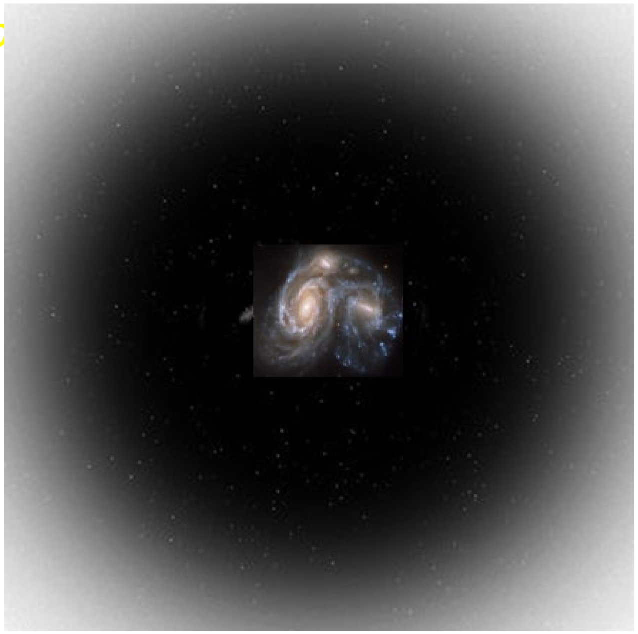
Observation of dark matter, from galaxies to clusters

COLLÈGE DE FRANCE
1530

Chaire Galaxies et Cosmologie

Ab



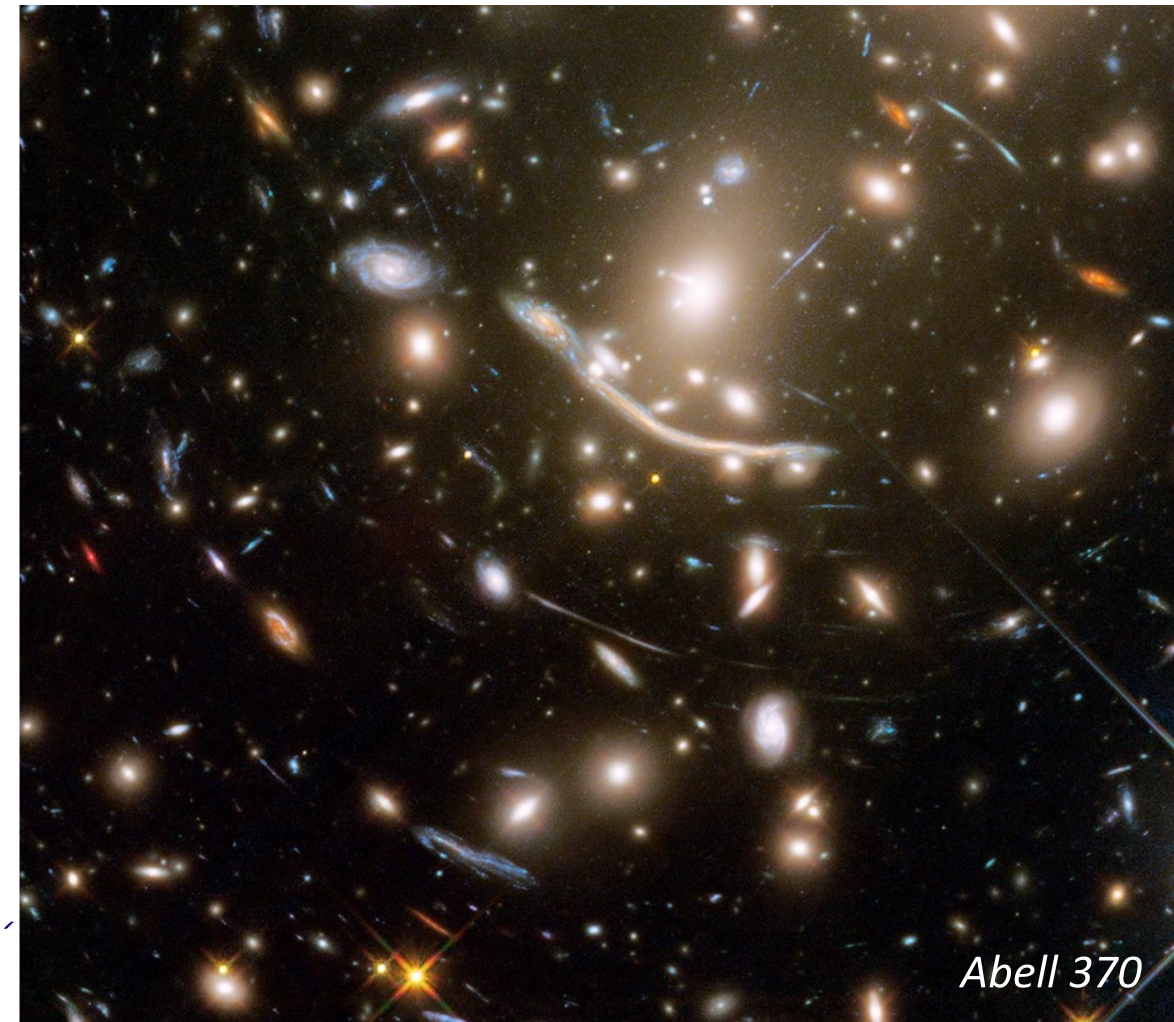
Françoise Combes

March 2024

l'Observatoire de Paris

LERMA

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique



The content of the Universe

- Baryons, ordinary matter 5%

- Exotic dark matter 25%
- Dark energy 70%

??

or cosmological constant

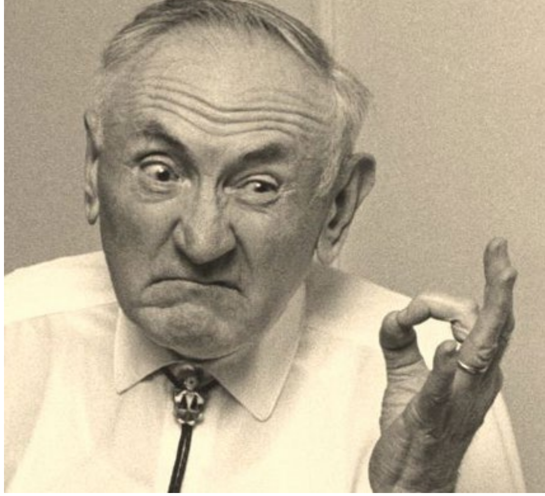
$\Omega = \rho/\rho_{crit}$

$\rho_{crit} = 10^{-29} g/cm^3$

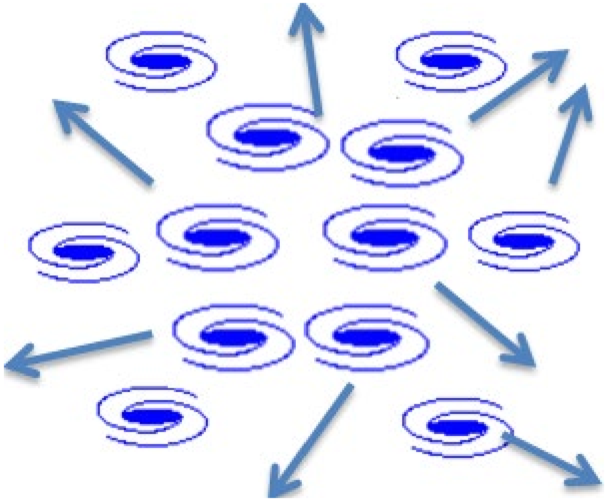
$$\rho_c = \frac{3H^2}{8\pi G}$$

First discoveries

1937 – Fritz Zwicky computes the mass of galaxy Clusters, using galaxy velocities



Fritz Zwicky



Coma cluster, V~1000km/s
M~ 5 10^{14} $M_\odot$

$M/L = 500\ M_\odot/L_\odot$

He proposes several hypotheses
-- dark matter in galaxies
-- matter in between galaxies + obscuration
-- test of Newton's law at large scale

Jan Oort

1932: Jan Oort speaks of dark matter in the solar neighborhood, in the Milky Way
➔Solids, dust, gas, dead celestial objects …

Vera Rubin

Dark matter in galaxies

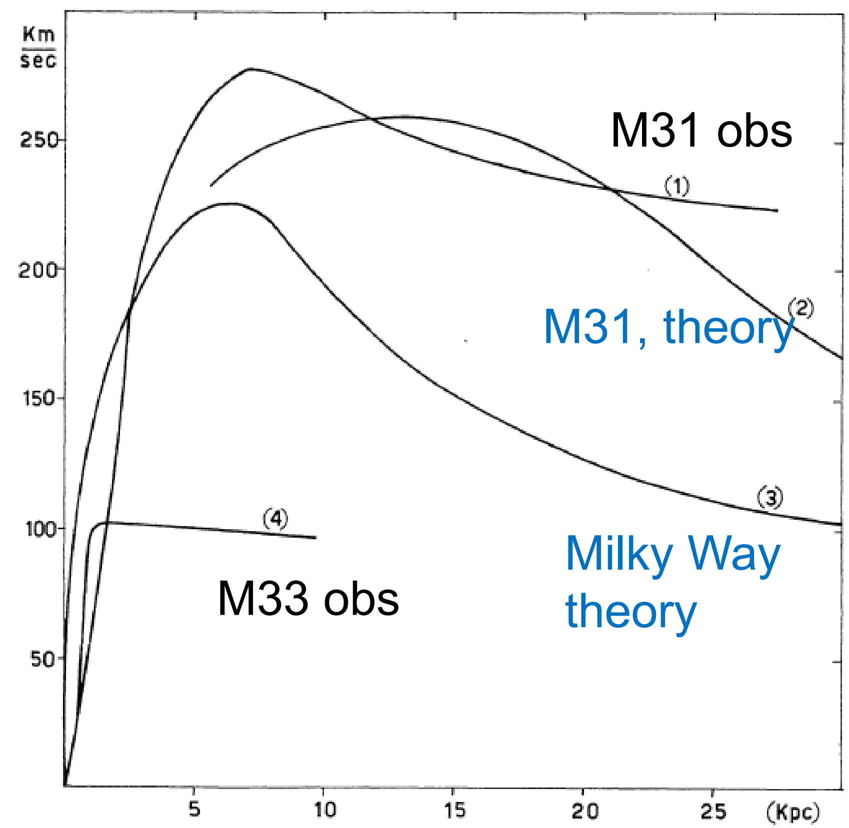
Rotation curves of stars and ionized gas (Hα and [NII] 0.6μm)

Optical: Rubin, Ford et al 1978

Radio: The 21cm line of hydrogen is discovered in 1951 (Ewen & Purcell)
The first rotation curves are published at the end of 1950s

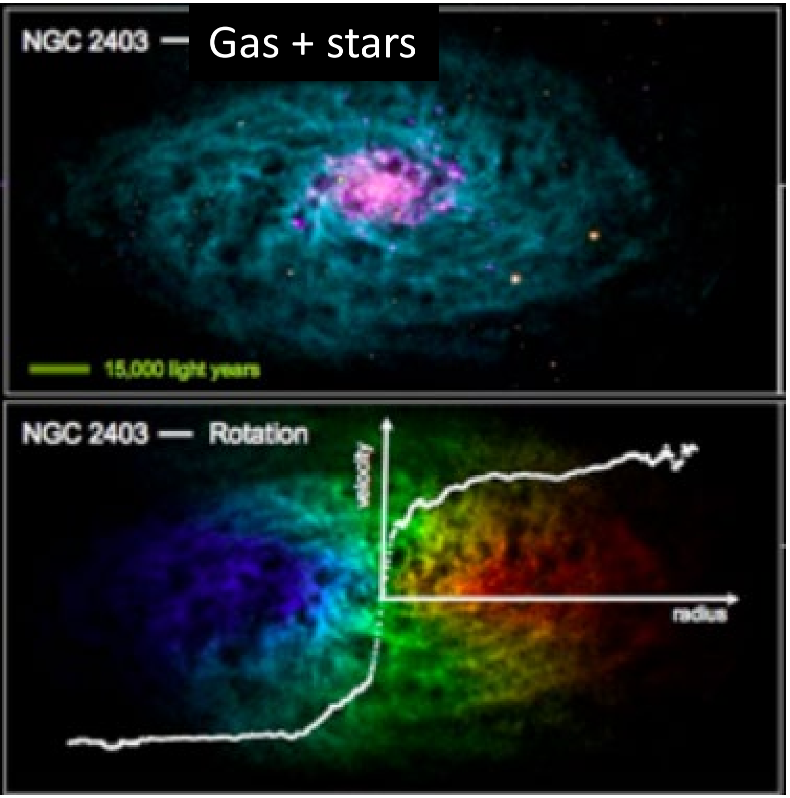
➔Flat Curves

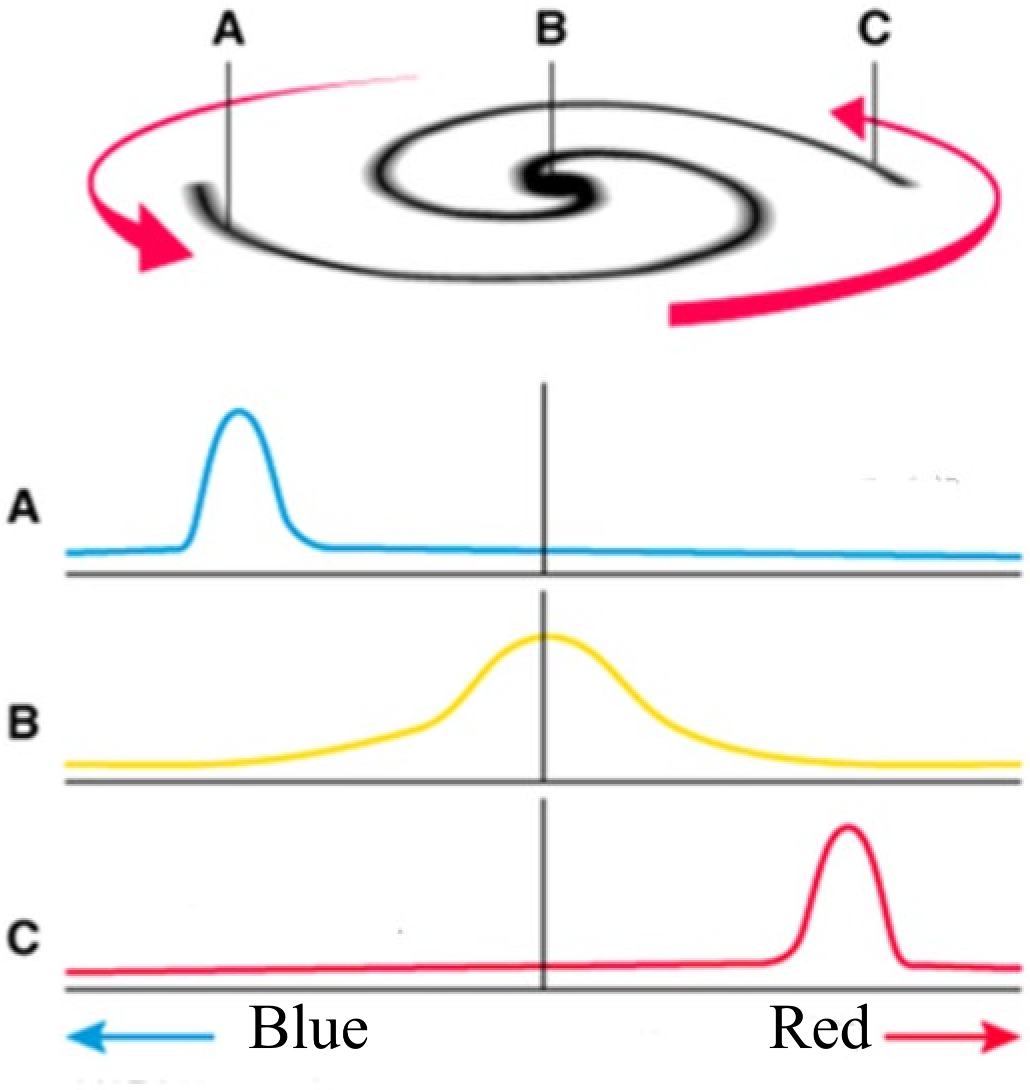
Interpretation at this epoch
M/L ratio increases with radius



How to build a rotation curve?

