Brown Dwarfs as Probes of the Particle Nature of Dark Matter: a Provocative Exploration

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Dark **M**atter Particle Landscape in a Nutshell

FDM fails to explain DM cores [2502.12030]

Macroscopic quantum effects
$m_{\mathrm{DM}} \gtrsim 10^{-22}$ eV

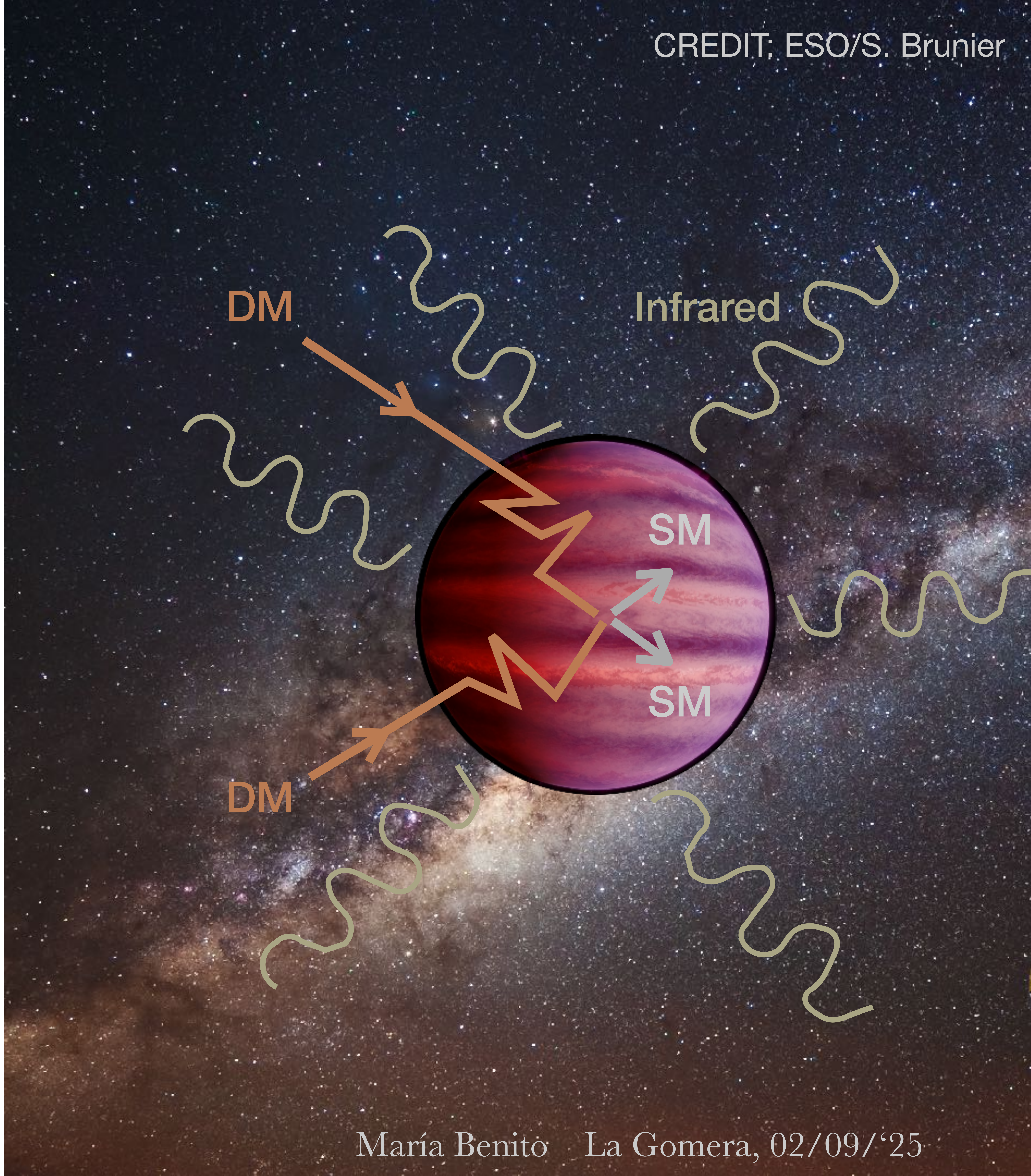
Brown Dwarfs (& Exoplanets) are new, excited and powerful detectors of DM

Leane & Smirnov [2010.00015]
Acevedo et al. [2405.02393]
Benito et al. [2405.09578]

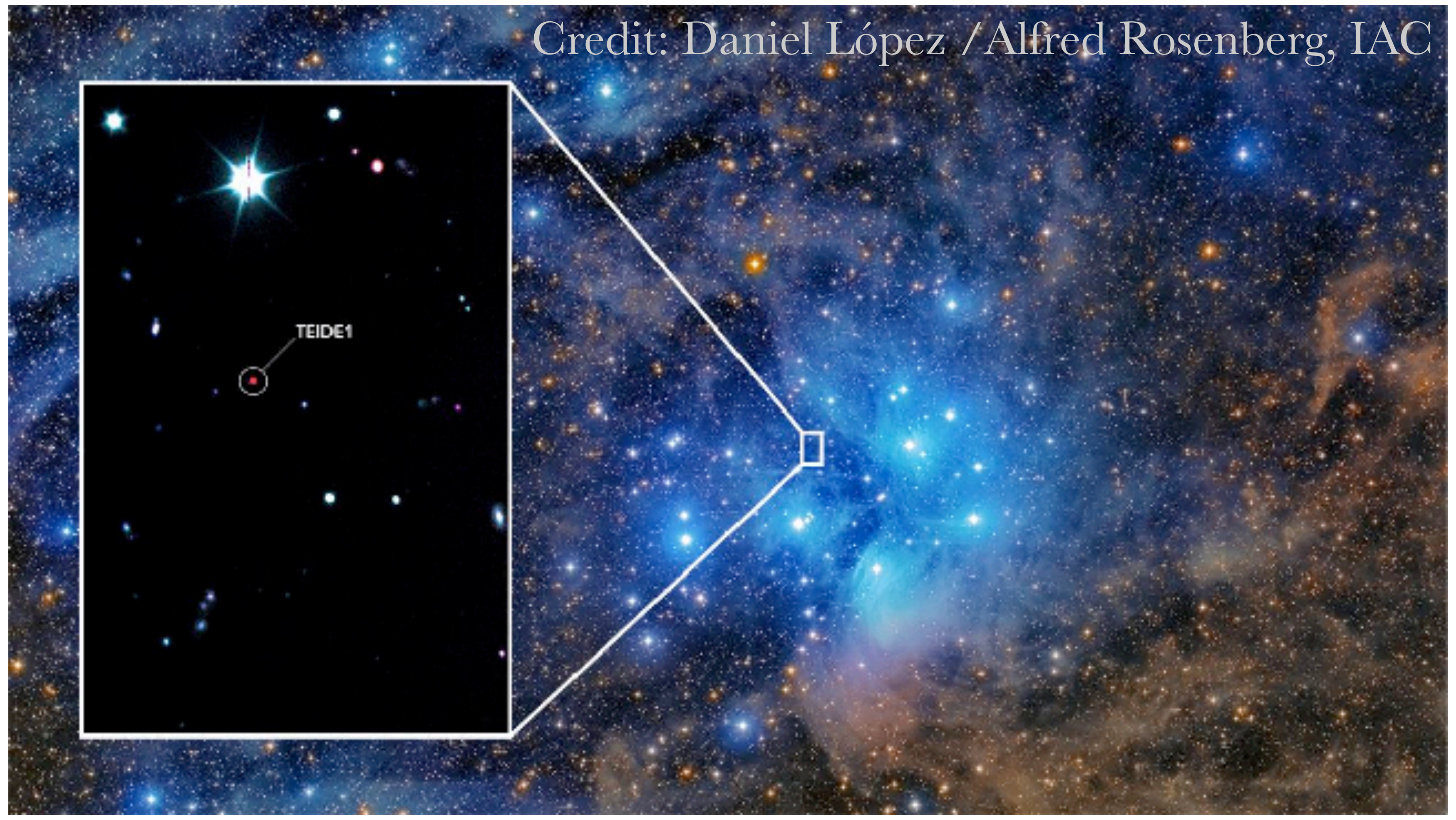
Must fit inside dwarf galaxies
$m_{\mathrm{DM}} \lesssim 10^{71}$ eV

