Galaxy formation in a dark matter dominated Universe: Successes and challenges

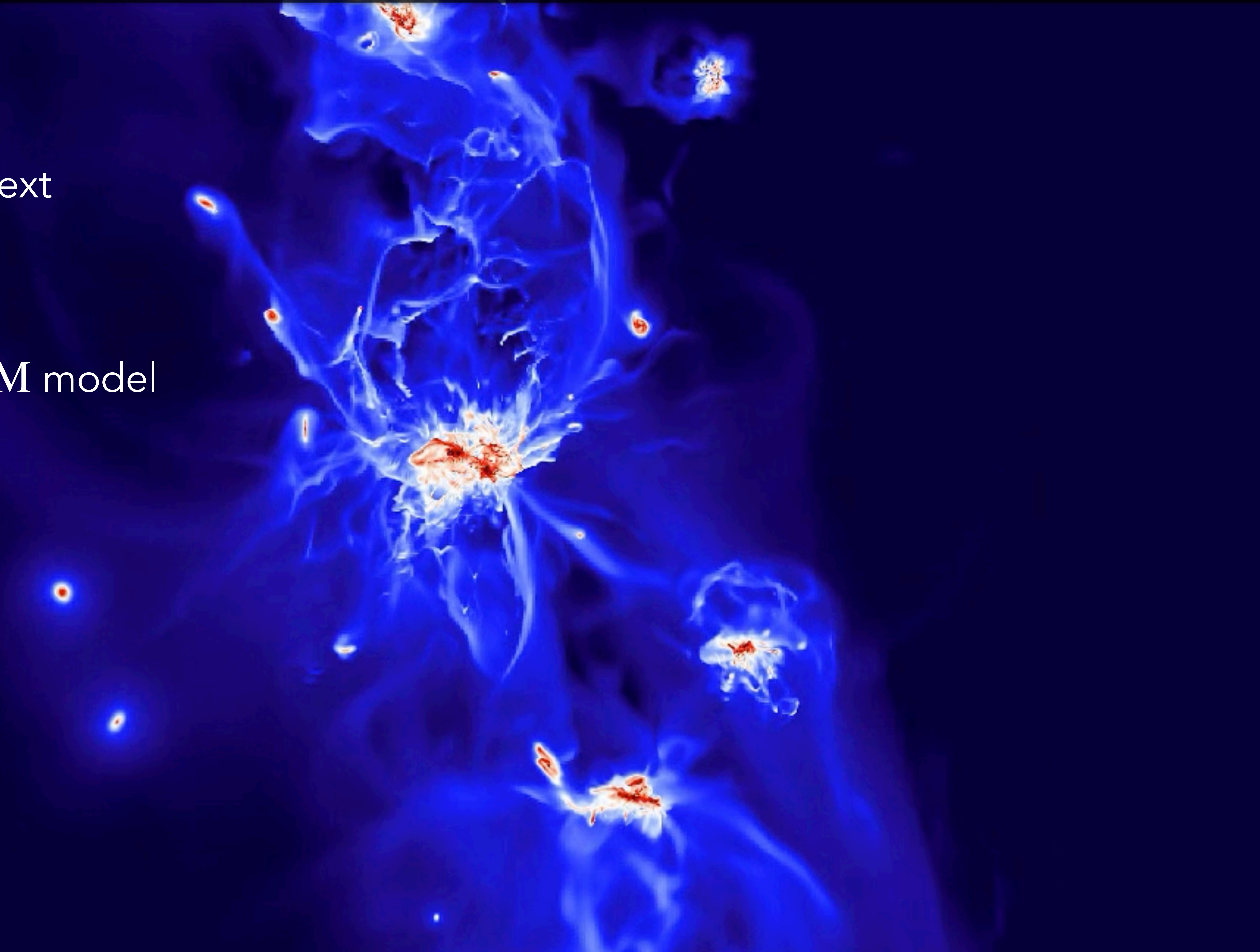
Oscar Agertz, Associate Professor in Astronomy, Lund University, Sweden

LUND UNIVERSITY

WALLENBERG ACADEMY FELLOWS

In this talk:

- Galaxy formation and the cosmological context
- Galaxy formation simulations
  - Historical problems and solutions
- Small scale challenges to the standard ΛCDM model



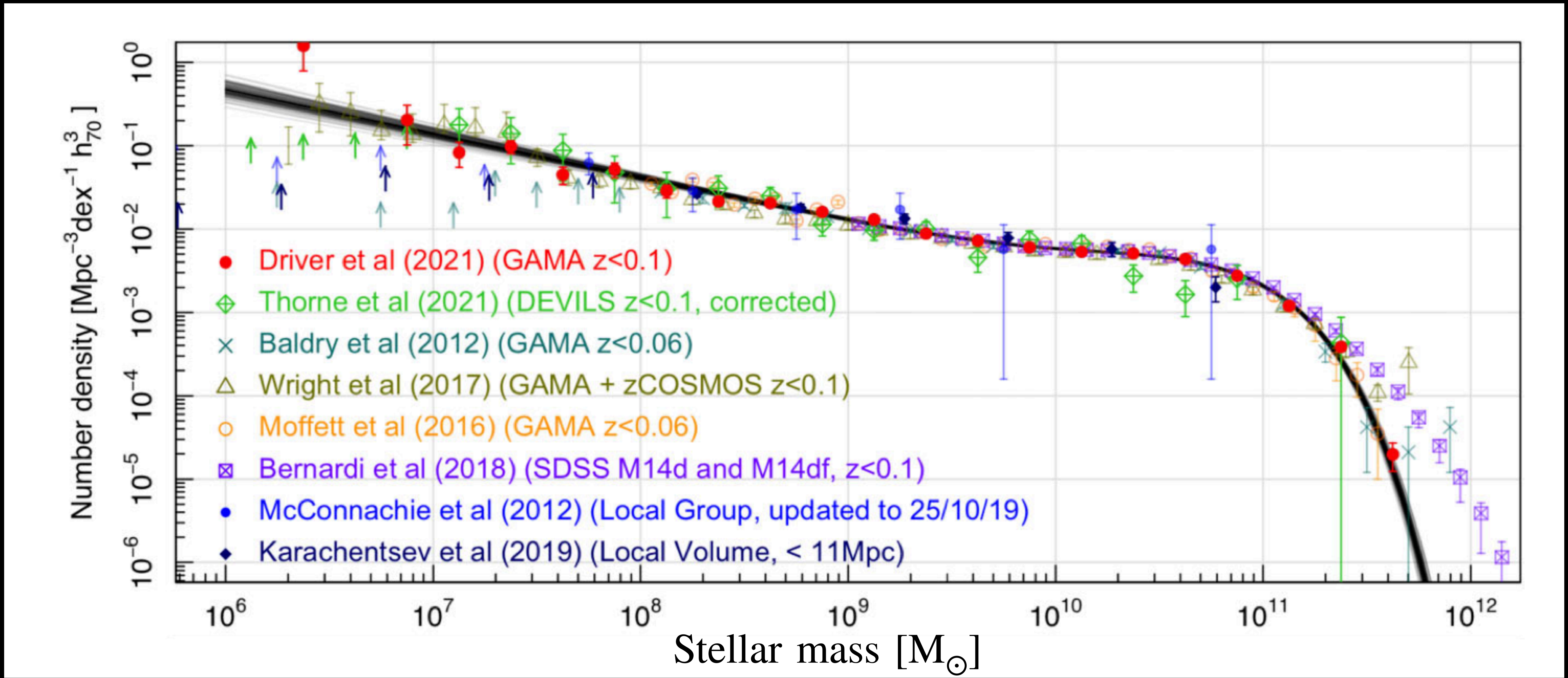
A few key problems

- Physics behind galaxy formation: role of gravity, gas in-and outflows, radiative processes, stellar evolutionary processes etc.
- Origins of galactic diversity, from tiny dwarf galaxies with little star formation, to large rapidly star forming discs, to dead ellipticals.
- Origins of disc galaxies like the Milky Way.

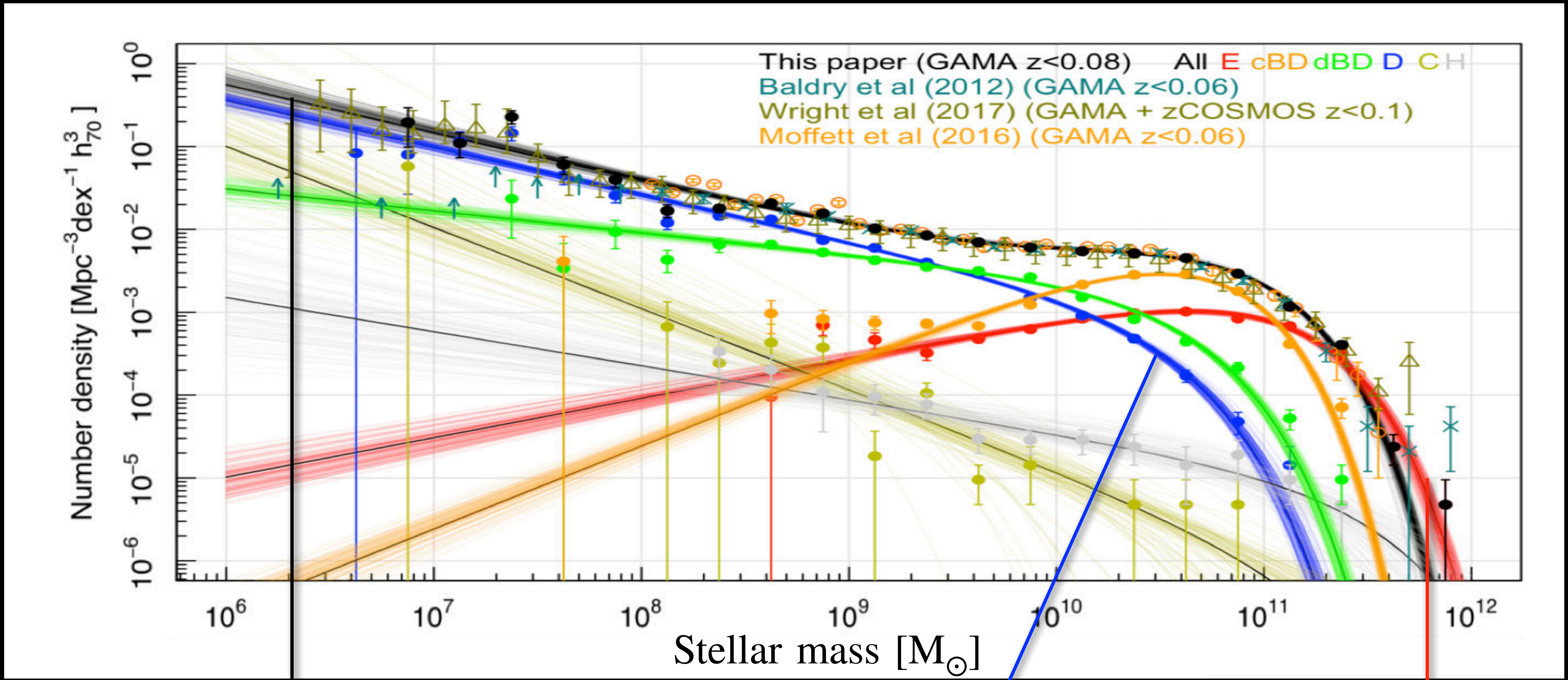
Credit:
ESA/Hubble & NASA

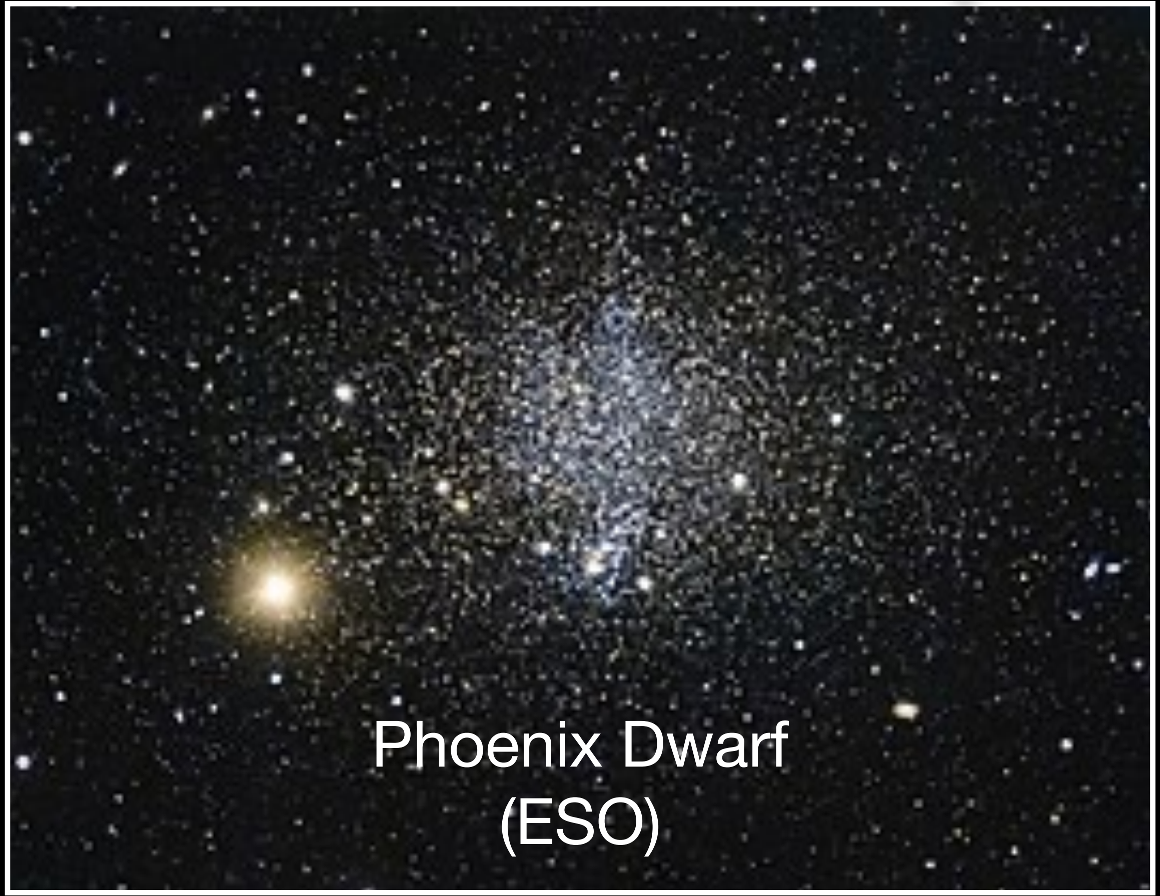
Acknowledgement: Judy Schmidt

The galactic inventory - density of galaxies vs. stellar mass vs. galaxy types



The galactic inventory - density of galaxies vs. stellar mass vs. galaxy types





Galaxy formation

Early stages and cosmological i

$$T_{\rm CMB}(z=0) = \frac{T_{\rm dec}}{1+z_{\rm dec}} = \frac{2925\,{\rm K}}{1071} \approx 2.73\,{\rm K}$$


Planck collaboration (2013)
Temperature
of the Universe
10¹⁰ Kelvin
Protons and
neutrons
freeze out
10⁹ Kelvin
Primordial
nucleosynthesis.
Hydrogen
(~75%) and
helium (~25%)
formation.
Density/temperature anisotropies
on the order of $\Delta \sim 10^{-5}$
~ 10,000 Kelvin
Photon/baryon decoupling.
Surface of last scattering
Big Bang
Time
1 second
15 minutes
400,000 years
13.8 Gyr

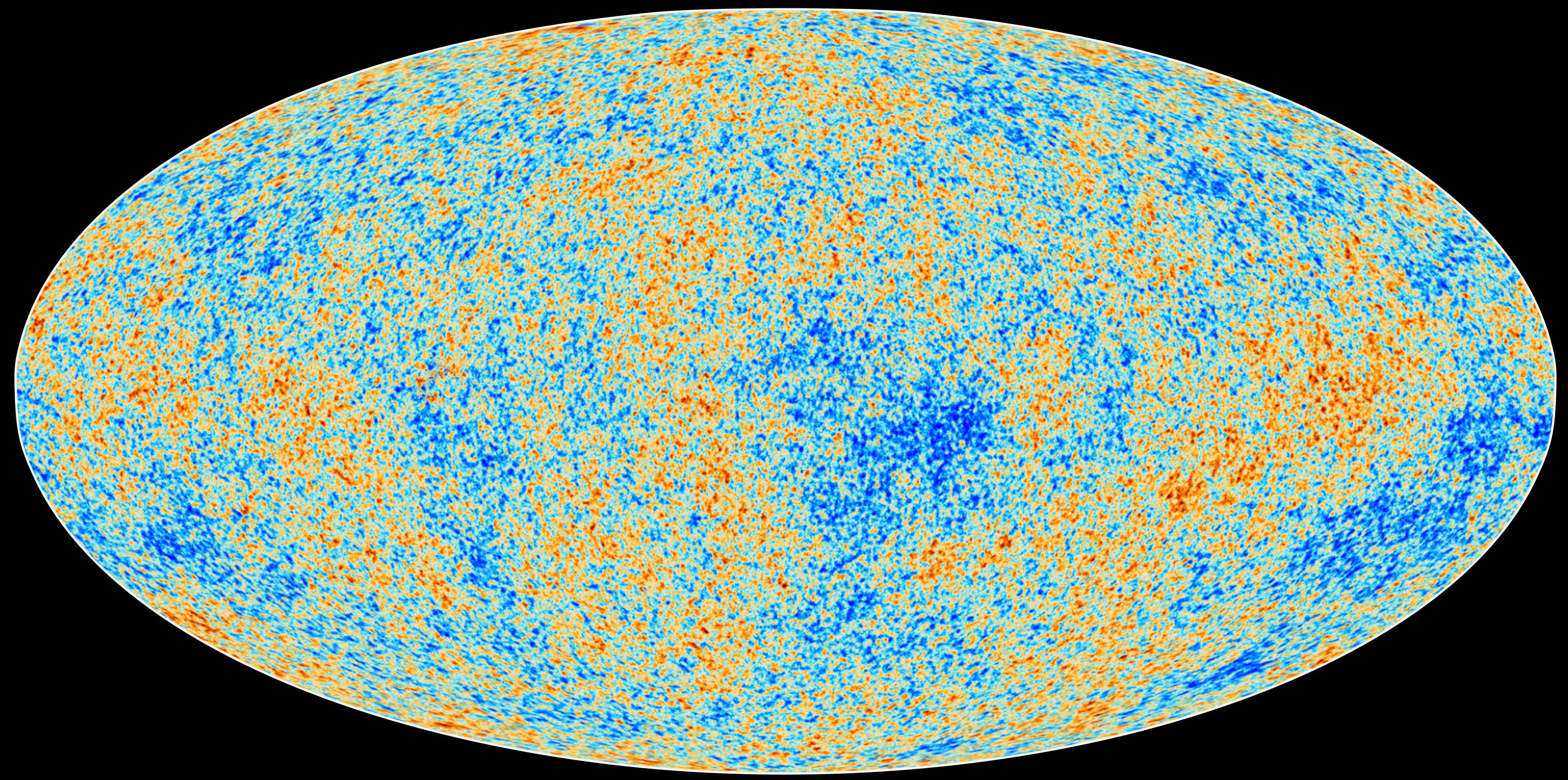

Planck collaboration (2013)
Temperature of the Universe
10^10 Kelvin
Protons and neutrons freeze out
10^9 Kelvin
Primordial nucleosynthesis. Hydrogen (~75%) and helium (~25%) formation.
Density/temperature anisotropies on the order of $\Delta \sim 10^{-5}$
~ 10,000 Kelvin
Photon/baryon decoupling. Surface of last scattering
Big Bang
Time
1 second
15 minutes
400,000 years
13.8 Gyr

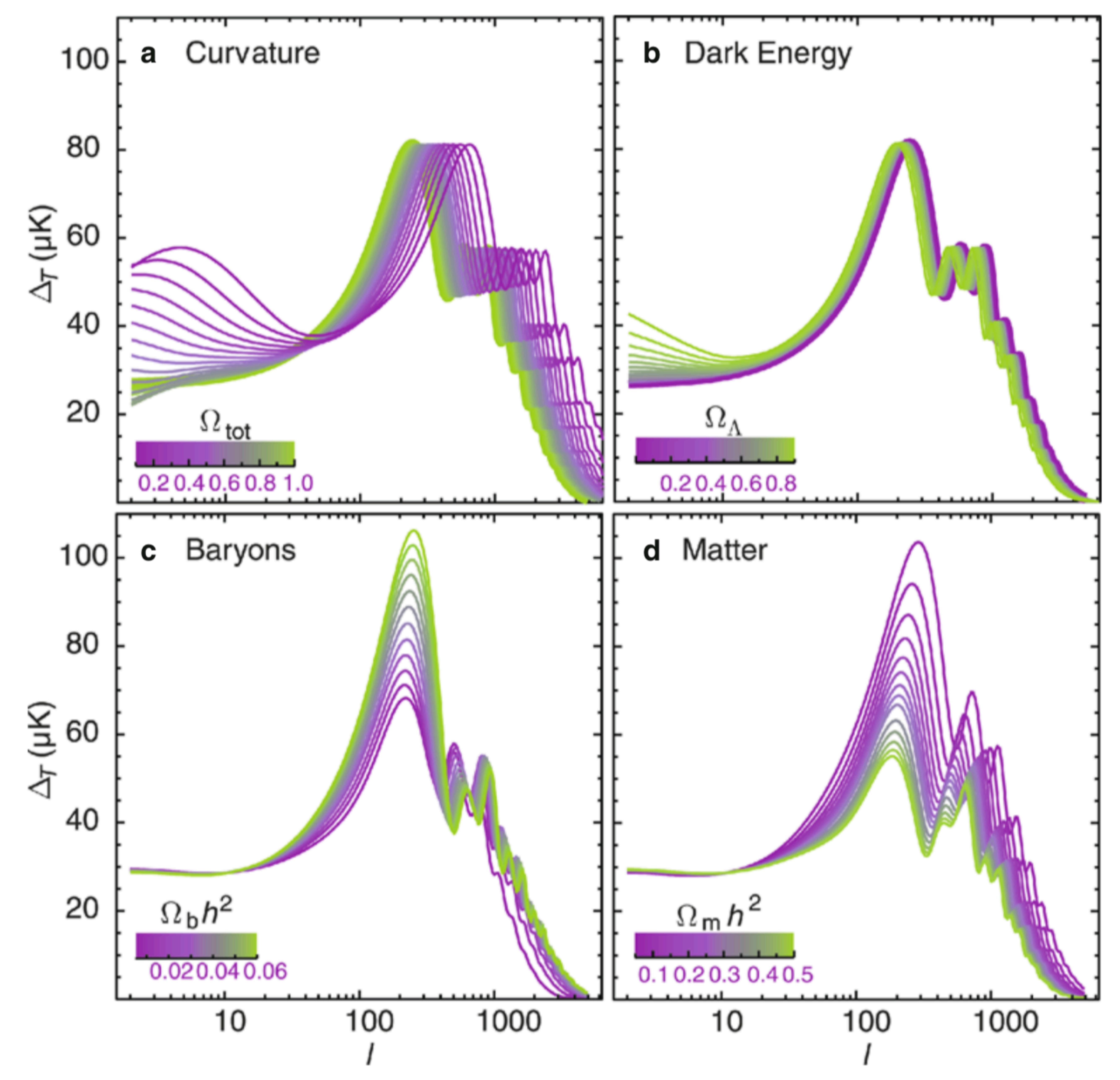
Temperature
of the Universe
Planck collaboration (2013)
10^{10} Kelvin
Protons and neutrons freeze out
10^{9} Kelvin
Primordial nucleosynthesis. Hydrogen (~75%) and helium (~25%) formation.
~ 10,000 Kelvin
Photon/baryon decoupling. Surface of last scattering
Structure formation
Big Bang
Time
1 second
15 minutes
400,000 years
13.8 Gyr

