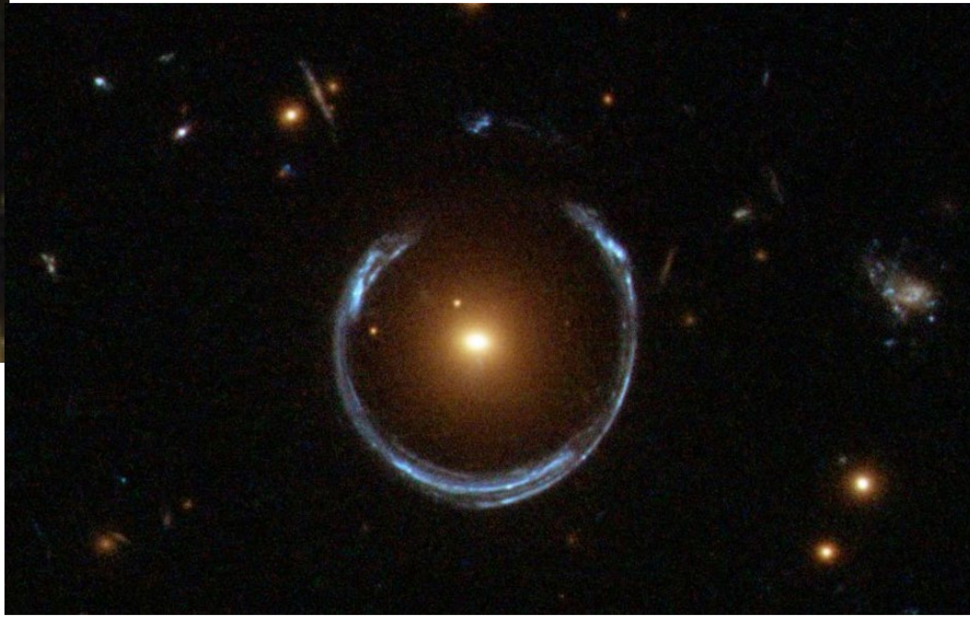
Dark matter in the Universe

COLLÈGE DE FRANCE 1530

Chaire Galaxies et Cosmologie



LRG-3-75: cosmic horse-shoe

Françoise Combes

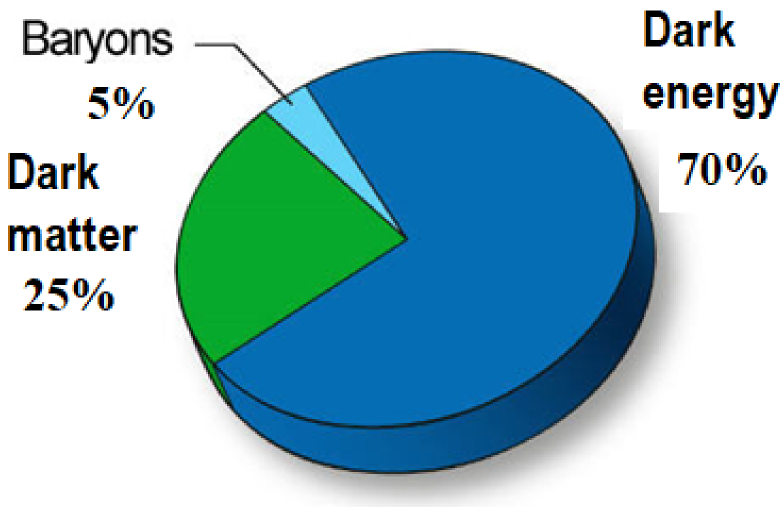
March, 2022

l'Observatoire de Paris

LERMA

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

The content of the Universe



Average density of the Universe
$\rho_c \sim 10^{-29}$ g/cm^3

$\Omega = \rho/\rho_c = 1$

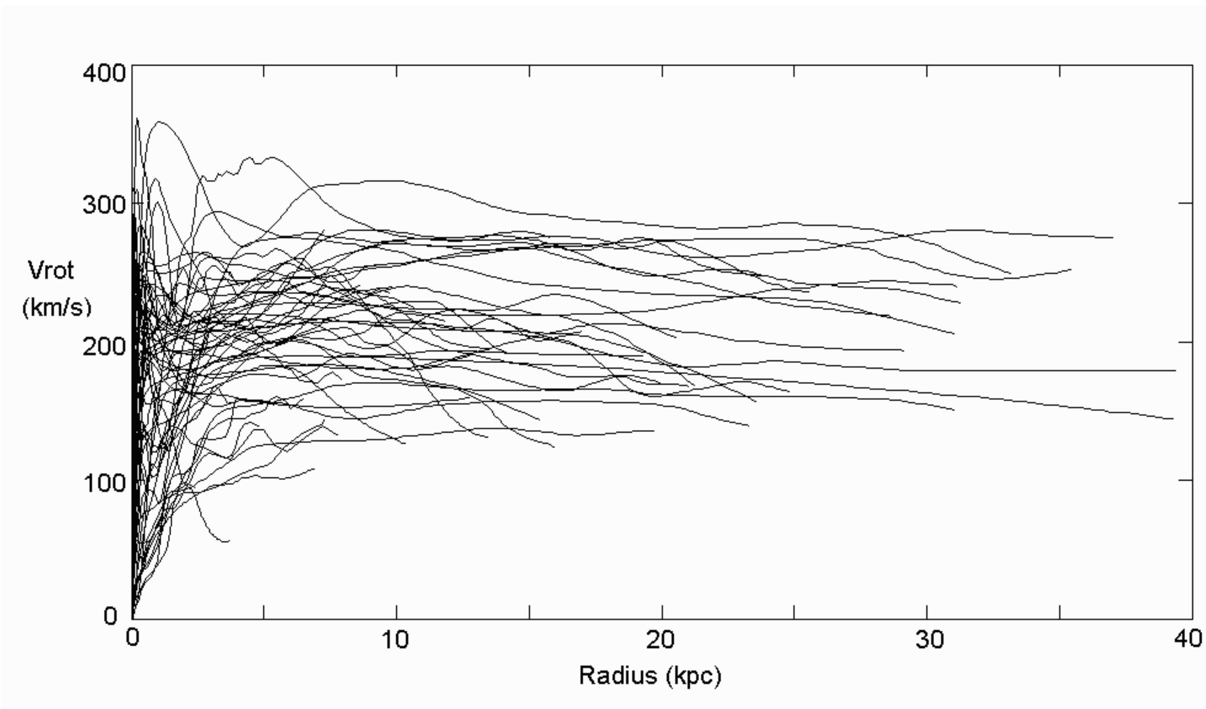
➔ Baryons= protons, neutrons, ordinary matter

➔ **Dark matter: exotic and unknown particles**

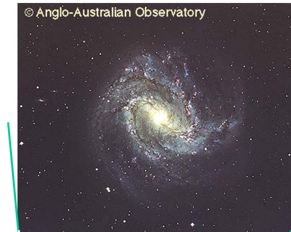
➔ Dark energy: repulsive force, accelerates the expansion