- Doppler effect
- Folding the two sides

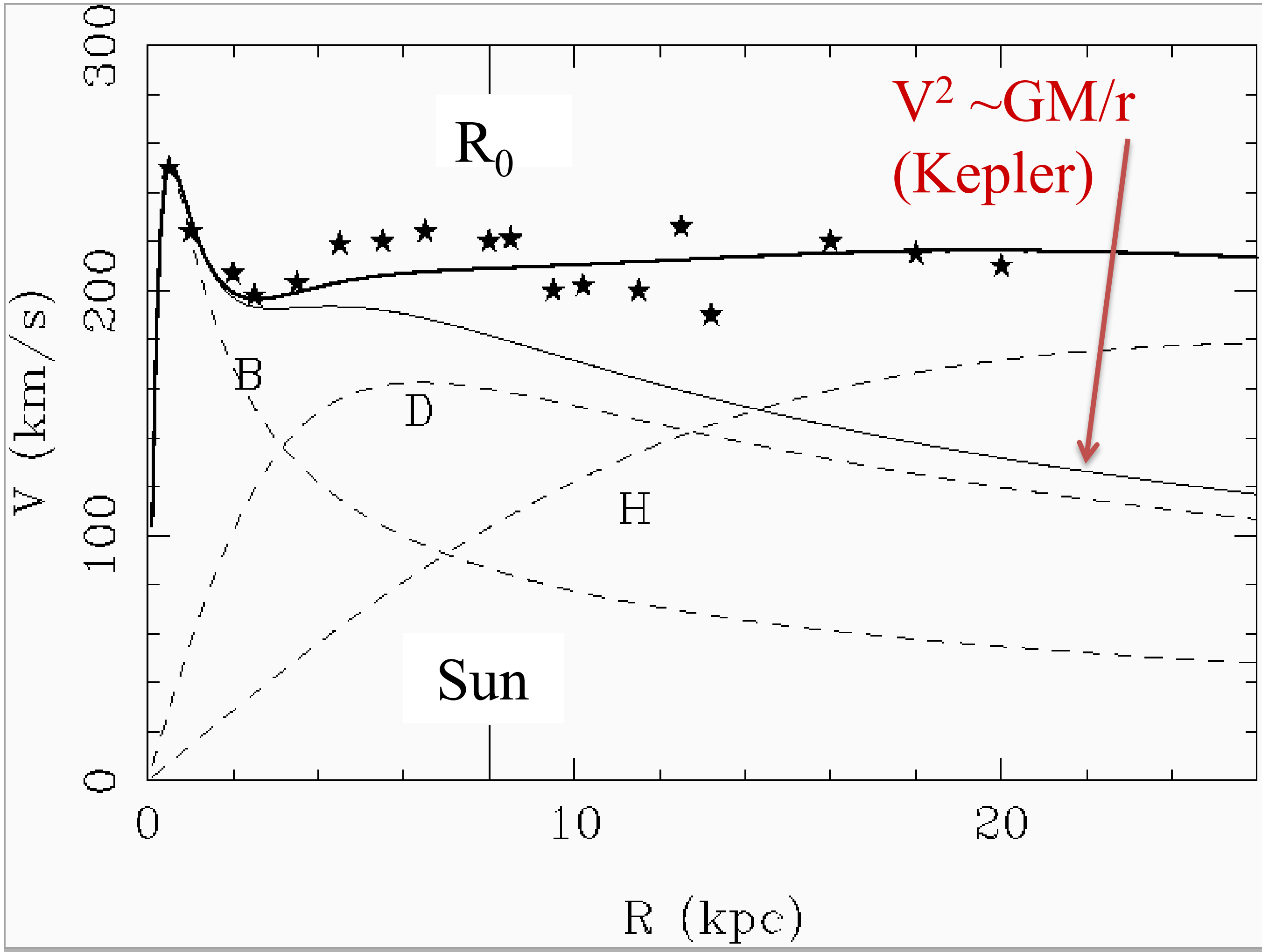




Our galaxy rotates too fast

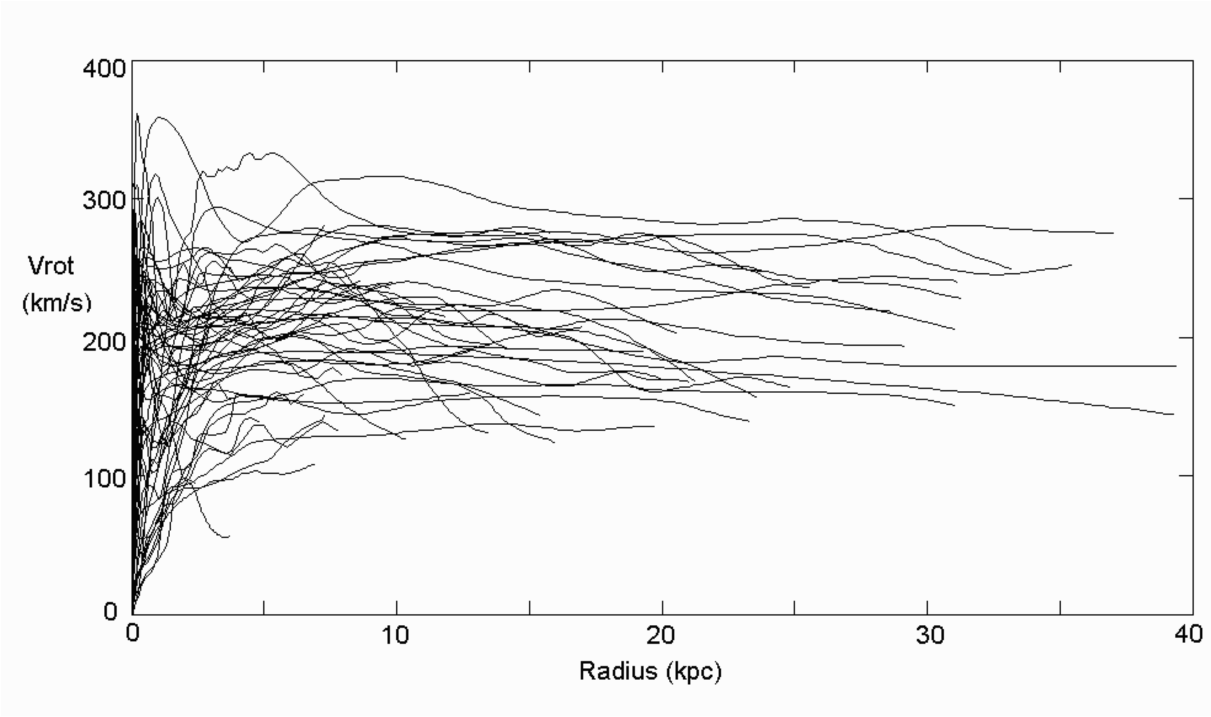
➔**Around galaxies**, dark matter halos
1960 to 1980: *difficult measures, uncertainties on M/L*

➔**Rotation curve** of our Galaxy
The Milky Way

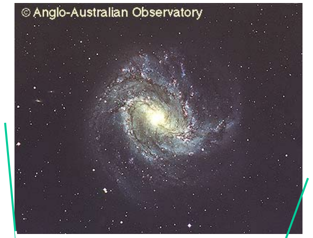


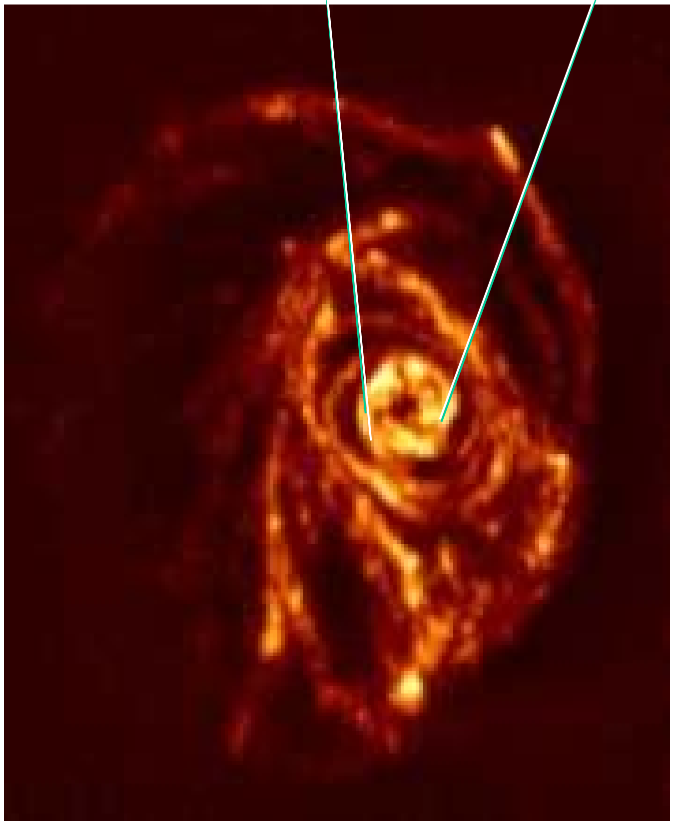
Atomic Hydrogen in galaxies

HI: map of atomic hydrogen
21cm in wavelength



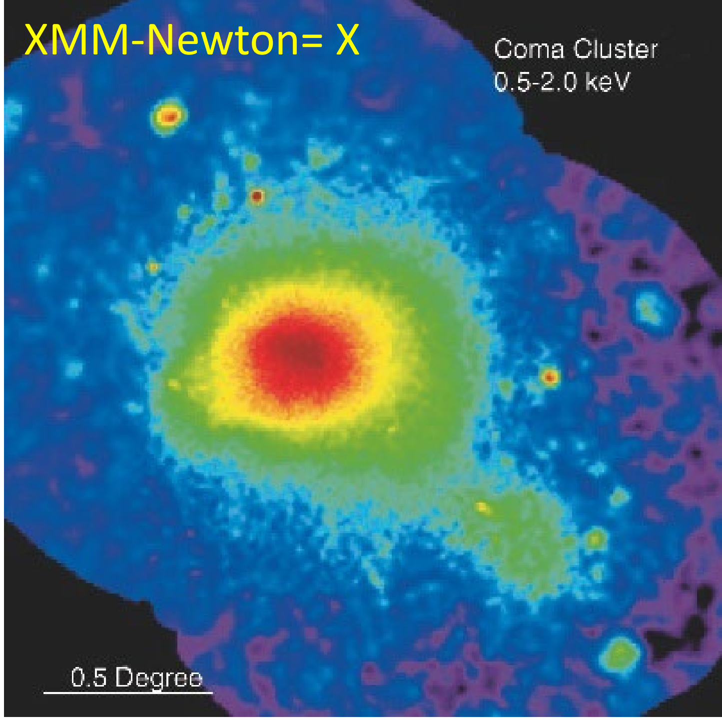
M83: optical





HI in M83: a galaxy similar to the Milky Way

Other wavelengths



X-ray satellites in **1966**
➔ Strong diffuse emission in Coma

Emission of very hot gas
$T \sim 10^8$ K, or 100 million degrees!
mass comparable to unseen matter?

Today M(hot gas) ~10 M(galaxies)
Dark matter remaining **~5 times visible mass**

Another blow to anthropomorphism: most of matter does not radiate at optical wavelengths, visible by human eye!

Density in the Univers

In 1980-2000

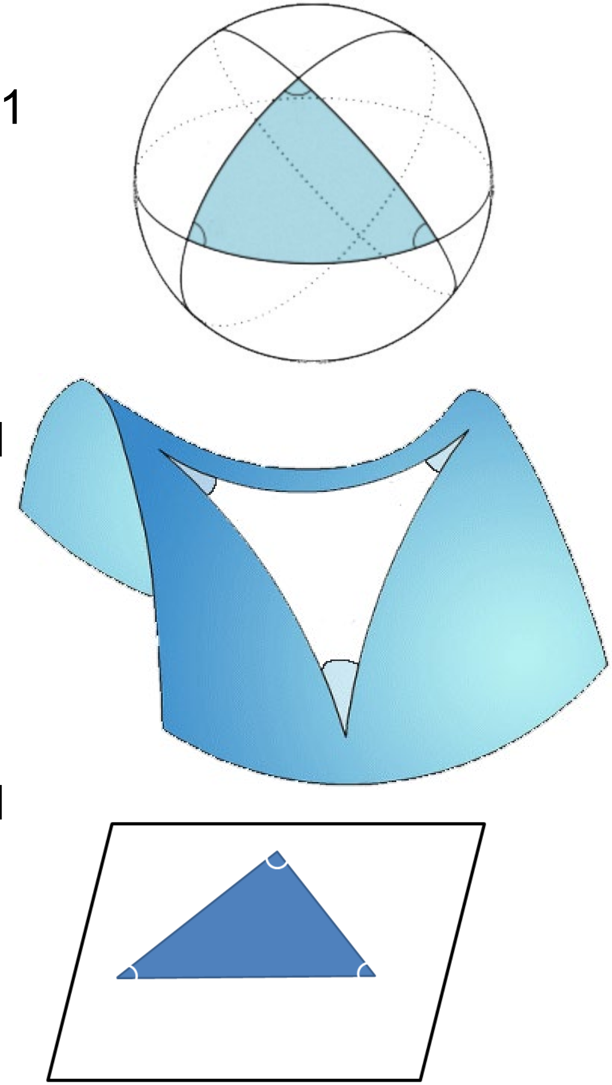
$\Omega \sim 0.1$ not far from Ω_b

Required by primordial nucleosynthesis (D, Li, He)