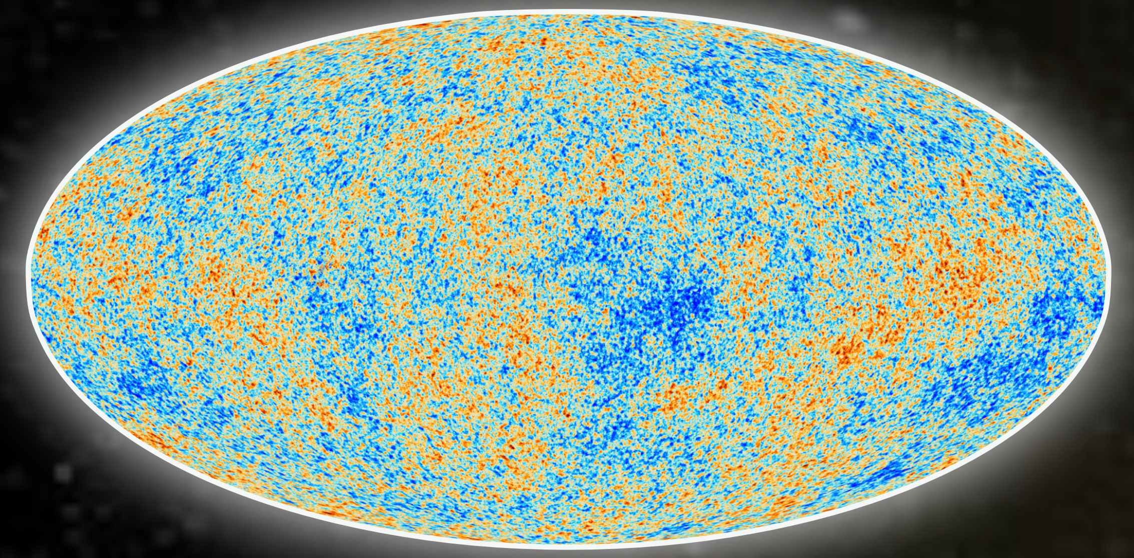
The cosmic energy budget

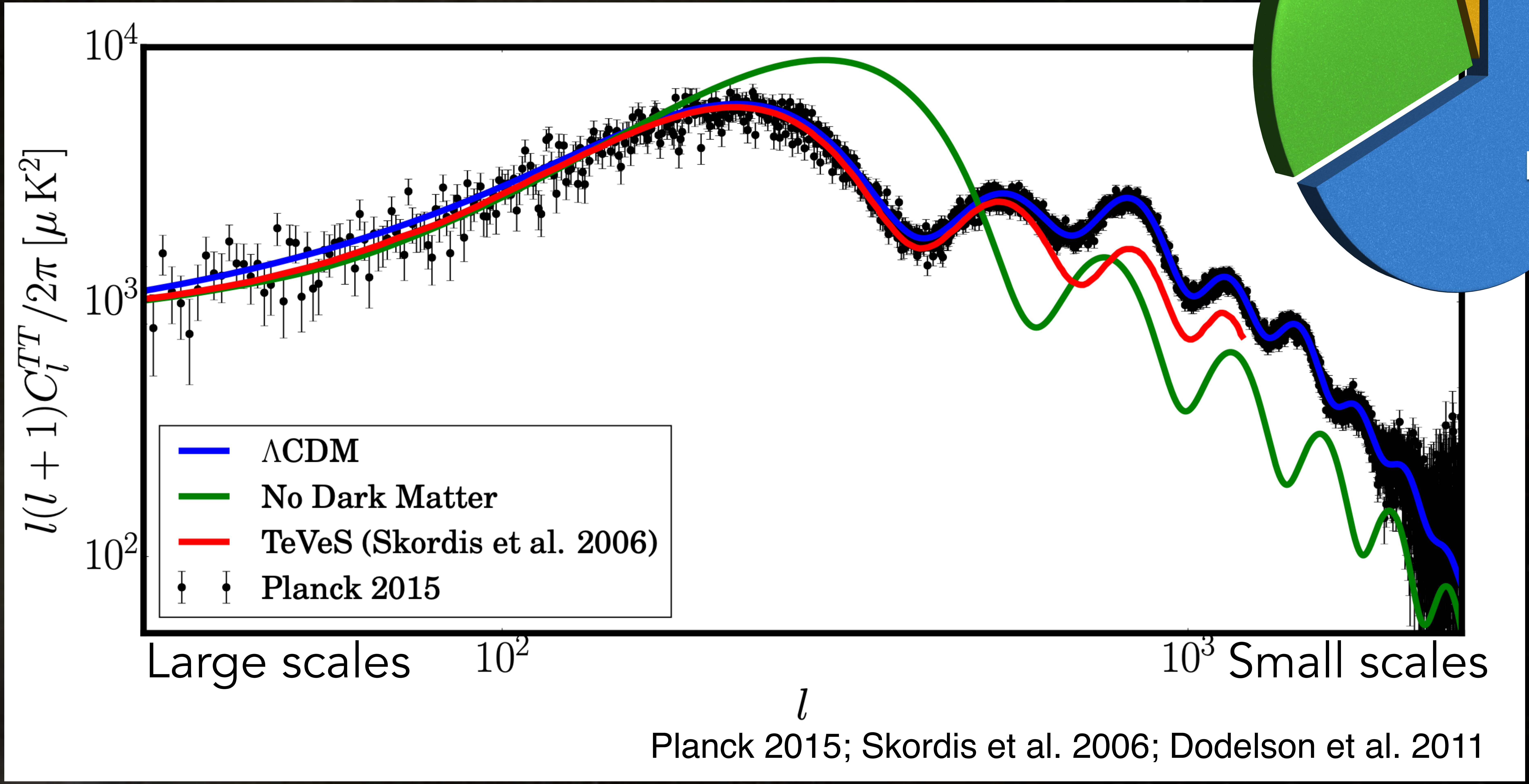
- Decompose the signal into spherical harmonics and compute the power spectrum.
- The baryonic acoustic oscillations depend on cosmological paramters (curvature, dark energy, total matter contents vs. baryon contents)

(e.g. review by Hu & Dodelson 2002)

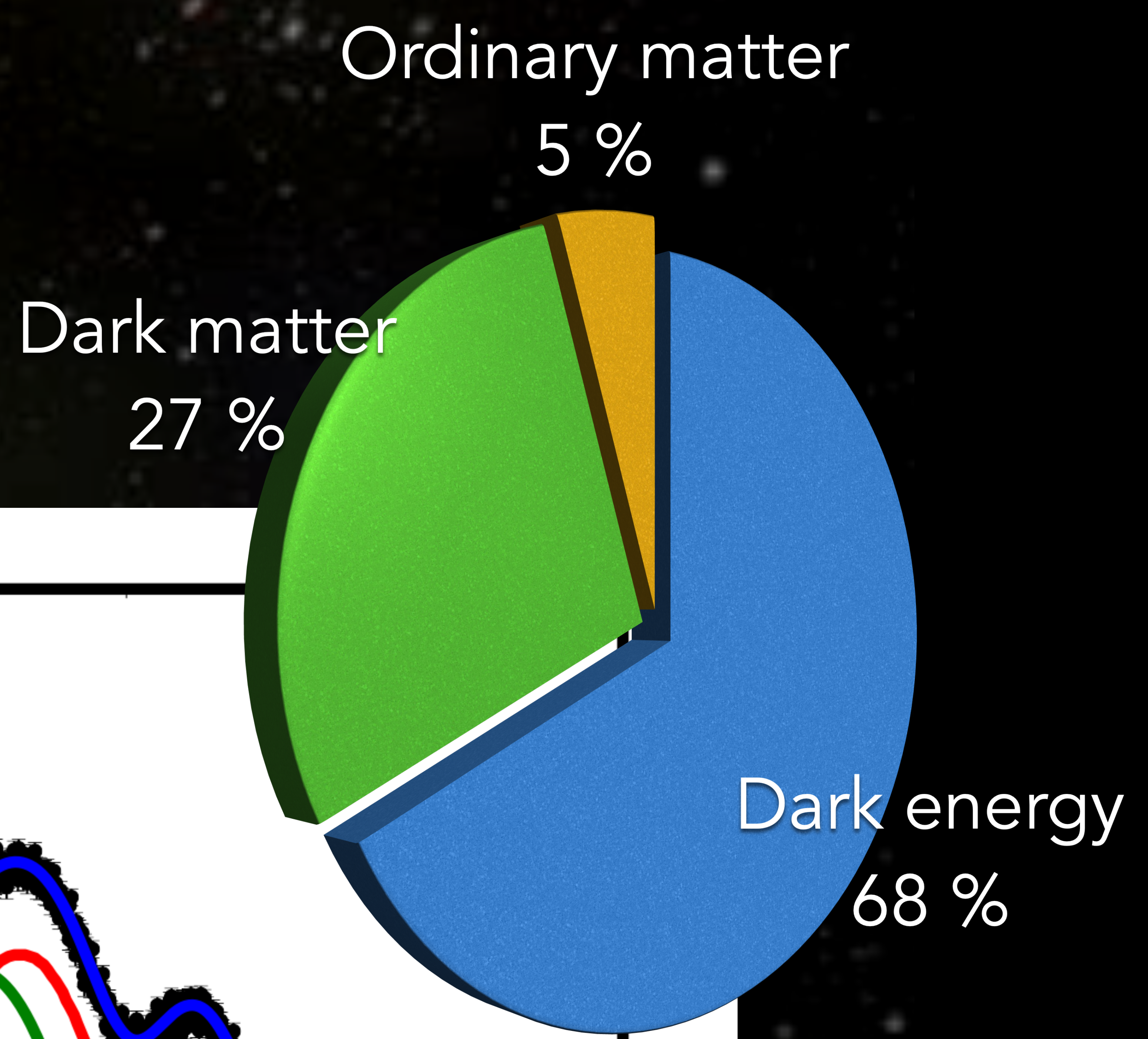








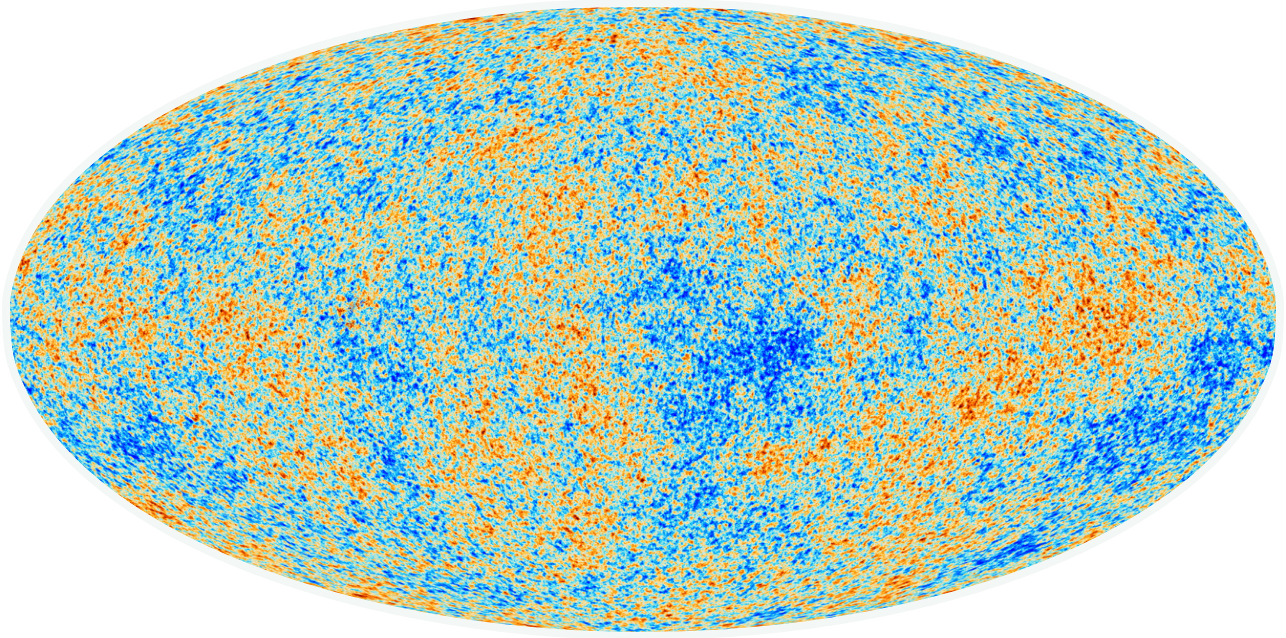
10^4
10^3
10^2
$l(l+1)C_l^{TT}/2\pi\,[\mu\mathrm{K}^2]$
ΛCDM
No Dark Matter
TeVeS (Skordis et al. 2006)
Planck 2015
Large scales
10^2
10^3
Small scales
l
Planck 2015; Skordis et al. 2006; Dodelson et al. 2011



Ordinary matter
5 %
Dark matter
27 %
Dark energy
68 %

Growth of cosmological perturbations - the need for dark matter

Density/temperature anisotropies on the order of $\Delta \sim 10^{-5}$



$$\Delta = \frac{\rho - \rho_0}{\rho_0} = \frac{\delta\rho}{\rho_0}$$

$a =$ expansion factor of the Universe

Hubble drag

Suppresses growth due to the expansion of the Universe

Pressure term

Due to the spatial variations in density.

$$\frac{\mathrm{d}^2\Delta}{\mathrm{d}t^2} + \boxed{2\left(\frac{\dot{a}}{a}\right)\frac{\mathrm{d}\Delta}{\mathrm{d}t}} = \boxed{4\pi G\rho_0\Delta} + \boxed{\frac{c_\mathrm{s}^2}{a^2}\boldsymbol{\nabla}_\mathrm{c}^2\Delta}$$

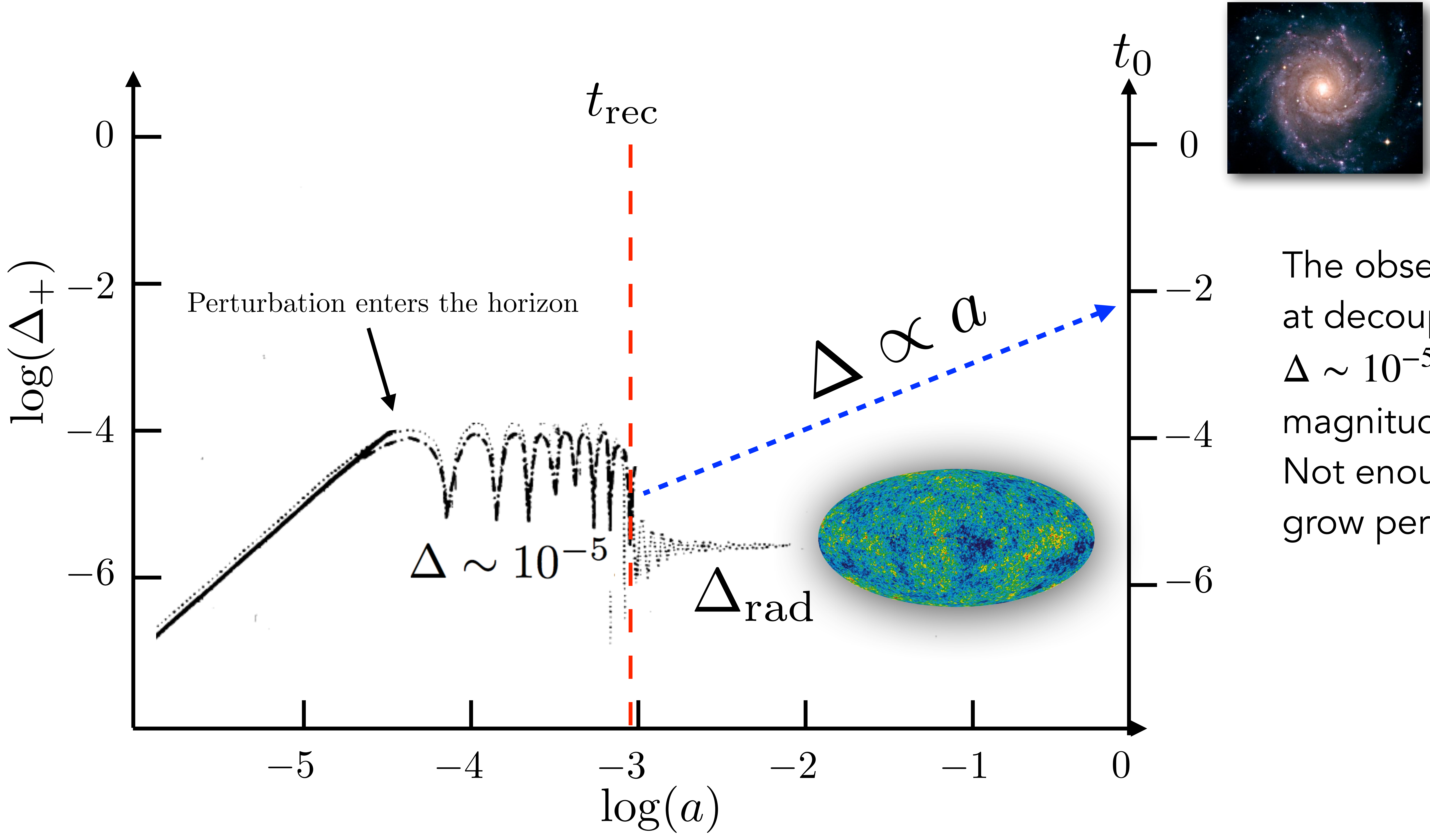
Gravity term

Perturbation growth via gravitational instability

Solution for an Einstein-de Sitter Universe: $(\Omega_{\mathrm{m},0} = 1, \Omega_{\Lambda,0} = 0, k = 0)$

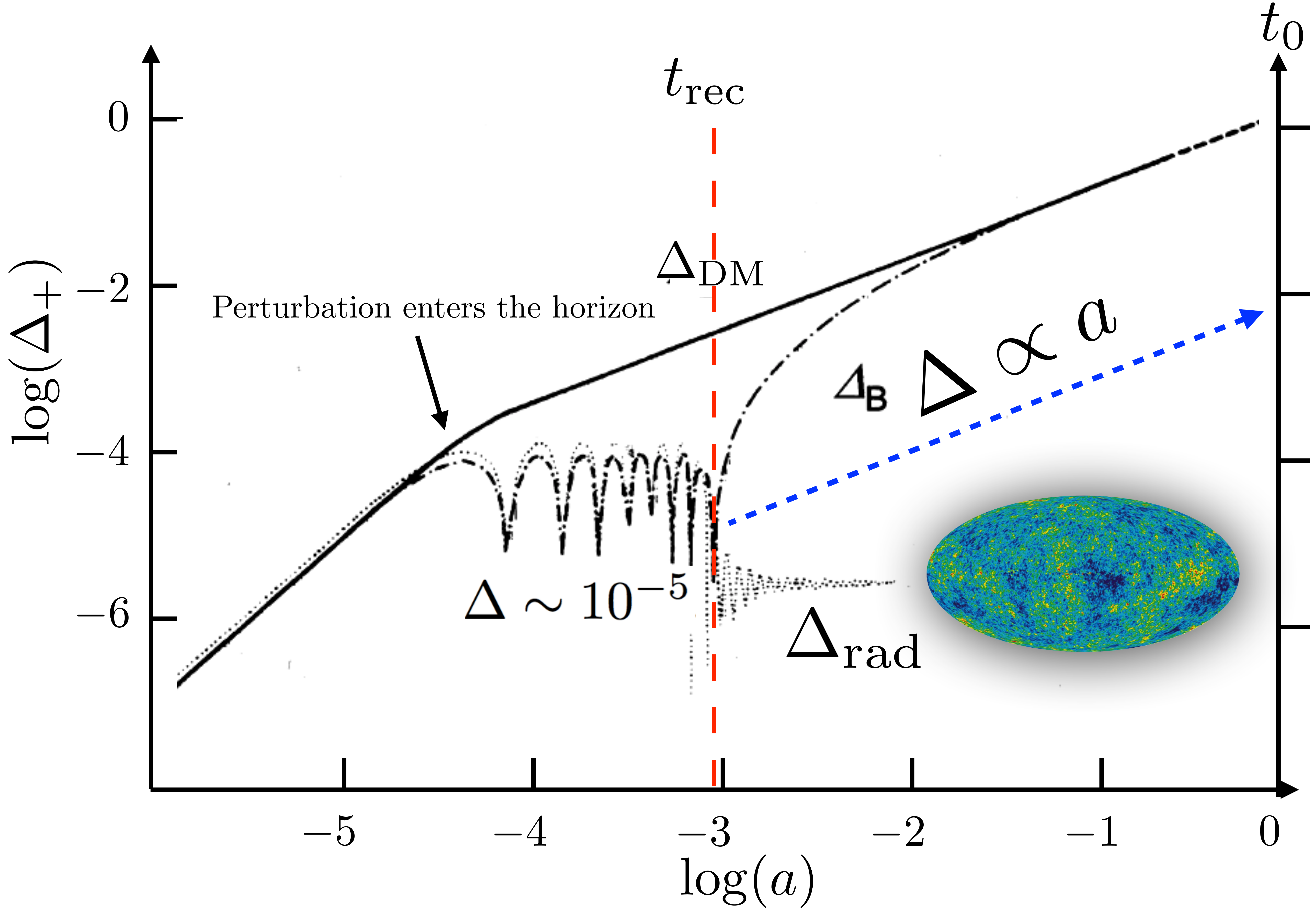
$$\Delta_+ = \Delta_0 t^{2/3} \propto a$$

Growth of cosmological perturbations - the need for dark matter



The observed contrast at decoupling is $\Delta \sim 10^{-5}$, 2 orders of magnitude too low!. Not enough time to grow perturbations!