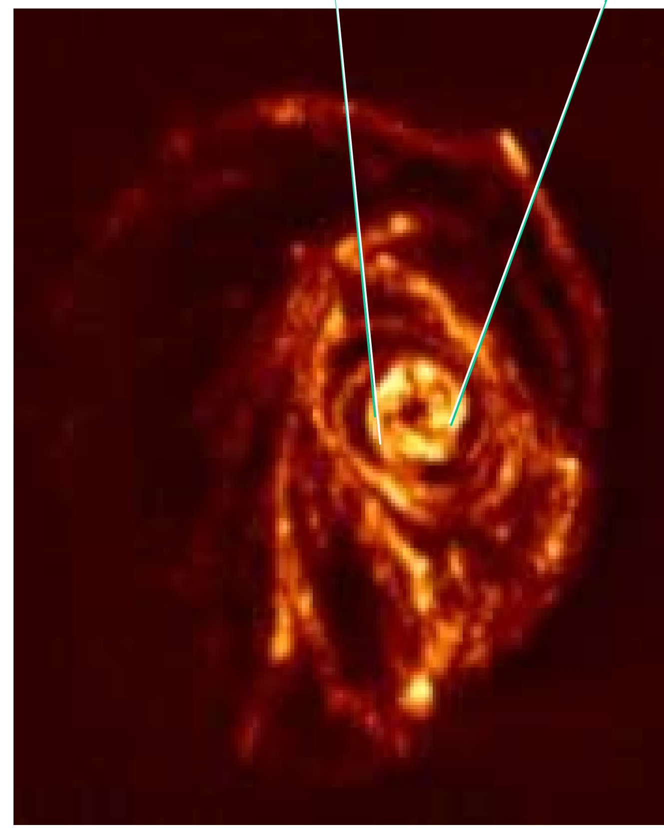
Atomic Hydrogen in galaxies

HI: map of atomic hydrogen
21cm in wavelength



M83: optical

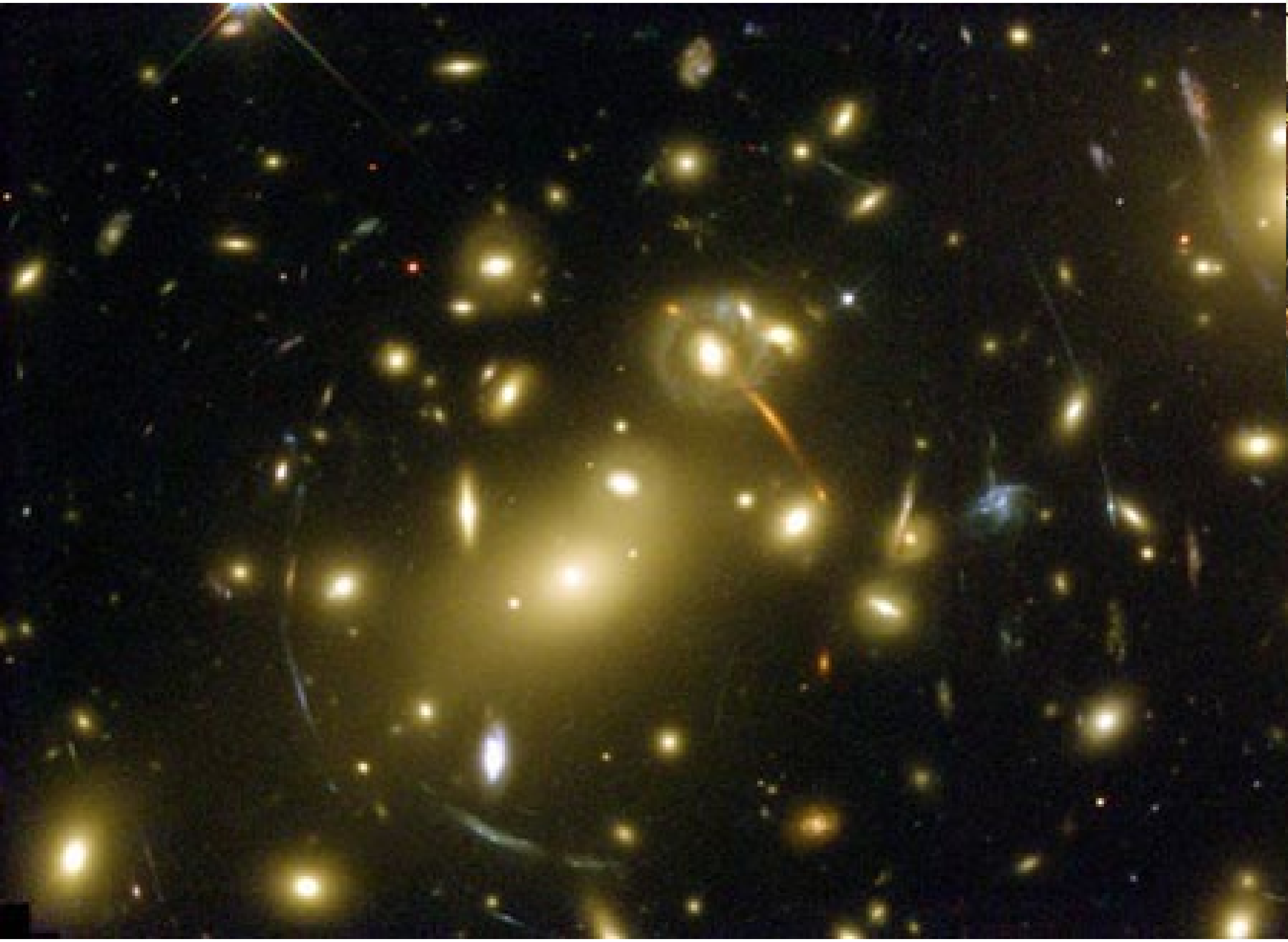




HI in M83: a galaxy similar to the Milky Way

Cartography of the dark matter

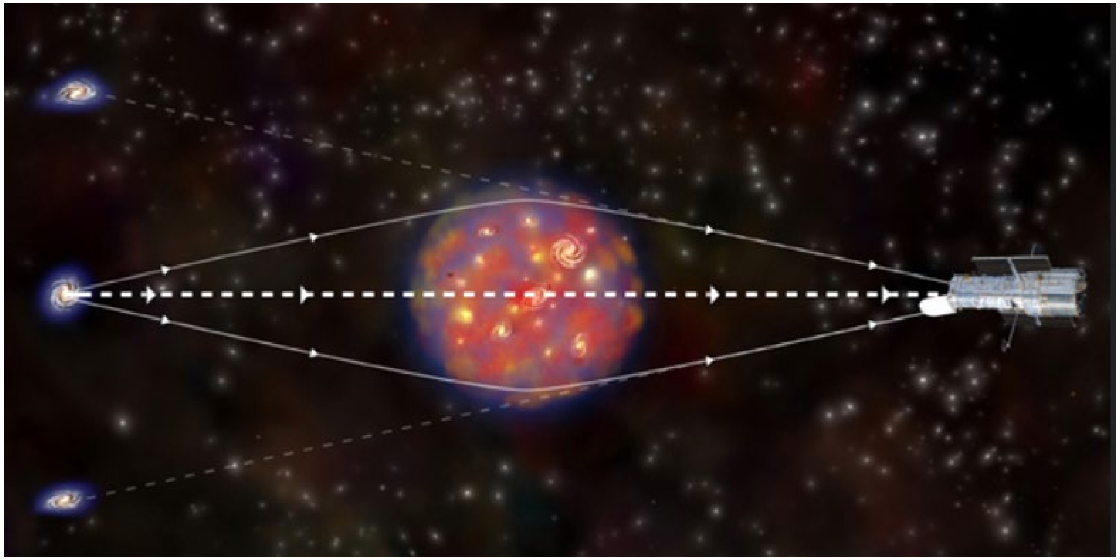
Gravitationnal lenses: strong regime

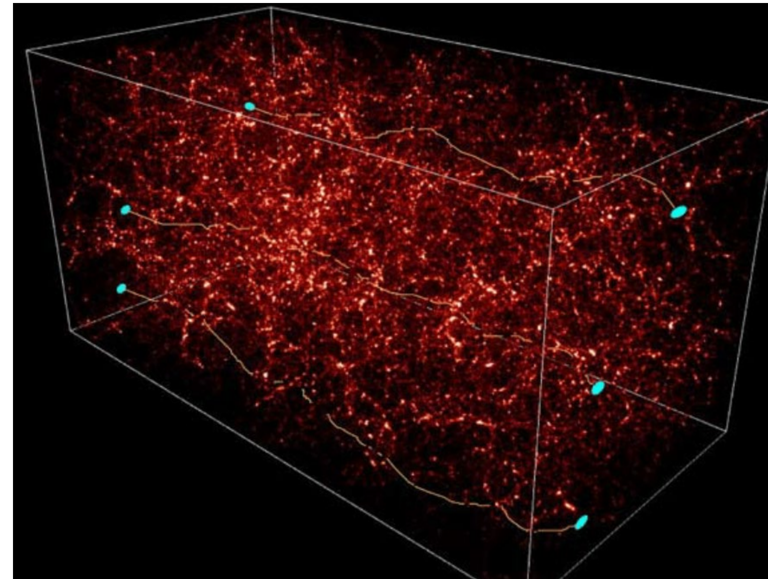


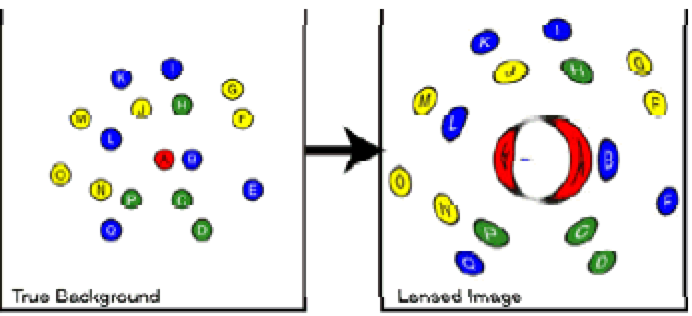
Abell 2218

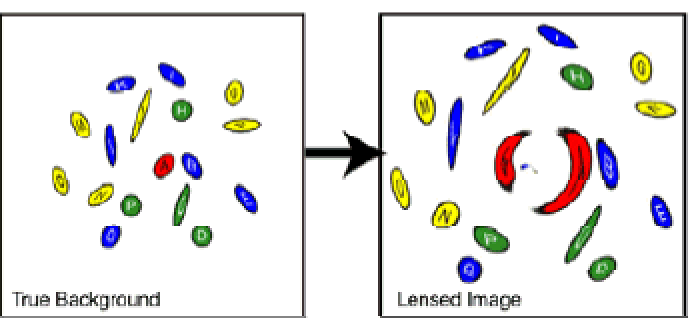
Vermeer: Le géographe

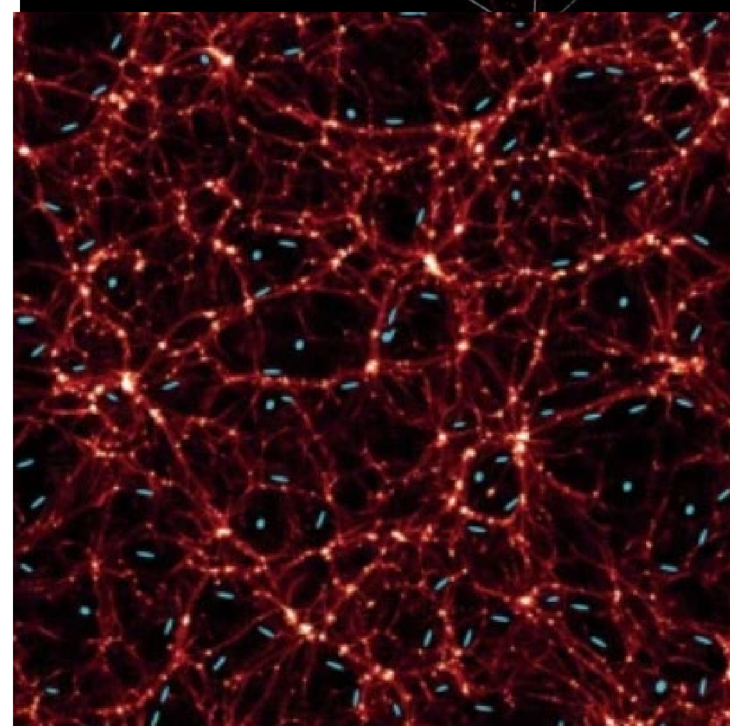
Gravitationnal lenses: weak regime





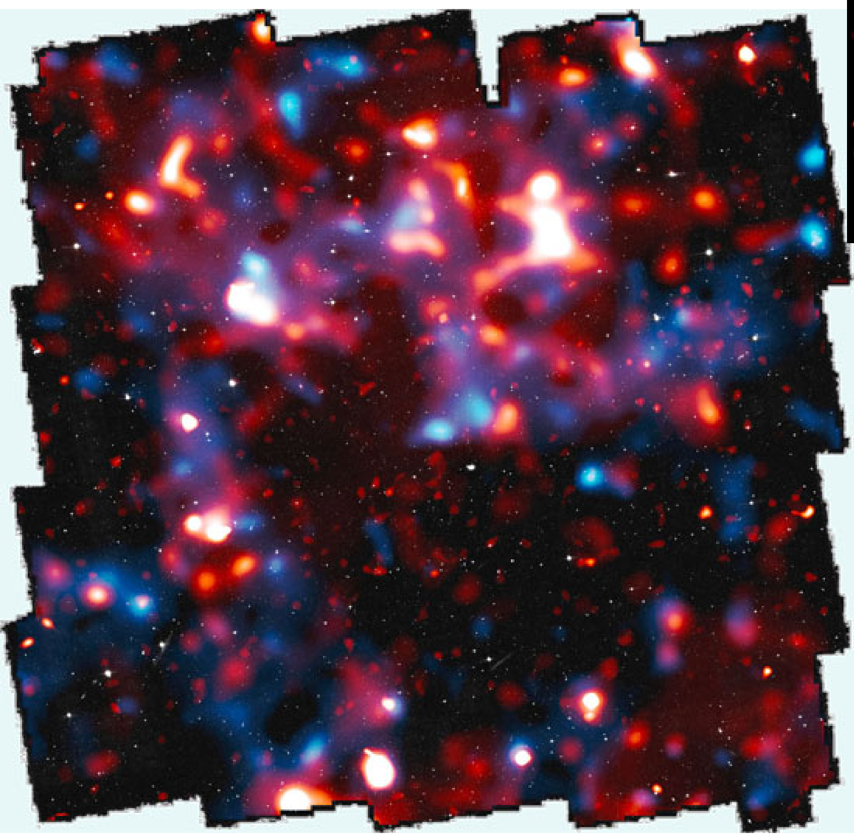


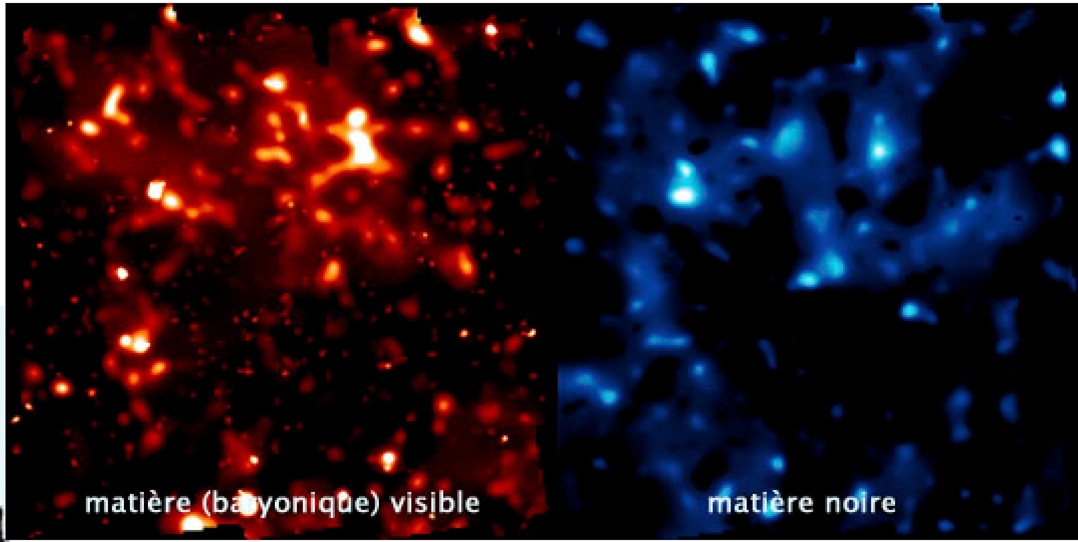




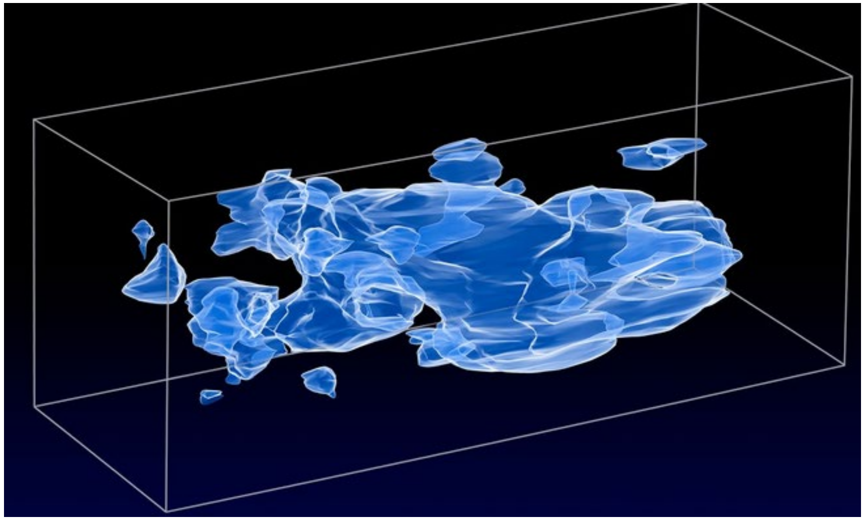
