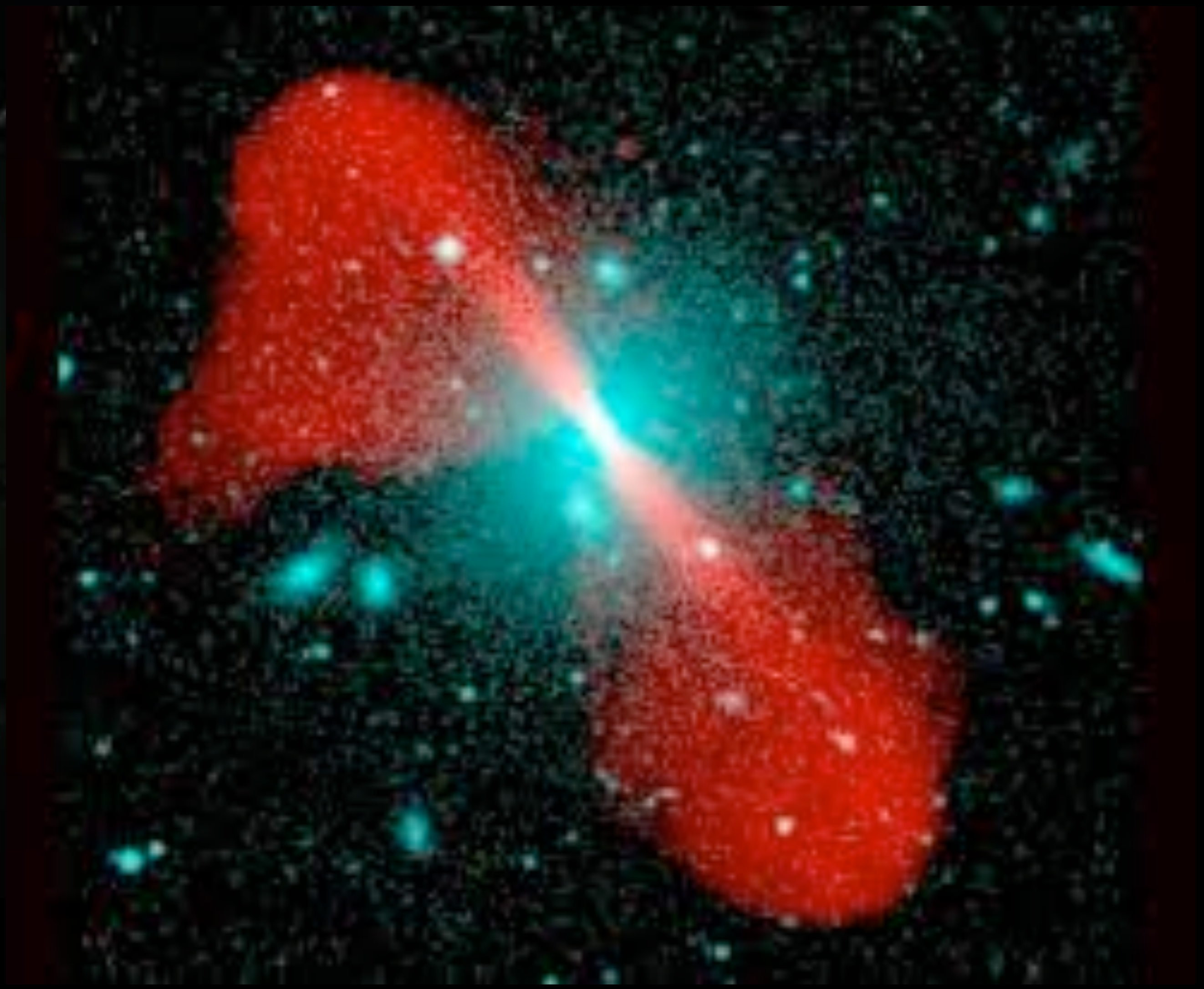
Galaxy formation



SKY 5 Jan 2022 Origins Meeting

But,
Galaxies do change!
Classic observational cosmology

$$\frac{kc^2}{R^2} = H_0^2(2q_0 - 1) \equiv H_0^2(\Omega_0 - 1)$$

$$dl^2 = R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right]$$

Ann. Rev. Astron. Astrophys. 1988. 26: 561–630

OBSERVATIONAL TESTS OF WORLD MODELS

Allan Sandage

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1. THE ELEMENTS OF PRACTICAL COSMOLOGY

The standard model of cosmology, based on what has come to be called the Friedmann-Lemaitre-Robertson-Walker (FLRW) model (hereinafter simply the Friedmann model), is now part of scientific culture. The most popular current version leads to the hot big bang (HBB) description of events near the beginning of the cosmic expansion, which has often been called a creation[2] moment at the beginning of physical time. In this review a prejudice in favor of the HBB [in contrast to cold beginnings discussed

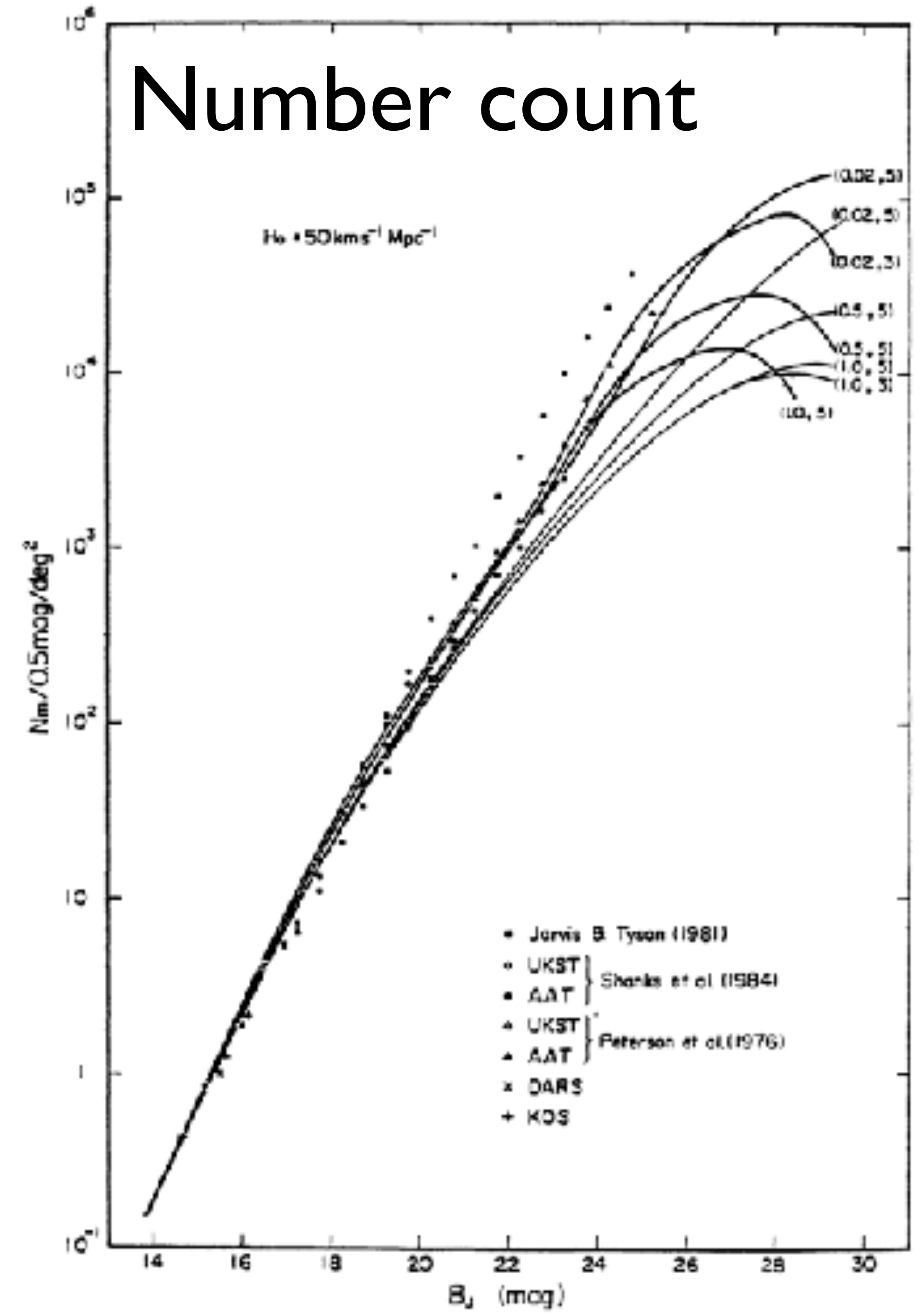


Figure 3 Comparison of predicted $A(m, q_0)$ functions with the observed *differential* counts (i.e. number at magnitude B_J in magnitude interval ± 0.25 mag) from various surveys. The four heavy lines to the left are for the marked values of q_0 and the redshift of galaxy formation, with luminosity evolution included. The four light lines to the right are the same but with zero luminosity evolution. The relations depend on H_0 only to set the time scale for

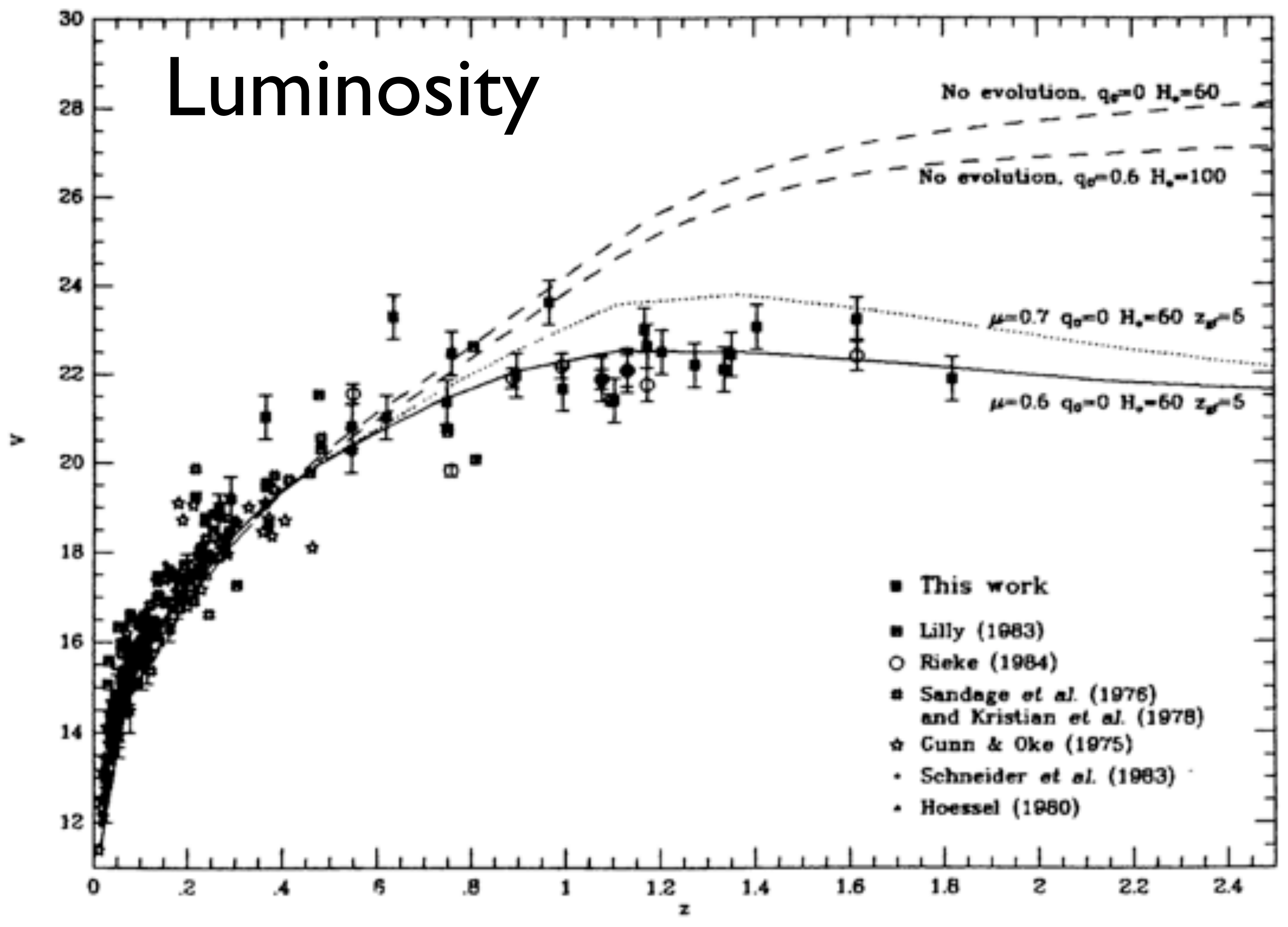


Figure 7 The $m(z)$ Hubble diagram (plotted differently from Figure 5, with V magnitude as ordinate and linearly with z) extended to large redshift. Predicted theoretical $m(z)$ lines for various q_0 values and evolutionary corrections (Bruzual models) are shown. The K corrections have been applied to the *theoretical* curves (from Djorgovski et al. 1985).

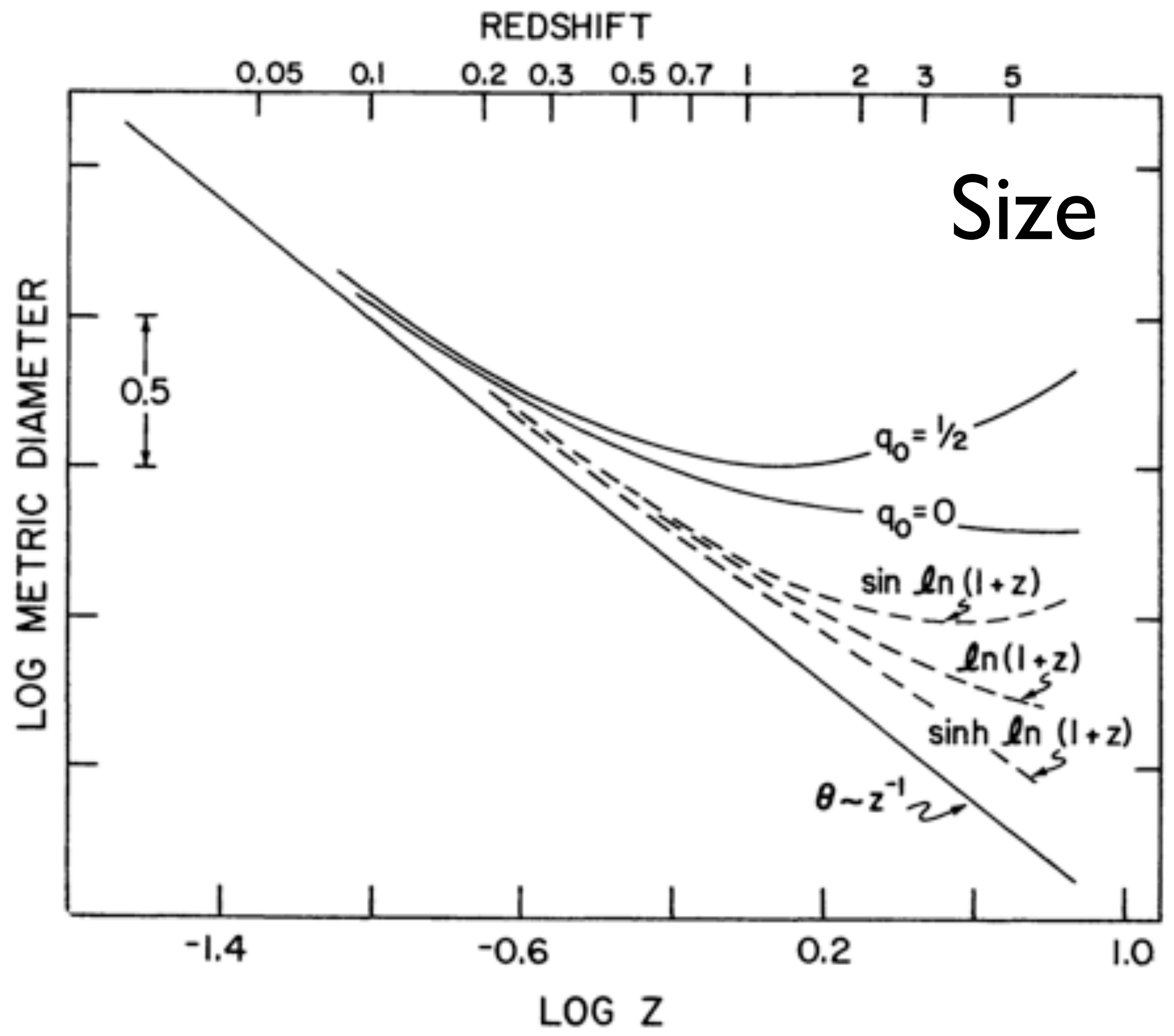


Figure 11 Theoretical angular size–redshift relations for $q_0 = 0$ and $q_0 = 1/2$ standard Friedmann models, and for three types of geometry for the tired-light speculation. The Euclidean $\theta \sim z^{-1}$ intuitive dependence is shown for purposes of comparison.

