Neutrinos from dark matter captured in celestial bodies

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Neutrino Frontiers

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Generalitat Valenciana
Conselleria d'Innovació, Universitats, Ciència i Societat Digital
Ministerio de Ciencia e Innovación
Agencia Estatal de Investigación

Neutrino-dark matter connections

Neutrinos

Dark matter

Neutrino-dark matter connections

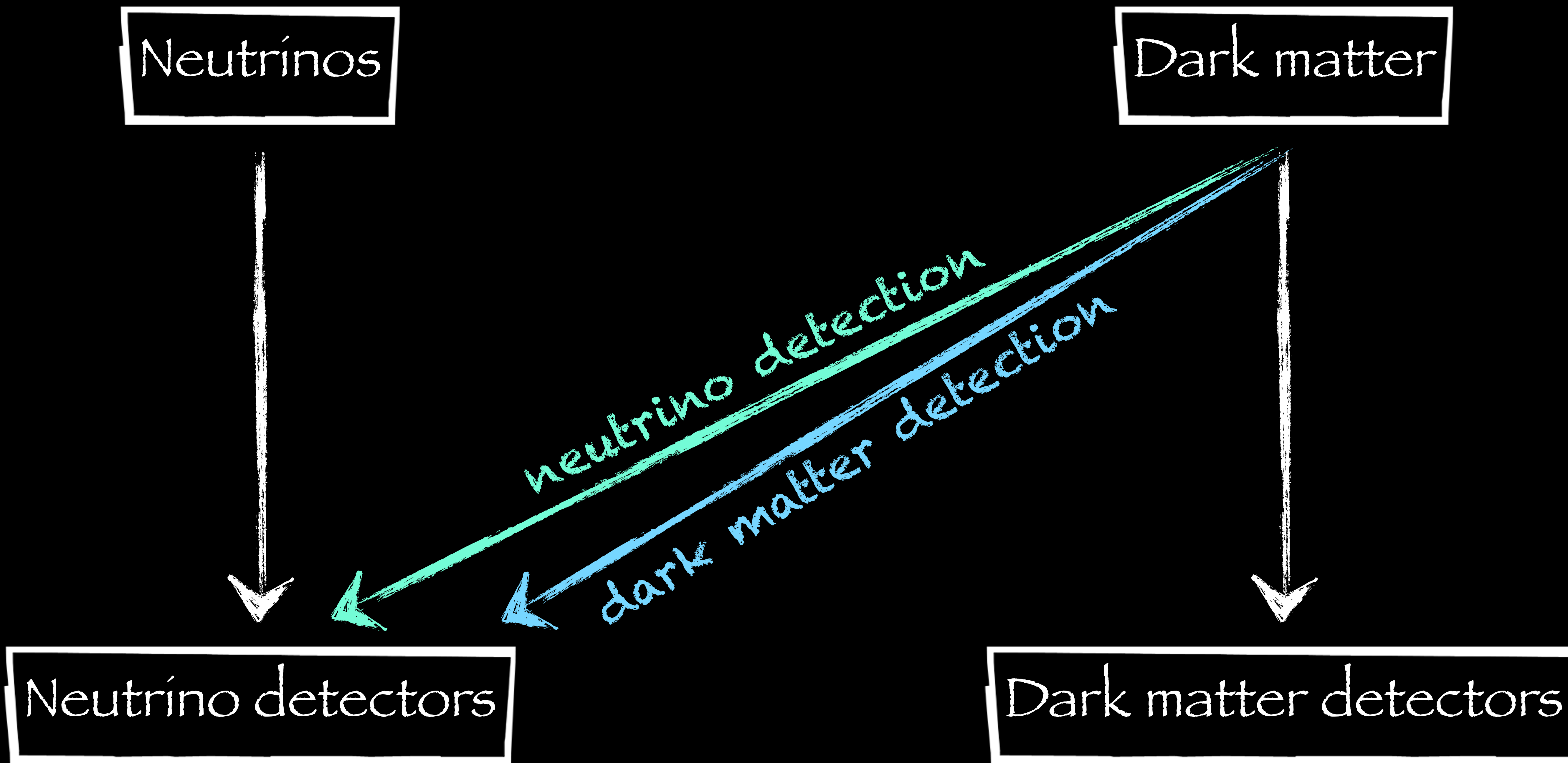
Neutrinos

Neutrino detectors

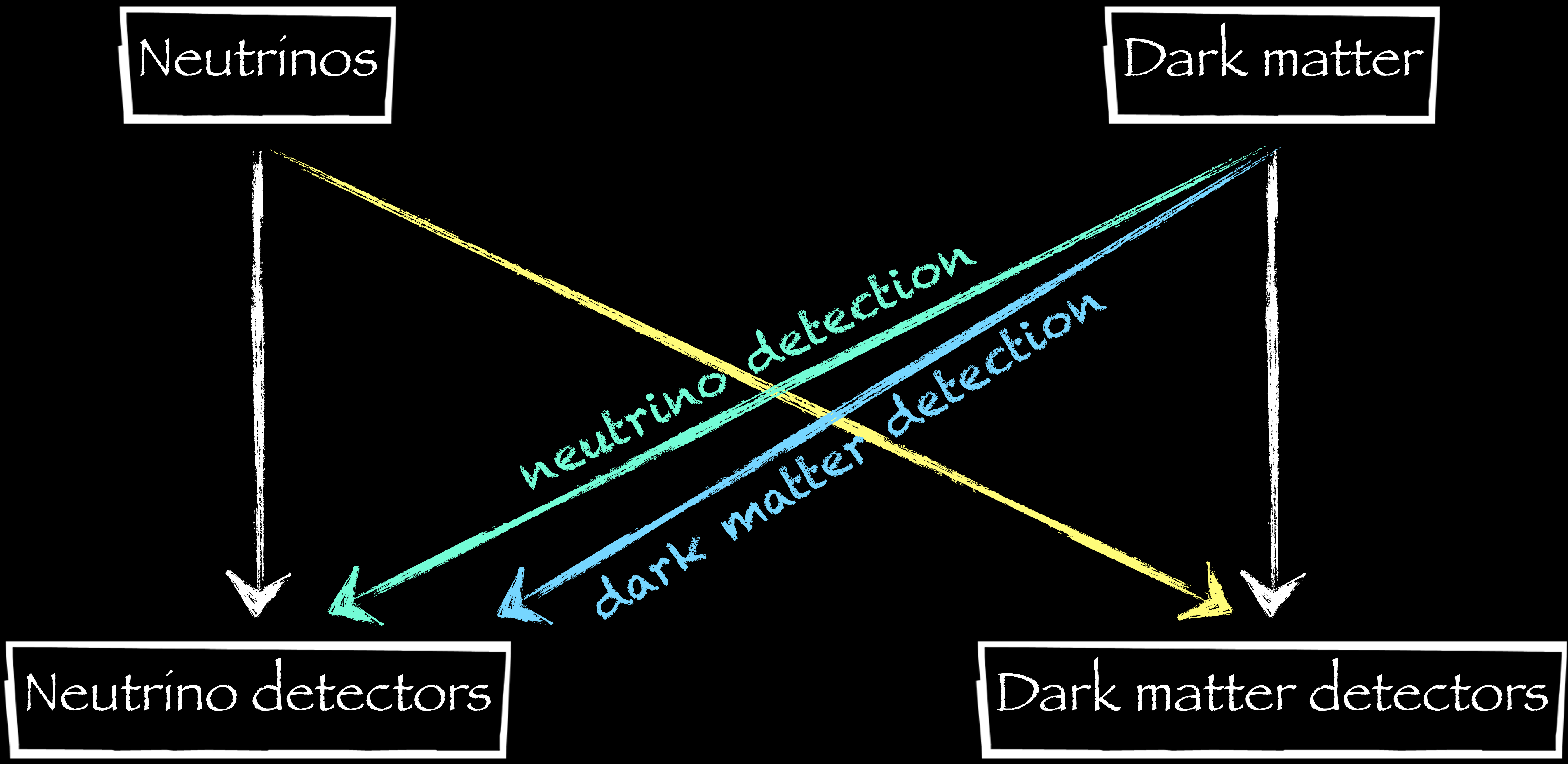
Dark matter

Dark matter detectors

Neutrino-dark matter connections



Neutrino-dark matter connections



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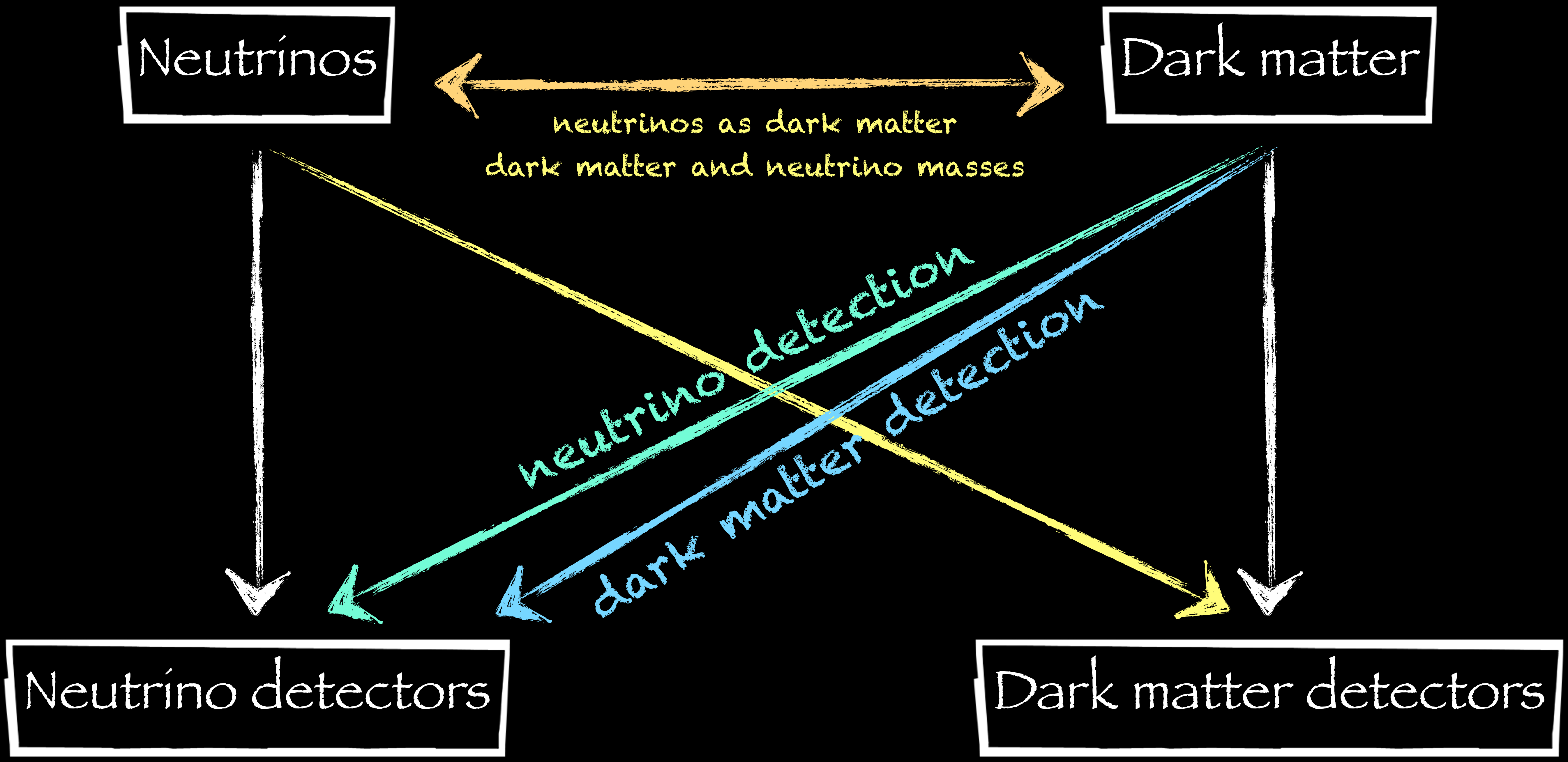

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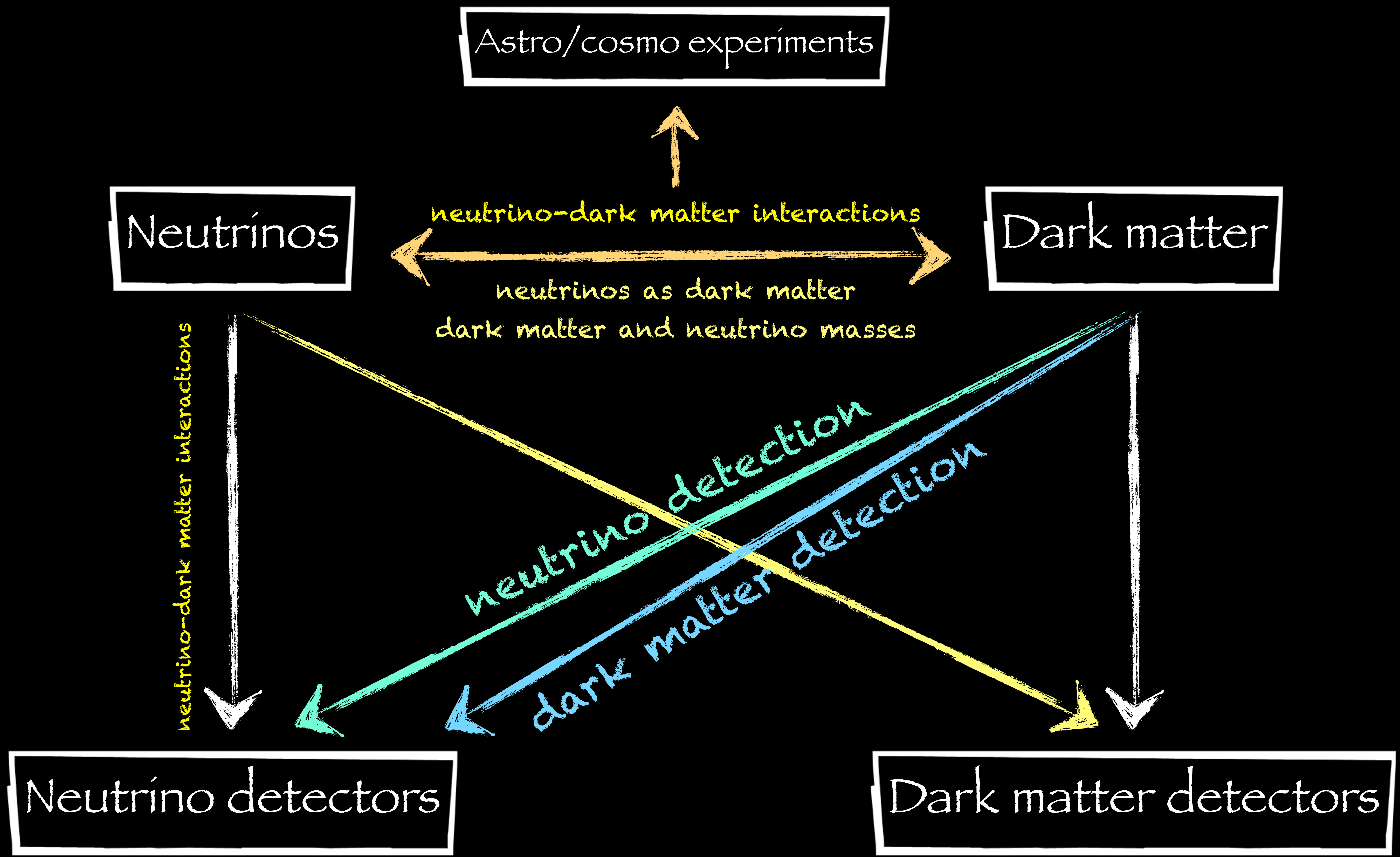
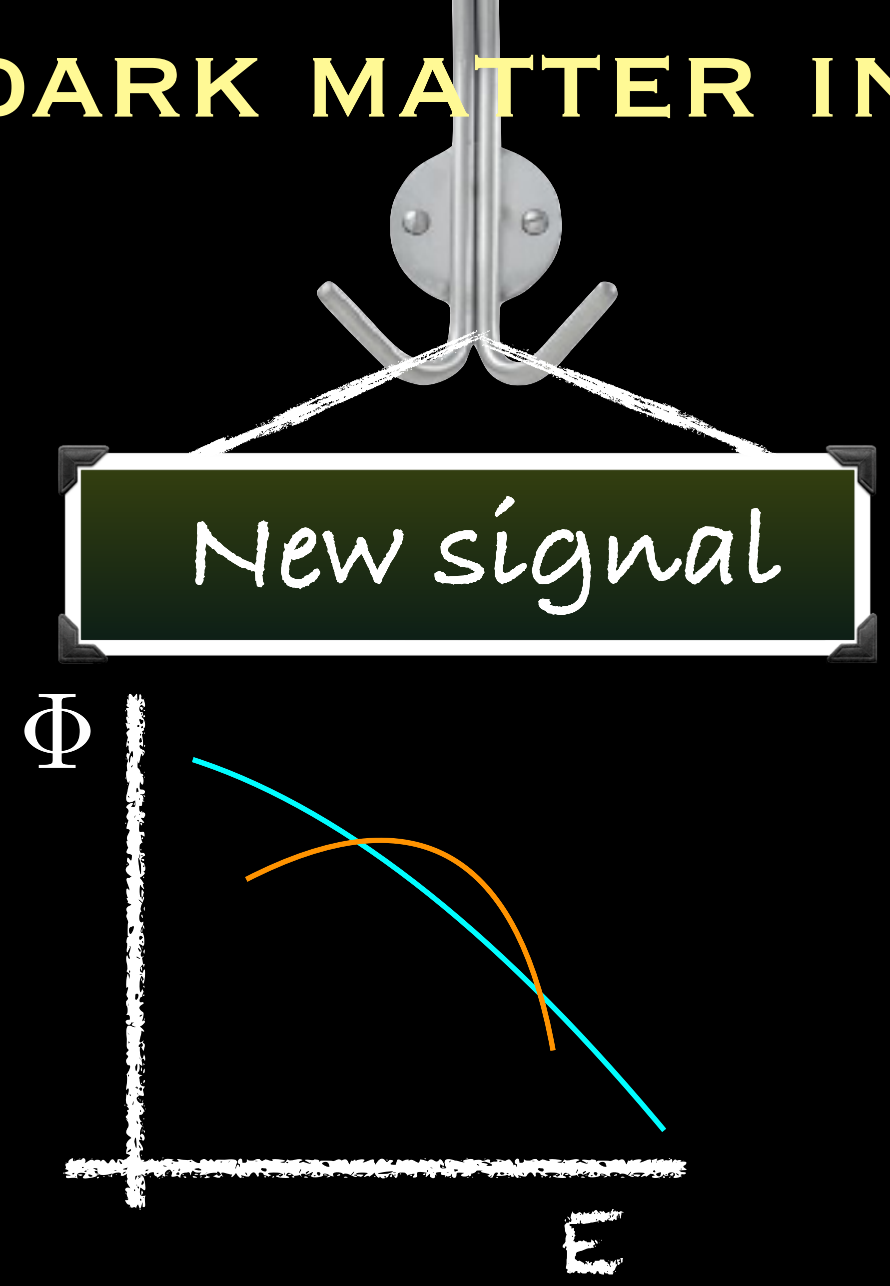


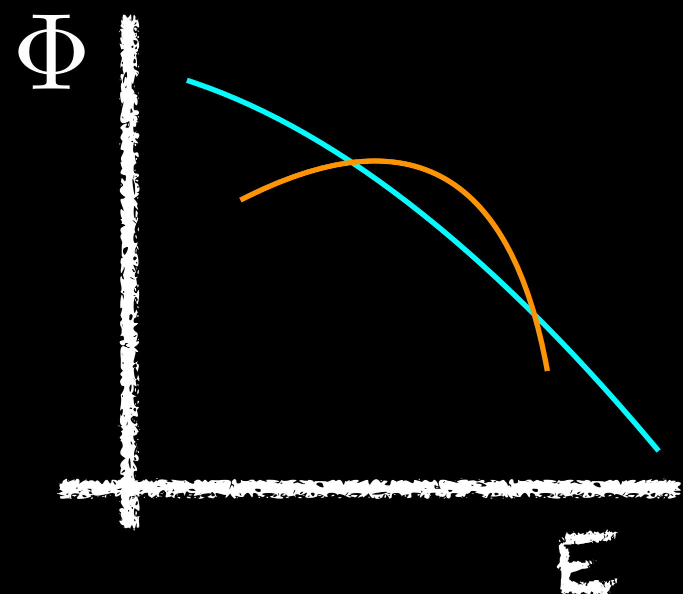
Neutrino-dark matter interactions

Neutrino-dark matter interactions

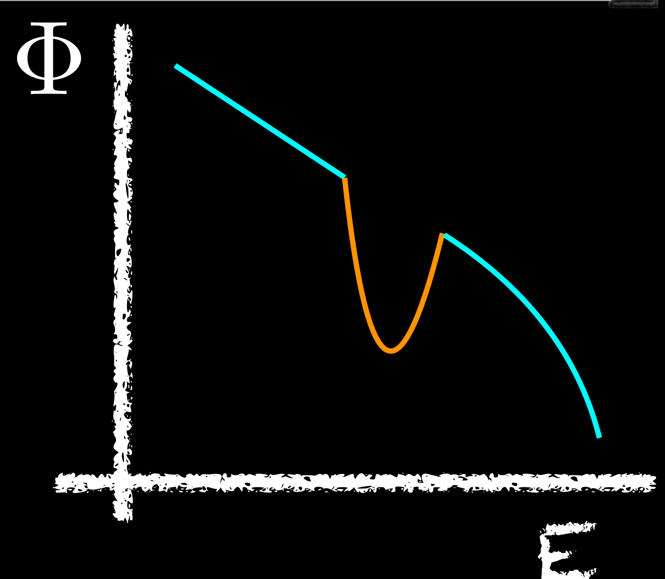


Neutrino-dark matter interactions

New signal

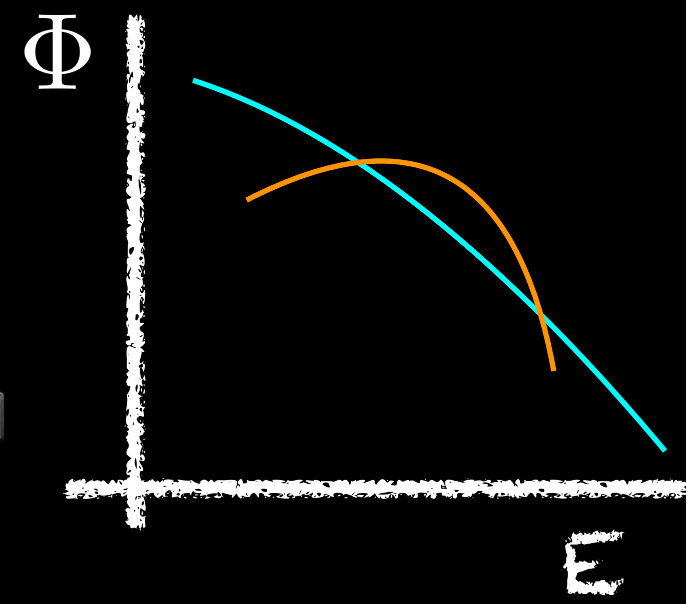


Features on known spectra

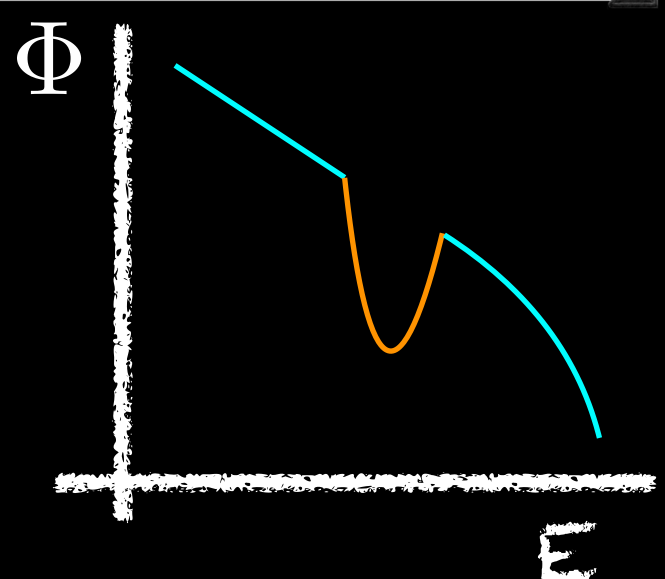


Neutrino-dark matter interactions

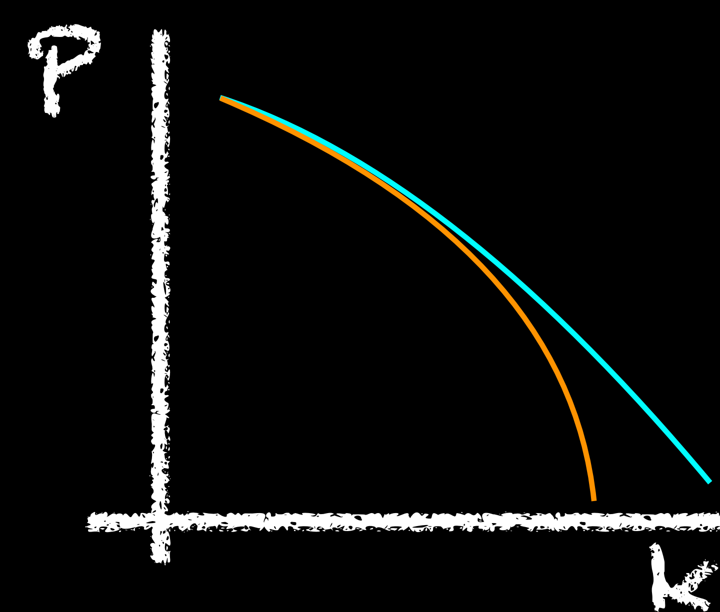
New signal



Features on known spectra



Cosmo/Astro effects



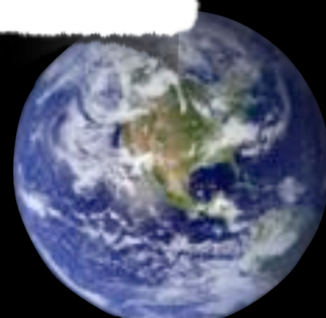
Sources of neutrinos

Natural sources

Farther away

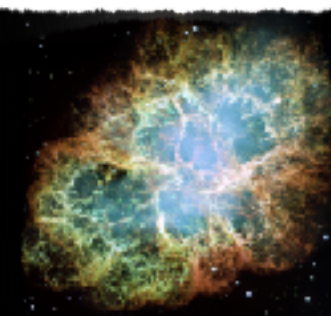
Atmosphere

Earth



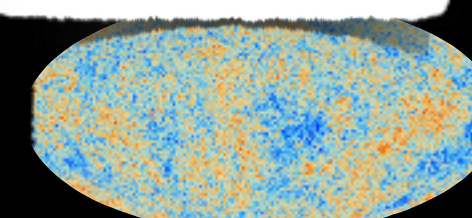
Sun

Supernova explosions



Astrophysical sources

Cosmic relics



Man-made sources

Nuclear reactors

Particle accelerators

Sources of neutrinos

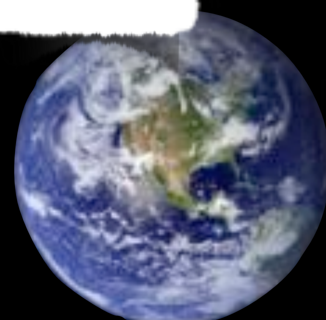
Natural sources

Exotics?

