Topics in Extragalactic Astronomy

1. Dark Matter

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topics

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2. evidence of dark matter (DM)
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4. X-ray emission in galaxy clusters
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prologue: Le Verrier and the anomalies in the planetary motions

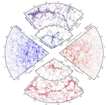
- Le Verrier (Aug 31, 1846) suggests that perturbations observed in Uranus' orbit were produced by a new, still unknown planet
- Galle (Sep 23, 1846) discovers Neptune
- Le Verrier (1859) suggests a new planet to explain the precession of the perihelion of Mercury
- Lescarbault (Sep 26, 1859) describes the transit of a unknown planet (Vulcan) over the Sun disk
- Liais, a French astronomer, was working at Observatório Nacional in Rio de Janeiro and had observed the Sun in the same time than Lescarbault, without noticing anything: his report buried definitely the idea of Vulcan
- Einstein (1915) explains the precession of the perihelion of Mercury with a new gravitational theory, the general relativity

- two problems with the orbits of planets: one solved by introducing a new planet and the other by changing the gravitational theory
- "anomalous motions" in the universe:
  new matter (dark matter/Neptune) or
  modifications in gravity (general relativity)?

brief history of dark matter (DM)

- Zwicky (~ 1930) finds that galaxy clusters have more mass than that in the form of stars and calls it “dark matter”
  “If this overdensity is confirmed we would arrive at the astonishing conclusion that dark matter is present with a much greater density than luminous matter”
  “From these considerations it follows that the large velocity dispersions in Coma (and in other clusters of galaxies) represents an unsolved problem”
- Babcock (1939) obtains long slit spectra of M31 and notices that the outer parts of the disk are rotating with unexpectedly high velocities
- Rubin & Ford (~ 1970) study the rotation curve of spiral galaxies and find that these objects are also dominated by “dark matter”
- Freeman (1970): evidence of a spheroidal dark halo
- Roberts & Whitehurst (1975): HI rotation curve up to ∼10 times the optical radius
- Ostriker & Peebles (1974): DM can help the stability of galactic disks
- Ostriker, Peebles & Yahil (1975): DM could be cosmologically significant
- Rees (1977): DM could be of a “more exotic character”, such as neutrinos with a small rest mass – an example of a WIMP or a “Weakly Interacting Massive Particle”
- White & Rees (1978): galaxy formation with CDM
- Bond et al. (1983): first use of “cold dark matter”
- White, Frenk & David (1984): numerical simulations show that hot dark matter does not reproduce the LSS (due to free streaming)
- Riess et al. (1998), Perlmutter et al. (1999): ΛCDM
- ...



Zwicky and the discovery of DM

- gravitational systems in equilibrium obey the virial theorem: potential (W) and kinetic (T) energies are related as $2T + W = 0$
- for a system of mass M, radius R and velocity dispersion σ: $T \sim M\sigma^2/2 \qquad W \sim -GM^2/R$
- then, $M \sim \frac{\sigma^2 R}{G}$

  the mass can be determined from the velocities and positions of galaxies

Bahcall (1999): analysis of the Coma cluster

- mass within a radius of 1.5h^{-1}Mpc:

$$M(\leq 1.5) \simeq 0.7 \times 10^{15} \left(\frac{\sigma_v}{1000 \text{ km s}^{-1}} \right)^2 h^{-1} M_\odot$$

(σ_v: radial velocity dispersion)

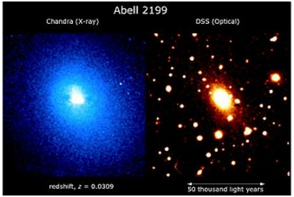
- components:
  - stars: $M_* = 1.0 \times 10^{13} \, h^{-1} \, M_\odot$
  - gas: $M_g = 5.5 \times 10^{13} \, h^{-3/2} \, M_\odot$
  - total: $M_T = 6.8 \times 10^{14} \, h^{-1} \, M_\odot$
- in this case $M/L \sim 350 \, M_\odot / L_\odot$

