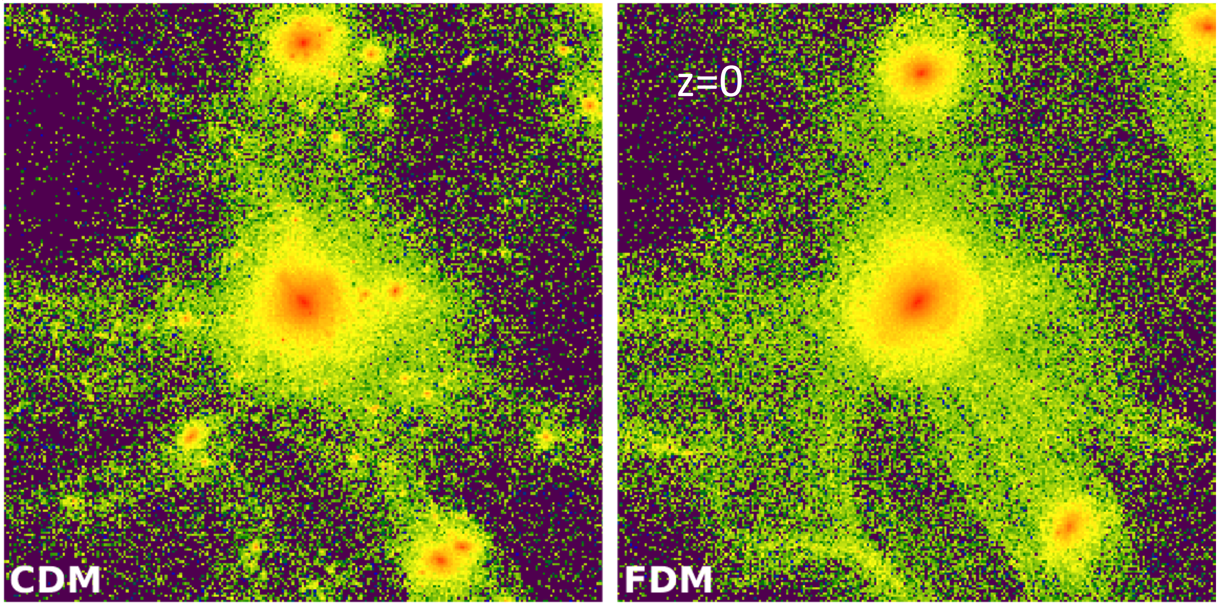
The dark matter puzzle

COLLÈGE DE FRANCE
1530

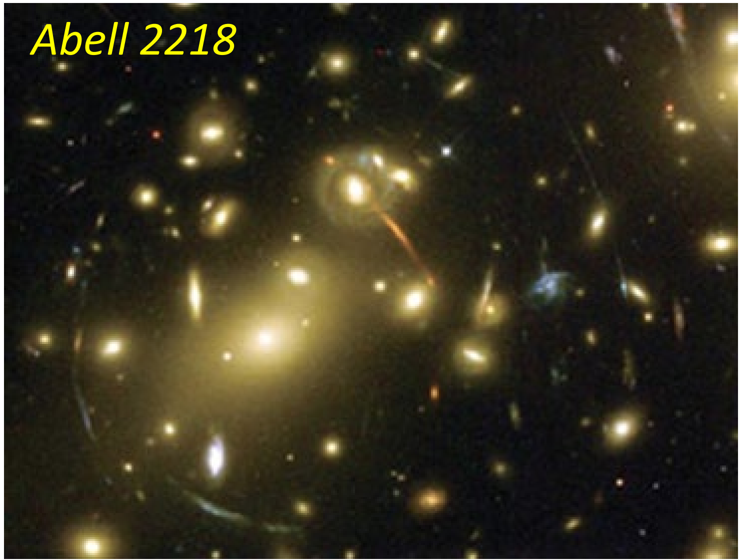
Chaire Galaxies et Cosmologie



WIMPS

Schwabe & Niemeyer 2022

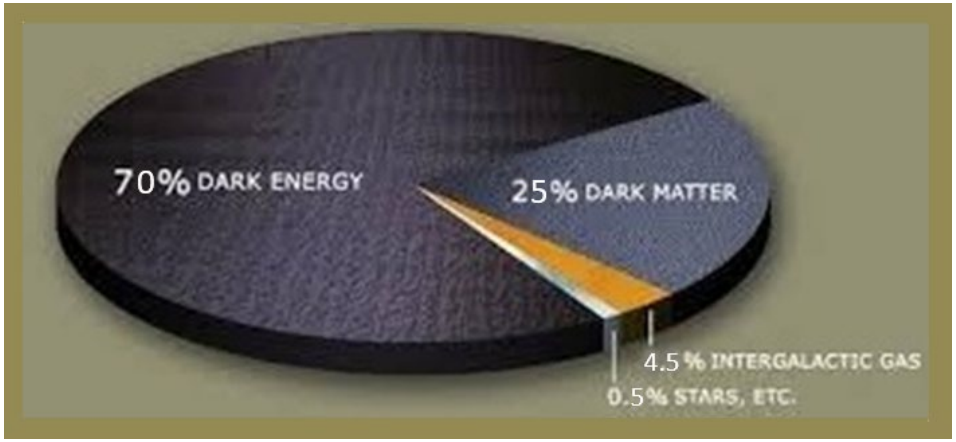
Ultra-Light Axions (ULA)
Scalar-field, non-interacting



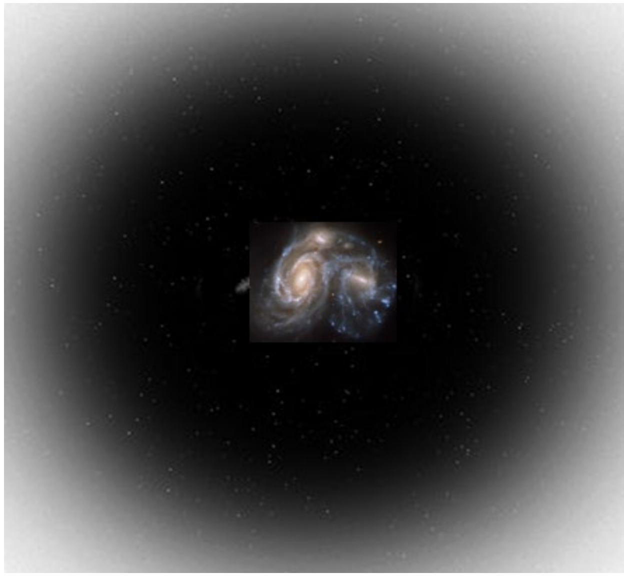
Françoise Combes
July, 2023

l'Observatoire de Paris
LERMA
Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

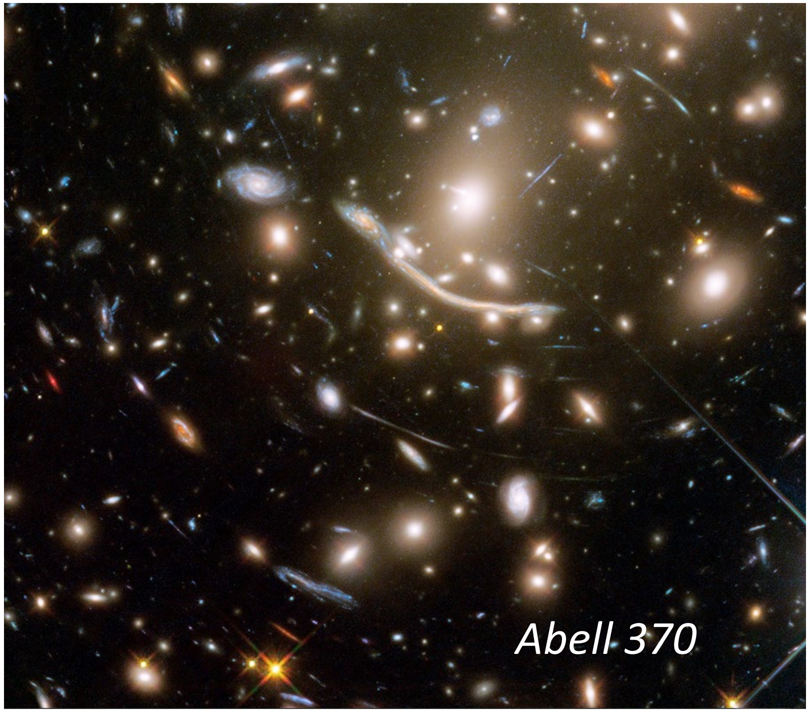
Where is the dark matter?



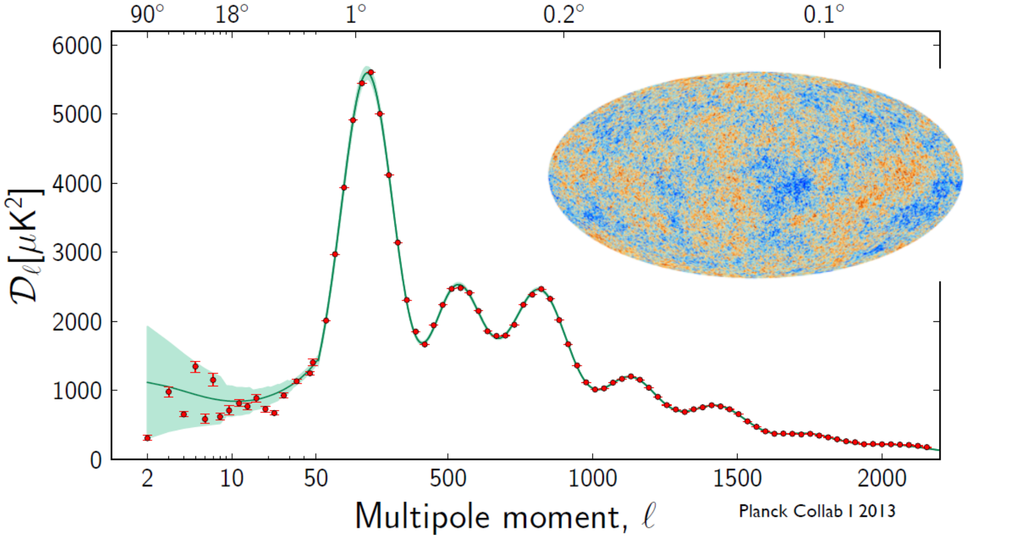
Galaxies



Galaxy clusters



Planck : power spectrum Ω_b, Ω_m, Ω_Λ



The WIMP miracle

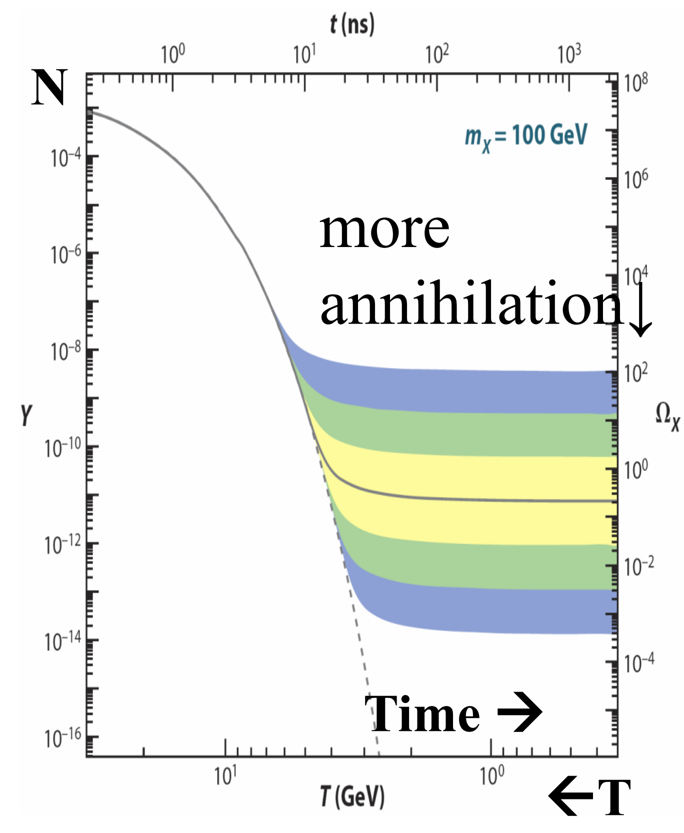
Possible to obtain the required abundance of dark matter with particles of mass **~100 GeV,** with the **weak interaction force**
annihilation rate **$<\sigma v>$ ~3 10^{-26} cm^3/s**