Dark Matter capture in Brown Dwarfs

Exoplanets & BDs: Smirnov & Leane ’20
Neutron stars & white dwarfs: Garani, Genolini, Hambye ’18, Bell et al ’20
Sun: Press & Spergel ’85, Gould ’87, Nauenberg ’87, Busoni, De Simone & Huang ’13, Garani & Palomares-Ruiz ‘17
Earth: Gould ’87, Gould, Frieman & Freese ‘89
Solar system planets: Krauss, Srednicki & Wilczek ’86



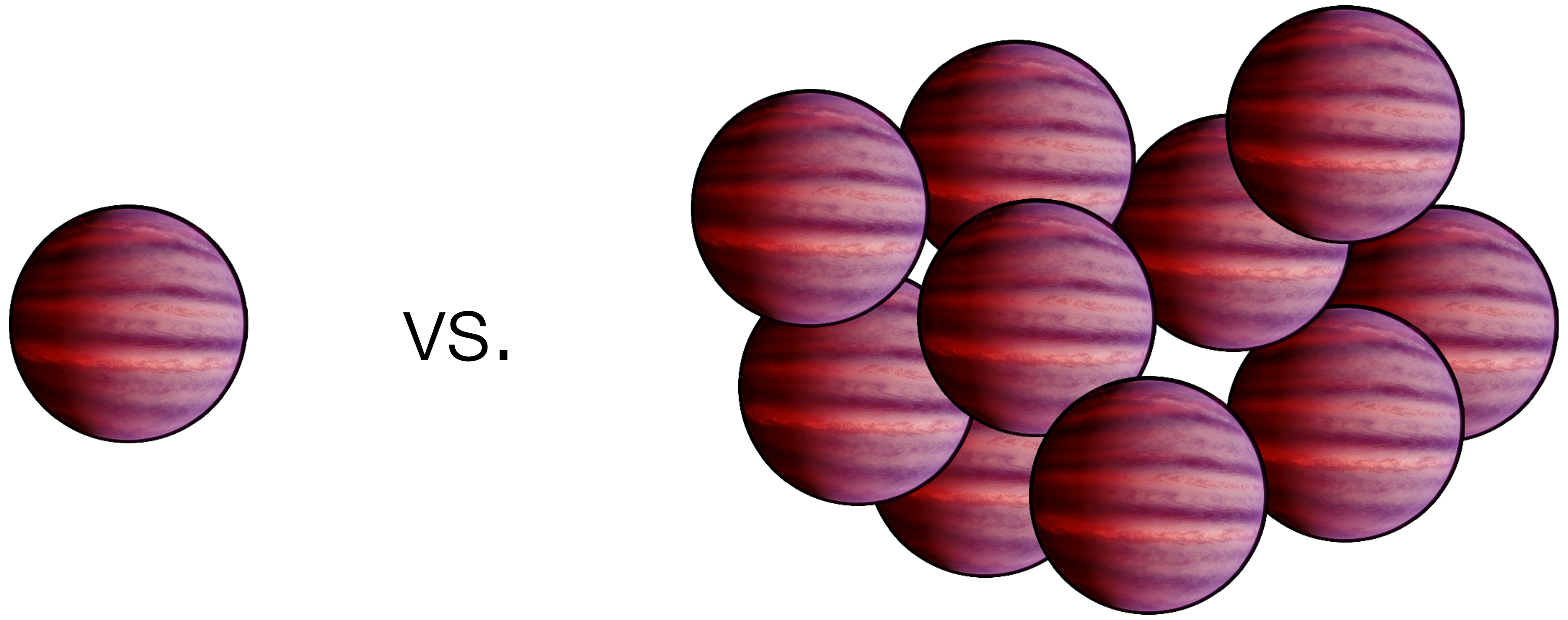
Why BDs?



Rebolo, Zapatero Osorio, Martín '95

➡ Promising field with thousands of BDs discovered and many upcoming telescopes and searches much beyond the Solar neighbourhood

