ADVANCING DARK MATTER THEORY WITH BLACK HOLES, EXPLODING COMPACT STARS, SUPERCOOL GAS, AND UNDERGROUND DETECTORS

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PI

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Underpinning everything we know:

$$\mathscr{L}_{SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + |D_\mu\phi|^2 - V(\phi) + i\bar{\psi}\not{D}\psi + \bar{\psi}_i y_{ij}\psi_j\phi + \mathrm{h.c.}$$

0 Higgs Boson

½ Leptons, Quarks, Neutrinos

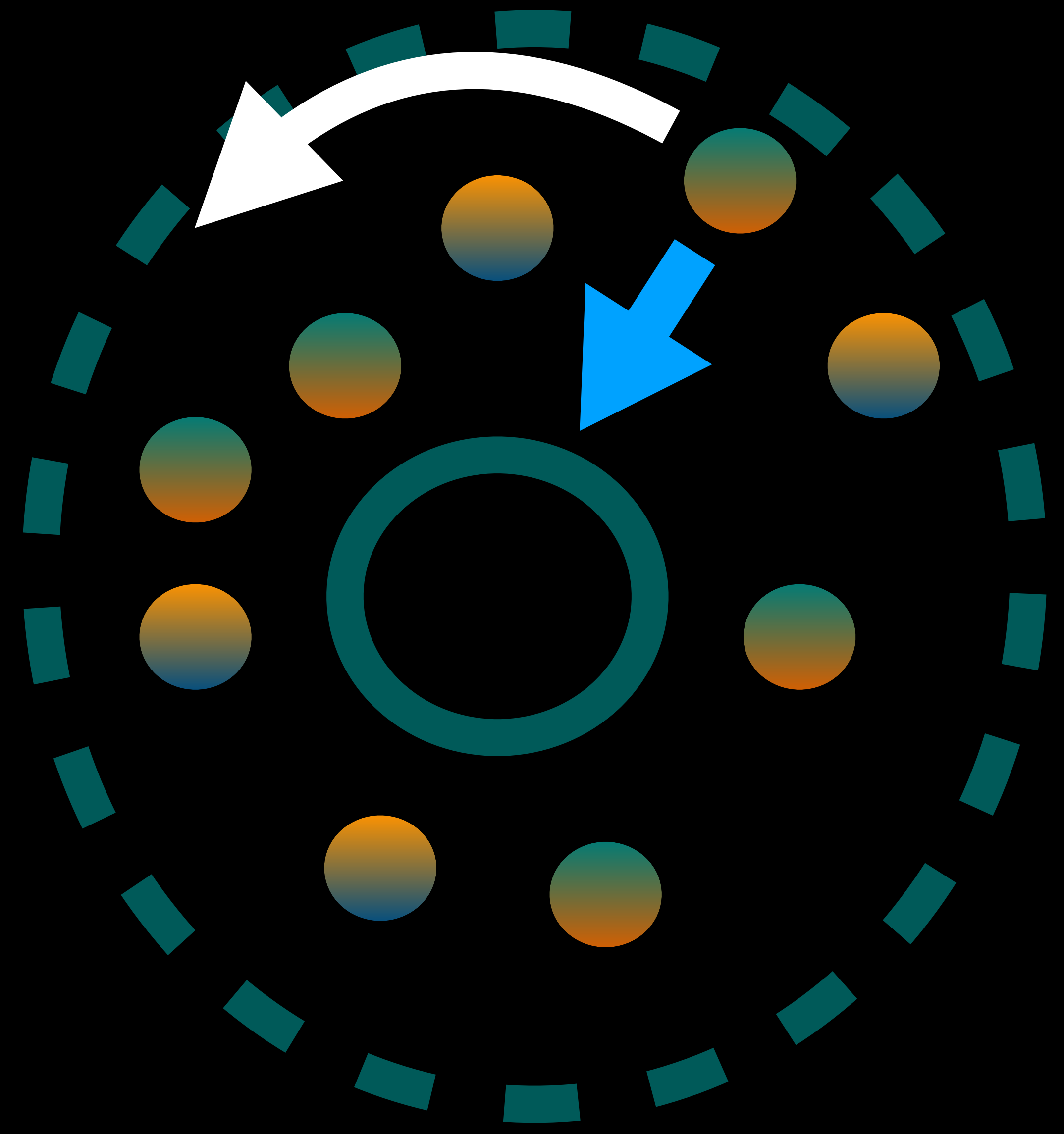
1 Photon, Weak boson, Gluons

3/2*

2 Graviton

What else?

Extra Mass Needed to Keep Galaxies Together



$$\frac{GMm_x}{r^2} = \frac{m_x v^2}{r}$$

$$v = \sqrt{\frac{GM}{r}}$$

Merry Go Round

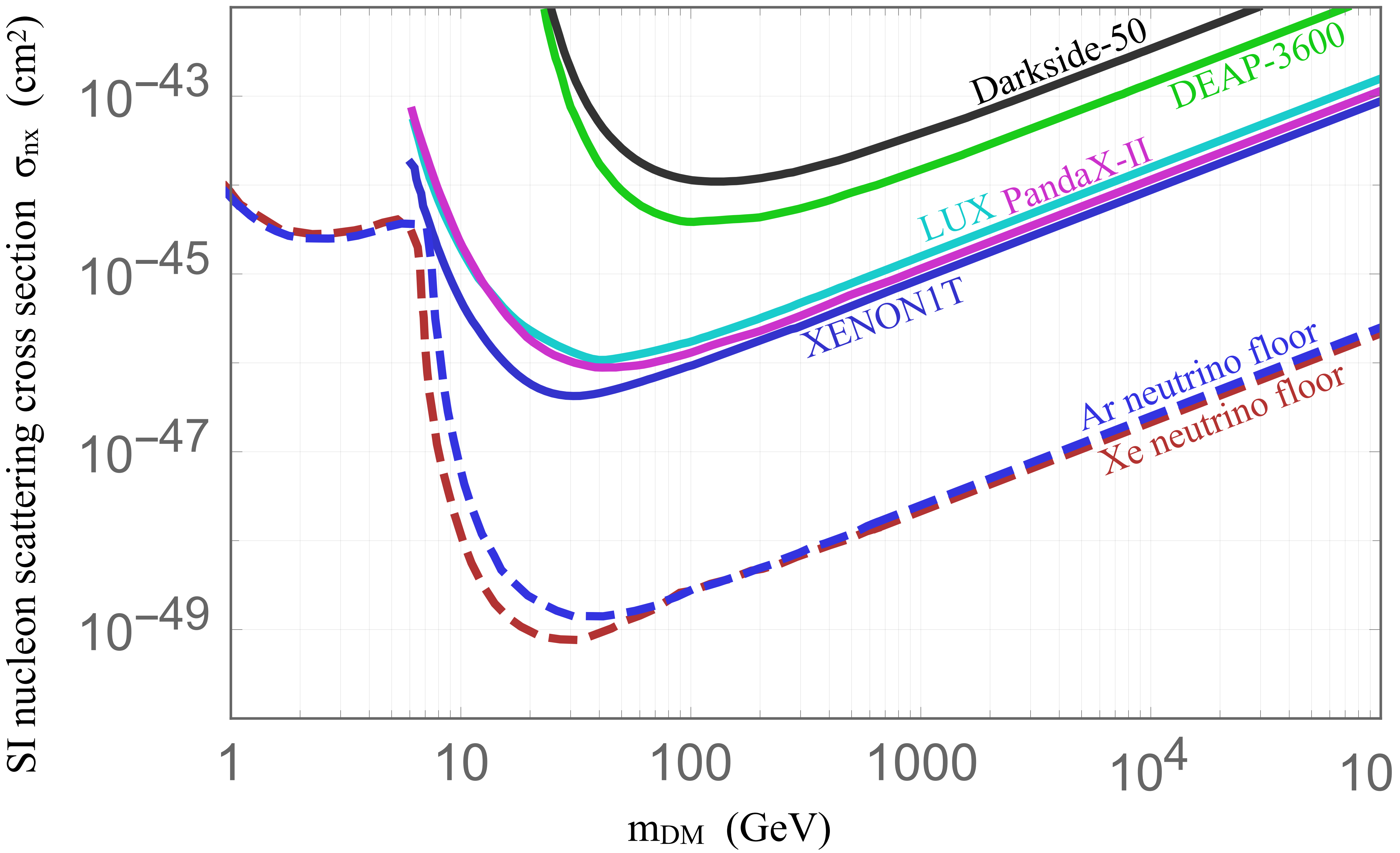
DARK MATTER

Density by earth: ~0.3 GeV/cm³

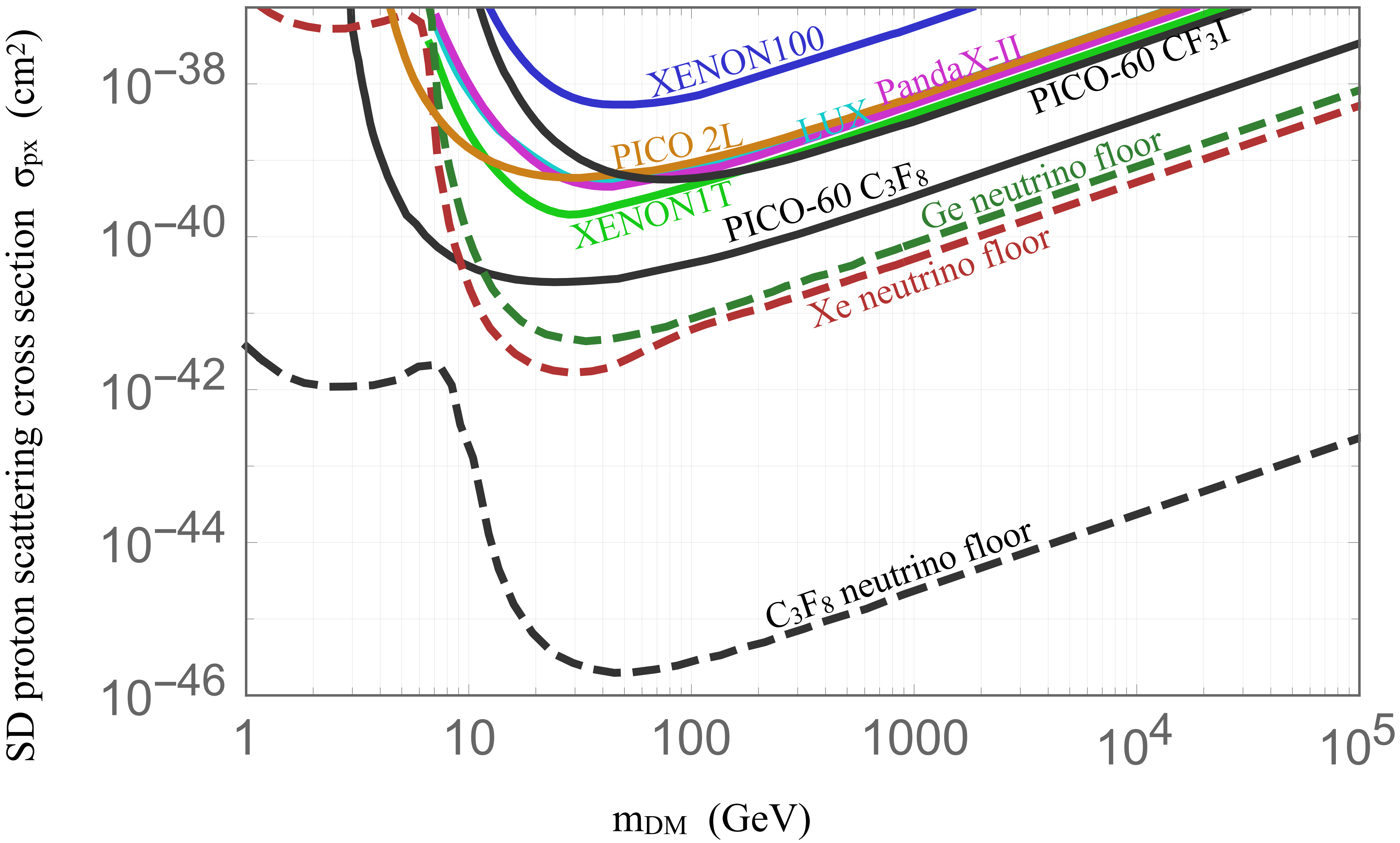
Velocity by earth: ~300 km/s

GeV ~ proton mass

SI

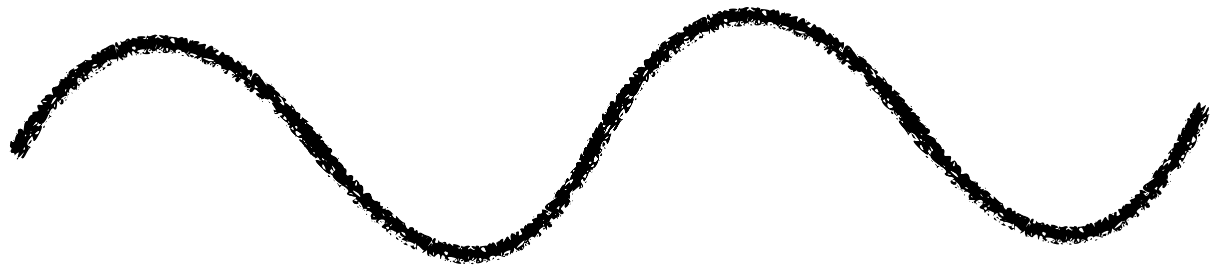


SD

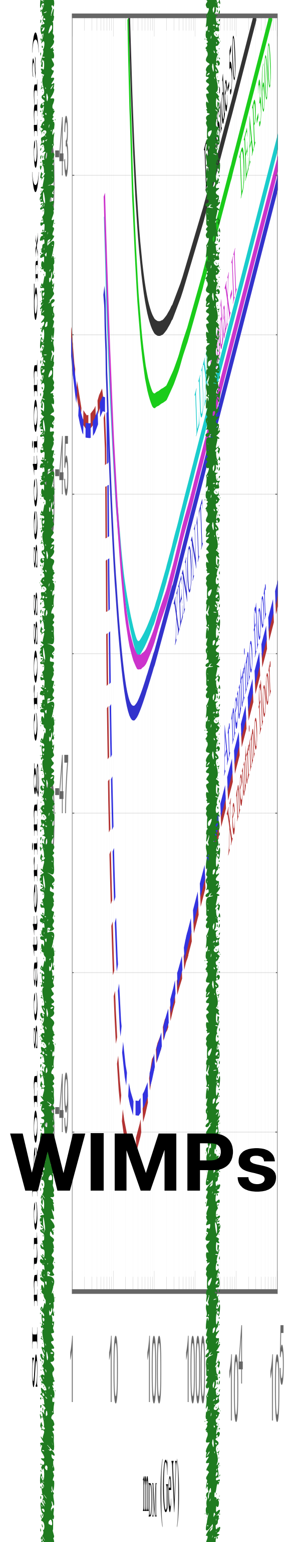


DARK MATTER

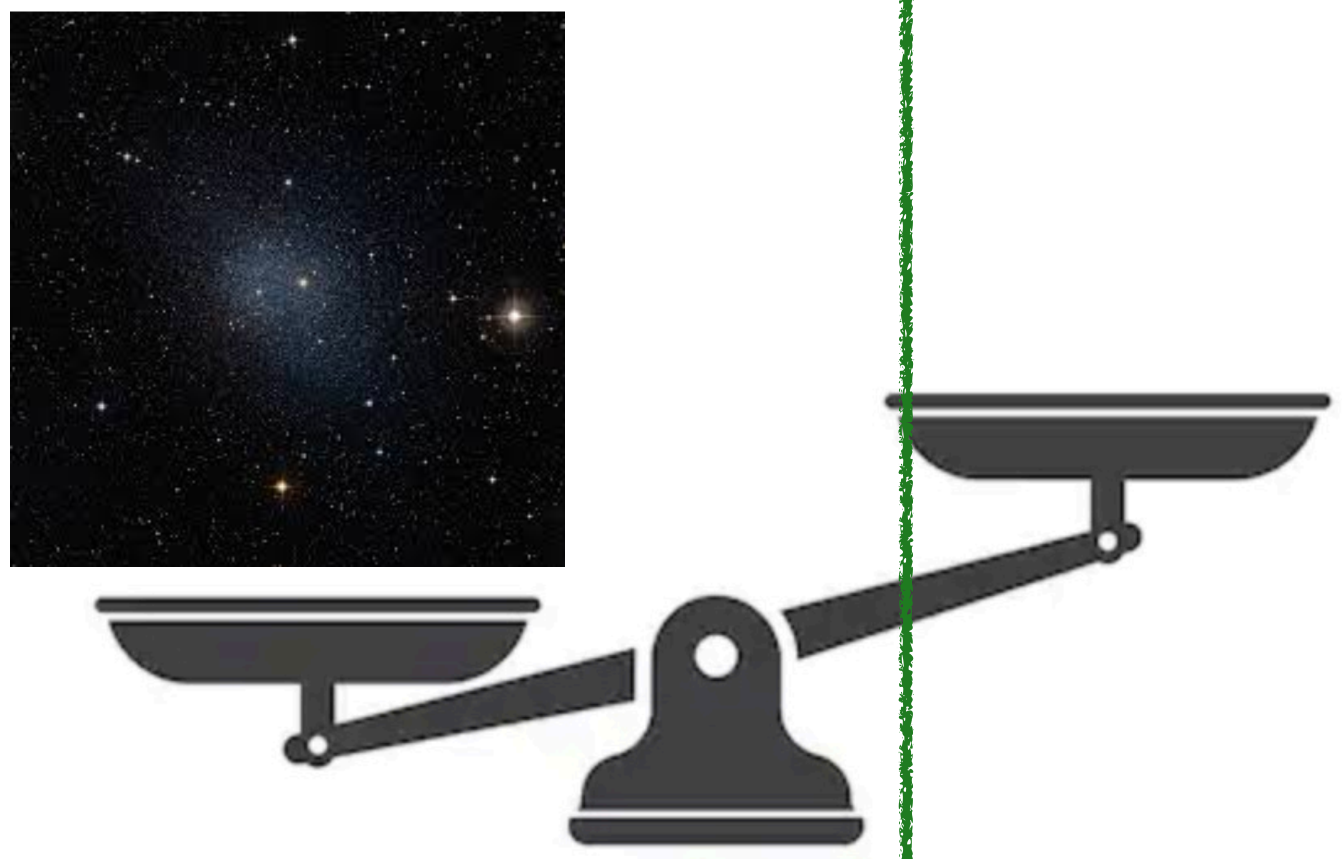
LOW MASS FRONTIER



de Broglie length = size of dwarf galaxy



HIGH MASS FRONTIER



Mass of Smallest Galactic Halos

10^{-30} 10^{-20} 10^{-10} 10^{0} 10^{10} 10^{20} 10^{30} 10^{40} 10^{50} 10^{60}

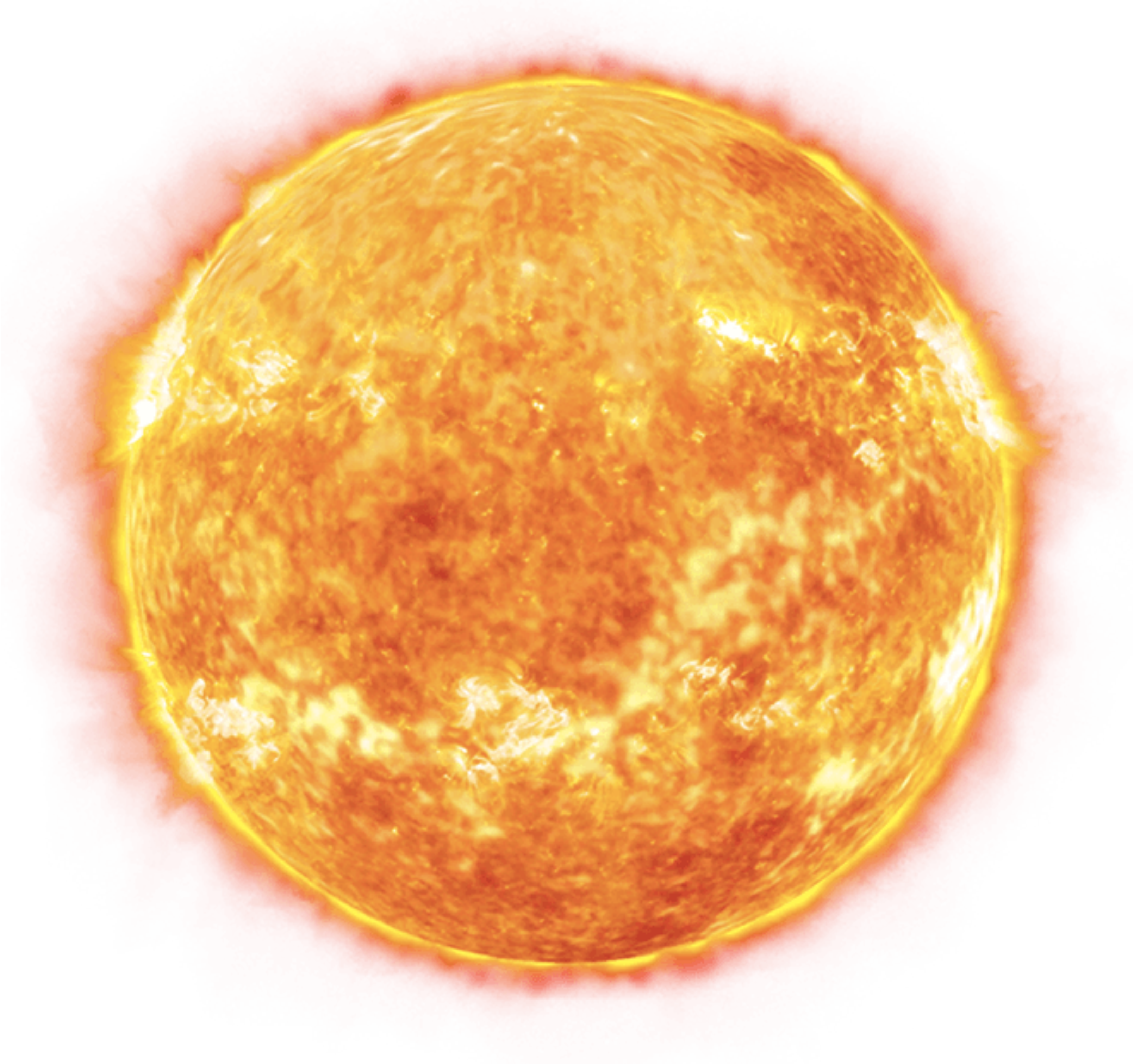
m_x (GeV)

NEW THINGS WE KNOW ABOUT DARK MATTER

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

★ Grad Students At Queen's University

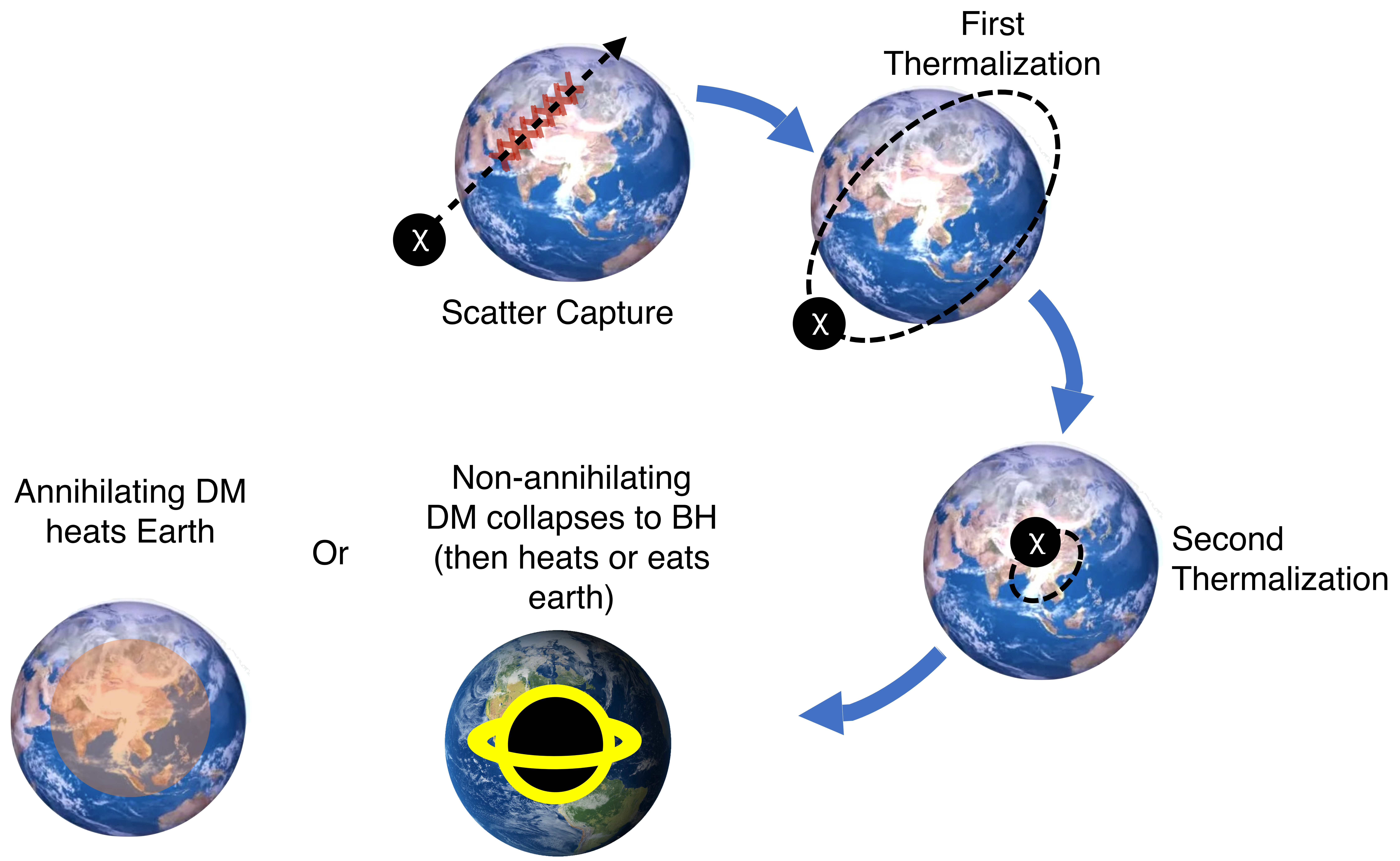
Stars and Planets As Dark Matter Detectors



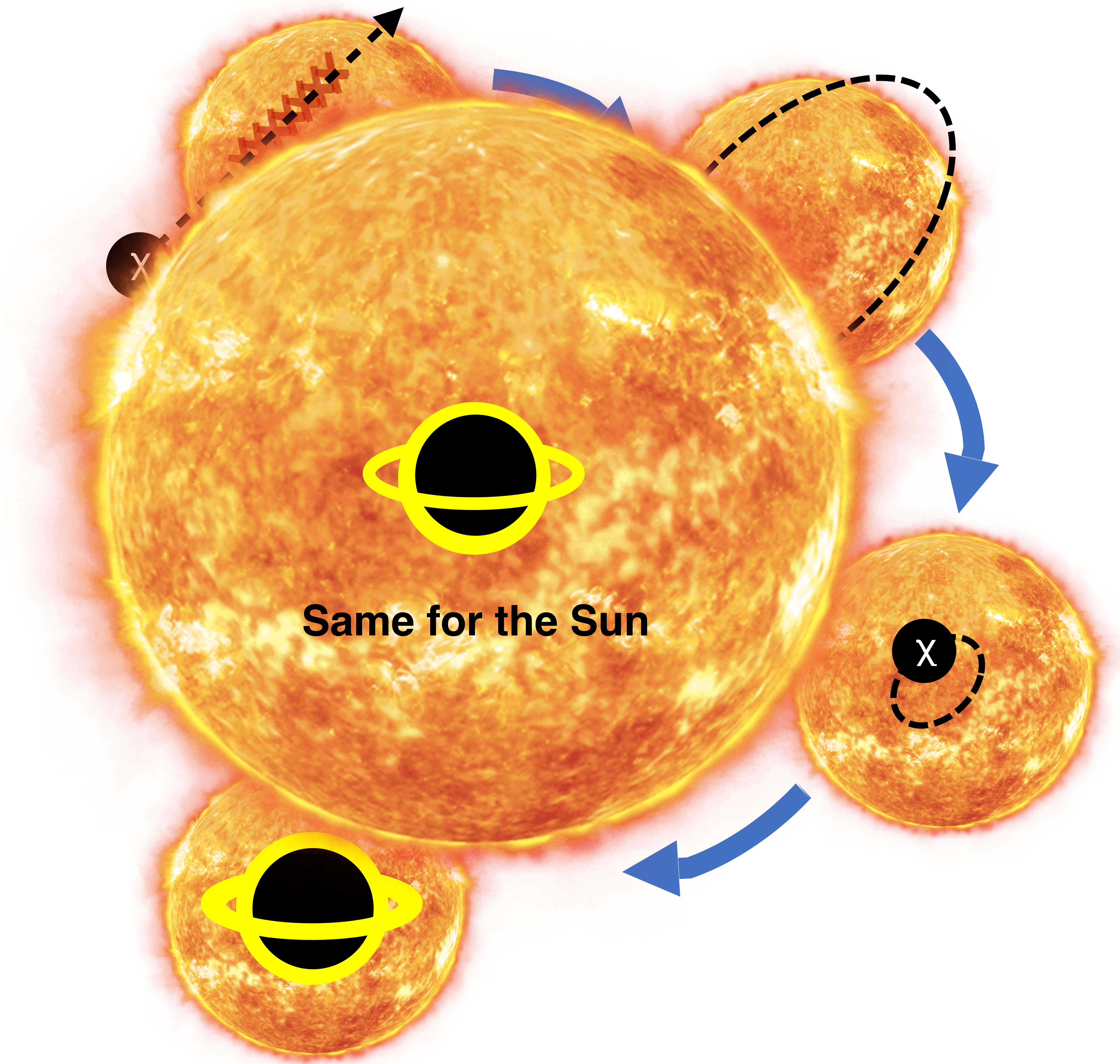
1909.11683
2012.09176
1405.1031
1904.11993
1505.07464

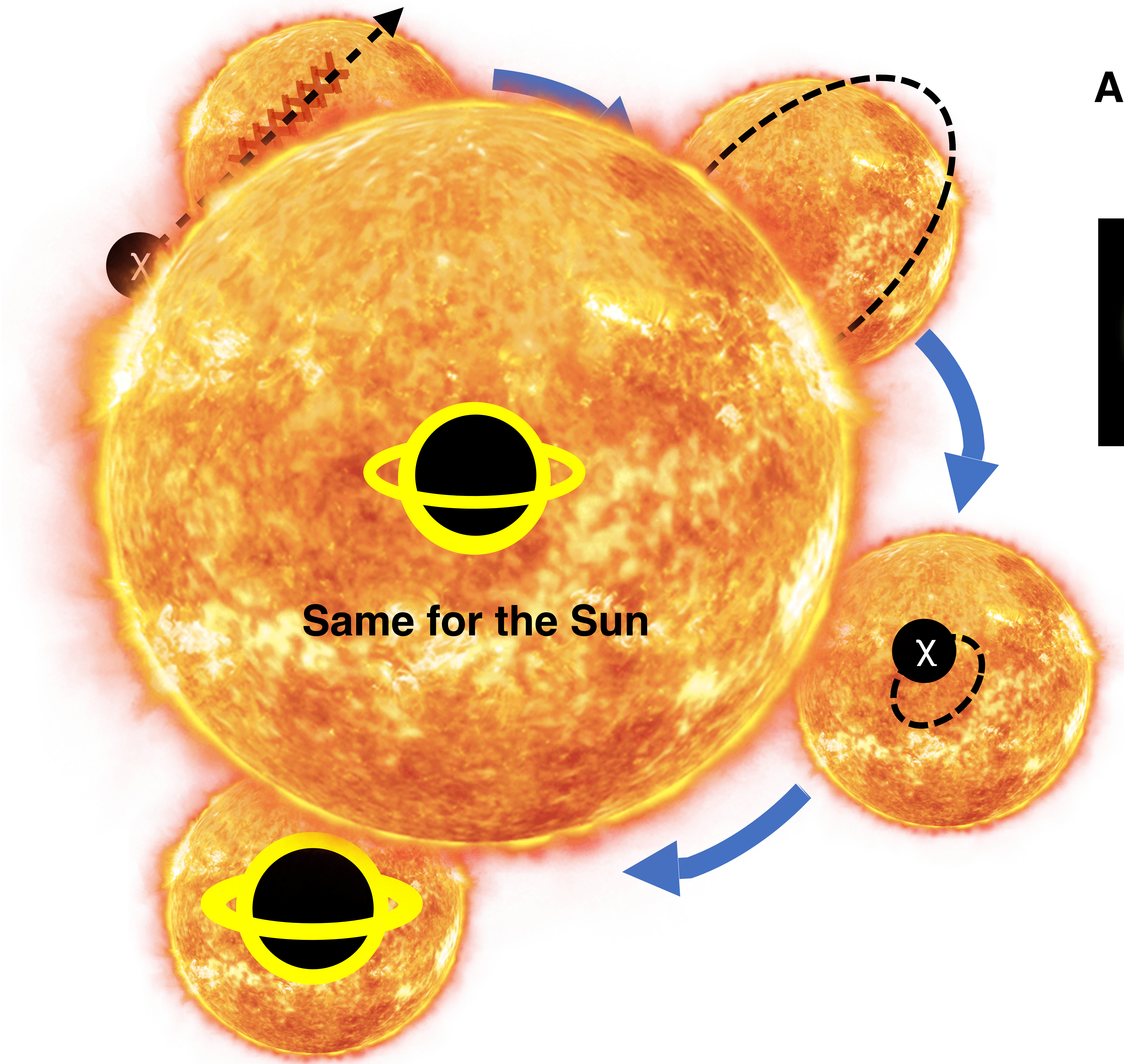
Javier Acevedo

Alan Goodman

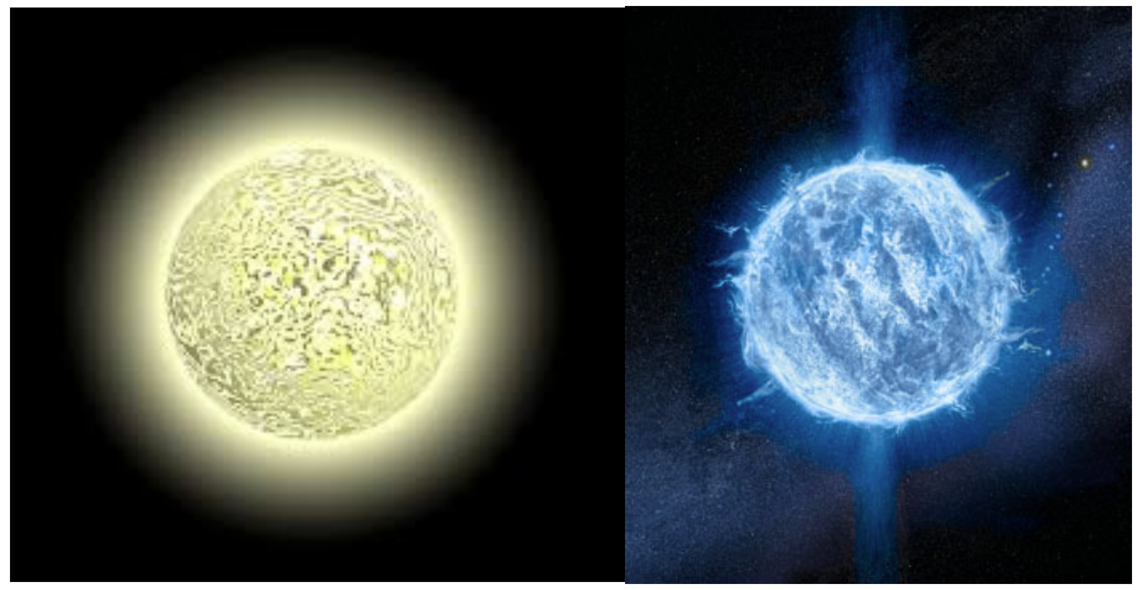


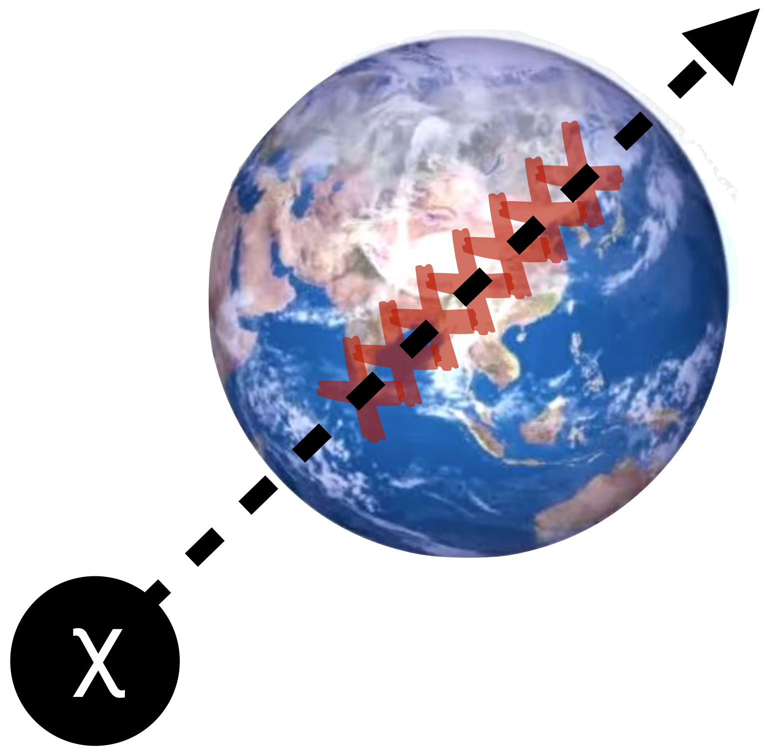
X
Scatter Capture
First Thermalization
X
X
Second Thermalization
Annihilating DM heats Earth
Or
Non-annihilating DM collapses to BH (then heats or eats earth)


X
X
Same for the Sun



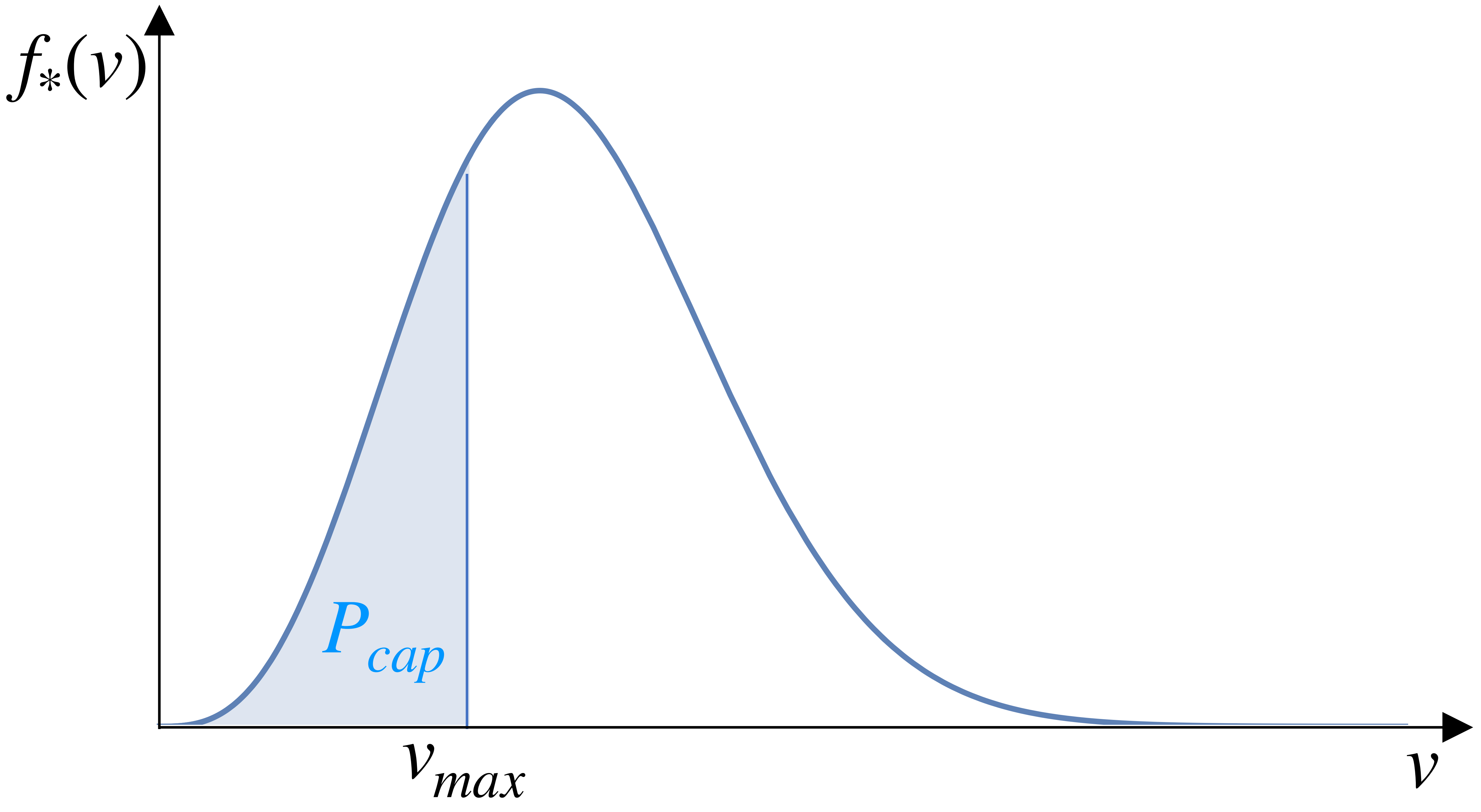
And White Dwarfs and Neutron stars





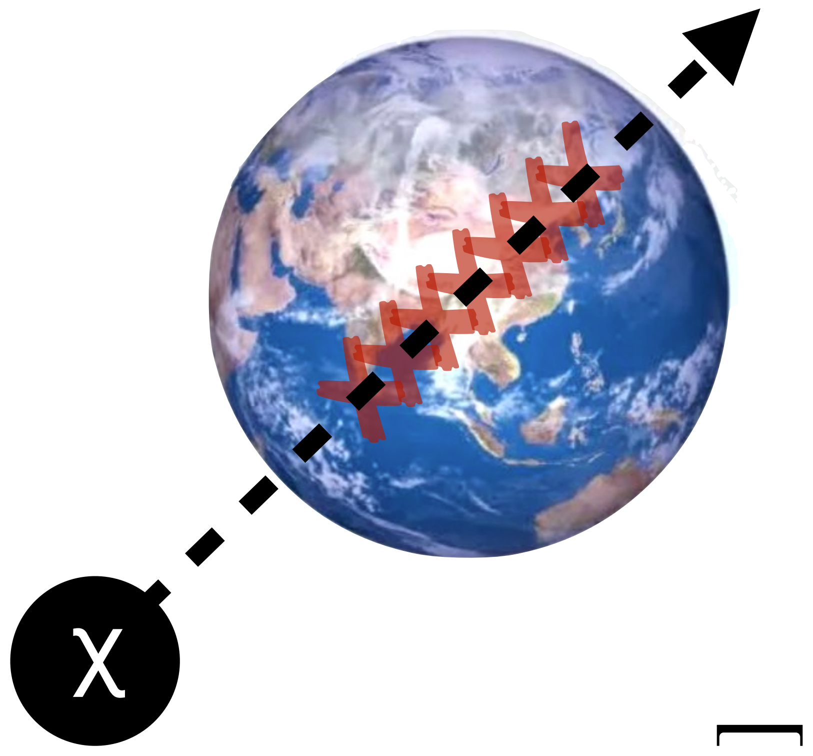
Scatter Capture

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

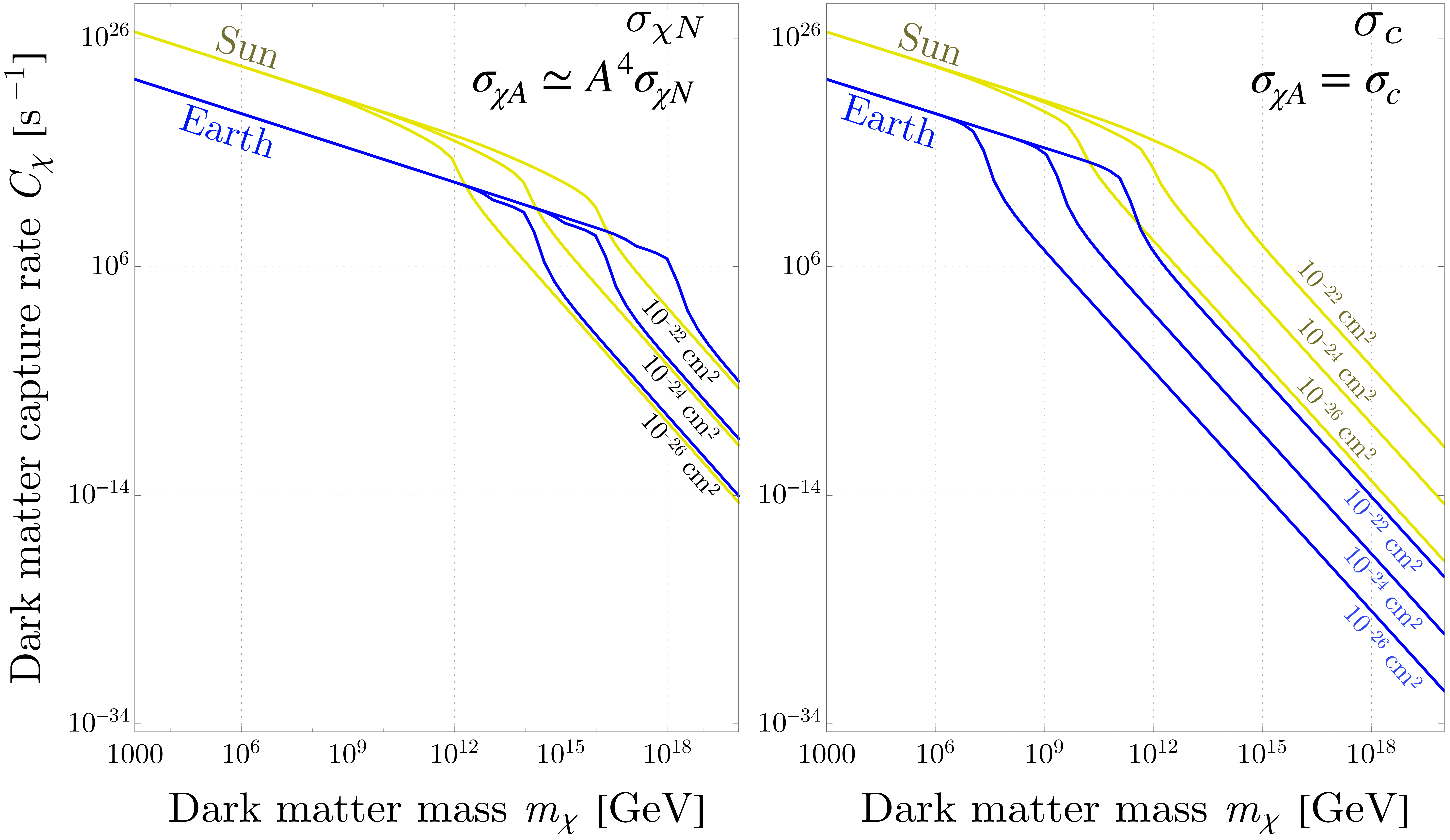


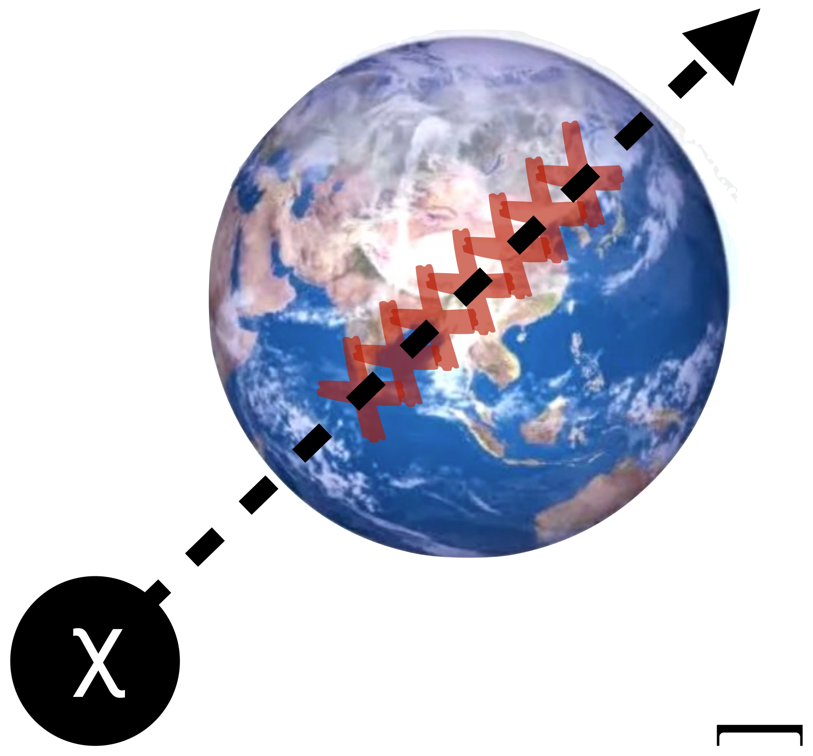
$$f_*(v) \sim \int_{-1}^{1} \mathrm{d}\cos\phi\, \left(v^2 - v_e^2\right)^{3/2} \exp\left(-\frac{\tilde{v}^2}{v_0^2}\right)\, \Theta(v - v_e)\, \Theta(v_{eg} - \tilde{v})$$

