Double-Disk Dark Matter

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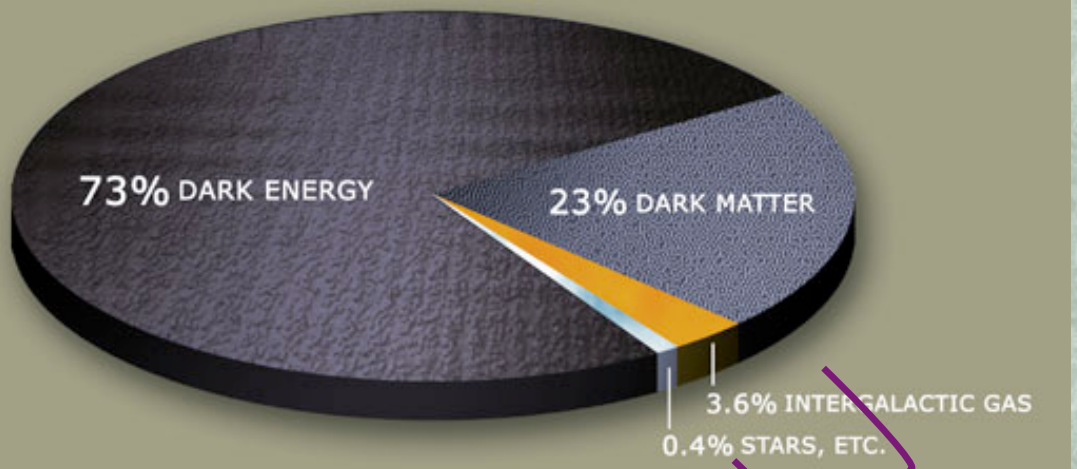
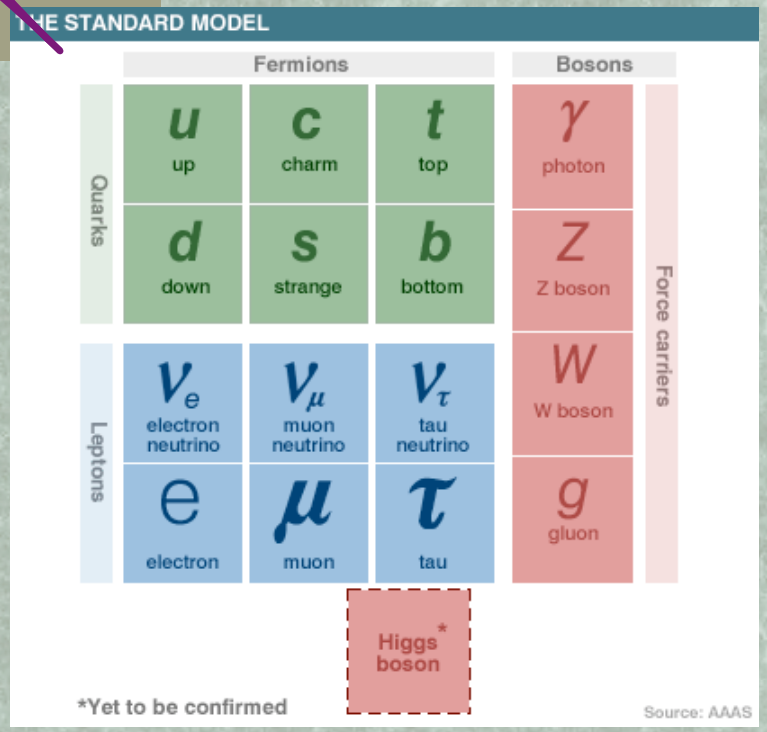
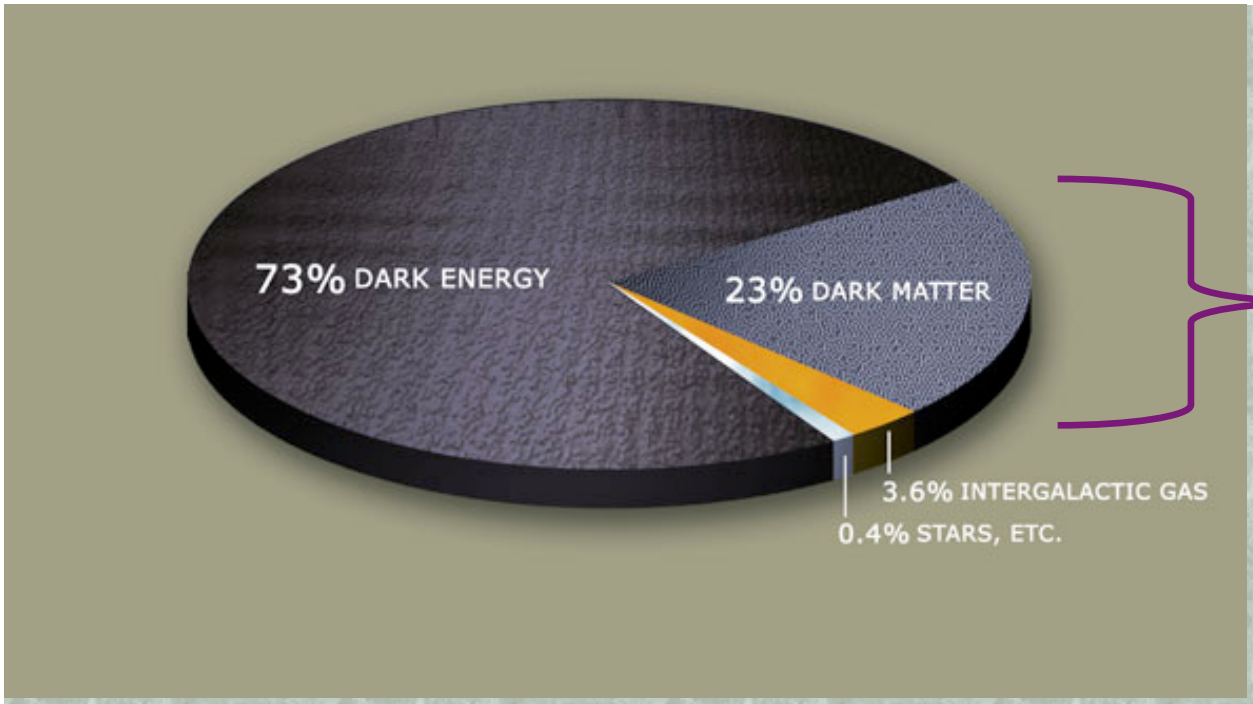