Gravitationnal shear (Cosmos field)

Red: X-ray gas
Blue: total matter





Baryons and dark matter are gathered in the same structures



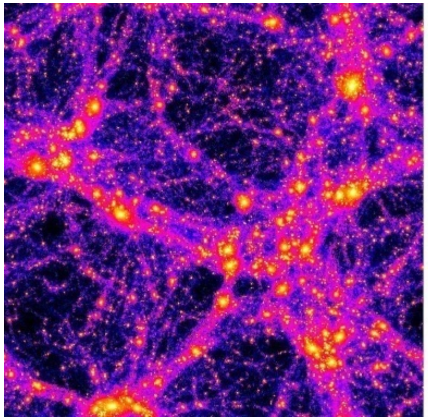
Massey et al 2007

Several kinds of dark matter

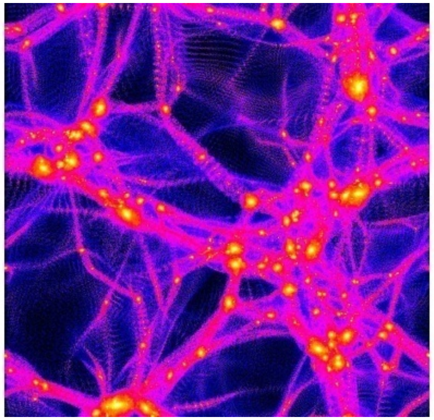
Hot (neutrinos)
Relativistic at decoupling
Cannot form the small structures, if m < 5 keV

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

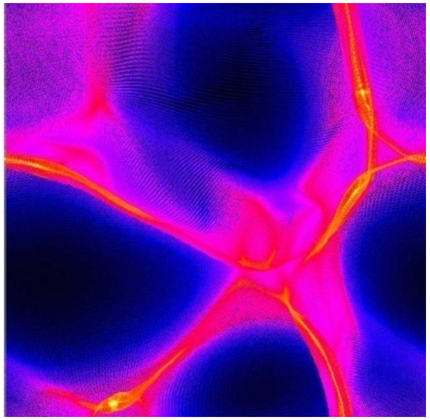
Cold model (CDM)

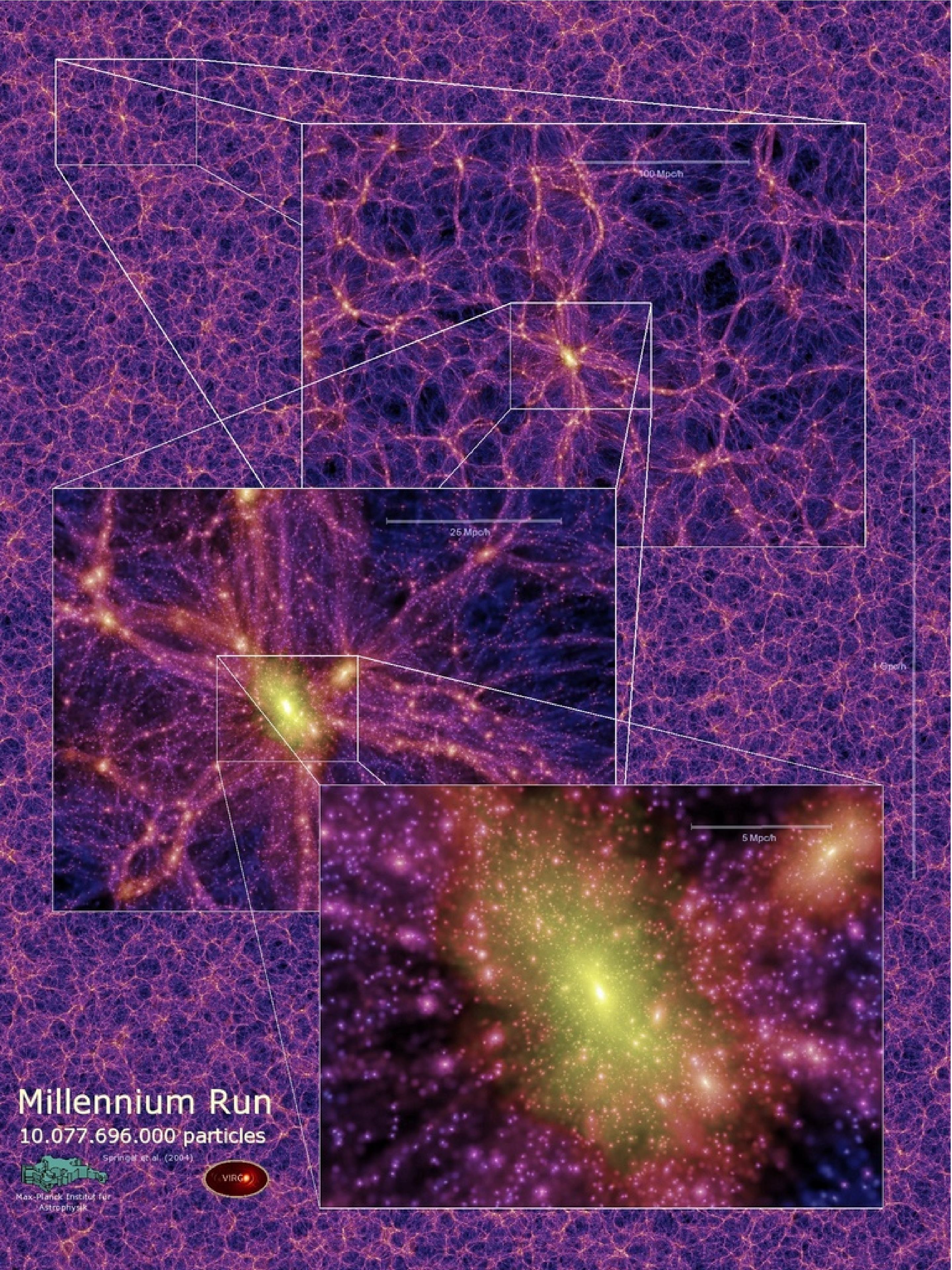


Warm



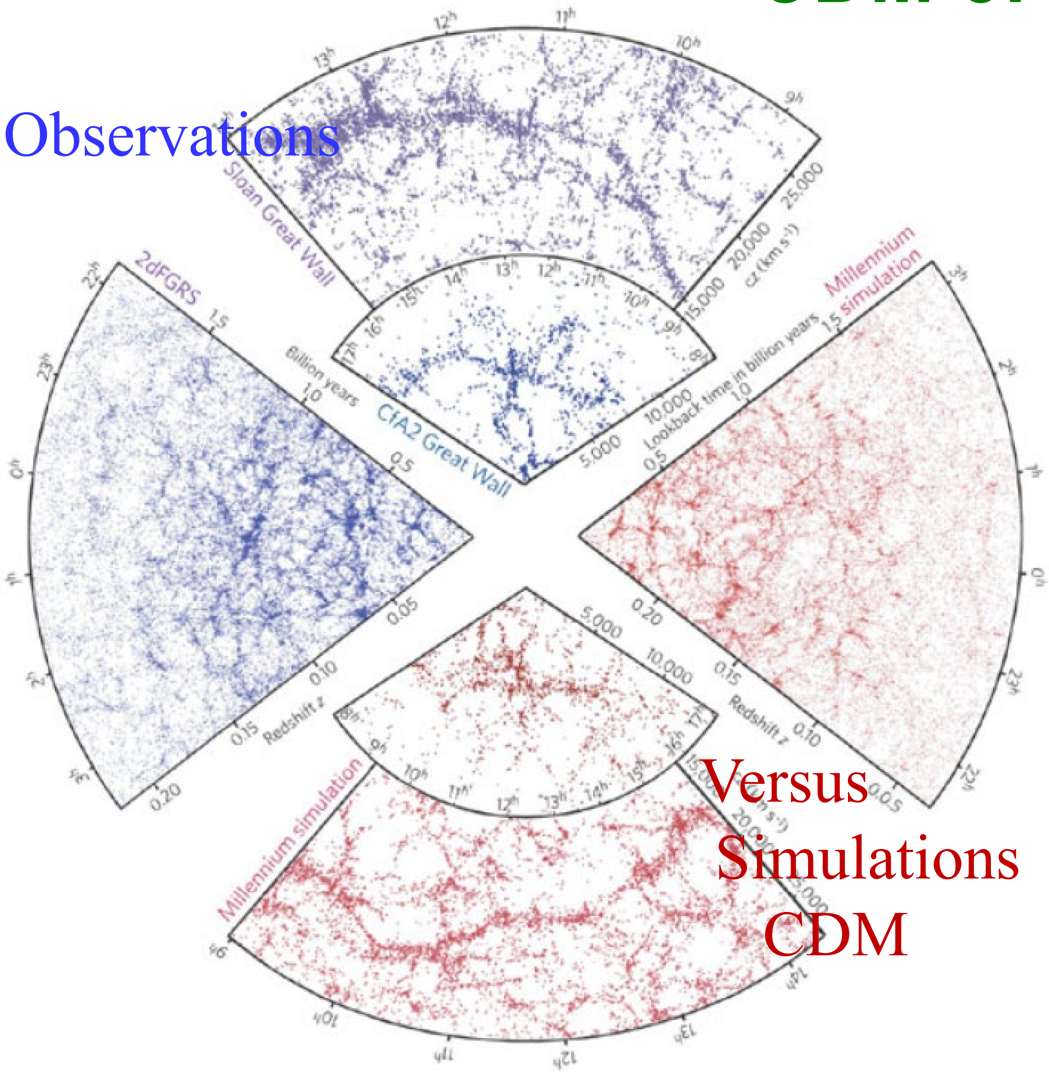
Hot model (HDM)




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

CDM or alternative models?

