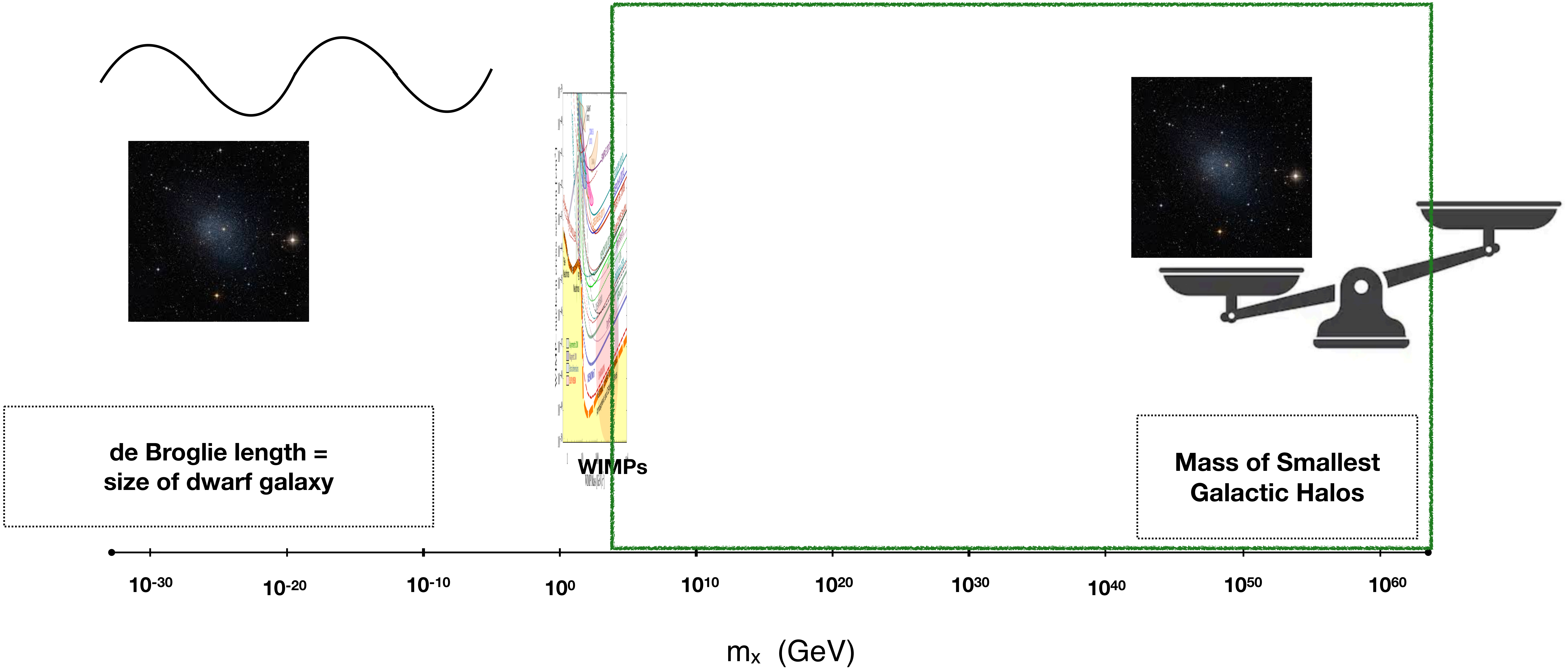
DARK MATTER AT THE HIGH MASS FRONTIER

Joseph Bramante

APCTP Workshop
Dark Matter as a Portal To New Physics

HIGH MASS DARK MATTER



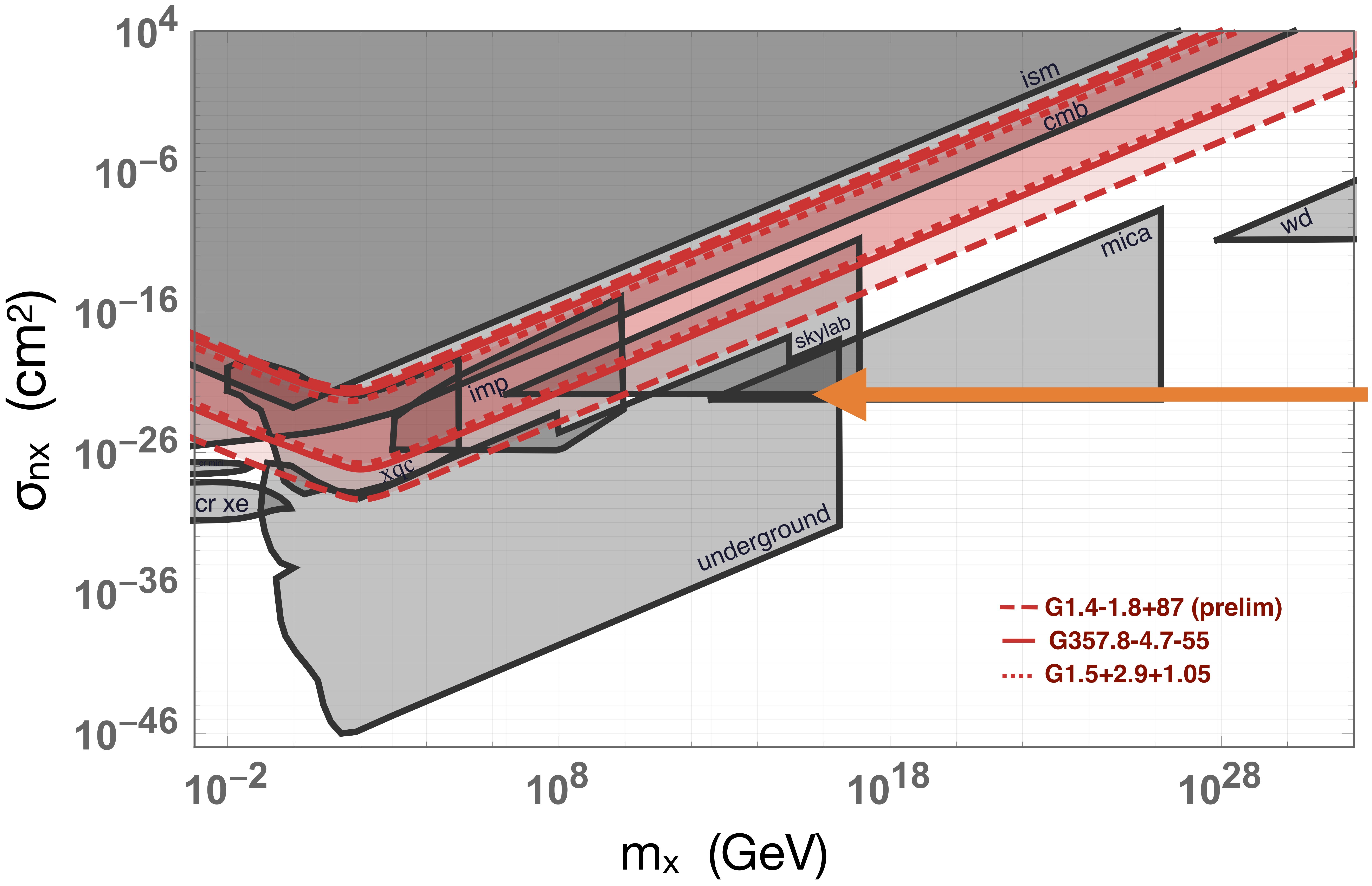
WHAT DO WE KNOW ABOUT HIGH MASS DARK MATTER?

- Direct detection experiments and multiscatter
  - with Benjamin Broerman, Rafael Lang, Nirmal Raj, Amit Bhoonah, Ningqiang Song
- Interstellar gas cloud cooling
  - with Amit Bhoonah, Fatemeh Elahi, Sarah Schon, Ningqiang Song
- Solar / terrestrial / martian / white dwarven / neutron stars
  - with Javier Acevedo, Alan Goodman, Joachim Kopp, Toby Opferkuch, Yu-Dai Tsai
- High mass cosmology, connection to asymmetries
  - with James Unwin, Amit Bhoonah, Simran Nerval, Ningqiang Song
- Accelerating dark matter
  - with Javier Acevedo, Alan Goodman

Multiscatter: models of dark matter interact many times in detectors.

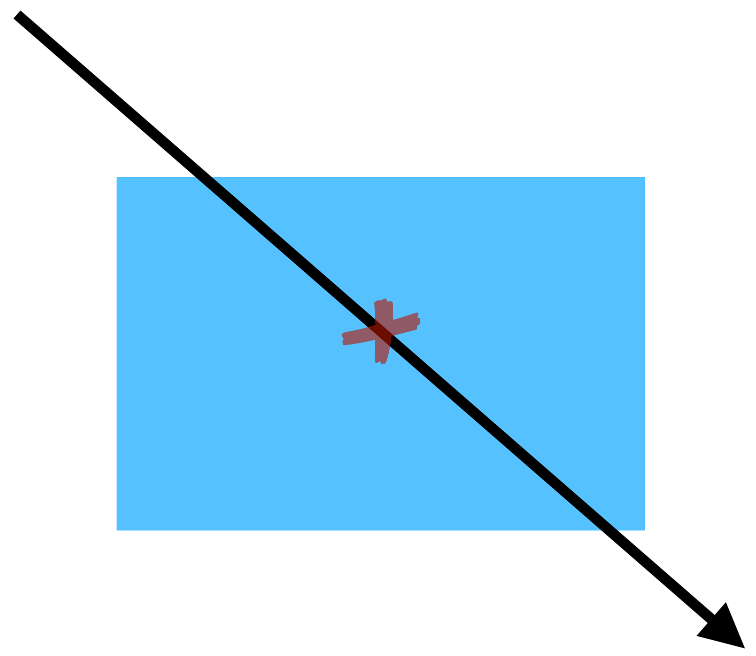
New searches for multiply interacting dark matter (MIMPs)

EXTRAPOLATING TO HIGH MASS DARK MATTER



Naive extrapolation fails, need new analyses.

EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



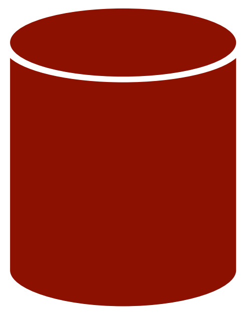
- If particles have velocity v (~0.001c), then sensitivity of detector sets a minimum energy threshold for detection

$$E_{th} \sim \mu_{nx}^2 v^2 / m_n$$

cross-section
for DM to hit
detector particle

mass of dark matter

EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



- Detector is composed of N_a atoms and observes for time t
- As DM mass increases, DM particle flux decreases, so cross-section sensitivity decreases as $1/m_x$

DM hits per atom

$$N_{hits} \sim N_a \overbrace{\sigma_{ax} n_x v_x t}$$

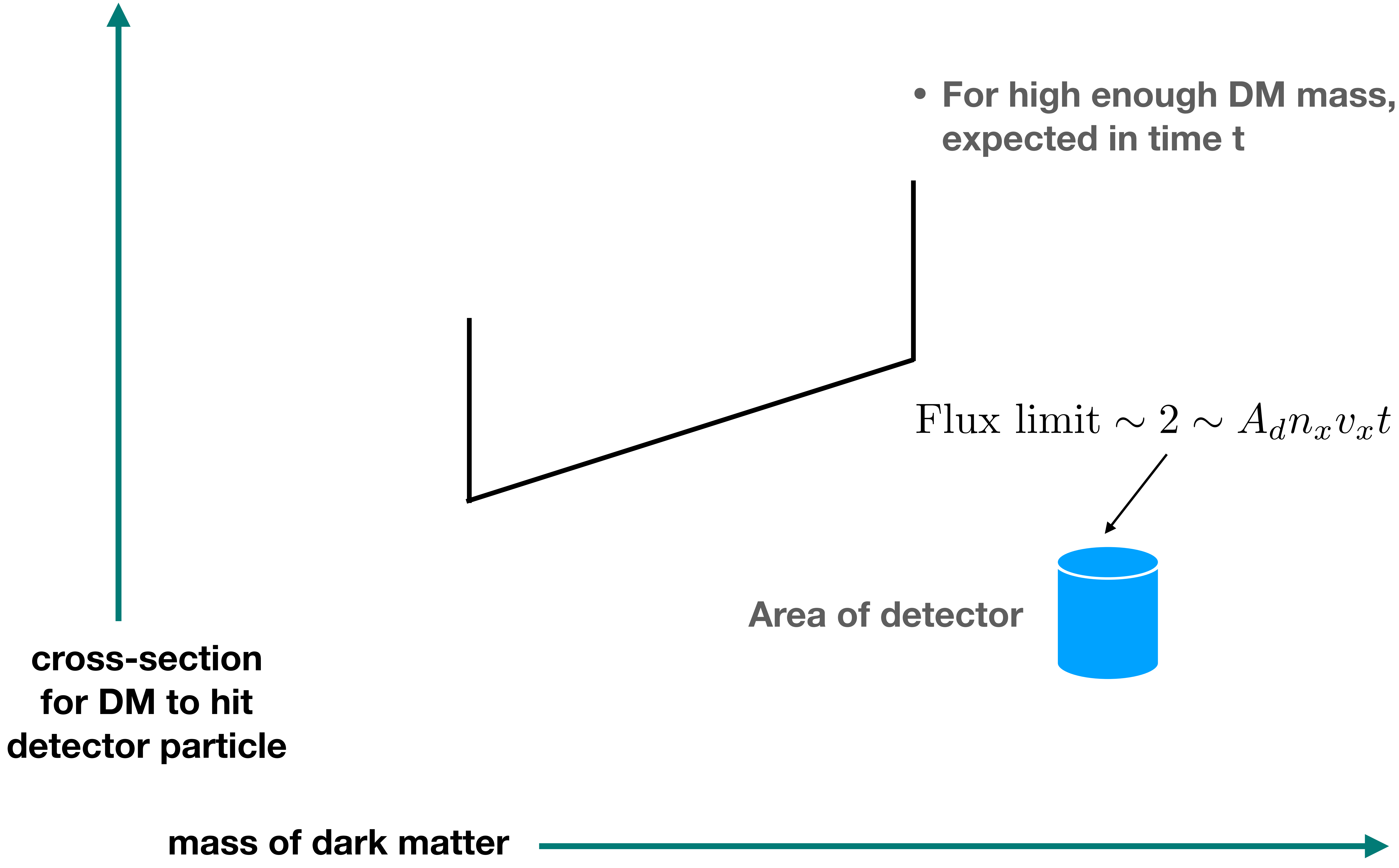
DM number density

cross-section for DM to hit detector particle

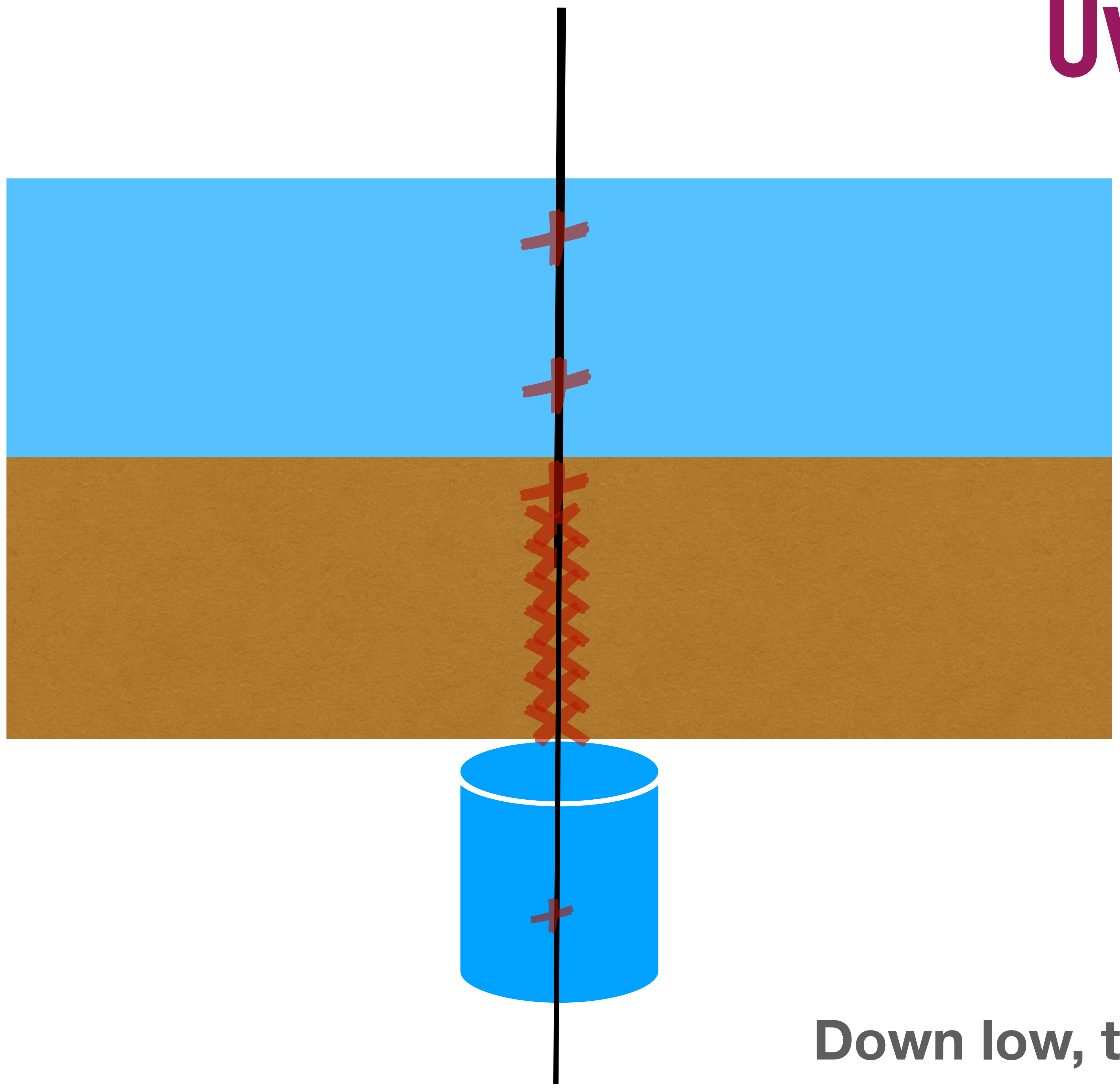
mass of dark matter

EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES

- For high enough DM mass, only a few DM particles expected in time t



Overburden



- **DM particles will be slowed through repeated scattering with atmosphere, earth, aluminum space station wall.**

Down low, too slow?

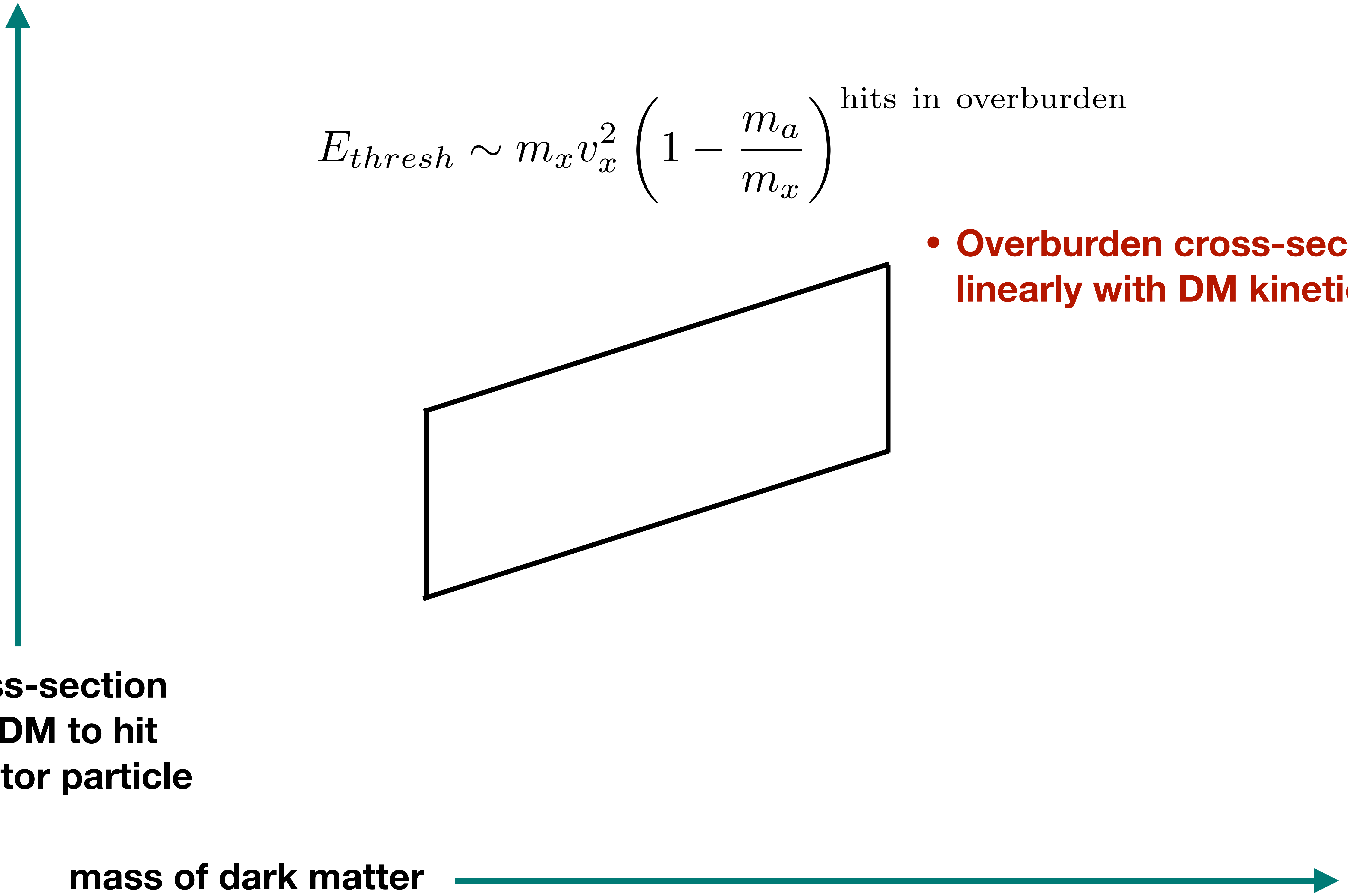
Length of overburden

$$E_{thresh} \lesssim E_i(1 - m_a/m_x)^{n_a \sigma_{ax} L_{ob}}$$

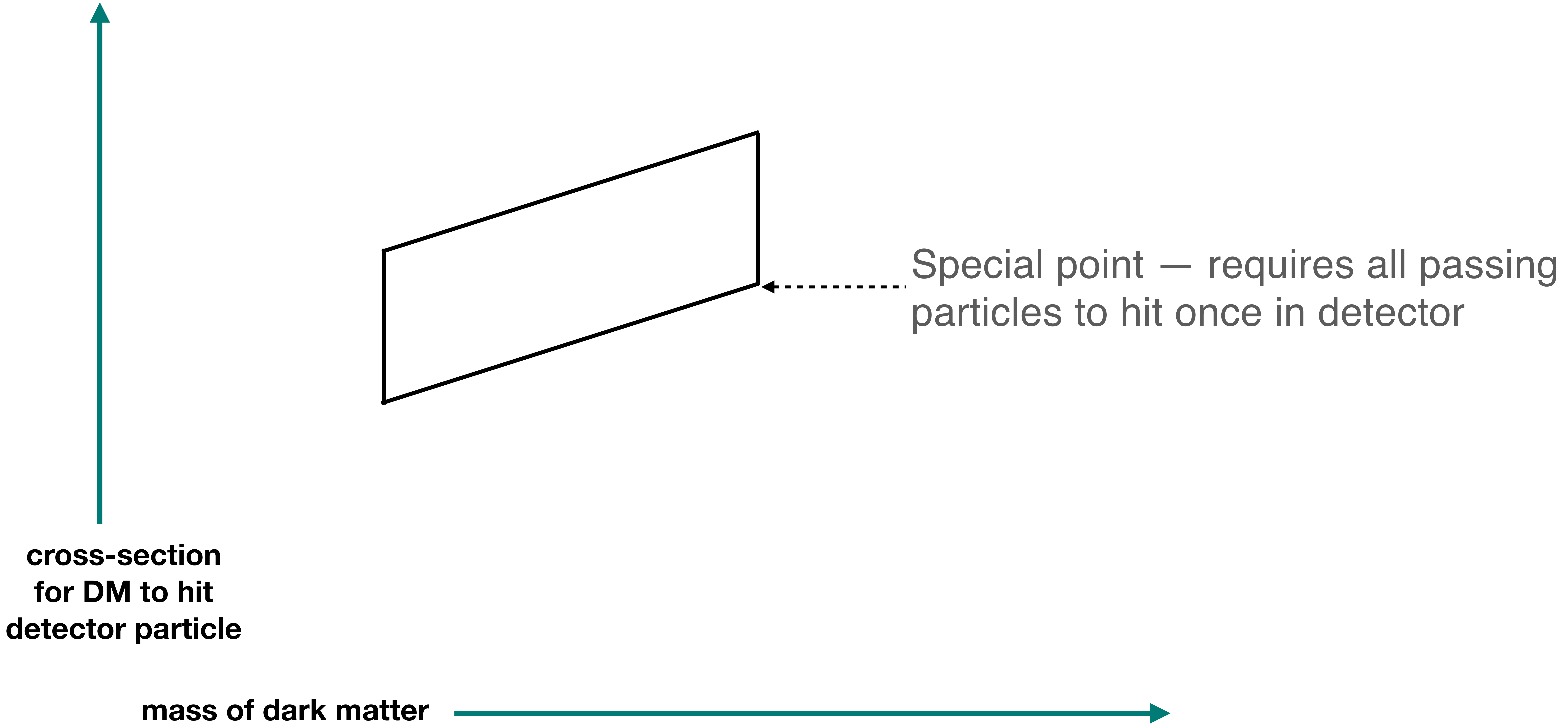
EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES

$$E_{thresh} \sim m_x v_x^2 \left(1 - \frac{m_a}{m_x}\right)^{\text{hits in overburden}}$$

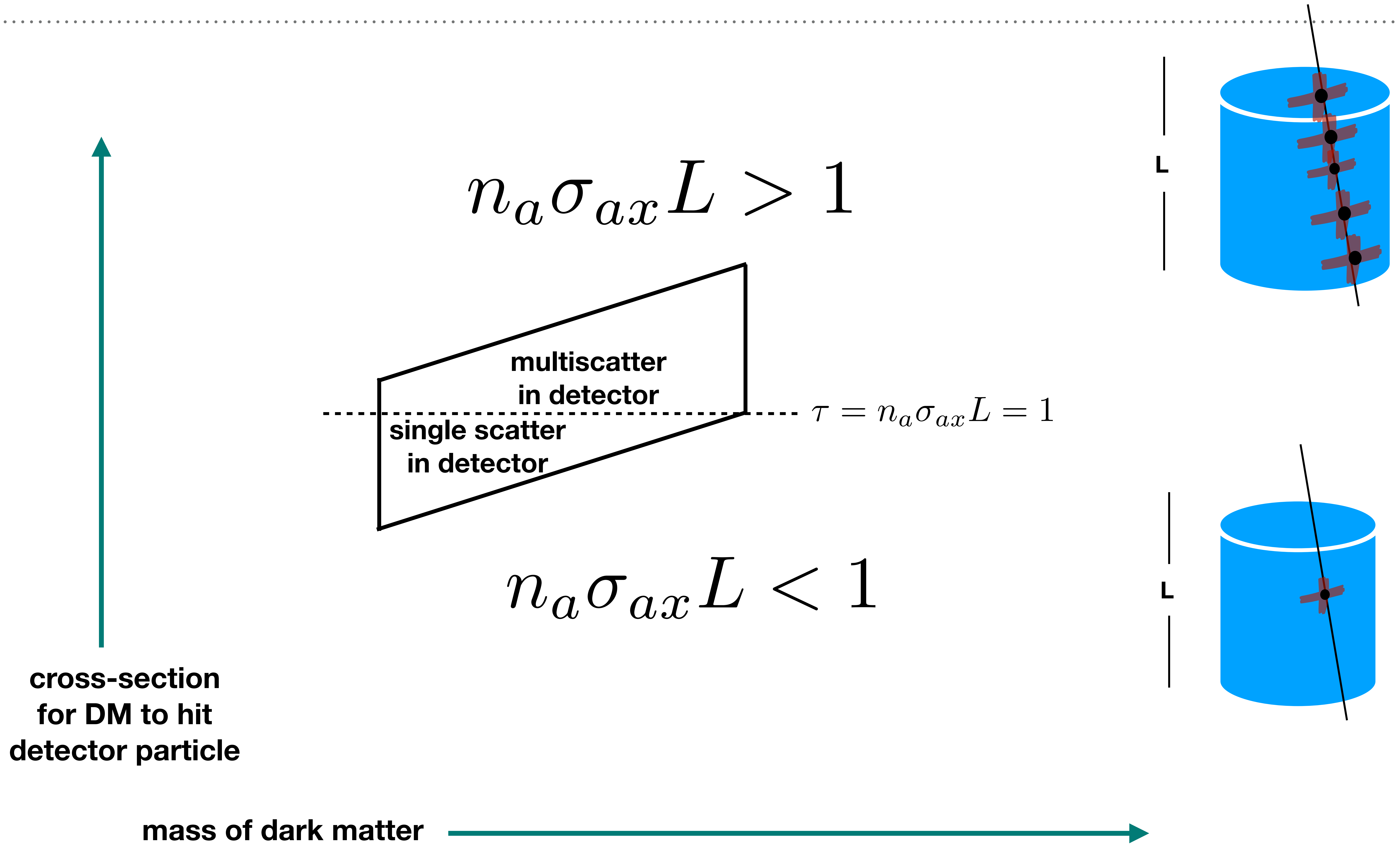
- Overburden cross-section increases linearly with DM kinetic energy ~$m_x v_x^2$



EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES

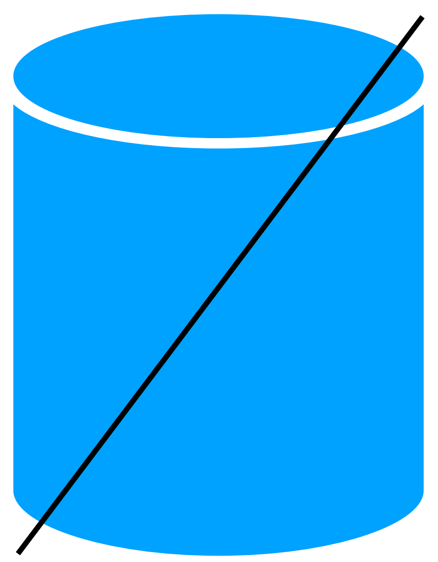


MULTISCATTER DARK MATTER DETECTION



Multiscatter frontier, in general

Transit time for a MIMP through
a meter is five microseconds

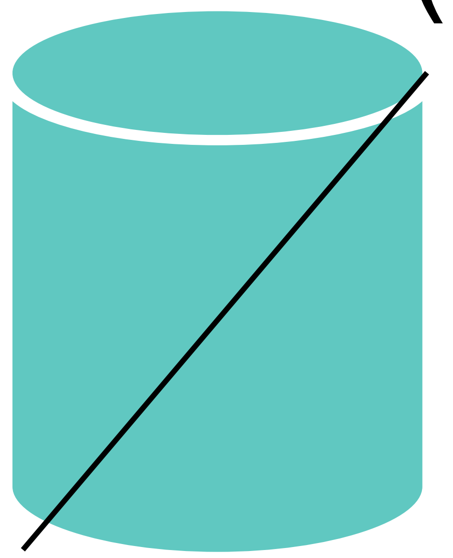


MIMP
5 μs

Individual nuclear scattering events typically
deposit ~10 keV

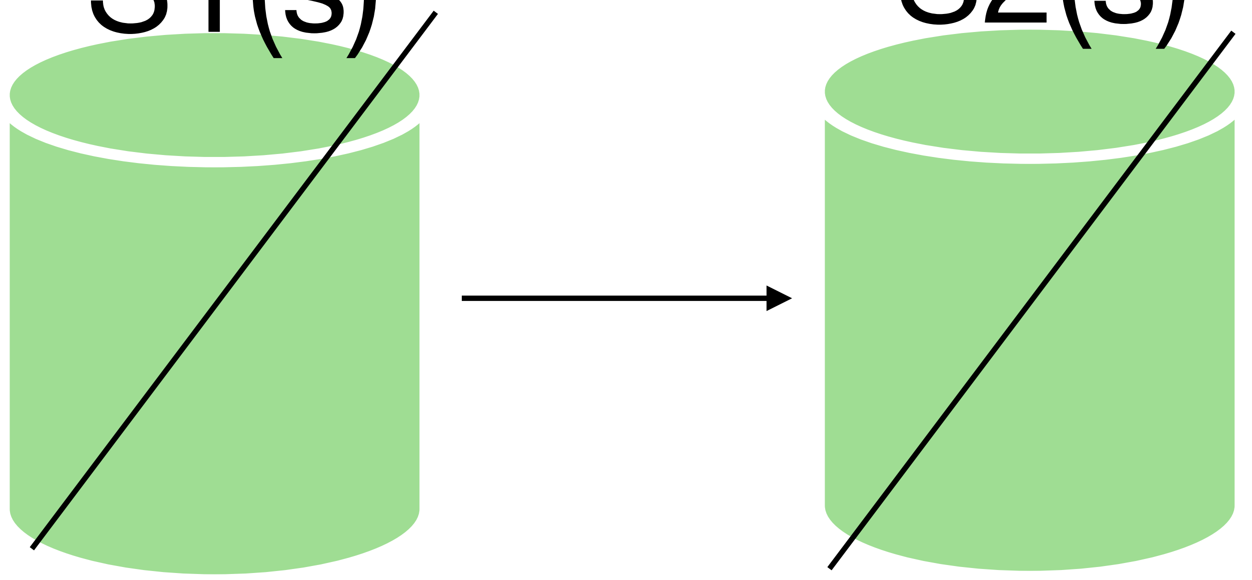
Bubble Chamber

bubble(s)



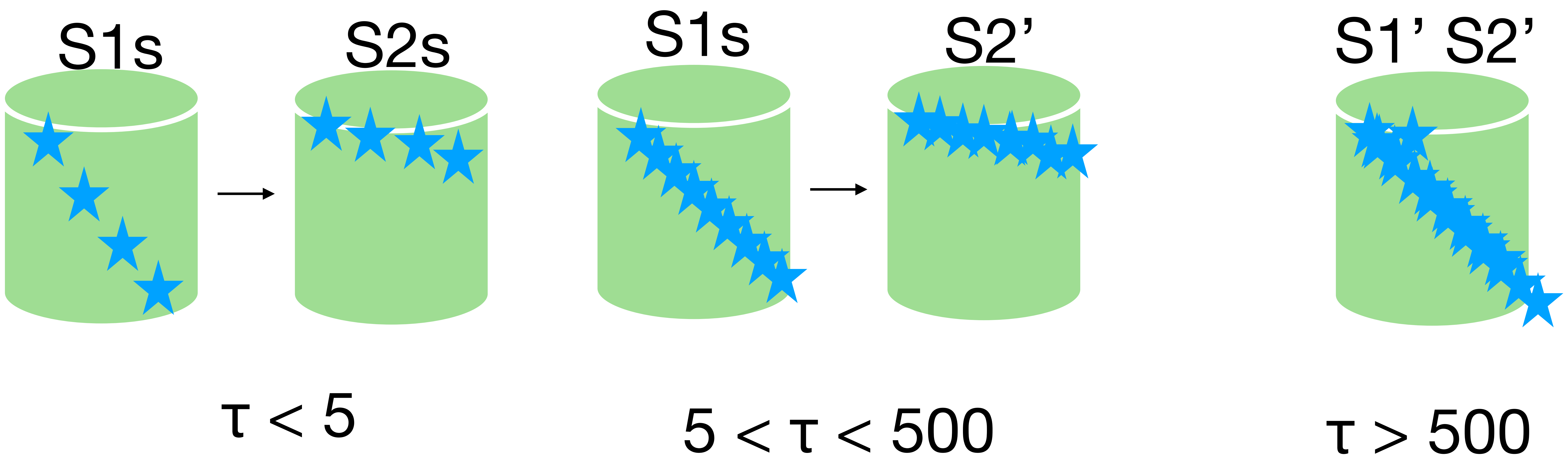
Time Projection Chamber

S1(s) S2(s)



Multiscatter frontier, Xenon TPC

S1 (10 ns)-prompt scintillator recoil flash   S2 (μs)-drifted electrons

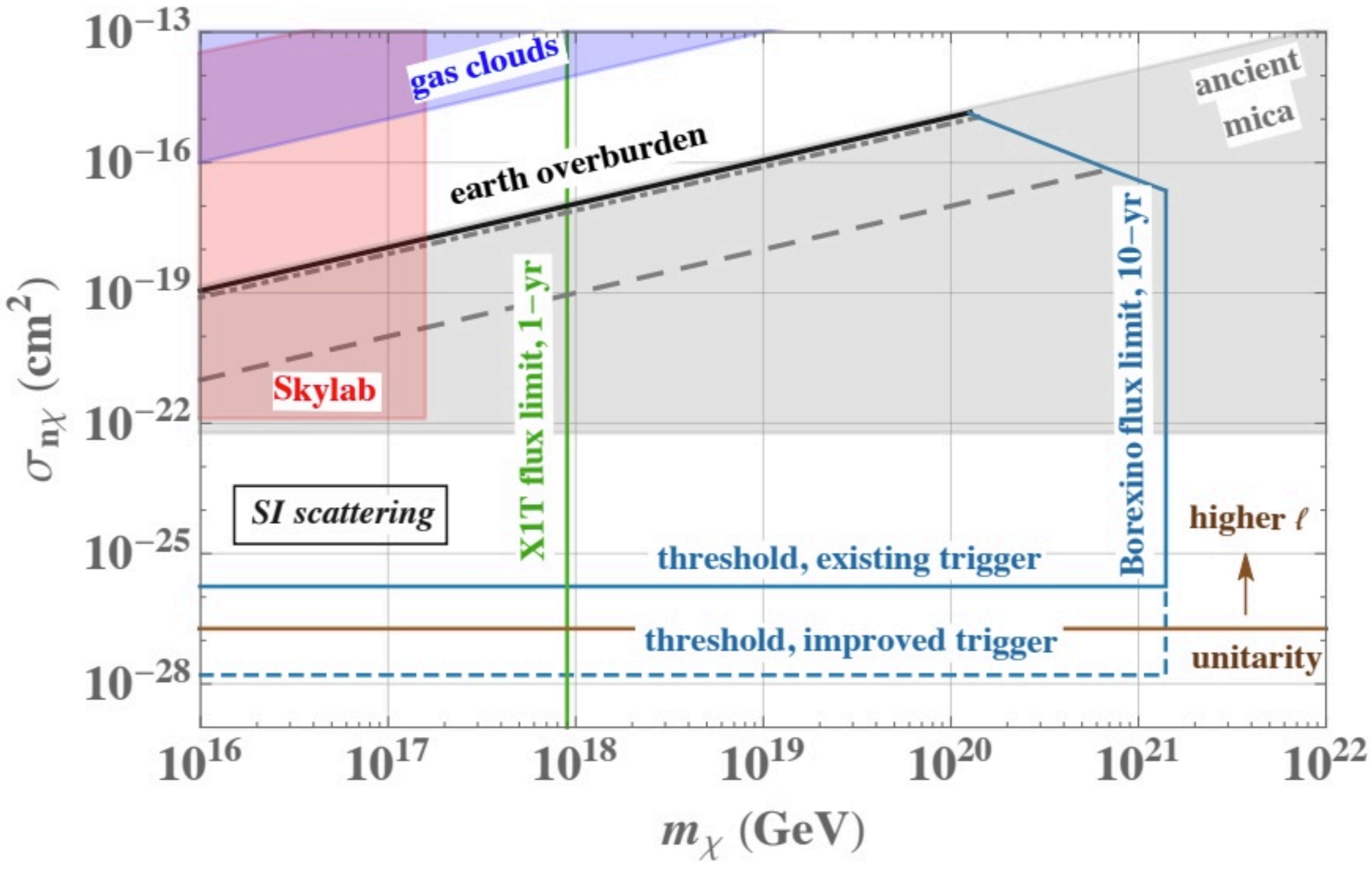


τ is the approximate number of hits per detector passage.
For τ > 5 (τ > 500) the S2 (S1) pulses merge
into elongated pulses S2' (S1').

For τ > 500, there will be overlap
between the S2′ and S1′ elongated pulses.

