Dark Matter Theory
Lecture 1

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Plan for the lectures

- Lecture 1: What we know about dark matter and what it could consist of.

- Lecture 2, 3: Dark matter particle candidates and their production mechanisms.

What we are looking for

Content:

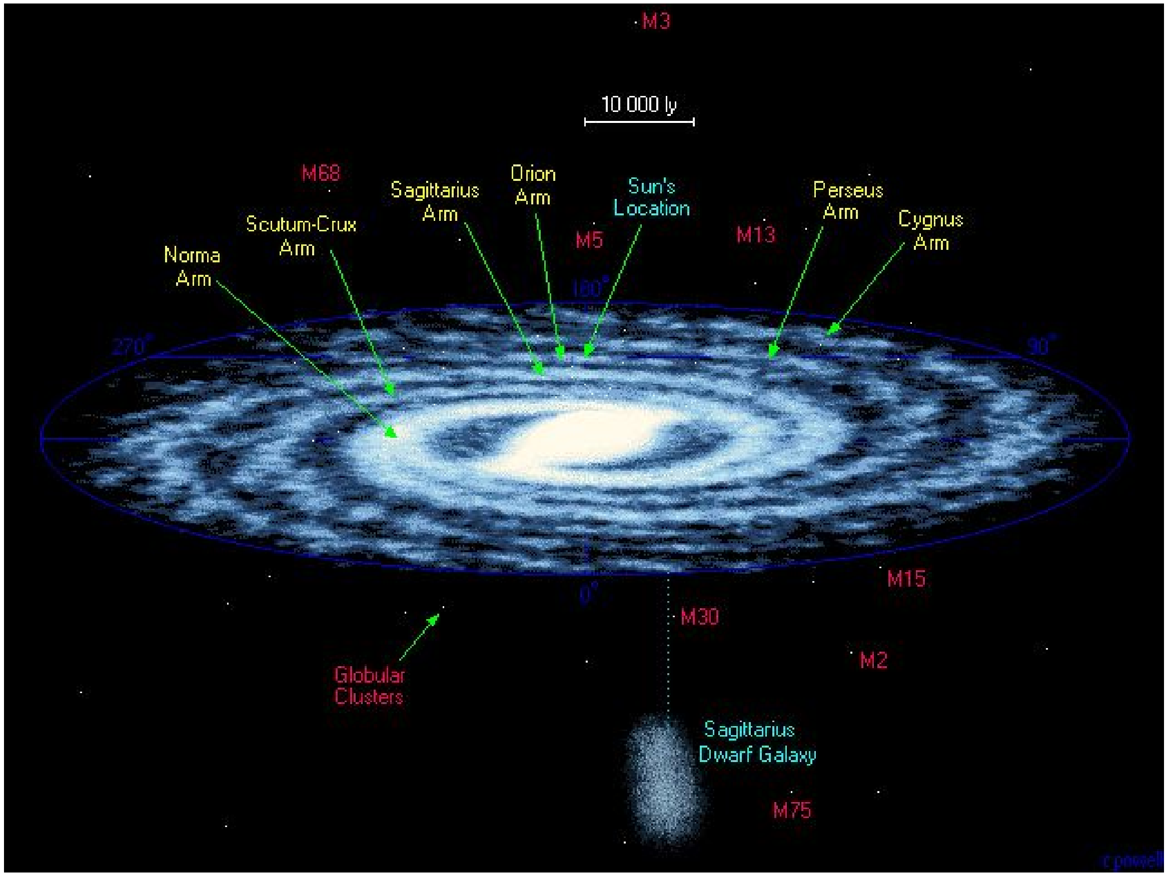
- Brief review of astrophysical/cosmological data.
- Brief reminder of what we know about dark matter.
- Implications for dark matter candidates

  - PBH or new particles? - CDM, WDM, PIDM, DDDM, SIDM?

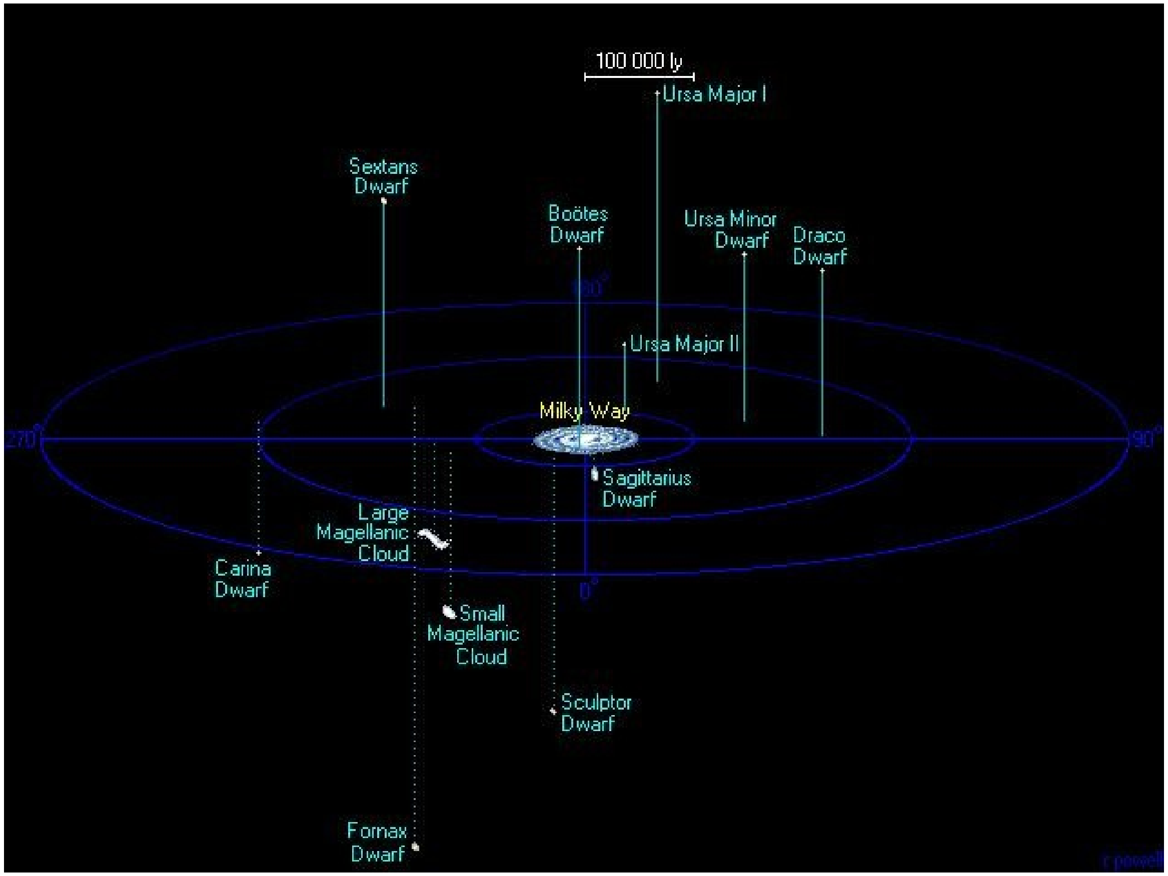
  - Kinetic mixing, Hidden or dark photons, Atomic DM, Mirror DM, WIMPs, FIMPs, SIMPs, Axions, ALPs, WISPs, sterile neutrinos...?

(Disclaimer: idiosyncratic choice of subjects-not complete lists of citations.)

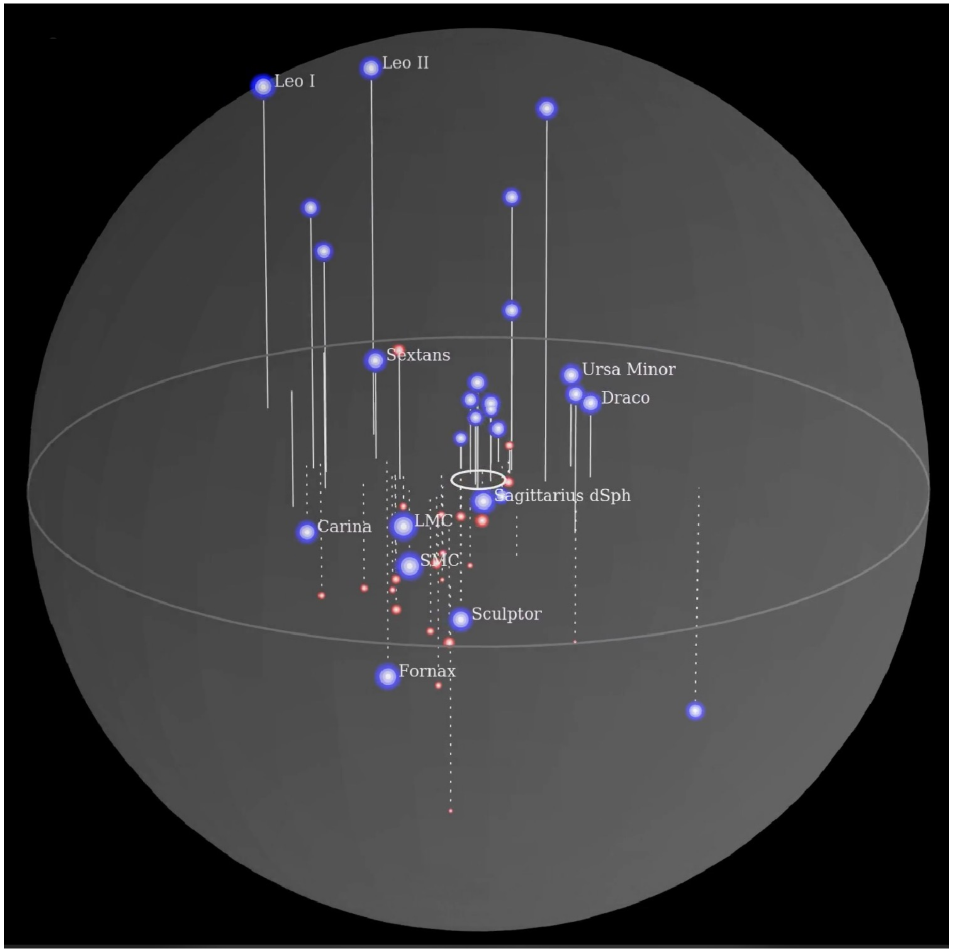
The Universe around us: Galaxies are the building blocks of the Universe. The Milky Way and the Sagittarius Dwarf galaxy its nearest satellite galaxy



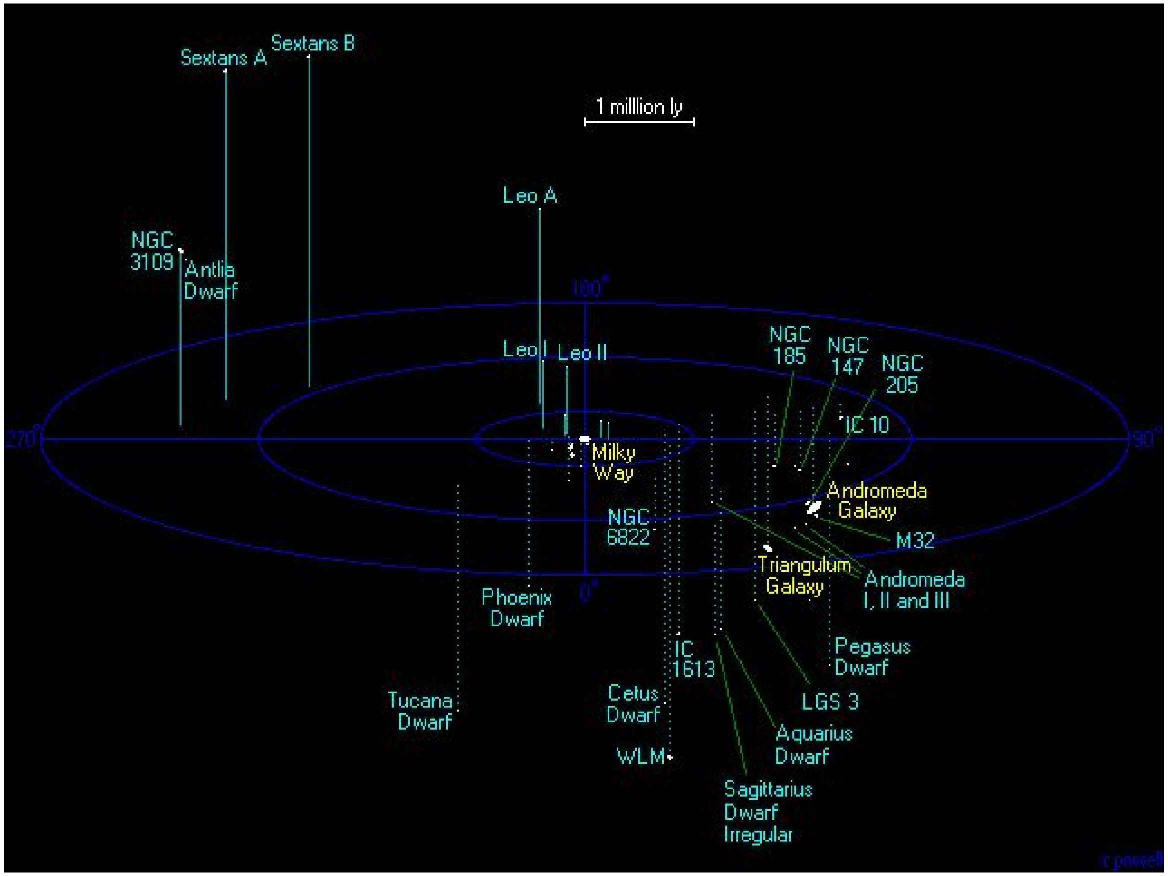
The Milky Way has many small satellite galaxies more than 40 dwarf galaxies found so far



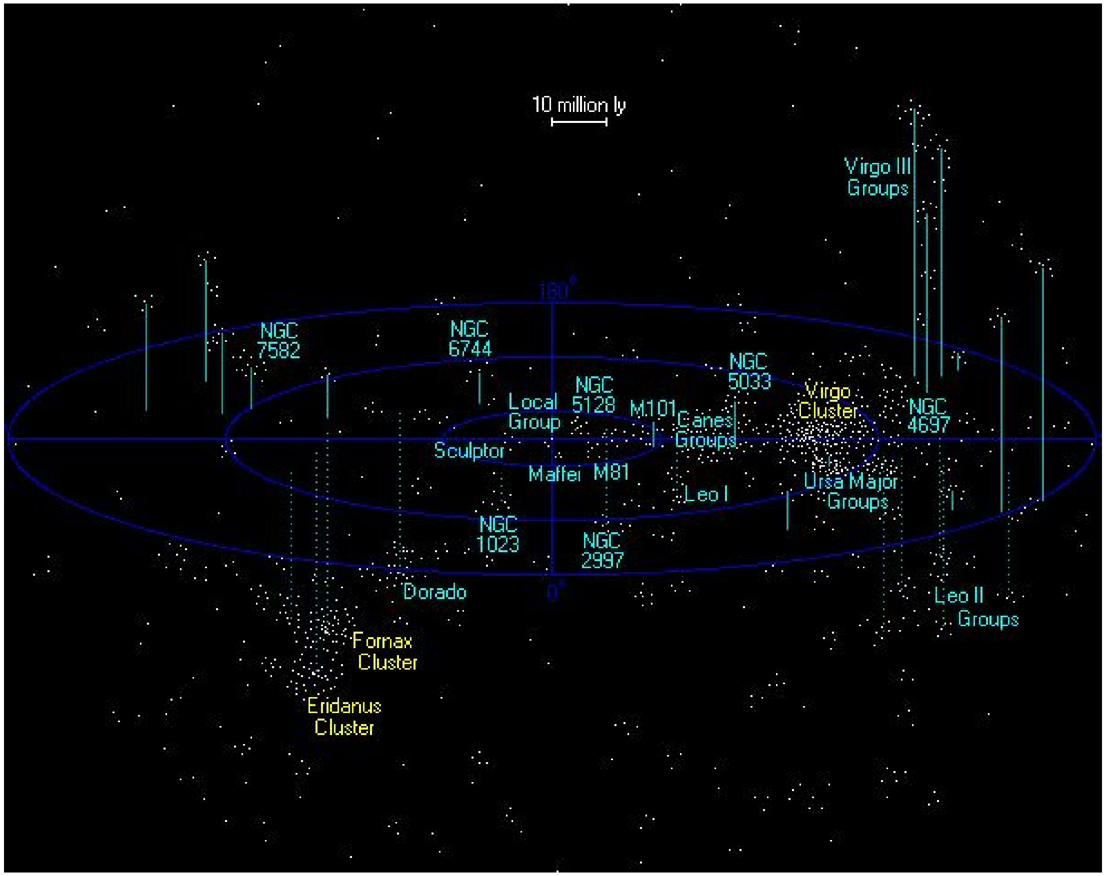
The Milky Way has many small satellite galaxies- dwarfs as of 2016 (in red DES)



