NCTS SSP Lectures 2024

Astrophysical Cosmology

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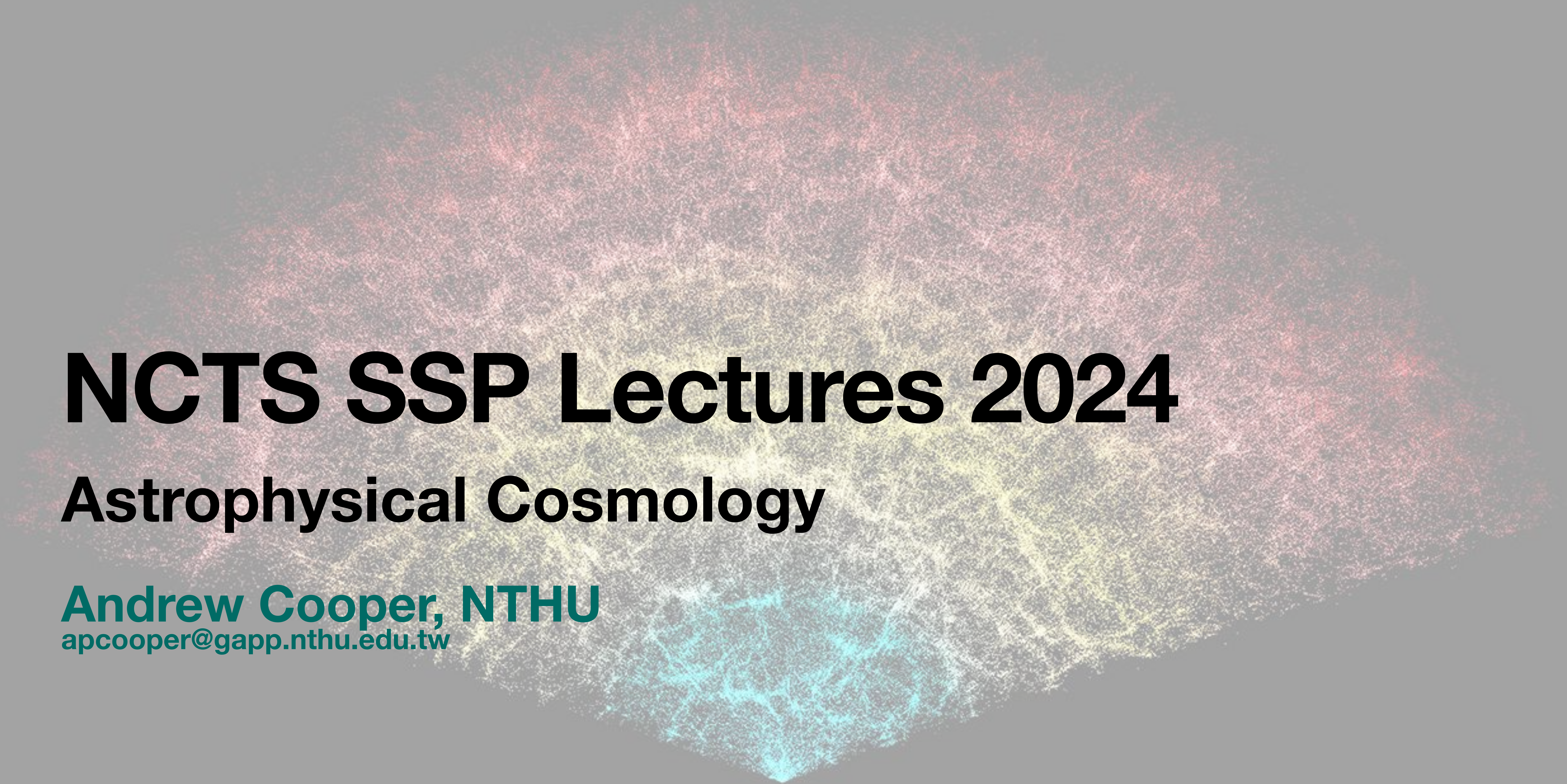

DESI Collaboration/NOIRLab/NSF/AURA/R. Proctor

NTU, July 1st 2024

There are many kinds of cosmologist…

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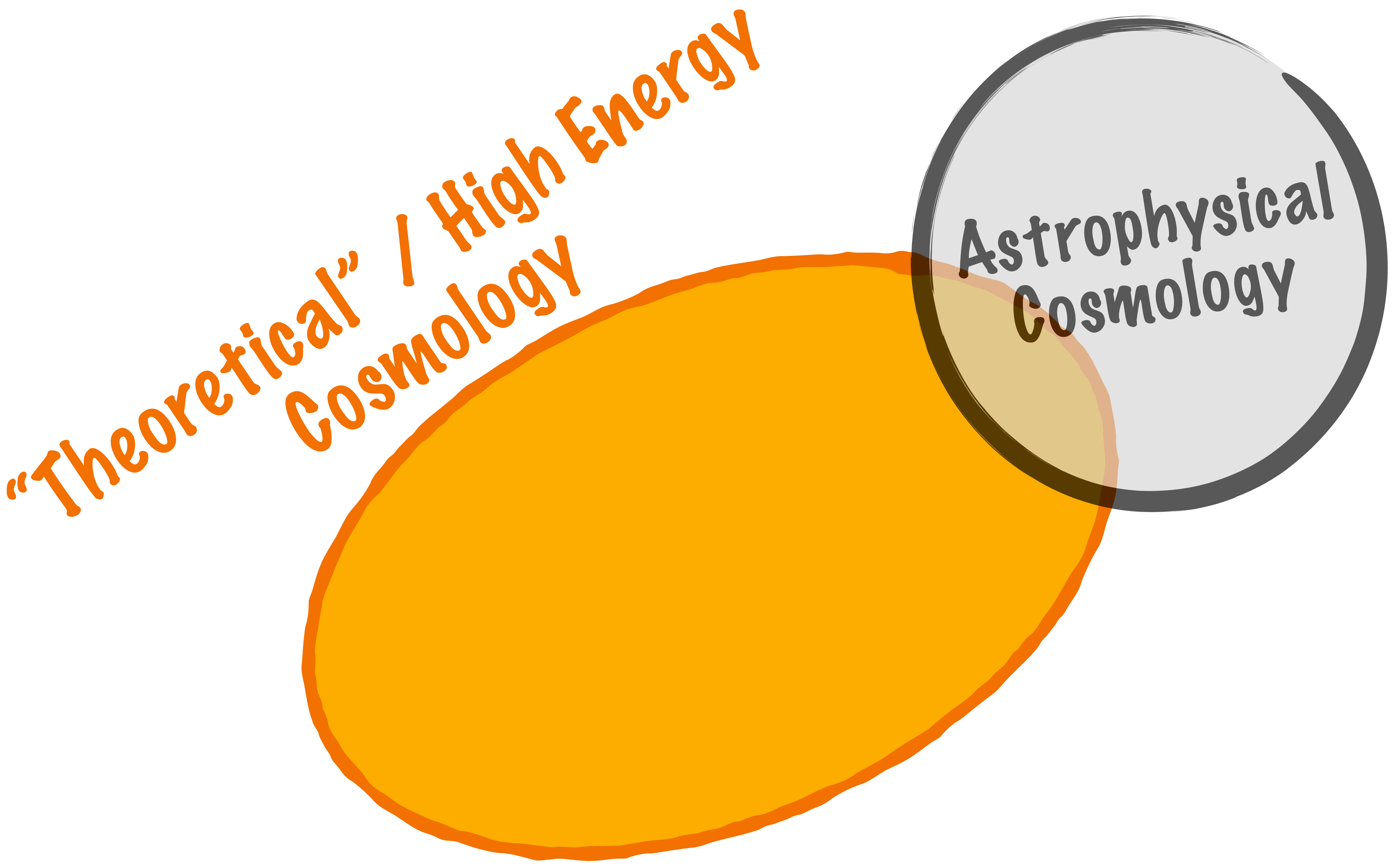
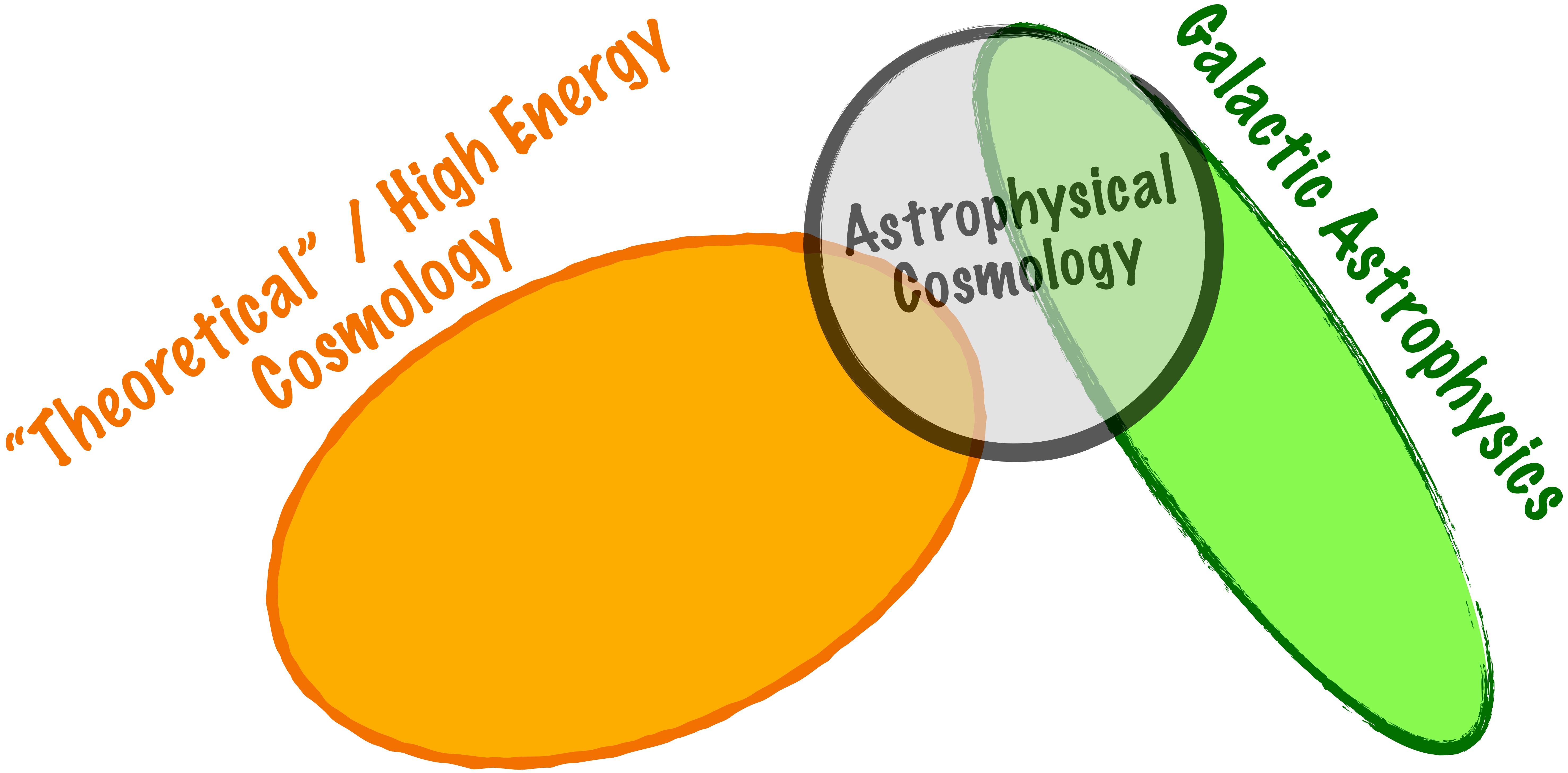
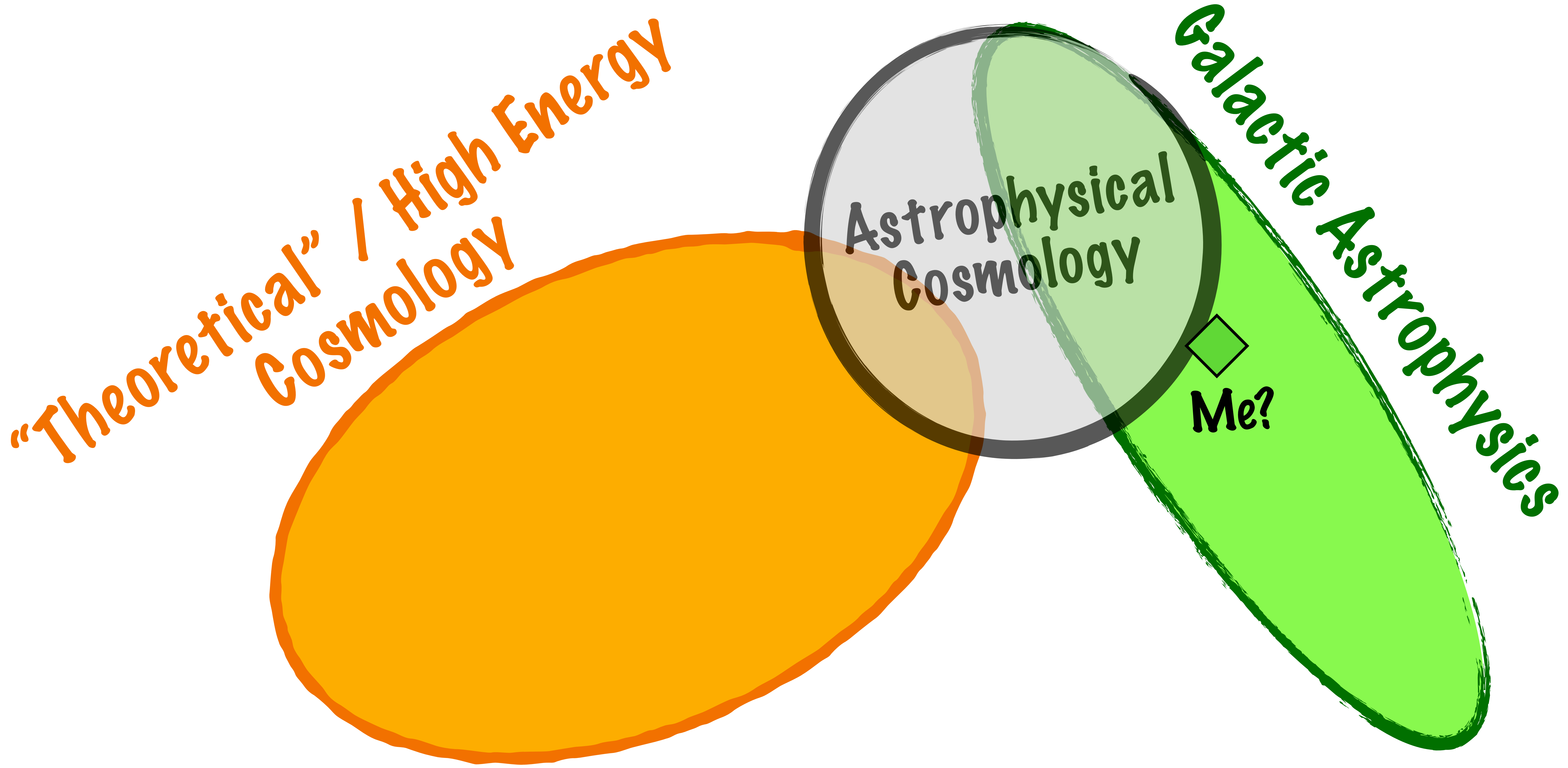


There are many kinds of cosmologist…



There are many kinds of cosmologist…



Cosmology Basics

Structure Formation

Recent Developments

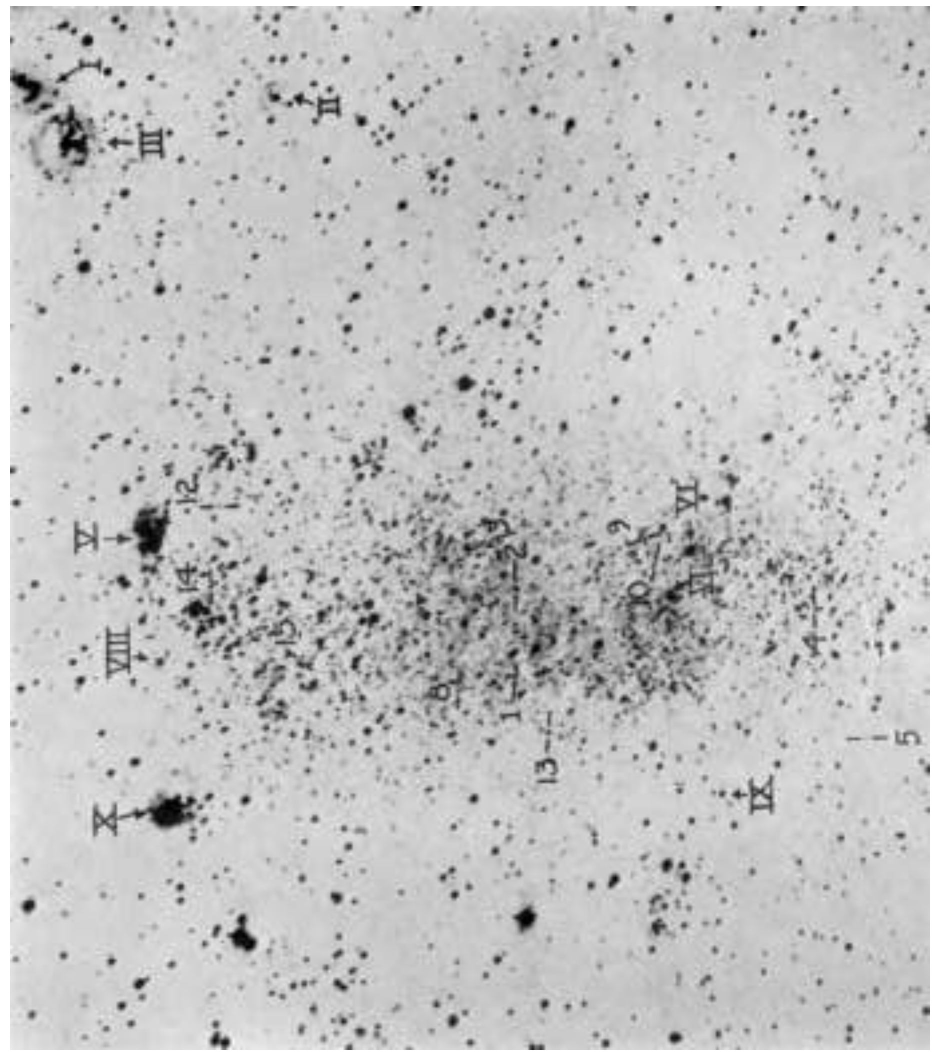
Astrophysics and Cosmology

How big is the Universe, how old is it, how has it changed? Where do galaxies come from?

"Astrophysical Cosmology" deals with:

- The story of the origin, evolution and ultimate fate of the Universe;
- The application of fundamental physics to the Universe as a whole;
- The initial and boundary conditions for galaxy formation.

100 years of “modern” cosmology



NGC 6822
Hubble (1925)

18/19C Nature, size of the Milky Way.

1910s GR

19/20C The place of the Sun in the Milky Way.

1910s Extragalactic redshift measurements

1920s GR models of an expanding universe

1920-1930 Nature of galaxies and their distances.

1930 Cosmic expansion.

1950s Galaxy formation? (astrophysics)

1960s QSO detections

1964 The Cosmic Microwave Background.

1970s Cold dark matter

1980s Inflation

1980s-1990s CDM galaxy formation!

1980s First galaxy redshift surveys.

1990s CMB anisotropies.

1990-2000 Large-scale structure.

1998 Accelerated expansion.

2000s Dark energy

Models of the Universe

- **‘Basic’ physics can be used to build cosmological models that make predictions we can test with astronomical observations.**
- The ingredients in these models represent the different types of “stuff” in the Universe: **baryonic** (ordinary) **matter**, **radiation**, **neutrinos**, **cold dark matter**, and **dark energy**.
- The last two are ‘known’ only indirectly, through their **effect** on other things; their true nature is still unknown.

Models of the Universe

- The components are distinguished by how their energy density (pressure) changes with volume (their *equations of state)*.
- The fundamental predictions of the models are the **rate at which the Universe expands** and **the rate at which structure in the Universe grows**.
- By observing how the real universe behaves and comparing to predictions, we can work out the actual mix of ingredients.

https://depositphotos.com/

istock.com

Basic idea: FLRW models and ΛCDM

Expansion factor:

$$x(t) = a(t)r$$

Hubble parameter:

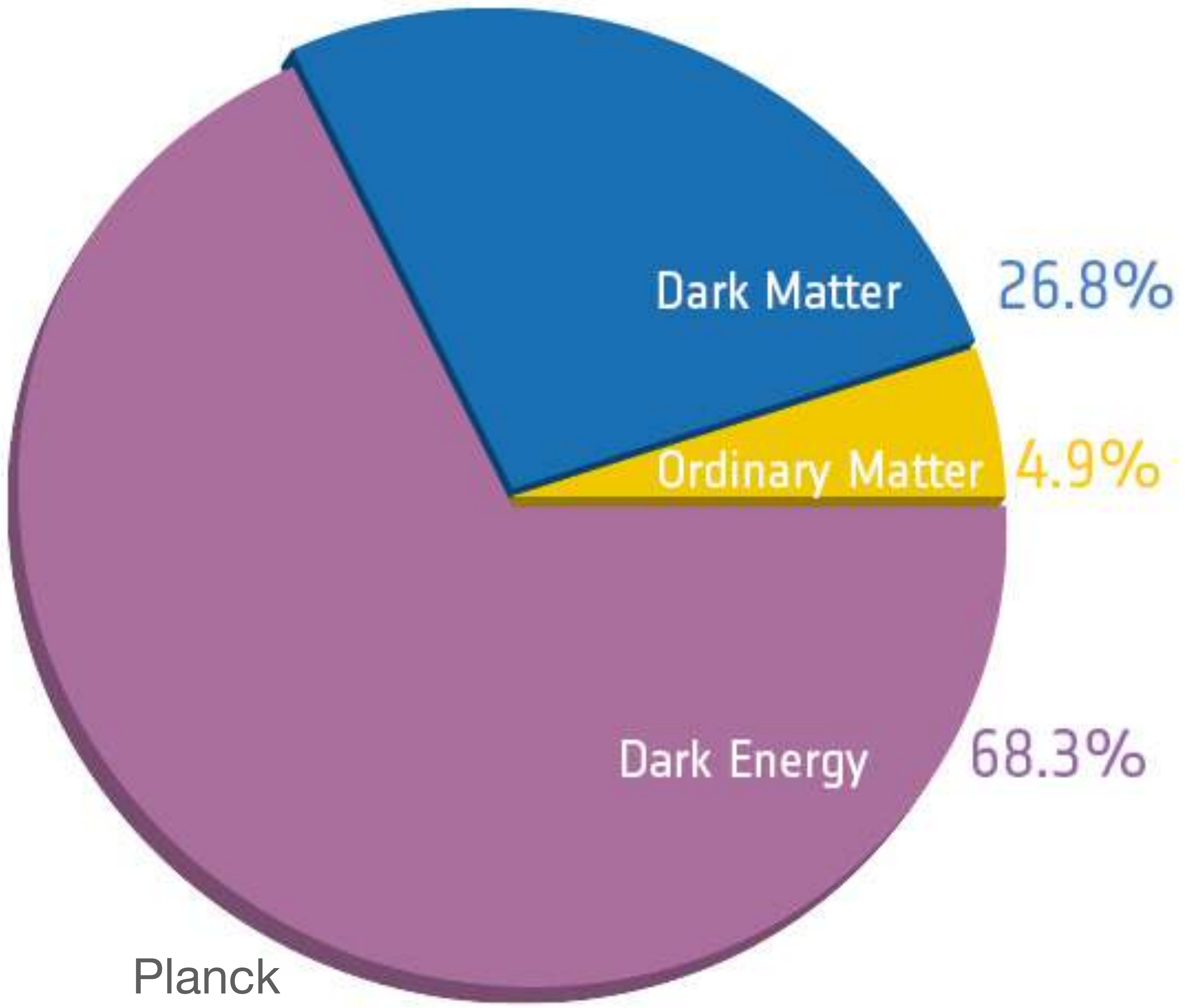
$$H(t) = \frac{\dot{a}}{a}$$

- **Friedman - Lemaître - Robertson - Walker**
- General relativity: spacetime is **dynamic**; it responds to the density of mass-energy.
- On large scales, the distribution of mass-energy in the universe is (assumed) **homogeneous**.
- The **background metric** evolves: **the distance between all points in spacetime grows or shrinks** ↑.
- The rate of growing or shrinking is a function of the density of all the 'ingredients' of the background mass-energy density (the Friedman equation ↓).

