Dark Matter Theory - 1

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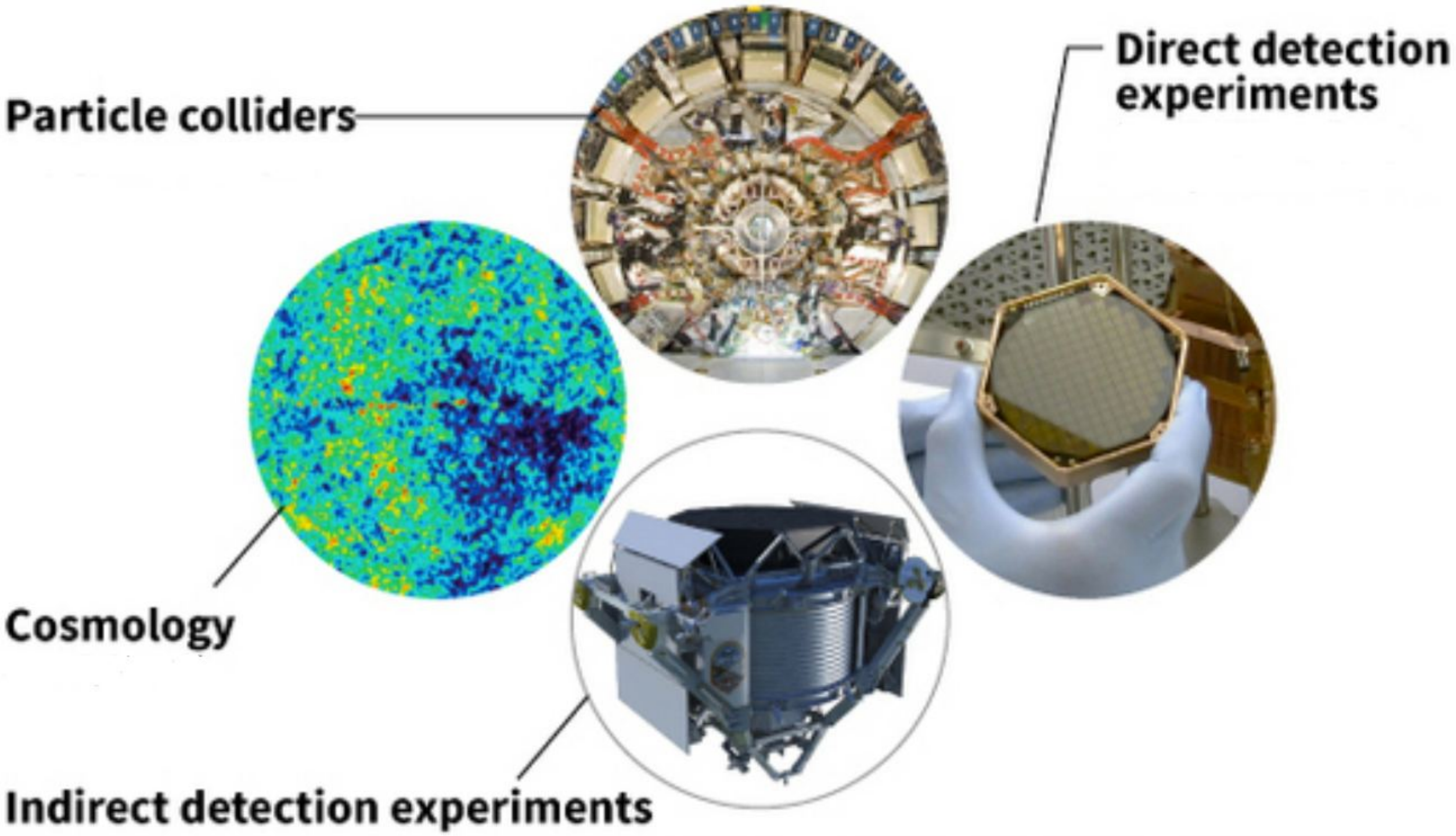
Invisibles School, July 10, 2013

The Hunt for Dark Matter, the most abundant form of matter in the Universe is multi-pronged involving ...



These will be covered separately in lectures, besides mine (some repetition unavoidable)

Content of lecture 1:

- Dark Matter (DM): what we know about it
- Particle DM candidates require Beyond the Standard Model physics
- Relic abundance calculations
- DM candidates as the earliest relics

(Subject is too vast for the time- so idiosyncratic choice of subjects. Citations disclaimer)

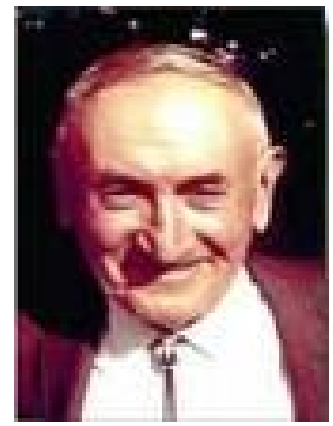
The DARK MATTER problem has been with us since 1930's, name coined by Fritz Swicky in Helvetica Physica Acta Vol6 p.110-127, 1933

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

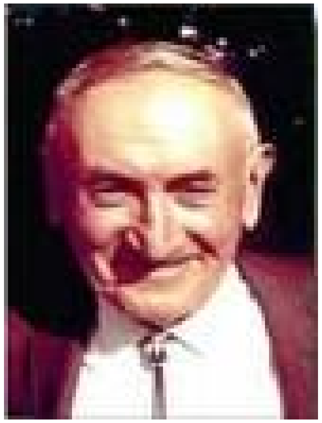
Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.



On page 122

gr/cm^3. Es ist natürlich möglich, dass leuchtende plus **dunkle (kalte) Materie** zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\bar{\varrho} \sim 10^{-28}$ gr/cm^3 erscheint daher nicht

Dark Matter discovered

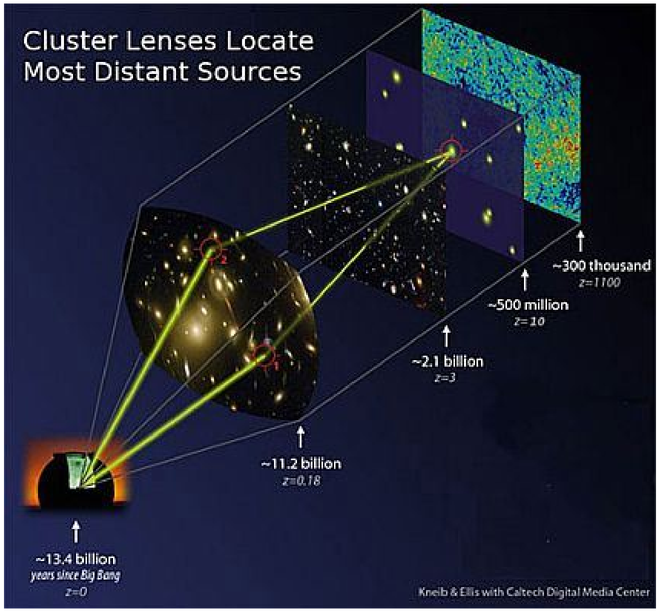


In 1930's Fritz Zwicky found the first indication of the DM.
Used the Virial Theorem in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only

Later: also gas in clusters moves too fast (is too hot - as measured in X-rays) to remain in it, unless there is DM.