Growth of cosmological perturbations - the need for dark matter



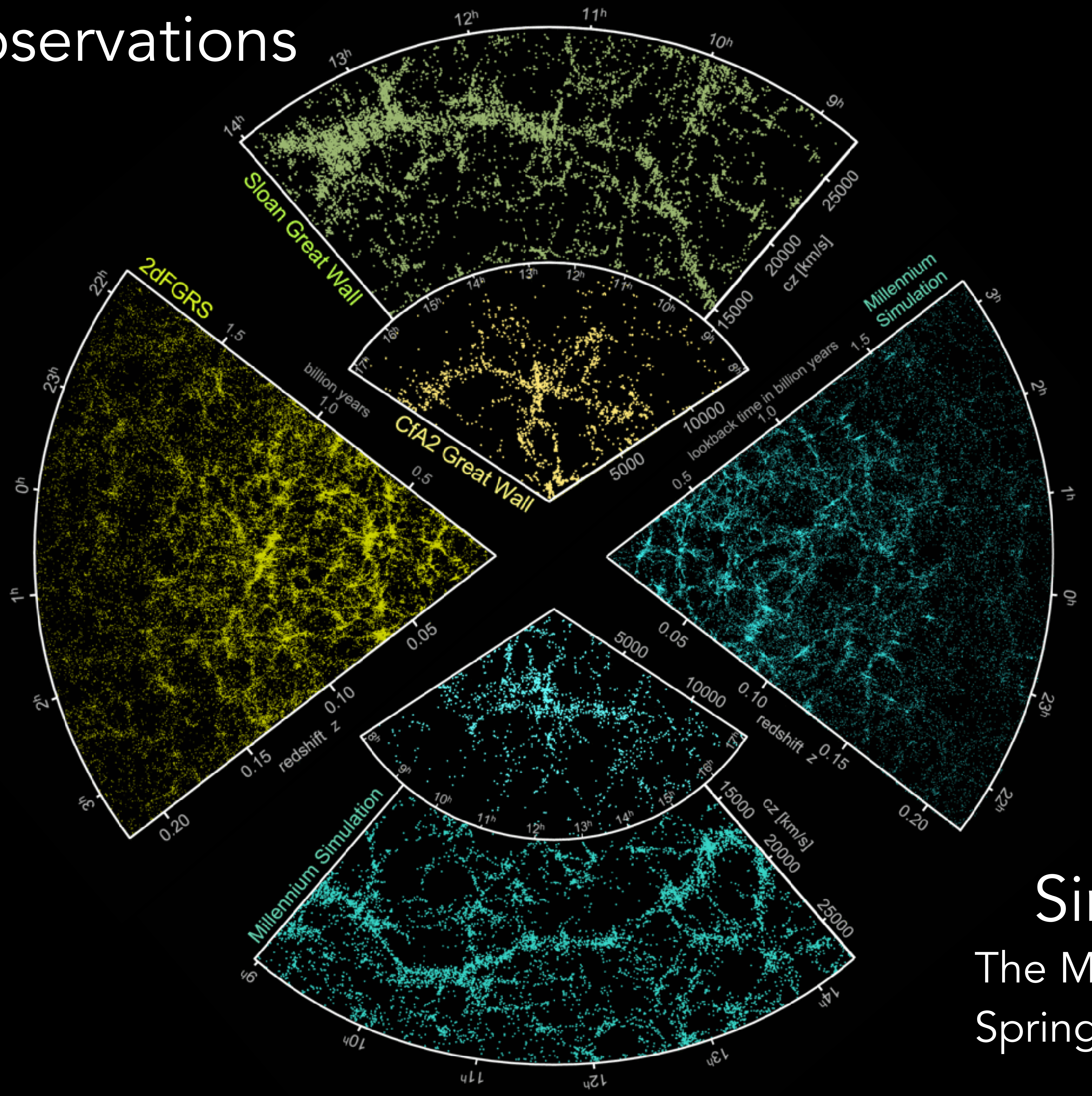
The observed contrast at decoupling is $\Delta \sim 10^{-5}$, 2 orders of magnitude too low!. Not enough time to grow perturbations!

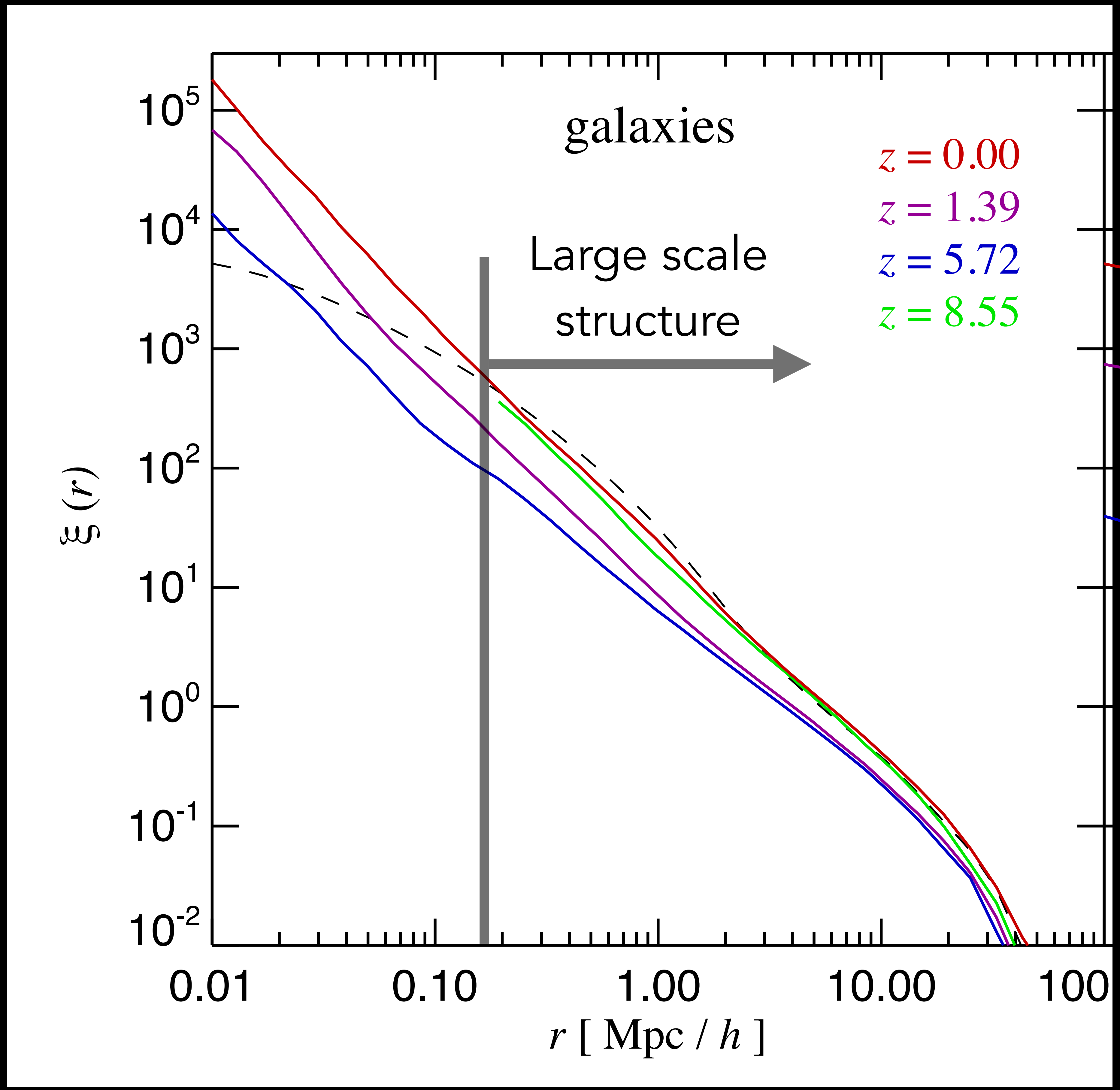
Gravity driven clustering of dark matter on large scales:

The origin of the cosmic web

Agertz (2018)

Observations





Simulations

The Millennium simulation

Springel (Nature, 2006)

Horizon-scale dark matter simulations

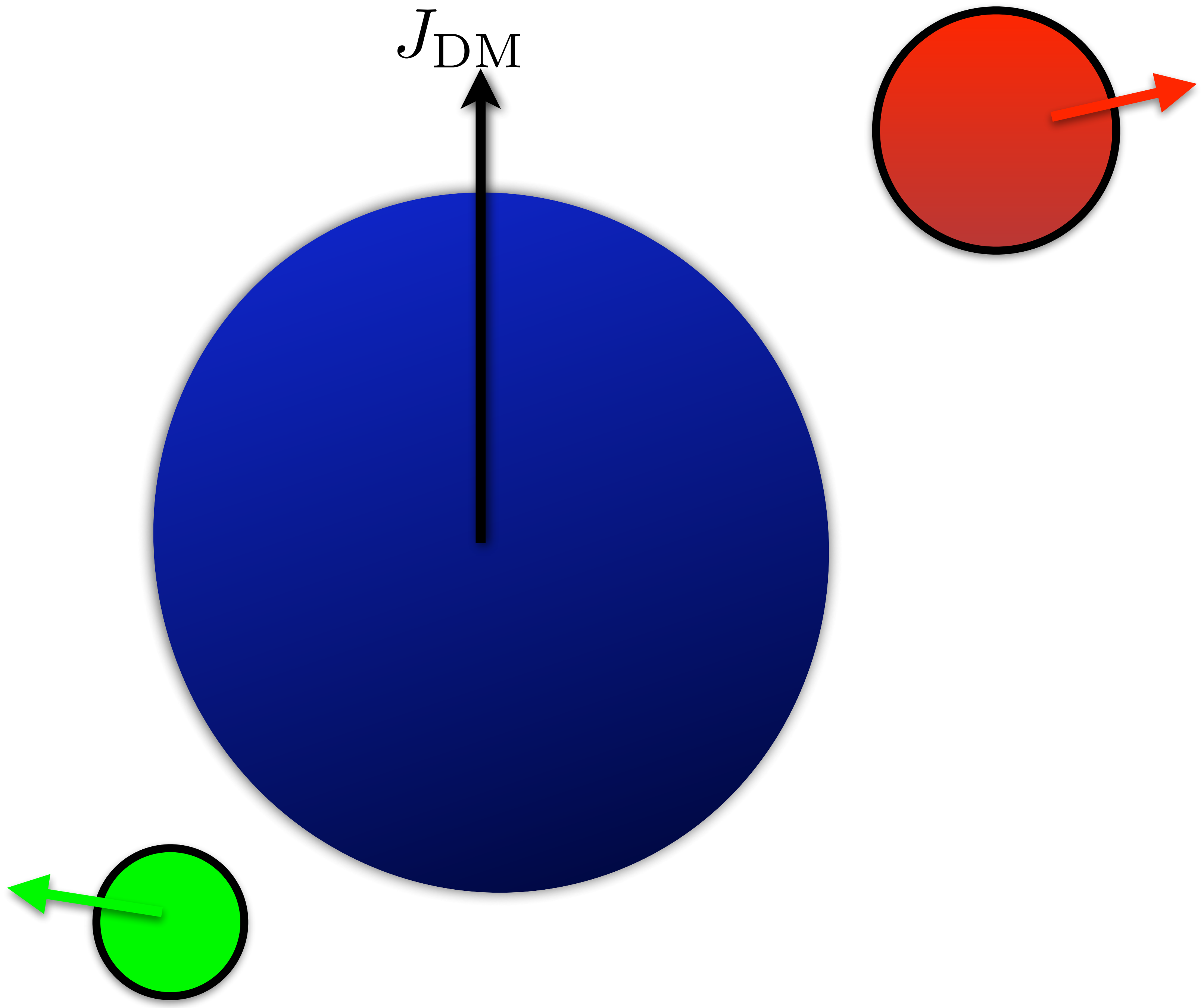
~ 4 billion parsecs
2 trillion dark matter “particles”

J. Stadel 2017, University of Zürich

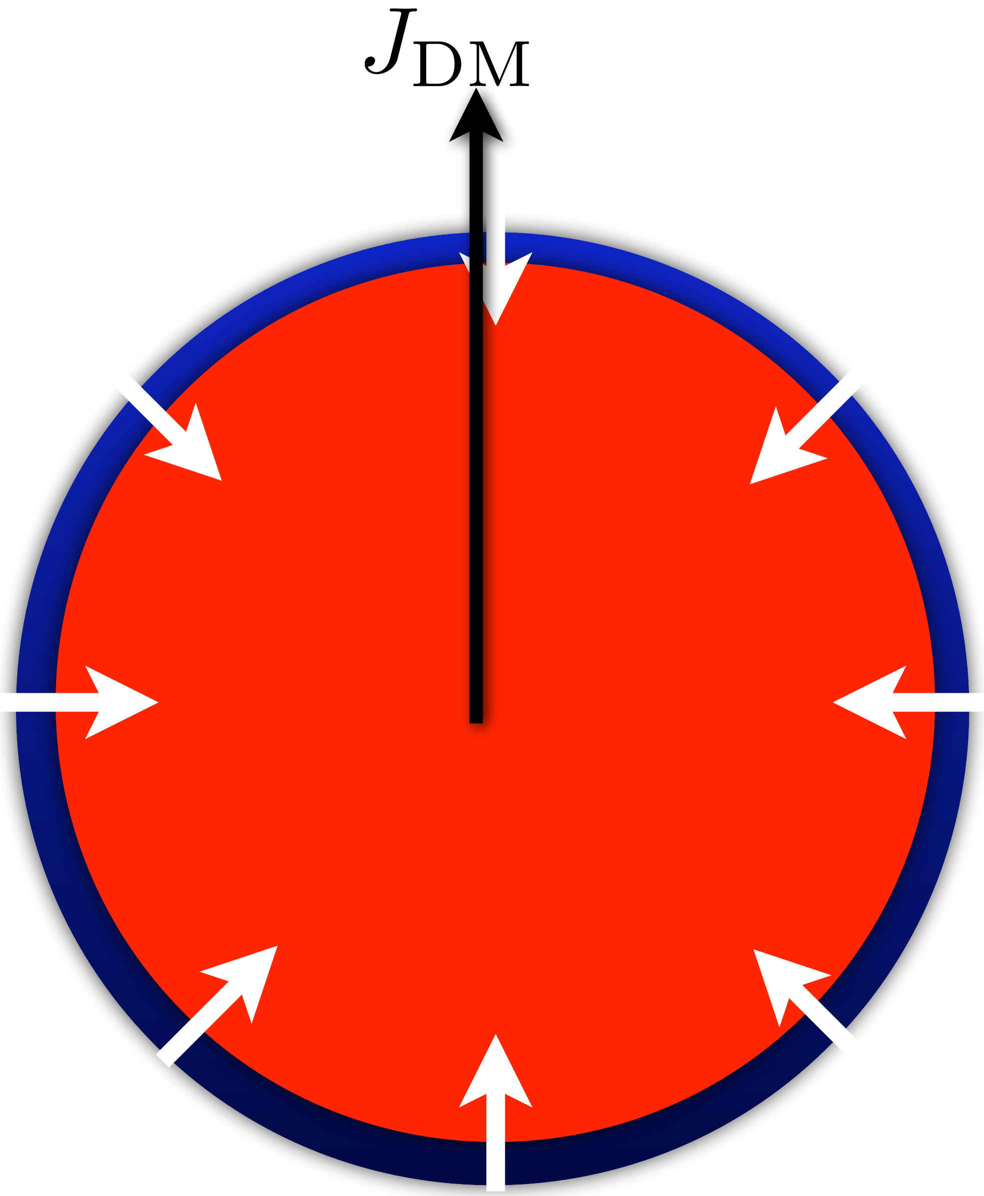

Milky Way mass halo
Dwarf
galaxy halo

Formation of galactic discs - a simple model

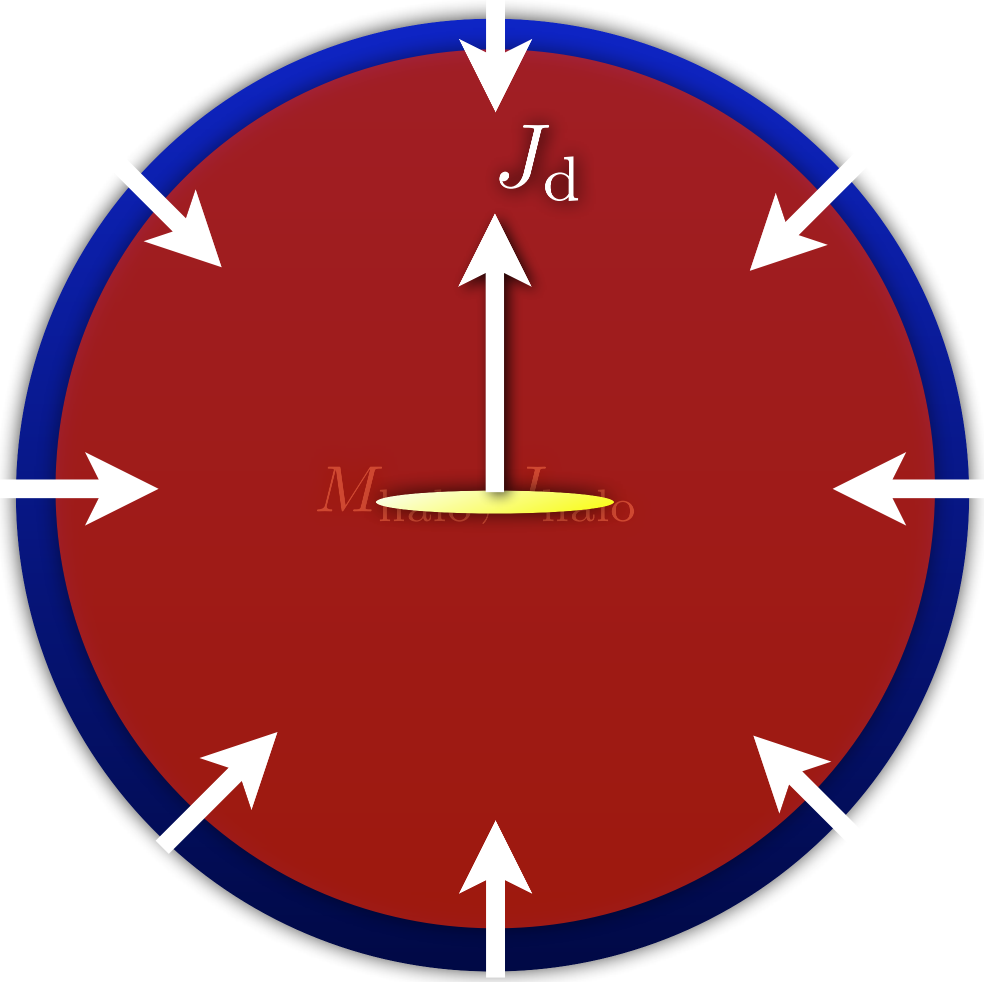
Mo, Mao & White (1998)



- A dark matter halo forms and acquires angular momentum due to tidal torques



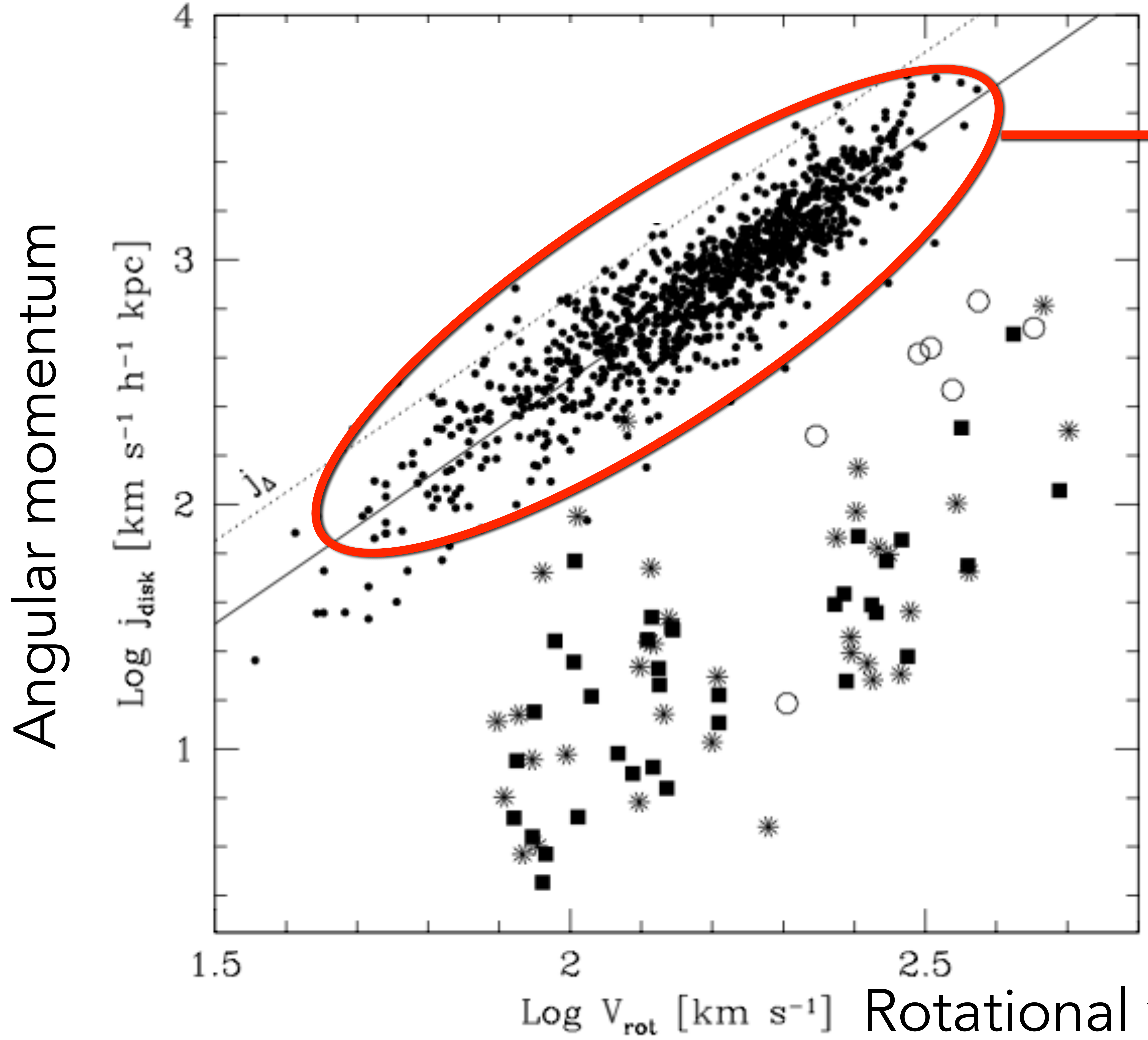
- Gas with the same angular momentum accretes onto the halo
- The gas shock heats but loses pressure support due to radiative cooling



- Angular momentum conservation leads to spin-up and at the halo center and an angular momentum-supported disc forms
- At high enough gas densities, stars form

Historical issues in simulations of galaxy formation:

Angular momentum



Courteau (1997)
Sb-Sc galaxies
(i.e. `discy' galaxies)

Numerical simulations

(Navarro & Steinmetz, 2000)

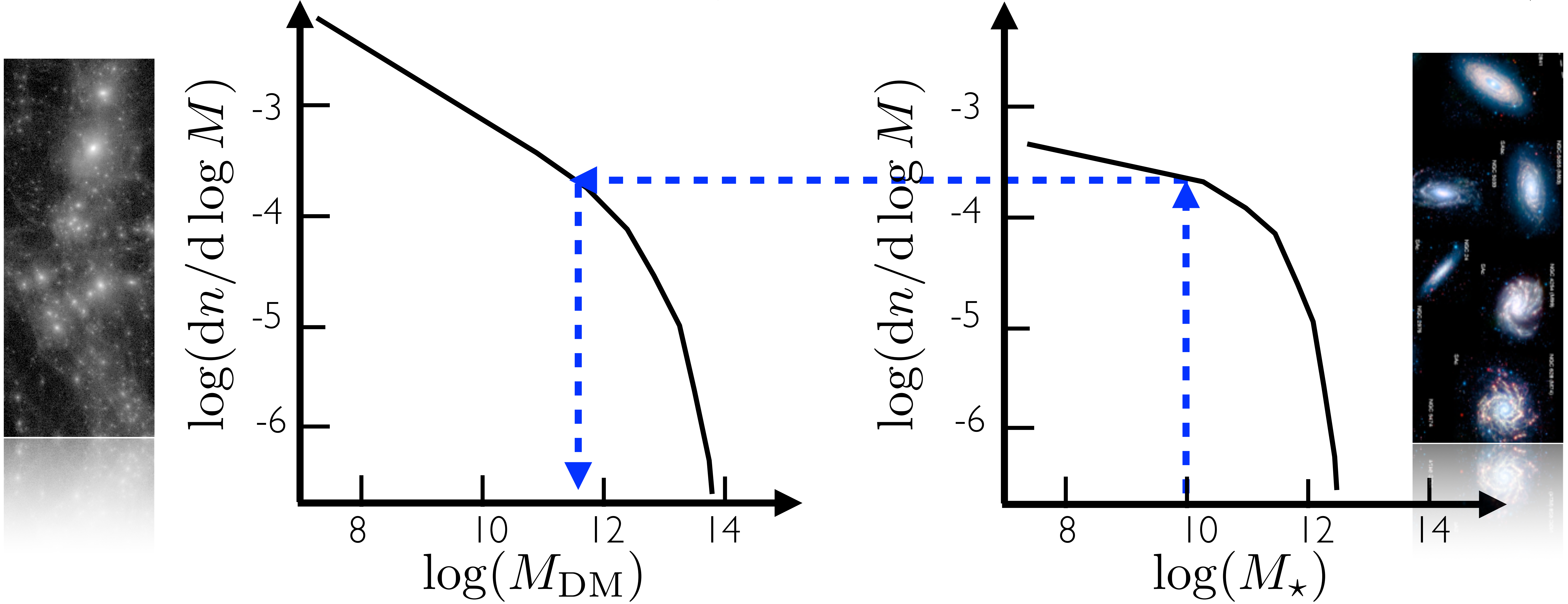
Not clear ***where*** angular momentum is lost (halo, disc-halo interface, disc?)