➡ Tens of thousands of millions in our Galaxy, almost as many as the stars



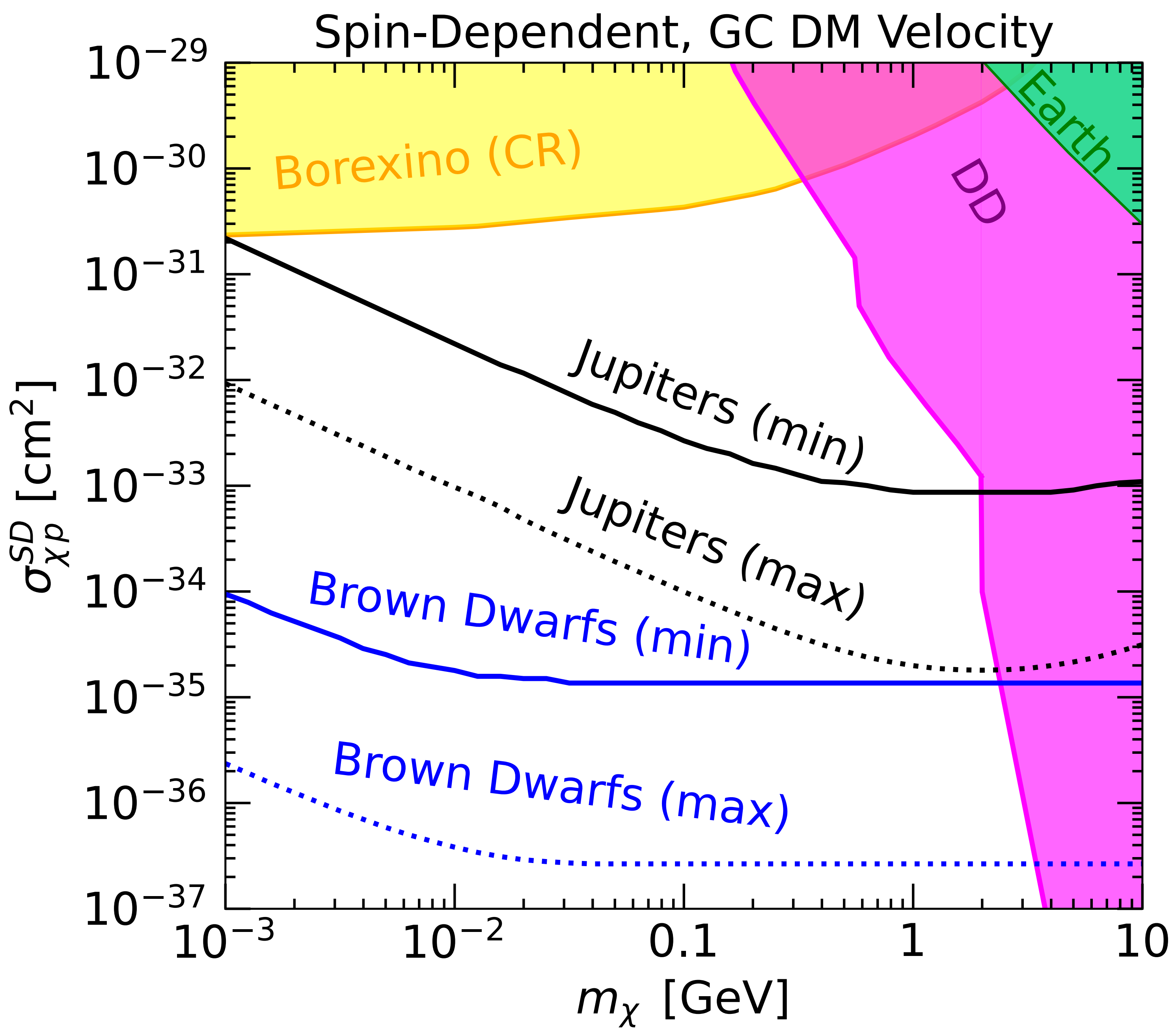
Is the anomalous signal due to DM or is it simply due to unknown systematics?

Why BDs?

➡ BDs Keep Their Cool

The lower the temperature of the celestial body, the clearer the DM signal

Sensitive to annihilating DM particles in sub-GeV & sub-MeV regimes (dependent on DM model)



Leane & Smirnov [2010.00015]
Acevedo et al. [2303.01516]

ATMO 2020 evolution model
Phillips et al [2003.13717]

What can we learn about Dark Matter with Brown Dwarfs?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Dark Matter halo parameters from overheated exoplanets via Bayesian hierarchical inference

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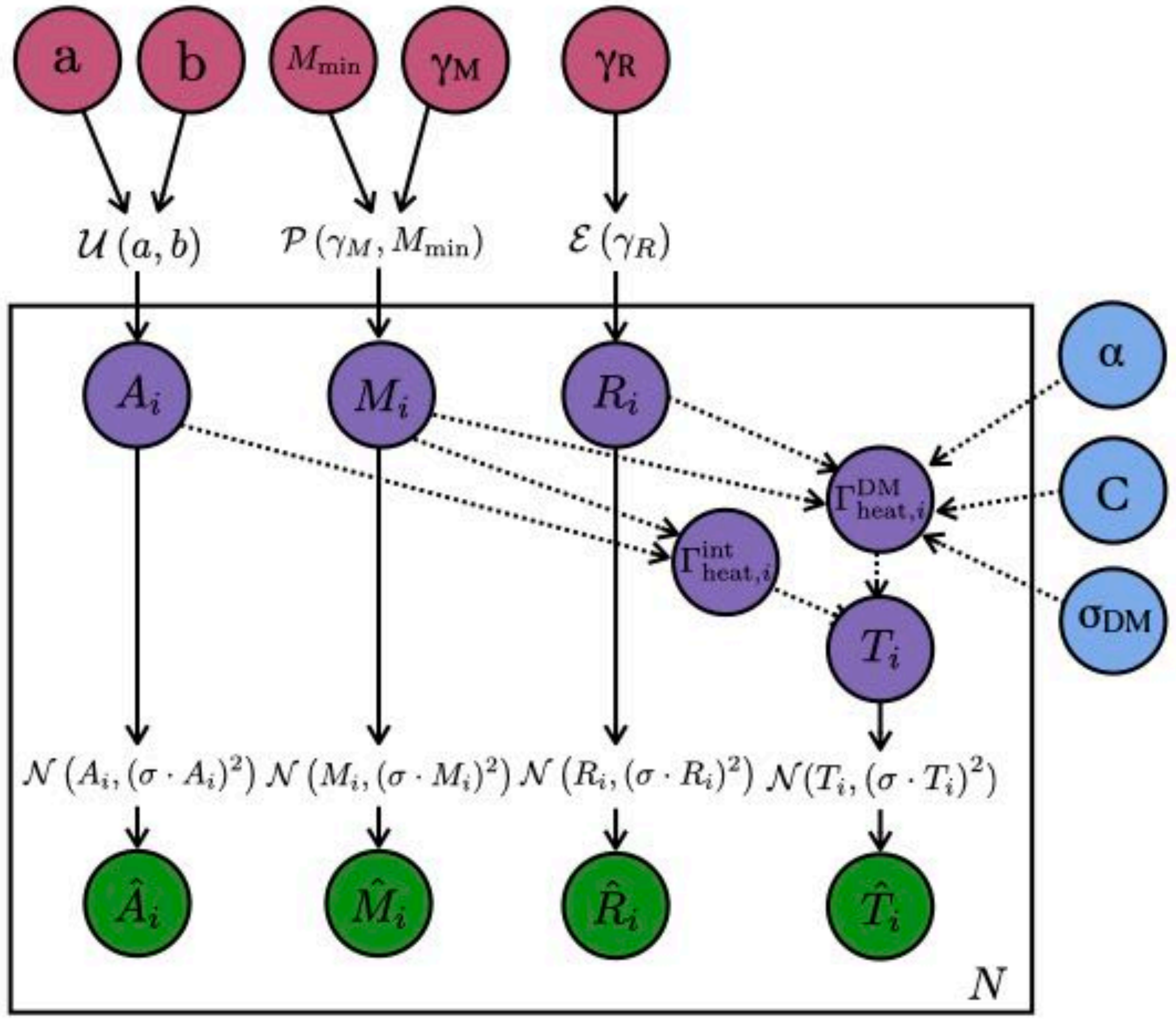
Bayesian **H**ierarchical **M**odel