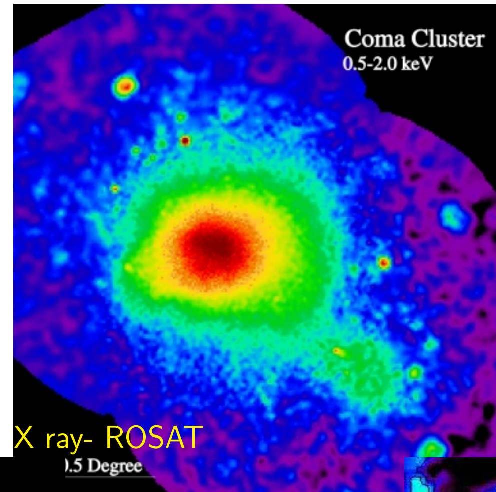
Another later method:
gravitational lensing

depends on all the intervening mass



DM dominates in galaxy clusters

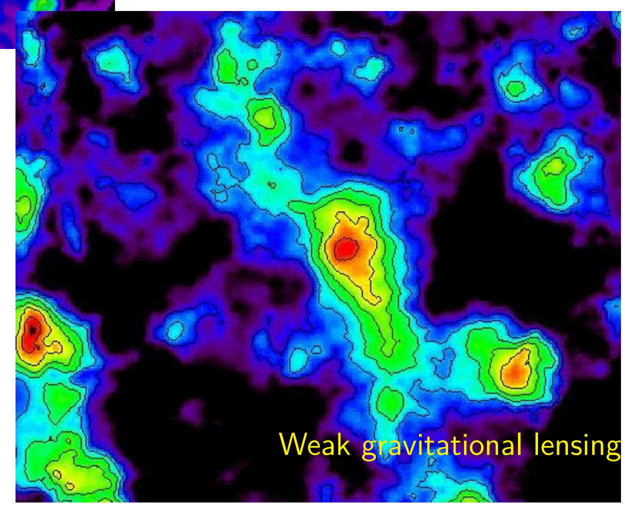
Coma cluster optical-Kitt Peak



X ray- ROSAT

$$\boxed{\frac{M}{M_{vis}} \simeq 6}$$

Strong gravitational lensing

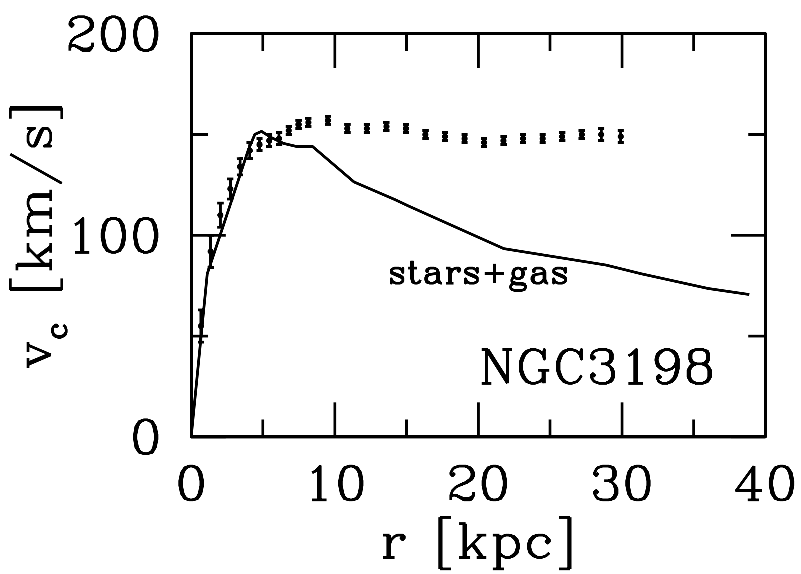


Weak gravitational lensing

J. Ostriker: in the first 40 years, the 1937 Comma Cluster Ap.J Zwicky paper had 10 citations!

Dark Matter rediscovered

In 1970's Vera Rubin found that the rotation curves of galaxies ARE FLAT!



$$\frac{GMm}{r^2} = m\frac{v^2}{r} \Rightarrow v = \sqrt{\frac{GM(r)}{r}}$$

$$v = const. \Rightarrow M(r) \sim r$$

even where there is no light!

1 pc = 3.2 ℓy

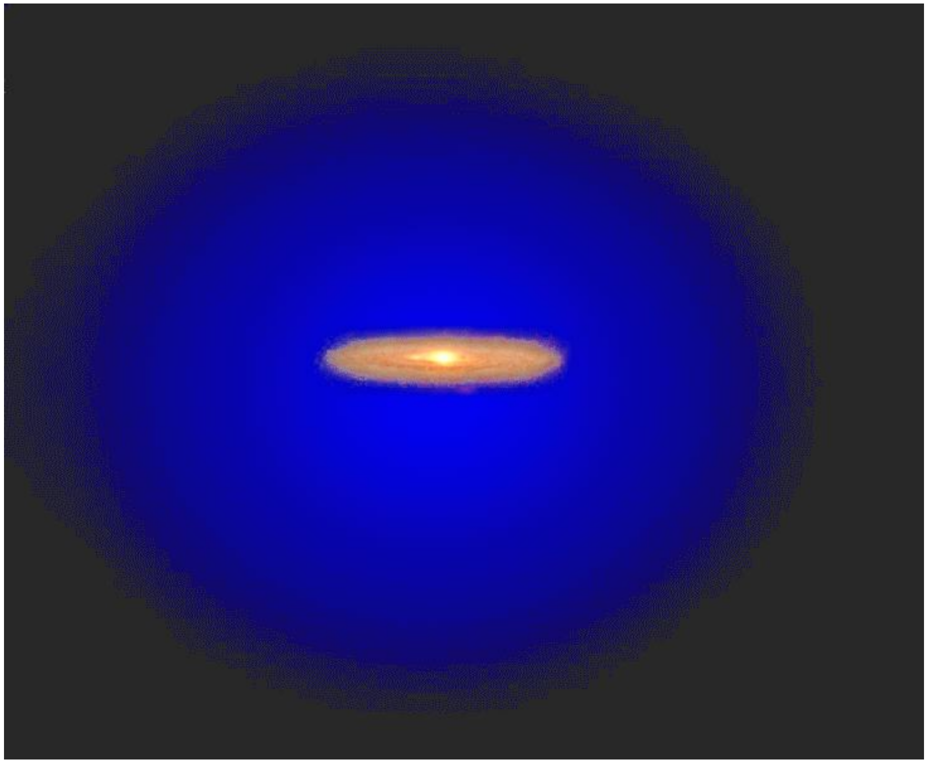
Dark Matter dominates in galaxies e.g. in NGC3198

$$M = 1.6 \times 10^{11} M_{\odot}(r/30\ \text{kpc})$$
$$M_{stars+gas} = 0.4 \times 10^{11} M_{\odot}$$

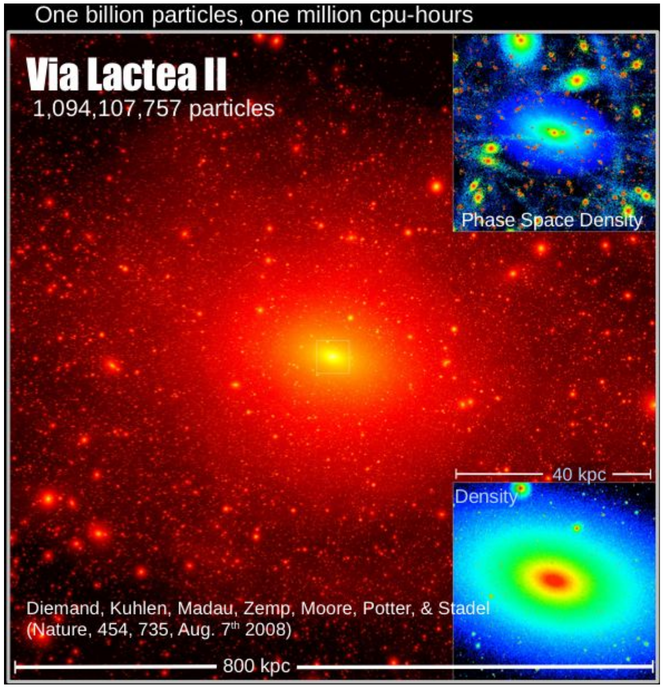
$$\boxed{\frac{M}{M_{vis}} > 4}$$

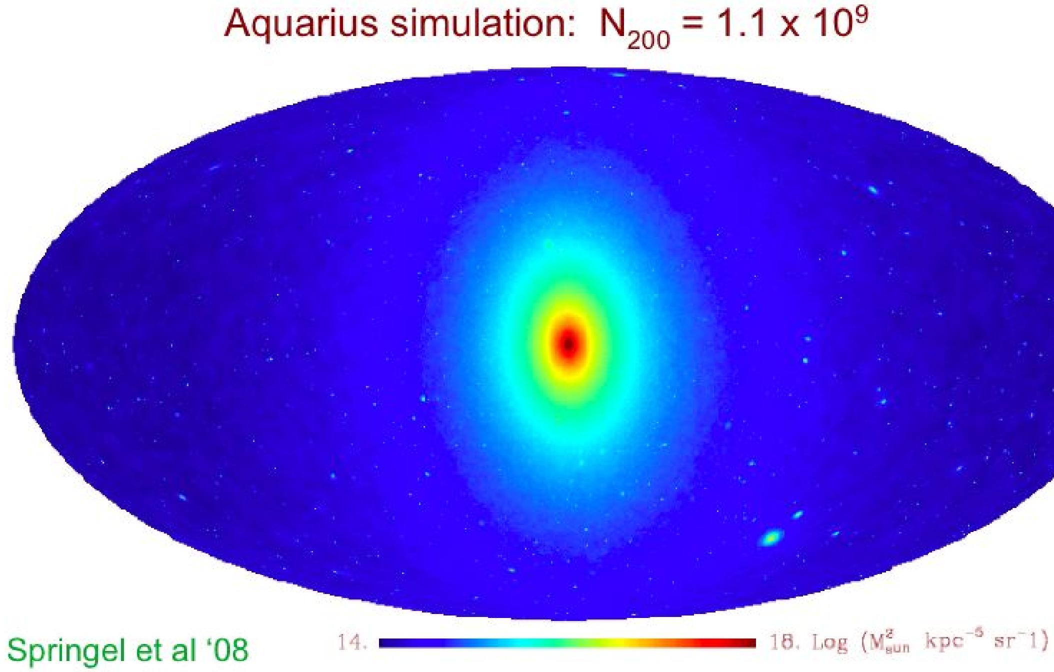
Galaxies have a Dark Halo containing 70 -80% of its mass