$\Omega > 1$

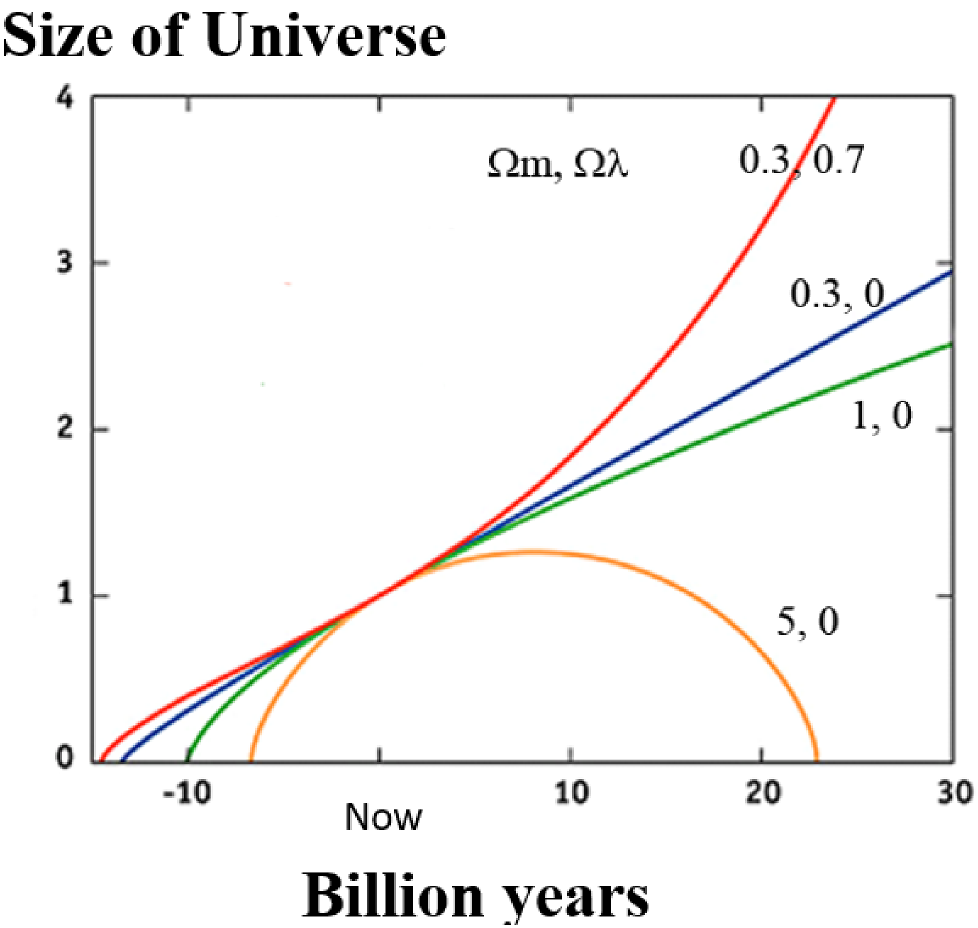
$\Omega < 1$

$\Omega = 1$



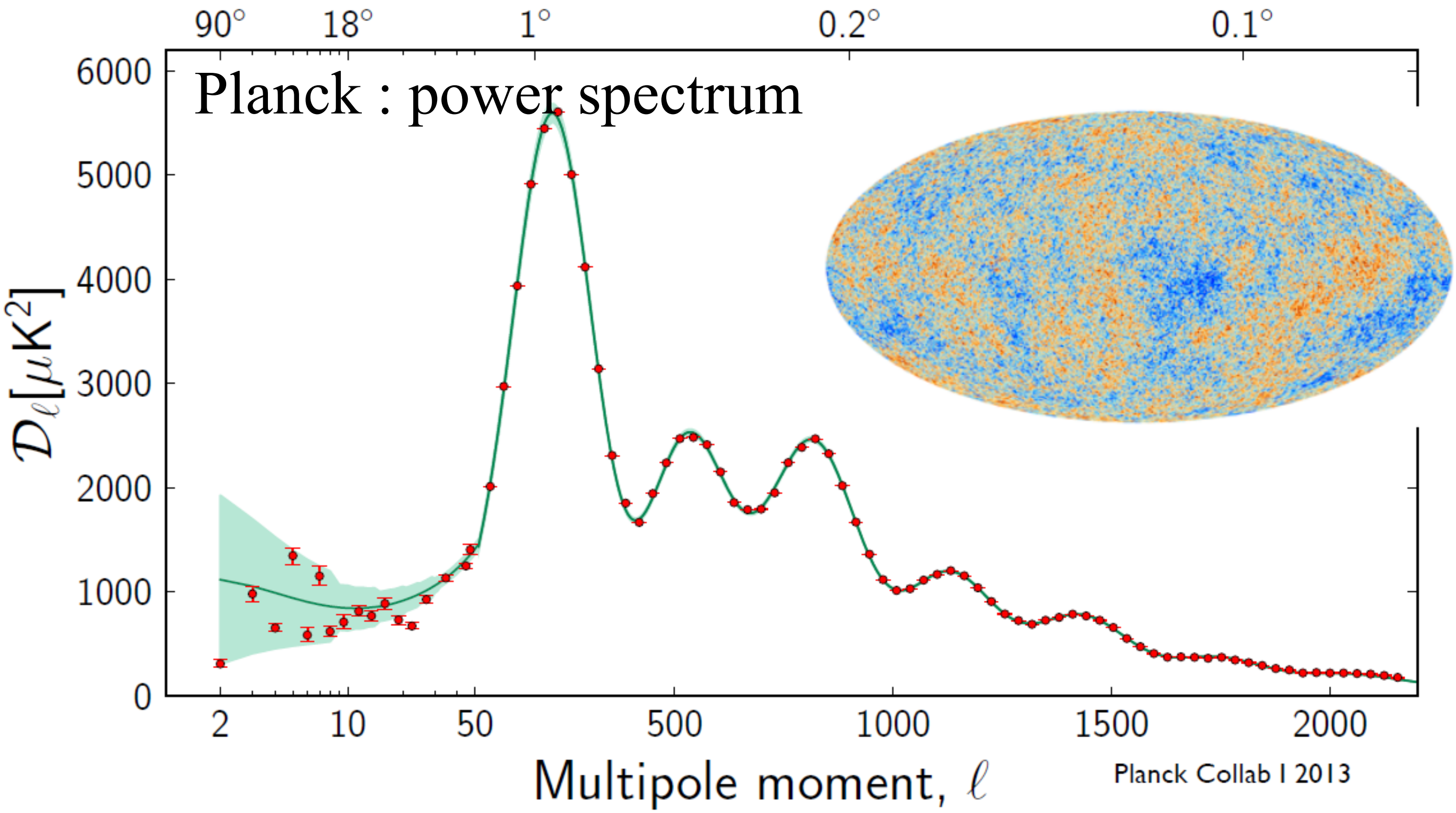
$$\Omega = \rho/\rho_{crit}$$

$$\rho_{crit} = 10^{-29} g/cm^3$$



The cosmic microwave background (CMB)

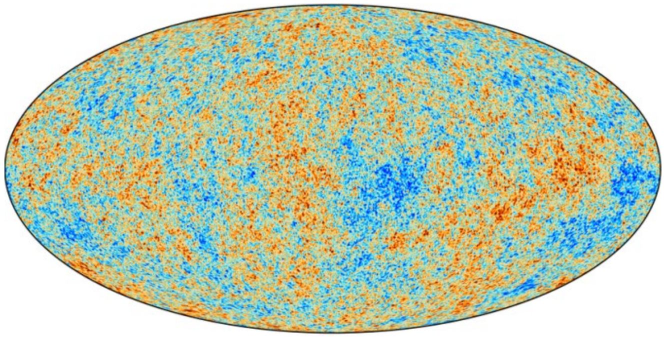
A mine of informations! Ω_b, Ω_m, Ω_Λ



T=13,8 Gyr

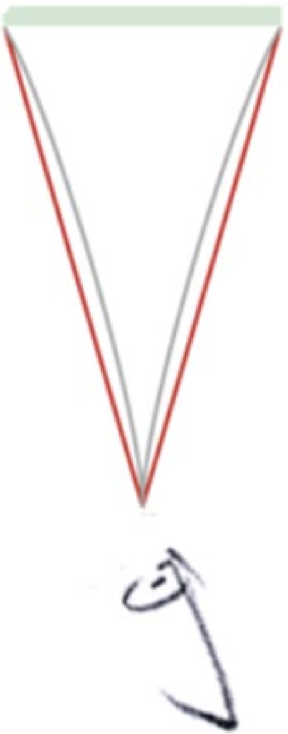
Vestige from the Big-Bang, Temperature 2.7 Kelvin (black-body)

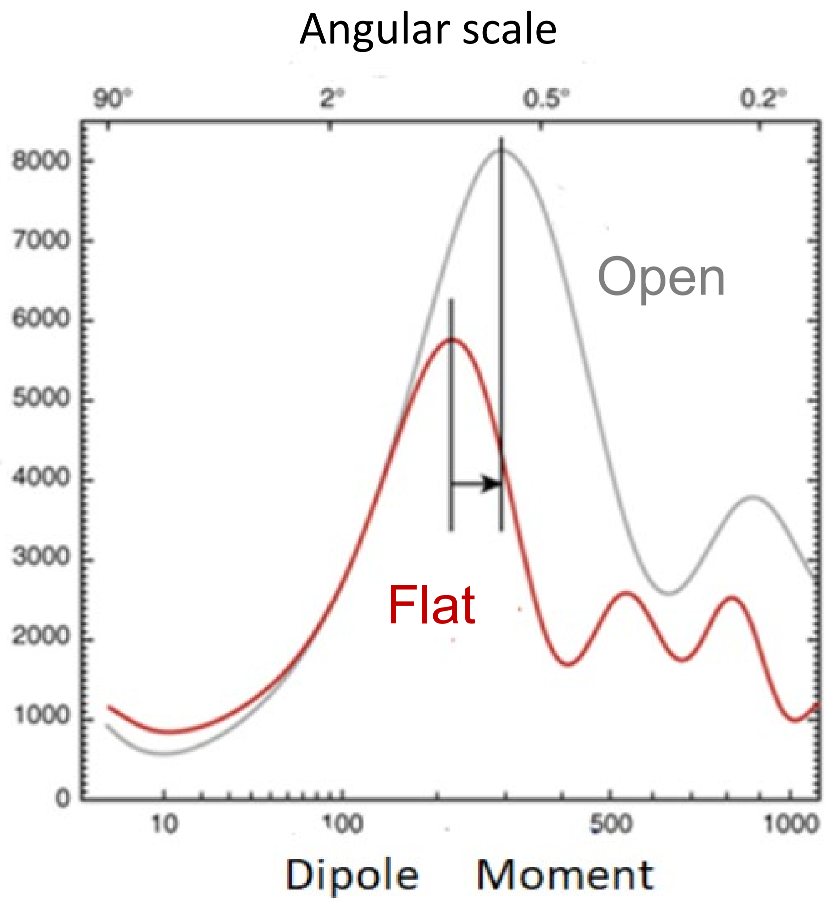
Zero curvature of the Universe



- Acoustic waves: photons + baryons
- ➔ size of the sound horizon, seen under the angle of ~1° (150kpc)

Standard Ruler
1° = 150kpc





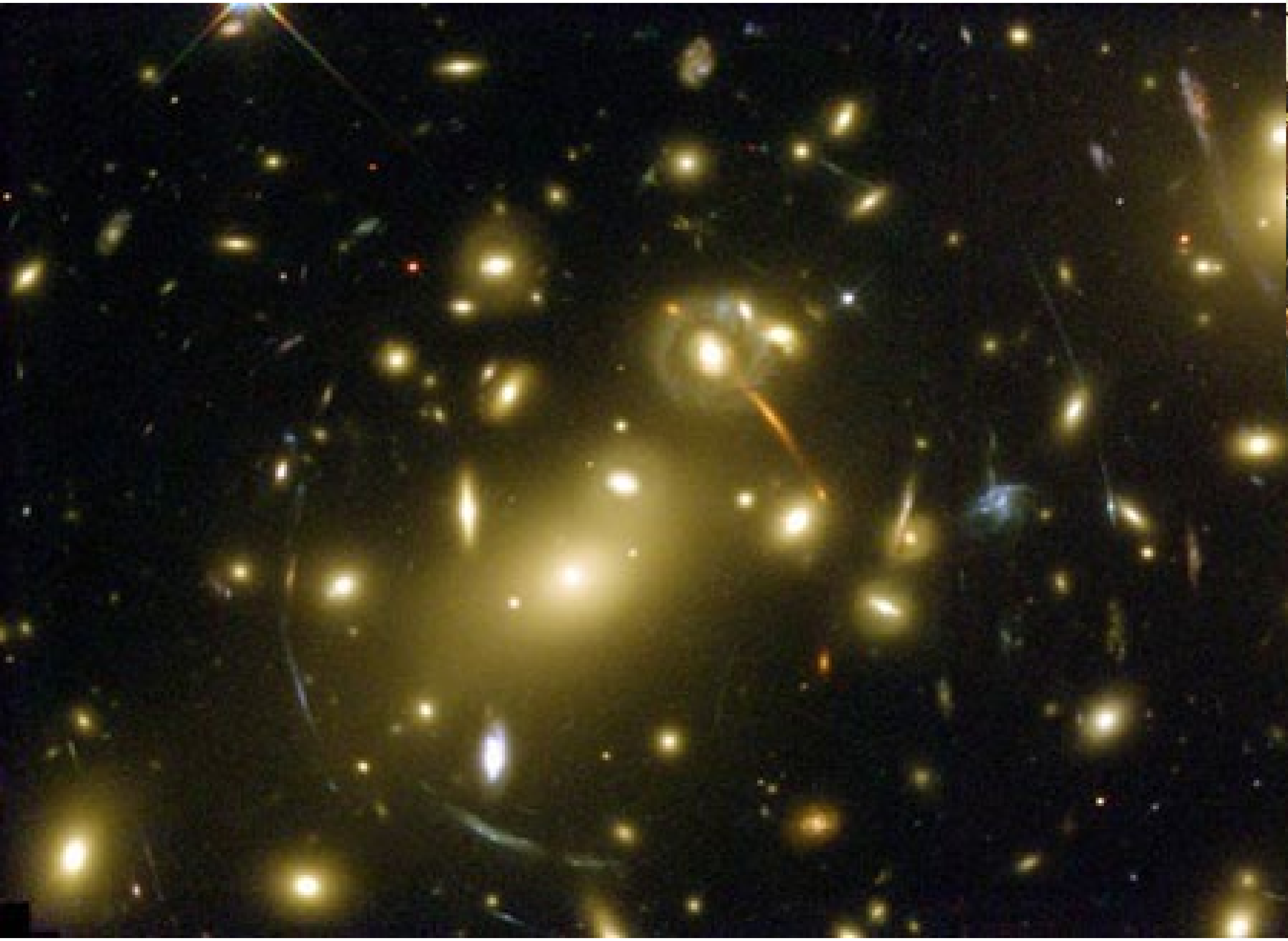
Curvature = $\Omega_m + \Omega_\Lambda - 1$

