Evidence for DM

(almost certainly)

DM **is** a BSM physics. SUSY?
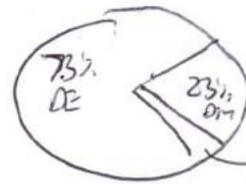
In order of ease of understanding

1. <u>Rotation curves</u> — Zwicky 1930's, Coma Cluster ⇒ 90% of matter does not shine (dunkle Materie).

   Virial thm $\langle T \rangle \sim \langle V \rangle$ to determine grav. pot. from speeds / redshifts

   — Vera Rubin 1970's, stars in Spiral galaxies

$$\frac{1}{2}\frac{v(r)^2}{r} \sim \frac{G M(r)}{r^2}$$

$M(r) \to$ const at large r

But $v \Rightarrow$ const at large r

$\Rightarrow M_{tot} \sim r$

$\int r^2 dr\, \rho = r \Rightarrow \rho \sim 1/r^2$.
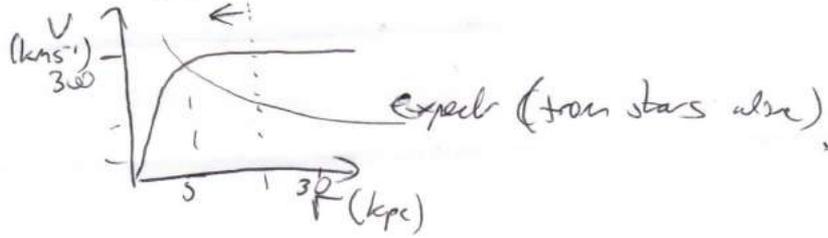
[local motion of stars gives
$$\rho_{DM}^{local} = (0.39 \pm 0.03)(1.2 \pm 0.2)(1 \pm \delta_{triax}) \text{ GeV}$$
Catena + Ullio / PDG ∫ (uses extra, global info) $\delta \lesssim 0.2$]
Bovy Tremaine

V (kms⁻¹) 300 ... expect (from stars alone) ... 5 30 r (kpc)

2. CMB

Many improvements over last decade + (COBE, WMAP, Planck, SPT, ACT, ...)
full sky   high res.

$$\delta T(\theta, \varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta, \varphi)$$

$$\langle \delta T^2 \rangle = \sum_{l,m} \langle |a_{lm}|^2 \rangle \frac{4\pi}{2l+1} = \sum_l C_l \frac{4\pi}{2l+1}$$

$\frac{l(l+1)C_l}{2\pi}$ ... Geometry ... Baryons/DM ... Inflation ... consistency checks ... l
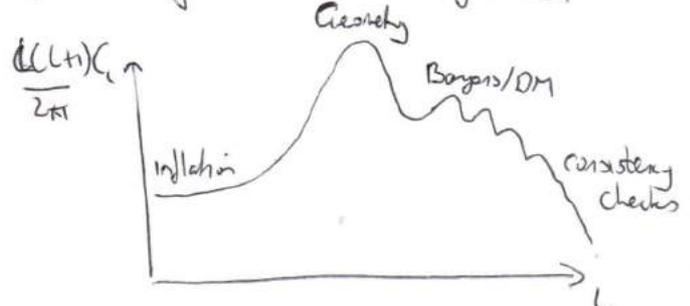
Snapshot of $z \sim 1100$, 380,000 yrs after BB. $T \sim eV$

Universe "well neutral"

CMB described by ~10 parameters

Linear growth after Matter ─ radiation equality. When? Depends on how much matter. $\implies$ size of instabilities.
(z ~ 2700) ~100,000 yrs   T~ few eV

If some matter not coupled to baryon/photon fluid it can start "growing" (seeding structure) at z ~ 2700. Baryons only grow after recombination per

LSS, BAO

Measure the same "wiggles of inflation" $\frac{\delta \rho}{\bar{\rho}} \sim 10^{-5}$ in Large Scale Structure or Baryon Acoustic Oscillations (BAO)