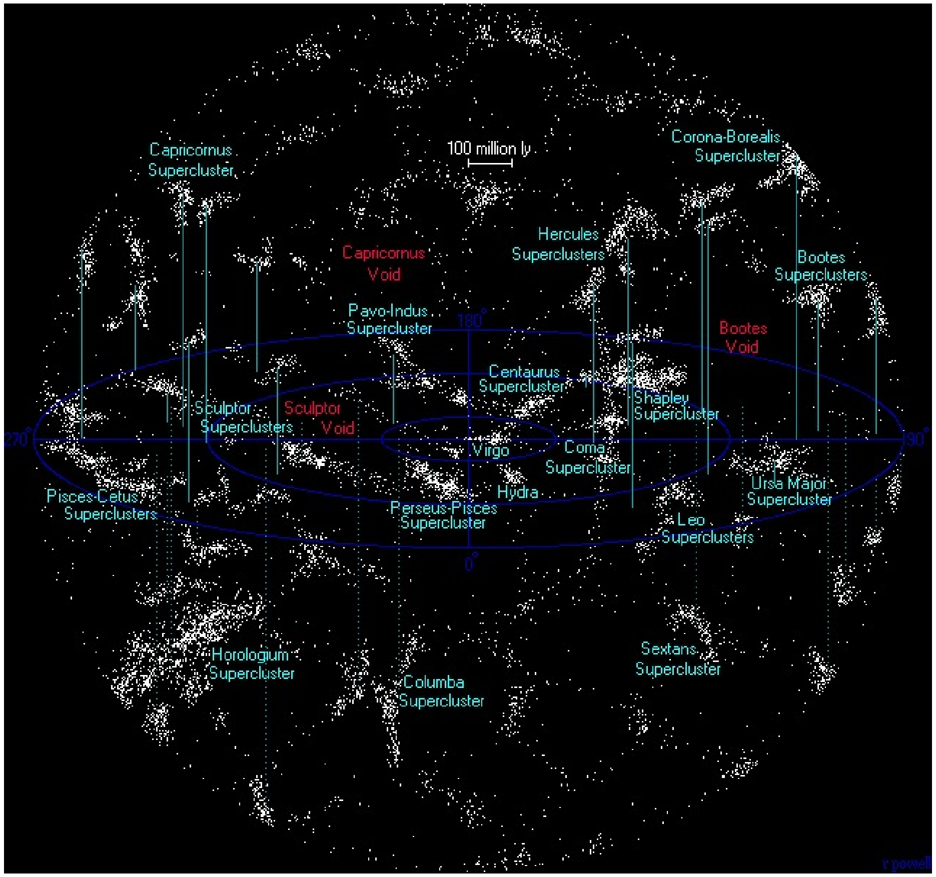
Galaxies come in groups, clusters, superclusters......Our Local Group of galaxies



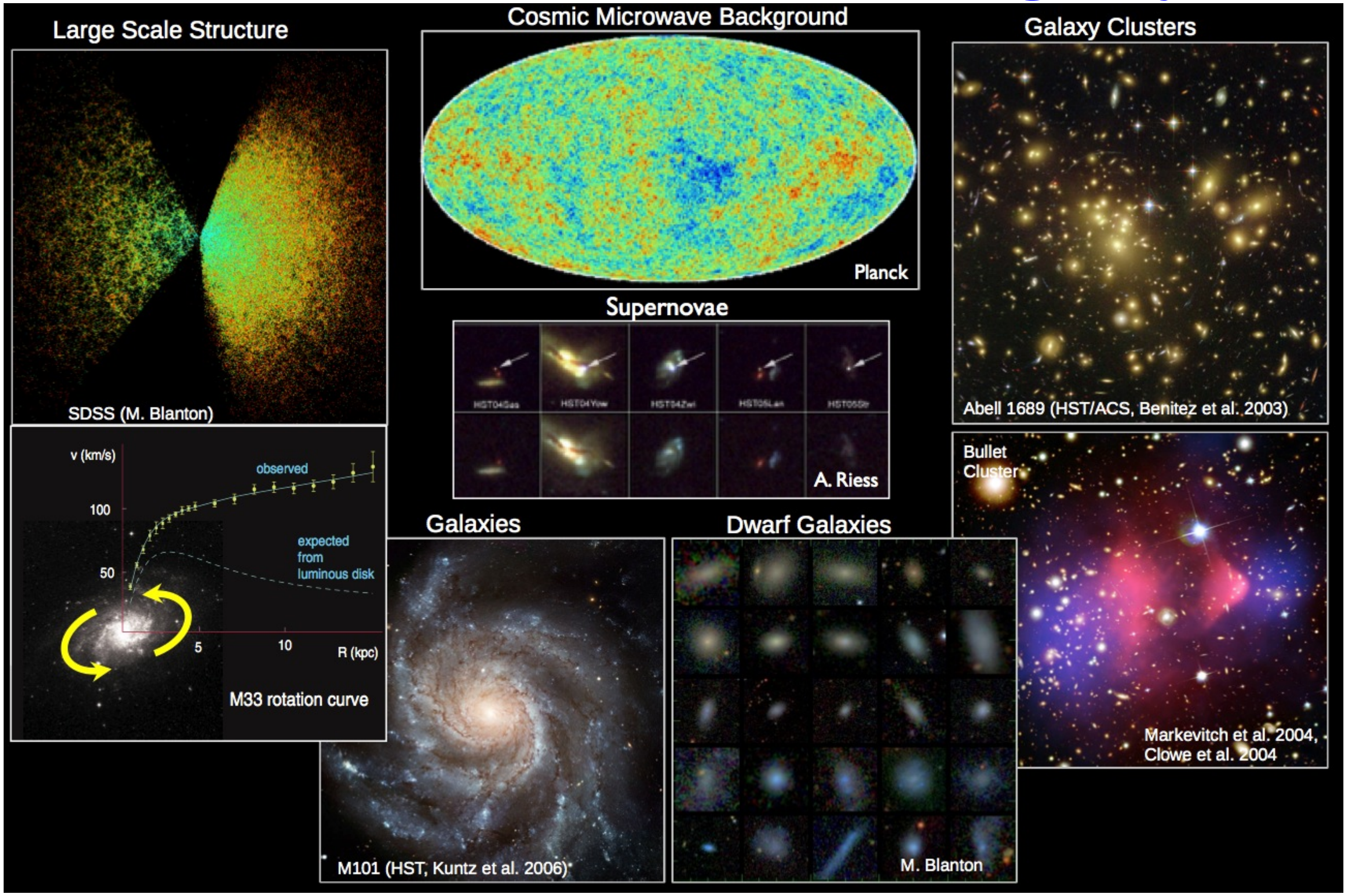
Galaxies come in groups, clusters, superclusters...... Our Local Group is in the outskirts of the Virgo Cluster



Galaxies are the building block of the Universe: they come in groups, clusters, (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,

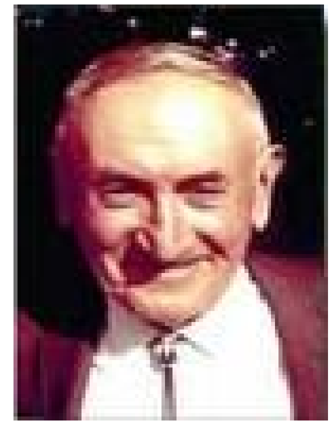
Fritz Zwicky, Helvetica Physica Acta Vol6 p.110-127, 1933

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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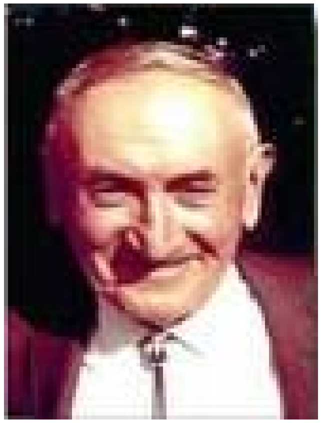
gr/cm³. Es ist natürlich möglich, dass leuchtende plus **dunkle (kalte) Materie** zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\varrho \sim 10^{-28}$ gr/cm³ erscheint daher nicht

used the Virial Theorem in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only. J. Ostriker: in the first 40y his seminal 1937 paper had 10 citations!

Dark Matter discovered

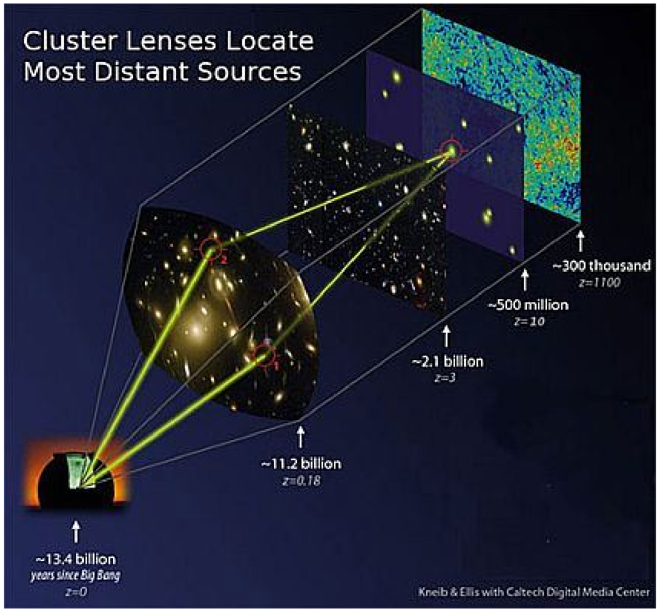
In 1930's Fritz Zwicky used the Virial Theorem in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only



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

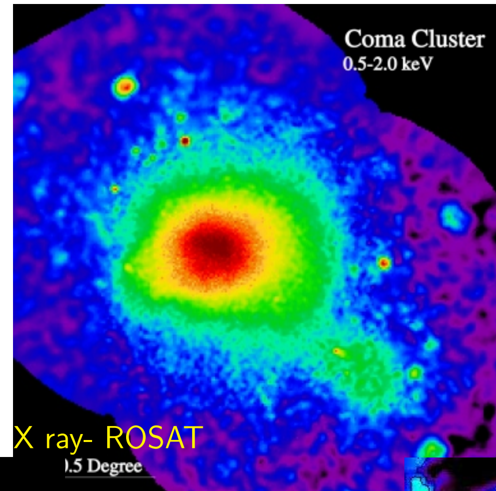
Another later method: gravitational lensing

depends on all the intervening mass



DM dominates in galaxy clusters

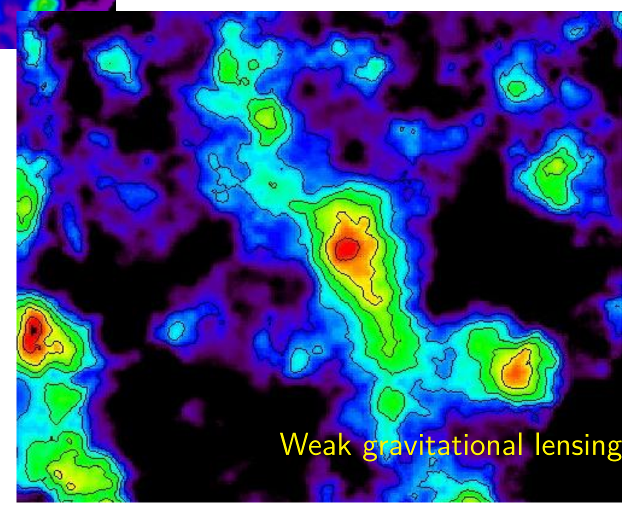

Coma cluster optical-Kitt Peak



X ray- ROSAT

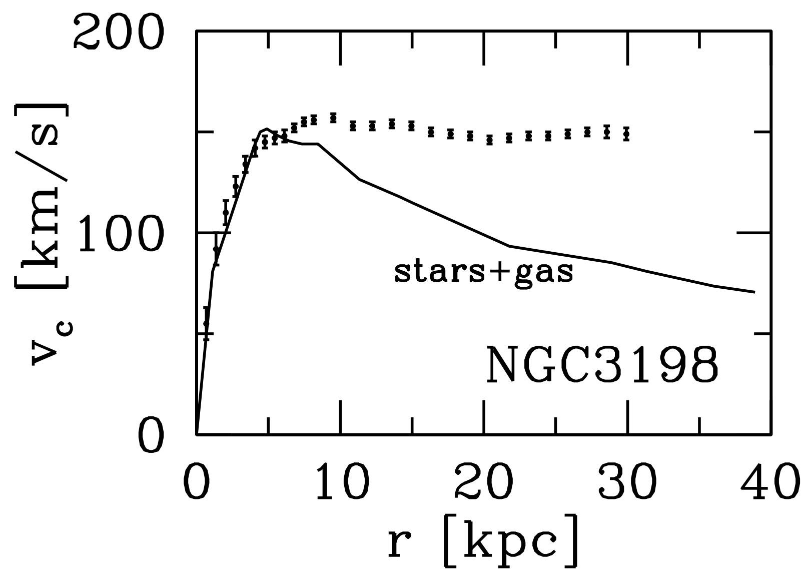
$$\boxed{\frac{M}{M_{vis}} \simeq 6}$$

Strong gravitational lensing


Weak gravitational lensing

Dark Matter rediscovered

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



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

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

even where there is no light!

1 pc = 3.2 ℓy

Dark Matter dominates in galaxies e.g. in NGC3198

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

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

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

Galaxy like ours have a Dark Halo which contains about 90% of its mass

At the largest scales:

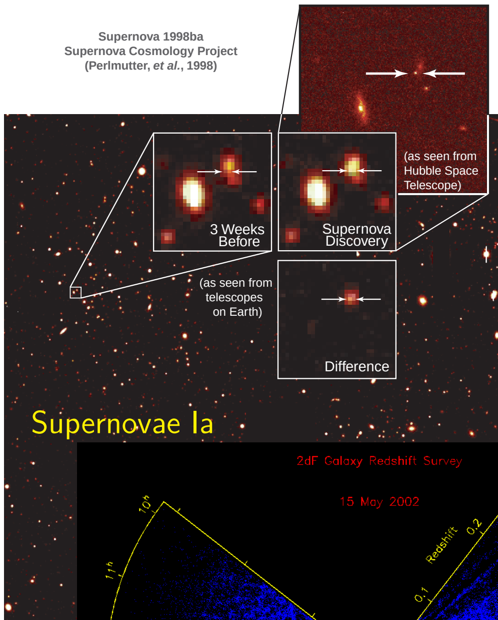
Use General Relativity

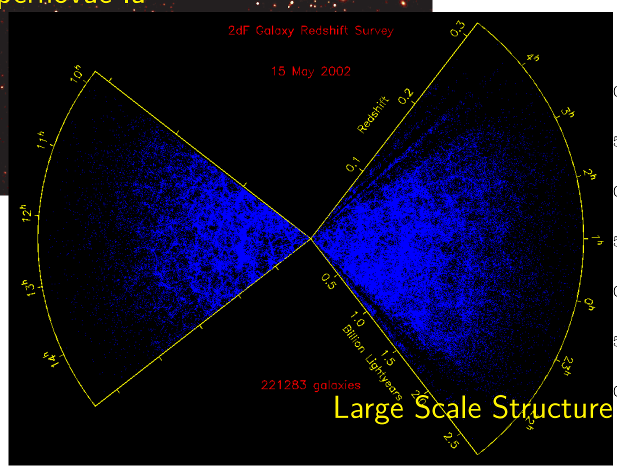
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} \left(+ \Lambda g_{\mu\nu} \right)$$

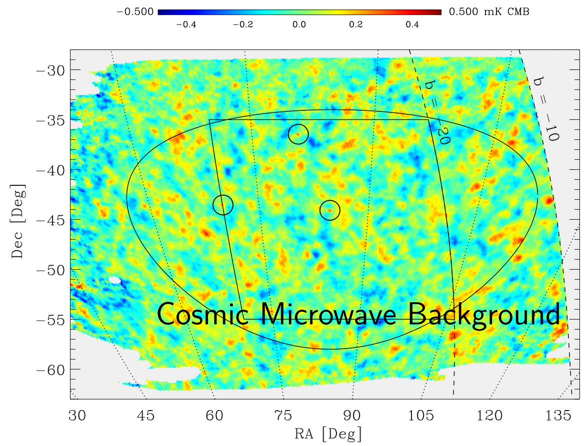
To relate:

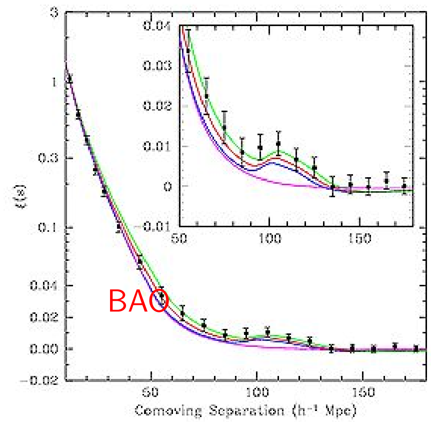
Spacetime geometry $\longleftrightarrow$ Mass-energy density

