Dark Matter Theory

Lecture 2

Graciela Gelmini - UCLA

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Content

- **What we know about dark matter** (continuation)
- **Particle DM candidates**
  - CDM, WDM, PIDM, DDDM, SIDM?
  - Kinetic mixing, Hidden or dark photons, Atomic DM, Mirror DM, WIMPs, FIMPs, SIMPs, Axions, ALPs, WISPs, sterile neutrinos...?
- **Particle DM production mechanisms**

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

  - "Non-thermal" DM: particles produced via other mechanics:
  - "freeze-in" due to out of equilibrium annihilations or decays (FIDM)
  - "freeze-in" due quantum mechanical flavor oscillations (sterile neutrinos)
  - boson condensate formation (axions)
  - decay of particles with thermal abundance or not, or the decay of strings,
  - during reheating after inflation or other phase transitions...

After 80 years, what we know about DM:

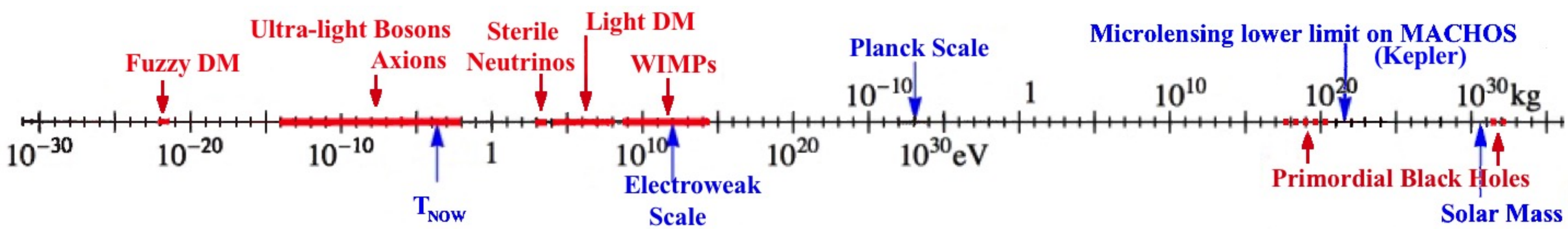
- **1- Attractive gravitational interactions and lifetime $>> t_U$**
- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless, but $\leq$10% of it could be dissipative.**
- **5- DM has 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 90 orders of magnitude.**

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

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



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.

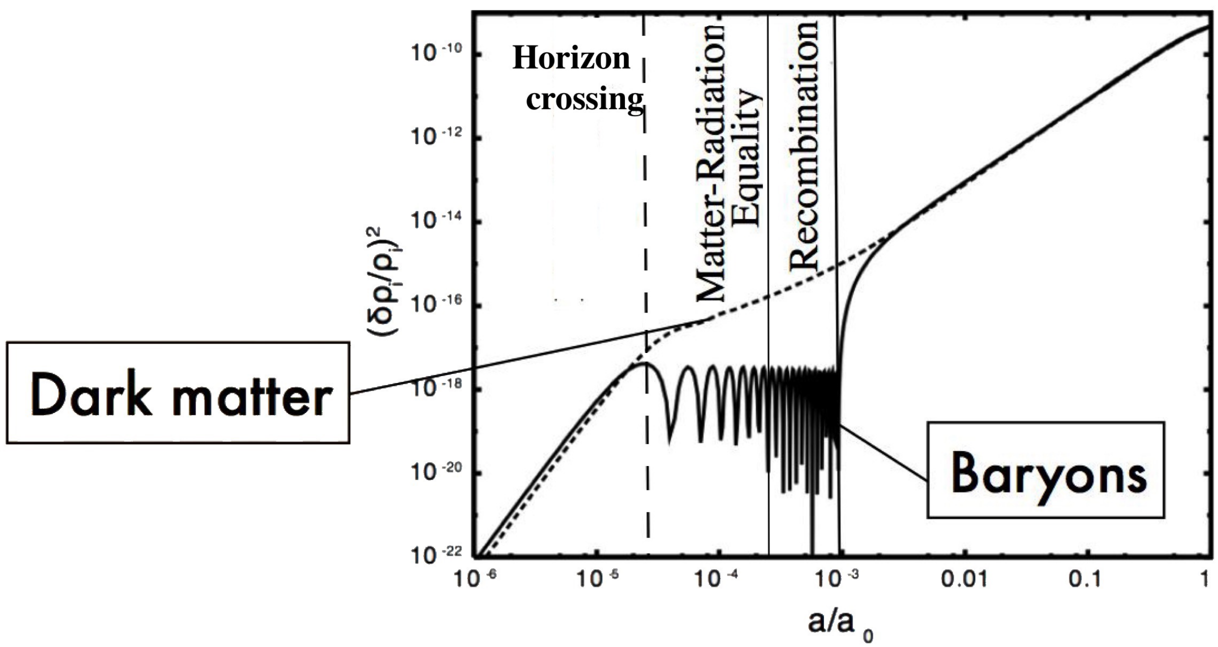
From now on I will concentrate on particle DM candidates

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 ≤10% 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 90 orders of magnitude.**
- **7- The bulk of the DM is "Cold" or "Warm"**(Non-relativistic or almost when dwarf galaxy core size structures start to form, $T \sim$ keV)
  "Double-Dark" model works well with CDM or WDM above galactic scales, distinction at sub-galactic scales. 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.