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



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

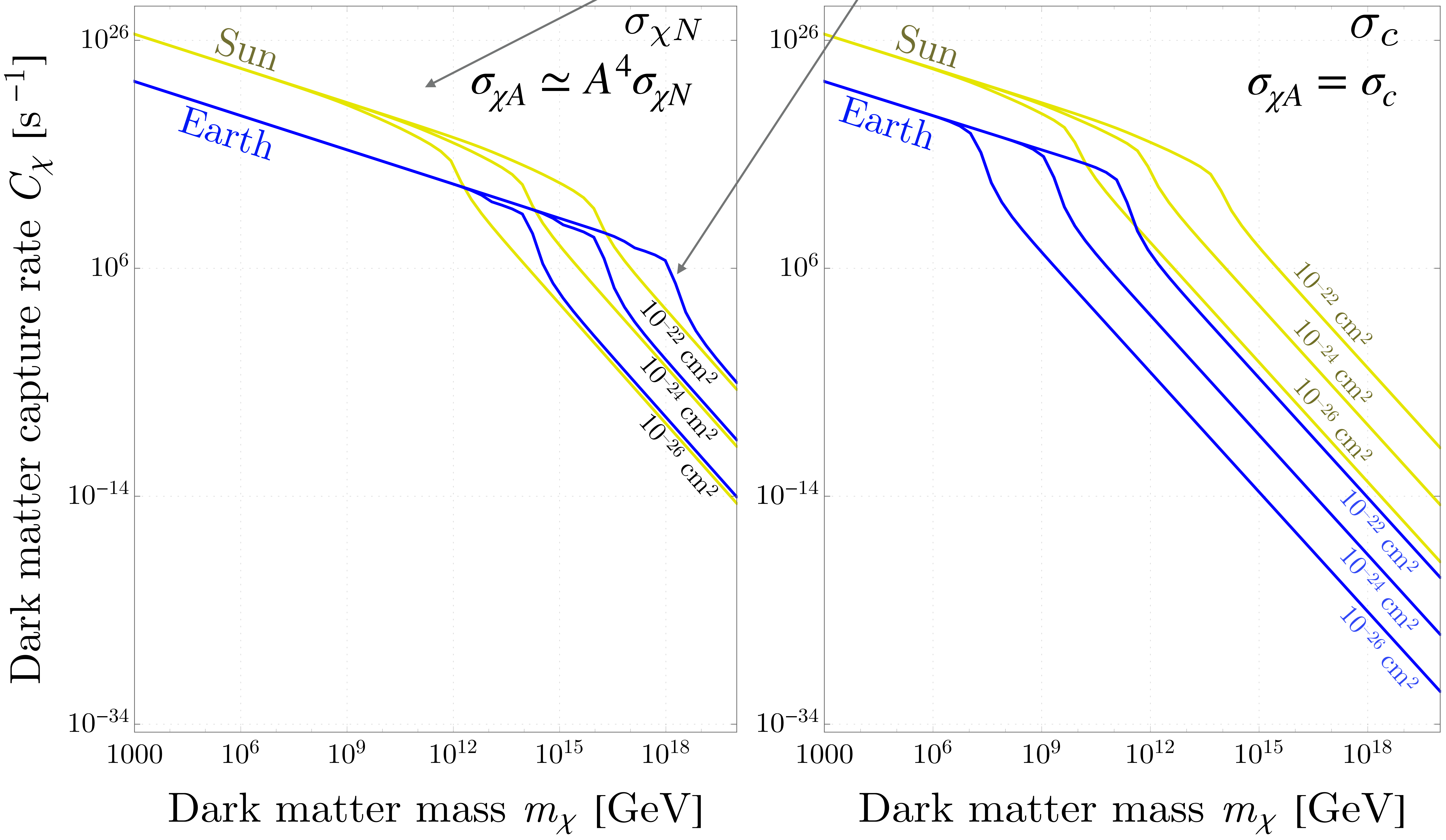




Single Scatter Capture

Multi Scatter Capture

Capture on core / low velocity MB tail



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

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

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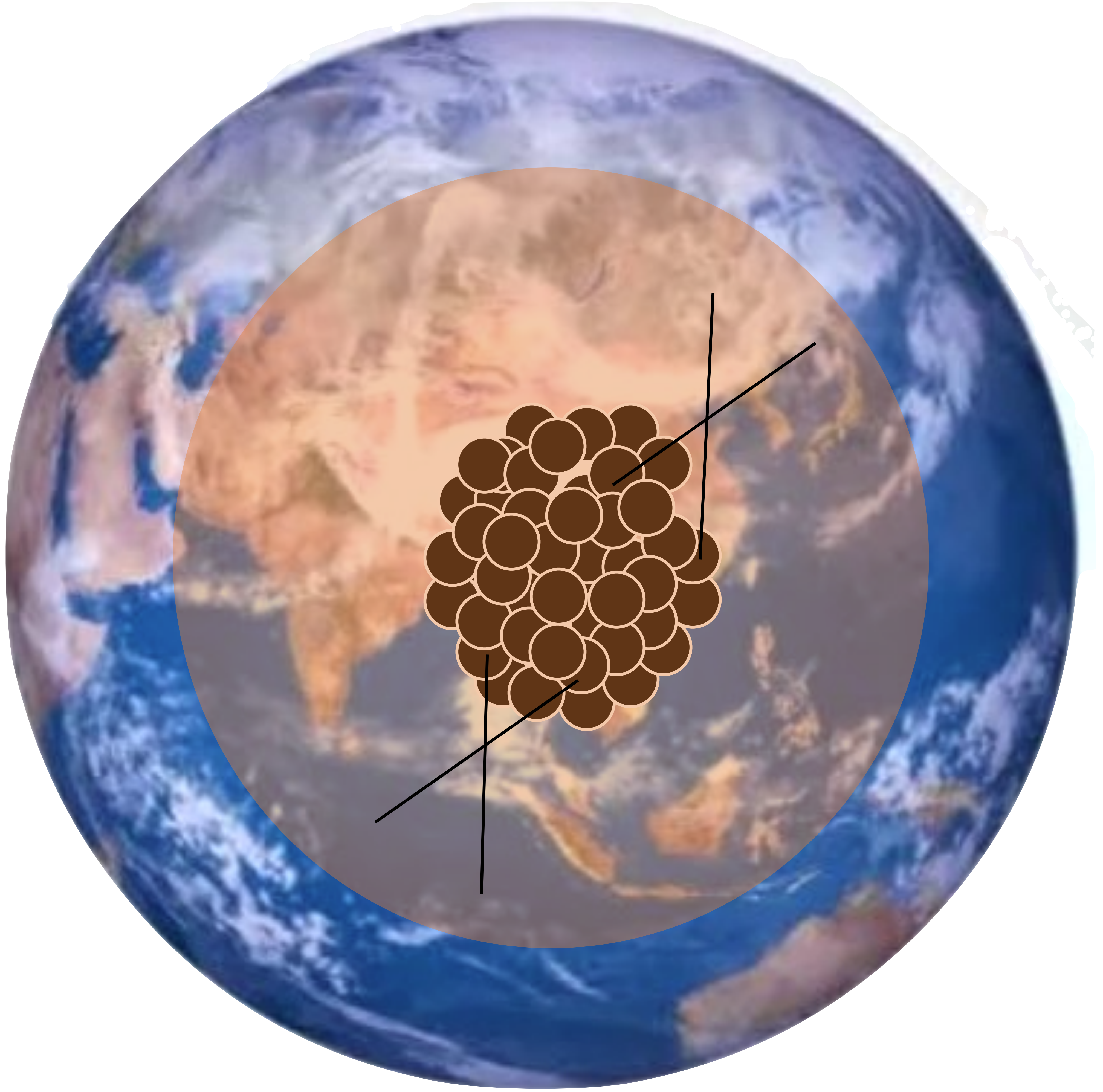
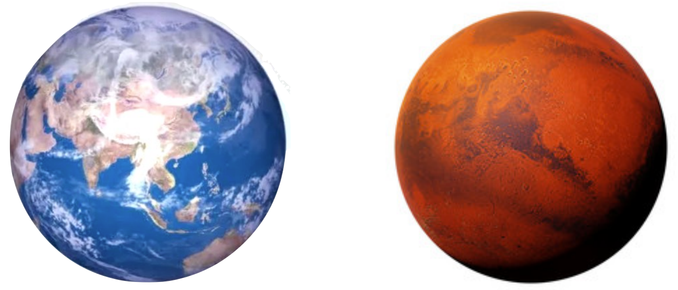
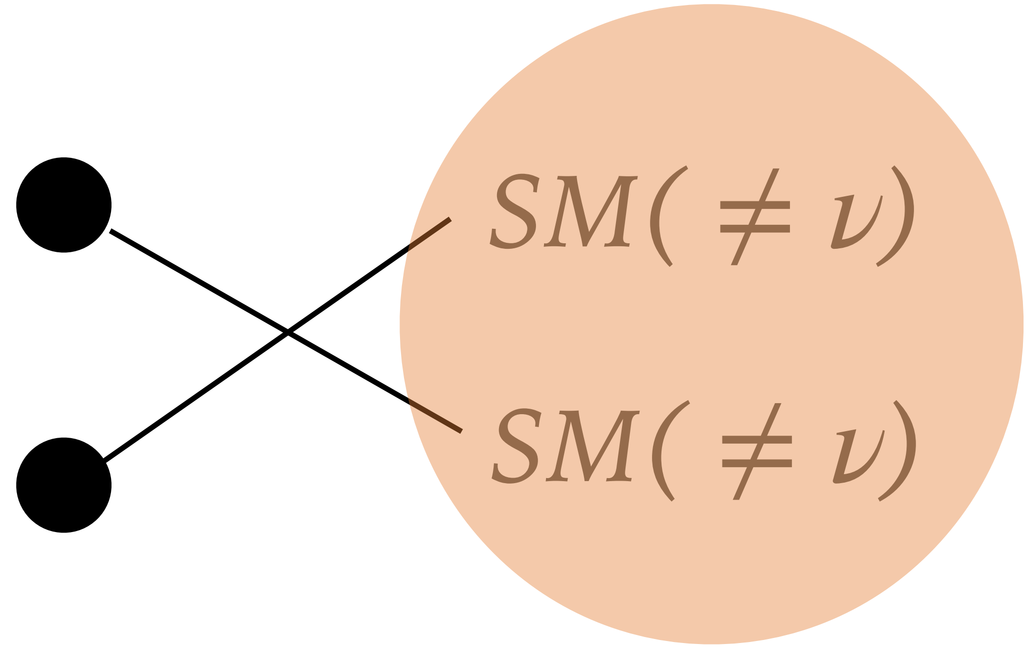
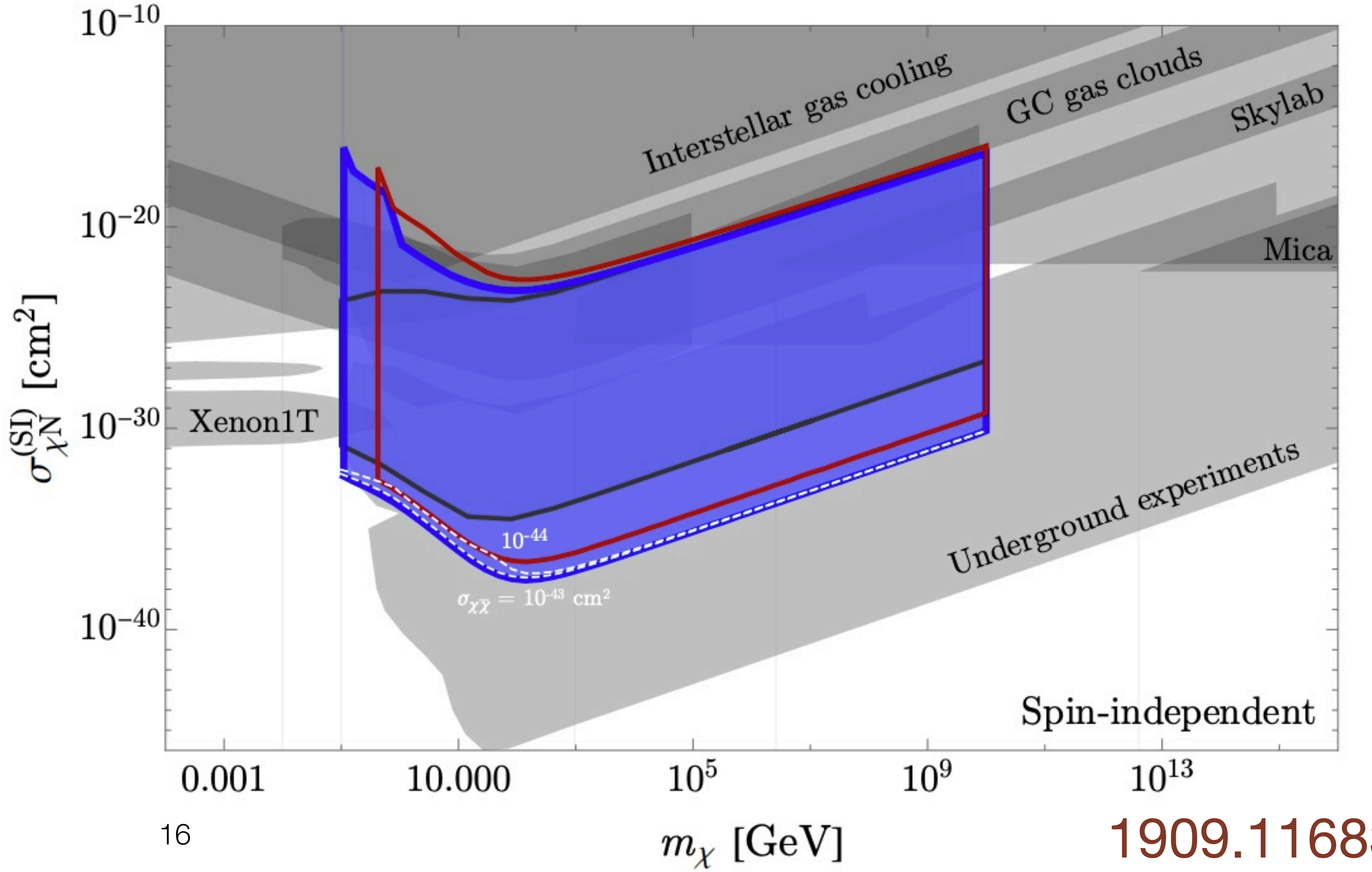


If they annihilate:
Earth/Martian heating!







1909.11683

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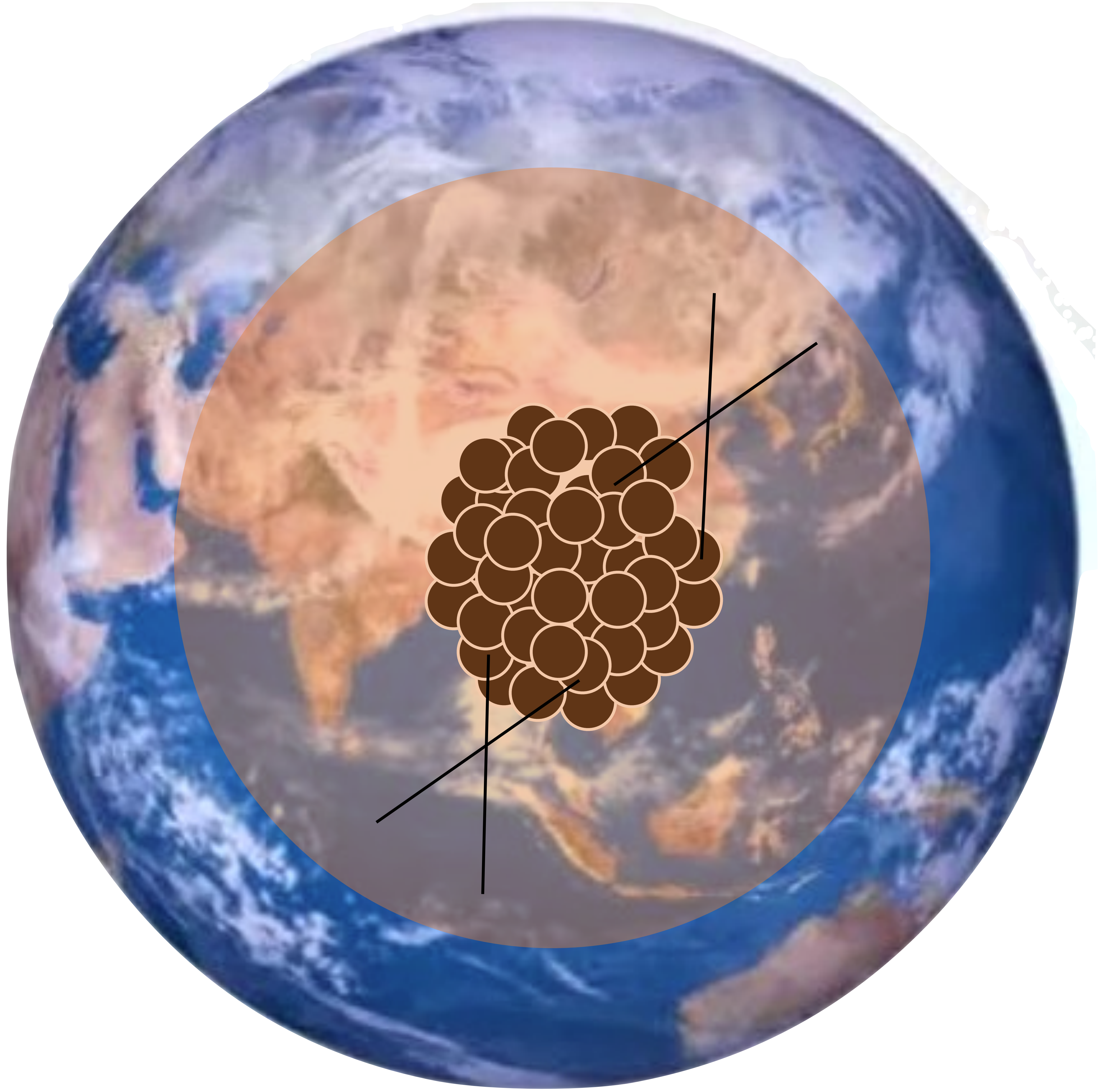

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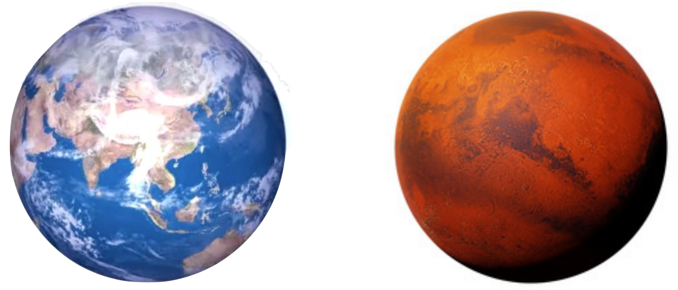

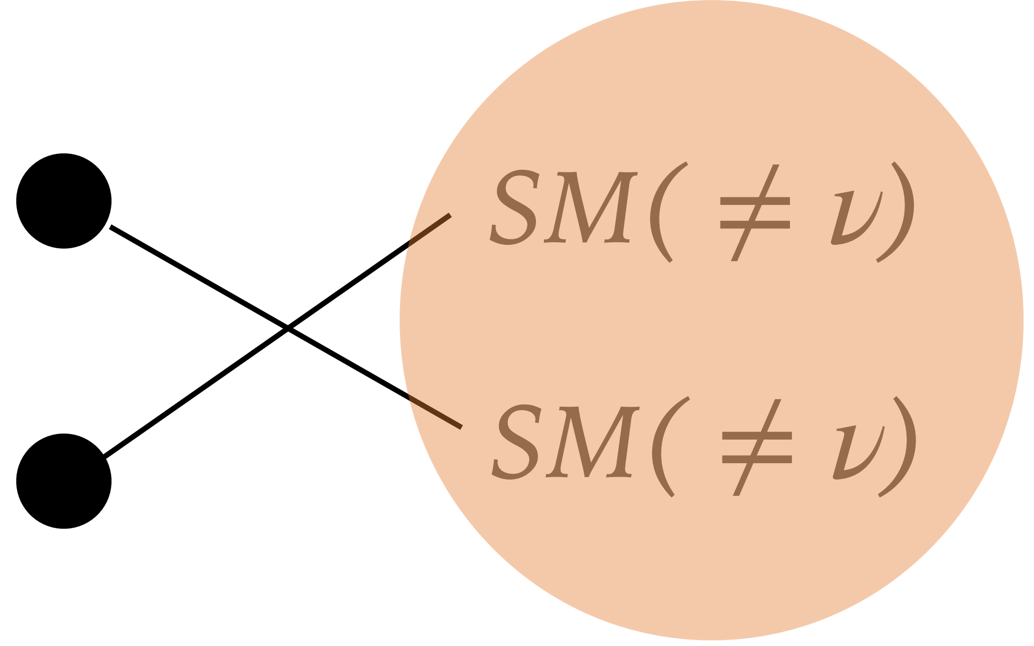

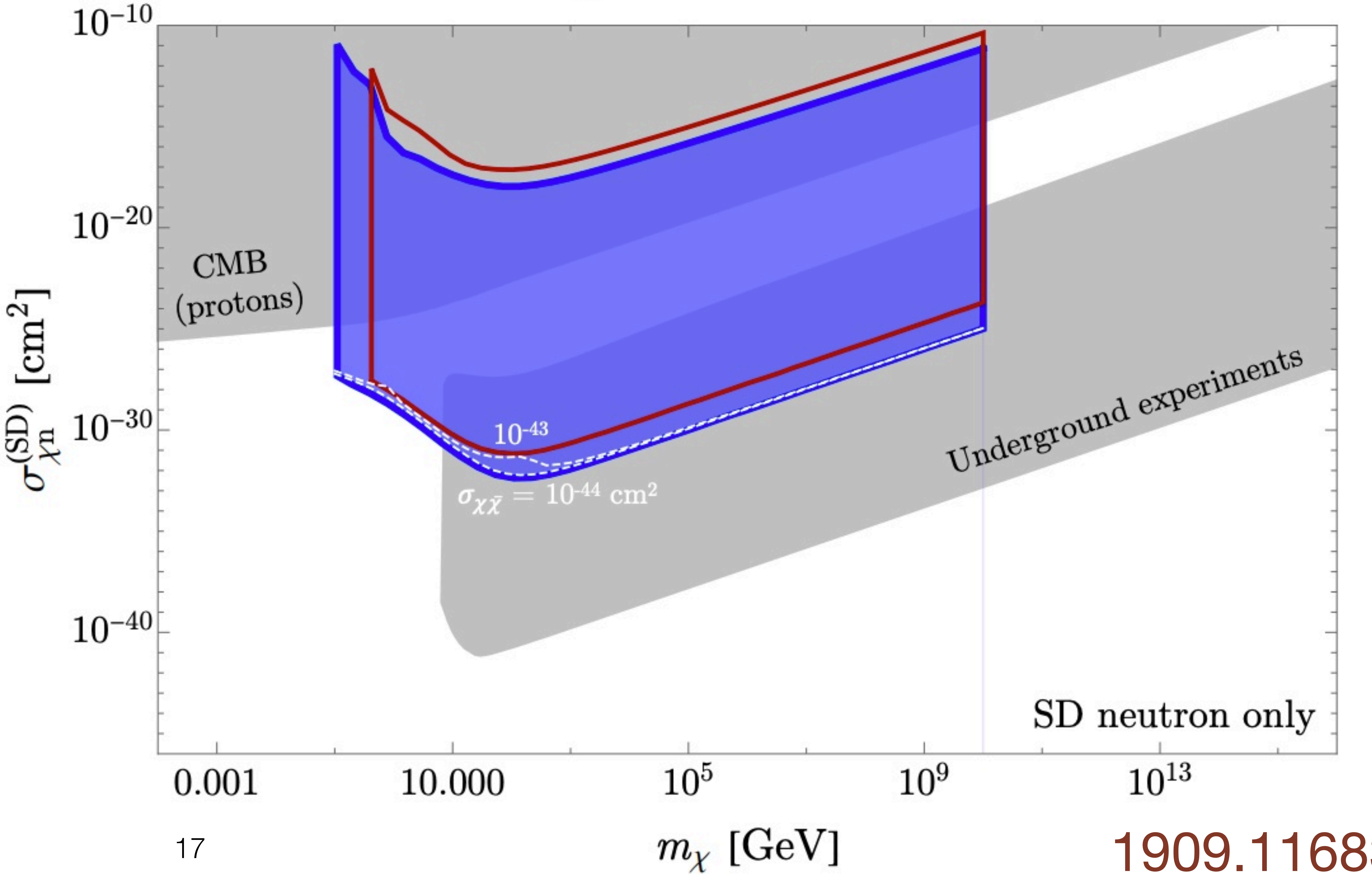

1909.11683

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

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

$SM(\neq \nu)$

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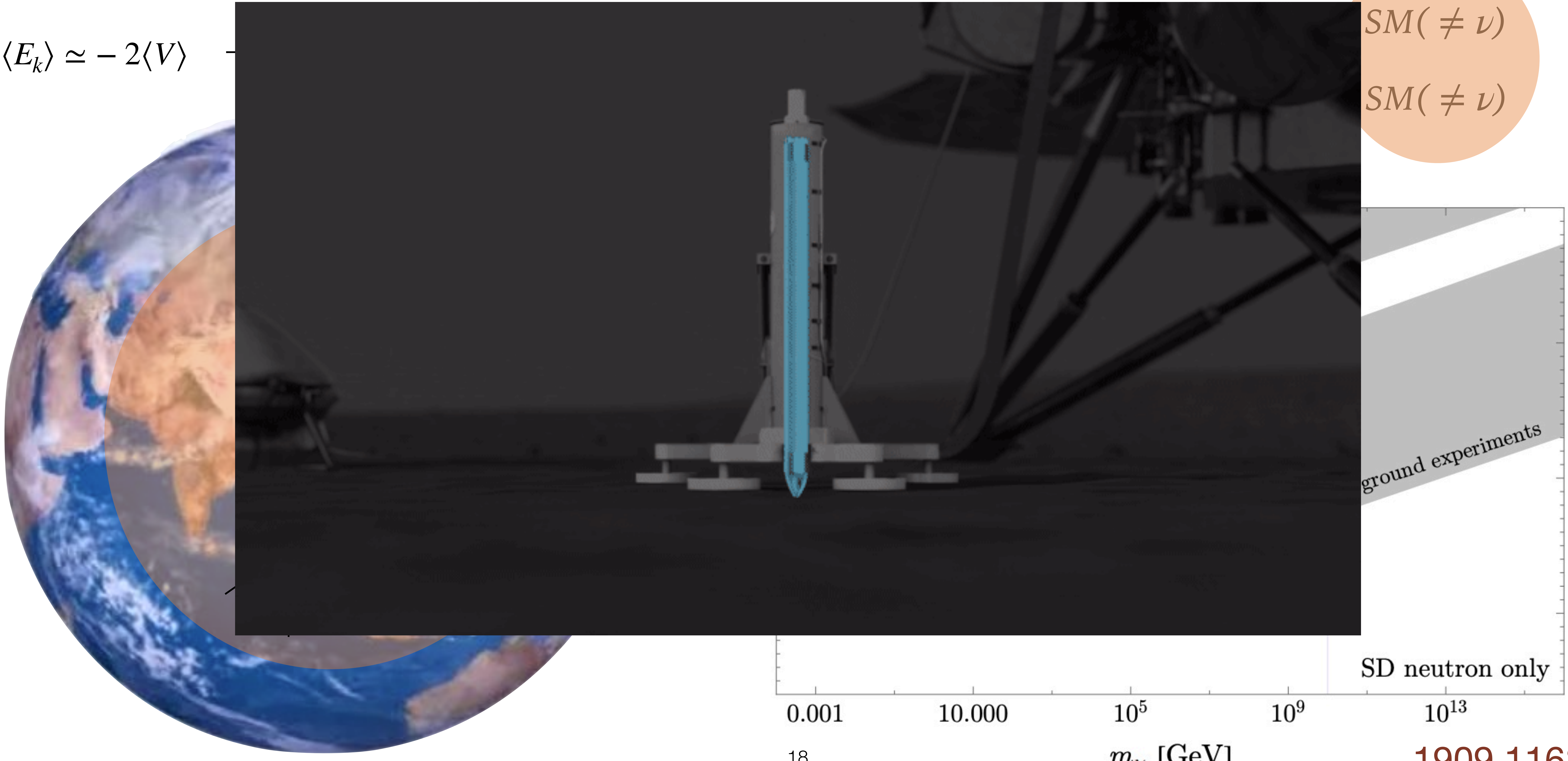

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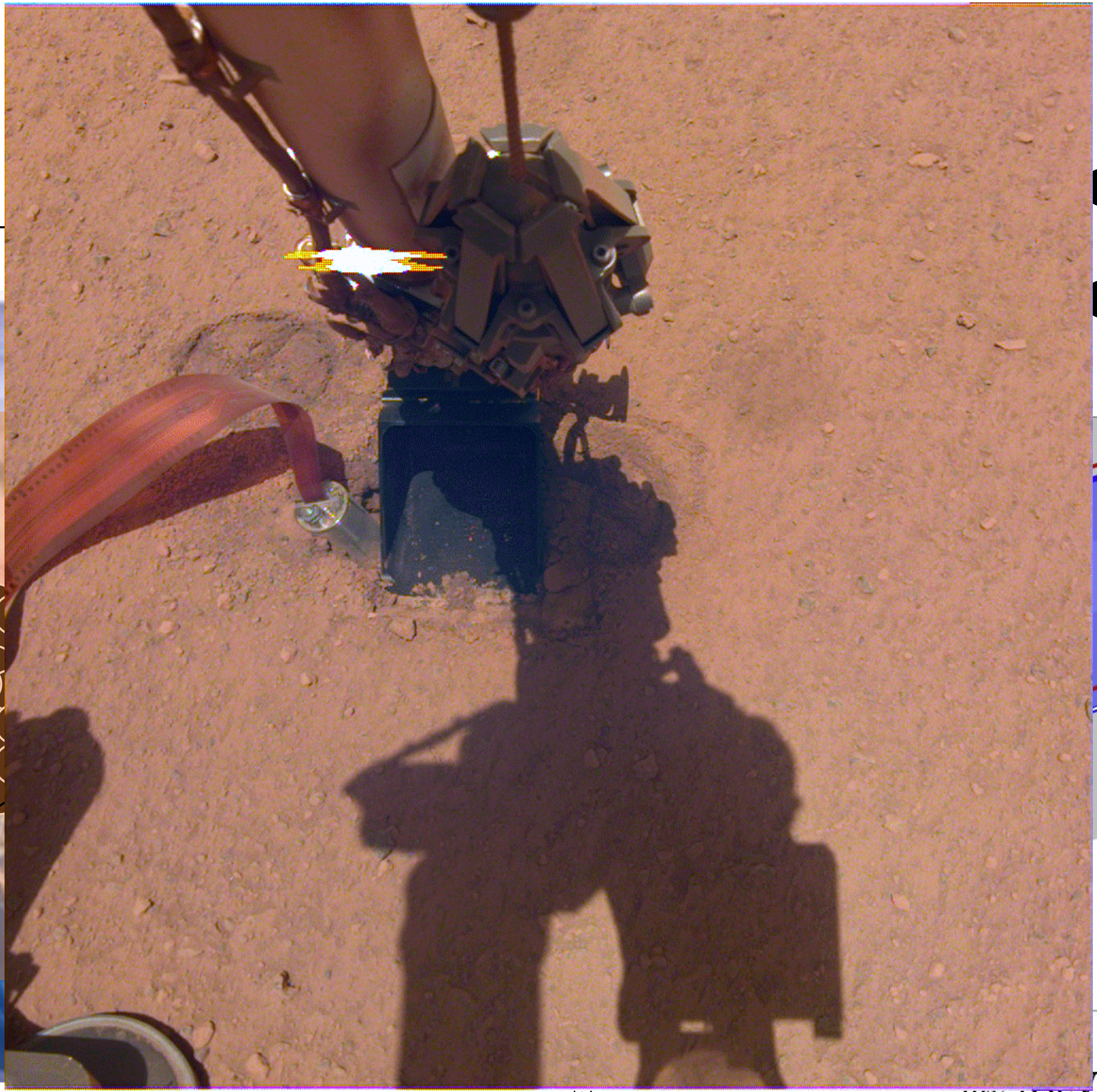

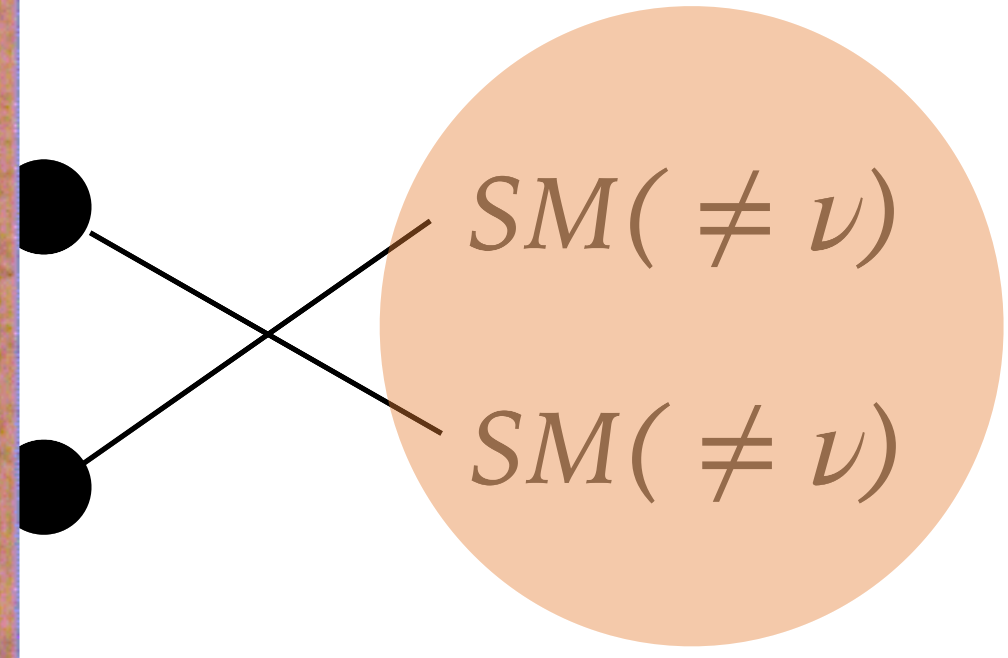

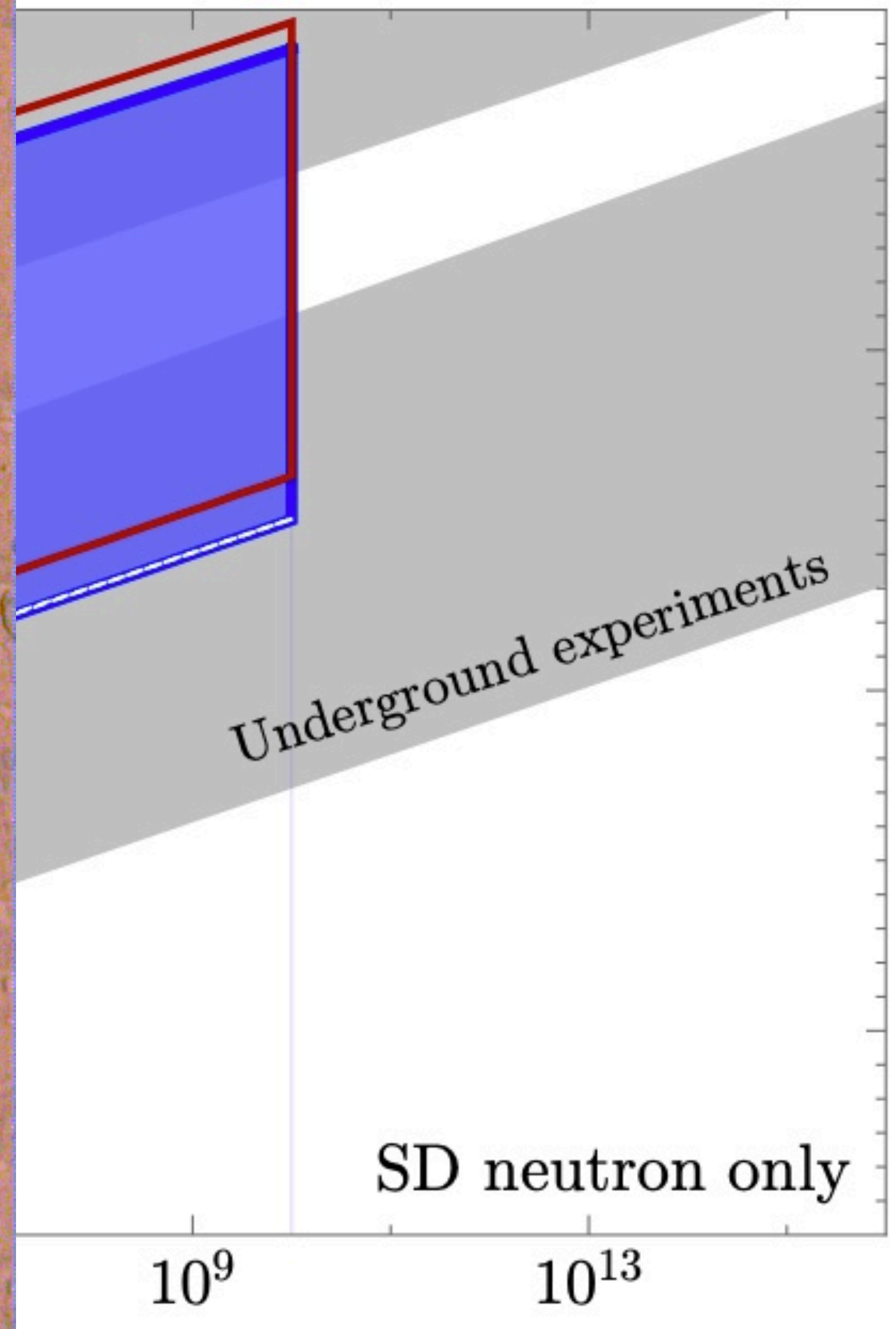

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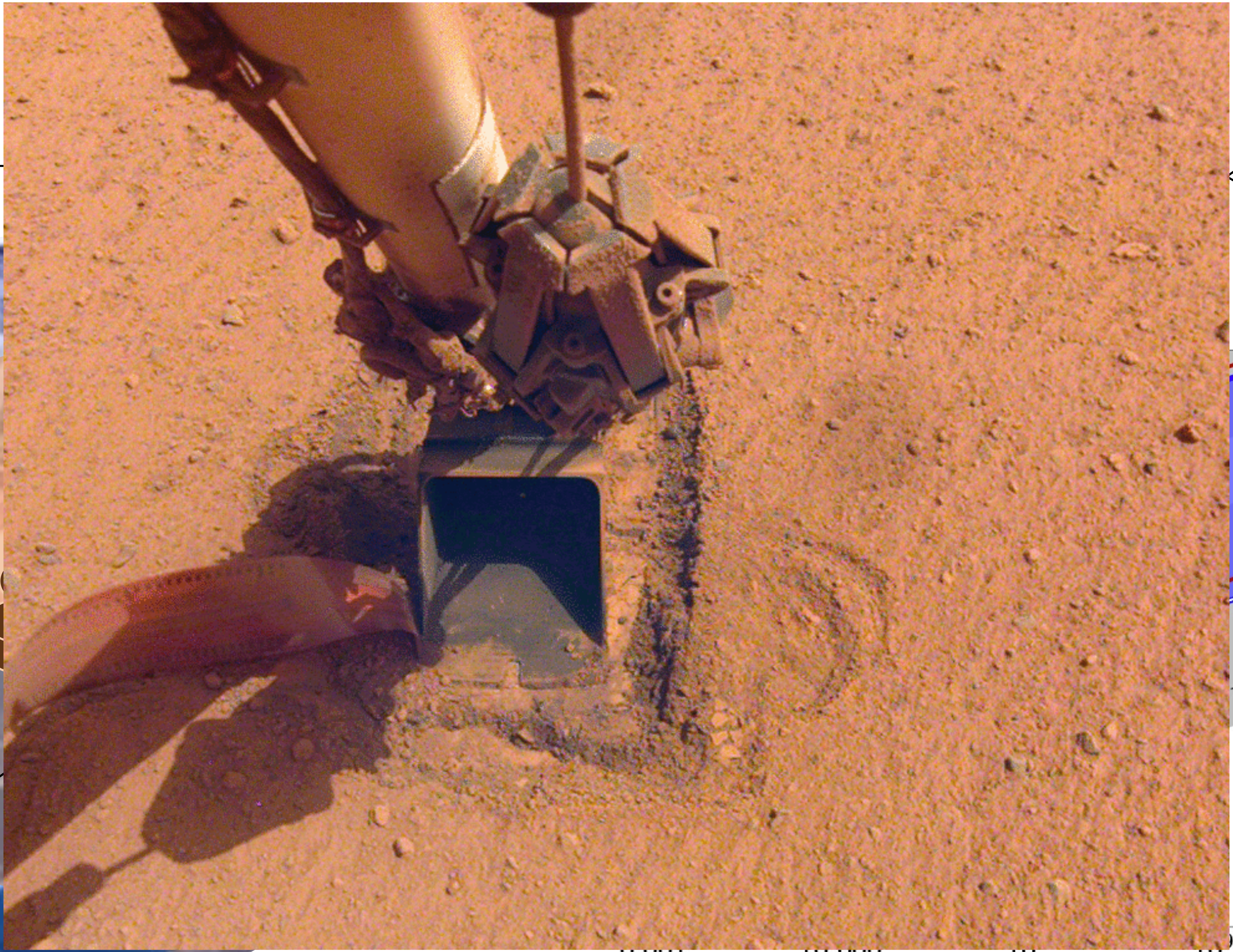

