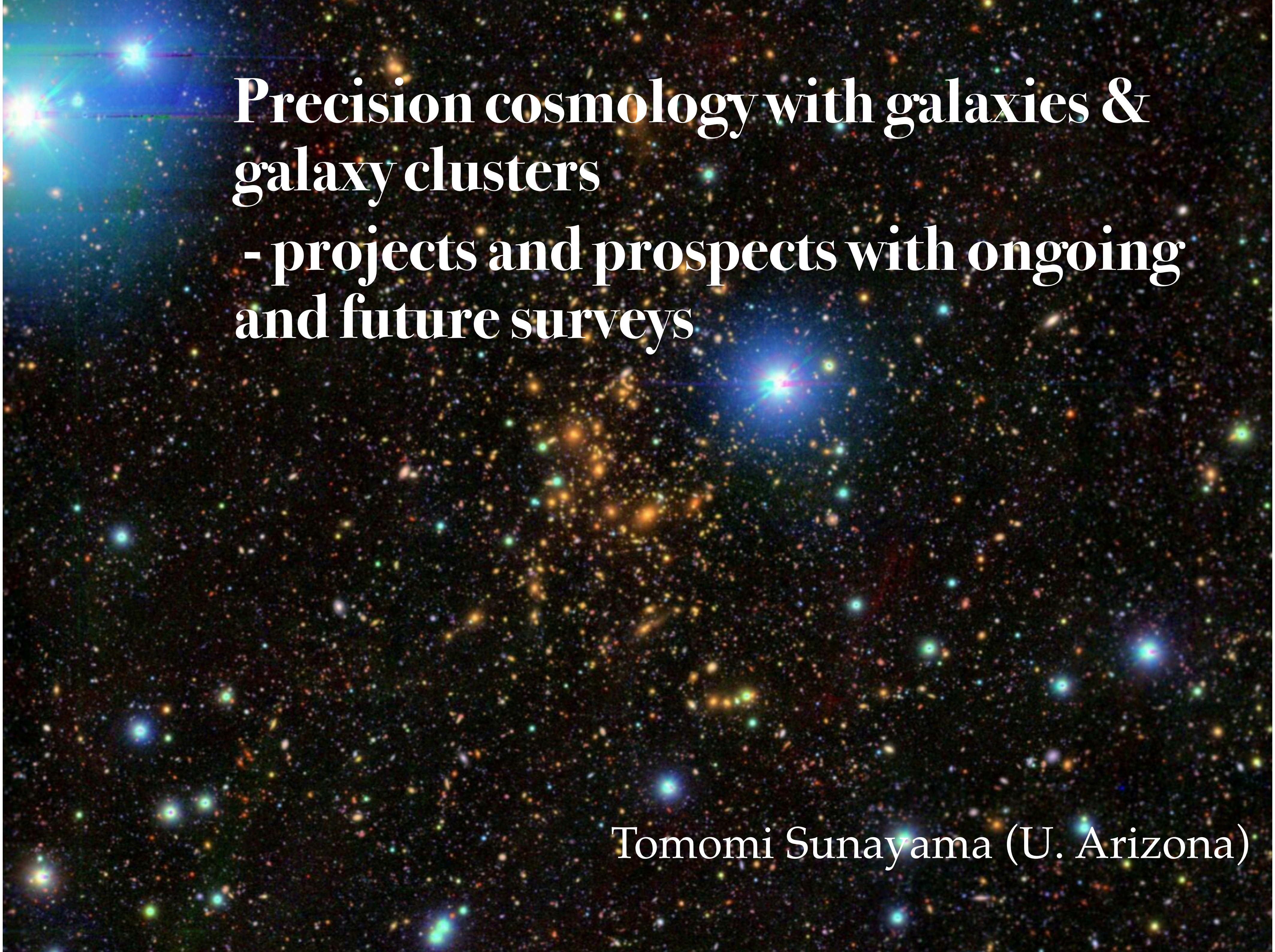


Precision cosmology with galaxies & galaxy clusters
- projects and prospects with ongoing and future surveys

Tomomi Sunayama (U. Arizona)

About me

Education and career path

Knox College
Major: Physics/Mathematics
Grew Scholar

Yale University
Physics
Advisor: Nikhil Padmanabhan

Kavli IPMU
Advisor: Masahiro Takada
- Leader of Subaru PFS Cosmology WG since 2019

JSPS/ACL Fellow
(Nagoya U./U.Arizona)
2020-present
Collaborators:
Elisabeth Krause
Hironao Miyatake
Eduardo Rozo

Spectroscopic Survey: BAO, RSD

Subaru PFS: clustering, forecast

Subaru HSC: Clusters/LSST, Roman

IL (USA)

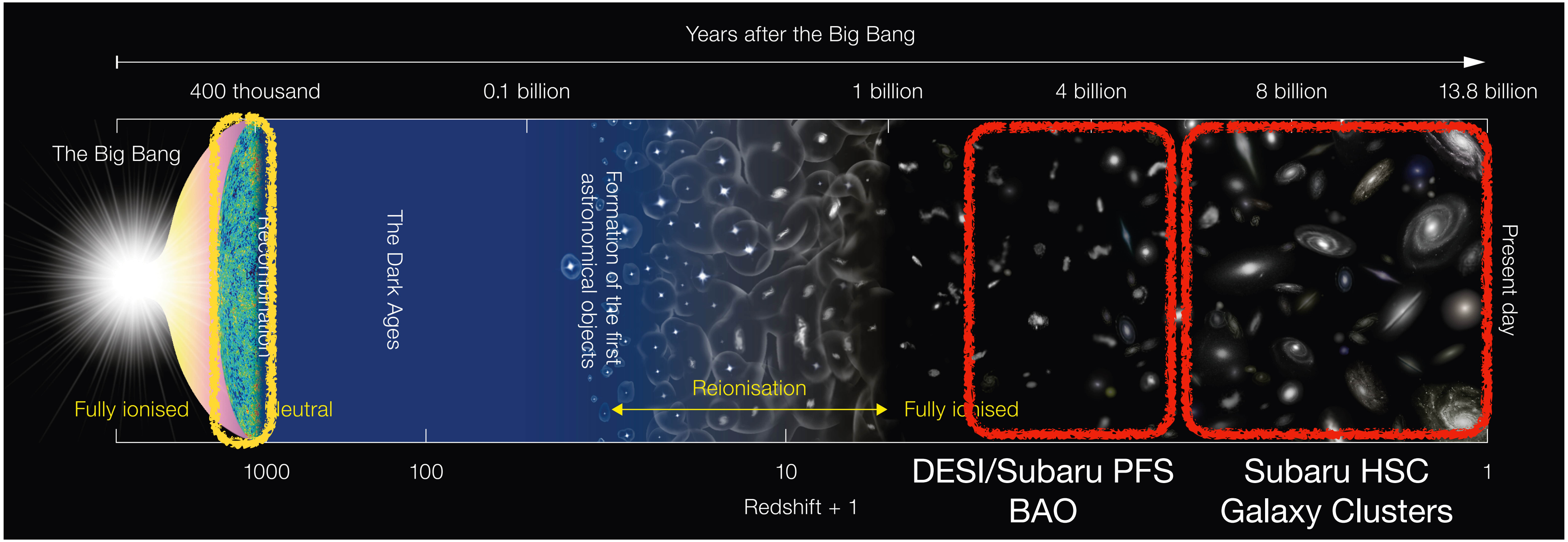
CT (USA)

Chiba (Japan)

AZ (USA)