15% of the total matter comes from a very complicated model: the Standard Model!

Our visible world deviates markedly from any principle of minimality!!



We always consider 85% of the total matter to be from minimal models of a cold, collisionless particle: WIMP, axion….

CDM paradigm is supported by observation of large-scale structure

Mild conflict with the observation of the sub-galactic structure leads to consideration of slightly less minimal models:

a. Self-interacting DM
b. Warm DM

under the assumption that DM has only one component

Have we exhausted all possibilities of dark matter sector?
Could the dark world be as complex as our world?
Could a dark sector as rich as our own exist just out of sight?

Double-Disk Dark Matter (DDDM or 3DM)

A small fraction of all dark matter has dissipative dynamics causing it to cool into a disk within Milky Way.

DDDM is more like a new kind of ordinary matter, constituting an invisible world that is literally parallel to our own.

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More generally, Partially Interacting Dark Matter (PIDM):

Only a subdominant component of DM has self-interactions.

DDDM is one example of PIDM that could lead to a dramatically different dark world cosmological history and distinctive observables.

Bounding the amount of DDDM

$$\epsilon \equiv \Omega_{\rm PIDM}/\Omega_{\rm DM}.$$

Current bounds on self-interacting DM from halo shapes only apply when all DM is self-interacting;

Bullet cluster implies that no more than 30% of the dark matter was lost to collisional effects

Oort limit: total amount of matter in the neighborhood of the Sun

$$\begin{aligned} \epsilon_{\rm disk} &\equiv M^{\rm disk}_{\rm DDDM}/M^{\rm gal}_{\rm DM} \\ \epsilon_{\rm disk} &\leq 0.05 \end{aligned}$$

Comparable to amount of baryons in the baryonic disk
(Only 1/3 of the baryons are in the disk)

Simplest model:

A dark sector has an unbroken $U(1)_D$ with coupling strength α_D
A heavy field, X, with mass m_X and charge +1 (analogous to our proton)
A light field, C, with mass m_C and charge -1 (coolant, analogous to our electron)

C and its anti-particle annihilate away in the early universe:
An asymmetic relic with net X and C number

X and its anti-particle would not completely annihilate away in the early universe:
A possible symmetric population of X and anti-X

X Xbar annihilation could lead to dramatically different indirect signals!