➡ Population (hyper)parameters (age distribution, initial mass function, # density profile)

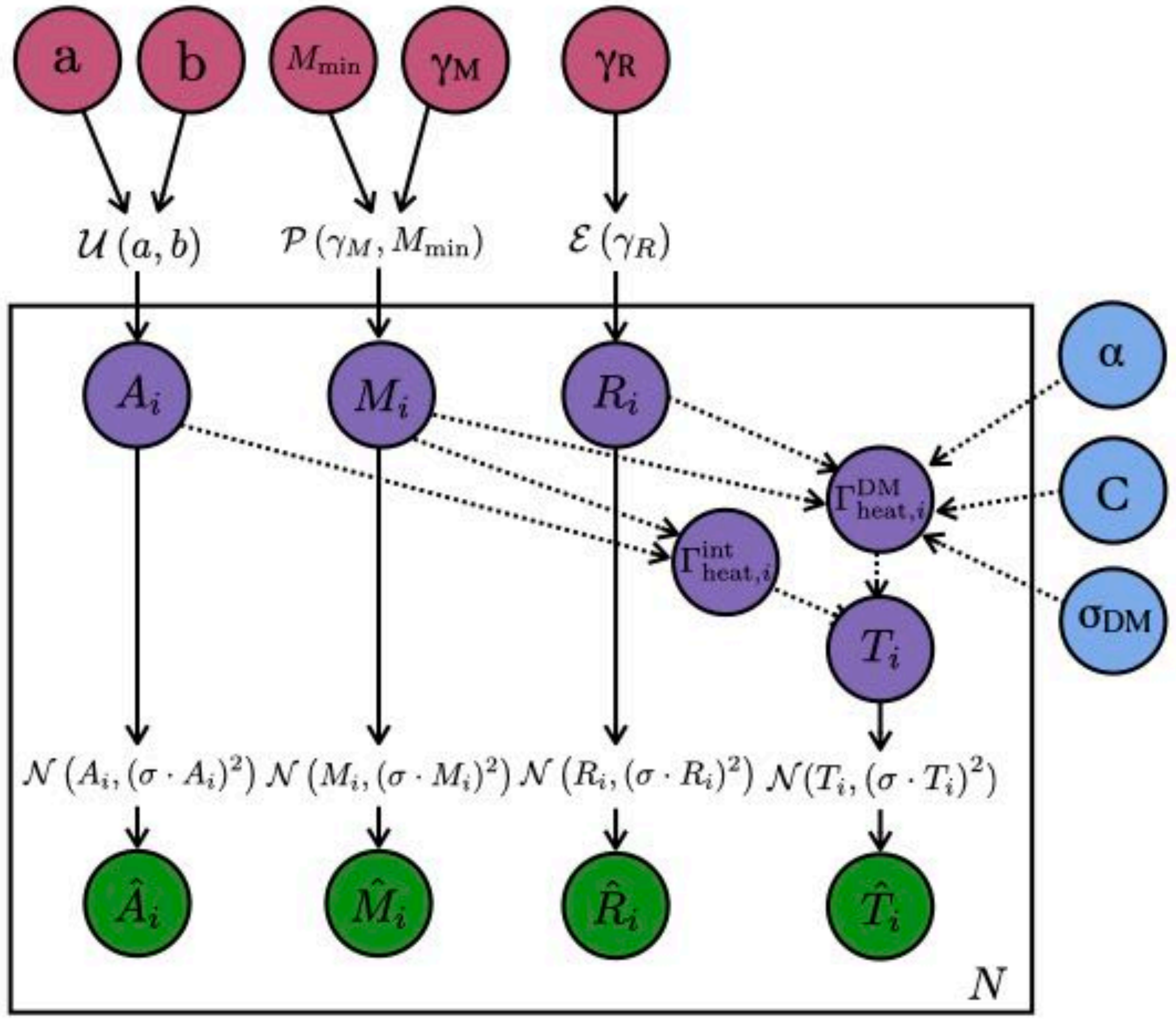
➡ True (unobserved) parameters

Generative data model

➡ Observation of N BDs (age, mass, distance to GC, temperature)

➡ DM halo parameters

Bayesian **H**ierarchical **M**odel



Total BD heat power

$$\Gamma^{\rm tot}_{\rm heat} = \Gamma^{\rm ext}_{\rm heat} + \Gamma^{\rm int}_{\rm heat} + \Gamma^{\rm DM}_{\rm heat} = 4\pi r^2_{BD}\sigma_{\rm SB}T^4_{\rm eff}\epsilon$$

External heat:

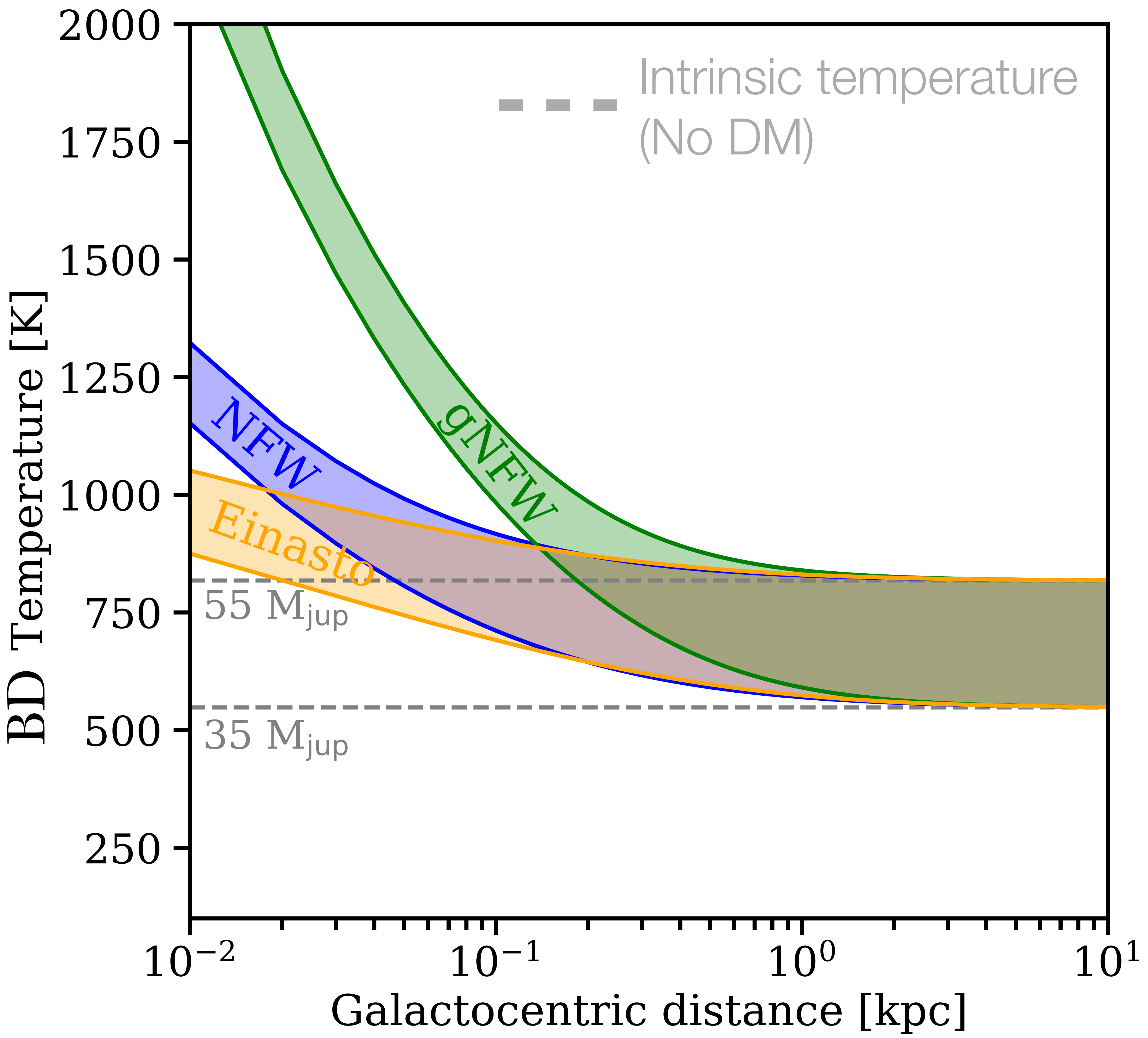
we assume it is negligible

Internal heat:

we assume ATMO 2020 model [Phillips et al. 2003.13717]

DM heat:

$$\Gamma^{\rm DM}_{\rm heat} = f\pi r^2_{BD}\rho_{\rm DM}(R)\bar{v}_{\rm DM}\left(1 + \frac{3}{2}\frac{v^2_{\rm esc}(r_{BD}, M)}{\sigma^2_{\rm DM}}\right)$$



Total BD heat power

$$\Gamma_{\rm heat}^{\rm tot} = \Gamma_{\rm heat}^{\rm ext} + \Gamma_{\rm heat}^{\rm int} + \Gamma_{\rm heat}^{\rm DM} = 4\pi r_{BD}^2 \sigma_{\rm SB} T_{\rm eff}^4 \epsilon$$

External heat:

we assume it is negligible

Internal heat:

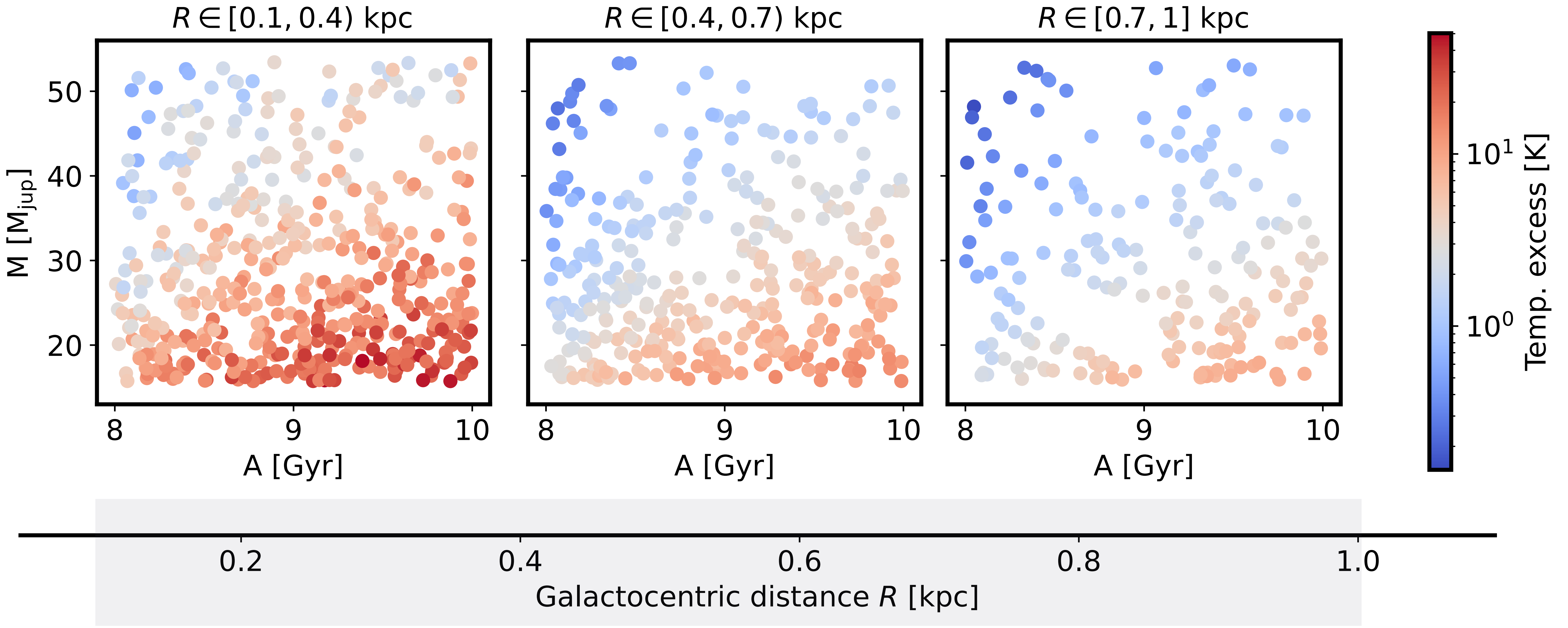
we assume ATMO 2020 model [Phillips et al. 2003.13717]

DM heat:

$$\Gamma_{\rm heat}^{\rm DM} = f\pi r_{BD}^2 \rho_{\rm DM}(R) \bar{v}_{\rm DM} \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2(r_{BD}, M)}{\sigma_{\rm DM}^2}\right)$$