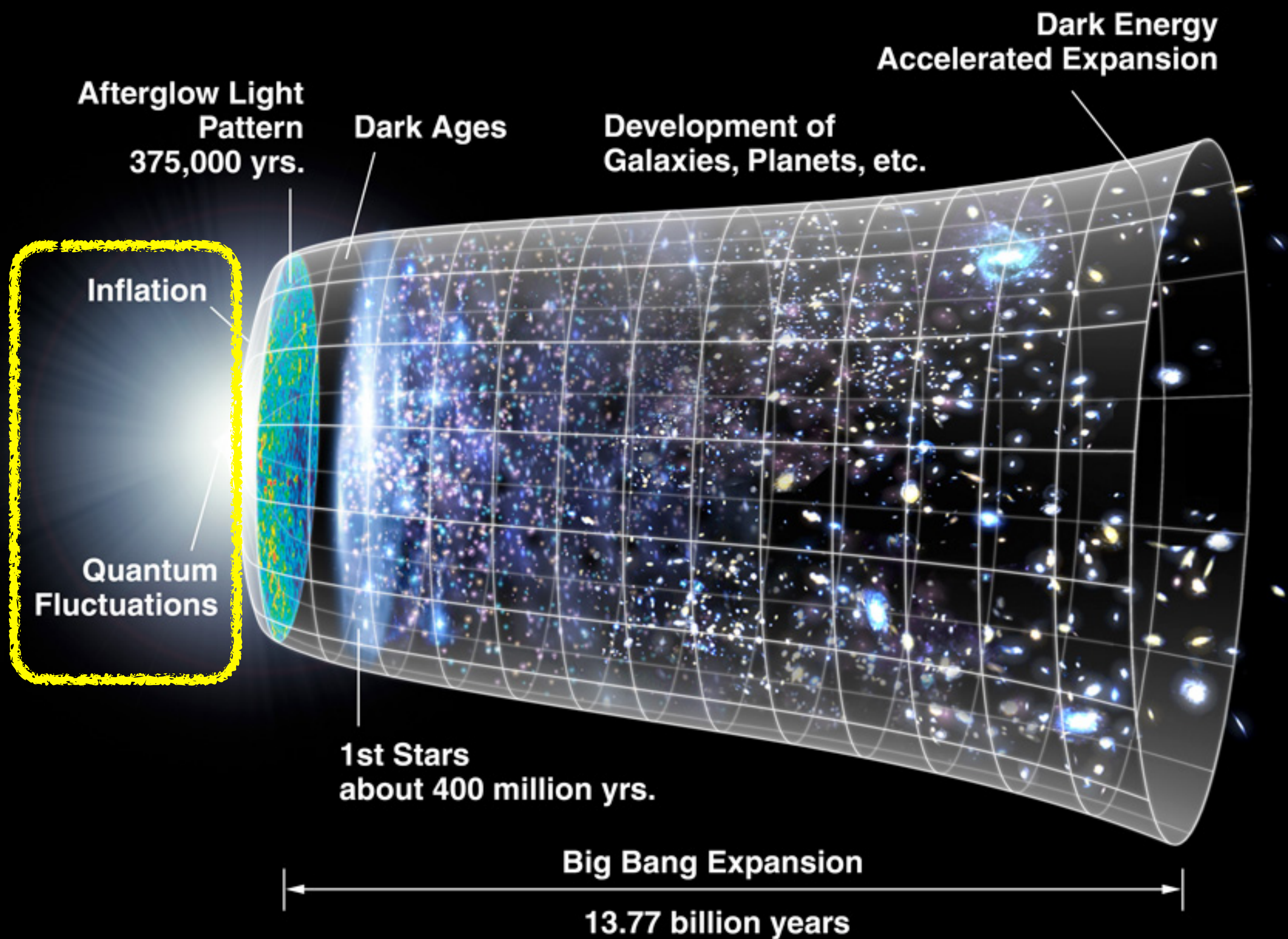
Nagoya (Japan)

Do we understand our Universe end-to-end?



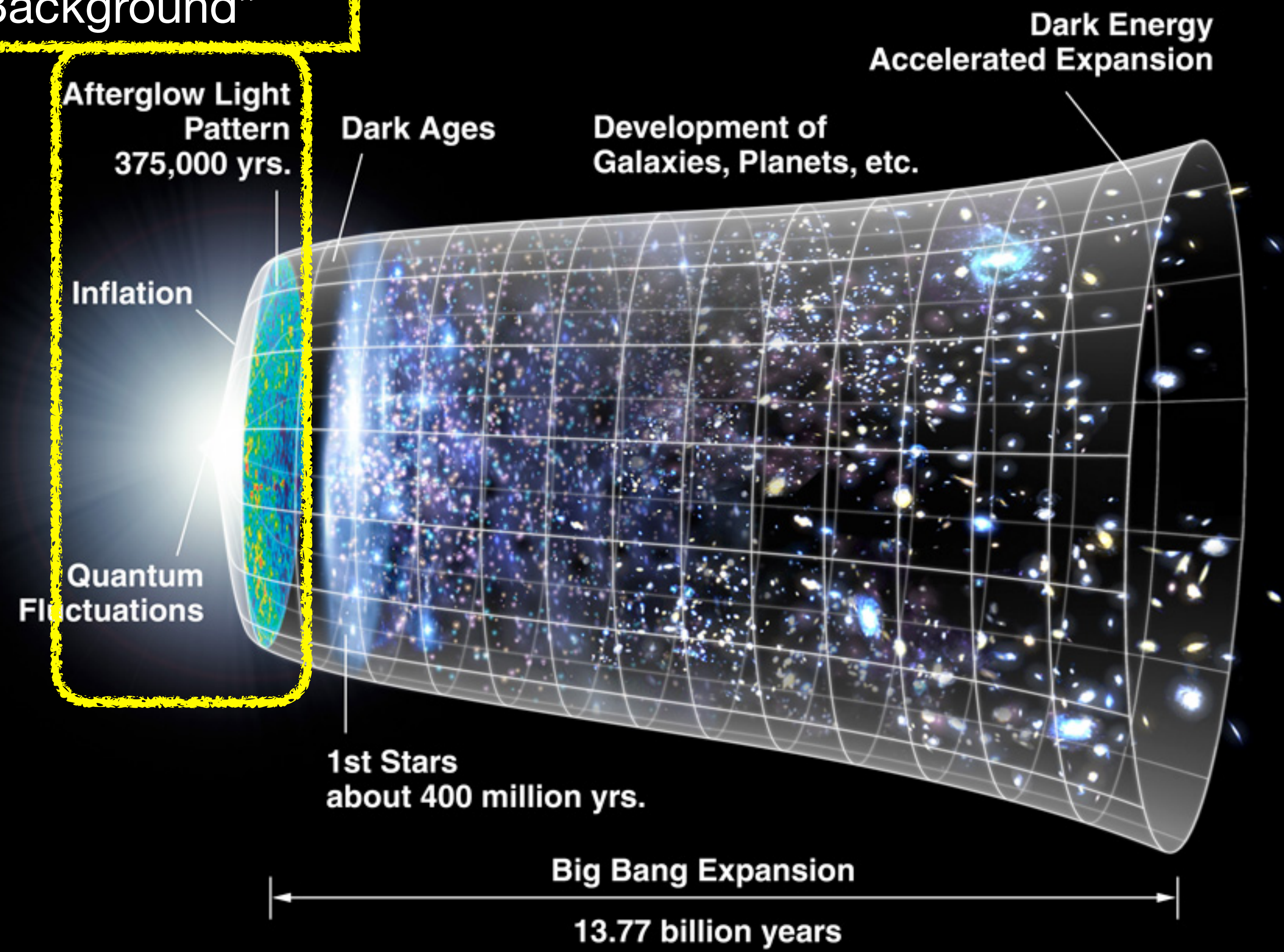
- Early universe measurement provides us the initial condition of the Universe
- Do we have a model to reproduce late-time observations?
  - current status
  - Things I did: Galaxy Clusters
  - Things I will do: Redshift-space distortion combined with gravitational lensing

