DARK MATTER

i) Evidence for DM / astro parameters

ii) Properties & constraints

iii) Candidates

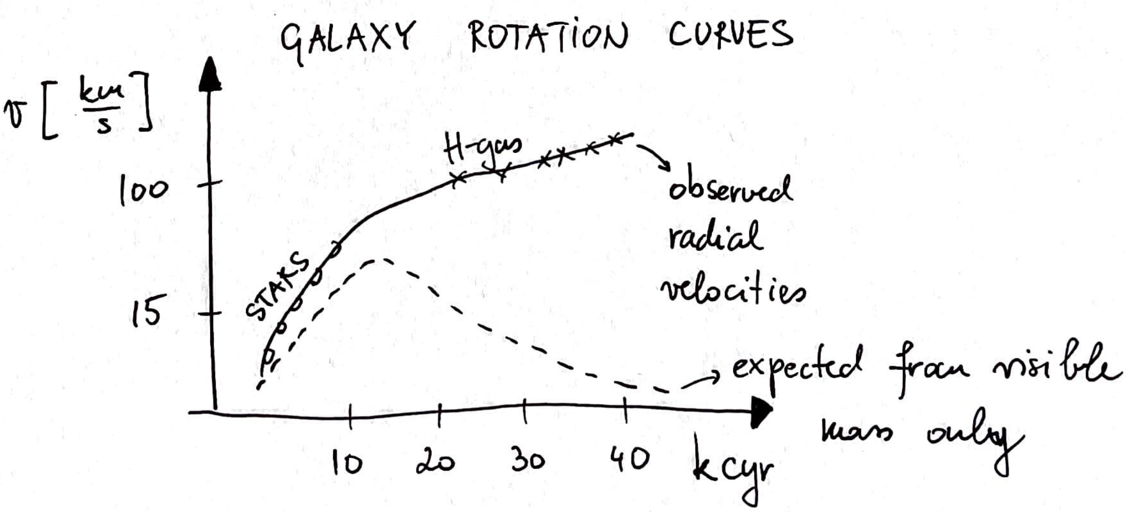
iv) Production (Freeze-out, Freeze-in, Dilution)

v) Detection prospects (direct, indirect, colliders)

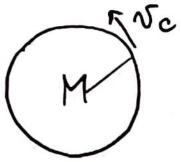
i) EVIDENCE FOR DM

- Up to now, we haven't observed DM in a lab, no DM particles were seen or produced in experiments.

- Astrophysical observations



- Newtonian derivation $v(M)$ gives



$$\frac{\cancel{m} MG}{R^{\cancel{2}}} = \cancel{m}\frac{v^2}{\cancel{R}} \quad , \quad v = \sqrt{\frac{MG}{R}}$$

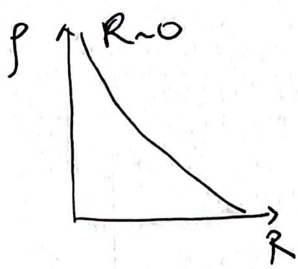
- Outside of the visible disk (sphere) we expect $M \sim$ const. and $v \propto R^{-1/2}$ (as in the figure).

- Thus to have $v \sim$ const. we need $M \propto R$ or ρ to scale as $\rho \propto \frac{1}{R^2}$ $\quad M \sim \int_0^R \rho \, dV \propto \int_0^R dr \, r^2 \frac{1}{r^2} \propto R$.

  Eventually, also ρ_{DM} shuts off, this is the DM halo.

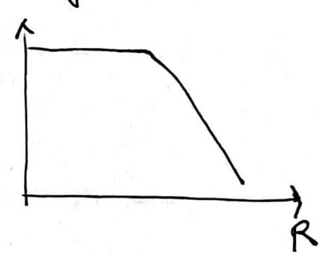
- <u>MASS PROFILES</u> $\rho(r)$ come from large scale simulations, we cannot measure them directly. They can be

