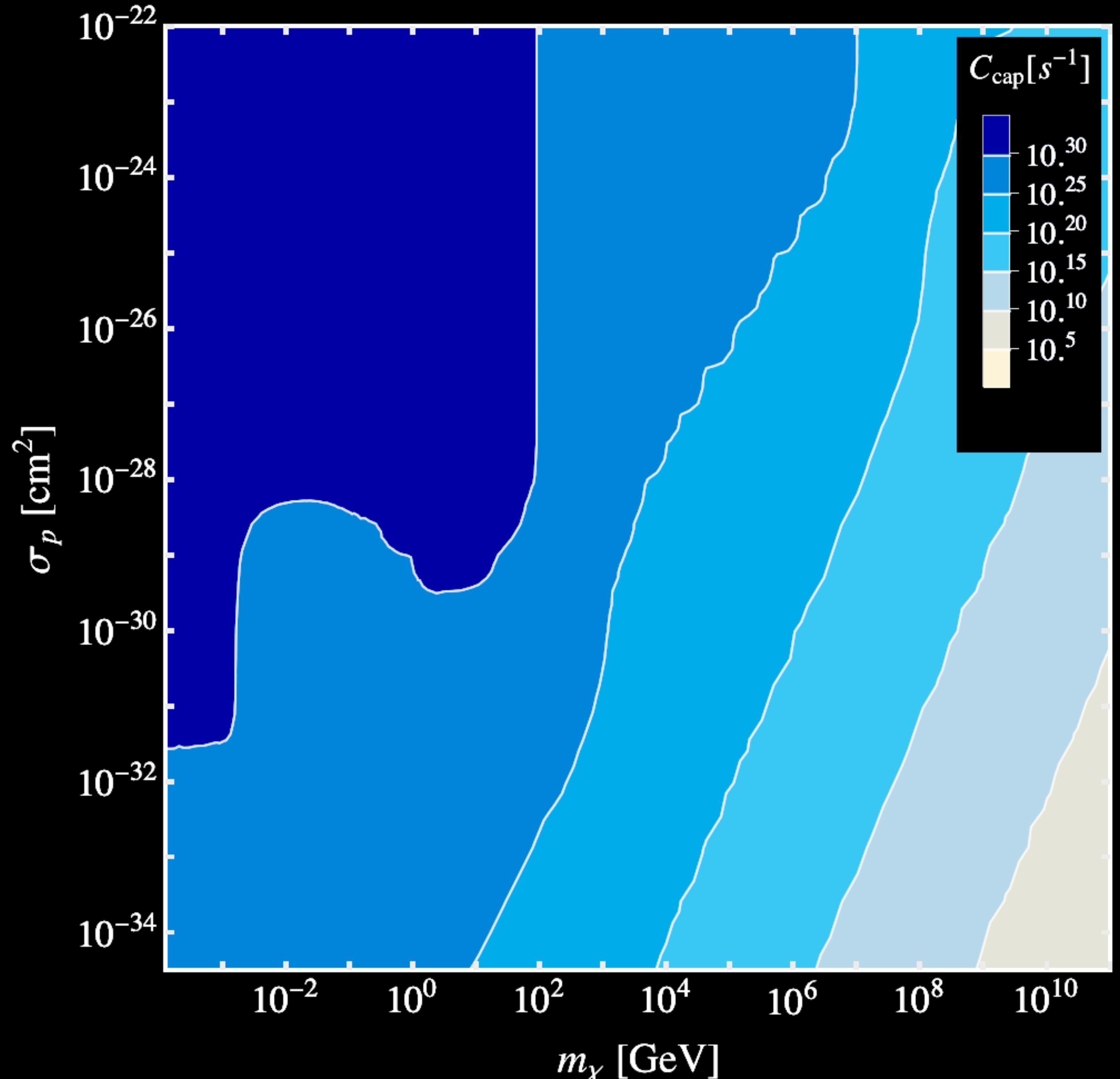
Isotopes	^{17}**O**	^{29}**Si**	^{1}**H**
Abundance [%]	~ 0.4	~ 4.7	~ 100
J	5/2	1/2	1/2
$\langle S_p \rangle$	-0.036	0.054	0.5
$\langle S_n \rangle$	0.508	0.204	0