P(k) ↑
CMB
cluster
weak lensing
Lyα
BAO $\longrightarrow$ sensitive to amount of baryons.
→ k

overlaps in ranges ✓
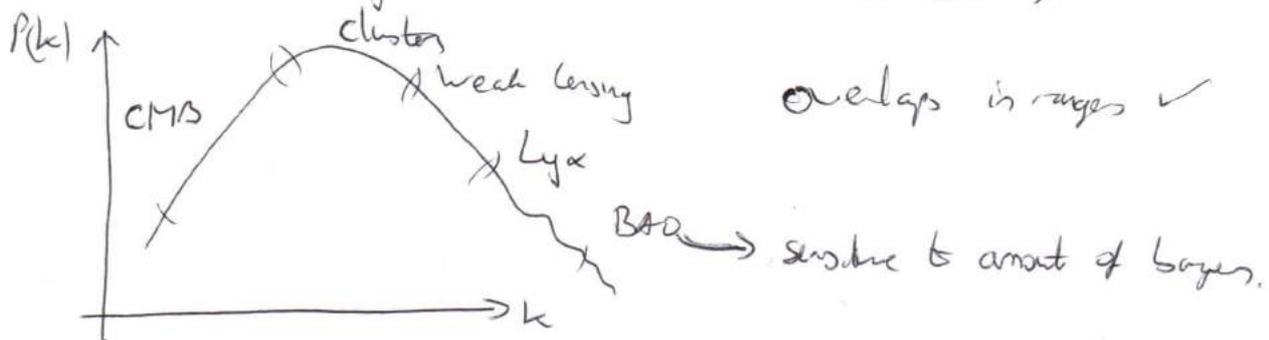
Peak + shape + wiggles all measure Ω_{matter}
→ M-R eq.

Existence of wiggles in CMB/LSS $\implies$ CDM not HDM
(room for some WDM)

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BBN Alpha, Beta, $\frac{Gamow}{Boulder}$

$t \sim 10s$

Soup of p, n, e, γ. At $T \lesssim 1$ MeV weak interactions "freeze out"

ie $\nu_e + n \gtrless p + e$ turns off. $\quad \frac{n}{p} \sim e^{-\Delta m / T} \sim 1/6$

$\eta_b = \frac{n_b}{n_\gamma} \sim 6 \times 10^{-10} \quad \leftarrow$ determines everything (approximately)

Deuterium bottleneck : B.E $= 2.2$ MeV if too many photons with $E > 2.2$ MeV

<u>all involve D</u> can nt form heavier elements
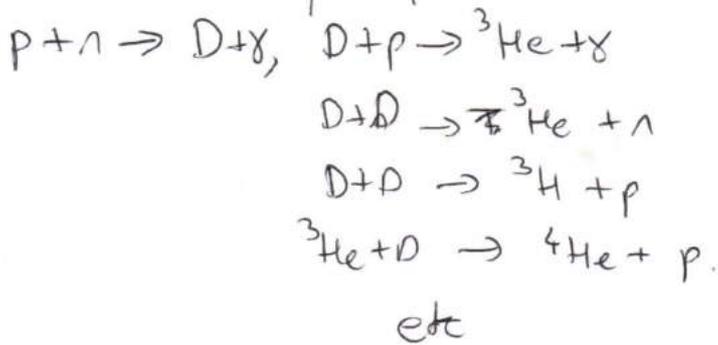
$p + n \rightarrow D + \gamma, \quad \overbrace{D + p \rightarrow {}^3He + \gamma}$ To get up chain of elements

$\qquad D + D \rightarrow {}^3He + n$ need $\eta^{-1} e^{-\Delta_D / T} \lesssim 1. \quad \textcircled{1}$

$\qquad D + D \rightarrow {}^3H + p$

$\qquad {}^3He + D \rightarrow {}^4He + p.$ $\underline{\text{less } 1 \gamma \; (2.2 \text{ MeV}) \text{ per baryon}}$

$\qquad\qquad etc$

Once $\textcircled{1}$ is true get all elements. Neutrons decay! $\Rightarrow \frac{n}{p} \rightarrow \frac{1}{7}$ after bottleneck

$T \sim 0.1$ MeV, $t \sim 100s$.

$\qquad$ Final prediction $Y_p \equiv \frac{\rho_{He}}{\rho_b} = \frac{2(n/p)}{1 + n/p} = \frac{2/7}{8/7} = 1/4.$

Measures number of baryons.