UNDERGROUND MULTISCATTER PROSPECTS

Scintillating Neutrino Detectors



1812.09325

1910.05380

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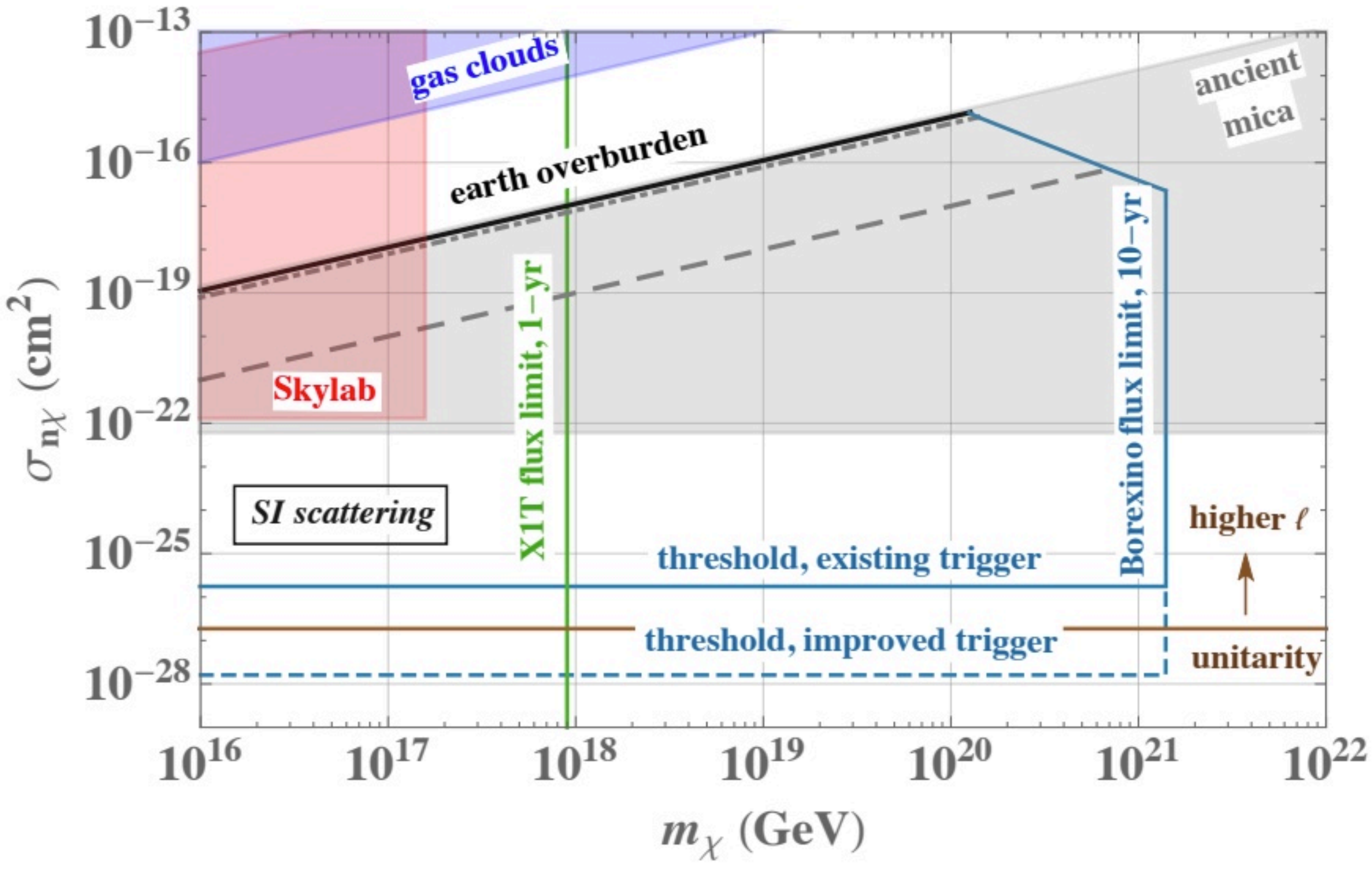
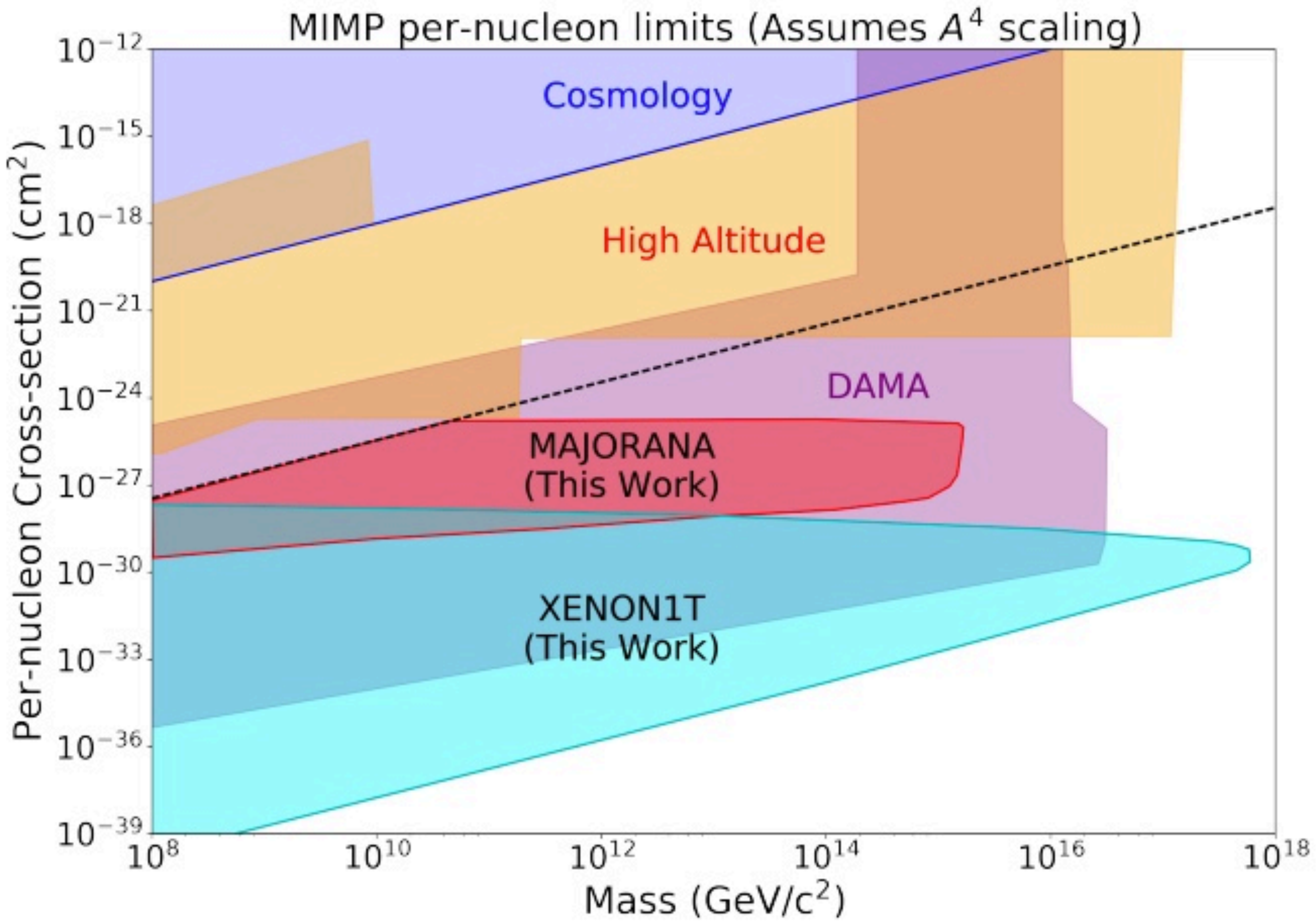


1812.09325

1910.05380

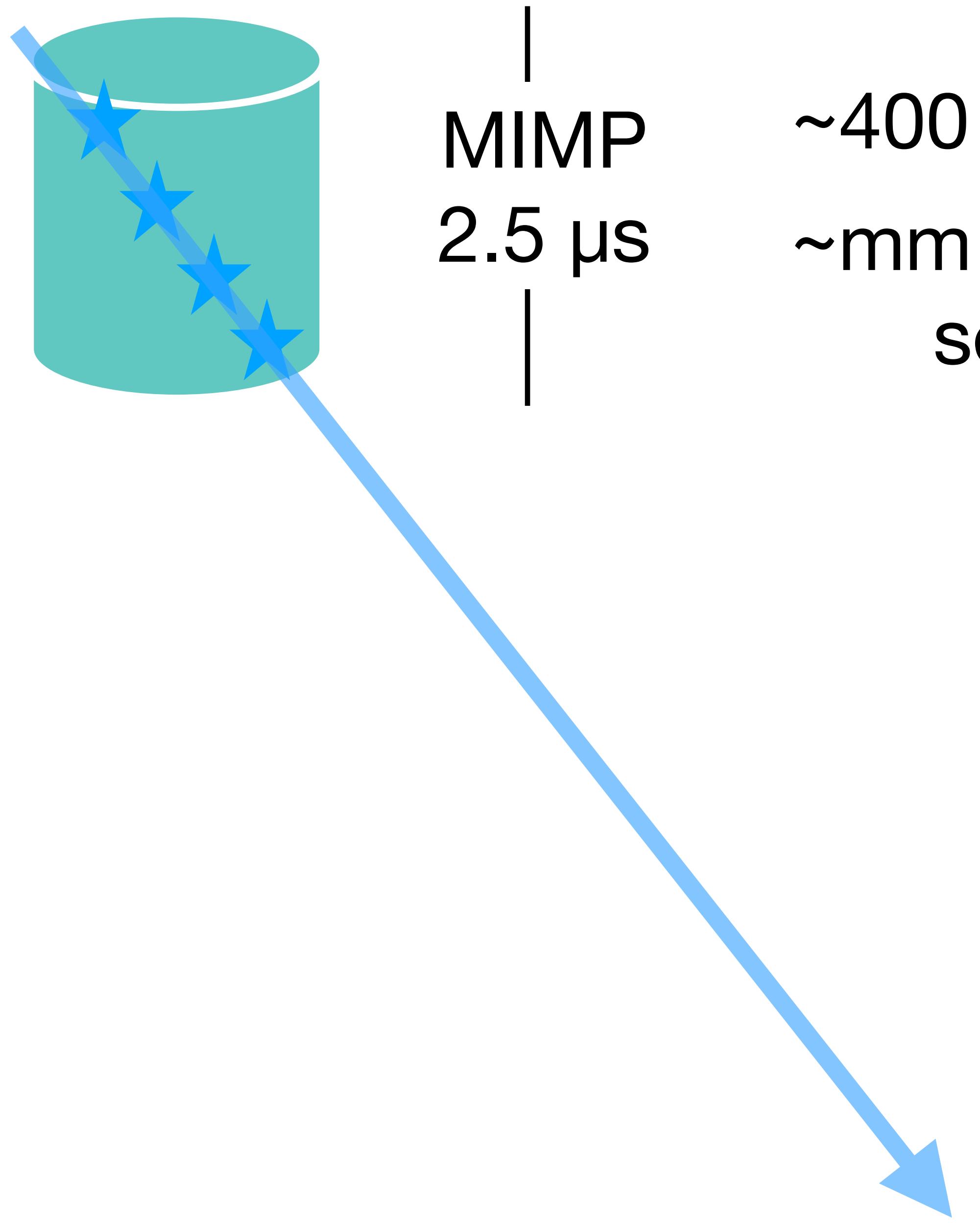
Underground Multiscatter Searches



1803.08044

2009.07909

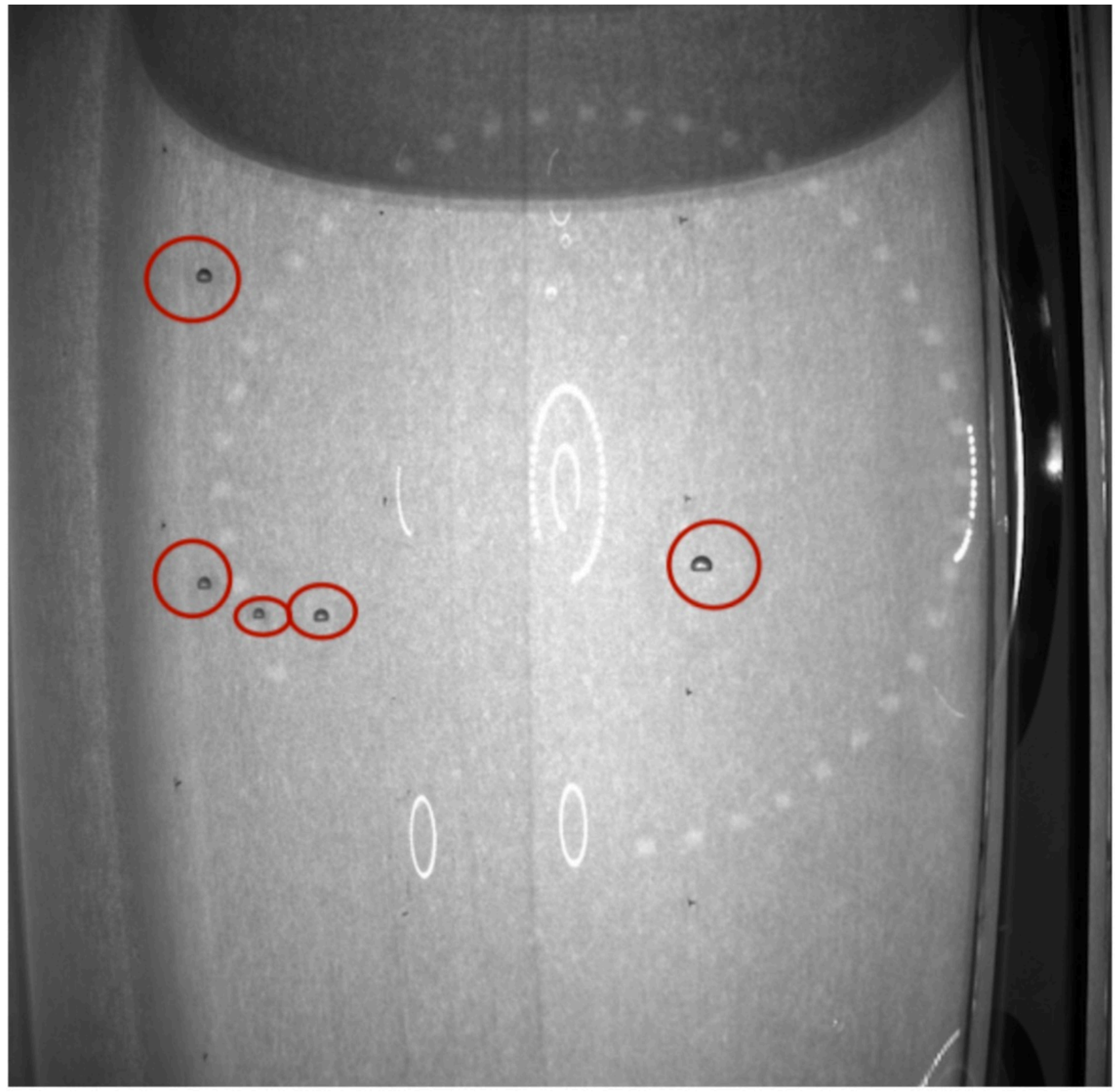
PICO-60 multiscatter search ongoing

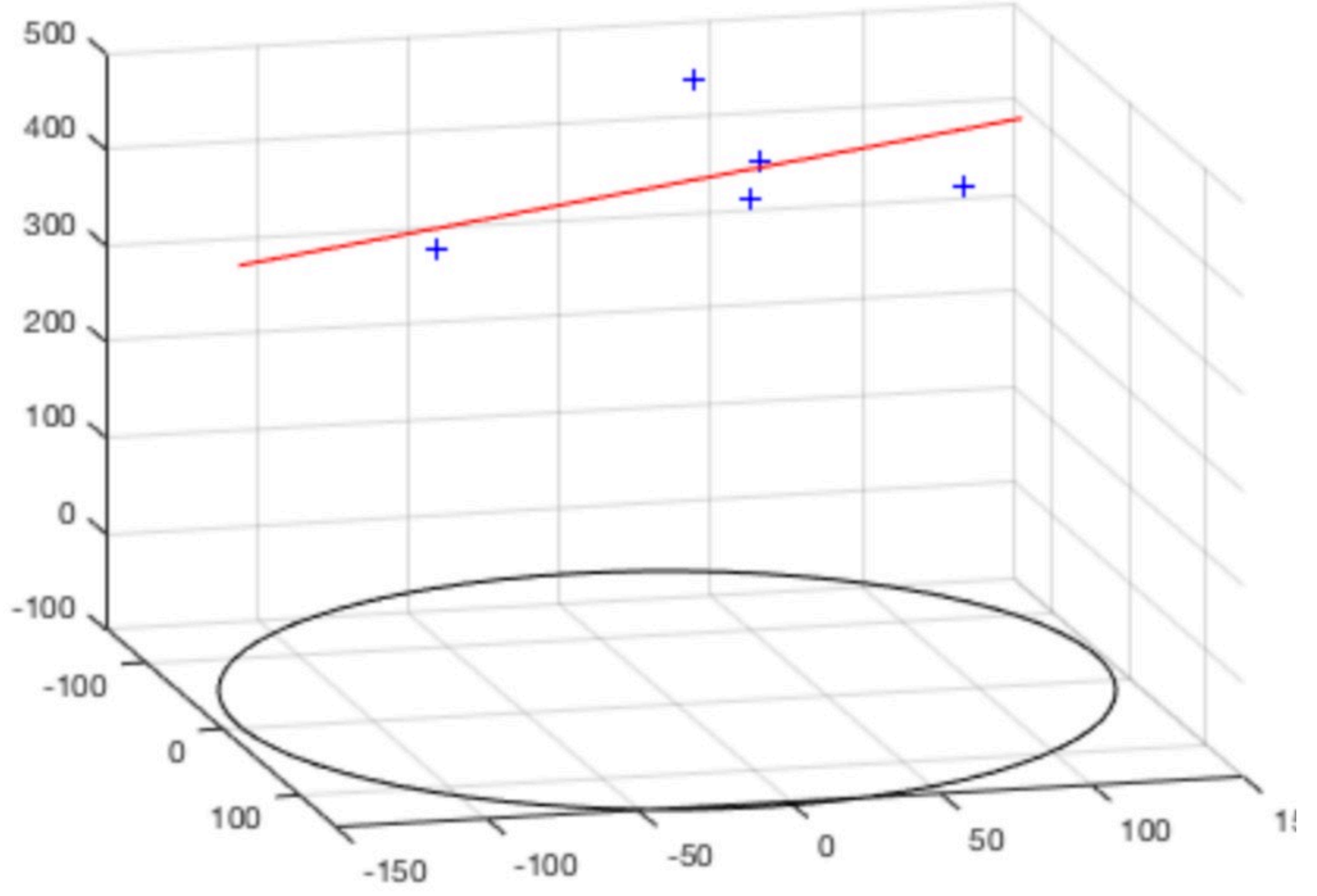


MIMP
2.5 μs

~400 ns acoustic sensors

~mm resolution stereo cameras
see bubbles (up to 500)





MIMP scatter should be highly collinear.
For <kilobarn cross-section.

Courtesy Ben Broerman, Queen's PhD student
ongoing analysis

$$\Omega_{\rm max} \lesssim \quad 1.7^\circ \left(\frac{m_a}{100\ {\rm GeV}}\right)\left(\frac{10^{13}\ {\rm GeV}}{m_x}\right)\left(\frac{L}{100\ {\rm cm}}\right)\left(\frac{n_a}{10^{22}/{\rm cm}^3}\right)^{1/3}.$$

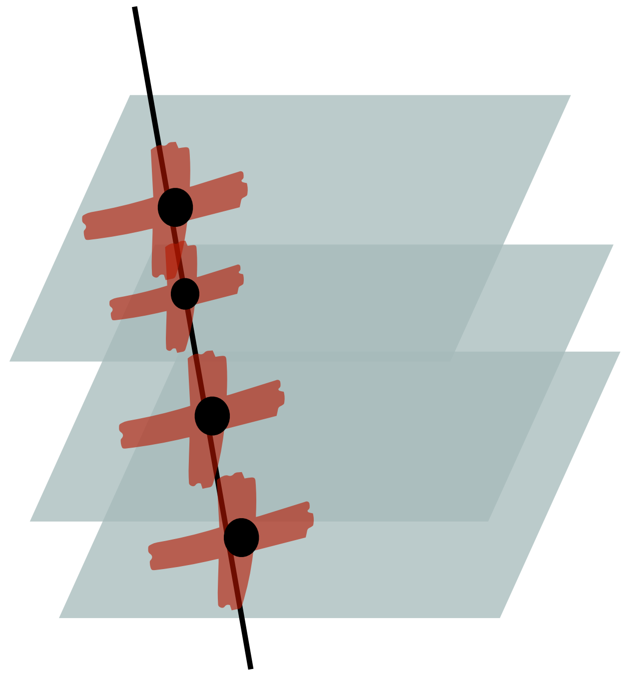
ETCHING PLASTIC SEARCHES FOR DARK MATTER

- *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



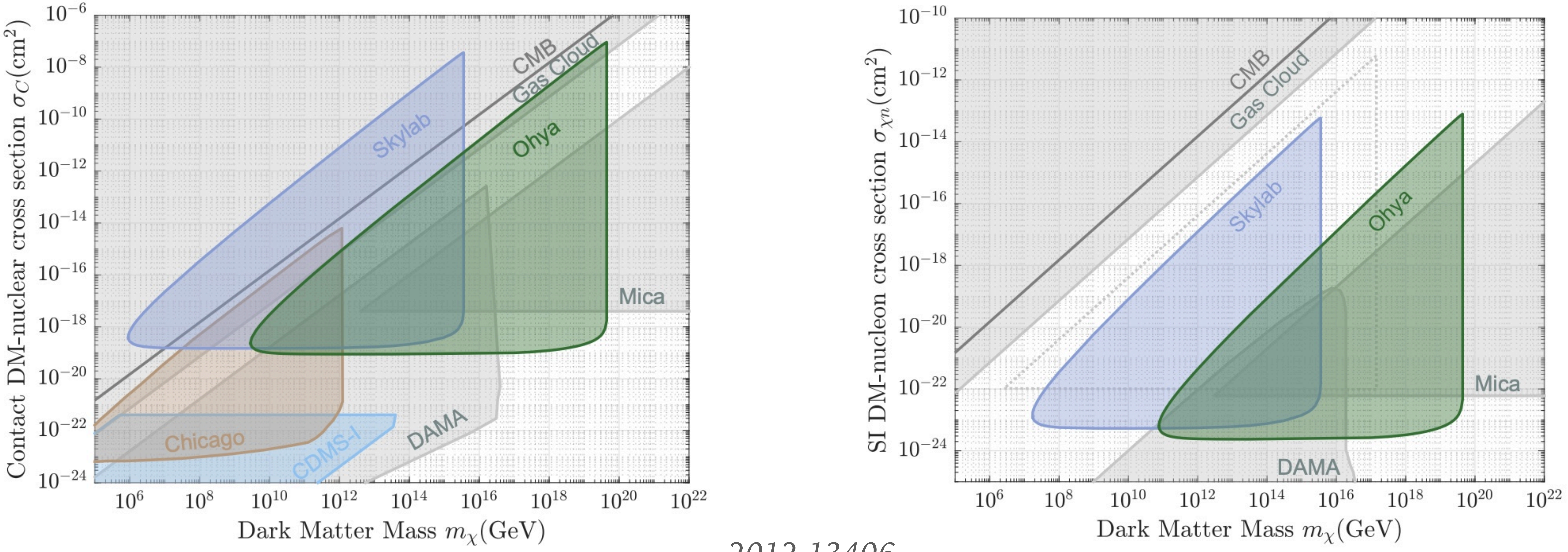
Ohya Quarry

(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 exactly*

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



2012.13406

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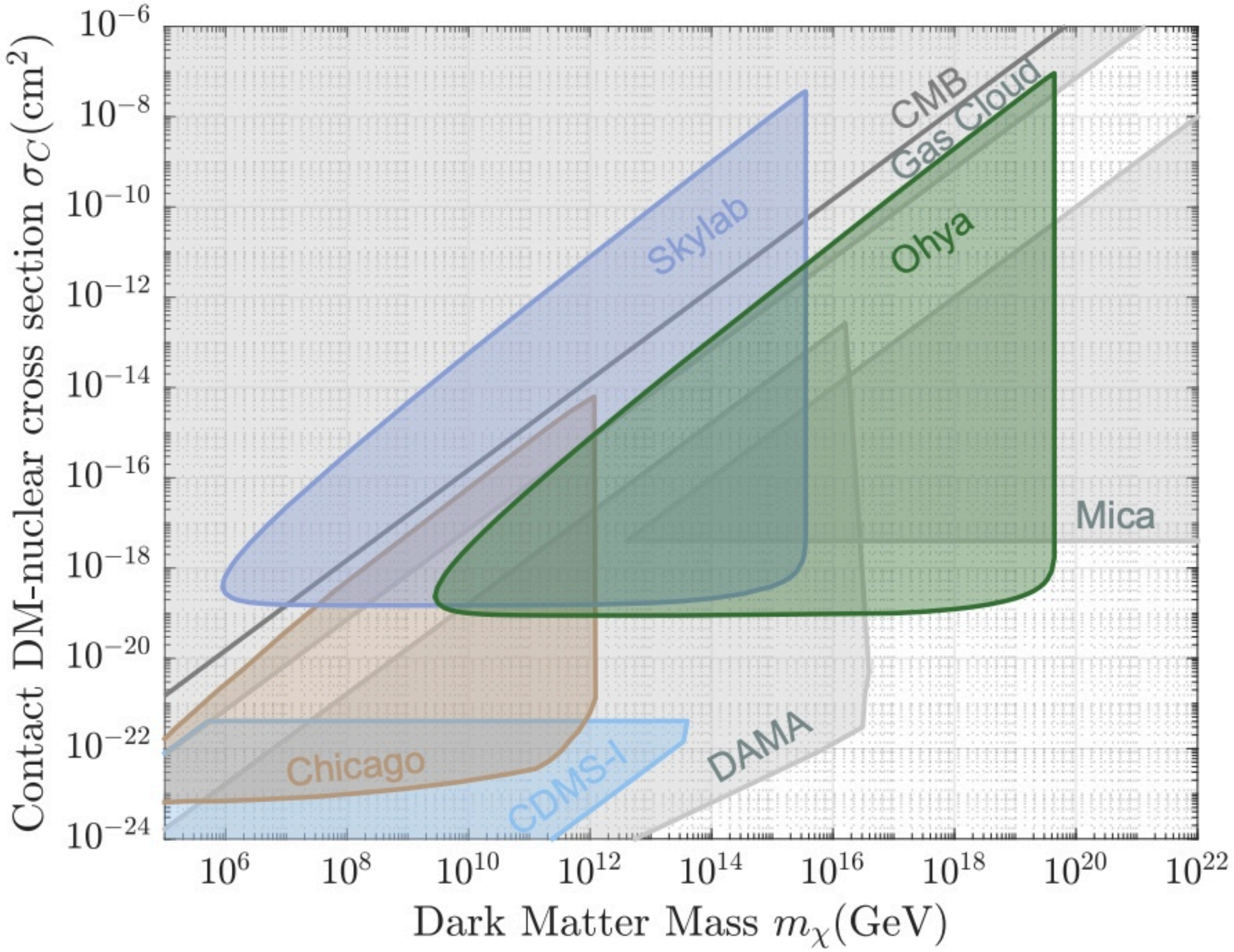
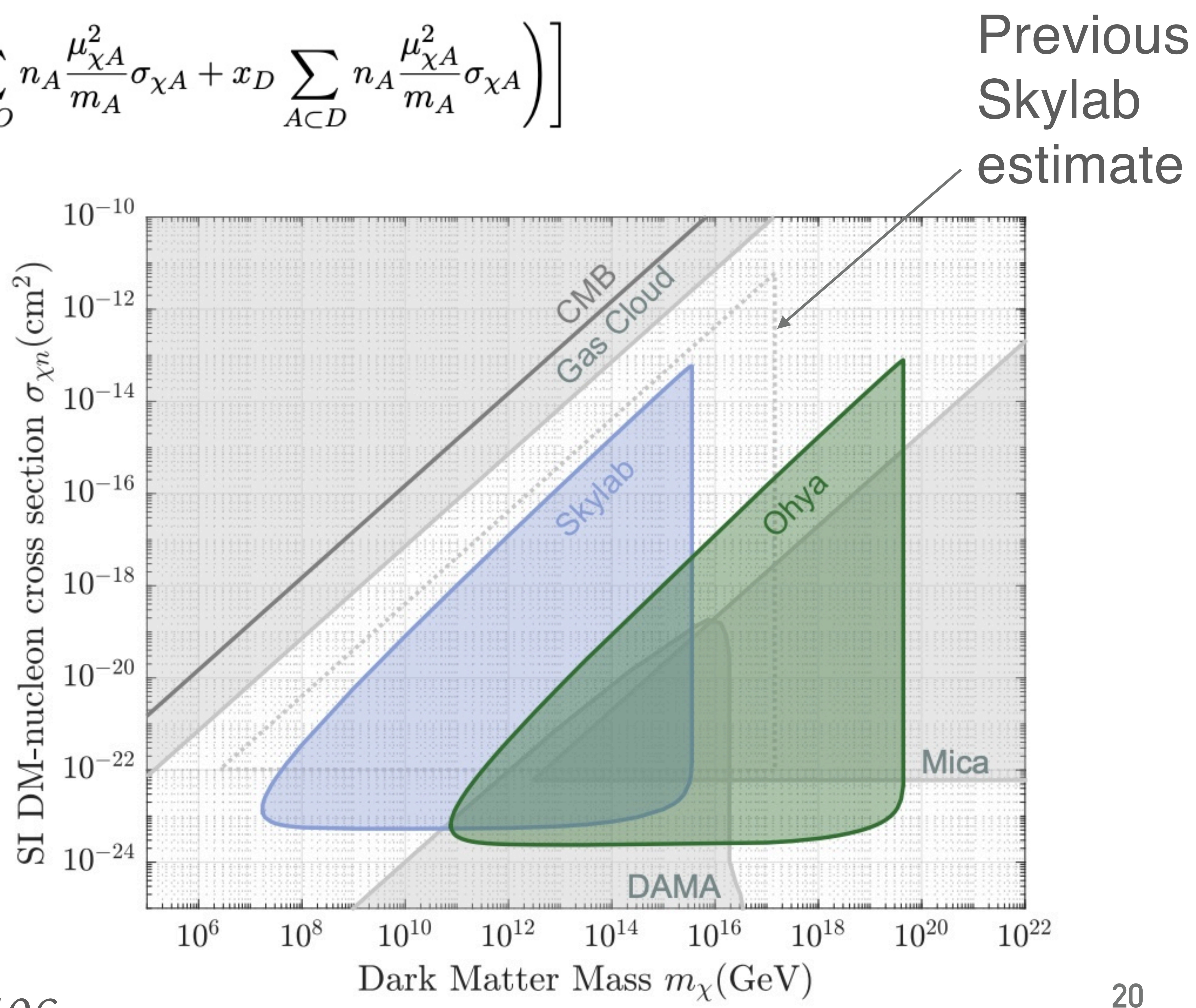
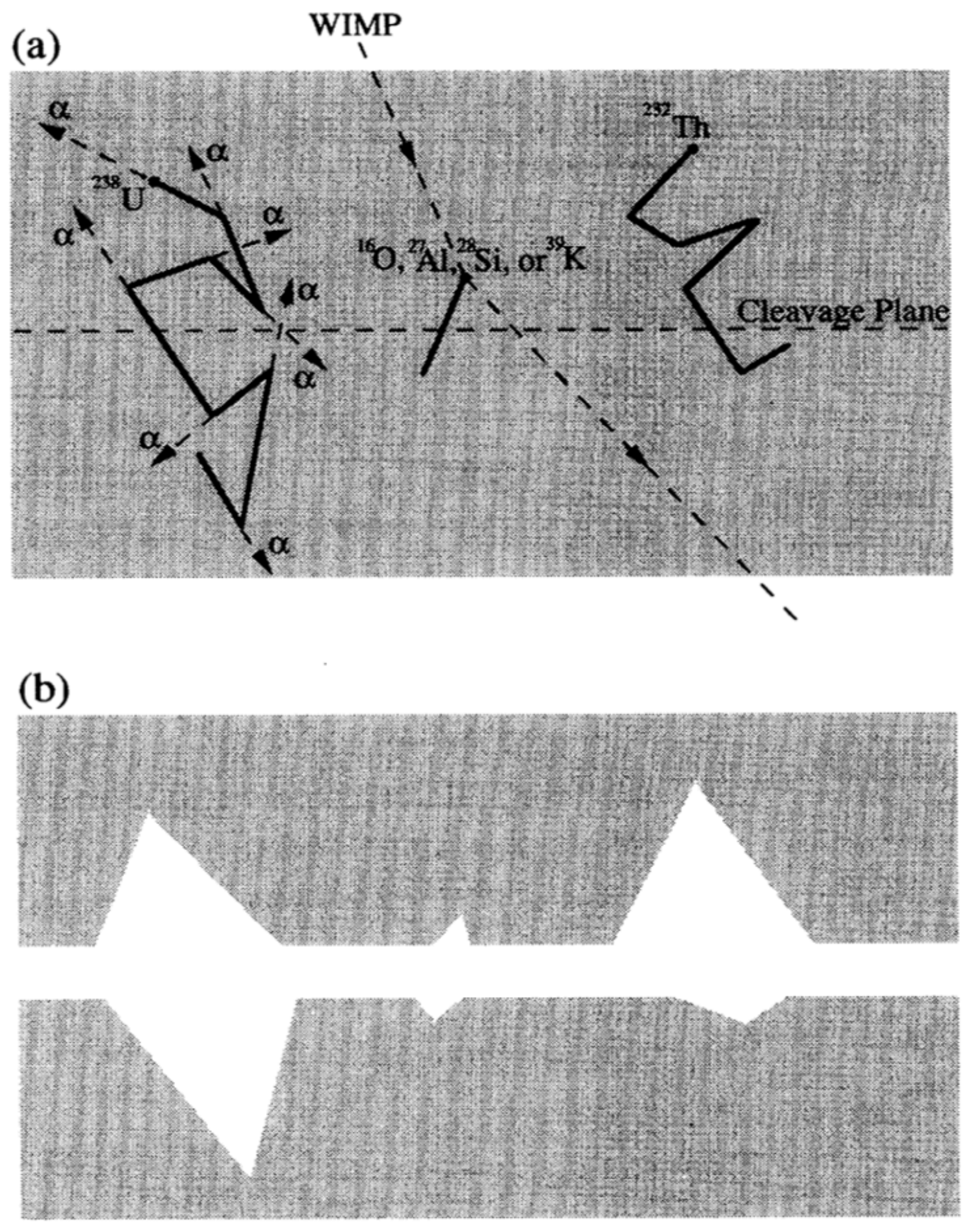
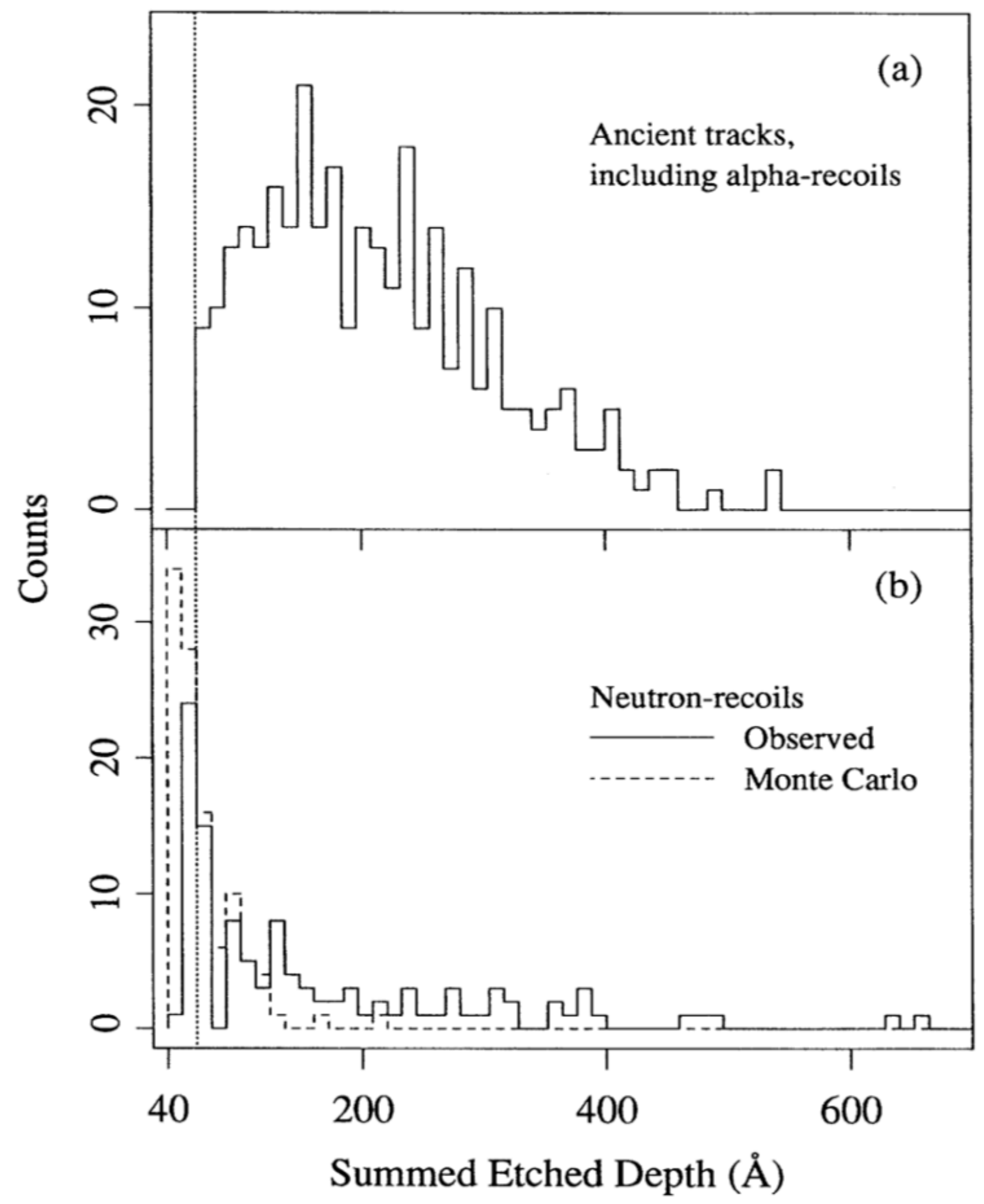




2012.13406

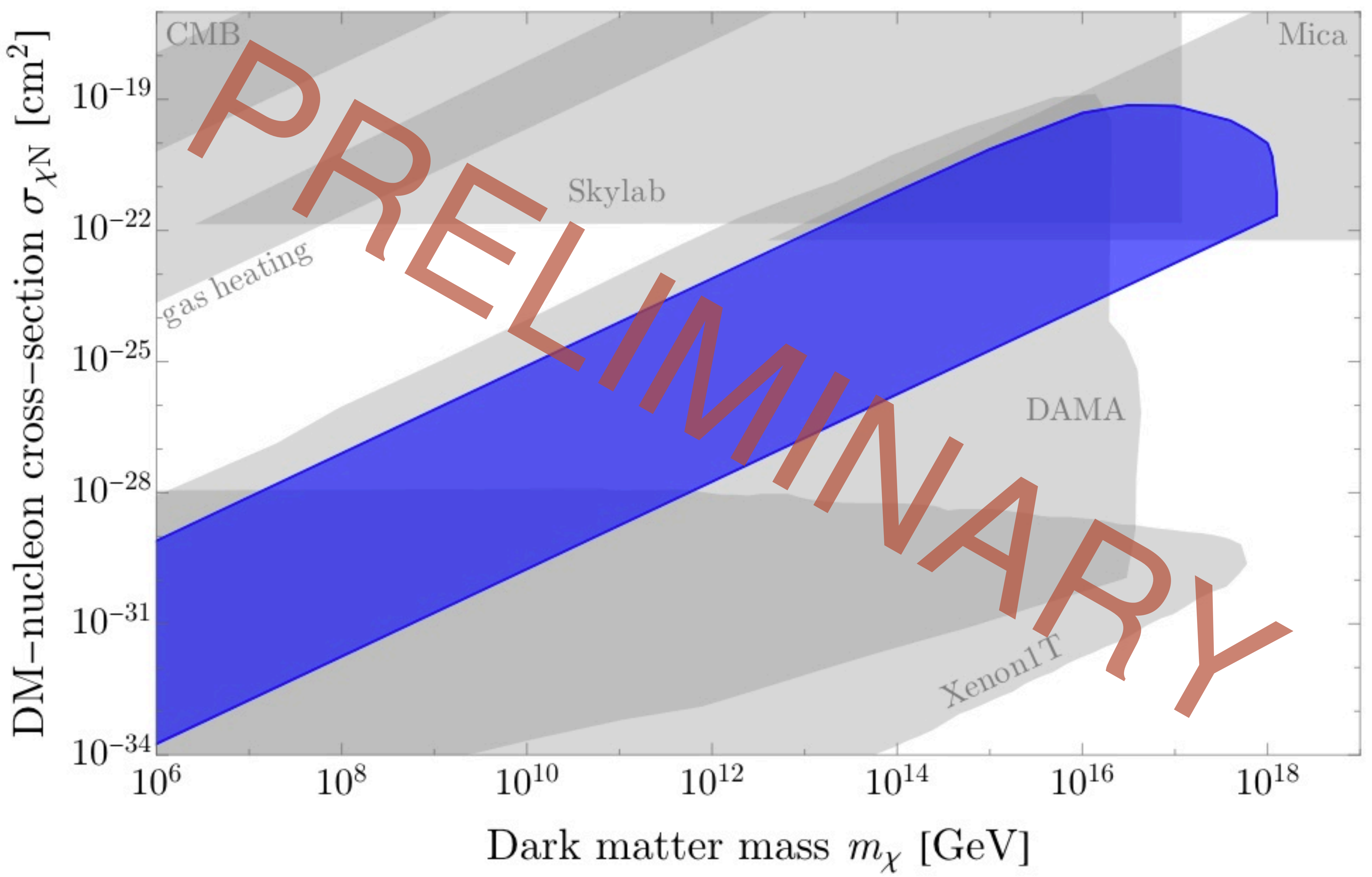
ANCIENT MICA SEARCH FOR DARK MATTER





➤ 1995 Snowden-Ifft et al. calibrated mica samples

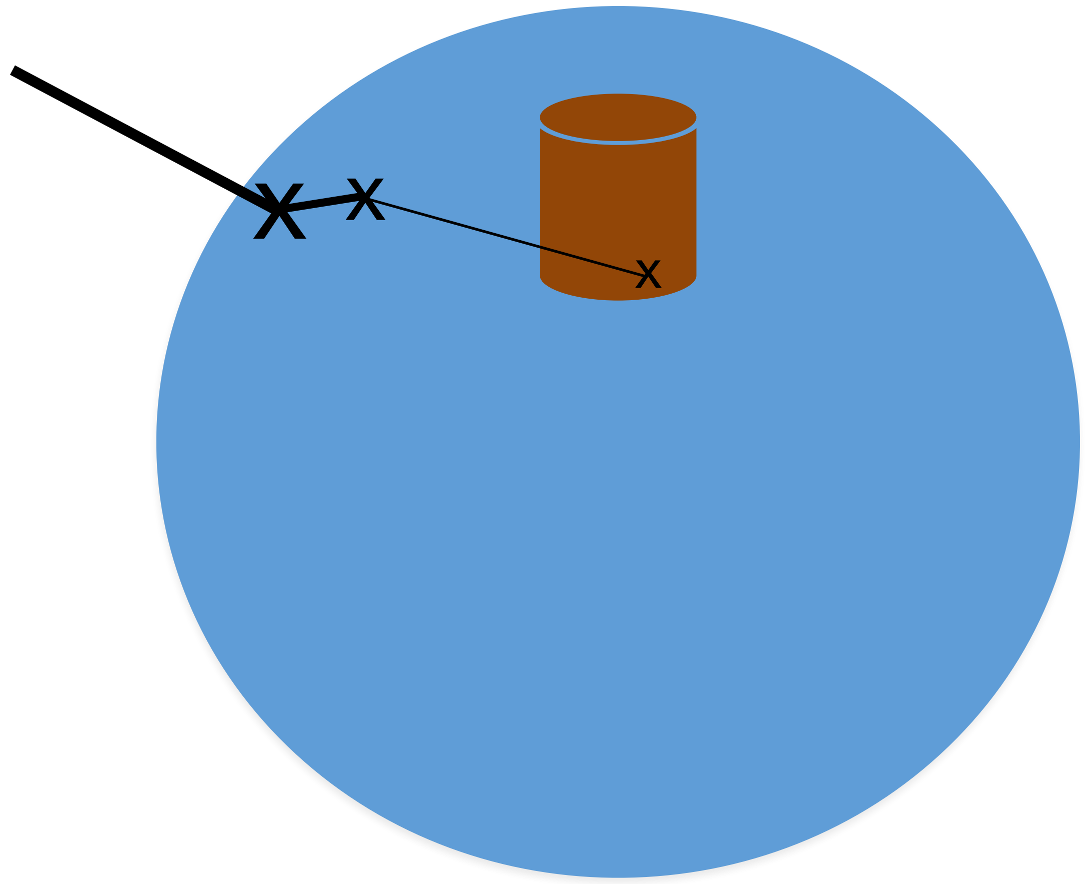
➤ Recast using crust and mica MC methods



Acevedo, JB, Goodman in prep

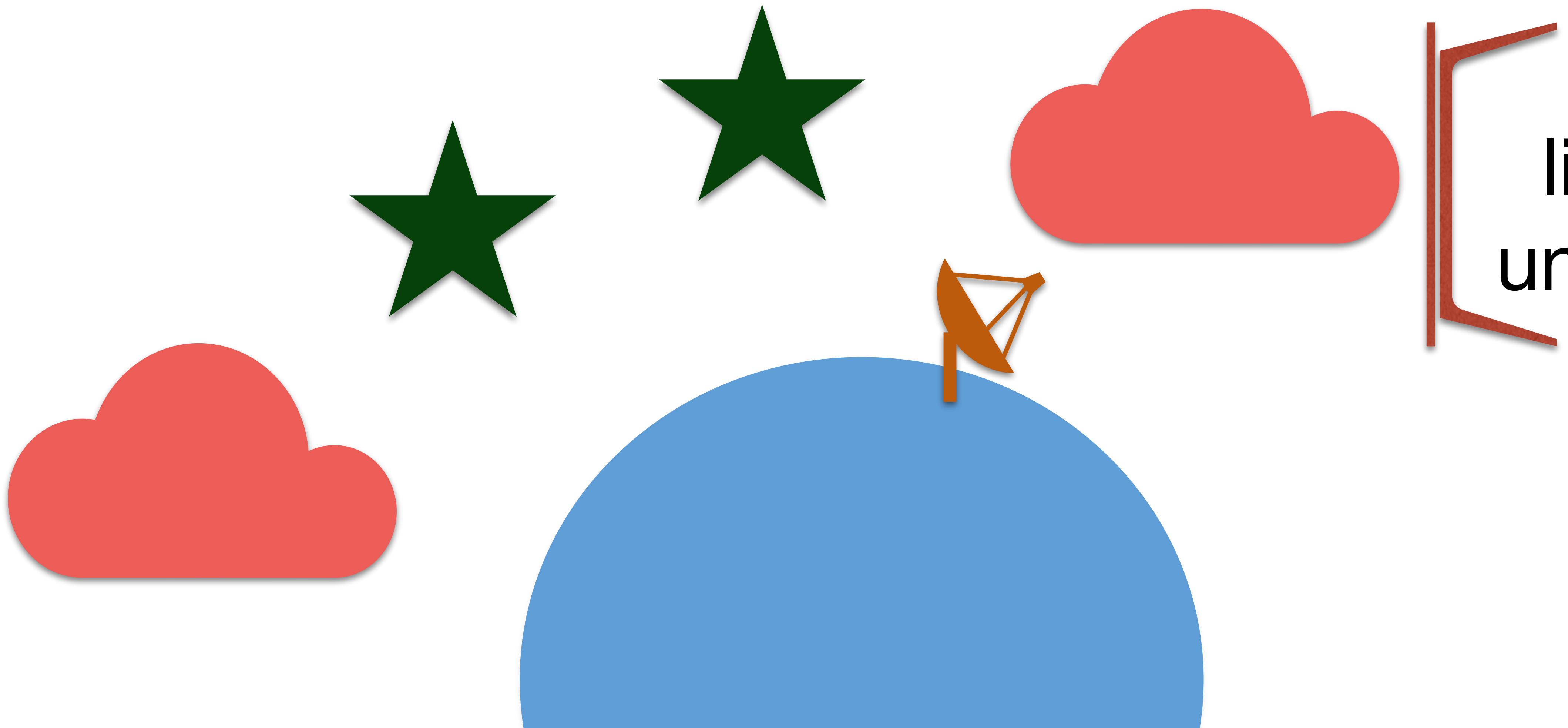
GAS CLOUDS

The earth and atmosphere block detection of strongly-interacting dark matter



dark matter kinetic energy < recoil threshold

Use detectors in space!



