Discovering dark matter at the high mass frontier

Kavli IMPU Seminar Nov 24, 2021

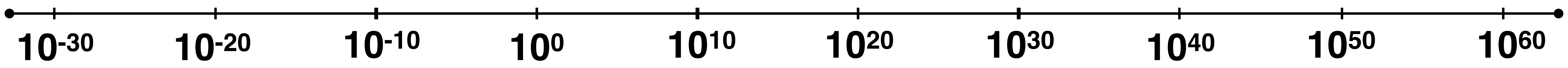
Joe Bramante

Queen's University

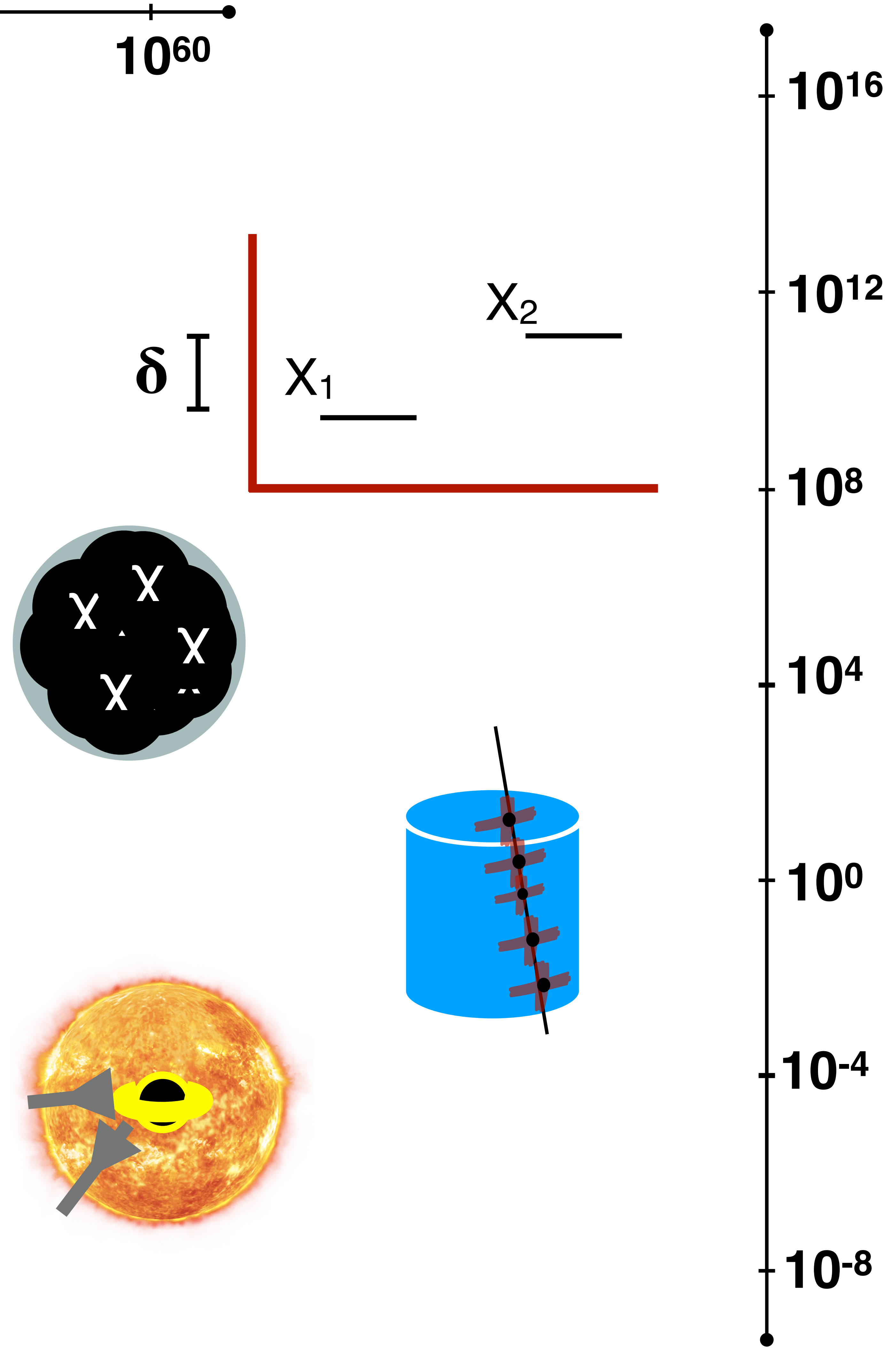
McDonald Institute

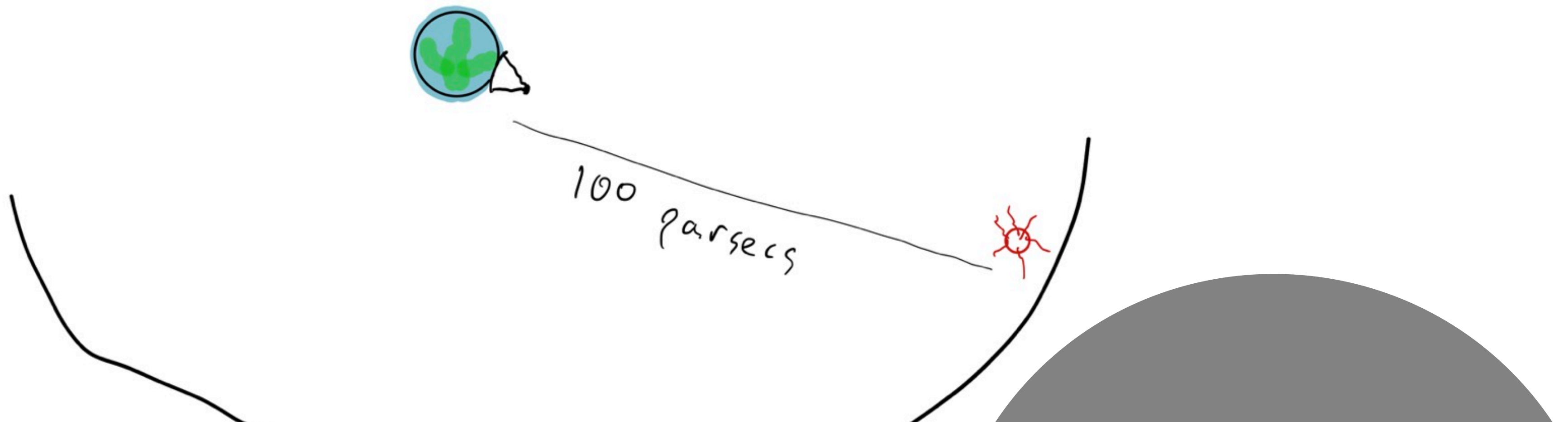
Perimeter Institute

Dark Matter at the High Mass Frontier



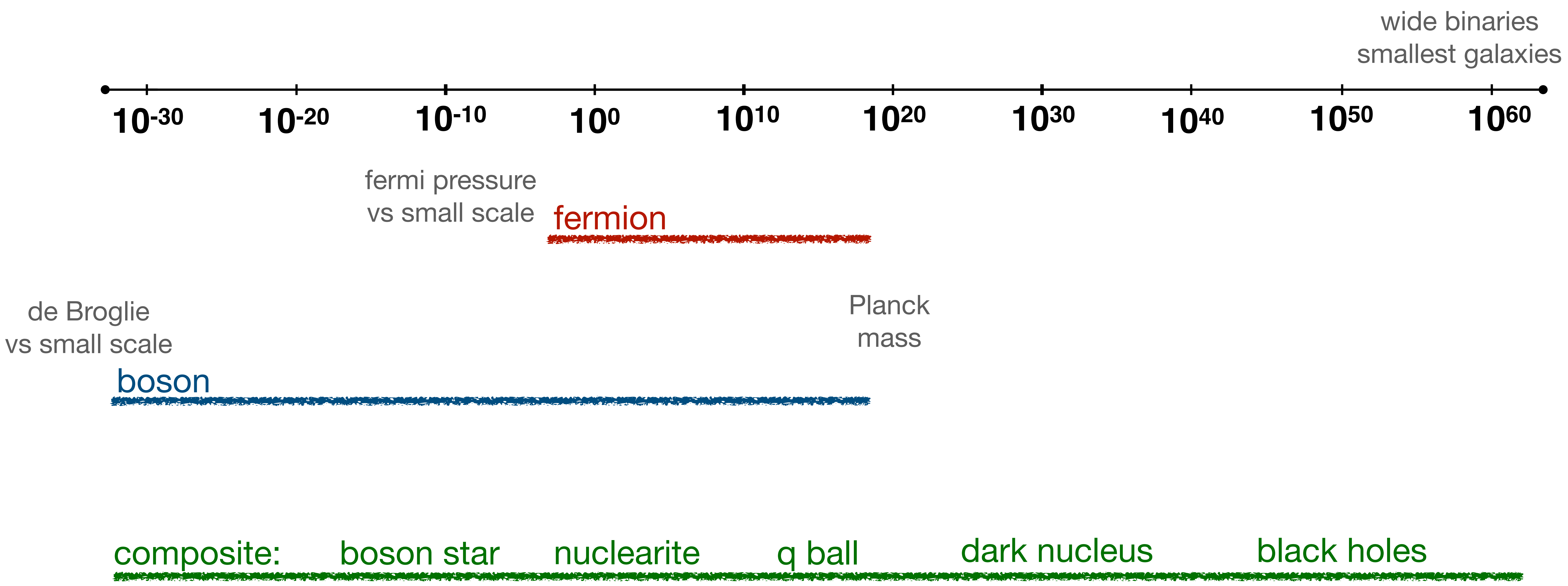
- Higgsino dark matter at high recoil and in neutron stars
- DM composite formation, Migdal, multi scatter detection
- Dark matter forming black holes in the Sun and Earth
- Thermal neutron star searches for (sub halo) dark matter





What do we know about dark matter?

mass in GeV



What do we know about dark matter?

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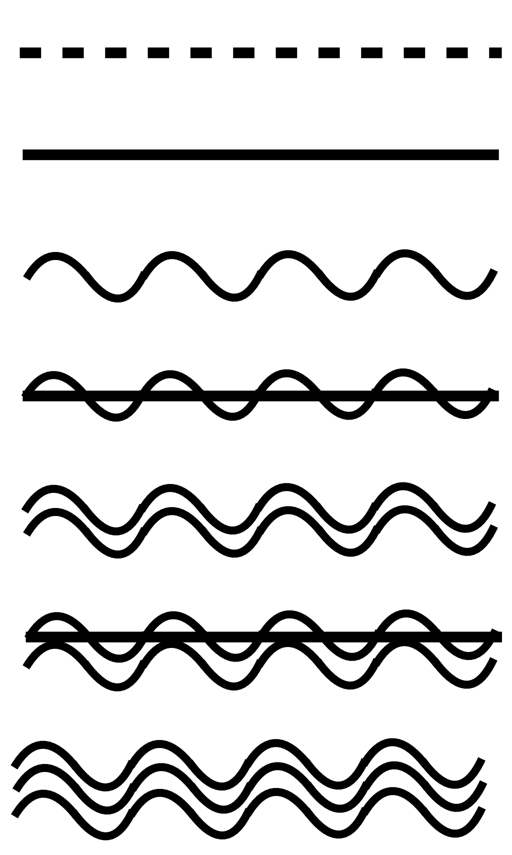
Dark Matter Models: SM Coupling and Detection

dark matter

fundamental

composite

spin



0

½

1

3/2

2

5/2

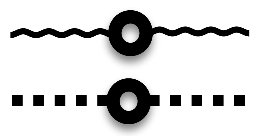
3

...

direct coupling

- Quarks
- Leptons
- Hypercharge Boson
- Weak Boson
- Higgs Boson
- Gluons…

mixing

- Dark Photon / Vector Portal
- Higgs Portal 
- (Sterile) Neutrino Mixing…

new intermediate field

- Scalar
- Fermion
- Vector…

Dark Matter Models: SM Coupling and Detection

annihilation · scattering · DM production

dark matter

fundamental

composite

spin

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½

1

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...

direct coupling

- Quarks
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- Gluons…

mixing

- Dark Photon / Vector Portal
- Higgs Portal
- (Sterile) Neutrino Mixing…

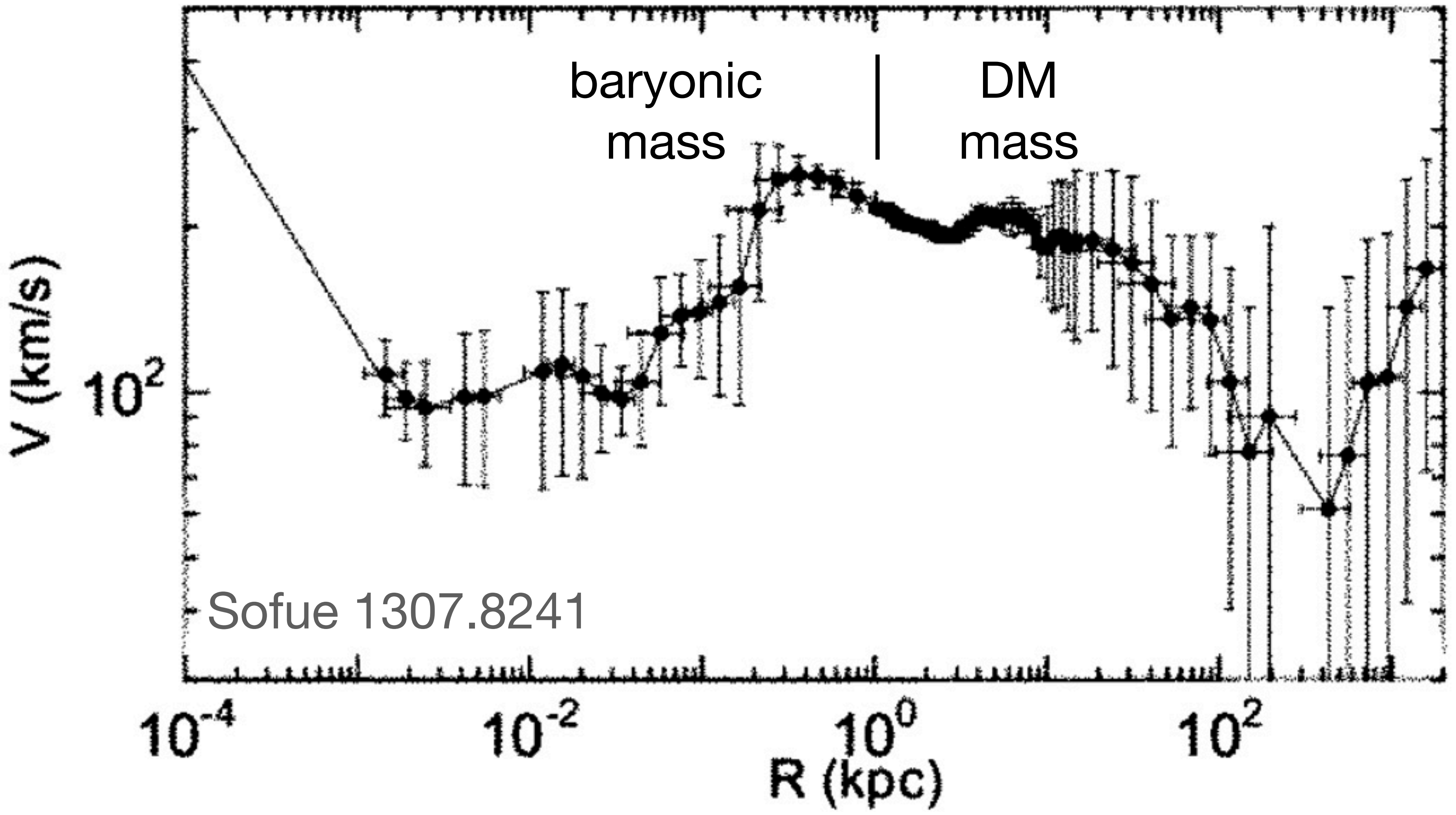
new intermediate field

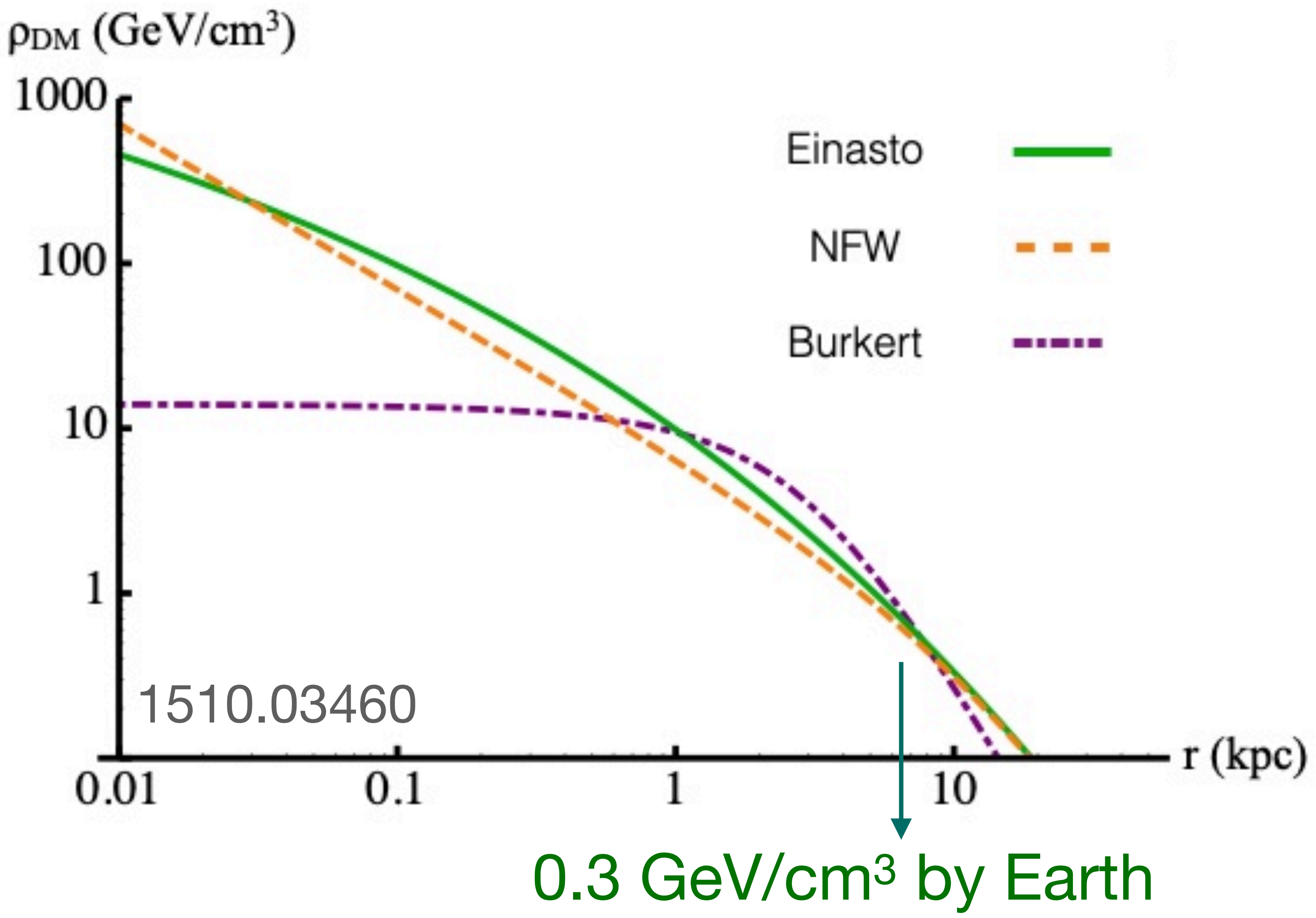
- Scalar
- Fermion
- Vector…

interactions	detector	mass of interacting SM particles in GeV
	interstellar gas	~10^{60}
	stars	
	planets	~10^{50}
	Super-K, IceCube (neutrinos)	~10^{35}
	HAWC, Fermi (gamma rays)	
	XENON1T, LZ, PandaX, SuperCDMS, PICO, SENSEI	~10^{30}
	ADMX, HAYSTAC	
	collider, beam dump	~10^{15}

Dark matter near us

global (~0.001c)





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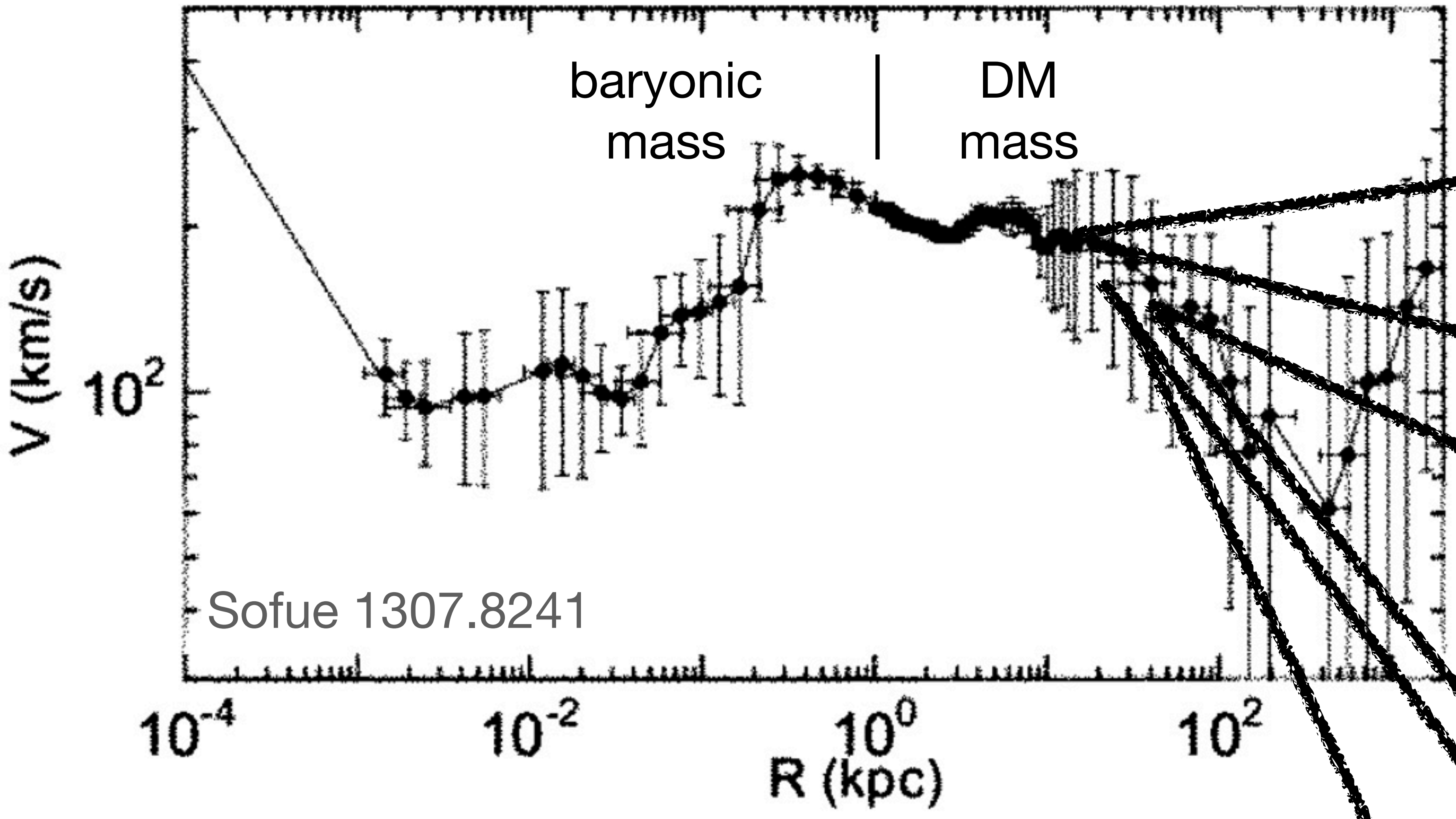
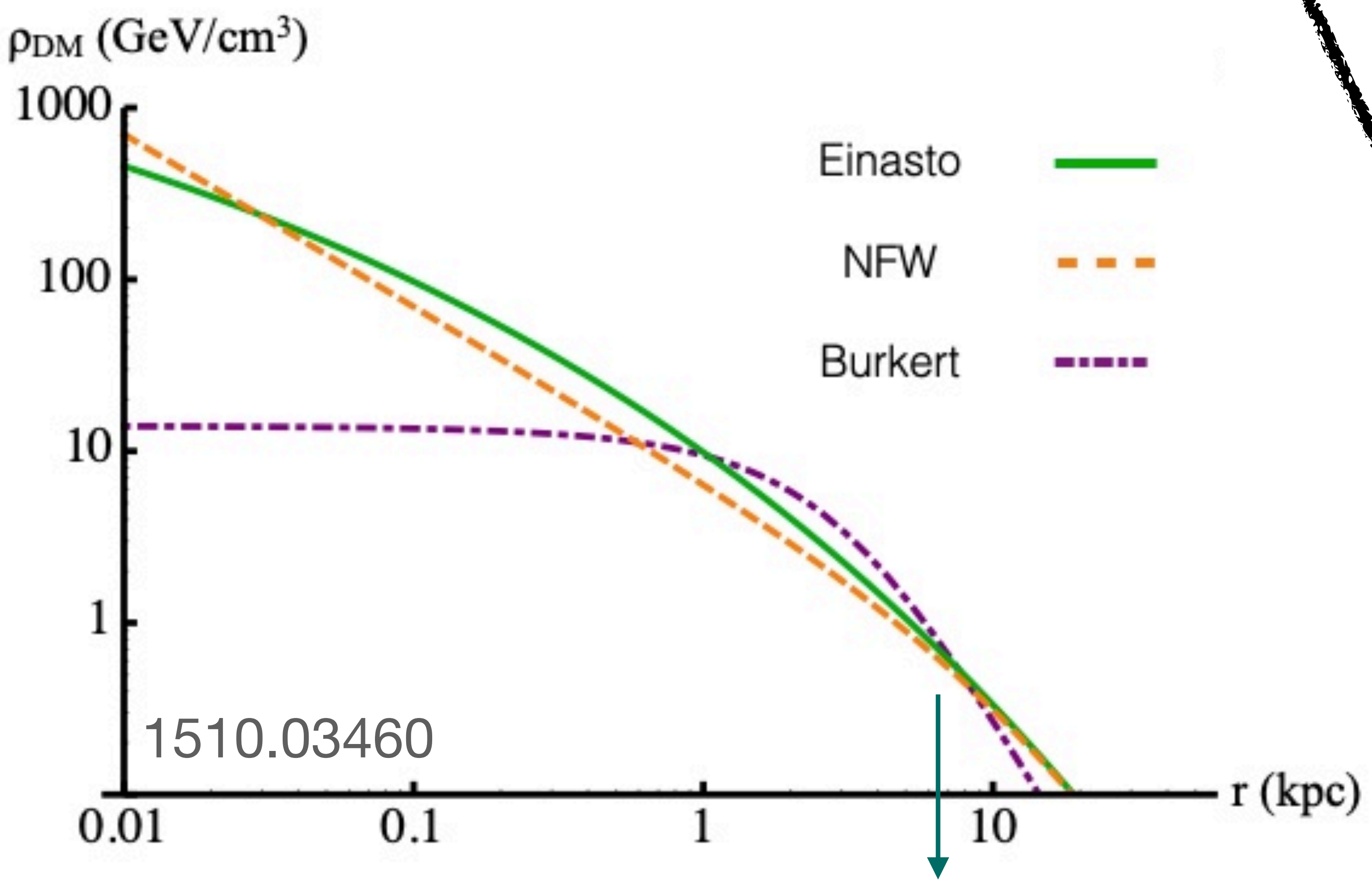
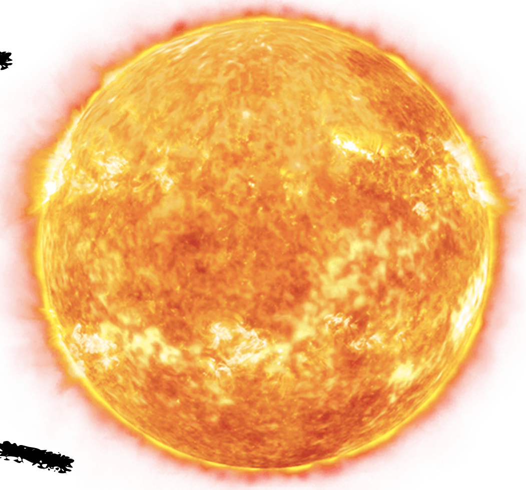




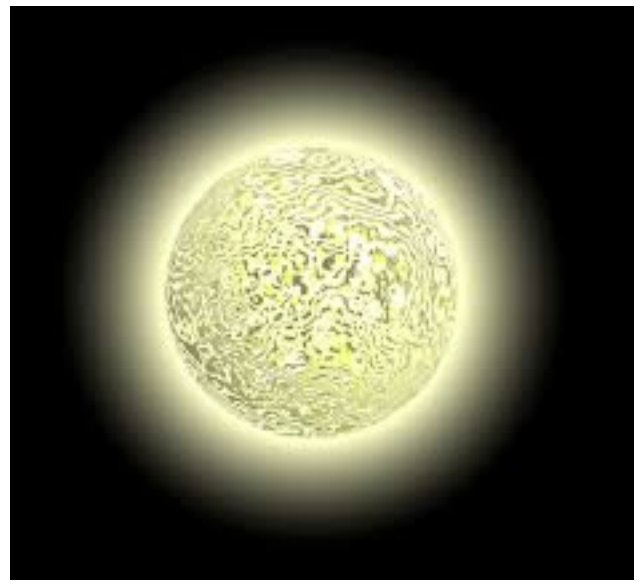
0.3 GeV/cm³ by Earth

local structure

Main Sequence ~0.002 c

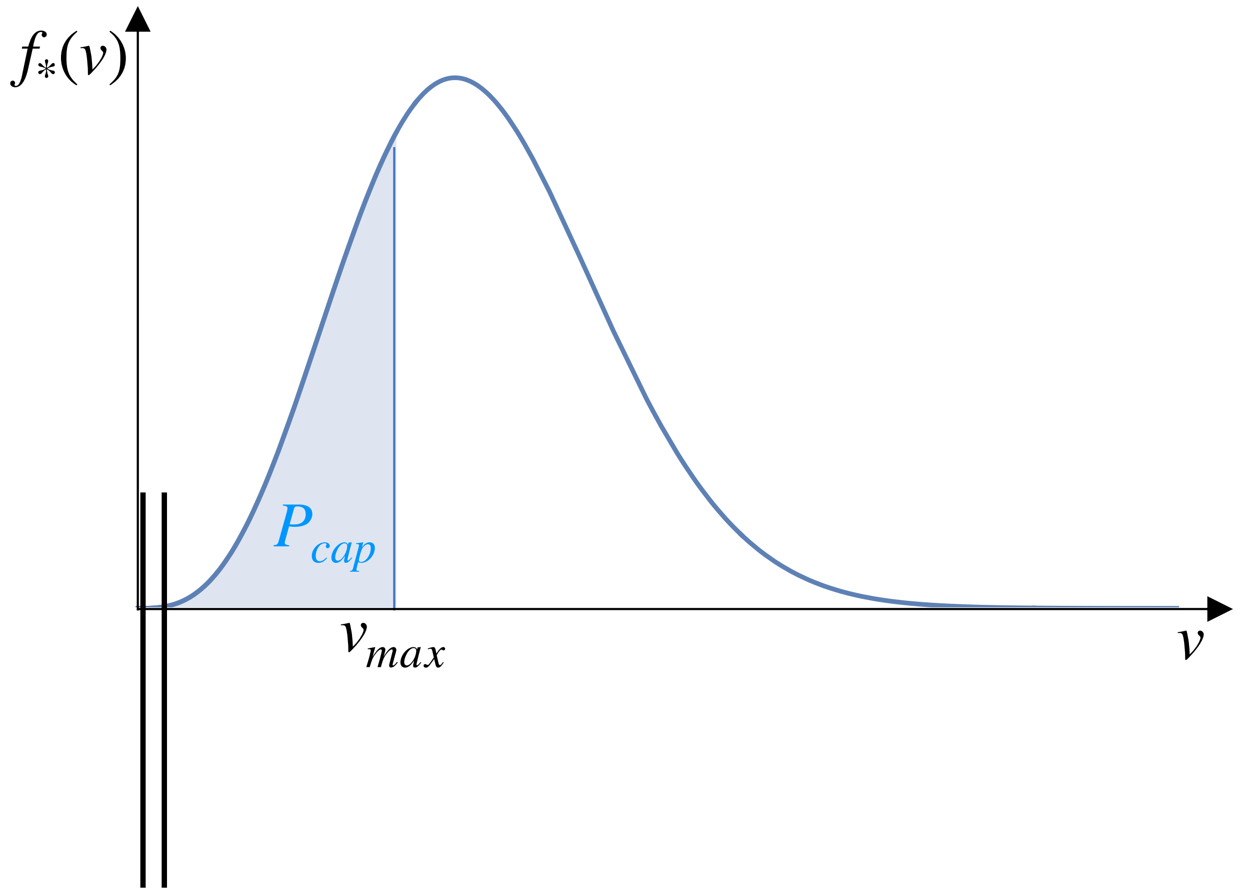


White Dwarf ~0.05 c

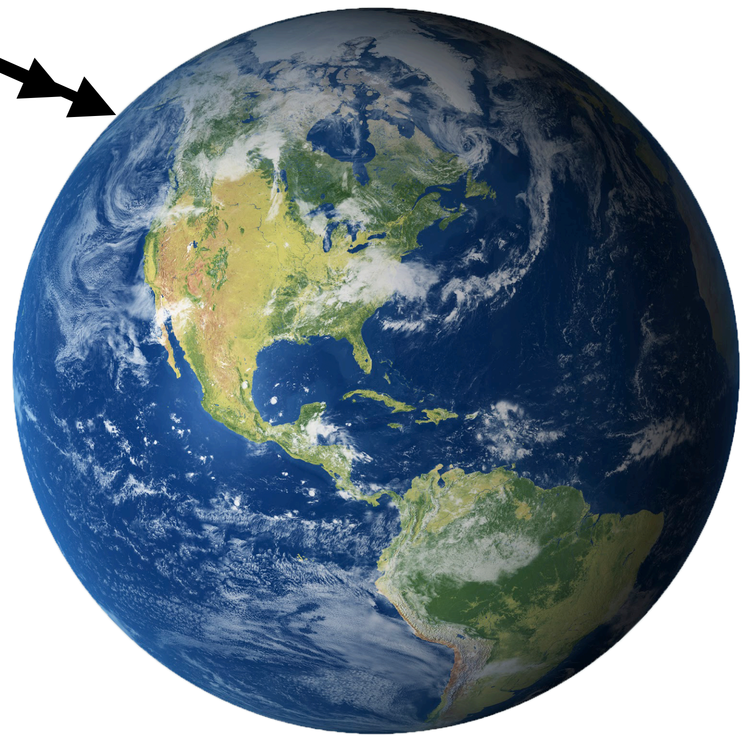


Neutron Star ~0.7 c

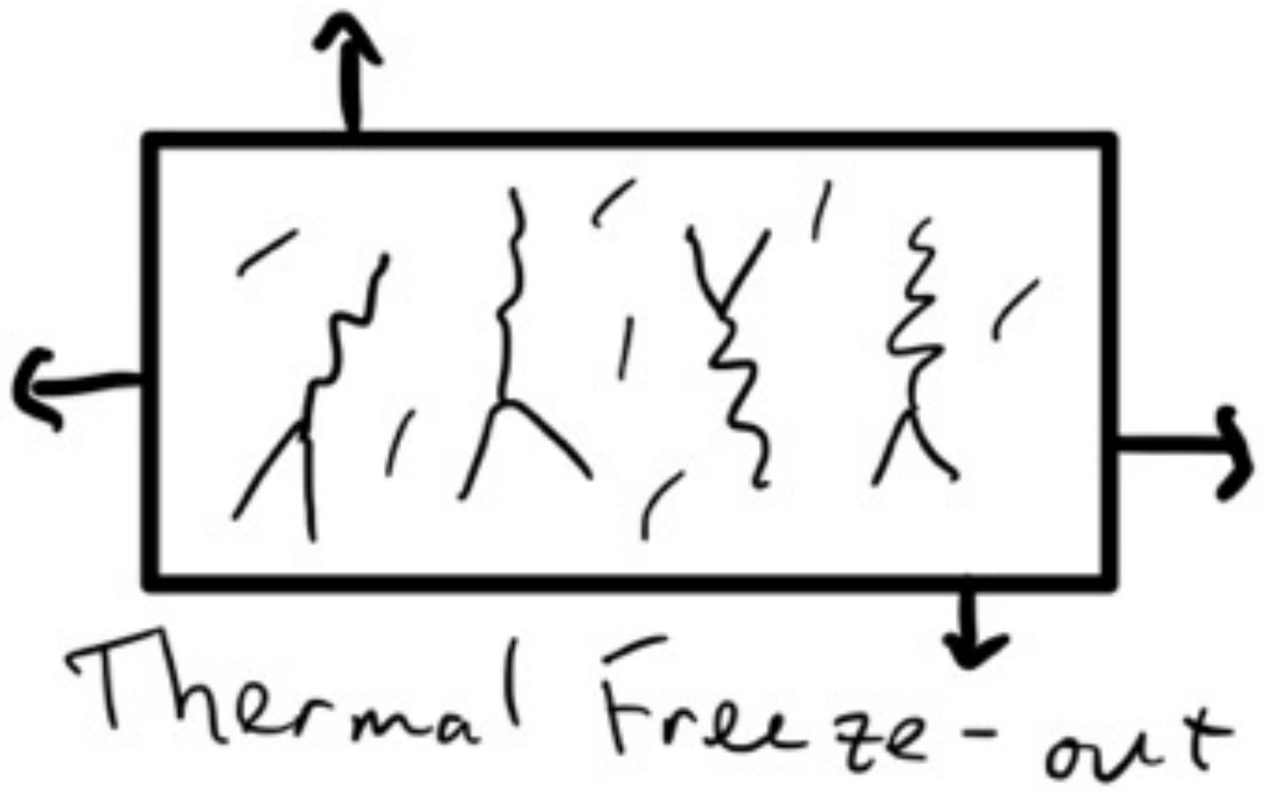
local fine structure



minimum DM speed > 11 km/s



The WIMP Miracle

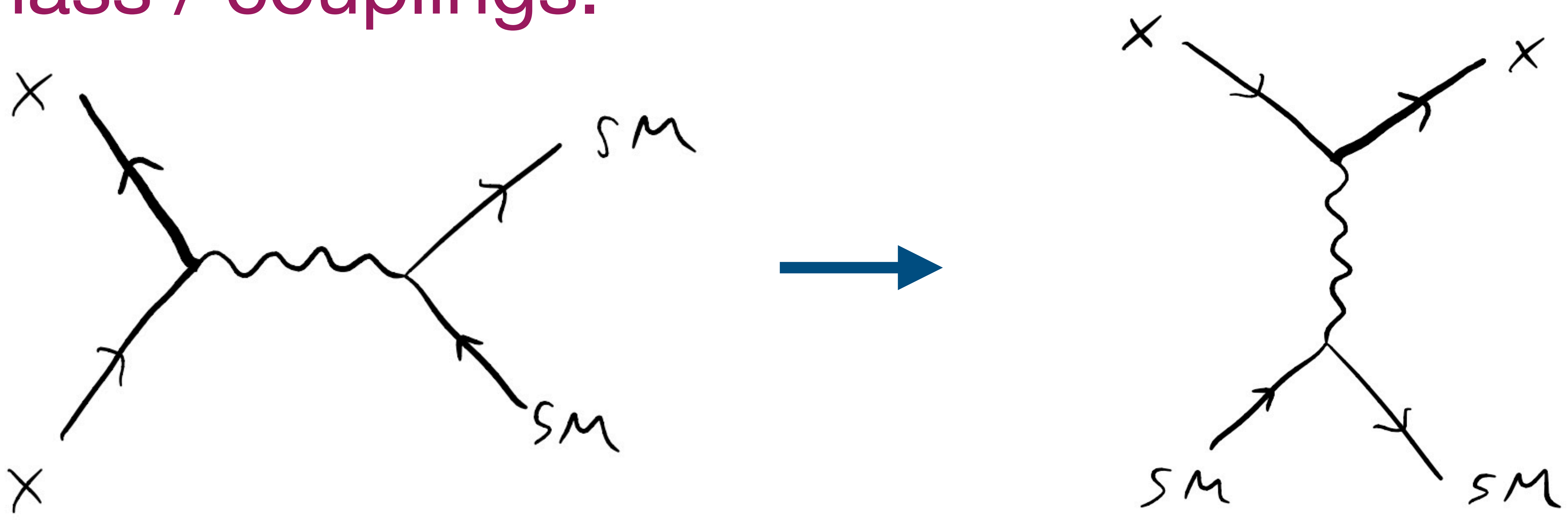


As the universe cools, dark matter falls out of thermal equilibrium, some portion annihilates to SM particles

$$\frac{m_x n_x}{n_\gamma} \sim \frac{x_f}{m_{pl} \langle \sigma_a v \rangle} \qquad x_f \sim \log[m_x^3 \langle \sigma_a v \rangle / H]$$

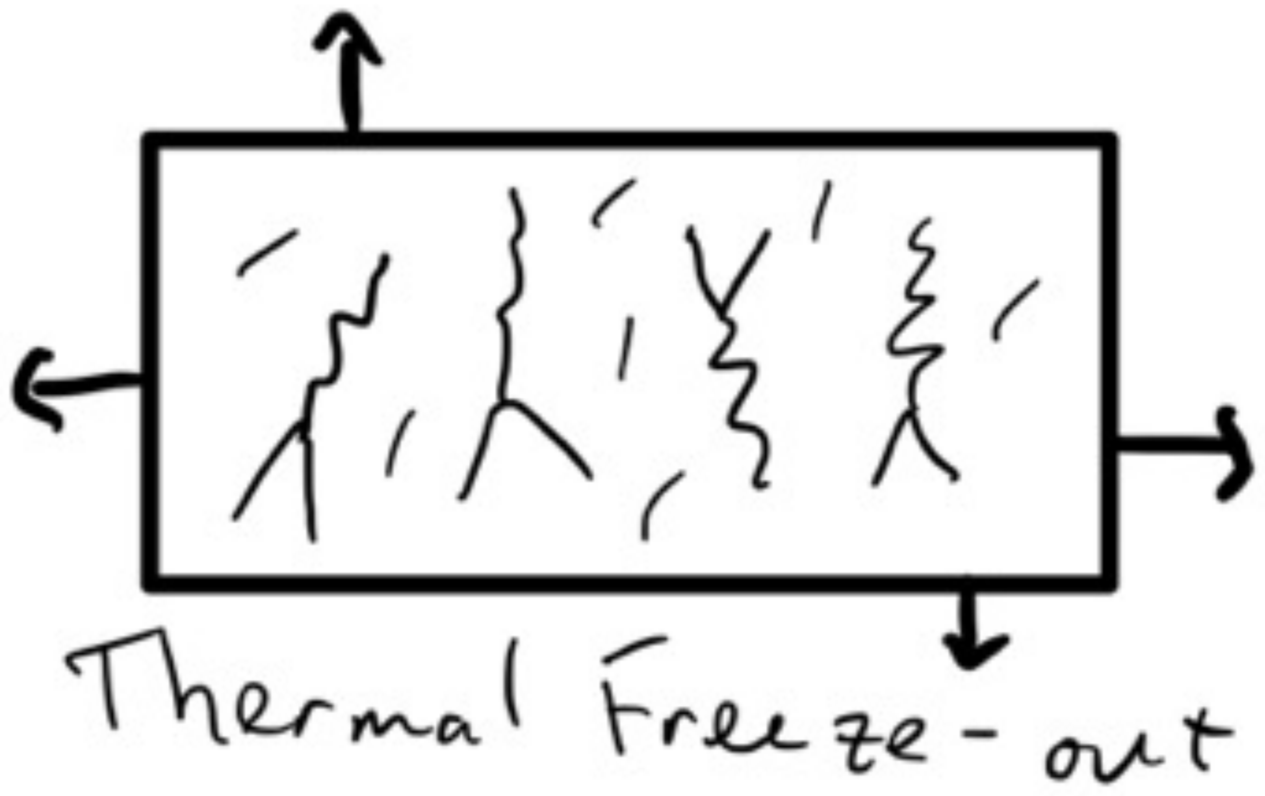
Observed DM relic abundance achieved for annihilation cross-section matching weak scale mass / couplings.

$$\Omega_x h^2 \sim 0.1 \left(\frac{m_{\mathrm{v}}}{100\ \mathrm{GeV}} \right)^2 \left(\frac{0.03}{\alpha_w} \right)^2$$



Some symmetry arguments imply interactions at dark matter experiments.

The WIMP Miracle



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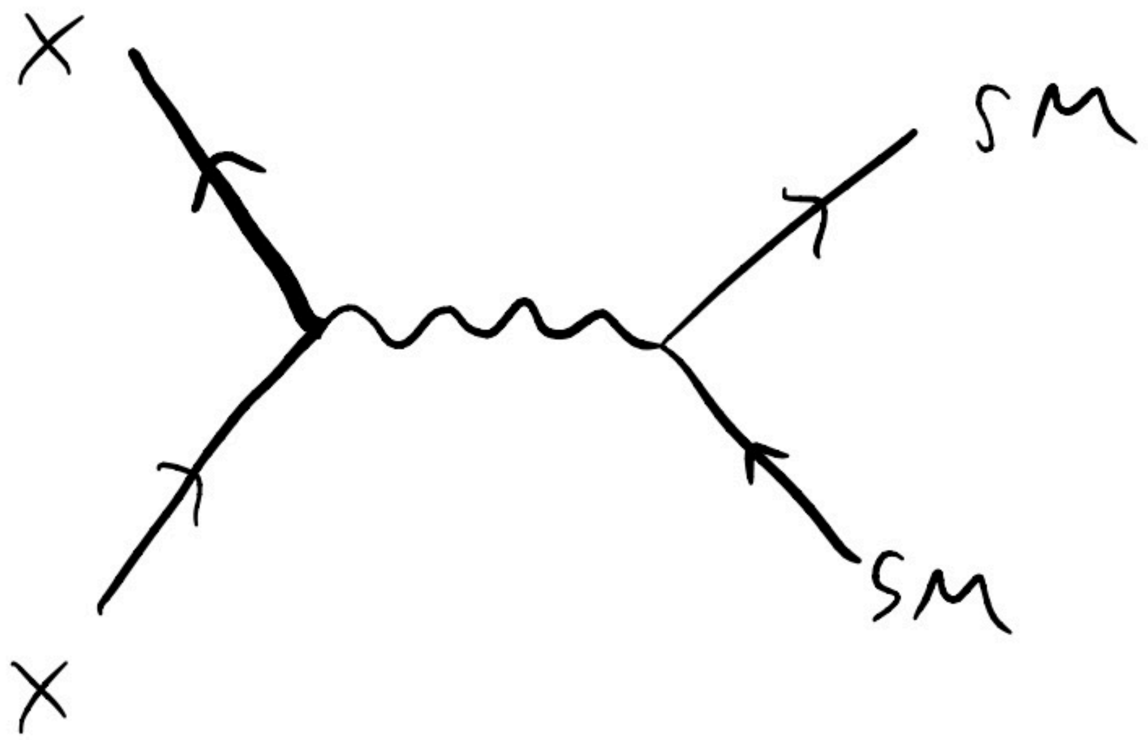

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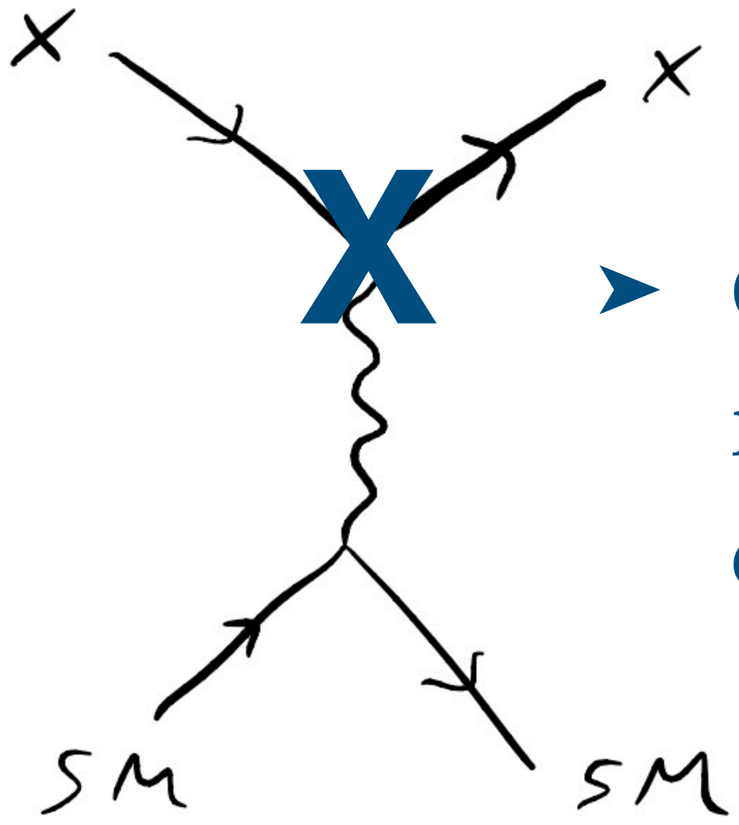
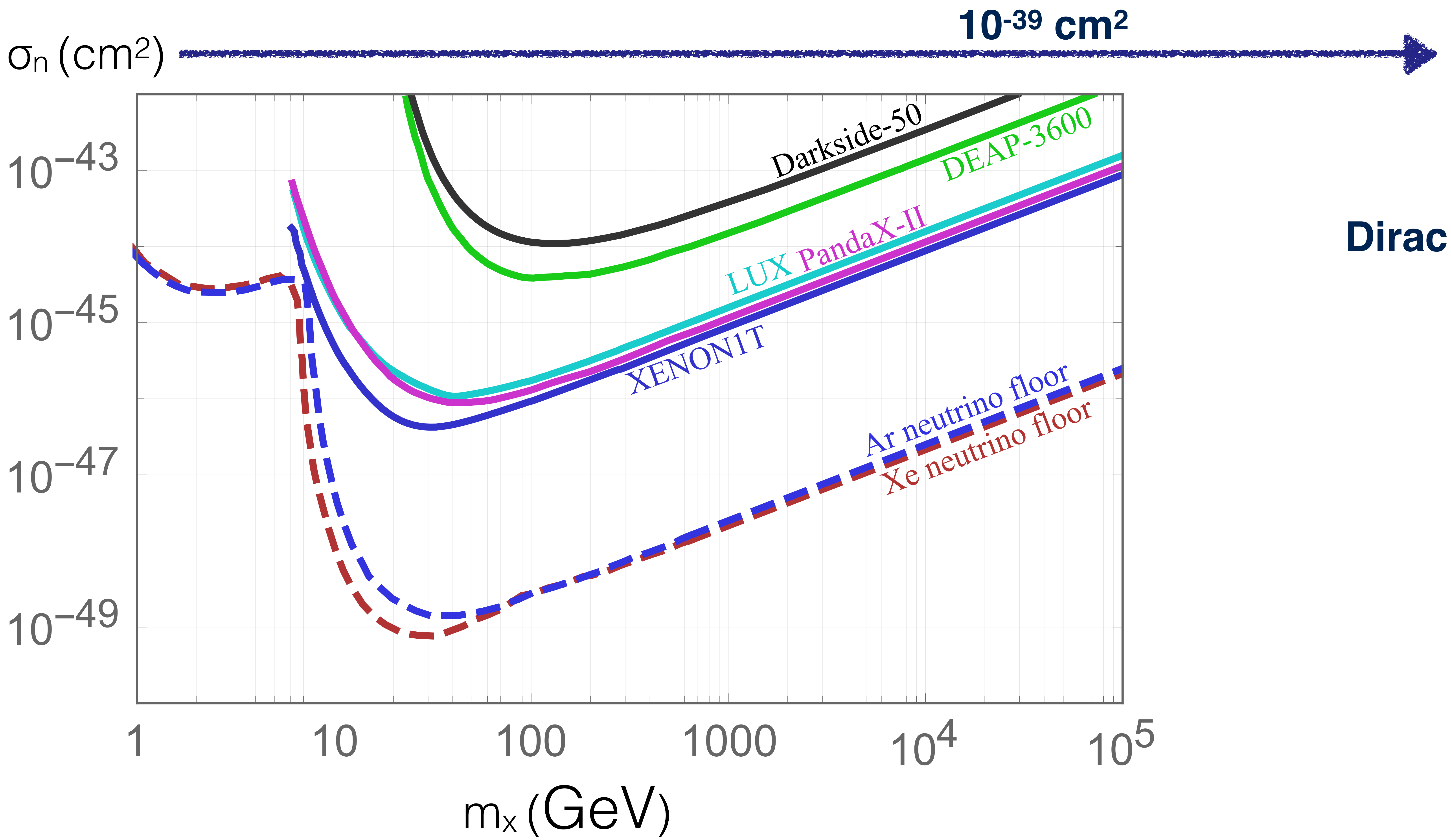


- Caveat: symmetry arguments require symmetry, and (for example) electroweak symmetry is broken

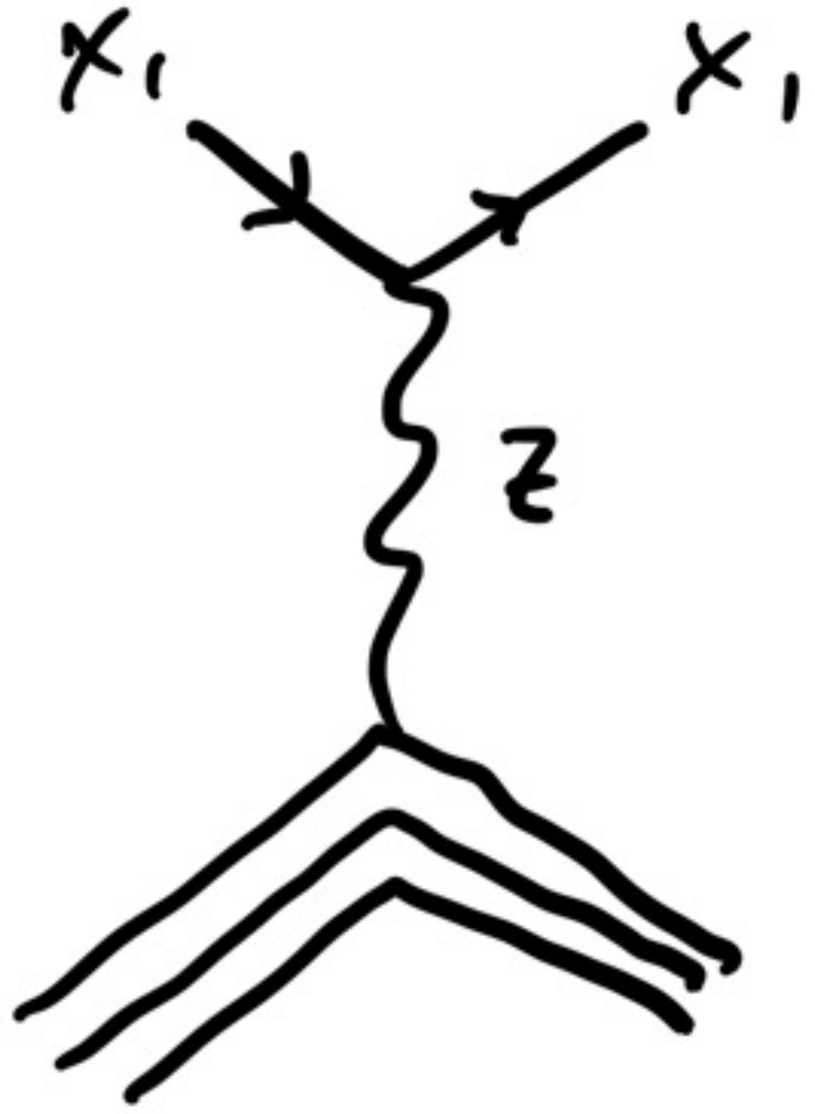
Some symmetry arguments imply interactions at dark matter experiments.

