Dark Matter
Part 1

Graciela Gelmini - UCLA

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Content Part 1: Lectures 1 to about 3:

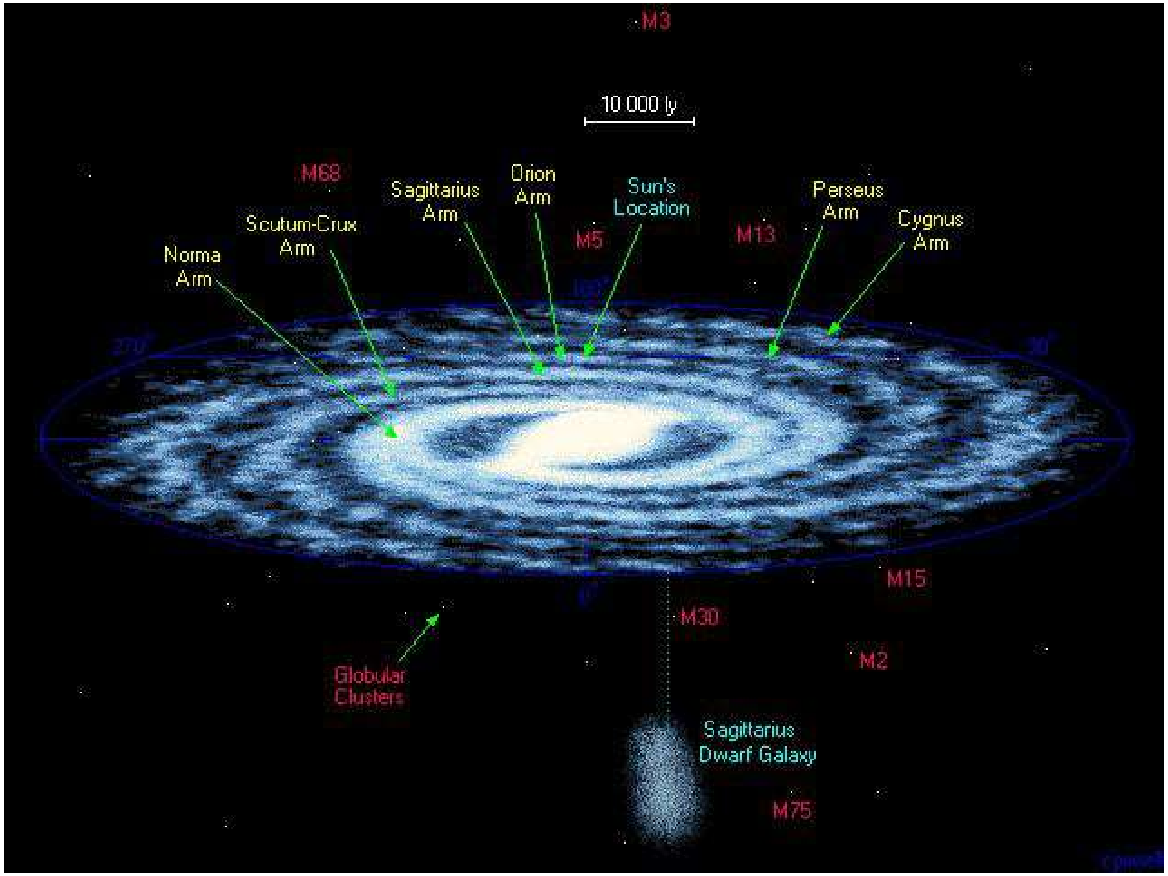
- Brief review of the observational evidence for Dark Matter (DM)
- What we know about DM and implications for DM candidates (PBH or particles? CDM, WDM, PIDM, DDDM, SIDM? Millicharge DM, kinetic mixing, Hidden (or Dark) Photons (HP or DP), Atomic DM, Mirror DM, WIMPs, FIMPs, SIMPs, ELDERs, Axions, ALPs, WISPs, FIPs...)
- Some DM production mechanisms for particle DM (freeze-out in std. and non-std pre-BBN cosmologies, freeze-in..)

Part 2: Lectures 3 to 5: Somewhere in lecture 3 we will start with

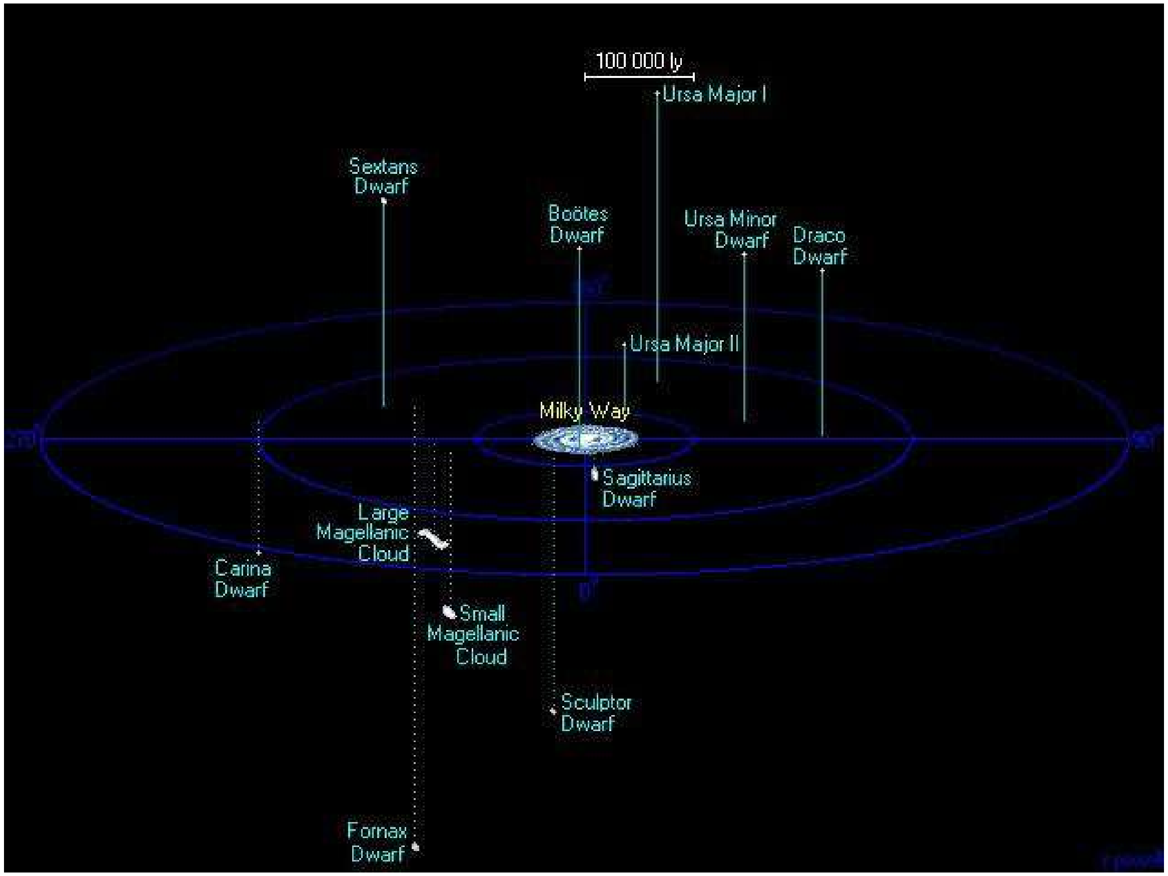
- DM laboratory and indirect searches of sterile neutrinos, WIMPs/LightDM/FIPs, and axions/ALPs

Disclaimer: idiosyncratic choice of subjects and not complete lists of citations

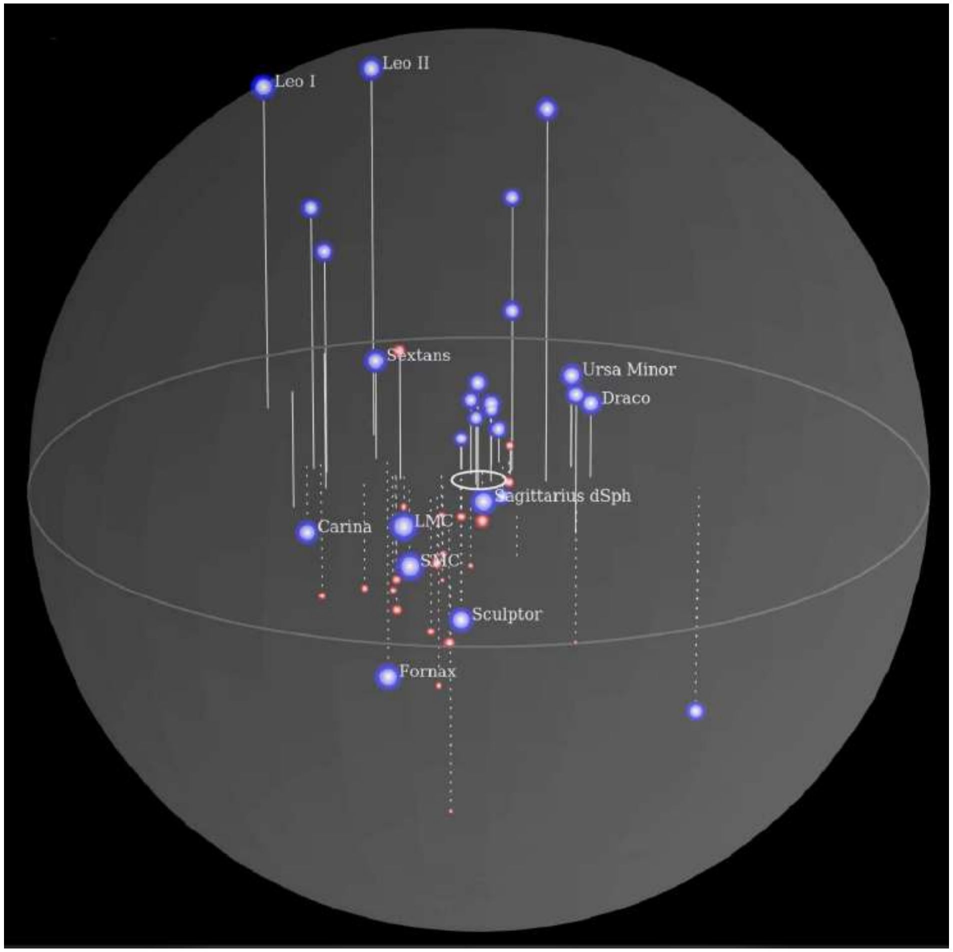
The Universe around us: Galaxies are the building blocks of the Universe. The Milky Way and the Sagittarius Dwarf galaxy its nearest satellite galaxy



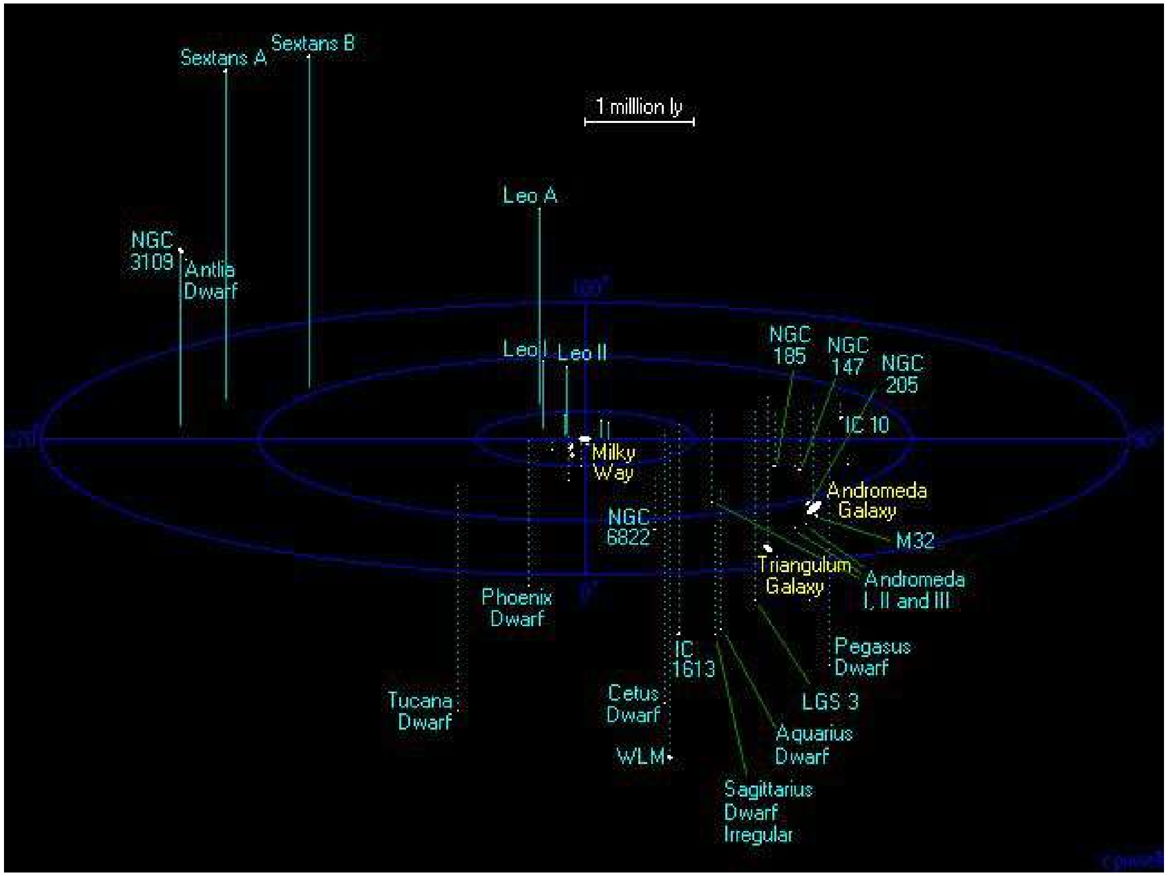
The Milky Way has many small satellite galaxies about 60 dwarf galaxies have been found so far



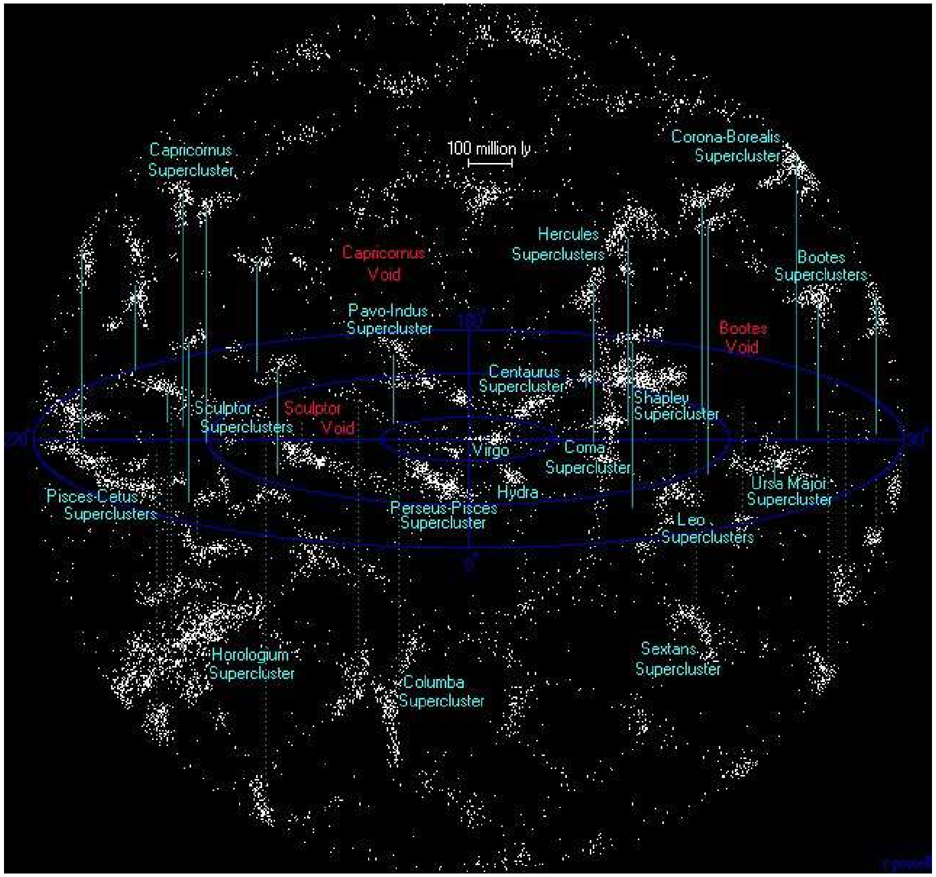
The Milky Way has many small satellite galaxies- dwarfs as of 2016 (in red DES)



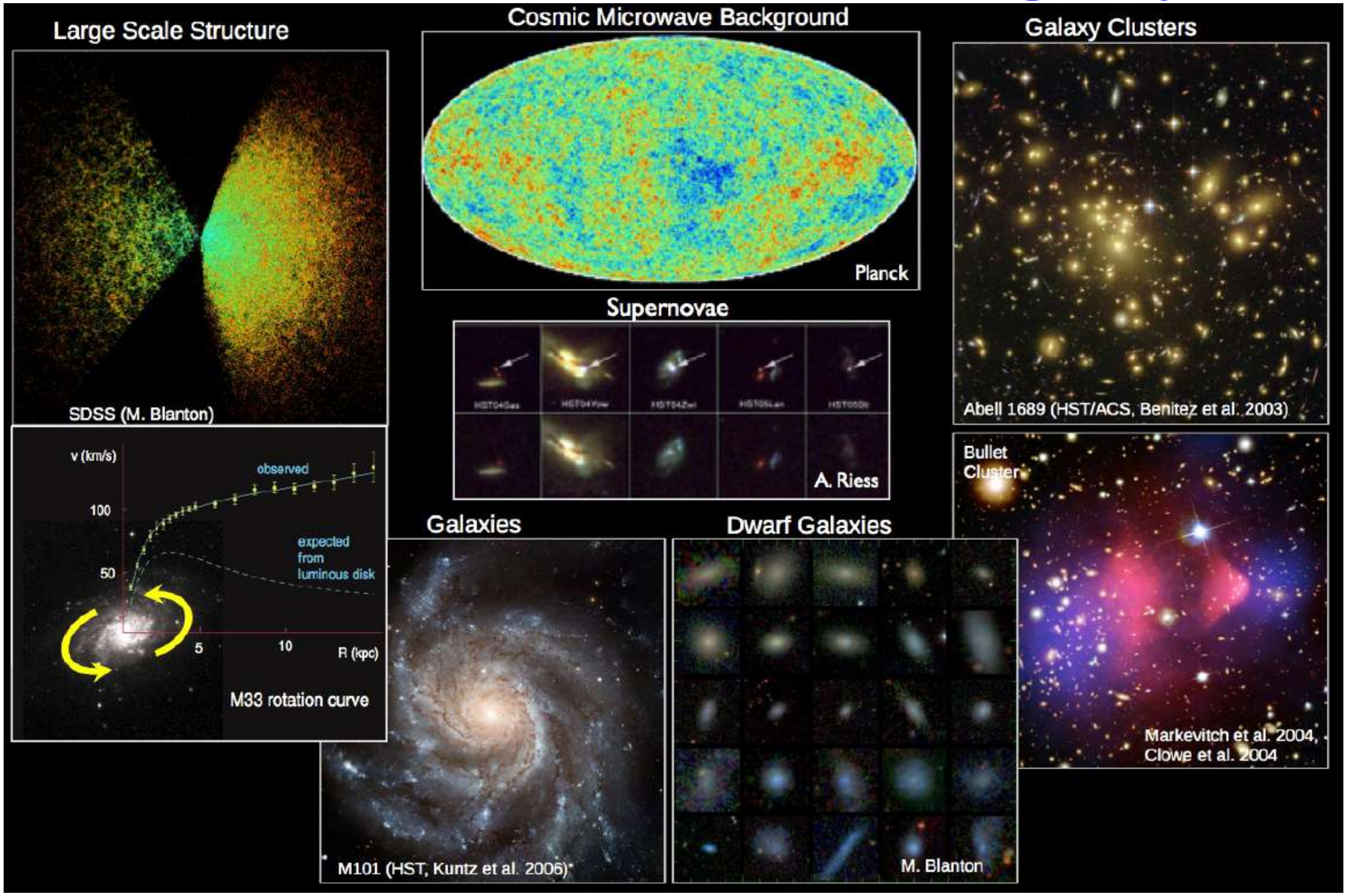
Galaxies come in groups, clusters, superclusters......Our Local Group of galaxies



Galaxies are the building blocks of the Universe: they come in groups, clusters, superclusters (which form “filaments, walls and voids”)



DM dominates all structures from dwarf galaxy scales on



The Dark Matter problem has been with us since 1930's,

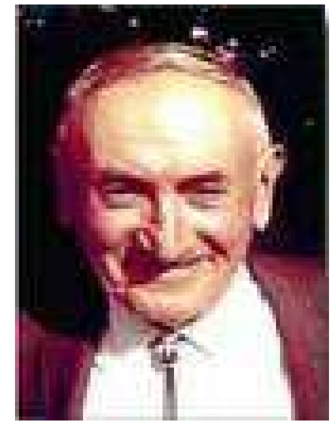
e.g. Fritz Zwicky, Helvetica Physica Acta Vol6 p.110-127, 1933

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.



