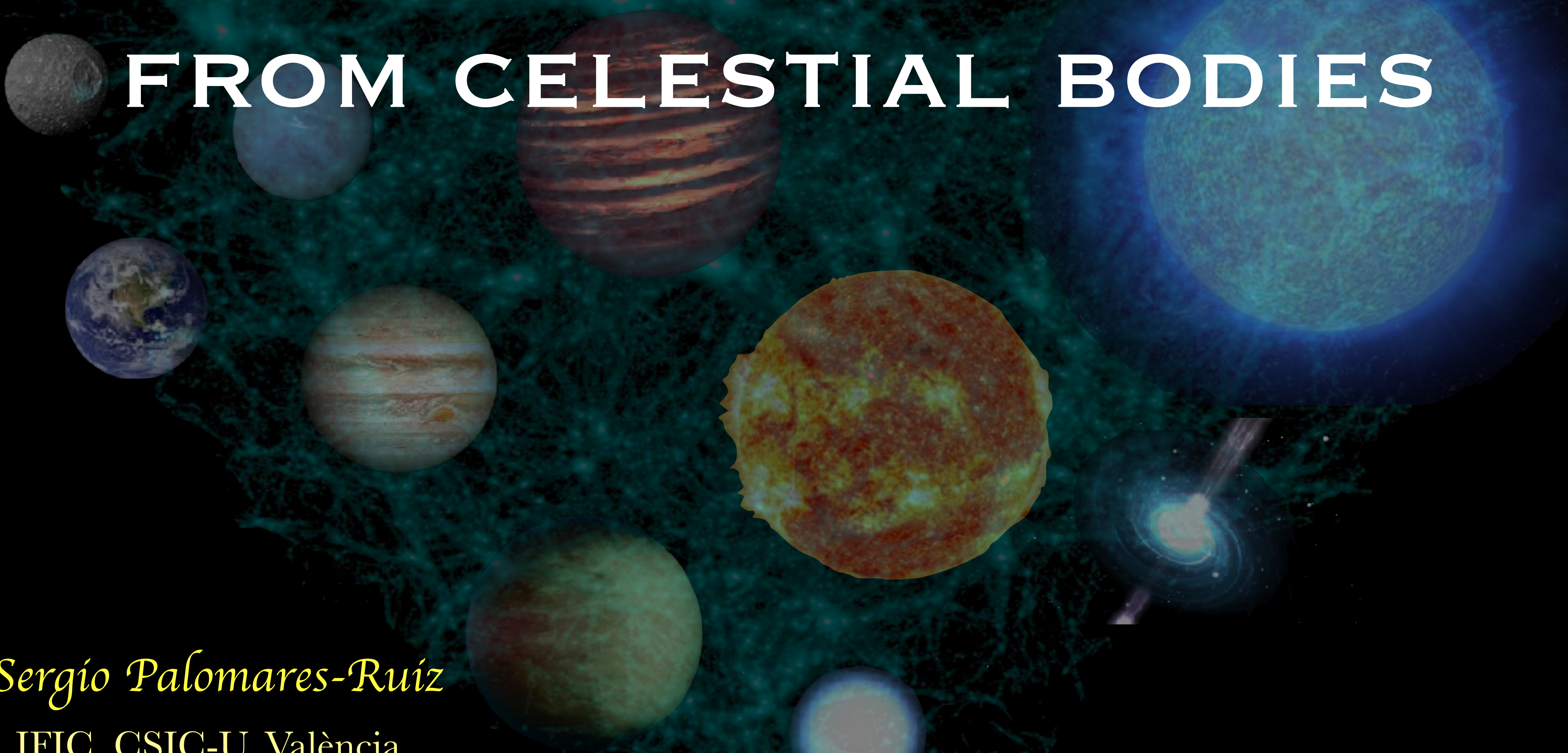
DARK MATTER EVAPORATION FROM CELESTIAL BODIES



Sergio Palomares-Ruiz

IFIC, CSIC-U. València

Dark Ghosts

Granada, 31st March - 1st April 2022

DARK MATTER EVAPORATION FROM CELESTIAL BODIES

OR...

WHAT IS THE MINIMUM DARK MATTER MASS FOR EFFICIENT DARK MATTER CAPTURE BY ANY SPHERICAL CELESTIAL BODY IN THE UNIVERSE?

Sergio Palomares-Ruiz

IFIC, CSIC-U. València

Dark Ghosts

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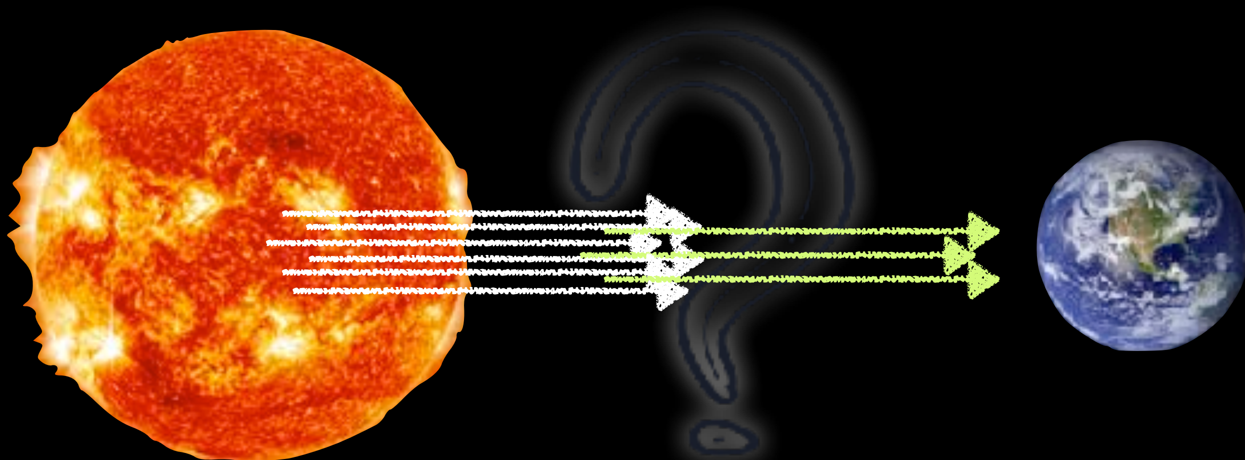
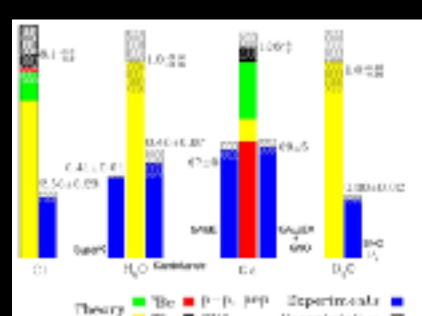
DM accumulation in celestial bodies

Modification of energy transfer

solve the solar neutrino problem





G. Steigman, C. L. Sarazin, H. Quintana, and J. Faulkner, Astron. J. 83: 1050, 1978

D. N. Spergel and W. H. Press, Astrophys. J. 294:663, 1985

J. Faulkner and R. L. Gilliland, Astrophys. J. 299:994, 1985

L. M. Krauss, K. Freese, W. Press, and D. Spergel, Astrophys. J. 299:1001, 1985

R. L. Gilliland, J. Faulkner, W. H. Press, and D. N. Spergel, Astrophys. J. 306:703, 1986

M. Nauenberg, Phys. Rev. D36:1080, 1987

DM annihilations could heat celestial bodies

L. M. Krauss, M. Srednicki, and F. Wilczek, Phys. Rev. D33:2079, 1986

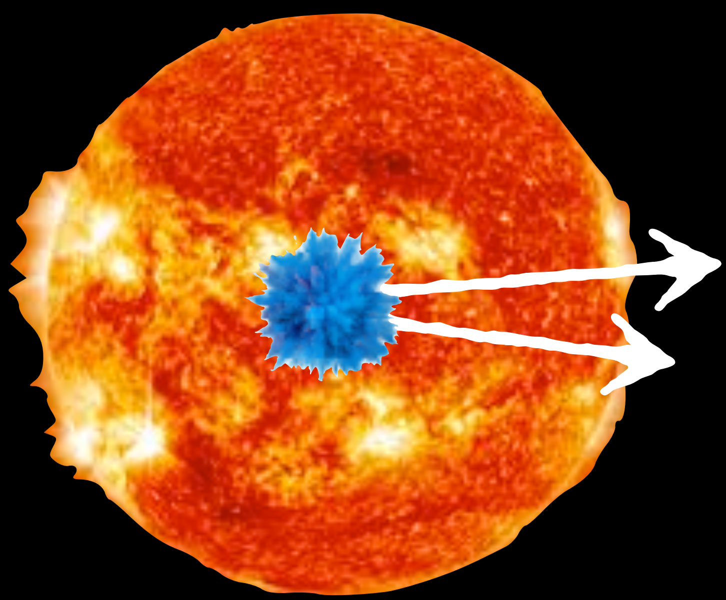
M. Fukugita, P. Hut, and N. Spergel, IASSNS-AST-88-26, 1988

M. Kawasaki, H. Murayama, and T. Yanagida, Prog. Theor. Phys. 87:685, 1992

DM accumulation in celestial bodies

Annihilation products

DM annihilations could produce neutrinos and, in secluded DM models, other detectable particles outside celestial bodies



J. Silk, K. A. Olive, and M. Srednicki, Phys. Rev. Lett. 55:257, 1985

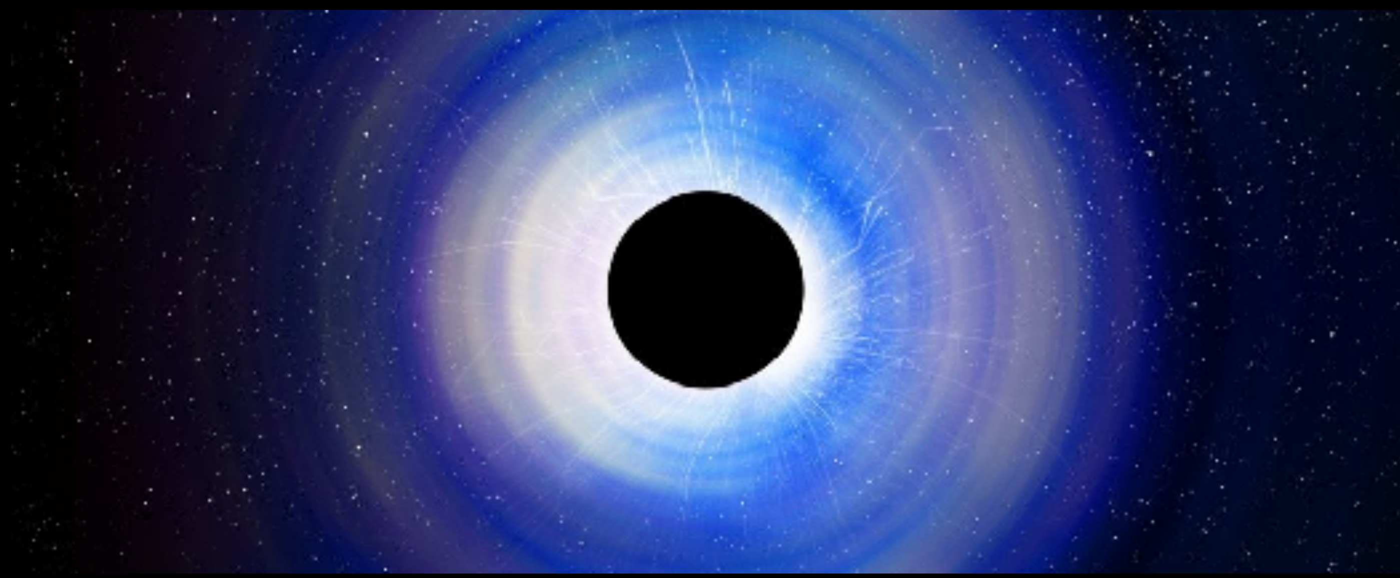
K. Freese, Phys. Lett. B167:295, 1986

L. M. Krauss, M. Srednicki, and F. Wilczek, Phys. Rev. D33:2079, 1986

T. K. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D34:2206, 1986

Collapse

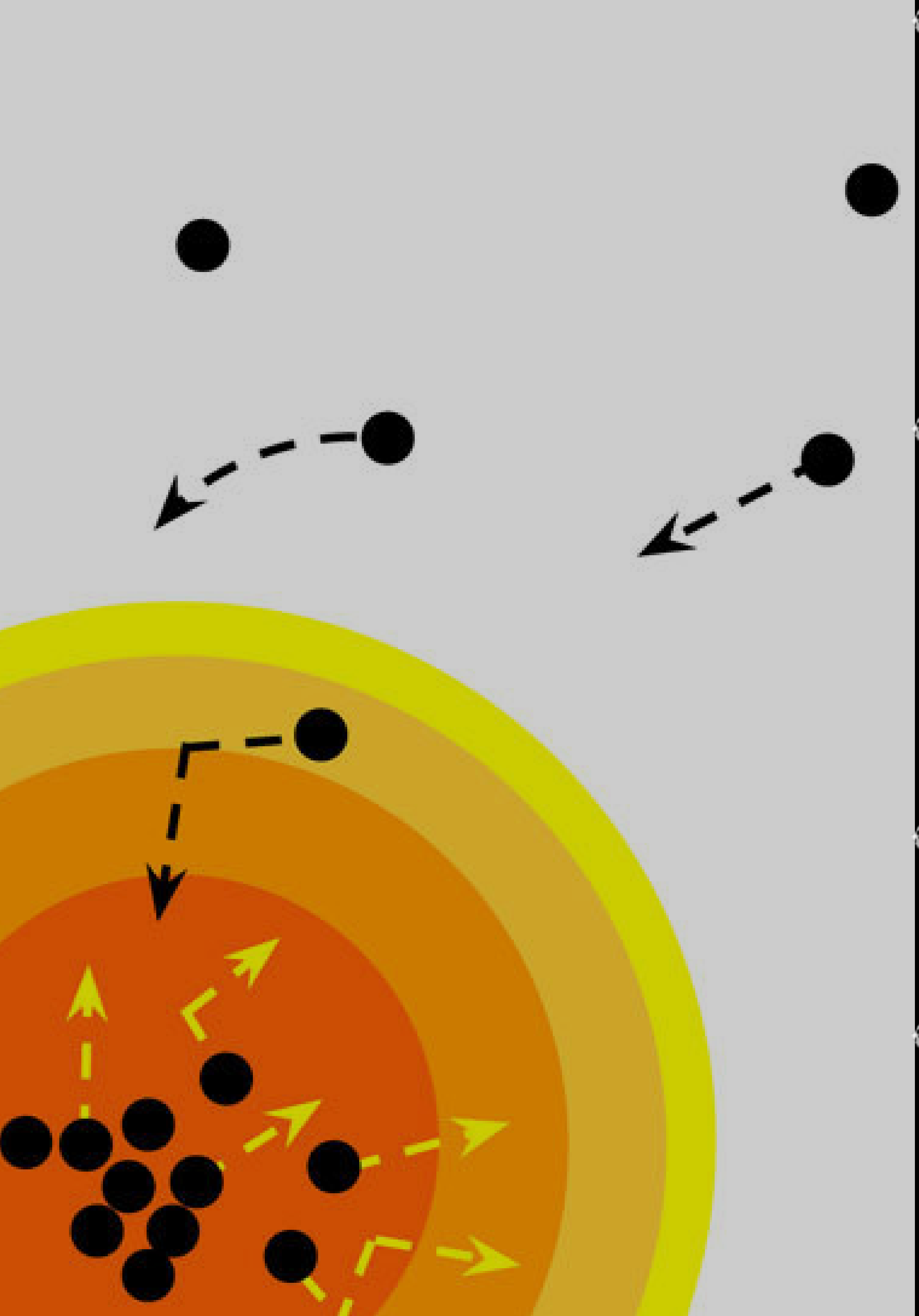
Under certain extreme conditions, DM could collapse in the interior of celestial bodies into a black hole



I. Goldman and S. Nussinov, Phys. Rev. D40:3221, 1989

A. Gould, B. T. Draine, R. W. Romani, and S. Nussinov, Phys. Lett. B238:337, 1990

DM accumulation in celestial bodies



- DM particles could elastically scatter off the nuclei of celestial bodies to a velocity smaller than the escape velocity, so that they get gravitationally bound and finally trapped inside
- Additional scatterings would give rise to an isothermal DM distribution (small cross sections) or DM particles would thermalize locally with the medium (large cross sections)
- Trapped DM particles could annihilate into SM particles
- But... if DM particles are very light, the chances of being quickly kicked out after further scatterings are very high: DM evaporates

DM evaporation mass

This is the result to remember

$$E_c / T_\chi \sim 30$$

escape energy of DM particles at the core of the capturing body

temperature of DM particles at the core of the capturing body (similar to the core temperature)

Evolution equation

T. K. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D34:2206, 1986

K. Griest and D. Seckel, Nucl. Phys. B283:681, 1987

$$\frac{dN_\chi(t)}{dt} = \mathtt{C} - \mathtt{A}\, N_\chi^2(t) - \mathtt{E}\, N_\chi(t)$$

Capture rate (velocity distribution and scattering cross section)

Annihilation rate (annihilation cross section)

Evaporation rate (distribution in the celestial body and scattering cross section)

$$N_\chi(t) = \mathtt{C}\,\tau_{\rm eq}\,\frac{\tanh(\kappa\, t/\tau_{\rm eq})}{\kappa + \frac{1}{2}\mathtt{E}\,\tau_{\rm eq}\,\tanh(\kappa\, t/\tau_{\rm eq})}$$

$$\kappa \equiv \sqrt{1 + (\mathtt{E}\,\tau_{\rm eq}/2)^2}$$

Equilibration time:

$$\tau_{\rm eq} = 1/\sqrt{\mathtt{A}\,\mathtt{C}}$$

If $\kappa\, t \ll \tau_{\rm eq}$: $N_\chi \simeq \mathtt{C}\, t$

equilibrium is not reached

If $\kappa\, t \gg \tau_{\rm eq}$ $\begin{cases} \mathtt{E}\,\tau_{\rm eq} \ll 1 : & N_\chi \simeq \mathtt{C}\,\tau_{\rm eq} \\ \mathtt{E}\,\tau_{\rm eq} \gg 1 : & N_\chi \simeq \dfrac{\mathtt{C}}{\mathtt{E}} \end{cases}$

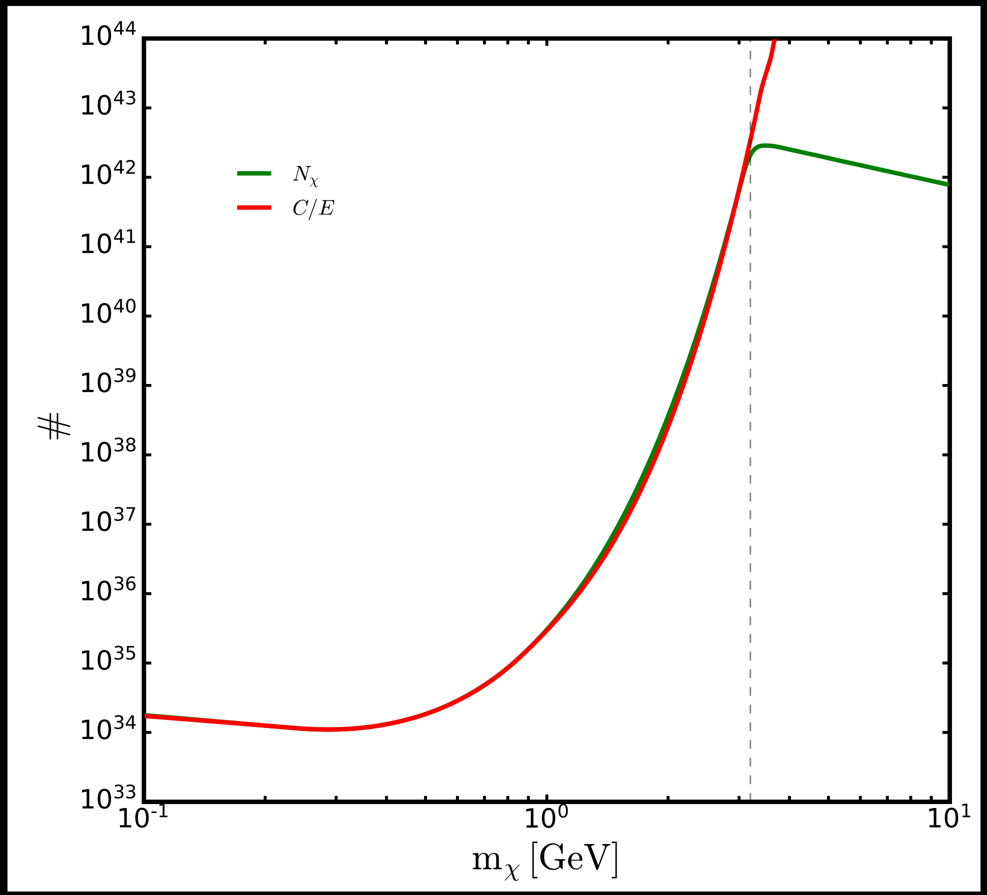
equilibrium between capture and annihilation

equilibrium between capture and evaporation

What is the minimum DM mass for evaporation not to be efficient?