$$\Omega_m + \Omega_\gamma + \Omega_\Lambda + \Omega_k = 1 \qquad \Omega_x = \frac{\rho_{x,now}}{\rho_{c,now}}, \ \rho_c = \frac{3H^2}{8\pi G}$$

$$\rho_{c,\mathrm{now}} \sim 1 \times 10^{11}\,\mathrm{M}_\odot\,\mathrm{Mpc}^{-3}$$

- **The current "baseline" model is called ΛCDM** →

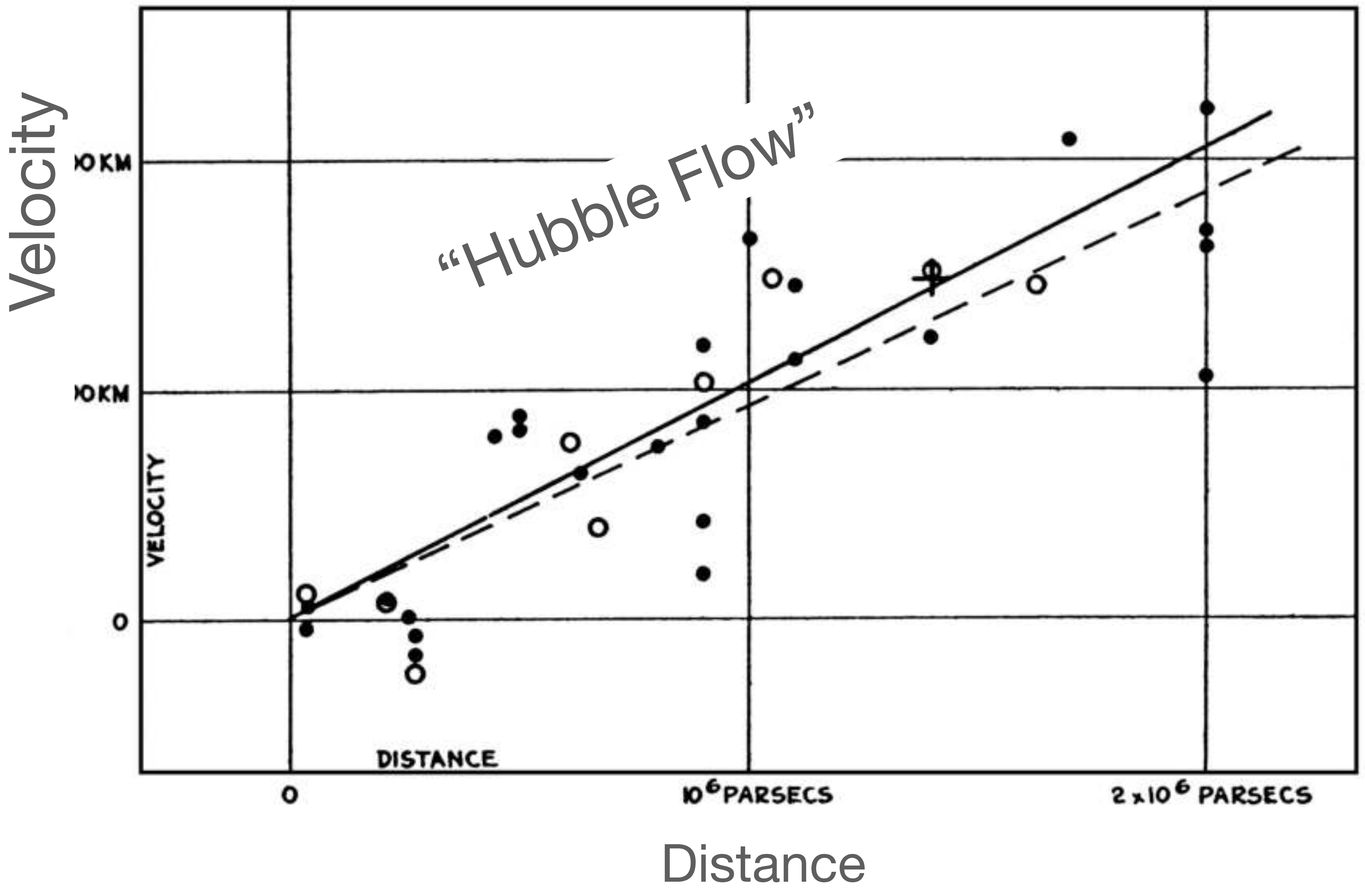


Planck

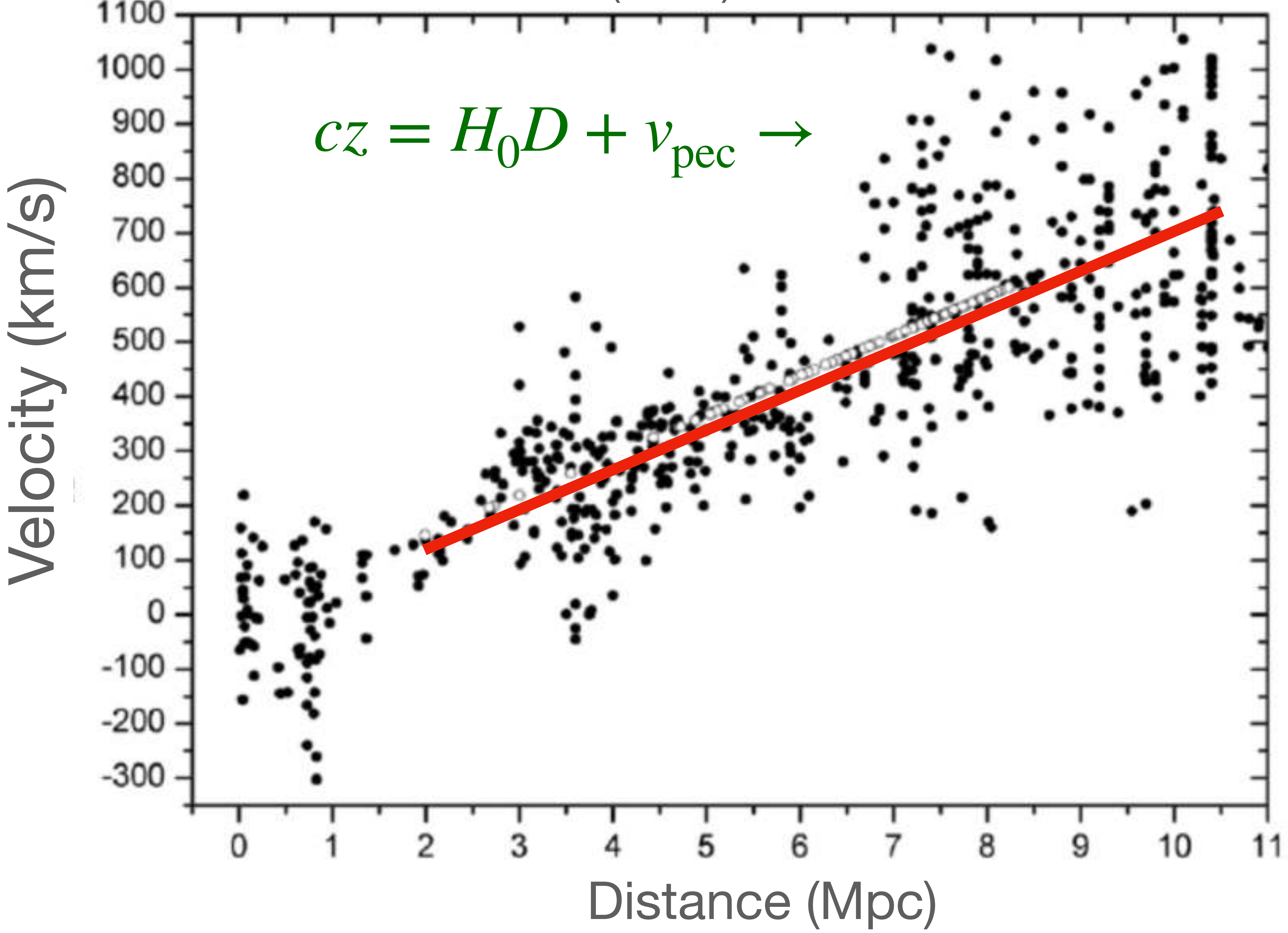
An expanding universe: H_0

- The universe is **expanding**. The **present-day** rate of expansion is the **Hubble Constant** $H_0 \simeq 65-70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (see later…). $v = H_0 d$, gives the recession speed of galaxies in the **local** universe.

Hubble (1929)



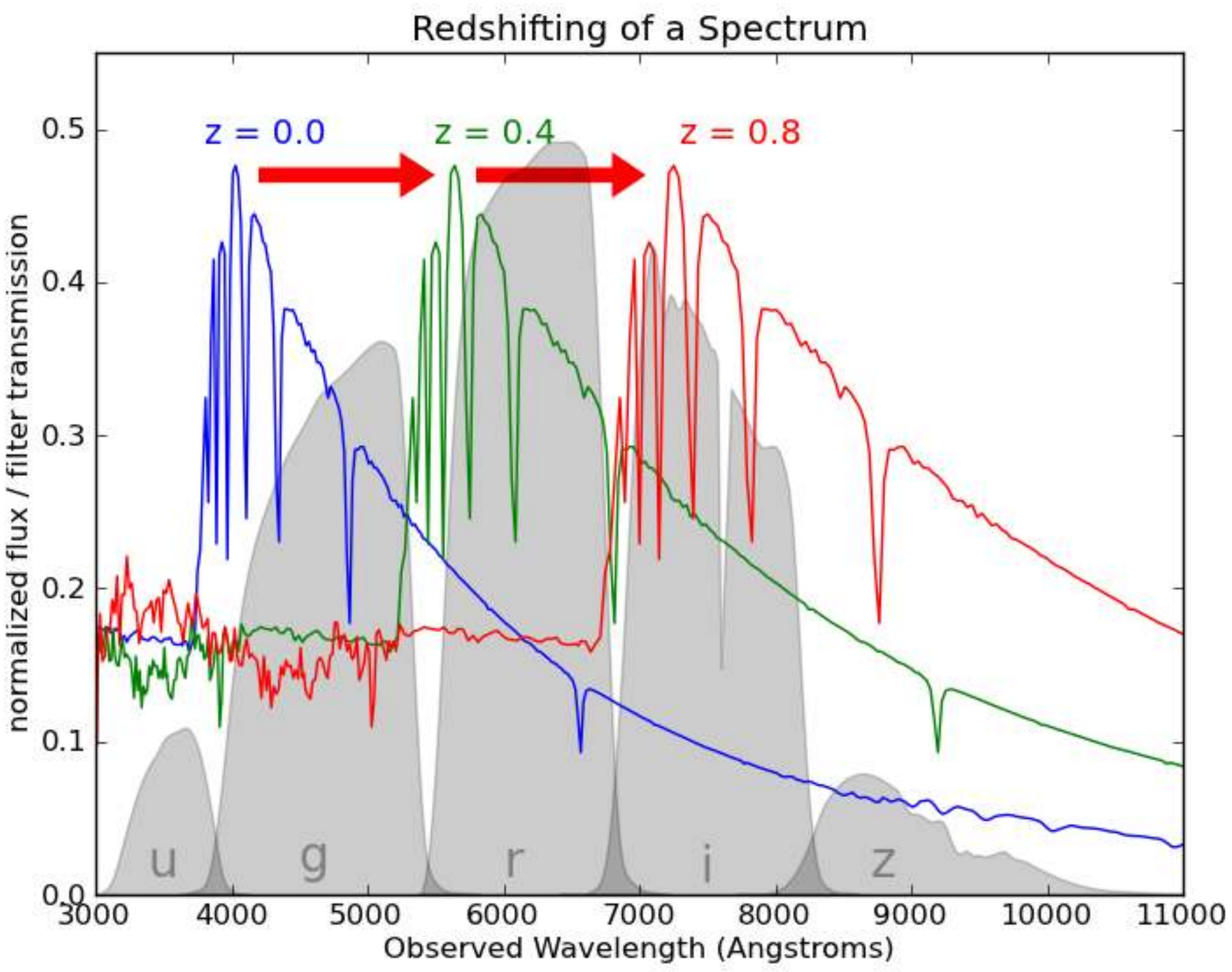
Karachentsev et al. (2013)



In the nearby universe, the Hubble flow is determined using ***standard candles:*** certain types of variable star and supernovae for which distance can be inferred from a known luminosity.

Cosmological redshift

- Photon **wavelengths** are "stretched" by the expansion; the spectra of distant galaxies are **red-shifted**.
- The cosmological **redshift** is a measure of the **relative expansion** between the present day and the time the light was emitted: $a = (1 + z)^{-1}$.



https://ogrisel.github.io/scikit-learn.org/sklearn-tutorial/tutorial/astronomy/regression.html

Relativistic effects

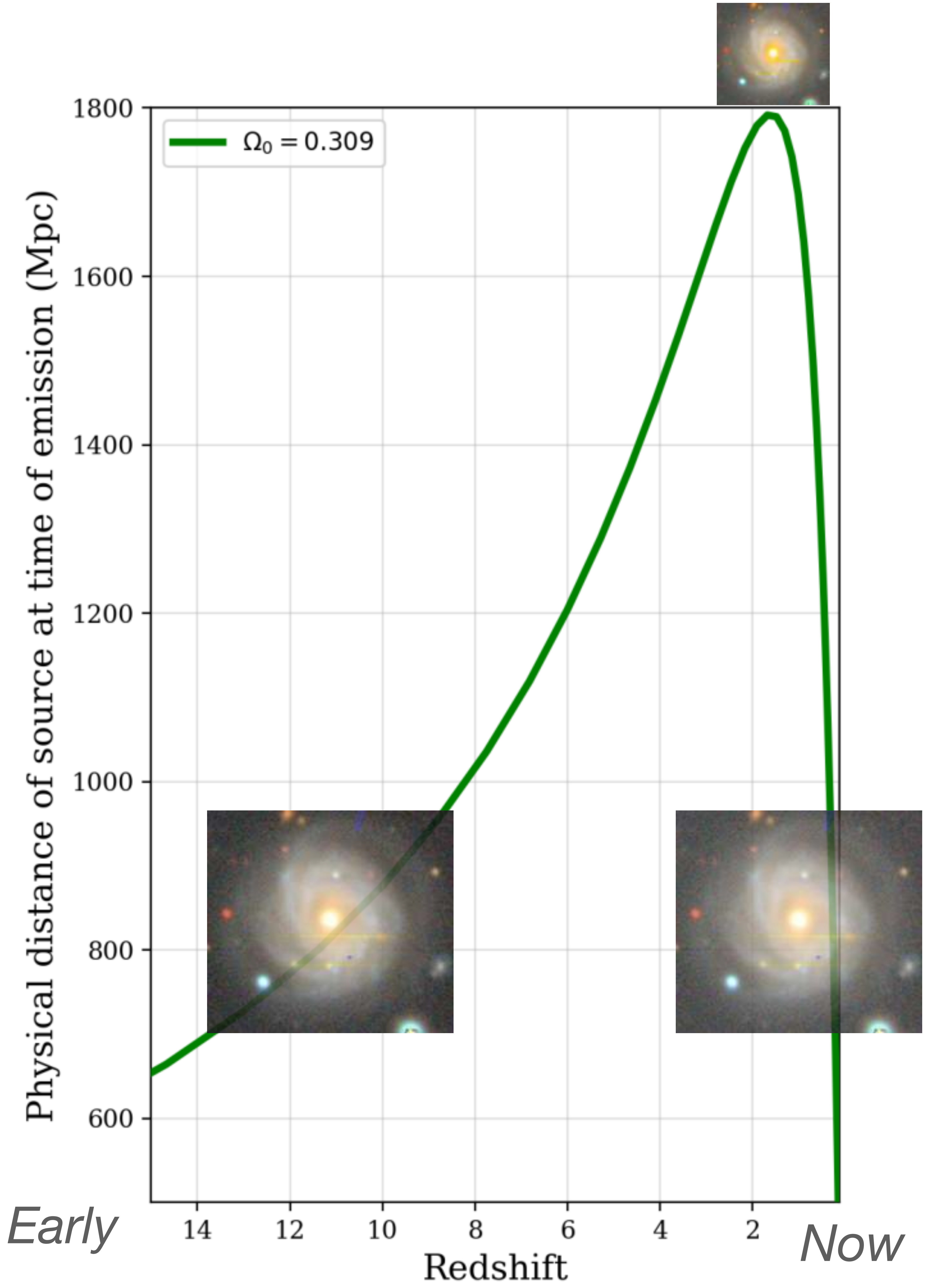
- Photons emitted in our direction travel towards us at the speed of light.
- The photons reaching us now have travelled different distances, depending on when they set off.
- In our local flat, static spacetime, we’re used to the idea that lightbulbs look smaller and fainter when they’re further away.
- In cosmological spacetime, the **actual distance photons have to travel to reach us “now”** is determined **by the expanding background**.
- This makes the relationship between apparent size, brightness and distance “complicated” (non-Euclidean).
- At cosmological distances, we need to know the expansion history to convert observed angles and brightnesses to physical sizes and luminosities.

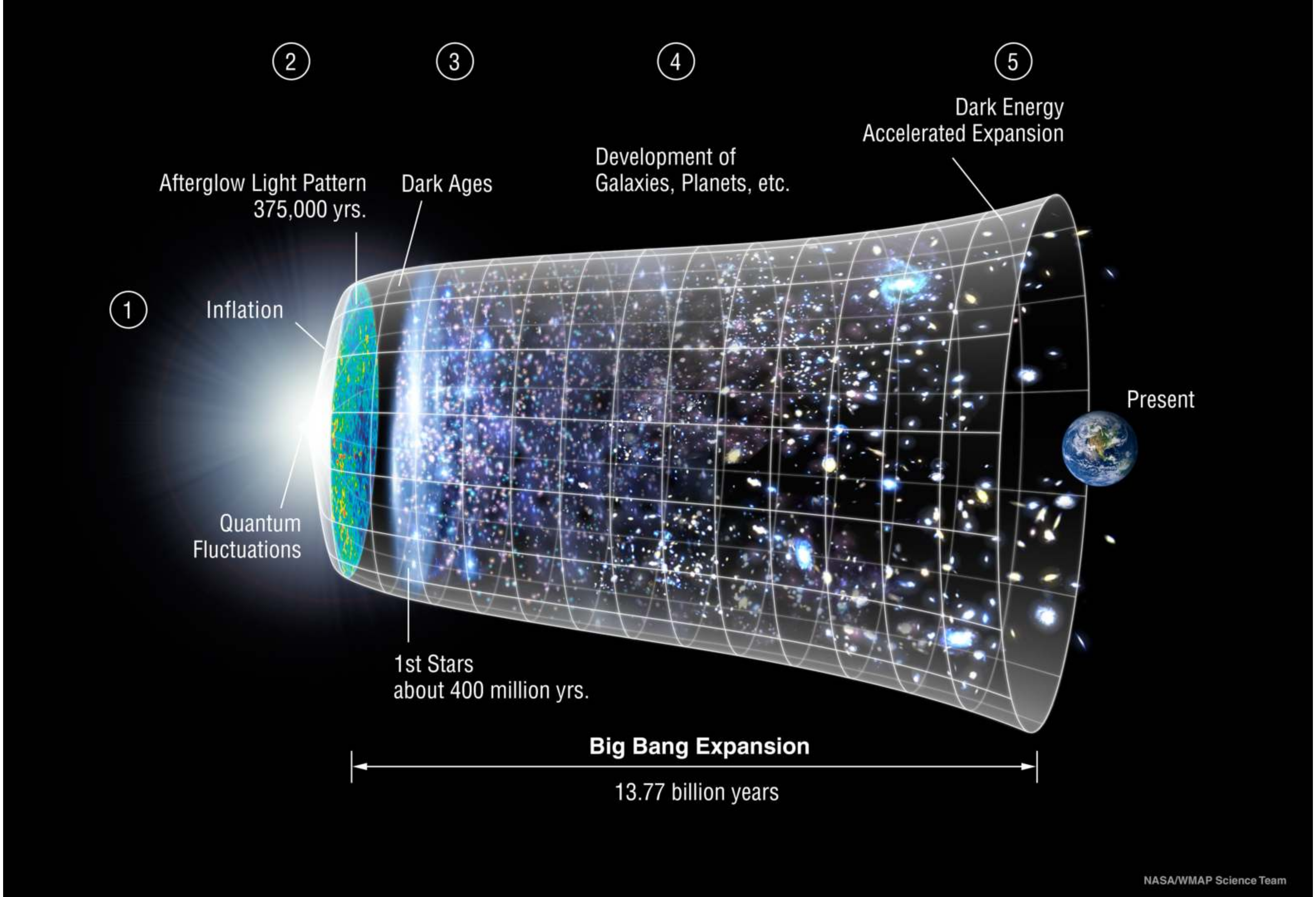
Angular sizes

- The apparent size of galaxies that "cross our lightcone" in the very early universe ($z \gtrsim 2$) *increases with redshift* because those galaxies were relatively *closer* to us when the photons set off; they were "delayed" by the rapid early expansion.

- The relationship between apparent angular size and redshift depends on the expansion history.