Effective relativistic degrees of freedom: BBN and CMB

Dark sector decoupled from the visible sector early and have its own T

For the U(1) model, $\xi \equiv (T_D/T_{\rm vis})$

$$\xi(t_{\rm BBN}) = \left(\frac{10.75}{86.25}\right)^{1/3} \approx 0.5$$

Entropy conservation

$$\Delta N_{{\rm eff},\nu}^{\rm BBN} = 0.20 \text{ for } {\rm U}(1)_D$$

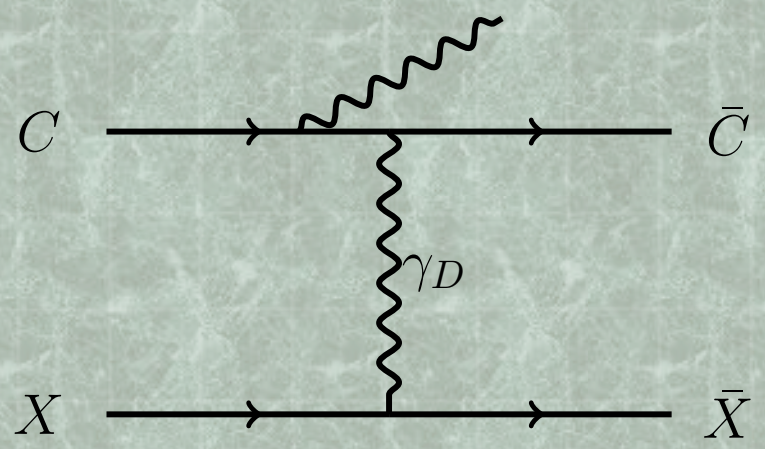
Additional effective neutrino species

$$\Delta N_{{\rm eff},\nu}^{\rm BBN} < 1.44 \text{ at } 95\% \text{ C.L.},$$

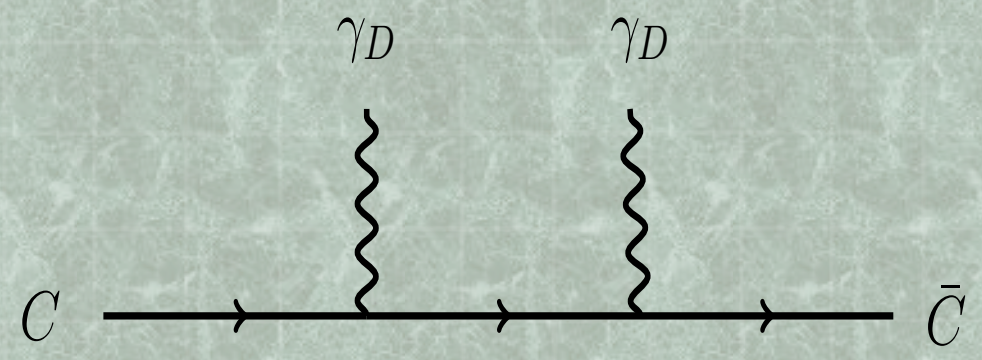
More generally, $SU(N)_D$ model satisfies the constraint for N <= 4

Cooling and Dark Disk formation:

DDDM falls into the galaxy, shock-heated to the virial temperature, which ionizes all the X and C particles. Dark plasma then cools through