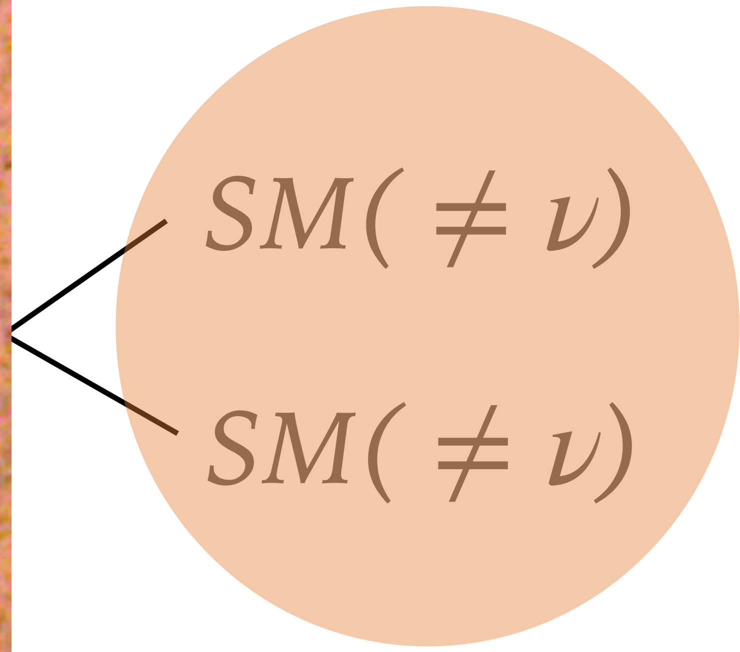

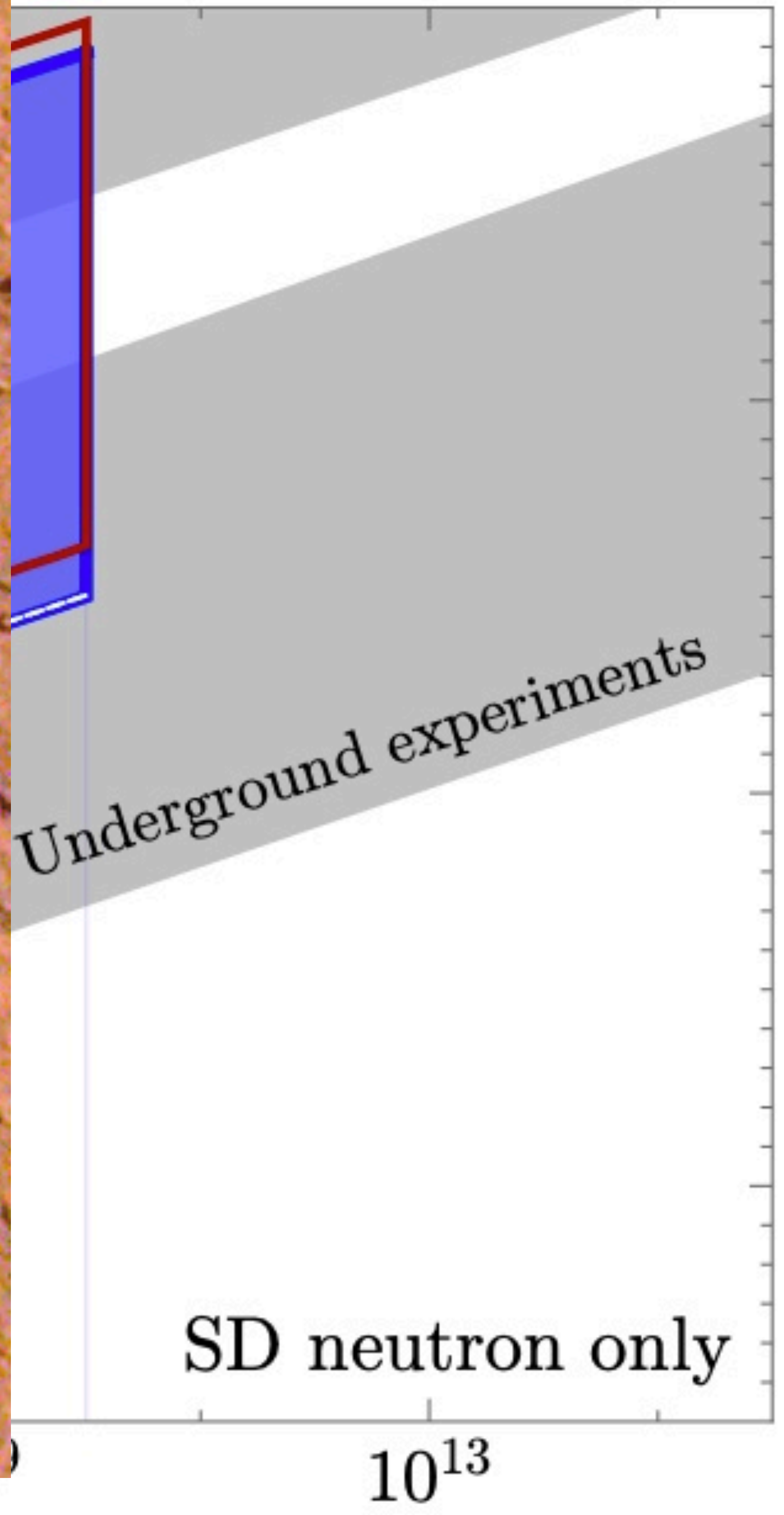

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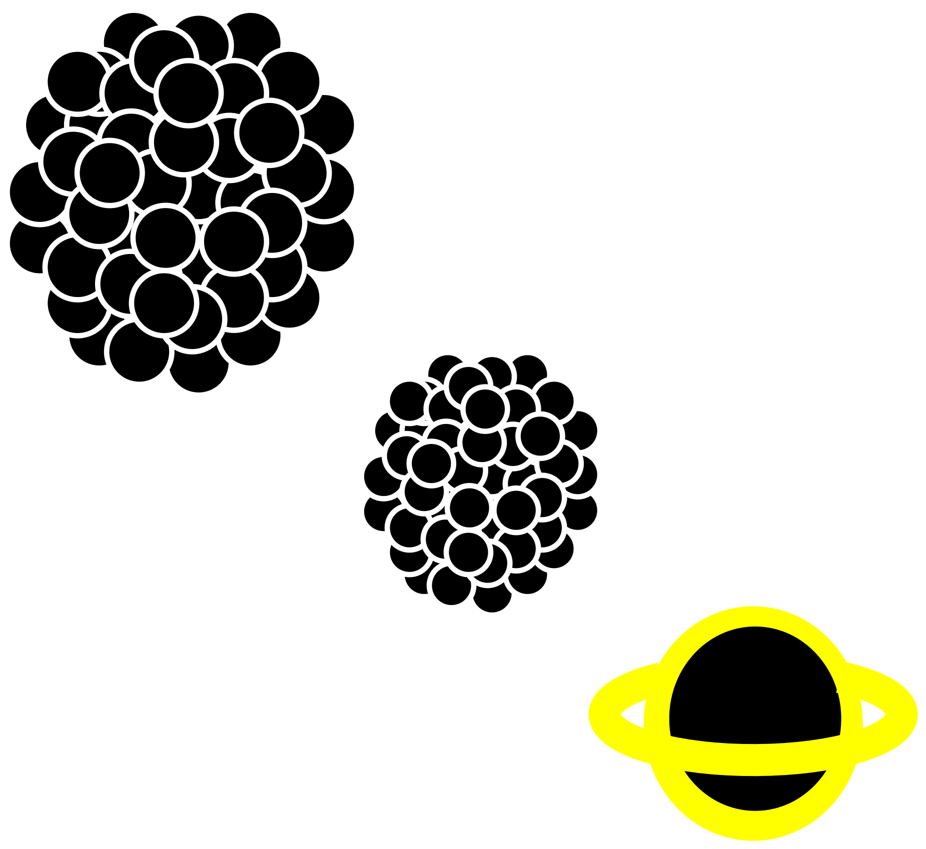
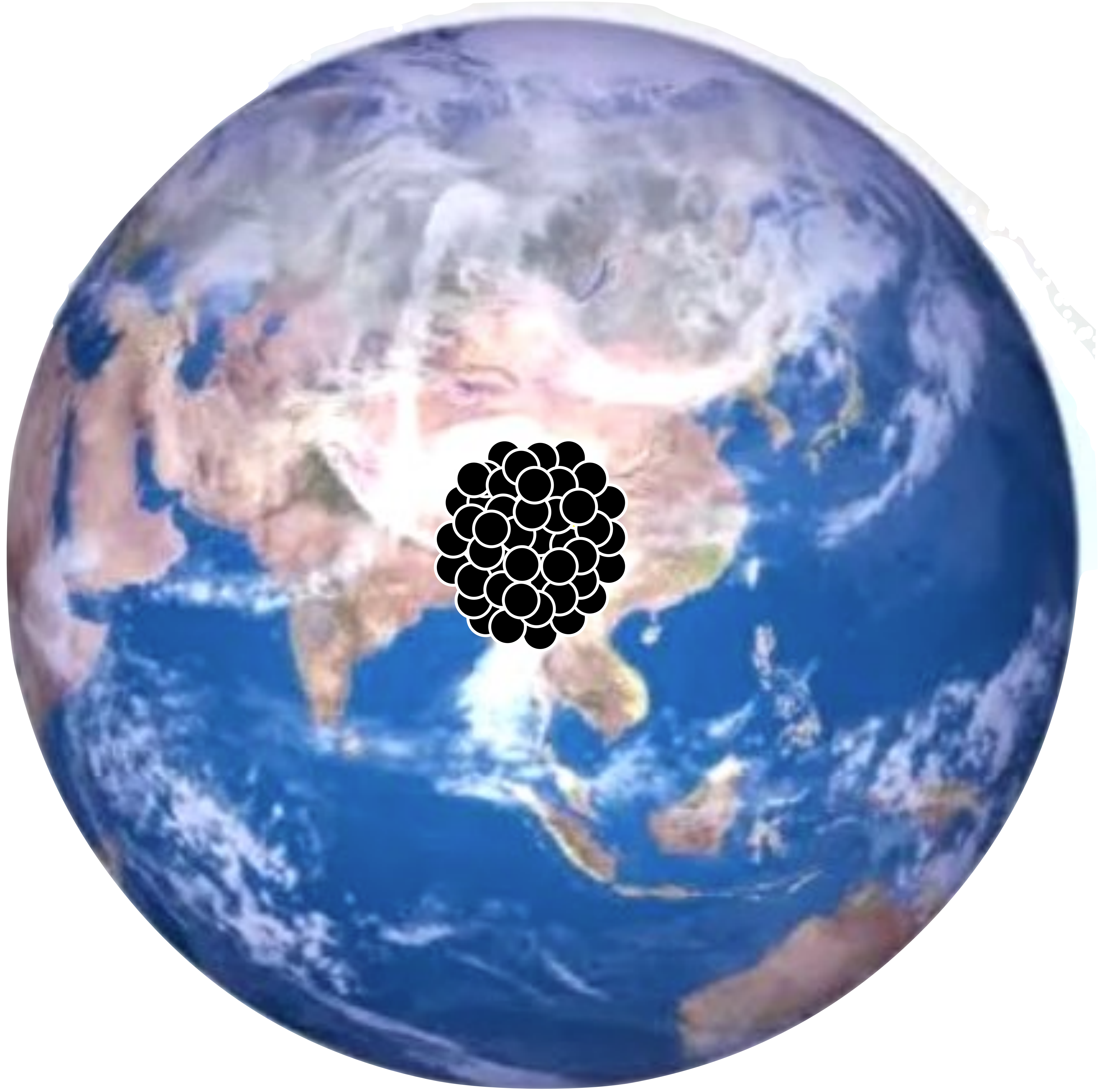
If they don't annihilate: collapse!



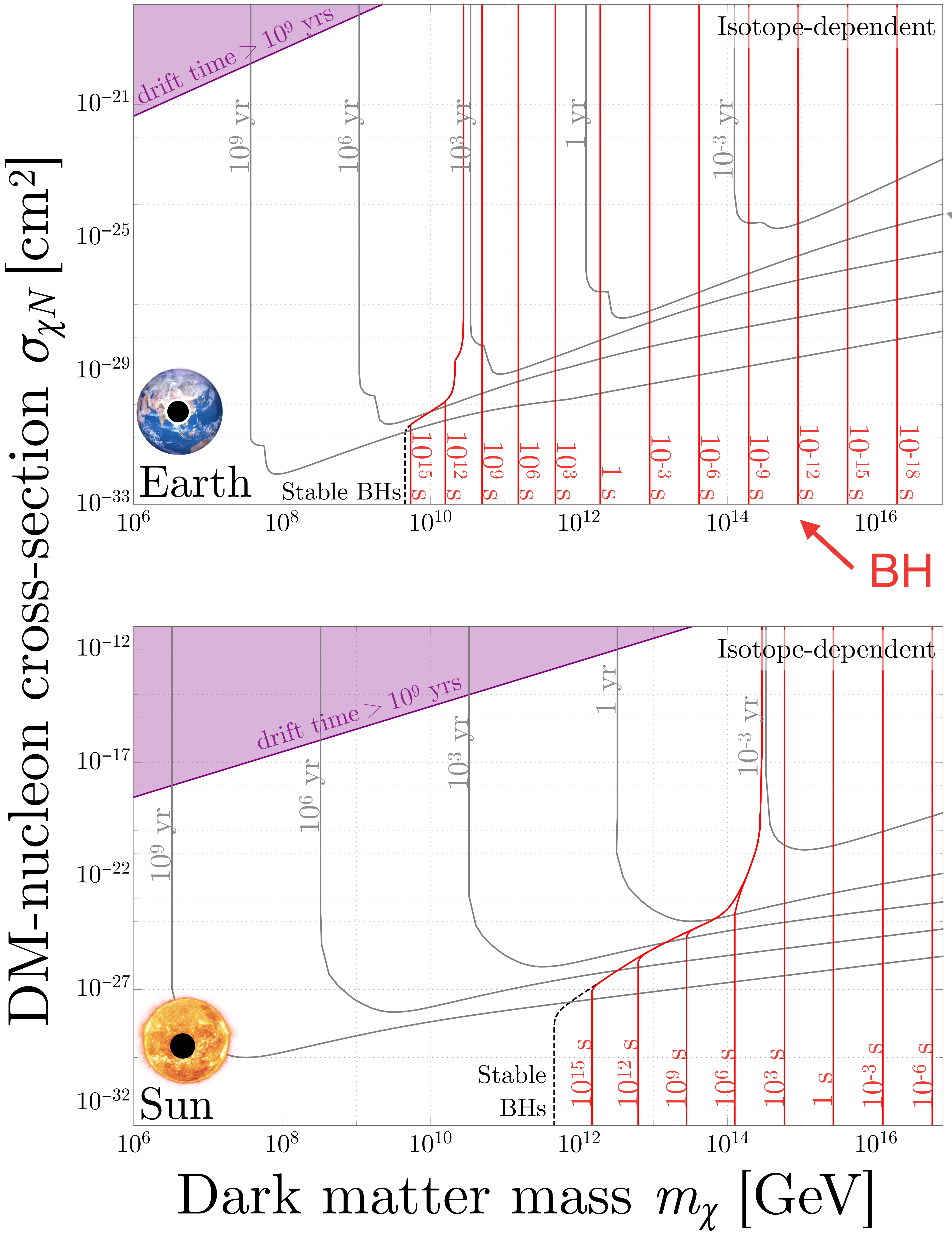


Jeans instability condition: $\rho_\chi \gtrsim \rho_\oplus$

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

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

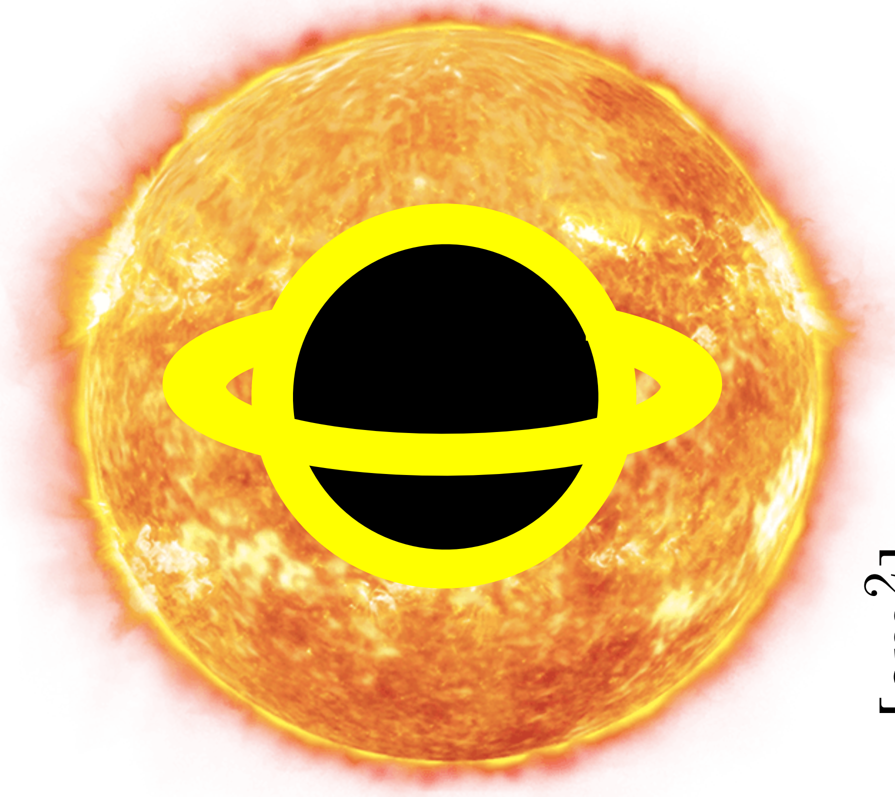
Critical mass for collapse: $M_{crit} = \max(M_f, M_{sg})$

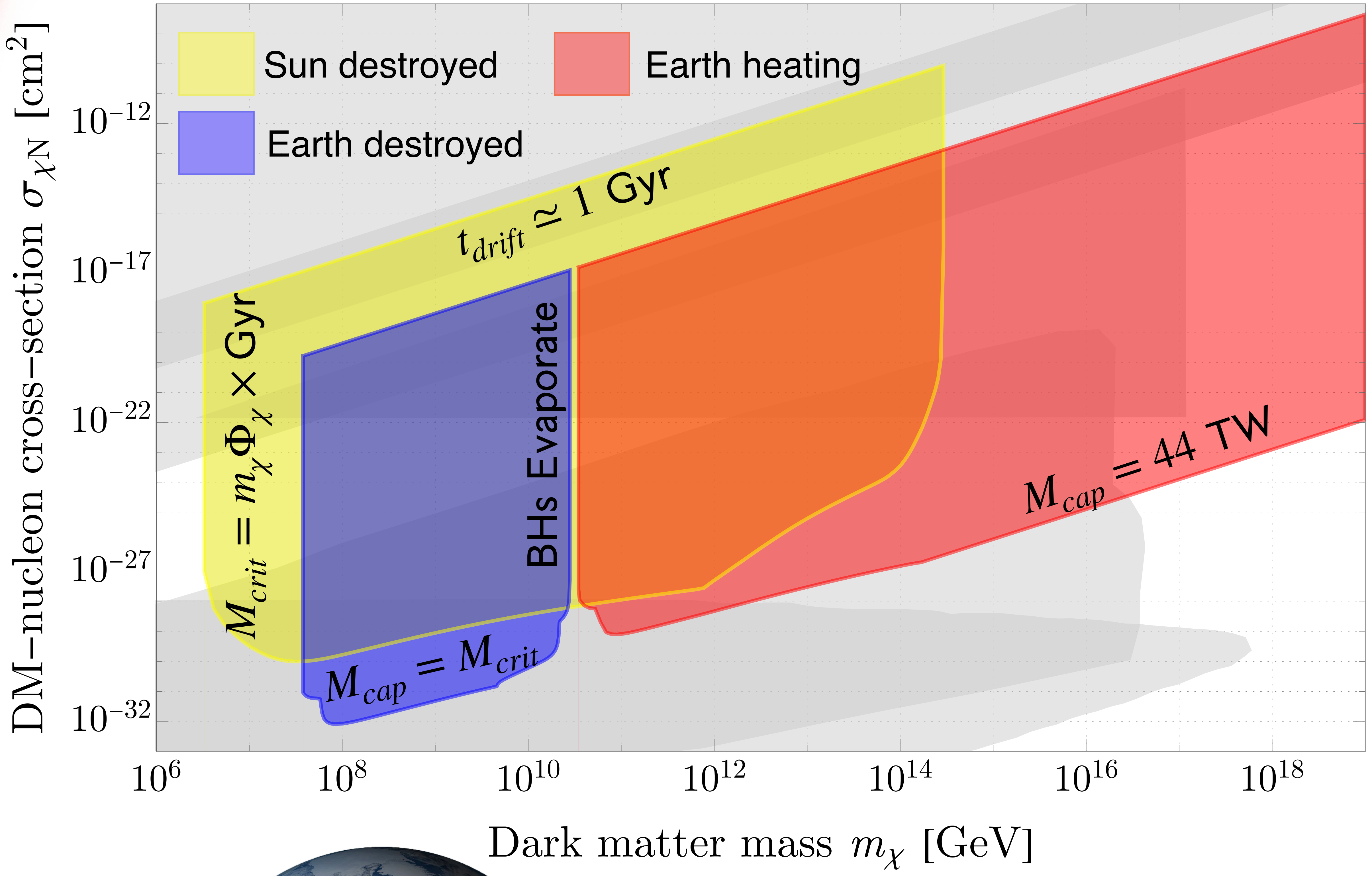


Fermi degeneracy condition: $M_{cap} \gtrsim \frac{M_{pl}^3}{m_\chi^2} = M_f$

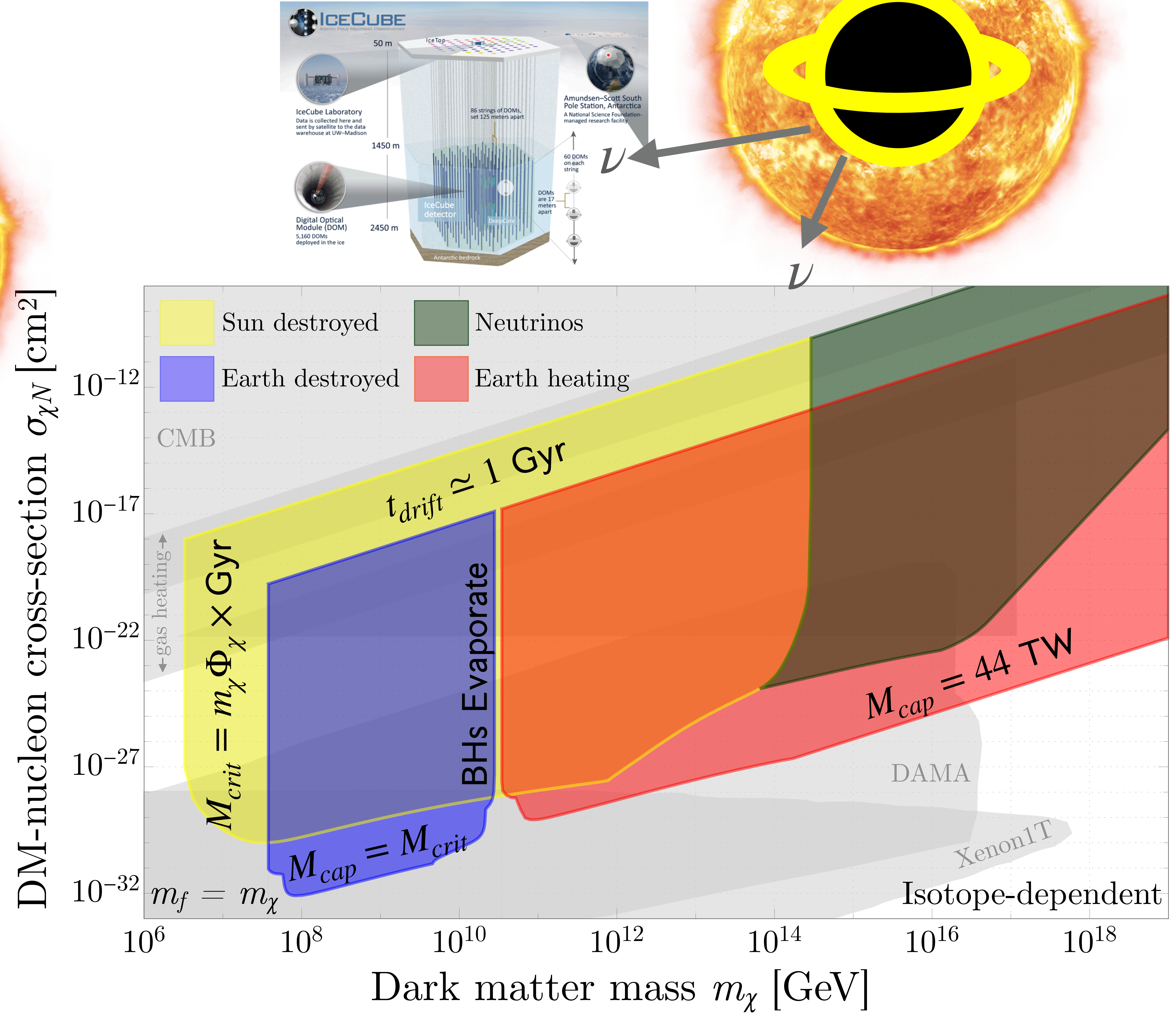
Self-gravitating condition: $M_{cap} \gtrsim \sqrt{\frac{3T_\oplus^3}{\pi G^3 m_\chi^3 \rho_\oplus}}$

Heavier dark matter forms lighter black holes, that tend to evaporate.




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
10^{-12}
10^{-17}
10^{-22}
10^{-27}
10^{-32}
DM–nucleon cross–section $\sigma_{\chi N}$ [cm^2]
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
Dark matter mass m_χ [GeV]

2012.09176



IceCube
ν
ν
Sun destroyed
Neutrinos
Earth destroyed
Earth heating
CMB
$t_{drift} \simeq 1$ Gyr
gas heating
$M_{crit} = m_\chi \Phi_\chi \times$ Gyr
BHs Evaporate
$M_{cap} = M_{crit}$
$M_{cap} = 44$ TW
DAMA
Xenon1T
Isotope-dependent
$m_f = m_\chi$
DM-nucleon cross-section $\sigma_{\chi N}$ [cm^2]
10^{-12}
10^{-17}
10^{-22}
10^{-27}
10^{-32}
10^{6}
10^{8}
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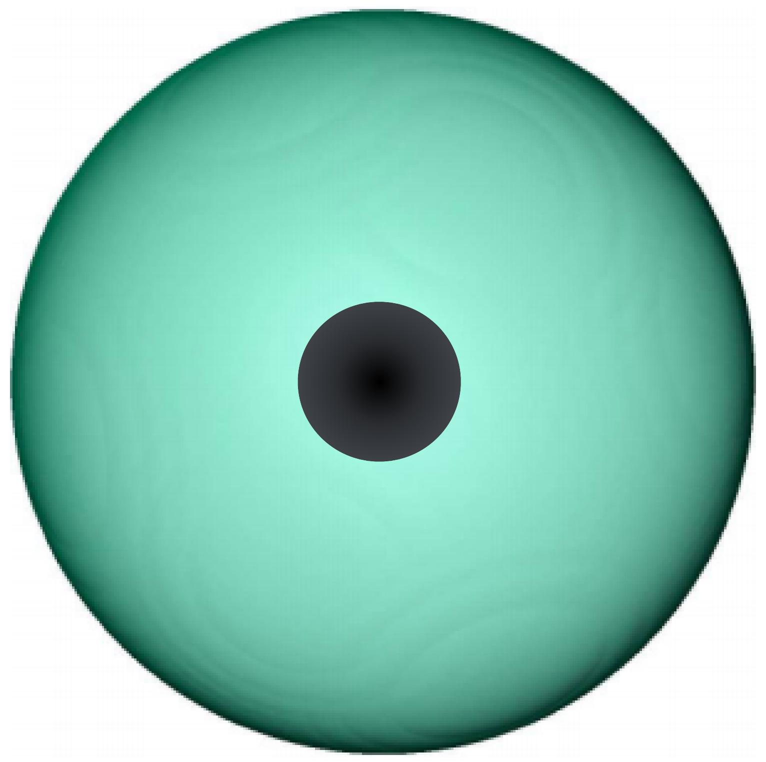
10^{14}
10^{16}
10^{18}
Dark matter mass m_χ [GeV]

2012.09176

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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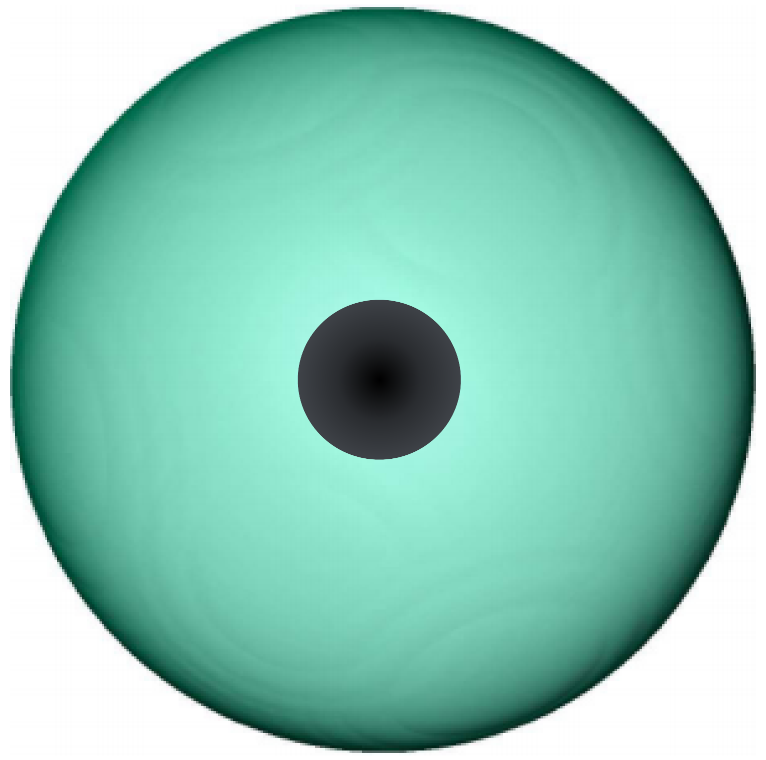

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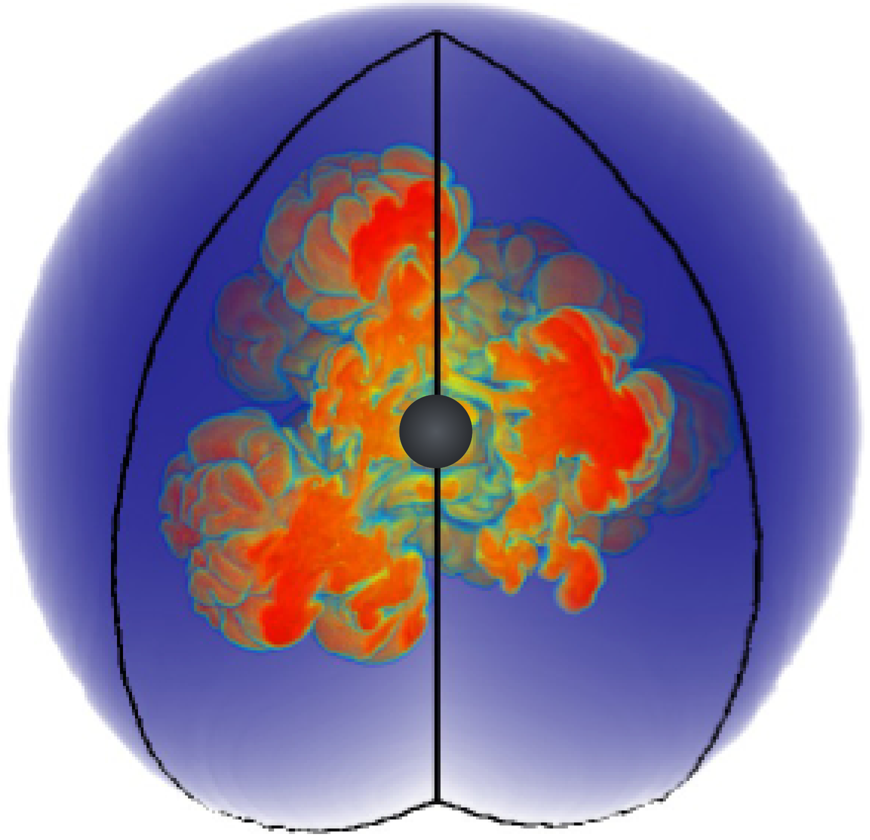
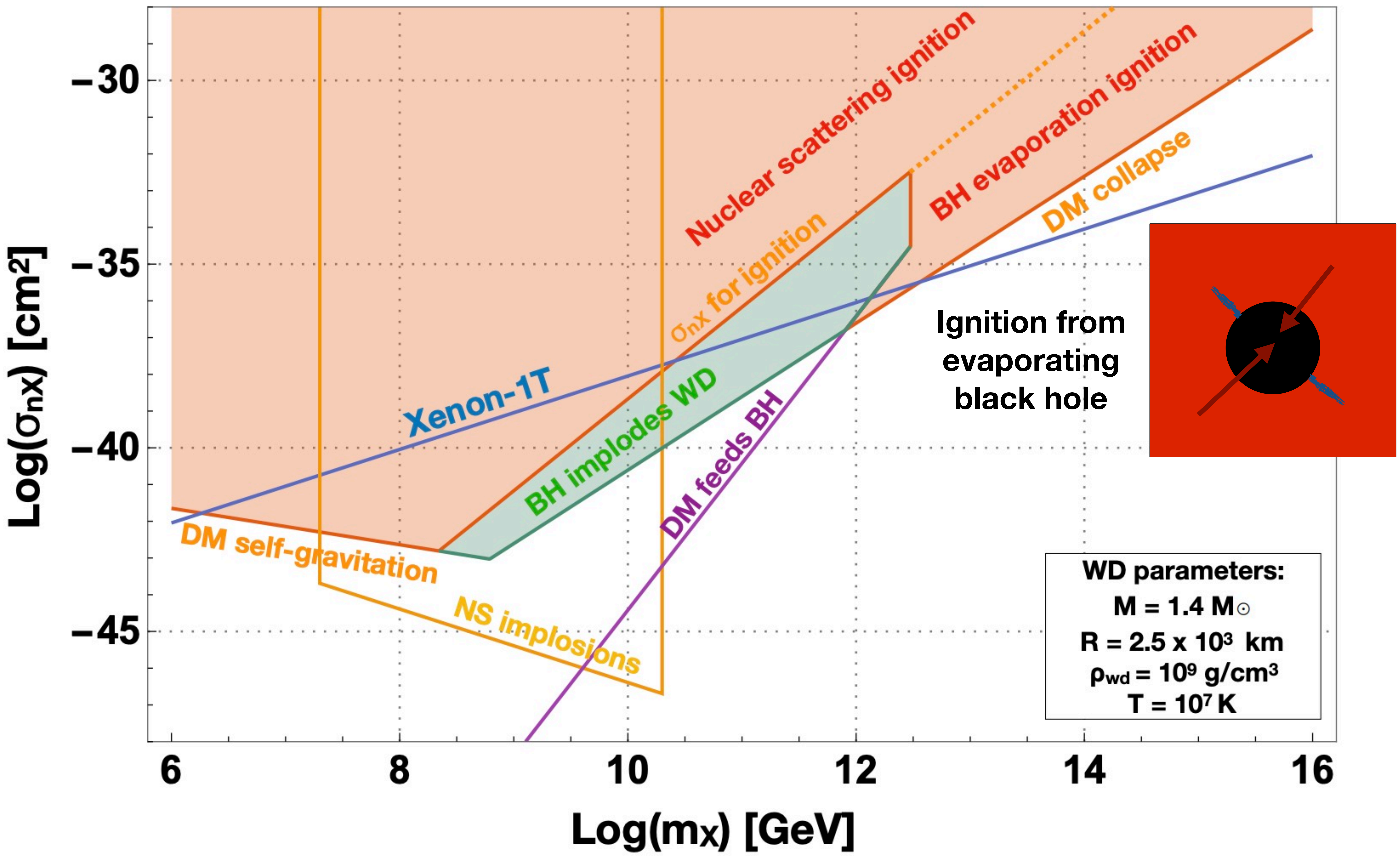


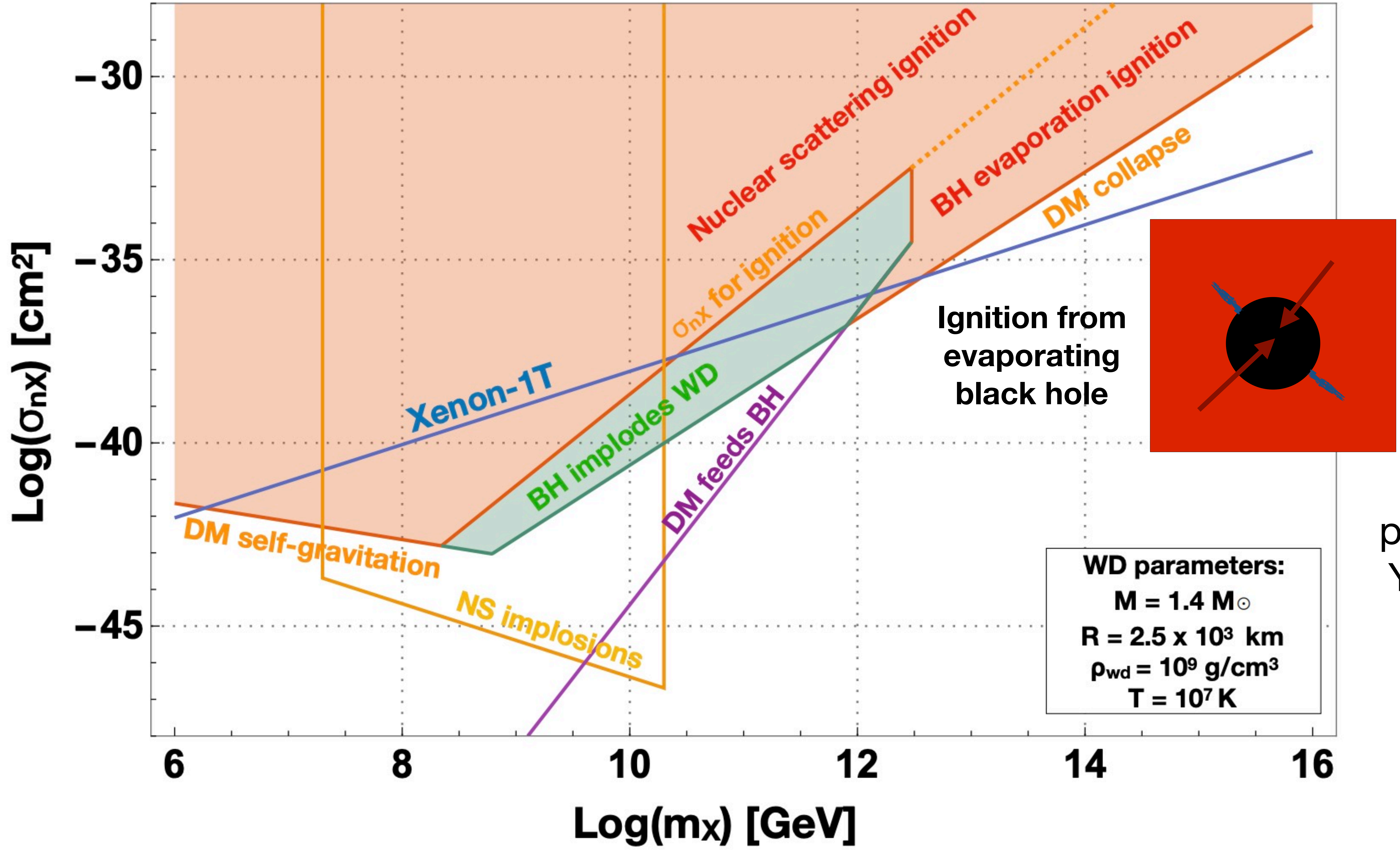
DM collapses, shedding gravitational potential energy through **scattering**, igniting a SNIa.