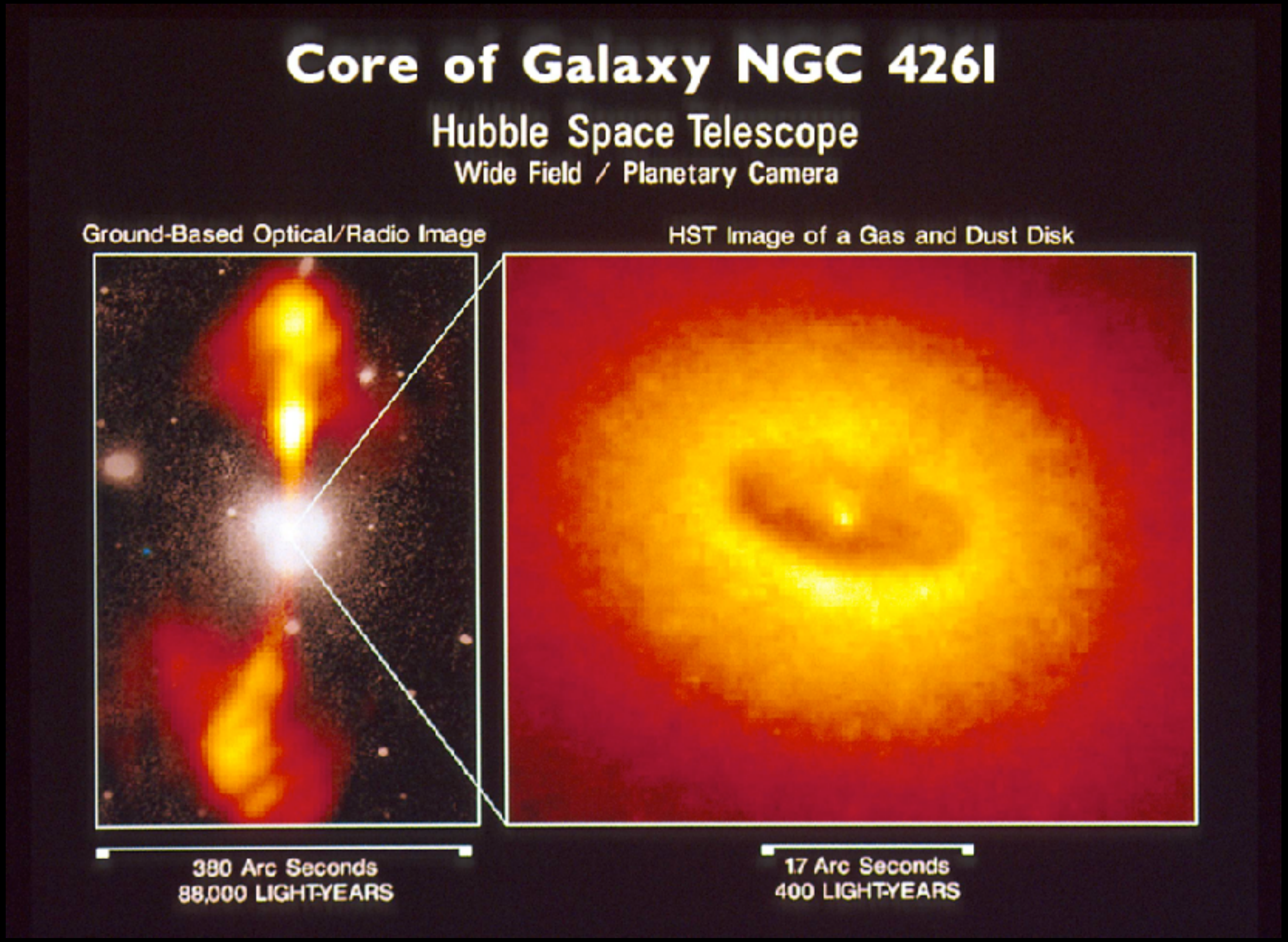
Galaxy challenge

Disc galaxies

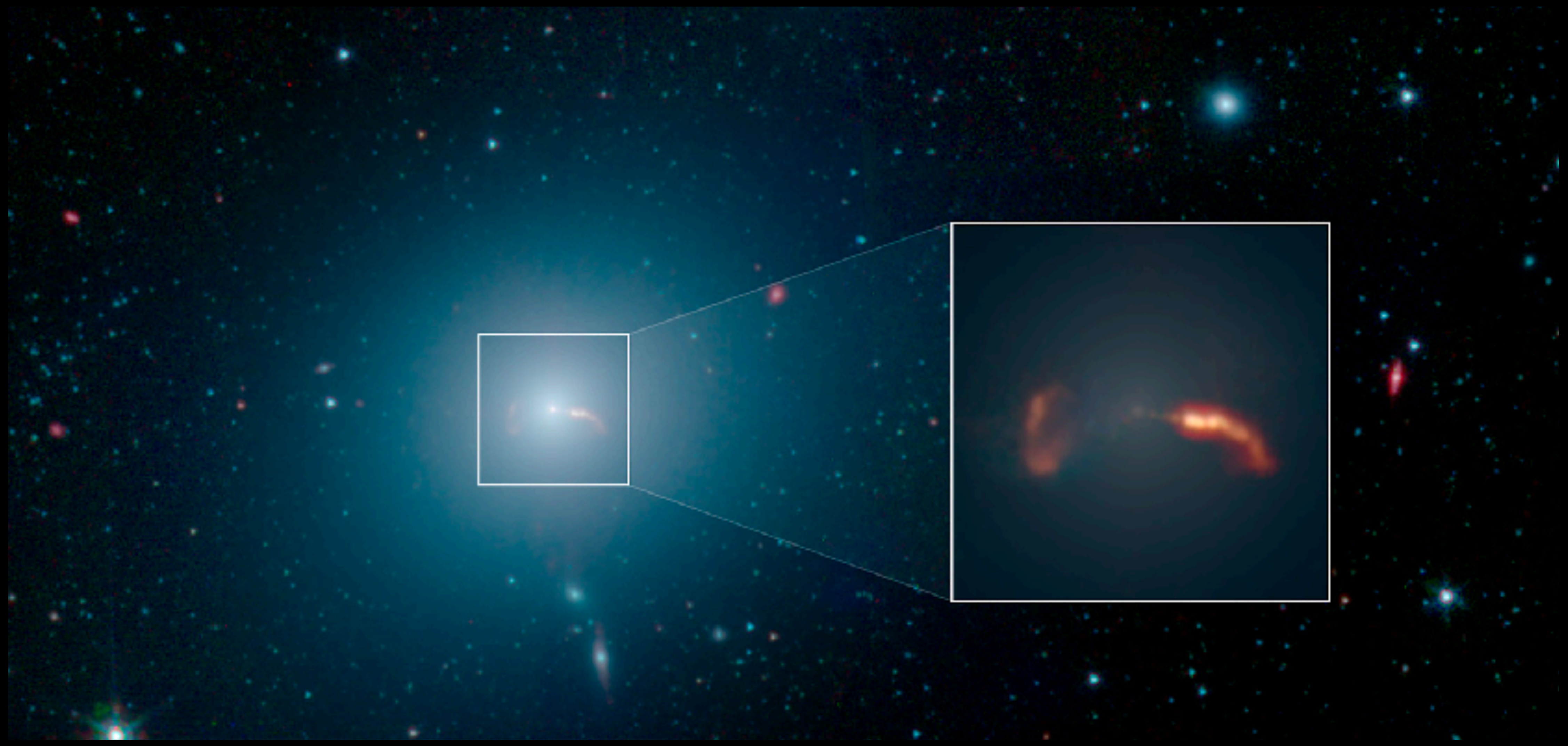
25000 ly

NGC 891
Credit: Hewholooks https://commons.wikimedia.org/wiki/File:NGC891HunterWilson.jpg

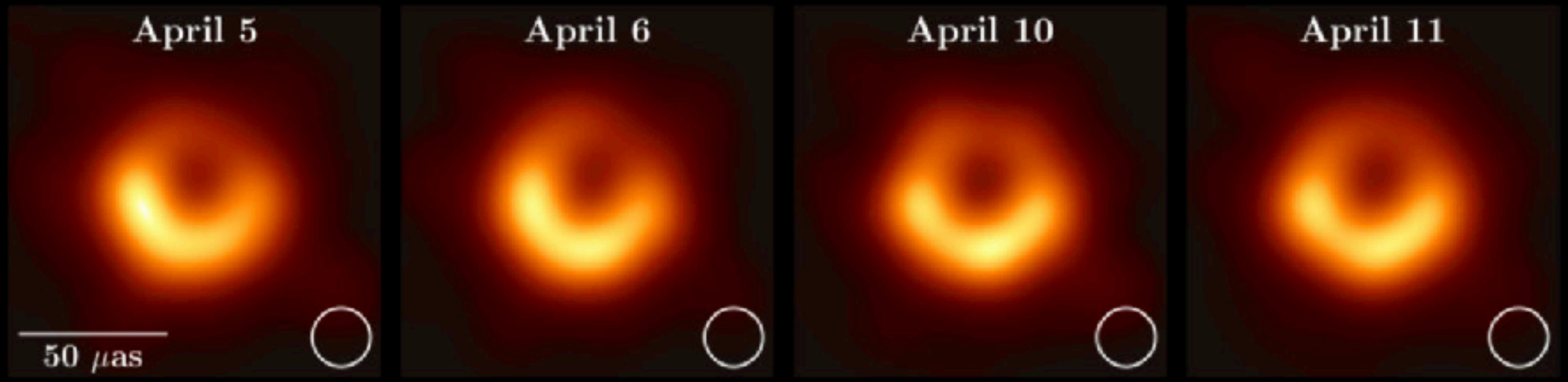
Galaxy challenge
Elliptical galaxies



M_star ~ 1e12, M_BH ~ 6.5e9 Msun



NASA/JPL/IPAC



Observations from the Event Horizon Telescope of the supermassive black hole at the center of the elliptical galaxy M87, for four different days. [EHT Collaboration et al 2019]

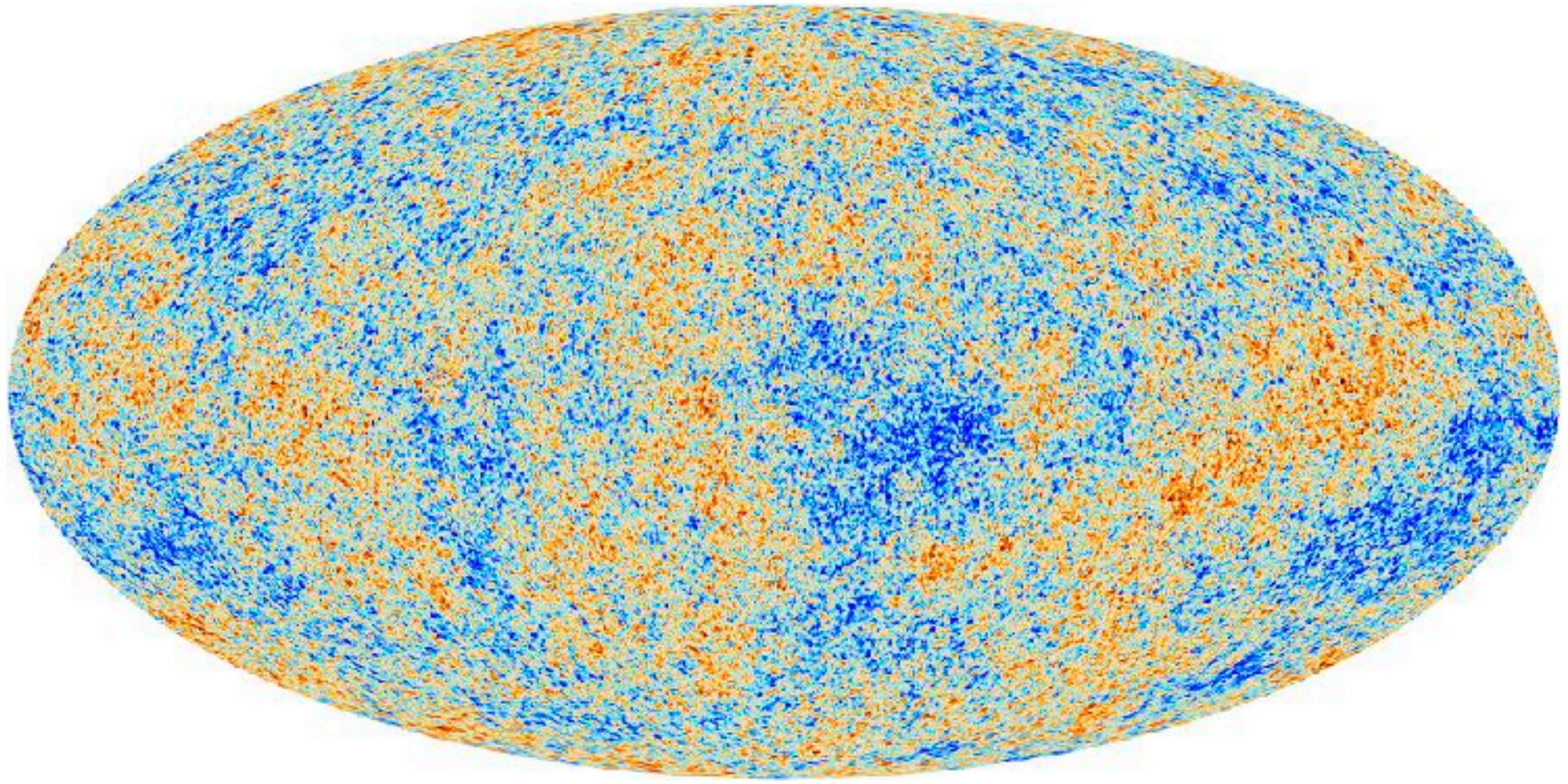
Understanding galaxies

- Cosmology
  - Cosmic expansion history
  - Dark matter
  - Energy budget
- Baryon physics

Hercules cluster
Credit: Stan Moorer http://www.stanmooreastro.com/astro_page.html

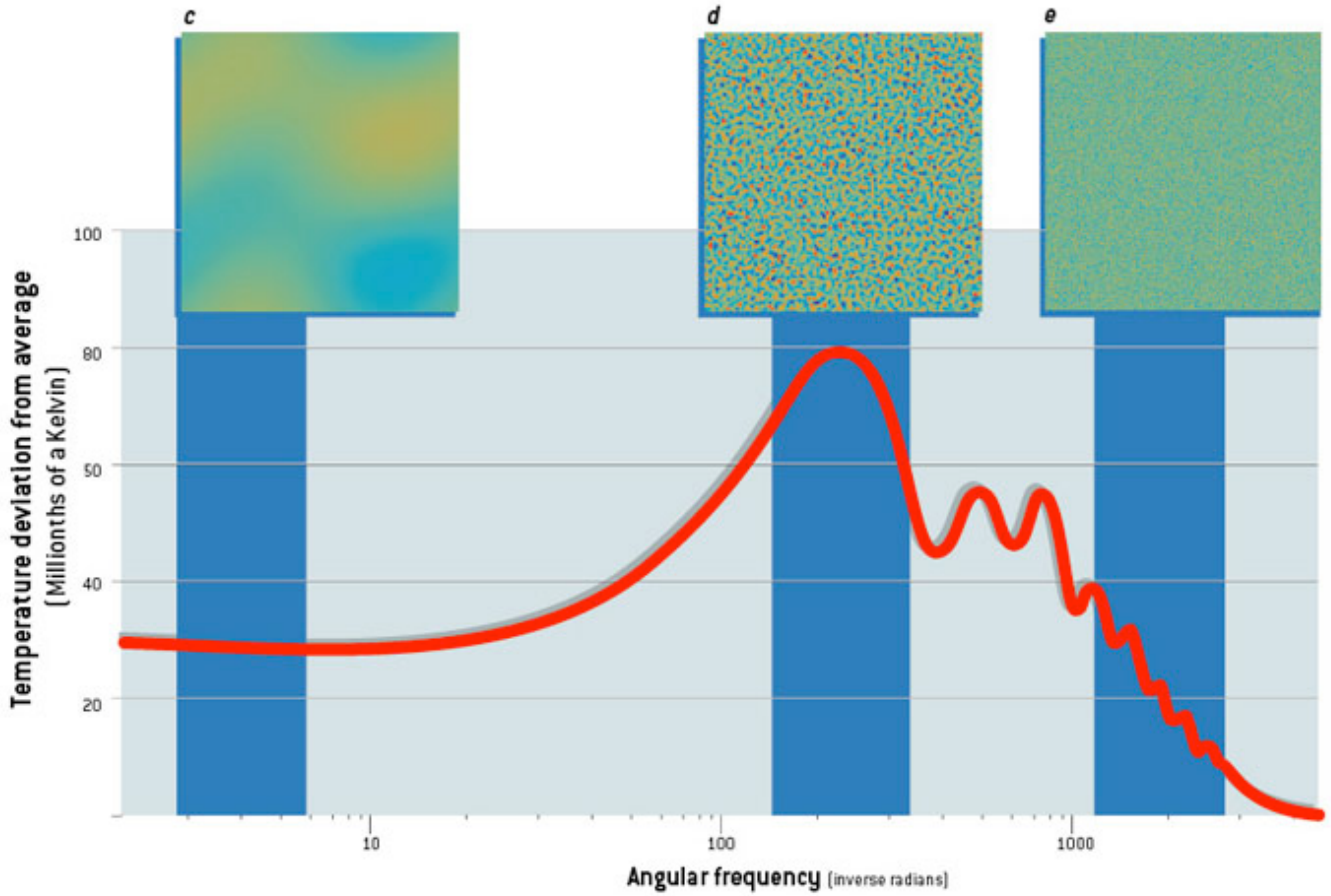
CMBA

Power spectrum



360 도

60도 1도 0.1도



신호의 세기

주파수 (각크기에 반비례)