➔ $\Omega_{tot} = 1 = \Omega_m + \Omega_\Lambda$

T=13,8 Gyr

Cartography of the dark matter

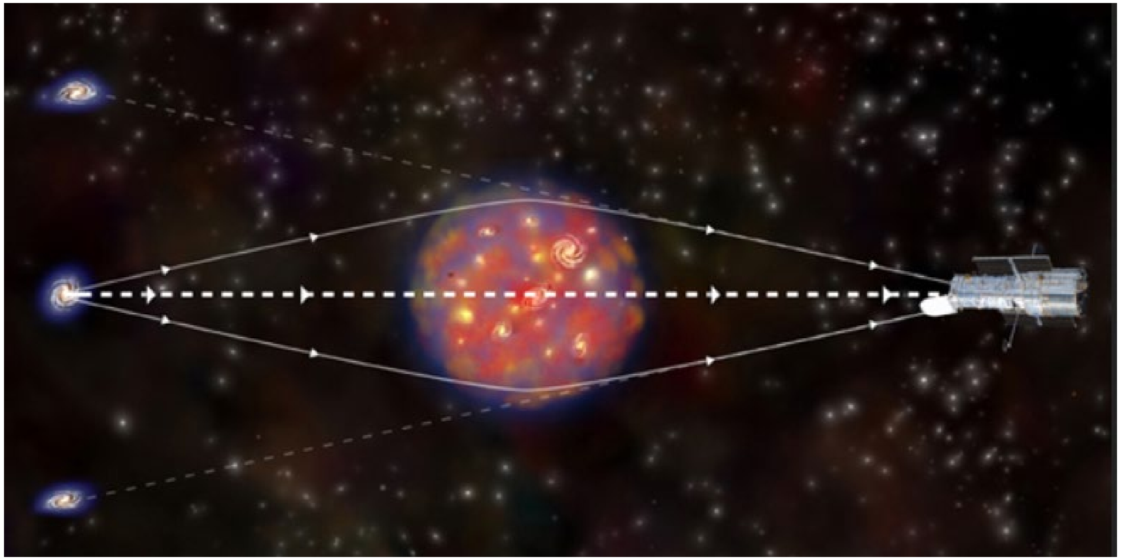
Gravitationnal lenses: strong regime

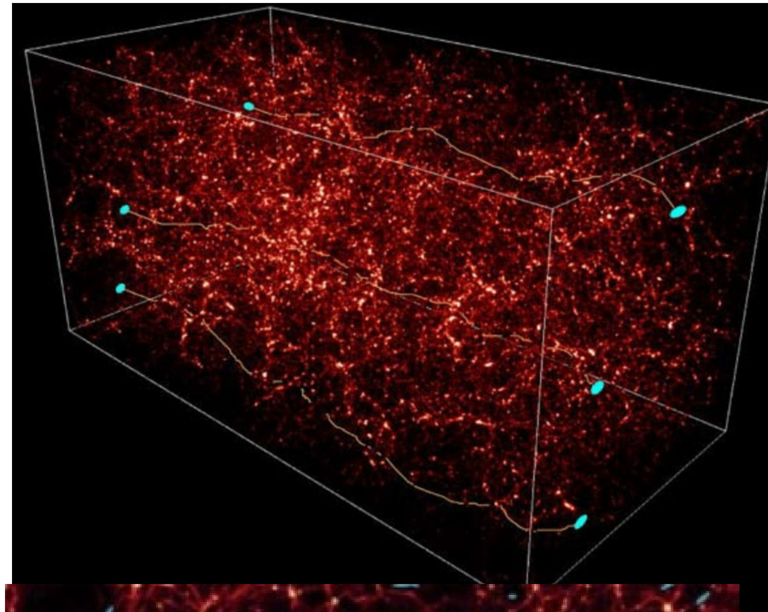


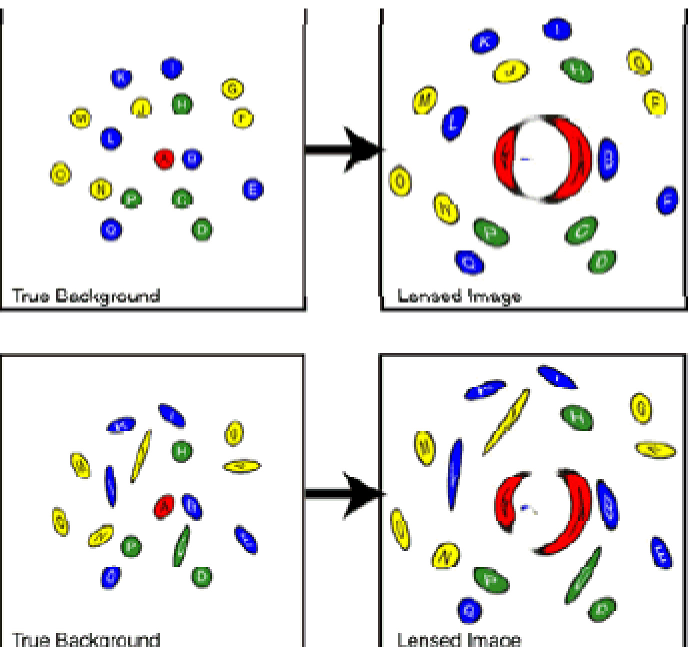
Abell 2218

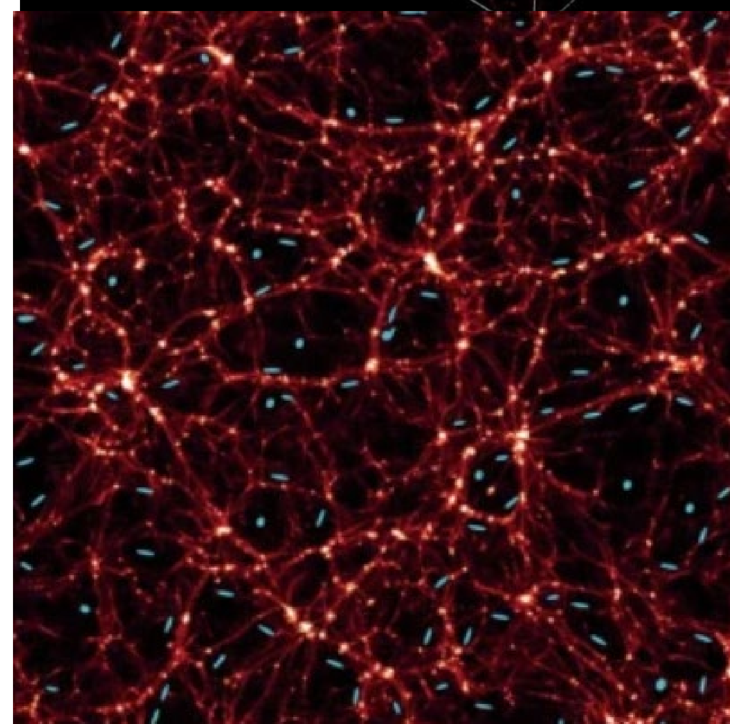
Vermeer: The geograph

Gravitationnal lenses: weak regime



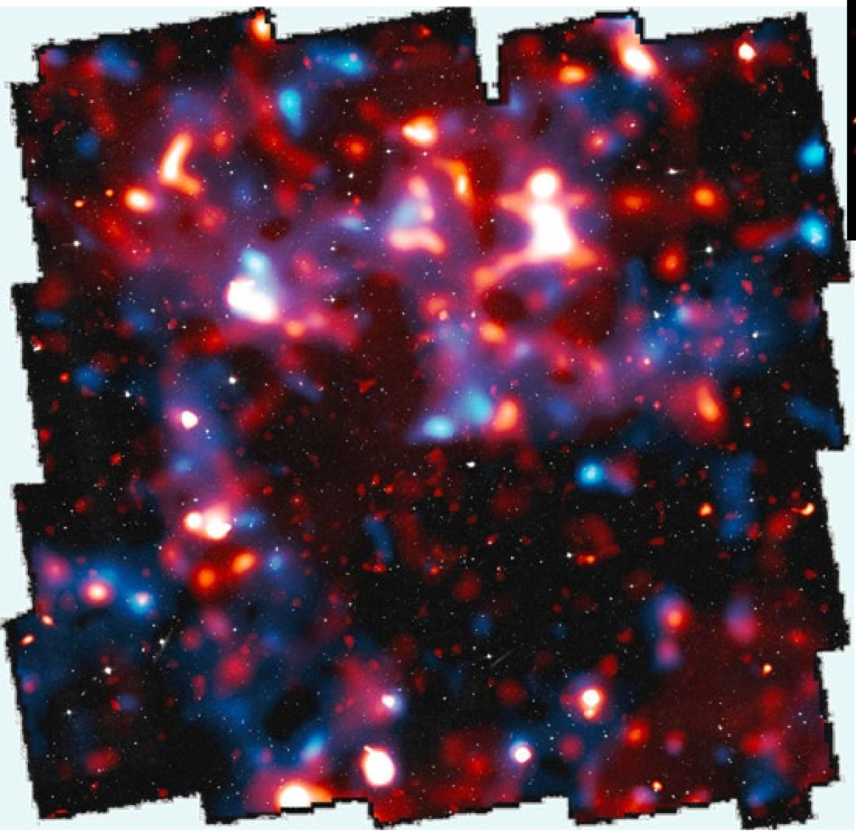


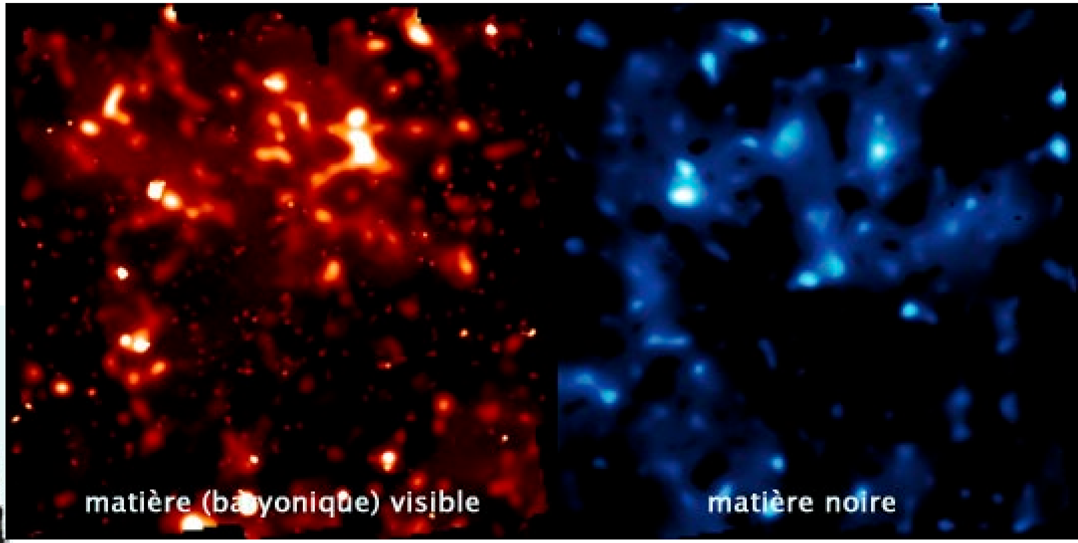




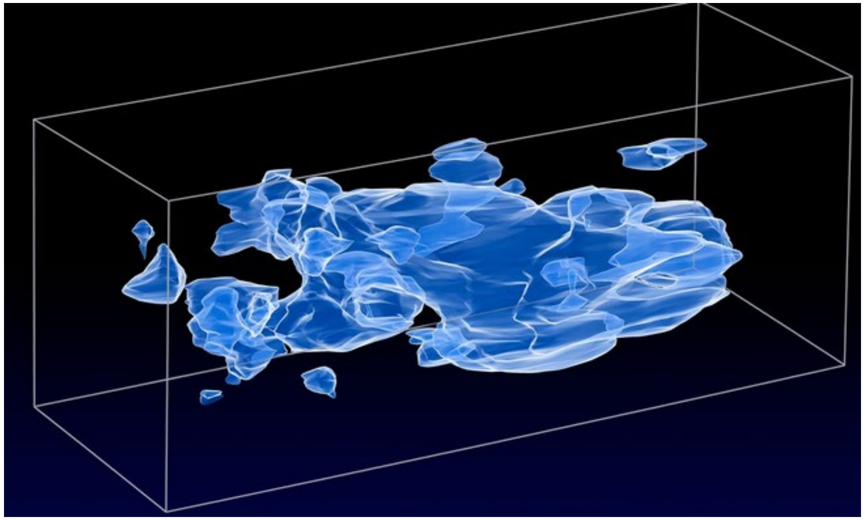
Gravitationnal shear (Cosmos field)

Red: X-ray gas
Blue: total matter





Baryons and dark matter are gathered in the same structures



Massey et al 2007

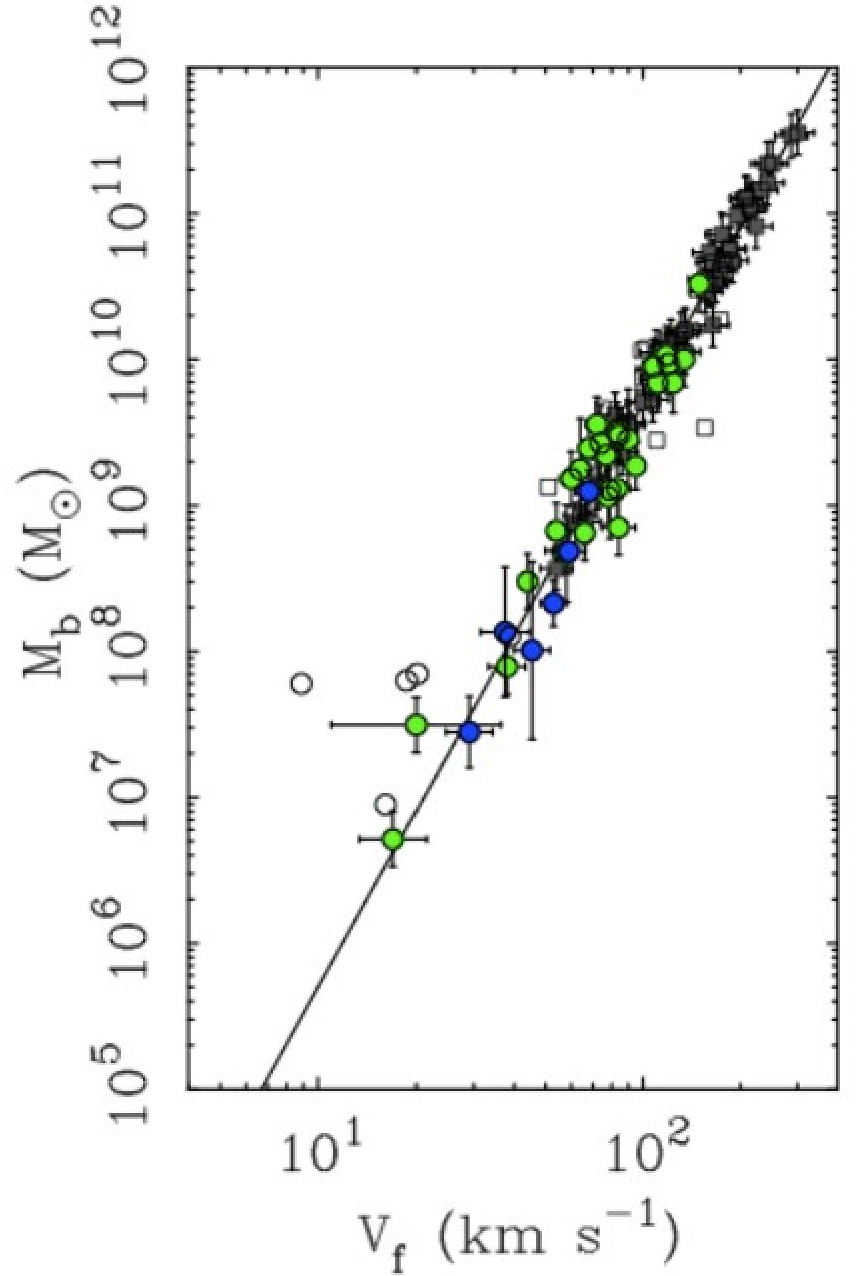
Tully-Fisher Relation

Relation between rotation Vf for spiral galaxies and their visible mass

➔Vf Indicator of dark matter

Not only stars, but gas
➔Baryonic TF

McGaugh et al 2000

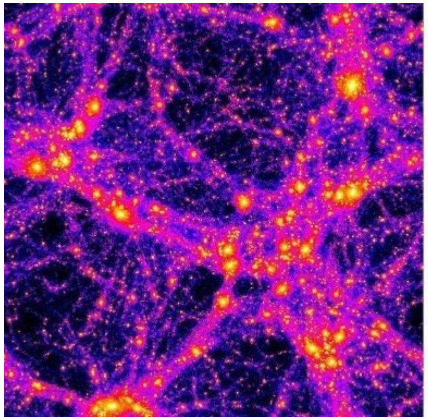


Several kinds of dark matter

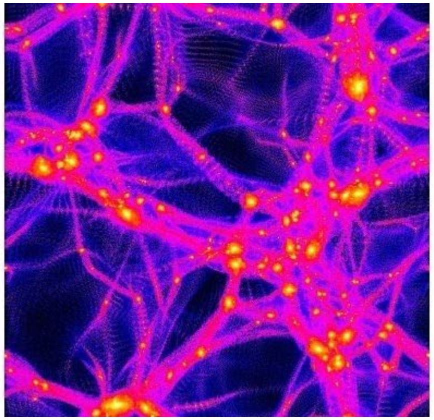
Hot (neutrinos)
Relativistic at decoupling
Cannot form the small structures, if m < 5 keV