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

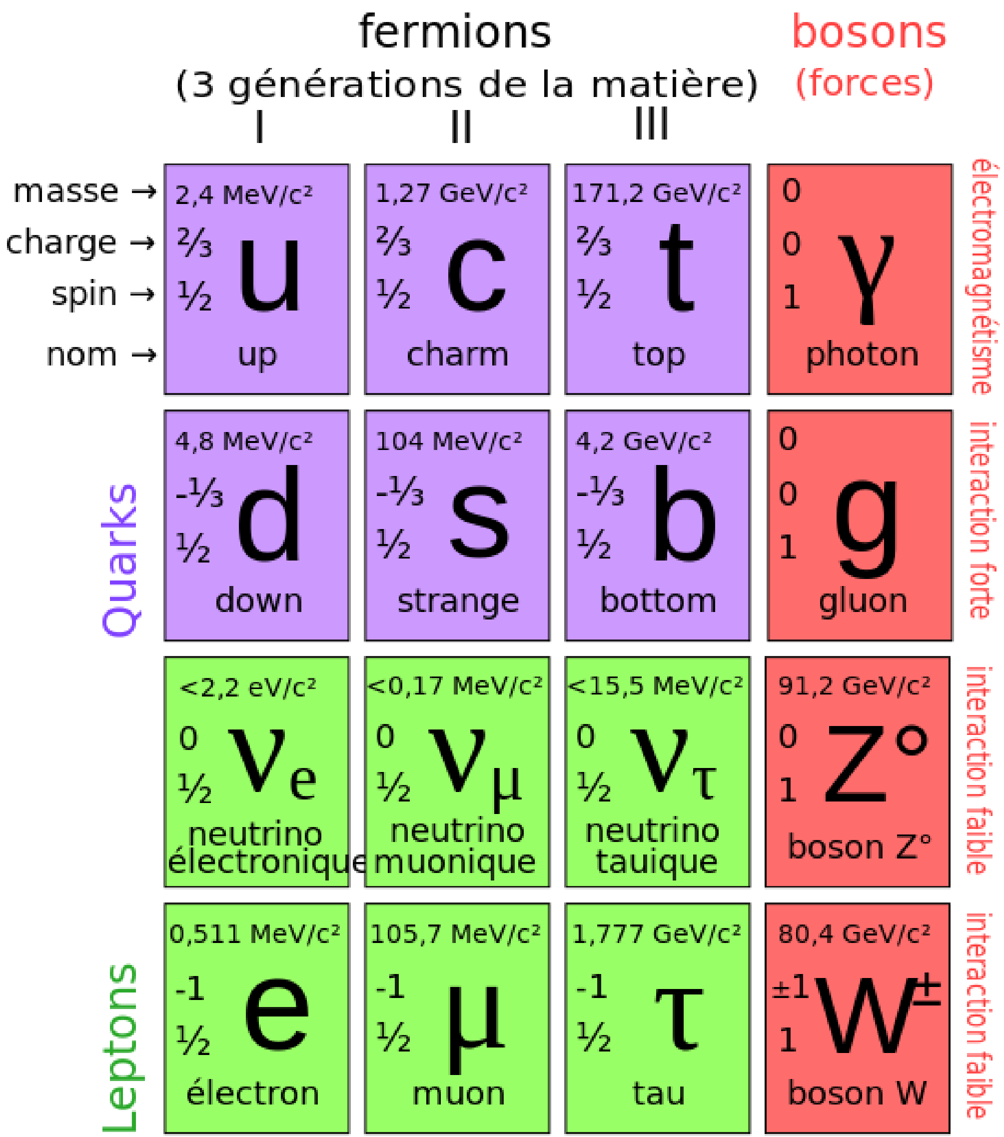
$n <\sigma v> \sim 1/t_{hubble}$

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

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



Particles beyond standard model?



From the Big-Bang

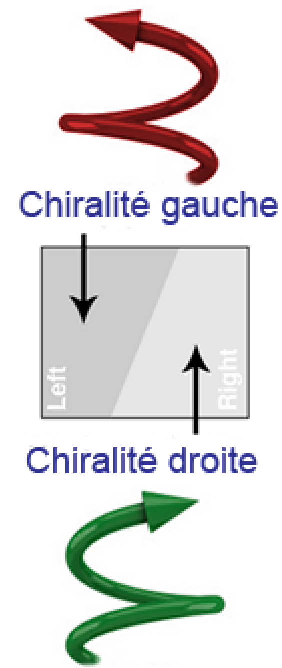
~400 photons /cm^3

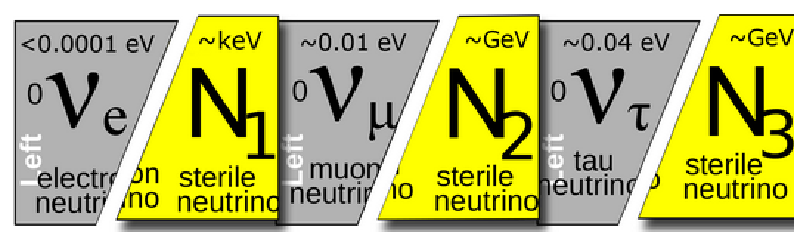
~300 neutrinos /cm^3

0,1 billions of billions/s cross us

➔**Search for WIMPS since 1985**

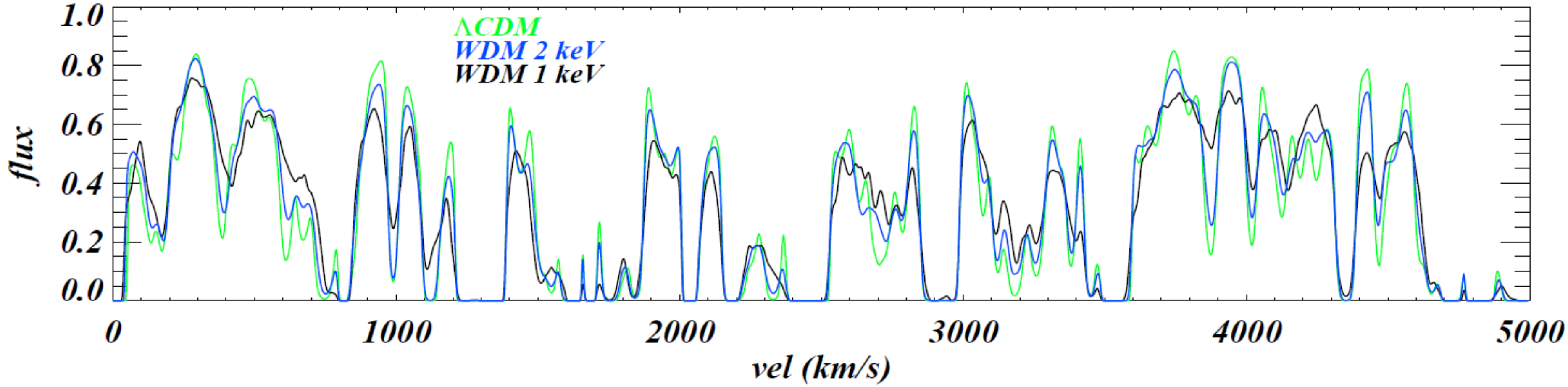
Extension to sterile neutrinos?

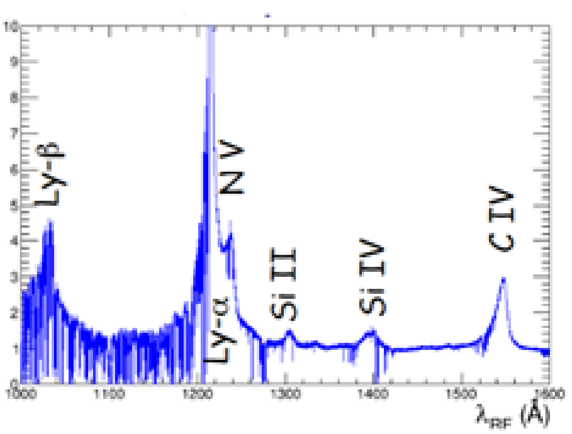




Ly-α: constraints on m(warm)

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)



