COLLÈGE DE FRANCE 1530

Chair Galaxies & Cosmology

Inaugural Lecture

The dark matter

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Astronomers at Collège (Royal) de France

Mainly Mathematicians at the beginning
P. Gassendi galilean astronomy ~1645
J-B Morin (1629-56), astrolog of Louis XIII
P. Gassendi, cautious, was teaching Ptolémée, Copernic, Tycho, only as « hypotheses».

Giordano Bruno
Royal Lecturer ~1580
Against geocentrism
For the plurality of worlds

In opposition to Descartes, he states the existence of vacuum

Goes beyond Galilée by generalising inertia principle

Observes eclipses, Mercury & Venus transits in front of the Sun

Pierre Gassendi
Royal Lecturer ~1645-55

Astronomers at Collège (Royal) de France

In France, mainly celestial mechanics,
J. Lalande, chair of Astronomy (1762-1804)
J-B. Delambre with his colleague P. Méchain from academy measures the meridian during revolution,
An epic of almost 10 years

Jérôme Lalande
Royal Lecturer, during 42 yrs!

J-B. Delambre
Imperial Lecturer ~1807-15

Celestial mechanics until XXe century
A. Dauvillier Cosmic Physics
A. Lallemand Physics Methods, Instruments
J-C. Pecker TheoreticalAstrophysics
A. Labeyrie Observationnal Astrophysics
G. Veneziano Particles, Gravitation & Cosmology

(pre-)History of dark matter

Two examples of « invisible matter »

1846- U. Le Verrier: systematic anomalies in the motion of Uranus,

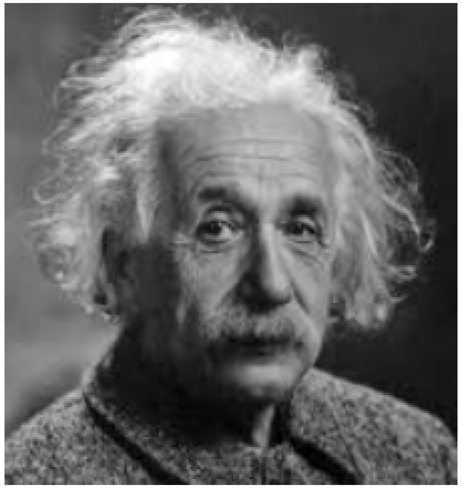
Predicts the existence of another planet, and its orbit

➔**Discovery of Neptune,** by Johanne Galle in Berlin

➔**1860** Advance of perihelie of Mercury by 43''/century unexplained

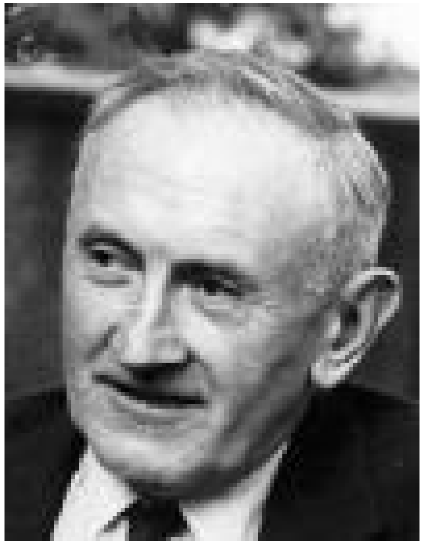
Proposes Vulcain, planet inside Mercury orbit

Not observed during the eclipse of 1860➔ belt of small bodies, the Vulcanoids?

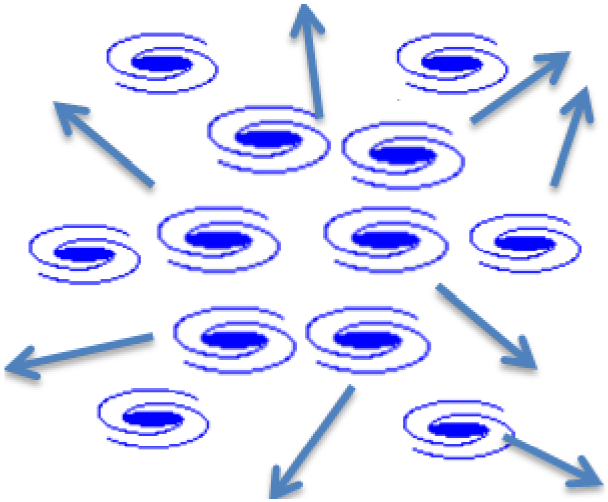


➔**1916** Einstein's General Relativity explains exactly the 43''

Brief history of dark matter



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

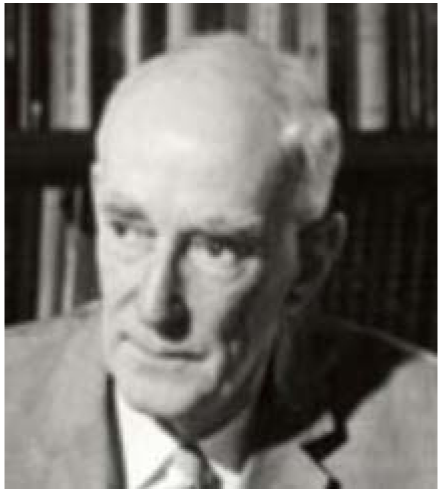


Coma cluster, V~1000km/s
$M \sim 5\ 10^{14}\ M_\odot$

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

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

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



Dark matter in galaxies

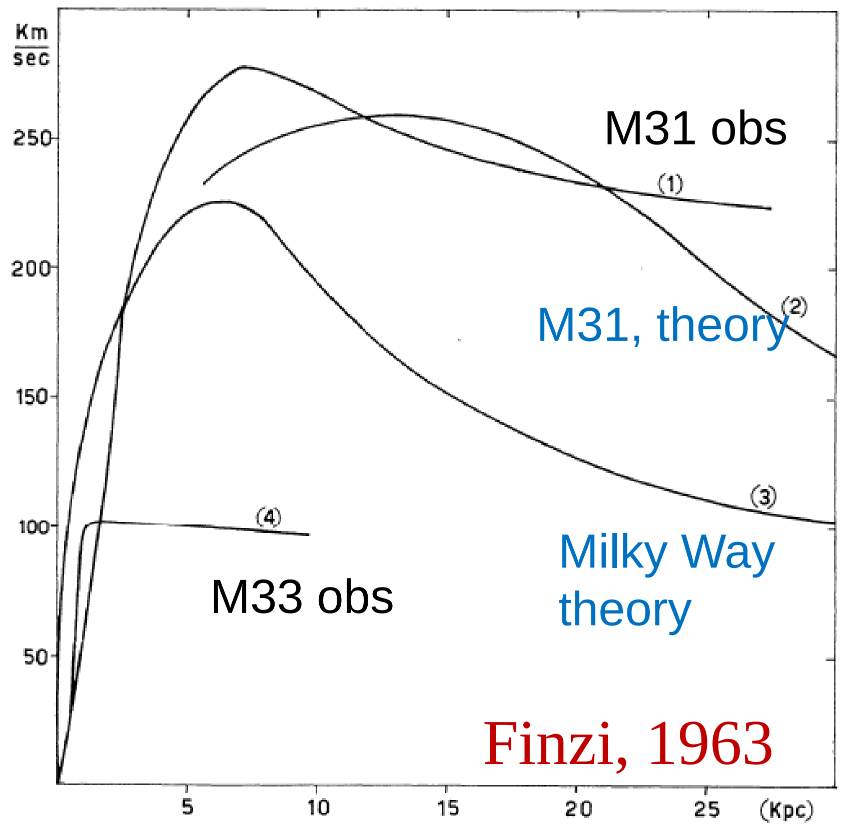
Rotation curves of stars and ionised gas (Hα and [NII] 0.6μm)

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

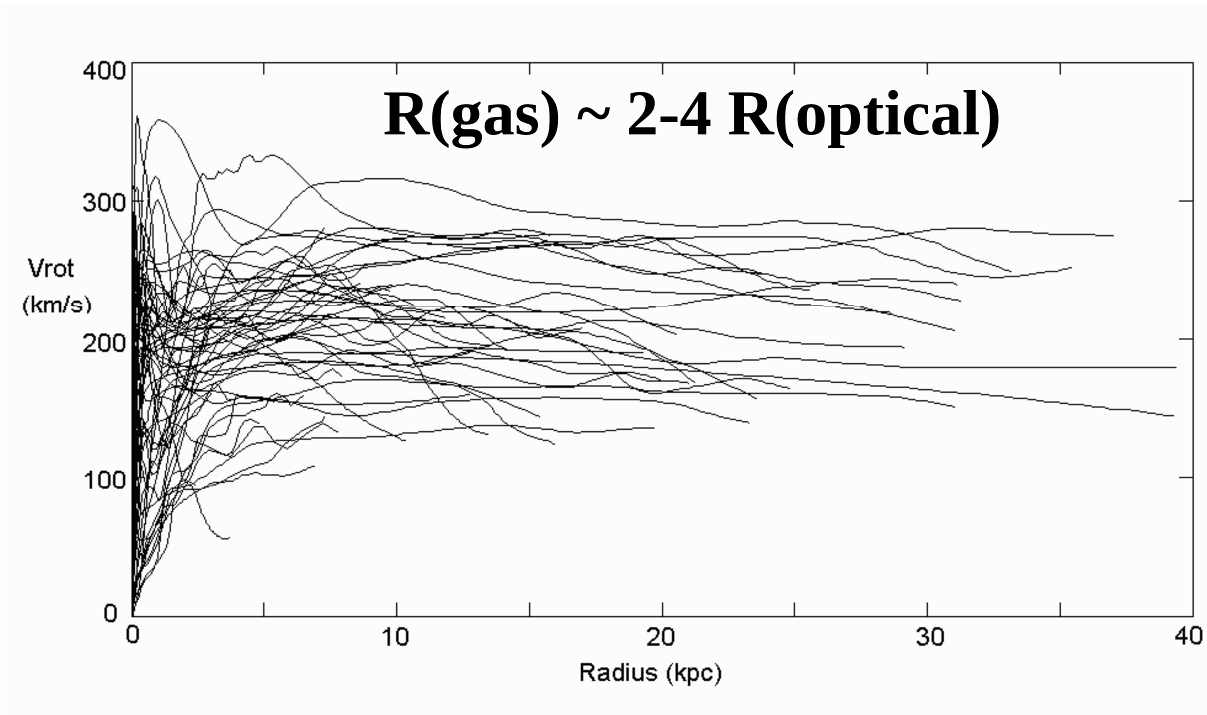
➔Flat Curves

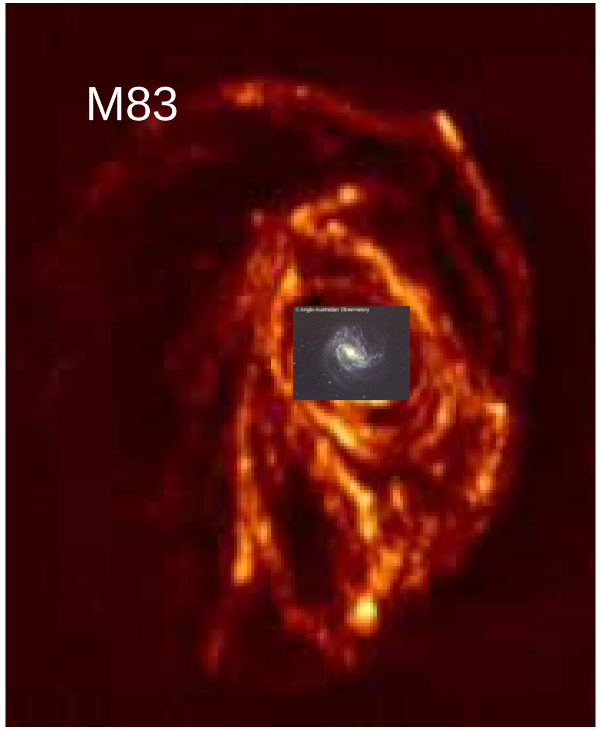
Interpretation at this epoch
M/L ratio increases with radius

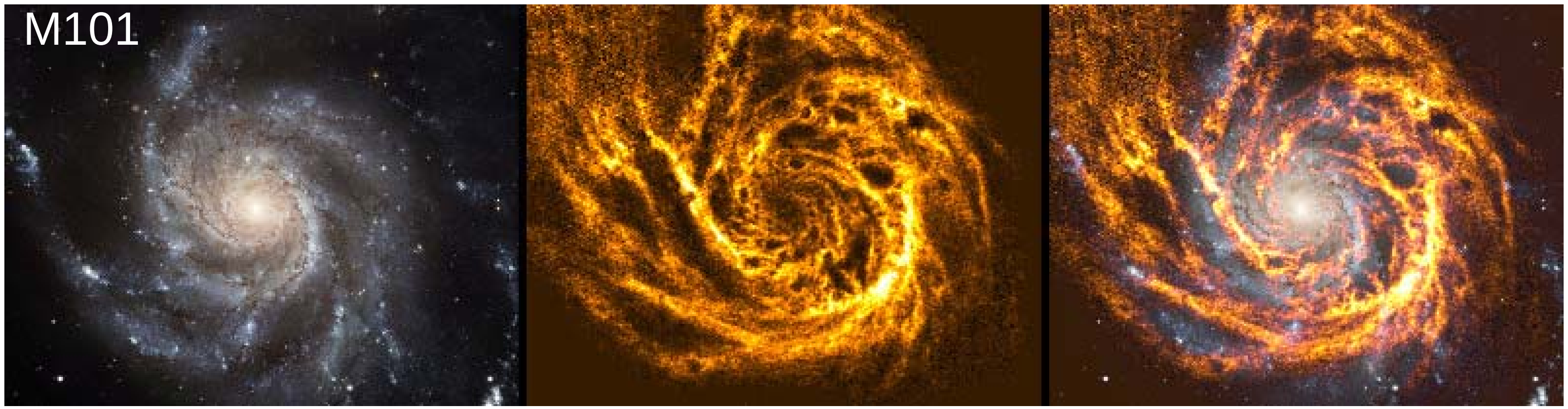


Arrigo Finzi (1963) proposes a gravitation law in $1/r^{\alpha}$ with $\alpha < 2$

Atomic Hydrogen in galaxies

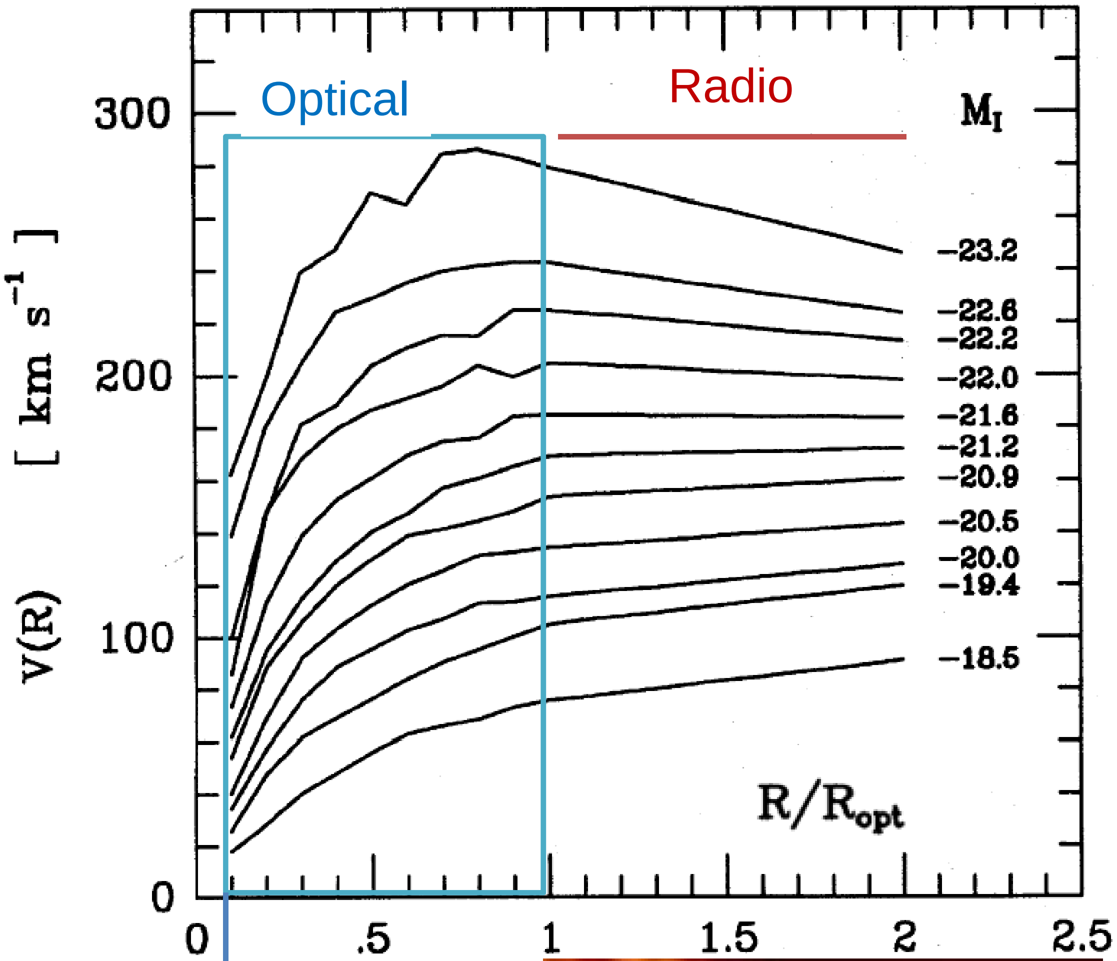




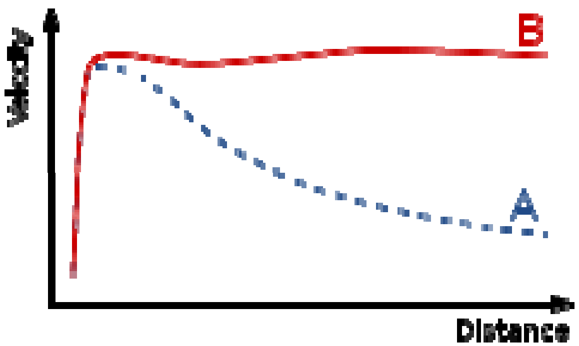


Flat rotation curves

~1980: Radio Interferometers
Dozens of rotation curves
R(gas) =2-4 x R(optical)



➔Dark matter established with certitude



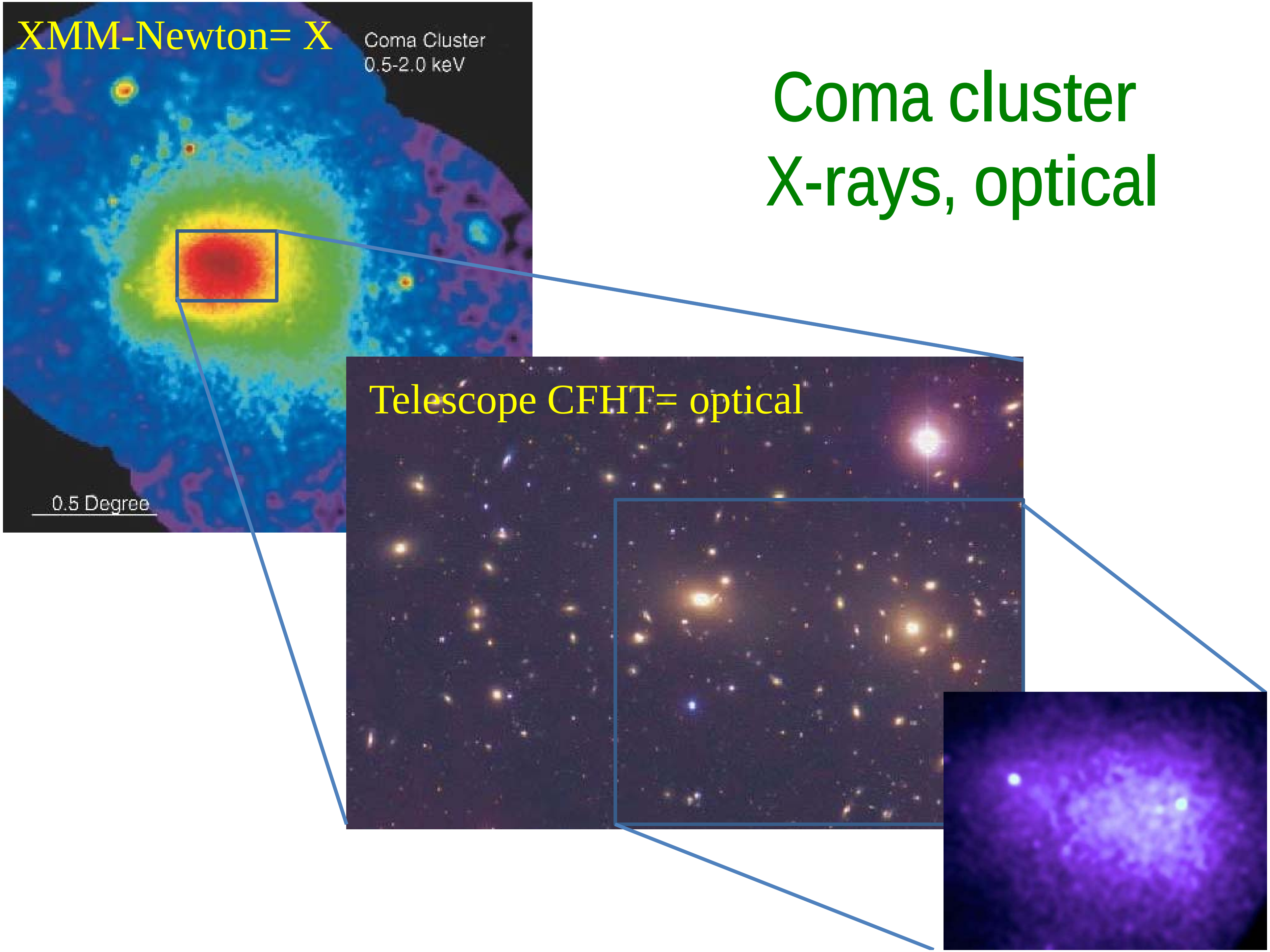
The missing mass shrinks….