Combined with CMB $\Rightarrow$ 2 types of matter

$\qquad\qquad \Rightarrow$ DM not coupled to photons

$\qquad\qquad\qquad \Rightarrow$ charge $\ll 1$

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Bullet cluster, train wreck cluster, Musket ball etc
_____

Gal A

Gal B

← lensing, matter

↑
X-rays, baryons, hot gas
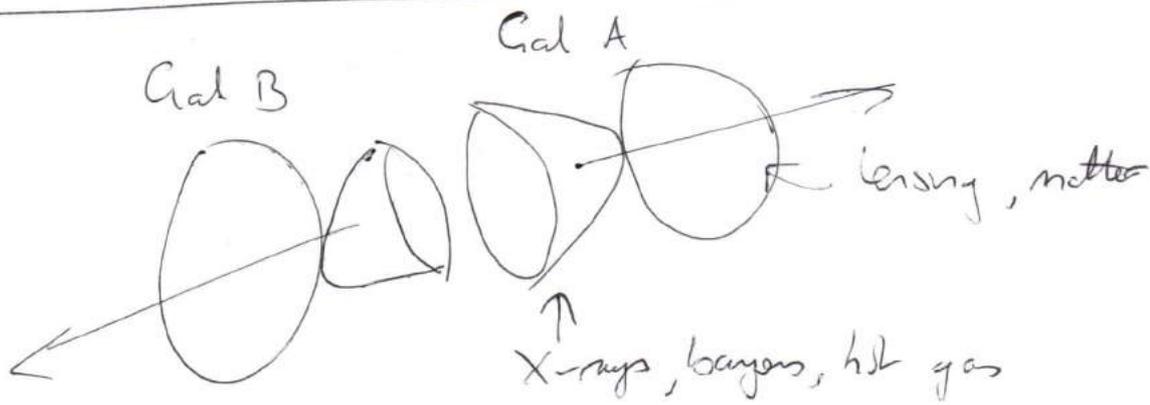
2 different matters. Different amounts of interaction.

DM − DM interactions : $\dfrac{\sigma_{\chi\chi}}{m_\chi} \lesssim \overset{1000}{\cancel{\%}}$ GeV^{-3} ($1 cm^2/g$).

(See Tulin + Yu 1705.02358)

Various "problems" may point towards $\sigma_{\chi\chi} \neq 0$

$\rightarrow$ core − cusp

$\left.\begin{array}{l} \text{too big to fail} \\ \text{Missing satellite} \end{array}\right\}$ $\dfrac{dN}{dM}\Big|_{obs} \neq \dfrac{dN}{dM}\Big|_{theory}$ (dwarfs)

Halo shapes / Clusters

DM Not coupled ~~to light~~ massless mediator $\rightarrow$ halos $\simeq$ ◯   not ────•

Long Lifetime.

(0904.2789)   DM still around $\rightarrow$ $\tau > 10^{17}$ s

Stronger bounds (channel depdended) from lack of antiparticles from galactic centre ~~etc~~/ nearby. eg $\chi \rightarrow e^+ e^-$ $\Rightarrow \tau > 10^{25}$ s $\left(\dfrac{TeV}{m_\chi}\right)$

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What are possibilities to DM?

MACHOS   Hard to make compatible w/ BBN e.g brown dwarfs, baryon nuggets etc
(0912.5297)   PBH form well before BBN and act as DM ✓
1607.06077)

Constrained by microlensing survey. eg EROS2 (67M stars in Magellanic cloud)
                                   MACHO
            CMB (accretion onto BH releases energy into CMB and disturbs it)

Very hard calculations
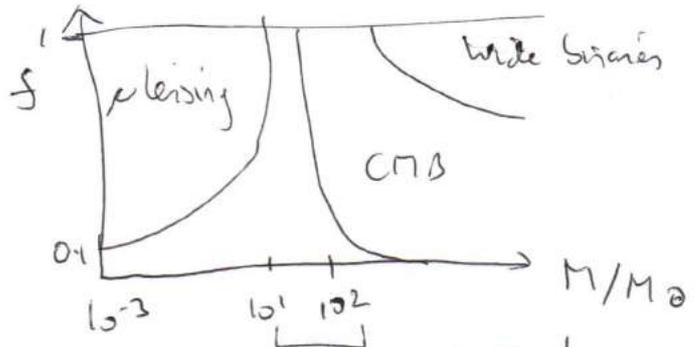
→ recent renewed interest → LIGO eoc
     30 M☉ BH = DM ??