Spin independent dark matter detection



$$\sigma_n \approx \frac{\alpha_W^2 \mu_{nX}^2}{M_Z^4}$$

Dirac fermion coupled through Z boson



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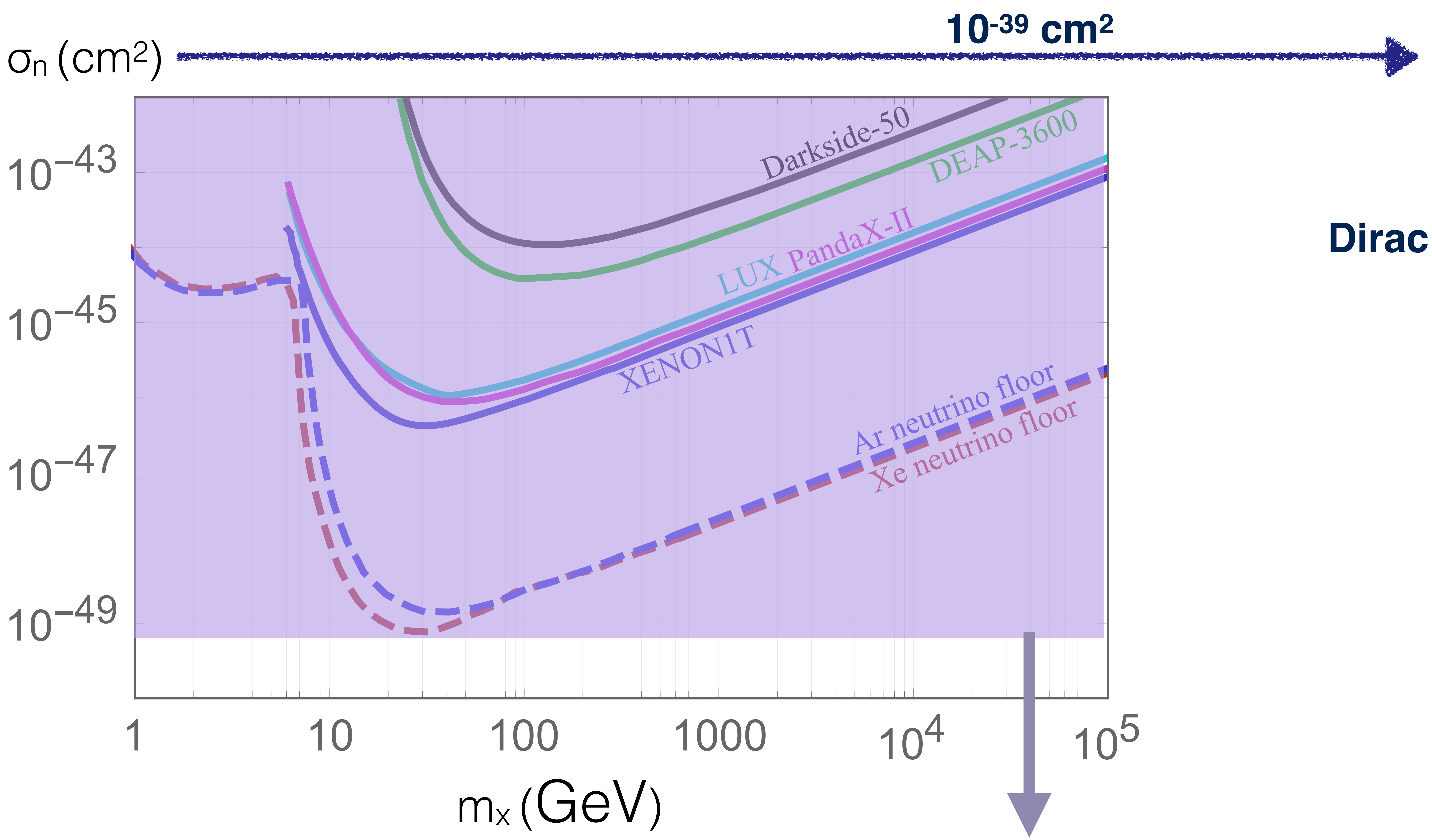

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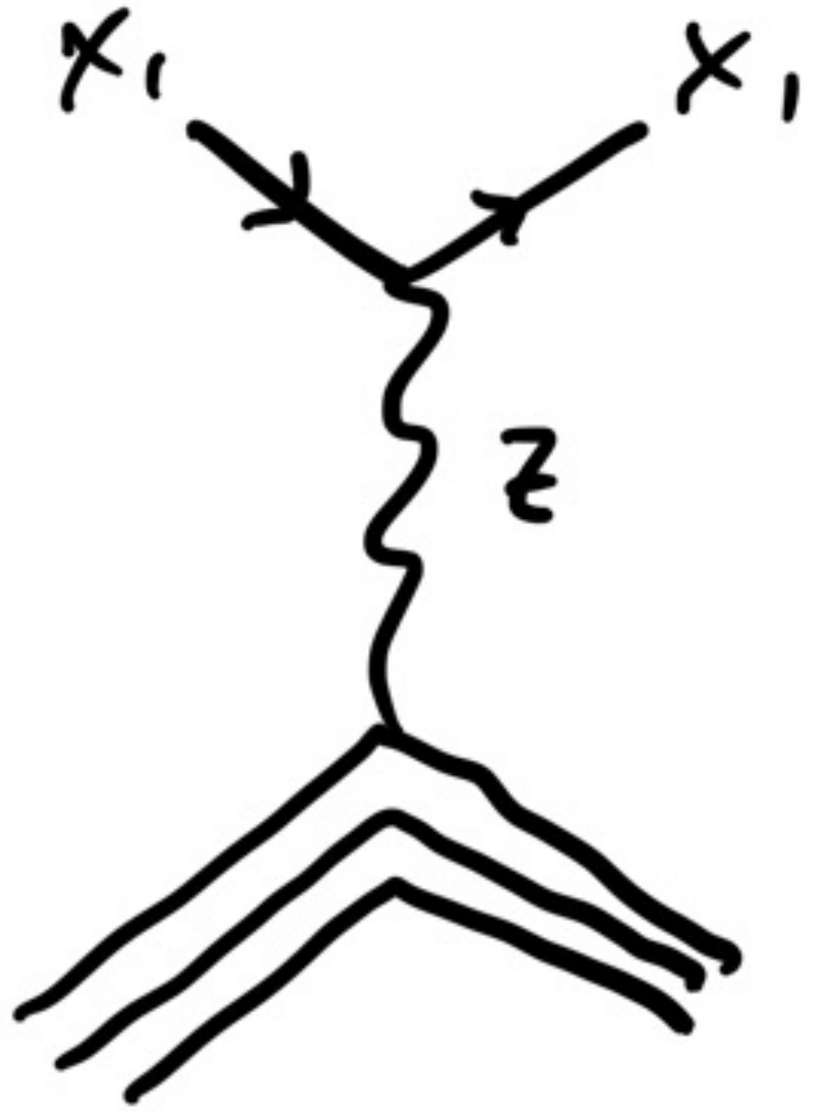
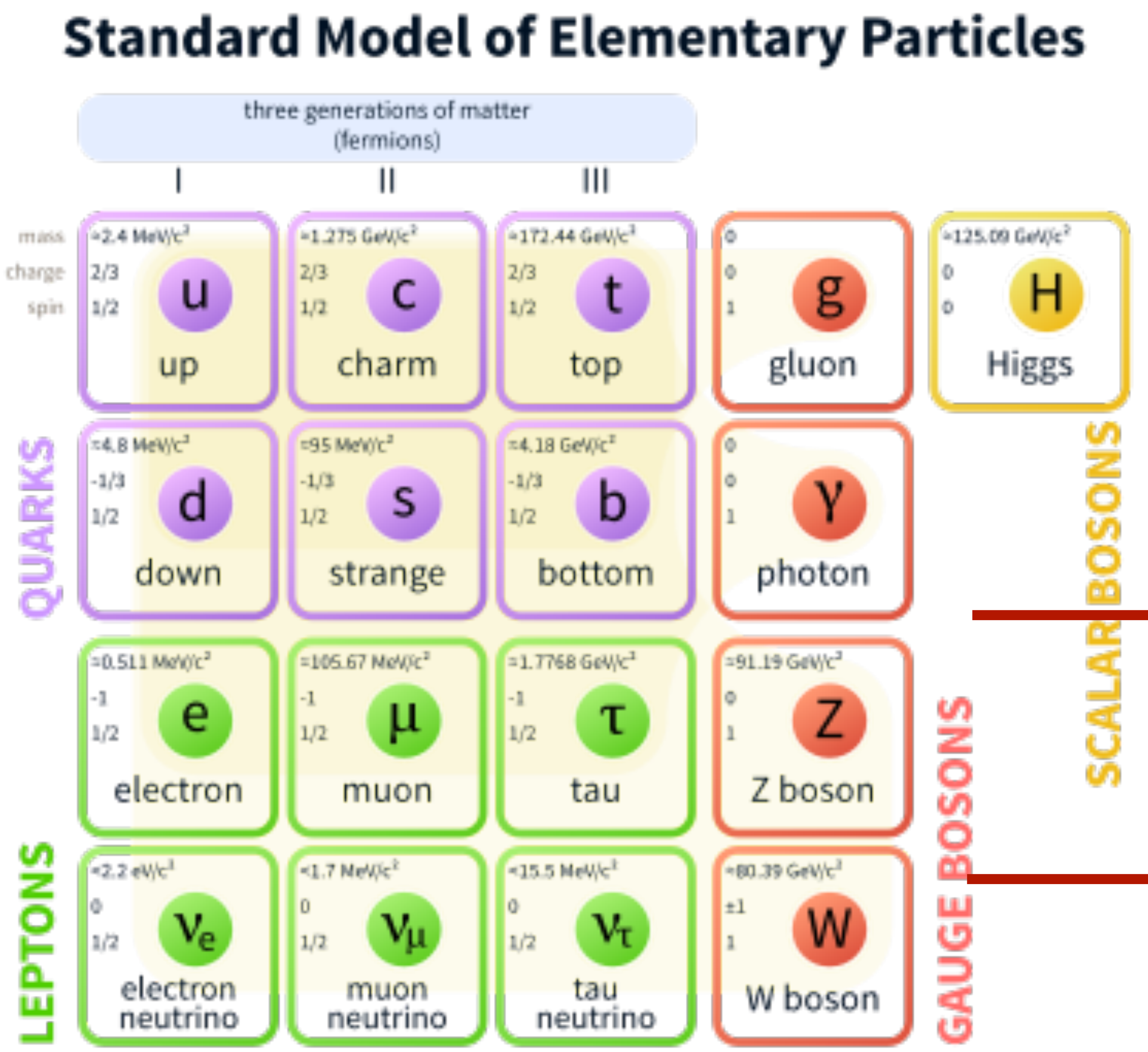


Plenty of WIMP(ish) models waiting to be found!

The Higgsino: Broken Symmetry for Dirac WIMP



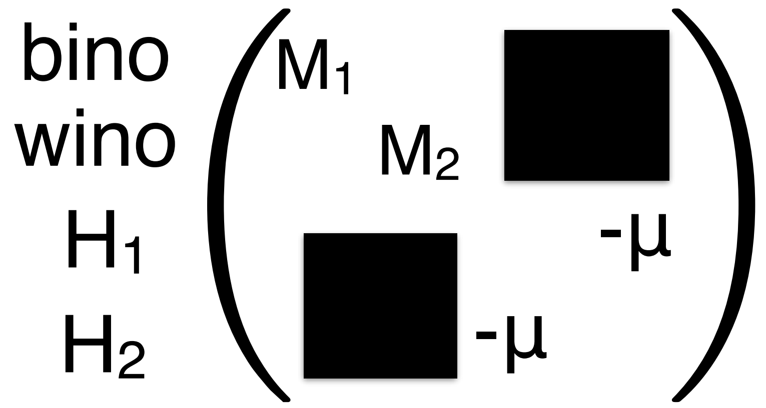
SUSY DM

Higgsino

Bino

Wino

EW Symmetry Breaking

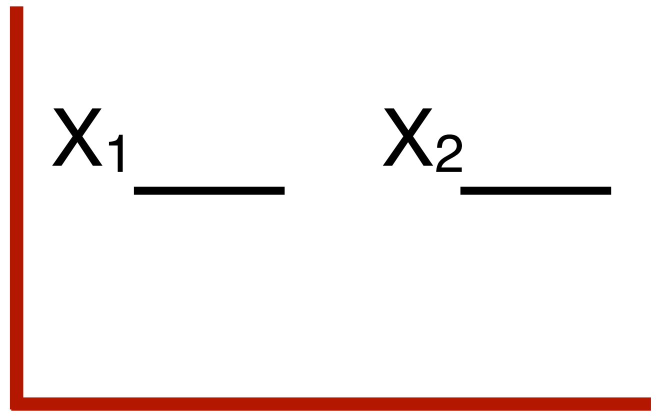


neutral components mix

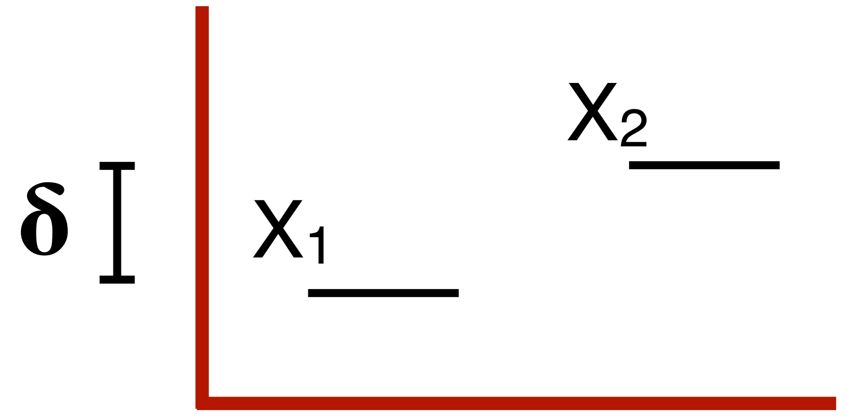
■ = **electroweak symmetry breaking (Z, W)**

M_1,M_2, ■, result in mass splitting **δ**

Higgsino neutral states



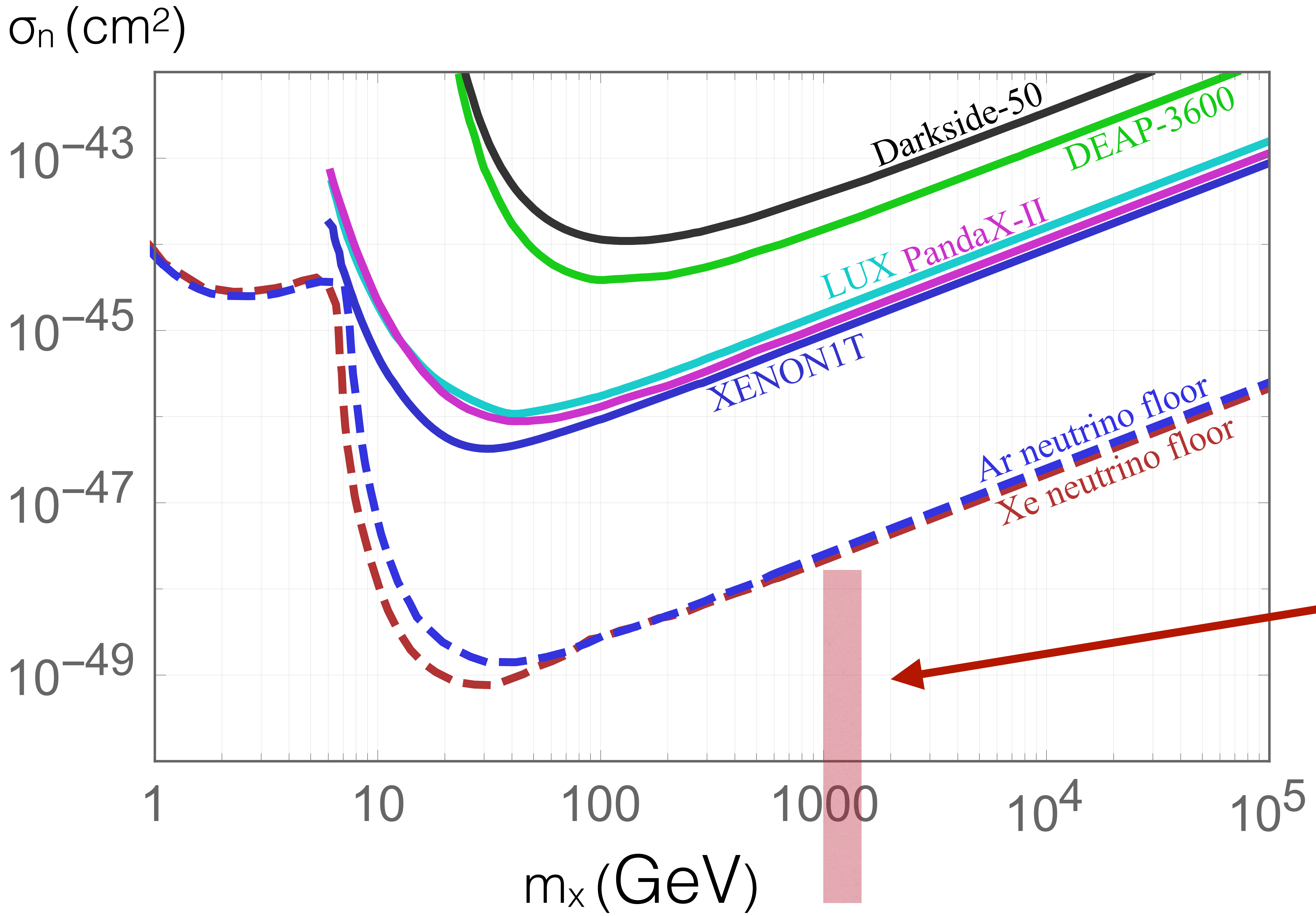
split after EWSB



e.g.

$$\delta \sim \mathrm{GeV}\left(\frac{\mathrm{TeV}}{M_1}\right)$$

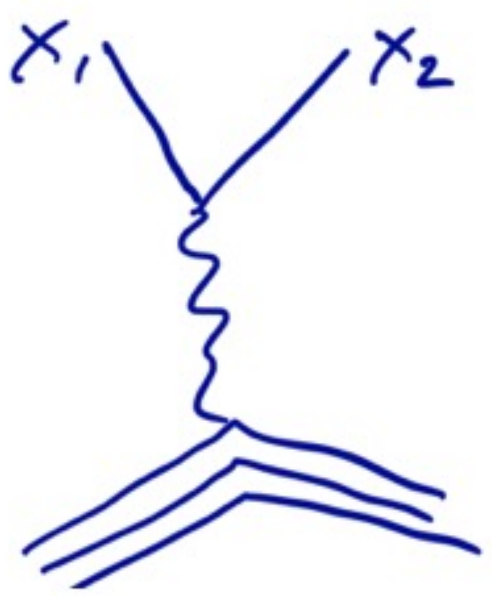
Underground dark matter detection, Higgsinos



Higgsino Dark Matter

Hisano et. al. 2013
Hill and Solon 2013

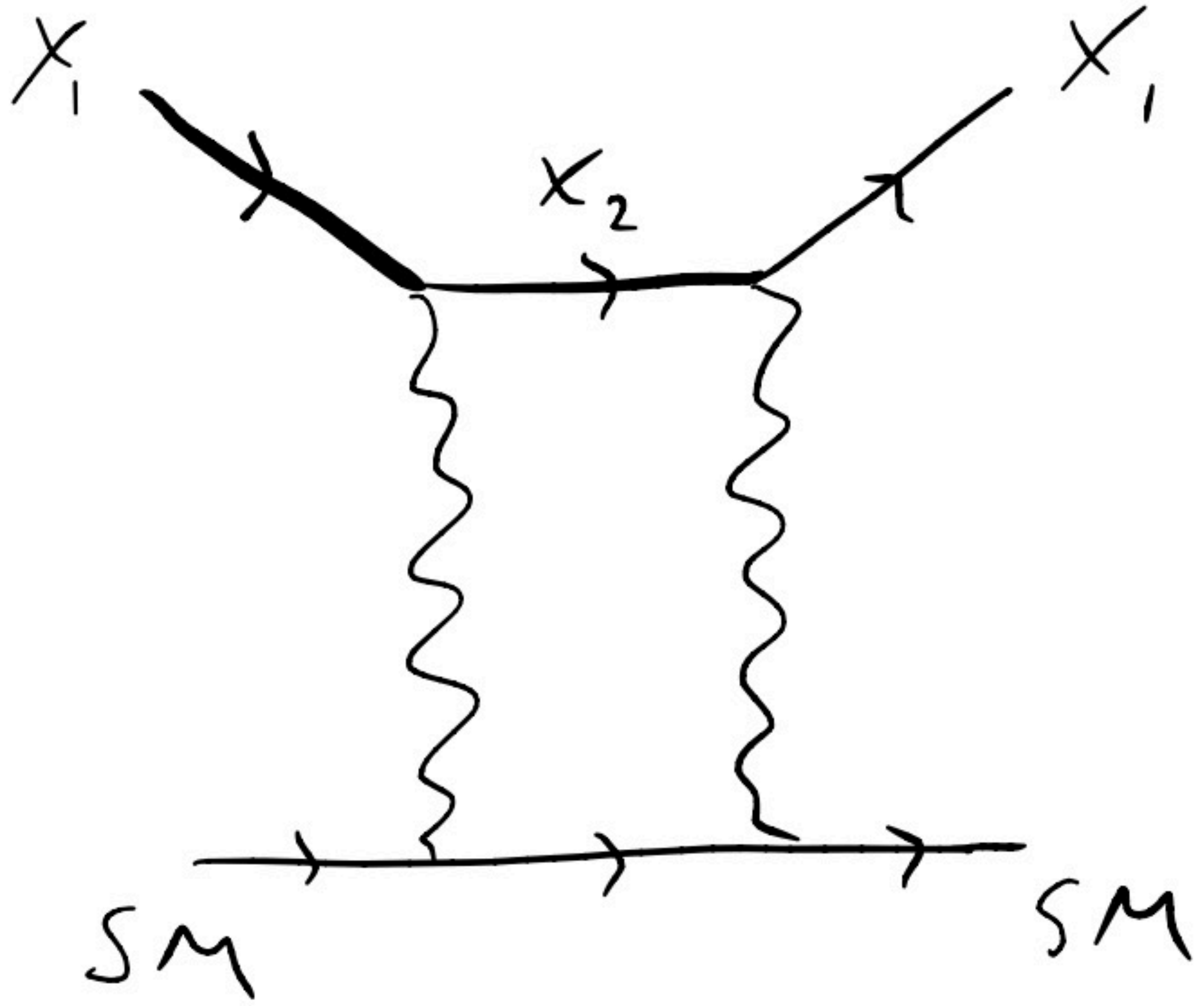
10^{-39} cm^2



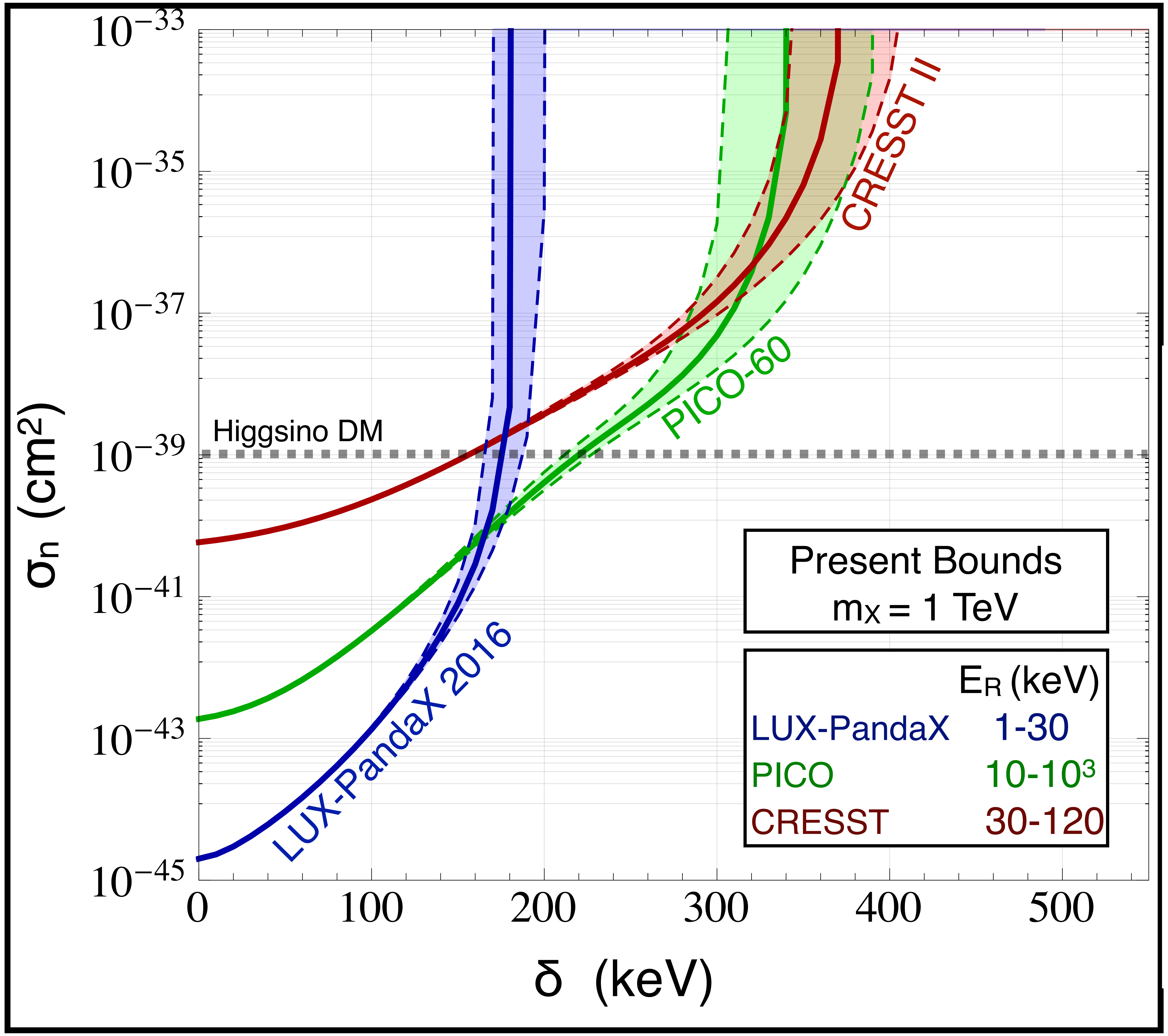
Interaction forbidden at $v \sim 0.001c$ by $X_1 \leftrightarrow X_2$

mass gap → $\delta \sim \mathrm{GeV} \left(\frac{\mathrm{TeV}}{M_1}\right)$

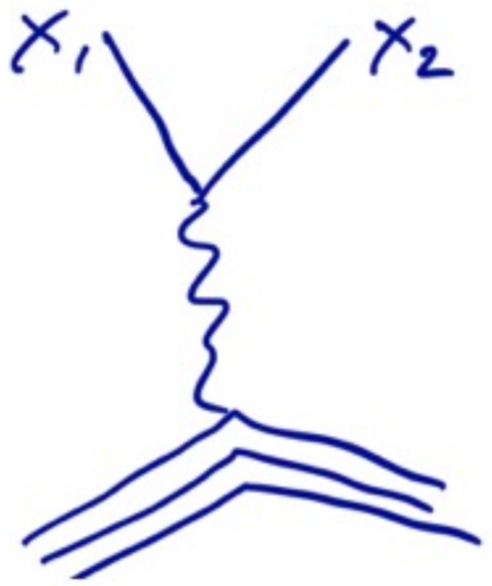
Loop suppressed scattering



Underground dark matter detection, Higgsinos



10^{-39} cm²



Interaction forbidden at v ~ 0.001c by $X_1 \leftrightarrow X_2$

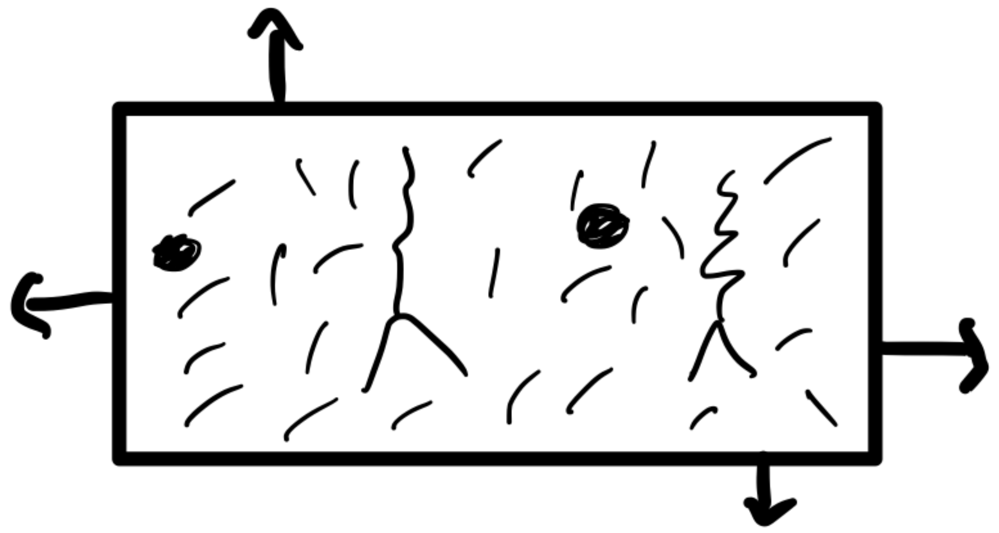
mass gap → $\delta \sim \text{GeV}\left(\frac{\text{TeV}}{M_1}\right)$

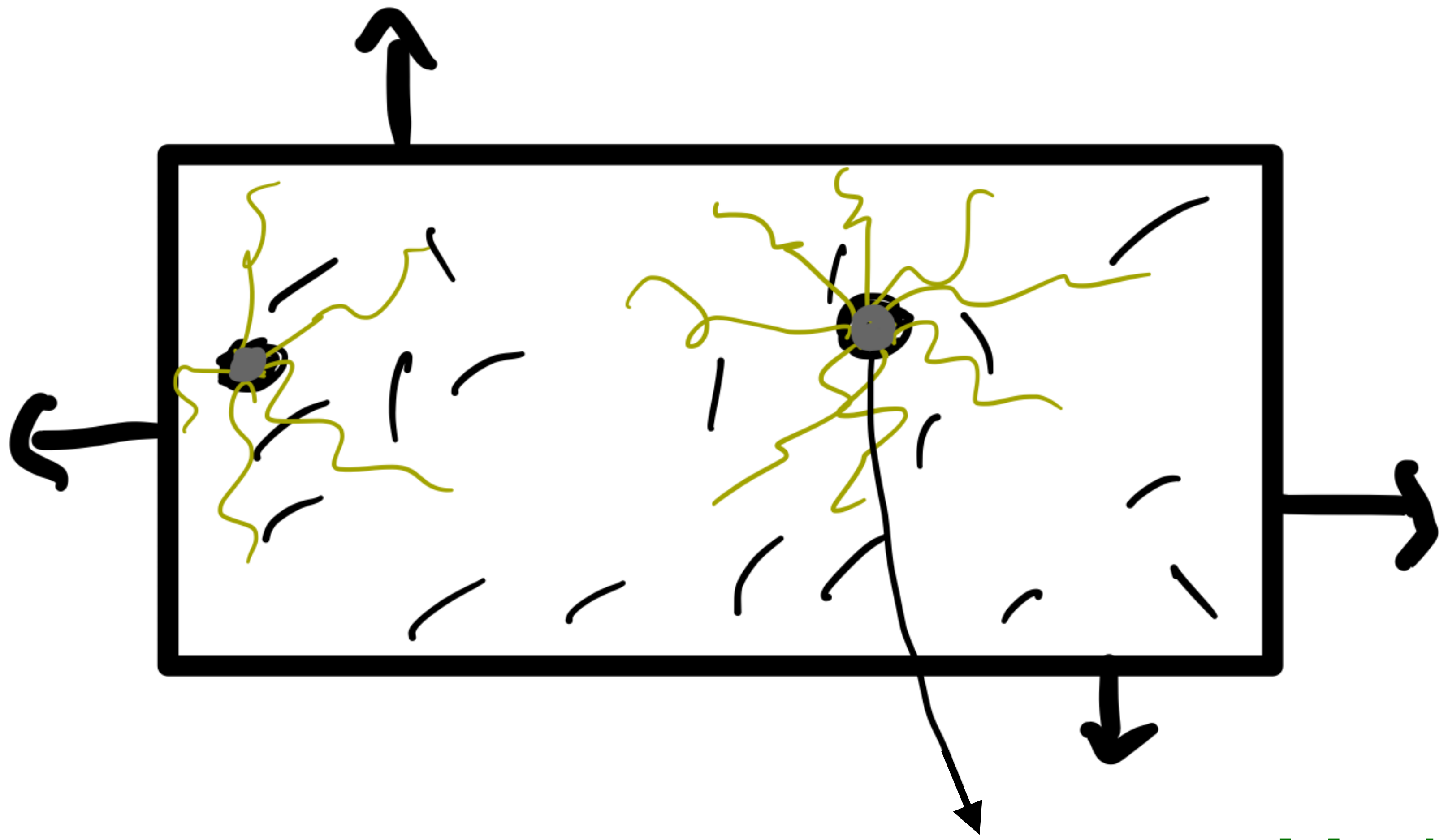
- Motivates High Recoil Inelastic Searches

- Also neutron stars

JB Fox Kribs Martin 1608.02662

Diluted WIMP Dark Matter: heavier





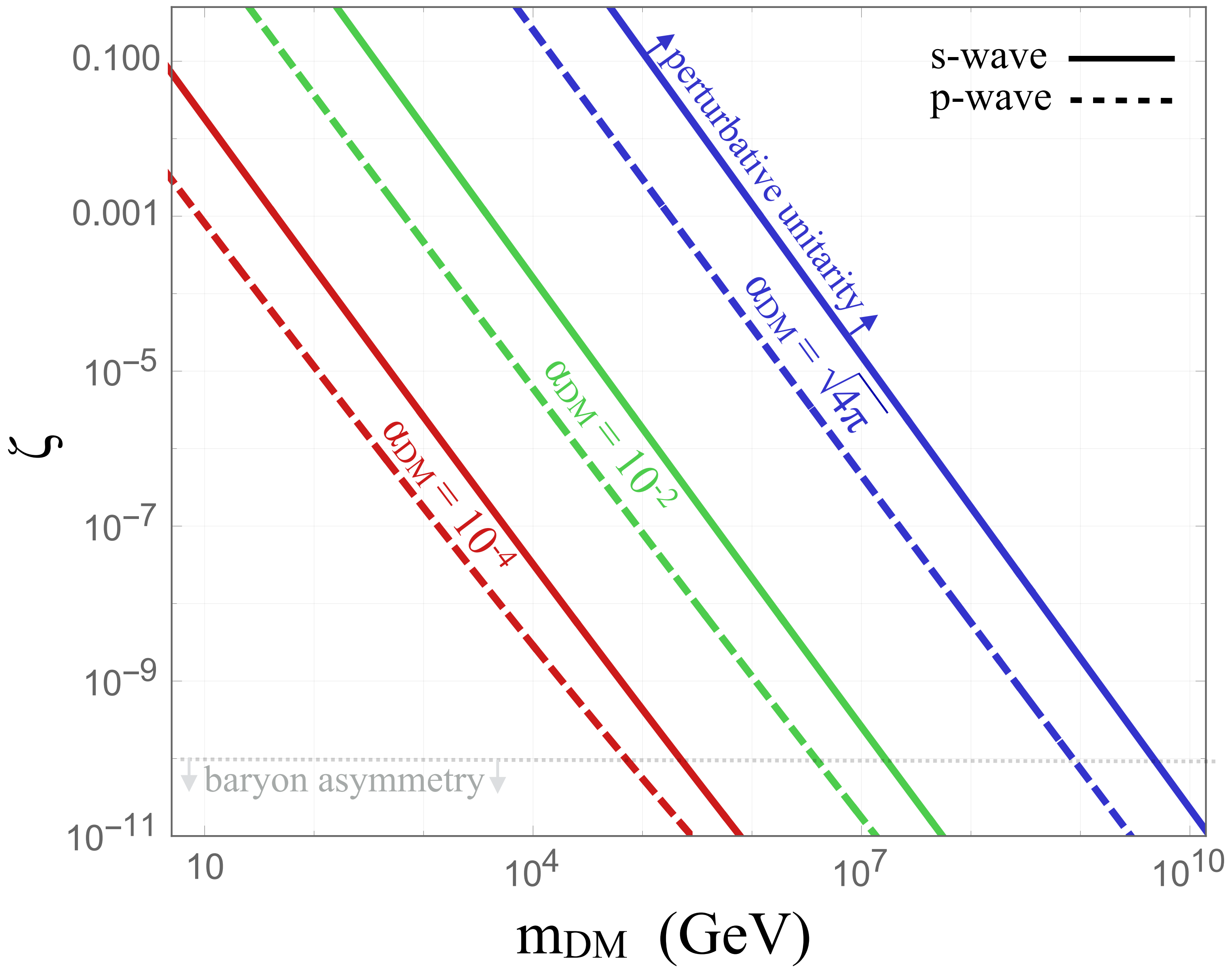
Overabundant freeze-out

Then dilution from decay →

$$\Omega_x h^2 \sim 0.1 \left(\frac{m_V}{PeV}\right)^2 \left(\frac{0.03}{\alpha_D}\right)^2 \left(\frac{\zeta}{10^{-8}}\right)$$

Motivation

-Matter dominated epoch
-Decay of asymmetry field (Affleck-Dine)
-Decay of inflaton
-Decay of modulus / gravitino
-Field associated with ~PeV dark sector



$$\zeta \equiv \frac{s_{ini}}{s_{fin}} = n_x \text{ dilution}$$

JB Unwin 1701.05859

see also e.g.
Allahverdi Dutta Sinha '11
Kane Shao Watson '11
Davoudiasl Hooper McDermott '15
Berlin Hooper Krnjaic '16

HIGH MASS ASYMMETRY, DILUTION, AND COMPOSITE DM

Consider a simple model of fermionic DM coupled by a scalar field

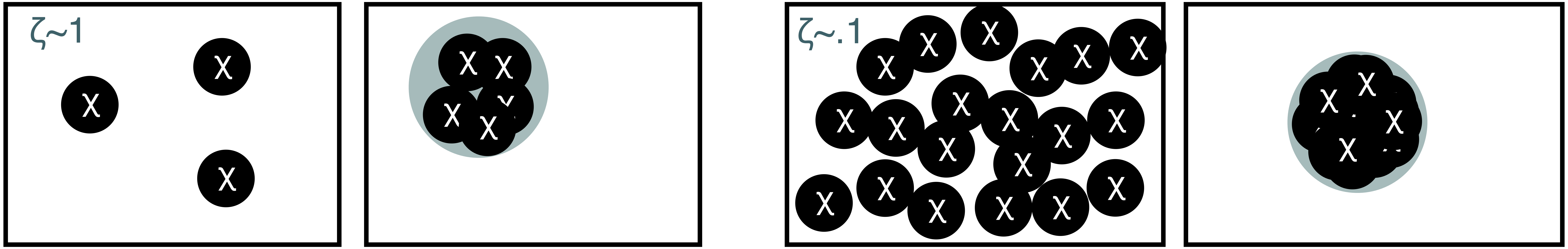
$$\mathscr{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\varphi X - \frac{1}{2}m_\varphi^2\varphi^2 + g_n\bar{n}\varphi n + \mathscr{L}_{SM},$$

see also e.g.
Wise Zhang ’14
Krnjaic Sigurdson ’14
Hardy Lasenby March-Russell ’14
Gresham Lou Zurek ‘17

Diluted dark matter has a freeze-out abundance that scales with ζ^{-1}

This overabundance of dark matter leads to very large $\varphi - X$ composites

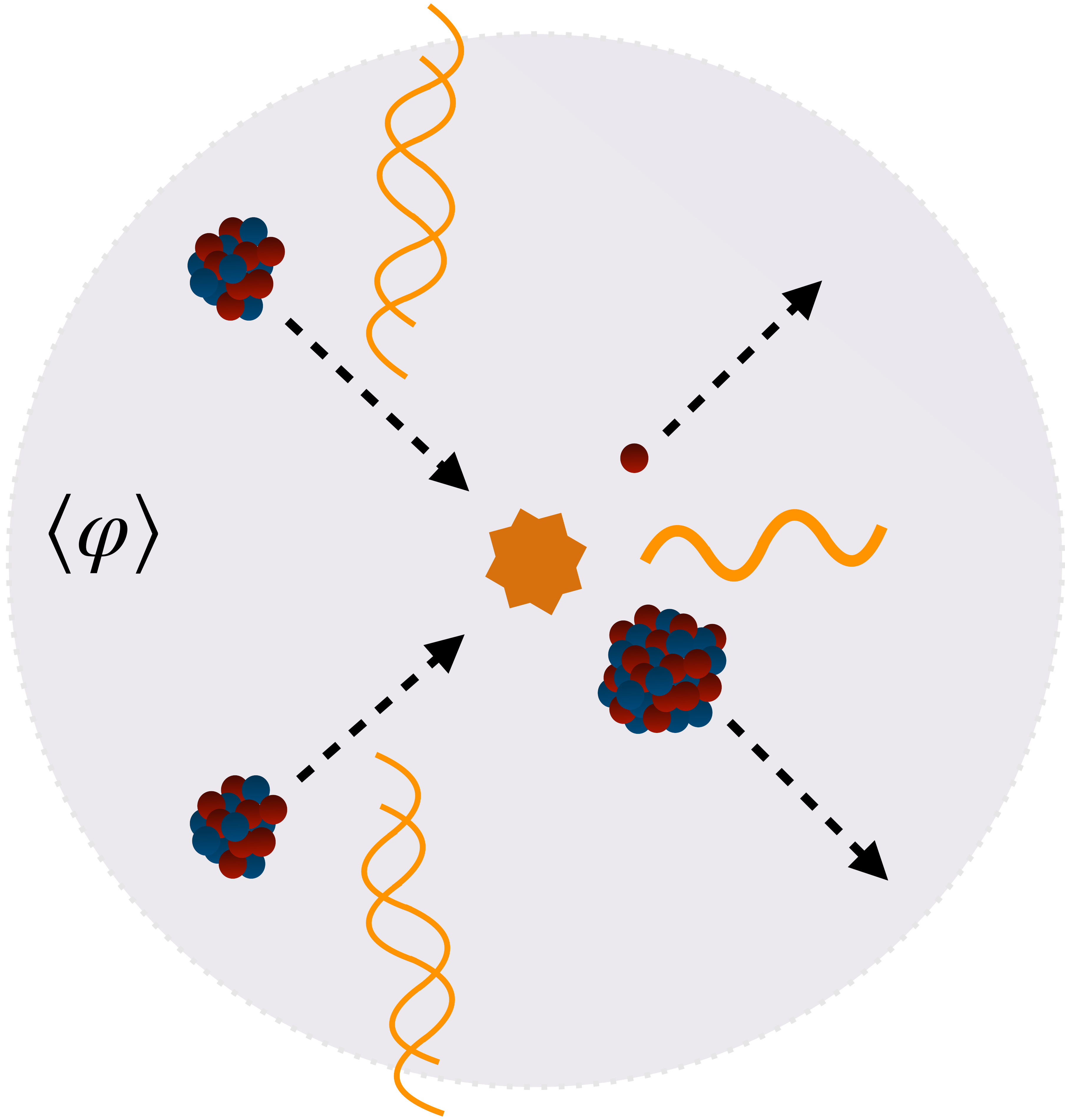
Acevedo JB Goodman 2012.10998



$$N_c = \left(\frac{2n_X\sigma_X v_X}{3H}\right)^{6/5} = \left(\frac{20\sqrt{g^*_{ca}}T_r T_{ca}^{3/2} M_{pl}}{\bar{m}_X^{7/2}\zeta}\right)^{6/5} \simeq 10^{27}\left(\frac{g^*_{ca}}{10^2}\right)^{3/5}\left(\frac{T_{ca}}{10^5\,\mathrm{GeV}}\right)^{9/5}\left(\frac{5\,\mathrm{GeV}}{\bar{m}_X}\right)^{21/5}\left(\frac{10^{-6}}{\zeta}\right)^{6/5}$$

Composite mass ranging from milligrams to thousands of tons

NEW SIGNATURES OF BIG COMPOSITE DARK MATTER



For a tiny nucleon-X coupling, can have ionization, nuclear fusion, bremsstrahlung from large dark matter composites.

$$\mathscr{L} \supset g_X \bar{X} \varphi X + g_n \bar{n} \varphi n + \mathscr{L}_{SM}$$

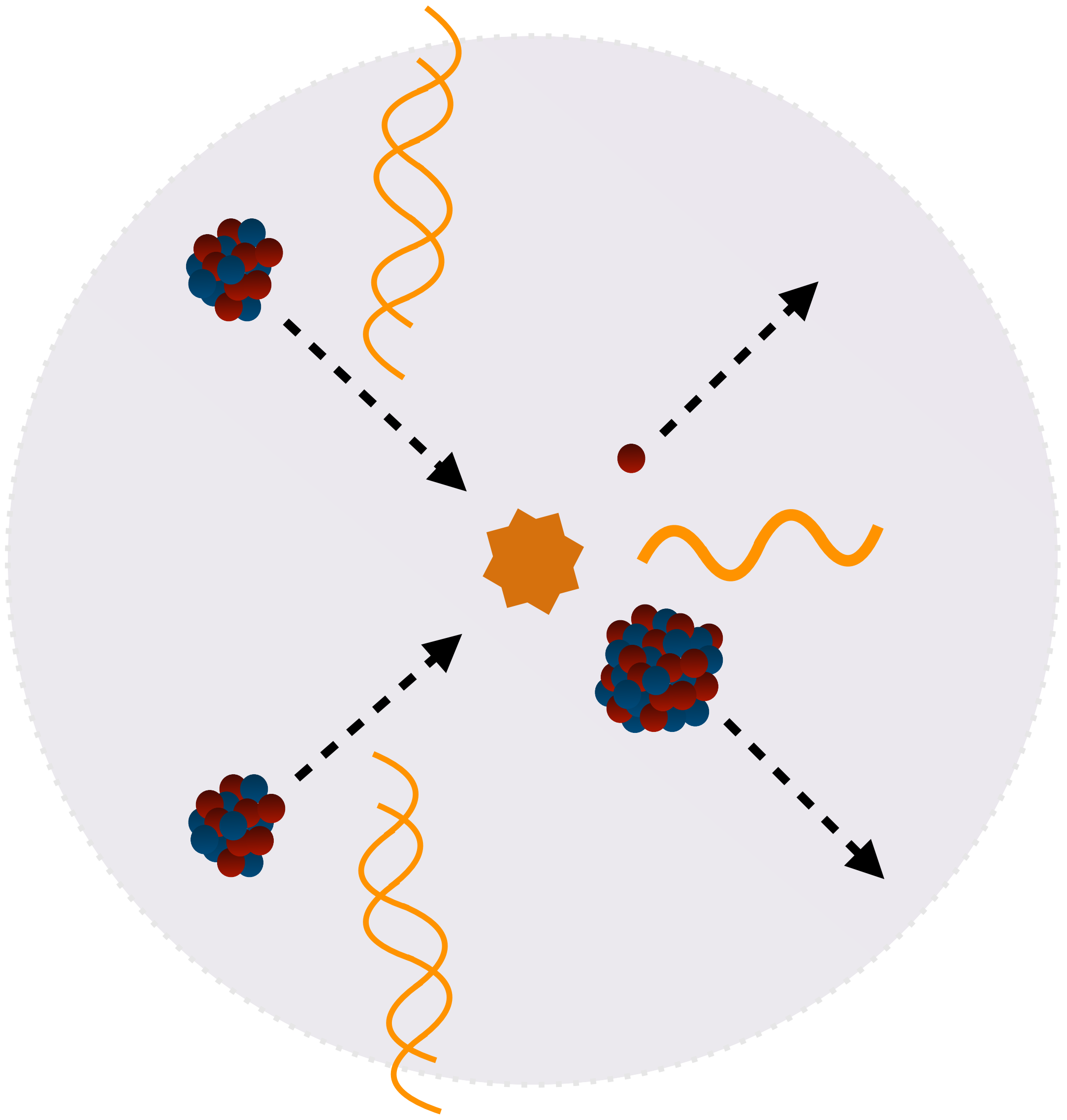
Javier Acevedo, JB, Alan Goodman *2012.10998*
2108.10889

INTERACTION SUMMARY

nuclear interactions with DM composite internal potential

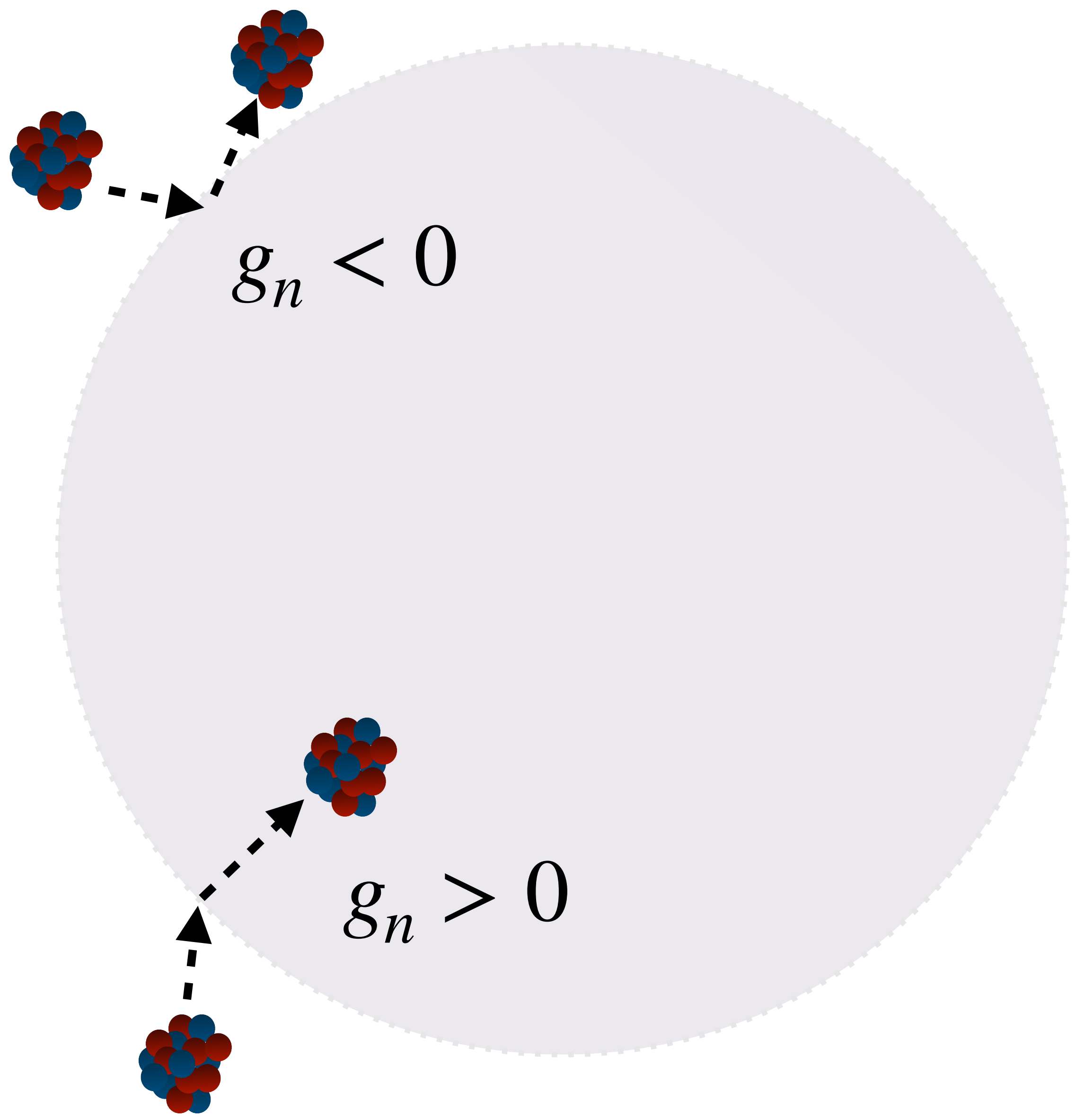
scattering with constituents

1.



