Evidence for DM

(ahunt century)

DM is in BSM physics. Sure?

In order of ease of understanding

1. Tully-Fornax curves
   - Znicky 1930; Coma Cluster-89%
   - of matter does not shine
     (Dunkle Materie)
   - Use Vn < T < n x D to determine mass, put: from speeds / redshifts

   \[ \frac{\sqrt{V_n^2}}{V} \sim \frac{G M(r)}{v^2} \]
   - M(r) = const. at large r
   - But V \sim const. at large r
   - \( \Rightarrow M \propto r \)
   - \( \int r^2 dr = r \Rightarrow p \sim \frac{1}{r^2} \)

2. CMB

Many improvements over last decade:

\( \langle \delta T^2 \rangle = \sum \sum \langle \alpha_m^2 \rangle = \sum \frac{C_l}{2\pi} \)

Snapshot of 2 \times 10^3, B\approx \, 200 \, y\, after BB.

Universe "real real"
CMB described by ~10 parameters
Linear growth after Matter-radiation equality. When? Depends on how much matter. \( \Rightarrow \) Size of island.

If some matter not coupled to baryon/photon fluid, it can start "growing" (seeding structure) at \( z \approx 2700 \). Baryons only grow after LSS, BAO.

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

![Diagram of CMB and BAO](image)

Peak + shape + wiggles all measure Matter
\( \Rightarrow M - \Omega \) eq.

Existence of wiggles in CMB/LSS \( \Rightarrow \) CDM not \( H_{0} \Omega_{0} \)
(CDM for some WDM)
BBN

Alpha, Beta, Gamma

\( t_{\text{10s}} \)

Soup of \( p, n, e, \gamma \). At \( T \leq 1 \text{ MeV} \) weak interactions "freeze out" \( \omega \gamma + n \geq \) p returns off.

\[
\frac{\Lambda}{p} \sim e^{-\frac{m\gamma}{T}} \approx 1/6
\]

\( \Lambda = n_0 \times 6 \times 10^{-10} \leftarrow \text{determines everything (approximately)} \)

Deutonum bottleneck: \( B.E. = 2.2 \text{ MeV} \) if too many photons with \( E > 2.2 \text{ MeV} \) can not form heavier elements.

\[
p + n \rightarrow D + \gamma, \quad D + p \rightarrow ^3\text{He} + \gamma
\]

To get up chain of elements, need \( \frac{1}{e^{\frac{m\gamma}{T}}} \leq 1 \)

\[
\text{less } 1.8 (2.2 \text{ MeV}) \text{ per baryon}
\]

\( \text{etc} \)

Once (5) is true gel all elements. Neutrons decay! \( \rightarrow \frac{1}{p} \rightarrow \frac{1}{7} \) after \( T = 0.1 \text{ MeV} \), \( t_{\text{10s}} \).

Fundamental prediction \( Y_p = \frac{^4\text{He}}{p_0} = \frac{Z(Z+1)}{1 + Z} = 0.24 \).

Measures number of baryons.

Combined with CMB \( \rightarrow 2 \) types of matter:

\( \rightarrow \text{DM not coupled to photons} \)

\( \Rightarrow \text{charge } < 1 \)
Bullet cluster, Trai, virial cluster, Michel Bell etc

Gal B

Gal A

X-rays, lensing, matter

2 different matters. Different amounts of interaction.

DM - DM interaction: \( \frac{\sigma_{\text{xx}}}{m} \leq \frac{1000}{m} \text{ GeV}^2 \) \( \text{cm}^{-2} \text{g}^{-1} \).

(See Tulin et al. 1705. 02358)

Various "problems" may point towards \( \sigma_{\text{xx}} \neq 0 \)

\( \text{core - core} \)

\( \text{too big to fail} \)

\( \text{missing satellites} \)

\( \frac{dN}{dm} \text{ los} \neq \frac{dN}{dm} \text{ theory} \)

Halo shapes / Clusters

\( \text{Not coupled tightly} \rightarrow \text{halos} \cong \bigcirc \text{ not} \)

Halo shapes / Clusters

Long lifetime.

\( \text{(0904. 2789)} \)

DM still around: \( T > 10^{17} \text{s} \)

Stronger bounds (chand degraded) from lack of antiparticles near galactic centre or Nearby. eg \( \chi \rightarrow e^+e^- \rightarrow \gamma > 10^{15} \text{s} \text{ GeV} \) \( \text{MeV} \).
What are possibilities for DM?

MACHOS

Had to make compatible w/ BBN e.g. brown dwarfs, nuggets etc.
PBH form well before BBN and act as DM

Constrained by microlensing survey. e.g. GRO92 (67 M sun in Magellanic cloud)
CMBS (accretion onto BH releases energy into CMBS could disrupt it)

Very hard calculations

Very hard calculations

recent renewed interest - LIGO event
30 M sun BH = DM??

MOND

Not going to talk about it

Particle DM

WIM (if needed) \text{Neff} \approx 100

$10^{-22}$ ev $10^{-20}$ ev $10^{-18}$ ev keV MeV GeV TeV PeV

QCD axion \text{SeeShell}

Fermi degeneracy pressure builds, Galaxy scale structure

"Fuzzy DM"

Hidden Sector \text{see Tongfei}

WIMP - weakly interacting massive particles