Dark Matter Theory and Laboratory Searches
Lecture 1

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2023 N3AS Summer School, Santa Cruz, July 15-24, 2023

Content Lecture 1:

- 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? kinetic mixing, Hidden or dark photons, Atomic DM, Mirror DM, WIMPs, FIMPs, SIMPs, ELDERs, Axions, ALPs, WISPs, FIPs...)

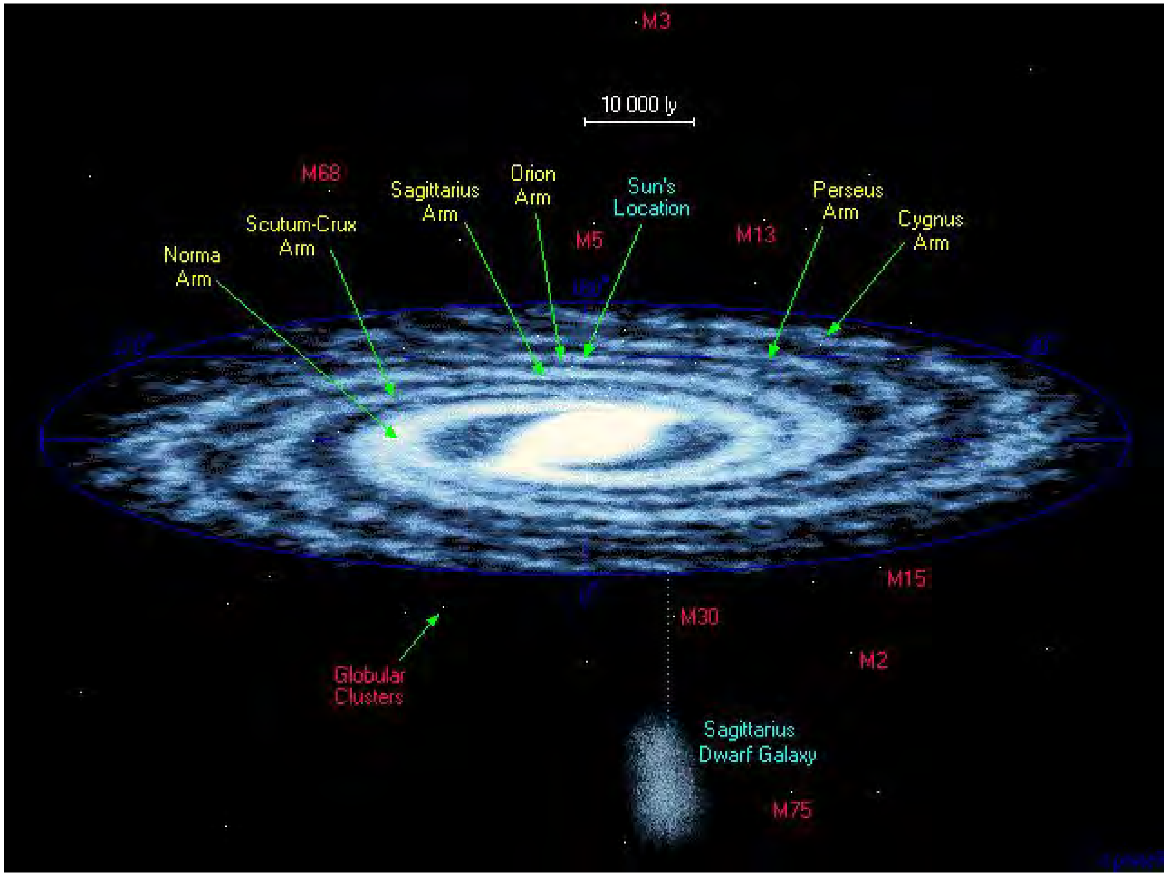
Lecture 2:

Some DM production mechanisms for particle DM (freeze-out in std. and non-std pre-BBN cosmologies, freeze-in..)