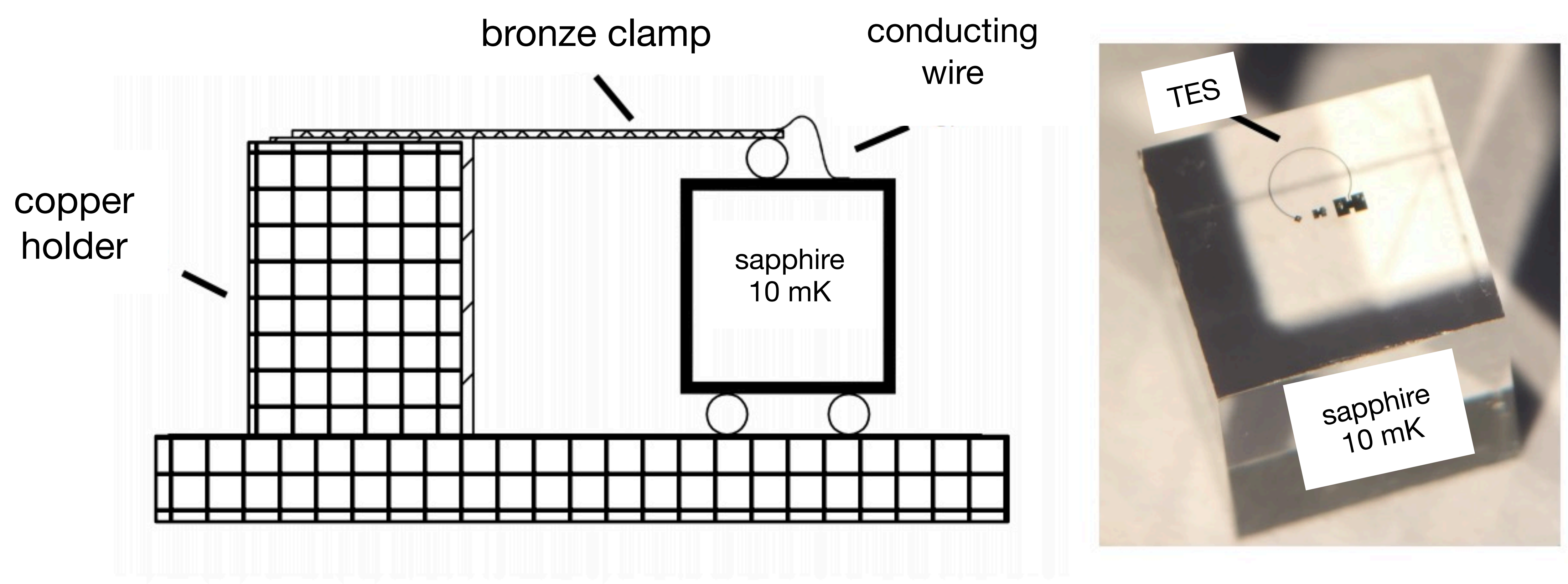
Interstellar gas

big
little overburden
unbound electrons

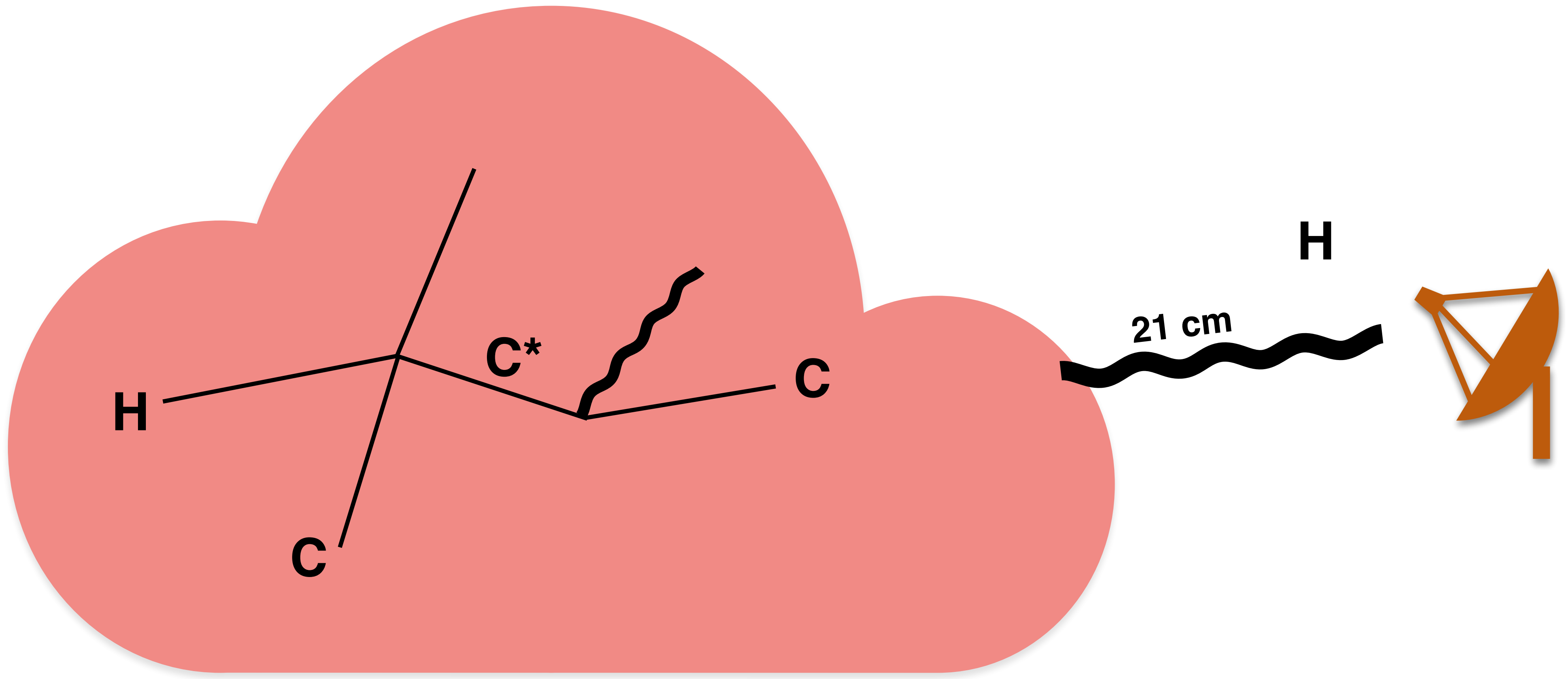
2010.07240
1812.10919
1806.06857

GAS CLOUDS AS CALORIMETRIC DETECTORS

CRESST sapphire
cooling: conducting wire
readout: TES thermal phonon

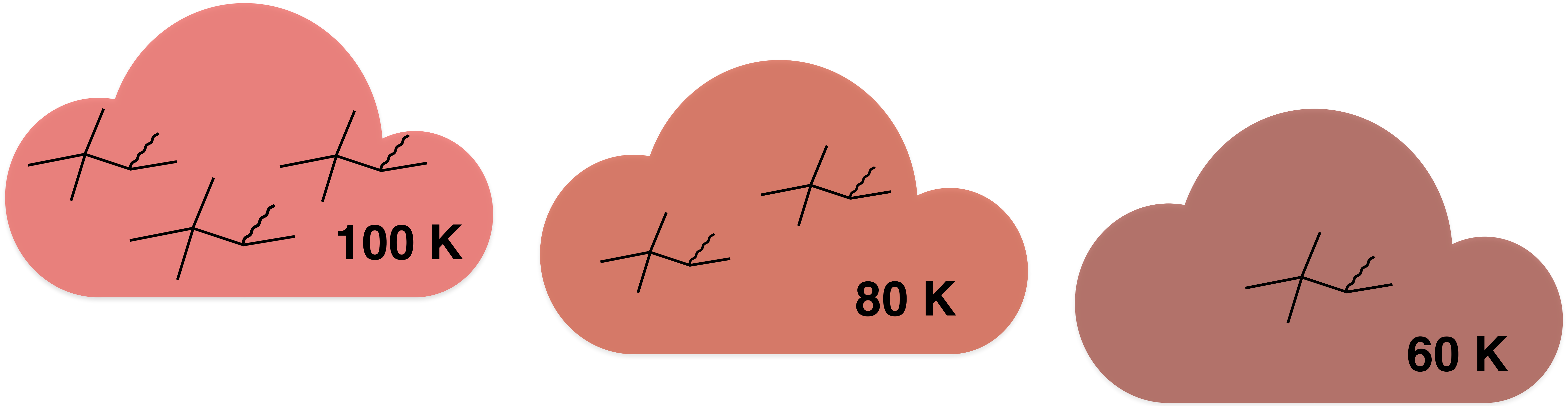


Cold Galactic gas clouds
cooling: carbon transitions
readout: 21 cm emission



GAS CLOUD COOLING

For 10-100 K gas clouds cooling results from electrons and hydrogen colliding with metal ions, and subsequent atomic de-excitation.



$$\text{Cooling rate} \propto n_{\mathrm{H}}^2 \sigma \sqrt{T/m}$$

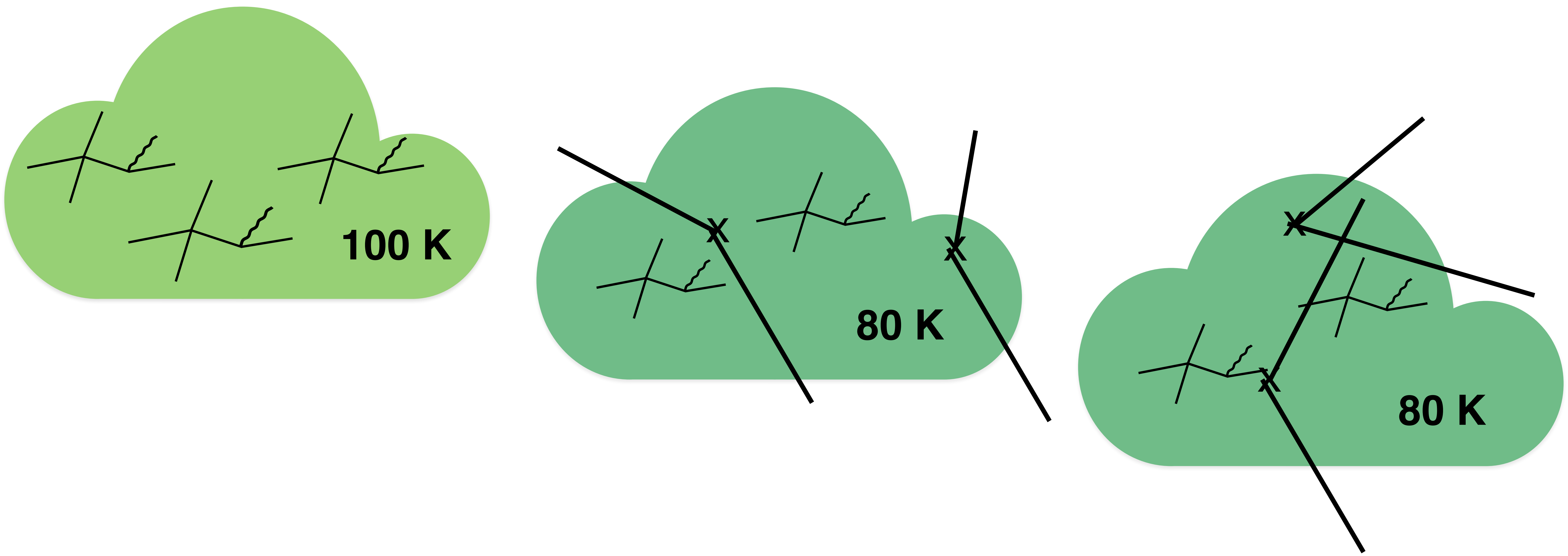
Collisions are rarer at lower temperatures.

**→So as the cloud cools,
the cooling rate decreases.**

GAS CLOUD DARK MATTER HEATING EQUILIBRIUM

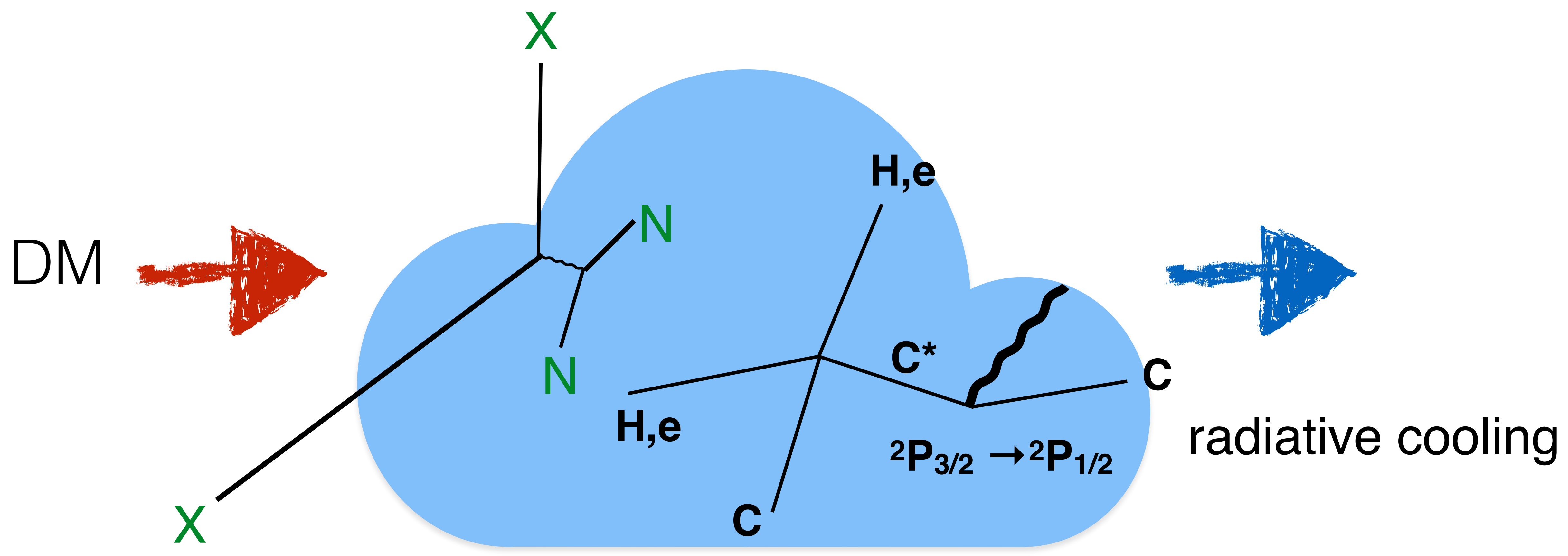
Cooling decreases with gas cloud temperature.

If dark matter predominantly heats the gas cloud,
the cloud will not cool below some temperature.



$$\text{Cooling rate} \geq \text{Dark matter heating rate}$$

GAS CLOUD BOUNDS



Conservative: assume all heating by DM

In reality:

(DM +)

cosmic rays

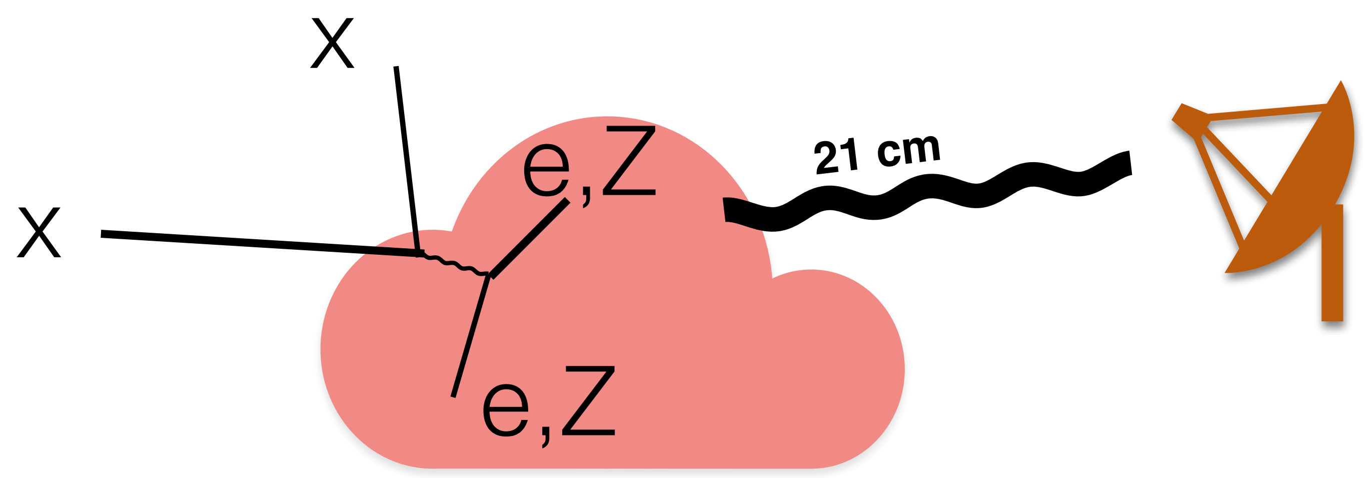
Xray/UV background

photoelectric heating via dust grains

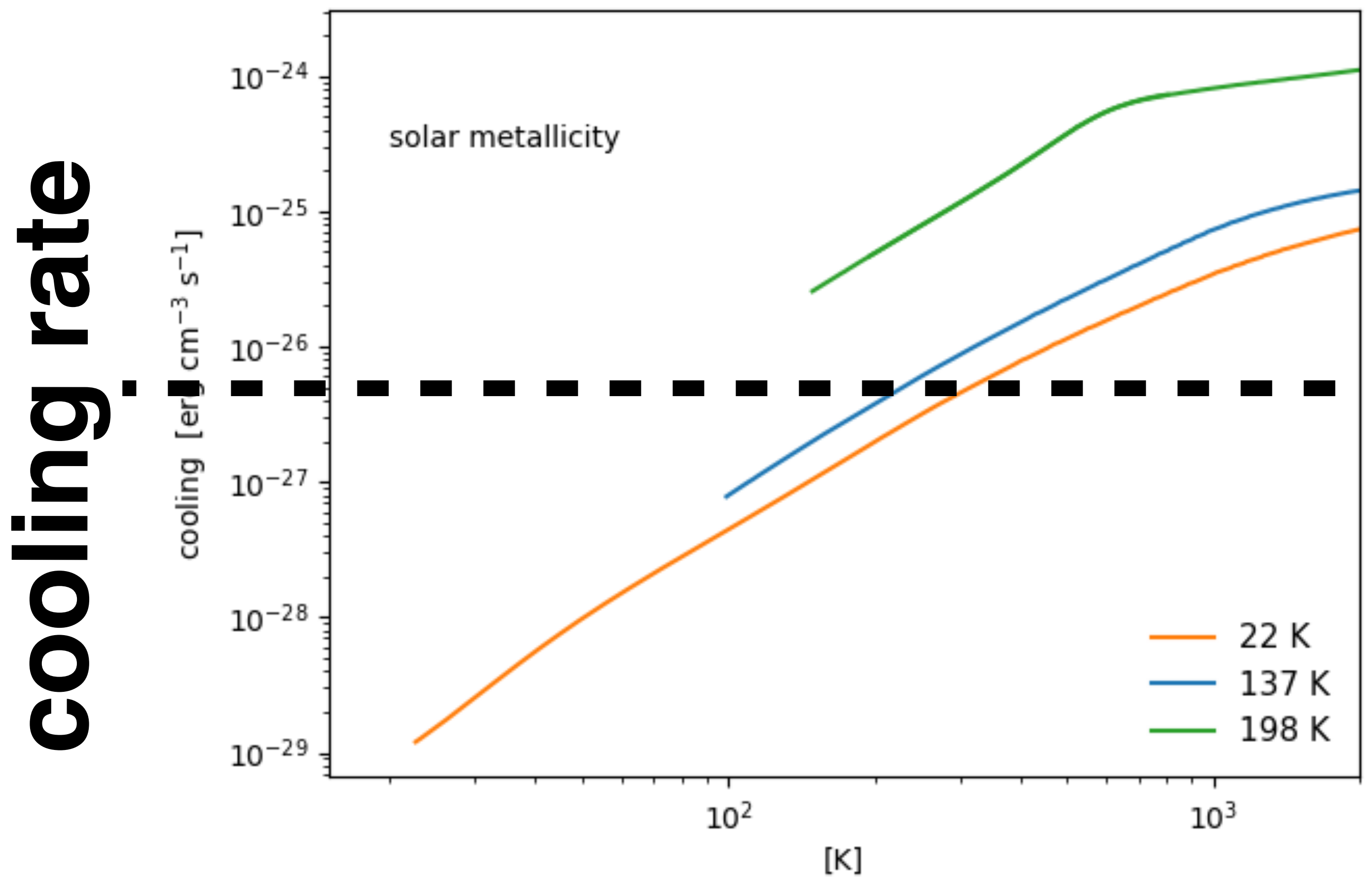
There are known ubiquitous heating sources, like cosmic UV background, cosmic rays, dust grain heating.

GAS CLOUD BOUNDS Class I

Infer the cooling rate of the gas from 21cm emission + models



Cooling curves are monotonic decreasing for T < 1000 Kelvin



Class I Bound

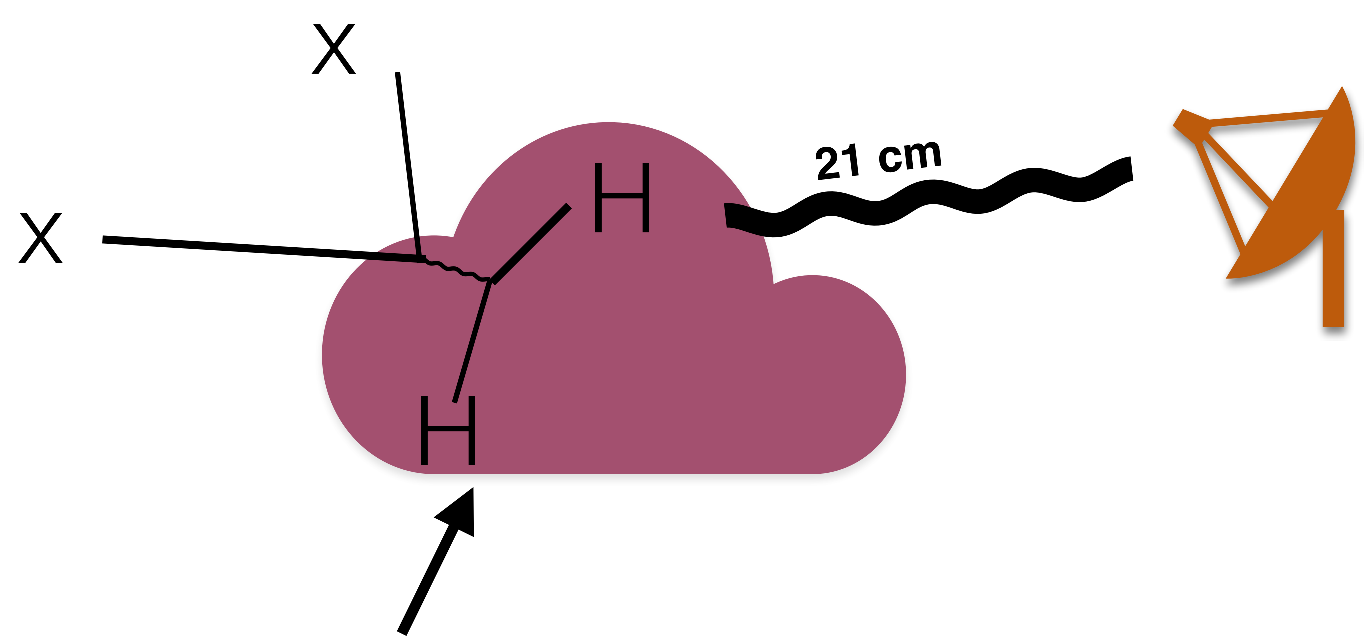
Dark heating < radiative cooling

Set bound on dark matter interacting with either unbound electrons or metals

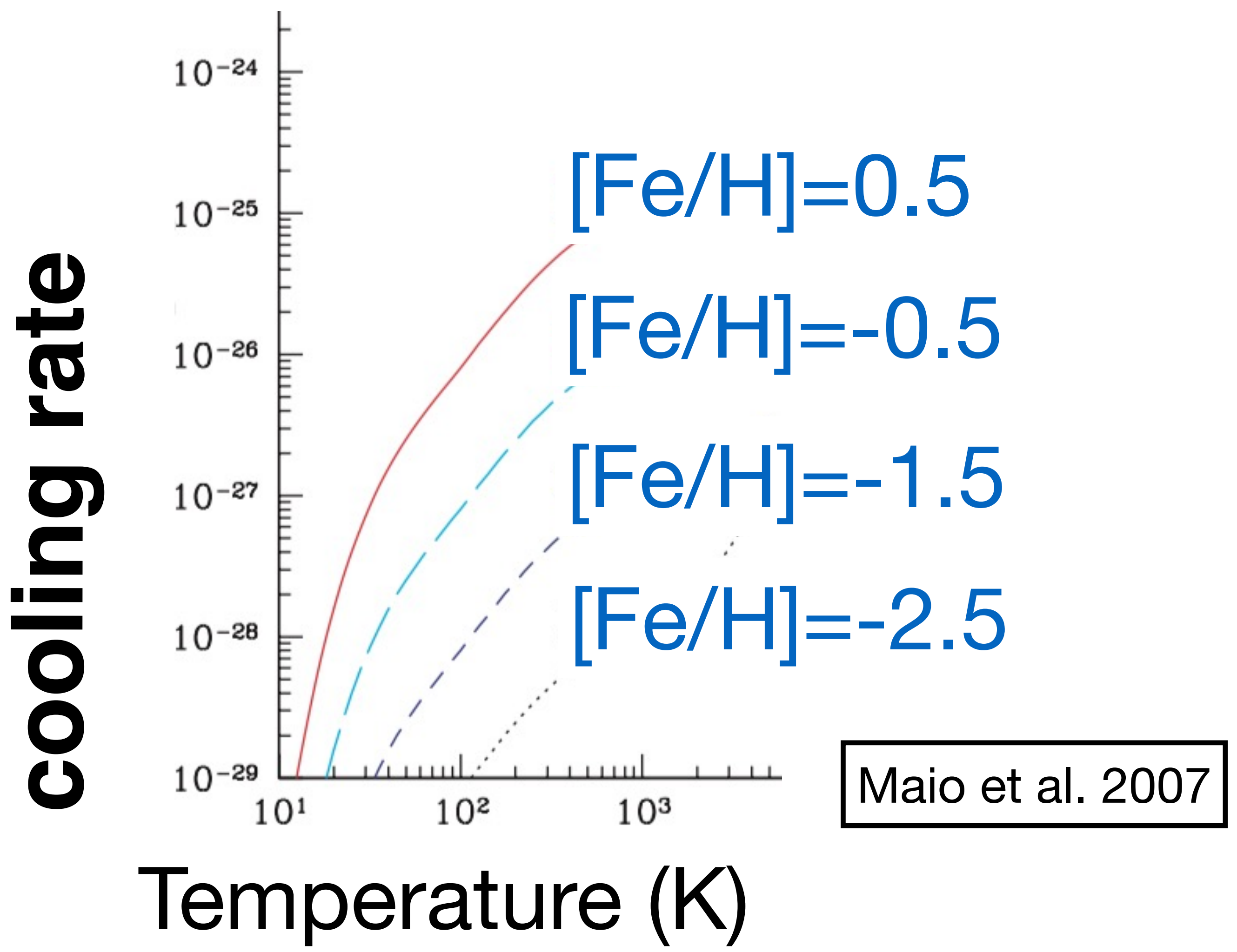
$$VCR = f(\mathrm{T}, \mathrm{n_H}, [\mathrm{Fe/H}])$$

GAS CLOUD BOUNDS Class II

Infer the cooling rate of the gas from 21cm emission + models



Same as Class I, but now consider scattering off of non-metals/electrons



Class II Bound

Dark heating < radiative cooling

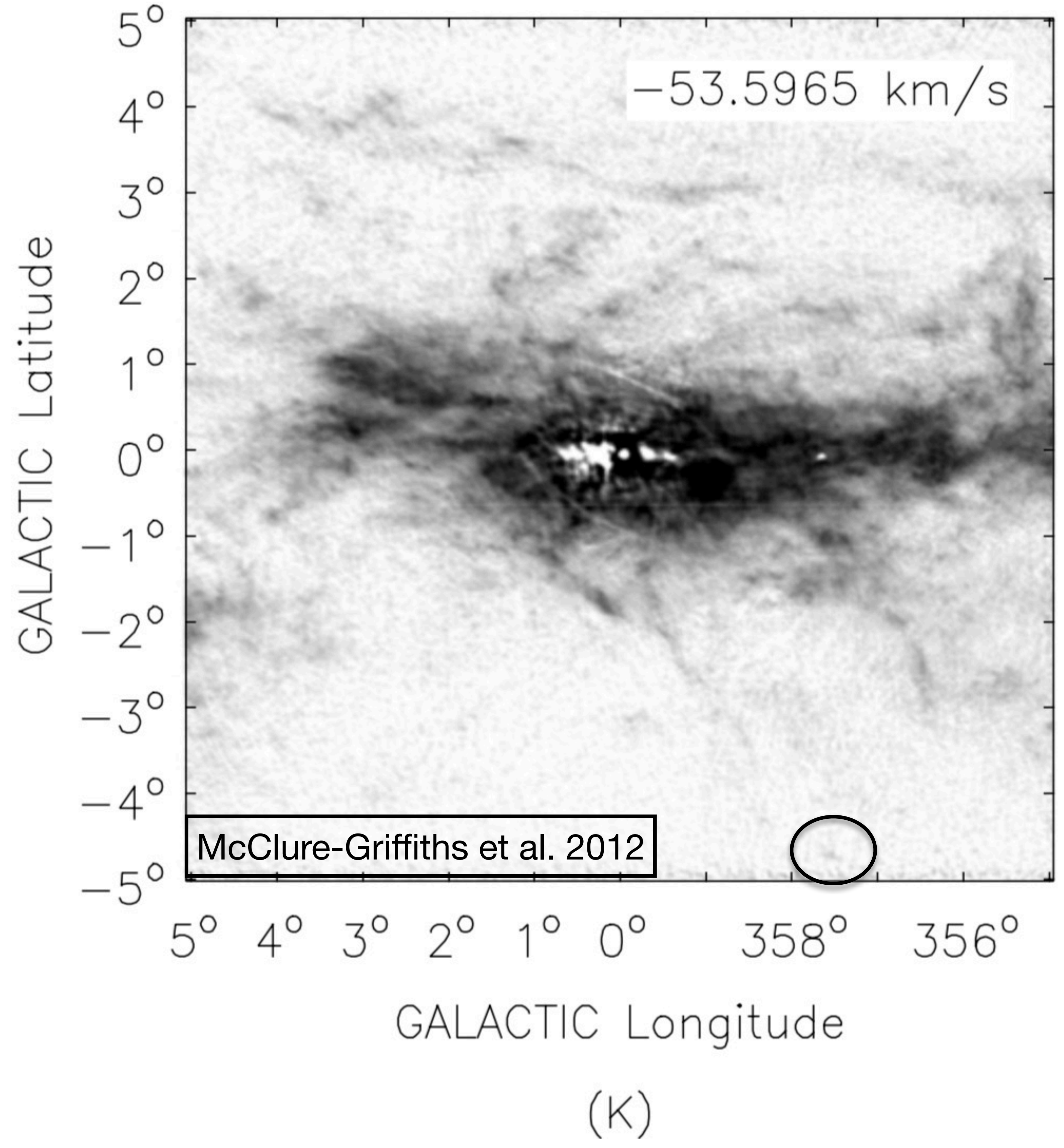
Should choose a conservative metallicity for a robust bound

Bound now depends on metallicity

$$VCR \propto [\mathrm{Fe/H}]$$

HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS

Gas Cloud 357.8-4.7-55



Δv from 21cm emission gives T<137 K

G357.8-4.7-55

M = 237 M⊙

r_{gc} = 12.9 pc

$n_n = 0.4\ cm^{-3}$

Tg [?] < 137 K

r_{los} ~ 800 pc

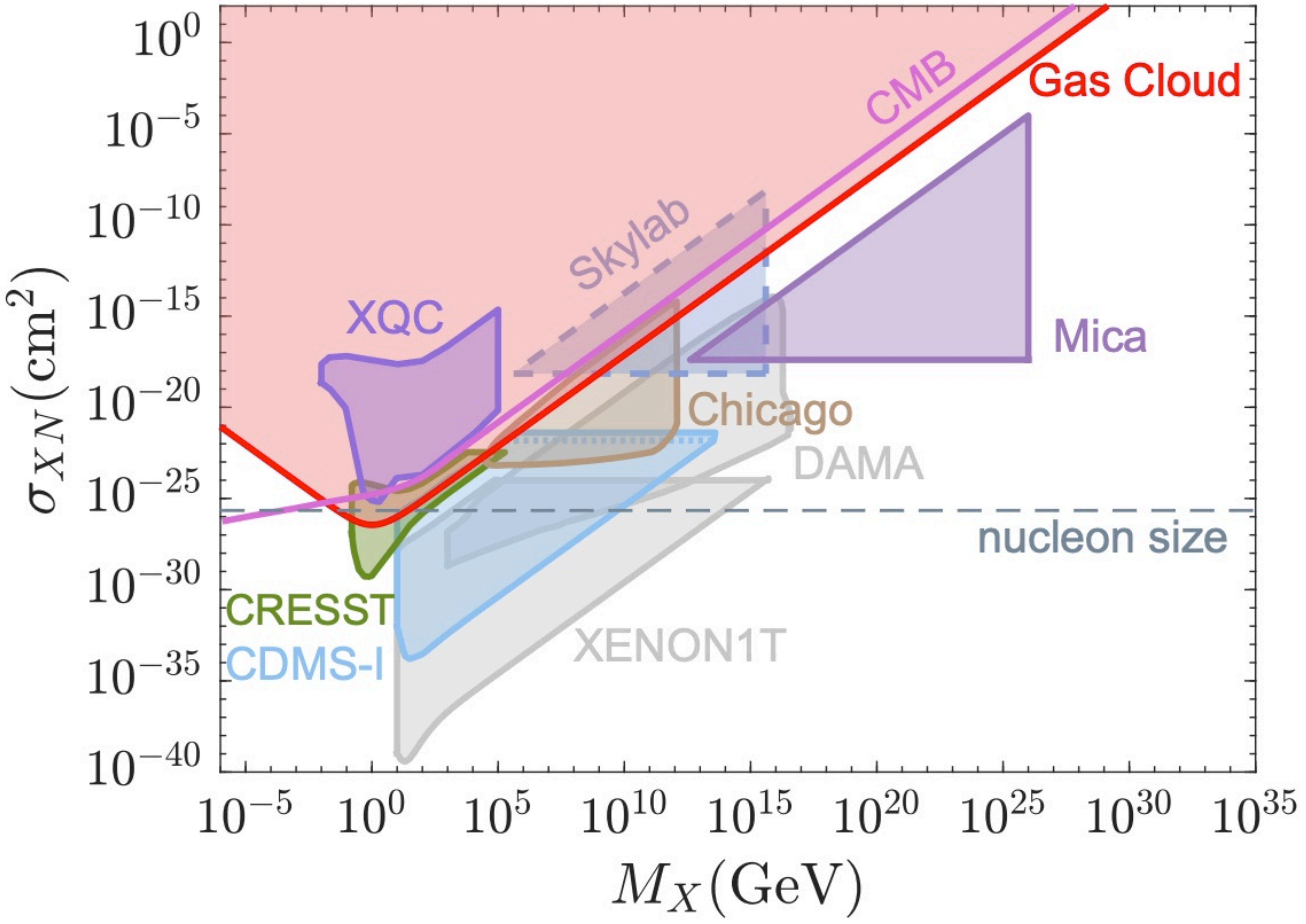
v_g = -54 km/s

5°

(assume spherical cloud)

HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS

- Fixed cross-section for scattering off all nuclei



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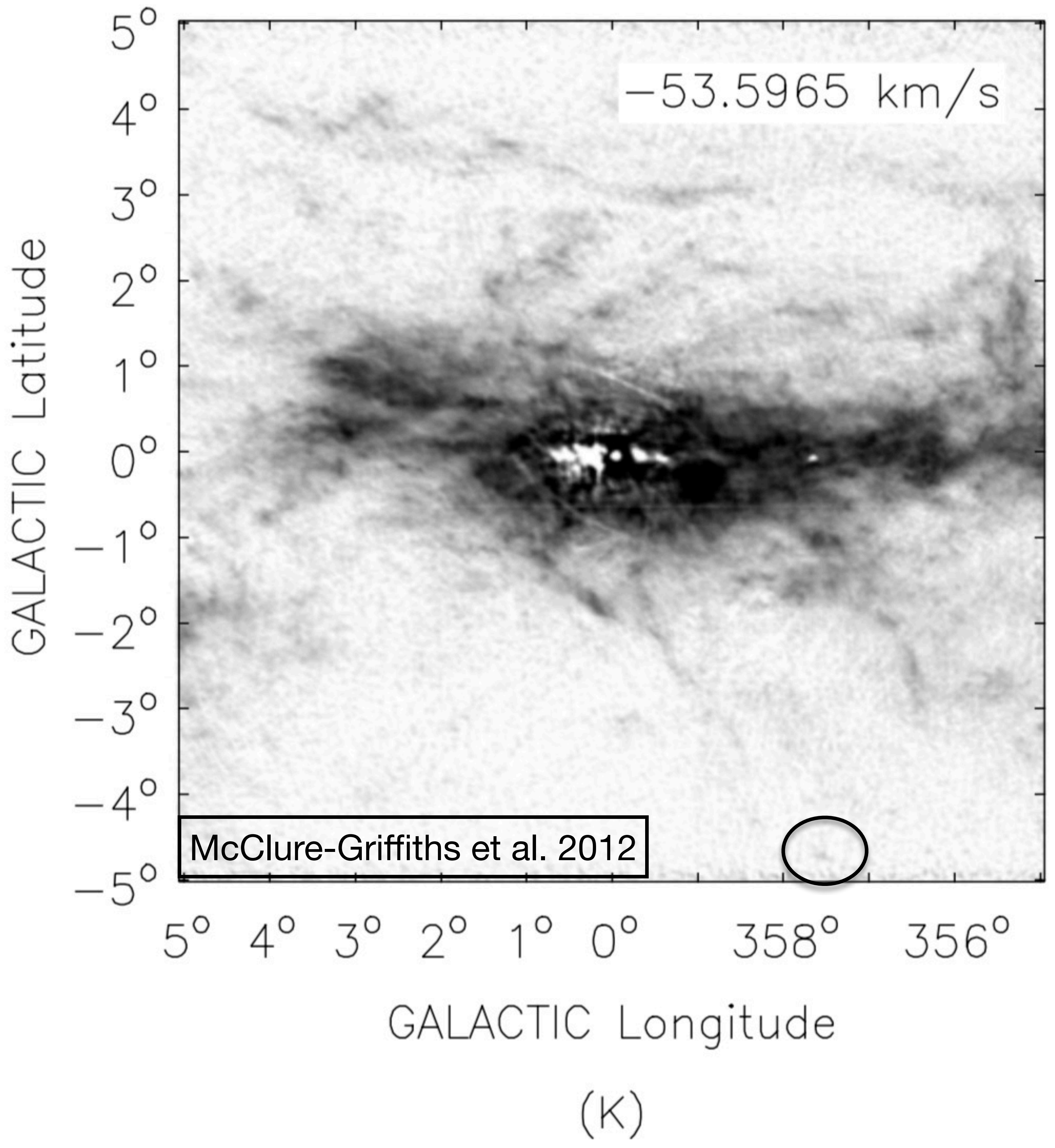