Farther away

Atmosphere

Earth



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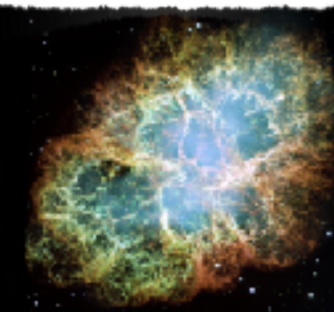
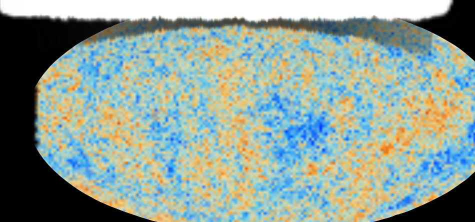
Supernova explosions



Astrophysical sources

Cosmic relics

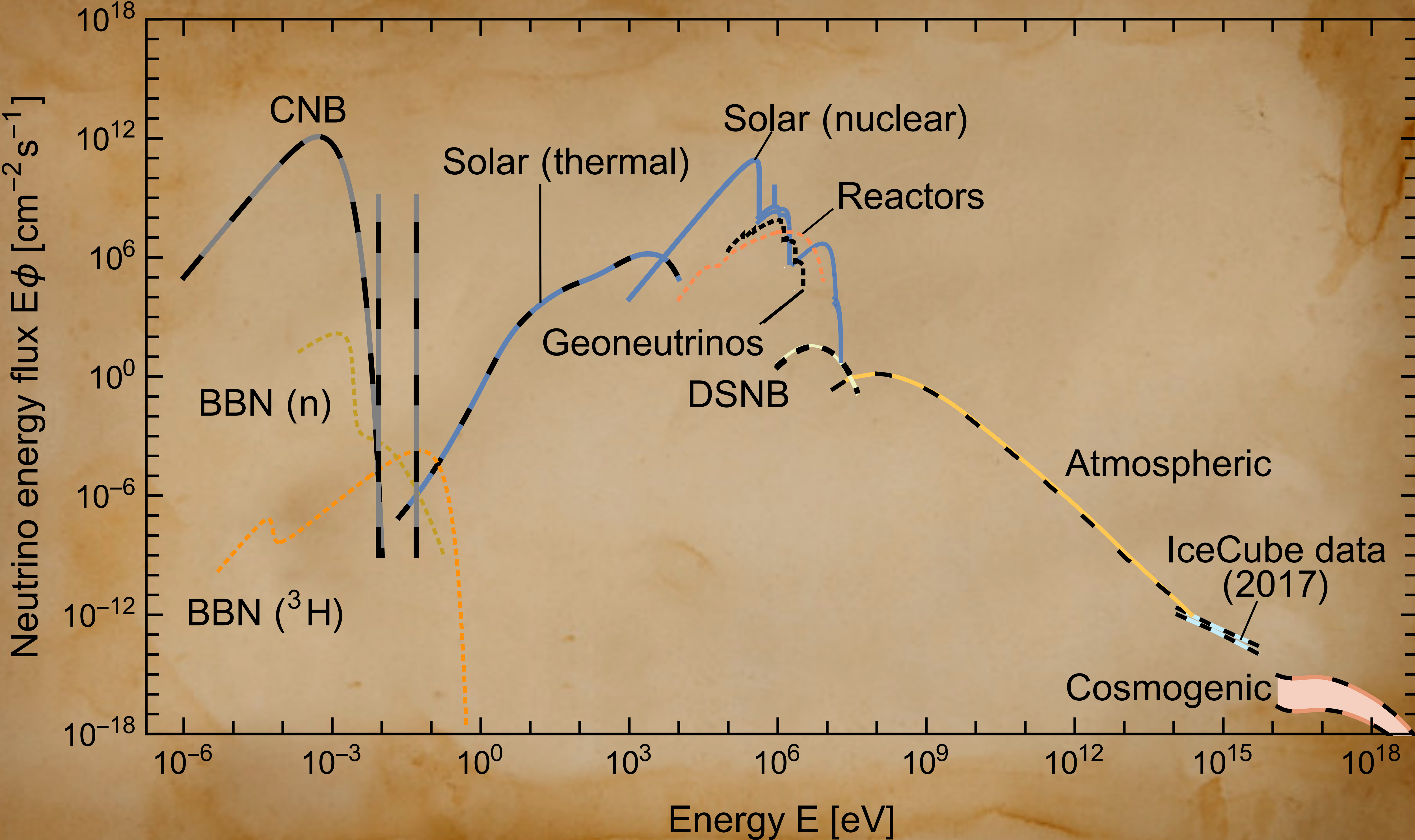


Man-made sources

Nuclear reactors

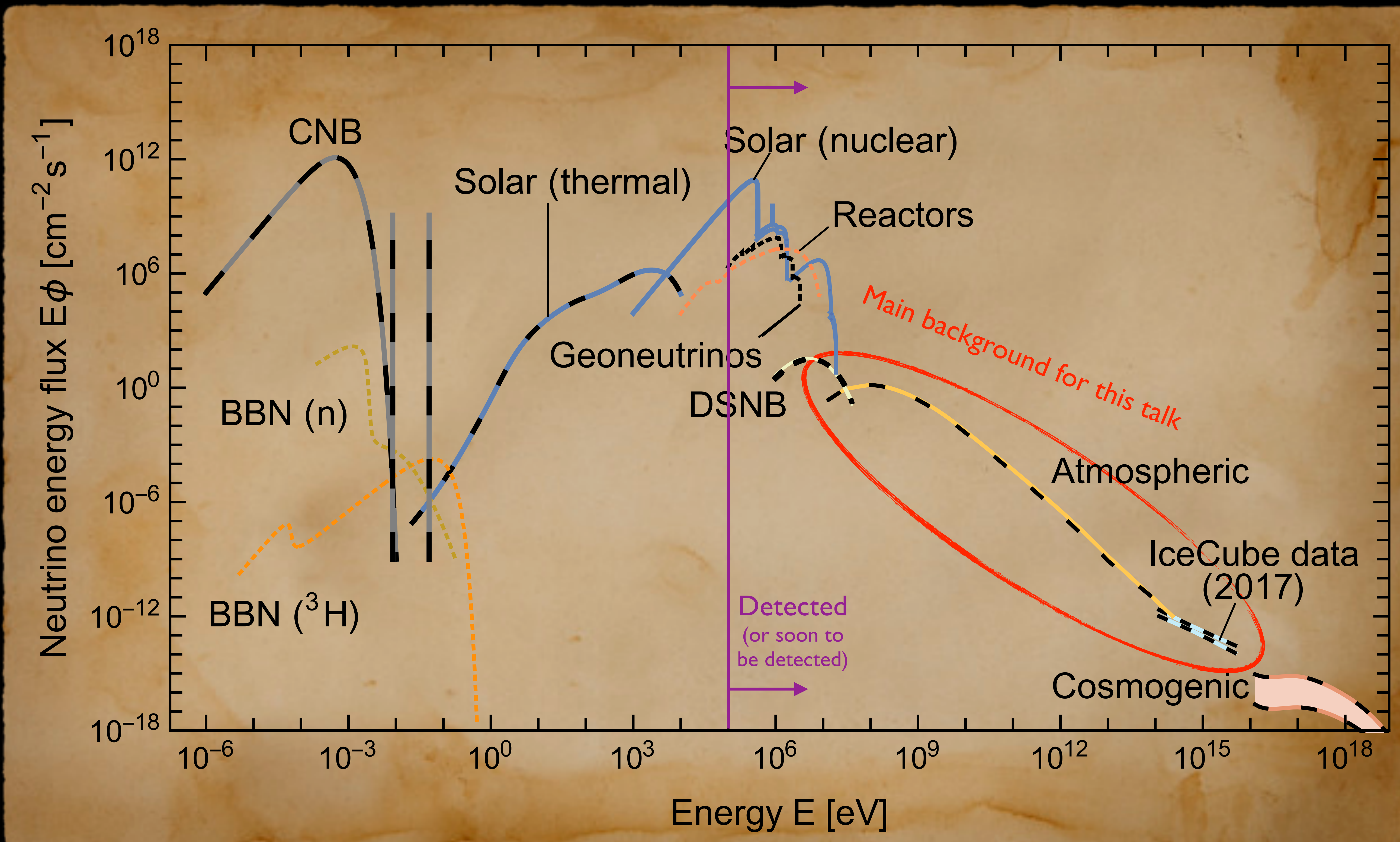
Particle accelerators

(Standard) Grand Unified Neutrino Spectrum



E. Vitagliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92:45006, 2020

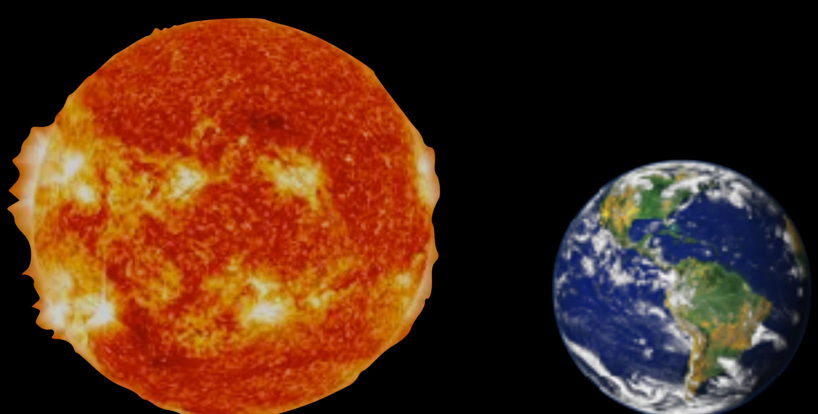
(Standard) Grand Unified Neutrino Spectrum



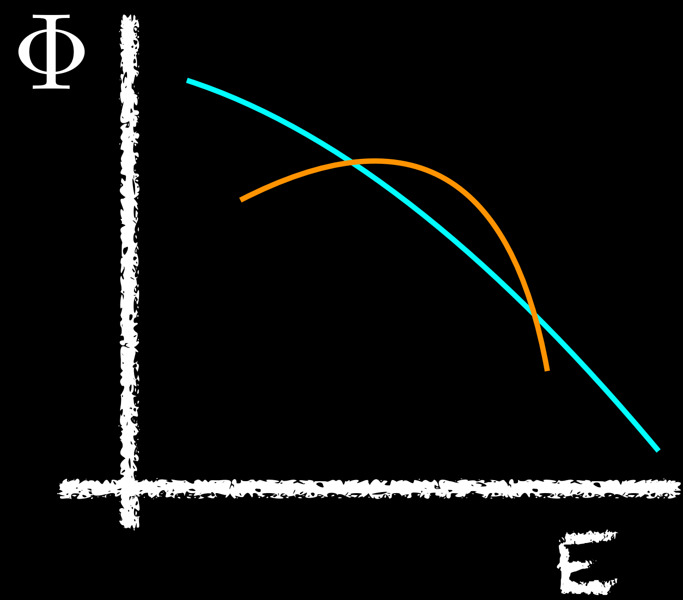
E. Vitagliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92:45006, 2020

Annihilation of captured DM in the Sun, Earth or other celestial bodies

Sensitive to scattering cross section

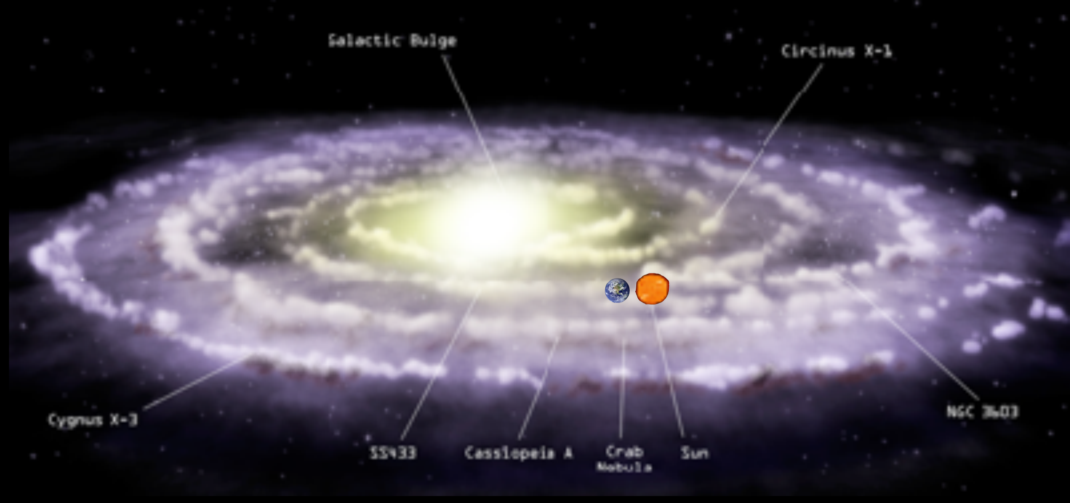


New signal



Annihilations/decays in halos

Sensitive to annihilation cross section (link to thermal production in the early Universe?) and lifetime

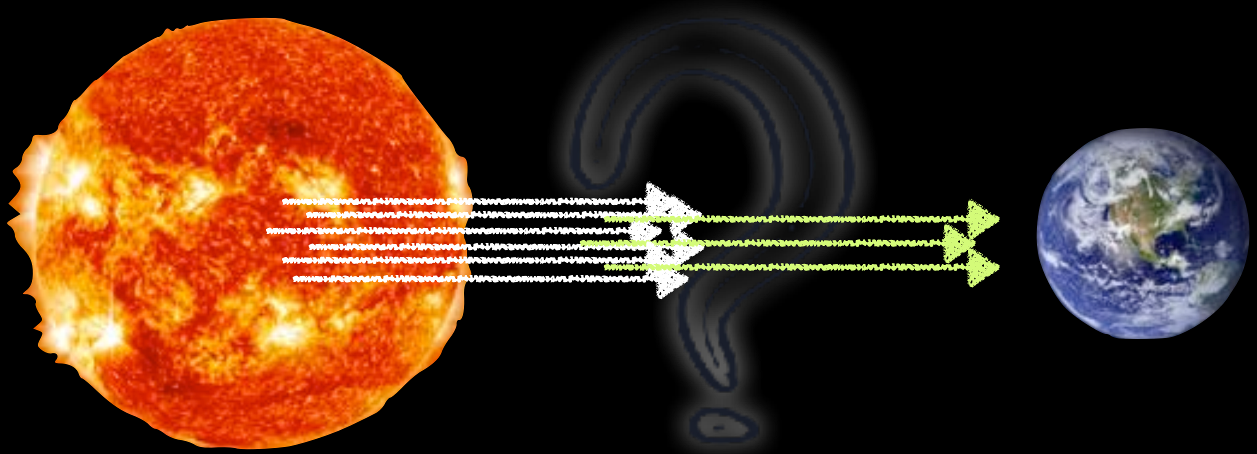


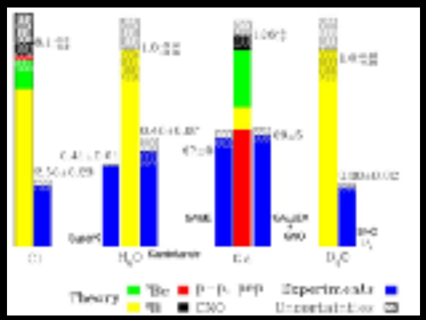
DM annihilations or decays

DM accumulation in celestial bodies

Modification of energy transfer

solve the solar neutrino problem





DM annihilations and scatterings could heat up 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

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

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

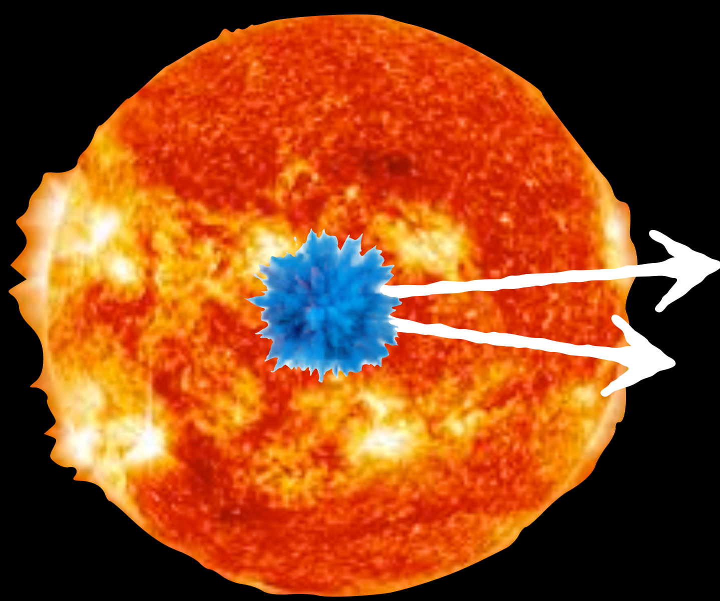
DM accumulation in celestial bodies

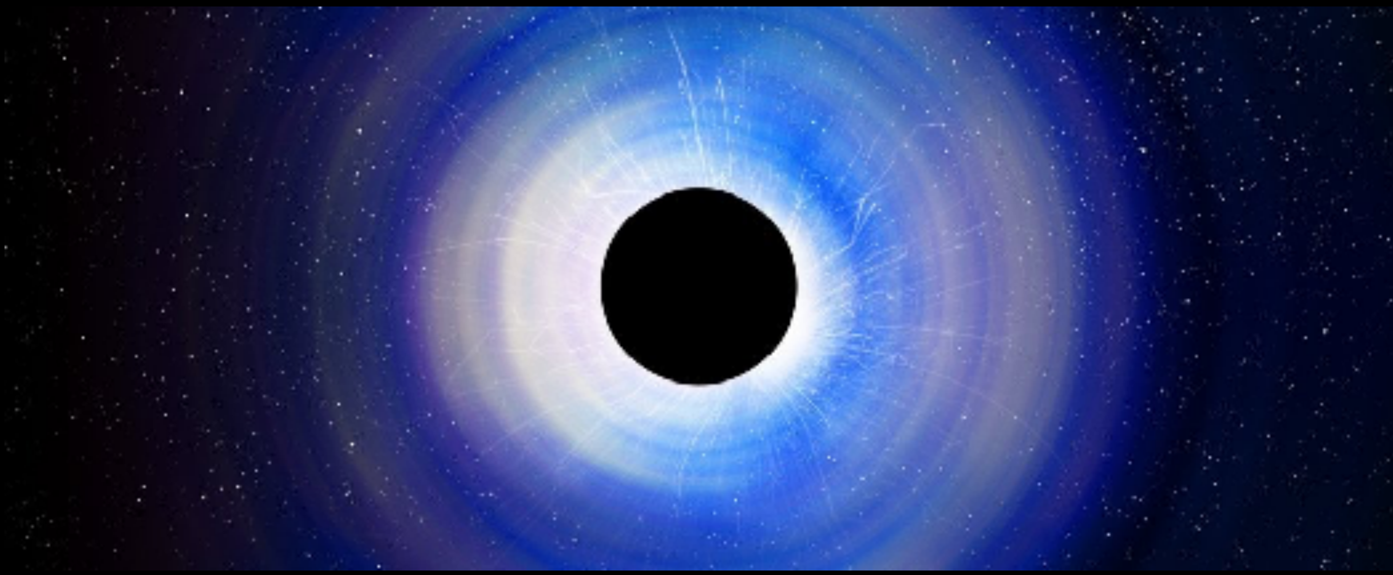
Annihilation products

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

Collapse

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

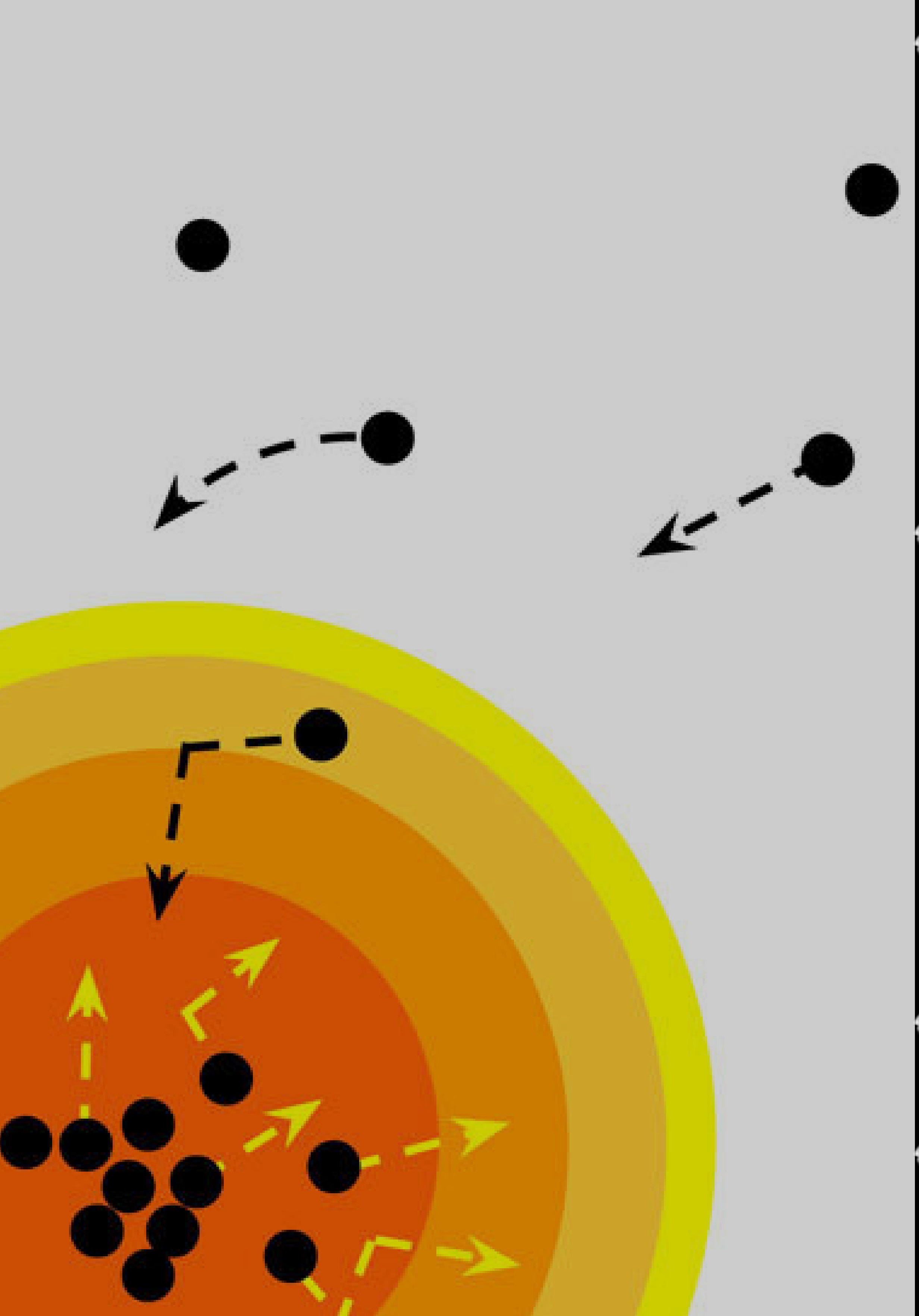




J. Silk, K. A. Olive, and M. Srednicki, Phys. Rev. Lett. 55:257, 1985
K. Freese, Phys. Lett. B167:295, 1986
L. M. Krauss, M. Srednicki, and F. Wilczek, Phys. Rev. D33:2079, 1986
T. K. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D34:2206, 1986

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 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
- Among the SM products, only neutrinos could escape

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)

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

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

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

equilibrium between capture and annihilation

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

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 evaporation

Main ingredients

Dark matter particles:

Maxwell-Boltzmann velocity distribution (in the galactic frame)

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

DM velocity at infinity

velocity of the celestial body (in the galactic frame)

angle between the DM particle and the celestial body velocities

DM - target particles scattering cross section

Properties of capturing celestial body

Targets:

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

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

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

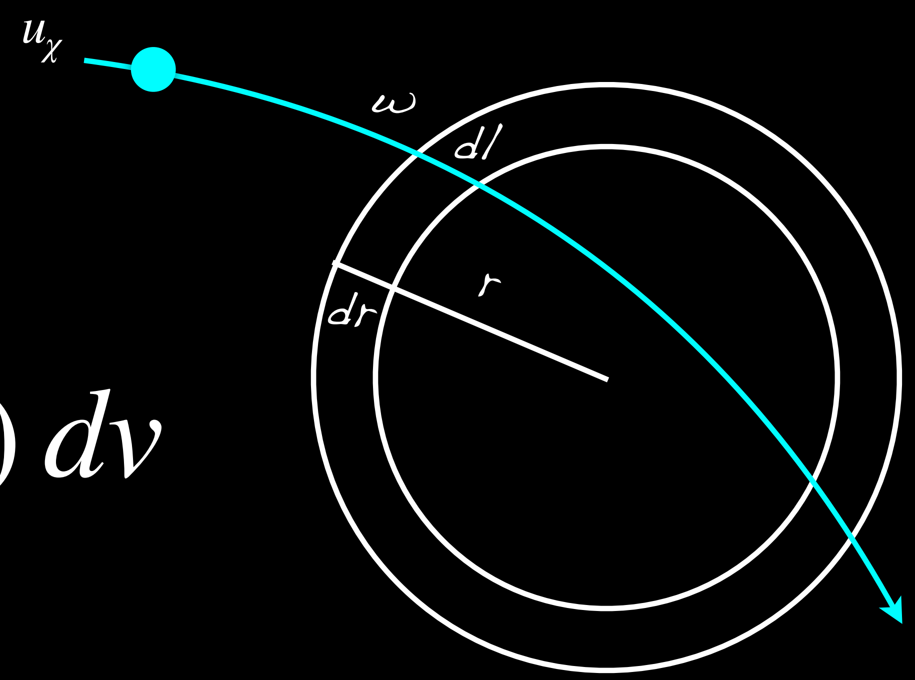
flux of DM particles reaching a spherical shell at radius r

rate of scattering from ω 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 ω 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 limit and neglecting the nuclear form factor, are reasonable approximations, so the calculation of the capture rate is relatively simple.

For weak cross sections (long mean free path):

A. Gould, Astrophys. J. 321:571, 1987

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

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

For very large cross sections (short mean free path): geometric limit

-> multiple scatterings

A. Gould, Astrophys. J. 387:21, 1992

J. Bramante, A. Delgado and A. Martin, Phys. Rev. D96:063002, 2017

$$C_{\rm geom} = \pi R^2 \left(\frac{\rho_\chi}{m_\chi}\right)\langle v\rangle_0 \left(1+\frac{3}{2}\frac{v_e^2(R)}{v_d^2}\right)\tilde\xi_1$$

Neutrinos from DM annihilations

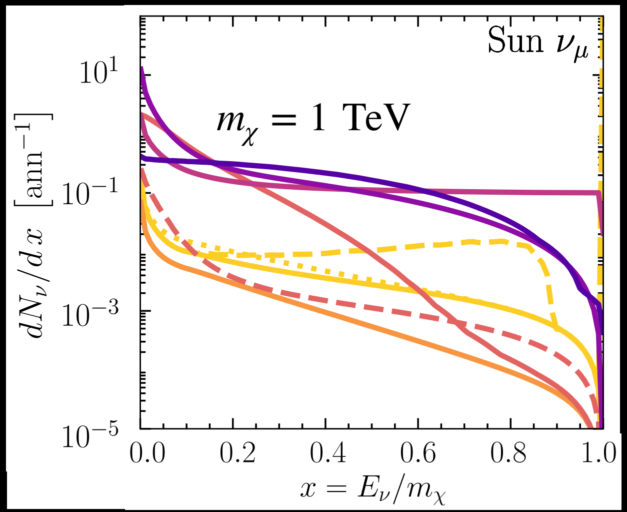
Rate:

$$\Gamma_\chi = \frac{1}{2}\,\mathrm{A}\,N_\chi^2$$

if equilibrium between capture and annihilation is reached and evaporation is negligible

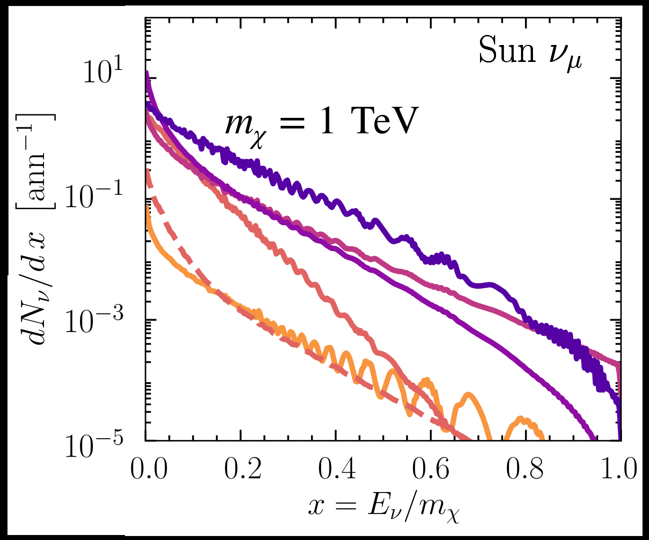
$$\Gamma_\chi = \frac{\mathrm{C}}{2}$$

Differential neutrino flux at detectors on Earth



Q. Liu, J. Lazar, C. A. Argüelles and A. Kheirandish, JCAP 10:043, 2020

$$\frac{d\Phi}{dE_\nu} = \frac{\Gamma_\chi}{4\,\pi\,d^2}\,\frac{dN_\nu}{dE_\nu}$$



Q. Liu, J. Lazar, C. A. Argüelles and A. Kheirandish, JCAP 10:043, 2020

Neutrino spectra from DM annihilations in the celestial body

Propagation through the celestial body and to the Earth: absorption and oscillations

See also: M. Cirelli et al., Nucl. Phys. B727:99, 2005
M. Blennow, J. Edsjö and T. Ohlsson, JCAP 01:021, 2008
M. Cirelli et al., JCAP 03:051, 2011
P. Baratella et al., JCAP 03:053, 2014

Some considerations

if equilibrium between capture and annihilation is reached and evaporation is negligible

$$\frac{d\Phi}{dE_\nu} \propto \frac{C}{d^2}$$

Neutrino flux grows...

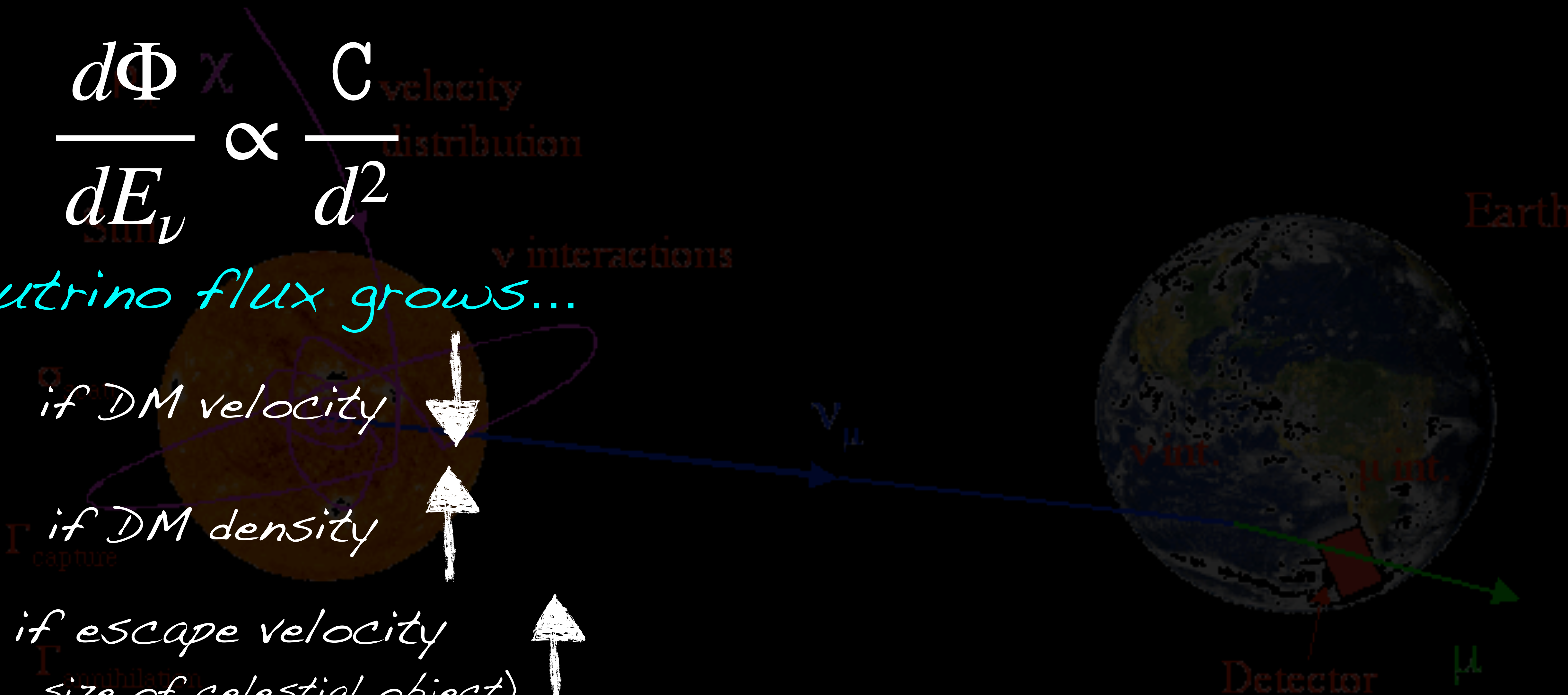
if DM velocity $\downarrow$

if DM density $\uparrow$

if escape velocity (i.e., size of celestial object) $\uparrow$

if cross section (up to a maximum) $\uparrow$

if DM mass similar to target mass



Some considerations

if equilibrium between capture and annihilation is reached and evaporation is negligible

$$\frac{d\Phi}{dE_\nu} \propto \frac{C}{d^2}$$

Neutrino flux grows...

if DM velocity $\downarrow$

if DM density $\uparrow$

if escape velocity (i.e., size of celestial object) $\uparrow$

if cross section (up to a maximum) $\uparrow$

if DM mass similar to target mass

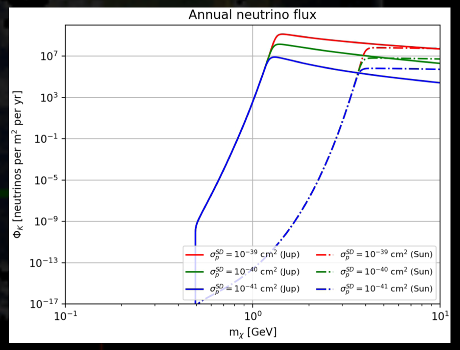
For maximal capture:

$$\frac{\Phi_\oplus}{\Phi_\odot} \simeq \frac{1}{10}\left(\frac{d_\odot}{R_\odot}\right)^2 \simeq 5 \cdot 10^3$$

otherwise (very roughly):

$$\frac{\Phi_\oplus}{\Phi_\odot} \simeq 6 \left(\frac{v_e^4(R_\oplus)}{v_d^2\, v_e^2(R_\odot)}\right)\left(\frac{M_\oplus}{M_\odot}\right)\left(\frac{m_N}{m_\chi}\right)\left(\frac{d_\odot^2}{R_\oplus^2}\right) \simeq 10^{-3}\left(\frac{10\,\mathrm{GeV}}{m_\chi}\right)$$

But, the flux from Jupiter at Jupiter's surface is similar to the flux from the Sun at Earth



G. M. French and M. Sher, Phys. Rev. D106:115037, 2022

Could the neutrino flux from all stars in the Milky Way be comparable to that from the Sun?