Observations



Versus
Simulations
CDM

→CDM Particles unfound

→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

The WIMP miracle

Possible to obtain the required abundance of dark matter with particles of mass **~100 GeV,** with the **weak force interaction**

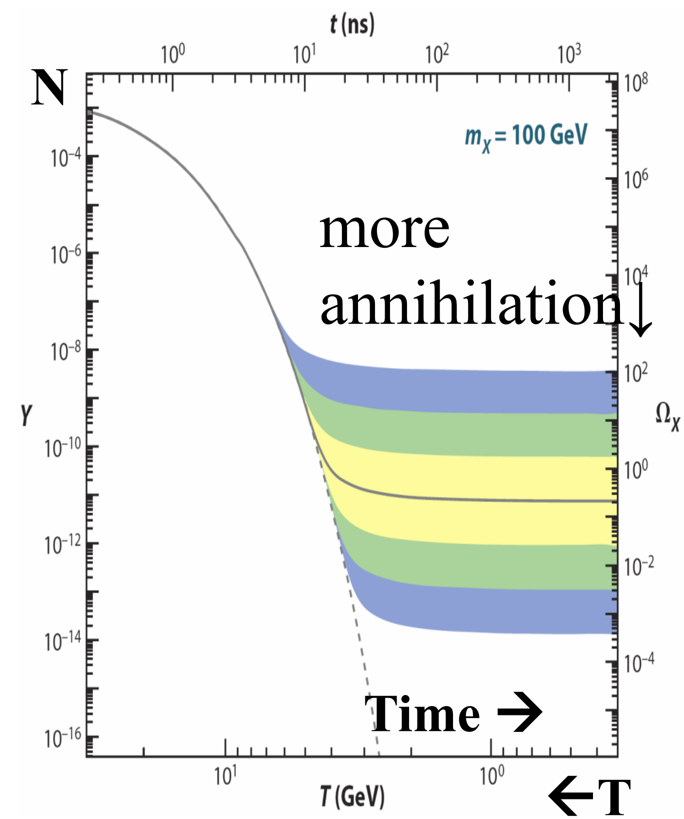
annihilation rate **$<\sigma v> \sim 3\ 10^{-26}\ cm^3/s$**

In early Universe, abundance of particules is « frozen », they decouple when their interaction

$n <\sigma v> \sim 1/t_{hubble}$

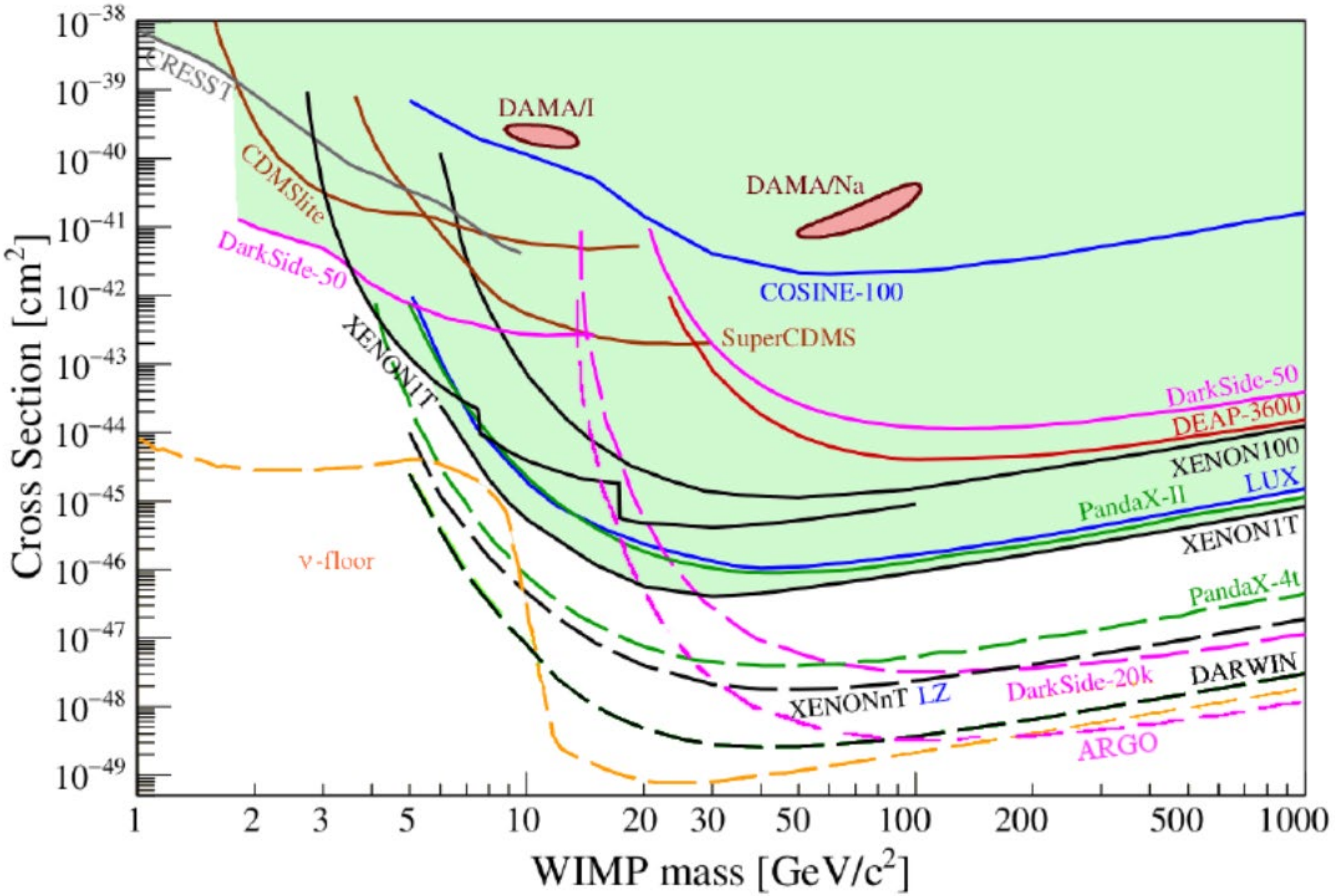
Coincidence: corresponds to the lightest particle of super-symmetry (neutralino)

But in LHC: no super-symmetry,
No new particle!



Present limits and Perspectives + ^{124}Xe

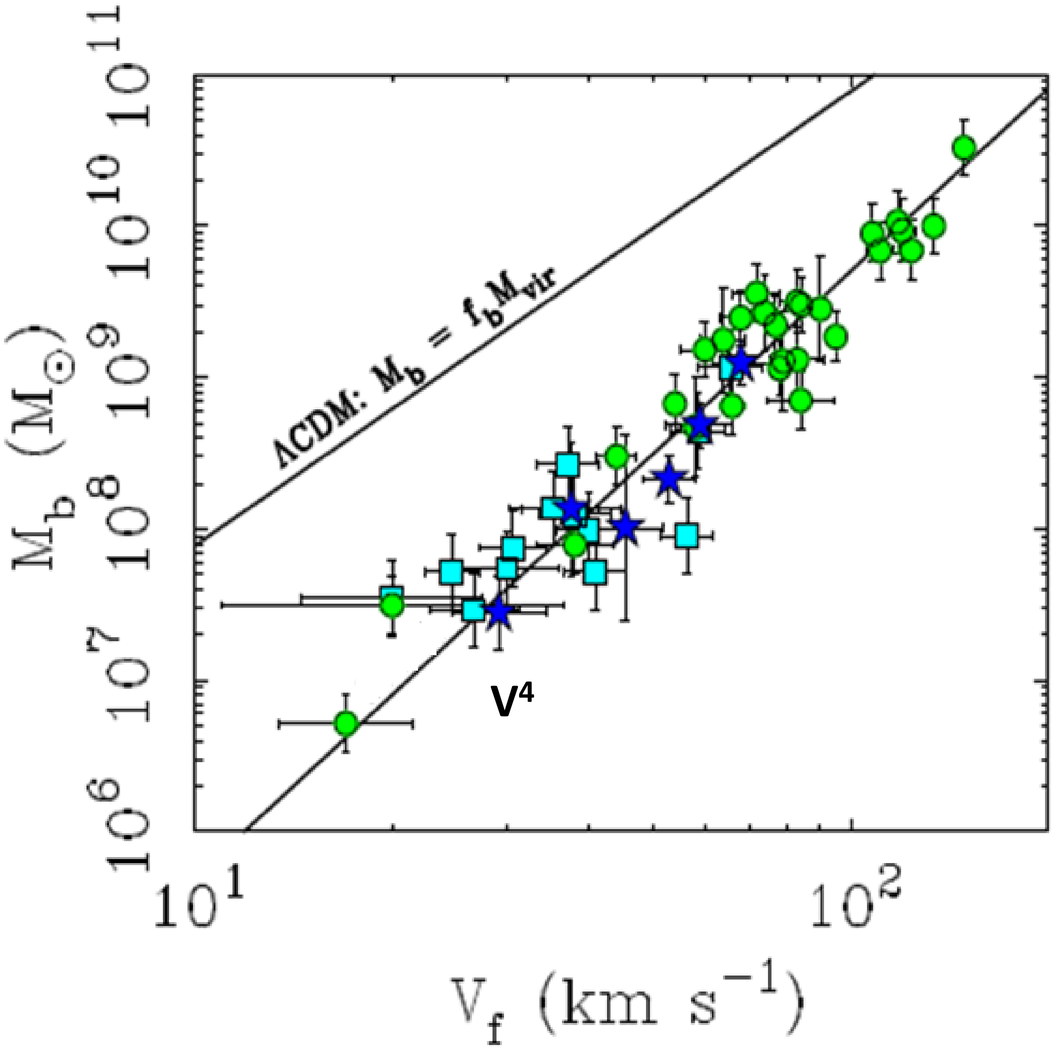
Xenon 1t (Gran Sasso): best limits today (2020-2022)
Soon, we will reach the neutrino's ground *(will detect solar neutrinos)*
Detection of the rarest decay 1.8 10^{22}yrs (April 19) 126 events in 2yrs



XENON*nT*
the largest detector and cryostat, 3.5t

➔8 tons soon

Tully-Fisher scaling relation



f_b universal fraction of baryons= 17%

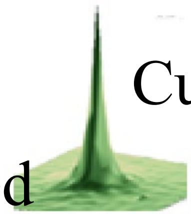
CDM: « Cold Dark Matter » standard model

➔most baryons are not in galaxies

Problems of the standard CDM model

➔**Prediction of "cusps" at the centre of galaxies**, not observed in particular absent in dwarf galaxies, dominated by dark matter