CUSPY



or

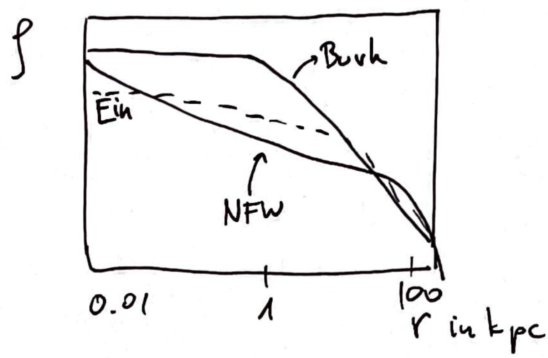
CORED



- Most popular parametrizations are

NFW (Cuspy)	EINASTO	BURKHERT (CORE)
$\rho_{NFW} = \frac{\rho_0}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$	$\rho_{EIN} = \rho_0 \, e^{-\frac{2}{\gamma}\left(\left(\frac{r}{r_s}\right)^{\gamma}-1\right)}$ $\gamma \sim 0.17$	$\rho_{Burk} = \frac{\rho_0}{\left(1+\frac{r}{r_s}\right)\left(1+\left(\frac{r}{r_s}\right)^2\right)}$

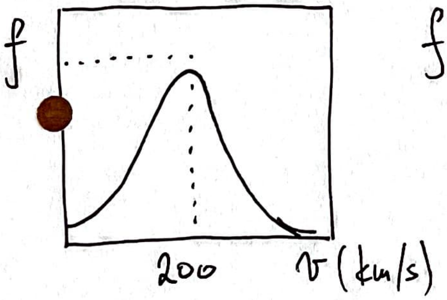
• In all cases $r_s \sim 20\,\mathrm{kpc}$, $\rho_0 \sim 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}$, $\rho_{cr} \sim \mathrm{GeV}/\mathrm{m}^3$



The DM local density $\rho_0 \simeq 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}$ is many orders of magnitude above $\rho_{cr} \sim \mathrm{GeV}/\mathrm{m}^3 \Rightarrow \rho_{DM} \sim \Omega_{DM}\rho_{cr} \sim \frac{1}{4}\cdot\mathrm{GeV}/\mathrm{m}^3$.

VELOCITY PROFILES

• For a virialized system, we expect a MB distribution



$$f(v_t) = \frac{v_t}{N_t}\, e^{-(v_t/\bar{v}_t)^{2\alpha_t}}, \quad \alpha_t \simeq 0.7$$

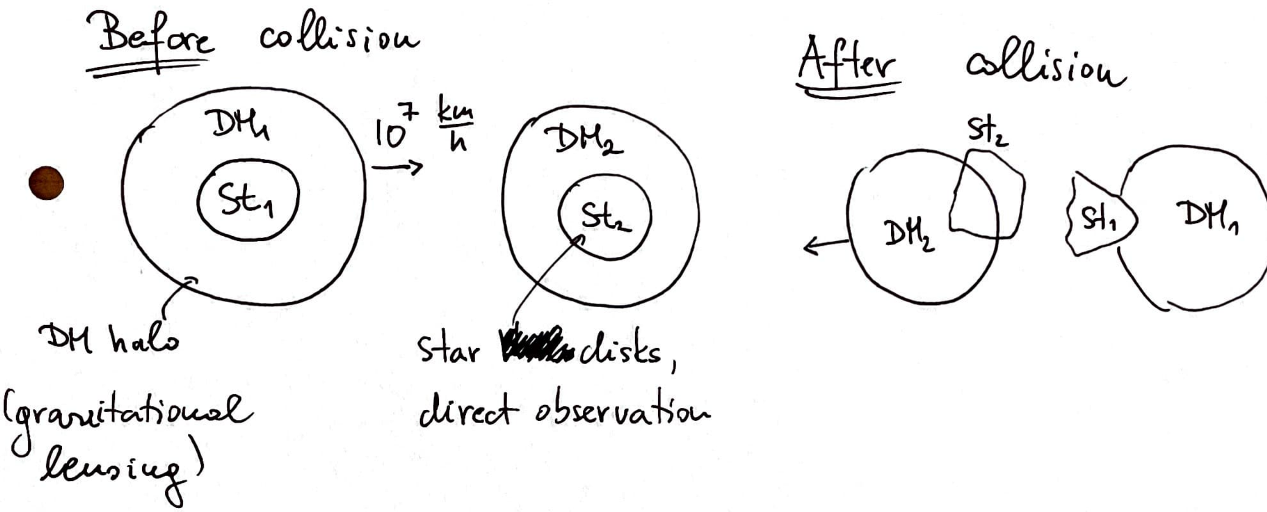
$$\bar{v} \sim 120\,\frac{\mathrm{km}}{\mathrm{s}}$$

See [0912.2358]

$\downarrow$

These quantities ρ_0 & f play an important role in (in)direct detection, where we wish to connect $\langle\sigma v\rangle$ to fluxes of γ's, $e^\pm$, ...