Artist view: visible disk surrounded by a DM halo



State of the art non-linear N-body simulations of Dark Haloes No baryons included (so no disk)! Sun at 8kpc from the center





Lots of subhalos and tidal streams at large distances from the galactic center. The chance of a random point close to the Sun lying in a substructure is $< 10^{-4}$

At the largest scales:

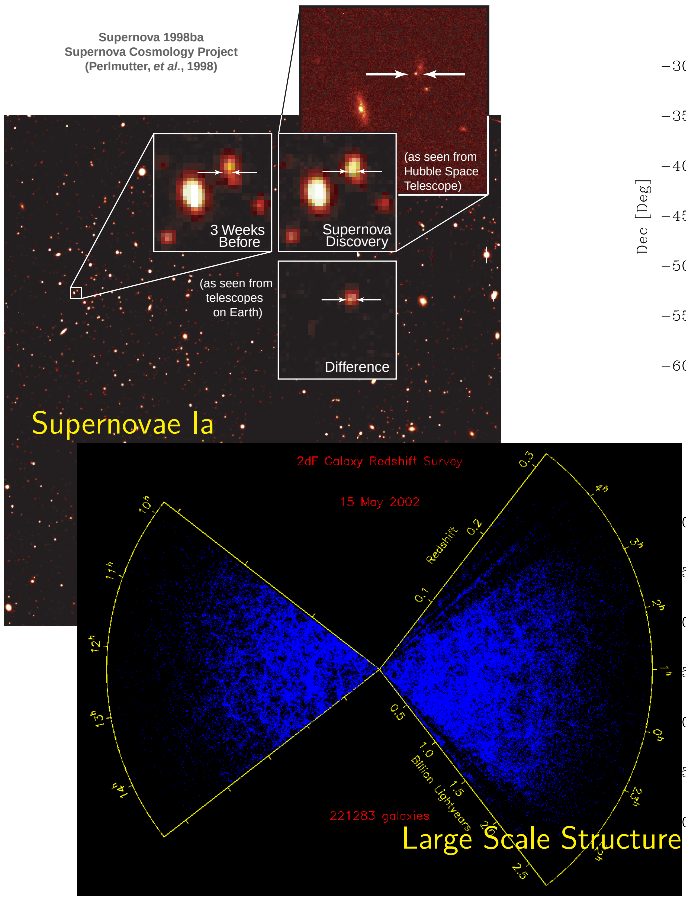
Use General Relativity

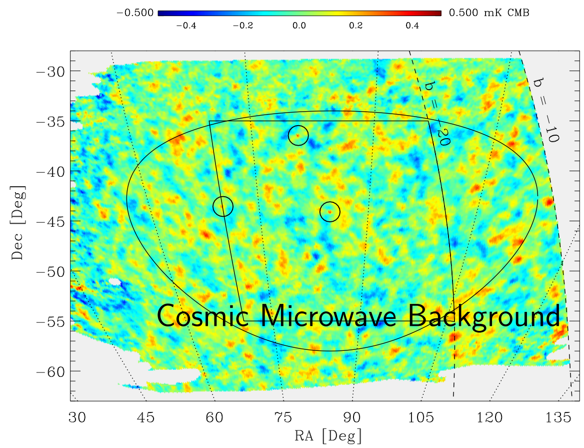
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} \left(+ \Lambda g_{\mu\nu} \right)$$

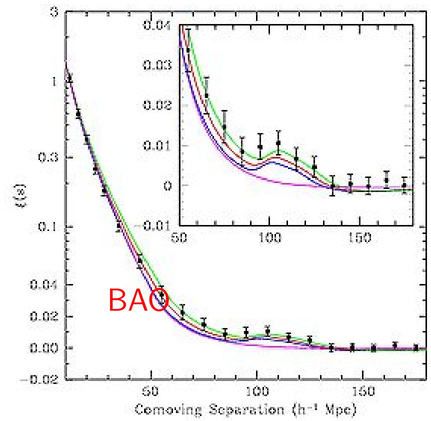
To relate:

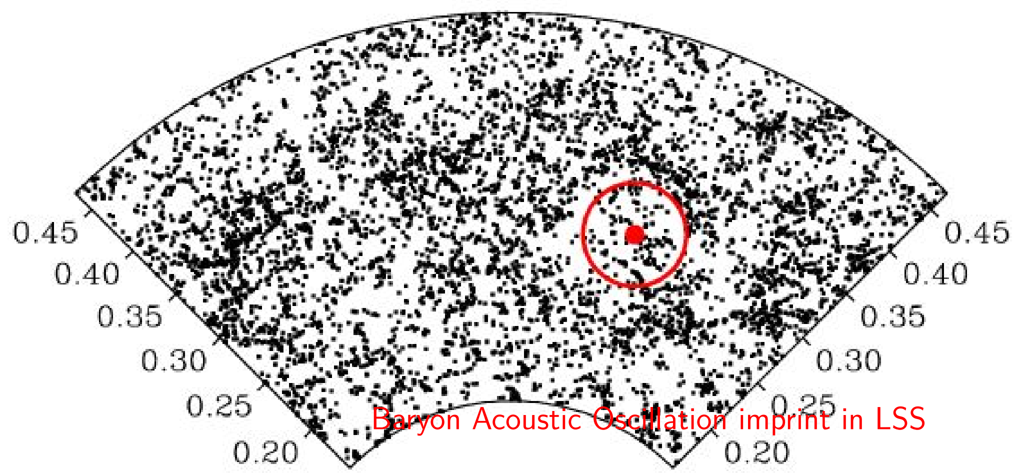
Spacetime geometry $\longleftrightarrow$ Mass-energy density

In the 1980's the Cosmological Constant was surely zero and the big question was: is $\Omega_{DM} = 1$? However in the 1990's **At the largest scales**