$$\left(\frac{d_{\mathrm{PC}}}{d_\odot}\right)^2 \sim 8 \cdot 10^{10}$$

Limits from the Sun

SK: (3902.7 + 4206.7) days

K. Choi et al. [Super-Kamiokande Collaboration], Phys. Rev. Lett. 114:141301, 2015

IceCube: 532 days

M. G. Aartsen et al. [IceCube Collaboration], Eur. Phys. J. C77:146, 2017

ANTARES: 13 yrs

C. Poirè et al. [ANTARES Collaboration], J. Phys. Conf. Ser. 2156:012039, 2021

Baksan: 24.12 yrs

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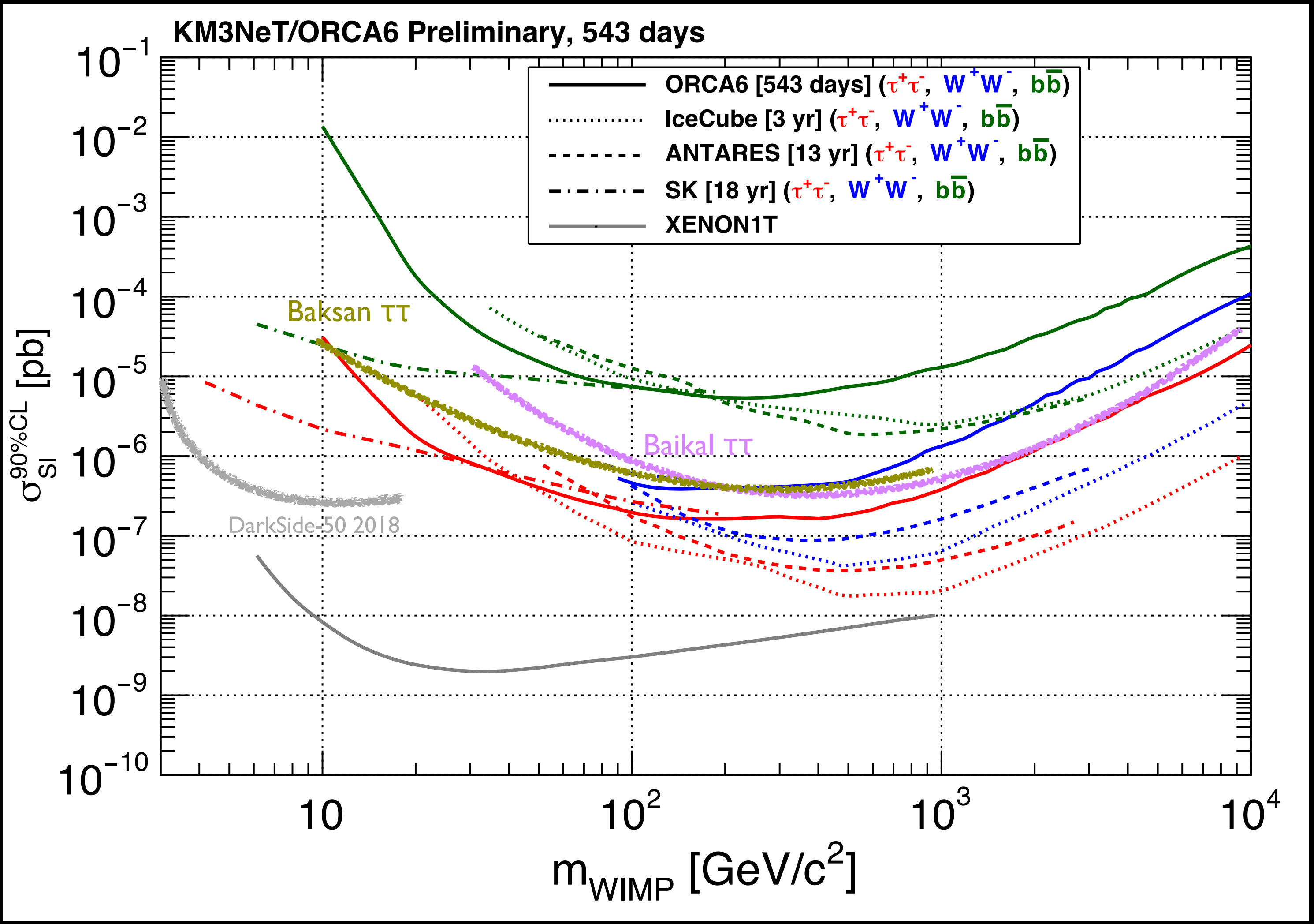
Baikal: 1038 days

A. D. Avrorin et al. [Baikal Collaboration], Astropart. Phys. 62:12, 2015

KM3NeT/ORCA 6: 543 days

A. Saina et al. [KM3NeT Collaboration], PoS (ICRC 2023) 1377, 2023



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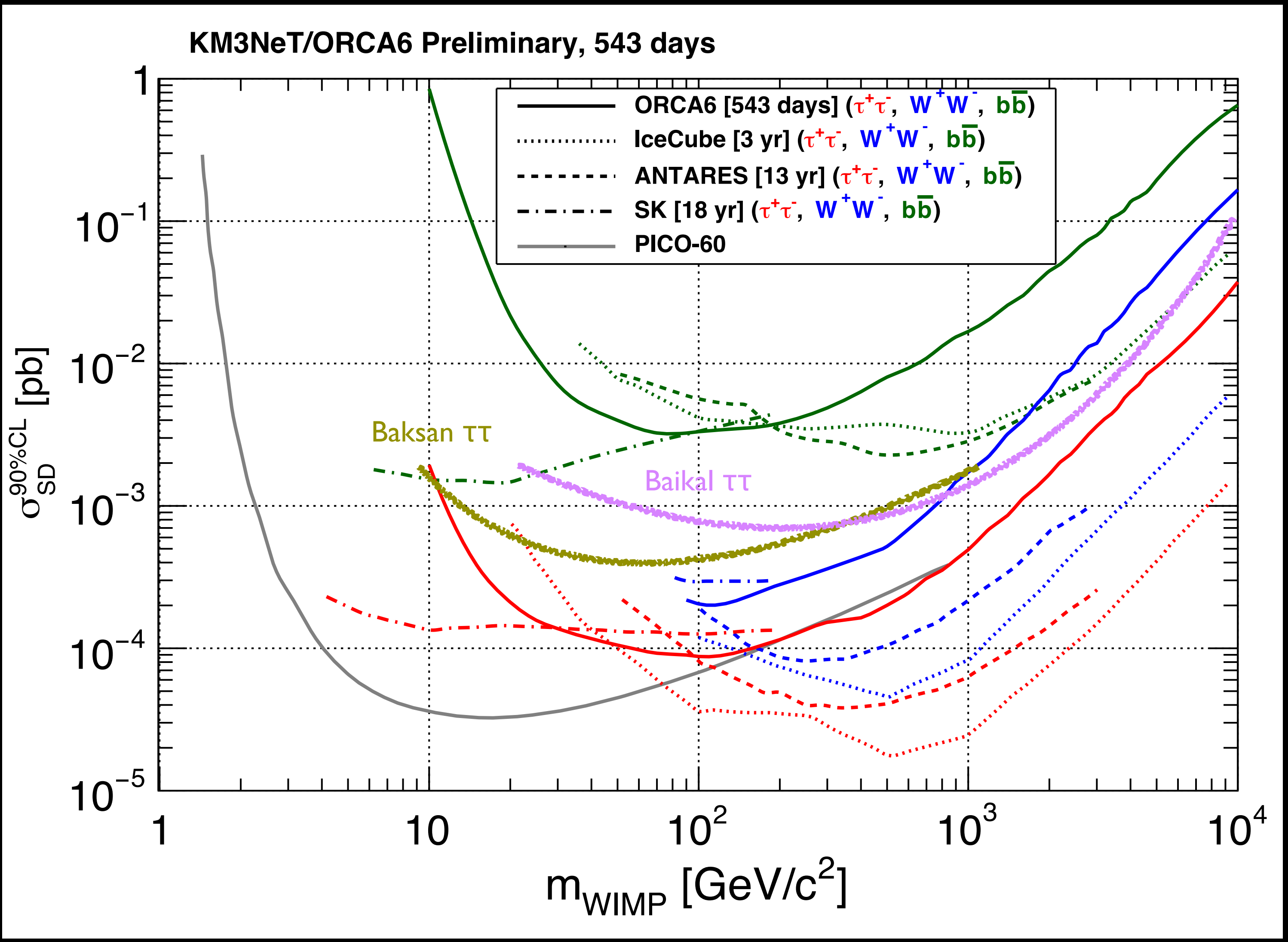

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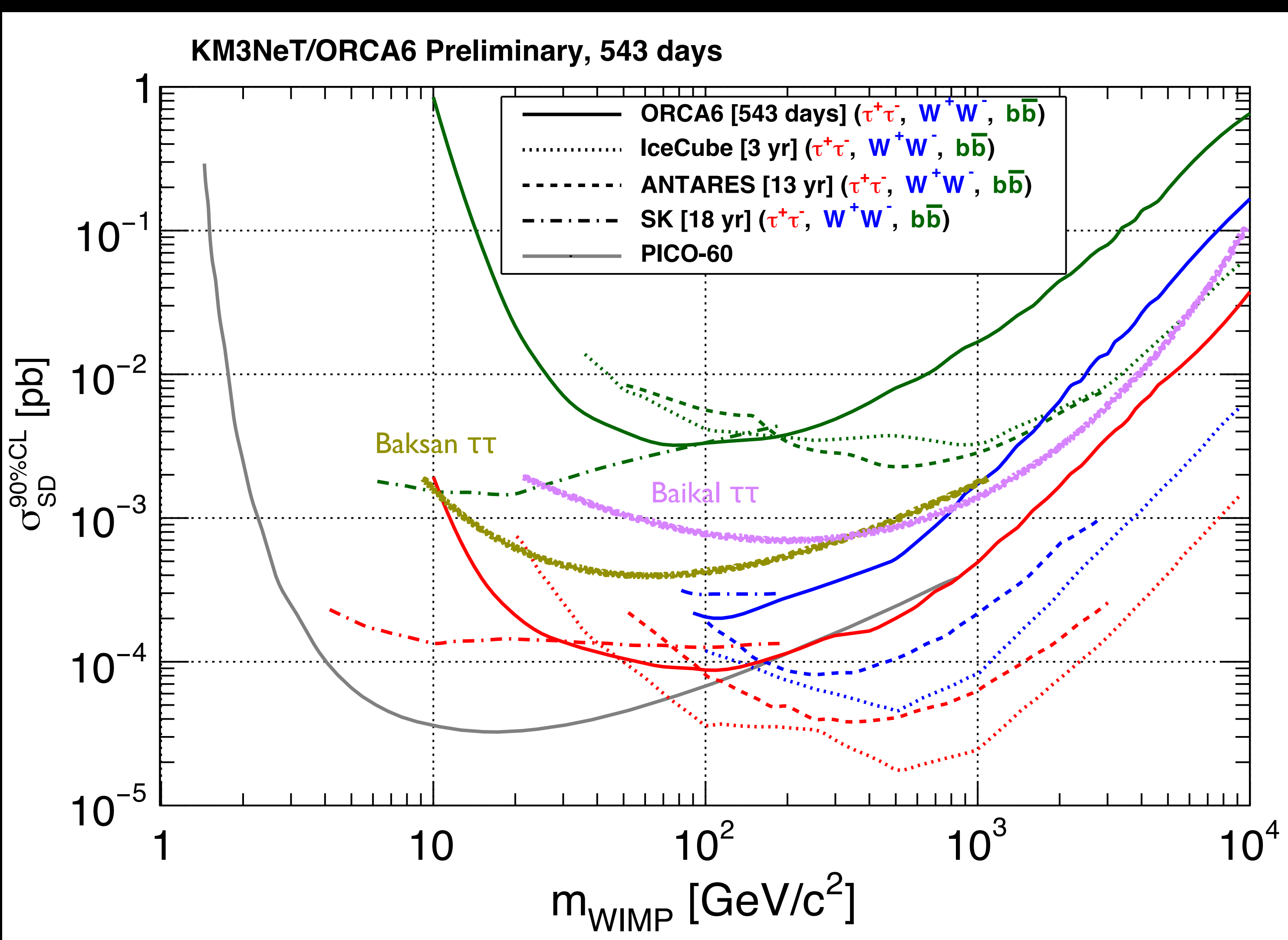
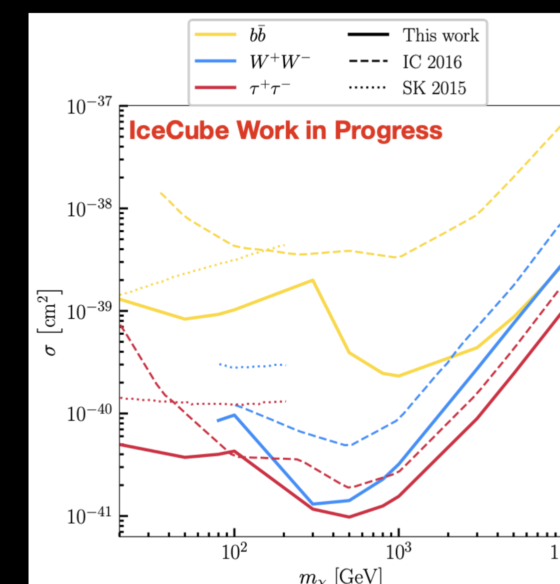


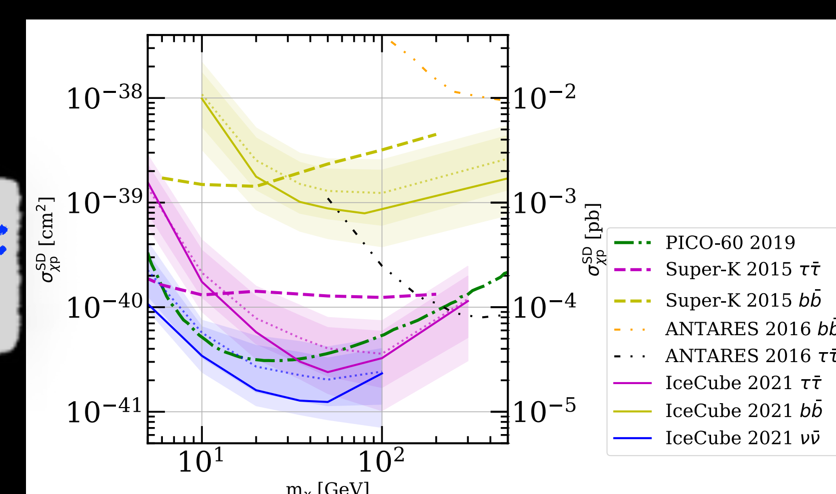
A. Saina et al. [KM3NeT Collaboration], PoS (ICRC 2023) 1377, 2023

IceCube: 9 years

J. Lazar et al. [IceCube Coll.], PoS (ICRC2021) 20, 2021



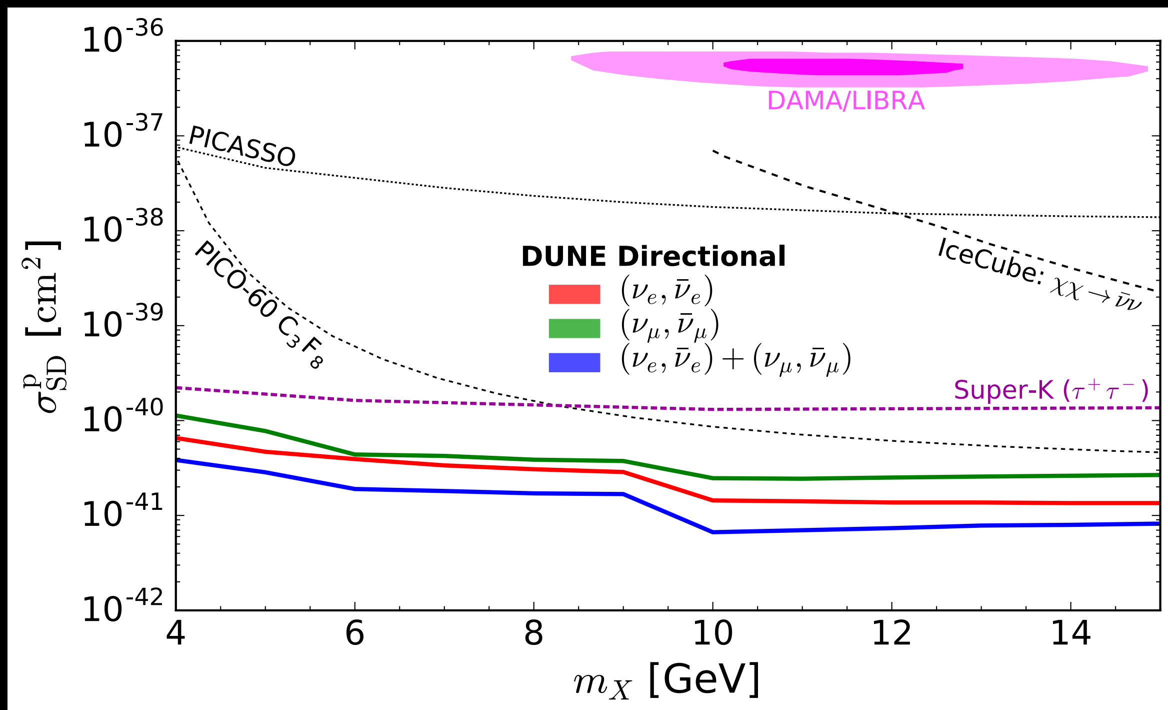
IceCube/DC: 7 years



R. Abbasi et al. [IceCube Collaboration], Phys. Rev. D 105:062004, 2022

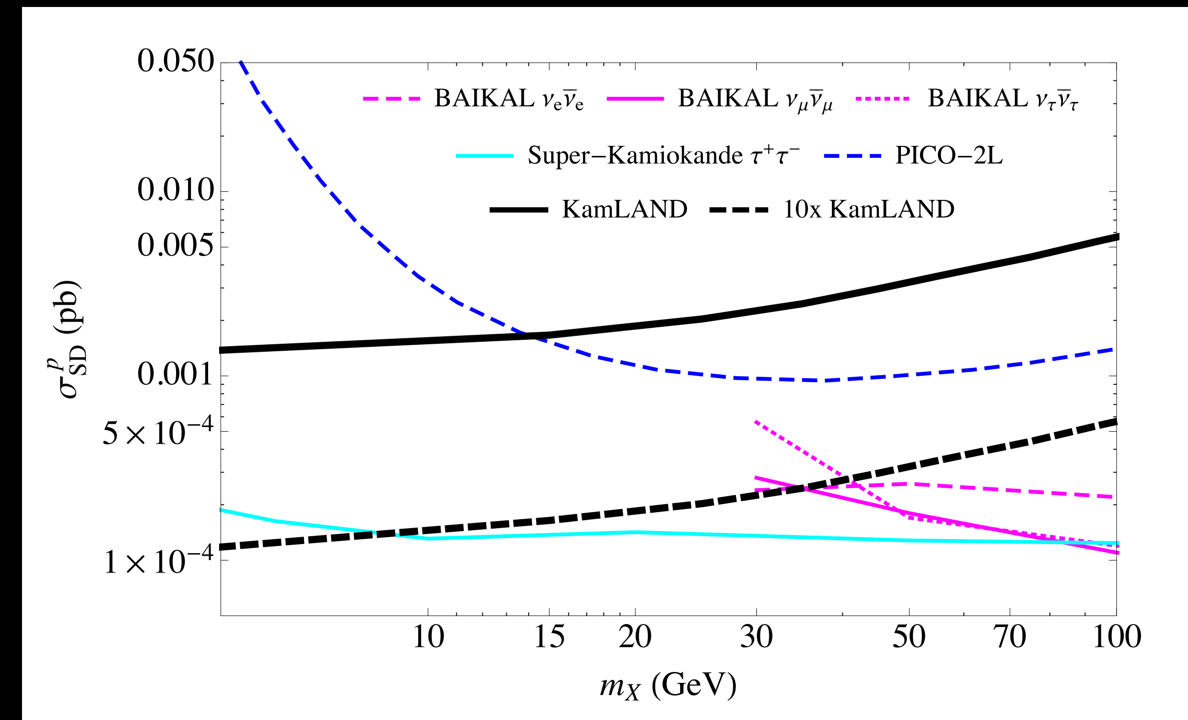
Limits from the Sun

Prospects for 380 kton · years of DUNE



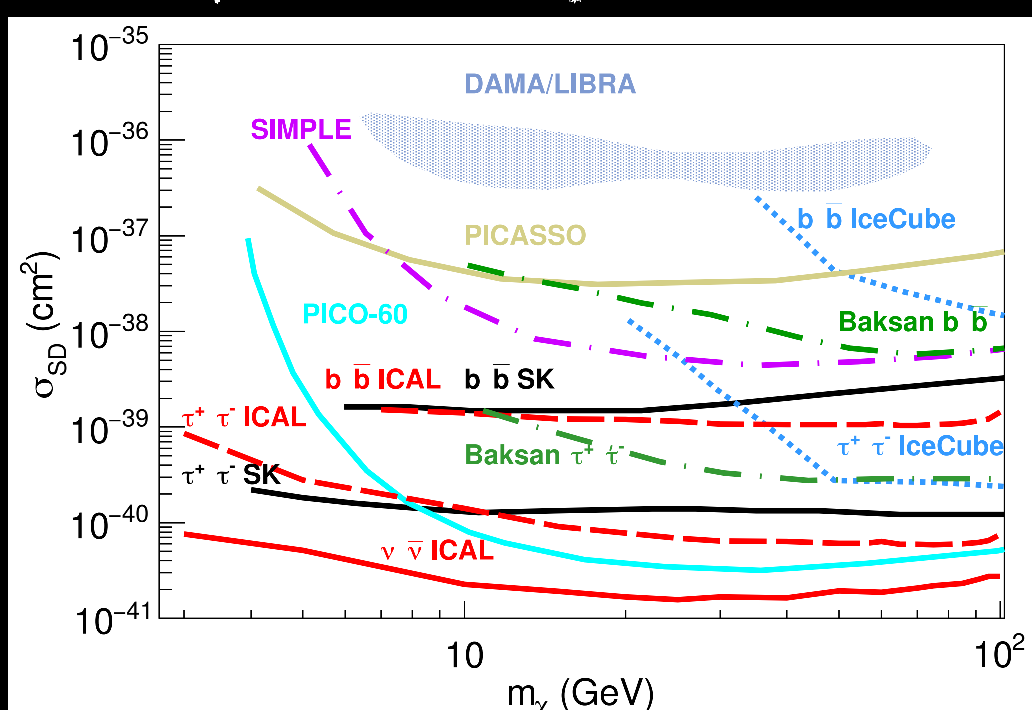
C. Rott, D Jeong, J. Kumar and D. Yaylali, JCAP 07:006, 2019

Using 10 years of KamLAND



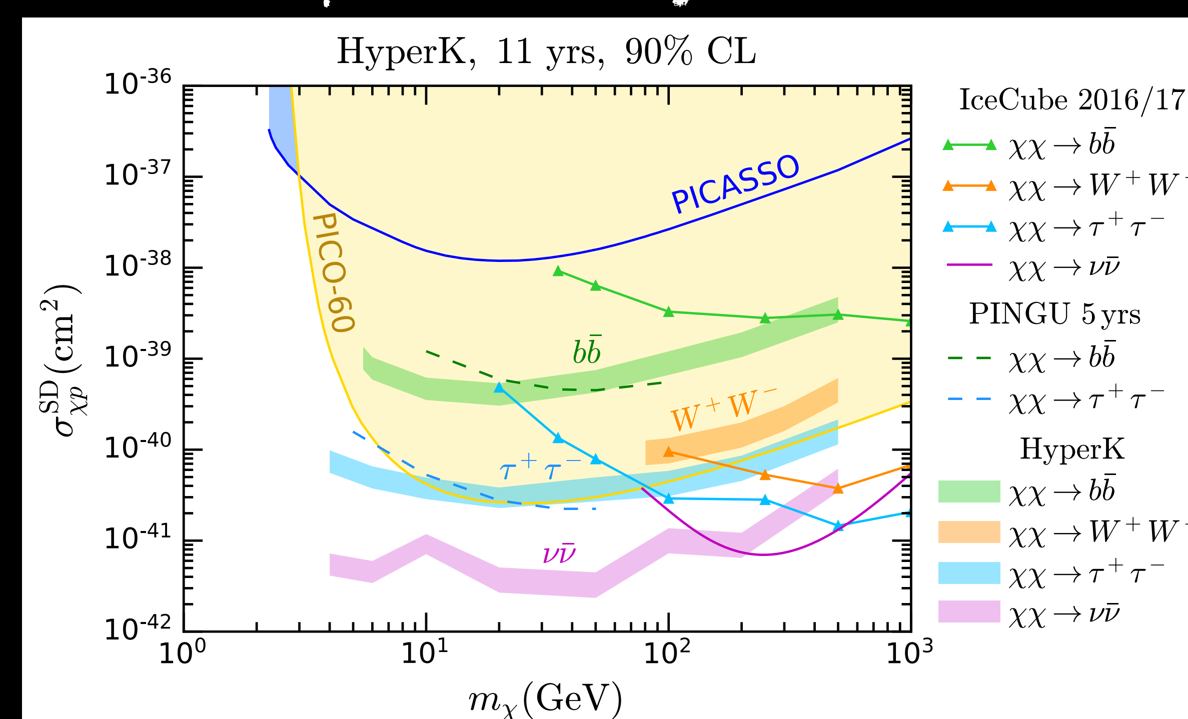
J. Kumar and P. Sandick, JCAP 06:035, 2015

Prospects for 10 years of INO



S. Choubey, A. Ghosh and D. Tiwari, JCAP 05:006, 2018

Prospects for 11 years of HK

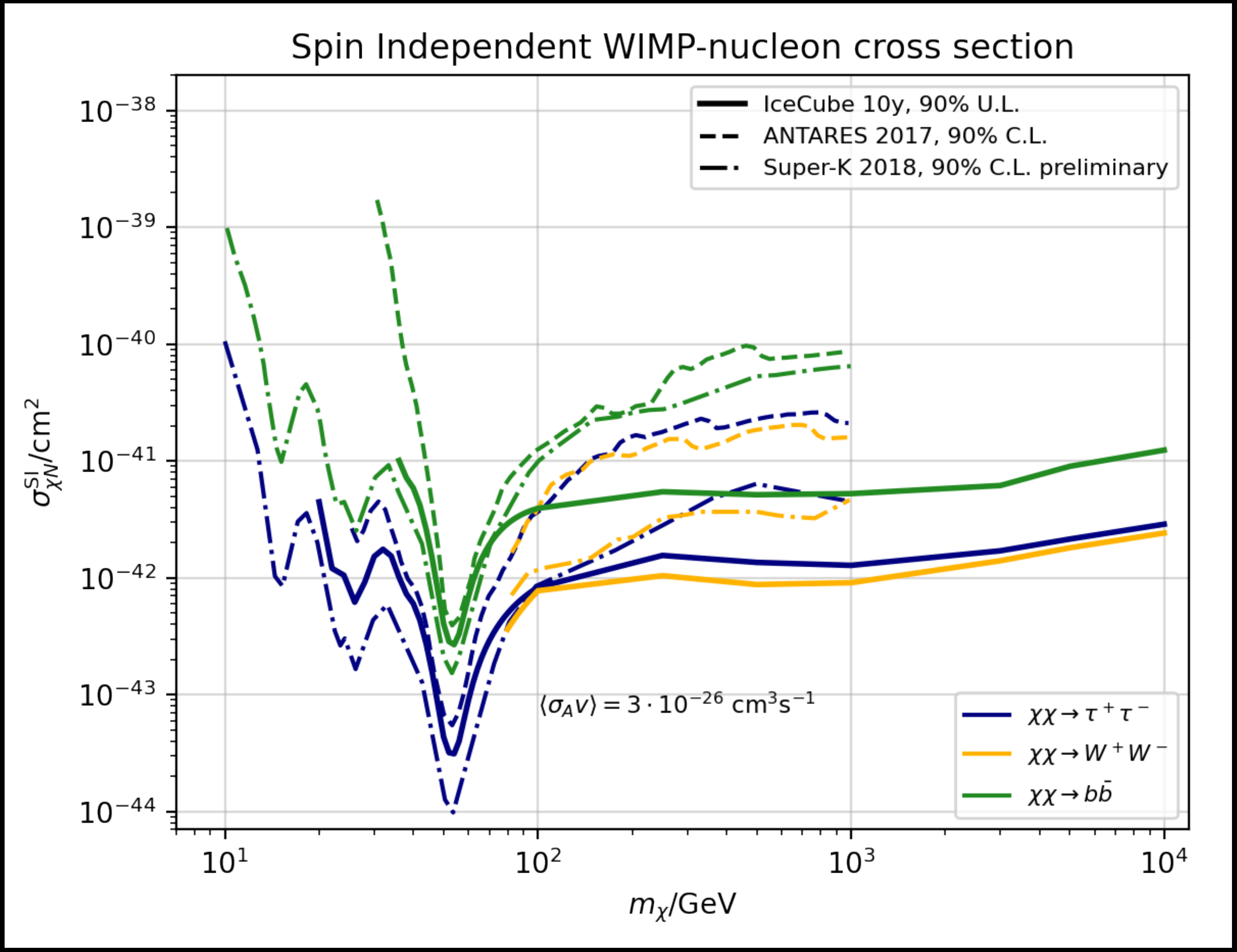


N. F. Bell, M. J. Dolan and S. Robles, JCAP 11:004, 2021

Limits from the Earth

Sensitive to spin-independent cross section

<1% elements with unpaired nucleons:
weak sensitivity to spin-dependent interactions



J. A. Aguilar-Sánchez et al. [IceCube Collaboration], PoS (ICRC2023) 1393, 2023

Usually only considered annihilations into
heavy quarks, gauge bosons or tau leptons...

What about annihilations into light quarks, muons or even electrons?

- Electrons/positrons do not produce neutrinos...
- Muons lose energy electromagnetically very rapidly and decay at rest

$$\tau_{stop} \approx 3 \cdot 10^{-10} \left(\frac{E}{10\ \mathrm{GeV}} \right) s \ll \tau_{decay} \approx 2 \cdot 10^{-4} \left(\frac{E}{10\ \mathrm{GeV}} \right) s$$

- Light-quark hadrons, as pions, are stopped via nuclear interactions and decay at rest

$$\tau_{\mathrm{int}} \approx 10^{-11} s \ll \tau_{decay} \approx 10^{-6} \left(\frac{E}{10\ \mathrm{GeV}} \right) s$$

Usually only considered annihilations into heavy quarks, gauge bosons or tau leptons...

What about annihilations into light quarks, muons or even electrons?

What about the low-energy (tens of MeV) neutrinos from pion and muon decays at rest?