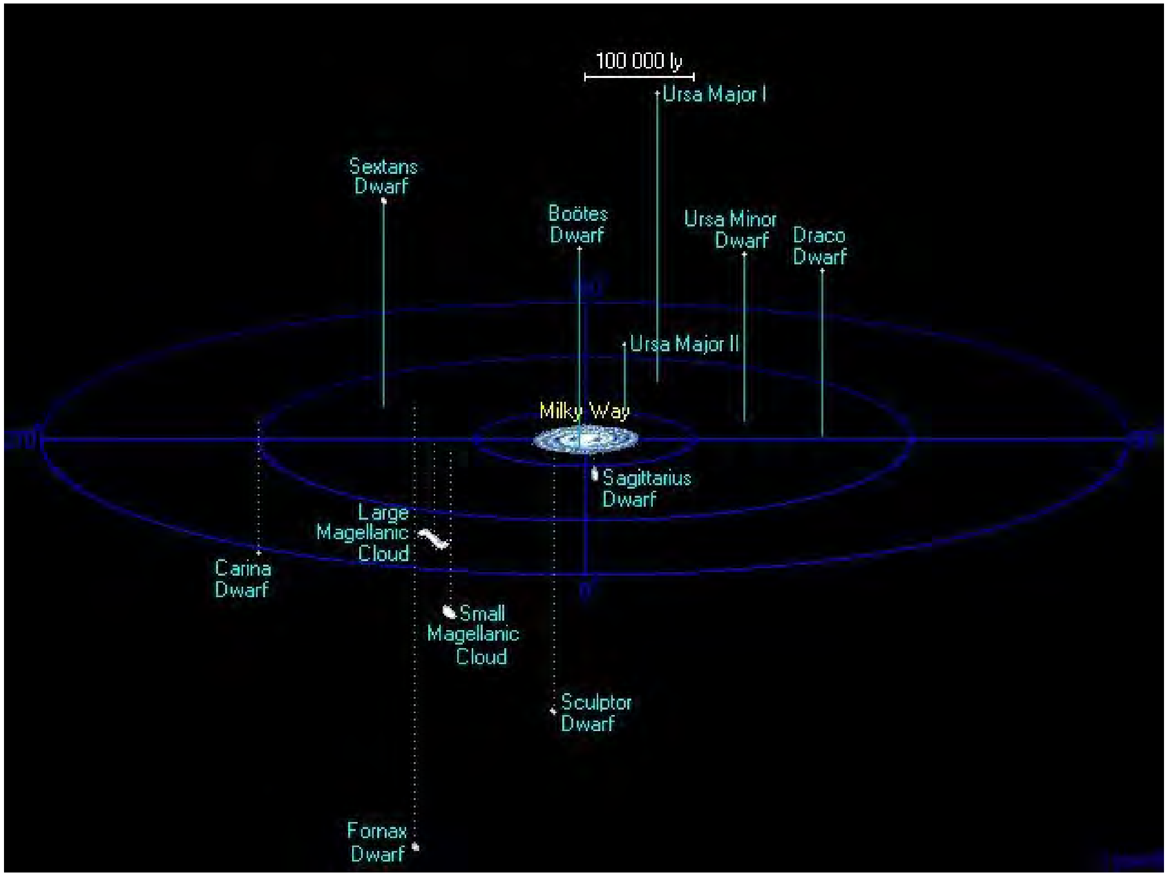
DM laboratory searches

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

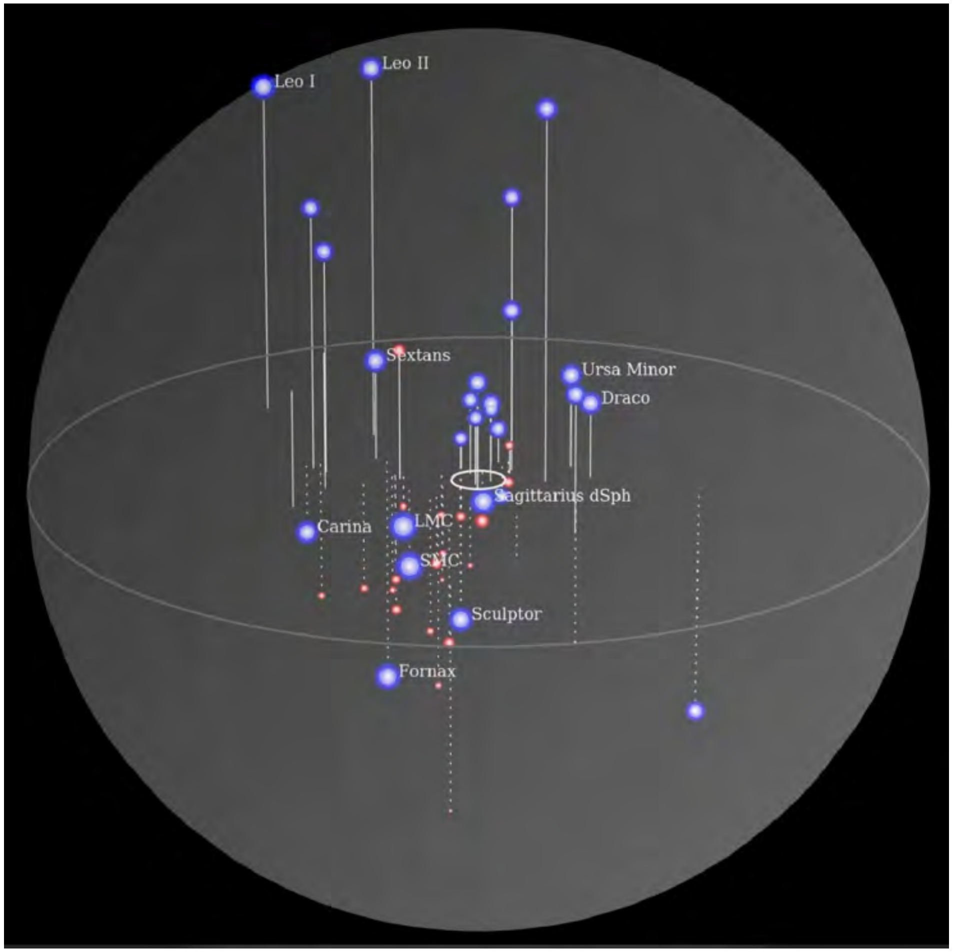
The Universe around us: Galaxies are the building blocks of the Universe. The Milky Way and the Sagittarius Dwarf galaxy its nearest satellite galaxy



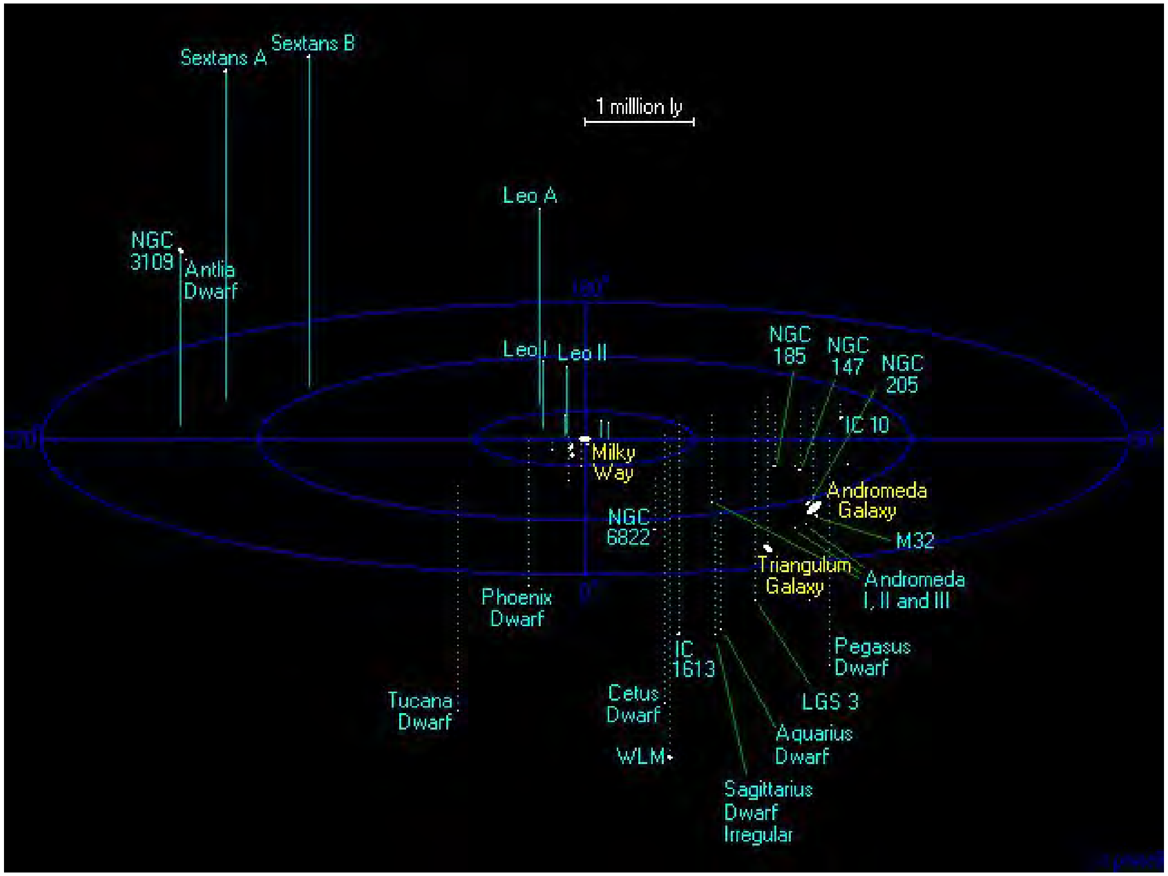
The Milky Way has many small satellite galaxies about 60 dwarf galaxies have been found so far



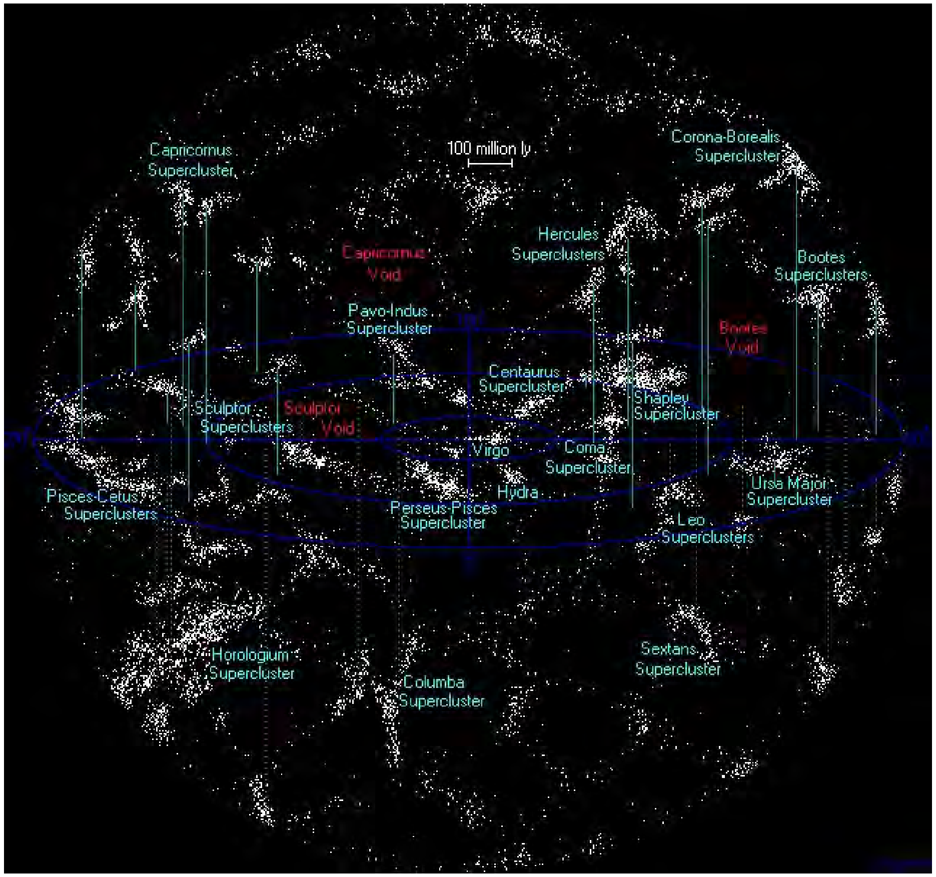
The Milky Way has many small satellite galaxies- dwarfs as of 2016 (in red DES)