The first X-ray satellites discover in **1966** (Boldt et al)
a very strong diffuse emission coming from the Coma clsuter
Felten et al **(1966)** interpret this emission as coming from very hot gas
at $T \sim 10^8$ K, or 100 millions of degrees!
And its mass is comparable to the missing mass

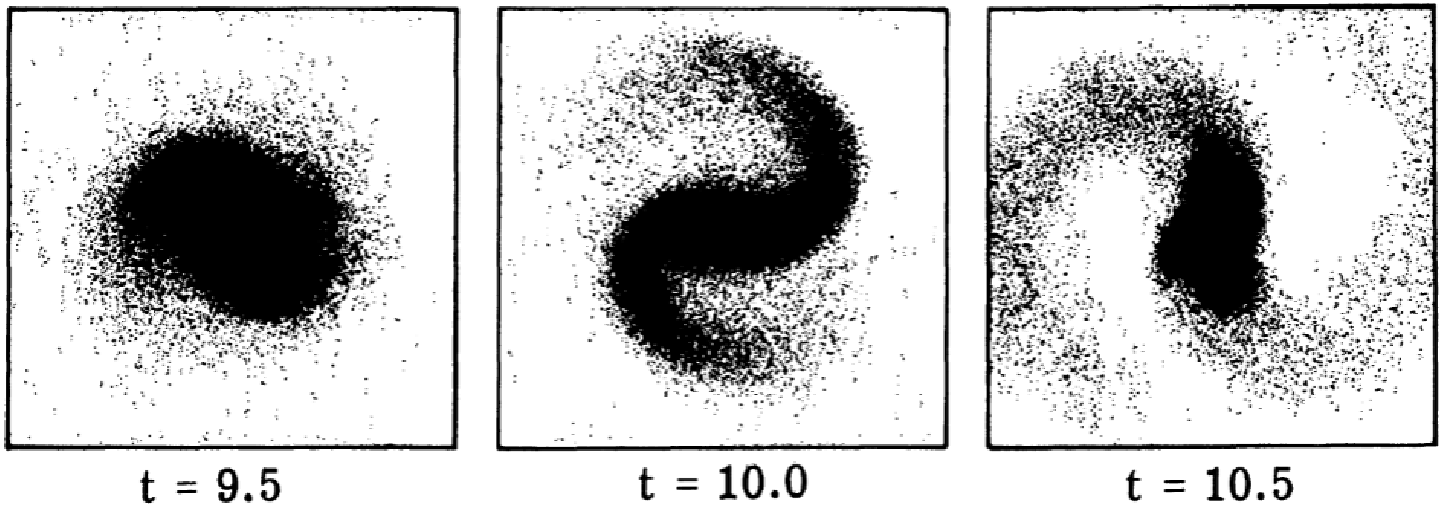
In fact, today we know that M(hot gas) ~10 M(galaxies)
So it remains some **dark matter ~6 times the visible mass**

Another blow to the anthropomorphism: most of the matter does not radiate at optical wavelengths, those that the eye can see!

Coma cluster
X-rays, optical



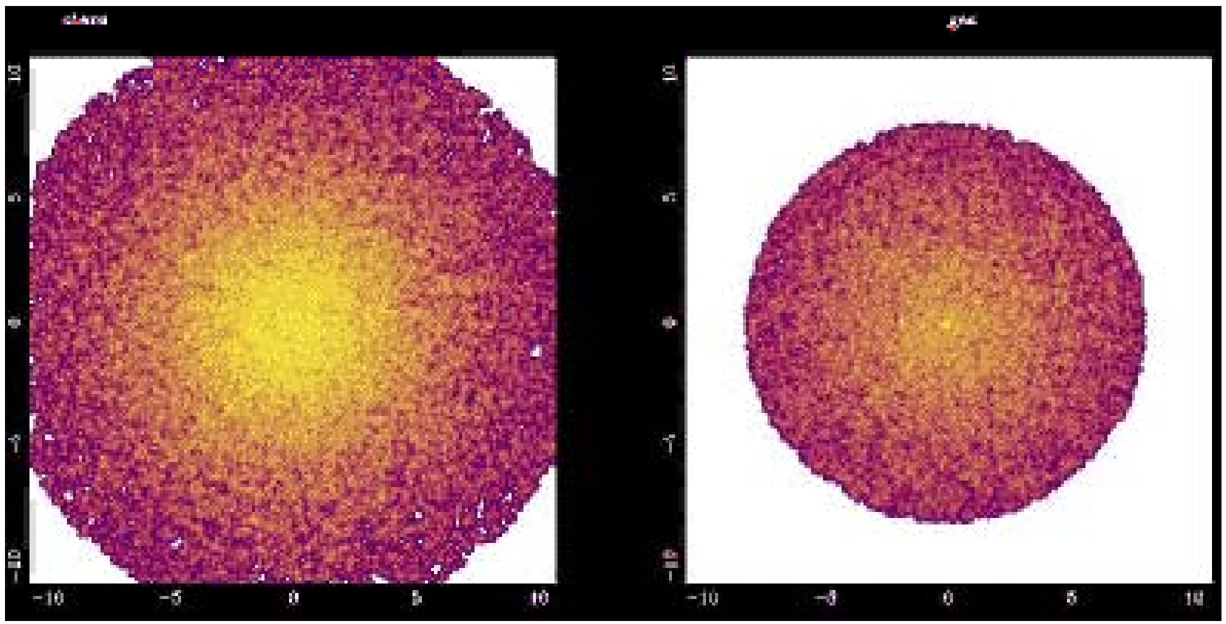
Stability of galaxy disks



Hohl 1971

Ostriker & Peebles 1973

Stars   Gas



Galaxies must be embedded in a dark halo

The dark matter becomes exotic

Until the beginning of 1980s, there was only ordinary matter
1984: change of paradigm!

- Cosmological background (3K) discovered **in 1965**,
- Primordial Nucleosynthesis in the Big-Bang **(1975)**

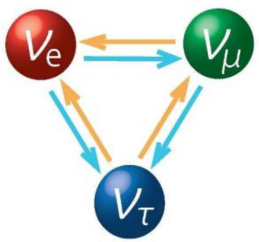
➔ The ordinary matter cannot be higher than 5% $\rho_{crit} = 10^{-29}$g/cm^3

- Primordial Fluctuations too small in the cosmological radiation

Neutrinos present with a density comparable to that of photons (~300/cm^3)

- Are they massive ? Solar Neutrinos problem

Explained by the exchange between the 3 neutrino flavors
This is the proof that neutrinos have a mass



Neutrinos and Dark matter

1976: and if the dark matter was consituted by neutrinos ?

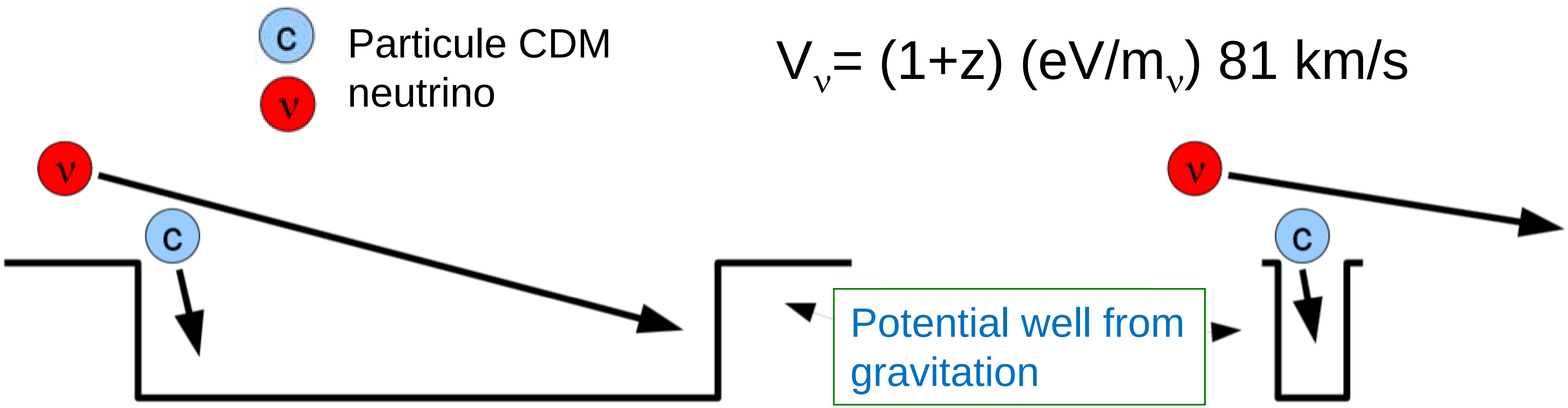
$$\Omega = \rho/\rho_c = \Sigma\, m(\text{neutrino}) / 45\ \text{eV}$$

If each = 15 eV, neutrinos can close the Univers (Ω=1)

1 eV = 1.8 10^{-33}g *m(electron) = 0,5 MeV*

Suppression of small-scale structures

$V_\nu = (1+z)\ (\text{eV}/m_\nu)\ 81$ km/s

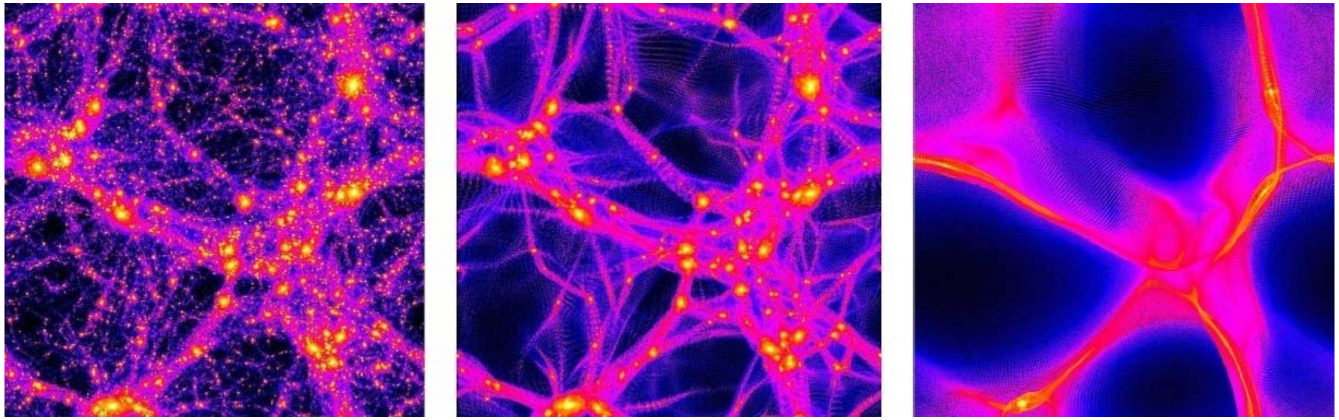


Types of dark matter

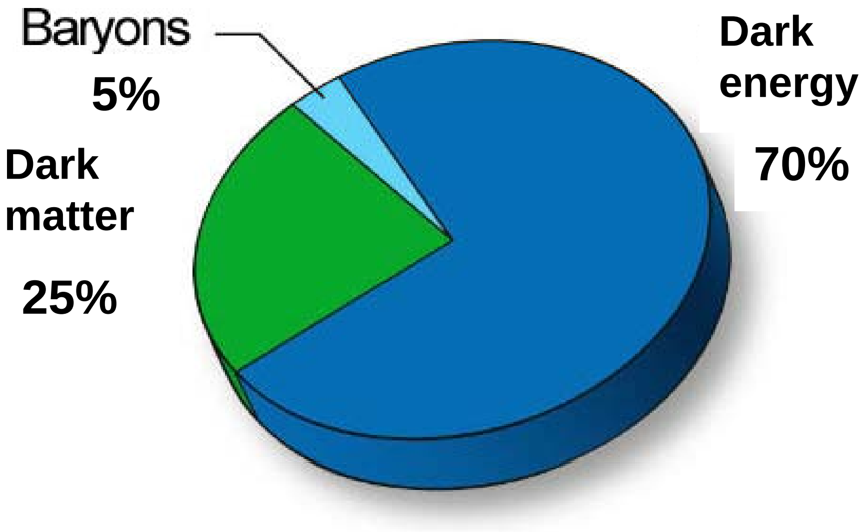
Hot (neutrinos)
Relativistic at decoupling
Cannot form the observed structures, if $m < 5$ keV

Cold (massive particles)
Non relativistic at decoupling
WIMPS
("weakly interactive massive particles")
Neutralinos: the lightest particle from supersymmetry theory

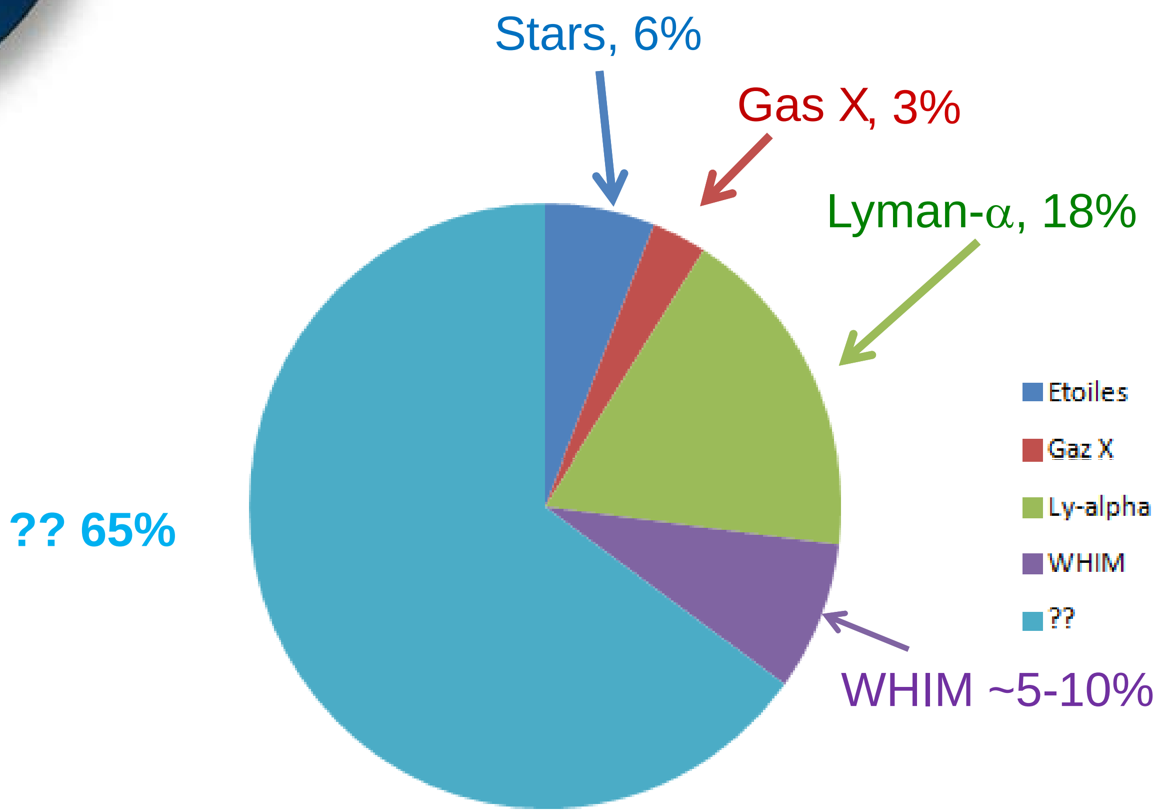
Cold *Warm* *Hot*



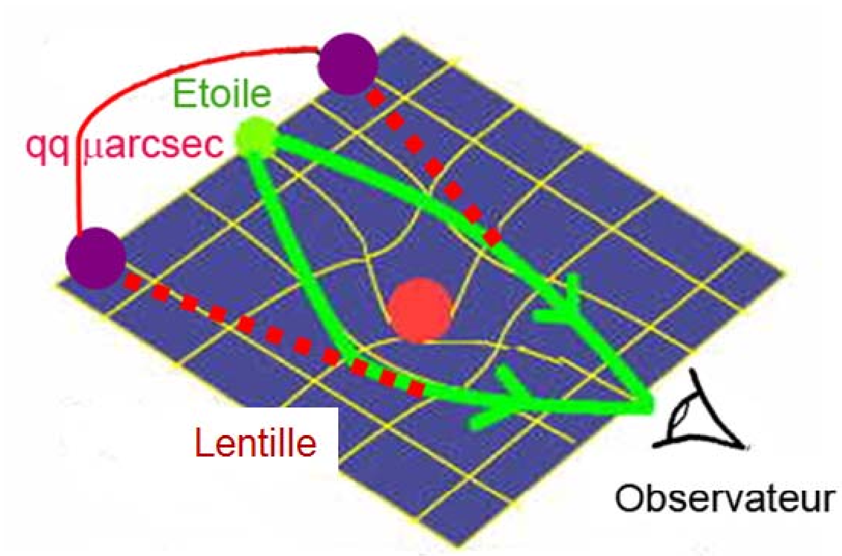
A lot is known now.... but so little



Among the baryons
(atoms, ordinary matter)



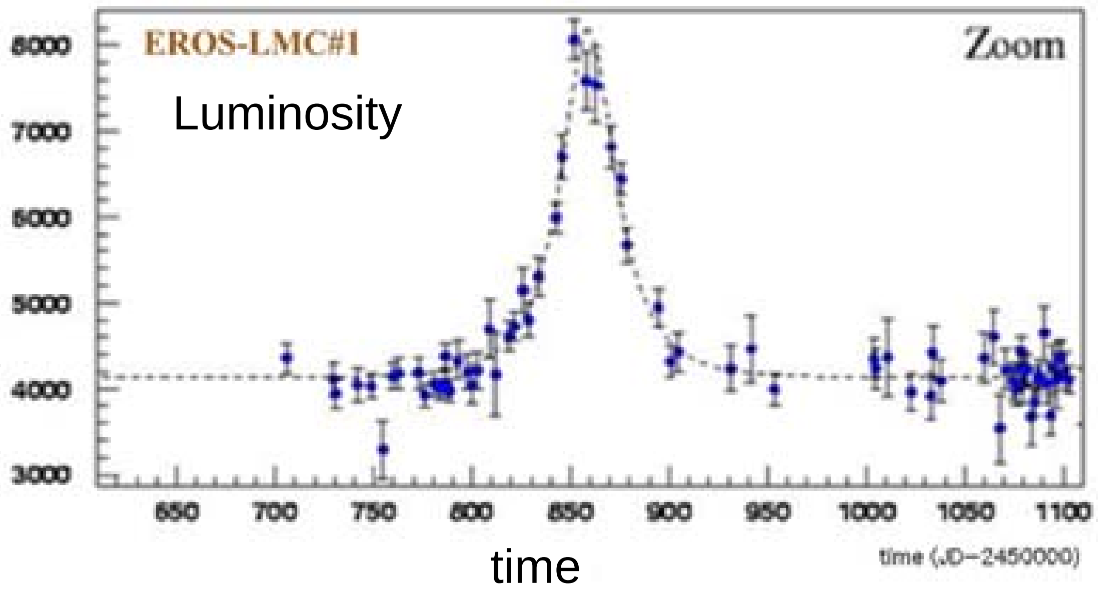
Gravitationnal micro-lensing



Distorsion of space
by the gravity

For a star-lens, the separation between images is 100 µarcsec

➔**Just an amplification ~30days**

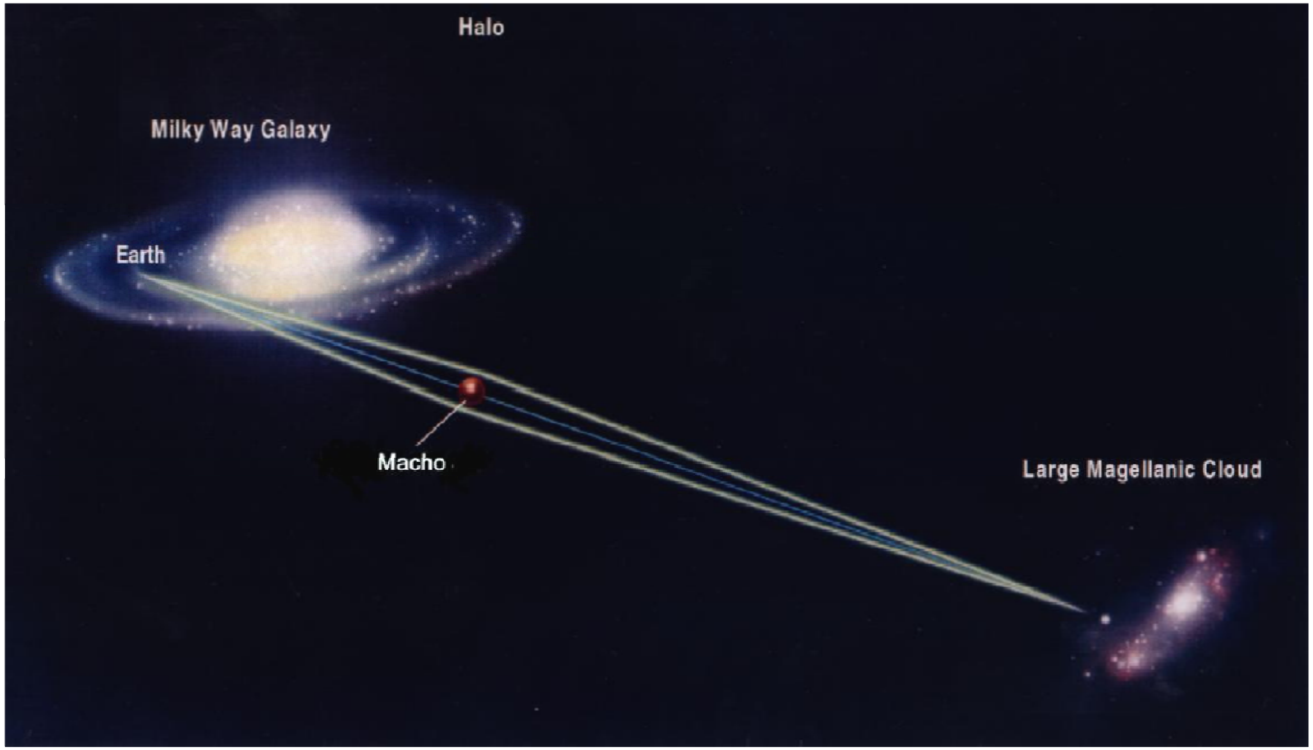


Baryonic dark matter

Under which form? Compact objects, brown dwarfs
MACHOS (**MA**ssive **C**ompact **H**alo **O**bjects)