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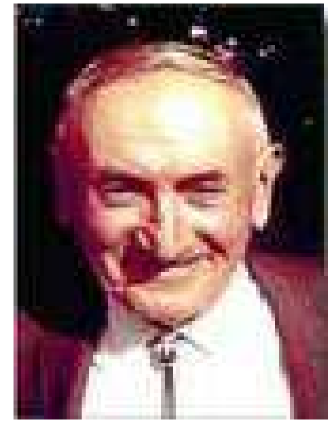
gr/cm^3. Es ist natürlich möglich, dass leuchtende plus **dunkle (kalte) Materie** zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\bar{\varrho} \sim 10^{-28}$ gr/cm^3 erscheint daher nicht

Dark Matter discovered



In 1930's Fritz Zwicky found one of the first indications 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

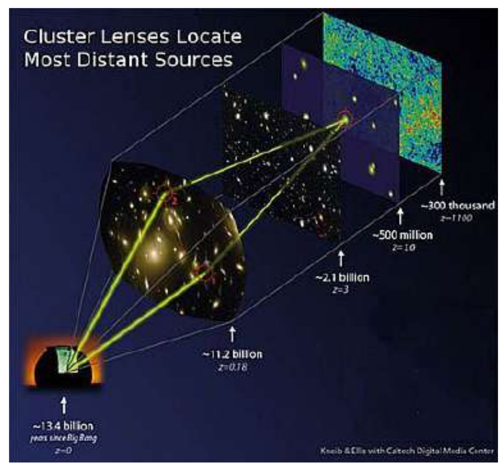
Example Virial Theorem: for planets $\dfrac{GM_\odot m}{r} = mv^2$

|Gravitational Potential Energy|=2×Kinetic Energy

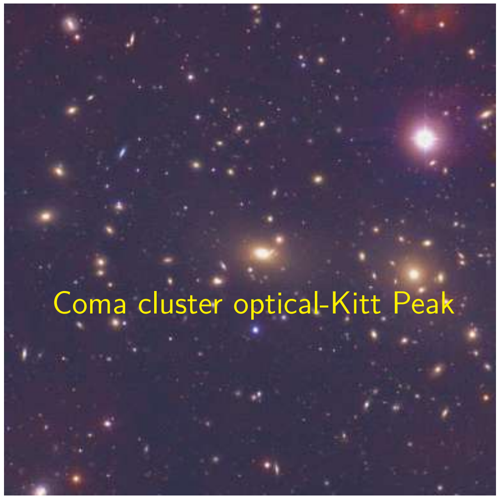
Later: also gas in clusters moves too fast (is too hot - as measured in X-rays) to remain in it, unless there is DM.

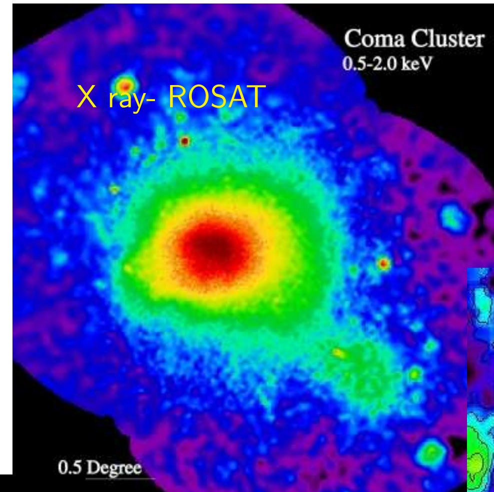
Another later method:
gravitational lensing

depends on all the intervening mass

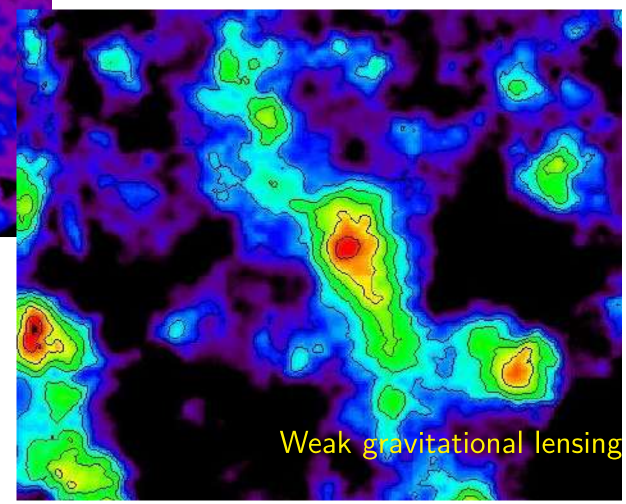


DM dominates in galaxy clusters



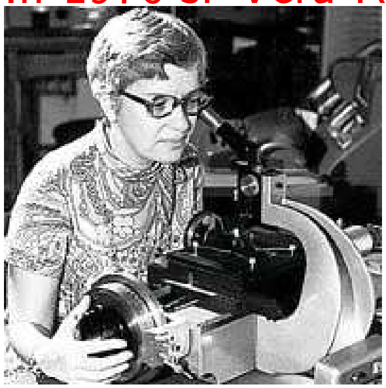


$$\boxed{\frac{M}{M_{\rm vis}} \simeq 6}$$



Dark Matter rediscovered

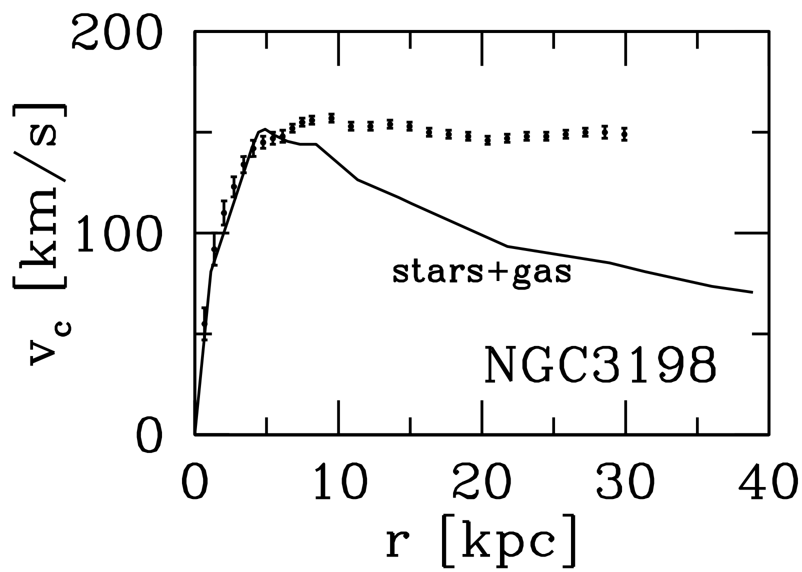
In 1970's: Vera Rubin and others found rotation curves of galaxies ARE FLAT!



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

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

even where there is no light!



(1 pc = 3.2 ℓy)

Dark Matter dominates in galaxies

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

$$M_{\text{stars+gas}} = 0.4 \times 10^{11} M_\odot$$

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

Galaxies like ours have a Dark Halo which contains about 85% of its mass

At the largest scales:

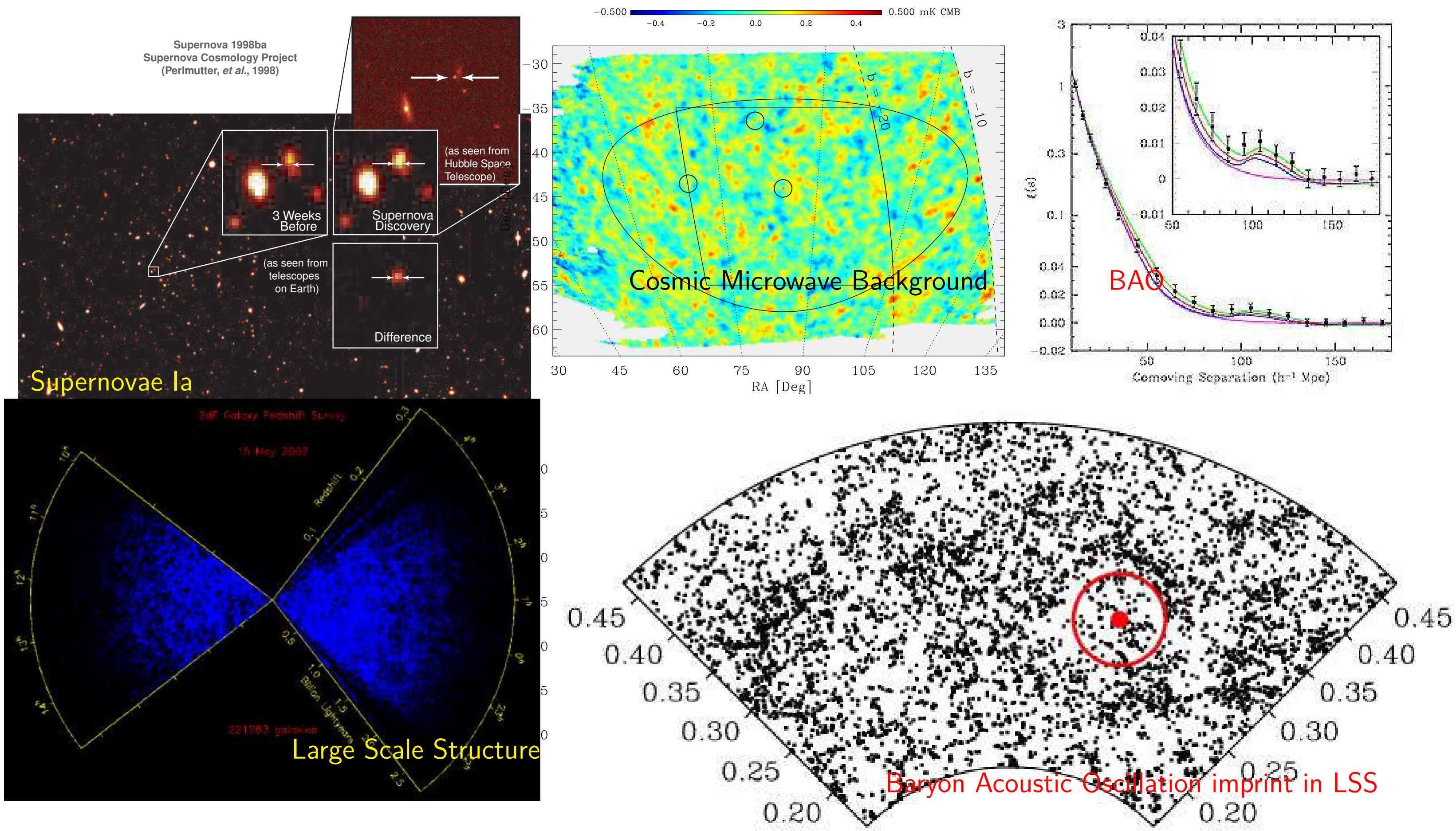
Use General Relativity

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

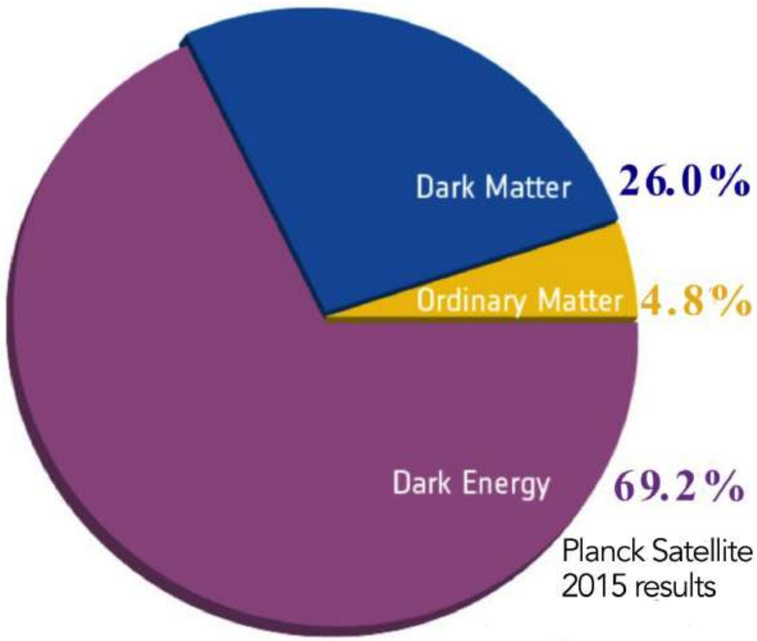
To relate:

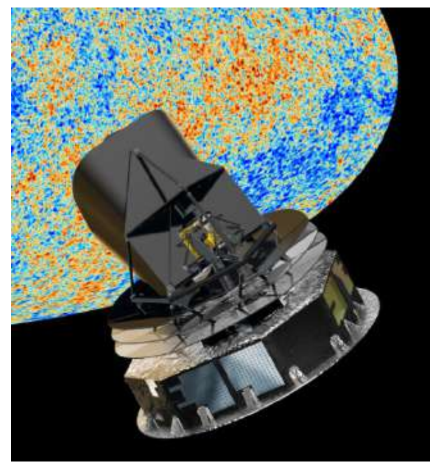
Spacetime geometry $\longleftrightarrow$ **Mass-energy density**

At the largest scales



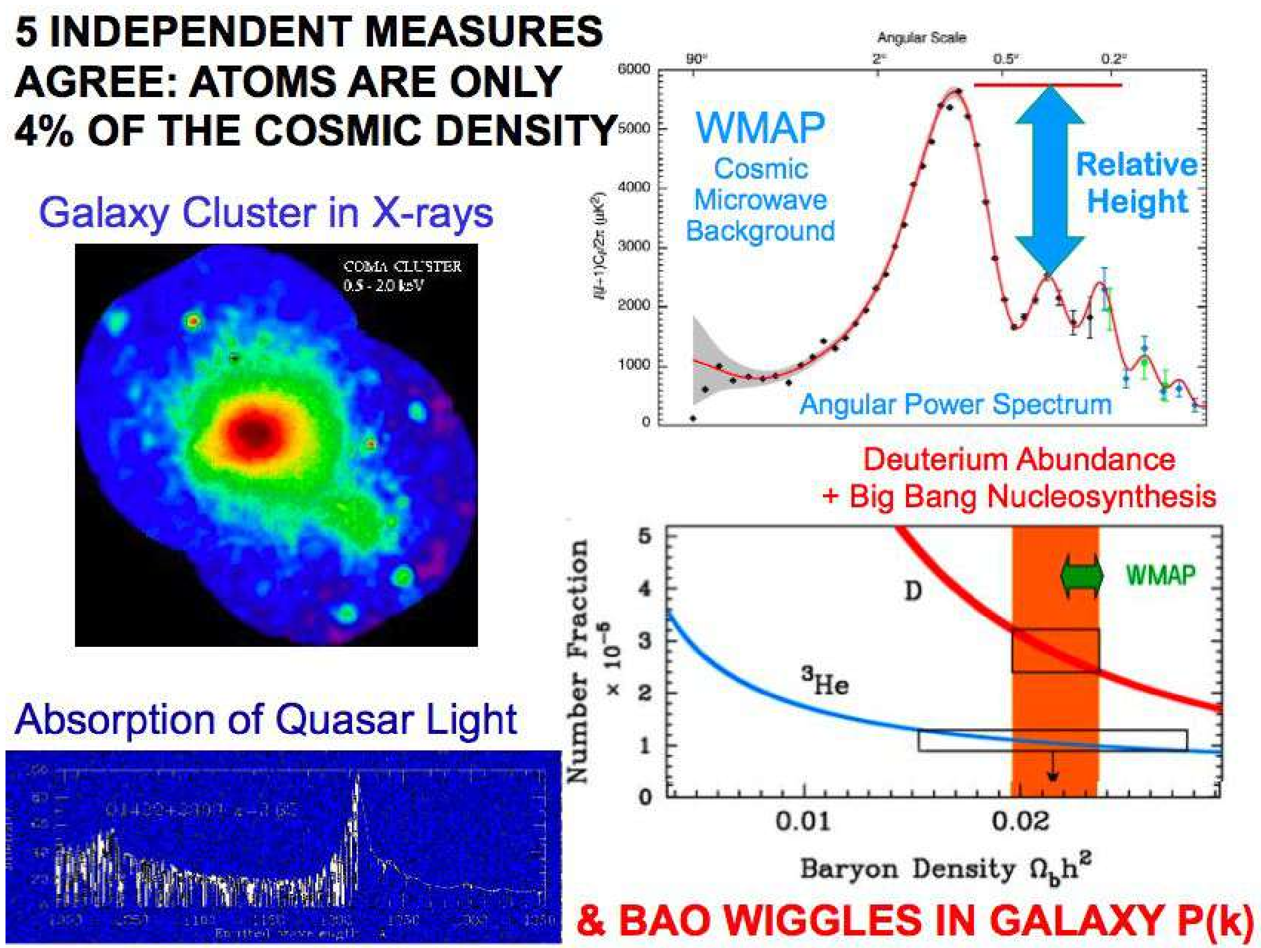
At the largest scales: the “Double-Dark” model





“DARK ENERGY” 69% (with repulsive gravitational interactions)
“MATTER” 31% (with usual attractive gravitational interactions- forms gravitationally bound objects) and most of it is **“DARK MATTER” 26%**

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



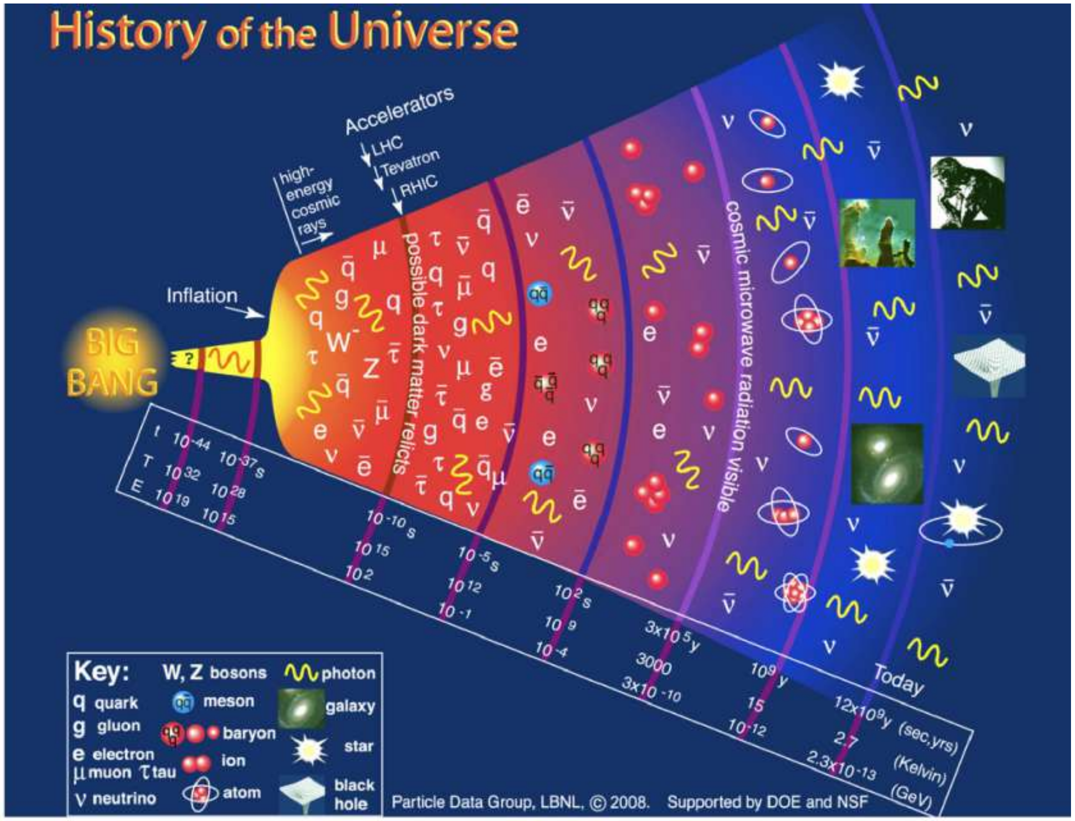
All data confirm the Big-Bang Model of a hot early Universe expanding adiabatically (T decreases inversely to the size of the Universe T$\sim 1/a$)

Earliest data (D, ^{4}He and ^{7}Li):
BBN (Big-Bang Nucleosynthesis)
t$\simeq$3-20min T$\simeq$MeV (blue line)

Radiation domination to Matter domination
t$\simeq$100kyr T$\simeq$3 eV

CMB emitted (atoms form)
(Cosmic Microwave Background)
t$\simeq$380kyr T$\simeq$eV

Now (Planck + other)
t=13.798$\pm$ 0.037$\times 10^9$ys



INFLATION

period of exponential expansion $a \sim e^{Ht}$ invoked to explain properties of the Universe not explained by the Big-Bang model such as

(a: scale factor of the Universe such that all linear scales $\lambda(t) = a(t)\lambda_{\rm present}$, $a_{\rm present} = 1$, $H = \dot{a}/a$: Hubble expansion rate),

- Homogeneity and isotropy: why parts of the Universe at distances larger than ct$_U$, never in physical contact otherwise, are very similar.

- The origin of the density inhomogeneities (as quantum fluctuations) leading to CMB anisotropies, structure formation in the Universe and BAO.