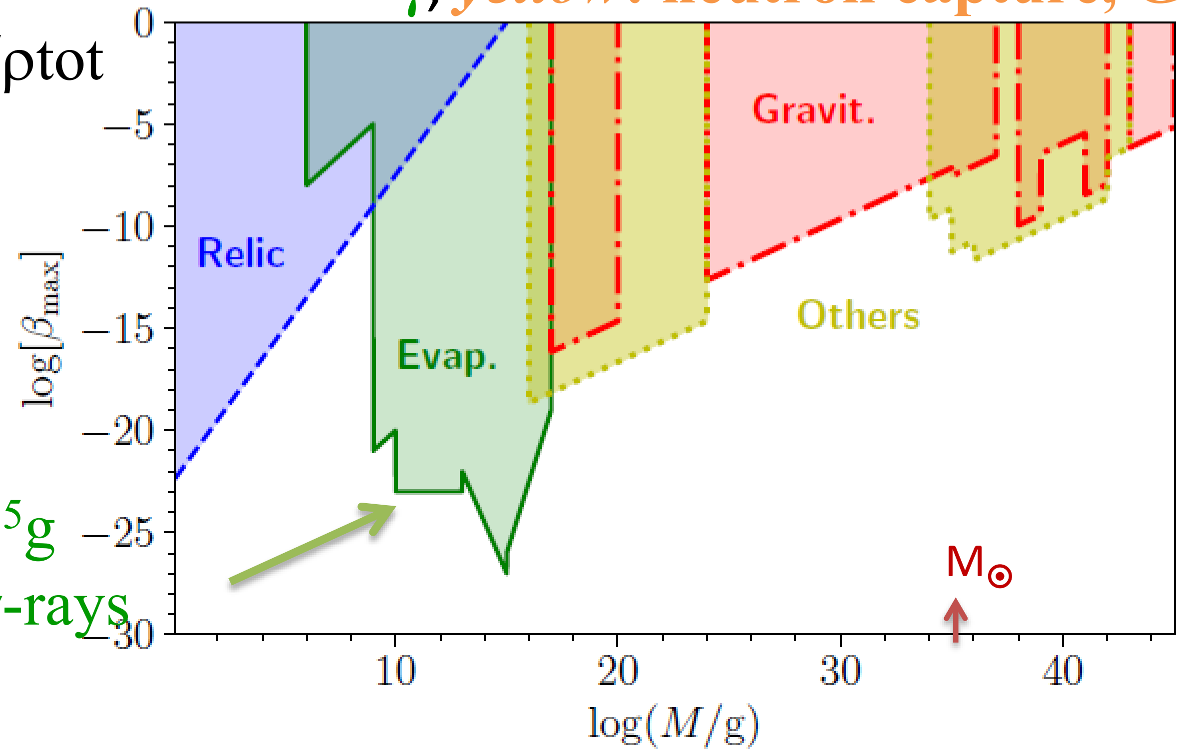


WDM, $\mathbf{m_X}$ **> 4.65 keV** thermal relics
$\mathbf{m_s}$ **> 29 keV** non-resonant production
Yeche et al (2017), Chabanier et al (2019)

Primordial Black holes

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

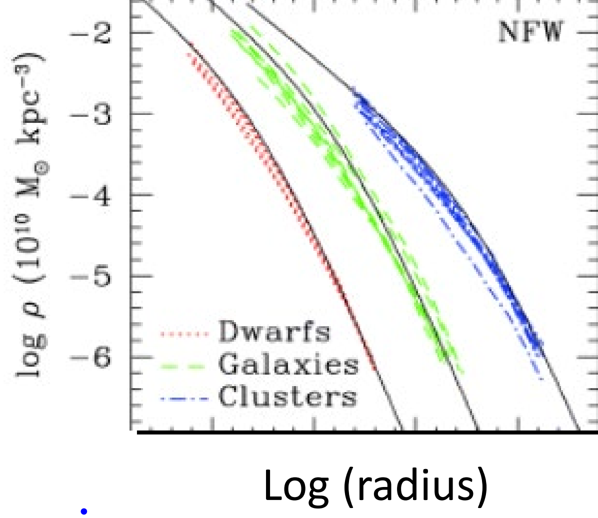
Candidates for the dark matter

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



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, $\lambda_{dB} = h/m_a v$
➔ λ_{dB} = 1-2 kpc

- In fact $\lambda_{dB} \sim$ 1-2 kpc for $m_a = 10^{-22}$ eV , and v~10km/s

For masses $m_a = 10^{-22}$ eV, quantum pressure prevents the formation of structures below Mcut = $3\ 10^8\ m_{22}^{-3/2}\ M_\odot$ *(Hui et al 2017)*

A long history

Already 40 yrs!
Baldeschi, Gelmini, Ruffini (1983)
Galactic dark matter halos made of
fermions of $m=10^{-3}$ eV,
or bosons of $m=10^{-24}$eV

Mass-size relation for equilibrium

$$MR = 9.9\hbar^2/Gm^2$$

For $M\sim 10^{12}M_\odot$ $R\sim 30$kpc
Sin (1994) rotation curves with pseudo Nambu-Goldstone boson

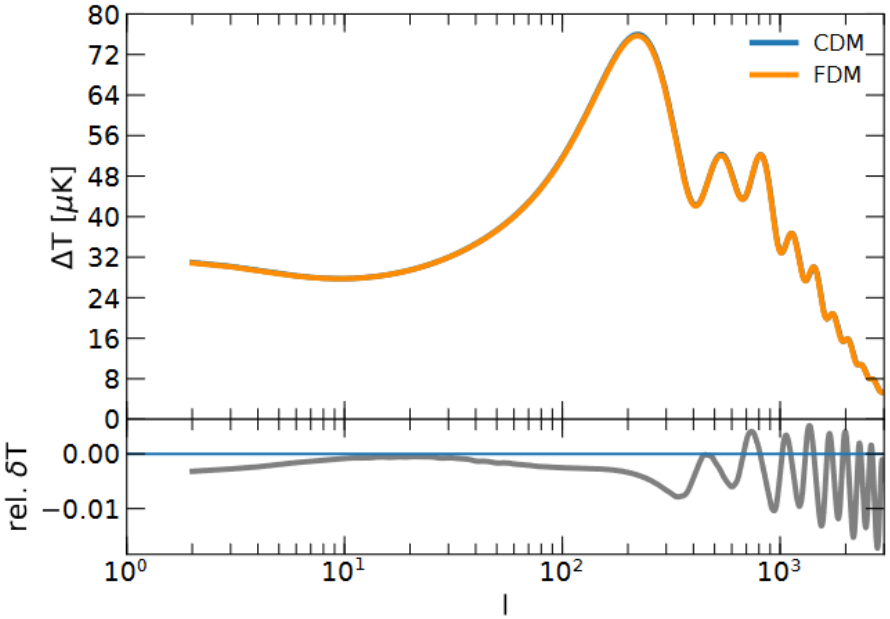
Hu et al (2000), are they self-interacting (SI) or not?
Scalar field SFDM → SI-SFDM
Böhmer & Harko (2007)

Hui et al (2017) review and revisit the problem: $m > 10^{-21}$ eV

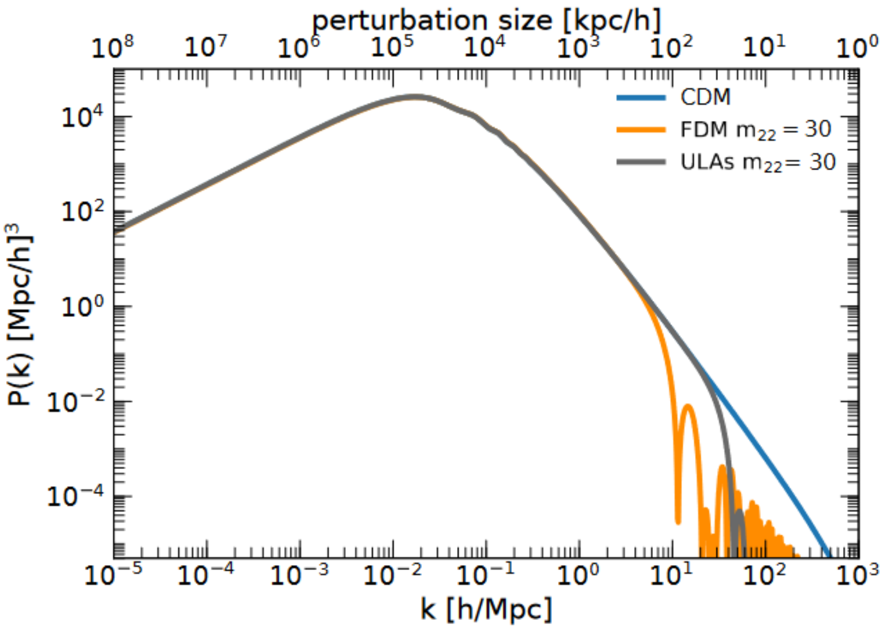
Fluctuation spectrum

Temperature anisotropies are undistinguishable from ΛCDM
Foidl & Rindler-Daller 2022

Scalar-field DM (SFDM without self-interaction →FDM)
Or Ultra-light actions (from QCD) → cut the high spatial frequencies k