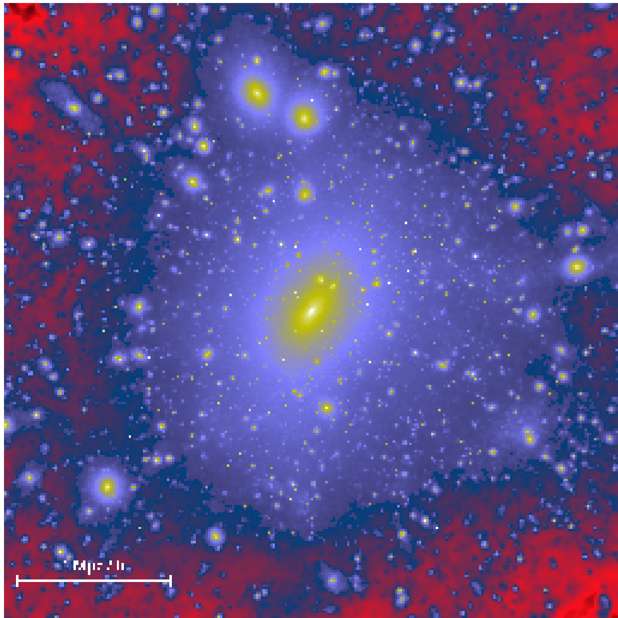
Cusp/core

predicted   observed

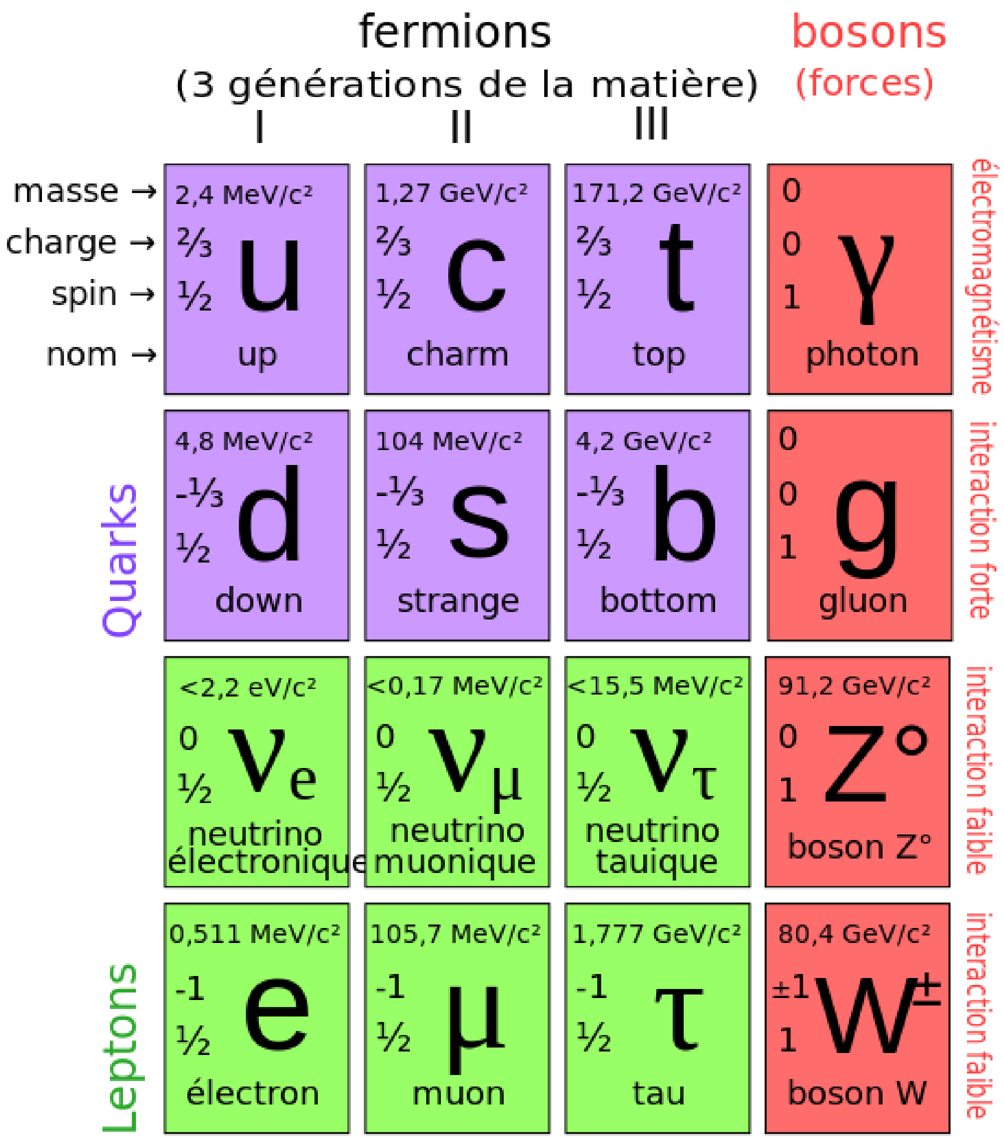
The dark matter profiles are not universal

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

The solution could come from the still unrealistic modeling of physical processes (star formation, feedback), lack of resolution of simulations, **or the nature of dark matter?**



Particles beyond standard model?

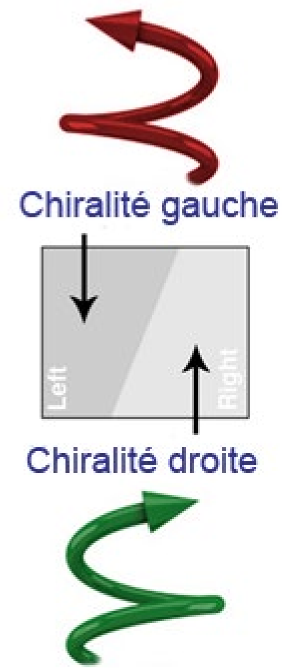


From the Big-Bang

~400 photons /cm^3

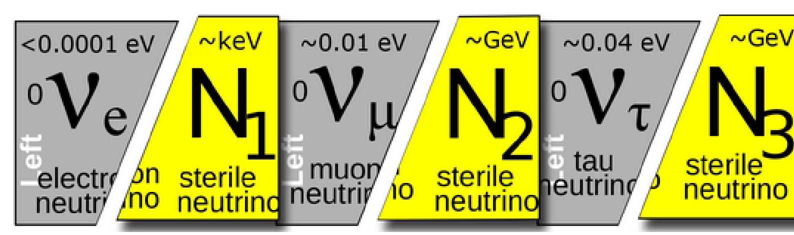
~300 neutrinos /cm^3

0,1 billions of billions/s cross us



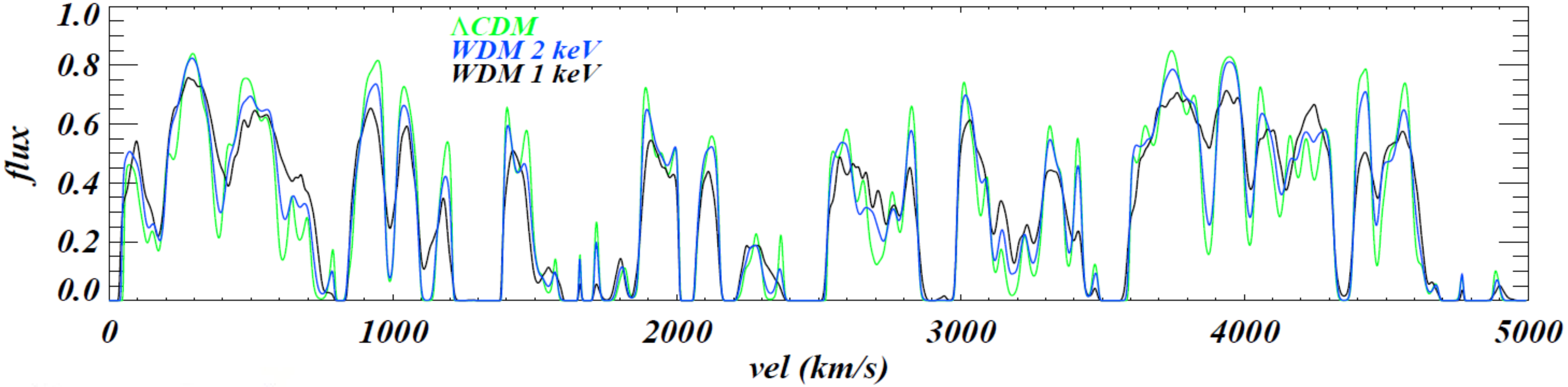
➔Search for WIMPS since 1985

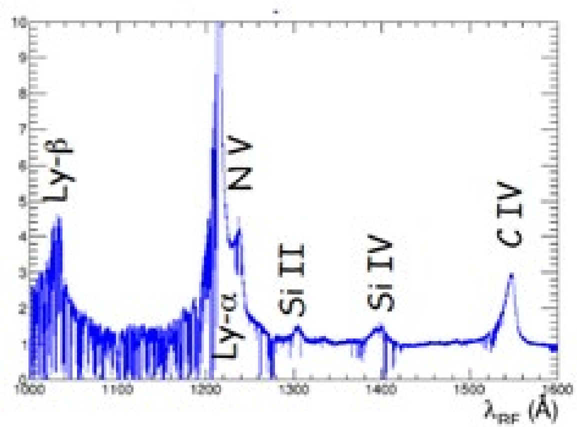
Extension to sterile neutrinos?



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^{-5}g at 10^{-43}s (minimum)**

10^{15}g at 10^{-23}s (evaporating now)

$1M_O$ at 10^{-5}s (maximum)

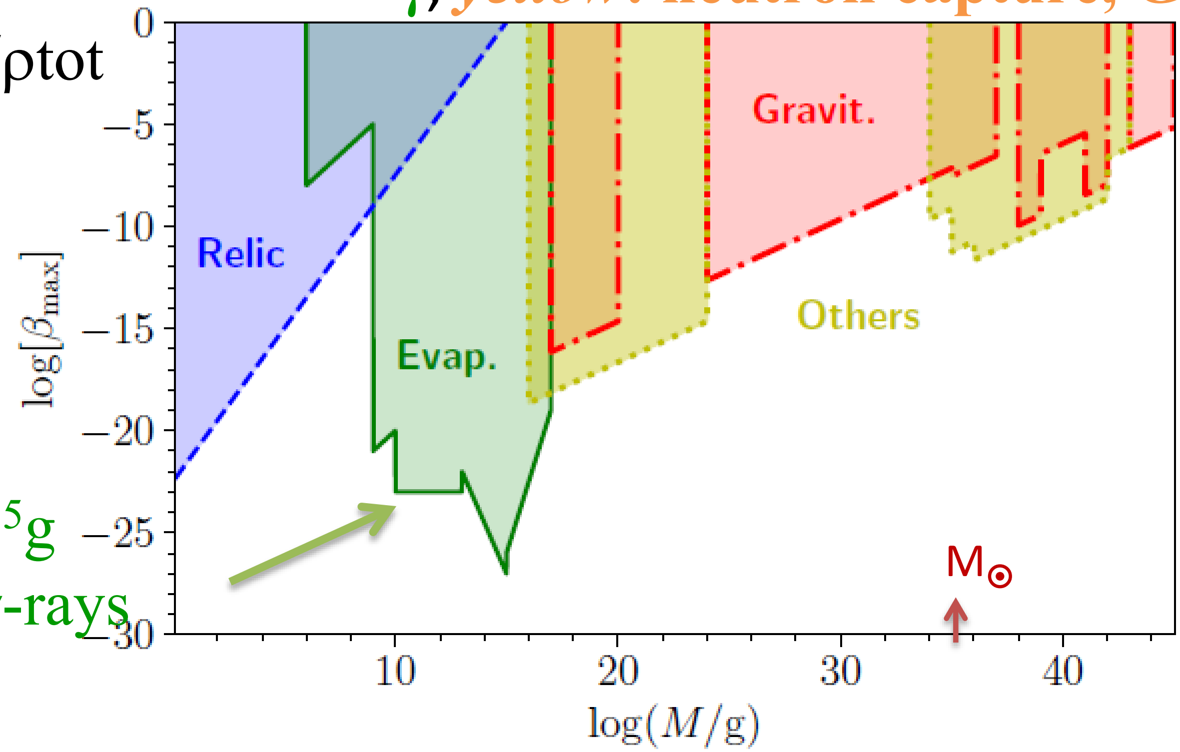
PBH formation requires strong inhomogeneities in the early inflation, and recollapsing local regions +phase transition, bubble collisions, collapse of strings or domain walls