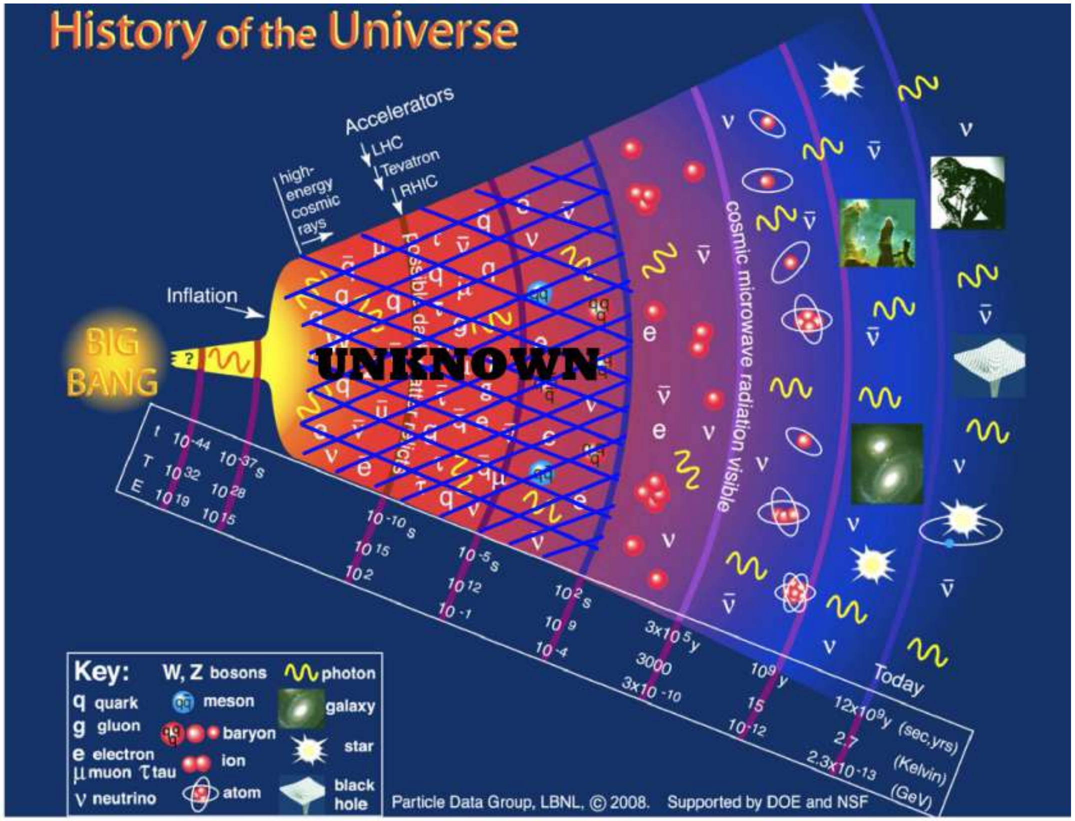
After it finishes, "reheating" produces a Radiation Dominated Universe with temperature $T_{\rm RH}$, expanding adiabatically.
Not possible to determine what T_{RH} is, except for $T_{RH} >$5 MeV!

All data confirm the Big-Bang Model of a hot early Universe expanding adiabatically (T decreases inversely to the size of the Universe T$\sim 1/a$)

Earliest data (D, ^{4}He and ^{7}Li):
BBN (Big-Bang Nucleosynthesis)
t $\simeq$3-20min T$\simeq$MeV

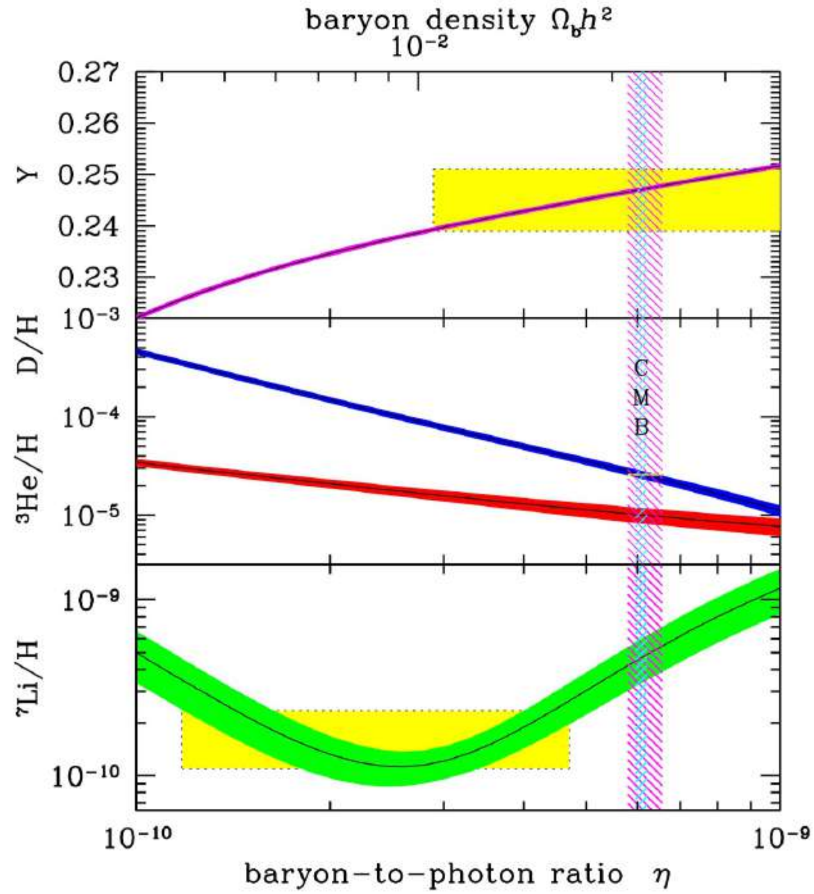
Cosmology before T$\simeq$5 MeV is UNKNOWN
De Salas et al 2015; Hasegawa et al 2019; De Bernardis, Pagano Mechiorri 2008; Hannestad 2004; Kawasaki, Khori, Sugiyama 2000 and 1999

For DM produced in this pre-BBN era, **different viable cosmological assumptions imply different relic abundance and spectrum**



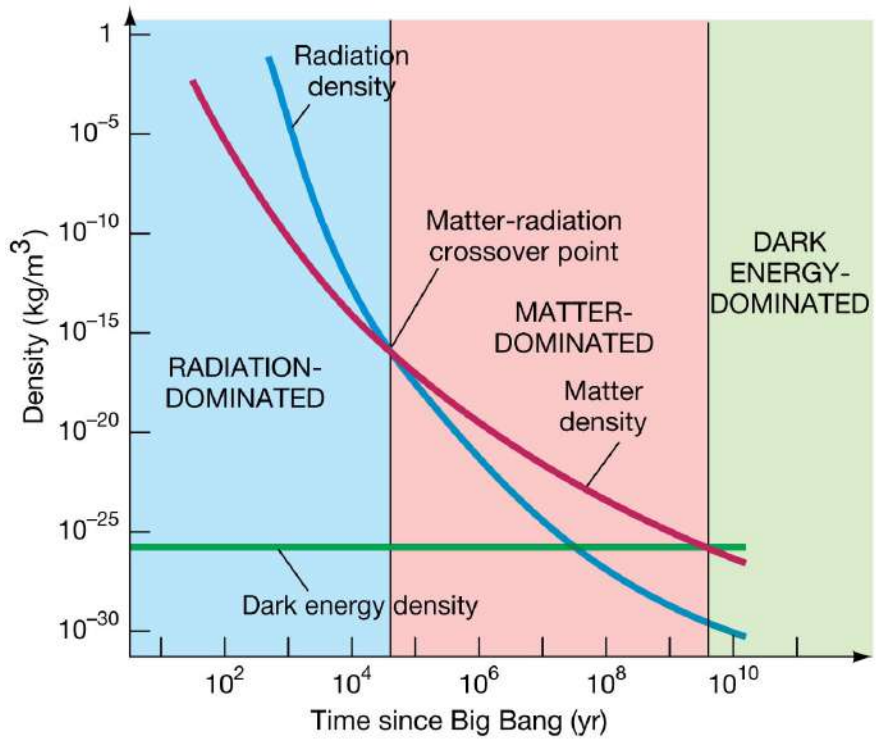
Big Bang Nucleosynthesis (BBN) $t \simeq$ 3-20min $T \simeq$MeV

Predicts the very different observed abundances of D, ^{4}He and ^{7}Li, the earliest relics



Radiation to Matter Domination t $\simeq$ 66 kyr T $\simeq$ 1 eV

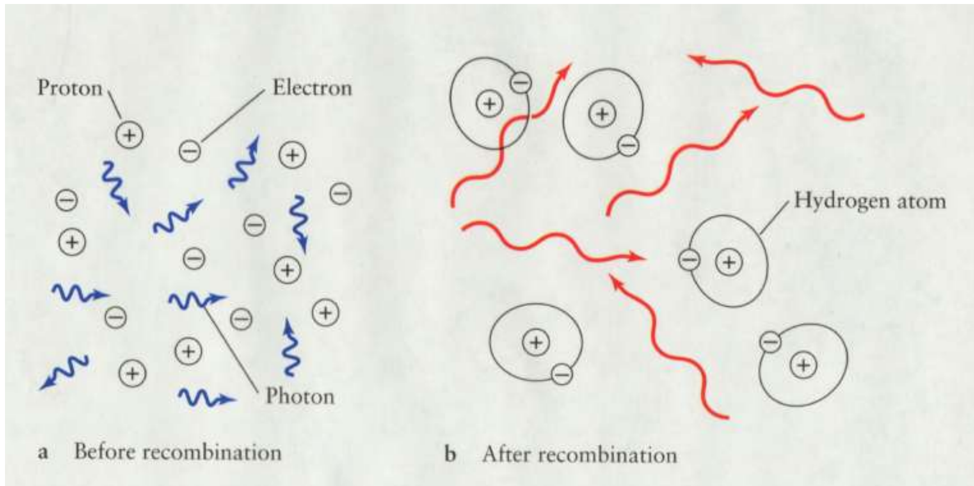
$$\rho_{rad} \sim T^4 \qquad \rho_{\rm m} = \frac{\text{Number} \times \text{Mass}}{\text{Volume}} \sim 1/a^3 \sim T^3$$



Now: DE dominates not matter, ρ_{DE} is constant.

Cosmic Microwave Background radiation t≃380 kyr T≃0.3 eV

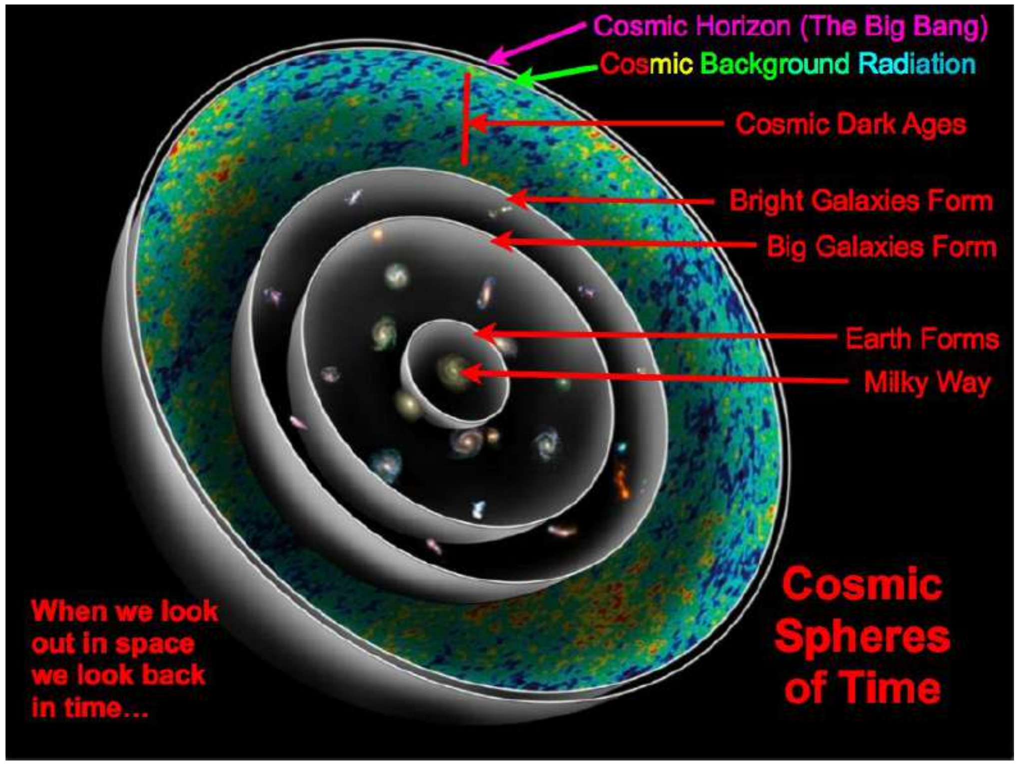
Emitted when atoms became stable for the first time, called "recombination"



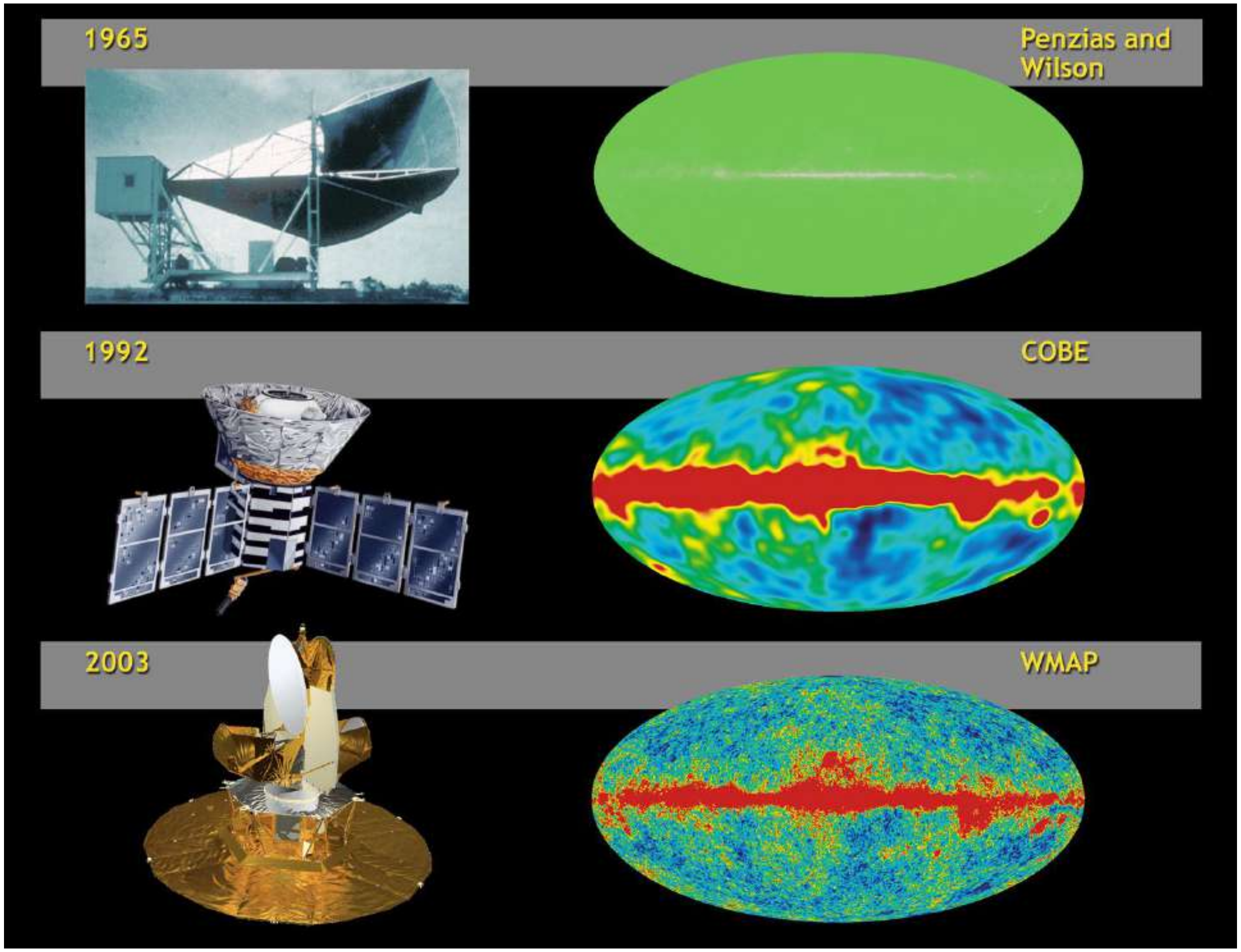
Due to the expansion of the Universe radiation cools to now (COBE, WMAP)
T$= 2.725 \pm 0.001^o$K$= 2.35 \times 10^{-4}$eV

"Recombination", is also called the "surface of last scattering" of the CMB....

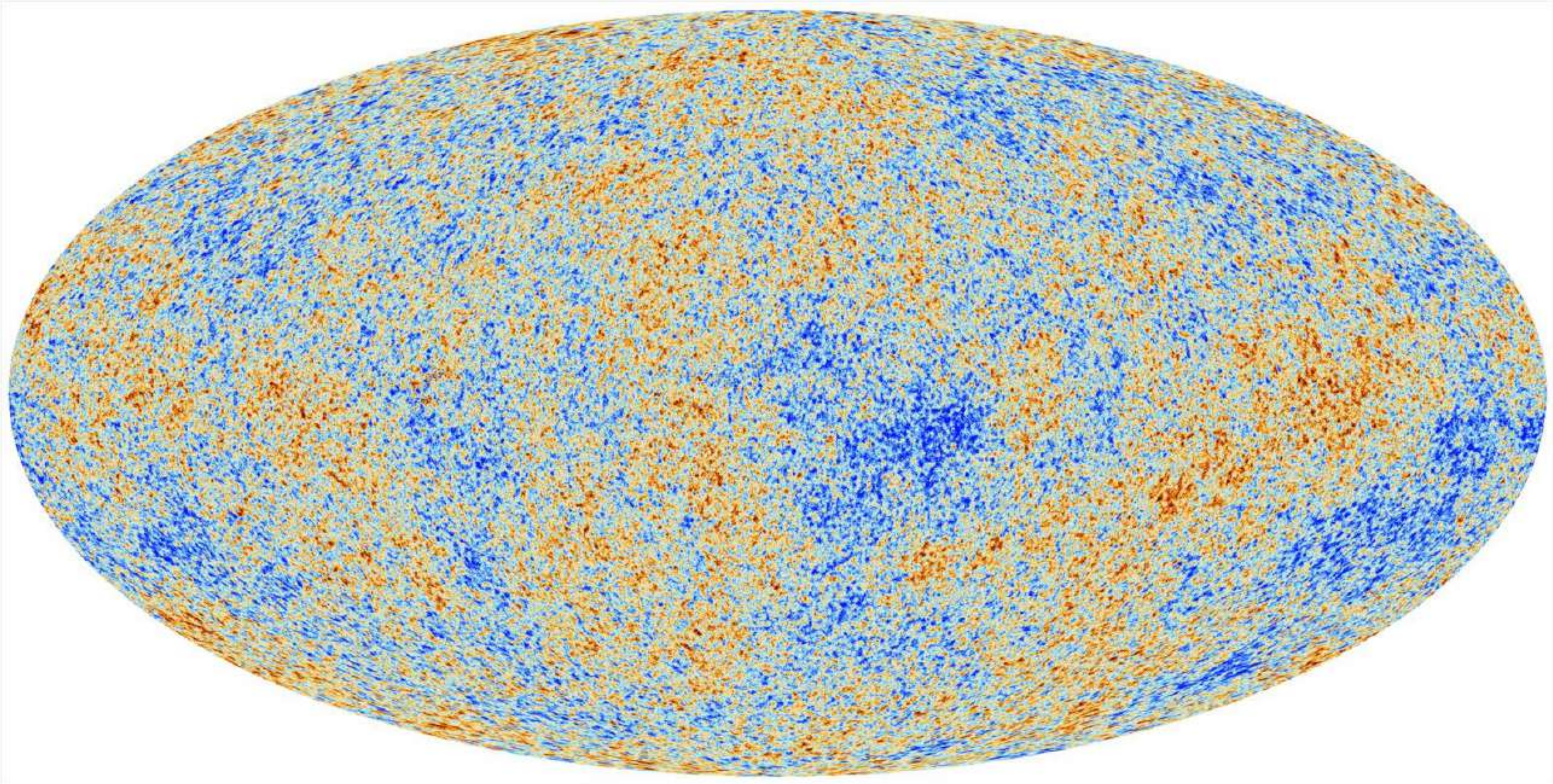
Far away is long ago We see galaxies within the distance light took to come to us since the first moment bright galaxies formed, before there was the "Cosmic Dark Age" with no stars, and before then we see the CMB emitted "recombination", when atoms became stable. Fig frm J. Primack



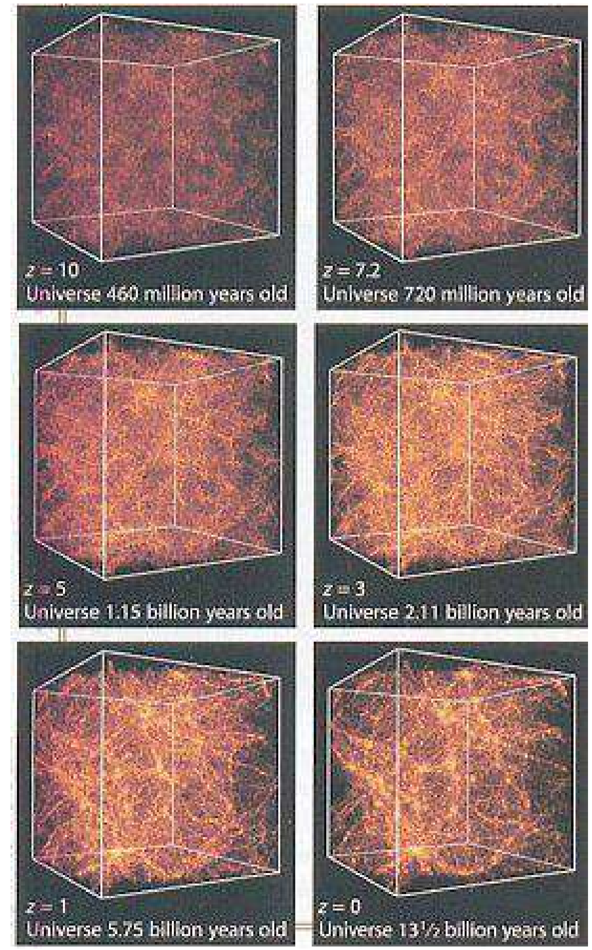
Cosmic Microwave Background radiation (CMB)



CMB anisotropies with PLANCK (2013) $(\delta T/T \simeq 10^{-4})$



Density inhomogeneities lead to CMB anisotropies and structure formation with BAO