Historical issues in simulations of galaxy formation:

The low efficiency of galaxy formation

Dark matter halo mass function (theory)

Stellar mass function (observed)

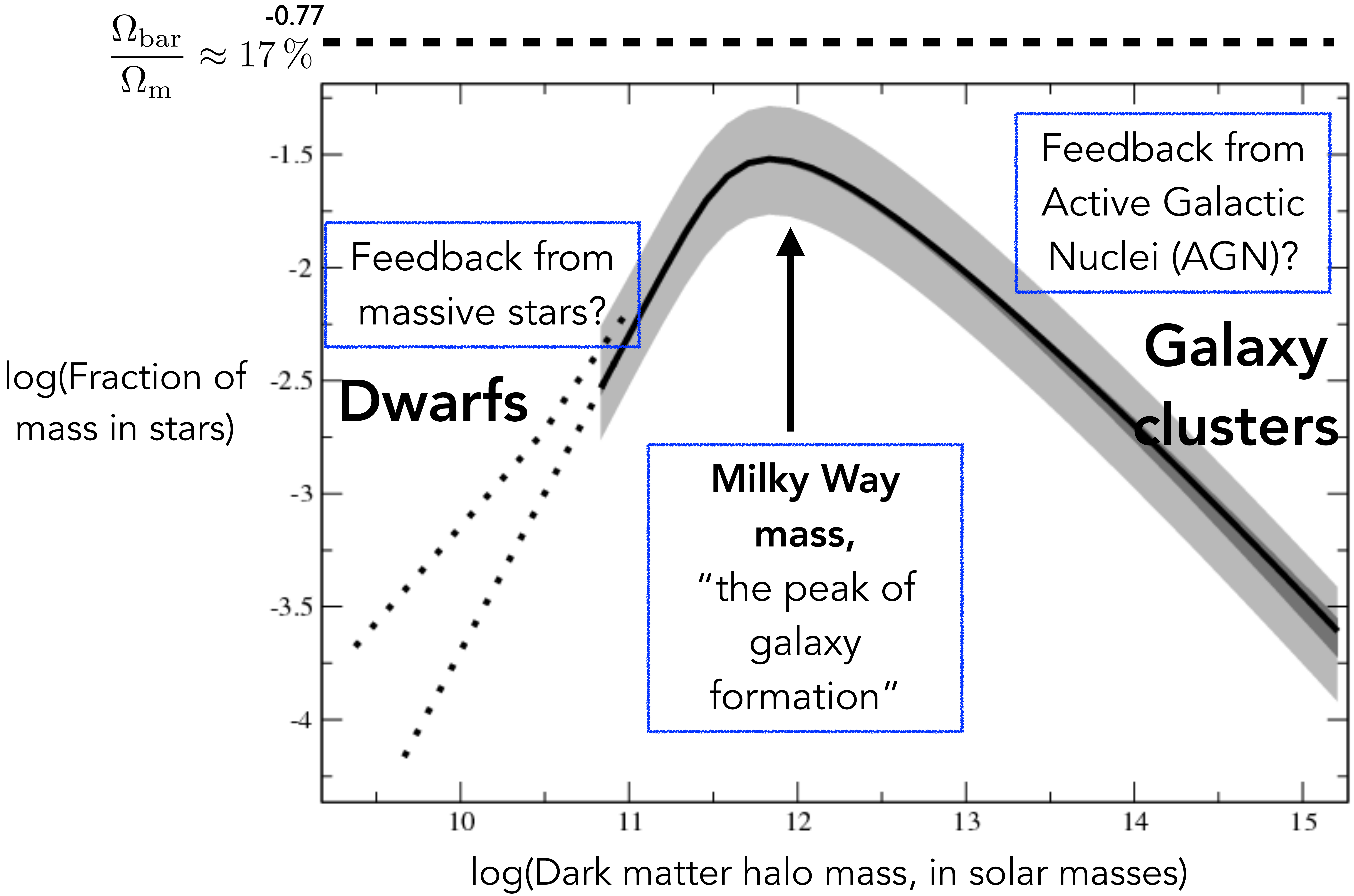


By matching abundances of galaxies and dark matter haloes, we can find a one-to-one mapping between galaxy and dark matter halo masses.

(e.g. Kravtsov, Berlind, Wechsler, et al 2004; Conroy, Wechsler & Kravtsov 2006; Conroy & Wechsler 2008)

Historical issues in simulations of galaxy formation:

The low efficiency of galaxy formation

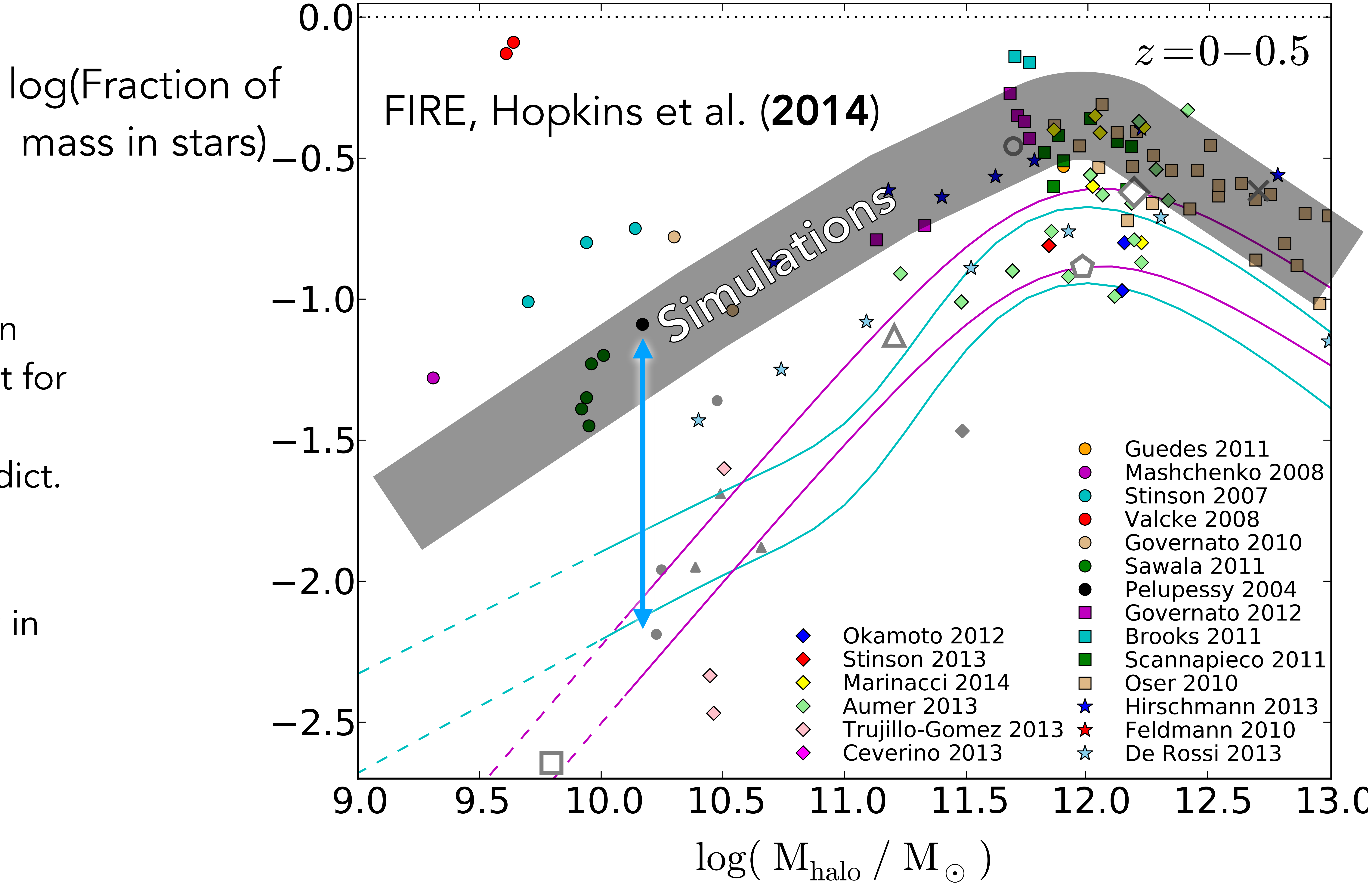


Moster et al. (2010)

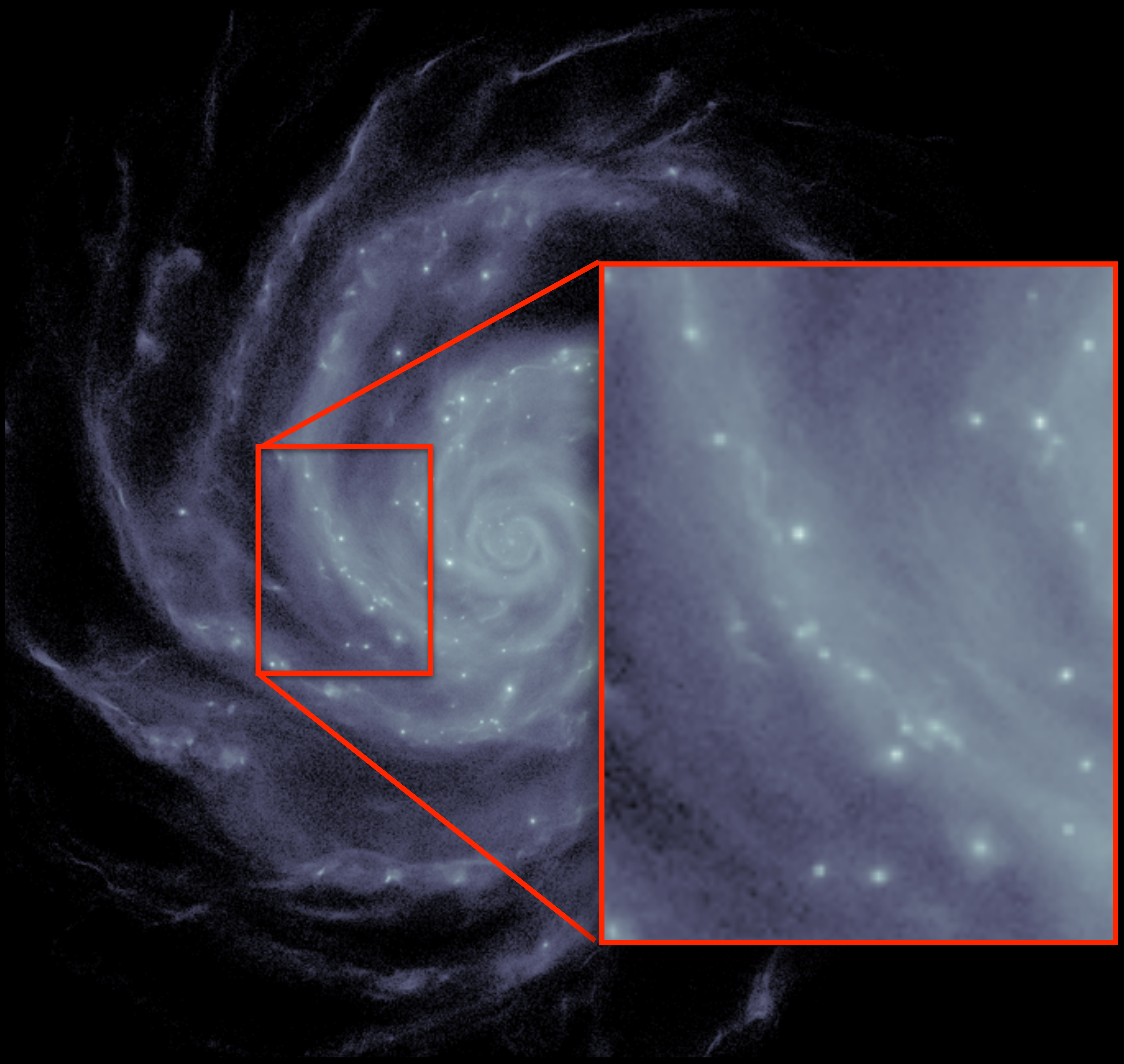
Historical issues in simulations of galaxy formation:

The low efficiency of galaxy formation

- Inefficient galaxy formation has been notoriously difficult for cosmological simulations to predict.
- But, the field has developed quickly in the past 10 years!

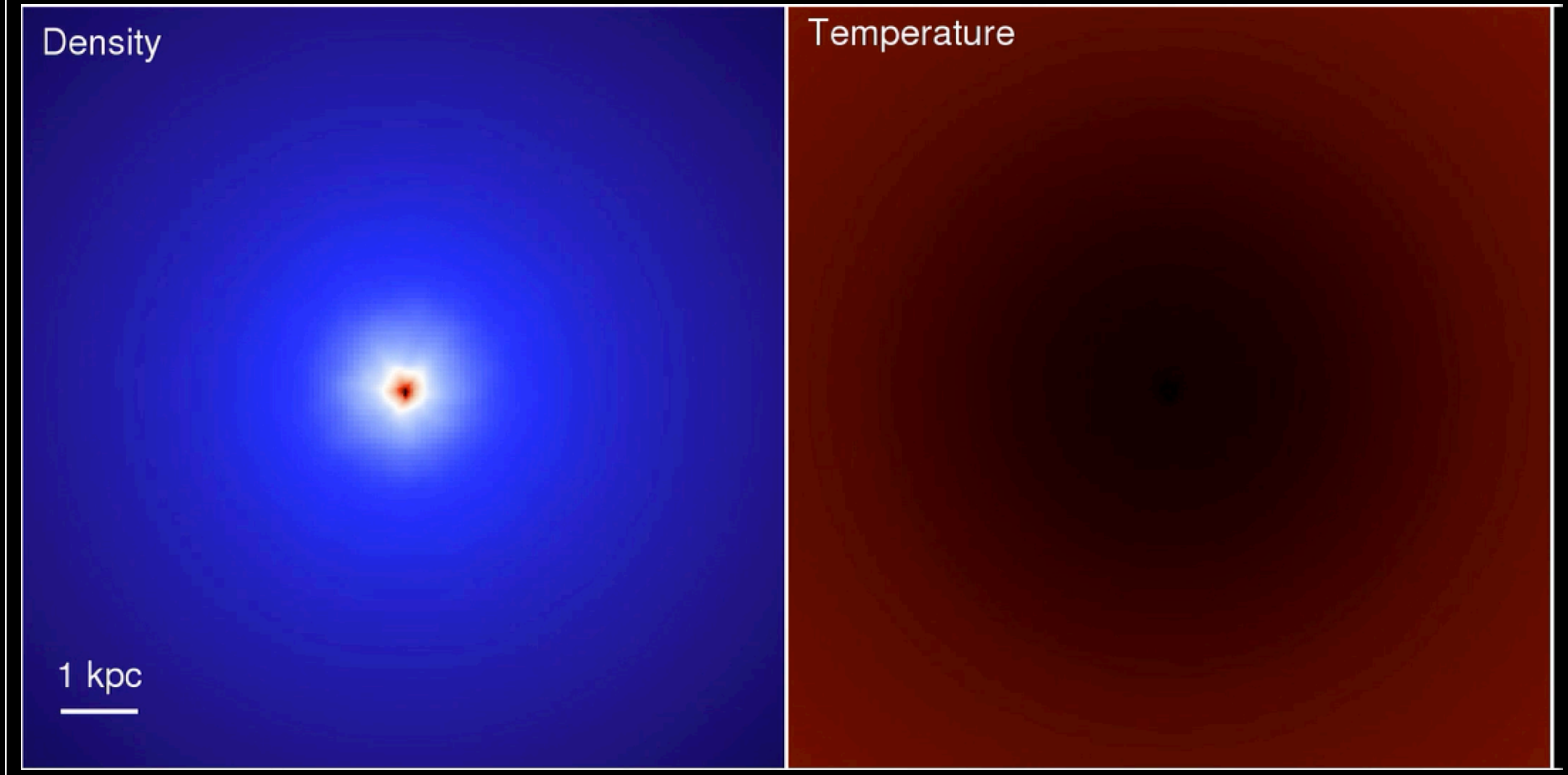


Numerical resolution



Feedback physics

- Star exploding as supernovae
- Stellar winds from massive and low mass stars
- Radiative transfer (multi-frequency, radiation pressure in dust etc)
- Magnetohydrodynamics + cosmic ray physics
- Black hole feedback
- …

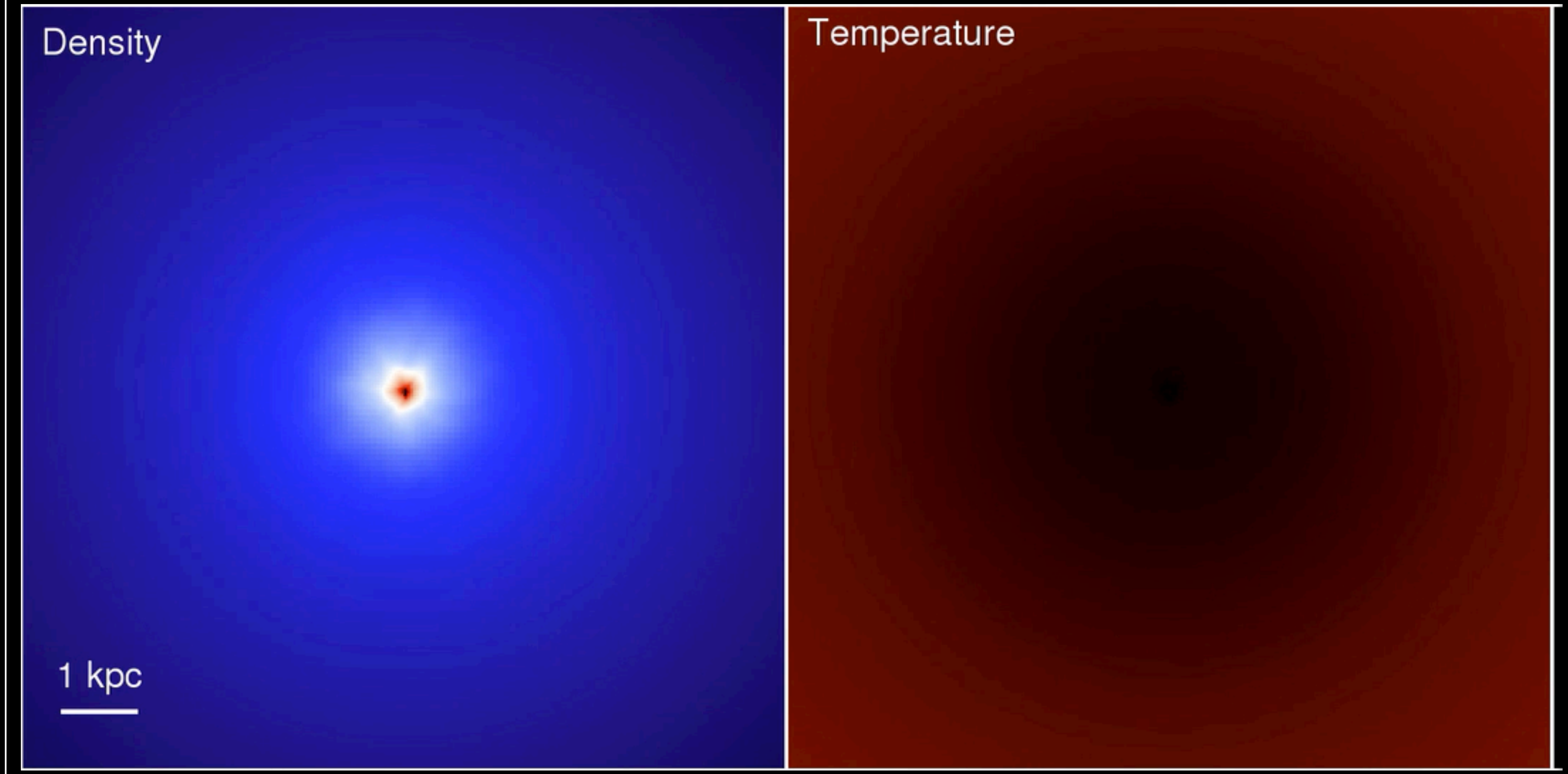


Feedback physics

- Feedback regulates star formation and promotes high angular momentum systems.
- Angular momentum problem: gone!
- Overcooling/efficiency problem: gone!
- Cosmological simulations may now be of high enough fidelity to study internal structures of galaxies.