Bounds on dark matter from an old GAIA White Dwarf



Javier Acevedo JB 1904.11993

Bounds on dark matter from an old GAIA White Dwarf

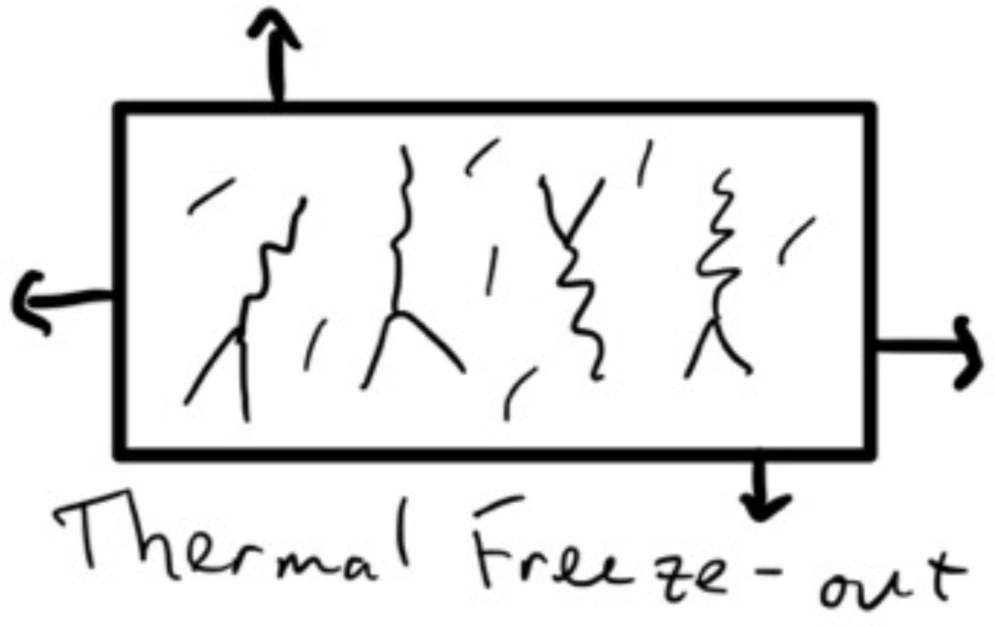


Ignition from evaporating black hole

Galaxy effects in progress with JA and Yilda Boukhtouchen

Javier Acevedo JB 1904.11993

Weakly interacting dark matter "miracle"



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

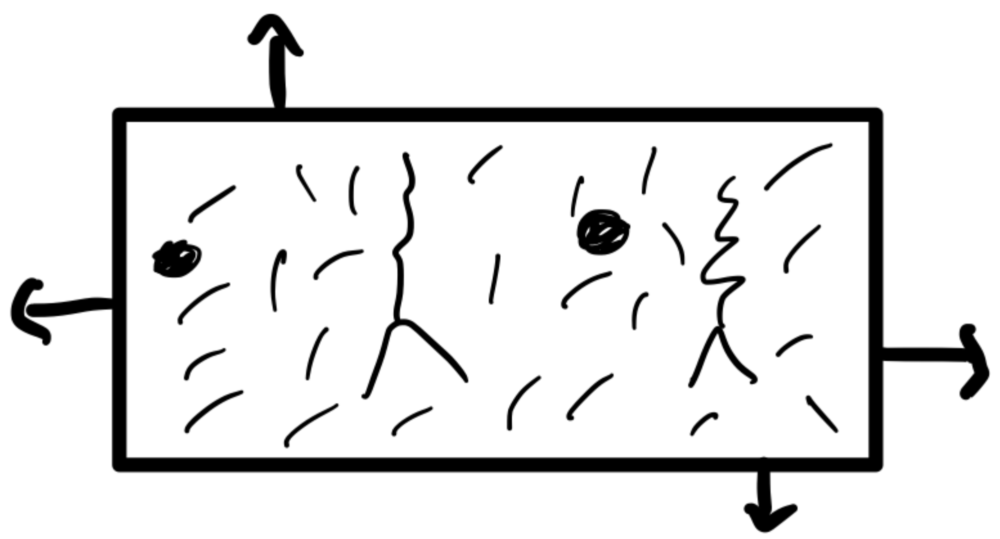
The final relic abundance depends on the annihilation cross-section, but only logarithmically on m_x

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

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

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

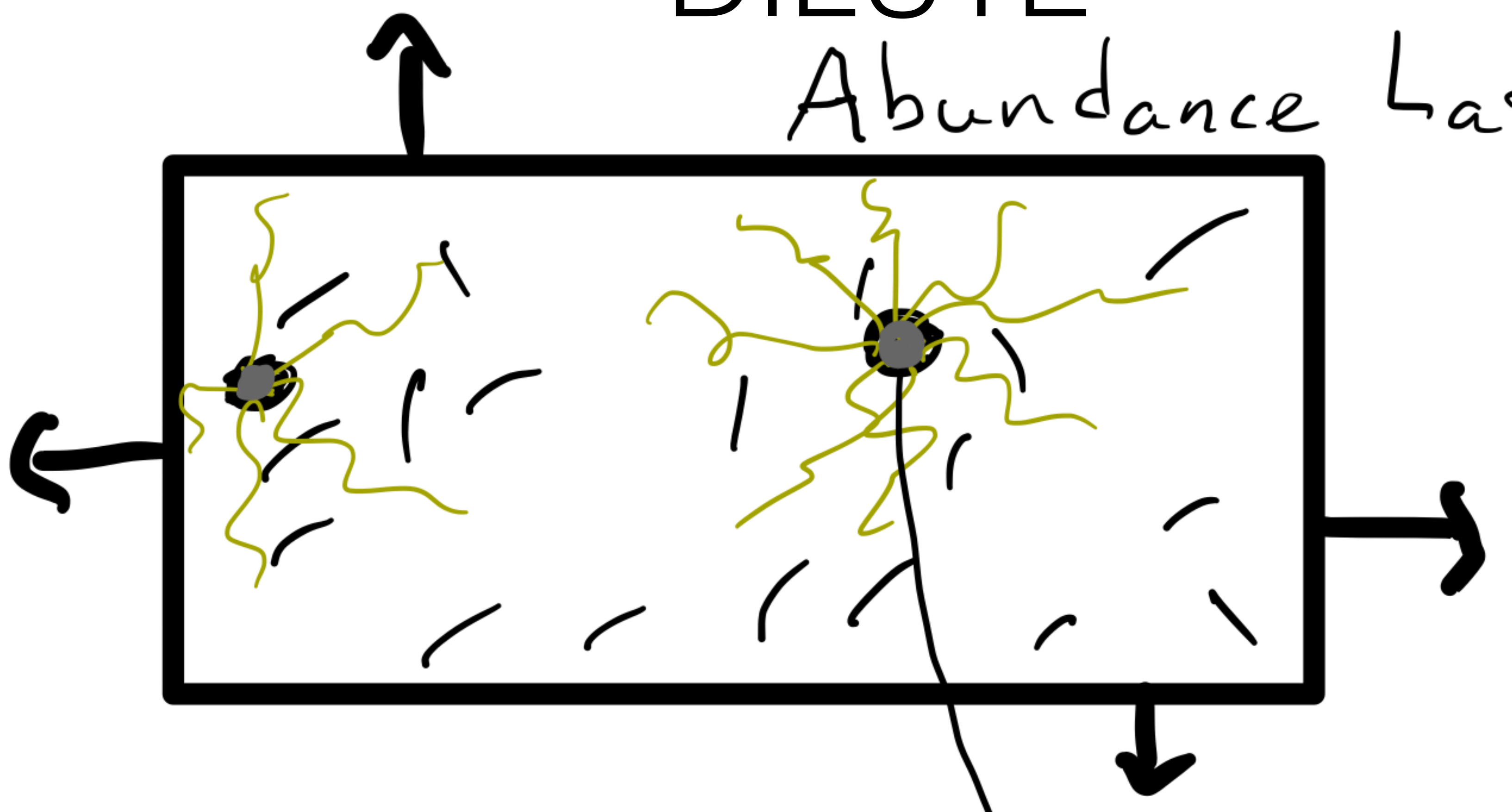
Dilute WIMPS



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

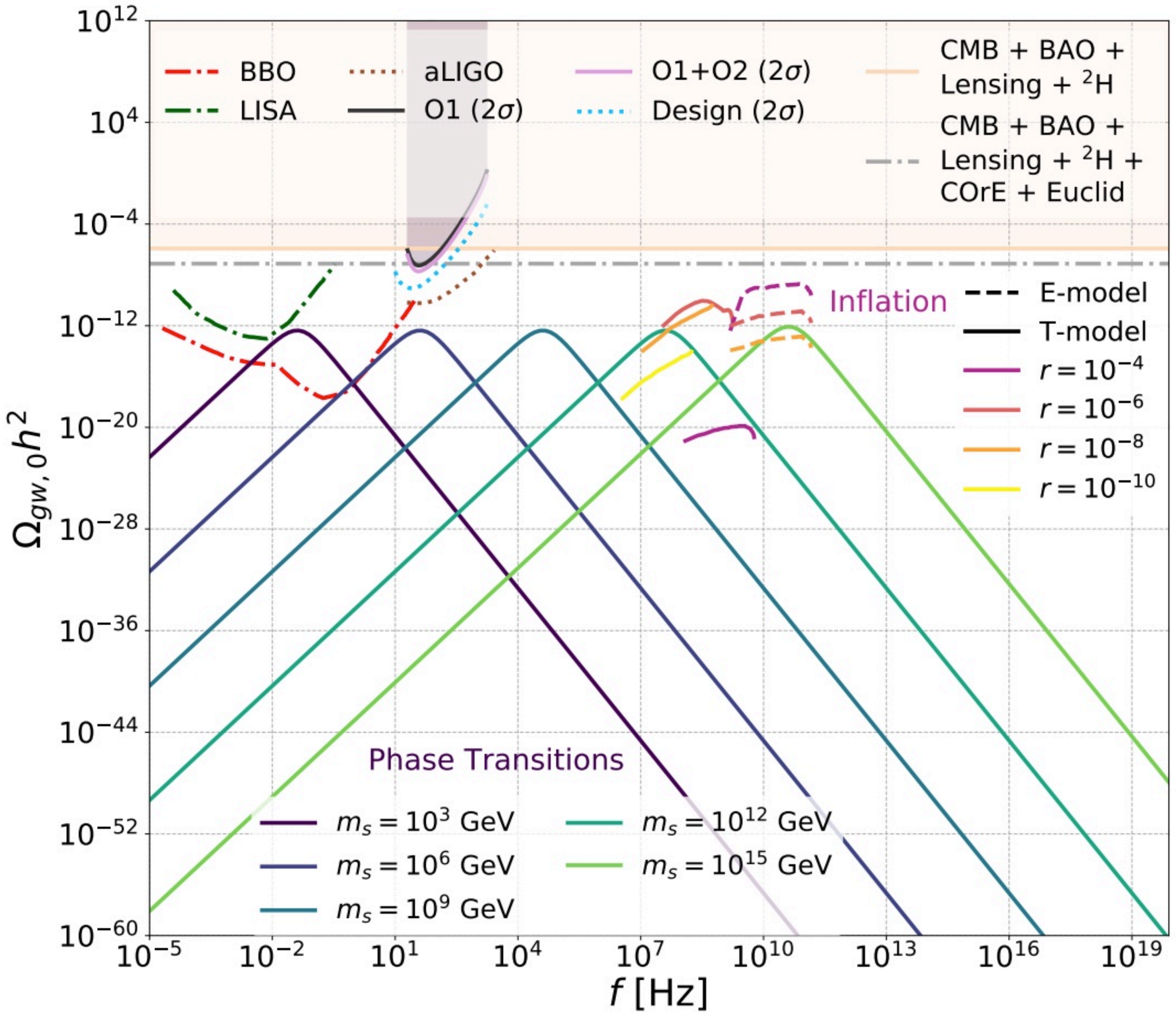
$$\zeta \equiv \frac{S_{initial}}{S_{final}}$$ { Δ entropy density from decays 

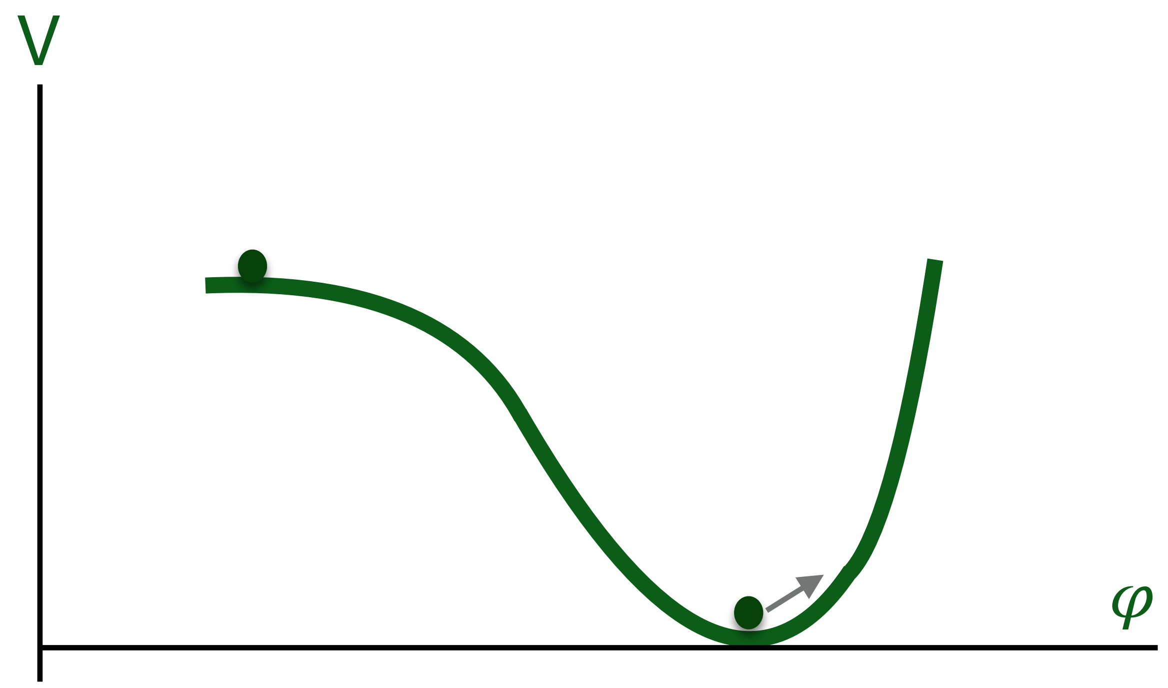
See also
Allahverdi Dutta Sinha '11
Kane Shao Watson '11
Davoudiasl Hooper McDermott '15
Berlin Hooper Krnjaic '16

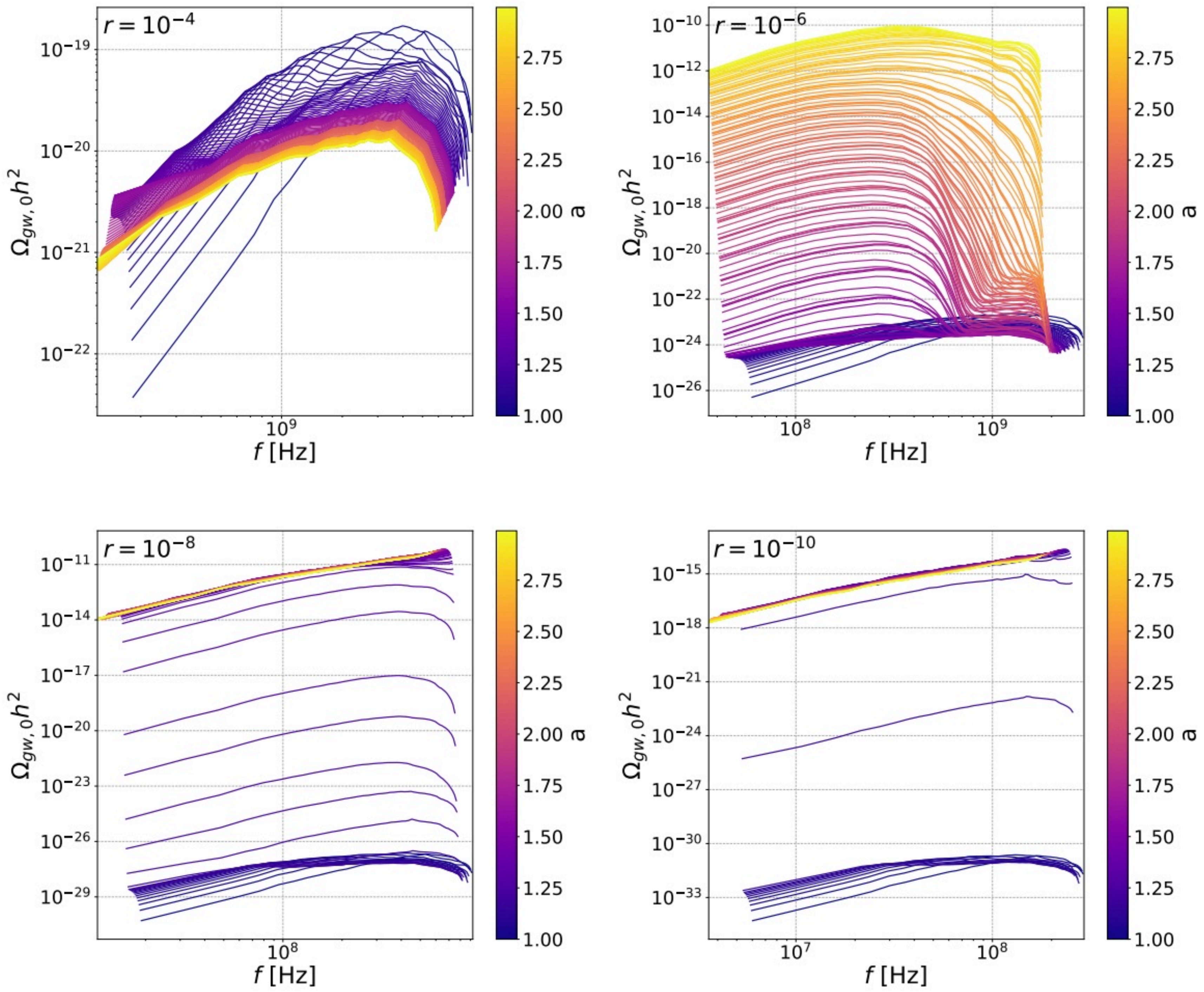
JB, Unwin '17

For super massive cosmologies: heavy scalar fields and gravitational waves!

$$\mathscr{L}_{mass} \supset y\bar{\chi}\chi\phi$$







Gravitational waves from an oscillating inflation, that could make dark matter heavy after inflation.

Simran Nerval

2008.12306

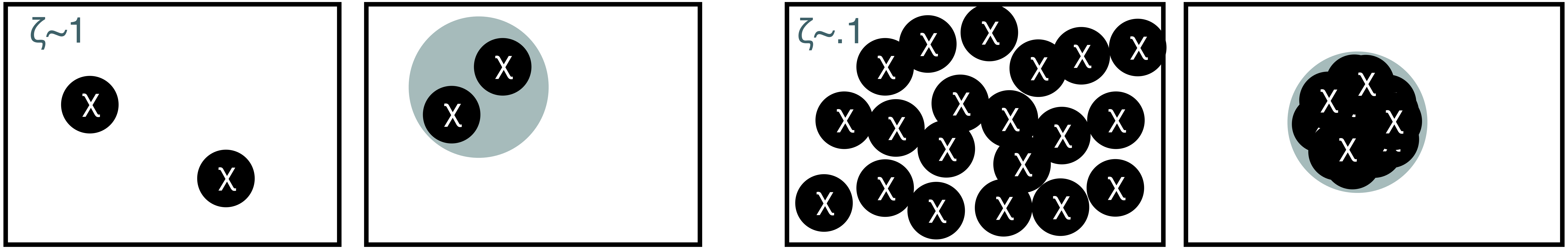
HIGH MASS ASYMMETRY, DILUTION, AND COMPOSITE DM

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

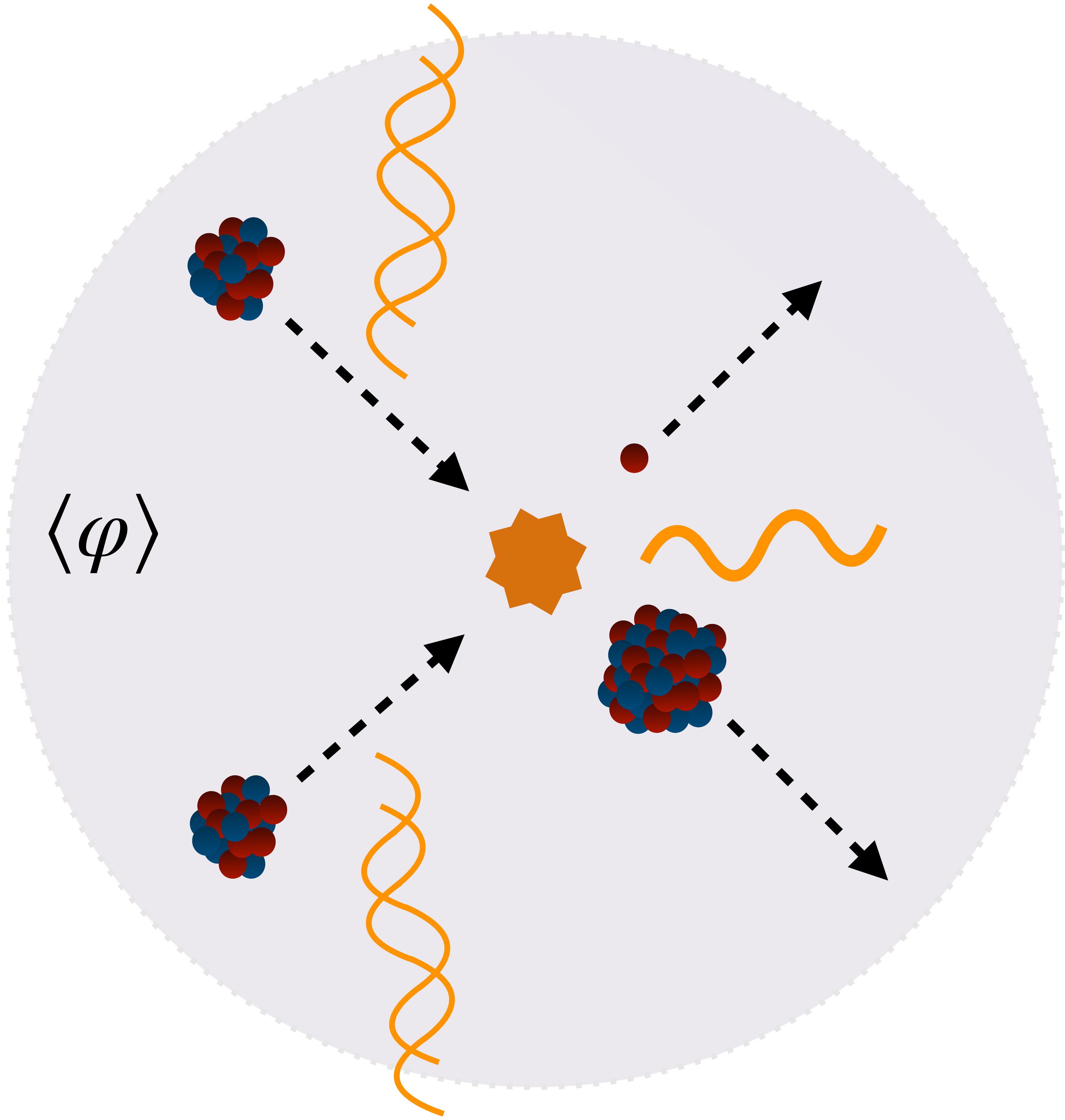


$$N_c = \left(\frac{2n_X\sigma_X v_X}{3H}\right)^{6/5} = \left(\frac{20\sqrt{g^*_{ca}}T_r T_{ca}^{3/2}M_{pl}}{\bar{m}_X^{7/2}\zeta}\right)^{6/5} \simeq 10^{27}\left(\frac{g^*_{ca}}{10^2}\right)^{3/5}\left(\frac{T_{ca}}{10^5\,\mathrm{GeV}}\right)^{9/5}\left(\frac{5\,\mathrm{GeV}}{\bar{m}_X}\right)^{21/5}\left(\frac{10^{-6}}{\zeta}\right)^{6/5}$$

Composite mass ranging from milligrams to thousands of tons

2012.10998

FOR BIG ENOUGH COMPOSITES

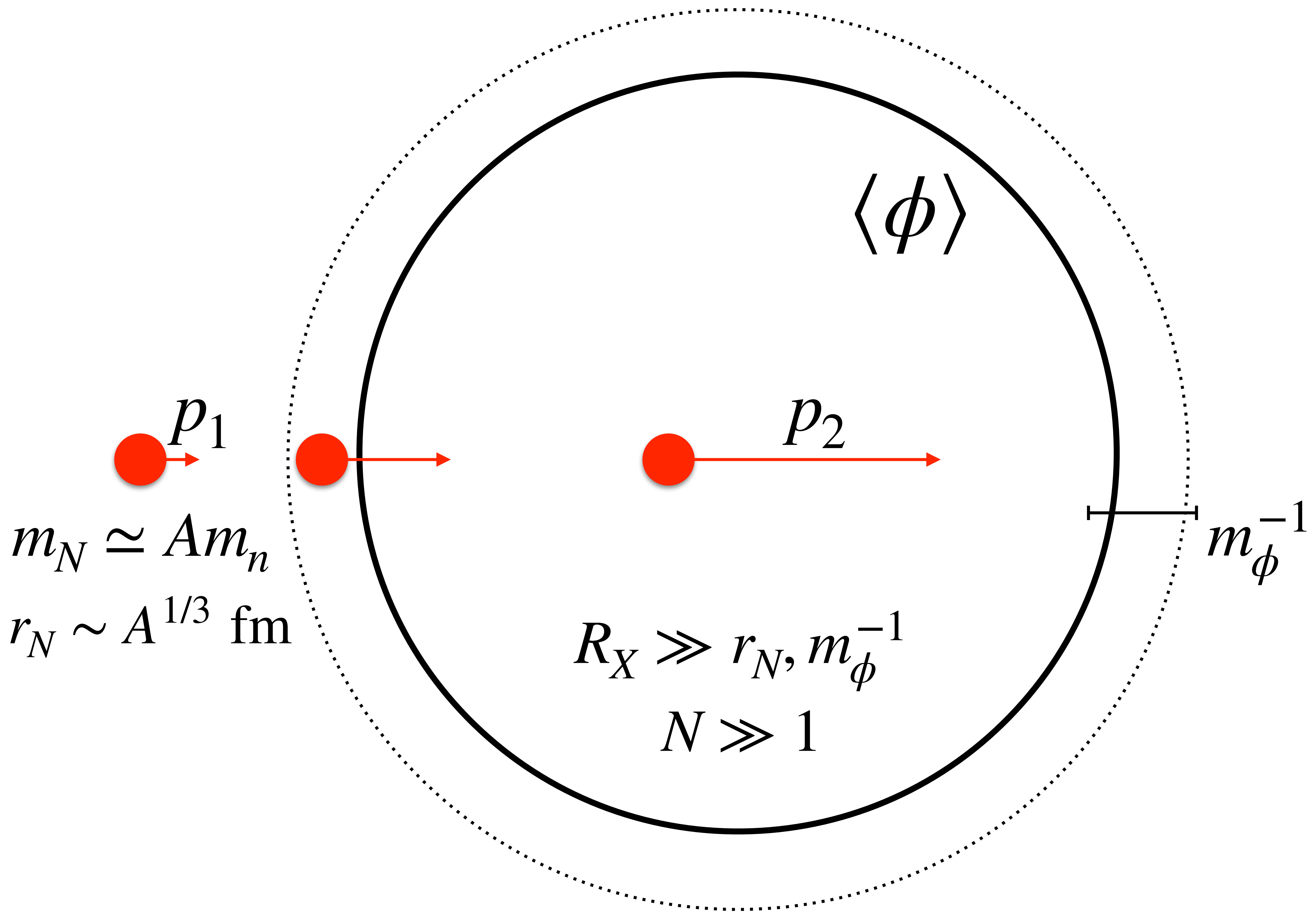


Nuclear fusion and bremsstrahlung inside large dark matter composites

Javier Acevedo, JB, Alan Goodman *2012.10998*

Nuclear coupling

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

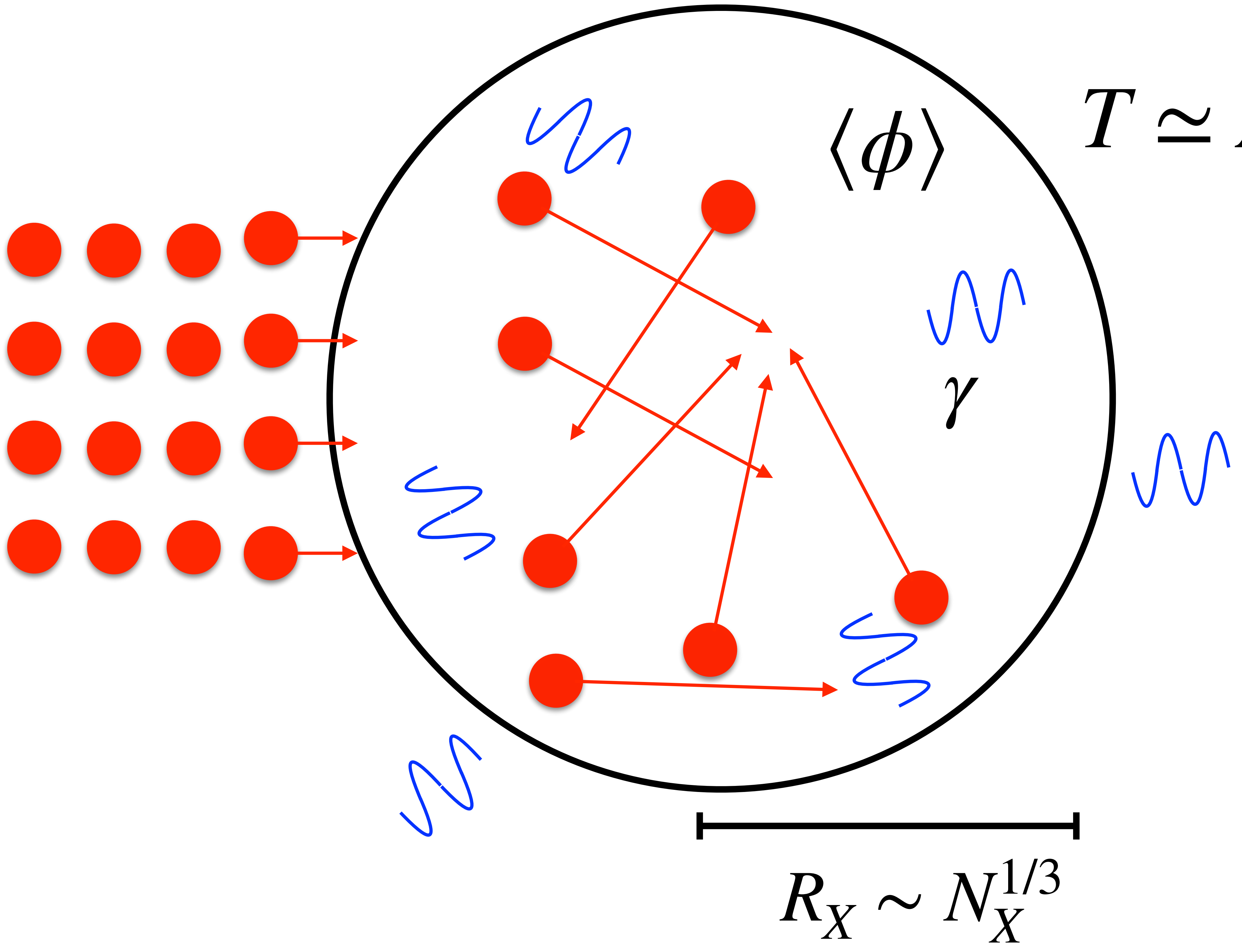


Nuclei will accelerate across the DM composite's boundary layer, because of the attractive potential, like gravity but stronger and shielded:

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

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

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



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

Ionization (Migdal, collisions)

Thermal bremsstrahlung

Thermonuclear fusion

↓ temperature/energy

Potential signatures of this effect?

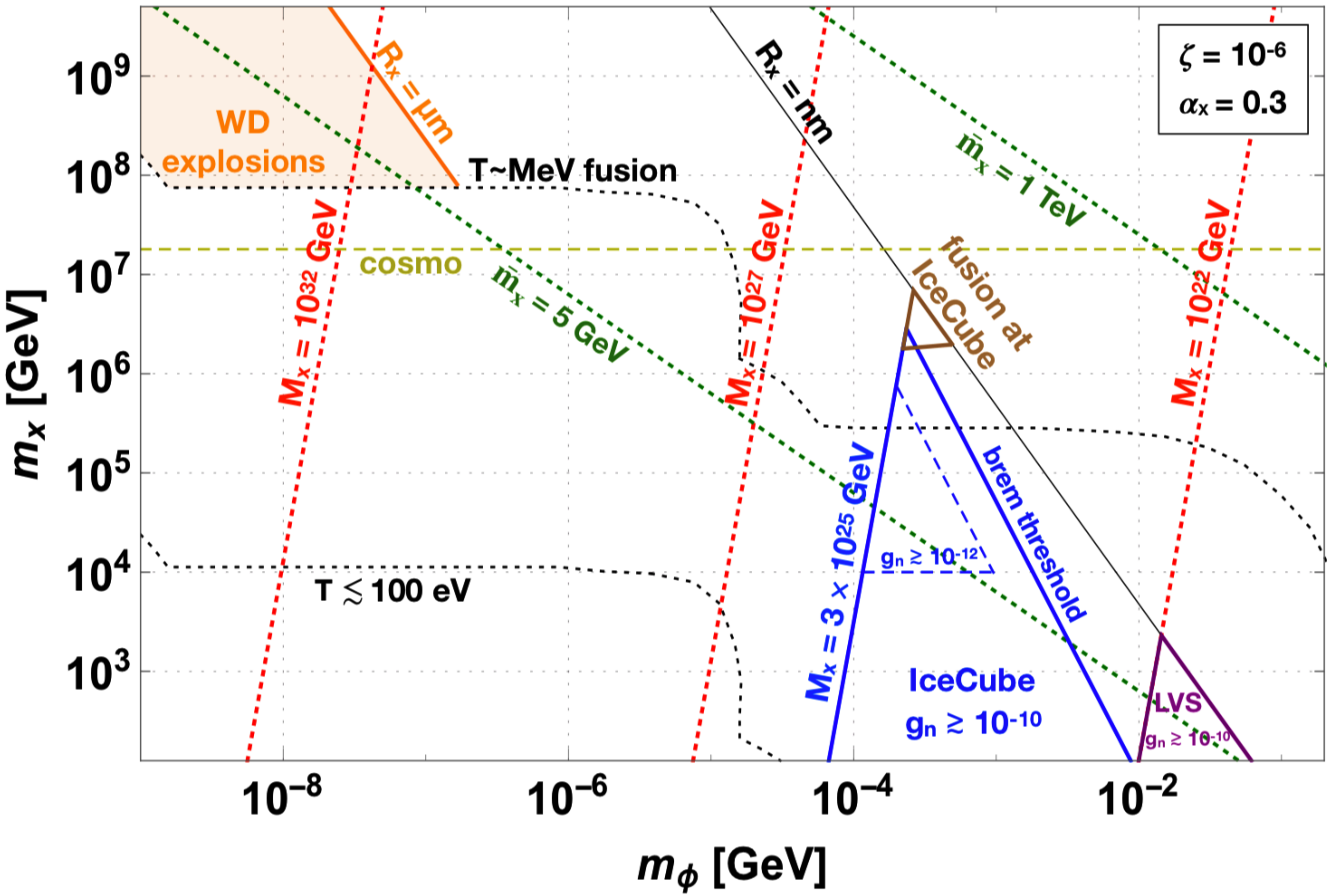
⟶ Direct detection

⟶ Type Ia supernovae

2012.10998

Parameter space for detection:

2012.10998

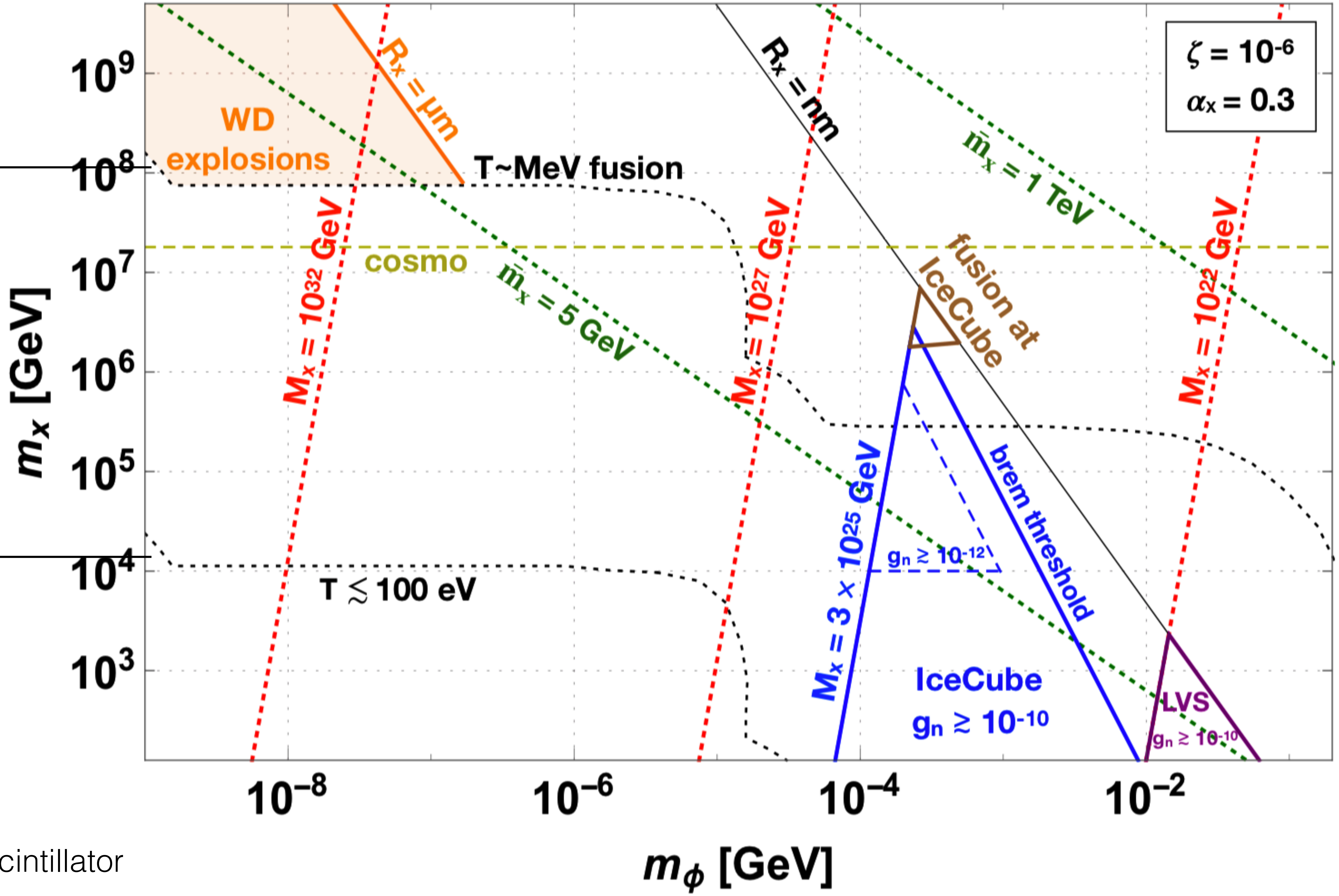


Parameter space of potential detectability:

2012.10998

increasing radius/mass

stellar cooling constraints



stellar cooling constraints

increasing temperature (fixed coupling)

increasing composite binding energy

LVS = large volume scintillator

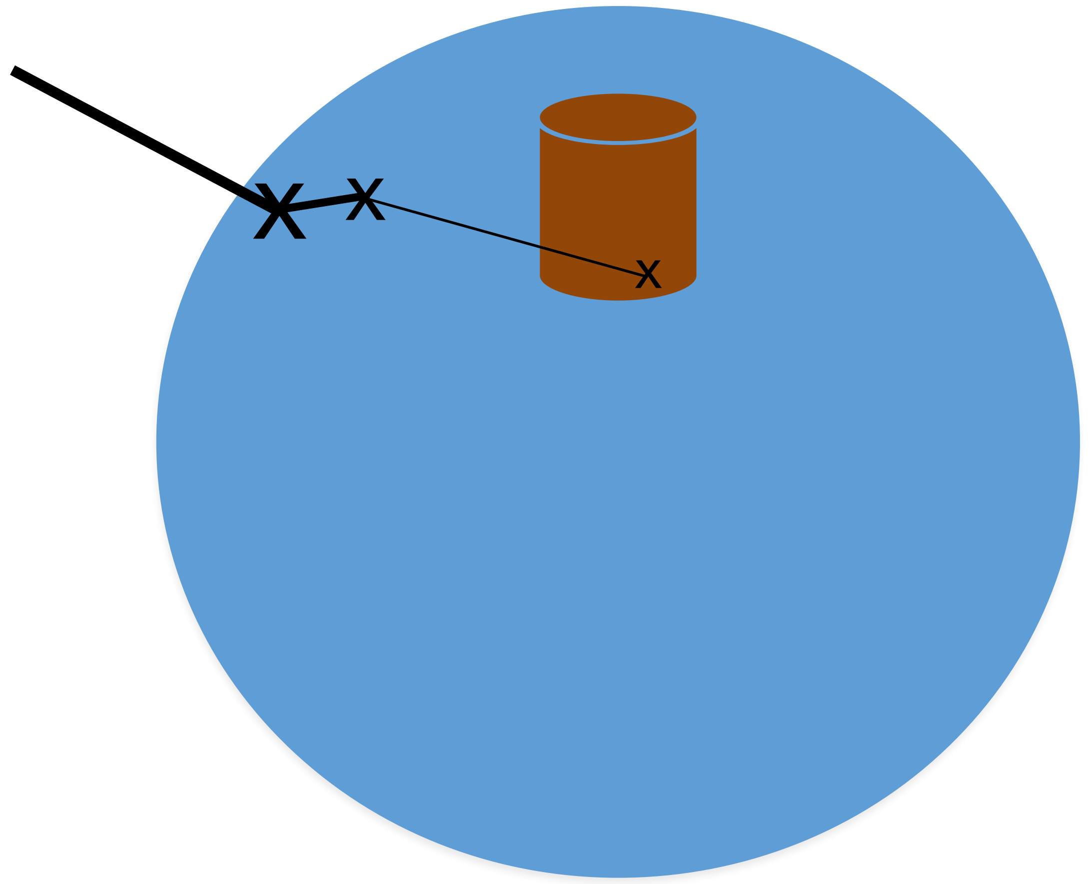
GAS CLOUDS

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

Amit Bhoonah

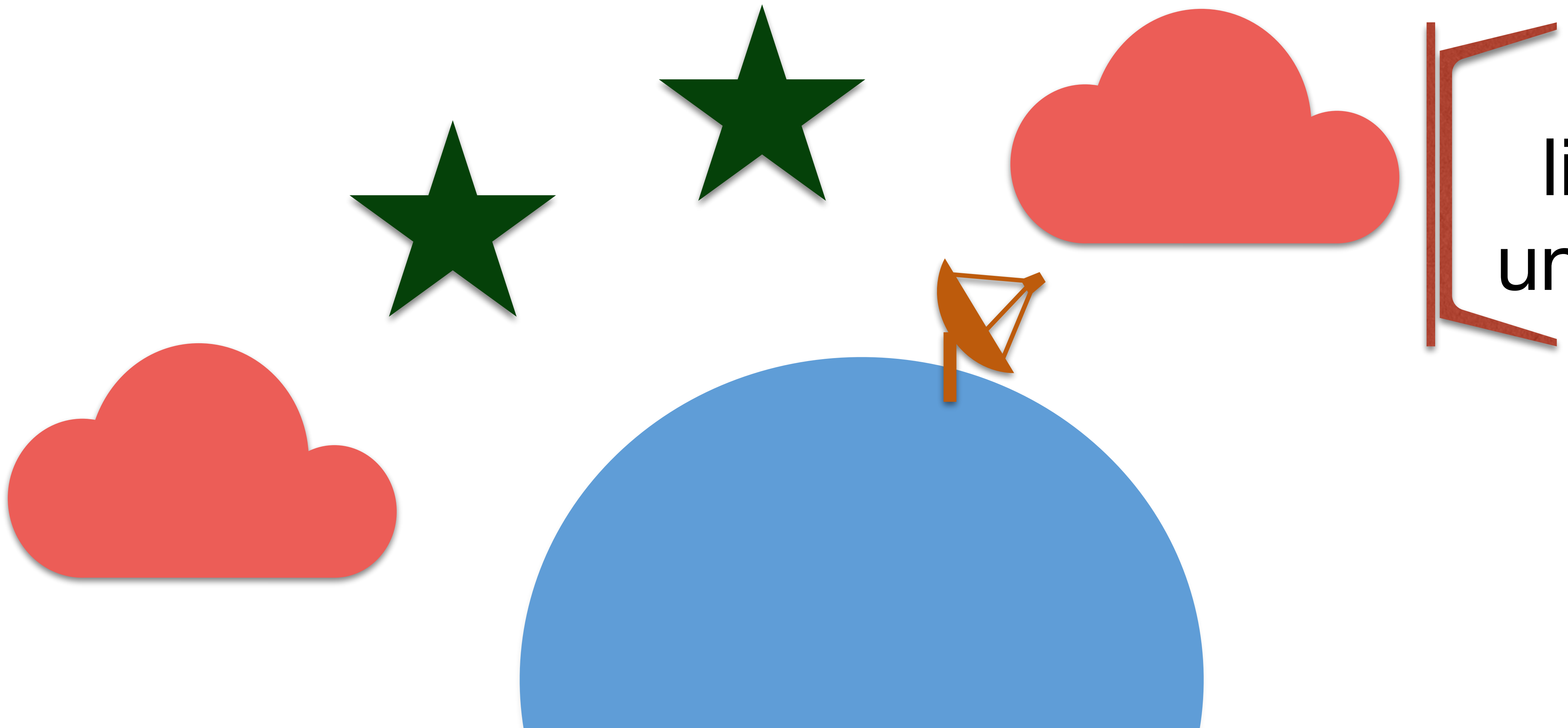
Fatemeh Elahi,
Sarah Schon,
Ningqiang Song

2010.07240
1812.10919
1806.06857



dark matter kinetic energy < recoil threshold

Use detectors in space!