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

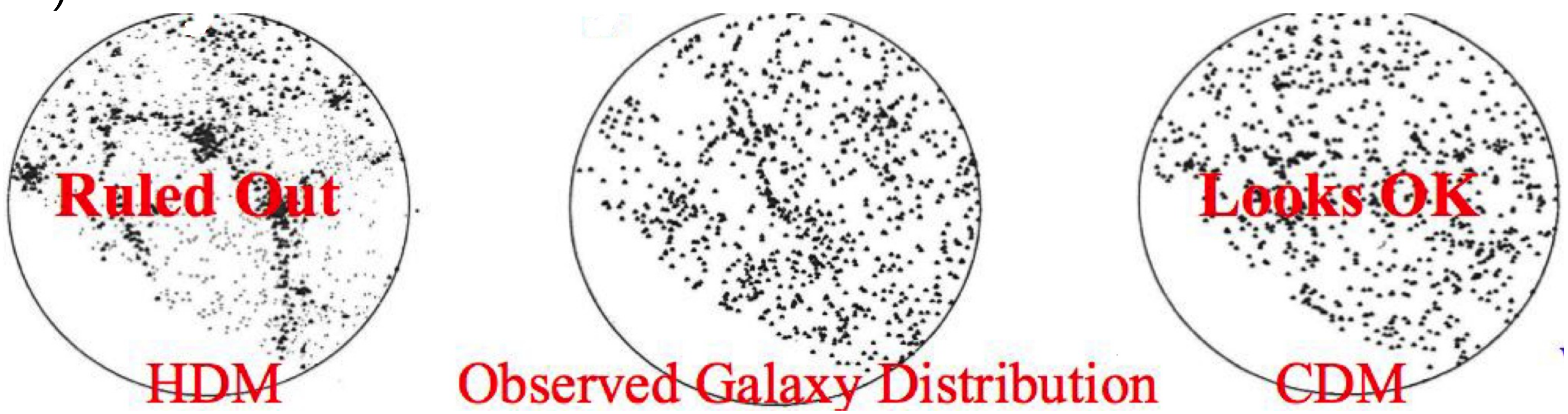


7- Dark Matter is “Cold” or “Warm”

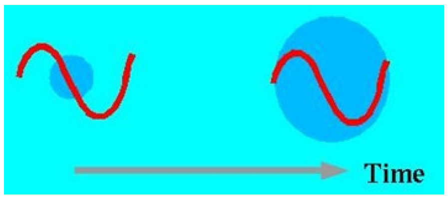
Dark Matter is classified as “HOT” or “WARM” of “COLD” if it is

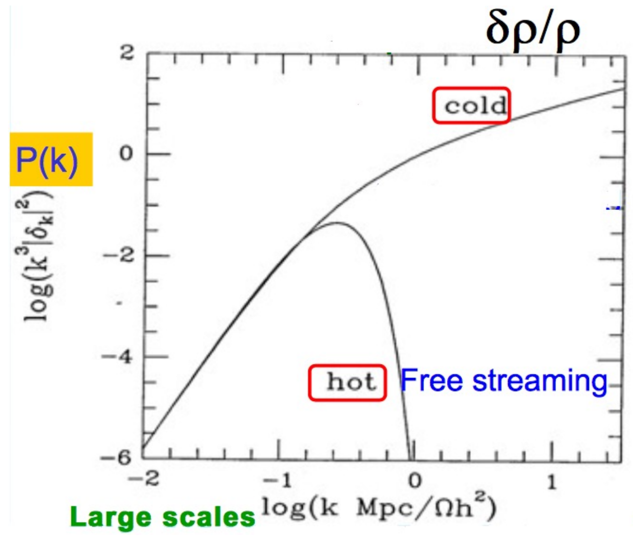
RELATIVISTIC (moves with c), SEMI-RELATIVISTIC or NON-RELATIVISTIC

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.



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.