Experiences of micro-lensing (MACHOs, EROS, OGLE)
The objects of mass $10^{-7}\,M_{\odot} < M < 5\,M_{\odot}$ are ruled out < 10% of halo

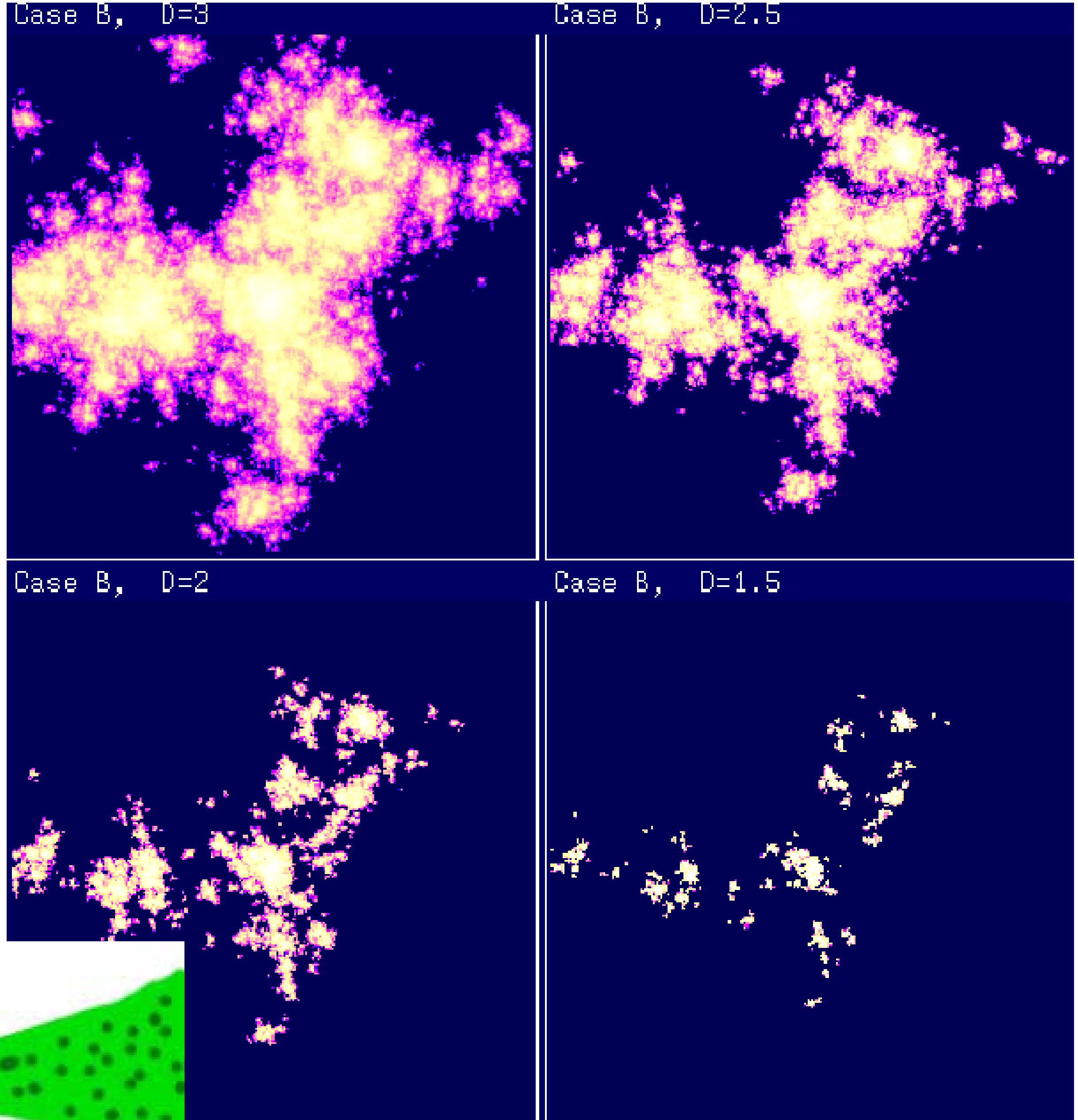
Millions of stars observed during more than 10 yrs

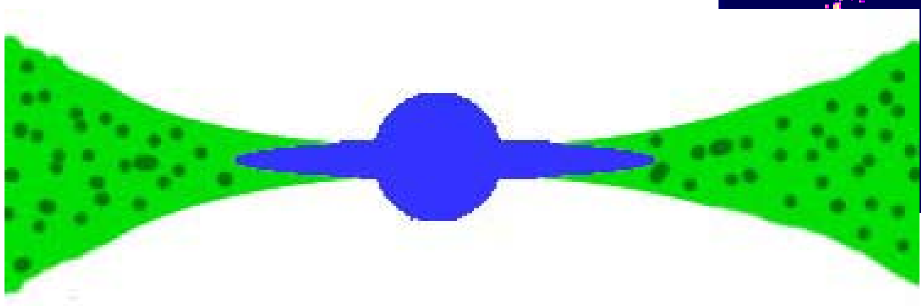


Where are the baryons: Cold H_2 gas?

The stability of H_2 gas
is due to its
Fractal structure

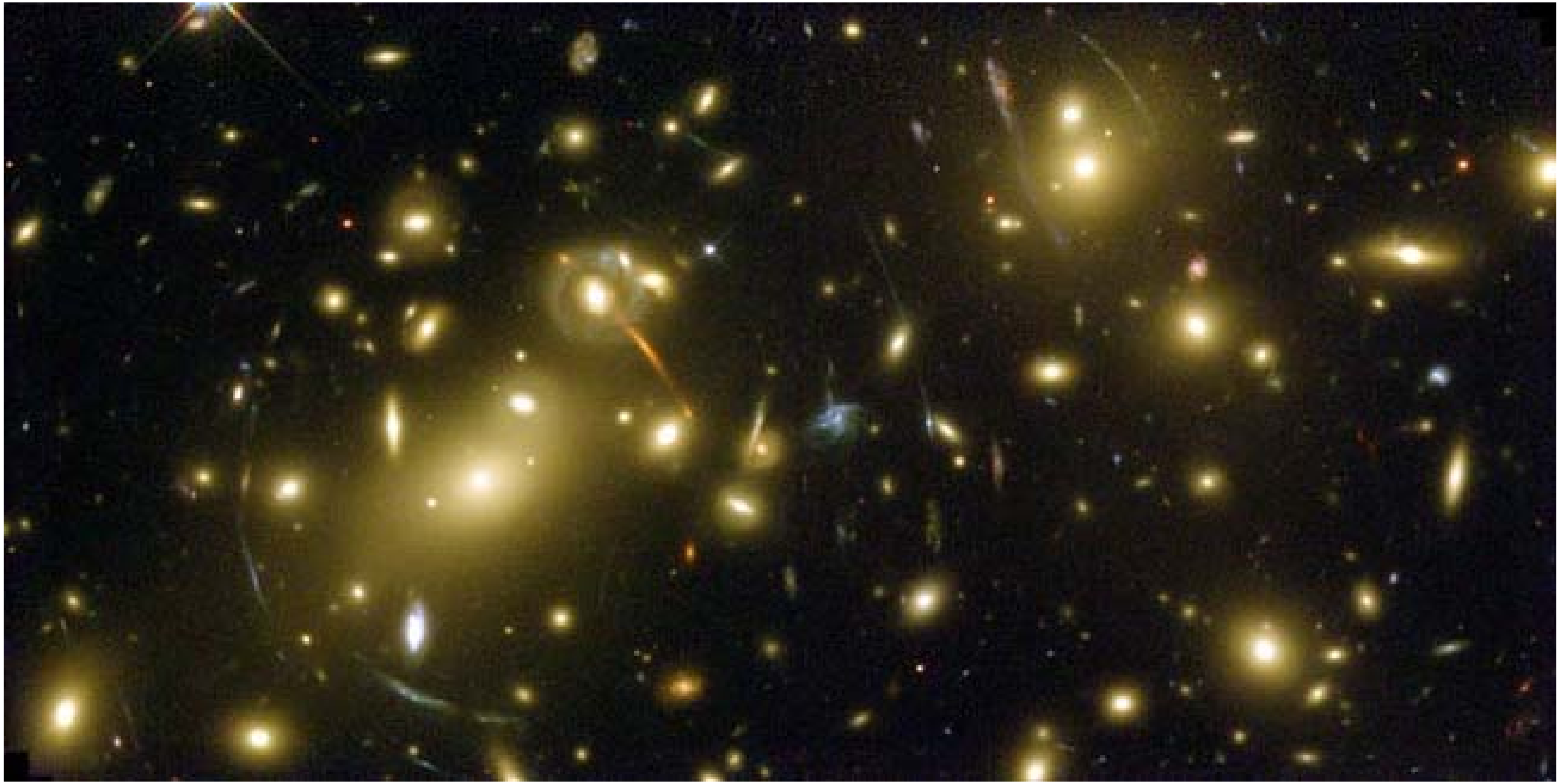
Mass ~ 10^{-3} $M_\odot$
density ~10^{10} cm^{-3}
size ~ 20 AU
$N(H_2)$ ~ 10^{25} cm^{-2}





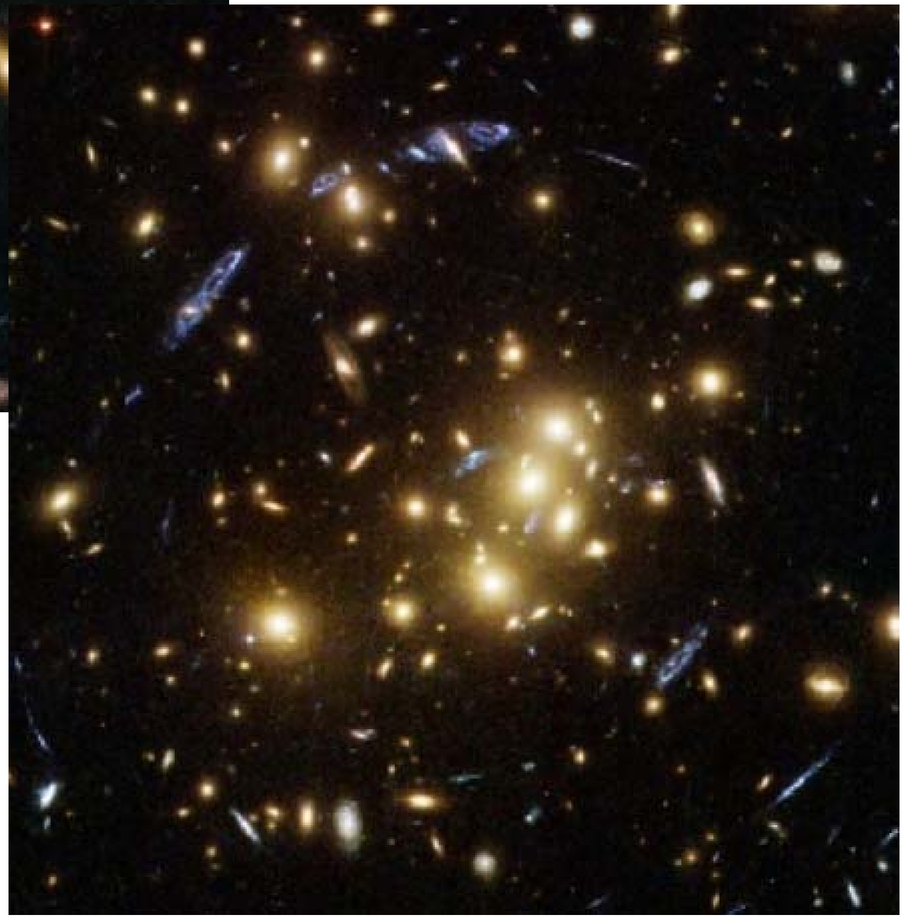
Pfenniger & Combes 1994

Strong gravitationnal lenses



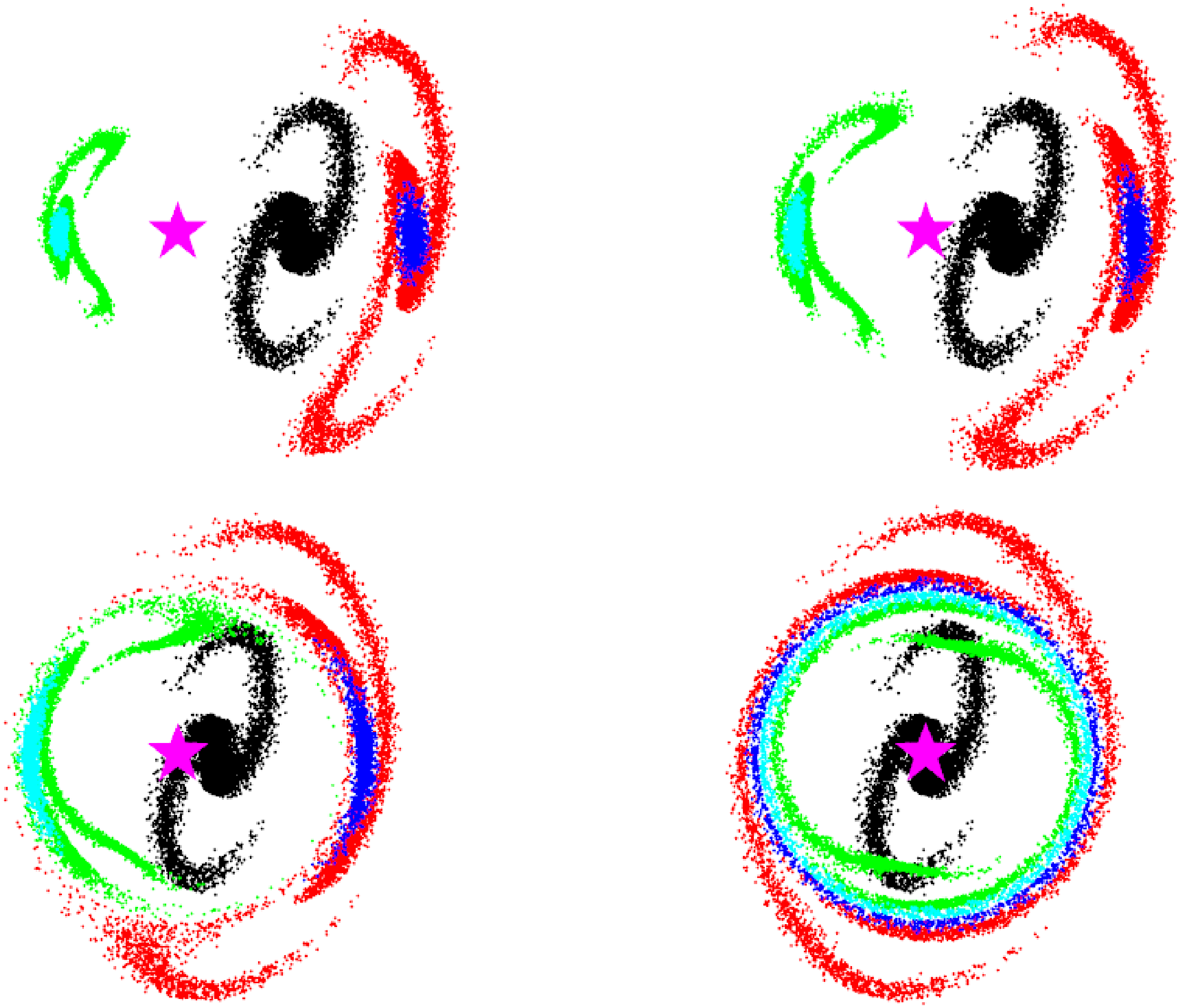
Abell 2218 HST

A370, the first arc discovered at the Toulouse Observatory (Soucail et al 1987)