X-ray emission in galaxy clusters

- clusters have a hot and extended intracluster medium which emits in X-rays (*bremsstrahlung* radiation)
  - temperature $T \sim 10^7 - 10^8$ K
  - density $n \sim 10^{-4} - 10^{-2}$ cm^{-3}
  - luminosity $L_X \sim 10^9 - 10^{11} L_\odot$
  - mass $M_{gas} \sim 0.05 - 0.5\, M_{tot}$
- assuming that the gas is in hydrostatic equilibrium,

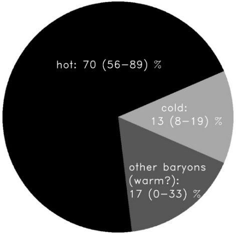
$$M(< r) \simeq \frac{2kTr}{G\mu m_p}$$

μ: mean molecular weight of the gas (~ 0.5 for an ionized plasma);
m_p: proton mass



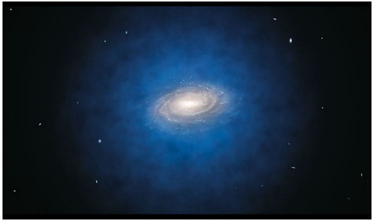
baryons in clusters (Ettori 2003):

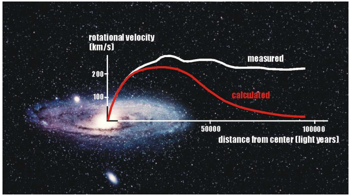
- baryon fraction: $M_b/M_{tot} \simeq (0.03 - 0.15)h^{-1.5}$
  median within 1.5 h^{-1} Mpc: 0.07$h^{-1.5}$
- 13%: stars
- 70%: hot gas
- 17%: “warm” material ($10^5 - 10^7$ K)

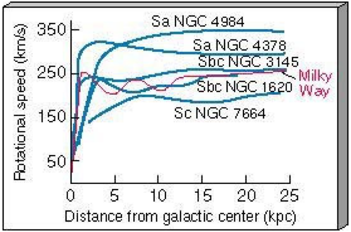


rotation curves

- Rubin, Ford & Kent (1970):
  - the rotation curves of disk galaxies are “flat”: $v_c = \frac{GM(<r)}{r}$
  - if $v_c \approx$ constant, $M(< r) \propto r$
- Freeman (1970): evidence of a spheroidal dark halo







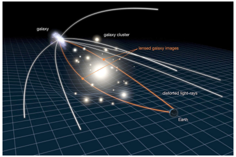
gravitational lensing

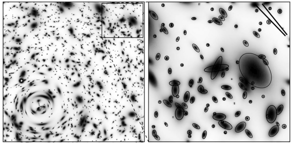
- GL: consequence of the light deflection by a massive body (Einstein, 1916)
- Einstein: the deflection of the light of a star by another is negligible
- Zwicky (1937): galaxies and clusters of galaxies can be efficient lenses
- 1979: discovery of the first double quasar by Walsh, Carswell & Weimann
- two regimes: weak lensing & strong lensing
  both can be used to determine mass

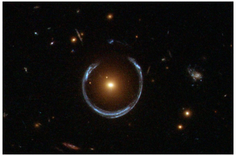
- a critical scale: the Einstein radius:
  the angular Einstein radius is

$$\theta_E = \sqrt{\frac{4GM}{c^2} \frac{D_{LS}}{D_L D_S}}$$

- M is the projected mass within θ_E
- D_L, D_S e D_{LS} are diameter distances to the lens, to the source, and between the lens and the source, respectively
- strong lensing occurs for $\theta \lesssim \theta_E$;
  weak lensing is measured at larger radii