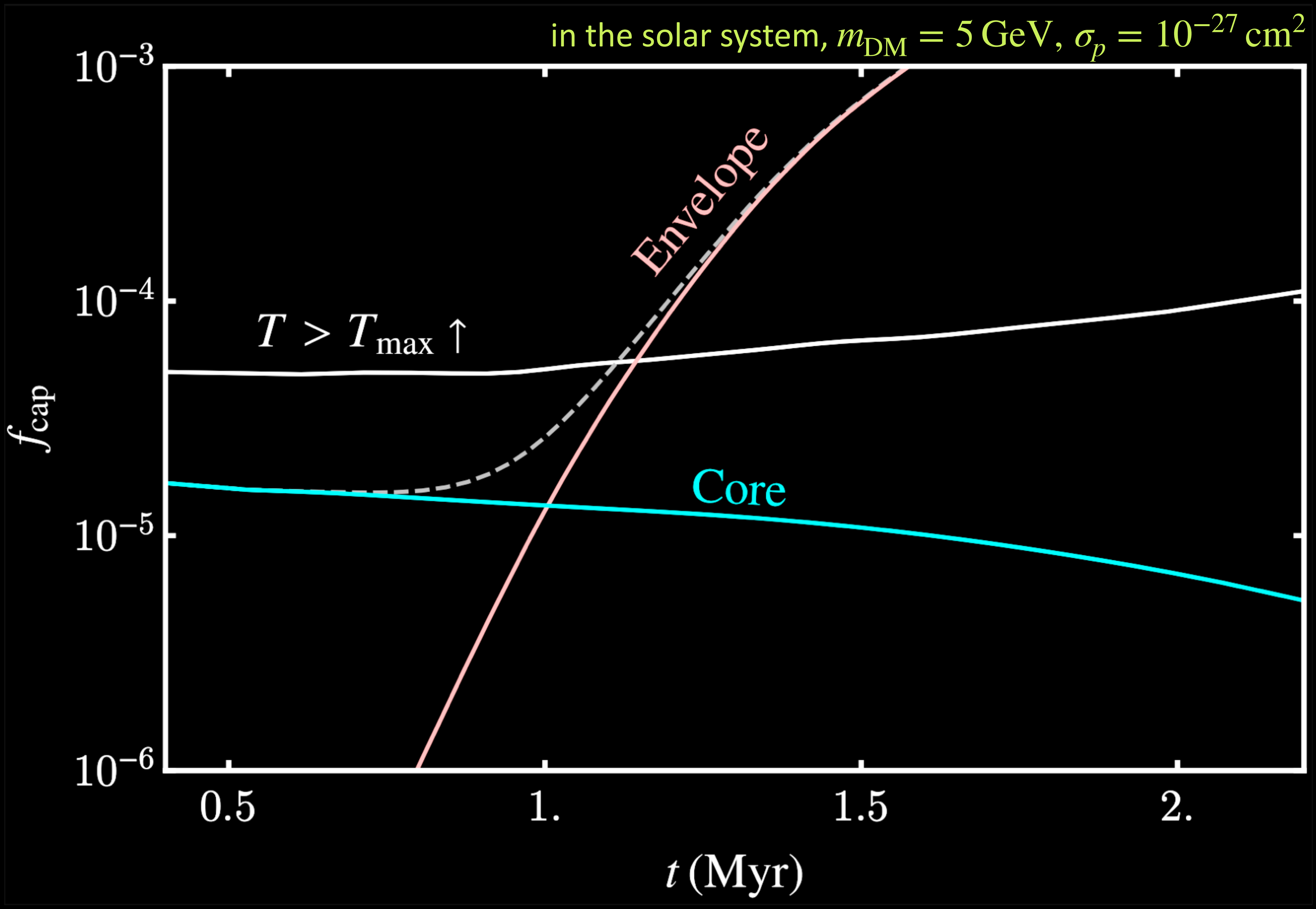
e.g. d'Angelo et al, Icarus 355, arXiv:2009.05575