CMBA

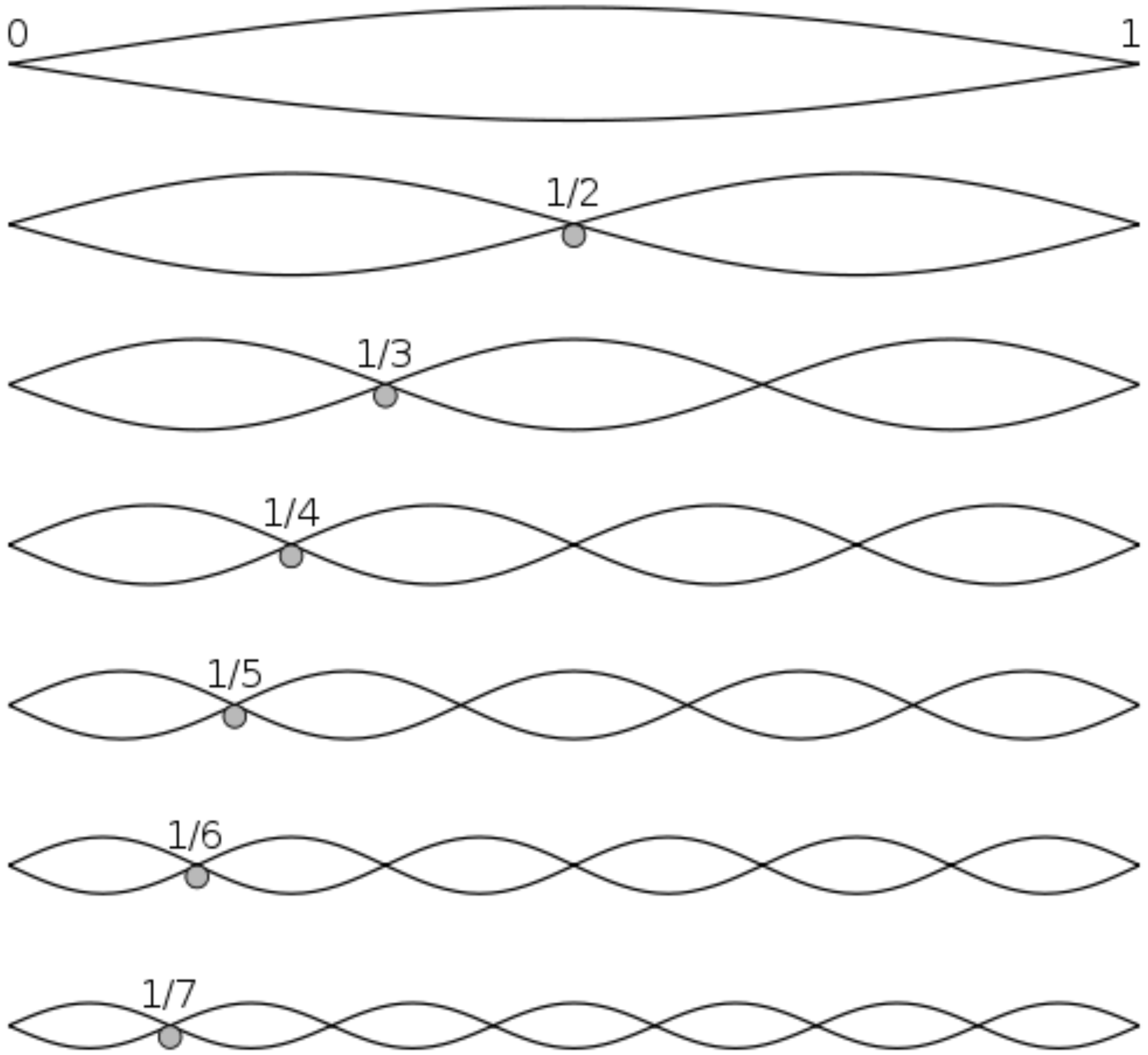
Sudden expansion (Inflation), producing density fluctuation

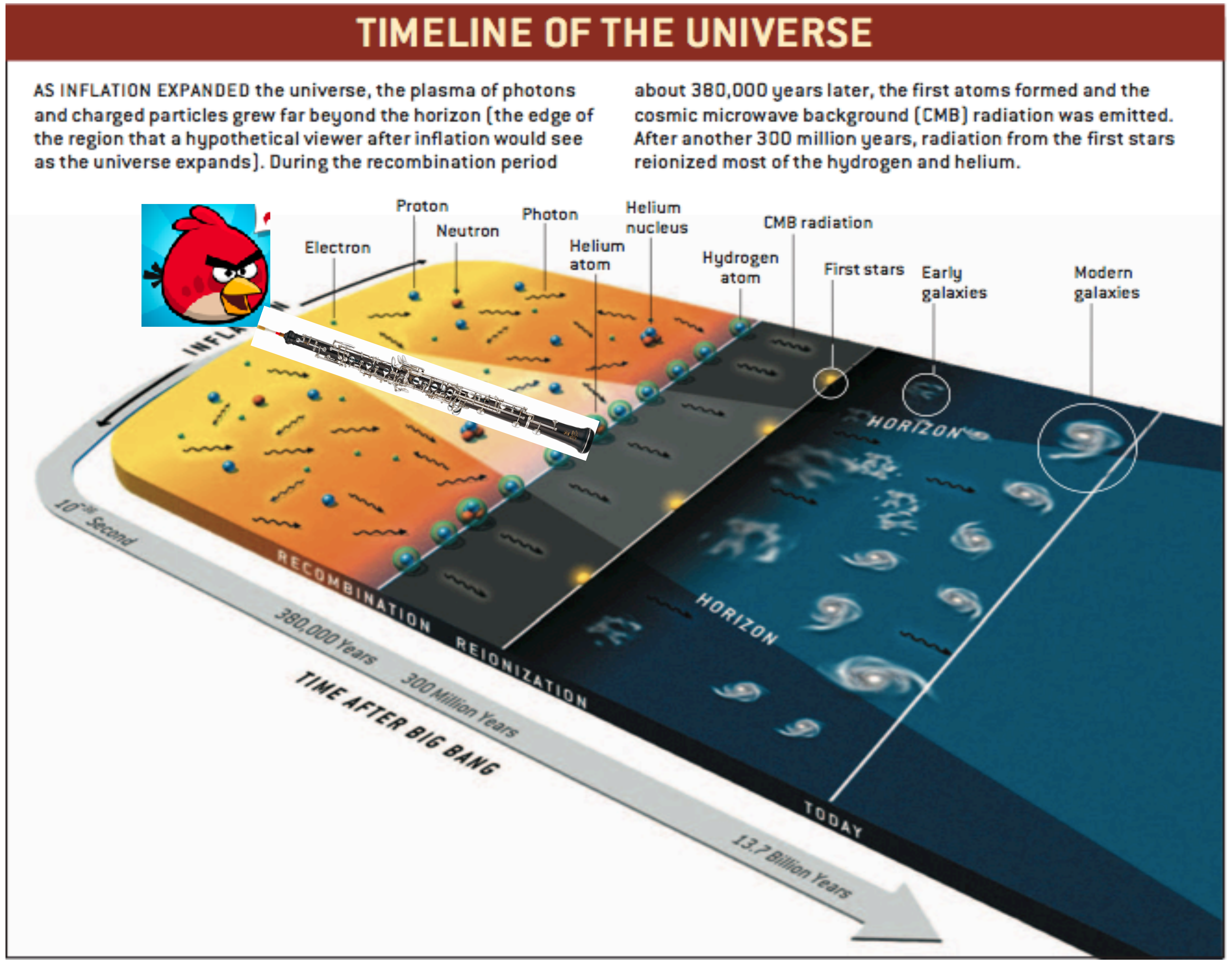
기본음 440Hz A4

제1 배음 880Hz A5

제2 배음 1320Hz E6

제3 배음 1760Hz A6





https://en.wikipedia.org/wiki/Overtone

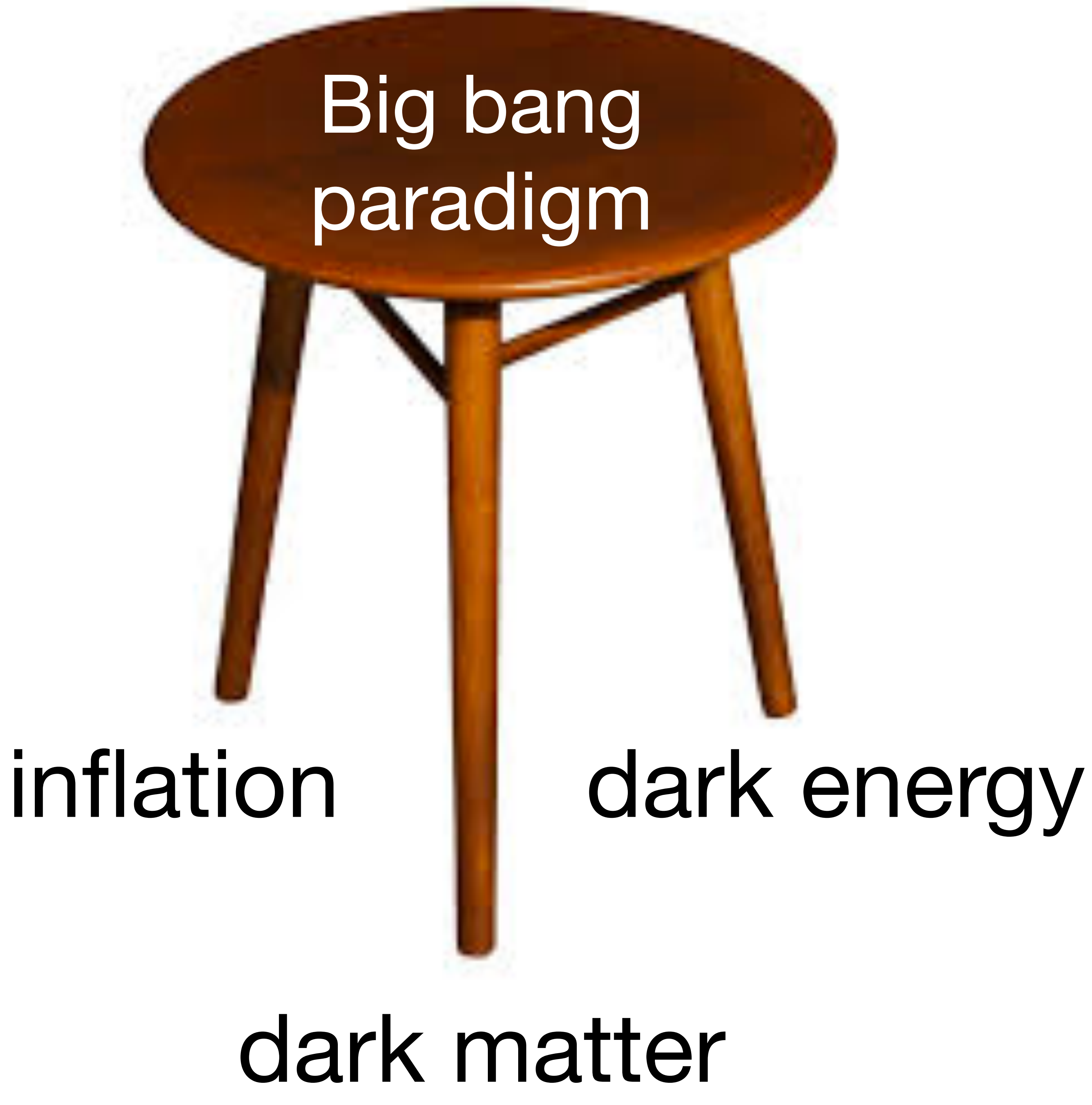
Credit: Wayne Hu http://background.uchicago.edu/~whu/SciAm/sym1.html

Concordance model

Summary

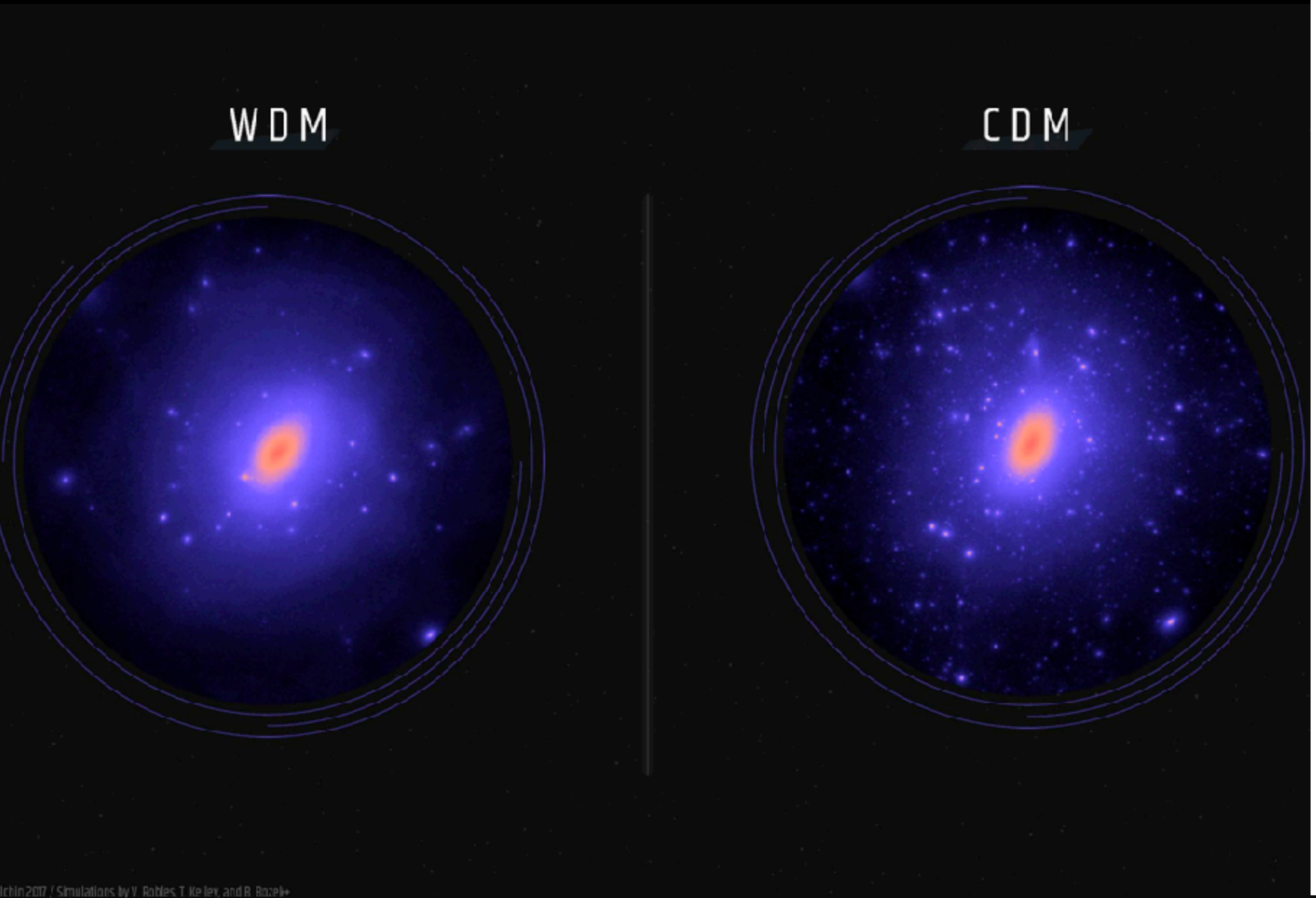
- $\Omega_{\rm bar} \sim 0.04$
- $\Omega_{\rm DM} \sim 0.24$
- $\Omega_{\Lambda} \sim 0.7$
- $\Omega_{\rm tot} \sim 1.0$
- Space geometry is flat
- Age of Universe ~ 13.7 Gyr
- Primordial density fluctuation

$$\frac{\delta\rho}{<\rho>} \sim 10^{-5}$$

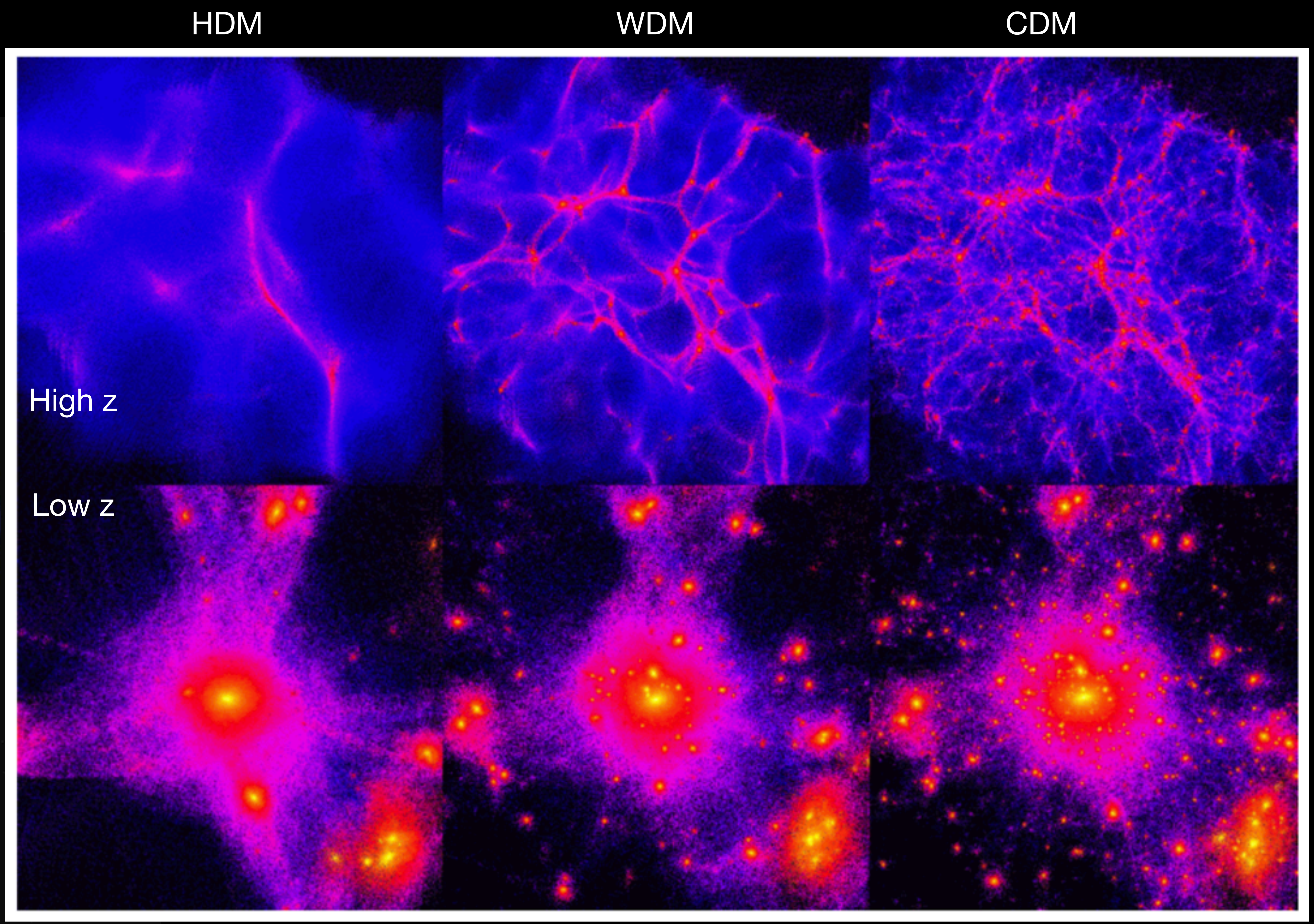


Cold dark matter

More substructures. Small structures form first.