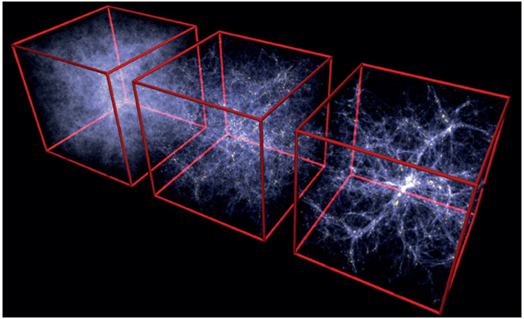


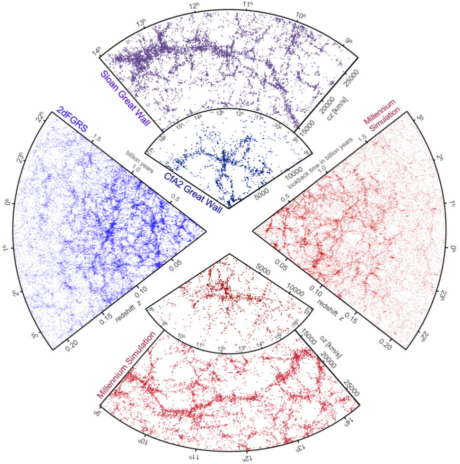




CDM and LSS

a major success of CDM is that it provides a very good description of the LSS (but ...)



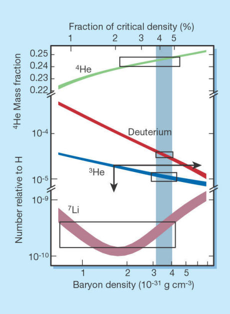


is DM baryonic?

the standard cosmological model puts strong constraints on the baryon density:

- the abundance of light elements, produced during the primordial nucleosynthesis (He, D, Li):
  $\Omega_b h^2 \approx 0.022$; for $h = 0.69$ we have $\Omega_b = 0.049$
- the power spectrum of the CMB temperature fluctuations:
  the position of the peaks depend on $\Omega_b h^2$
  Planck 2015: $\Omega_b \approx 0.049$ $\quad$ $\Omega_m \approx 0.308$

these results suggest that most of the matter can't be baryonic!

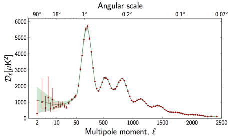


inventory of baryonic matter:

- stars: $\Omega \simeq 0.0025$
- neutral H and He (atomic and molecular): $\Omega \simeq 0.0008$
- ionized gas (in clusters): $\Omega \simeq 0.0013$
- warm gas (groups): $\Omega \simeq 0.005$
- warm gas (around "isolated" galaxies): $\Omega \simeq 0.004$
- sum of known baryons: $\Omega \simeq 0.014$
- unknown baryons: $\Omega \simeq 0.030$

possibly most of the missing gas is cold/warm gas around galaxies or in

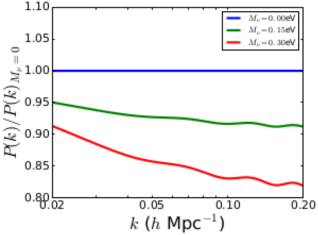
non-luminous clouds

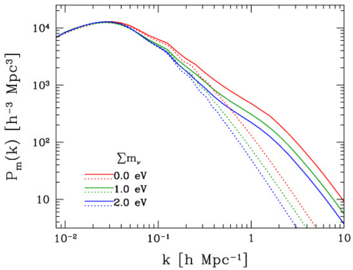


neutrinos as dark matter

- ν: neutrinos are a kind of dark matter that we know exist!
- three species: ν_e, ν_μ, ν_τ
- solar neutrino oscillations: neutrinos have mass
- they are relativistic: “hot dark matter” (HDM): their free streaming erases small density fluctuations
- top-down scenario of structure formation:
  - if all DM were in form of neutrinos the first structures to form would be very large
  - smaller structures would be produced by fragmentation of large structures
- the free streaming of neutrinos let their imprint in the CMB and in the galaxy distribution, and these features allow to constrain the neutrino mass
- astrophysics provides strong constraints on the neutrino mass!
- Cuesta, Niro & Verde (2016):

	CMB only	CMB+$\tau_{\rm reio}$	CMB+$P(k)$	CMB+BAO
	[16]	[17]	[5]	[1]
M_ν (eV)	< 0.49	< 0.34	< 0.30	< 0.16