The capture fraction

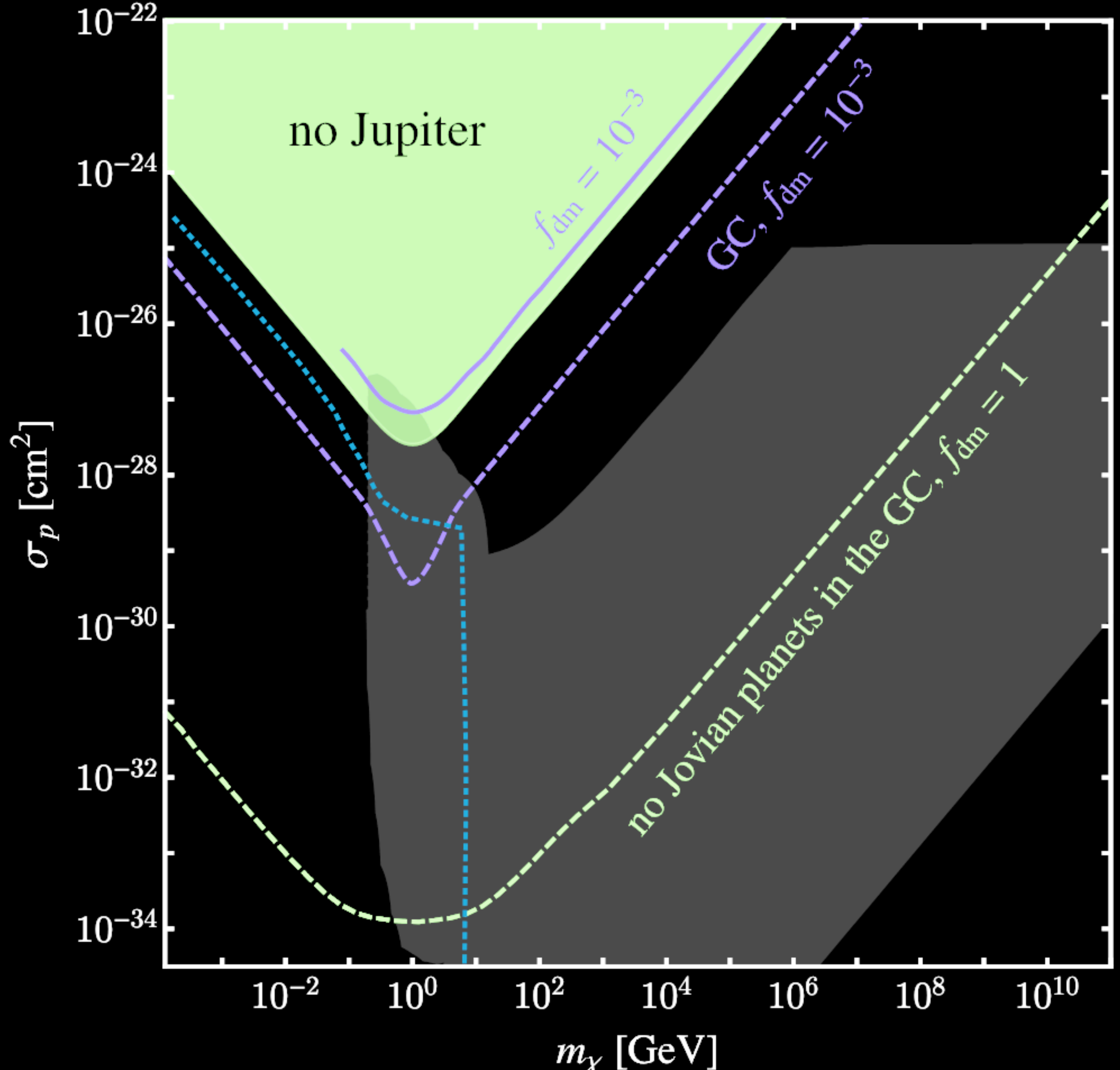
Spin-dependent example



Formation of Jovian planets