Credit: Bullock & Boylan-Kolchin 2017/ Simulations by V. Robles, T Kelley, & B. Bazek+

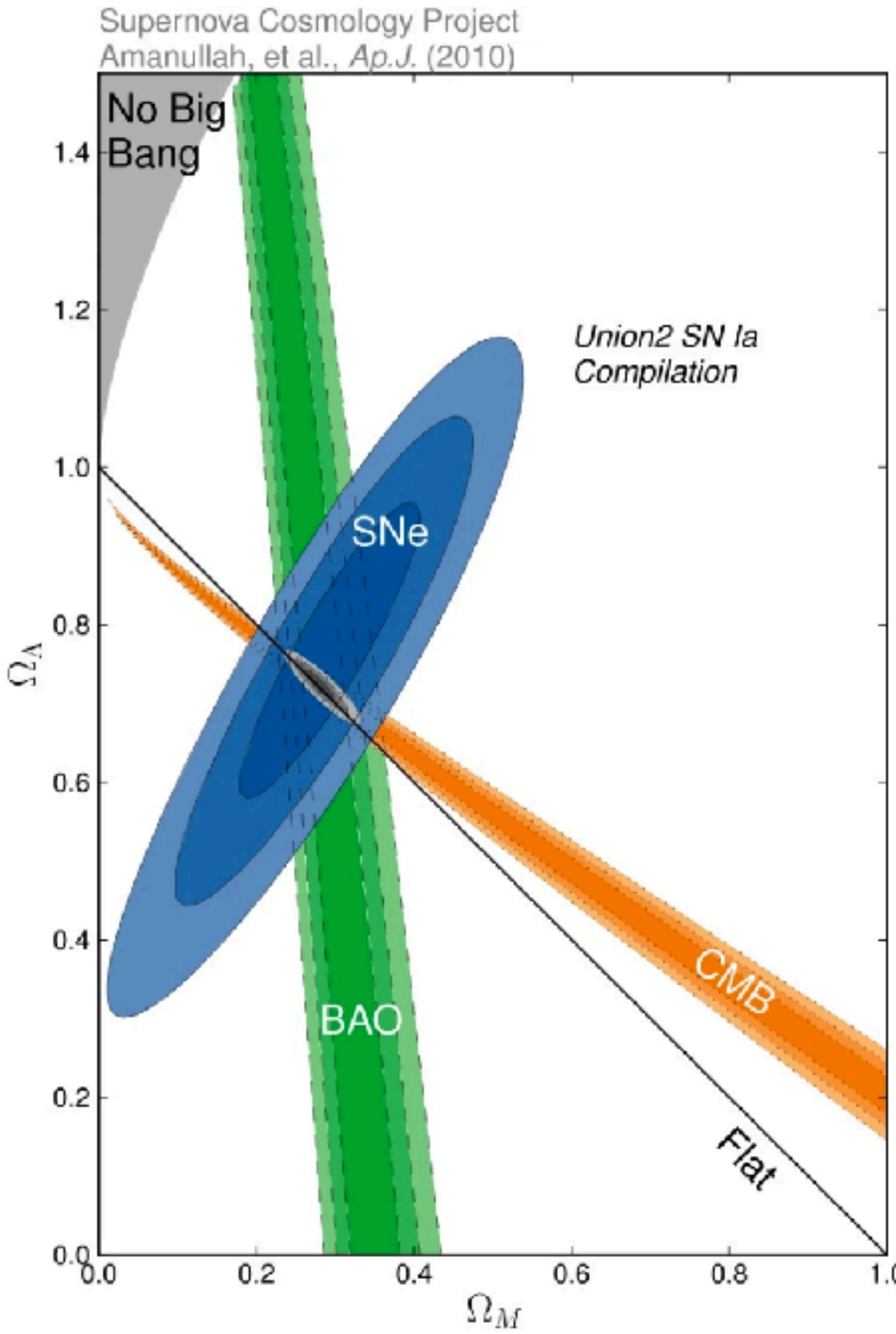


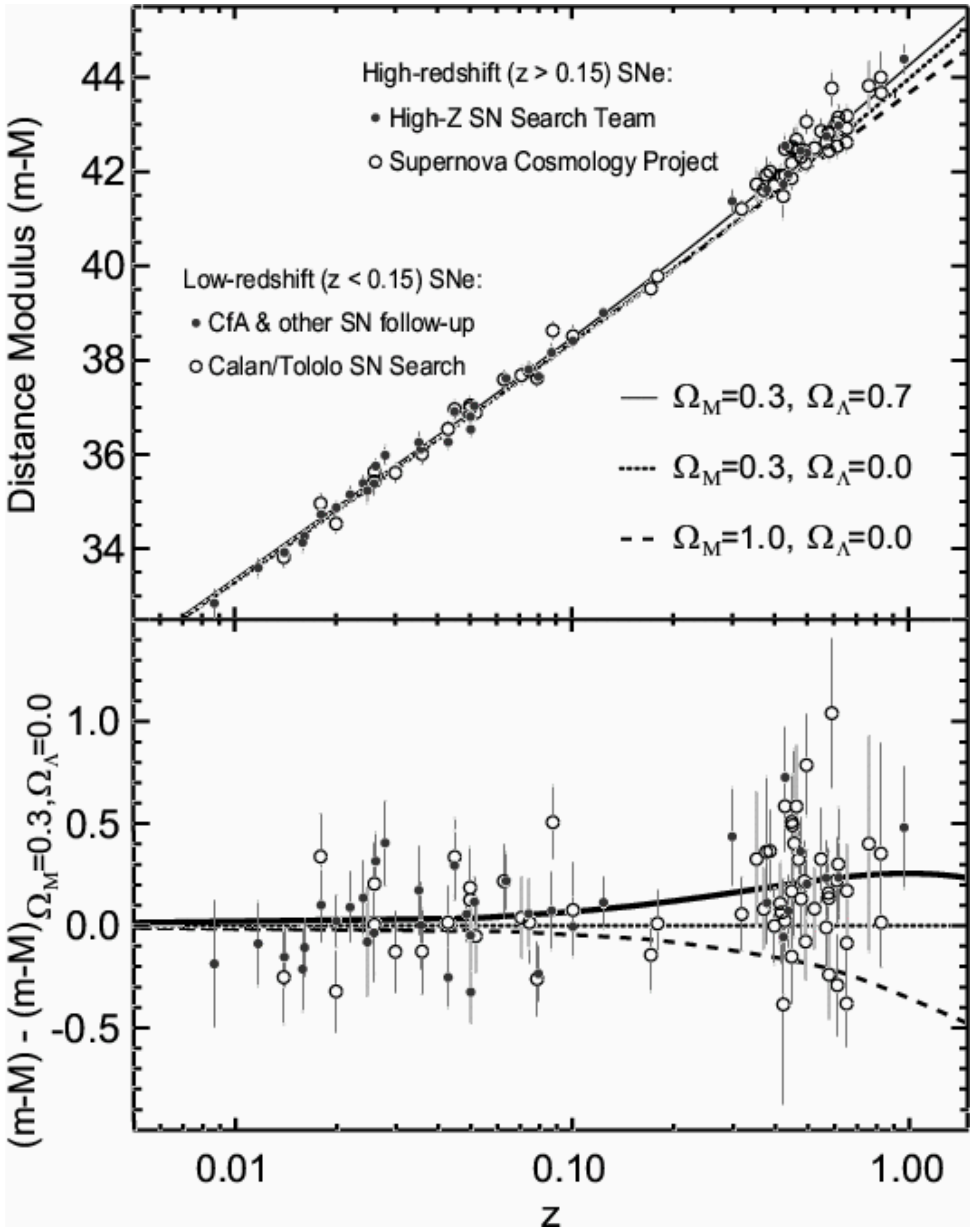
Courtesy ITC @ University of Zurich

Dark energy

Accelerating expansion

- $\Omega_\Lambda \sim 0.7$
- Making the Universe geometry flat
- And accelerating expansion?
- Is supernova cosmology robust?