The evaporation rate grows exponentially for low masses: light DM particles are easily kicked out

e.g., G. Busoni, A. De Simone and W.-C. Huang, JCAP07:010, 2013



Adapted from R. Garani and SPR, JCAP 1705:007, 2017

$$\left| N_\chi(t; m_{\rm evap}) - \frac{\mathrm{C}(m_{\rm evap})}{\mathrm{E}(m_{\rm evap})} \right| = 0.1\, N_\chi(t; m_{\rm evap})$$

If equilibrium is reached: $$\mathrm{E}(m_{\rm evap})\, \tau_{\rm eq}(m_{\rm evap}) = 1/\sqrt{0.11}$$

Capture of DM by celestial bodies

W. H. Press and D. N. Spergel, Astrophys. J. 296:679, 1985
A. Gould, Astrophys. J. 321:571, 1987
G. Busoni, A. De Simone, P. Scott and A. C. Vincent, JCAP 10:037, 2017

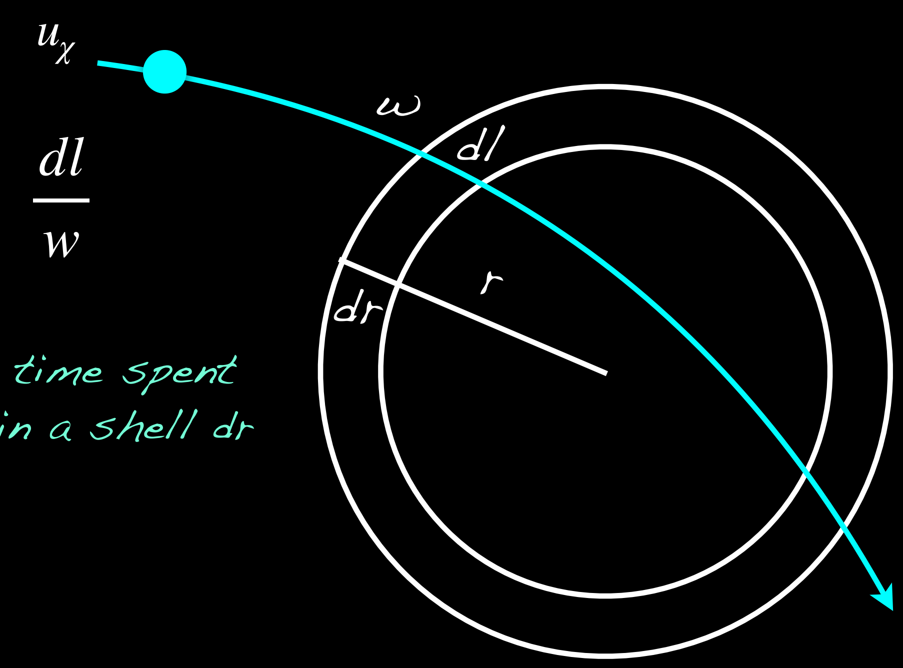
$$dC = s_{\rm cap}(r) \quad \times \quad 4\pi r^2 \left(\frac{\rho_\chi}{m_\chi}\right) f_{v_{\rm cb}}(u_\chi)\, u_\chi\, du_\chi \,\frac{d\cos^2\theta}{4} \quad \times \quad \Omega^-_{v_e}(w) \quad \times \quad \frac{dl}{w}$$

suppression factor to account for large optical depths

flux of DM particles reaching a spherical shell at radius r

rate of scattering from w to a speed less than the escape velocity

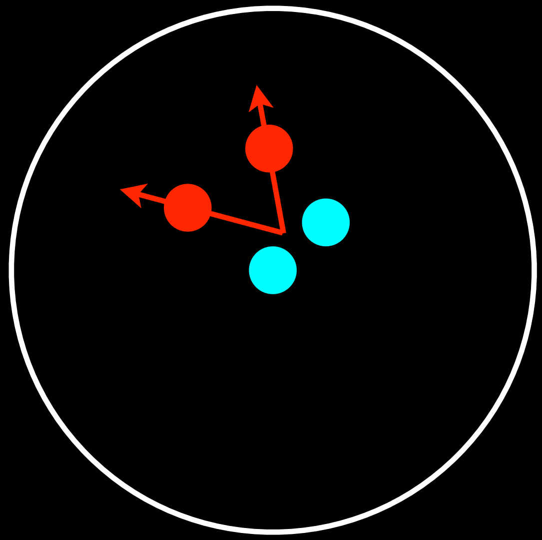
time spent in a shell dr



After DM particles get captured, further scatterings with target nuclei would approximately thermalize them at a temperature T_χ and attain a velocity distribution that can be approximated as Maxwell-Boltzmann

Annihilation of DM in celestial bodies

A. Gould, Astrophys. J. 321:560, 1987
A. Gould and G. Raffelt, Astrophys. J. 352:669, 1990



$$A = \langle \sigma_A v_{\chi\chi} \rangle \frac{\int_0^{R_\odot} n_\chi^2(r,t)\, 4\pi r^2\, dr}{\left(\int_0^{R_\odot} n_\chi(r,t)\, 4\pi r^2\, dr\right)^2}$$

Evaporation of DM from celestial bodies

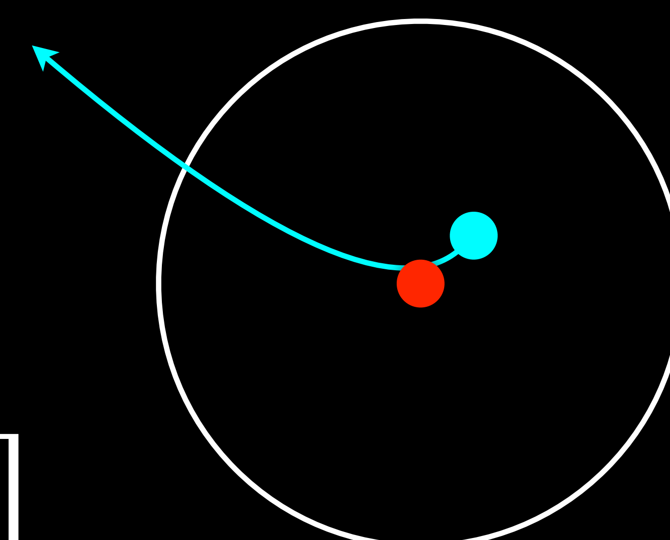
G. Steigman, C. L. Sarazin, H. Quintana, and J. Faulkner, Astron. J. 83:1050, 1978
D. N. Spergel and W. H. Press, Astrophys. J. 294:663, 1985
K. Griest and D. Seckel, Nucl. Phys. B283:681, 1987
A. Gould, Astrophys. J. 321:560, 1987
A. Gould, Astrophys. J. 356:302, 1990

$$\mathrm{E} = \sum_i \int_0^R s_{\rm evap}(r)\, n_\chi(r,t)\, 4\pi r^2\, dr \int_0^{v_e(r)} f_\chi(\mathbf{w}, r)\, \Omega^+_{v_e}(w)\, 4\pi w^2\, dw$$

$s_{\rm evap}$: suppression factor to account for the fraction of DM particles that, even with a speed higher than the escape velocity, would actually escape due to further scatterings on their way out of the celestial body

f_χ: thermalized DM distribution

$\Omega^+_{v_e}$: rate of scattering from speed w to $v > v_e$



For weak cross sections (thin regime) and for $m_\chi = m_i$:

$$\mathrm{E} \simeq \sum_i \left[\frac{1}{V_s} \frac{2}{\sqrt{\pi}} \left(\frac{2\, T_\chi}{m_\chi} \right)^{1/2} \left(\frac{E_c}{T_\chi} \right) e^{-E_c/T_\chi} \right] N_i(r_{0.95})\, \sigma_i$$

$N_i(r_{0.95})$: number of targets within a radius such that $T(r_{0.95}) = 0.95\, T_\chi$

escape energy at the core $\quad E_c = \frac{1}{2} m_\chi v_{e,0}^2$

Evaporation of DM from celestial bodies

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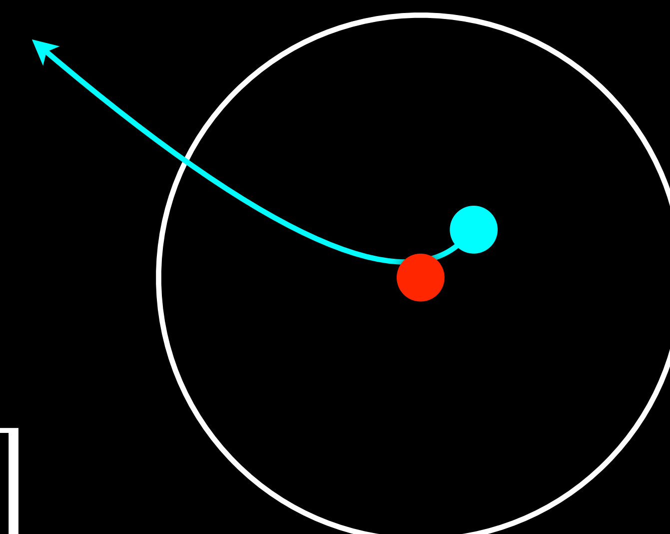

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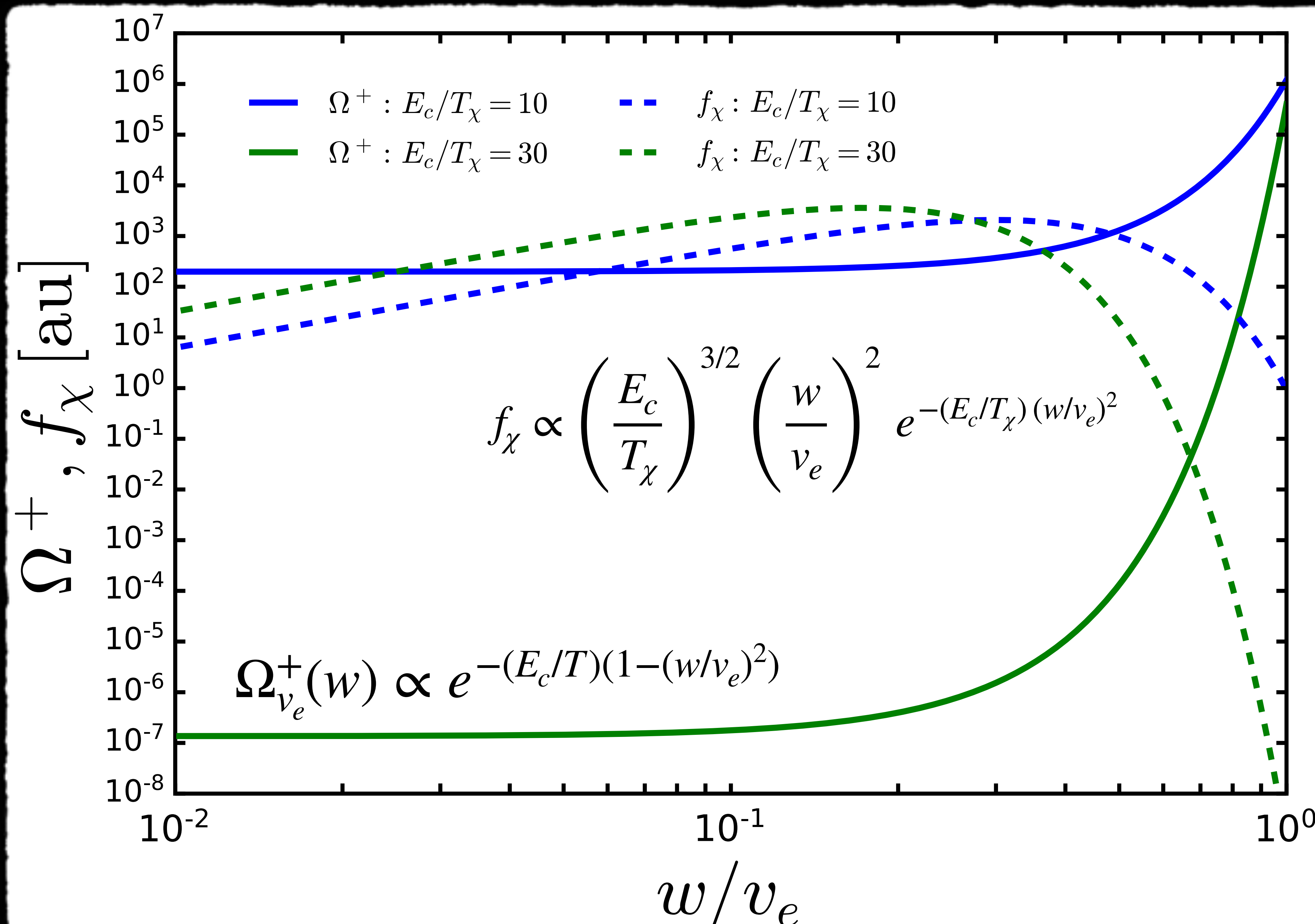
Evaporation of DM from celestial bodies

a tale of two (exponential) tails

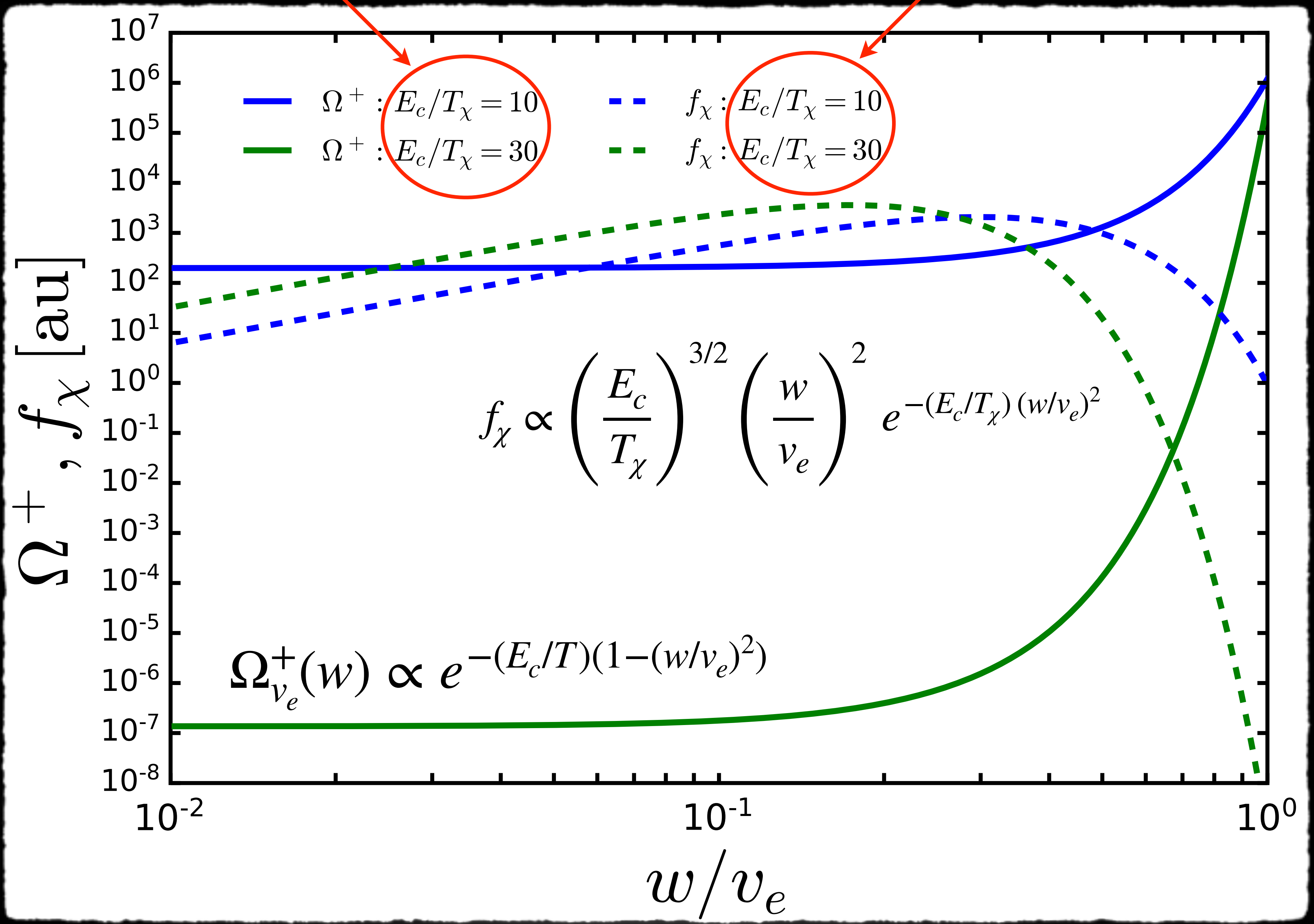


R. Garani and SPR, arXiv:2104.12757

Evaporation of DM from celestial bodies

a tale of two (exponential) tails

Only a factor of 3 in the DM mass, but many orders of magnitude in the evaporation rate



R. Garani and SPR, arXiv:2104.12757

DM evaporation mass

(in equilibrium)

$$\mathtt{E}(m_{\rm evap})\,\tau_{\rm eq}(m_{\rm evap}) = \frac{\mathtt{E}(m_{\rm evap})}{\sqrt{\mathtt{C}(m_{\rm evap})\,\mathtt{A}(m_{\rm evap})}} = 1/\sqrt{0.11}$$

Saturation limit:

G. Busoni, A. De Simone, P. Scott and A. C. Vincent, JCAP 10:037, 2017

$$\mu_i \equiv \frac{m_\chi}{m_i} \quad ; \quad \mu_{-,i} \equiv \frac{\mu_i - 1}{2}$$

$$\mathtt{C}_{\rm sat} = \frac{3}{4}\pi R^2 \left(\frac{\rho_\chi}{m_\chi}\right)\langle v\rangle_0 \left(\frac{3}{2}\frac{v_e^2(R)}{v_d^2}\right)\begin{cases} 1 & ; \quad \frac{3}{2}\frac{v_e^2(R)}{v_d^2}\frac{\mu_i}{\mu_{-,i}^2} \gg 1 \\ \frac{1}{4}\left(\frac{3}{2}\frac{v_e^2(R)}{v_d^2}\right)\frac{\mu}{\mu_-^2} & ; \quad \frac{3}{2}\frac{v_e^2(R)}{v_d^2}\frac{\mu_i}{\mu_{-,i}^2} \ll 1 \end{cases}$$

$$\mathtt{A} \simeq \frac{\langle \sigma_A v_{\chi\chi}\rangle}{V_s}$$

$$\mathtt{E} \simeq \frac{1}{V_s}\frac{2}{\sqrt{\pi}}\left(\frac{2\,T_\chi}{m_\chi}\right)^{1/2}\left(\frac{E_c}{T_\chi}\right) e^{-E_c/T_\chi} N_{0.95}\,\sigma^{\rm geom}$$

$$V_s = 4/3\pi\, r_s^3$$

$$r_s \simeq 0.1\,R$$

escape energy at the core: $E_c = \frac{1}{2} m_\chi v_{e,0}^2$

$$N_{0.95}\,\sigma^{\rm geom} \simeq 0.1\,\pi R^2$$

DM evaporation mass

For $\frac{3}{2}\frac{v_e^2(R)}{v_d^2}\frac{\mu_i}{\mu_{-,i}^2} \gg 1$

$$\left(\frac{E_c}{T_\chi}\right) e^{-E_c/T_\chi} \simeq 7\times 10^{-12} \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{1.5\times 10^7\ \mathrm{K}}{T_\chi}\right)^{1/2} \left(\frac{\rho_\chi}{0.4\ \mathrm{GeV/cm^3}}\right)^{1/2} \left(\frac{270\ \mathrm{km/s}}{v_d}\right)^{1/2} \left(\frac{\langle\sigma_A v_{\chi\chi}\rangle}{3\times 10^{-26}\ \mathrm{cm^3/s}}\right)^{1/2}$$

For the Sun:

$$E_c/T_\chi \simeq 29 \to m_{\mathrm{evap}} \simeq 3.2\ \mathrm{GeV} \quad [v_{e,0}^2 = 5\, v_{e,R}^2\,, \quad T_\chi = 0.9\, T_c]$$

D. N. Spergel and W. H. Press, Astrophys. J. 294:663, 1985
T. K. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D34:2206, 1986
K. Griest and D. Seckel, Nucl. Phys. B283:681, 1987
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A. Gould, Astrophys. J. 321:560, 1987

For $\frac{3}{2}\frac{v_e^2(R)}{v_d^2}\frac{\mu_i}{\mu_{-,i}^2} \ll 1$

$$\left(\frac{E_c}{T_\chi}\right) e^{-E_c/T_\chi} \simeq 2\times 10^{-14}\left(\frac{3\,\mu}{\mu_-^2}\right)^{1/2}\left(\frac{M}{M_\oplus}\right)\left(\frac{R_\oplus}{R}\right)^{1/2}\left(\frac{6000\ \mathrm{K}}{T_\chi}\right)^{1/2}\left(\frac{\rho_\chi}{0.4\ \mathrm{GeV/cm^3}}\right)^{1/2}\left(\frac{270\ \mathrm{km/s}}{v_d}\right)^{3/2}\left(\frac{\langle\sigma_A v_{\chi\chi}\rangle}{3\times 10^{-26}\ \mathrm{cm^3/s}}\right)^{1/2}$$

For the Earth:

$$E_c/T_\chi \simeq 34 \to m_{\rm evap} \simeq 13\ \mathrm{GeV} \quad [v_{e,0}^2 = 1.9\,v_{e,R}^2\,, \quad T_\chi = T_c]$$

K. Freese, Phys. Lett. B167:295, 1986
L. M. Krauss, M. Srednicki and F. Wilczek, Phys. Rev. D33:2079, 1986
A. Gould, J. A. Frieman and K. Freese, Phys. Rev. D39:1029, 1989
R. Garani and P. Tinyakov, Phys. Lett. 804:135403, 2020

So what is the DM evaporation mass for all those celestial bodies out there?

Main properties of celestial bodies

Mass-radius relation

from observations

Mass-core temperature relation

from models

Mass-escape velocity relation

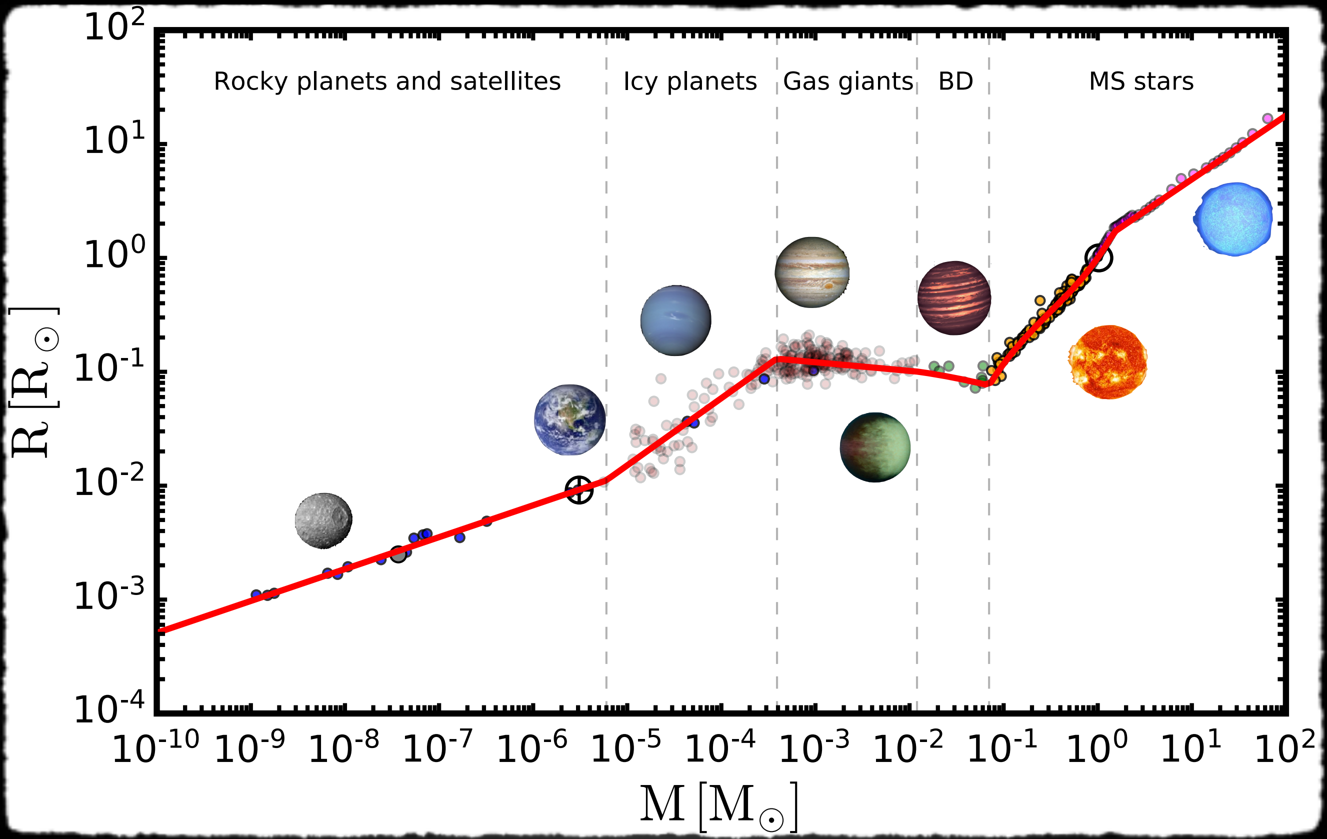
from (polytropic) models

Equilibration time

for the geometric cross section, $\sum_i N_i \sigma_i = \pi R^2$

R. Garani and SPR, arXiv:2104.12757

Main properties of celestial bodies



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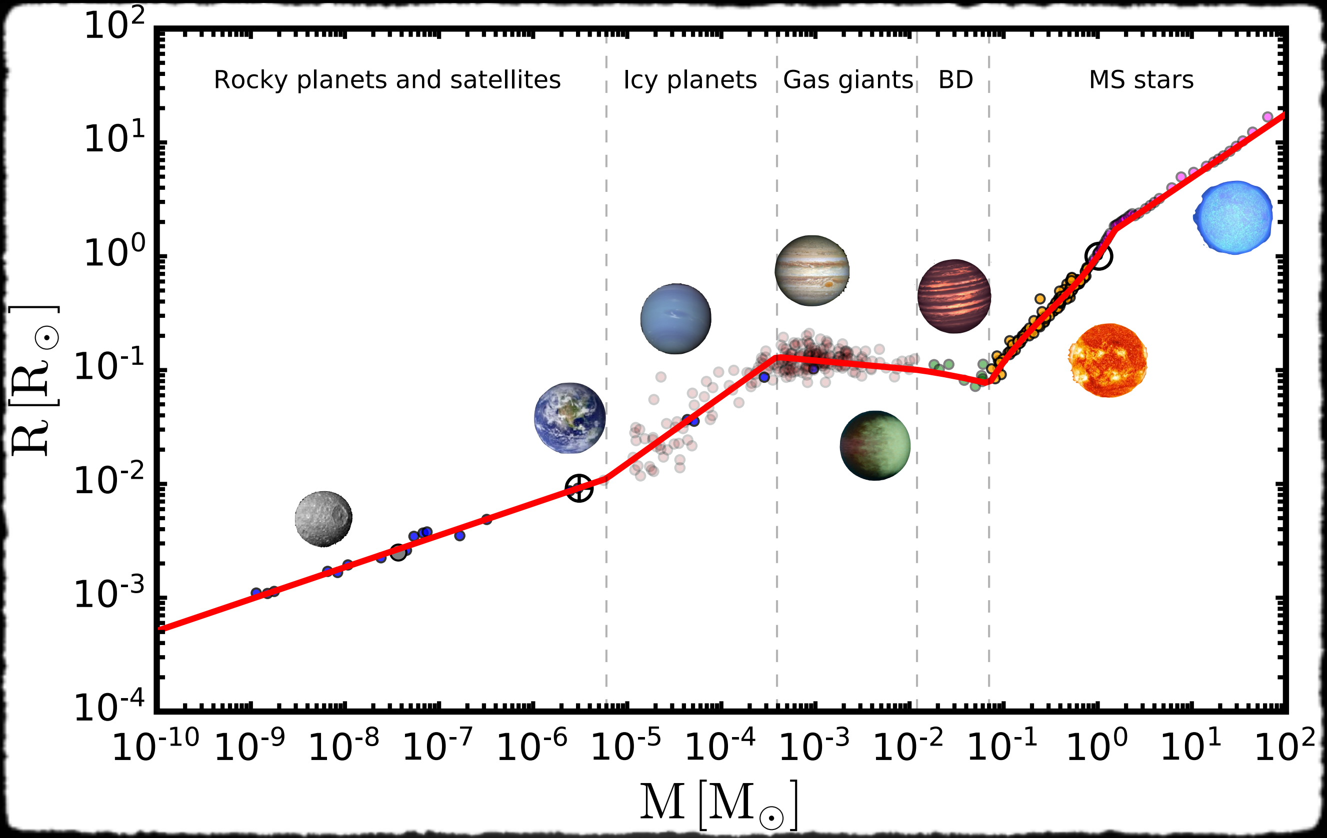