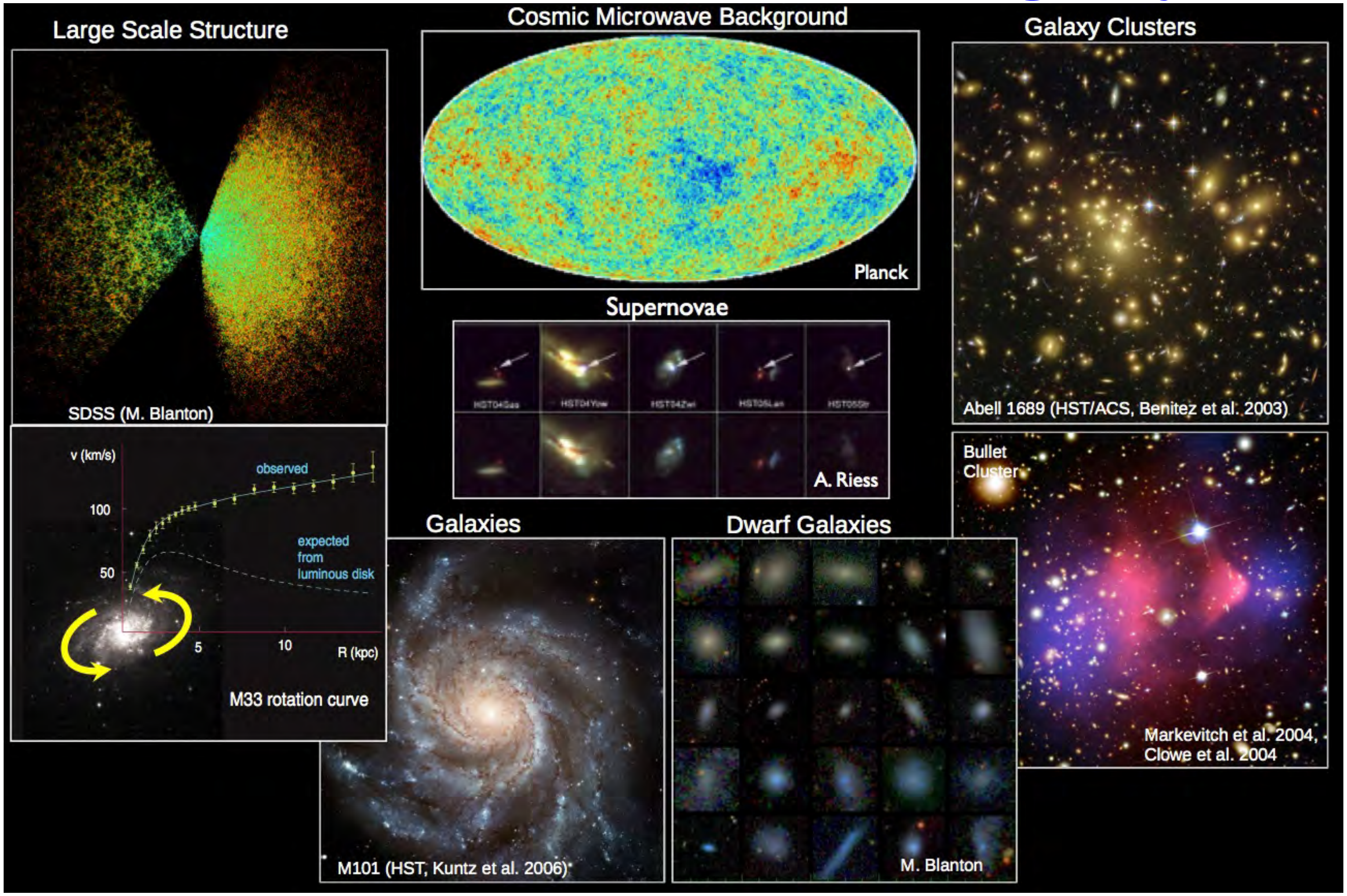
Galaxies come in groups, clusters, superclusters......Our Local Group of galaxies



Galaxies are the building block of the Universe: they come in groups, clusters, (which form "filaments, walls and voids")



DM dominates all structures from dwarf galaxy scales on



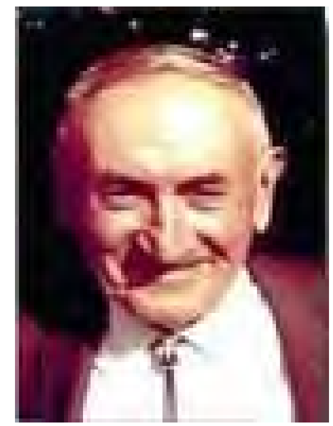
The Dark Matter problem has been with us since 1930's,

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

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)



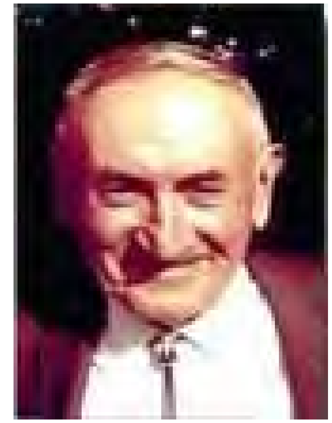
Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung 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.

On page 122

gr/cm³. 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/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!

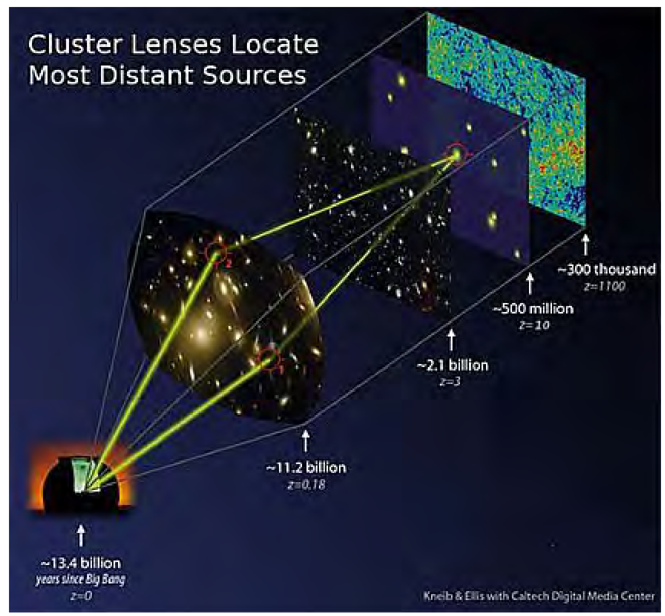
Dark Matter discovered



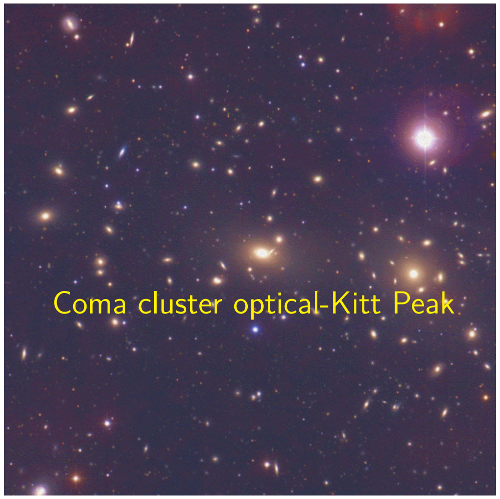
In 1930's Fritz Zwicky found the first indication of the DM.
Used the Virial Theorem in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only

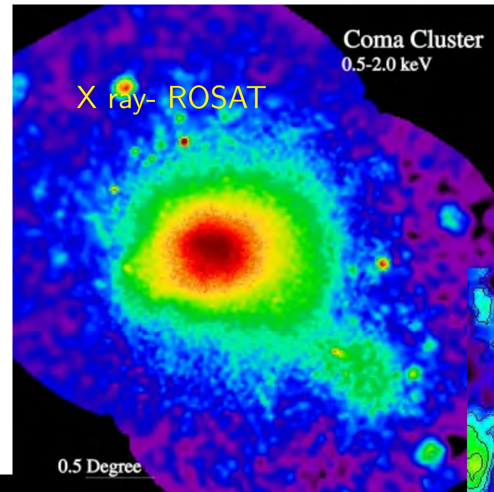
Later: also gas in clusters moves too fast (is too hot - as measured in X-rays) to remain in it, unless there is DM.