Cold (massive particles)
Non relativistic at decoupling
WIMPS
("weakly interactive massive particles")
Neutralinos: particle **m~100GeV**
The lightest supersymmetric particle

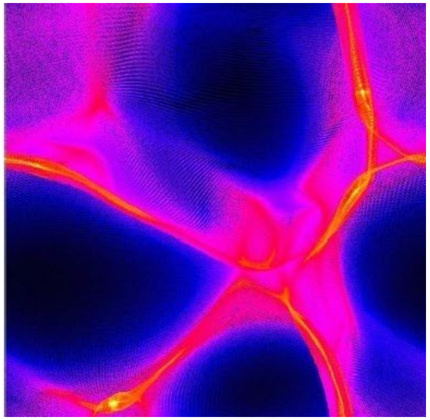
Cold model (CDM)

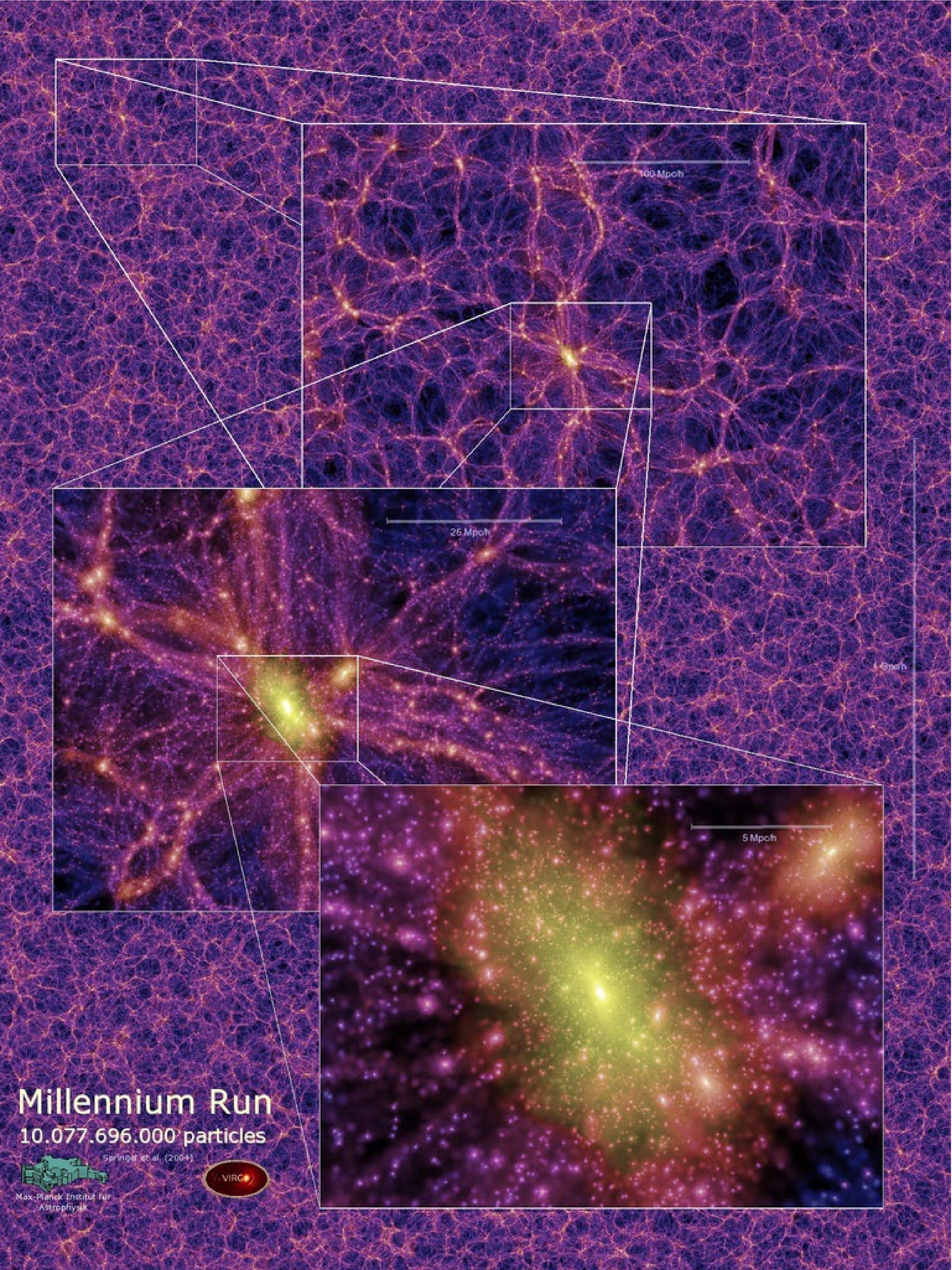


Warm



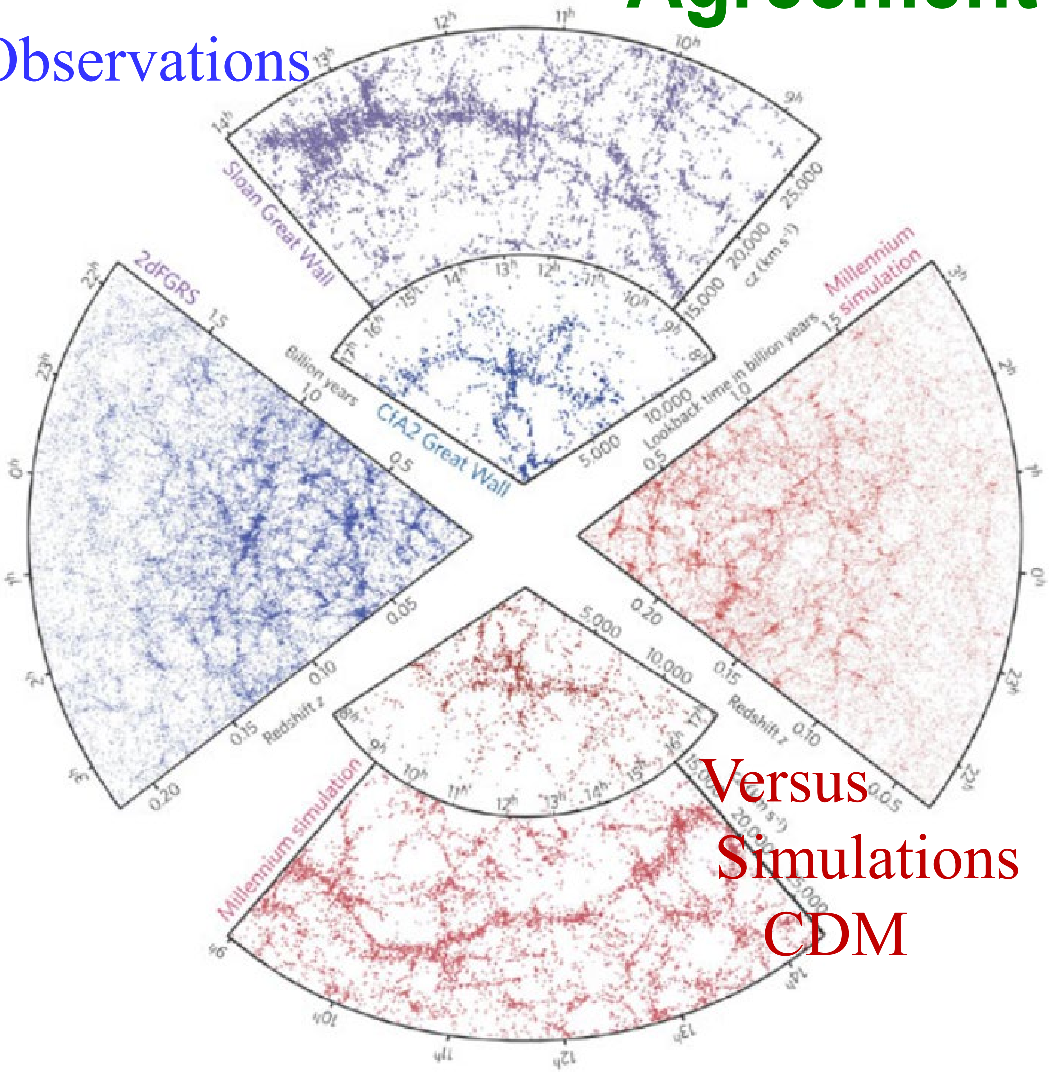
Hot model (HDM)




100 Mpc/h
25 Mpc/h
5 Mpc/h
1 Gpc/h
Millennium Run
10.077.696.000 particles
Springel et al. (2004)
Max-Planck Institut für Astrophysik
VIRGO

Agreement at large-scales

Observations



Versus
Simulations
CDM

BUT

→Problems for galaxies

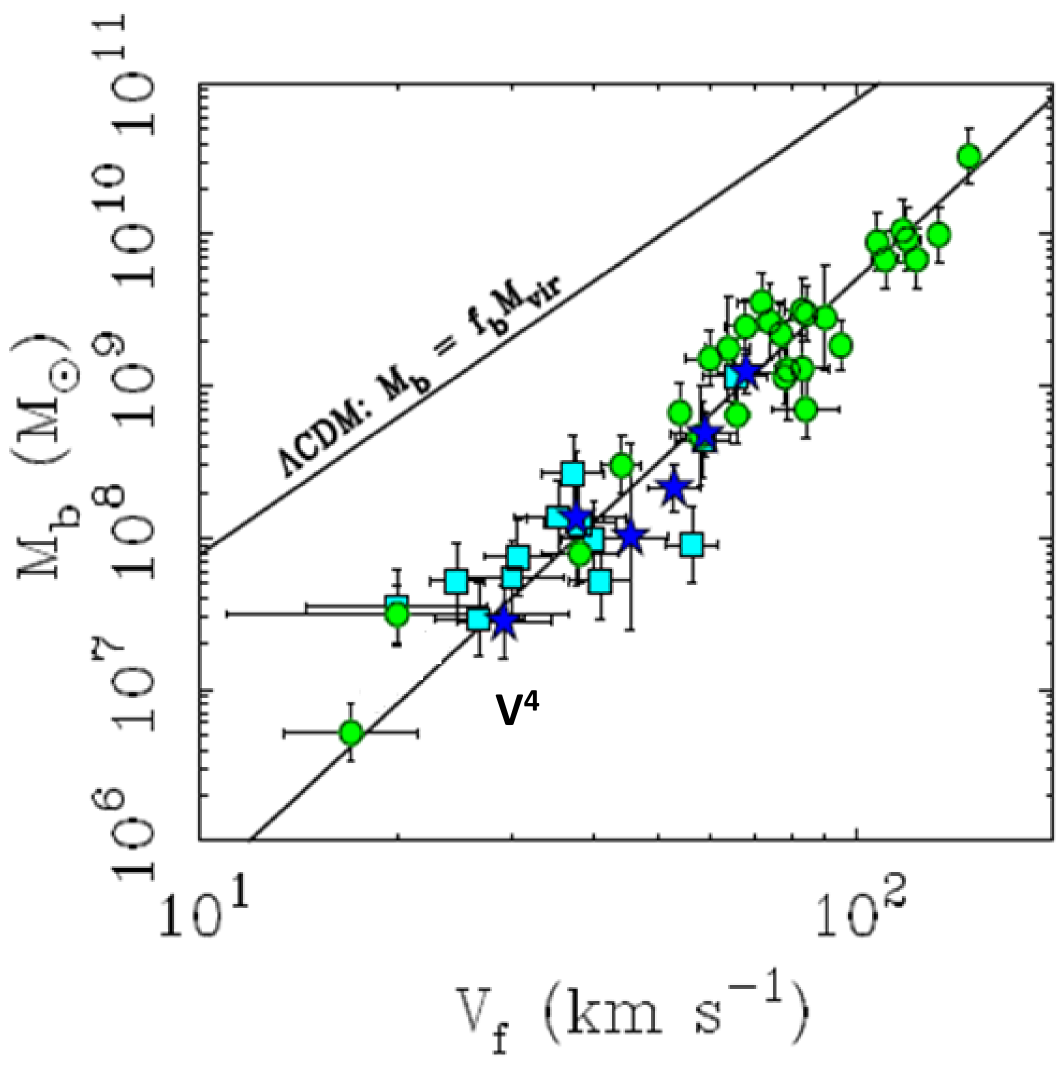
Cusps versus cores

Missing satellites

Majority of baryons is outside galaxies

Simulations reproduce well large scale structures of galaxies:
Cosmic web, filaments, walls and great walls,
void structures, granularity of super-clusters