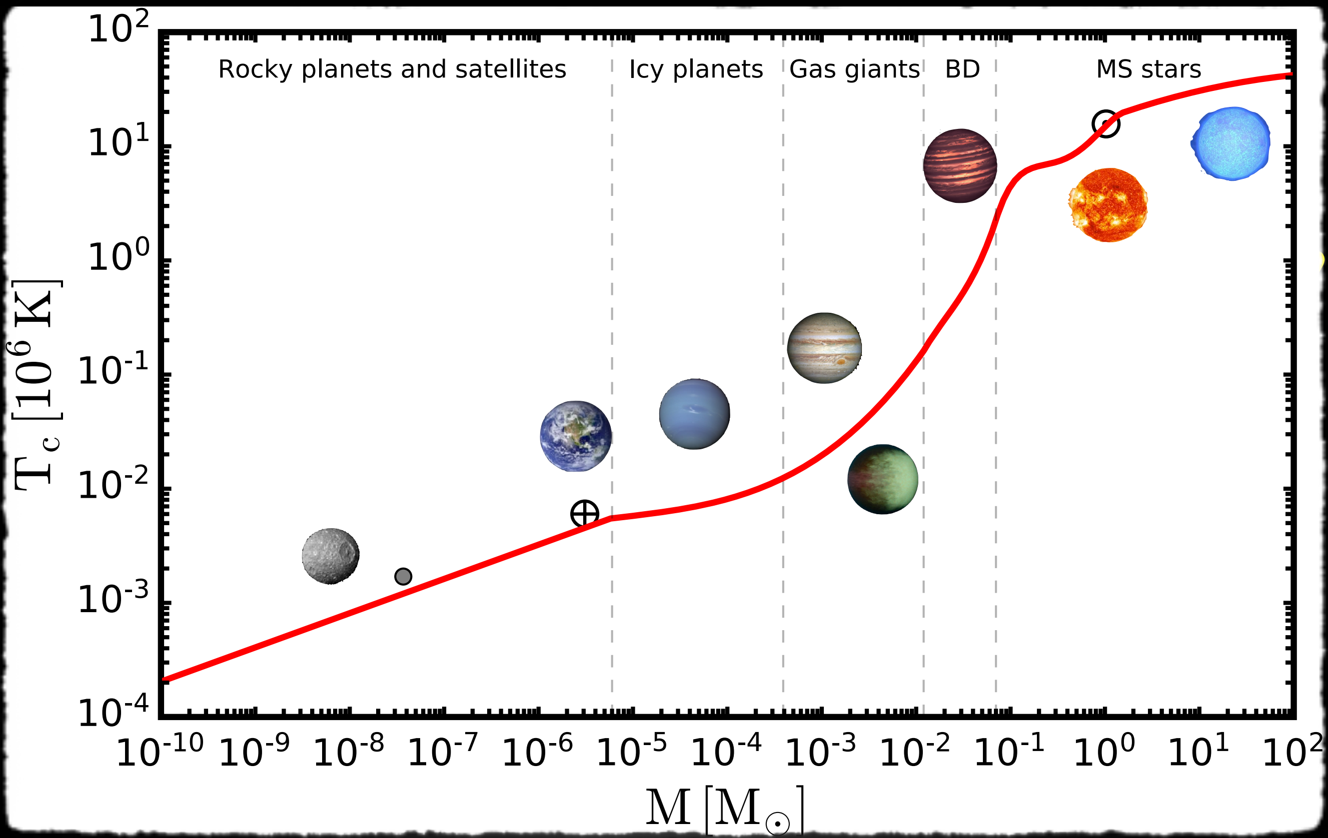

Mass-escape velocity relation

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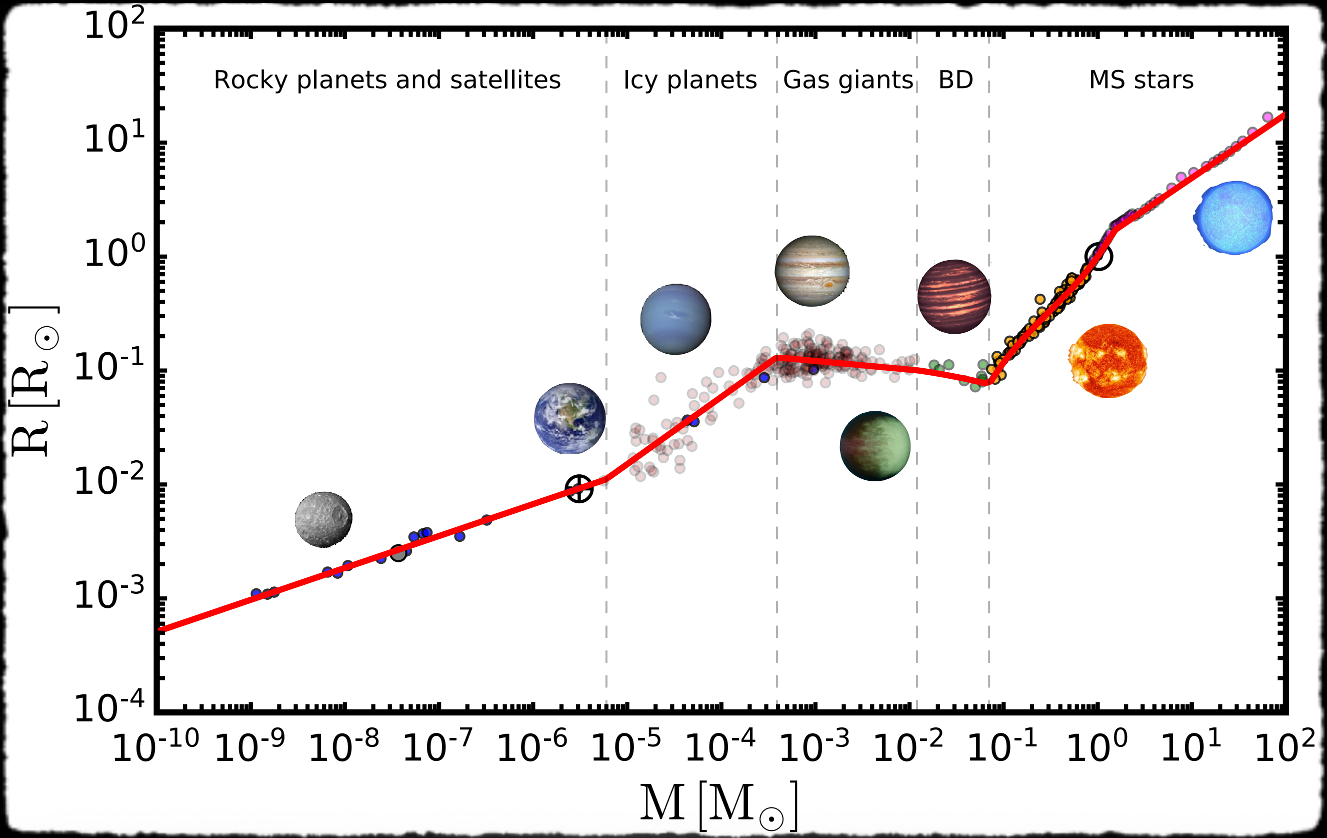

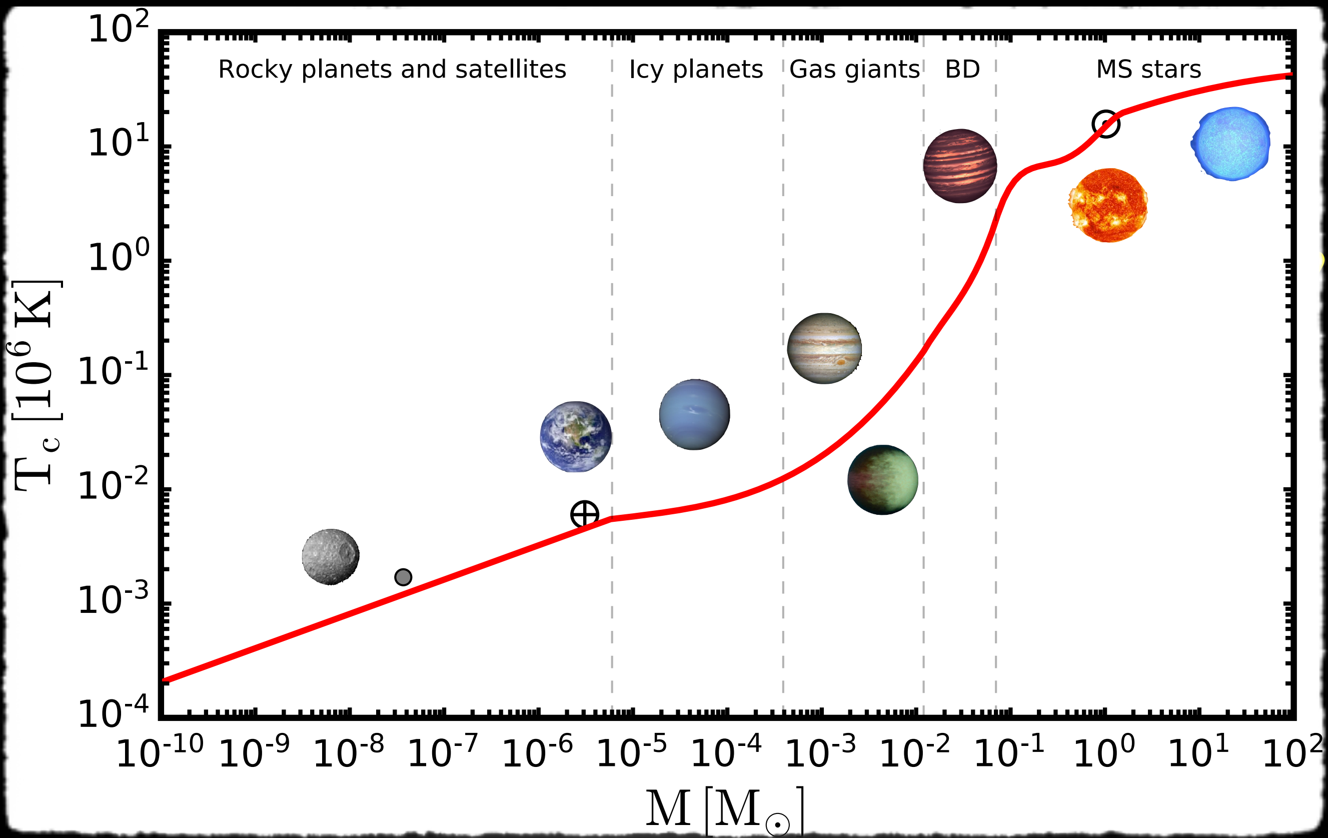

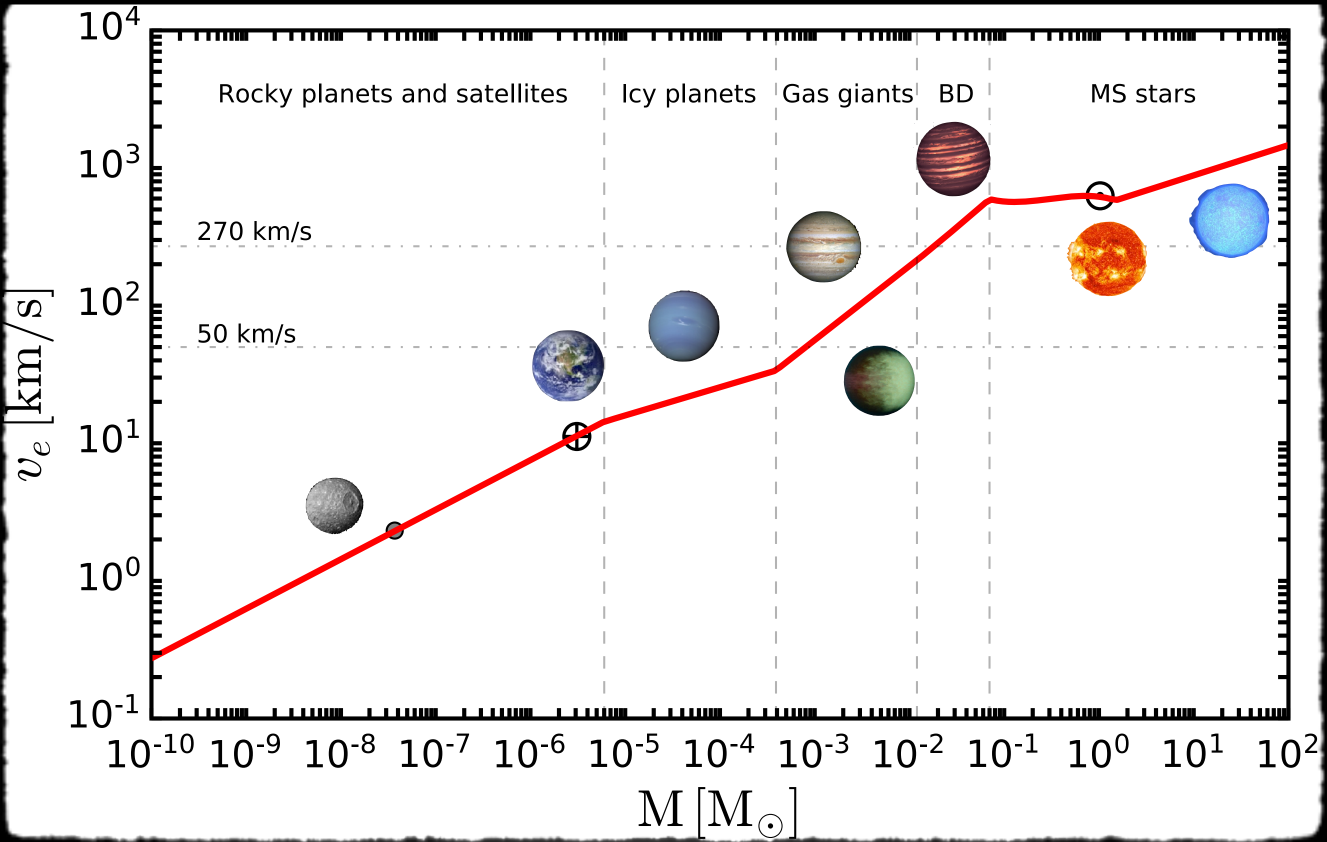

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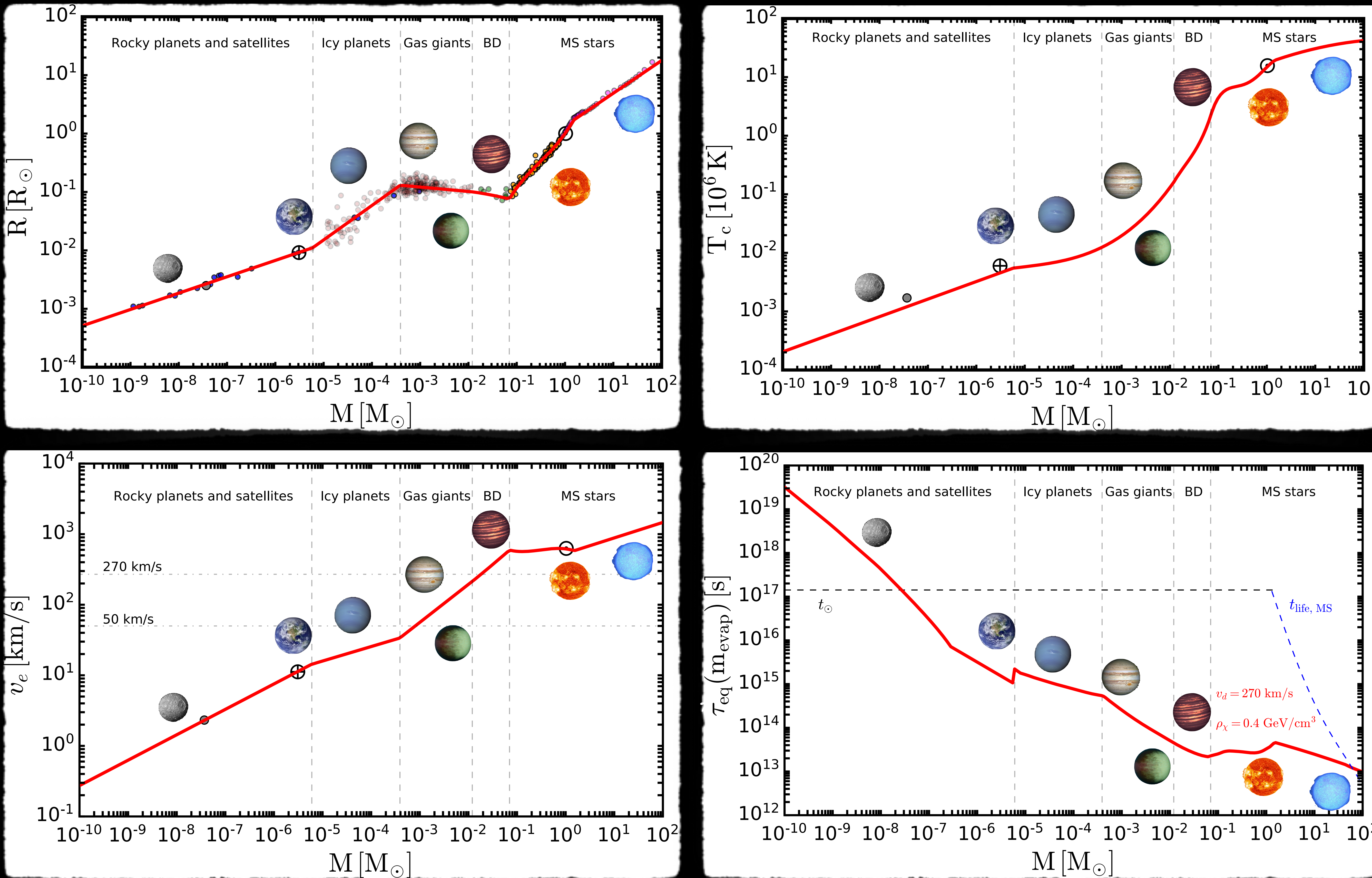
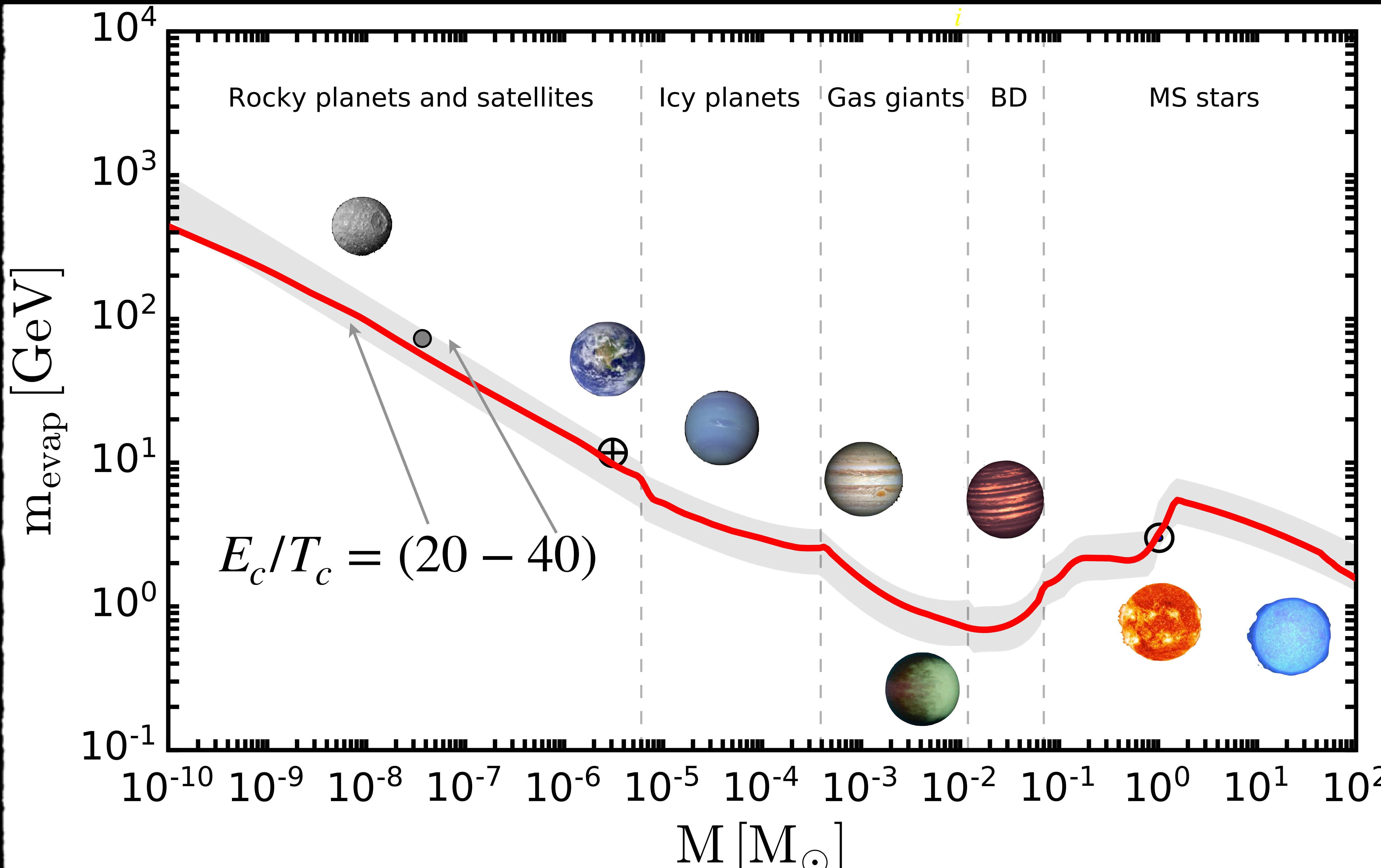