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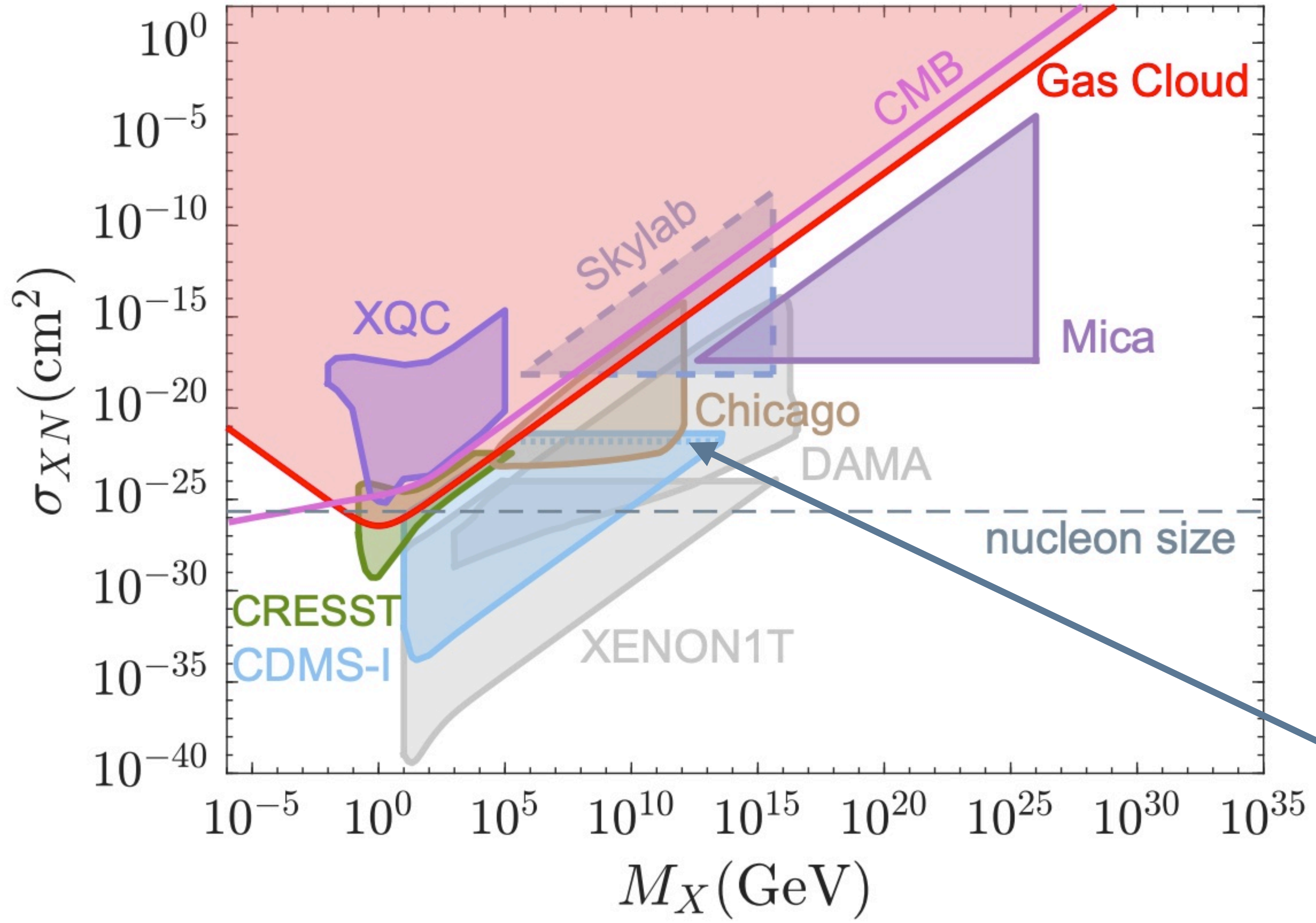
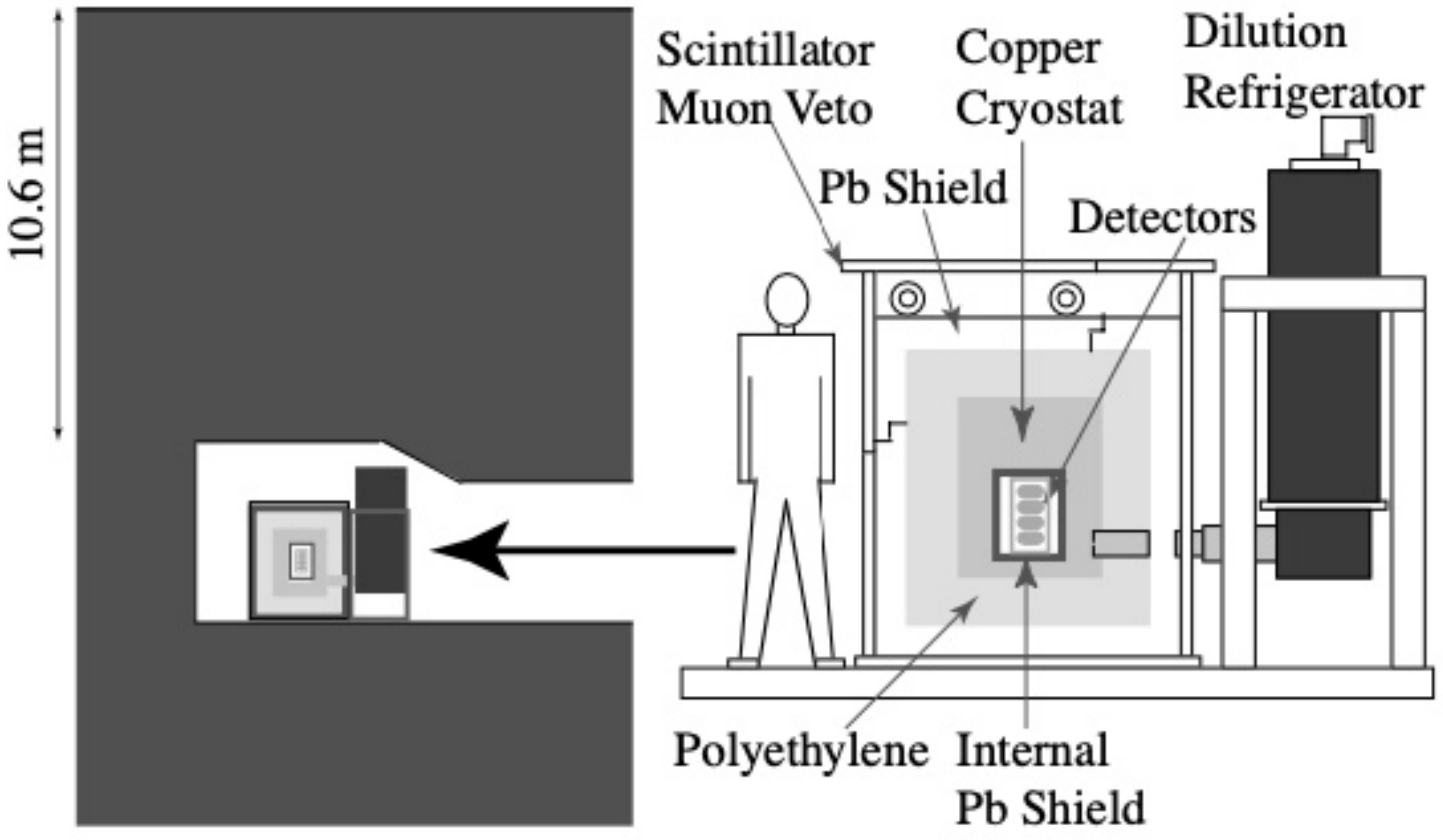
2010.07240

HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS





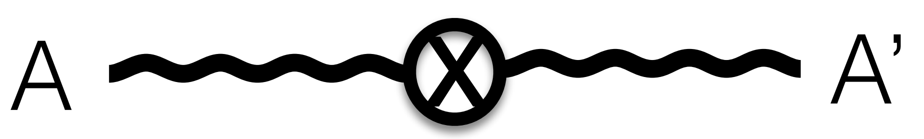
Also update on CDMS-I limit using multi scatter

(Muon veto rejects strong interactions)

2010.07240

HEAVY COMPOSITE DM IN GAS CLOUD, LONG-RANGE INTERACTIONS

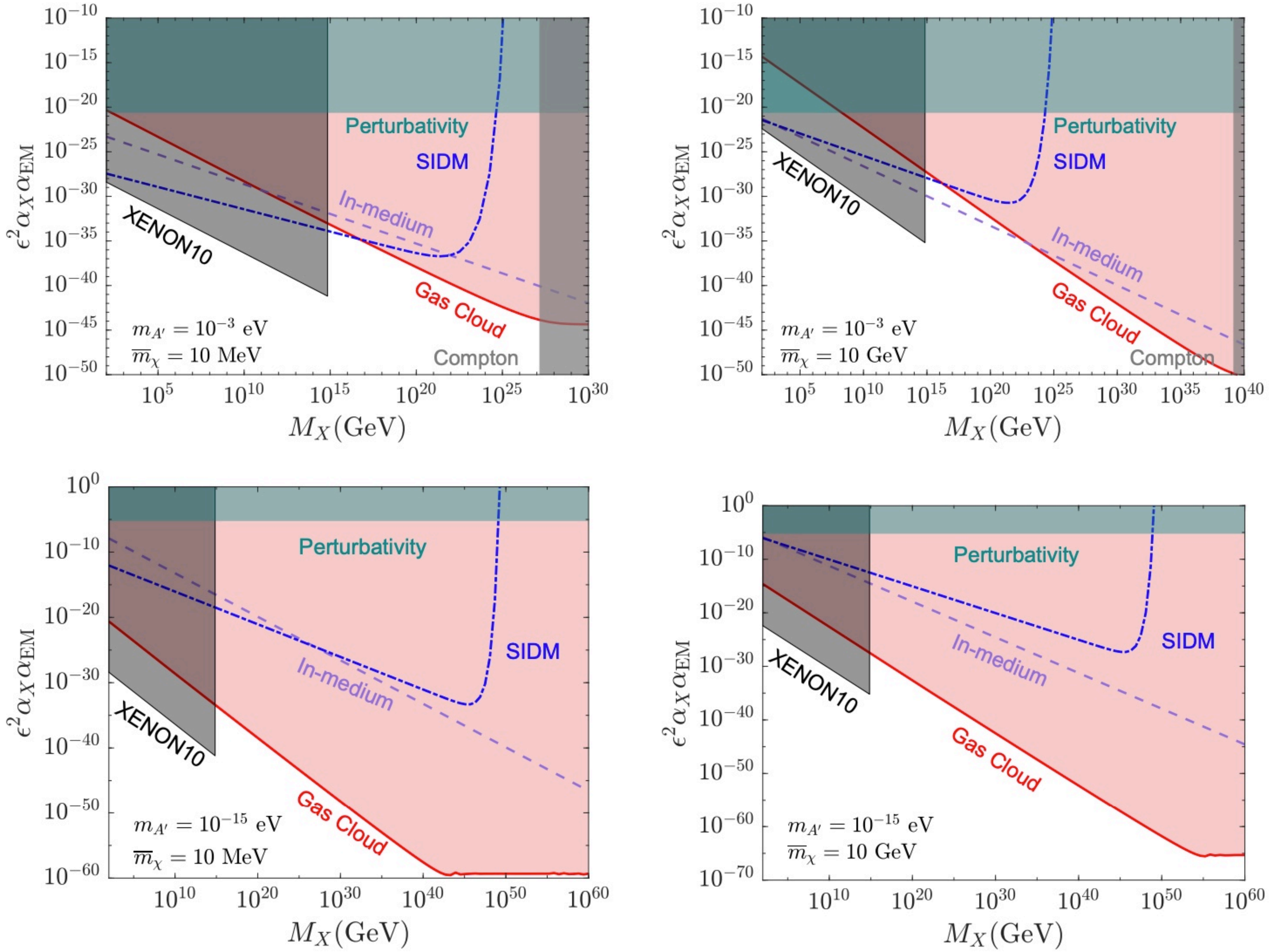
Vector Portal Dark Matter



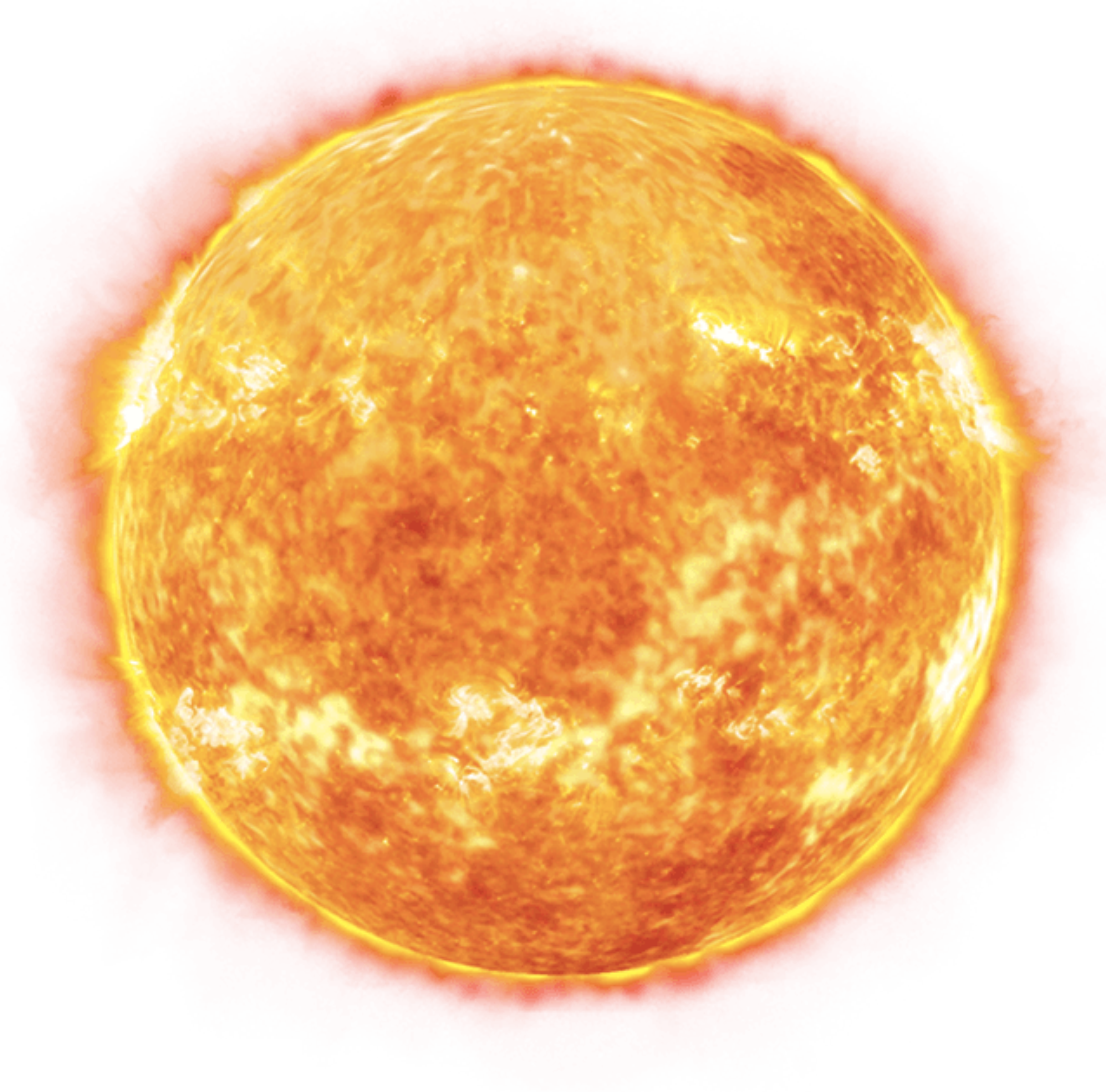
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\kappa}{2} F_{\mu\nu} F'^{\mu\nu} - g_D A'_\mu \bar{\chi} \gamma^\mu \chi$$

Mediator with a mass, can be applied to millicharged in the nearly massless limit.

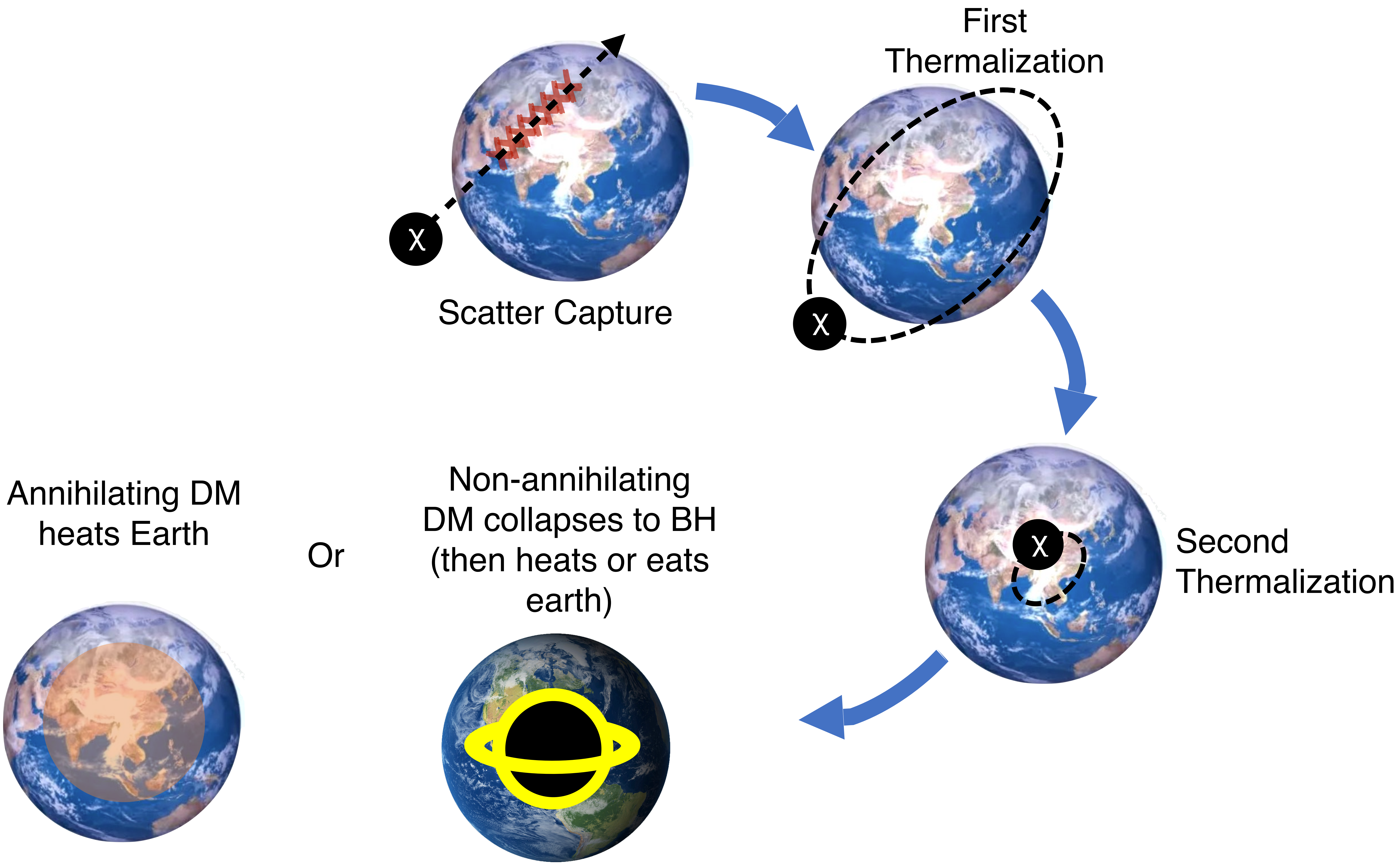
2010.07240

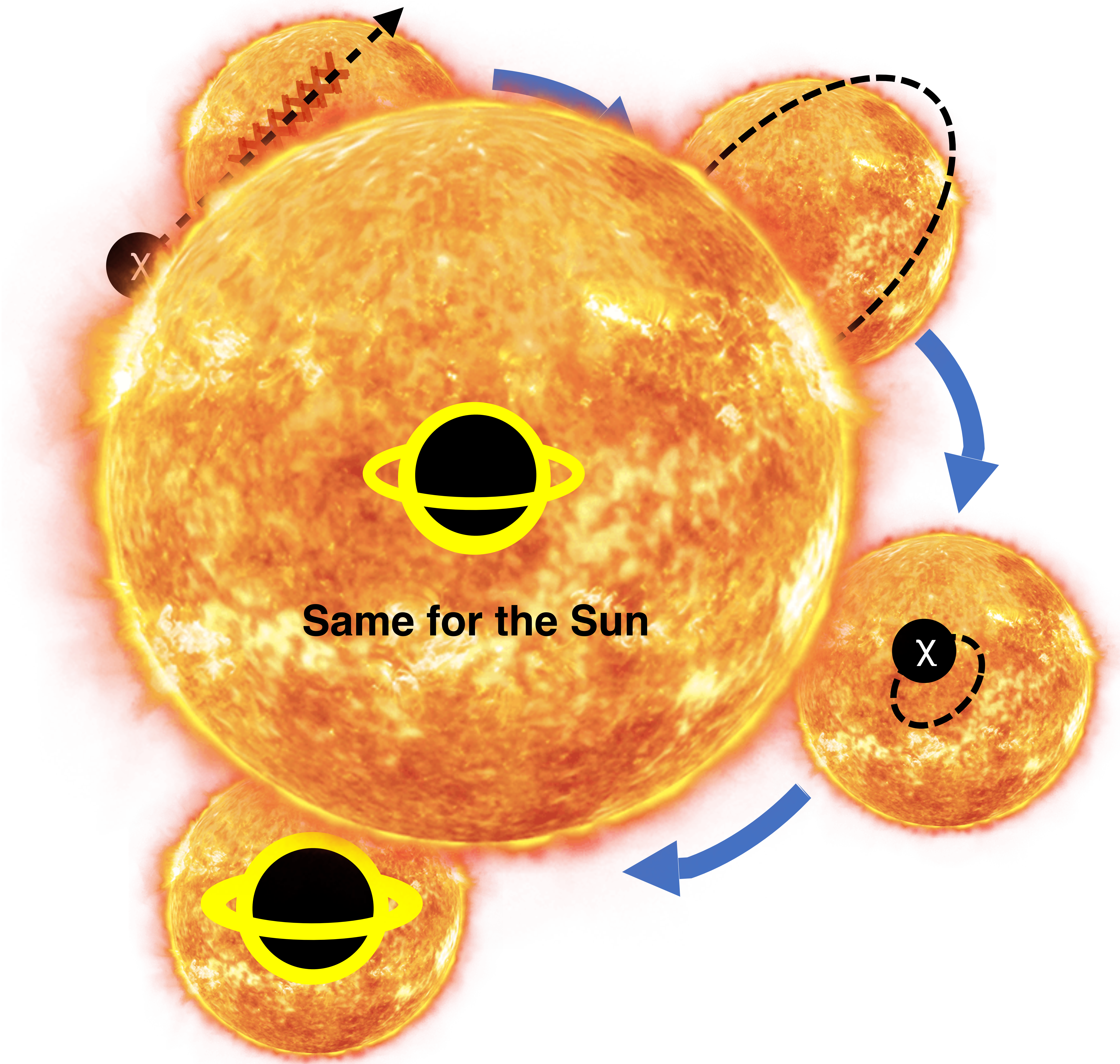


Stars and Planets As Dark Matter Detectors

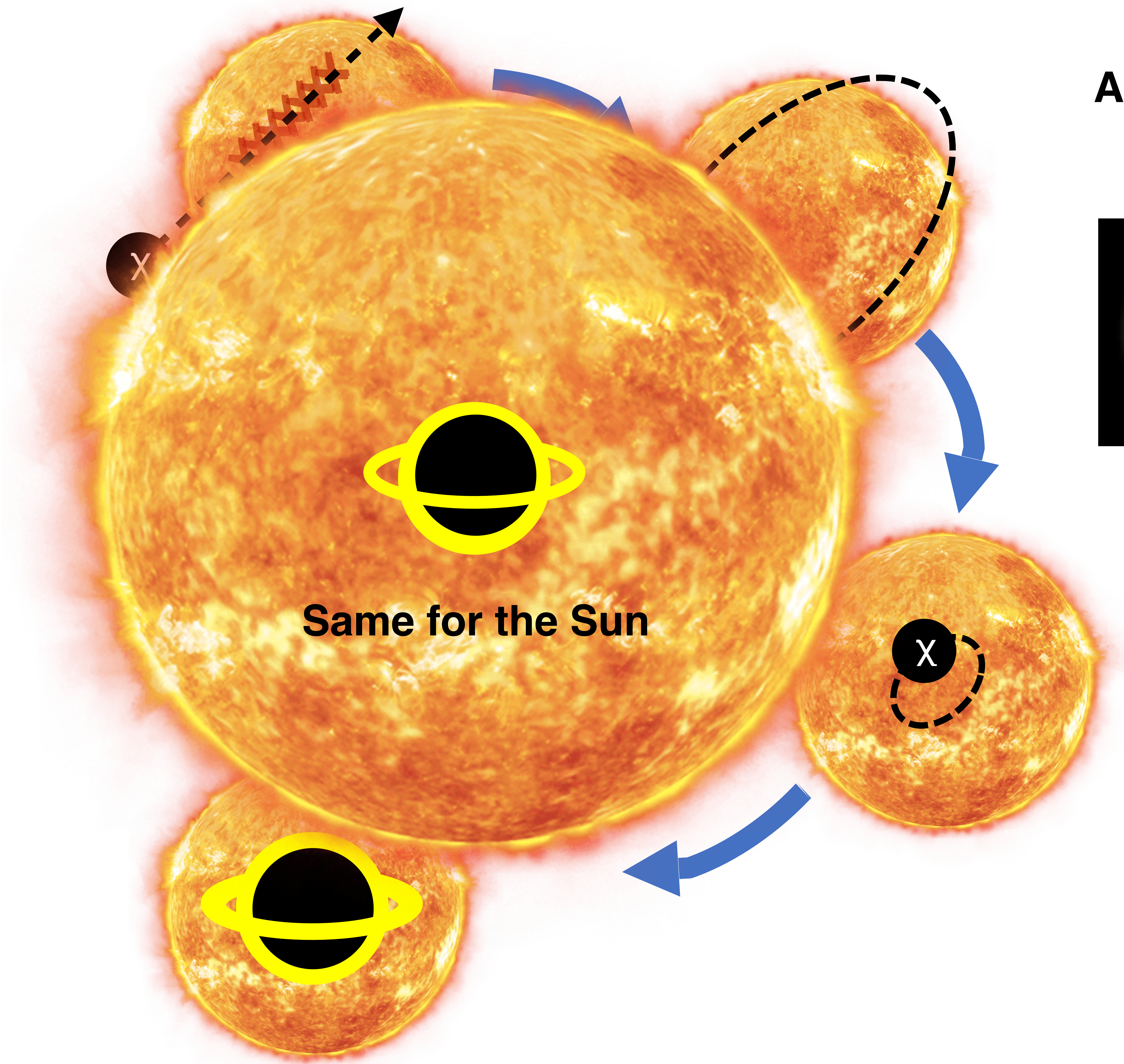


Special thanks to Alan Goodman

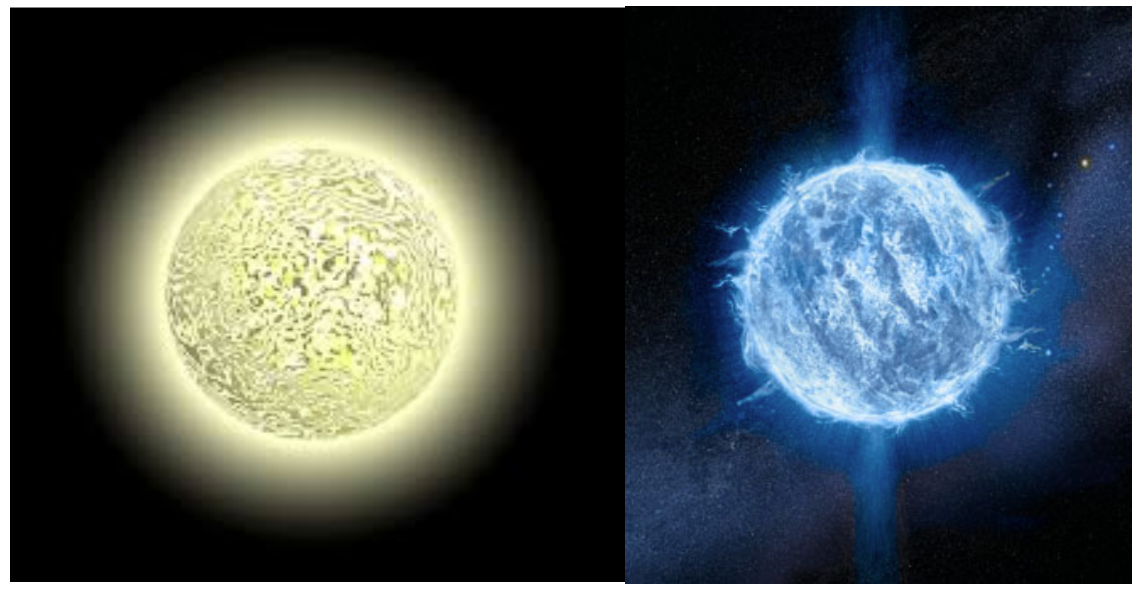

χ
Scatter Capture
First
Thermalization
χ
χ
Second
Thermalization
Annihilating DM
heats Earth
Or
Non-annihilating
DM collapses to BH
(then heats or eats
earth)

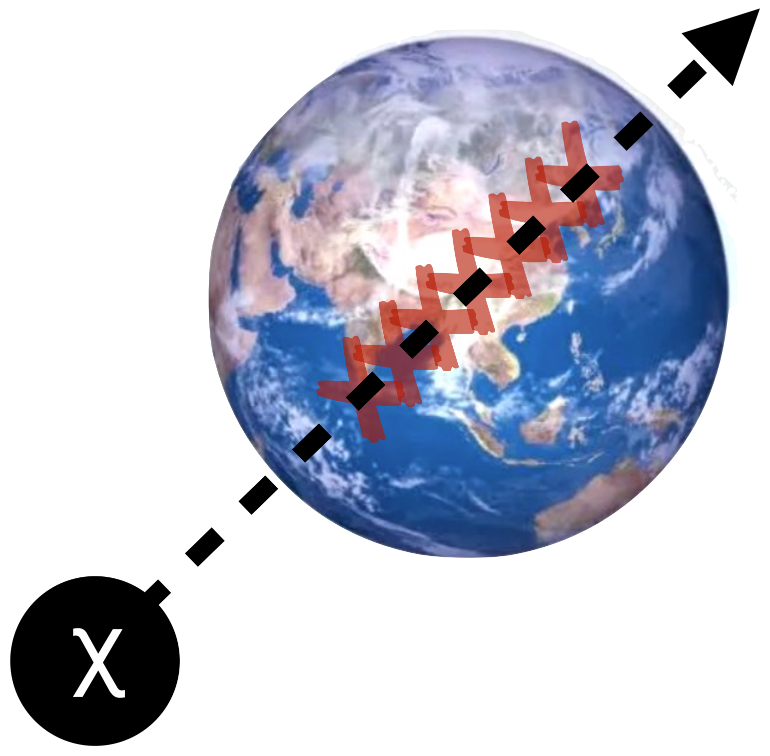


X
Same for the Sun
X



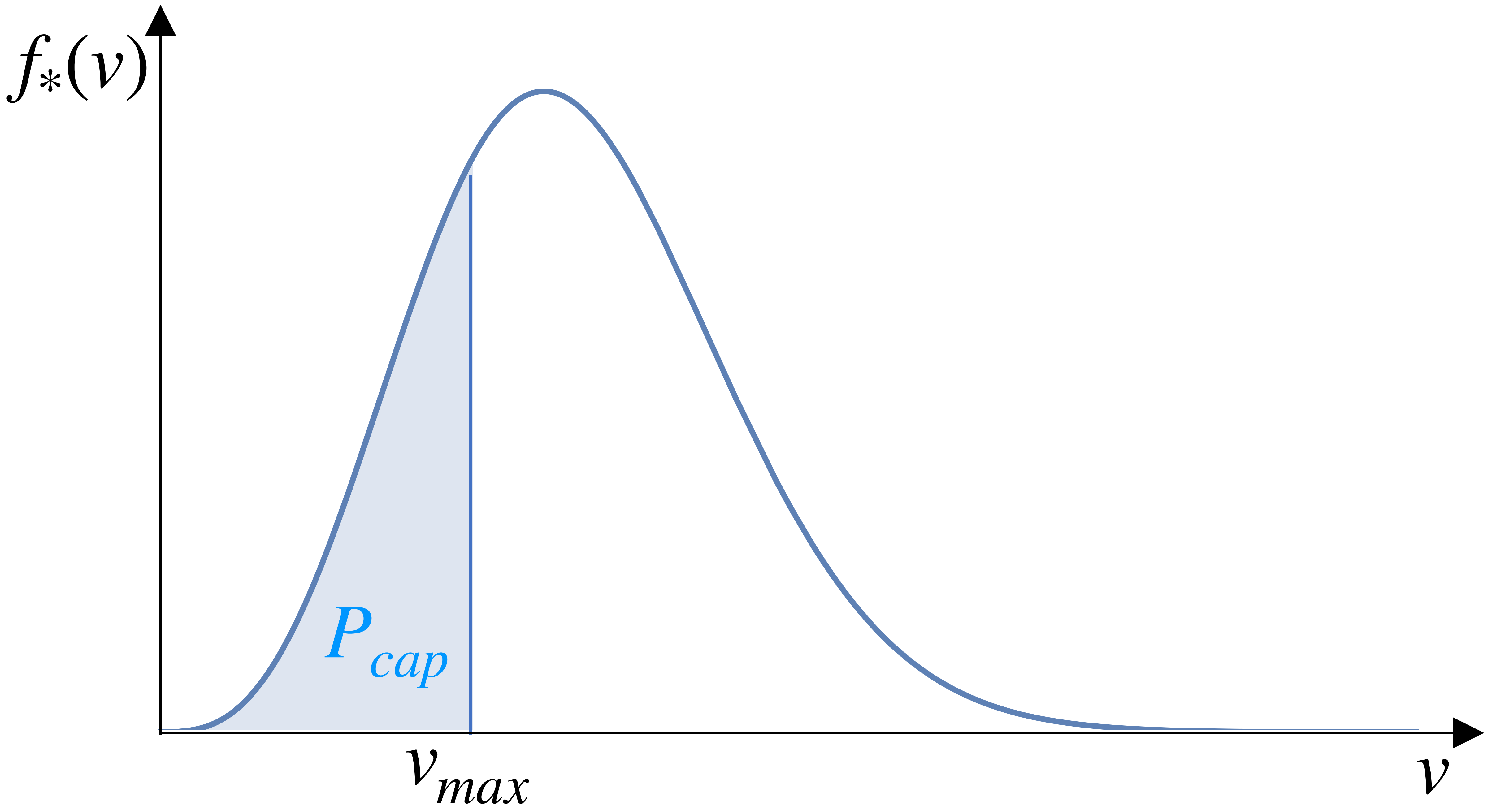
And White Dwarfs and Neutron stars





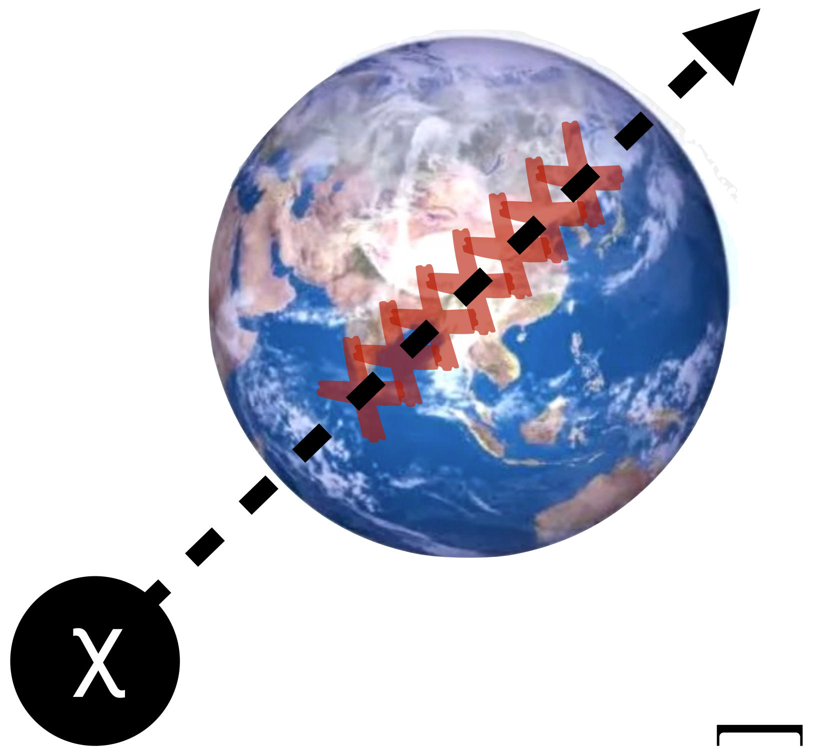
Scatter Capture

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

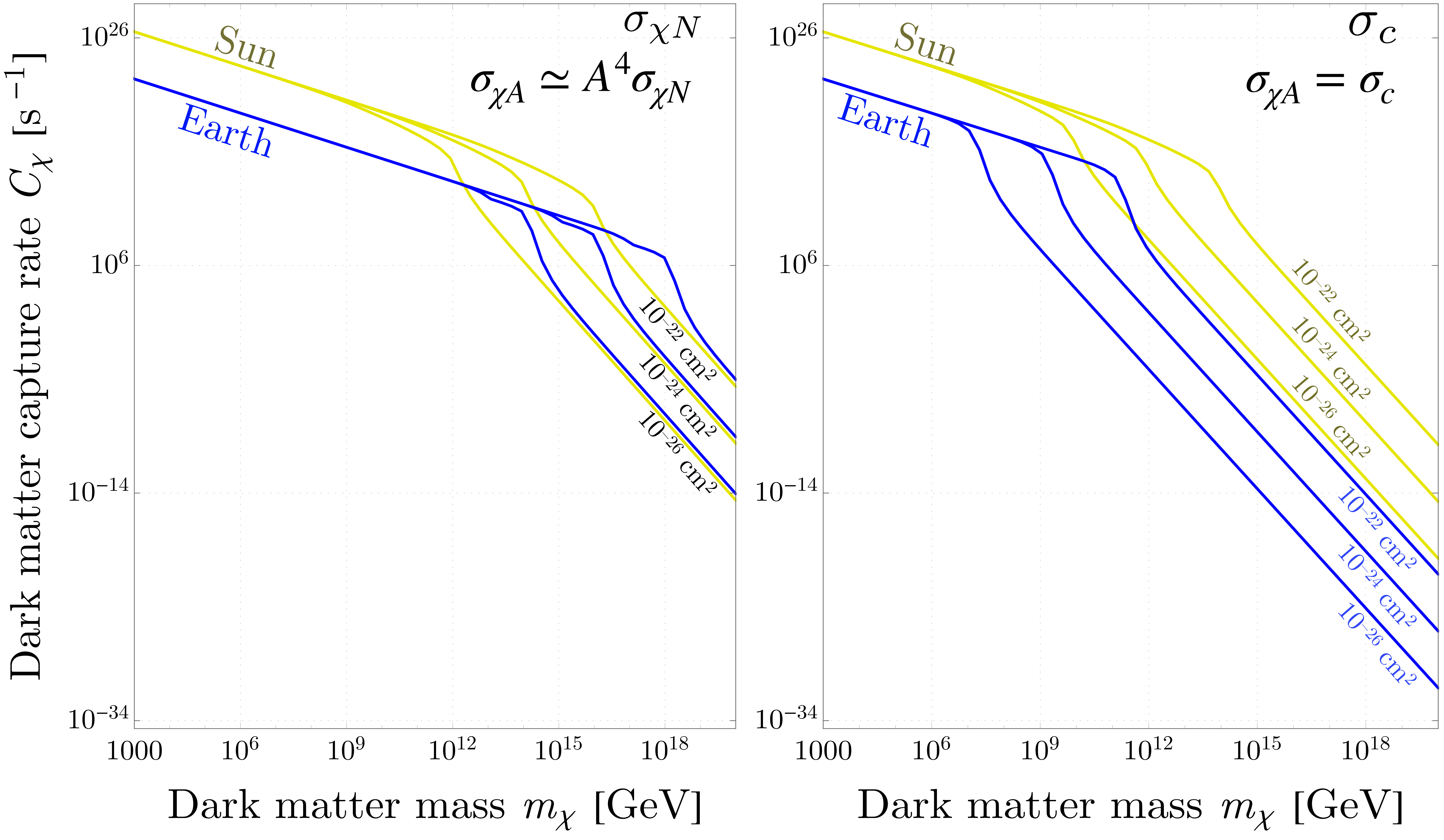


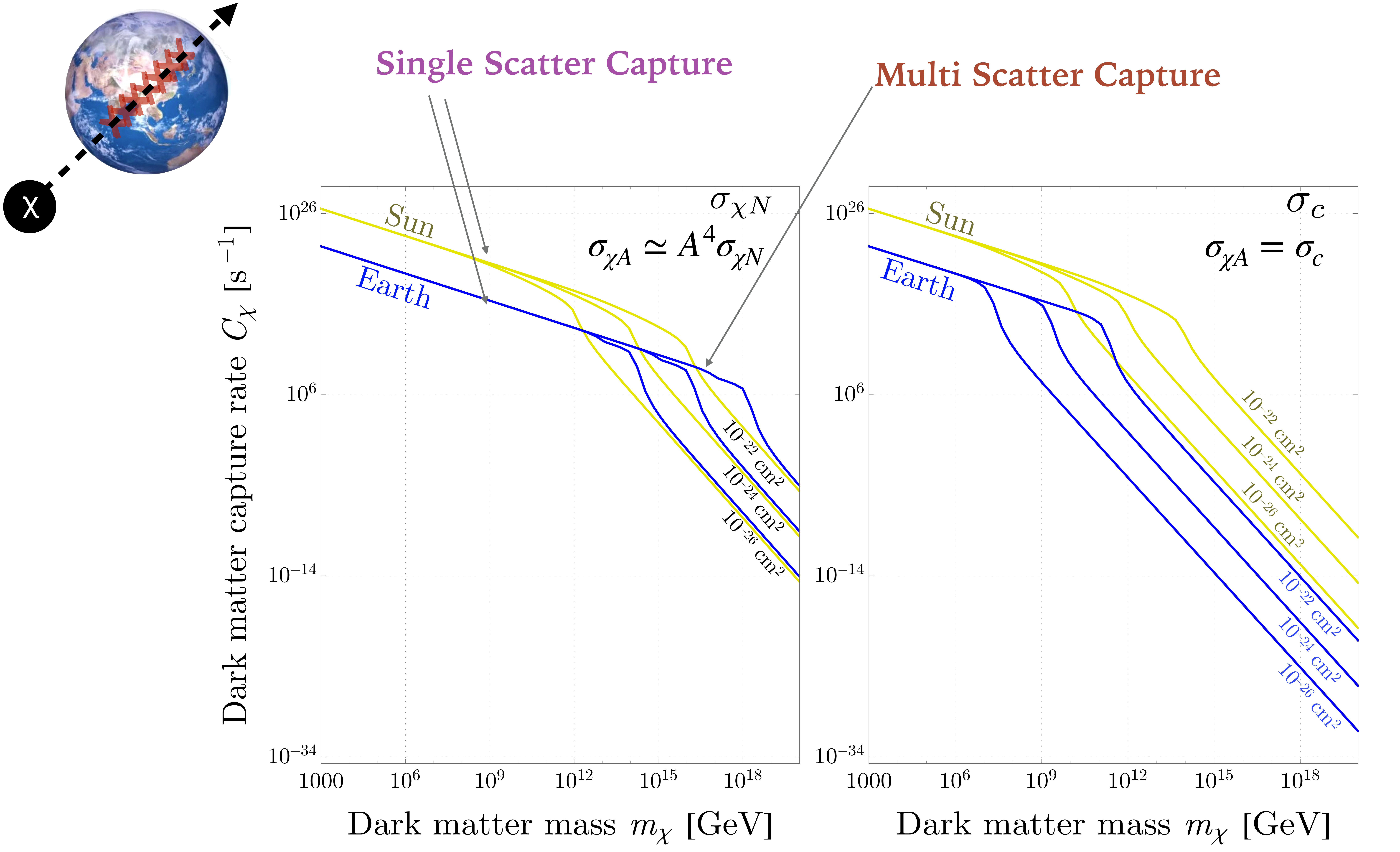
$$f_*(v) \sim \int_{-1}^{1} \mathrm{d}\cos\phi \, \left(v^2 - v_e^2\right)^{3/2} \exp\left(-\frac{\tilde{v}^2}{v_0^2}\right) \, \Theta(v - v_e) \, \Theta(v_{eg} - \tilde{v})$$