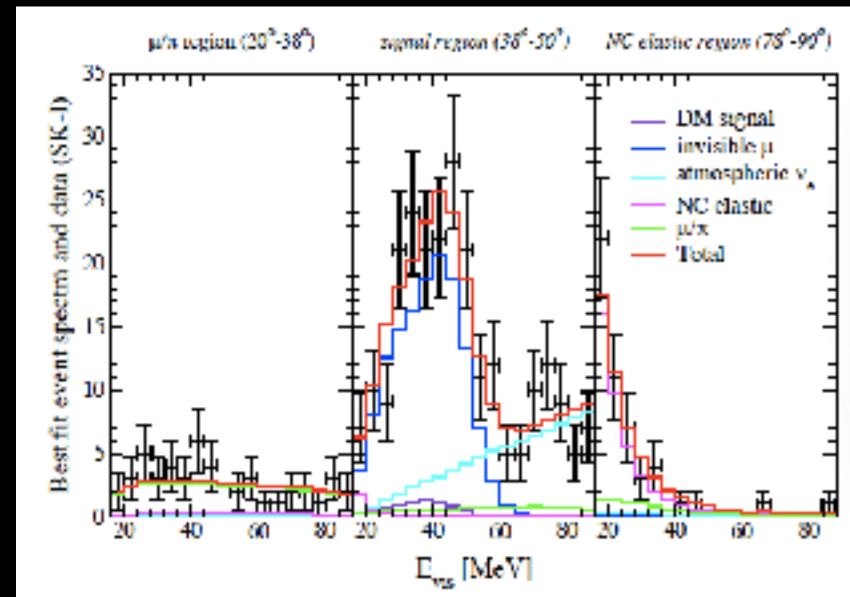
C. Rott, J. Siegal-Gaskins and J. F. Beacom, Phys. Rev. D88:055005, 2013

N. Bernal, J. Martín-Albo and SPR, JCAP 08:011, 2013

- ... as pions, are stopped via nuclear interactions and decay at rest

$$\tau_{\rm int} \approx 10^{-11} s \ll \tau_{decay} \approx 10^{-6} \left(\frac{E}{10 \text{ GeV}} \right) s$$

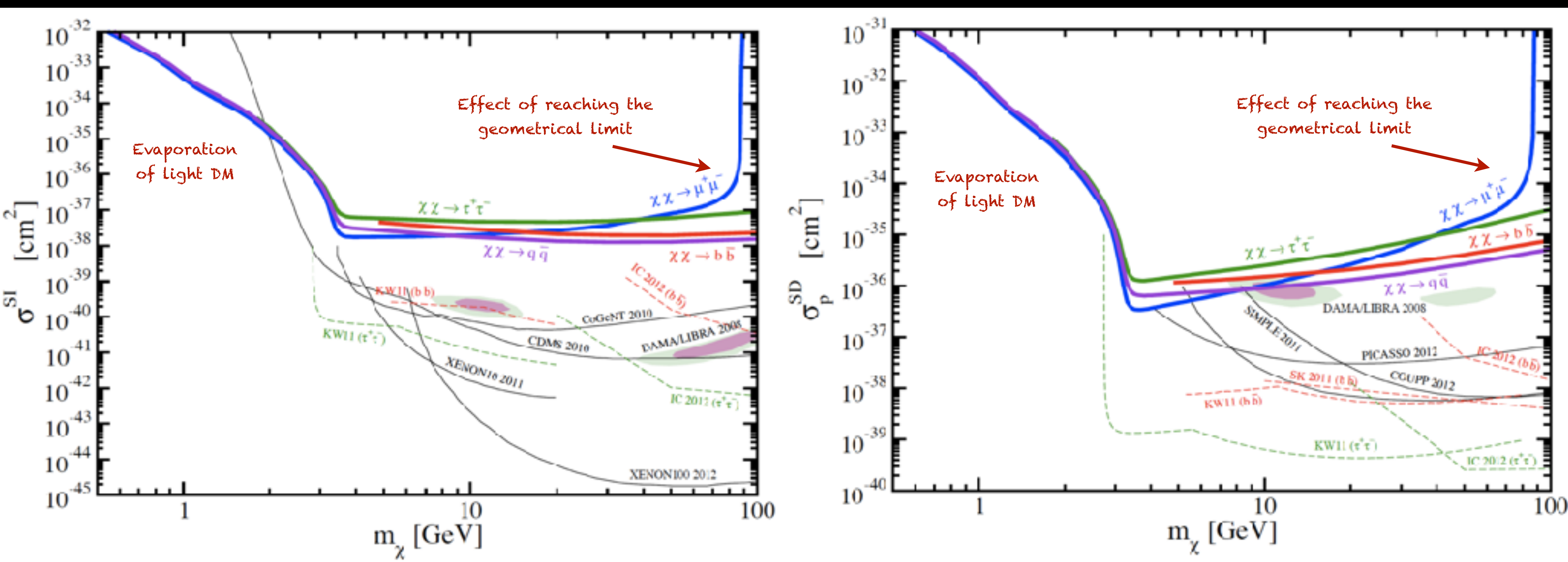
Using SK data
(DSNB analysis)



Unique limits
(from DM in the Sun)
on annihilations into
light quarks or muons

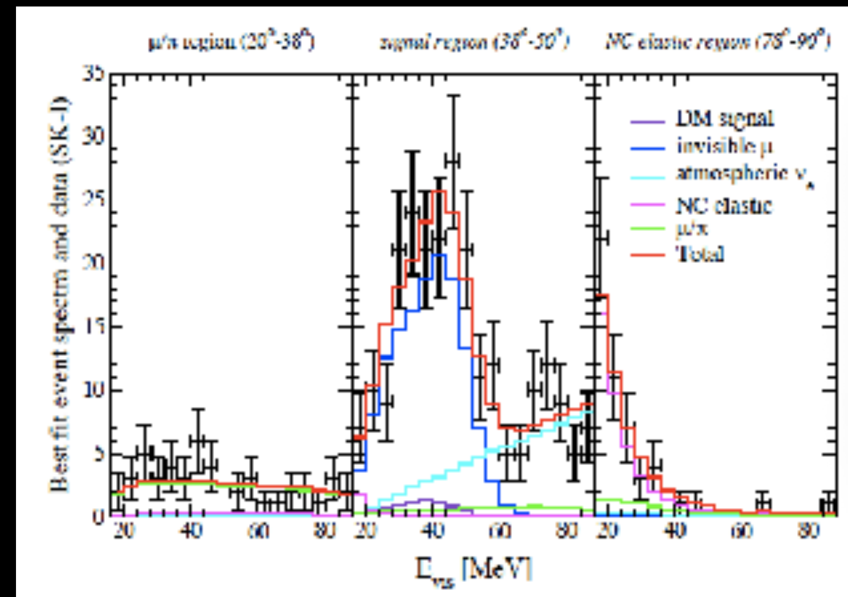
spin-independent

spin-dependent



N. Bernal, J. Martín-Albo, SPR, JCAP 08:011, 2013

Using SK data (DSNB analysis)



Unique limits (from DM in the Sun) on annihilations into light quarks or muons

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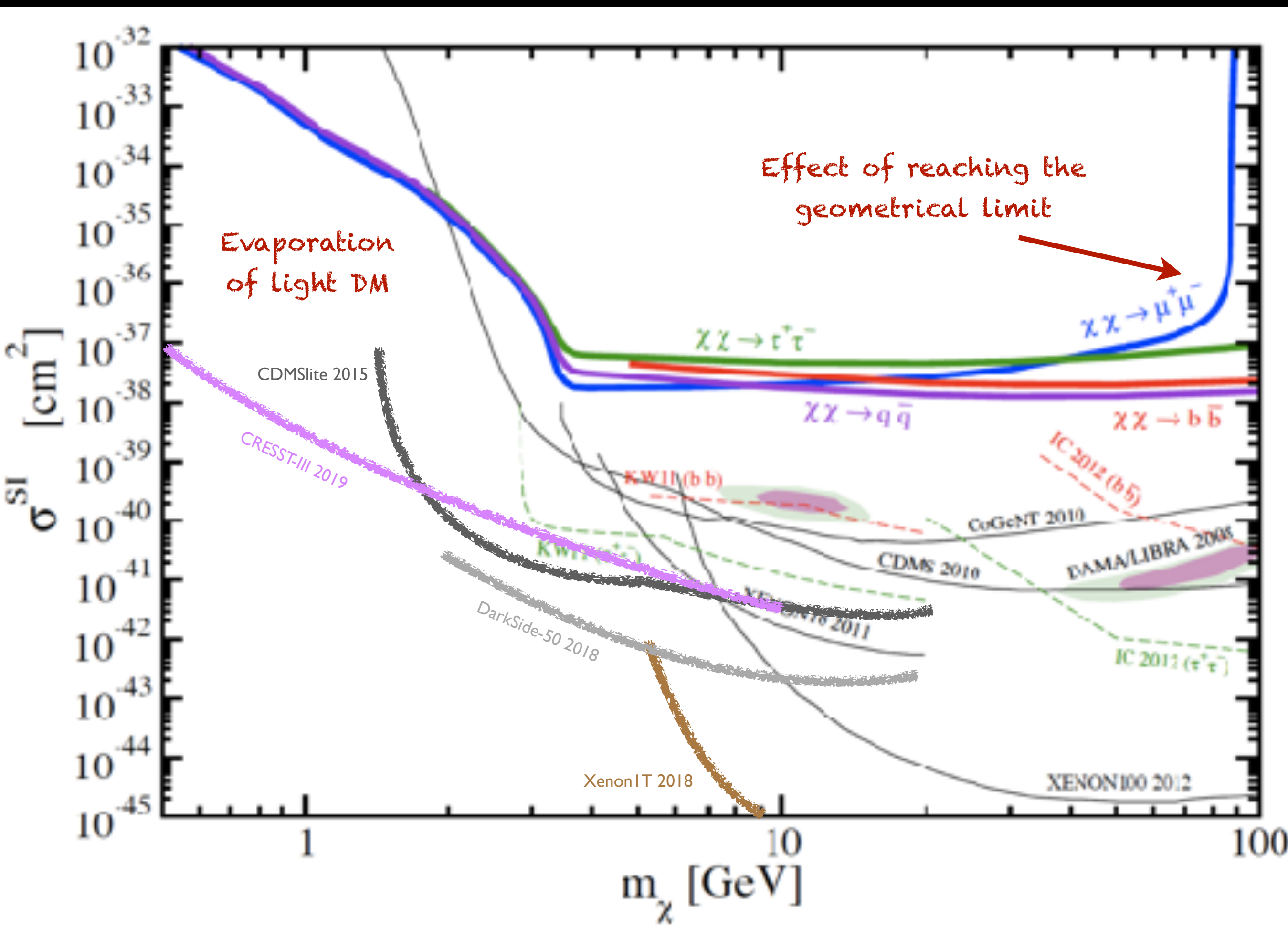
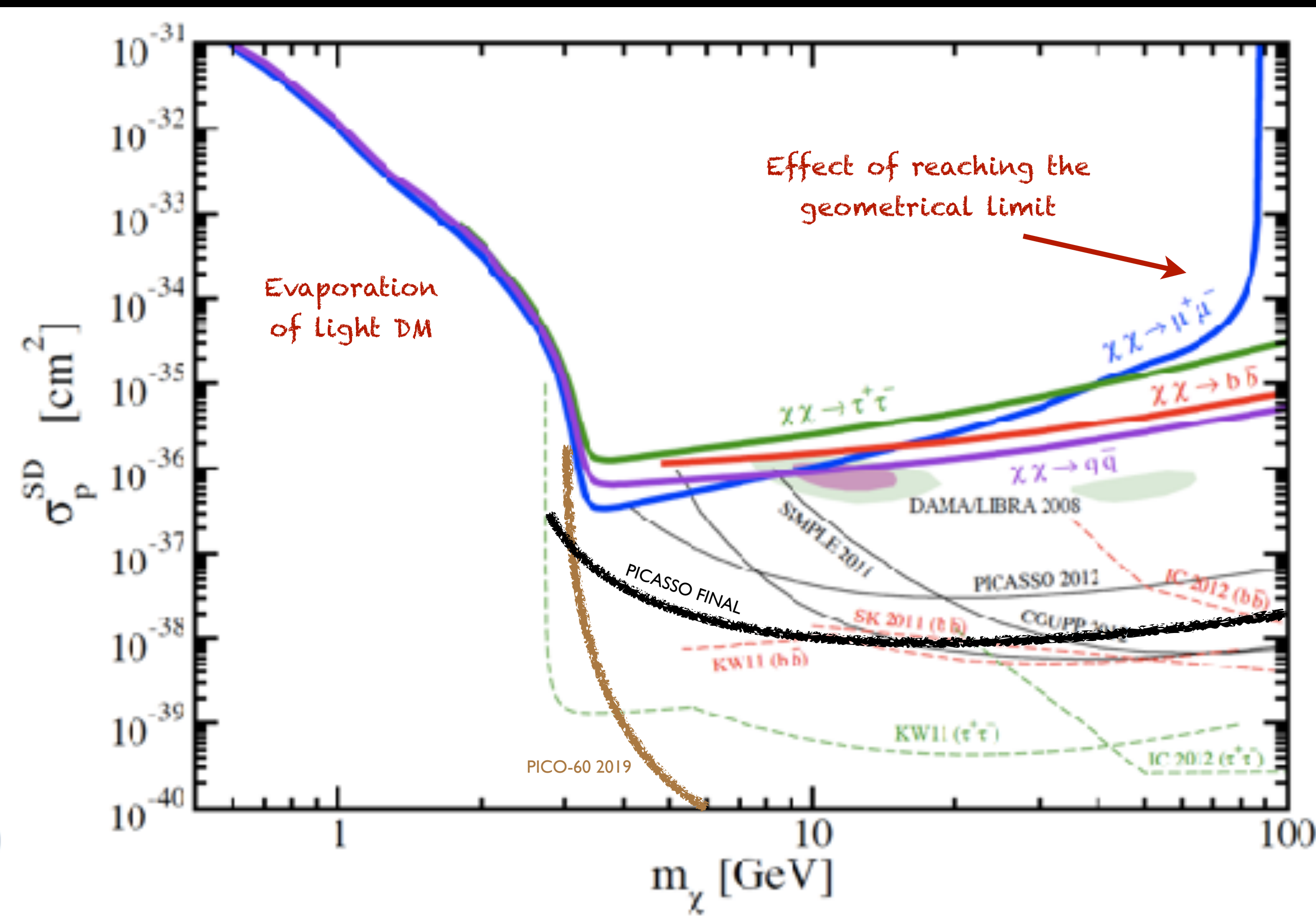
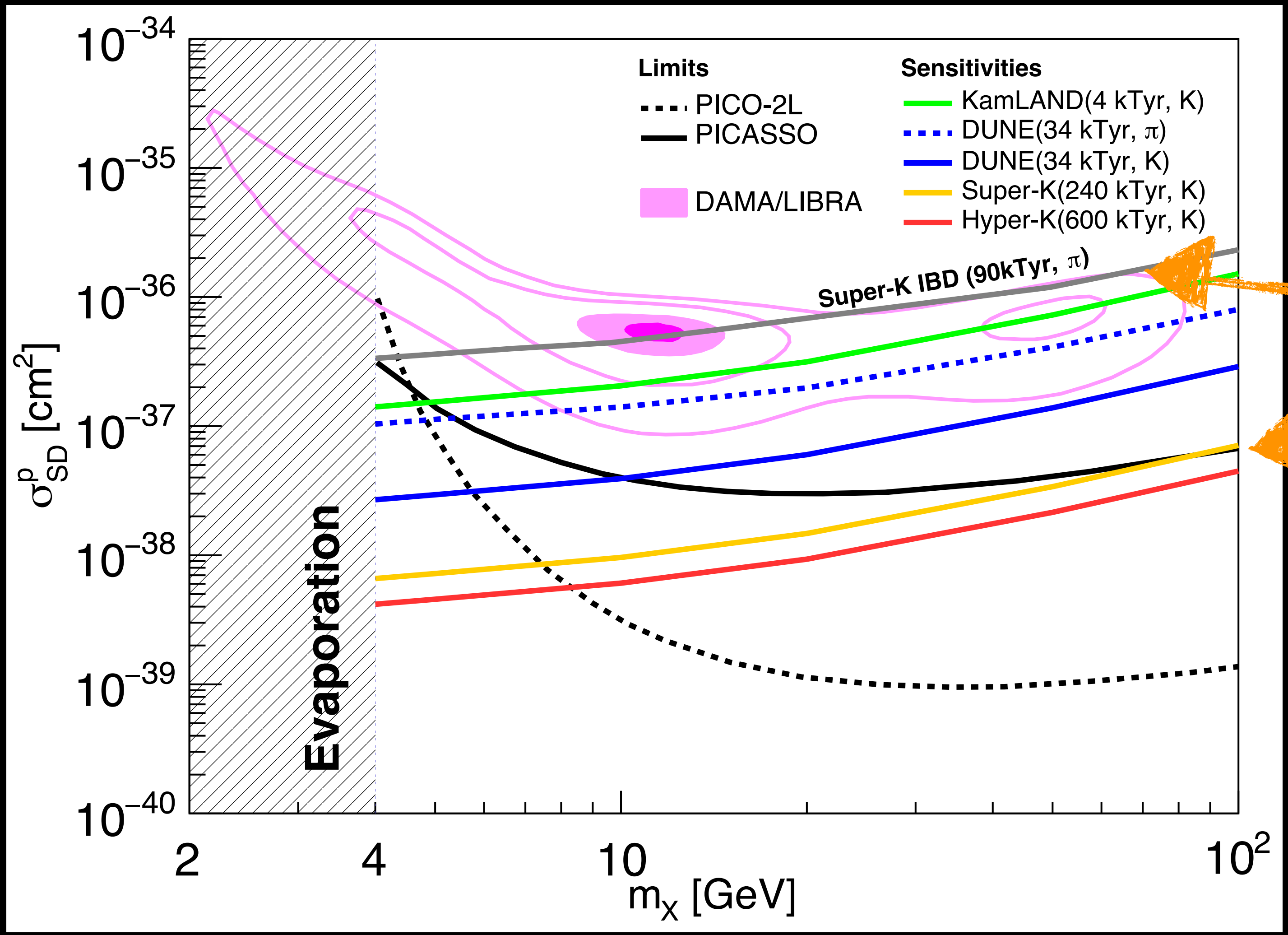




N. Bernal, J. Martín-Albo, SPR, JCAP 08:011, 2013

There could also be a contribution from low-energy neutrinos from kaon decays at rest



higher energy neutrinos: even better than neutrinos from pion decays at rest

C. Rott, S. In, J. Kumar and D. Yaylali, JCAP 11:039, 2015

See also:

C. Rott, S. In, J. Kumar and D. Yaylali, JCAP 01:016, 2017

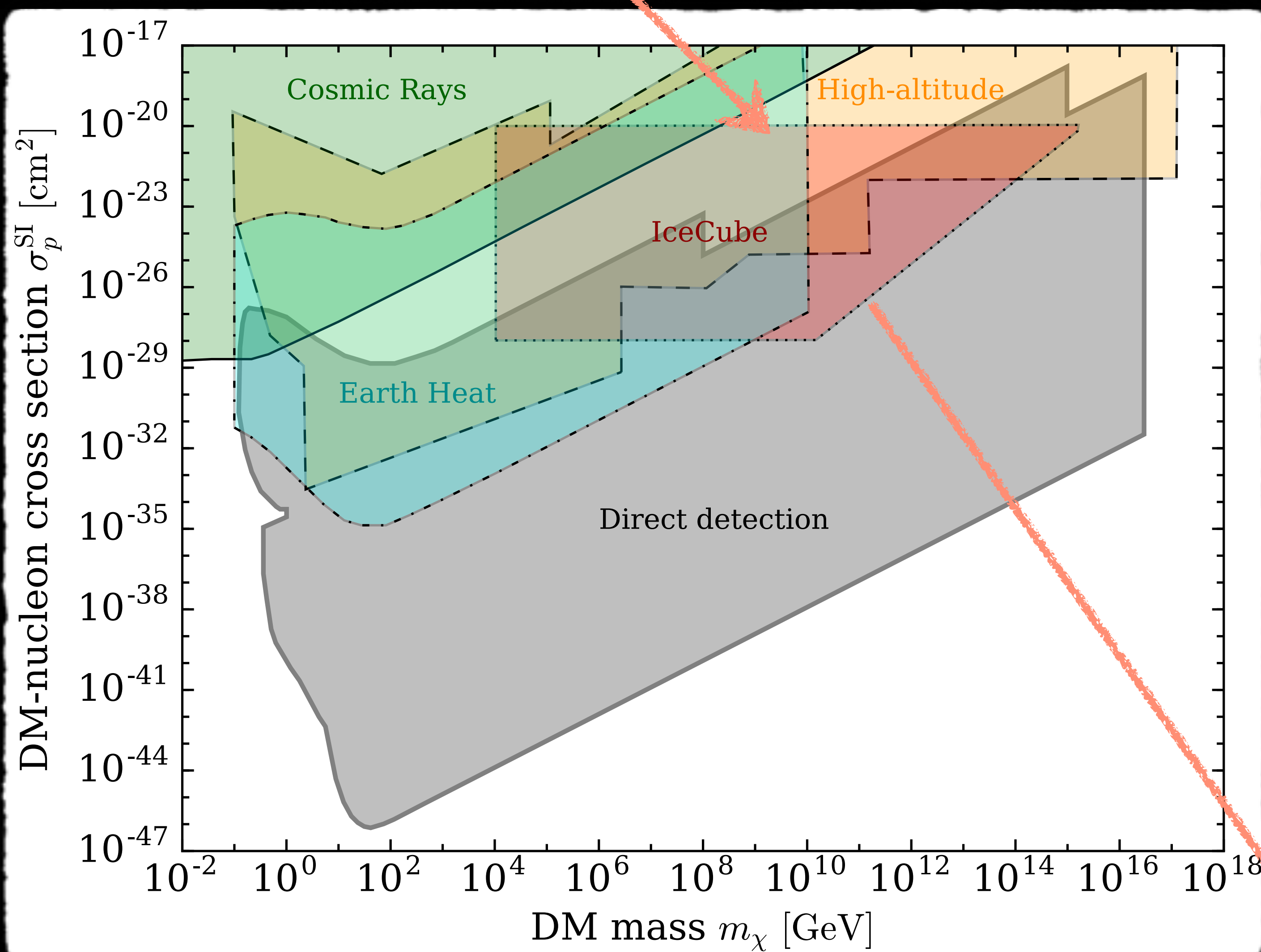
A. Abed Abed et al. [DUNE Collaboration], JCAP 10:065, 2021

Strongly interacting dark matter: Sun

I. F. M. Albuquerque, L. Hui and E. W. Kolb, Phys. Rev. D64:083504, 2001

104.3 days with IC22

I. F. M. Albuquerque and C. Pérez de los Heros, Phys. Rev. D81:063510, 2010



B. J. Kavanagh, Phys. Rev. D97:123013, 2018

Thick regime:

very high interaction probability

$$n\,\sigma\,R_\odot \gg 1$$

A. Gould, Astrophys. J. 387:21, 1992

J. Bramante, A. Delgado and A. Martin, Phys. Rev. D96:063002, 2017

However... (for large DM masses) the typical momentum transfer (per collision) is ~ m_N/m_{DM}

Key quantity: $$q \equiv \frac{m_\chi}{m_N\, n\, \sigma\, R_\odot}$$

R. H. Cyburt et al., Phys. Rev. D65:123503, 2002

G. D. Mack, J. F. Beacom and G. Bertone, Phys. Rev. D76:043523, 2007

G. D. Mack and A. Manohar, J. Phys. G40:115202, 2013

... and many others recently

$q > 1$: very rare collisions → capture rate scales with inverse of DM mass squared

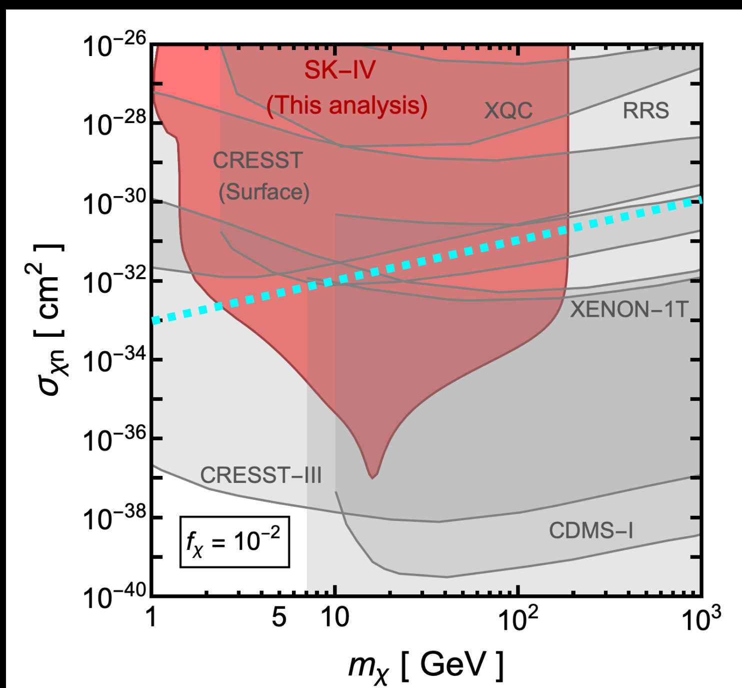
$q < 1$: efficient energy transfer → capture rate scales with inverse of DM mass

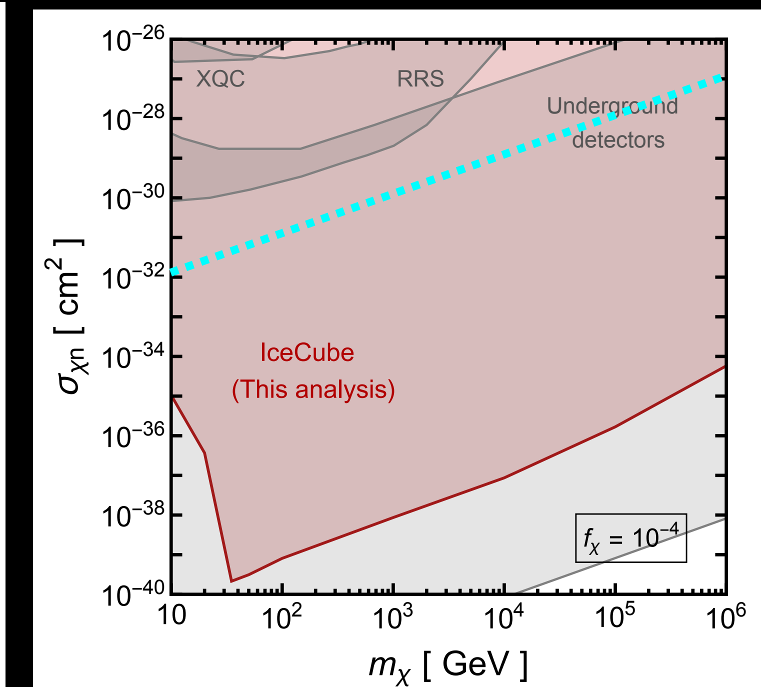
For applicability of model independence:

M. C. Digman et al., Phys. Rev. D100:063013, 2019

Strongly interacting dark matter: Earth

DM annihilations in the Earth: neutrinos from pion decays and prompt neutrinos





M. Pospelov and A. Ray, JCAP 01:029, 2024

However, it assumes maximal capture for some DM masses and cross sections

$$q \simeq 5 \left(\frac{m_\chi}{10^6\ \mathrm{GeV}}\right)\left(\frac{10^{-28}\ \mathrm{cm}^2}{\sigma}\right)\left(\frac{R}{R_\oplus}\right)^2\left(\frac{M_\oplus}{M}\right)$$

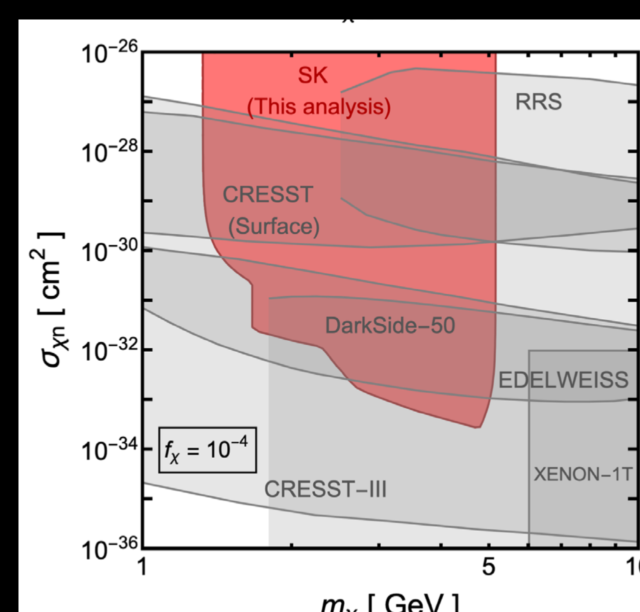
* Actually, the key quantity is $A_N^2 \equiv \frac{3\,v_e^2}{v_d^2}\frac{1}{q}$

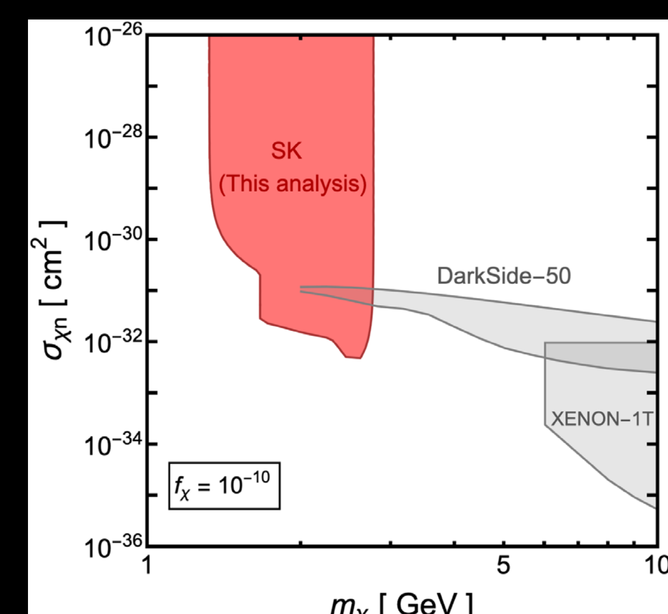
If $A_N^2 \gg 1$ the approximation is ok

J. Bramante, A. Delgado and A. Martin, Phys. Rev. D96:063002, 2017

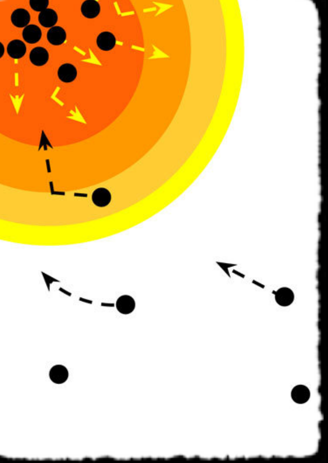
DM annihilations inside the detector (SK)

Only light DM, not concentrated in the center of Earth





D. McKeen, D. E. Morrissey, M. Pospelov, H. Ramani and A. Ray, Phys. Rev. D131:011005, 2023



Scatterings off electrons

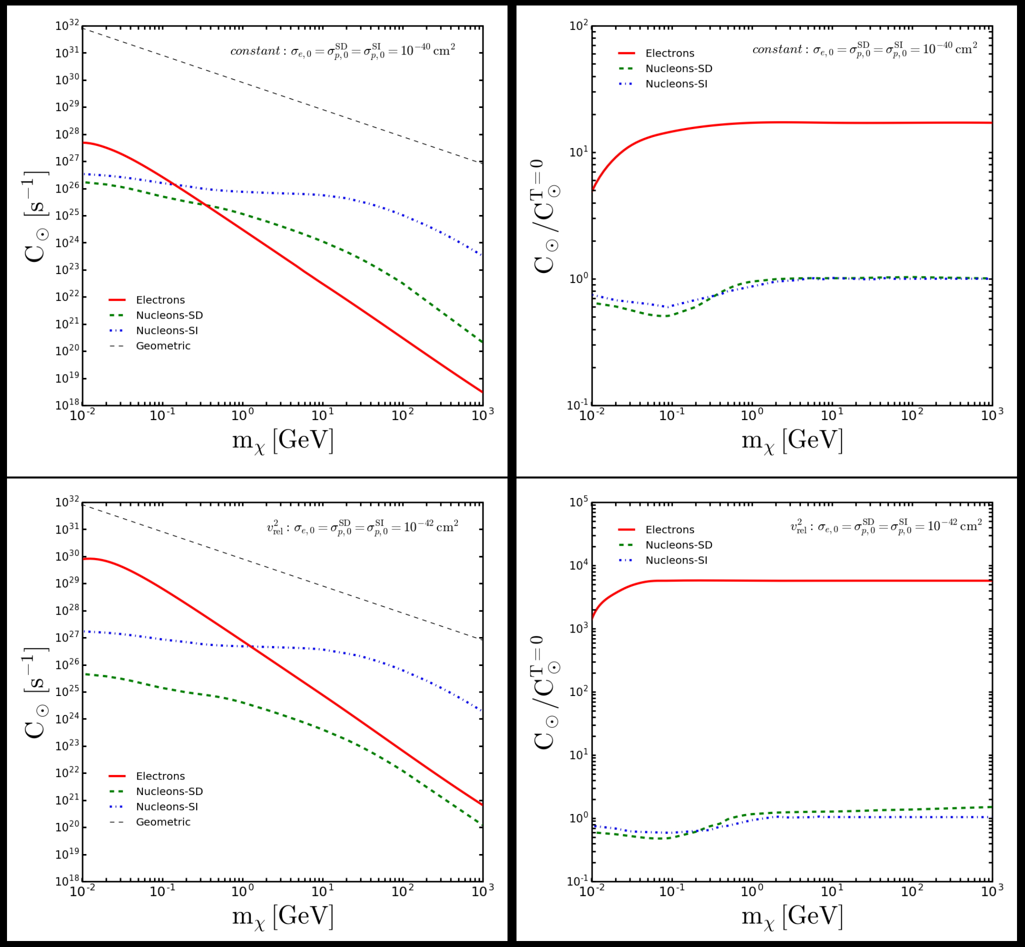
What about interactions with electrons?