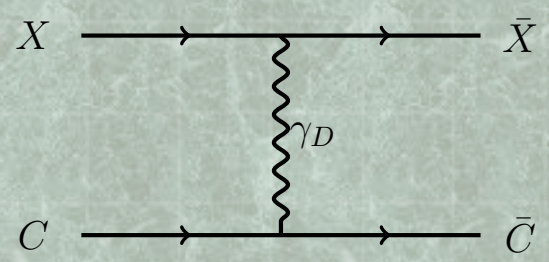


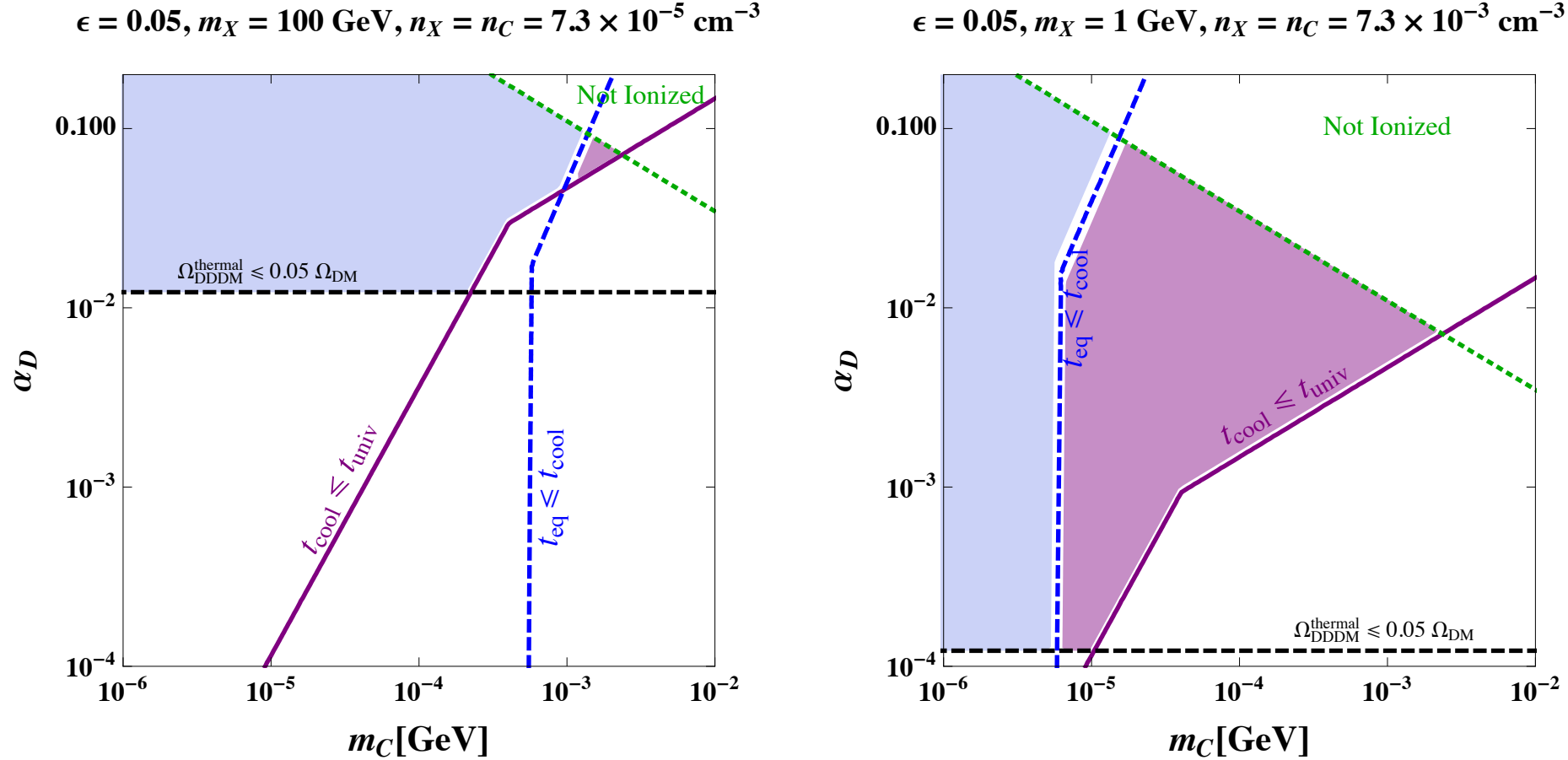
Bremsstrahlung cooling



Compton cooling

In both cases, C loses energy dominantly; then X cools through Rutherford scattering