Ensures all DM is slower than the galactic escape velocity, $v_{eg} = 528$ km/s, but faster than Earth's escape velocity



$$C_\chi(m_\chi, \sigma) = 4\pi R_\oplus^2 \langle v_\chi \rangle \frac{\rho_\chi}{m_\chi} P_{cap}(m_\chi, \sigma)$$



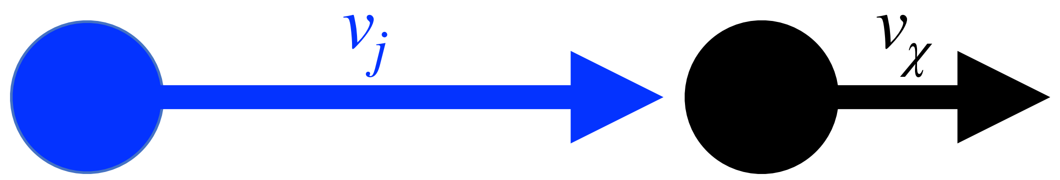


χ
Single Scatter Capture
Multi Scatter Capture
$\sigma_{\chi N}$
$\sigma_{\chi A} \simeq A^4 \sigma_{\chi N}$
Sun
Earth
10^{-22} cm²
10^{-24} cm²
10^{-26} cm²
10^{26}
10^{6}
10^{-14}
10^{-34}
1000
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
Dark matter capture rate C_χ [s^{-1}]
Dark matter mass m_χ [GeV]
σ_c
$\sigma_{\chi A} = \sigma_c$
Sun
Earth
10^{-22} cm²
10^{-24} cm²
10^{-26} cm²
10^{-22} cm²
10^{-24} cm²
10^{-26} cm²
Dark matter mass m_χ [GeV]

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

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



$$\left(\frac{dE}{dt}\right)_{vis} \ll \left(\frac{dE}{dt}\right)_{in} \longrightarrow$$

Use viscous regime scaling, gives longest thermalization time

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

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

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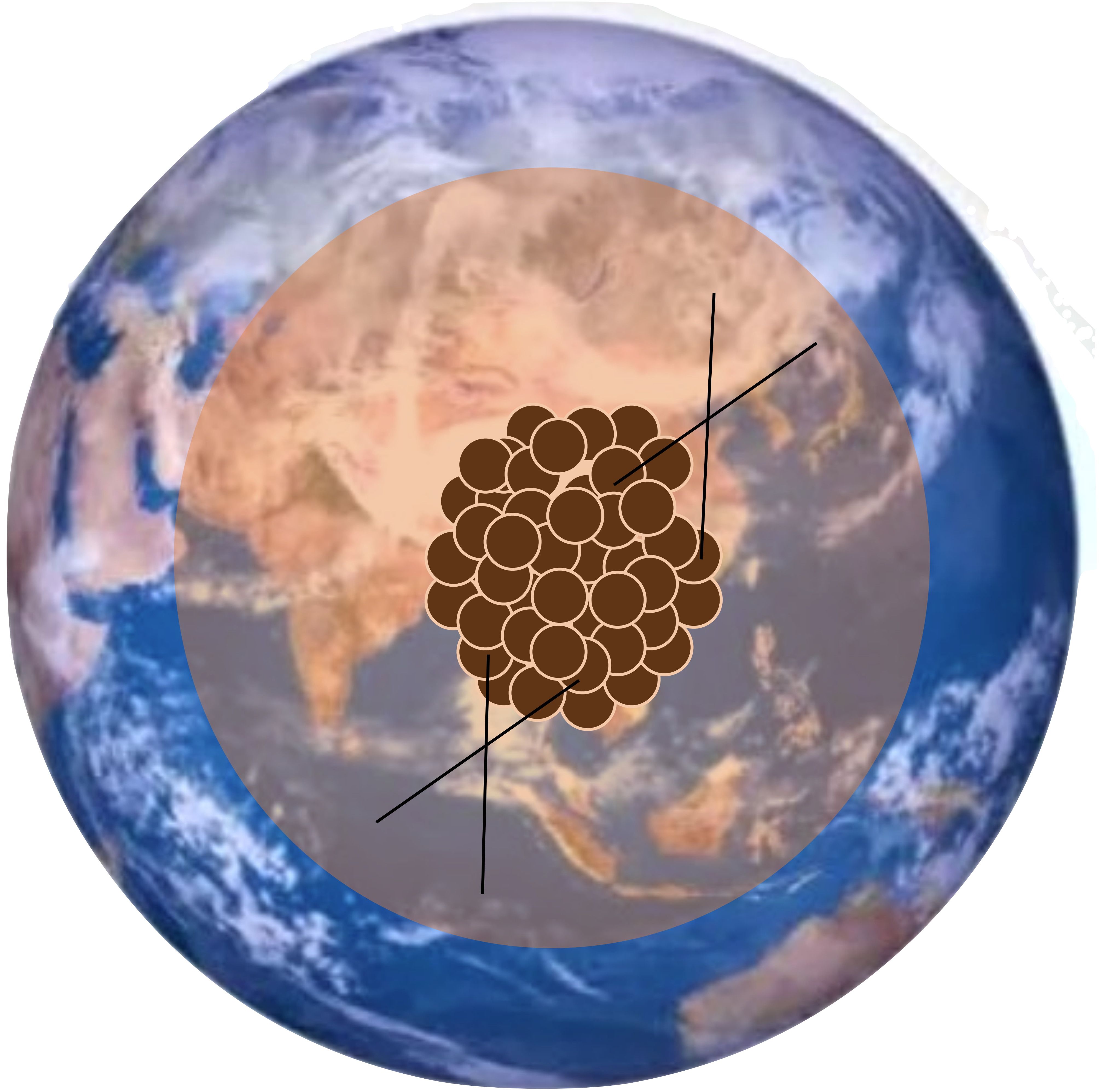
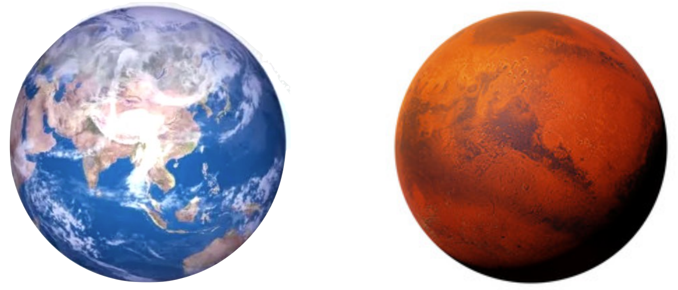
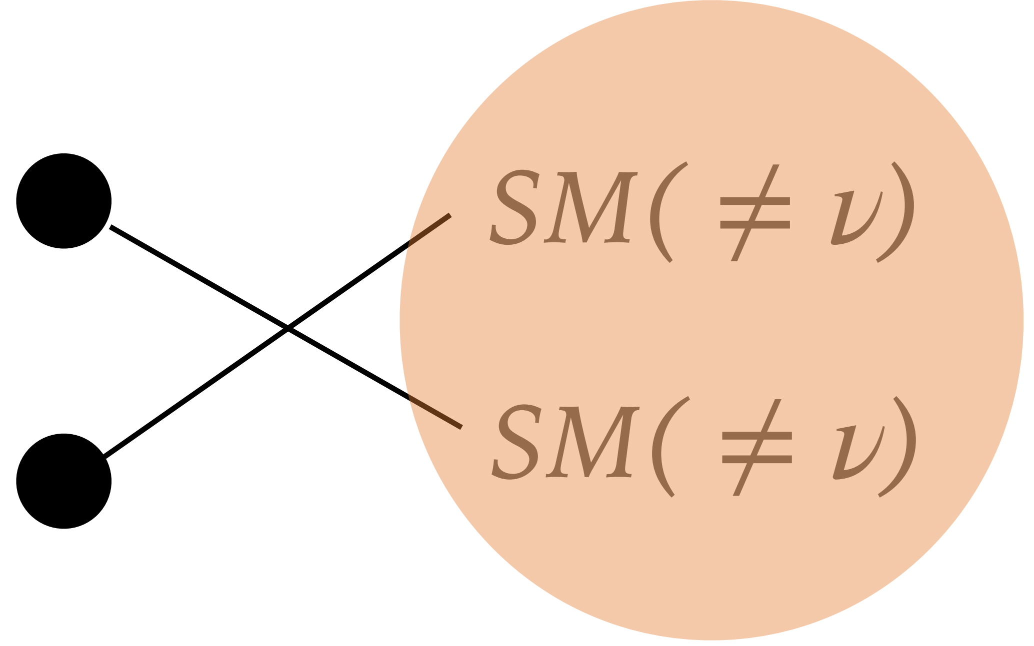
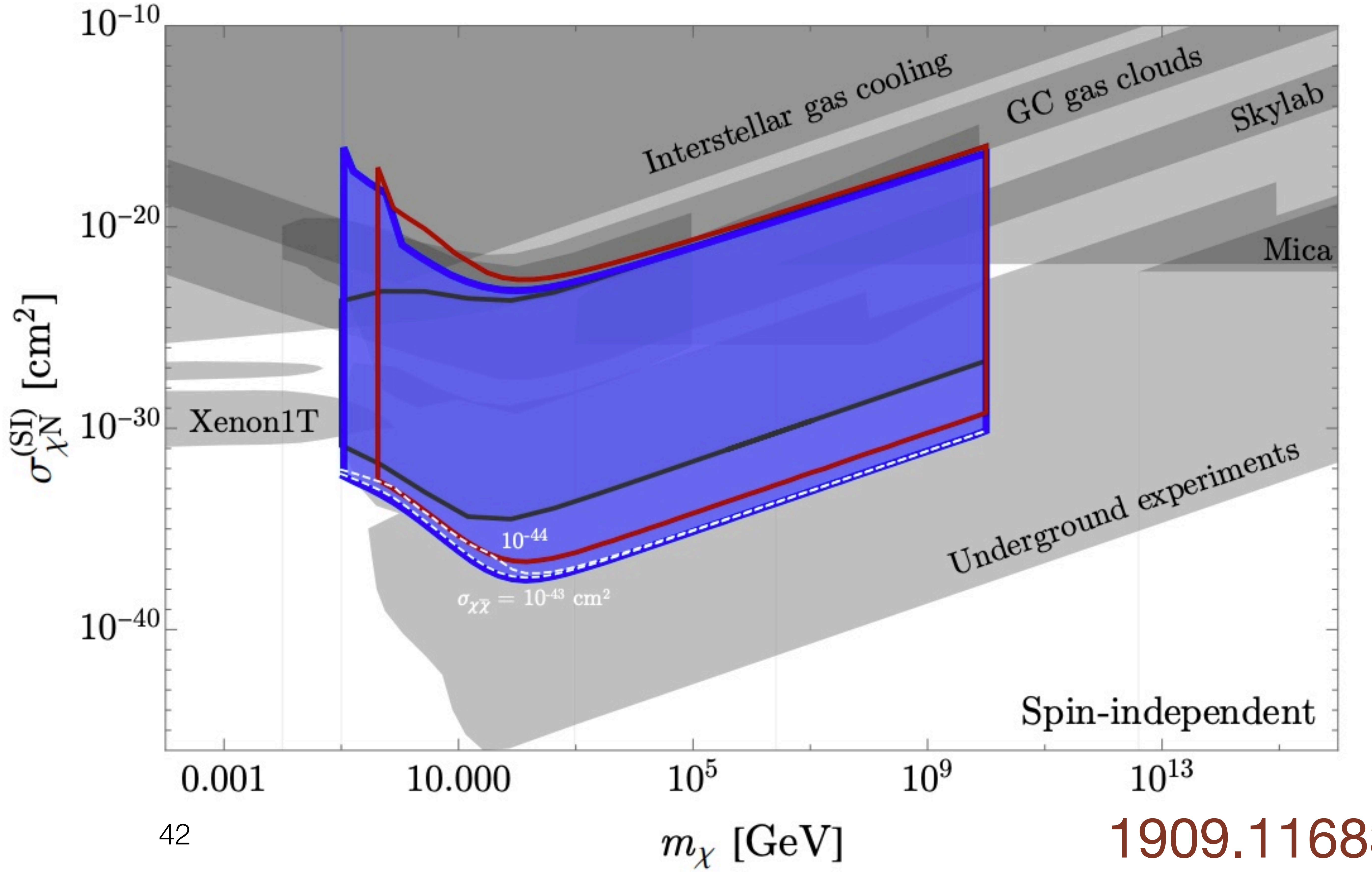


If they annihilate:
Earth/Martian heating!







1909.11683

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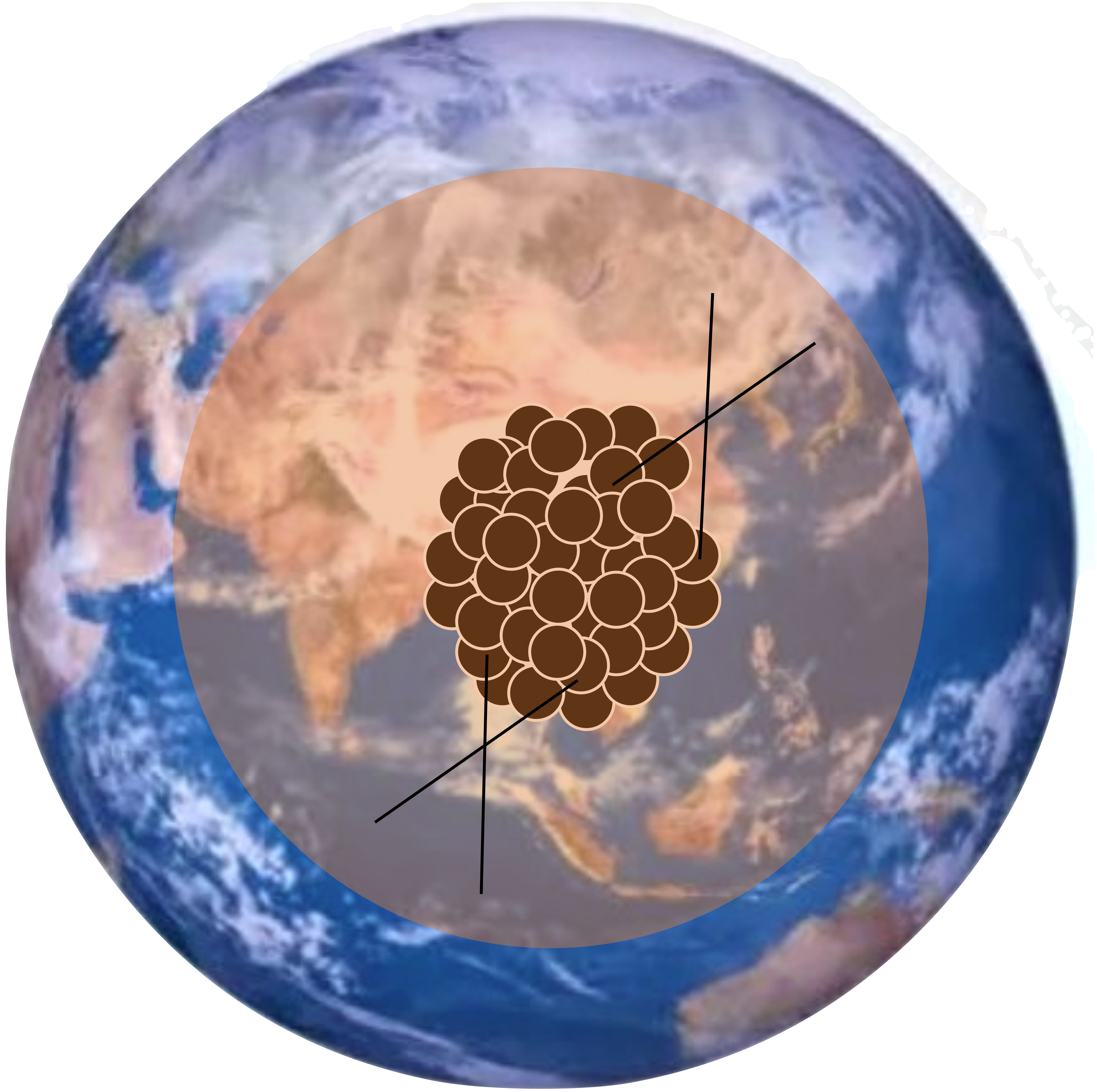

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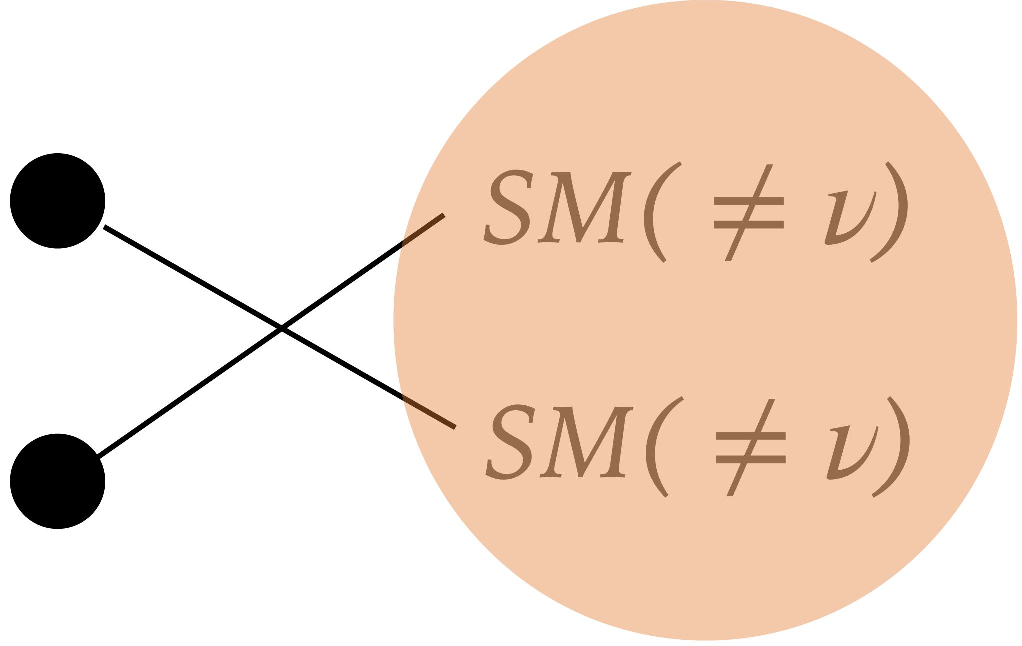
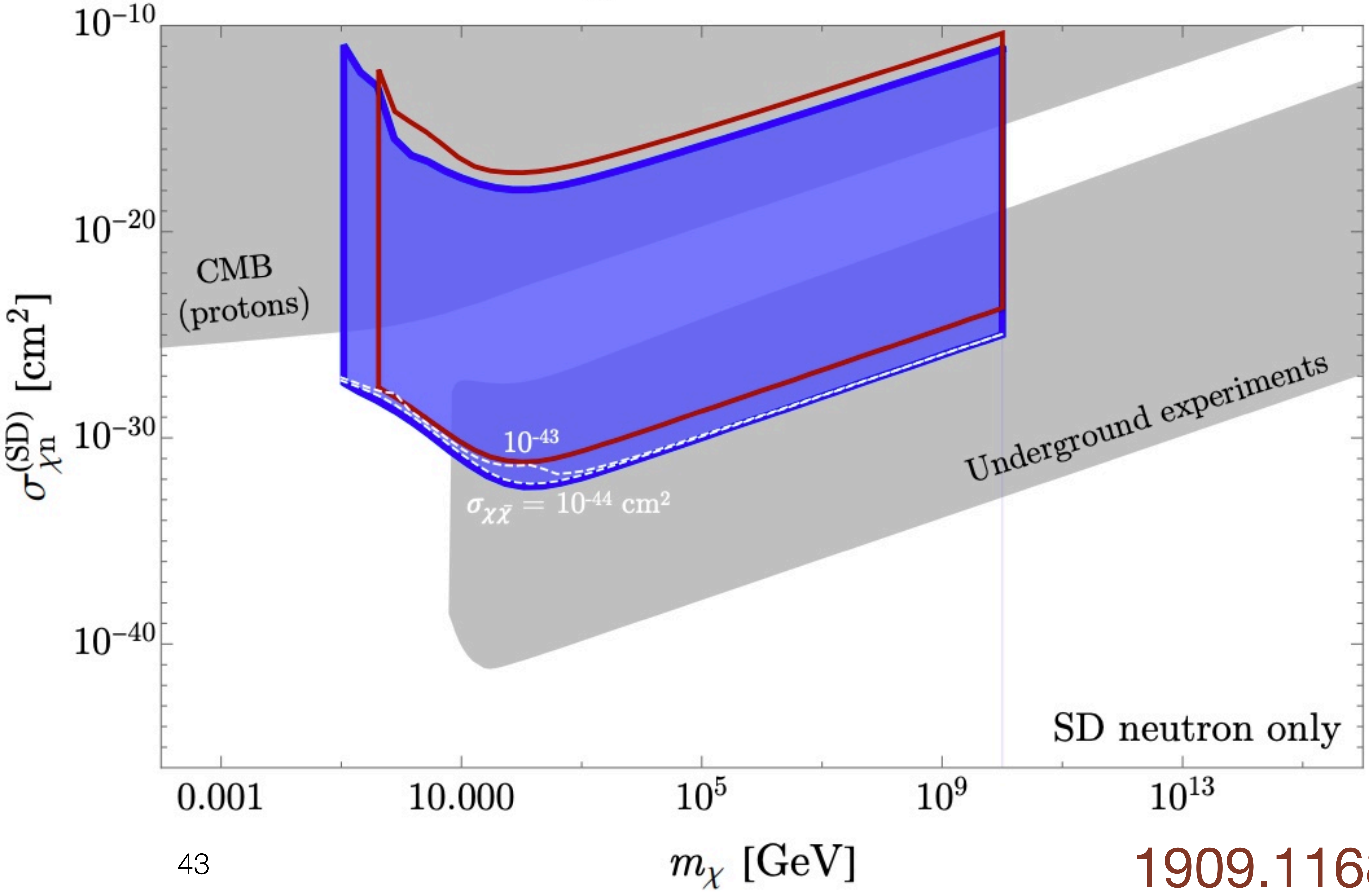
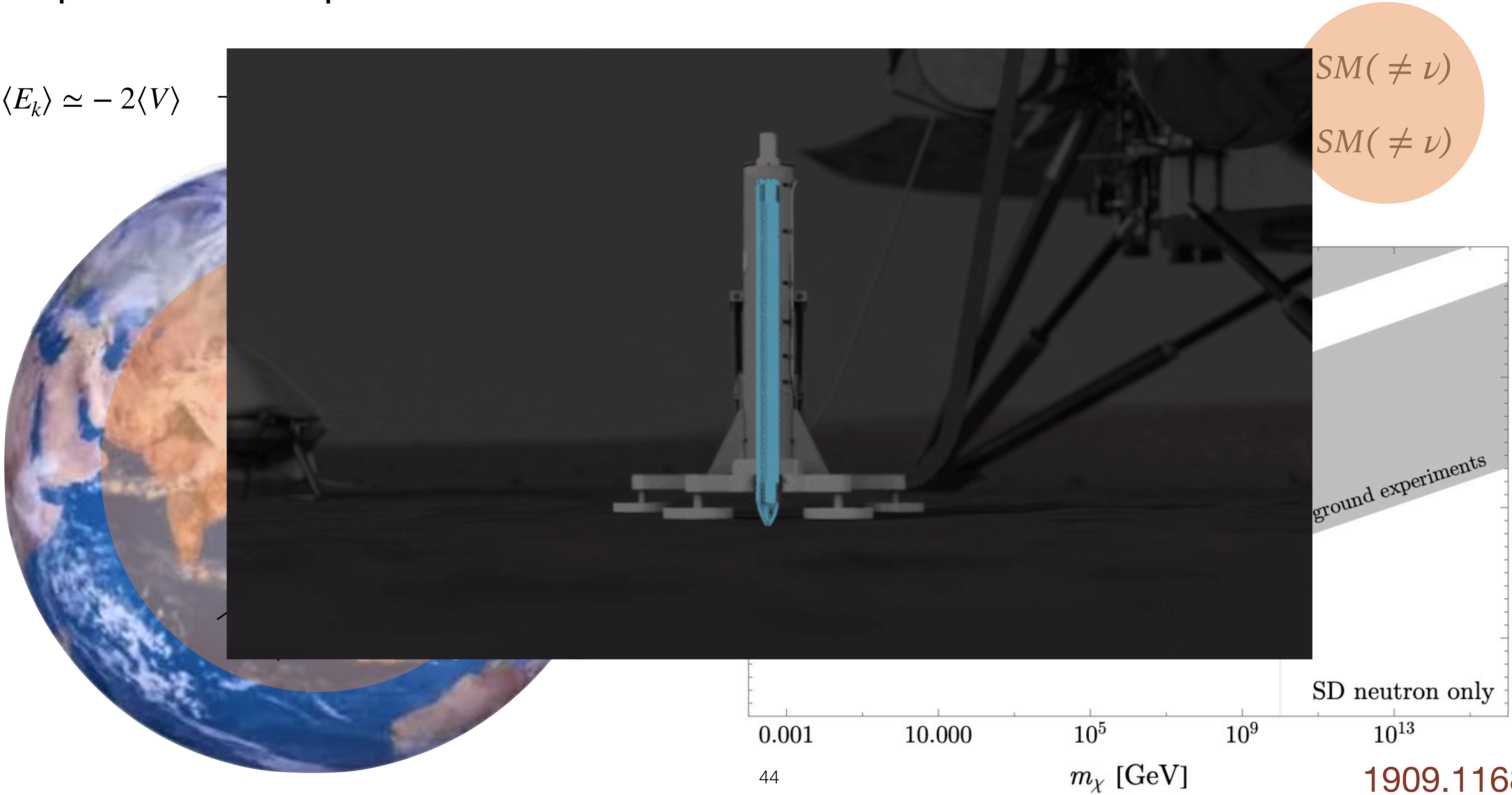




1909.11683

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

$\langle E_k \rangle \simeq -2\langle V \rangle$



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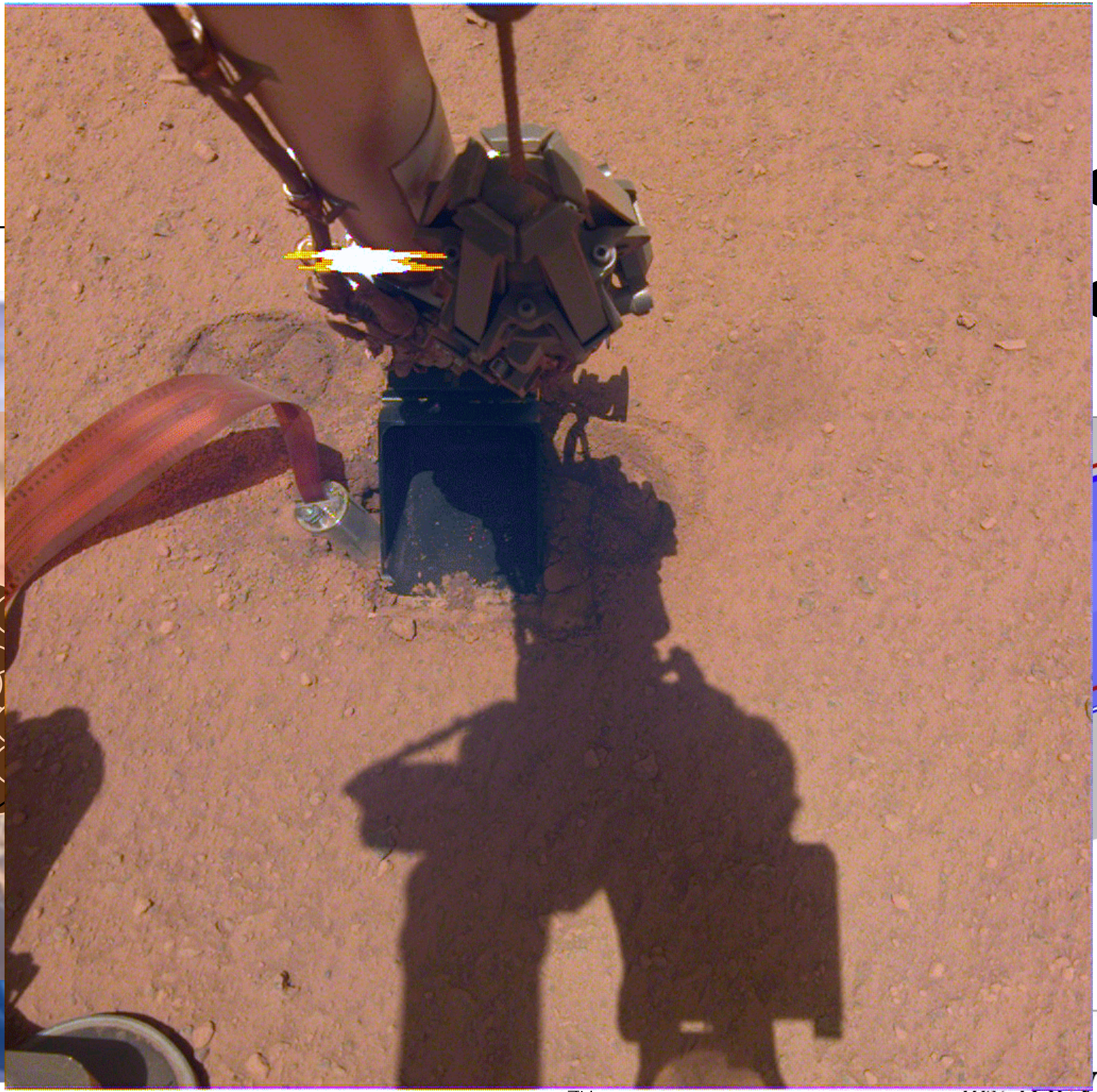
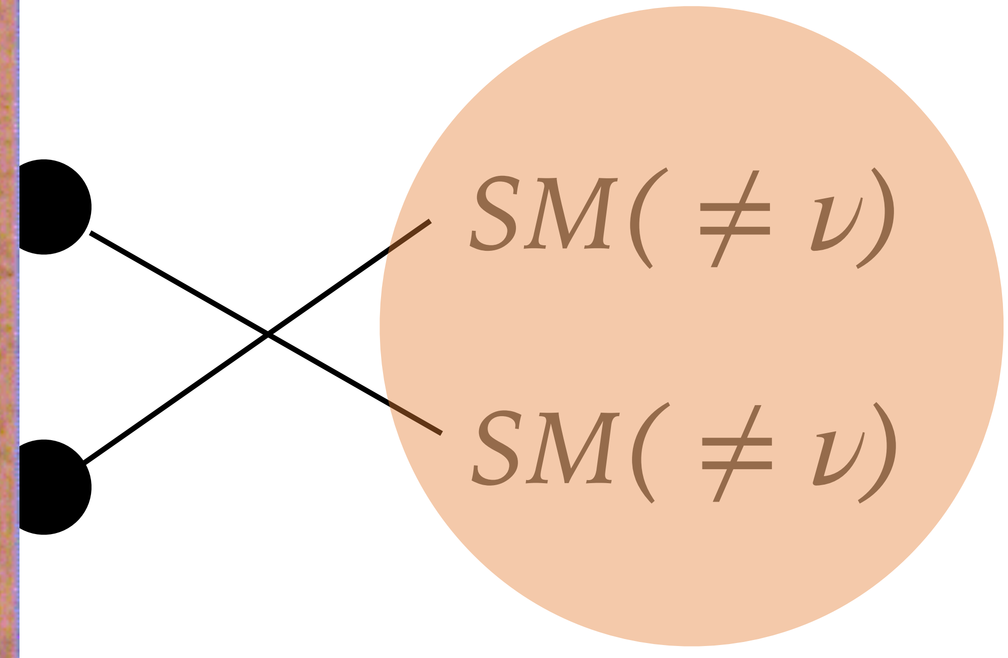
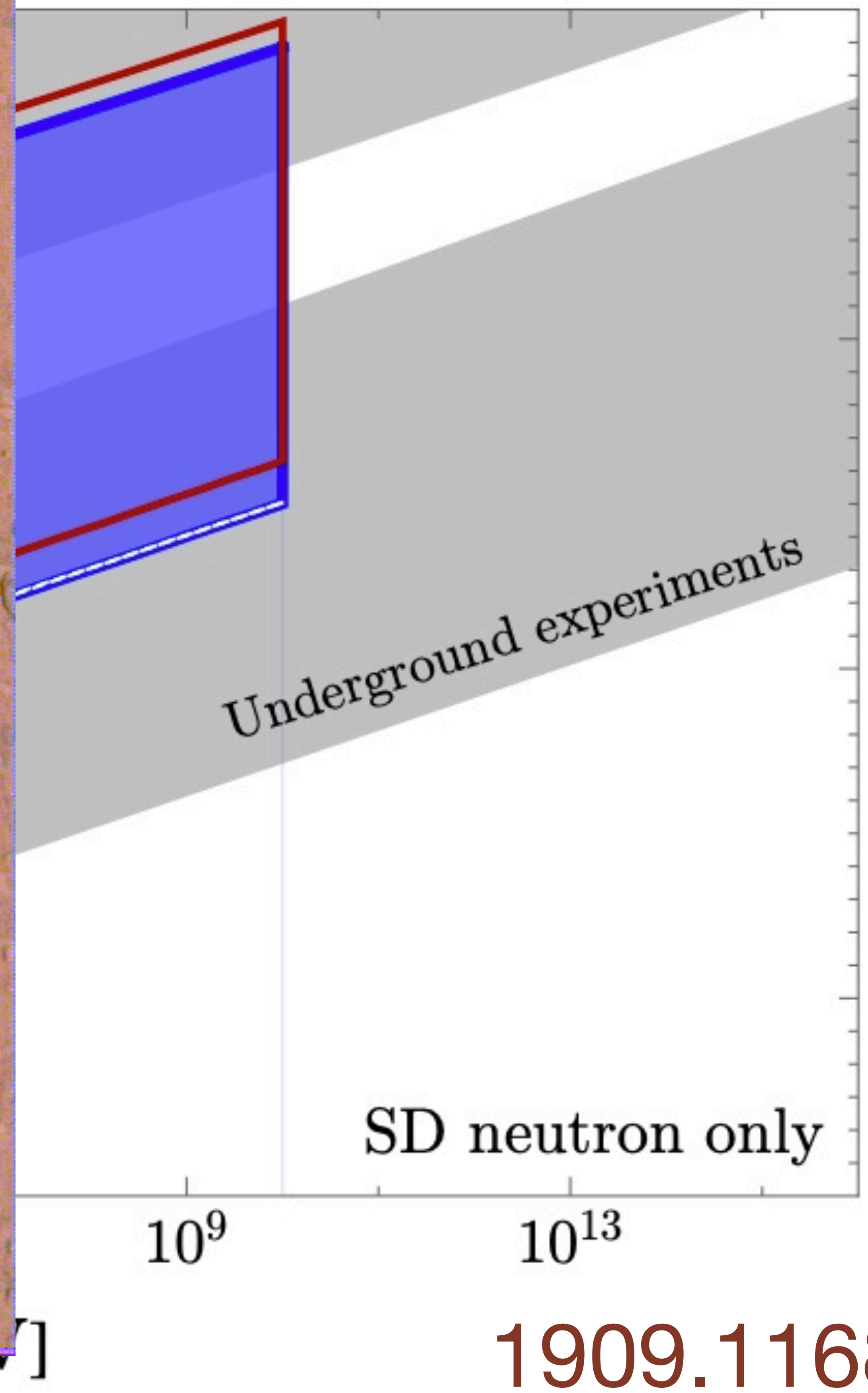
$\langle E_k \rangle \simeq -2 \langle V \rangle$