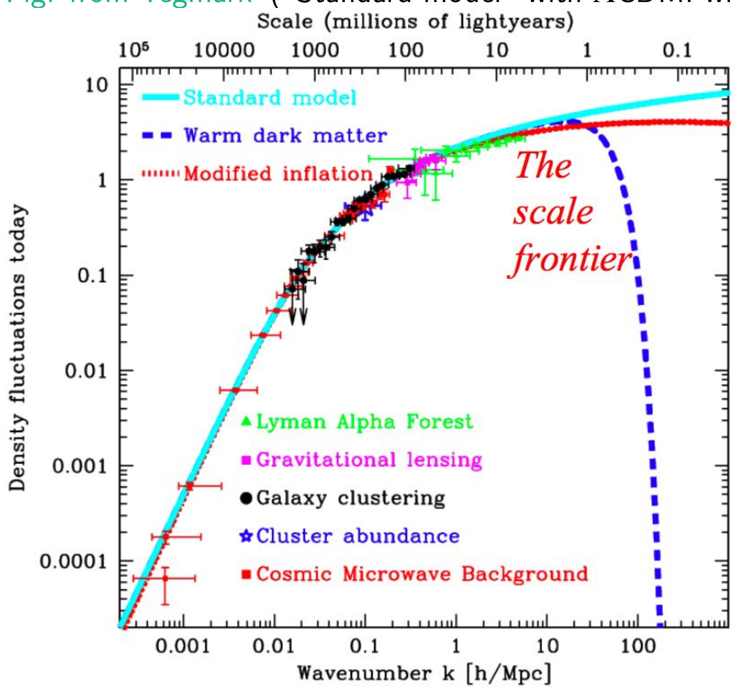
The differences are at smaller scales where observations and their interpretation are still not conclusive.

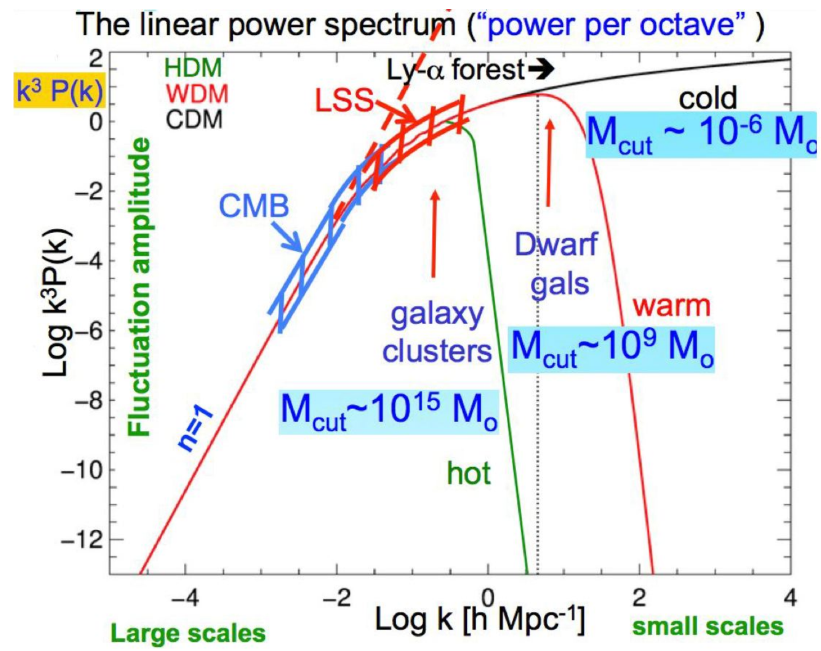
With WDM only structures of dwarf-galaxy cores size and larger survive.

