Gas clouds as dark matter detectors

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Work with
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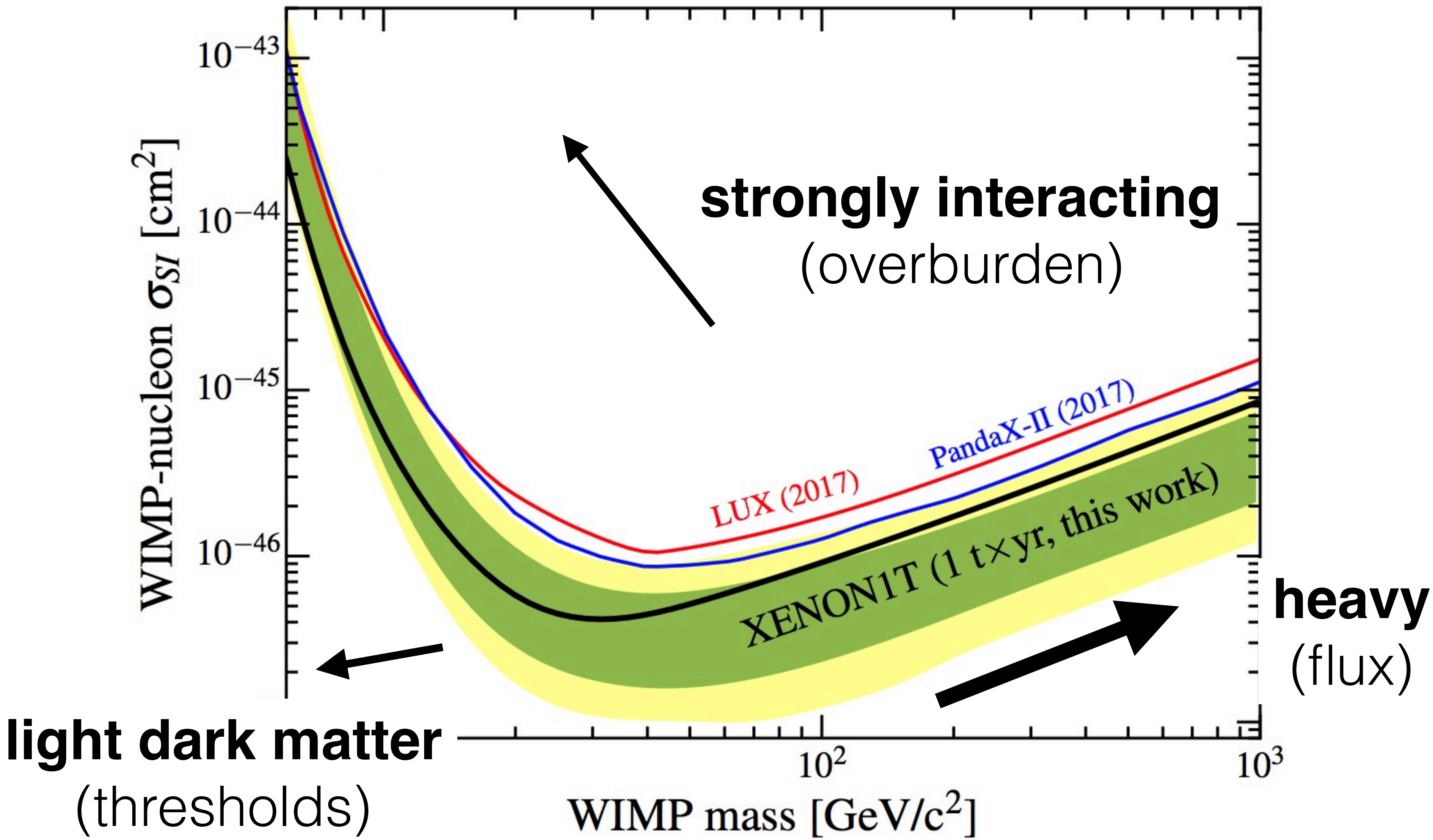
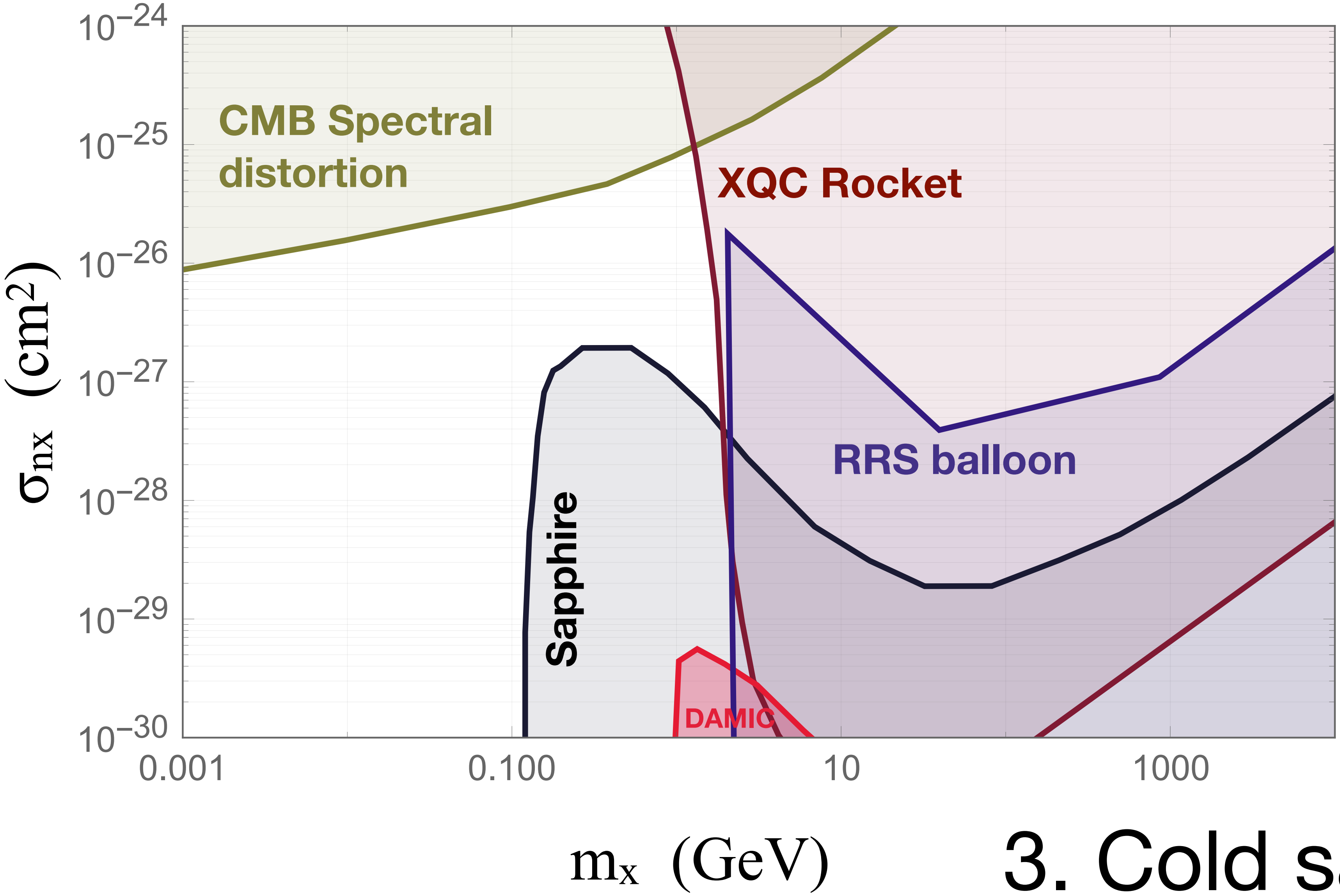
Expanding the search for dark matter



Xenon1T 2018

Detecting MeV-TeV mass strongly interacting DM



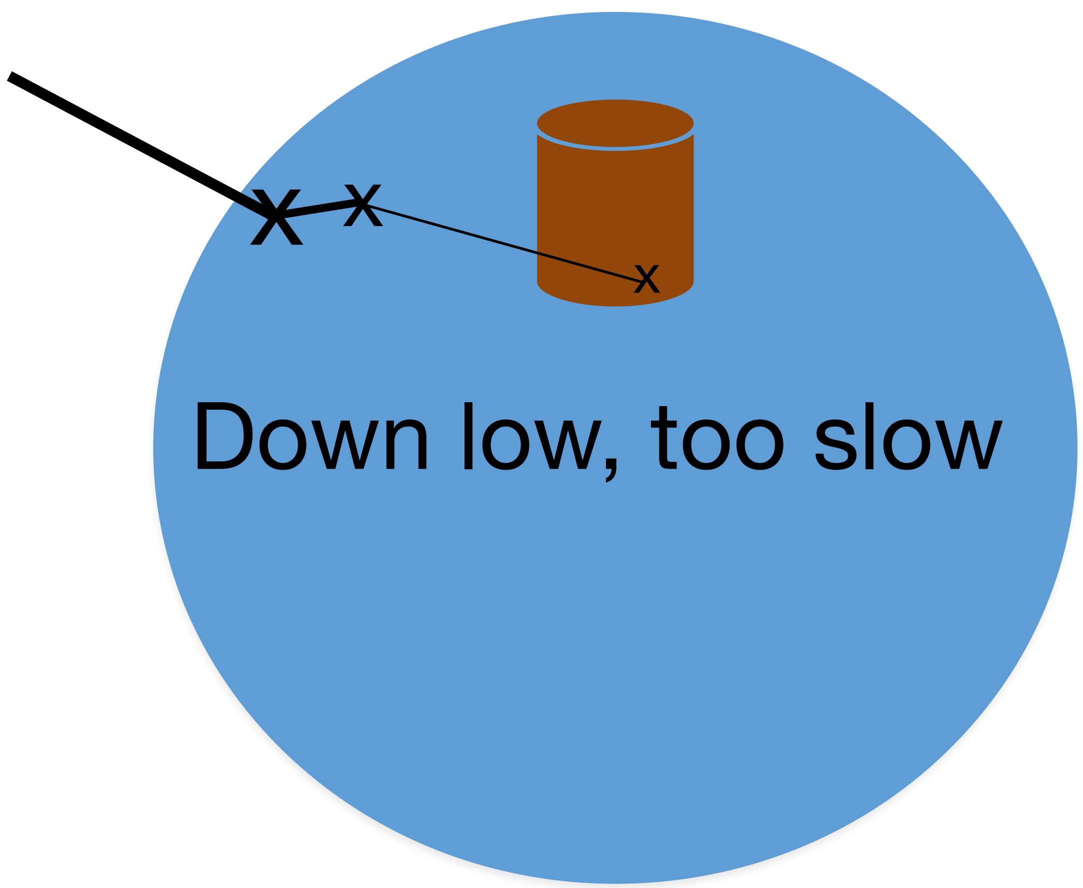
1. XQC rocket

2. RRS balloon

3. Cold sapphire (1 m)

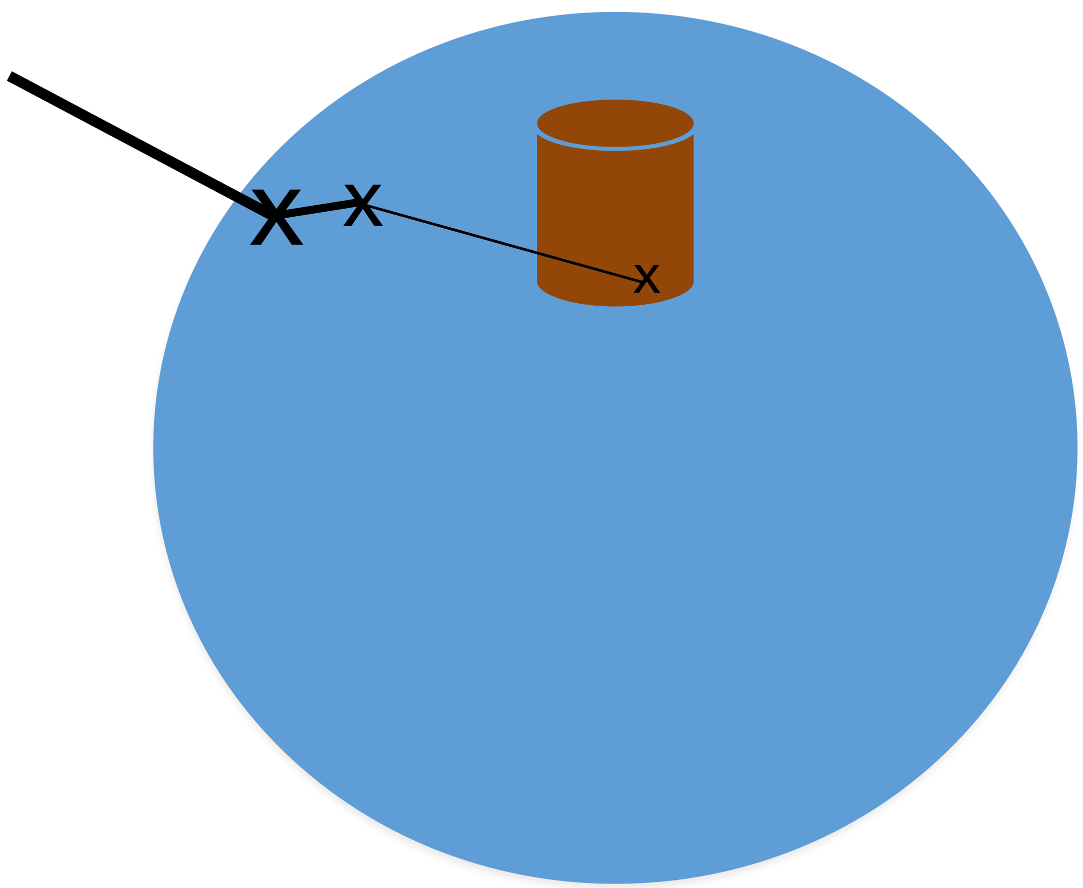
4. DAMIC (100 m)

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



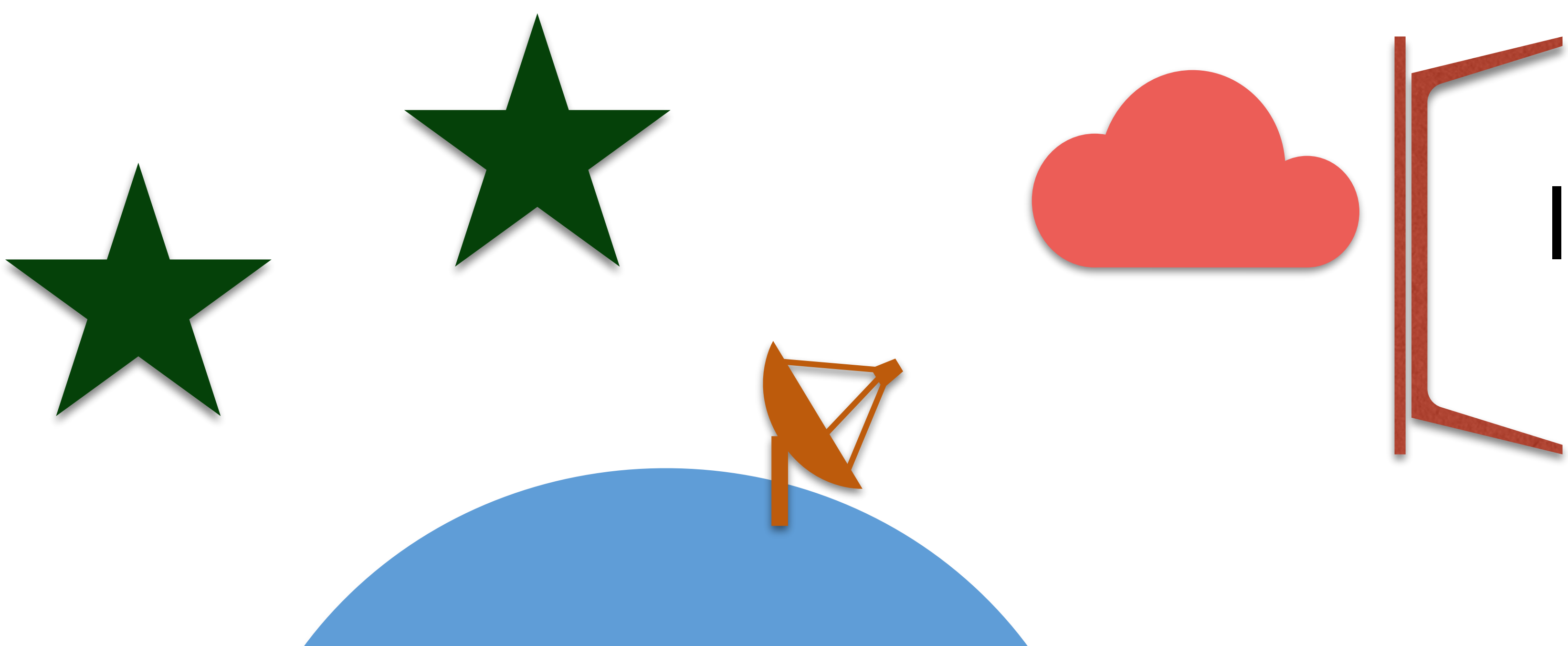
dark matter kinetic energy < recoil threshold

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



dark matter
kinetic energy <
recoil threshold

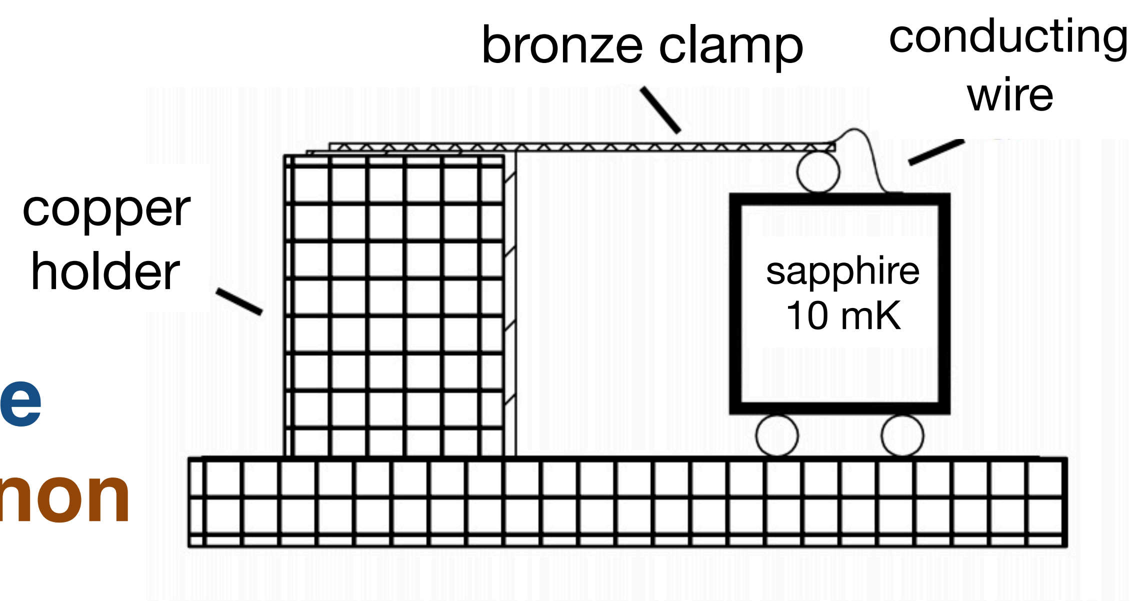
Use detectors in space!