R. Garani and SPR, arXiv:2104.12757

DM evaporation mass

for the geometric cross section, $\sum_i N_i \sigma_i = \pi R^2$



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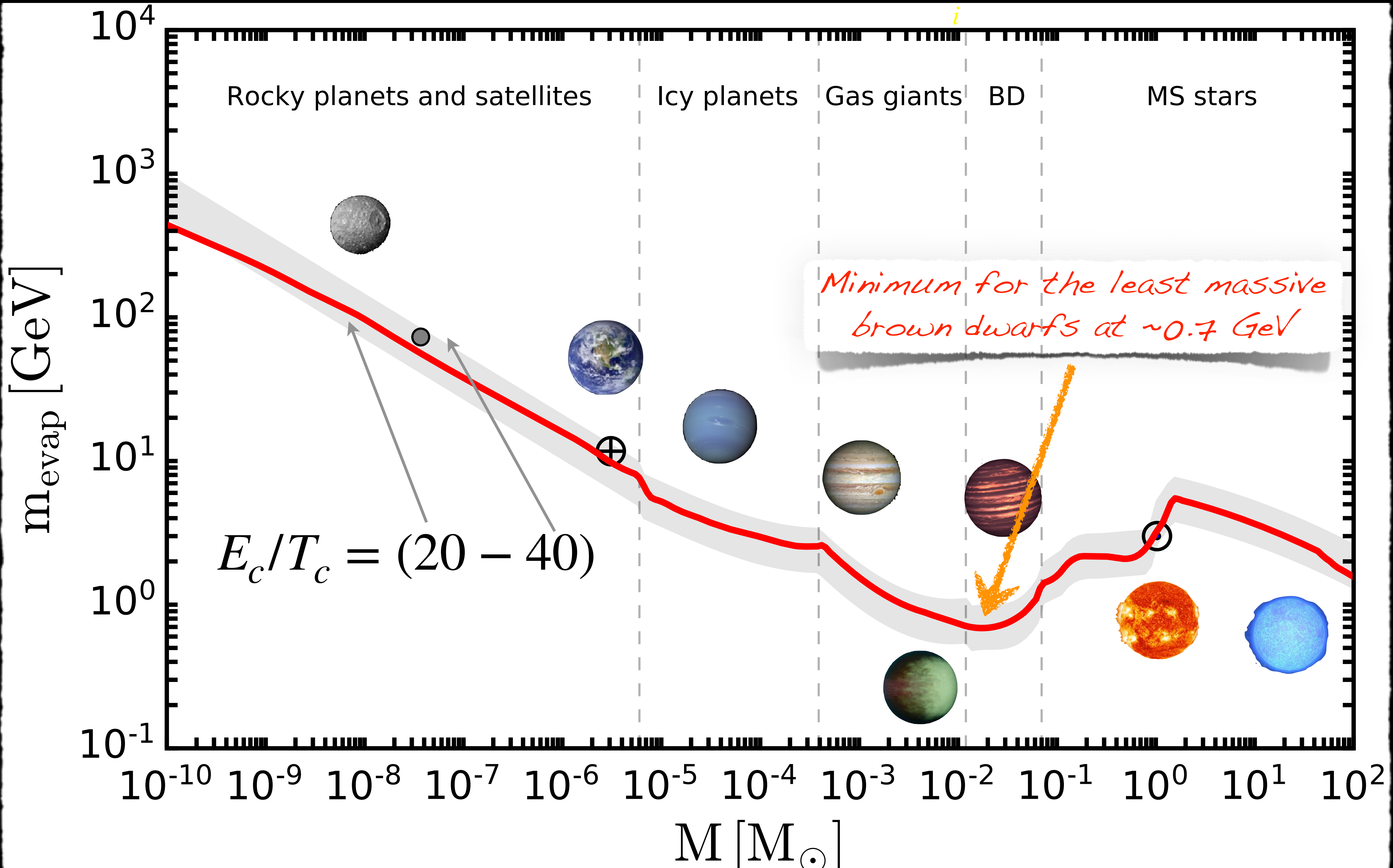
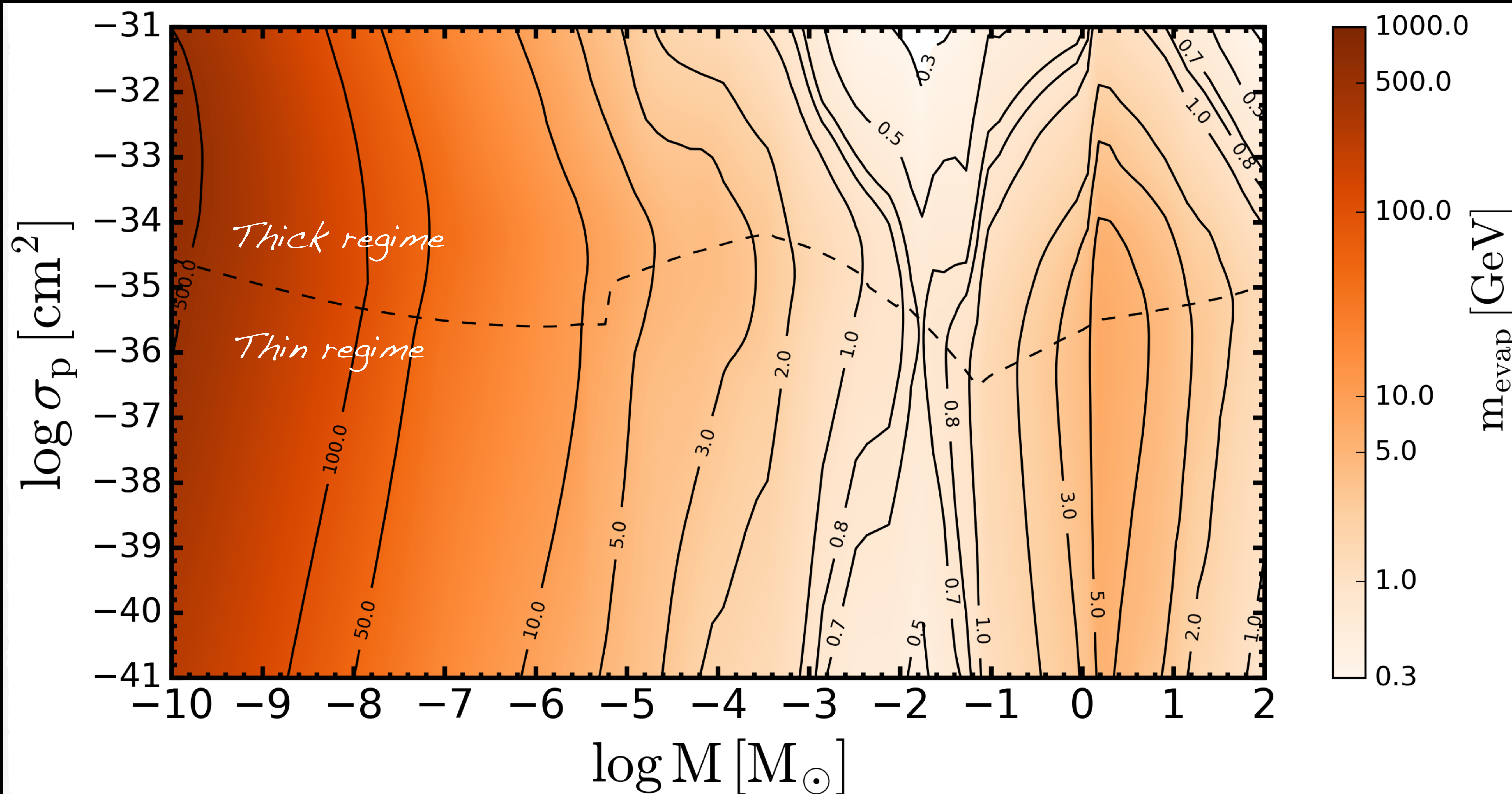


R. Garani and SPR, arXiv:2104.12757

DM evaporation mass for a range of SI cross sections

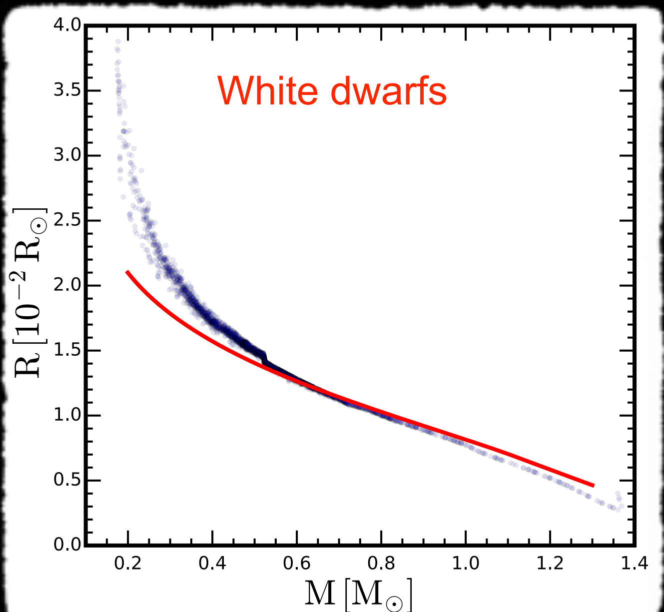


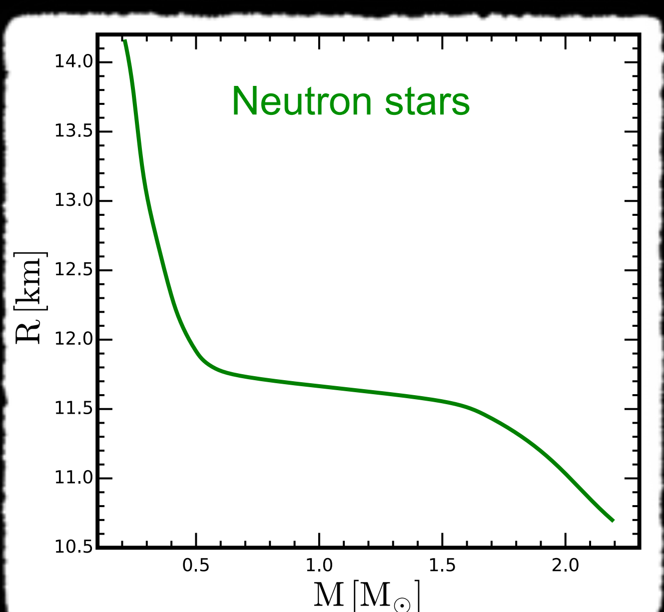
R. Garani and SPR, arXiv:2104.12757

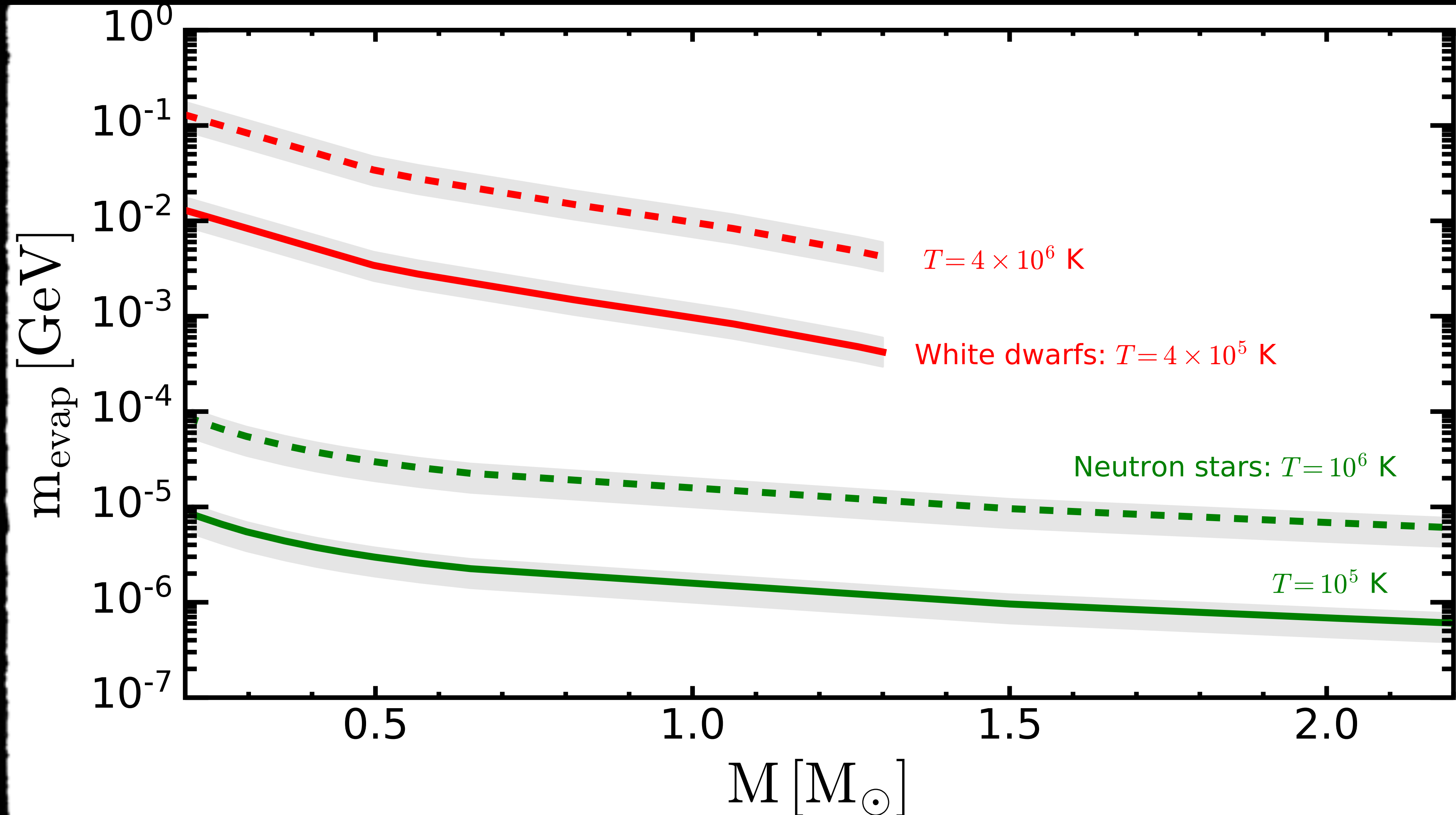
White dwarfs and neutron stars

Much more compact bodies:

very high escape velocity → very low DM evaporation mass







R. Garani and SPR, arXiv:2104.12757

see also: N. F. Bell, G. Busoni, M. E. Ramírez-Quezada, S. Robles and M. Virgato, JCAP 10:083, 2021

The DM evaporation mass in the Sun ($E_c/T_\chi \simeq 30$) is known for over three decades

Similarly, the DM evaporation mass in the Earth ($E_c/T_\chi \simeq 35$) is also known for over three decades

Moreover, the DM evaporation mass had also been estimated for other planets, brown dwarfs and other stars

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So why caring about all this now?

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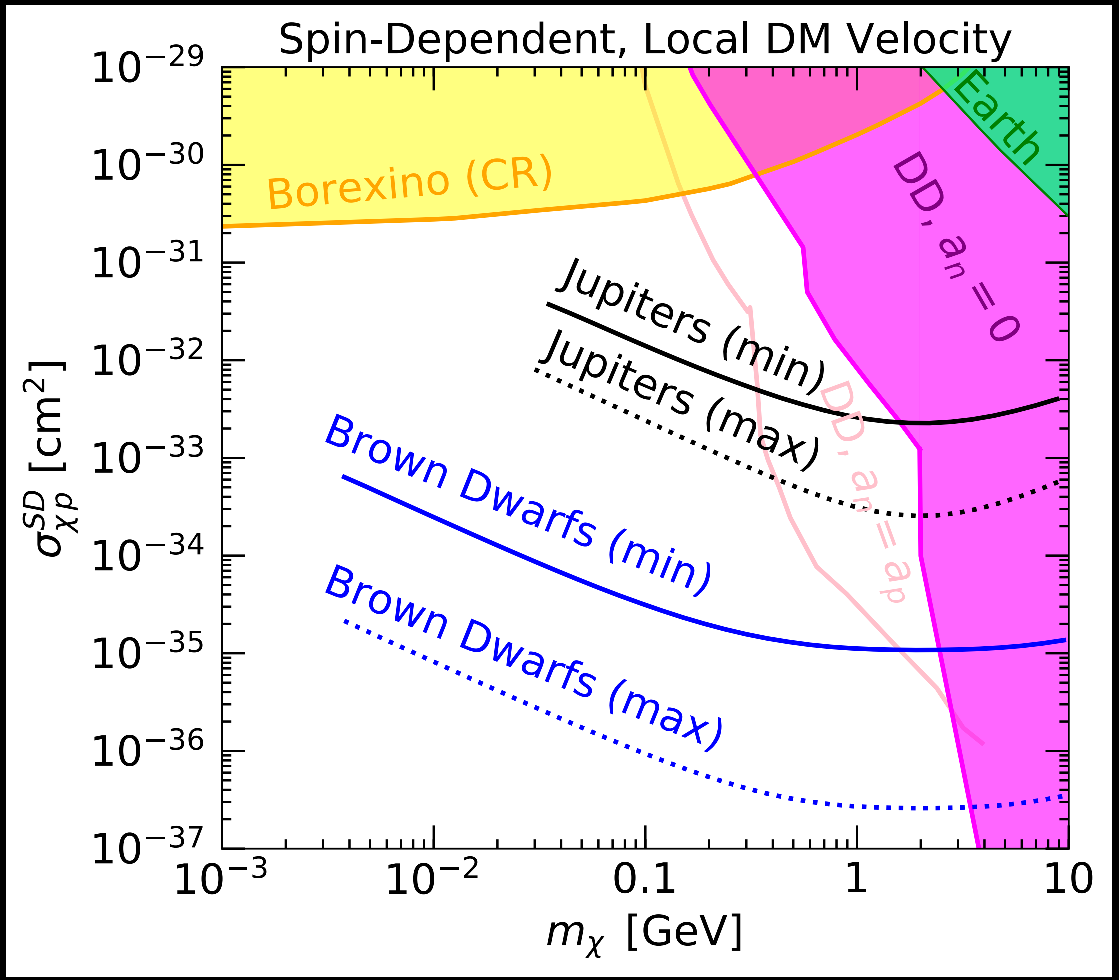
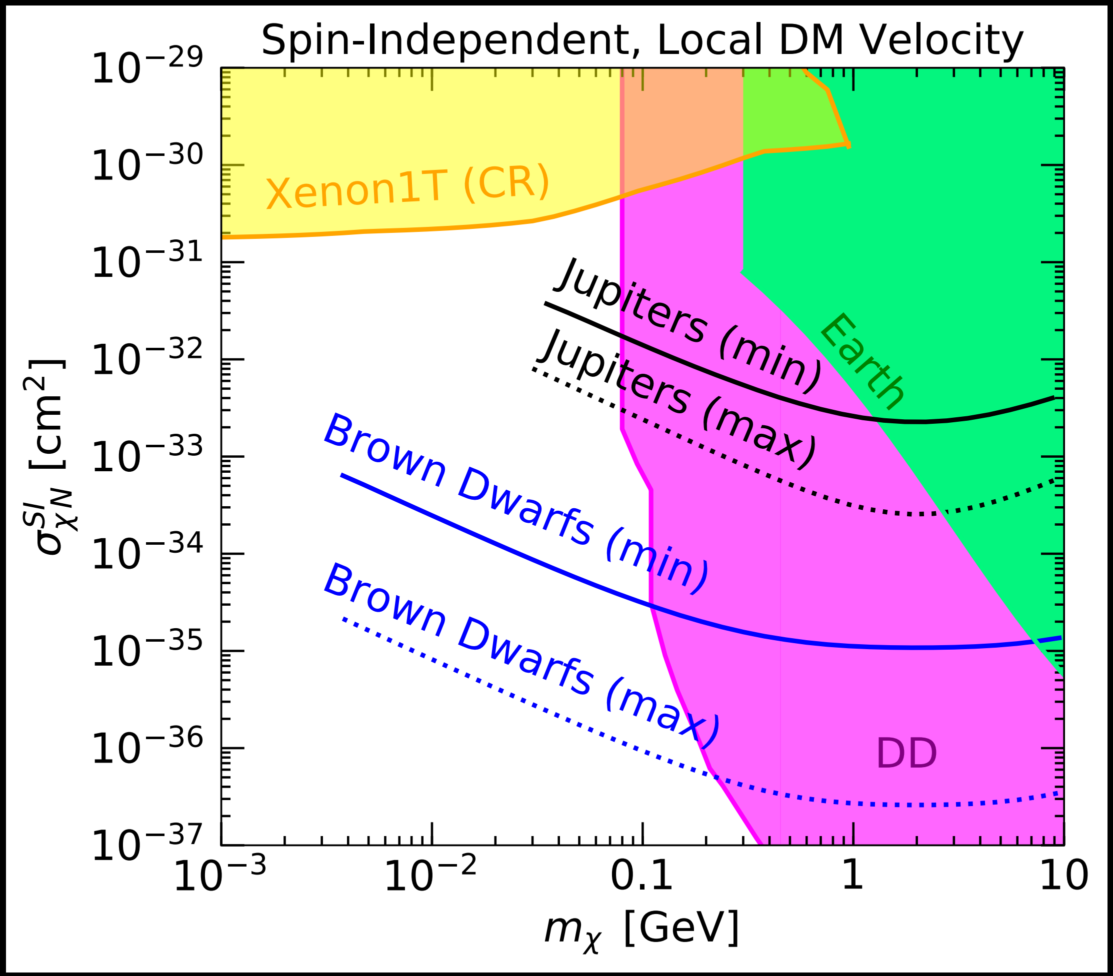
They are not correct

Heating of exoplanets and brown dwarfs





R. K. Leane and J. Smirnov, Phys. Rev. Lett. 126:161101, 2021

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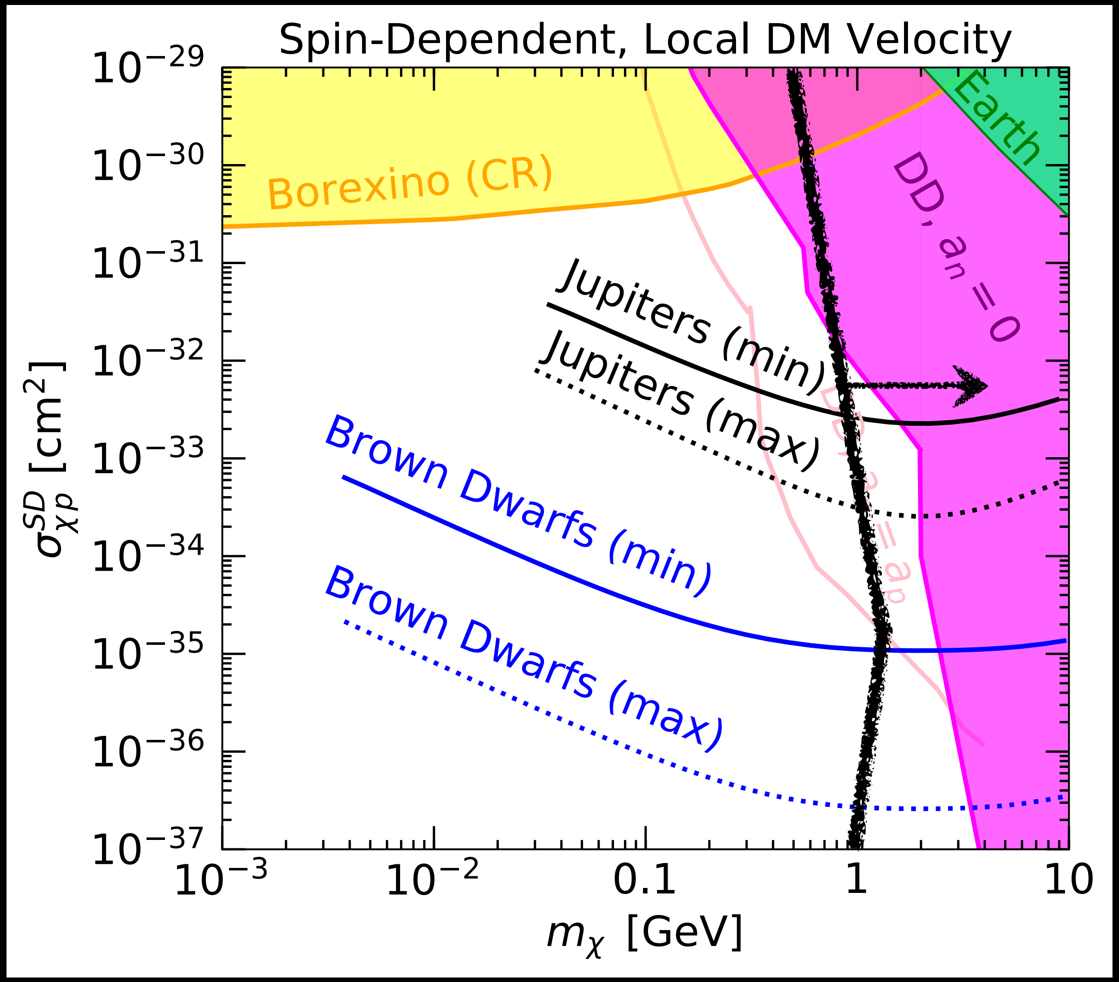