How does our Universe evolve? - Brief history of the Universe

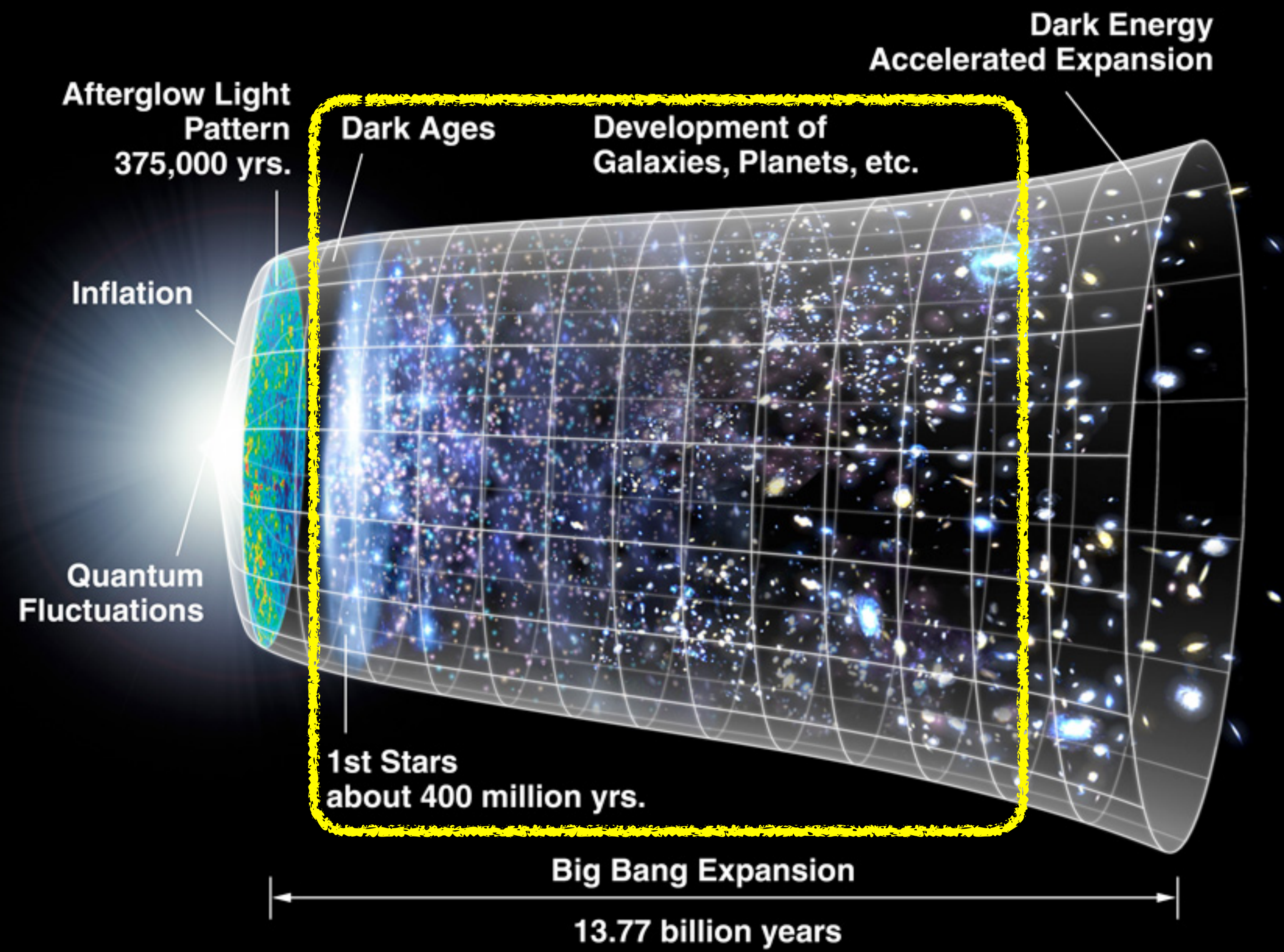


How does our Universe evolve? - Brief history of the Universe

“Cosmic Microwave Background”



How does our Universe evolve? - Brief history of the Universe



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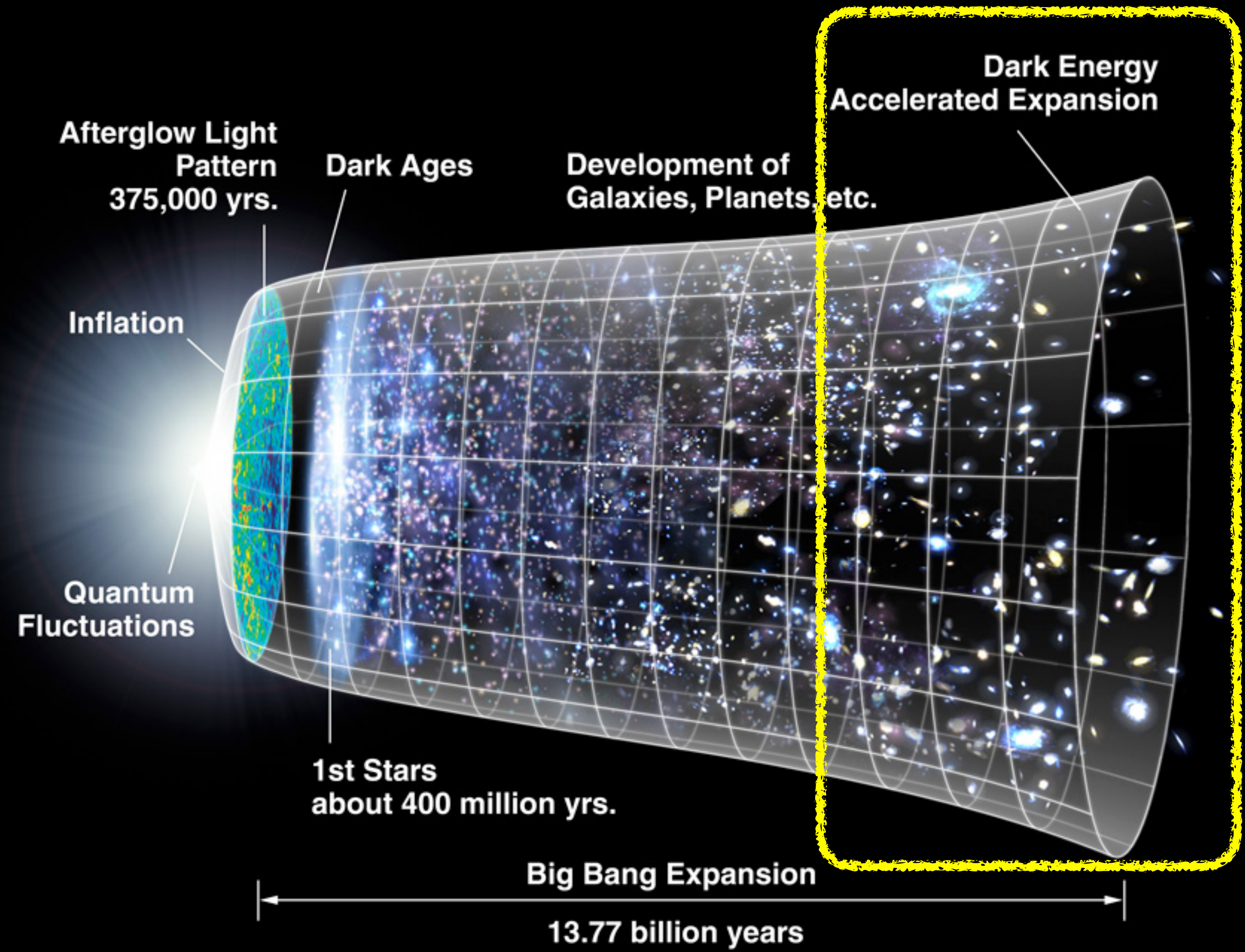