$\epsilon = 0.05, m_X = 100$ GeV, $n_X = n_C = 7.3 \times 10^{-5}$ cm^{-3}
Not Ionized
$\Omega_{\rm DDDM}^{\rm thermal} \leqslant 0.05\ \Omega_{\rm DM}$
$t_{\rm cool} \leqslant t_{\rm univ}$
$t_{\rm eq} \leqslant t_{\rm cool}$
α_D
m_C[GeV]
$\epsilon = 0.05, m_X = 1$ GeV, $n_X = n_C = 7.3 \times 10^{-3}$ cm^{-3}
Not Ionized
$t_{\rm eq} \leqslant t_{\rm cool}$
$t_{\rm cool} \leqslant t_{\rm univ}$
$\Omega_{\rm DDDM}^{\rm thermal} \leqslant 0.05\ \Omega_{\rm DM}$
α_D
m_C[GeV]

Dark plasma acquires angular momentum from tidal torques, so as it cools it forms a rotationally supported disk.

vertical velocity dispersion set by the temperature when cooling stops

$$z_d \approx \sqrt{\frac{2\overline{v_z^2}}{\pi G_N \rho_{\rm center}}} \approx 1.2 \frac{\overline{v_z^2}}{10^{-6}} \frac{R_d}{\epsilon}.$$

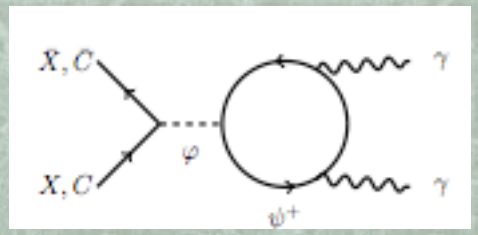
$$z_d \approx 2.5 \text{ pc} \left(\frac{\alpha_D}{0.02}\right)^2 \frac{m_C}{1 \text{ MeV}} \frac{100 \text{ GeV}}{m_X}$$

Assume cooling stops when recombination happens

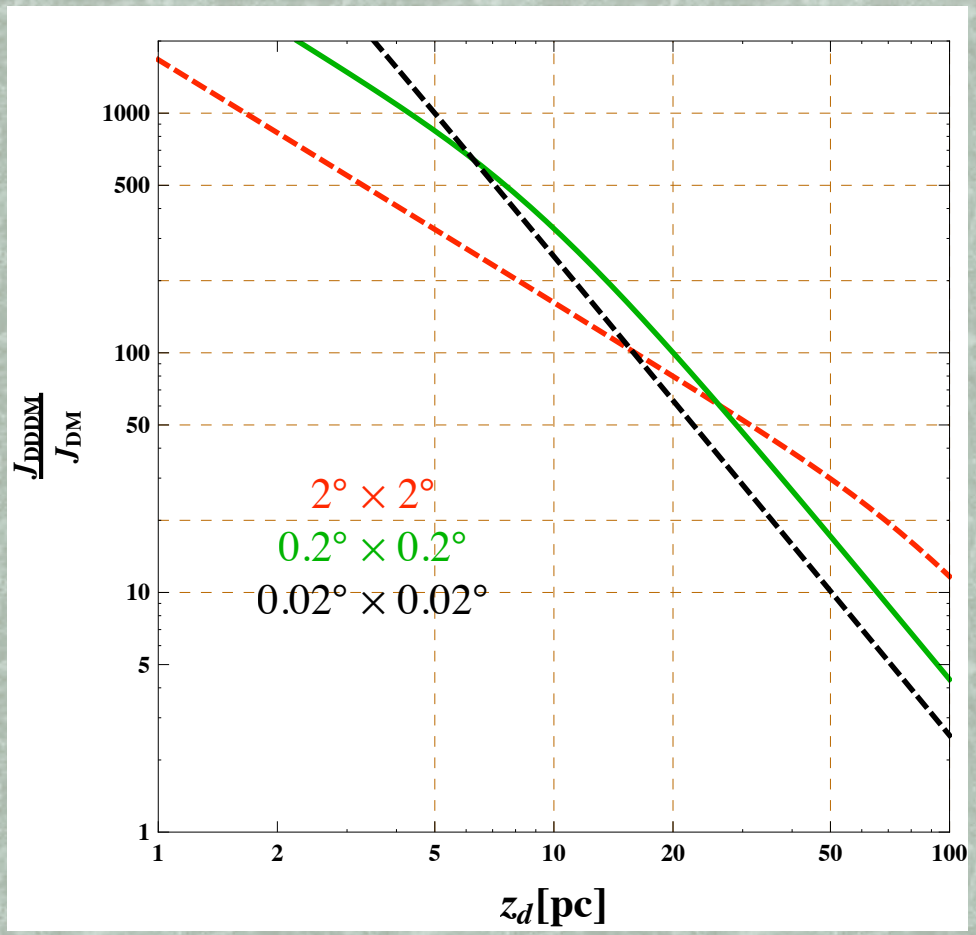
Further cooling is possible from atomic/molecular processes