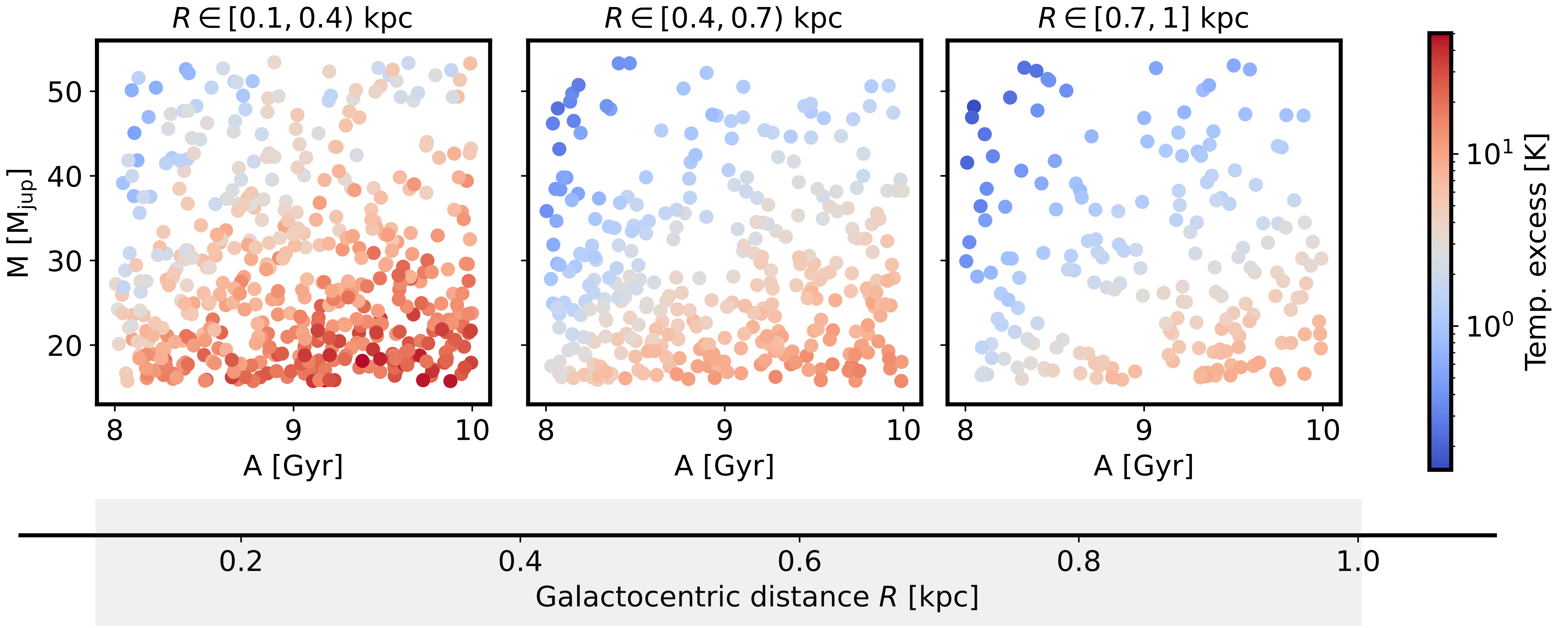
$$\Gamma_{\rm heat}^{\rm DM} \propto \rho_{\rm DM}(R)$$