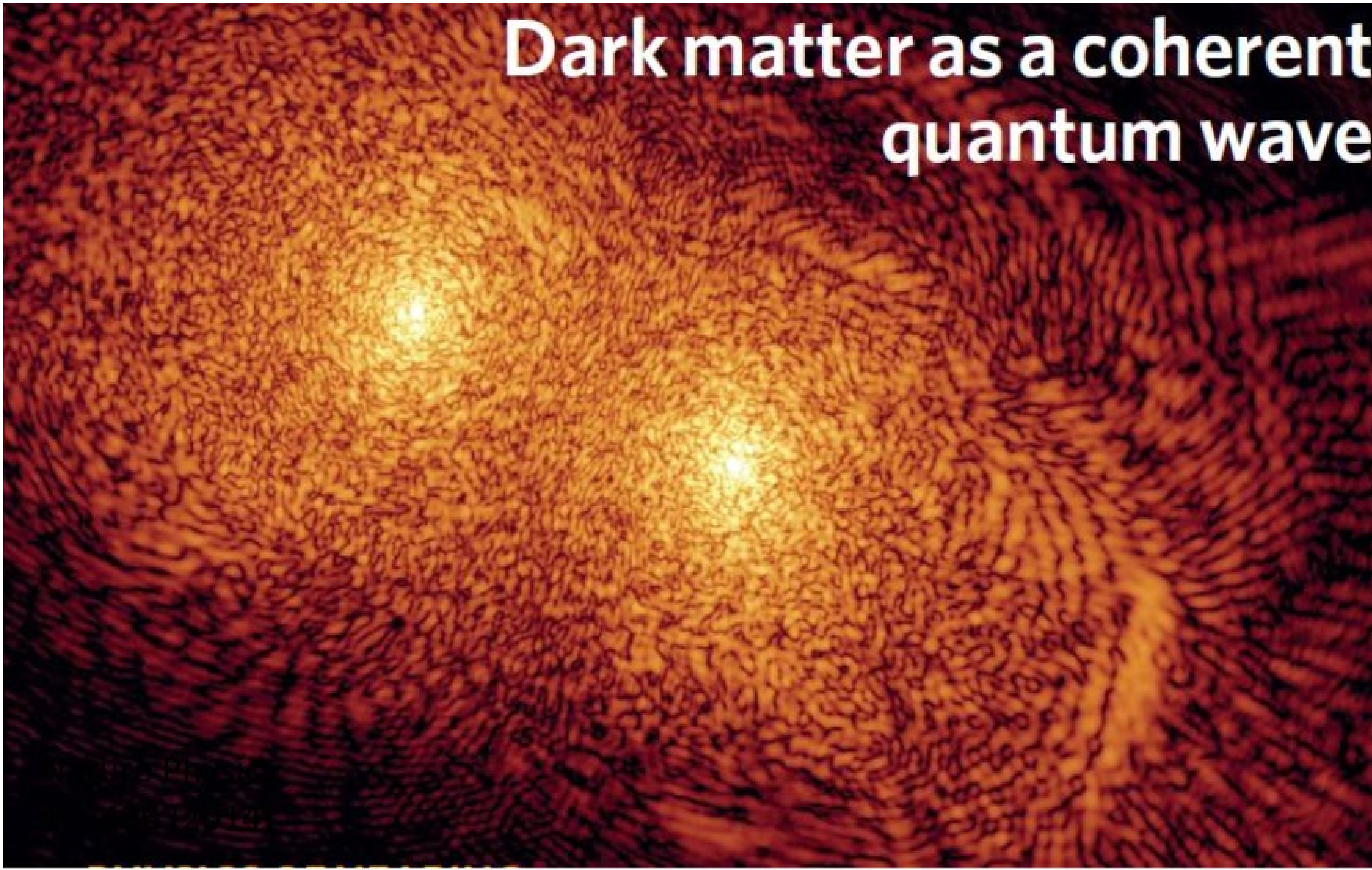


CMB acoustic modes

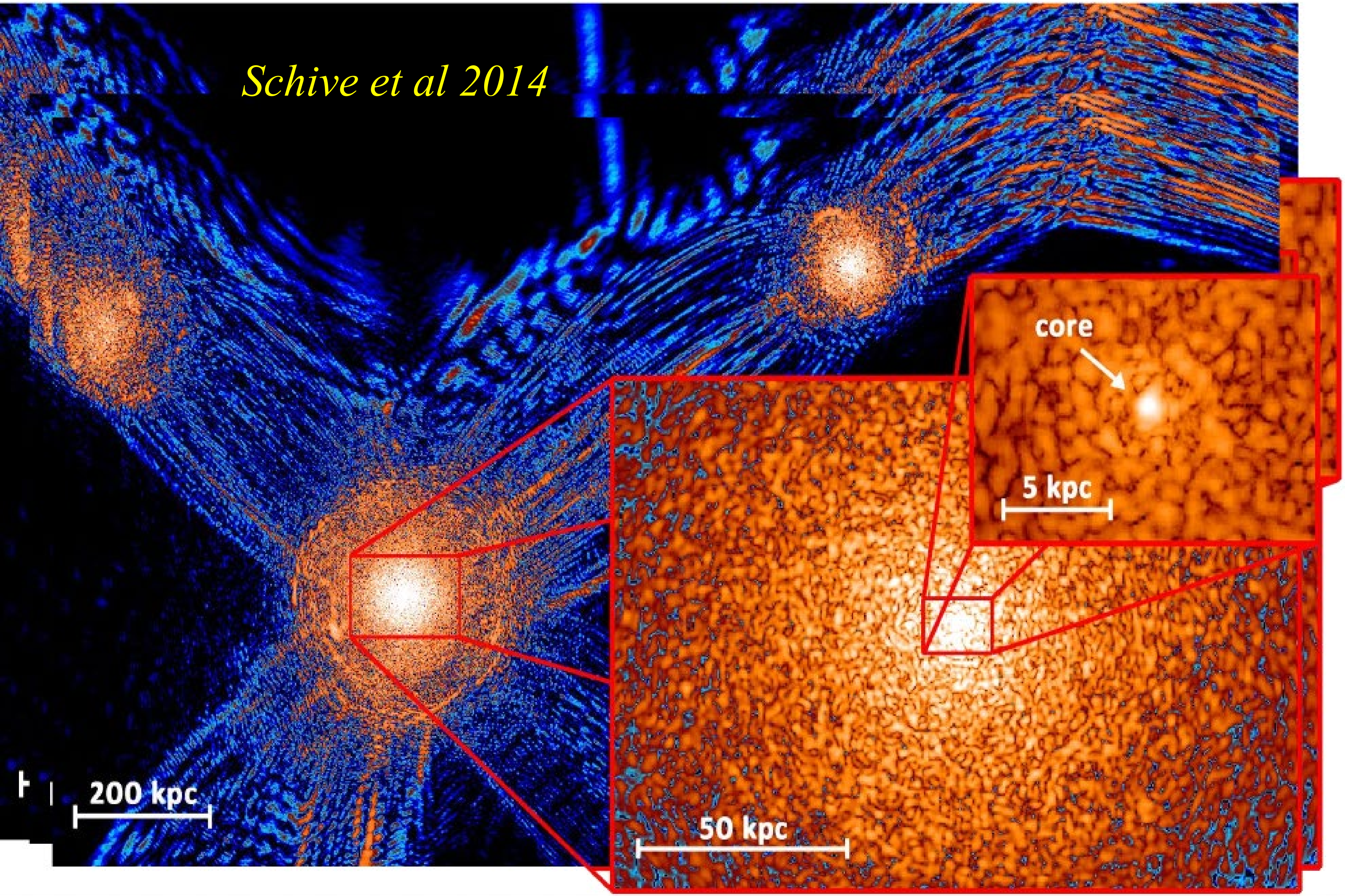


Simulations AMR: eq. Schrödinger- Poisson

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



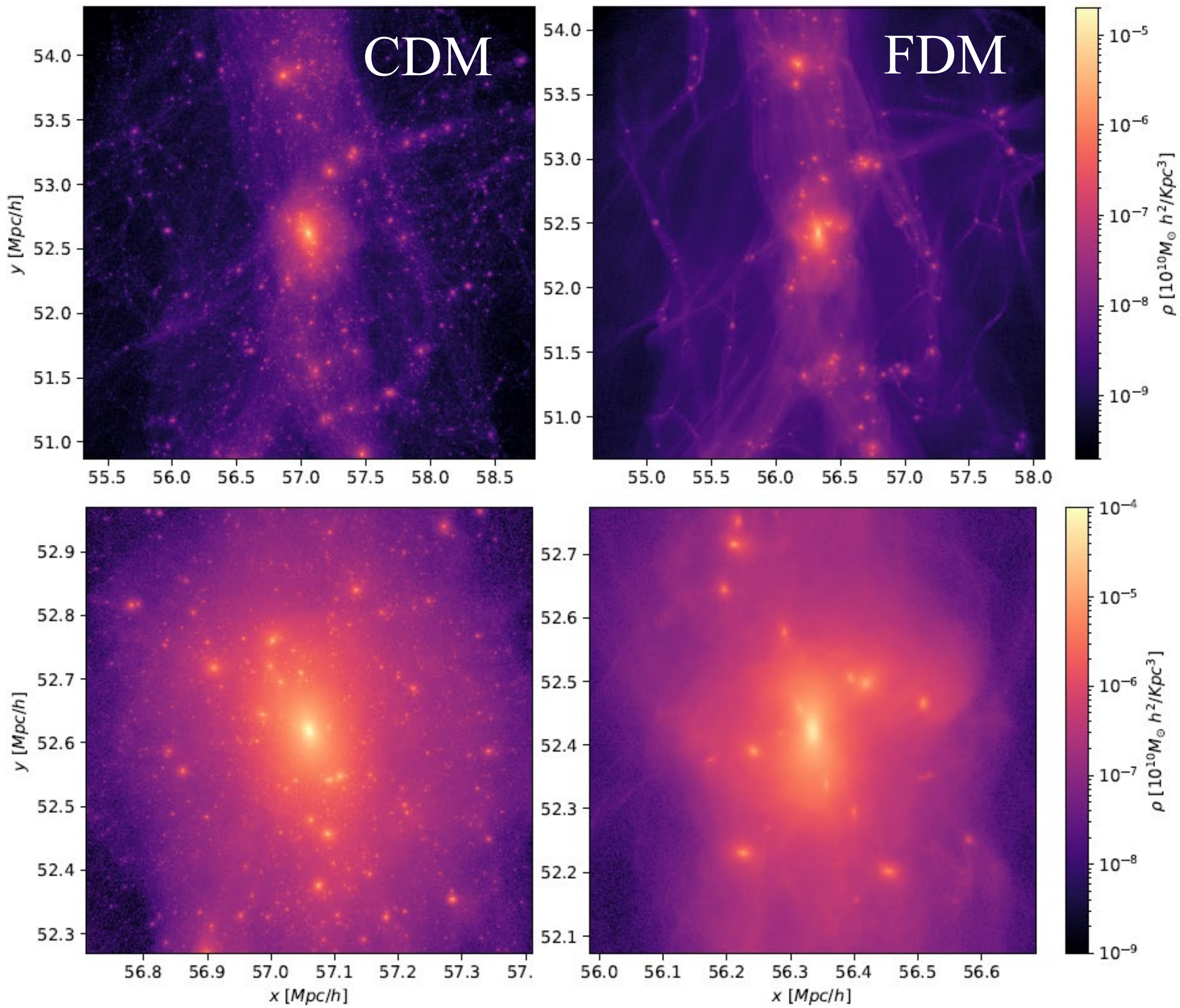
Quantum interferences: 9 orders of magnitude



Milky Way: Aquarius, satellites

Nori et al 2023 AX-GADGET, compared with CDM

Expected scaling law $\rho_c \sim R_c^{-4}$ while observations say $\rho_c \sim R_c^{-1}$