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

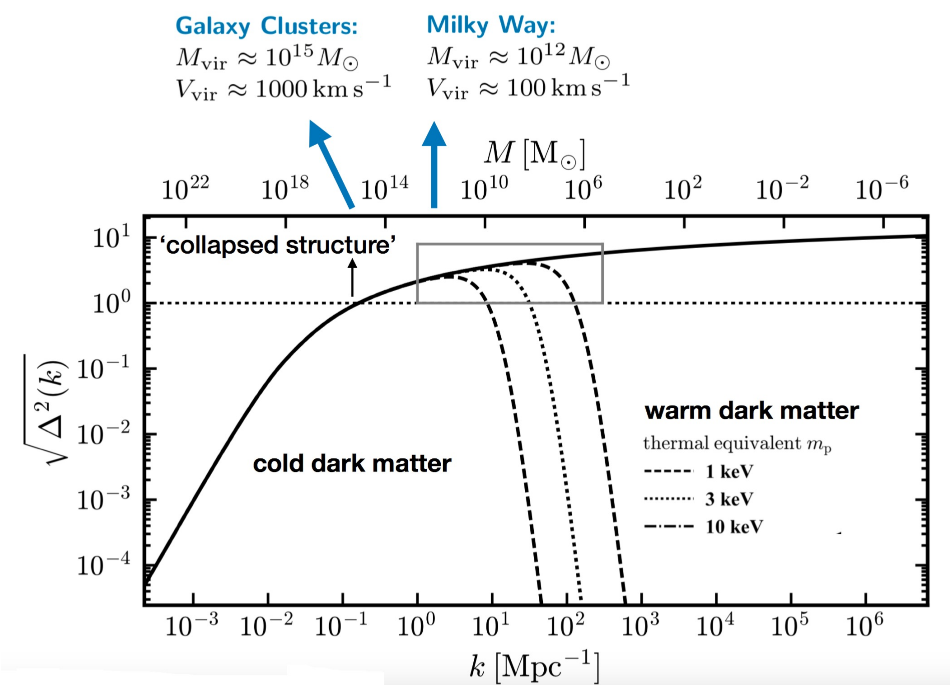


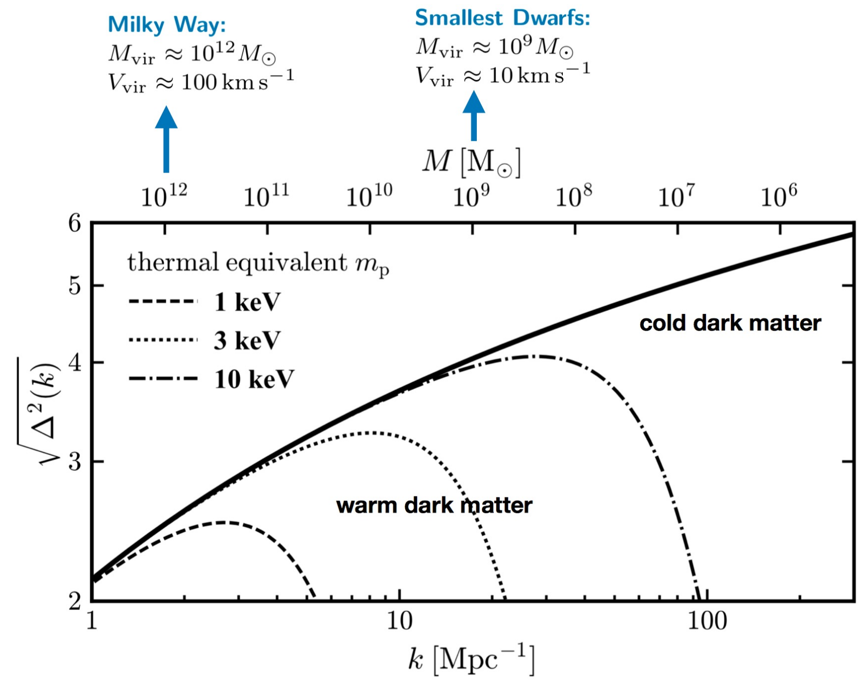


Distinguishing CDM-WDM-SIDM-mixed DM and baryonic effects at sub-galactic scales is where most of the structure formation simulations and observational efforts are directed at present.