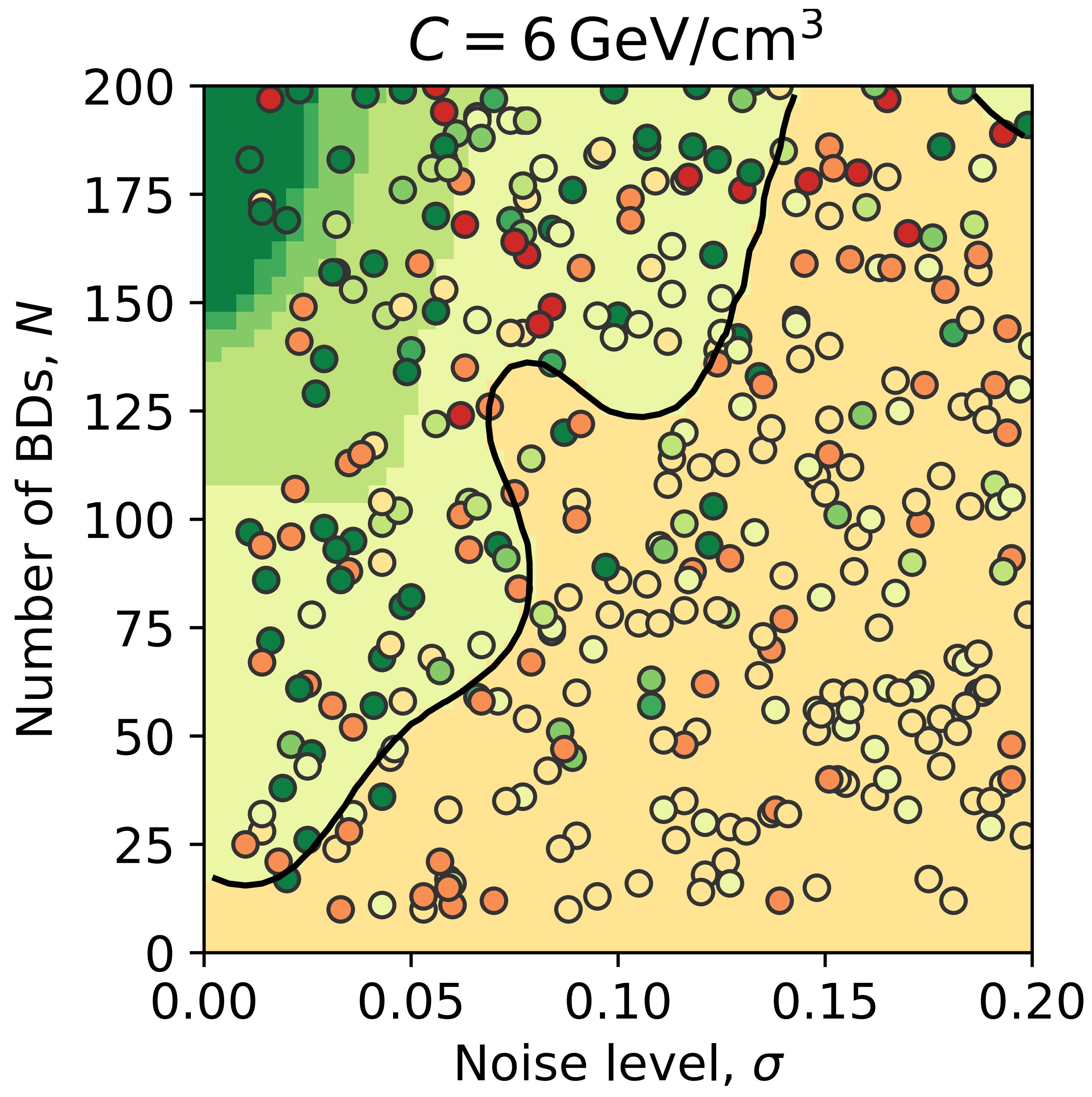
Indirect Dark Matter Signal



Indirect Dark Matter Signal

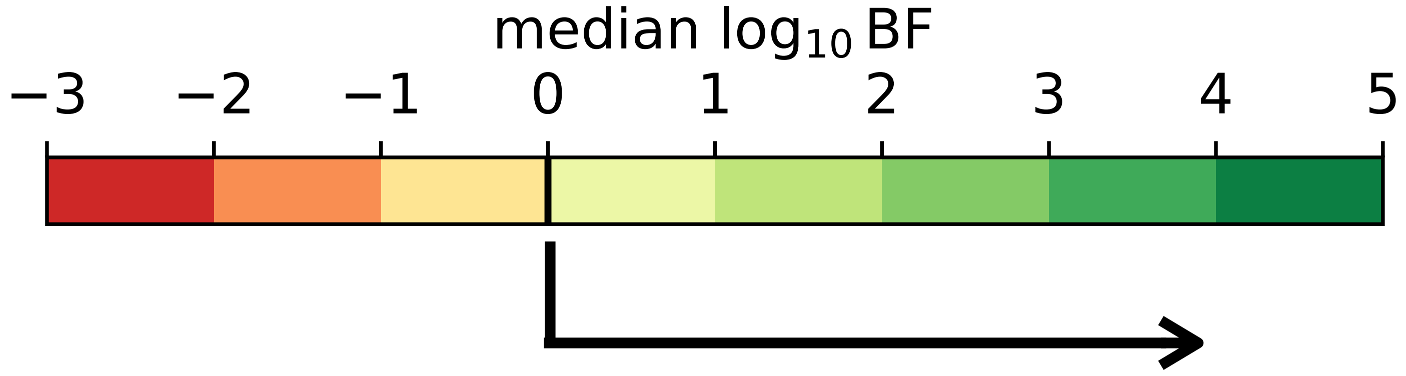
Detection





Bayes **F**actor

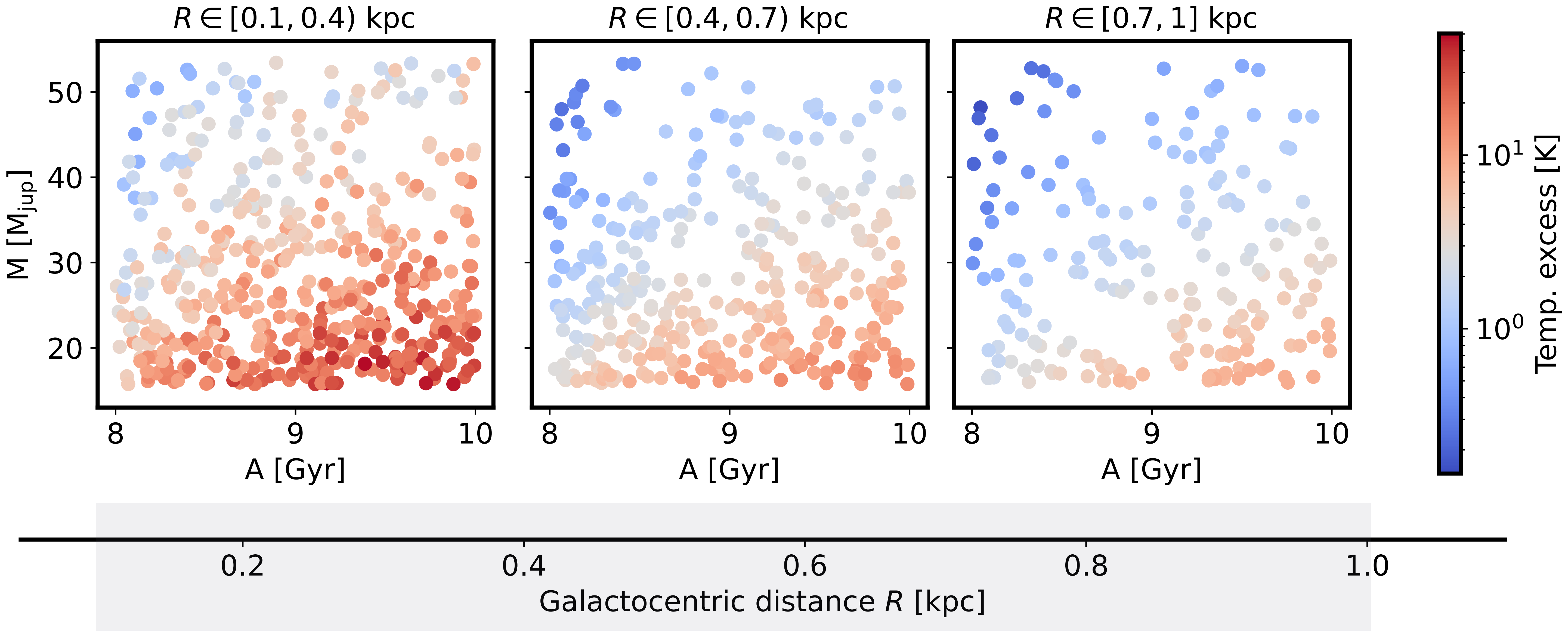
$$\mathrm{BF} = \frac{p(\mathrm{data}|\mathtt{DM})}{p(\mathrm{data}|\mathtt{no\text{-}DM})} = \frac{\text{evidence w/ DM heating contribution}}{\text{evidence for standard BD evolution}}$$