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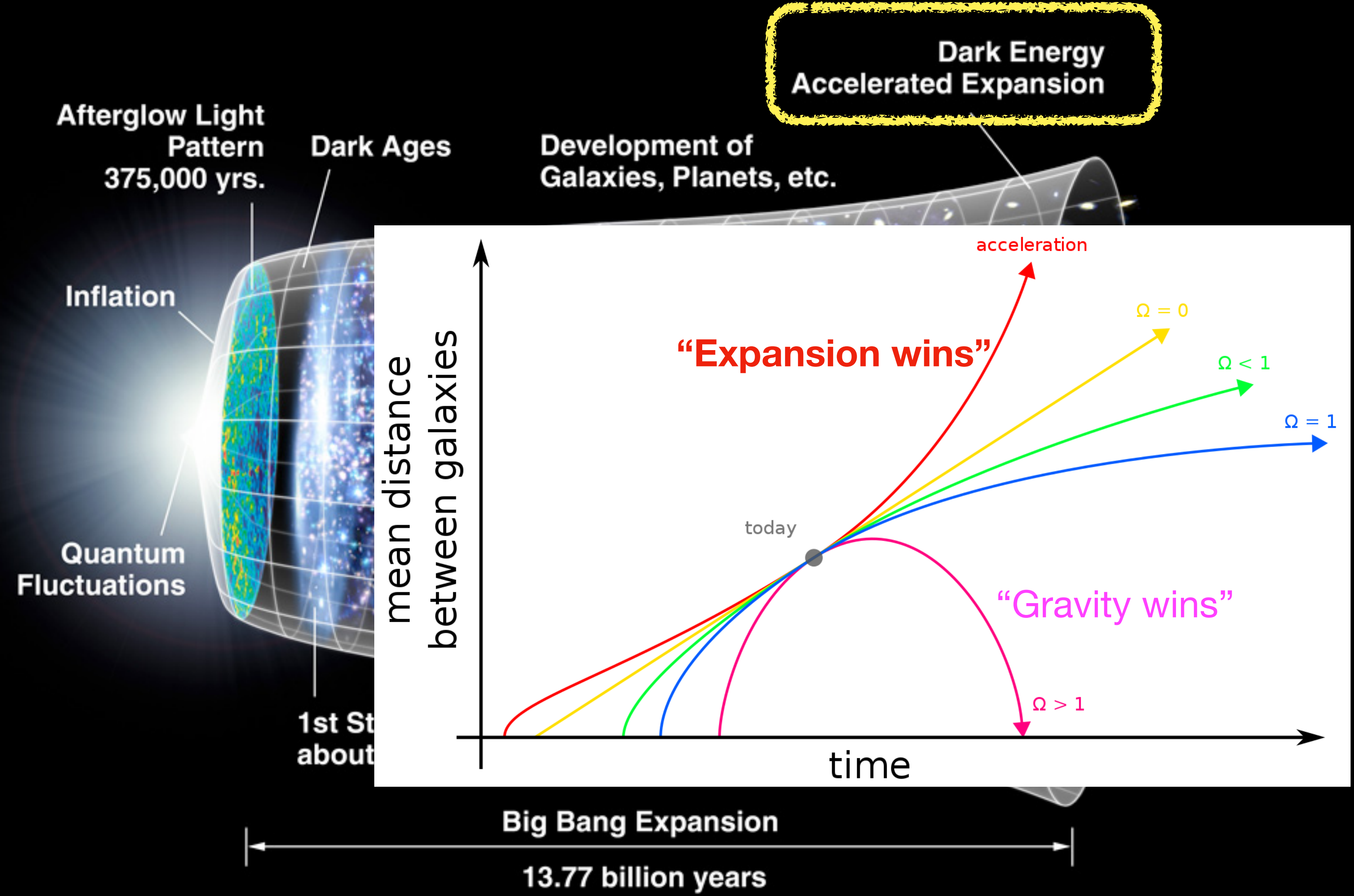