e.g. Carr et al 2010, 2016

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

Small masses evaporate

Gutierrez et al 2017

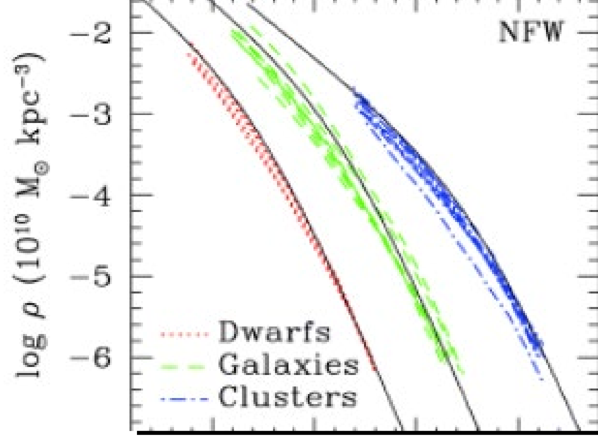
Candidates for the dark matter

New physics, beyond the standard model SM

Kaluza-Klein DM in UED
Kaluza-Klein DM in RS (Randall-Sundrum)
Axion
Axino
Gravitino
Photino
SM Neutrino
Sterile Neutrino
Sneutrino
Light DM
Little Higgs DM
Wimpzillas
Cryptobaryonic DM
Q-balls

Champs (charged DM)
D-matter
Cryptons
Self-interacting
Superweakly interacting
Braneworld DM
Heavy neutrino
Neutralino (WIMP)
Messenger States in GMSB
Branons
Chaplygin Gas
Split SUSY
Primordial Black Holes
Mirror Matter
…

Fuzzy dark matter



Log (radius)

Cusps exist in galaxy clusters, but not in galaxies
In dwarf galaxies, cores of ~1kpc

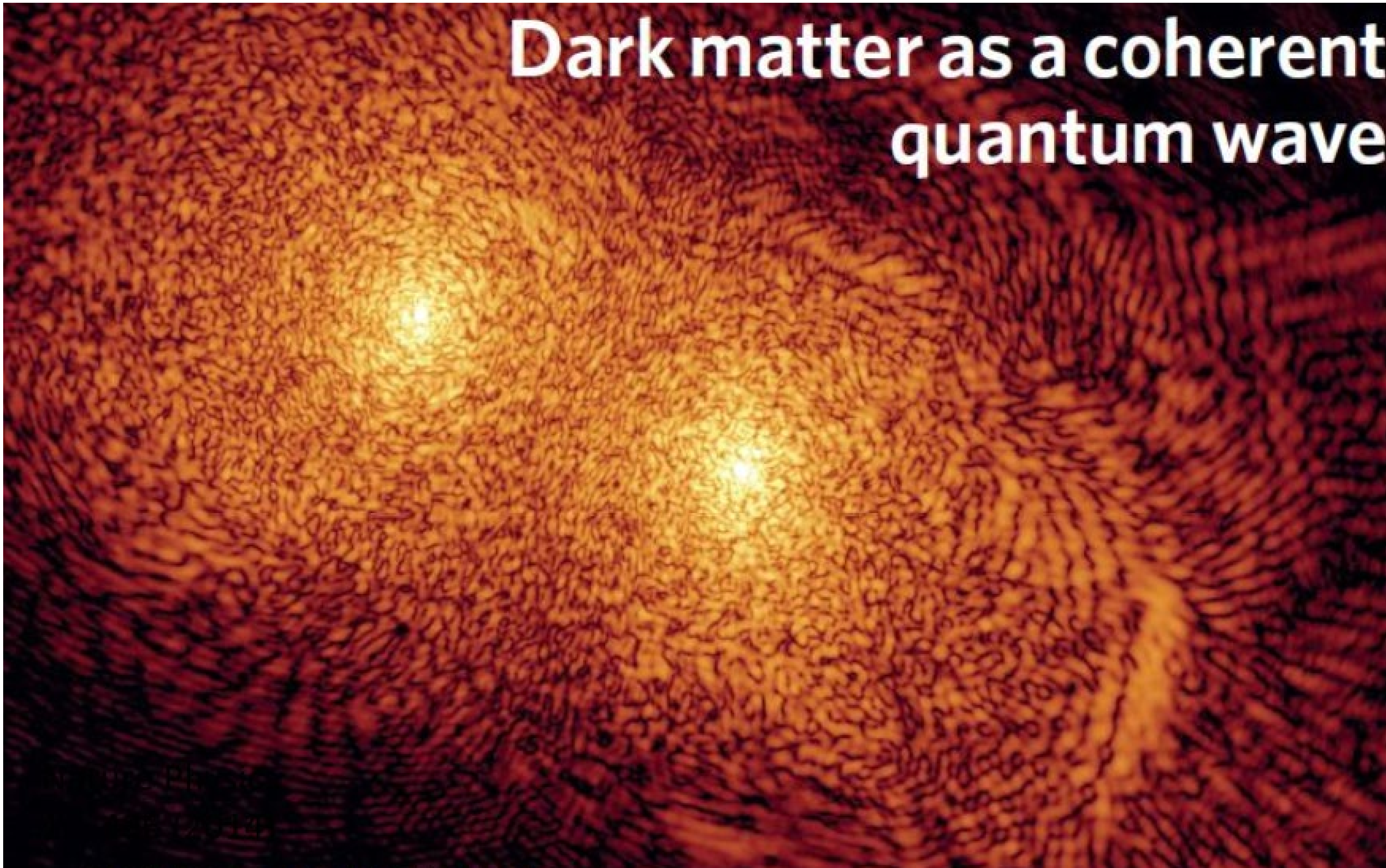
Bosons generated in non-thermal mechanisms ➔ axions *(ALP, Marsh 2016)* cold particles, which can collapse
BEC "Bose-Einstein condensate", macroscopic state at low T

- Finite mass, very small, λ de Broglie, λ comp = $h/m_a v$
➔ λ comp = 1-2 kpc

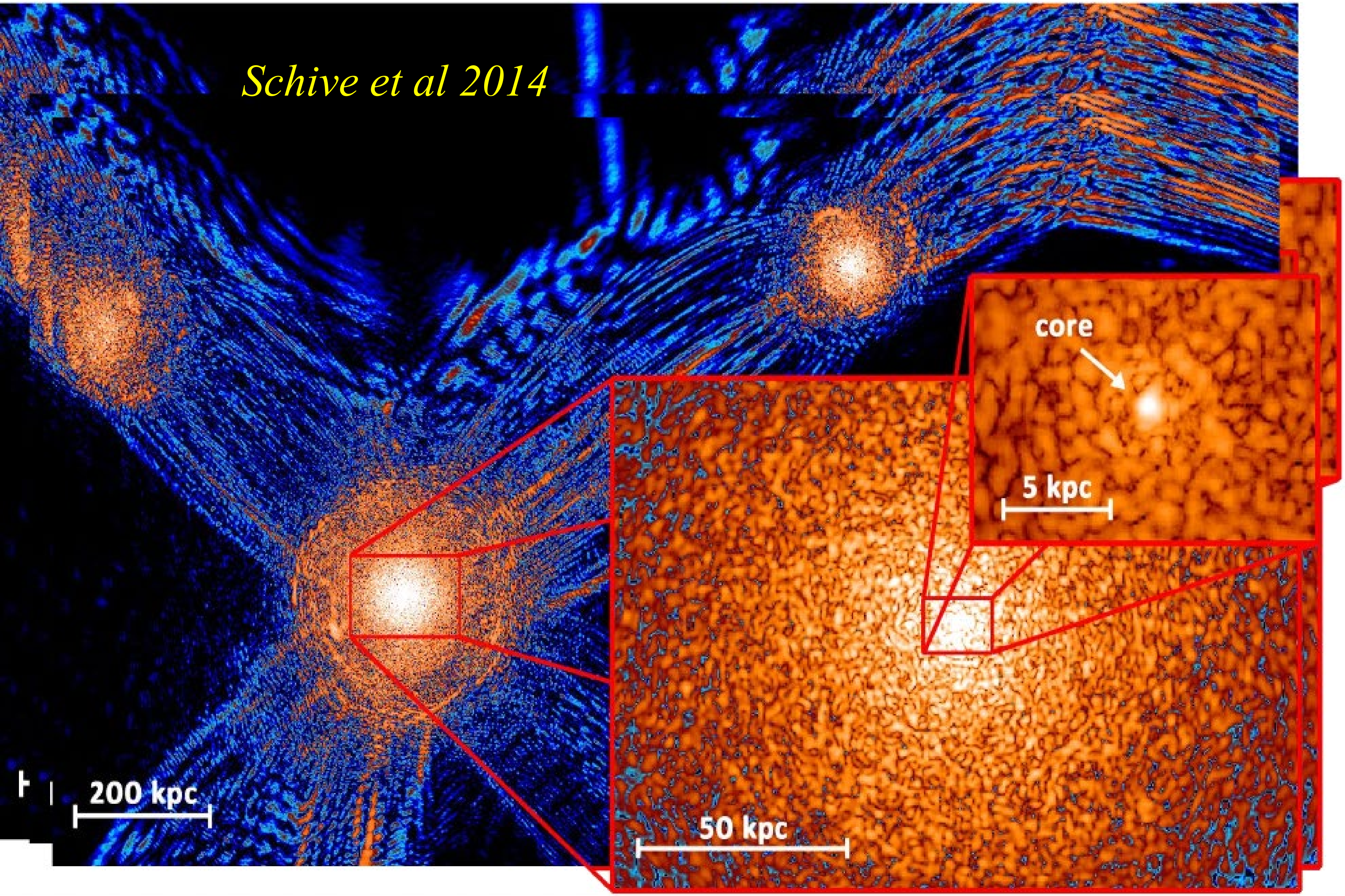
- In fact λ comp ~ 1-2 kpc for $m_a = 10^{-22}$ eV , and v~10km/s

Simulations AMR: eq. Schrödinger- Poisson

Core= soliton, Halo= clumpy aspect + wavy (Schive +2014)