$\Sigma = 150 M_o/pc^2$

Donato et al 2009

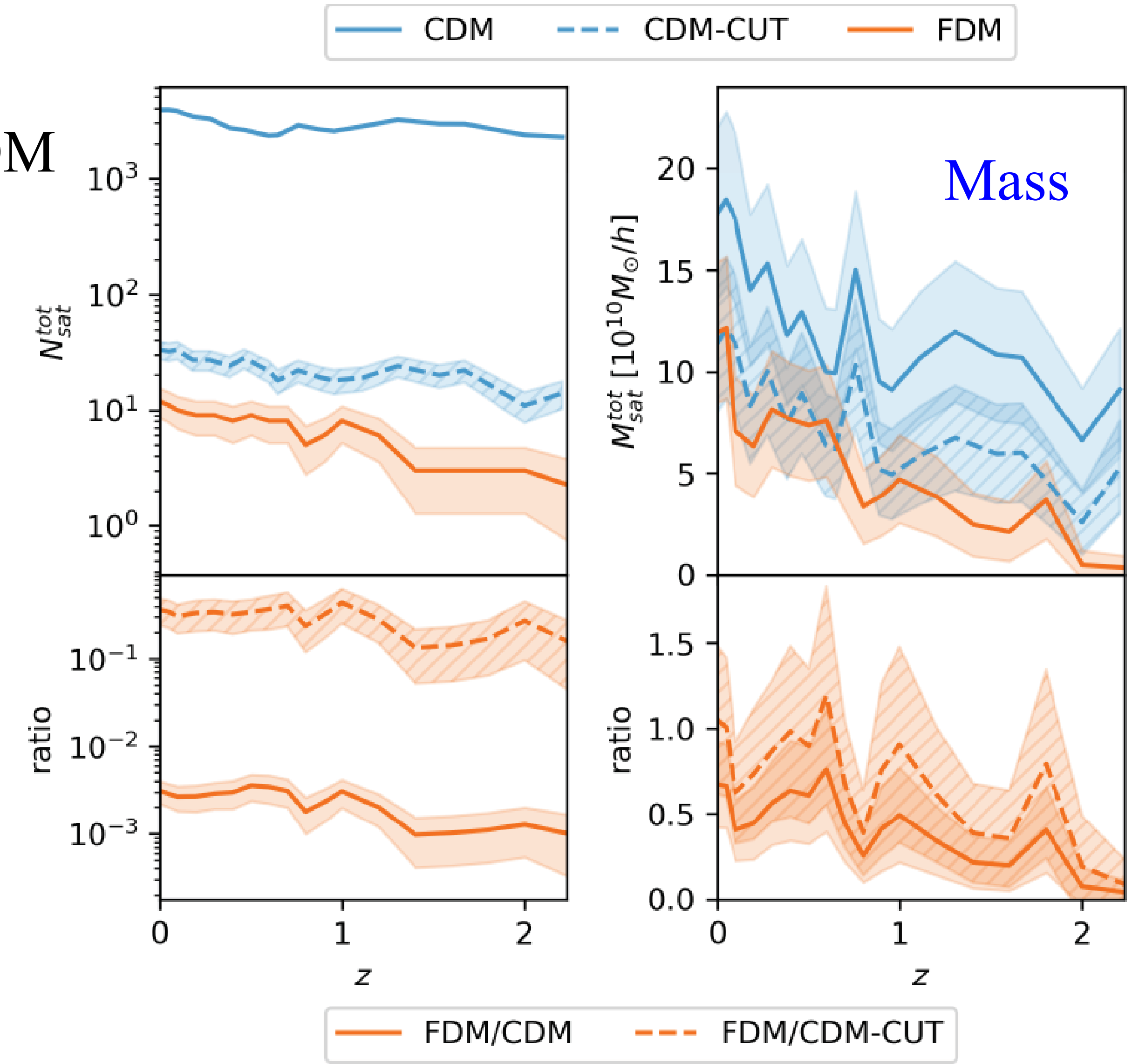
Zoom x 5

Milky Way: Aquarius, satellites

Nori et al 2023

Comparison with CDM and also when Msat > Mcut only

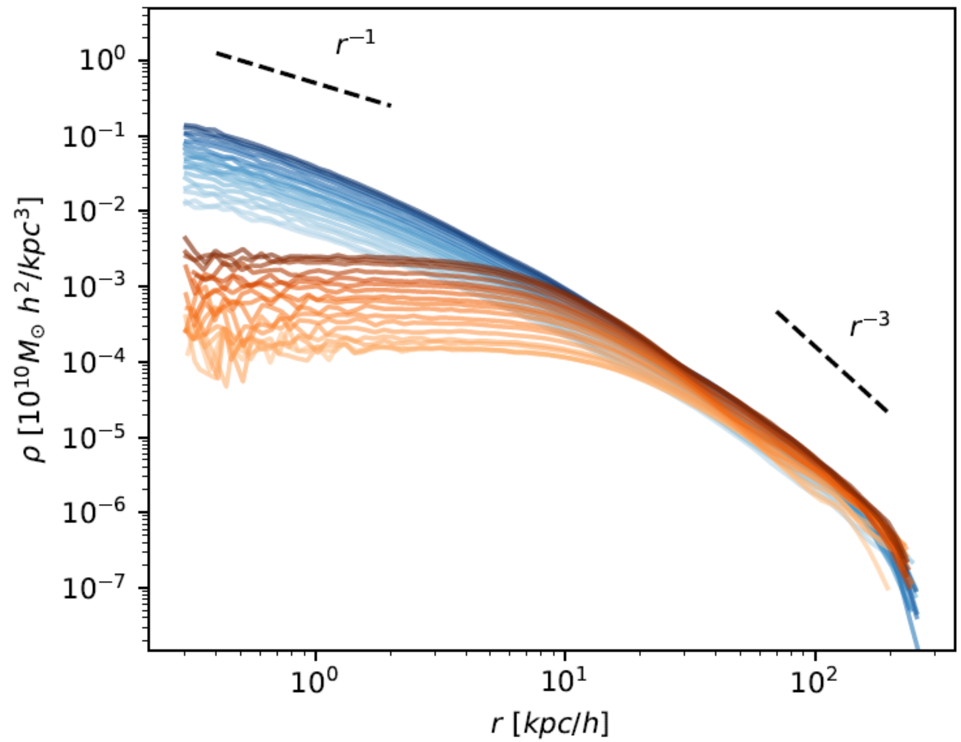
(CDM-CUT)