"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

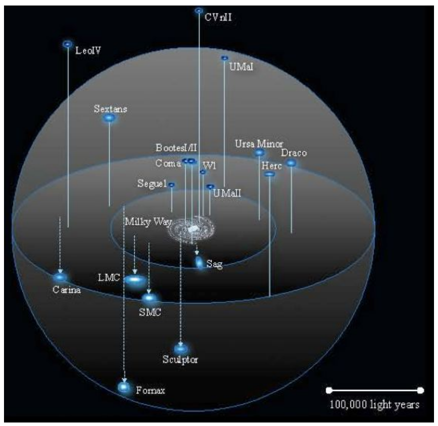


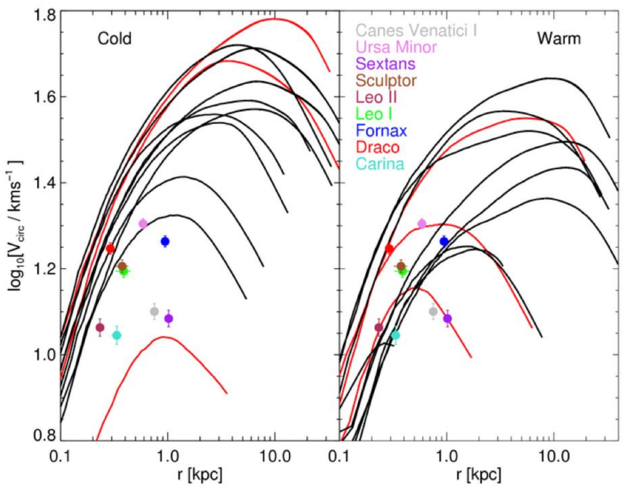


If it has a thermal spectrum, $\bar{E} \simeq 3T$, WDM requires $m \simeq$ keV

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

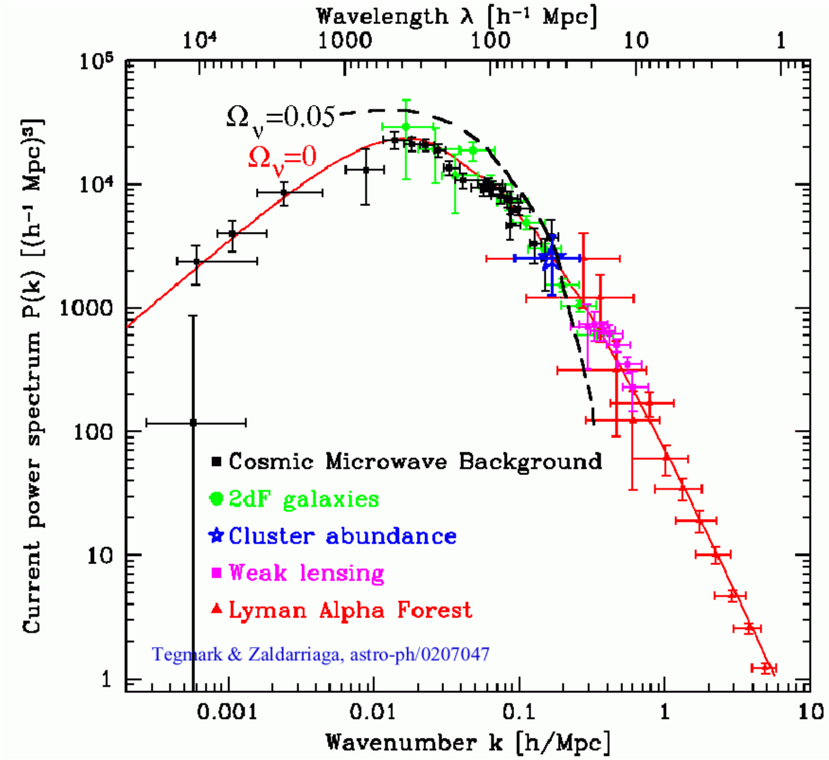




TBTF problem also in Andromeda and the local group? Dwarf Galaxies cored instead of cuspy? CDM rejected so either WDM or velocity dependent SIDM? But baryonic feedback from supernovae and active galactic nuclei can "flatten out" the core of a galaxy's DM profile (so can lead to smaller star velocities)

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

$\Omega_\nu h^2 \simeq \Omega_{DM} h^2 (\Sigma m_\nu / 10 eV)$, $\Omega_{DM} h^2 \simeq 0.11$ 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...

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)*)

8- Particle DM candidates require new physics beyond the SM!

Particle DM require BSM physics-Which BSM physics?

starting from those requiring the smallest modification of the Standard Model.
- sterile neutrinos,
- axions
- WIMPs, superWIMPs, ALPs, WISPs, whole dark sectors...

- Either BSM models produced by reasons other than the DM e.g. Supersymmetric models Technicolor or other composite models, "Little Higgs" models, Inert Doublet models, which provide the main potential discoveries at the LHC and also WIMP DM candidates... or axions (strong CP problem) or sterile neutrinos (ν masses).

- Or "Boutique models", made to be DM-not to solve any SM problem produced largely ad-hoc to try to explain DM hints in direct or indirect DM searches or SIDM or dissipative DM etc, may provide novel signatures for the LHC- e.g. dark sectors coupled to the SM via a "portal" i.e. a small coupling to one type of SM particle (γ's and Z's, the Higgs boson, neutrinos)

Instead of "The Fifty Shades of Gray" we have here "The 500 shades of dark"...

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- **6- Mass within some 90 orders of magnitude.**
- **7- The bulk of the DM is Cold or Warm** (NR or quasi when $T \sim$ keV)
- **8- Particle DM requires Beyond Standard Model physics**

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

  Particle DM candidates must have the right relic 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.

Some members of the particle DM candidates zoo

- WIMPs "Weakly Interacting Massive Particles": have close to weak order interactions with the SM particles.

Models: lightest particle carrying a conserved charge in most BSM UV 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 scenario)

Mass: GeV to 100 TeV

- Difference between WIMPs and "Light DM" (LDM) This is a recent distinction: in direct DM detection, WIMPs scattering on nuclei deposits enough energy to be detected ($E_{\text{threshold}} \simeq$ keV). LDM does not.

Elastic non-relativistic DM-Nucleus collision: the maximum recoil energy imparted to a nucleus by a WIMP moving with v is

$$E_{max} = 2\mu^2 v^2/M$$

$\mu = \dfrac{mM}{(m+M)}$: reduced mass, m: WIMP mass, M: is the nucleus mass.