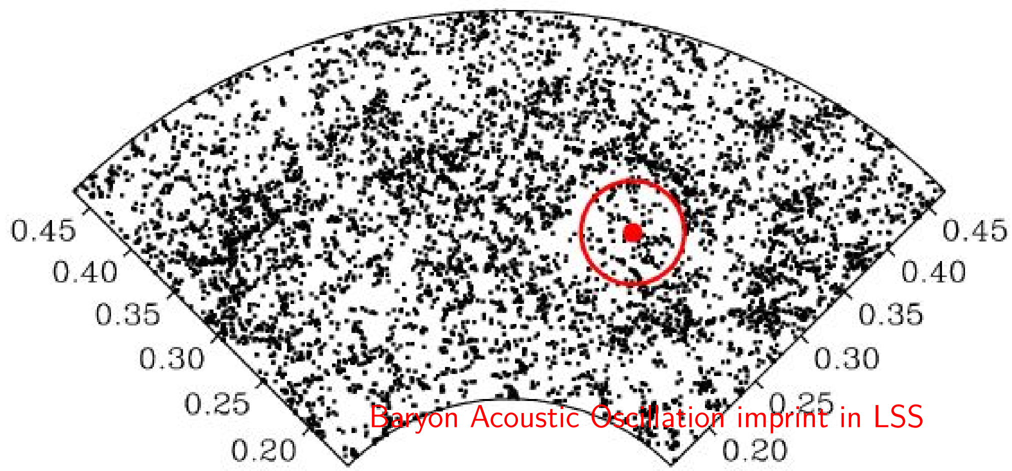
At the largest scales



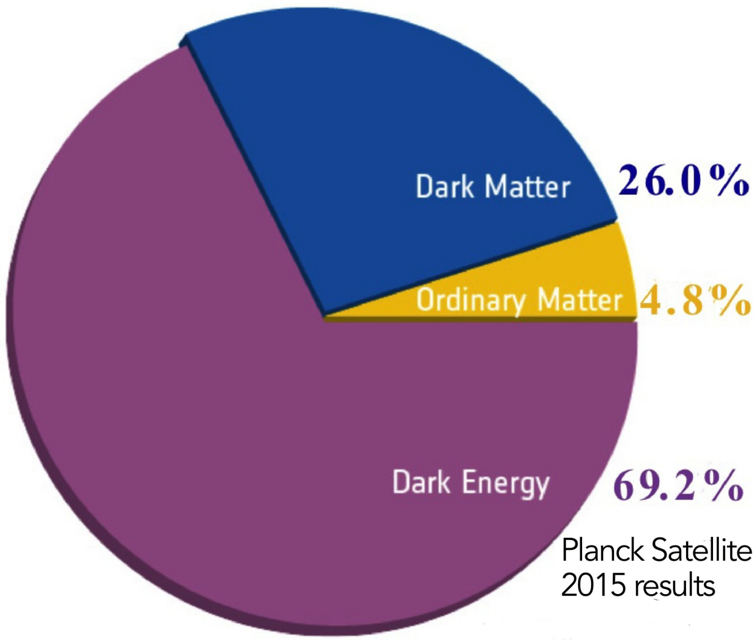


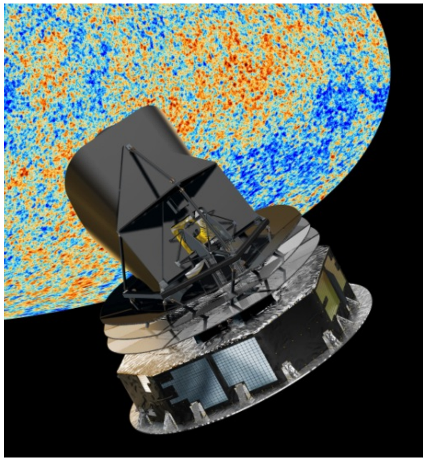






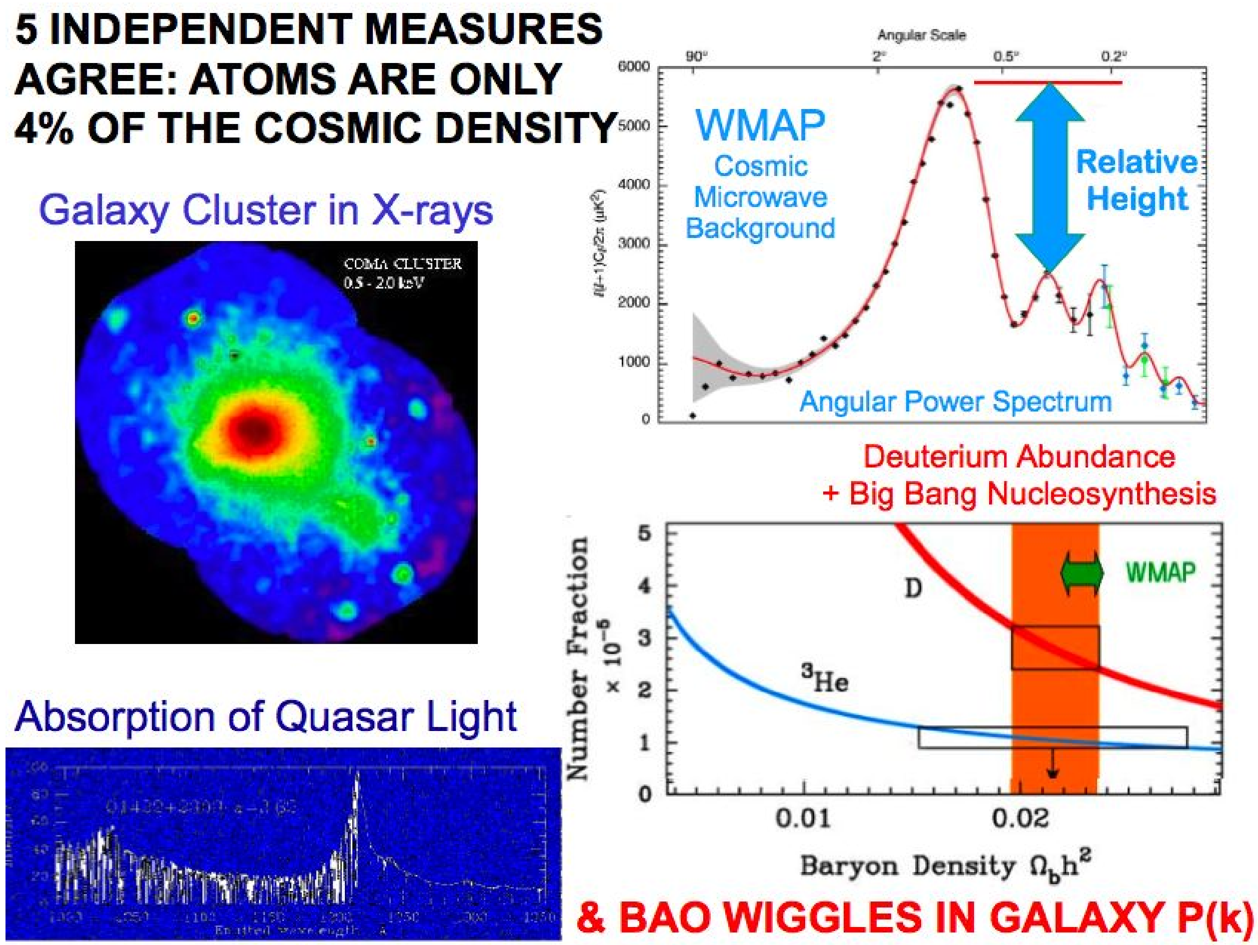
At the largest scales: the "Double-Dark" model





"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



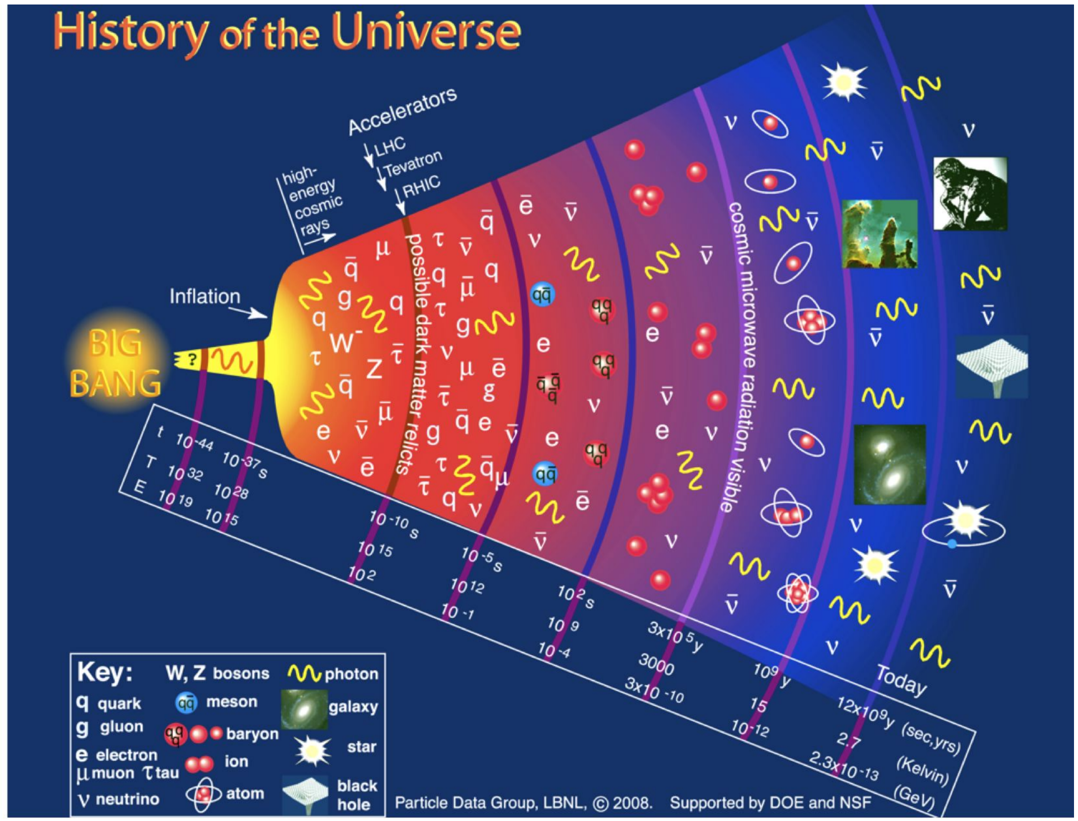
All data confirm the Big-Bang Model of a hot early Universe expanding adiabatically (T decreases inversely to the size of the Universe)

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

Radiation domination to Matter domination
t≃66kyr T≃1 eV

CMB emitted (atoms form)
(Cosmic Microwave Background)
t≃380kyr T≃ 0.3 eV

Now (Planck + other)
t=13.798± 0.037×10^{9}ys



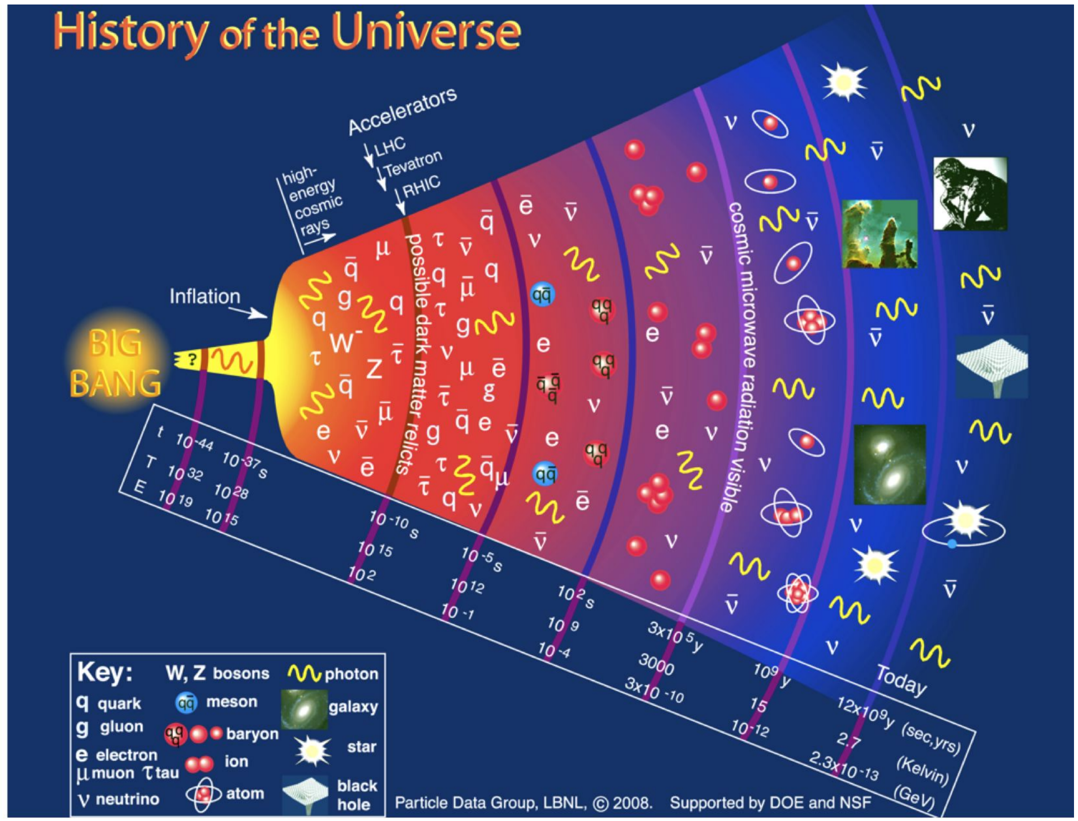
Before BBN?

INFLATION?

period of exponential expansion $a \sim e^{Ht}$

H: Hubble parameter,

a:scale factor of the Universe



After "reheating", finishes in a Radiation Dominated Universe with temperature

T_{RH}

expanding adiabatically

$a \sim 1/T \sim t^{1/2}$

BBN implies $T_{RH} > 5$ MeV

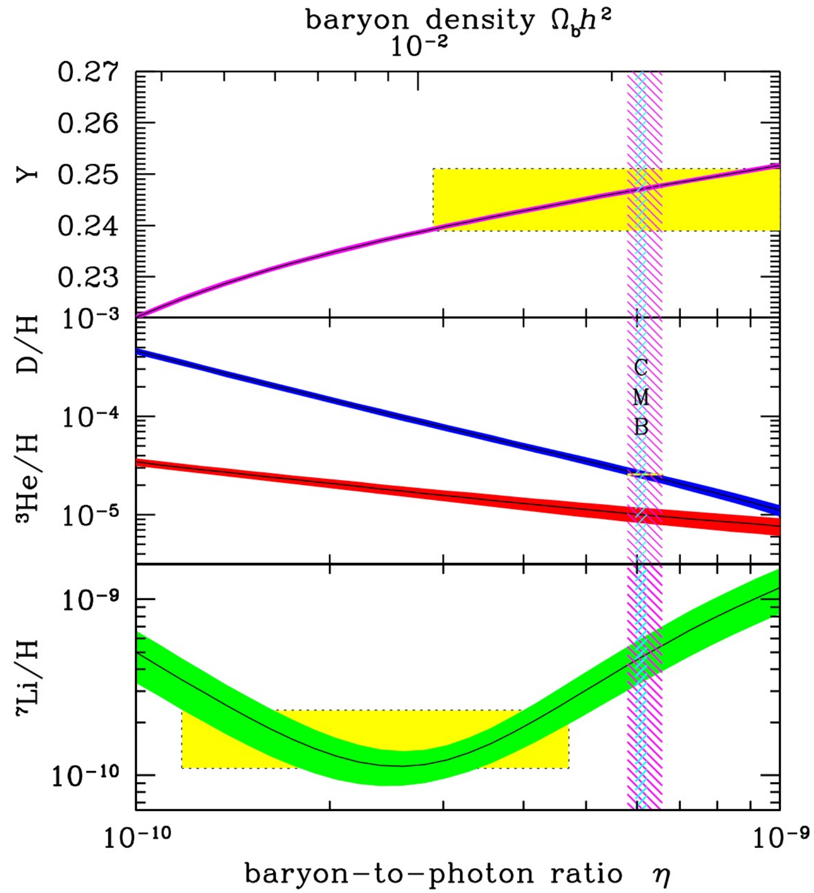
INFLATION invoked to explain properties of the Universe not explained by the Big-Bang model such as

- 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 leading to structure formation in the Universe (as quantum fluctuations).

Not possible to determine what is T_{RH}, except T_{RH} >5 MeV!