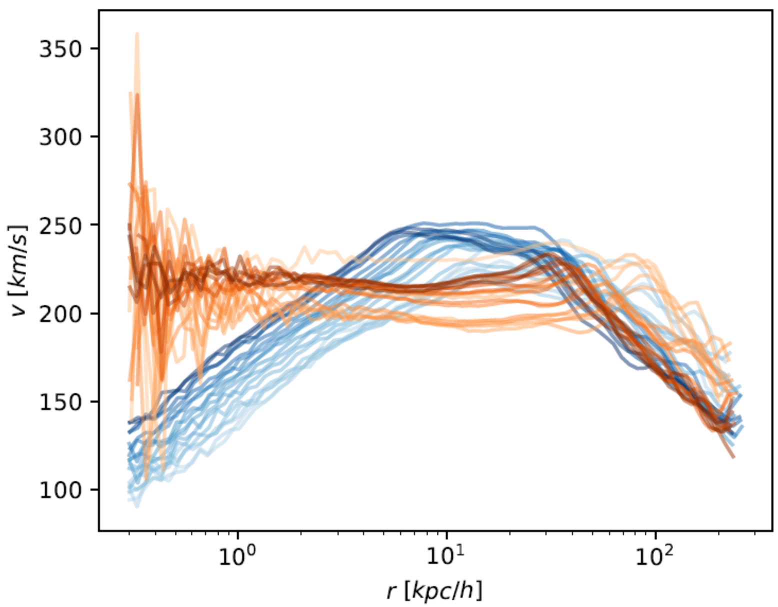


Evolution with redshift

Nori et al 2023

z=4 to z=0,
From light to dark lines



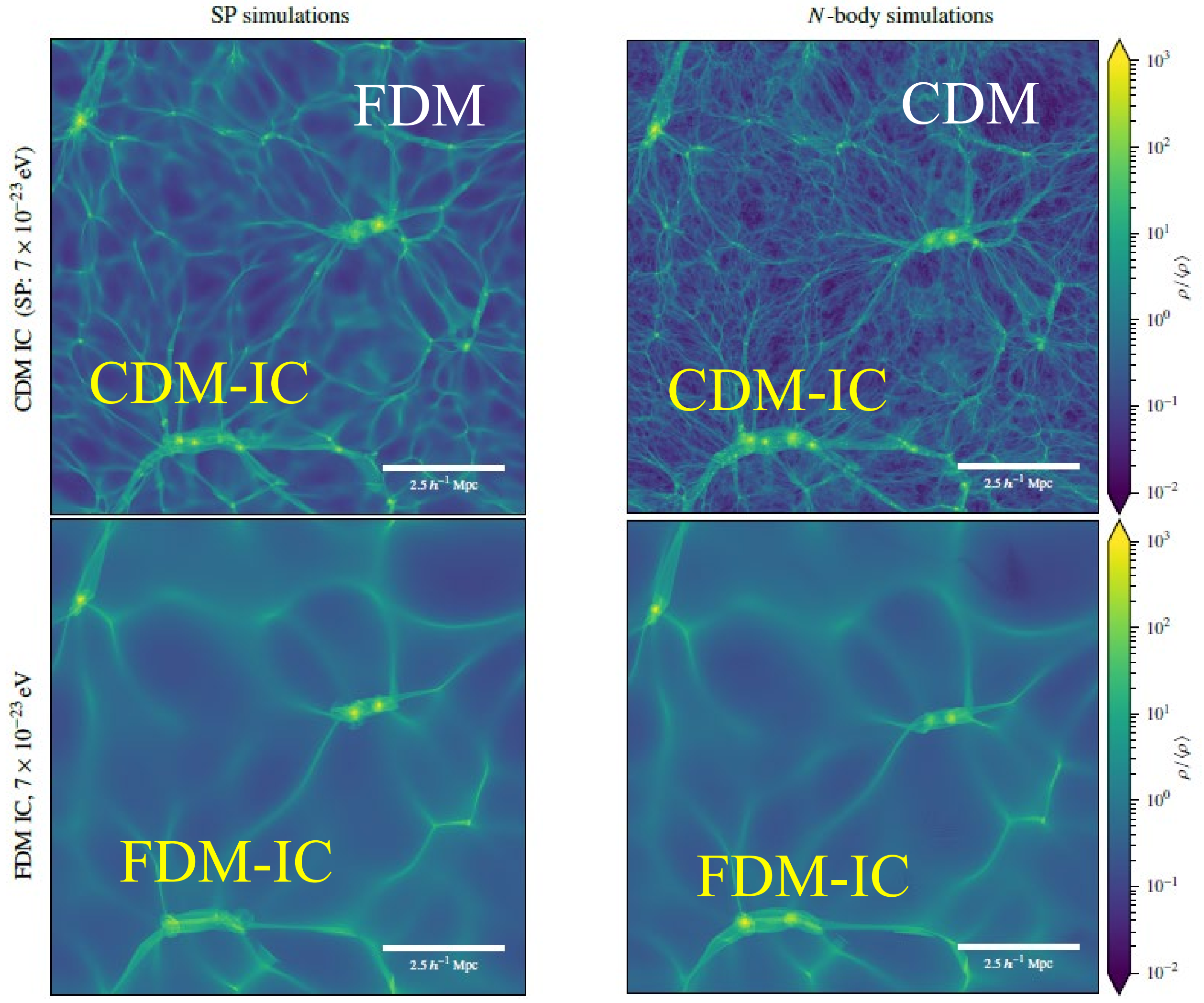


Even if density curves flatten
the asymptotic equilibrium
is not reached at z=0

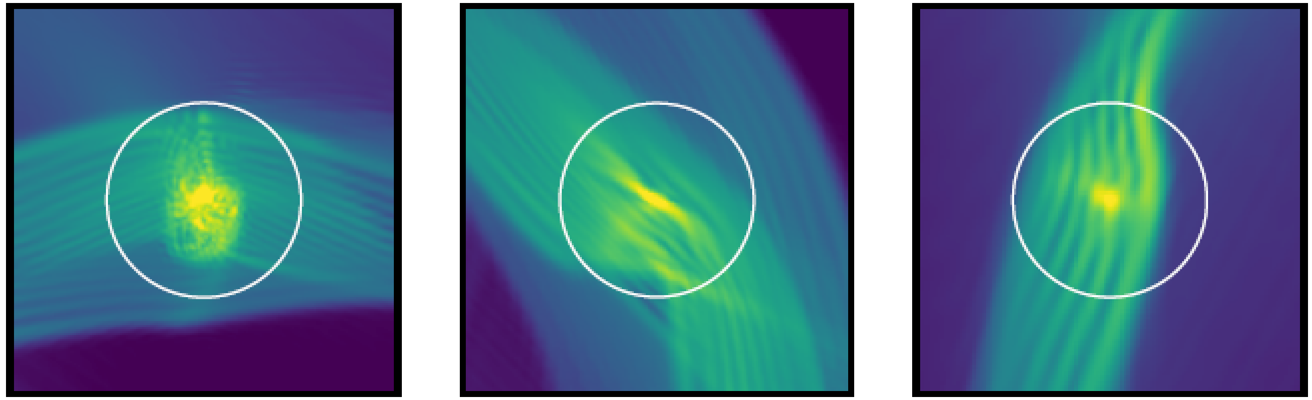
Halo mass function and filaments

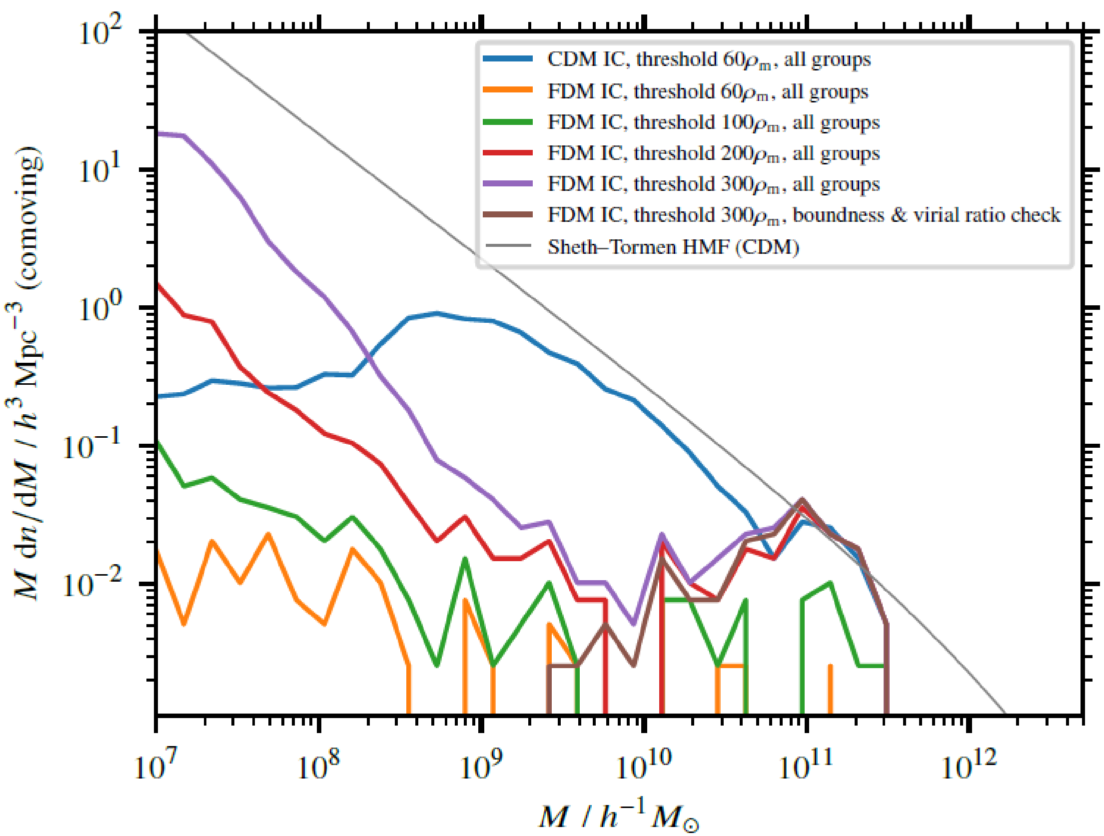
May & Springel 2022 AxiREPO

Due to the mass cut-off, halos are linked with thin flaments



Filaments do not fragment!





May & Springel 2022

Search for structures have to increase threshold

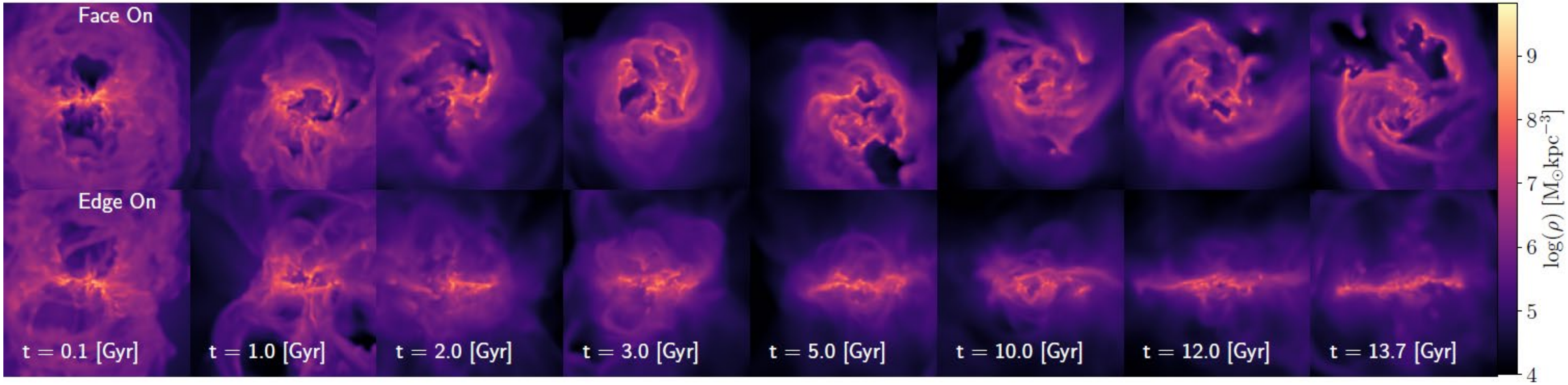
Big problem of resolution, to resolve the de Broglie length

Simulations of a dwarf galaxy

Assuming gas and star formation, stochastic and stationnary
Inducing fluctuations, different from white noise (n=0)

Ramses simulation of an isolated dwarf galaxy (Read et al 2016)
$M_{200} = 10^9 M_\odot$, fg=0.15, concentration 22.23

Cusp is mitigated in a Hubble time *(Hashim et al 2023)*

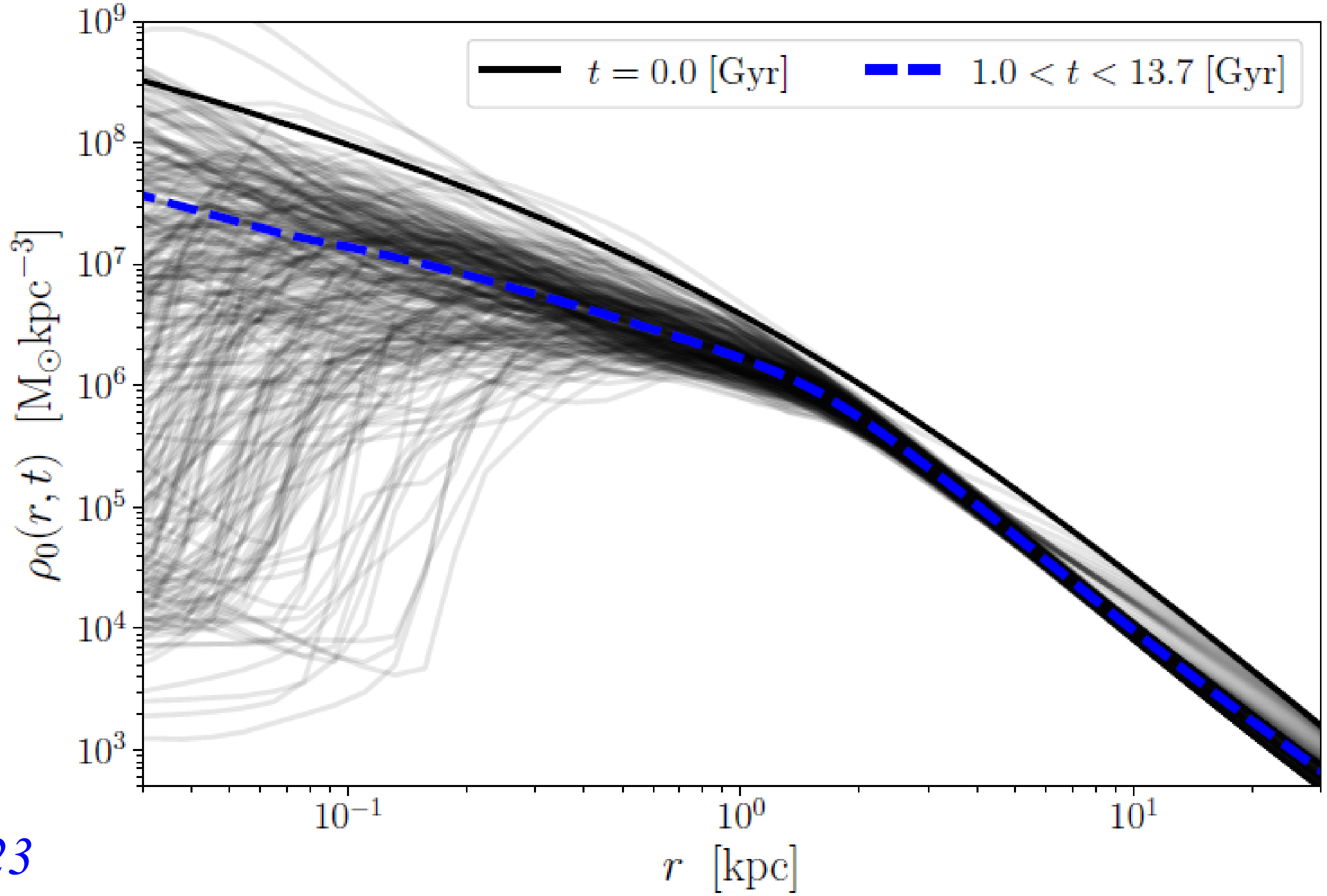


Box = 5kpc Important fluctuations due to SF, SN

Core formation ?