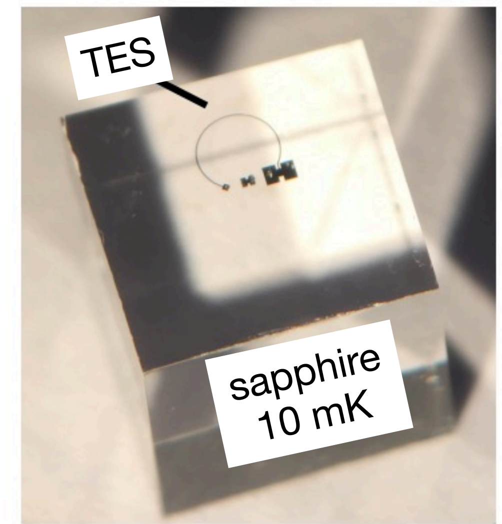


big
less overburden
free electrons

Galactic center gas clouds: new calorimetric detectors

CRESST sapphire
cooling: conducting wire
readout: TES thermal phonon





Galactic center gas clouds: new calorimetric detectors

CRESST sapphire
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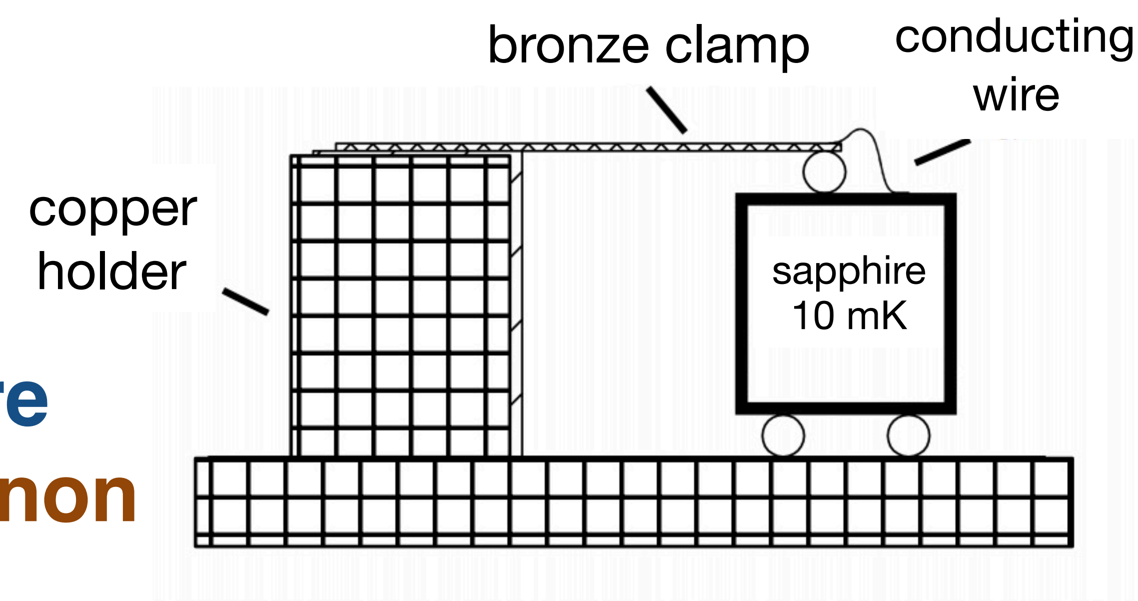
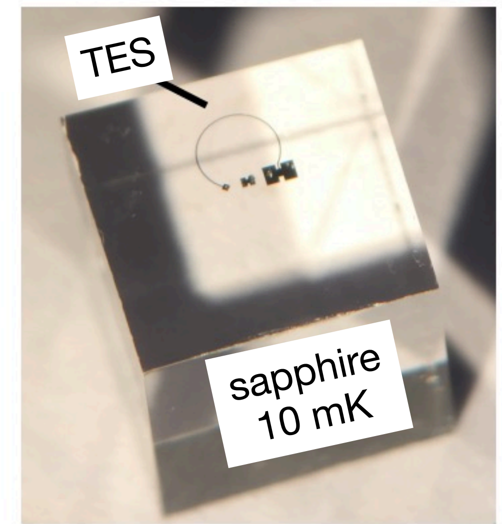
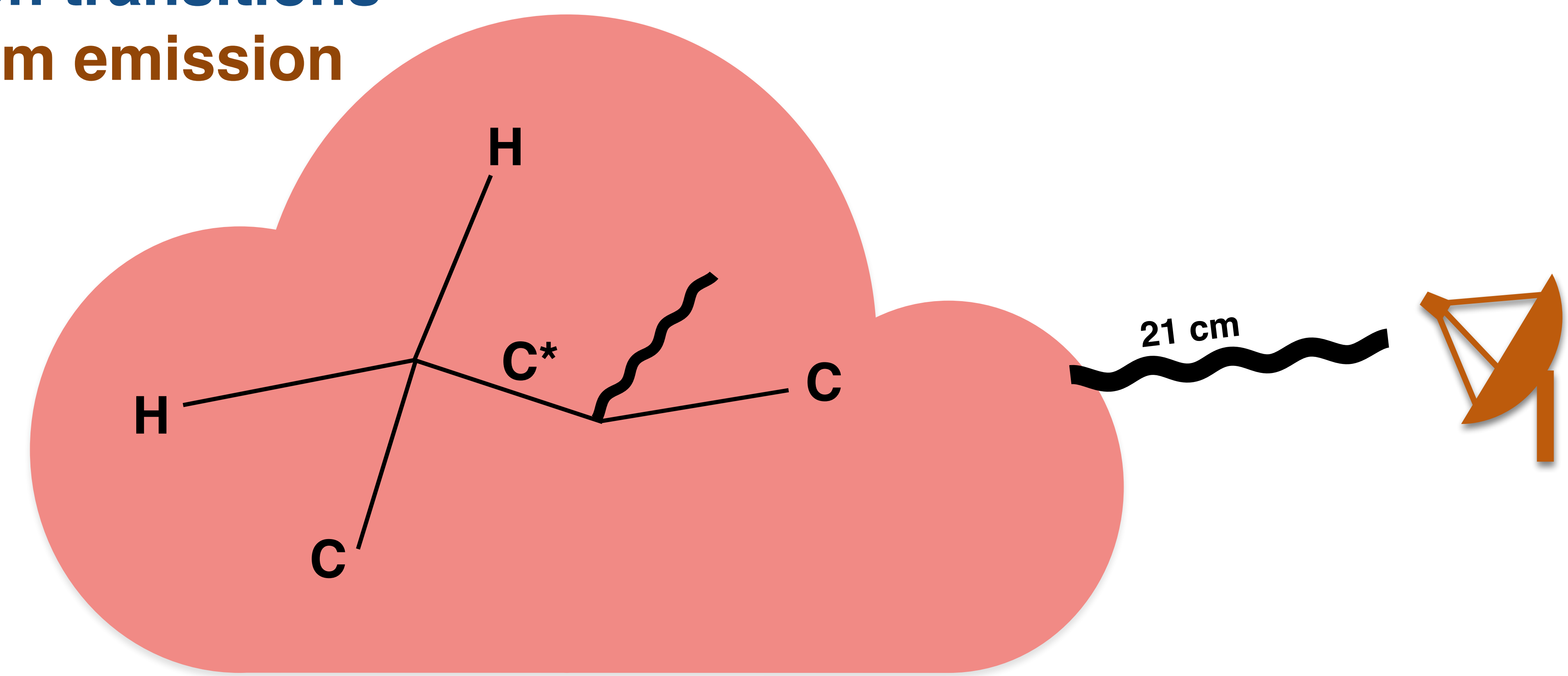


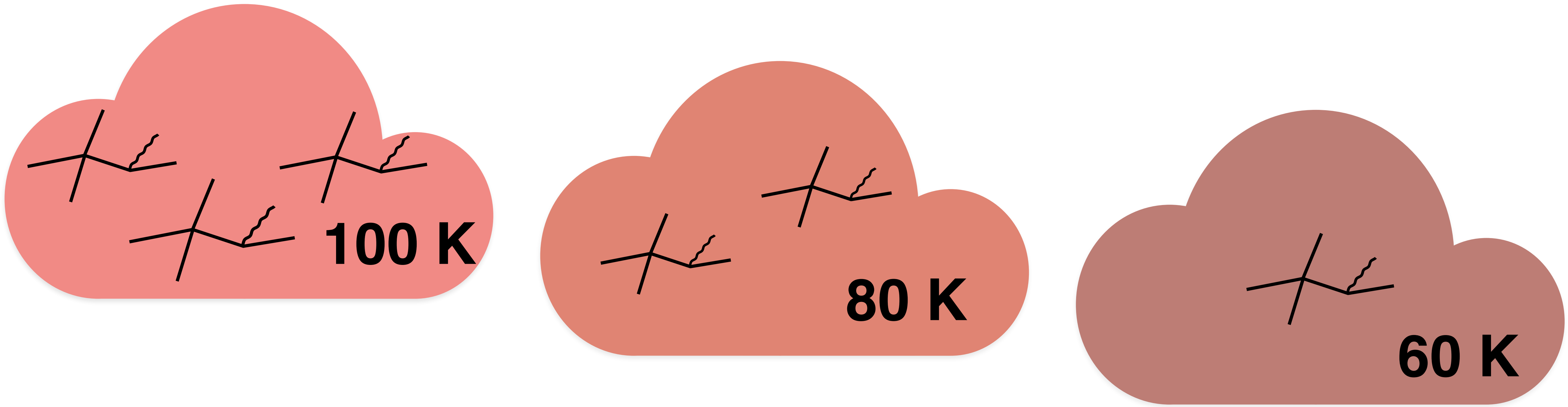


Cold Galactic Center gas clouds
cooling: carbon transitions
readout: 21 cm emission



Calibration

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



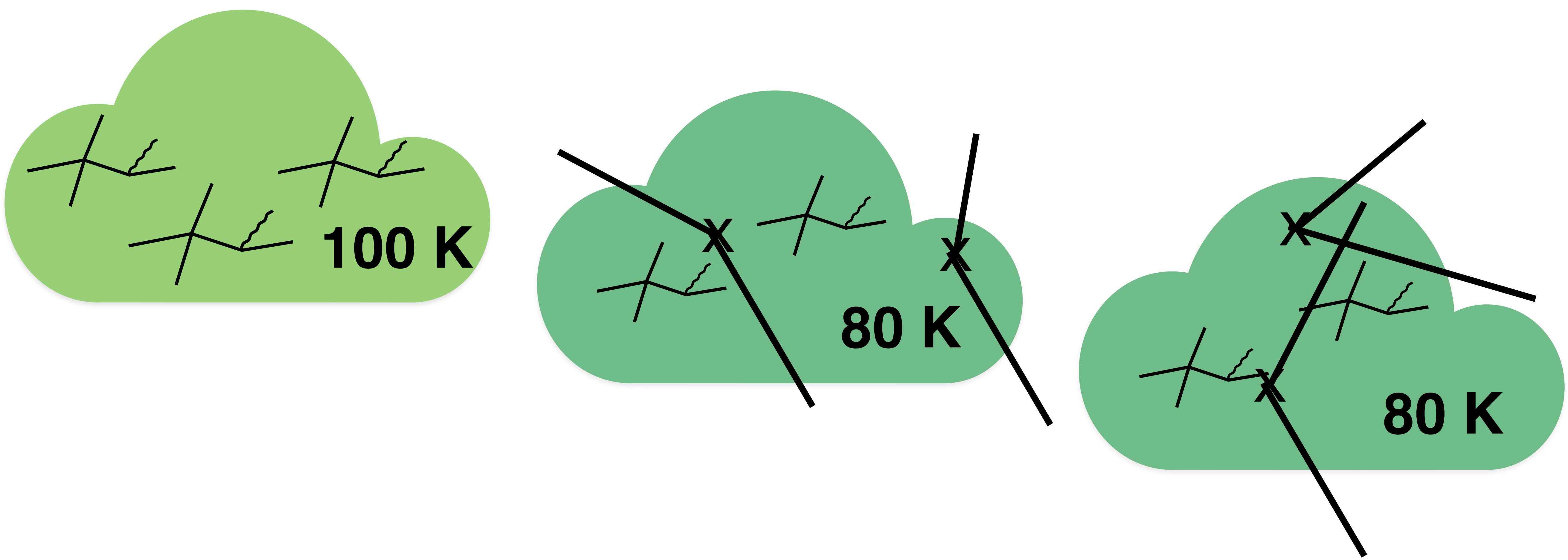
$$\text{Cooling rate} \propto n_{\mathrm{H}}^2 \sigma \sqrt{T/m}$$

Collisions are rarer at lower temperatures.

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

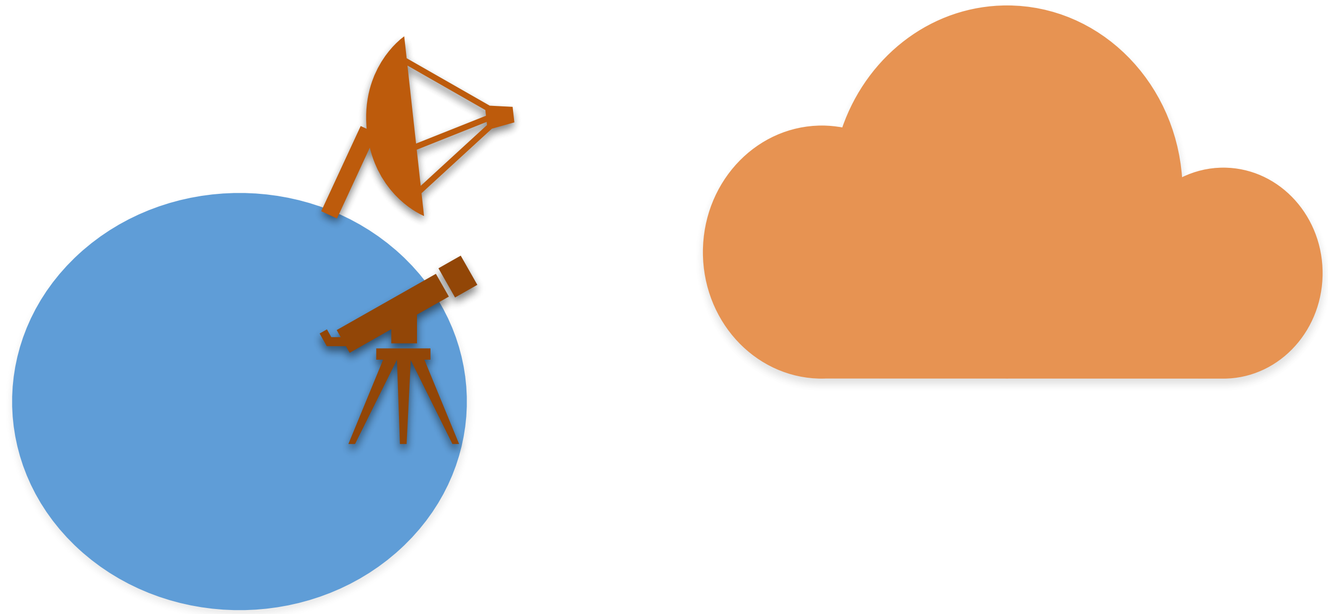
Cooling decreases with gas cloud temperature.