Tully-Fisher scaling relation

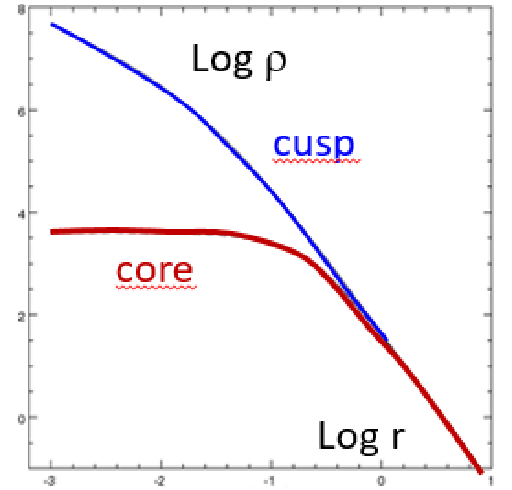


f_b universal fraction of baryons= 17%

CDM: « Cold Dark Matter » standard model

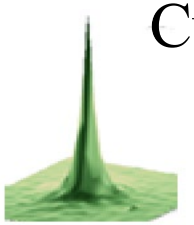
➔most baryons are not in galaxies

Problems of the CDM model



➔ **Prediction of "cusps" at the centre of galaxies**

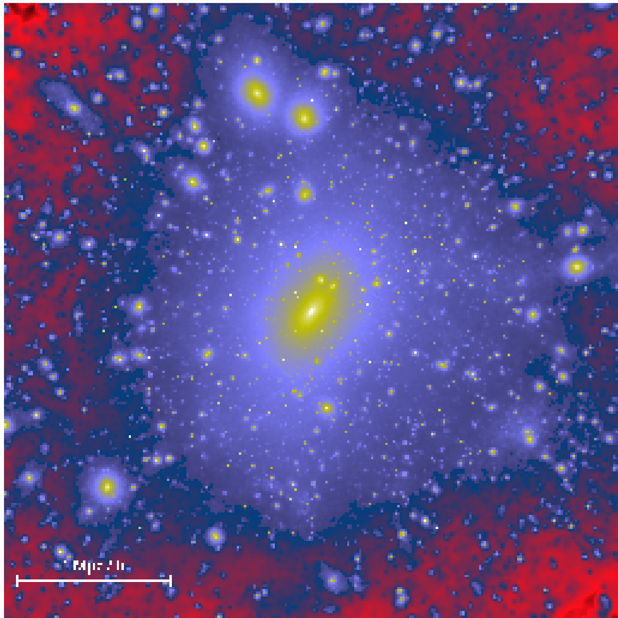
Cusp/core

predicted   observed

➔ **Prediction of a large number of satellites around galaxies**

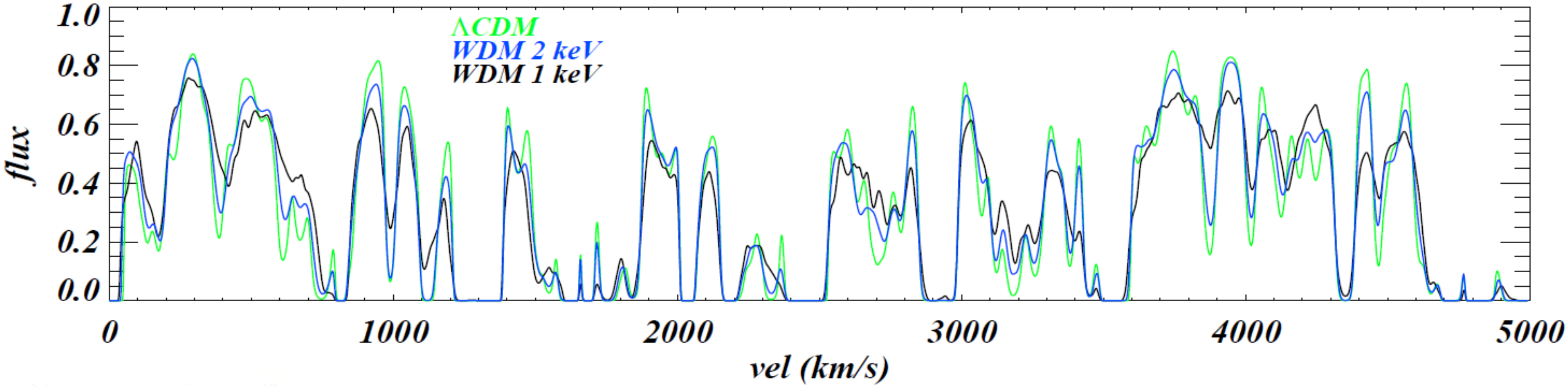
The solution could come from the still unrealistic modeling of physical processes

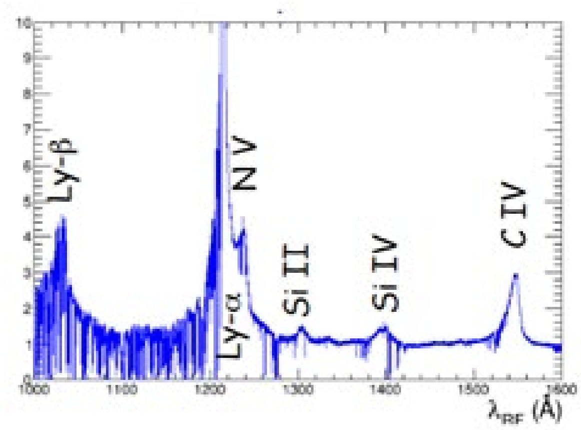
or the nature of dark matter?



Ly-α: constraints on m(warm)

25 quasars z >4: spectra obtained at Keck *(Viel et al 2013)*
Ly-α forest and comparison with simulations $m_{WDM} > 3.3$ kev (2σ)





WDM, $\mathbf{m_X > 4.65}$ **keV** thermal relics
$\mathbf{m_s > 29}$ **keV** non-resonant production
Yeche et al 2017, Chabanier et al 2019

Primordial Black holes as DM ?

$\mathbf{R_S = 2GM/c^2 = 3(M/M_\odot)\ km \Rightarrow \rho_S = 10^{18}(M/M_\odot)^{-2}\ g/cm^3}$

Only form in early Universe, cosmological density $\rho \sim 10^6 (t/s)^{-2} g/cm^3$

➔PBHs should form with horizon mass at formation $M_{hor}(t)$ in ct

$M_{PBH} \sim c^3 t/G =$ **10^{15}g at 10^{-23}s (evaporating now)**

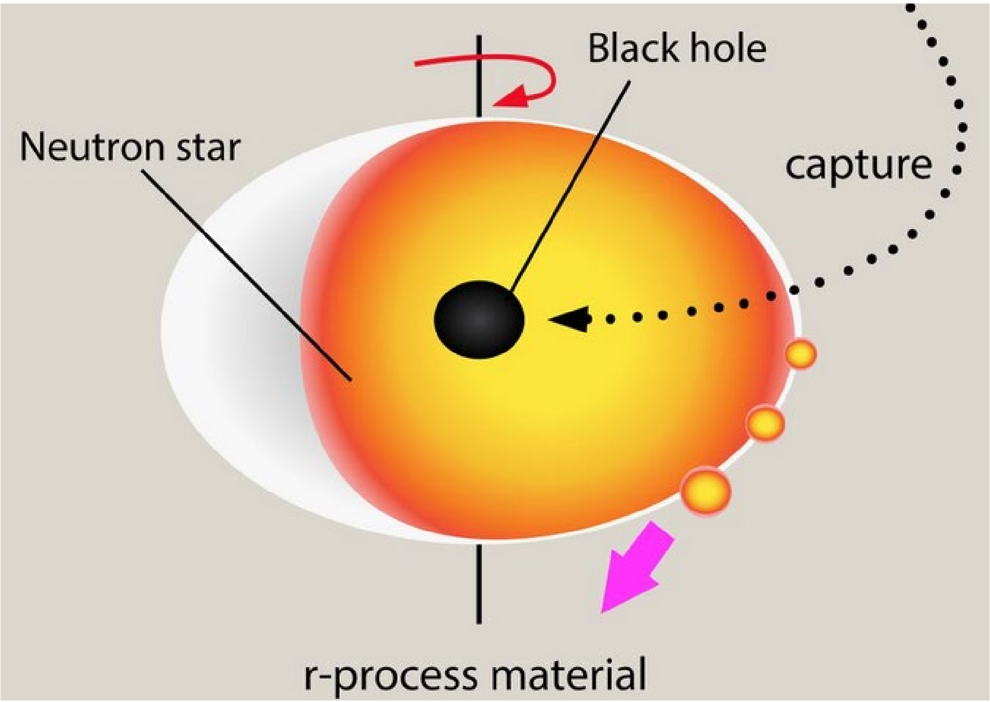
$1 M_\odot$ at 10^{-5}s (maximum)

PBH formation requires strong inhomogeneities in the early inflation, and recollapsing local regions

e.g. Carr et al 2010, 2016

Exclusion of the last windows for PBH

Encounter of the PBH with a neutron star
➔ Destruction of the neutron star



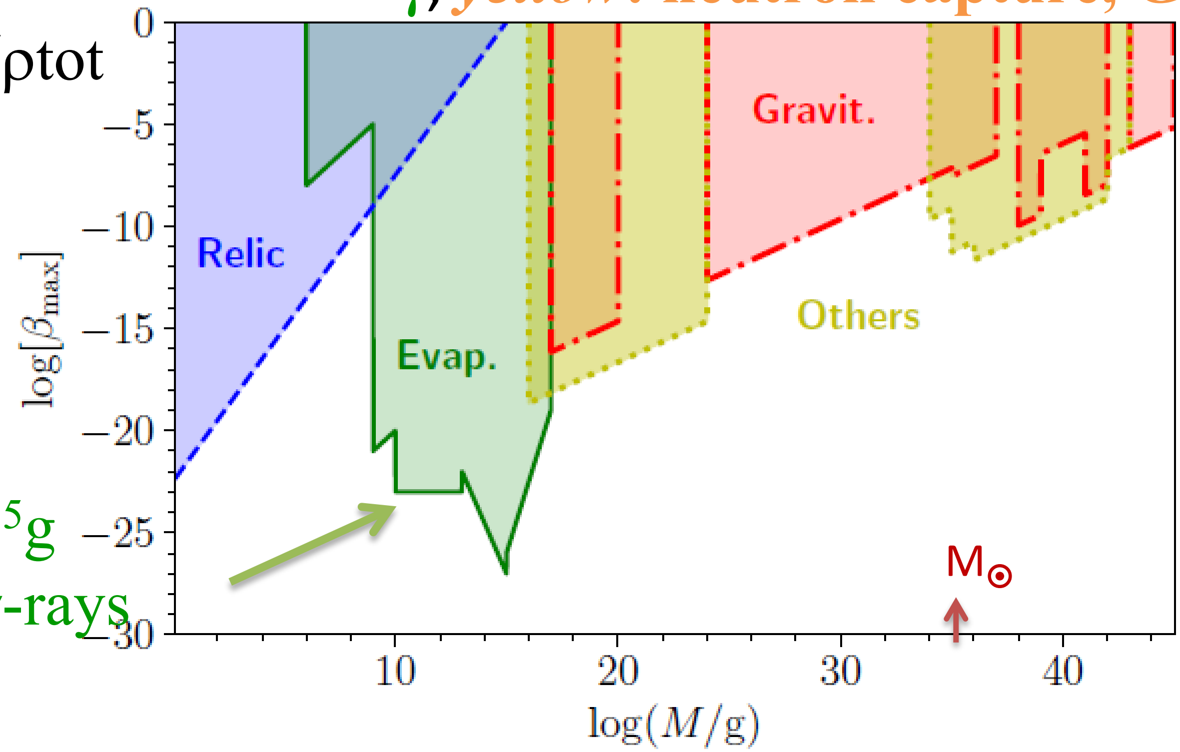
Cotner & Kusenko 2017

Pani & Loeb 2014

Primordial Black holes

γ, *yellow*: neutron capture, GW

$\beta = \rho PBH/\rho tot$



For M~10^{15}g too many γ-rays produced

Since PBH form in the radiative era, they can be considered as non-baryonic, and =CDM

However, their mass is limited by MACHOS, EROS experiments

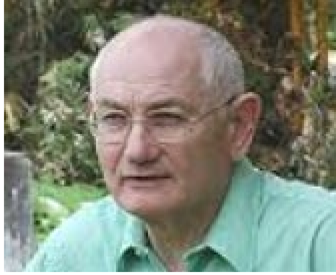
Gutierrez et al 2017

Modified gravity

Either Newton law ➔ dark mattre
Or a modified gravity law

Catching a black cat in the dark of night
is the hardest thing ever,
especially if there is no cat

MOND = MOdified Newton Dynamics



At weak acceleration

$a << a_0$ MOND regime $a = (a_0\, a_N)^{1/2}$

$a >> a_0$ Newtonian $a = a_N$

$a_0 = 10^{-10}$ m/s^2 ~ 10^{-11}g

Milgrom (1983)

Asymptotically

$a_N \sim 1/r^2$ ➔ $a \sim 1/r$

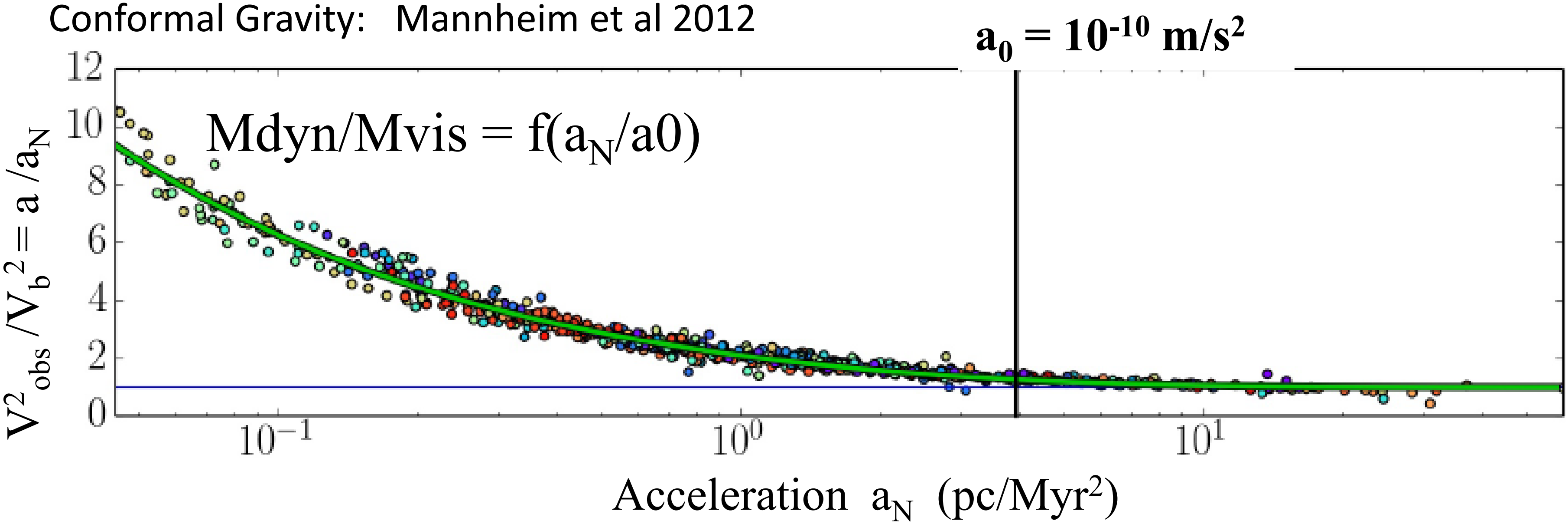
➔ $V^2 = cste$

Covariant theory: TeVeS

➔Gravitationnal lenses

Bekenstein 2004

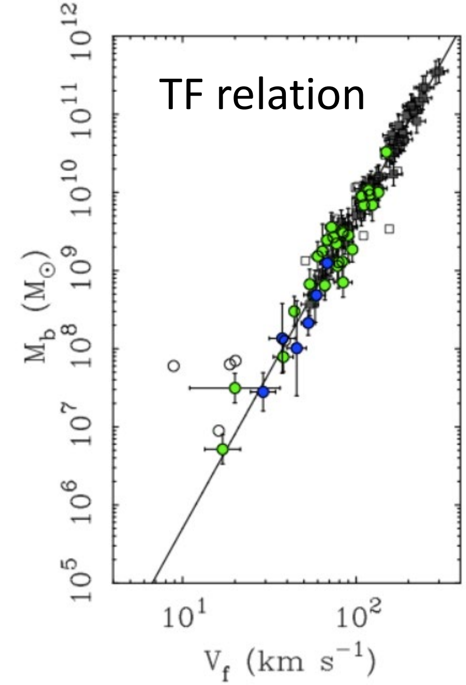
Conformal Gravity: Mannheim et al 2012



Success at weak surface densities

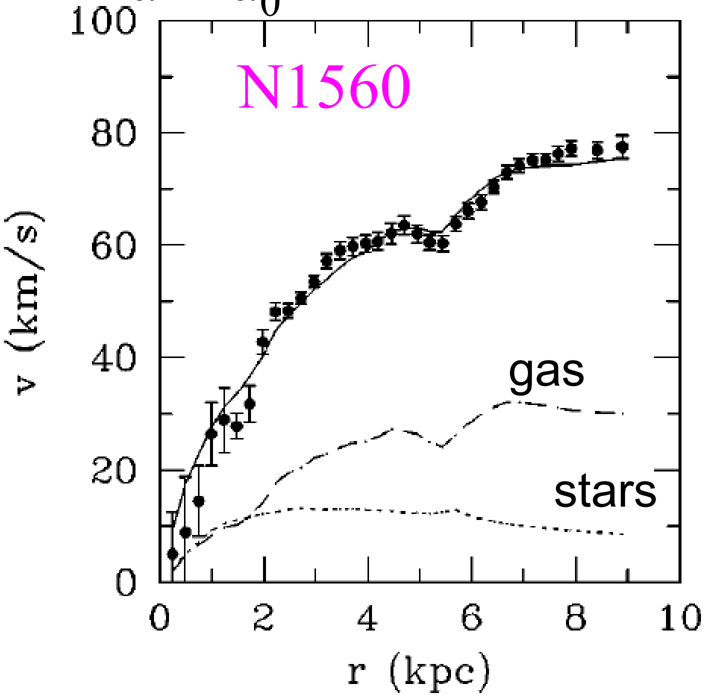
$\Sigma < \Sigma_0 \sim 150\ M_\odot/pc^2$, ➔the critical acceleration a_0