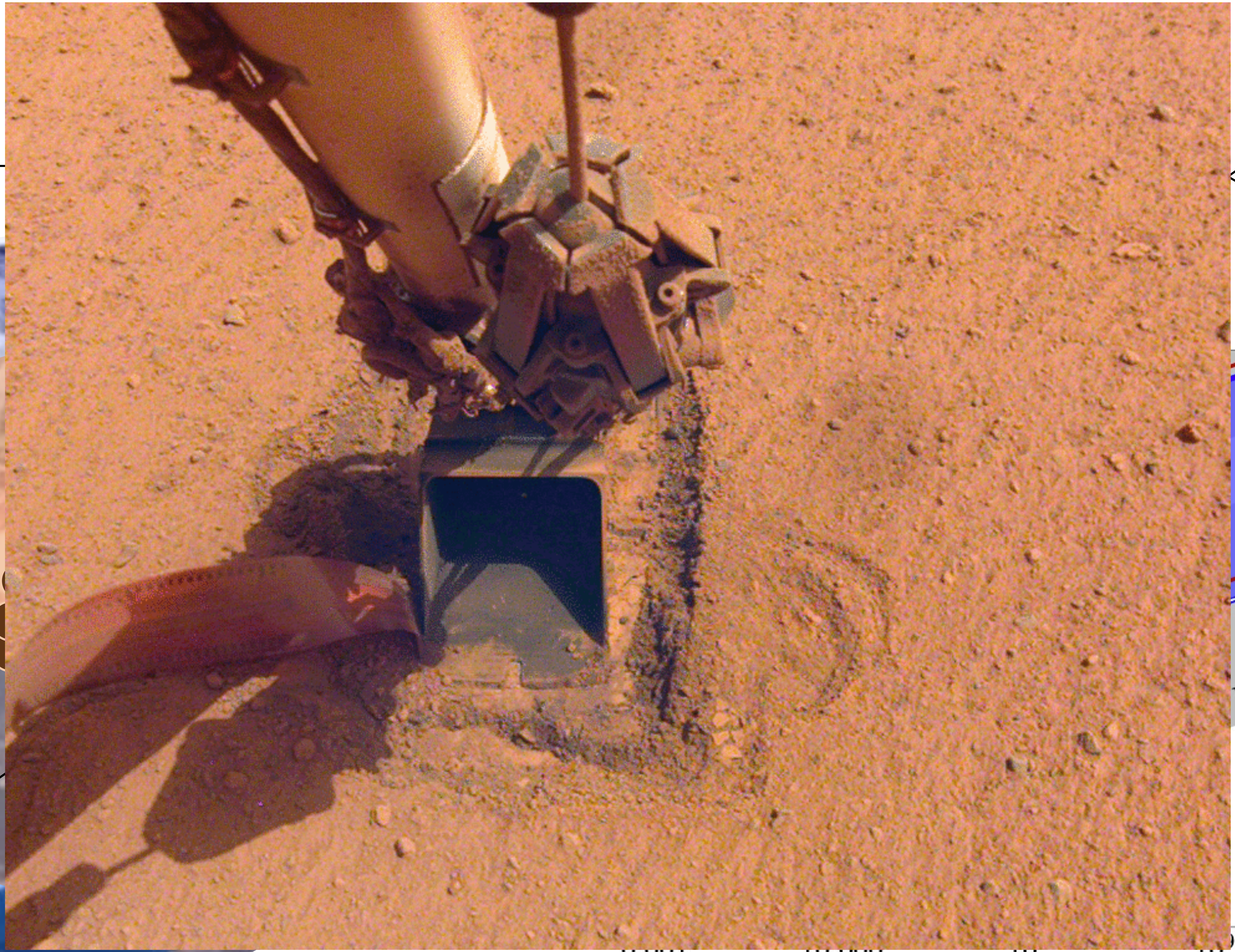


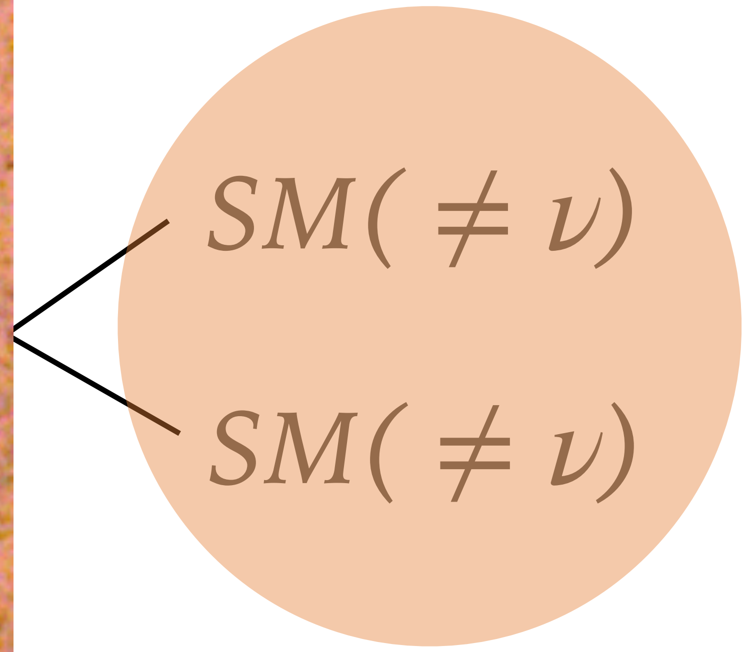


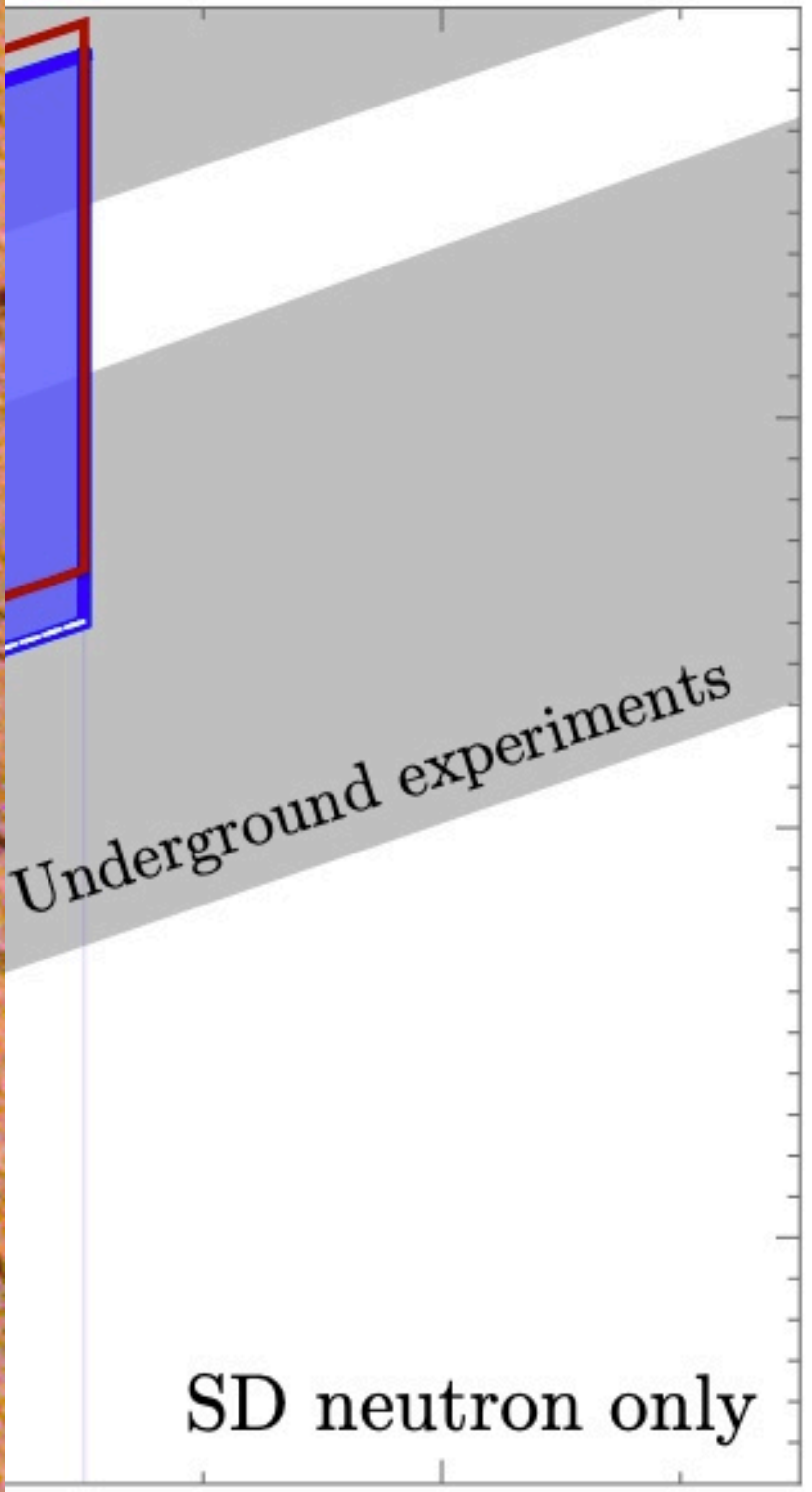


1909.11683

$\langle E_k \rangle \simeq -2 \langle V \rangle$

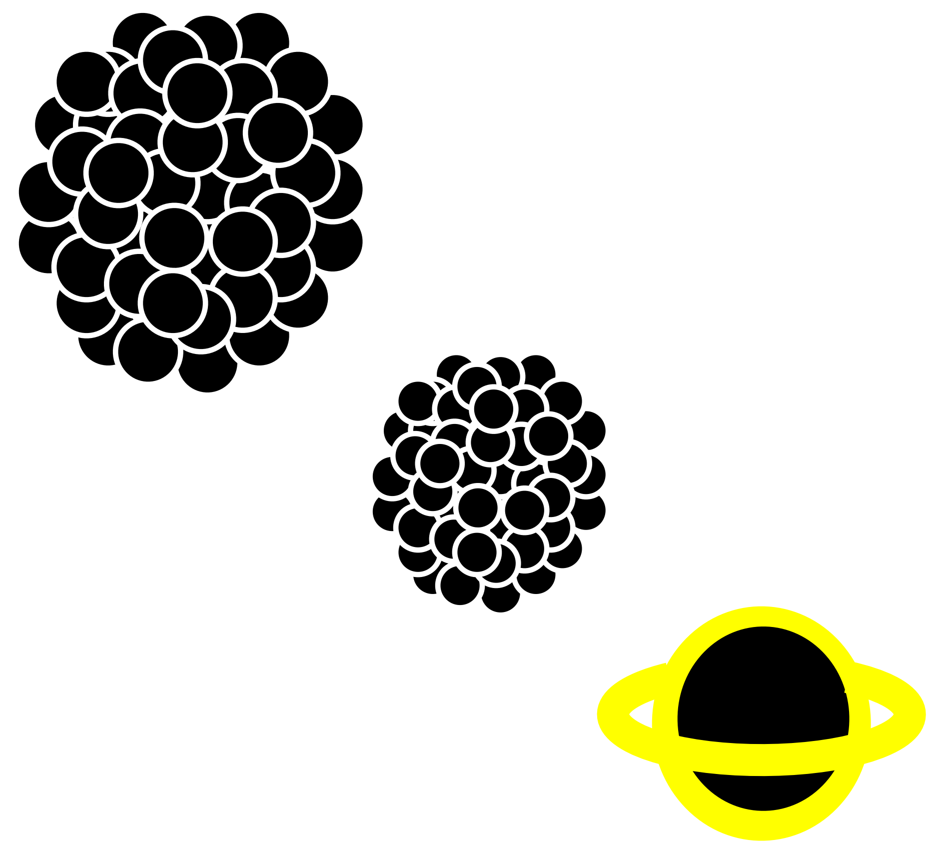






1909.11683

If they don’t annihilate: collapse!



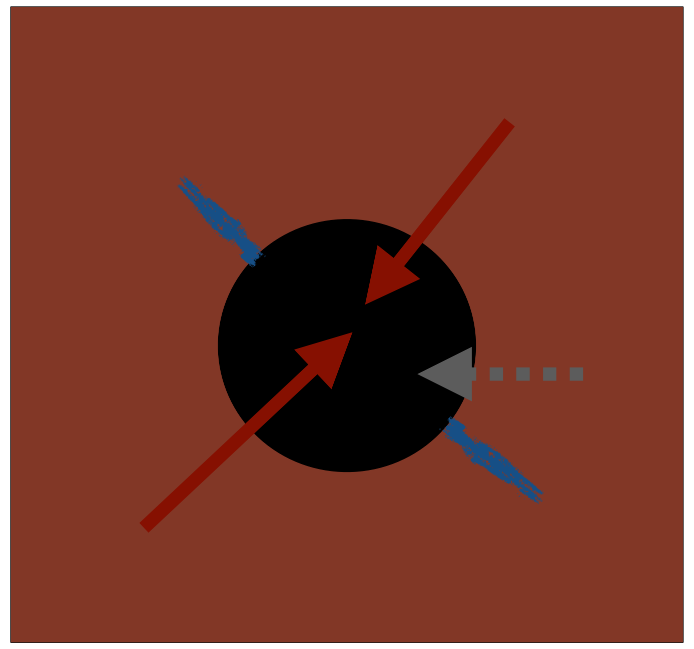
Jeans instability condition: $\rho_\chi \gtrsim \rho_\oplus$

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

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

Critical mass for collapse: $M_{crit} = \max(M_f, M_{sg})$

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)

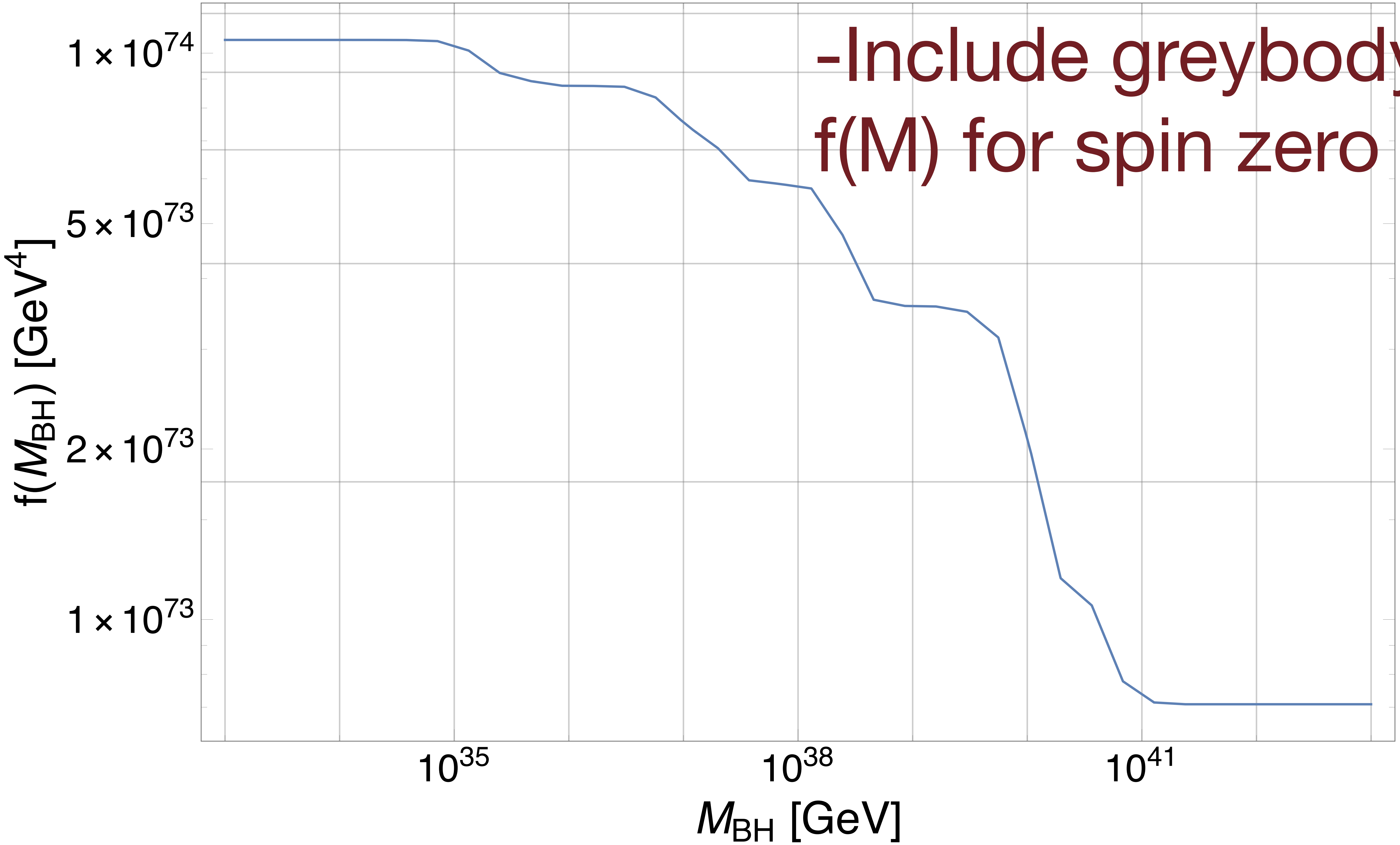
Hawking radiation:
- Causes BH to shrink
- Larger for smaller BHs (heavier DM)

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

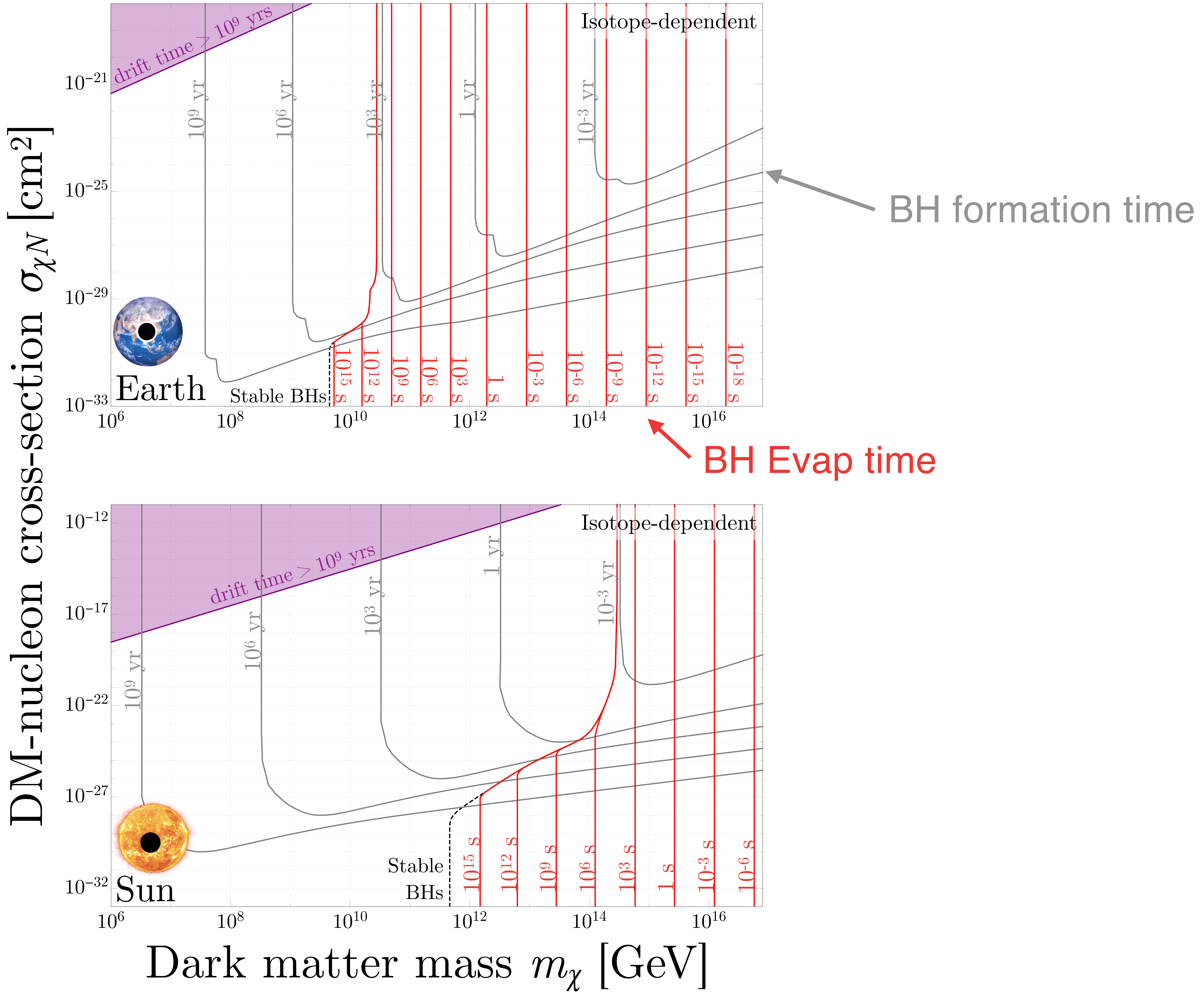
	Earth	**Sun**
Max destructive m_χ Hawking = Bondi + $m_\chi \Phi_\chi$	2.7×10^{10} GeV	3×10^{14} GeV
Min evaporative m_χ Hawking = Bondi	4.5×10^9 GeV	4.6×10^{11} GeV

BH evolution

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



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


DM-nucleon cross-section $\sigma_{\chi N}$ [cm^2]
Dark matter mass m_χ [GeV]
Earth
Sun
Isotope-dependent
drift time > 10^9 yrs
Stable BHs
BH formation time
BH Evap time
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
10^{-21}
10^{-25}
10^{-29}
10^{-33}
10^{-12}
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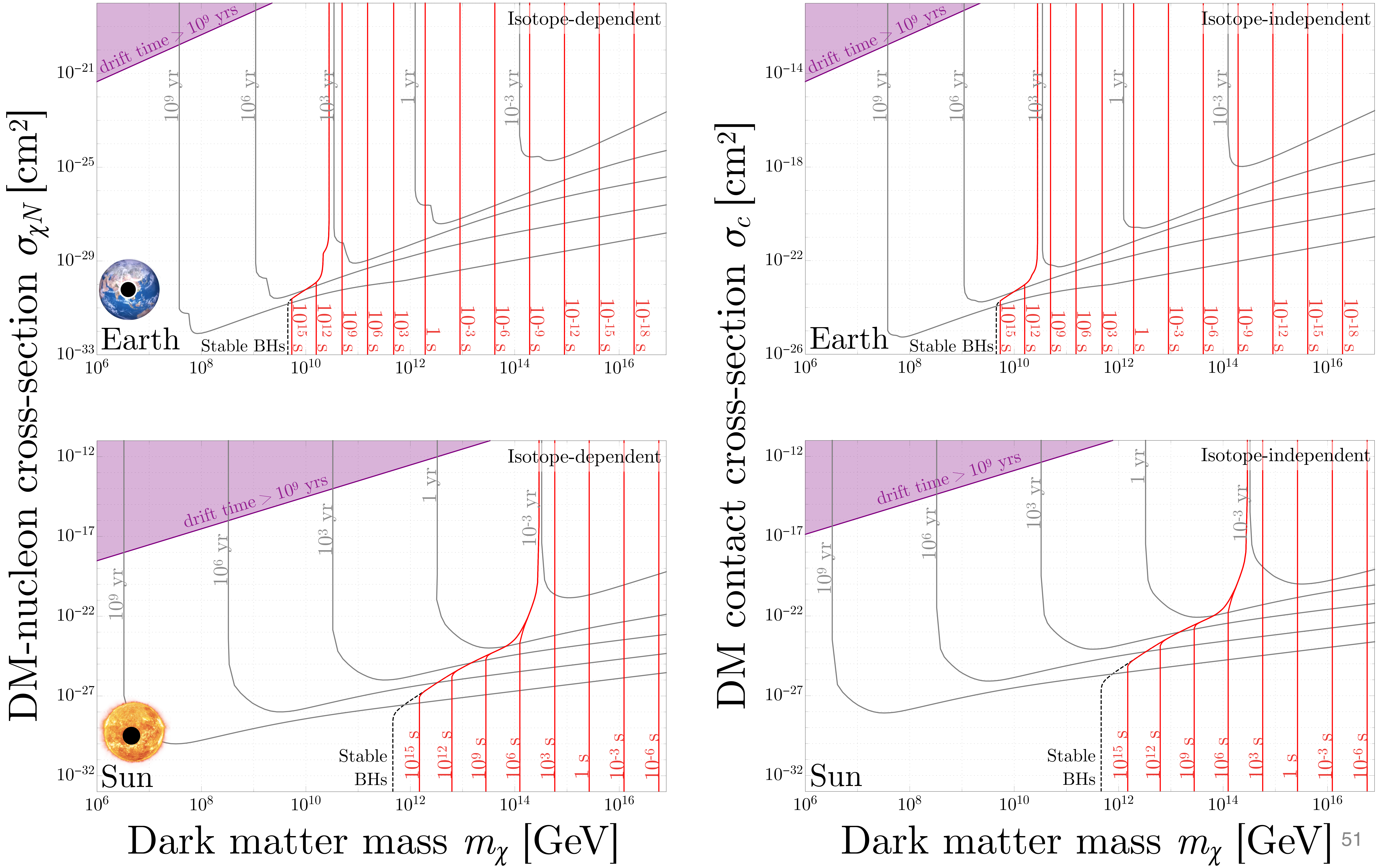
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}



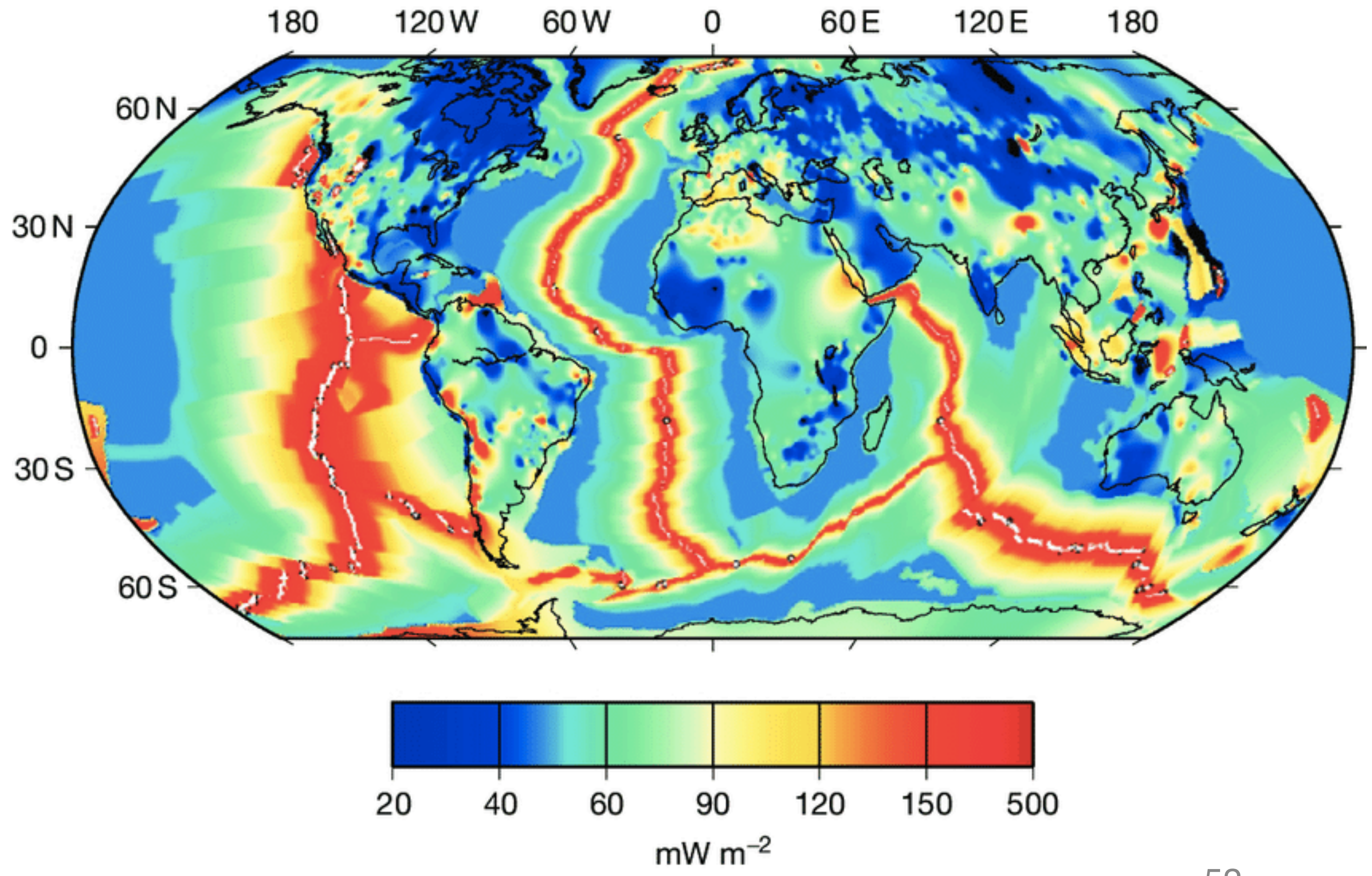
Isotope-dependent
Isotope-independent
drift time > 10^9 yrs
Earth
Sun
Stable BHs
DM-nucleon cross-section $\sigma_{\chi N}$ [cm^2]
DM contact cross-section σ_c [cm^2]
Dark matter mass m_χ [GeV]
Dark matter mass m_χ [GeV]

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

For evaporating BHs:
Exclude DM models that would:
(1) overheat the Earth

(a) $m_\chi C_\chi \geq 44$ TW
(b) $t_{evap} + t_{form} \lesssim 1$ kyr
(c) $t_{drift} \lesssim 1$ Gyr

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



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

For evaporating BHs:
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(a) $t_{drift} \lesssim 1$ Gyr

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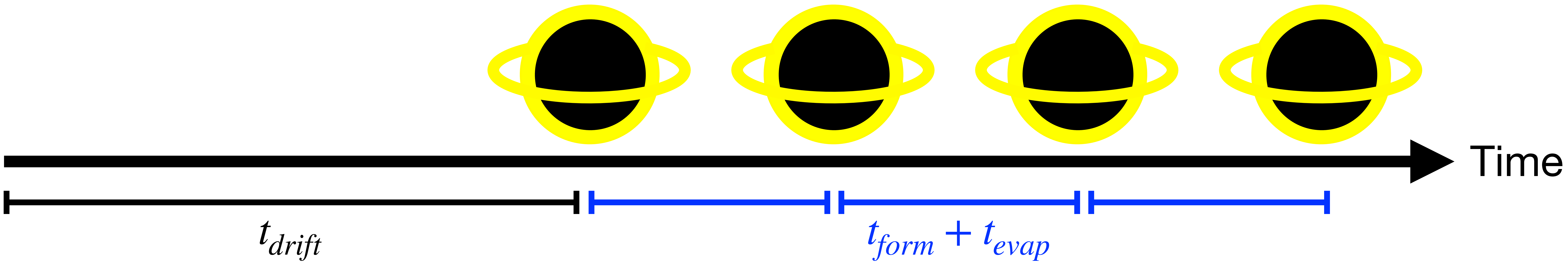
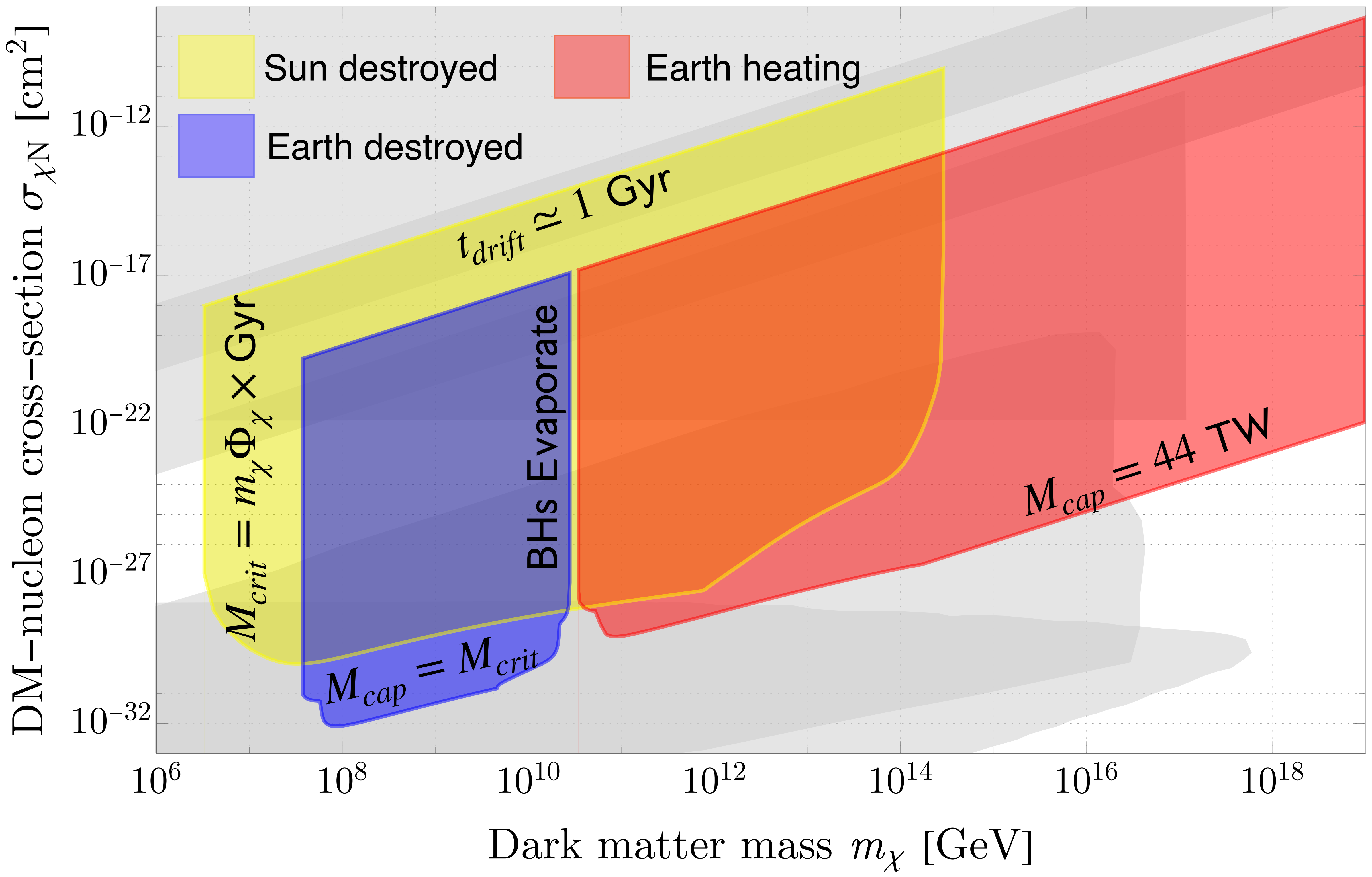
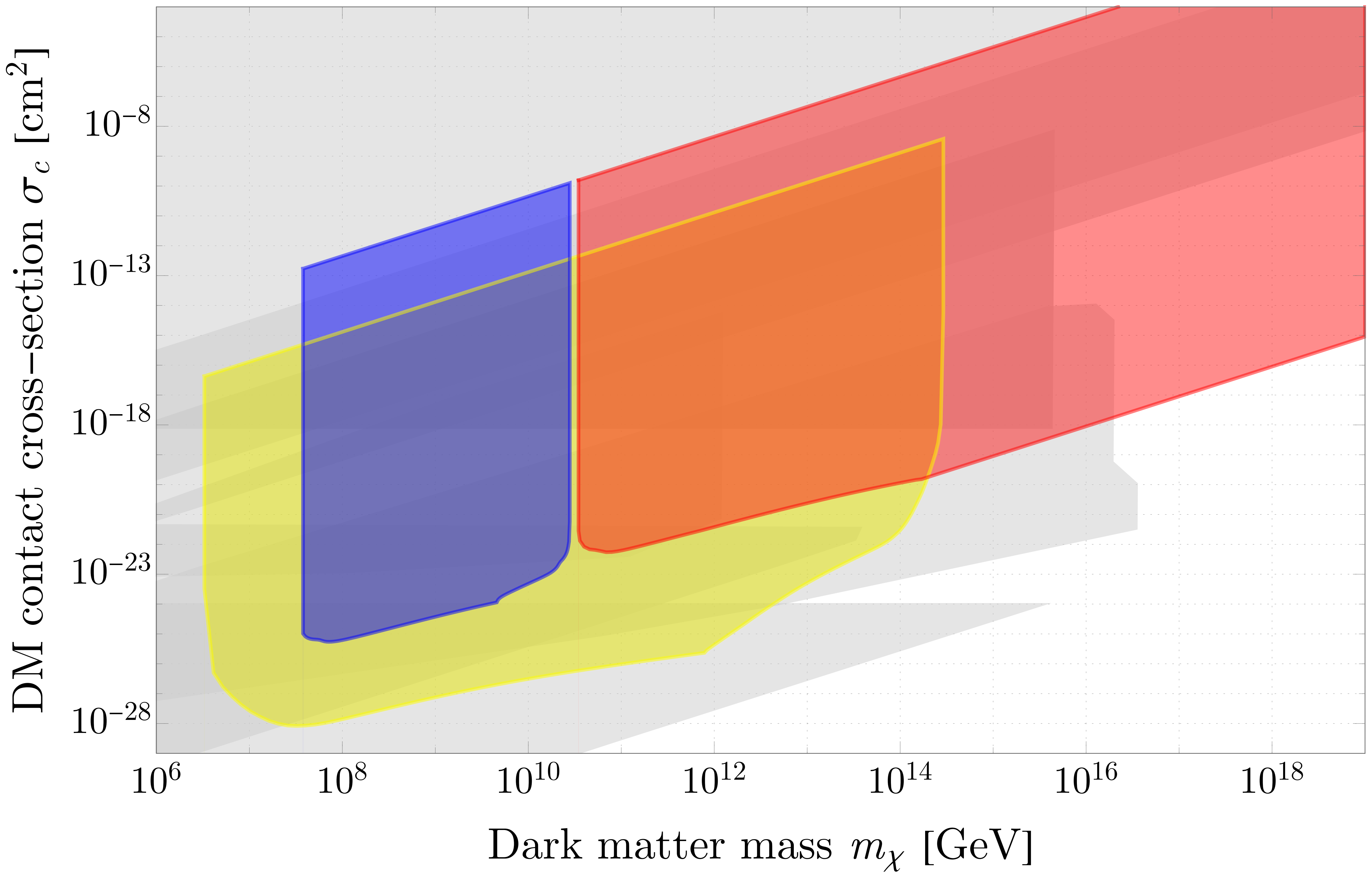
strongly interacting DM





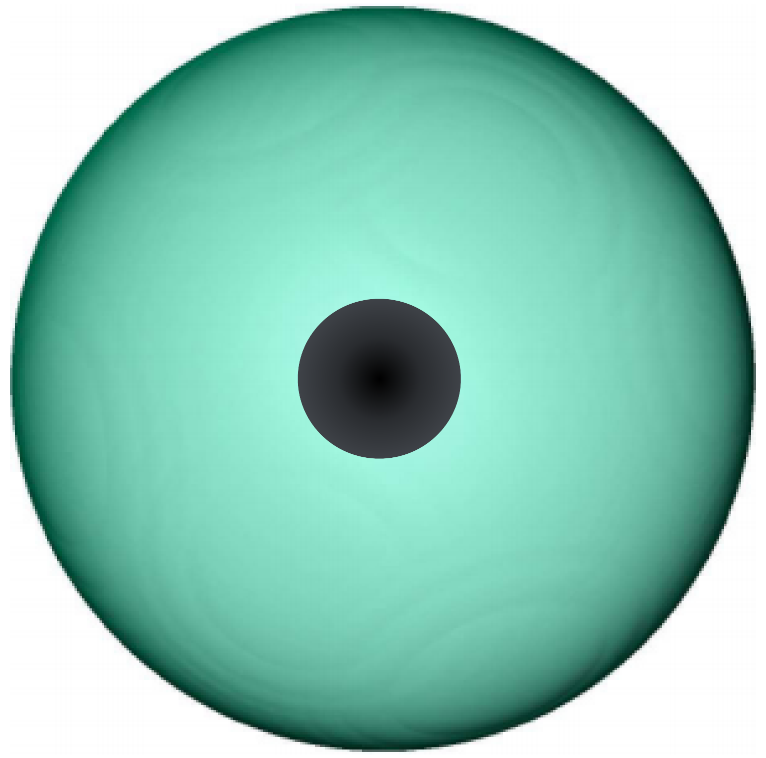
Sun destroyed
Earth heating
Earth destroyed
$t_{drift} \simeq 1$ Gyr
$M_{crit} = m_\chi \Phi_\chi \times$ Gyr
BHs Evaporate
$M_{cap} = M_{crit}$
$M_{cap} = 44$ TW
DM−nucleon cross−section $\sigma_{\chi N}$ [cm^2]
Dark matter mass m_χ [GeV]



DM contact cross−section σ_c [cm^2]
Dark matter mass m_χ [GeV]

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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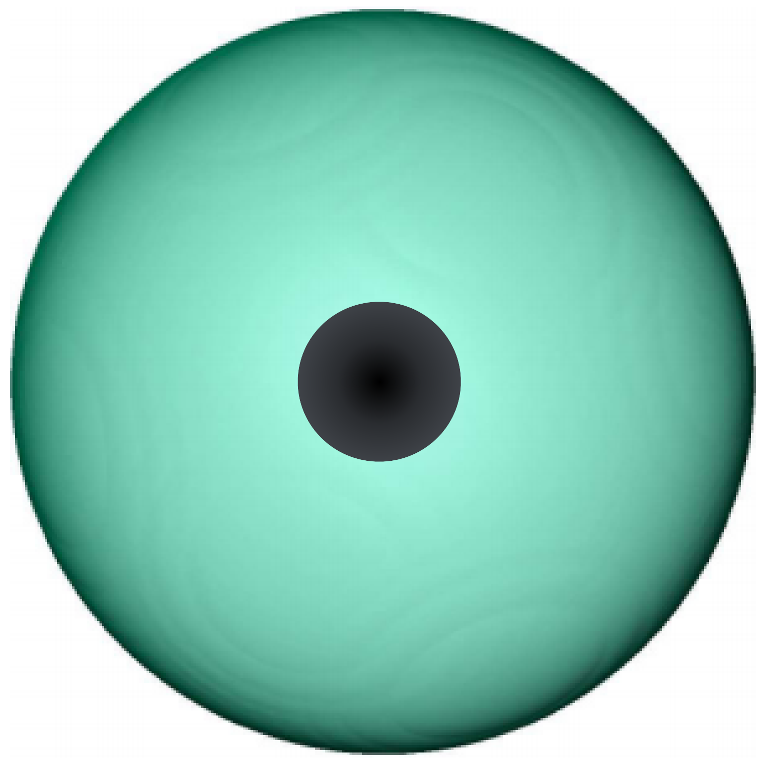

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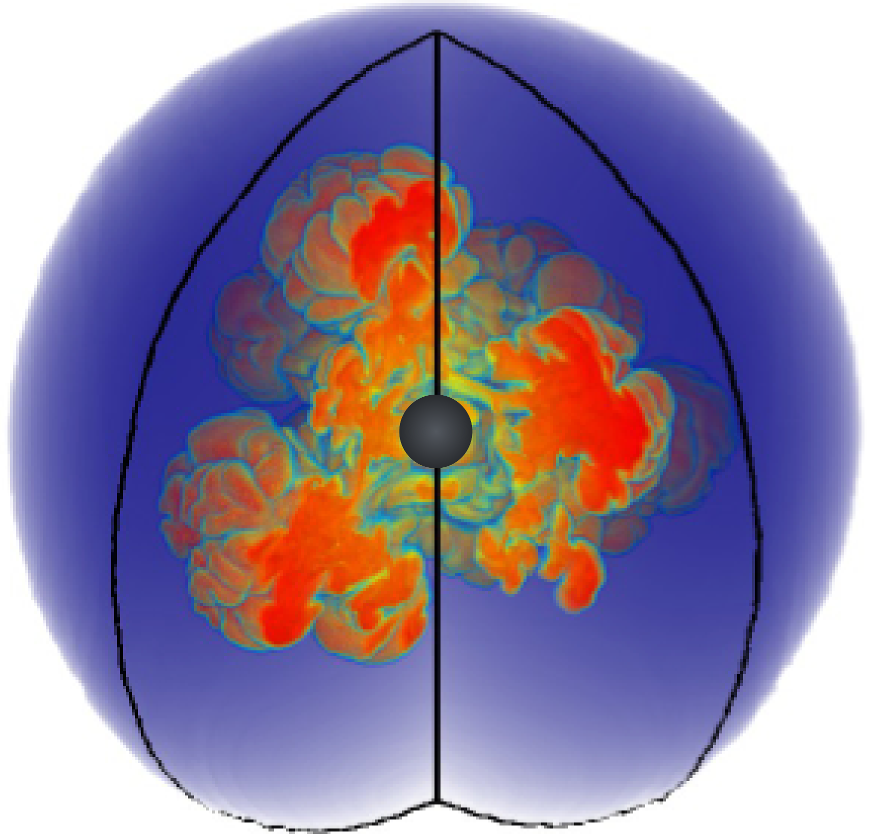
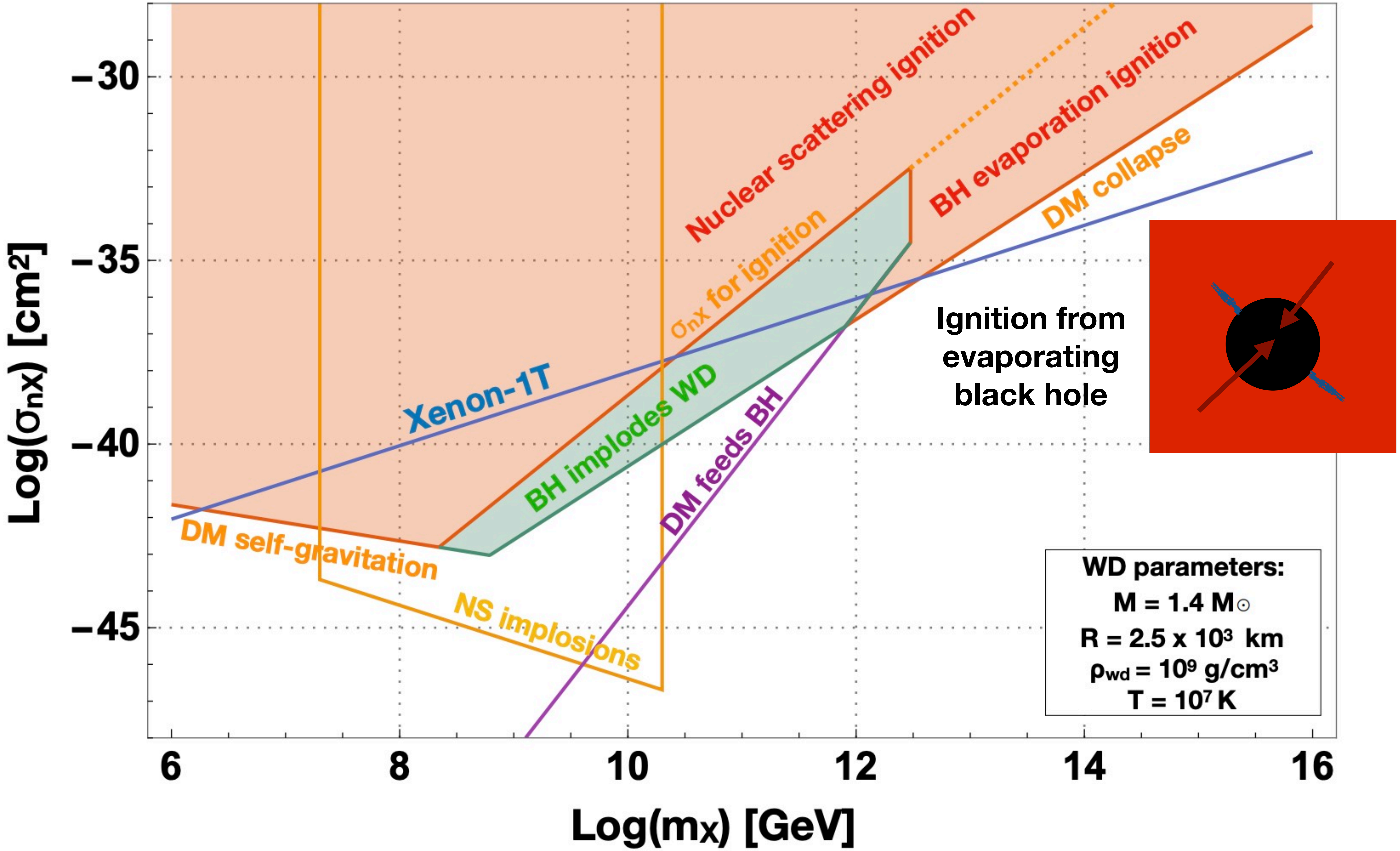


DM collapses, shedding gravitational potential energy through **scattering**, igniting a SNIa.