DDDM disk can be thinner than the baryonic disk ($z_d \sim 100$ pc) if X is heavier than 1 GeV, though it can thicken due to collisional processes analogous to those for baryons.

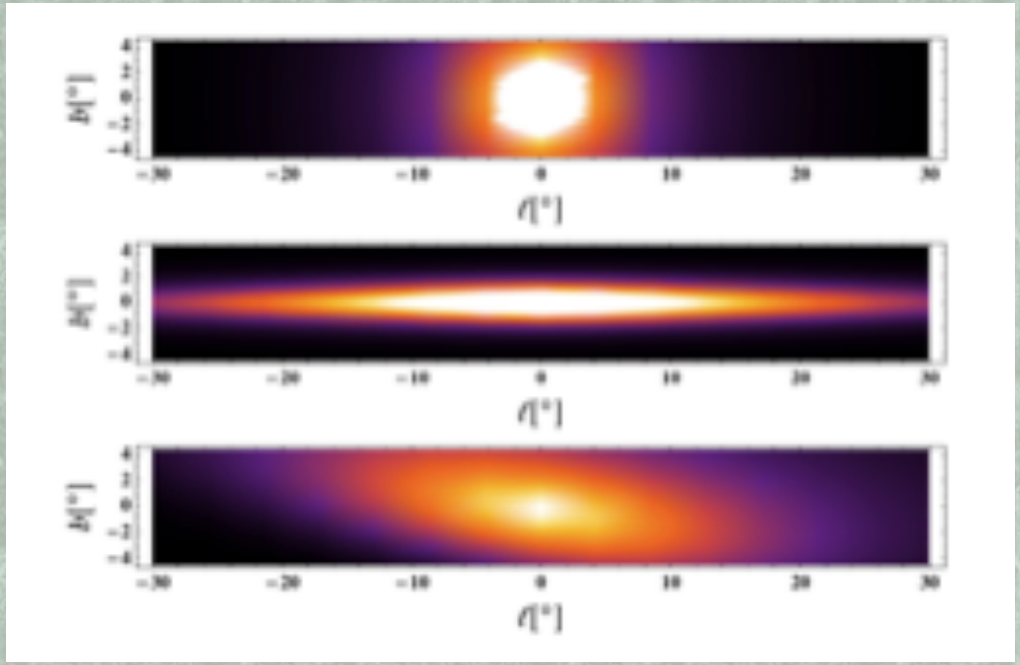
Indirect detection: X Xbar ➔ γ γ



A possible local density enhancement $$J = \int_{\rm roi} db\, dl \int_{\rm l.o.s} \frac{ds}{d_\odot} \cos b \left(\frac{\rho(r)}{\rho_\odot}\right)^2 ,$$