For a review, see Naab & Ostriker (2017)

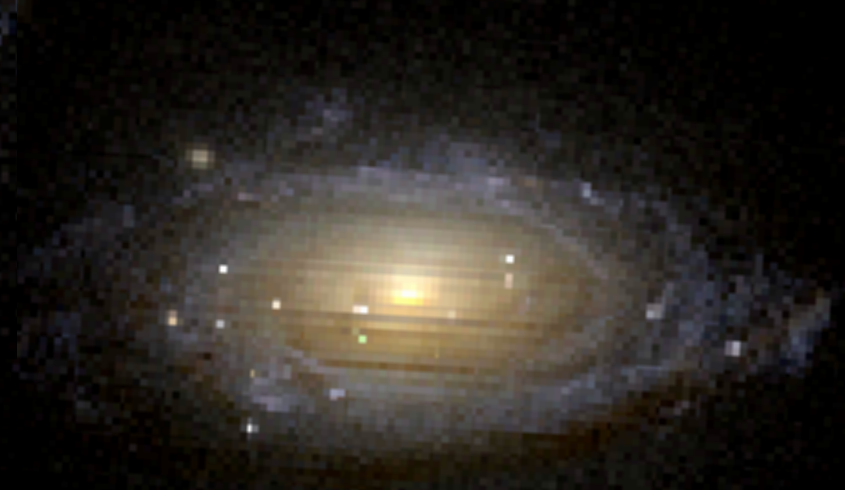
- Star exploding as supernovae
- Stellar winds from massive and low mass stars
- Radiative transfer (multi-frequency, radiation pressure in dust etc)
- Magnetohydrodynamics + cosmic ray physics
- Black hole feedback
- …

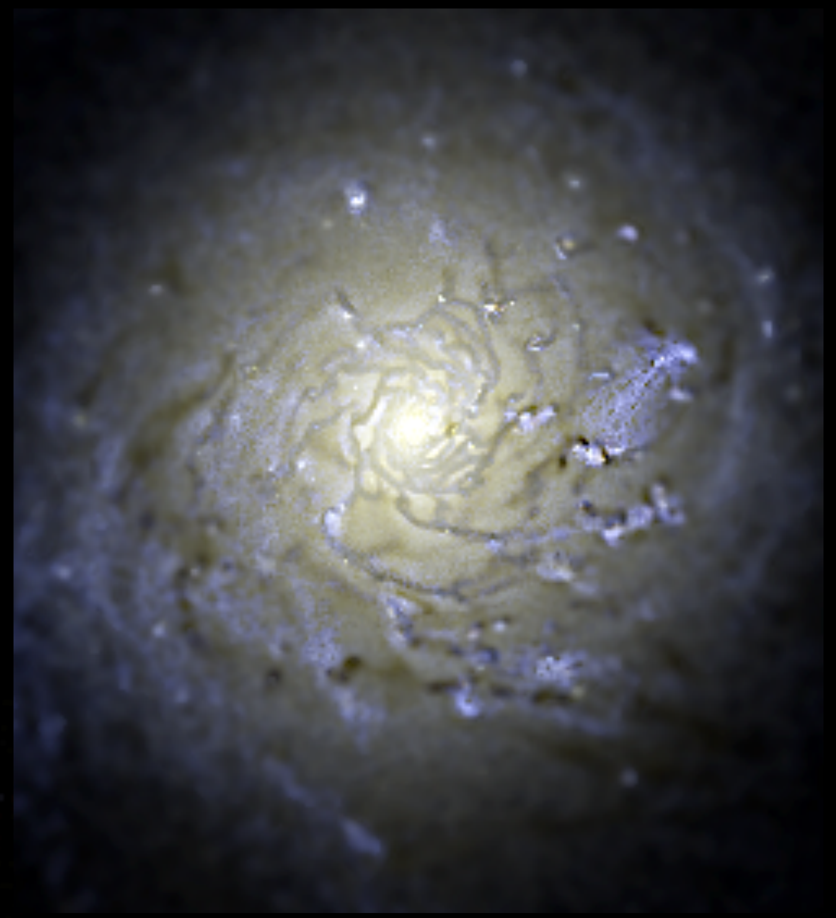


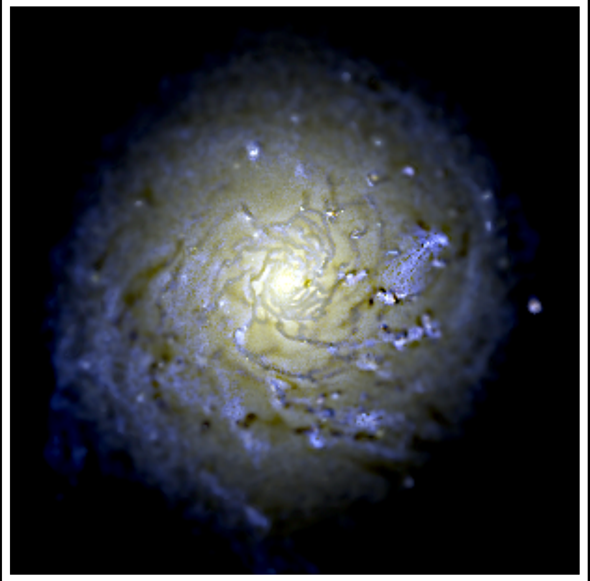
Examples of recent progress: The VINTERGATAN project

(Agertz et al. 2021, Renaud et al. 2021a,b, Segovia Otero et al. 2022…)

- Cosmological zoom simulations of galaxies forming in $10^{12}\ \mathrm{M}_{\odot}$ dark matter halos (adaptive mesh refinement, RAMSES, Teyssier 2002).
- Origins of stellar discs
- Also, cosmic phases of star formation, role of environment/assembly history for disc formation, etc.

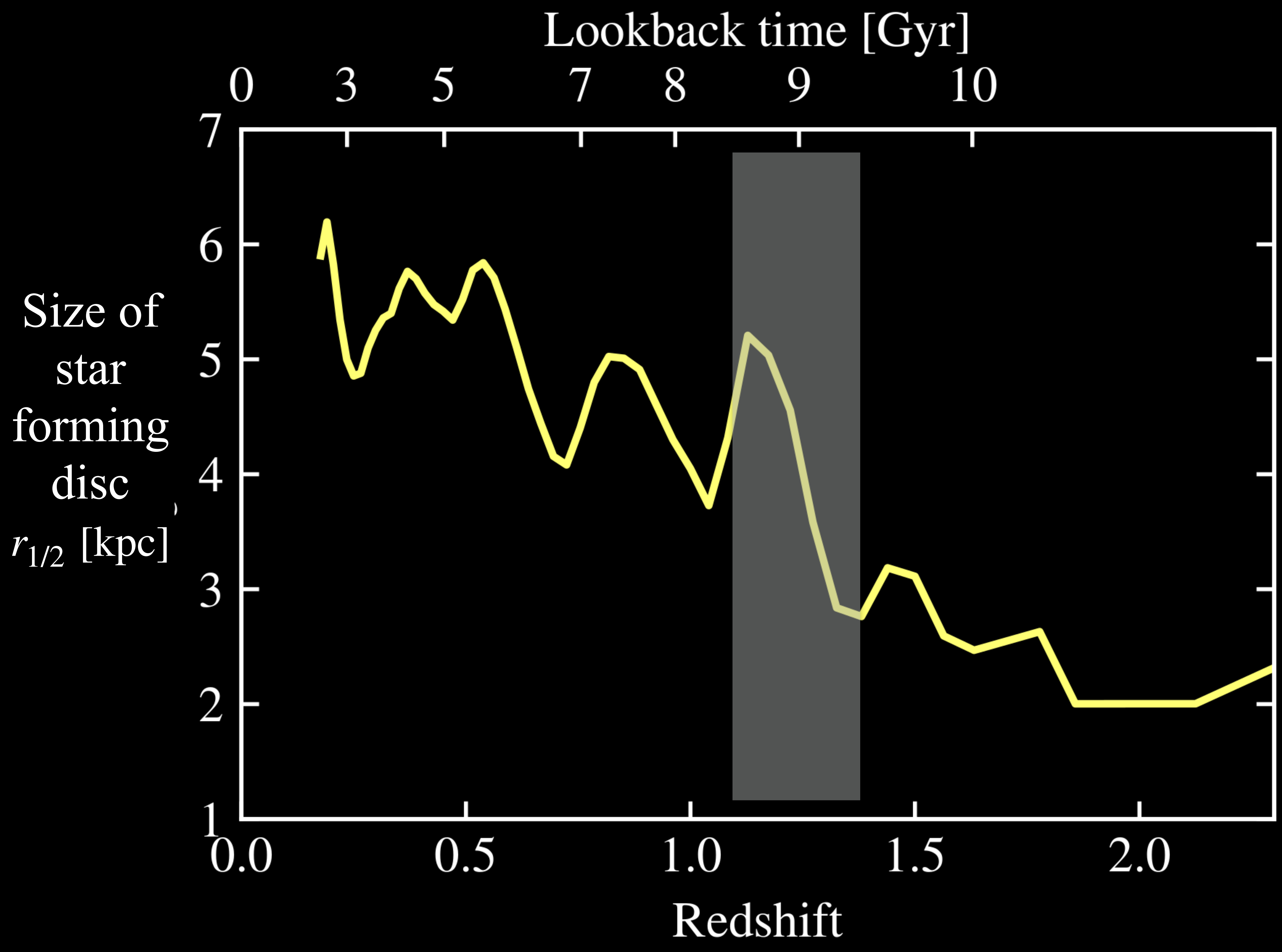


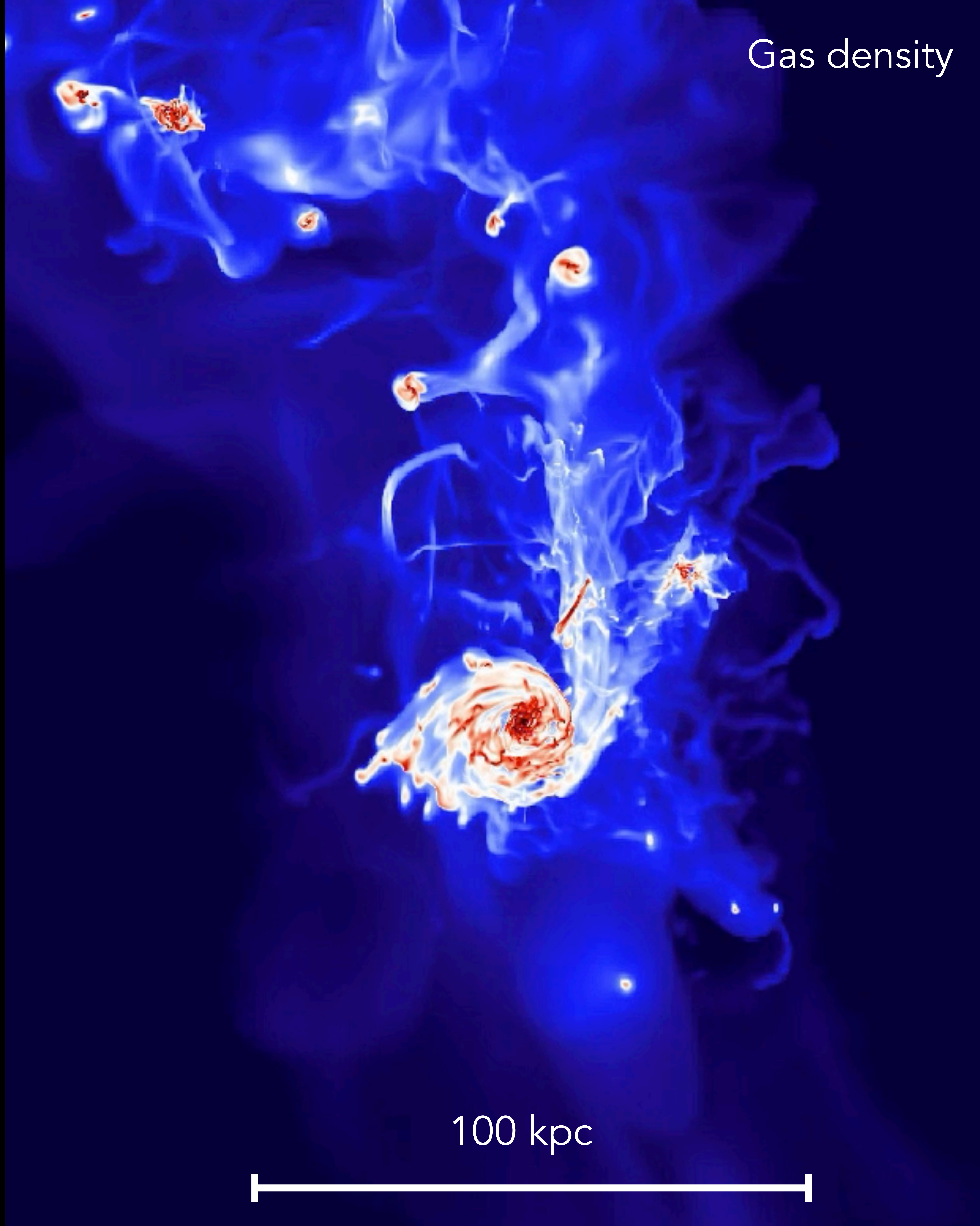


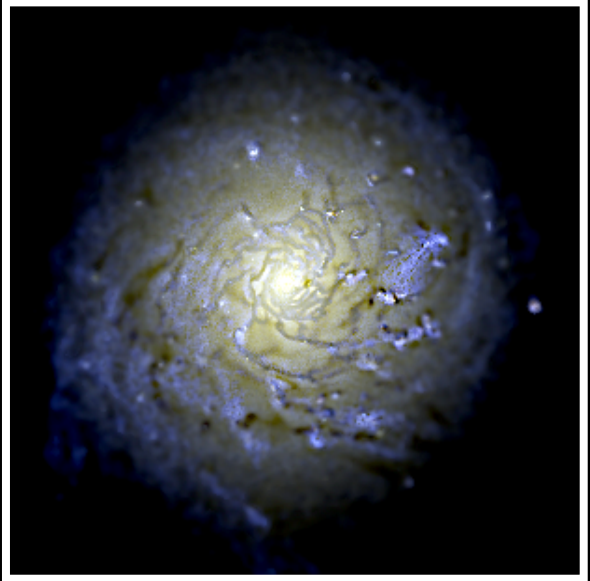


Inflows, the last major merger and rapid disc growth at z~1

(Agertz et al. 2021, Renaud et al. 2021a,b)

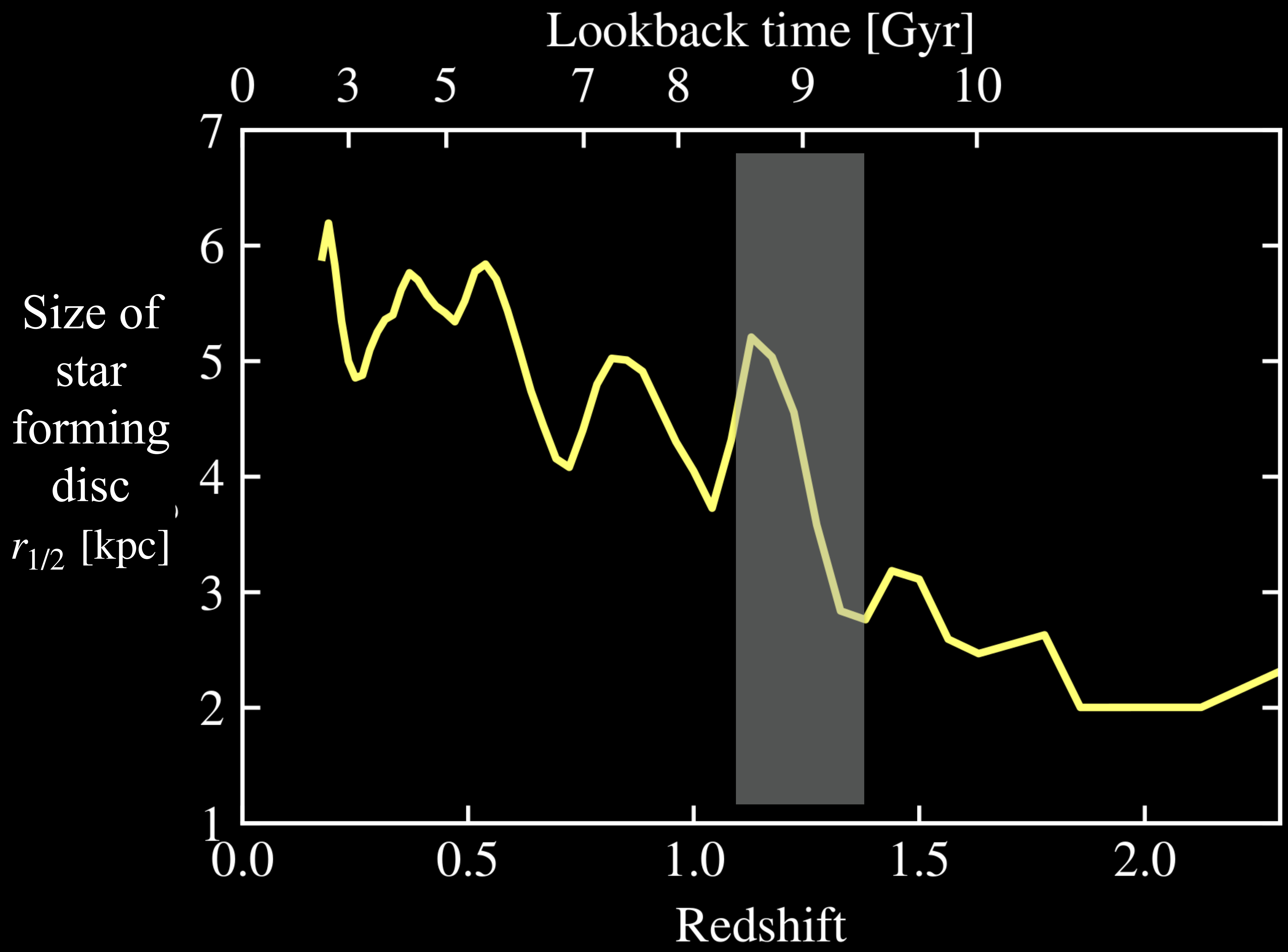


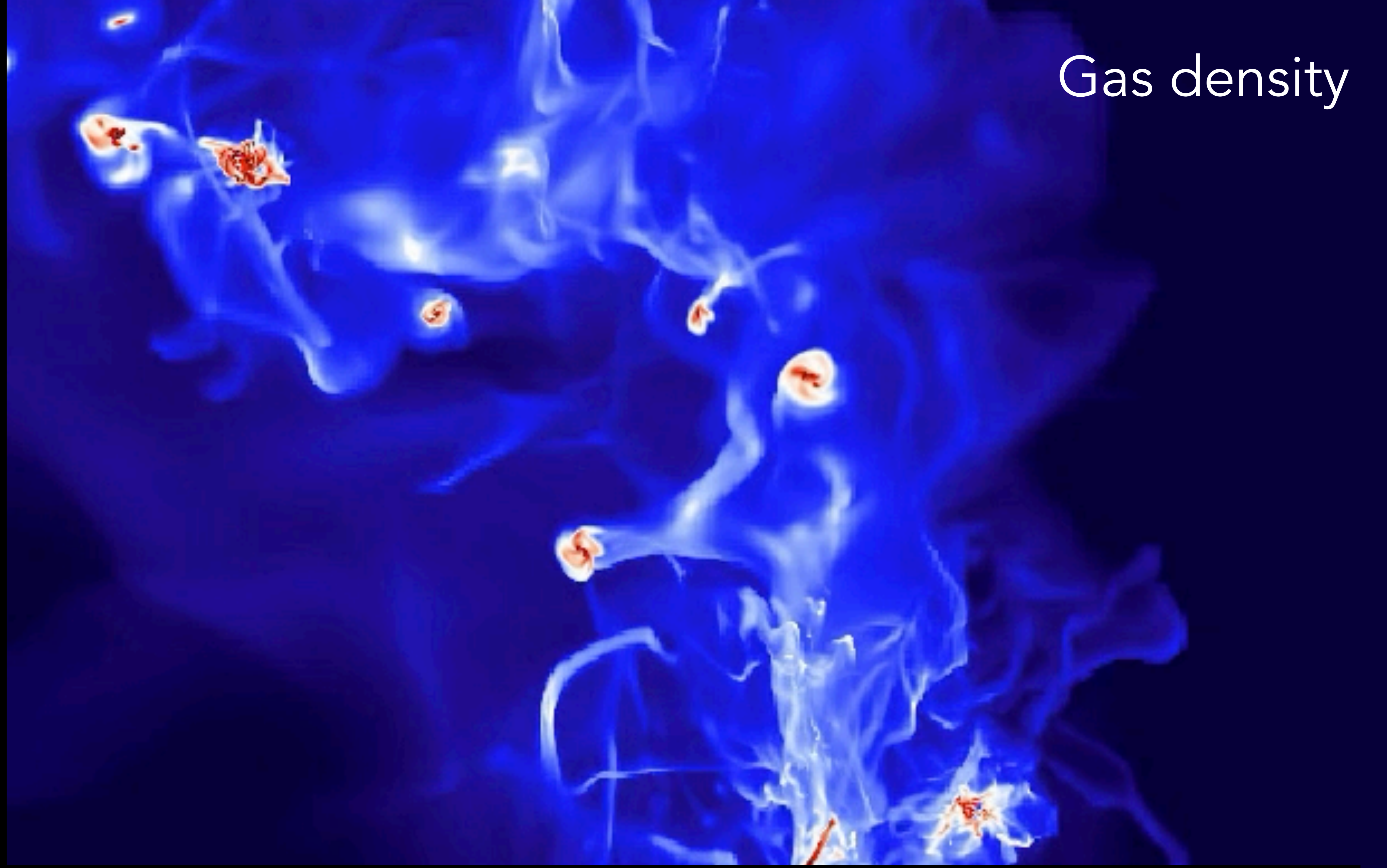




Inflows, the last major merger and rapid disc growth at z~1

(Agertz et al. 2021, Renaud et al. 2021a,b)



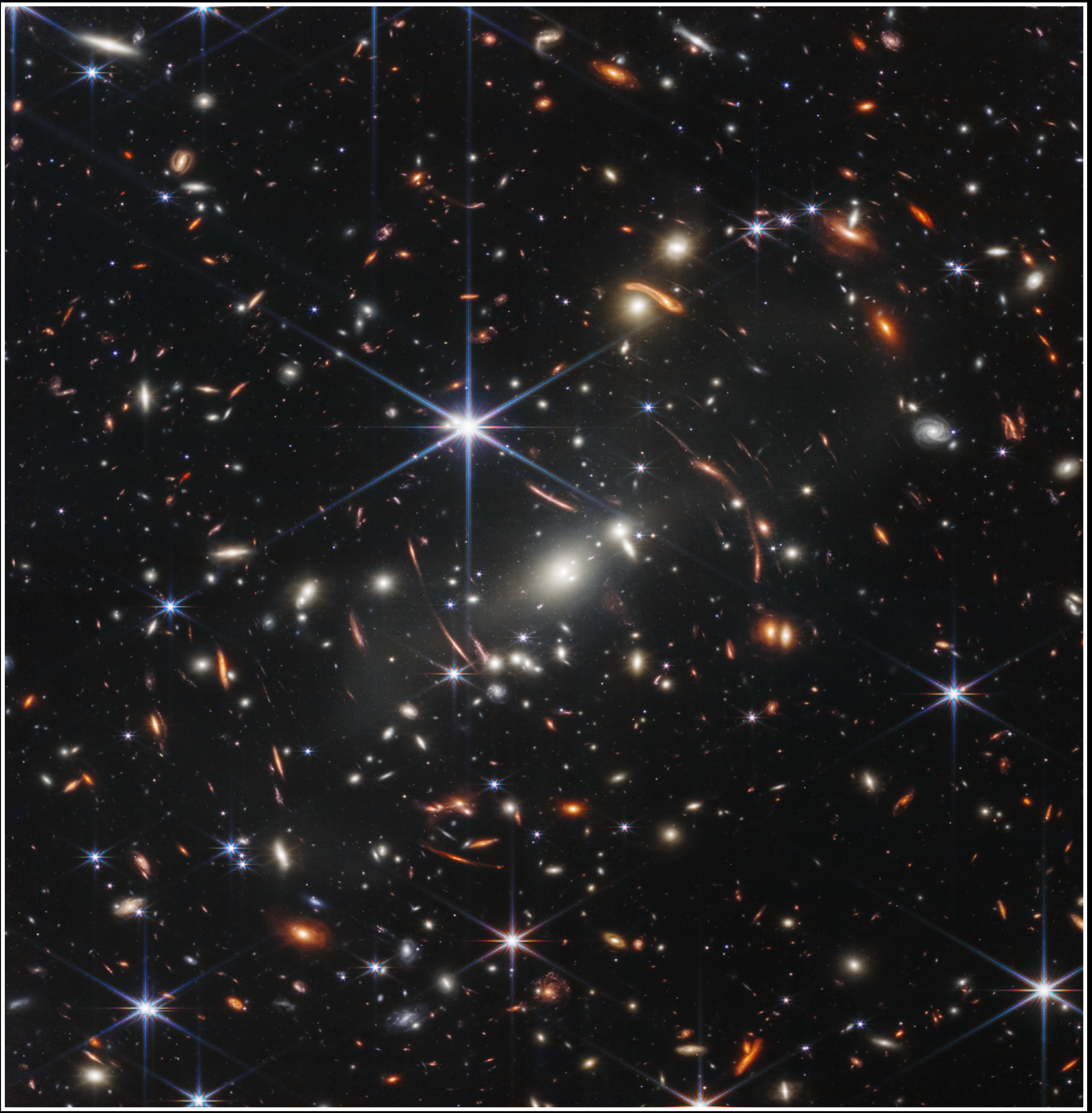


- Physics: optimal conditions for gas accretion + rich in angular momentum + no more disc “spin flips” due to mergers.
  e.g. Dekel et al (2020)