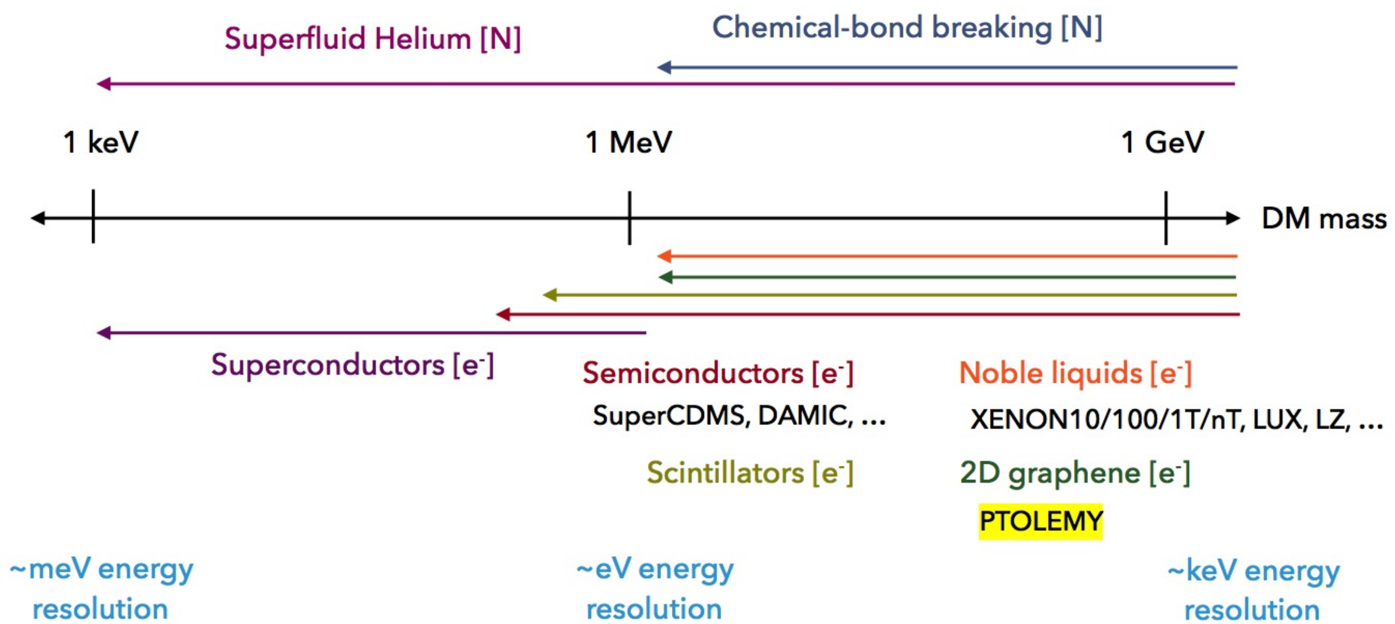
LDM with mass $m \simeq$ keV to GeV E_{max} is below threshold for most direct DM experiments: for $m << M$, $\mu = m$, thus

$$E_{max} = 2\mu^2 v^2/M \simeq 20\text{eV}\left(\frac{m}{100\text{MeV}}\right)^2\left(\frac{10\text{GeV}}{M}\right)$$

but LDM could deposit enough energy interacting with electrons (electron ionization or electronic excitation or molecular dissociation) Bernabei et al. 0712.0562; Kopp et al. 0907.3159; Essig, Mardon & Volansky, 1108.5383; Essig et al. 1206.2644; Batell, Essig & Surujon 1406.2698

Many ideas for sub-GeV "Light Dark Matter" (LDM) direct detection are being actively explored

"Dark Sector Workshop", 1608.08632, DOE workshop "U.S. Cosmic Visions: New Ideas in Dark Matter" in March of 2017



Materials that could be used to probe LDM, by scattering off electrons [e^-] or inelastic scattering nuclei [N] (photon emission in the nuclear recoil, breaking of chemical bonds in molecules or crystals, multi-phonon processes in superfluid helium or insulating crystals)

- FIMPs, "Feebly Interacting Massive Particles" (or "Frozen In Massive Particles"): have interactions of order much weaker than weak, very small couplings Hall, Jedamzik, March-Russell & West, 0911.1120...; see e.g. Bernal, Heikinheimo, Tenkanen, Tuominen &Vaskonen 1706.07442, ...

Models: moduli/modulinos of string theory compactifications with mass generated by the weak-scale SUSY breaking, right-handed sneutrino in Dirac neutrino models within weak scale SUSY (which requiere a coupling $\sim 10^{-13}$), GUT-scale-suppressed interactions, DM with small kinetic mixing coupling to the SM, DM though a Higgs portal...

Production: never reach thermal equilibrium, freeze-in as DM or freeze-in and decay to the DM

Mass: sub eV to 100's TeV

- SIMPs, "Strongly Interacting Massive Particles": Old 1990's SIMPs had strong interactions with the SM particles! Did not survive.

Revived in 2014 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

Models: could be e.g. a pseudo-Nambu-Goldstone 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- assumes kinetic equilibrium of dark and visible sectors so they have the same temperature

Mass: 100 keV - 10's MeV (they are "Light DM" LDM)

- PIMPs, "Planckian Interacting Massive Particles":
assume new physics comes only at the Planck scale M_P Garny, Sandora & Sloth 1511.03278

Models: effective couplings of DM in a hidden sector connected only with gravitational order interactions to the SM.