Distinctive spatial distributions



Normal DM Einasto profile

DDDM disk aligned with ours

DDDM disk misaligned with ours by 18°

Other possible signatures

- N_{eff} : Planck satellite

- Large-scale structure:
CMB, galaxy-galaxy correlation function

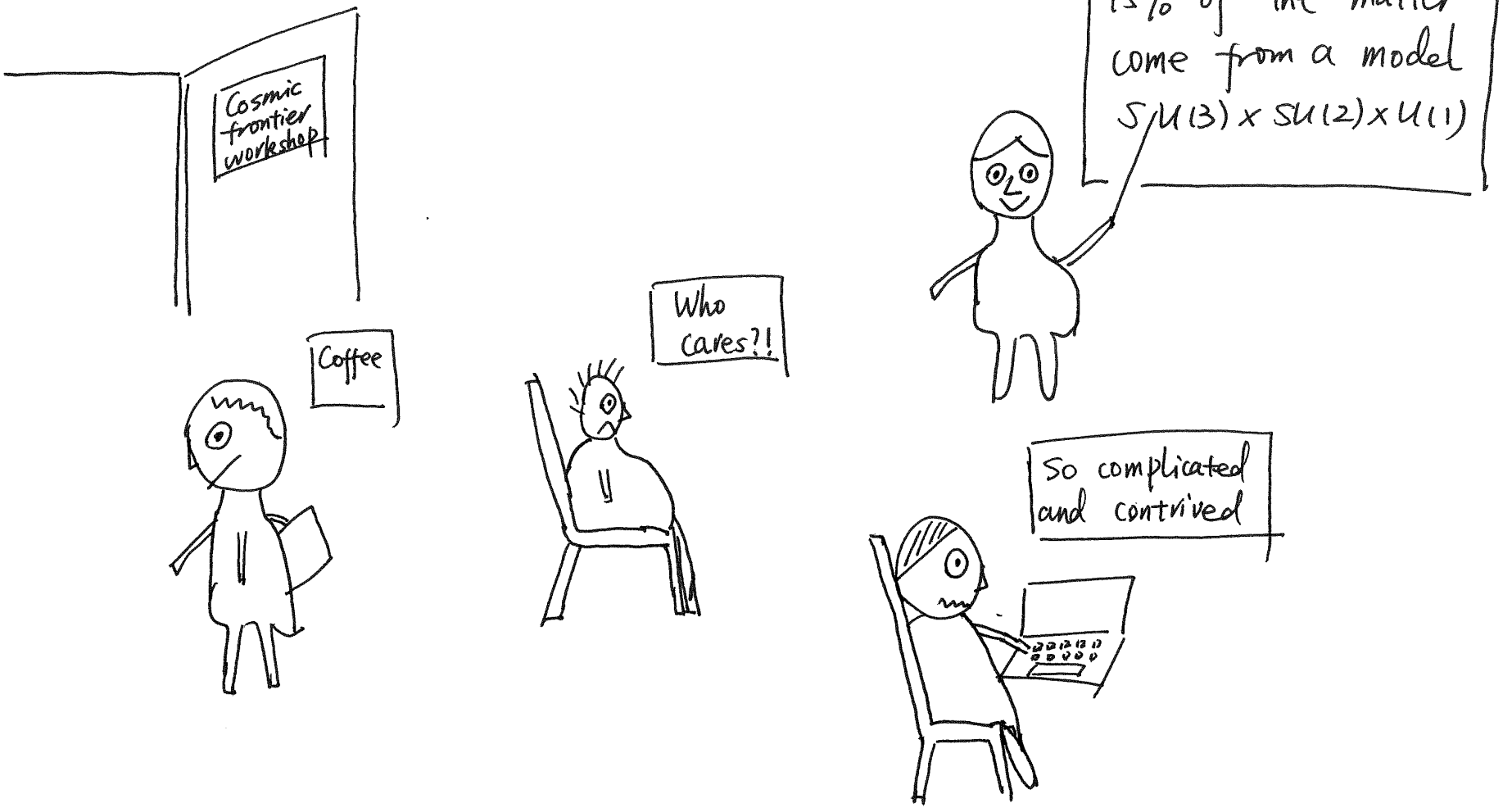
- Small-scale structure

- Surveys of star motions in the Milky way: Gaia satellite

- Microlensing from compact DDDM objects
or other lensing from DDDM disk

- Direct detection, solar capture

On a dark planet



Backup

Bounding the amount of DDDM

Oort limit: total amount of matter in the neighborhood of the Sun

$$\epsilon_{\rm disk} \equiv M^{\rm disk}_{\rm DDDM}/M^{\rm gal}_{\rm DM}$$
$$\epsilon_{\rm disk} \leq 0.05$$