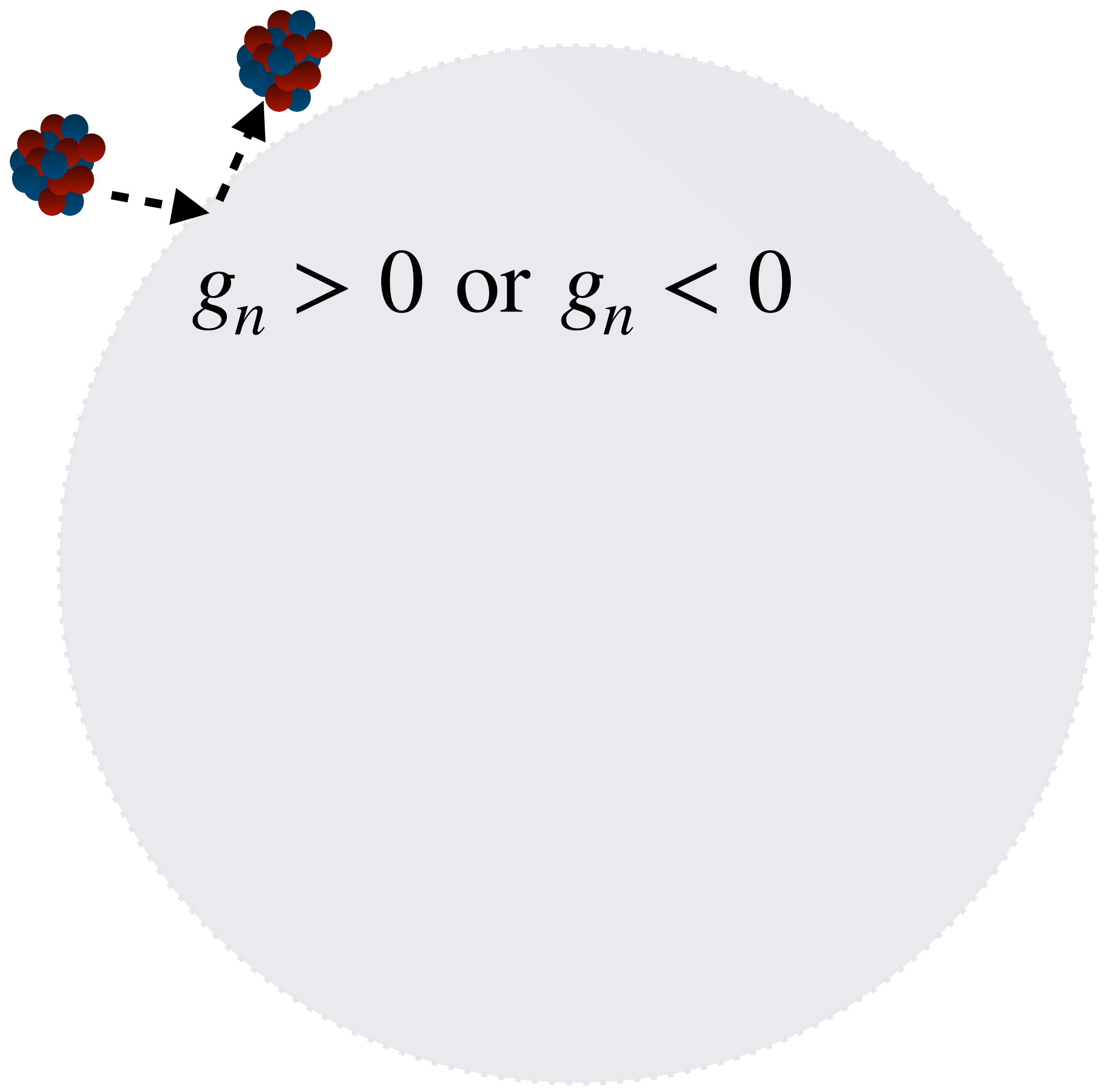
$\langle \varphi \rangle \lesssim m_N,\ g_n > 0$

2.



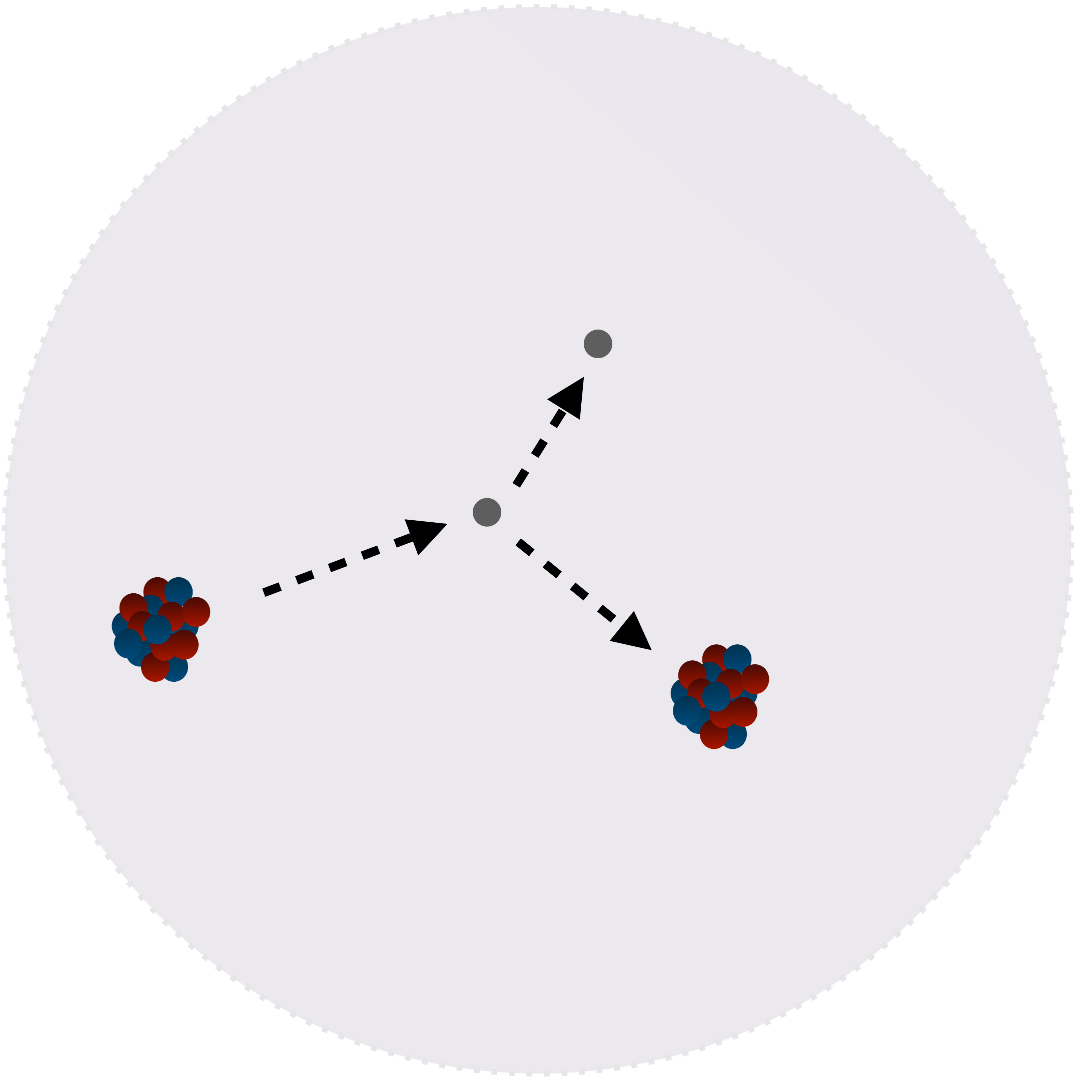
$\langle \varphi \rangle \ll m_N$

3.



$\langle \varphi \rangle > m_N$

4.

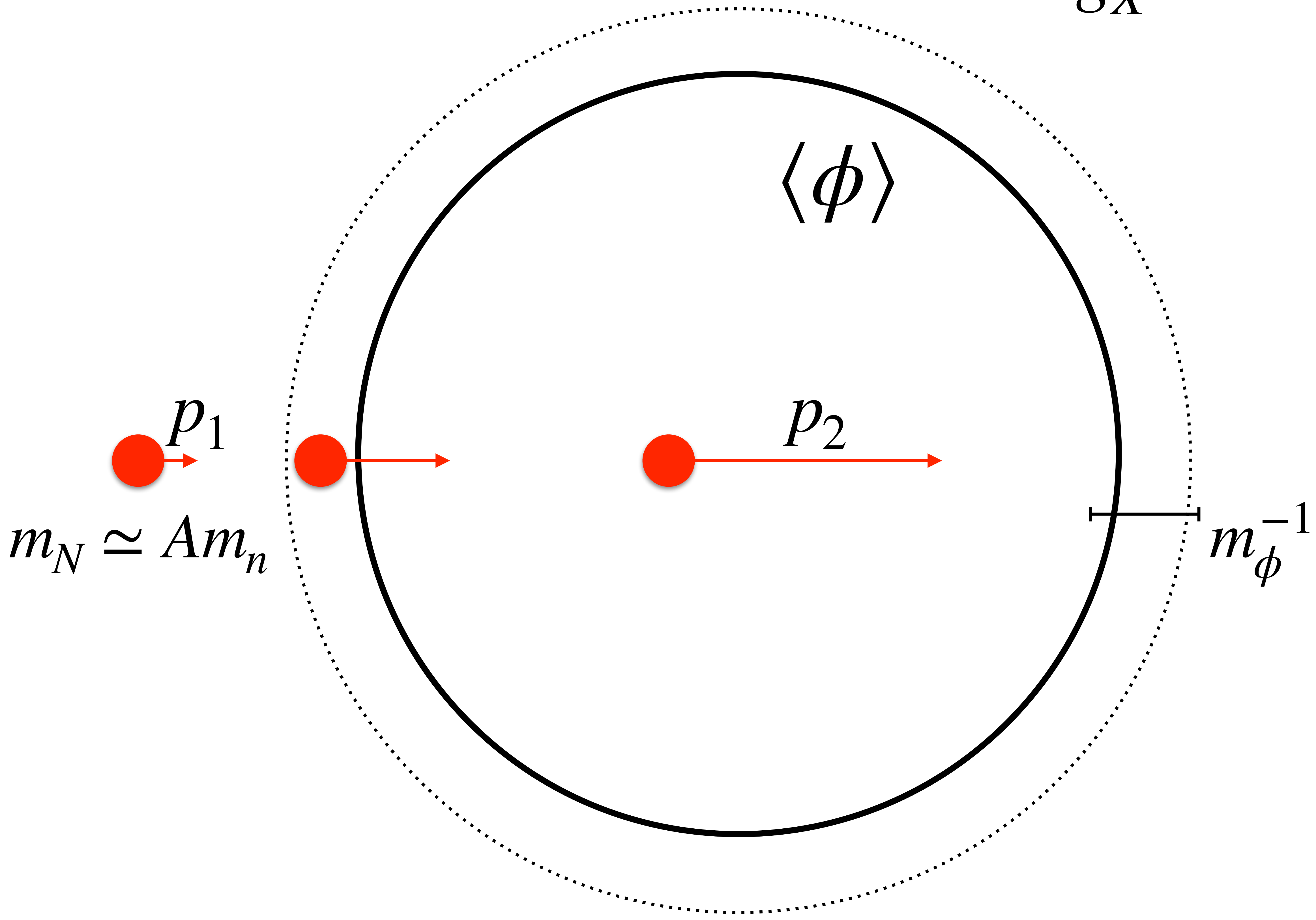


(suppressed for parameters we will consider)

Nuclear coupling

Consider an interaction term with SM nucleons $\mathscr{L} = \mathscr{L}_0 + g_n \bar{n}\phi n$

for large N composite: $\langle\phi\rangle \simeq \dfrac{m_X}{g_X}$



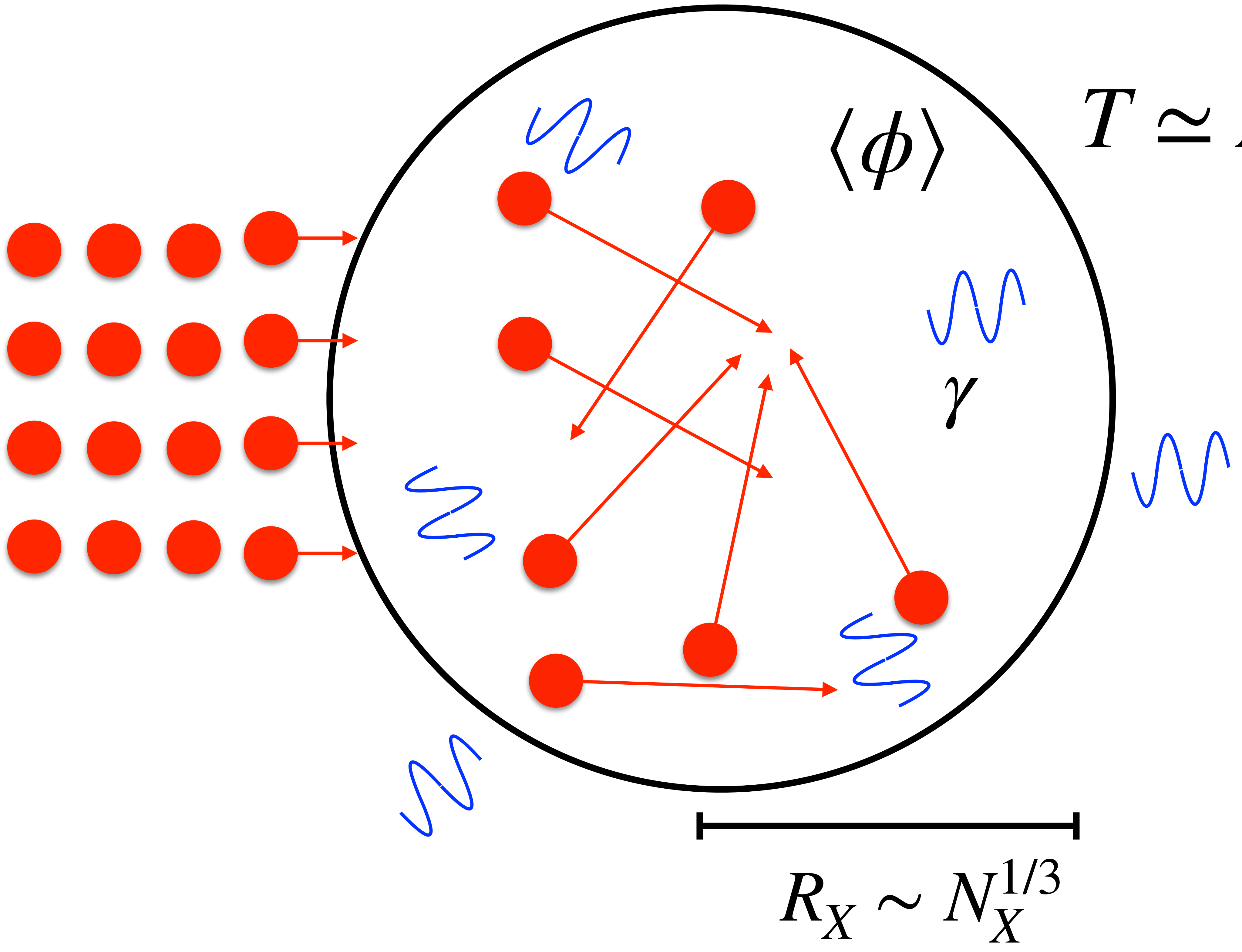
Nuclei will accelerate across the DM composite's boundary layer, because of the attractive potential, like gravity but stronger and shielded:

$$p_1^2 + m_N^2 = p_2^2 + (m_N - A g_n \langle\phi\rangle)^2$$

$$A g_n \langle\phi\rangle = \frac{A g_n m_X}{g_X} = \frac{p_2^2 - p_1^2}{2 m_N}$$

Heated nuclei in composite interior

$\langle\phi\rangle \propto m_X \sim \text{TeV} - \text{EeV}$ acceleration is substantial even for $g_n \ll 1$



$T \simeq A g_n \langle\phi\rangle$

Ionization (Migdal, collisions)

Thermal bremsstrahlung

Thermonuclear fusion

increasing temperature/energy

Potential signatures of this effect?

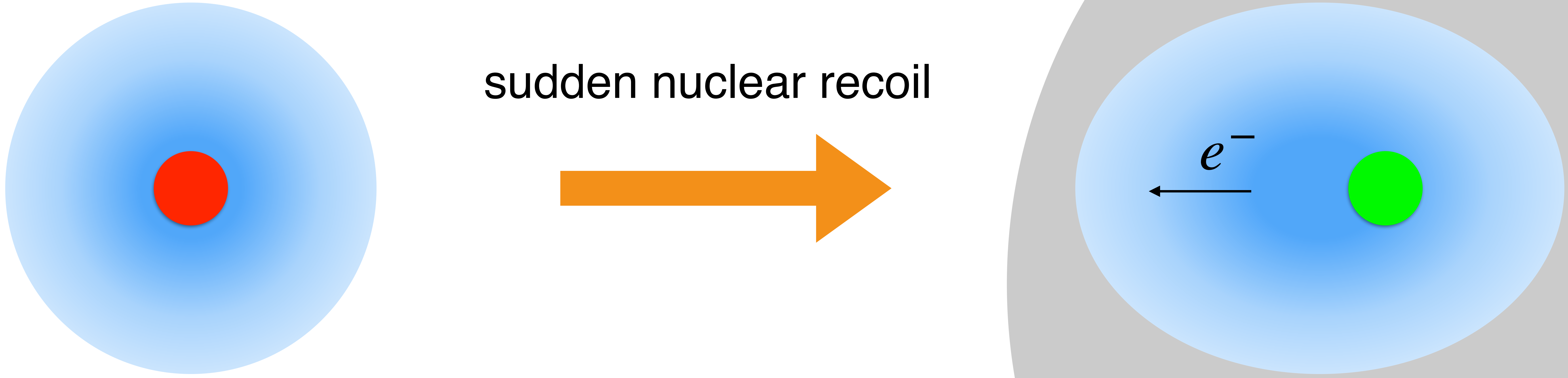
→ Ionizing dark matter

→ Neutrino detectors

→ Type Ia supernovae

Migdal Effect at DD Experiments

$\Delta t_{\text{interact}} \ll \tau_{e^-}\ ,\ R_a/v_N$ Migdal approximation



$$|\psi\rangle \simeq e^{\left(-i m_e \sum_j \mathbf{v}\cdot\hat{\mathbf{x}}_j\right)} |\psi_0\rangle$$

$\tau_{e^-} \sim 10^{-17}\ \text{s}$ electron orbital period

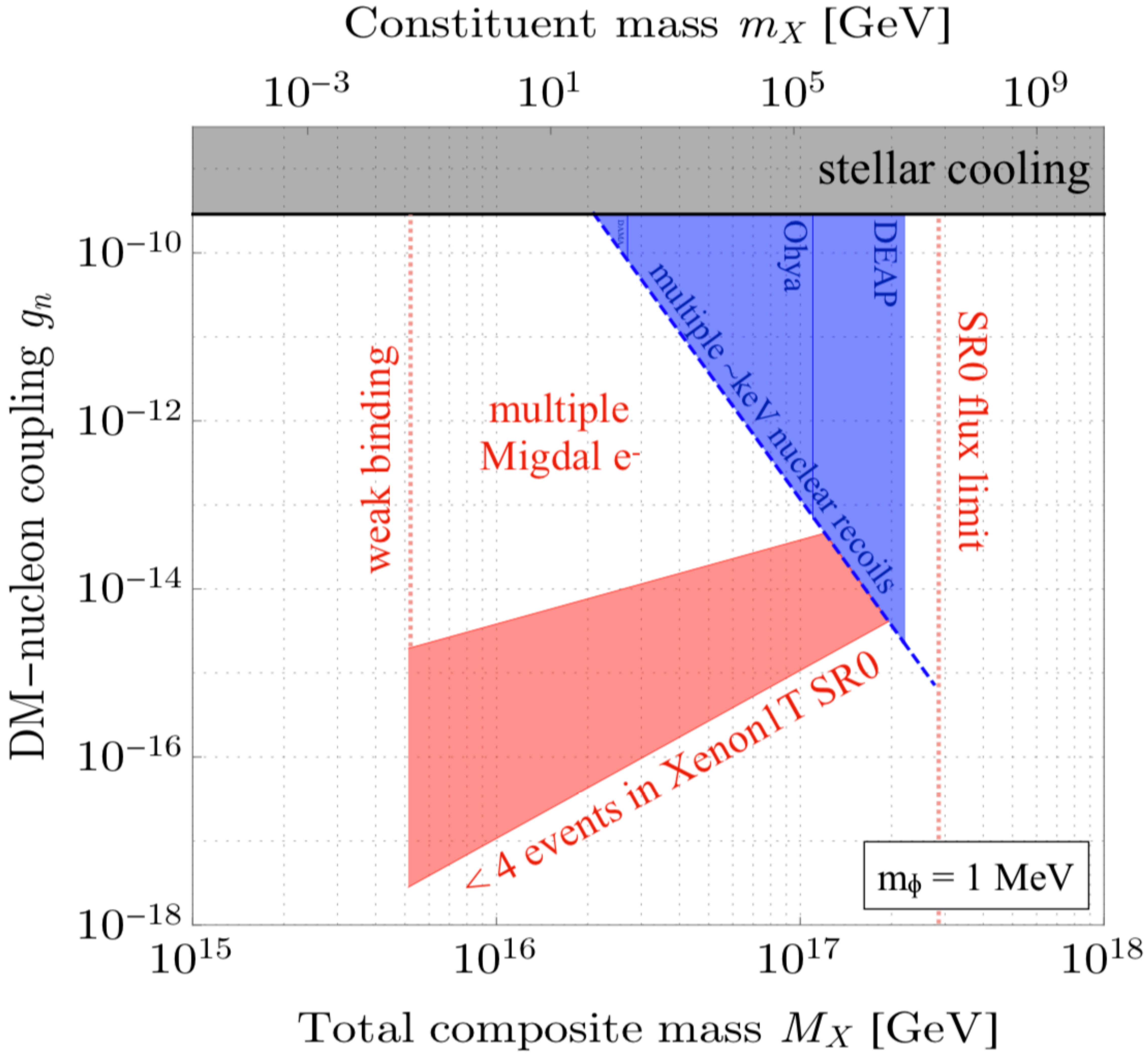
$$\frac{R_a}{v_N} \sim 10^{-15}\ \text{s} \left(\frac{g_n}{10^{-10}}\right)^{-\frac{1}{2}} \left(\frac{m_X}{\text{TeV}}\right)^{-\frac{1}{2}}$$

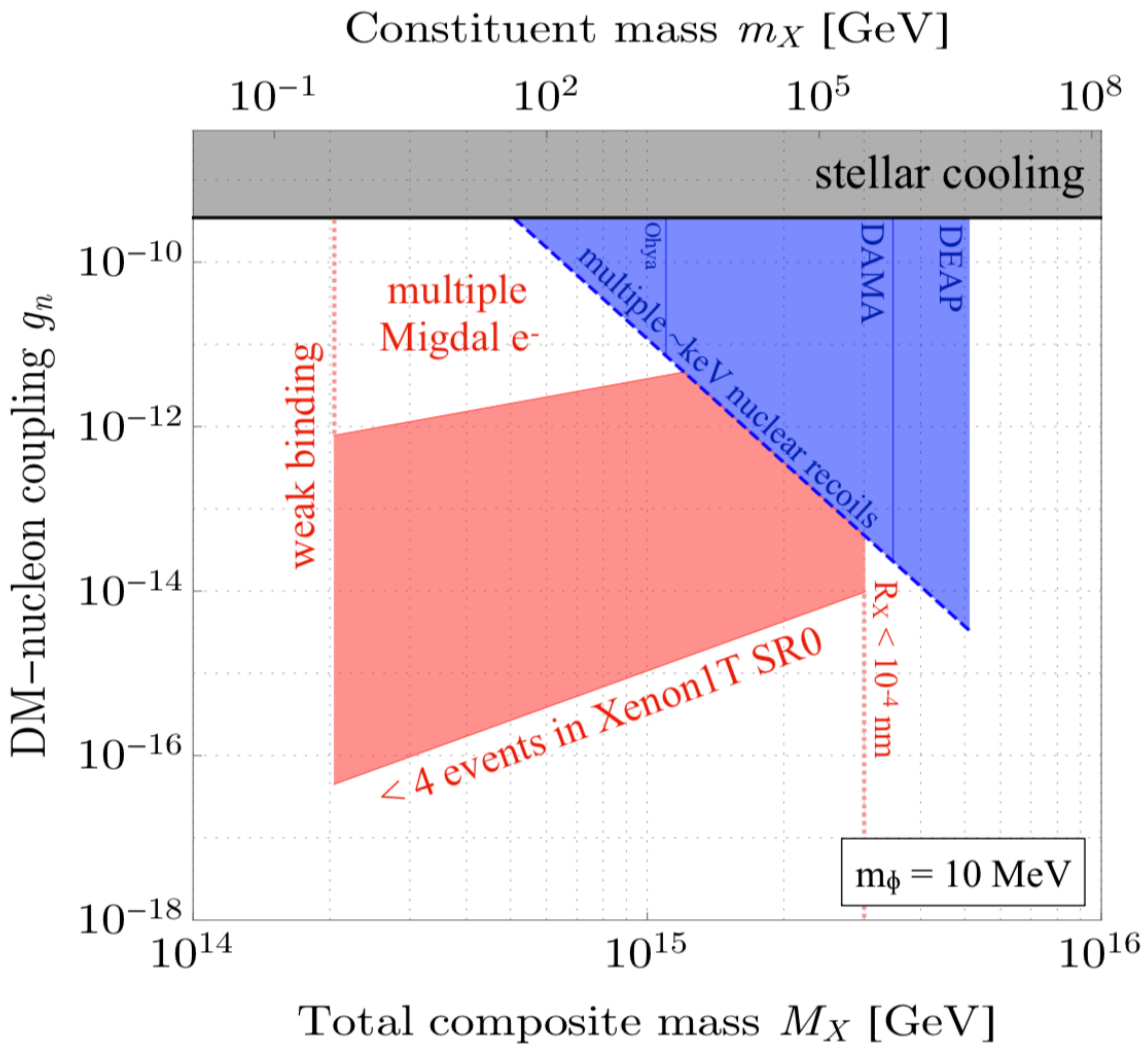
$R_a \sim 10^{-8}\ \text{cm}$

$$\Delta t_{\text{interact}} = \tau_{\text{accel}} \simeq \frac{1}{m_\phi v_X} \simeq 10^{-19}\ \text{s} \left(\frac{m_\phi}{\text{MeV}}\right)^{-1} \ll \tau_{e^-}$$

Migdal Bounds

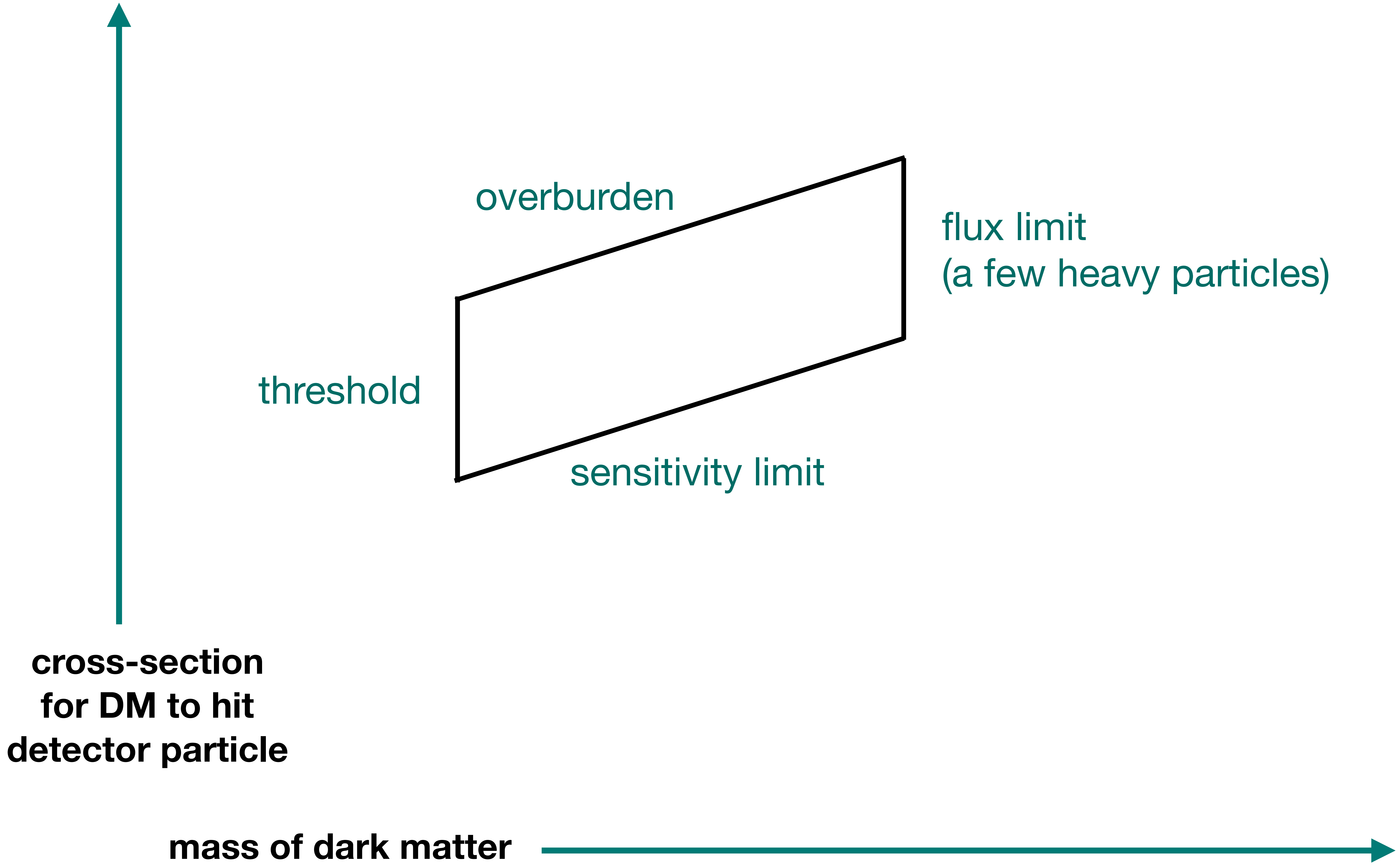
Composite masses/radii determined by m_X, cosmology with $\alpha_X = 0.3$



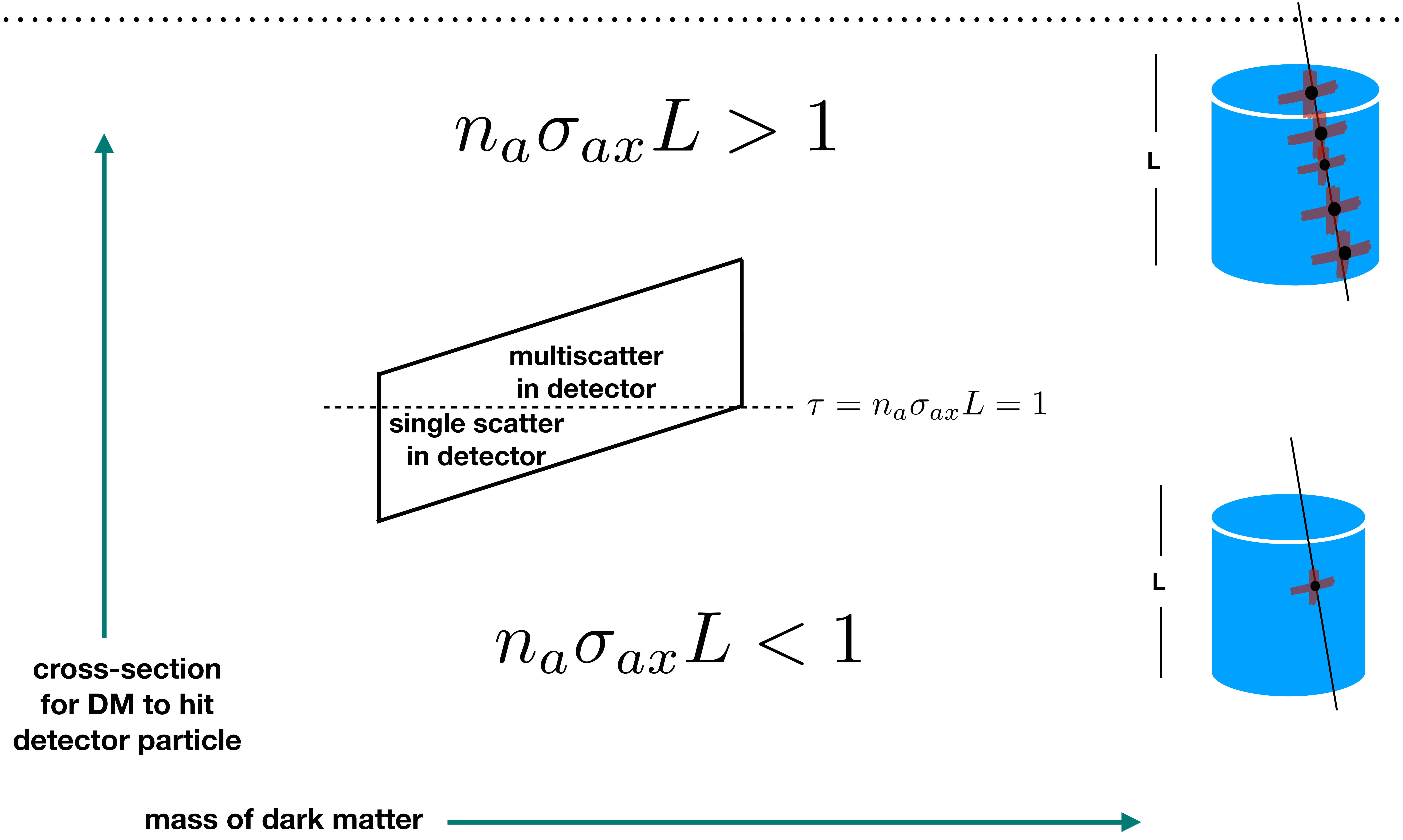


Acevedo, JB, Goodman, 2108.10889

Multiscatter dark matter detection

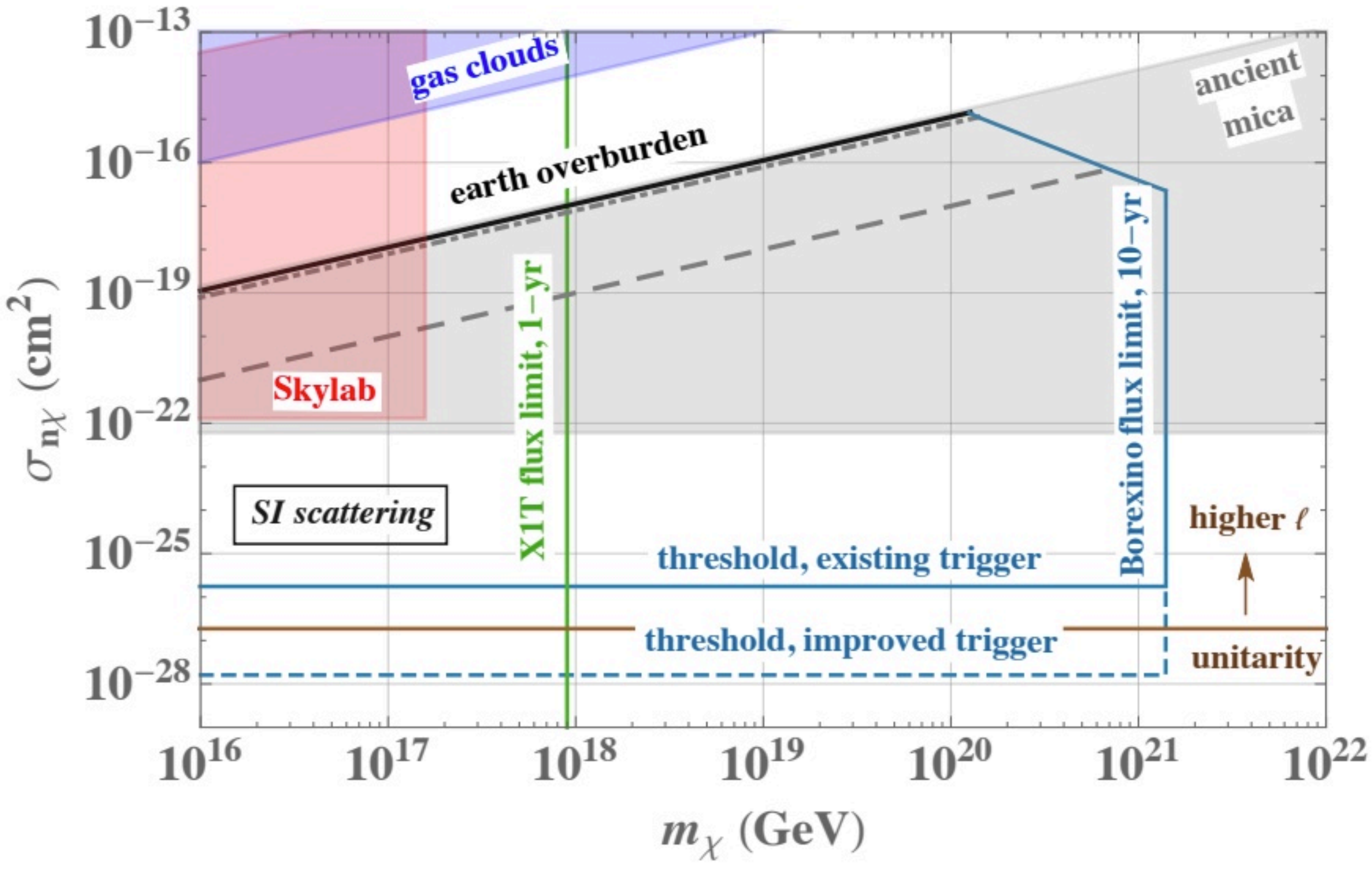


Multiscatter dark matter detection



Underground multiscatter prospects

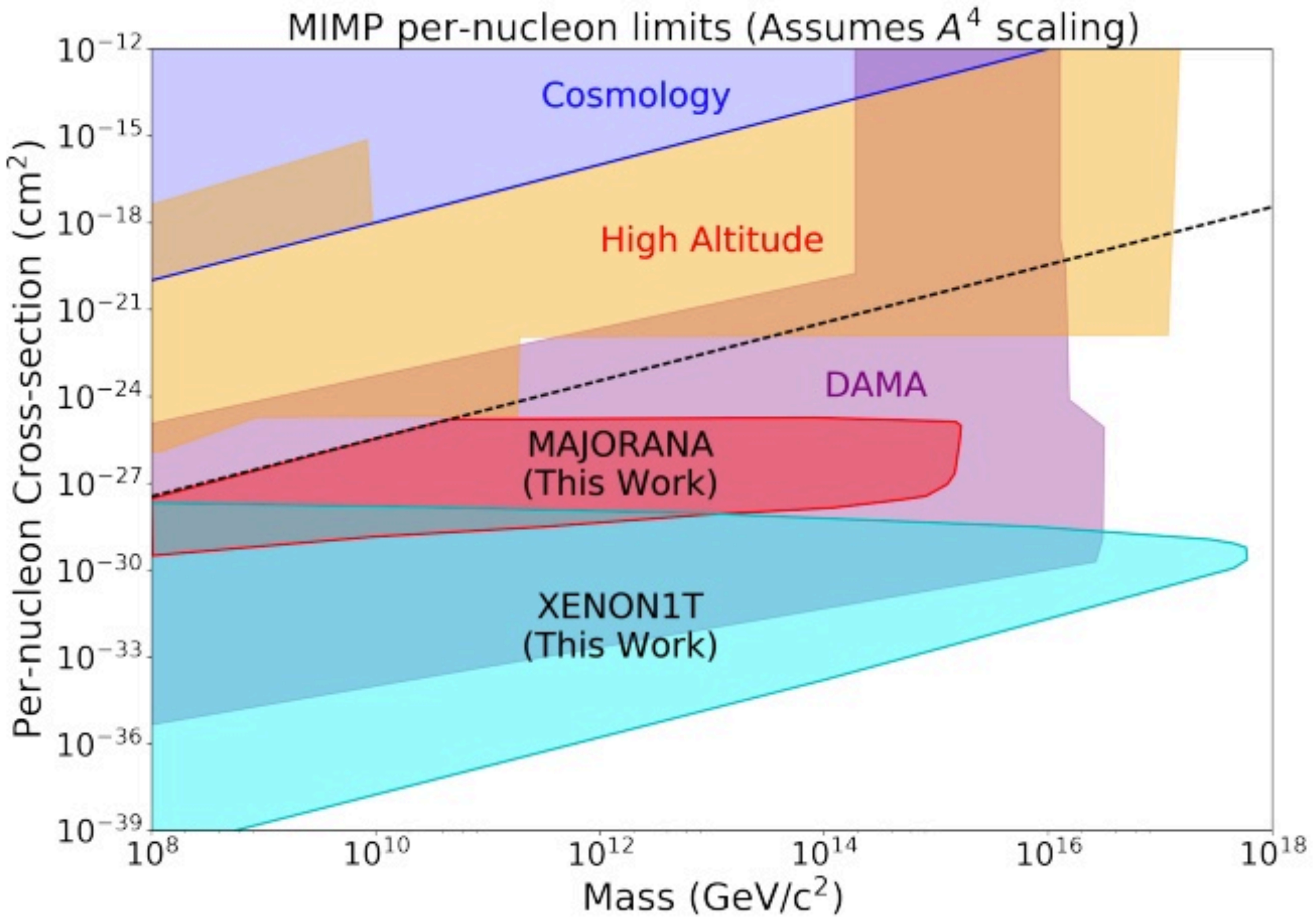
Scintillating Neutrino Detectors



JB Broerman Kumar Lang Pospelov Raj 1812.09325

1803.08044 1910.05380

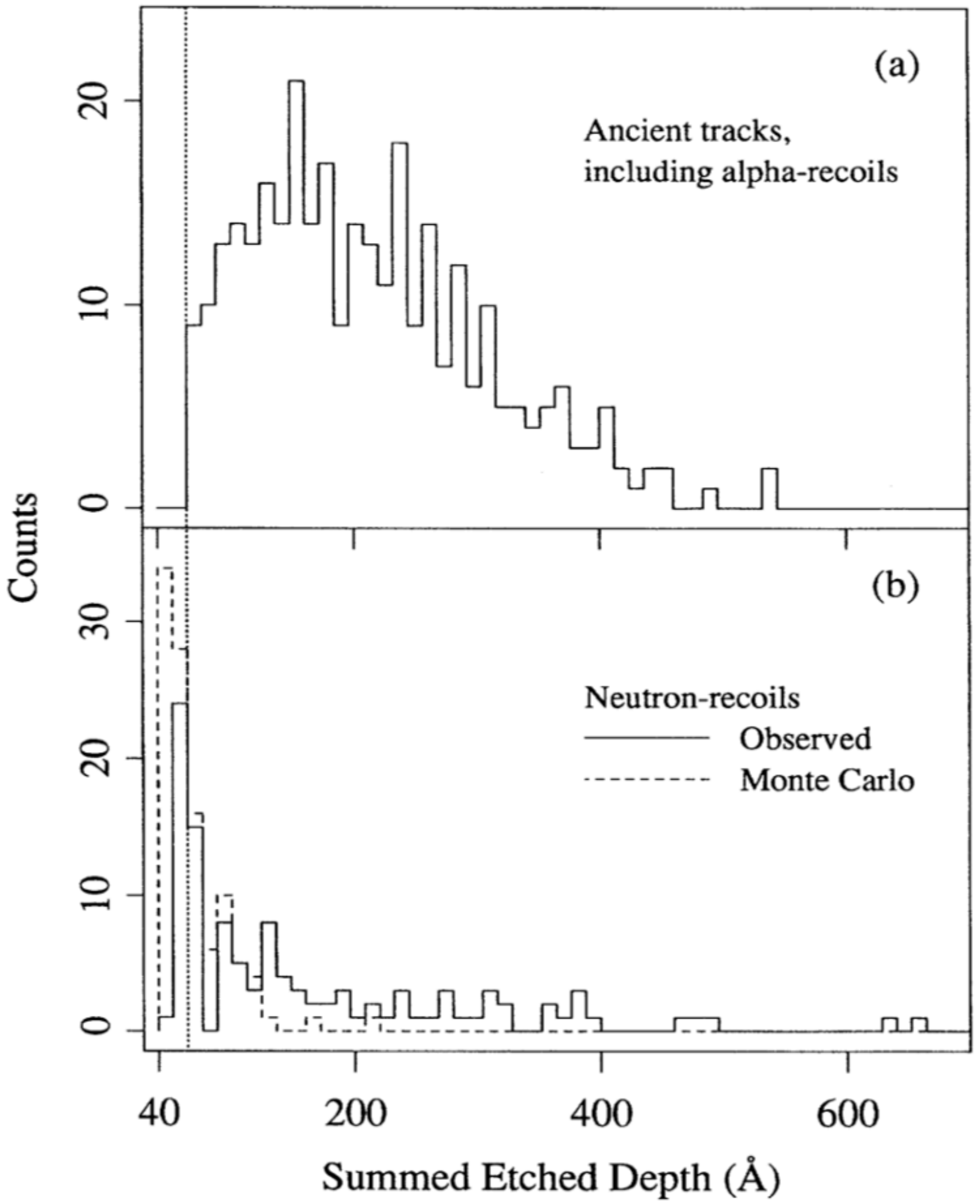
Underground Multiscatter Searches

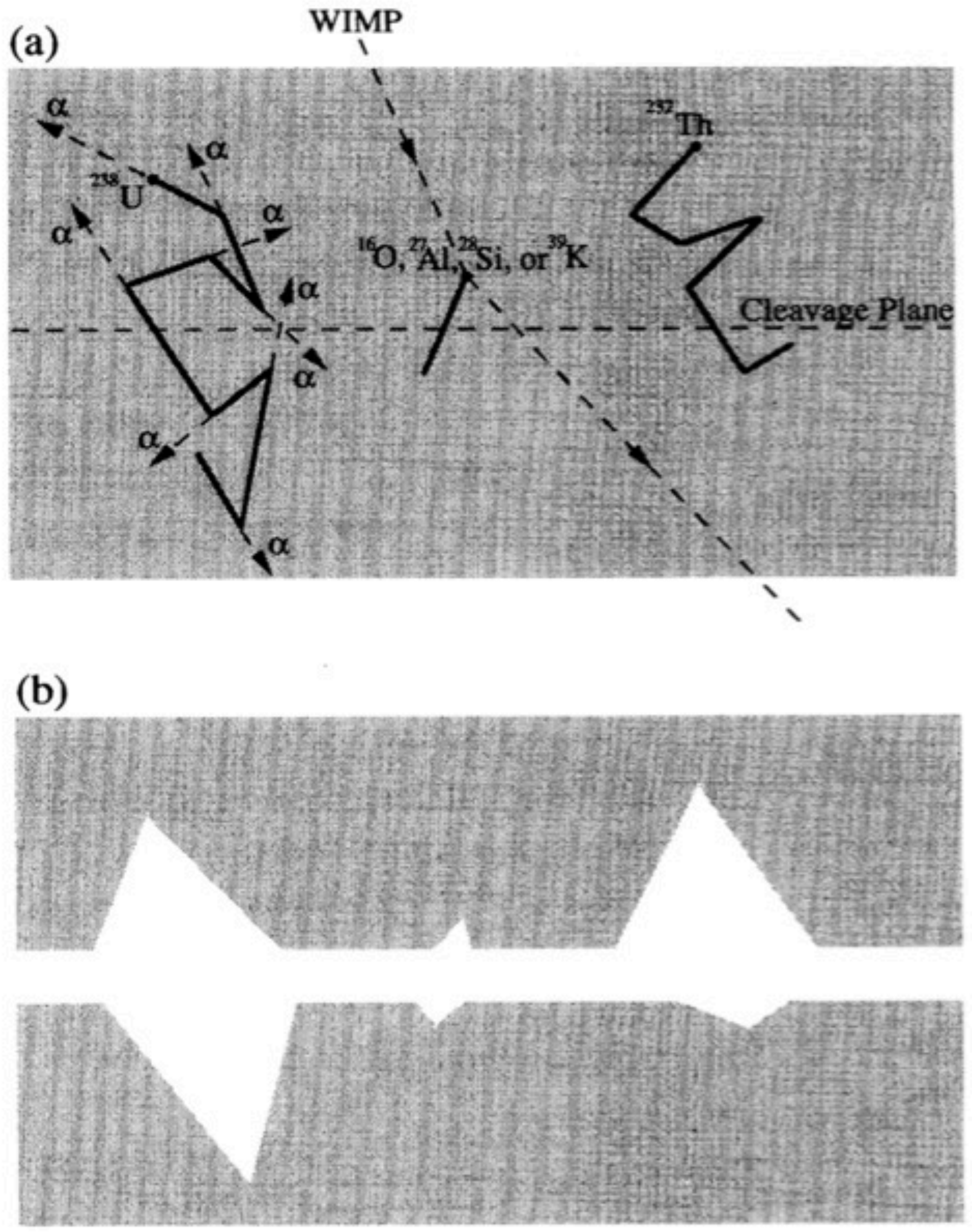


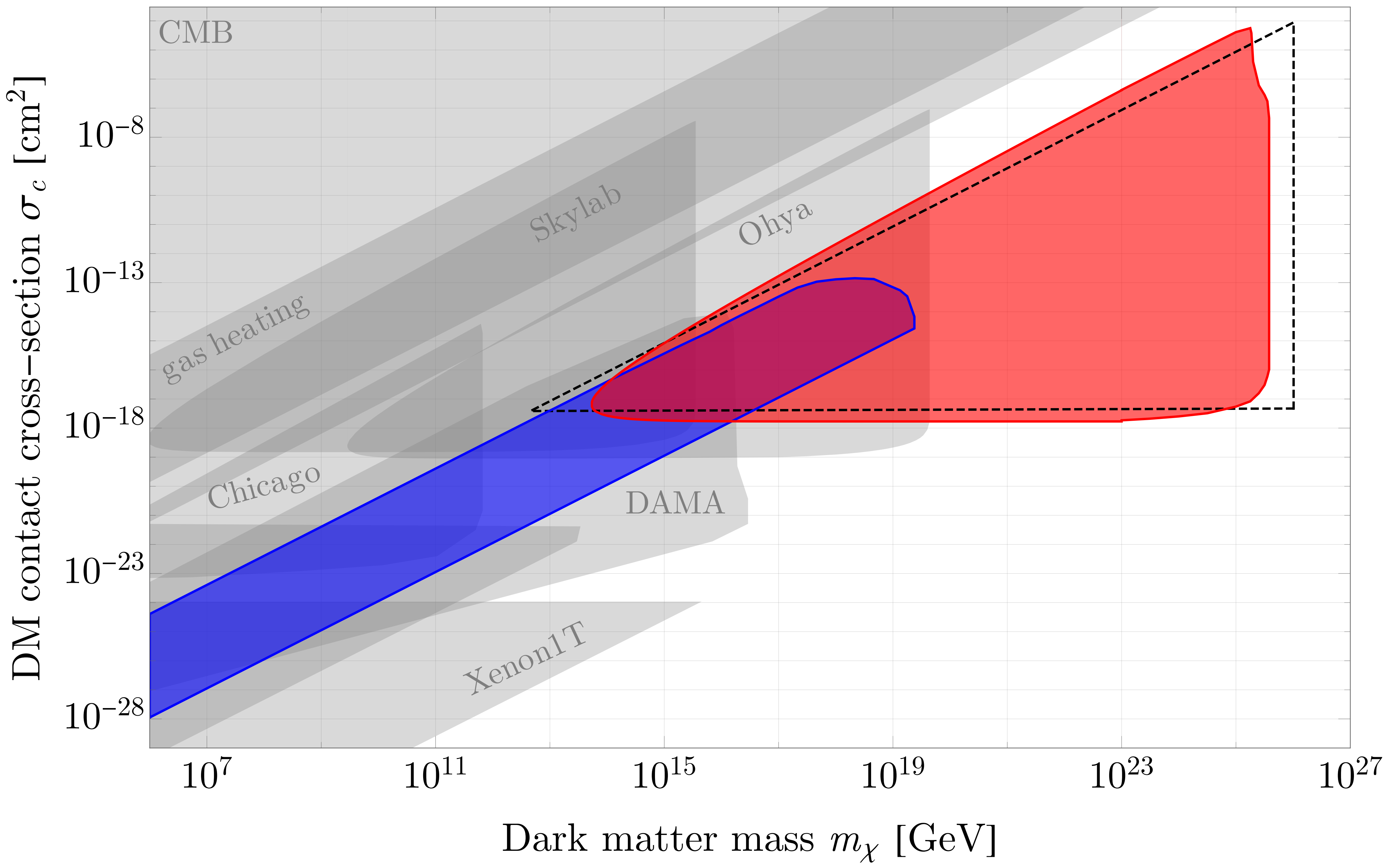
Ongoing work at PICO, XENON1T

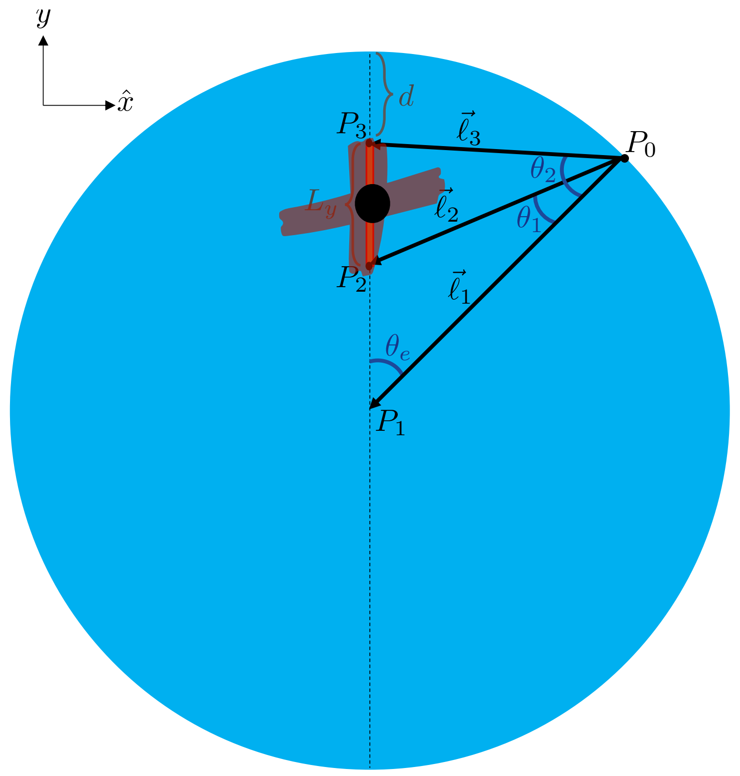
2009.07909

Ancient search for new particles: mica









- Calibrated and etched mica samples from Price 1986, Snowden-Ifft 1995
- Reanalyzed mica data using overburden

Acevedo, JB, Goodman 2105.06473
Bhoonah, JB, Courtman Song 2012.13406

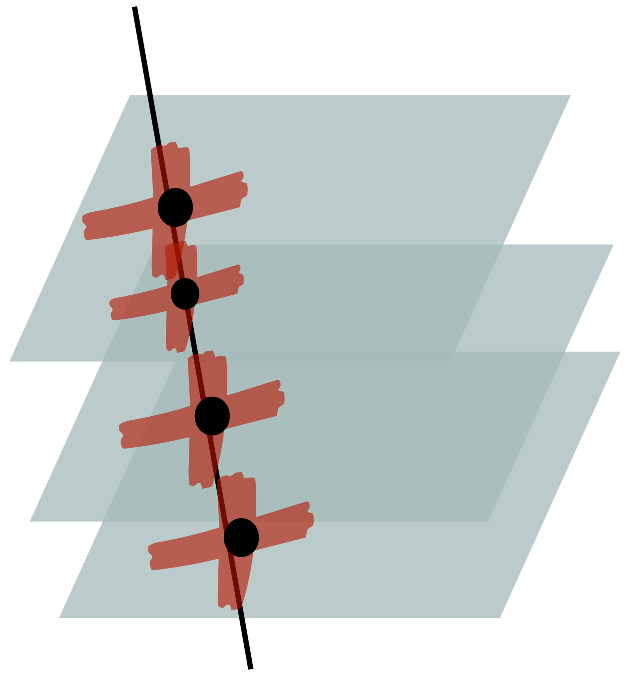
ETCHING PLASTIC SEARCHES FOR DARK MATTER

- *Two searches in 1978 and 1990 for cosmic rays and monopoles using acid-etched plastic track detectors*
- *Still have best sensitivity for some high mass dark matter, for different reasons*