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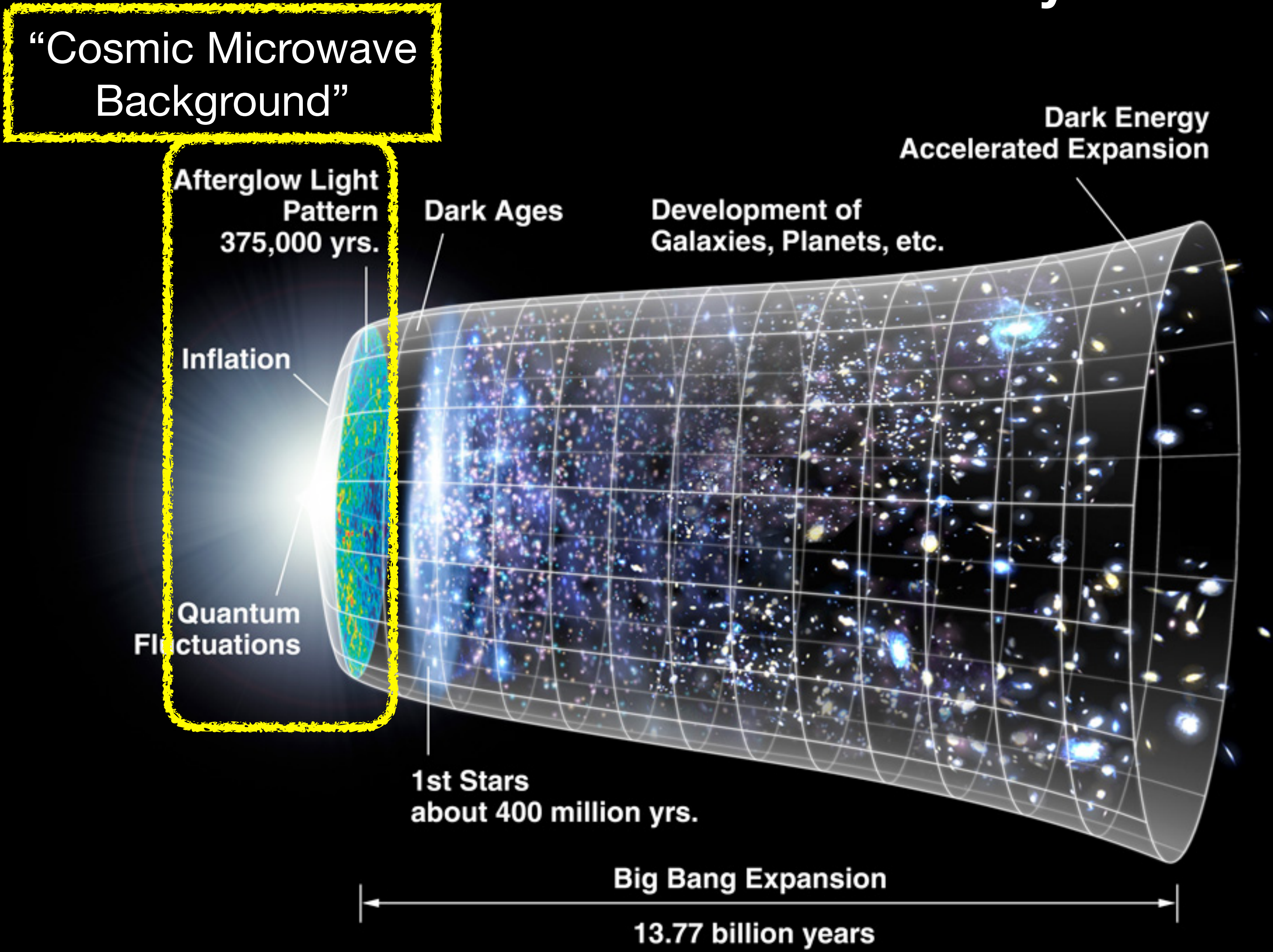
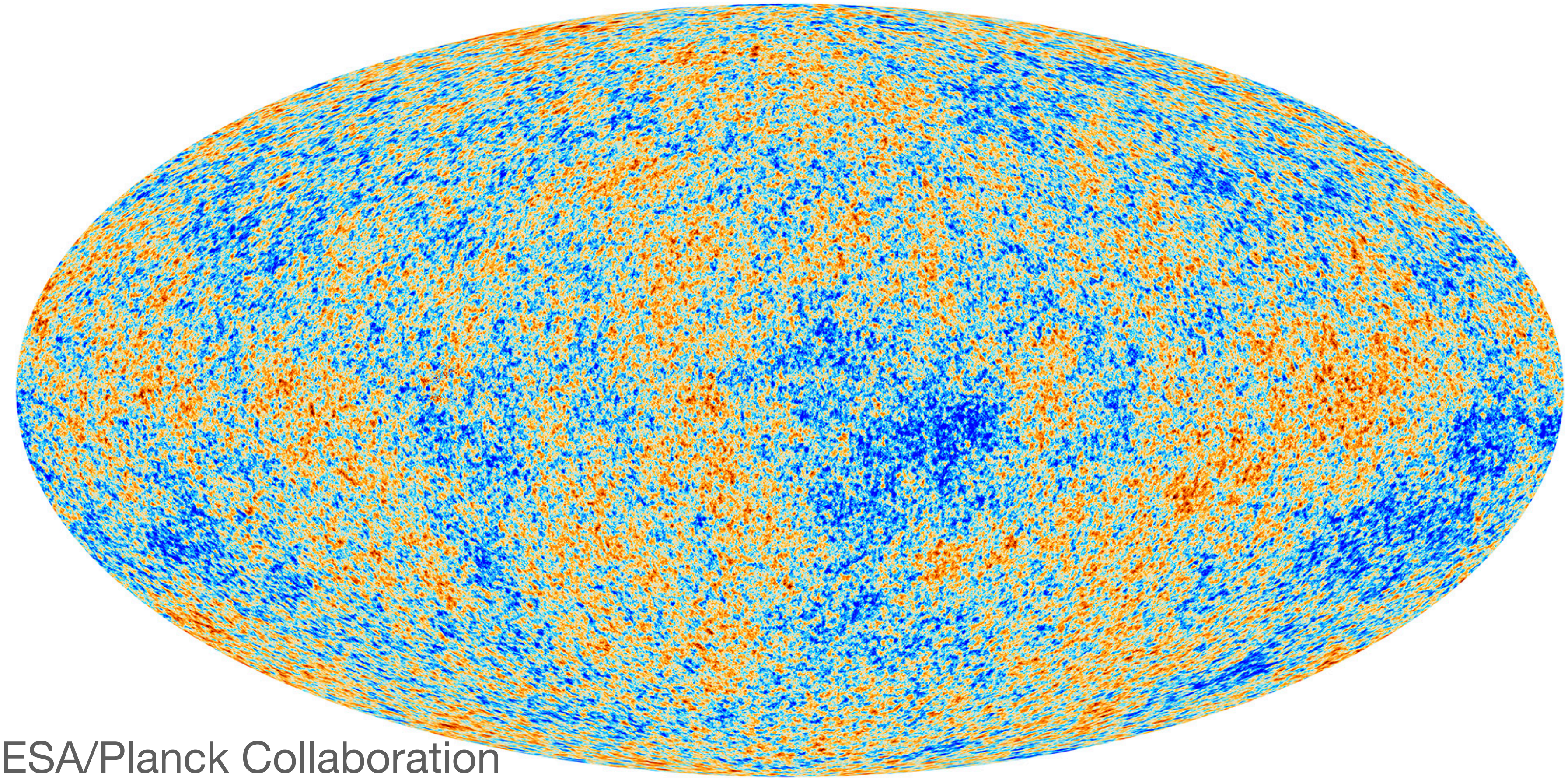


Cosmic Microwave Background (CMB)

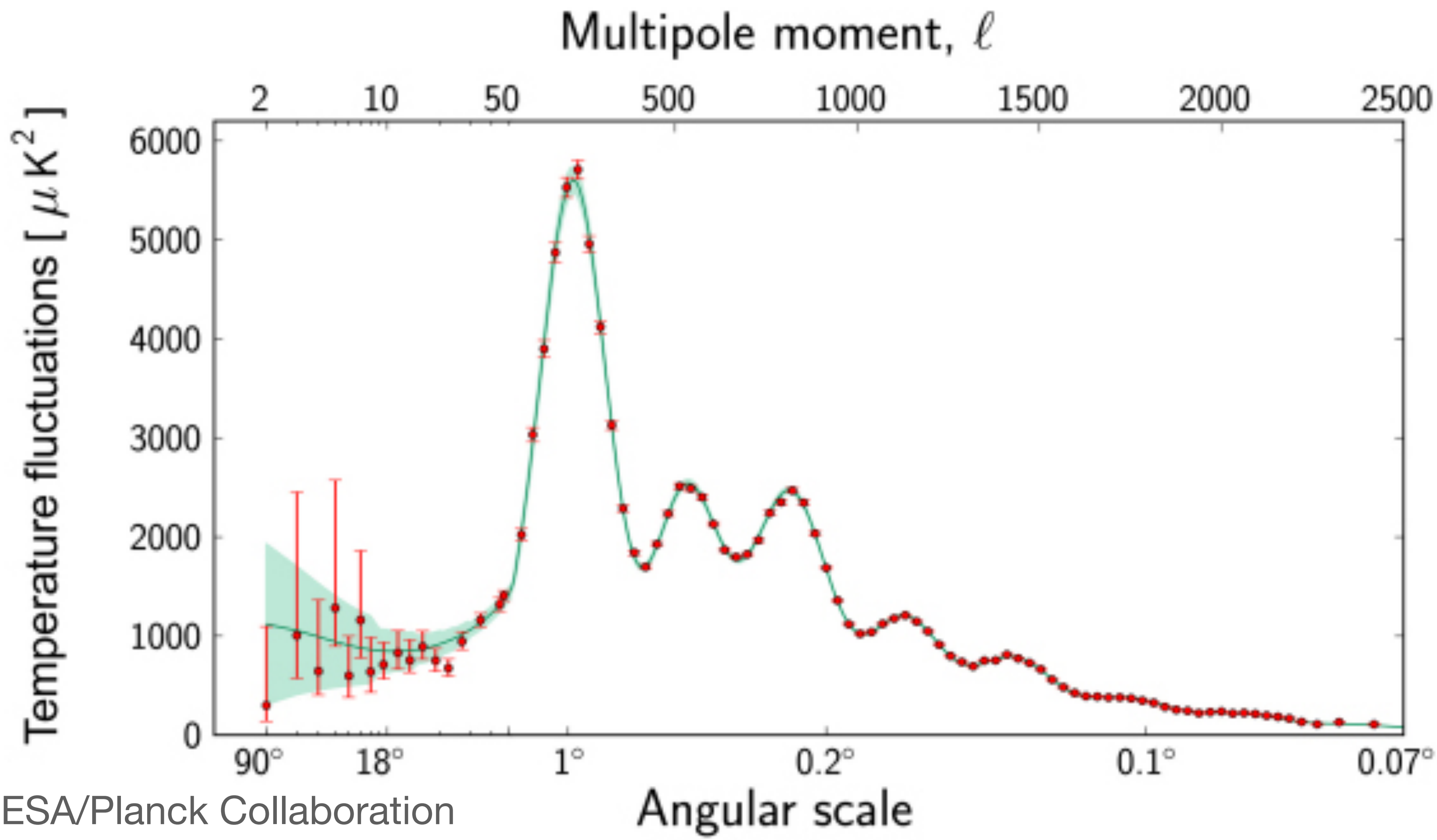
- The farthest and oldest light that we can observe directly
- The Universe is homogeneous and isotropic