At "recombination" small density inhomogeneities

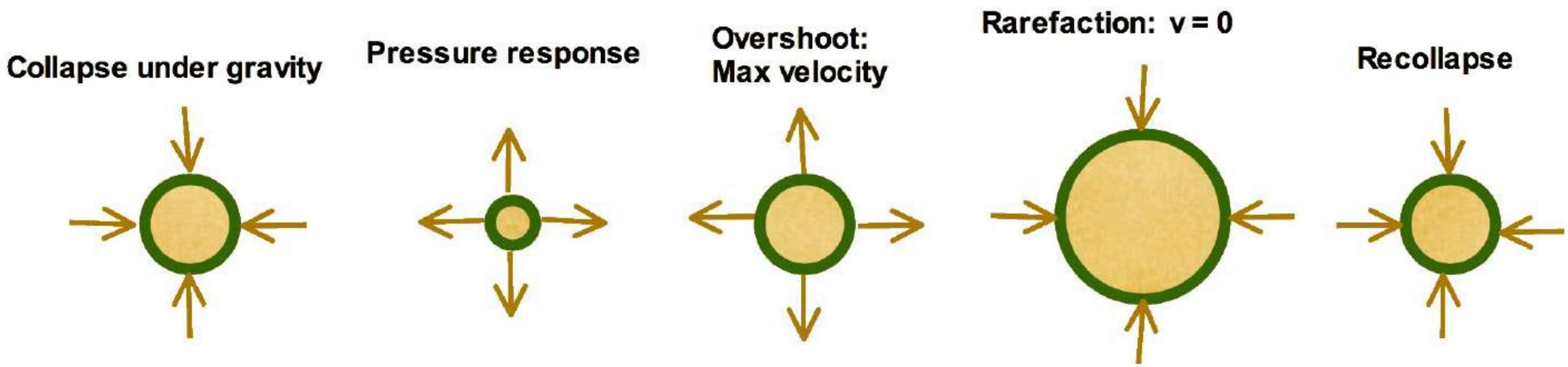
$$\frac{\delta\rho}{\rho} = \frac{\rho - \bar{\rho}}{\bar{\rho}} \text{ produce } \frac{\delta T}{T} \simeq 10^{-4}$$

due to standing pressure waves,

and structure through gravitational collapse

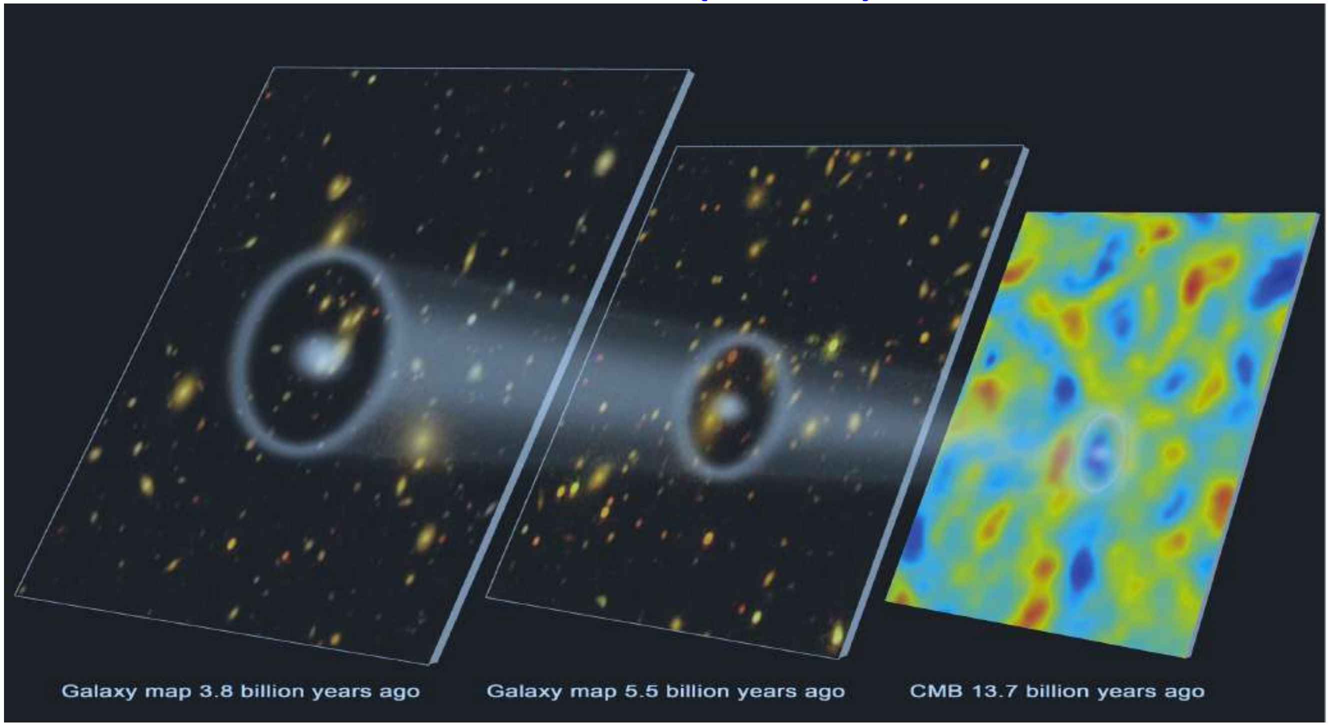
Pressure standing oscillations before recombination

Before recombination, gravity attraction + repulsion due to the pressure in the photon-electron-baryon plasma, produce standing waves, hotter compression zones and cooler rarefaction zones



When atoms become stable, photons escape (and reach us as the CMB radiation) and show us the hotter and cooler regions as CMB anisotropies and baryons remain in spherical shells of predictable radius which are seen as Baryon Acoustic Oscillations (BAO) in the Matter Power Spectrum (SDSS 2005, BOSS 2012)

Baryon Acoustic Oscillations (BAO)

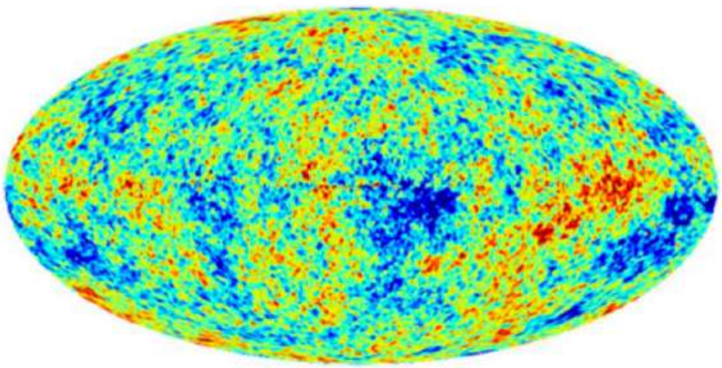


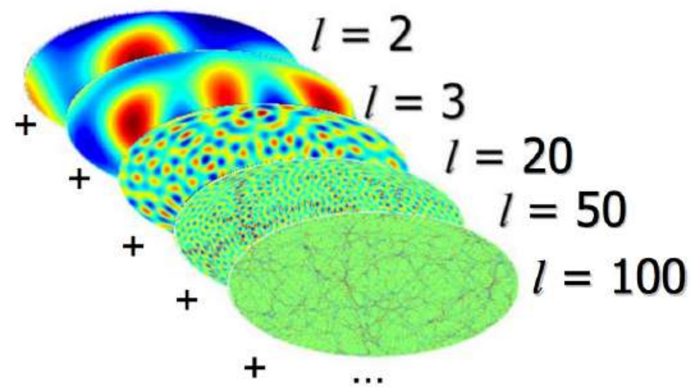
In a region with high initial density, there was high pressure in the baryon-photon fluid which propagated as an expanding spherical sound wave. After recombination the photons go off with speed c and baryons are left sitting in a spherical shell around the initial excess density of DM (part of the baryons fall back to the center attracted by the DM).

CMB Anisotropies Angular Power Spectrum

The amplitude of the fluctuations as function of scale is quantified by the Power Spectrum, $P(k)$ = square of the Fourier amplitude as function of k.
For functions on a sphere we use an expansion in Spherical Harmonics

$$\frac{\delta T}{T}(\hat{n}) = \sum_{\ell,m} a_{\ell,m} Y_{\ell,m}(\hat{n})$$



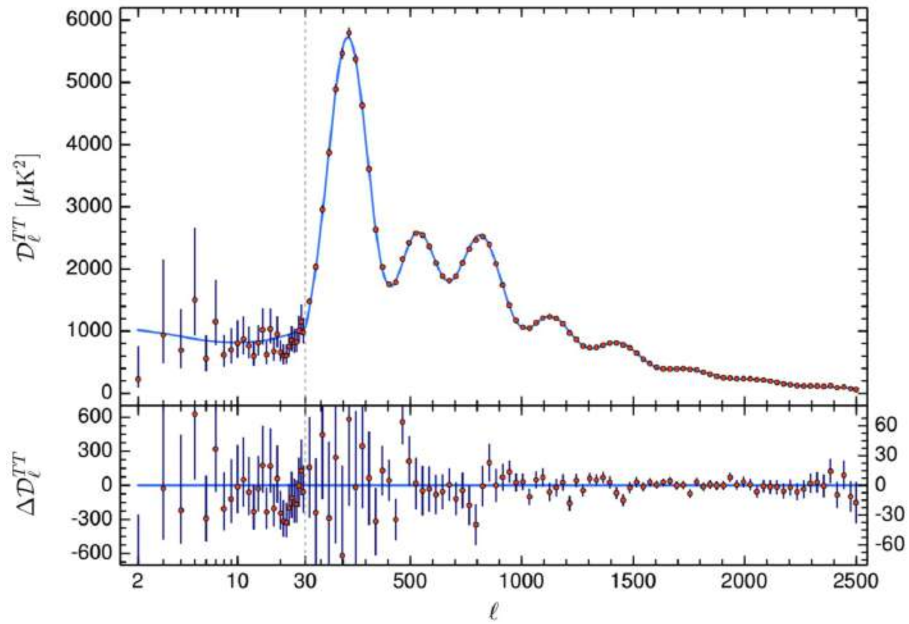


Location: $\hat{n}=(\theta,\phi)$, Angular Power Spectrum: $C_\ell = \dfrac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell,m}|^2$

CMB Anisotropies Angular Power Spectrum

C_ℓ also defines the T-T auto-correlation function ($P_\ell(\cos\theta)$: Legendre Polynomial)

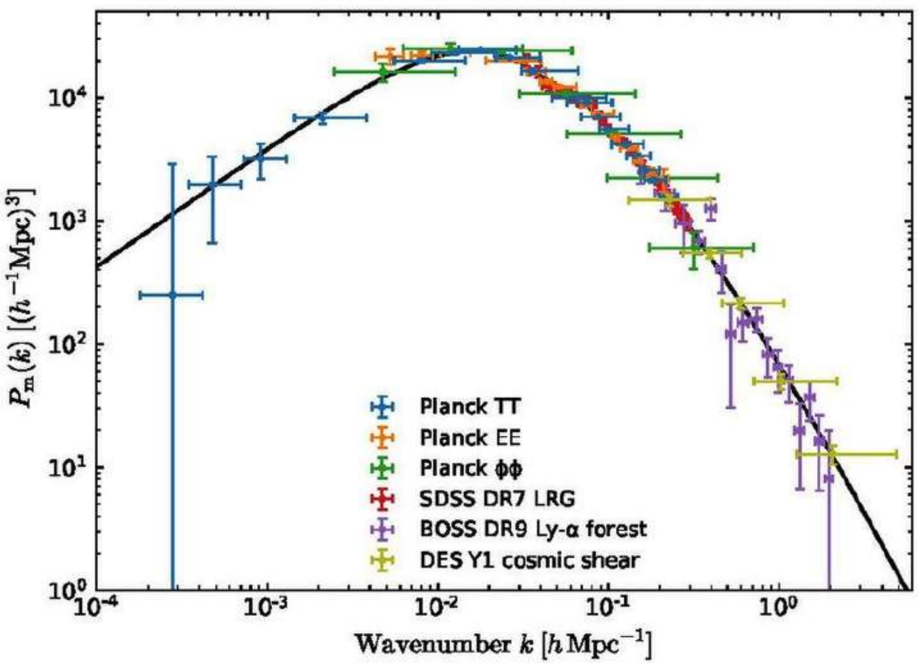
$$C(\theta) = \langle \frac{\delta T}{T}(\hat{n_1})\frac{\delta T}{T}(\hat{n_2})\rangle = \frac{1}{4\pi}\sum_\ell (2\ell+1)C_\ell P_\ell(\cos\theta)$$



After Planck: 7 peaks. Line: ΛCDM prediction. Angular features at $\Delta\theta \simeq 2\pi/\ell$ in degrees. 1st peak at $\Delta\theta \simeq 1^o \Longrightarrow$ Universe is spatially flat, $\Omega = \rho_{\rm total}/\rho_c = 1$

Matter Power Spectrum $P(k)$ - The wiggles are BAO

$$\frac{\delta\rho}{\rho}(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}, \quad \langle\frac{\delta\rho}{\rho}(\vec{x}_1)\,\frac{\delta\rho}{\rho}(\vec{x}_2)\rangle = \int \frac{d^3k}{(2\pi)^3} P(k)\; e^{i\vec{k}\cdot(\vec{x}_1 - \vec{x}_2)}$$



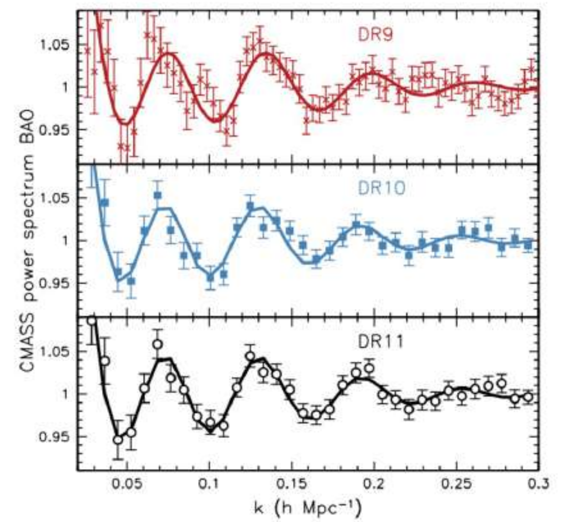


Figure 16. The CMASS BAO feature in the measured reconstructed power spectrum of each of the BOSS data releases, DR9, DR10, and DR11. The data are displayed with points and error-bars and the best-fit model is displayed with the curves. Both are divided by the best-fit smooth model. We note that a finer binning was used in the DR9 analysis.

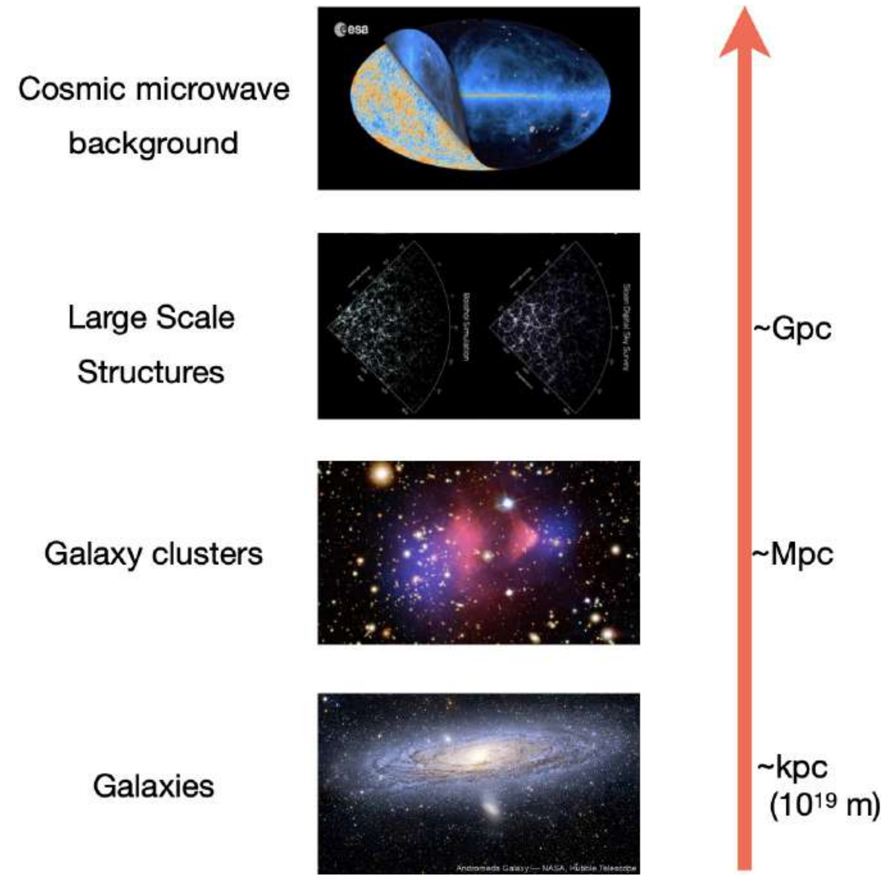
The role of DM is essential in explaining the CMB anisotropy spectrum, and the Large Scale Structure and BAO spectrum

After 90 years, what we know about DM:

- **1- Has attractive gravitational interactions and is stable (or has a lifetime $>> t_U$)**

- **2- So far DM and not modified dynamics + only visible matter**
  We have no evidence that DM has any other interaction but gravity. Could departures from the law of gravity itself explain the data instead of DM?

  Very difficult to account for all the DM effects, present and in the early Universe



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  From time to time models appear trying to replace DM- E.g. MOND "Modified Newtonian Dynamics" (Mordehai Milgrom,1983) and its covariant generalization "Tensor-Vector Scalar-TeVeS" (J. Bekenstein, 2004) failed to explain CMB and BAO precision data after 2015
  Claim by Skordis and Zlosnik 2007.00082 PRL127, 161302 (2021) that another MOND extension"Aether-Scalar-Tensor- AeST extension of GR agrees with all phenomenological tests which have so far been made"- more studies required to test its validity.

This is the idea behind

Modified Newtonian Dynamics-MOND (Mordehai Milgrom,1983)

at very small accelerations $a < a_0 \simeq 10^{-8}$cm/s^2 Newton's Law is modified

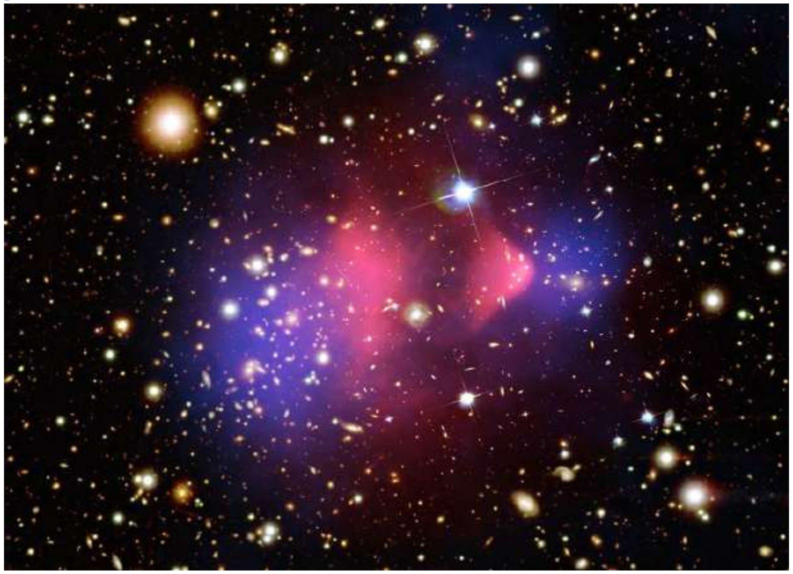
$$F_{Gravity} = \frac{GMm}{r^2} = ma\frac{a}{a_0} = \frac{mv^4}{a_0 r^2} \Rightarrow v = \text{constant independent of } r$$

using that the centripetal acceleration is $a = \dfrac{v^2}{r}$

MOND is only non-relativistic, so cannot be tested on cosmological scales (e.g. gravitational lensing). MOND's covariant generalizations of GR contain new fields that play to some extent the role of dark matter.

Evidence for DM and not [TeVeS+ only visible matter]

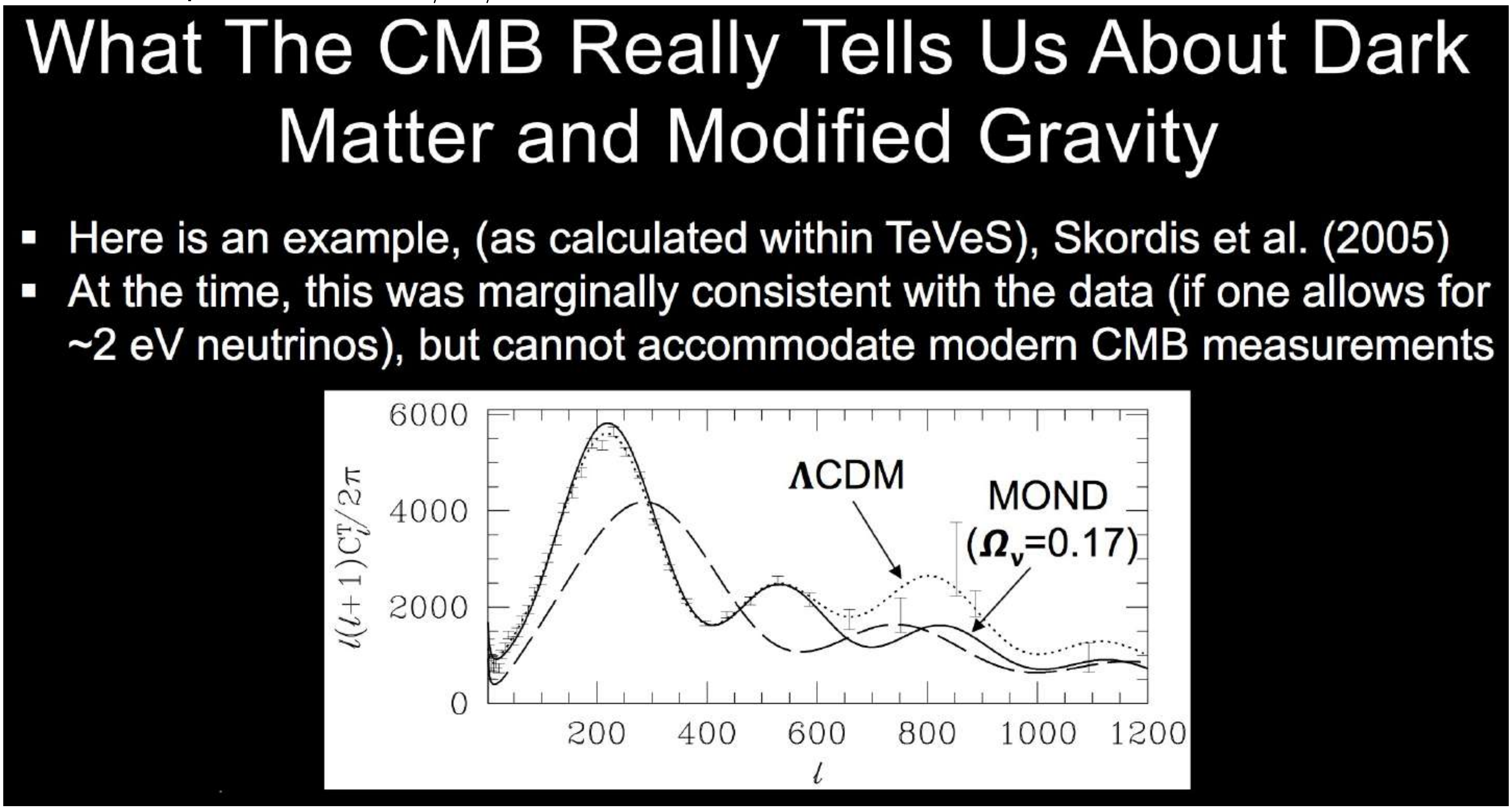
“Bullet Cluster”- 2004



Two galaxies collided and passed through each other leaving behind the visible (interacting) matter (hot gas seen by Chandra in X-rays -pink) which is not where most of the mass of the cluster (seen via gravitational lensing-blue) is.