Bounds on dark matter from an old GAIA White Dwarf



Ignition from evaporating black hole

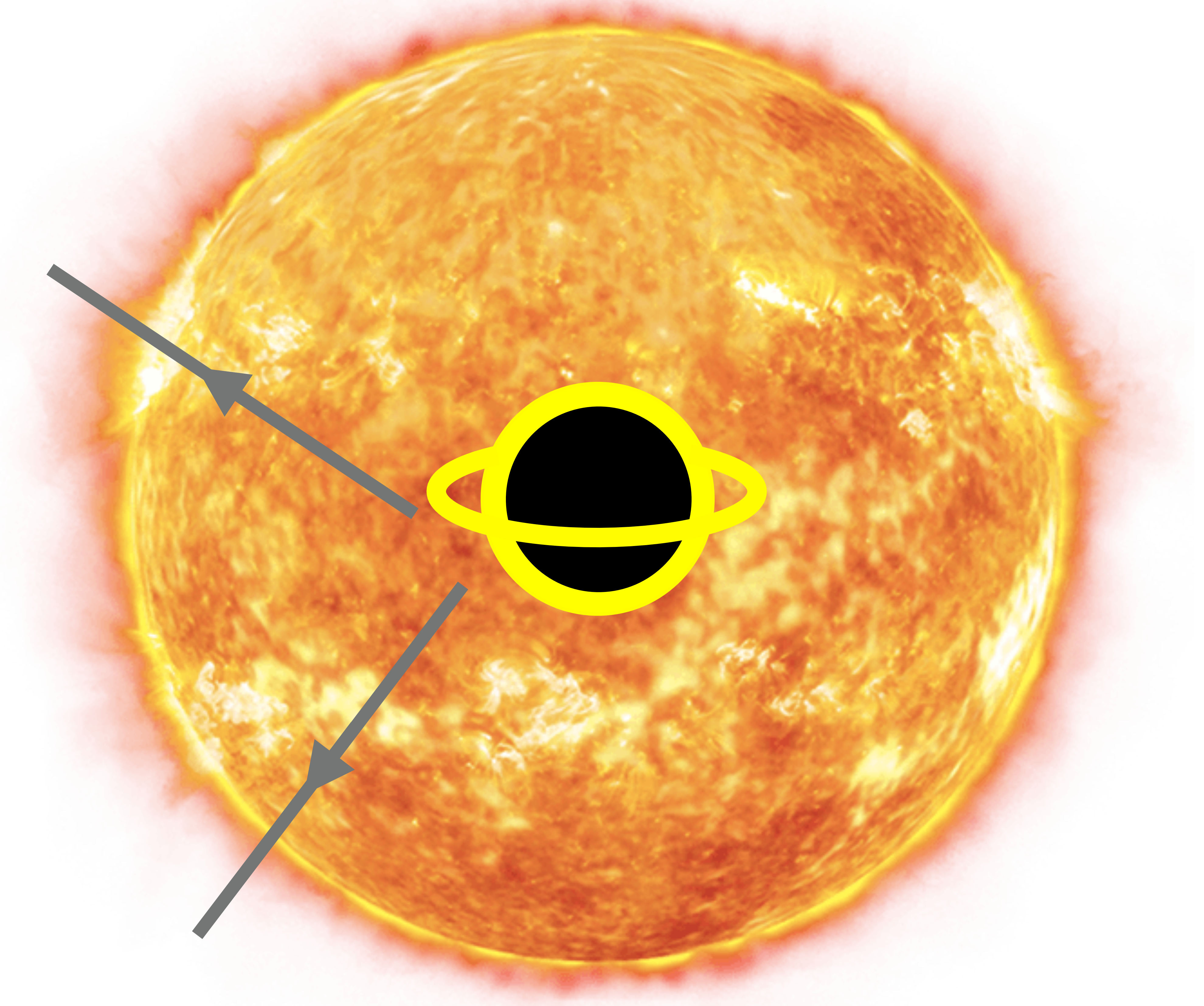
Javier Acevedo JB 2019

Neutrinos From Black Holes in the Sun

Signal Characteristics:
- Flavour universal
- Blackbody temperature

$$T(M_{BH}) = \frac{1}{8\pi G M_{BH}}$$

- Transient
- Directional

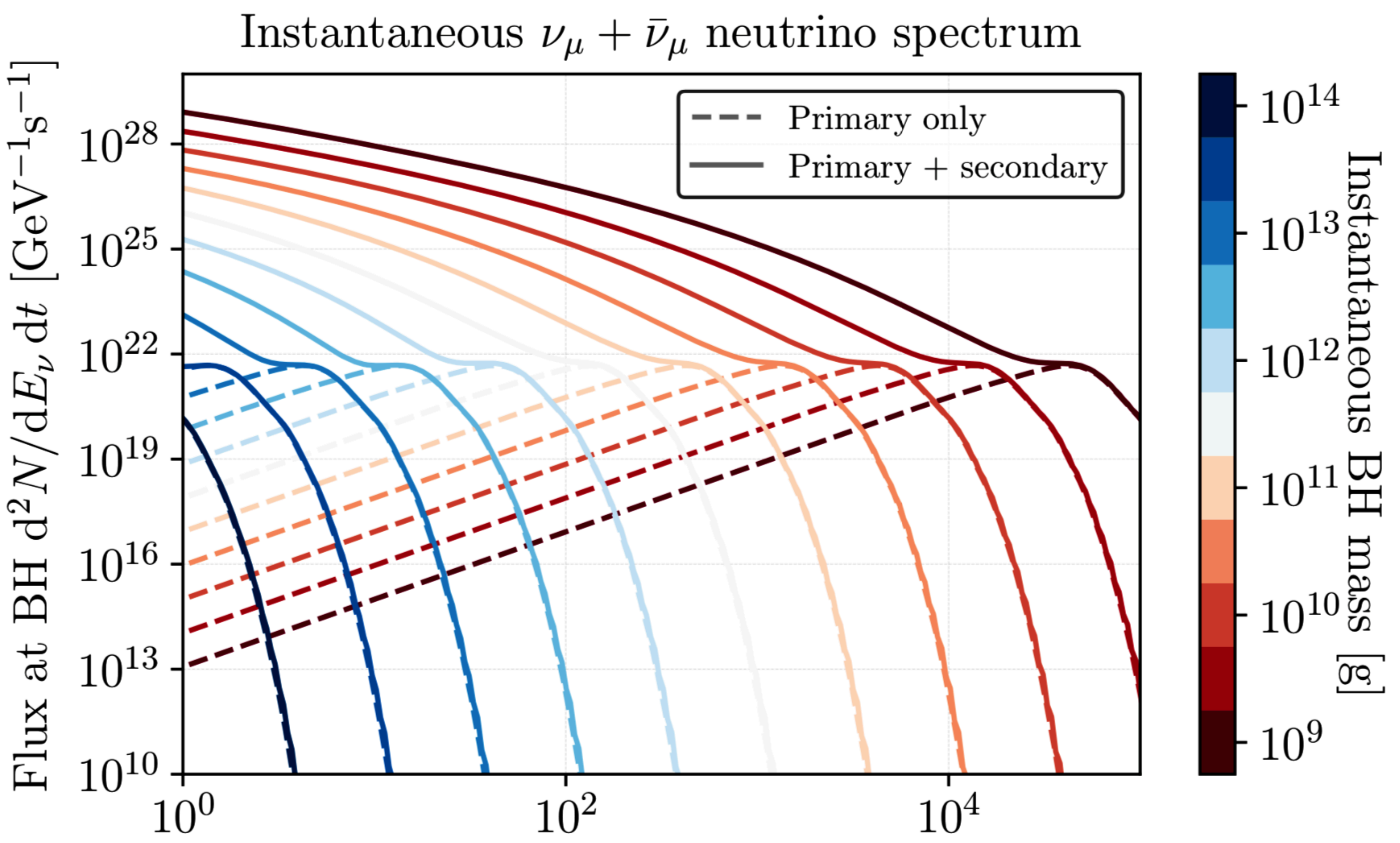


Spectra:
- Primary: $\nu_\alpha \bar{\nu}_\alpha$ pairs emitted at event horizon
- Secondary: decays of unstable primary particles/hadrons

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

- - - Primaries - direct BH production of muon neutrinos

— Secondaries - muon neutrinos produced in particle showers



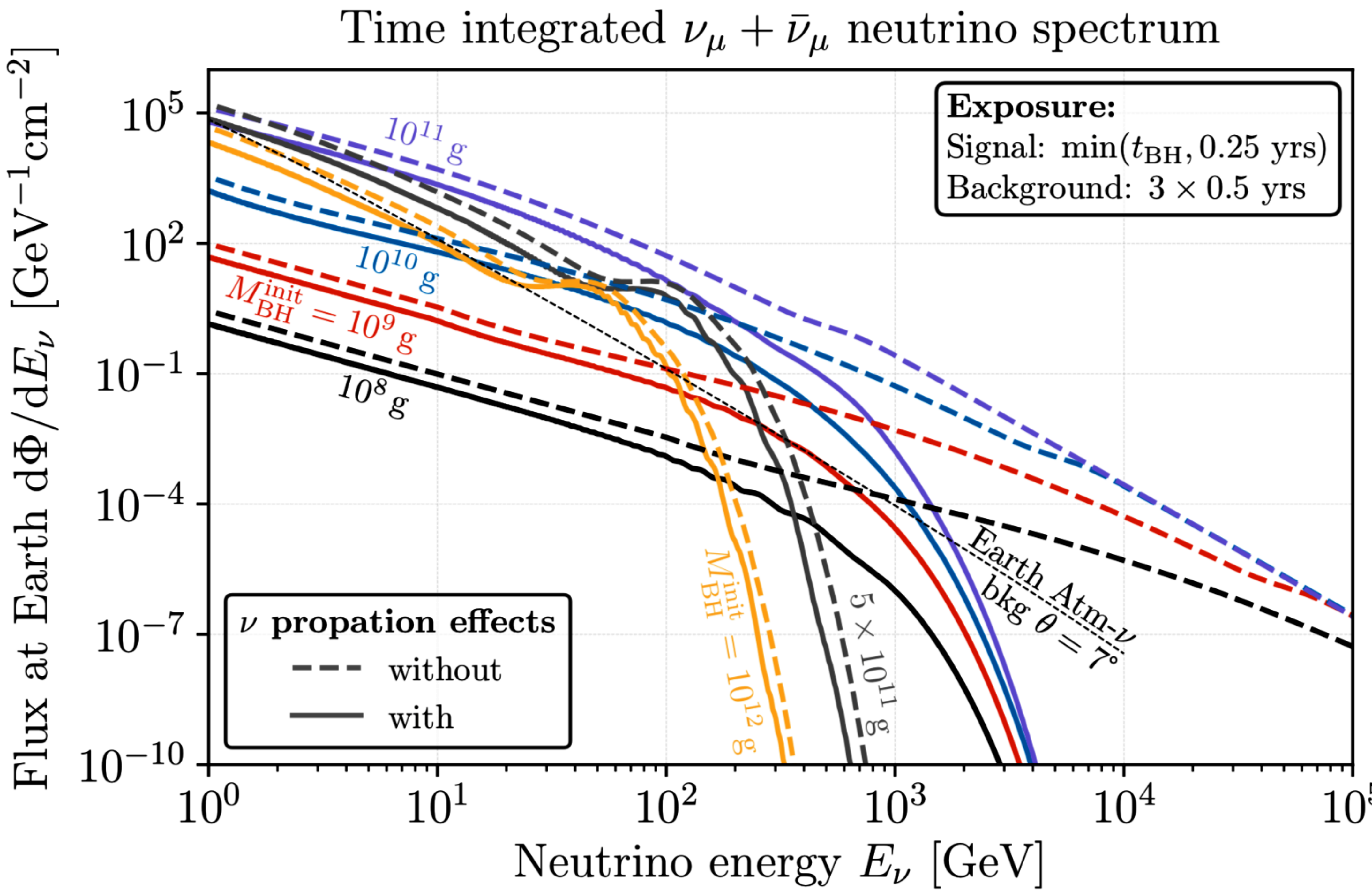
Integrated spectra:

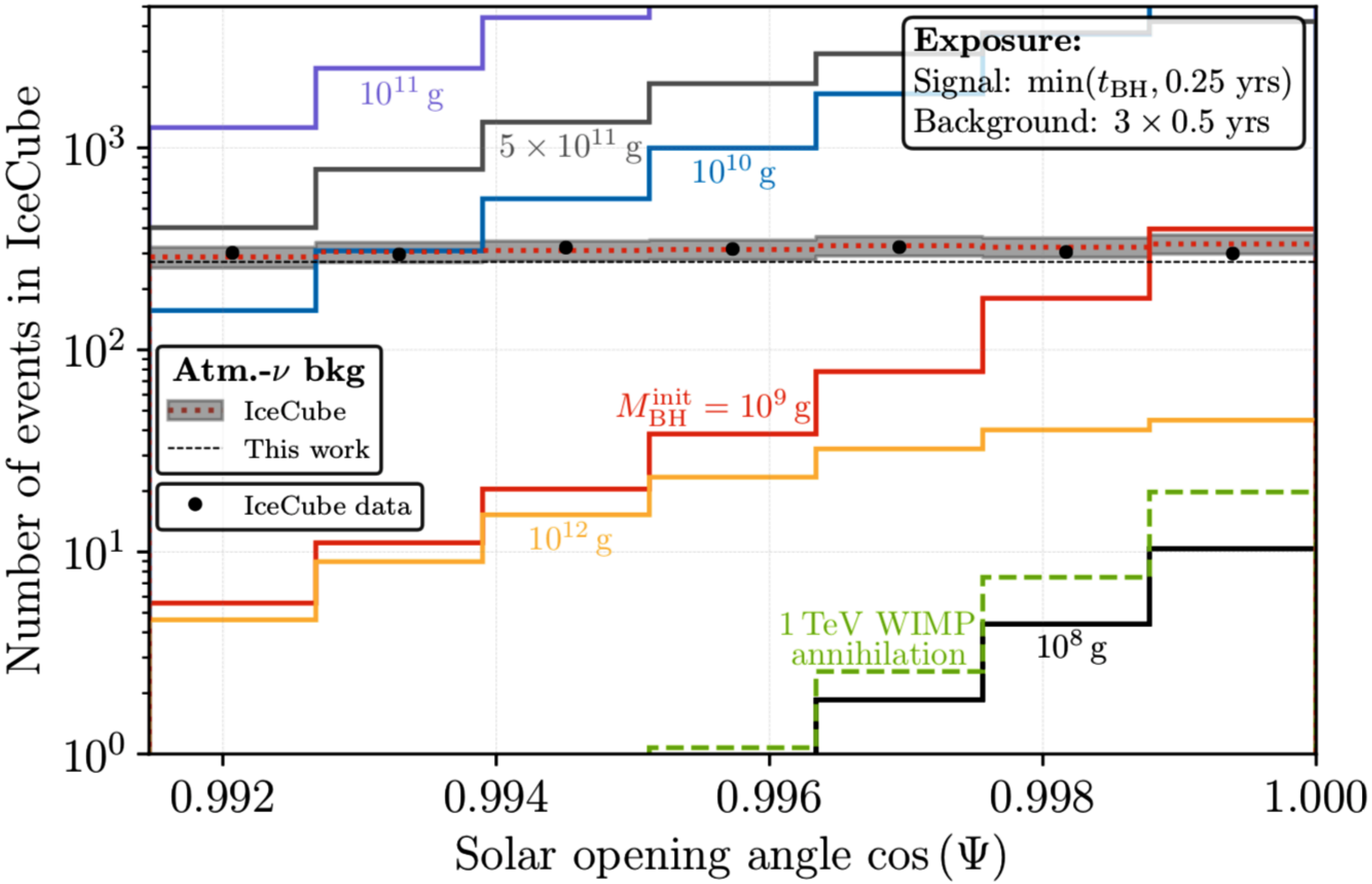
$$\frac{dM_{BH}}{dt} = -\frac{f(M_{BH})}{(GM_{BH})^2}$$

$$f(M_{BH}) = \sum_i g_i \int_0^\infty \frac{E}{2\pi} \frac{\Gamma_{s_i}(M_{BH}, E)}{e^{E/T_{BH}} \pm 1}$$

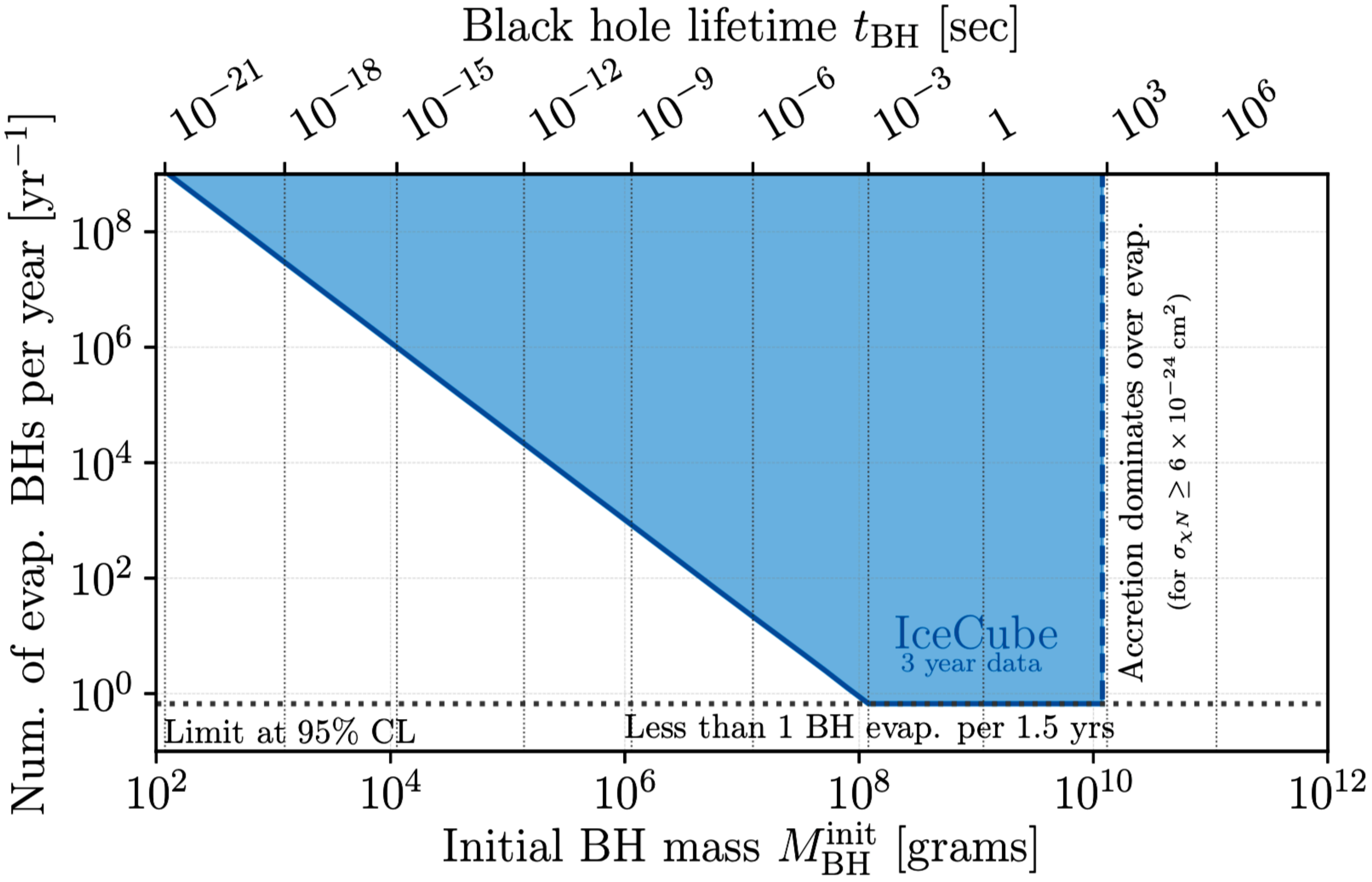
- - - no prop

— prop effects





Analysis recast from IceCube's 1612.05949



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

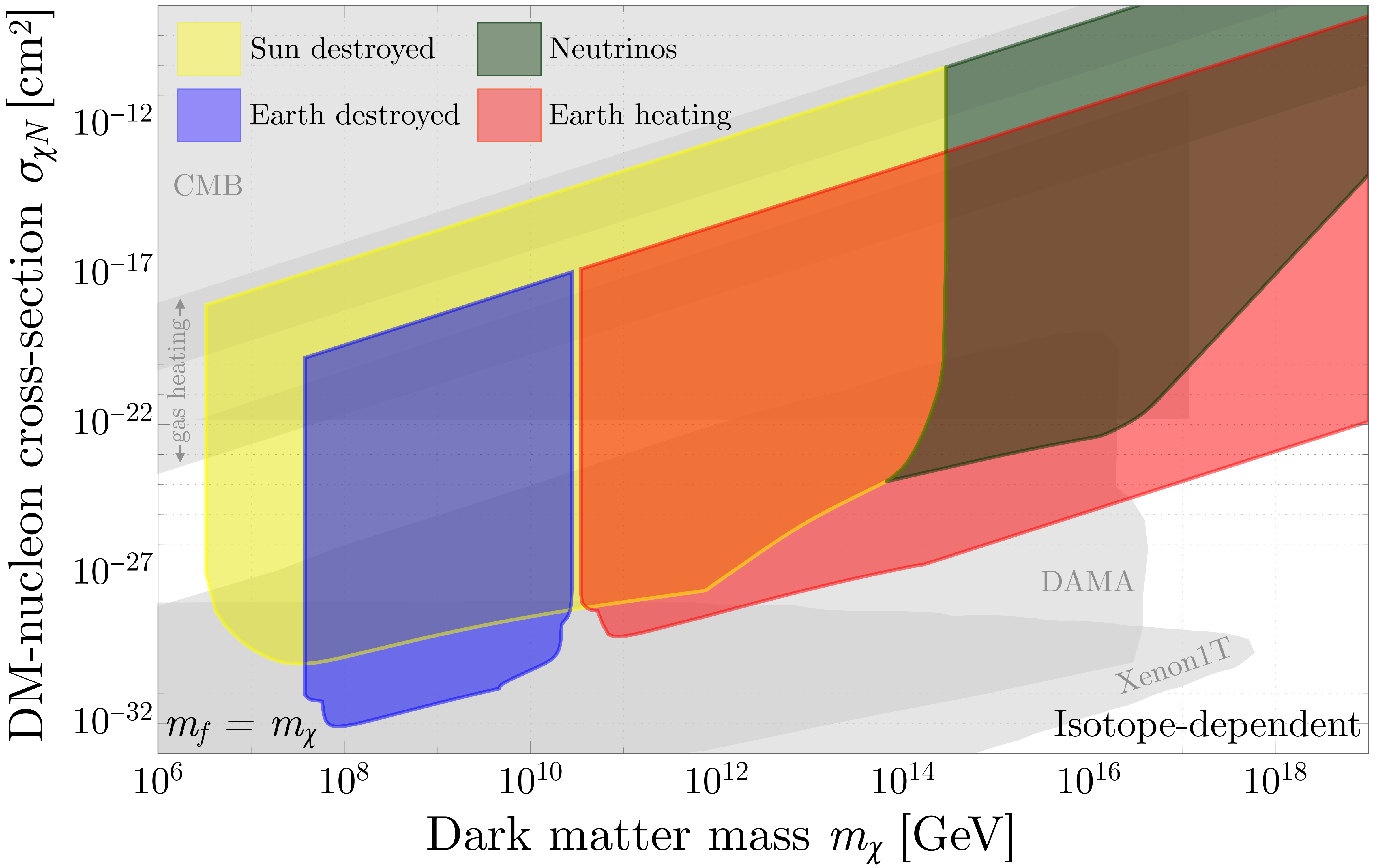
Need multiple evaporating BHs

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

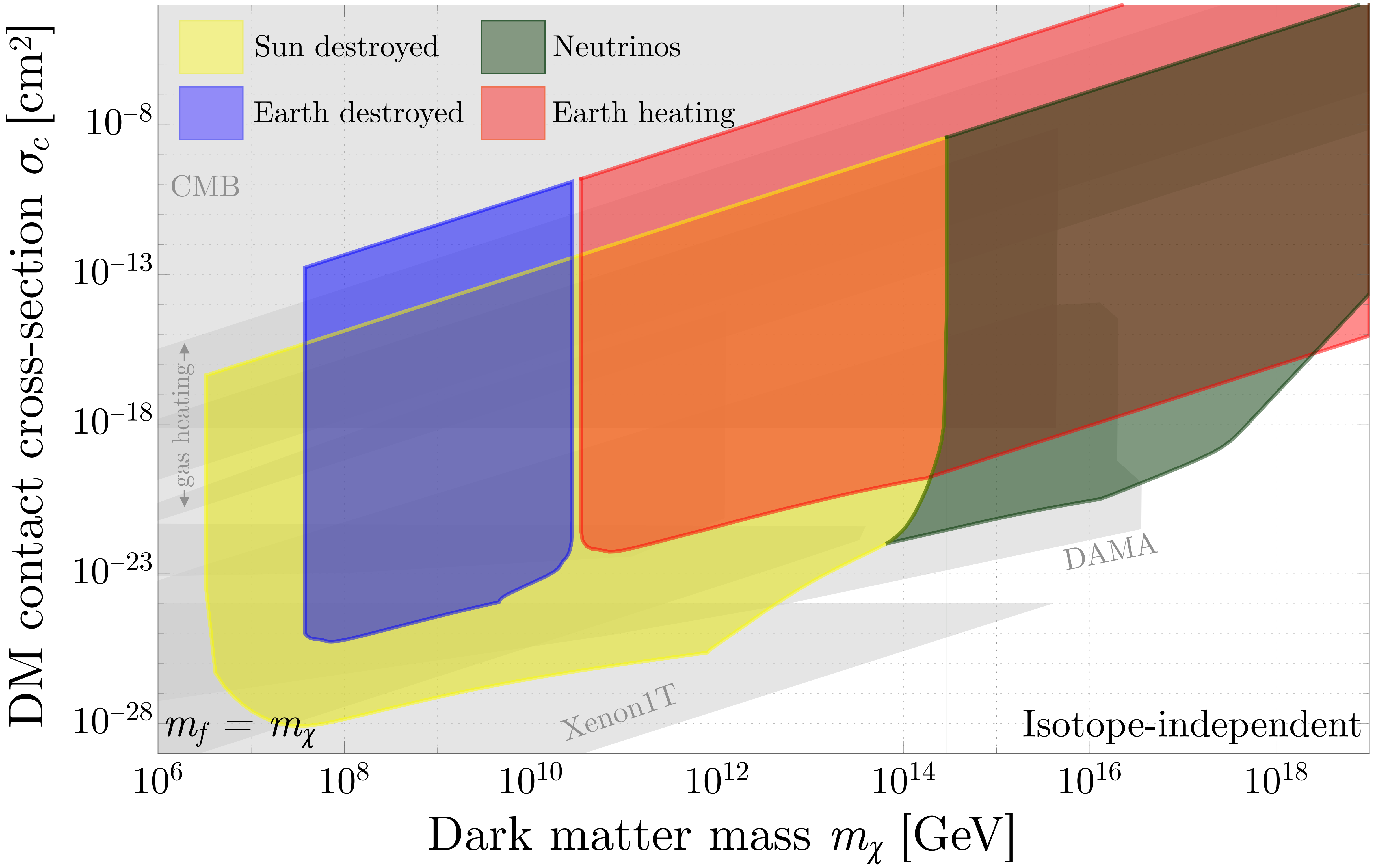
single evaporating BH suffices

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

BHs do not evaporate



Sun destroyed
Neutrinos
Earth destroyed
Earth heating
CMB
gas heating
DAMA
Xenon1T
$m_f = m_\chi$
Isotope-dependent
DM-nucleon cross-section $\sigma_{\chi N}$ [cm^2]
10^{-12}
10^{-17}
10^{-22}
10^{-27}
10^{-32}
10^{6} 10^{8} 10^{10} 10^{12} 10^{14} 10^{16} 10^{18}
Dark matter mass m_χ [GeV]



Sun destroyed
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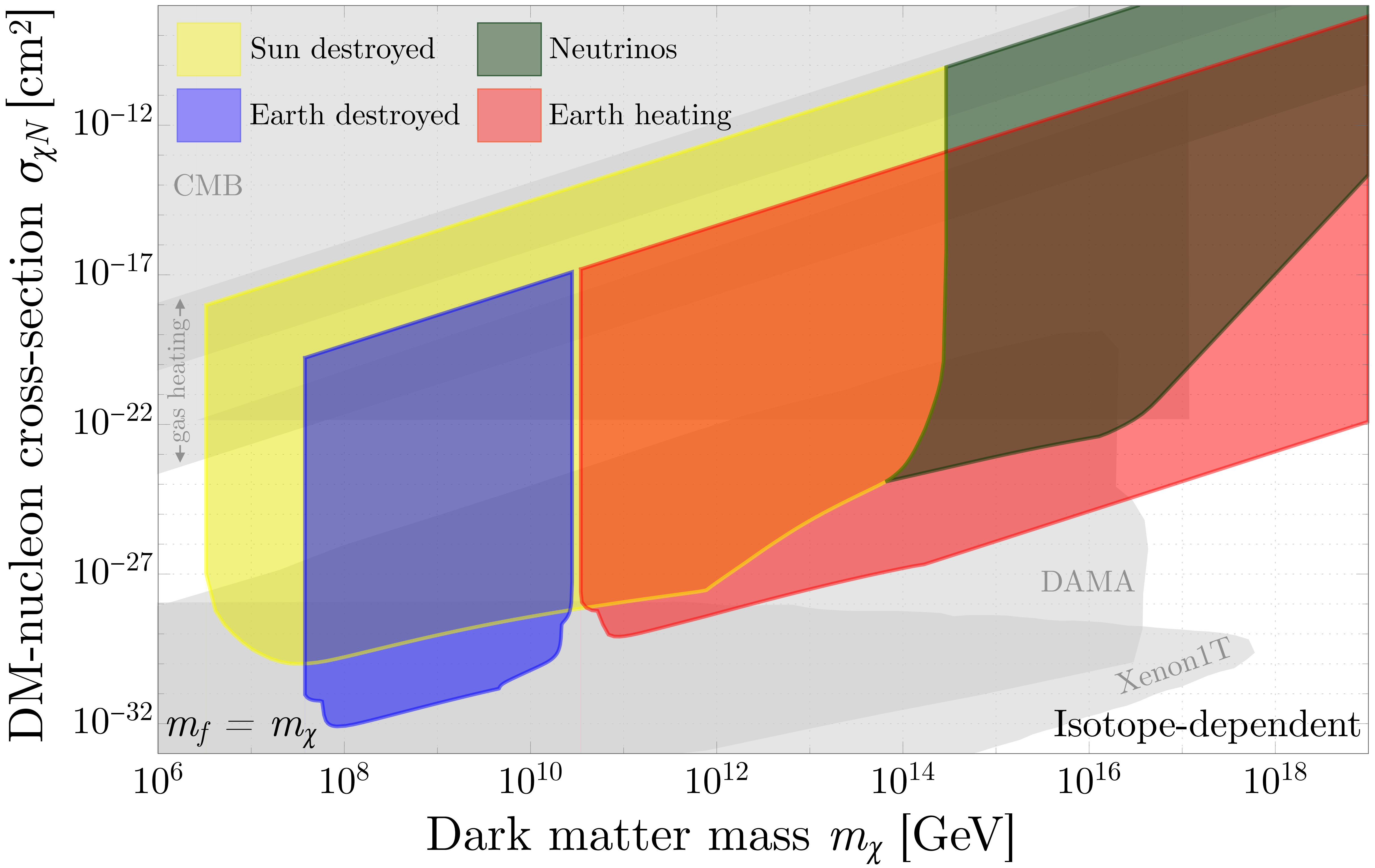
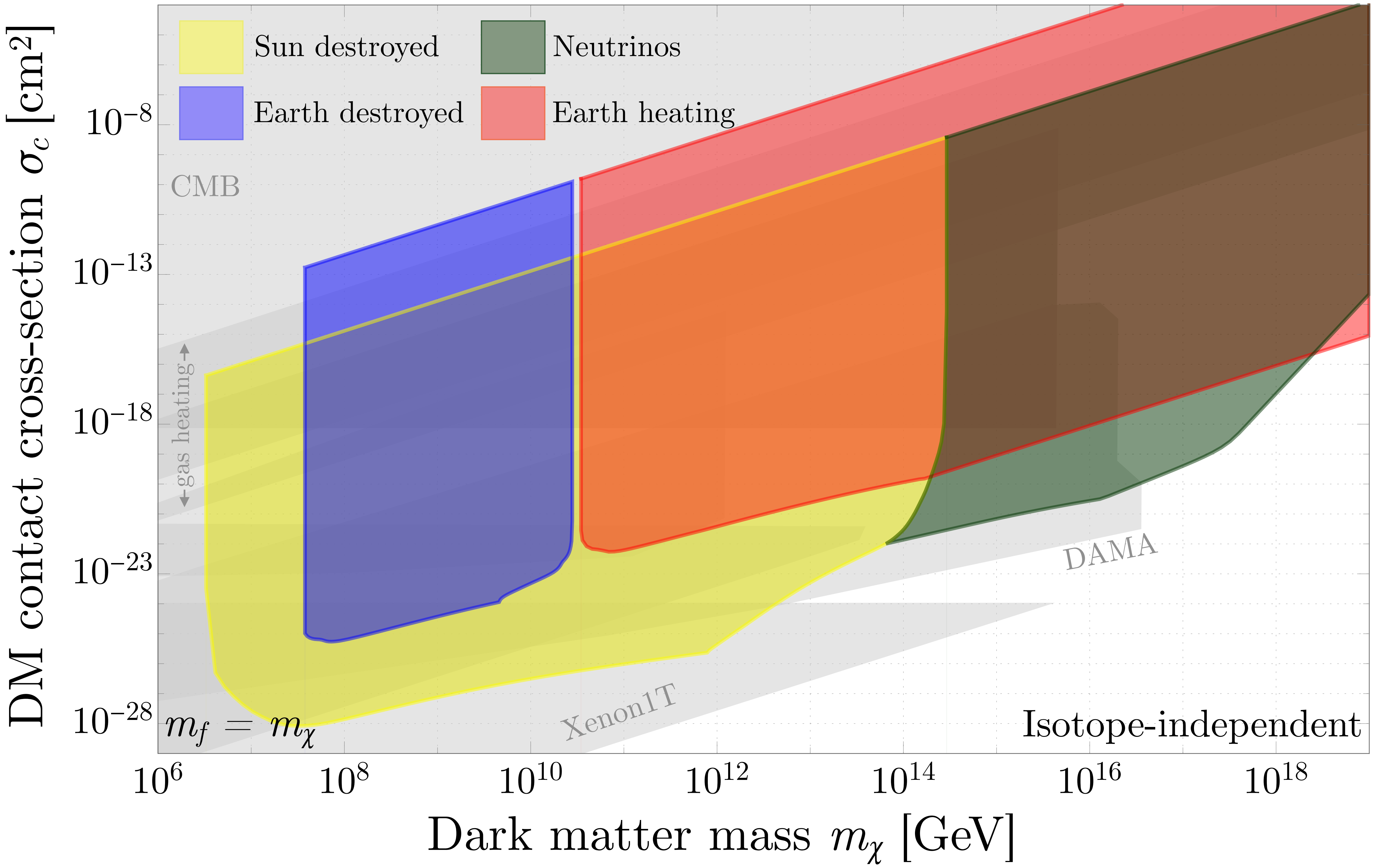
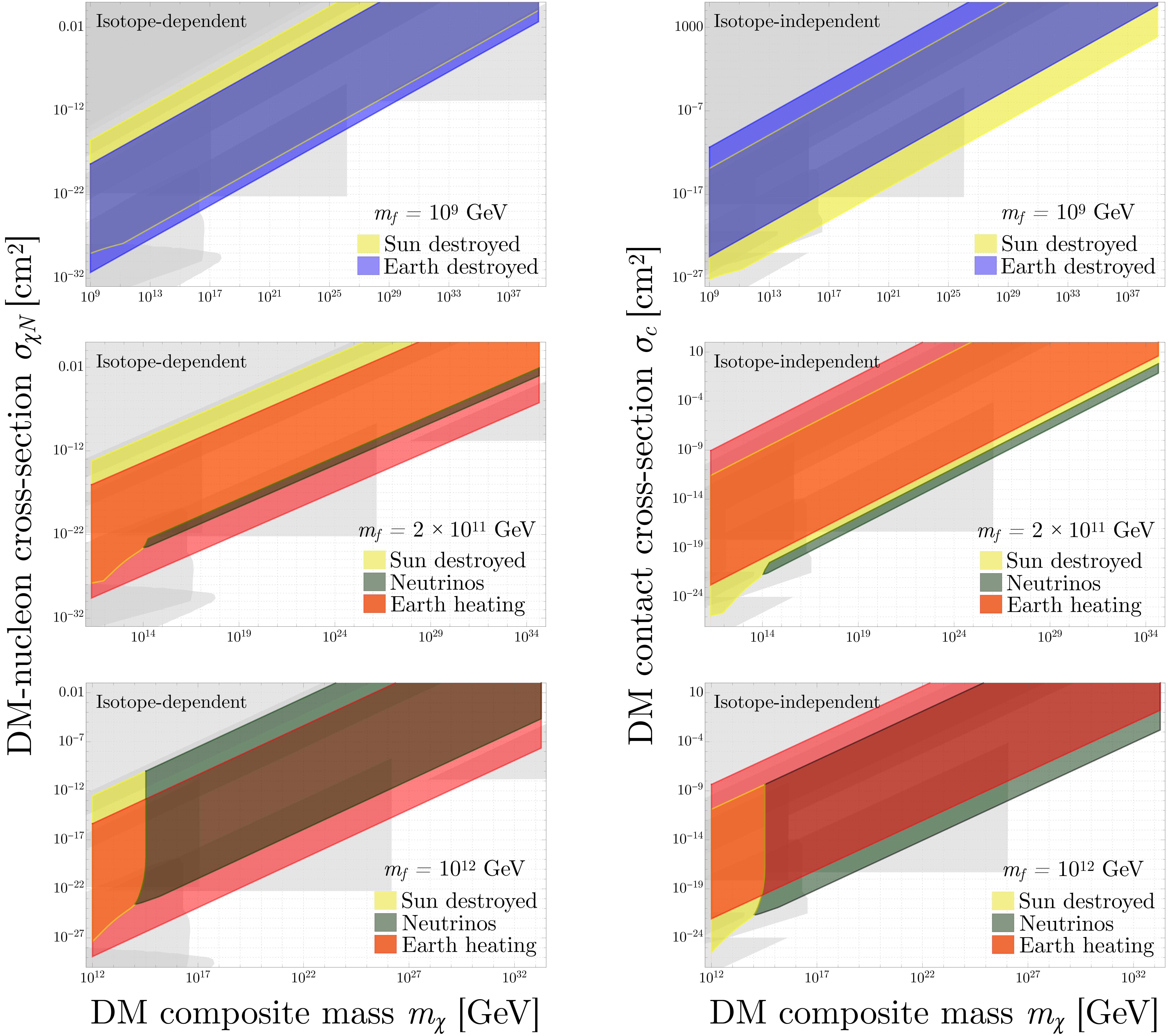
Dark matter mass m_χ [GeV]

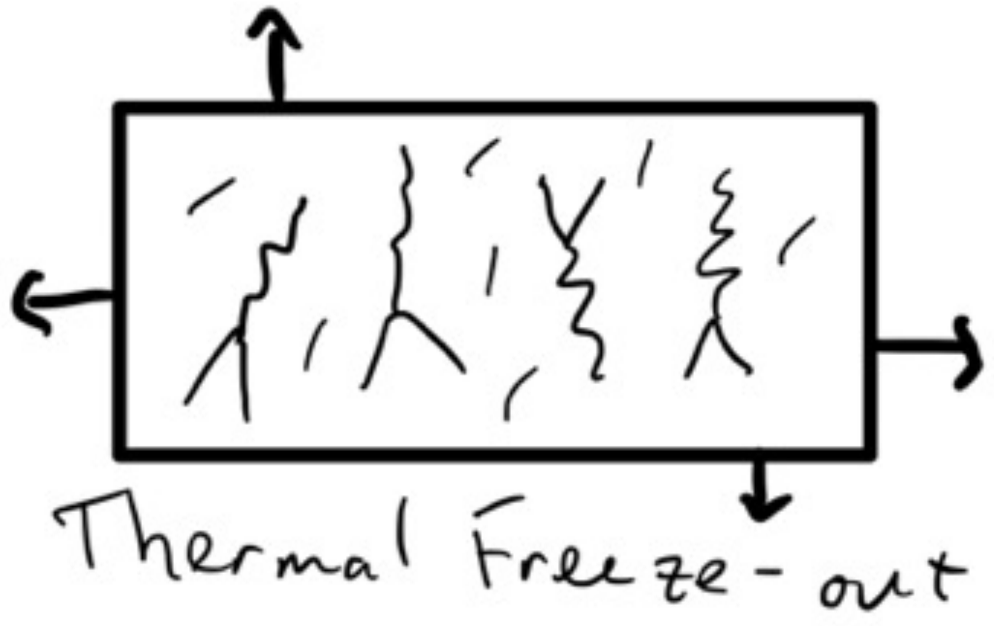




$$M_{crit} = \frac{M_{pl}^3}{m_f^2}$$


Isotope-dependent
$m_f = 10^9$ GeV
Sun destroyed
Earth destroyed
Isotope-independent
$m_f = 10^9$ GeV
Sun destroyed
Earth destroyed
Isotope-dependent
$m_f = 2 \times 10^{11}$ GeV
Sun destroyed
Neutrinos
Earth heating
Isotope-independent
$m_f = 2 \times 10^{11}$ GeV
Sun destroyed
Neutrinos
Earth heating
Isotope-dependent
$m_f = 10^{12}$ GeV
Sun destroyed
Neutrinos
Earth heating
Isotope-independent
$m_f = 10^{12}$ 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]