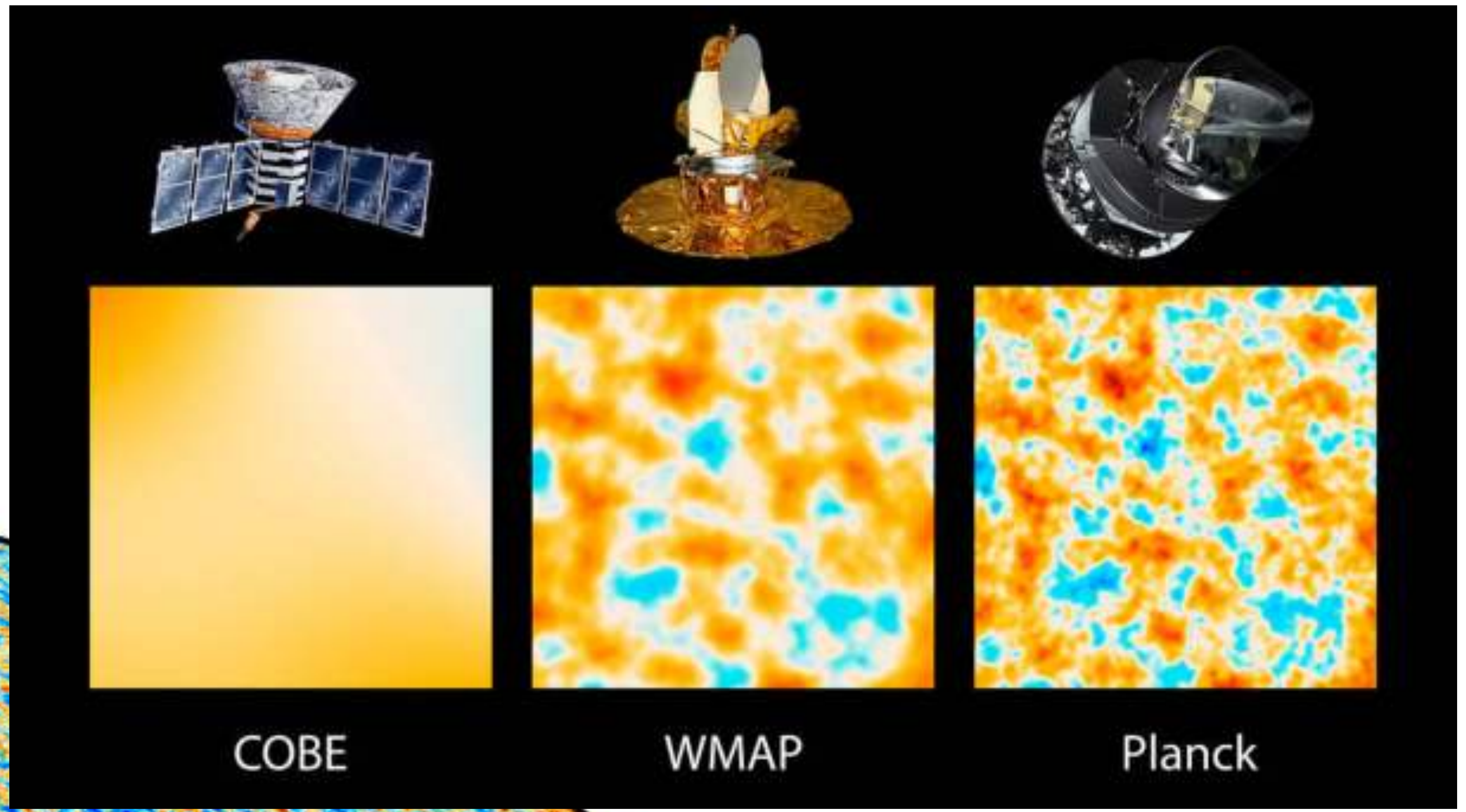
- As well as standard candles, we can measure the expansion history of the universe using features of known physical size as *standard rulers.*

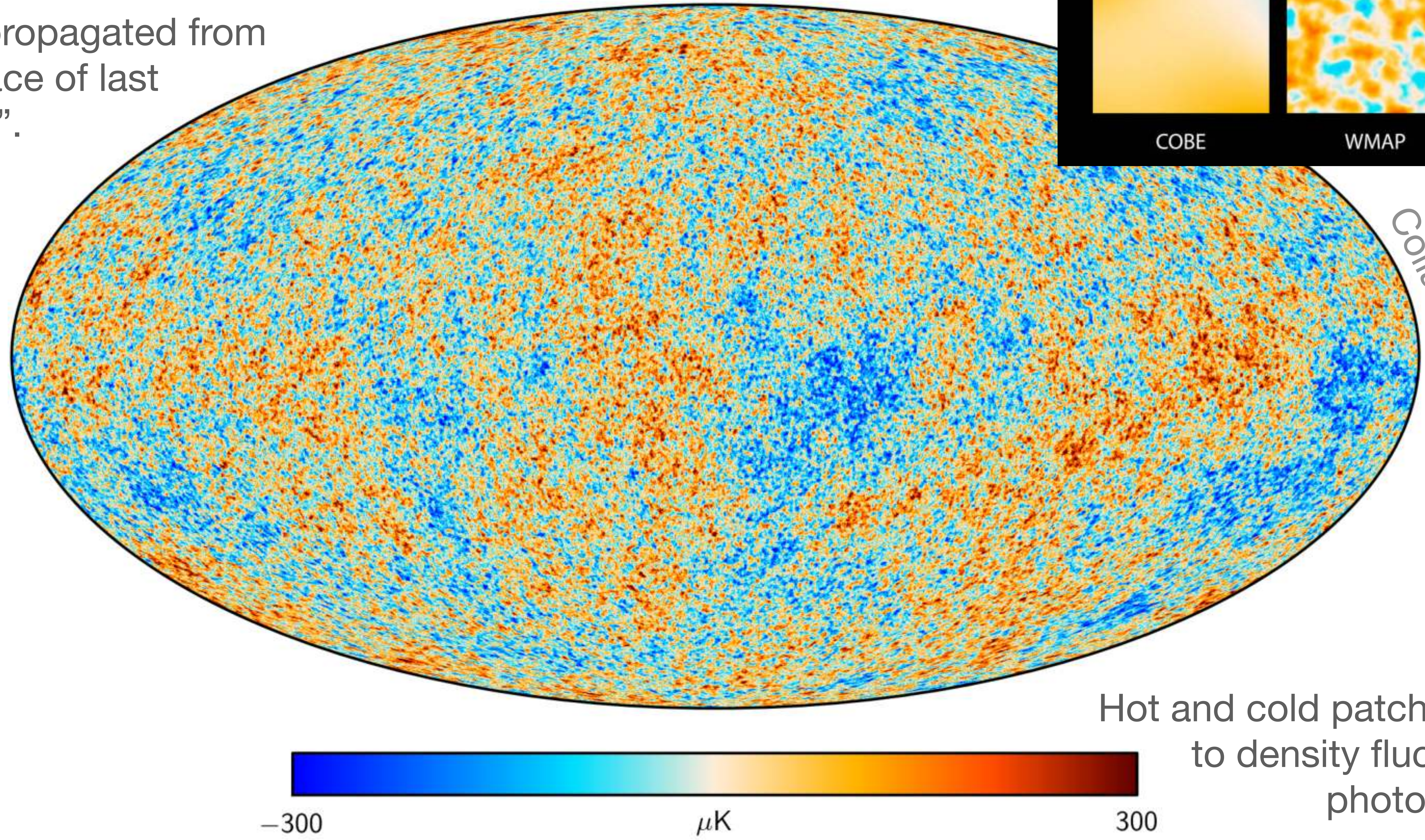



2
3
4
5
Dark Energy
Accelerated Expansion
Development of
Galaxies, Planets, etc.
Afterglow Light Pattern
375,000 yrs.
Dark Ages
1
Inflation
Present
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

The cosmic microwave background

Photons propagated from the "surface of last scattering".

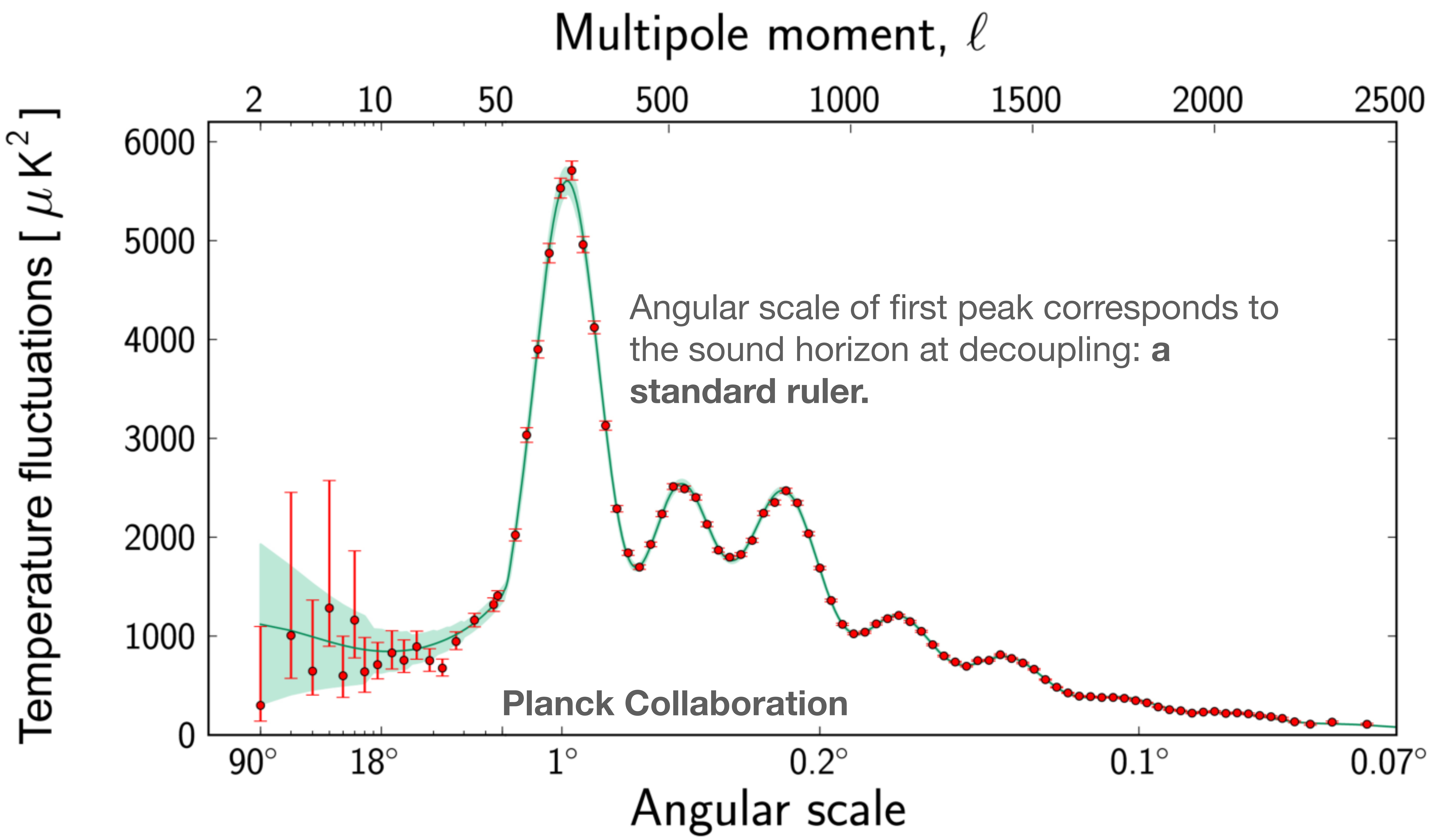




Planck Collab.

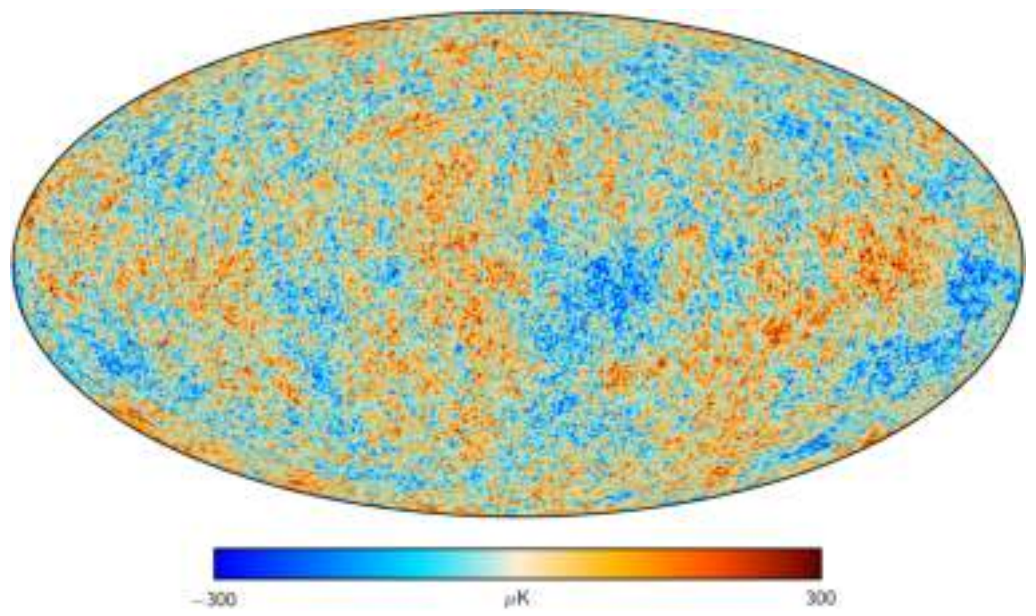
Hot and cold patches correspond to density fluctuations in the photon-baryon fluid.

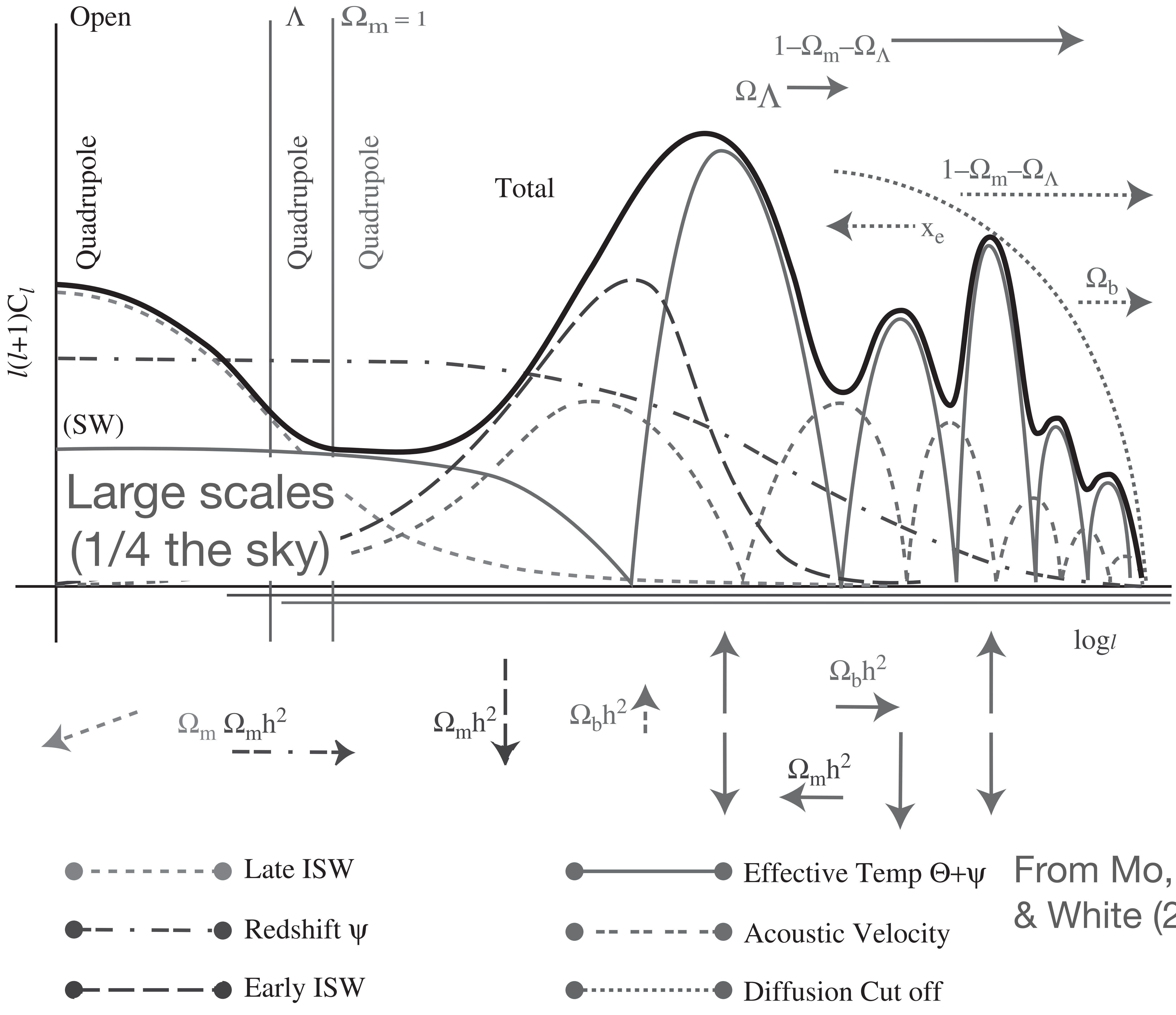
The acoustic peaks



The plasma era, dark matter and flatness

Strength of fluctuations vs. scale

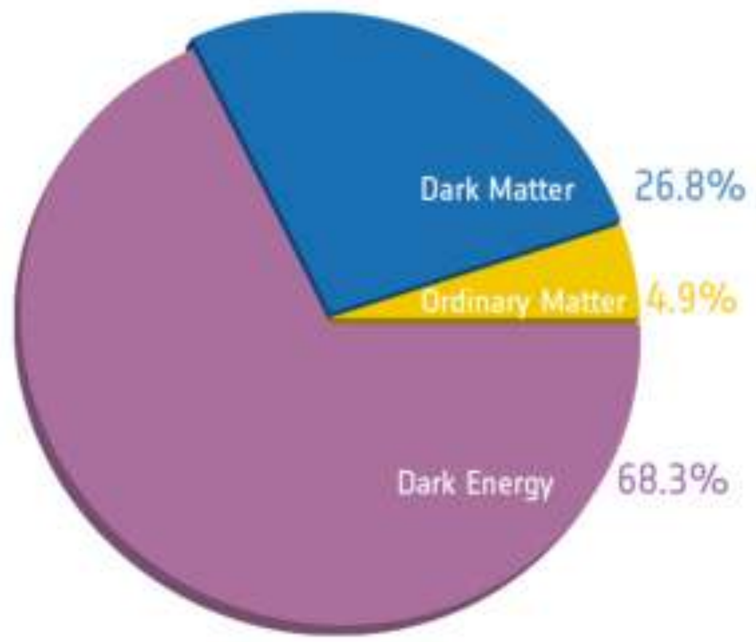




Small scales (~10 Mpc today)

From Mo, van den Bosch & White (2010)

"Missing mass" implied by $\Omega_m \approx 5\Omega_b$ matches other astrophysical evidence for Dark Matter



H_0

Accelerated expansion and Λ

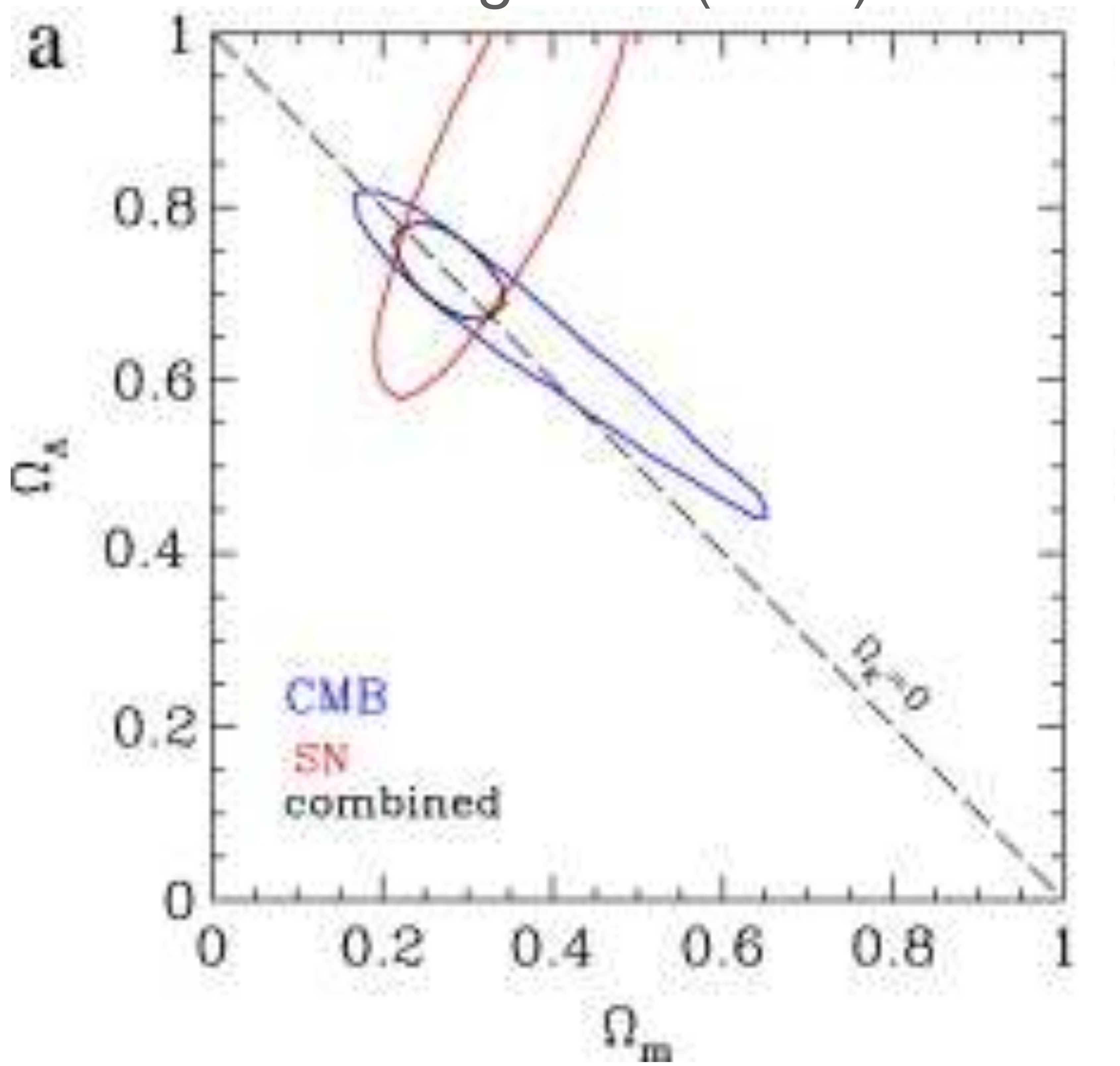
The CMB data imply a “flat” universe with low matter density, $\Omega_m \sim 0.3$.

The dominant contribution to the *present day* energy density must be something that doesn’t cluster under gravity.

The “simplest” explanation is a cosmological constant, Λ: **constant** energy density per unit volume, such that $\Omega_m \sim 0.7$.

The decisive evidence for this is provided by the accelerating expansion inferred from supernova luminosity distances, measured at $z < 1$.

Weinberg et al. (2013)



Dark energy

To explain accelerated expansion (in GR), we postulate a mysterious source of energy density with negative pressure! A cosmological constant is just one of many possibilities.

$$w \equiv \frac{p_{DE}}{\rho_{DE}}$$

$w = -1$ for Λ

$w \sim -1.02$ according to Planck 2018

No reason w *has* to be a constant. The CMB has little to say about this: need measurements over a large range of redshift.

$$w(a) = w_0 + w_a(1 - a)$$

See Linder et al. (2002): https://arxiv.org/pdf/astro-ph/0208512

Evolving w changes $H(z)$ and the rate at which structure grows $\implies$ by measuring these things, we can constrain w_0 and w_a.

This is the goal of many big cosmological "experiments" happening now and in the near future.

Cosmological basics: summary

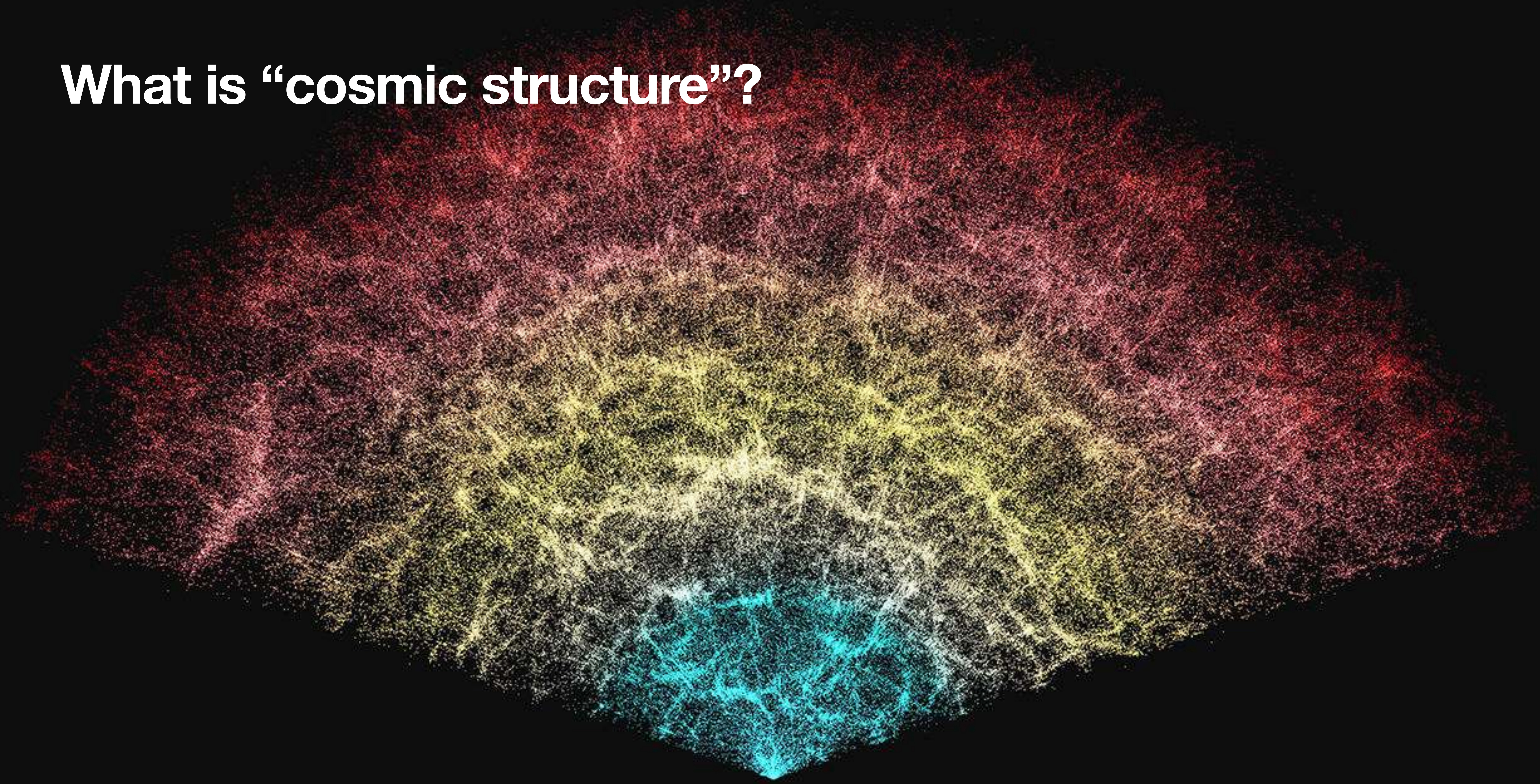
- Undergraduate-level physics works pretty well to make an empirical model of *almost* everything we see in the Universe.
- Where observational facts can't be explained from first principles, a handful of **surprisingly** simple empirical "tweaks" are introduced (**initial conditions? → inflation; missing mass? → dark matter; accelerated expansion? → Λ / dark energy**).
- Given the huge range of predictions they can make, this empirical model has very few parameters and is extremely well constrained by observations.
- Of course, we still want to understand *what it all means*.

