Title: Gas Clouds as Dark Matter Detectors

Speakers: Sarah Schon

Series: Particle Physics

Date: June 14, 2019 - 1:00 PM

URL: http://pirsa.org/19060035

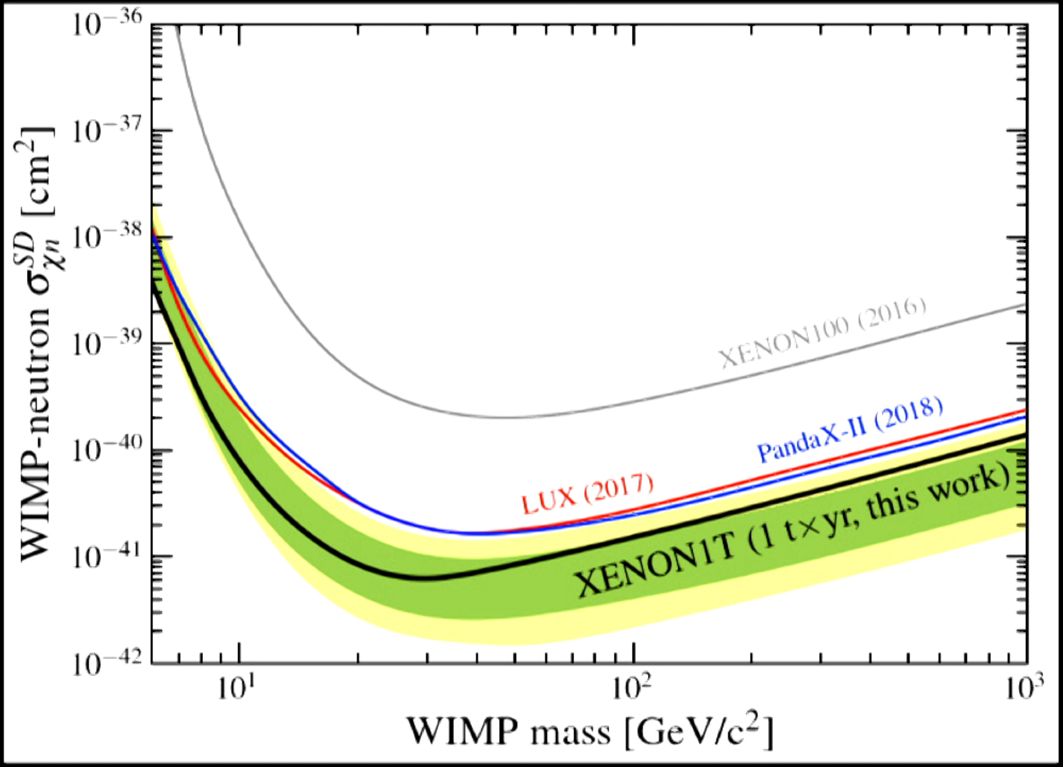
Abstract: Atomic hydrogen gas clouds originating from the Galactic Center offer a novel way to test dark matter phenomenology. By exploiting the inefficient gas cooling rates at low temperatures, bounds for various interactions between dark and baryonic matter can be set. We demonstrate this new method and present limits for a number of dark matter models including ultra-light dark photons and super-heavy candidates.

Gas Clouds as Dark Matter Detectors

Amit Bhoonah, Joseph Bramante, Fatemeh Alahi, Sarah Schon

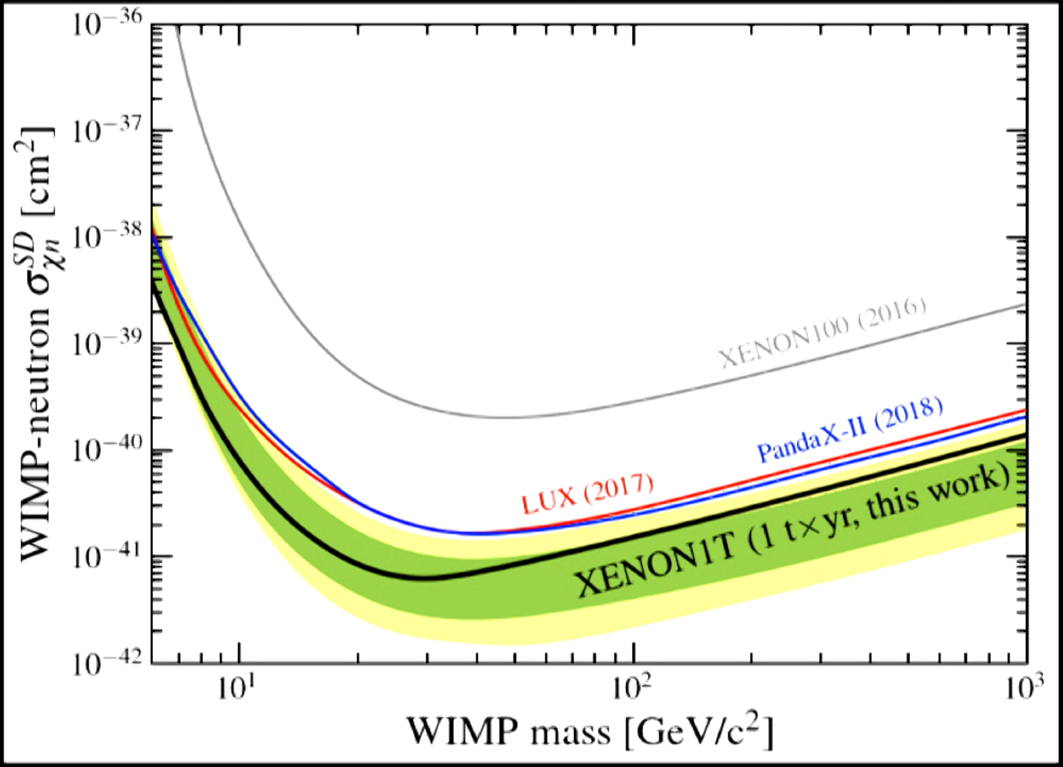
ArXiv:1806.06857
ArXiv:1812.10919

Direct DM Detection



Xenon 1T 2018

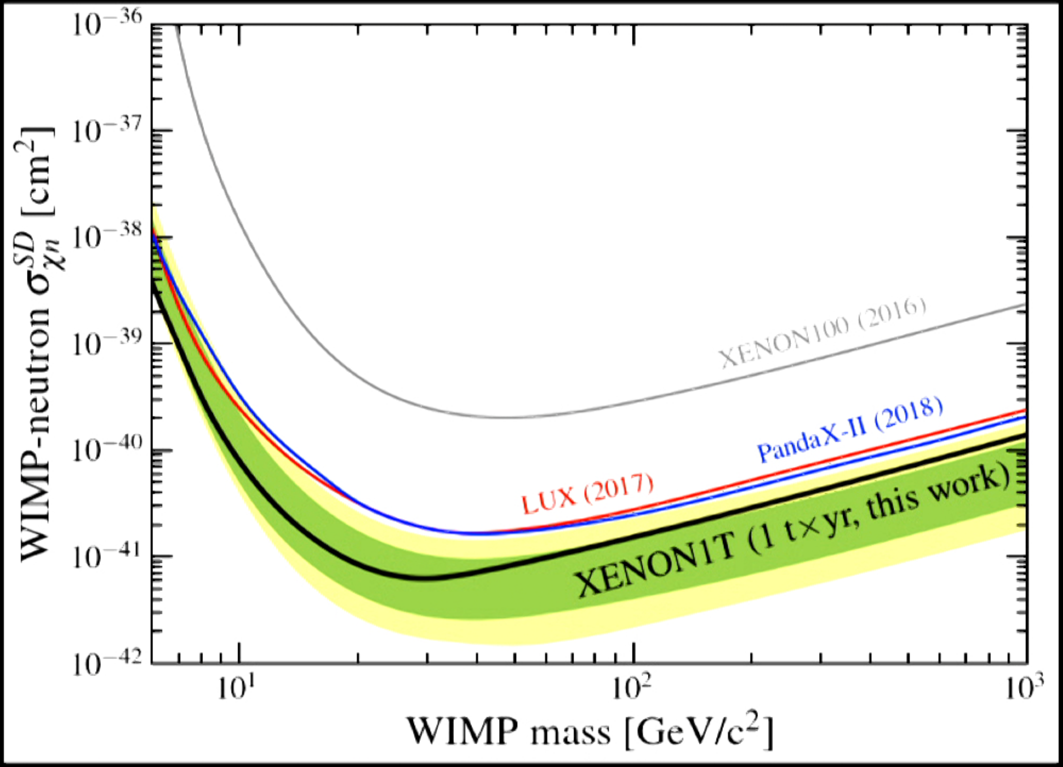
Direct DM Detection



Xenon 1T 2018

light DM (thresholds)

Direct DM Detection

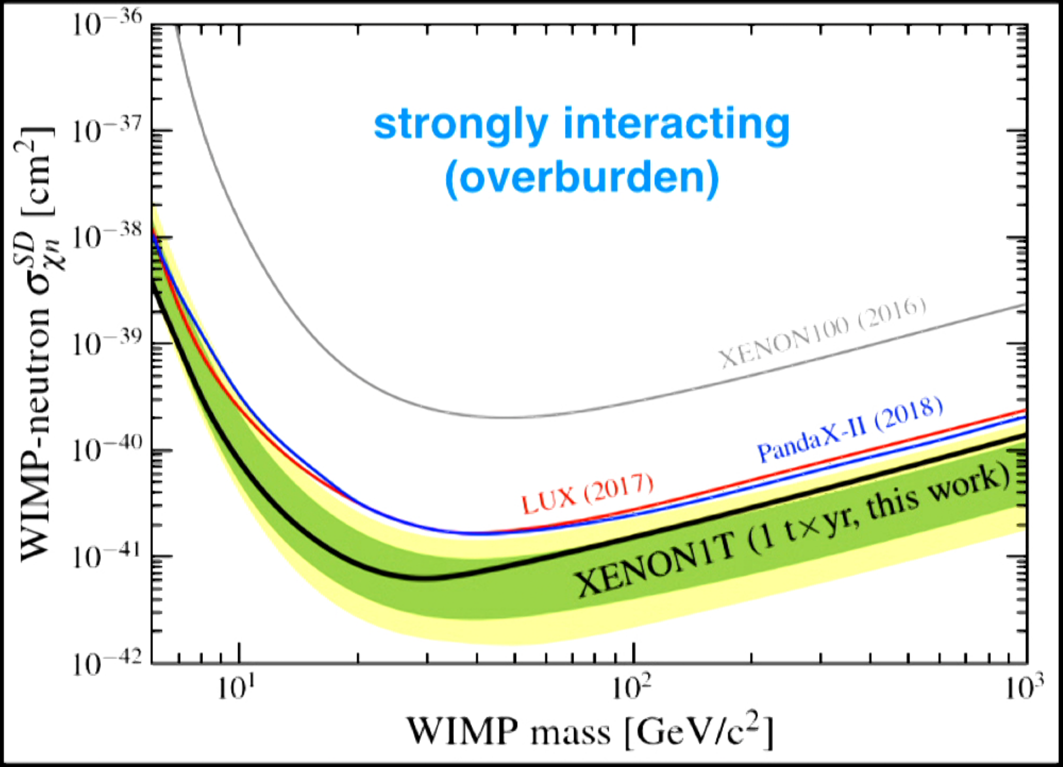


Xenon 1T 2018

light DM
(thresholds)

heavy DM
(flux)