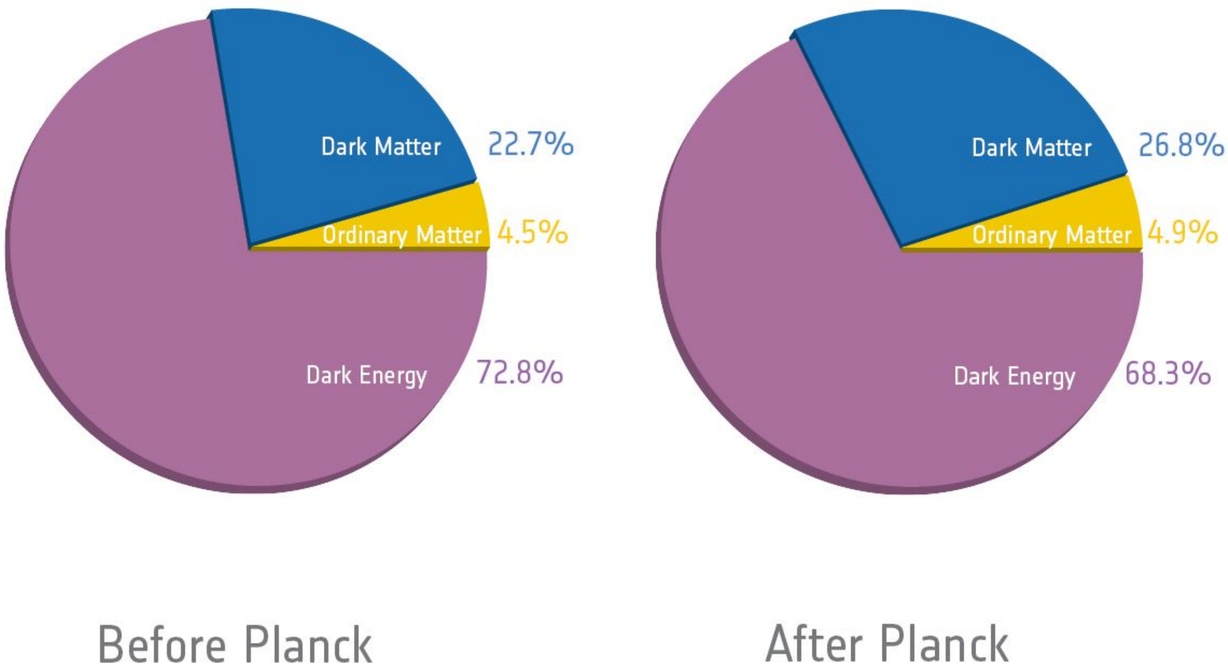






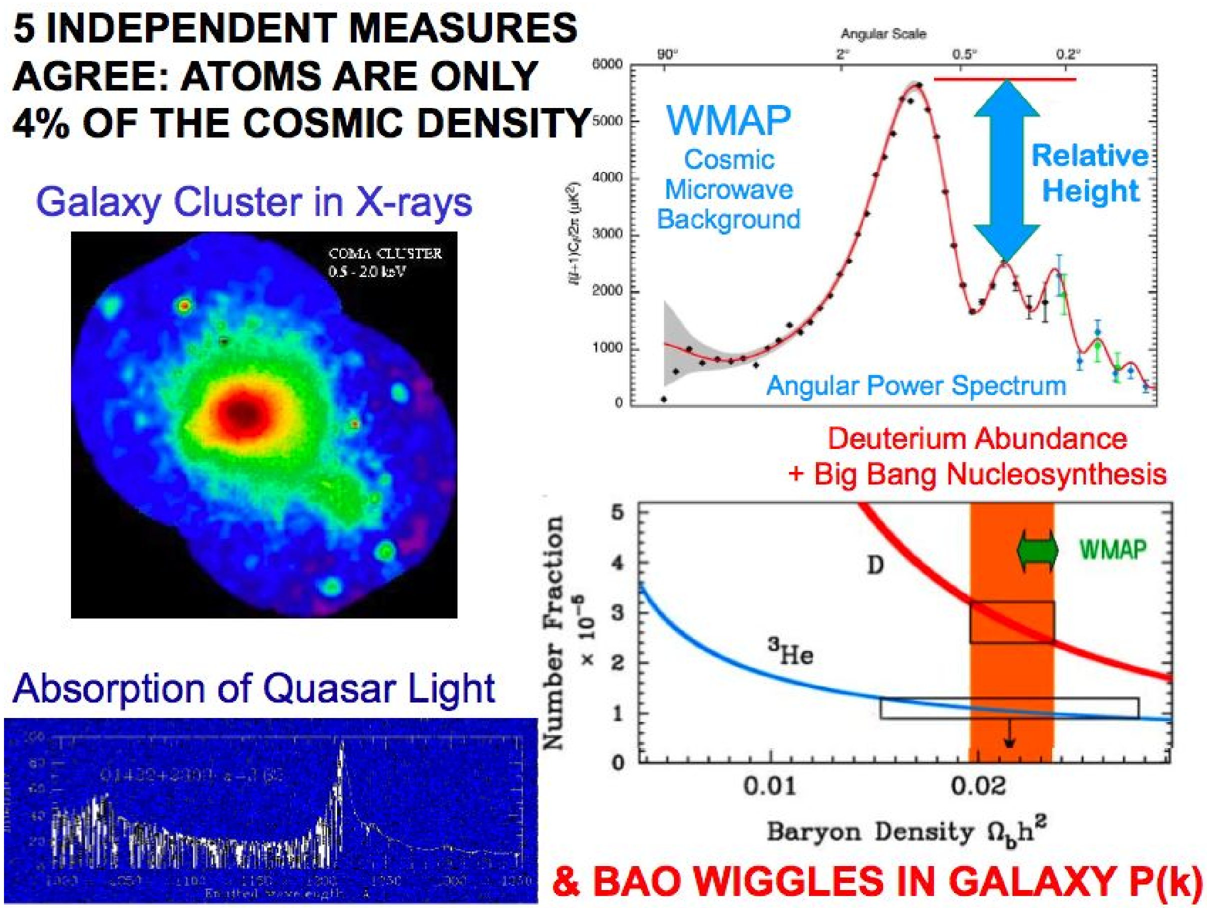


At the largest scales: the "Double-Dark" or "Concordance" model



"DARK ENERGY" (with repulsive gravitational interactions)
"DARK MATTER" (probably new elementary particles)!
Note: $\Omega_{DM} h^2 = 0.1153 \pm 0.0019$ for WMAP-9 and 0.1187 ± 0.0017 for Planck- h is different

Our type of matter is only $< 5\%$. Fig: from J. Primack 2010



so most of the DM is non-baryonic

After 80 years, what we know about DM:

- **Attractive gravitational interactions and stable (or lifetime $>> t_U$)**
- **Dark matter and not MOND**

Dark Matter or Modified gravity?

Do we need "Dark Matter", an unknown material with gravitational self-attraction, dissipationless, collisionless or we can do with just baryons and modified gravity?

MOND (MOdified Newtonian Dynamics- Mordehai Milgrom,1983) proposes a modification of Newton's Second Law - F$_{Grav} \not\propto$ acceleration but F$_{Grav} = ma^2/a_0$ for $a < a_0$ with only baryons to explain the flatness of the rotation curves of galaxies at large distances form the center

$$\frac{GMm}{r^2} = m\frac{v^4}{r^2} \Rightarrow v = \text{constant independent of } r$$

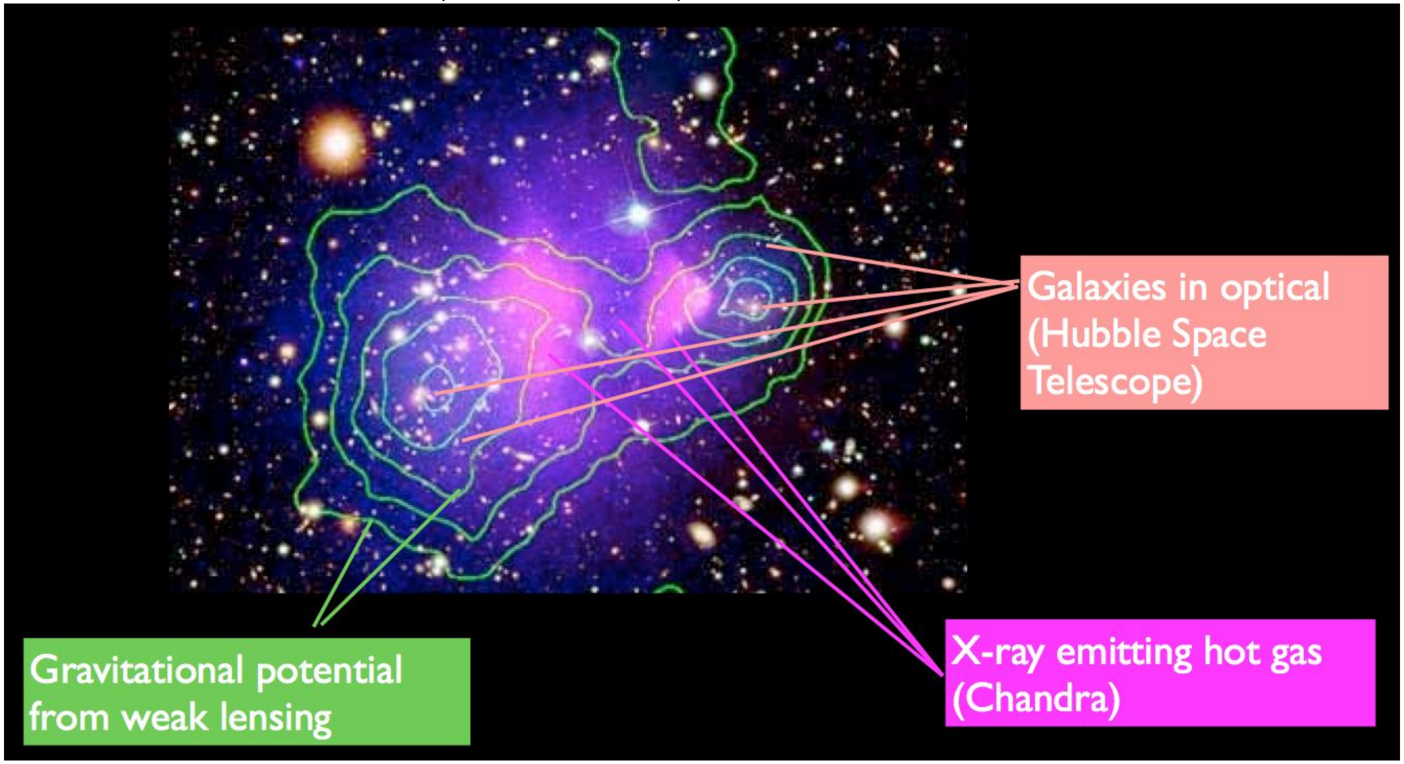
MOND is only non-relativistic and so cannot be tested on cosmological scales.