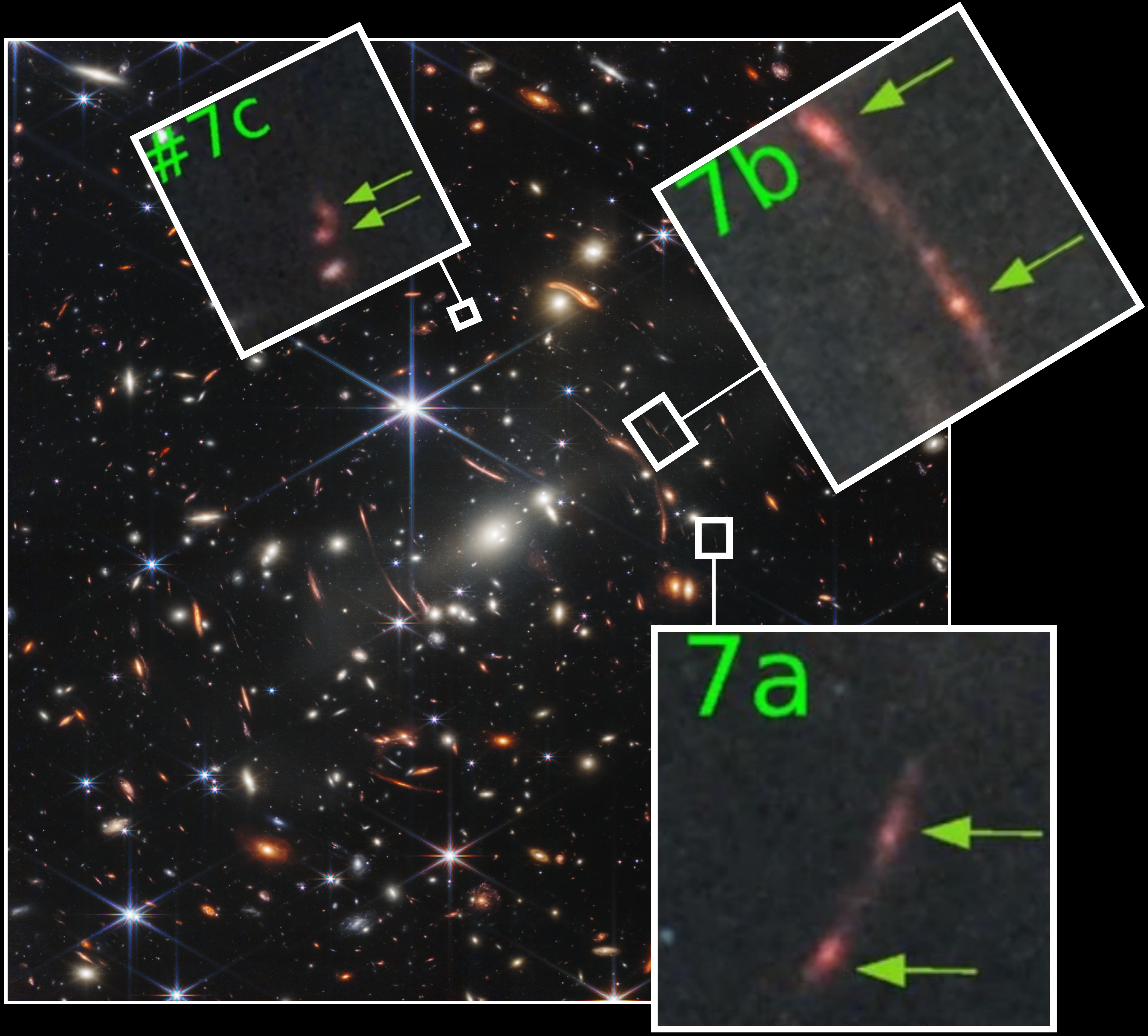
- Rapid disc formation from cosmic inflows has a distinct imprint on the chemistry of the stars. The simulation predict the same structure as the Milky Way, i.e. an old “thick” disc and a younger extended “thin” disc.

NASA & White House, press conference, Monday 11 July, 2022

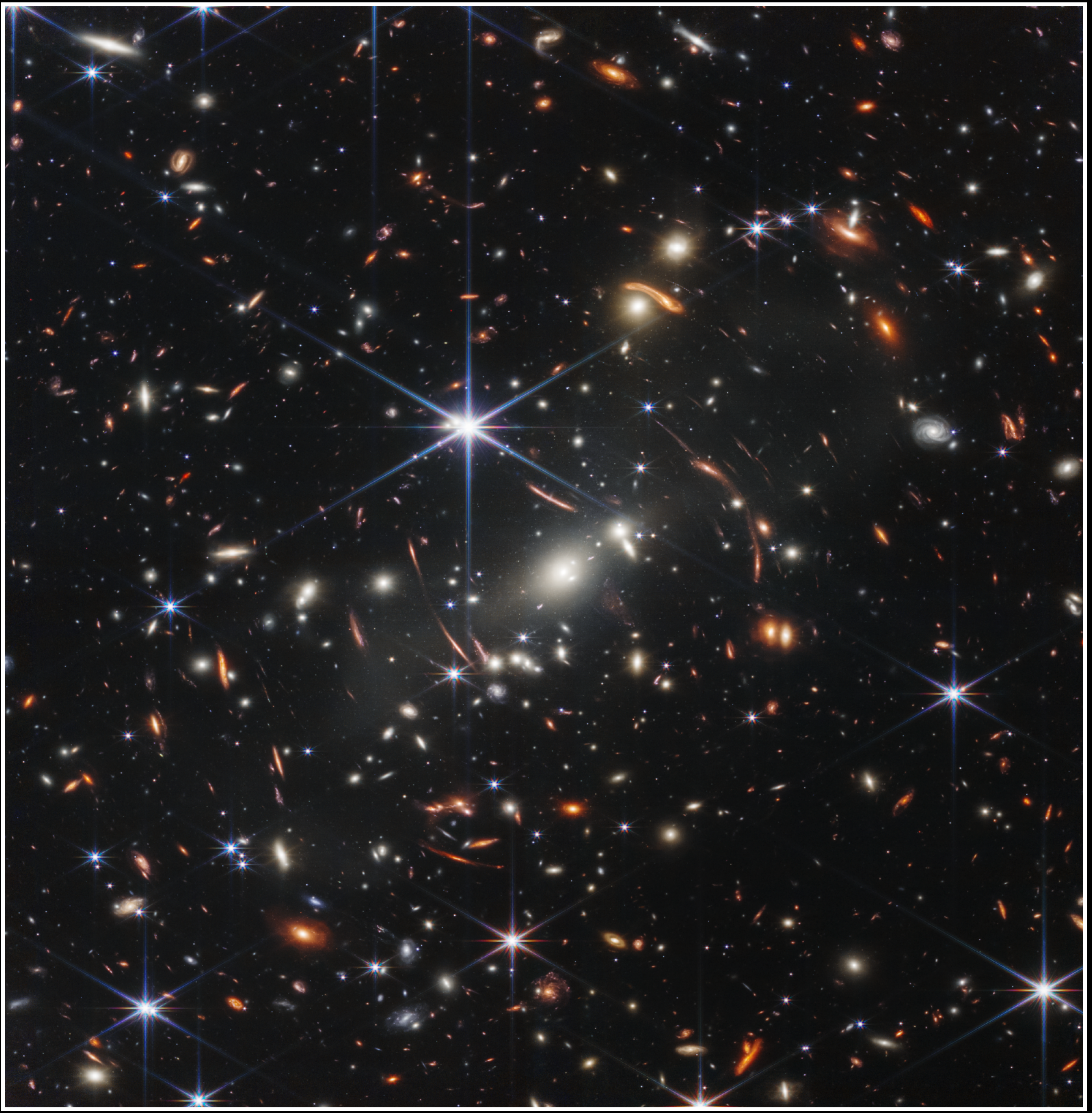
James Webb Telescope (NASA)
is already revolutionizing our understanding of galactic structure, star formation, and the most distant galaxies ever observed



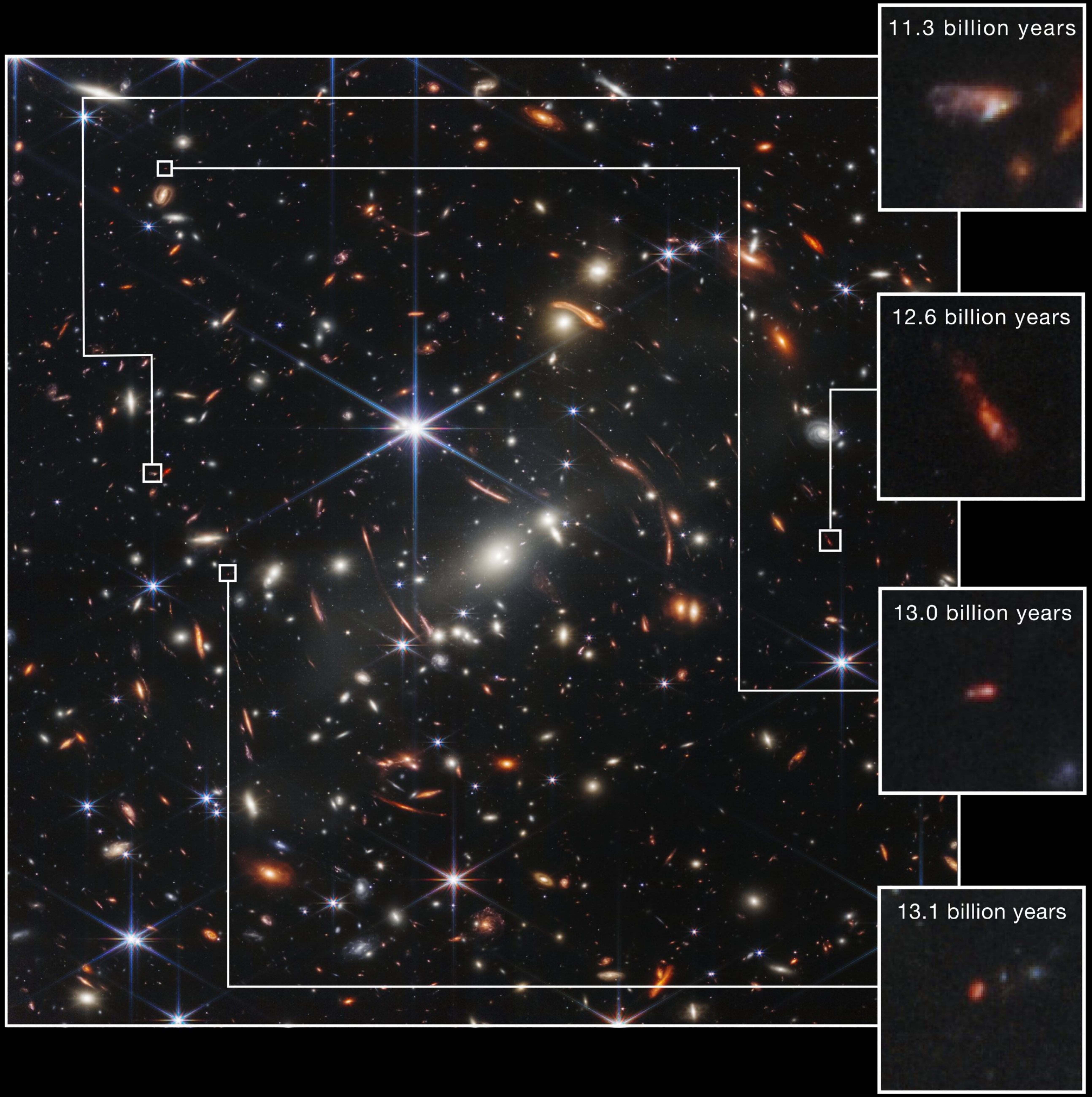
James Webb Telescope (NASA)
is already revolutionizing our understanding of galactic structure, star formation, and the most distant galaxies ever observed



James Webb Telescope (NASA)
is already revolutionizing our understanding of galactic structure, star formation, and the most distant galaxies ever observed



James Webb Telescope (NASA)
is already revolutionizing our understanding of galactic structure, star formation, and the most distant galaxies ever observed

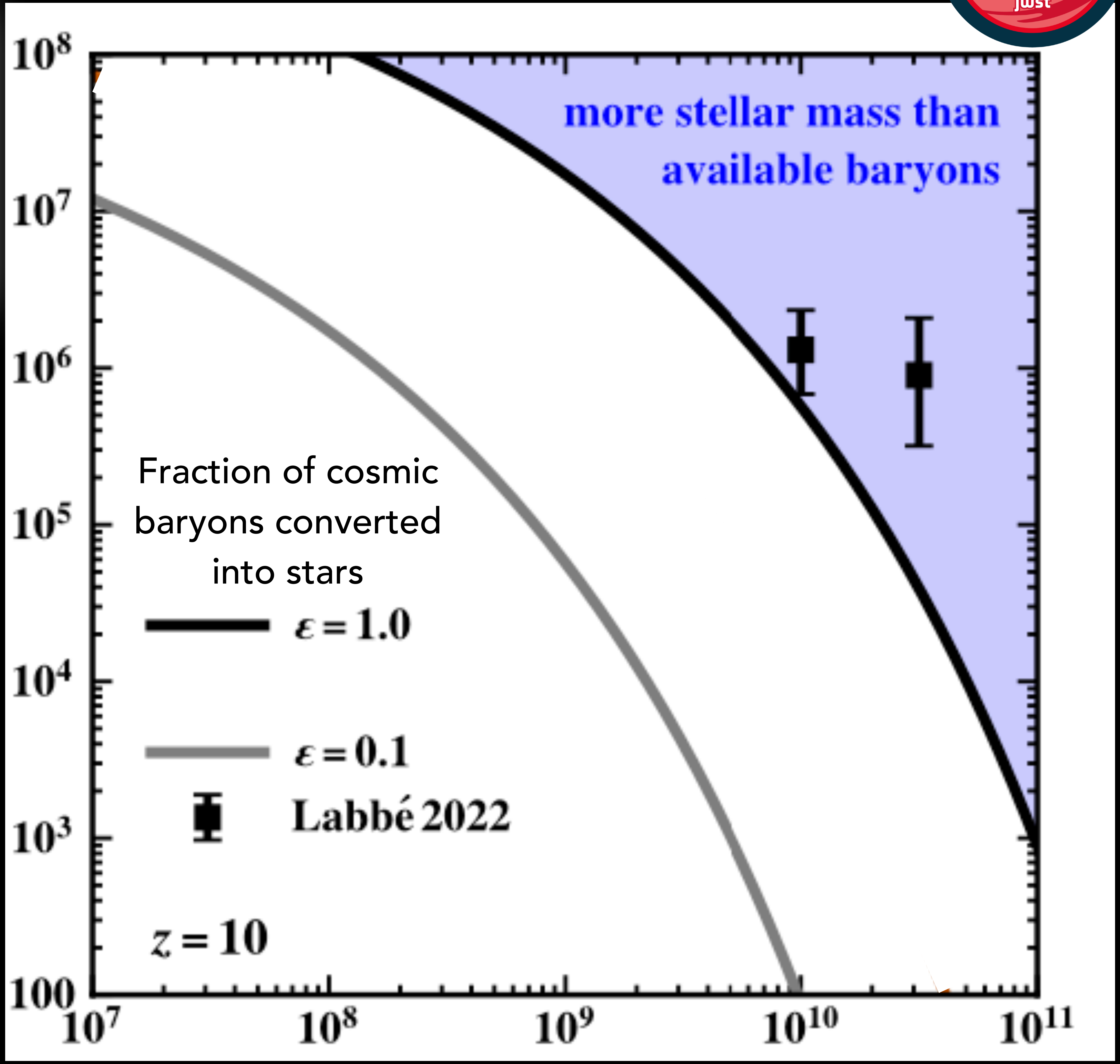


Stress testing ΛCDM with high-redshift galaxy candidates

Michael Boylan-Kolchin⋆
Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, TX 78712-1205, USA

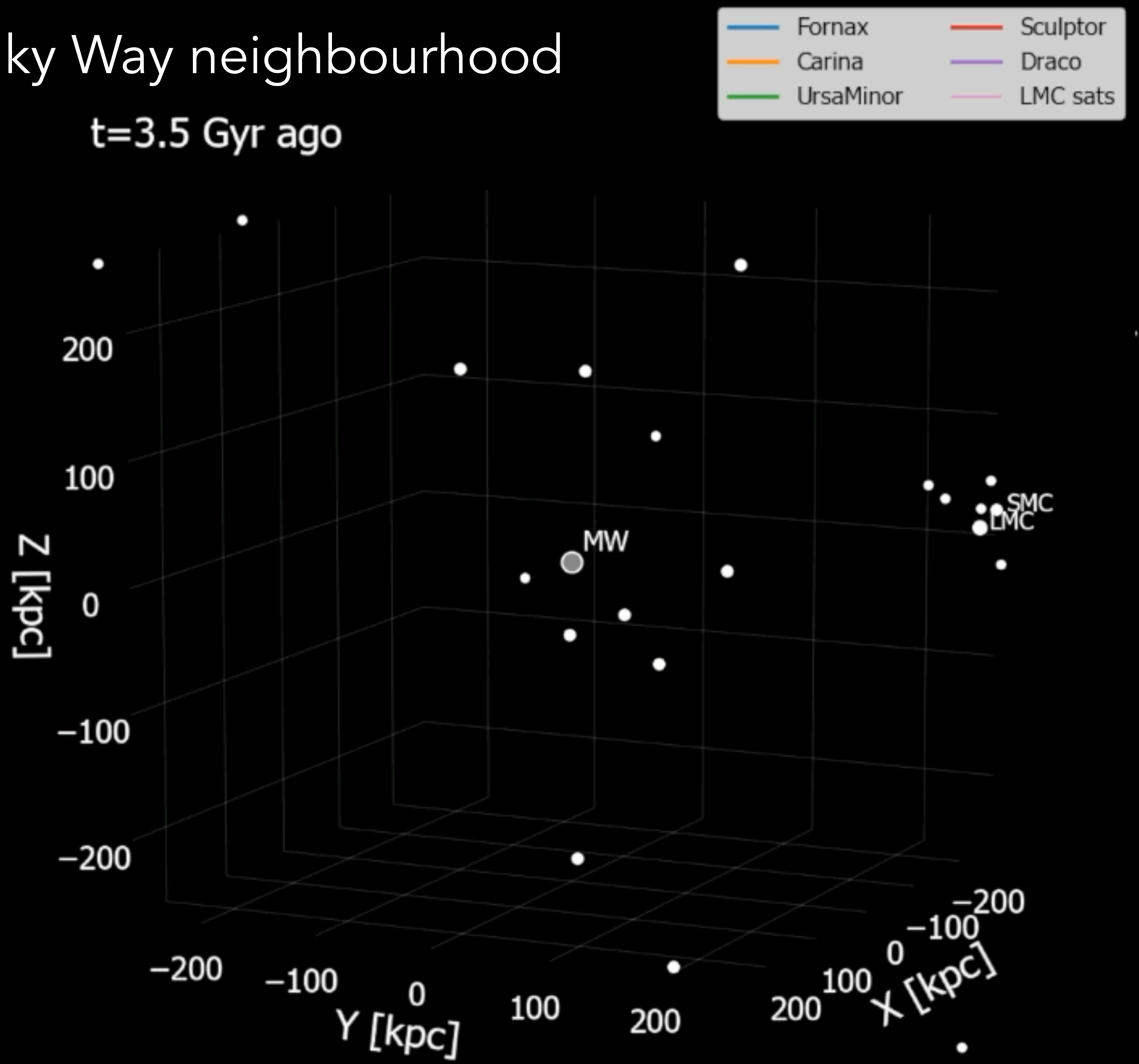
Draft version, 2 August 2022

Stellar mass density [solar masses Mpc^{-3}] contained within galaxies more massive than $M_\star$