Direct DM Detection



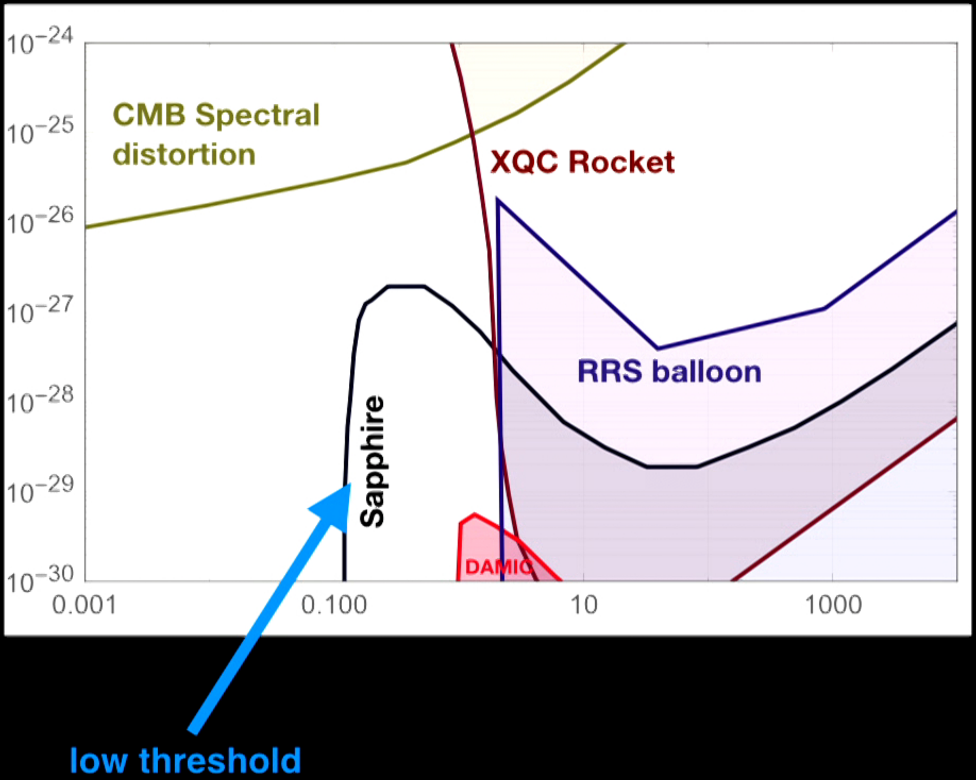
strongly interacting
(overburden)

Xenon 1T 2018

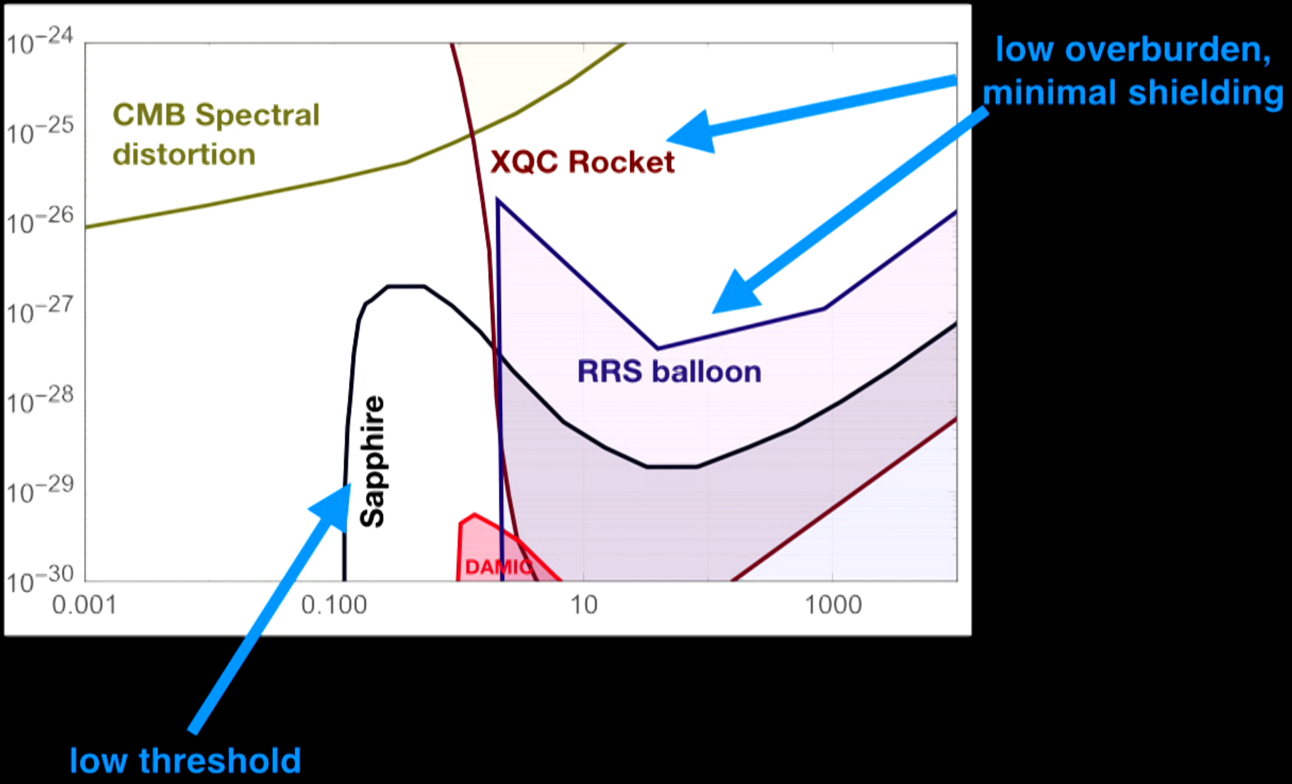
light DM
(thresholds)

heavy DM
(flux)

Strongly Interacting DM Searches



Strongly Interacting DM Searches



low overburden, minimal shielding

low threshold

Astrophysical DM Searches

(go big or go home)

Advantages

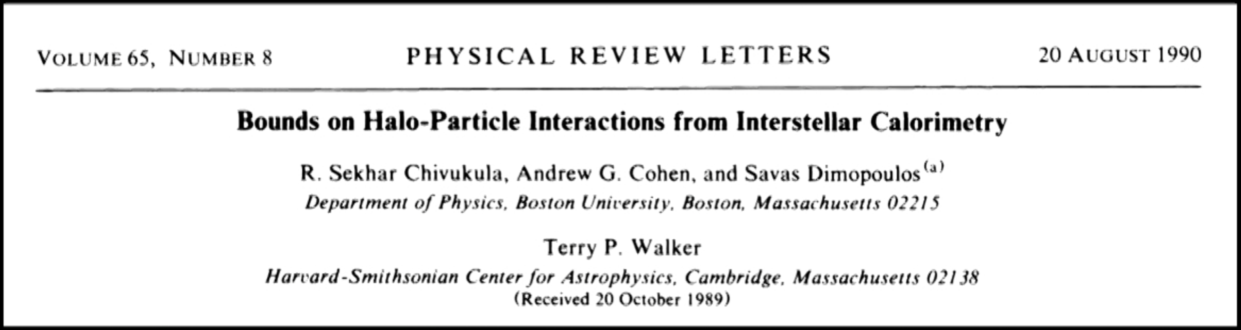
- large scales/objects
- long exposure times
- high densities, energies, temperatures etc

Disadvantages

- uncontrolled, not fully understood environments
- strong backgrounds
- observational limitations

Galactic DM Detectors

Constraints from the ISM

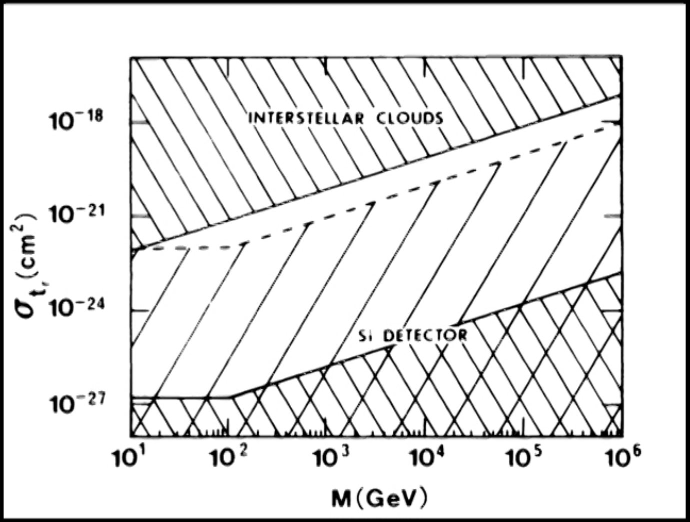

VOLUME 65, NUMBER 8 PHYSICAL REVIEW LETTERS 20 AUGUST 1990

Bounds on Halo-Particle Interactions from Interstellar Calorimetry

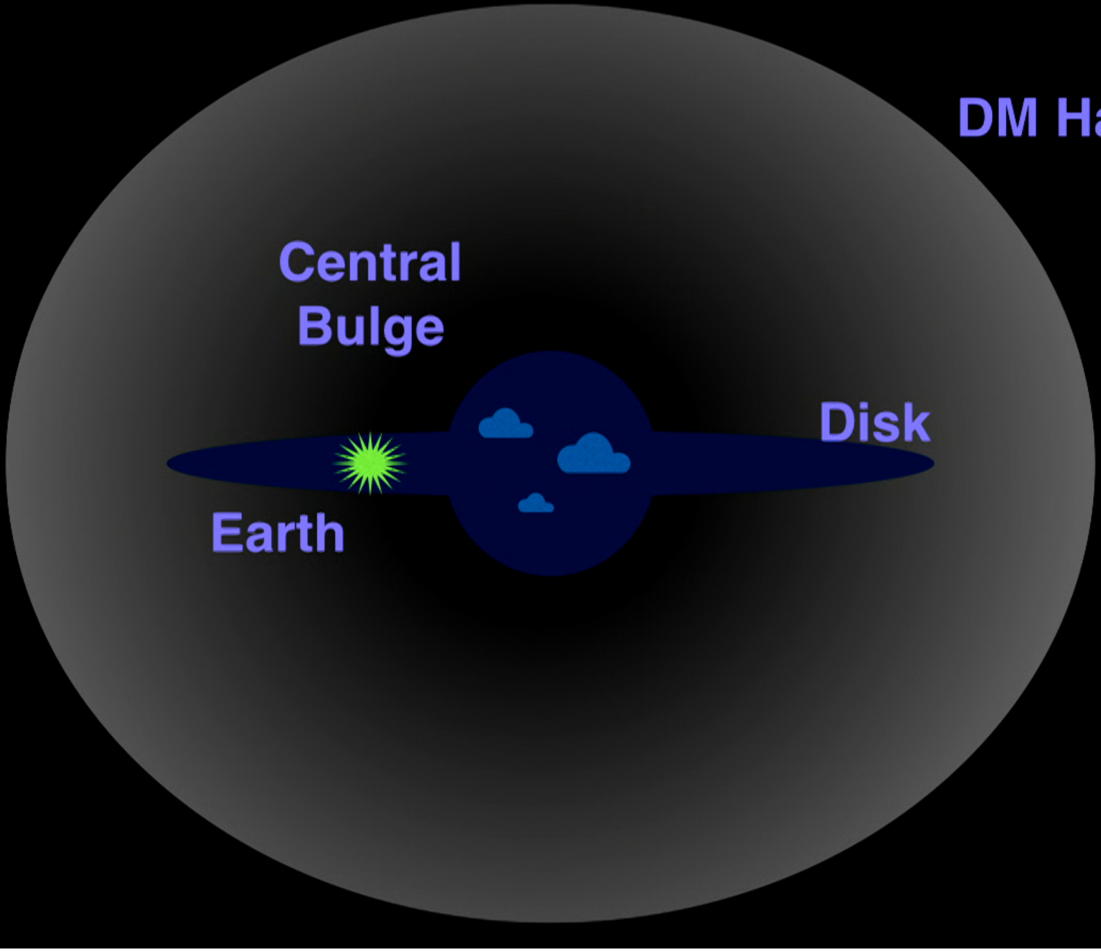
R. Sekhar Chivukula, Andrew G. Cohen, and Savas Dimopoulos[(a)]
Department of Physics, Boston University, Boston, Massachusetts 02215