Credit: ESA/Planck Collaboration

CMB can tell us energy budget of our Universe

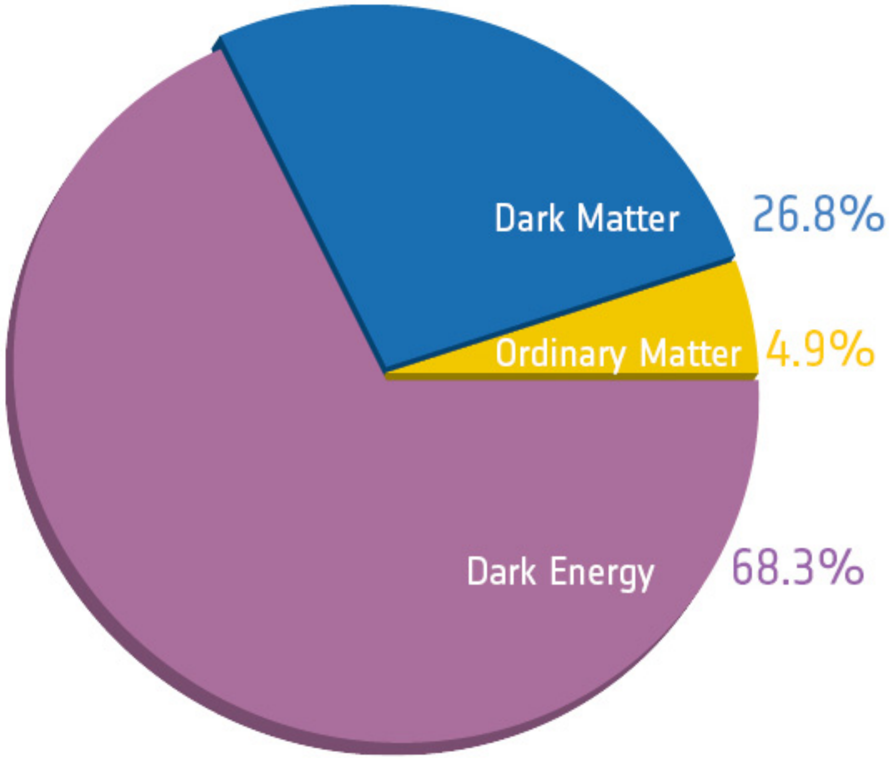
- The model fits the data remarkably well!



Credit: ESA/Planck Collaboration

Standard model of the Universe: ΛCDM

Era of precision cosmology



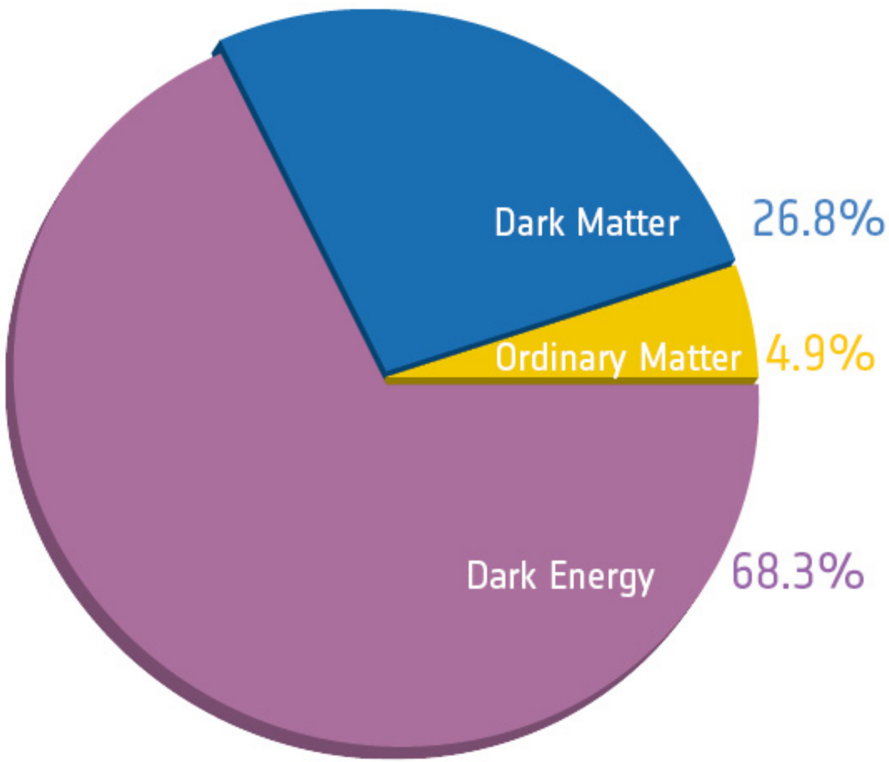
Credit: ESA/Planck Collaboration

- Dark Energy(DE)
  - accelerates the expansion
  - dominate the total energy density
  - first measured by SNeIa
- geometrically flat

We assume DE density doesn't change in time (cosmological constant: Λ) and GR works on all scale