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 Particles" in a particular Kaluza-Klein model Holthausen & Takahashi 0912.2262)

- Axions and ALPs, "Axion-Like Particles":
The axion is the pseudo-Goldstone boson of a spontaneously broken axial U(1) global symmetry introduced by Peccei and Quinn in 1977, $U(1)_{PQ}$ to solve the strong CP problem of QCD (Weinberg and Wilczek in 1978 realized the PQ model predicted an axion).
The original axion was soon rejected experimentally. So the "invisible axion" models were proposed (Kim- 1979, Shifman, Vainshtein, Zakharov (SVZ)-1980 and Dine, Fischler, Srednicki-1980 and Zhitnisky-1981 (DFSZ)

ALPs are other hypothetical pseudo-GB (among which Majorons and familons...)

Production: as a boson condensate or radiated from axion topological strings

Axion DM mass: 10^{-4} to 10^{-10} eV (for ALPs is very model dependent but light)

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

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....

WIMPZILLAS, heavy particles created during reheating after inflation) Kolb, Chung & Riotto 1998,

Q-balls, non-topological solitons created as a fragmentation of a scalar condensate) Kusenko 1997, Kusenko &Shaposhnikov 1997,

Sterile neutrinos...

Particle DM production mechanisms

- "Thermal" DM: particles produced via interactions with the thermal bath and reach equilibrium with visible matter. Then "decouple" or "freeze-out".

- "Non-thermal" DM: particles produced via other mechanics:
  - "freeze-in" due to out of equilibrium annihilations or decays...
  - "freeze-in" due quantum mechanical flavor oscillations,
  - boson condensate formation,
  - decay of particles which may or may not have a thermal abundance, or the decay of strings,
  - during reheating after inflation or other phase transitions...

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

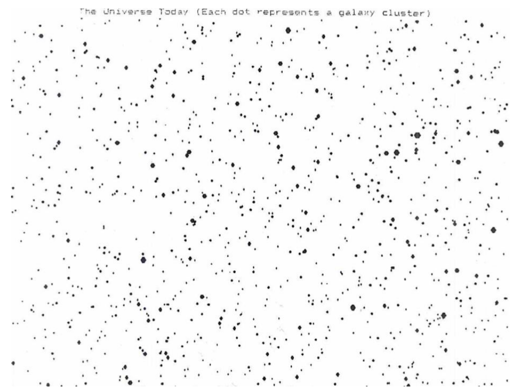
- The expansion has no center: all inter-distances grow in the same way

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

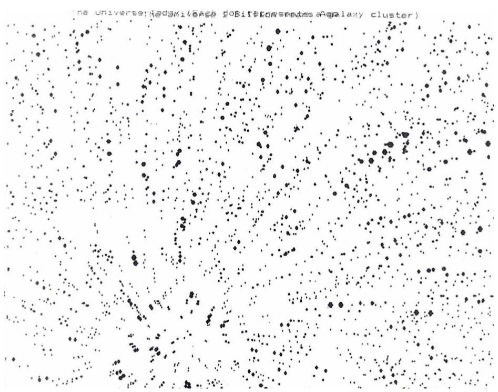
  $a(t)$: scale factor of the Universe
  $H(t) \equiv \dot{a}/a$ (constant in space, not in time)