Quantum interferences: 9 orders of magnitude



MOND = MOdified Newton Dynamics

At weak acceleration

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

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

Asymptotically

$a_N \sim 1/r^2 \rightarrow a \sim 1/r$

$\rightarrow V^2 = \text{cste}$

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

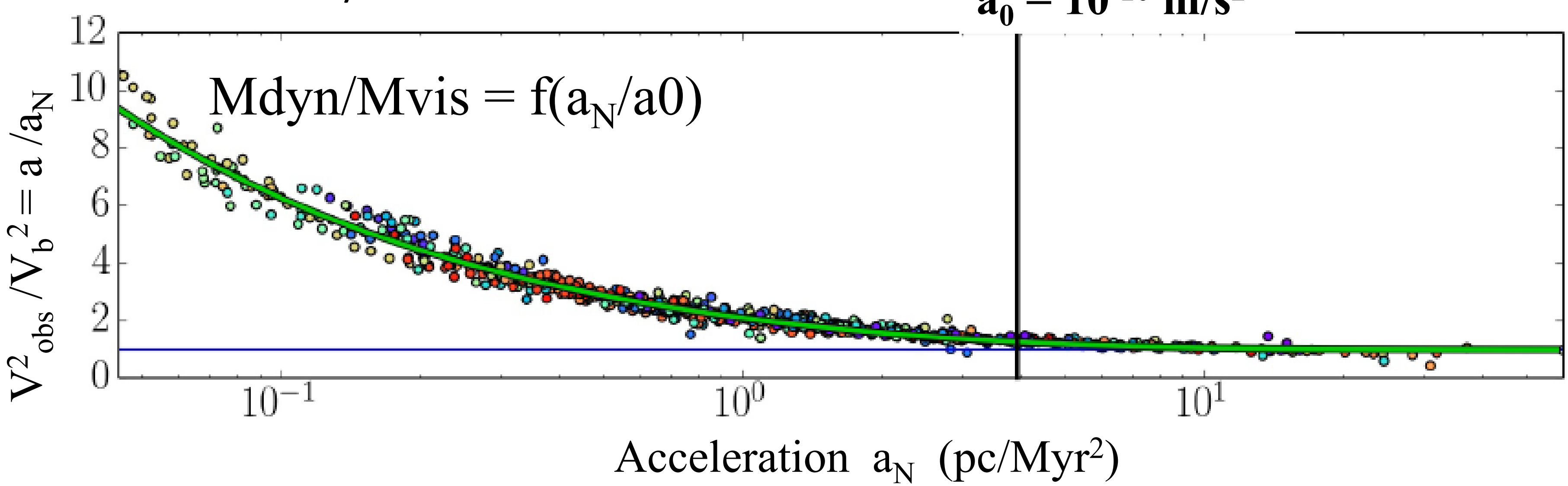
Milgrom (1983)

Covariant theory: TeVeS

$\rightarrow$ Gravitationnal lenses

Bekenstein 2004

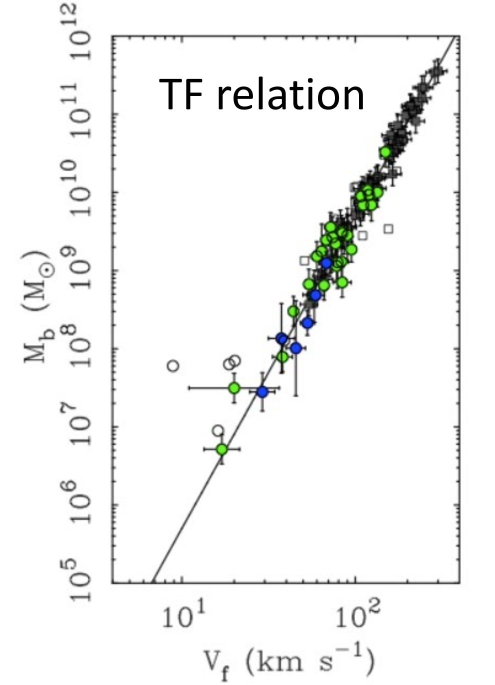
Conformal Gravity: Mannheim et al 2012



Success at weak surface densities

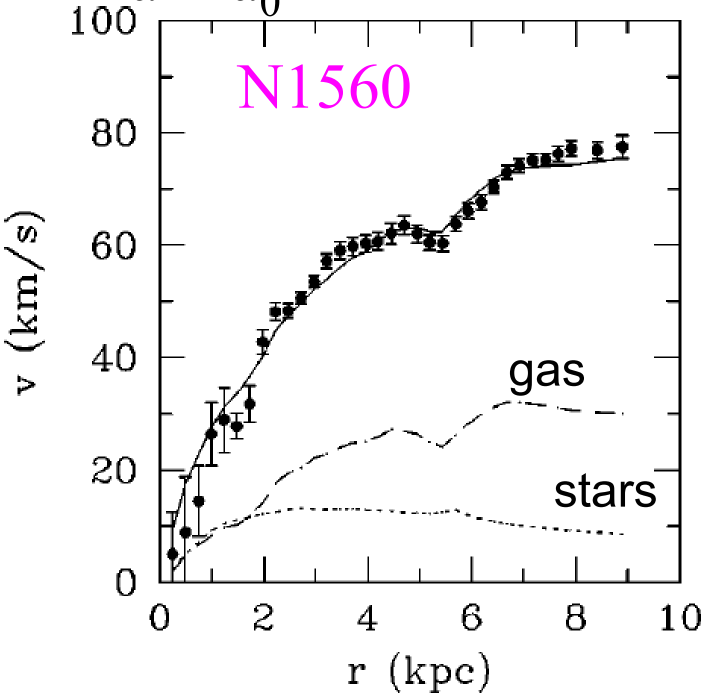
$\Sigma < \Sigma_0 \sim 150\ M_\odot/pc^2$, ➔the critical acceleration a_0

In particular dwarf galaxies

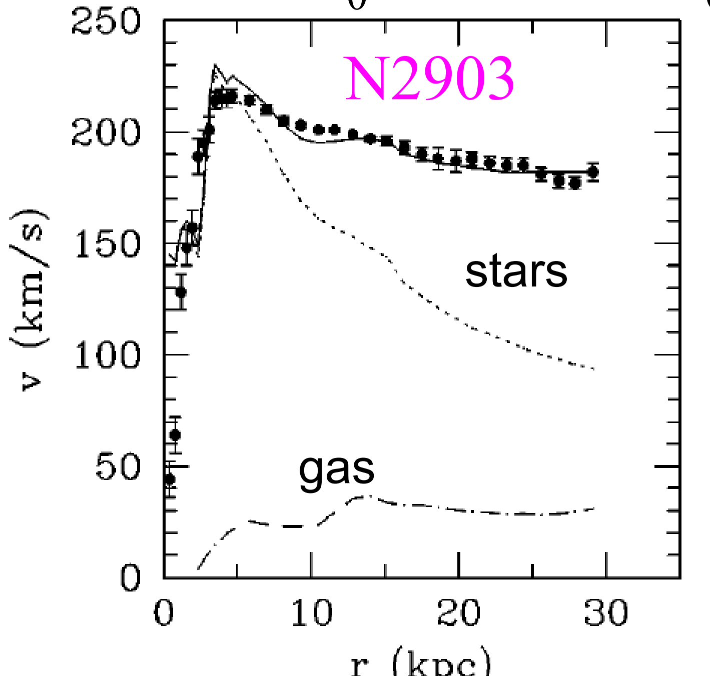


The rotation curves of all galaxy types

$a \ll a_0$

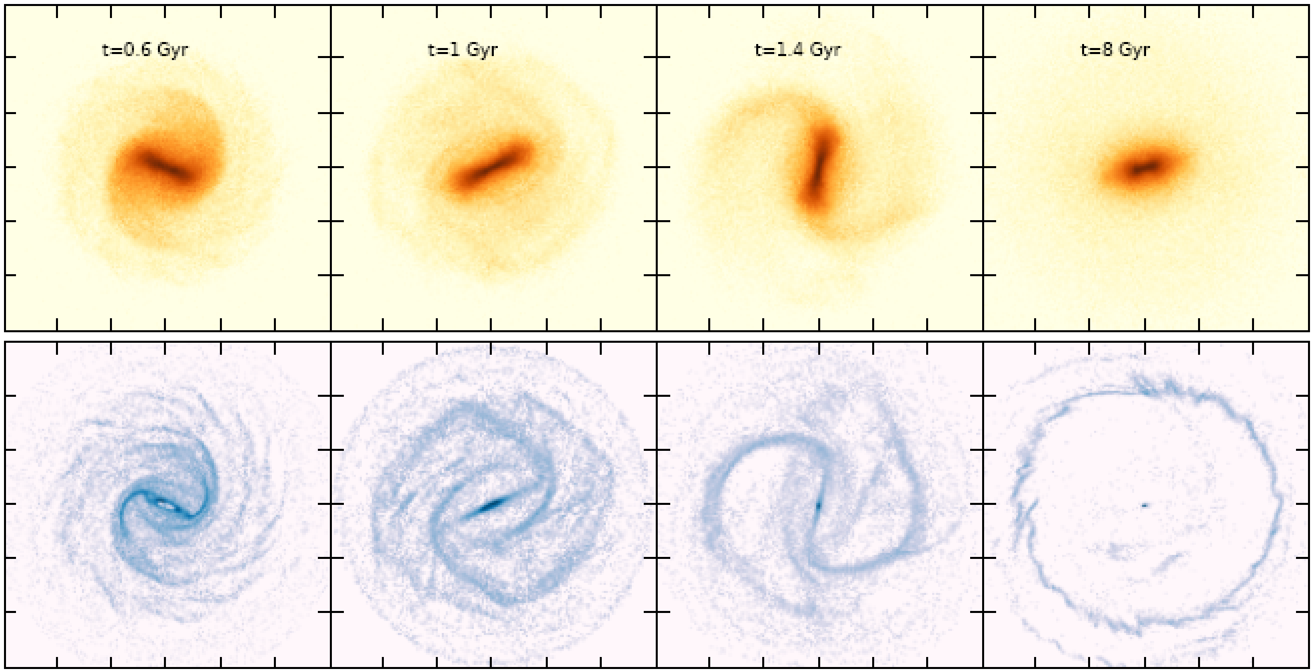


$a > a_0$ $a \ll a_0$



Influence of the dark halo ?

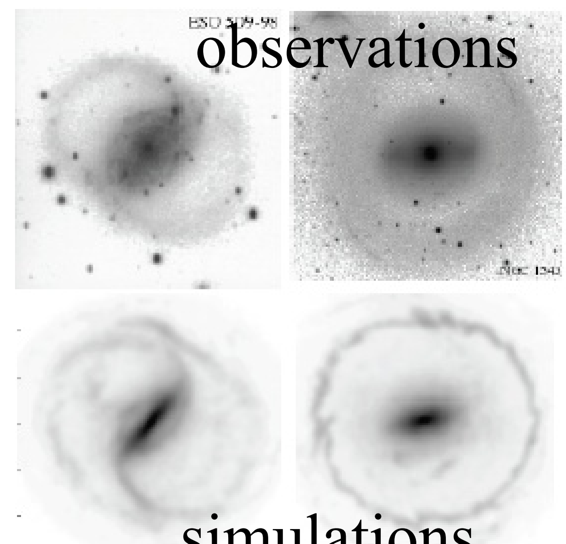
Dynamics of galaxies,
Formation of spirals and bars *Tiret & Combes 2007, 2008*