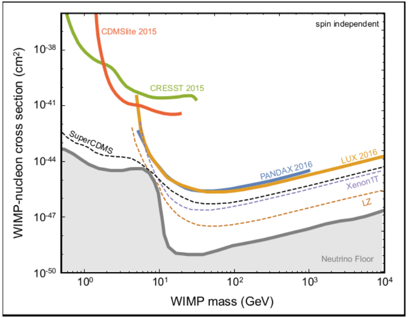
dark matter as unknown particles

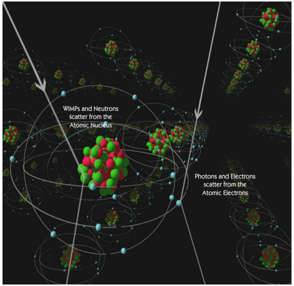
- relic particles from the Big Bang
- Cold Dark Matter: the CDM paradigm
  - matter: not a new theory of gravitation
  - dark: do not interact with photons
  - cold: non relativistic particles (at time of decoupling)
- "popular" candidate: the WIMPs- *weakly interacting massive particles*
  - they do not interact with photons but could interact weakly with baryonic matter
  - mass $\sim$100 GeV
  - an example of WIMP which appears in super-symmetric theories:

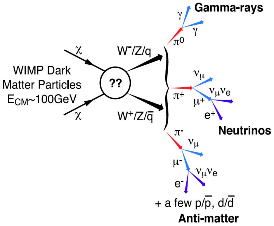
    the *neutralino*, the lightest of the super-symmetrical particles
- another candidate: the *axion*
  - appears in quantum chromodynamics
  - masses between 10^{-5} - 10^{-2} eV
  - uncertainty of $\sim$16 orders of magnitudes

experimental detection of dark matter

- direct detection
  - dark matter elastically scatters off nuclei
  - nuclear recoils detected by phonons, scintillation, ionization,...
- indirect detection
  - dark matter may pair annihilate to photons, neutrinos, positrons, antiprotons, antideuterons, ...



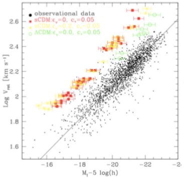


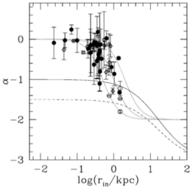


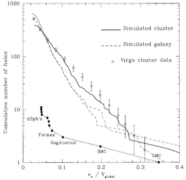
problems with CDM

but the CDM model faces some problems, mostly at small scales:

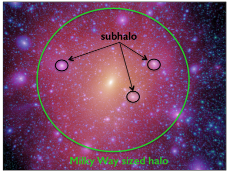
- the angular momentum problem (e.g. Navarro & Steinmetz 2000)
  the size of a simulated disk galaxy is smaller than the real size of disk galaxies at the same stellar mass
- the cusp-core problem (e.g. de Block et al.2001)
  the central densities of CDM halos in simulations are cusped (NFW profile), whereas the density profiles of Low Surface brightness galaxies (supposed dominated by DM) show a core-like structure
- the missing satellite problem (e.g. Klypin et al.1999)
  there are much more satellites around Milky Way sized galaxies in the simulations than is observed
- the too big to fail problem (Boylan-Kolchin et al. 2011)
  the population of subhalos within galactic halos in simulations have higher central densities than the satellites of the Milky Way







V.Springel et al.2008

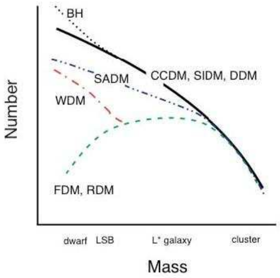


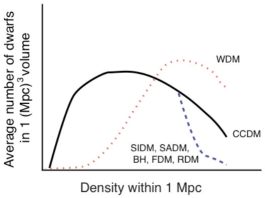
“solutions”:

- the culprit are the baryons: small halos lost their baryons and did not form stars; in more massive halos baryons may also destroy the central cusp...
- the culprit is DM: maybe DM is not just CDM

alternatives to CDM

- numerical simulations assume that interactions between CDM particles are gravitational only
- this may not be true and DM particles may have additional properties
- Ostriker & Steinhardt (2003): several ideas about self interaction of DM particles or interactions with the baryons
- examples:
  SIDM (*strongly self-interacting dark matter*)
  RDM (*repulsive dark matter*)
  SADM (*self-annihilating dark matter*)
  DDM (*decaying dark matter*)
  FDM (*fuzzy dark matter*)
  WDM: *warm dark matter*
  BH (*black holes*)
- different types of DM lead to different
  galaxy mass function,
  satellite abundances,
  star formation histories,
  halo density profiles
- (notice that DM may comprise more than one type of particle)





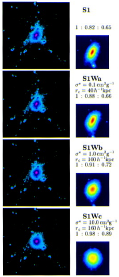
alternatives to CDM

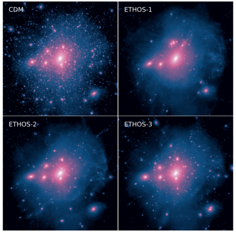
- self-interacting dark matter: simulations by Yoshida et al. (2000)
    - it is assumed that DM particles can suffer elastic collisions, like billiard balls
    - they have a mean free path $\lambda = 1/n\sigma$, where n is the number density of DM particles and σ is the self-interaction cross section
    - few interactions may affect strongly the halos
    - problem: the value of σ that solves the satellite problem

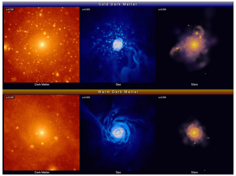
      produces halos too rounded
- ETHOS: “effective theory of structure formation”

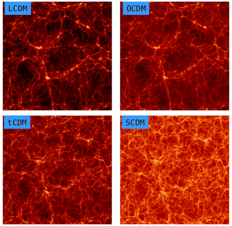
  (Vogelsberger et al. 2016)
    - dark matter particles are massive and can interact with two other types of particles: one massless (akin to photons and dubbed dark radiation), and one very massive (a force carrier, like photons carrying the electromagnetic force)
    - consequences: very small halos are erased;

      profiles are cored, not cuspy
- warm dark matter (particles with mass $\sim$1 keV; Yepes et al. 2013)





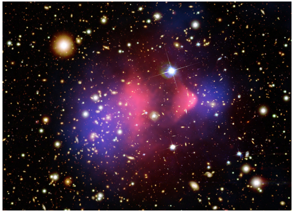


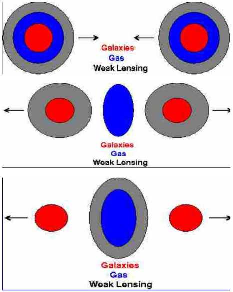


the Bullet Cluster and the nature of DM

DM or modified gravity (MG)?

- Bullet cluster: high velocity (~ 4500 km/s) encounter of two galaxy clusters
- the hot gas of the clusters was shocked, removed, and is found between the two clusters
- DM and MG make different previsions for what should happen in the system:
  - in MG the mass is baryonic (there is no DM)
  - in ΛCDM most of the matter is DM and most of the baryons are in the hot intracluster medium (ICM); stars in galaxies follow DM
  - in this collision most of the gas is detached from the stars: if we measure the mass distribution with weak lensing we expect that:
    - MG: the weak lensing peak would be in the gas
    - CDM: the peak would be where galaxies (and DM) are
- data is consistent with the DM interpretation!

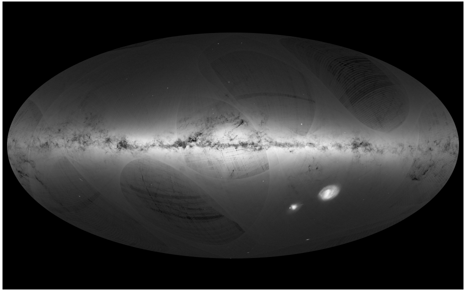




prospects for the near future:

Gaia satellite:

- constraints on the DM potential and local DM distribution
- reconstruction of the Milky Way formation history
- interaction with galactic streams?



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