Terry P. Walker
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138
(Received 20 October 1989)

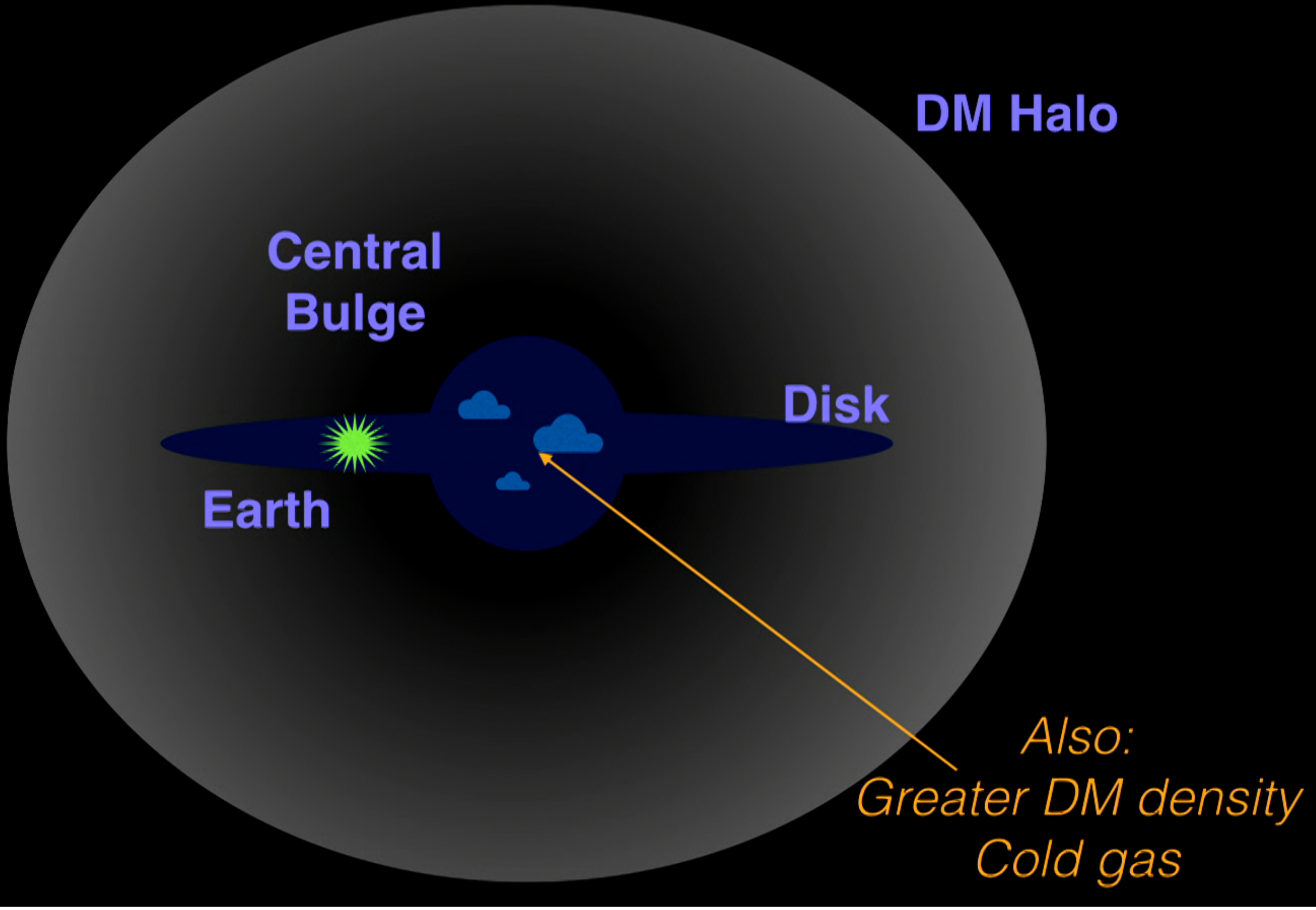
- Assume thermal equilibrium
- Halo DM at greater temperature than gas
- T~30-80 , 10 -200 cm^-3
- Cooling via deexcitation of C*+



Galactic Center

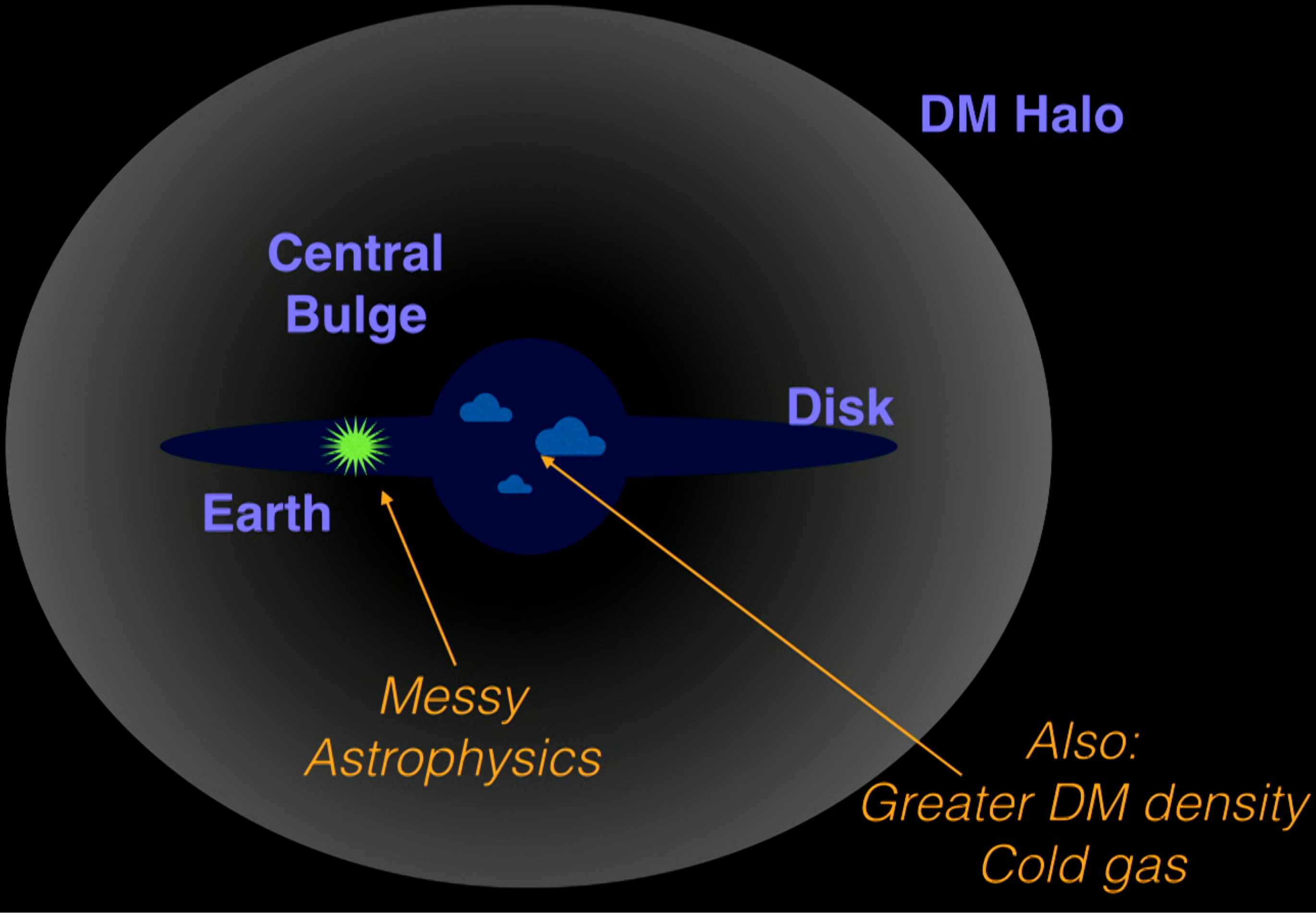


Galactic Center

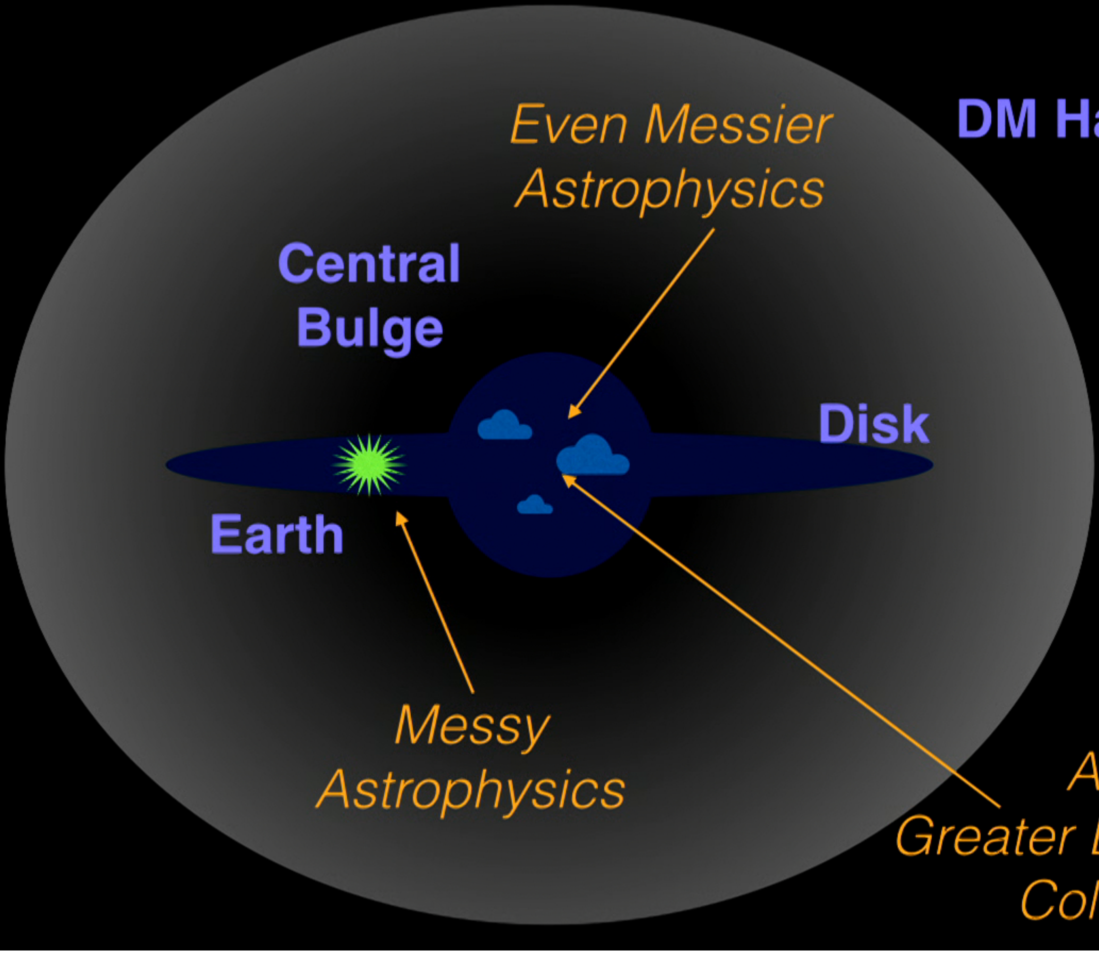


Also:
Greater DM density
Cold gas

Galactic Center



Galactic Center



DM Halo

Even Messier Astrophysics

Central Bulge

Disk

Earth

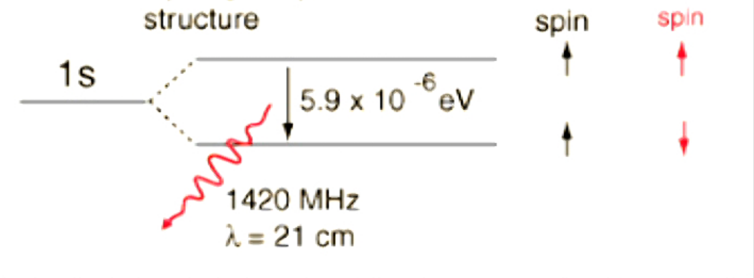
Messy Astrophysics

Also:
Greater DM density
Cold gas

HI Surveys

The 21cm line refers to the hyperfine spin flip transition of neutral Hydrogen in it's ground state. Key to observing atomic Hydrogen.