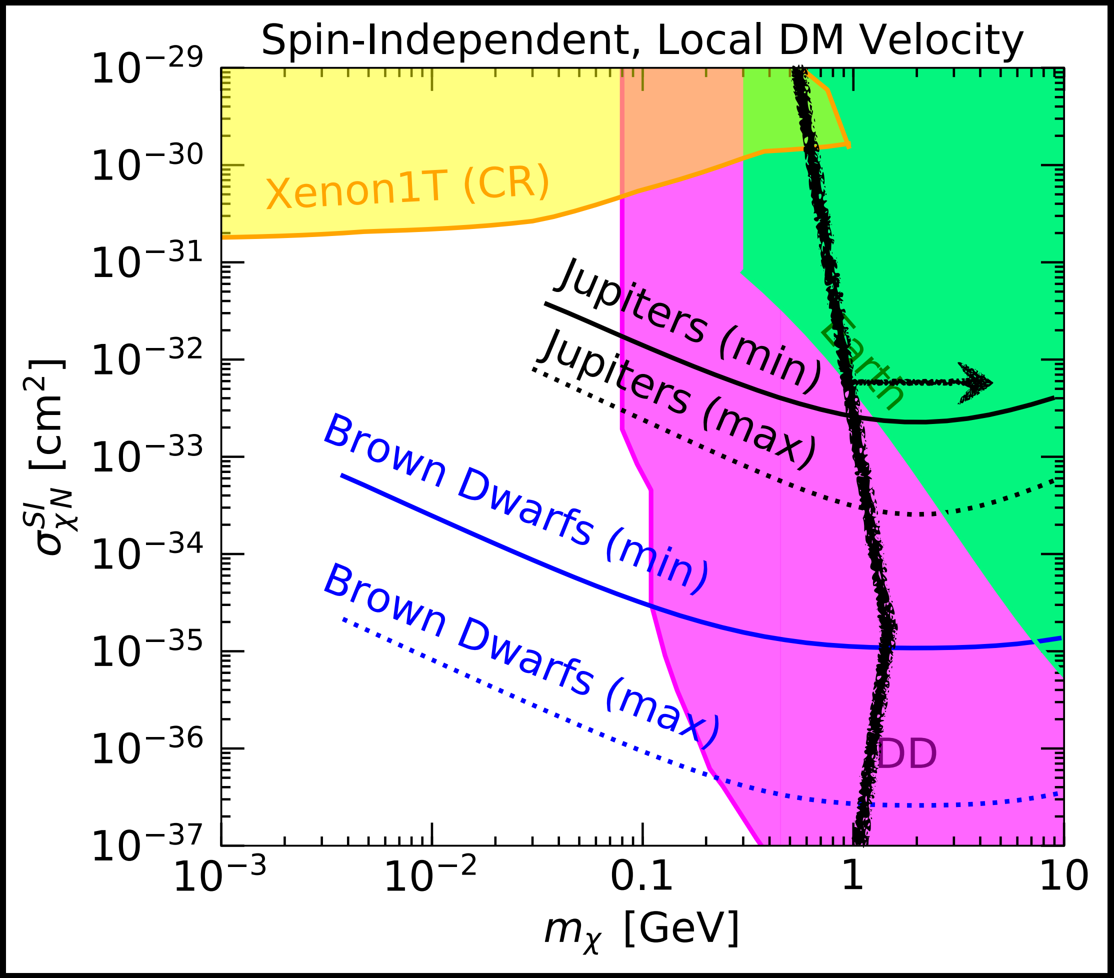

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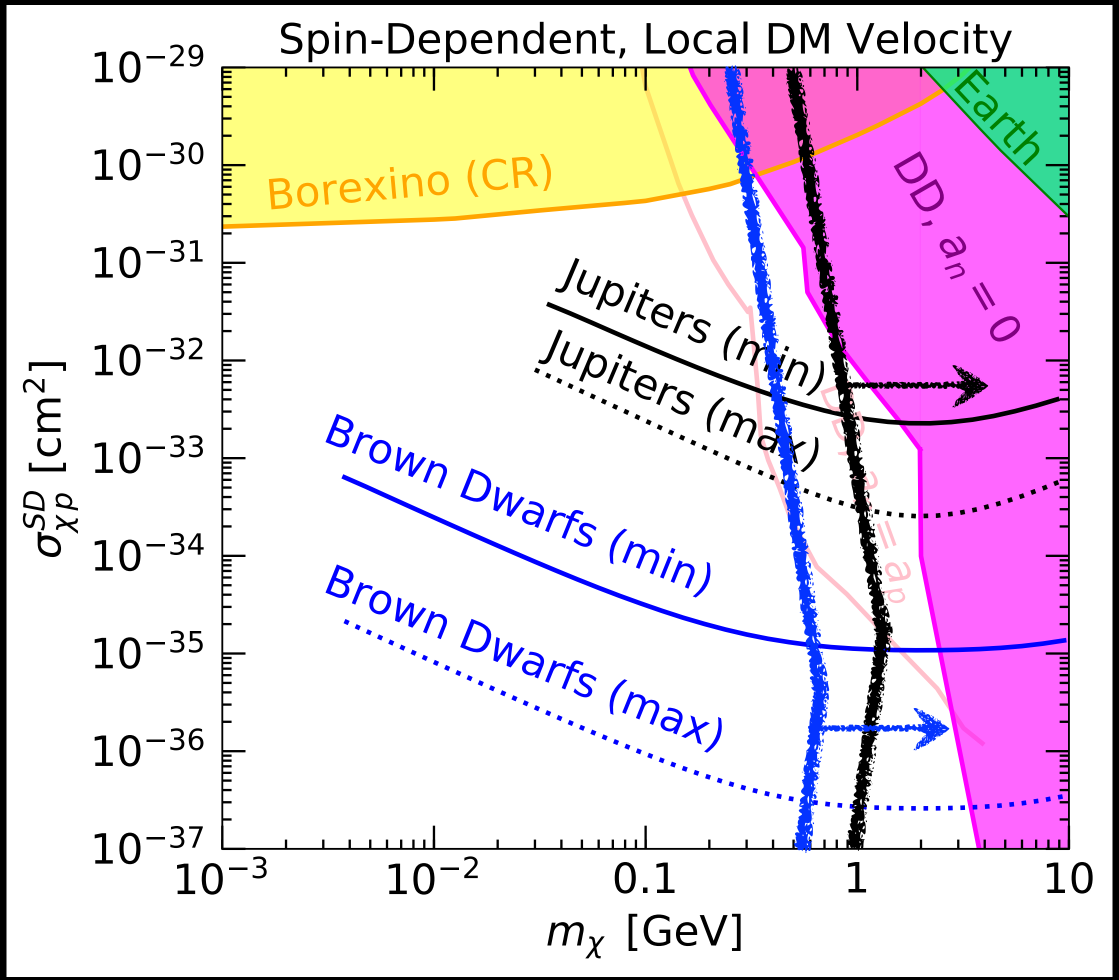

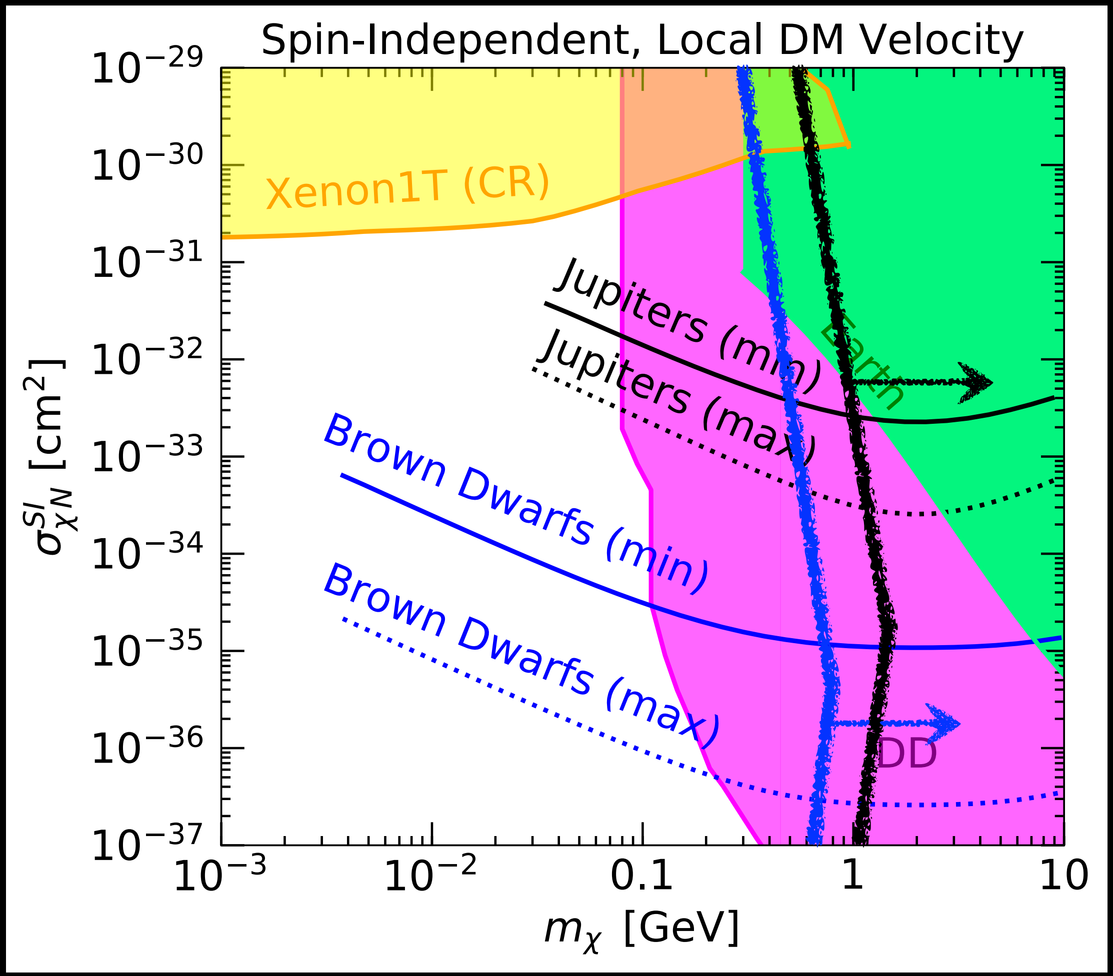

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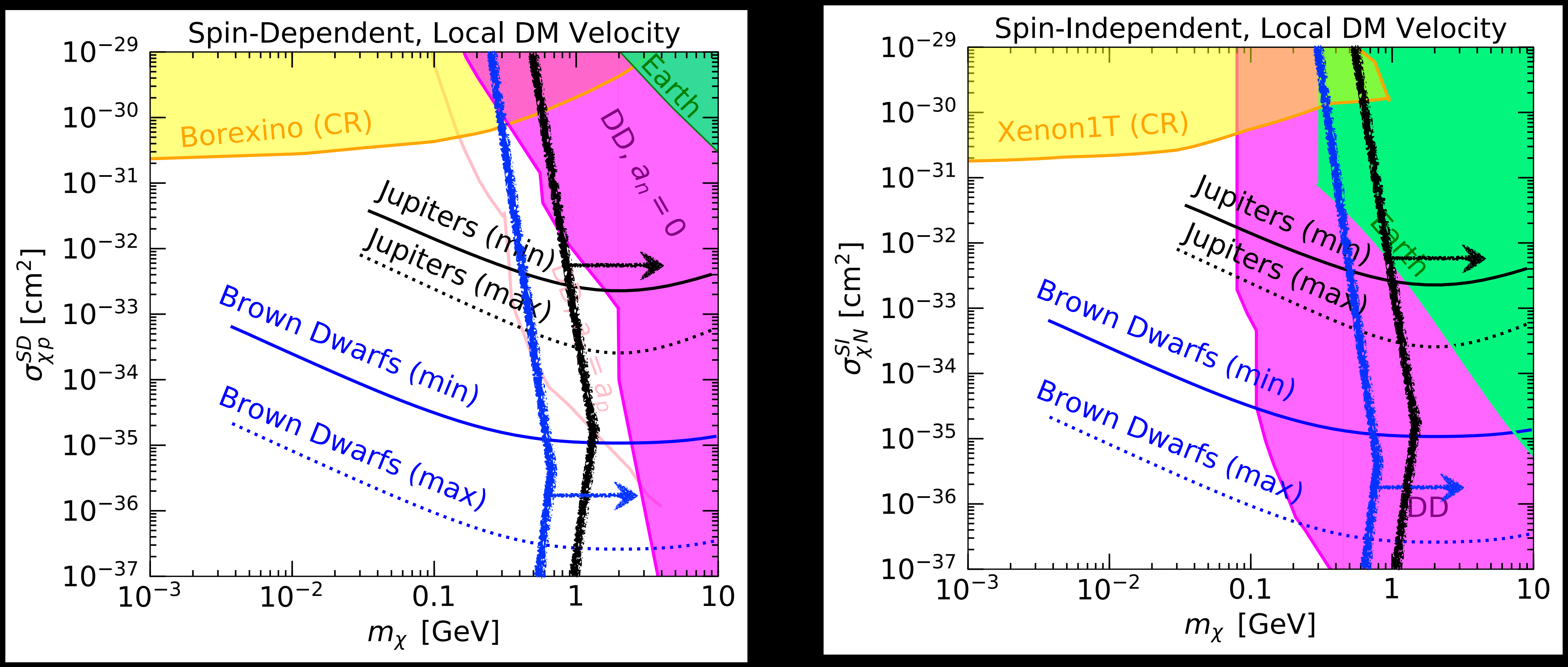

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although this is not the escape energy!

Supposedly, this is a condition on the most probable velocity, $E_c/T_\chi \simeq 1$.
However, the DM evaporation mass is set along the exponential tail!

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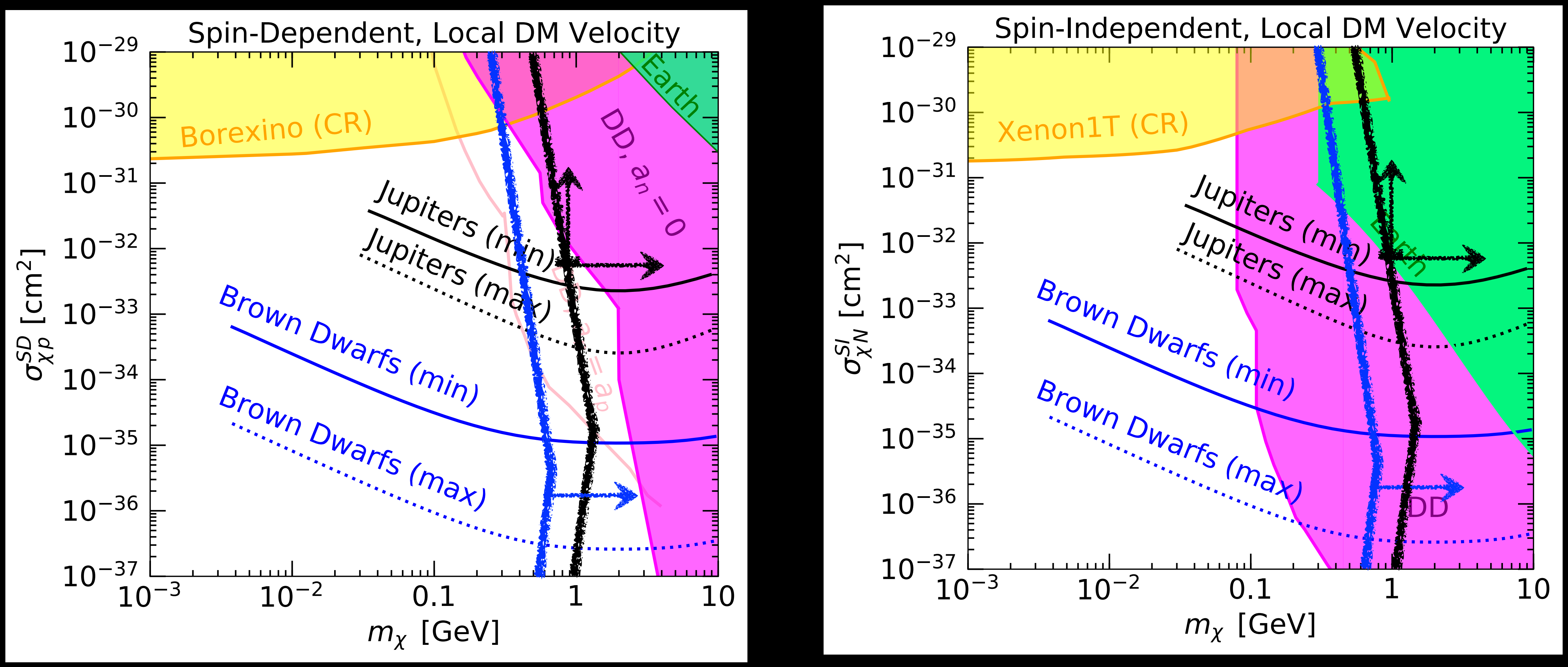

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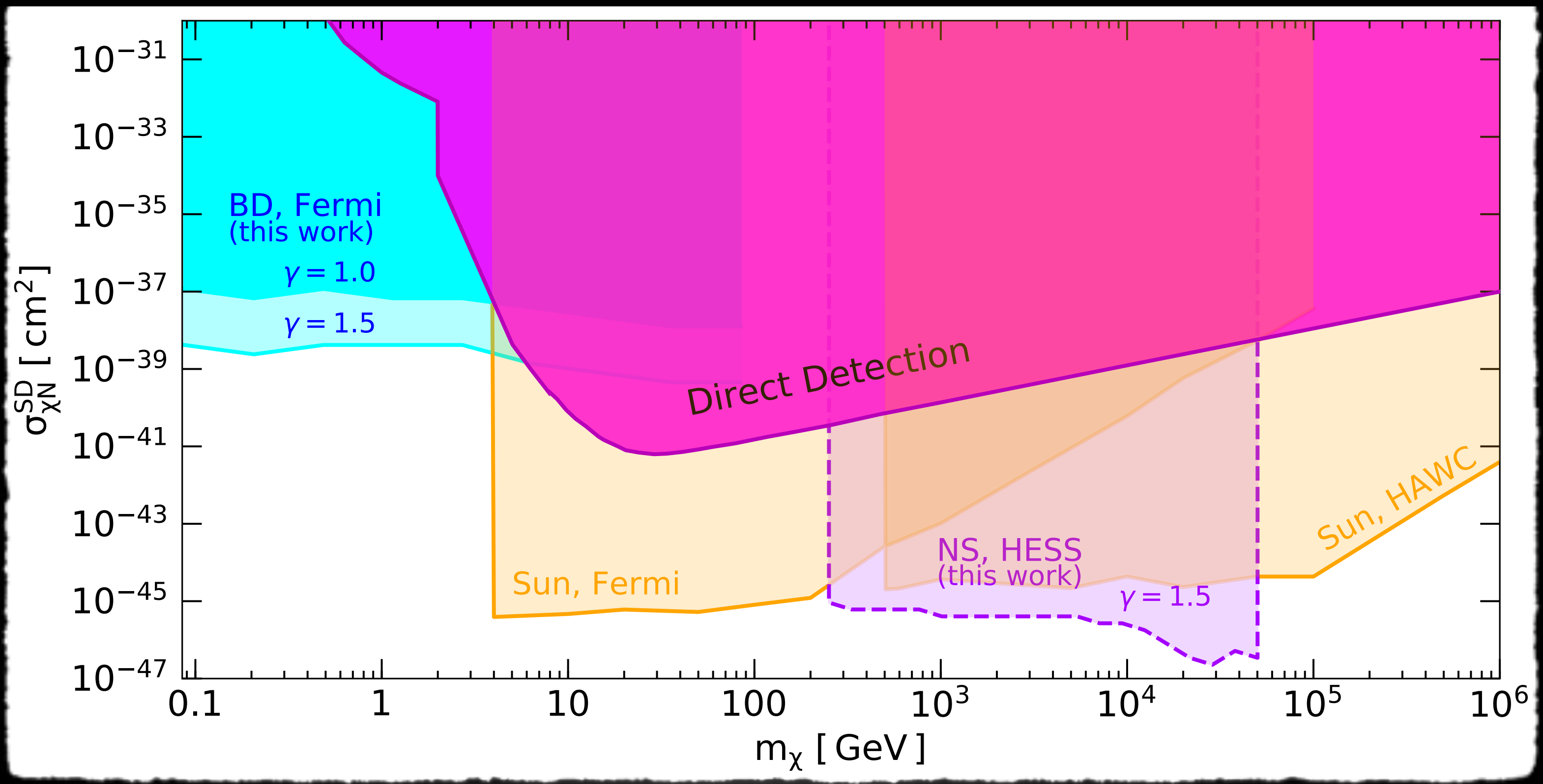
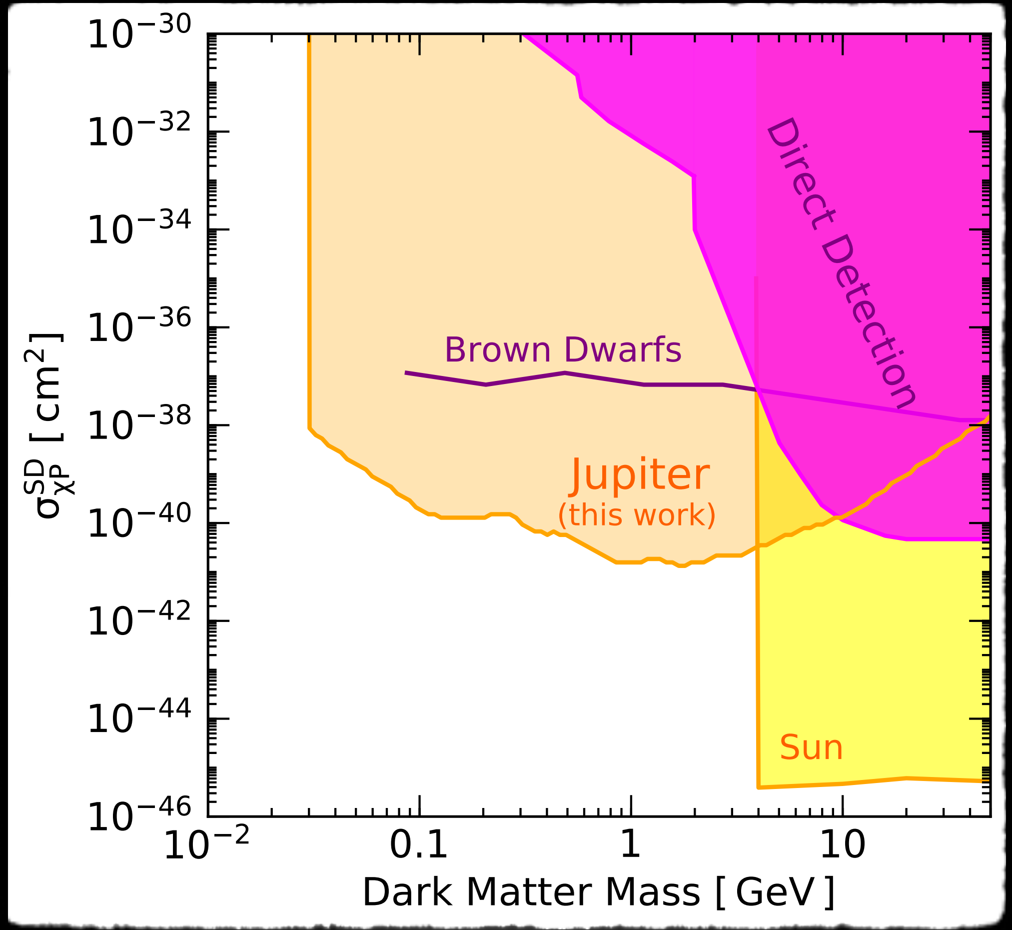
Secluded DM: gamma-rays