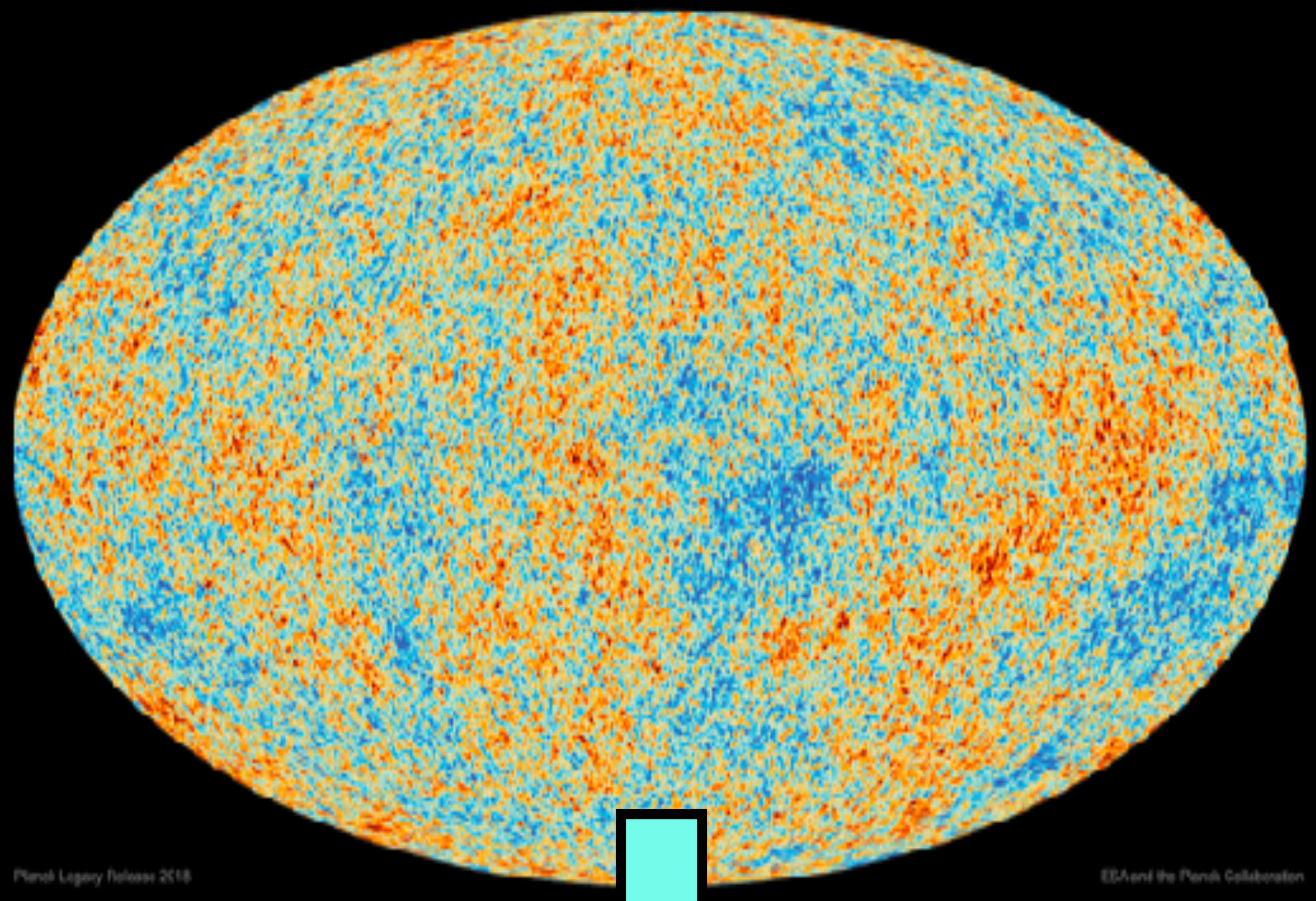


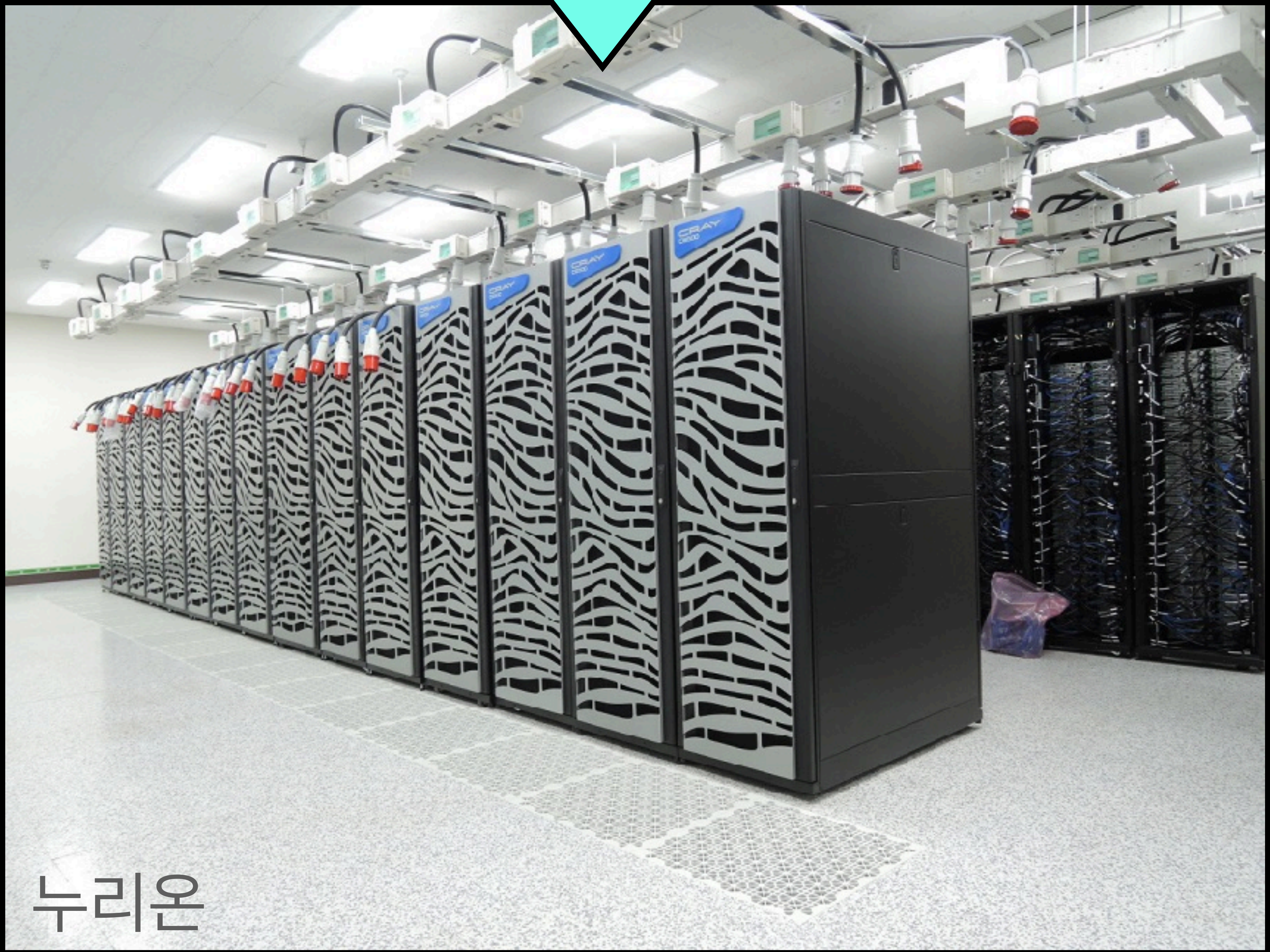


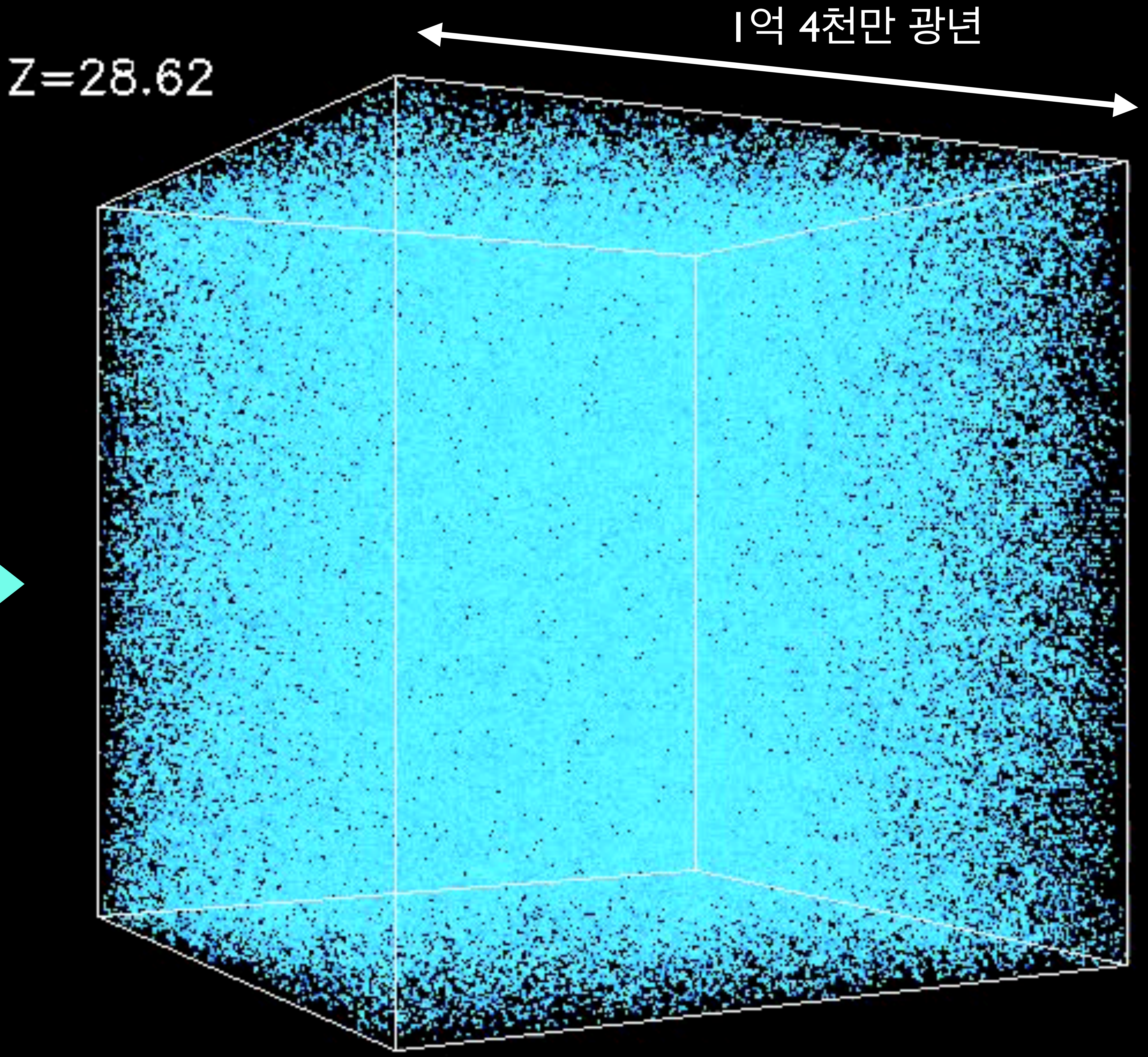
Perlmutter & Scmidt (2003)

Structure formation

Primordial density fluctuation

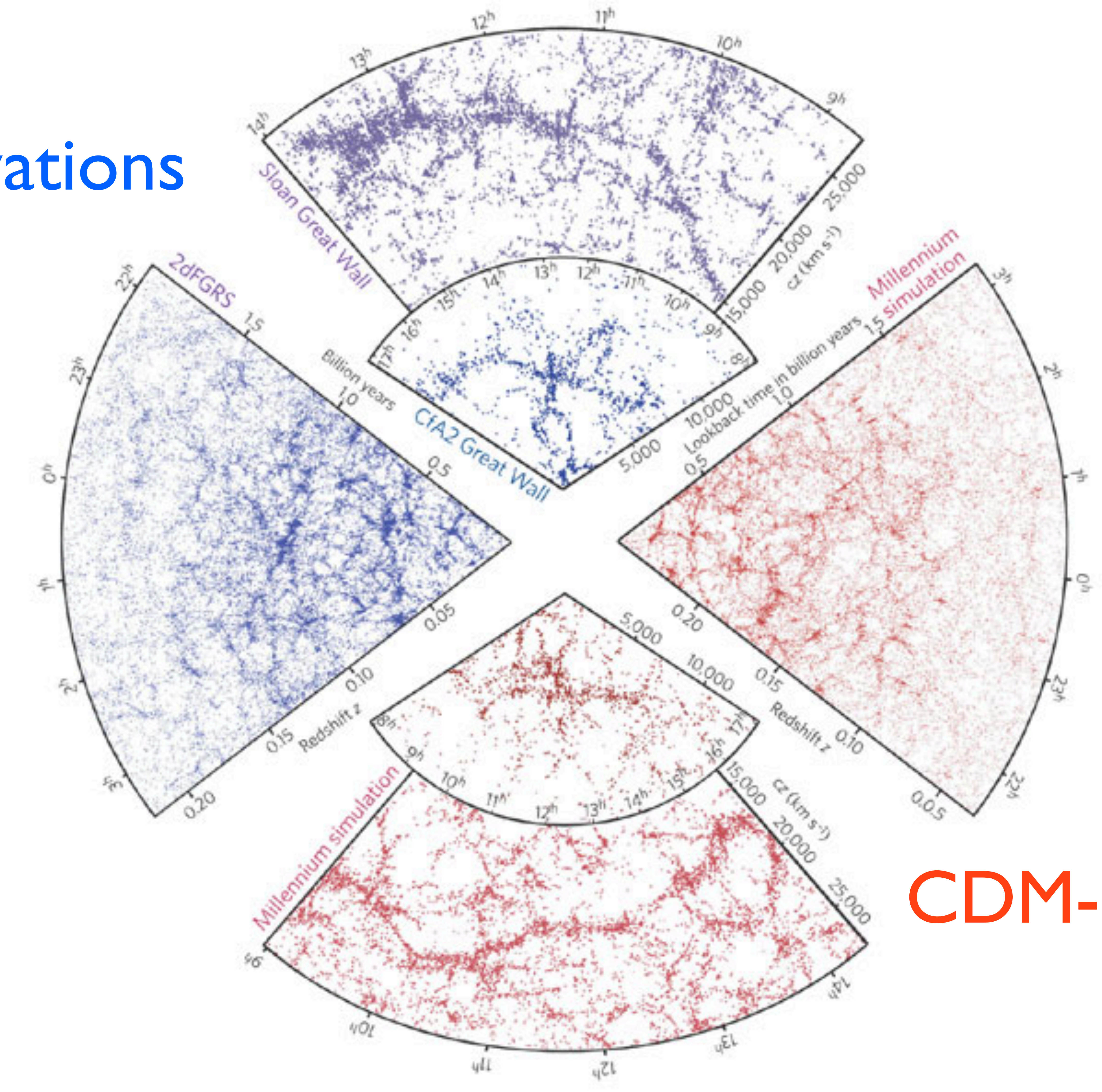






Credit: A. Kravtsov & A. Klypin

Observations



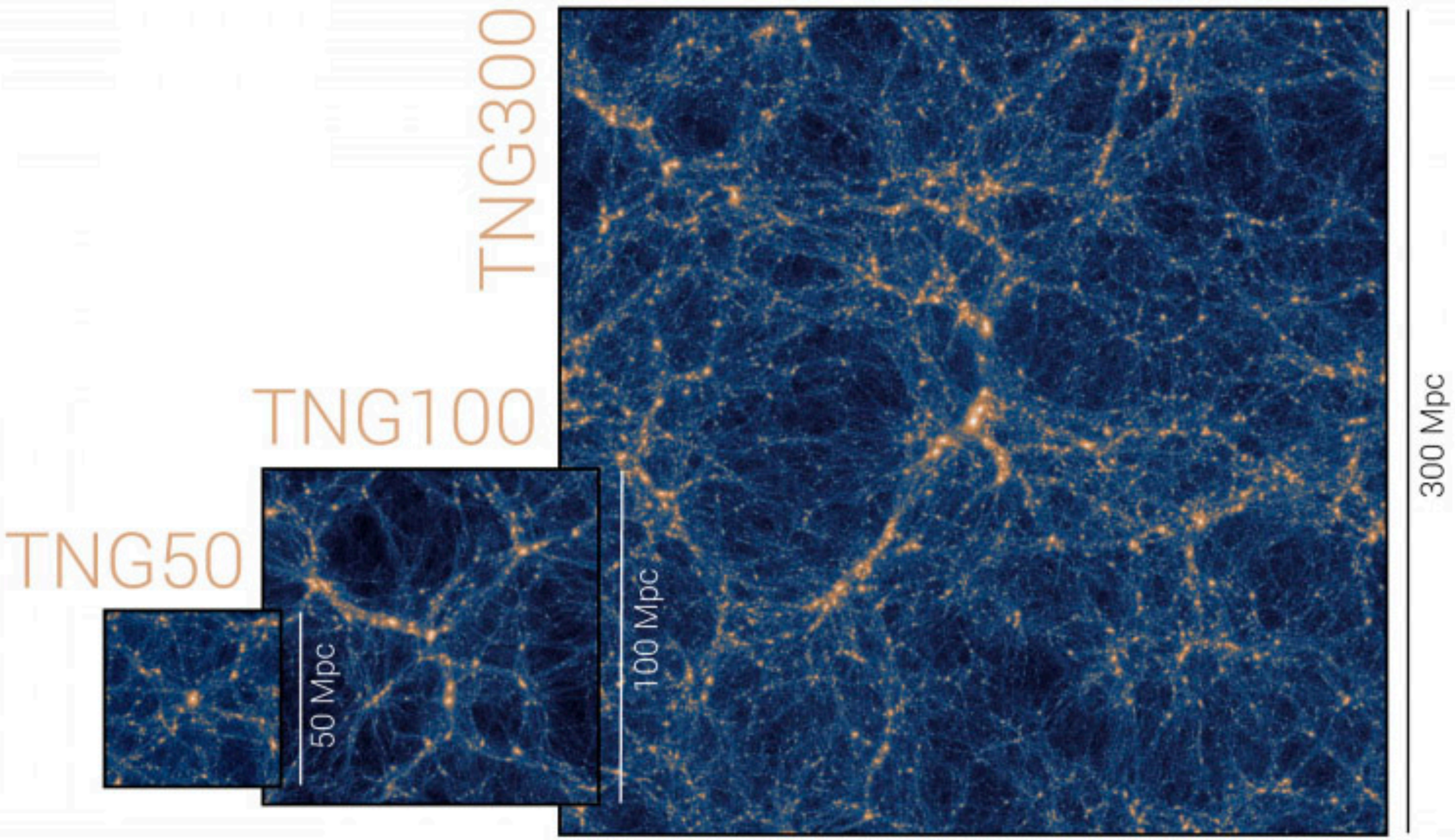
CDM-only simulation

Millennium simulation
Springel et al. 2006

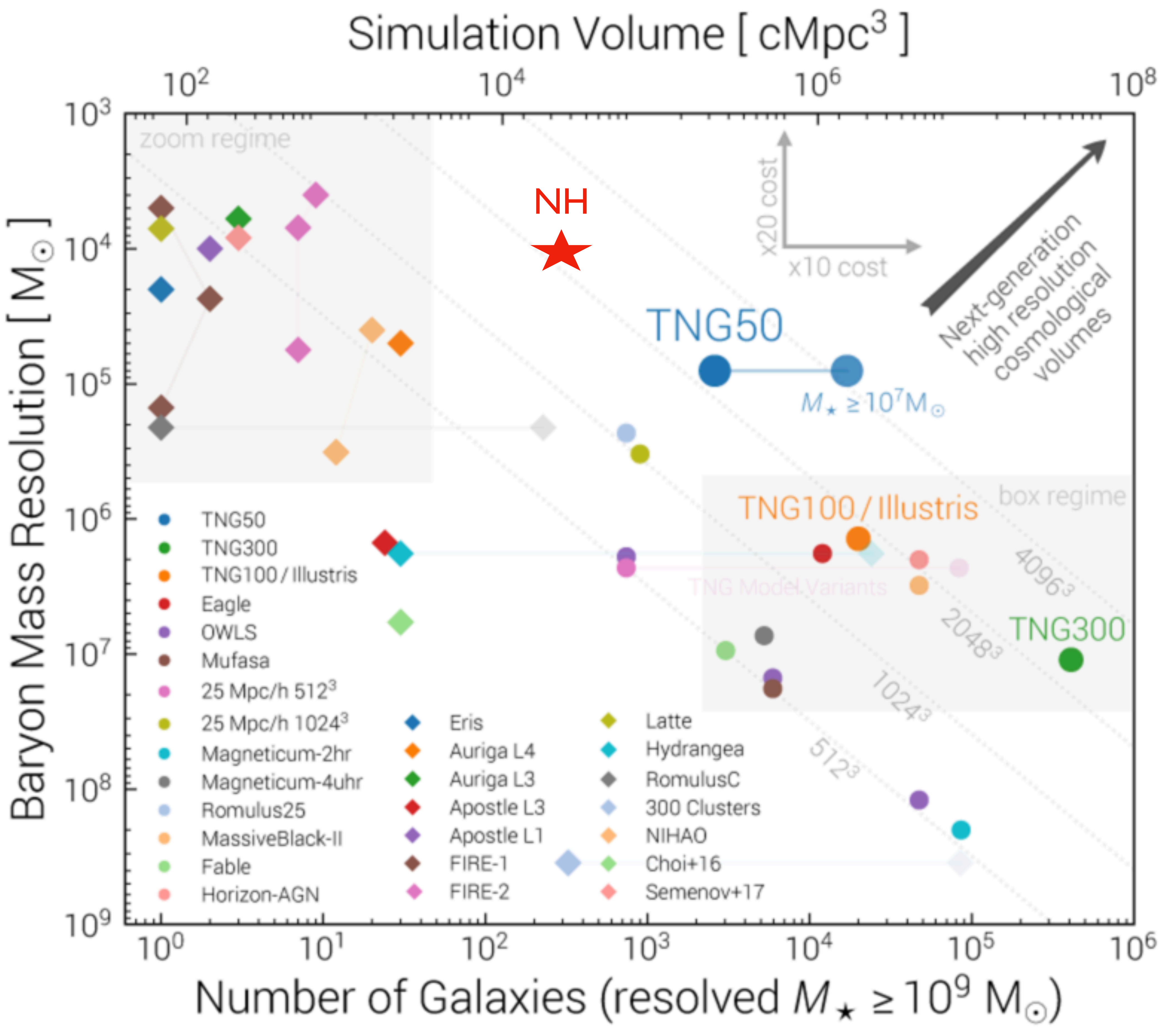
Cosmological hydrodynamic simulations

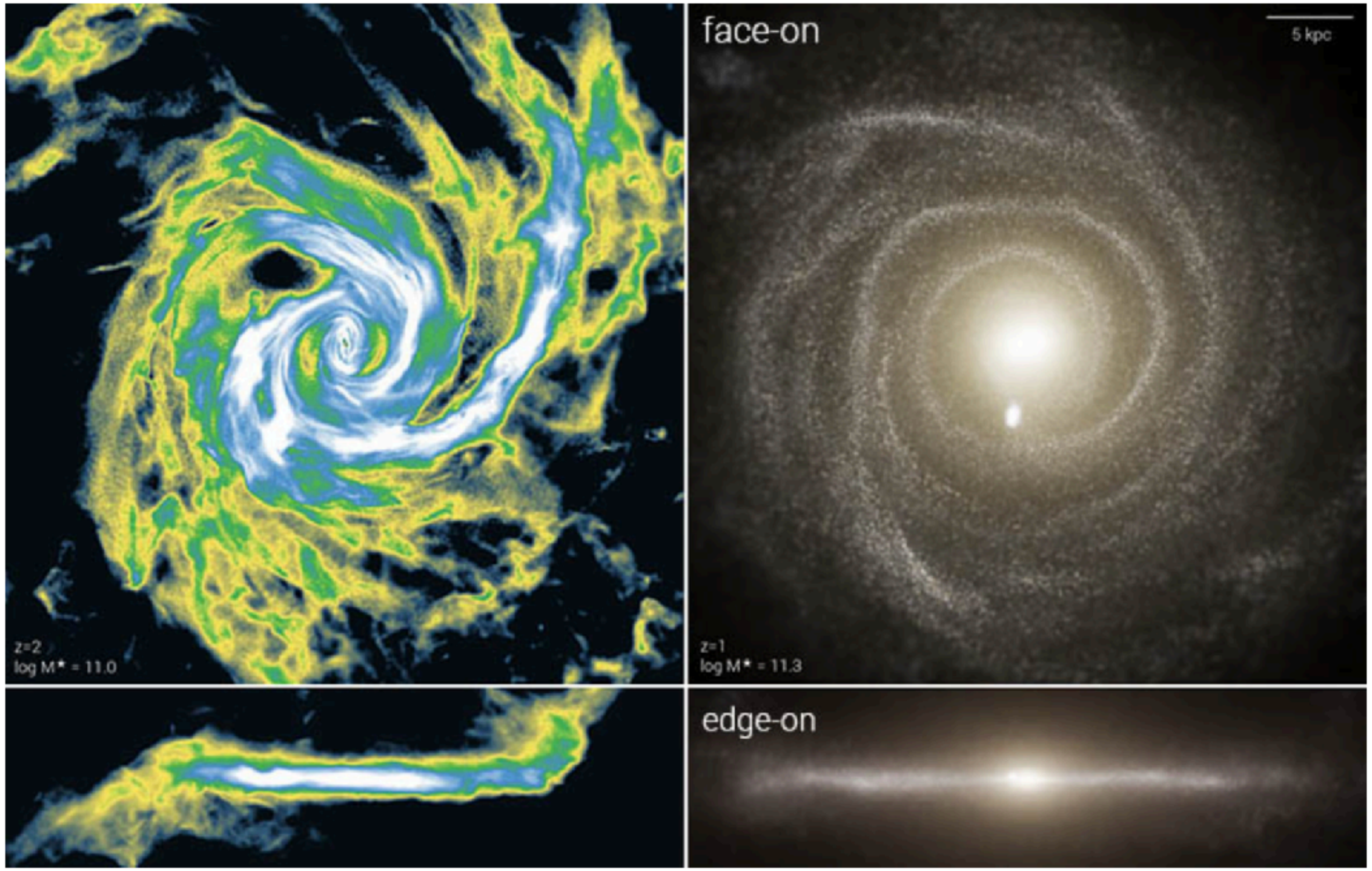
Of galaxy formation

- Gravity + hydrodynamics
- + Astro-baryon physics
  - Gas cooling, star formation
  - Black hole physics
  - Chemical evolution
- 2014: dx ~ 1 kpc
  - EAGLE (SPH)
  - Horizon-AGN (AMR)
  - Illustris (moving mesh)
- ~2020
  - IllustrisTNG50: dx~0.3
  - NewHorizon: dx~0.04