Weakly interacting dark matter "miracle"



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

The final relic abundance depends on the annihilation cross-section, but only logarithmically on m_x

$$\Omega_x h^2 \propto \frac{x_{FO}}{\sigma_0} \quad | \quad x_{FO} \propto \ln[m_x]$$

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

The thermal relic annihilation cross-section matches the couplings and mass of the weak force, "wimp miracle"

DM Mass Unitarity Limit

Griest, Kamionkowski, '87

1. Assume freeze-out abundance set with annihilation

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

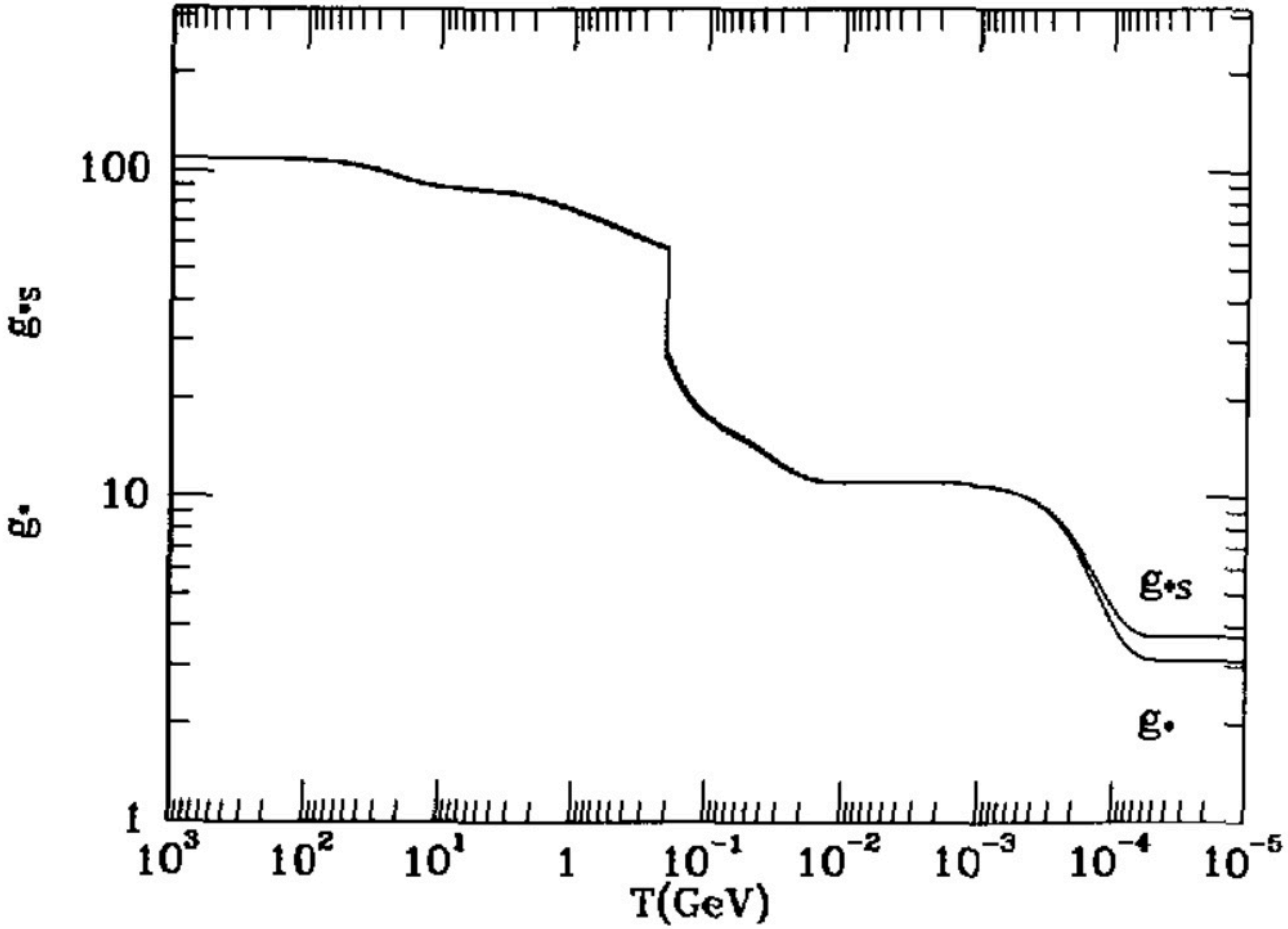
2. Require the annihilation cross-section not exceed a perturbative bound

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

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 caveat: Entropy changes in the early universe



Kolb and Turner 1988

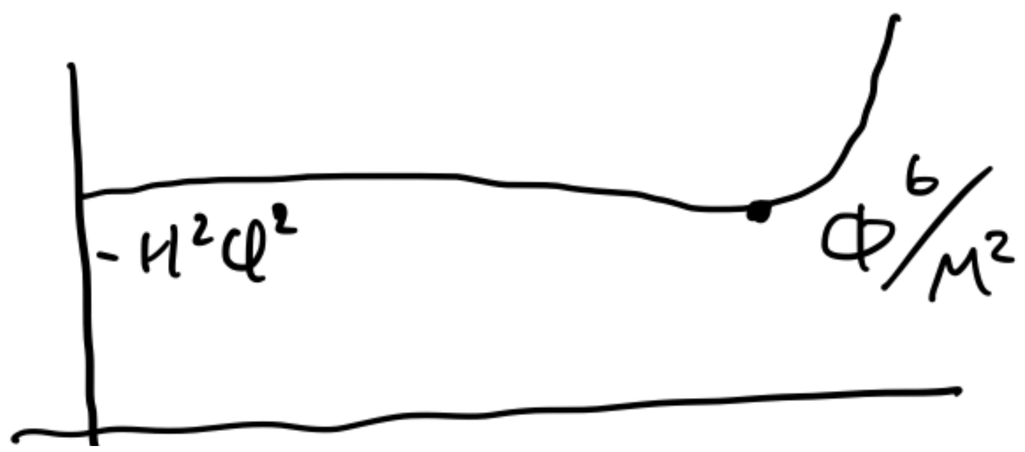
Degrees of Freedom in SM-only Universe

AD Baryogenesis

Afleck, Dine '85
Linde '85
Dine, Randall, Thomas '95

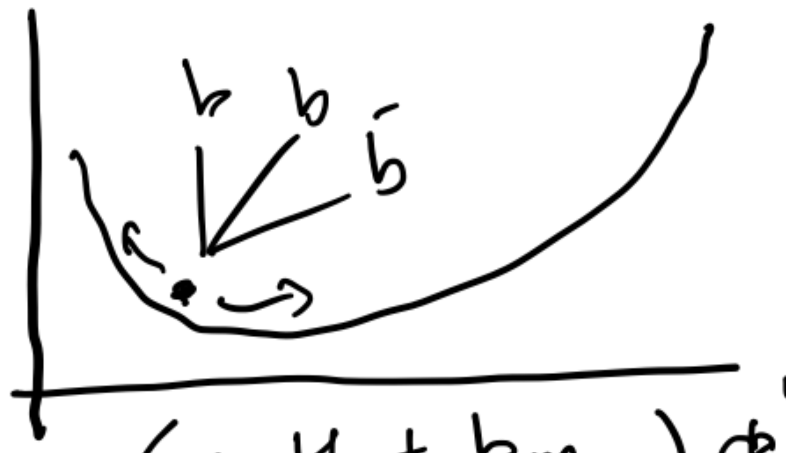
1. Baryo-charged scalar gets vev during inflation

$$V_{AD} = m_\phi^2 |\phi|^2 - H^2 |\phi|^2 + \frac{\phi^6}{M^2} + \not{CP}$$



2. Baryo-charged scalar decays (CP violating)

after inflation $H \lesssim M_\phi$



$(aH + b m_\phi)\phi^4/M + h.c.$

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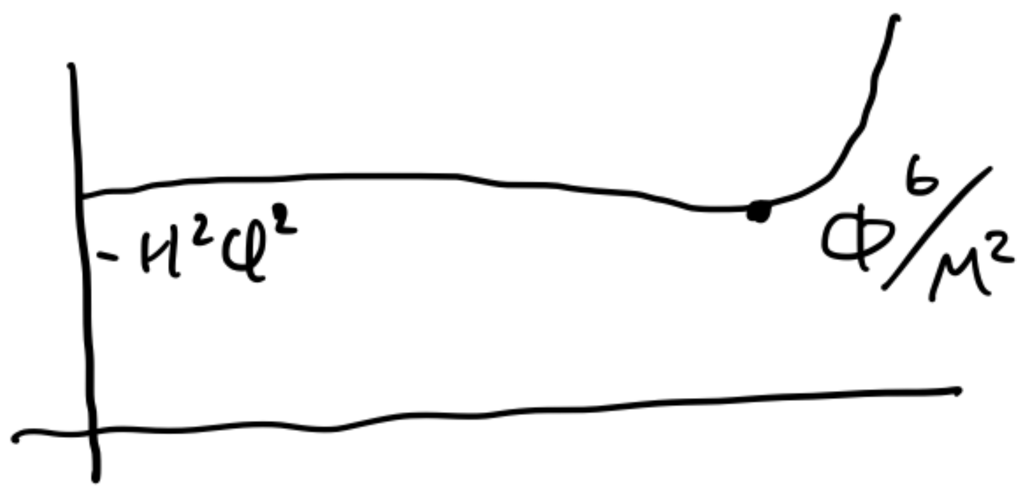

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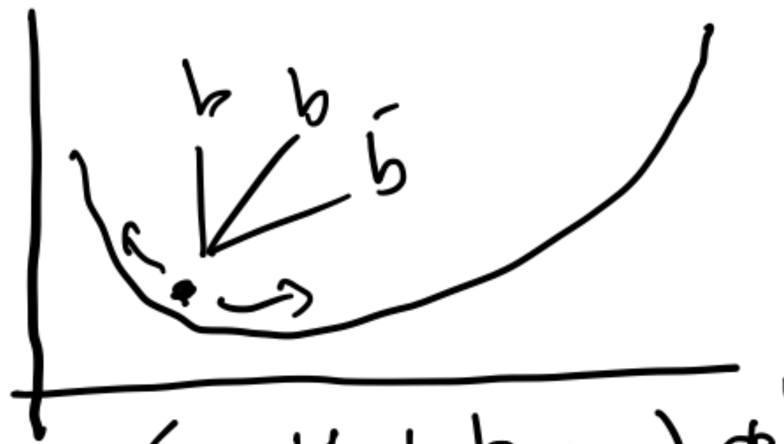
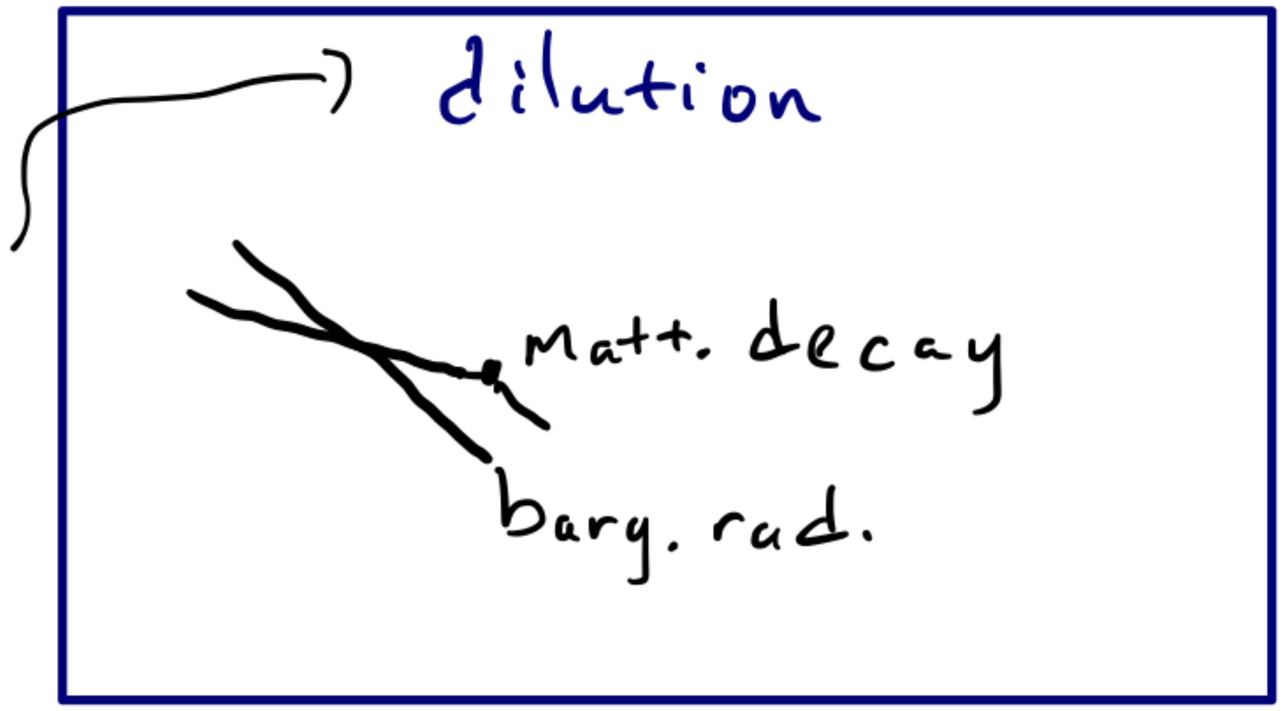


$(aH + bm_\varphi)\Phi^4/M + h.c.$

3. Oops! too many baryons, need → dilution



Main point: $\eta_b \sim 1 - 10^{-8}$ for a simple baryo-charged scalar

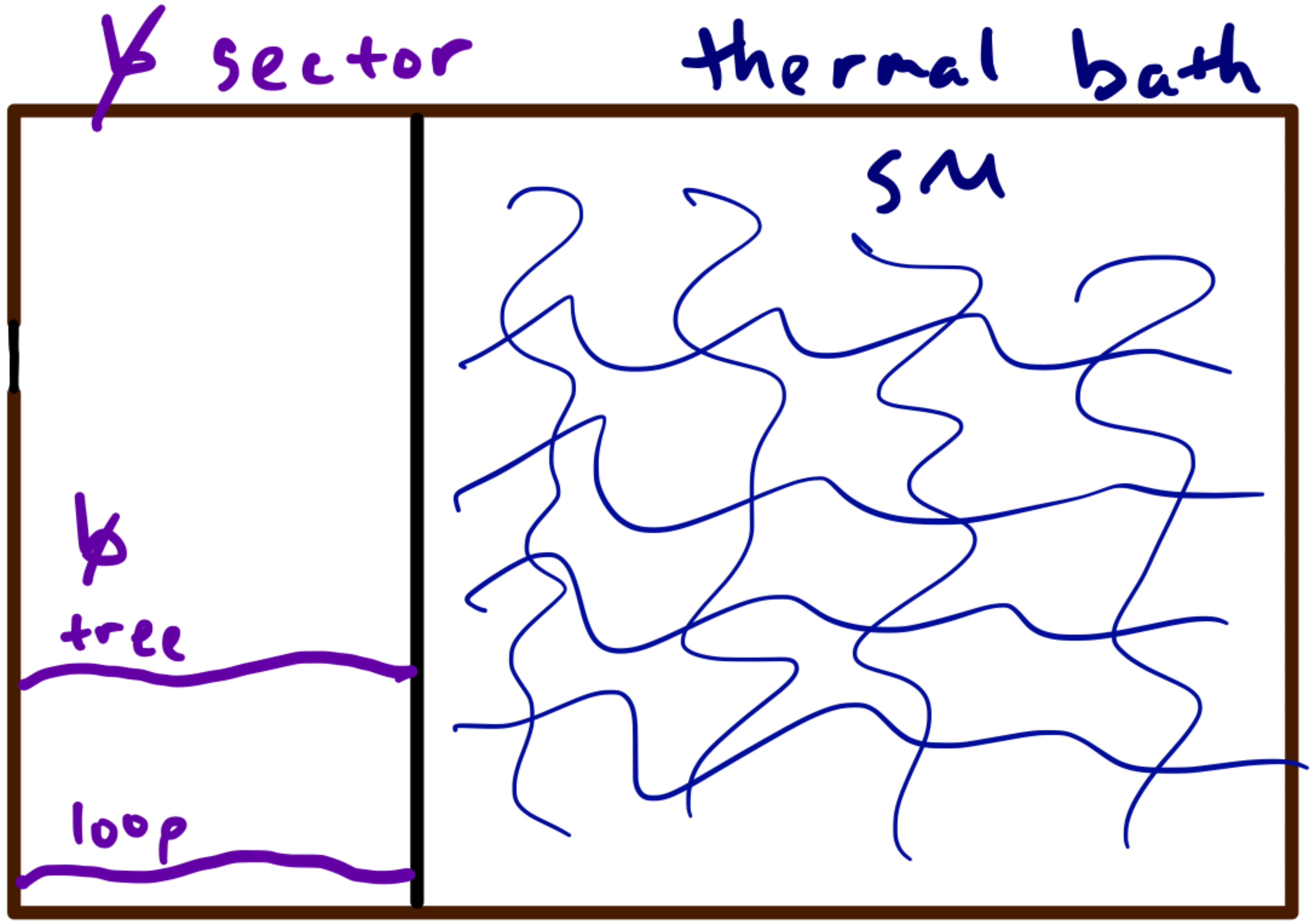
$\eta_b = 10^{-10}$ observed, need dilution.

Why too many baryons?

If: $\mathcal{O}(1)$ CP violating decays

And: $\rho_\phi \sim \rho_u$

↑ $\not{B}$ sector



$$\eta_B \simeq \frac{n_b}{\rho_u^{3/4}} \left(\zeta \right)$$

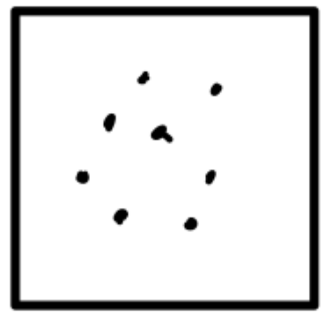
$n_b \sim [10^{-5} - 1]$ for any $\not{B}$ sectors with $\mathcal{O}(1)$ couplings

High Scale Baryon Asymmetry Cosmology Dilutes Abundances

1. Stat. field

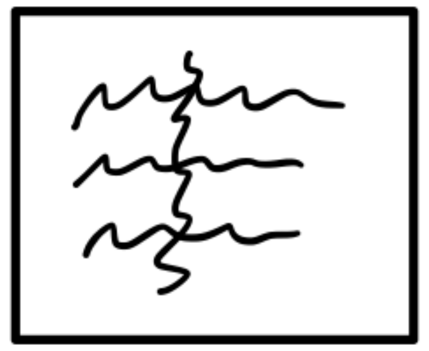
2. matt. field

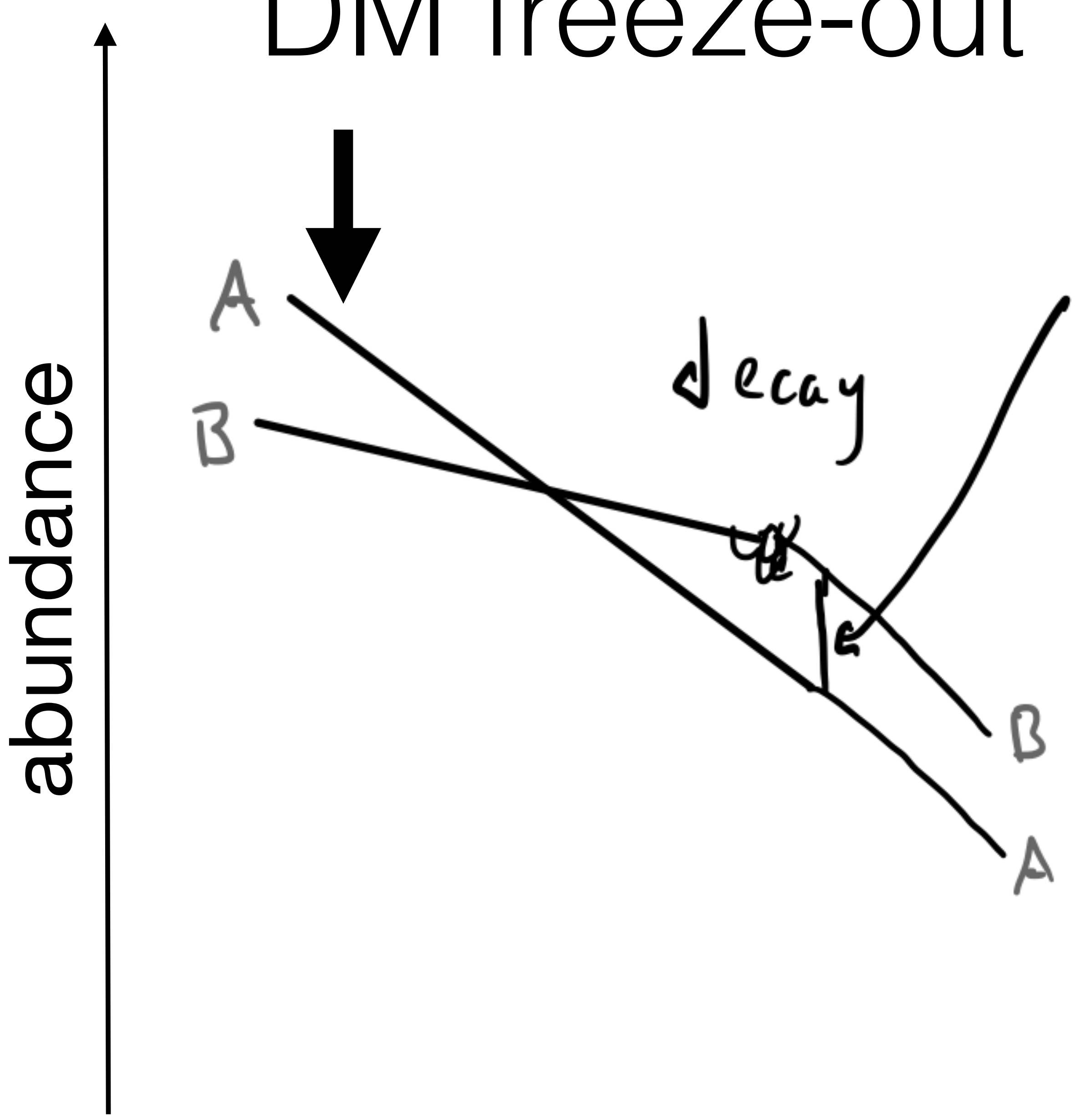
or



$\Gamma < H$

3. rad. field





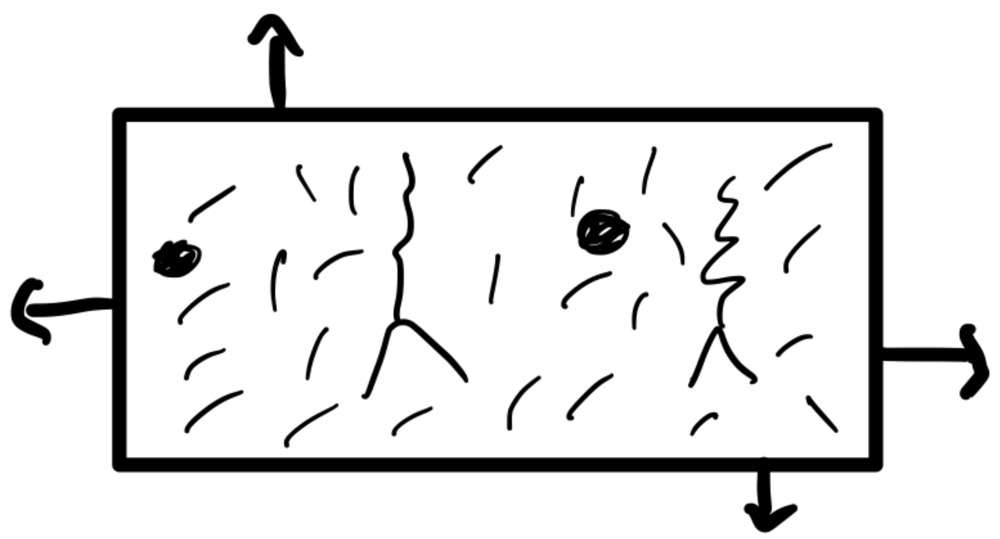
$$\zeta \equiv \frac{\rho_A^{3/4}}{\rho_B^{3/4}}$$

$$\Omega h^2 \to \Omega h^2 \zeta$$

dilation

- B : slow decaying inflatons, moduli, GUT mass states, AD fields...
- A : Typically SM w/DM, baryons

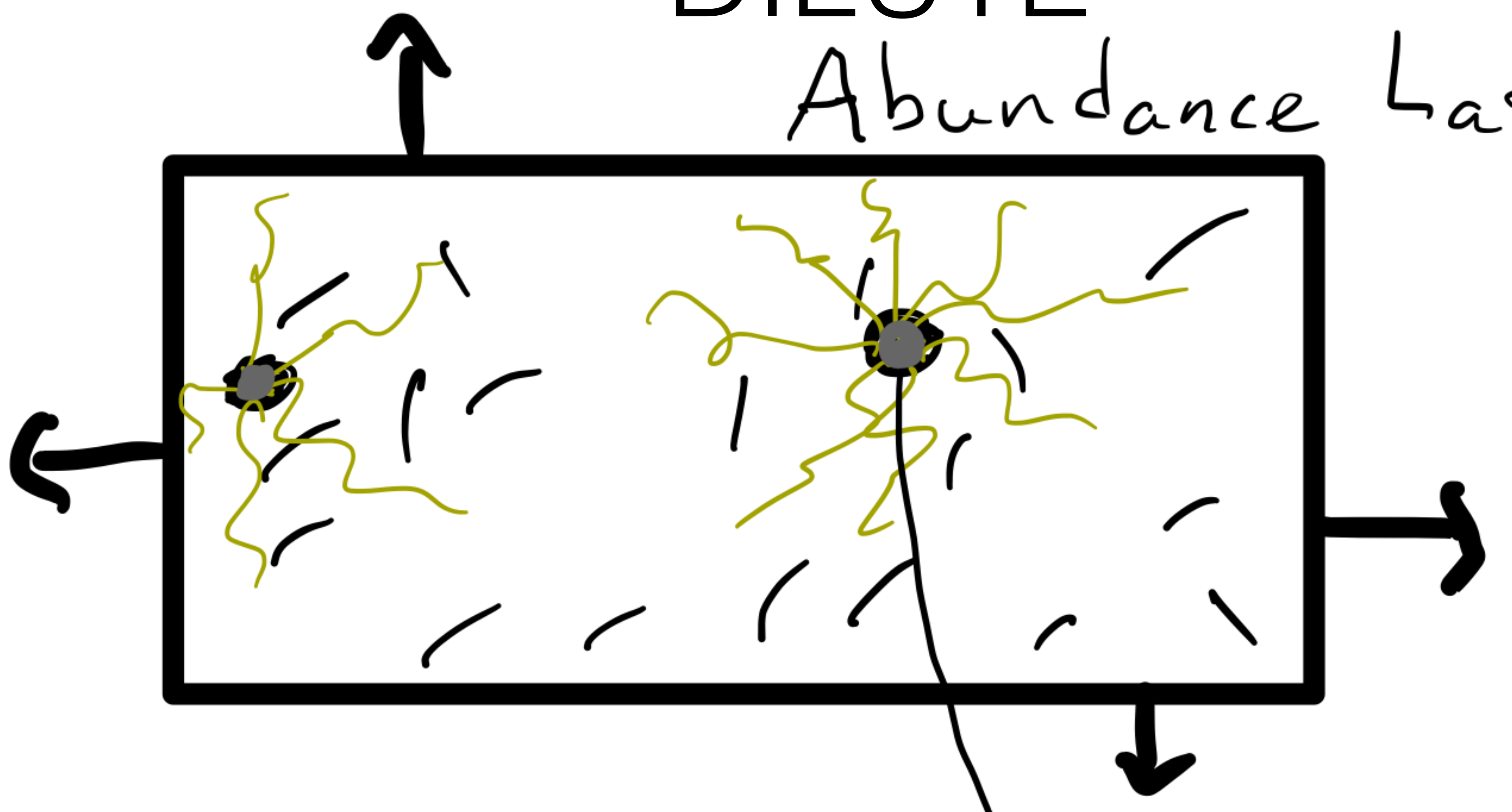
Dilute WIMPS



Overabundant Freeze-out

DILUTE

Abundance Later



Late time dilution from decaying states

$$\Omega_{DM}h^2 \sim 0.1 \left(\frac{m_v}{PeV}\right)^2 \left(\frac{0.03}{\alpha}\right)^2 \left(\frac{\zeta}{10^{-8}}\right)$$

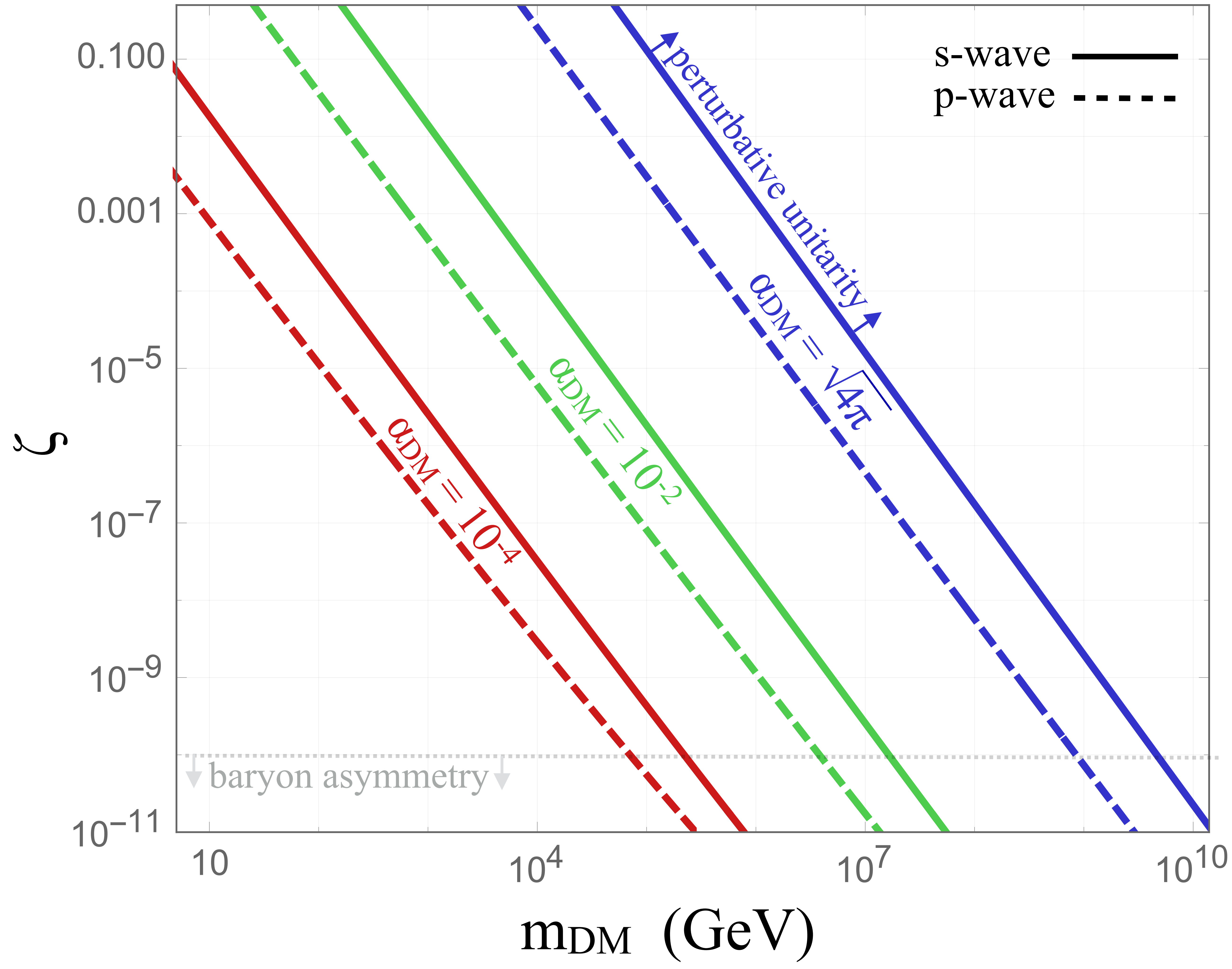
DILUTION FACTOR ζ

$$\zeta \equiv \frac{S_{initial}}{S_{final}}$$ { Δ entropy density from decays 

See also
Allahverdi Dutta Sinha '11
Kane Shao Watson '11
Davoudiasl Hooper McDermott '15
Berlin Hooper Krnjaic '16

JB, Unwin '17

Much lower DM annihilation cross-section in diluted universe



- **Increasing dilution implies freeze-out dark matter masses up to 10^{10} GeV**
- **Super-GUT masses if DM produced out of equilibrium**

JB, Unwin 1701.05859

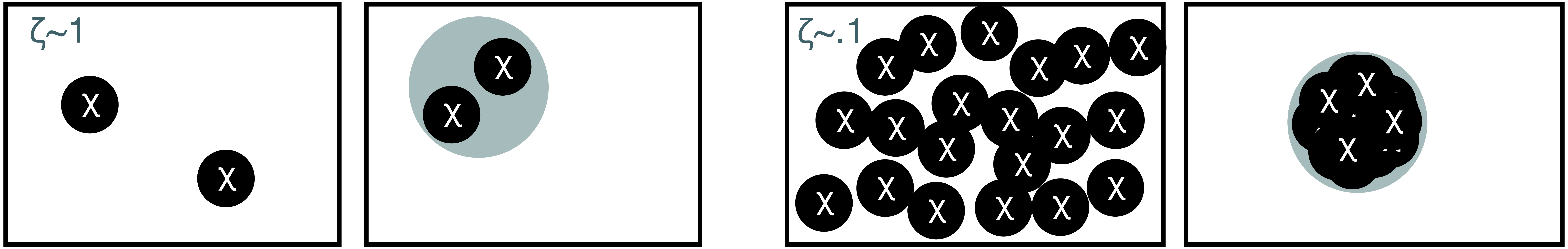
HIGH MASS ASYMMETRY, DILUTION, AND COMPOSITE DM

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

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

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

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



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

Composite mass ranging from milligrams to thousands of tons

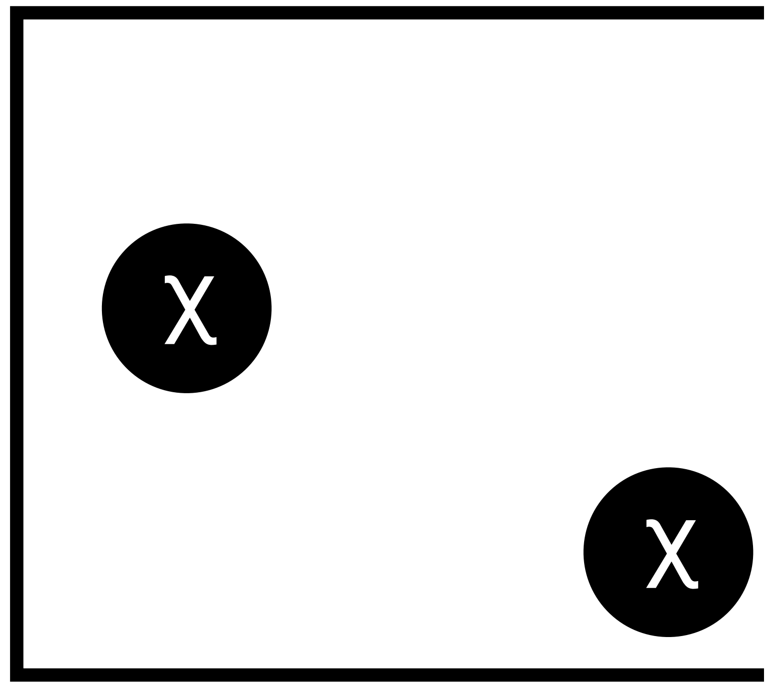
2012.10998

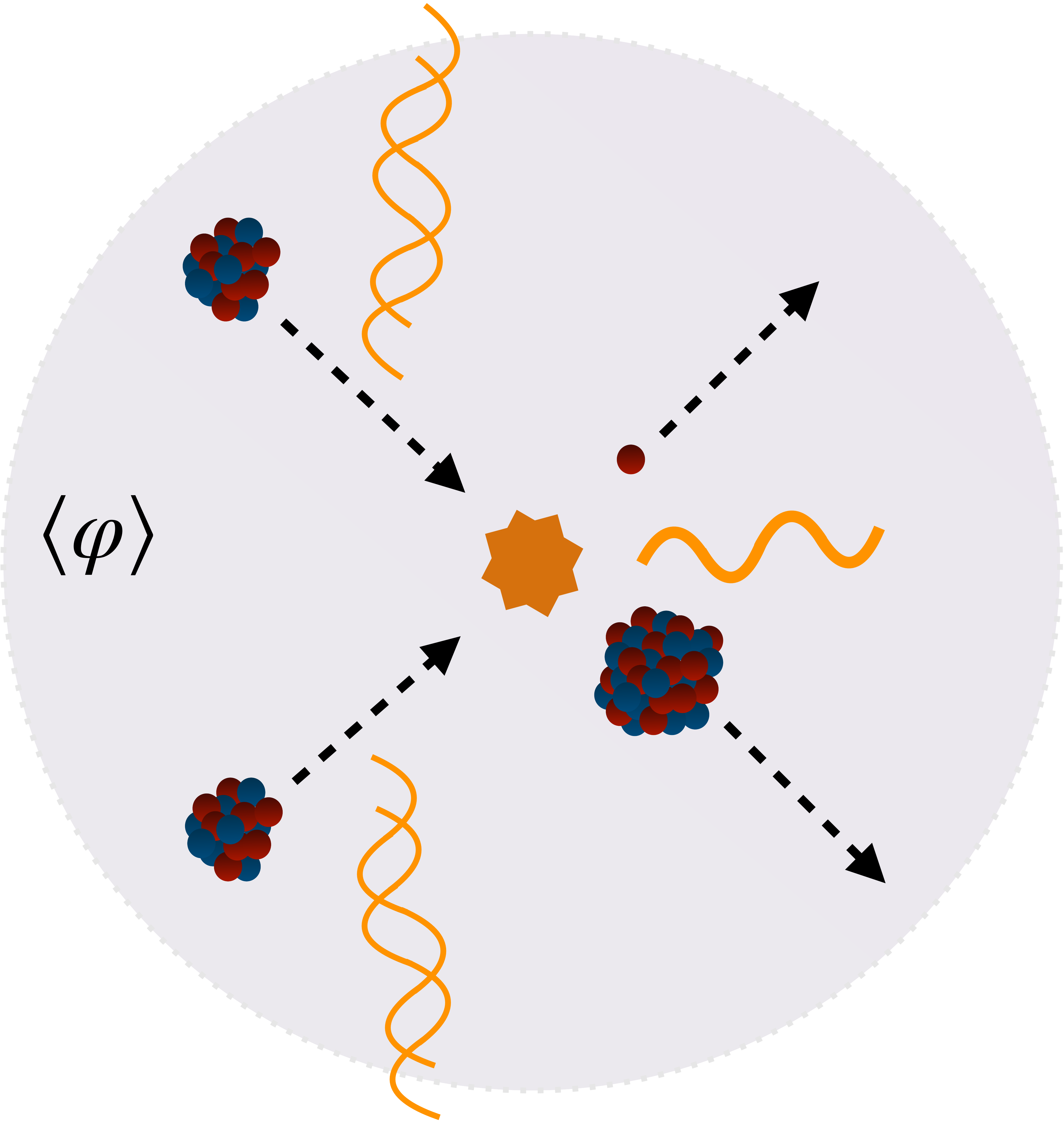
HIGH MASS ASYMMETRY, DILUTION, AND COMPOSITE DM

Consider a simple

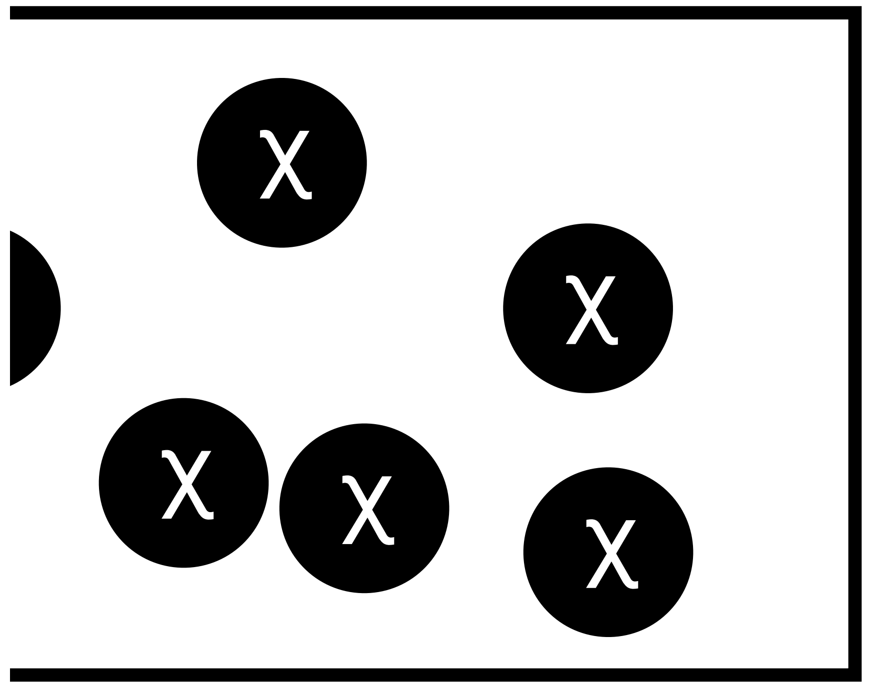
$$\mathscr{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma$$

Since diluted dark





h ζ^{-1}



This overabundan

mposite DM

$$N_c = \left(\frac{2n_X\sigma_X v_X}{3H}\right)^{6/5}$$

$$\left(\frac{5\,\mathrm{GeV}}{\bar{m}_X}\right)^{21/5}\left(\frac{10^{-6}}{\zeta}\right)^{6/5}$$

Fusion inside dark matter — Javier presents on Friday *2012.10998*

THE HIGH MASS DARK MATTER FRONTIER

- Direct detection experiments and multiscatter
- Interstellar gas cloud cooling
- Solar / terrestrial / martian / white dwarven / neutron stars

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Upcoming work:

- Accelerative dark matter
- Mineral searches for heavy dark matter
- Composite cosmology