R. K. Leane, T. Linden, P. Mukhopadjyay and N. Toro, Phys. Rev. D103:075030, 2021



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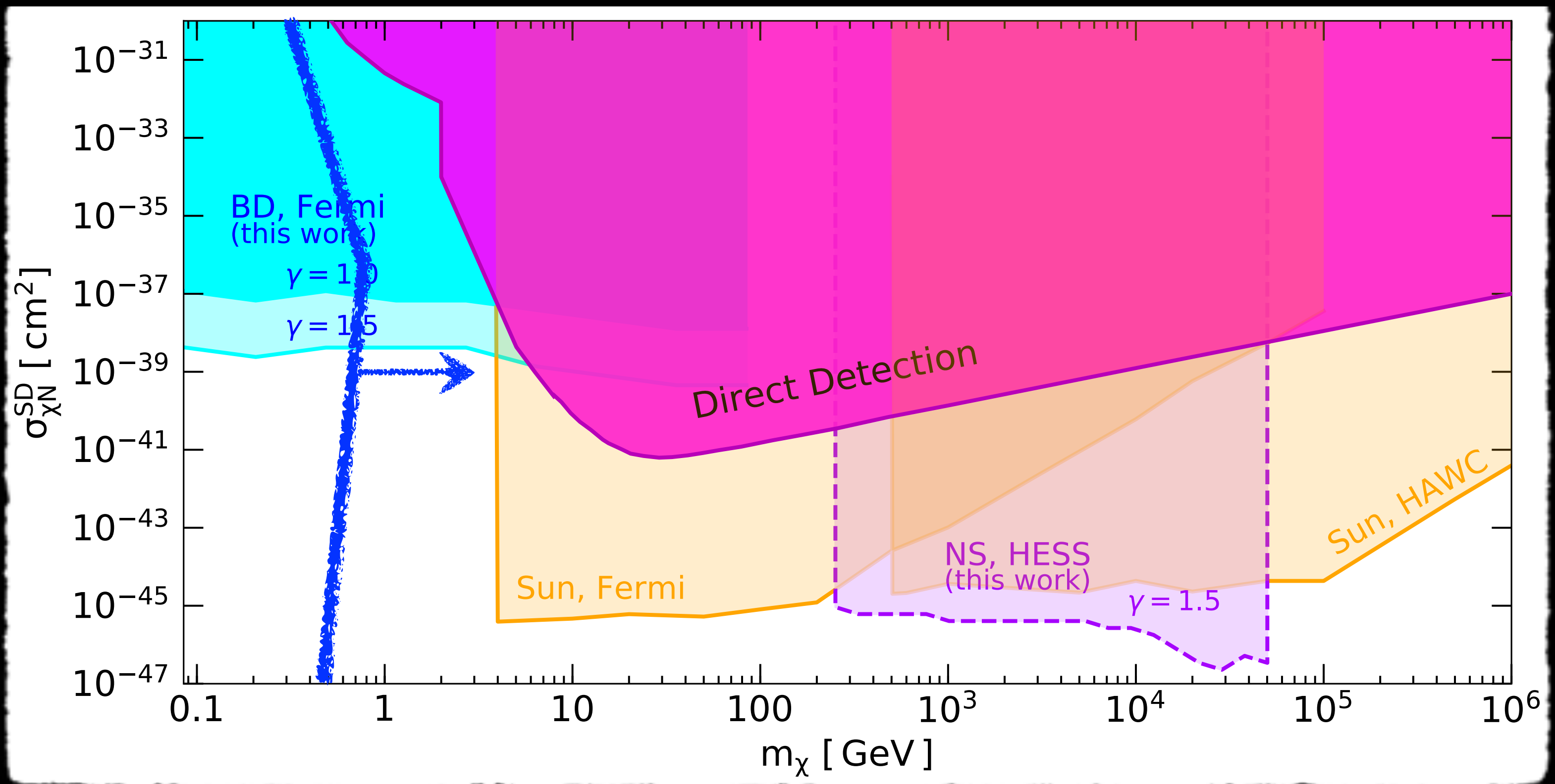

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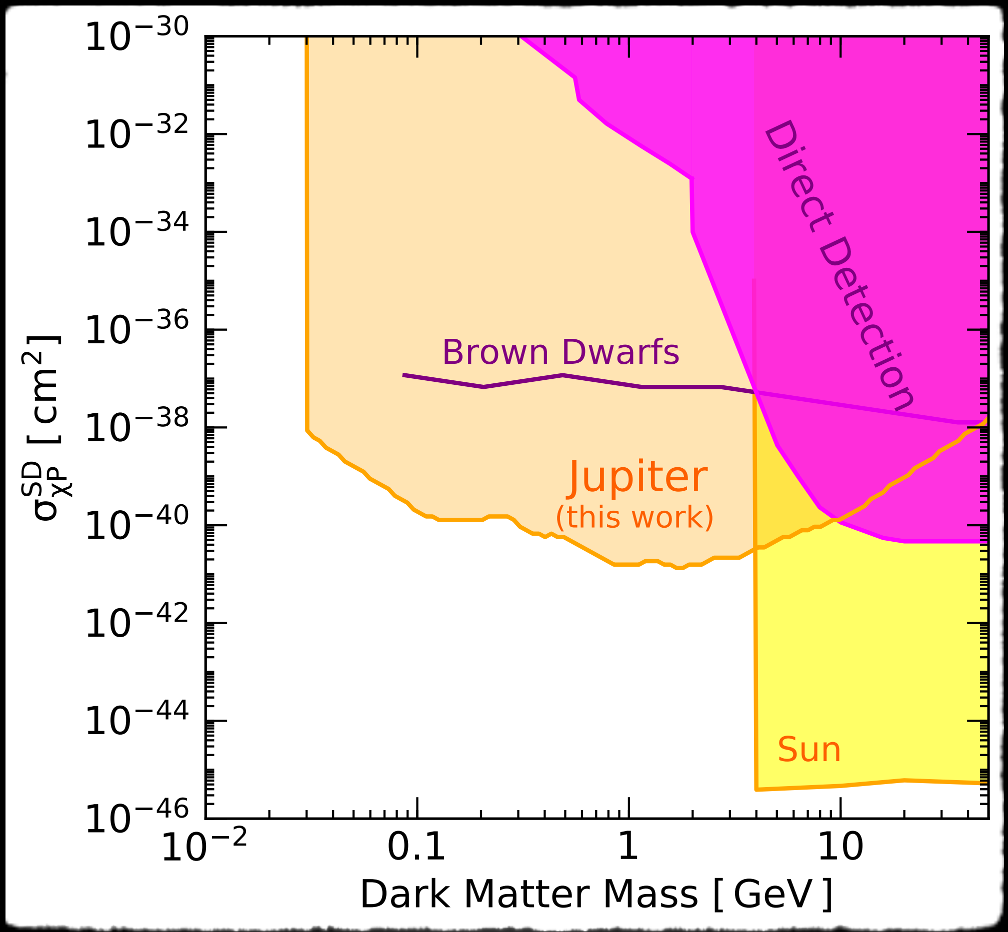

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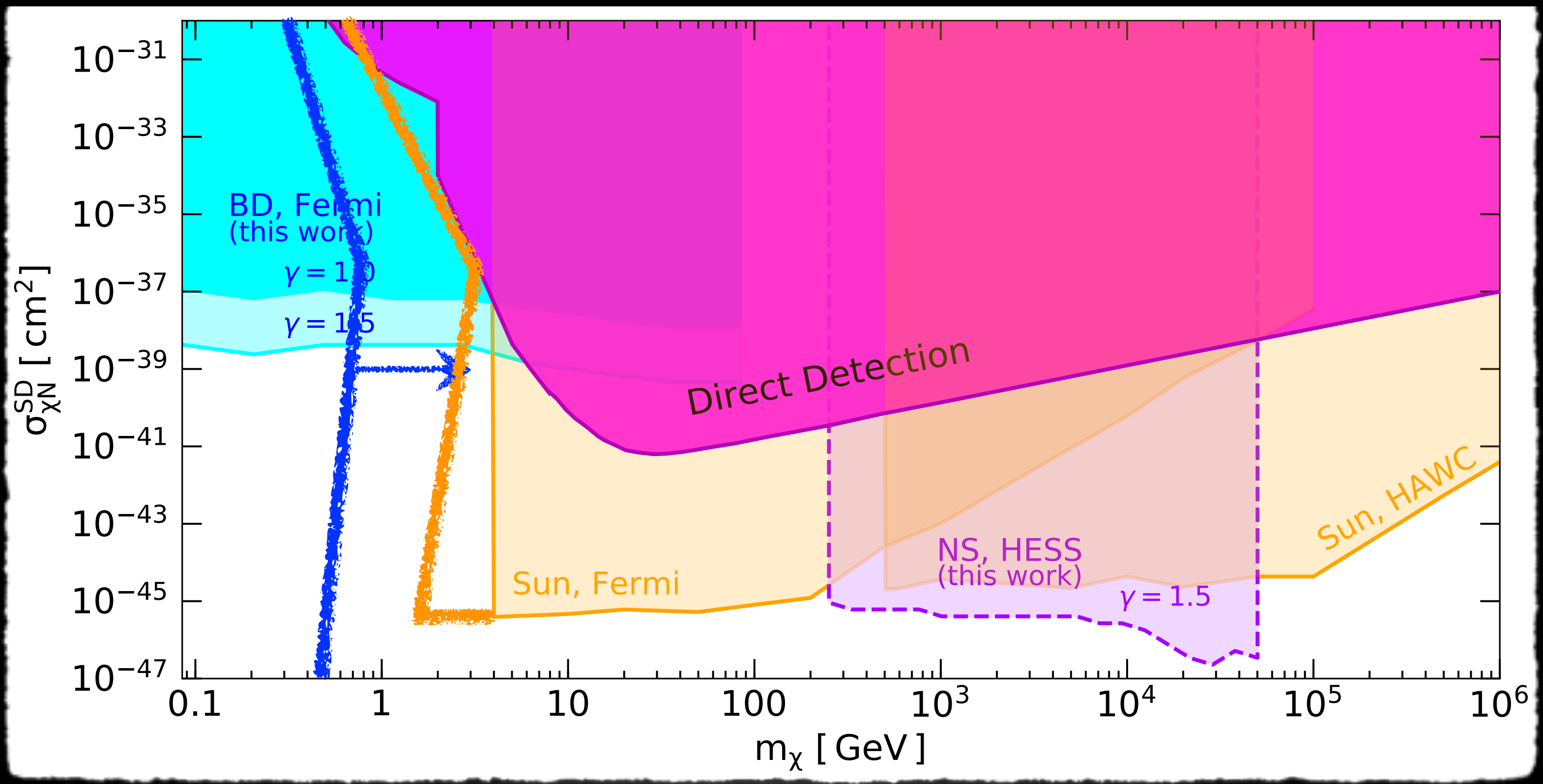

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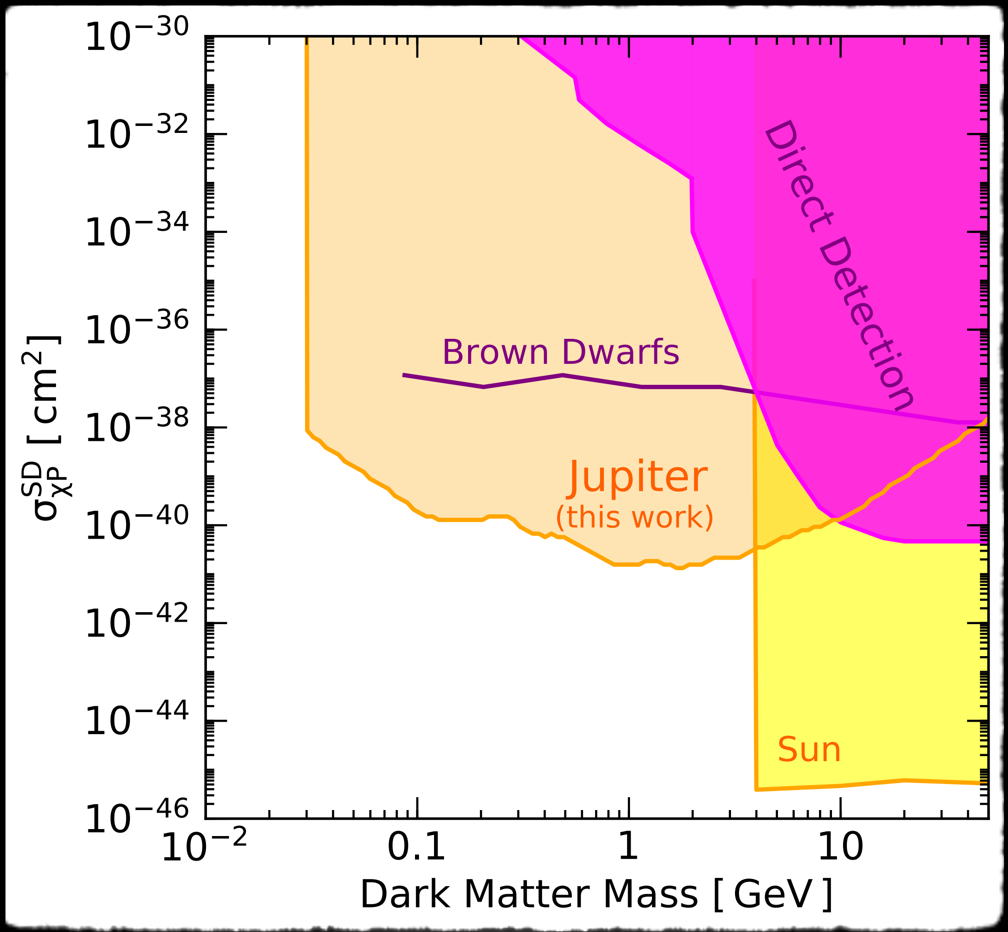

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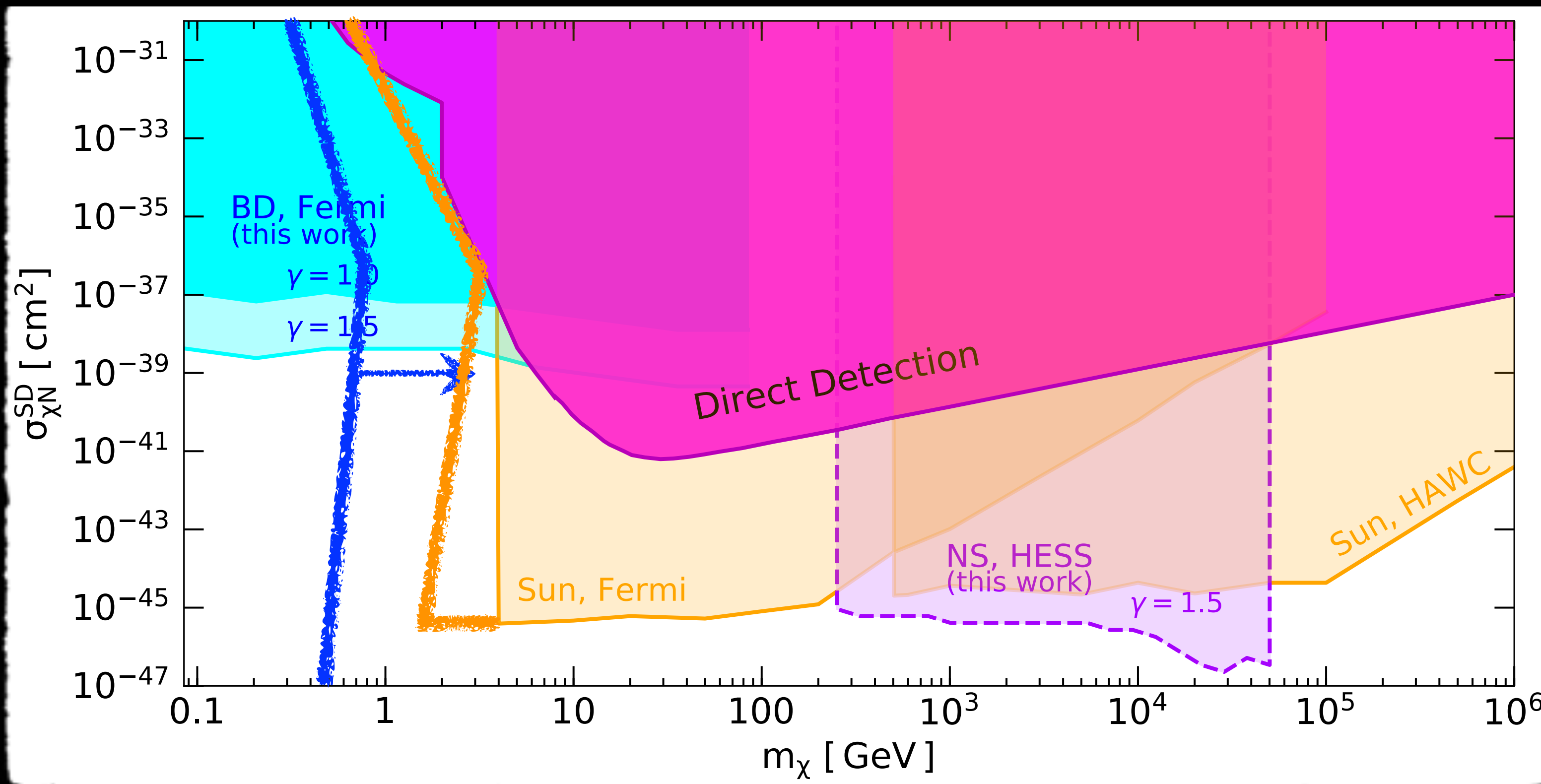

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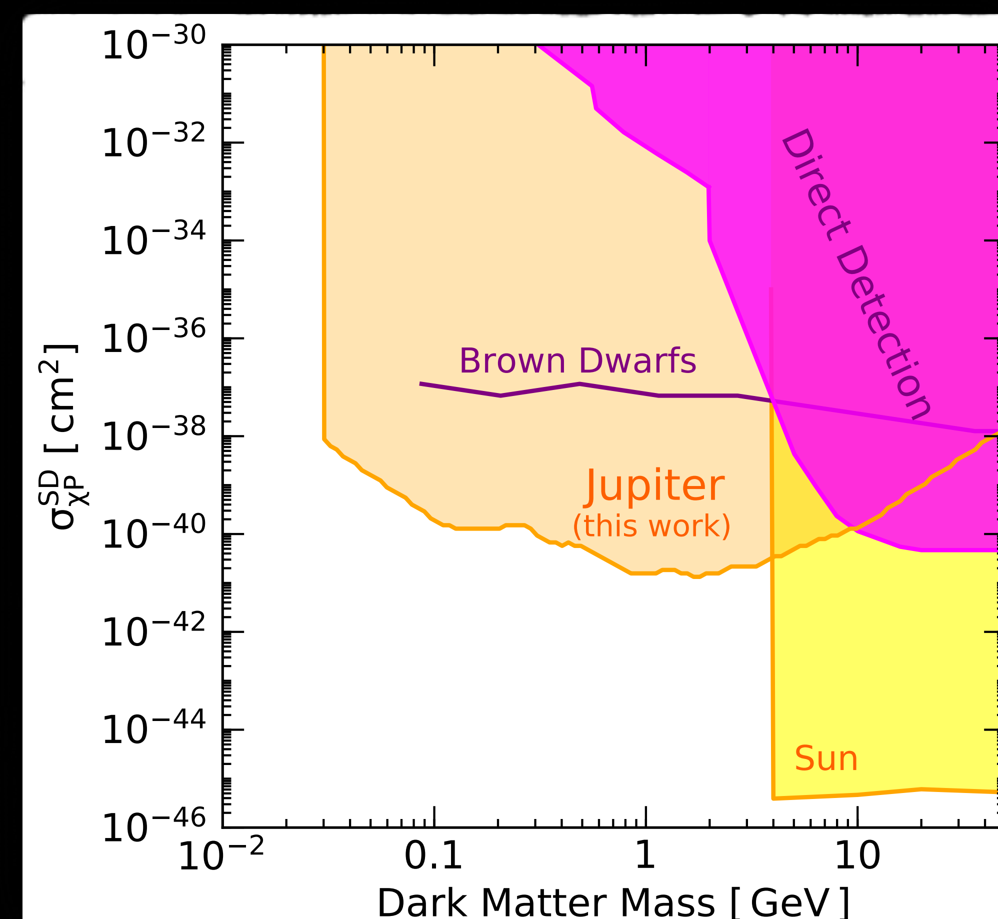

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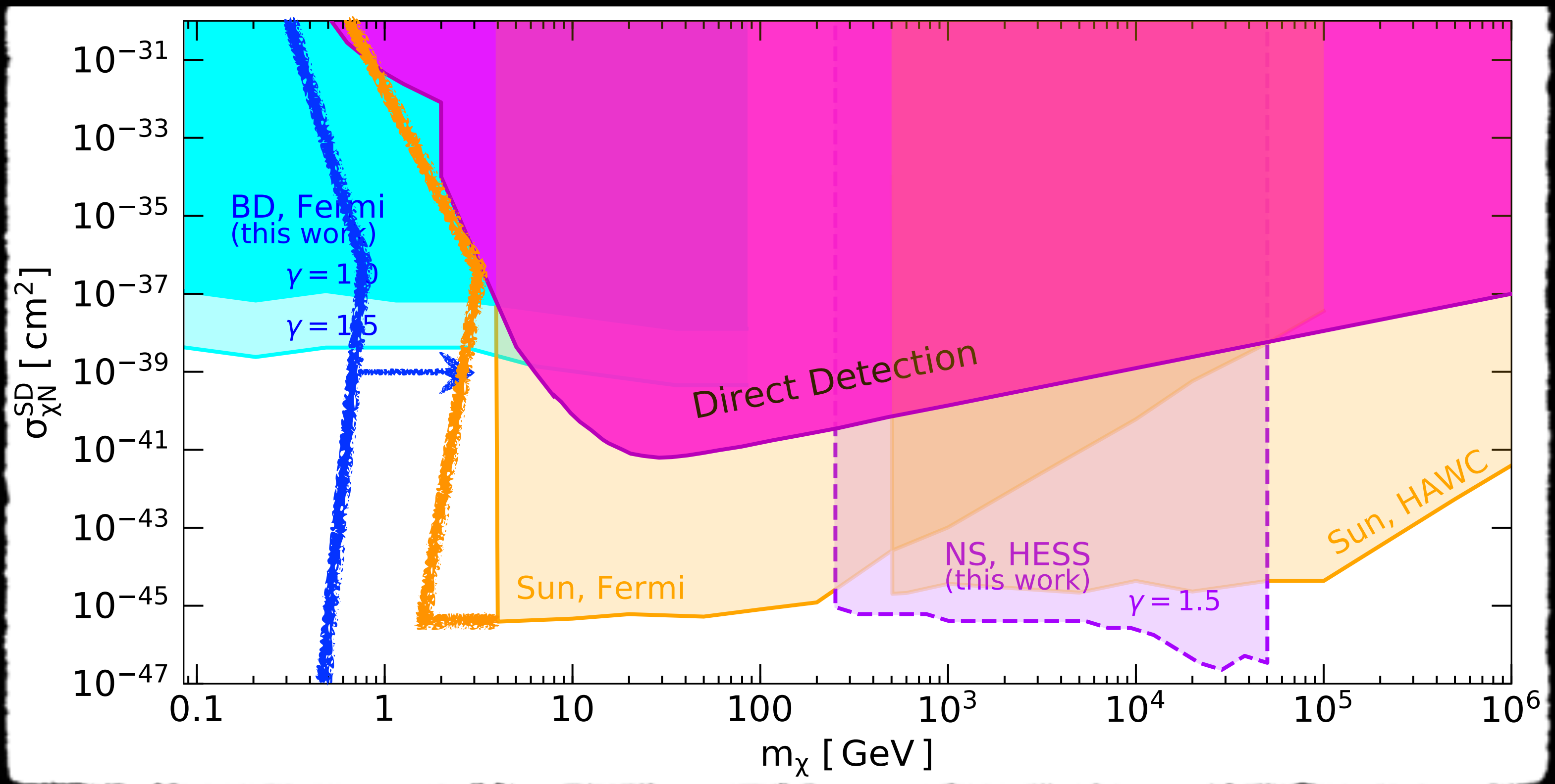