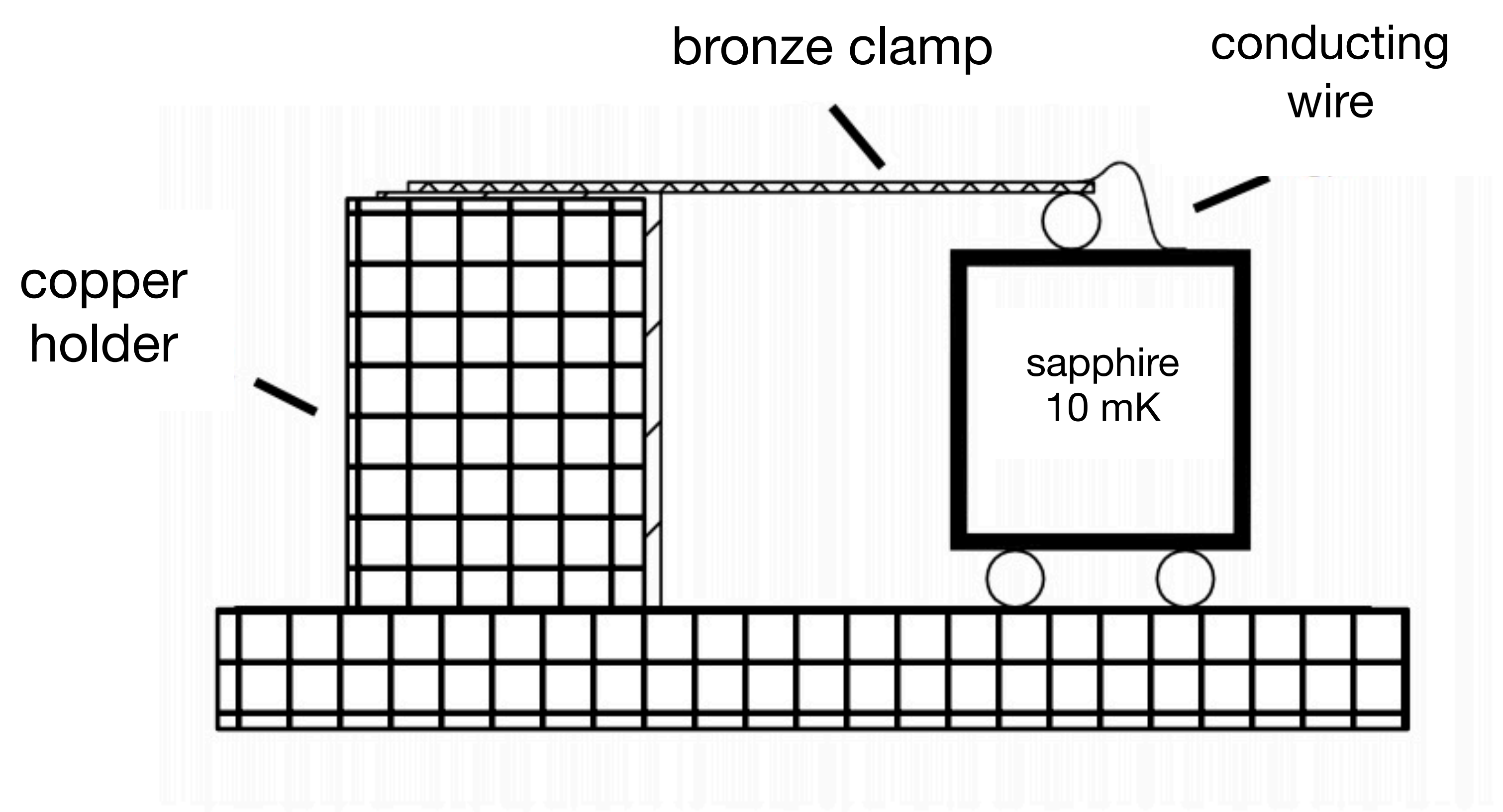


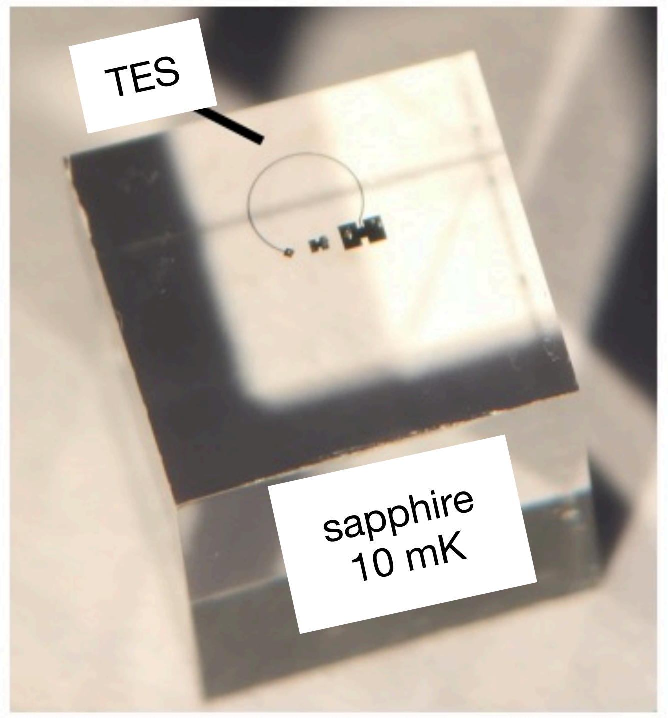
<u>Interstellar gas</u>

big
little overburden
unbound electrons

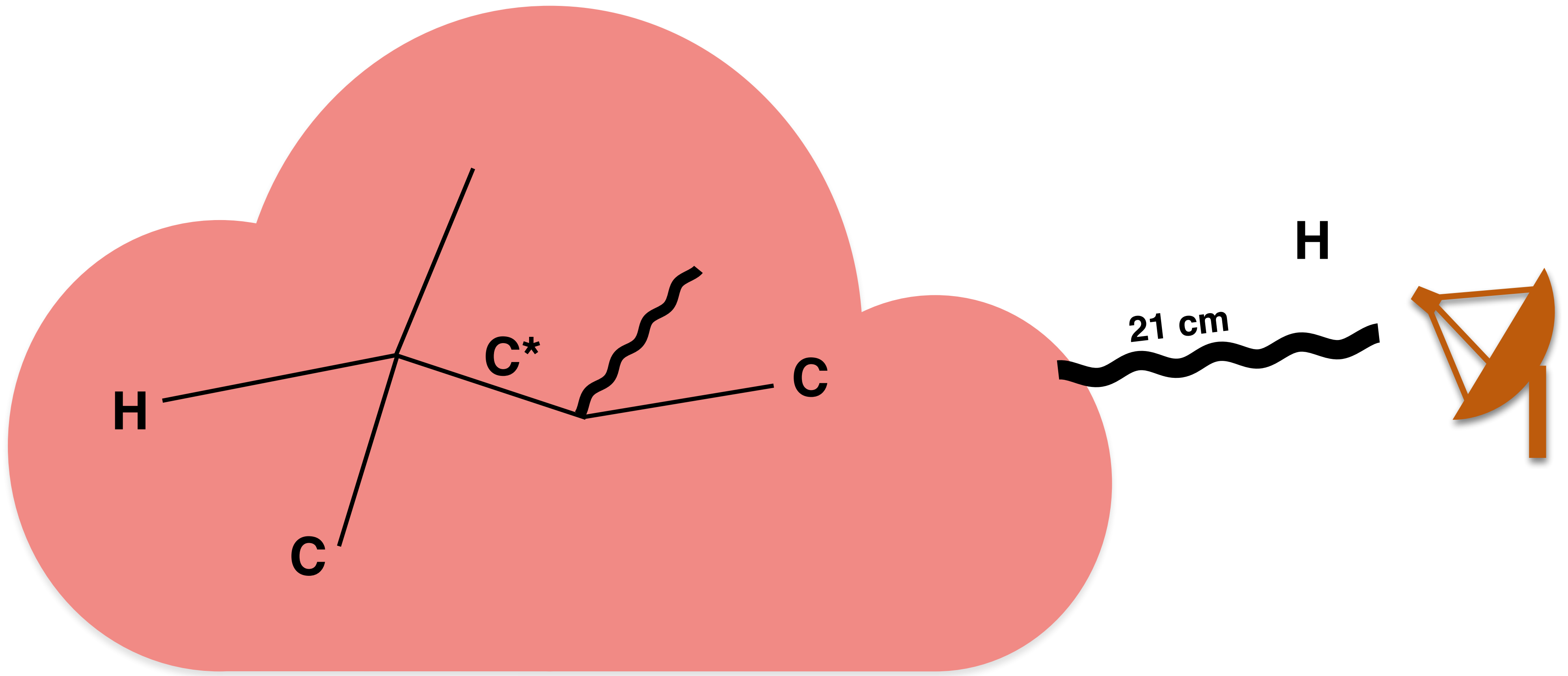
GAS CLOUDS AS CALORIMETRIC DETECTORS

CRESST sapphire
cooling: conducting wire
readout: TES thermal phonon



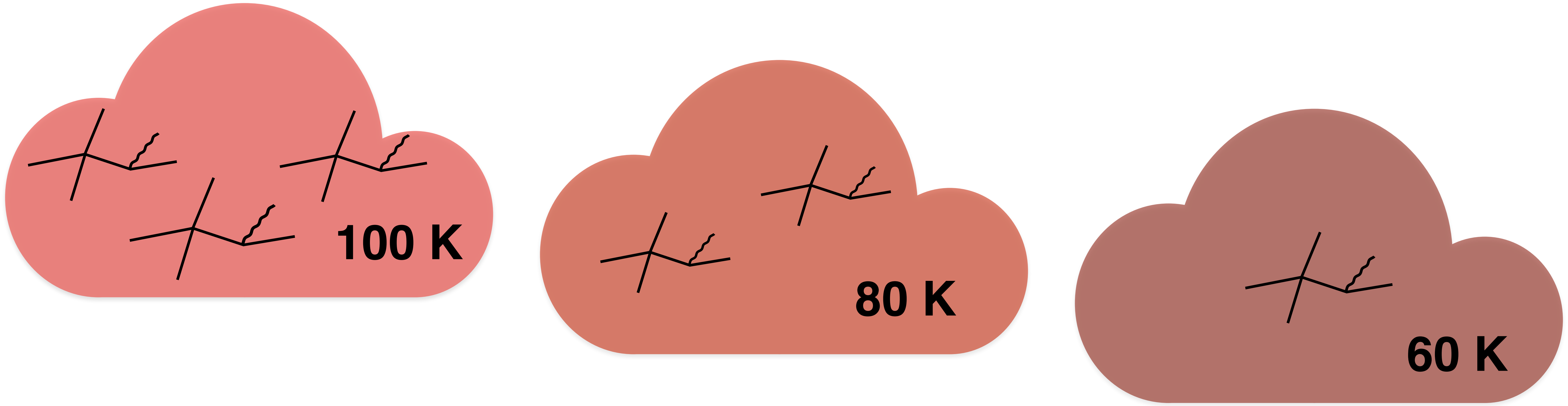


Cold Galactic gas clouds
cooling: carbon transitions
readout: 21 cm emission



GAS CLOUD COOLING

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



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

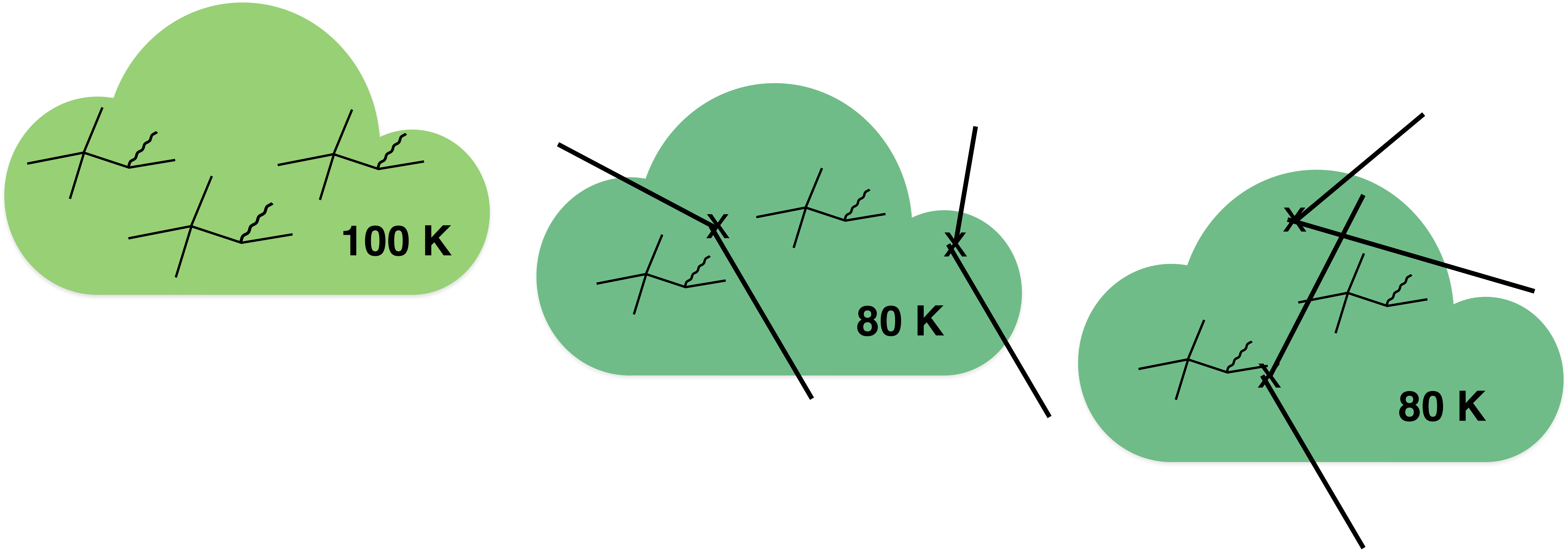
Collisions are rarer at lower temperatures.

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

GAS CLOUD DARK MATTER HEATING EQUILIBRIUM

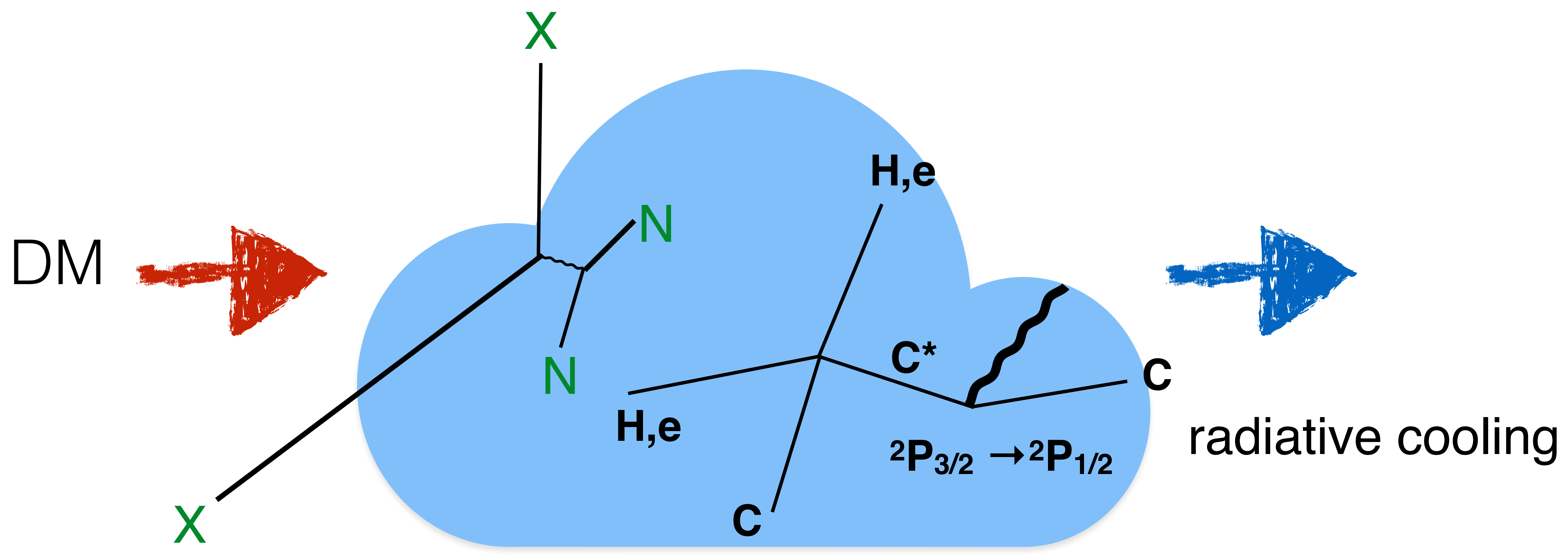
Cooling decreases with gas cloud temperature.

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

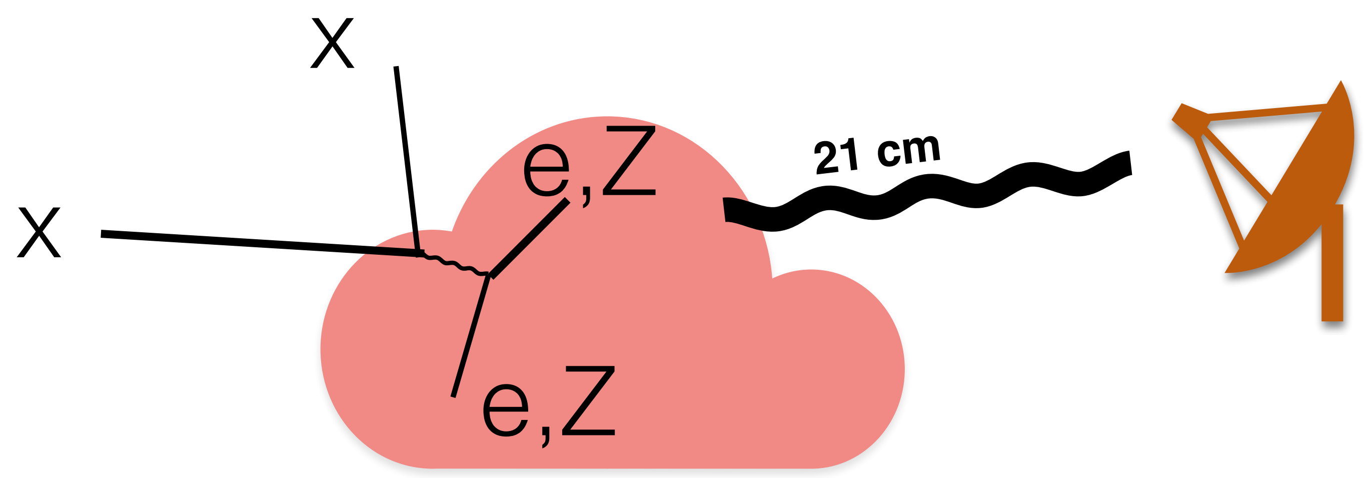
Xray/UV background

photoelectric heating
via dust grains

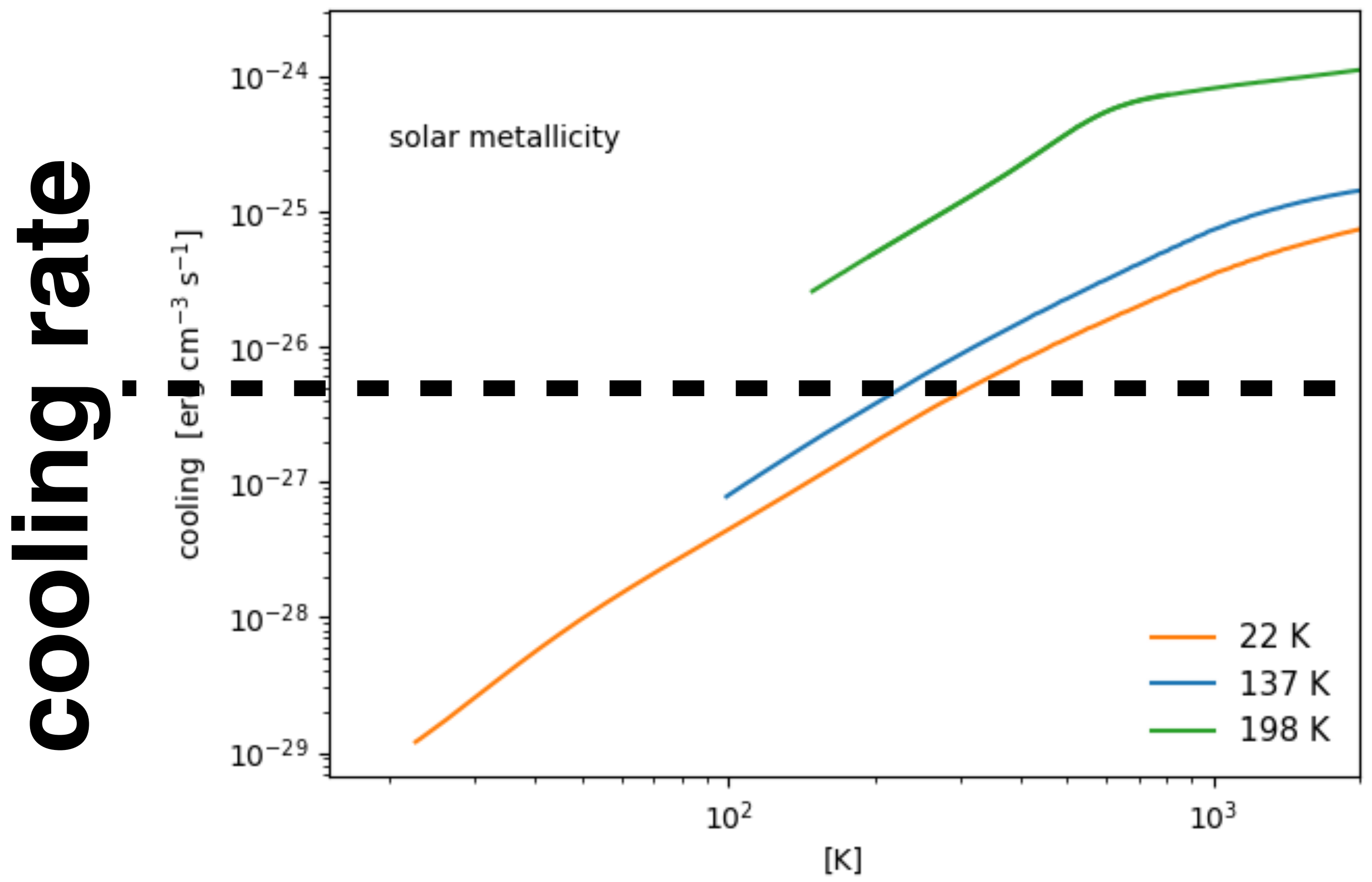
There are known ubiquitous heating sources, like cosmic UV background, cosmic rays, dust grain heating.

GAS CLOUD BOUNDS

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



Cooling curves are monotonic decreasing for T < 1000 Kelvin



Class I Bound

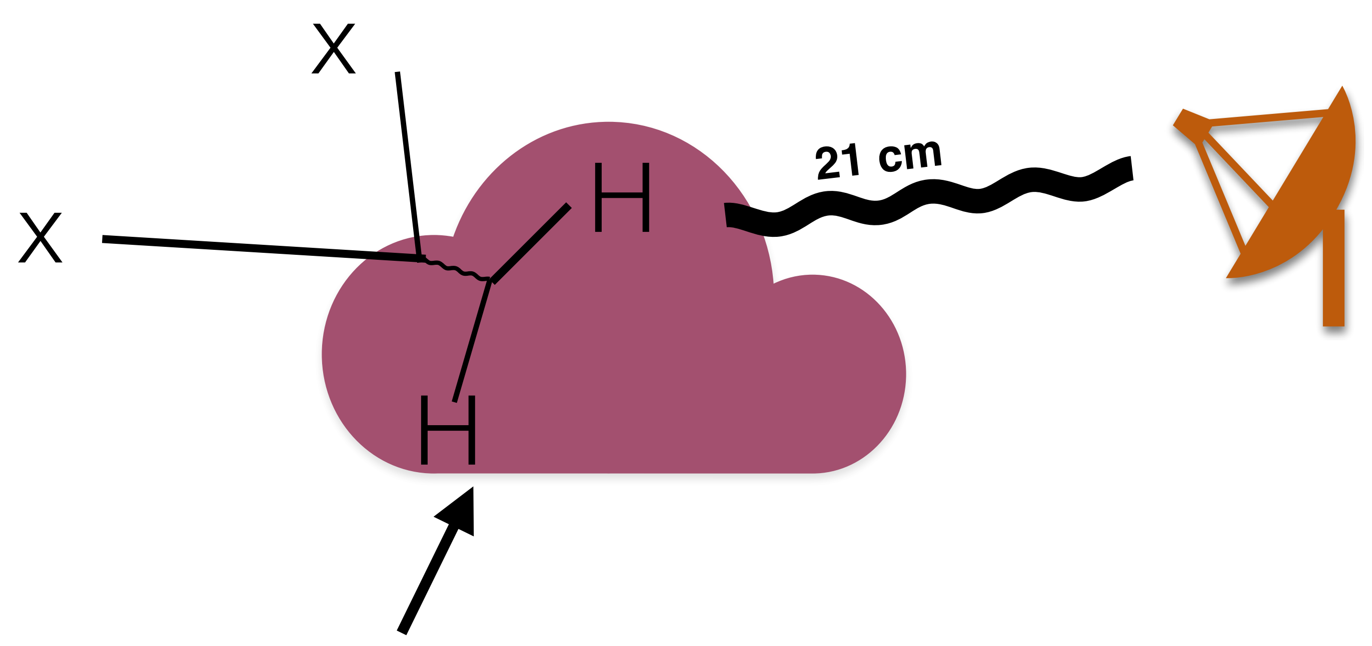
Dark heating < radiative cooling

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

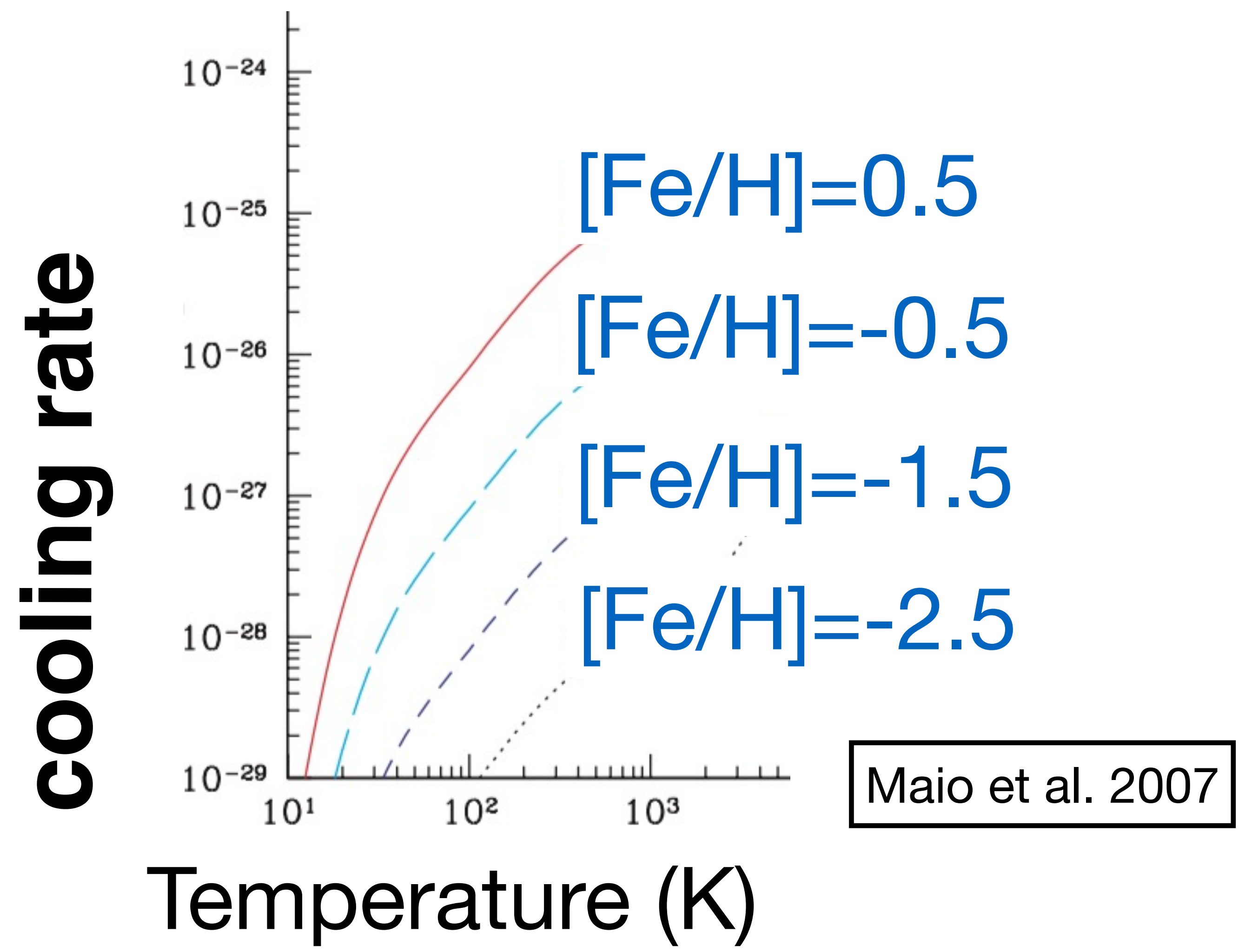
$$VCR = f(\mathrm{T}, \mathrm{n_H}, [\mathrm{Fe/H}])$$

GAS CLOUD BOUNDS

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

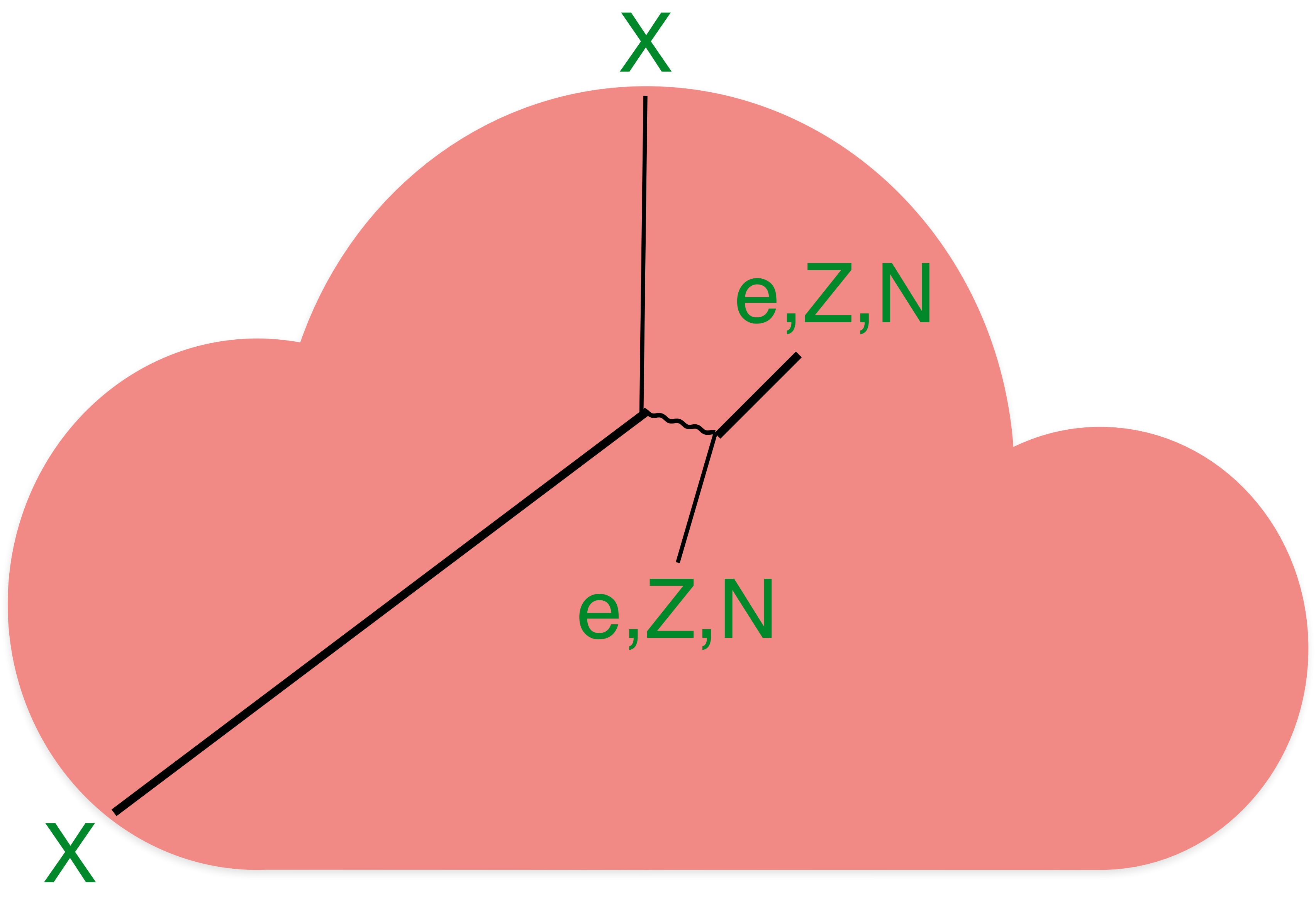
Bound now depends on metallicity

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

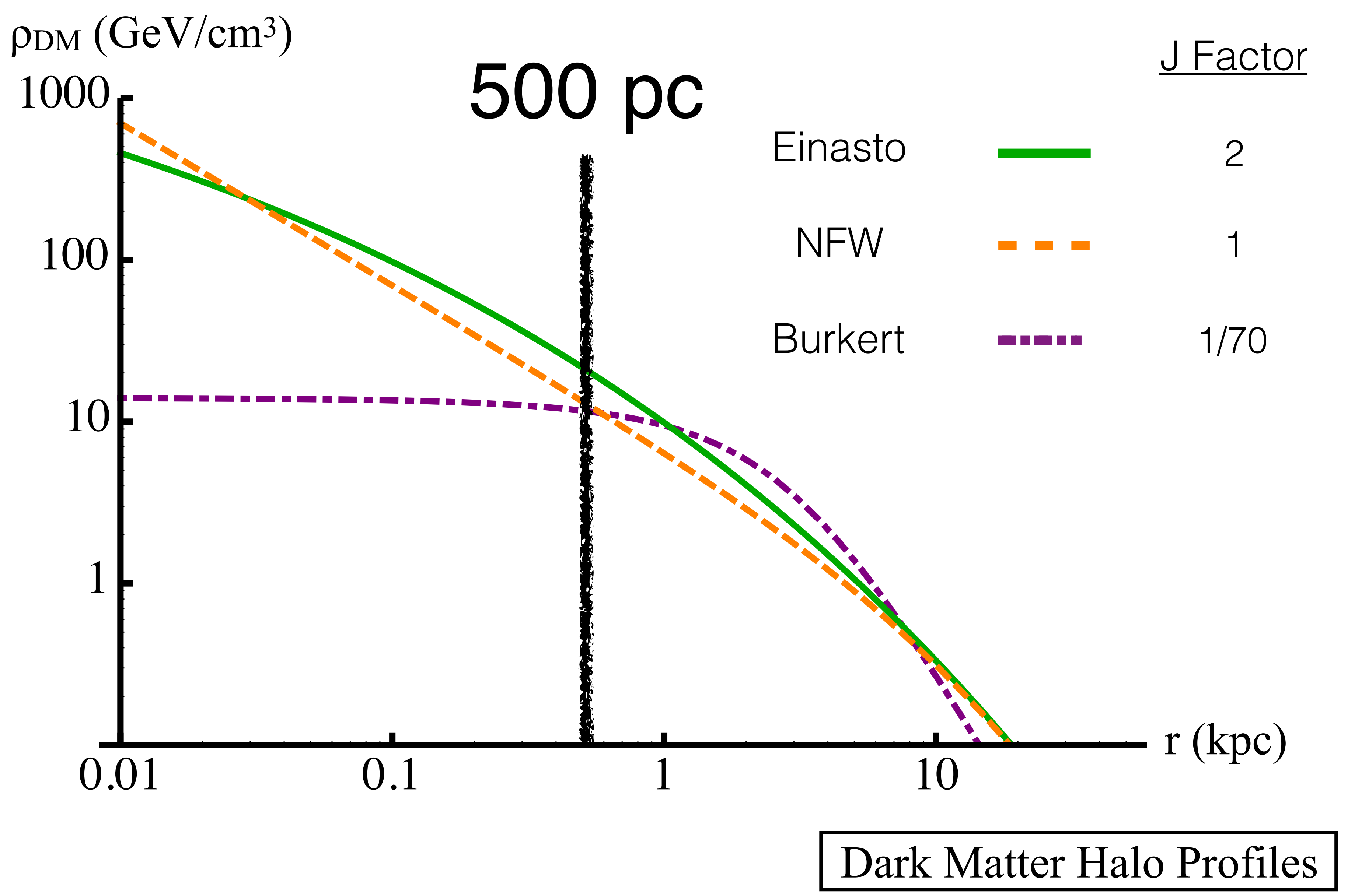
Dark matter interactions heat gas clouds

e.g.

$$DHR \approx n_{\rm x}\sigma_{\rm Nx}v_{\rm x}E_{\rm nr}$$



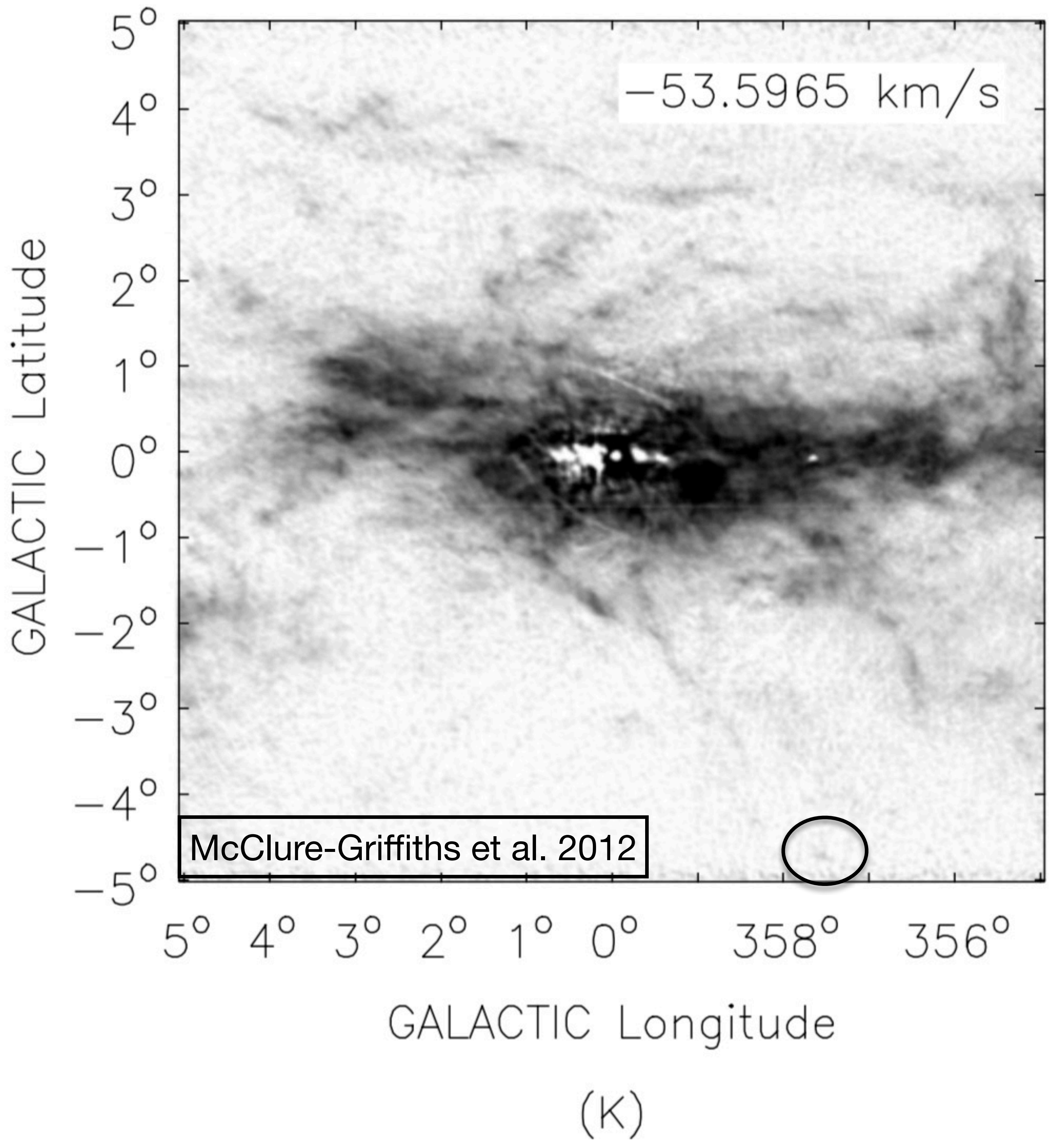
At ~500 pc from GC, relatively insensitive to halo profile



$\rho \sim 10$ GeV/cm^3

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

$M = 237\ M_\odot$

$r_{gc} = 12.9$ pc

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

T_g ? < 137 K

$r_{los} \sim 800$ pc

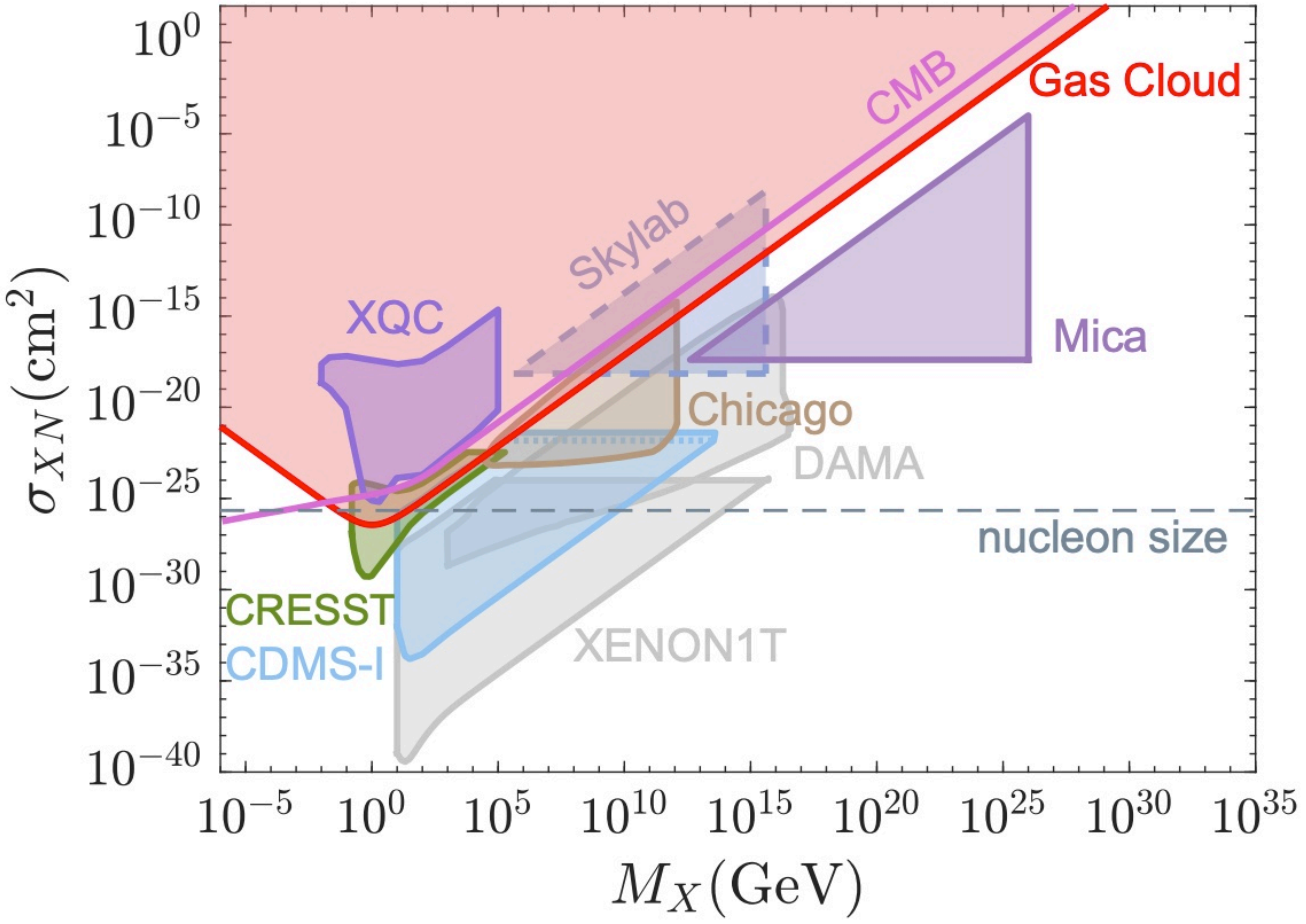
$v_g = -54$ km/s

5°

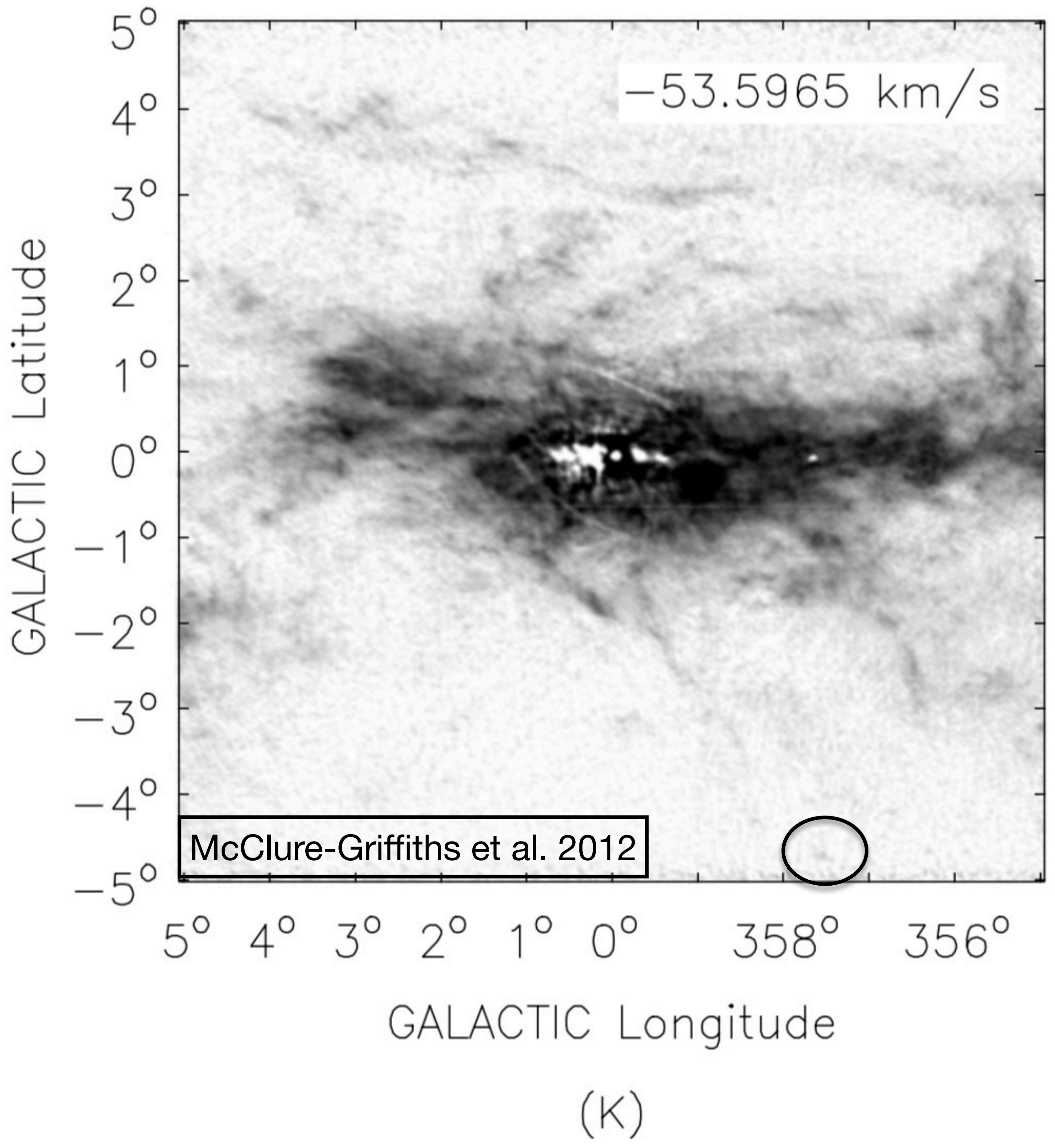
(assume spherical cloud)

HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS

- Fixed cross-section for scattering off all nuclei



Gas Cloud 357.8-4.7-55



Δv from 21cm emission gives T<137 K

G357.8-4.7-55

$M = 237\ M_\odot$

$r_{gc} = 12.9$ pc

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

Tg ? < 137 K

$r_{los} \sim 800$ pc

$v_g = -54$ km/s

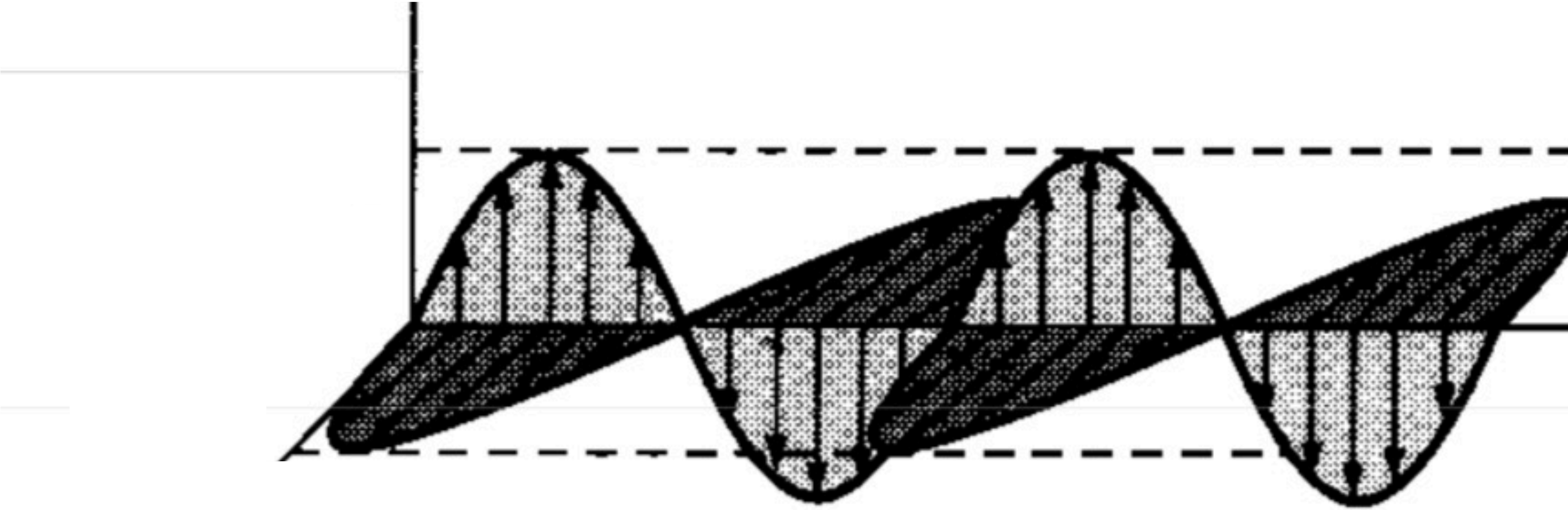
5°

(assume spherical cloud)

2010.07240

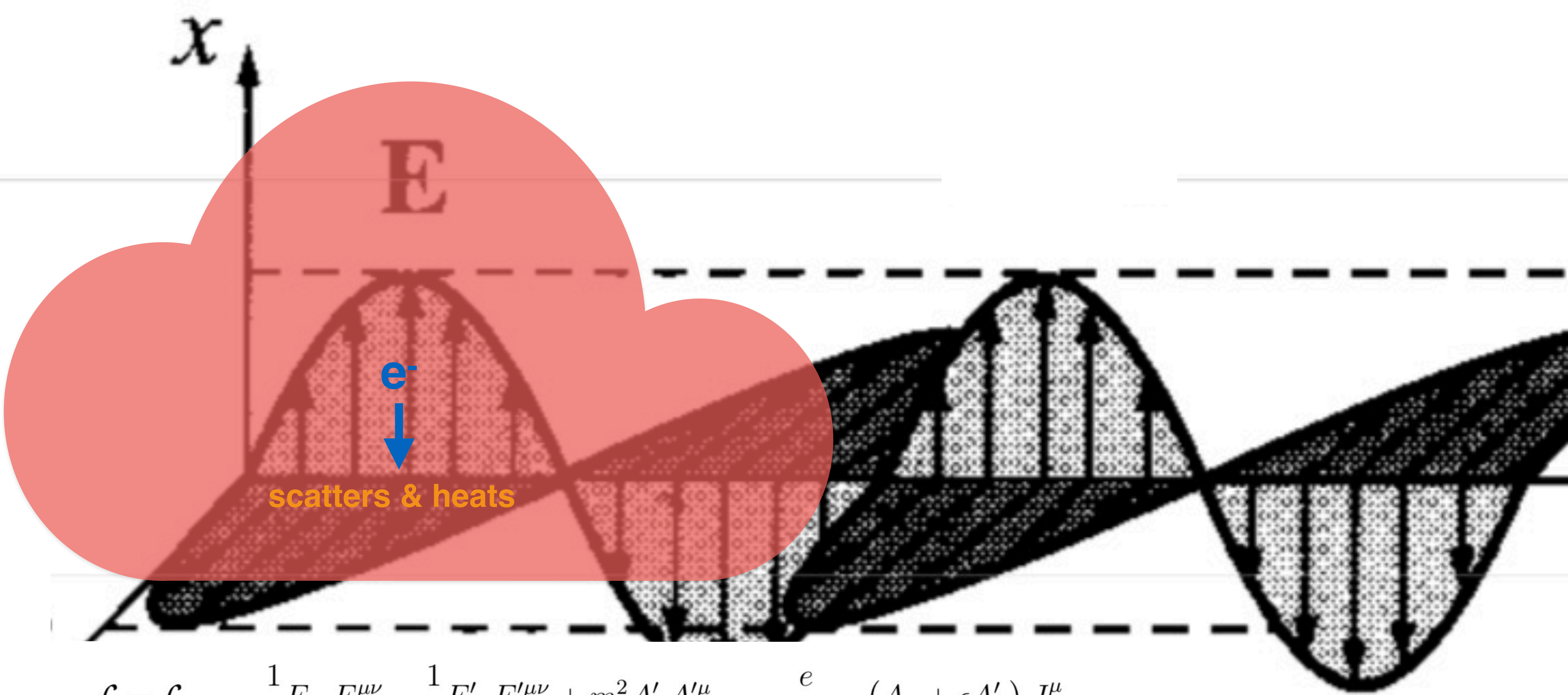
Ultra Light Dark Photon Dark Matter

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2 A'_\mu A'^\mu - \frac{e}{(1+\epsilon)^2}\left(A_\mu + \epsilon A'_\mu\right) J^\mu_{EM}$$



Dark matter could be an extremely light wave, with properties similar to a photon

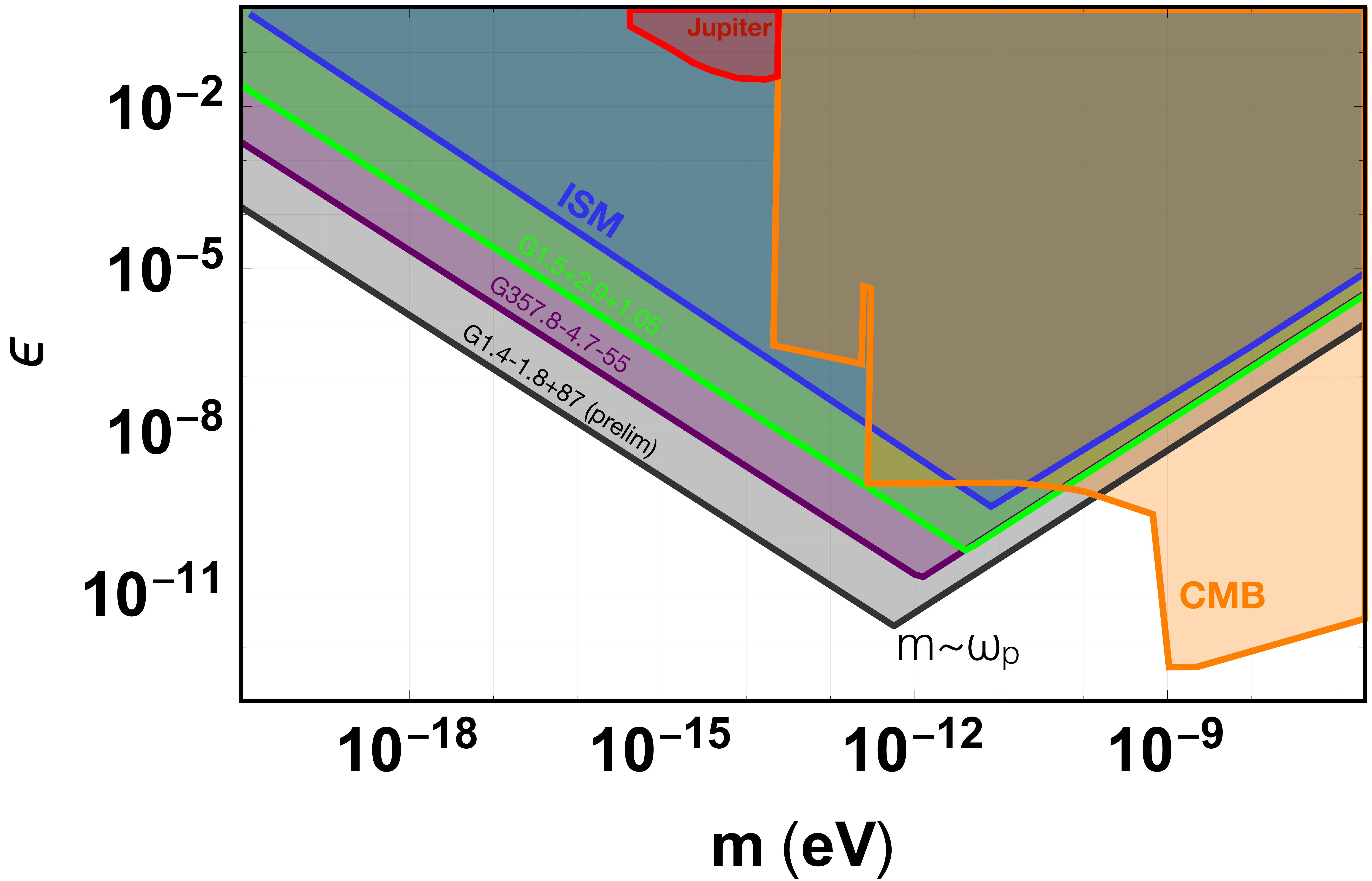
Ultra Light Dark Photon Dark Matter Heats Gas Clouds



$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2 A'_\mu A'^\mu - \frac{e}{(1+\epsilon)^2}\left(A_\mu + \epsilon A'_\mu\right) J^\mu_{EM}$$

$$\gamma_h = \begin{cases} -\frac{\nu}{2}\left(\frac{m}{\omega_p}\right)^2 \frac{\epsilon^2}{1+\epsilon^2}, & m \ll \omega_p \\ -\frac{\nu}{2}\left(\frac{\omega_p}{m}\right)^2 \frac{\epsilon^2}{1+\epsilon^2}, & m \gg \omega_p; \end{cases}$$

Gas Cloud Bounds on Fuzzy Dark Photons



- Solar / terrestrial / martian / white dwarven / neutron stars
- Interstellar gas cloud cooling - ultraheavy and ultralight dark matter
- Oscillating scalar fields boosting DM mass, sourcing gravitational waves
- Nuclear fusion inside dark matter

- Solar / terrestrial / martian / white dwarven / neutron stars
- Interstellar gas cloud cooling - ultraheavy and ultralight dark matter
- Oscillating scalar fields boosting DM mass, sourcing gravitational waves
- Nuclear fusion inside dark matter

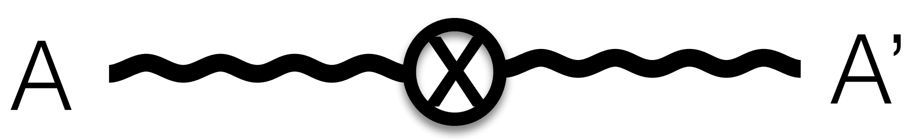
Upcoming work:

- Accelerative dark matter
- Mineral searches for heavy dark matter
- Composite cosmology
- Using macro coherent atomic transitions to search light new particles

Backup Slides

HEAVY COMPOSITE DM IN GAS CLOUD, LONG-RANGE INTERACTIONS

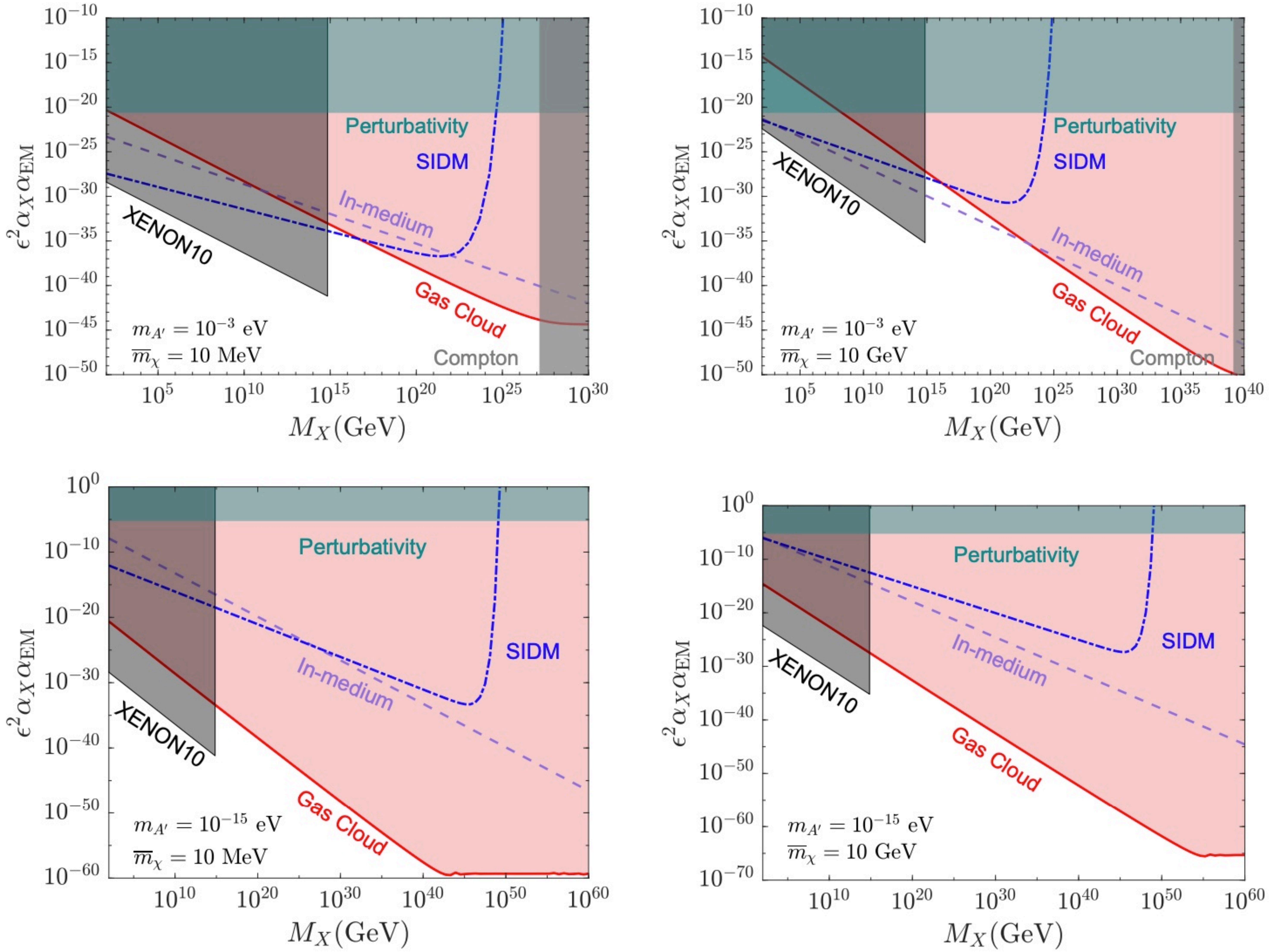
Vector Portal Dark Matter



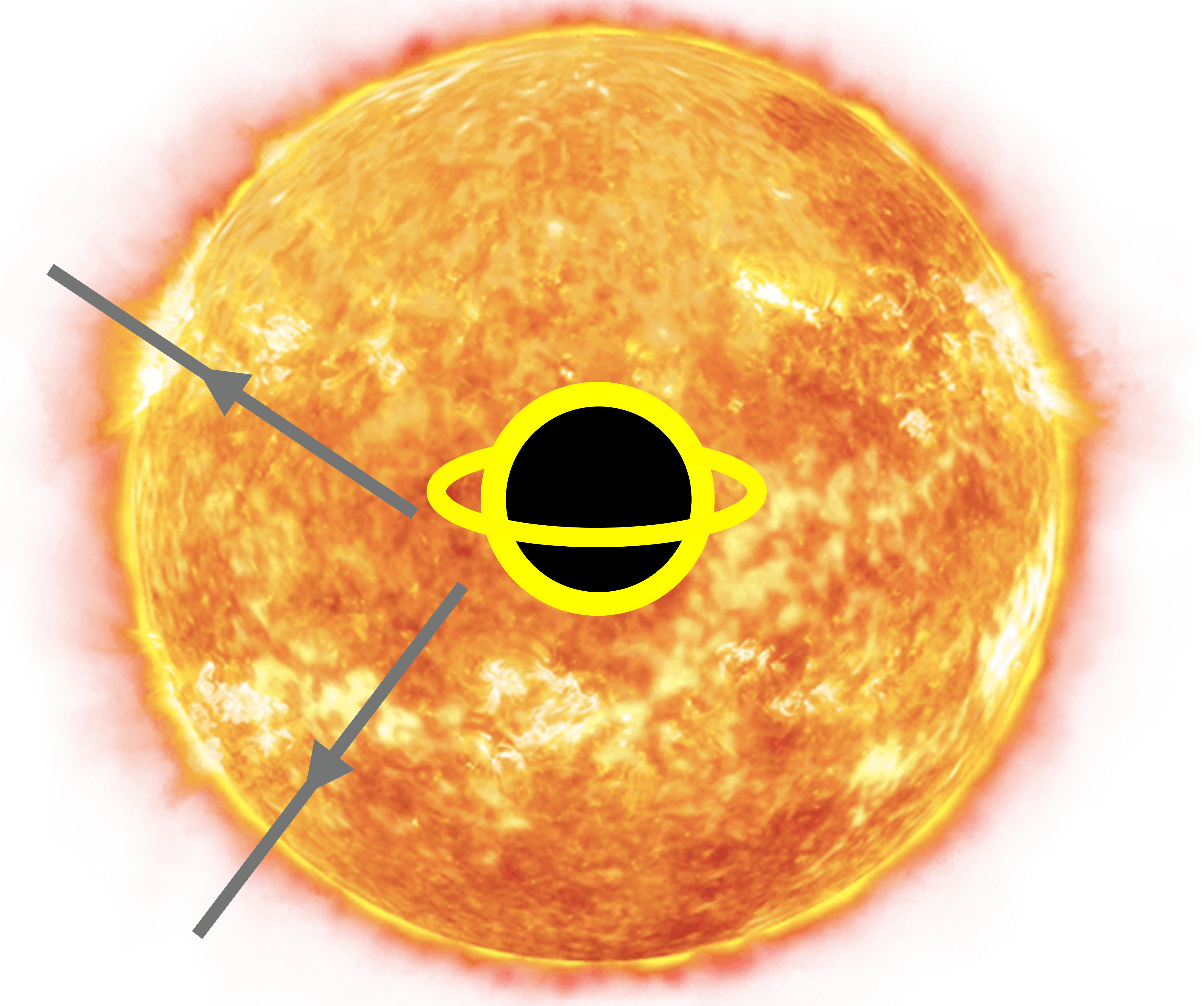
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\kappa}{2}F_{\mu\nu}F'^{\mu\nu} - g_D A'_\mu \bar{\chi}\gamma^\mu\chi$$

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

2010.07240



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

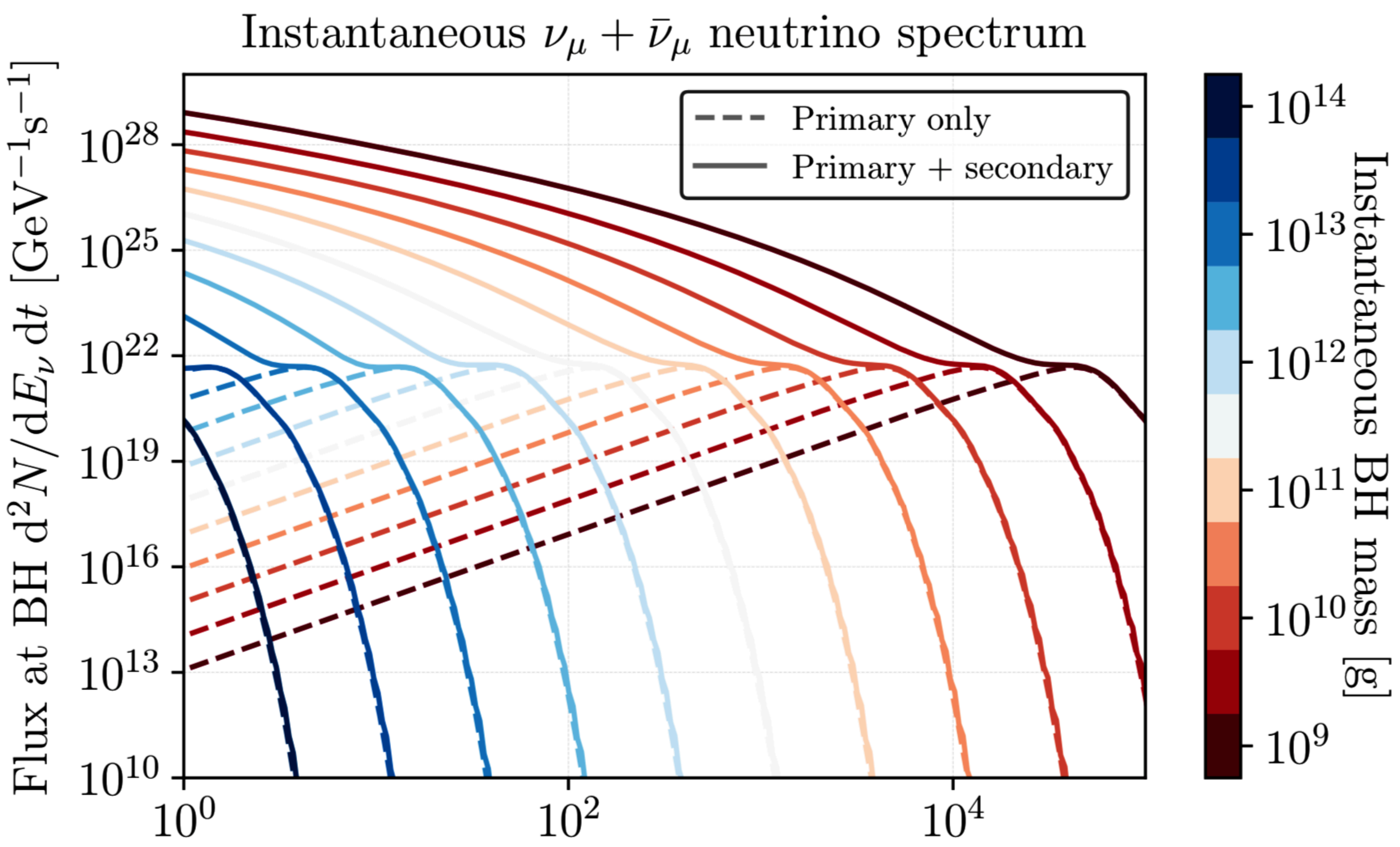
Spectra:

- 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



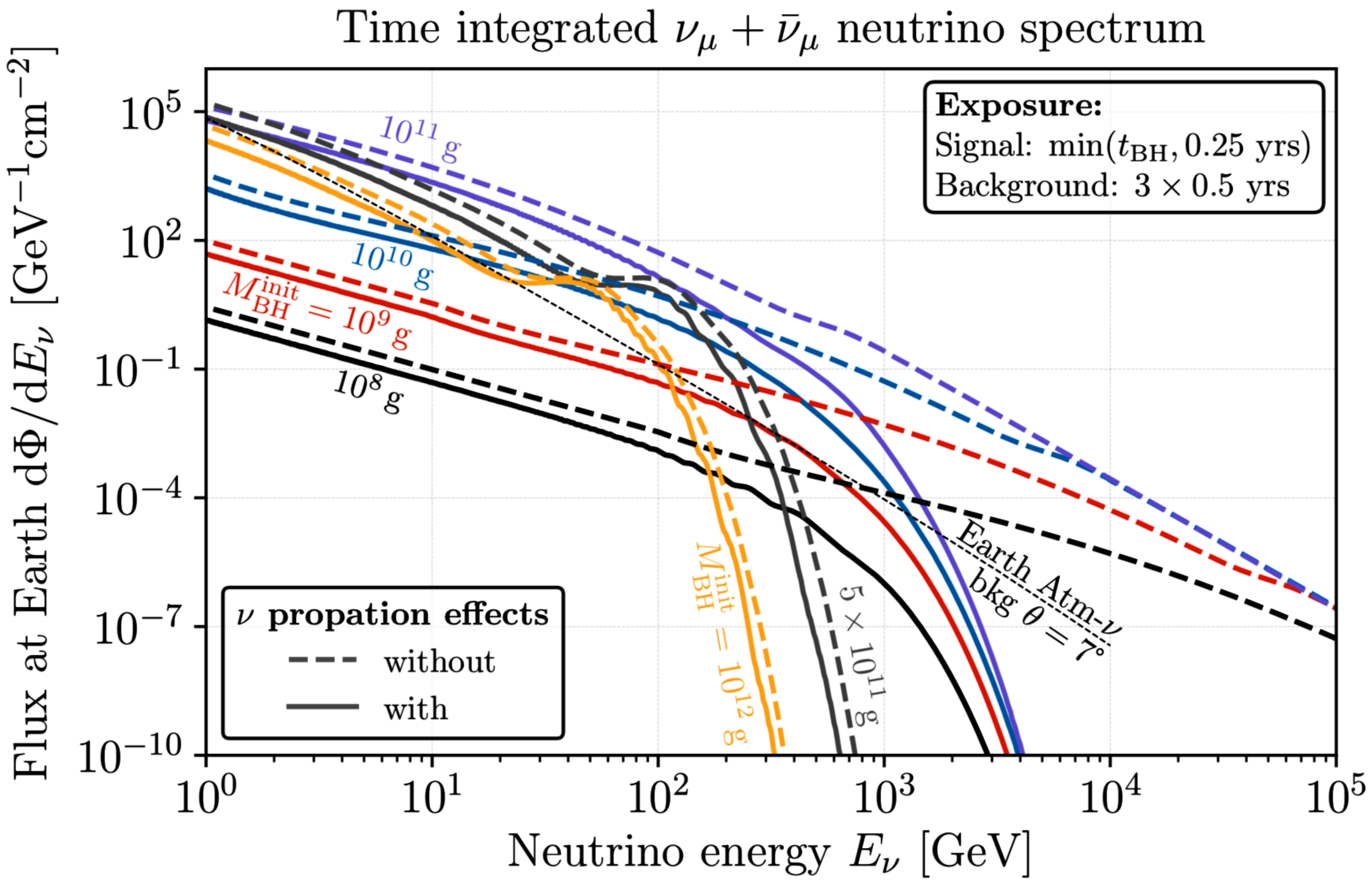
Integrated spectra:

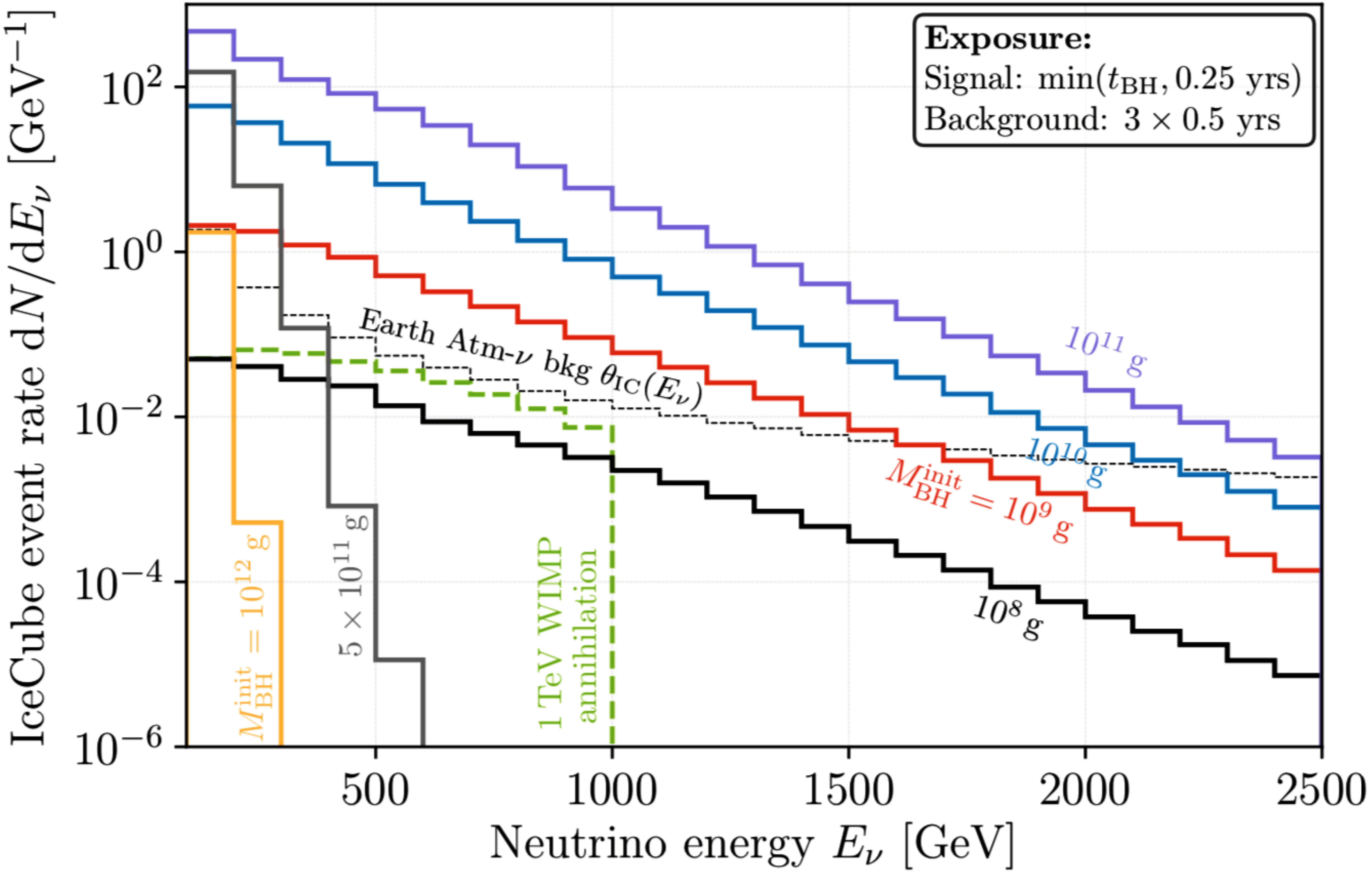
$$\frac{dM_{BH}}{dt} = -\frac{f(M_{BH})}{(GM_{BH})^2}$$

- - - no prop

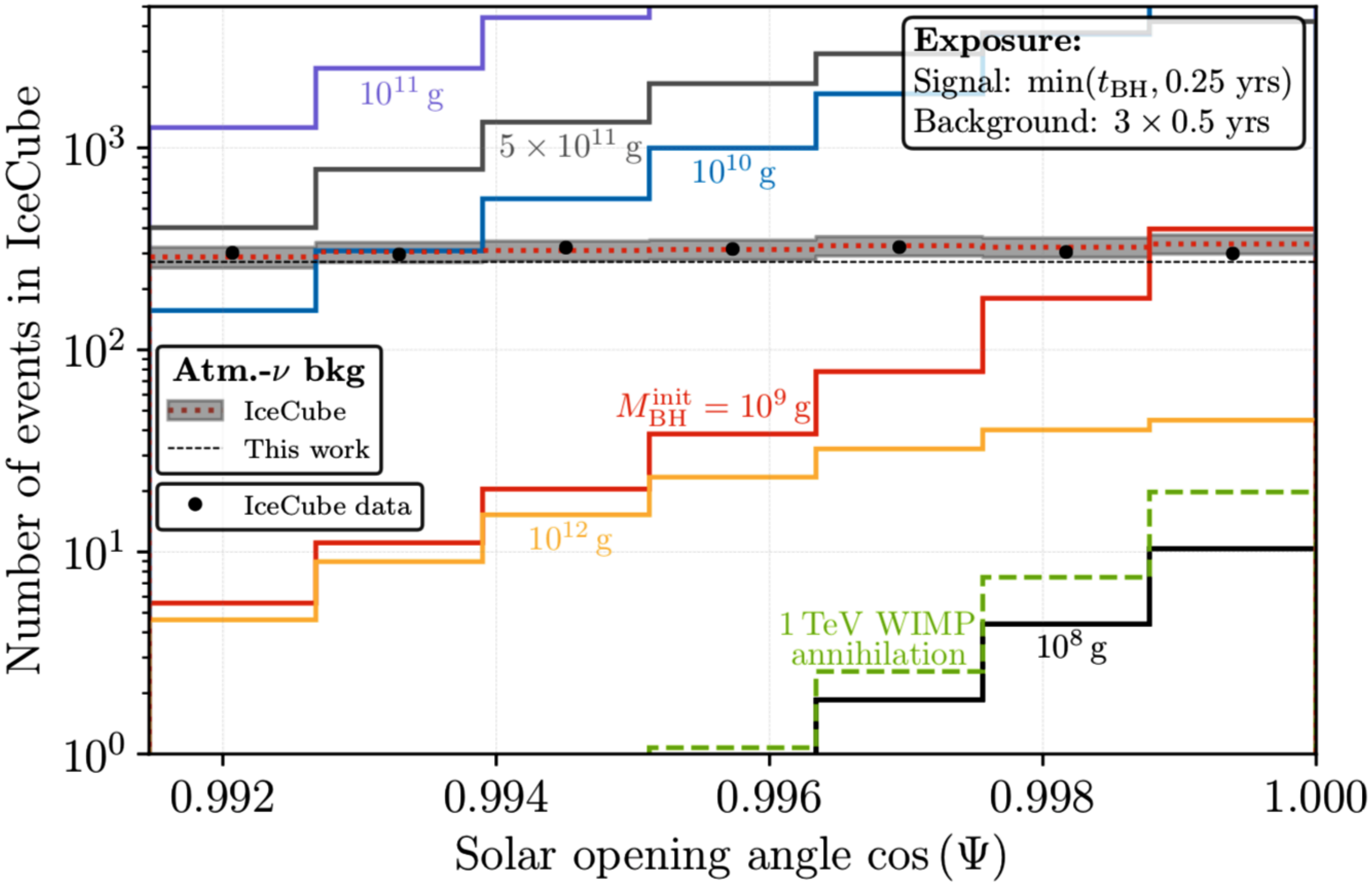
—— prop effects

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

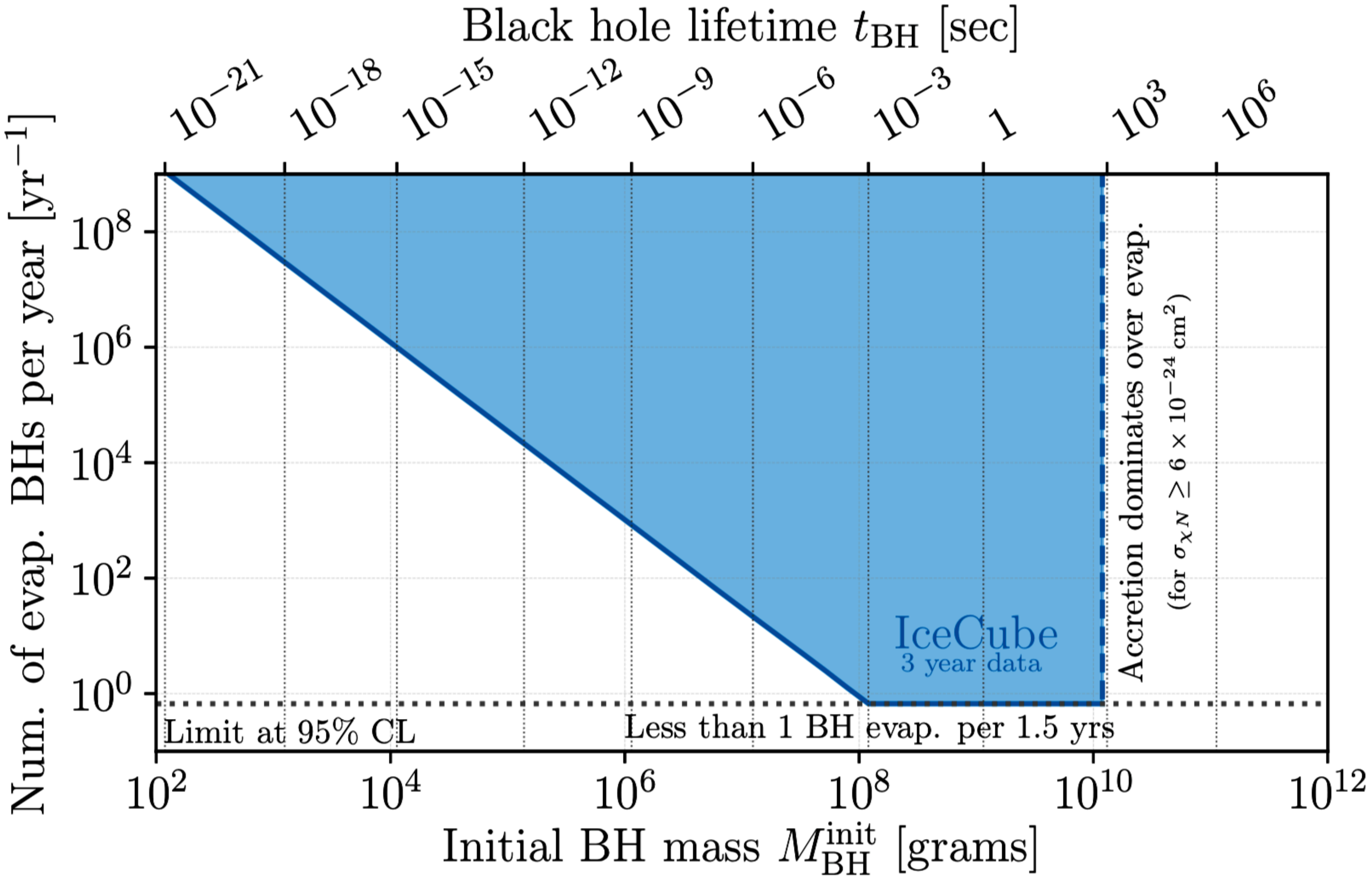




Exposure:
Signal: min(t_{BH}, 0.25 yrs)
Background: 3 × 0.5 yrs
10^{11} g
10^{10} g
$M_{BH}^{init} = 10^9$ g
10^8 g
Earth Atm-ν bkg $\theta_{IC}(E_\nu)$
$M_{BH}^{init} = 10^{12}$ g
5×10^{11} g
1 TeV WIMP annihilation
IceCube event rate dN/dE_ν [GeV^{-1}]
Neutrino energy E_ν [GeV]
10^2
10^0
10^{-2}
10^{-4}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



Analysis recast from IceCube's 1612.05949



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

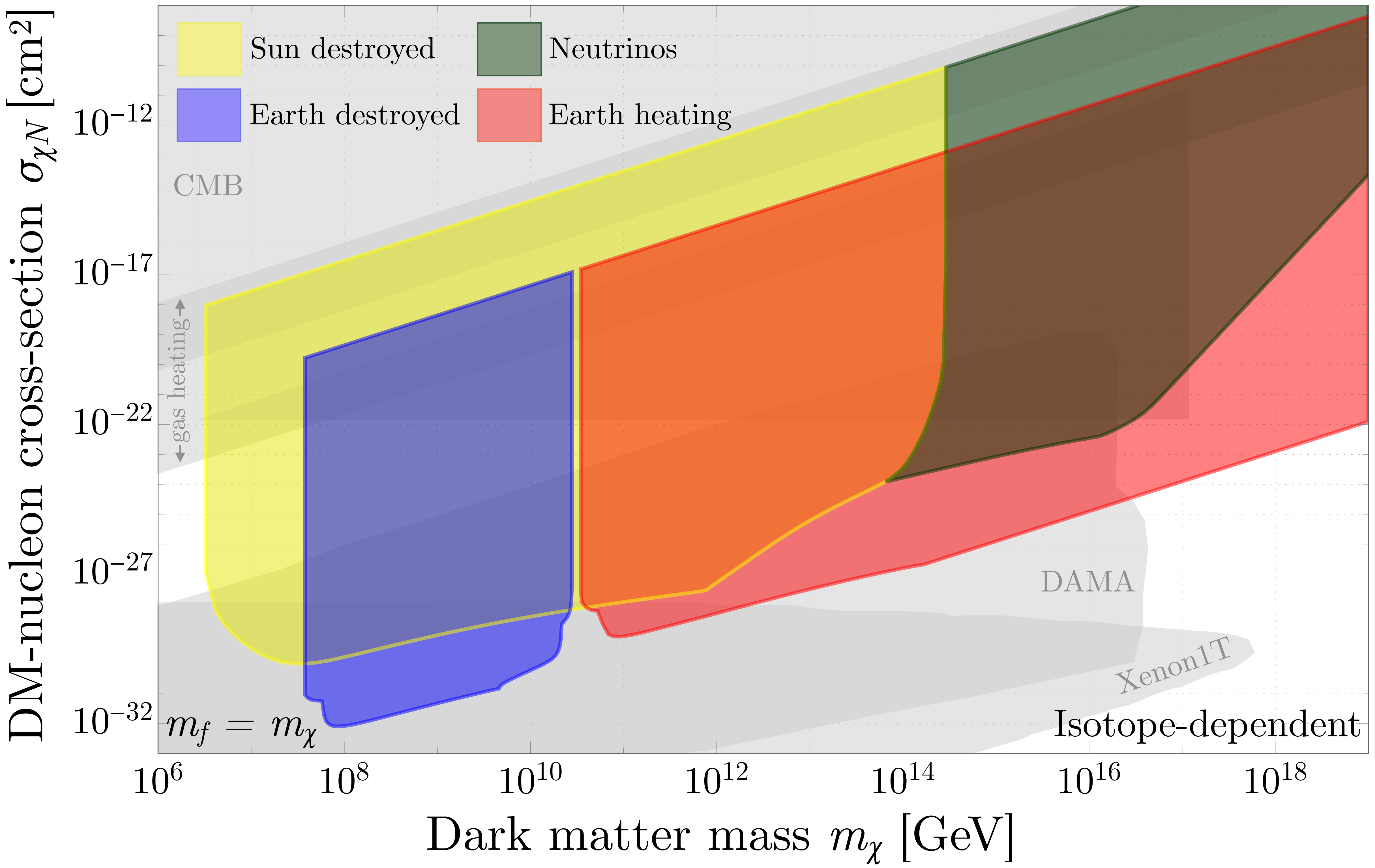
Need multiple evaporating BHs

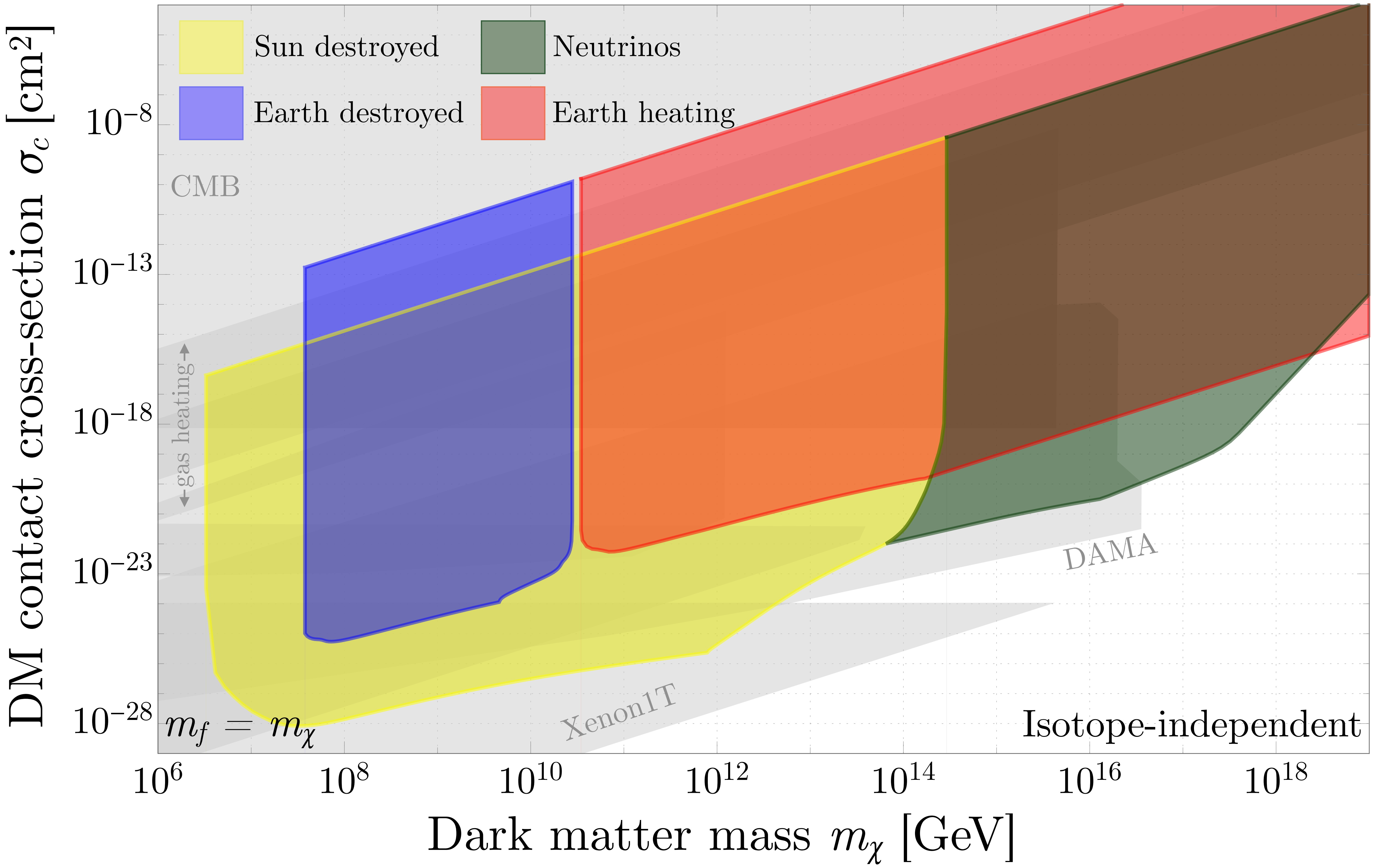
$10^8 \text{ g} \lesssim M_{BH}^{init} \lesssim 4 \times 10^{10}$ g