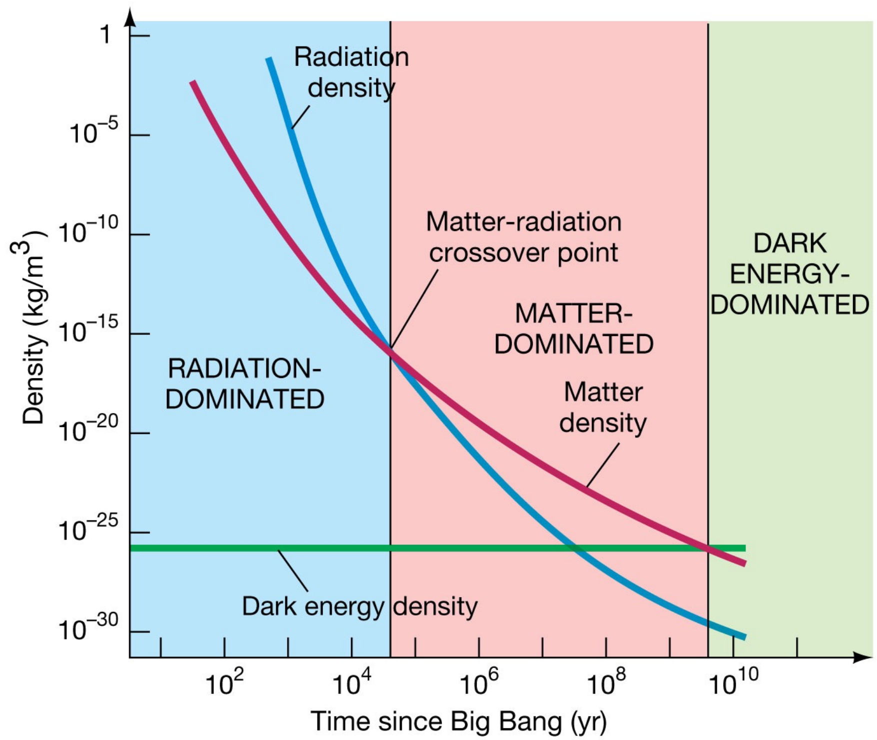
Big Bang Nucleosynthesis (BBN) t $\simeq$ 3-20min T$\simeq$MeV

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

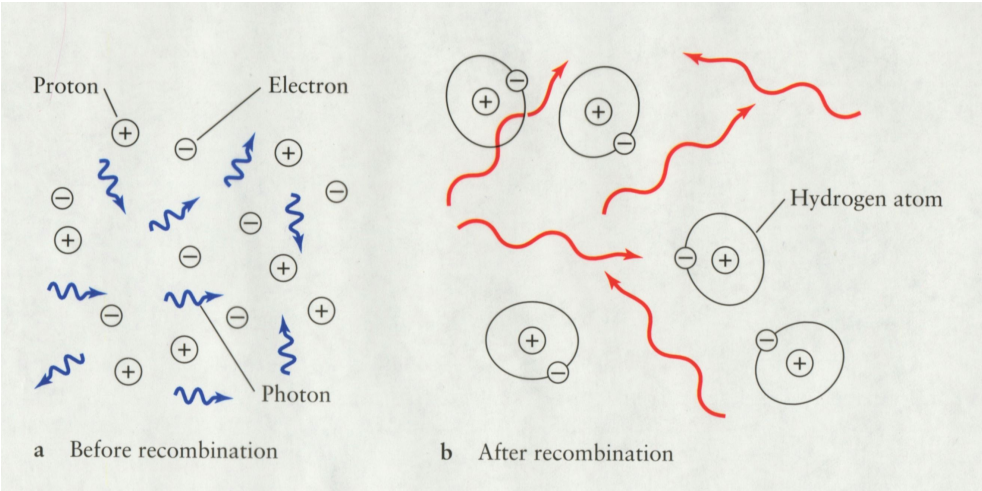
$$\rho_{rad} \sim T^4 \qquad \rho_m = \frac{Number \times Mass}{Volume} \sim 1/a^3 \sim T^3$$



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

Cosmic Microwave Background radiation t $\simeq$ 380 kyr T$\simeq$ 0.3 eV

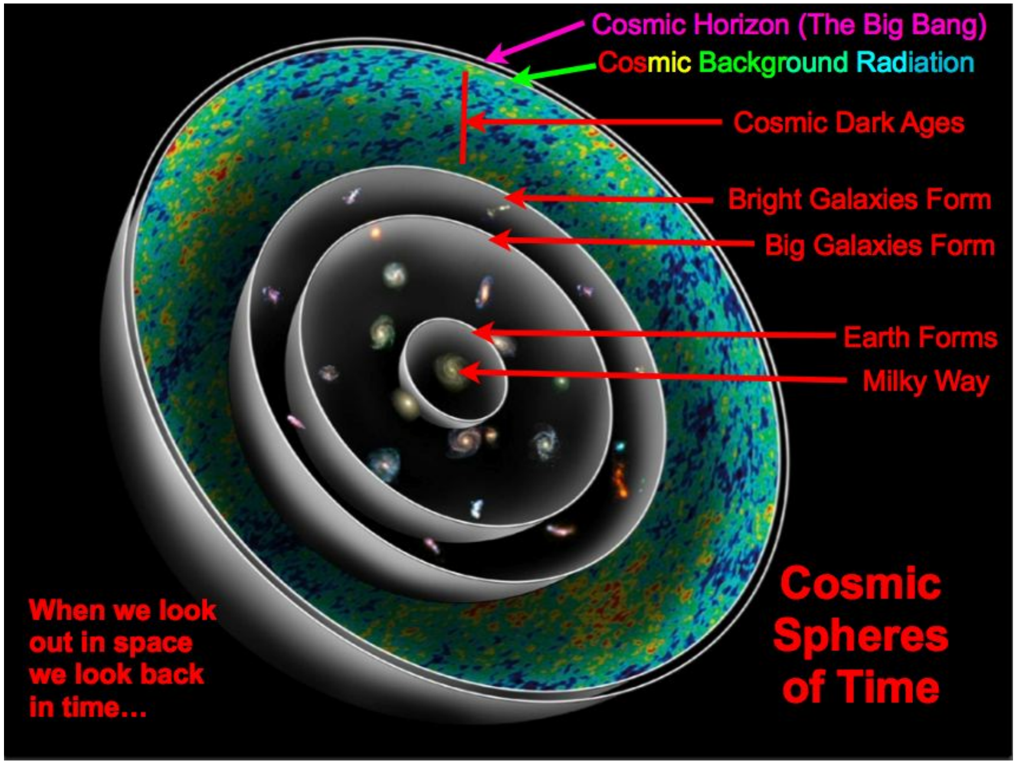
Emitted when atoms became stable for the first time, at "recombination"



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 (thus now $\rho_{rad}/\rho_c \equiv \Omega_{rad} = 1.23 \times 10^{-5}, \Omega_{total} = 1$)

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

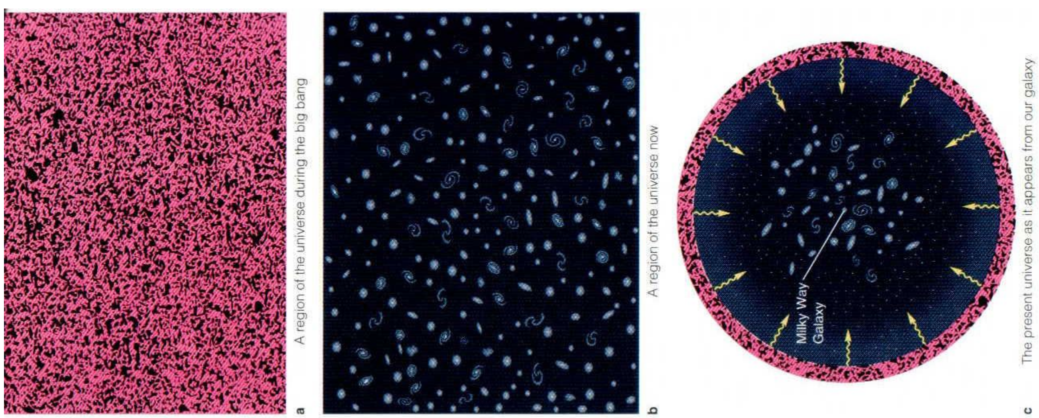
Far away is long ago We see the galaxies within the distance light took to come to us since the first moment bright galaxies formed, before there was the "Cosmic Dark Age" with no stars, and before then the CMBR was emitted at "recombination", when atoms became stable. Fig frm J. Primack

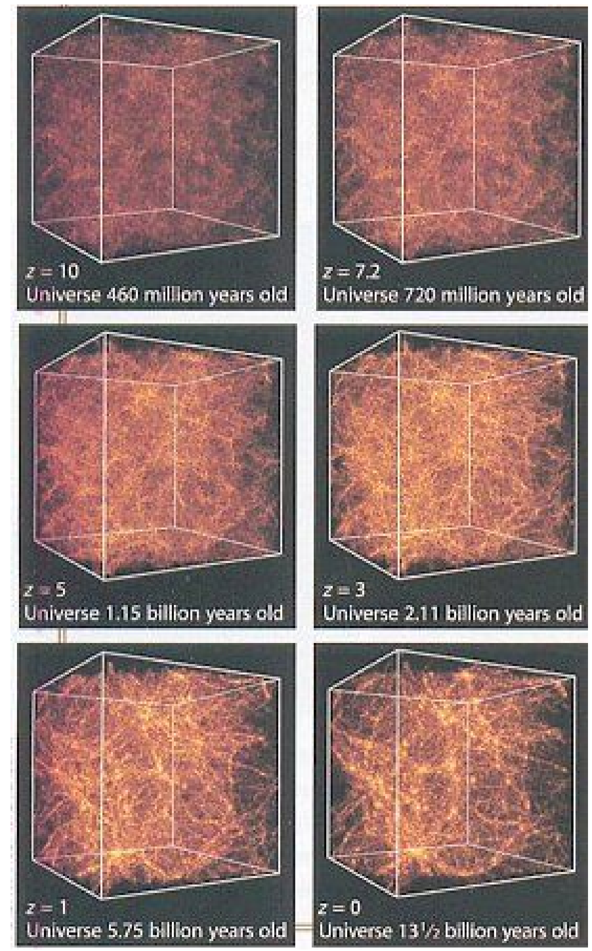


Inhomogeneities lead to structure formation

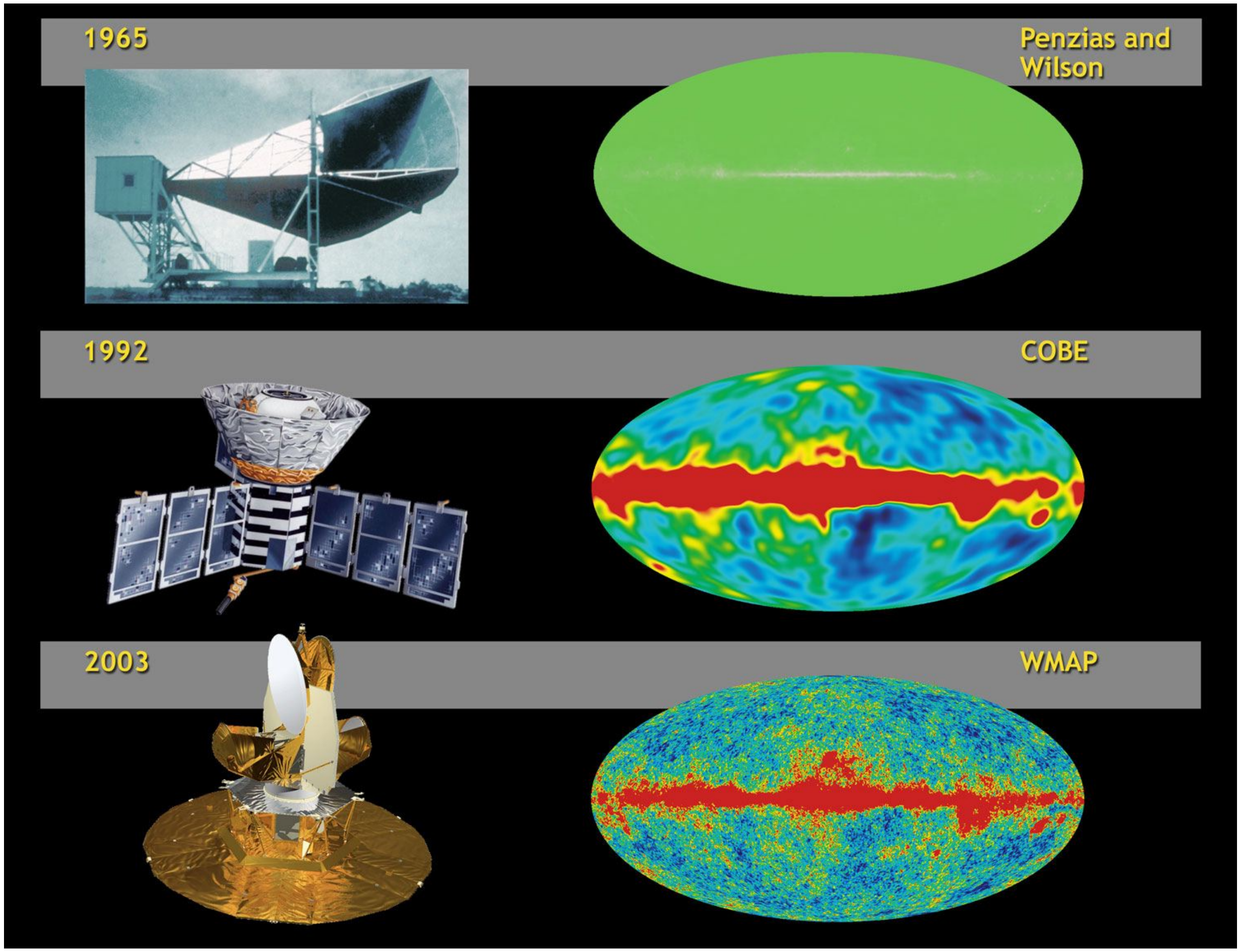
At “recombination” small density inhomogeneities $\frac{\delta\rho}{\rho} = \frac{\rho - \bar{\rho}}{\bar{\rho}}$ produce CMB anisotropies $\frac{\delta T}{T} \simeq 10^{-4}$