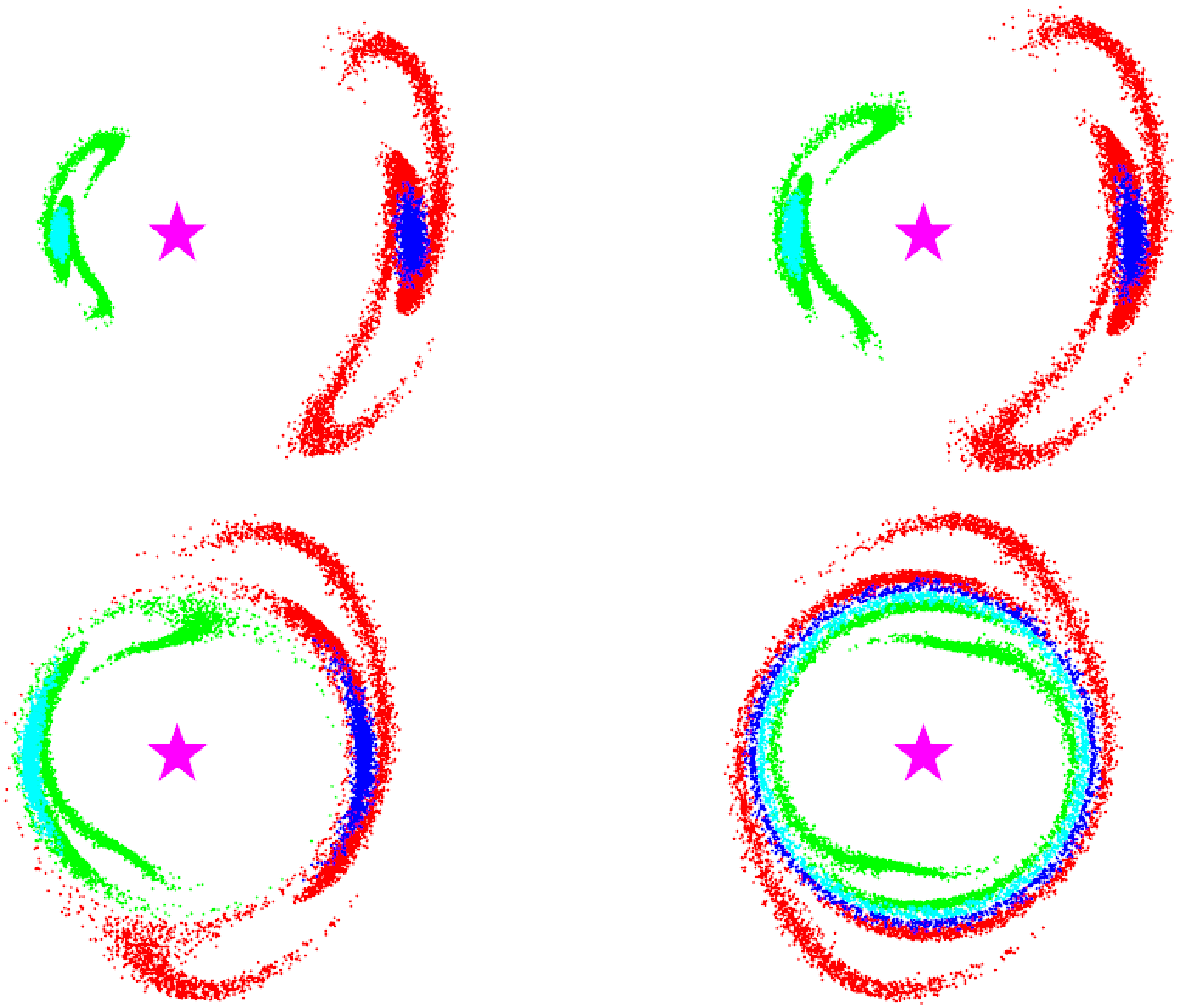


Strong lenses: arcs

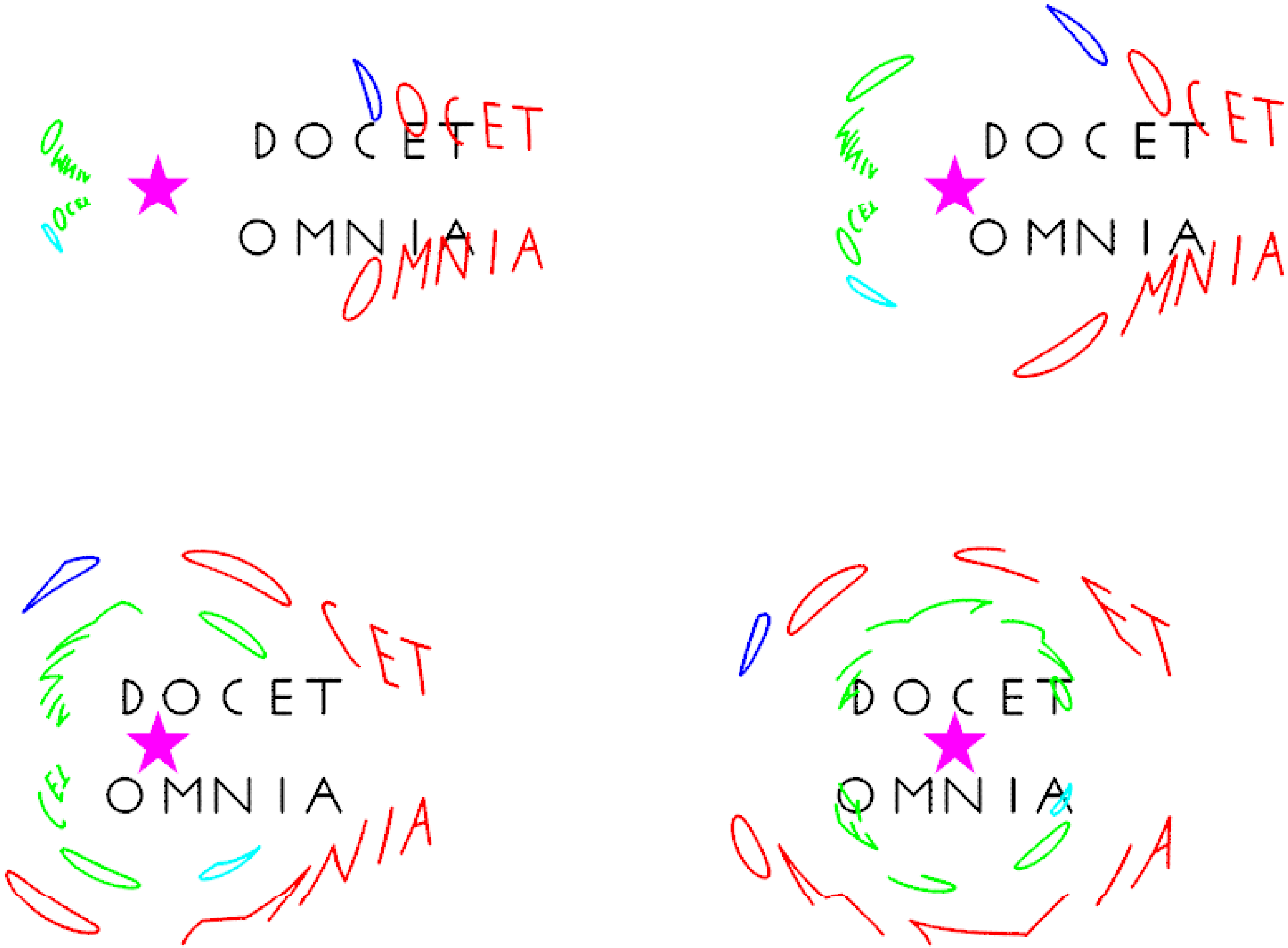
Images of a spiral galaxy



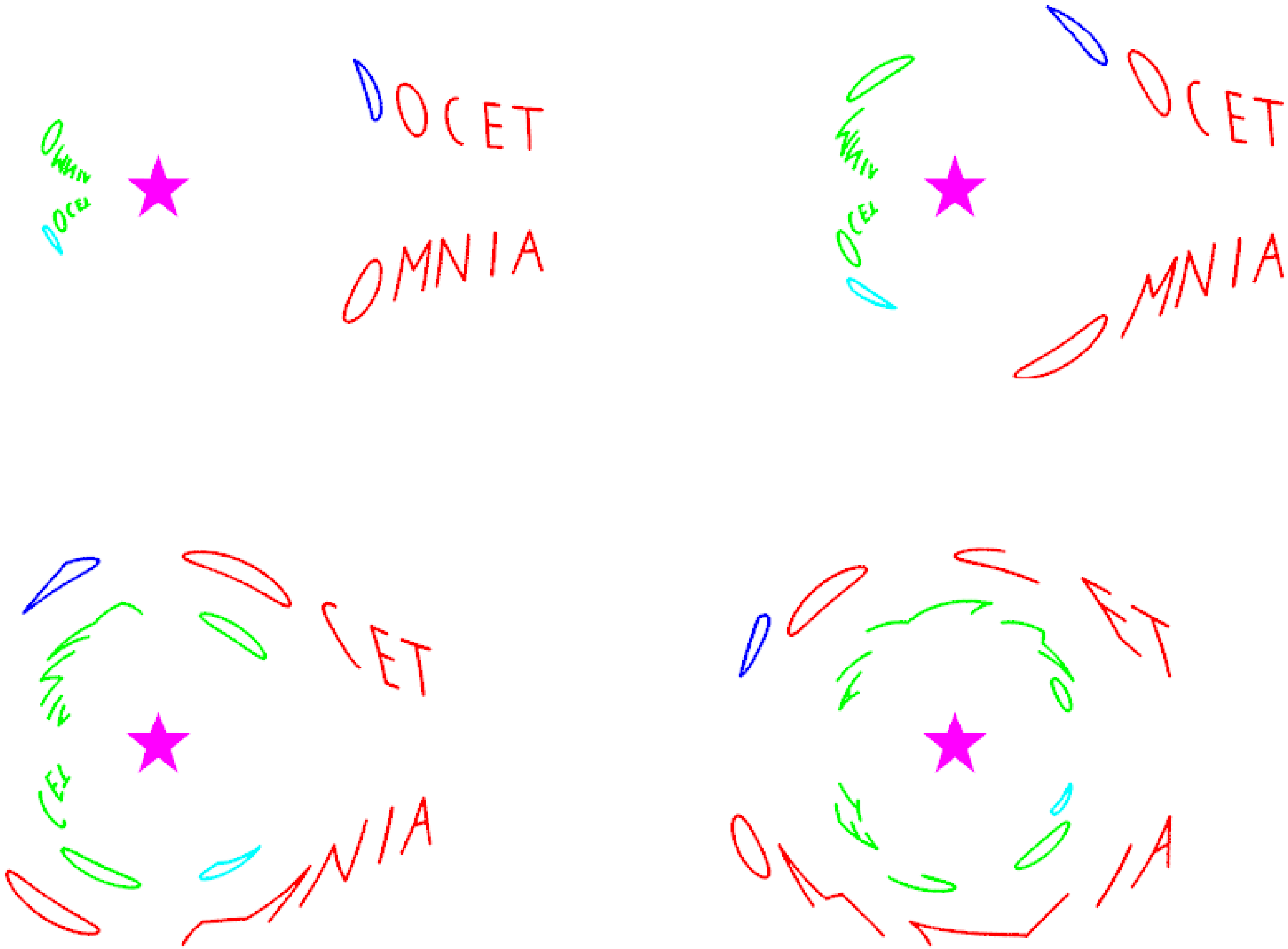
Images of a spiral galaxy



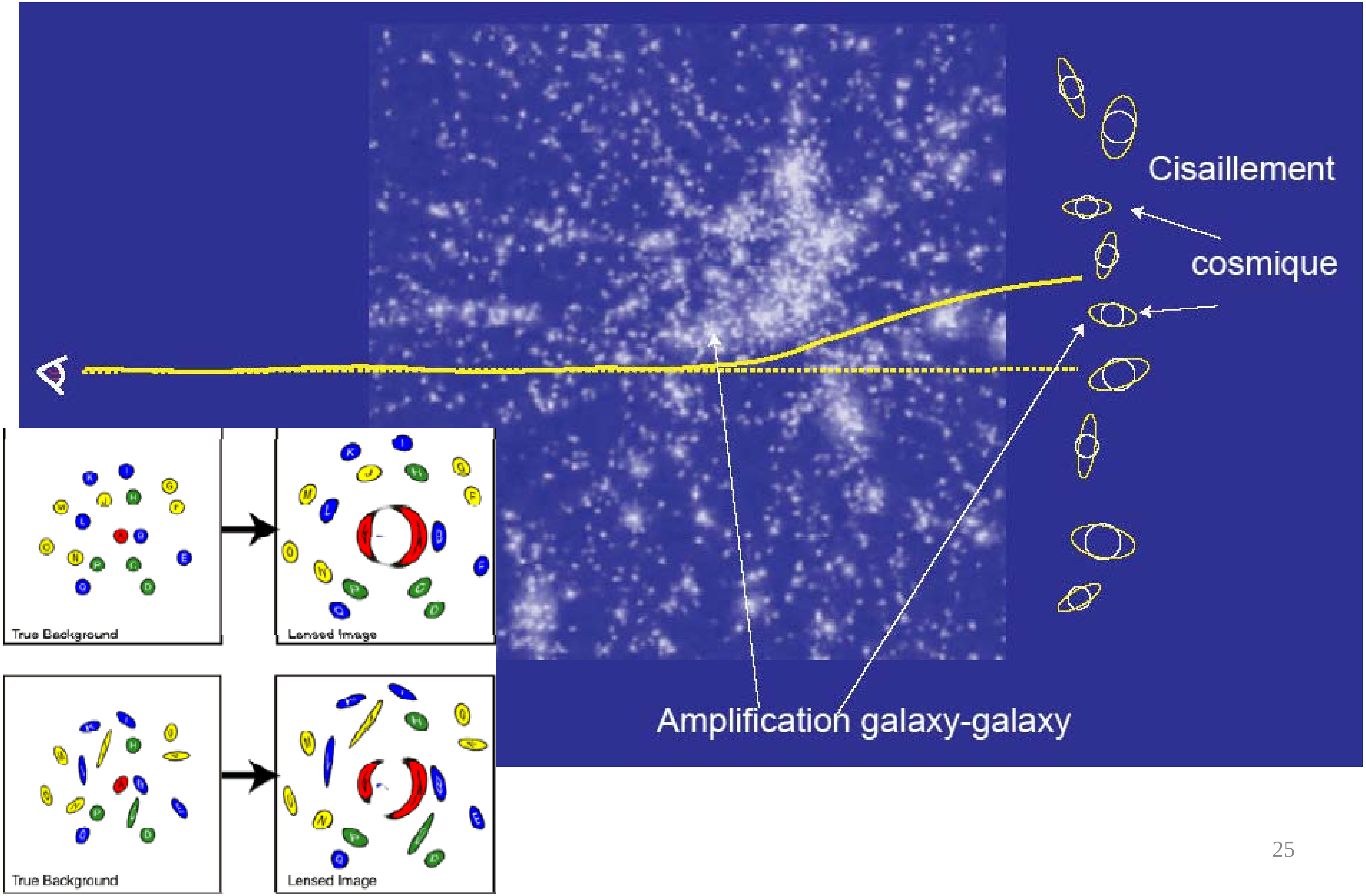
Other images



Other images



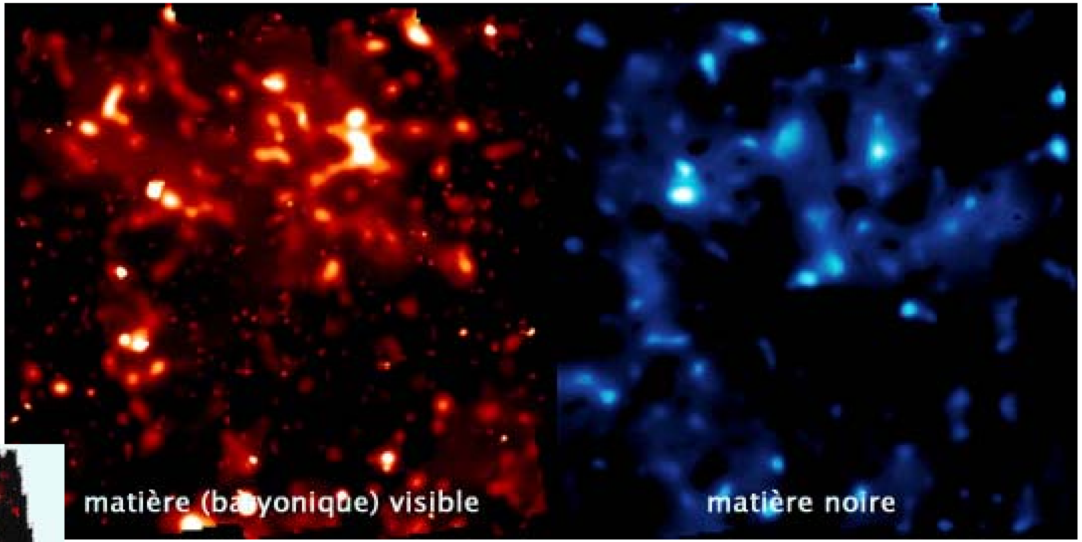
Weak gravitationnal lensing

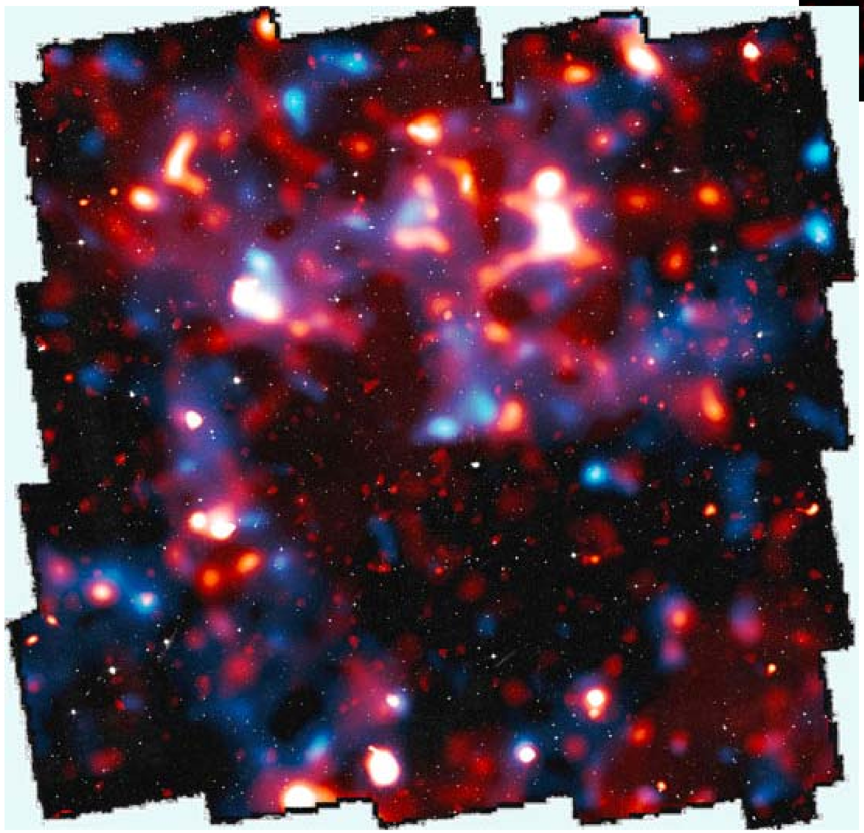


Gravitationnal shear

Red: gas X
Blue: total mass

Cosmos field

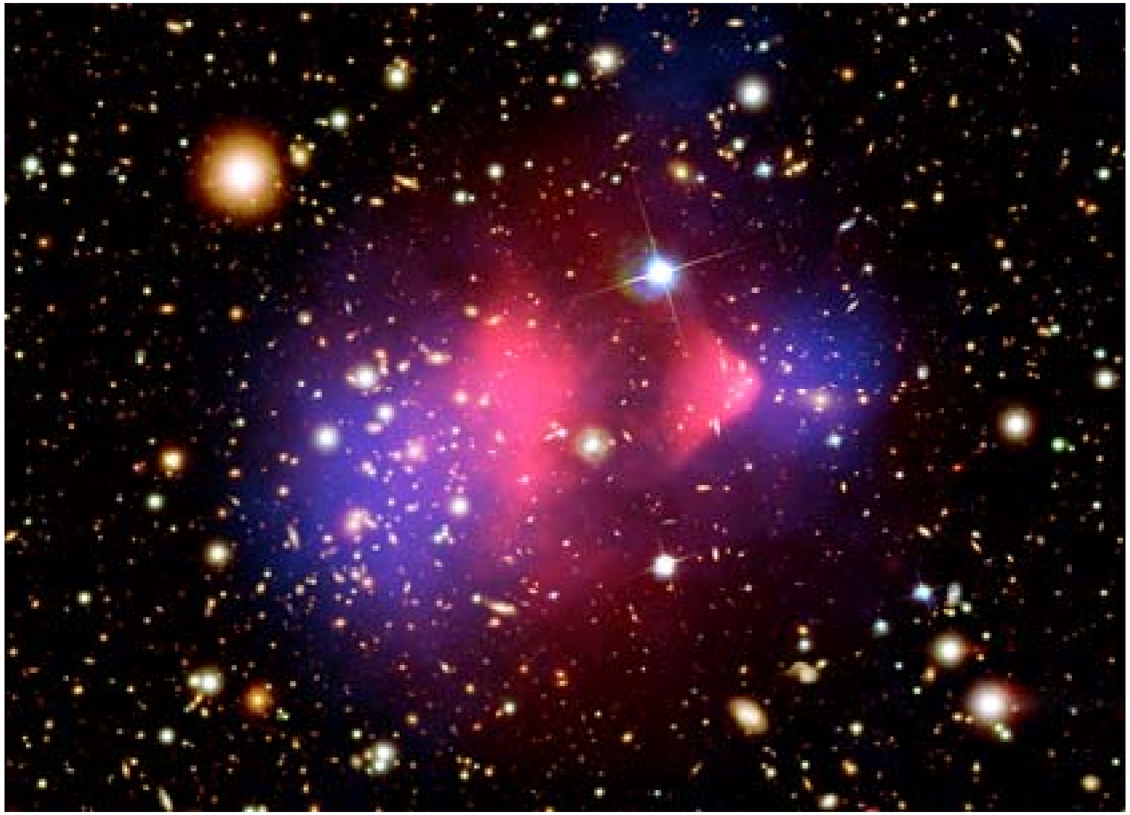




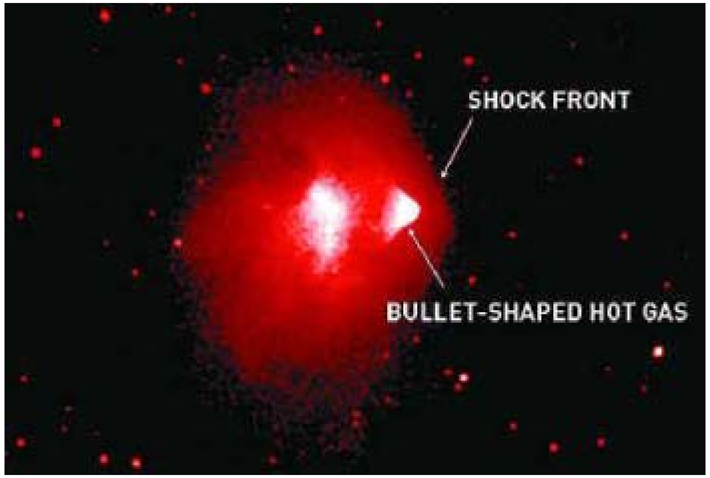
Constraints on the dark matter, and also the dark energy

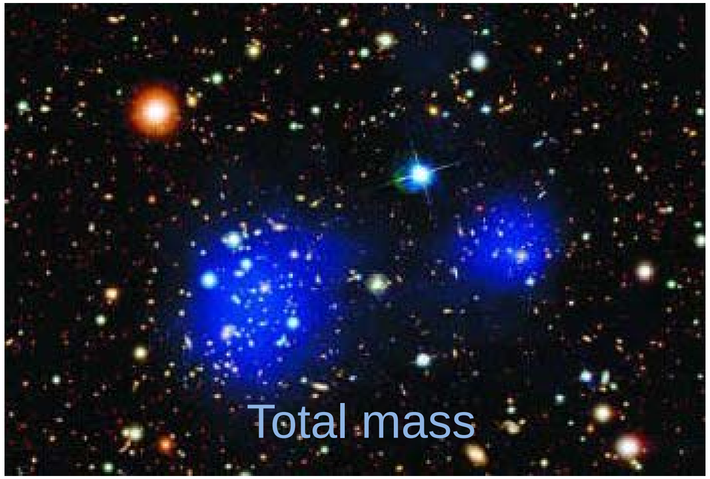
Massey et al 2007

The bullet cluster



Gas X





Proof of the existence of non-baryonic matter

V=4700km/s (Mach 3)

The modified gravity theories the require some other non-collisional matter: neutrinos or dark baryons

Abell 520

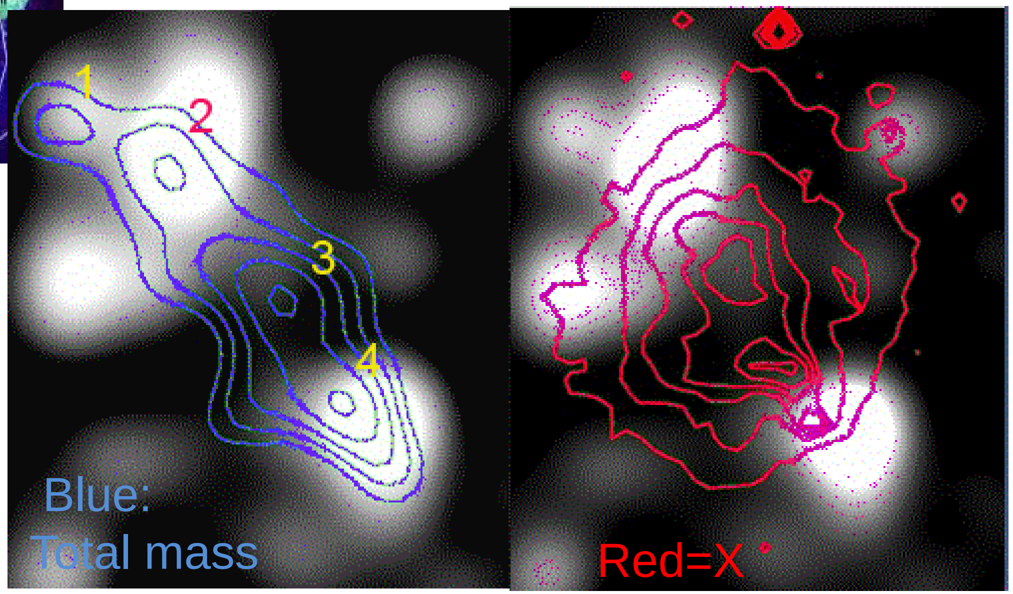
z=0.201

Red = gas X

Contours = lensing (total mass)

➔The dark matter coïncides with the gas X but not with the galaxies

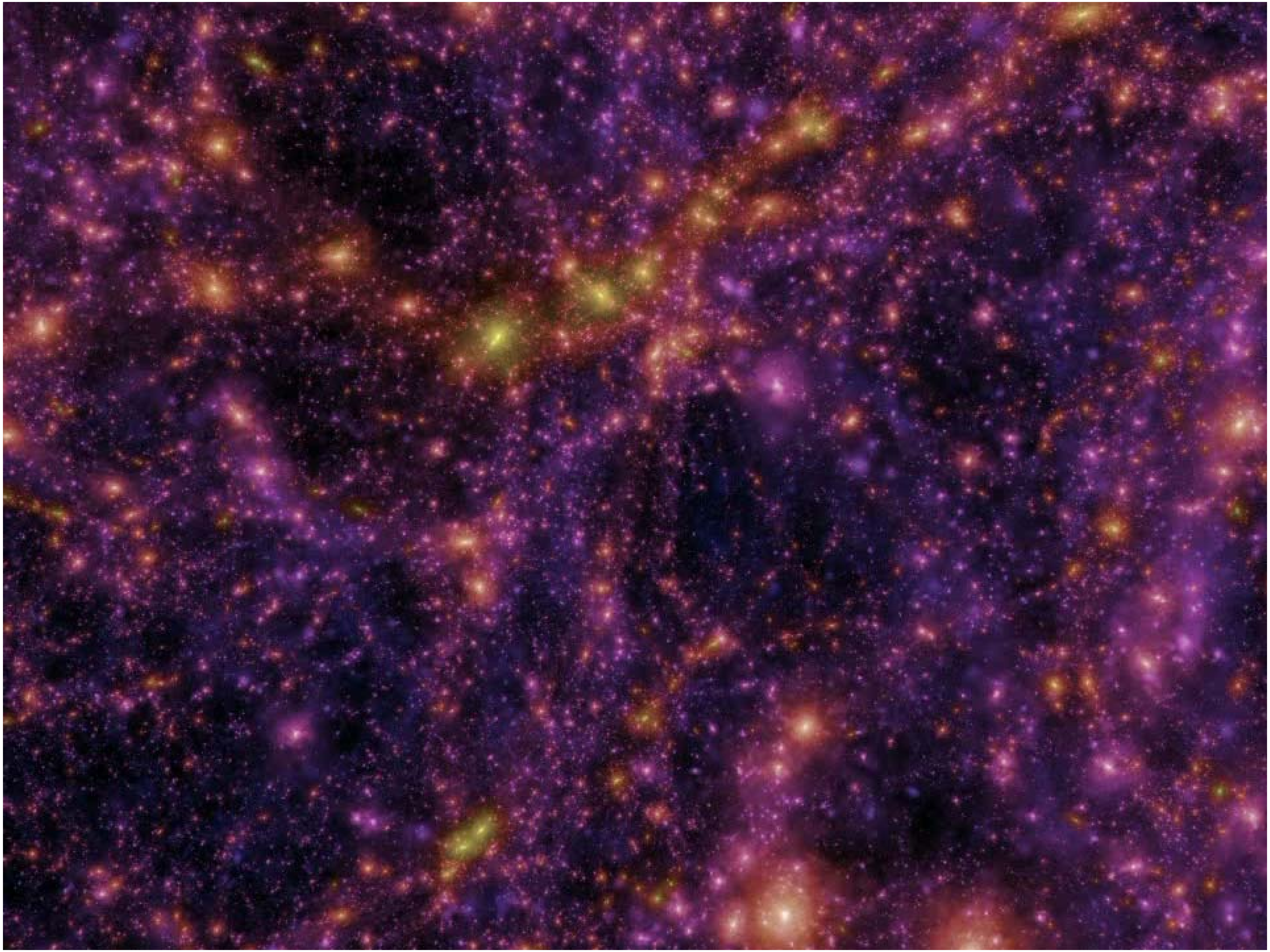
Case opposite to the bullet!