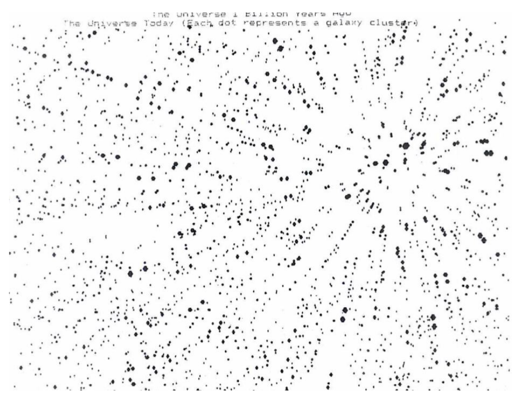
Expansion of the Universe

Sometime in the past



Now

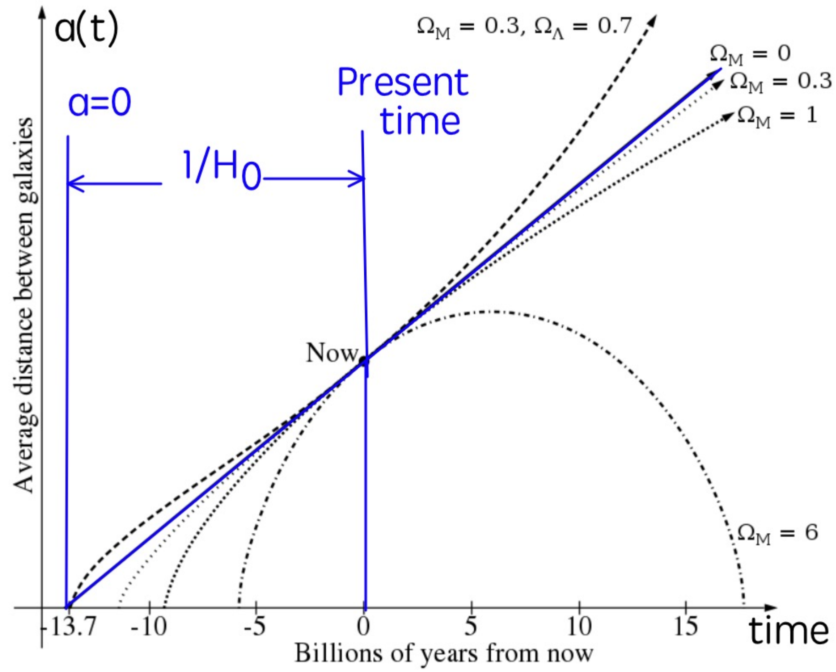




The galaxy from which we observe, seems always the center of expansion

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

$$t_U \simeq 1/H$$



(END parenthesis)

Equilibrium

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

Adiabatic expansion: entropy per coming volume $= sa^3 d_0^3 \sim T^3 a^3$ is conserved, thus $T \sim 1/a$
T is decreasing at a rate $\dot{T}/T = -\dot{a}/a = -H$ (H: expansion rate of the Universe) and reaction rates must exceed the rate of change of T to maintain equilibrium

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

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

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

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

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

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

Decoupling

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

When Γ decreases faster than H as T decreases, at **Decoupling:**

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

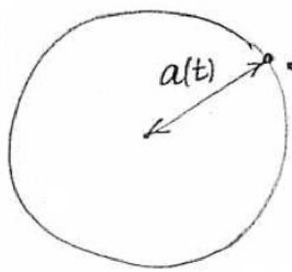
(and $\Gamma < H$ for $T < T_D$)
We need to know the expansion rate of the Universe $H(T)$. In GR is given by Friedmann Equation $H^2 = \frac{8\pi}{3} G/3\rho - k/a^2 + \Lambda/3$, where $k = 0$ for a flat Universe and Λ is negligible in the early Universe

Friedmann Eq. for the expansion rate H from Newtonian gravity:

Back-of-an-envelope calculation (literally!)

What is H? Use a Newtonian argument (only matter)

Consider a sphere of density ρ, radius $a(t)$



test particle of mass m, $M = \frac{4}{3}\pi a^3 \rho$

$$E_{particle} = \frac{m\,\dot{a}(t)^2}{2} - \frac{GMm}{a(t)}$$

With only matter, Universe is flat $\Longleftrightarrow$ $E_{particle} = 0$

Using $H = \frac{\dot{a}}{a}$ and $\frac{\dot{a}^2}{2} = G\frac{4}{3}\pi\frac{a^3\rho}{a}$ $\Rightarrow$ $\boxed{H^2 = \frac{8}{3}\pi G \rho}$

In GR this is valid for $\rho = \rho_{matter} + \rho_{rad.} + \rho_\Lambda$ (in GR $\rho_\Lambda = \rho_{\rm DE}$) . Gravity const. $G \simeq 1/M^2_{Planck}$, $M^2_{Planck} \simeq 10^{19}$GeV. RD Universe: $\rho = \rho_{rad} \sim T^4$. So for radiation $H \simeq \dfrac{T^2}{M_P}$

Actual calculation involves the Bolzmann Transport Equation:

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

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_A v \rangle_T \left[(n_\chi)^2 - \left(n_\chi^{eq}\right)^2 \right]$$

$P\bar{P} \to \chi\bar{\chi}$

dilution by Universe expansion

thermally averaged annihilation cross section

$\chi\bar{\chi} \to P\bar{P}$

expansion: $n \sim a^{-3} \to \frac{dn}{dt} = -3\frac{\dot{a}}{a}n = -3Hn$

annihilation: $n \sim e^{-t/t_A}$ thus $\frac{dn}{dt} = -n/t_A$, $t_A \simeq \lambda_{M.F.P}/v = 1/\sigma_A n v$

creation: stop expansion at T, wait for equilibrium so $\frac{dn}{dt} = 0$

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

Bolzmann Transport Equation and the conservation of entropy

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

where $s = \dfrac{2\pi^2}{45}\, g_{\text{s- eff}}(T)\, T^3$ is the entropy density and T the photon temperature

can be combined into a single equation for $Y = n/s$, and use $x = m/T$ (Kolb & Olive Phys Rev D33,1202,1986; Kolb&Turner book, Gelmini&Gondolo 1009.3690 and refs therein)

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

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

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

Thus when $\Gamma/H << 1$ the number per comoving volume $(Y \simeq n/a^3)$ becomes constant.