J. Kopp, V. Niro, T. Schwetz and J. Zupan, Phys. Rev. D80:083502, 2009

smaller mass of targets ⟶ thermal motion is crucial

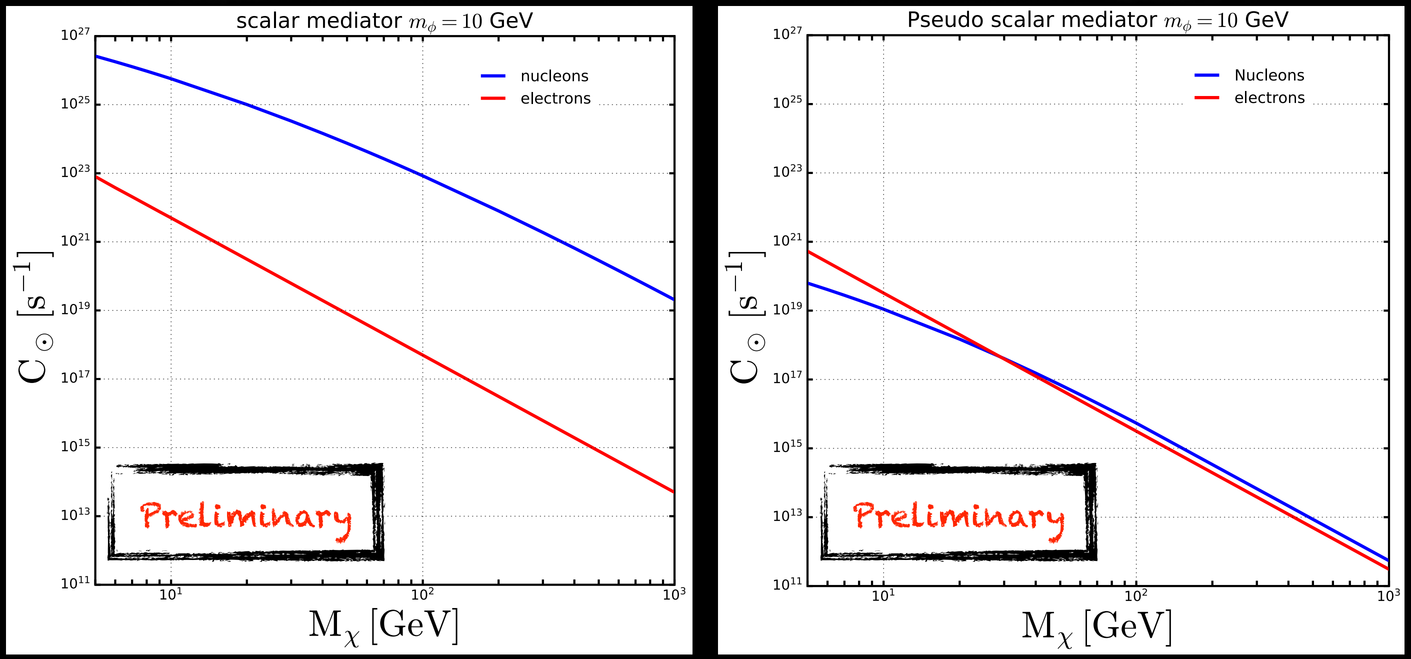
constant scattering cross section

velocity-dependent scattering cross section



R. Garani and SPR, JCAP 05:007, 2017

In leptophilic scenarios, DM-nucleon could occur at loop level and this could dominate the capture process



R. Garani and SPR, in preparation

2-photon exchange dominates in some cases

2-loop from factor computed in

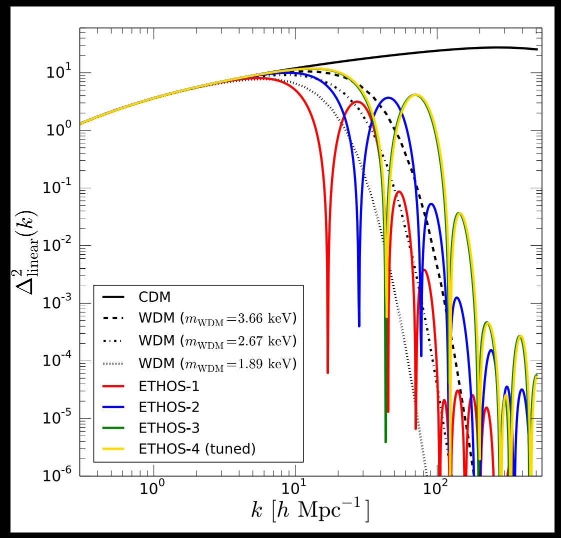
R. Garani, F. Gasparotto, P. Mastrolia, H. J. Munch, SPR and A. Primo, JHEP 12:212, 2021

Self-interacting dark matter

D. N. Spergel and P. J. Steinhardt, Phys. Rev. Lett. 84:3760, 2000

Suppresses small-scale structure

C. Boehm, P. Fayet and R. Schaeffer, Phys. Lett. B518:8, 2001



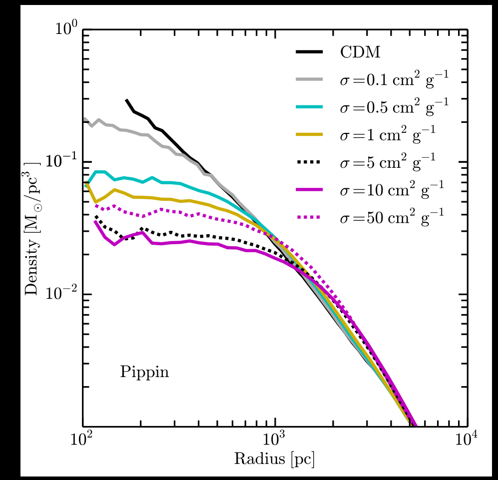
M. Vogelsberger et al., MNRAS 460:1399, 2016

Alleviates cusp-core, too-big-to-fail problems

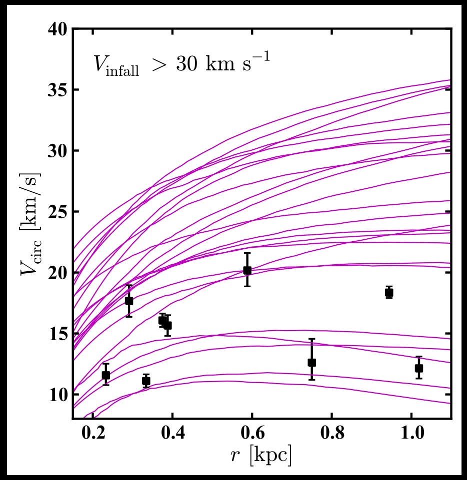
R. A. Flores and J. R. Primack, Astrophys. J. 427:L1, 1994

B. Moore, Nature 370:629, 1994

M. Boylan-Kolchin, J. S. Bullock and M. Kaplinghat, MNRAS 415:L40, 2011; MNRAS 422:1203, 2012



O. D. Elbert et al., MNRAS 453:29, 2015



M. Boylan-Kolchin, J. S. Bullock and M. Kaplinghat, MNRAS 422:1203, 2012

Capture in the Sun

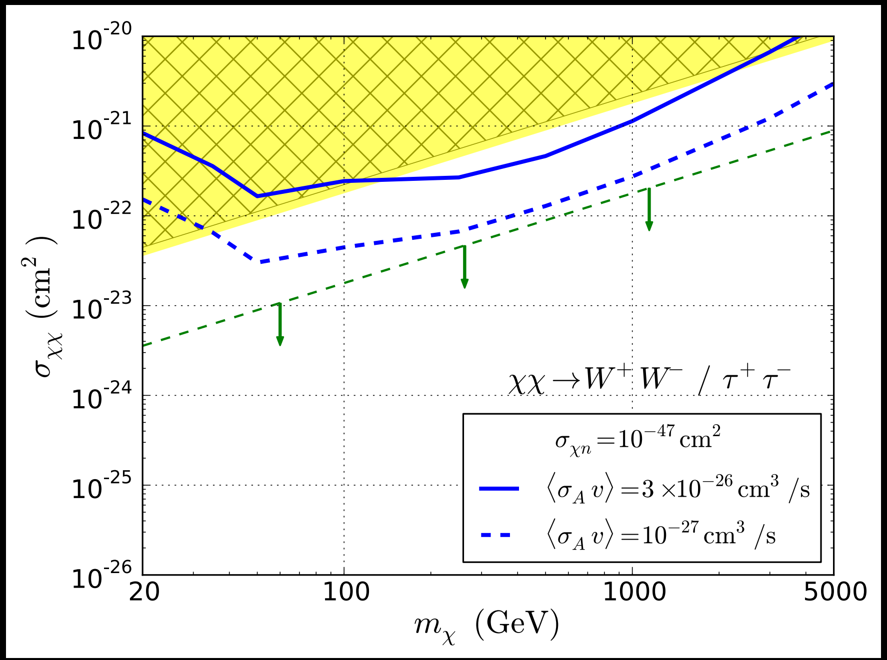
A. R. Zentner, Phys. Rev. D80:063501, 2009

$$\frac{dN_\chi(t)}{dt} = \mathrm{C} + \mathrm{C_s}\, N_\chi(t) - \mathrm{A}\, N_\chi^2(t)$$

Self interactions enhance the capture rate

DM could reach equilibrium, even if it wouldn't without self-interactions

317 days IC79



I. F. M. Albuquerque, C. Pérez de los Heros and D. S. Robertson, JCAP 02:047, 2014

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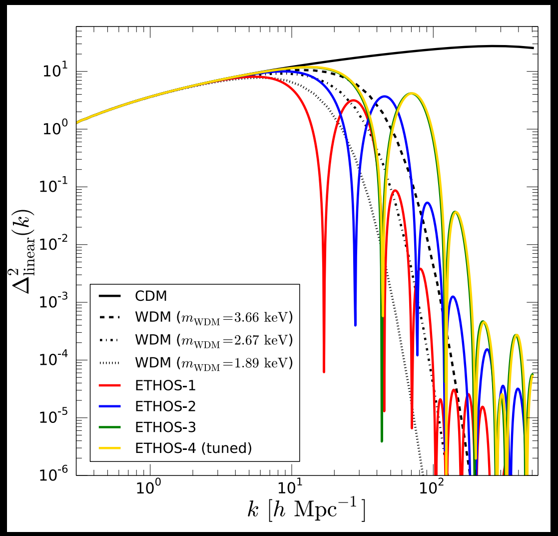

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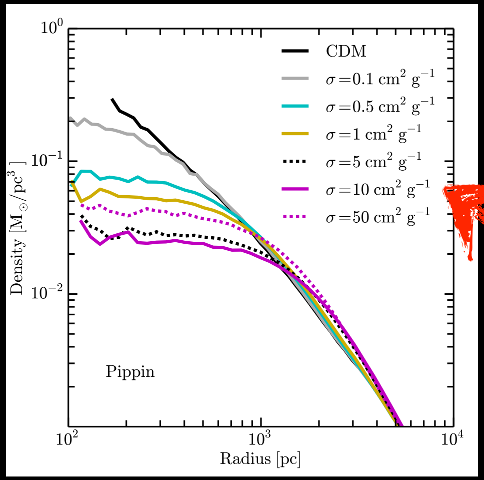

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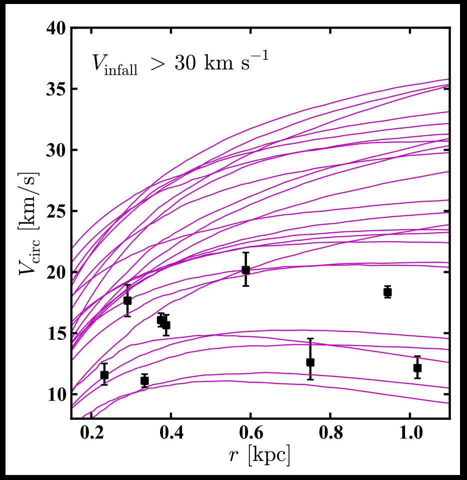

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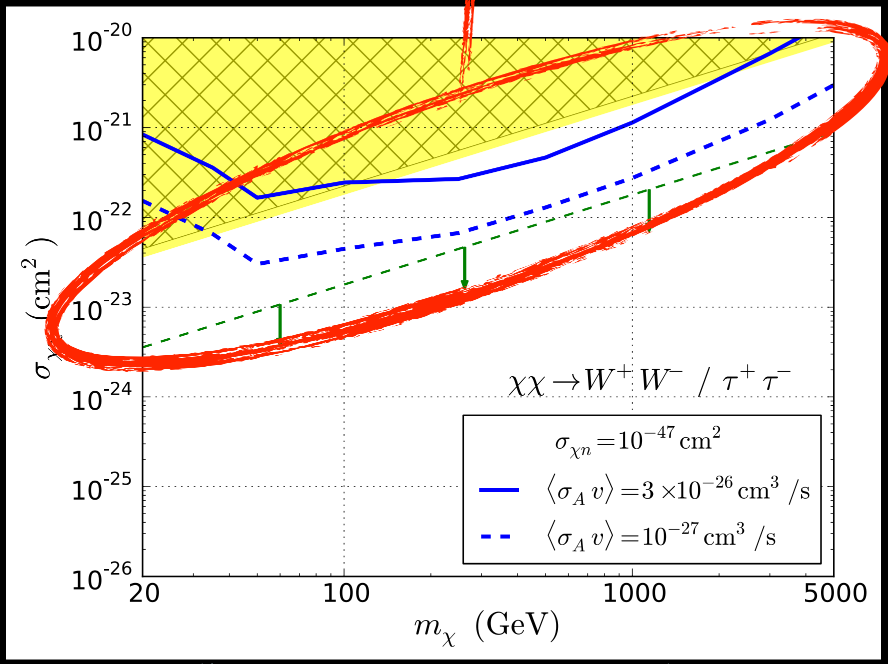

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Self-interacting dark matter

Some extra terms are required:

$$\frac{dN_\chi(t)}{dt} = \mathtt{C} + \left(\mathtt{C_s} - \mathtt{E} - \mathtt{C_e}\right) N_\chi(t) - \left(\mathtt{A} + \mathtt{E_s}\right) N_\chi^2(t)$$

self-capture

A. R. Zentner,
Phys. Rev. D80:063501, 2009

self-ejection

C. Gaidau and J. Shelton,
JCAP 06:022, 2019

self-evaporation

C.-S. Chen, F.-F. Lee, G.-L. Lin
and Y.-H. Lin, JCAP 10:049, 2014

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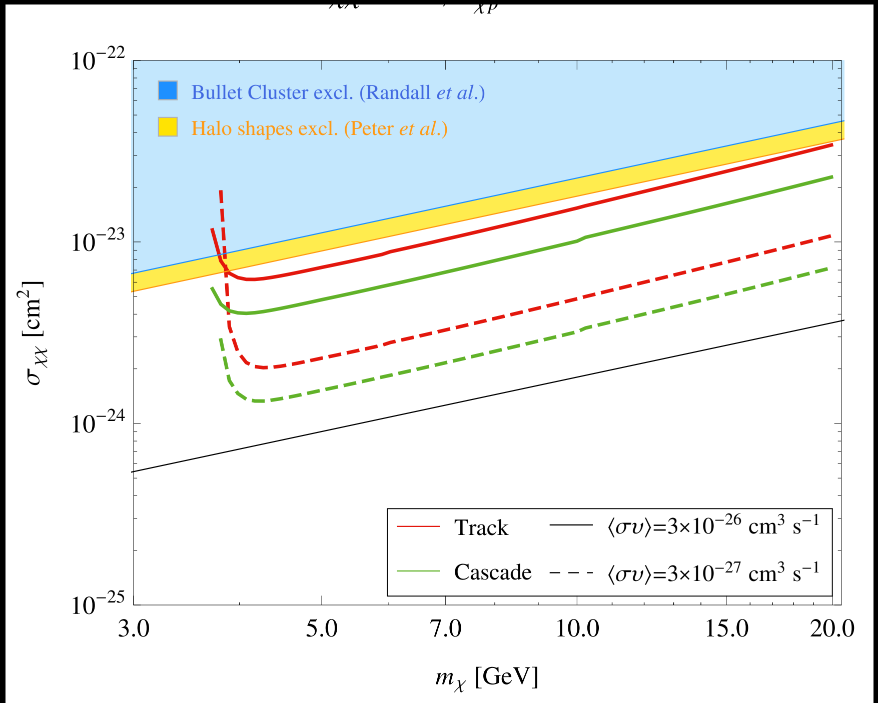
IC-PINGU: 5 years



Self-interacting dark matter

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A. R. Zentner,
Phys. Rev. D80:063501, 2009

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JCAP 06:022, 2019

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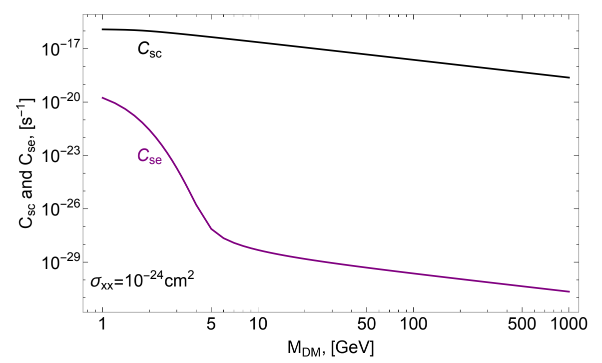
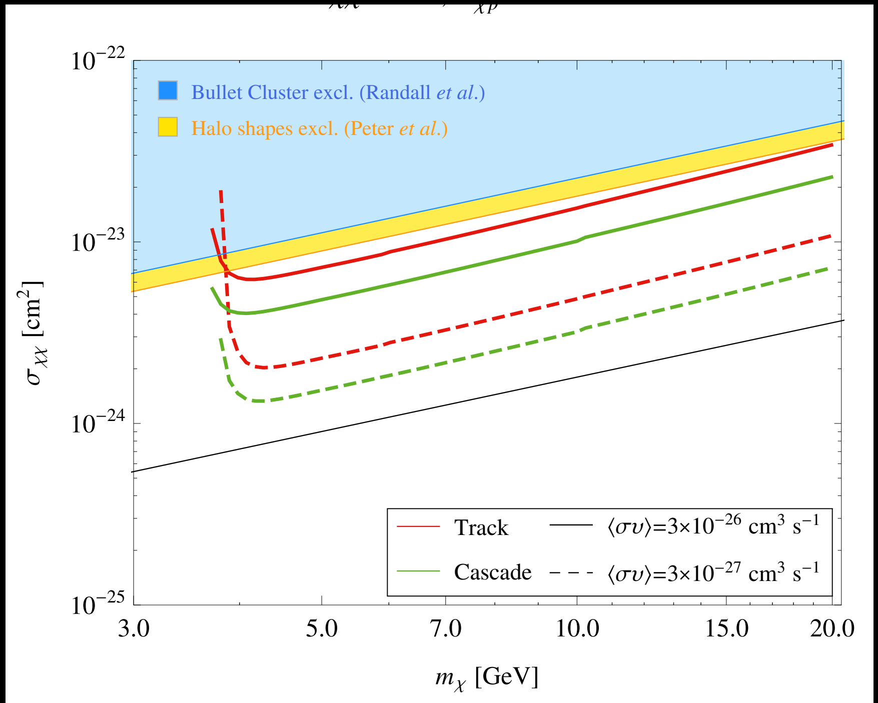
For the Sun: $C_s > C_e$

enhanced capture



IC-PINGU: 5 years



Self-interacting dark matter

Some extra terms are required:

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self-capture

A. R. Zentner,
Phys. Rev. D80:063501, 2009

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C. Gaidau and J. Shelton,
JCAP 06:022, 2019

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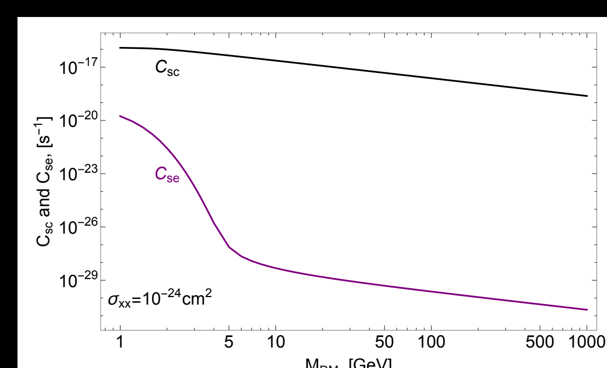
and Y.-H. Lin, JCAP 10:049, 2014

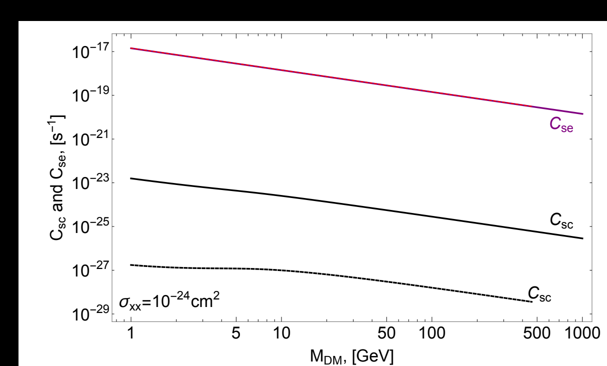
For the Sun: $\mathtt{C_s} > \mathtt{C_e}$

enhanced capture

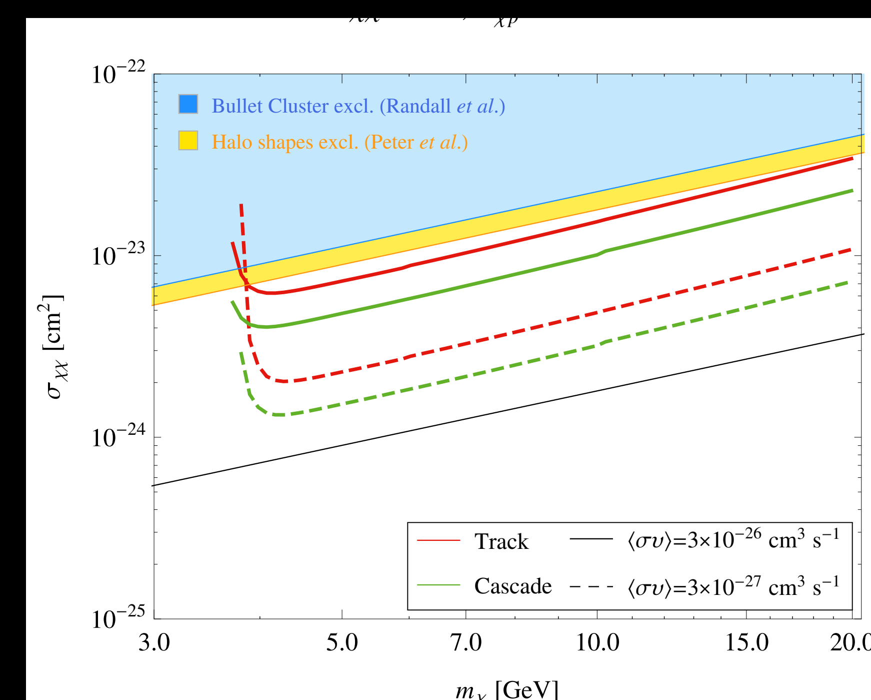


For the Earth: $\mathtt{C_s} < \mathtt{C_e}$

suppressed capture

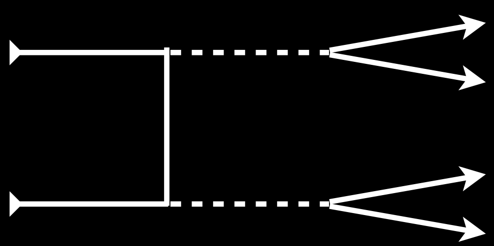


IC-PINGU: 5 years



Secluded dark matter

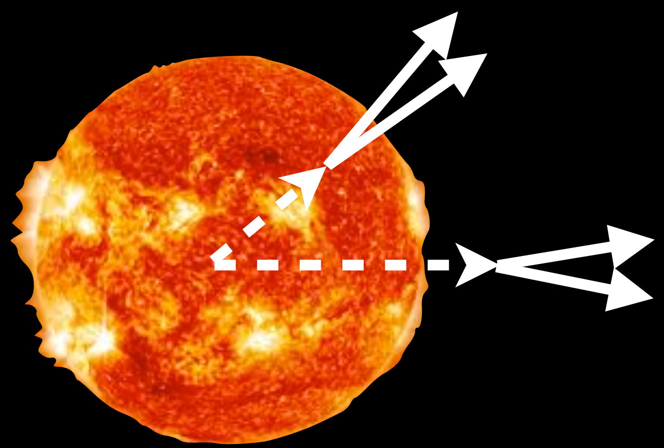
Metastable mediator (dark photon, dark scalar...)
coupled to DM, that subsequently could decay into SM particles



M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B662:53, 2008

Neutrino signals from the Sun:

Once captured, DM would annihilate into mediators, which would (partially) escape the Sun and decay into SM before reaching the Earth



P. Meade et al., JHEP 06:029, 2010

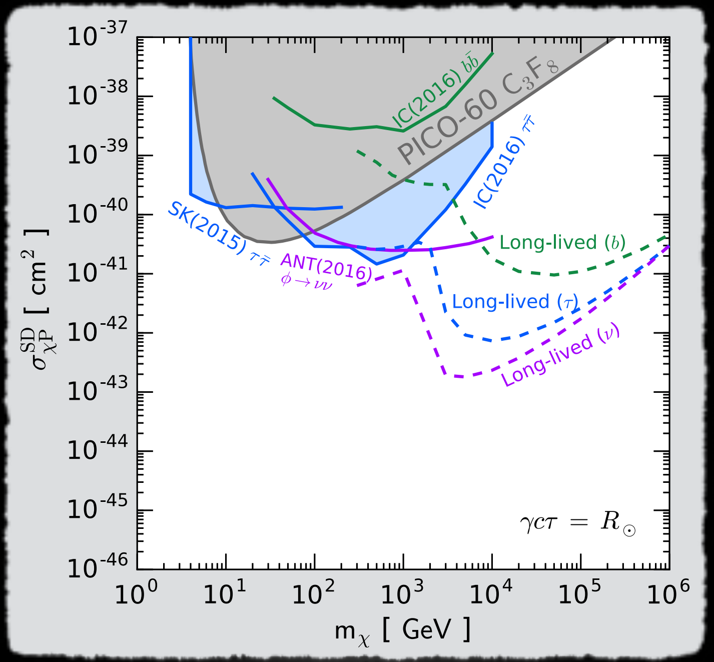
P. Schuster, N. Toro and I. Yavin, Rhys. Rev. D81:016002, 2010

N. F. Bell and K. Petraki, JCAP 04:003, 2011

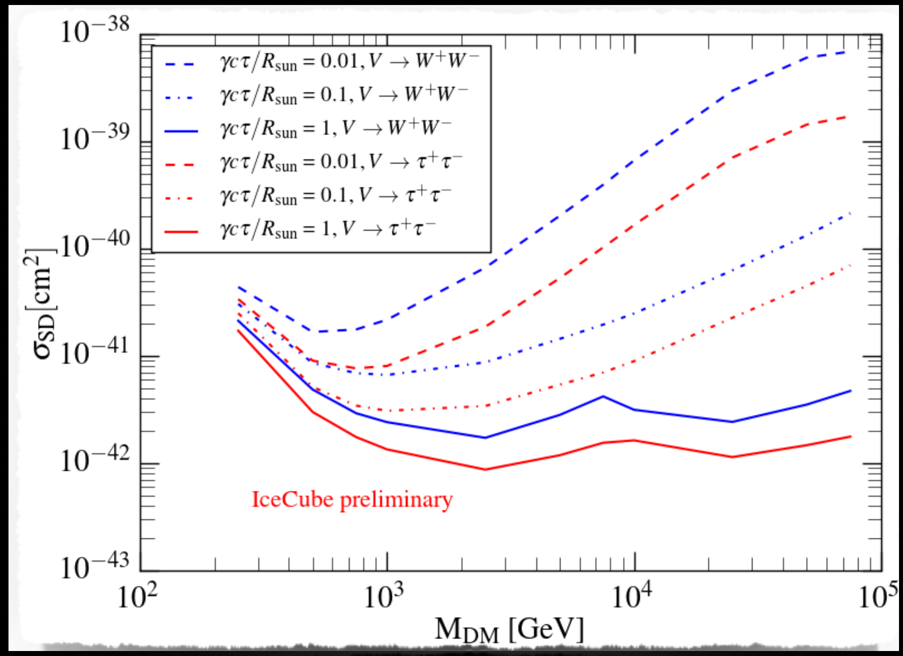
IceCube: 6 years

Higher energy neutrinos: mainly from pions/kaons if decays occur outside the Sun

Less absorption: more important for higher energy neutrinos and thus, for larger DM masses



R. K. Leane, K. C. Y. Ng, J. F. Beacom, Phys. Rev. D95:123016, 2017



C. Tönnis et al. [IceCube Collaboration], PoS (ICRC2021) 521, 2021

See also: D. S. Robertson and I. F. M. Albuquerque, JCAP 02:056, 2018
C. Niblaeus, A. Beniwal and J. Edsjö, JCAP 11:011, 2019

S. Adrián-Martínez et al. [ANTARES Coll.], JCAP 05:016, 2017
M. Ardid et al., JCAP 04:010, 2017

More on secluded dark matter

Self-interactions (dissipative DM):
in addition to adding a capture component, they could result in a lower velocity dispersion (dark disc)