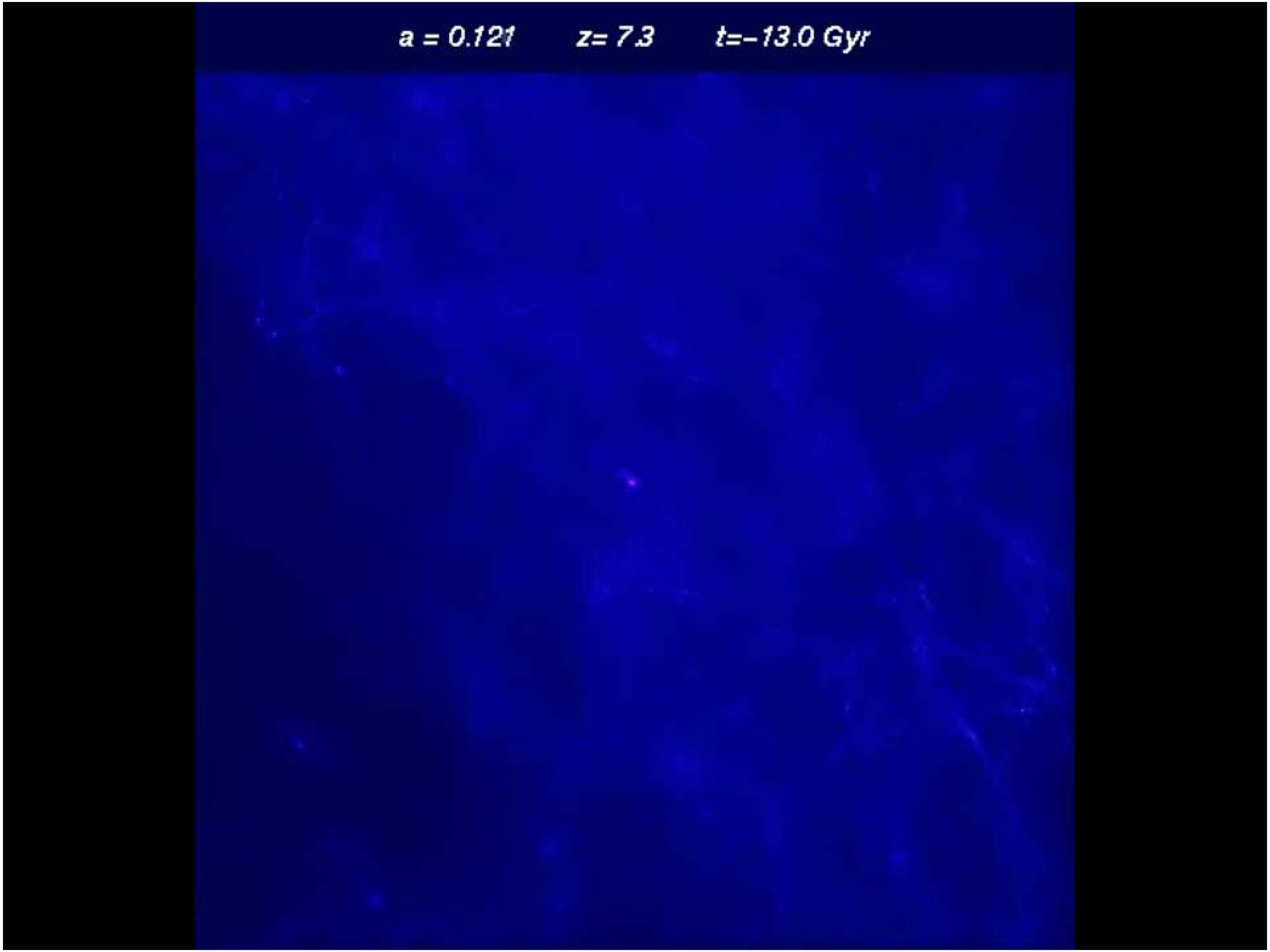


Constraints on the collision cross section of dark matter particles

Mahdavi et al 2007, Clowe et al 2012
Jee et al 2012, Jee et al 2014

Astronomers re-create the Universs

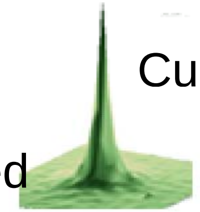



a = 0.121 z= 7.3 t=−13.0 Gyr

Problems of the standard Λ-CDM model

➔**Prediction of cusps in the center of galaxies**, which are not observed in particular in dwarf Irr, dominated by dark matter

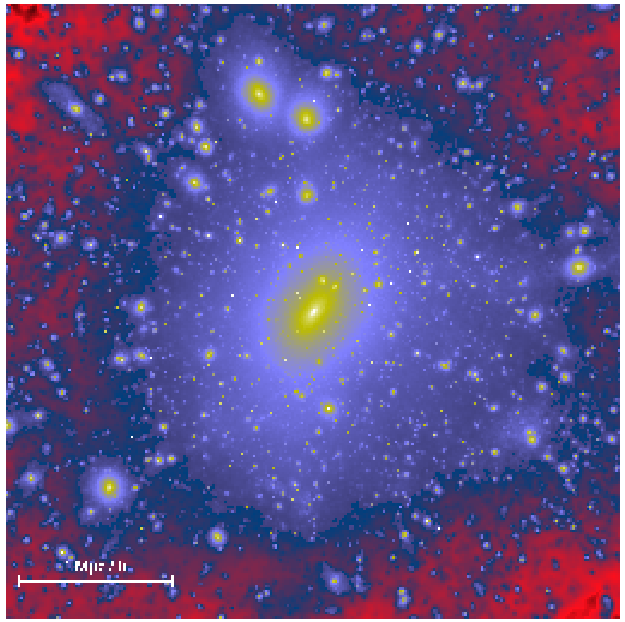
Cusp/core

predicted   observed

The dark matter radial profiles are not universal

➔**Prediction of a large number of small halos (not observed)**

The solution to these problems could come from the lack of realism of physical processes (star formation feedback), from lack of resolution of simulations, or from the nature of dark matter



What are the constituants of the Universe ?

Earth
Air
Water
Fire

Platon Aristote

Baryons, Leptons
Photons, WIMPs
Quintessence ?

©Raphael (1510)

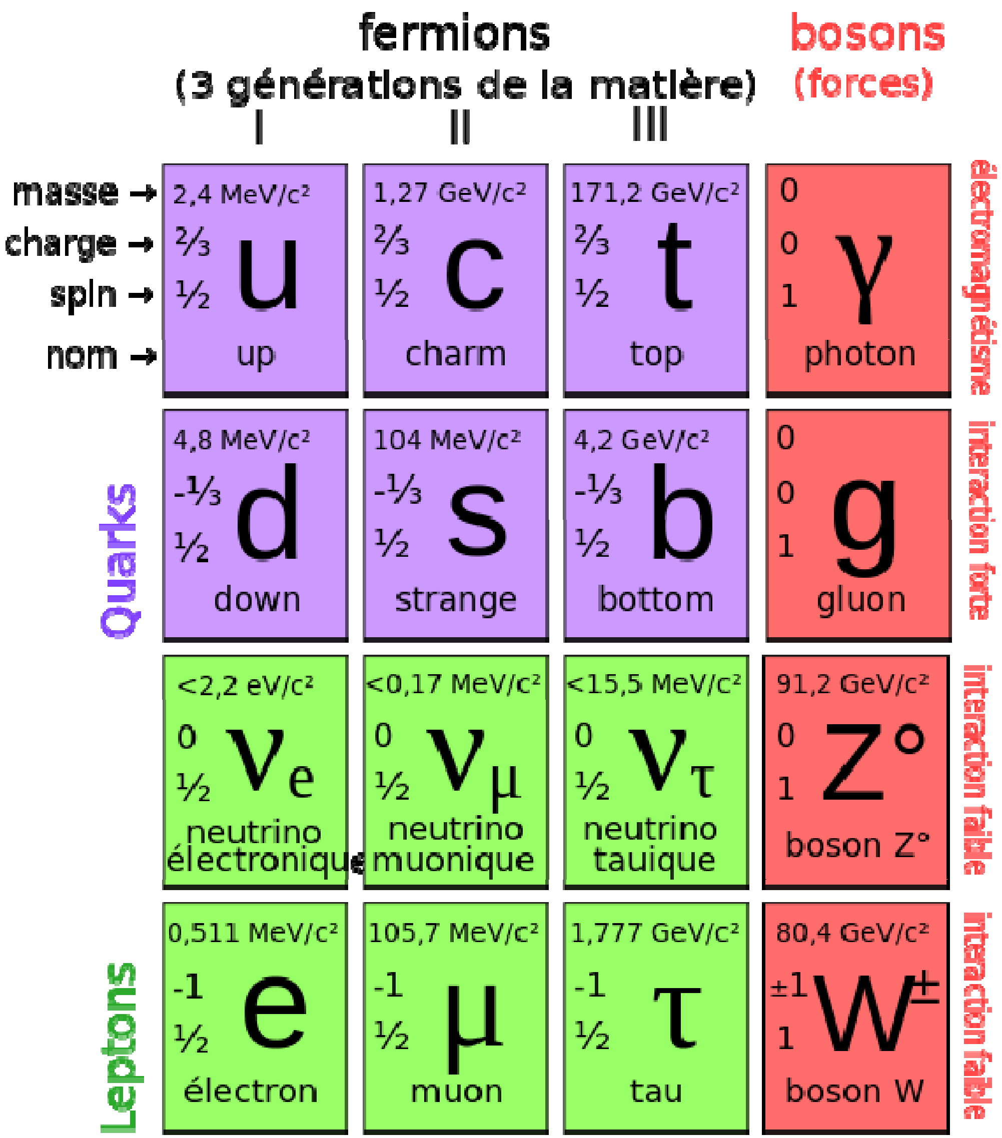
Candidates for the dark matter (DM)

New physics, beyond the standard model SM

DM Kaluza-Klein in UED
DM Kaluza-Klein in RS
Axion
Axino
Gravitino
Photino
SM Neutrino
Sterile Neutrino
Sneutrino
Light DM
DM small Higgs
Wimpzillas
Cryptobaryonic DM
Q-balls

Champs (charged DM)
D-matter
Cryptons
Self-interacting DM
Superweak DM
Braneworld DM
Heavy Neutrino
Neutralino
Messenger states in GMSB
Branons
Chaplygin gas
Split SUSY
Primordial black holes
Mirror Matter
etc…

Particles in the standard model



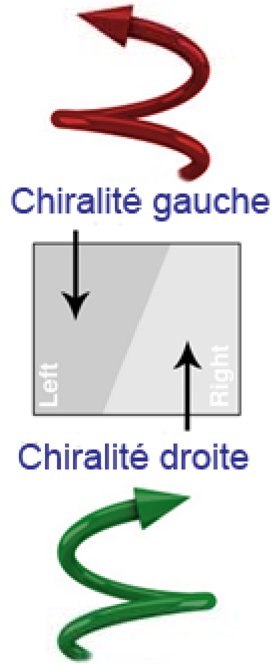
From the Big-Bang

~400 photons /cm^3

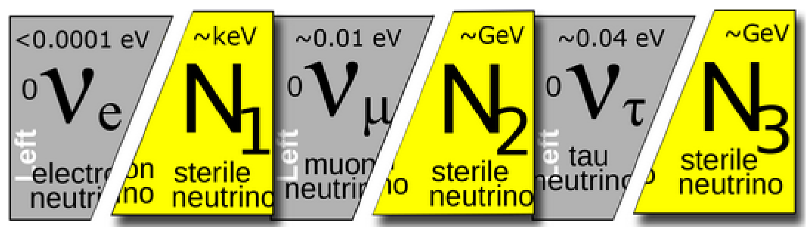
~300 neutrinos /cm^3

0,1 billions of billions per sec crossing you

➔Search for WIMPS since 1985

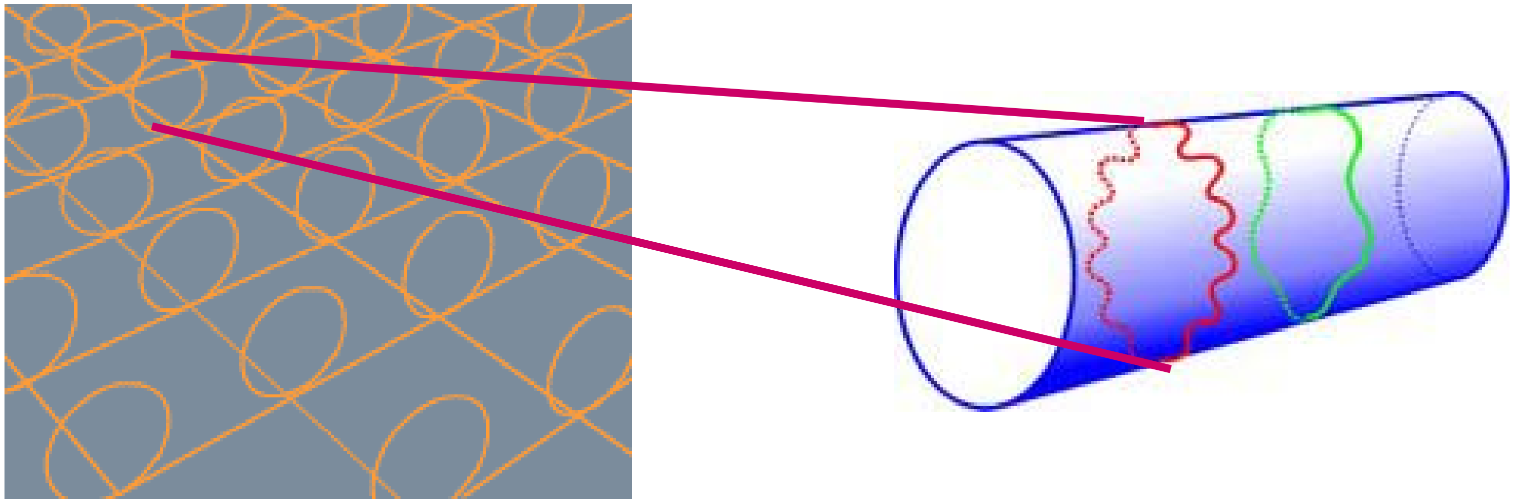


Extension to sterile neutrinos?



Universal extra dimensions

- Kaluza-Klein: extra dimensions



Compactification of the extra dimension in each point

Periodic conditions → quantification of impulsion

Universal: any field propagates in the 5th dimension

The WIMP miracle

It is possible to obtain the required abundance of dark matter with particles of mass **~100 GeV,** interacting with the weak force
Annihilation cross section **$<\sigma v>$ ~3 10^{-26} cm^3/s**

The abundance of particles is « frozen », they are decoupled when their interaction rate **n $<\sigma v>$ ~1/t_{hubble}**
They can still be created spontaneously as far as $mc^2 < kT$
Their relic density can be computed by
$\Omega = 6\ 10^{-27}\ cm^3/s\ /\ <\sigma v>$ **~0.2** for $<\sigma v> = 3\ 10^{-26}\ cm^3/s$

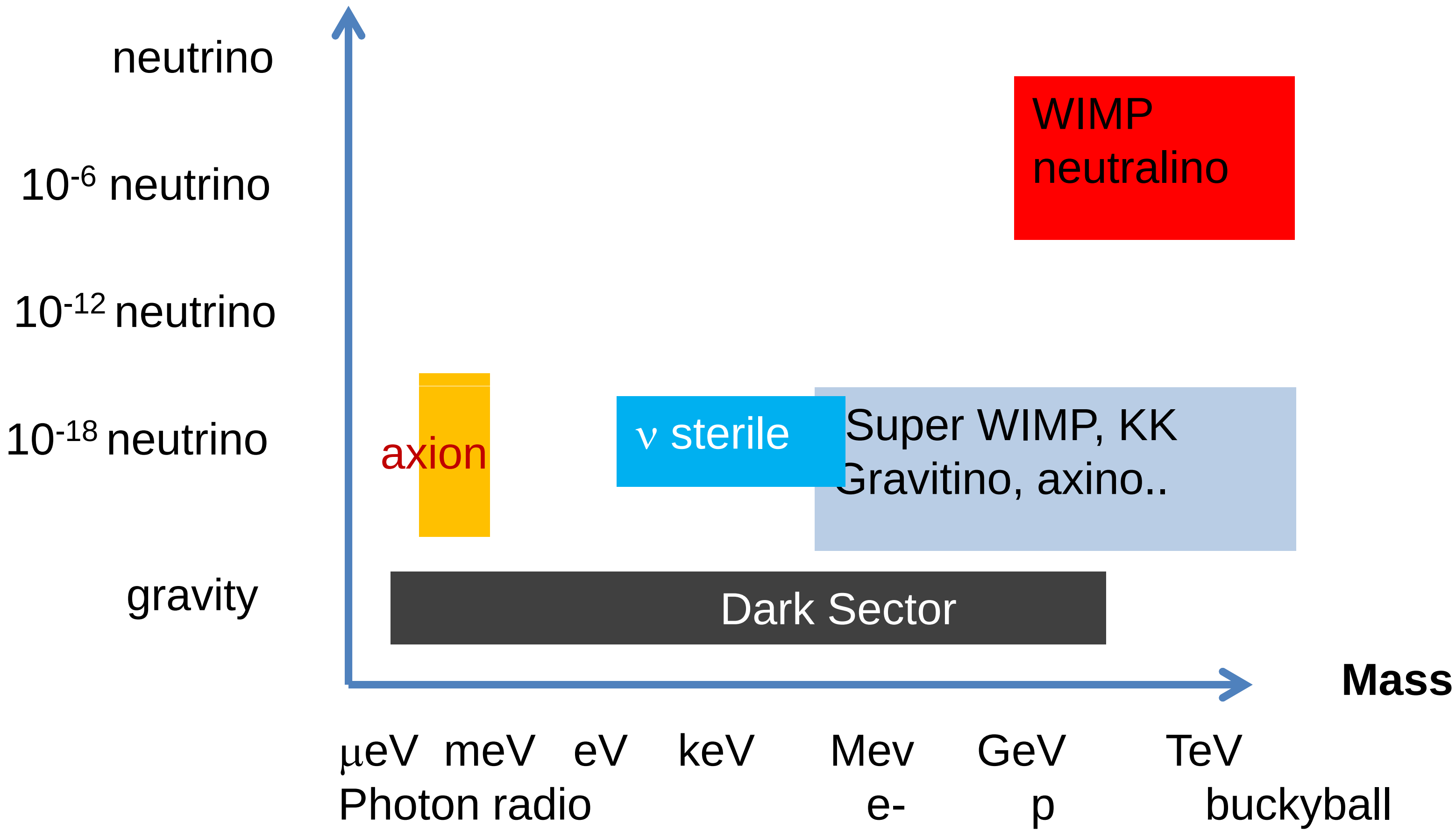
Coincidence: this corresponds to the lightest particle in the super-symmetric model (neutralino)

Which interaction?