$$\frac{T_s}{T_*} = -\ln(\frac{n_1}{3n_0}) \qquad T_* = \frac{h\nu_{21}}{k_b} \qquad \nu_{21} = \frac{\nu_{21}^0}{1+z}$$



HI Surveys

The spin temperature couples to the surrounding radiation and gas fields

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

HI Surveys

The spin temperature couples to the surrounding radiation and gas fields

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

CMB

HI Surveys

The spin temperature couples to the surrounding radiation and gas fields

Gas Temp

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

CMB

Colour Temp

HI Surveys

The spin temperature couples to the surrounding radiation and gas fields

Gas Temp

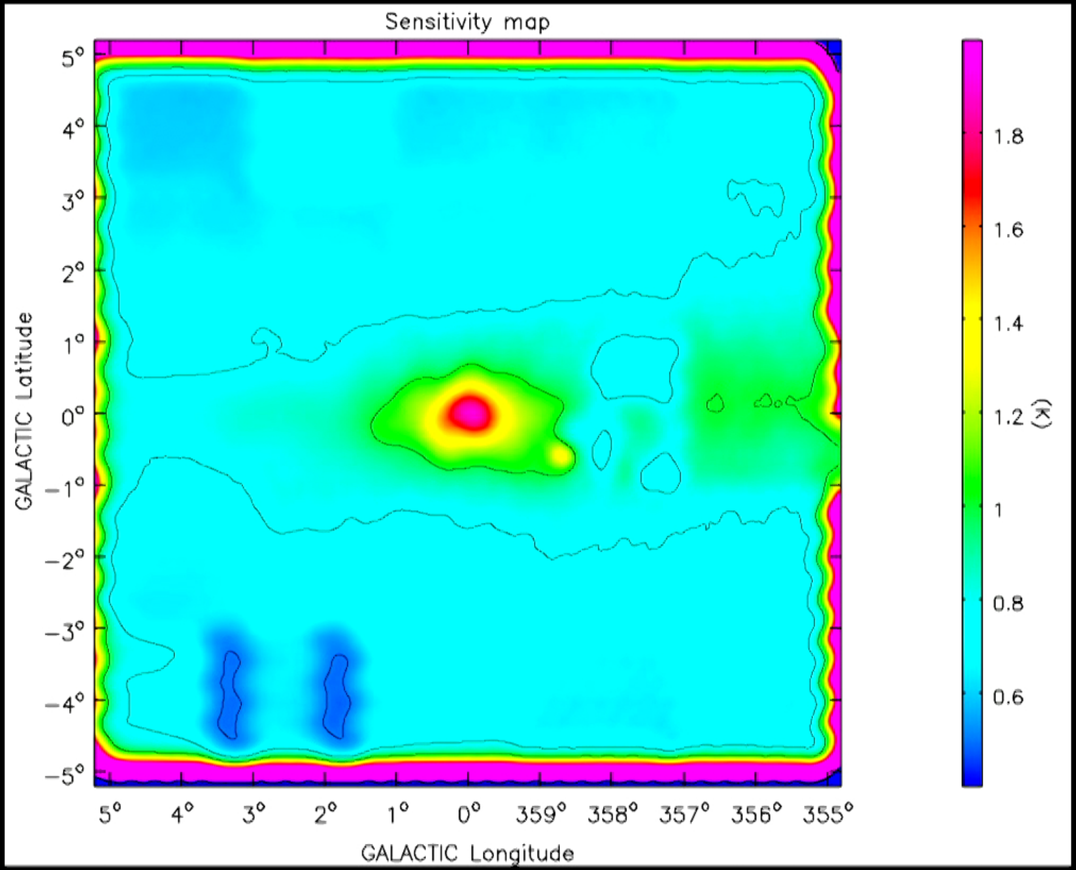
$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

CMB

Colour Temp

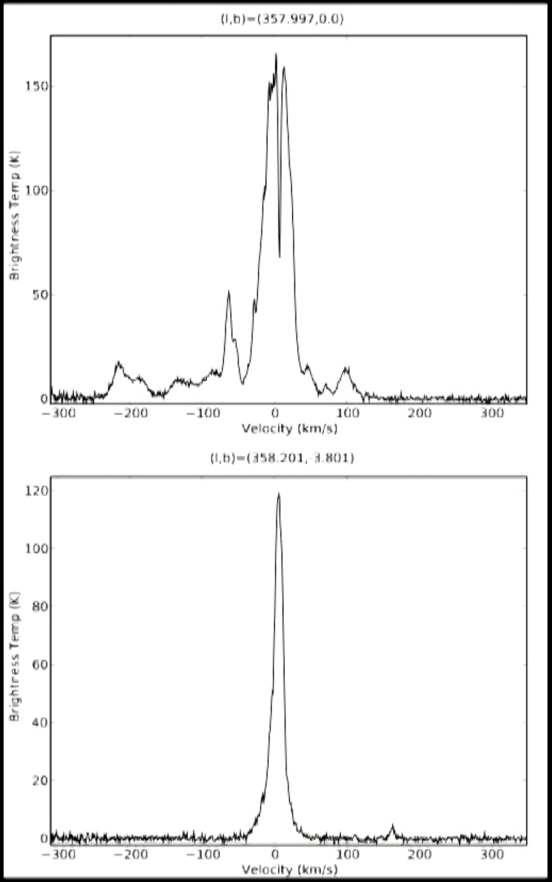
$$\delta T_b \simeq \frac{3}{32\pi} \frac{A_{10c^3 h \bar{n}_H^0}}{\nu_{21}^2 k_b} \frac{T_s - T_\gamma}{T_s} \frac{(1+z)^2}{H(z)} (1+\delta)\bar{x}_{HI} \quad \tau \ll 1$$

ATCA HI Galactic Center Survey

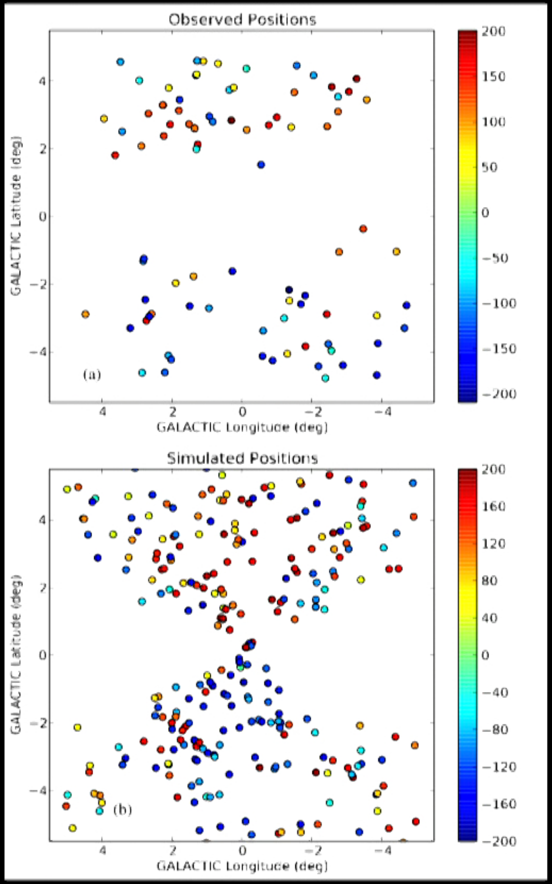


McClure-Griffiths et al 2012

GC Gas Clouds



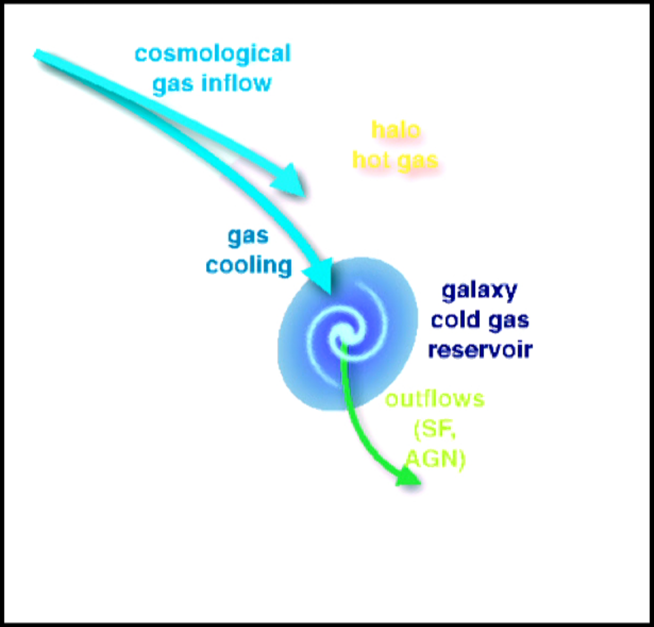
McClure-Griffiths 2012

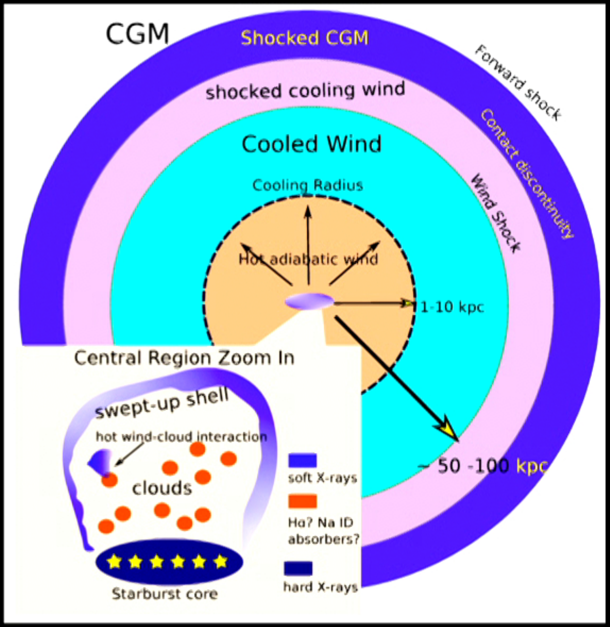


McClure-Griffiths 2013

Gastrophysics

Gas accretes onto the halo, cools to form stars and is expelled through AGN feedback and stellar winds