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



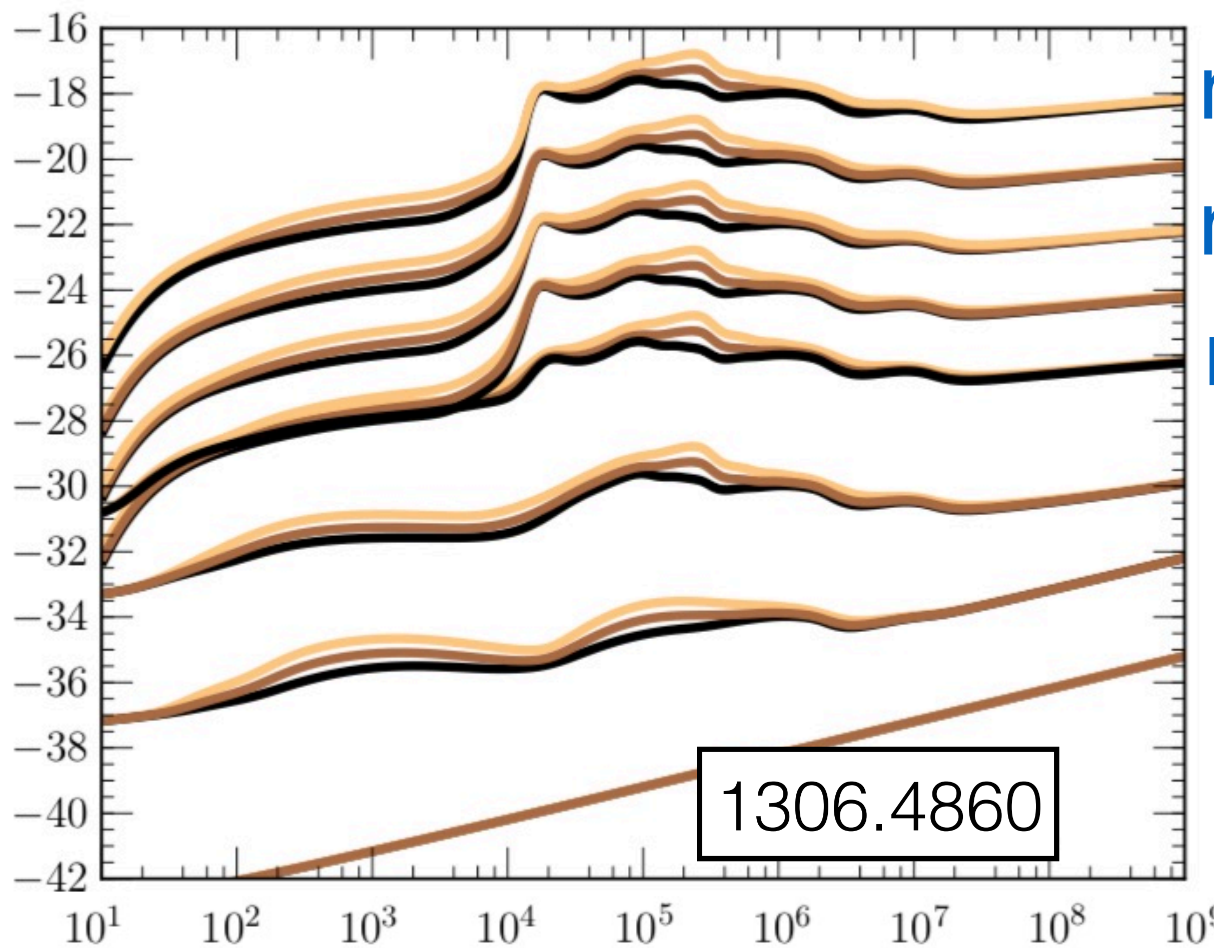
$$\text{Cooling rate} \geq \text{Dark matter heating rate}$$

Calibration



Simple models of gas cloud cooling match emission line measurements of gas clouds near earth.

volumetric cooling rate Log[erg/s/cm^3]



Temperature (K)

$n_H = 100/cm^3$

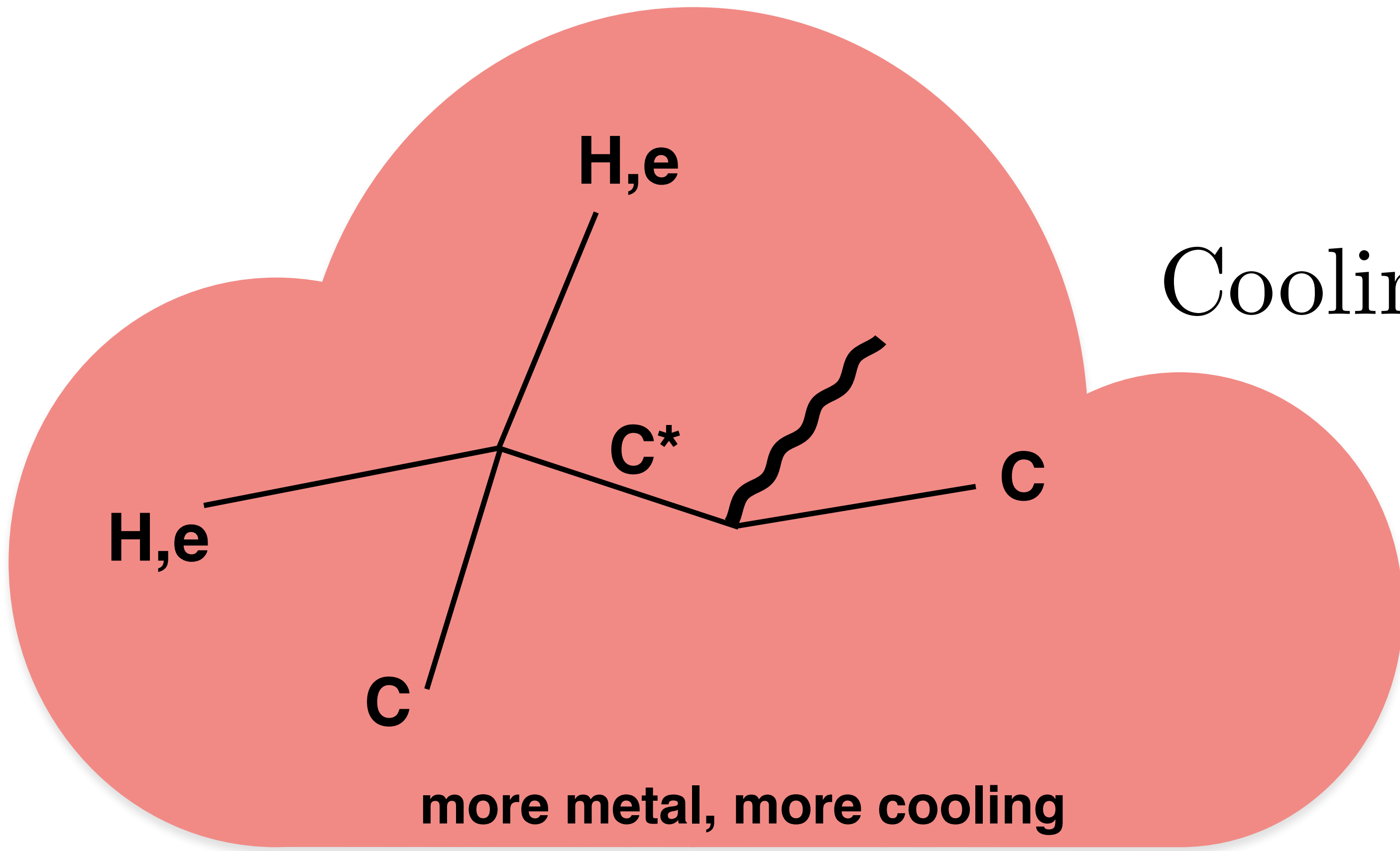
$n_H = 1/cm^3$

$n_H = .01/cm^3$

linear scaling with nuclear collision rate

Metallicity

Gas cloud cooling increases with gas metallicity



$$\text{Cooling rate} \propto n_H \boxed{n_C} \sigma \sqrt{T/m}$$

(for T~10-1000 K)

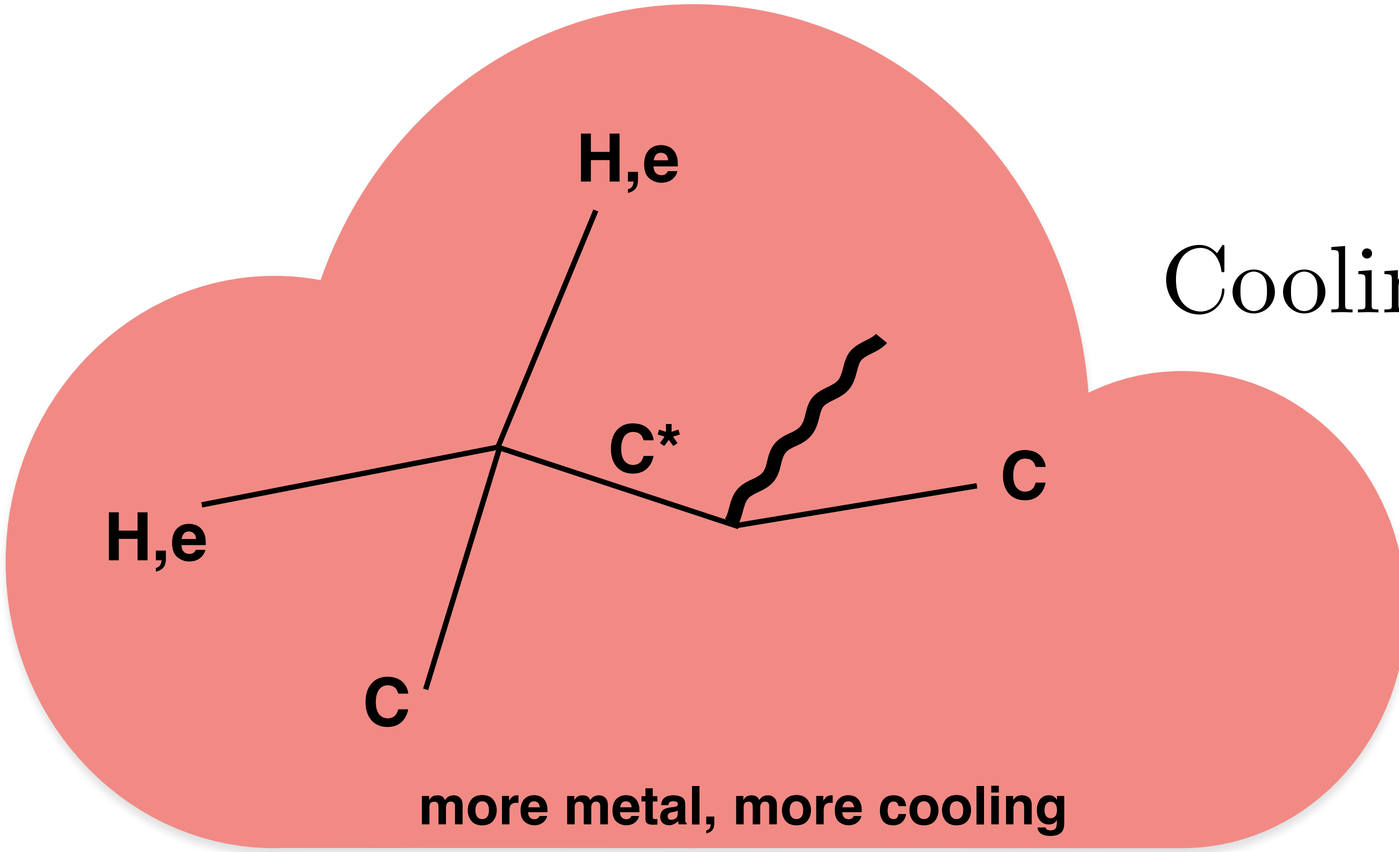
Metallicity definitions

$$\mathrm{Log_{10}[C \times n_{Fe}/n_H]} \equiv [Fe/H]$$

$$[Fe/H] \equiv 0, \ \text{solar}$$

Metallicity

Gas cloud cooling increases with gas metallicity



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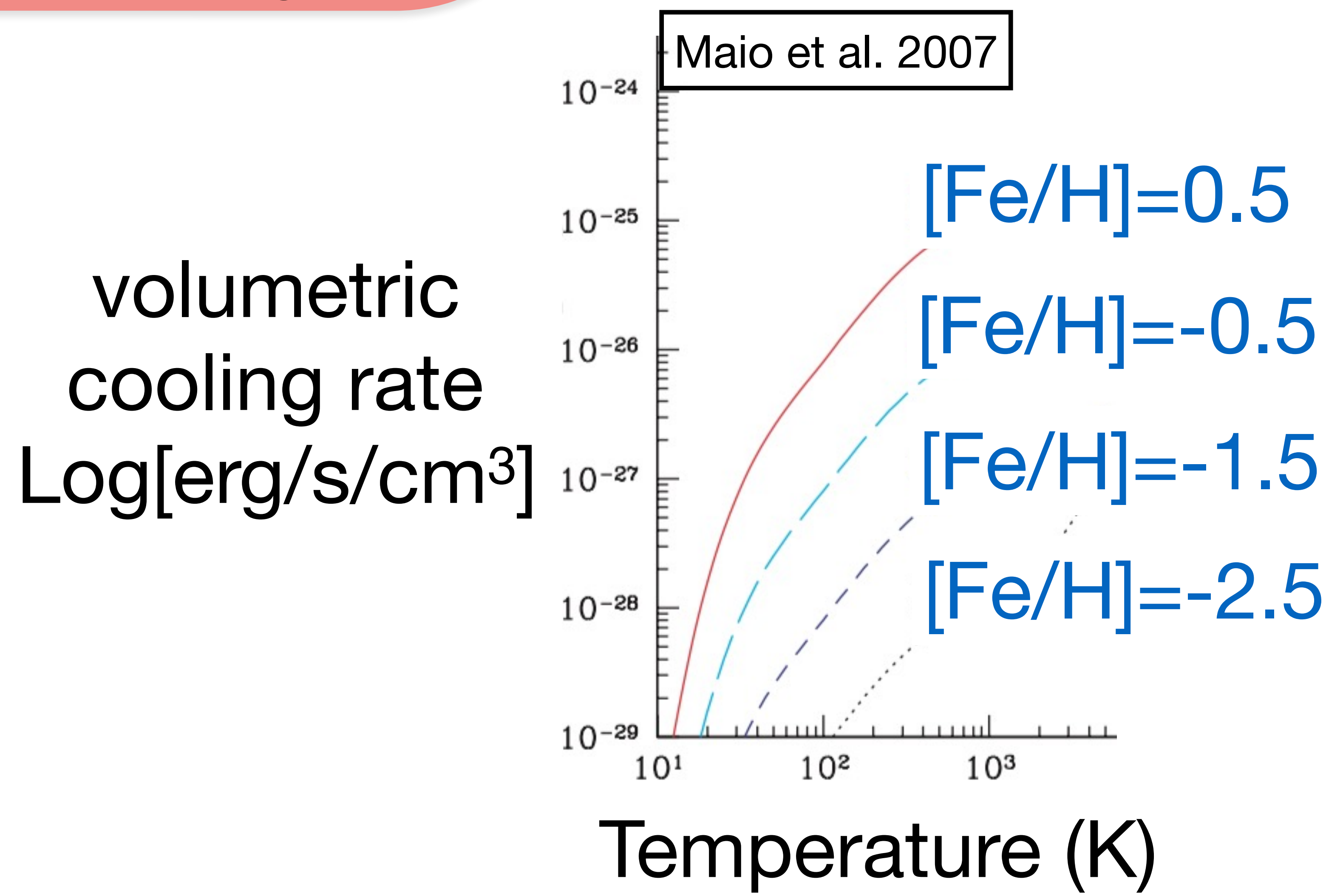
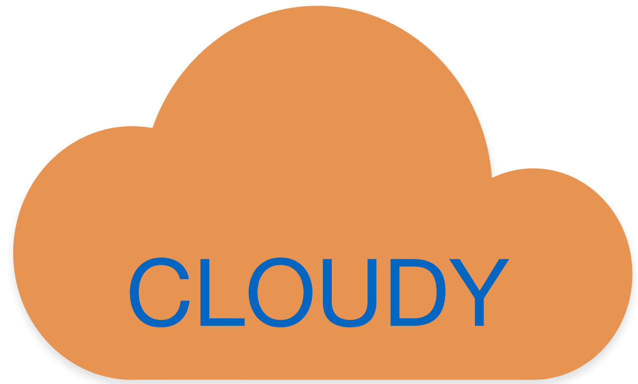
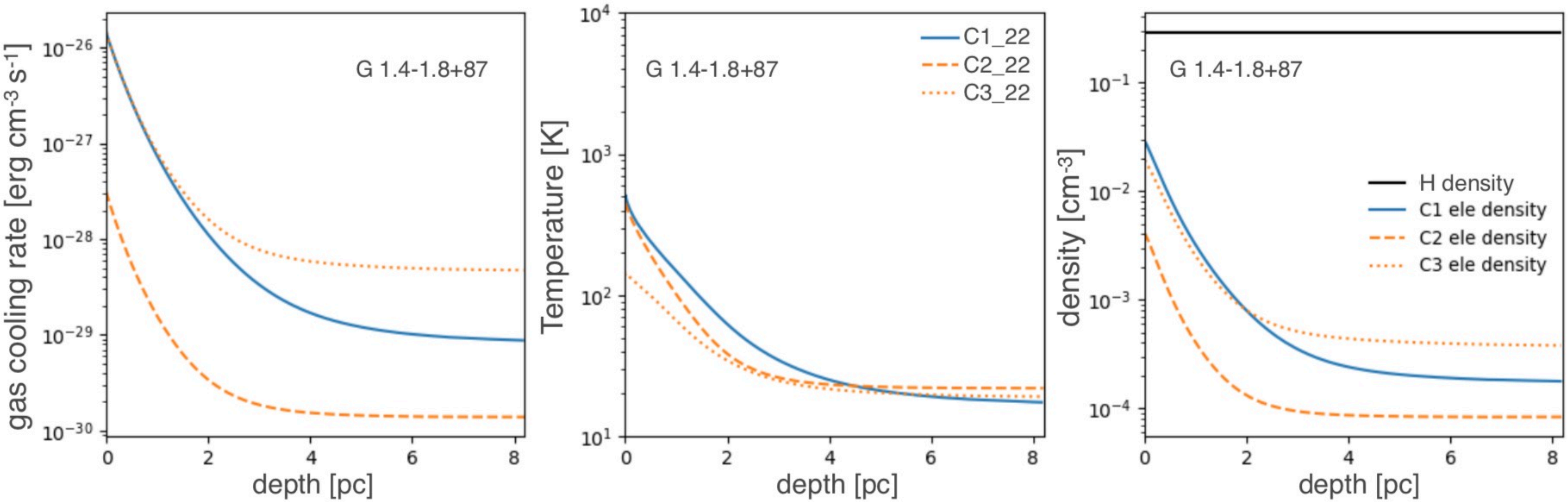