$+$gravitational collapse

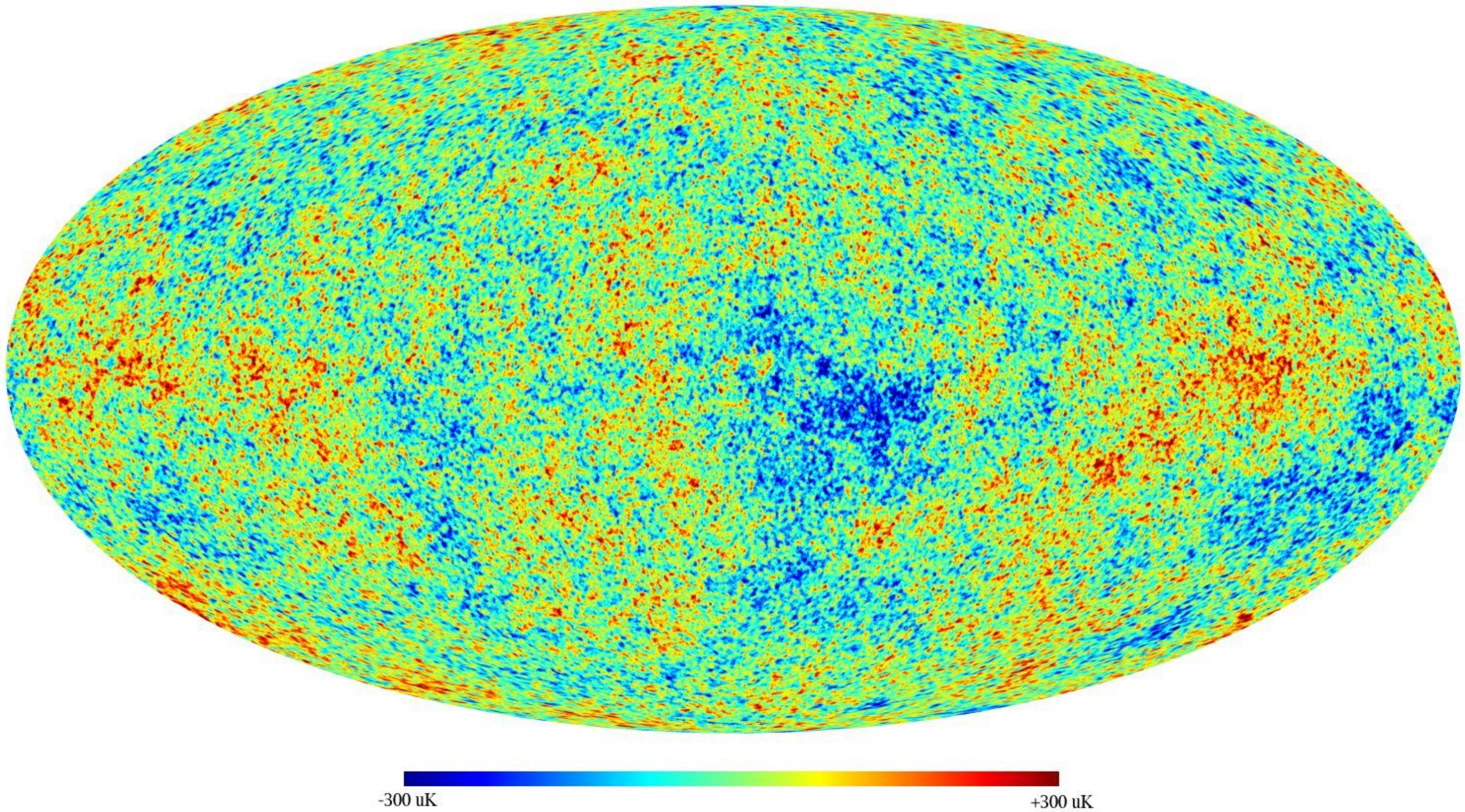




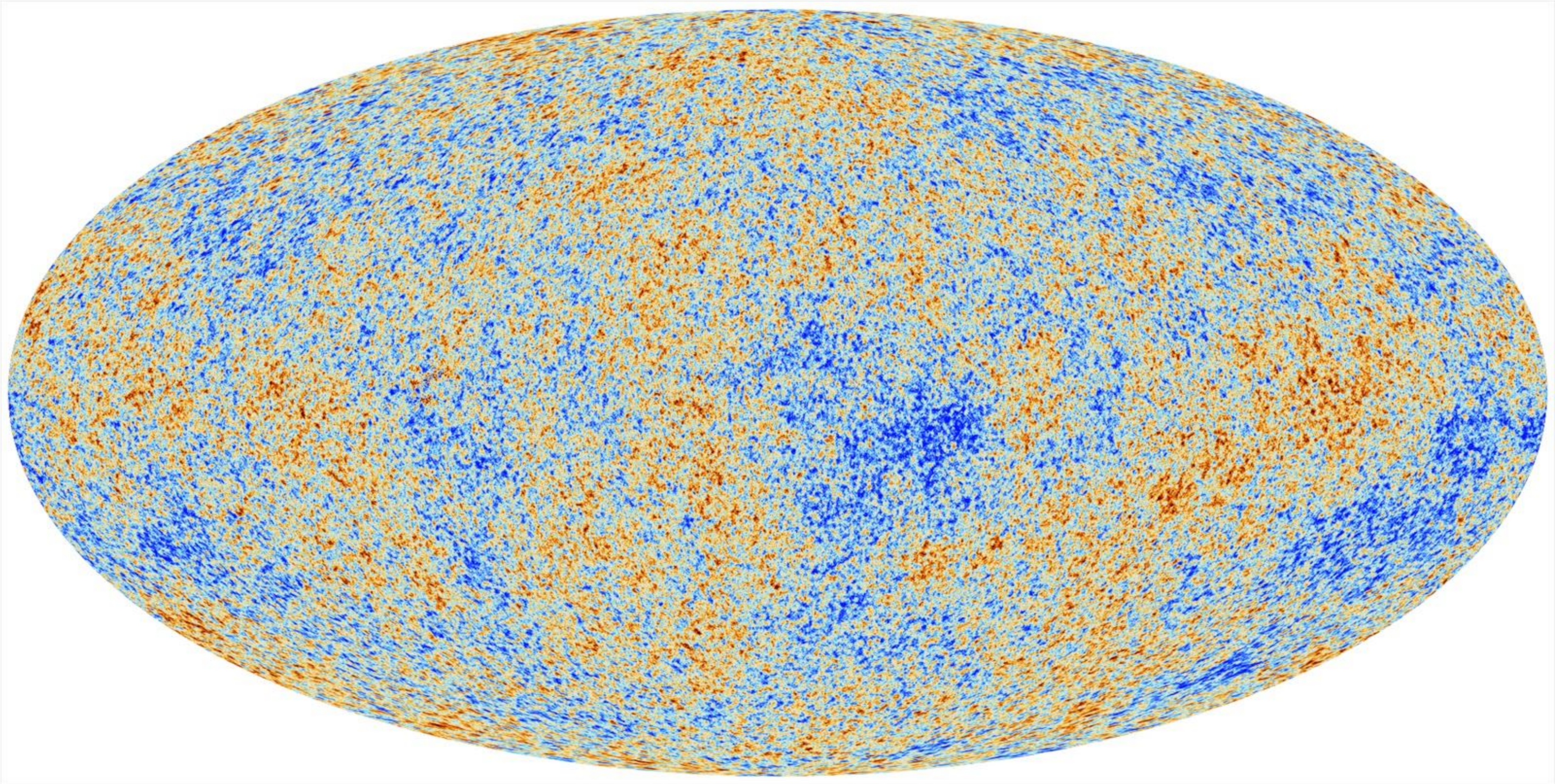
Cosmic Microwave Background radiation (CMB)



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

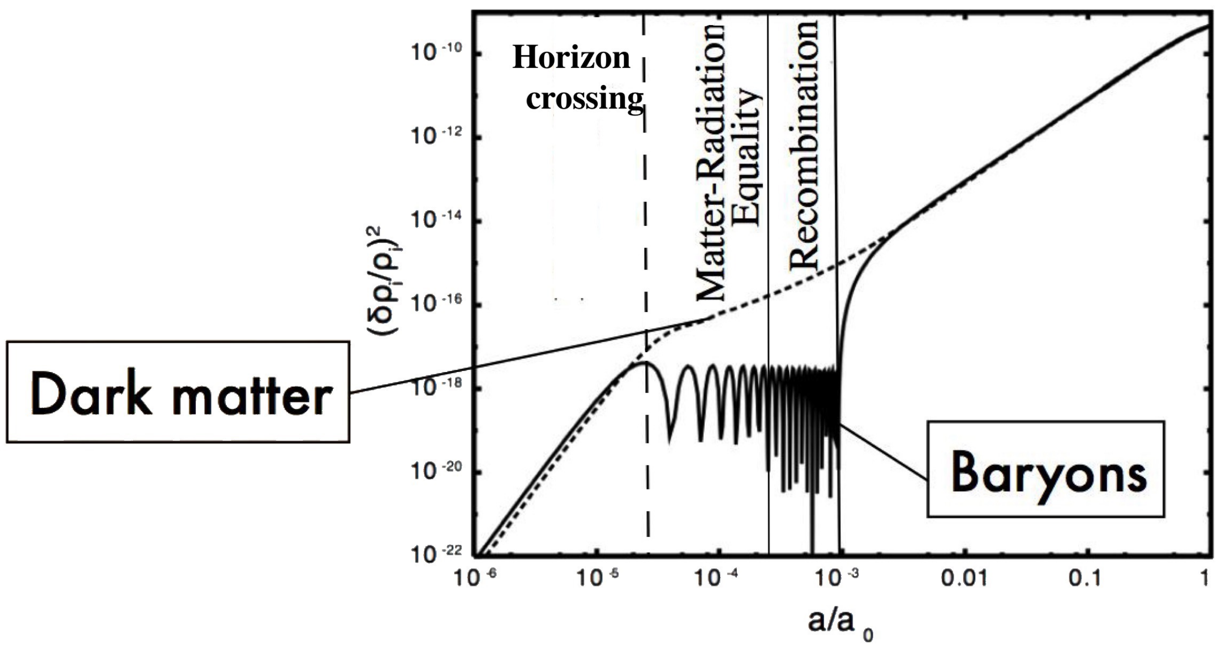


CMB anisotropies with PLANCK (2013) ($\delta T/T \simeq 10^{-4}$)



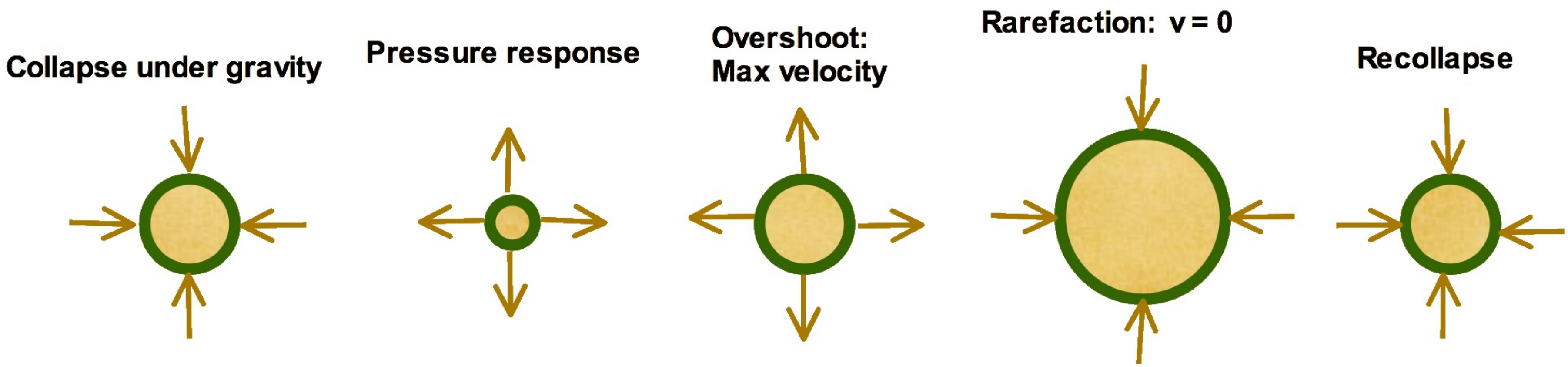
Dark Matter is needed for Structure Formation

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^{-4} to 10^{-1} but need > 1



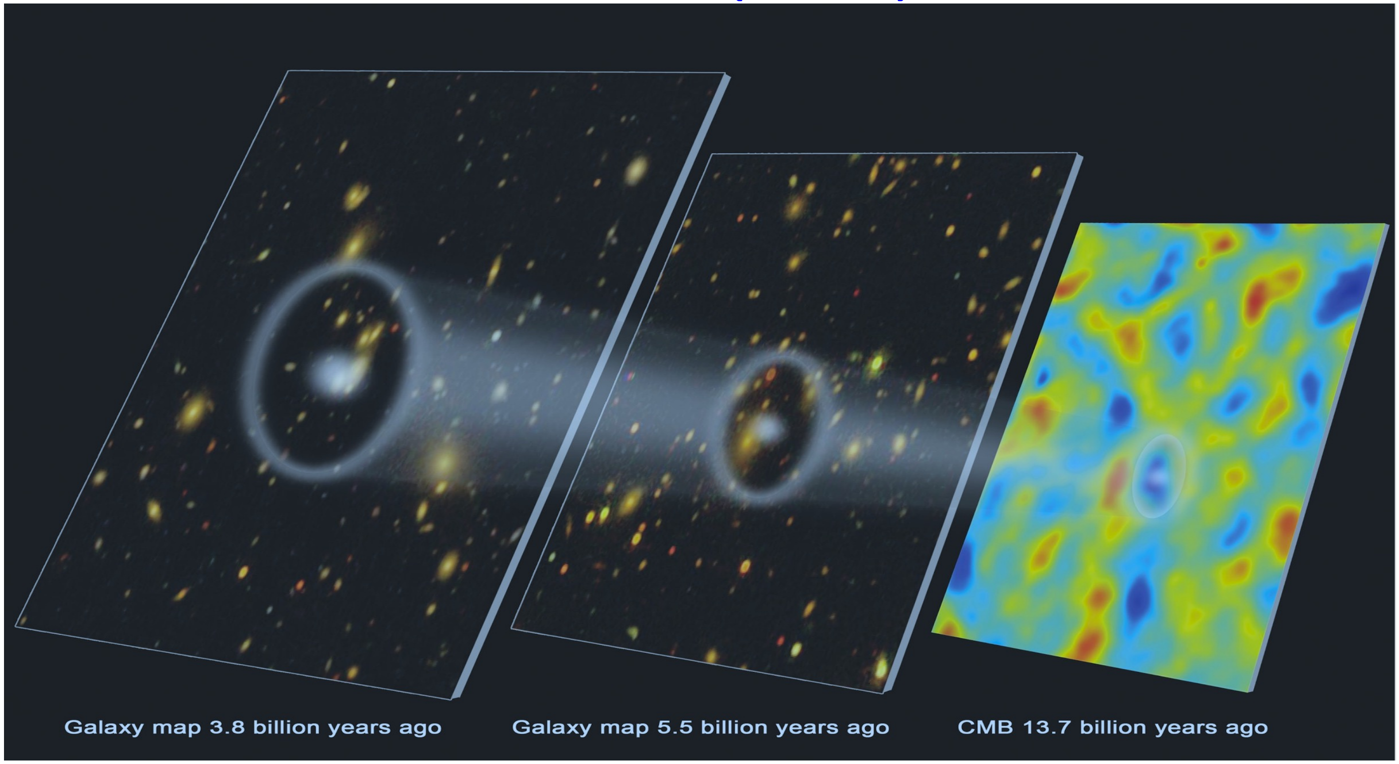
Pressure standing oscillations before recombination

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)

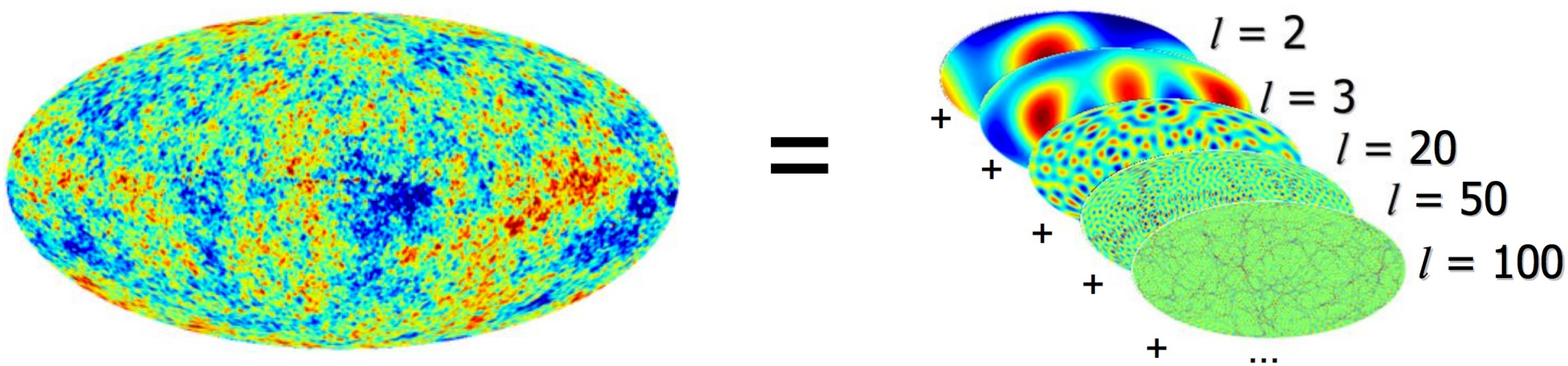


In a region with high initial density, there was high pressure in the baryon-photon fluid which propagated as an expanding spherical sound wave. After recombination the photons go off with speed c and baryons are left sitting in a spherical shell around the initial excess density of DM.

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

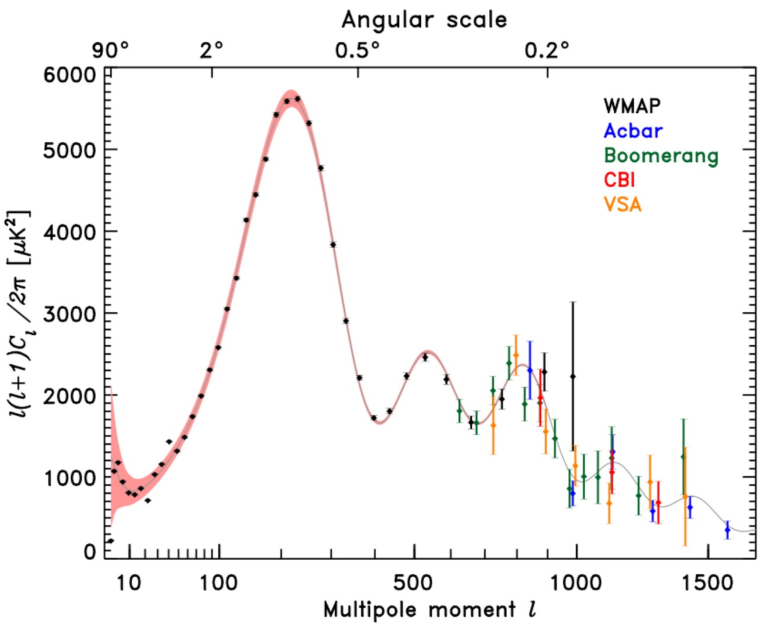
CMB Anisotropies Angular Power Spectrum

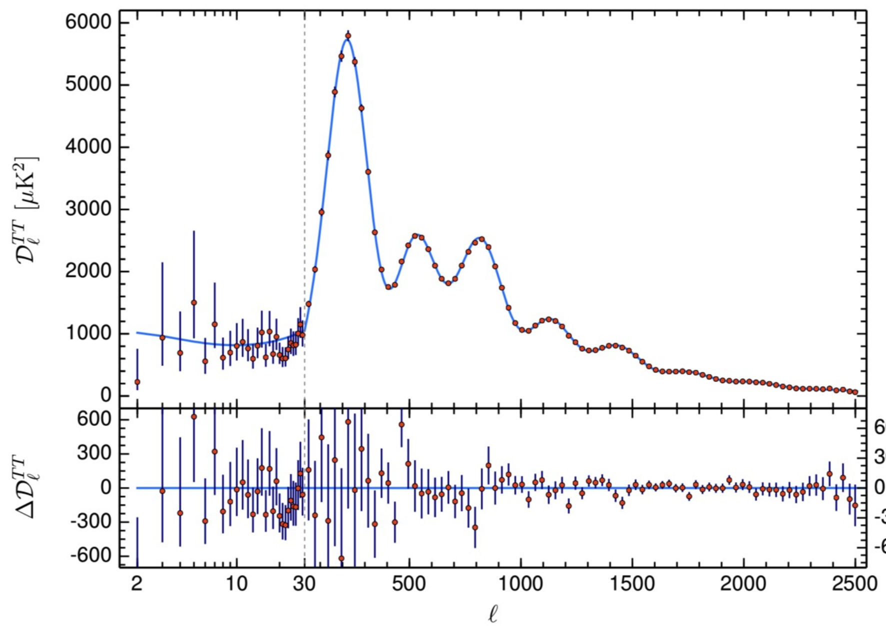
C_ℓ also defines the T-T auto-correlation function ($P_\ell(\theta)$: Legendre Polynomial)

$$C(\theta) = \langle \frac{\delta T}{T}(\hat{n}_1)\frac{\delta T}{T}(\hat{n}_2)\rangle = \frac{1}{4\pi}\sum_\ell (2\ell+1)C_\ell P_\ell(\theta)$$