MOND/TeVeS with only visible matter cannot explain this system: needs 2-3$\times$more matter - i.e. some form of Dark Matter (Dark Cluster Baryonic Matter?) MOND/AeST claims it can

Dan Hooper talk- KITP 4/30/2018 "In Defense of Dark Matter"-in debate with Eric Verlinde



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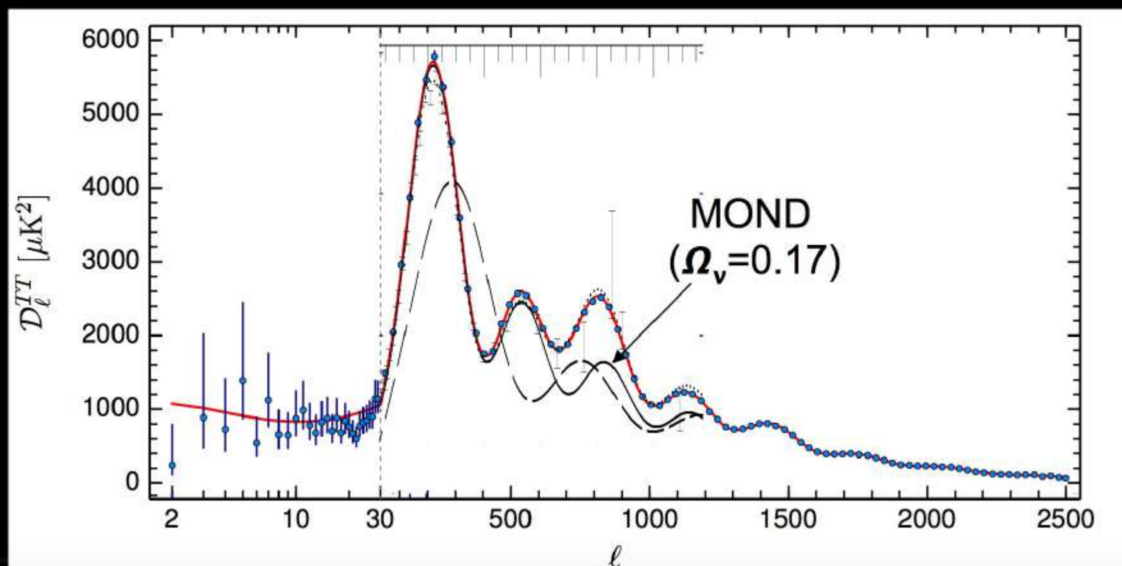
What The CMB Really Tells Us About Dark Matter and Modified Gravity

- Here is an example, (as calculated within TeVeS), Skordis et al. (2005)
- At the time, this was marginally consistent with the data (if one allows for ~2 eV neutrinos), but cannot accommodate modern CMB measurements



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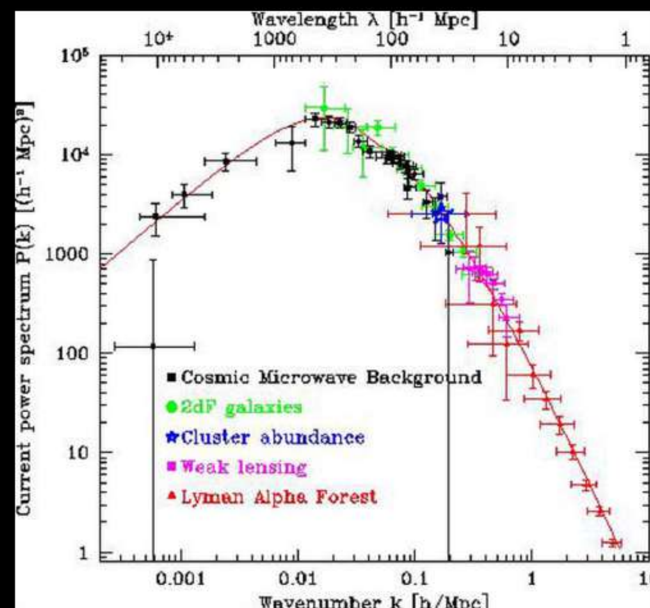
Matter Power Spectrum

- If you look closely, you can see small wiggles in the matter power spectrum, resulting from baryon acoustic oscillations (BAO)
- These BAO are small in standard ΛCDM cosmology, because they are suppressed as baryons fall into the potential wells formed by dark matter – only a few percent of the primordial oscillations survive



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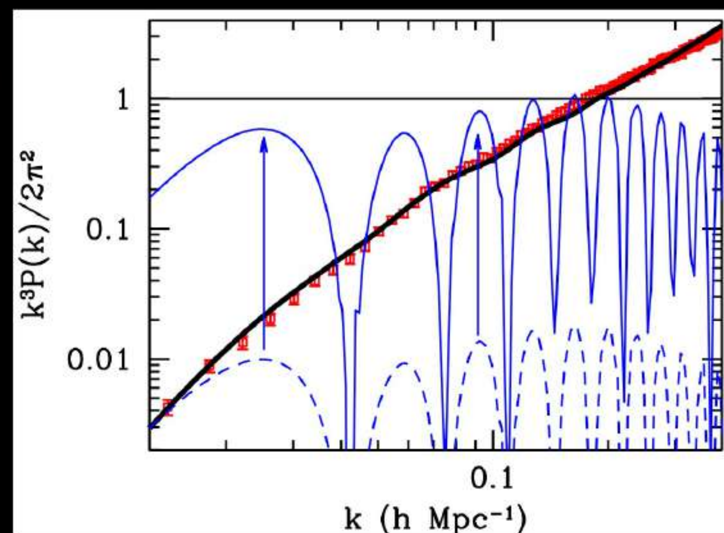
- These BAO are small in standard ΛCDM cosmology, because they are suppressed as baryons fall into the potential wells formed by dark matter – only a few percent of the primordial oscillations survive
- In a universe without dark matter, however, these oscillations should be *much* larger
- Even if structure growth is somehow enhanced through modifications of gravity, without dark matter, BAO should be ~30 times larger than observed



Dodelson (2011)

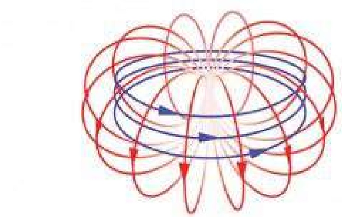
After 90 years, what we know about DM:

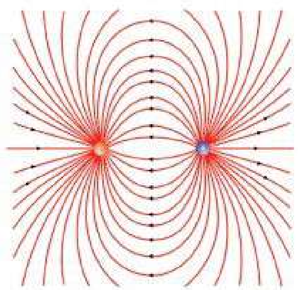
- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light** but could have a very small electromagnetic coupling such as:

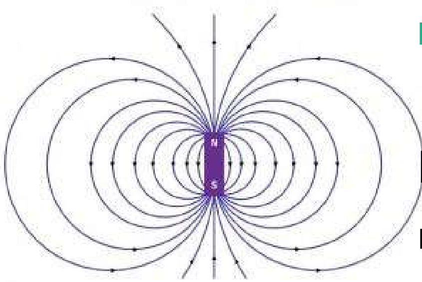
  — "electric or magnetic dipole DM", or"anapole DM"

  —"Milli-Charged DM" which can be part of "Atomic DM", with dark protons and dark electrons forming dark atoms or "Mirror DM" whose Lagrangian is a copy of that of the SM, but for the mirror particles,

Small electromagnetic couplings







Anapole moment DM (ADM) Ho-Scherrer 1211.0503

Proposed by Zel'dovich in Sov. Phys. JETP 6, 1184 (1958): breaks C and P, but preserves CP - 1st measured in 1997 (in Cesium-133 atoms)

C. S. Wood et al, Science 275, 1759 (1997)

$$\mathrm{L} \simeq \frac{g}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma_5\psi\partial^\nu \mathrm{F}^{\mu\nu} \quad \rightarrow \quad \mathrm{H}_{\mathrm{Anapole}} \sim \vec{\sigma} \times \vec{\mathrm{B}}$$

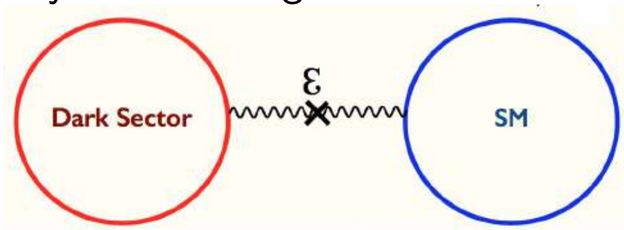
Magnetic (MDM), Electric (EDM) Dipole Moment DM Pospelov & Veldhuis 2000, Sigurdson, Doran, Kurylov, Caldwell Kamionkowsky 2004, 2006, Maso, Mohanty, Rao 2009, Fortin, Tait 2012, many more

$$\mathrm{L} \simeq \bar{\psi}\sigma_{\mu\nu}(d_{\mathrm{m}} + d_e\gamma_5)\psi \mathrm{F}^{\mu\nu} \rightarrow \mathrm{H}_{\mathrm{MDM}} \sim d_{\mathrm{m}}\vec{\sigma}.\vec{\mathrm{B}}, \;\; \mathrm{H}_{\mathrm{EDM}} \sim d_e\vec{\sigma}.\vec{\mathrm{E}}$$

Dipole moments are zero for Majorana fermions (although transition moments are not) and the first non-zero moment is the Anapole Moment

Can have a rich "Dark Sector" similar to visible sector, with hidden gauge interactions and flavor Foot 2004, Huh at al 2008, Pospelov, Ritz, Voloshin 2008, Arkani-Hamed et al.,2009, Kaplan et al 0909.0753 and 1105.2073. . .

"Millicharged DM" Unbroken U$_{\rm dark}$(1) hidden gauge symmetry that would give rise to bound states "kinetic coupling" $\epsilon F_{\mu\nu}F^{\mu\nu}_{\rm dark}$



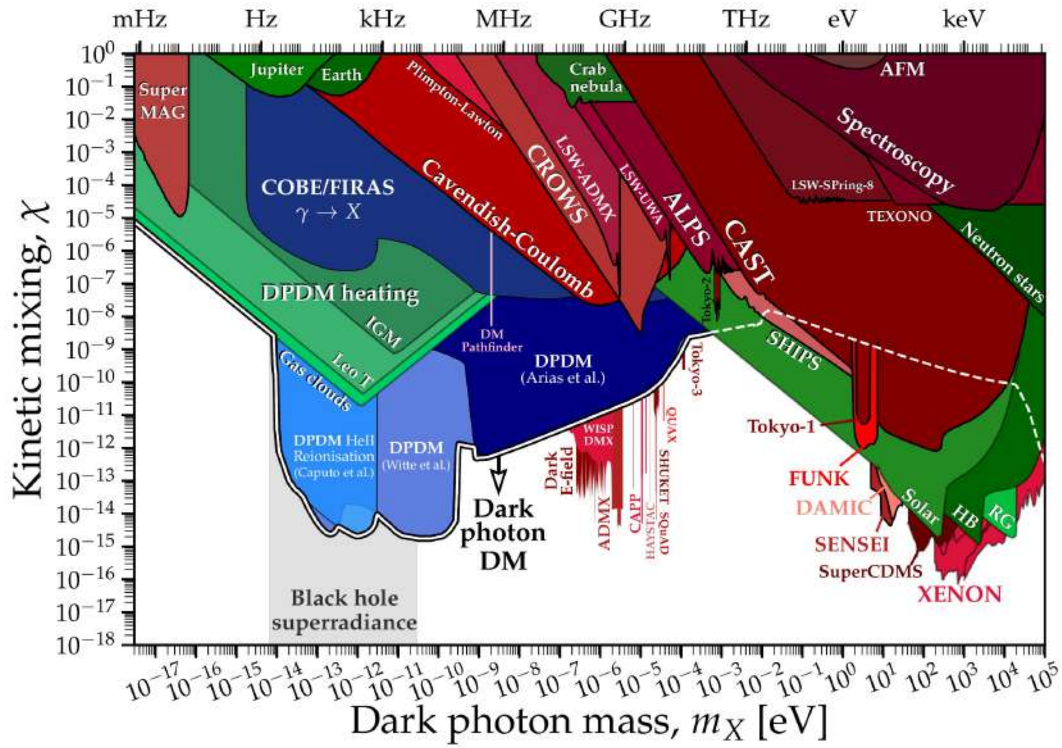
Diagonalized gauge boson kinetic terms: em photon $A_\mu(J^\mu_{\rm em}+\epsilon g J^\mu_{\rm dark})$ (g is U$_{\rm dark}$(1) coupling).
Holdom 1986, Burrage et al 0909.0649 Kaplan 0909.0753 1105.2073 Cline, Zuowei Liu, and Wei Xue 1201.4858

"Atomic DM" with dark analogues of p, e, H coupled to a new U'(1) and Dark Atoms may scatter elastically or inelastically depending on the choice of parameters Goldberg Hall 1986; Feng, Kaplinghat, Tu 0905.3039; Ackerman 2009. . .

"Dark" or "Hidden"-Photons (HP) themselves can be the DM- but "Light DM" or lighter
Pospelov, Ritz& Voloshin 0807.3279; Arias etal1201.5902

Limits of Hidden-Photons (HP) Compilation in Caputo et al 2105.04565

HP's can be very light CDM (LDM or lighter). χ is here the mixing ϵ in $\epsilon F_{\mu\nu} F^{\mu\nu}_{\rm dark}$ and m_χ is the HP mass.



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- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless** i.e. cannot cool by radiating as baryons do to form disks in the center of galaxies, or their extended dark halos would not exist.

  But $<$**few% could be** (radiating "dark photons" or other light dark particles) "Partially Interacting DM (PIDM)" and a special case of it "Double Disk DM" (DDDM) Fan, Katz, Randall & Reece 1303.1521-1303.3271

  A Dark Disk was shown to arise in some CDM simulations (Read et al. 2008; Purcell et al. 2009; Ruchti et al. 2014) but with some dissipative DM it should be a pervasive feature of all disk galaxies- (and "kill the dinosaurs"...?! Randall& Reece 1403.0576) GAIA data in solar neighbourghood placed stringent upper limits (and are consistent with no-dark disk) (Windmark et al 2021)

After 90 years, what we know about DM:

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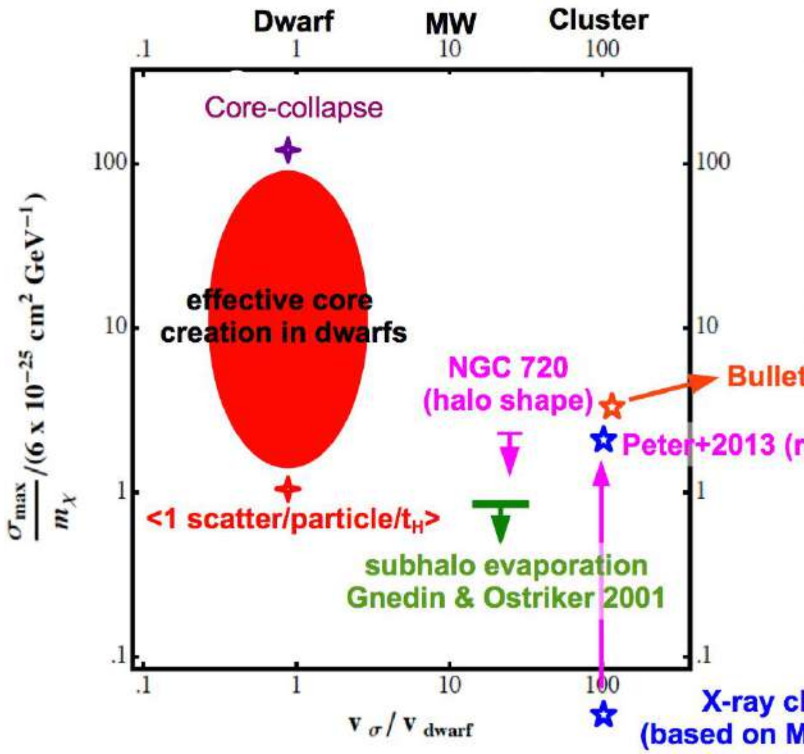
- **4- The bulk of the DM must be nearly dissipationless but $\leq$few% of it could be dissipative** (so dark sector)
- **5- DM has been mostly assumed to be collisionless, however the upper limit on DM self-interactions is huge**

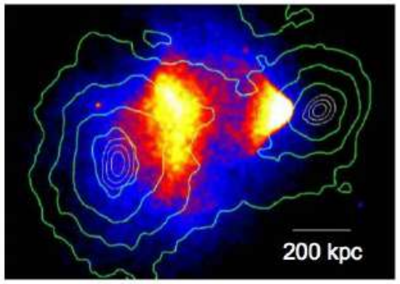
Bullet cluster + non-sphericity of galaxy and cluster halos
$\sigma_{\rm self}/{\rm m} \leq 1$ cm^2/g $=$ 2 barn/GeV $= 2\times 10^{-24}$ cm^2/ GeV
by comparison e.g. ^{235}U-neutron capture cross section is a few barns!
Self Interacting DM (SIDM) just below limit- otherwise same as collisionless

(Limit on $\sigma_{\rm self}/m$ comes from requiring a self-interaction mean free path with ρ known $\lambda_{\rm mfp} \simeq 1/[n\sigma_{\rm self}] = m/[\rho\sigma_{\rm self}]$ long enough, $n = \rho/m$ is DM number density, rate $\Gamma = v/\lambda$)

Self Interacting DM (SIDM)

Fig. from Jesus Zavala Franco



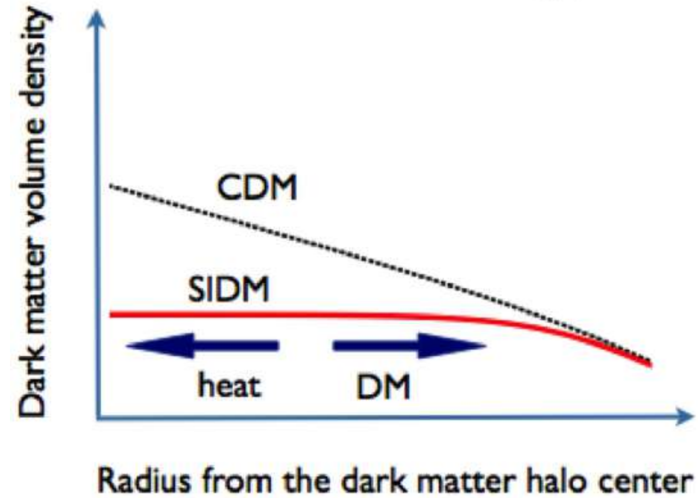


Buckley & Fox 2010
Loeb & Weiner 2011

Spergel & Steinhardt 2000 proposed SIDM with $\sigma \simeq (m/\text{GeV})(\text{Mpc}/\lambda_{\text{mfp}})$ barns.