- Another important observation comes from the Bullet cluster Chandra X-ray @ $z = 0.3$. It gives a very compelling evidence for the existence of local (not cosmo) DM.



- The interpretation is that visible matter scatters, while DM halos simply pass through one another. This limits the size of DM self-interactions to

$$\sigma_{DMDM} \ll \sigma_{np}$$

- The earliest proof of DM came from comparing the virialized mass with the observed one.

$$M(R)\langle v^2\rangle \cong 3 v_{\parallel}^2 M = \frac{GM^2}{R}$$

$$M_{vis} \sim 10^{14} M_{\odot} < M_{grav.} \sim 10^{15} M_{\odot}$$

DARK MATTER PROPERTIES

In order to have a viable particle candidate, we need to satisfy certain criteria on the

MASS

CHARGE

SELF-INTERACTION

LIFETIME

MASS RANGE

typical galaxies

DM halos : $M_{DM} \sim 10^{12} M_\odot$, $R_{DM} \sim 100$ kpc

Dwarfs : $M_{Dsph} \sim 10^7 M_\odot$, $R_{Dsph} \sim$ kpc

smaller galaxies, dominated by DM.

$\Downarrow$

LOWER LIMITS for : $\begin{cases} \text{FERMIONS} & \text{(Pauli blocking)} \\ \text{BOSONS} & \text{(too fuzzy when too light)} \end{cases}$

BOSONS: We know v from $v = \sqrt{\frac{GM}{R}}$. But light particles behave as waves with $\lambda_{dB} = \frac{1}{p} = \frac{1}{mv}$.
 mv = const.

- The wavelength λ_{dB} should be below R, otherwise the galaxy becomes too large, it puffs up.

$$\lambda_{dB} < R \Rightarrow \frac{1}{mv} = \frac{1}{m}\sqrt{\frac{R}{GM}} < R$$

$$m > \frac{1}{\sqrt{GMR}} \sim \frac{M_{pe}}{\sqrt{MR}} \overset{dSPh}{\sim} \underbrace{10^{-21}\,eV}_{\text{FUZZY DM.}} = \text{TINY}$$

FERMIONS : Here, the bound comes from the Pauli exclusion principle and is more stringent.

$$f_{BE} = \frac{1}{e^{E/T} - 1}$$ gets to large occupancy for $E \ll T$

$$f_{FD} = \frac{1}{e^{E/T} + 1}$$ goes to at most $\frac{1}{e^0 + 1}$, so

for a typical fermion $s = 1/2$ $\quad g f_{FD} = 2 f_{FD} < 1$

$$n = g\int_p f \;, \quad N = \int_x\int_p \underset{\overset{\wedge}{1}}{(gf)}.$$

$$\Rightarrow M_{DM} = m_{DM} \int_x\int_p (gf)$$

- We can estimate : $\int d^3x = V \sim R^3 \quad \left(\frac{4\pi}{3} R^3\right)$