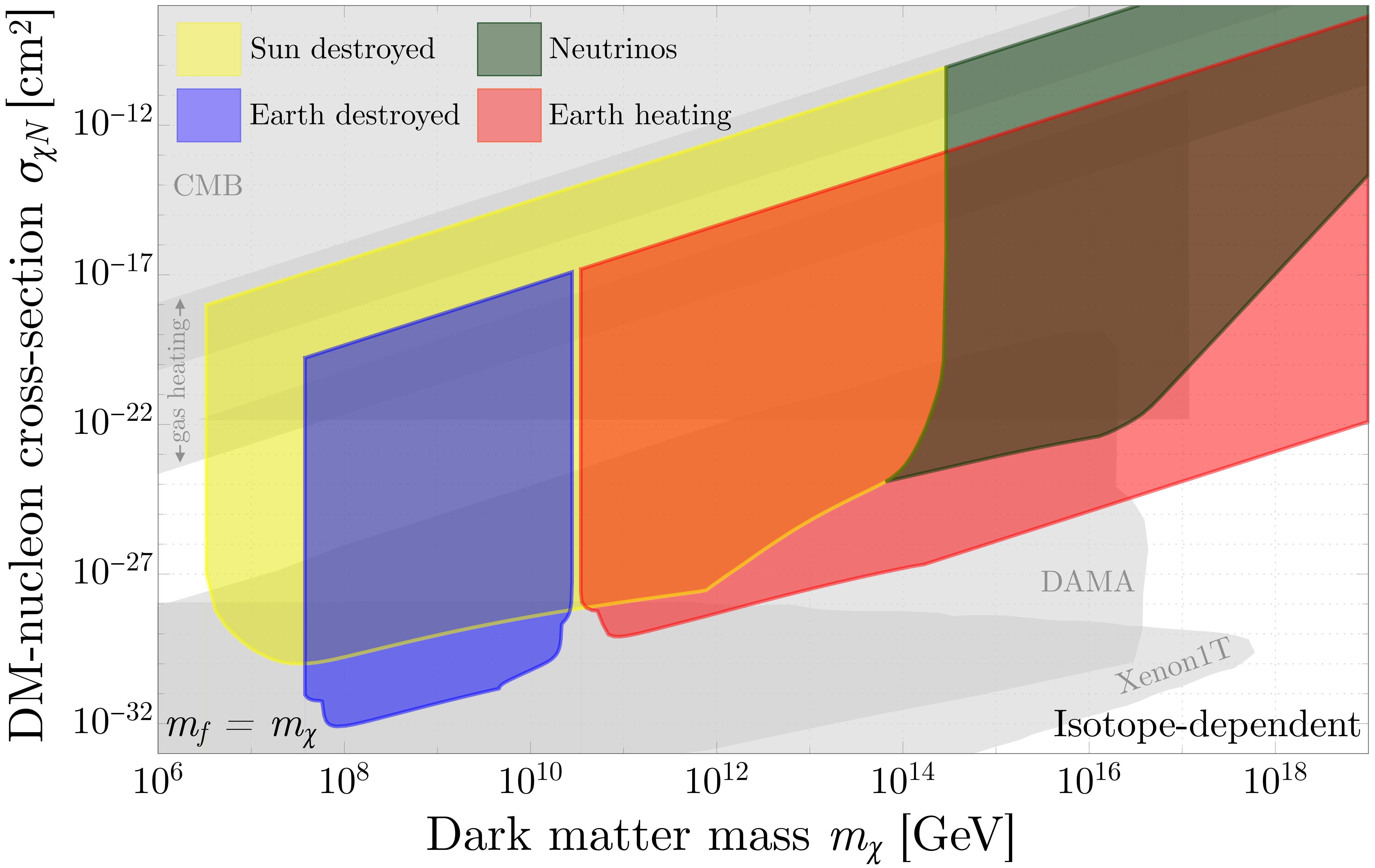
single evaporating BH suffices

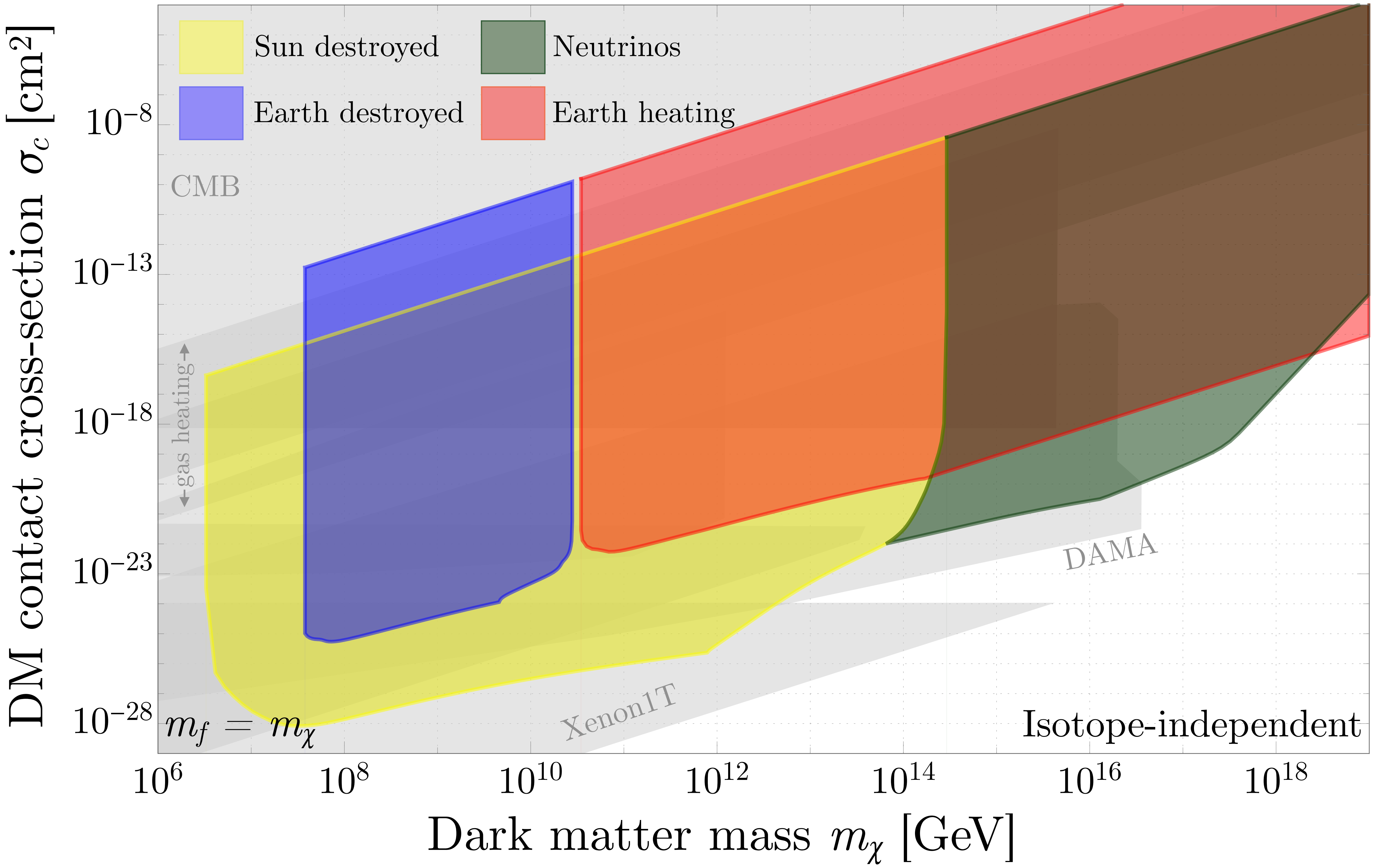
$M_{BH}^{init} \gtrsim 4 \times 10^{10}$ g

BHs do not evaporate

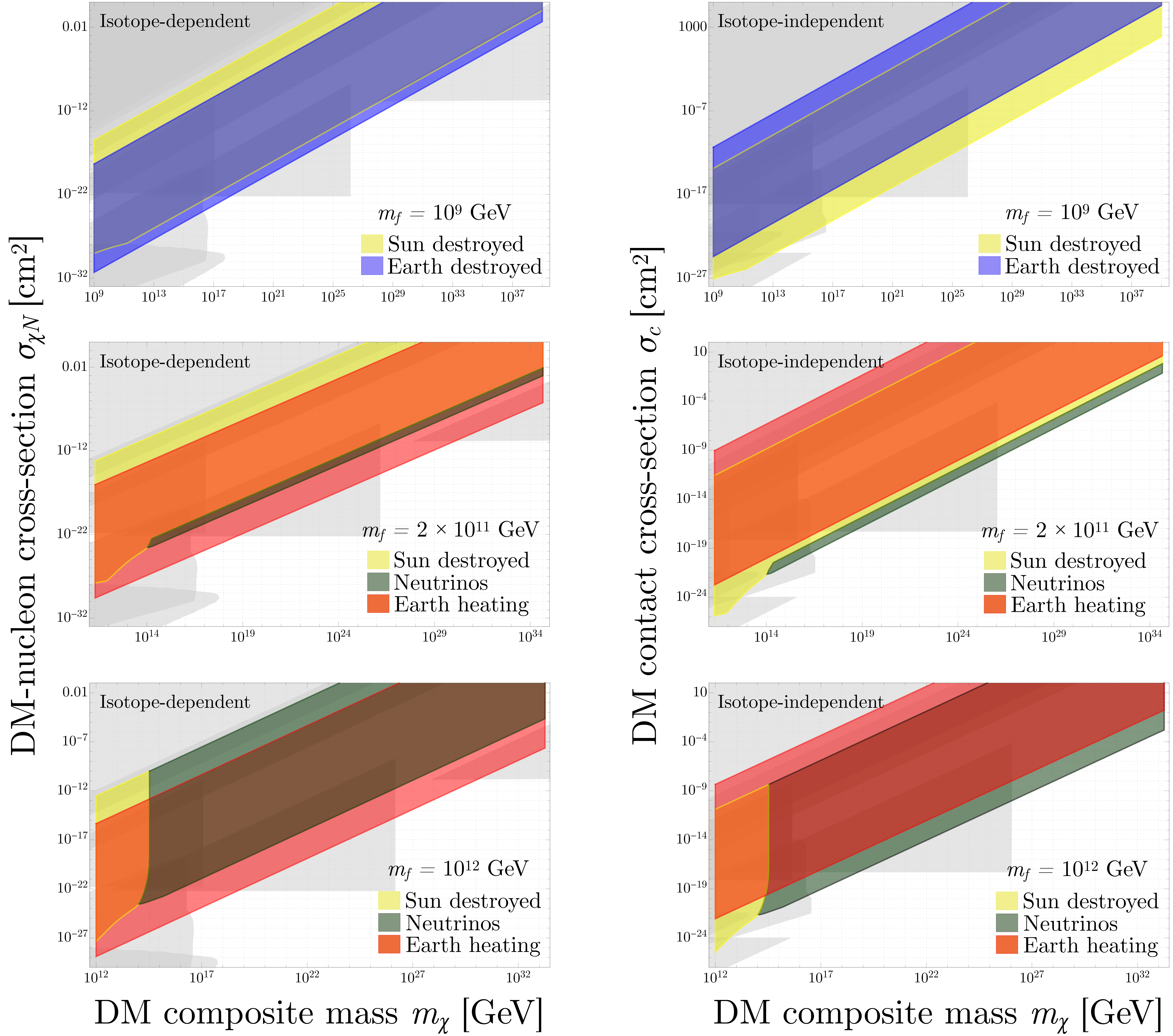

Sun destroyed
Neutrinos
Earth destroyed
Earth heating
CMB
gas heating
DAMA
Xenon1T
$m_f = m_\chi$
Isotope-dependent
DM-nucleon cross-section $\sigma_{\chi N}$ [cm^2]
Dark matter mass m_χ [GeV]


Sun destroyed
Neutrinos
Earth destroyed
Earth heating
CMB
gas heating
DAMA
Xenon1T
$m_f = m_\chi$
Isotope-independent
DM contact cross-section σ_c [cm^2]
Dark matter mass m_χ [GeV]





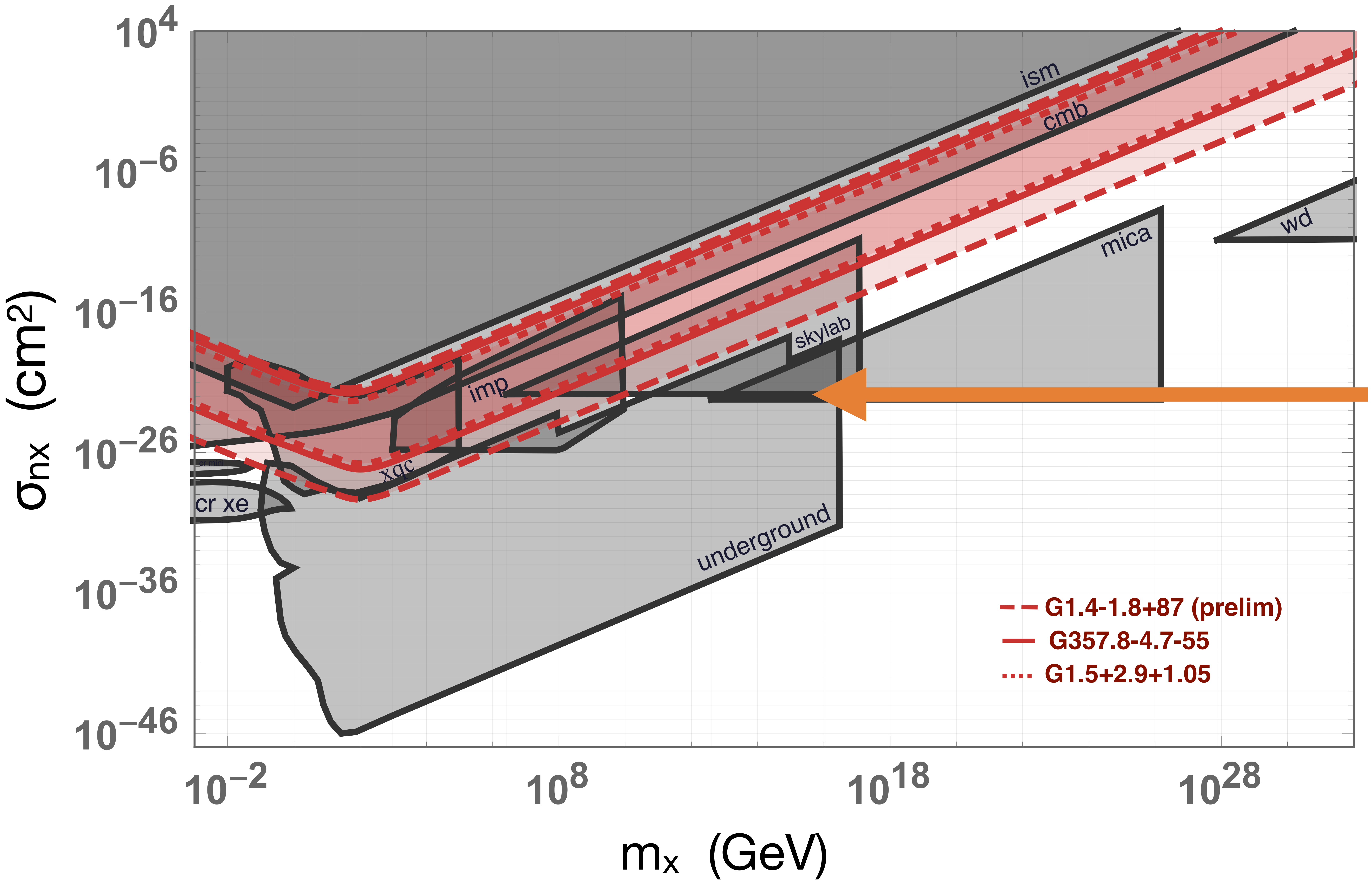
$$M_{crit} = \frac{M_{pl}^3}{m_f^2}$$


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]

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

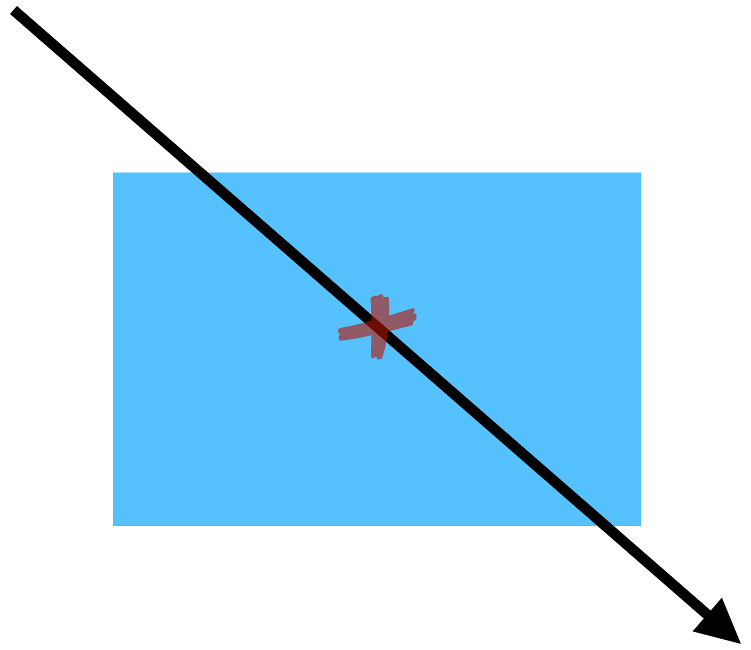
New searches for multiply interacting dark matter (MIMPs)

EXTRAPOLATING TO HIGH MASS DARK MATTER



Naive extrapolation fails, need new analyses.

EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



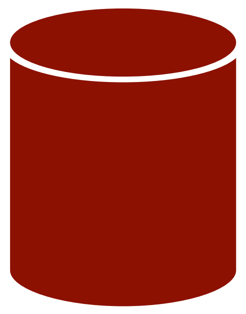
- If particles have velocity v (~0.001c), then sensitivity of detector sets a minimum energy threshold for detection

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

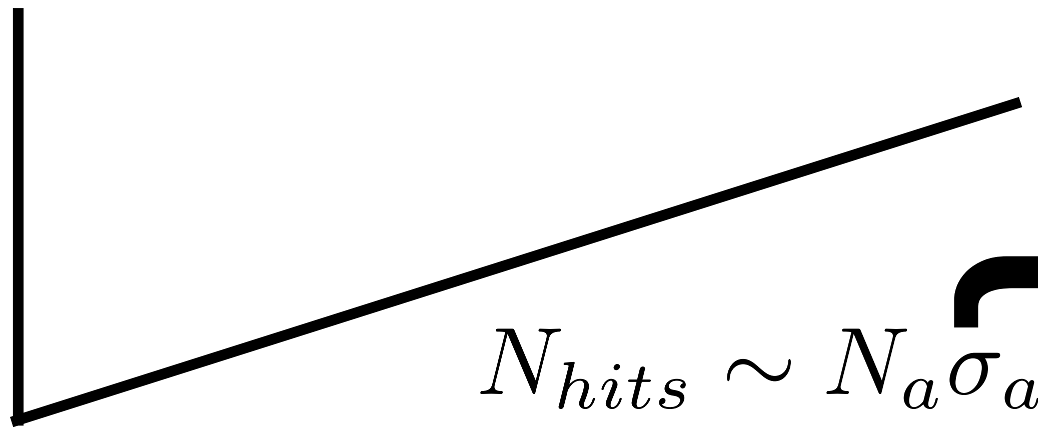
cross-section for DM to hit detector particle

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

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

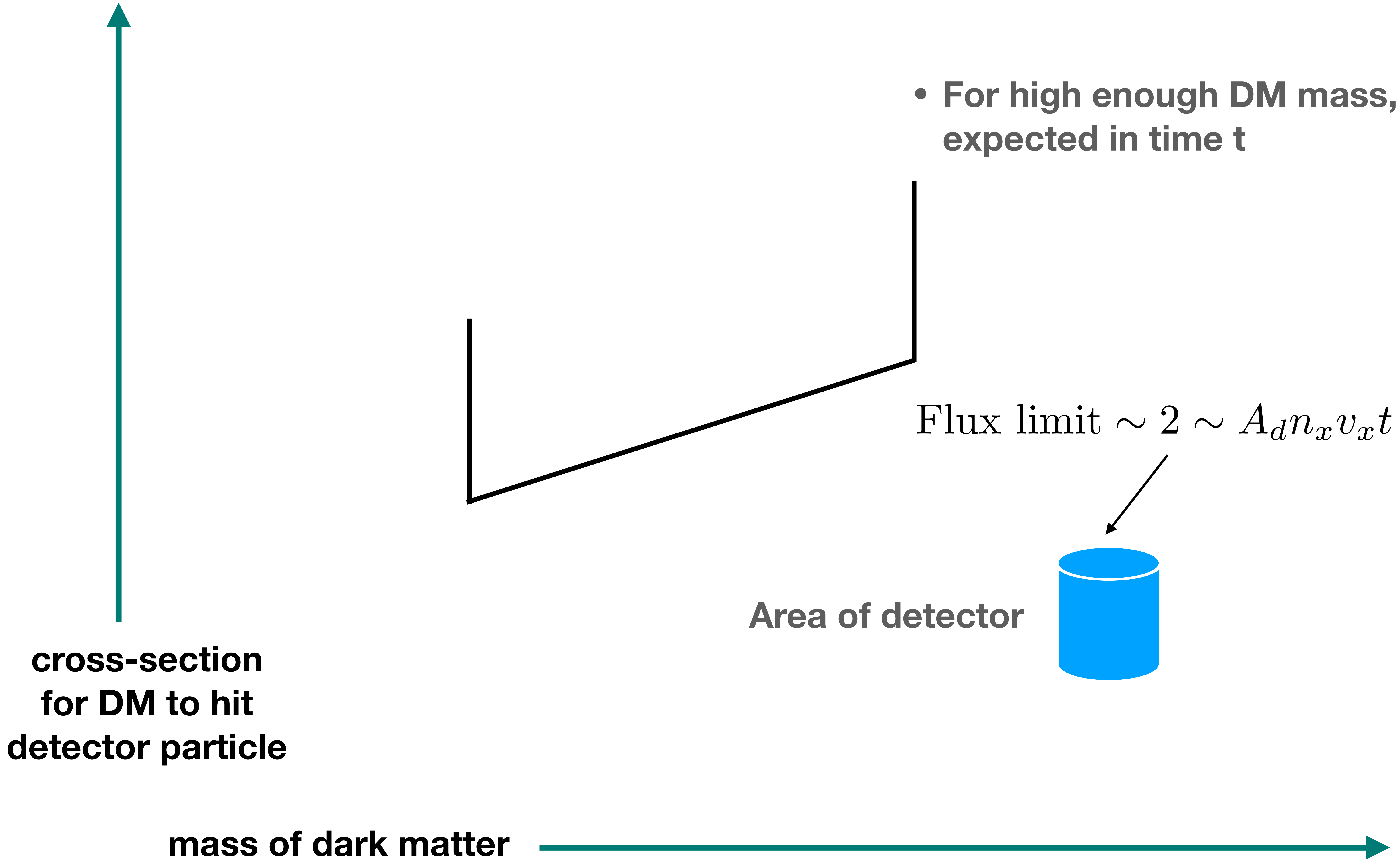
DM number density

cross-section
for DM to hit
detector particle

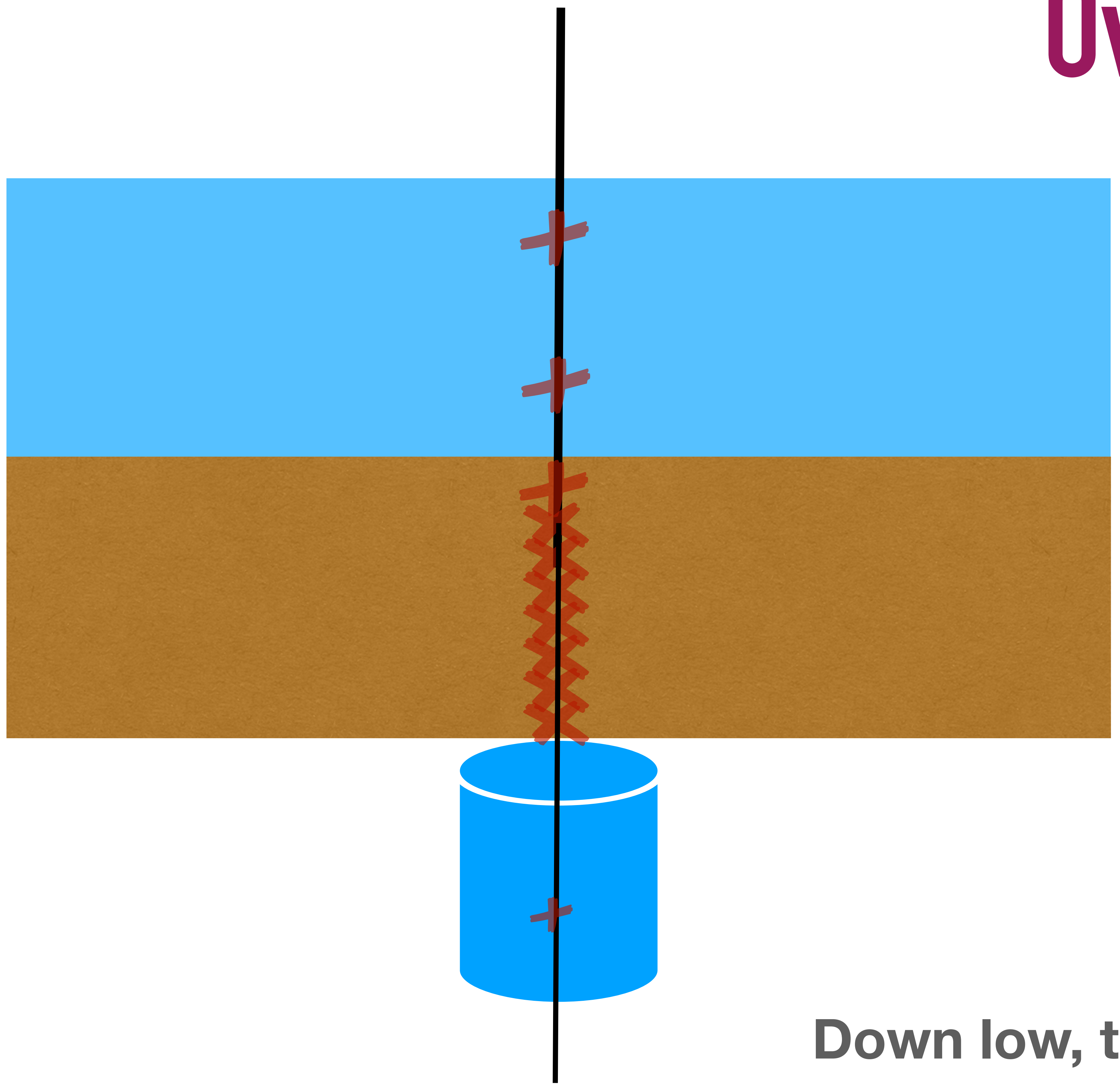
mass of dark matter

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?

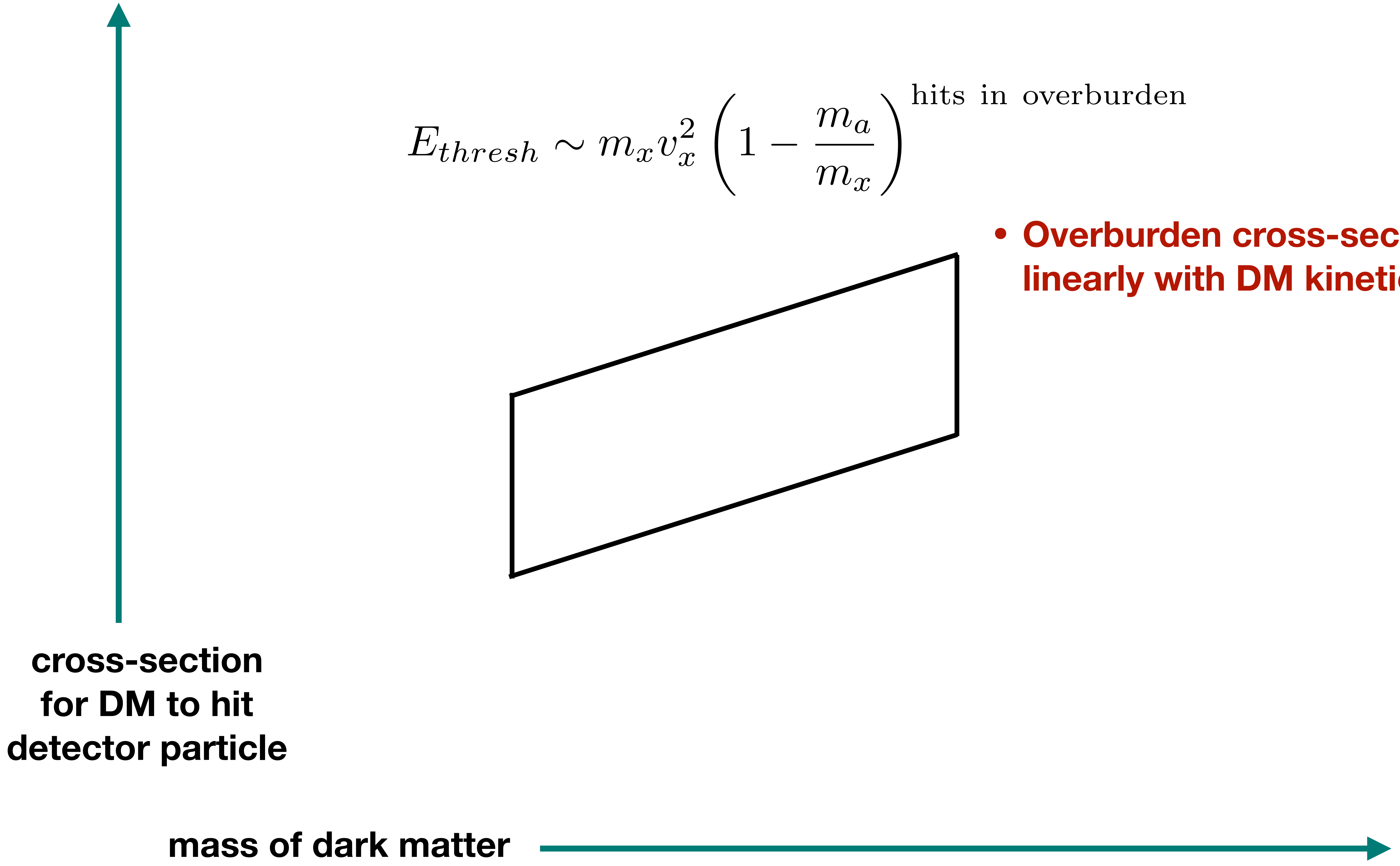
Length of overburden

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

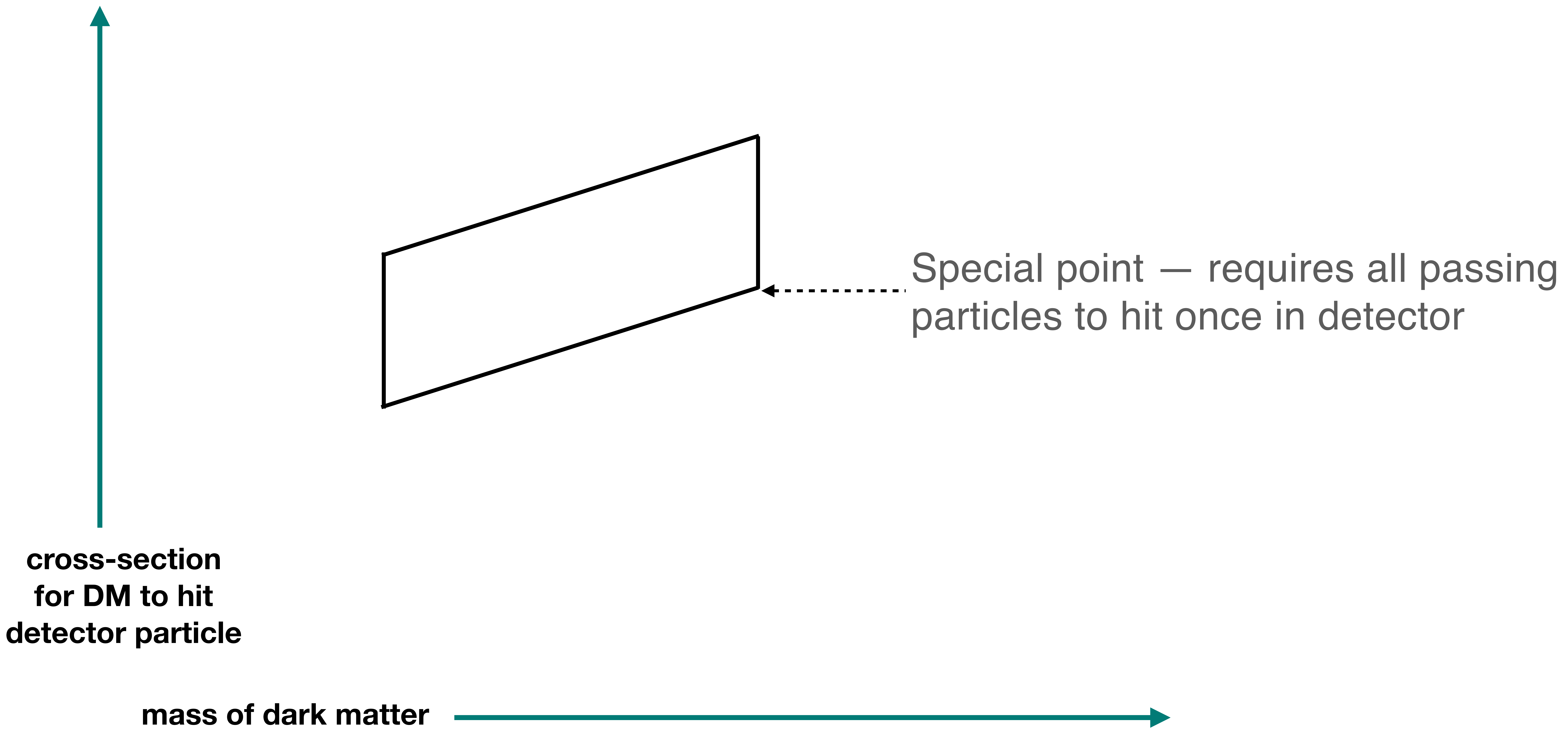
EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES

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

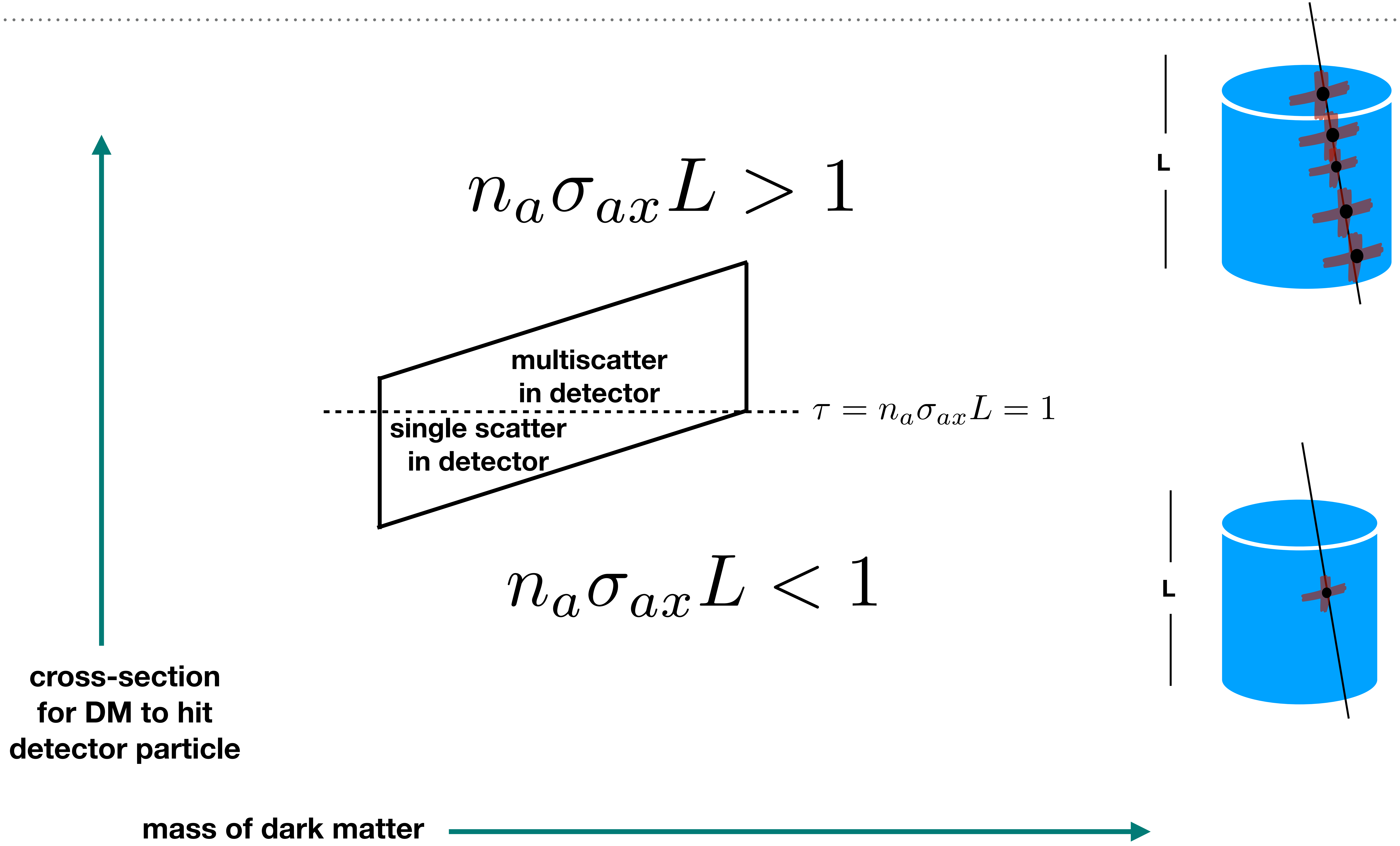
- Overburden cross-section increases linearly with DM kinetic energy $\sim m_x v_x^2$



EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES

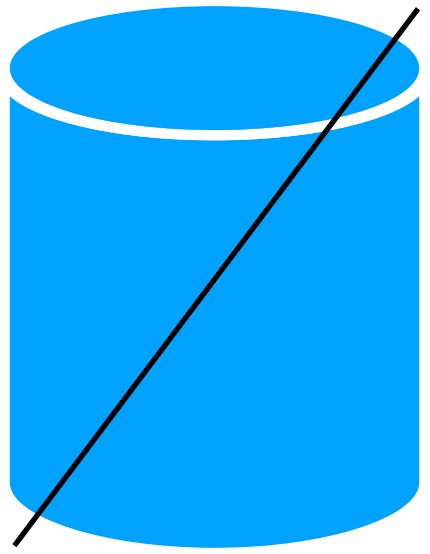


MULTISCATTER DARK MATTER DETECTION



Multiscatter frontier, in general

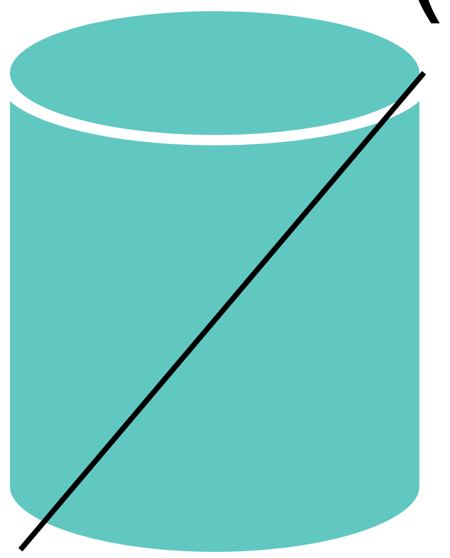
Transit time for a MIMP through
a meter is five microseconds



Individual nuclear scattering events typically
deposit ~10 keV

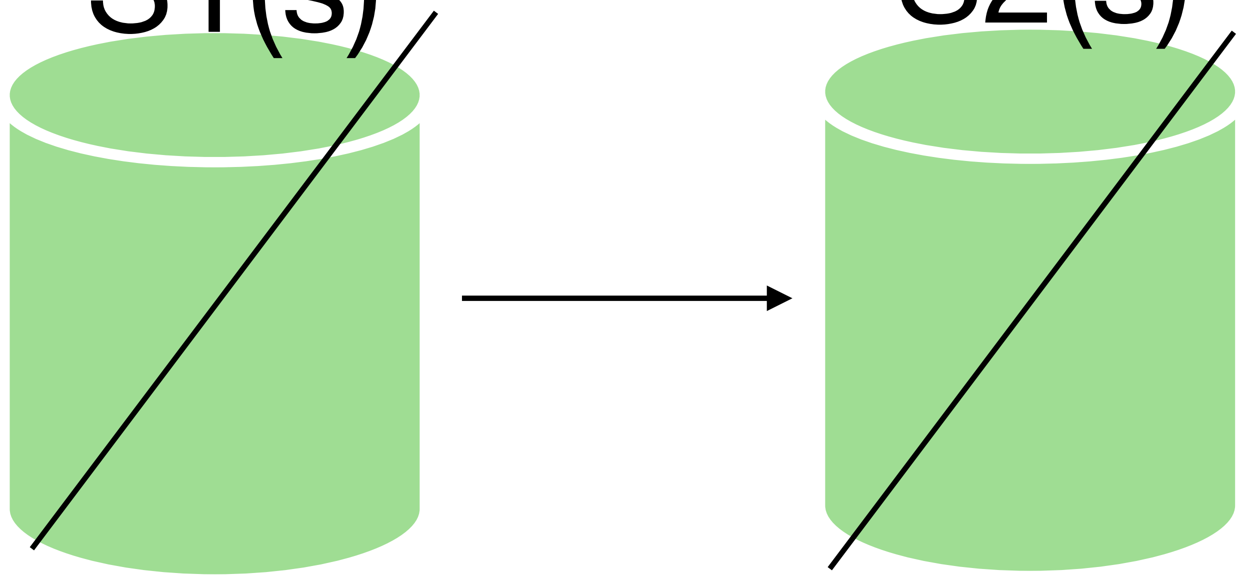
Bubble Chamber

bubble(s)



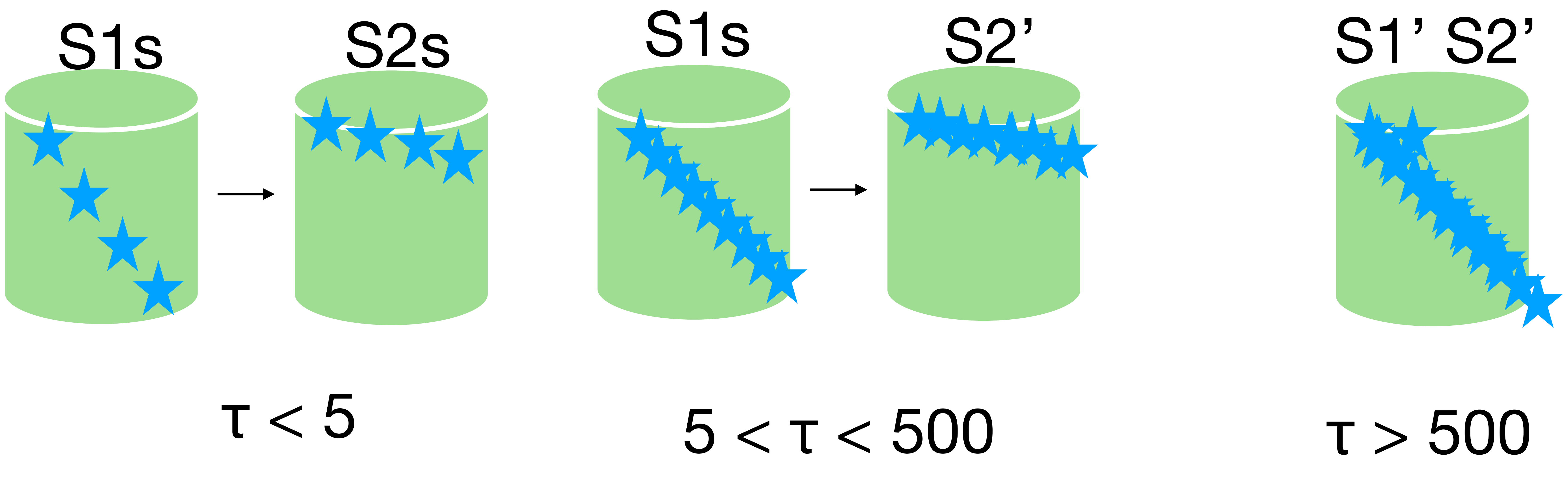
Time Projection Chamber

S1(s) S2(s)



Multiscatter frontier, Xenon TPC

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

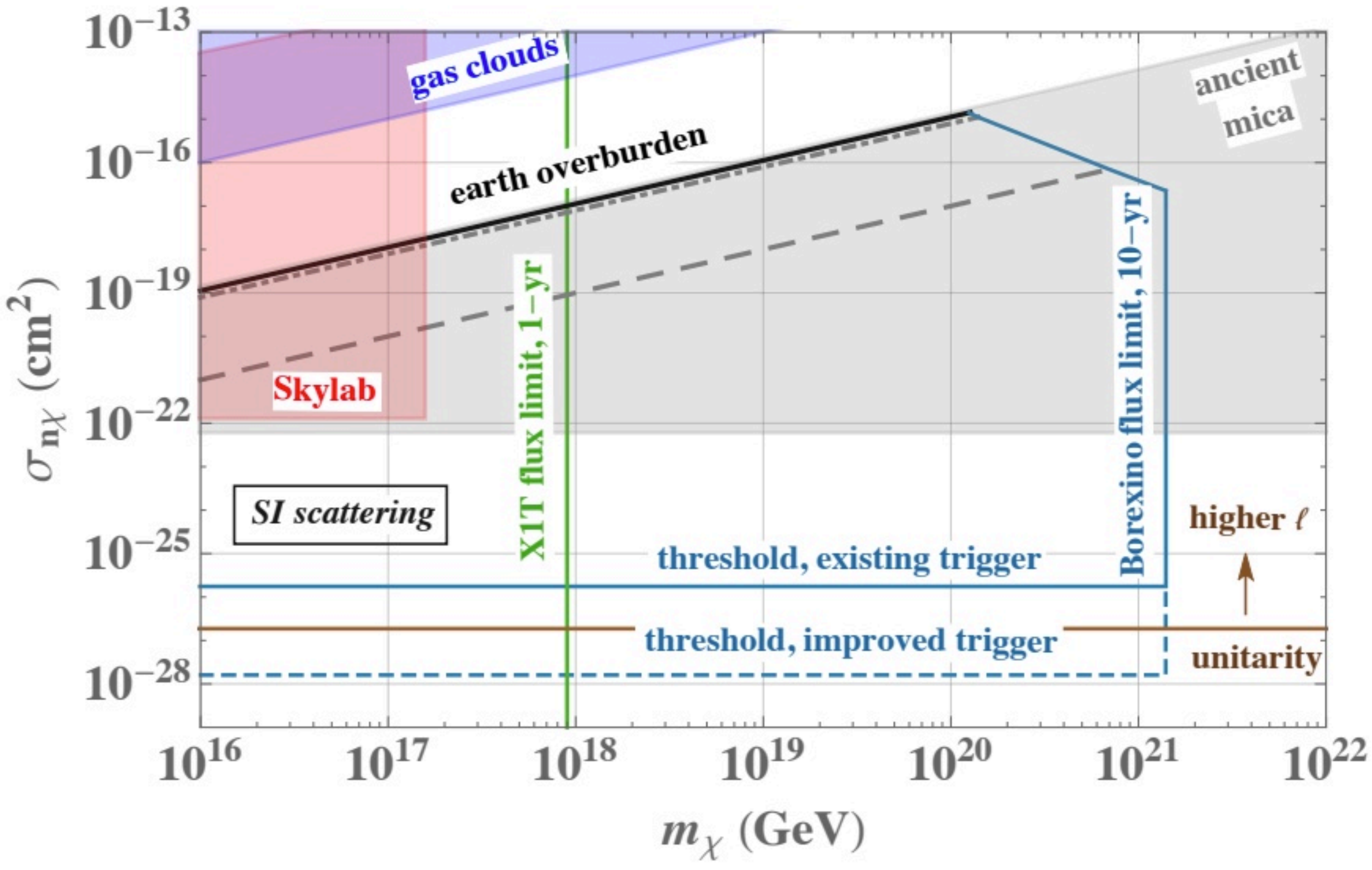


τ is the approximate number of hits per detector passage.
For τ > 5 (τ > 500) the S2 (S1) pulses merge
into elongated pulses S2' (S1').