SIDM should not affect large structures (large v), only smaller ones (smaller v)

Self Interacting DM (SIDM) would erase small scale structure and flatten out the central regions of dwarf galaxies (forming a core)

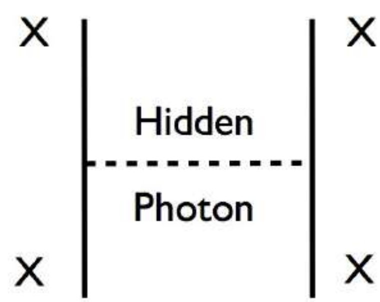


Having a large self interaction at smaller scales and a negligible one at large scales points to light mediators ϕ (best DM $m_X \simeq$15 GeV, $m_\phi \simeq$15 MeV)

(Feng, Kaplinghat& Yu 2009, Buckley& Fox (2009), Loeb&Weiner (2010), Tulin, Yu& Zurek 2012, 2013...)

$$\sigma \sim \frac{\alpha_X^2}{m_X^2 v^4}$$

$m_X v >> m_\phi$



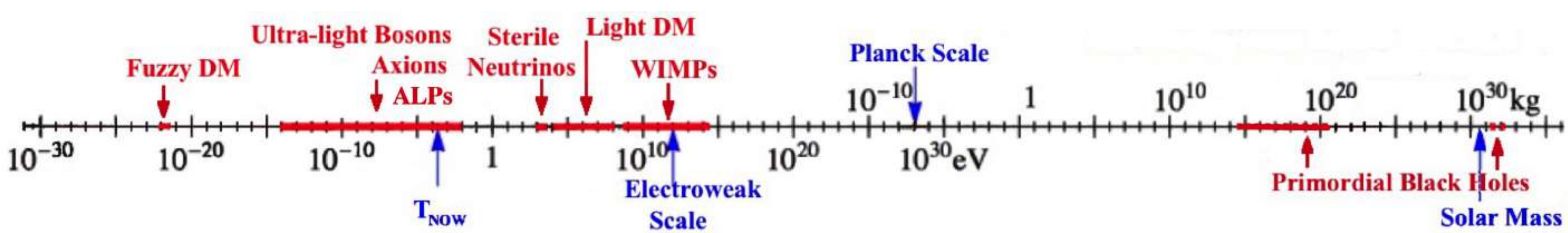
(Recall that the virial speed is larger in more massive structures)

- **6- The mass of the major component of the DM has only been constrained within some 70 orders of magnitude.**

$$10^{-31}\ \text{GeV} \leq \textbf{mass} \leq 10^{-10} M_\odot = 10^{41}\text{GeV} = 2\times 10^{14}\text{kg}$$

Upper limit on Primordial Black Holes (PBH), in the "asteroid" mass range

Lower limit: "Fuzzy DM", boson with de Broglie wavelength 1 kpc Hu, Barkana, Gruzinov, 2000 (or "Tremaine-Gunn" limit 0.2-0.7 $\times 10^{-6}$ GeV $\leq$ mass for DM particles which reached thermal equilibrium - depending on boson-fermion and d.o.f. - based on maximum possible phase-space occupation number in galaxies (best from dSph's) Tremaine-Gunn 1979; Madsen 1990, 1991, 2001; Boyarksky, Ruchayskiy and Iakubovskyi 2008; Alvey et al 2020...)

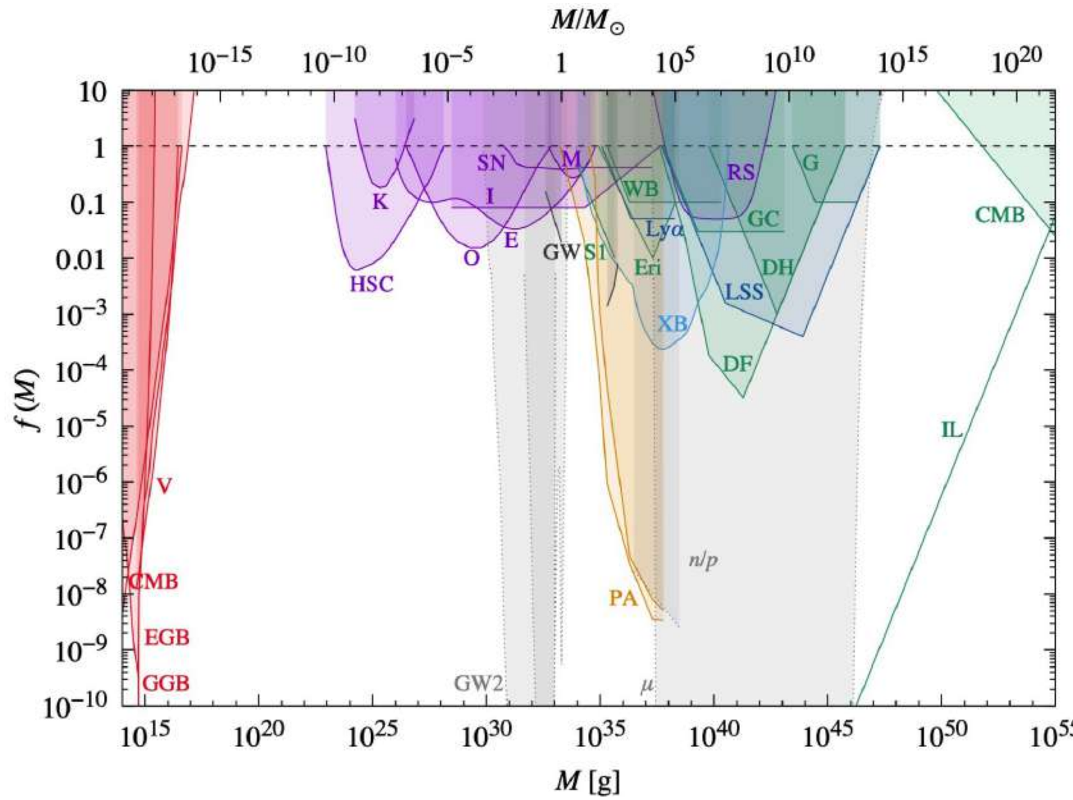


PBH as DM

Compilation of bounds on the PHB/DM density fraction f for monochromatic mass function

(Carr and Kuhnel 2021, Green and Kavanagh 2020)

In the "asteroid mass" range 10^{-16} $M_\odot$ to 10^{-10} $M_\odot$ PBH could be all of the DM.



(Limits from PBH from evaporation, γ-rays- EGB: Extra Galactic Back., GGB: Galactic, V: e^+ from Voyager 1, Limits from fempto-, micro- and milli-gravitational lensing: HSC Subaru, K Kepler, M/E/O MACHO/EROS/OGLE, RS: radio sources, Limits from dynamics- WB: wide-binary disruption, Eri: star cluster survival in Eridanus II, GC: accretion in n stars there would destroy them, XR: accretion on X-ray binaries, G: galaxies tidal disruption LSS Poisson fluctuations PA: Planck CMB anisotropies Backgrounds- μ: CMB spectral distortions,GW2: 2nd order GW emission CMB: dipole, IL: incredulity limit= 1PBH / Hubble volume)

PBH as DM

PBH are hypothetical type of black hole not formed by the gravitational collapse of a large star but in the early Universe (Zel'dovich and Novikov, 1966; Hawking, 1971; Carr and Hawking, 1974) Many scenarios for PBH formation, include:

- density perturbations in the early Universe (see e.g. Carr 1975; Yokoyama 1997, Garcia -Bellido, Linde, Wands 1996; Ballesteros, Taoso 2018)

- bubble collisions Hawking, Moss, Stewart 1982, Lewicki and Vaskonen 2020

- the collapse of cosmic strings Hawking 1989

- scalar field dynamics Klopov, Malomed , Zeldovich 1985; Cotner, Kusenko 2017

- scalar long-range interactions Flores, Kusenko 2021

- collapse of domain walls Garriga, Vilenkin, Zhang 2015; Deng Garriga, Vilenkin 2016; Ferre et al 2019; Gelmini et al 2023

- collapse of vacuum bubbles in multi-field inflationary scenarios Deng, Vilenkin 2017; Kusenko et al 2020

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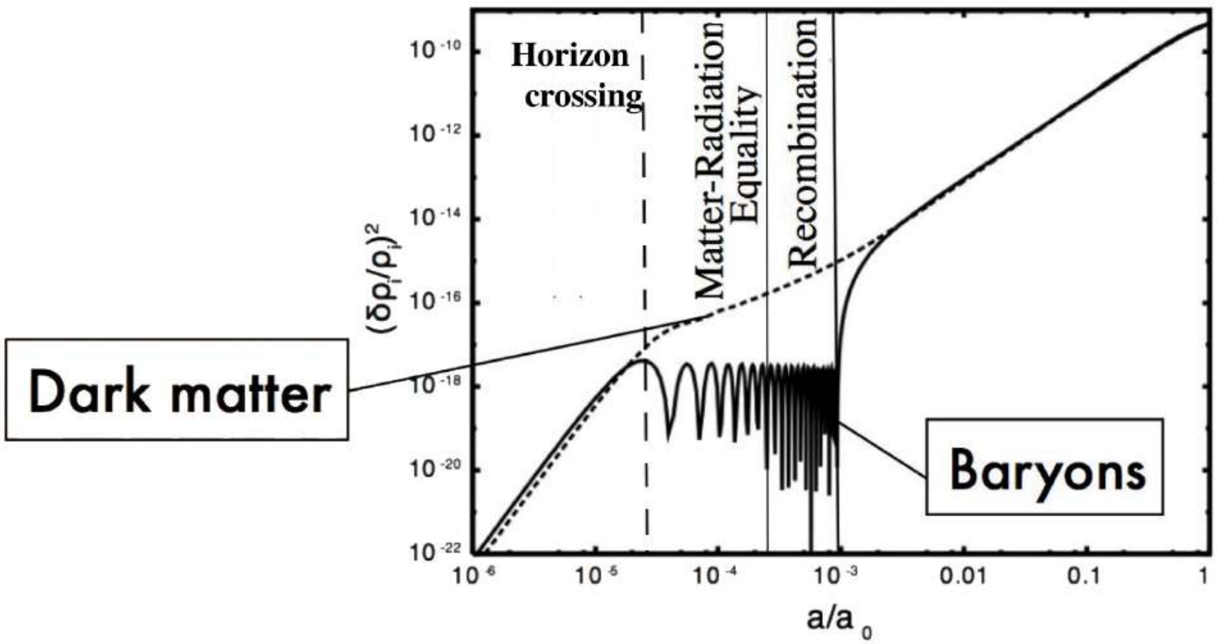
- **6- Mass within some 70 orders of magnitude.**
- **7- The bulk of the DM is Cold or Warm**

Dark Matter is needed for Structure Formation

Structure in baryons cannot grow until "recombination" (before: photon pressure empedes collapse). After, baryons must fall into potential wells of DM, or not enough time for structures to form: in Matter-Dominated Universe, gravitational collapse implies $(\delta\rho/\rho)_{\mathrm{matter}} \sim a$, thus $(\delta\rho/\rho)_{\mathrm{matter}}$ could go from 10^{-4} to 10^{-1} but need >1

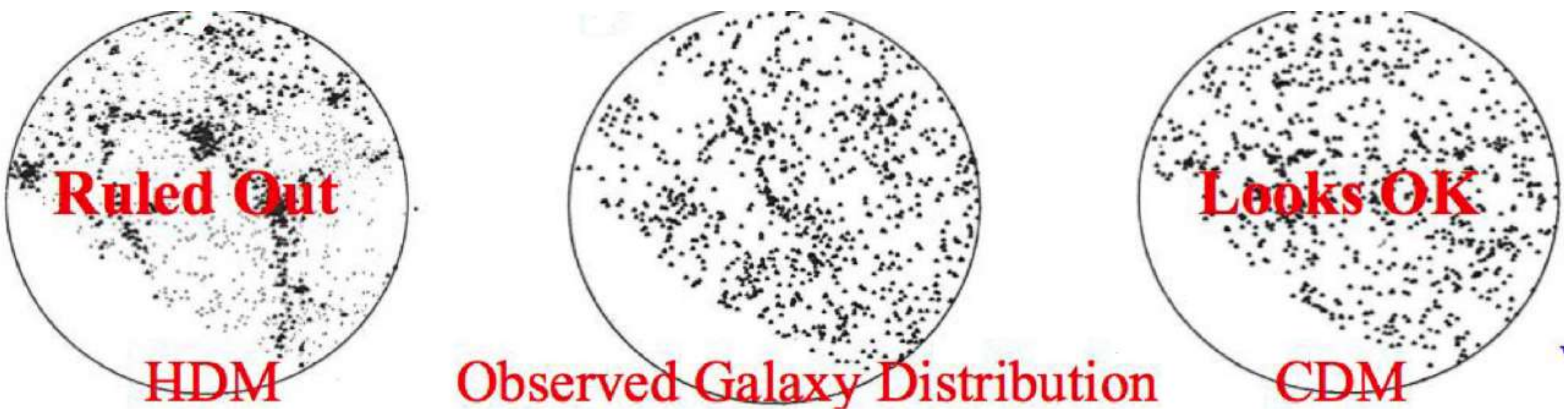


7- Dark Matter is "Cold" or "Warm"

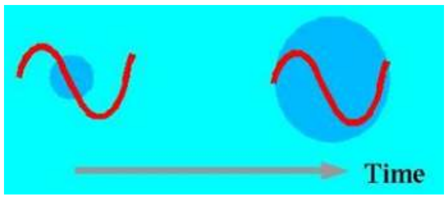
Dark Matter is classified as "HOT" or "WARM" of "COLD" if it is

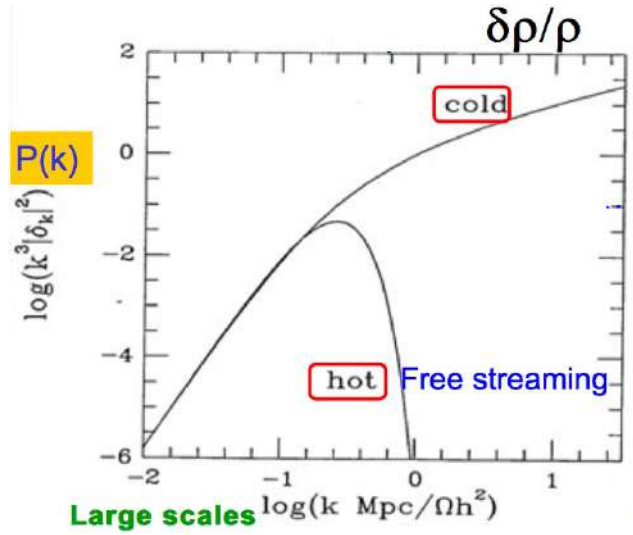
RELATIVISTIC (moves with c), SEMI-RELATIVISTIC or NON-RELATIVISTIC

at the moment dwarf galaxy core size structures start to form (when $T \sim$ keV).
We know since the 1980's (Fig. S. White 1986) that these structures (or smaller ones) form first and structure cannot form with relativistic matter.



Free-streaming HDM erasures density fluctuations by free streaming.
A "free streaming" particle propagates through a medium without scattering.
HDM: Free streaming length of a relativistic particle=ct the horizon size,
Thus as inhomogeneities in HDM enter within the horizon (ct) they are erased.





CDM: Free streaming of non-relativistic particles= vt, with v $<<$ c

Dark Matter is "Cold" or "Warm"

Both work well at scales larger than dwarf galaxies.

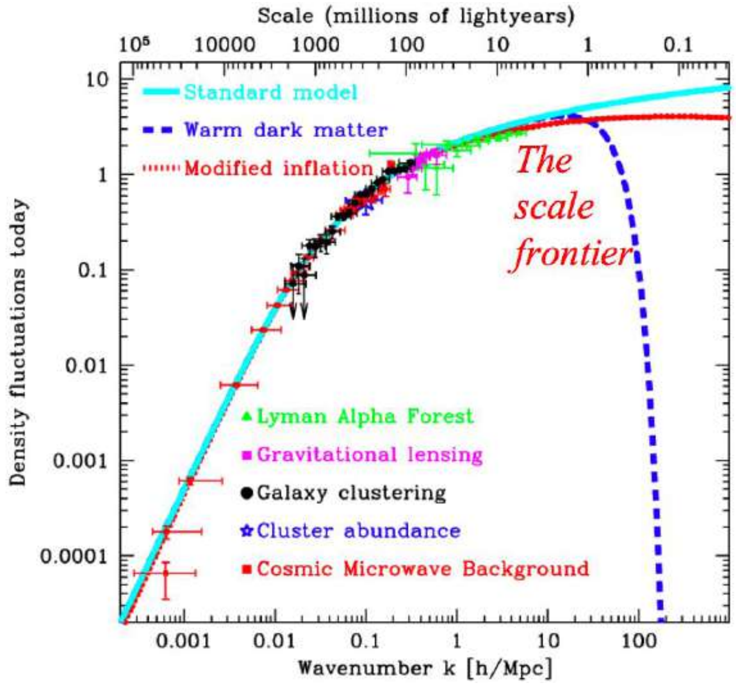
The differences are at smaller scales where observations and their interpretation are still not conclusive.

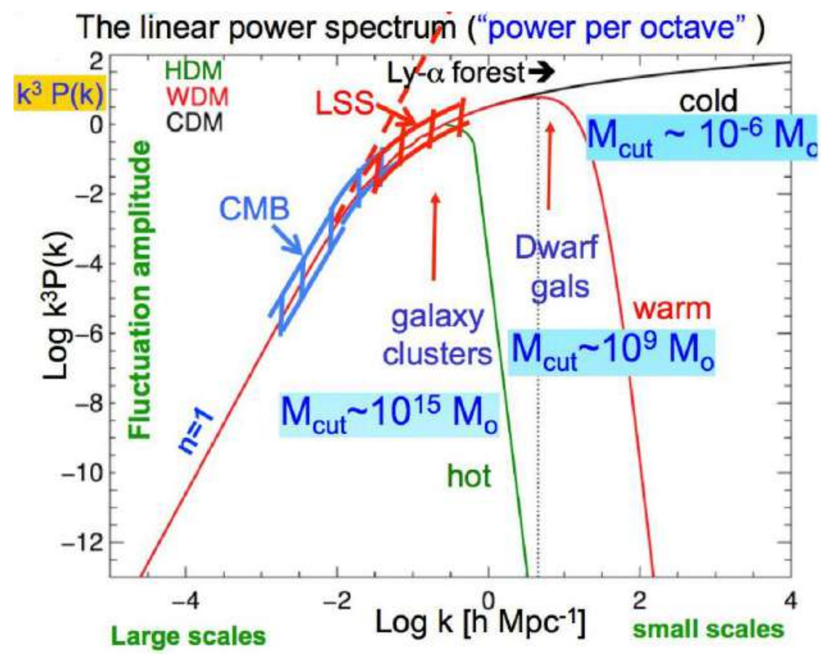
With WDM only structures of dwarf-galaxy cores size and larger survive.

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

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

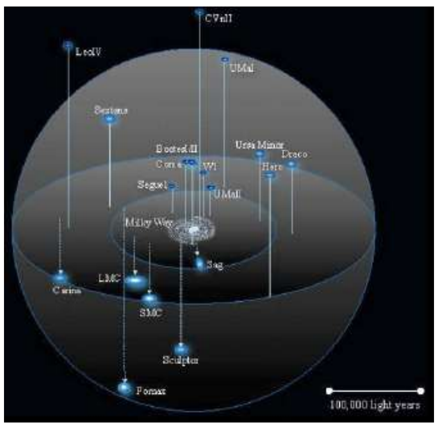
Fig: from Tegmark ("Standard model" with ΛCDM: with Cold DM) Fig: from Carlos Frenk

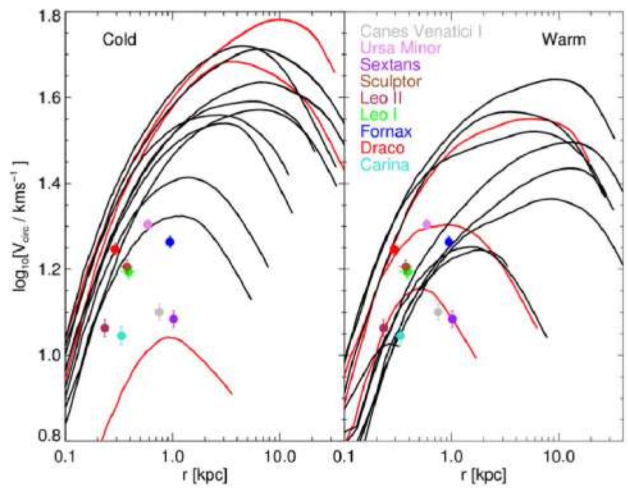




Potential problems for pure collisionless CDM

Predicts too many Milky Way Dwarf Galaxies? Very high resolution simulations (of only CDM) find massive dense subhaloes **"too big to fail"** to form lots of stars, but none of the observed satellites of the MW or Andromeda have stars moving as fast as would be expected in them Boylan-Kolchin 2011, Tollerud et al 2014

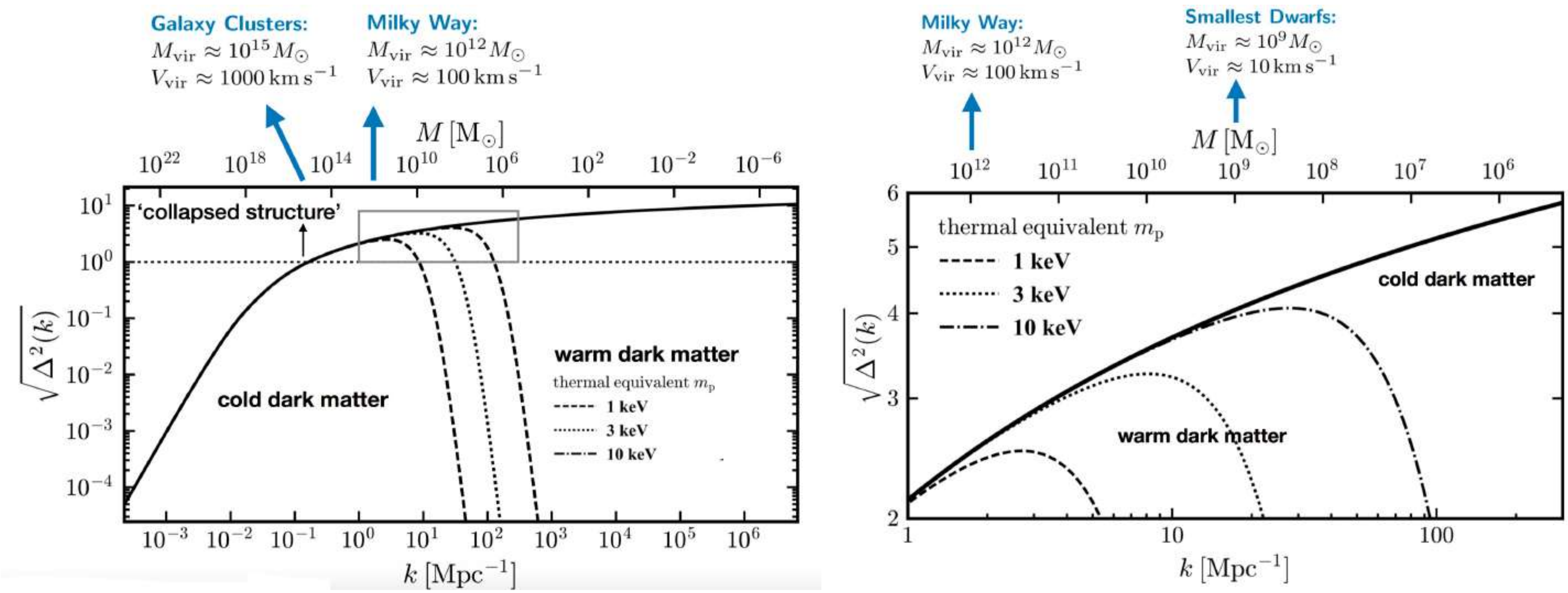




TBTF problem also in Andromeda and the local group? Dwarf Galaxies cored instead of cuspy? CDM rejected so either WDM or velocity dependent SIDM? But baryonic feedback from supernovae and active galactic nuclei can "flatten out" the core of a galaxy's DM profile (so can lead to smaller star velocities)