The slope of the radial density distribution is smoothed out, although not tending to a flat core

Trelax= 13.2 Gyr



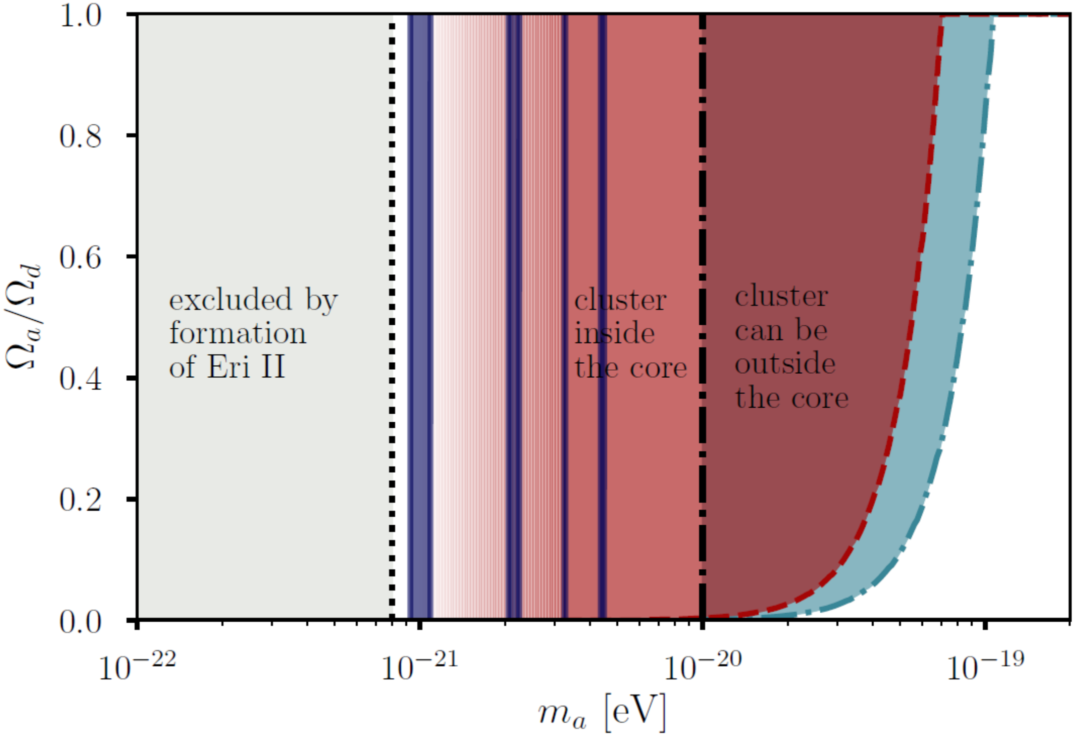
Hashim et al 2023

The case of Eridanus II

In this ultrafaint dwarf galaxy, there exists an old star cluster, which existence and size put also a constraint

Heating due to core oscillations ➔ $m_a > 10^{-19}$ eV

Marsh & Niemeyer 2018



May be the region inside the core is not completely valid

There are resonances for the oscillations

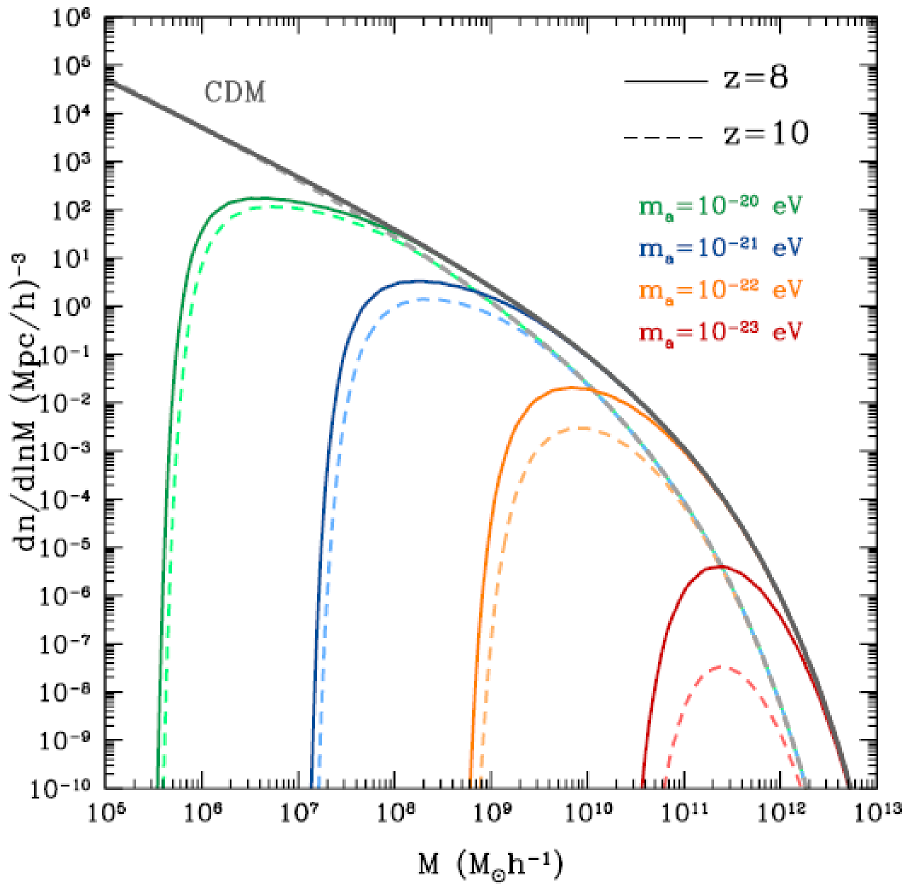
High-z massive galaxies?