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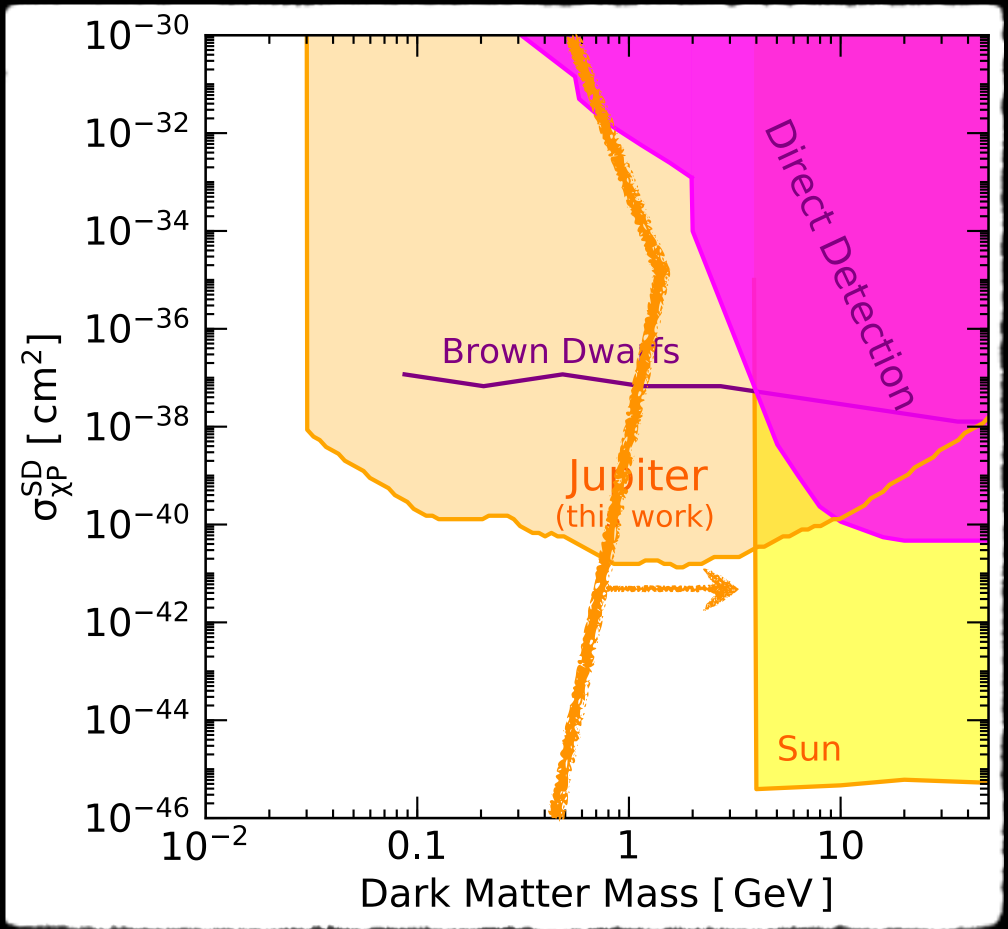

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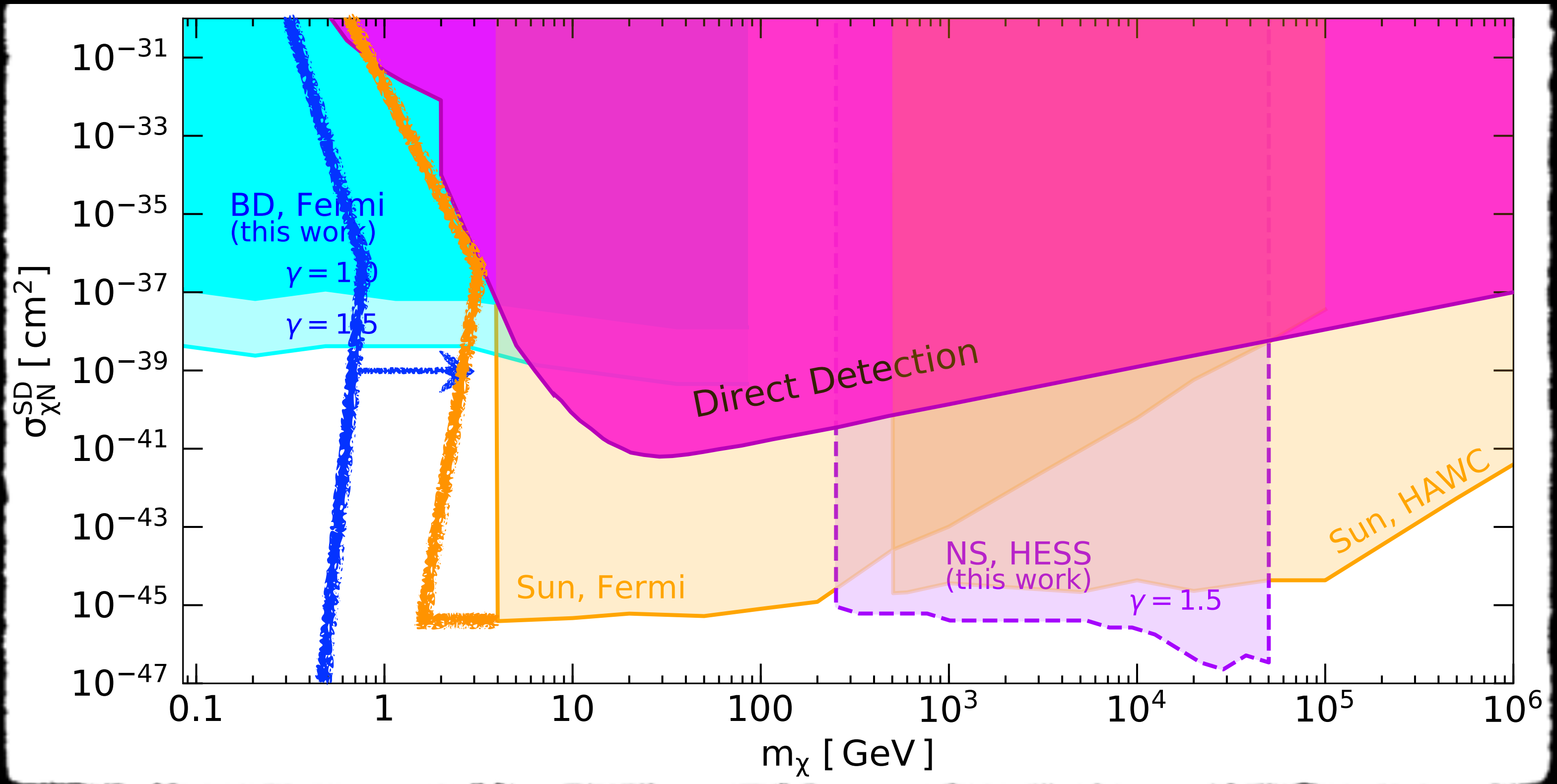

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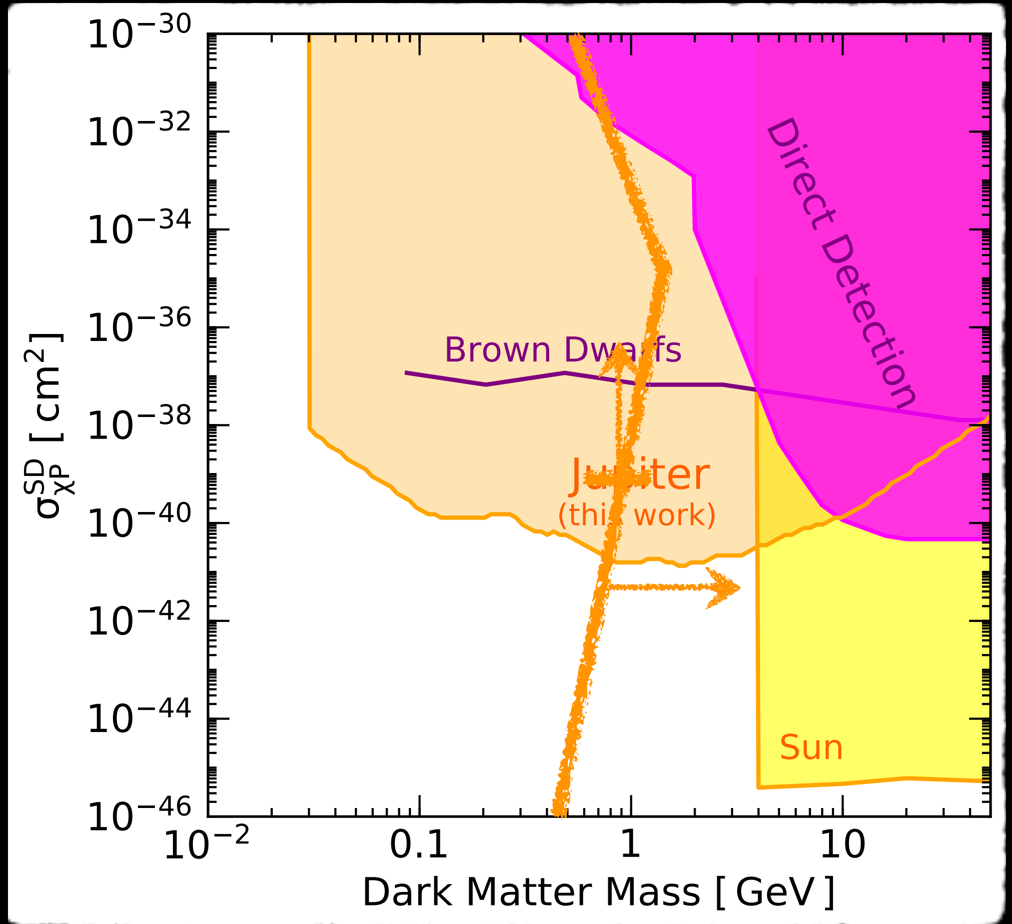

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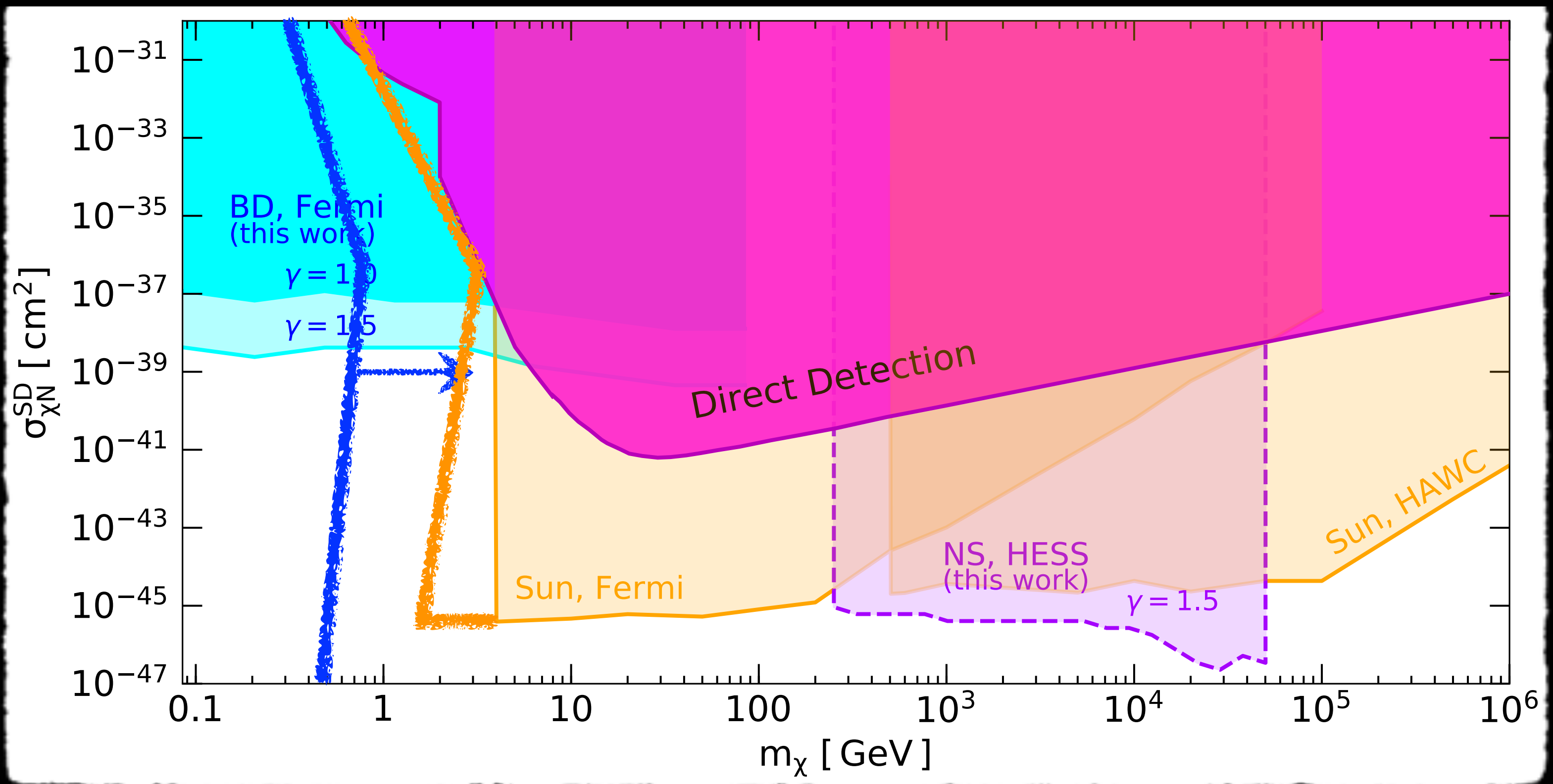

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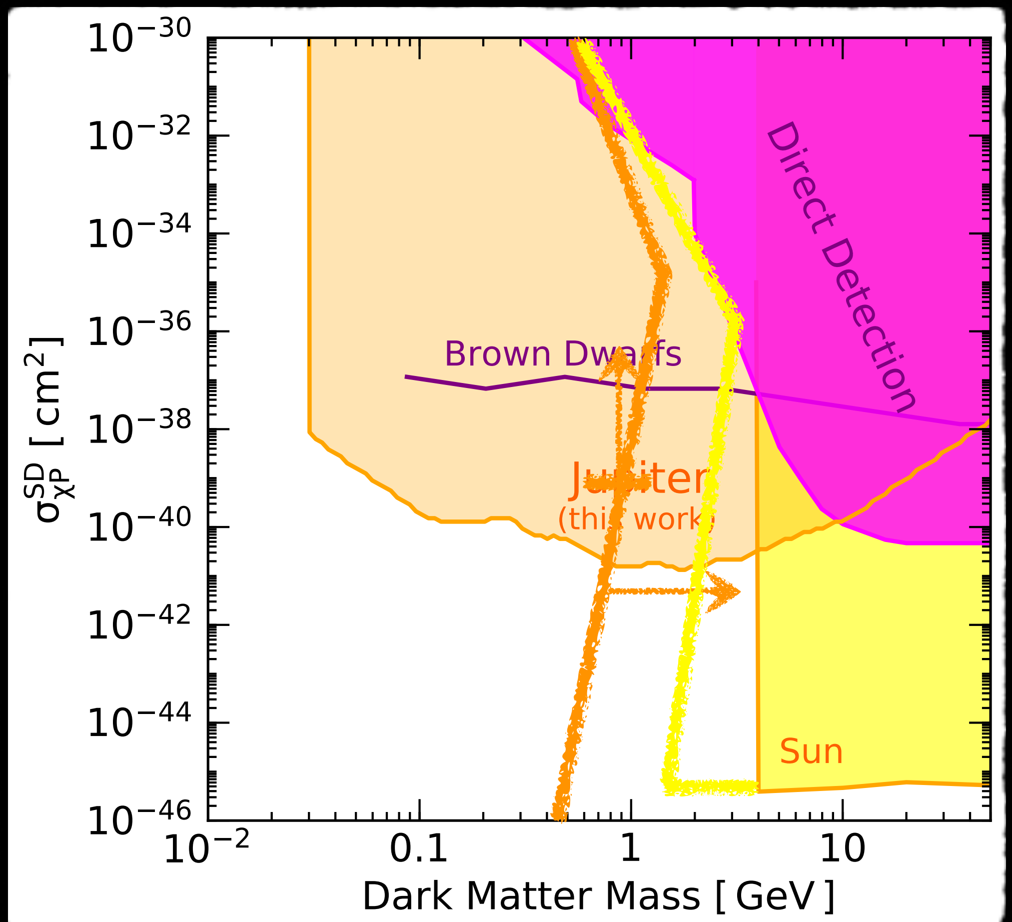

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Is there a way out?

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Location / Annihilation cross section

logarithmic dependence: a factor of 2 in the DM evaporation mass implies a factor of $e^{30} \sim 10^{13}$ in the DM density/velocity or in the annihilation cross section

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Location / Annihilation cross section	SD vs SI scattering cross sections
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additional source of DM capture and evaporation

in the thin regime → larger cross sections imply larger DM evaporation mass

in the thick regime → self-scatterings are excluded by current bounds

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Uncertainties in core temperature

related to mass and radius via the virial theorem

Conclusions

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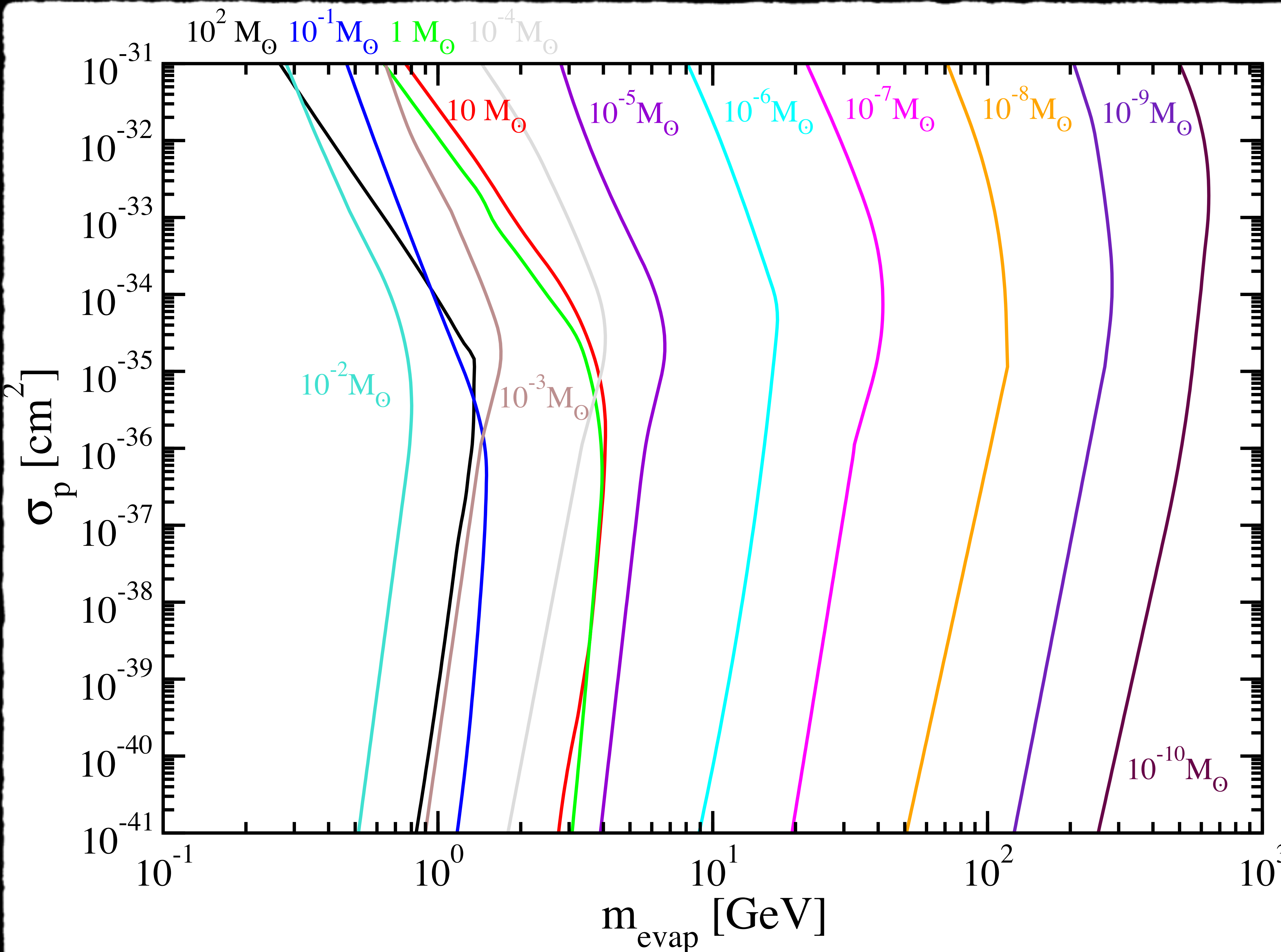
Some recent calculations underestimate the DM evaporation mass by more than an order of magnitude, so the implied phenomenological applications need to be revised

Backup



$10^2 M_\odot$ $10^{-1} M_\odot$ $1 M_\odot$ $10^{-4} M_\odot$
$10 M_\odot$
$10^{-5} M_\odot$
$10^{-6} M_\odot$
$10^{-7} M_\odot$
$10^{-8} M_\odot$
$10^{-9} M_\odot$
$10^{-2} M_\odot$
$10^{-3} M_\odot$
$10^{-10} M_\odot$
σ_p [cm^2]
m_{evap} [GeV]

Main ingredients

Dark matter particles:

Maxwell-Boltzmann velocity distribution (in the galactic frame)

$$f_{v_{cb}}(u_\chi) = \frac{1}{2}\int_{-1}^{1} f_{gal}\left(\sqrt{u_\chi^2 + v_{cb}^2 + 2\,u_\chi\,v_{cb}\,\cos\theta}\right) d\cos\theta = \sqrt{\frac{3}{2\pi}}\frac{u_\chi}{v_{cb}\,v_d}\left(e^{-\frac{3\,(u_\chi - v_{cb})^2}{2\,v_d^2}} - e^{-\frac{3\,(u_\chi + v_{cb})^2}{2\,v_d^2}}\right)$$

DM velocity at infinity

velocity of the celestial body (in the galactic frame)

angle between the DM particle and the celestial body velocities

Target nuclei:

Maxwell-Boltzmann velocity distribution, with temperature T(r)

$$f_i(\boldsymbol{u}, r) = \frac{1}{\sqrt{\pi^3}}\left(\frac{m_i}{2\,T(r)}\right)^{3/2} e^{-\frac{m_i\,u^2}{2\,T(r)}}$$

DM - nuclei scattering cross section

Capture of DM by celestial bodies

W. H. Press and D. N. Spergel, Astrophys. J. 296:679, 1985
A. Gould, Astrophys. J. 321:571, 1987

G. Busoni, A. De Simone, P. Scott and A. C. Vincent, JCAP 10:037, 2017

$$dC = s_{\rm cap}(r) \quad \times \quad 4\pi r^2 \left(\frac{\rho_\chi}{m_\chi}\right) f_{v_{\rm cb}}(u_\chi)\, u_\chi\, du_\chi \frac{d\cos^2\theta}{4} \quad \times \quad \Omega^-_{v_e}(w) \quad \times \quad \frac{dl}{w}$$

suppression factor to account for large optical depths

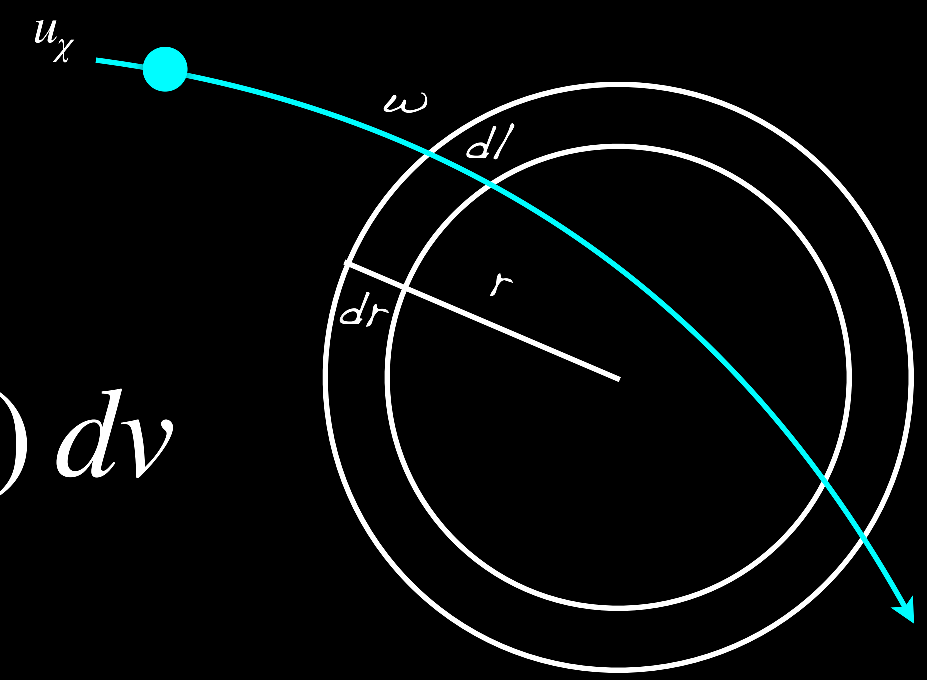
flux of DM particles reaching a spherical shell at radius r

rate of scattering from w to a speed less than the escape velocity

time spent in a shell dr

DM velocity at the distance r due to the gravitational field

$$w^2(r) = u_\chi^2 + v_e^2(r)$$



$$\Omega^-_{v_e}(w) = \sum_i \int_0^{v_e} R_i^-(w \to v)\, dv$$

rate of scattering from speed w to $v < v_e$

$$R_i^-(w \to v) = \int n_i(r) \frac{d\sigma_i}{dv} \sqrt{u^2 + w^2 - 2\,u\,w\,\cos\theta_i}\, f_i(u)\, du\, d\cos\theta_i$$

differential scattering cross section

velocity distribution of target nuclei

Capture of DM by celestial bodies

If target particles are nuclei, the zero-temperature approximation is reasonable (and relatively simple) for the calculation of the capture rate