"Double-Dark" model works well with CDM or WDM above galactic scales, distinction at sub-galactic scales Figs: from James Bullock, Boylan-Kolchin, ARAA, 2017

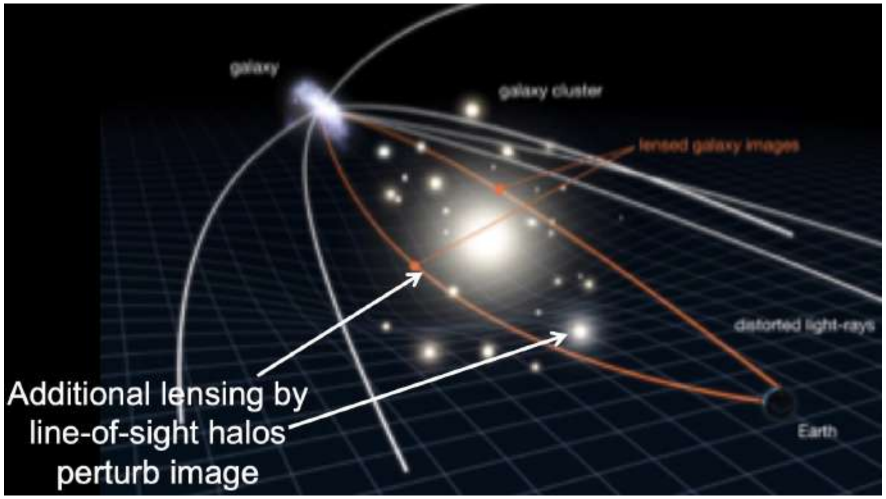
Only it has a thermal spectrum or similar, $\bar{E} \simeq 3T$, WDM requires $m \simeq$ keV

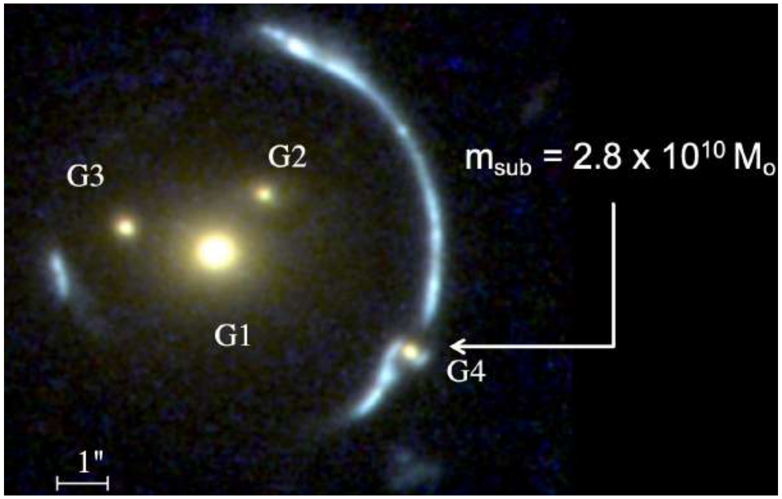


Distinguishing CDM-WDM-SIDM-mixedDM and baryonic effects at sub-galactic scales is where most of the structure formation simulations and observational efforts are directed at present.

Strong gravitational lensing may be the way to distinquish WDM and CDM!

Figs: from Carlos Frenk talk June 2024- S.Vegetti et al 1002.4708



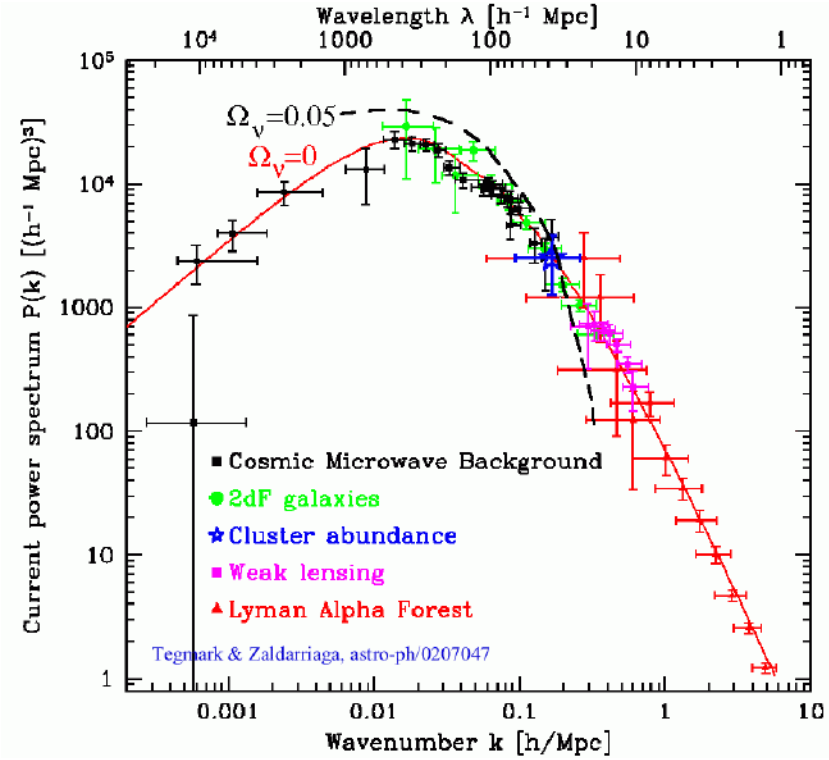


When the source and the lens are well aligned leads to an Einstein ring. Dark haloes in the light path distort the ring. Can detect haloes as small as 10^8 M$_\odot$. **With WDM should find NO $10^8 M_\odot$. With CDM should find MANY**

(e.g. He, Frenk et al 1907.01680, 2010.13221, 2209.10566)

Only SM DM candidates: ν's

Large scale structure



Laboratory data

$m_1 < 2$ eV
$\Delta m^2_{13} \sim 2.5 \times 10^{-3}$eV^2
$\Delta m^2_{12} \sim 7.6 \times 10^{-5}$eV^2
so 0.06eV$< m_{\nu_i} <$2 eV $(*)$

But Hot DM

In equilibrium to T$\simeq$3MeV

CMB: N$_{eff}$= 2.99$\pm$0.17

$\Sigma m_\nu < 0.12$ eV

$\Omega_\nu h^2 \simeq \Omega_{DM} h^2 (\Sigma m_\nu / 10\text{eV})$, $\Omega_{DM} h^2 \simeq 0.11$ thus $(*)$ implies $0.001 \leq \Omega_\nu \leq 0.04$

No CDM or WDM particle candidate in the SM!

In the SM only **neutrinos** are part of the DM- they are light m$<$ eV and in equilibrium until BBN, $T \simeq 1$ MeV thus they are **Hot DM (HDM)**

But many in extensions of the SM!

Warm dark matter (WDM):

- sterile neutrino, gravitino, non-thermal WIMPs and many more...

Cold dark matter (CDM):

- WIMPs, axions, gravitinos, WIMPZILLAs, solitons (Q-balls) and many more...

(WIMPs, Weakly Interacting Massive Particles
but wimp $=$ a weak, cowardly, or ineffectual person *(Merriam-Webster Dictionary)*)

Particle DM requires new physics beyond the SM!

8- Particle DM candidates require BSM physics But which type of BSM? **The scope of DM models has changed since the 70's:**

- 1980's: DM candidates were an afterthought, models proposed exclusively to solve problems in Standard Model, such as SUSY, Technicolor, "Little Higgs" models (electroweak hierarchy), Peccei-Quinn symmetry (strong CP problem), see-saw models (neutrino masses) - which also contain DM candidates: WIMPs, axions, sterile neutrinos

- 1990's: DM candidates were mandatory in all BSM models

- Since 2000's: DM/ Dark Sector models independent of solving any SM problem

Models made to fit DM hints and/or predict novel DM signals and experiments to detect them, without regard for completion of the SM- but have implications for accelerators e.g. search for light mediators, displaced vertices... Led to all types of DM and interactions, to "dark sectors" seen through **"portals"**, i.e. a small coupling to one type of SM particle (could be γ's and Z's, the Higgs boson, neutrinos), classified according to possible experimental signals....

Some members of the particle DM candidates zoo

- WIMPs "Weakly Interacting Massive Particles": about weak order interactions with the SM. Lightest particle carrying a conserved charge in most BSM complete models (SUSY, composite models,"Little Higgs" models, Inert Doublet models...): LSP (Lightest Supersymmetric Partner-R parity), 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), LIP (Lightest Inert Particle)...
Production: reach thermal equilibrium via 2 DM$\rightarrow$2 SM interactions and freeze-out, or in the decay of another WIMP (SuperWIMP case) Mass: GeV to 100 TeV

- FIMPs, "Feebly Interacting Massive Particles" (or "Frozen-In-Massive-Particles"): have interactions of order much weaker than weak Hall, Jedamzik, March-Russell & West, 0911.1120...; see e.g. Bernal, Heikinheimo, Tenkanen, Tuominen &Vaskonen 1706.07442
Moduli/modulinos of string theory compactifications with mass from weak-scale SUSY breaking,GUT-scale-suppressed interactions, with small kinetic mixing coupling to the SM or through a Higgs portal...
Production: never reach thermal equilibrium, freeze-in as DM or freeze-in and decay to DM Mass: sub eV to 100's TeV

- SIMPs, "Strongly Interacting Massive Particles": Old 1990's SIMPs had strong int. with the SM- revived as strongly SELF-interacting but very weakly coupled to the SM Hochberg, Kuflik, Volansky & Wacker, 1402.5143; Kuflik *et al* 1411.3727; Choi & Lee 1505.00960; Lee&Seo 1504.00745; Bernal&Chu 1510.08527; Bernal, Garcia-Celt& Rosenfeld 1510.08063; Hochberg, Kuflik &Murayama 1512.07917; Ho, Toma &Tsumura,1705.00592...

E.g. p-NG bosons of a strongly coupled confining hidden sector, with kinetic mixing with the SM (photon or Z') or Higgs portal

Production: reach thermal equilibrium and freeze-out in the dark sector due to 3→2 or 4→2 DM to DM interactions,"Cannibalism"- assumes kinetic equilibrium of dark and visible sectors so they have the same temperature

-ELDERs, "ELastically DEcoupling Relic" type of SIMP with DM-SM elastic scattering. Kufflick, Perelstein, Lorier, Tsai 1512.04545 Mass: 100 keV - 1 GeV (they are "Light DM" LDM)

- PIMPs, "Planckian Interacting Massive Part.": assumes new physics comes at M_P Garny, Sandora & Sloth 1511.03278 Hidden sector DM with gravitational order SM interaction

Production: soon after a very high T reheating inflationary period- many variations

Mass: most typical close to M_P (Similar to GIMPs, "Gravitationally Interacting Massive Part." in a KK model Holthausen & Takahashi 0912.2262)

- Axions and ALPs, "Axion-Like Particles": The axion is a pseudo-Nambu Goldstone boson of a spontaneously broken axial U(1) global symmetry introduced by Peccei and Quinn in 1977 to solve the strong CP problem of QCD (Weinberg and Wilczek, 1978). ALPs are other hypothetical pseudo-GB (among which majorons and familons...)

Production: as a boson condensate or radiated from axion topological defects (strings and walls) Axion DM mass: 10^{-10}- 10^{-4} eV (for ALPs, model dependent)

- WISPs, "Weakly Interacting Slim Particles": a combined name for axions/ALPs (spin zero) and dark (or hidden sector) photons (spin 1).

- FIPs, "Feebly Interacting Particles": All particles with very small coupling to the SM particles

Still others: "Dynamical DM (DDM)" dark sector with a vast number of particle species whose SM decay widths are balanced against their cosmological abundances- shorter lived has smaller densities Dienes &Thomas 2011, "Mirror DM" (from a hidden "dark" copy of the SM- could or not interact via kinetic mixing) Blinnikov %Khlopov 1982, Kolb, Seckel %Turner 1985, Foot, Lew %Volkas 1991...., Q-balls (non-topological solitons created as a fragmentation of a scalar condensate) Kusenko 1997, Kusenko &Shaposhnikov 1997, sterile neutrinos (or dark fermions included in FIPs)...

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- **8- Particle DM requires BSM physics**

Particle DM is required to have the DM density. Caveat: the computation of the relic abundance and velocity distribution of particle DM candidates produced before $T \simeq 5$ MeV depend on assumptions made regarding the thermal history of the Universe.

Particle DM production

- **"Thermal" DM**: produced via interactions with the thermal bath and reach equilibrium with visible matter. Then "decouple" or "freeze-out" (e.g. WIMPs, SIDM)

- **"Non-thermal" DM**: particles produced via other mechanics:
  - "freeze-in" due to out of equilibrium annihilations or decays (e.g. FIDM)
  - "freeze-in" due quantum mechanical flavor oscillations (e.g. sterile neutrinos)
  - boson condensate formation (e.g. axions/ALPS)
  - decay of particles with thermal abundance or not (e.g. SuperWIMPs, FIMPs)
  - decay of cosmic strings or cosmic walls (e.g. axions/ALPS)
  - during reheating after inflation or other phase transitions. (e.g.PIMPs, GIMPs)...

Let us review the thermal production first

Parenthesis: a, H, and t_U

- 1929- Hubble- far away galaxies recede from us: $v = Hd$ "Hubble Law"

  $H(t)$=Hubble parameter, the value of H now is the Hubble constant $H_0 \simeq 70$ km/Mpc s (1pc= 3.2ℓy)

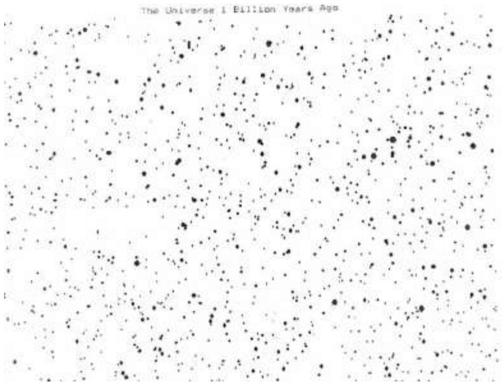
  + Cosmological Principle ="we are not special"
  = **Universe is expanding**

- The expansion has no center: all inter-distances grow in the same way

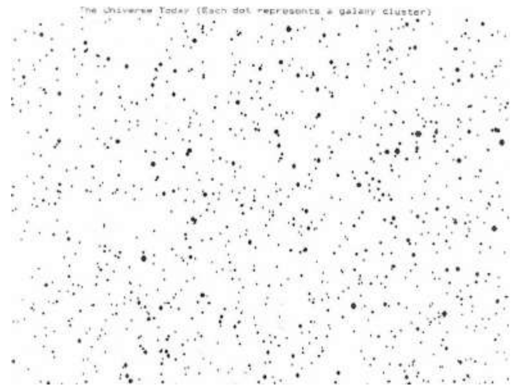
  $$d(t) = a(t) d_0 \Rightarrow v = \dot{d} = \frac{\dot{a}}{a} d$$

  $a(t)$: scale factor of the Universe
  $H(t) \equiv \dot{a}/a$ (constant in space, not in time)

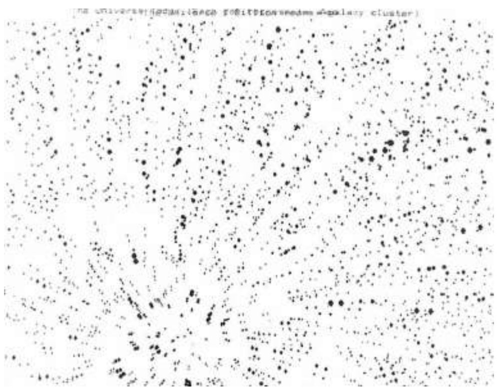
Expansion of the Universe

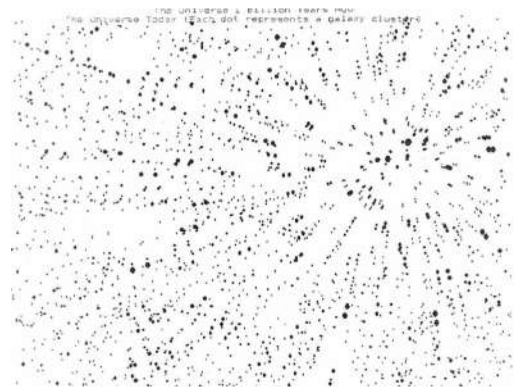


Sometime in the past



Now

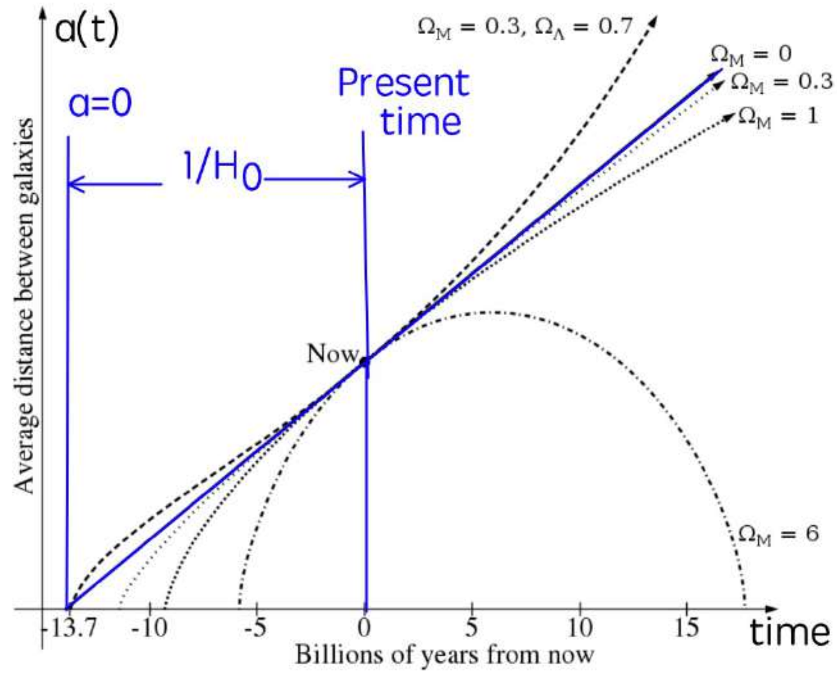




The galaxy from which we observe, seems always the center of expansion

Lifetime of the Universe t_U: counted from $a = 0$ forwards

$$t_U \simeq 1/H$$



(END parenthesis)

Equilibrium

Chemical Equilibrium: particle number changing reaction rate is fast,
Kinetic Equilibrium: momentum exchange reactions are fast (w.r.t. H)

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

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

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

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

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

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

$\Gamma(T)$ 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 the expansion rate of the Universe $H(T)$. In GR is given by the Friedmann Equation $H^2 = (8\pi G/3)\rho - k/a^2 + \Lambda/3$, where $k = 0$ for a flat Universe and Λ is negligible in the early Universe.