Another later method:
gravitational lensing
depends on all the intervening mass

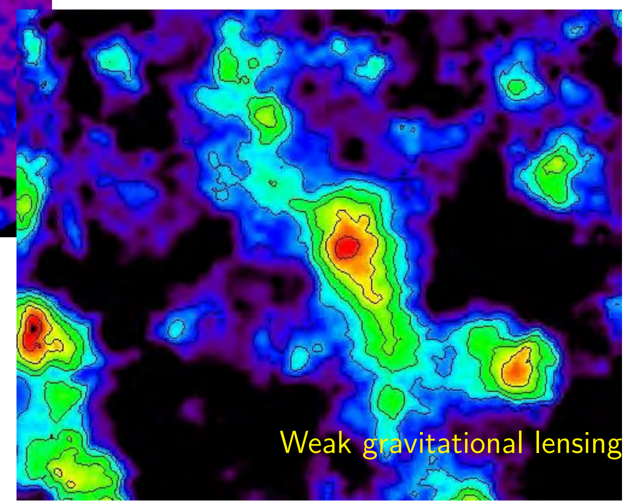


DM dominates in galaxy clusters



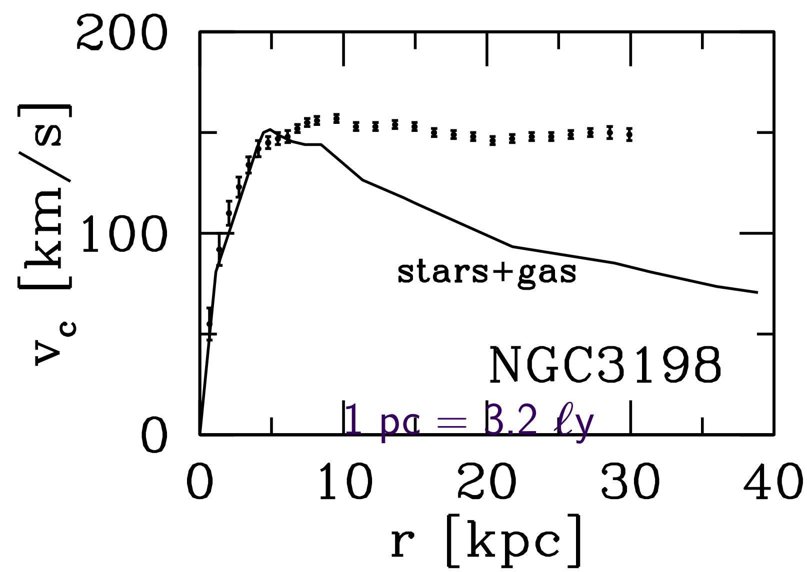


$$\boxed{\frac{M}{M_{\text{vis}}} \simeq 6}$$



Dark Matter rediscovered

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



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

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

even where there is no light!

Dark Matter dominates in galaxies e.g. in NGC3198

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

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

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

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

At the largest scales:

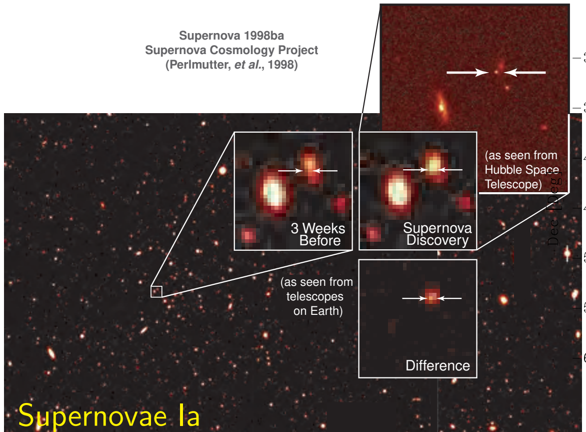
Use General Relativity

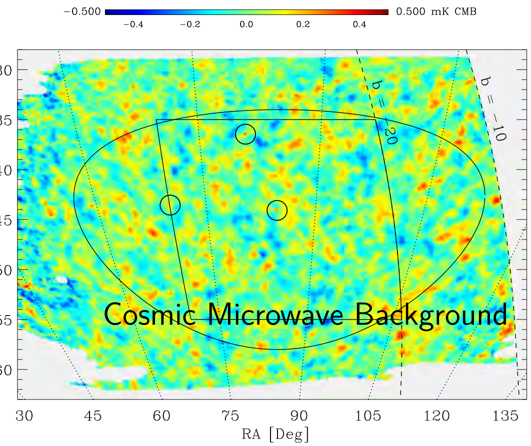
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} \left(+\Lambda g_{\mu\nu}\right)$$

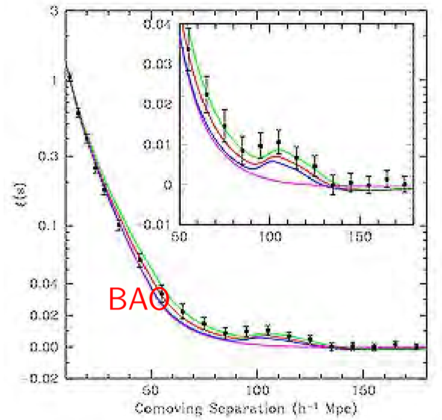
To relate:

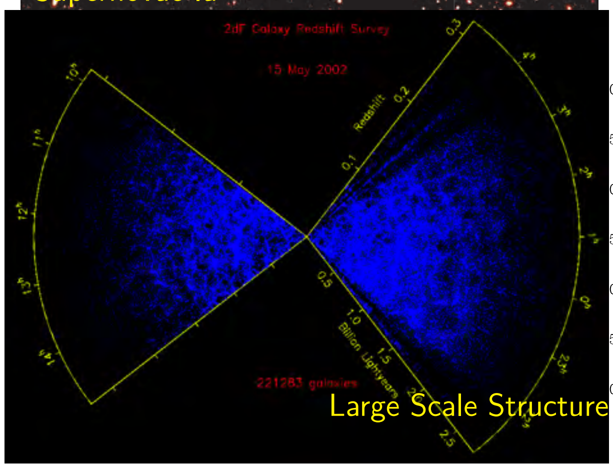
Spacetime geometry $\longleftrightarrow$ Mass-energy density