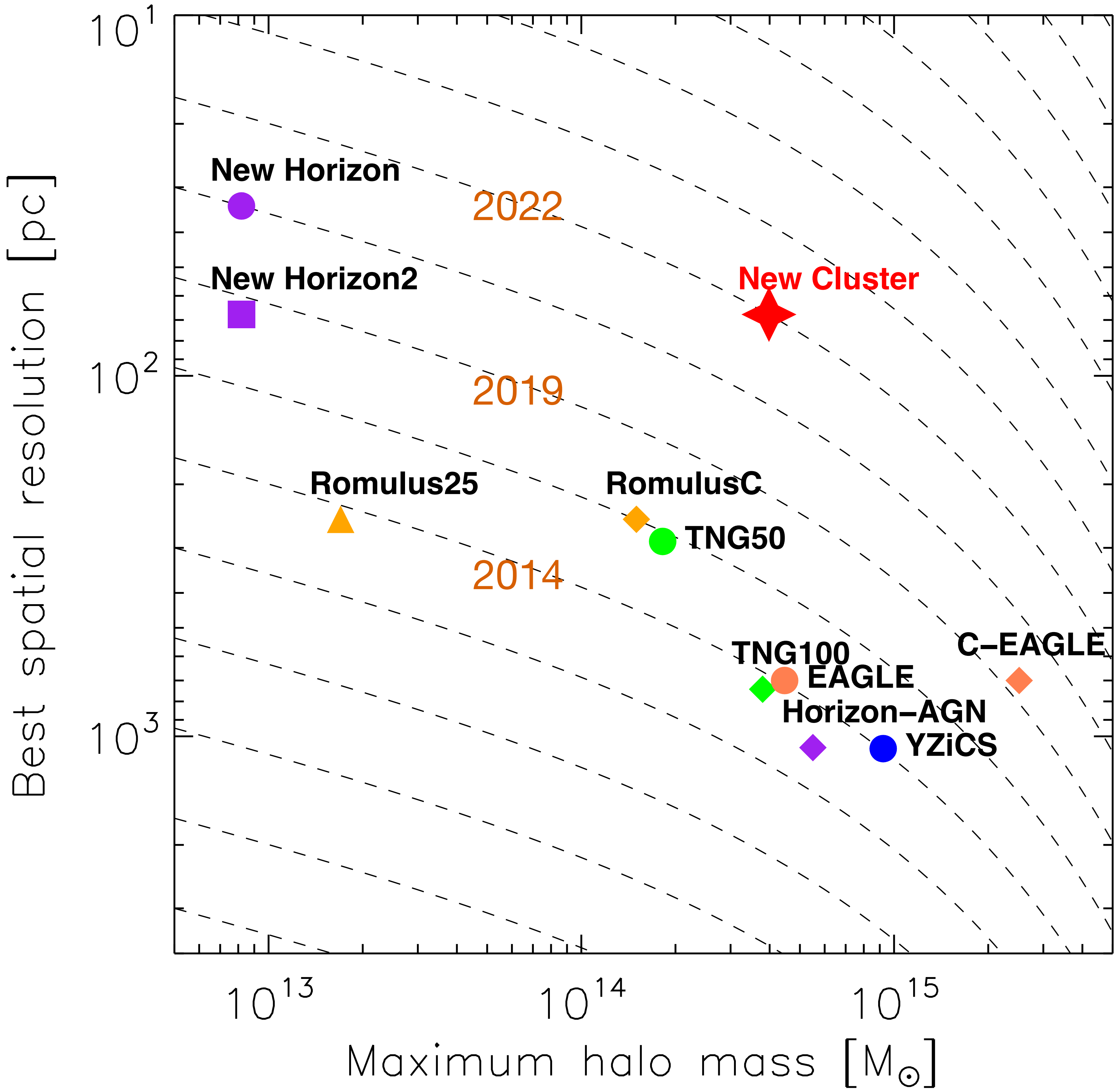
TNG & NewHorizon





Credit: https://www.tng-project.org/about/

TNG & NewHorizon



NewHorizon

슈퍼 컴퓨팅

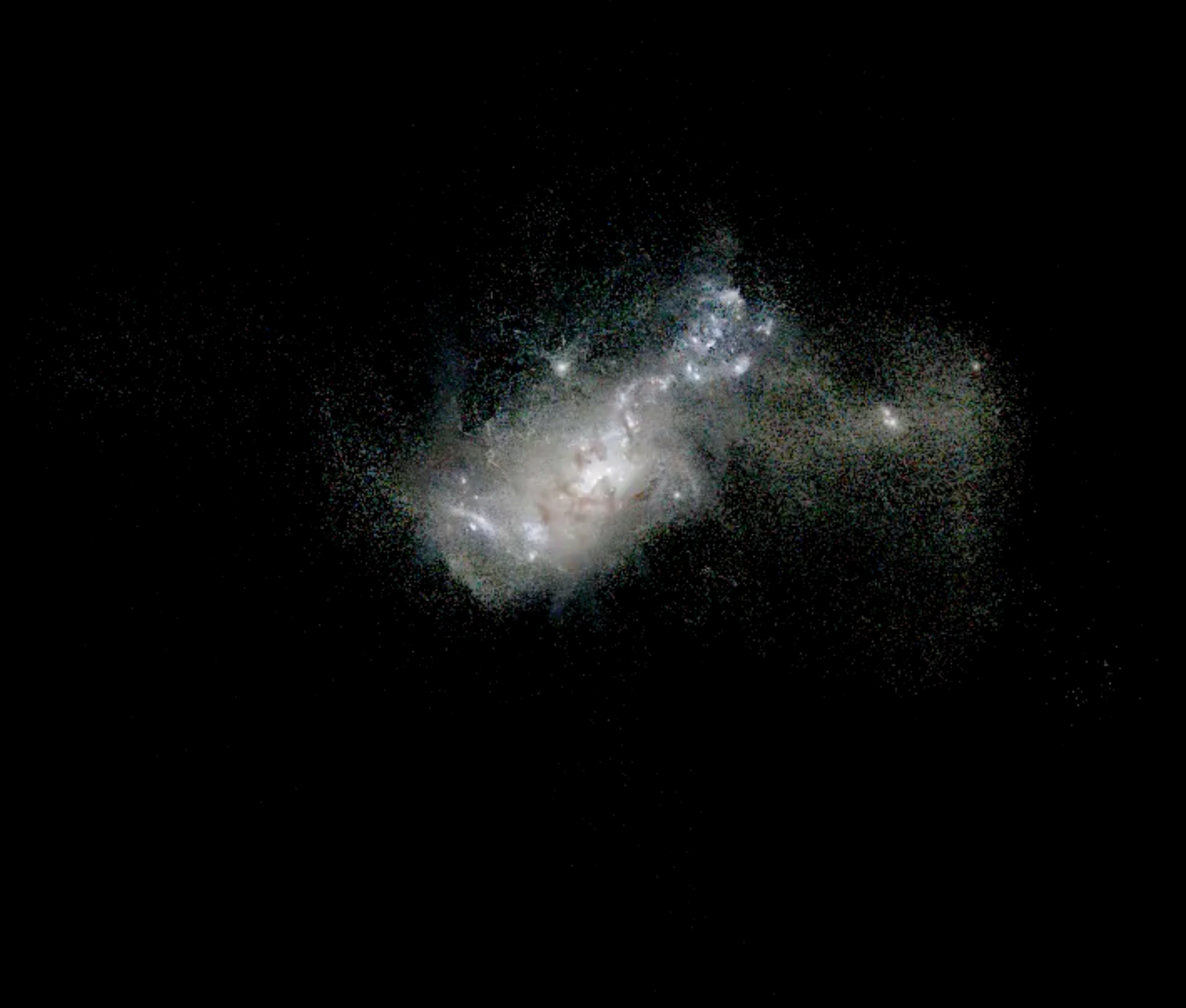
NewHorizon simulation
IAP-Yonsei-Oxford coll.
4800 cores
80 Mhr (2017-2020)
6천만 광년

암흑 물질
고온 기체
별

Credit: NewHorizon: 이진수 (연세대)

은하형성

Face-on view



Edge-on view

Galaxy challenge

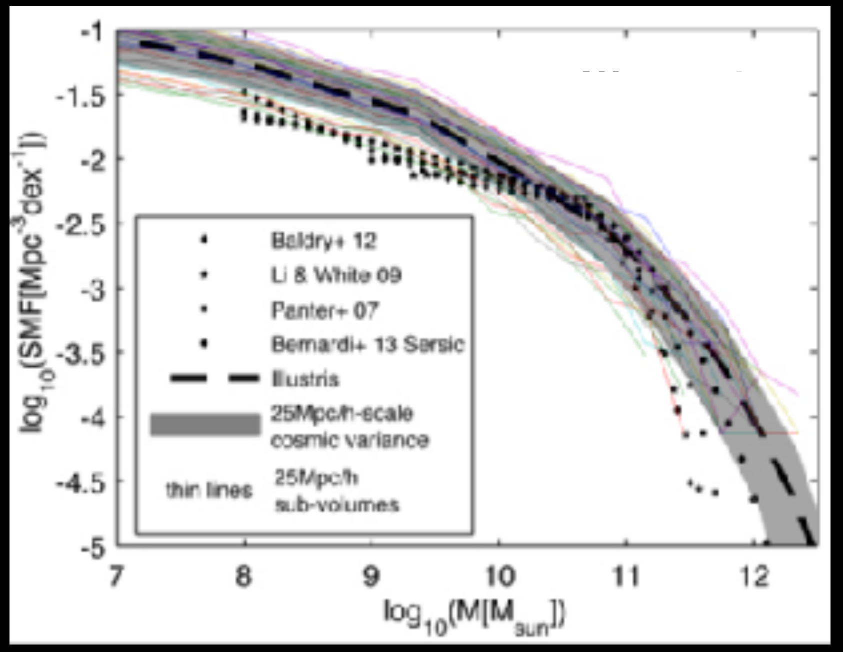
Disc galaxies

25000 ly

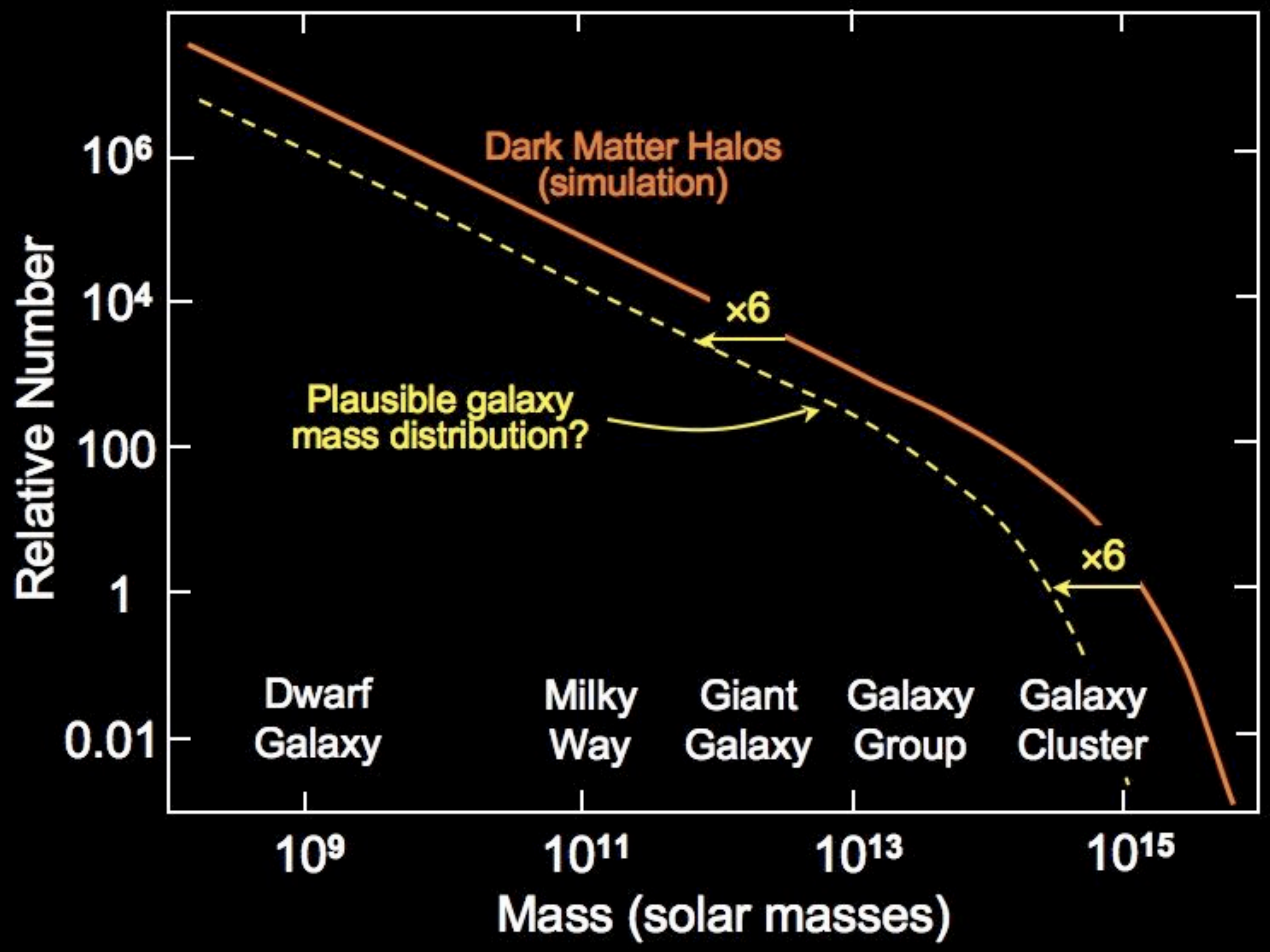
NGC 891
Credit: Hewholooks https://commons.wikimedia.org/wiki/File:NGC891HunterWilson.jpg