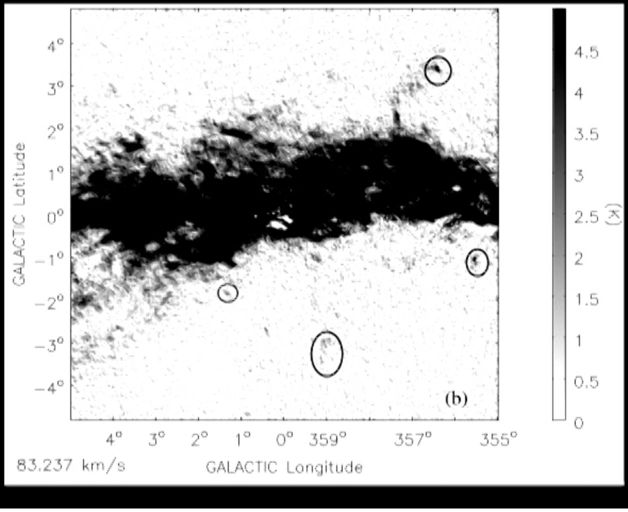




Zhang 2018

A Soufflé of Gas Clouds

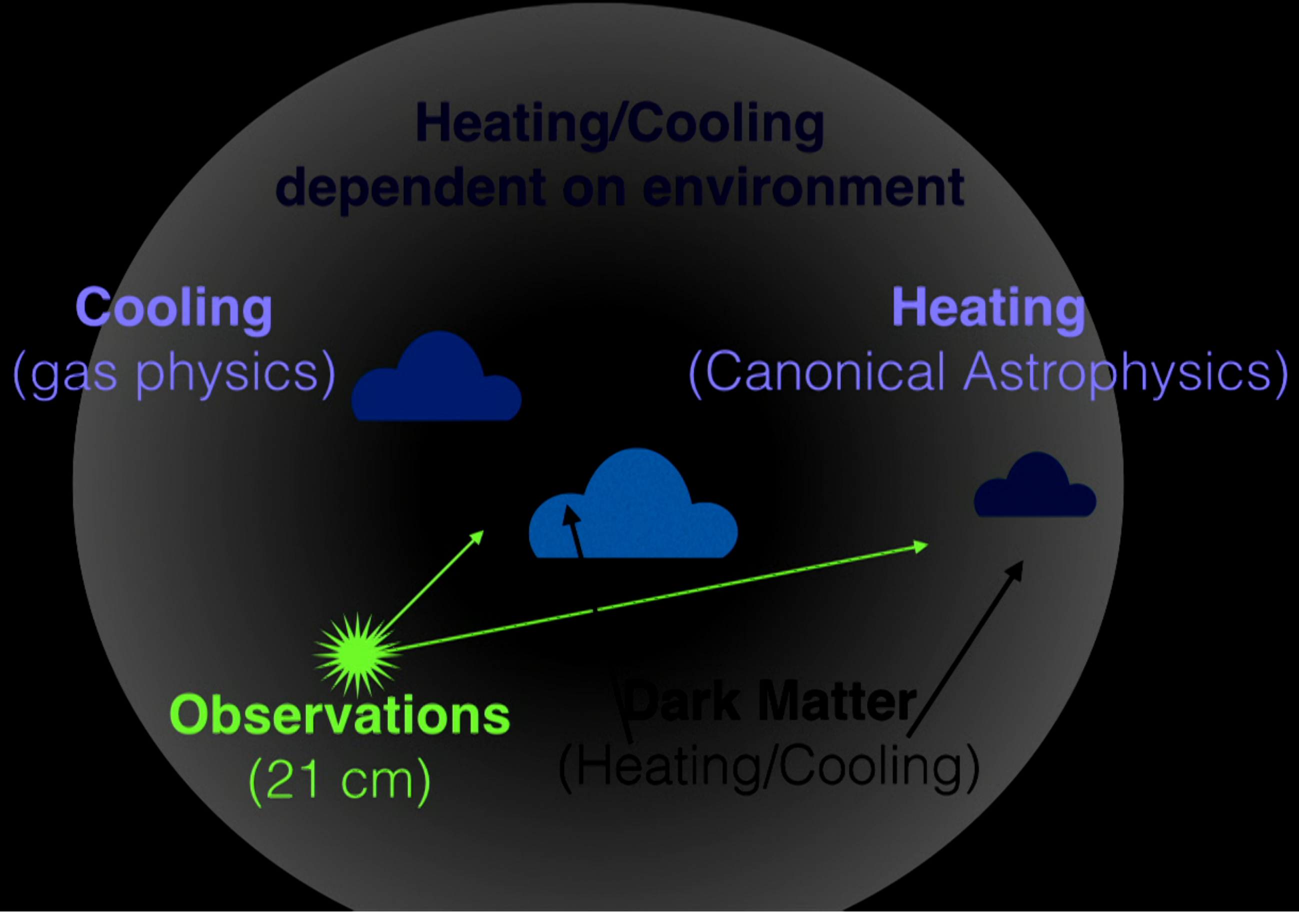
	Mass [M_sol]	r [pc]	n [cm^_3]	T [K]	v [km/s]
G1.4-1.8+87	17	8.2	0.3	22*	87.2
G357.8-4.7-55	237	12.9	0.4	137	-54
G1.5+2.9+105	311	12.3	1	198	105.7



McClure-Griffiths 2013

Gas Clouds as Calorimeters

Gas Cloud Calorimeters: A How To



Heating/Cooling dependent on environment

Cooling
(gas physics)

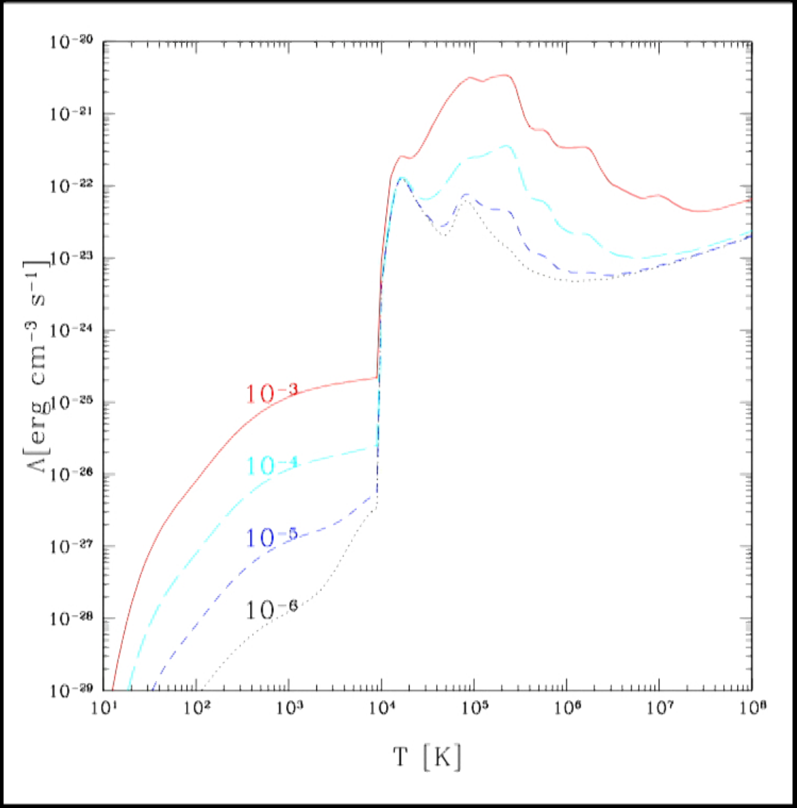
Heating
(Canonical Astrophysics)

Observations
(21 cm)

Dark Matter
(Heating/Cooling)

Cooling

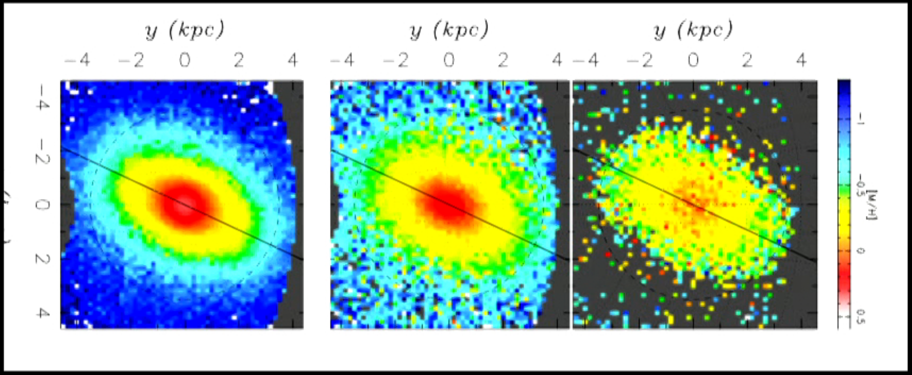
- **Cooling dependent on the temperature, density and chemical composition of gas**
- **Metals dominate below 10^4 K, though molecules are also important at extremely low temperatures and high densities**



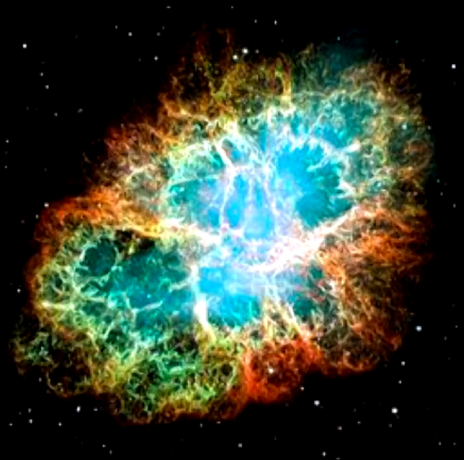
Maio et al 2007

Metallicity

- For cold gas, metals are the primary cooling mechanism
- Uncertainty comes from observational challenges, gas mixing within the Milky Way and depletion due to dust/grains



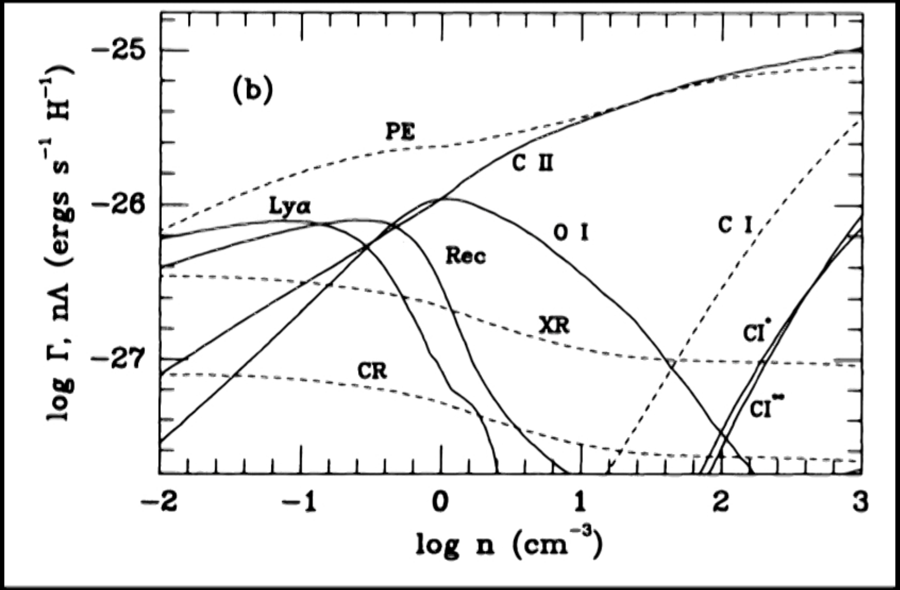
Perez et al 2017



NASA/ESA

Heating

- photoelectric heating by grains and ionisation
- UV background
- X-rays
- Cosmic Rays
- magneto/ hydrodynamic heating
- interstellar shocks