TeVeS (Jacob Bekenstein, 2004) MOND's generalization, contains new fields that could be interpreted as cold dark matter, interacting only gravitationally. It does not reproduce the pattern of CMB peaks.

There are other ideas, like conformal gravity, but are less studied

Best evidence for Dark Matter and not MOND

"Bullet Cluster"- 2004 (Fig from Gondolo)



Baryons are at the center but gravitational potential has two lateral wells

Best evidence for Dark Matter and not MOND

"Bullet Cluster"- 2004

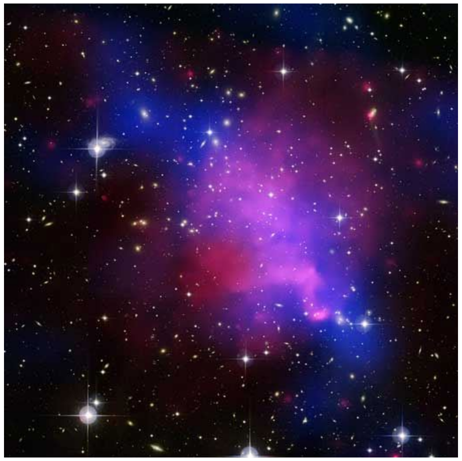
Two galaxies collided leaving behind the

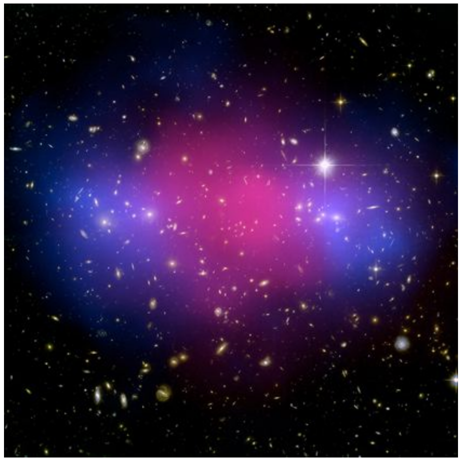
visible (interacting) matter (hot gas detected by Chandra in X-rays -pink) which is not where most of the mass of the cluster (seen through gravitational lensing-blue) is.

MOND with only baryons cannot explain this system (needs 2-3×more matter and propose eV ν_s or some Dark Cluster Baryonic Matter?)- MOND successful up to galactic scales.

Dark Matter exists! Three examples of spatial segregation so far....

"bullet cluster" 2004 "train wreck" 2007 "baby-bullet" 2008





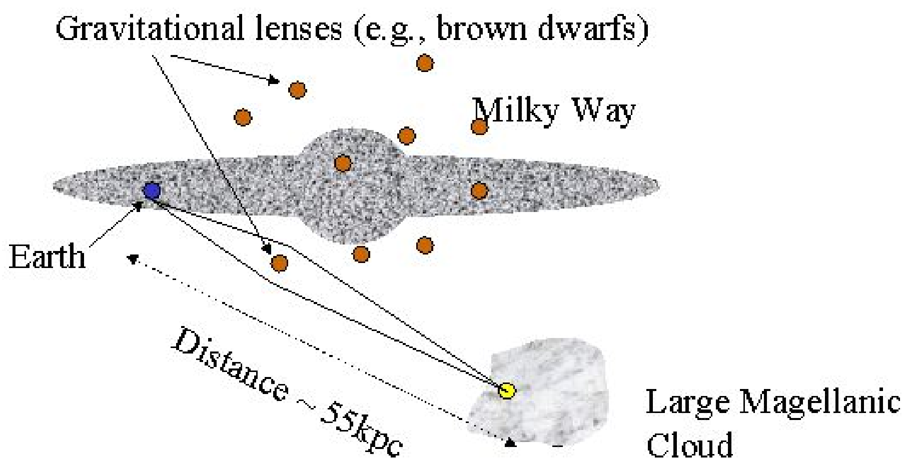
The visible mass, hot gas detected by Chandra in X-rays (pink), is not where the mass of the cluster seen through gravitational lensing (blue) is.

Bound on DM self-interaction: $\sigma/m < 0.7\mathrm{cm}^2/\mathrm{g}$=1.3 barn/GeV, S.Randall et al. 2008-arXiv 0704.0261- Spergel Steinhardt-2000 "self-interacting dark matter" (SIDM) range was 0.5 to 6.0 cm^2/g)

After 80 years, what we know about DM:

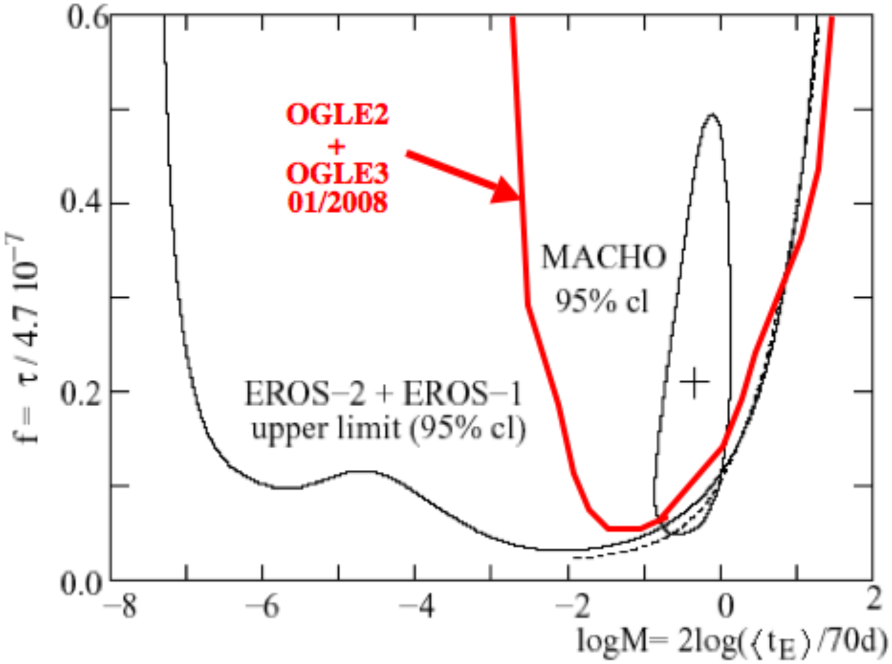
- **Attractive gravitational interactions and stable (or lifetime $>> t_U$)**
- **Dark matter and not MOND**
- **mass?** $m \leq 10^{-7} M_{\odot} = 10^{50}$GeV (limits on MACHOS astro-ph/0607207)

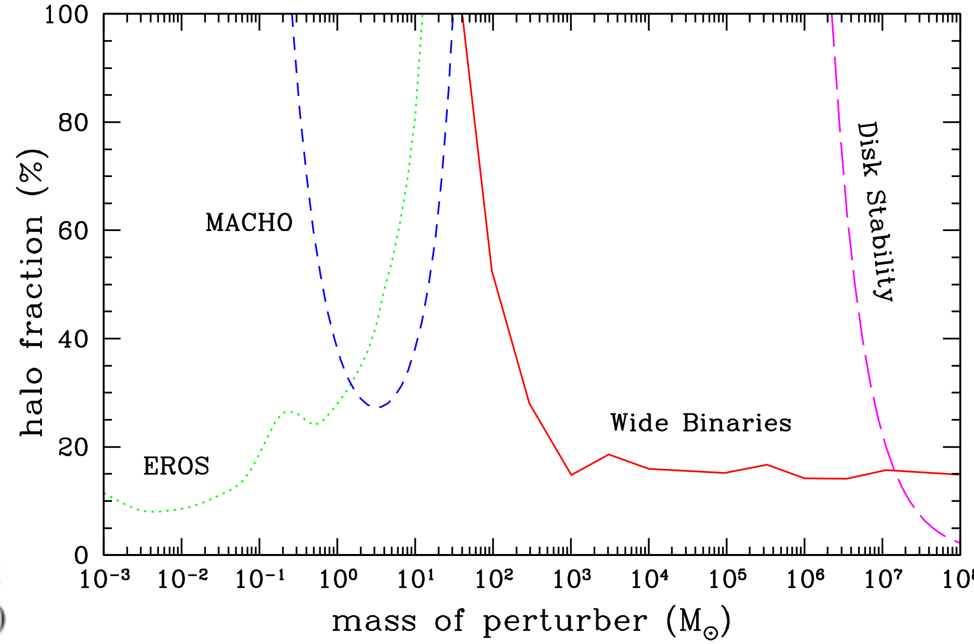
Dark Matter: not MACHOS (Massive Astrophysical Compact Halo Objecs) They were searched for using gravitational "microlensing" of stars in near satellite galaxies and the GC: multiple images are superposed producing an "anti-eclipse" (star becomes brighter for a while).