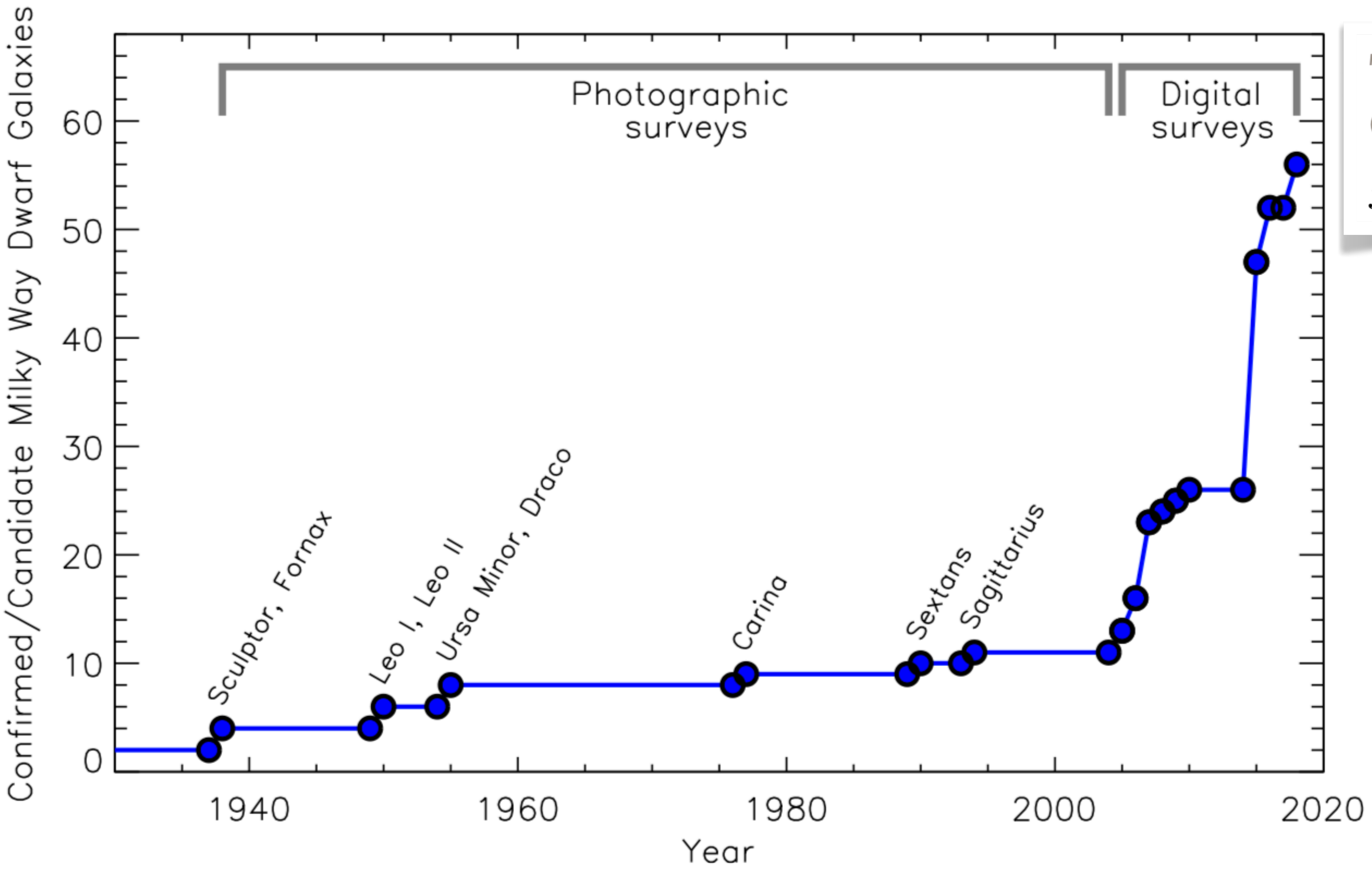
$M_\star$, stellar mass [solar masses]

Dwarf galaxies Milky Way neighbourhood



Credit: Ekta Patel

Digitial surveys have revolutionized the dwarf galaxy census



The Faintest Dwarf Galaxies

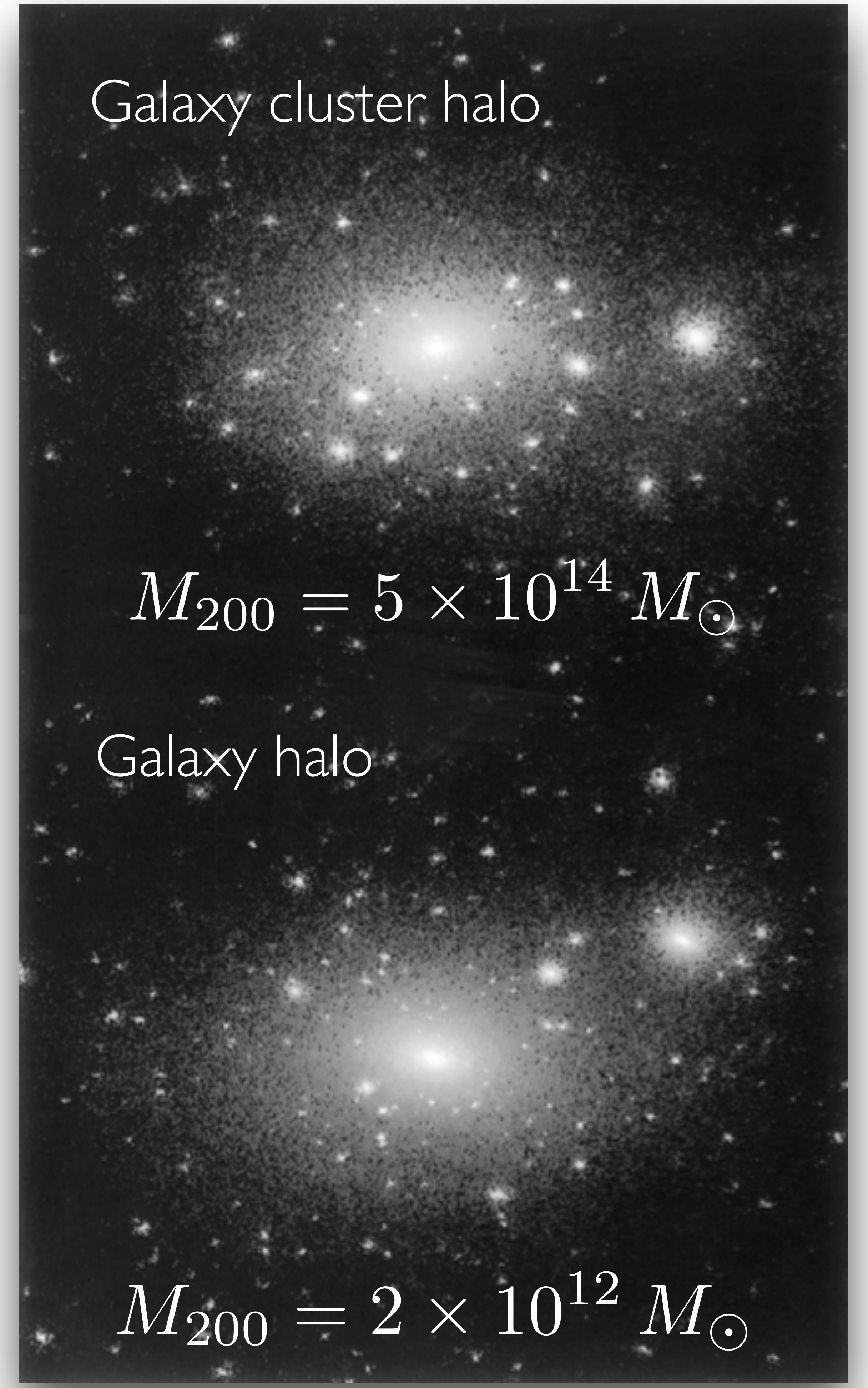
Joshua D. Simon[1] ARA&A (2019)

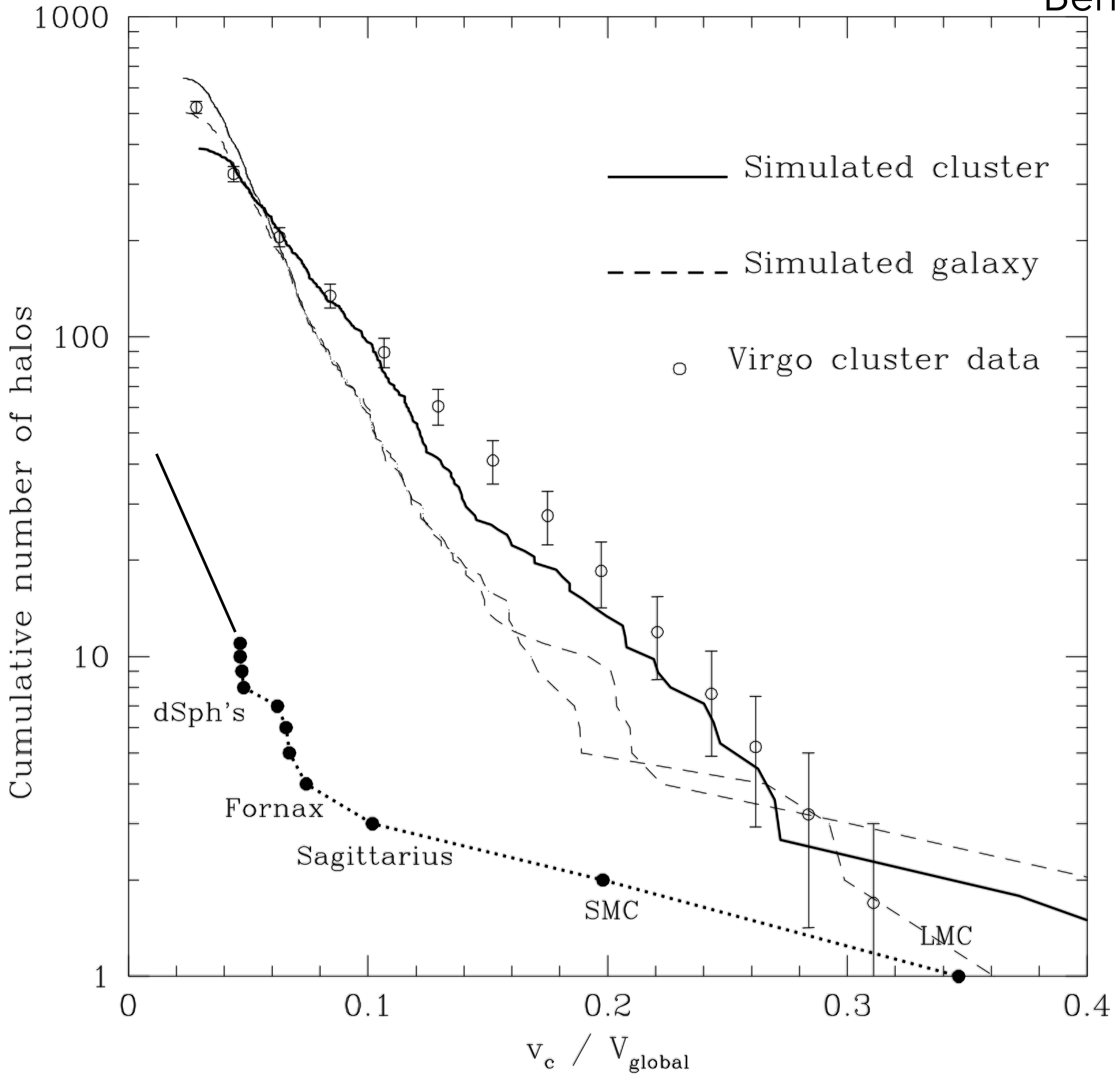
The missing satellites problem

- Dark matter substructure mass functions are almost universal
- Substructure in galaxy clusters is accounted for
- Most satellites appear to be missing in galactic haloes!

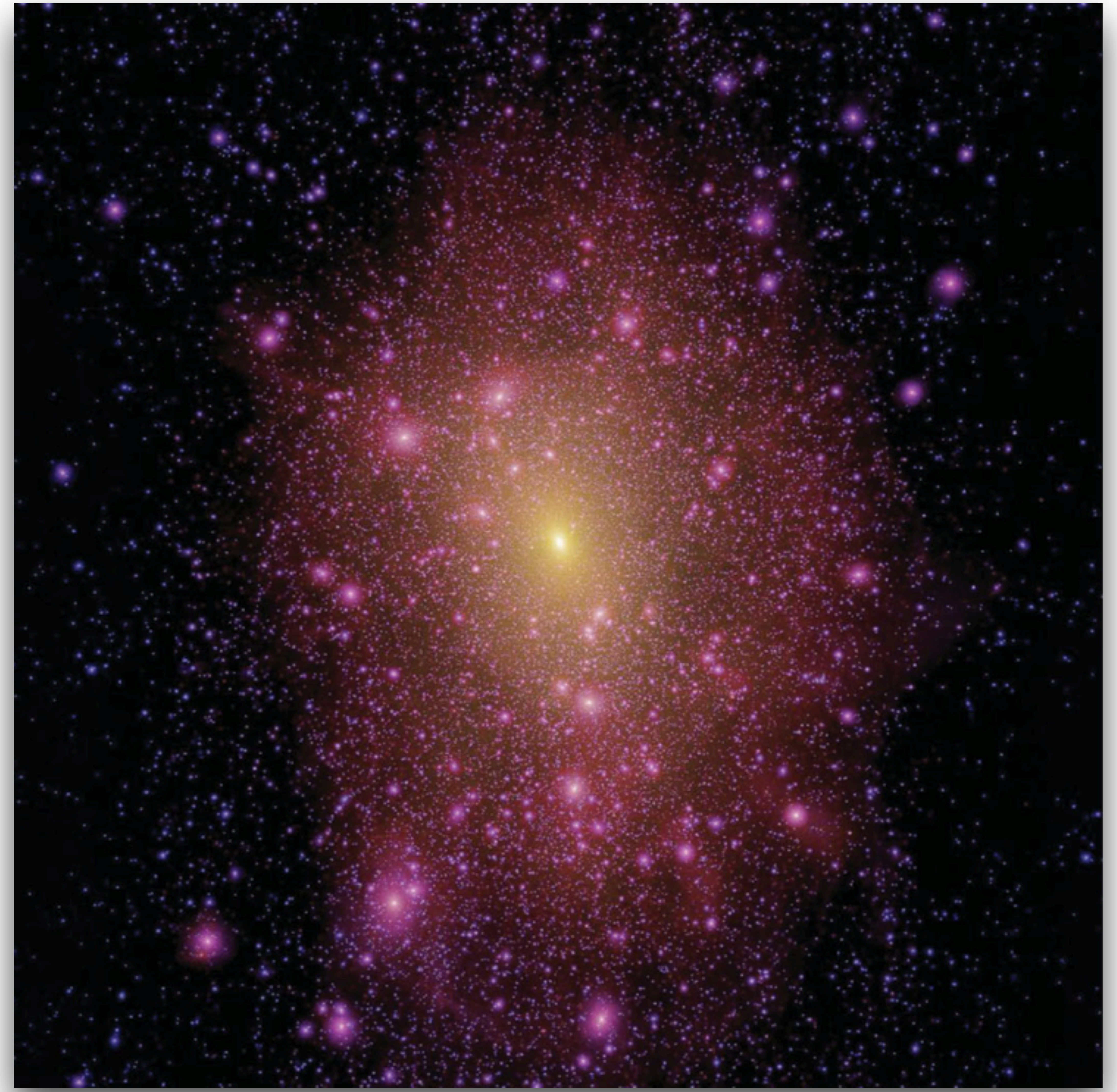
Moore et al. (1999)
Klypin et al. (1999)


Ben Moore

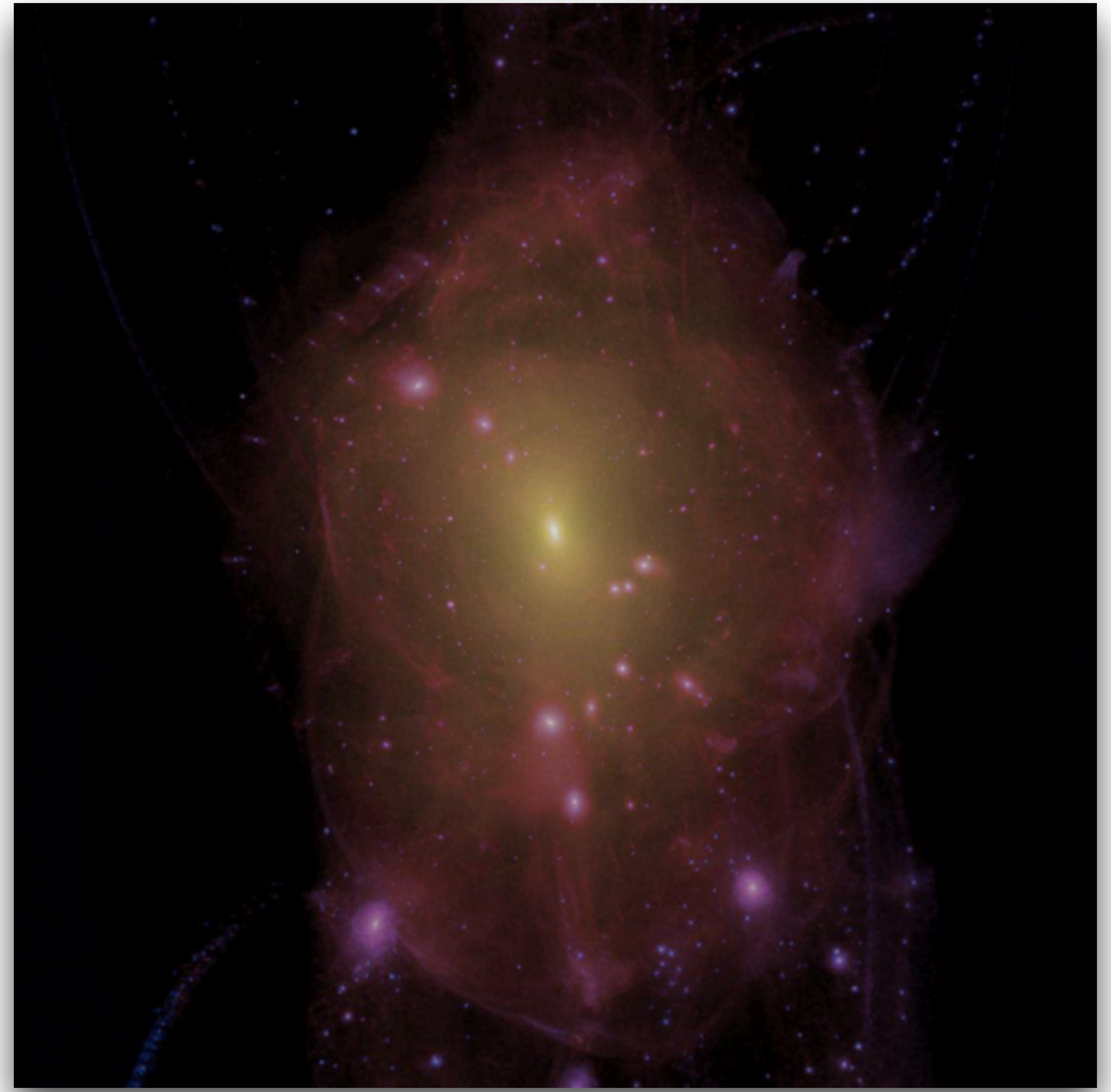




Possible solution 1: Dark matter is not “cold”!



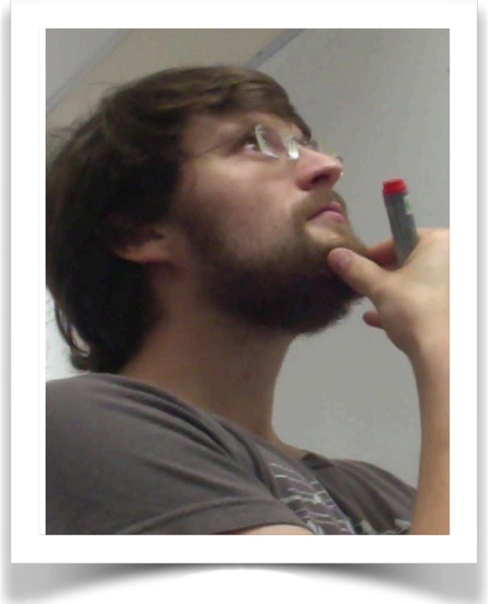
Cold Dark Matter (Mass of ~100 GeVs)



Warm Dark Matter (Mass of ~2 keV)

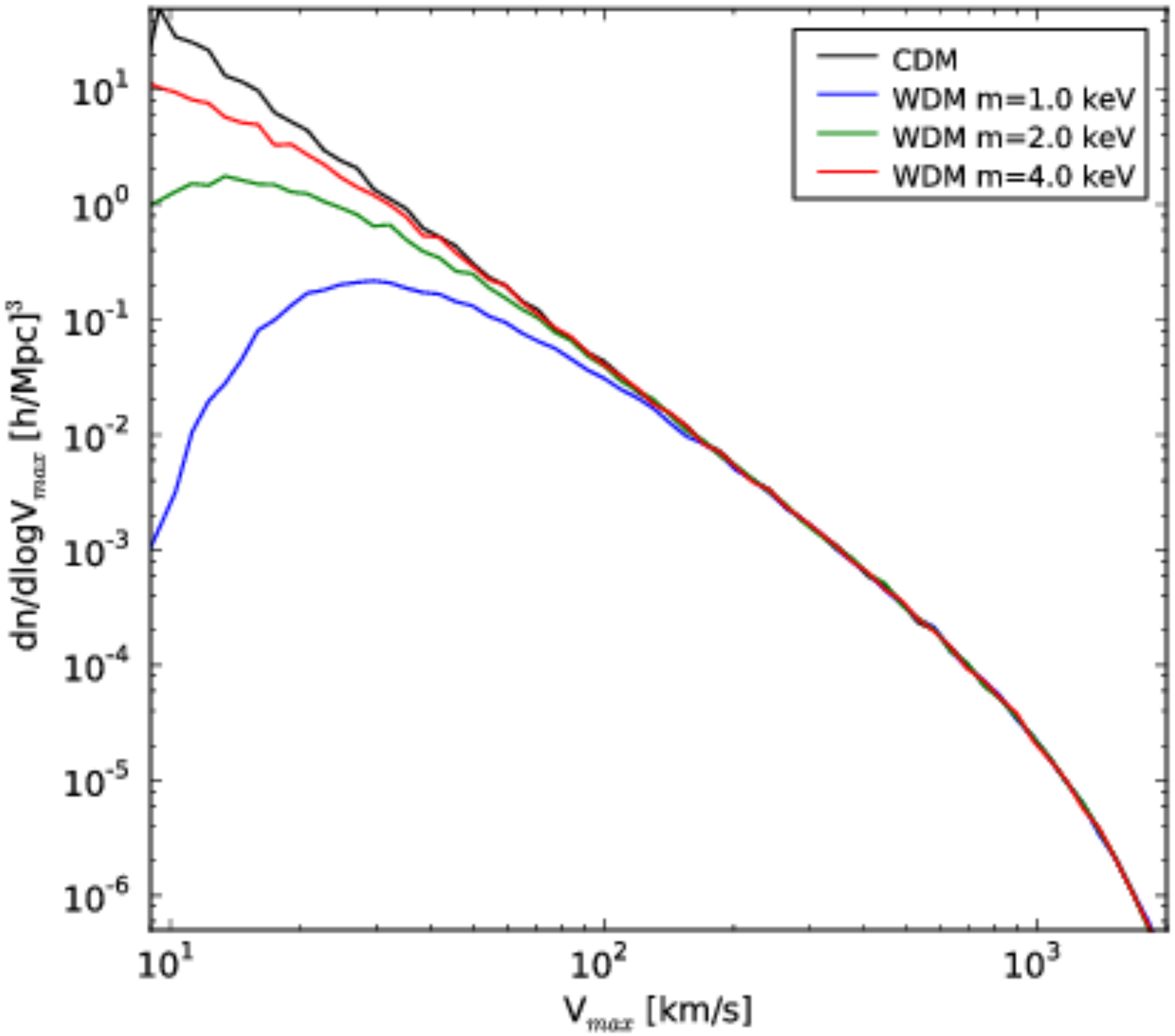
Lovell et al. (2012

Possible solution 1: Dark matter is not “cold”!