Before Planck: Only 3 peaks of the TT angular power spectrum observed

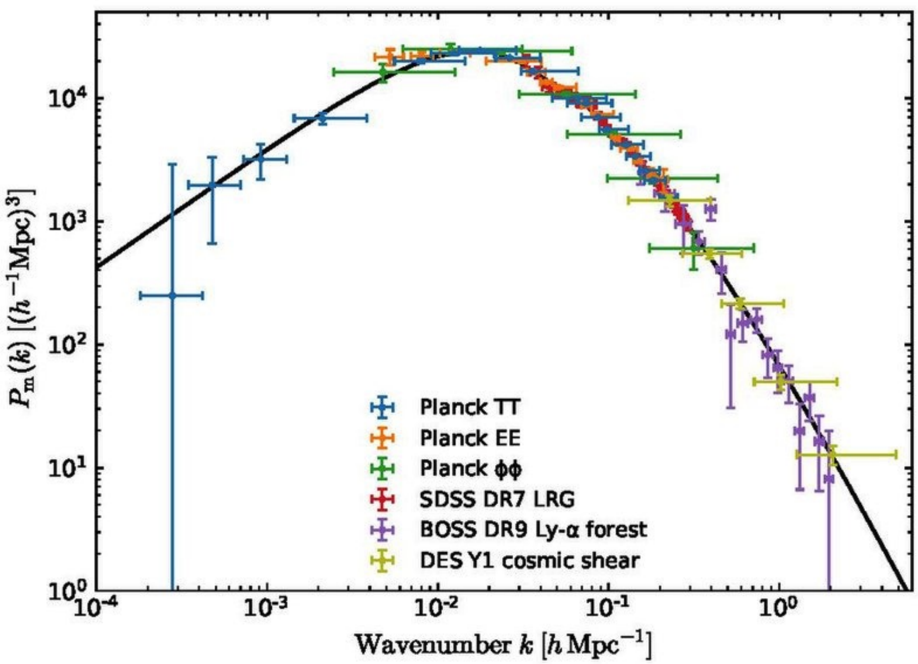
After Planck: 7 TT peaks, E-modes, precision parameter determination.





Matter Power Spectrum $P(k)$

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



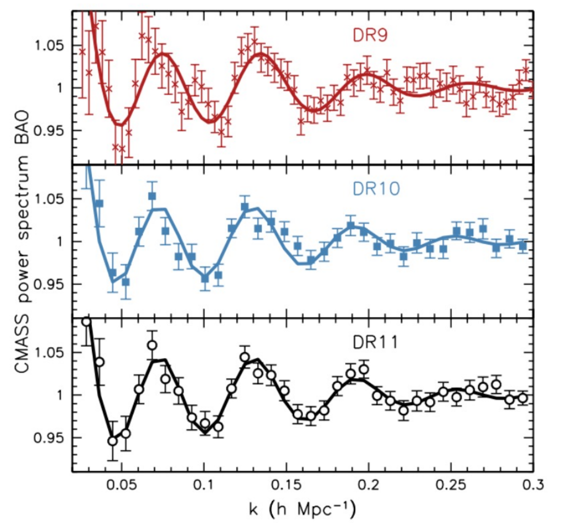


Figure 16. The CMASS BAO feature in the measured reconstructed power spectrum of each of the BOSS data releases, DR9, DR10, and DR11. The data are displayed with points and error-bars and the best-fit model is displayed with the curves. Both are divided by the best-fit smooth model. We note that a finer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

After 80 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**

  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?

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

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

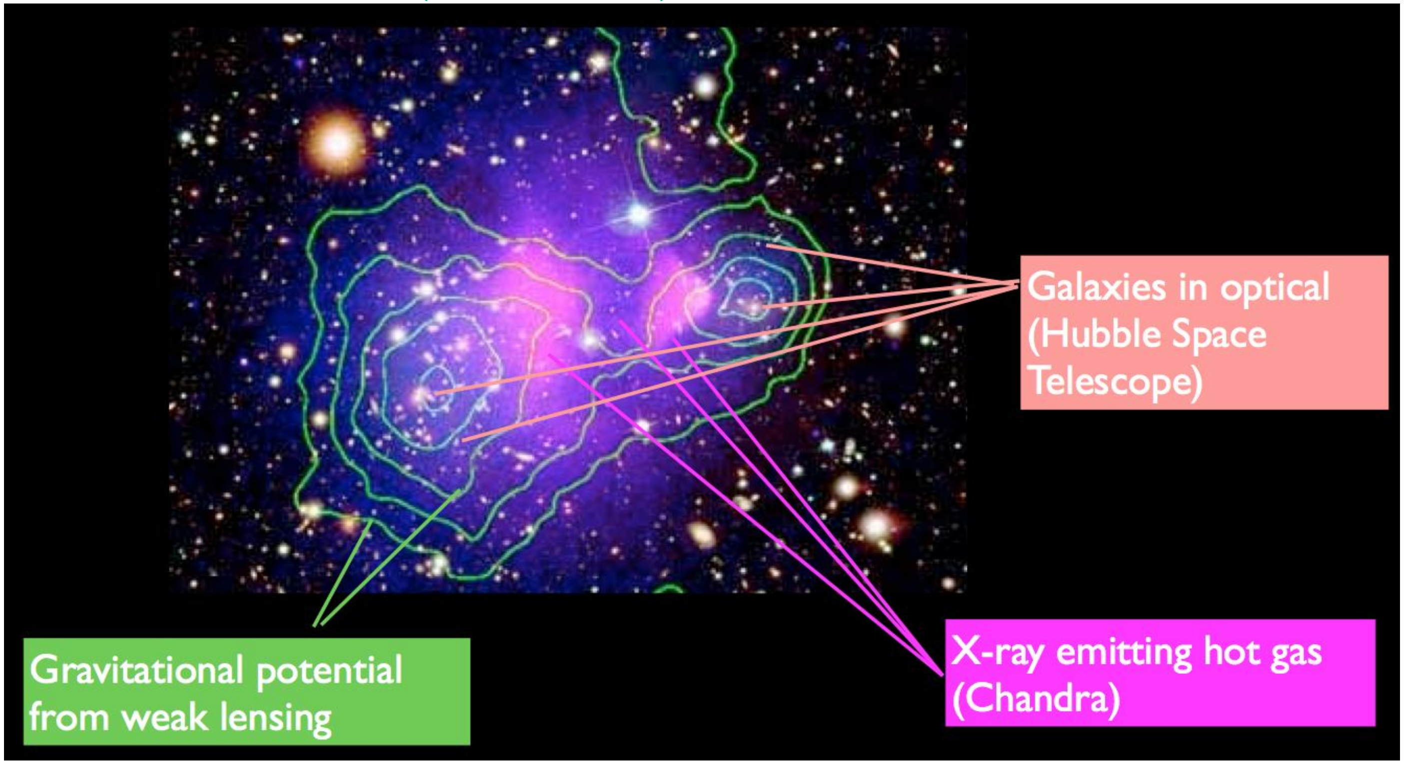
using that the centripetal acceleration is $a = \dfrac{v^2}{r}$

MOND is only non-relativistic, so cannot be tested on cosmological scales (e.g. gravitational lensing). TeVeS (J. Bekenstein, 2004) MOND's generalization, contains new fields that could be interpreted as cold dark matter, interacting only gravitationally. It does not explain consistently all the data as DM does.

There are other ideas, like Eric Verlinde's "emergent gravity" models

DM and not just [MOND+ visible matter]

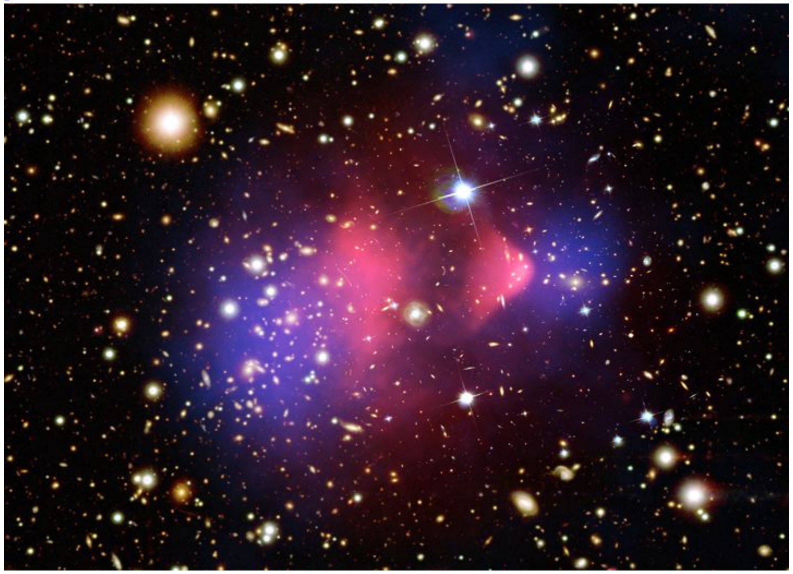
"Bullet Cluster"- 2004(Fig from Gondolo)



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

DM and not [MOND+ 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 with only visible matter cannot explain this system: needs 2-3×more matter - i.e. some form of Dark Matter(Dark Cluster Baryonic Matter?)

After 80 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**

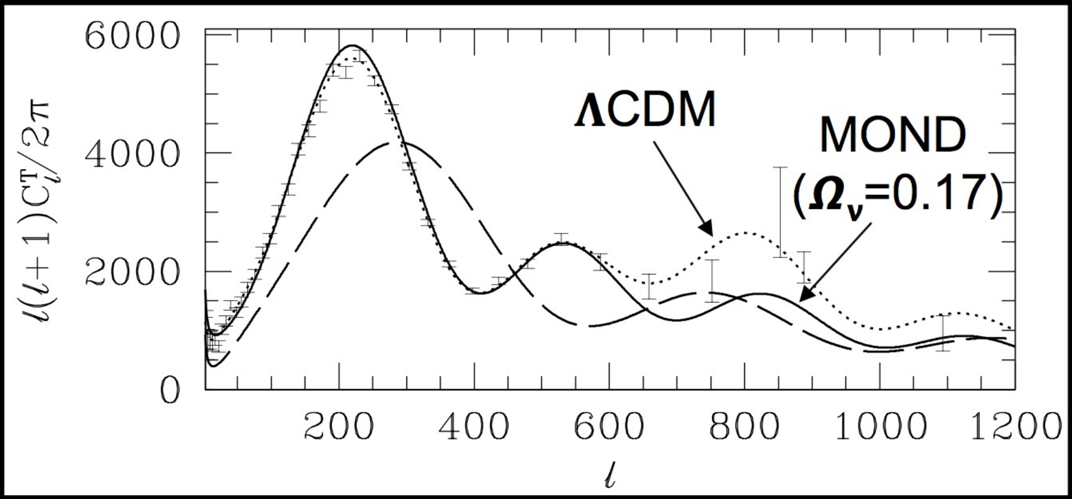
Dark Matter is defined by the role it has in astrophysics and cosmology: formation of structure in the Universe, galaxy rotation curves, galaxy morphologies, CMB anisotropy spectrum, BAO...

No proposed "alternative to Dark Matter" explains the CMB anisotropy spectrum and the BAO

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

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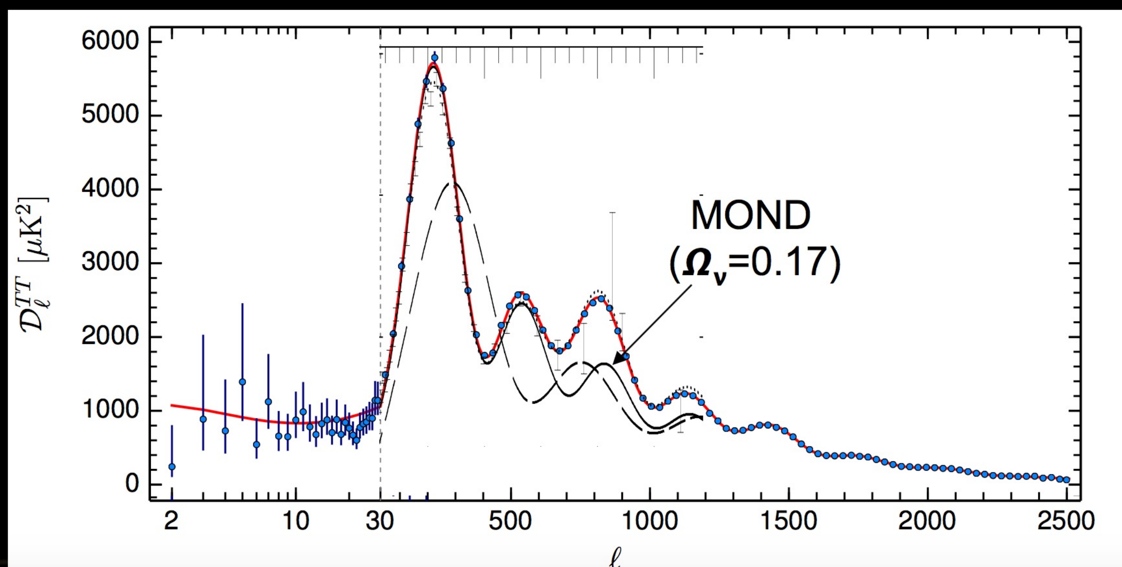
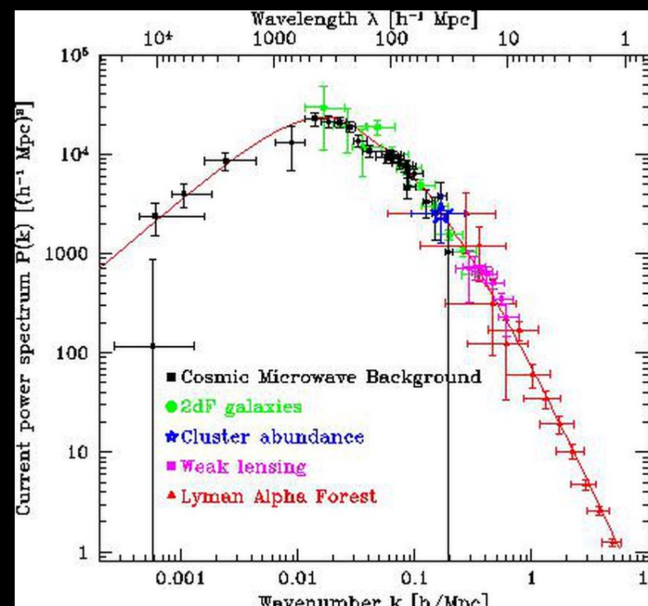
- Here is an example, (as calculated within TeVeS), Skordis et al. (2005)
- At the time, this was marginally consistent with the data (if one allows for ~2 eV neutrinos), but cannot accommodate modern CMB measurements



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

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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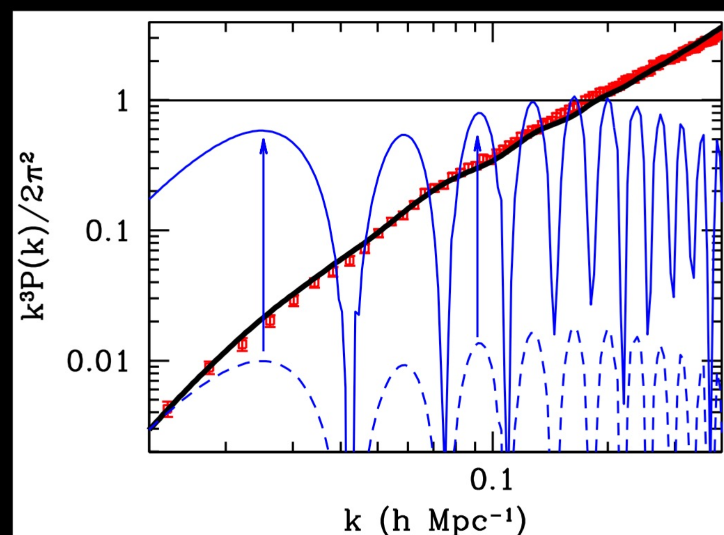
- In a universe without dark matter, however, these oscillations should be *much* larger
- Even if structure growth is somehow enhanced through modifications of gravity, without dark matter, BAO should be ~30 times larger than observed



Dodelson (2011)

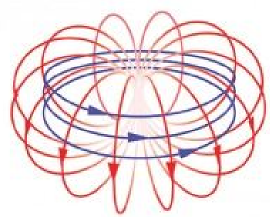
After 80 years, what we know about DM:

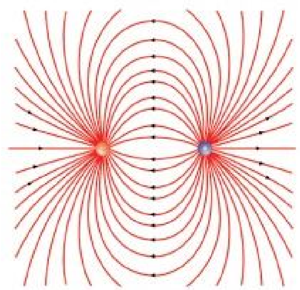
- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light** i.e. it is either neutral or with a very small electromagnetic coupling such as:

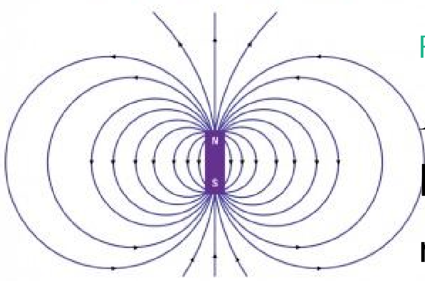
  "Milli-Charged DM" which can be part of "Atomic DM", with dark protons and dark electrons forming dark atoms or "Mirror DM" whose Lagrangian is a copy of that of the SM, but for the mirror particles,

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

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 - first measured experimentally in Cesium-133 atoms C. S. Wood et al, Science 275, 1759 (1997)

$$L = \frac{g}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma_5\psi\partial^\nu F^{\mu\nu} \quad \rightarrow \quad H_{anapole} \sim \vec{\sigma} \times \vec{B}$$

Annihilation is purely p-wave- $\sigma_{scattering} \sim \alpha Z^2 \mu_T v^2$.