Cosmology Basics

Structure Formation

Recent Developments

What is “cosmic structure”?



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What is “cosmic structure”?

C. Lamman / DESI collab.

Initial conditions for structure formation?

- Almost all cosmological observations are based on the properties of **structures** like galaxies or the CMB anisotropies.
- FLRW models assume a homogeneous background. This obviously isn't true on "small" scales, even at very early times.
- We can blame the CMB temperature anisotropies on matter density perturbations: hotter or colder spots correspond to regions of higher or lower density.
- After decoupling, fluctuations can **grow** under gravity (the growth of fluctuations in the DM starts well before decoupling). This "explains" where galaxies come from, and their large-scale structure

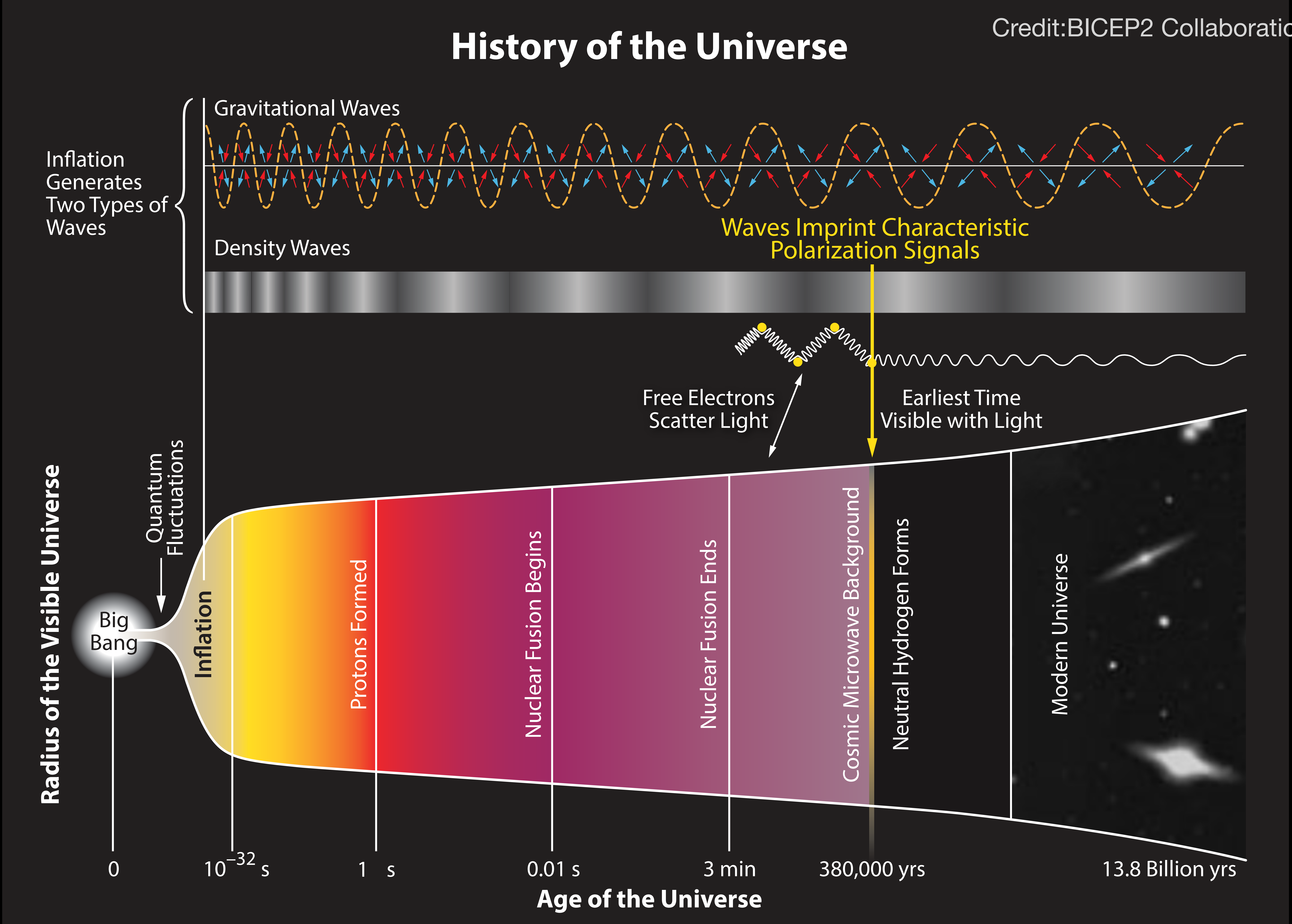
Inflation!

- How come we have density fluctuations in the first place?
- To explain the CMB anisotropies, we need the fluctuations to be “built in” to the initial conditions somewhere around $z \to \infty$.
- That’s hard: everything should get smoother at earlier times!
- This **serious** problem is solved by postulating **inflation**: a **brief** period of very, very, very, very, very rapid expansion at (extremely) early time.
- This is accepted because very simple models of inflation also “fix” other kinds of ‘initial condition’ problems with FLRW models.

- Inflation takes quantum-mechanical fluctuations in the *very* early Universe and "blows them up" to cosmic scales during a phase of accelerated expansion, in pretty much exactly the same way as Dark Energy seems to be doing now.

- Except, a **lot** stronger, and somehow inflation **stopped**…

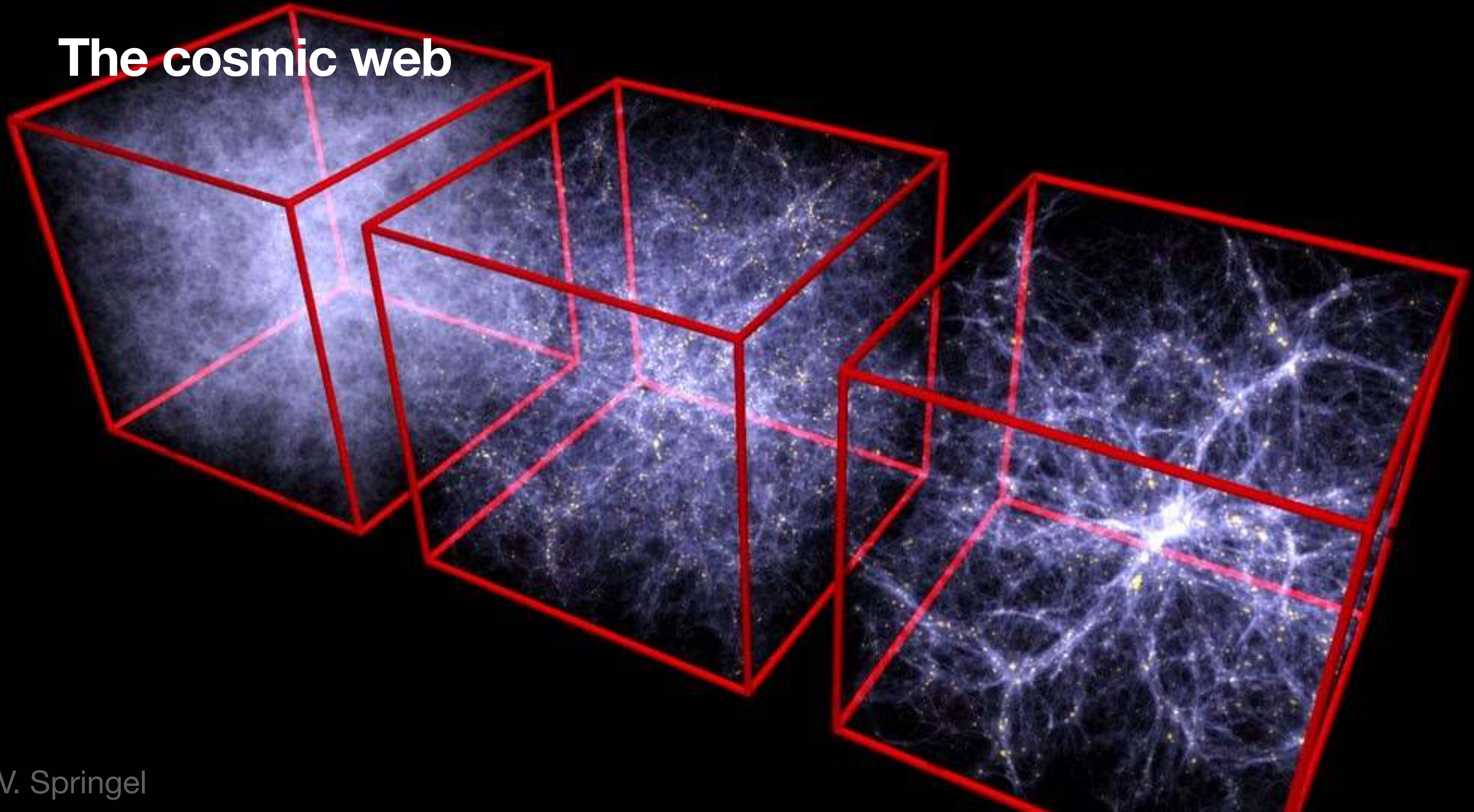
- Instead of "dark energy" we have **the inflaton**.



The growth of structure after recombination

- Accepting inflation, and with cosmological parameters from the CMB, we can say with some confidence what **gravitating matter** was doing ~300,000 years after the Big Bang.
- After that (i.e. for the next ~ 13.5 billion years) it's all about $F = -\dfrac{GMm}{r^2}$.
- **Overdensities grow**. Regions of higher-than-average (dark matter) density collapse under gravity. The baryons follow along (after recombination).
- Starting from CMB initial conditions, we can follow the collapse with perturbation theory or (more accurately) with explicit **simulations**.

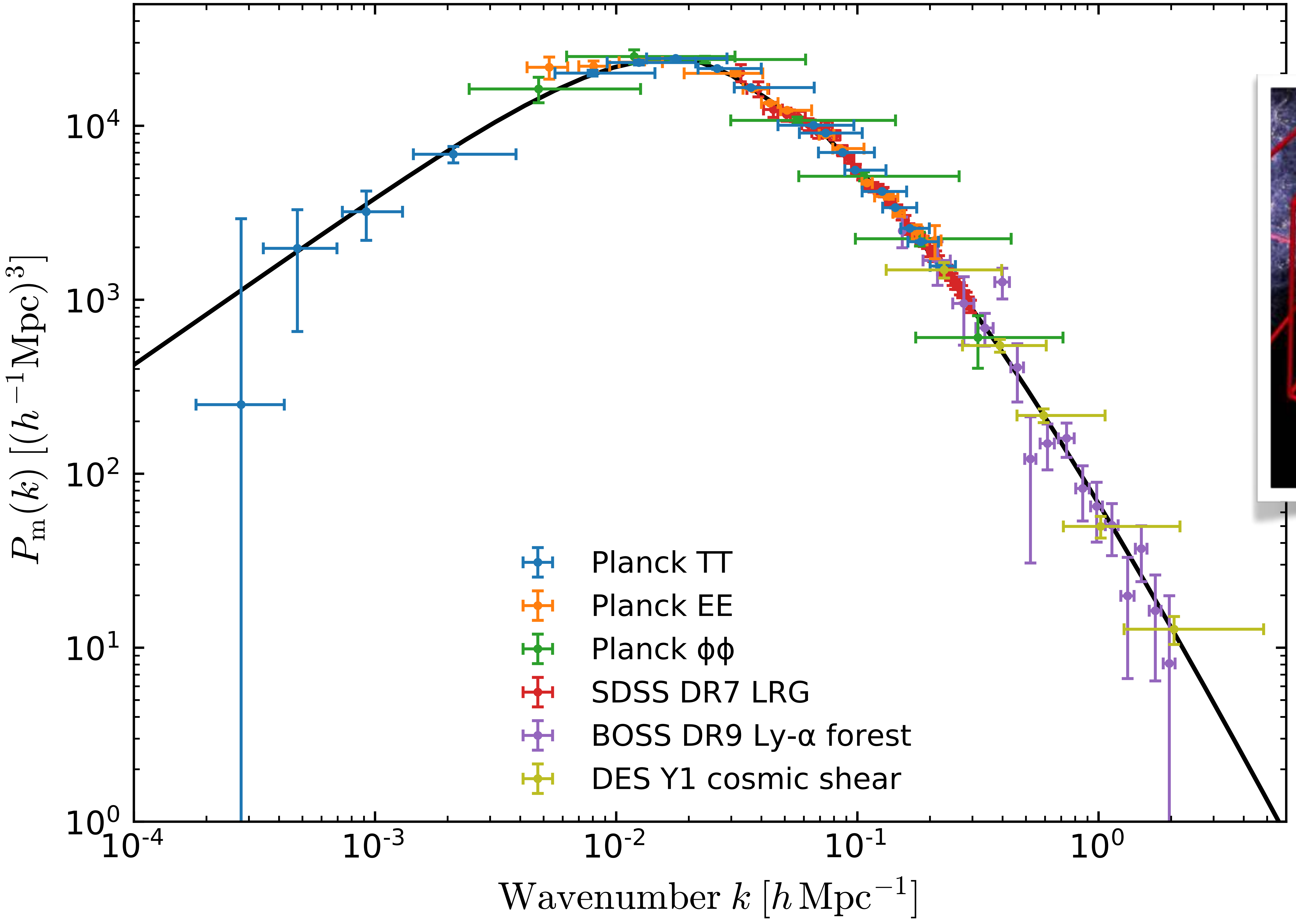
The cosmic web

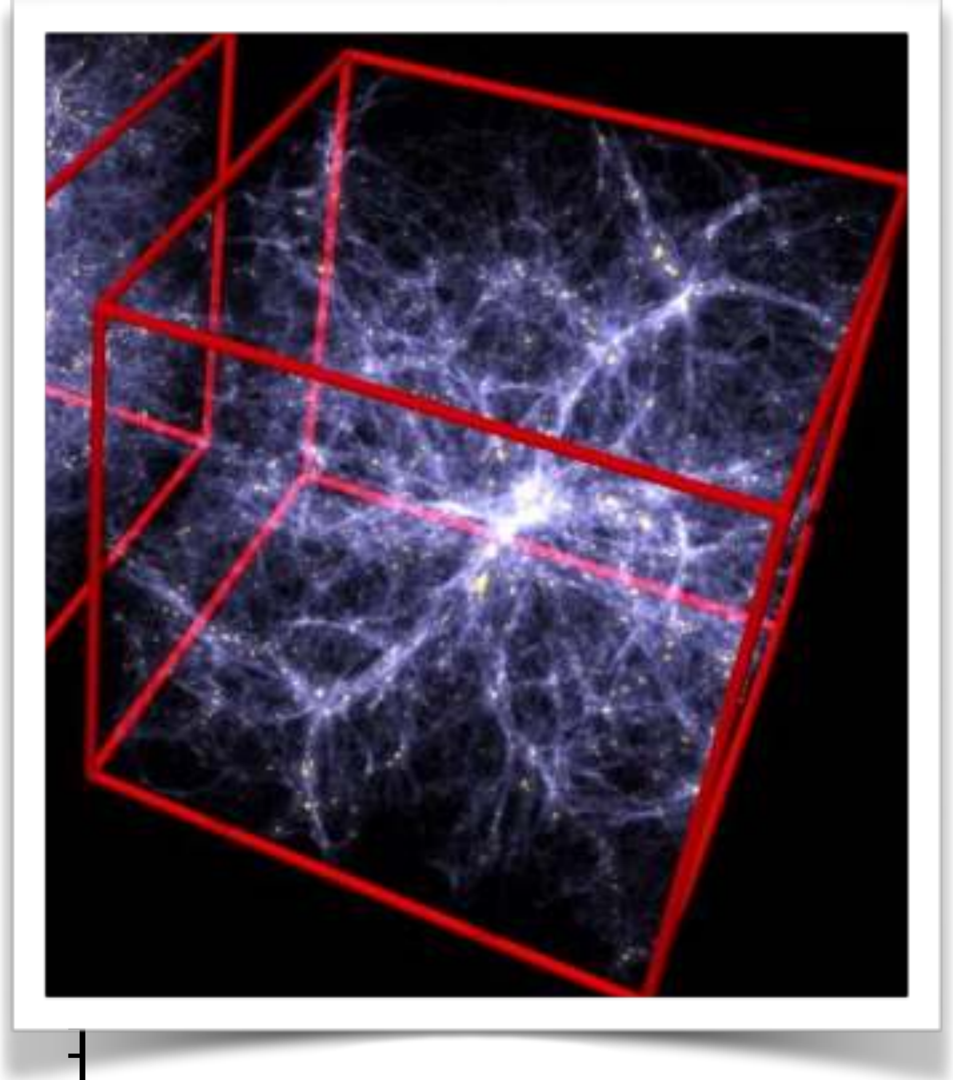


V. Springel

The matter power spectrum

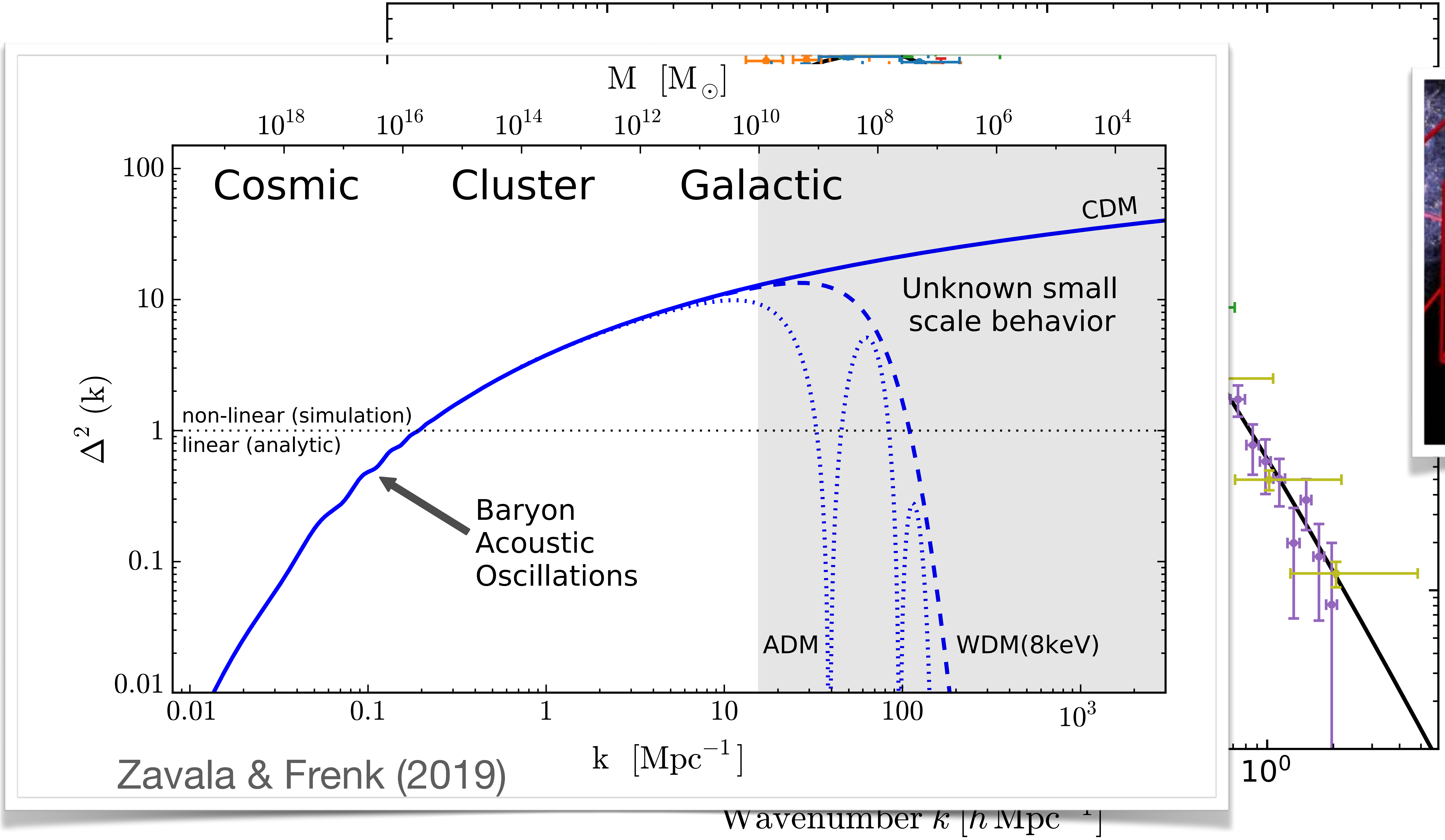
Planck Collab. (2018)



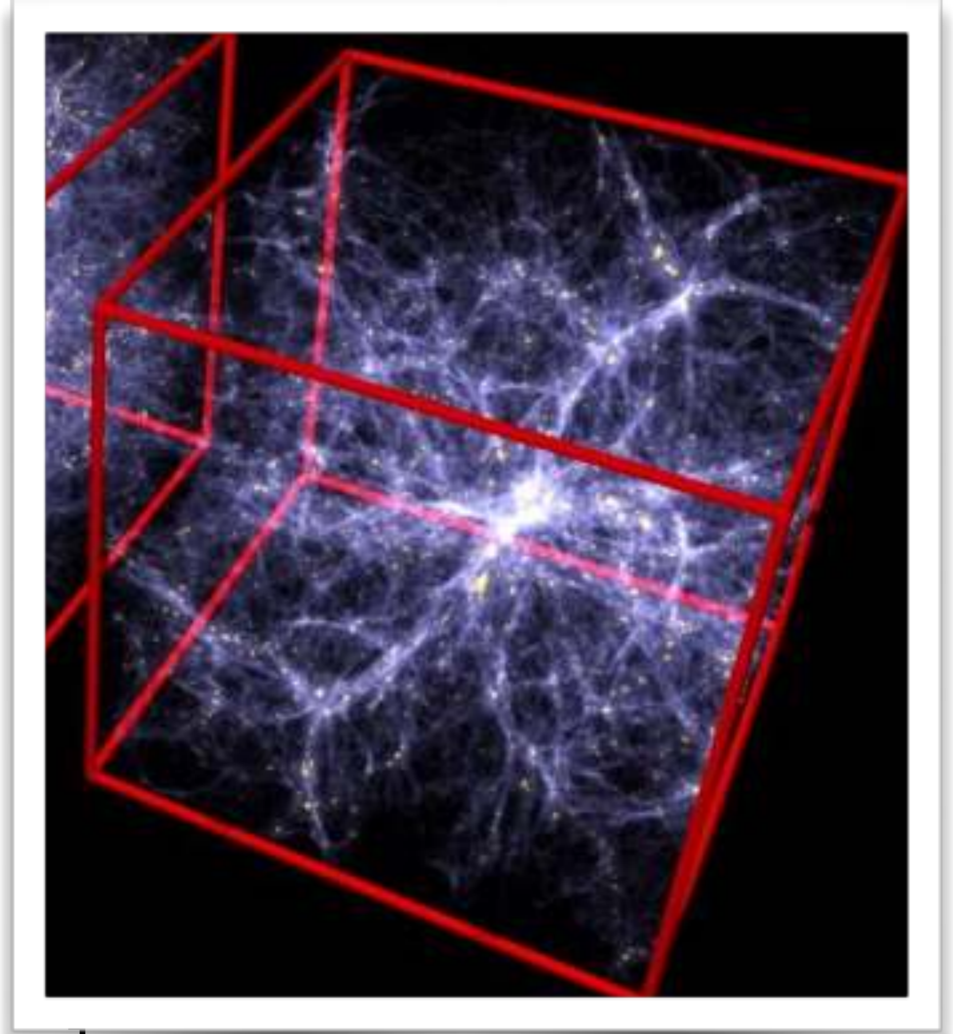


The matter power spectrum

Planck Collab. (2018)



Zavala & Frenk (2019)



Dark matter halos

- Overdense regions “turn around” from the cosmic expansion and **collapse** under gravity.