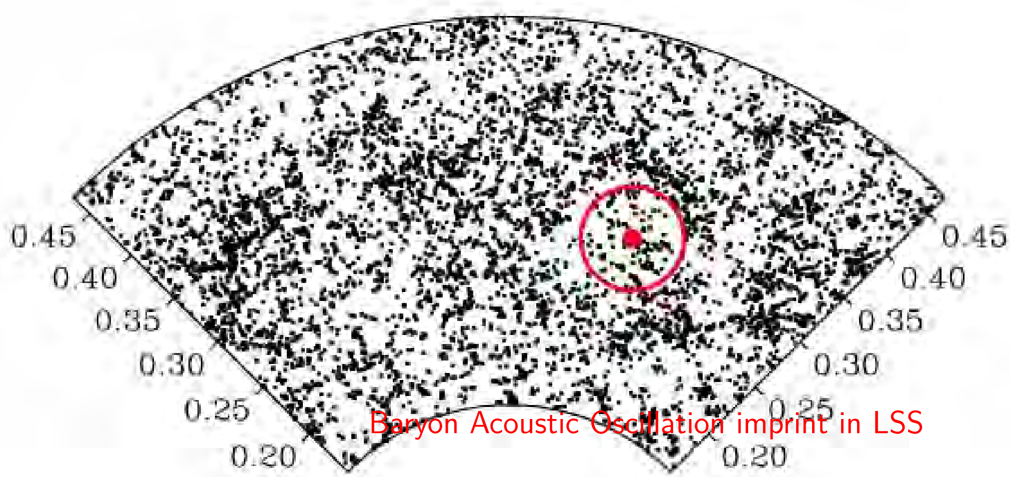
At the largest scales



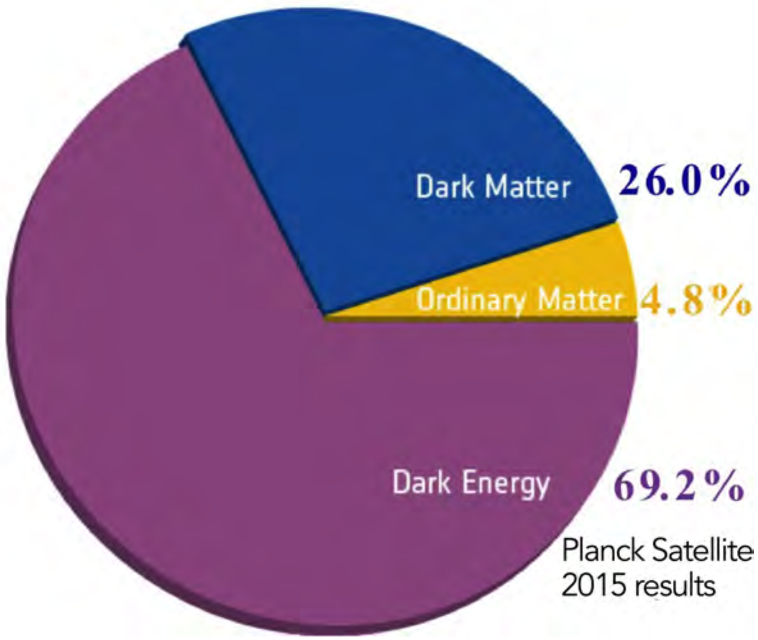


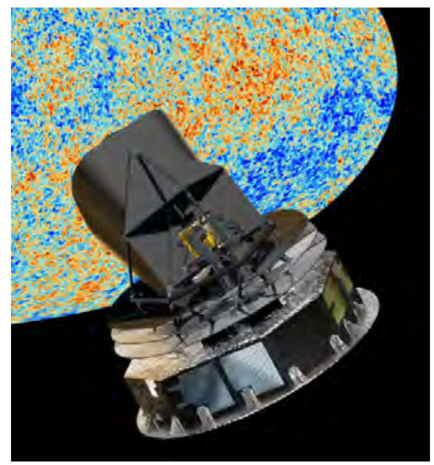






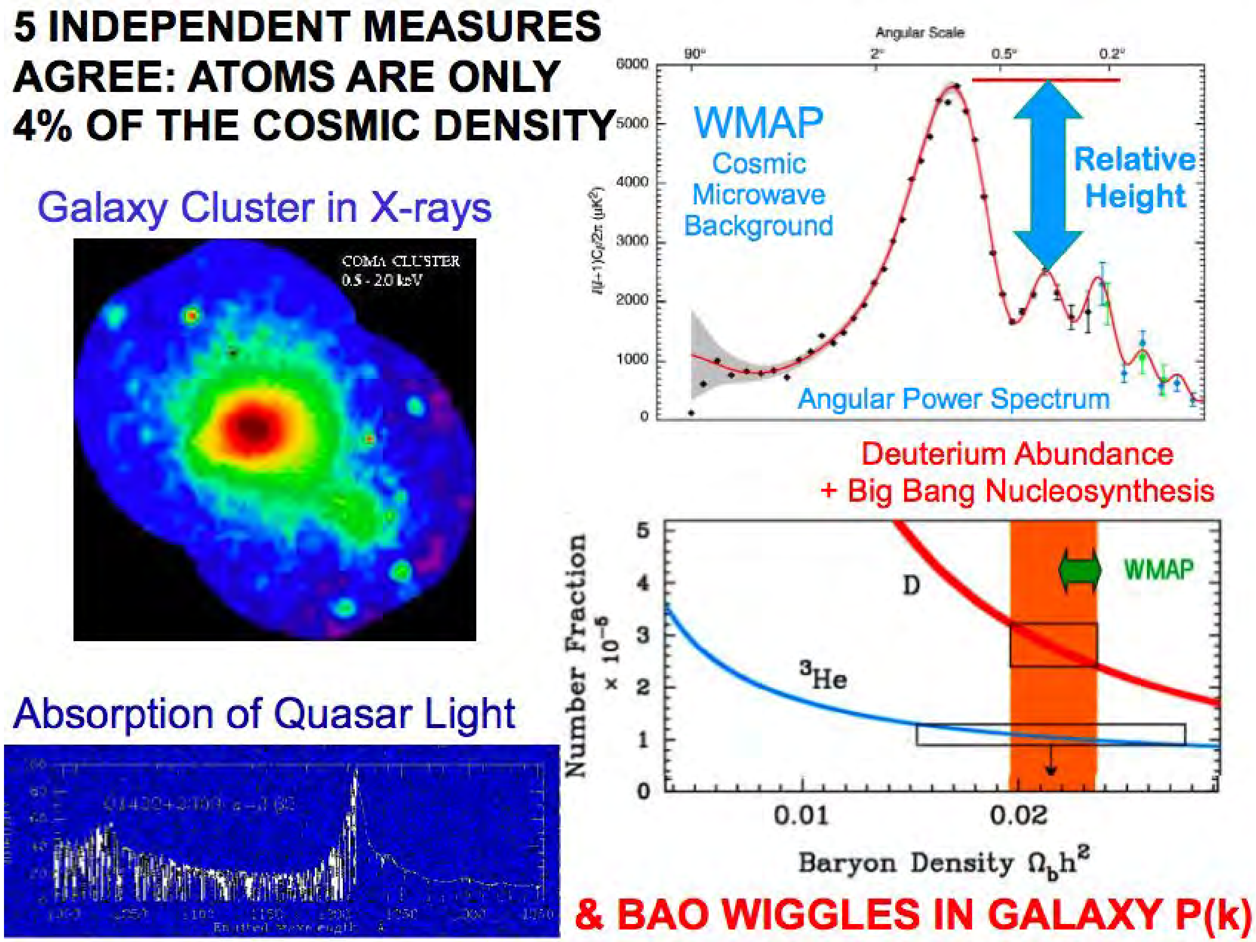
At the largest scales: the "Double-Dark" model





"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



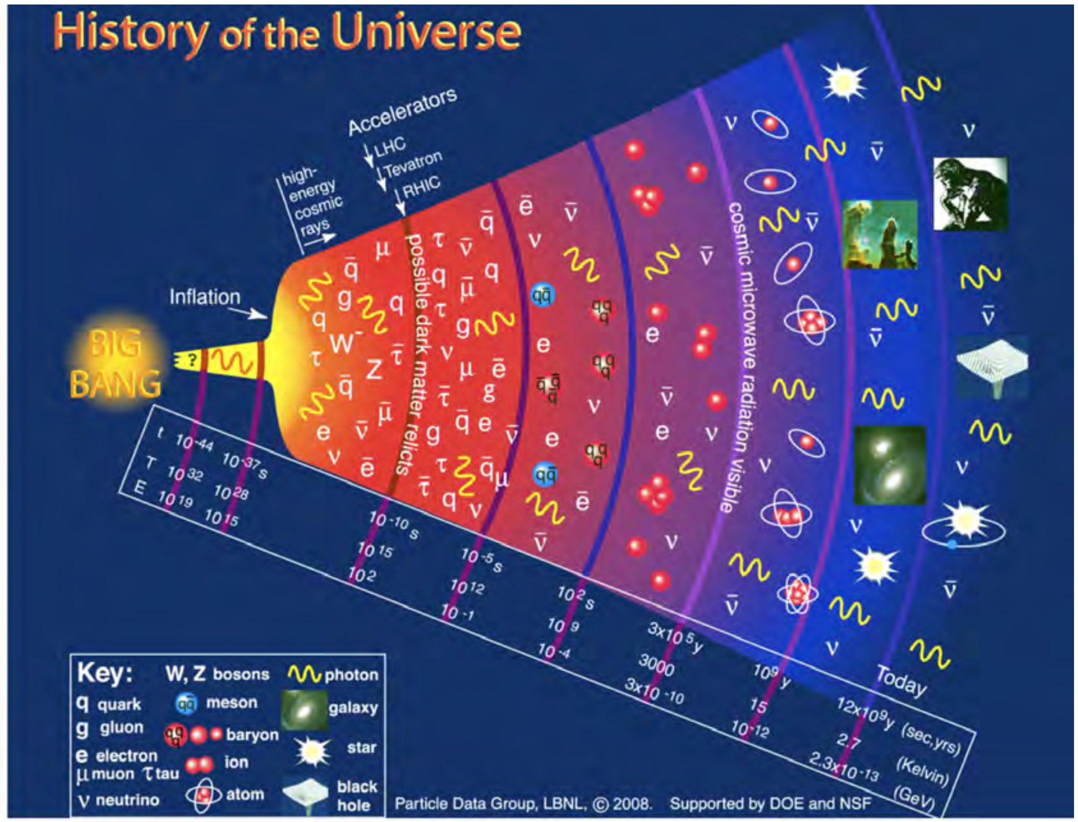
All data confirm the Big-Bang Model of a hot early Universe expanding adiabatically (so T decreases inversely to the size of the Universe)