Dark Matter: not MACHOS EROS, 2009 M. Moniez arXiv:0901.0985 [astro-ph.GA]

Combined with older results for larger masses: Yoo, Chaname, Gould, ApJ**601**, 311, 2004





MACHO searches combined with bounds on granularity of the DM: $m < 10^{3-4} \mathrm{M}_{Sun}$

Not enough of $m > 10^{-7}$ M_{Sun} objects. Elementary particles then?

After 80 years, what we know about DM:

- **Attractive gravitational interactions and stable (or lifetime $>> t_U$)**
- **Dark matter and not MOND**
- 10^{-31} GeV $\leq$**mass**$\leq 10^{-7} M_{\odot} = 10^{50}$GeV (limits on MACHOS astro-ph/0607207)
  (“Fuzzy DM”, boson Bohr radius$=$ 1 kpc Hu, Barkana, Gruzinov, astro-ph/0003365)
  or 0.2-0.7 $\times 10^{-6}$ GeV$\leq$ mass (for particles which reached equilibrium - depending on boson-fermion and d.o.f. Tremaine-Gunn 1979; Madsen, astro-ph/0006074)

After 80 years, what we know about DM:

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- **Dissipationless** i.e. cannot cool by radiating as baryons do to collapse in the center of galaxies- i.e. either neutral or charged but very heavy or with a very small electromagnetic coupling ("Milli-Charged DM", "electric and magnetic dipole DM", "anapole DM")

  Charged Massive Particles (CHAMPs) De Rujula, Glashow & Sarid 1990: stable charged particle can act as nearly collisionless DM if its mass is sufficiently high. Severe limits on its abundance except if $100(q_\chi/e)^2 < m_\chi < 10^8(q_\chi/e)^2$ TeV, where magnetic fields prevent particles in the halo from entering or staying in the galactic disk, (and hence are non-detectable on Earth).
  Chuzoy & Kolb 0809.0436

- **Collisionsless** Collisions make haloes round, but they are triaxial. Self interactions with huge upper limit $\boldsymbol{\sigma_{\mathrm{self}}/\mathrm{m}} \leq$0.1cm^2/g=0.7 barn/GeV (from non-sphericity of galaxy and cluster halos) Peter et al 1208.3026 (^{235}U-n cross section is a few barns!).

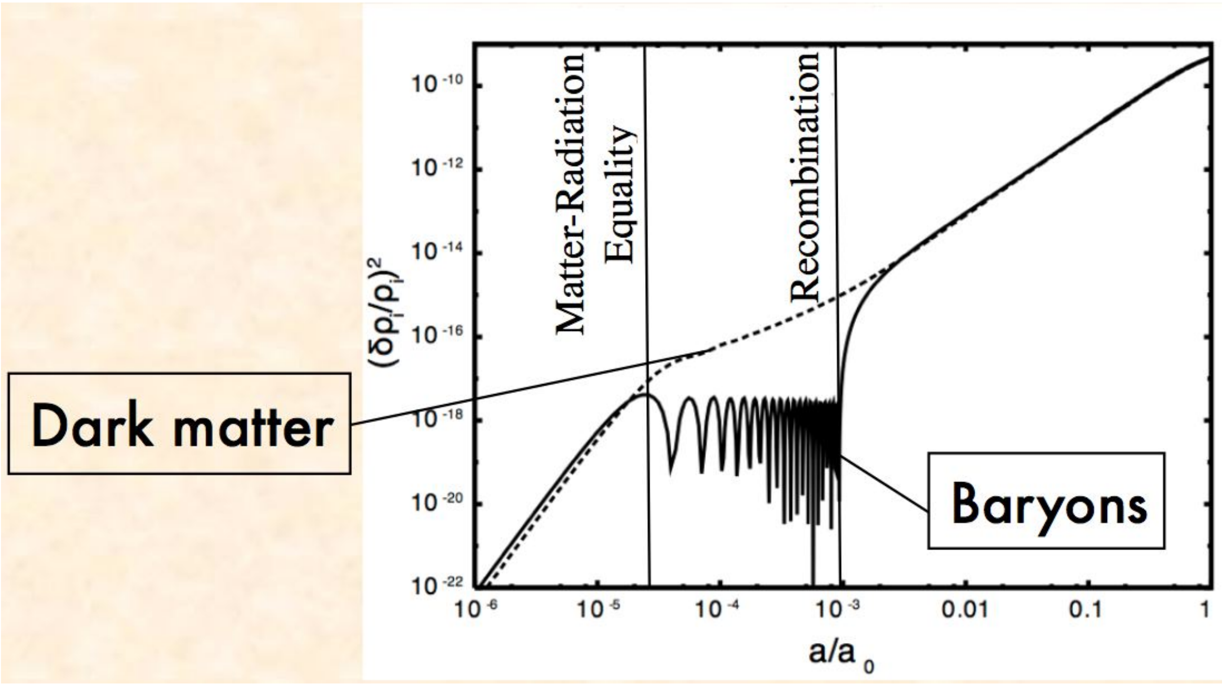
  Collissions would also erase small scale structures (which may be welcome). This is why Spergel & Steinhardt 2000 proposed self-interacting dark matter (SIDM) with $\sigma \simeq (m/\mathrm{GeV})(\mathrm{Mpc}/\lambda_{mfp})$ barns

- **Cold or Warm, thus not included in the Standard Model of EP**

- We need new particle candidates with the **right relic abundance** $\leq \Omega_{DM}$ (but not necessarily calculated with the "STANDARD" pre-BBN era assumptions) BBN is the earliest episode from which we have data. Before T= 4MeV we make assumptions about the Universe!

Dark Matter is needed for Structure Formation

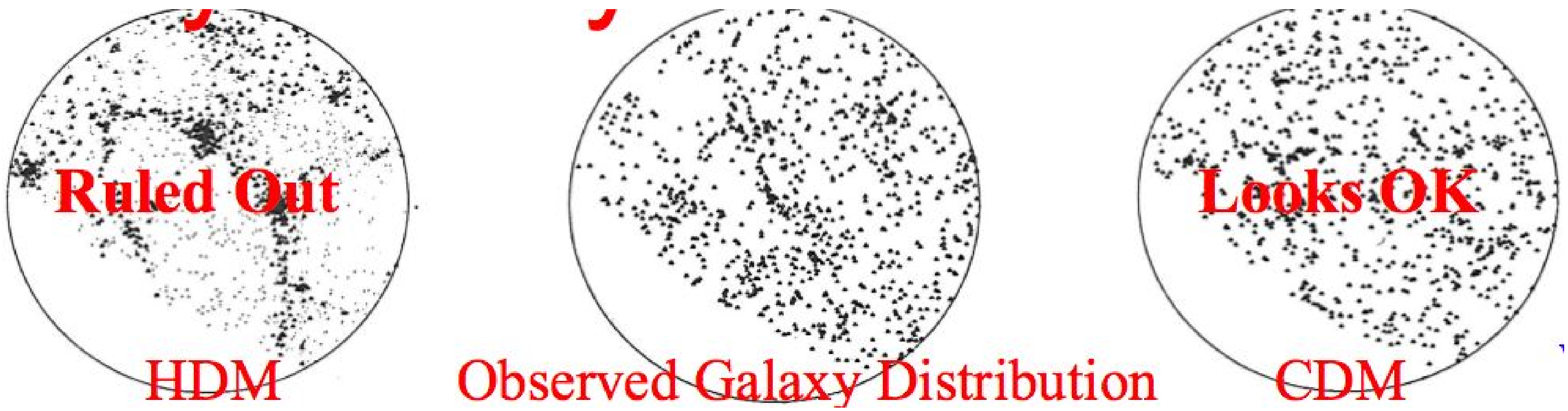
Structure in baryons cannot grow until "recombination" -(before: photon pressure in plasma).Baryons must fall into potential wells of DM, or not enough time for structures to form: in Matt-Dom Universe $(\delta\rho/\rho)_m \sim a$ could go from 10^{-5} to 10^{-2} but need > 1



Dark Matter: is “cold” or “warm”

Hot DM(HDM): relativistic when a galactic size perturbations enter into the horizon $ct_U = \lambda_{Galaxy}$ $(T \sim 1keV)$

Thus galaxy size inhomogeneities do not survive. If dominant, superclusters would form first (1986, Simon White) and later galaxies through fragmentation. But, not enough time to do so.“top-bottom” scenario fails.