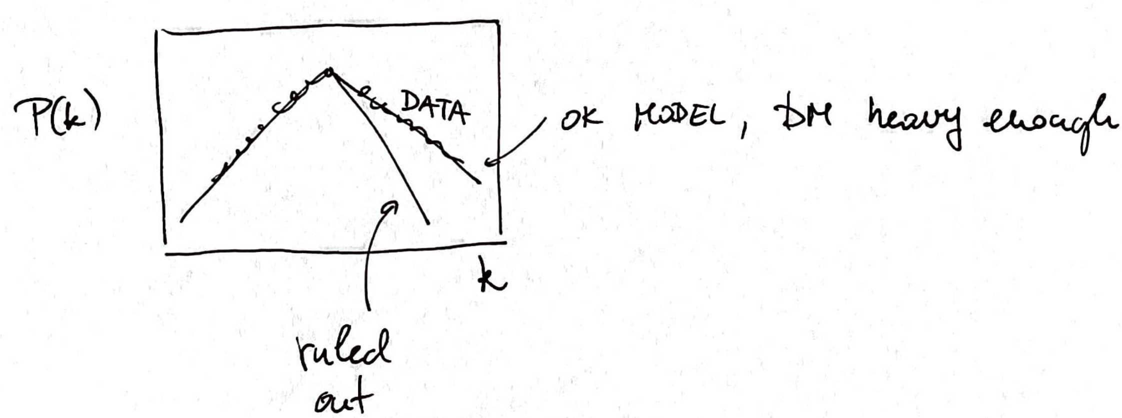
while $\int d^3p \sim (m v)^3$ and $v^2 = \frac{GM}{R}$

Now : $M < m_{DM} \, R^3 \, m_{DM}^3 \left(v^3 = \left(\frac{GM}{R}\right)^{3/2} \right) = M_{max}$

OR : $m_{DM} > \left(M \, (GR)^3 \right)^{-1/8}$.

$\underset{DSPh}{\sim}$ $\underline{\underline{0.5 \text{ keV}.}}$

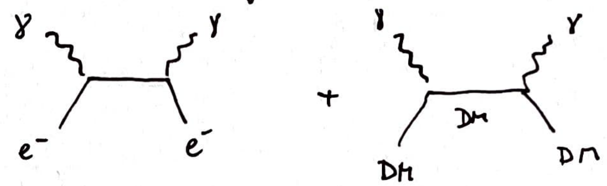
- Similar constraints come from the matter power spectrum $P(k)$ and Lyman-α observations.



CHARGE

DM does not shine and has to have $Q_{DM} < Q_{max}$.

The strongest bounds is cosmological from recombination. If DM were charged like e^-, the photons would scatter:

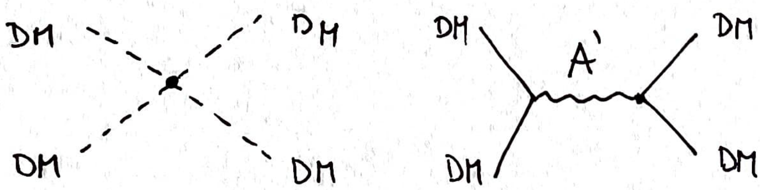


usual Compton   new channel from DM

$$Q_{DM} \lesssim 3.5 \cdot 10^{-7} \left(\frac{m_{DM}}{\text{GeV}}\right)^{0.6} \qquad \text{[PDG '21]}$$

SELF-INTERACTION

While DM couples weakly to the SM ($\gamma, e^-, p^+, \ldots$), it may have a relatively strong self-coupling.



This is most strongly bounded by the BULLET CLUSTER

$$\frac{\sigma_{DMDM}}{m_{DM}} \lesssim 1.2 \, \frac{\text{cm}^2}{\text{g}} = 0.8 \, \frac{\text{barn}}{\text{GeV}}$$

nucleon-nucleon : $\frac{\sigma_{pn}}{m_p} \sim 10 \, \frac{\text{barn}}{\text{GeV}}$ = LARGE

The usual WIMP : $y \sim 0.5$, $m_{DM} \sim 100\,\text{GeV} \simeq M_W$

$(\hbar c)^2 = 1 \sim 0.4$ mbarn GeV^2 $\quad \sigma_{DM\,DM} \simeq \dfrac{\alpha_W}{M_W^4}\, m_{DM}^2$

$$\simeq \frac{\alpha_W^2}{M_W^2} \sim 10^{-8}\,\text{GeV}^{-2}$$

So : $\dfrac{\sigma_{WW}}{m_{DM}} = 10^{-13}\ \dfrac{\text{barn}}{\text{GeV}}$ $\qquad = 10^{-8}$ mbarn

TINY

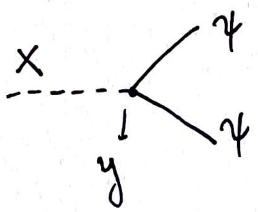
DARK MATTER CANDIDATES

LIFETIME DM needs to be cosmologically stable with

$\tau_{DM} > \tau_U \simeq 15$ byr or $\Gamma_{DM} \lesssim \dfrac{1}{10^{10}\,\text{yr}} \lesssim 10^{-41}$ GeV.
$(\hbar = 1)$

This is extremely small and one typically needs to suppress the DM - SM interactions.