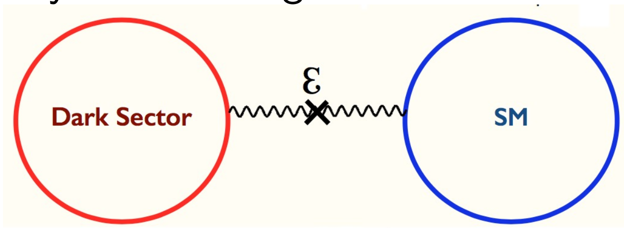
Magnetic (MDM), Electric (EDM) Dipole Moment DM Pospelov & Veldhuis 2000, Sigurdson, Doran, Kurylov, Caldwell Kamionkowsky 2004, 2006, Maso, Mohanty, Rao 2009, Fortin, Tait 2012 many more

$$L = -(i/2)\bar{\psi}\sigma_{\mu\nu}(d_m + d_e\gamma_5)\psi F^{\mu\nu} \quad \rightarrow \quad H_{MDM} \sim d_m\vec{\sigma}.\vec{B} \quad H_{EDM} \sim d_e\vec{\sigma}.\vec{E}$$

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$_{dark}$(1) hidden gauge symmetry that would give rise to bound states "kinetic coupling" $\varepsilon F_{\mu\nu} F^{\mu\nu}_{dark}$



Diagonalized gauge boson kinetic terms: em photon $A_\mu(J^\mu_{em} + \varepsilon g J^\mu_{dark})$ (g is U$_{dark}$(1) coupling).

Holdom 1986, Burrage et al 0909.0649 D. E. Kaplan 0909.0753 1105.2073 Cline, Zuowei Liu, and Wei Xue 1201.4858

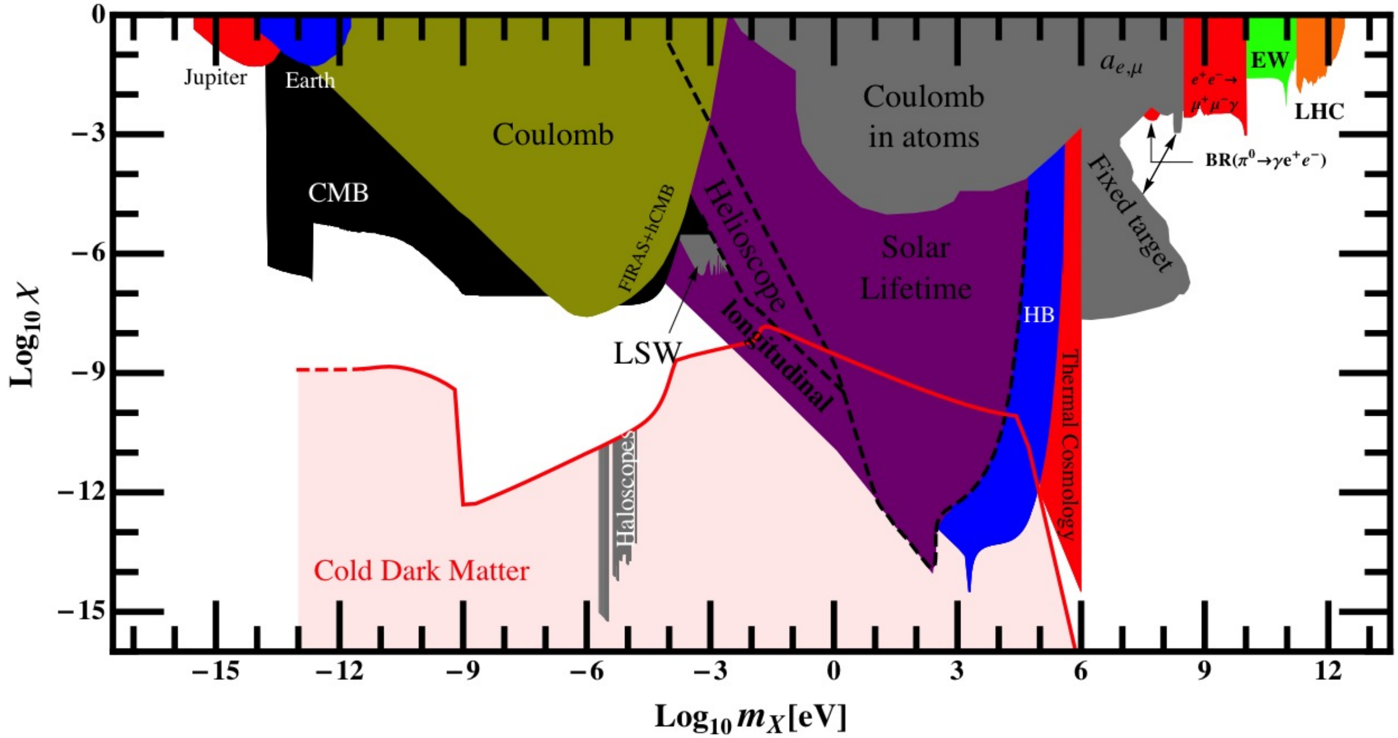
"Atomic DM" with dark analogues of p, e, H coupled to a new U'(1) and Dark Atoms may scatter elastically or inelastically depending of the choice of parameters Goldberg Hall 1986; Feng, Kaplinghat, Tu 0905.3039; Ackerman 2009. . .

"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 Jaeckel 1303.1821

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



After 80 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**
- **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 $<$ **10% 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 non-dissipative CDM simulations including baryonic matter, but with dissipative DDDM it should be a pervasive feature of all disk galaxies (and "kill the dinosaurs"?! Randall& Reece in 2014 proposed that periodic extinctions may occur when we pass through a Dark Disk inclined with respect to the visible disk)

After 80 years, what we know about DM:

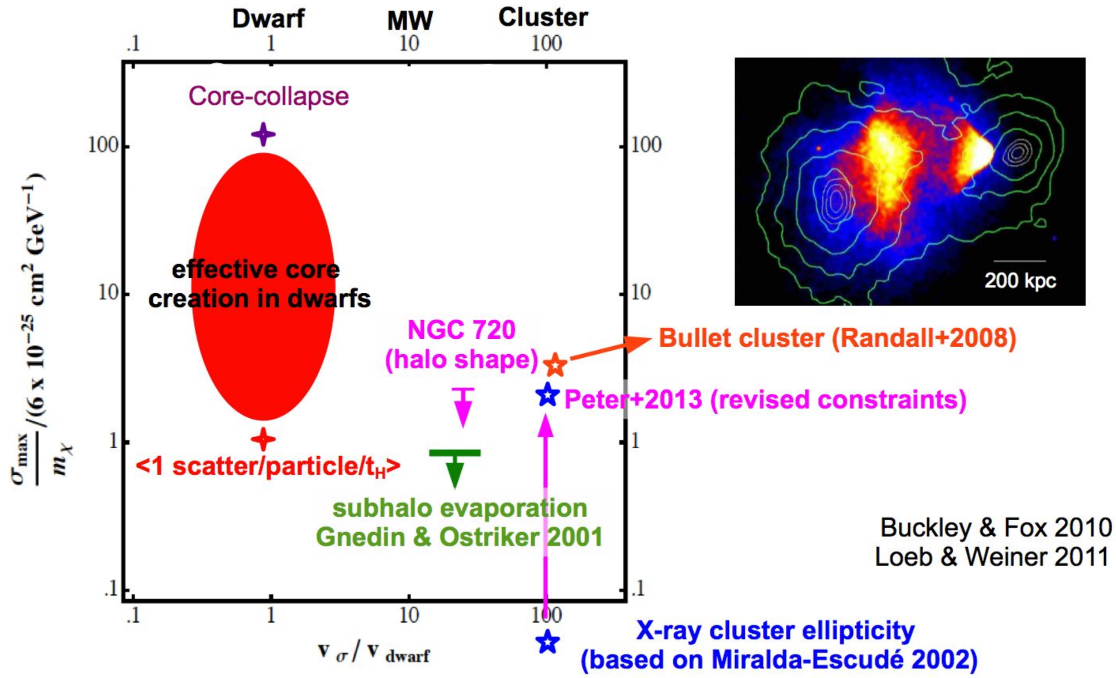
- **1- Attractive gravitational interactions and lifetime $>> t_U$**
- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless but $\leq$10% of it could be dissipative** (so dark sector)
- **5- DM has been mostly assumed to be collisionless, however the upper limit on DM self-interactions is huge**

$\boldsymbol{\sigma_{\mathrm{self}}/\mathrm{m}} \leq 1\ \mathrm{cm}^2/\mathrm{g} = 2\ \mathrm{barn/GeV} = 2{\times}10^{-24}\ \mathrm{cm}^2/\ \mathrm{GeV}$
by comparison e.g. ^{235}U-neutron capture cross section is a few barns!
Self Interacting DM (SIDM) just below limit (WIMPs: $\sigma_{DM-p} < 10^{-46} cm^2/10\mathrm{GeV}$)

(Limit on σ_{self}/m ratio comes from requiring self-interaction mean free path $\lambda_{mfp} \simeq 1/n\sigma_{self} = m/\rho\sigma_{self}$ be long enough, $n = \rho/m$ is the DM number density)

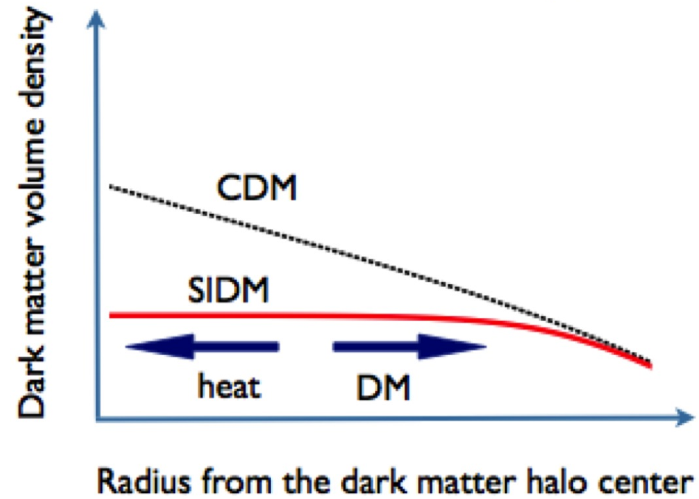
Self Interacting DM (SIDM)

Fig. from Jesus Zavala Franco



Collissions would also erase small scale structure, and turn cusps into cores in dwarf galaxies if cross section close to upper limit (SIDM) and v-dependent This is why Spergel & Steinhardt 2000 proposed self-interacting dark matter (SIDM) with $\sigma \simeq (m/\mathrm{GeV})(\mathrm{Mpc}/\lambda_{mfp})$ barns

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 $m_{DM} \simeq$15 GeV, $m_\varphi \simeq$15 MeV.

(Feng, Kaplinghat& Yu 2009,

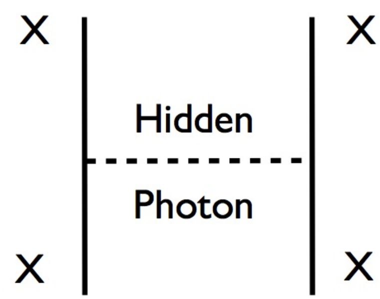
Buckley& Fox (2009),

Loeb&Weiner (2010),

Tulin, Yu& Zurek 2012, 2013...)

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

$m_X\, v >> m_\phi$



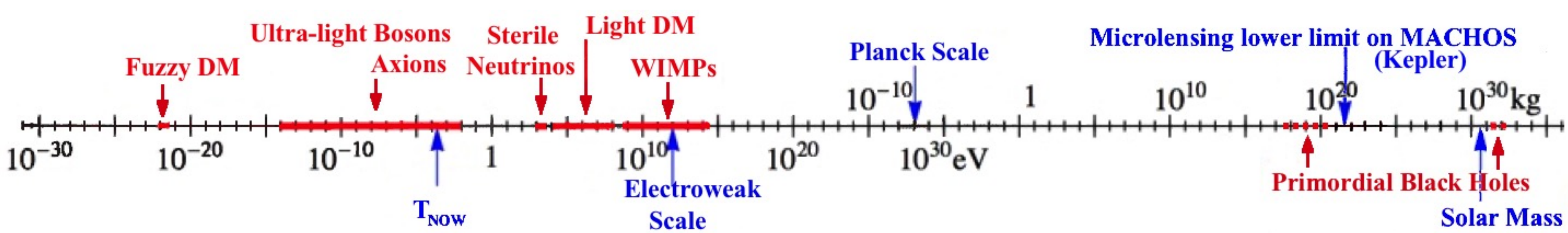
(Recall that the virial speed is larger in more massive structures)

- **6- The mass of the major component of the DM has only been constrained within some 90 orders of magnitude.**

$10^{-31}\mathrm{GeV} \leq \mathbf{M} \leq 10^{-10} M_\odot = 10^{47}\mathrm{GeV} = 2\ 10^{20}\mathrm{kg}$ (window $\simeq 10 M_\odot = 10^{58}\mathrm{GeV}$??)

Lower limit:"Fuzzy DM", boson with de Broglie wavelength 1 kpc Hu, Barkana, Gruzinov, 2000

Upper limit on MACHOS: Moniez 0901.0985, Yoo, Chaname, Gould, ApJ**601**, 311, 2004; Griest, Cieplak and Lehner 1307.5798, Niikura *et al.* 1701.02151



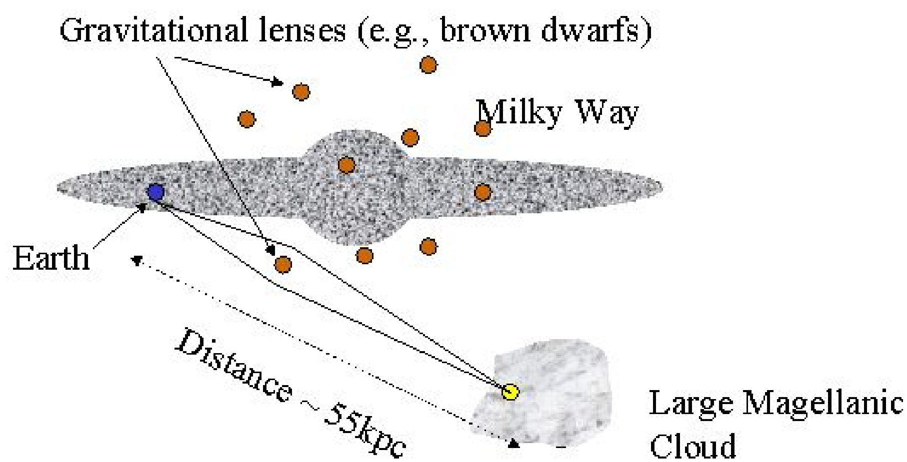
Problem with MACHOS: how would they form? Could be Primordial Black Holes but limits constrain them to be only a fraction of the DM for large mass ranges.