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



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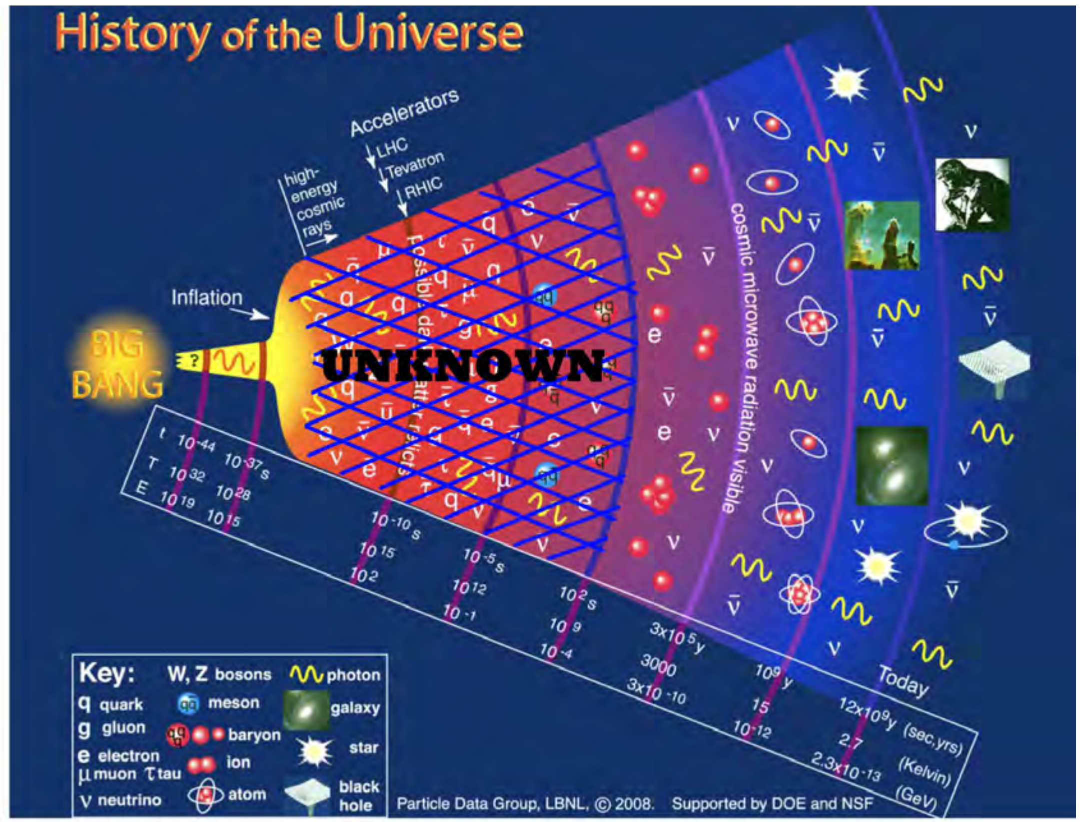
t $\simeq$ 3-20min T$\simeq$ MeV

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 era, **different viable cosmological assumptions imply different relic abundance and 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? So far no specific model can account for all the DM effects.

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** 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"

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"

$$\epsilon F_{\mu\nu} F^{\mu\nu}_{\rm dark}$$

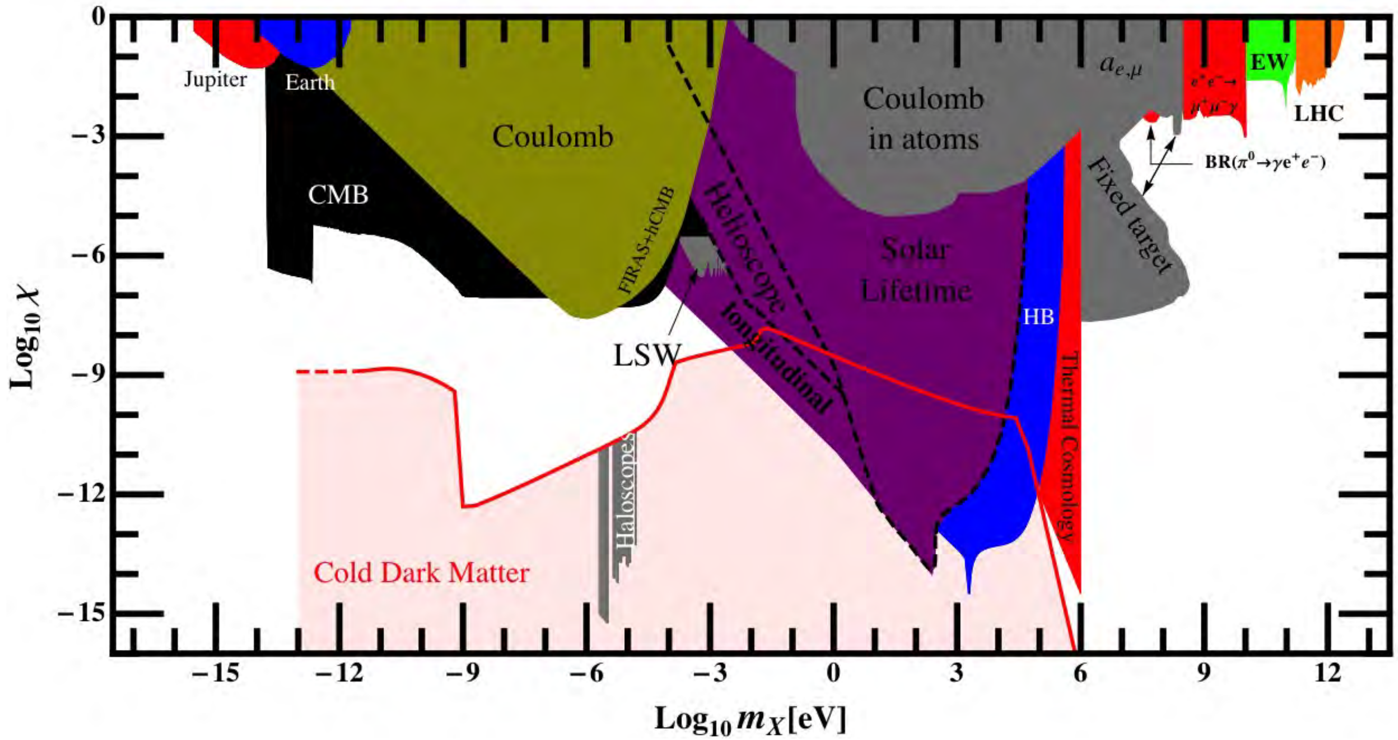
Diagonalized gauge boson kinetic terms: em photon $A_\mu (J^\mu_{em} + \epsilon g J^\mu_{dark})$ (g is $U_{\rm dark}(1)$ coupling). Thus $Q_{\rm em} \simeq \epsilon Q_{\rm dark}$ Holdom 1986 , Burrage et al 0909.0649 D. E. Kaplan 0909.0753 1105.2073 Cline, Zuowei Liu, and Wei Xue 1201.4858

"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 parametersÉ Goldberg Hall 1986; Feng, Kaplinghat, Tu 0905.3039; Ackerman 2009. . .

"Dark" or "Hidden"-Photons (DP or HP) themselves can be the DM- but LDM 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 $\epsilon F_{\mu\nu} F^{\mu\nu}_{\rm dark}$ and m_χ is the HP mass.