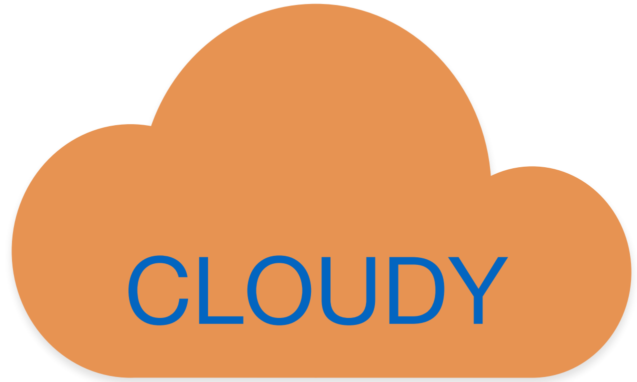
Better Calibration



Use gas cooling code to model Galactic Center Gas Clouds



Better Calibration



Use gas cooling code to model Galactic Center Gas Clouds

Model	$\bar{T}$ [K]	radius [pc]	$\bar{\rho}$ [cm^{-3}]	$Z/Z_\odot$	grains	UV	CR [s^{-1}]	$\bar{n}_e$ [cm^{-3}]	ave. cooling [erg cm^{-3}s^{-1}]
C1-22	22	8.2	0.29	1	no	0.1	1×10^{-18}	2.3×10^{-4}	1.9×10^{-29}
C2-22	22	8.2	0.29	0.1	no	1.9×10^{-3}	1.9×10^{-19}	9.7×10^{-5}	1.6×10^{-30}
C3-22	22	8.2	0.29	5	no	0.1	5×10^{-18}	5.6×10^{-4}	6.2×10^{-28}
C1-137	137	12.9	0.421	1	yes	1	5×10^{-17}	1×10^{-3}	3.4×10^{-28}
C2-137	137	12.9	0.421	0.1	yes	1	3×10^{-18}	5×10^{-4}	8.2×10^{-29}
C3-137	137	12.9	0.421	5	yes	1	1.9×10^{-16}	6.2×10^{-3}	6.1×10^{-27}
C1-198	198	12.3	1.57	1	yes	1	2.9×10^{-16}	1.2×10^{-2}	2.4×10^{-26}
C2-198	198	12.3	1.57	0.1	yes	1	1.1×10^{-16}	7.4×10^{-3}	8.2×10^{-27}
C3-198	198	12.3	1.57	5	yes	1	1.4×10^{-15}	4.5×10^{-2}	1.5×10^{-25}

Better Calibration

High Z
Implies High C/Fe/e

Use gas cooling code to model Galactic Center Gas Clouds

DM Model	$\bar{T}$ [K]	radius [pc]	$\bar{\rho}$ [cm^{-3}]	$Z/Z_\odot$	grains	UV	CR [s^{-1}]	$\bar{n}_e$ [cm^{-3}]	ave. cooling [erg cm^{-3}s^{-1}]
C1-22	22	8.2	0.29	1	no	0.1	1×10^{-18}	2.3×10^{-4}	1.9×10^{-29}
C2-22	22	8.2	0.29	0.1	no	1.9×10^{-3}	1.9×10^{-19}	9.7×10^{-5}	1.6×10^{-30}
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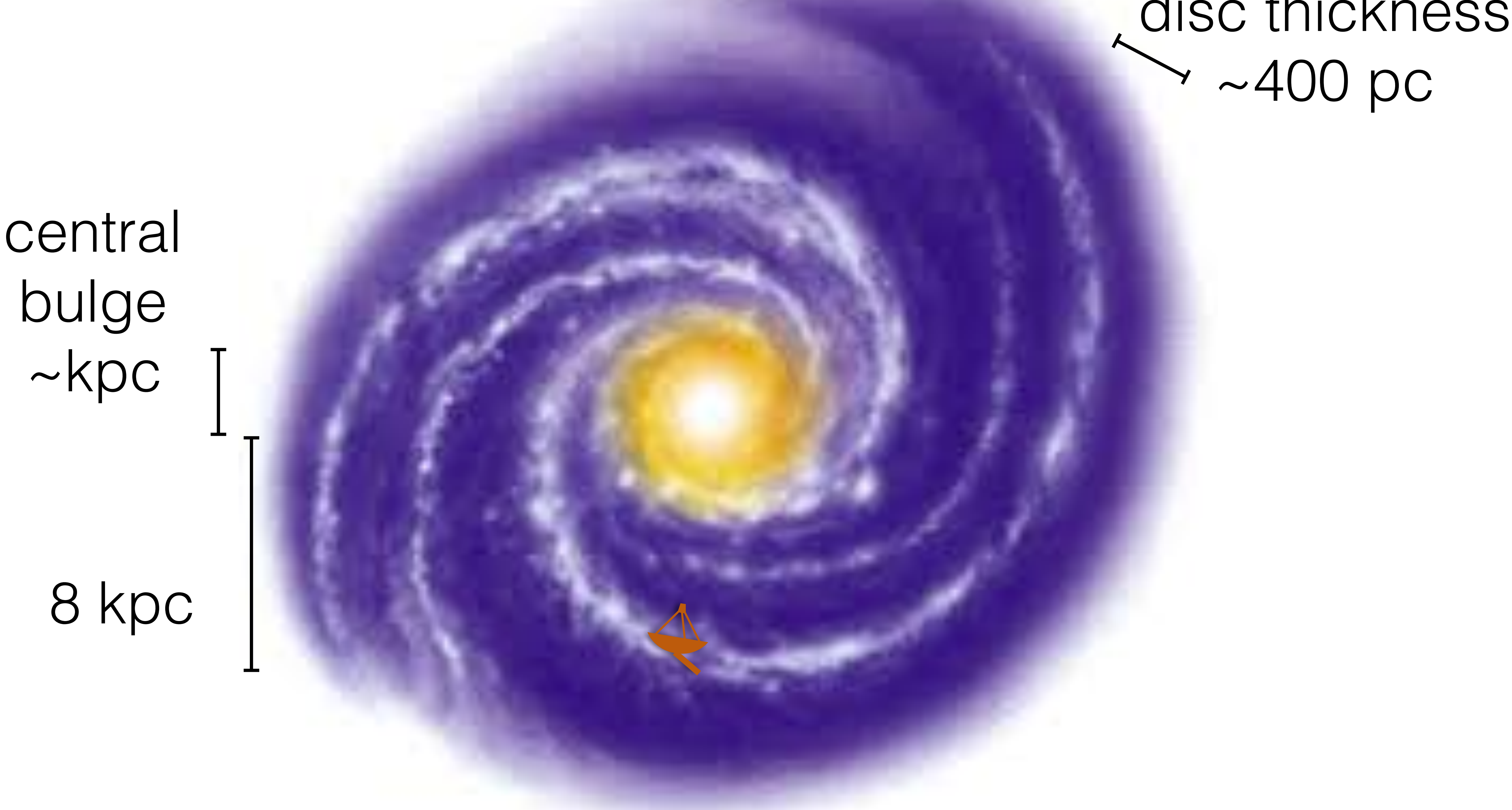
C1-198	198	12.3	1.57	1	yes	1	2.9×10^{-16}	1.2×10^{-2}	2.4×10^{-26}
C2-198	198	12.3	1.57	0.1	yes	1	1.1×10^{-16}	7.4×10^{-3}	8.2×10^{-27}
C3-198	198	12.3	1.57	5	yes	1	1.4×10^{-15}	4.5×10^{-2}	1.5×10^{-25}

Increasing metallicity increases cooling,
but also increases iron density (nuclear scattering)
and free electron density (electron scattering & dark photon heating)

Detection

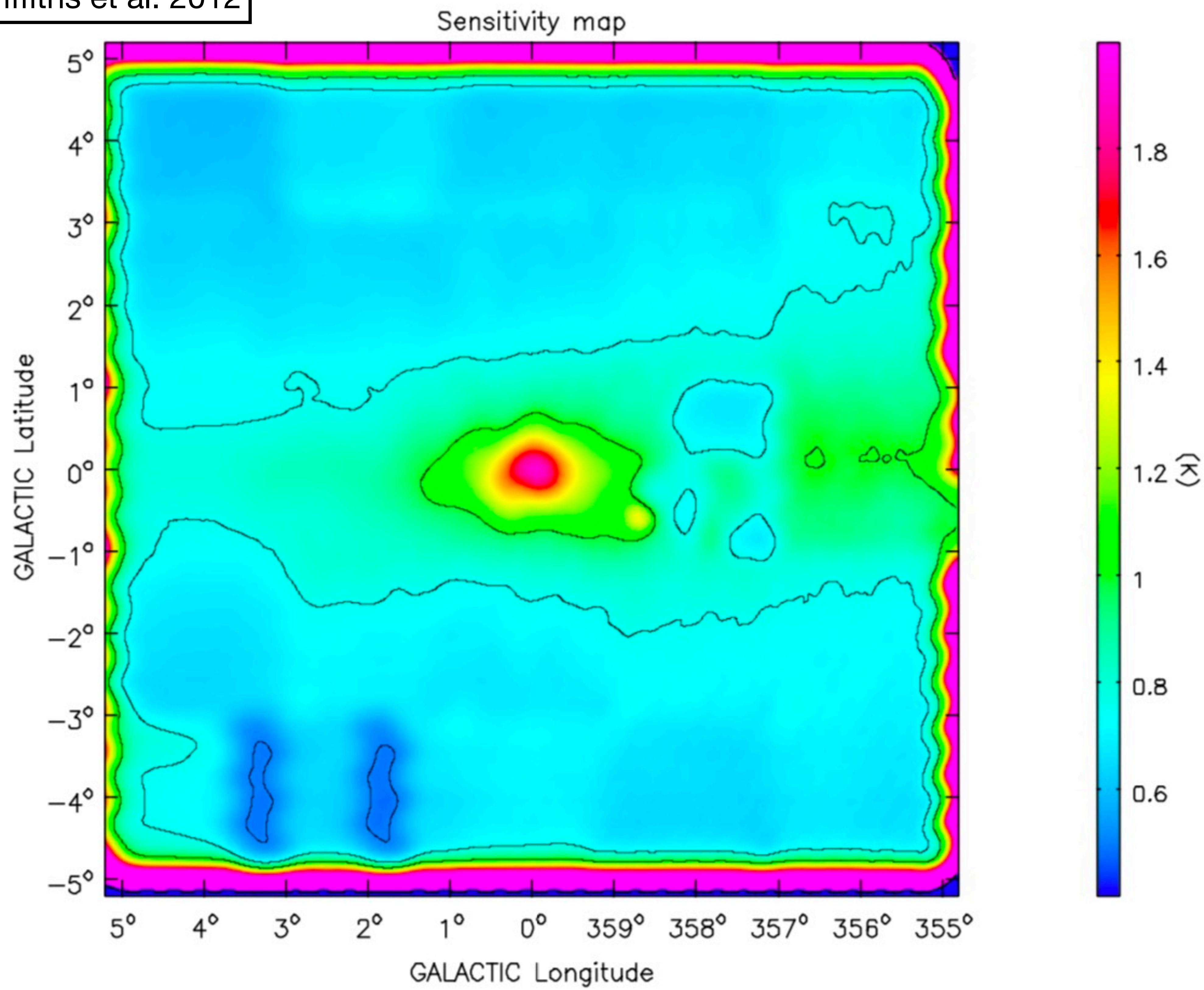
parsec = 3 x 10^{18} cm



21 cm Imaging of Milky Way Galactic Center

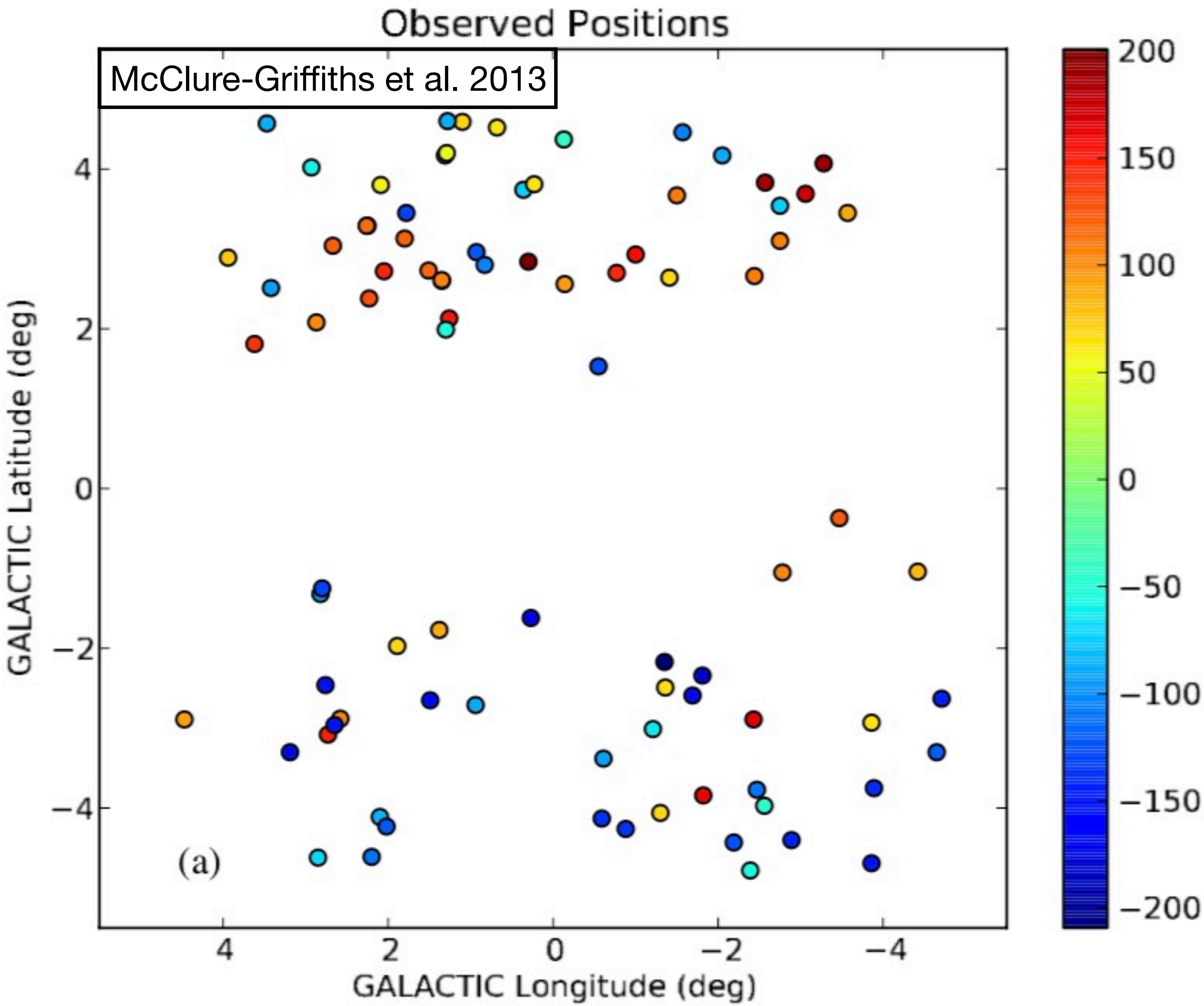
Green Banks Telescope detection of galactic center gas clouds using 21 cm emission