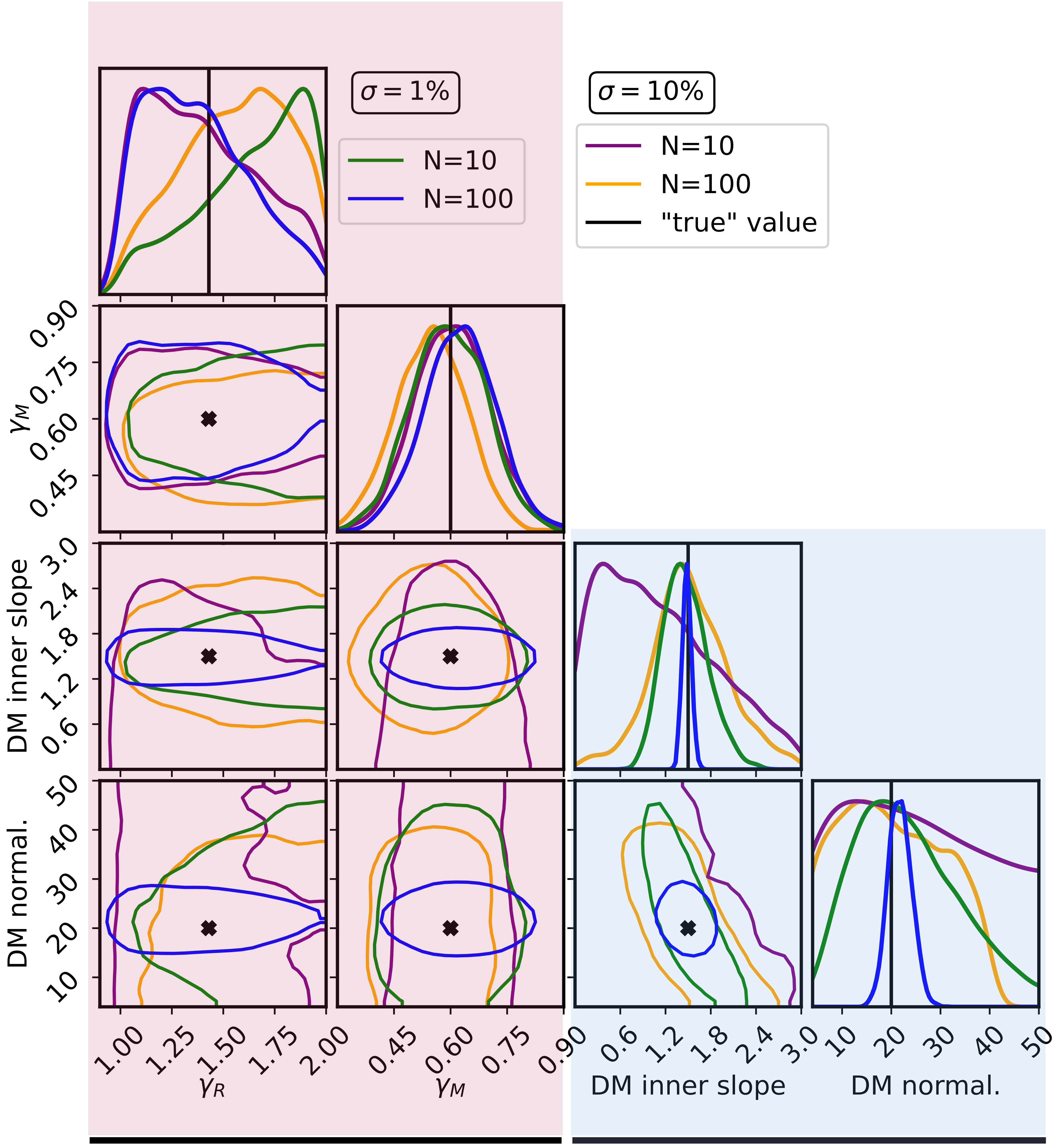


Able to detect DM-overheated BDs

Indirect Dark Matter Signal

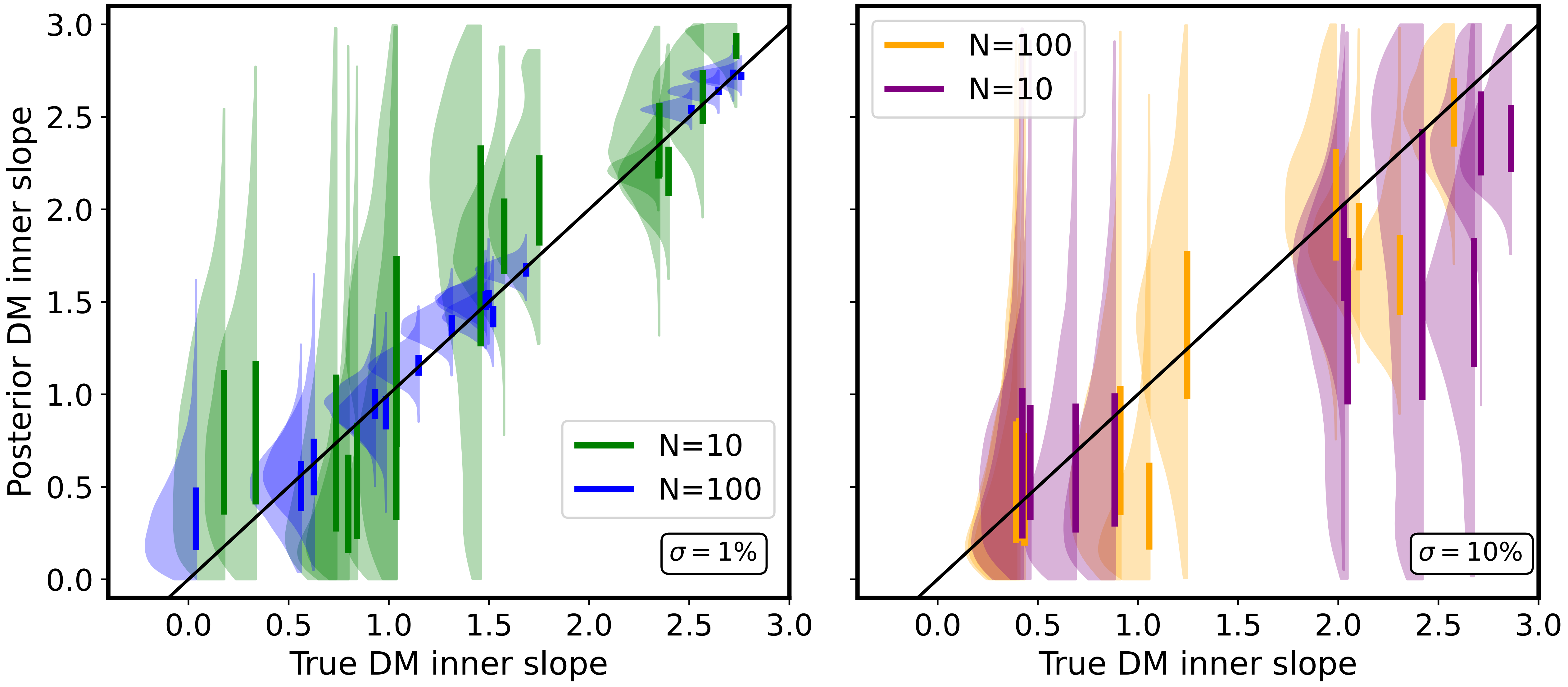
Parameter Inference





BD population parameters

DM halo parameters



➡ Detection of DM-overheated BDs within 1 kpc of our Galaxy remains feasible with datasets of around 100 BDs, assuming DM density profiles in agreement with extrapolations from the stellar disc rotation curve

➡ Realistic but optimistic 10% measurement uncertainties require approximately 100 BDs for DM parameter inference, while larger uncertainties require sample sizes exceeding 100 BDs

Bonus

Brown Dwarfs can also be used to test modified gravity (see e.g. MB & Wojnar [2101.02146])

Can we transform science-fiction into reality?

[*Experimental challenge*] Infer first the mass of free-floating BDs in the Galactic center region through microlensing, plus follow-up observation of these objects with JWST to further determine their temperature.