Shortcomings of models

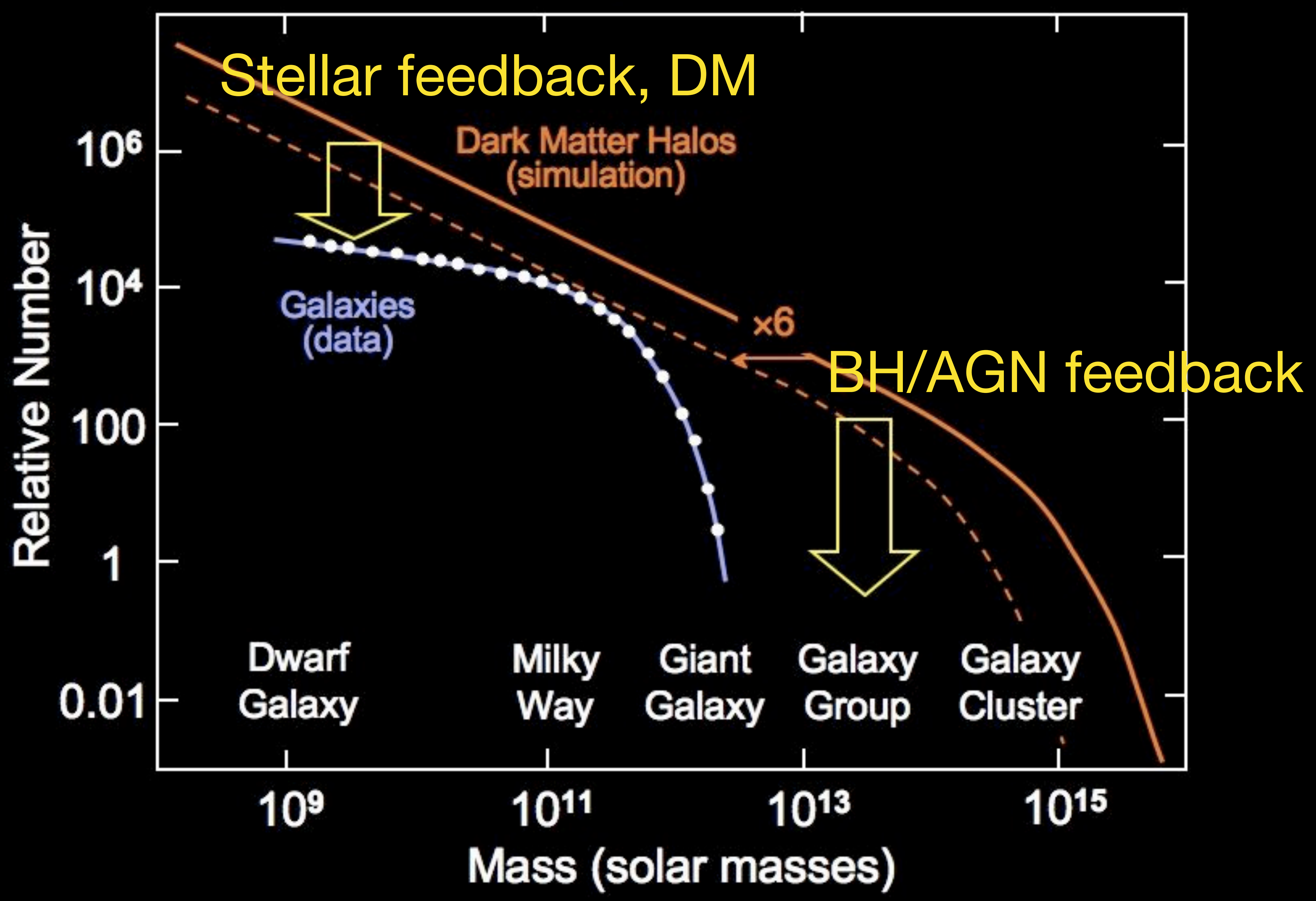
1) luminosity function problem



(Expected) Halo and Galaxy Mass Distributions



(Actual) Halo and Galaxy Mass Distributions

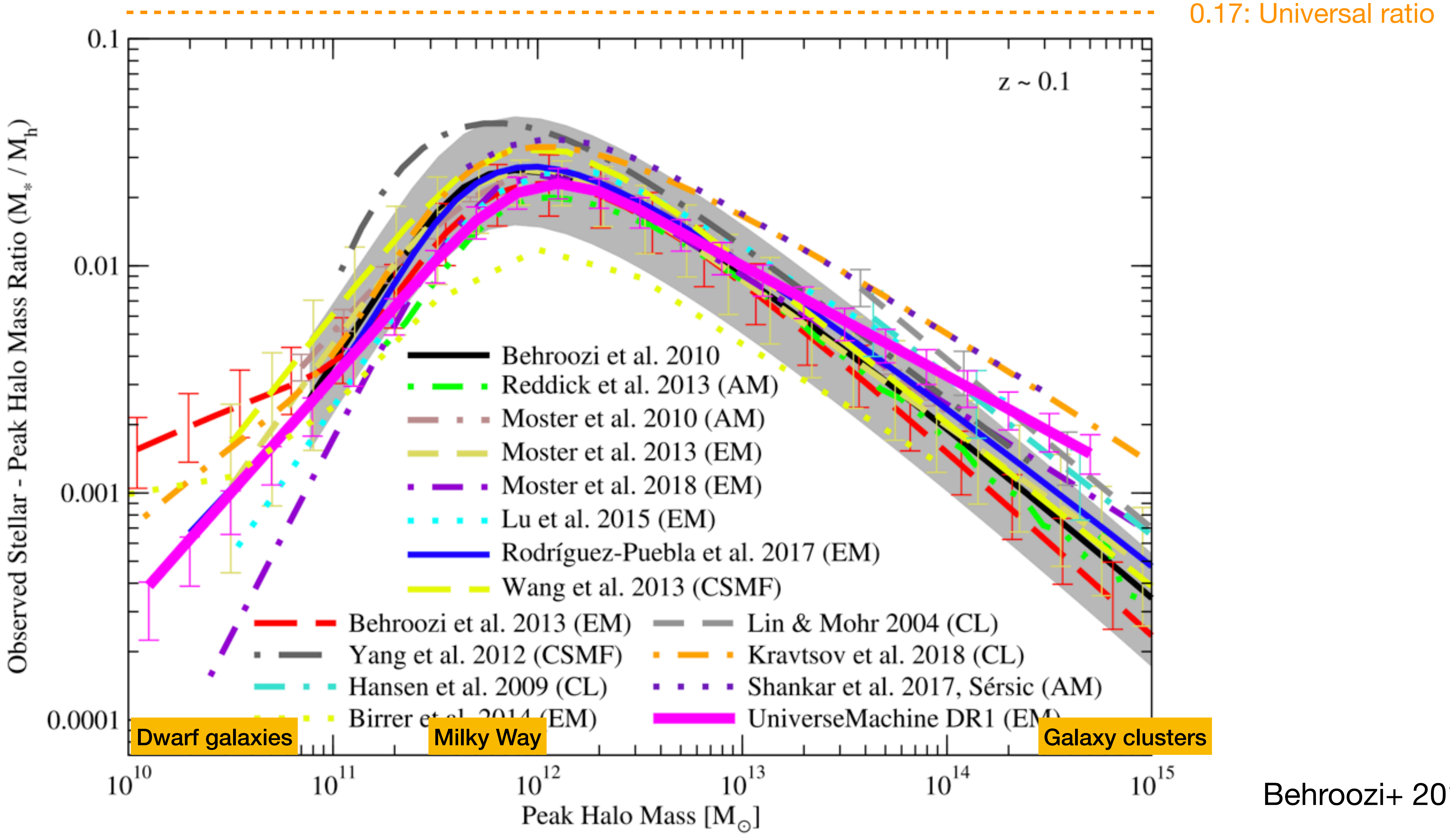


Credit: astro.virginia.edu

Shortcomings of models

1) luminosity function problem

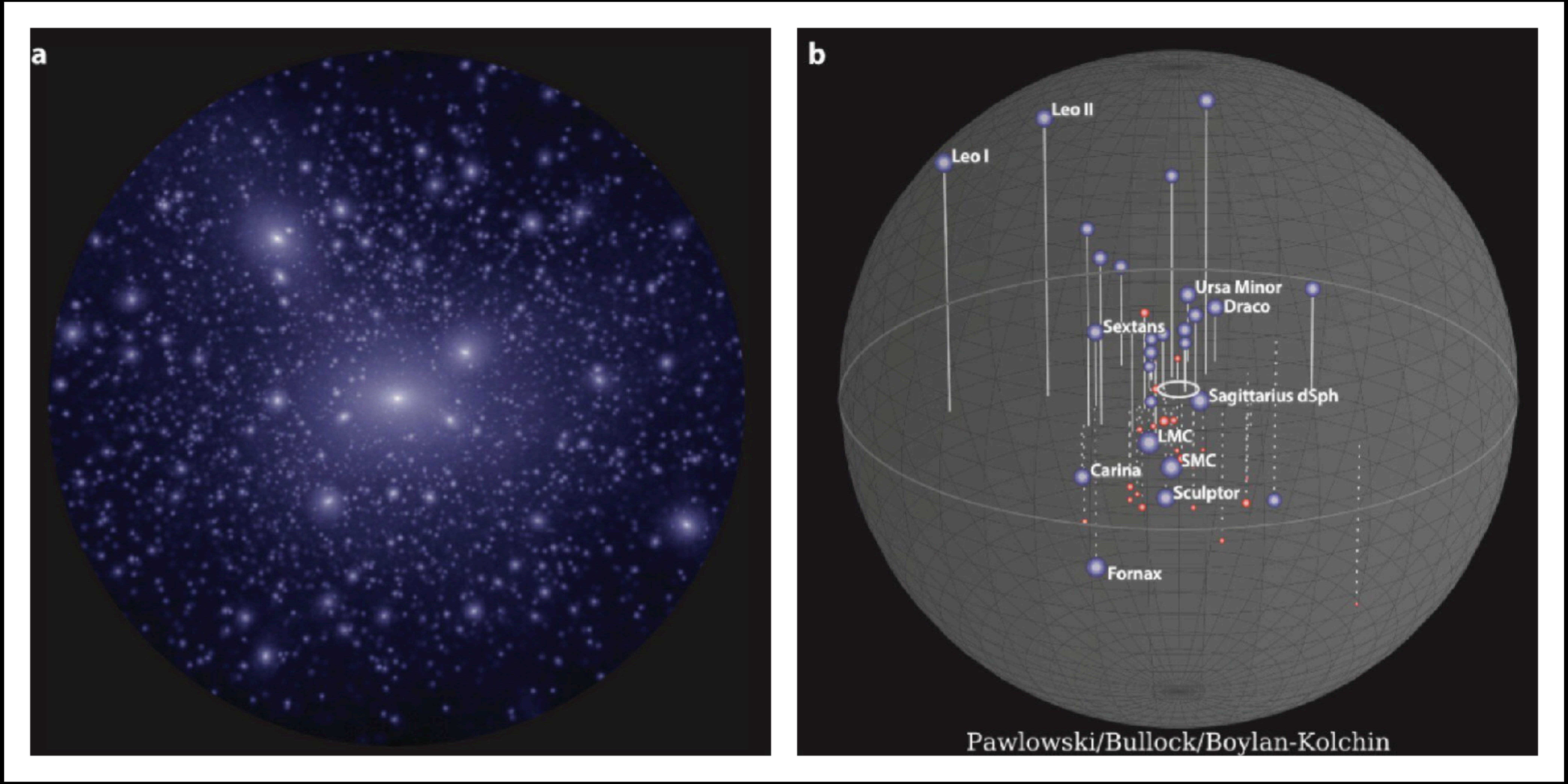
$$\frac{M_*}{M_{\text{halo}}}$$



Behroozi+ 2019

Shortcomings of models

2) missing satellite problem



Shortcomings of models

2) missing satellite problem

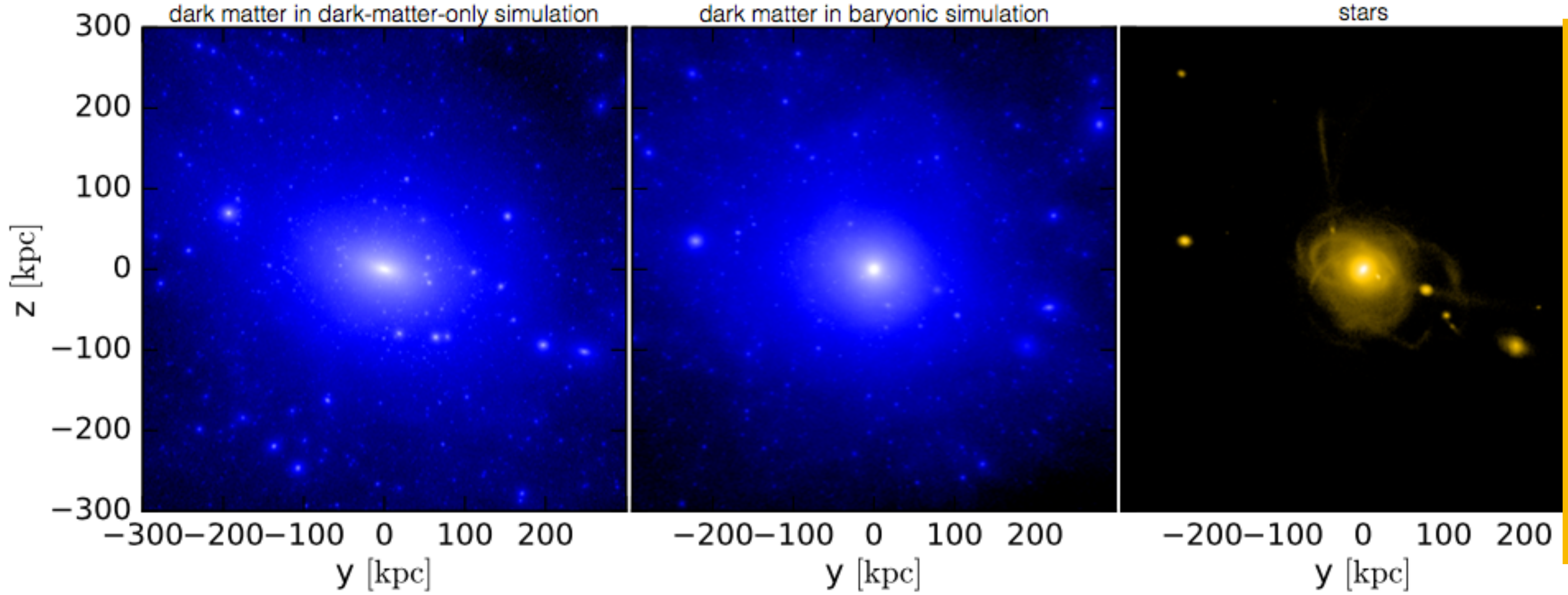
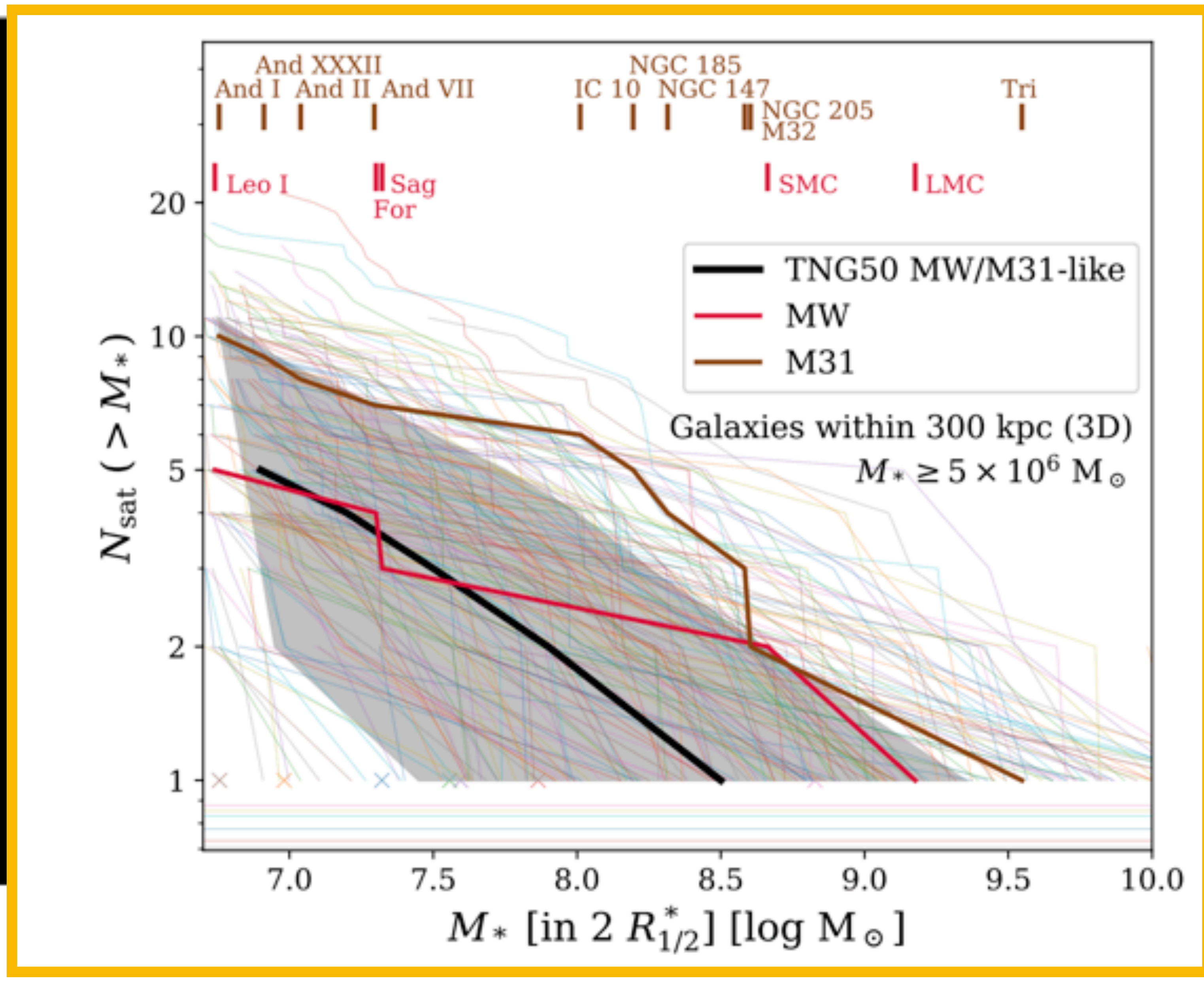


Figure 1. Projected mass surface densities of Milky Way-mass host in the Latte simulation at $z = 0$: dark matter in the dark-matter-only simulation (left); dark matter (middle) and stars (right) in the baryonic simulation. Color scale is logarithmic, spanning $10^4 - 10^9\ M_\odot\ kpc^{-2}$, same in all panels. Compared with dark-matter-only, the baryonic simulation contains *significantly* (≈ 10×) fewer subhalos at fixed $V_{circ,max}$. Of these subhalos, only 9 host a satellite galaxy with $M_{star} > 3 \times 10^5\ M_\odot$.