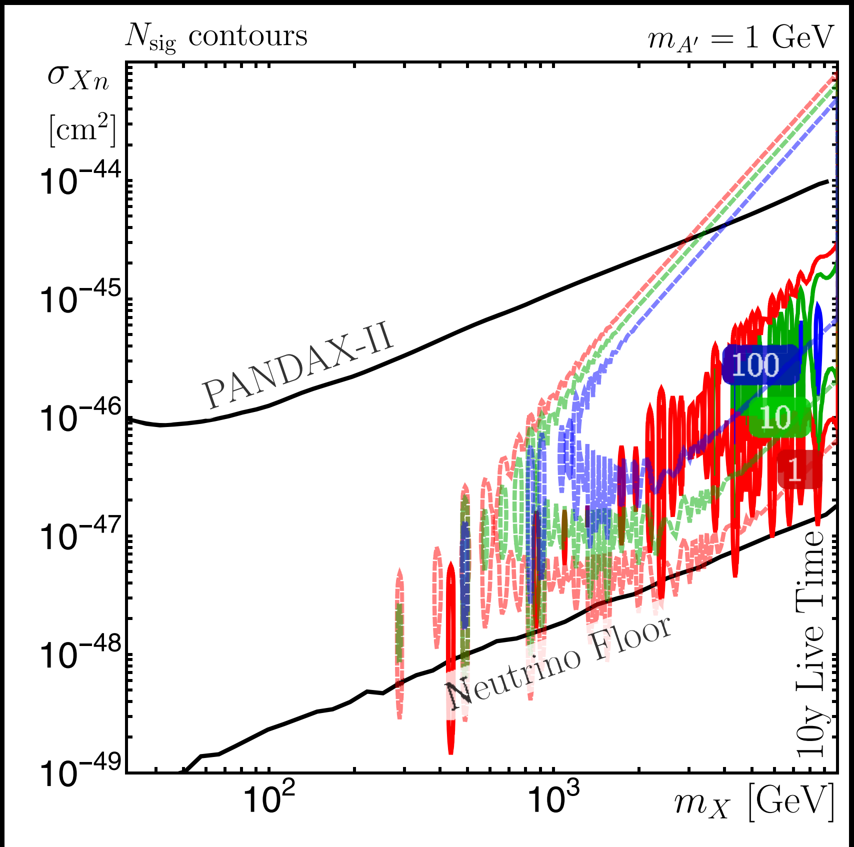
T. Bruch et al., Phys. Lett. B674:250, 2009
J. Fan, A. Katz and J. Shelton, JCAP 06:059, 2014

Long-range interactions: Sommerfeld enhanced annihilation cross section → particularly important for Earth signals

C. Delaunay, P. J. Fox and G. Perez, JHEP 05:099, 2009
J. Chen, Z.-L. Liang, Y.-L. Wu and Y.-F. Zhou, JCAP 12:021, 2015
J. L. Feng, J. Smolinsky and P. Tanedo, Phys. Rev. D93:015014, 2016

Di-muon signals from the Earth: collinear pair of muons

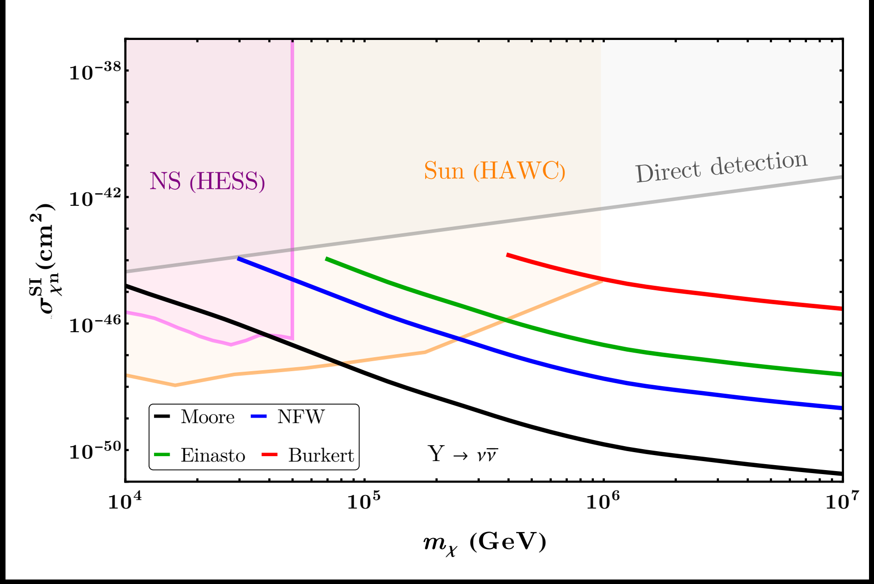
P. Meade, S. Nussinov, M. Papucci and T. Volansky, JHEP 06:029, 2010



J. L. Feng, J. Smolinsky and P. Tanedo,
Phys. Rev. D93:015014, 2016
Phys. Rev. D96:099901, 2017 [erratum]

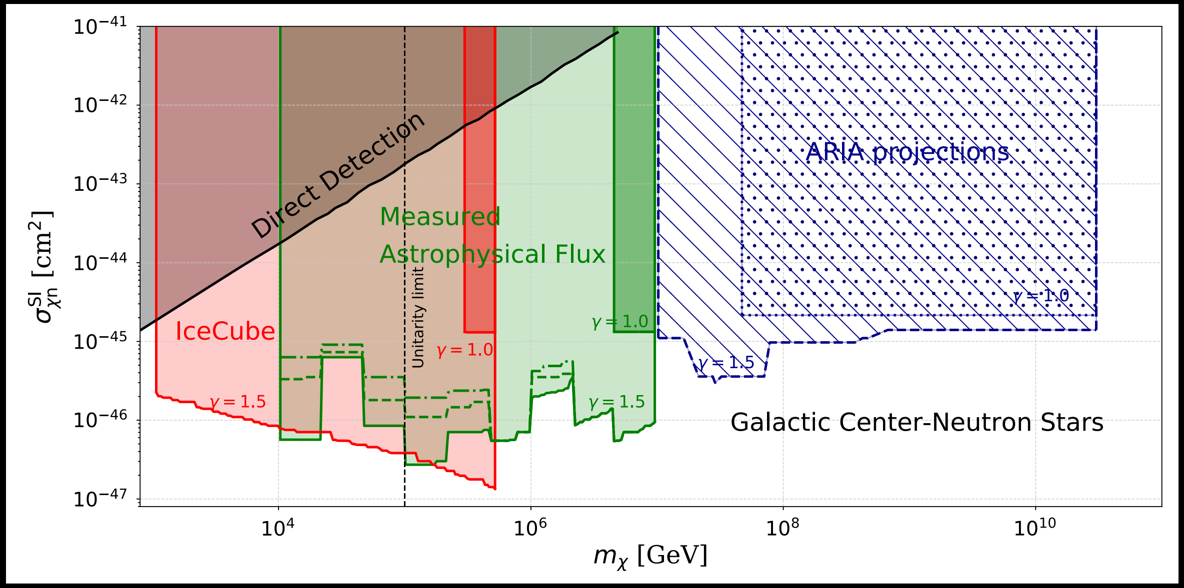
Secluded dark matter: other objects

From neutron stars



D. Bose, T. N. Maity and T. S. Ray, JCAP 05:001, 2022

Sensitivity... although the exposure is not indicated



T. T. Q. Nguyen and T. M. P. Tait, Phys. Rev. D107:115016, 2023

Using measured high-energy neutrino fluxes

From brown dwarfs within 20 pc

P. Bhattacharjee and F. Calore, Particles 7(2):489, 2024

although, it includes incorrect assumptions about detection prospects

Inelastic dark matter

Two dark matter components $\delta = m_{\chi_2} - m_{\chi_1}$

constraints are relaxed as inelastic dark matter interactions produce less energetic nuclear recoils compared to elastic interactions

Limits from direct detection experiments can be relaxed

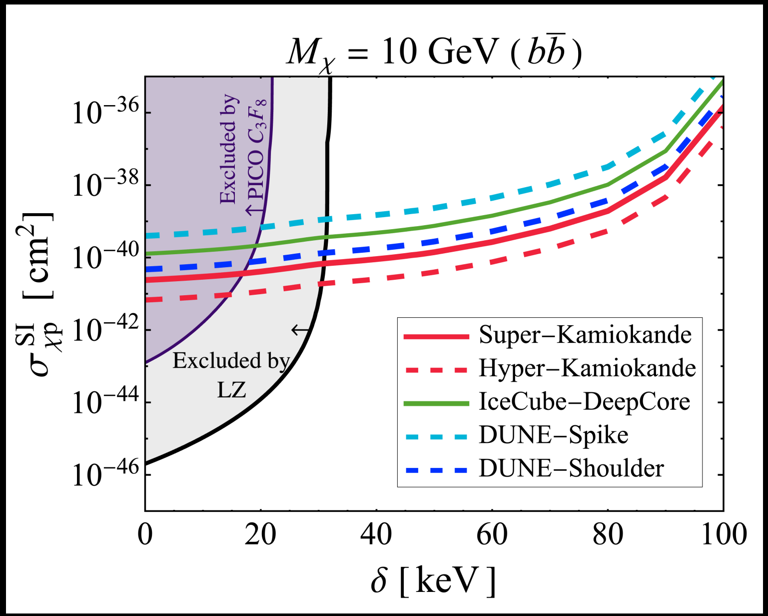
D. Smith and N. Weiner, Phys. Rev. D64:043502, 2001

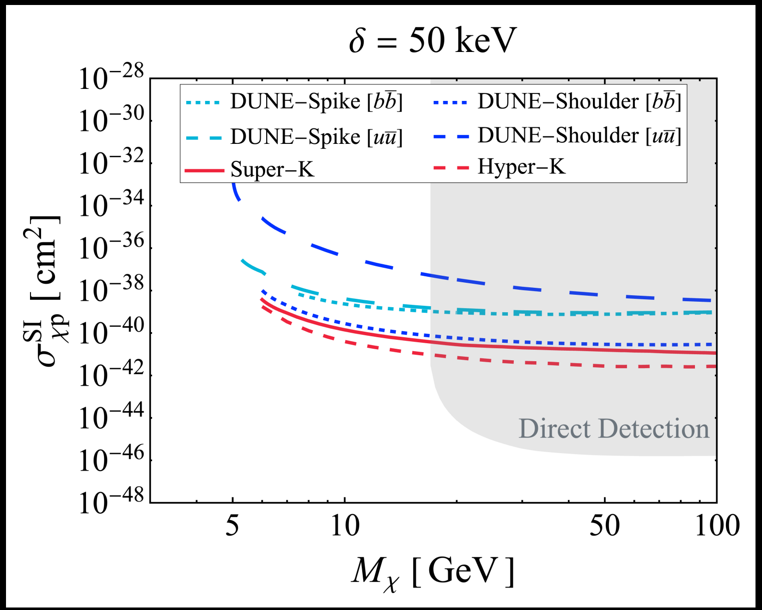
Capture rate in the Sun can also be reduced

S. Nussinov, L.-T. Wang and I. Yavin, Phys. JCAP 08:037, 2009

A. Menon, R. Morris, A. Pierce and N. Weiner, Phys. Rev. D82:015011, 2010

J. Kumar, J. G. Learned, K. Richardson and S. Smith, Phys. Rev. D86:073002, 2012





B. Chauhan, M. H. Reno, C. Rott and I. Sarcevic, JCAP 01:030, 2024

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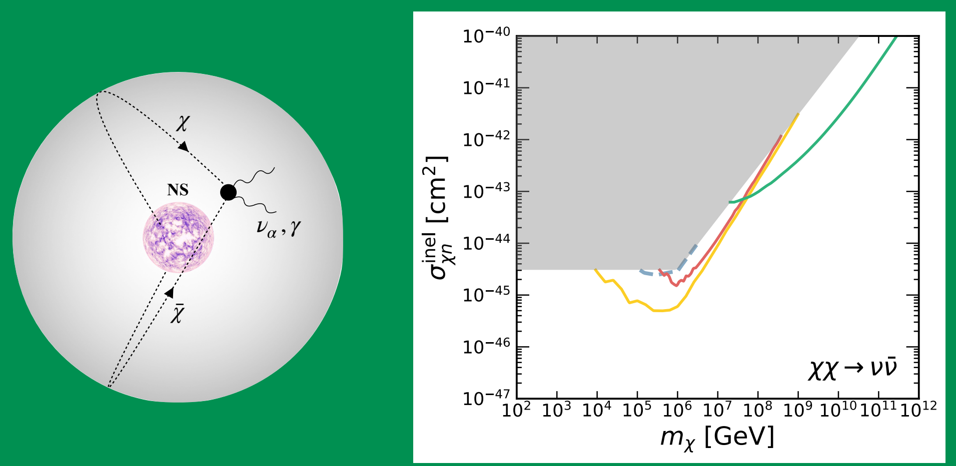
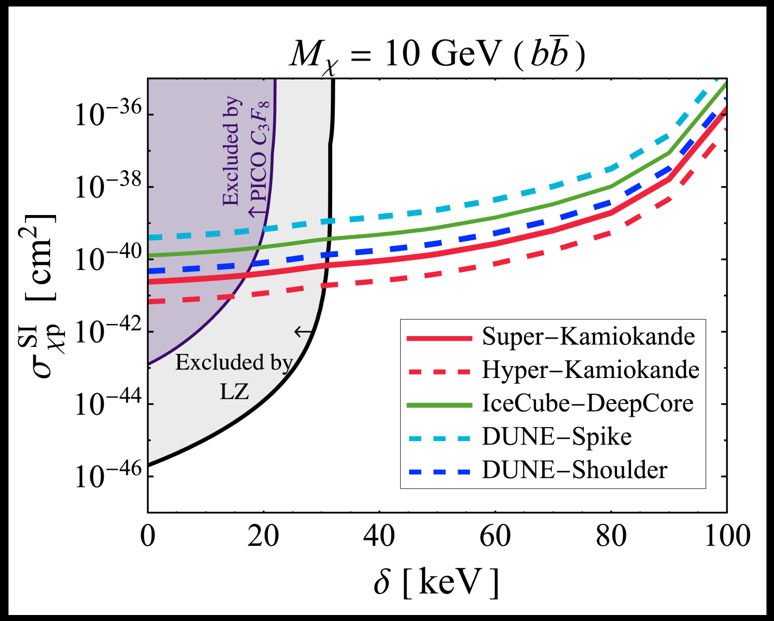
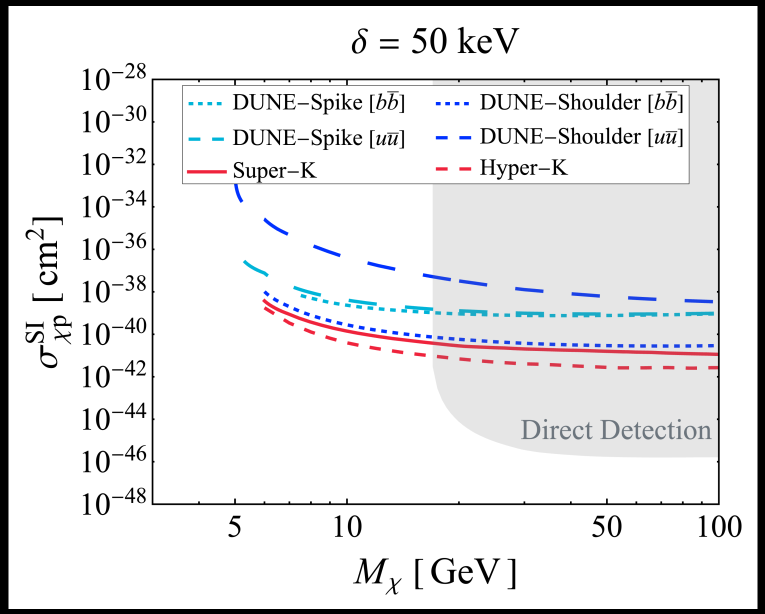
J. Kumar, J. G. Learned, K. Richardson and S. Smith, Phys. Rev. D86:073002, 2012

Inelastic DM annihilating outside neutron stars



J. F. Acevedo, J. Bramante, Q. Liu and N. Tyagi, arXiv:2404.10039





B. Chauhan, M. H. Reno, C. Rott and I. Sarcevic, JCAP 01:030, 2024

Other scenarios/probes

Neutrinos from partly asymmetric DM

K. Murase and I. M. Shoemaker, Phys. Rev. D94:063512, 2016

Neutrinos from fully asymmetric DM from bound state formation

X. Chu, R. Garani, C. Garcia-Cely and T. Hambye, JHEP 05:045, 2024

Neutrinos from BH evaporation inside the Sun or Earth

J. F. Acevedo, J. Bramante, A. Goodman, J. Kopp and T. Opferkuch, JCAP 04:026, 2021

Modifications of solar neutrino fluxes due to the accumulation of DM

I. Lopes and J. Silk, Science 330:462, 2010

Boosted DM from the decay of a heavier DM component could scatter off a nucleus or electron of the detector

J. Berger, Y. Cui and Y. Zhao, JCAP 02:005, 2015

K. Kong, G. Mohlabeng and J.-C. Park, Phys. Lett. B743:256, 2015

H. Alhazmi et al., JHEP 04:158, 2017

J. Berger et al., Phys. Rev. D103:095012, 2021

Can DM particles of any mass be efficiently captured?

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NO

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If DM particles are very light, the chances of being quickly kicked out after further scatterings are very high:

DM evaporates

Can DM particles of any mass be efficiently captured?

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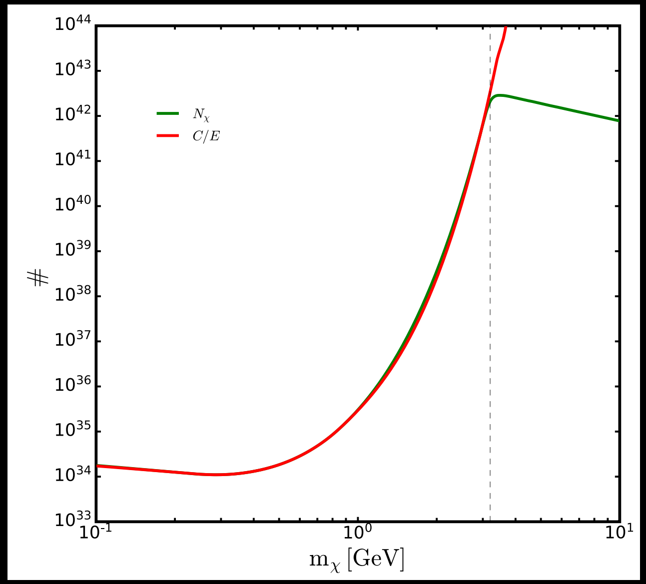
If DM particles are very light, the chances of being quickly kicked out after further scatterings are very high:
DM evaporates

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



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

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

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

If equilibrium is reached:

$$\mathrm{E}(m_{\rm evap})\, \tau_{\rm eq}(m_{\rm evap}) = 1/\sqrt{0.11}$$

DM evaporation mass

This is the result to remember

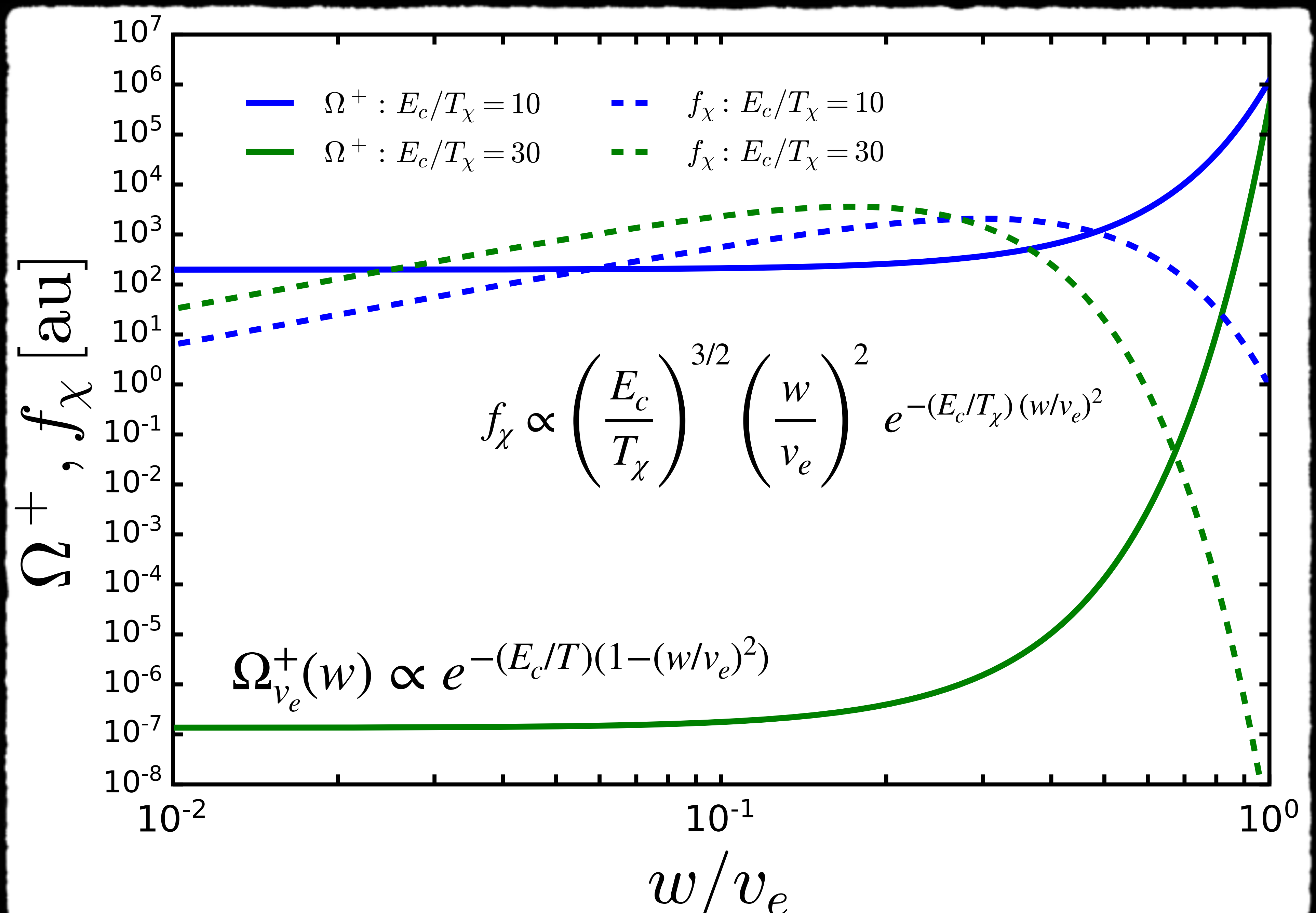
$$E_c / T_\chi \sim 30$$

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)

Evaporation of DM from celestial bodies

a tale of two (exponential) tails

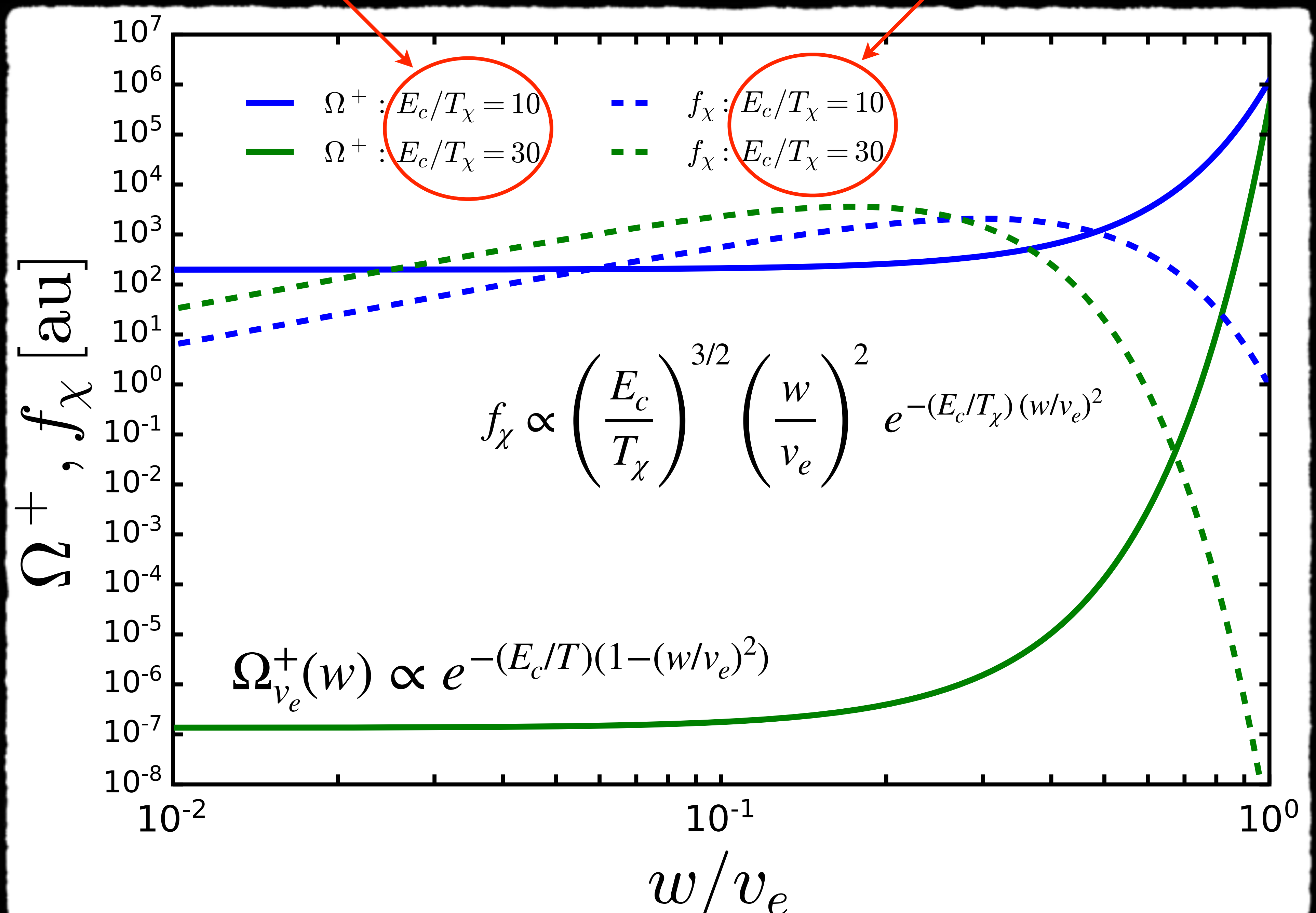


R. Garani and SPR, JCAP 05:042, 2022

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, JCAP 05:042, 2022

DM evaporation mass

(in the saturation limit)

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

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:

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

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

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

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

A. Gould, Astrophys. J. 321:560, 1987

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

For the Earth:

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

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

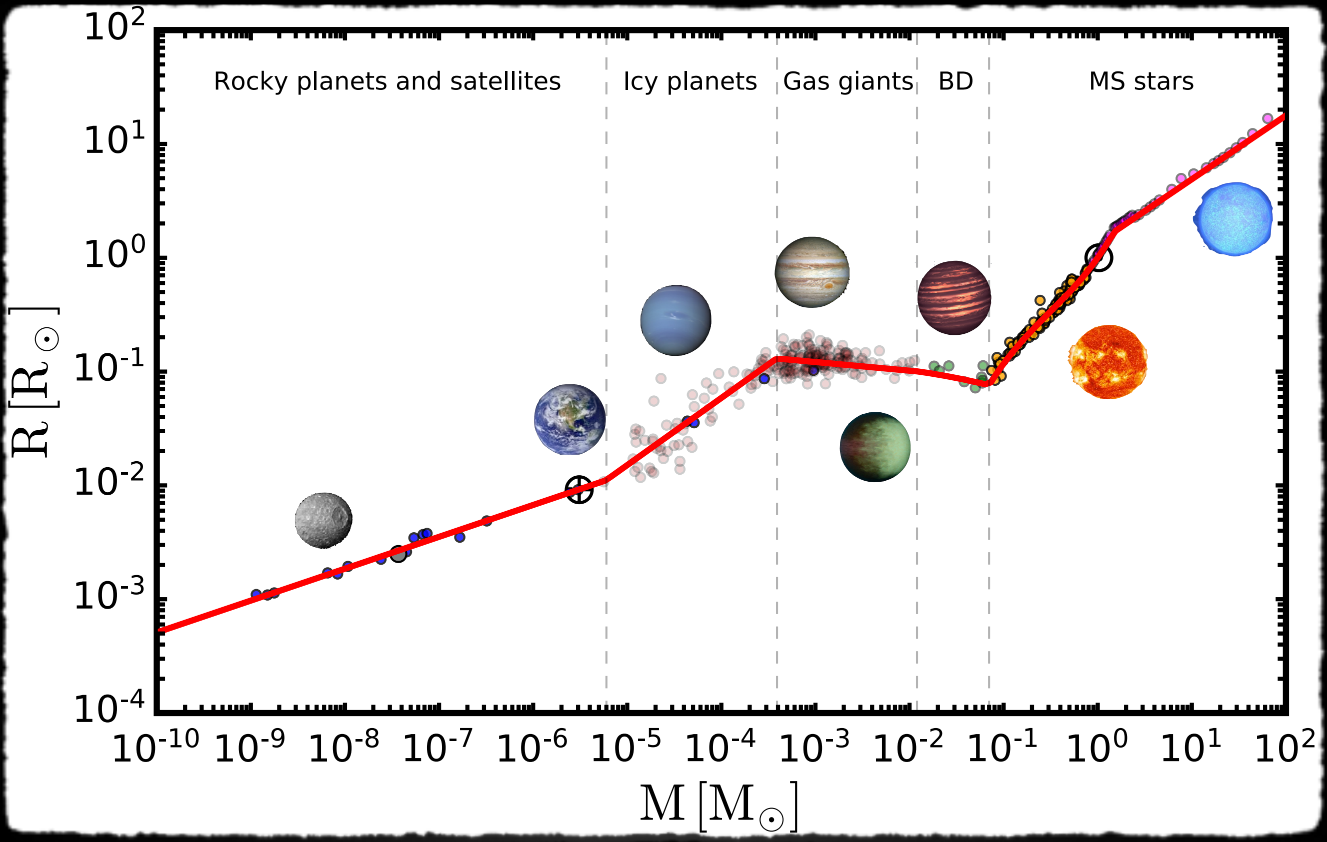
from (polytropic) models

Equilibration time

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

R. Garani and SPR, JCAP 05:042, 2022

Main properties of celestial bodies



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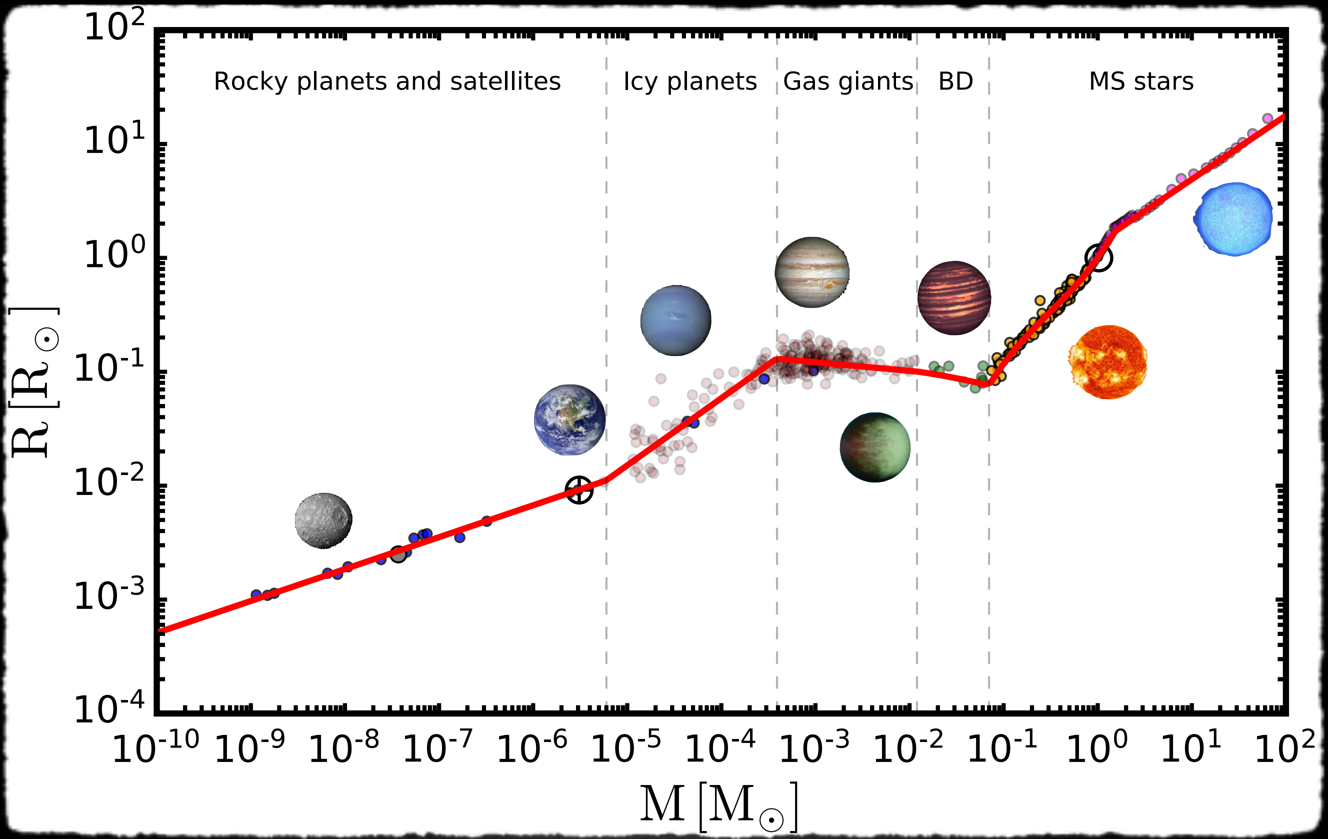