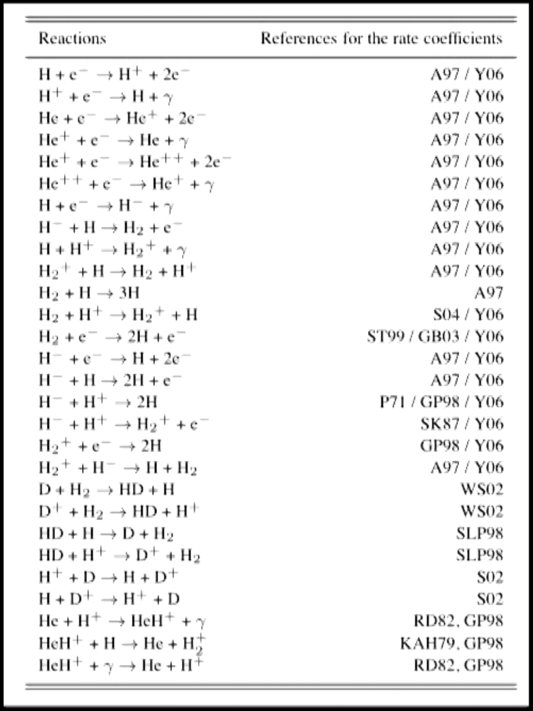


Wolfire et al 1995

Chemical Network

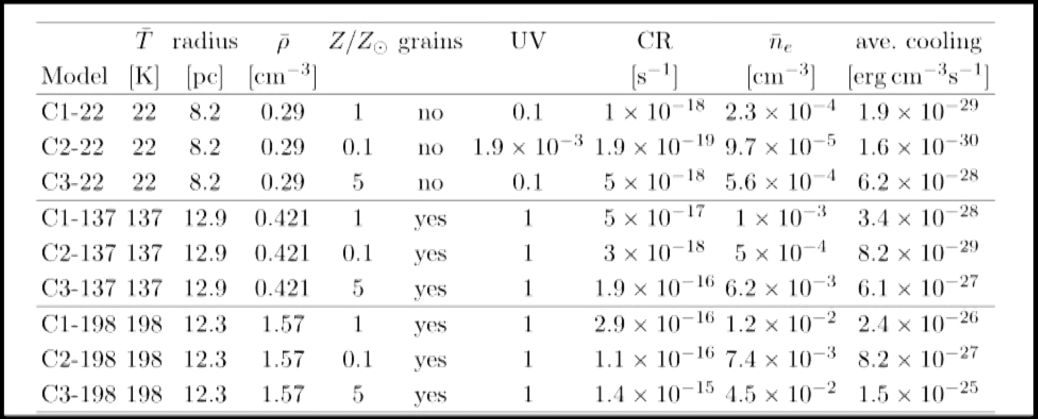
$$\frac{\partial n_i}{\partial t} = \sum_{j \neq i} n_j R_{ji} + \mathrm{source} - n_i (\sum_{ji} R_{ij} + \mathrm{sink}) = 0\,[\mathrm{cm}^{-3}\mathrm{s}^{-1}],$$

Processes such as photo and collisional ionisation, recombination and charge exchange act as ‘sinks’ and ‘sources’ for different species

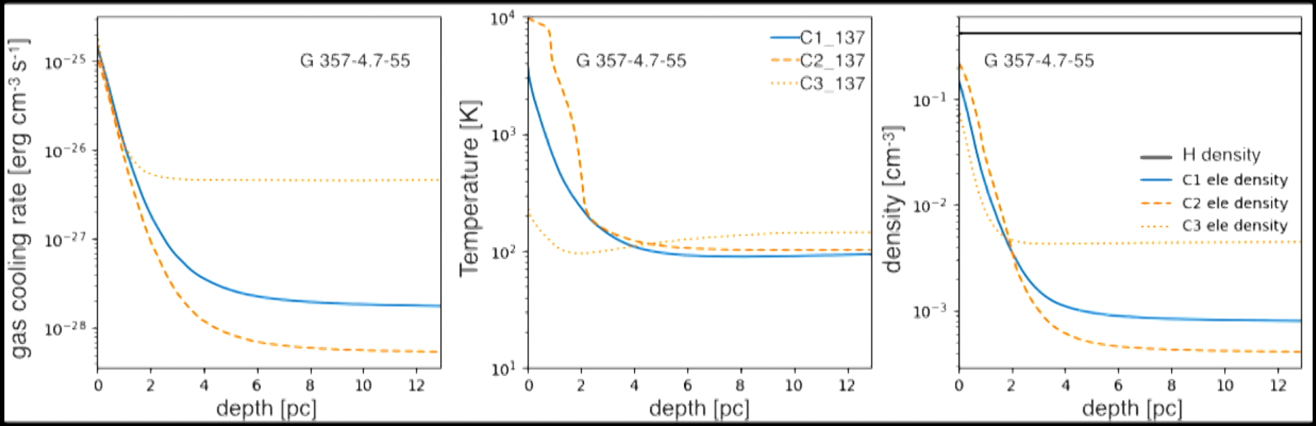


Reactions	References for the rate coefficients
$H + e^- \rightarrow H^+ + 2e^-$	A97 / Y06
$H^+ + e^- \rightarrow H + \gamma$	A97 / Y06
$He + e^- \rightarrow He^+ + 2e^-$	A97 / Y06
$He^+ + e^- \rightarrow He + \gamma$	A97 / Y06
$He^+ + e^- \rightarrow He^{++} + 2e^-$	A97 / Y06
$He^{++} + e^- \rightarrow He^+ + \gamma$	A97 / Y06
$H + e^- \rightarrow H^- + \gamma$	A97 / Y06
$H^- + H \rightarrow H_2 + e^-$	A97 / Y06
$H + H^+ \rightarrow {H_2}^+ + \gamma$	A97 / Y06
${H_2}^+ + H \rightarrow H_2 + H^+$	A97 / Y06
$H_2 + H \rightarrow 3H$	A97
$H_2 + H^+ \rightarrow {H_2}^+ + H$	S04 / Y06
$H_2 + e^- \rightarrow 2H + e^-$	ST99 / GB03 / Y06
$H^- + e^- \rightarrow H + 2e^-$	A97 / Y06
$H^- + H \rightarrow 2H + e^-$	A97 / Y06
$H^- + H^+ \rightarrow 2H$	P71 / GP98 / Y06
$H^- + H^+ \rightarrow {H_2}^+ + e^-$	SK87 / Y06
${H_2}^+ + e^- \rightarrow 2H$	GP98 / Y06
${H_2}^+ + H^- \rightarrow H + H_2$	A97 / Y06
$D + H_2 \rightarrow HD + H$	WS02
$D^+ + H_2 \rightarrow HD + H^+$	WS02
$HD + H \rightarrow D + H_2$	SLP98
$HD + H^+ \rightarrow D^+ + H_2$	SLP98
$H^+ + D \rightarrow H + D^+$	S02
$H + D^+ \rightarrow H^+ + D$	S02
$He + H^+ \rightarrow HeH^+ + \gamma$	RD82, GP98
$HeH^+ + H \rightarrow He + H_2^+$	KAH79, GP98
$HeH^+ + \gamma \rightarrow He + H^+$	RD82, GP98