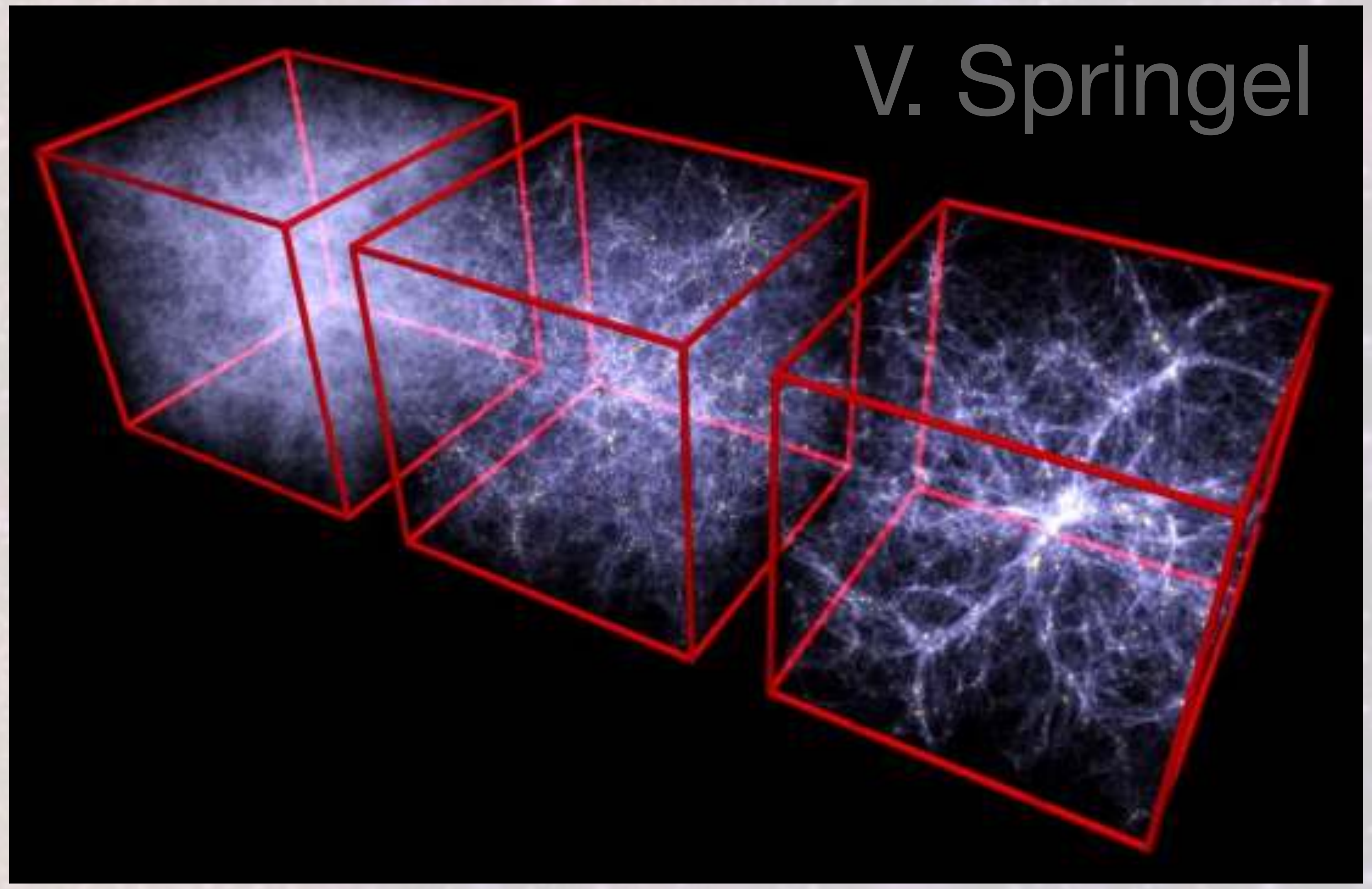
- Gravitational contraction of (collisionless) DM **stops** when **equilibrium** is reached between the **kinetic and potential energy** of the bound material The overdensity is said to be **virialized** (virial theorem: $2T = -W$).

- This happens at $\rho \approx 200\,\bar{\rho}$. Virialized clumps are called dark matter **halos**.

- At any given time there is a **characteristic mass scale** with this density. Loosely speaking:

    - Fluctuations on larger scales (more mass) almost always collapse late; these are galaxy clusters!

    - Smaller scales (less mass) may collapse early (if they are in a dense environment on a larger scale, e.g. the cores of galaxy clusters) or late (if they are isolated, e.g. dwarf galaxies).



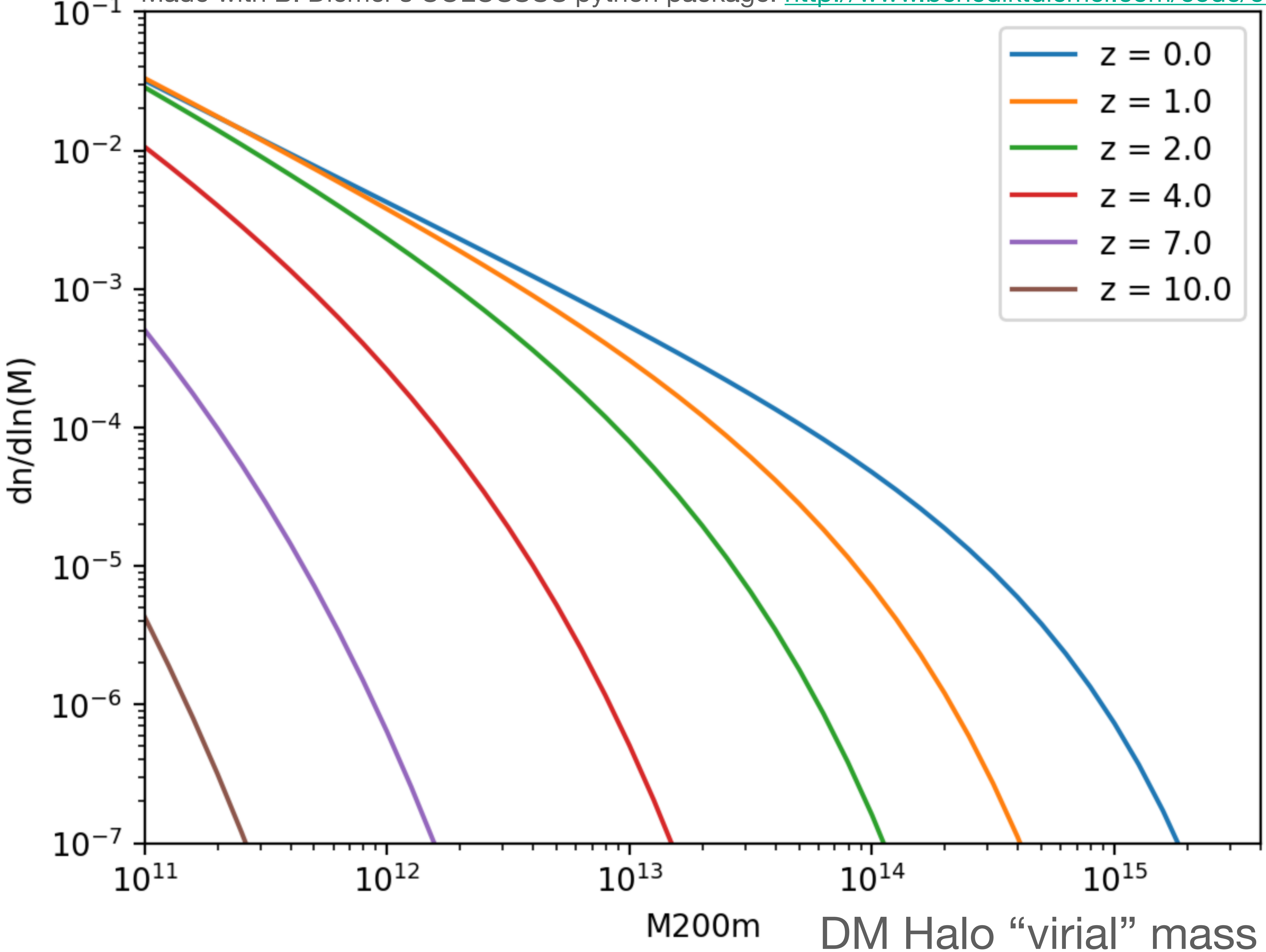

V. Springel

The dark matter halo mass function

Given initial conditions, **the number of virialized objects of a given mass at any given time** can be predicted by an analytic theory (direct simulations are even better).

Number of halos per unit volume per decade in mass

Made with B. Diemer's COLOSSUS python package: http://www.benediktdiemer.com/code/colossus/



DM Halo "virial" mass

Galaxies and their halos

In a CDM-like cosmogony, **virial mass** is the fundamental parameter of galaxy formation.

Baryons (hydrogen atoms) settle into **hydrostatic equilibrium** in virialized halos. The corresponding **virial temperature** determines what happens next.

Total mass of baryons in a halo is $\sim \Omega_b/\Omega_{DM}$ (if halo potential is deep enough to trap gas at ambient temperature of intergalactic medium).

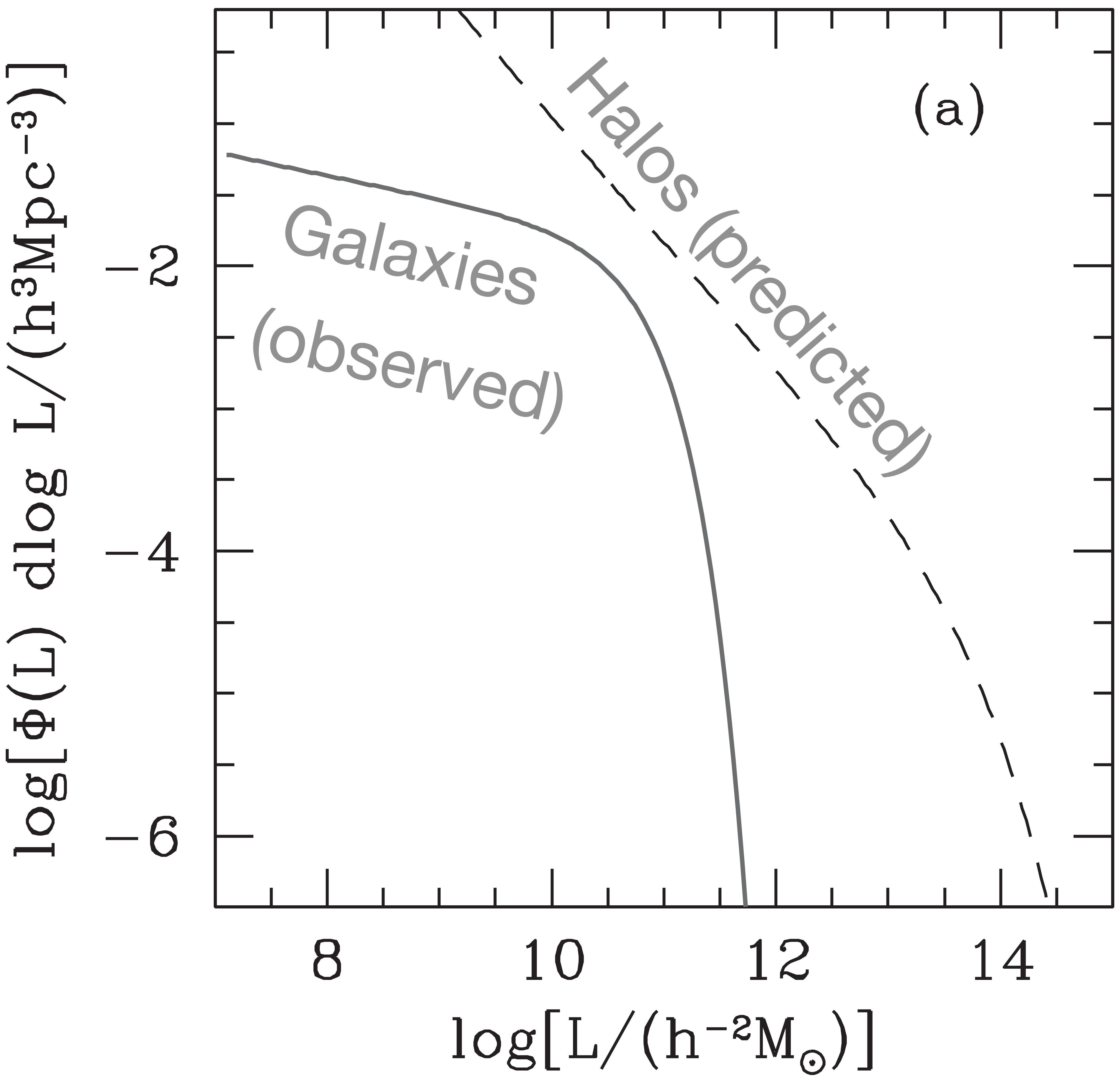
To form galaxies, some of those baryons have to **cool down**. Main cooling process is the emission of photons due to collisional excitation of the bound electrons.

This process can only cool the gas efficiently above $T_{\rm vir} \sim 10^4\,{\rm K}$.

Which galaxies live in which halos?

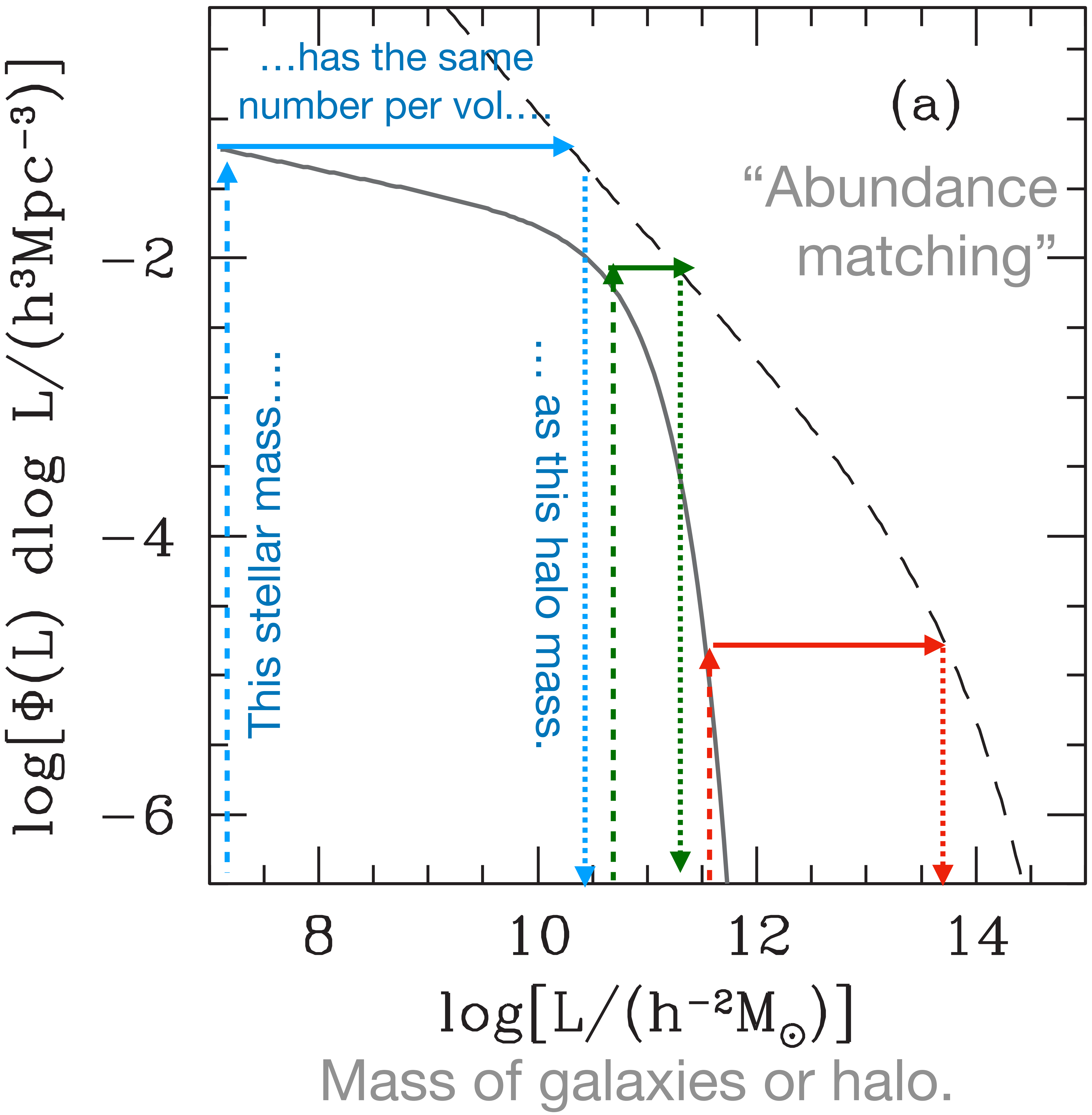
Number of galaxies or halos per unit volume

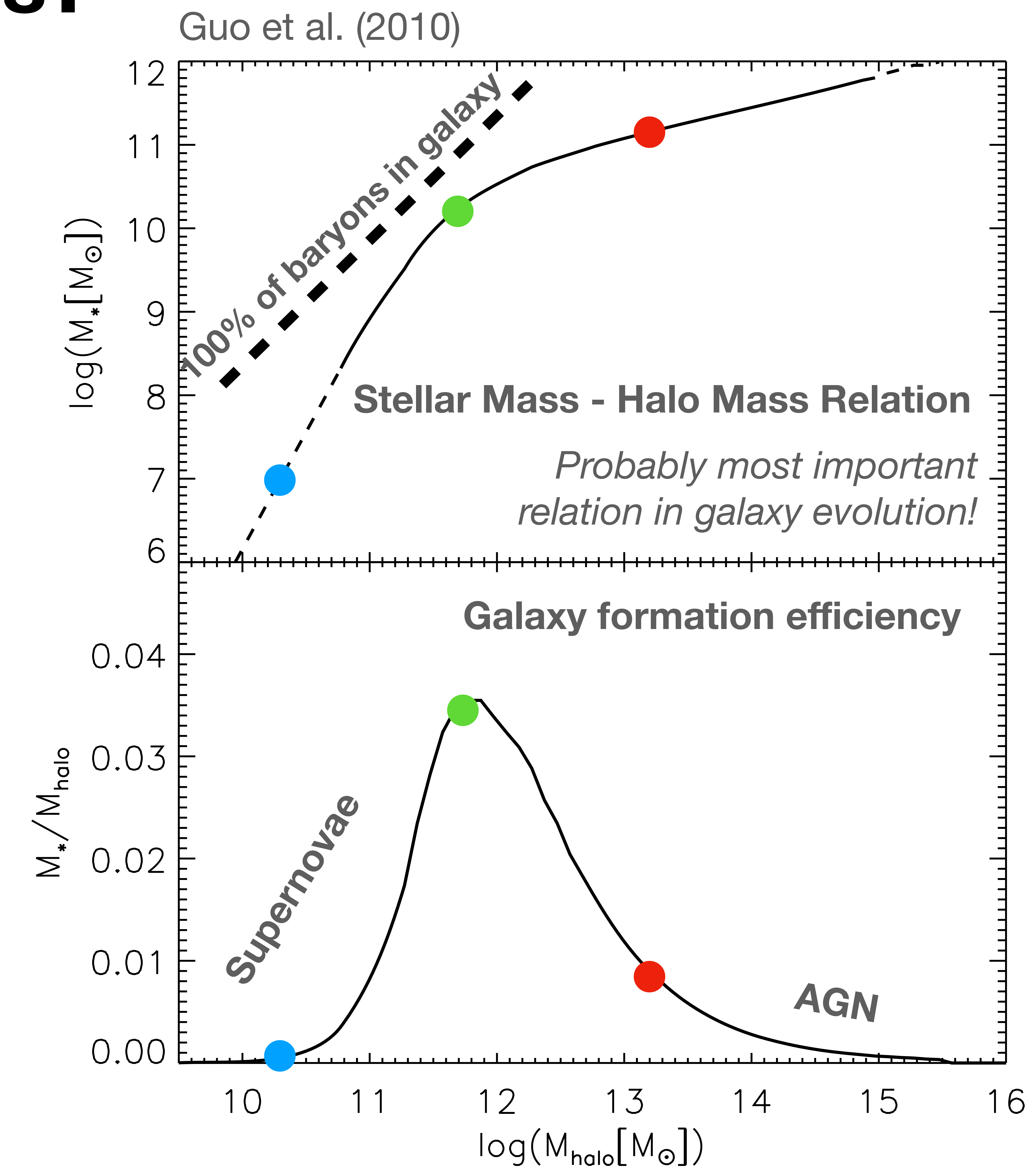
From Mo, van den Bosch & White (2010)



Mass of galaxies or halo.

Which galaxies live in which halos?

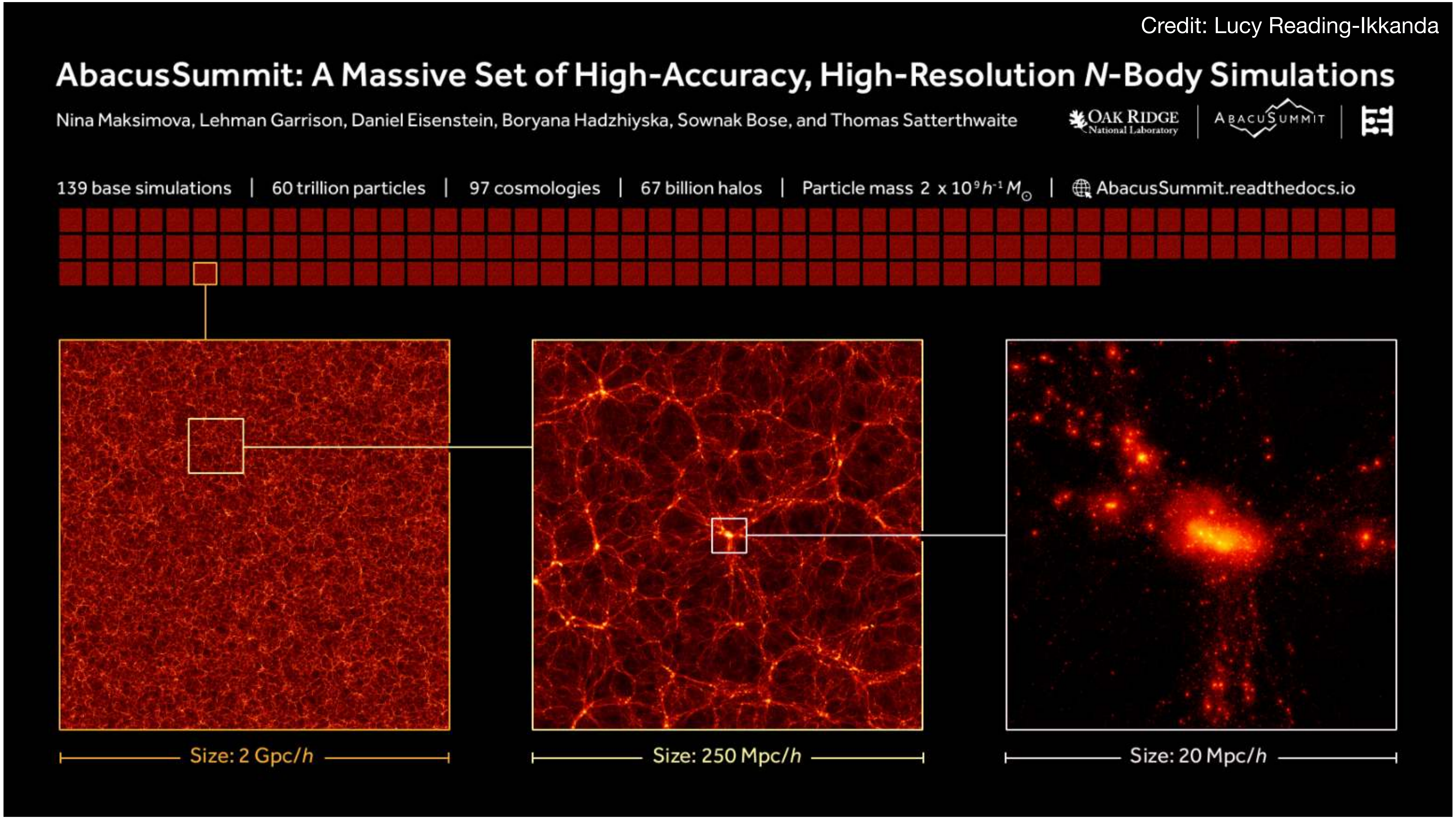




See also: https://www.cosmosim.org/

N-Body simulations

https://abacussummit.readthedocs.io/



The cosmological simulator's toolkit

These are just examples, many other alternatives available!