MOND   — not going to talk about it

Particle DM
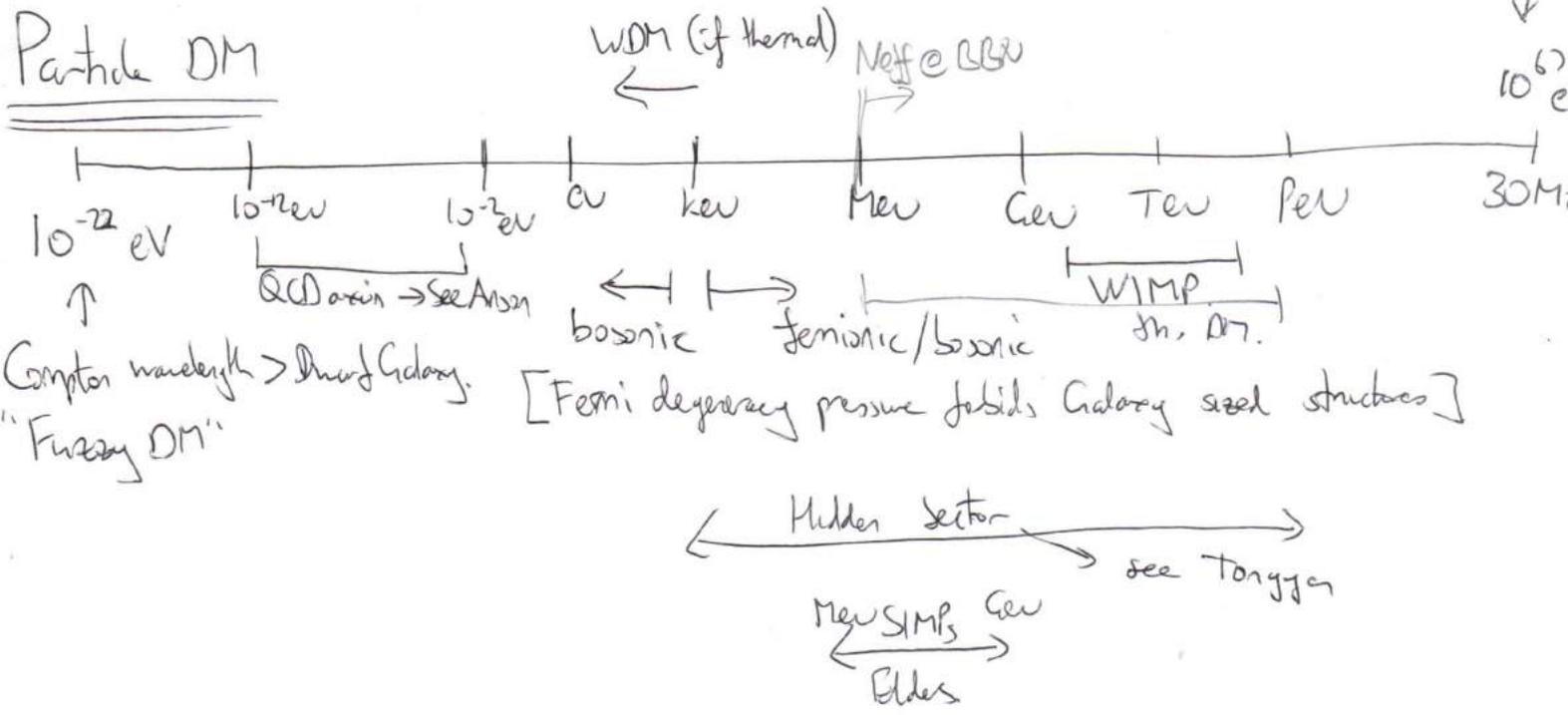
WIMP — weakly interacting massive particle.

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