EXAMPLE : Scalar DM X coupled to SM fermions ψ



$\Gamma_X = \dfrac{m_X}{8\pi}\, y^2$ (even from dim. anl. $[\Gamma] = 1$)

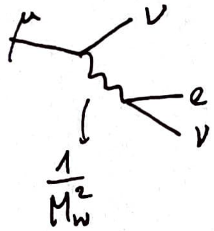
$\Downarrow$

$\mathcal{L} \ni y\, \bar\psi X \psi$, $[y] = 0$ $\qquad \Gamma_X < \left(\dfrac{m_X}{\text{GeV}}\right)\left(\dfrac{y}{10^{-20}}\right)^2.$

Needs $y \sim 10^{-20}$, which is extremely small. In the SM $y_t \sim \mathcal{O}(1)$, $y_e \sim 10^{-6}$.

- for 3-body, the situation is similar

remember μ-decay



$$\Gamma_\mu \simeq \frac{\alpha_2^2}{M_W^4} m_\mu^5$$

α_2^2 ← need smaller couplings

m_μ^5 → or much lighter DM

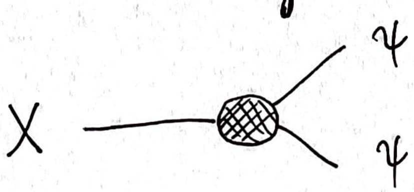
M_W^4 ← need heavy mediators

- Multi-body final states get extra phase space factors of $(8\pi)^{2n}$, but ultimately cannot suppress Γ (loops become dominant).

SYMMETRY : Imposing a symmetry on the Lagrangian can protect the DM from decaying.

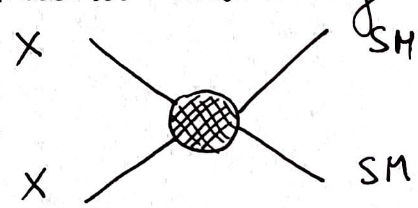
$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM}$; Z_2 mirror symmetry : DM → − DM
SM → SM

Forbids decays



$Z_2 = -1 \neq Z_2 = 1 \cdot 1 = 1$

Allows scattering



$Z_2 = (-1)(-1) = 1$, $Z_2 = 1^2 = 1$ ✓

Some models : SM + scalar (real or $\mathbb{C}$) singlet S × Z_2

+ scalar doublet = INERT HIGGS MODEL
(or higher multiplets of $SU(2)_L$)

• A very popular setup (used to be) is SUPERSYMMETRY

SUSY: $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{MSSM}$

SM		MSSM
γ, Z, W, g		$\tilde{\gamma}, \tilde{Z}, \tilde{W}, \tilde{g}$
q, ℓ	$\xLeftrightarrow{\text{R-parity}}$	$\tilde{q}, \tilde{\ell}$
h		$\tilde{H}_1, \tilde{H}_2$

• Each particle has a superpartner which has different (opposite) spin statistics : fermions $\overset{MSSM}{\Longleftrightarrow}$ bosons

$$R = (-1)^{3(B-L)+2S}$$ acts as Z_2, if exact, the lightest state can be DM

• AXIONS : these are very light ($m_a < 0.1\,eV$) pseudo-scalar particles. They are remnant (Goldstone bosons) of a certain symmetry, broken at very high scales $f_a \gtrsim 10^{10}\,GeV$. This symmetry would explain why strong interactions conserve CP.

• STERILE NEUTRINOS : $m_\nu > 0$ from oscillations, can be explained by adding RH sterile neutrinos ν_s. With $m_{\nu_s} \gtrsim keV$ and suppressed couplings to the SM, they may be good (warm) DM.

- There is a range of other options
  - super-light 10^{-21} eV fuzzy DM
  - primordial black holes (microscopic)
  - gravitinos
  - Kaluza-Klein states from X-dimensions.
- However, there was no <u>prediction</u> of Dark matter and there is no universally preferred framework.