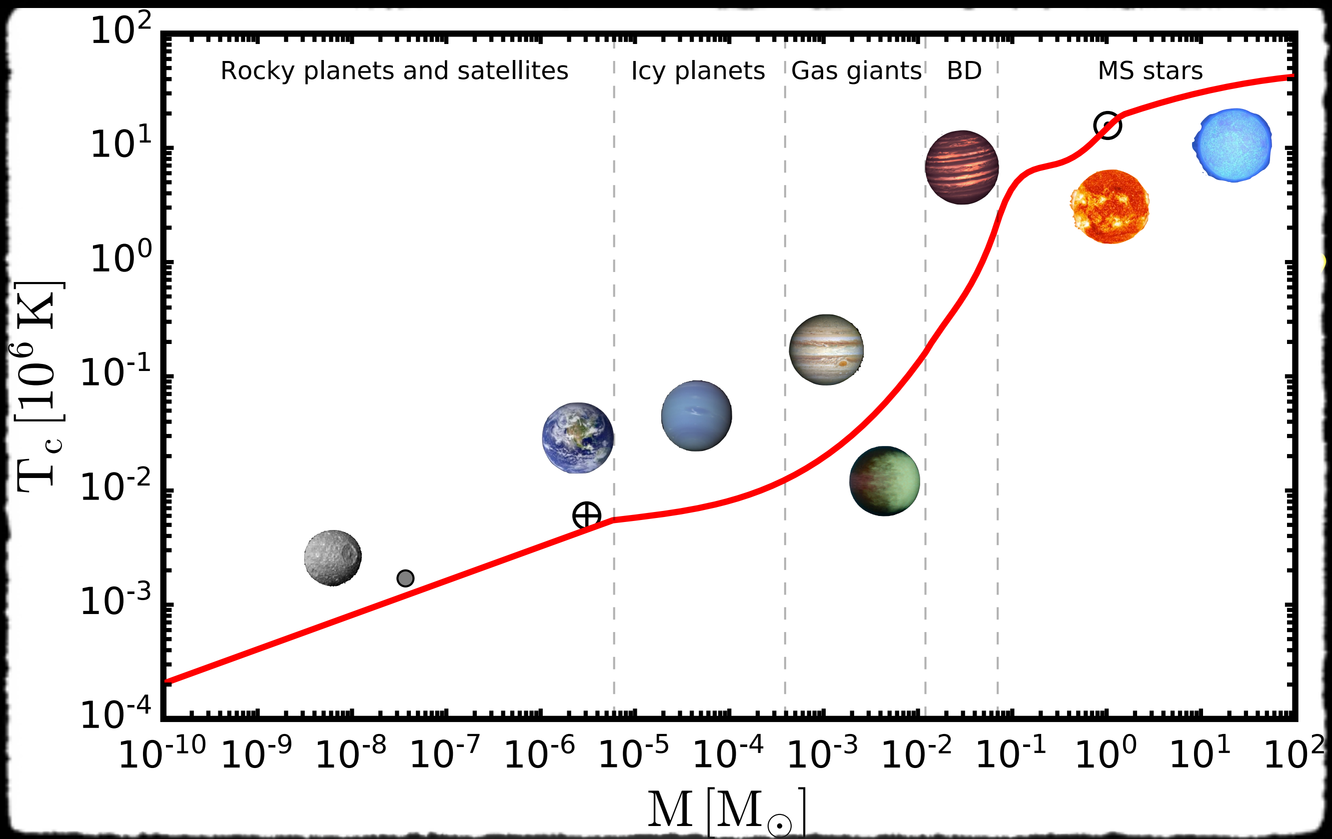

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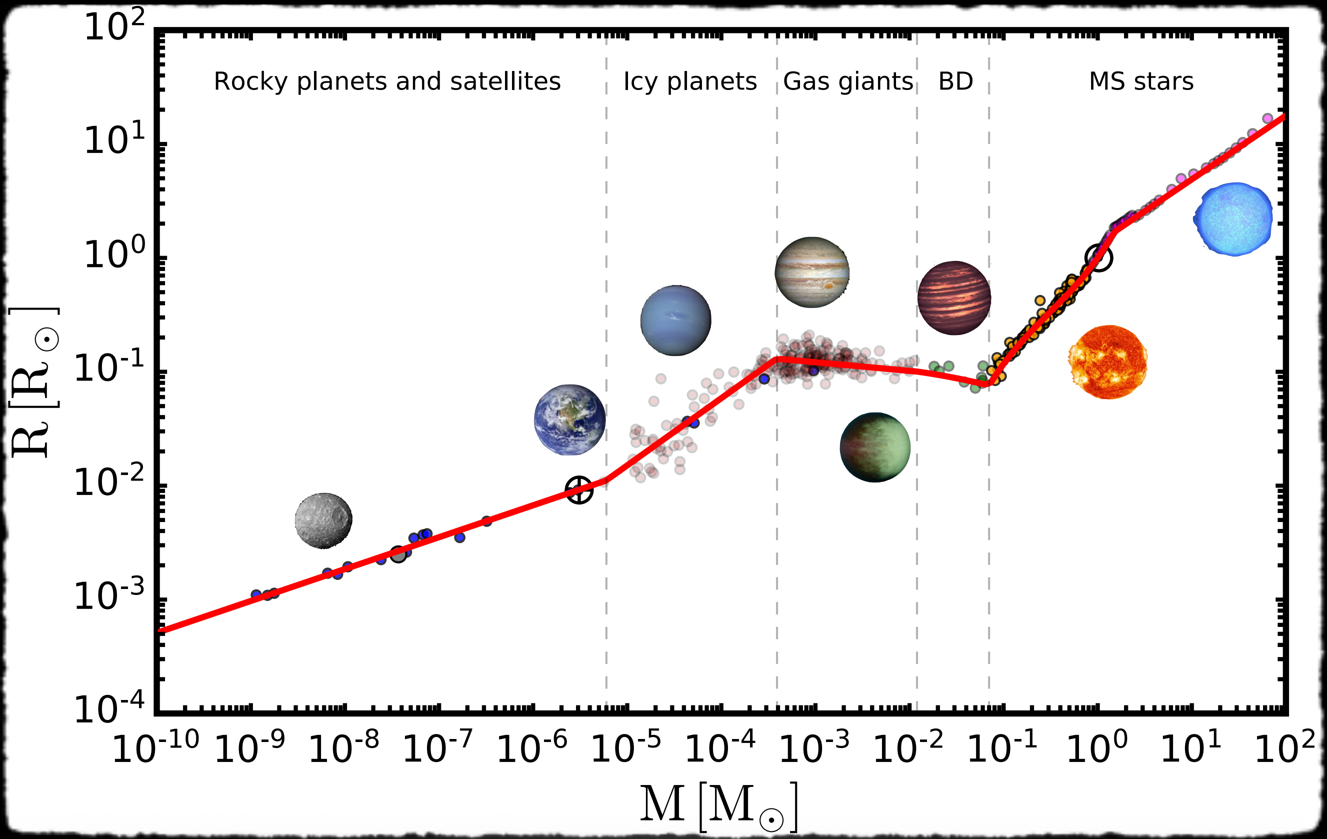

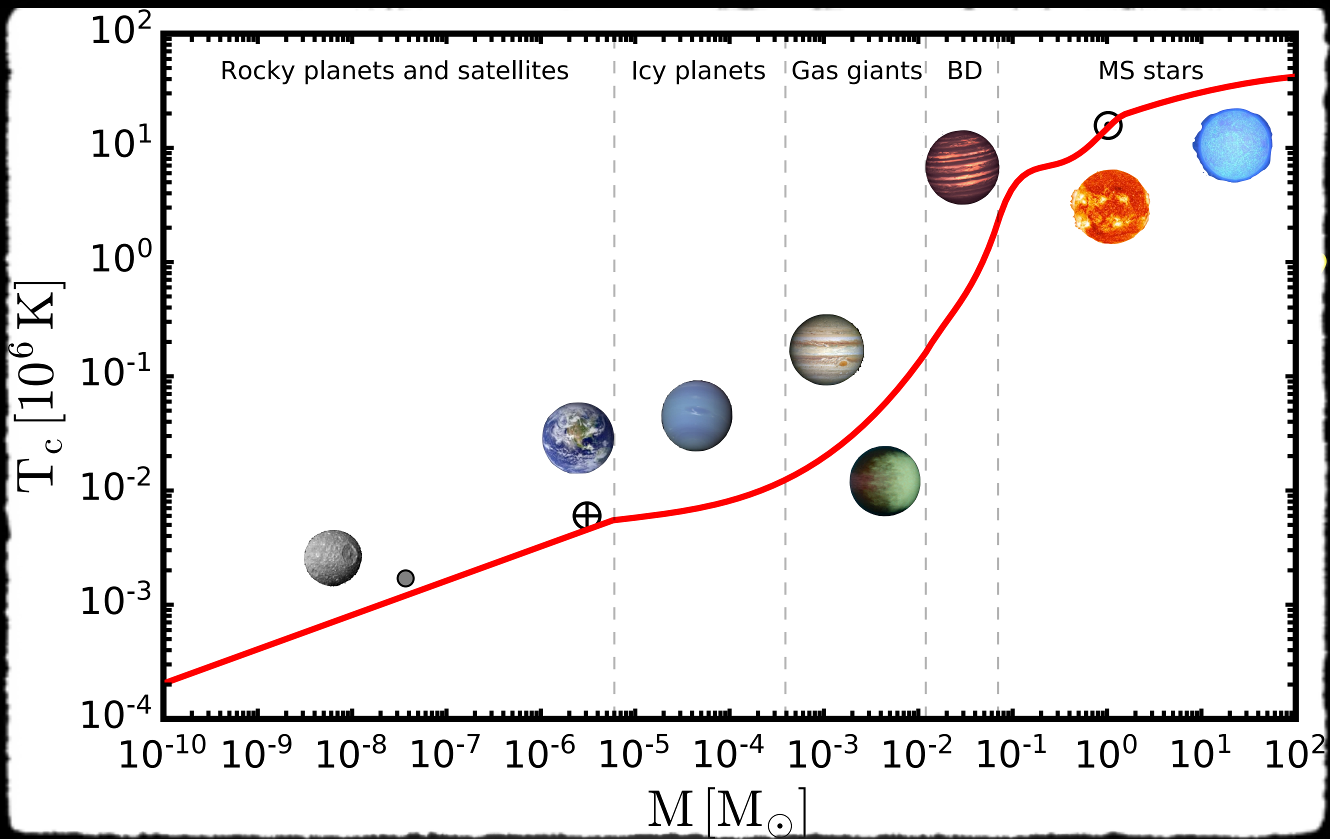

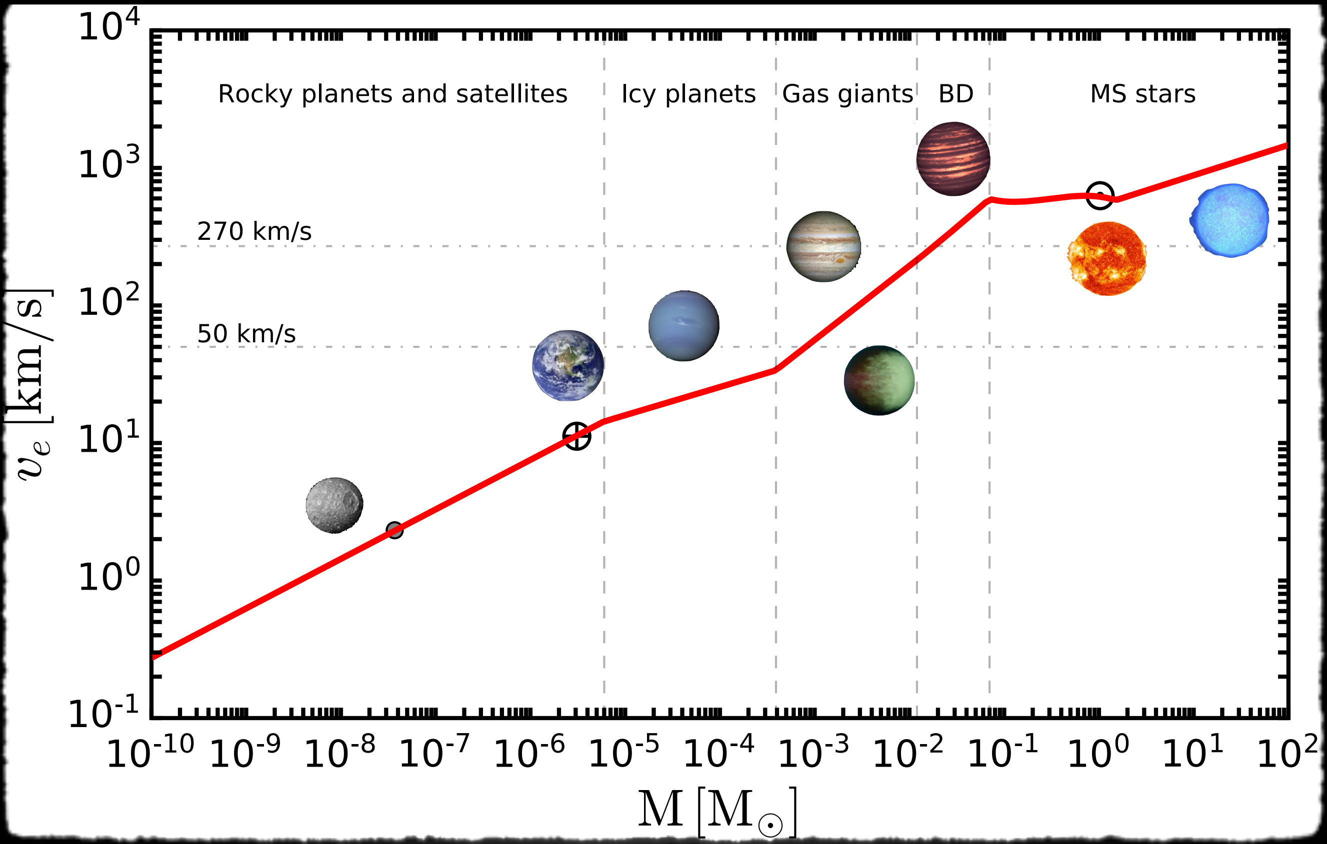

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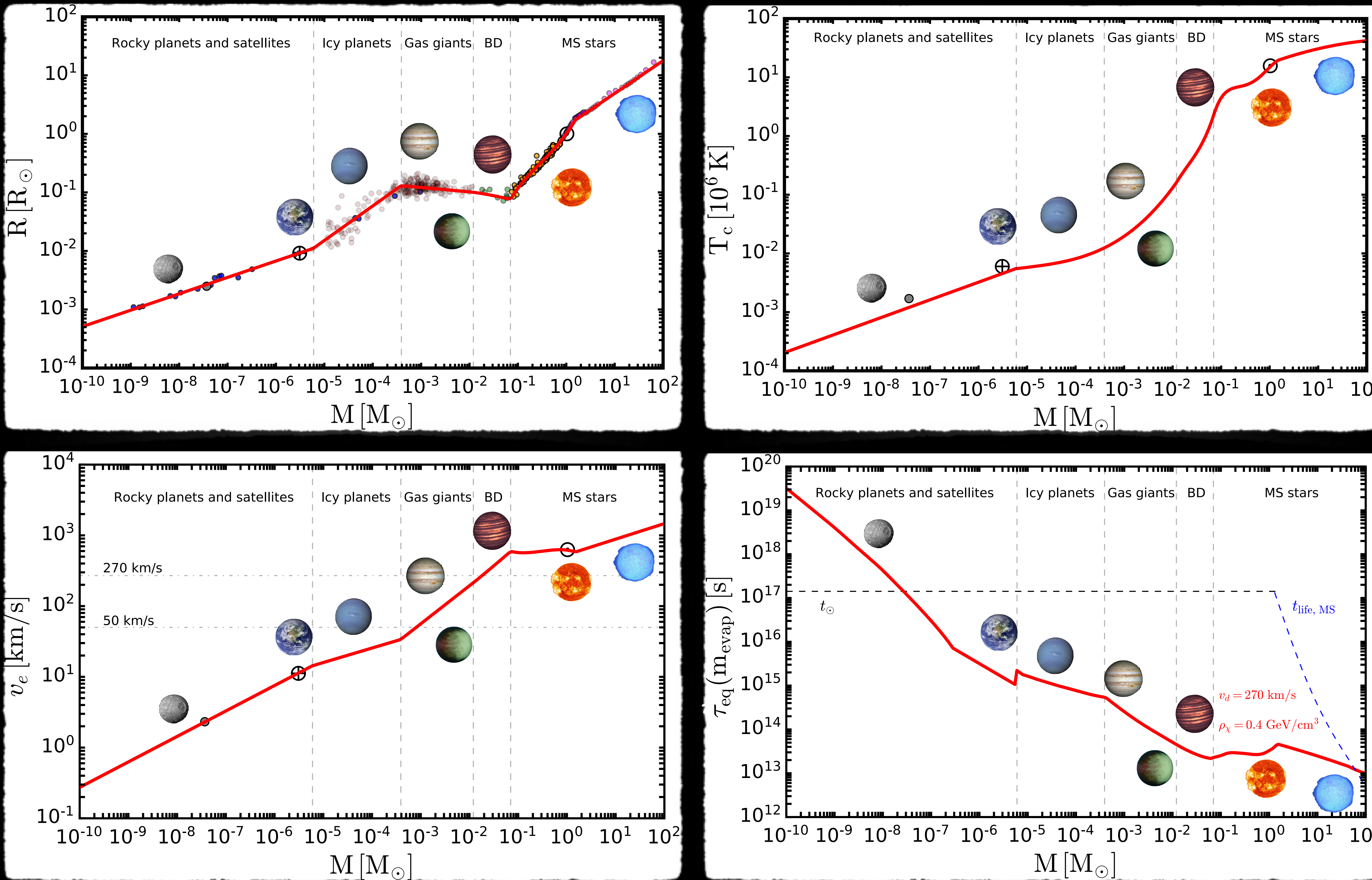

R. Garani and SPR, JCAP 05:042, 2022

DM evaporation mass

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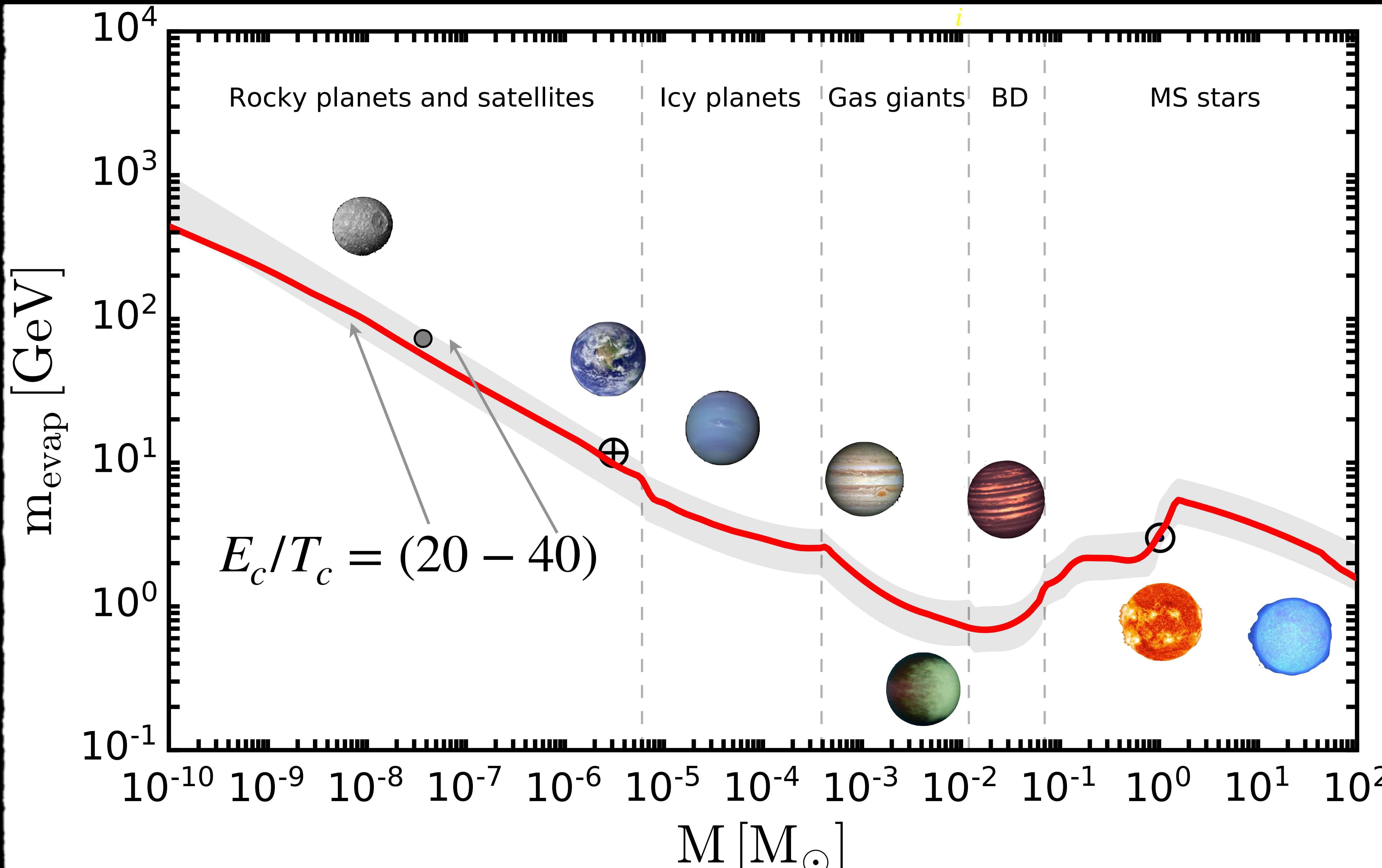

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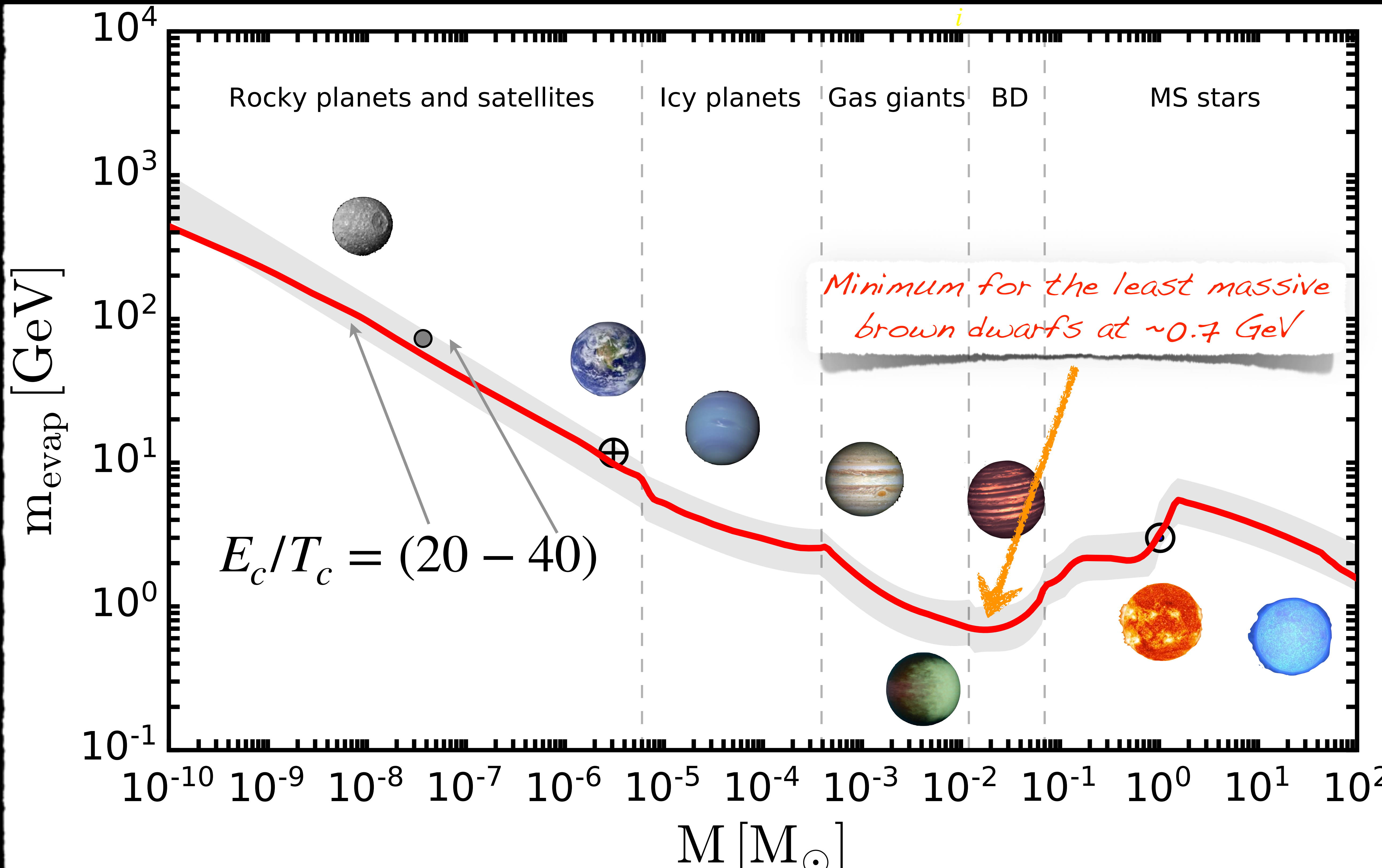
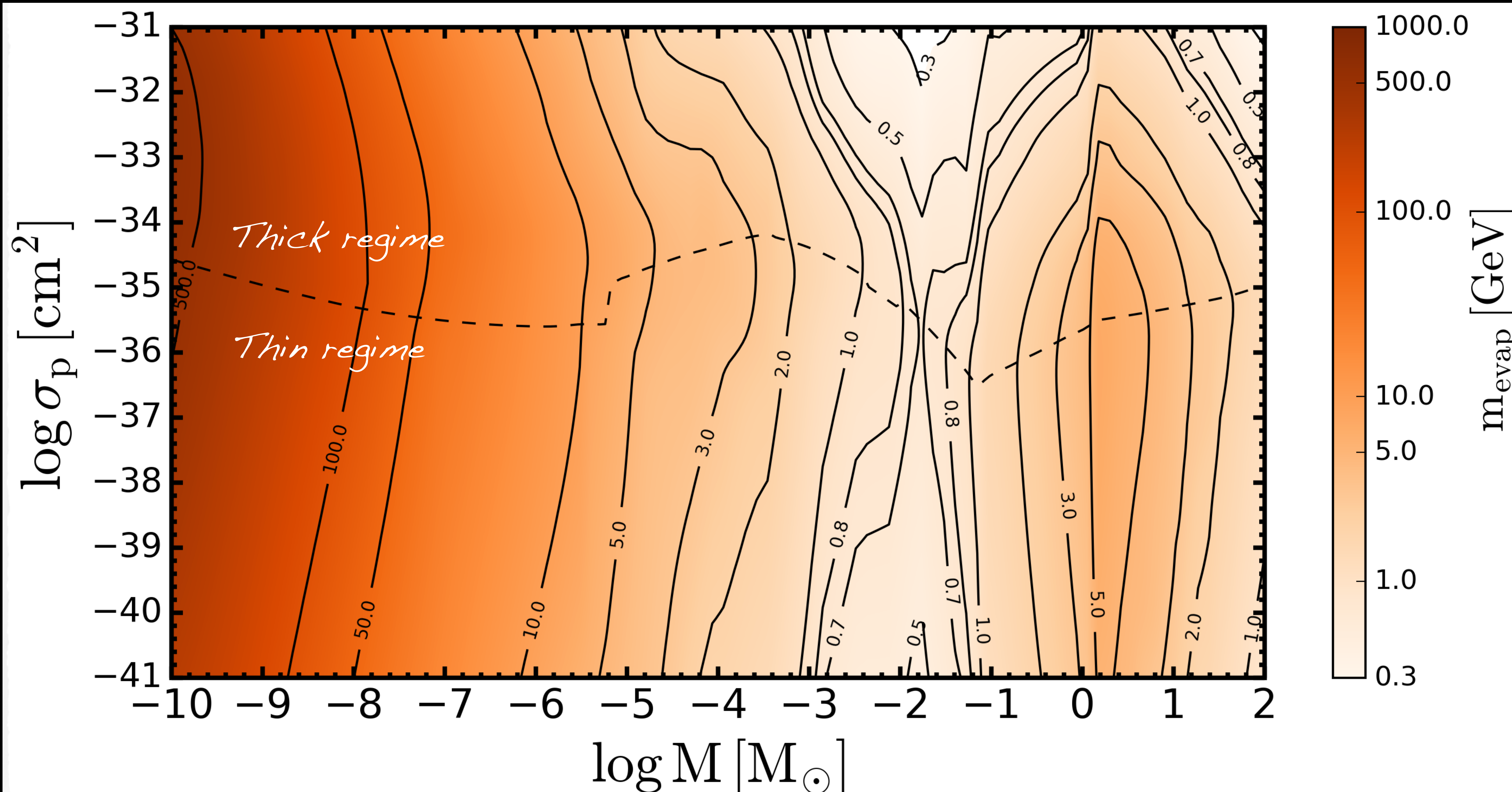