In particular dwarf galaxies

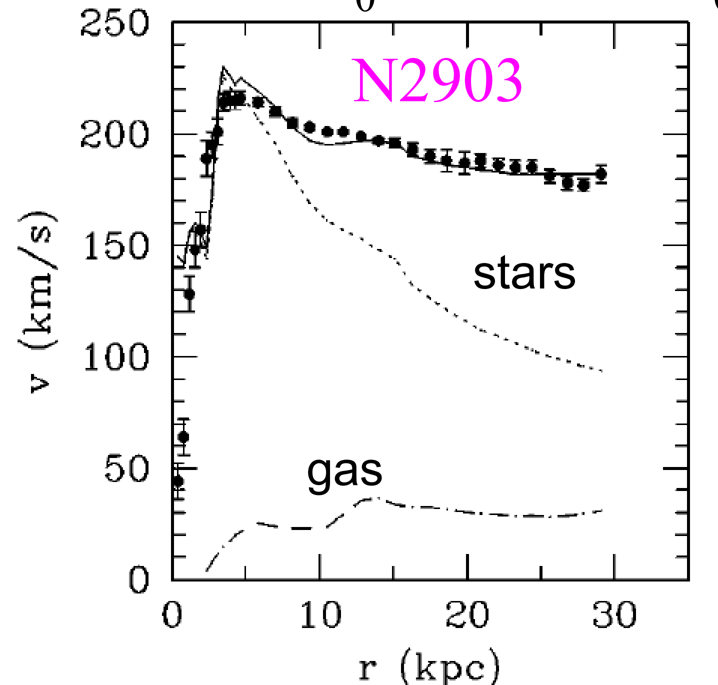


The rotation curves of all galaxy types

$a \ll a_0$



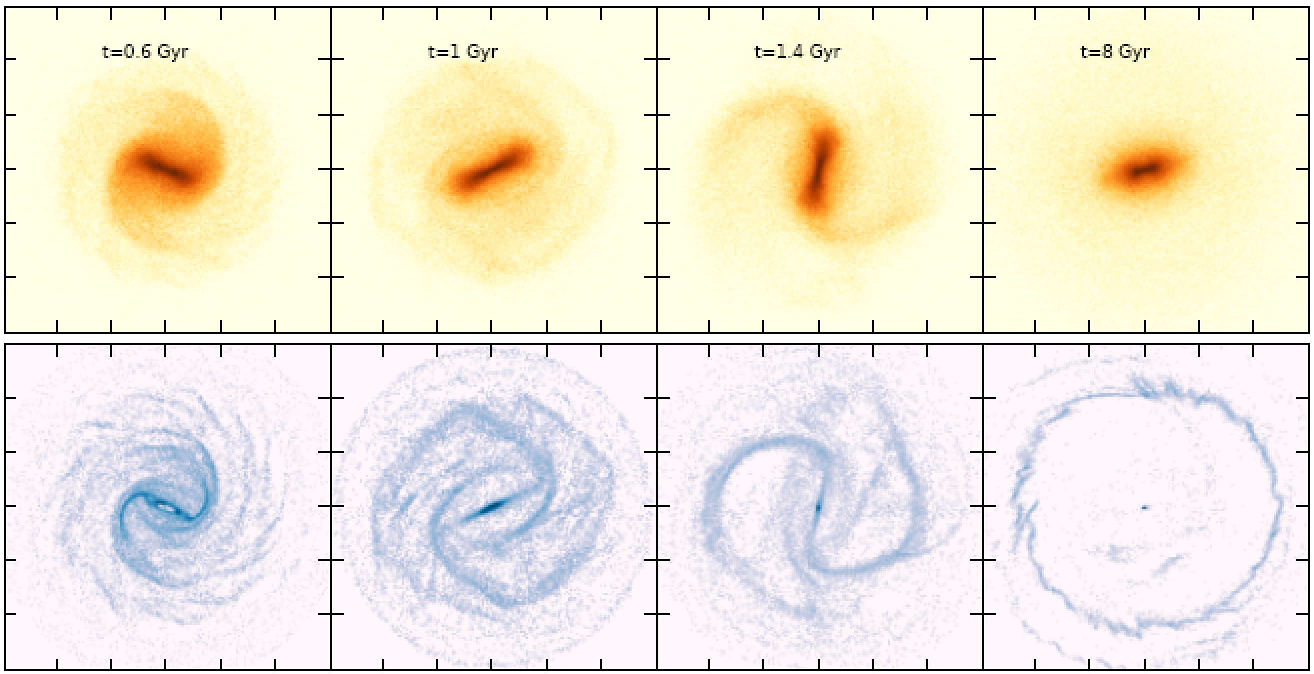
$a > a_0$ $a \ll a_0$



Influence of the dark halo ?

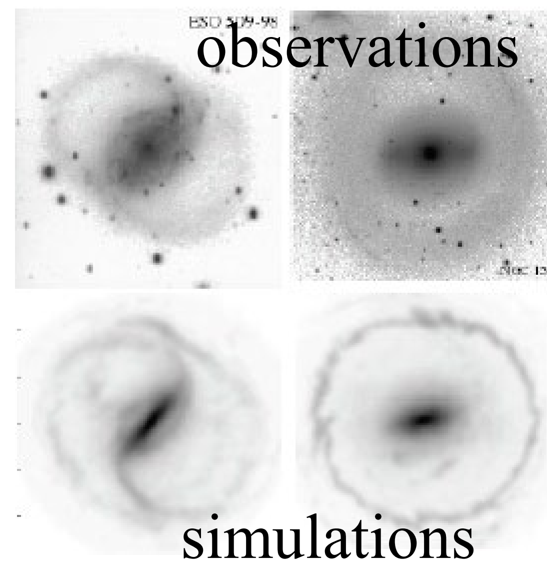
Dynamics of galaxies,
Formation of spirals and bars

Tiret & Combes 2007, 2008



Stars

Gas



EFE (External Field Effect)

Potential in the MONDian regime $\Phi(r) = (GMa_0)^{1/2} \ln r$

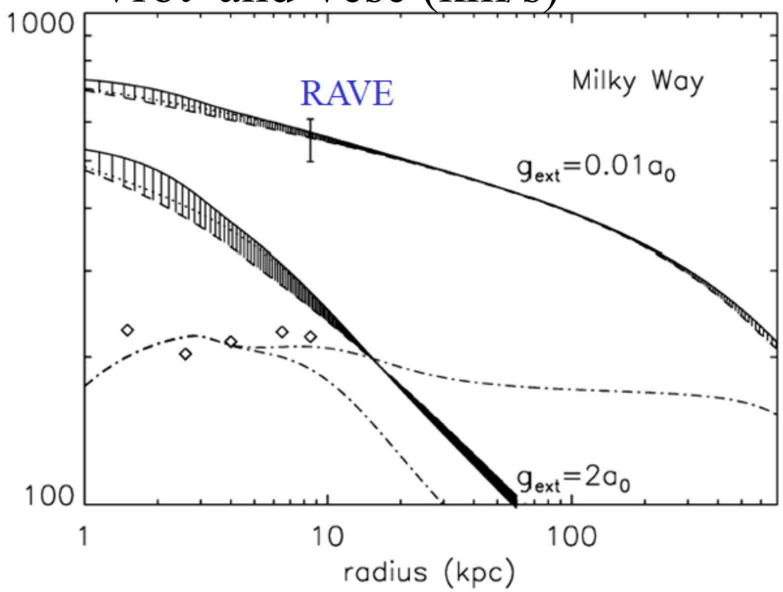
$\frac{1}{2} V_{esc}^2 = \Phi(\infty) - \Phi(r)$ ➔ no escape possible!

But a galaxy is never totally isolated ➔ External field effect (EFE)

If external field g_e is in the **X** direction

At large radii, equivalent to a dilatation Δ

Vrot and Vesc (km/s)



Wu et al 2007

Where $g \ll g_e \ll a_0$

Keplerian dependence, with renormalization

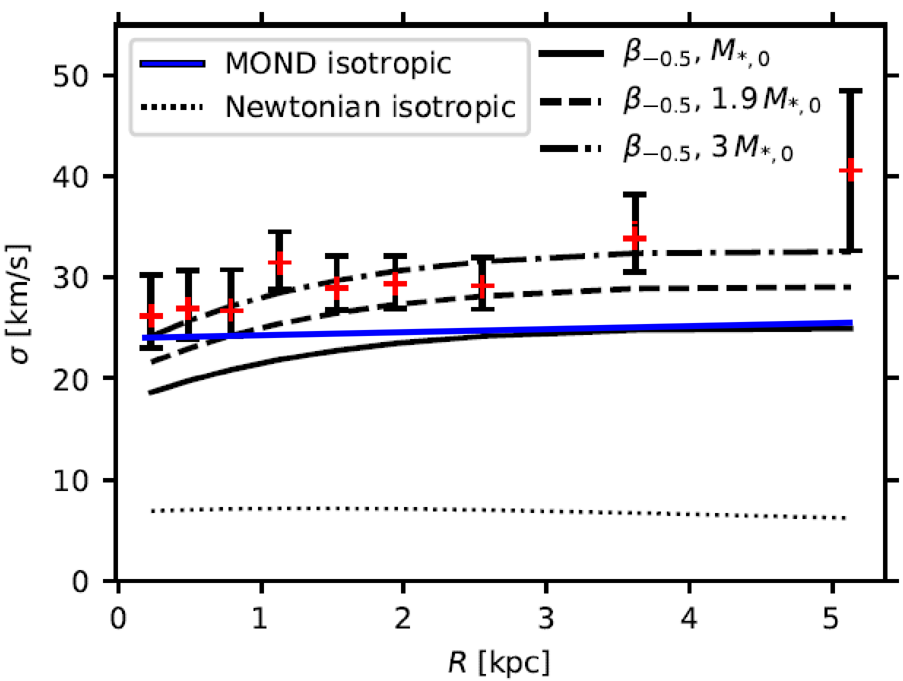
G ➔ Ga_0/g_e

UDG (Ultra-Diffuse Galaxies), Galaxy Groups

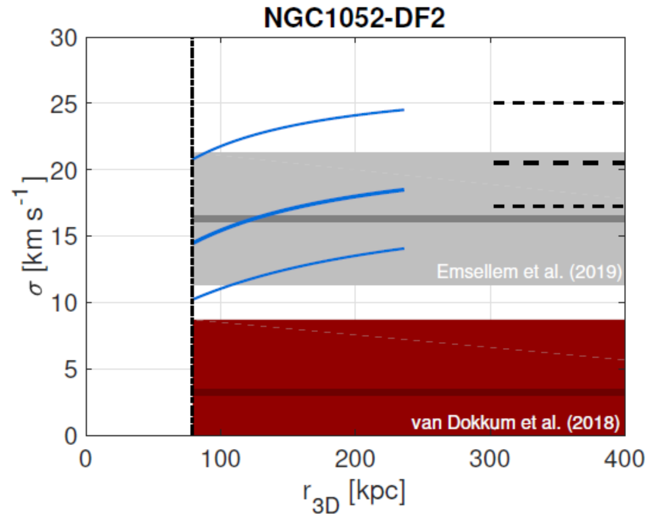
Deep MOND regime, for UDG *(Famaey et al 18, Müller et al 18, Bilek+ 19)* and groups *(Milgrom 2018, 2019)*