Stars

Gas

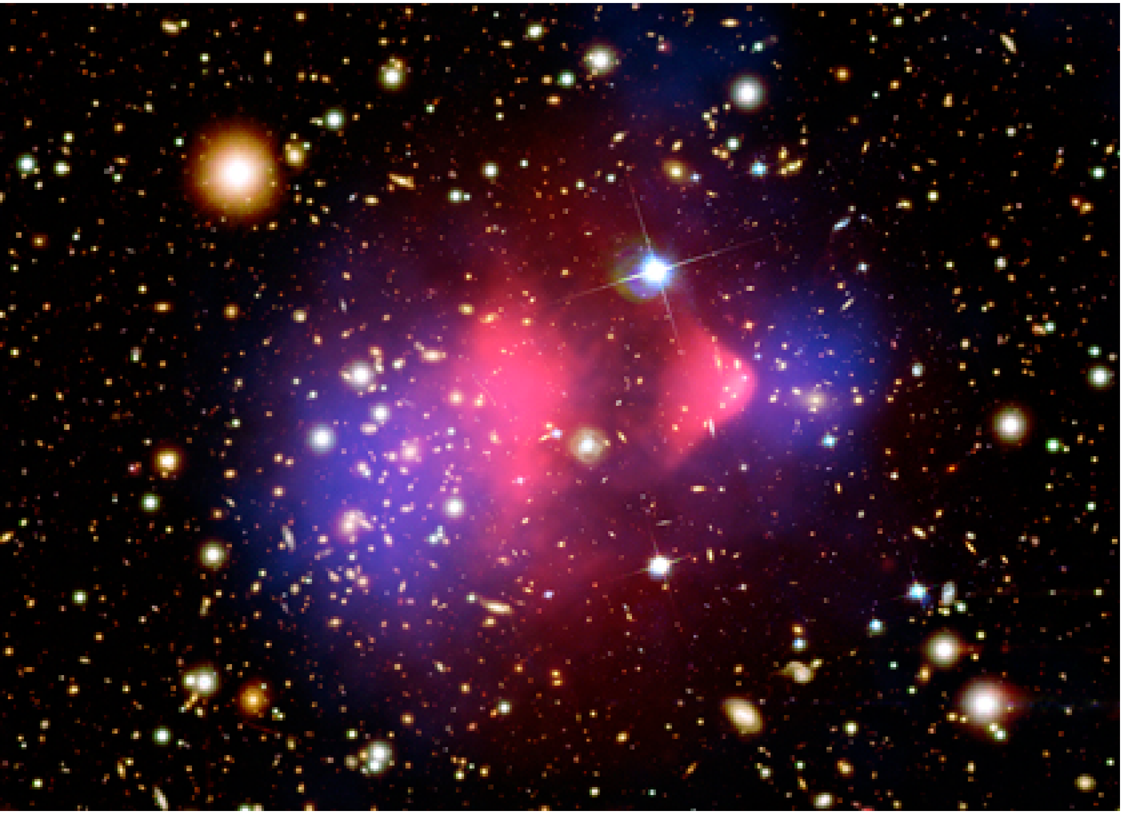
observations

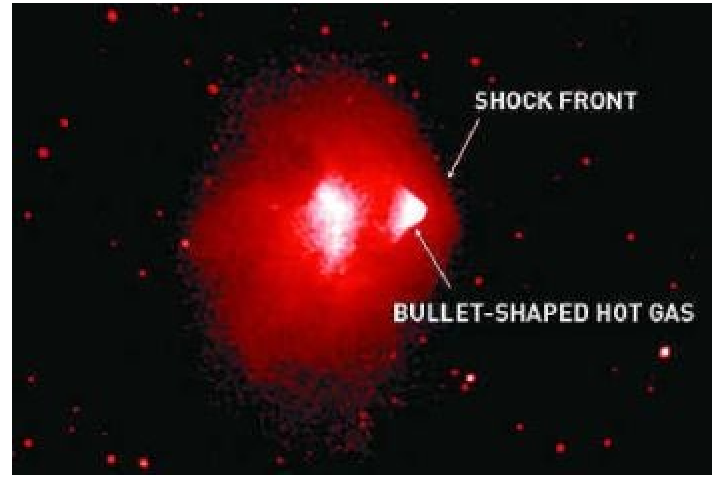


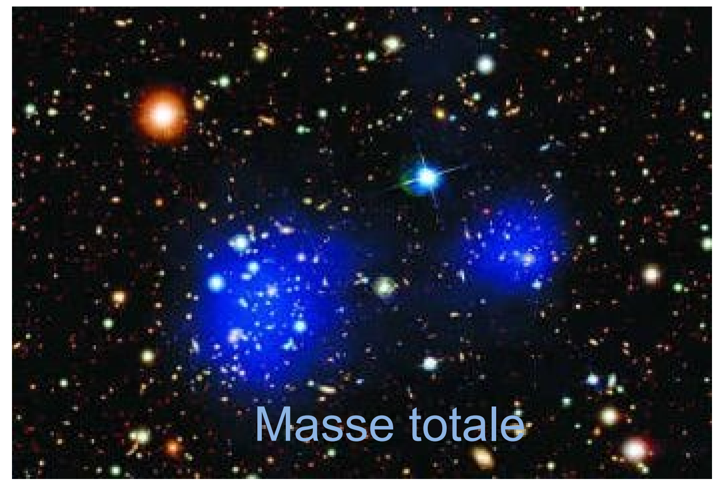
simulations

TeVeS covariant theory →but unstable
ruled out by gravitational waves ($c_{GW} \neq c$)
But Skordis et al 2019, new version, with $c_{GW}=c$

The bullet cluster







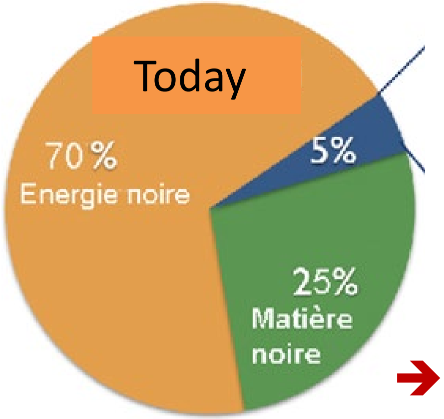
Rare case of violent collision, allowing to separate components

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

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

V=4700km/s (Mach 3)

Clowe et al 2006



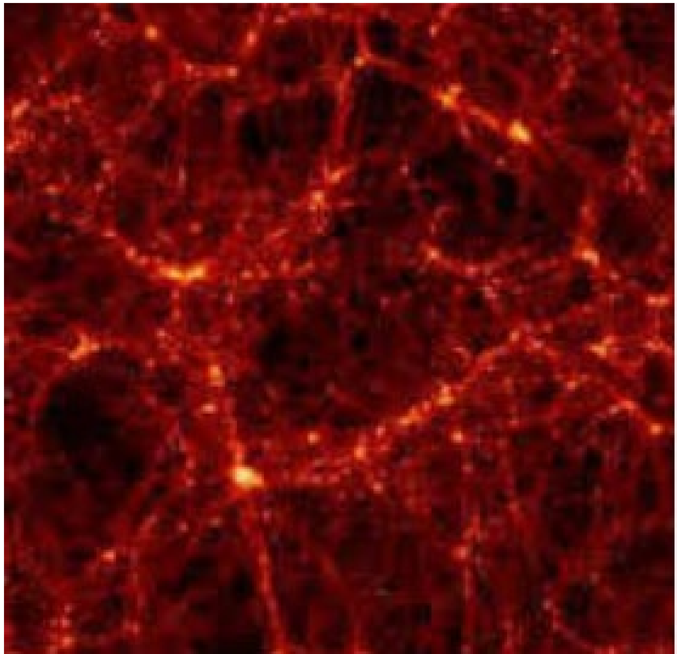
Where are all the baryons?

➔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

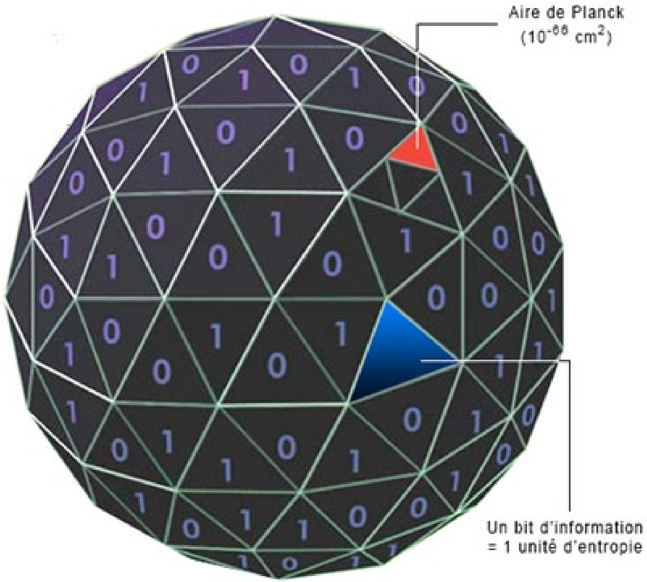


Emergent gravity

The gravity is not a fundamental force, but a **maximisation of entropy**

The entropy of **quantum intrication**

Inspired by
Entropy and thermodynamics of horizon (Bekenstein-Hawking)
Holographic theory (Gerard ‘t Hooft)



Verlinde E.: 2010, On the origin of gravity and Newton laws
Verlinde E.: 2016, Emergent gravity and the dark Universe

This principle retrieves the MOND dynamics

The entropy is diffuse in the universe as the dark energy

Dark matter, when $\Sigma < a_0/8\pi G$, the apparent dark matter

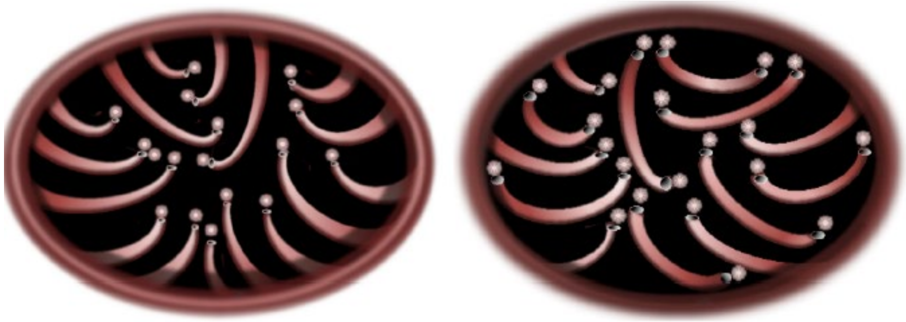
$$\frac{2\pi}{\hbar a_0} M_D^2 = \frac{A(r)}{4G\hbar}\frac{M_B}{d-1} \qquad \text{or} \qquad \Sigma_D^2(r) = \frac{a_0}{8\pi G}\frac{\Sigma_B(r)}{d-1}. \quad d=4$$

Or $g_D^2 = g_N\, a_0/6$, which is the MOND relation *(Milgrom 1983)*

Hypothesis: we live in a de Sitter space Λ; $\Omega_b \sim 5\%$ baryons $\Lambda=0.95$

$\Omega_D^2 = 4/3\ \Omega_b \ \rightarrow\ \Omega_D = 0.26$

The Λ corresponds to the intrication of microscopic elements



This boost of **gravity (dark matter)** occurs when the entropy of quantum intrication of matter falls below the entropy of dark energy

Emergent gravity vs MOND in clusters

Gravity is boosted , as soon as acceleration << a_0 ~c H

g_D= sqrt (a_0 . g_B/6), alors $g = g_D + g_B$

$$\int_0^r \frac{GM_D^2(r')}{r'^2} dr' = \frac{M_B(r) a_0 r}{6}.$$

The acceleration becomes 2 to 3 x in MOND
In galaxy clusters
$g = g_B (1+1/x)$ with $x^2 = 6/(cH)\, g_B/(1+3\, d_B)$

Lagrangian proposed, Vector field giving DM & DE
Hossenfelder 2017

The dark matter puzzle

Galaxies + X-ray hot gas: **0.5%** of total
Ordinary matter (5%):   65% non identified

Exotic dark matter:
Particles still unknown, beyond standard model
Masses between **10^{-22} eV** (axions) & **10^{12} eV** (WIMPs)
searched for during **35yrs**
➔**Fuzzy Dark Matter**
➔Neutrinos, contrained by Ly-α :   **$m_X > 4.65$ keV & $m_s > 28.8$ keV**

Problems of standard dark matter models at galaxy scale
➔ solution in baryonic physics
➔ **or in modified gravity**, 5^{th} force, quantum gravity, **entropic force**