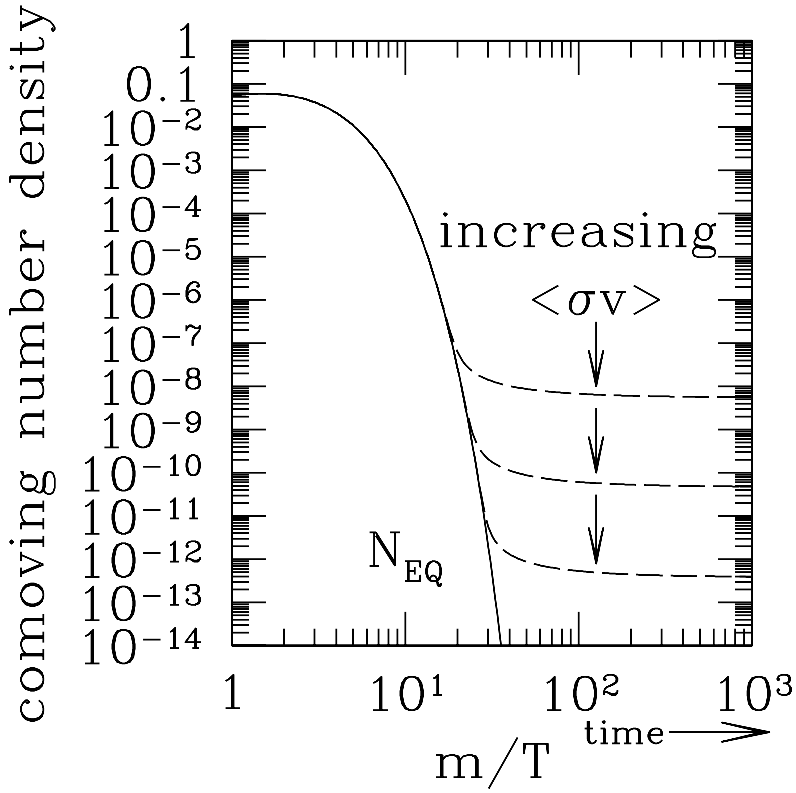
"Thermal WIMPs" Solving the Boltzmann Transport Equation

Standard calculations: start at $T > T_{\rm fo} \simeq m_\chi/20$ and assume that

- WIMPs reach equilibrium while Universe is radiation dominated
- No particle asymmetry
- Chemical decoupling (freeze-out) when $\Gamma_{\rm ann} = \langle \sigma v \rangle \, n \leq H$,
- No entropy change in matter+radiation

$$\Omega_{\rm std} h^2 \approx 0.2 \, \frac{3 \times 10^{-26} {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle}$$

Weak annihilation cross section
$\sigma_{\rm annih} \simeq G_F^2 T^2 \simeq 3 \times 10^{-26} {\rm cm}^3/{\rm s}$
is enough to get $\Omega = \Omega_{DM} \simeq 0.2$!
"WIMP Miracle"



$<\sigma v>$= average over a thermal momenta distrib. (aver. over initial and sum over final states)

"Thermal WIMPs"

The freeze-out for weak-strength interactions occurs at $x_{fo} \equiv m/T_{\rm fo} \simeq 20$, when the typical WIMP speed is $v_{\rm fo} = (3T_{\rm fo}/m)^{1/2} \simeq 0.27c$ (recall $\langle {\rm E_k} \rangle = 3kT/2$) and the relic density is

$$\Omega h^2 \simeq 0.1 \left(\frac{x_{\rm fo}}{20}\right) \left(\frac{60}{g_{\rm eff}}\right)^{1/2} \frac{3 \times 10^{-26}\ {\rm cm^3/s}}{a + (3b/x_{\rm fo})},$$

where $\langle \sigma_A^{\rm NR} v \rangle \simeq a + b\langle v^2 \rangle + O(v^4)$
a and bv^2 correspond to s-wave and p-wave annihilation, respectively.

in the SM: $g_{\rm eff}$ =10.75 at 1MeV $< T <$ 100 MeV
$g_{\rm eff} \simeq$60 above the QCD phase transition
$g_{\rm eff} \simeq$100 at $T > m_{\rm top}$

Kinetic Decoupling of Non-Relativistic particles $T < m$

At **chemical decoupling or freeze-out**: the number density is fixed.
At **kinetic decoupling**: the exchange of momentum with the radiation bath ceases to be effective. It happens after chemical decoupling:

The fraction of the WIMP momentum lost per collision with the plasma is small (T/m) thus

$$\Gamma_{\rm E-loss} \simeq \Gamma_{\rm scatt}\frac{T}{m} << \Gamma_{\rm scatt}$$

$$T_{\rm k.d.} \simeq 15 \text{ MeV} \left(\frac{m}{100\text{GeV}}\right)^{1/4} << T_{\rm f.o.} \simeq 5 \text{ GeV} \left(\frac{m}{100\text{GeV}}\right)$$

For different WIMP candidates $T_{kd} \sim 10$ MeV to a few GeV (Profumo, 2006).
At kinetic decoupling, WIMPs are in thermal equilibrium with the radiation, and their characteristic speed is $v(T_{\rm kd}) \simeq \sqrt{T_{\rm kd}/m}$. At $T < T_{\rm kd}$, v redshift: $v \sim a^{-1} \sim T$

$$v_{\text{WIMP}}(T) \simeq \sqrt{\frac{T_{\rm kd}}{m}}\left(\frac{T}{T_{\rm kd}}\right)$$

until WIMPs fall into structures and get their viral velocity.

Caveats to Thermal WIMPs as Dark Matter

- Asymmetric DM We owe our very existence to a particle-antiparticle asymmetry so why not also the DM? Requires non-self conjugated DM particles- e.g. cannot be Majorana fermions (Nussinov 85; Gelmini, Hall, Lin 87; Kaplan 92; Barr, Chivukula, Fahri 90; Enkvist, MacDonald 98; Gudnason, Kouvaris, Sannino 05; Kaplan, Luty, Zurek 09; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....among others)
- Non-Standard Pre-Big bang Nucleosynthesis (pre-BBN) cosmology WIMP relic abundance is fixed before BBN, a moment in the Universe from which we have so far no data. (See e.g. Gelmini et al hep-ph/0605016, or Gelmini, Gondolo 1009.3690 and refs. therein)
  $T \simeq \dfrac{m}{20} > 5$ MeV for $m > 100$ MeV!
  Salas *et al* "Bounds on very low reheating scenarios after Planck" 1511.0067
- WIMPs may be unstable and decay into the dark matter (Super-WIMP scenario). (Feng, Rayaraman, Takayama 03; Feng, Smith 04)
- WIMPs can be produced in decays of other particles (Sigurdson, Kamionkowski 04; Kaplinghat 05) WIMPs could even be WDM if created late in decays are never in kinetic equilibrium with the bath.

Asymmetric DM (ADM) Idea almost as old as the "WIMP miracle"
For baryons $A_B = (n_B - n_{\bar{B}})/n_\gamma \simeq 10^{-9}$, and annihilation ceases when no $\bar{B}$ left, and $n_B/n_\gamma \simeq 10^{-9}$ Assume $A_{\rm DM}$ and A_B generated by similar physics, $A_{\rm DM} \simeq A_B$ so $n_{\rm DM} \simeq n_B$

$$\frac{\Omega_{\rm DM}}{\Omega_B} \simeq \frac{n_{DM} m_{\rm DM}}{n_B m_N} \simeq \frac{m_{\rm DM}}{m_N}$$

$\Omega_{\rm DM}/\Omega_B \simeq 5$ if $m_{\rm DM} \simeq 5$ GeV. So ADM explains why $\Omega_{\rm DM}/\Omega_B \simeq O(1)$

GeV scale ADM in hidden/mirror sector, or pNGB in Technicolor or low scale strong interactions....
Also possible TeV scale ADM in Technicolor: $A_{DM} \simeq A_B \exp\left(-m_{DM}/T_{\rm weak}\right)$

(Nussinov 85; Gelmini, Hall, Lin 87; Barr, Chivukula, Fahri 90; Barr, 1991; Kaplan 92; Enkvist, MacDonald 98; Dodelson, Greene and Widrow, 1992; Fujii and Yanagida, 2002; Kitano and Low, 2005; Gudnason, Kouvaris, Sannino 05; Kitano, Murayama and Ratz, 2008; Kaplan, Luty, Zurek 09; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....)

Main characteristic: no annihilation rate after freeze-out.

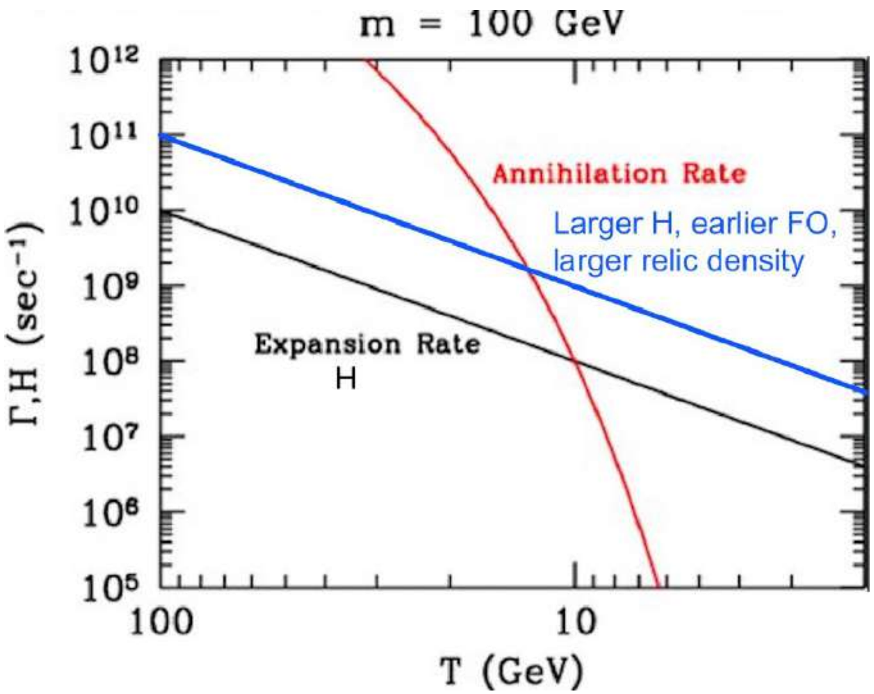
DM as the earliest relic, from before BBN

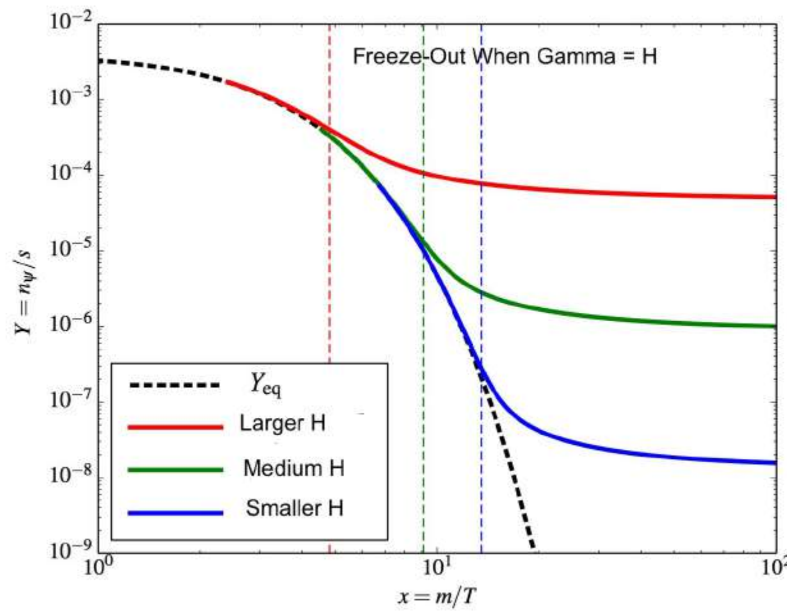
Relic densities change in non-Standard pre-BBN Cosmologies
For DM densities due to freeze-out:

- **Increase** the density by increasing the expansion rate at freeze-out [e.g. quintessence-scalar-tensor models] or by creating DM from particle (or topological defects) decays [non-thermal production].
- **Decrease** the density by reducing the expansion rate at freeze-out [e.g. scalar-tensor models], by reducing the rate of thermal production [low reheating temperature] or by producing radiation after freeze out [entropy dilution].

Non-std scenarios are more complicated and many times not complete (in terms of baryon number generation, for example). But if a experimental result would hint at one of them, they could be completed...

Freeze Out: effect of a non-standard expansion rate H





See e.g. G.G. and P. Gondolo, PRD 74 (2006) 023510, ; G.G., P. Gondolo, A. Soldatenko and C. E. Yaguna, PRD 74 (2006) 083514 and PRD 76 (2007) 015010; G.G. Ji-Haeng Huh and Rehagen JCAP 08 (2013) 003

WIMP density as cosmology probe

WIMP properties be used to find out about the cosmology before BBN. . .

This is not a new idea

MASSIVE PARTICLES AS A PROBE OF THE EARLY UNIVERSE

John D. BARROW

Astronomy Centre, University of Sussex, Brighton BN1 9QH, UK

Received 29 January 1982
(Revised 30 March 1982)

The survival density of stable massive particles with general annihilation cross section is calculated in a cosmological model that expands anisotropically in its early stages ($t < 1$ s). It is shown that the faster average expansion rate leaves a larger present density of surviving particles than in a model that expands isotropically. This allows particle survival calculations to be employed as a probe of the dynamics of the early universe prior to nucleosynthesis. Several examples of heavy lepton, nucleon and monopole survival are discussed.

WIMP density as cosmology probe

WIMP properties used to find out about the cosmology before BBN. . .

This is not a new idea

Thermal relics: Do we know their abundances?

Marc Kamionkowski and Michael S. Turner

Physics Department, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433
and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500

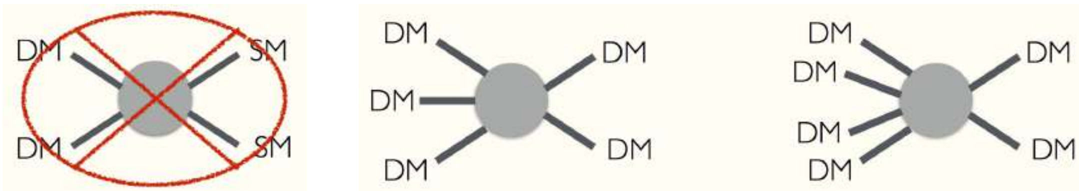
(Received 25 May 1990)

The relic abundance of a particle species that was once in thermal equilibrium in the expanding Universe depends upon a competition between the annihilation rate of the species and the expansion rate of the Universe. Assuming that the Universe is radiation dominated at early times the relic abundance is easy to compute and well known. At times earlier than about 1 sec after the bang there is little or no evidence that the Universe *had* to be radiation dominated, although that is the simplest—and standard—assumption. Because early-Universe relics are of such importance both to particle physics and to cosmology, we consider in detail three nonstandard possibilities for the Universe at the time a species' abundance froze in: energy density dominated by shear (i.e., anisotropic expansion), energy density dominated by some other nonrelativistic species, and energy densi-

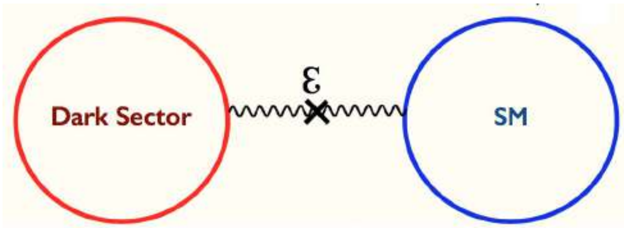
Dark-sector thermal production: Freeze-out of SIMPs

Hochberg, Kuflik, Volansky & Wacker, 1402.5143; Kuflik, Hochberg, Murayama, Volansky & Wacker, 1411.3727

Assumes



The 3 or 4 DM $\rightarrow$ 2 DM "Cannibalism" processes reduce $n_{\rm DM}$ when $T < m_{\rm DM}$ and heat up the DM. So as to not end as Hot DM there must be kinetic coupling (i.e. effective momentum exchange) with visible matter. This also equalizes the temperature in both sectors



3$\rightarrow$2 freeze-out: $\Gamma \simeq n_{\rm DM}^2 \left(\alpha_{\rm eff}^3/m_{\rm DM}^5\right) \simeq H(T)$, with $x_{\rm fo} \simeq 20$, $m_{\rm DM} \simeq$40MeV, $T_{\rm fo} \simeq$ 2MeV

4$\rightarrow$2 freeze-out: $\Gamma \simeq n_{\rm DM}^3 \left(\alpha_{eff}^4/m_{\rm DM}^8\right) \simeq H(T)$ for $x_{\rm fo} \simeq$14, $m_{\rm DM} \simeq$0.1MeV, $T_{\rm fo} \simeq$ 7keV

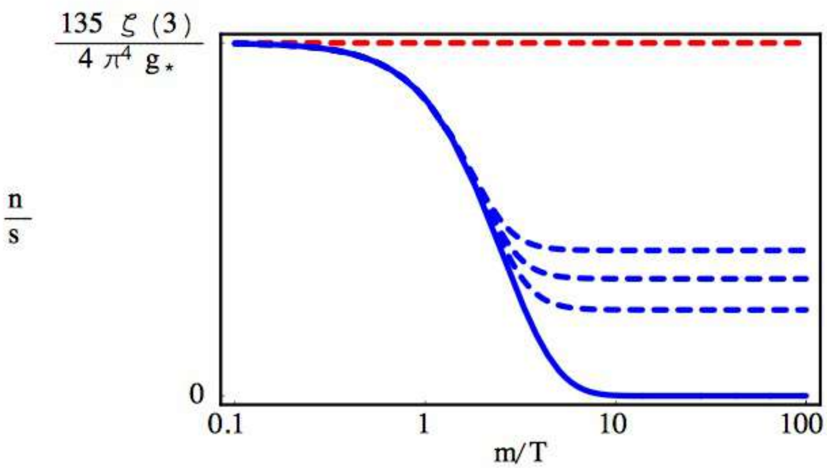
(The quantities in the large brackets are here obtained just on dimensional grounds).

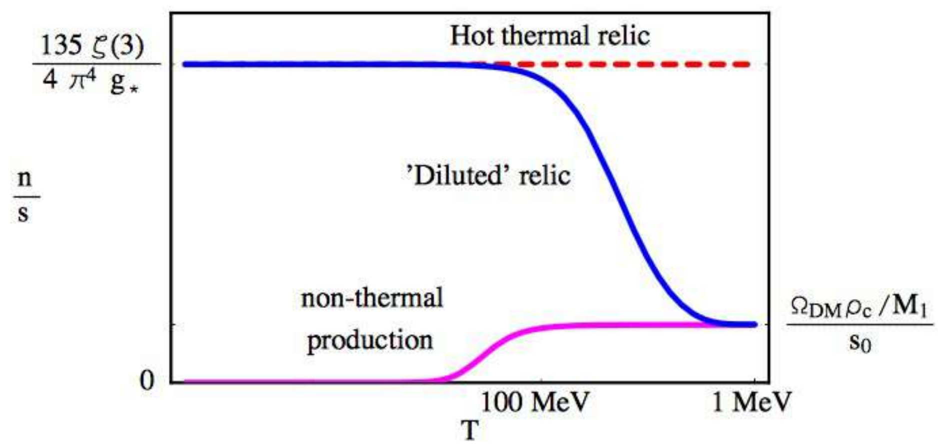
ELDERs have also DM SM$\rightarrow$ DM SM elastic scattering which determines fo.

Thermal production: Early freeze-out and entropy dilution

DM particles could freeze-out very early and entropy dilution due to particles annihilating after they decouple reduces their abundance (e.g.sterile neutrinos)

LEFT: Thermal production- RIGHT: Thermal equilibrium+decoupling plus dilution, or freeze-in.

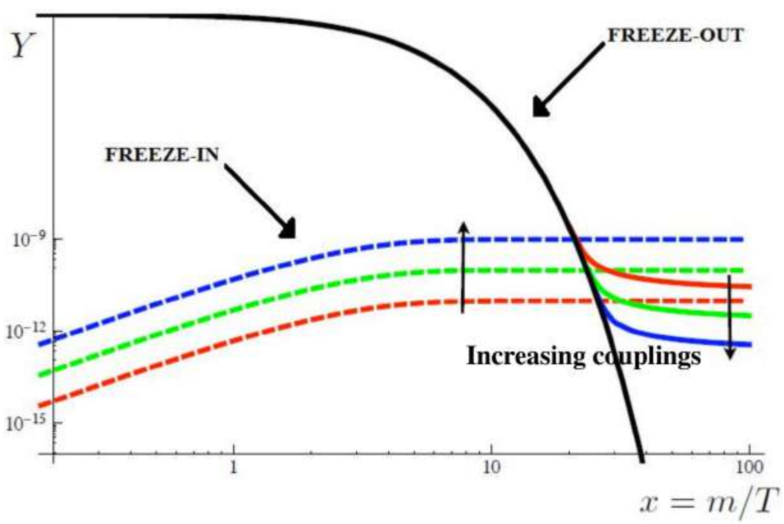


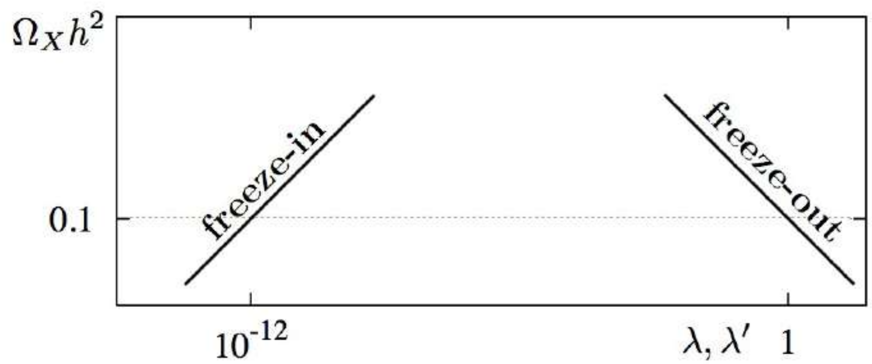


Non thermal mechanism: Freeze-in of FIMPs Hall, Jedamzik, March-Russell & West, 0911.1120...; see e.g. Bernal, Heikinheimo, Tenkanen, Tuominen &Vaskonen 1706.07442 and ref. therein

Particles produced at a low rate, never reach equilibrium with the bath. Density fixed when production stops. Example: Higgs Φ portal Lagrangian for a hidden sector FIMP$=$ a real singlet scalar S, $\lambda_{\rm sh} < 10^{-7}$ so S does not thermalize.

$$V(\Phi, s) = \mu_{\rm h}^2 \Phi^\dagger \Phi + \lambda_{\rm h}(\Phi^\dagger \Phi)^2 + \frac{1}{2}\mu_{\rm s}^2 s^2 + \frac{\lambda_{\rm s}}{4} s^4 + \frac{\lambda_{\rm sh}}{2}\Phi^\dagger \Phi s^2$$





Non thermal mechanism: Freeze-in of sterile neutrinos

The 3 (left-handed) neutrinos of the SM are called "active neutrinos" because they have full strength weak interactions, but others with no weak interactions (right-handed) thus called **"sterile"** ν_s (Bruno Pontecorvo- 1967)
ν_s, can be easily added to the SM (one or more).

ν_s can be created via active-sterile neutrino oscillations, either without (Dodelson & Widrow 1994) or with (Shi & Fuller 1998) a large Lepton Asymmetry L (L-driven MSW conversion), and respectively be Warm DM or "less warm" DM.

For two-neutrino active-sterile mixing where $|\nu_{\alpha,s}\rangle$ are interaction eigenstates (α left handed, s right-handed) and $|\nu_{1,2}\rangle$ are mass eigenstates, $m_1 << m_2 \equiv m_s$
$|\nu_\alpha\rangle = \cos\theta\ |\nu_1\rangle + \sin\theta\ |\nu_2\rangle$;
$|\nu_s\rangle = -\sin\theta\ |\nu_1\rangle + \cos\theta\ |\nu_2\rangle$

ν_s can also be produced in the decay of other particles (e.g. new scalar fields or heavier sterile neutrinos). **Continue in Part 2.**