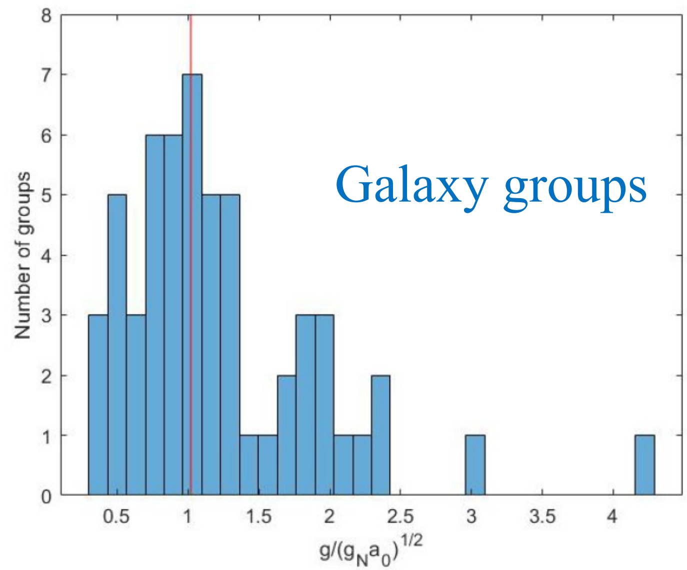
EFE can reduce the apparent DM content

t_{virial} to be compared to $t_{\text{EFE variation}}$

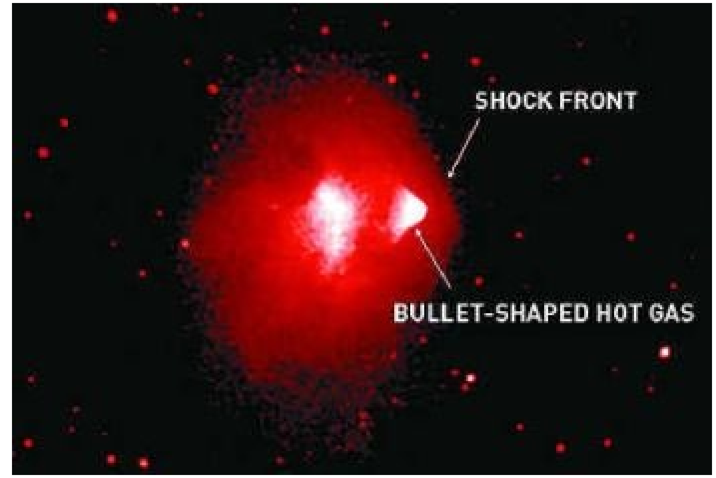


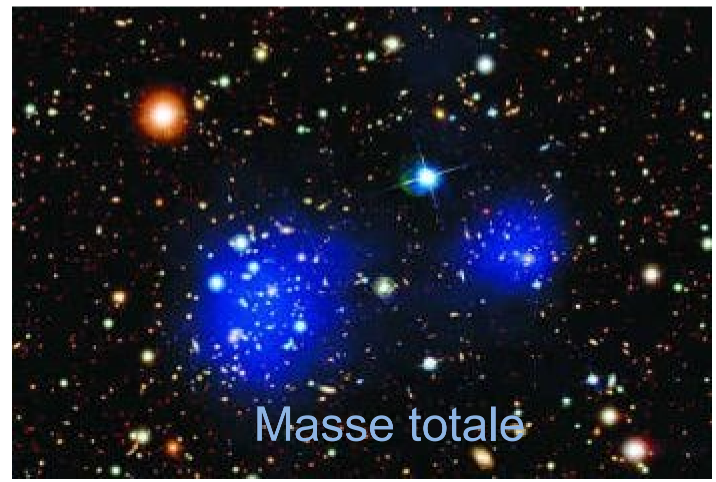
Dragonfly 44 Bilek et al 2019





The bullet cluster





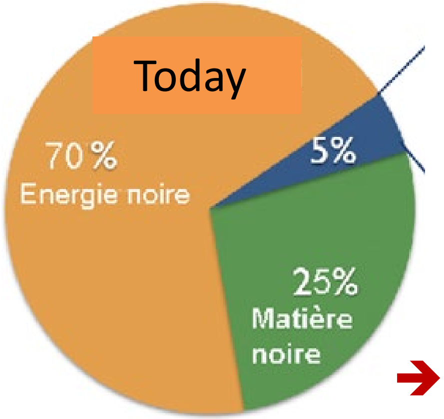
V=4700km/s (Mach 3)

Rare case of violent collision, allowing to separate components

➔ Limit on $\sigma_{DM}/m_{DM} < 1\ cm^2/g$

For modified gravity, need of non-collisionnal matter: neutrinos or dark baryons

Clowe et al 2006



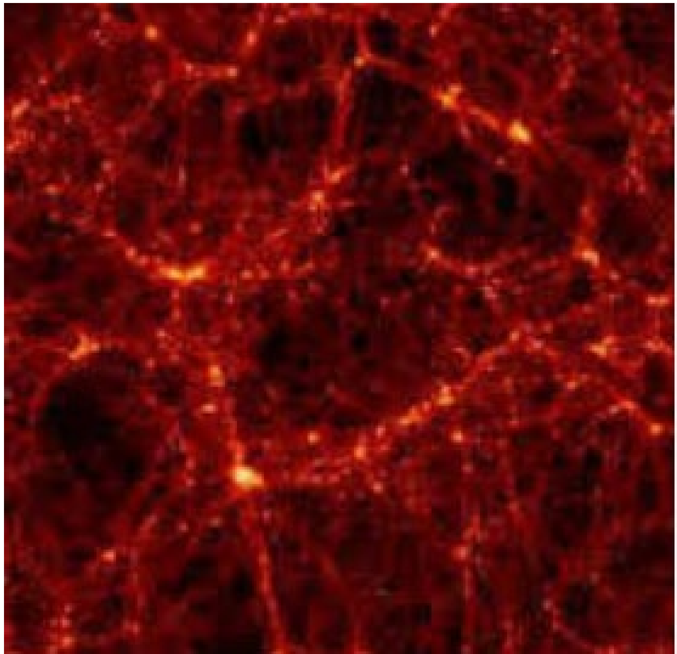
Where are all the baryons?

➔6% in galaxies (stars); 3% in galaxy clusters (X-ray)

➔~18% in the Lyman-alpha forest (cosmic filaments)

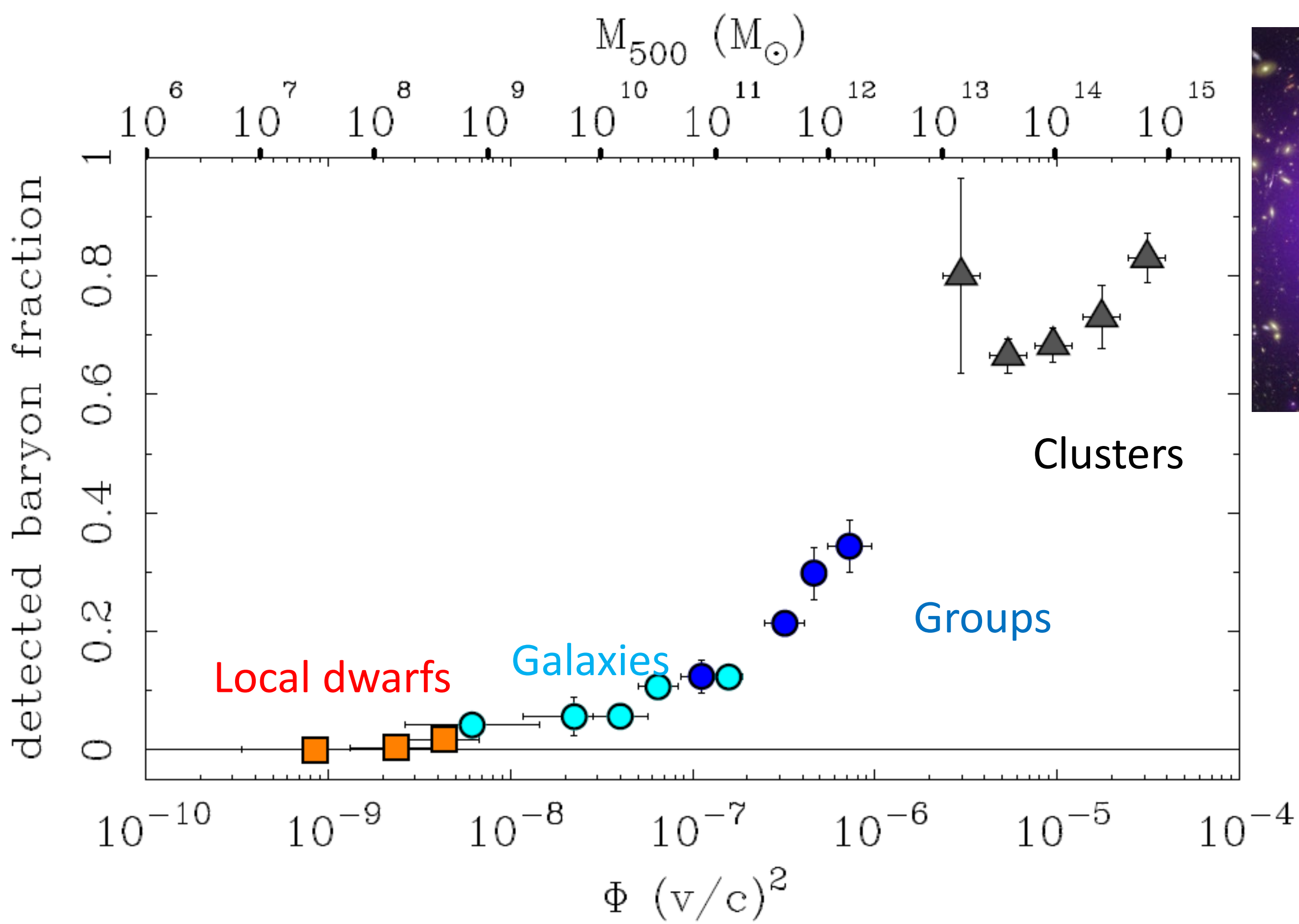
➔~10% in the WHIM (Warm-Hot Intergalactic Medium) 10^5-10^6K
OVI lines

➔63% are not yet identified!
The majority are not in galaxies



Fraction of detected baryons

Fraction = Mb / (0.17 M_{500}) M_{500} dynamical mass in R_{500}
R_{500} radius where density is 500 x the mean cosmic density



Neutron-star merger: measure of c_{GW}

A gamma-ray burst observed 1,74 sec after the merger GW170817

Distance of galaxy NGC4993, 40 Mpc (~130 million yrs, or 4 10^{15} seconds)

$$\left| \frac{c_{\rm GW}^2}{c^2} - 1 \right| < 6 \times 10^{-15}$$

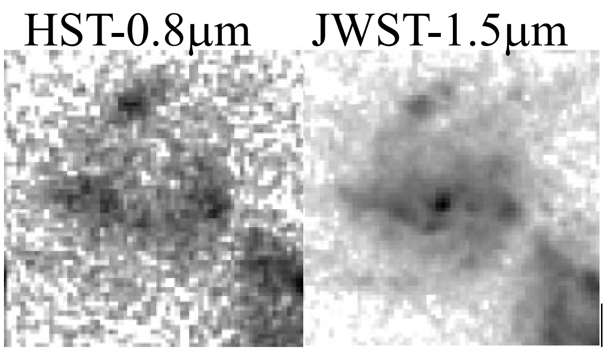
Eliminates a large number of scalar-tensor gravity theories

•Recent relativistic MOND, compatible with CMB and LSS power spectrum ***(Skordis & Zlosnik 2021)***

The JWST revolution

1- Remote galaxies: 10 times more disks

Spirals, Bars, Hubble sequence up to z>6

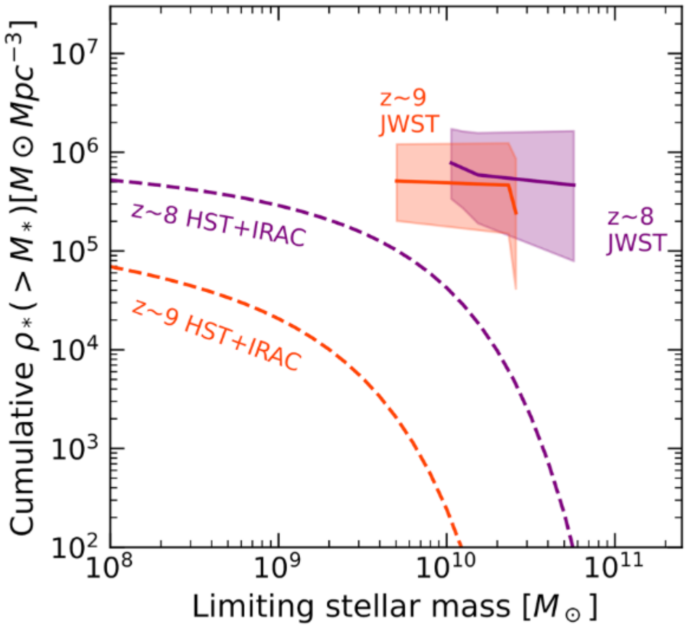


2- Galaxies form very early

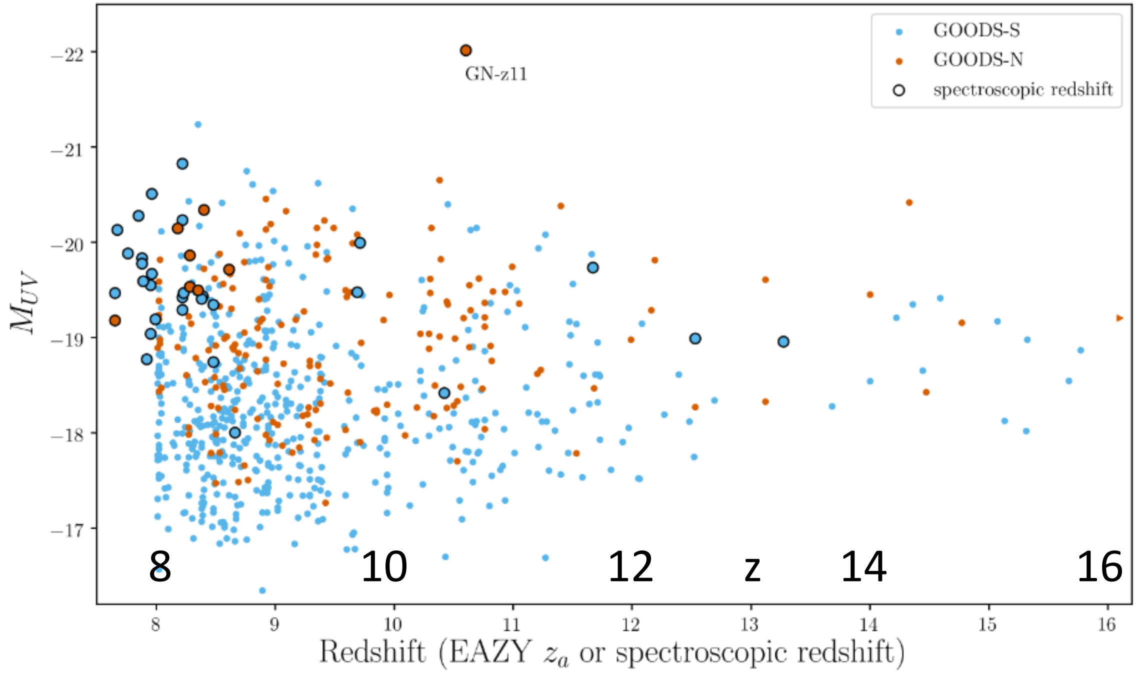
Large number of massive galaxies

Modify the cosmologic model?

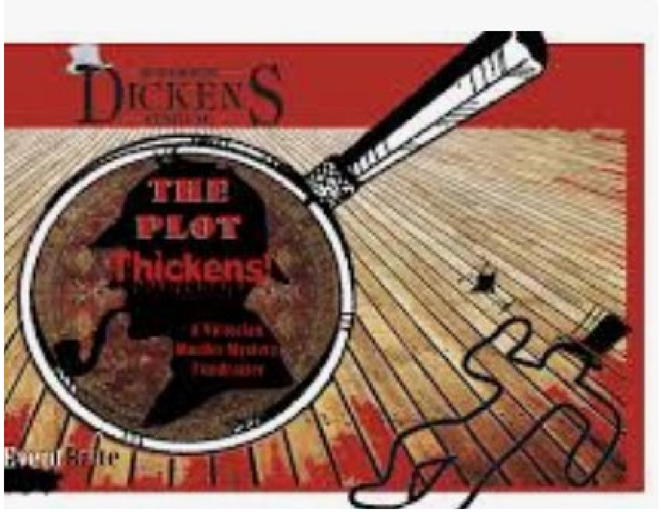
Labbe et al 2023



Hainline et al 2023



The mystery thickens



Galaxies + X-ray hot gas: **0.5%** of total
Ordinary matter (5%): 60% non identified

Exotic dark matter:
Particles still unknown, mass over 34 orders of magnitude
searched for **during 38yrs**

→ **or modified gravity**, 5^{th} force