Standard model of the Universe: ΛCDM

Things we don't know…

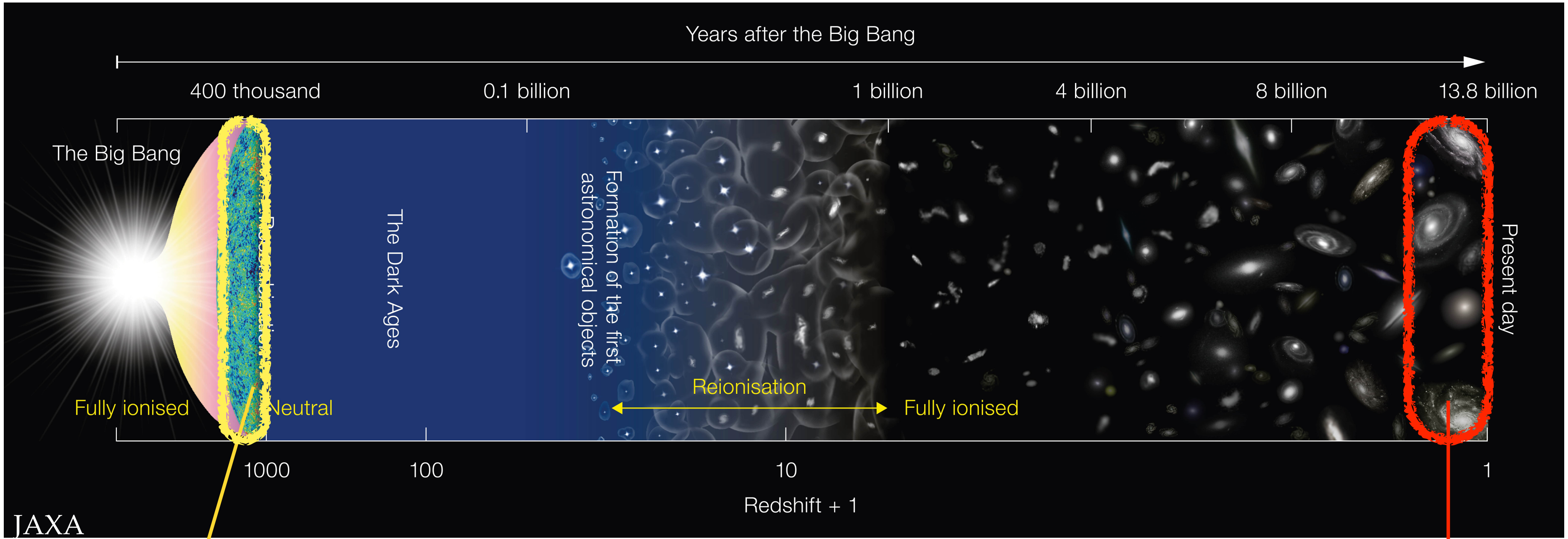


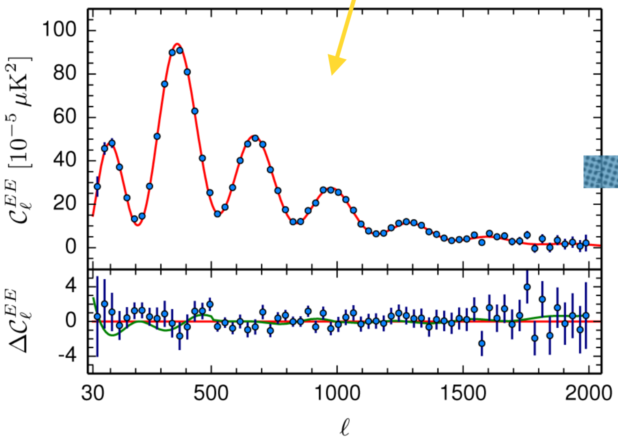
Credit: ESA/Planck Collaboration

DE **requires** new physics beyond the standard model of elementary particles and fields

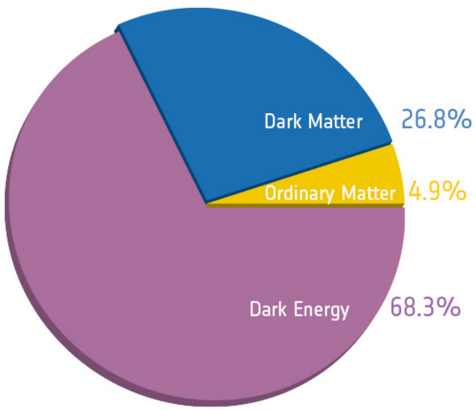
- Dark Energy
  - cosmological constant Λ
  - does the DE density change in time? (e.g., dynamic scalar field)
  - due to break down of General Relativity (GR)?

Stress test ΛCDM using large-scale structure probes





ESA / Planck



?

Large scale structure probes

- Gravitational Lensing
- Galaxy clusters
- Galaxy clustering

Outline

1. Brief history of the Universe
   - Standard cosmological model: ΛCDM
2. Galaxy Clusters
   - Tension in growth of structure
   - Optical clusters as a cosmological probe
3. Baryon Acoustic Oscillation
   - DESI Y1 cosmology result
   - Future perspective

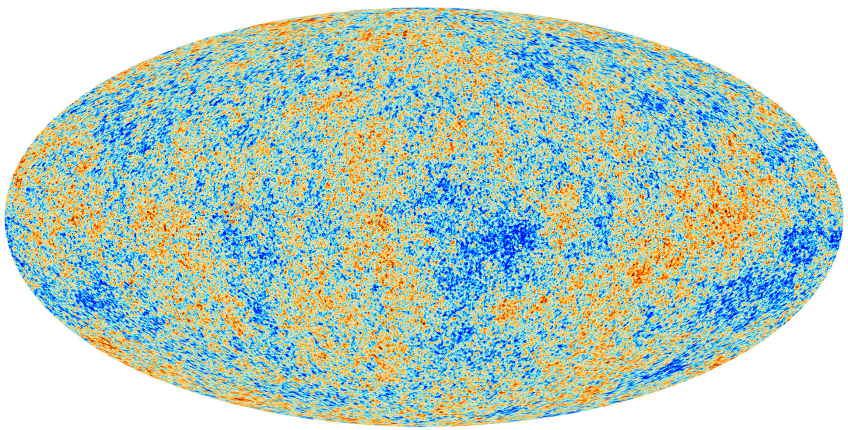
Test the evolution of the structure

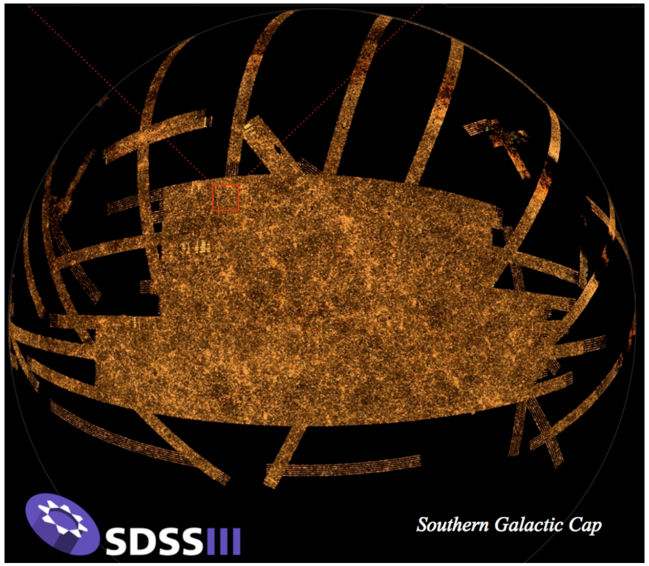
Amplitude of matter density fluctuations