Basic cosmological calculatuions	**astropy.cosmology**	https://docs.astropy.org/en/stable/cosmology/index.html
Making density power spectra ("Boltzmann codes")	**CAMB** **CLASS**	https://camb.readthedocs.io/en/latest/ https://lesgourg.github.io/class_public/class.html
Turning power spectra into N-body initial conditions	**MUSIC**	https://www-n.oca.eu/ohahn/MUSIC/
Running cosmological N-Body models and building lightcones	**GADGET 4**	https://wwwmpa.mpa-garching.mpg.de/gadget4/
Finding dark matter halos in N-body simulations and making merger trees	**SUBFIND / SUBFIND-HBT** **ROCKSTAR** **AHF**	(built in to Gadget-4) https://github.com/yt-project/rockstar http://popia.ft.uam.es/AHF/
Analysing N-Body simulations	**PyNBody** **NBodyKit**	https://pynbody.github.io/pynbody/ [although often DIY] https://nbodykit.readthedocs.io/en/latest/index.html
Halo growth / Press-Schechter	**Parkinson, Cole & Helly (2008)**	https://astro.dur.ac.uk/~cole/merger_trees/
Empirical galaxy-halo models	**UniverseMachine**	https://bitbucket.org/pbehroozi/universemachine/src/main/
Halos / HOD	**HaloTools**	https://halotools.readthedocs.io/

Structure formation: summary

- “Astrophysical” cosmology: quantifying the evolution of cosmic structure.
- **Primordial perturbations → plasma era → cosmic web → galaxy formation.**
- Measurements of the cosmological parameters are approaching $\sim 1\,\%$ from CMB and redshift surveys; **galaxy formation** (assuming $\sim \Lambda\mathrm{CDM}$) is *just about* a **solved problem**, to the extent required for the use of galaxies as cosmological tracers.
- The most important factors in understanding galaxy evolution are:
  - *The evolution of the dark matter halo mass function;*
  - *The tight (but not linear) relationship between galaxy mass and halo mass.*

Cosmology Basics

Structure Formation

Recent Developments

(In “late-universe”, astrophysical cosmology)

The Dark Energy Spectroscopic Instrument

- ★ 4m telescope
- ★ 5000 fibers
- ★ Optical/NIR
- ★ 100,000 spectra/night

- ★ International consortium, led by LBNL
- ★ In Taiwan: NTU, NTHU

www.desi.lbl.gov

Precise measurements of the **baryon acoustic oscillation scale** at different redshifts.

The Baryon Acoustic Oscillations

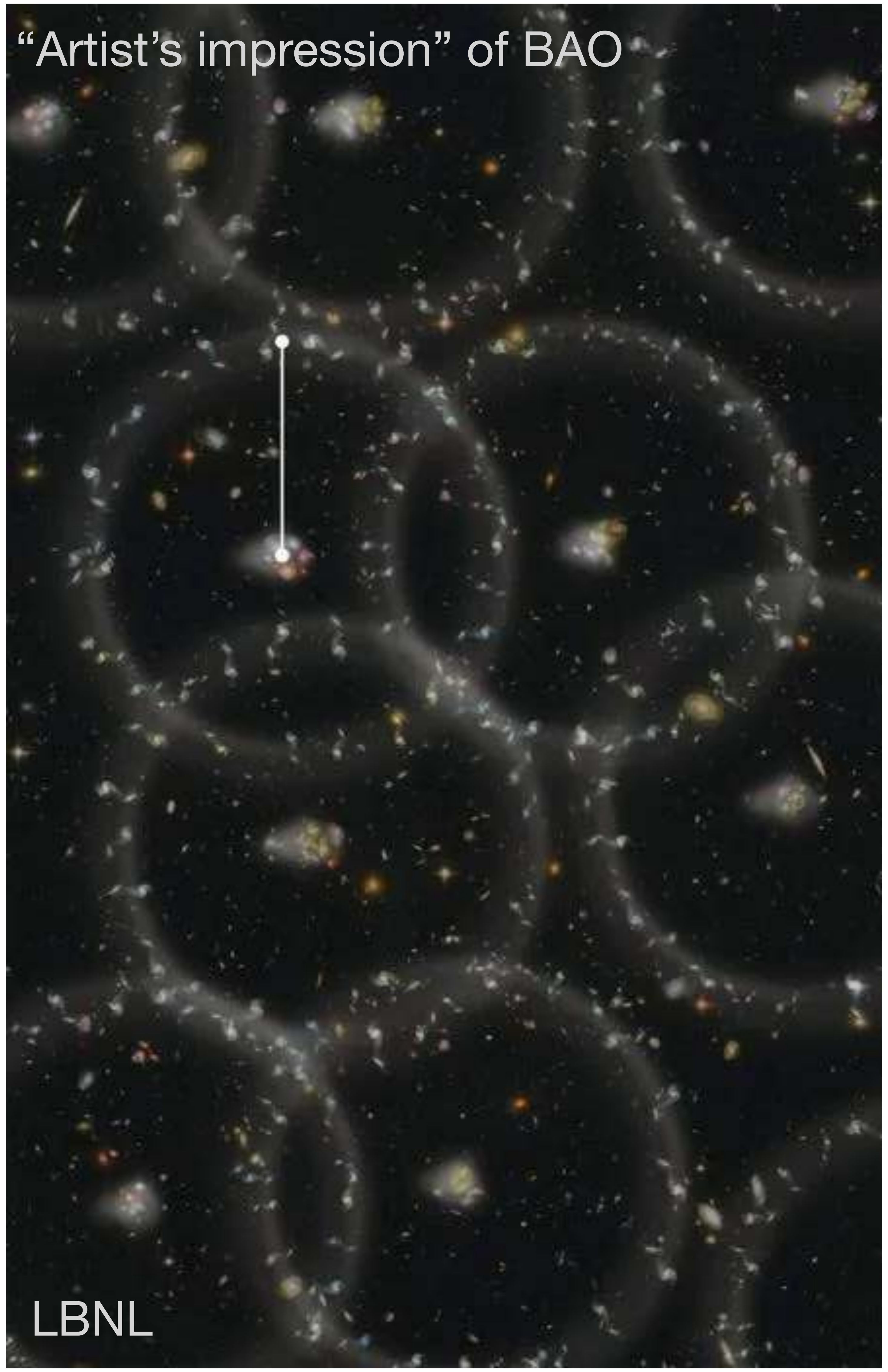
The scale of the sound horizon at the time of decoupling is imprinted on the correlation function of matter (halos and galaxies) as well as radiation (CMB).

In principle, we can measure the matter correlation function at any redshift.

At all redshifts, we expect to find an excess number of galaxy pairs with separations on the scale of the acoustic peak.

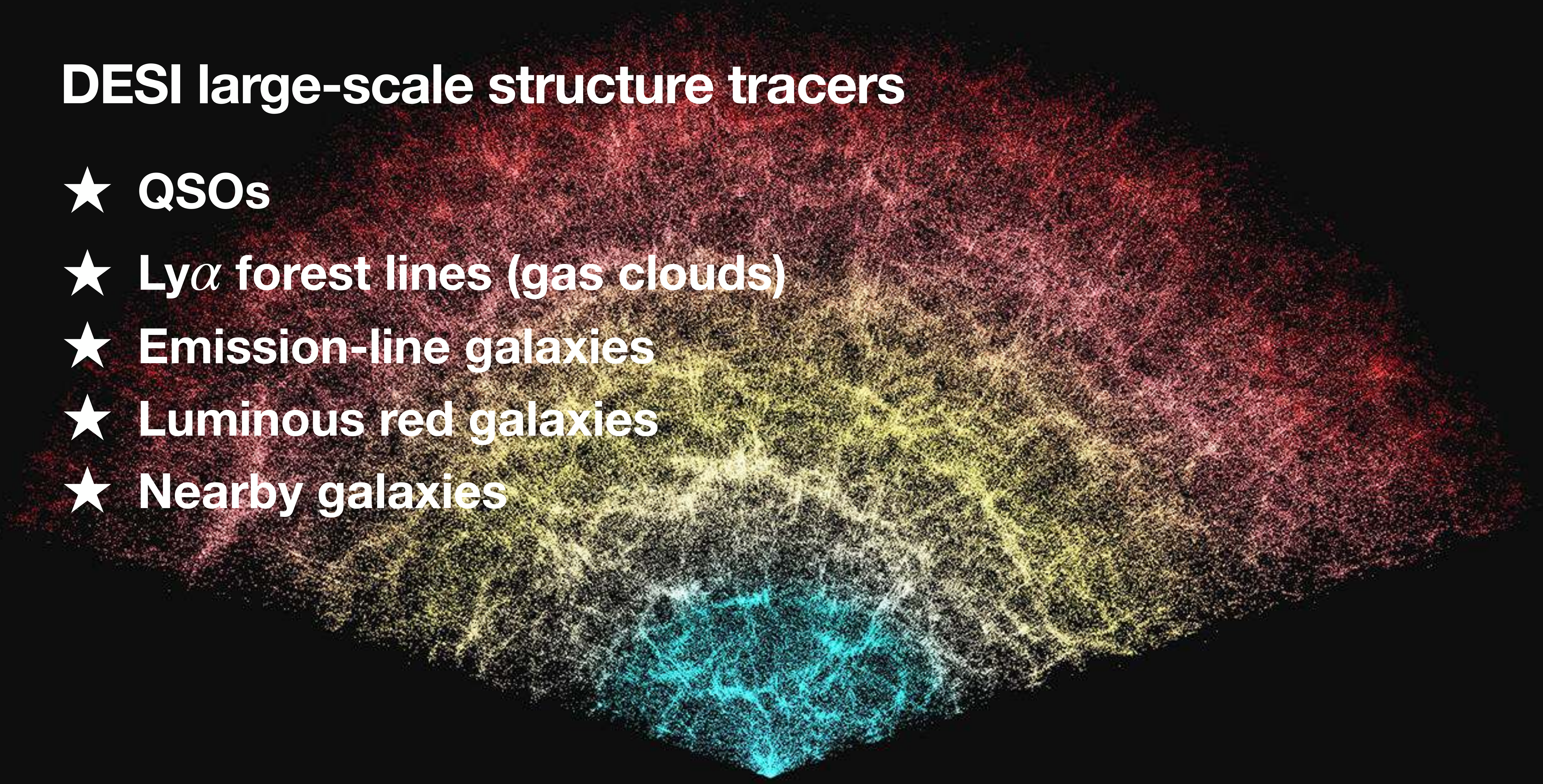
This BAO scale is a standard ruler. We can use it measure the angular diameter distance to any given redshift, and also infer $H(z)$.

The BAO is a weak, statistical signal — the more volume and more redshifts, the better!



DESI large-scale structure tracers

- ★ QSOs
- ★ Lyα forest lines (gas clouds)
- ★ Emission-line galaxies
- ★ Luminous red galaxies
- ★ Nearby galaxies



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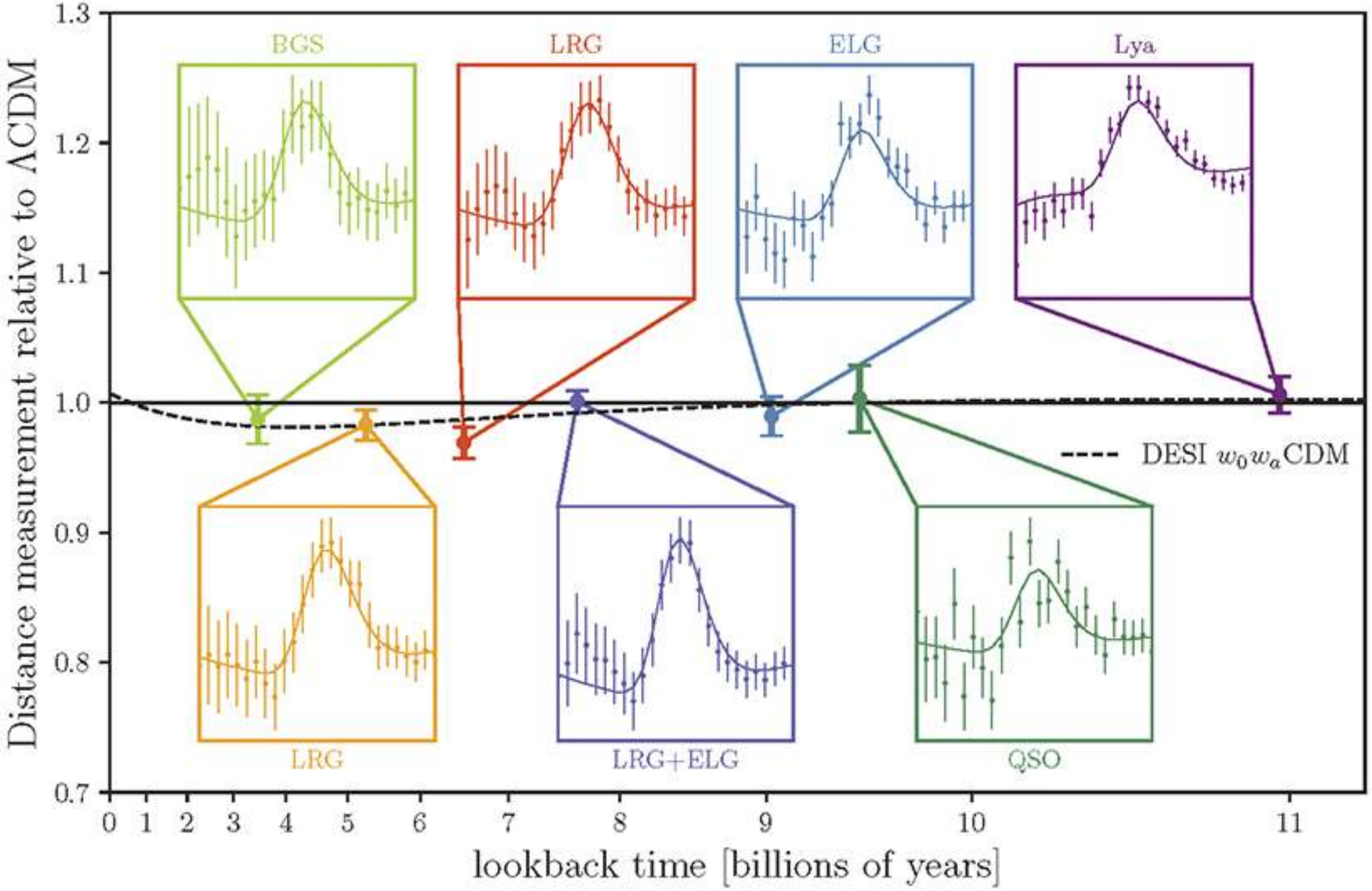
Baryon Acoustic Oscillations in DESI (first data, April 2024)

https://data.desi.lbl.gov/doc/papers/



5.7 million redshifts
~3x SDSS

DESI Collaboration et al. (2024) astro-ph/2404.03002

DESI 2024 VI: Cosmological Constraints from the measurements of Baryon Acoustic Oscillations

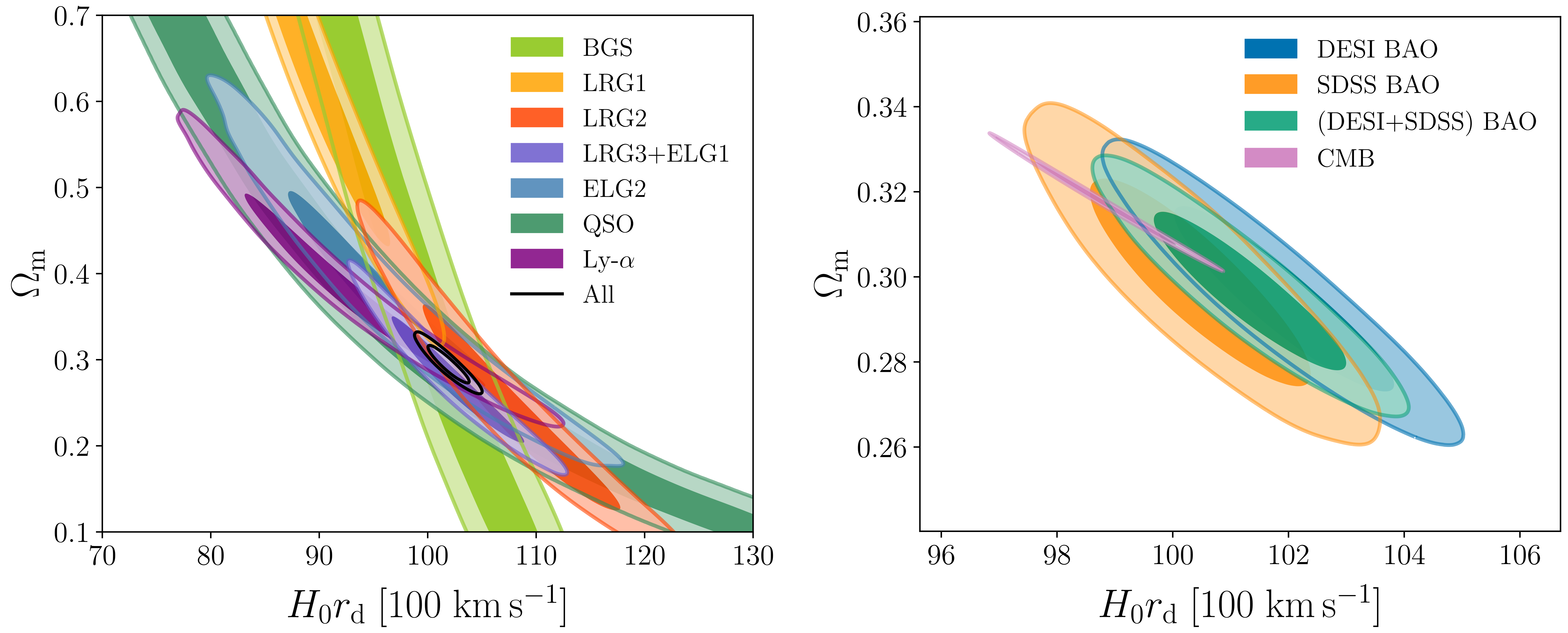
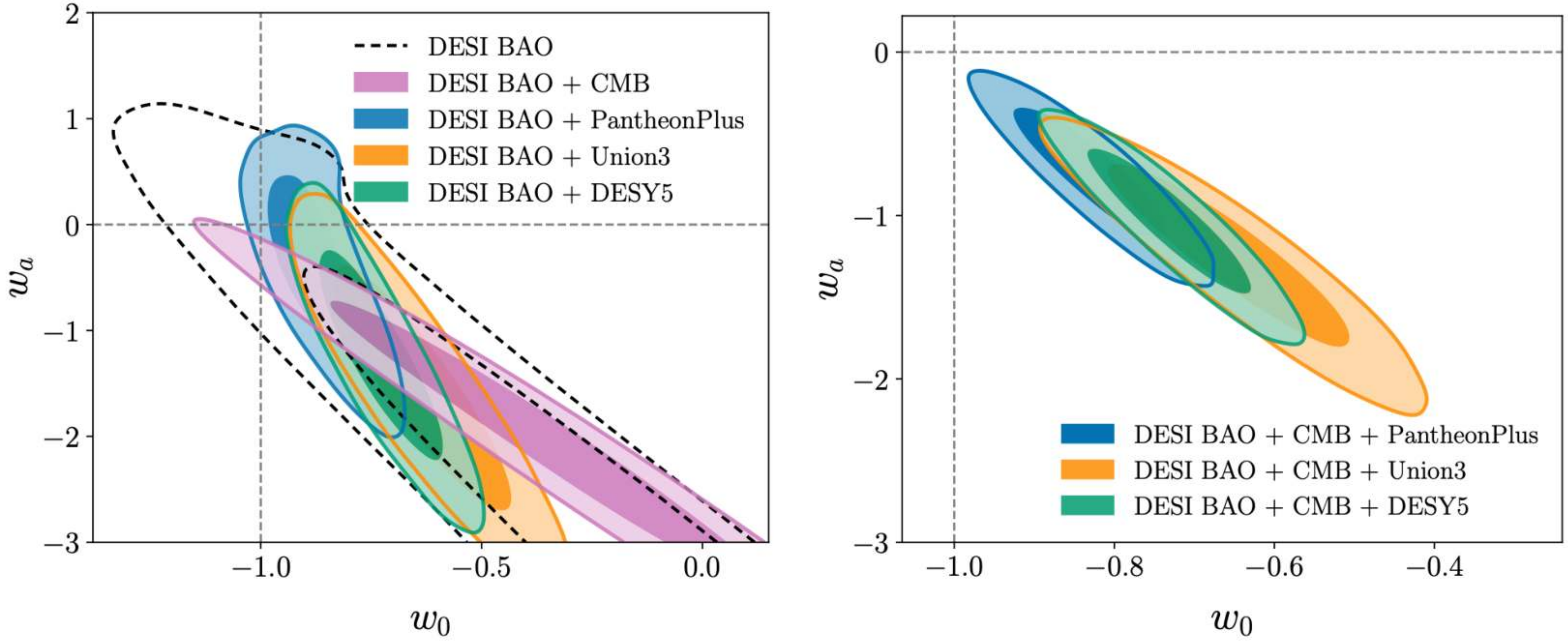


Figure 2. *Left panel:* 68% and 95% credible-interval contours for parameters Ω_m and $r_d h$ obtained for a flat ΛCDM model from fits to BAO measurements from each DESI tracer type individually, as labeled. Results from all tracers are consistent with each other and the change in the degeneracy directions arises from the different effective redshifts of the samples. *Right panel:* the corresponding results in flat ΛCDM for fits to BAO results from all DESI redshift bins (blue), the final SDSS results from [139] (orange), and the combination of these two as described in the text (green). The corresponding result from the CMB (including CMB lensing) is shown in pink.

Evolving Dark Energy

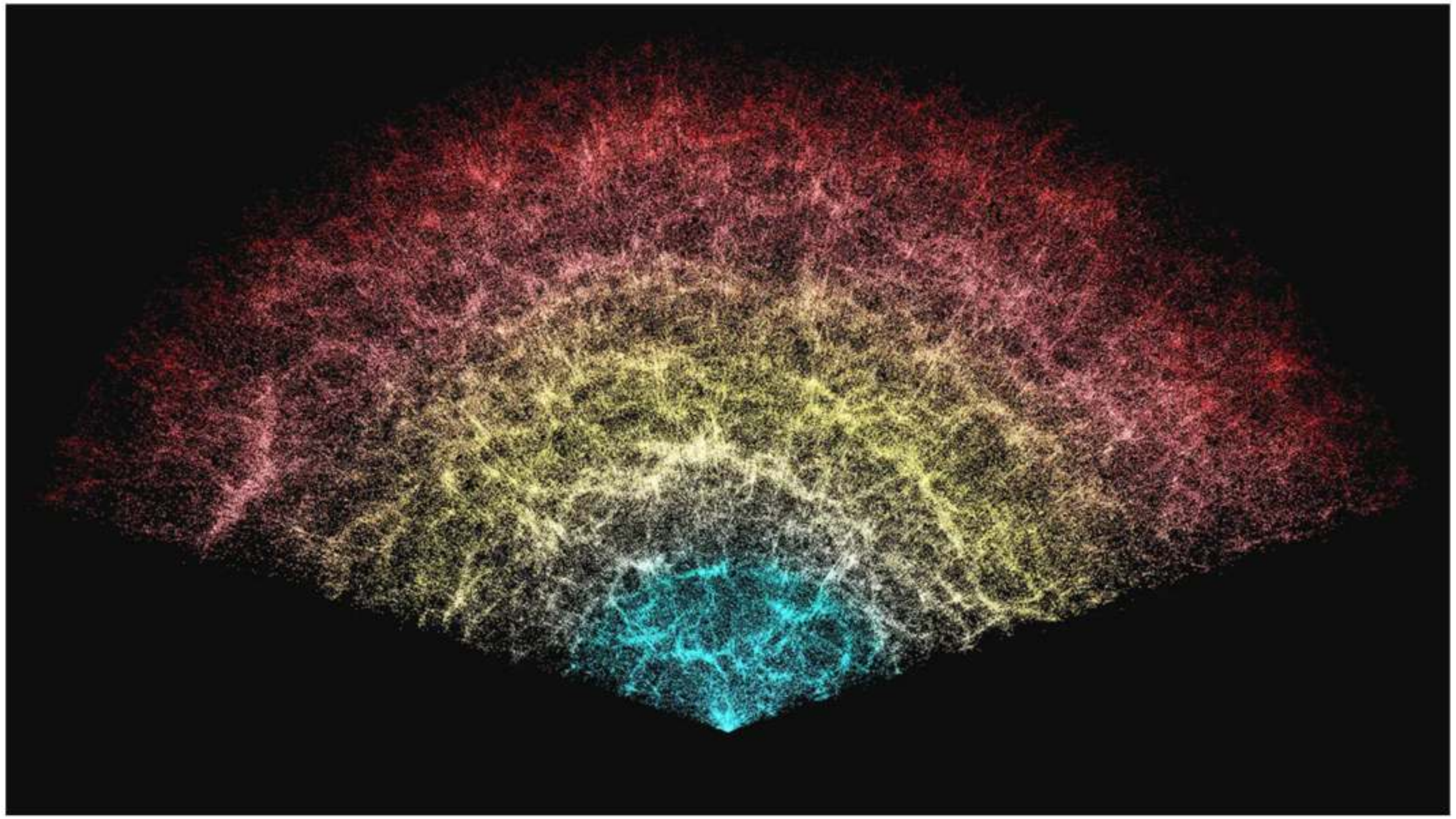


Tentatively, DESI-Y1 adds to weak evidence from other probes favouring DE that had a somewhat more negative EoS in the past.