Gong et al 2022 JWST found numerous galaxies 7<z<11

Big problem if star formation is made in the whole mass function of galaxies

➔ Too many UV to reionize the Universe
Contradiction to Planck CMB

FDM, but also WDM with sterile neutrinos
→Suppress small-mass galaxies



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

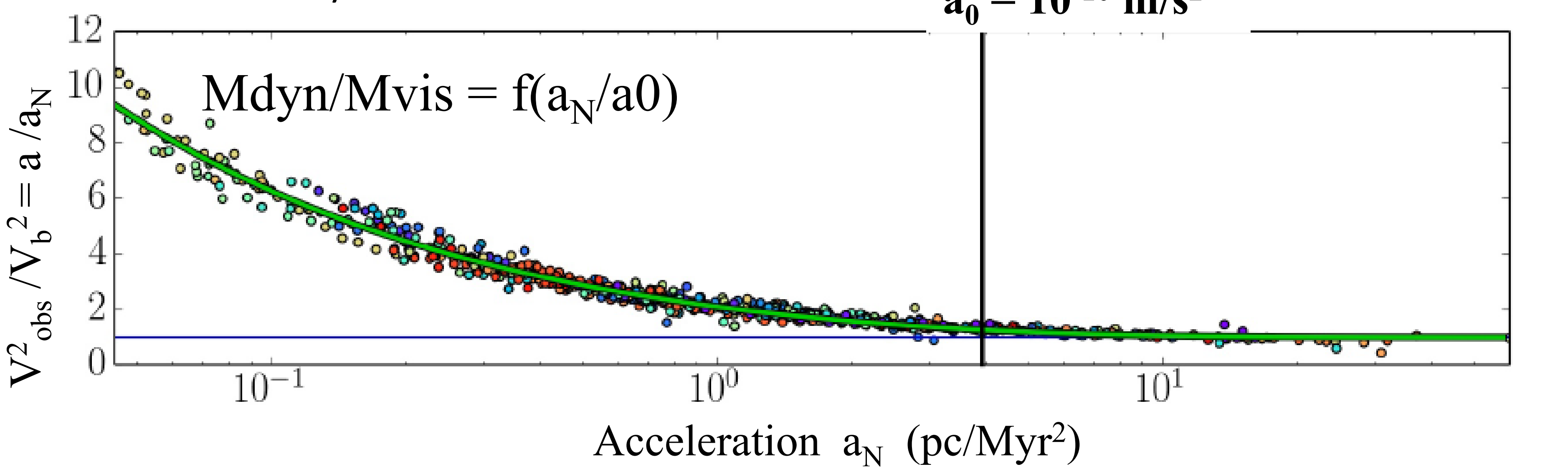
Covariant theory: TeVeS

➔Gravitationnal lenses

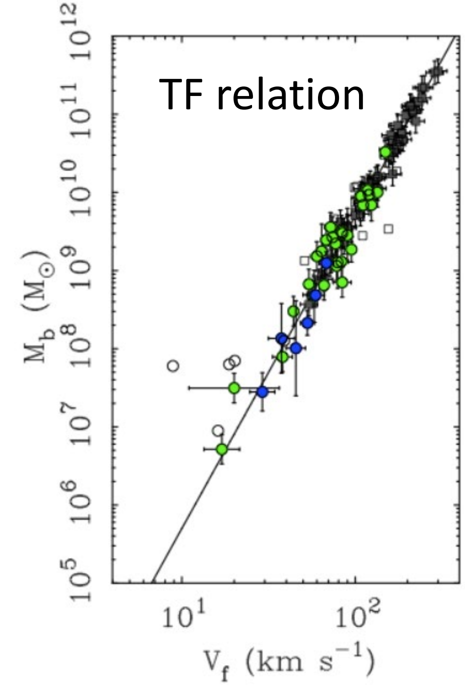
Bekenstein 2004

Conformal Gravity: Mannheim et al 2012

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



Success at weak surface densities

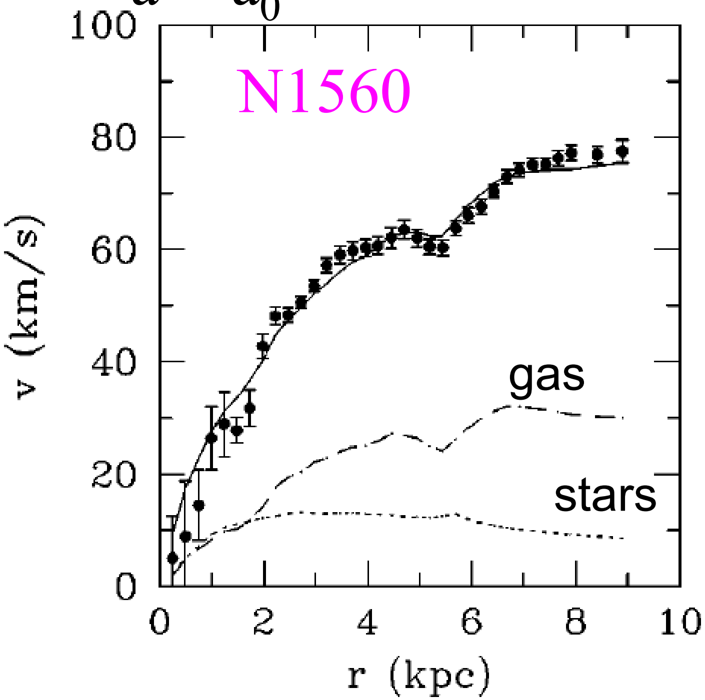


$\Sigma < \Sigma_0 \sim 150\ M_\odot/pc^2$, ➔the critical acceleration a_0

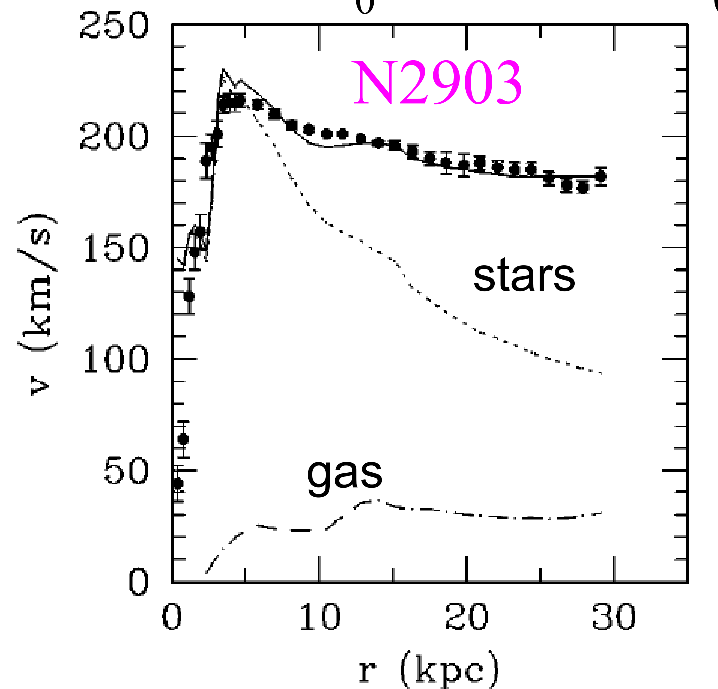
In particular dwarf galaxies

The rotation curves of all galaxy types

$a \ll a_0$

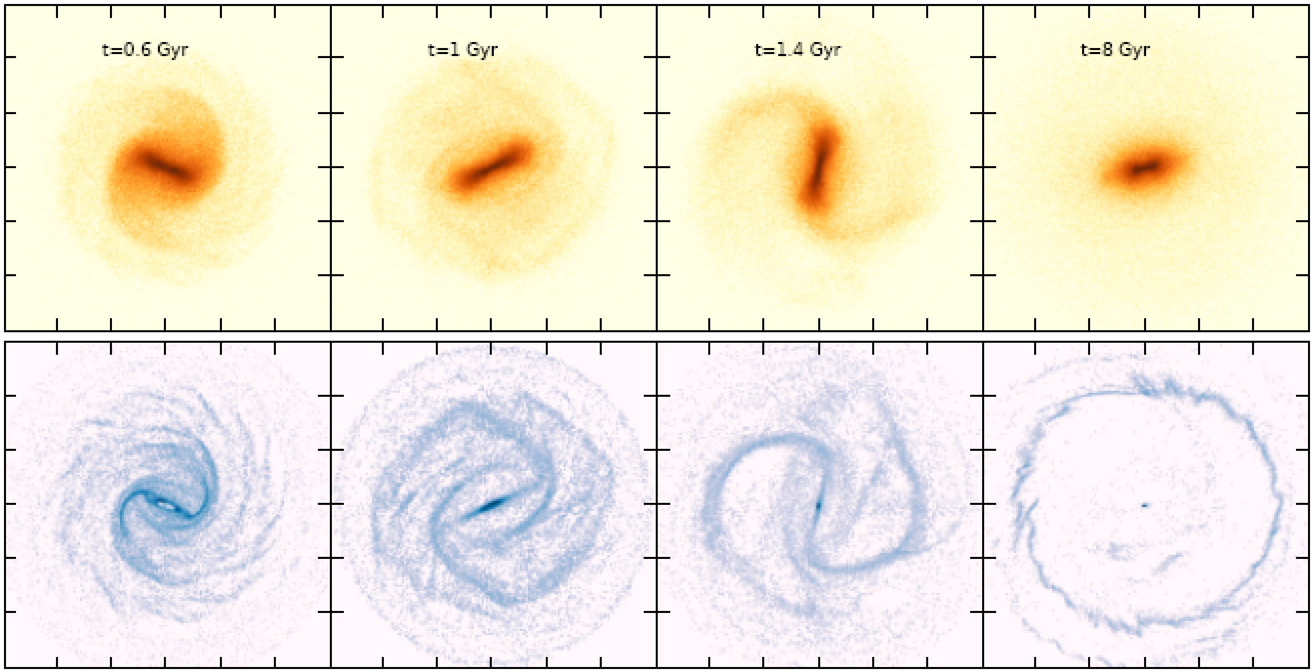


$a > a_0$ $a \ll a_0$



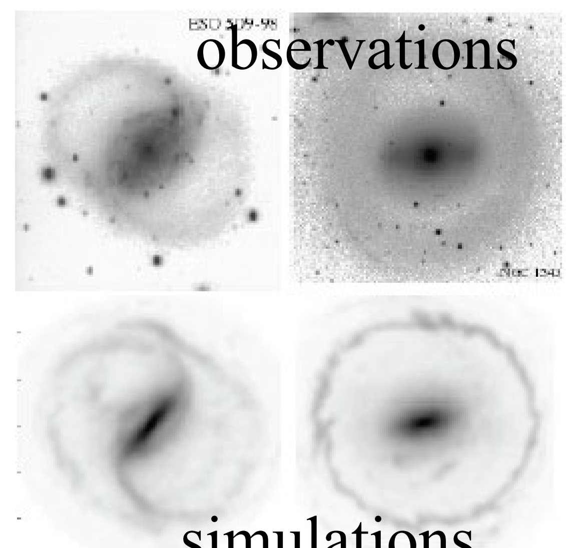
Influence of the dark halo ?

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



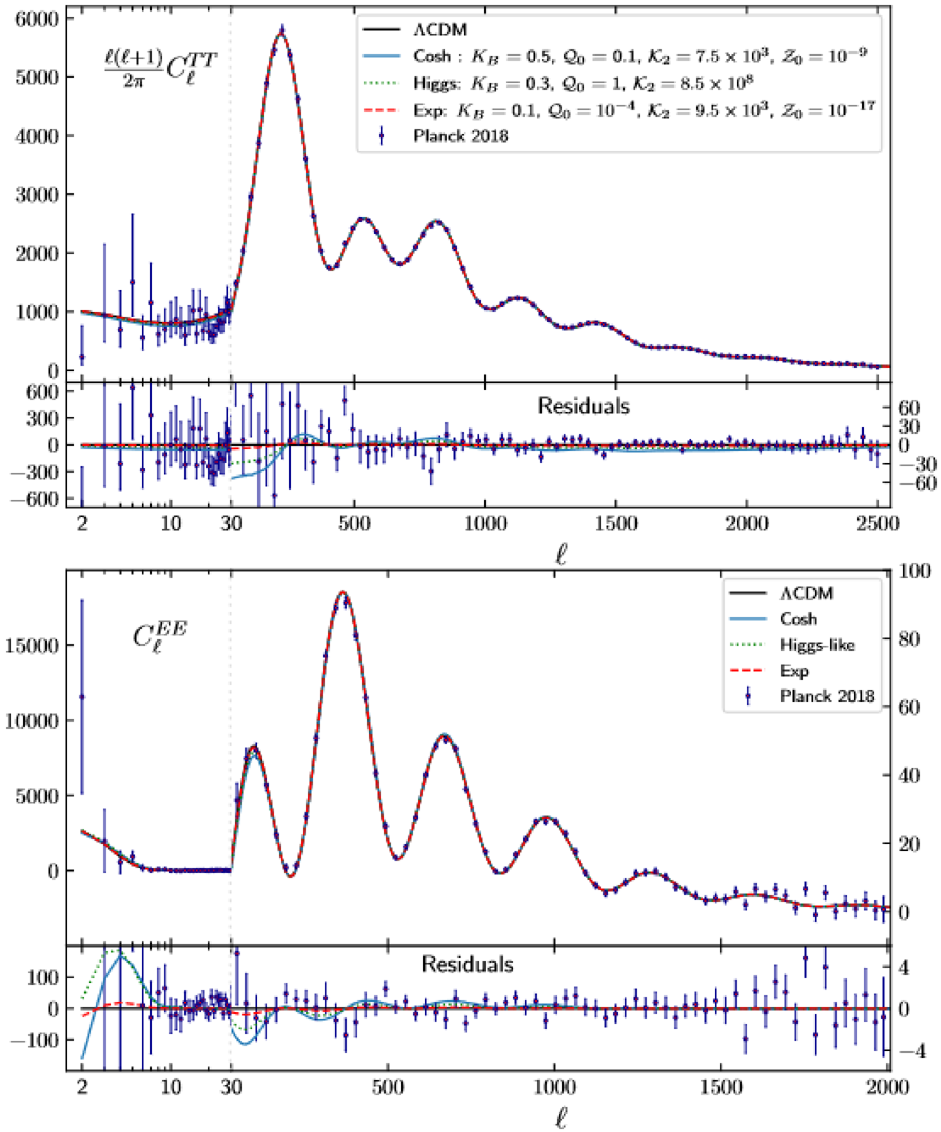
Stars

Gas



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

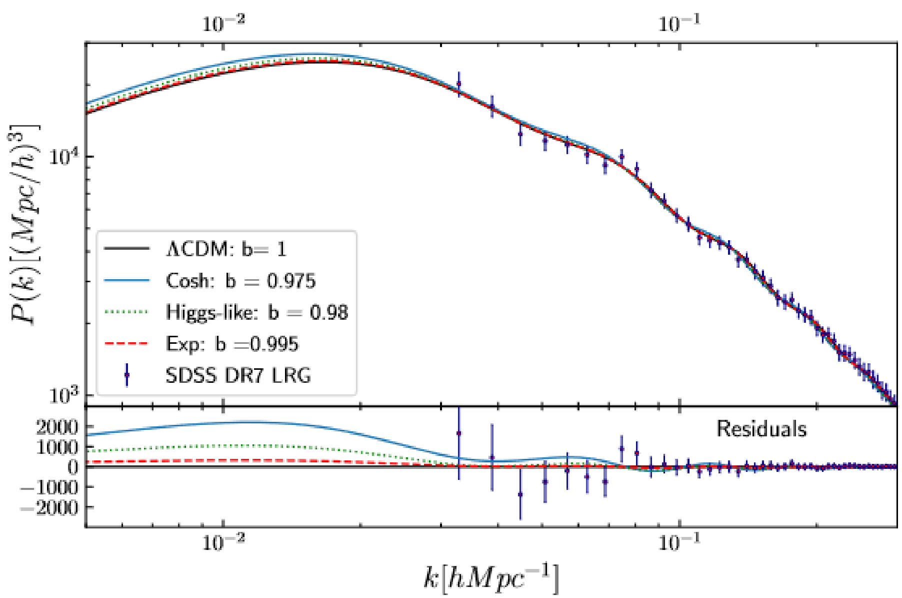
New theory with Vector field



Unit time-like vector

Gravitational lensing

$c_{GW} = c$



Skordis & Zlosnik 2021

Summary: axions or modified gravity?

Many constraints on the mass m_a, but not definitive

Some baryons+DM simulations (Aquarius, AX-Gadget, AxiREPO)

Approximations: cut-off of small structures (but negative pressure?)
SP fluid, Madelung approx, SI or not? Repulsive quantum force?

Interactions SMBH and soliton? (same order of masses)

Lyman-α forest? ➔ $m > 21\ 10^{-22}$ eV *(Nori et al 2019)*

Small halos (dwarfs) are less dense, larger cores
Massive halos, denser, unresolved solitons