Surface density

$$\Sigma(|z| < z_0) \equiv \int_{-z_0}^{z_0} \rho(z) dz$$

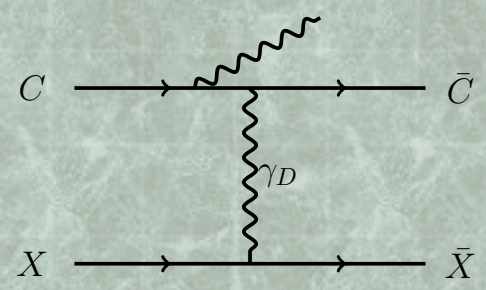
Allowed dark surface density from observation

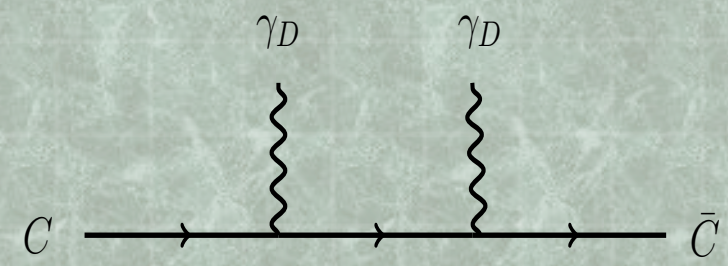
$$\Sigma_{\rm dark}(|z| < 1.1 \text{ kpc}) \lesssim 46 \ M_\odot/{\rm pc}^2.$$

Model DDDM disk as an isothermal sheet

$$\rho(R, z) = \frac{\epsilon M^{\rm gal}_{\rm DM}}{8\pi R_d^2 z_d} \exp(-R/R_d) {\rm sech}^2(z/2z_d).$$

Cooling and Dark Disk formation:

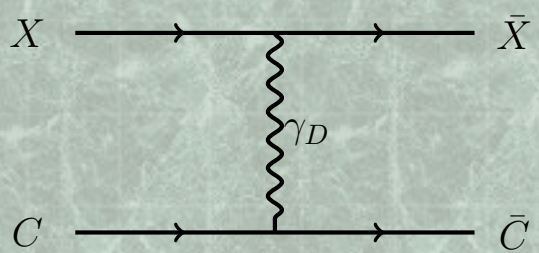




$$t_{\rm brem} \approx \frac{3}{16}\frac{n_X+n_C}{n_X n_C}\frac{m_C^{3/2}T_{\rm vir}^{1/2}}{\alpha_D^3}$$
$$\approx 10^4\,{\rm yr}\,\sqrt{\frac{T_{\rm vir}}{\rm K}}\frac{{\rm cm}^{-3}}{n_C}\left(\frac{\alpha_{\rm EM}}{\alpha_D}\right)^3\left(\frac{m_C}{m_e}\right)^{\frac{3}{2}},$$

$$t_{\rm Compton} \approx \frac{135}{64\pi^3}\frac{n_X+n_C}{n_C}\frac{m_C^3}{\alpha_D^2\left(T_D^0(1+z)\right)^4}$$
$$\approx 4\times 10^{12}\,{\rm yr}\,\frac{n_X+n_C}{n_C}\left(\frac{\alpha_{\rm EM}}{\alpha_D}\right)^2\left(\frac{2\,{\rm K}}{T_D^0(1+z)}\right)^4\left(\frac{m_C}{m_e}\right)^3$$

In both cases, C loses energy dominately; then X cools through Rutherford scattering



$$t_{\rm eq} = \frac{m_X m_C}{2\sqrt{3\pi}\alpha_D^2}\frac{(E_C/m_C)^{3/2}}{n_C\log\left(1+\frac{v_C^4 m_C^2}{\alpha_D^2 n_C^{2/3}}\right)}$$
$$= 4.3\times 10^4\ {\rm yr}\left(\frac{\alpha}{\alpha_D}\right)^2\left(\frac{m_X}{1\ {\rm GeV}}\right)^{\frac{5}{2}}\left(\frac{m_e}{m_C}\right)^{\frac{1}{2}}\frac{{\rm cm}^{-3}}{n_C}\frac{10}{\log\left(1+\frac{v_C^4 m_C^2}{\alpha_D^2 n_C^{2/3}}\right)}$$