Dark Matter is "Cold" or "Warm"

DM cannot be Hot DM(HDM): i.e relativistic when galactic size perturbations enter into the horizon, $ct_U = \lambda_{Galaxy}$ which happens when $T \sim 1keV$

Warm DM (WDM): is semi-relativistic when $T \sim 1keV$

Cold DM (CDM): is non-relativistic when $T \sim 1keV$

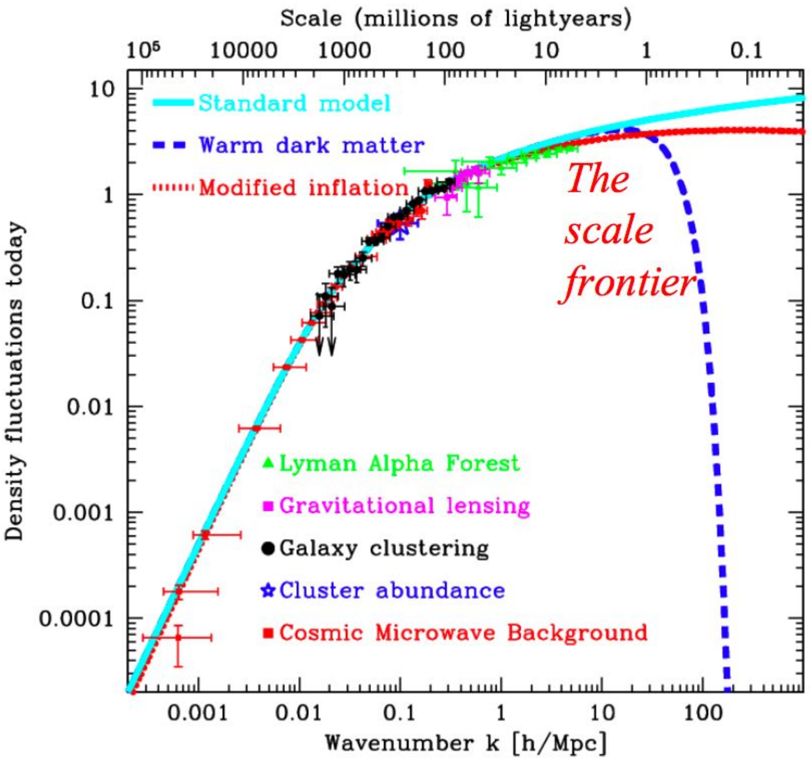
With WDM inhomogeneities of dwarf-galaxy size and larger survive.

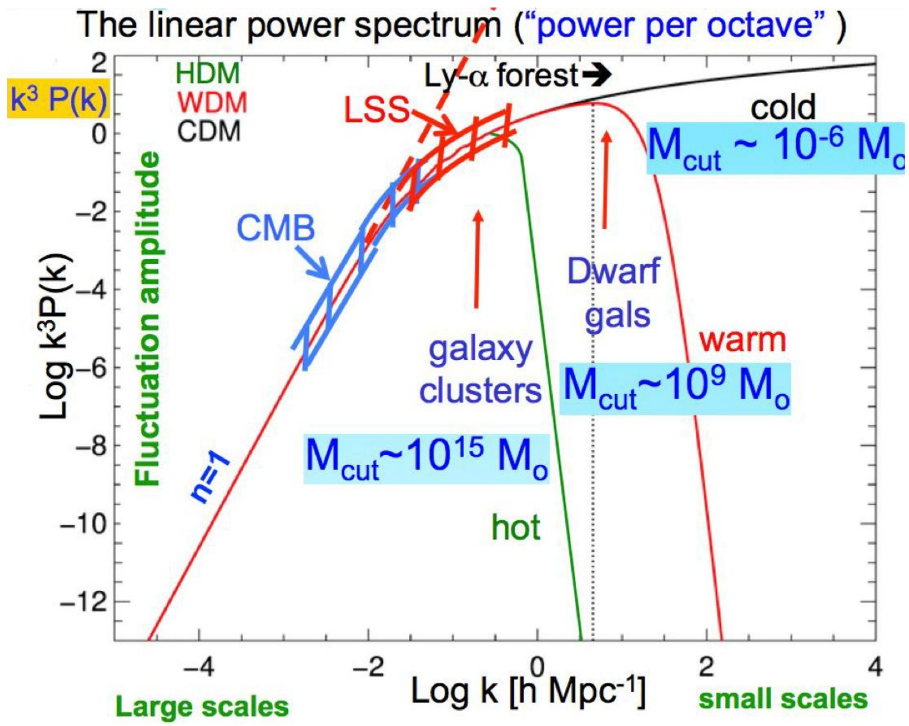
With CDM inhomogeneities much smaller than galaxy size survive. Galaxies and clusters form "bottom-up", by coalescence of smaller structures which form first. Some of the small structures remain in the larger ones (DM mini-haloes within galactic haloes).

"Double-Dark" model works well with CDM or WDM above galactic scales, distinction at sub-galactic scales

Fig: from Tegmark ("Standard model" with ΛCDM: with Cold DM)

Fig: from Carlos Frenk

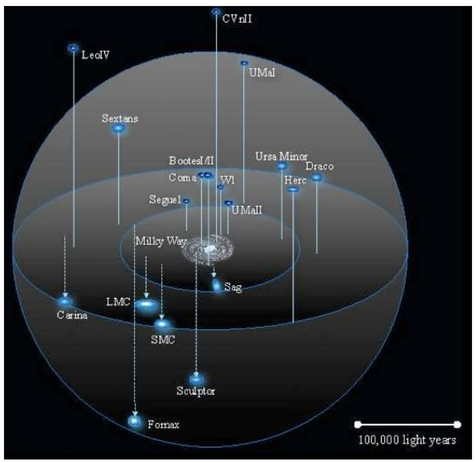


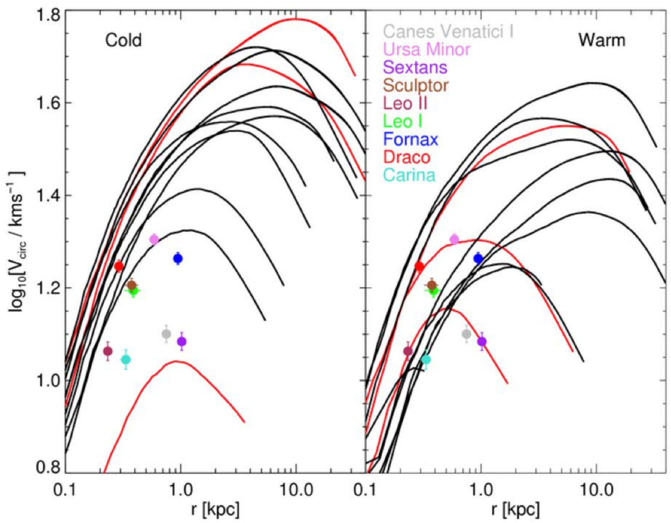


Potential problems for CDM in Milky Way Dwarf Galaxies

Very high resolution simulation (with only DM) find massive dense subhaloes **"too big to fail"** to form lots of stars, but none of the observed satellites of the Milky Way or Andromeda have stars moving as fast as would be expected in these densest sub-halos. Lovell et al. '11 and 12;

Fig: from Carlos Frenk





CDM rejected unless effect of baryons is important, or Milky Way mass $< 0.8 \times 10^{12} M_\odot$ (rather than 2×10^{12} $M_\odot$) Vera-Ciro et al 1202.6061; Wang teal 1203.4097

Otherwise: wither WDM or velocity dependent DM self interactions with huge $\sigma_{self}/m \simeq 0.1$ to 1 barn/GeV (^{235}U-n cross section is a few barns!)

No CDM or WDM particle candidate in the SM!