Constraints: spin-dependent DM



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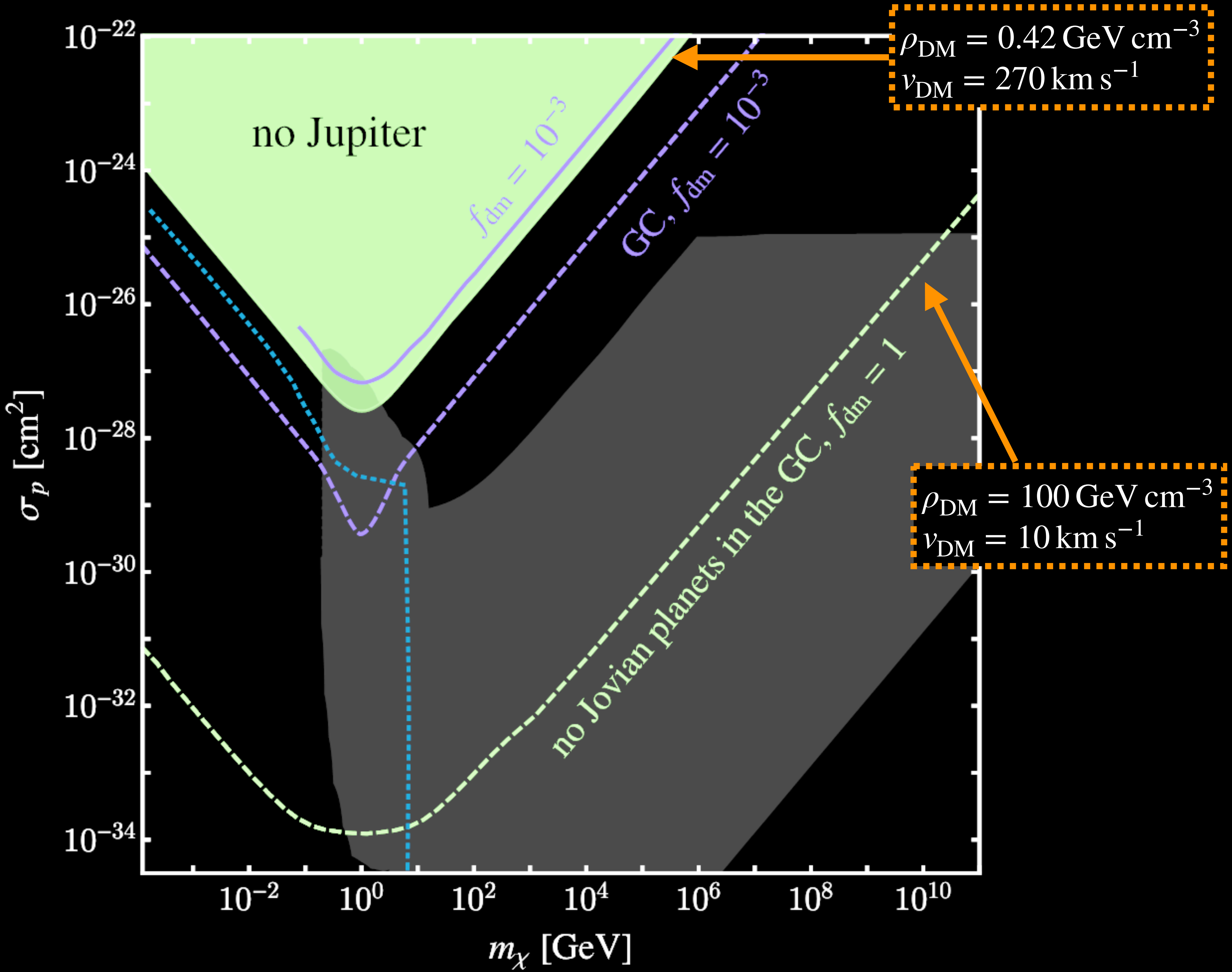