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**
- **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- GAIA data in solar neighburghood placed stringent upper limits (and are consistent with no-dark disk) (Windmark et al 2021)

After 90 years, what we know about DM:

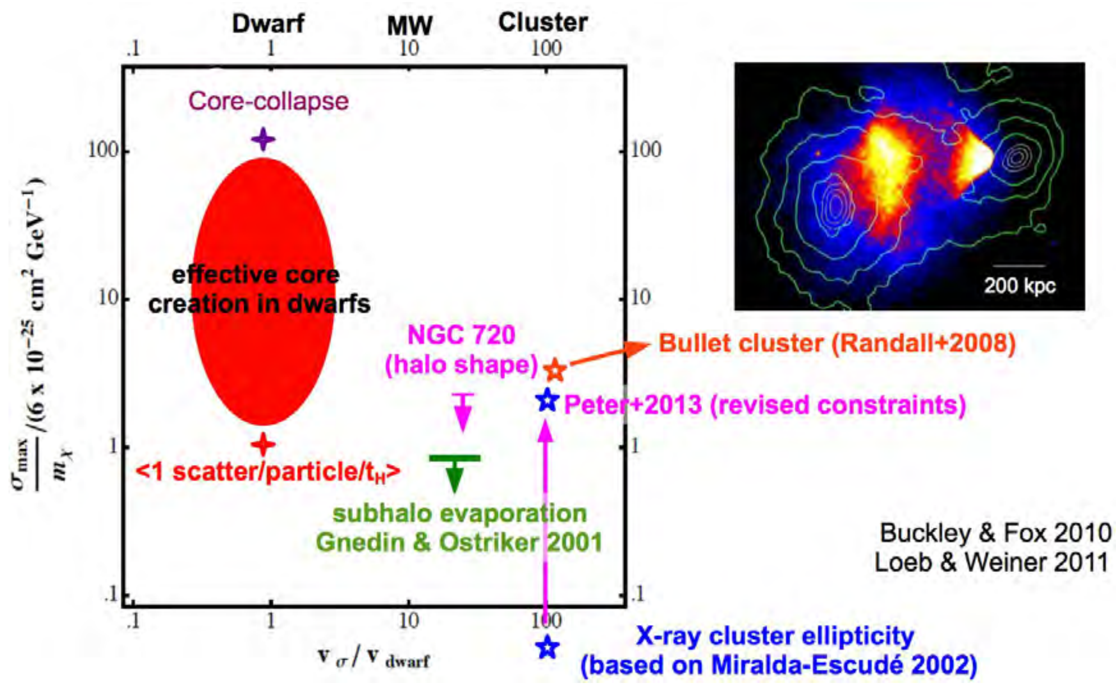
- **1- Attractive gravitational interactions and lifetime $>> t_U$**
- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless but $\leq$few% of it could be dissipative** (so dark sector)
- **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 $\sigma_{\rm self}/m$ ratio comes from requiring self-interaction mean free path $\lambda_{mfp} \simeq 1/n\sigma_{\rm self} = m/\rho\sigma_{\rm self}$ be long enough, $n = \rho/m$ is the DM number density)

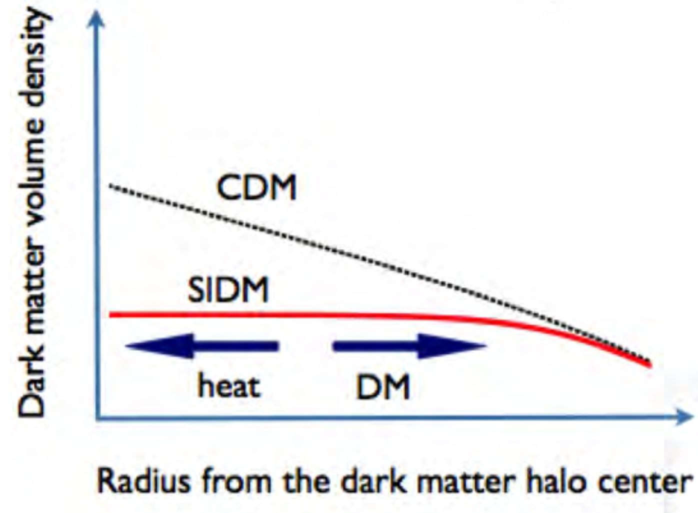
Self Interacting DM (SIDM)

Fig. from Jesus Zavala Franco



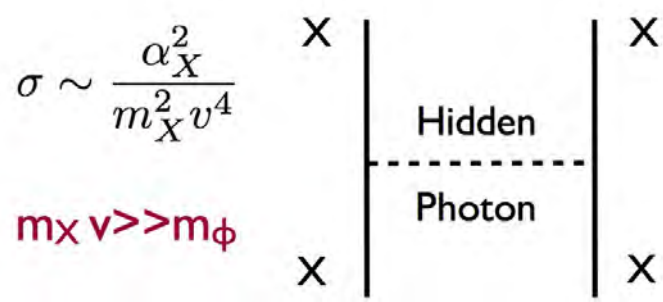
Spergel & Steinhardt 2000 proposed self-interacting dark matter (SIDM) with $\sigma \simeq (m/\text{GeV})(\text{Mpc}/\lambda_{mfp})$ barns SIDM should not affect large structures (large v), only smaller ones (smaller v)

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...)



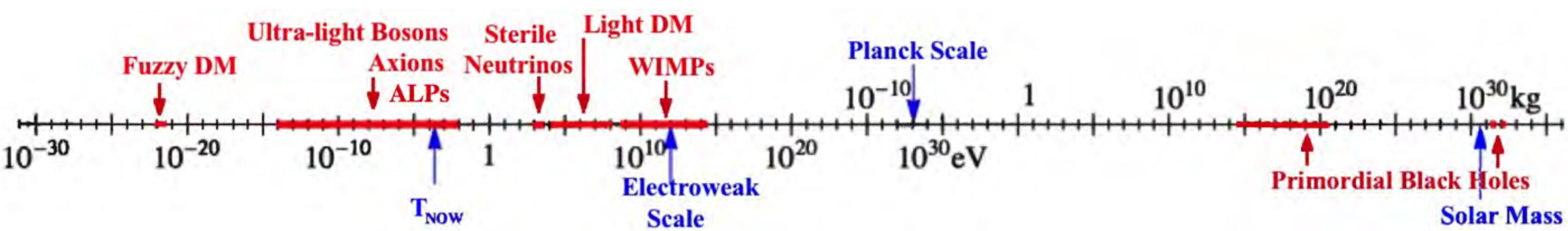
(Recall that the virial speed is larger in more massive structures)

- **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 "asteroid" mass range

Lower limit: "Fuzzy DM", boson with de Broglie wavelength 1 kpc Hu, Barkana, Gruzinov, 2000 (or 0.2-0.7 $\times 10^{-6}$ GeV $\leq$ mass for non-interacting 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...)

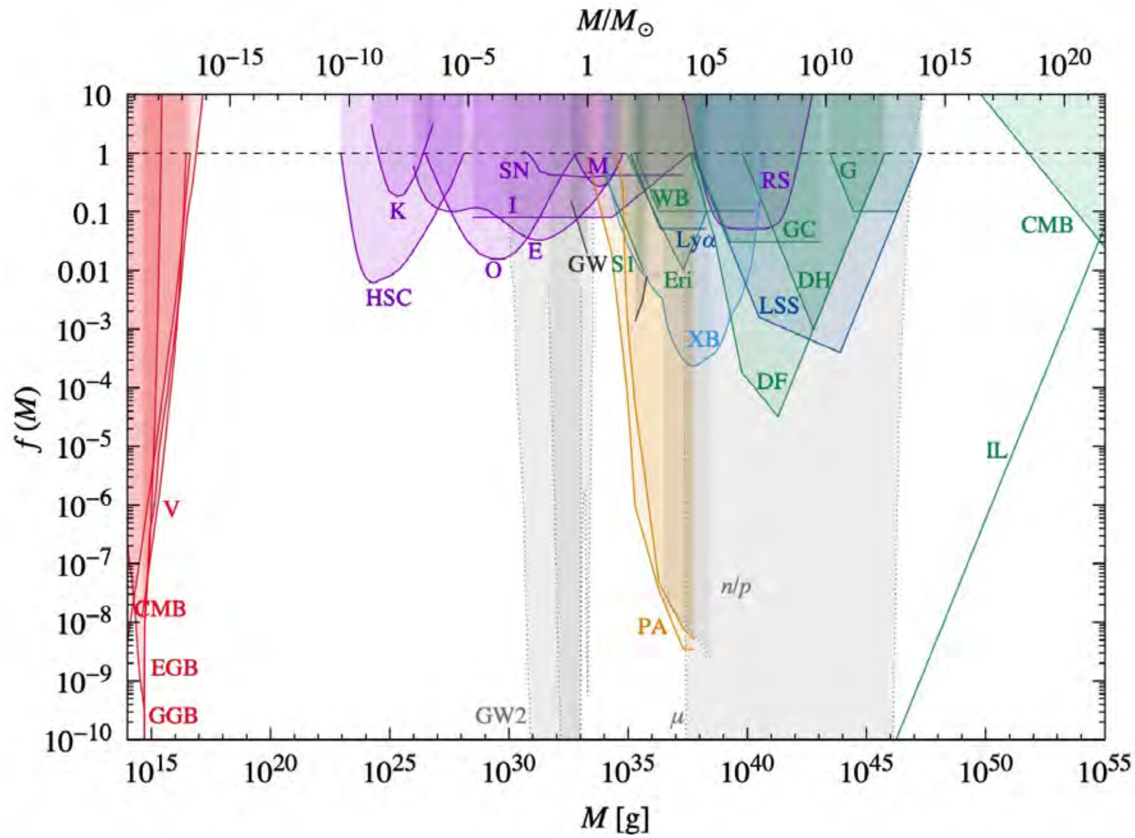


PBH as DM

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 disrruption LSS Poisson fluctuations PA: Planck CMB anisotropies Backgrounds: μ CMB spectral distortions, 2nd order GW emission CMB: dipole, IL: incredulity limit= 1PBH / Hubble volume)