McClure-Griffiths et al. 2012



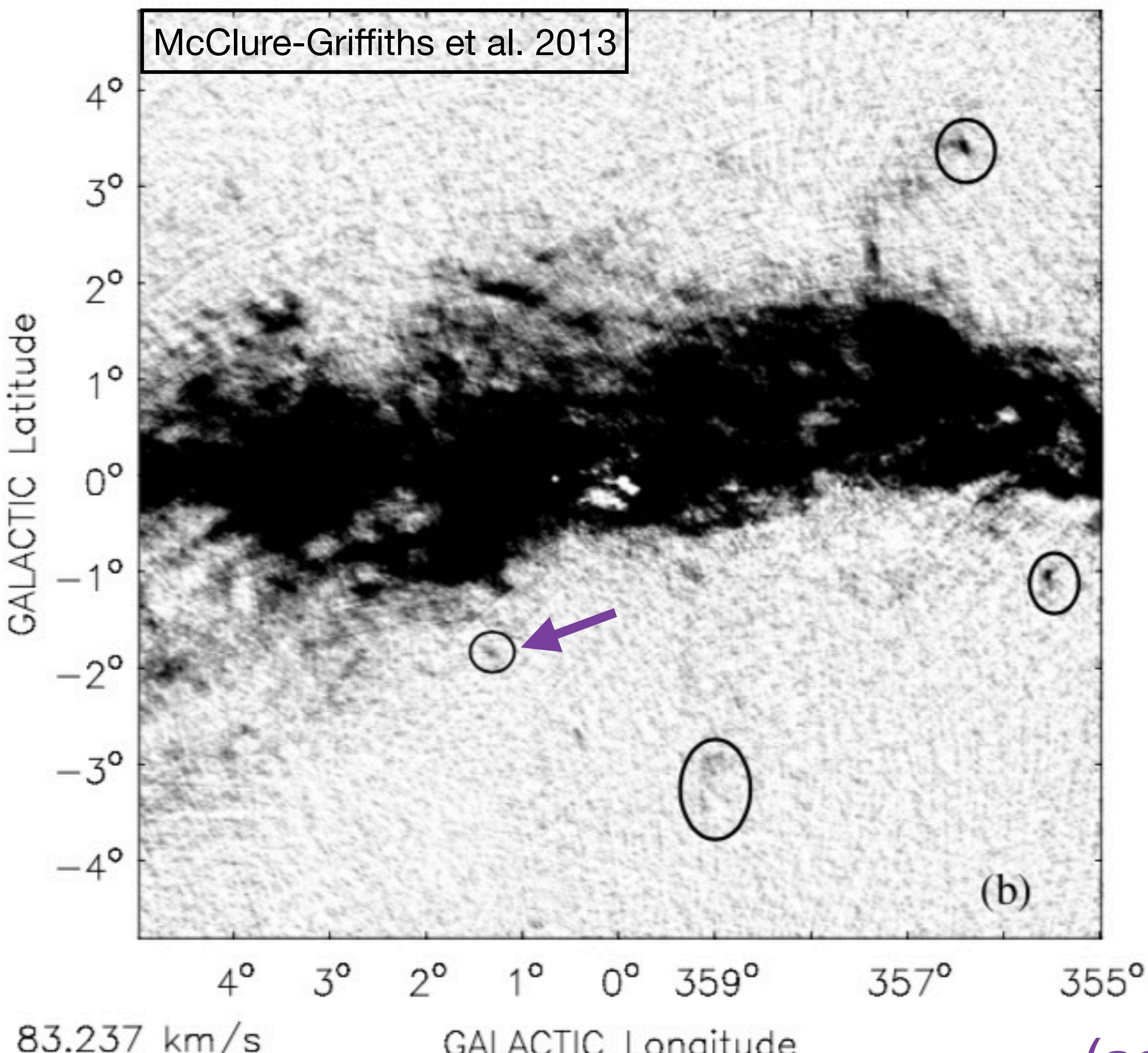
Gas clouds found within ~kpc of the Galactic Center

150 pc



velocity in Milky Way rest frame (km/s)

Gas Cloud 1.4-1.8+87



Δv from 21cm emission gives T

GC1.4-1.8+87

$M = 17\ M_\odot$

$r_{gc} = 8.2$ pc

$n_n = 0.3\ cm^{-3}$

$Tg < 22K$

$r_{los} = 332pc$

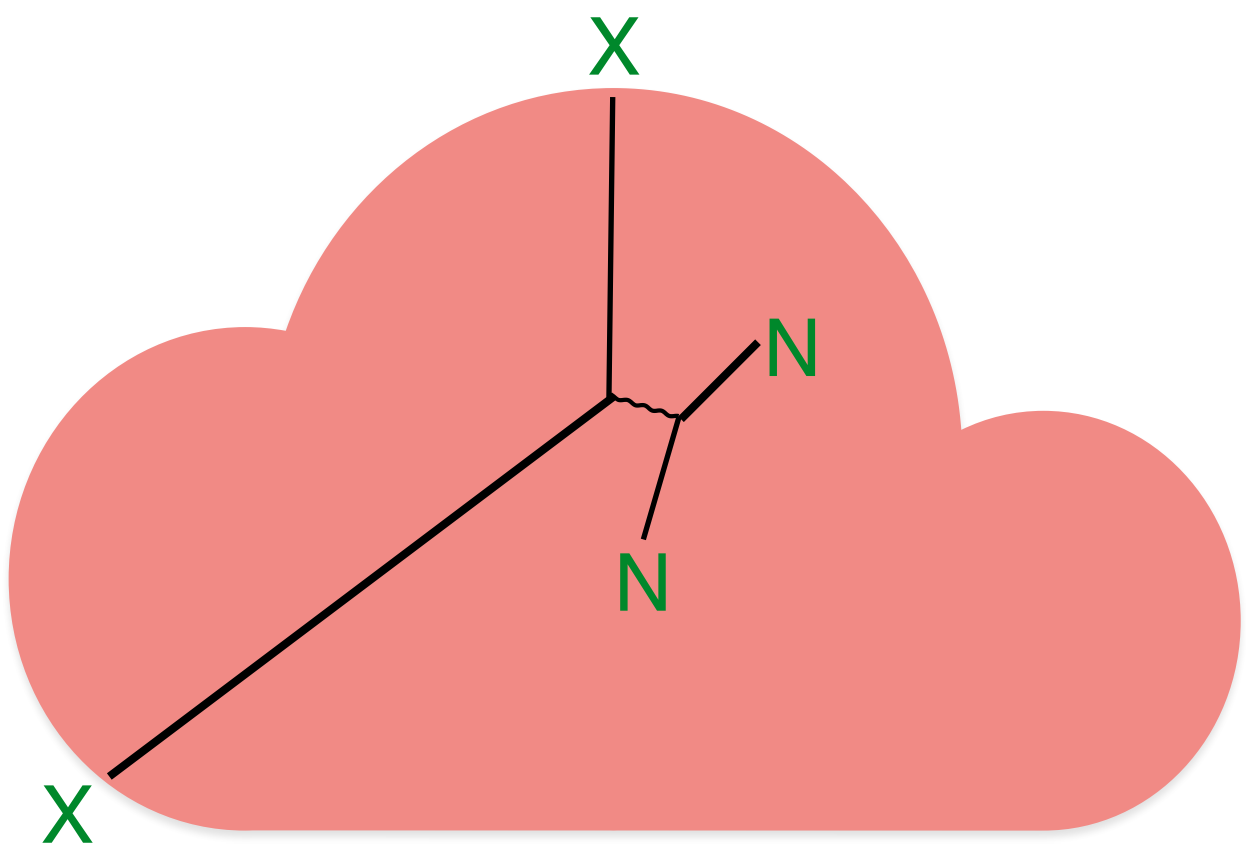
$v_g = 87.2$ km/s

(assume spherical cloud)

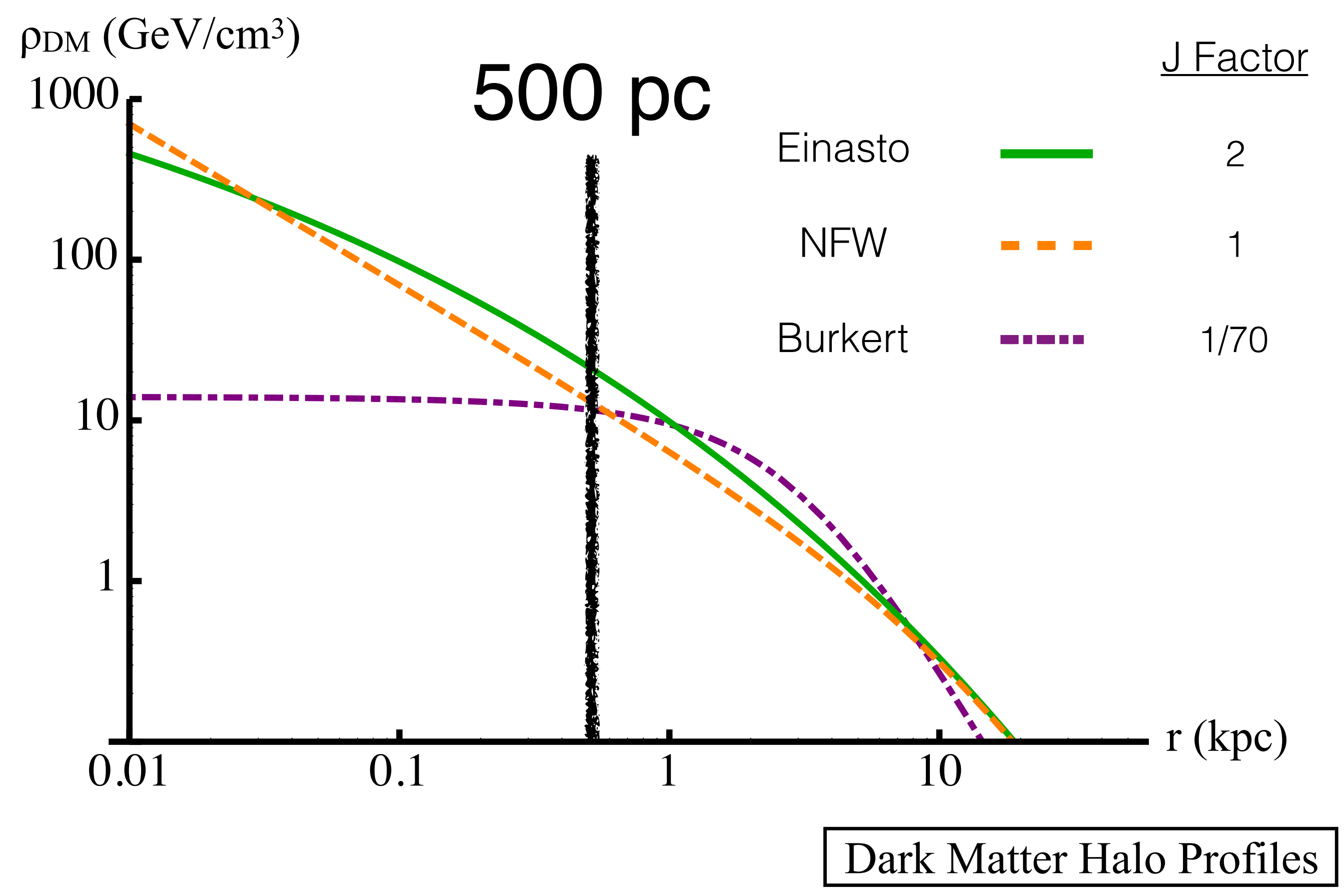
Dark matter interactions heat gas clouds

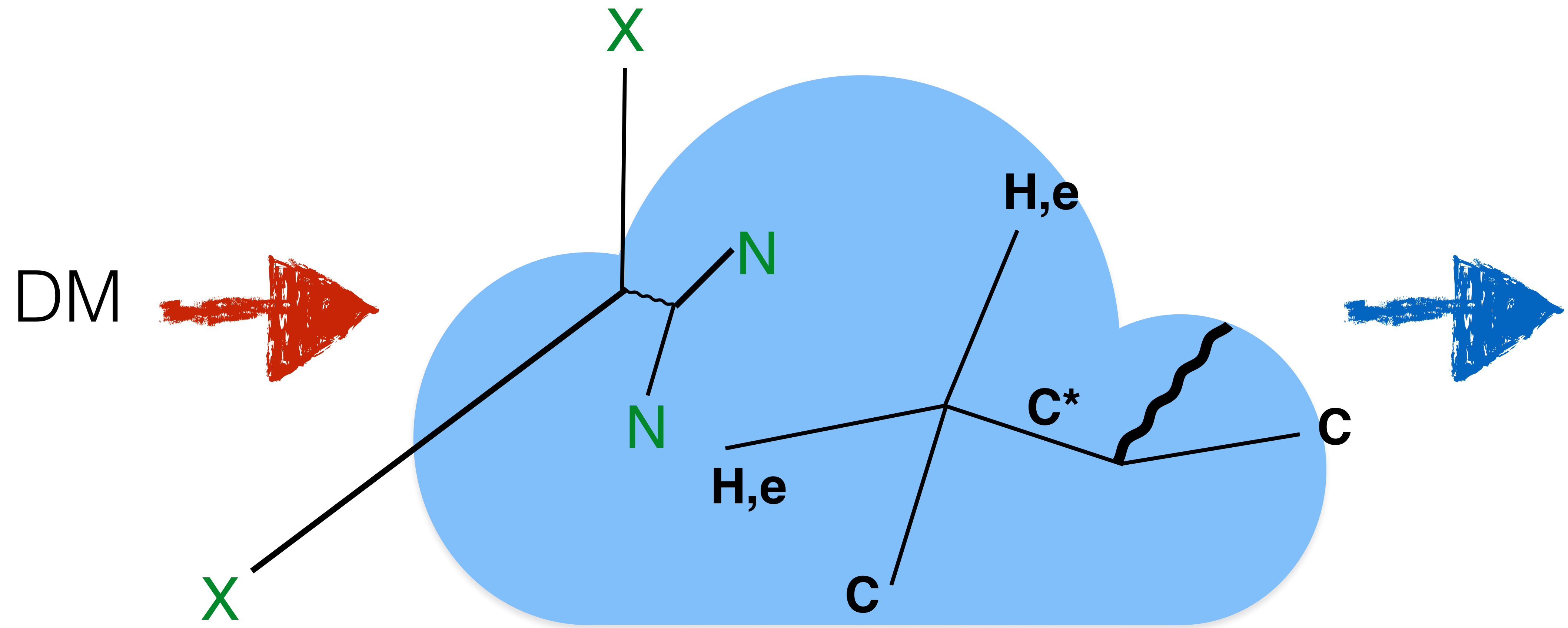
e.g.