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

UNDERGROUND MULTISCATTER PROSPECTS

Scintillating Neutrino Detectors

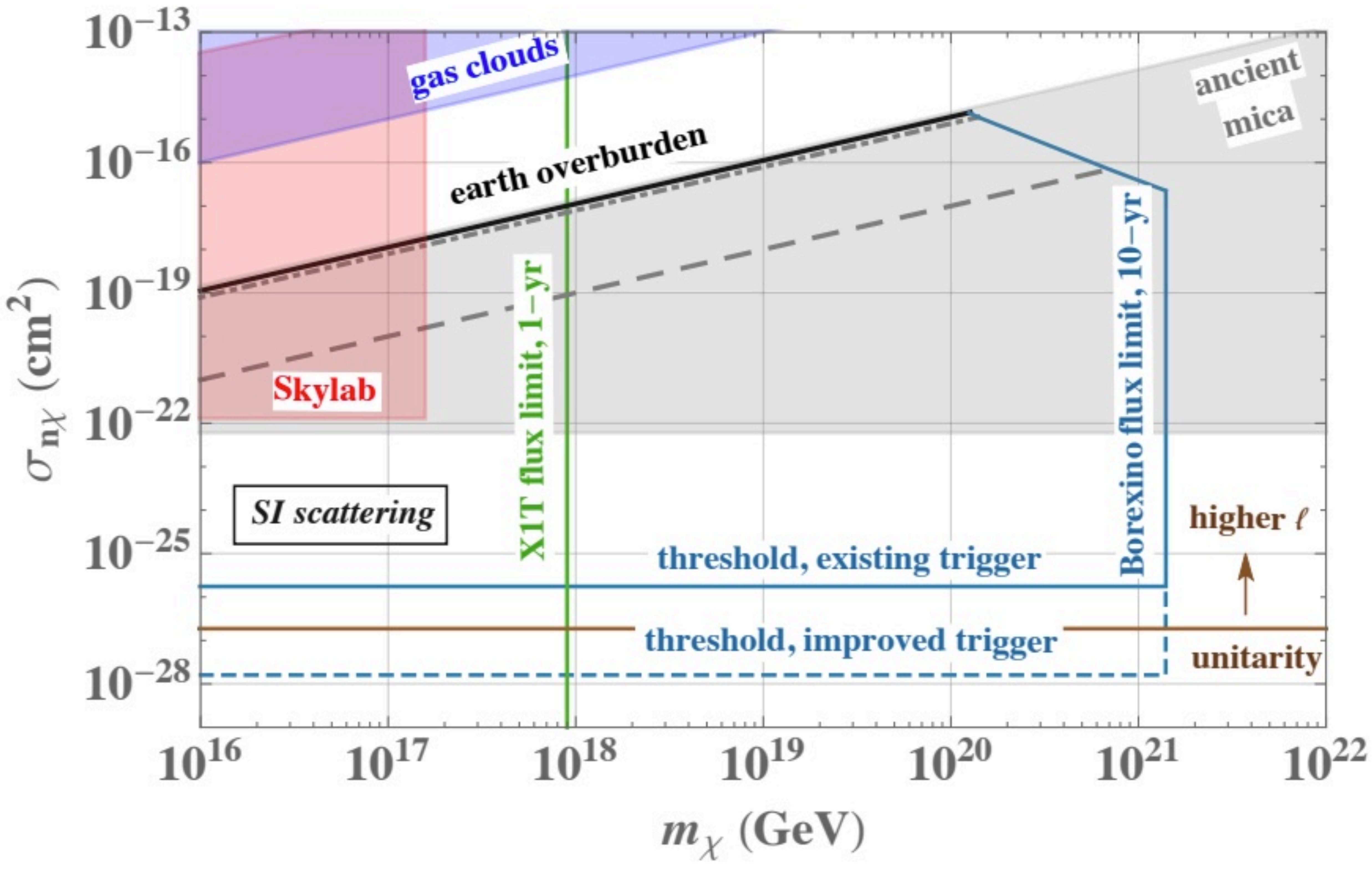


1812.09325

1910.05380

UNDERGROUND MULTISCATTER PROSPECTS

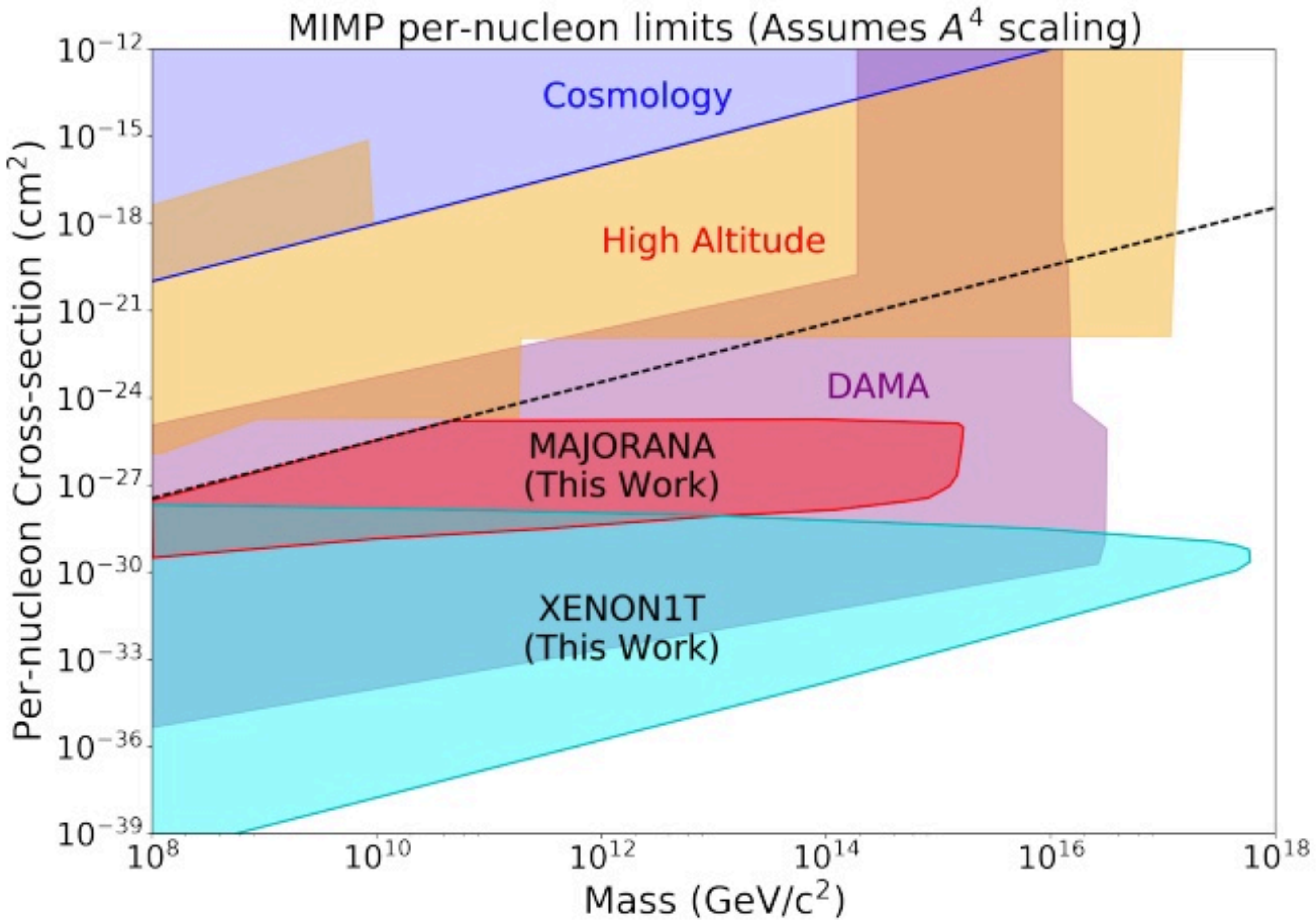
Scintillating Neutrino Detectors



1812.09325

1910.05380

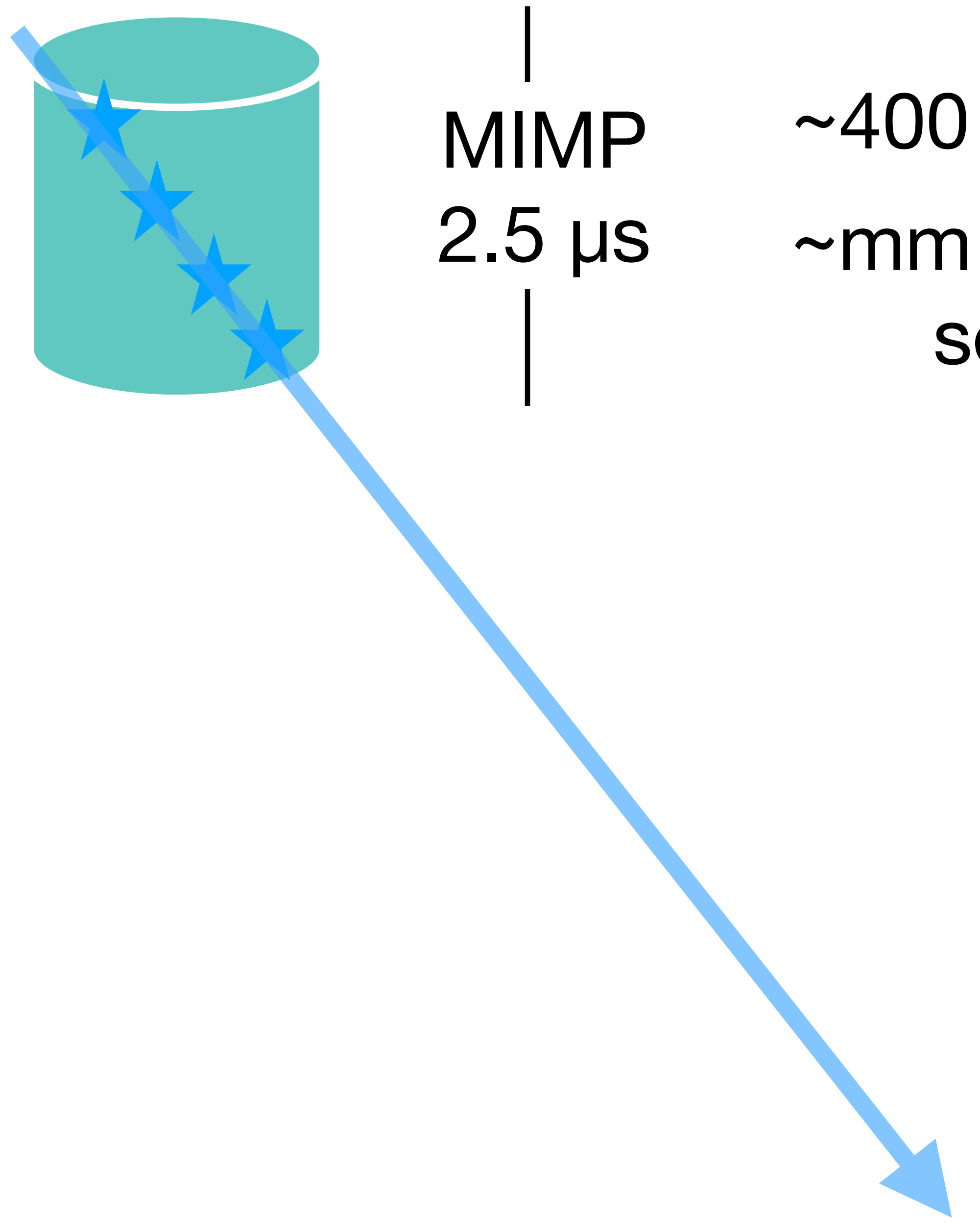
Underground Multiscatter Searches



1803.08044

2009.07909

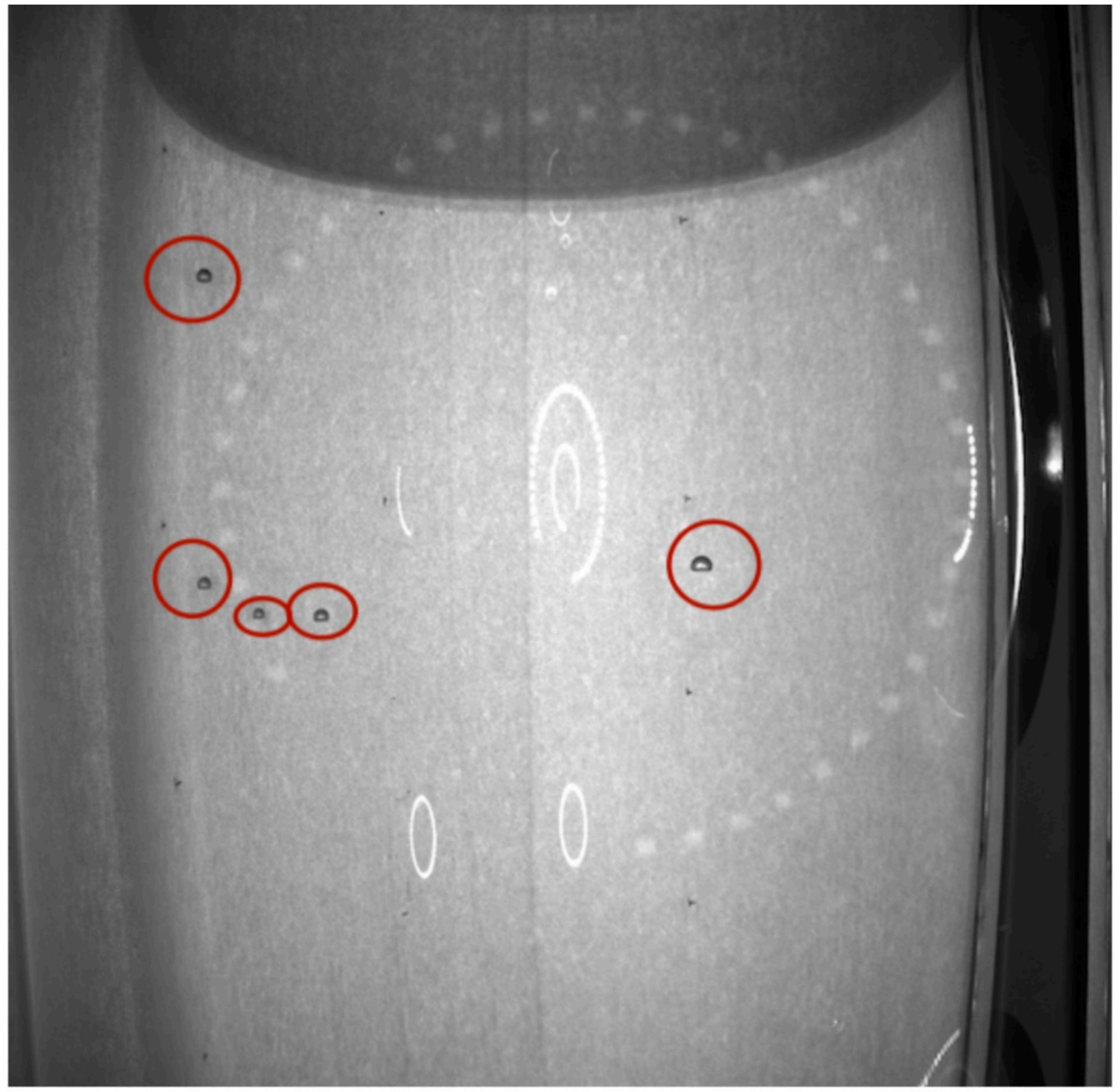
PICO-60 multiscatter search ongoing

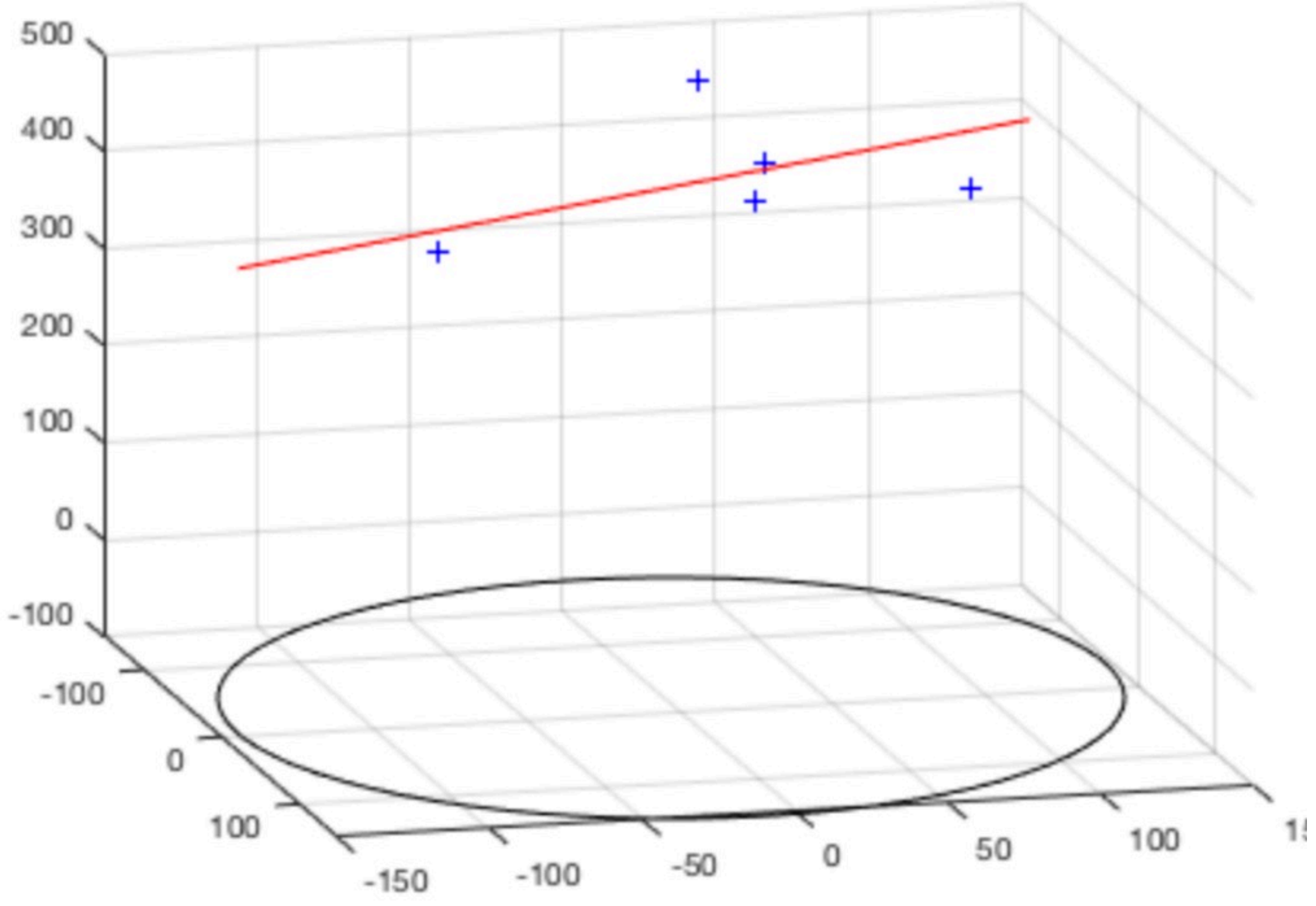


MIMP
2.5 µs

~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

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

ETCHING PLASTIC SEARCHES FOR DARK MATTER

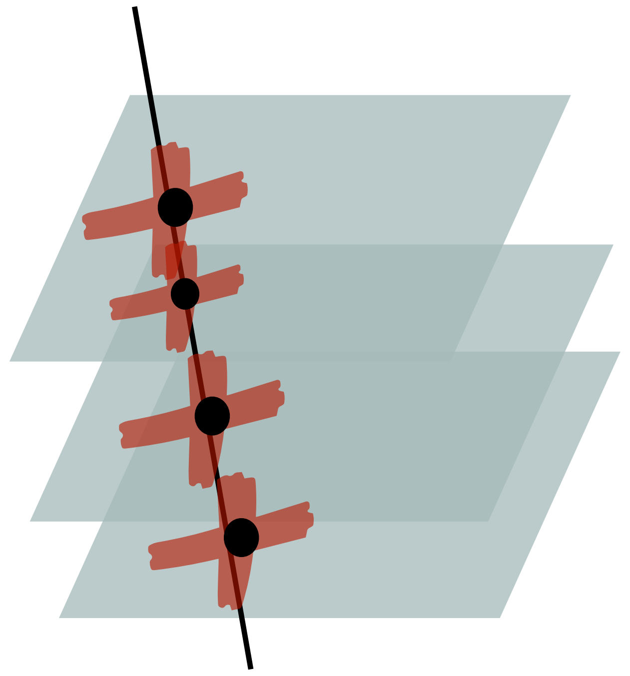
- *Two searches in 1978 and 1990 for cosmic rays and monopoles using acid-etched plastic track detectors*
- *Still have best sensitivity for some high mass dark matter, for different reasons*

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



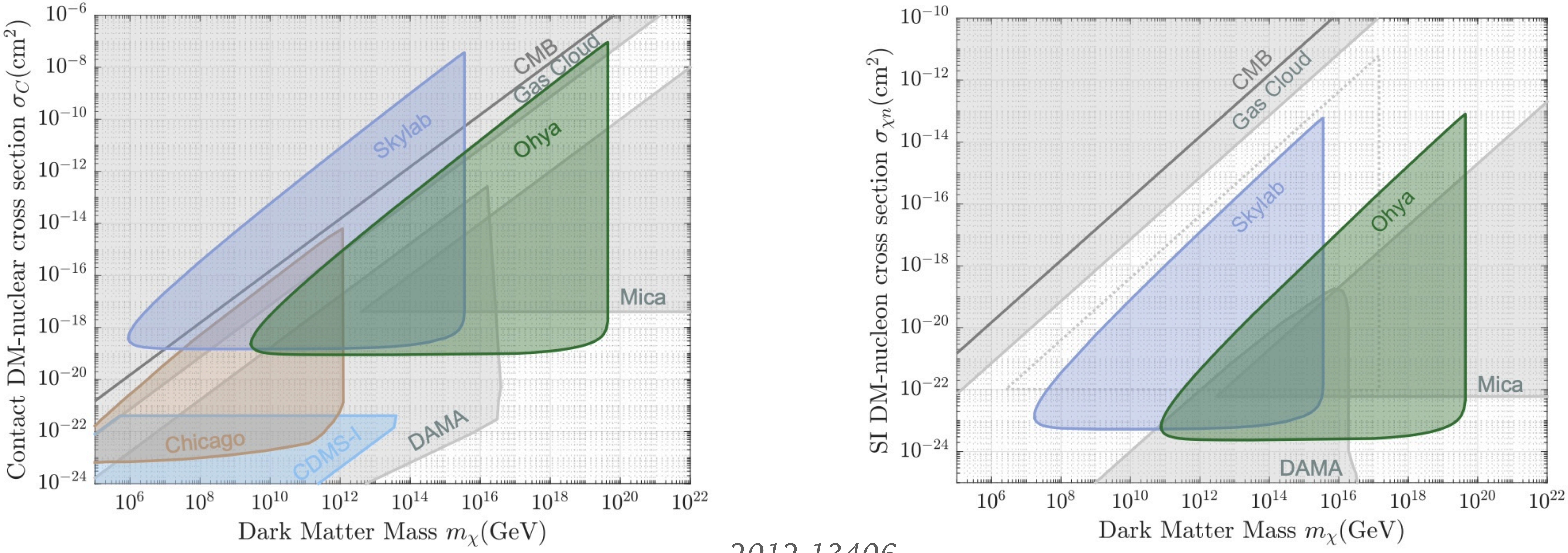
Ohya Quarry

(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*

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

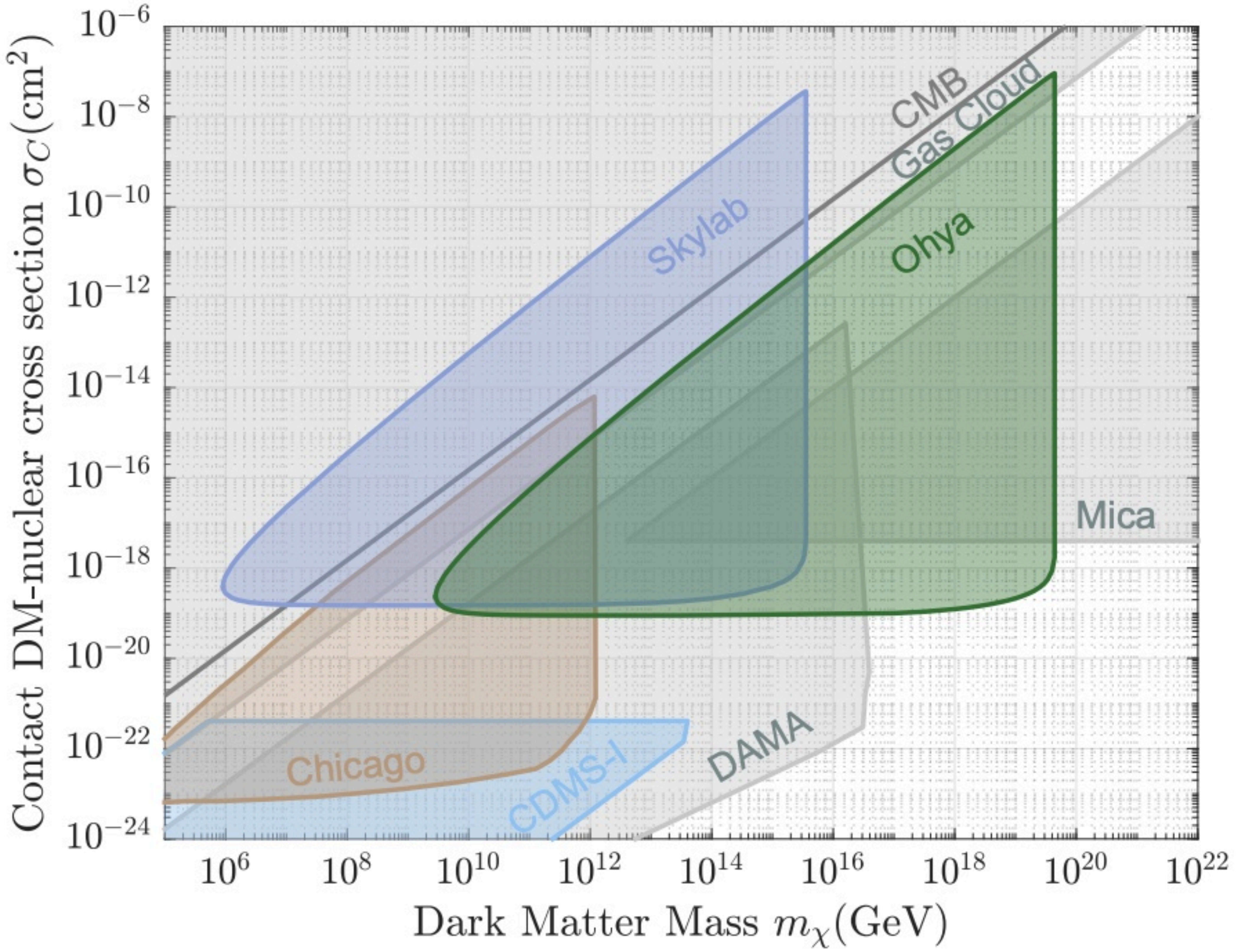


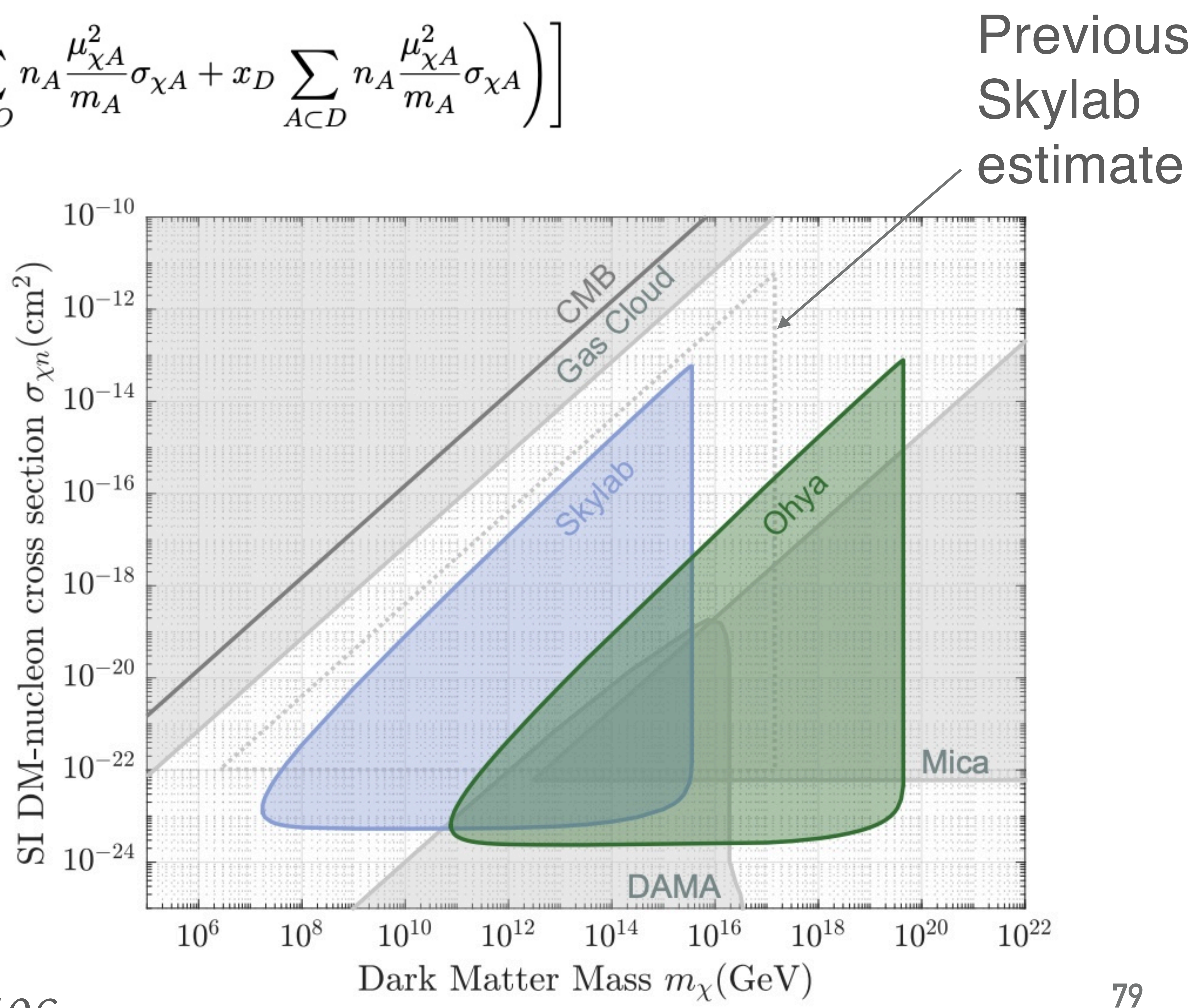
2012.13406

ETCHING PLASTIC SEARCHES FOR DARK MATTER

➤ *Use realistic dark matter density and velocity distribution, solve for overburden+etching exactly*

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





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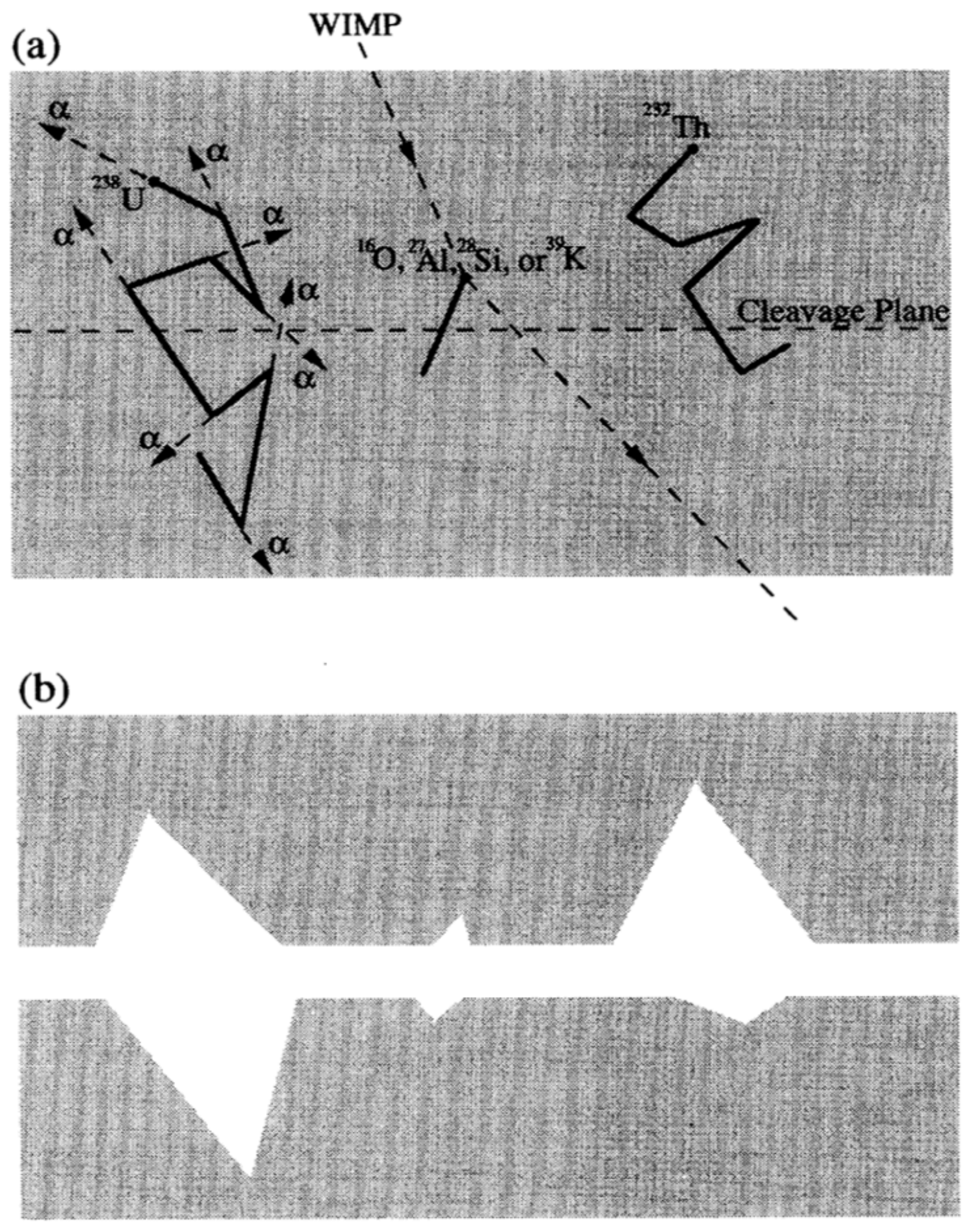
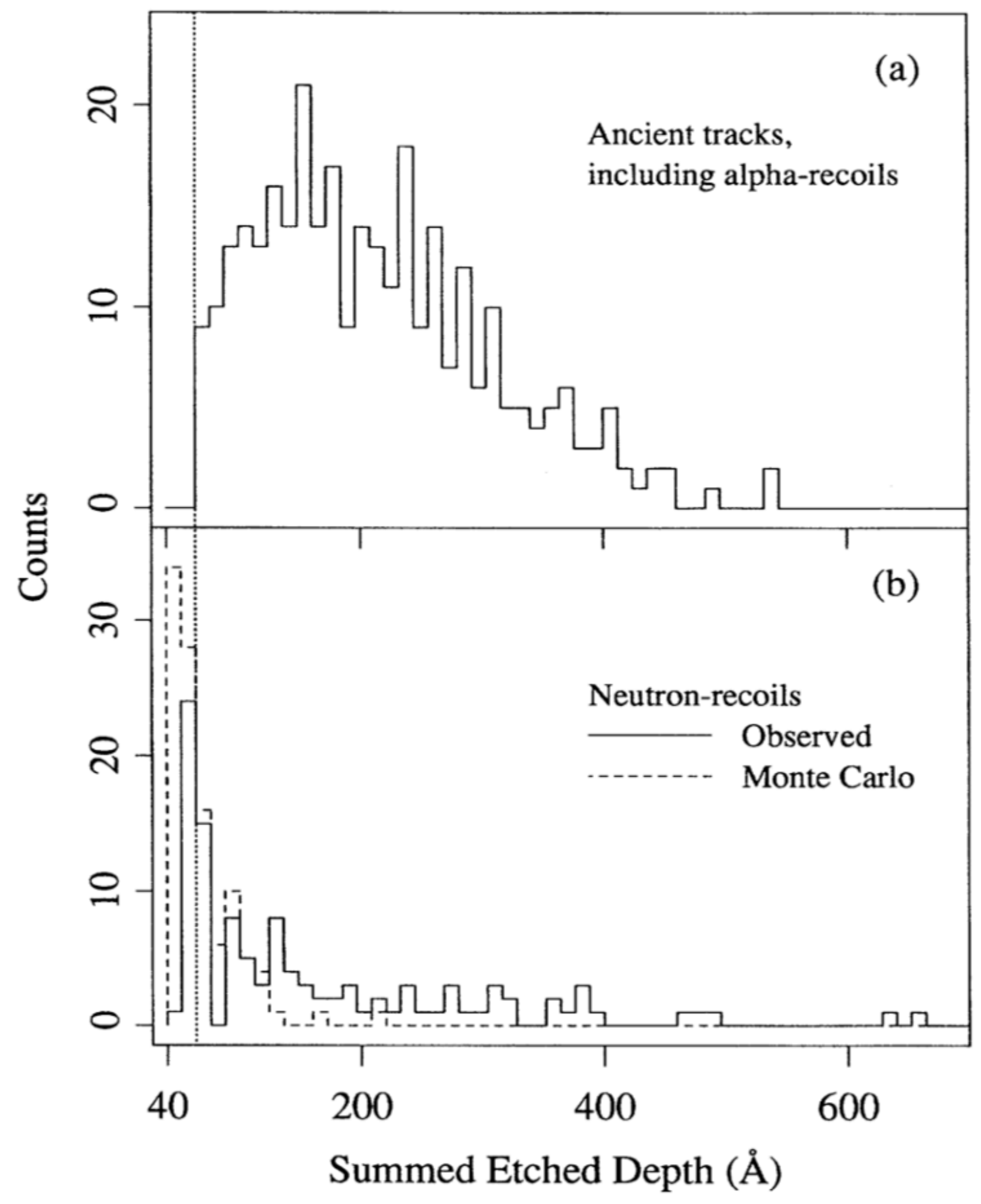
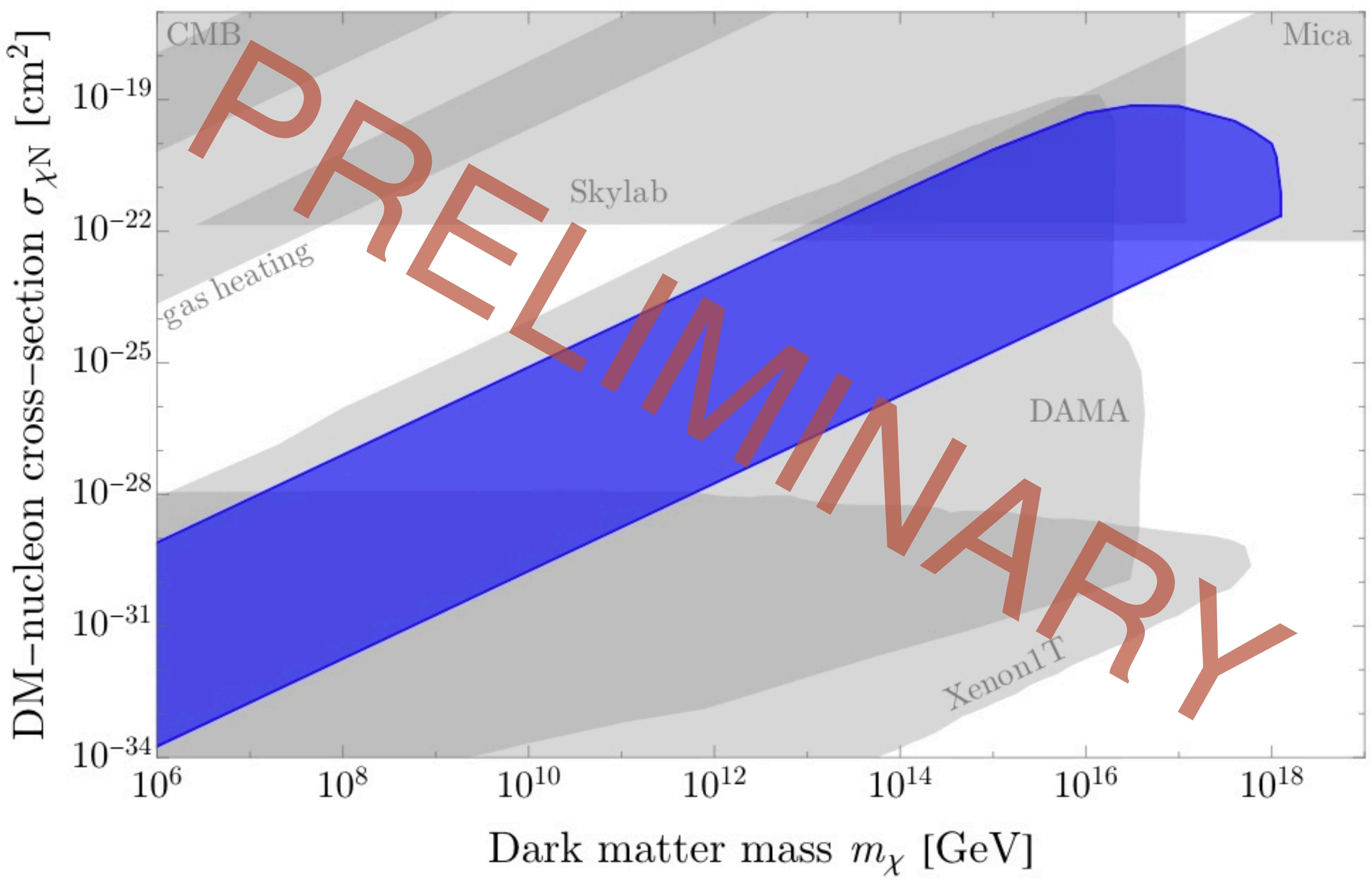
ANCIENT MICA SEARCH FOR DARK MATTER





- ➤ Recast using crust and mica MC methods



- ➤ 1995 Snowden-Ifft et al. calibrated mica samples

Acevedo, JB, Goodman in prep