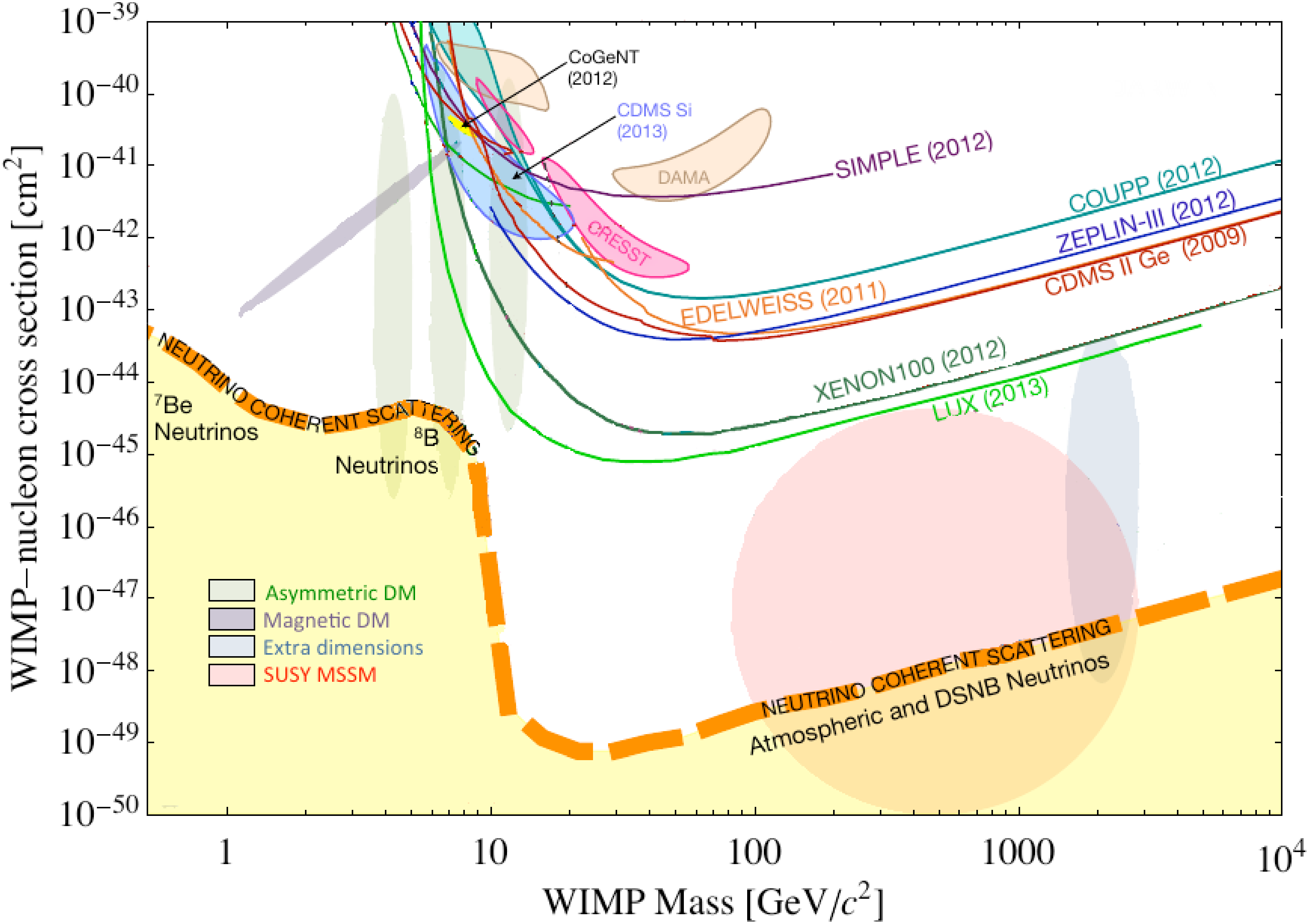
Mass domain > 20 orders of magnitude

Force of the interaction

Axions (solution to the problem of the CP-symmetry)– Primordial black holes?

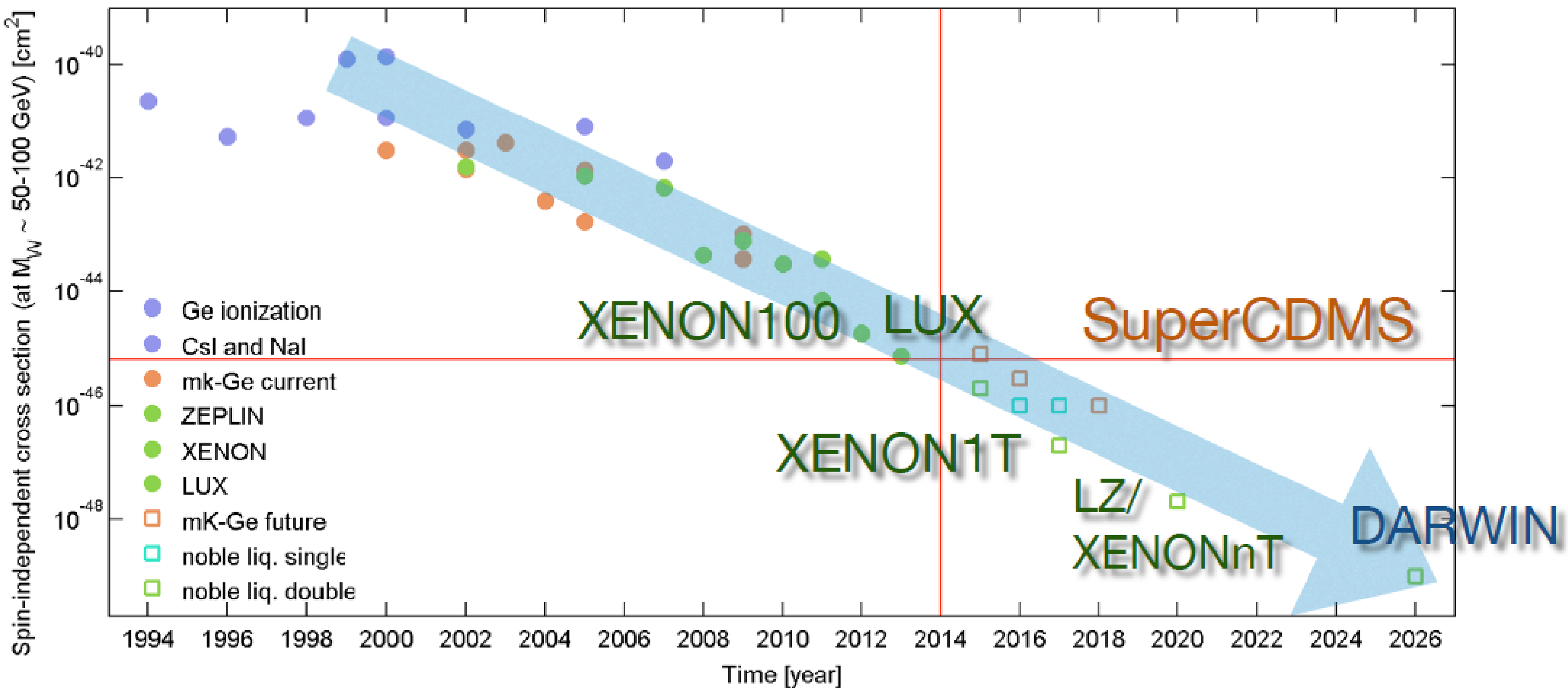


Detection limits



Future and Perspectives

Gain about a factor **10 *every 2 yrs***
Detection may be in 2026…



The Confucius cat (or the hunt for ghosts)

To catch a black cat in the obscurity of a dark night is the most difficult task
especially when there is no cat

MOND = Modified Newtonian Dynamics

At weak acceleration

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

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

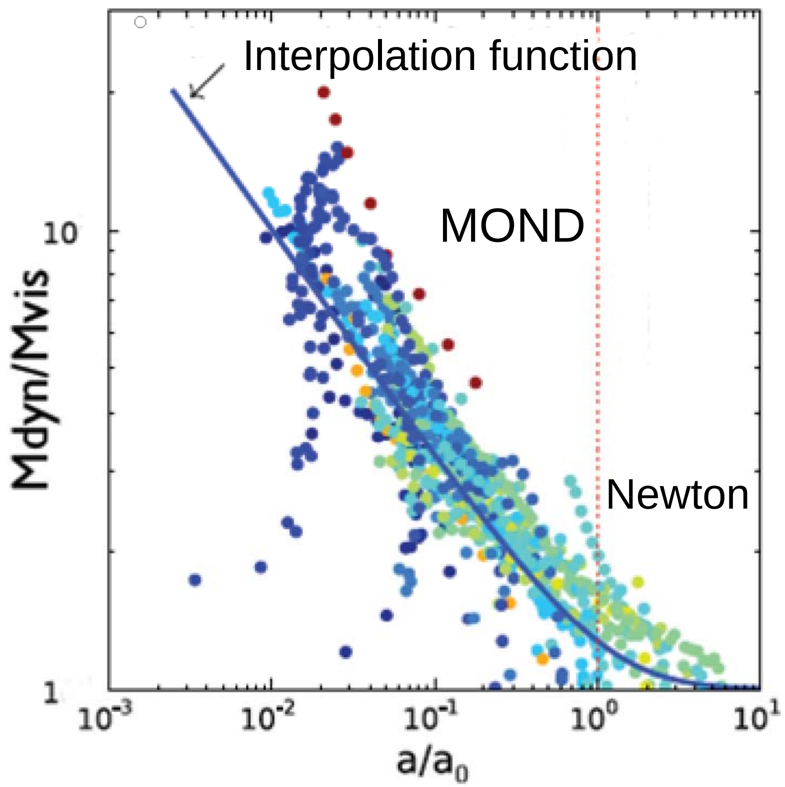
$a_0 = 1.2\ 10^{-10}\ m/s^2 \sim 10^{-11} g$
Milgrom (1983)

Asymptotically

$a_N \sim 1/r^2$ ➔ $a \sim 1/r$ ➔ $V^2 = cste$

Covariant Theory: TeVeS
➔Gravitationnal lensing

Mdyn/Mvis = f(a_N/a0)

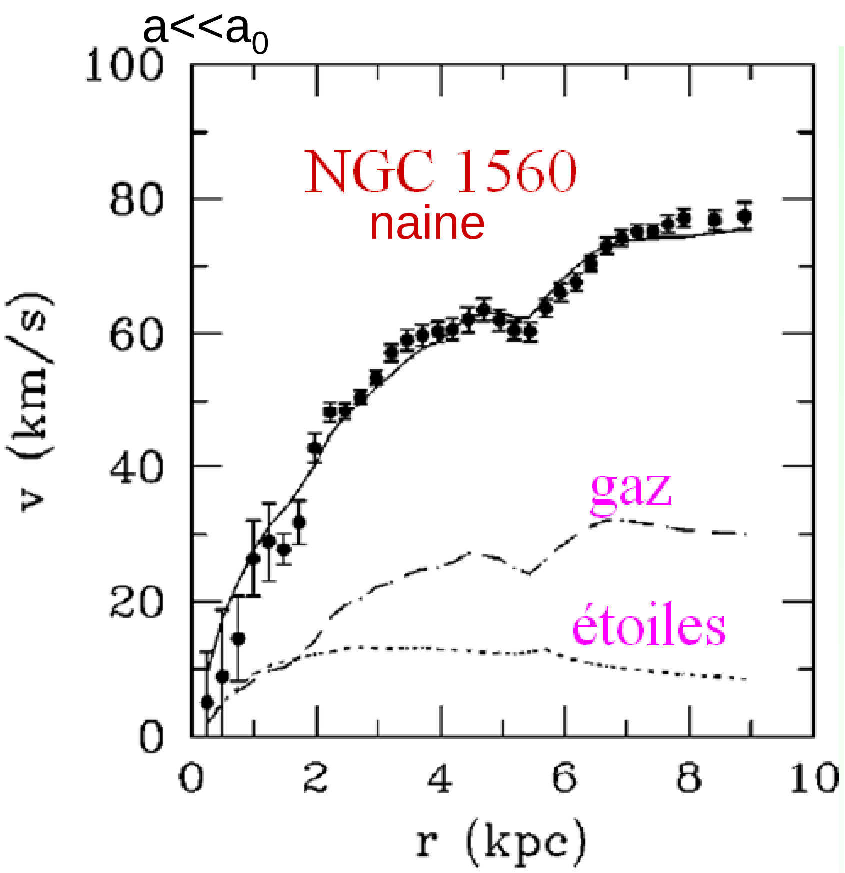


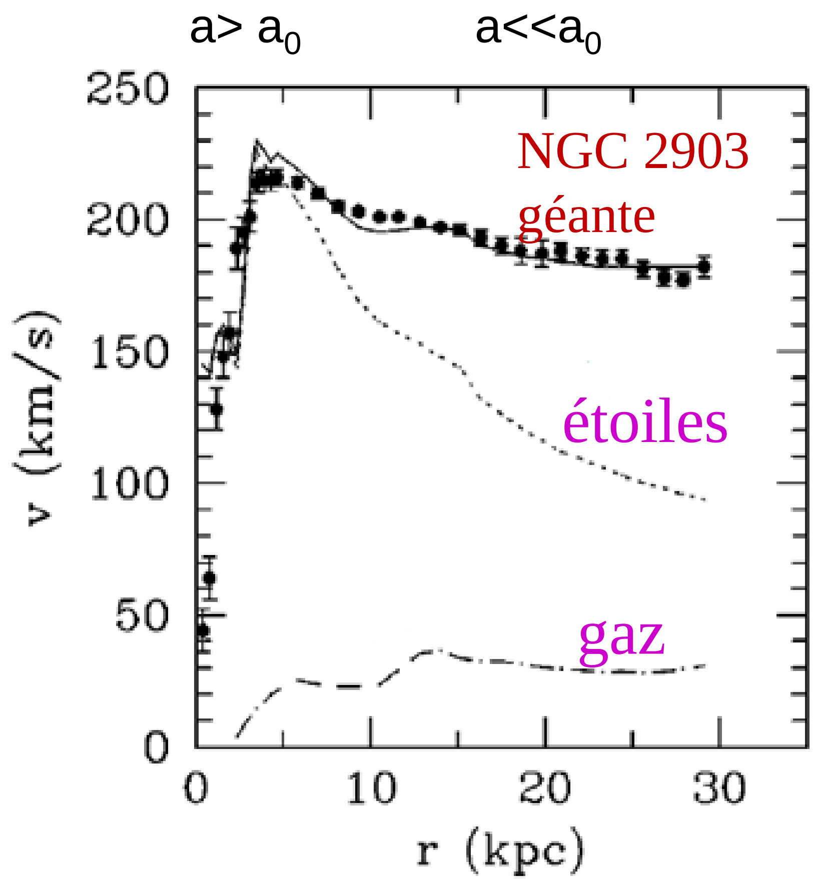
$$\nabla \cdot [\mu(|\nabla\phi|/a_0)\nabla\phi] = 4\pi G\rho$$

New Poisson equation

Rotation curves with MOND

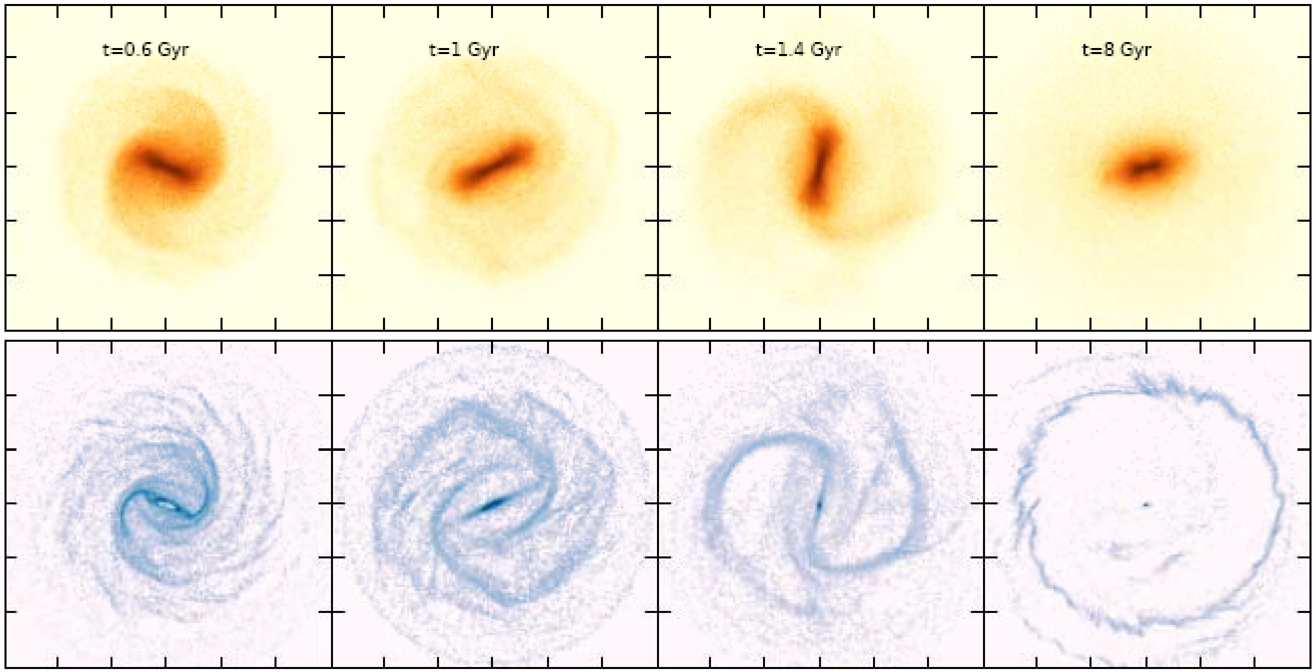
The rotation curves are reproduced for any galaxy type (dwarfs, giants)





Influence of the dark halo

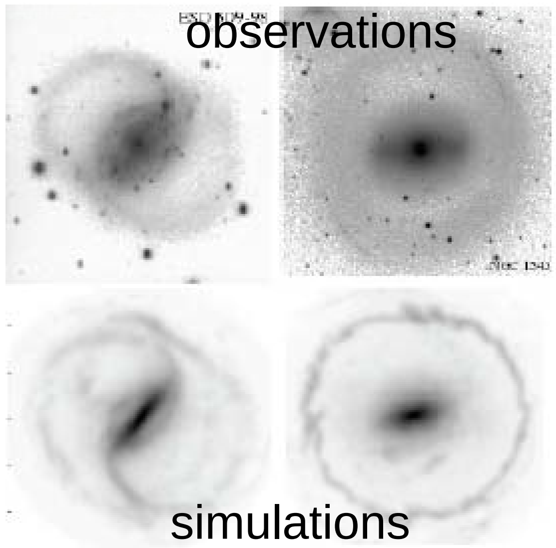
Dynamics of galaxies,
Formation of spirals and bars



Stars

Gas

observations



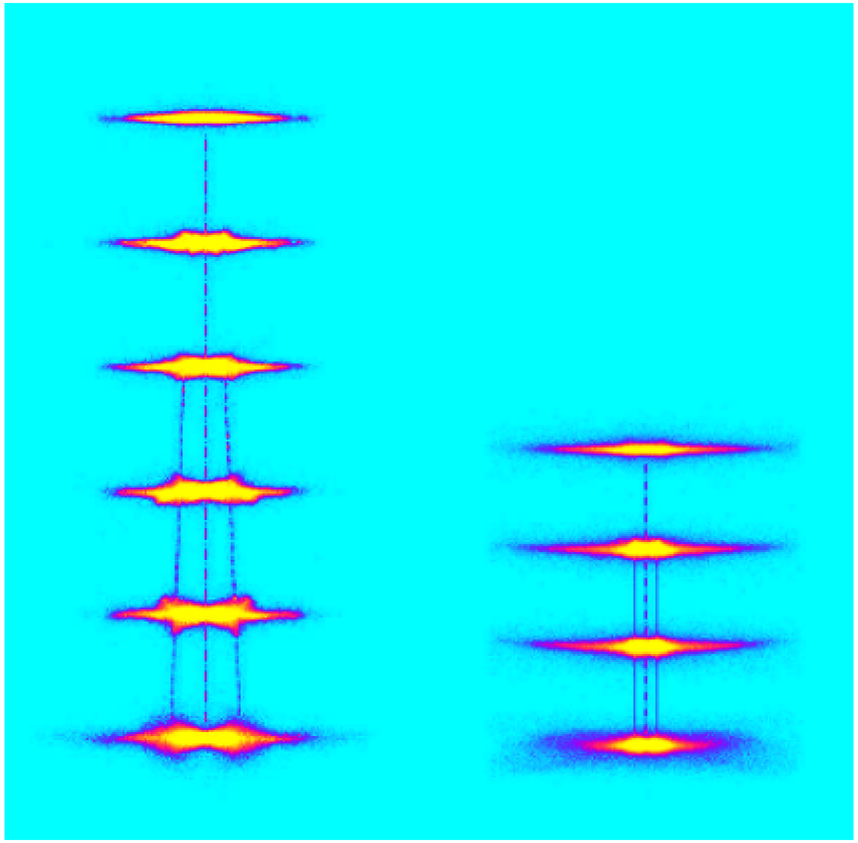
simulations

Rings at resonances
➔ Yield the bar pattern speed

Tiret & Combes 2007

Strength and speed of the bar with and without DM

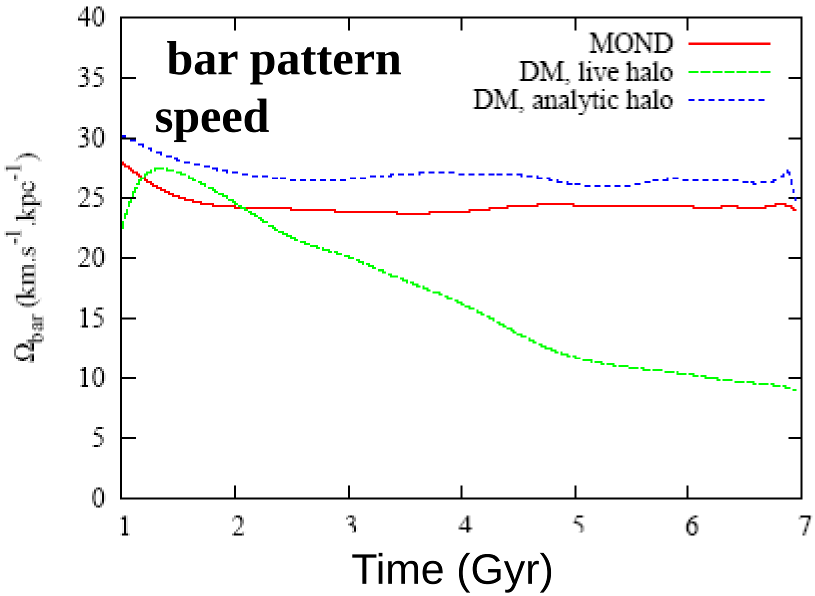
With DM   Without DM (MOND)