Skylab

	Skylab	Ohya
Area A	1.17 m^2	2442 m^2
Duration t	0.70 yr	2.1 yr
Zenith cutoff angle	$\theta_D = 60°$	$\theta_D = 18.4°$
Detector material	0.25 mm thick Lexan × 32 sheets	1.59 mm thick CR-39 × 4 sheets
Detector density	1.2 g cm^{-3} Lexan	1.3 g cm^{-3} CR-39
Detector length at θ_D	1.6 cm	0.66 cm
Overburden density	2.7 g cm^{-3} Aluminum	2.7 g cm^{-3} Rock
Overburden length at θ_D	0.74 cm	39 m

Bhoonah, JB, Courtman, Song
2012.13406



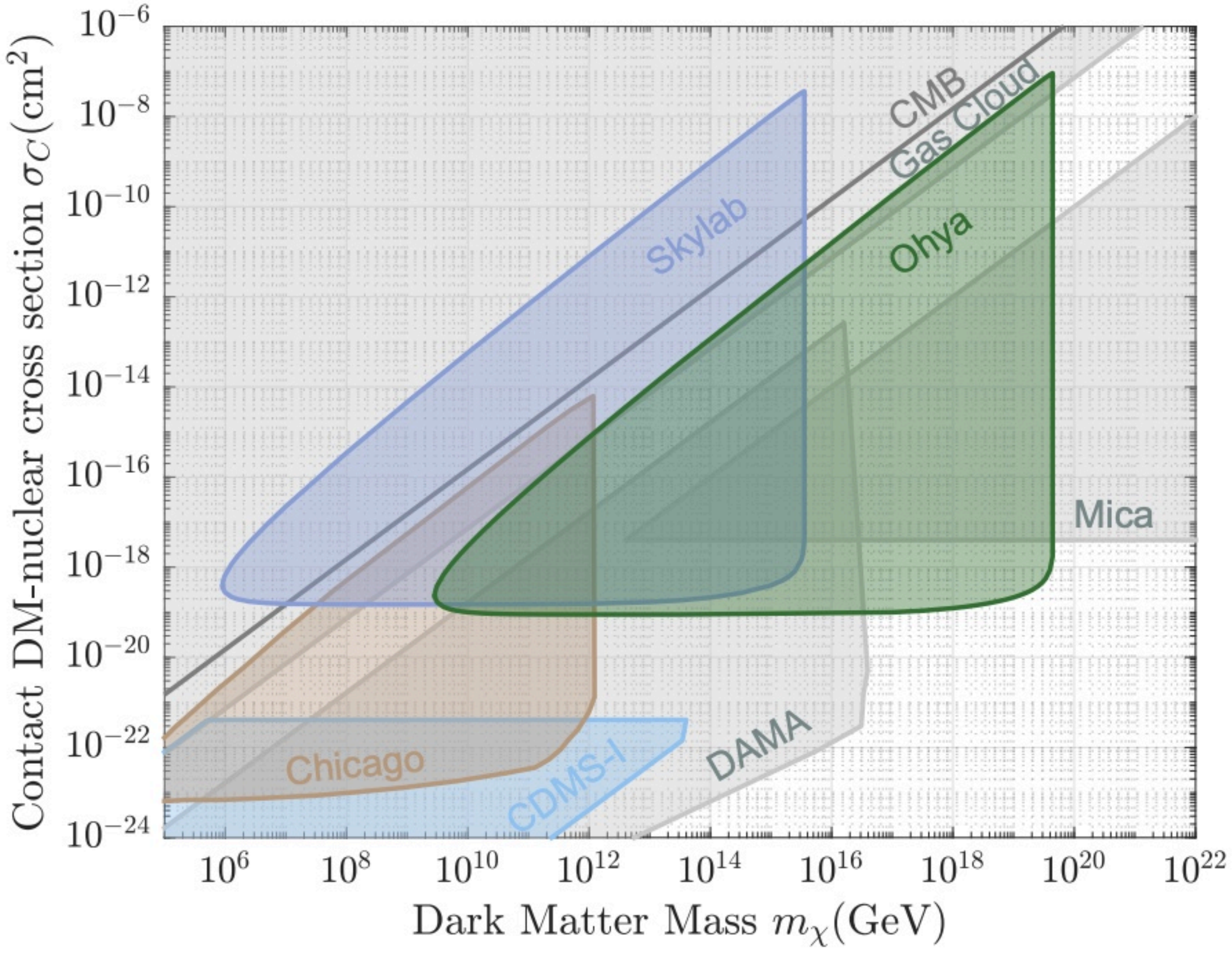
Ohya Quarry

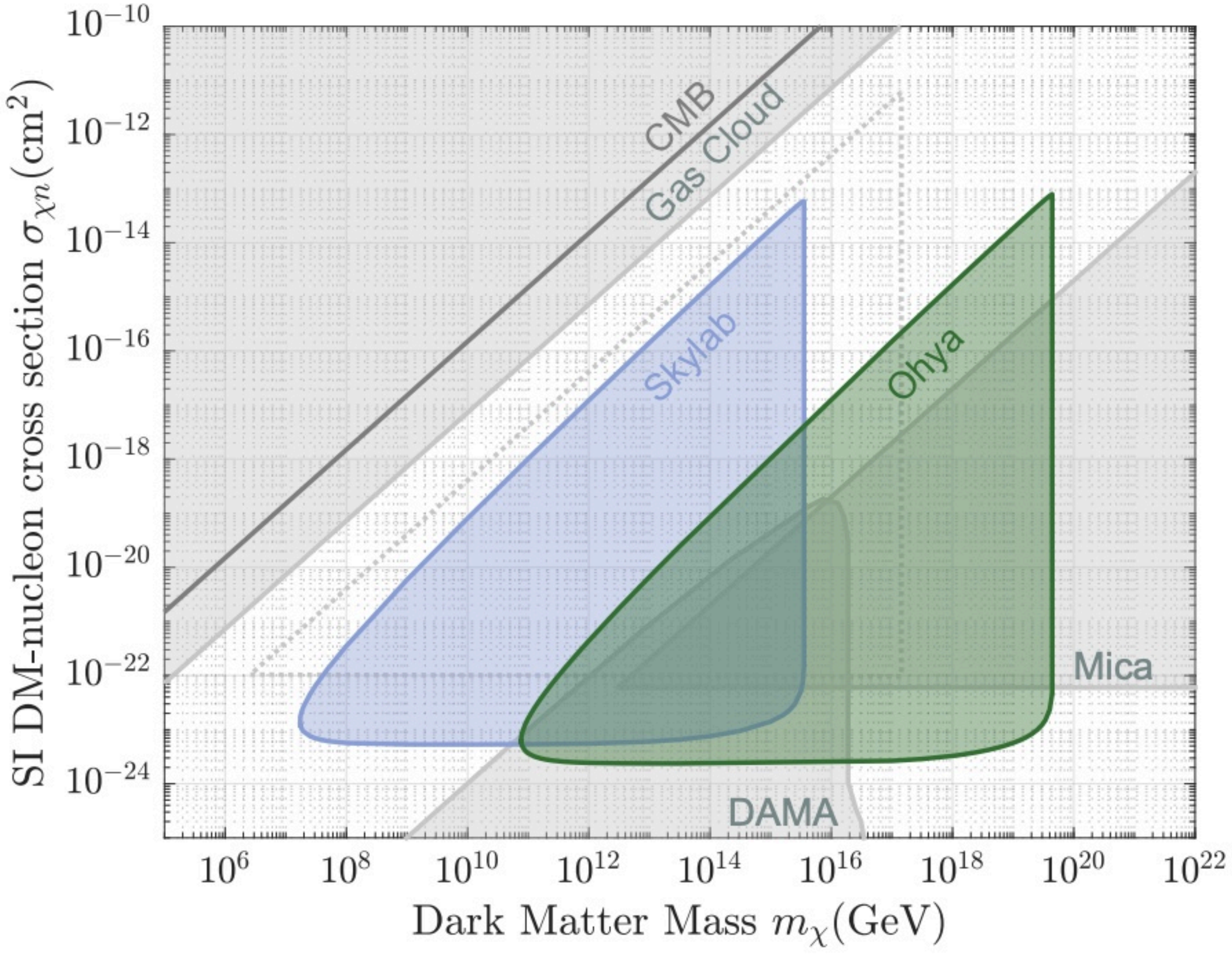
(see also Starkman, Gould, Esmailzadeh Dimopoulos 1990)

ETCHING PLASTIC SEARCHES FOR DARK MATTER

- *Use realistic dark matter density and velocity distribution, solve for overburden+etching sensitivity*

$$\left.\frac{dE}{dx}\right|_{th} = \frac{2E_i}{m_\chi}\left(\sum_{A\subset O}\frac{\mu_{\chi A}^2}{m_A}n_A\sigma_{\chi A}\right)\exp\left[\frac{-2}{m_\chi}\left(x_O\sum_{A\subset O}n_A\frac{\mu_{\chi A}^2}{m_A}\sigma_{\chi A}+x_D\sum_{A\subset D}n_A\frac{\mu_{\chi A}^2}{m_A}\sigma_{\chi A}\right)\right]$$

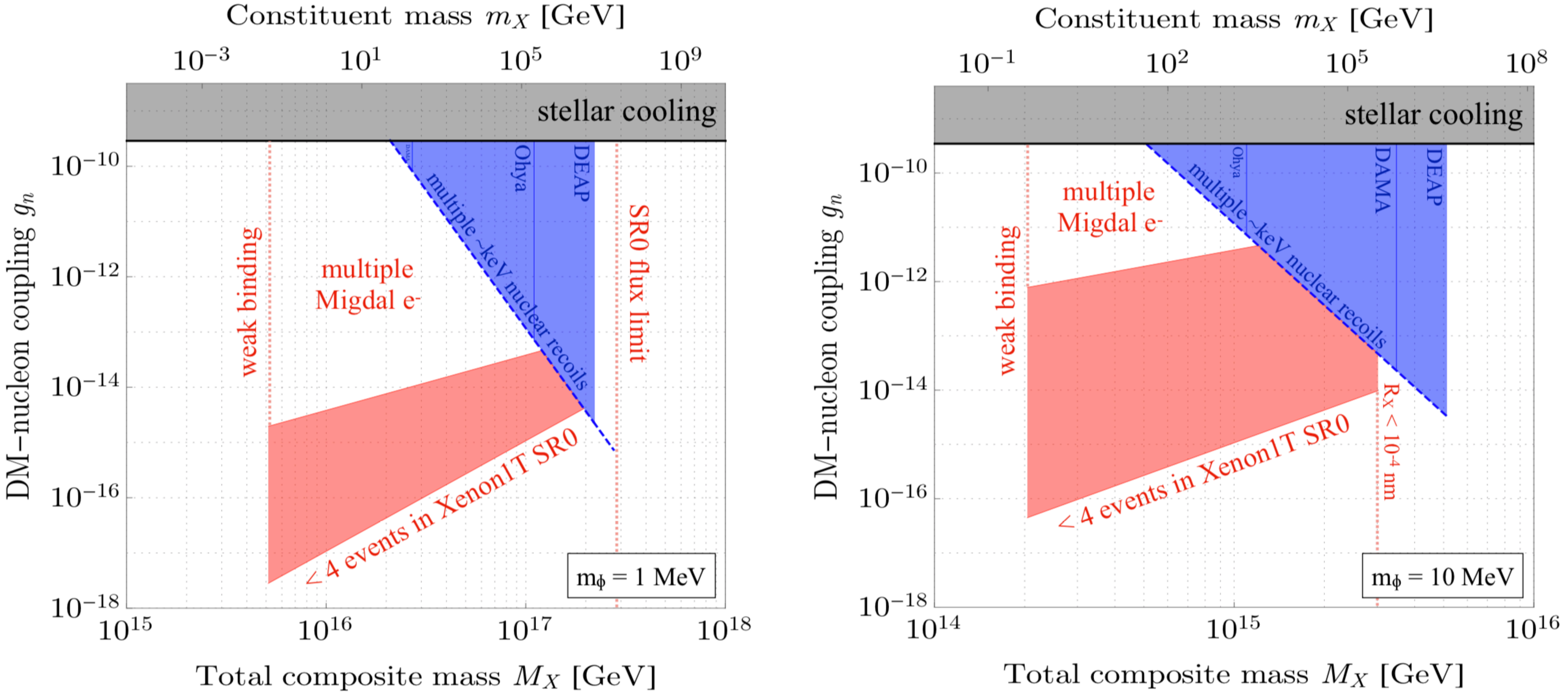




Bhoonah, JB, Courtman, Song 2012.13406

Migdal Bounds

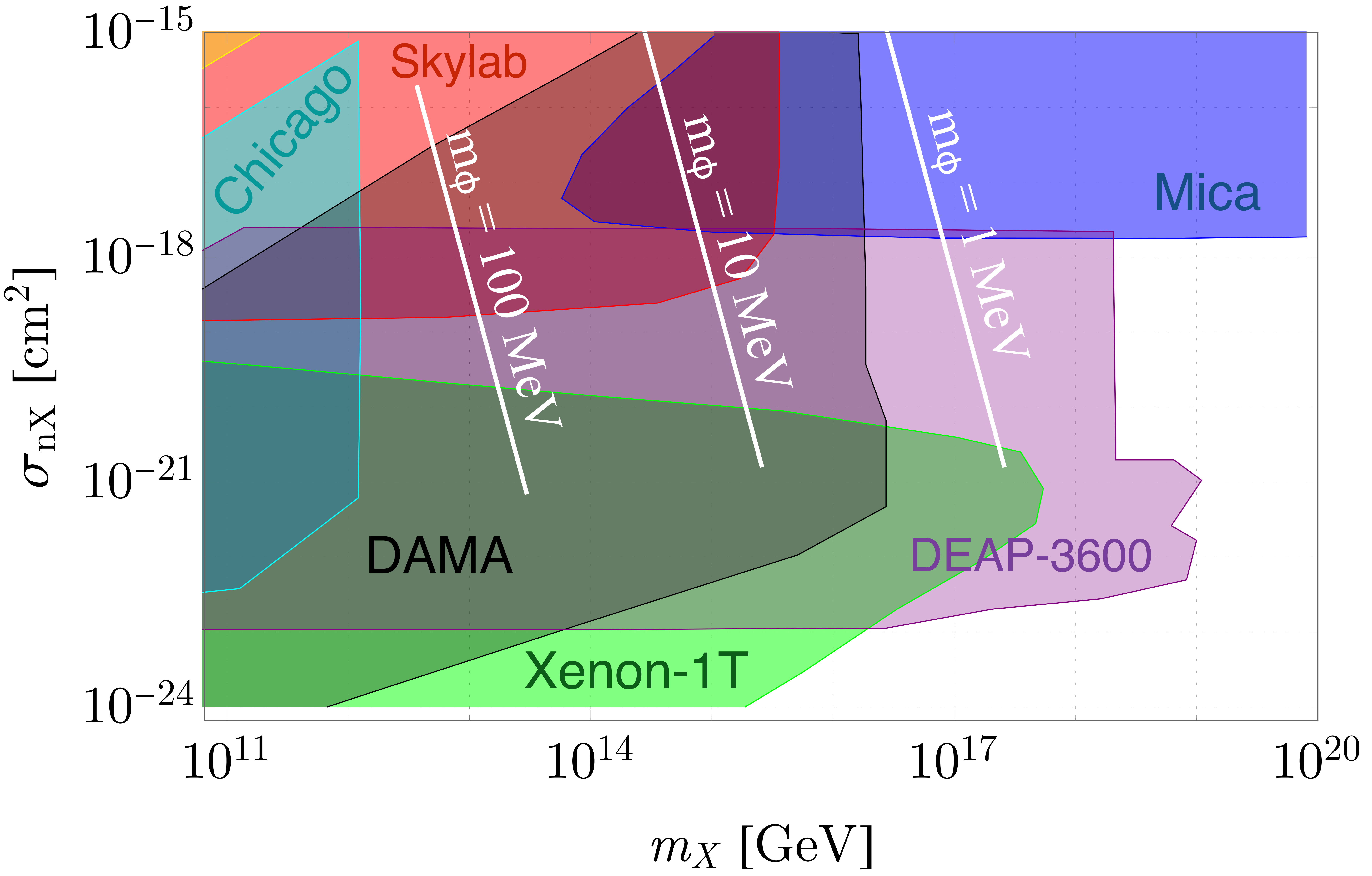
Composite masses/radii determined by m_X, cosmology with $\alpha_X = 0.3$



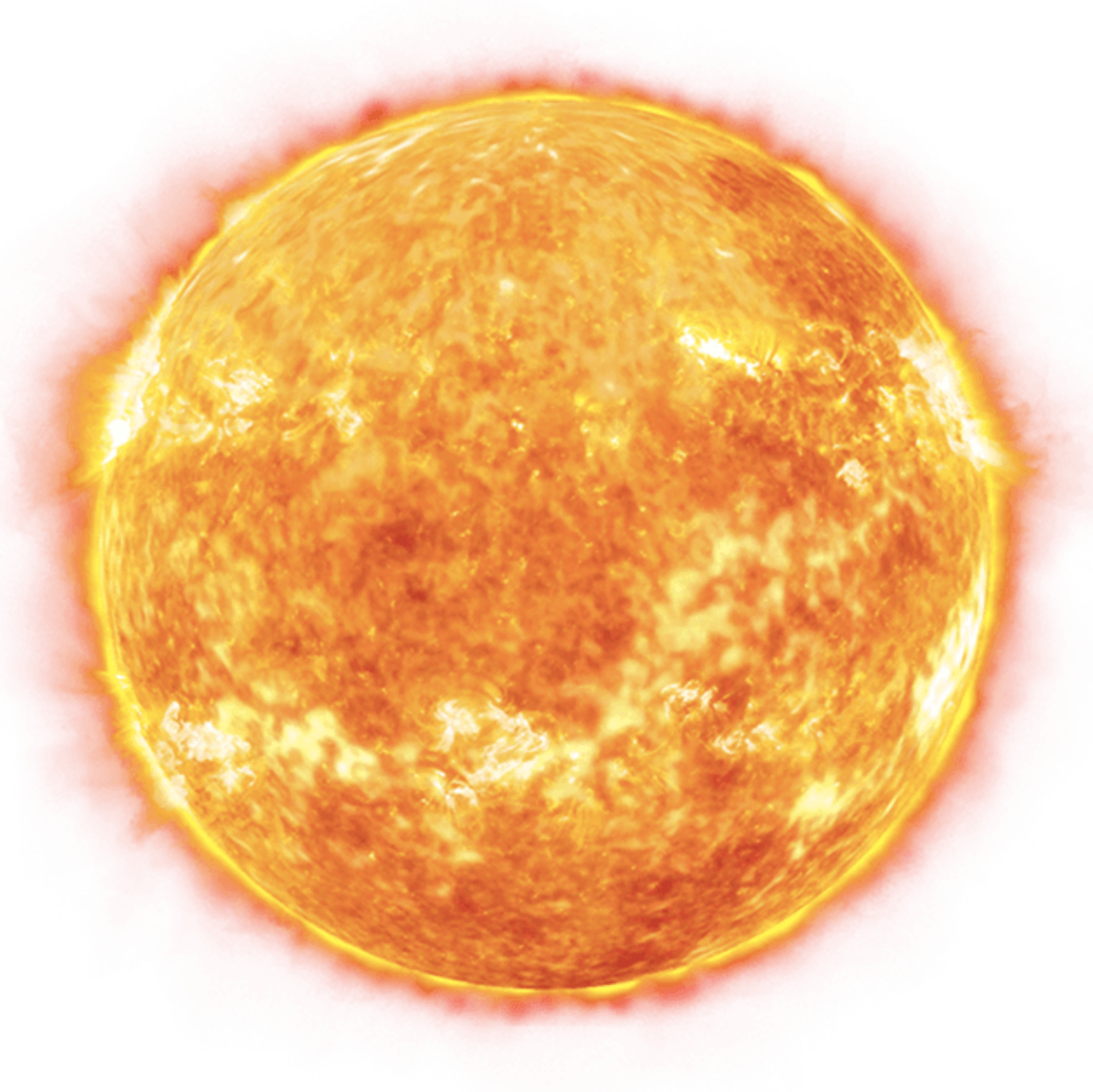
Acevedo, JB, Goodman, 2108.10889

Acevedo, **JB**, Goodman, 2105.06473
Adhikari et. al., DEAP collaboration, 2108.09405

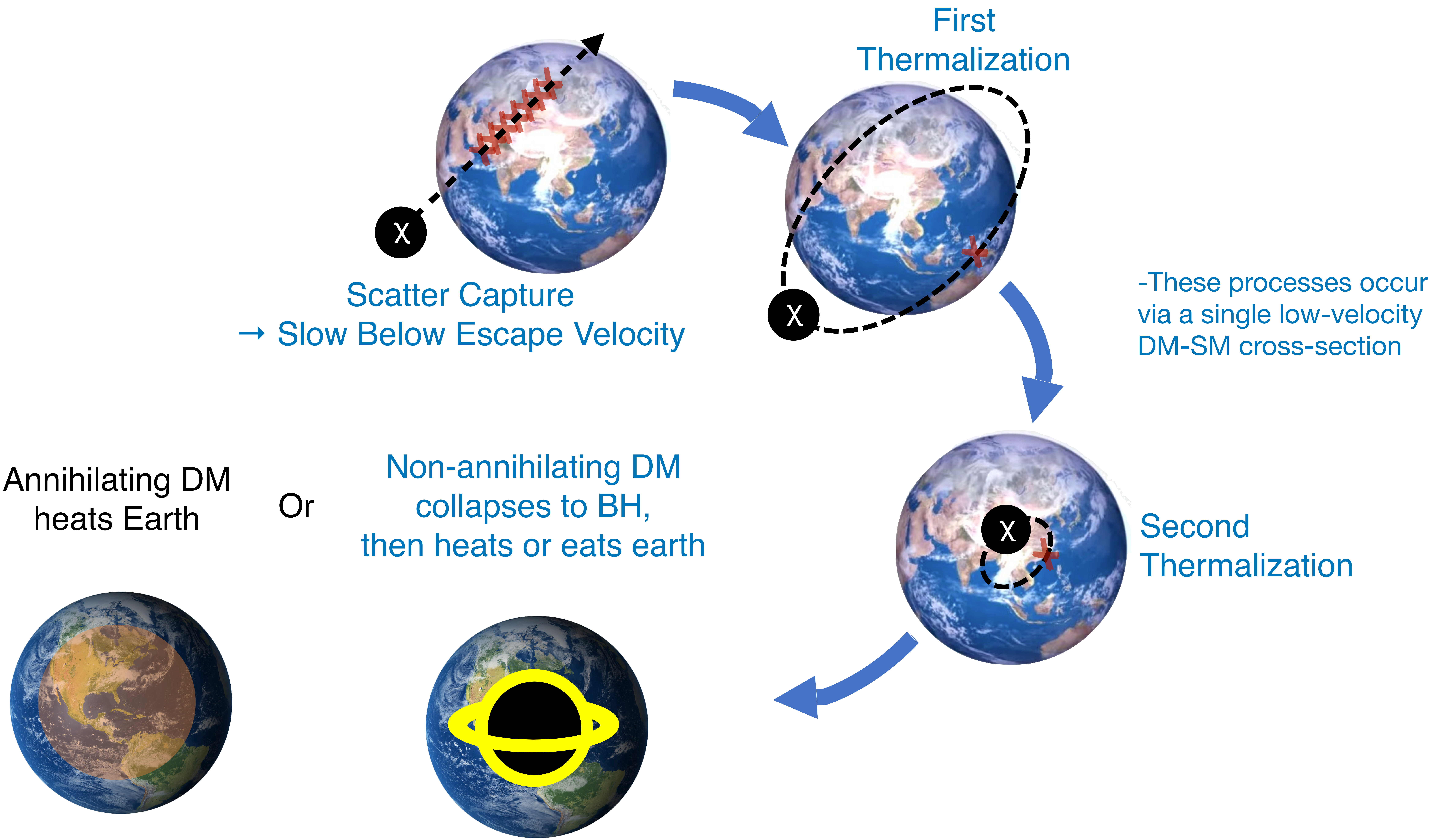
Summary of experimental bounds:

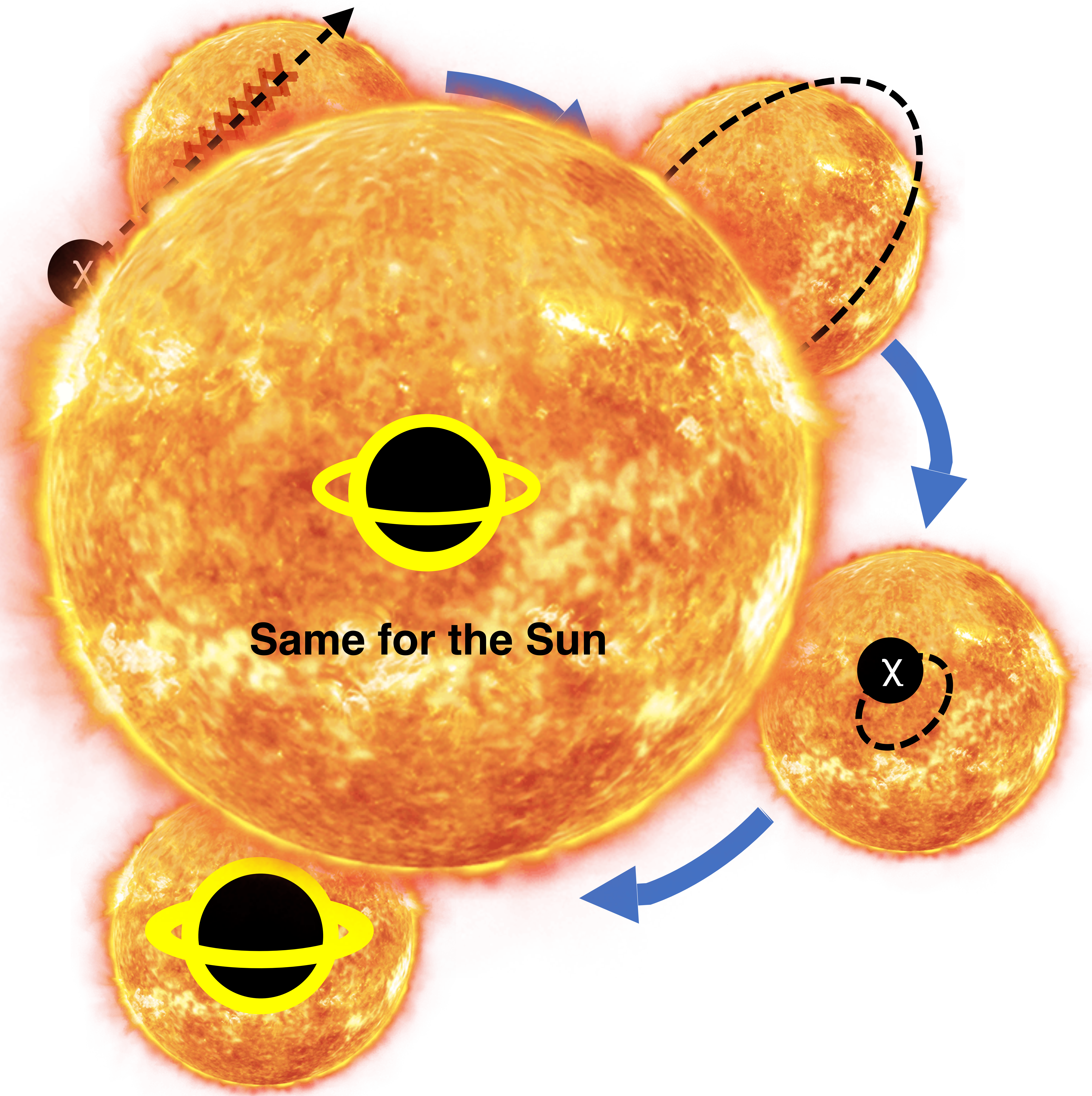


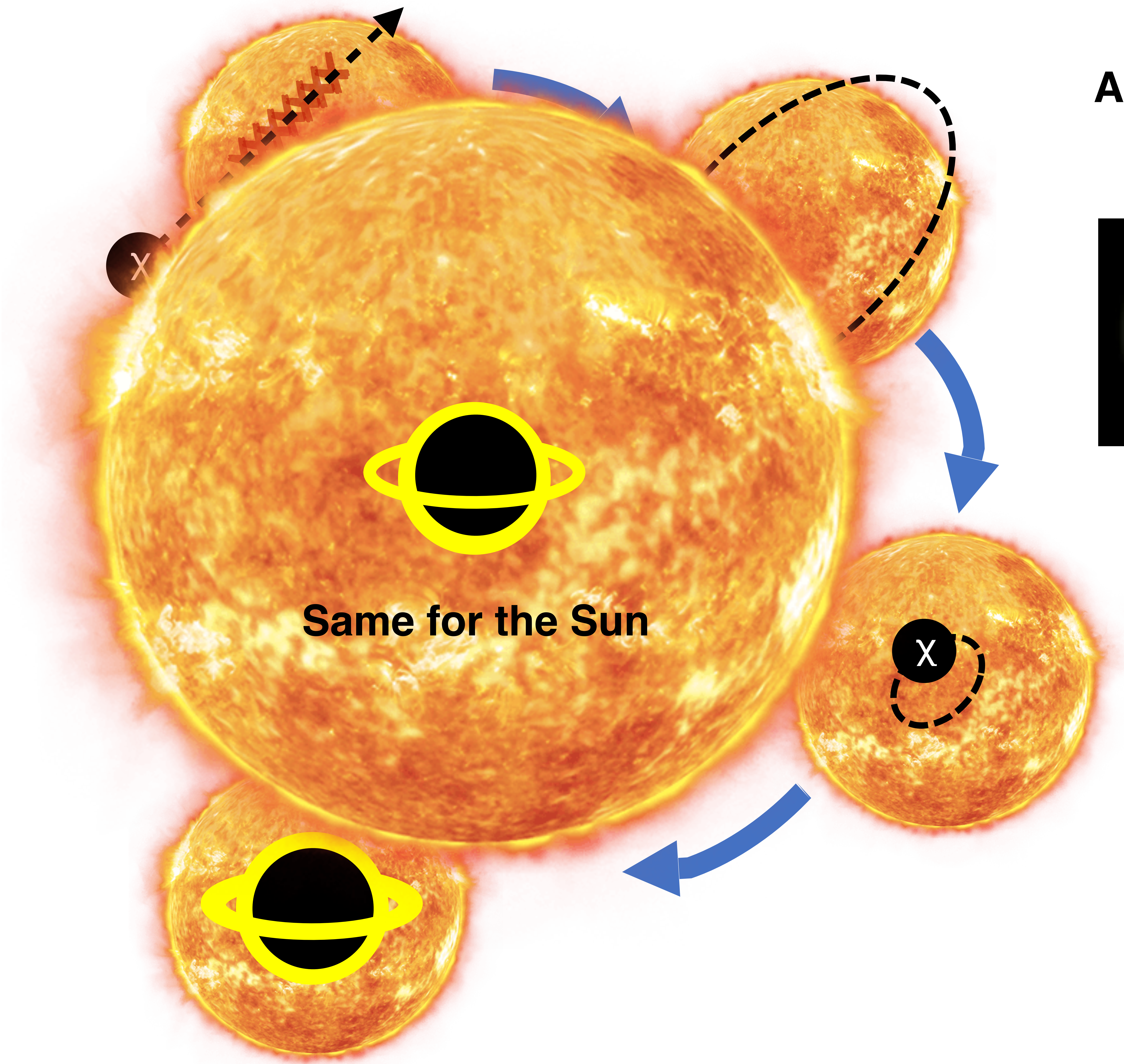
Stars and Planets As Dark Matter Detectors



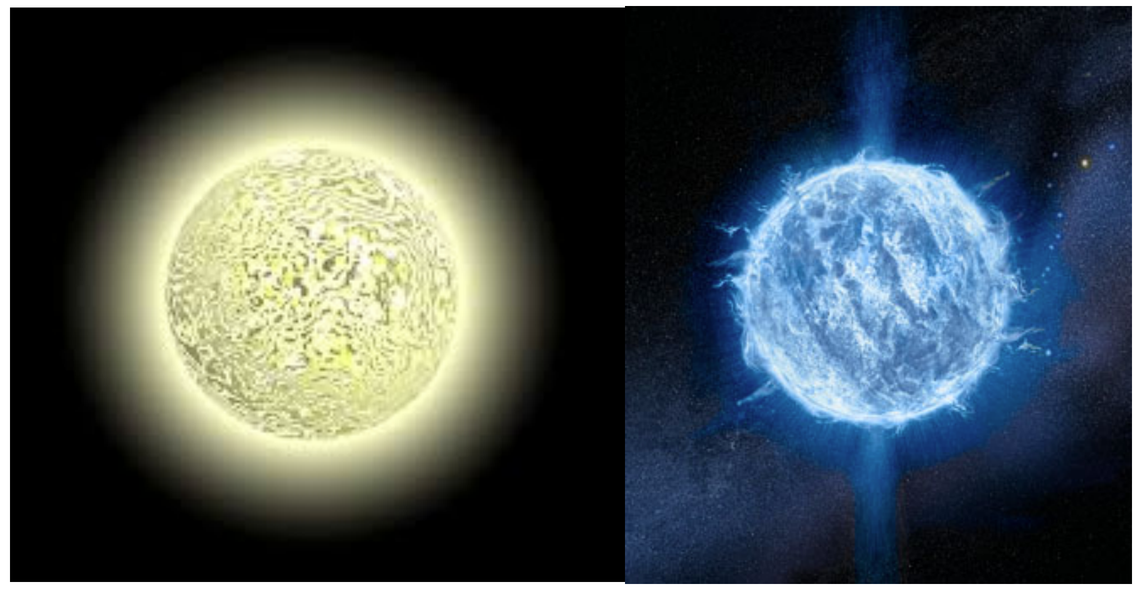
Acevedo, JB, Goodman, Kopp, Opferkuch 2012.09176
1909.11683
1405.1031
1505.07464
1904.11993

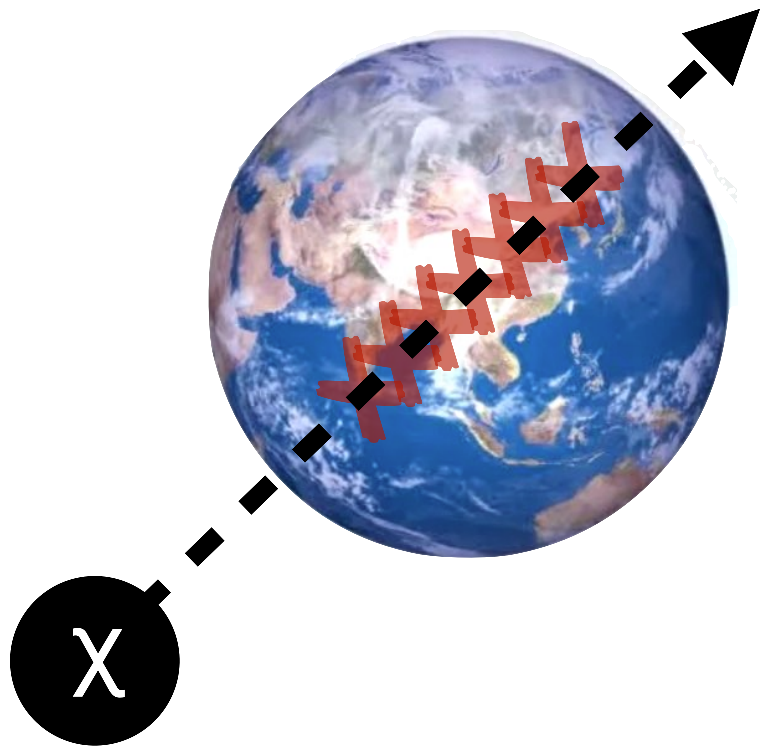

First
Thermalization
X
Scatter Capture
→ Slow Below Escape Velocity
X
-These processes occur
via a single low-velocity
DM-SM cross-section
X
Second
Thermalization
Annihilating DM
heats Earth
Or
Non-annihilating DM
collapses to BH,
then heats or eats earth


X
Same for the Sun
X



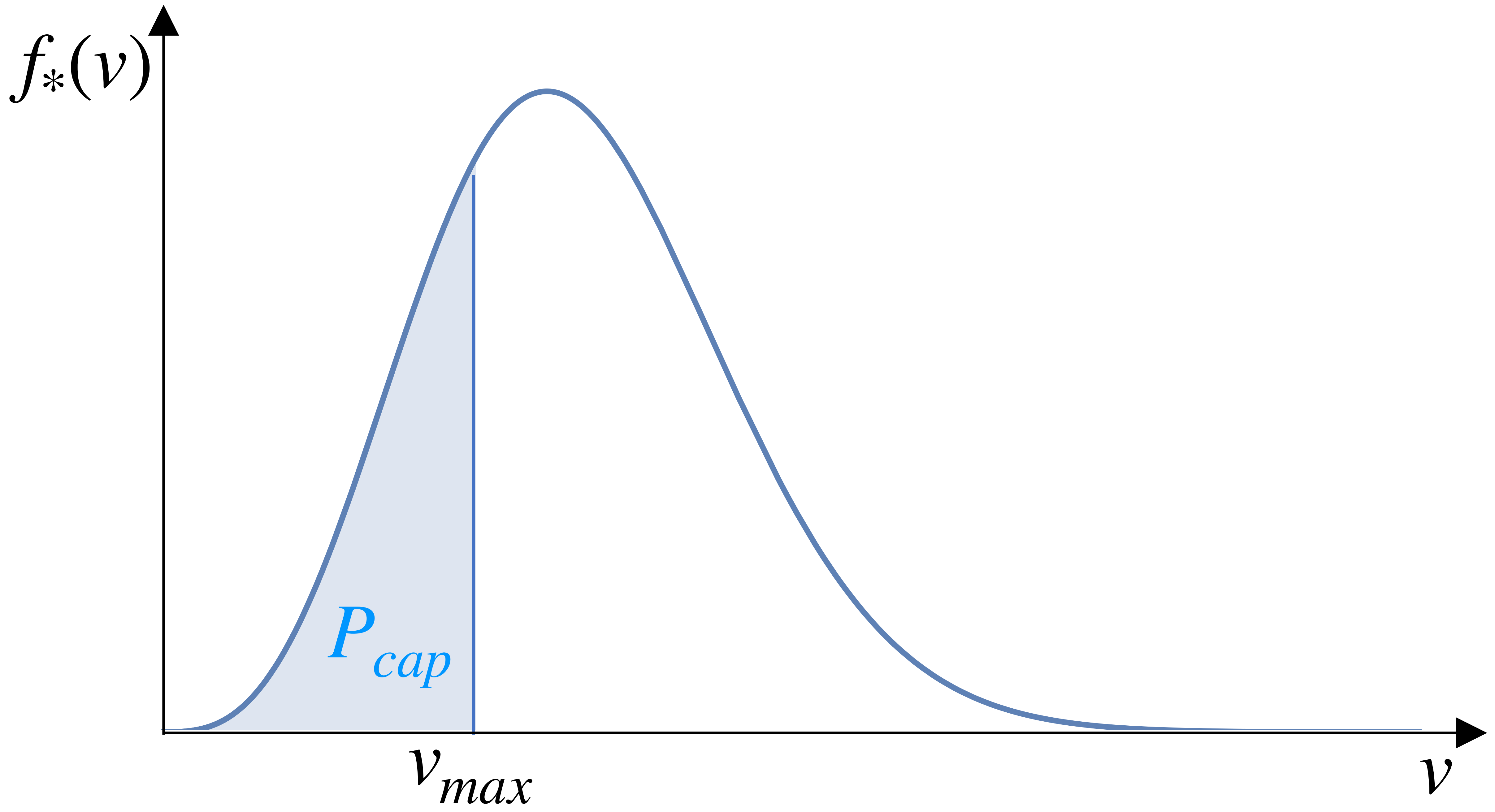
And White Dwarfs and Neutron stars





Scatter Capture

For high mass DM, need proper Earth frame DM distribution, since capture is often dominated by low-velocity DM

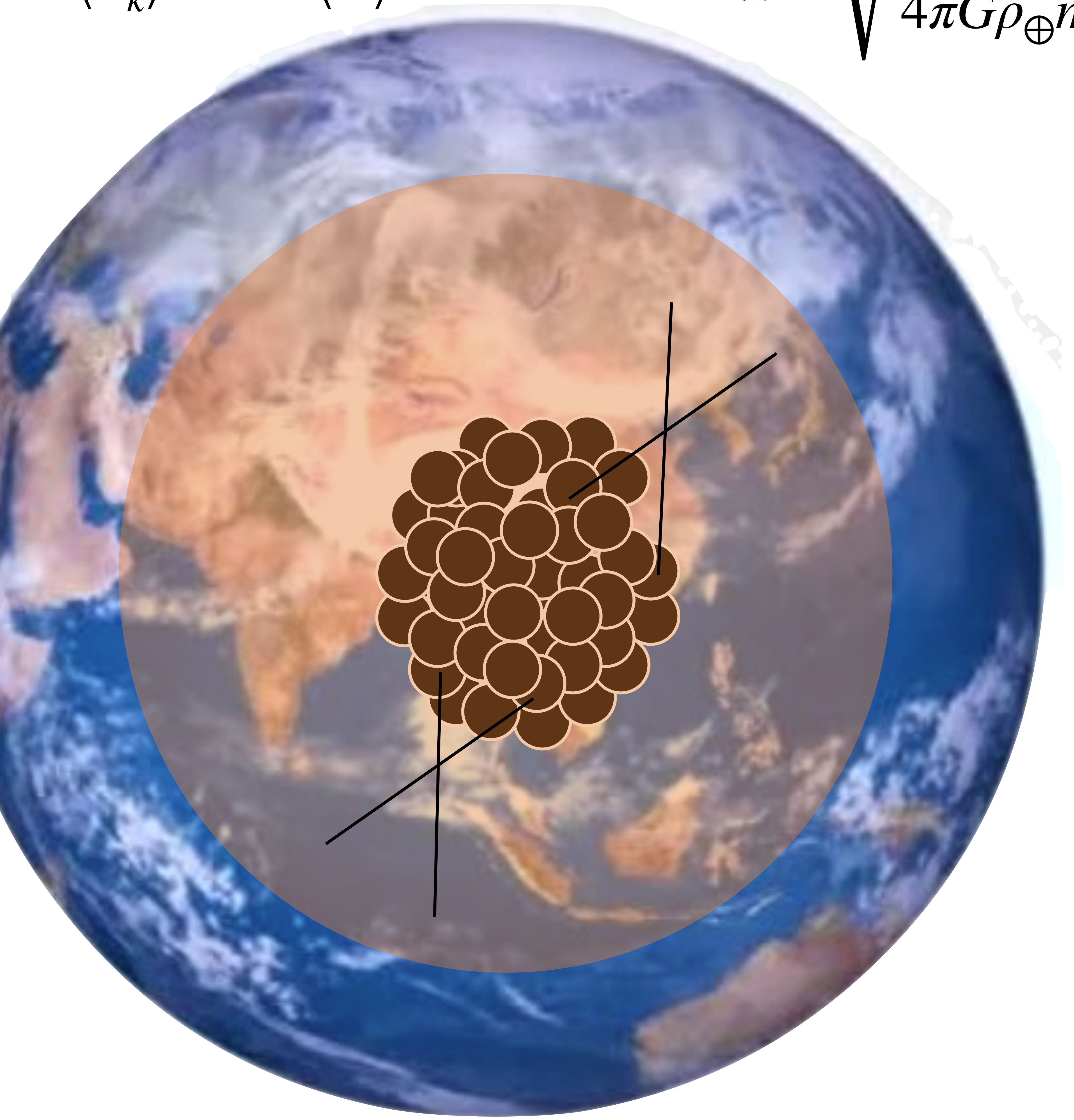


$$f_*(v) \sim \int_{-1}^{1} \mathrm{d}\cos\phi \, \left(v^2 - v_e^2\right)^{3/2} \exp\left(-\frac{\tilde{v}^2}{v_0^2}\right) \, \Theta(v - v_e) \, \Theta(v_{eg} - \tilde{v})$$

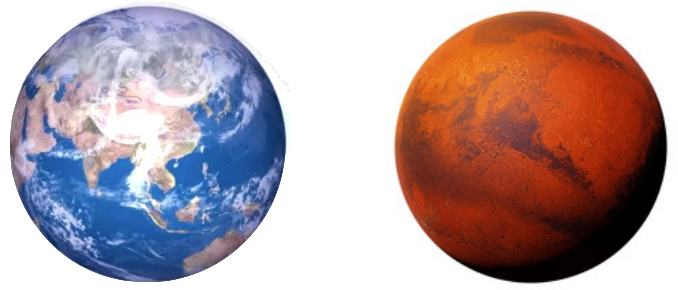
DM is slower than galactic escape velocity $v_{eg} \sim 550$ km/s, but faster than Earth's escape velocity

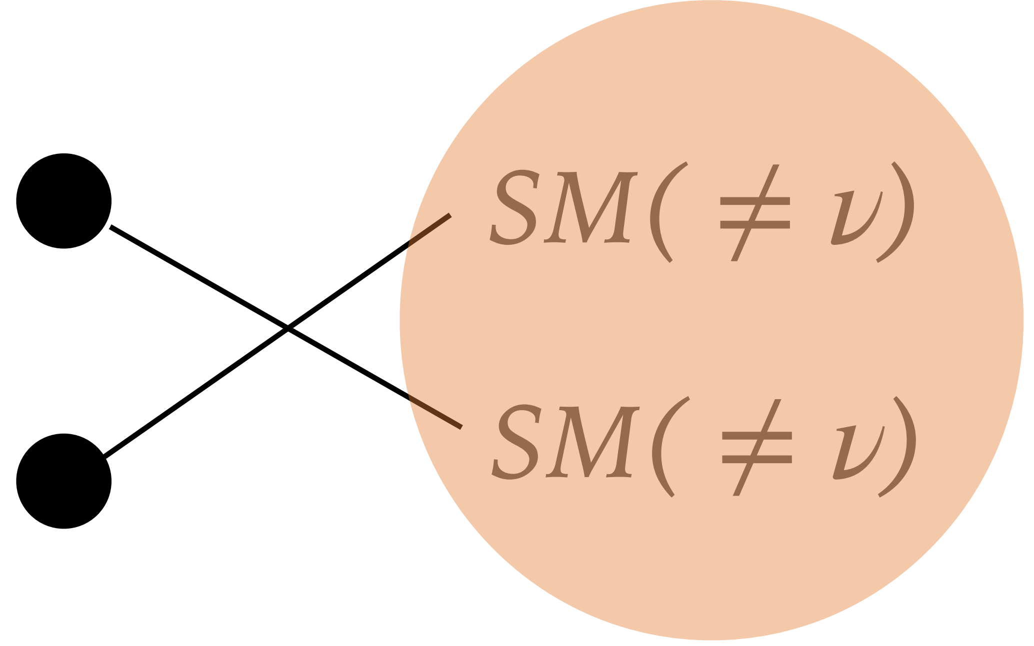
Sphere of DM particles in the Earth settle at thermal radius:

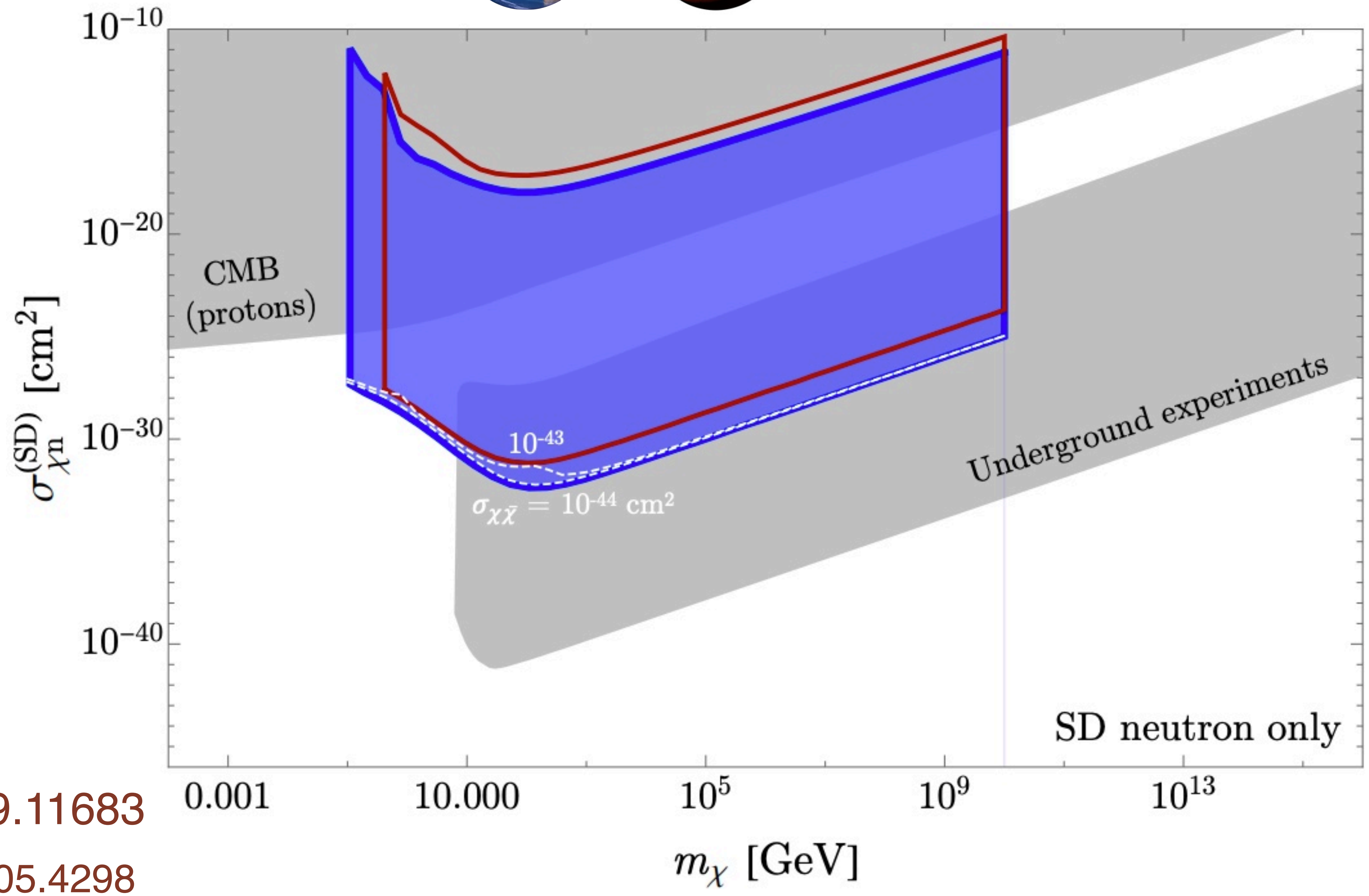
$$\langle E_k \rangle \simeq -2\langle V \rangle \longrightarrow r_{th} = \sqrt{\frac{9T_\oplus}{4\pi G \rho_\oplus m_\chi}} \lesssim \mathcal{O}(\text{km})$$



If they annihilate:
Earth/Martian heating!



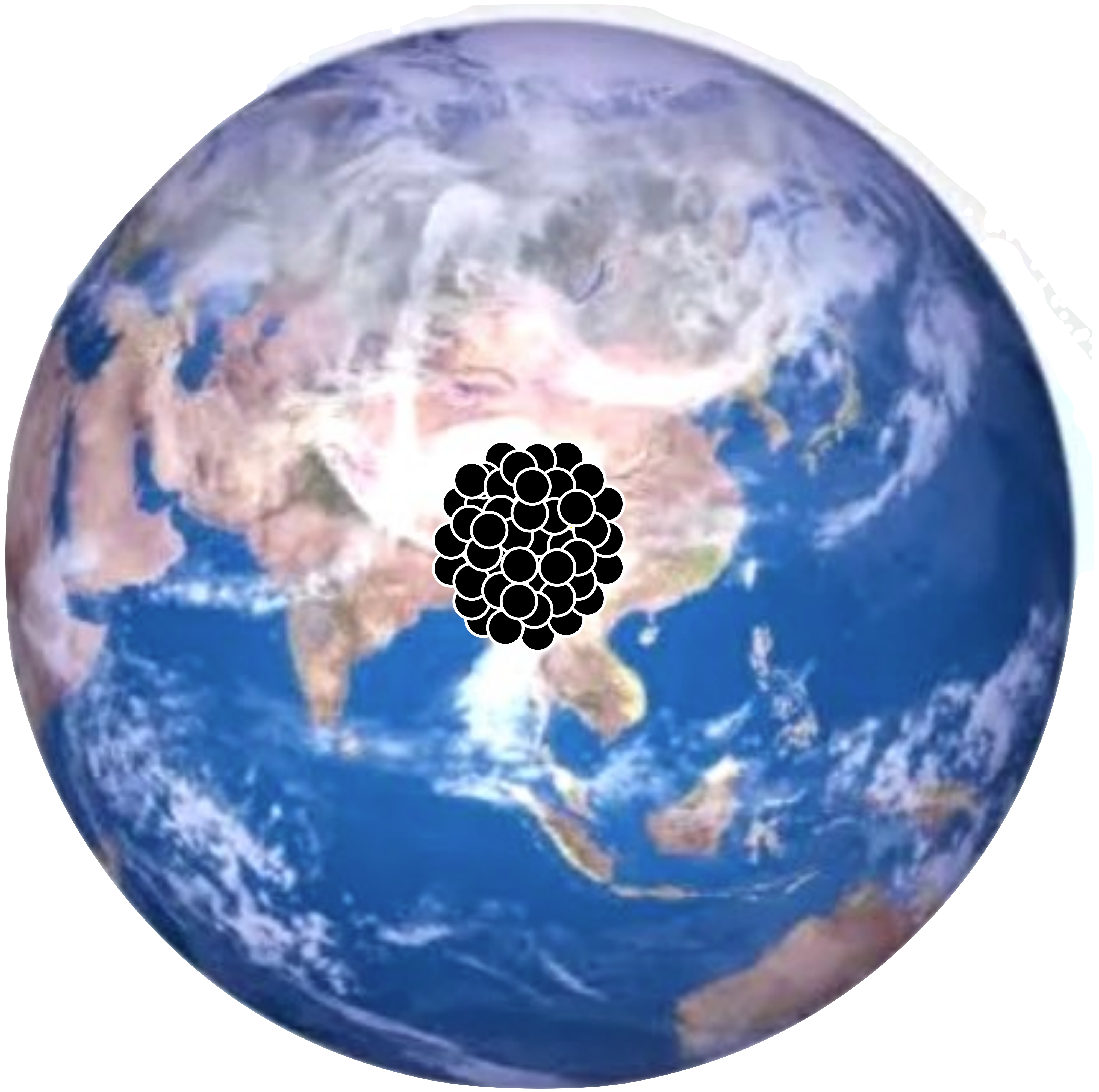




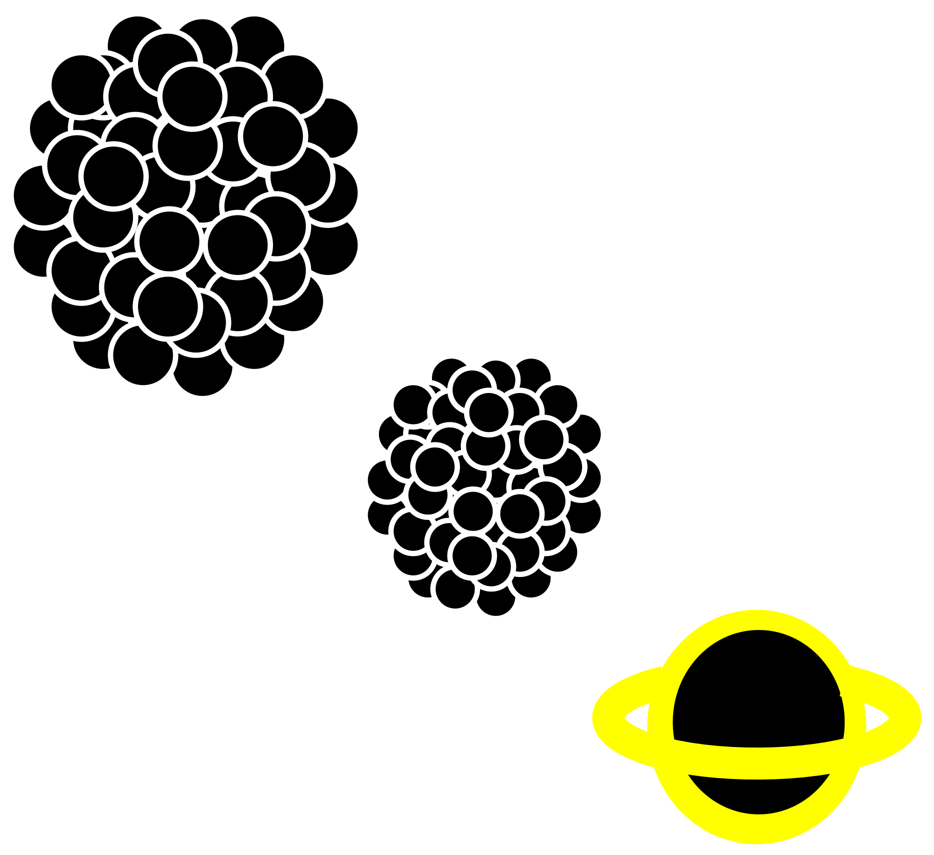
JB, Buchanan, Goodman, Lodhi 1909.11683

see also Mack, Beacom, Bertone 0705.4298

If they don’t annihilate: collapse!