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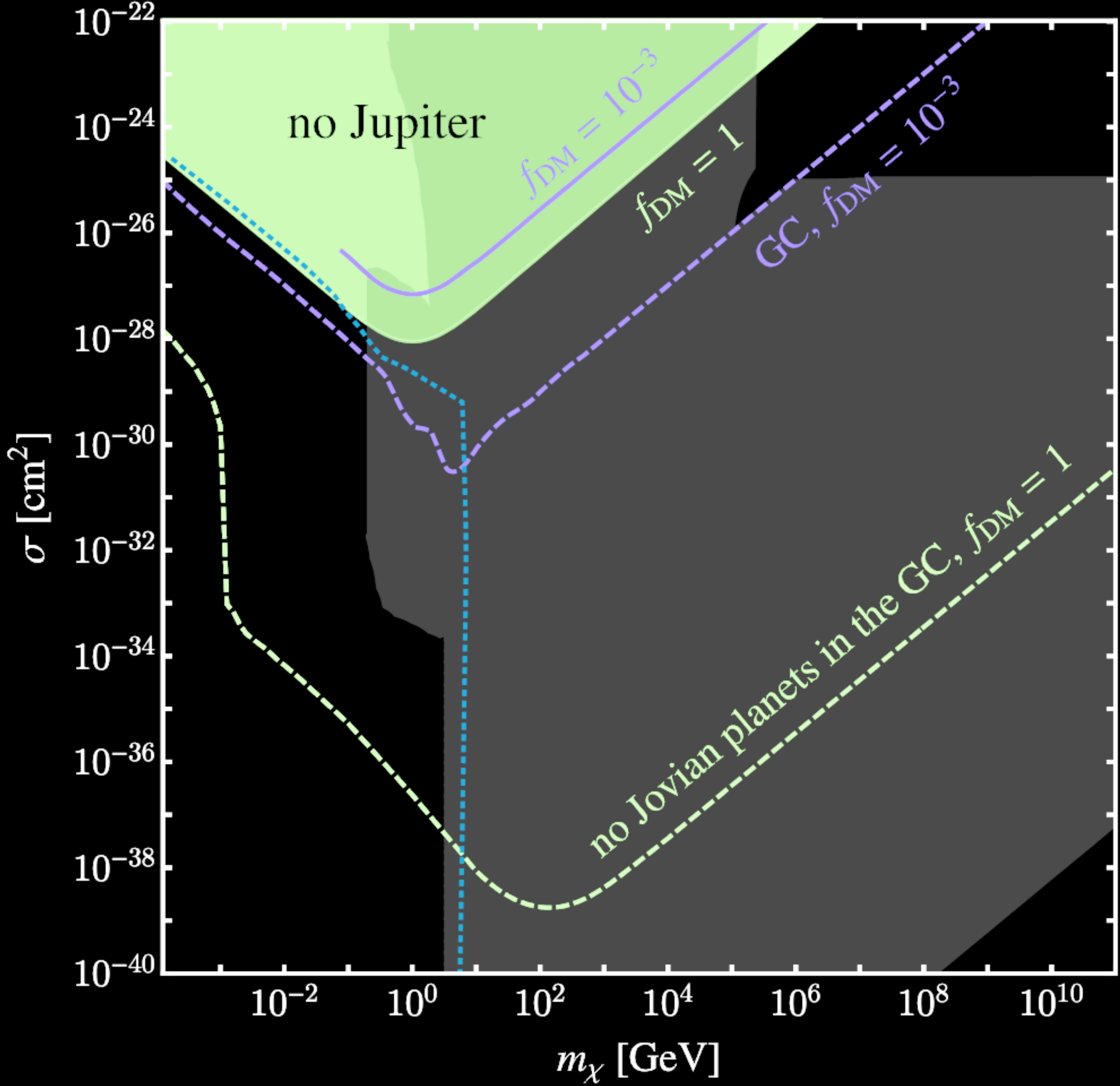
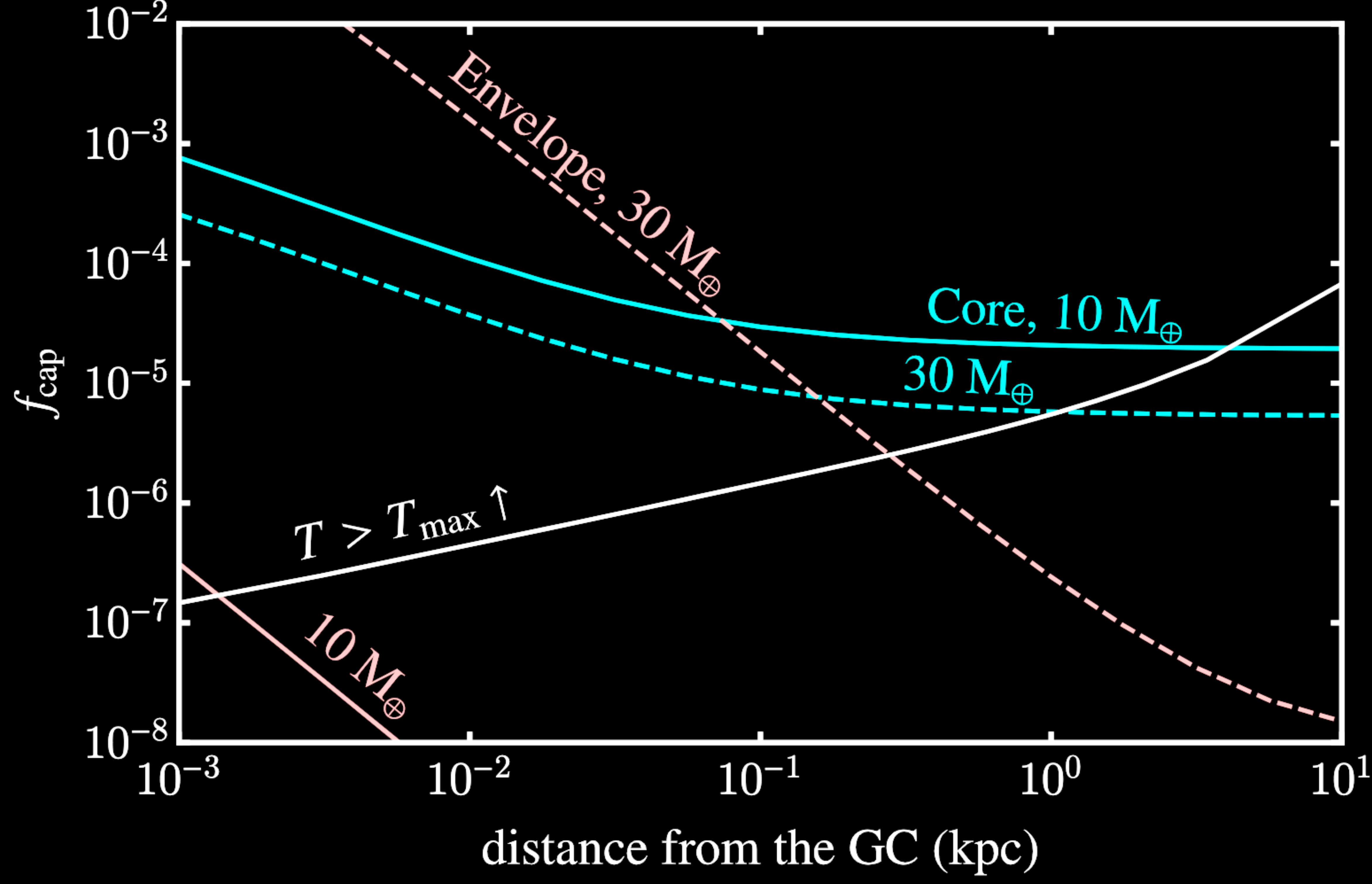


Variation with distance from the GC



To conclude

- The formation of Jovian planets is very sensitive to extra heat sources
- (Relatively) strongly interacting dark matter may disrupt this formation at the onset of gas accretion, or at some point during its growth
  - The existence of Jupiter in our solar system can be used to constraint dark matter
  - Observations of Jovian planets in the Galactic Center lead to even stronger constraints
- Future work: simulations + direct observation of planet formation in the presence of DM heating

Thank you!

…ask me anything you like!

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