Science and technology | Dark secrets

The dominant model of the universe is creaking

Dark energy could break it apart



PHOTOGRAPH: DESI COLLABORATION/NOIRLAB/NSF/AURA/R. PROCTOR

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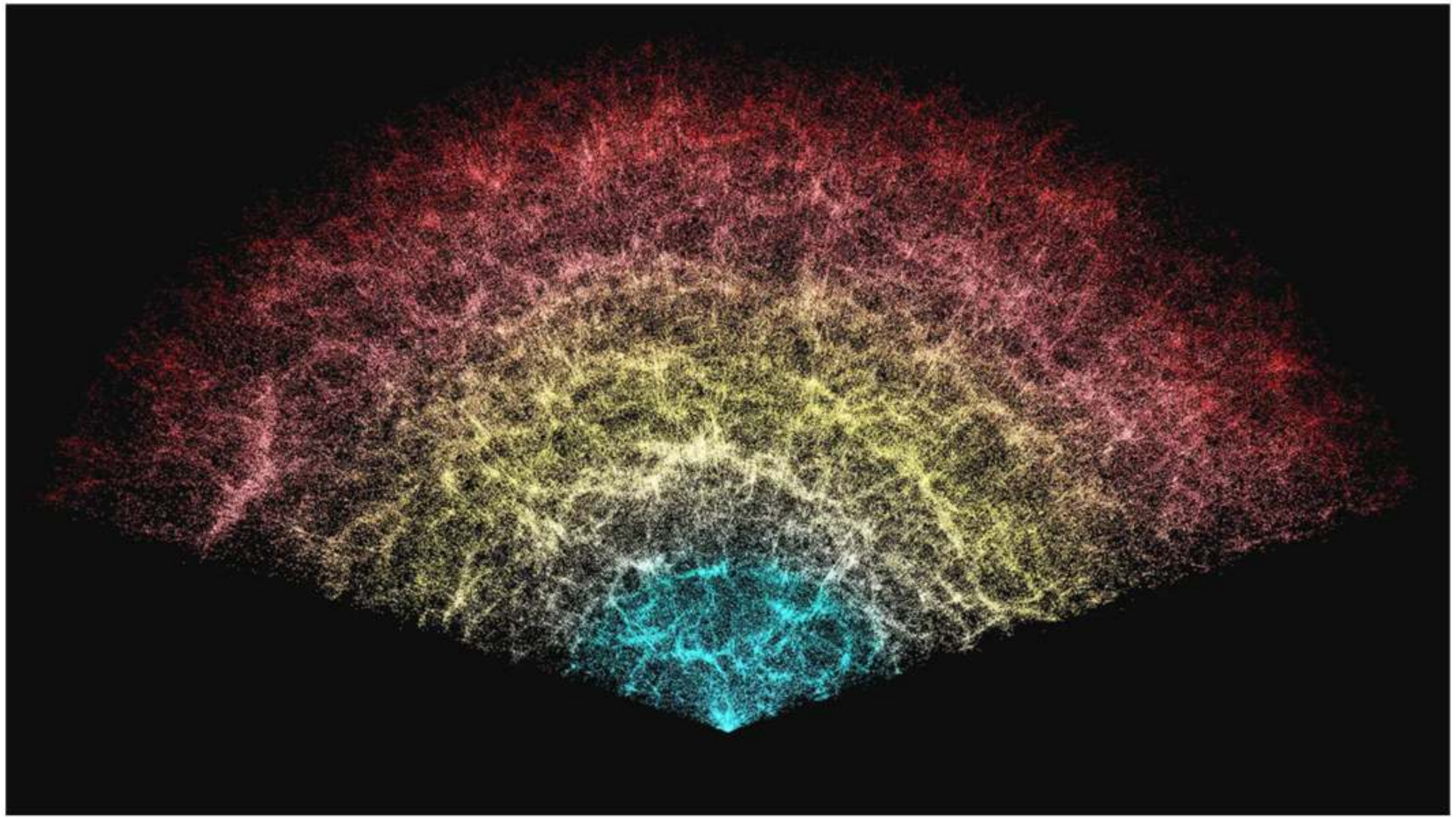
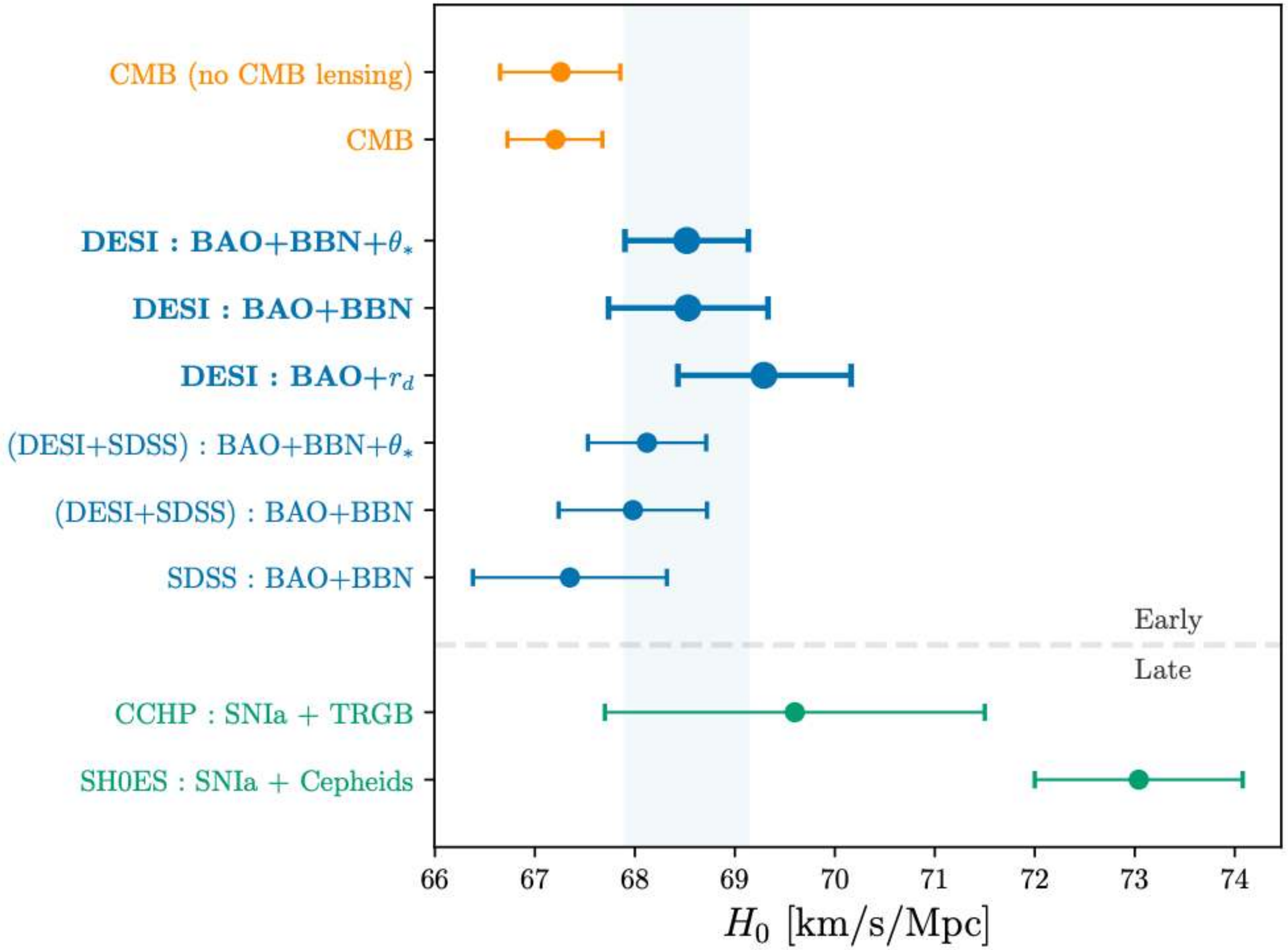


PHOTOGRAPH: DESI COLLABORATION/NOIRLAB/NSF/AURA/R. PROCTOR

H_0 Tension?

- Early-universe (CMB, **DESI**) measurements of H_0 favour $67 - 69\,\mathrm{km\,s^{-1}}$ but late-universe measurements (e.g. supernovae) favour $70 - 75\,\mathrm{km\,s^{-1}}$; a $\sim 5\sigma$ discrepancy.



DESI Collaboration et al. (2024)
astro-ph/2404.03002

H_0 Tension?

[Kamionkowski & Riess (2023) Ann. Rev. Nucl. Part. Sci, 73:153-180](#)

- No obvious sign (yet) that this is due to underestimated errors/systematics. Plenty of debates and theories!
- Previous problems of this kind have been "fixed" by postulating inflation and dark energy.
- An early-time fix involves reducing the sound horizon before recombination with "early" dark energy, or tweaks to pre-CMB photon/baryon physics.
- Late-time fixes are more controversial (for a review see e.g. [Di Valentino et al. 2021](#) — there are 100s of papers on this subject every year!)
- (Note also not-directly-related-but-somewhat-similar "S_8 tension" in CMB-predicted vs. observed growth of structure.)

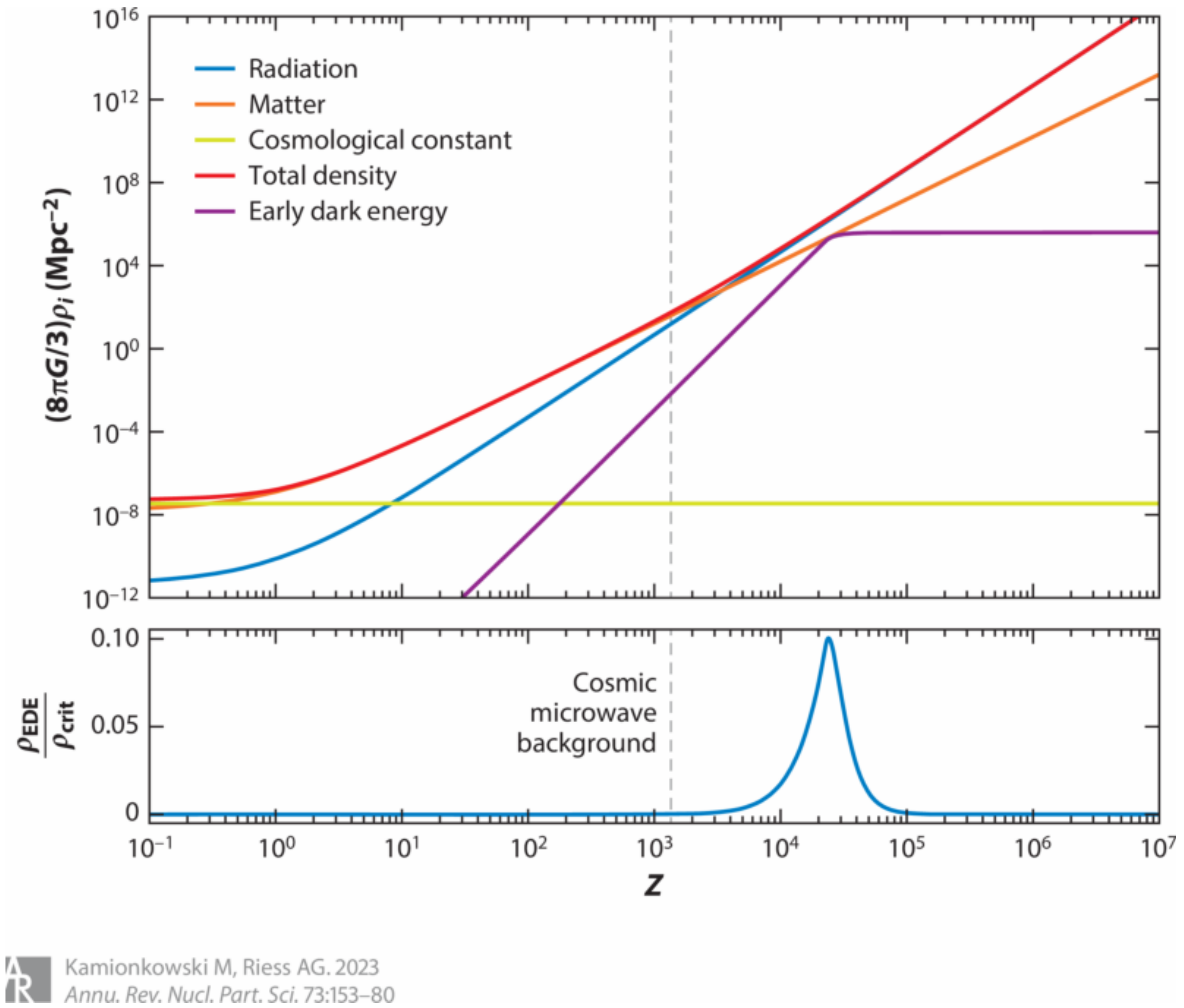


Figure 7

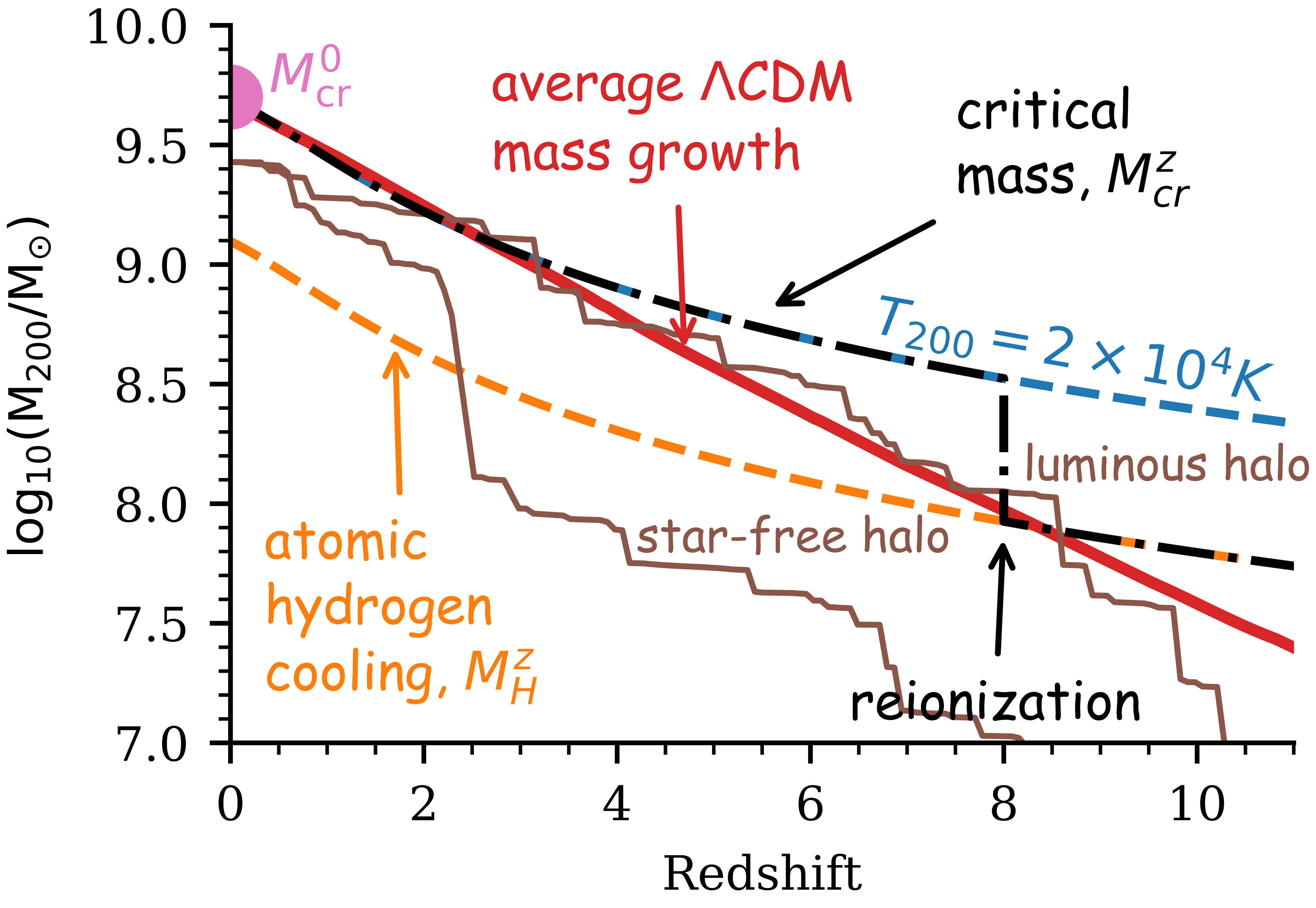
The evolution of the energy densities of radiation, nonrelativistic matter (baryons and cold dark matter, and the cosmological constant as a function of redshift (so time increases to the left, with the Big Bang far off to the right and today off to the left.) Also shown is the energy density postulated for early dark energy (EDE). The bottom panel shows the fractional contribution of EDE to the total energy density. The EDE curves are schematic—the key point is that it contributes $\sim 10\%$ a bit before recombination but is otherwise dynamically unimportant. Figure courtesy T. Karwal.

Small-scale constraints on ΛCDM

- 10-20 years ago, there was a lot of discussion about "small-scale problems" with ΛCDM.
- There never really was a "missing satellites problem".
- However, we still don't know where exactly the cutoff in the matter power spectrum is, or how galaxy formation works at the lowest masses and earliest times.
- Small-scale galaxy formation and dynamics could still be our best hope to learn more about the nature of the dark matter (with astronomy):
    - Lensing
    - Stellar stream perturbations
    - Globular cluster formation
- Unfortunately we still don't understand the nuts and bolts of galaxy formation well enough to turn small scale observations into rigorous tests of cosmology.

Benitez-Llambay & Frenk (2020)

Schematic picture of the impact of cosmic reionization on galaxy formation



Little red dots?

Akins et al. (2024)

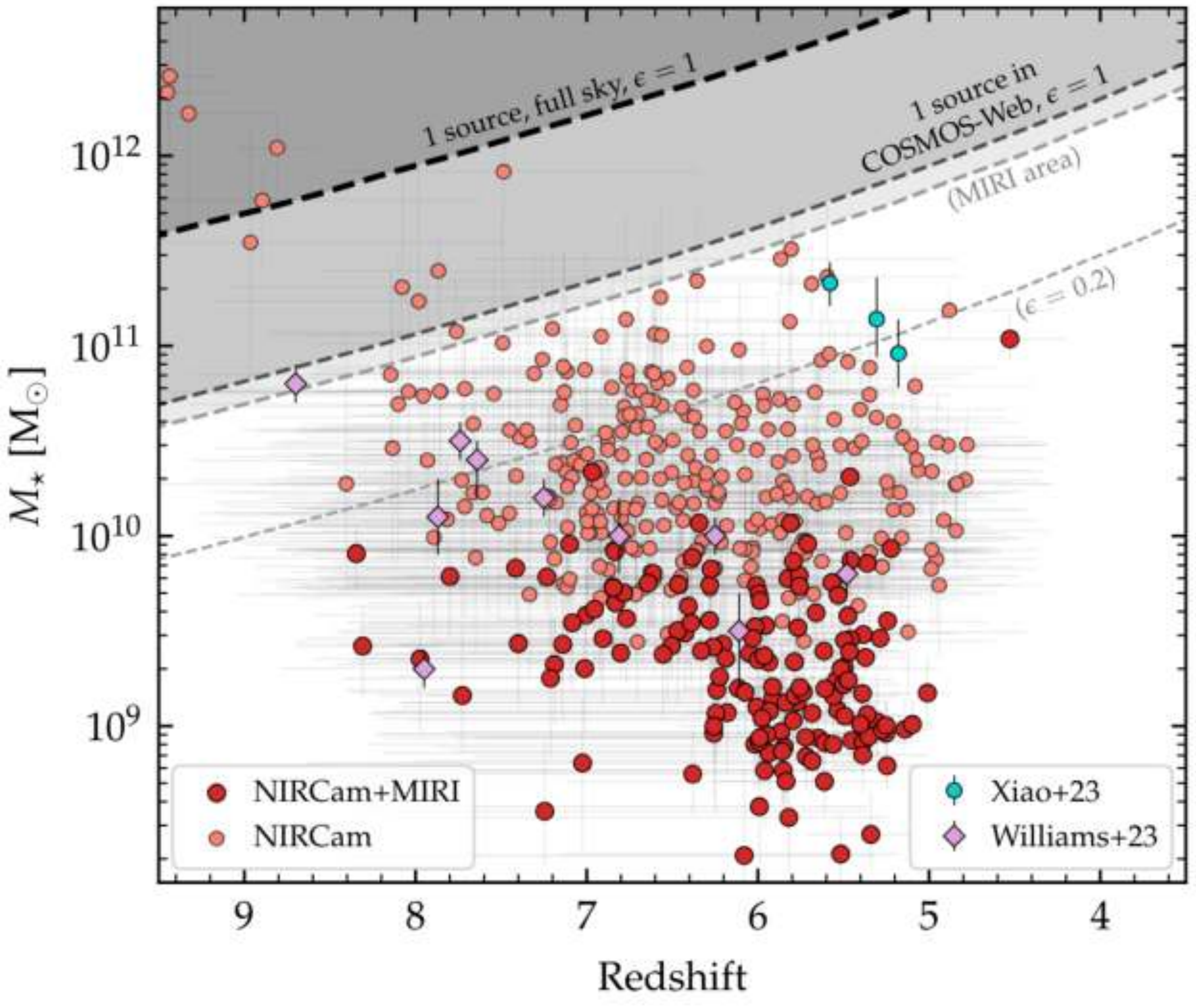
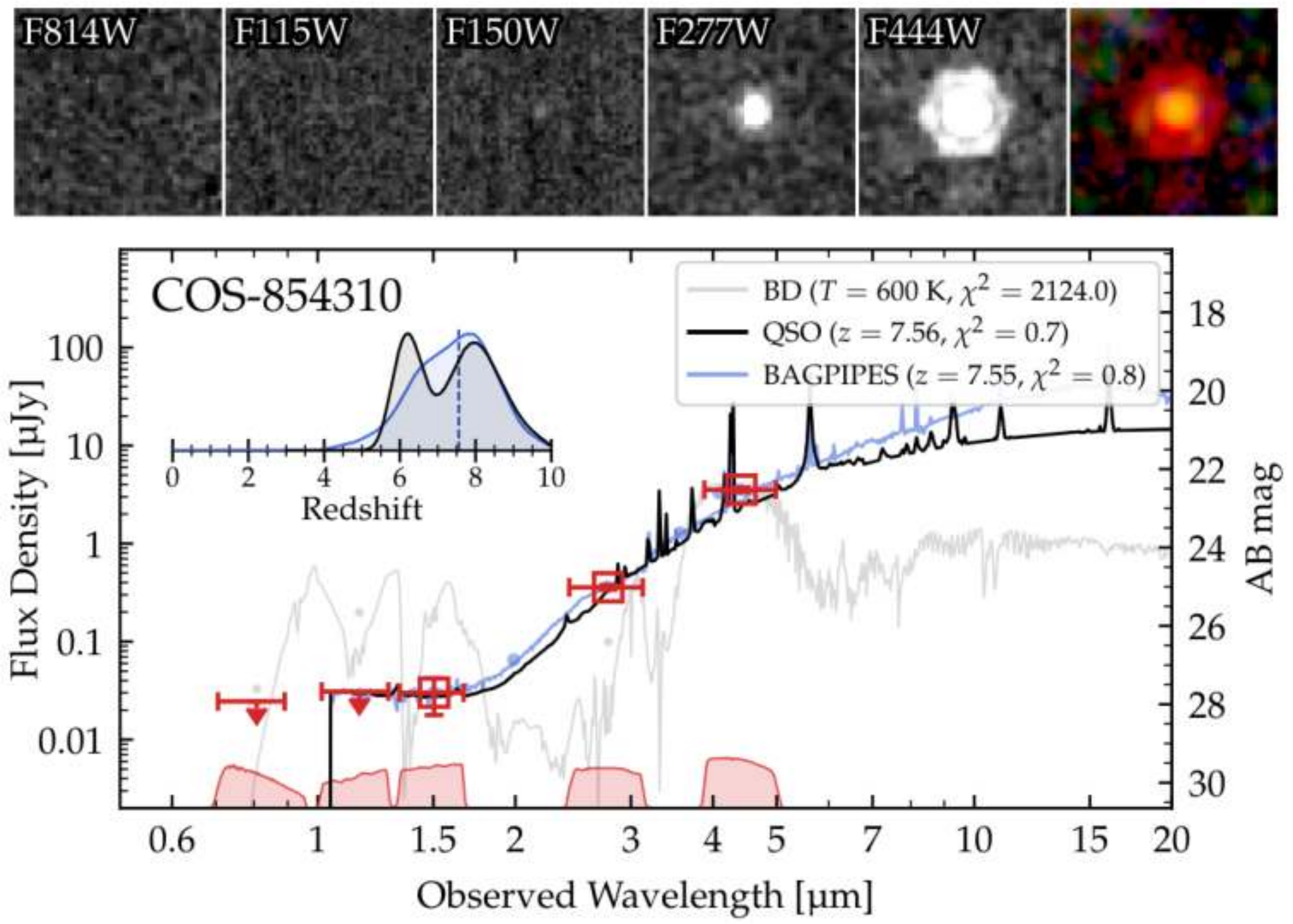


Figure 10. Stellar mass vs. redshift from galaxy SED fitting with bagpipes. The dashed lines indicate the maximum stellar mass we would expect to find in a given volume based on the halo mass function (assuming a global star-formation efficiency $\epsilon = 1$, or $\epsilon = 0.2$ for a more realistic assumption). We plot the stellar masses inferred for "little red dots" in JADES from Williams et al. (2023), as well as the three ultra-massive objects identified in Xiao et al. (2023).