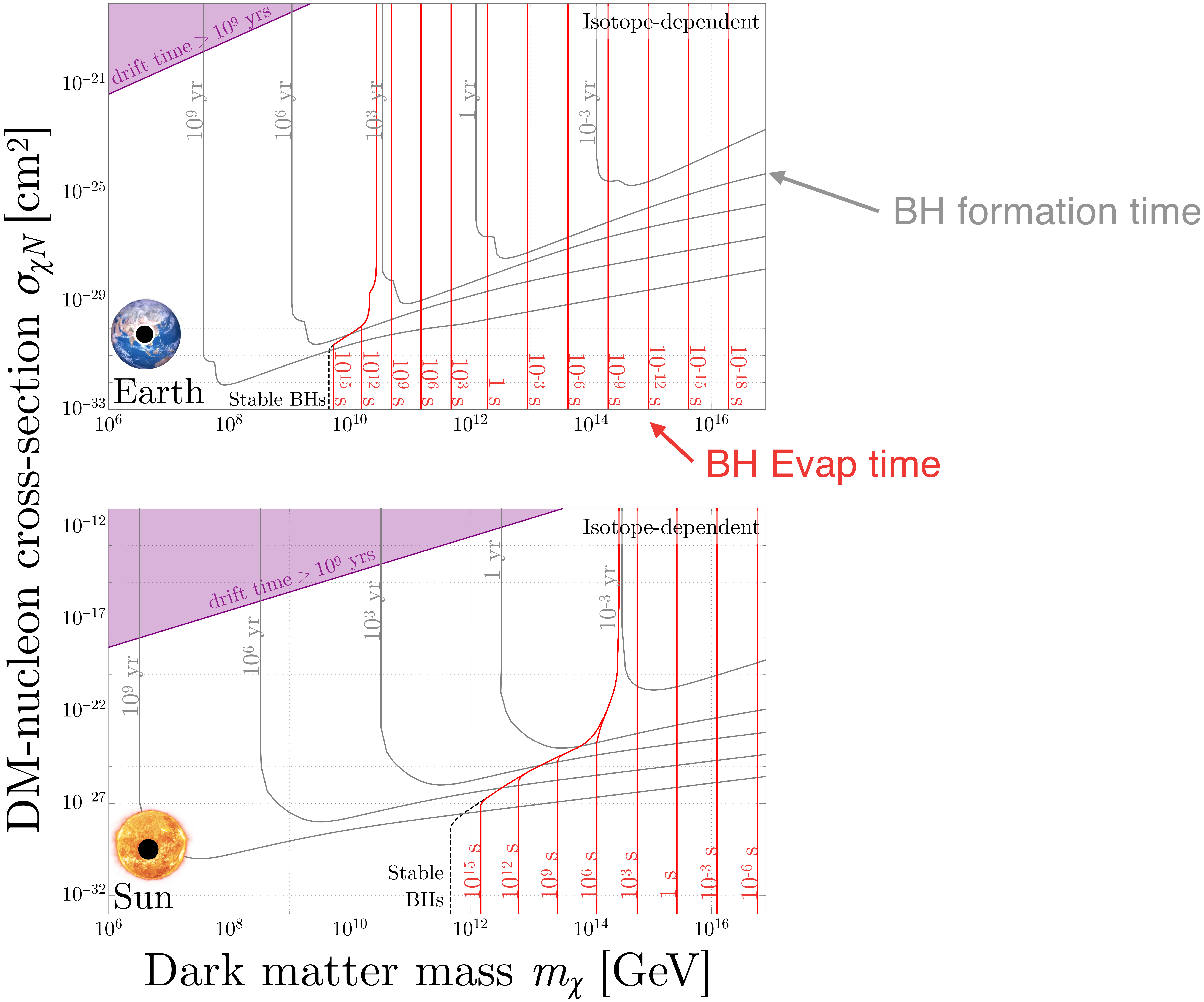
<u>Conditions</u>



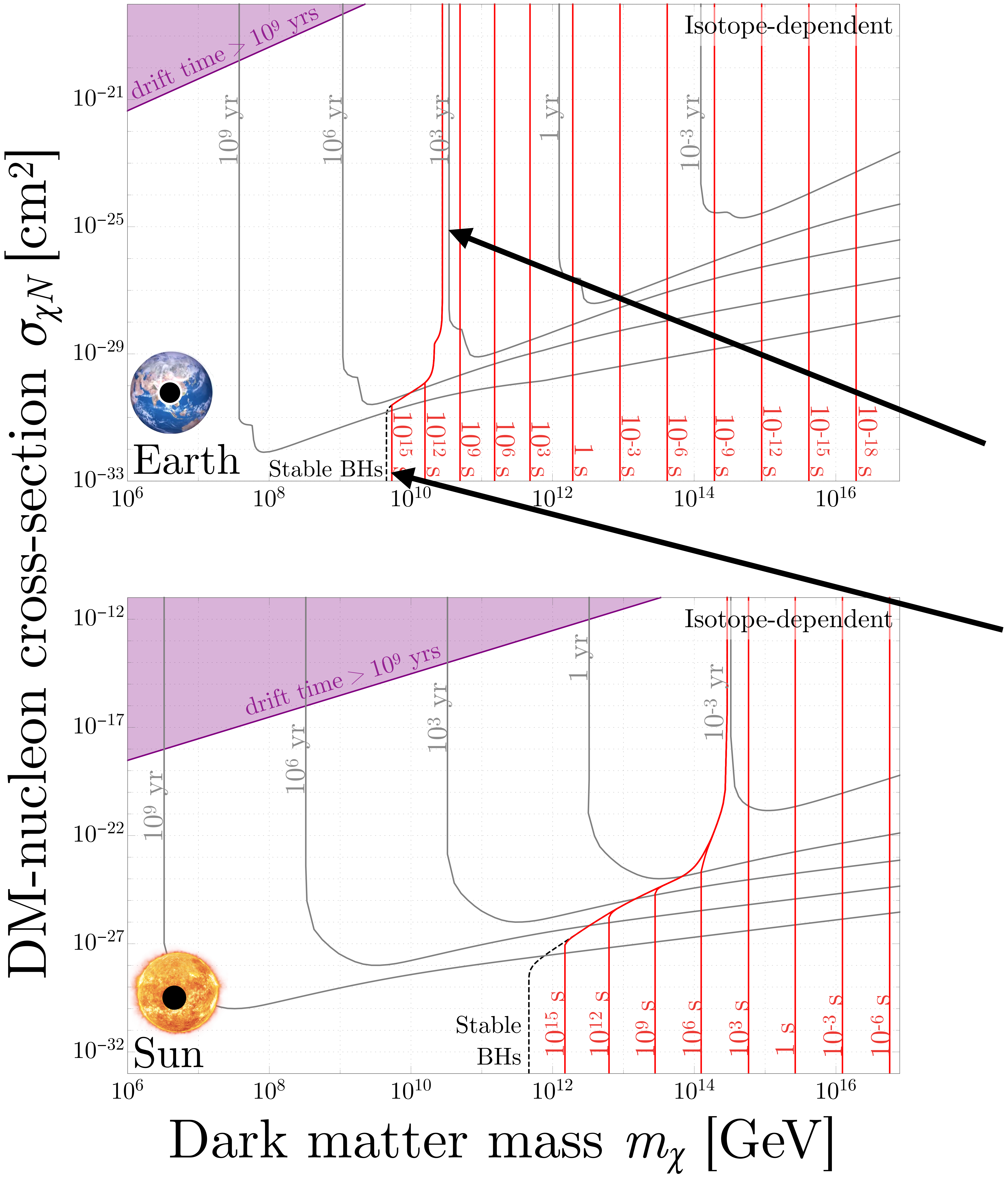
Jeans instability: $\rho_\chi \gtrsim \rho_\oplus$

Self-gravitating: $M_{cap} \gtrsim \sqrt{\frac{3T_\oplus^3}{\pi G^3 m_\chi^3 \rho_\oplus}} = M_{sg}$

Fermi degeneracy: $M_{cap} \gtrsim \frac{M_{pl}^3}{m_\chi^2} = M_f$



DM-nucleon cross-section $\sigma_{\chi N}$ [cm^2]
Dark matter mass m_χ [GeV]
Isotope-dependent
drift time > 10^9 yrs
10^9 yr
10^6 yr
10^3 yr
1 yr
10^{-3} yr
10^{15} s
10^{12} s
10^9 s
10^6 s
10^3 s
1 s
10^{-3} s
10^{-6} s
10^{-9} s
10^{-12} s
10^{-15} s
10^{-18} s
Stable BHs
Earth
Sun
BH formation time
BH Evap time



Earth

Max destructive m_χ

Hawking = Bondi + $m_\chi \Phi_\chi$

2.7×10^{10} GeV

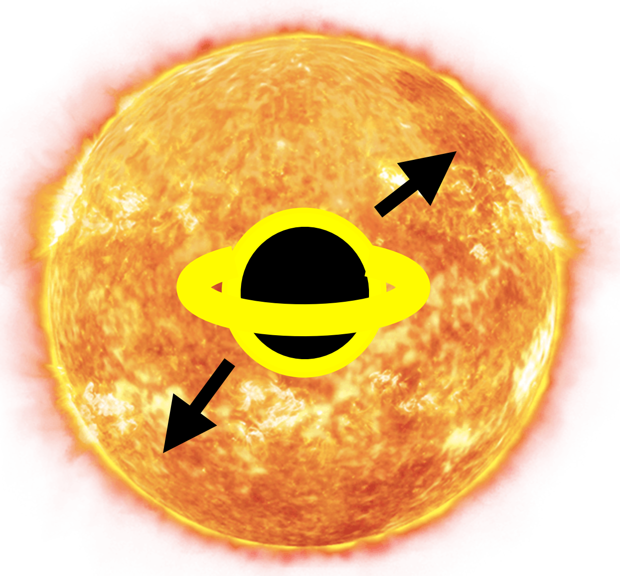
Min evaporative m_χ

Hawking = Bondi

4.5×10^{9} GeV

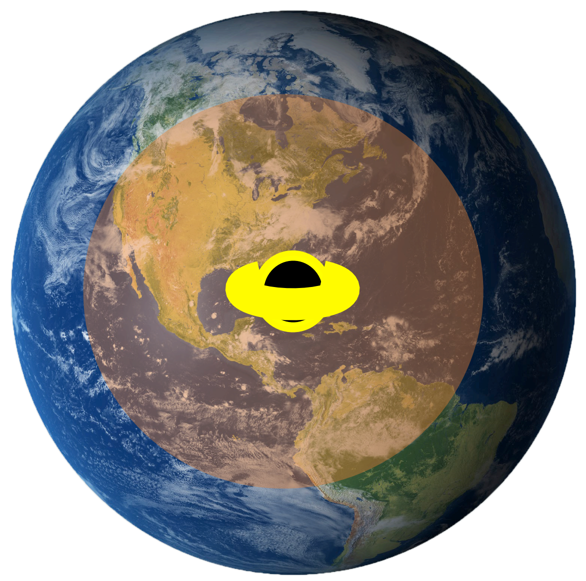
- Upshot: higher mass DM implies smaller black holes formed
  Two factors: fermi and thermalization

- Smaller black holes evaporate

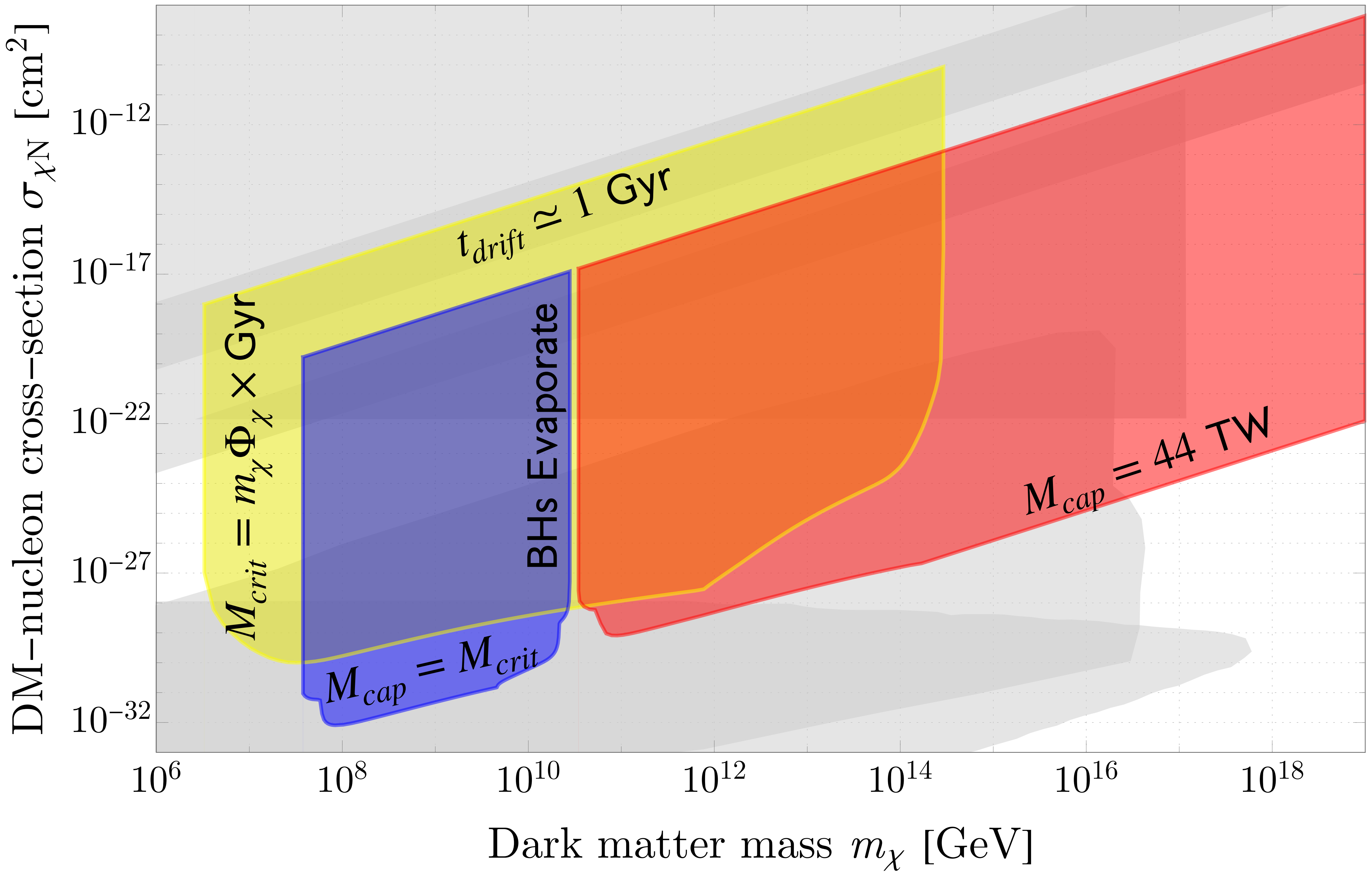


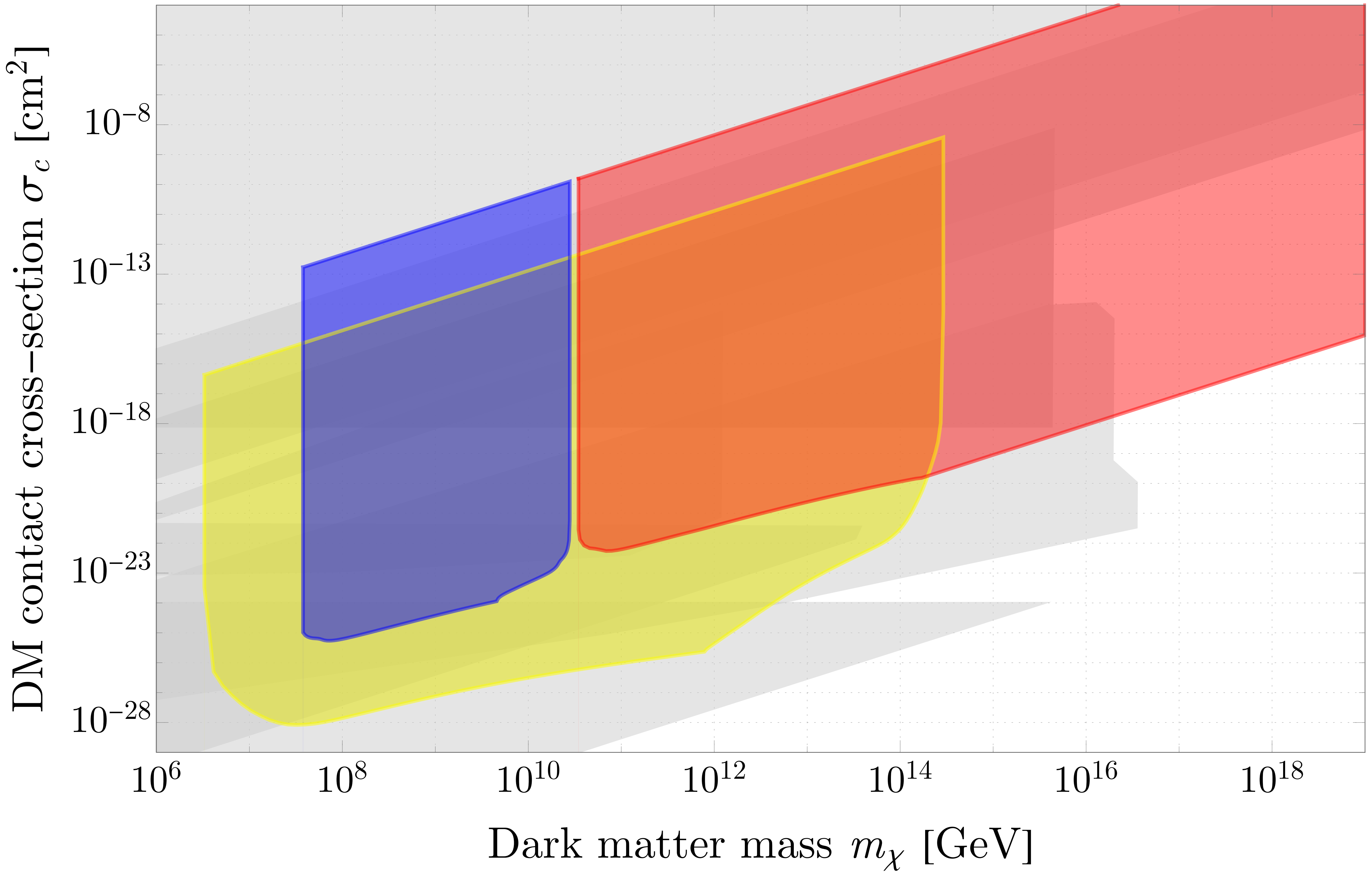
Sun destroyed

Earth destroyed



Earth heating





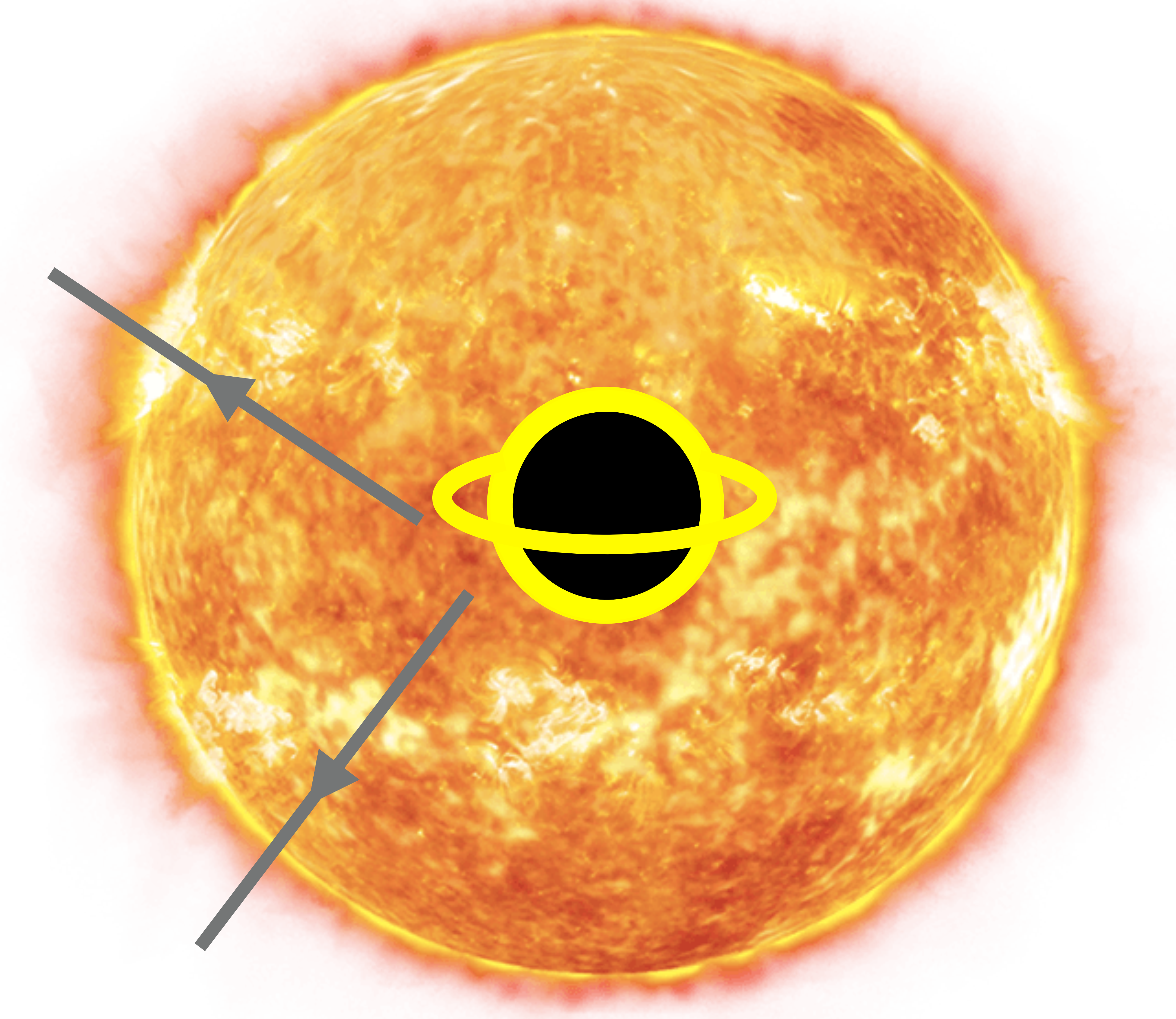
Neutrinos From Black Holes in the Sun

Signal

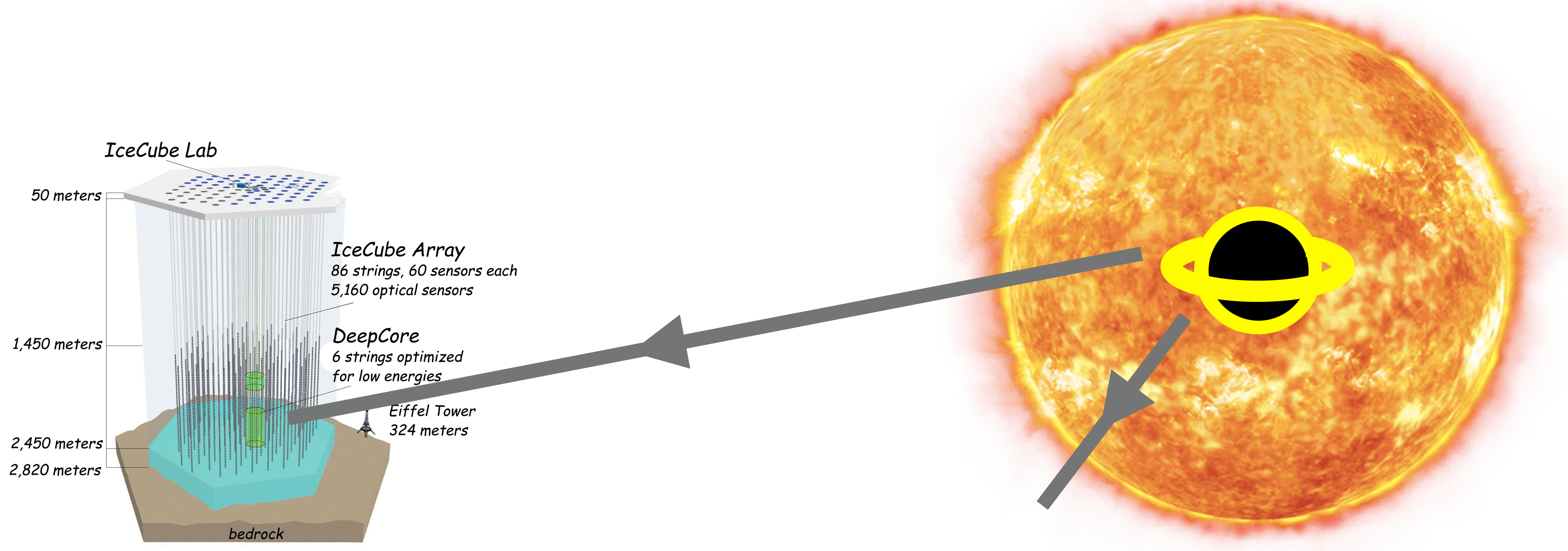
- Flavour universal
- Blackbody (with gray body factors) $T = \frac{1}{8\pi G M_{BH}}$
- Transient, directional

Spectra

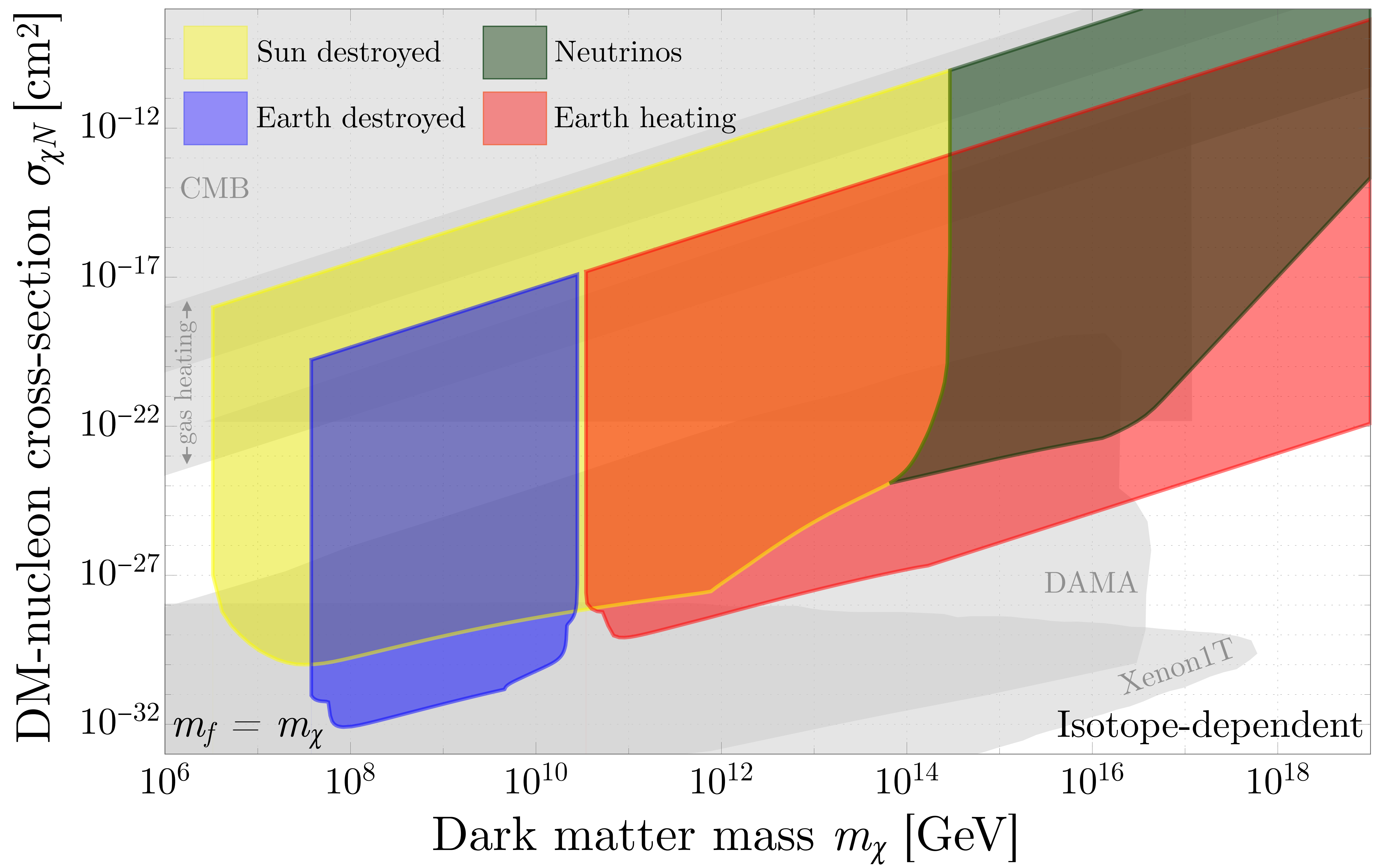
- Primary $\nu_\alpha \bar{\nu}_\alpha$ pairs emitted at event horizon
- Secondary decays

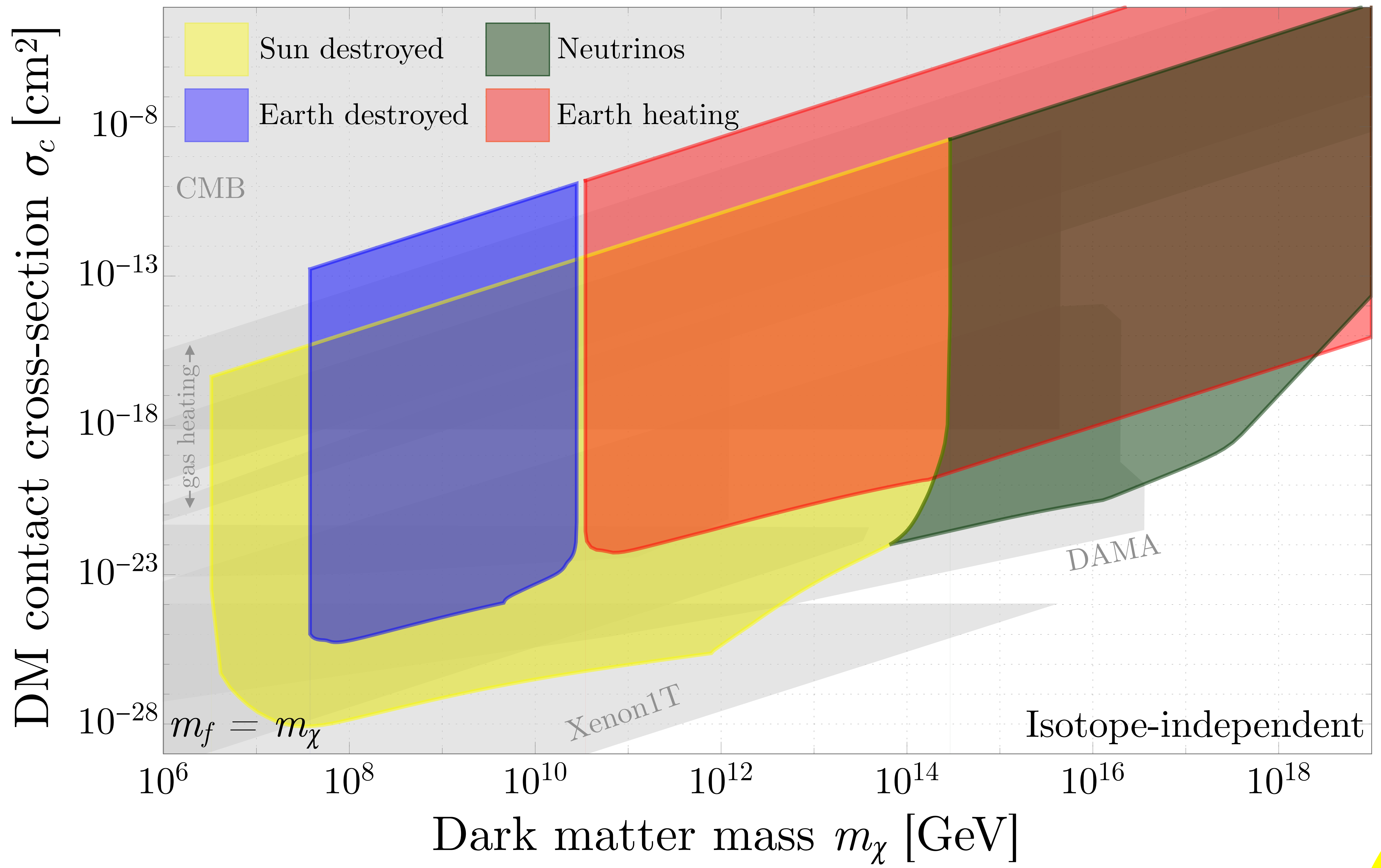


BlackHawk (Hawking radiation) + PYTHIA (hadronization) + nuSQuIDS (propagation)



Neutrinos from BHs in sun

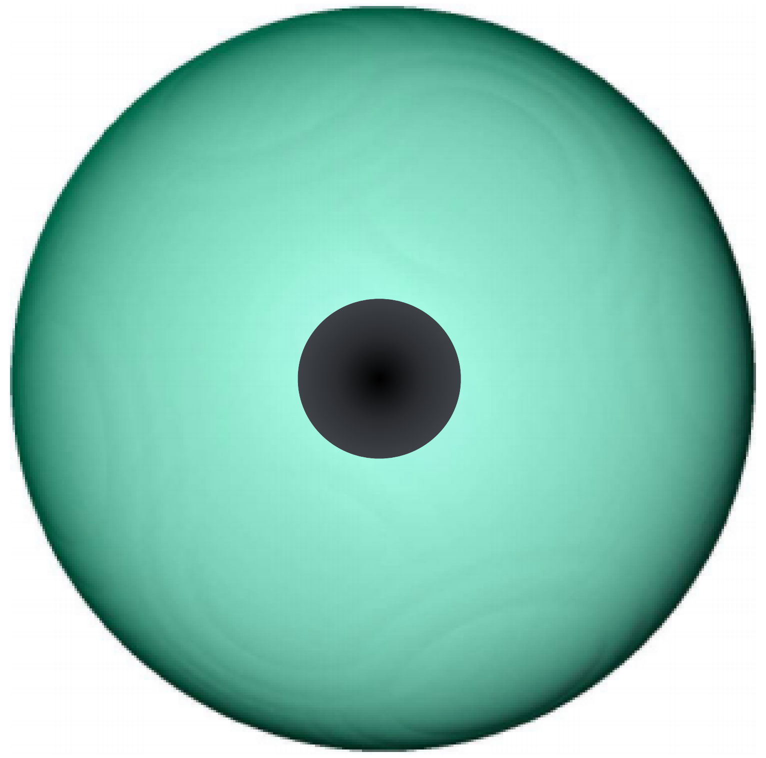




Acevedo, JB, Goodman, Kopp, Opferkuch 2012.09176

Heavy Dark Matter Ignition of Type Ia Supernovae

In order to ignite a carbon-oxygen white dwarf, the dark matter must be **heavy** so that it thermalizes inside a small volume within the white dwarf, and collects to the point of collapse within ~10^{10} years.



DM collects to the point of self-gravitation.

Harmonic Oscillator potential

$$k_B T \sim G \rho_{wd} m_x r_{th}^2$$

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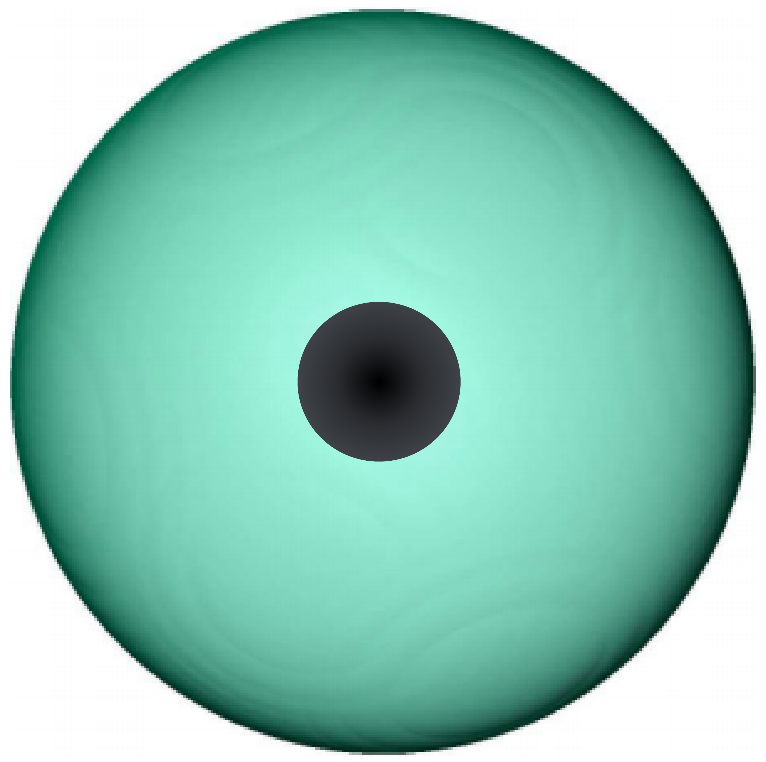

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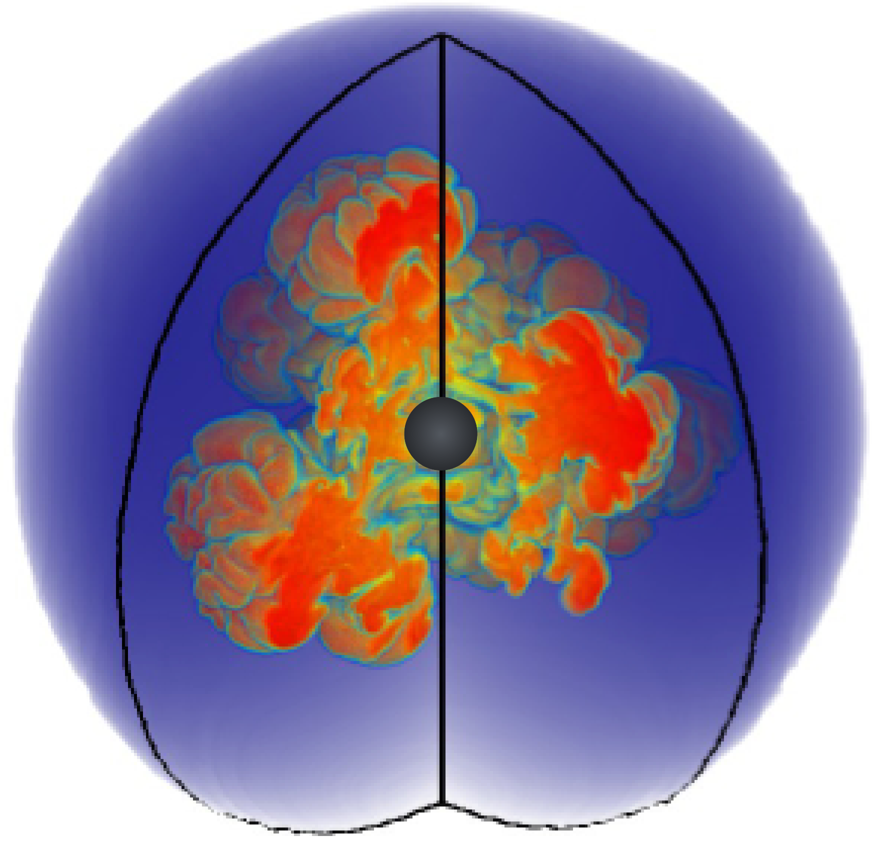
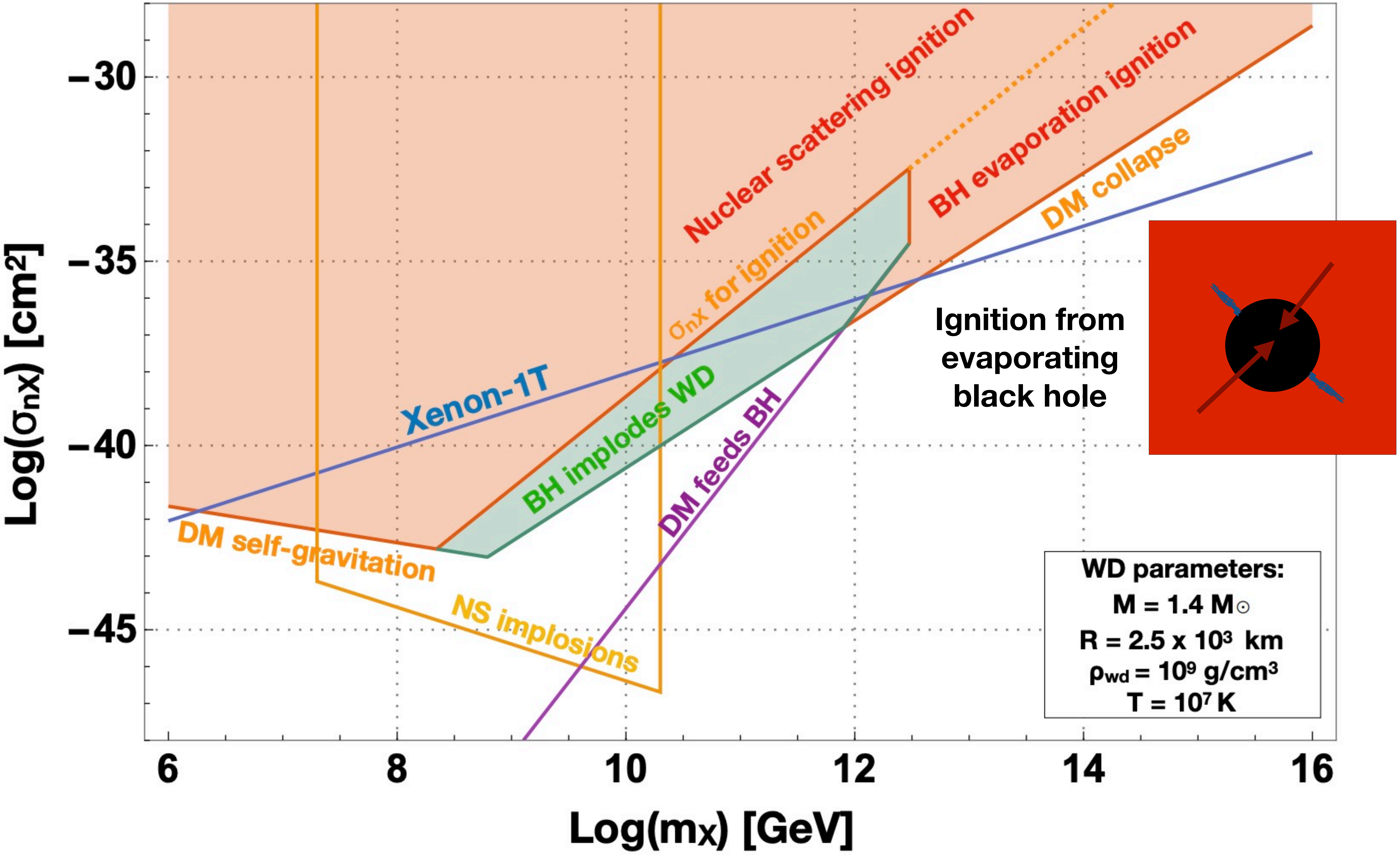


DM collapses, shedding gravitational potential energy through **scattering**, igniting a SNIa.

Bounds on dark matter from GAIA White Dwarf dataset



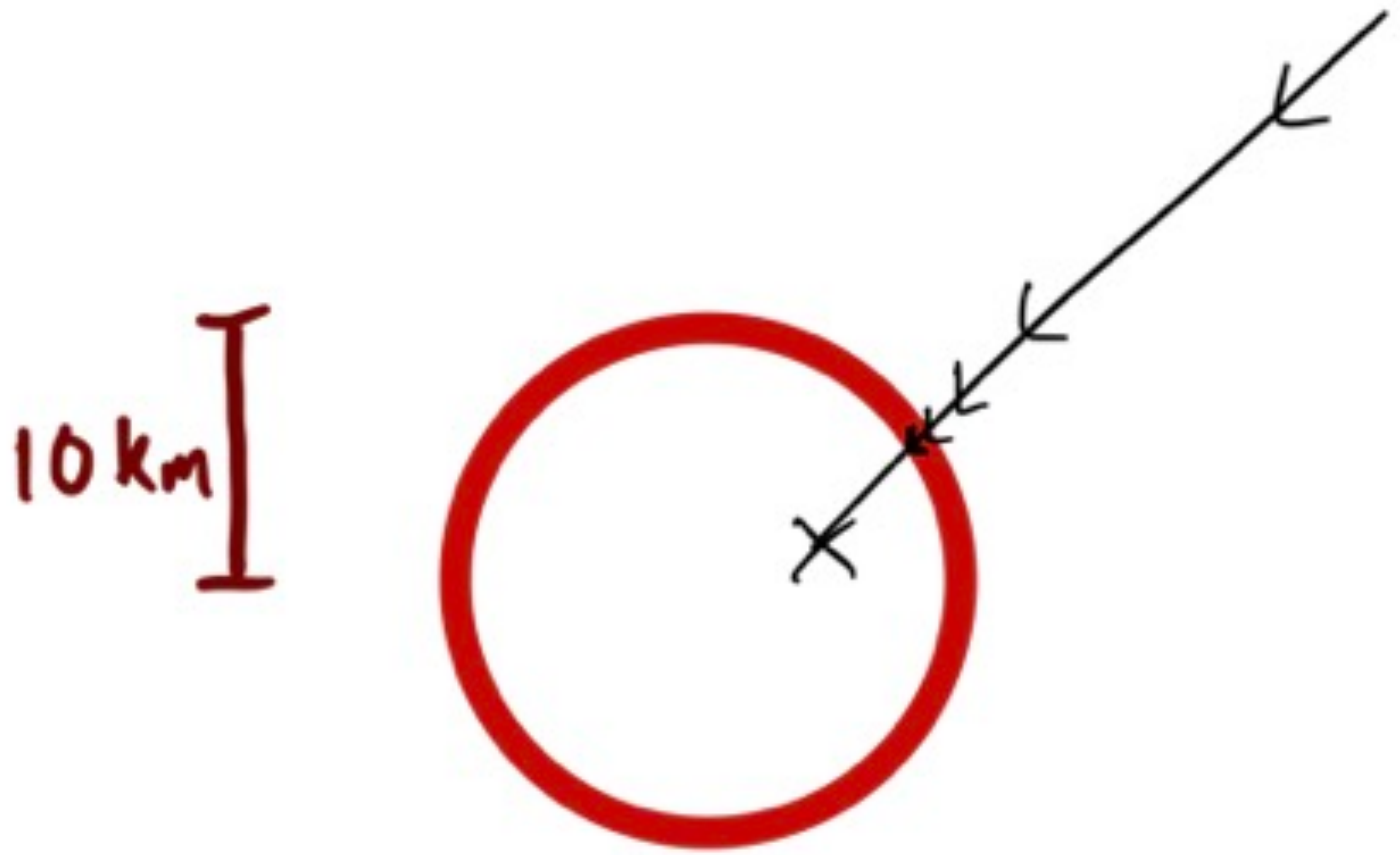
Ignition from evaporating black hole

Javier Acevedo JB 2019

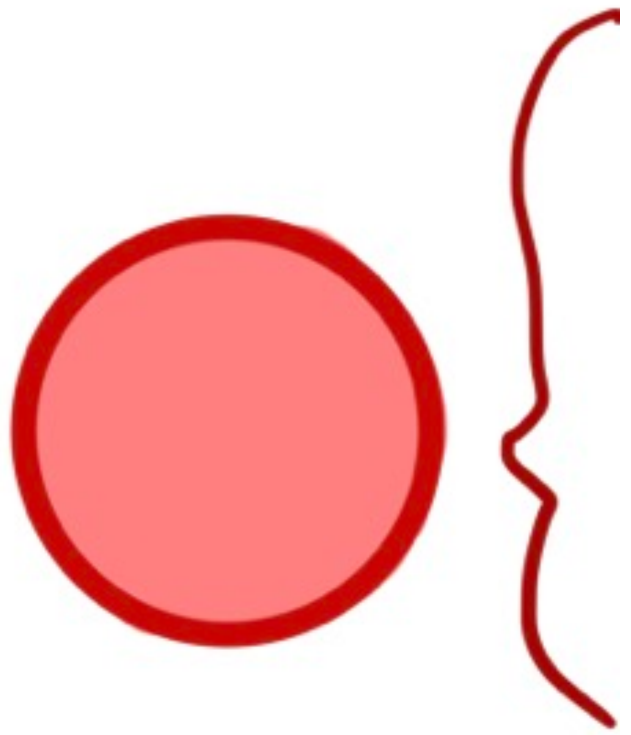
Neutron stars: nature's dark matter accelerators

- ➤ Neutron stars accelerate dark matter to beyond freezeout speeds

$$v_{esc} = \sqrt{\frac{2GM}{R}} \sim 0.7c$$



- ➤ Dense, accept a large DM flux



- fiducial mass of $\sim 10^{57}$ GeV
- neutrons:protons:electrons $\sim 10:1:1$
- flux of ~ 100 grams of DM/second

Neutron stars: broad reach for particle dark matter

1. EFT, Spin-Dependent, Spin-Independent, Strongly Interacting, Electroweakino, Inelastic
2. Leptophilic dark matter
3. Self-interacting dark matter
4. Heavy DM, baryon and lepton annihilating DM, compressed WIMPs, co-annihilating DM
5. Winos, Higgsinos, Precision Capture, Pasta Capture
6. Muonphilic
7. Asymmetric (converts NSs into black holes)

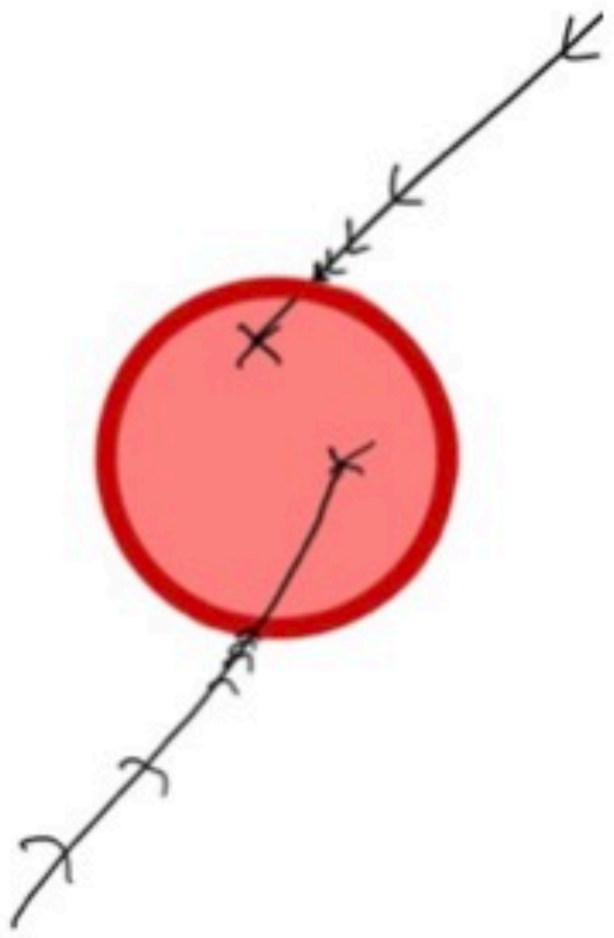
Kouvaris 2007
Bertone, Fairbairn 2007
JB Delgado, Martin 2017
Baryakhtar, JB, Li, Linden, Raj 2017
Raj, Tanedo, Yu 2017
Acevedo, JB, Leane, Raj 2019
Bell, Busoni, Robles 2019
Joglekar, Raj, Tanedo, Yu 2019
Chen, Lin 2018
Jin, Gao 2018
Hamaguchi, Nagata, Yanagi 2019
Garani, Genolini, Hambye 2018
Keung, Marfatia, Tseng 2020
Bai, Berger, Korwar, Orlofsky 2020
Camargo, Queiroz, Sturani 2019
Bell, Busoni, Robles 2020
Garani, Heeck 2019
Goldman, Nussinov 1989
Kouvaris, Tinyakov 2011
McDermott, Yu, Zurek 2011
JB, Fukushima, Kumar 2013
Bell, Melatos, Petraki 2013
Bertoni, Nelson, Reddy 2014
JB, Linden 2014
JB, Elahi 2015

(more…)

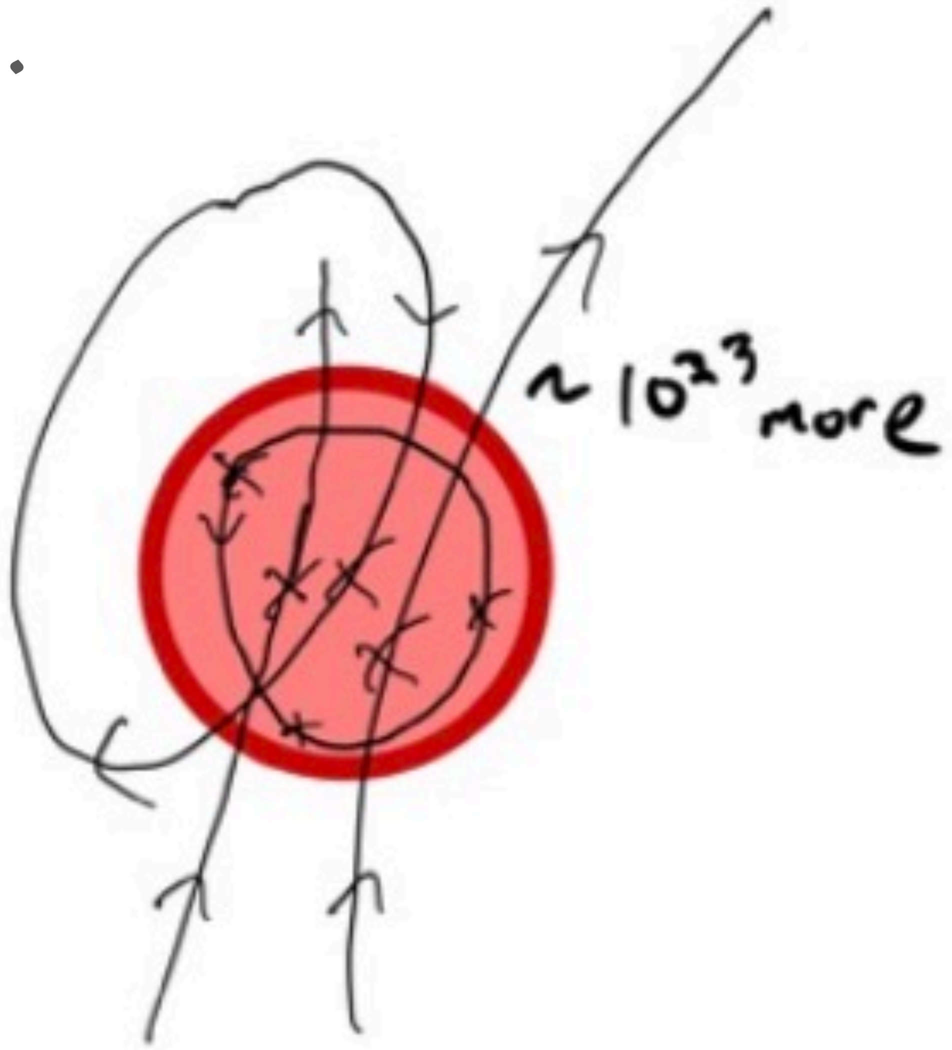
Dark matter kinetic and annihilation heating of neutron stars

1. Dark matter accelerated to ~0.7c by neutron star
2. DM deposits kinetic energy by scattering and re-scattering in the neutron star (may also annihilate in the NS)
3. Heats NS to 1750 K if all DM captured, 2500 K with annihilation (for 0.4 GeV/cm^3)

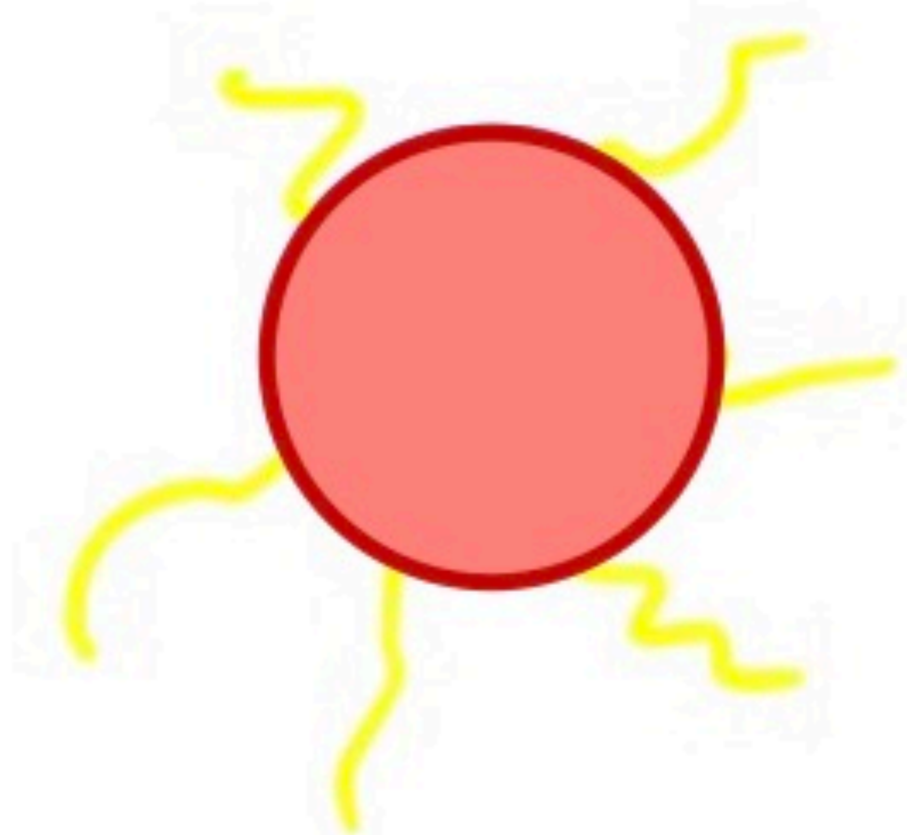
1.