Wetzel+ 2016

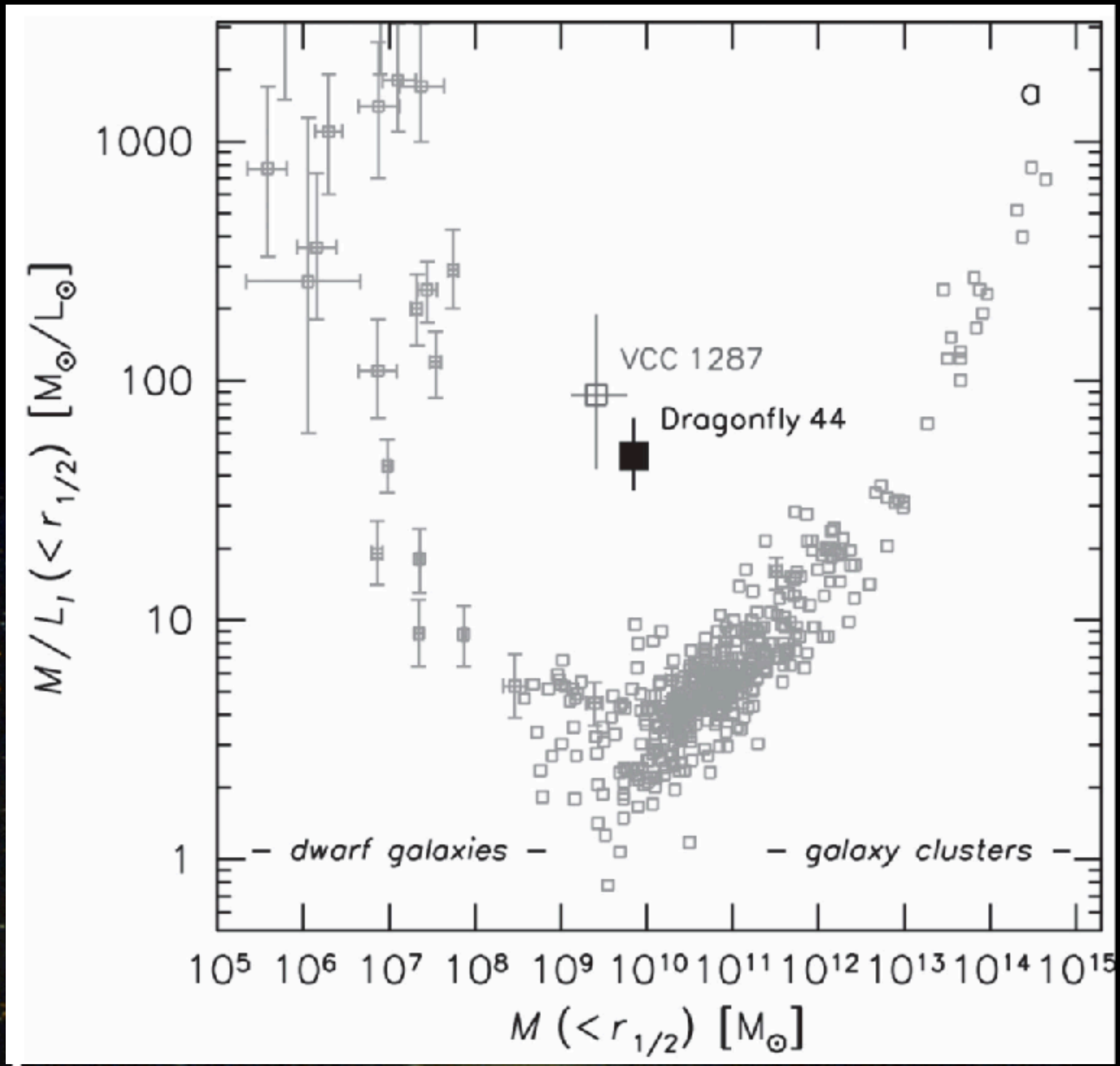


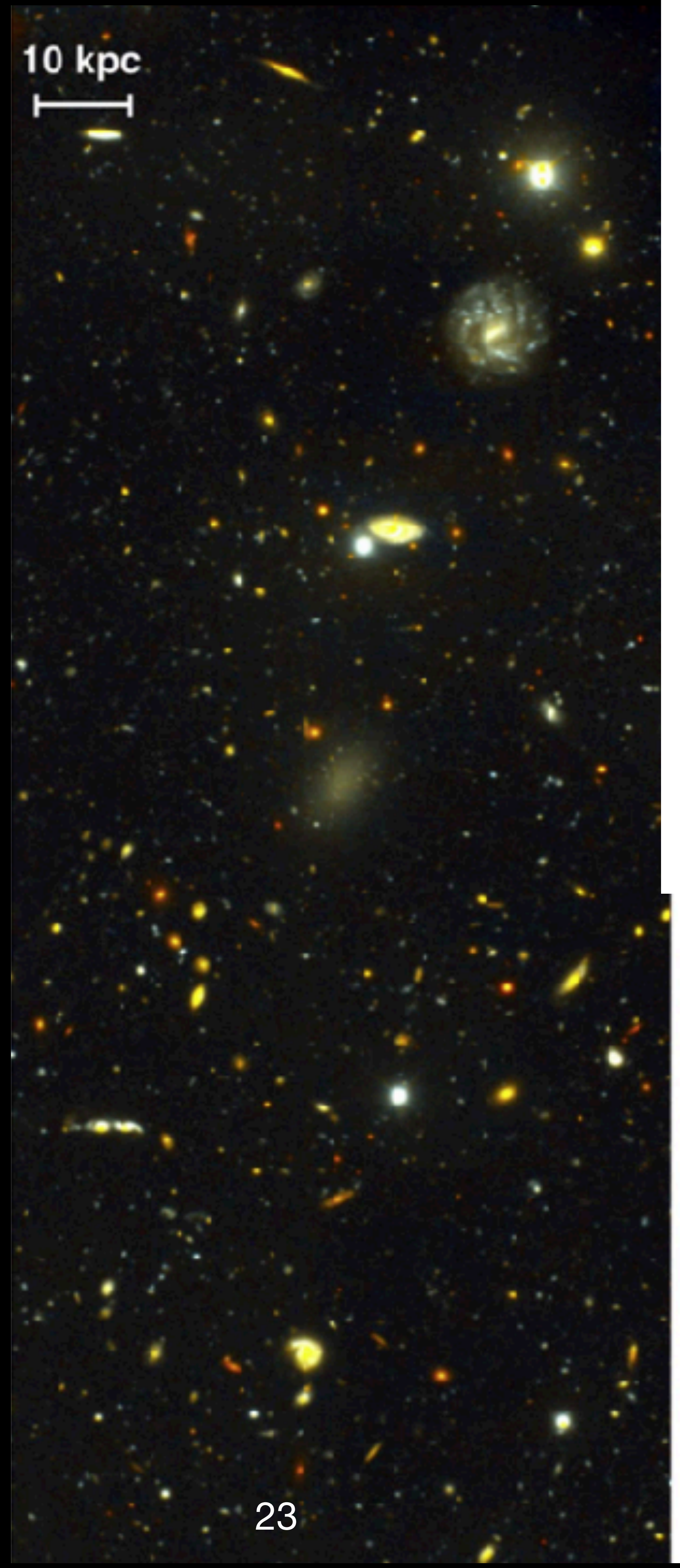
Engler+ 20121

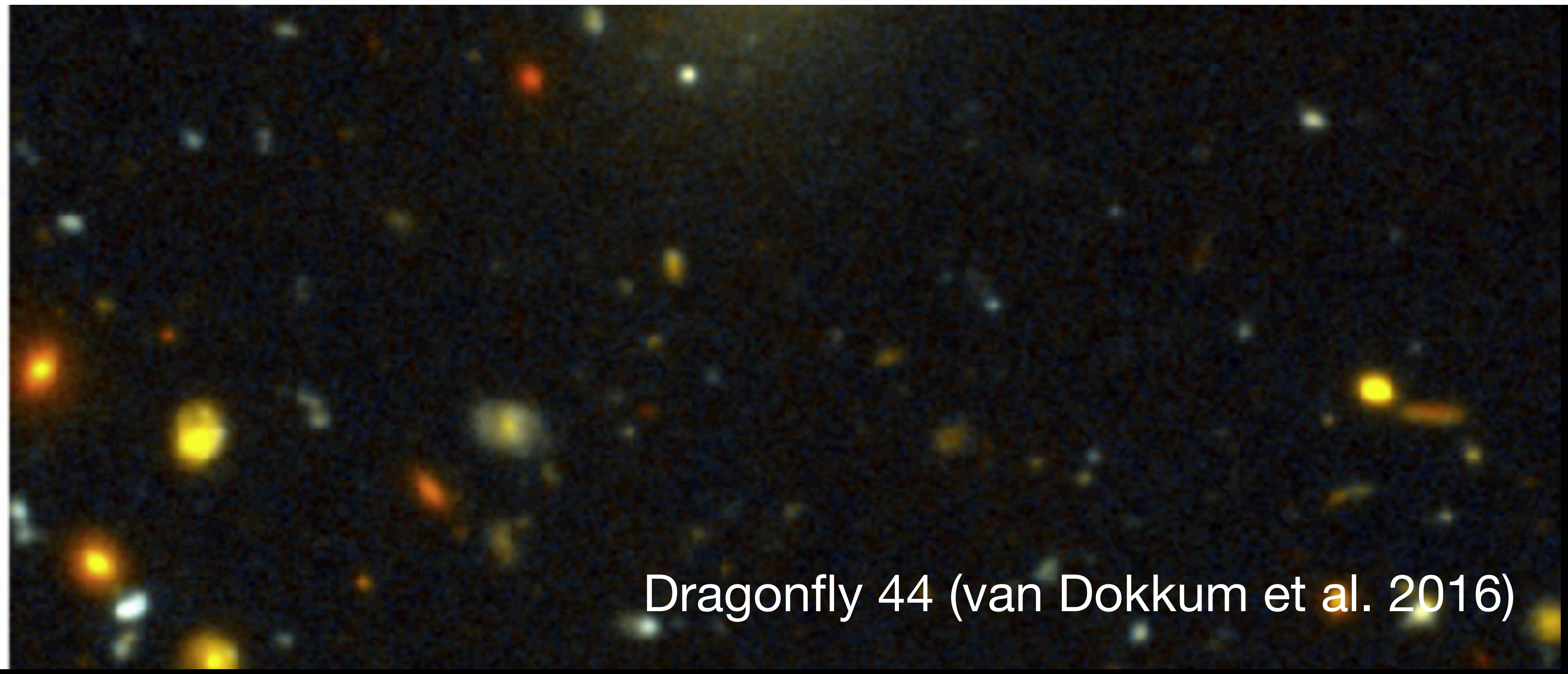
Shortcomings of models

3) ultra-diffuse galaxies

- Dragonfly 44 (van Dokuum+ 2016)
  - In Coma cluster
  - 33.5 hr with Deimos/Keck II
  - Based on 94 GCs
  - $M_{dyn} \sim MW$
  - $M_{*} \sim 1/20\ MW$
  - DM dominant?





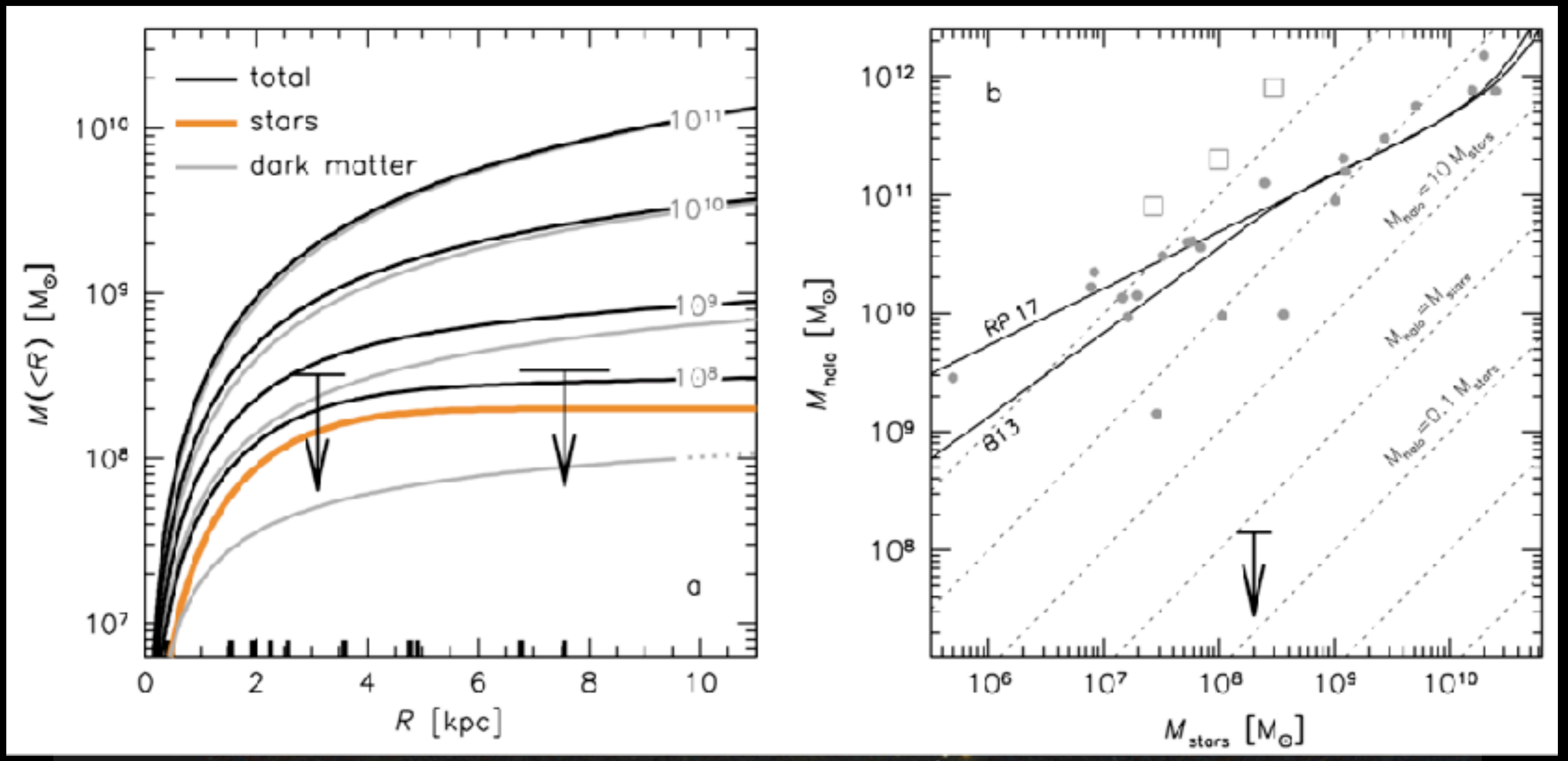


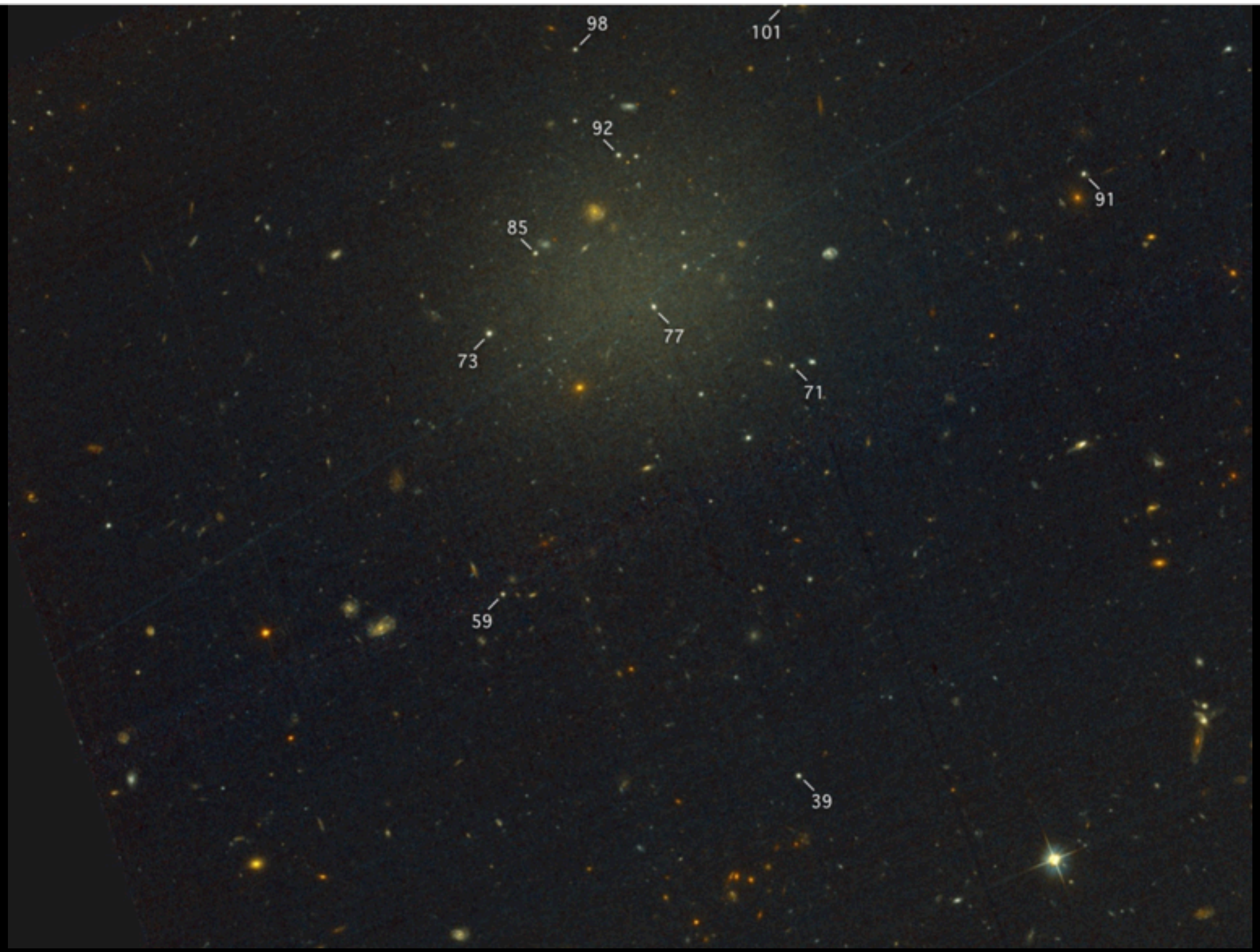
Dragonfly 44 (van Dokkum et al. 2016)

Shortcomings of models

3) ultra-diffuse galaxies

- NGC 1052-DF2 (van Dokuum+ 2018)
  - NGC 1052 group
  - HST + Deimos/Keck II
  - Based on 10 GCs
  - $M_{dyn,3.5Re} \lesssim 3.4 \times 10^8 \ M_\odot$
  - $M_* \sim 2 \times 10^8 \ M_\odot \sim 1/300 \ MW$
  - $R_e \sim 2.2 \ kpc \sim MW$
  - Compatible with no DM





NGC 1052-DF2 (van Dokkum et al. 2018)

Outstanding questions

- Is dark energy real?
- Is dark matter real? Is it cold?
- Are the issues of the strange properties of galaxies caused by DM or astrophysical nature?
- Is the missing satellite problem gone? (NewHorizon)
- Ultra diffuse galaxies (NewHorizon)
- Current efforts are heavily biased to astrophysics.