For weak cross sections (long mean free path):

$$C_{\text{weak}} = \left(\frac{\rho_\chi}{m_\chi}\right)\langle v\rangle_0 \sum_i N_i \sigma_i \left\langle \frac{\hat{\phi}}{\langle\hat{\phi}\rangle_i}\left(1 - \frac{1-e^{-B_i^2}}{B_i^2}\right)\xi_1(B_i)\right\rangle_i \left(\frac{3}{2}\frac{v_e^2(R)}{v_d^2}\langle\hat{\phi}\rangle_i\right)$$

$$B_i^2(r) \equiv \frac{3}{2}\frac{v_e^2(r)}{v_d^2}\frac{\mu_i}{\mu_{-,i}^2} \quad ; \quad \mu_i \equiv \frac{m_\chi}{m_i} \quad ; \quad \mu_{-,i} \equiv \frac{\mu_i - 1}{2} \quad ; \quad \hat{\phi}(r) \equiv \frac{v_e^2(r)}{v_e^2(R)} \quad ; \quad \langle\hat{\phi}\rangle_i \equiv \frac{\int_0^R \hat{\phi}(r)\, n_i(r)\, 4\pi\, r^2\, dr}{N_i}$$

For large cross sections (short mean free path): the saturation limit

$$C_{\text{sat}} = \frac{\pi R^2}{\sum_i N_i \sigma_i}\left(\frac{\rho_\chi}{m_\chi}\right)\langle v\rangle_0 \left[\sum_i N_i \sigma_i \left(1 - \frac{1-e^{-B_i^2(R)}}{B_i^2(R)}\right)\right] \xi_1(B_i(R)) \left(\frac{3}{2}\frac{v_e^2(R)}{v_d^2}\right)$$

Annihilation of DM in celestial bodies

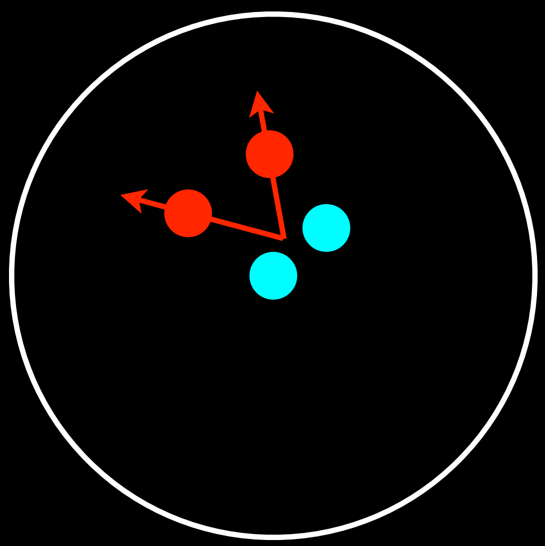
After DM particles get captured, further scatterings with target nuclei would approximately thermalize them at a temperature T_χ and attain a velocity distribution that can be approximated as Maxwell-Boltzmann

$$f_\chi(\mathbf{w}, r) = \frac{e^{-w^2/v_\chi^2(r)}\,\Theta(v_e(r) - w)}{\sqrt{\pi^3}\,v_\chi^3(r)\left(\mathrm{Erf}\left(\frac{v_e(r)}{v_\chi(r)}\right) - \frac{2}{\sqrt{\pi}}\frac{v_e(r)}{v_\chi(r)}\,e^{-v_e^2(r)/v_\chi^2(r)}\right)}$$

$$v_\chi(r) \equiv \sqrt{\frac{2\,T_\chi(r)}{m_\chi}}$$

A. Gould, Astrophys. J. 321:560, 1987 A. Gould and G. Raffelt, Astrophys. J. 352:669, 1990

$$\mathrm{A} = \langle \sigma_A v_{\chi\chi} \rangle \frac{\int_0^{R_\odot} n_\chi^2(r,t)\,4\pi r^2\,dr}{\left(\int_0^{R_\odot} n_\chi(r,t)\,4\pi r^2\,dr\right)^2}$$



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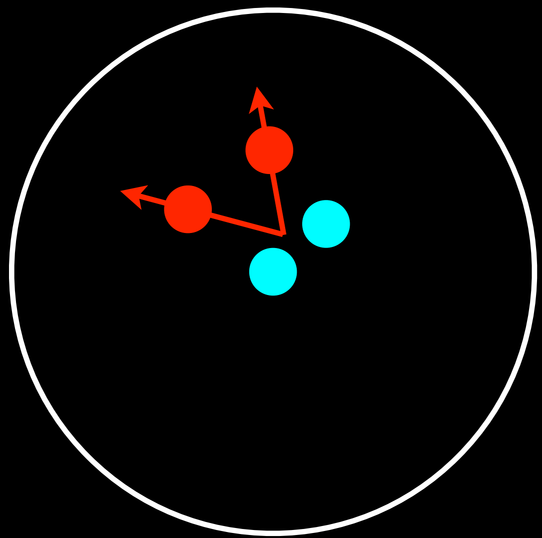


thin regime: isothermal thick regime: LTE

$$n_\chi(r,t) f_\chi(\mathbf{w}, r) = \left(1 - \mathfrak{f}(K)\right)\, n_{\chi,\mathrm{iso}}(r,t) f_{\chi,\mathrm{iso}}(\mathbf{w}, r) + \mathfrak{f}(K)\, n_{\chi,\mathrm{LTE}}(r,t) f_{\chi,\mathrm{LTE}}(\mathbf{w}, r)$$

$$\mathfrak{f}(K) = \frac{1}{1 + (K/0.4)^2}$$

Knudsen number

$$n_{\chi,\mathrm{iso}}(r,t) = N_\chi(t) \frac{e^{-m_\chi \phi(r)/T_\chi}}{\int_0^R e^{-m_\chi \phi(r)/T_\chi}\, 4\pi r^2\, dr} \quad ; \quad n_{\chi,\mathrm{LTE}}(r,t) = n_{\chi,\mathrm{LTE},0}(t) \left(\frac{T(r)}{T(0)}\right)^{3/2} \exp\left(- \int_0^r \frac{\alpha(r') \frac{dT(r',t)}{dr'} + m_\chi \frac{d\phi(r')}{dr'}}{T(r')}\, dr' \right)$$

D. N. Spergel and W. H. Press, Astrophys. J. 294:663, 1985
J. Faulkner and R. L. Gilliland, Astrophys. J. 299:994, 1985
K. Griest and D. Seckel, Nucl. Phys. B283:681, 1987

M. Nauenberg, Phys. Rev. D36:1080, 1987
A. Gould and G. Raffelt, Astrophys. J. 352:654, 1990

Main properties of celestial bodies

Mass, radius, composition, and density and temperature profiles

- Polytropic equations of state ($P = K\rho^{\gamma}$) represent a reasonable first-order approximation for the interior of most celestial bodies (for the DM evaporation mass details are not important): two free parameters

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial \Phi}{\partial r}\right) = 4\pi G\rho(r) \quad ; \qquad \frac{\partial P}{\partial r} = -\frac{\partial \Phi}{\partial r}\rho(r)$$

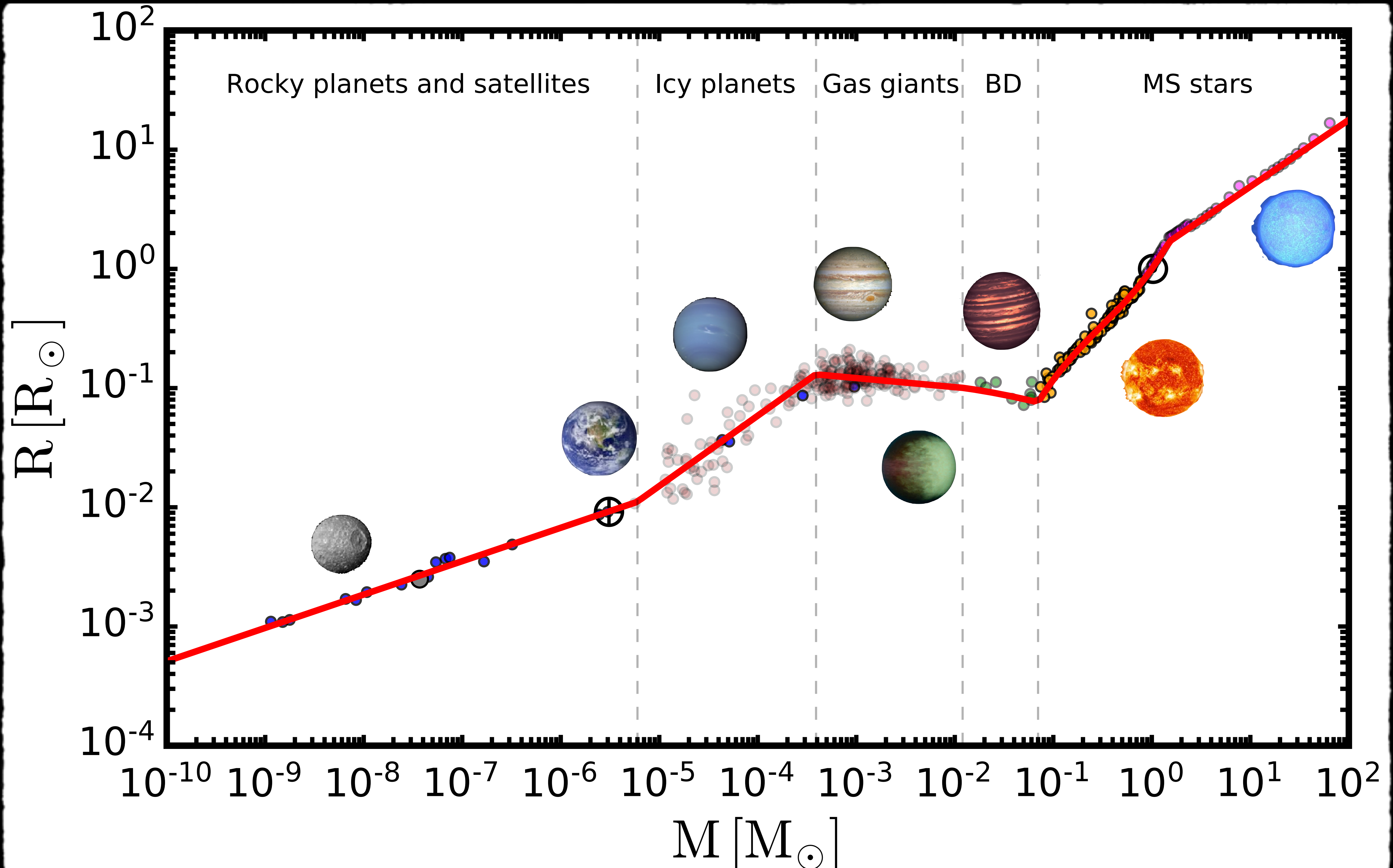
- Mass-radius relation obtained from observations

- Temperature profile can be obtained from the virial theorem

- Core temperature obtained from models

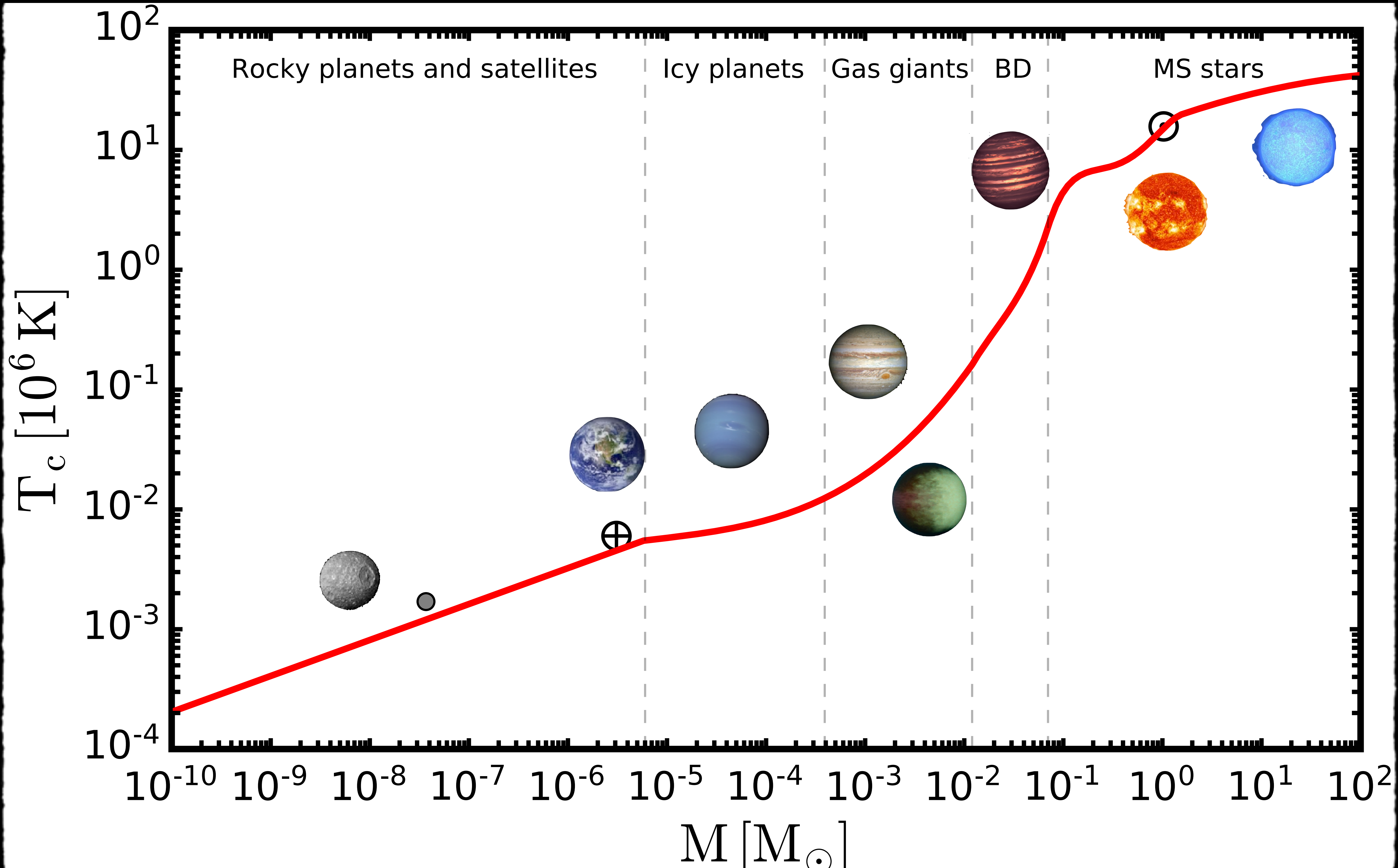
- Simplified composition (not very critical): hydrogen, helium, carbon, oxygen, water, silicate perovskite and iron

Mass-radius relation



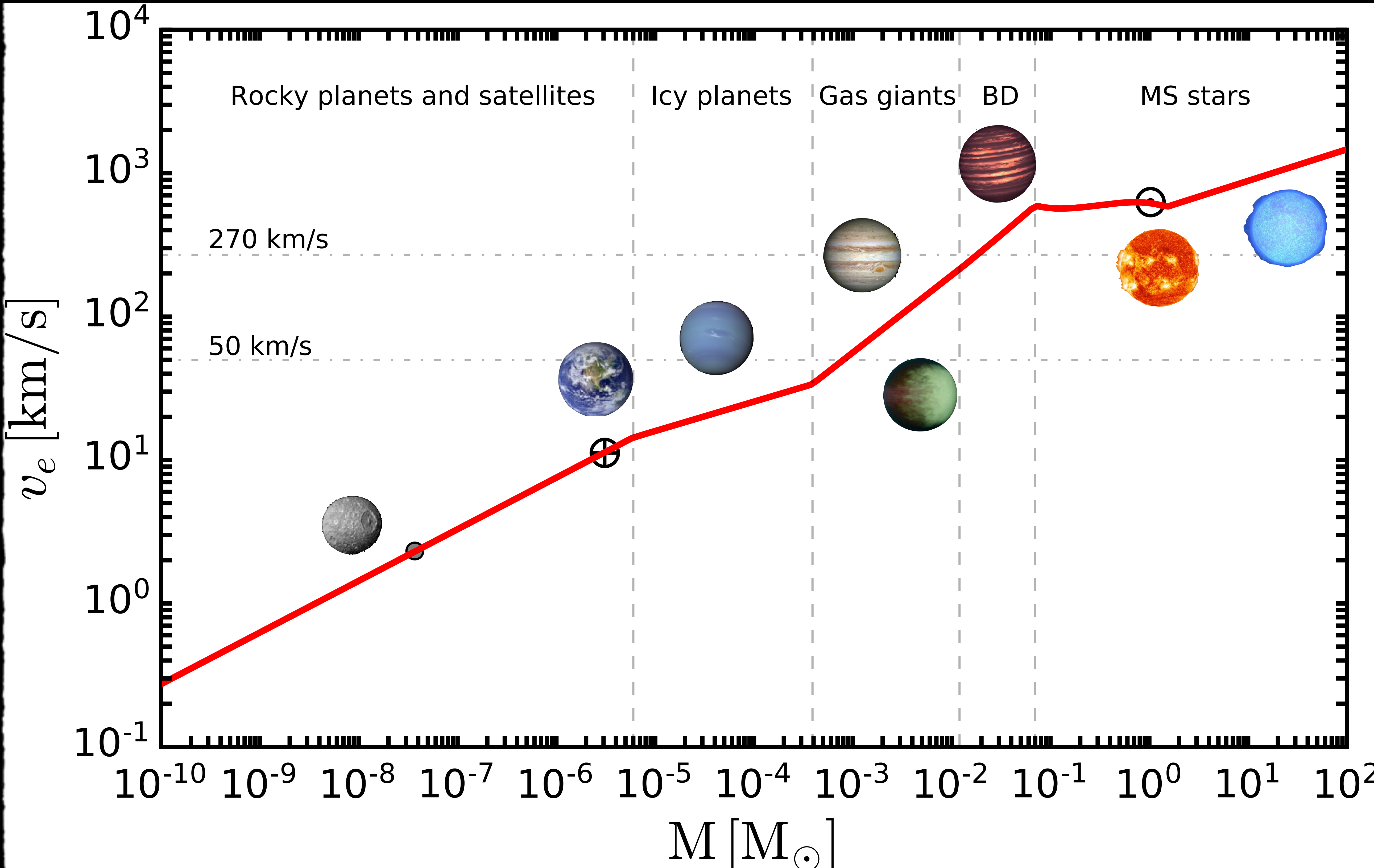
R. Garani and SPR, arXiv:2104.12757

Mass-core temperature relation



R. Garani and SPR, arXiv:2104.12757

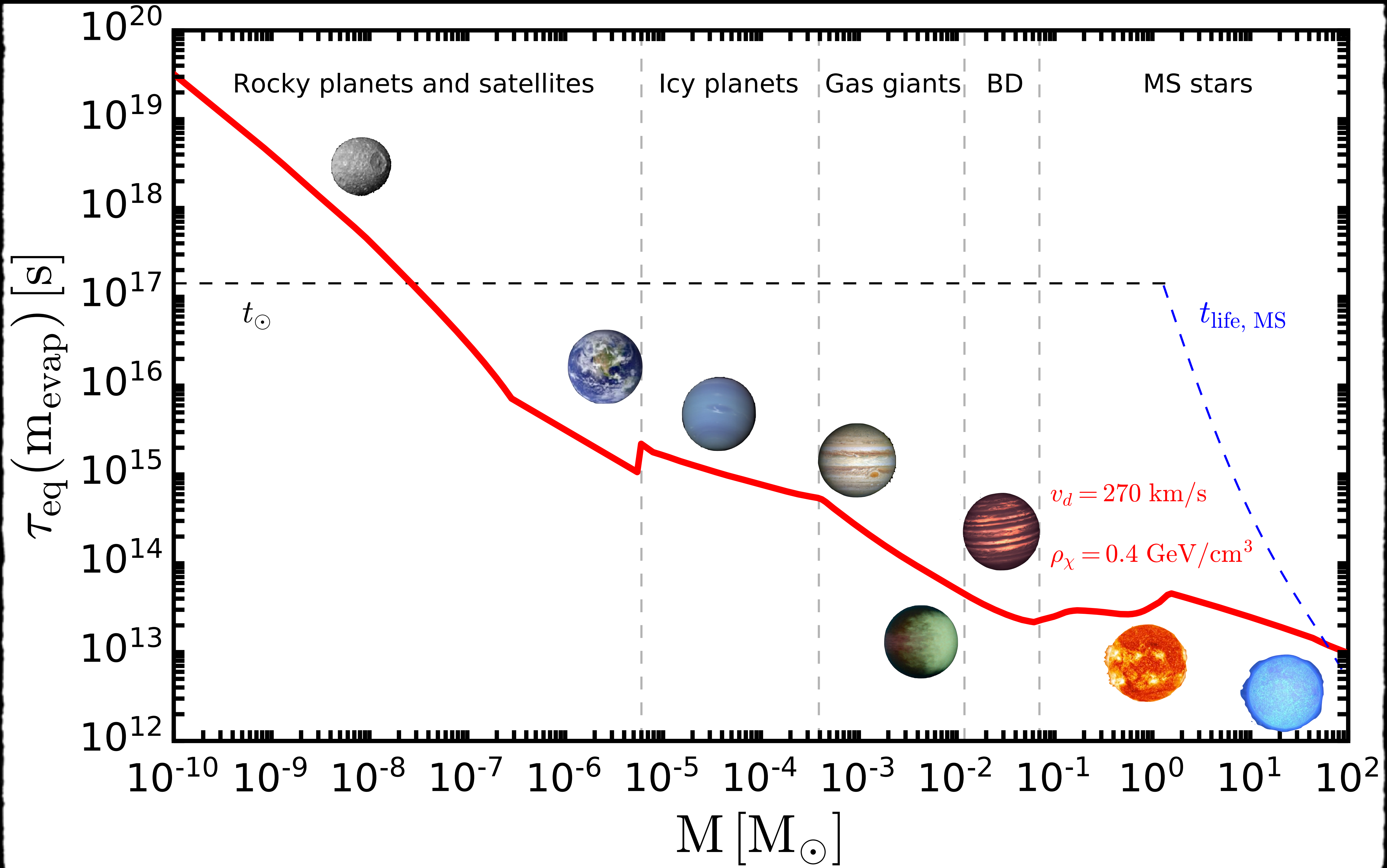
Mass-escape velocity relation



R. Garani and SPR, arXiv:2104.12757

Equilibration time

for the geometric cross section, $\sum N_i \sigma_i = \pi R^2$



R. Garani and SPR, arXiv:2104.12757