2.



3.



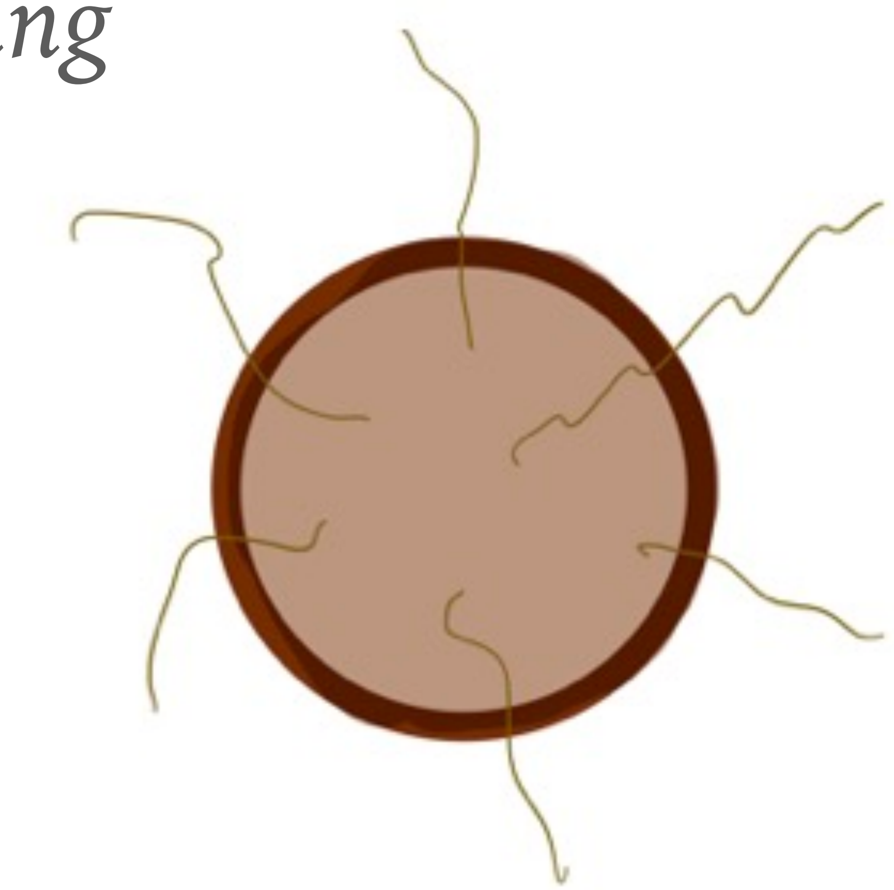
T~1750 / 2500 K, for NS near Earth

Dark matter kinetic and annihilation heating of neutron stars

1. Dark matter accelerated to ~0.7c by neutron star
2. DM deposits kinetic energy by scattering and re-scattering in the neutron star (may also annihilate in the NS)
3. Heats NS to 1750 K if all DM captured, 2500 K with annihilation (for 0.4 GeV/cm³)

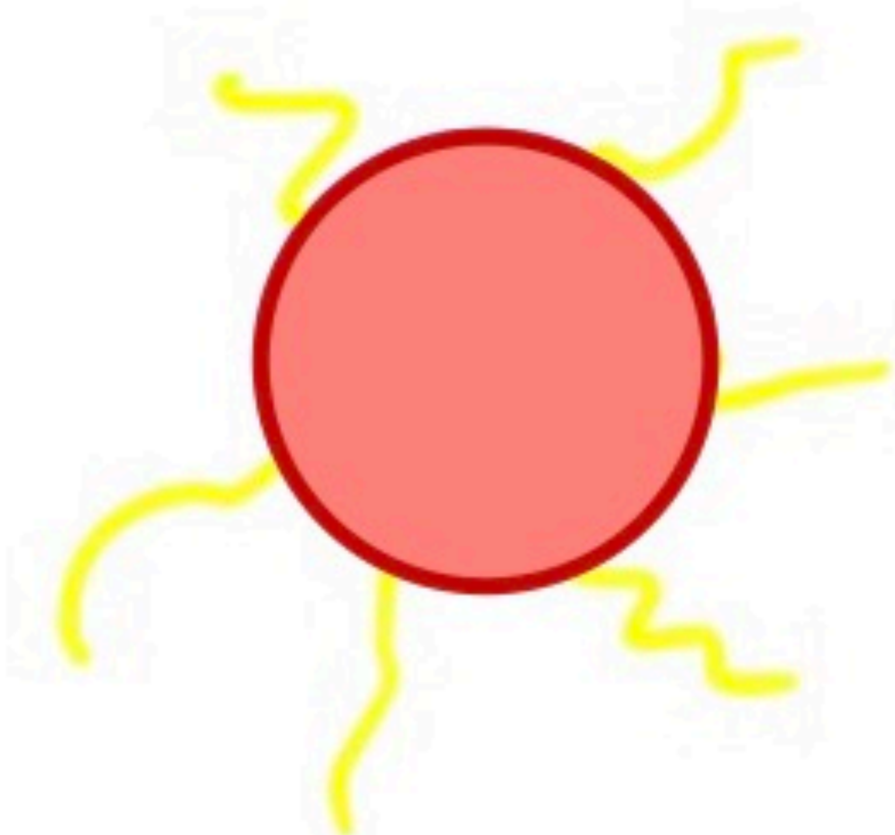
0. Compare to NS without DM heating

$$T_{eff}^{\infty} \sim 100 \text{ K} \left(\frac{\text{Gyr}}{t}\right)^{1/2}$$



e.g. Yakovlev Pethick astro-ph/0402143
Page Lattimer et al. astro-ph/0403657

3.

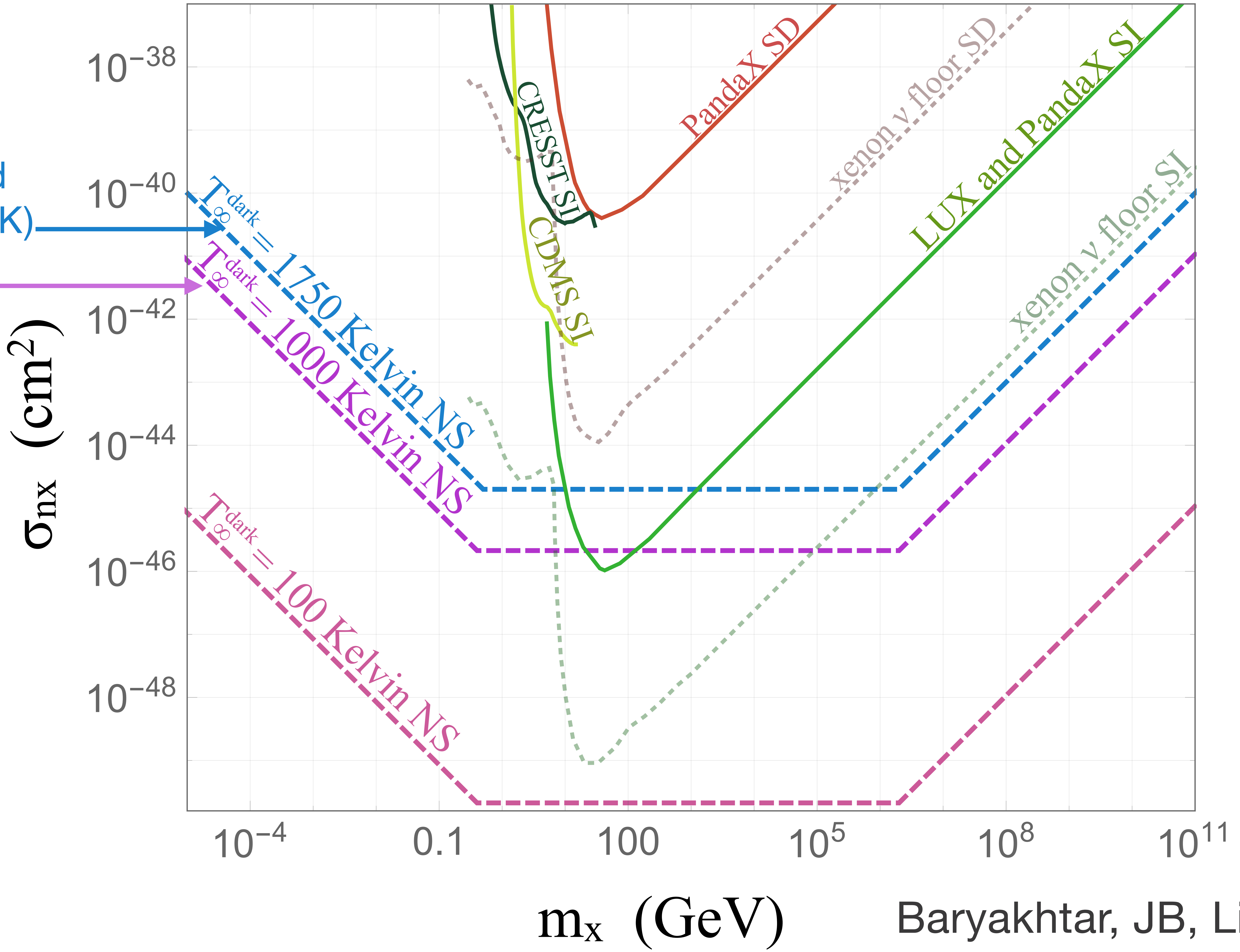


T~1750 / 2500 K, for NS near Earth

Neutron Star Dark Matter Heating Sensitivity

all incoming DM captured (ann. T~2500 K)

10% incoming DM captured (ann. T~1400 K)

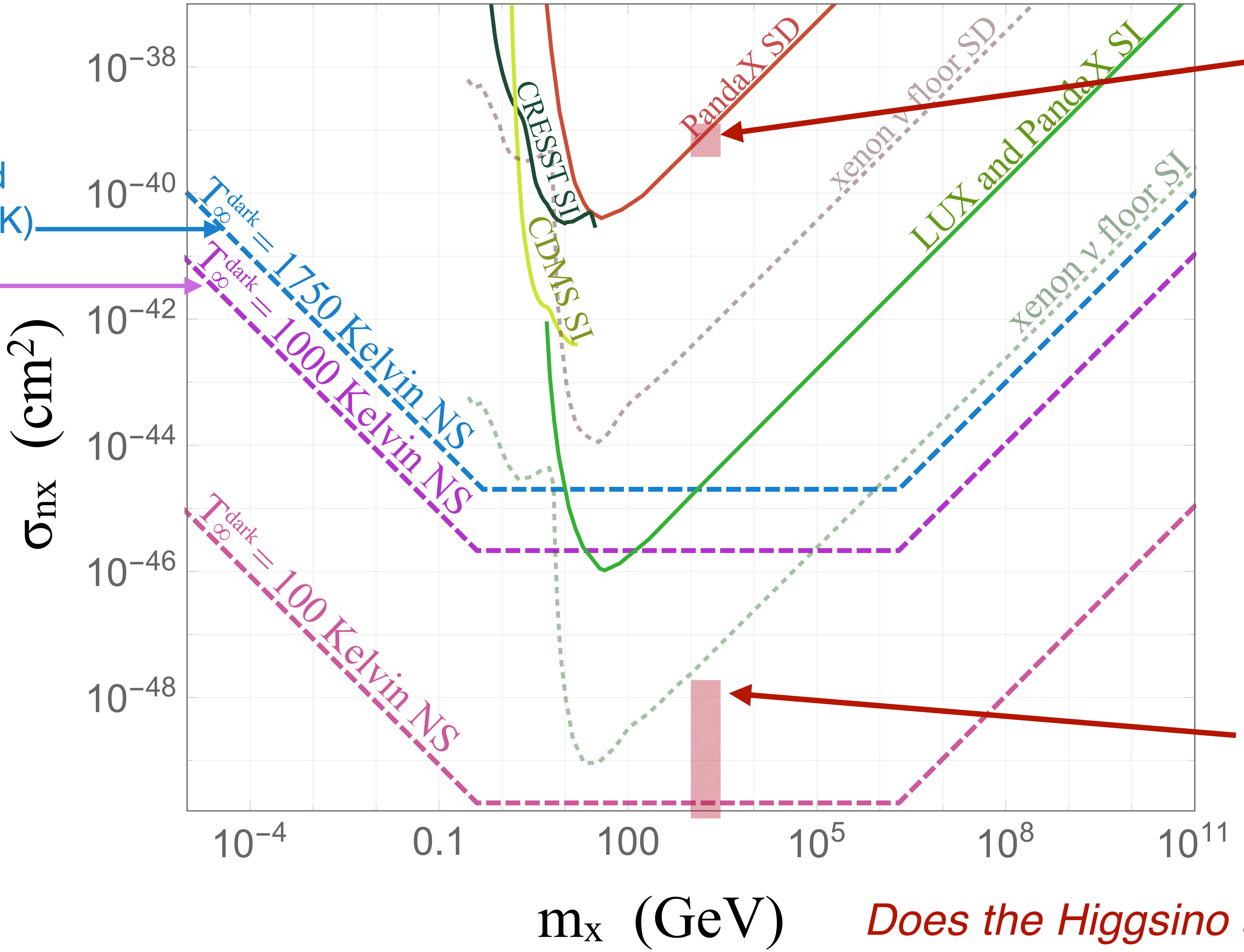


Baryakhtar, JB, Li, Linden, Raj 2017

Neutron Star Dark Matter Heating Sensitivity

all incoming
DM captured
(ann. T~2500 K)

10% incoming
DM captured
(ann. T~1400 K)

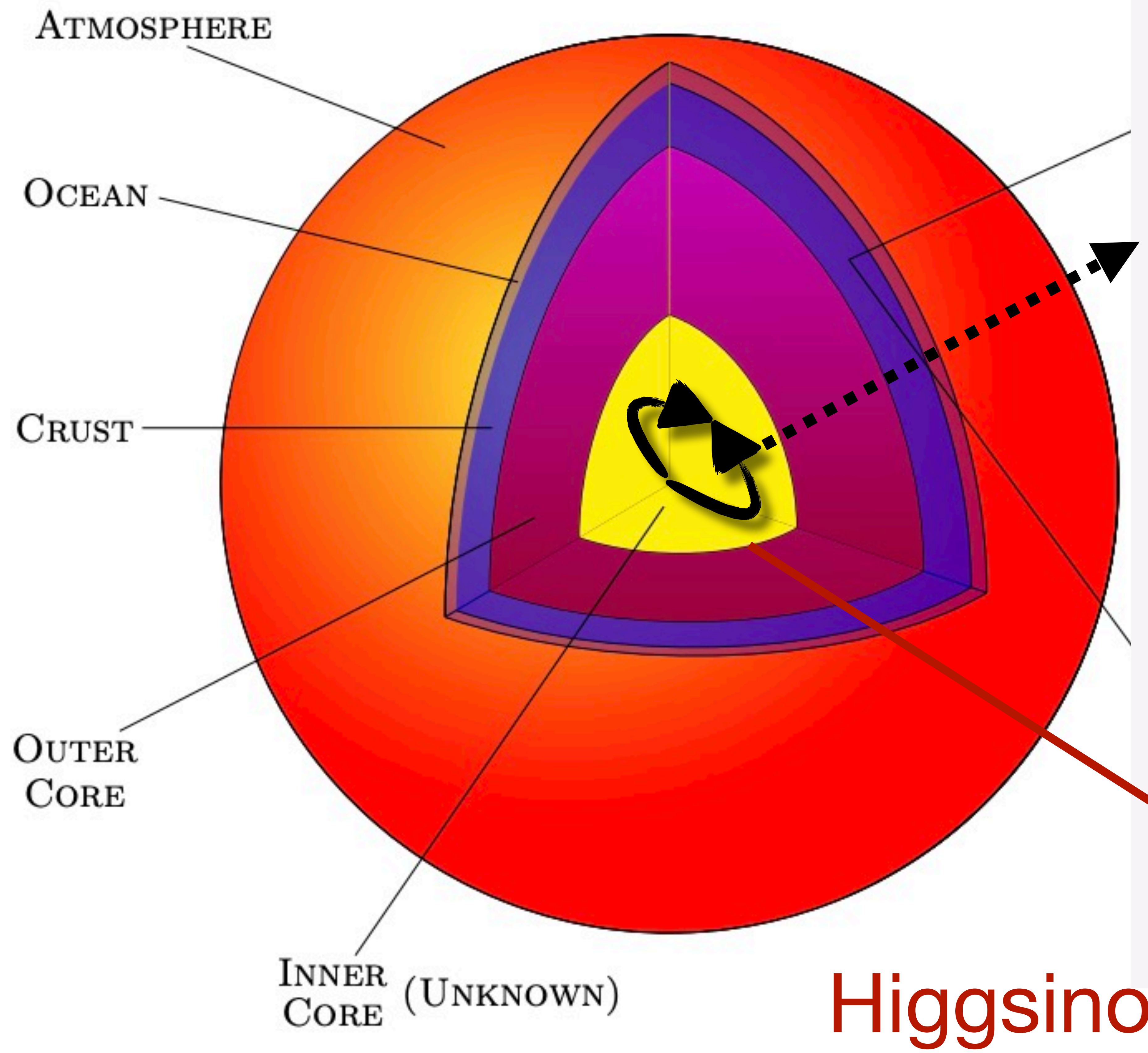


Higgsino DM
in a NS, 0.7c

Higgsino DM
at 0.001c

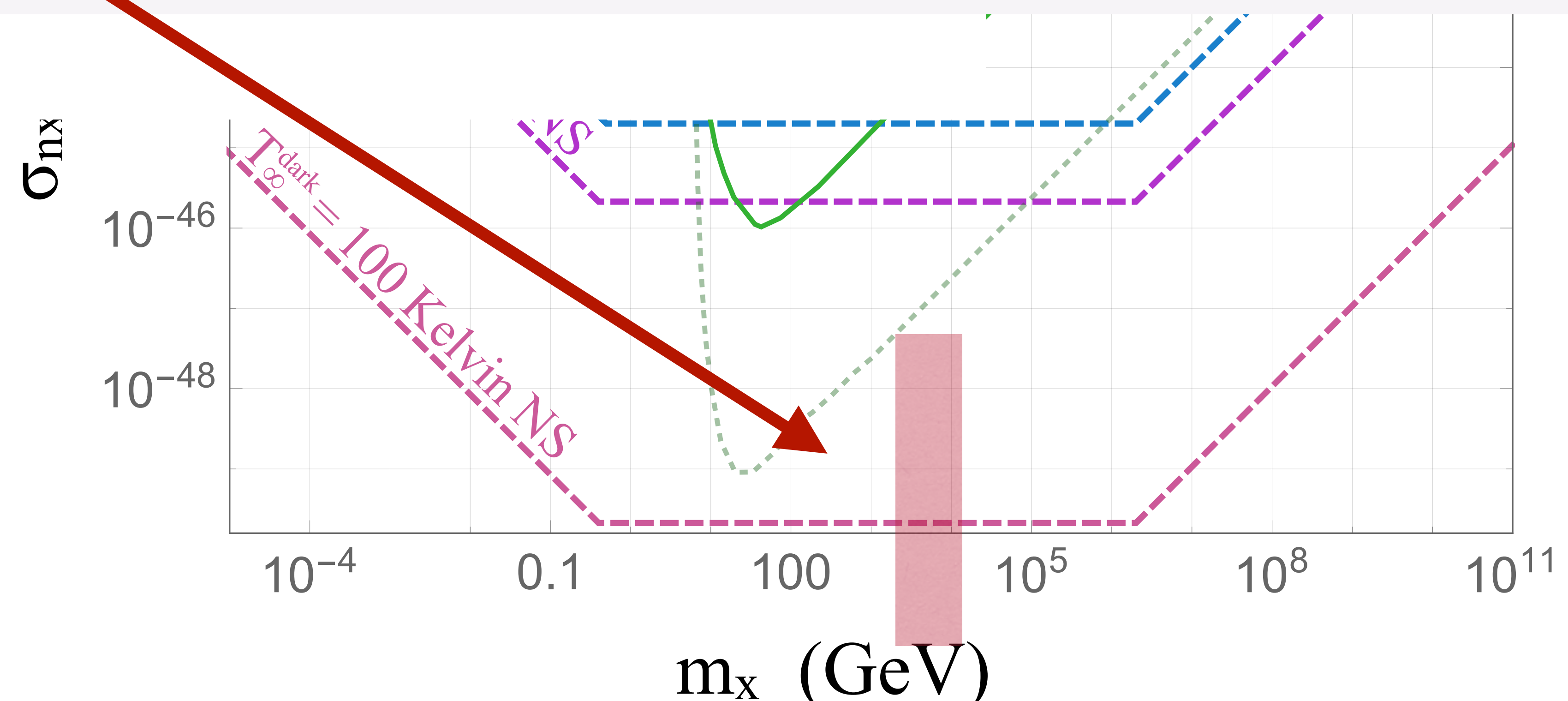
Does the Higgsino annihilate in a NS?

Neutron Star Pasta Cooker: Higgsinos (and WIMPS) annihilate in NS

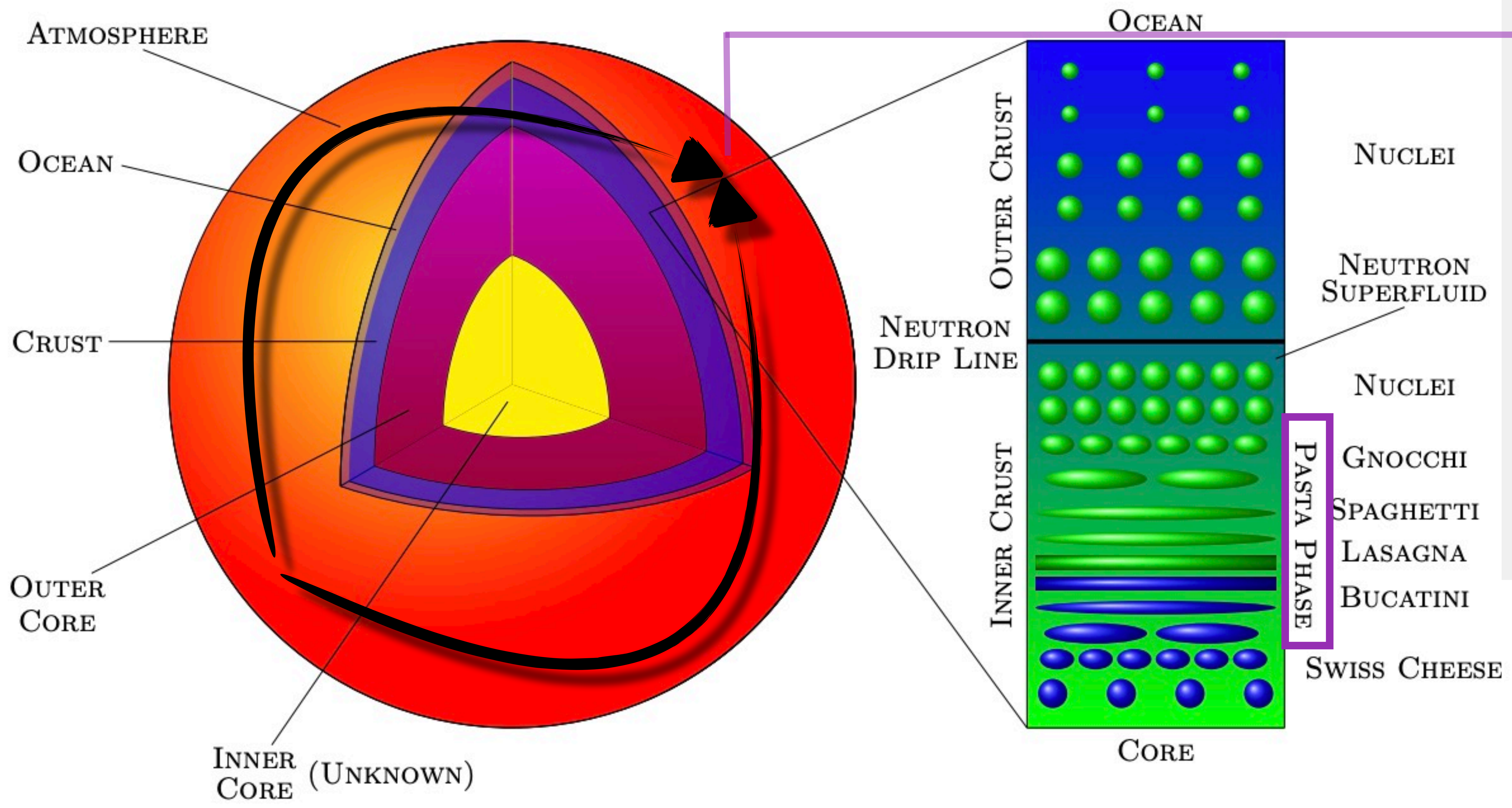


- Standard NS heating calculation uses DM annihilation at low velocities, settling in NS core
- DM-neutron cross-section is unbounded for DM that settles into NS core because of accidental loop-level nucleon coupling cancellation and pdf uncertainties
- The timescale for DM settling in NS core can't be computed without (v << c) cross-section

Higgsino DM at v << c



Neutron Star Pasta Cooker: Higgsinos (and WIMPS) annihilate in NS



- Solution: annihilation in "pasta" region as limiting case

$$\tau_{eq} \propto R_{ann}^{(3-2\ell)/2}$$

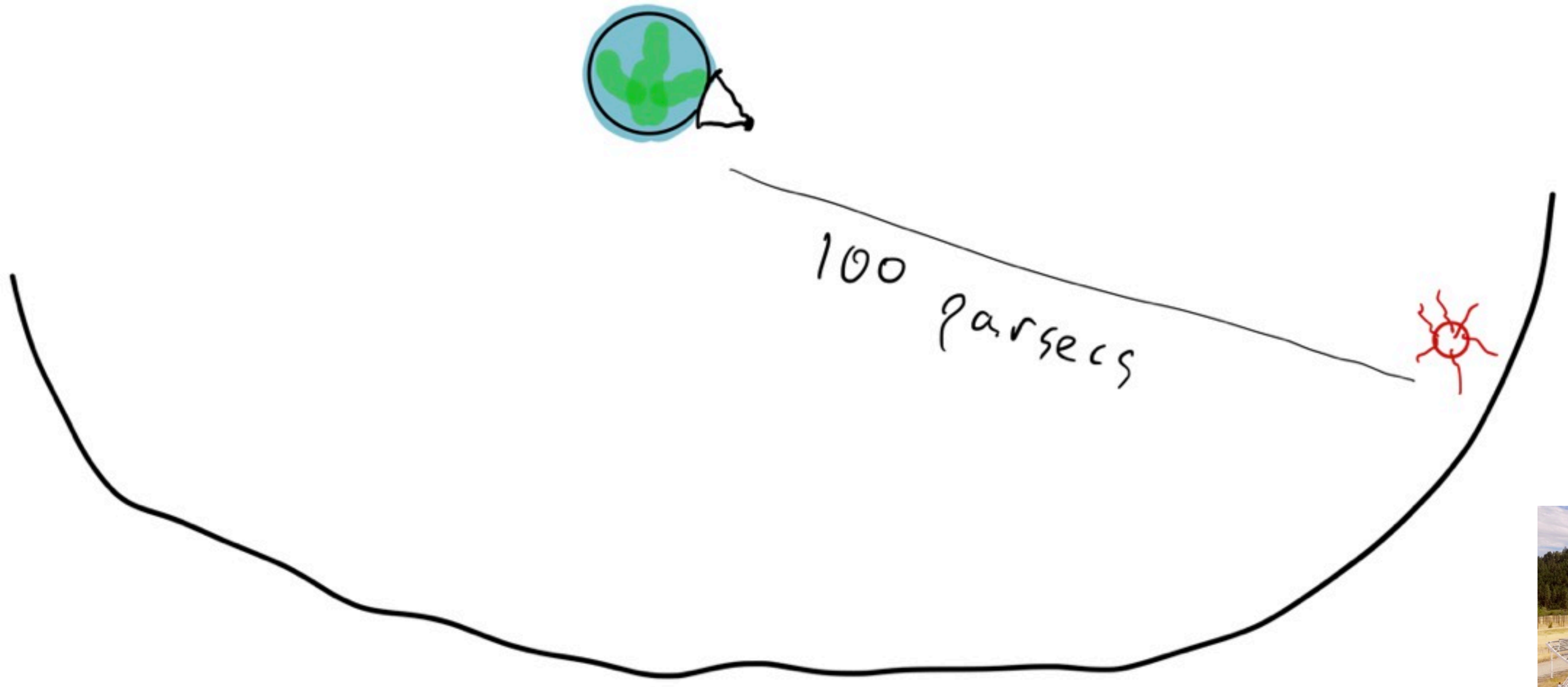
- DM annihilates at ~0.1c much like in the early universe
- keV-PeV mass WIMPs annihilate, for s-wave (l=0), p-wave (l=1), $\langle \sigma_a v \rangle = 3 \times 10^{-26}\,\frac{\mathrm{cm}^3}{\mathrm{s}}$, with

$$\tau_{eq} \lesssim 10^4 \text{ yrs} \left(\frac{m_x}{\mathrm{TeV}}\right)^{1/2}$$

Where τ_{eq} is the time for annihilation-capture equilibrium

Acevedo, JB, Leane, Raj 1911.06334

Looking for Higgsinos with 30+ meter telescopes



ELT 2σ sensitivity estimates

annihilation of WIMPs, Higgsinos

$$t \sim 3 \times 10^6 \text{ sec} \left(\frac{d}{100 \text{ pc}}\right)^4$$ (Y band)

kinetic only

$$t \sim 10^6 \text{ sec} \left(\frac{d}{30 \text{ pc}}\right)^4$$ (K band)

Radio observations of nearby pulsars

	d (pc)	period (s)
J1057-5226	90	0.19
J0736-6304	95	4.86
J0834-60	100	0.38
J0711-6830	110	0.005
J0749-68	110	0.91
J0924-5814	110	0.71

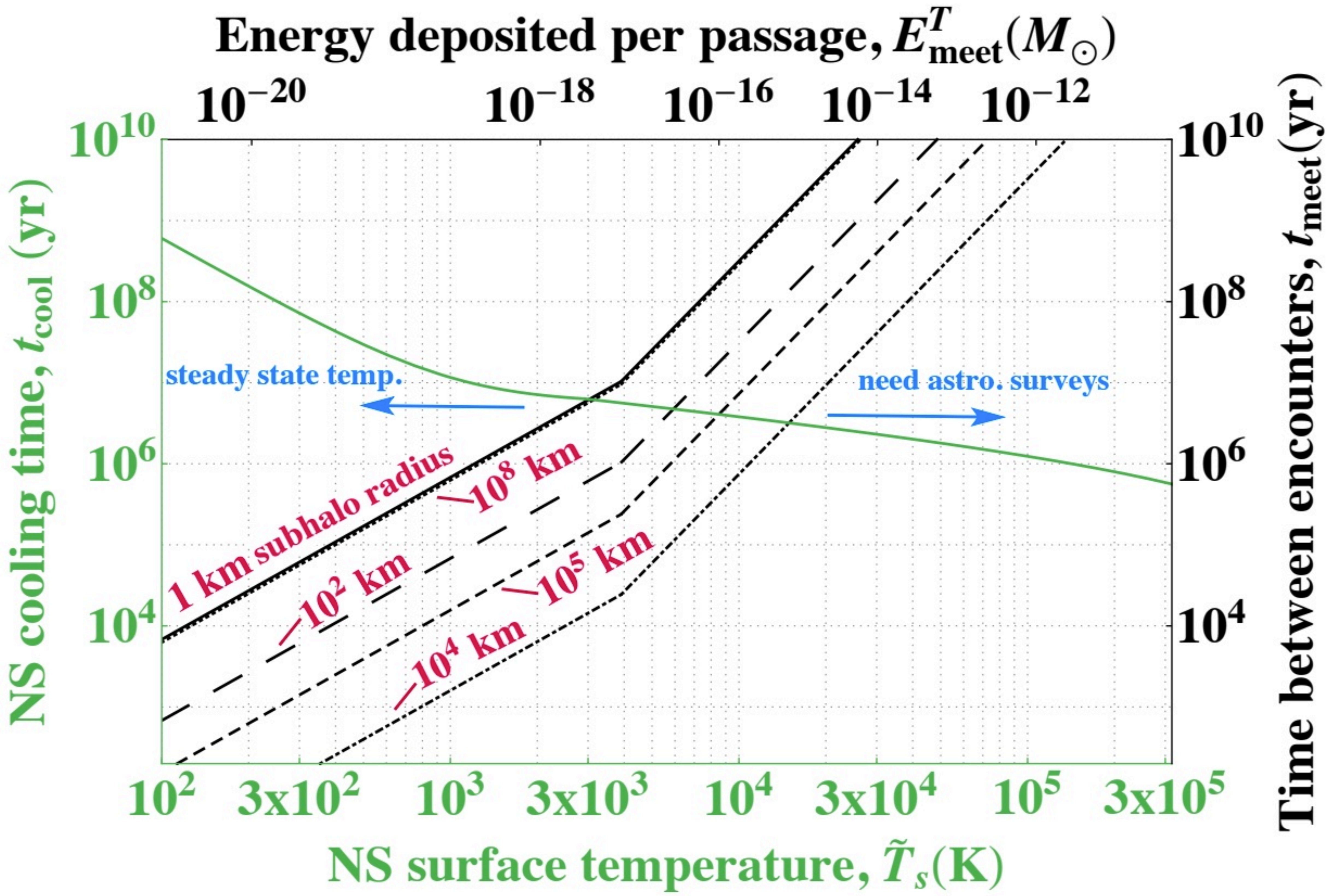
-YMW16 dispersion measure distances

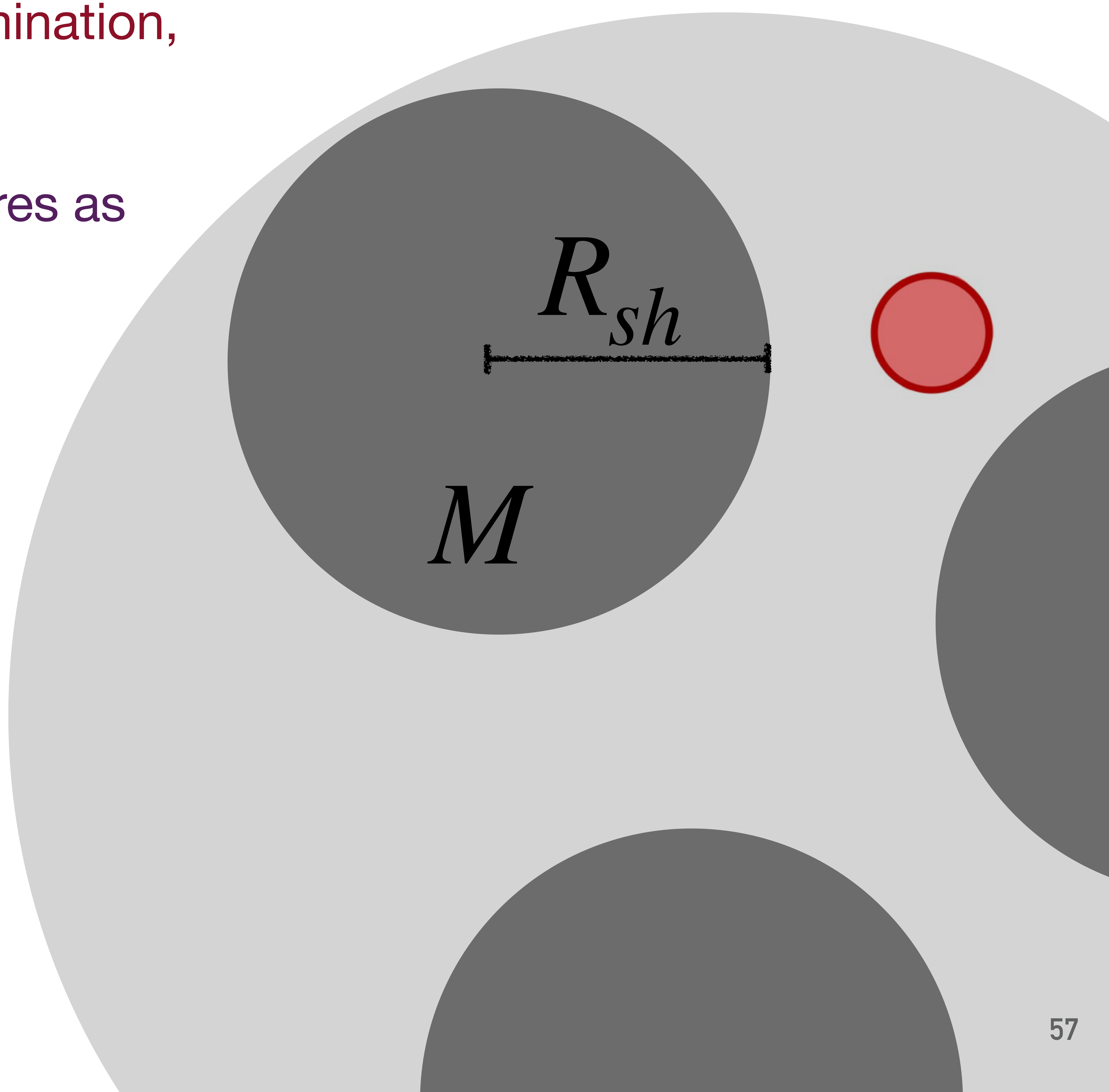
What about dark matter in subhalos?

JB, Kavanagh, Raj 2109.04582

- Subhalo dark matter arises from early matter domination, dissipative dark matter, extra small scale power

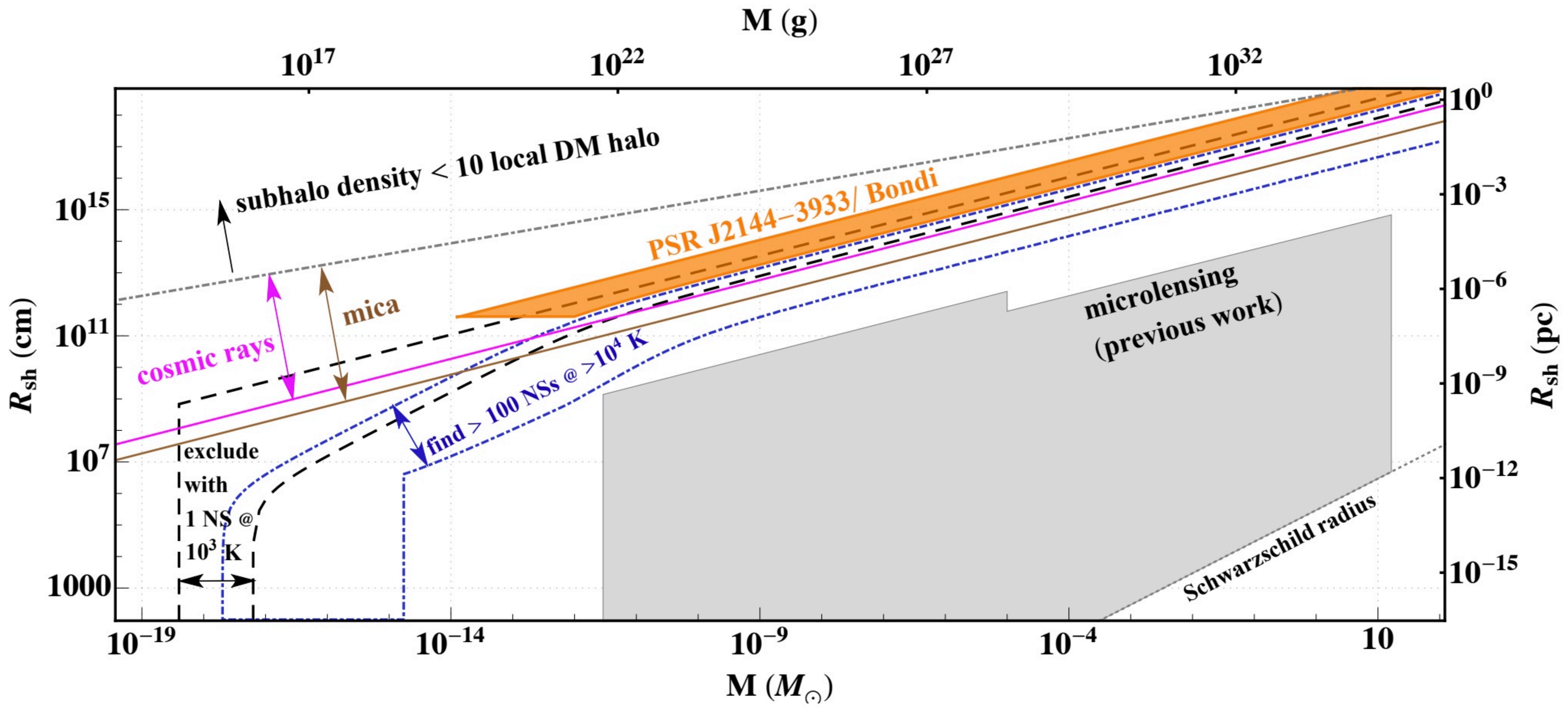
- Neutron stars could be heated to high temperatures as they pass through subhalos, dense with DM

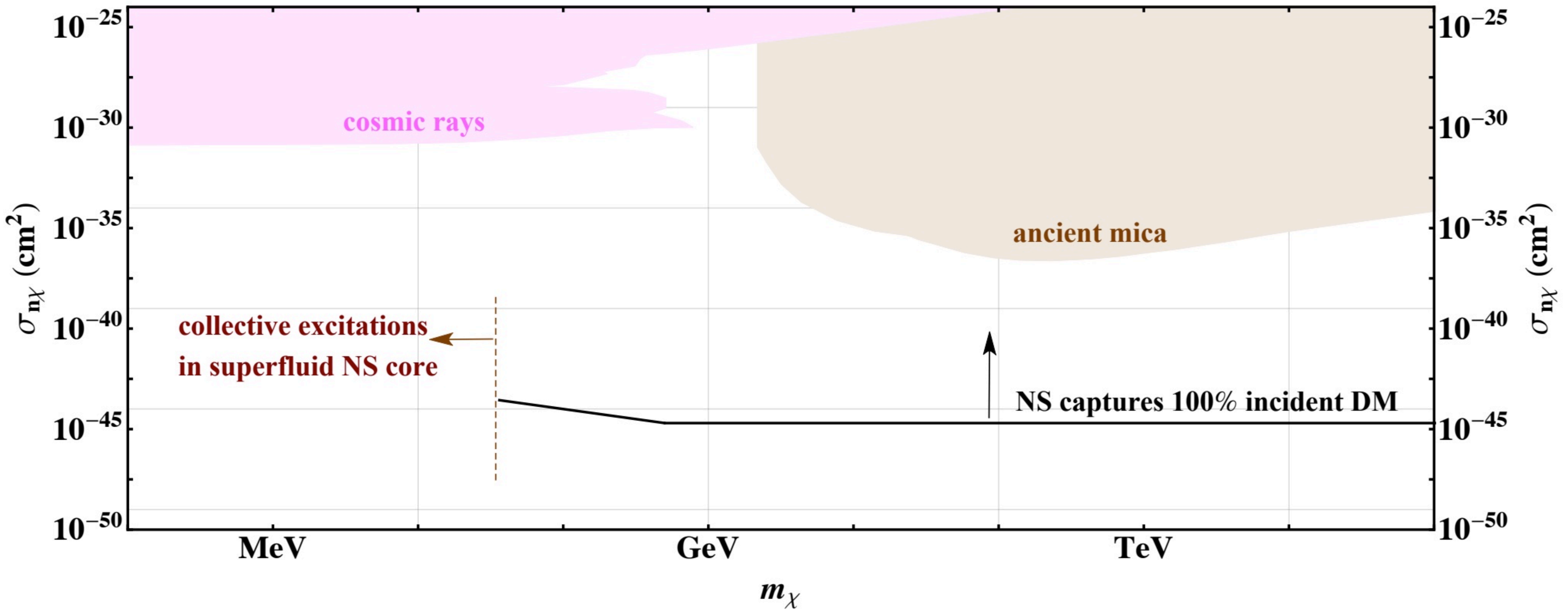




New bounds on subhalo dark matter from neutron stars

JB, Kavanagh, Raj 2109.04582





New bounds on subhalo dark matter from neutron stars

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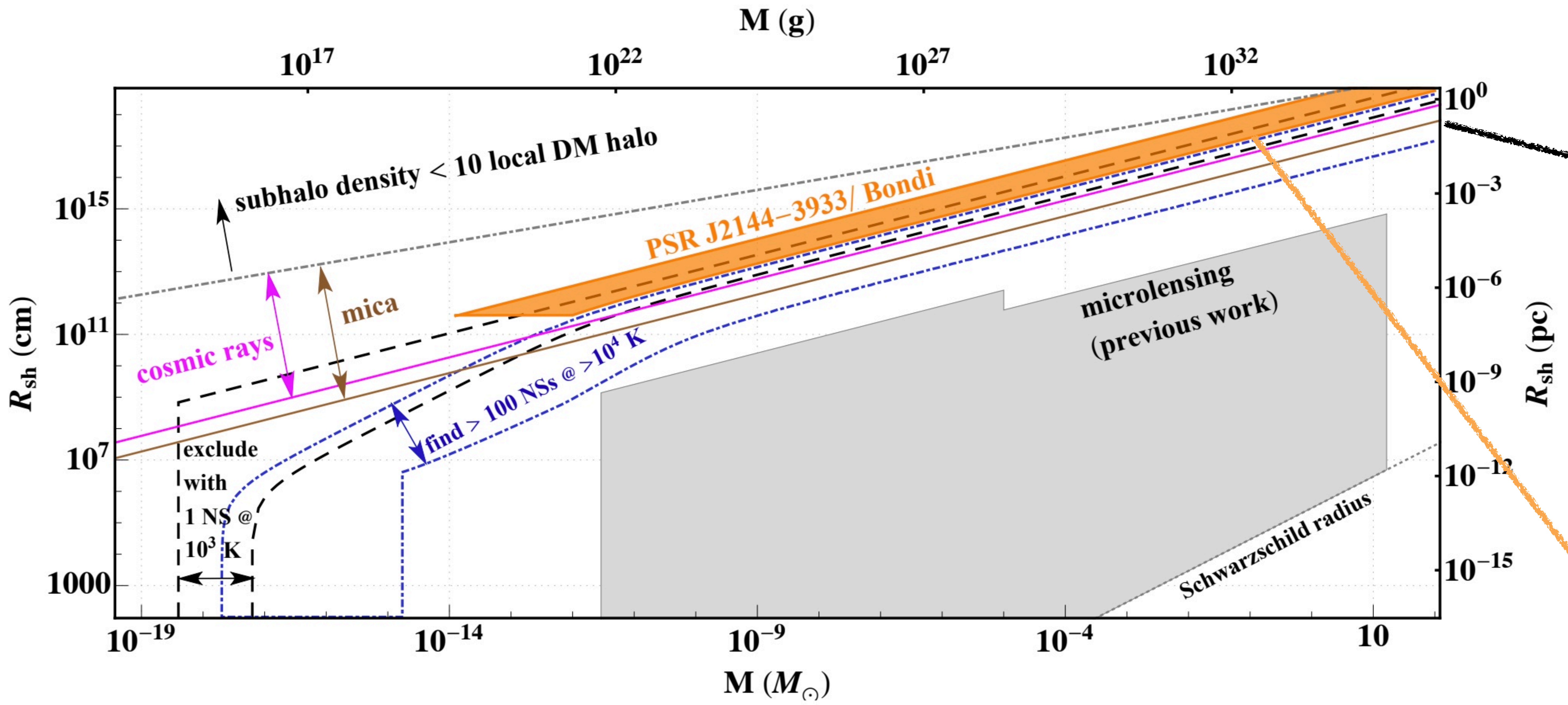
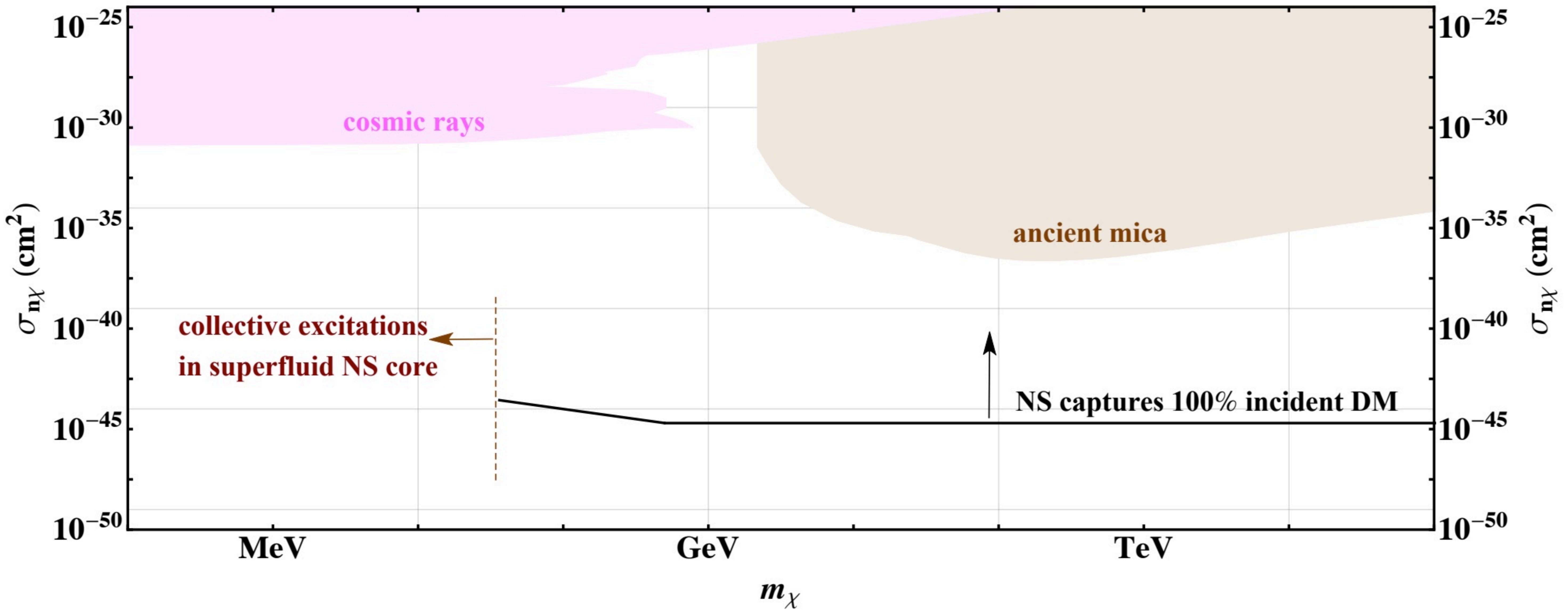
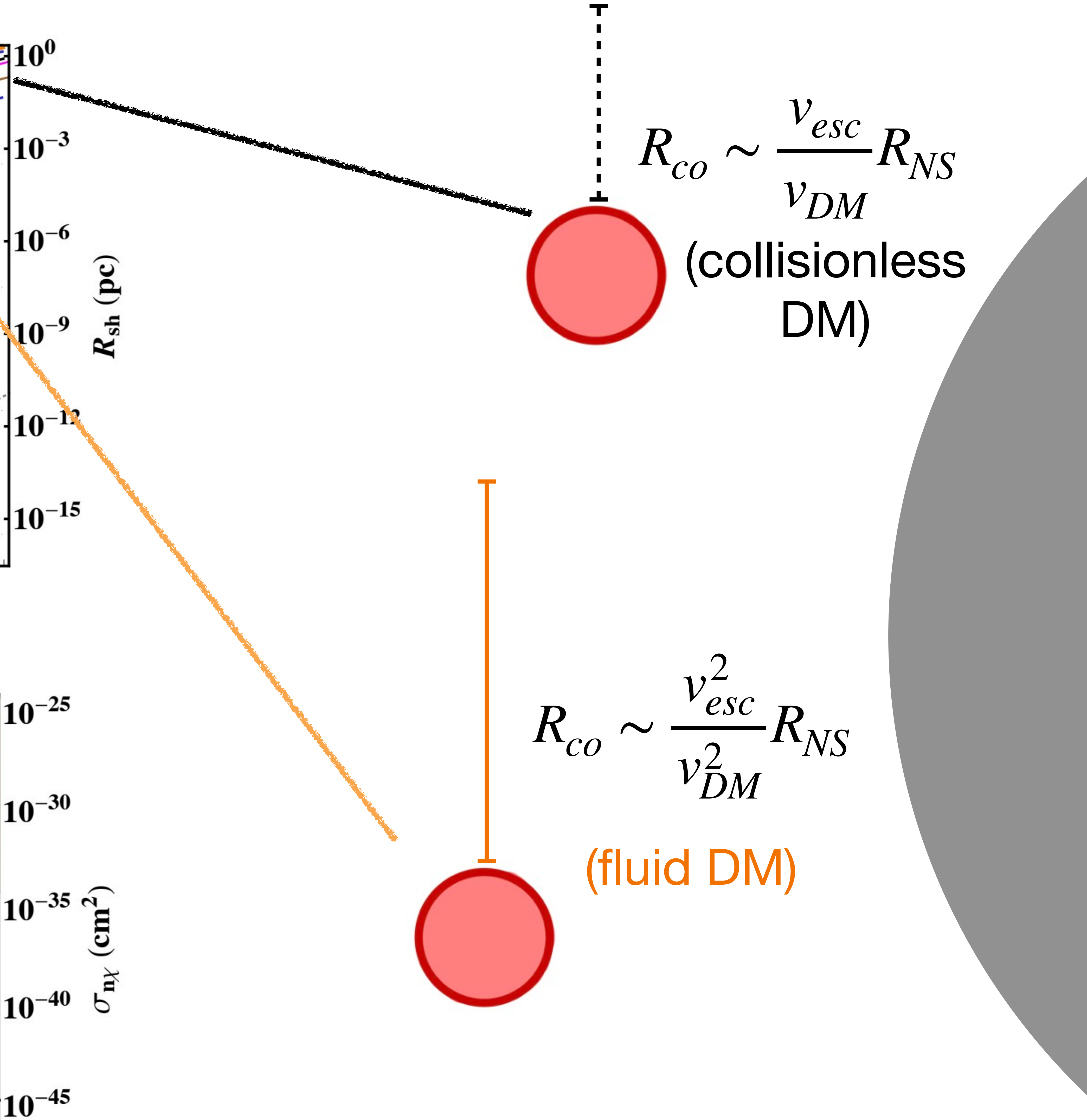






$$R_{co} \sim \frac{v_{esc}}{v_{DM}} R_{NS}$$

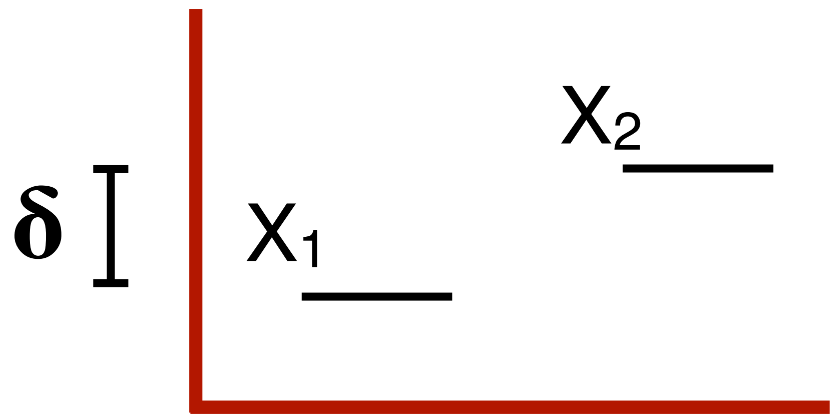
(collisionless DM)

$$R_{co} \sim \frac{v_{esc}^2}{v_{DM}^2} R_{NS}$$

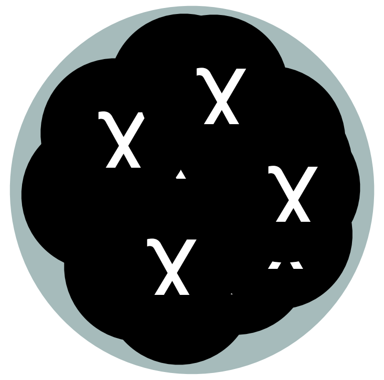
(fluid DM)