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

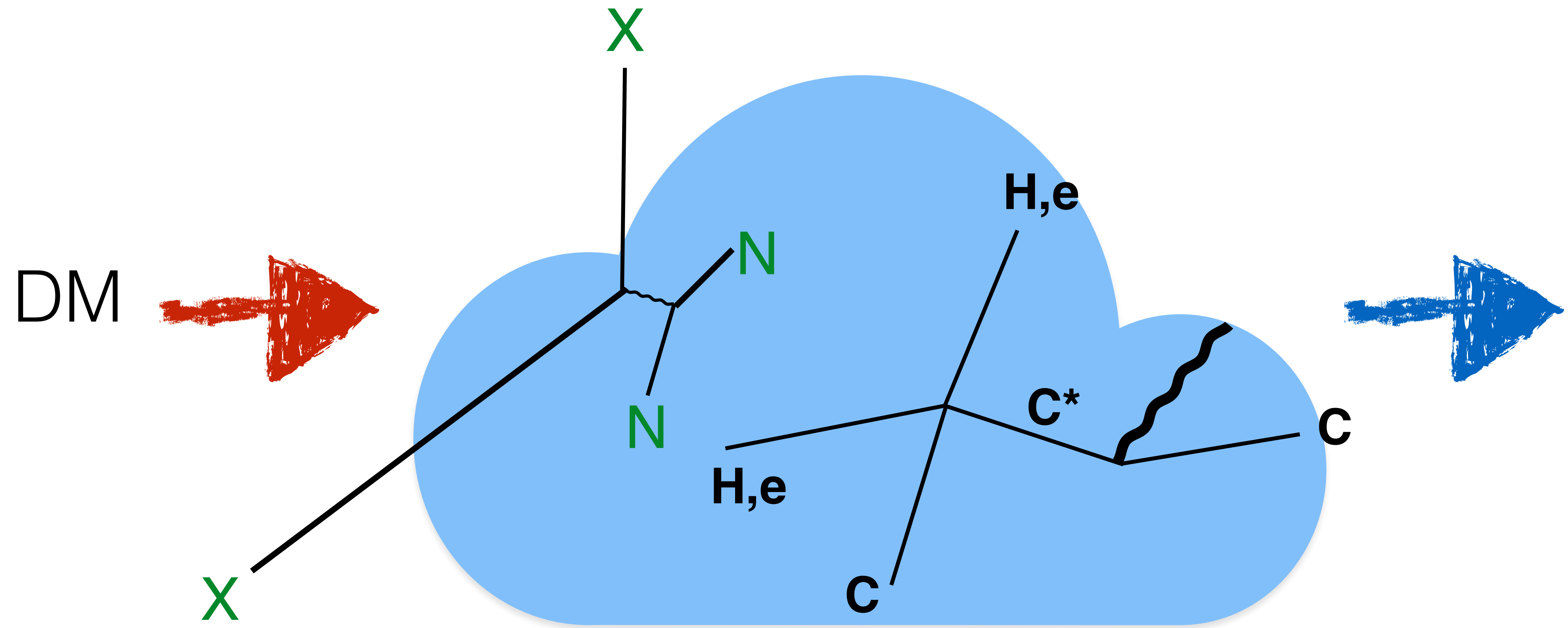


At ~500 pc from GC,
insensitive to halo profile





Conservatively: assume all heating by DM



Conservatively: assume all heating by DM

In reality:

DM + cosmic rays

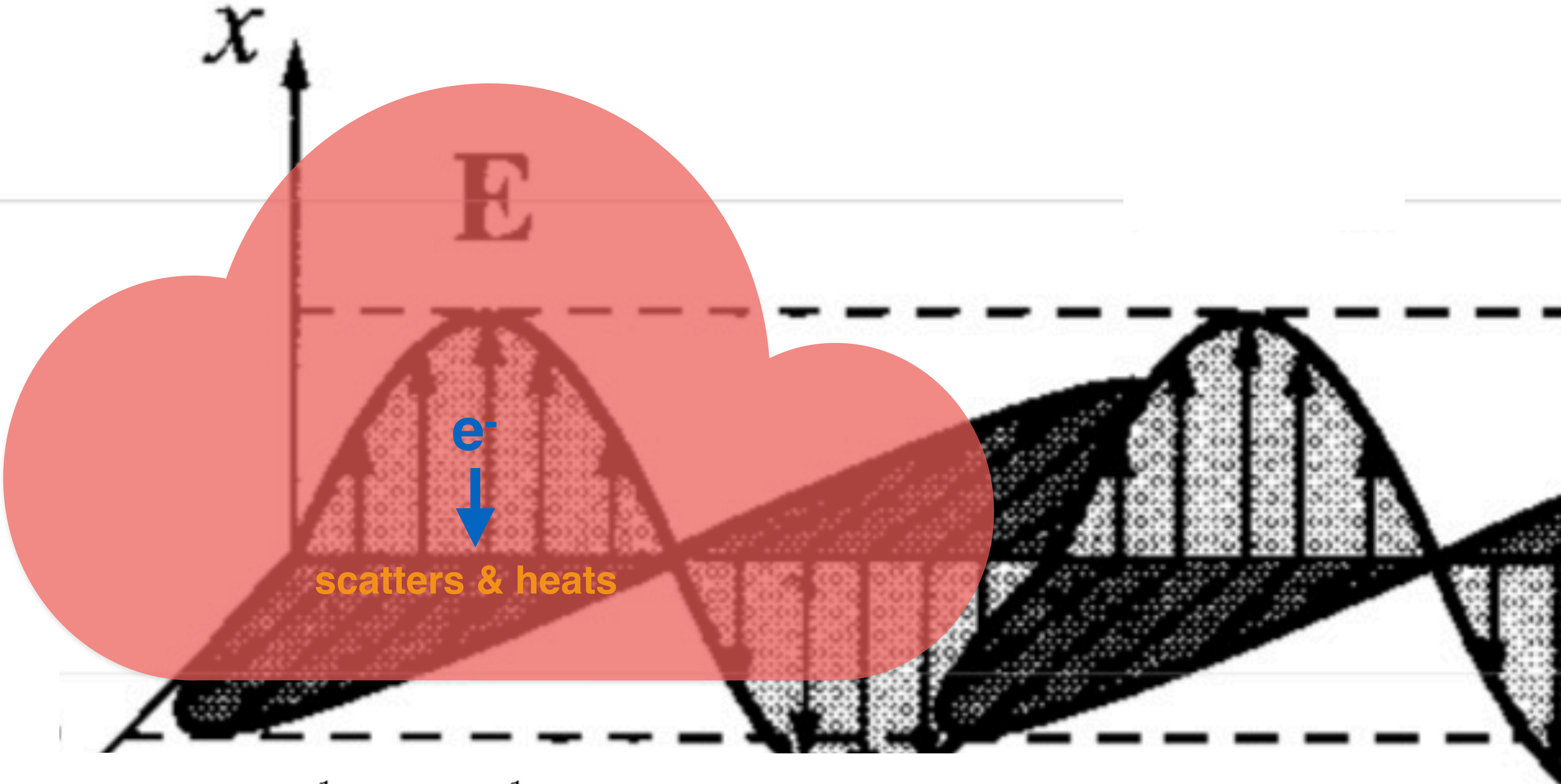
UV background

photoelectric heating

There are known ubiquitous heating sources, like cosmic UV background, cosmic rays, dust grain heating (see upcoming work).

Gas Cloud Detection of Dark Matter

Ultra Light Dark Photon Dark Matter

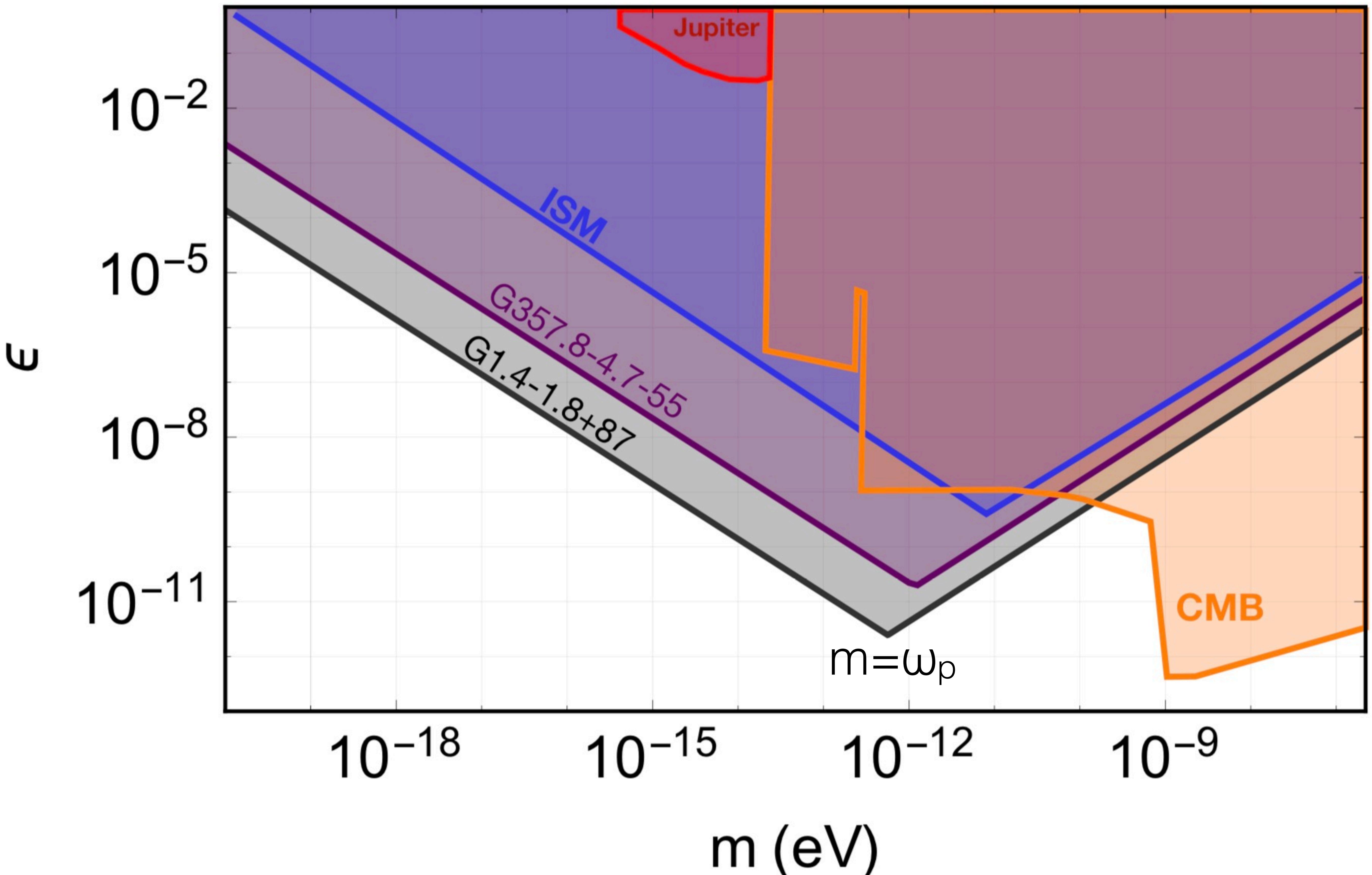


$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2 A'_\mu A'^\mu - \frac{e}{(1+\epsilon)^2}\left(A_\mu + \epsilon A'_\mu\right) J^\mu_{EM}$$

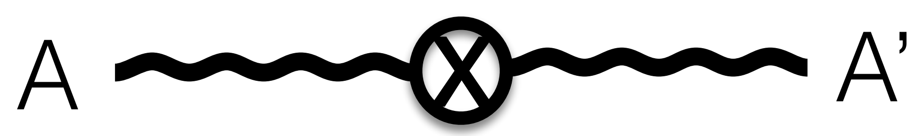
$$\gamma_h = \begin{cases} -\frac{\nu}{2}\left(\frac{m}{\omega_p}\right)^2 \frac{\epsilon^2}{1+\epsilon^2}, & m \ll \omega_p \\ -\frac{\nu}{2}\left(\frac{\omega_p}{m}\right)^2 \frac{\epsilon^2}{1+\epsilon^2}, & m \gg \omega_p; \end{cases}$$

Dubovsky et al 2015

Gas Cloud Bounds on Fuzzy Dark Photons



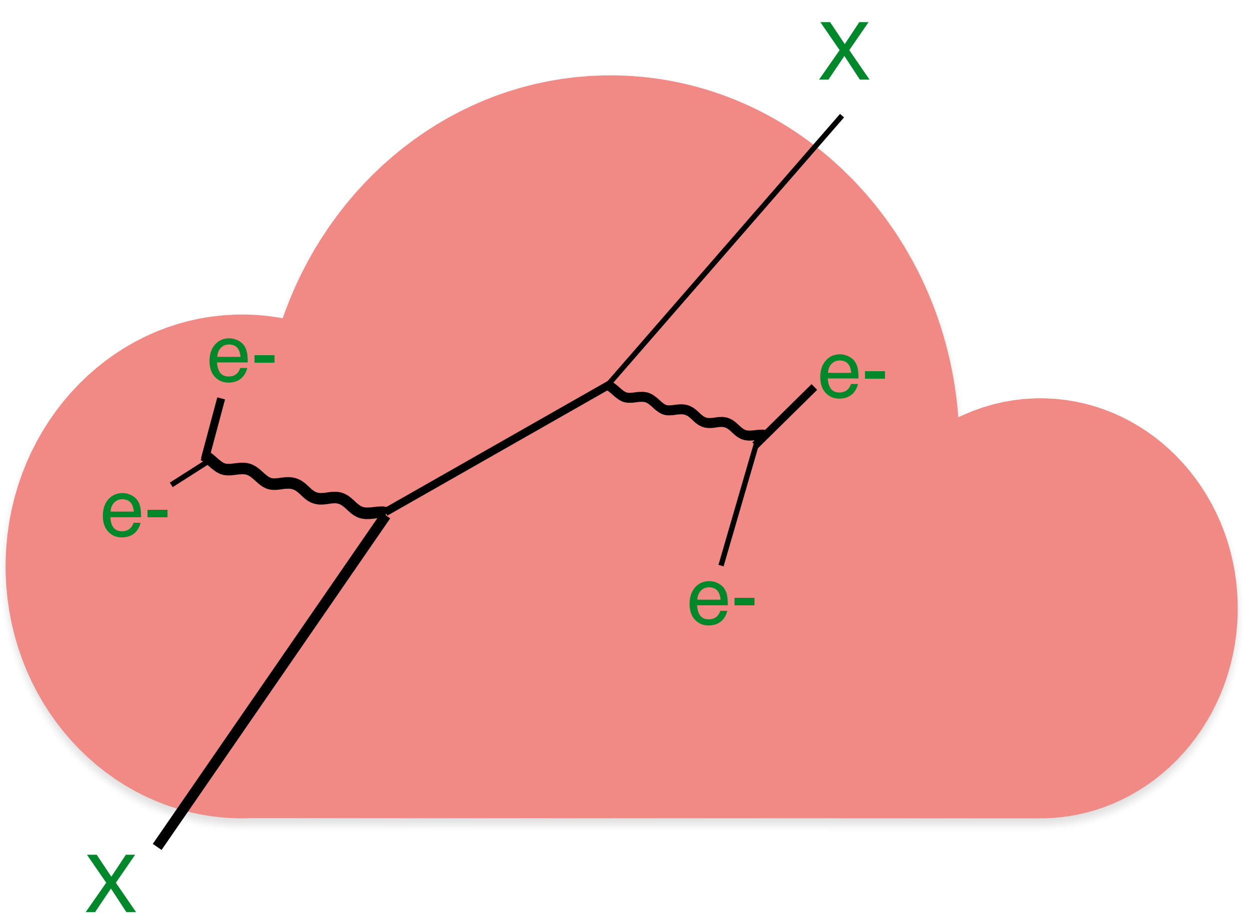
Millicharged dark matter



$$\mathcal{L} = \mathcal{L}_{\rm SM} + |D_\mu \Phi|^2 - V(\Phi) - \frac{1}{4}{F'}^2_{\mu\nu} + \epsilon {A'}_\mu \partial_\nu F^{\mu\nu} + \bar{X}(iD_\mu \gamma_\mu - m_X)X$$

for $m_{A'} << q$, effectively ε-charged DM

MDM deposits most energy into free electrons in cloud



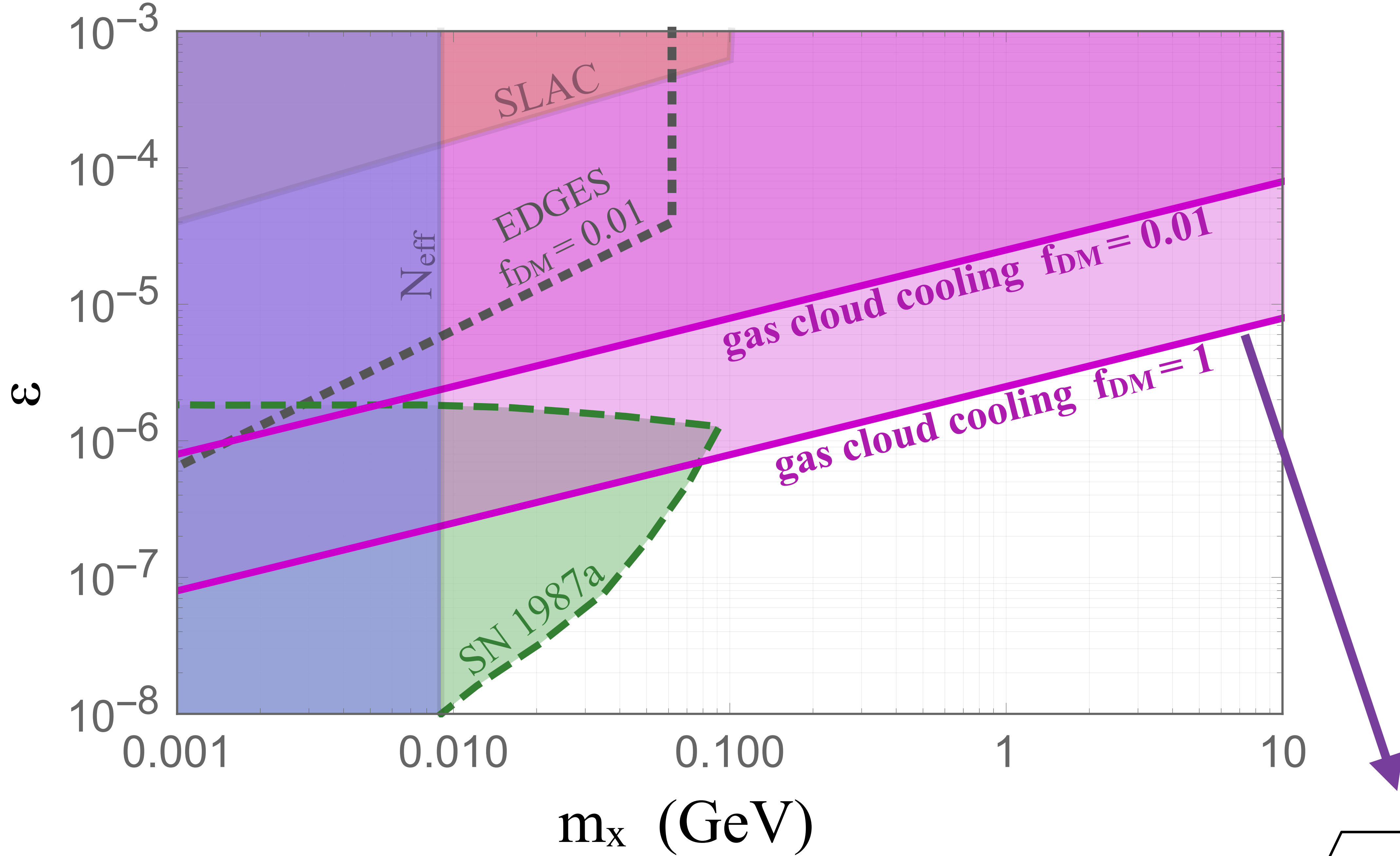
Bethe

$$\frac{dE}{dx} = \frac{2\pi n_{\rm e} \epsilon^2 \alpha_{\rm em}^2}{m_{\rm e} v_{\rm x}^2} \left(\ln \left[\frac{2\mu_{\rm ex}^2 v_{\rm x}^2 / m_{\rm e}}{\lambda_d^{-2}/(2m_{\rm e})} \right] - v_{\rm x}^2 \right)$$