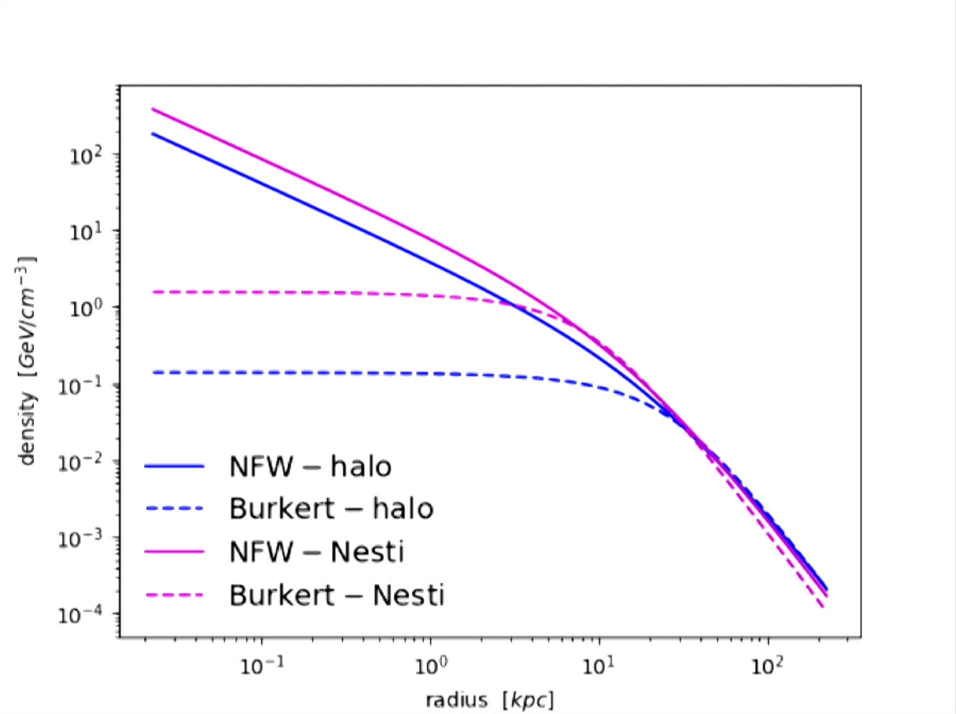
CLOUDY Models



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}

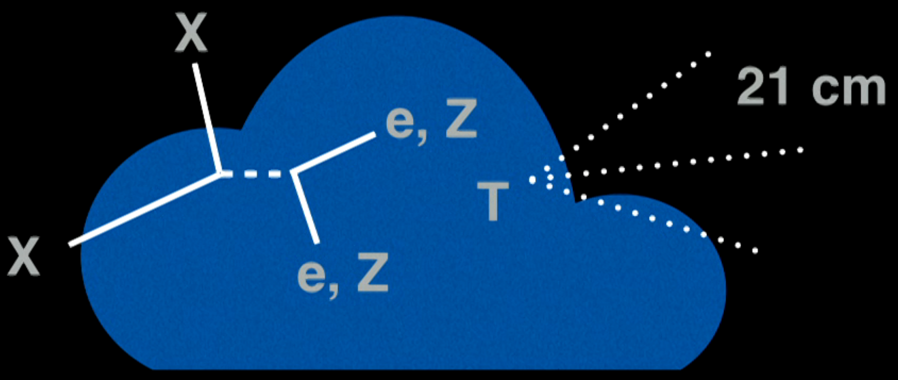


Dark Matter Halo Models



Class I Bound

DM interaction with either electrons or metals

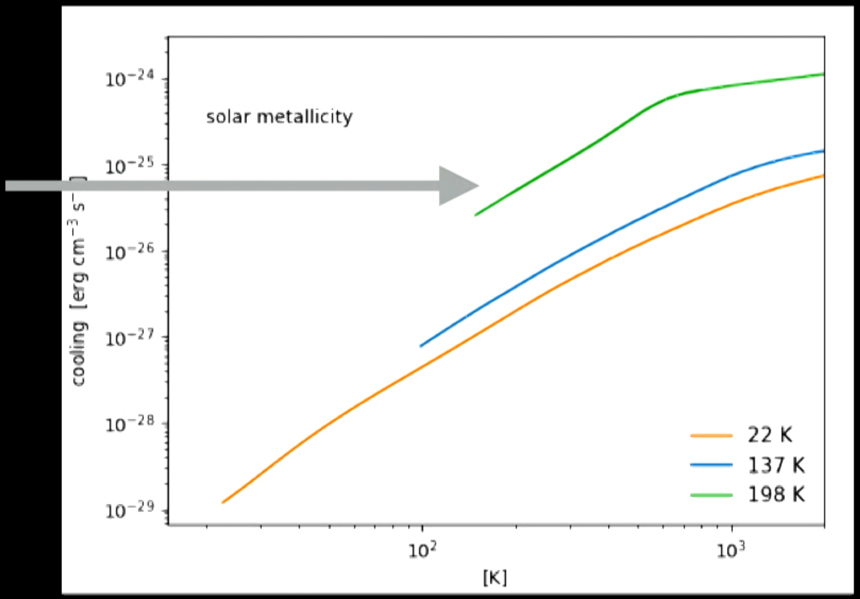


DM heating < radiative cooling

Class 1 Bound

DM interaction with either electrons or metals

Monotonic decreasing with T

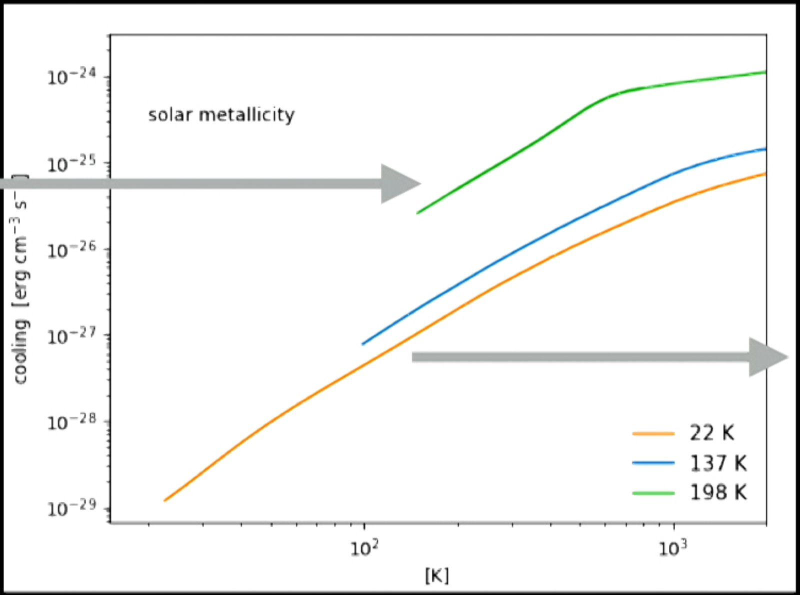


DM heating < radiative cooling

Class 1 Bound

DM interaction with either electrons or metals

Monotonic decreasing with T

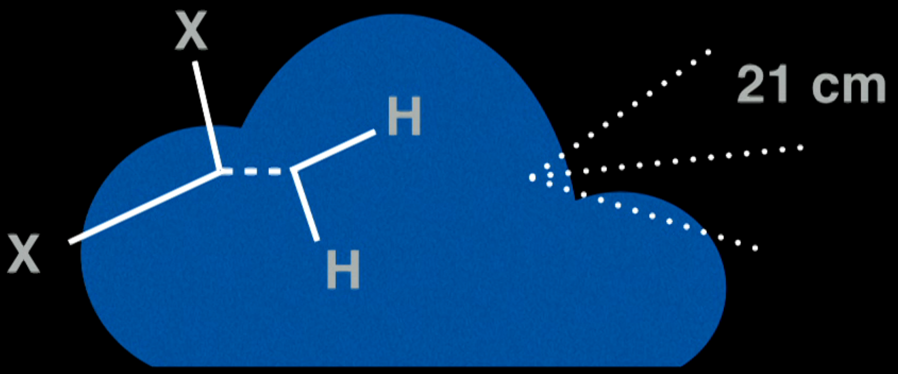


bound independent of [Fe/H]

DM heating < radiative cooling

Class II Bound

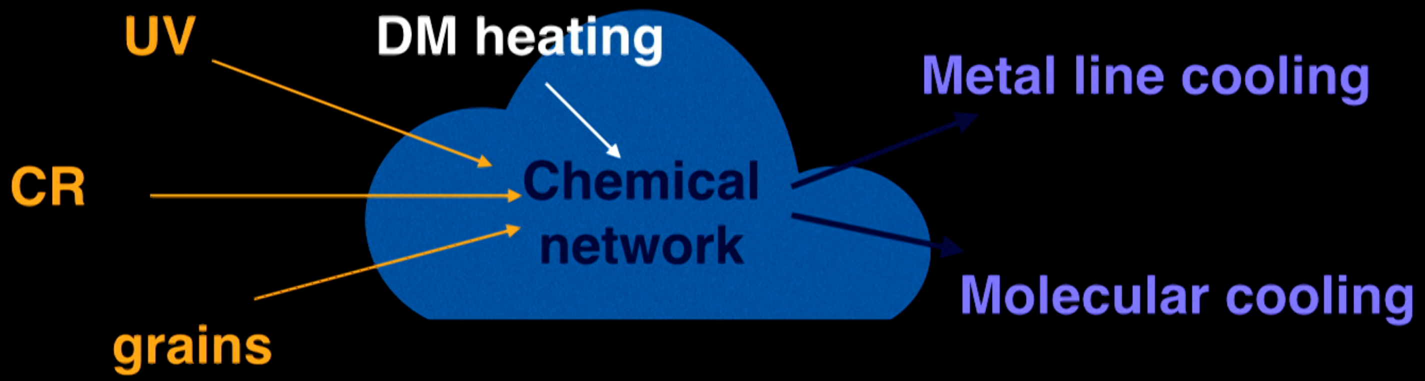
DM interaction with non-metals



DM heating < radiative cooling

Conservative Bounds

- High metallicity -> Efficient heating
- DM only heat source -> really other sources such as UV background, cosmic rays, photo-heating off of grains (some not well constrained, shielding from dust)



UV

DM heating

Metal line cooling

CR

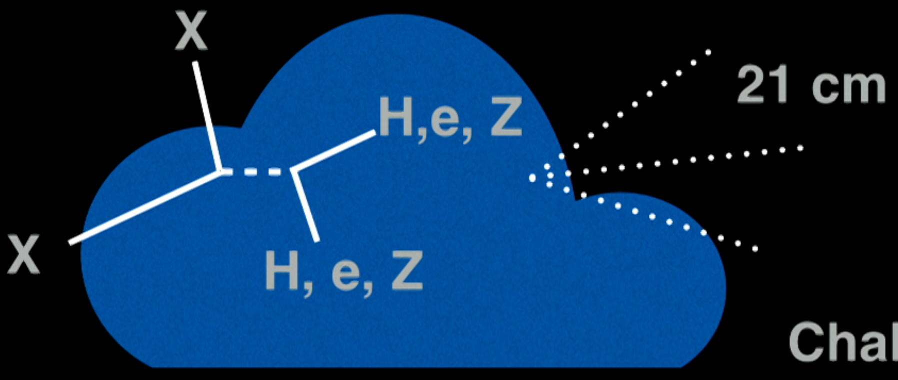
Chemical network

Molecular cooling

grains

Class III Bound

DM interaction with either electrons, metals or non-metals



Challenging

DM cooling + radiative cooling = astro-heating

DM Bounds

Ultra Light Dark Photon DM

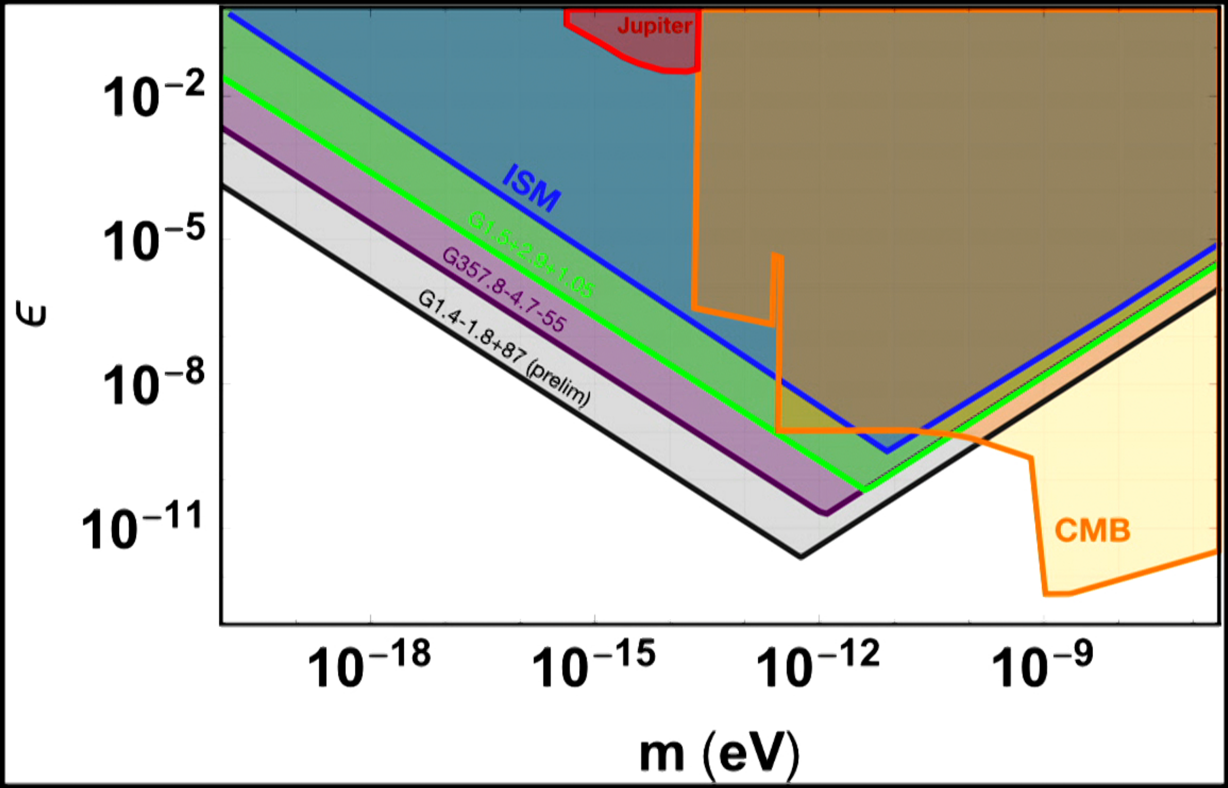
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2 A'_\mu A'^\mu - \frac{e}{(1+\epsilon)^2}\left(A_\mu + \epsilon A'_\mu\right) J^\mu_{EM},$$

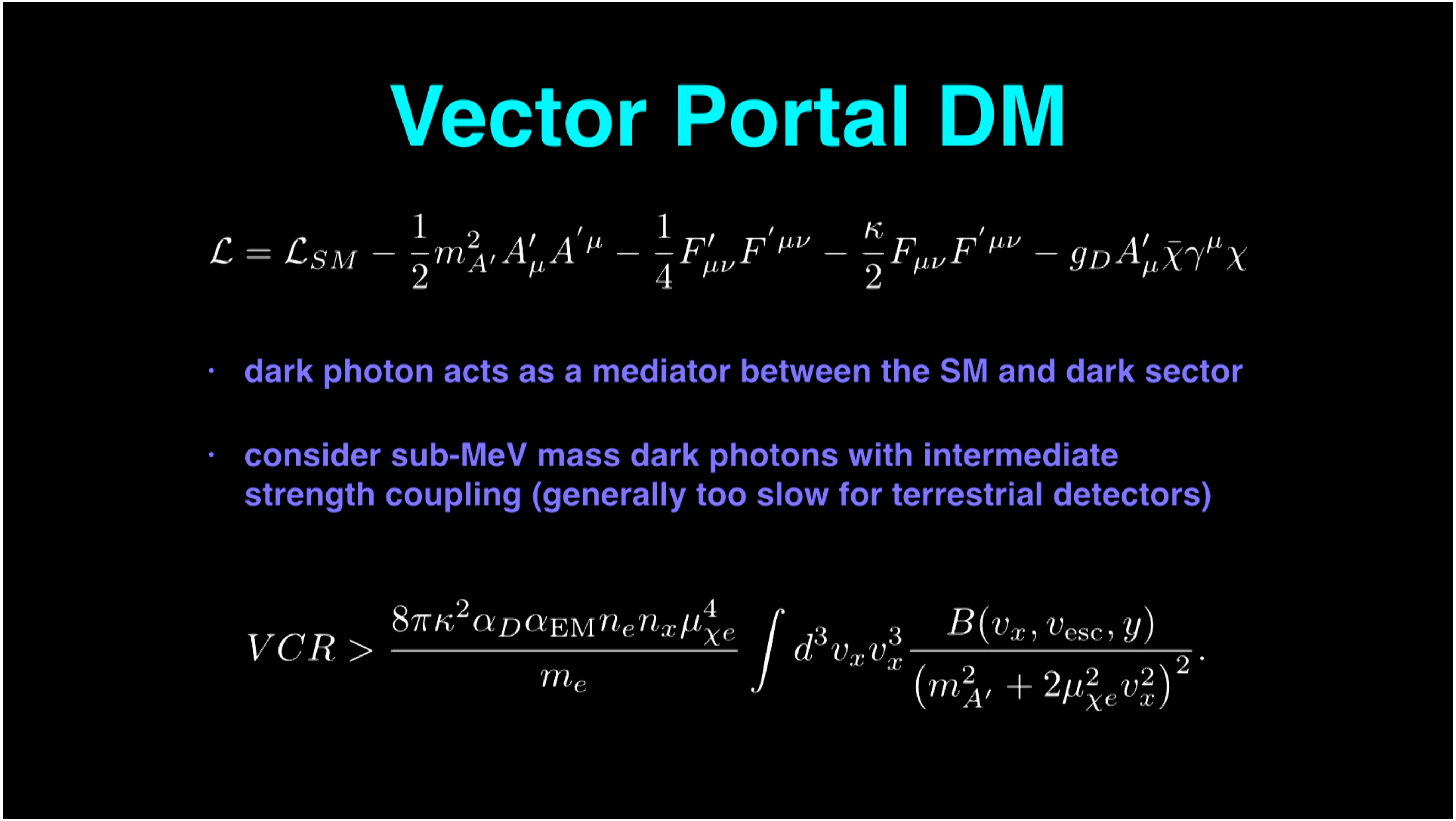
- ultra light dark photon produces an oscillating electric field through mixing with the SM photon > Dubovsky 2015!
- free electrons and ions in the gas are accelerated by this field and eventually scatter and heat the gas

$$\omega_p = \sqrt{\frac{4\pi n_e}{m_e}} \approx 5 \times 10^{-13}\ eV \left(\frac{n_e}{2 \times 10^{-4}\ \mathrm{cm}^{-3}}\right)^{1/2}$$