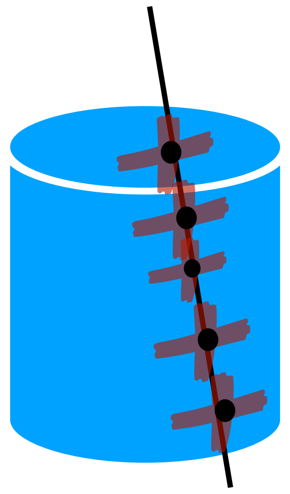
Dark Matter at the High Mass Frontier

- Higgsino dark matter at high recoil and in neutron stars

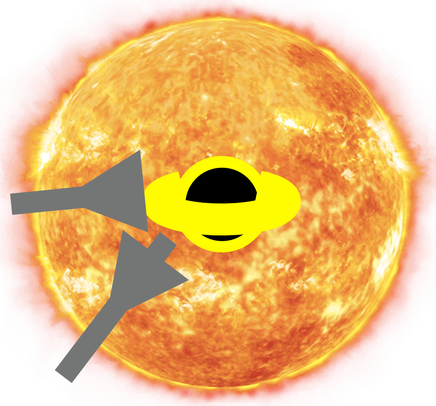


- DM composite formation, Migdal, multi scatter detection

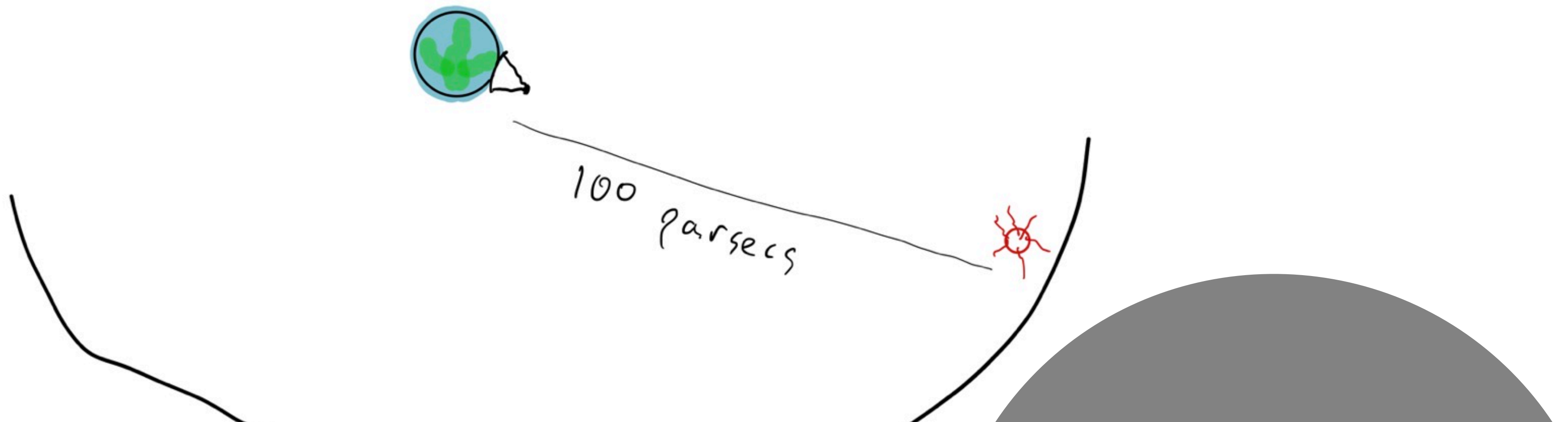


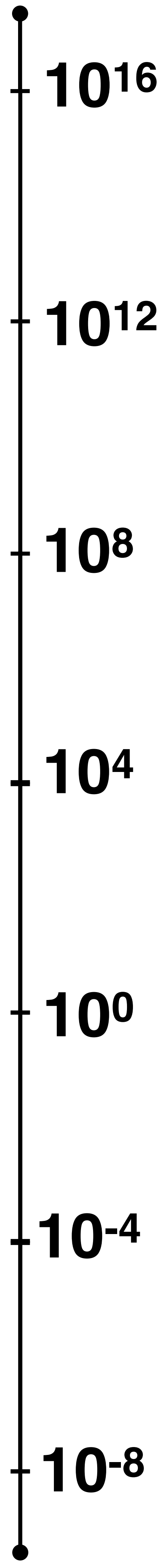


- Dark matter forming black holes in the Sun and Earth



- Thermal neutron star searches for (sub halo) dark matter

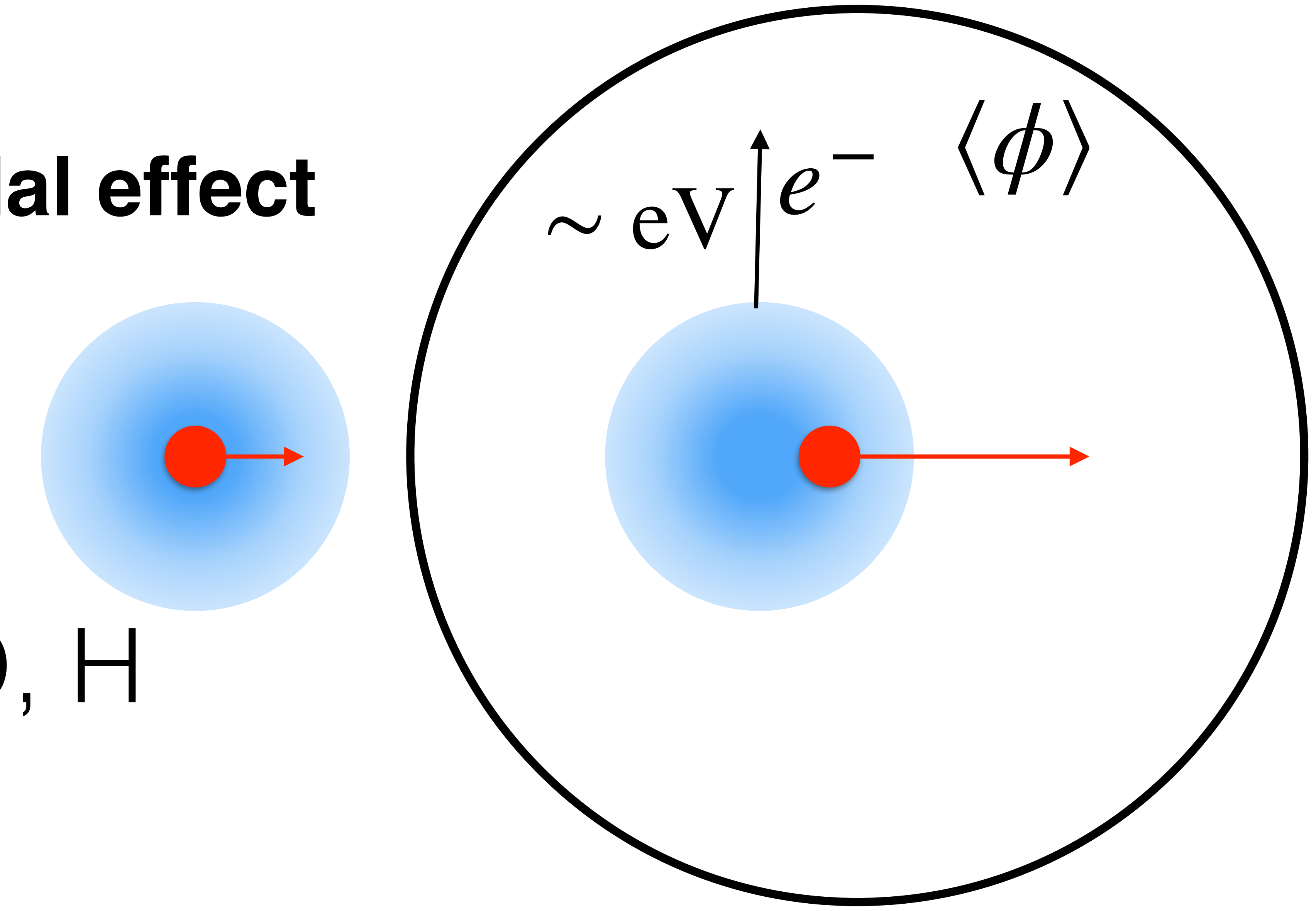




Thanks!

1) Ionization $R_X m_\phi \gg 1$

Migdal effect



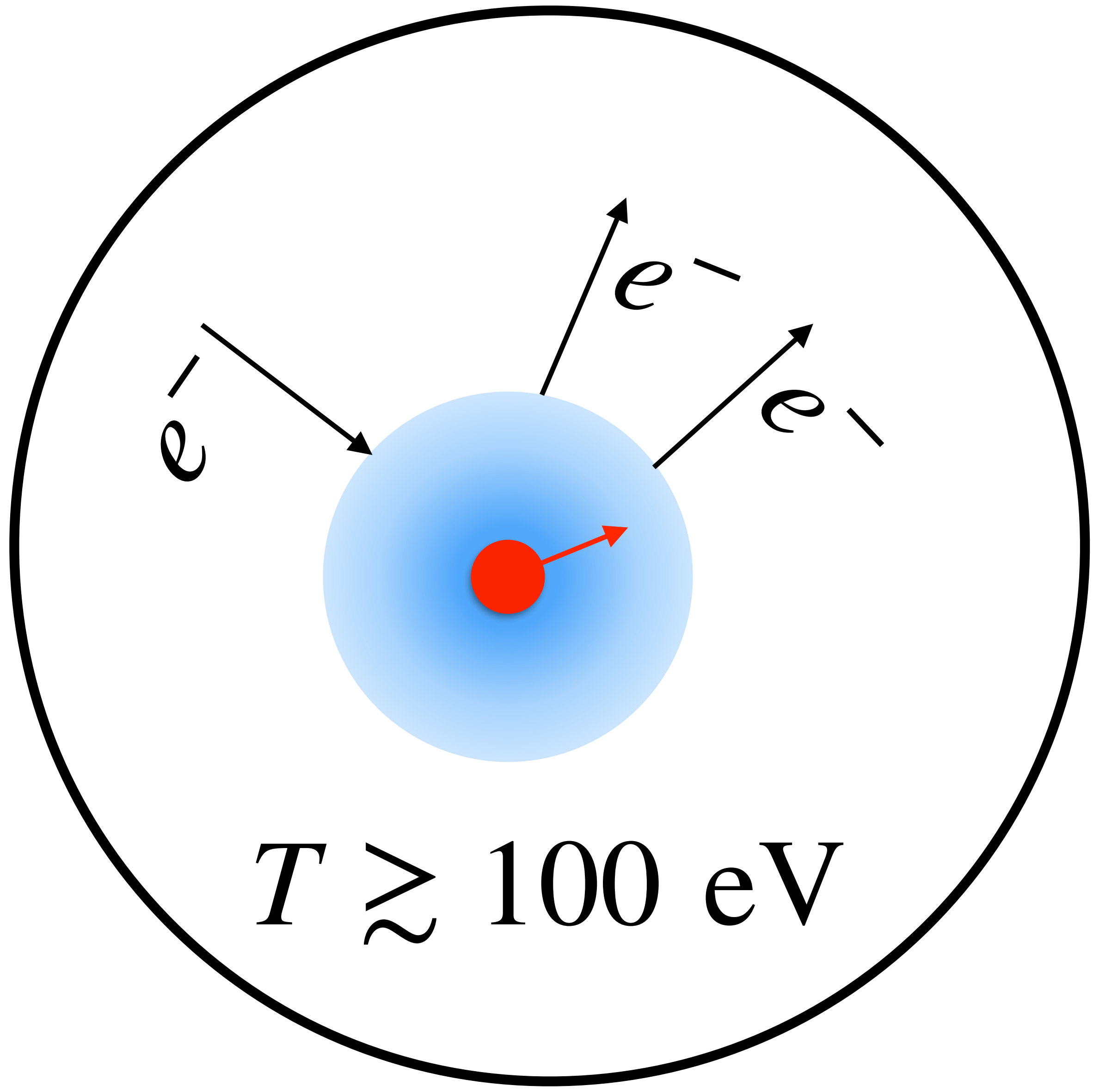
C, O, H

acceleration timescale:

$$\tau_{accel} \simeq (m_\phi v_X)^{-1}\left(1 + \frac{2V_n}{m_N v_X^2}\right)^{-\frac{1}{2}} \lesssim 10^{-18}\ \mathrm{s}\left(\frac{10\ \mathrm{keV}}{m_\phi}\right)$$

electrons are unbound w/ prob $f_e \gtrsim 10^{-2}$

Collisional ionization



ionization from e- impacts:

$$\left(f_e n_e v_N \sigma_i\right)^{-1} \lesssim 10^{-15}\ \mathrm{s}$$

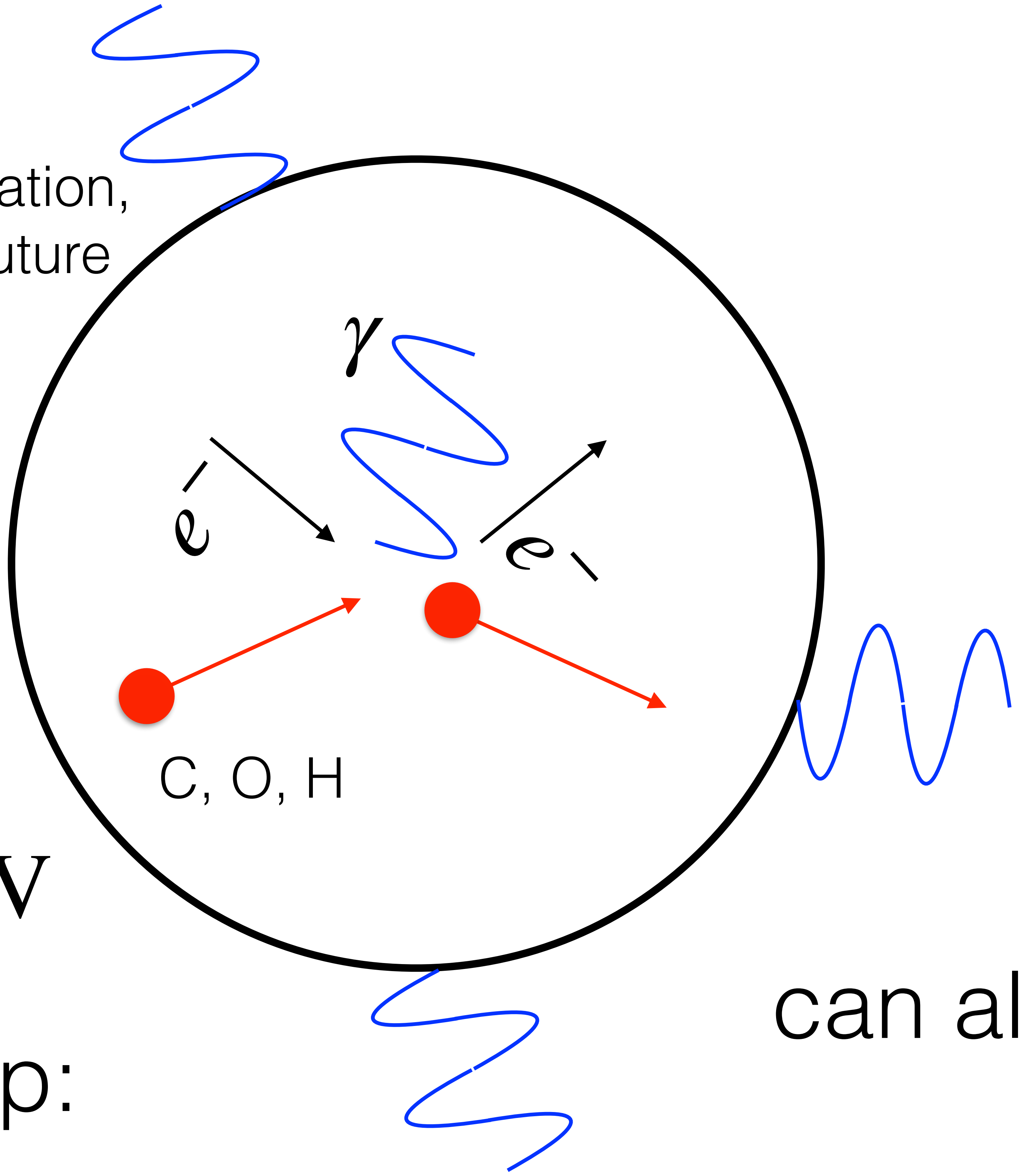
$n_e \sim 10^{23}\ \mathrm{cm}^{-3}$

$\sigma_i \gtrsim 10^{-17}\ \mathrm{cm}^2$

$T \gtrsim 100$ eV → ionized composite interior

2) Bremmsstrahlung

radiative recombination, line emission for future work



$T \gtrsim 100$ eV

photon mfp:

$$(n_e \sigma_T)^{-1} \simeq 5 \text{ cm} \gg R_X$$

$$\sigma_T \simeq 10^{-24} \text{ cm}^2$$

radiated energy rate for plasma:

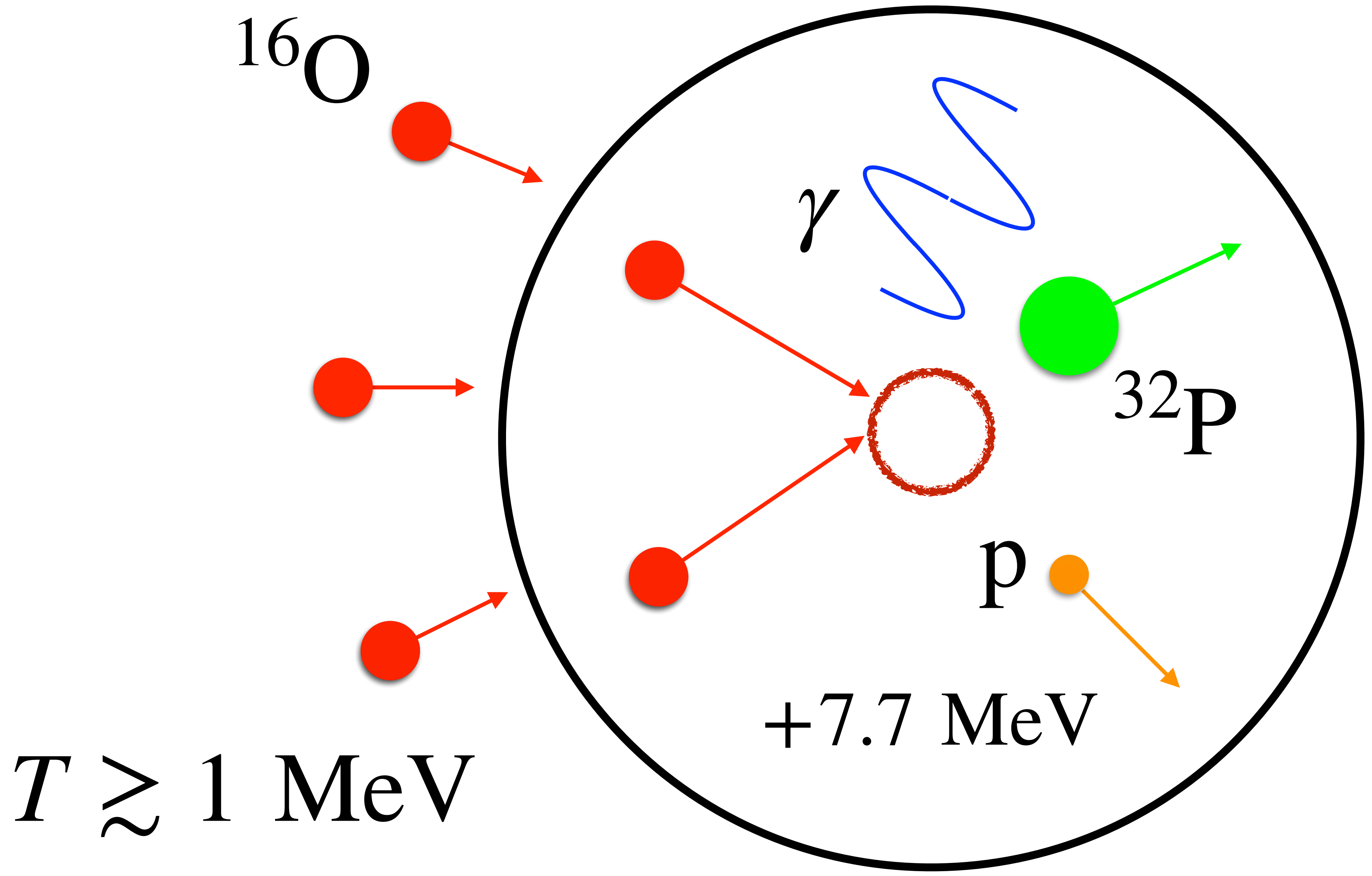
$$\dot{E}_{brem} = \int j_\omega(T)\, d\omega dV \simeq$$

$$\simeq 10^{10} \text{ GeV s}^{-1} \left(\frac{m_X}{\text{TeV}}\right)^{\frac{3}{2}} \left(\frac{R_X}{\text{nm}}\right)^{3} \left(\frac{g_\phi}{1}\right)^{-\frac{1}{2}} \left(\frac{g_n}{10^{-10}}\right)^{\frac{1}{2}}$$

can also compute stopping length:

$$L_{stop} \simeq 2 \text{ km} \left(\frac{m_X}{\text{TeV}}\right)^{\frac{3}{2}} \left(\frac{m_\phi}{10 \text{ keV}}\right)^{2} \left(\frac{g_n}{10^{-10}}\right)^{-\frac{1}{2}} \left(\frac{g_\phi}{1}\right)^{-\frac{3}{2}} \left(\frac{v_X}{200 \text{ km s}^{-1}}\right)^{3}$$

3) Fusion



reaction rate per unit volume:

$$R_{th}(T \simeq \mathrm{MeV}) \sim 10^{24}\ \mathrm{cm}^{-3}\ \mathrm{s}^{-1} \left(\frac{\rho}{1\ \mathrm{g\ cm}^{-3}}\right)^2$$

Caughlan & Fowler, 1988

average energy release: $\bar{Q} \sim 10$ MeV

rare to occur while in detection volume:

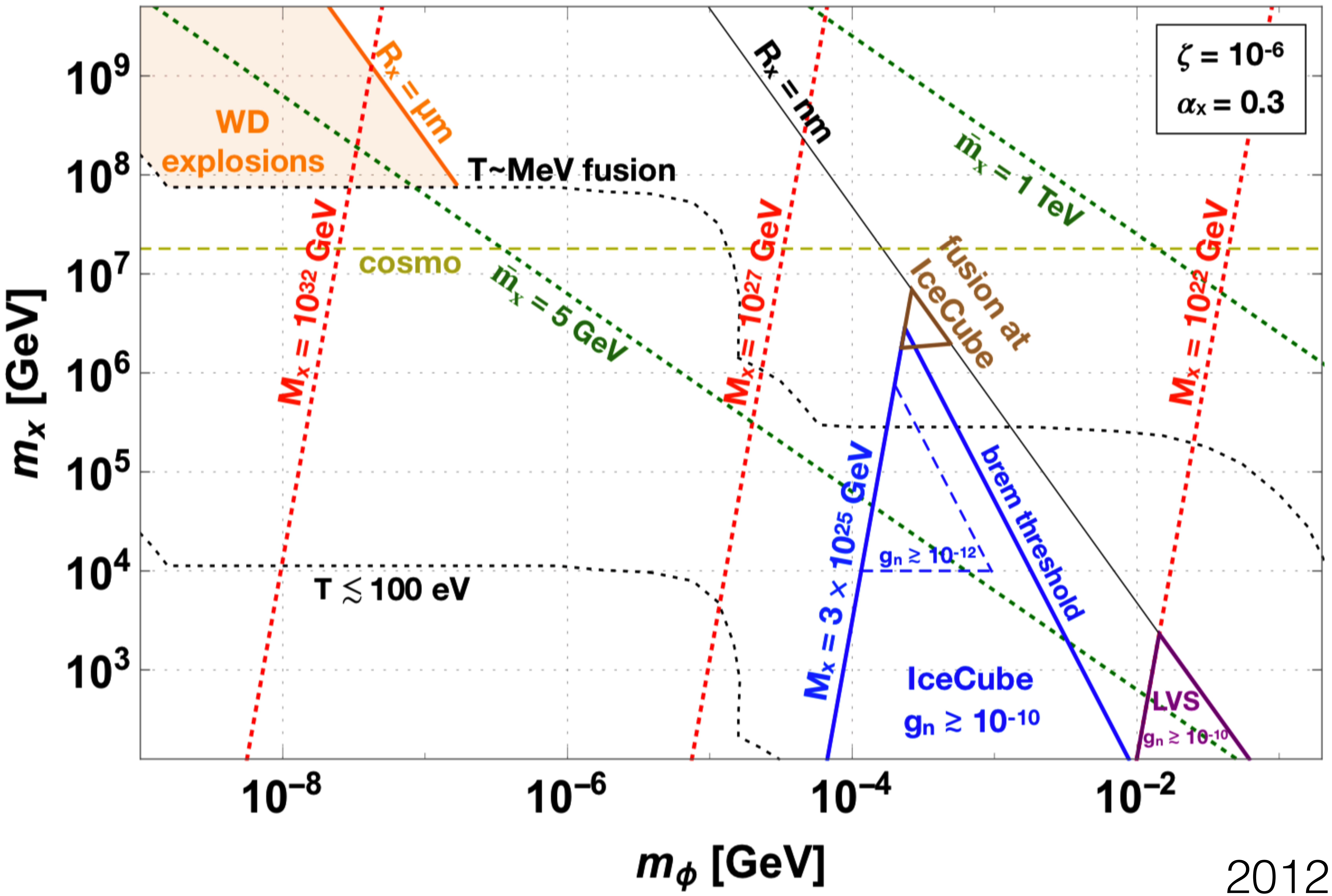
more complete reaction network left for future work

(e.g. disintegration/recapture)

SNO+ too small $\longrightarrow M_X \lesssim 10^{22}$ GeV

IceCube requires $T \gtrsim 5$ MeV $\longrightarrow$ ~1 reaction per crossing

Parameter space for detection: 2012.10998

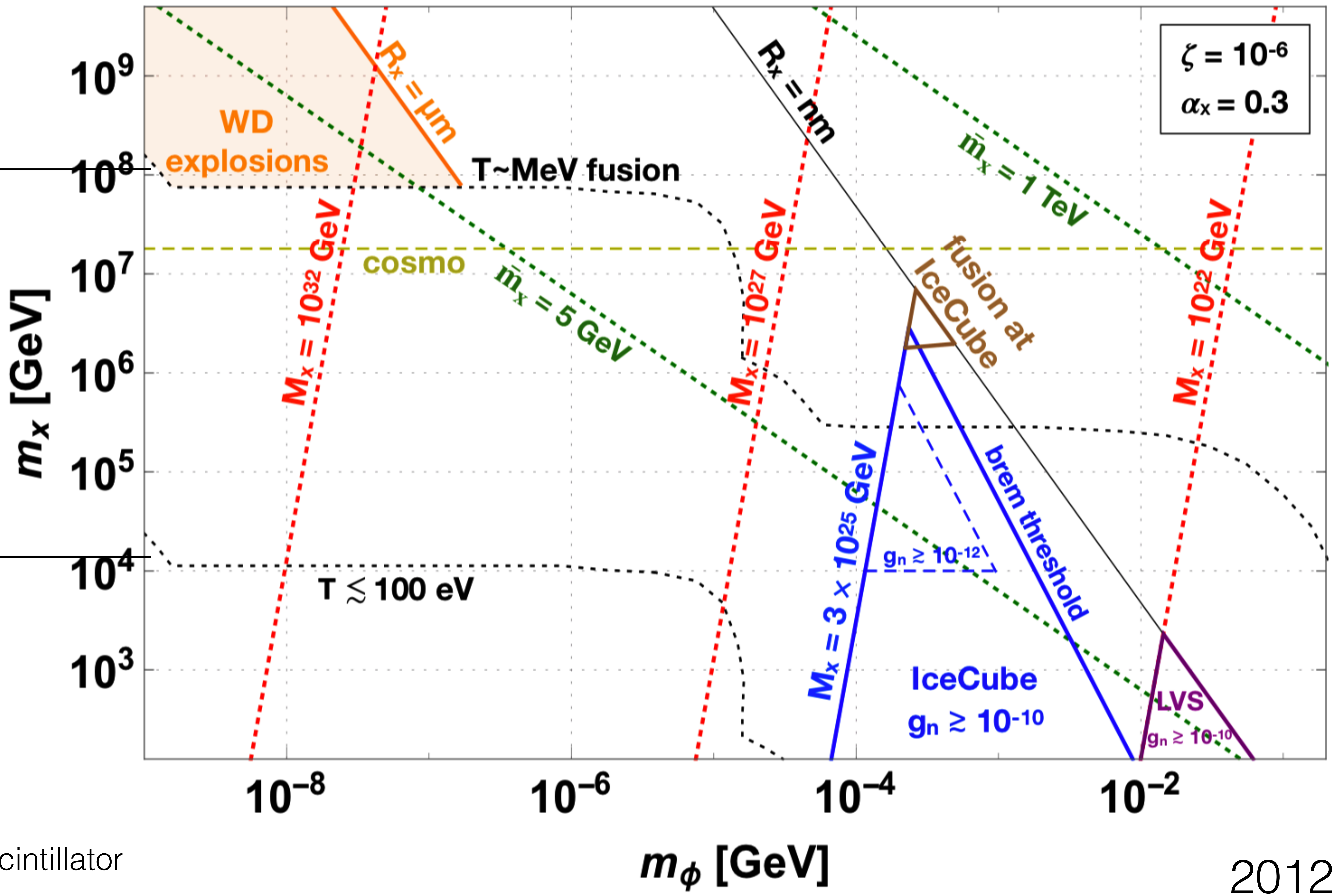


2012.10998

Parameter space of potential detectability:

increasing radius/mass

stellar cooling constraints



stellar cooling constraints

increasing temperature (fixed coupling)
increasing composite binding energy

LVS = large volume scintillator

2012.10998

1611.05852
1709.07882

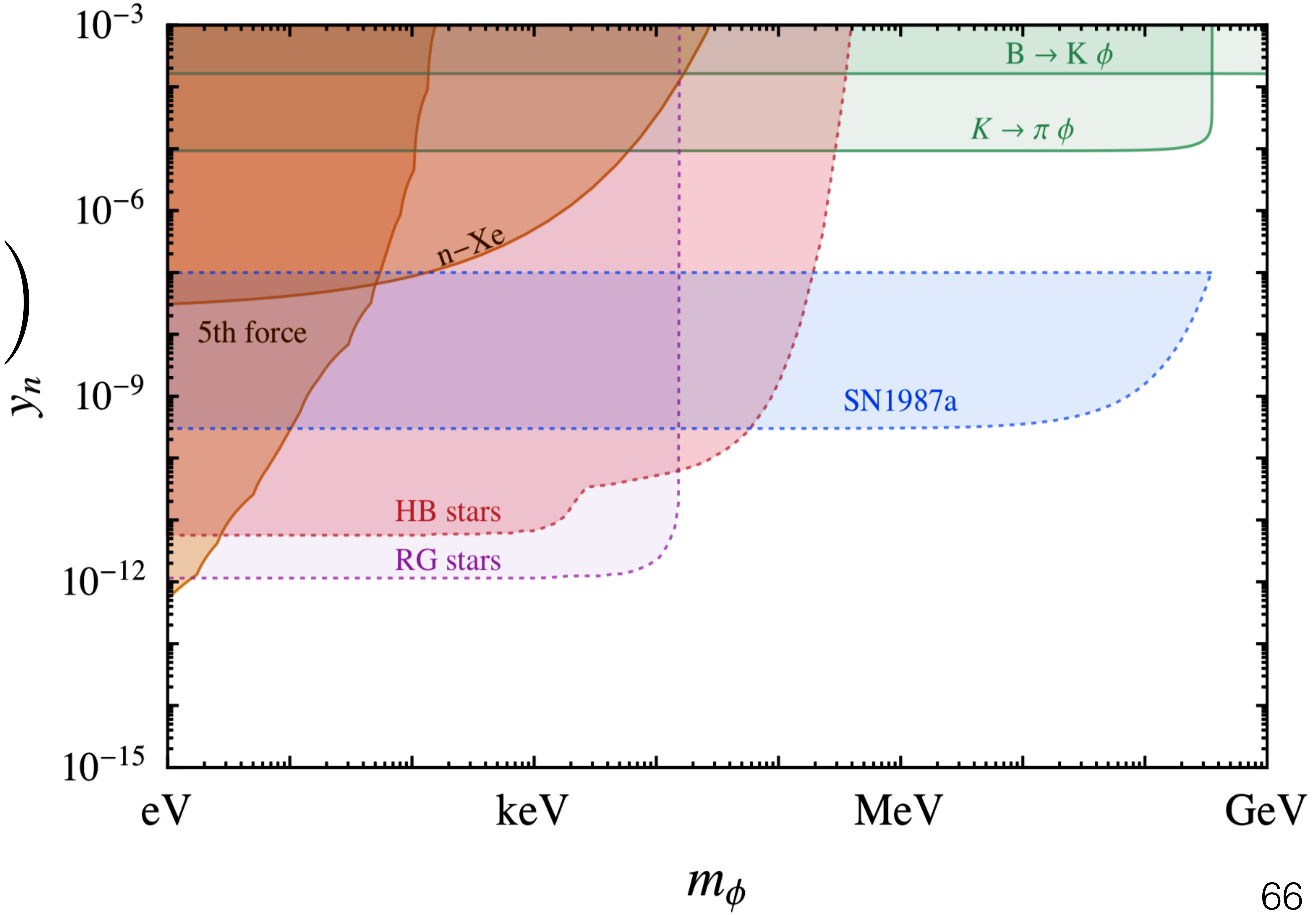
Stellar cooling bounds on coupling limit the kinetic energy:

$$\Delta E \simeq A g_n \left(\frac{m_X}{g_\phi}\right)$$

$$\lesssim \mathrm{keV} \left(\frac{g_n}{10^{-10}}\right)\left(\frac{m_X}{\mathrm{TeV}}\right)\left(\frac{1}{g_\phi}\right)\left(\frac{A}{10}\right)$$

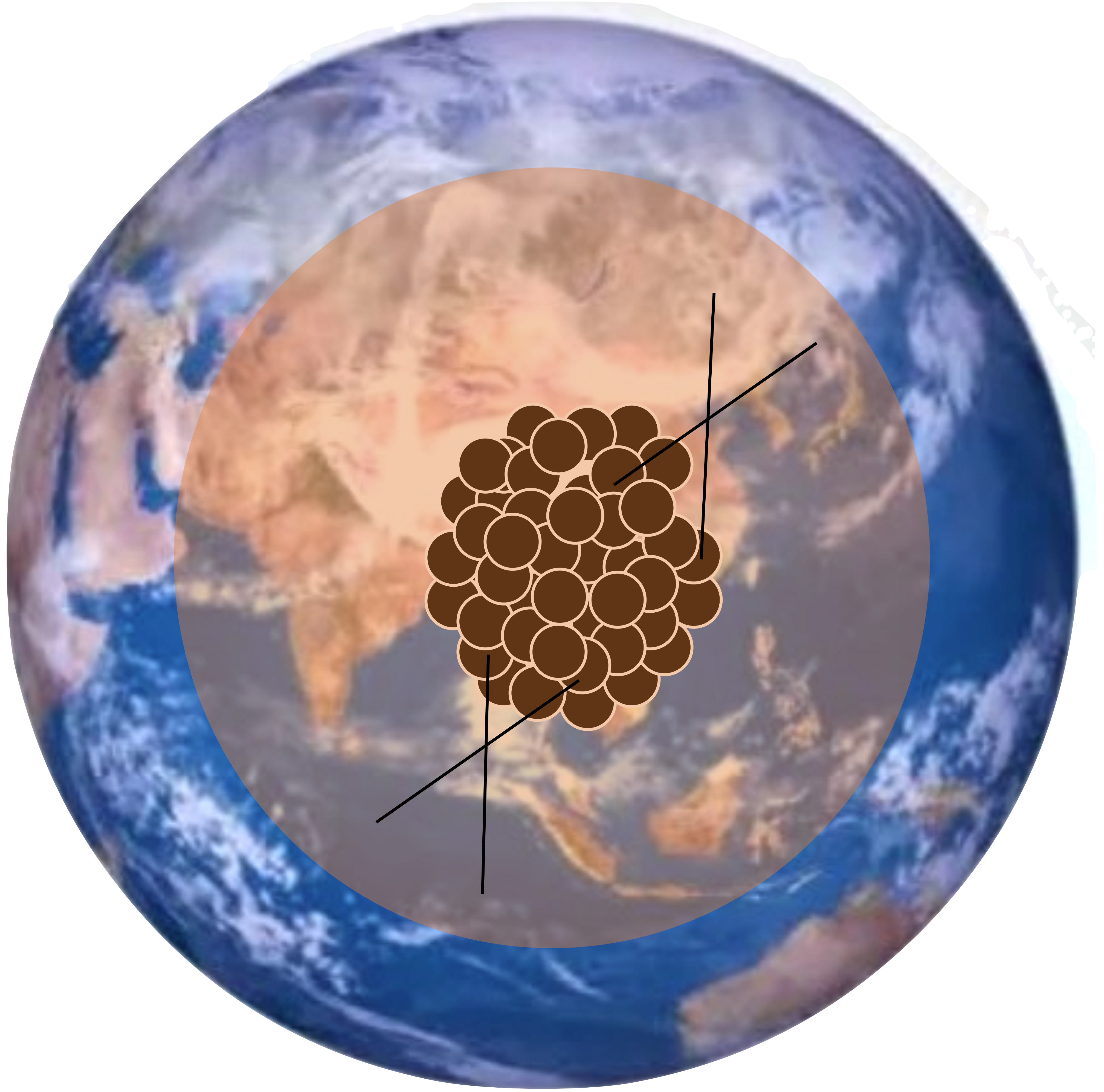
for ϕ masses < eV

5th force searches further constrain coupling

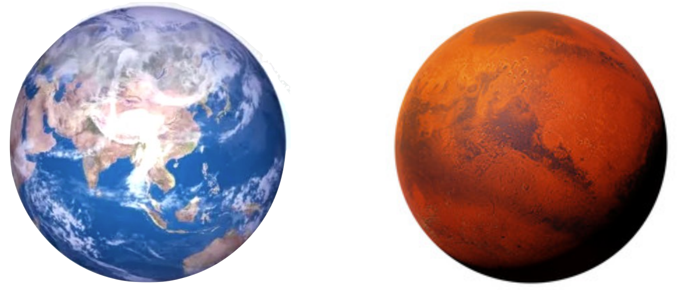


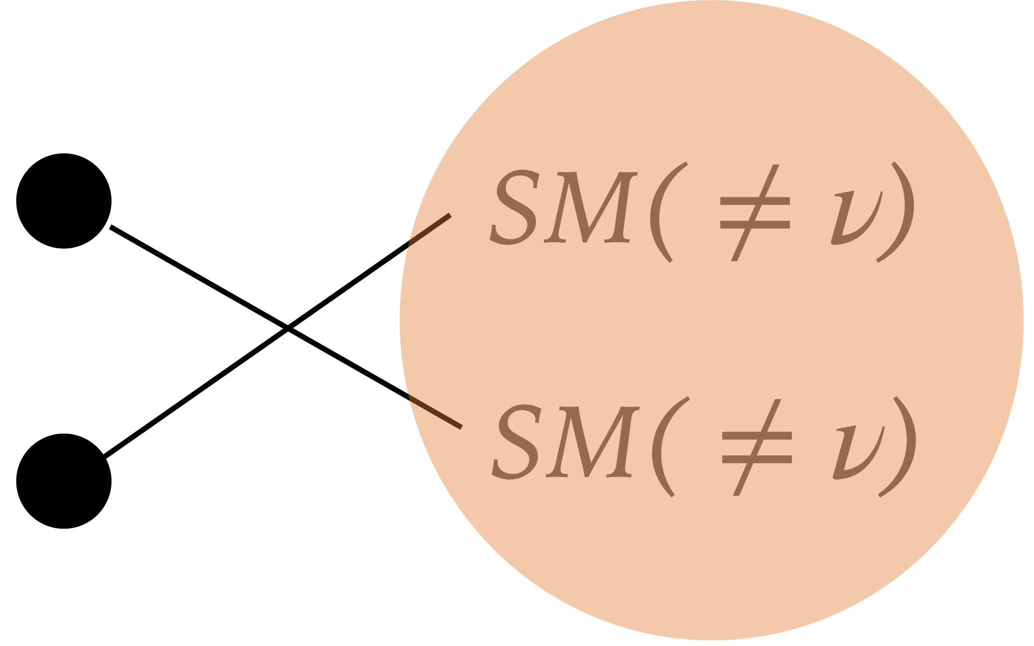
Sphere of DM particles in the Earth settle at thermal radius:

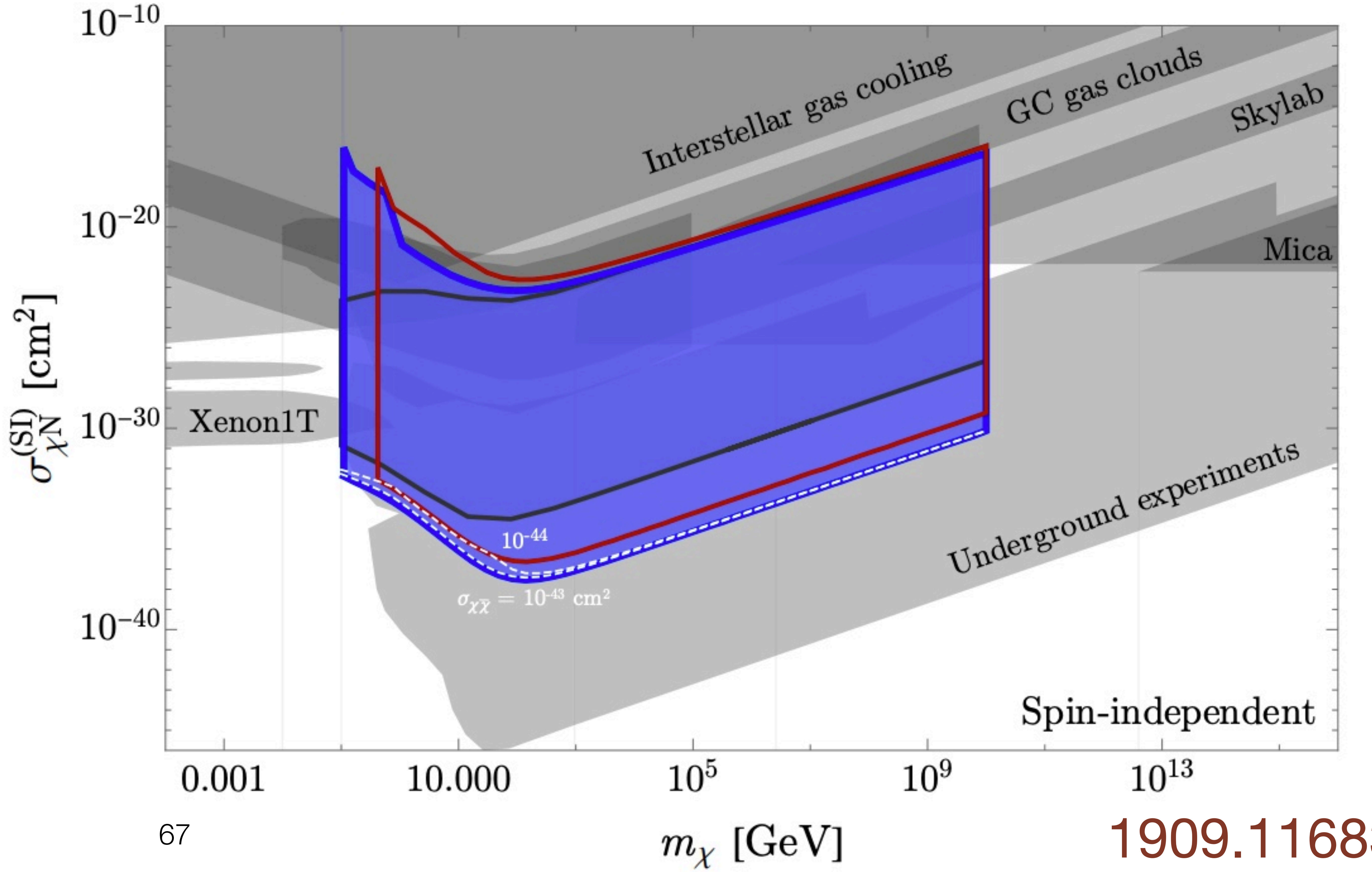
$$\langle E_k \rangle \simeq -2\langle V \rangle \longrightarrow r_{th} = \sqrt{\frac{9T_\oplus}{4\pi G \rho_\oplus m_\chi}} \lesssim \mathcal{O}(\mathrm{km})$$



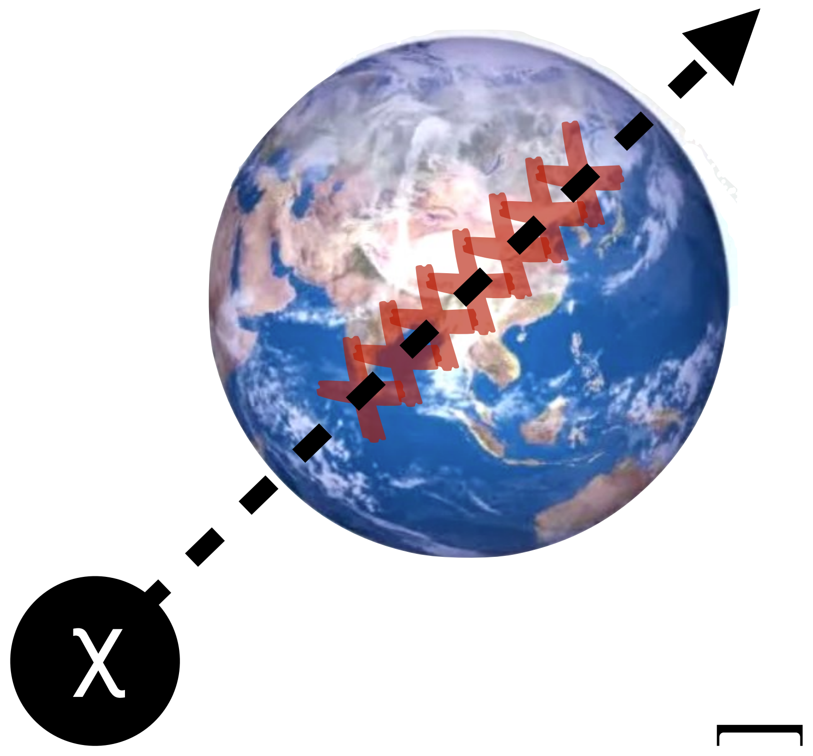
If they annihilate:
Earth/Martian heating!