Limits on MACHOS (Massive Astrophysical Compact Halo ObjectS):

Microlensing: cannot be the bulk of the DM if **mass** $\geq 2{\times}10^{-9} M_\odot \simeq 2 \times 10^{48}$ GeV

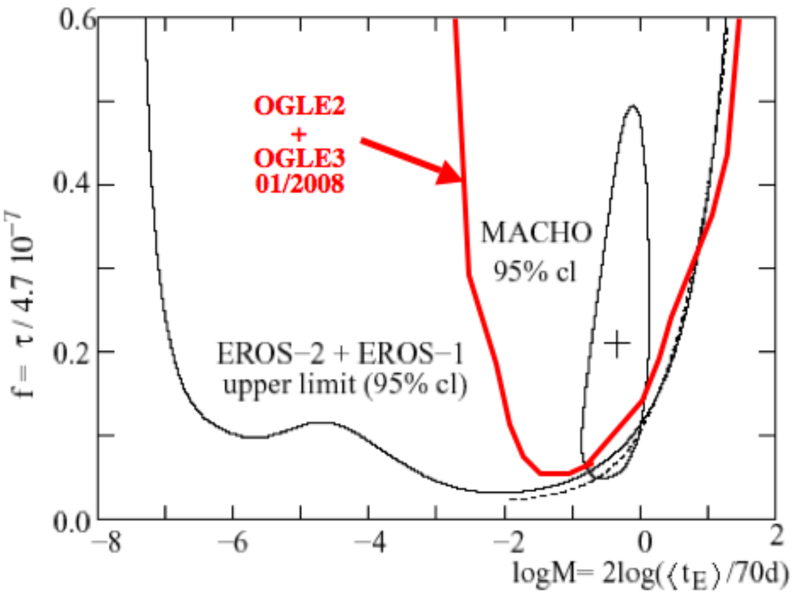
MACHO and EROS collaborations 2009 M. Moniez arXiv:0901.0985 [astro-ph.GA], Griest, Cieplak and Lehner 1307.5798

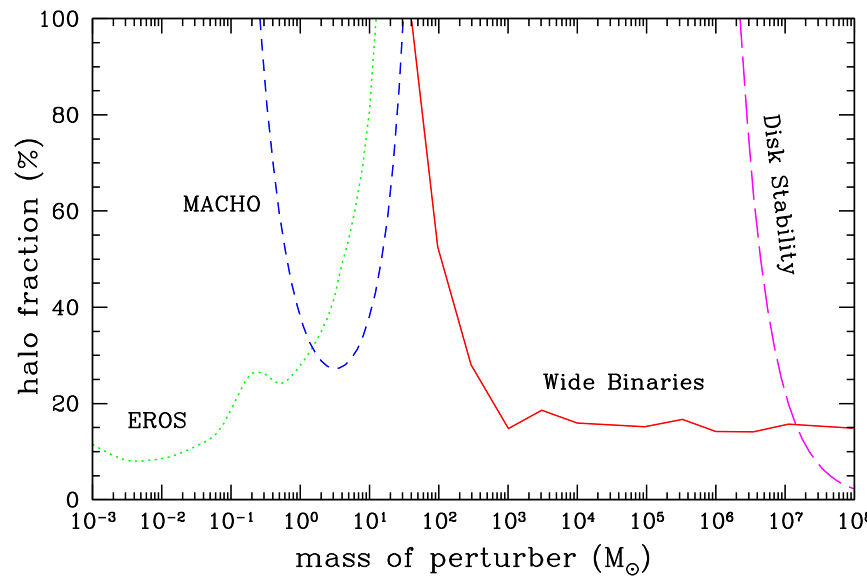
Searched for using gravitational "microlensing" of stars in satellite galaxies and the Galactic Center: multiple images are superposed producing an "anti-eclipse" (star becomes brighter for a while).



Dark Matter: not MACHOS

M. Moniez arXiv:0901.0985 [astro-ph.GA] Combined with older results for larger masses: Yoo, Chaname, Gould, ApJ**601**, 311, 2004 Griest, Cieplak and Lehner 1307.5798





2009 limit: $m > 10^{-7}$ M$_\odot$ cannot be the bulk of the DM (M$_\odot$ = 10^{57}GeV)

2013 limit: (using Kepler satellite data) m >2 10^{-9} M$_\odot$ cannot either.

Notice, possible window 20 M$_\odot$< m <100 M$_\odot$? (LIGO M$_{BH}$ $\simeq$ 30M$_\odot$)

Problem with MACHOS: how would they form?

Dark Matter: could be Primordial Black Holes (PBH)?

PBH are a hypothetical type of black hole not formed by the gravitational collapse of a large star but in an early phase transition, before BBN (thus non-baryonic)

Zel'dovich and Novikov, 1966; Hawking, 1971; Carr and Hawking, 1974

Many limits exclusively applying to BH:

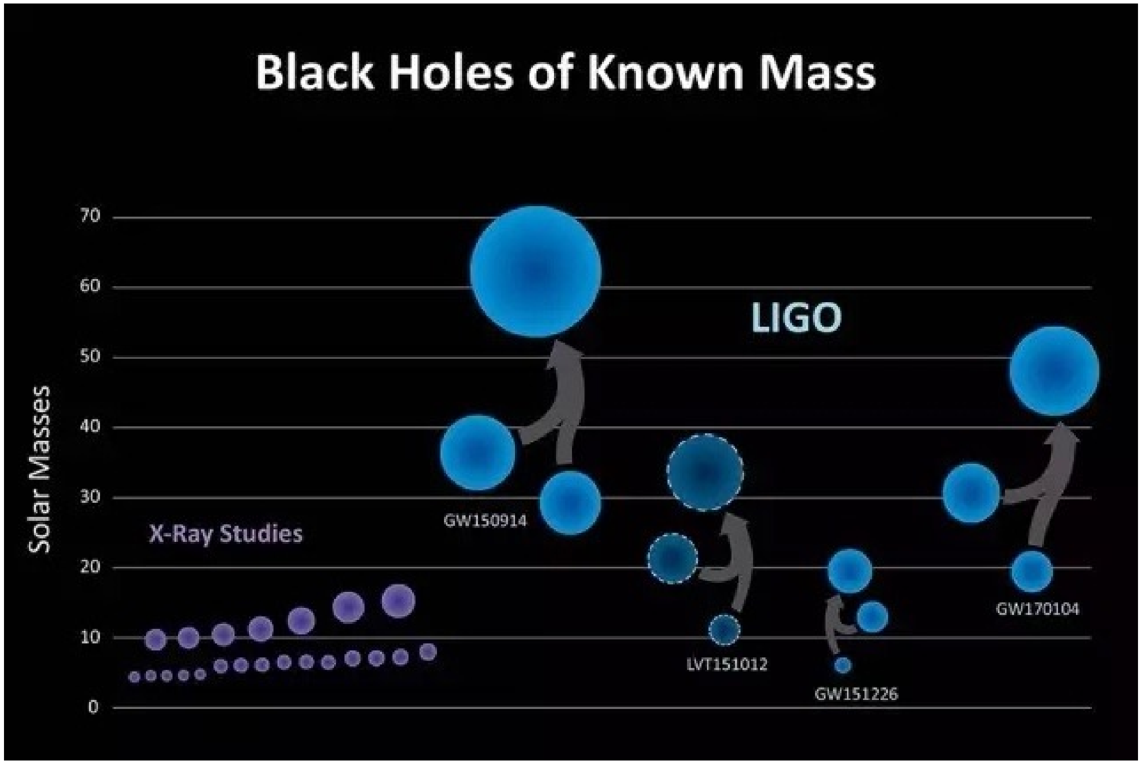
- $M > 10^{15}$g $= 6 \times 10^{38}$ GeV, lighter would have evaporated by now
- $M > 10^{17}$g or evaporating BH would have been observed (by EGRET and Fermi)
- 5 10^{17}g$< M < 10^{20}$g excluded by non-observation of "femtolensing" of GRB 1204.2056

Revised: wave effects (wavelength larger than Schwartzschild radius) and finite source size effects

- 10^{16}g$< M < 10^{22}$g excluded- its accretion in stars would destroy compact remanent 1209.6021
- 3 10^{18}g$<M<$ 5 10^{24}g excluded- its accretion in n stars in GC would destroy them (NS limit) 1301.4984 Revised: required a too high density in GC1807.11495
- $M >$ 100 $M_\odot$= 2 10^{35}g excluded by absence of CMB spectral distortions 0709.0524

Many limits revised after LIGO's BH-BH mergers events!

LIGO: several BH-BH merger events $M_{BH} \simeq 10 - 100 M_\odot$



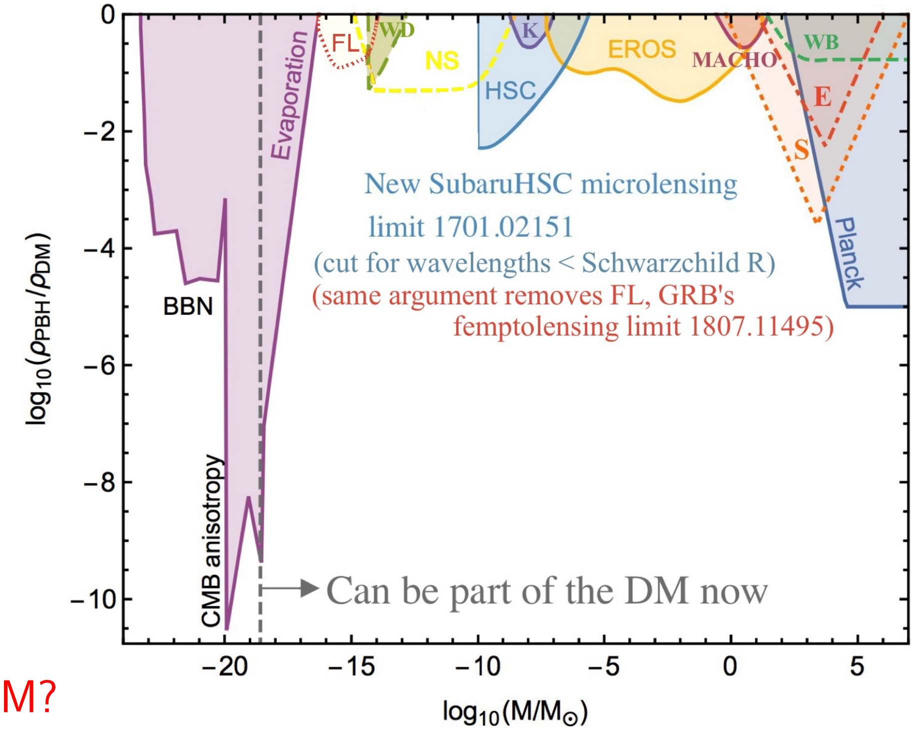
Could LIGO BH ~10's $M_\odot$ be most of the DM? Bird etal. 1603.00464, Clesse&Garcia-Bellido 1501.07565, 1603.05234

Could Dark Matter be Primordial Black Holes (PBH)?

compilation of bounds on PBH DM density fraction f for single mass PHB (dashed limits can be avoided with special assumptions)

Carr, Tenkanen and Vaskonen 1706.03746 + modified

($M_\odot = 10^{57}$GeV)



Could LIGO BH ~10's $M_\odot$ be most of the DM?

Bird etal. 1603.00464, Clesse&Garcia-Bellido 1603.05234, 1501.07565; and before the LIGO events Frampton 0905.3632, Frampton, Kawasaki, Takahashi &Yanagida 1001.2308

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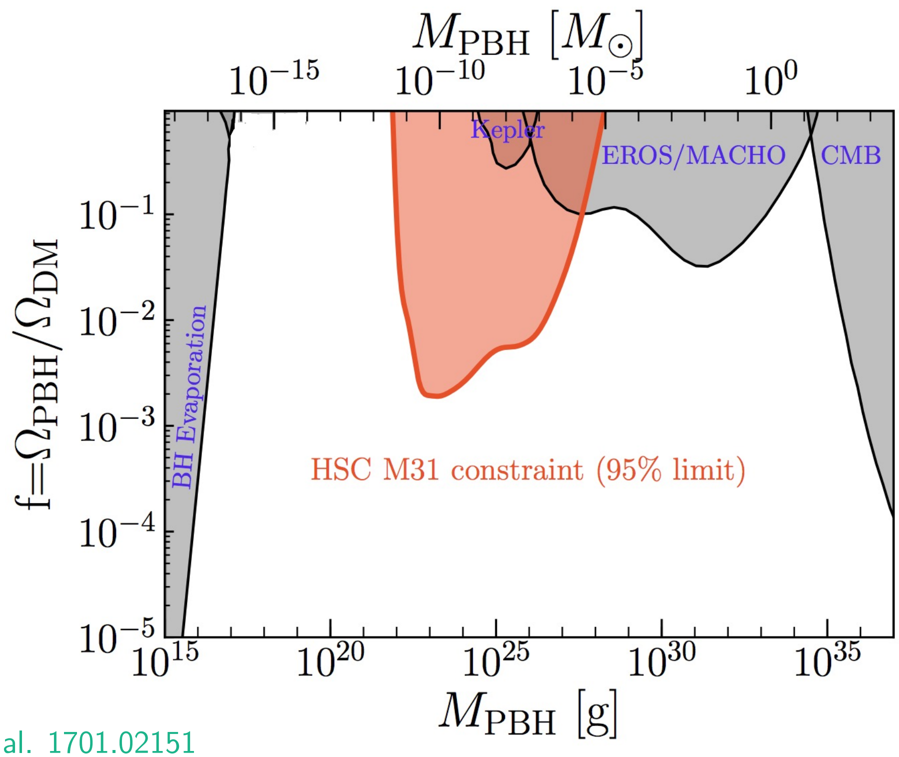


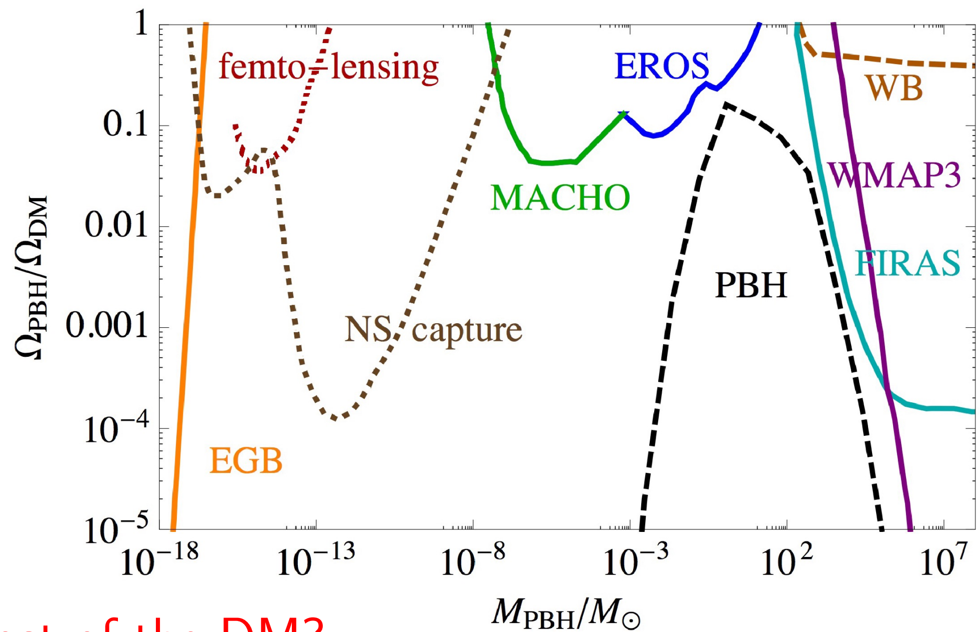
New Subaru/HSC camera limit Niikura et al. 1701.02151
They also have a candidate PBH event consistent of a PBH of mass 10^{-7} $M_\odot$.

Dark Matter: could be Primordial Black Holes (PBH)?

PHB with an extended mass function (e.g. dashed black) could be the whole of the DM

Fig from Garcia-Bellido 1702.08275,

Clesse, Garcia-Bellido 1501.07565



Could LIGO BH ∼10's $M_{\odot}$ be most of the DM?

Bird, *et al.* 1603.00464, Clesse&Garcia-Bellido 1603.05234; and before the LIGO events Frampton 0905.3632, Frampton, Kawasaki, Takahashi &Yanagida 1001.2308

This is a testable idea: the LIGO BH-BH merger events should be distributed like the DM and not like the visible matter. They could instead be stellar black holes, either from normal or Pop III stars, and thus distributed as visible matter.

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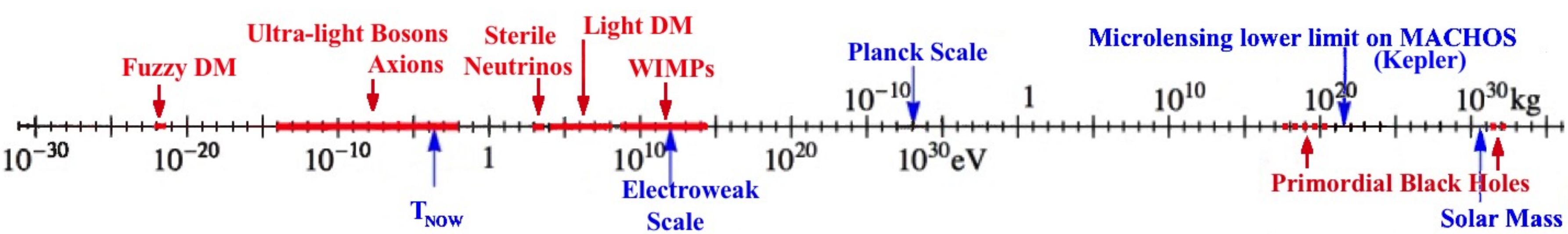

The limits on MACHOS and PBH, and the fact that particle candidates can have the right relic abundance to be the DM, constitute the only observational arguments we have in favor of DM elementary particle candidates.

From now on I will concentrate on particle DM candidates