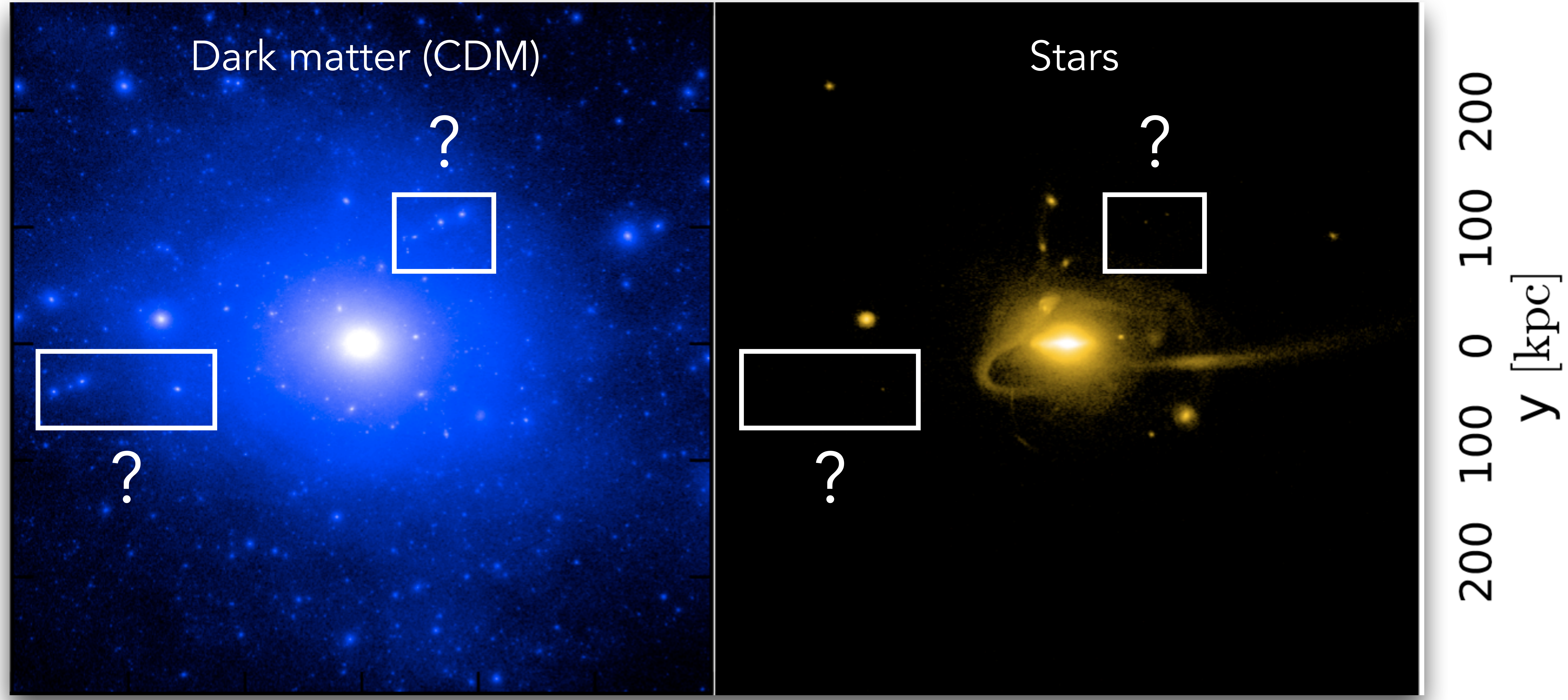
Schneider et al. (2016)

Number density of dark matter haloes



Peak circular velocity —> mass

Possible solution 2: supernova explosions and "baryon physics" make star formation inefficient in small dark matter halos



Wetzel et al. (2016)

- Substructure mass functions ***seem*** compatible with observations (Milky Way and Andromeda)

nature astronomy

REVIEW ARTICLE

https://doi.org/10.1038/s41550-022-01689-w

Check for updates

Baryonic solutions and challenges for cosmological models of dwarf galaxies

2022

Laura V. Sales[1]✉, Andrew Wetzel[2] and Azadeh Fattahi[3]

ΛCDM tensions with dwarf galaxies

No tension	Uncertain	Weak tension	Strong tension
Missing satellites	$M_{\star}$–M_{halo} relation	Too big to fail	Diversity of rotation curves
	Core–cusp	Diversity of dwarf sizes	Satellite planes
		Quiescent fractions	

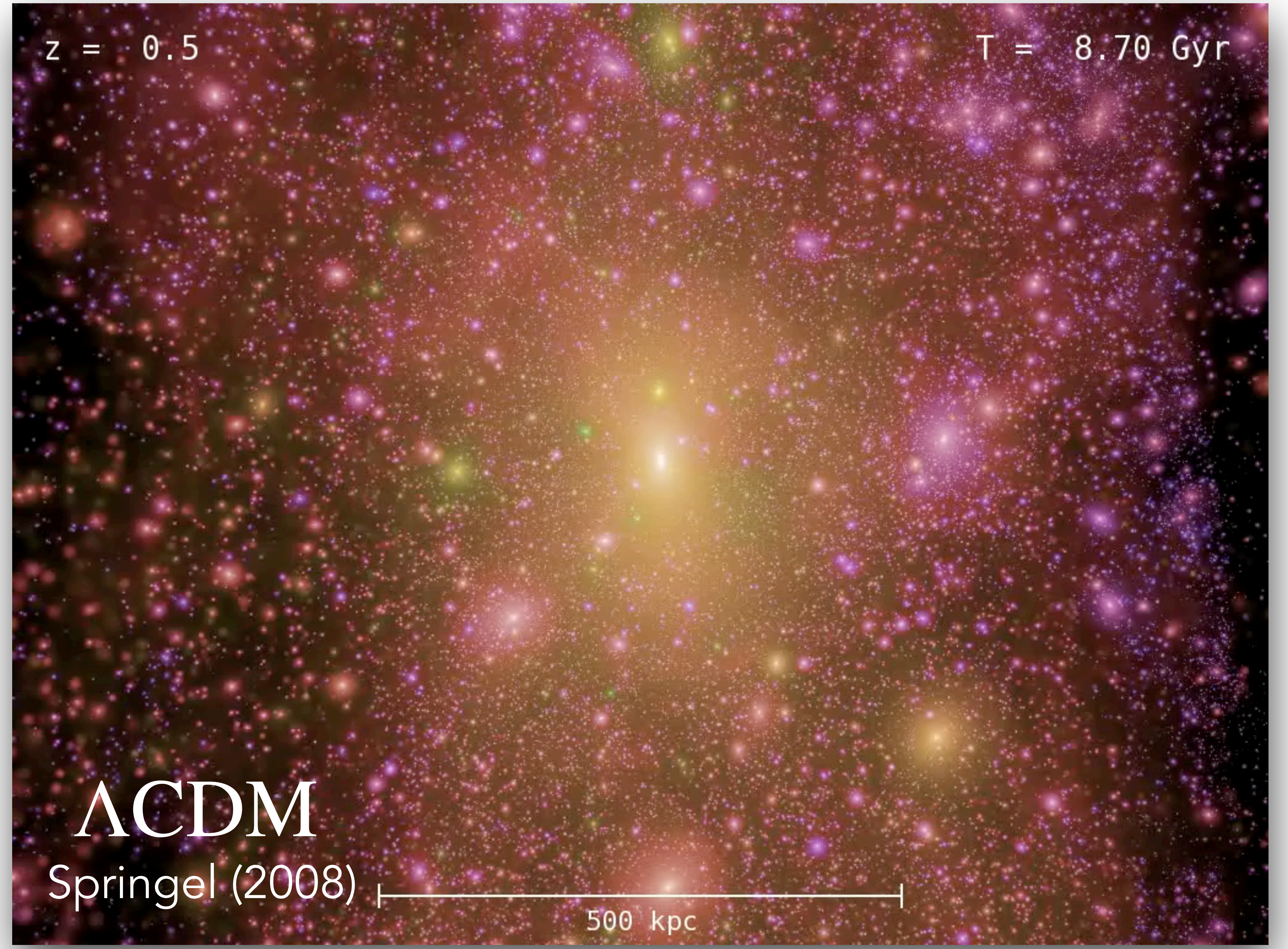
THE PLANES OF SATELLITE GALAXIES PROBLEM, SUGGESTED SOLUTIONS, AND OPEN QUESTIONS

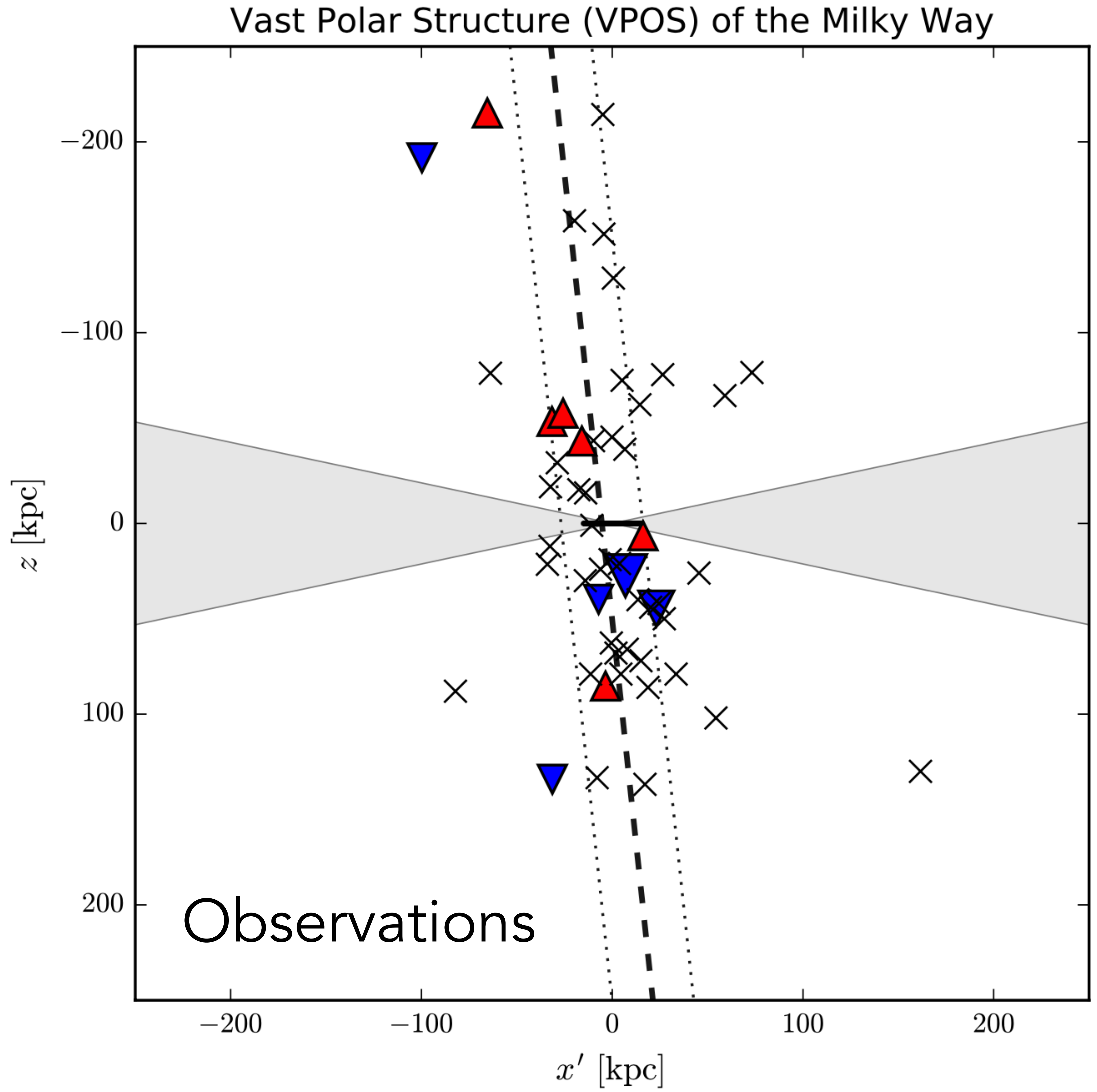
2018

MARCEL S. PAWLOWSKI*

Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
marcel.pawlowski@uci.edu

Problem: ΛCDM predicts a close to isotropic distribution of dwarf galaxy-hosting sub-halos. In the Milky Way, dwarf galaxies are disitrbuted in a plane. This is a very rare constellation in ΛCDM!





To make progress, we need a census of dwarf galaxies around MANY more hosts than just the Milky Way (and Andromeda)!

ARRAKIHS

Analysis of Resolved Remnants of Accreted galaxies as a Key Instrument for Halo Surveys

esa


ESA Science
@esascience

NEW Excited to announce Arrakihs as the latest member of the @esascience fleet!

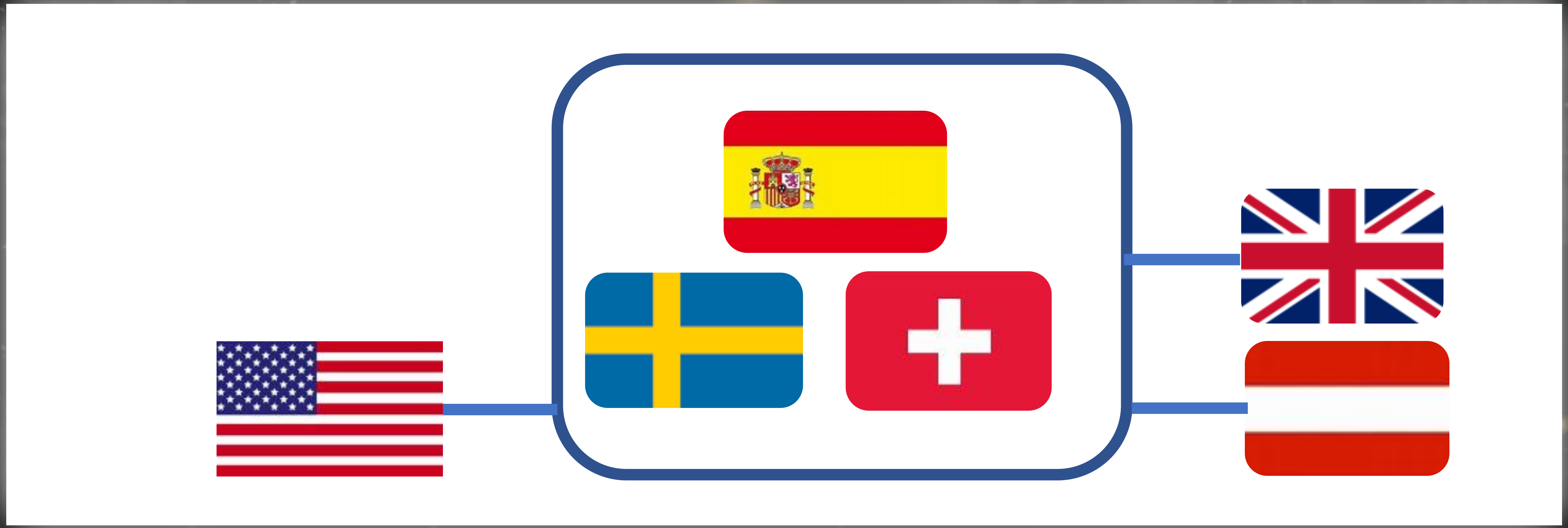
Set to launch in the early 2030s, this fast-class mission will image faint nearby galaxies, providing important measurements to test open questions in #cosmology.

More info 👉 cosmos.esa.int/web/call-for-m...

ALT

IFCA and ESA

11:23 AM · Nov 4, 2022 · Twitter Web App



LUND UNIVERSITY

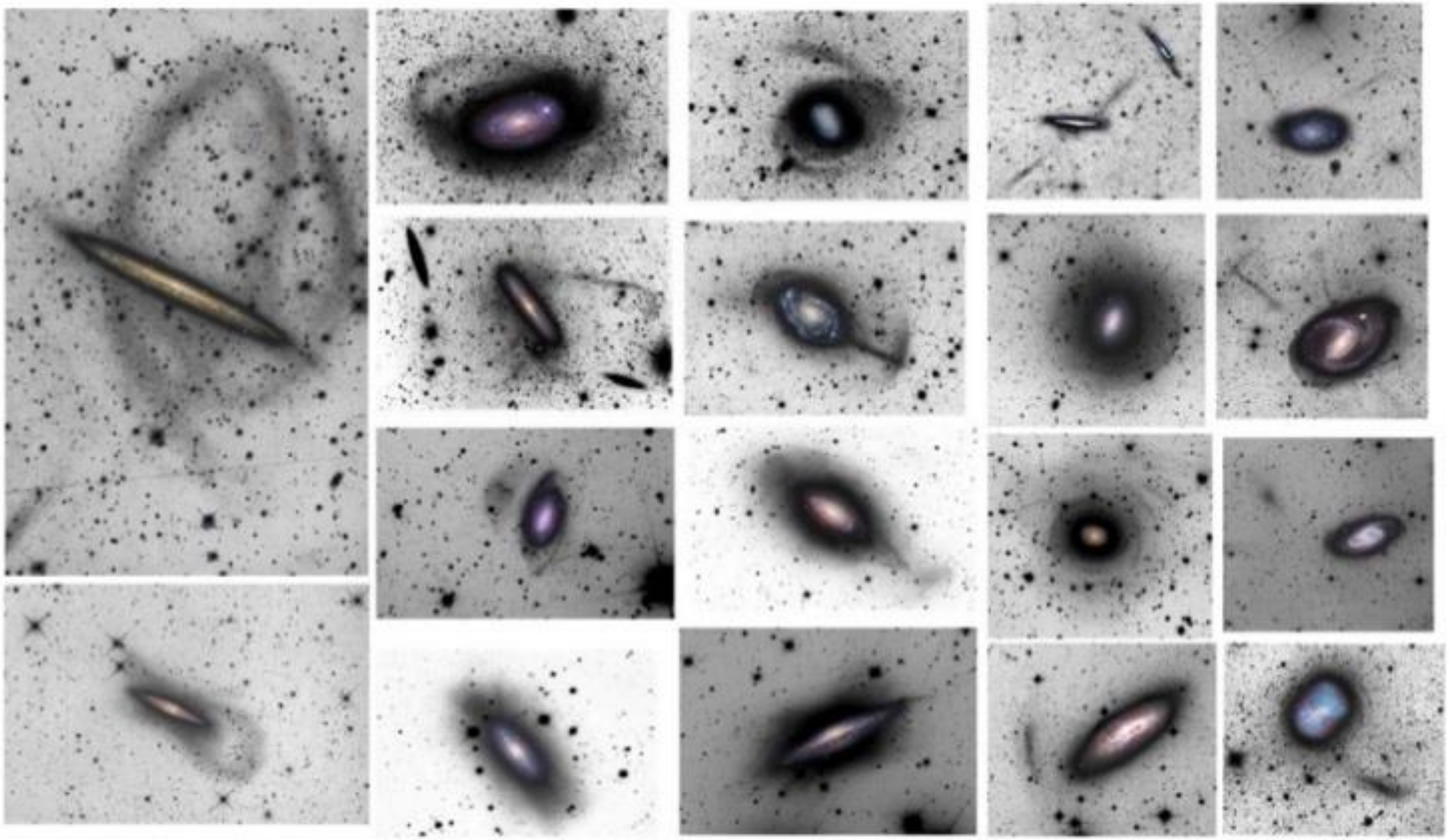


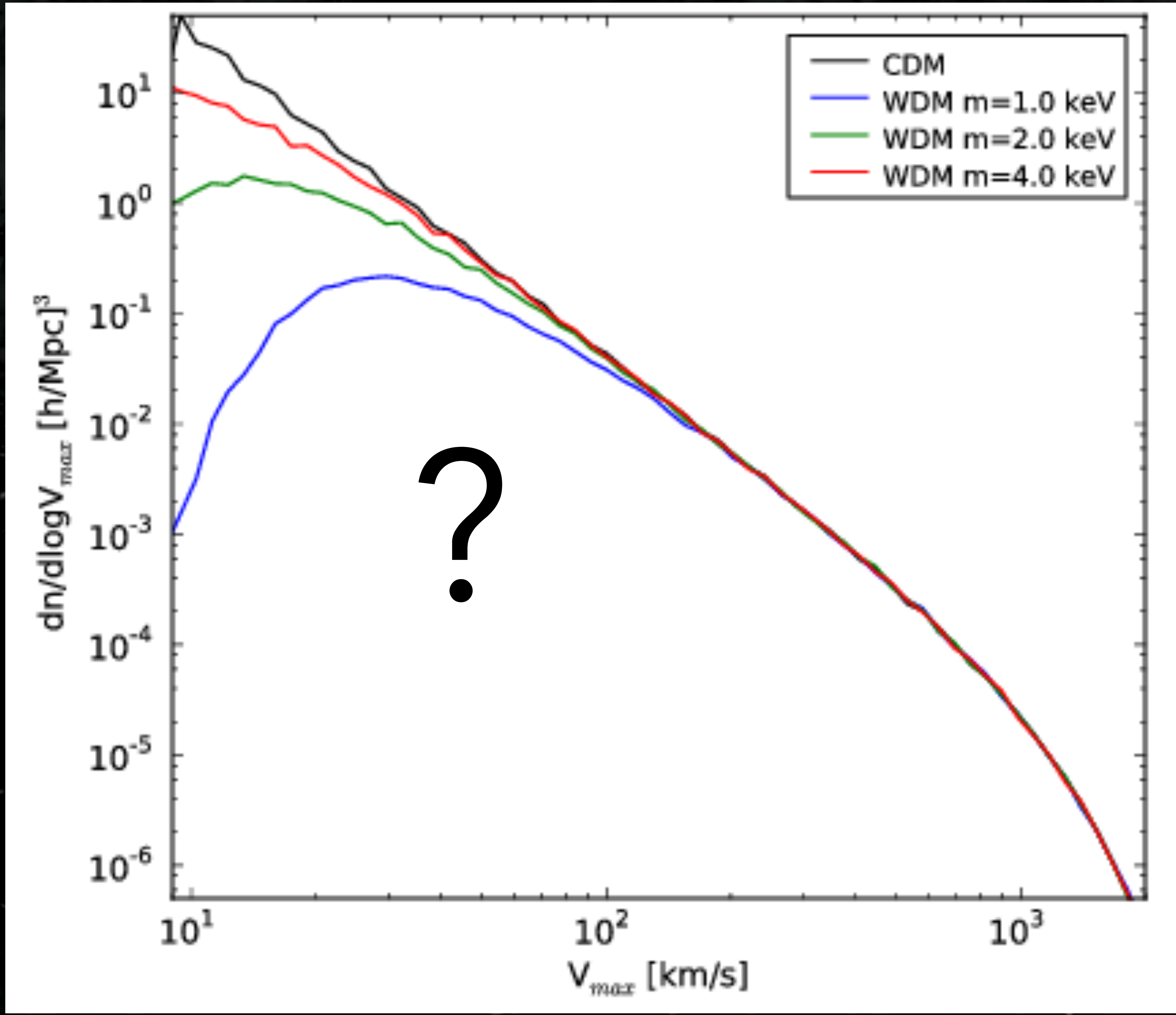
Figure 2: Luminance filter images of nearby galaxies from the Stellar Tidal Stream Survey showing large, diffuse light structures in their outskirts (Martínez-Delgado et al., 2010, 2012, 2015)

ARRAKIHS will observe 3-4 magnitudes deeper than this in close to 100 massive galaxies!

ARRAKIHS

The Nature of dark matter can be probed by:

- Abundance and masses of the faintest satellite galaxies. What is the “edge” of galaxy formation? (caveats: baryonic physics)
- Perturbations to stellar streams. Dark matter halos are lumpy, with the level of ‘lumpiness’ depending on the dark matter particles mass/energy.



ARRAKIHS

The Nature of dark matter can be probed by:

- Abundance and masses of the faintest satellite galaxies. What is the “edge” of galaxy formation? (caveats: baryonic physics)
- Perturbations to stellar streams. Dark matter halos are lumpy, with the level of ‘lumpiness’ depending on the dark matter particles mass/energy.