Dynamical friction much larger in presence of DM

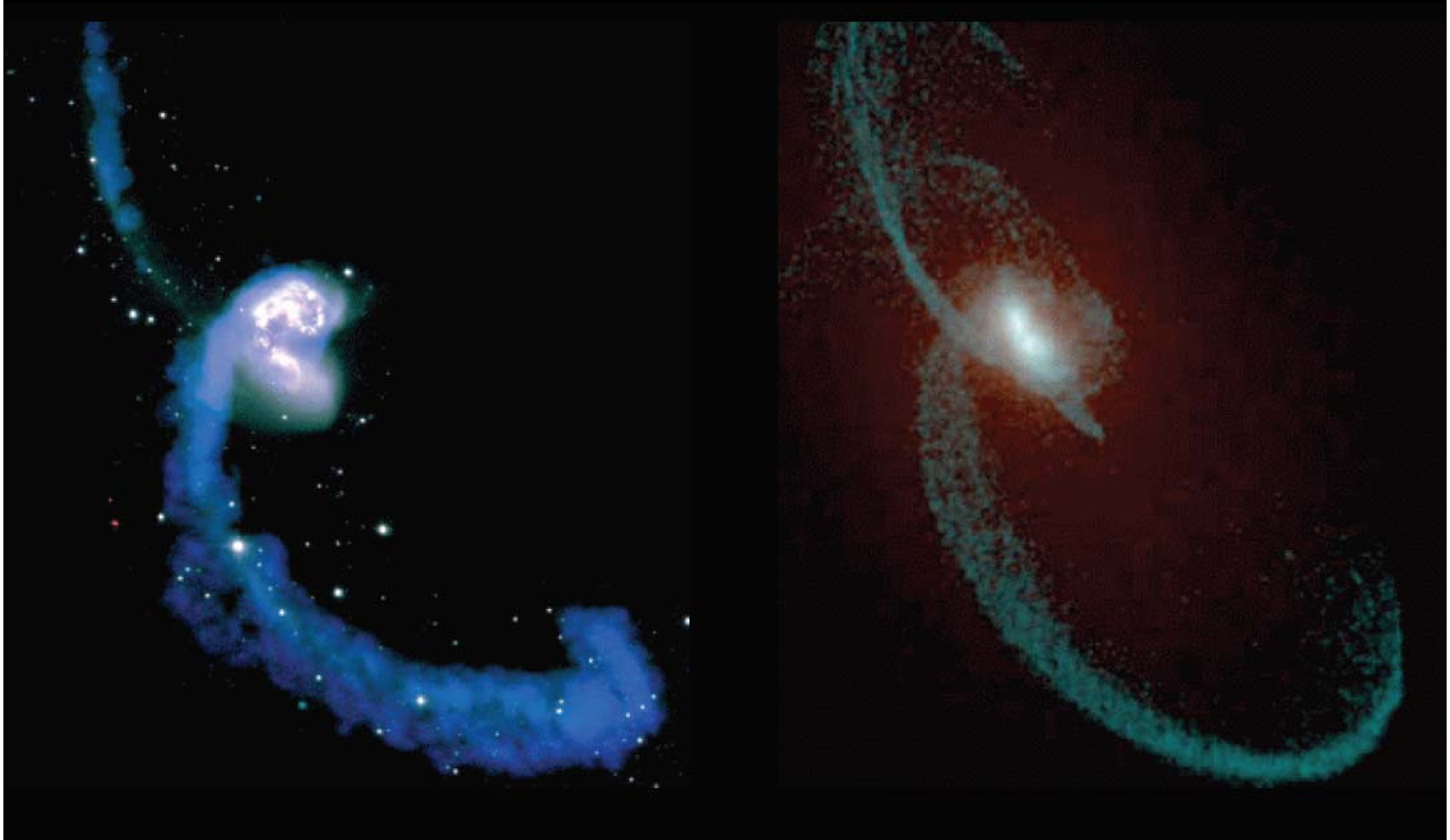
Slowing down of the bar

➔ Different vertical resonances



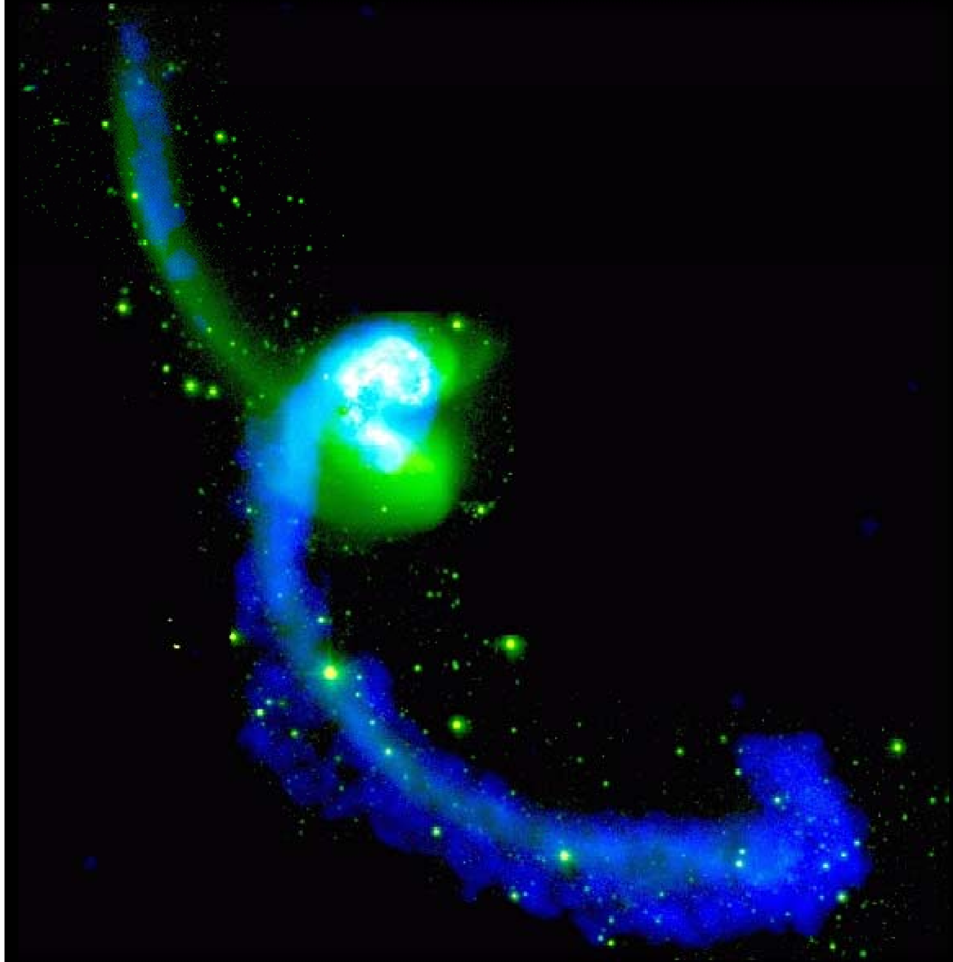
Tiret & Combes 2007

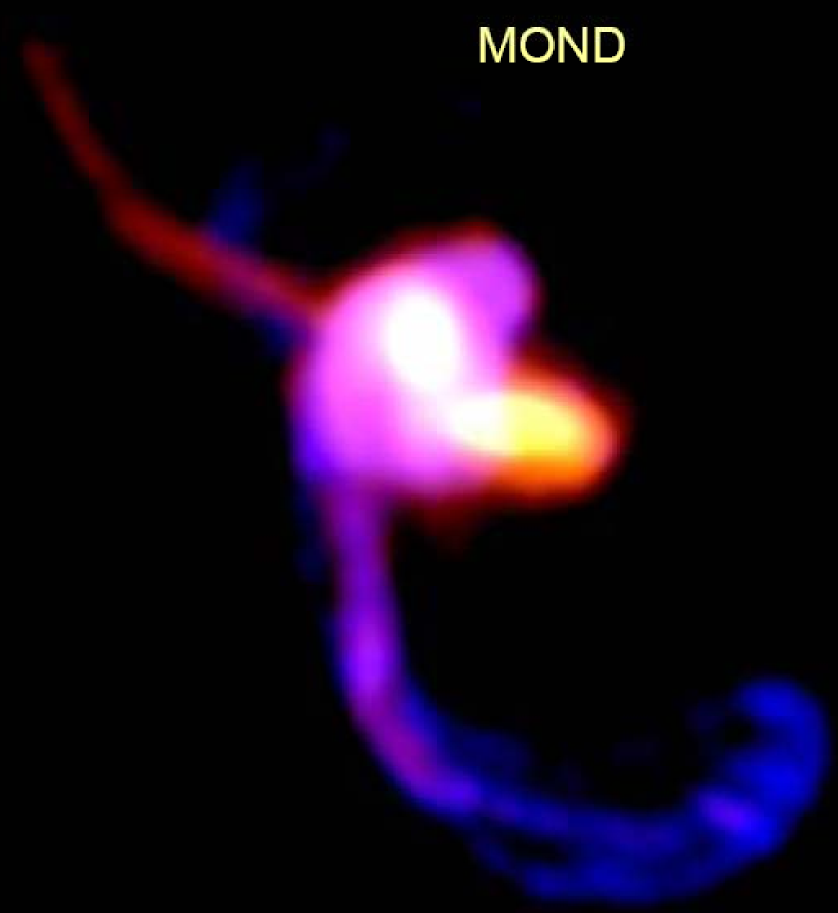
Simulations of Antennae



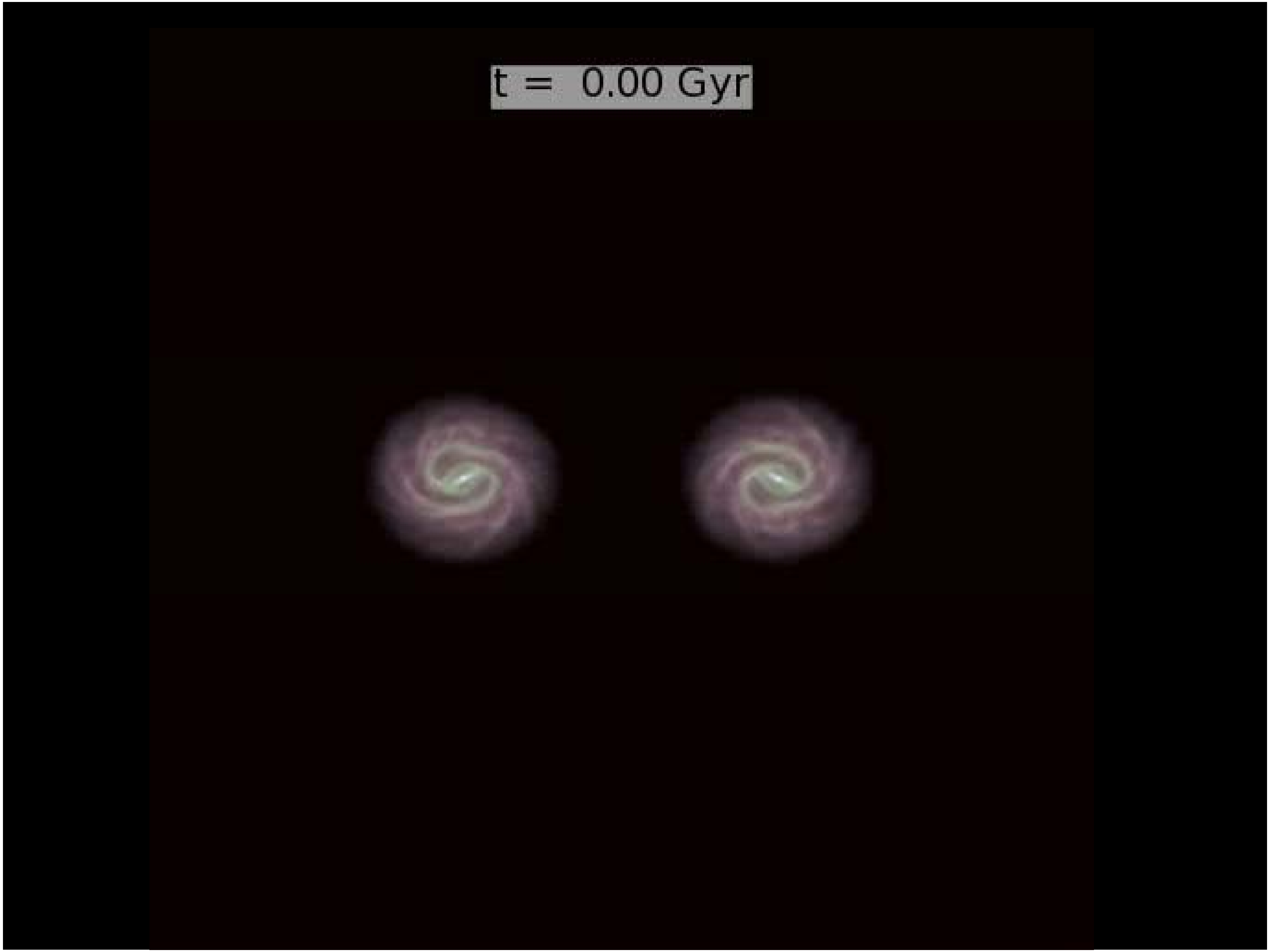
Simulations with DM (Barnes 1998)

Simulations of Antennae



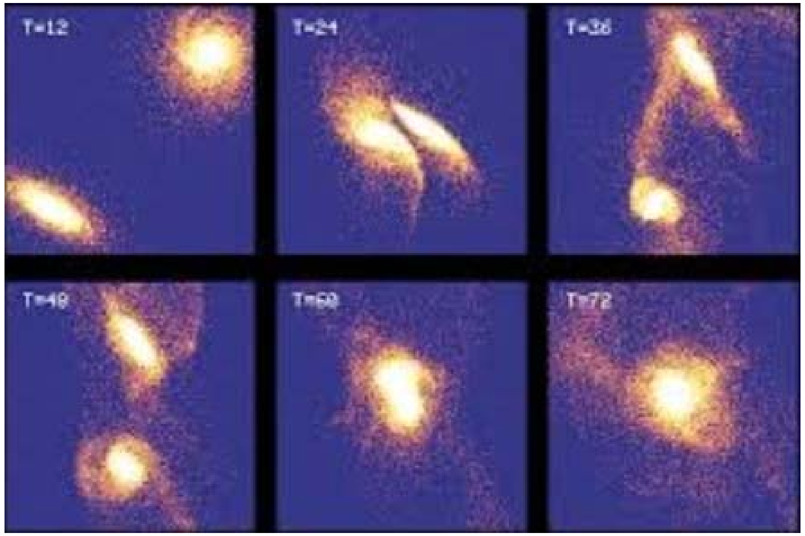


Tiret & Combes 2008

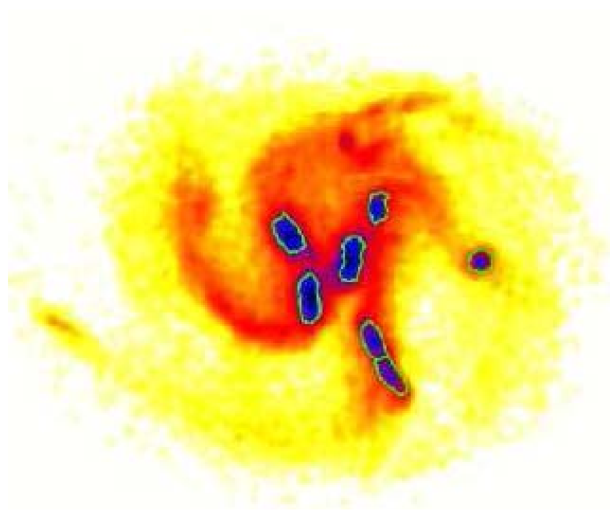

t = 0.00 Gyr

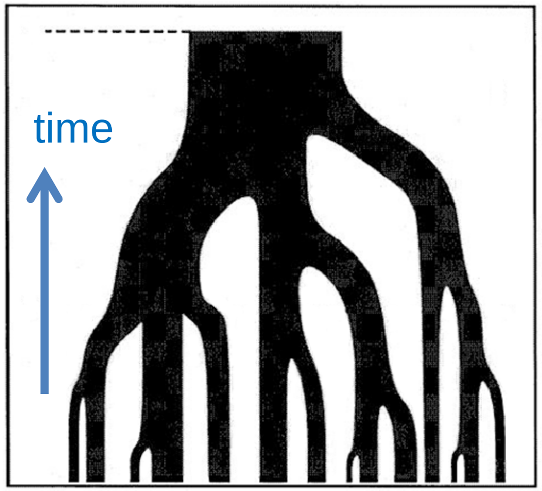
Formation of bulges

Formation by galaxy mergers
Major and minor mergers

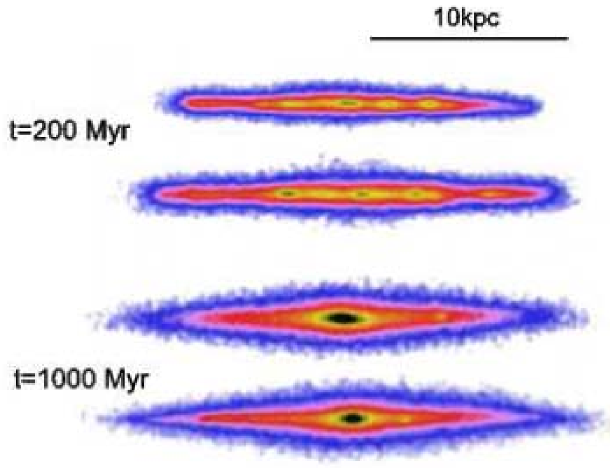


Clumpy galaxies





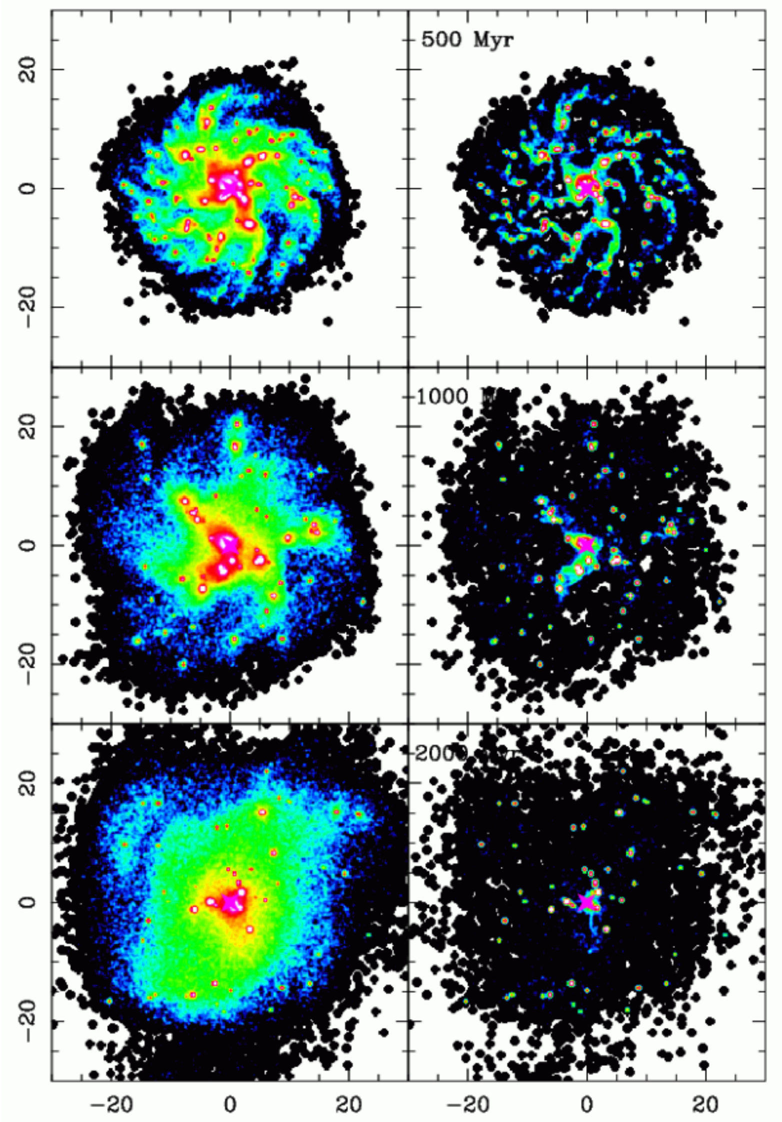
Cancellation of angular
 momentum after
multiple mergers



Bournaud et al 2007

Formation of galaxies without bulge ?