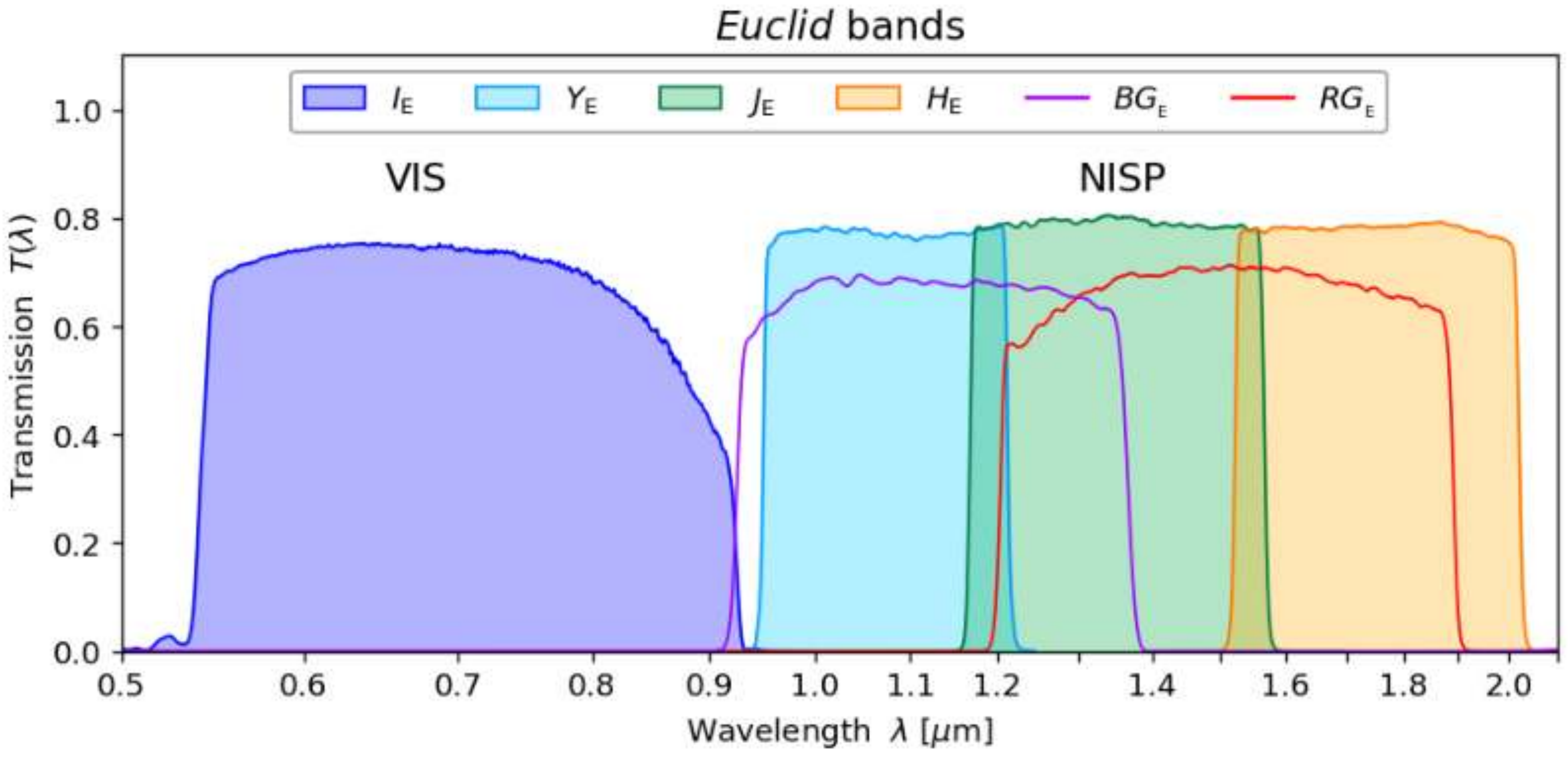
Akins et al. (2024)



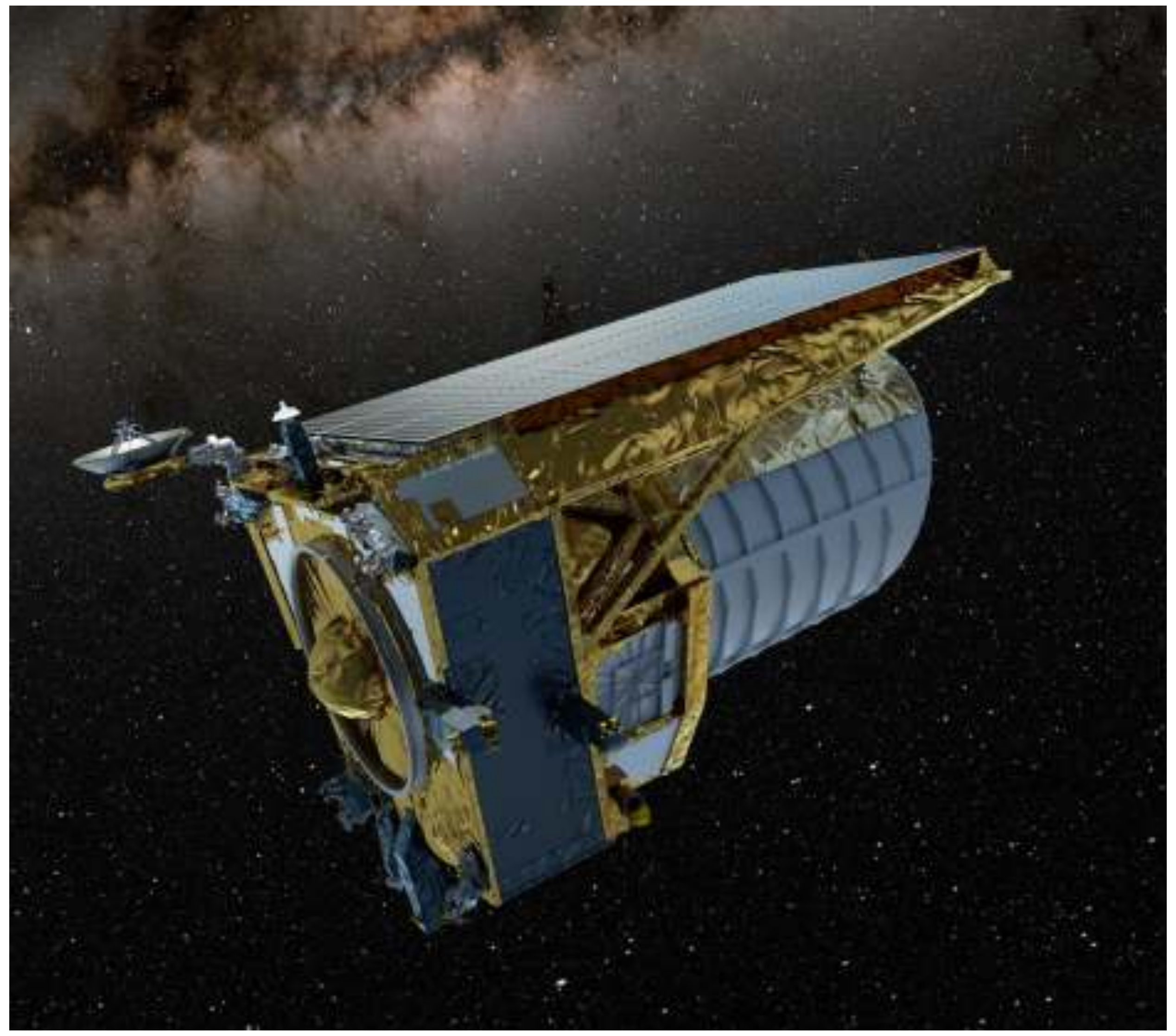
- JWST is opening up tests of galaxy formation at much higher redshift.
- In principle these could challenge models of structure formation — again, provided we can get past much greater uncertainty in models of galaxy evolution.

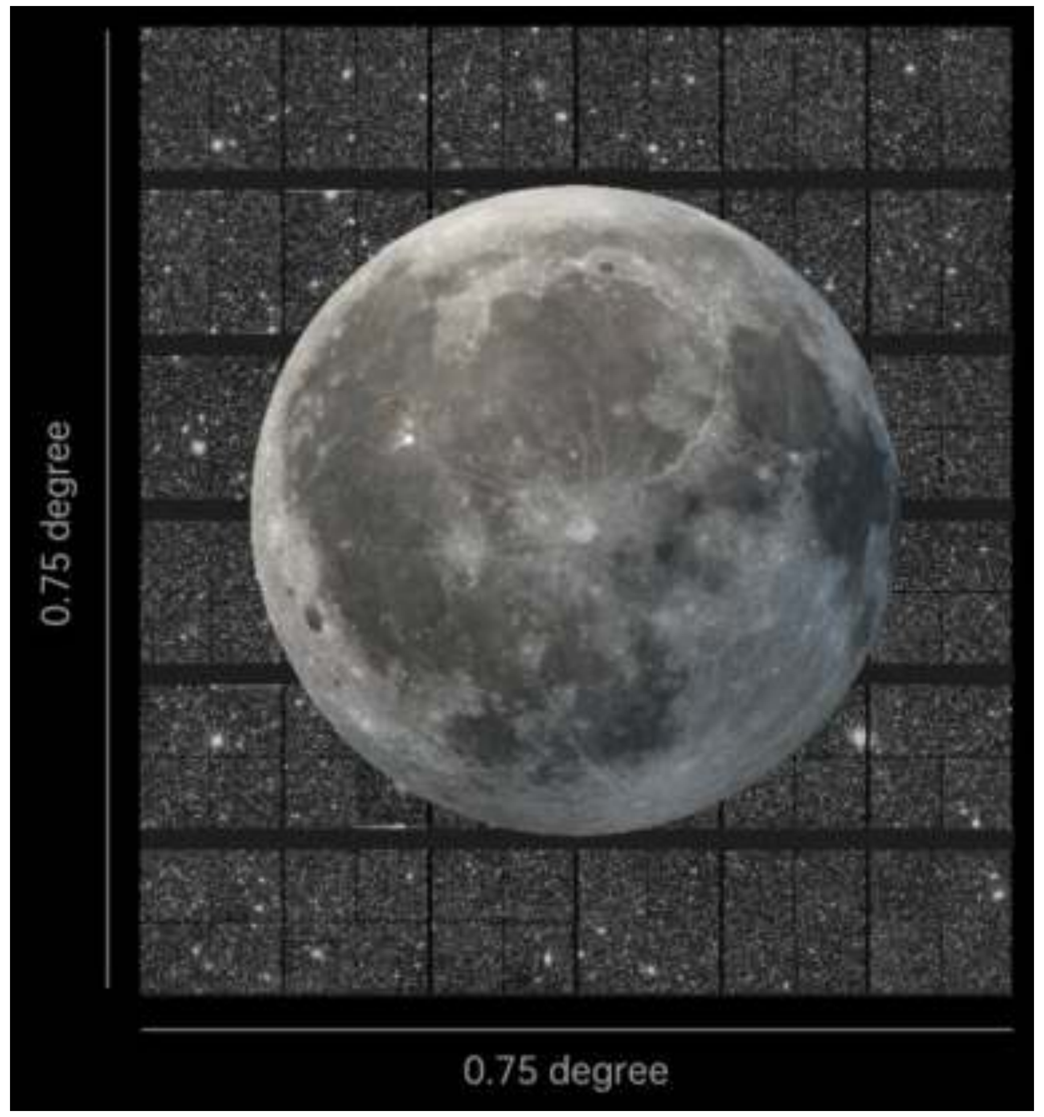
Euclid

- 15k sq. deg. imaging to $\sim 28 - 29\,\mathrm{mag\,arcsec}^{-2}$ (NIR/VIS) + $R \sim 400$ NIR spectroscopy (for Hα redshifts).
- Galaxy clustering and weak lensing.

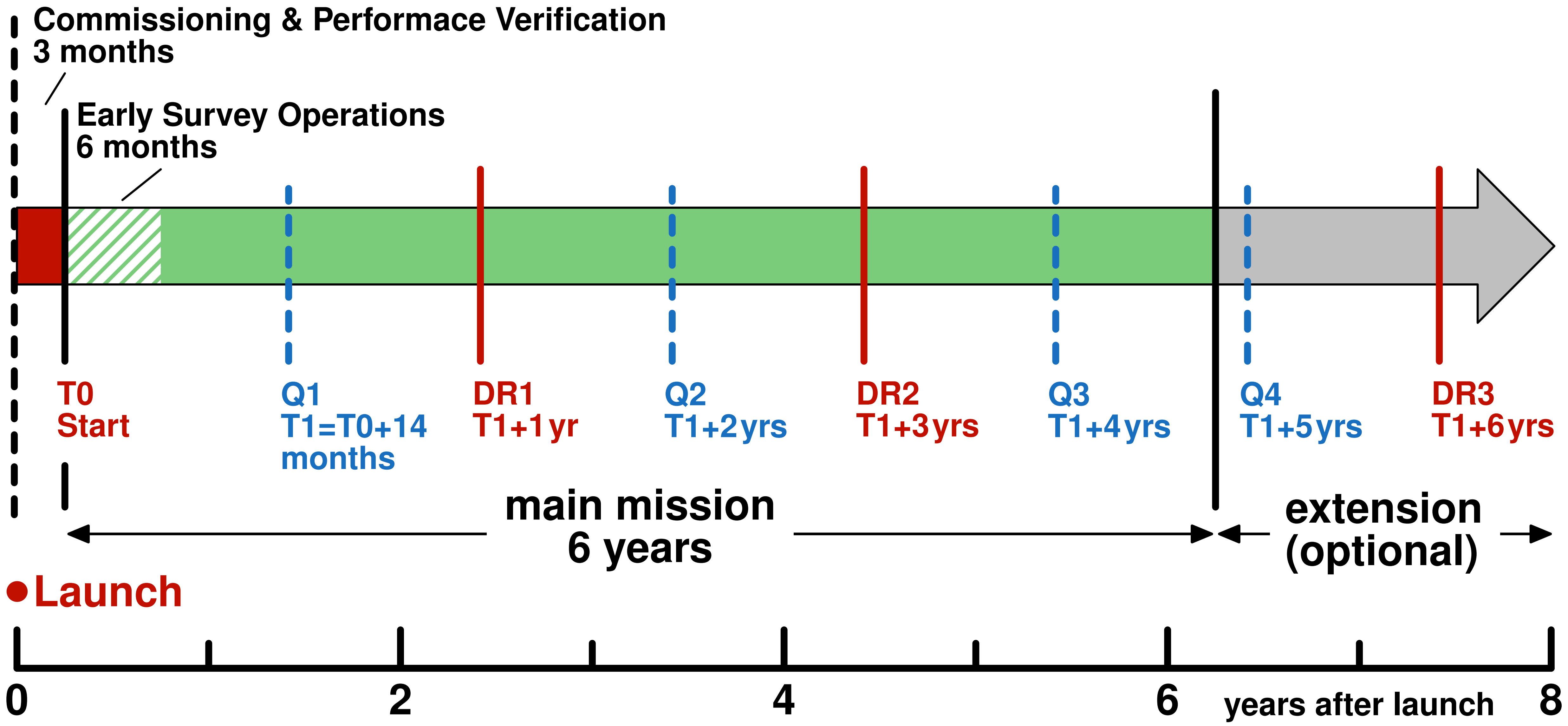


https://www.euclid-ec.org/science/overview/





https://www.euclid-ec.org/public/press-releases/first-science-results-and-exclusive-ero-data/

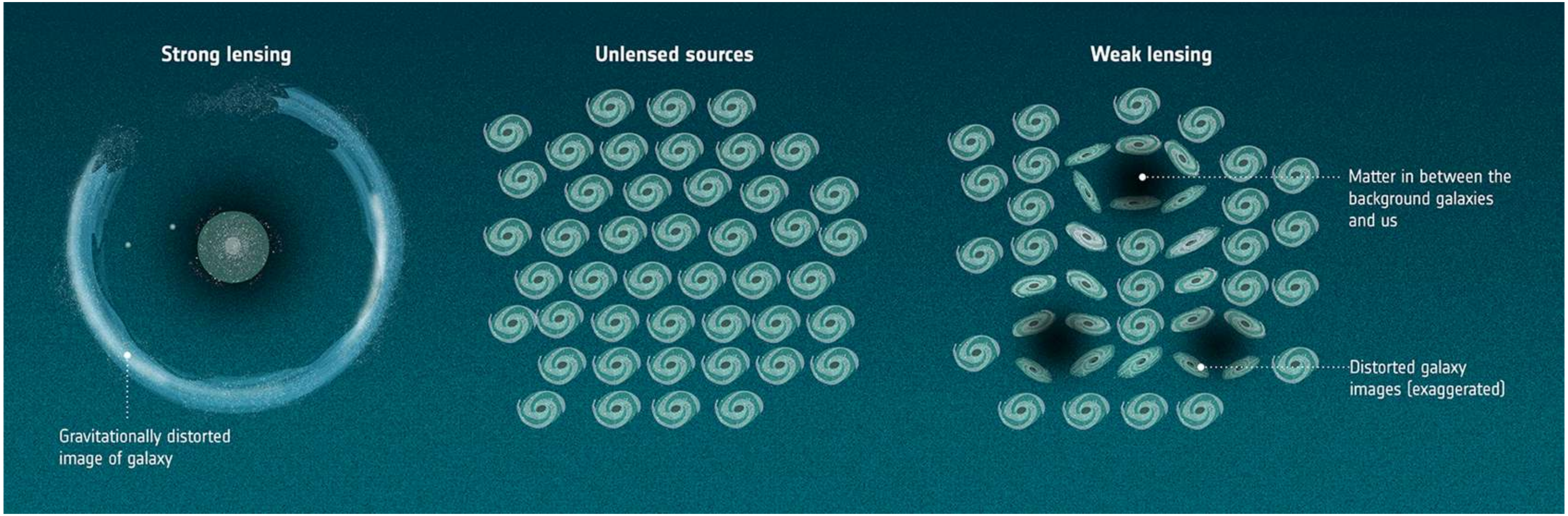


2025

Scaramella et al. (2019)

Euclid

- Weak mensing: measure H(z) from galaxy shapes + redshifts. Galaxies at z → mass → potential → distortions of galaxies at $z' > z$.
- Needs very accurate accounting of systematics from imaging, 'intrinsic alignments' etc.



https://www.euclid-ec.org/mapping-the-dark-universe-with-gravitational-weak-lensing/

Euclid

Spectacular HST-like wide-field images of nearby galaxies.

https://www.euclid-ec.org/public/press-releases/first-science-results-and-exclusive-ero-data/

Other hot topics in cosmology

- Big-Bang nucleosynthesis and cosmic abundances!
- Cluster cosmology! (**DESI**, Euclid, JWST, LSST, Simons Obs.)
- Reionization! HI intensity mapping! (SKA and others)
- The Lyα forest! (**DESI**)
- Neutrino masses (including **DESI**)!
- Primordial non-gaussianity (including **DESI**)!
- Primordial gravitational waves!
- Cosmic transients (high-z supernovae, radio/gamma-ray bursts)
- Alternative gravity!?

Summary

- The ΛCDM model makes lots of readily testable predictions and is extremely well constrained by observations.
- It is **enormously successful** as a scaffolding for predictive models of galaxy formation, based on the fundamental idea that **galaxies form in virialized dark matter halos**.
- ΛCDM is likely incomplete, and none of its key ingredients are explained from fundamental physical principles.
- The roadmap of cosmological observations involves measuring the **positions and velocities of galaxies** with ever-greater precision, and at ever-higher redshift.
- Modifications are only likely to affect our understanding of galaxy formation at **very early times** and on very **small scales**. Vice versa, observations at small scales/early times could uncover physics beyond ΛCDM!
- Effects are subtle; contributions to better understanding galaxy evolution are important for cosmology!

References and Further Reading

- Textbooks (basic / astrophysical)
  - **Liddle** *An Introduction to Modern Cosmology*, 3rd Edition (ISBN: 9781118502143)
  - **Ryden** https://doi.org/10.1017/9781316651087
  - **Huterer** https://doi.org/10.1017/9781009070232
  - **Mo, van den Bosch & White** https://doi.org/10.1017/CBO9780511807244
  - **Peacock** https://doi.org/10.1017/CBO9780511804533
  - **Peebles** *Principles of Physical Cosmology* (ISBN: 9780691209814) [classic]

- Textbooks (advanced / early universe)
  - **Weinberg** *Cosmology* (ISBN: 9780198526827) [classic]
  - **Baumann** https://doi.org/10.1017/9781108937092

- A few useful review articles:
  - Davis *"Cosmological constraints on dark energy",* https://arxiv.org/abs/1404.7266
  - Davis & Lineweaver "*Expanding Confusion: common misconceptions of cosmological horizons and the superluminal expansion of the Universe"* https://arxiv.org/abs/astro-ph/0310808
  - Lahav & Liddle, PDG Reviews *"Cosmological Parameters"* https://pdg.lbl.gov/2024/reviews/rpp2024-rev-cosmological-parameters.pdf
  - Weinberg & White, PDG Reviews, "Dark Energy": https://pdg.lbl.gov/2024/reviews/rpp2024-rev-dark-energy.pdf