Only DM in the SM are active neutrinos, which are light $m <$ eV's and are in equilibrium at $T \simeq 1$ MeV thus they are Hot Dark Matter

But many in extensions of the SM!

Warm dark matter (WDM):

- sterile neutrinos, gravitinos, non-thermal WIMPs

Cold dark matter (CDM):

- "axions", WIMPs (Weakly Interacting Massive Particles) which require a quantum number to stabilize them. i.e. LSP or variants LKP, LZP, LTP (or many others), gravitinos, WIMPZILLAs, solitons (Q-balls) and many more

Particle DM requires new physics beyond the SM!

Very little for sterile neutrinos, more for axions (needed for QCD) and much more for WIMPs . . .

WIMPs require new physics at the EW scale

New physics is expected at O(TeV) scale because of Spontaneous Symmetry Breaking arguments (totally independently of the DM issue) BSM models such as Supersymmetry, Technicolor, large extra spatial dimensions (possibly warped), "Little Higgs" model... which provide the main potential discoveries at the LHC and also DM candidates mostly WIMPs: LSP, Lightest Technibaryon, LKP (Lightest KK Particle) or LZP (in Warped SO(10) with Z3), LTP (Lightest T-odd heavy γ in Little Higgs with T-parity)

But the new physics to explain DM may be different....,

many new models trying to account for "hints" of light WIMPs in several dark matter searches e.g. "secluded" or "intermediate state" models with DM charged under a broken hidden gauge symmetry and interacting with the SM through a light boson ("dark photon")...

Made to fit DM-not to solve the EW hierarchy (attest to the ingenuity of theorists to explain everything)... may provide novel signatures for the LHC

DM Relic abundance

- “Thermal”: particles produced via interactions with the thermal bath, reach equilibrium and then decouple or “freeze-out”

- “Non-thermal”: particles produced via the decay of others, which may or may not have a thermal abundance, or they decay into others

Let us review the thermal relic abundance first

Equilibrium

Chemical Equilibrium: particle number reaction rate is fast,
Kinetic Equilibrium: momentum exchange reactions are fast

T is decreasing at a rate $\dot{T}/T = -\dot{a}/a = -H$ and reaction rates must exceed the rate of change of T to maintain equilibrium

$$\Gamma > H \text{ or } t_{Reaction} \simeq 1/\Gamma > t_U \simeq 1/H$$

$(m << T)$ Relativistic equilibrium number density: (g_i= degrees of freedom-$g_\gamma = 2$)

$$n_i = \frac{g_i}{2}\frac{411}{cm^3}\left(\frac{T}{2.725^o K}\right)^3$$

$(m >> T)$ Non-Relativistic equilibrium number density: (Boltzmann distribution)

$$n_i = g_i\left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$$

$\Gamma(T)$ usually decreases faster than $H(T)$ as T decreases....

Decoupling

Chemical Decoupling or freeze-out: the number density is fixed. (per comoving volume, i.e. $n \sim T^3$)
Kinetic Decoupling: the exchange of momentum with the radiation bath ceases to be effective

When Γ decreases faster than H as T decreases,

at **Decoupling:**

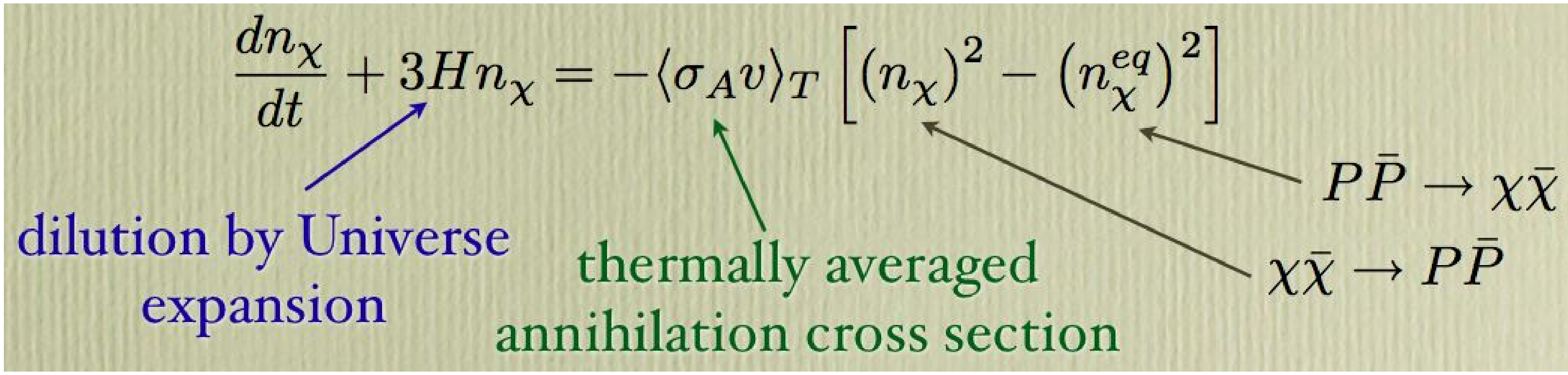
$$\Gamma(T_D) = H(T_D)$$

(and $\Gamma < H$ for $T < T_D$)

We need to know $H(T)$. In GR given by $H^2 = 8\pi G/3\rho - k/a^2 + \Lambda/3$, where $k = 0$ for a flat Universe and Λ is negligible in the early Universe

Actual calculation involves the Bolzmann Transport Equation:

Assuming no particle-antiparticle asymmetry, i.e. $n_\chi = n_{\bar\chi}$



expansion: $n \sim a^{-3} \to \frac{dn}{dt} = -3\frac{\dot a}{a}n = -3Hn$
annihilation: $n \sim e^{-t/t_A}$ thus $\frac{dn}{dt} = -n/t_A$, $t_A \simeq \lambda_{M.F.P}/v = 1/\sigma_A n v$
creation: stop expansion at T, wait for equilibrium so $\frac{dn}{dt} = 0$

χ freeze-out when $\Gamma_A(T_{f.o.}) = \langle\sigma_A v\rangle_{T=T_{f.o.}}\, n^{eq}(T_{f.o.}) \simeq H$

Bolzmann Transport Equation and the conservation of entropy

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{ann} v \rangle \, (n^2 - n_{eq}^2) \qquad\qquad \frac{ds}{dt} = -3Hs$$

where $s = \frac{2\pi^2}{45} g_{s-eff}(T)\, T^3$ is the entropy density and T the photon temperature can be combined into a single equation for $Y = n/s$, and use $x = m/T$ (Kolb & Olive Phys Rev D33,1202,1986; Kolb&Turner book, Gelmini&Gondolo 1009.3690 and refs therein)

$$\frac{dY}{dx} = \frac{1}{3H} \frac{ds}{dx} \langle \sigma v \rangle \, (Y^2 - Y_{eq}^2)$$

When $g_{s-eff}(T)$ is approximately constant then we get,

$$\frac{x}{Y_{eq}} \frac{dY}{dx} = -\frac{\Gamma_A}{H} \left[\left(\frac{Y^2}{Y_{eq}^2} \right) - 1 \right] \qquad\qquad \Gamma_A = n_{eq} \langle \sigma v \rangle$$

Thus when $\Gamma/H << 1$ the number per comoving volume $(Y \simeq n/a^3)$ becomes constant.
(Problem 1.a: cast the Boltzmann eq. in this form, 1.b: assume an asymmetry $Y_\chi - Y_{\bar{\chi}} = A$)

Decoupling of Relativistic Particles $m < T$ (active neutrinos)

Back-of-an-envelope calculation (litterary!) (This is Problem 2)

At decoupling

$$\Gamma \simeq n\sigma c \simeq G_F^2 T_{fo}^5 = H = \sqrt{\frac{8}{3}\pi G\rho} \simeq \frac{T_{fo}^2}{M_{Planck}}$$

putting numbers in, this emplies

$$T_{fo} \simeq MeV$$

Recall, the Fermi constant $G_F \simeq 10{-}5/$ GeV^2

Gravity const. $G \simeq 1/M_{Planck}^2$, $M_{Planck}^2 \simeq 10^{19}$GeV. RD Universe: $\rho = \rho_{rad} \sim T^4$.

This is when BBN is happening, and we have data on the Universe then.

(Since $n_{EQ} \sim T^3$ the frozen species still tracks the equilibrium density. Just after e^+e^- annihilate, heat-up γ's $T_\nu = (4/11)^{1/3}T$ and $n_{\nu_i} = (3/4)(T_\nu/T)^3 n_\gamma$)