Debye screening

$$\lambda_{\rm d} = \sqrt{T_{\rm g}/(4\pi\alpha_{\rm em} n_{\rm e})}$$

Millicharged dark matter



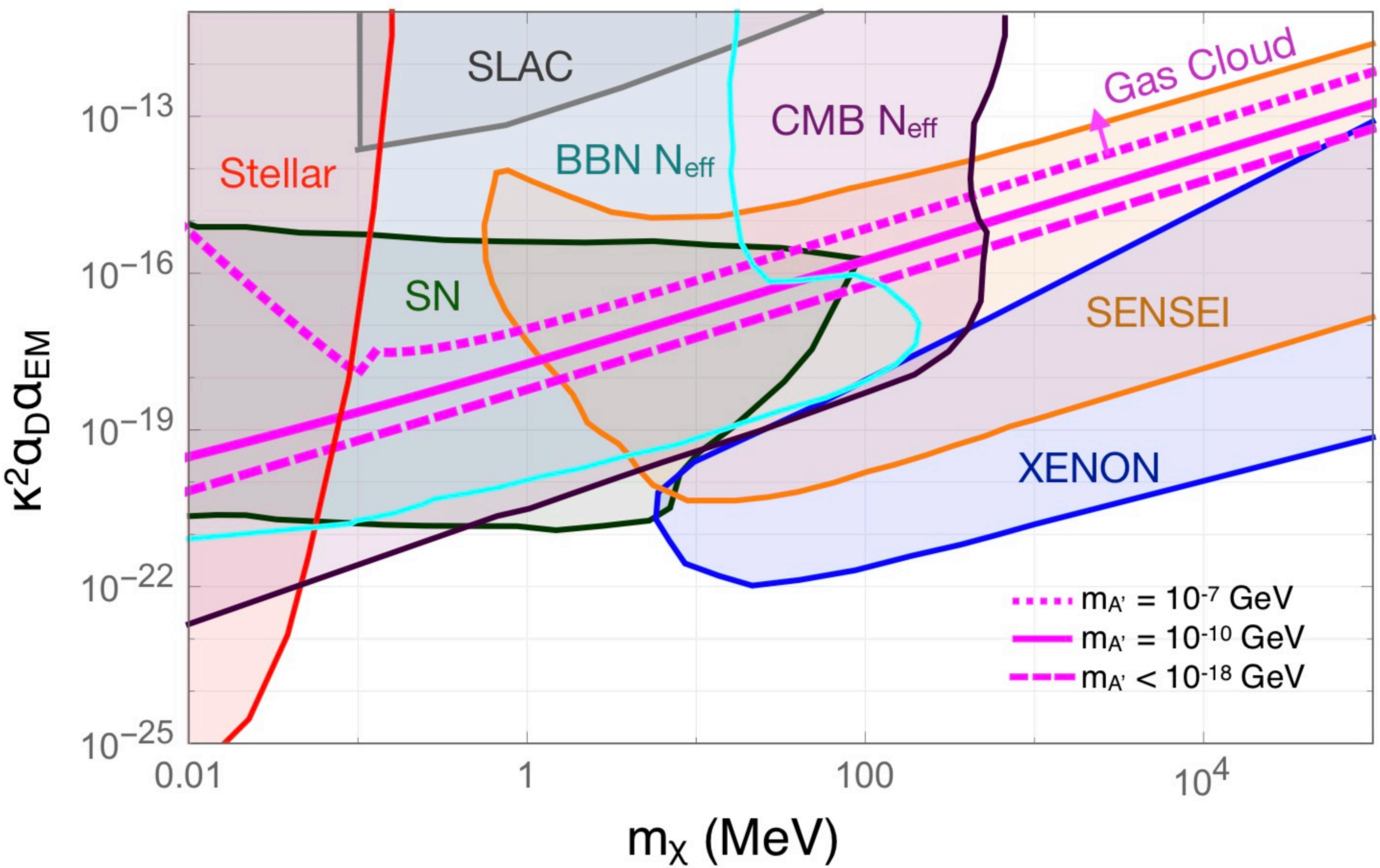
$$\epsilon \propto \sqrt{\rho_x / m_x}$$

[Fe/H] proof

Metallicity leaves bound nearly unchanged because higher metallicity increases heating linearly by increasing free electron number density.

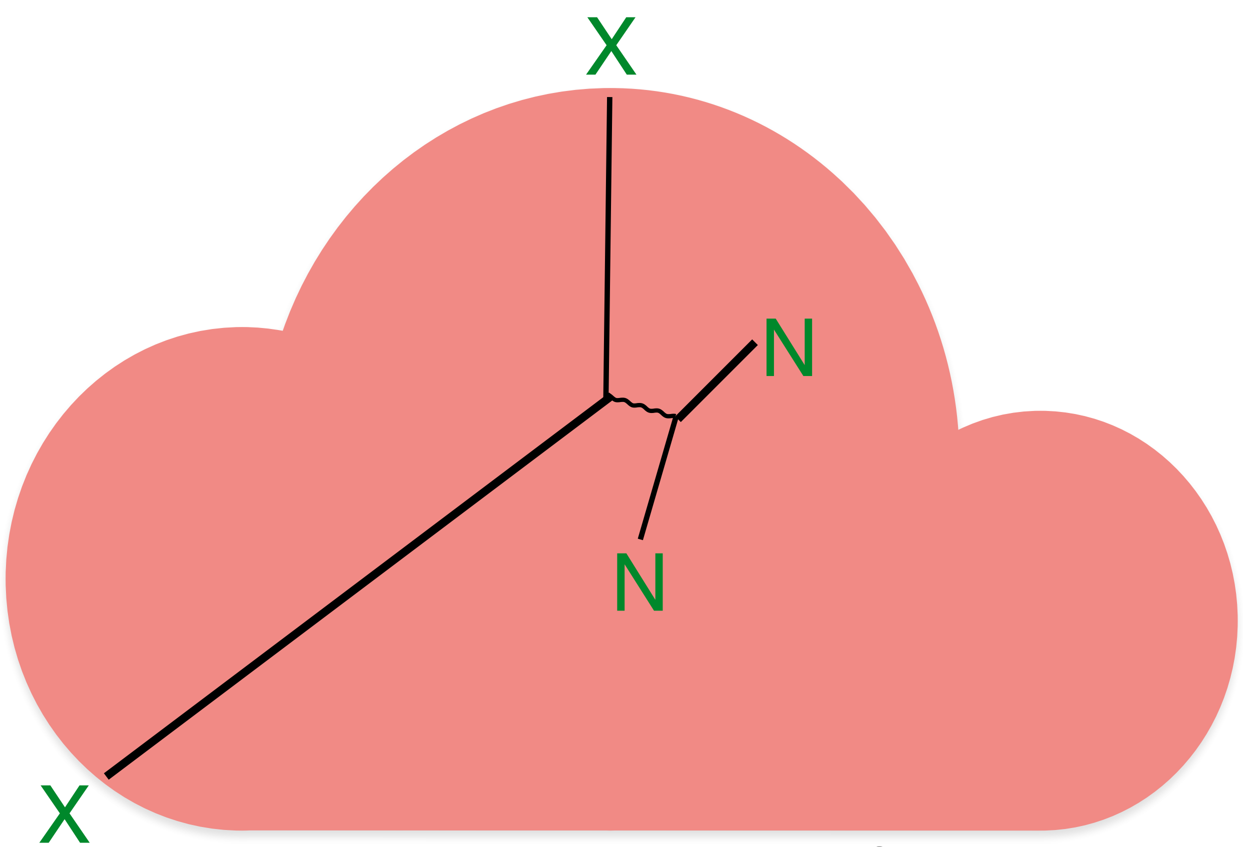
Vector Portal Dark Matter

Mediator with a mass.



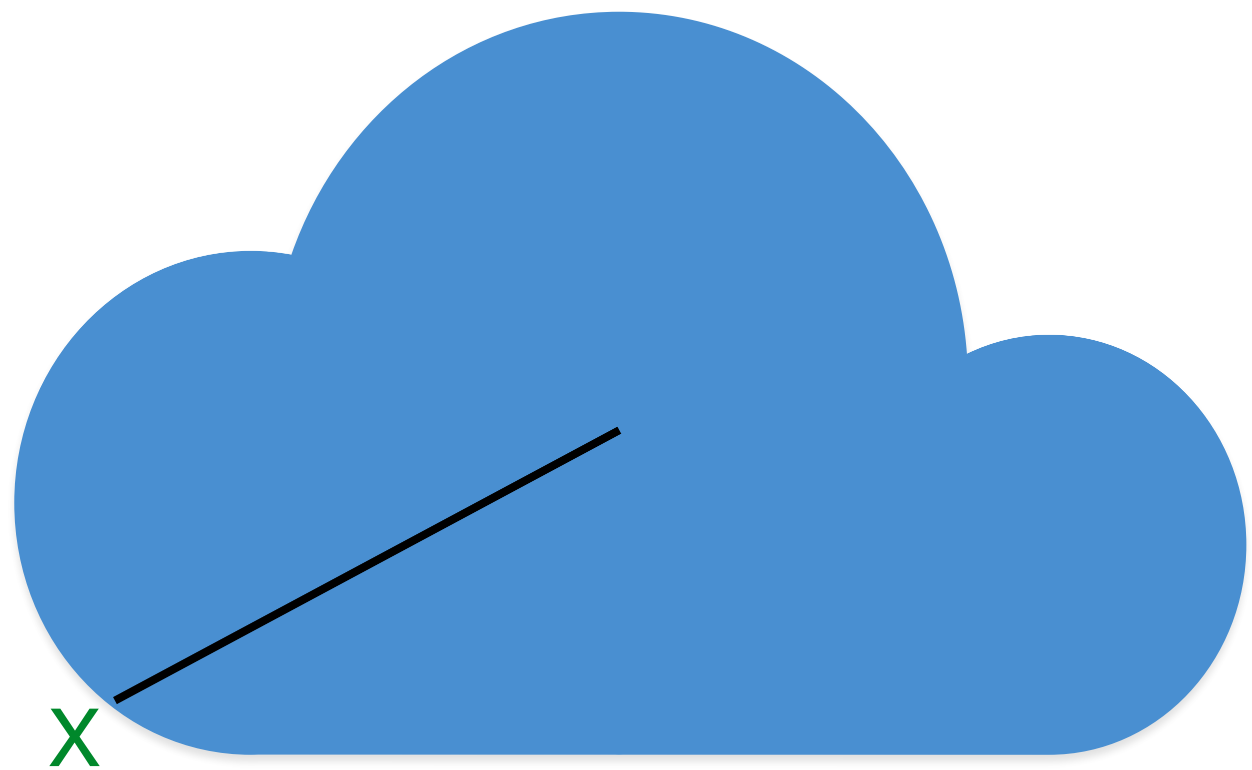
Dark matter nucleon scattering (strongly interacting, composite, super heavy)

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



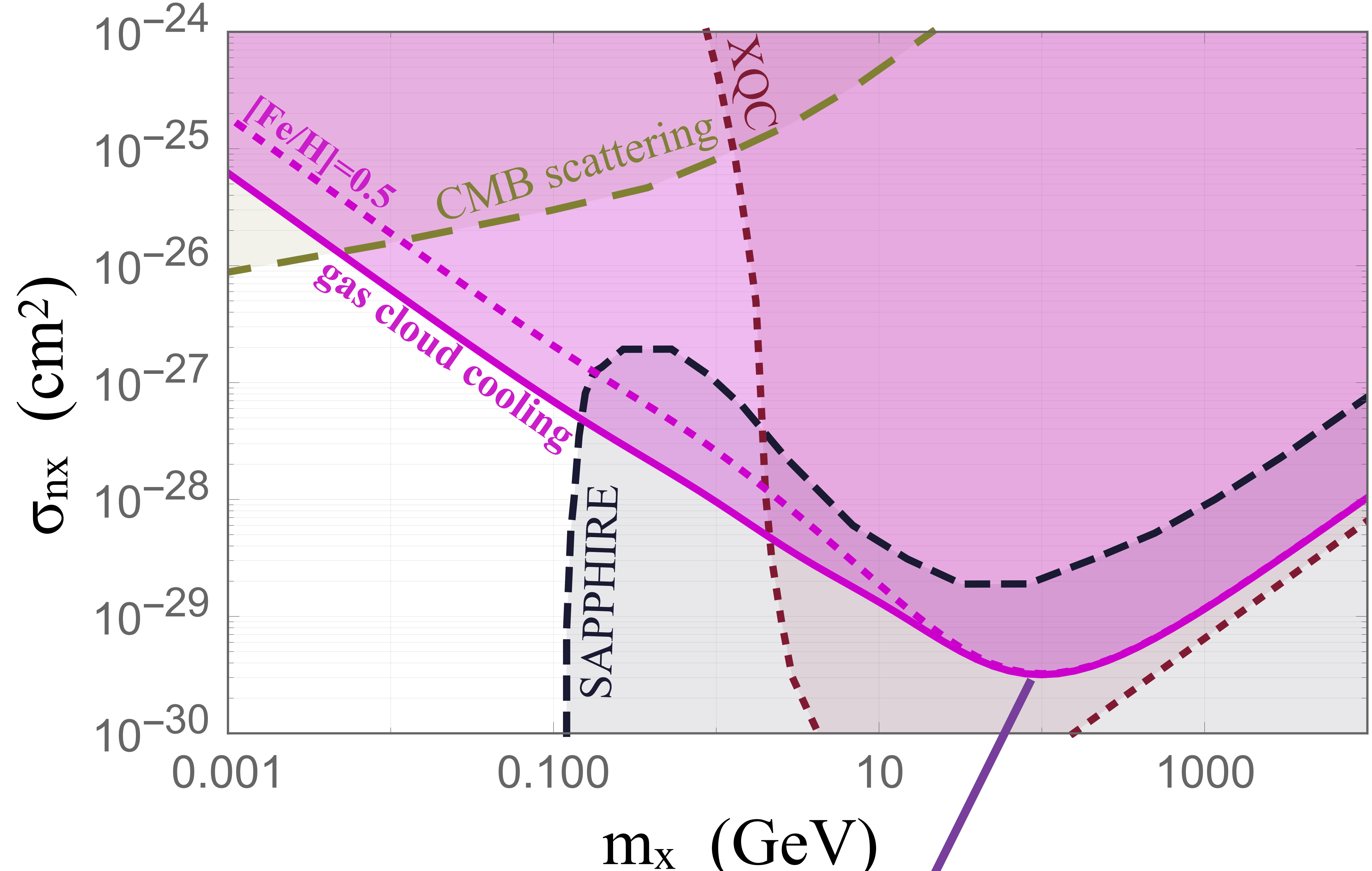
$$\sigma_{\mathrm{Nx}} = A^2 F_{\mathrm{A}}^2(E_{\mathrm{nr}}) \frac{\mu_{\mathrm{Nx}}^2}{\mu_{\mathrm{nx}}^2} \sigma_{\mathrm{nx}}$$