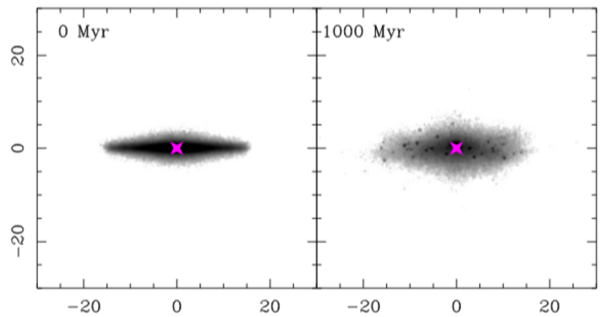
evolution MOND



Young galaxies 50% of gas,
➔form clumps of gas and stars

Absence of dark matter
➔Weak dynamical friction
Clumps are dispersed by star formation feedback before arriving to the center

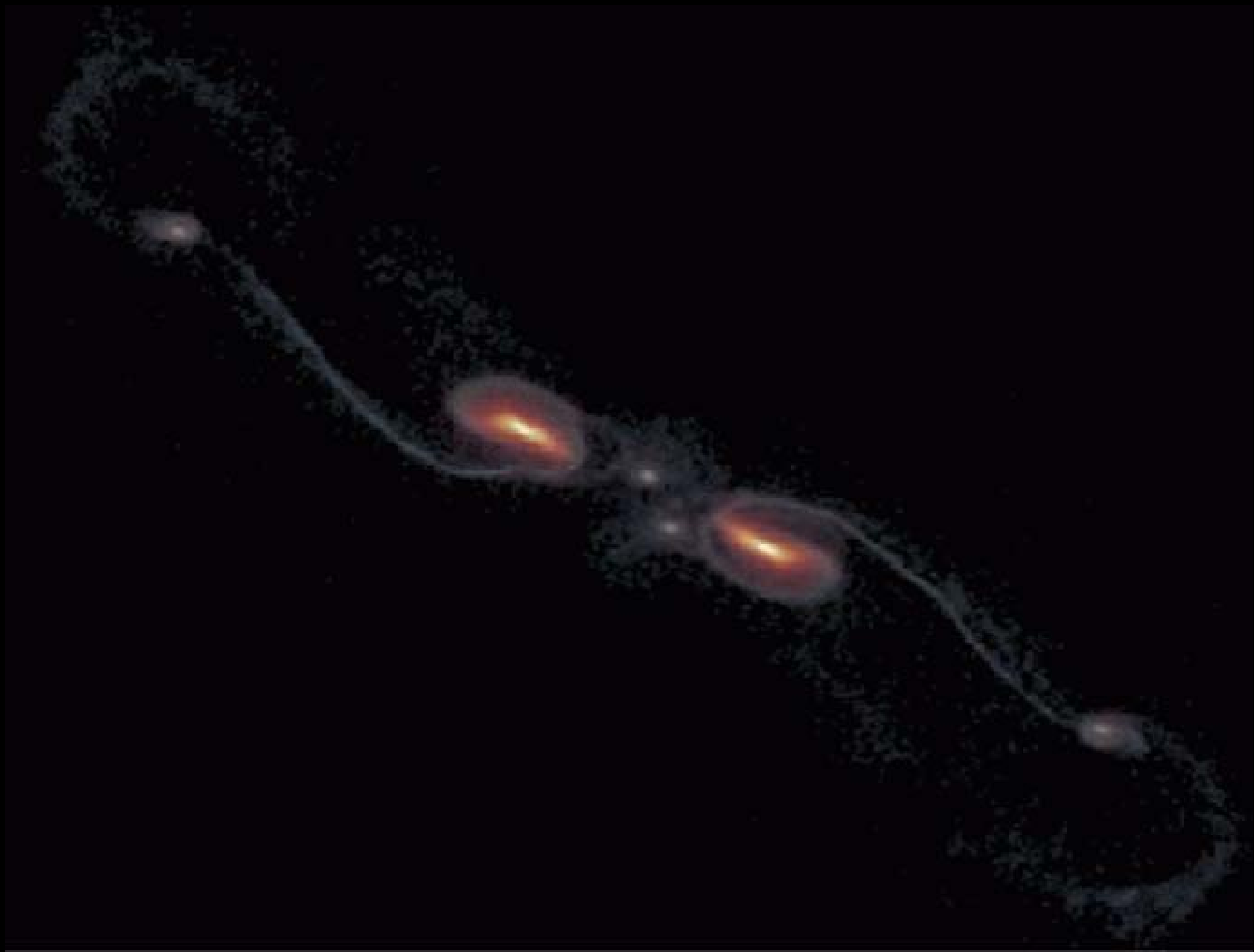
Formation of bulge (Newton)



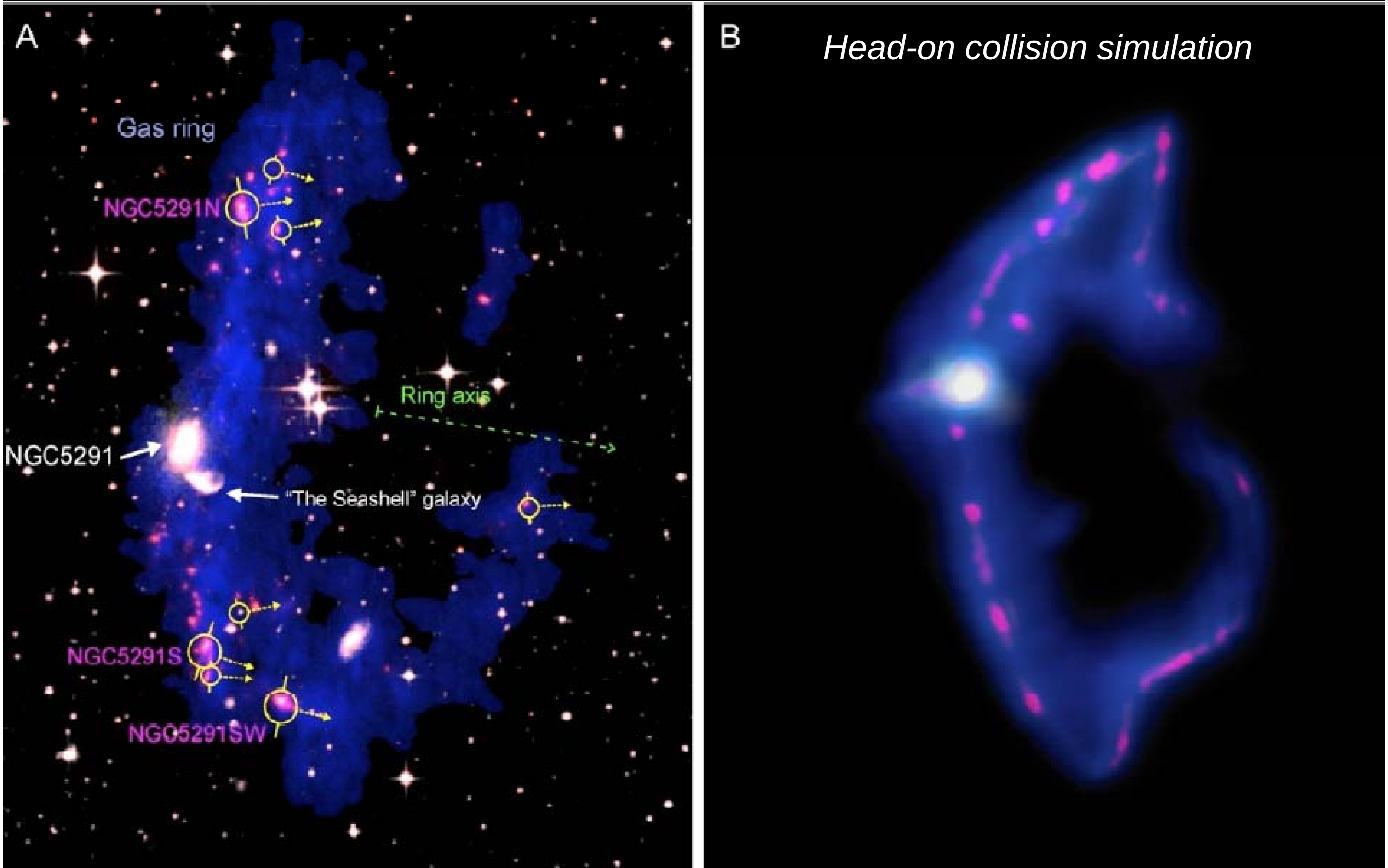
Combes 2014

Formation of Tidal Dwarf Galaxies

Exchange of angular momentum in the disk:
➔easier with MOND to form tidal dwarfs



Tidal dwarfs in NGC 5291

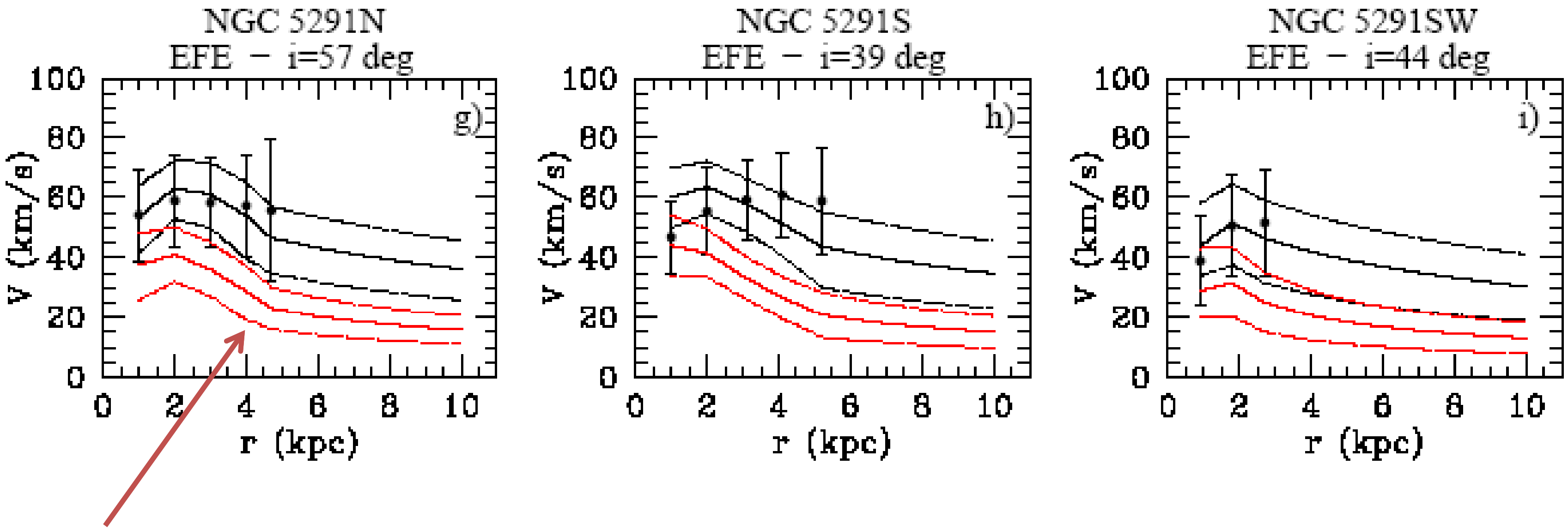


Bournaud et al 2007

Dynamics of tidal dwarfs

These dwarf galaxies, formed very late, should not possess any dark matter, in the standard model

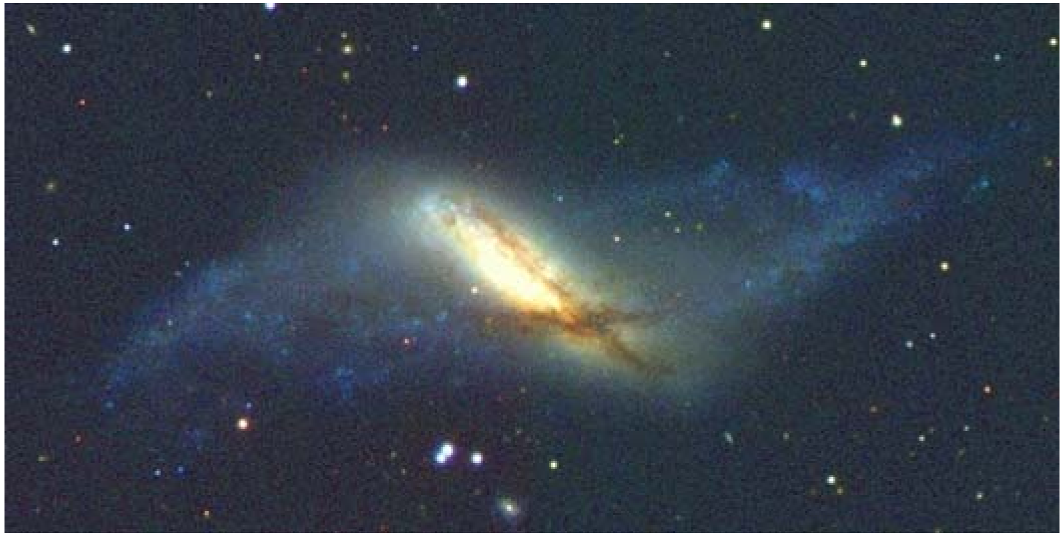
However observations reveal **flat rotation curves**
➔**Natural for MOND**

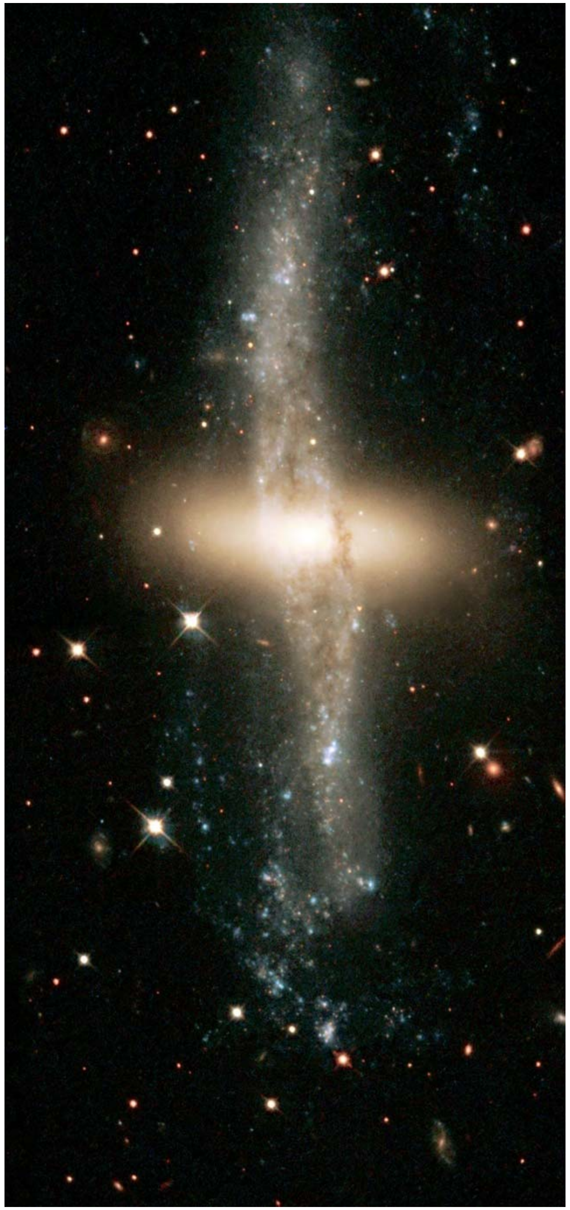


Red: predictions of the standard DM

Gentile et al 2007

Polar rings and cosmic accretion

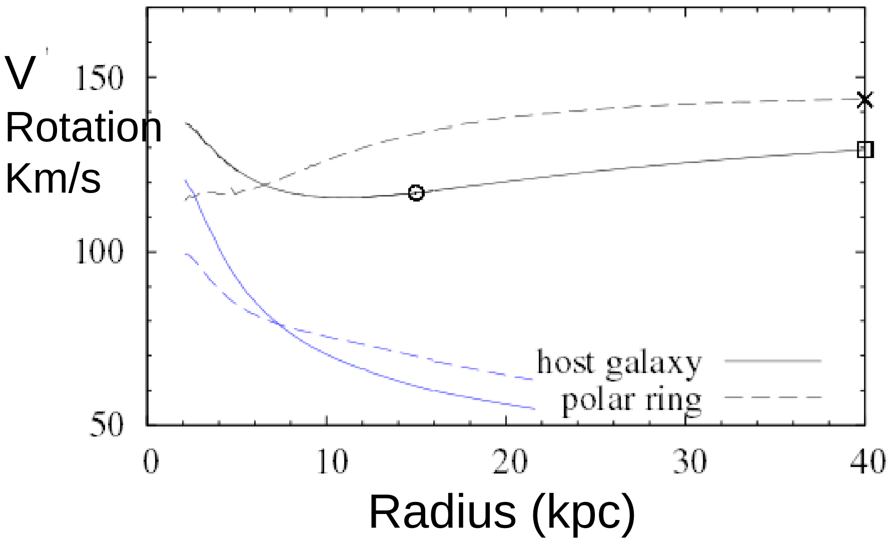




➔Polar rings are an opportunity to test the 3D distribution of dark matter

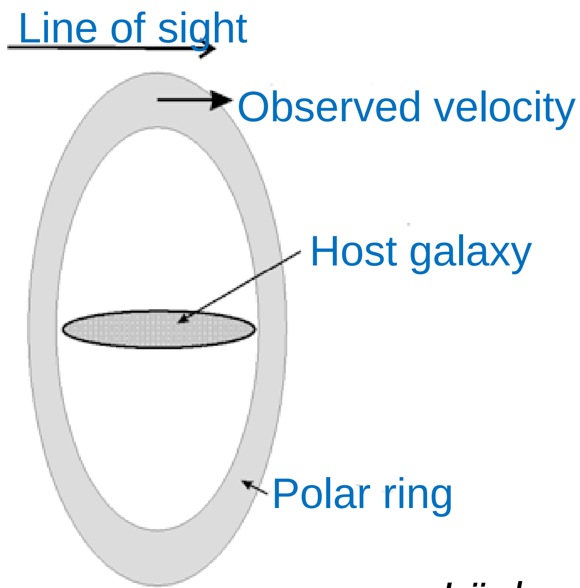
➔The rotation velocity is higher in the polar disk, with respect to the equatorial disk

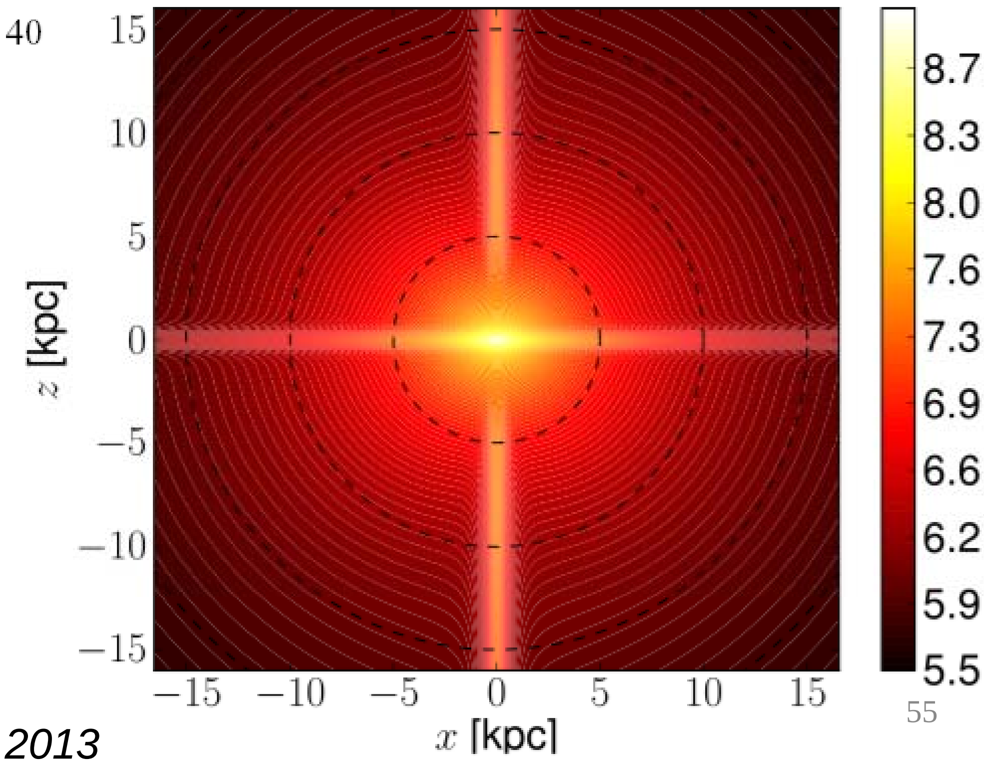
Polar rings with MOND



➔Larger velocity in the polar disk obtained naturally

Map of the « ghost » equivalent dark matter





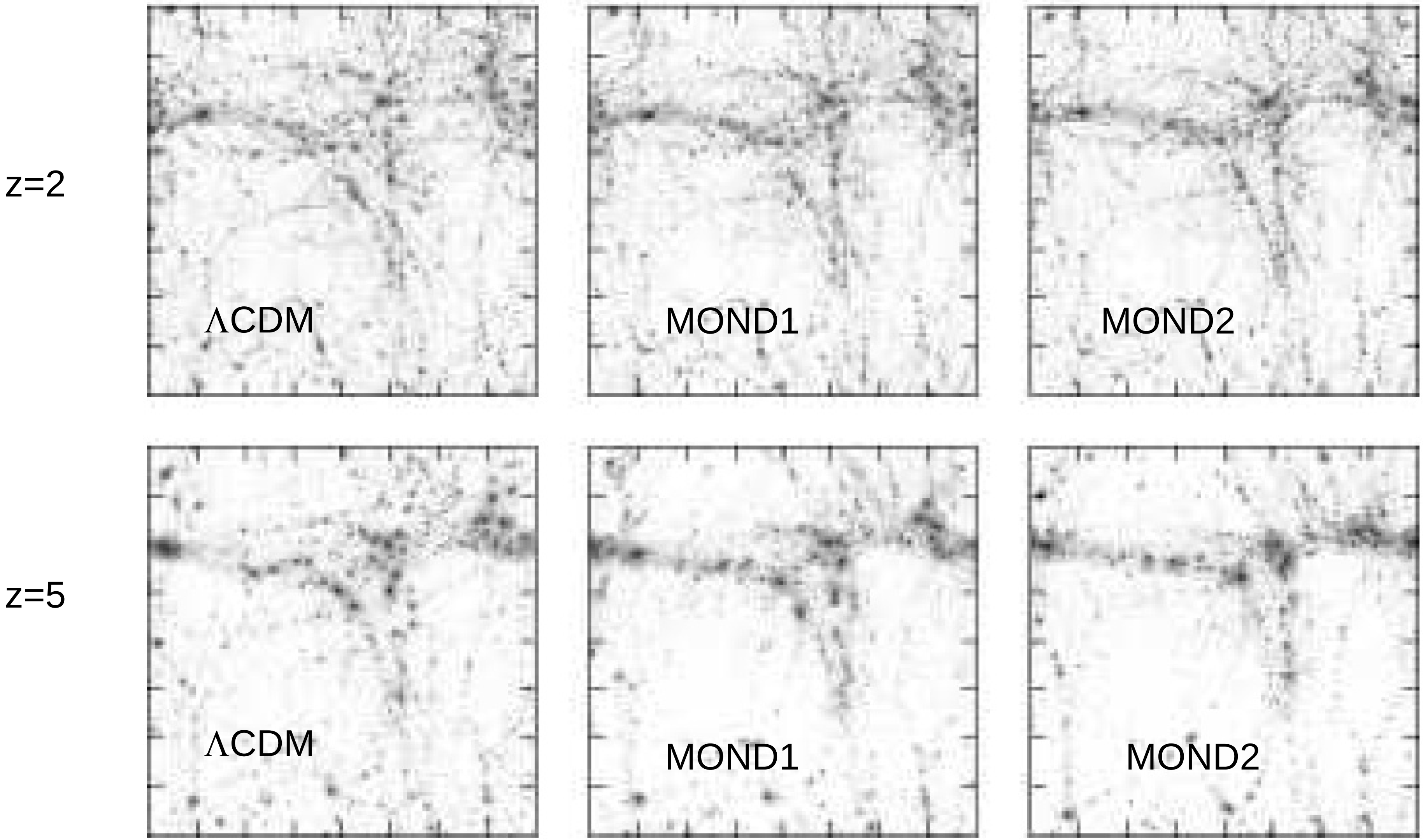
Lüghausen et al 2013

MOND cosmological simulations

Start z=50, dissipation-lss matter, 2 models vs standard ΛCDM

Earlier formation of structures

Llinares et al 2009



Universe content: what is it?

The visible part, galaxies = **0.3%** of the total
Dark baryons: very hot gas ? Very cold gas ?

Non-baryonic dark matter:
Particles still unknown, beyond the standard model
Masses between 10^{-6} eV (axions) and 10^{12} eV (WIMPs)
Searched for since **30yrs**

Problems of dark matter models for galaxy formation & evolution
-- solution to be found in **baryonic physics**
-- **or modified gravity**, 5^{th} force, could also solve the problem of dark energy