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

Ultra Light Dark Photon DM





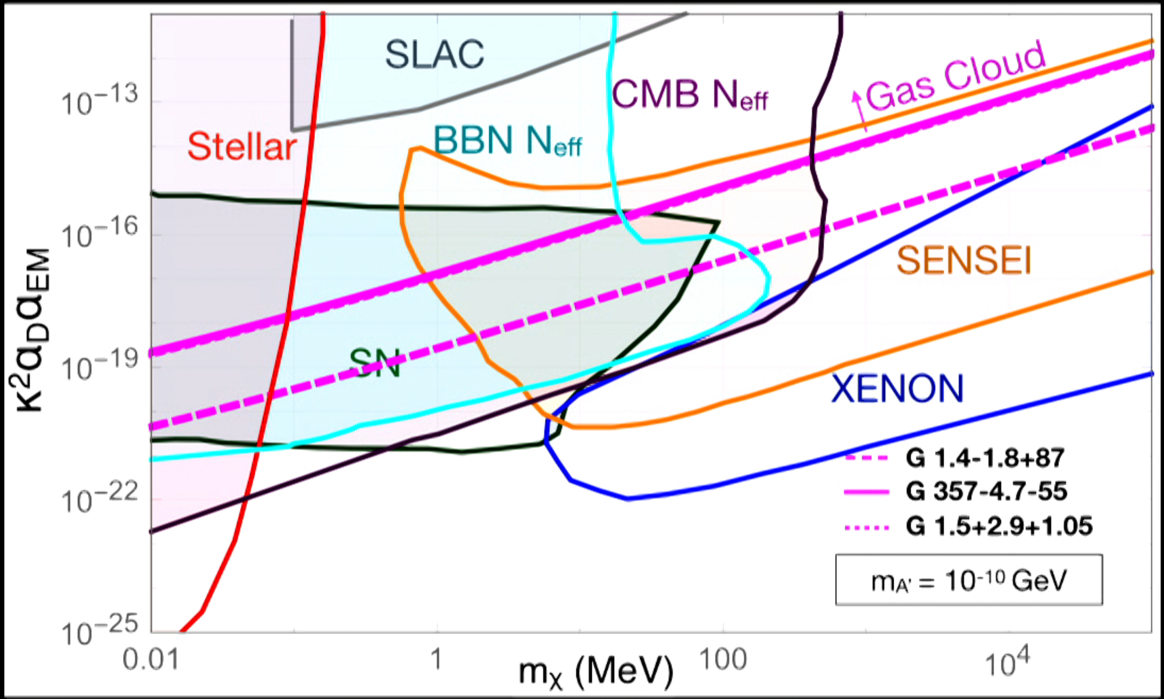
Vector Portal DM

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

- dark photon acts as a mediator between the SM and dark sector
- consider sub-MeV mass dark photons with intermediate strength coupling (generally too slow for terrestrial detectors)

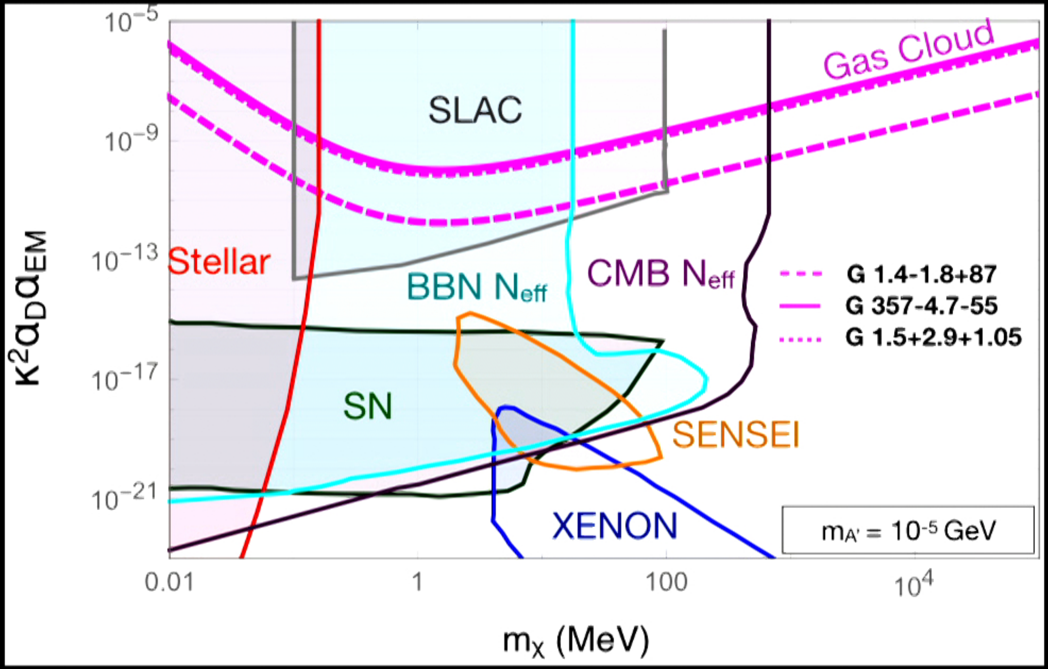
$$VCR > \frac{8\pi\kappa^2 \alpha_D \alpha_{\rm EM} n_e n_x \mu_{\chi e}^4}{m_e} \int d^3 v_x v_x^3 \frac{B(v_x, v_{\rm esc}, y)}{\left(m_{A'}^2 + 2\mu_{\chi e}^2 v_x^2\right)^2}.$$

Light Mediator



$$\kappa^2\alpha_D\alpha_{\rm EM} < \frac{VCR}{n_e}\left[\frac{2\pi n_x}{m_e}\int d^3v_x\, \frac{B(v_x, v_{\rm esc}, y)}{v_x}\log\left(\frac{2\mu_{\chi e}^2 v_x^2}{(\max[1/\lambda_d, m_{A'}])^2}\right)\right]^{-1}.$$

Heavy Mediator



$$\kappa^2\alpha_D\alpha_{\rm EM} < \frac{VCR}{n_e}\left[\frac{8\pi n_x \mu_{\chi e}^4}{m_e}\int d^3v_x\ v_x^3\,\frac{B(v_x, v_{\rm esc}, y)}{m_{A'}^4}\right]^{-1},$$

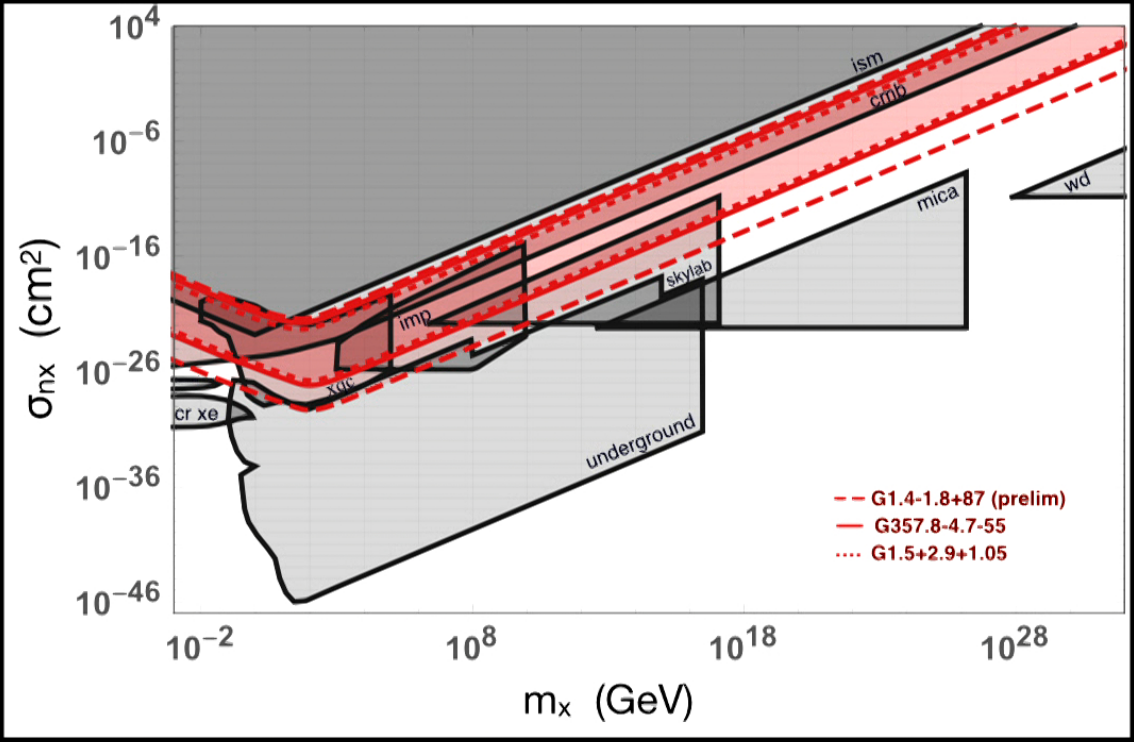
DM Nucleon Scattering
(strongly interacting, composite and super heavy)

$$\sigma_{nx} = \left(\frac{\mu_{nx}}{\mu_{Nx}\ A}\right)^2 \sigma_{Nx} \frac{1}{F_A^2(E_{nr})}$$

- **for effective heating of entire cloud we require DM to retain at least half its kinetic energy after reaching its centre**

$$\frac{E_f}{E_i} = \prod_A \left(1 - \frac{4 z m_N m_x}{(m_N + m_x)^2}\right)^{n_A \sigma_{Nx} r} ,$$

DM Nucleon Scattering



$$m_x \simeq 3 \times 10^{60}\ \mathrm{GeV} \left(\frac{r_g}{10\ \mathrm{pc}}\right)^2 \left(\frac{\rho_x}{10\ \mathrm{GeV/cm^3}}\right) \left(\frac{v}{0.001c}\right) \left(\frac{t_g}{10^6\ \mathrm{yrs}}\right) \left(\frac{10}{N_f}\right).$$

Summary

- Astrophysical objects provide valuable new settings to test DM models, avoiding some of the limitations of terrestrial detectors

- Careful modelling and understanding of astrophysical backgrounds/environments remains crucial

- Cold Galactic Center gas clouds act as useful detectors of ultra light dark photons, milli-charged DM, vector portal models, DM models with nucleon scattering