overburden



Require dark matter has most of its kinetic energy when it reaches the center

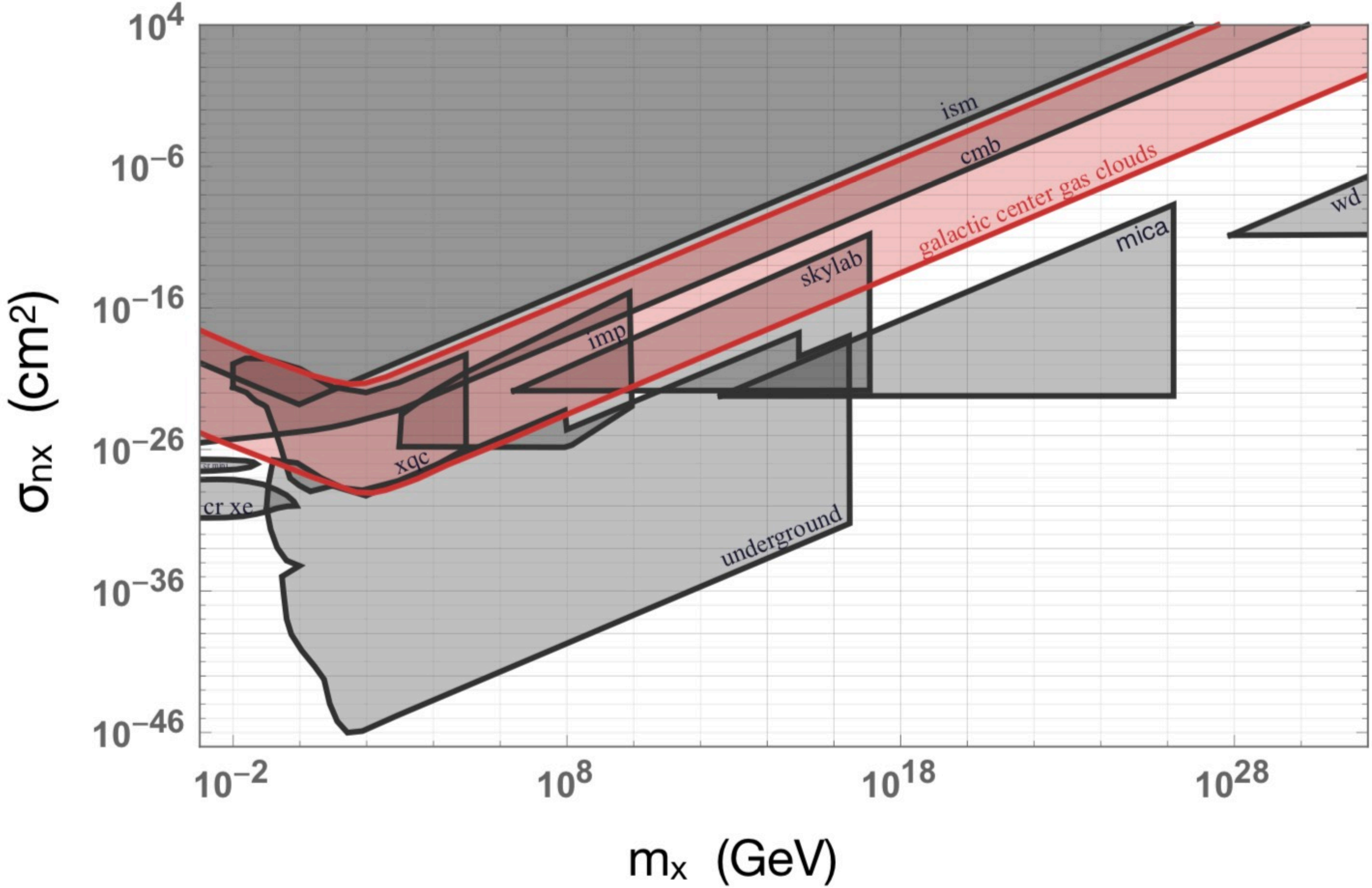
Dark matter nucleon scattering - low mass



$$\text{Heating rate}_A \sim (n_x \sigma_{Ax} v_x)(\mu_{Ax}^2 v_x^2 / m_A)$$

rate recoil energy

Dark matter nucleon scattering



Summary

Galactic center gas clouds are
useful dark matter detectors

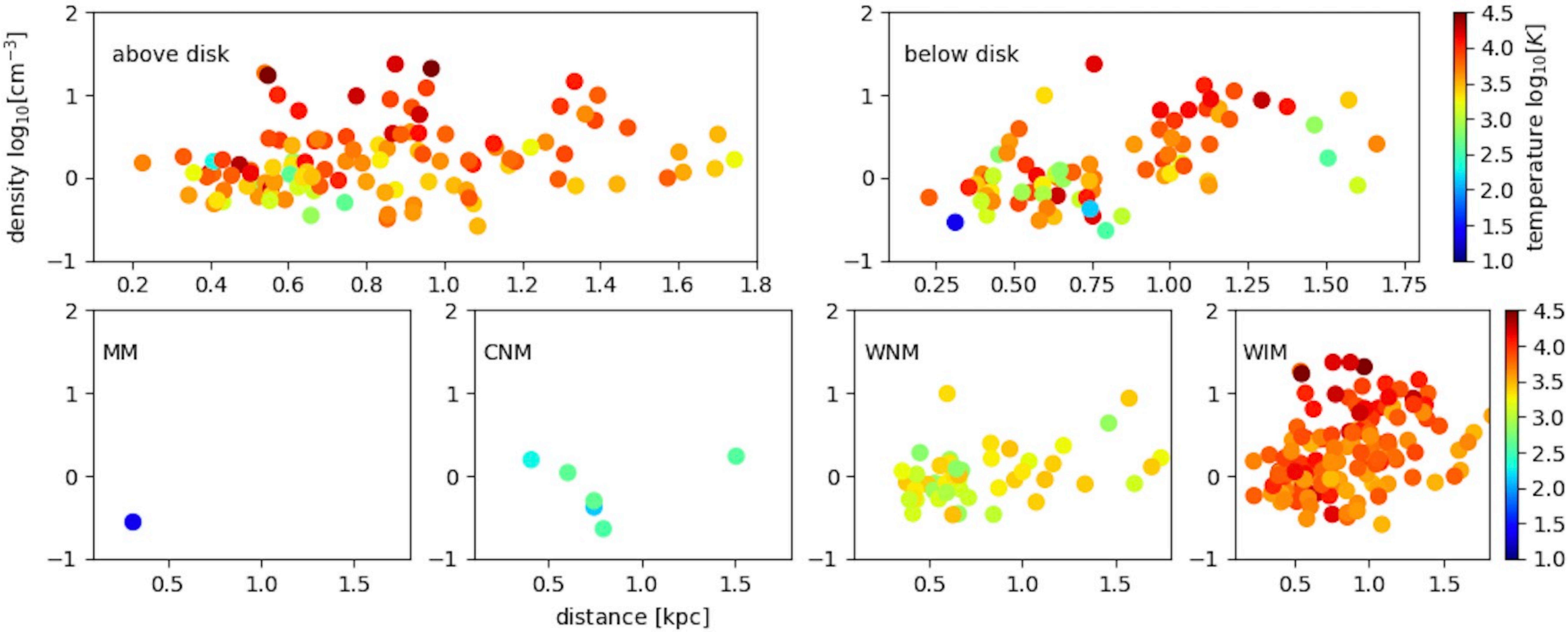
10^{-22} - 10^{-10} eV mass dark photon dark matter

Millicharged dark matter,
less screened by galactic magnetic fields

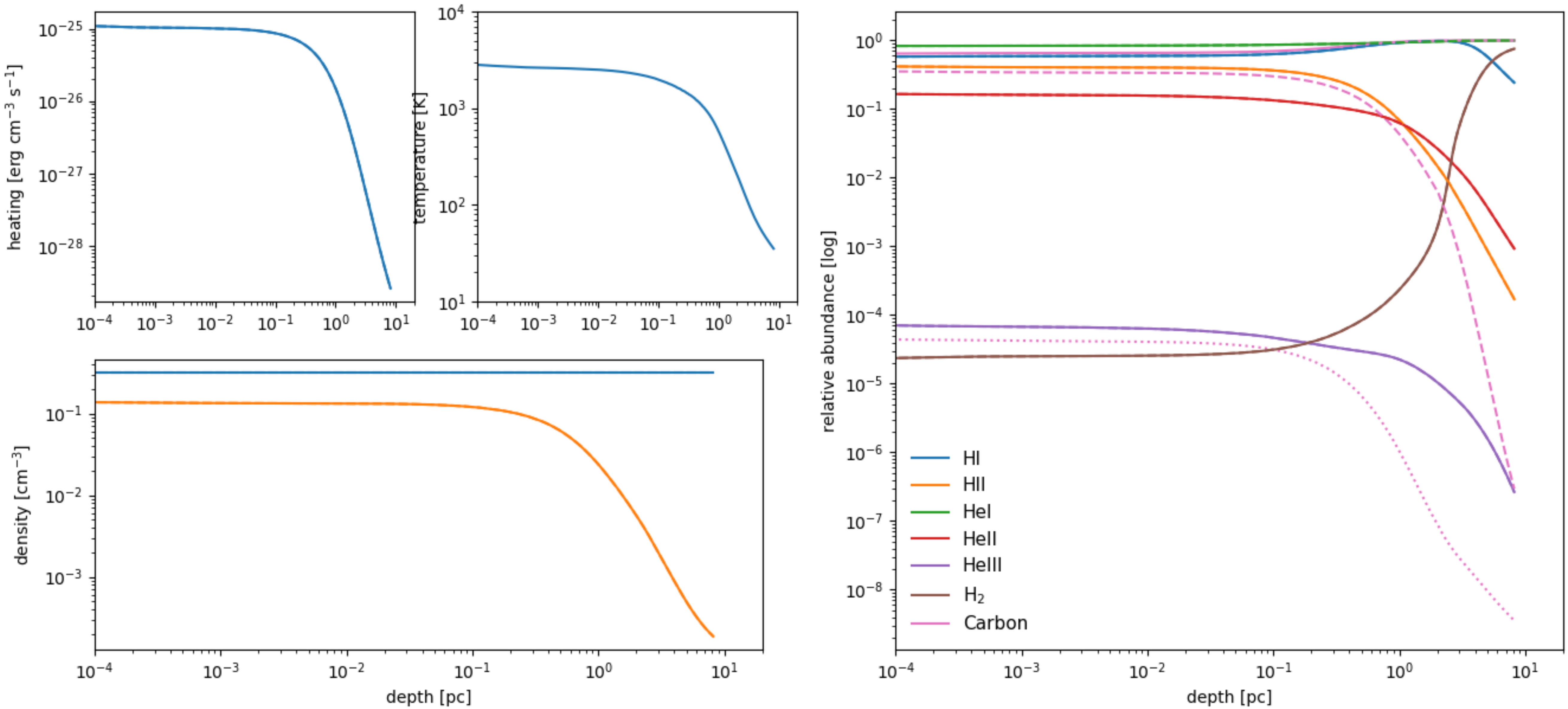
Sub-GeV Mediator Mass
Vector Portal dark matter

Dark matter nucleon scattering
for 0.01-10^{60} GeV mass dark matter

Gas cloud locations



Gas cloud cooling, some atomic abundances



Milky Way Magnetic Field Screening of Millicharged DM

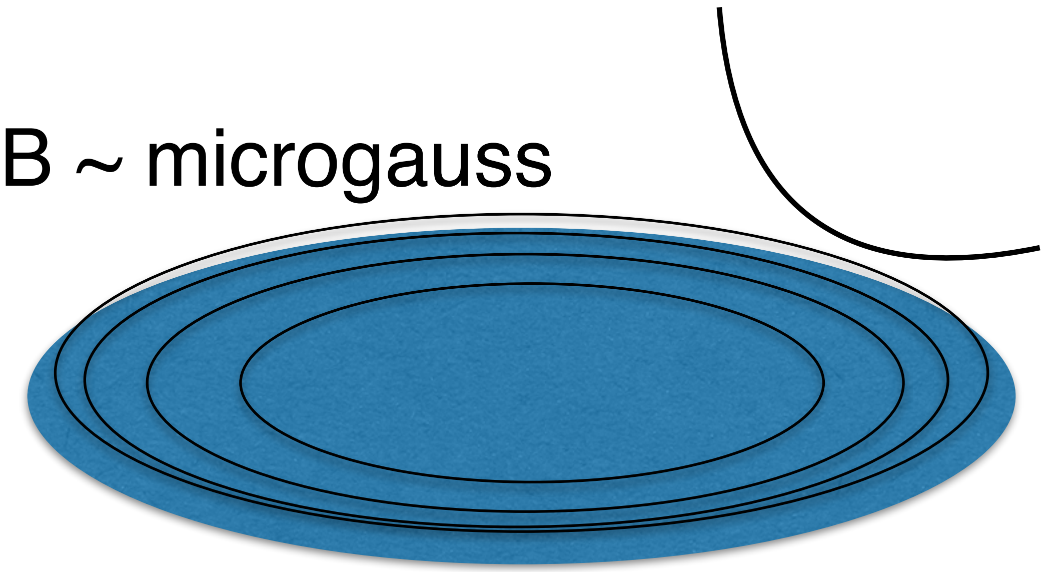
Magnetic fields screen charged dark matter from entering disk.

Chuzhoy, Kolb 0809.0436

Irregularities let some mDM through

McDermott, Yu, Zurek 1011.2907

B ~ microgauss



$\epsilon > 5 \times 10^{-13}(m_x/\mathrm{GeV})$ screened

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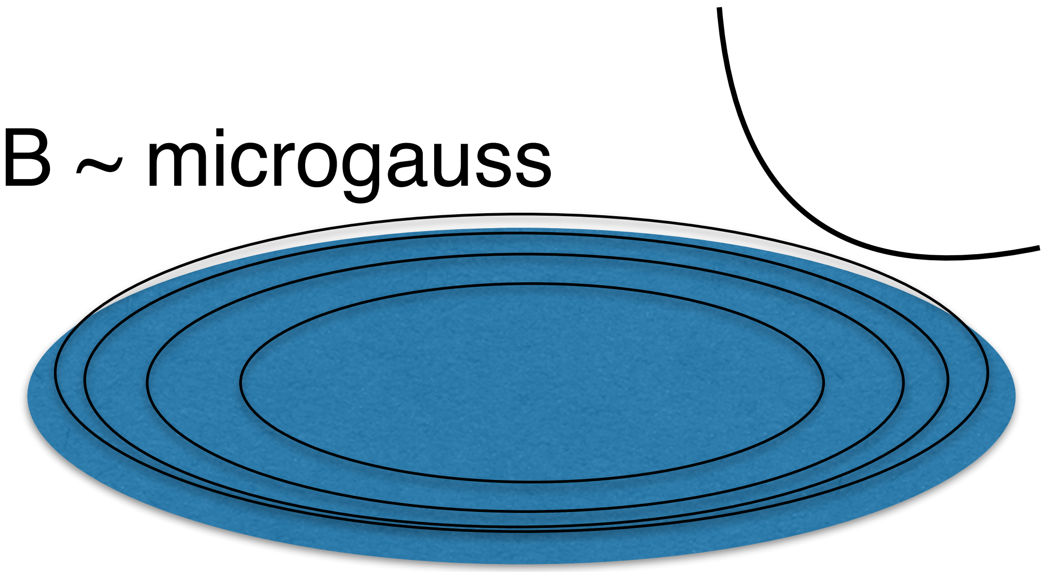


Irregularities let some mDM through

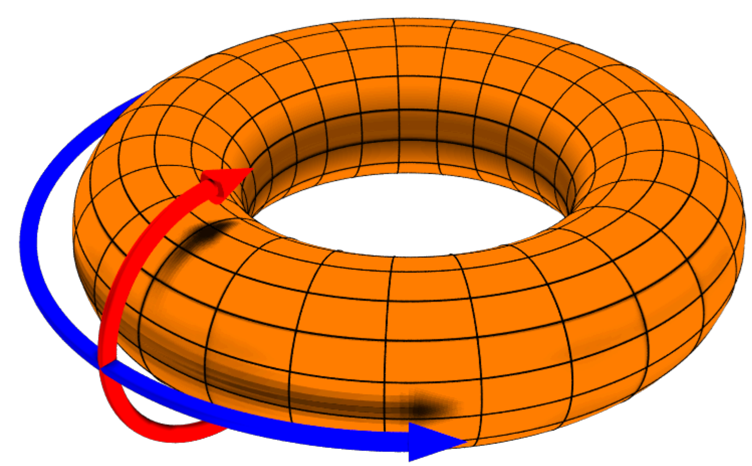
McDermott, Yu, Zurek 1011.2907

$\epsilon > 5 \times 10^{-13} (m_{\mathrm{x}}/\mathrm{GeV})$ screened

However: above 100 parsecs in the galactic center, magnetic fields won't screen halo dark matter

150 pc

1009.0584



toroidal to poloidal
magnetic field orientation
transition above ~100 pc in GC