PBH as DM 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

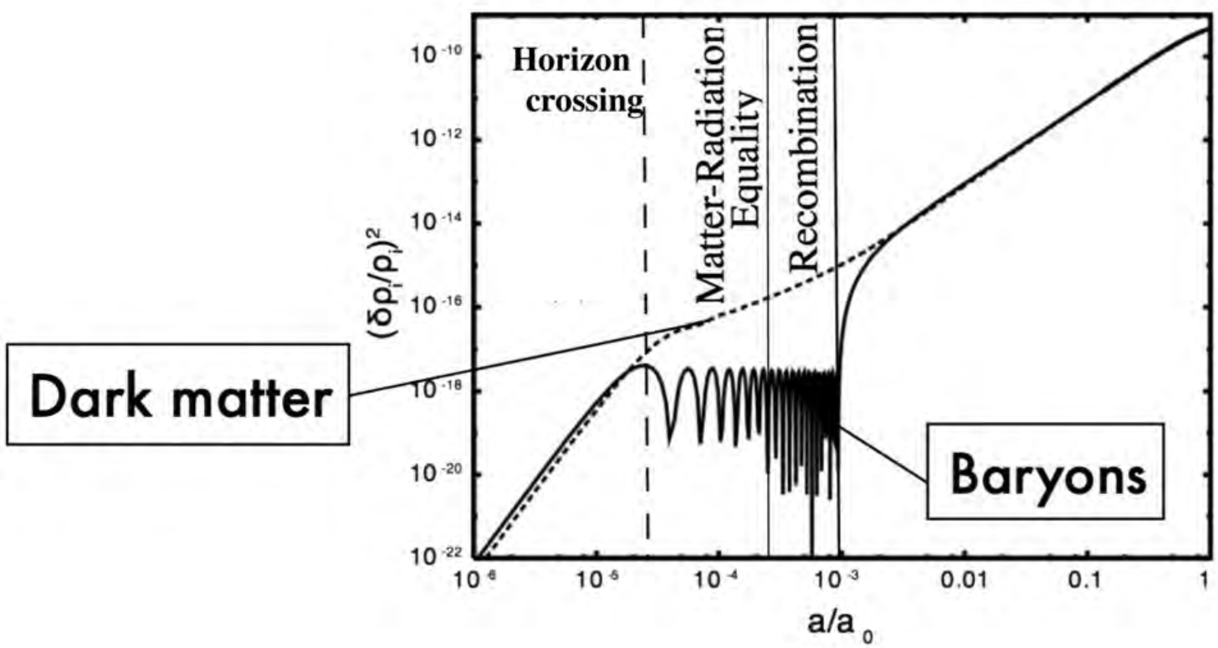
- collapse of vacuum bubbles in multi-field inflationary scenarios Deng, Vilenkin 2017; Kusenko et al 2020

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** $\leq$**few% of it could be dissipative.**
- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit** $\sigma_{\rm self}/{\rm m} \leq$ **2 barn/GeV**
- **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 in plasma).Baryons must fall into potential wells of DM, or not enough time for structures to form: in Matt-Dom Universe $(\delta\rho/\rho)_m \sim a$ could go from 10^{-5} to 10^{-2} but need > 1



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.

"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)

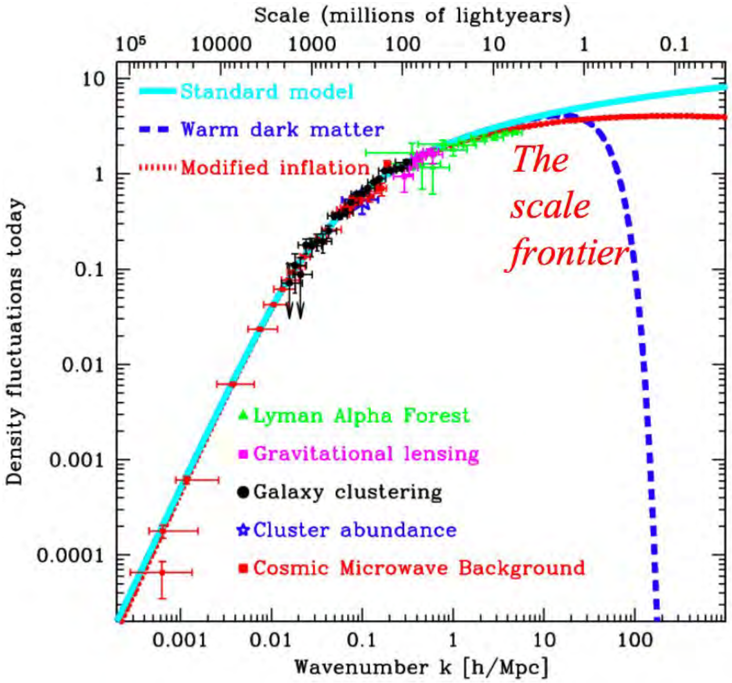
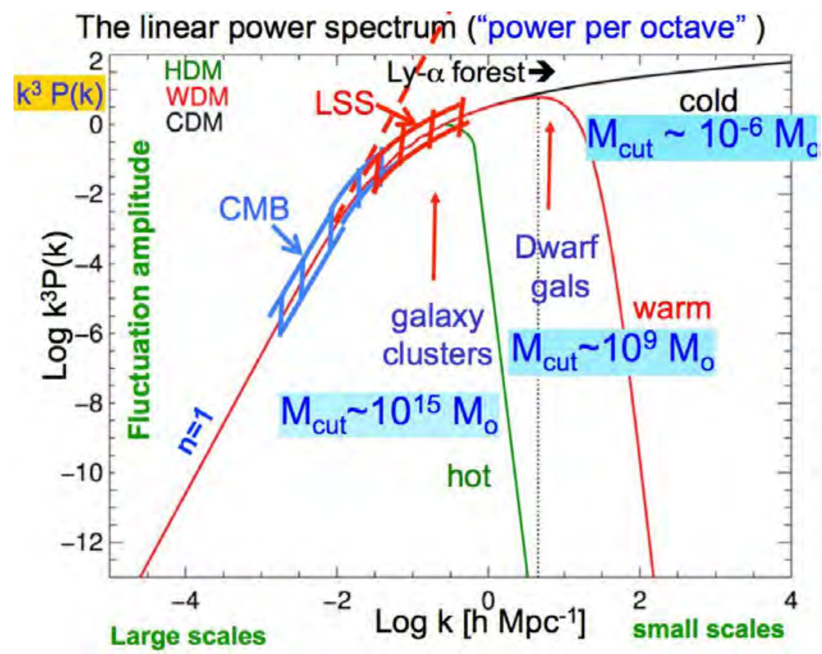


Fig: from Carlos Frenk



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

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$\rightarrow$2 or 4$\rightarrow$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/or 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)...

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**
- **4- The bulk of the DM must be nearly dissipationless**
- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit $\sigma_{\rm self}/{\rm m} \leq$ 2 barn/GeV**
- **6- Mass within 70 orders of magnitude.**
- **7- The bulk of the DM is Cold or Warm**
- **8- Particle DM requires BSM physics**

  In the SM neutrinos are part of the DM, but Hot DM

  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.