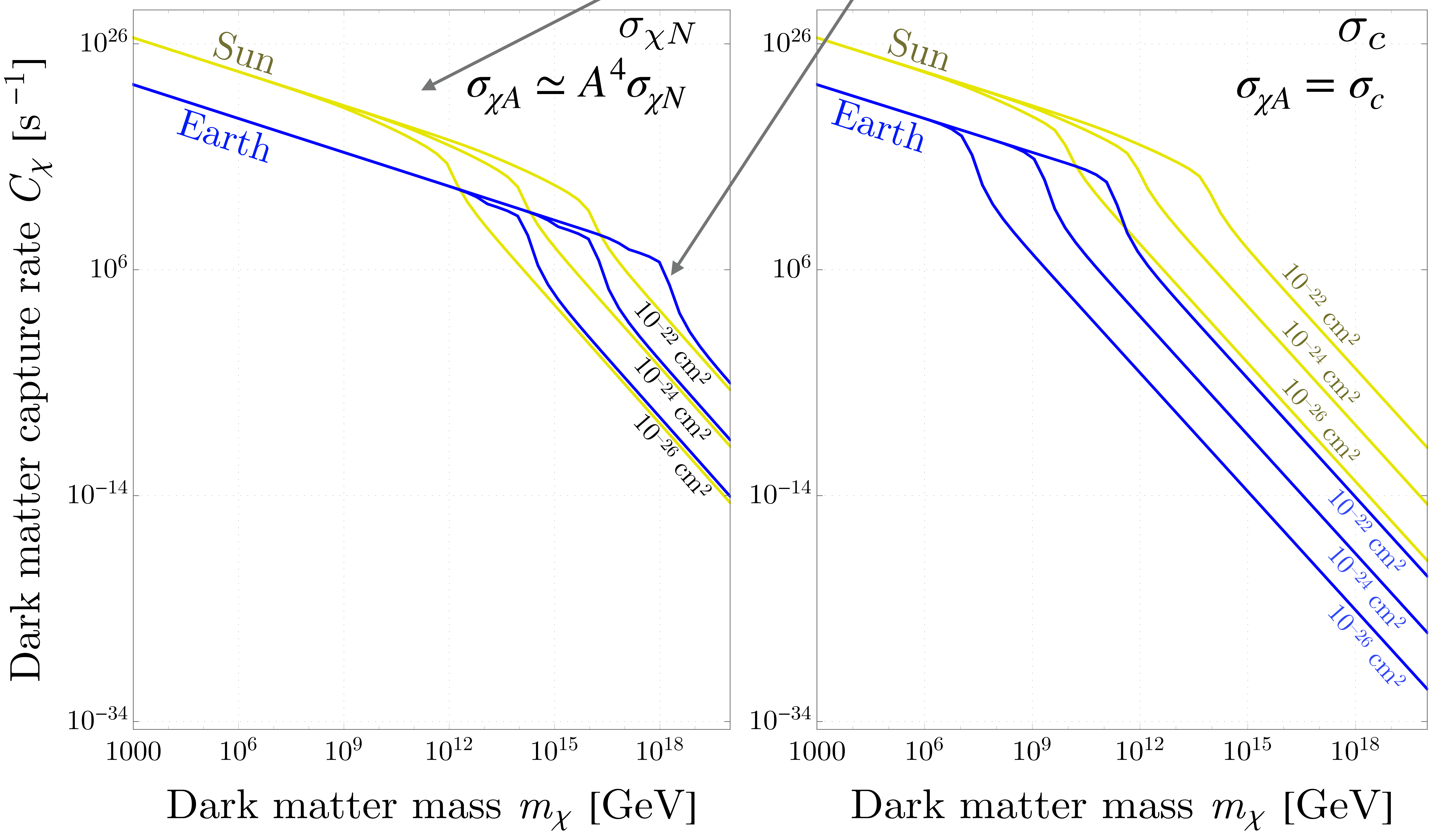
1909.11683



Single Scatter Capture

Multi Scatter Capture

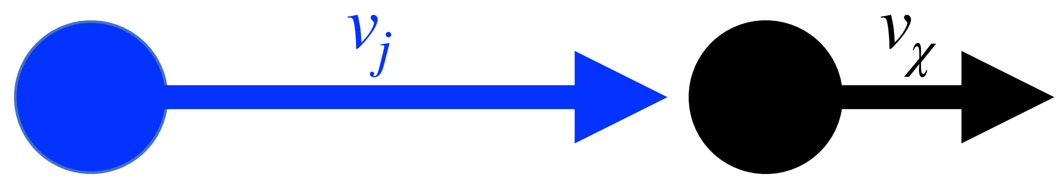
Capture on core / low velocity MB tail



Thermal velocity of nuclei $v_j \simeq \sqrt{\frac{3T_\oplus}{m_j}}$

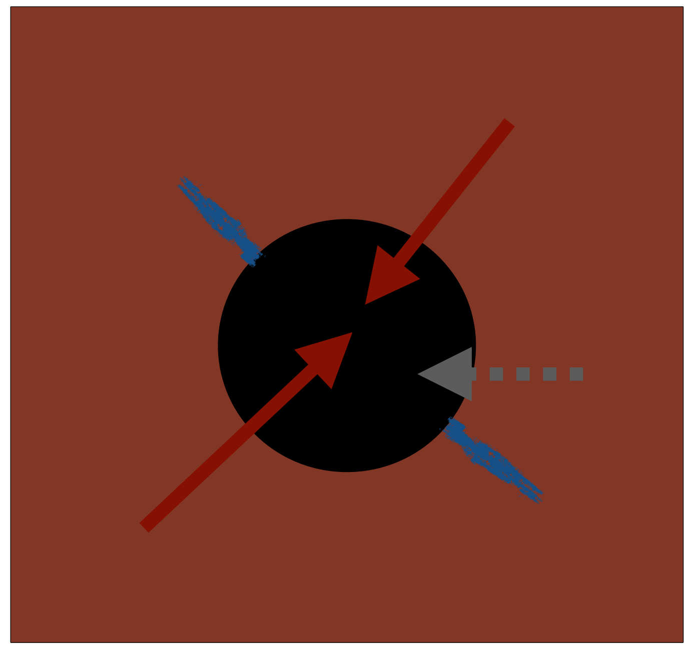
$$\left(\frac{dE}{dt}\right)_{in} \simeq -\rho_j \sigma_{\chi j} v_\chi^3$$ 'inertial' regime $v_\chi \gg v_j$

$$\left(\frac{dE}{dt}\right)_{vis} \simeq -\rho_j \sigma_{\chi j} v_j v_\chi^2$$ 'viscous' regime $v_\chi \ll v_j$



$$\left(\frac{dE}{dt}\right)_{vis} \ll \left(\frac{dE}{dt}\right)_{in}$$ → **Use viscous regime scaling, gives longest thermalization time**

BH evolution



$$\frac{dM_{BH}}{dt} \simeq B \times M_{BH}^2 - \frac{H}{M_{BH}^2} + C$$

Bondi Accretion:
- Causes BH to grow
- Larger for larger black holes (lighter DM)

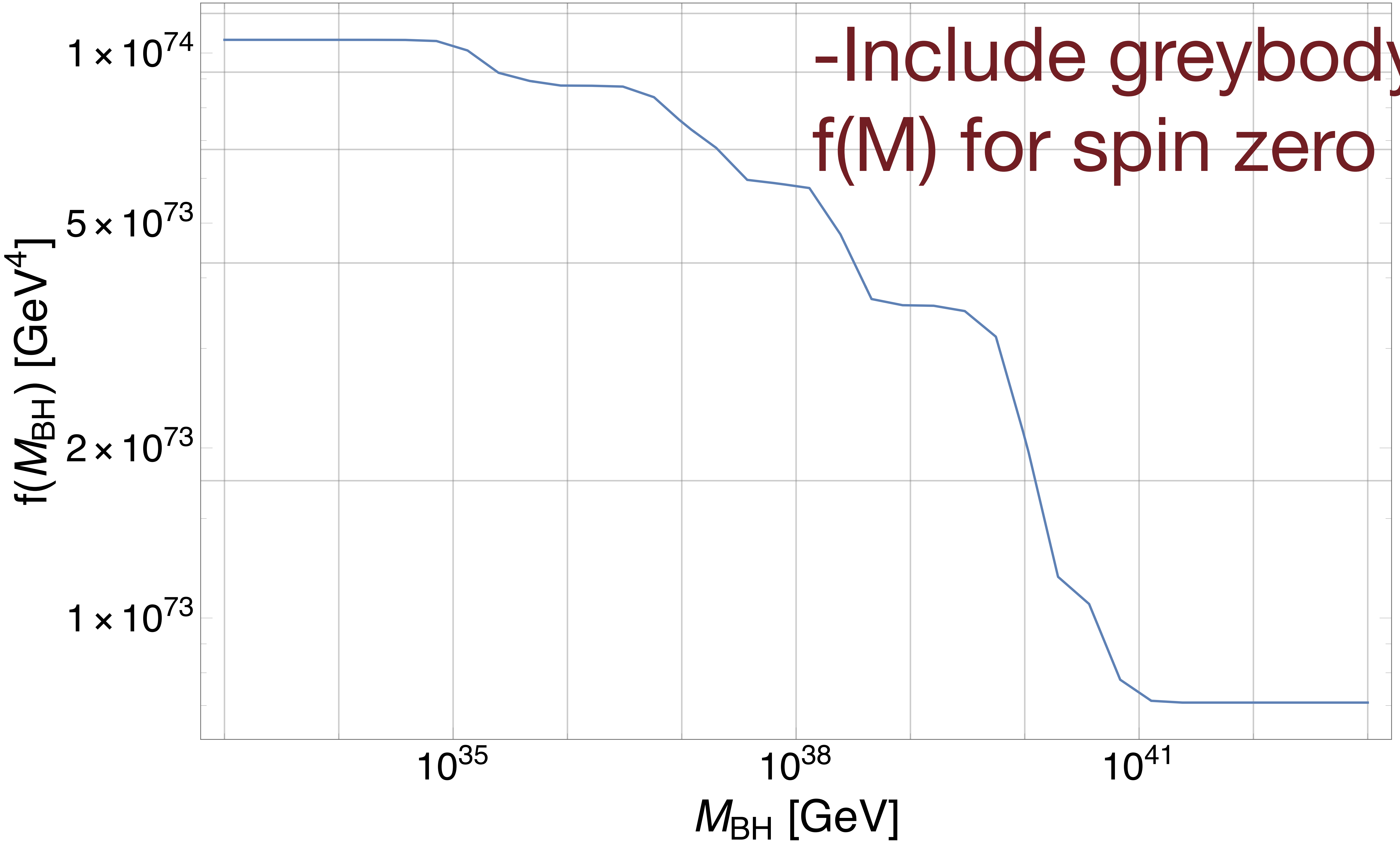
Hawking radiation:
- Causes BH to shrink
- Larger for smaller BHs (heavier DM)

Dark Matter Accretion:
- Causes BH to grow
- Independent of DM or BH mass
- Has a maximum value of $m_\chi \Phi_\chi \simeq 3000$ TW $\simeq 10^{25}$ GeV/s

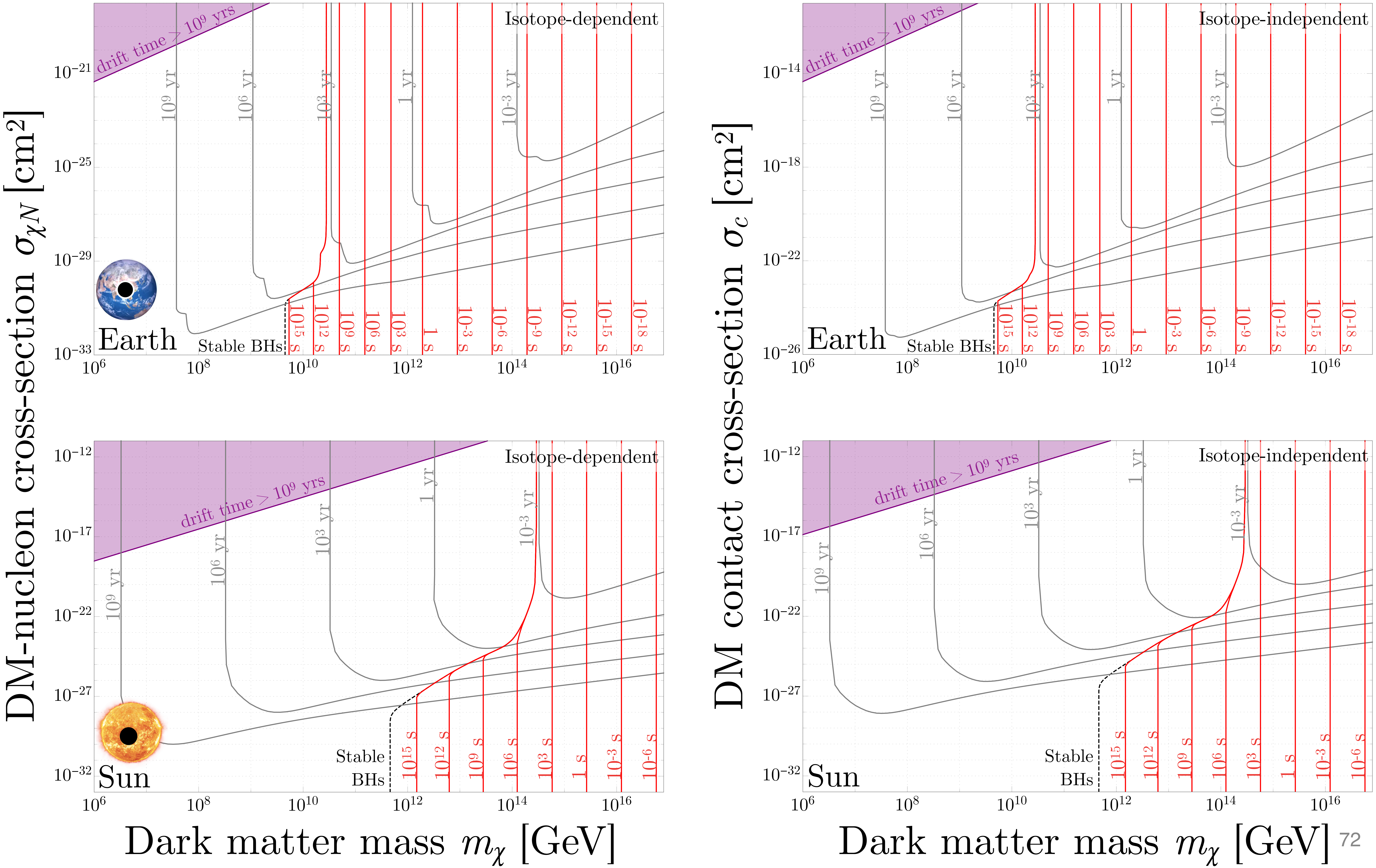
	Earth	**Sun**
Max destructive m_χ Hawking = Bondi + $m_\chi \Phi_\chi$	2.7×10^{10} GeV	3×10^{14} GeV
Min evaporative m_χ Hawking = Bondi	4.5×10^{9} GeV	4.6×10^{11} GeV

BH evolution

$$\frac{\mathrm{d}M_{BH}}{\mathrm{d}t} = \frac{4\pi\rho_{\oplus}(GM_{BH})^2}{c_s^3} - \frac{f(M_{BH})}{15360\pi(GM_{\mathrm{BH}})^2} + m_\chi C_\chi$$



-Include greybody factor f(M) for spin zero BH


DM-nucleon cross-section $\sigma_{\chi N}$ [cm^2]
DM contact cross-section σ_c [cm^2]
Dark matter mass m_χ [GeV]
Dark matter mass m_χ [GeV]
Isotope-dependent
Isotope-independent
drift time > 10^9 yrs
Earth
Sun
Stable BHs
Stable BHs
10^9 yr
10^6 yr
10^3 yr
1 yr
10^{-3} yr
10^{15} s
10^{12} s
10^9 s
10^6 s
10^3 s
1 s
10^{-3} s
10^{-6} s
10^{-9} s
10^{-12} s
10^{-15} s
10^{-18} s

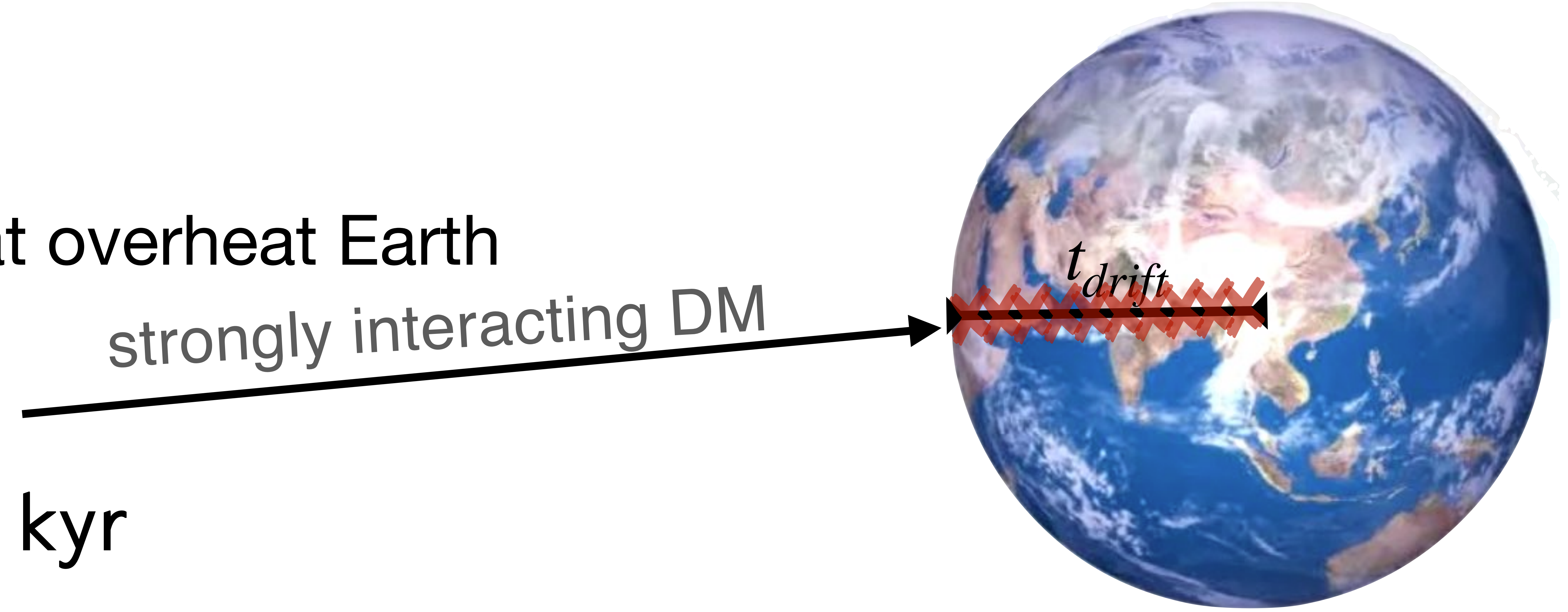
For destructive BHs:
Exclude DM models that form faster than a billion years

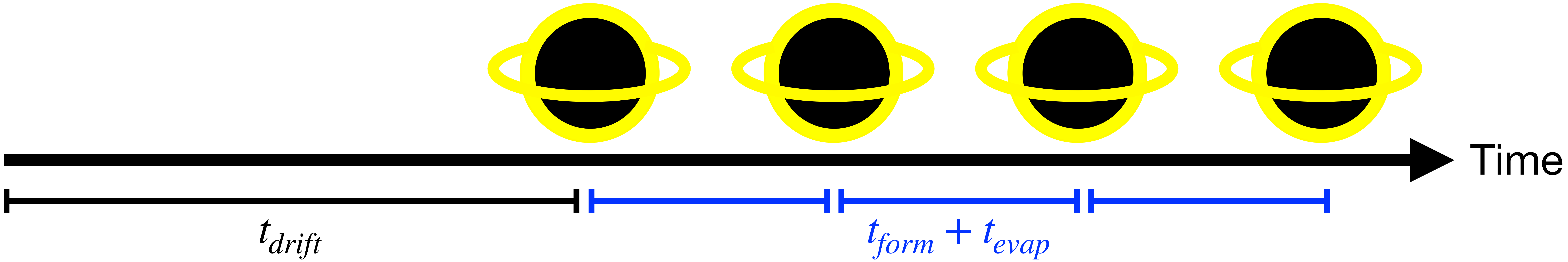
For evaporating BHs:
Exclude DM models that overheat Earth

(a) $t_{drift} \lesssim 1$ Gyr

(b) $t_{evap} + t_{form} \lesssim 1$ kyr

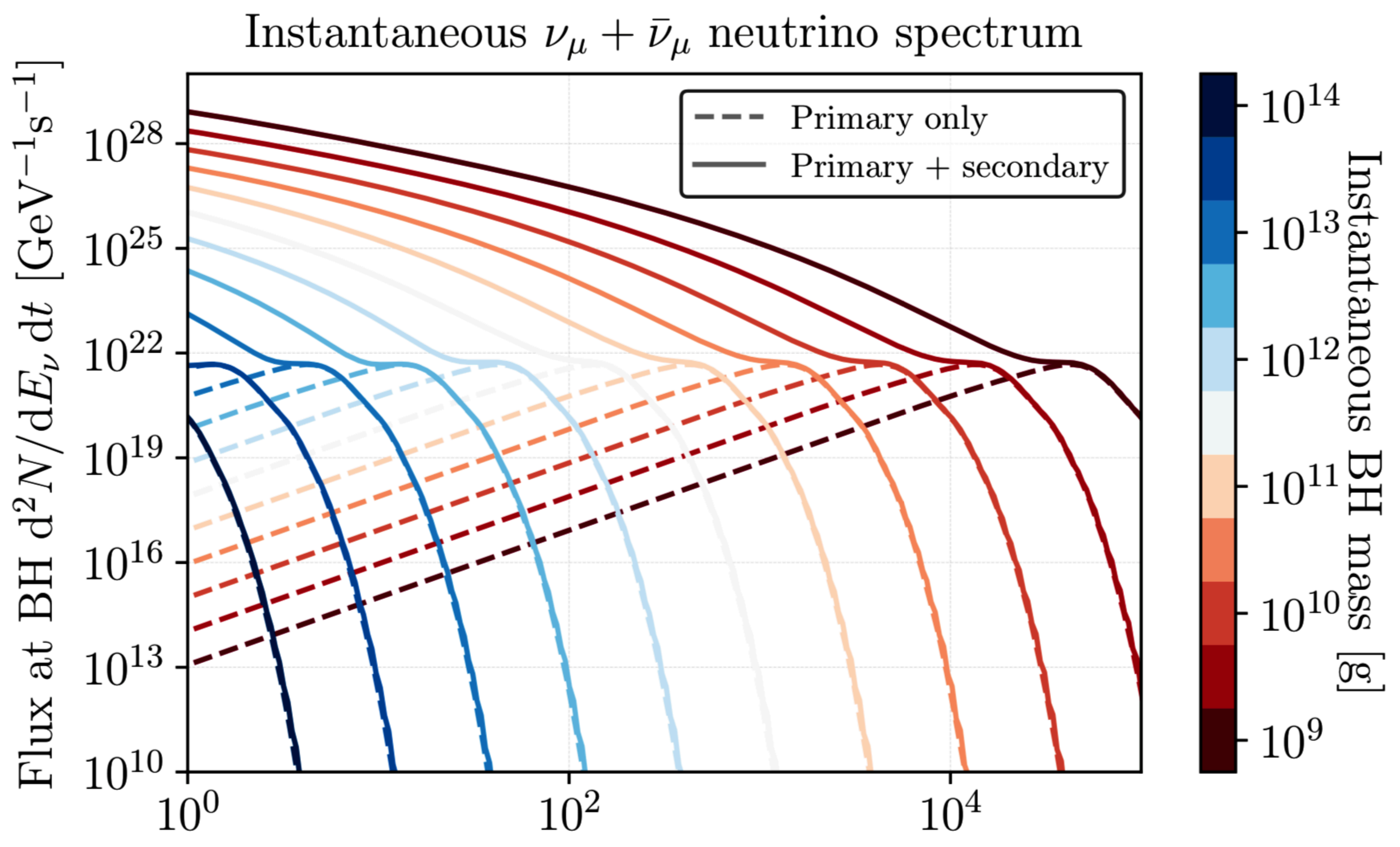
(c) $m_\chi C_\chi \geq 44$ TW





- - - Primaries - direct BH production of muon neutrinos

—— Secondaries - muon neutrinos produced in particle showers



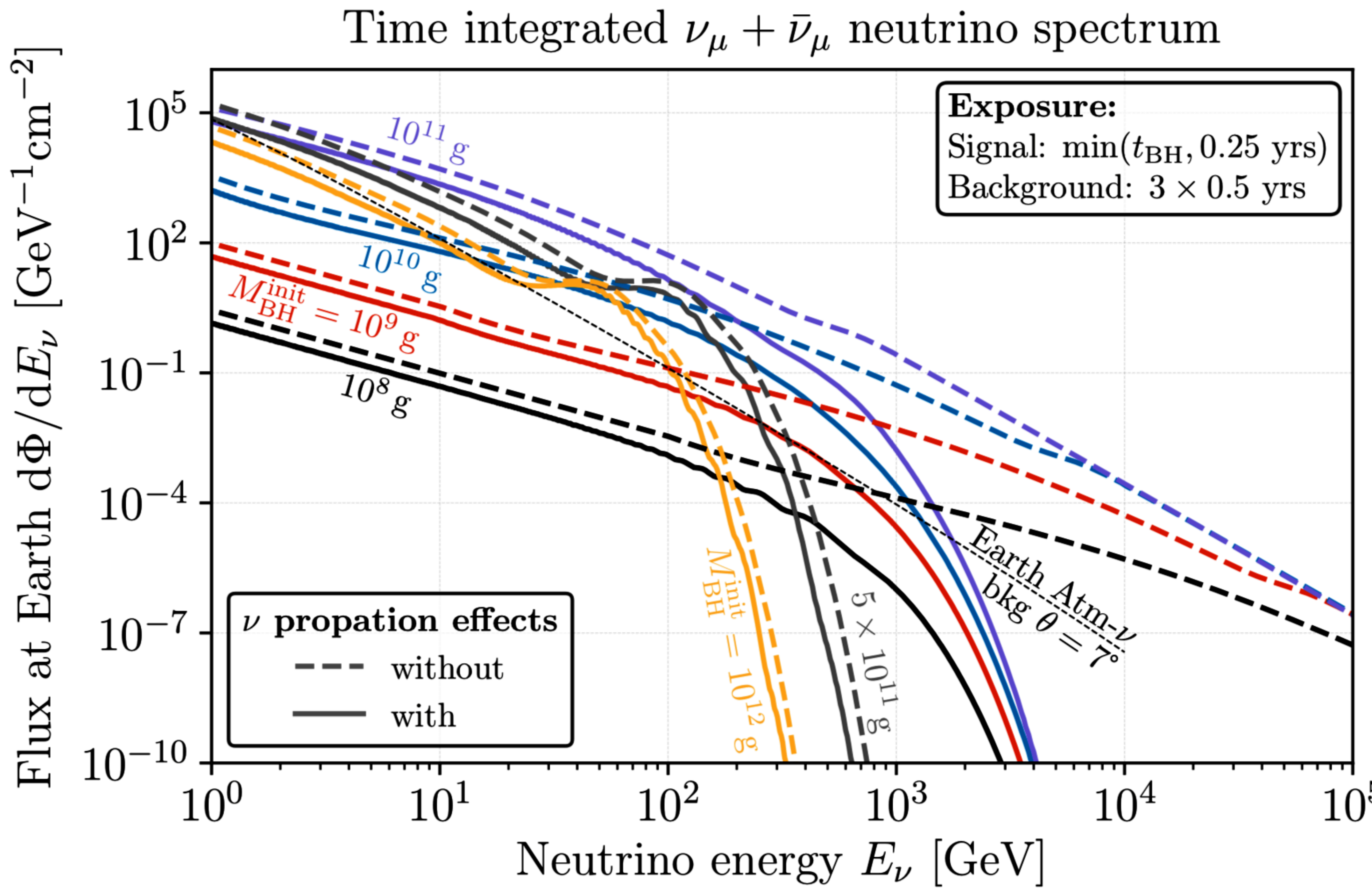
Integrated spectra:

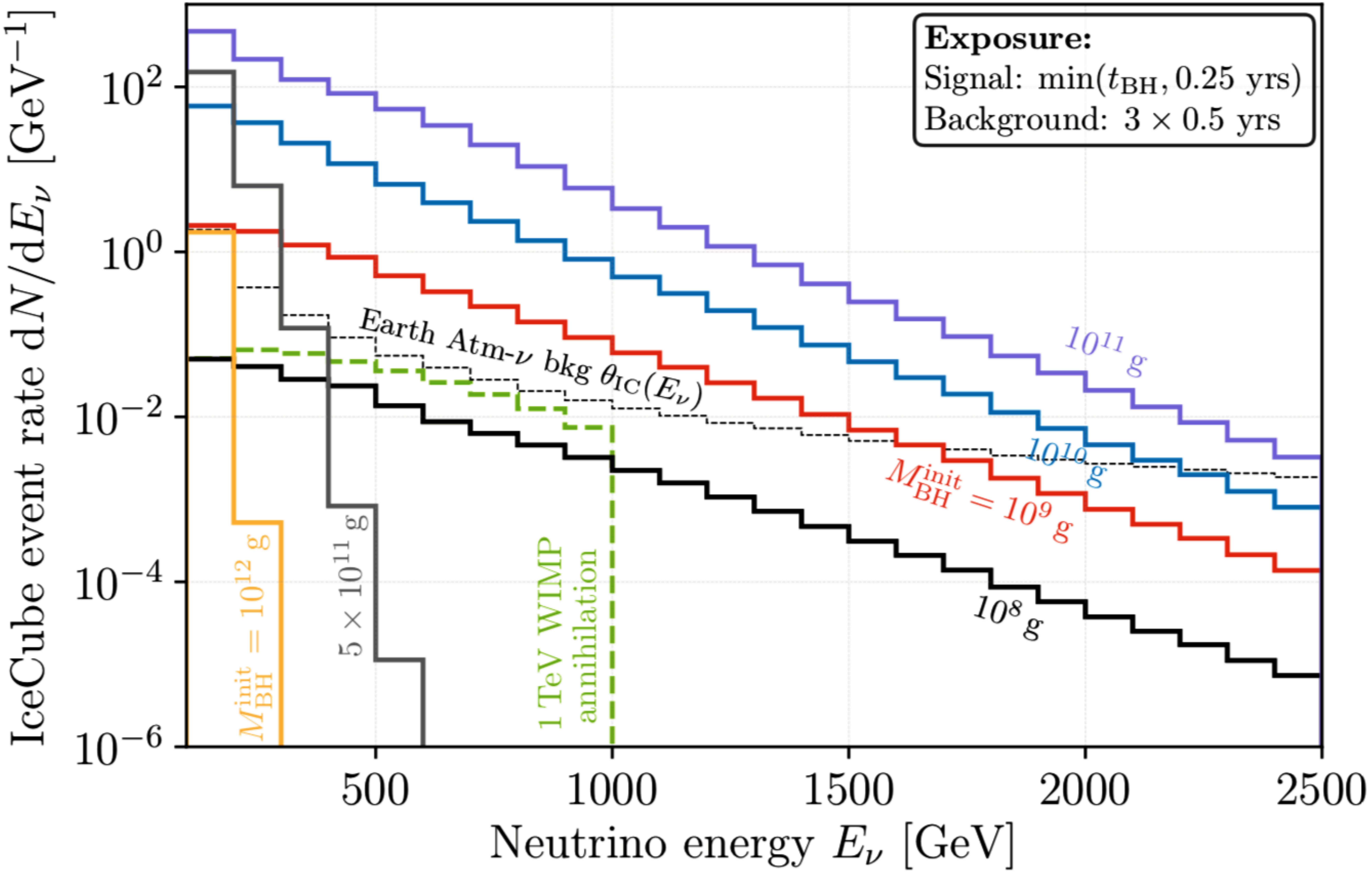
$$\frac{\mathrm{d}M_{BH}}{\mathrm{d}t} = -\frac{f(M_{BH})}{(GM_{BH})^2}$$

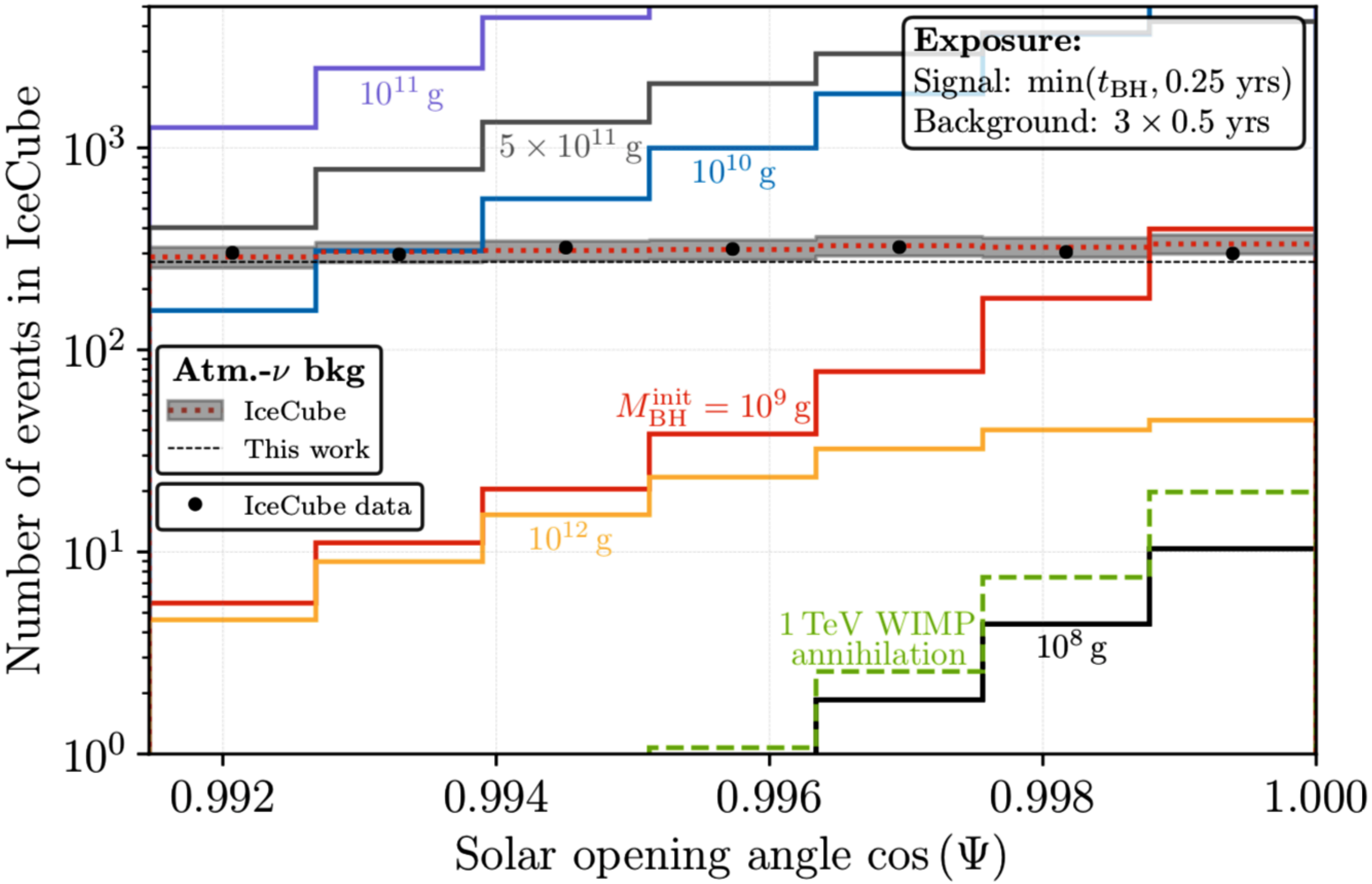
- - - no prop

—— prop effects

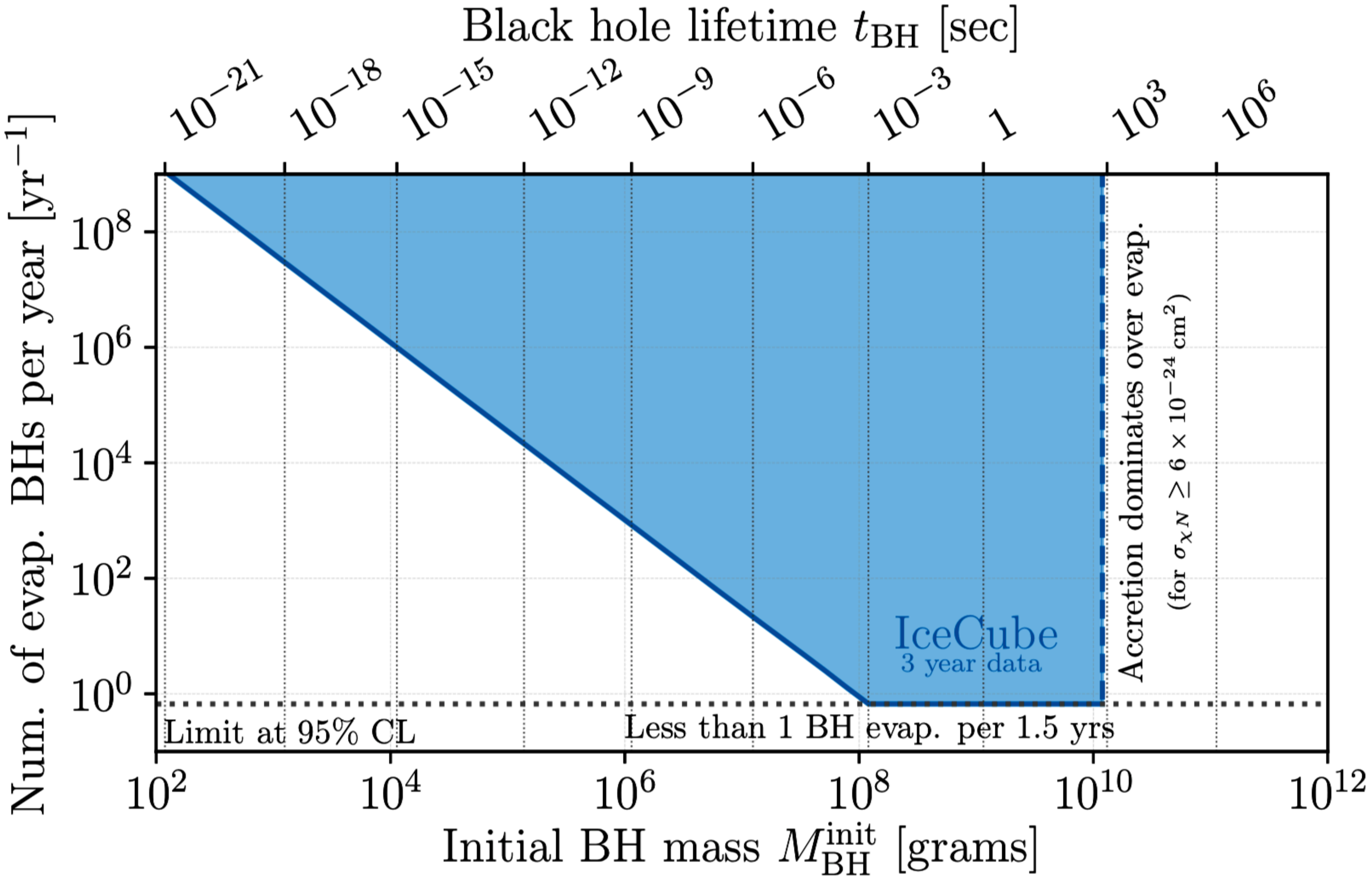
$$f(M_{BH}) = \text{greybody factor}$$




Exposure:
Signal: min(t_{BH}, 0.25 yrs)
Background: 3 × 0.5 yrs
IceCube event rate dN/dE_ν [GeV^{-1}]
Neutrino energy E_ν [GeV]
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
500
1000
1500
2000
2500
Earth Atm-ν bkg $\theta_{IC}(E_\nu)$
10^{11} g
10^{10} g
$M_{BH}^{init} = 10^9$ g
10^8 g
$M_{BH}^{init} = 10^{12}$ g
5×10^{11} g
1 TeV WIMP annihilation



Analysis recast from IceCube's 1612.05949



$M_{BH}^{init} \lesssim 10^8$ g

Need multiple evaporating BHs

10^8 g $\lesssim M_{BH}^{init} \lesssim 4 \times 10^{10}$ g

single evaporating BH suffices

$M_{BH}^{init} \gtrsim 4 \times 10^{10}$ g

BHs do not evaporate

For destructive BHs:
Exclude DM models that form faster than a billion years

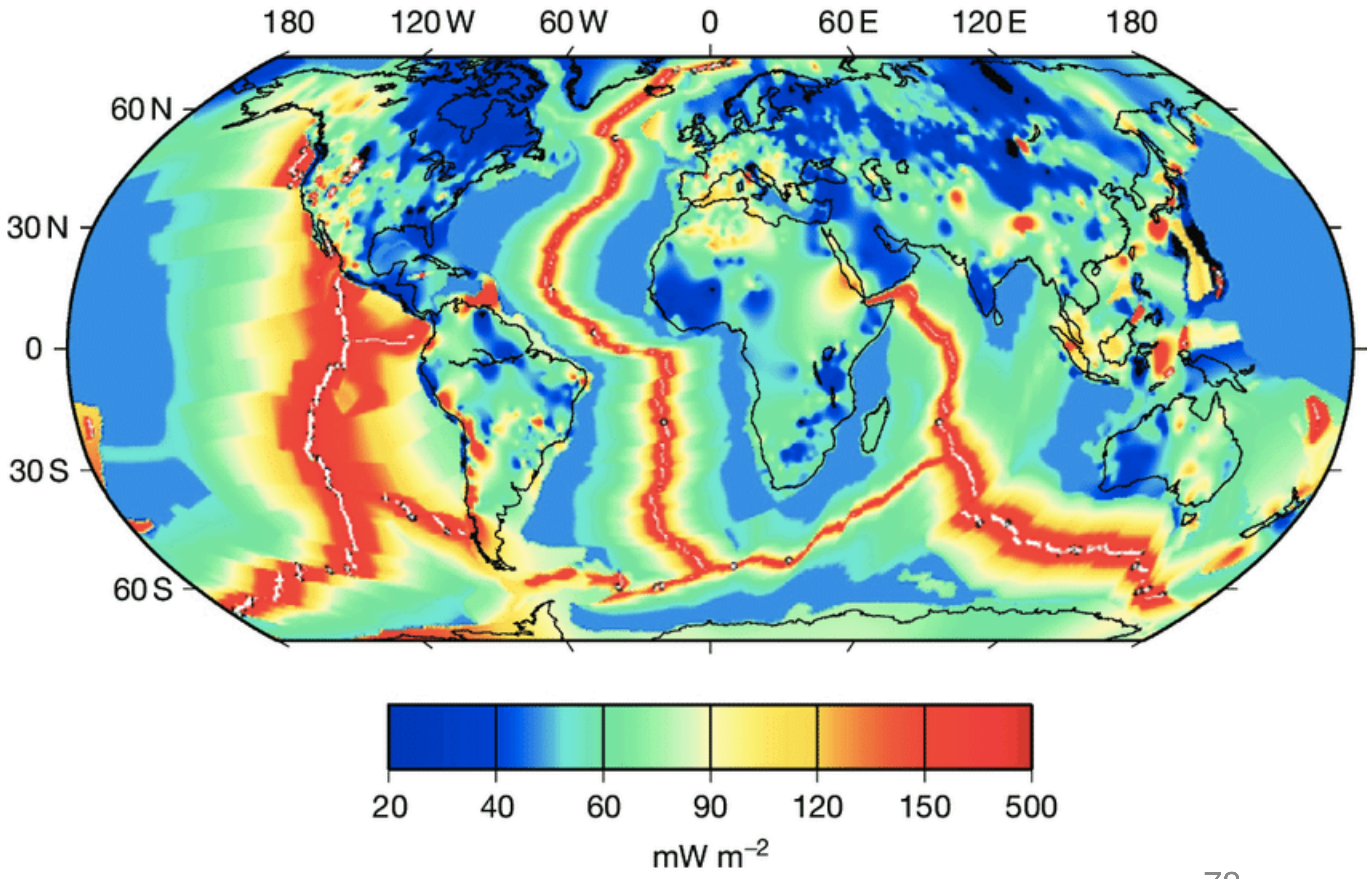
For evaporating BHs:
Exclude DM models that overheat Earth

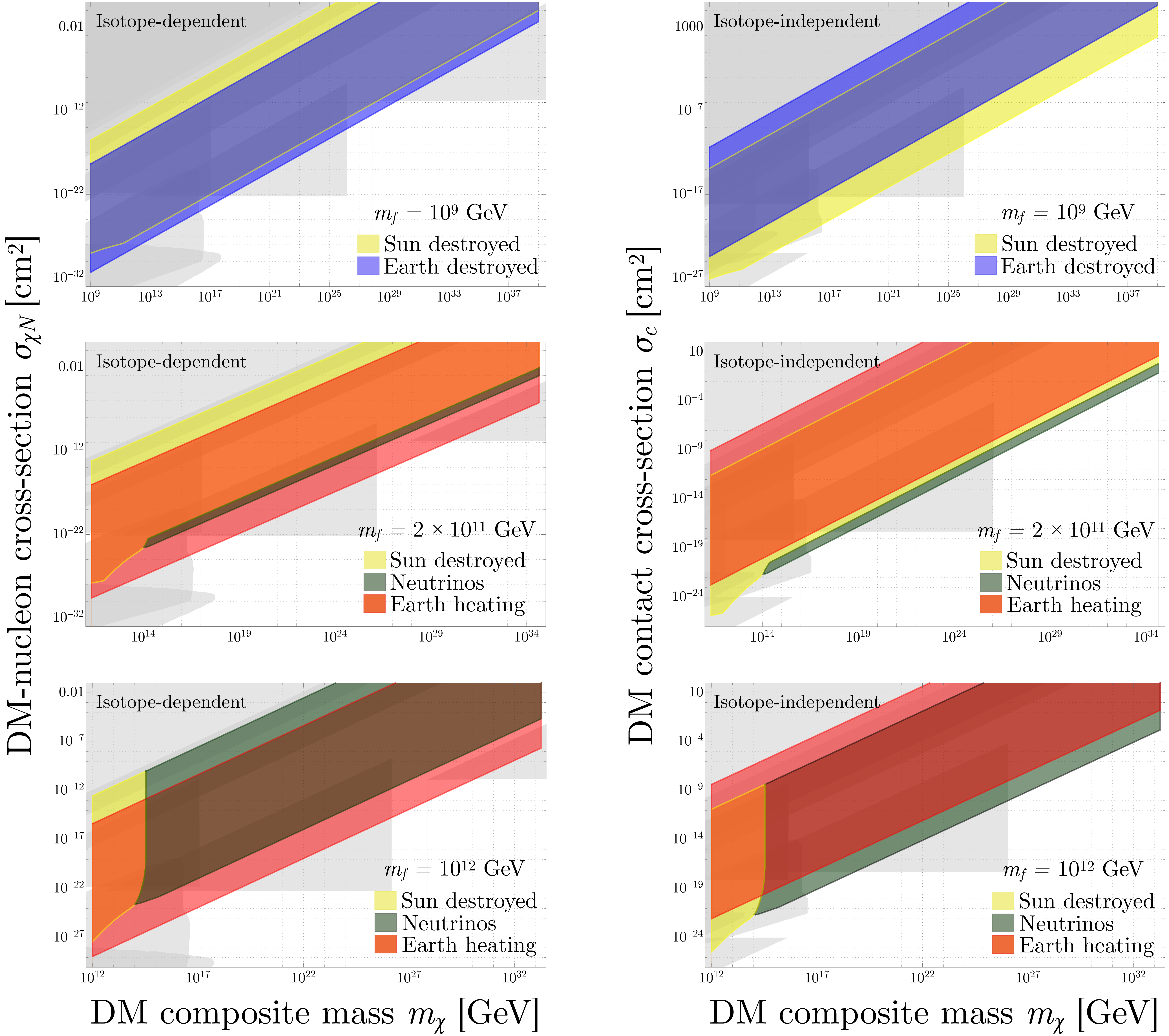
(a) $t_{drift} \lesssim 1$ Gyr

(b) $t_{evap} + t_{form} \lesssim 1$ kyr

(c) $m_\chi C_\chi \geq 44$ TW

J. Mareschal and C. Jaupart, *Heat Flow Measurements* (2011)




Isotope-dependent
Isotope-independent
$m_f = 10^9$ GeV
Sun destroyed
Earth destroyed
$m_f = 2 \times 10^{11}$ GeV
Sun destroyed
Neutrinos
Earth heating
$m_f = 10^{12}$ GeV
Sun destroyed
Neutrinos
Earth heating
DM-nucleon cross-section $\sigma_{\chi N}$ [cm^2]
DM contact cross-section σ_c [cm^2]
DM composite mass m_χ [GeV]
DM composite mass m_χ [GeV]

DM Mass Unitarity Limit

Griest, Kamionkowski, '87

1. Assume freeze-out abundance set with annihilation

$$\sigma_0 \sim \text{picobarn} = 10^{-36}\ \text{cm}^2$$

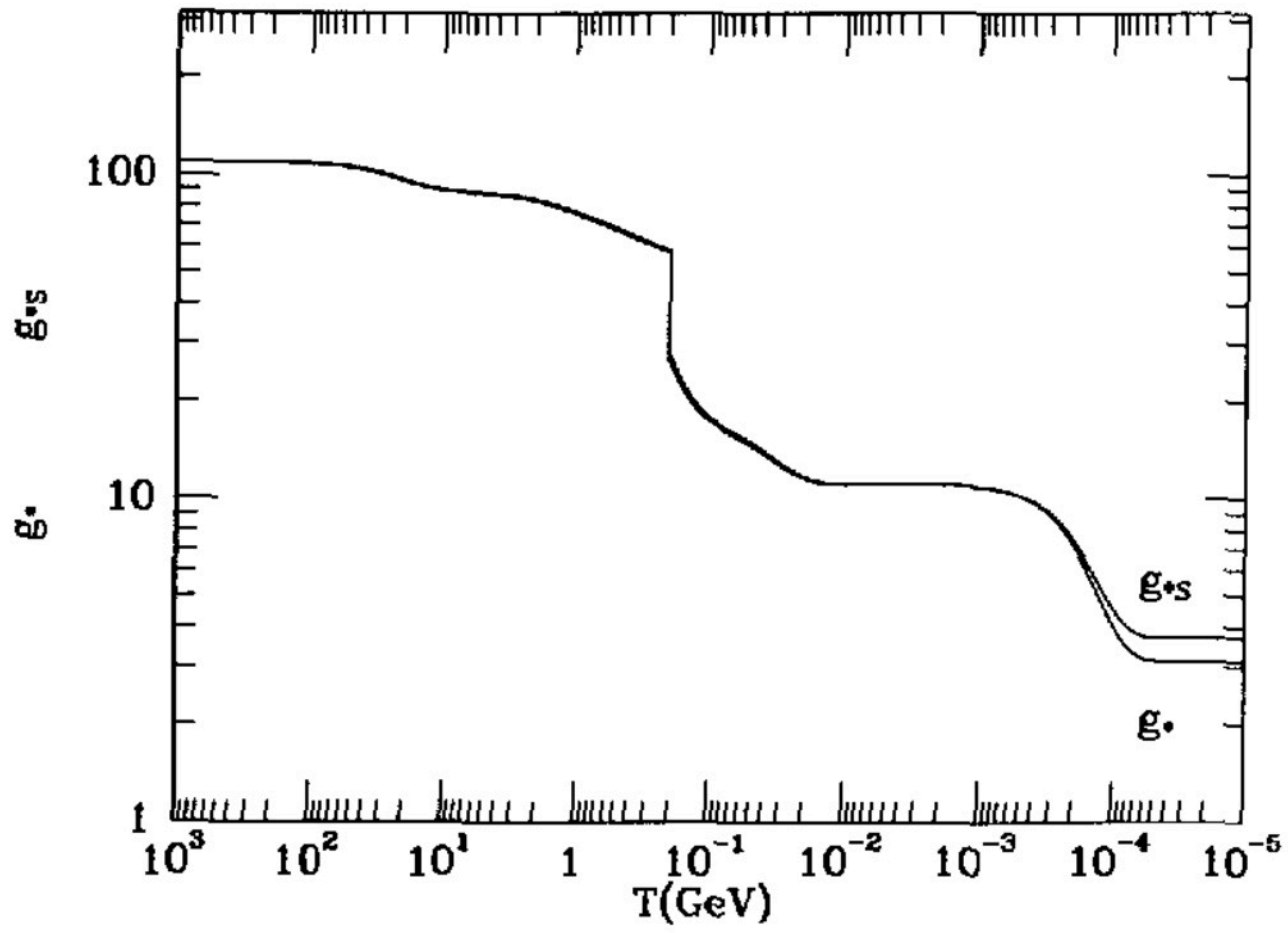
2. Require the annihilation cross-section not exceed a perturbative bound

$$\sigma_0 \lesssim 4\pi/m_{\rm DM}^2$$

3. Then because this cross-section is a picobarn for thermal freeze-out, the suggestion for frozen out dark matter mass is

$$m_{\rm DM} \lesssim 100\ \text{TeV}$$

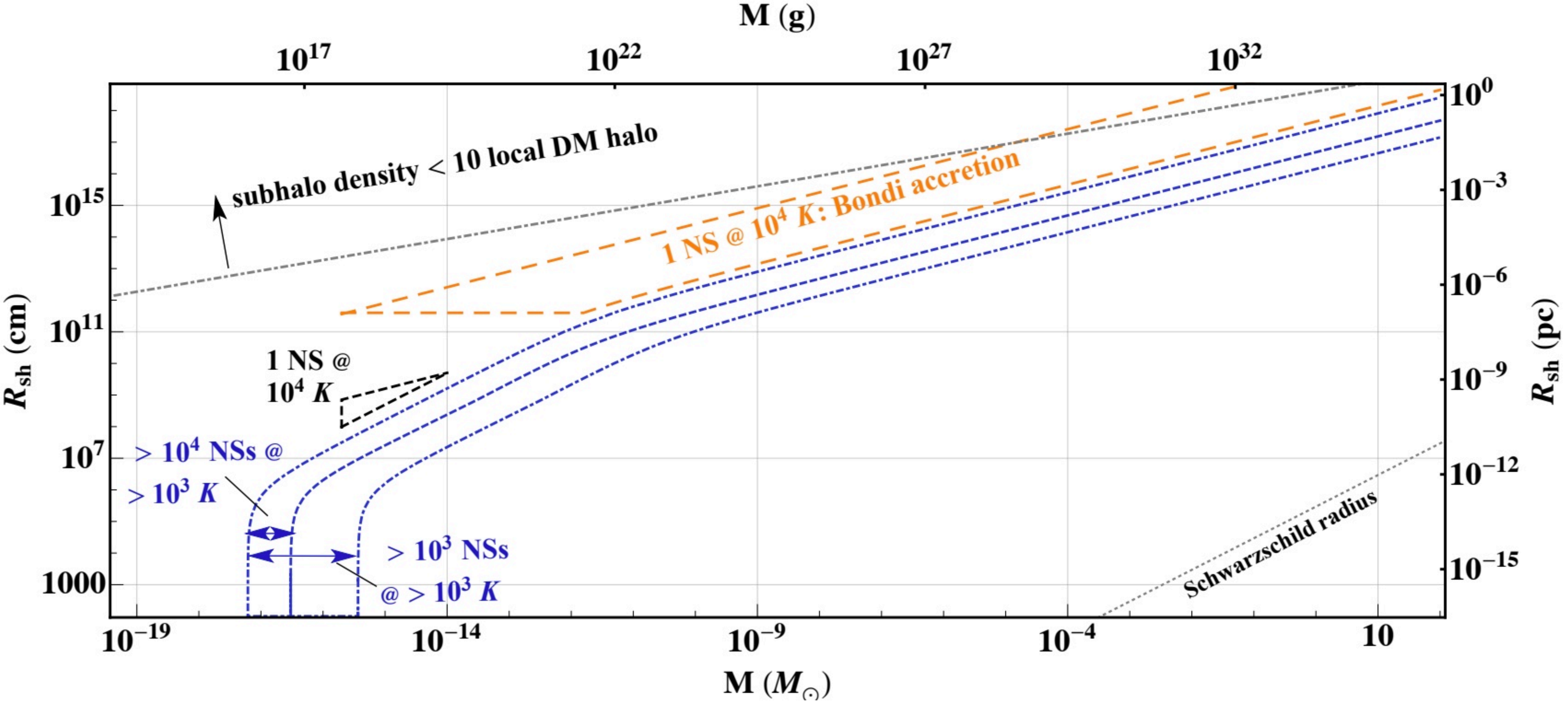
Unitarity mass limit does not apply to most cosmologies.
Example: entropy changes in the early universe



Kolb and Turner 1988

Also: Matter domination, chemical potential, gravitational production, freeze-in, asymmetric reheating, direct production from decay, moduli fields, preheating…

Prospects for DM detection using neutron stars I



Prospects for DM detection using neutron stars II