R. Garani and SPR, JCAP 05:042, 2022

DM evaporation mass for a range of SI cross sections

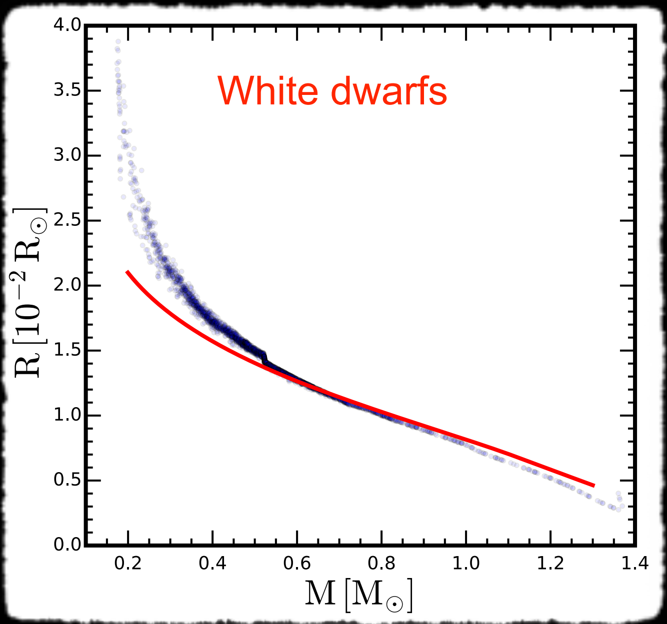


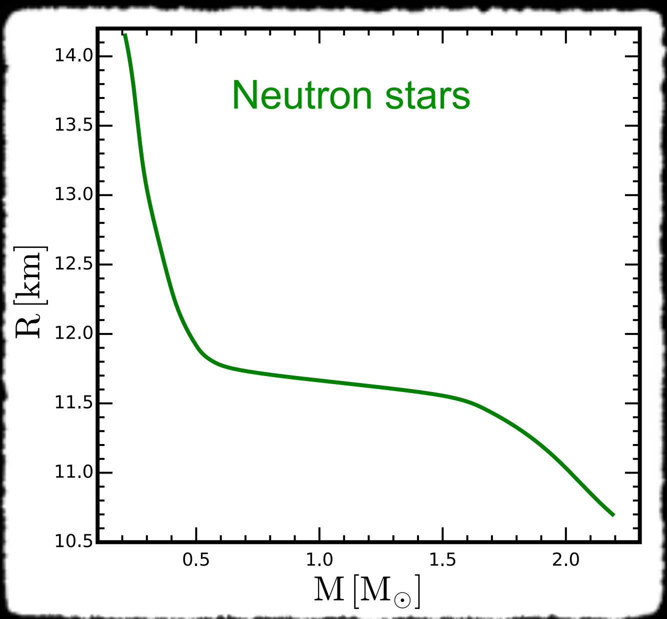
R. Garani and SPR, JCAP 05:042, 2022

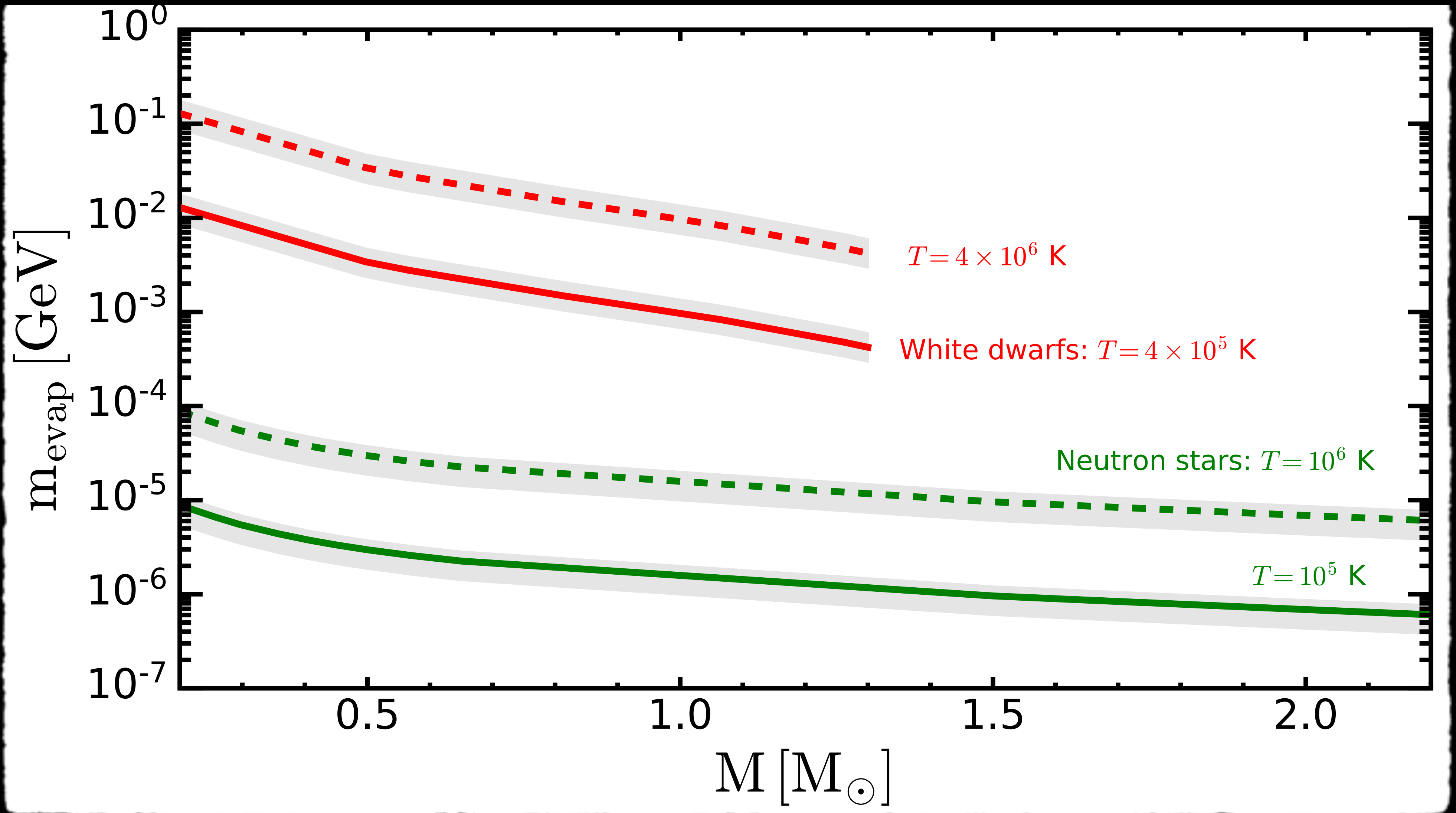
White dwarfs and neutron stars

Much more compact bodies:

very high escape velocity → very low DM evaporation mass







R. Garani and SPR, JCAP 05:042, 2022

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?

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

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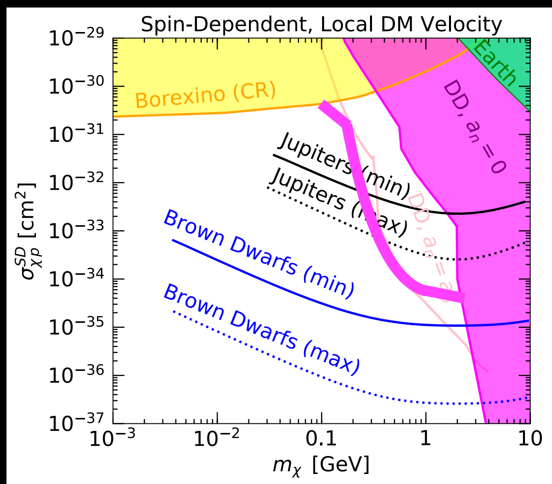
Moreover, the DM evaporation mass had also been estimated for other planets, brown dwarfs and other stars

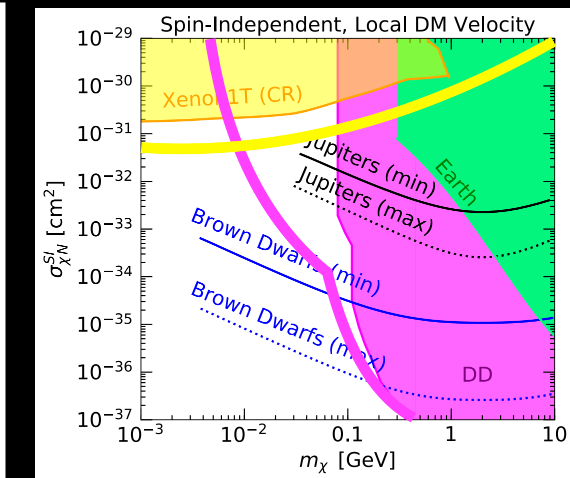
So why caring about all this now?

In addition to performing a systematic study, recently, there have been claims in the literature of DM evaporation masses in the MeV range for Jupiter-like planets and brown dwarfs, with equally strong phenomenological claims

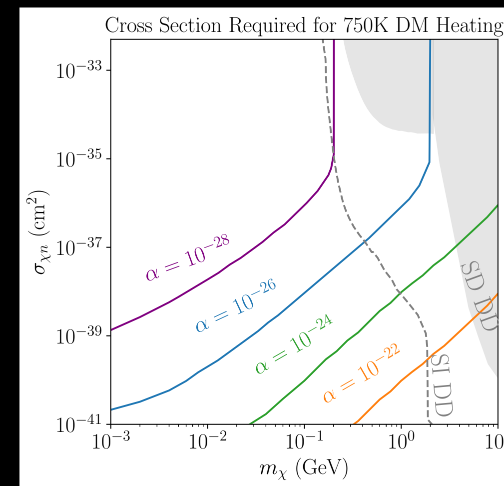
(or even that there could be no evaporation at all)

Heating of exoplanets and brown dwarfs



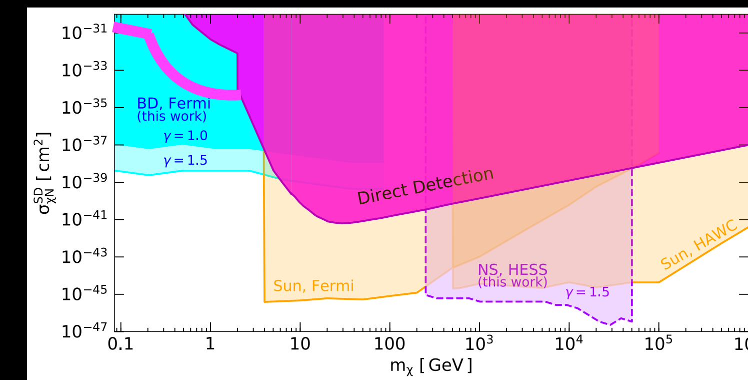


R. K. Leane and J. Smirnov, Phys. Rev. Lett. 126:161101, 2021

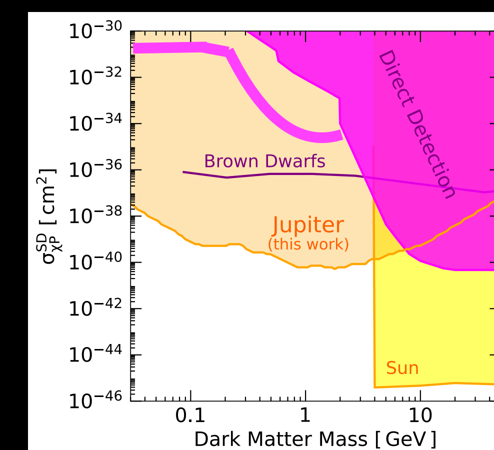


J. F. Acevedo, R. K. Leane and A. J. Reilly, arXiv:2405.02393

Secluded DM in brown dwarfs and Jupiter

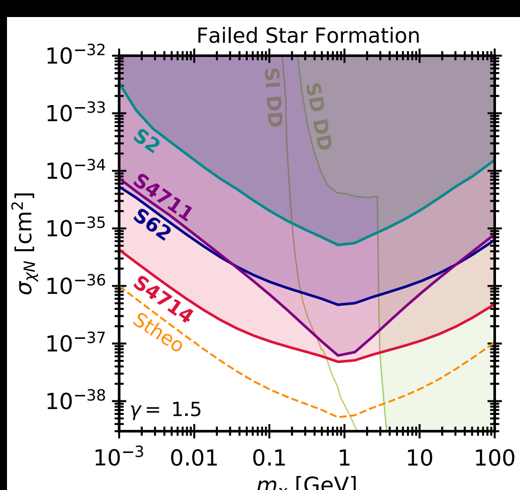


R. K. Leane, T. Linden, P. Mukhopadjyay and N. Toro, Phys. Rev. D103:075030, 2021



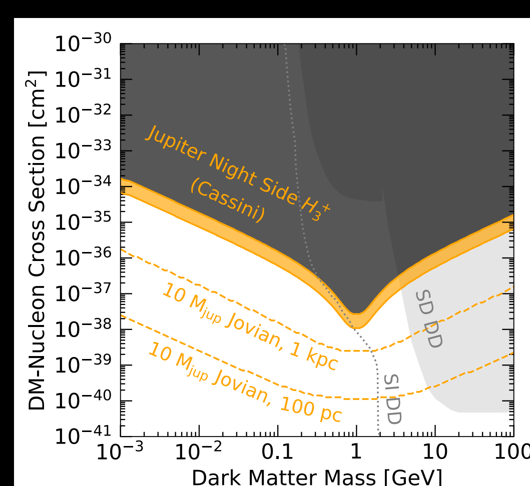
R. K. Leane and T. Linden, Phys. Rev. Lett. 131:071001, 2023

Failed star formation



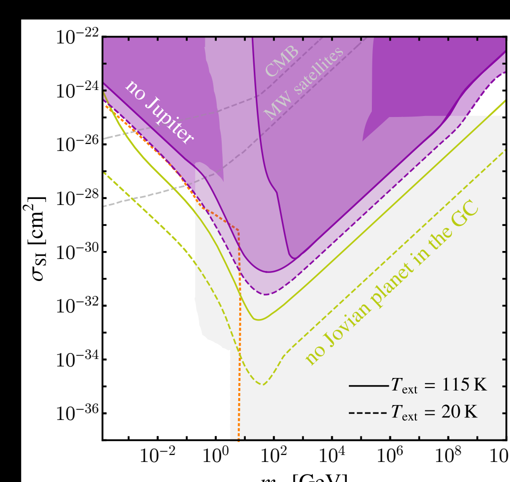
I. John, R. K. Leane and T. Linden, Phys. Rev. D109:123041, 2024

DM ionization on Jupiter

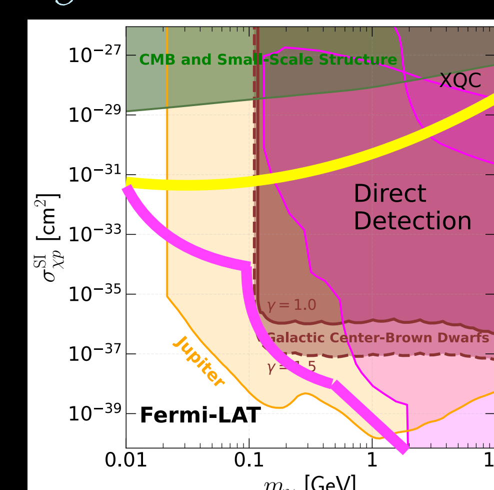


C. Blanco and R. K. Leane, Phys. Rev. Lett. 132:261002, 2024

Disruption of planet formation



D. Croon and J. Smirnov, arXiv:2309:02495



T. Linden, T. T. Q. Nguyen and T. M. P. Tait, arXiv:2402.01839

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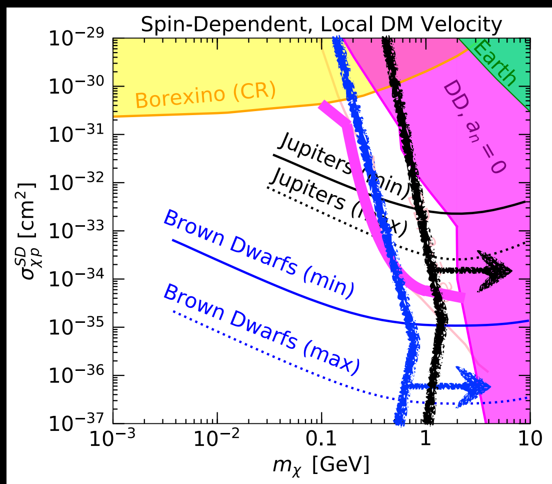

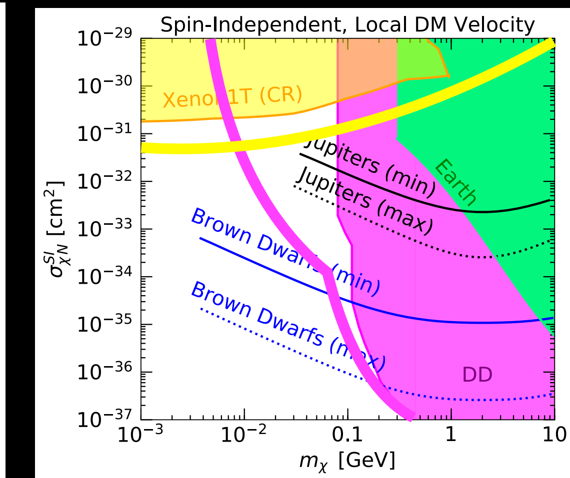

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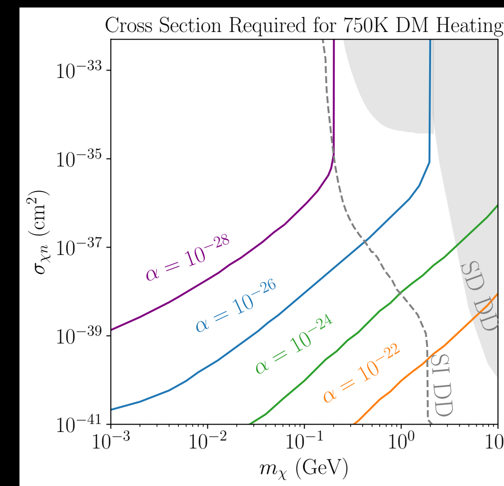

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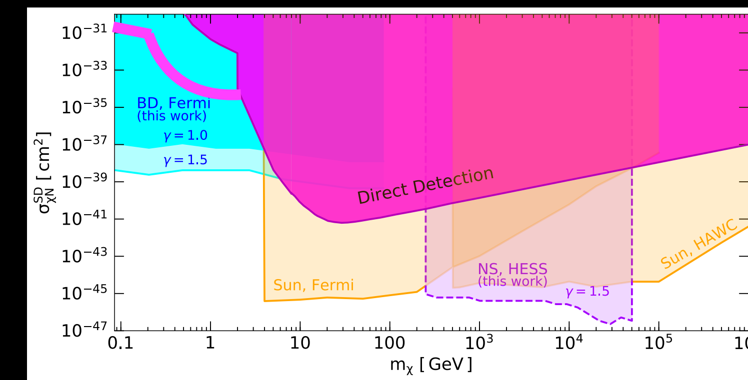

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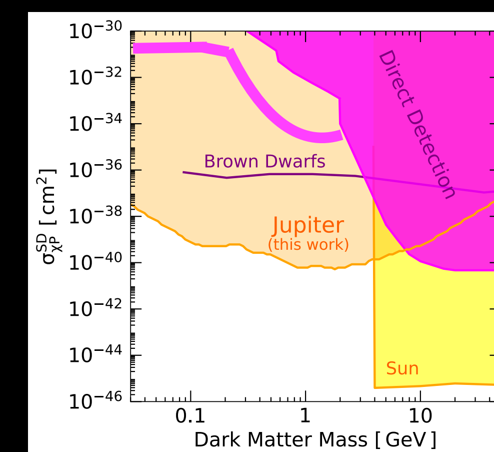

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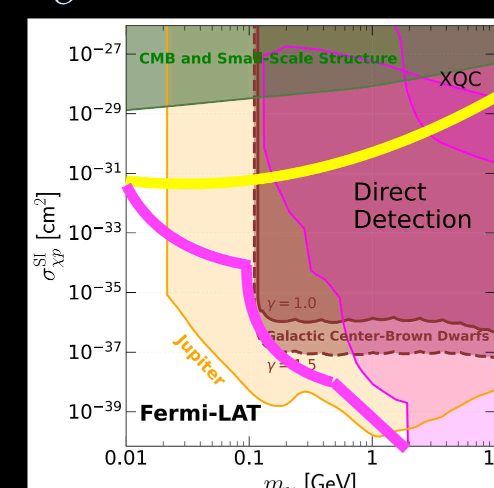
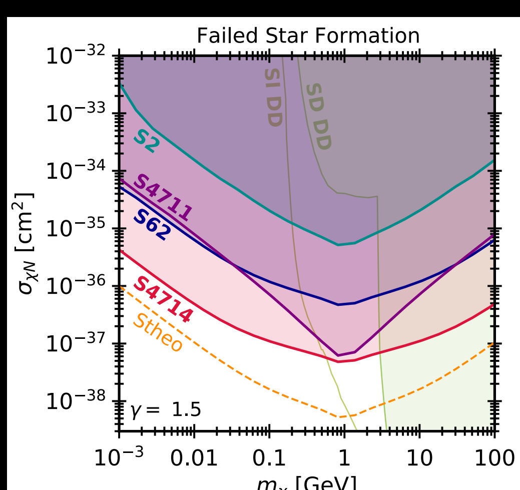


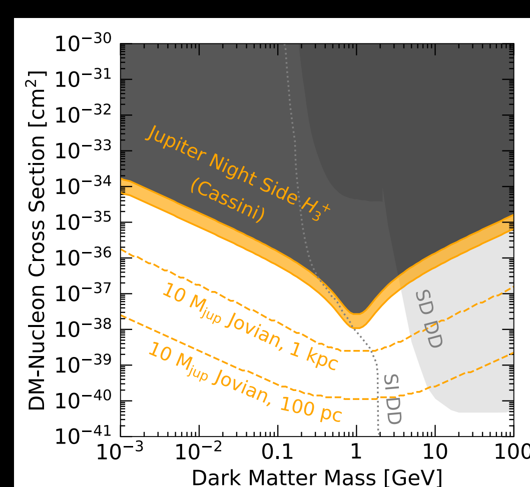
T. Linden, T. T. Q. Nguyen and T. M. P. Tait, arXiv:2402.01839

Failed star formation



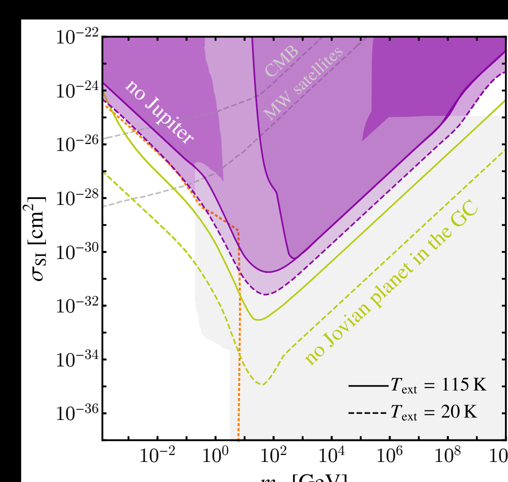
I. John, R. K. Leane and T. Linden, Phys. Rev. D109:123041, 2024

DM ionization on Jupiter



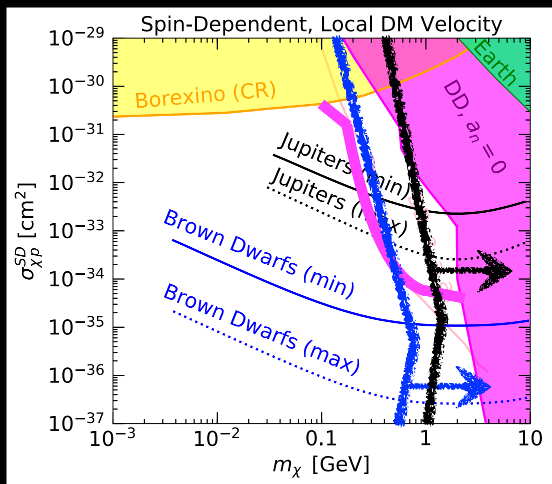
C. Blanco and R. K. Leane, Phys. Rev. Lett. 132:261002, 2024

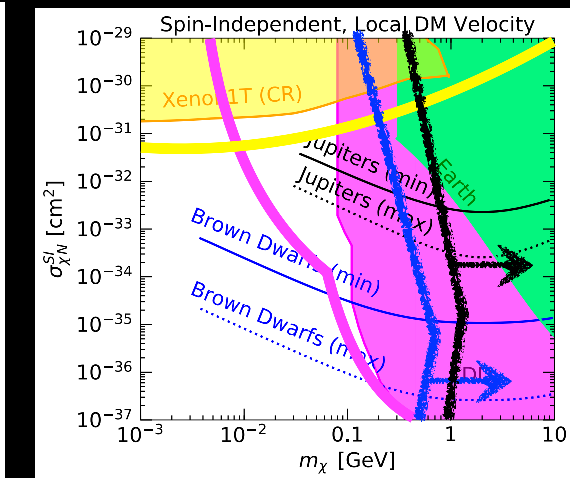
Disruption of planet formation



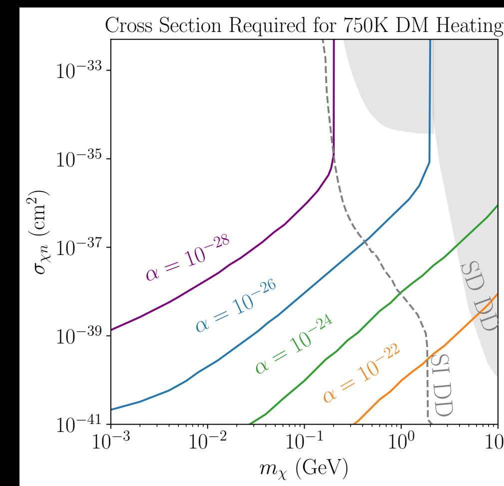
D. Croon and J. Smirnov, arXiv:2309:02495

Heating of exoplanets and brown dwarfs



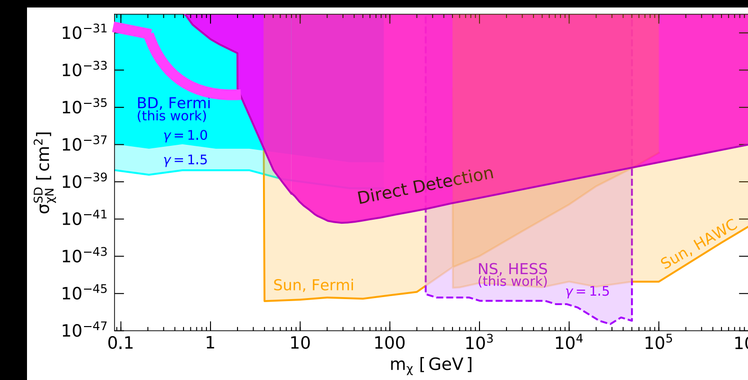


R. K. Leane and J. Smirnov, Phys. Rev. Lett. 126:161101, 2021

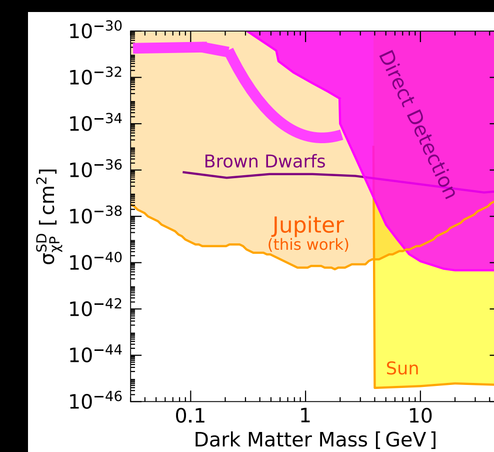


J. F. Acevedo, R. K. Leane and A. J. Reilly, arXiv:2405.02393

Secluded DM in brown dwarfs and Jupiter



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



R. K. Leane and T. Linden, Phys. Rev. Lett. 131:071001, 2023

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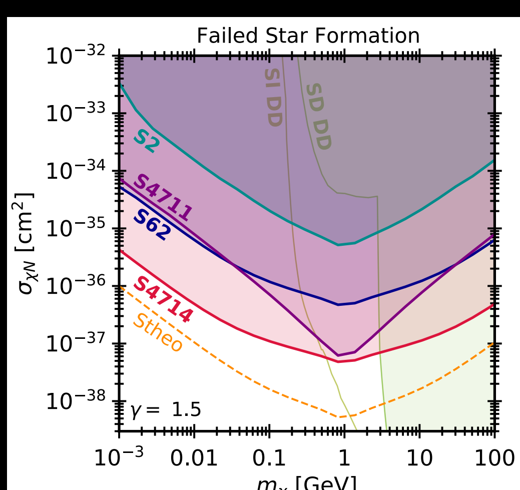

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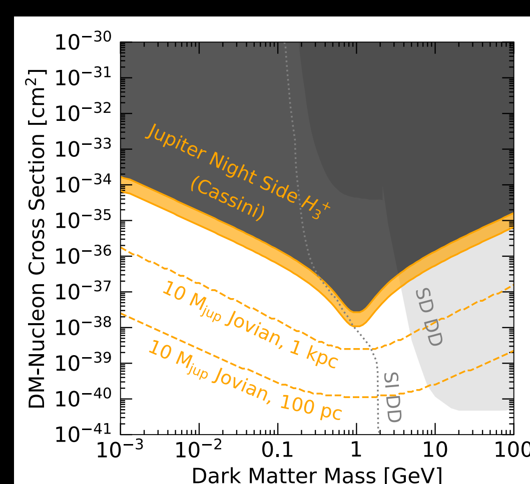

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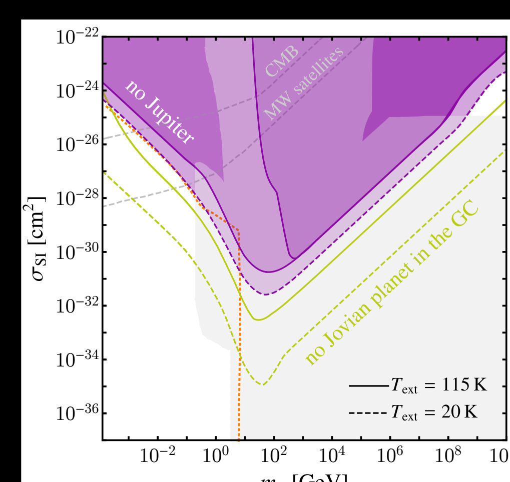
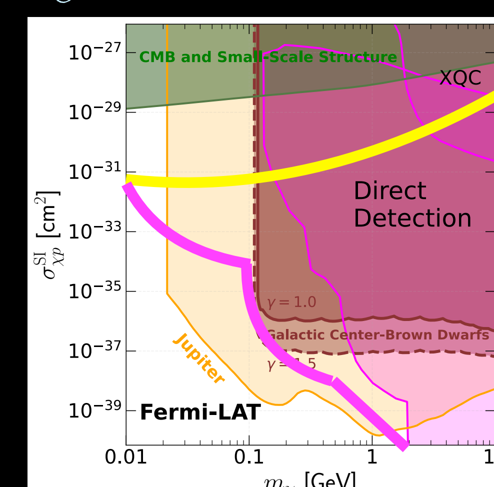


D. Croon and J. Smirnov, arXiv:2309:02495



T. Linden, T. T. Q. Nguyen and T. M. P. Tait, arXiv:2402.01839

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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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additional source of DM capture and evaporation

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

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Long-range interactions

J. F. Acevedo, R. K. Leane and J. Smirnov, JCAP 04:038, 2024

would require extreme fine-tuning

contact DM interactions would generate strong 5th force

Conclusions

DM accumulation in celestial bodies can be probed with neutrinos in many different ways

However, not all DM candidates could get efficiently captured in all celestial bodies

DM evaporation masses below ~100 MeV are very difficult to reach, even invoking extreme conditions, except for extremely large cross sections