$$A_s \xrightarrow{\Lambda\text{CDM?}} \sigma_8$$

Primordial amplitude constrained by the CMB

Present-day amplitude constrained by late-time observations



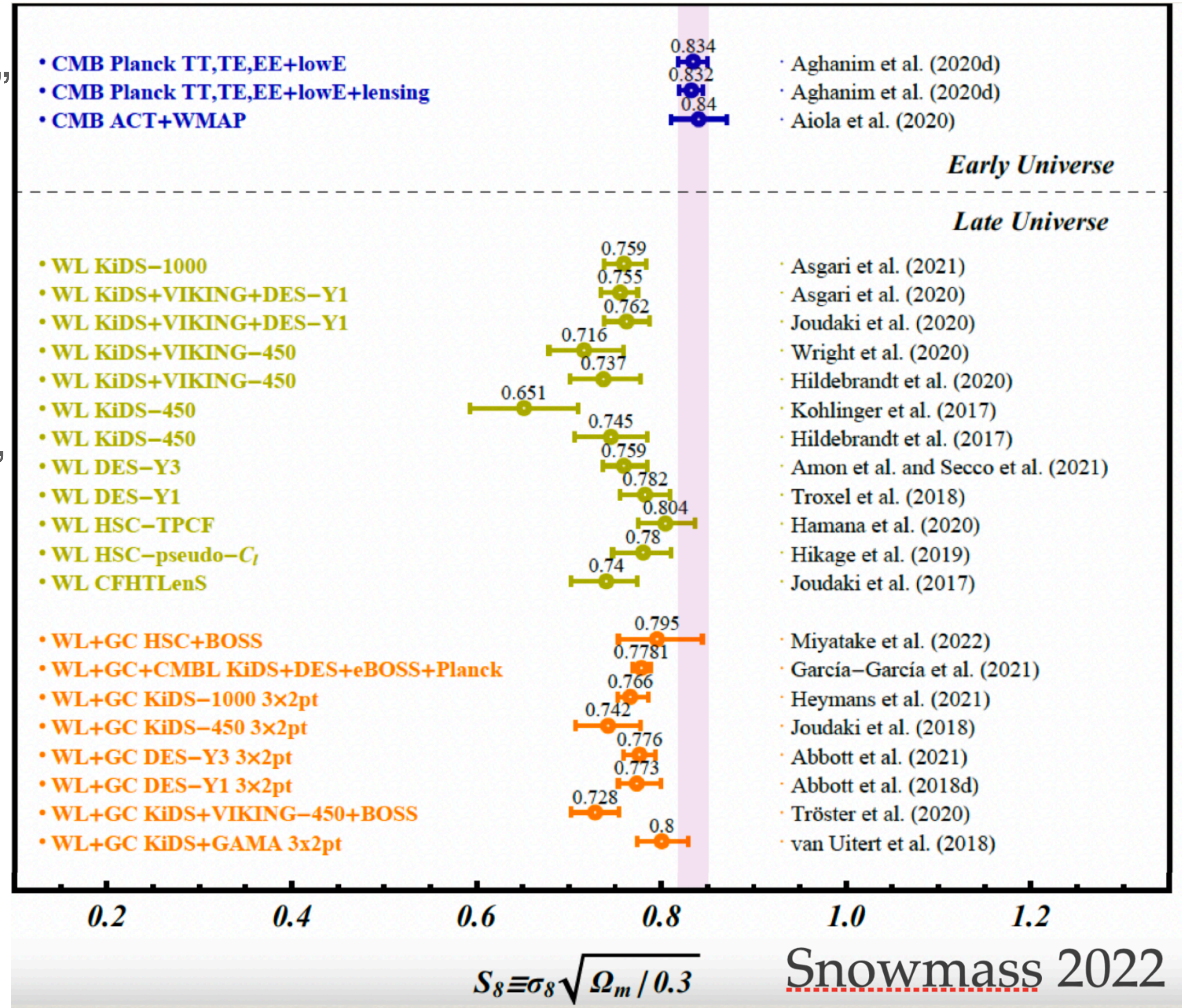


S8 Tension: accumulated evidence of disagreement

- σ_8 measures "clumpiness" of the Universe

"Early-Universe probe"

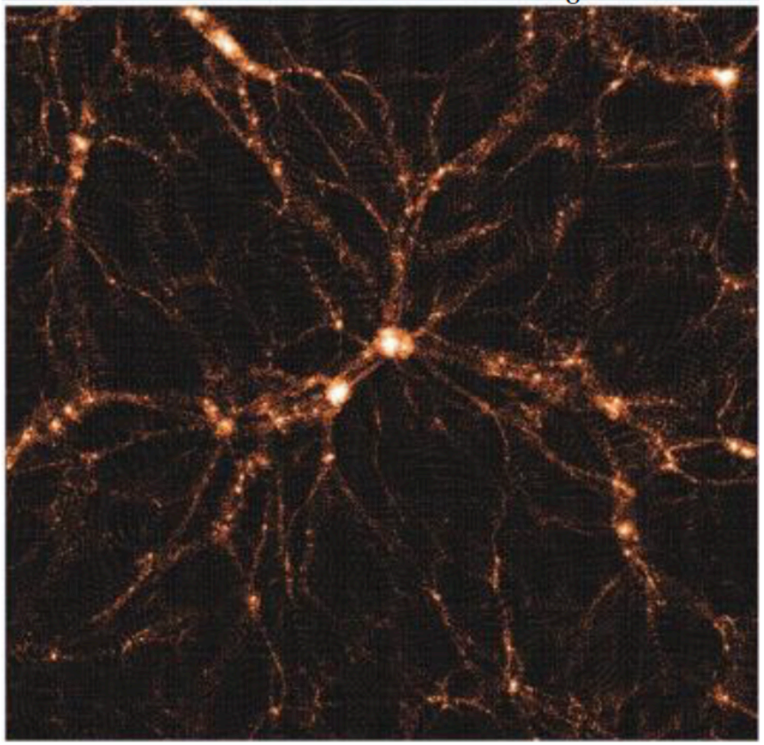
"Late-Universe probe"



How does S8 tension look like?

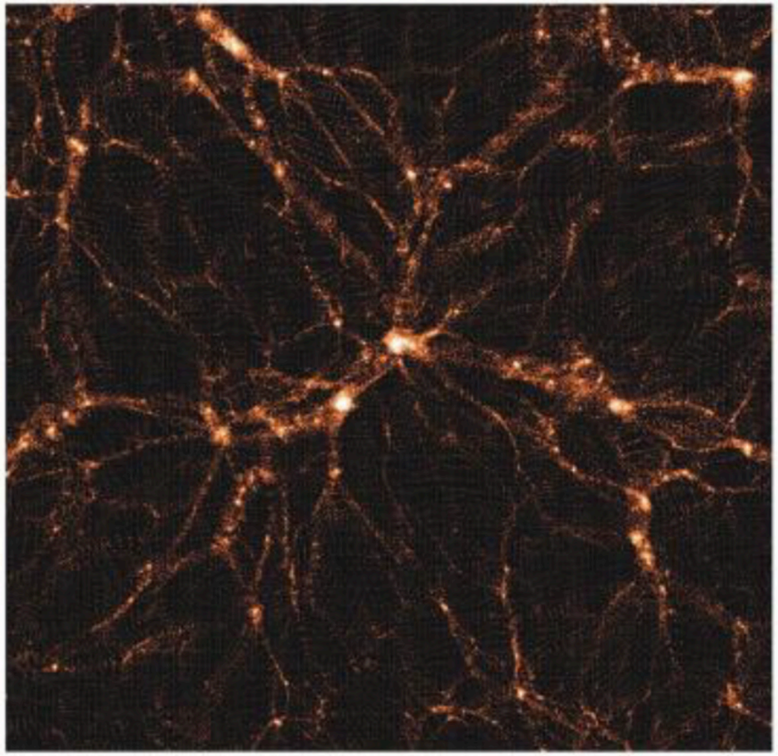
- Comparison between the Universe measured from HSC-Y1 lensing and predicted from Planck CMB

Planck 2020 Primary CMB: $S_8 = 0.83$



Planck Collaboration (2020)

HSC-Y1 cosmic shear: $S_8 = 0.78$



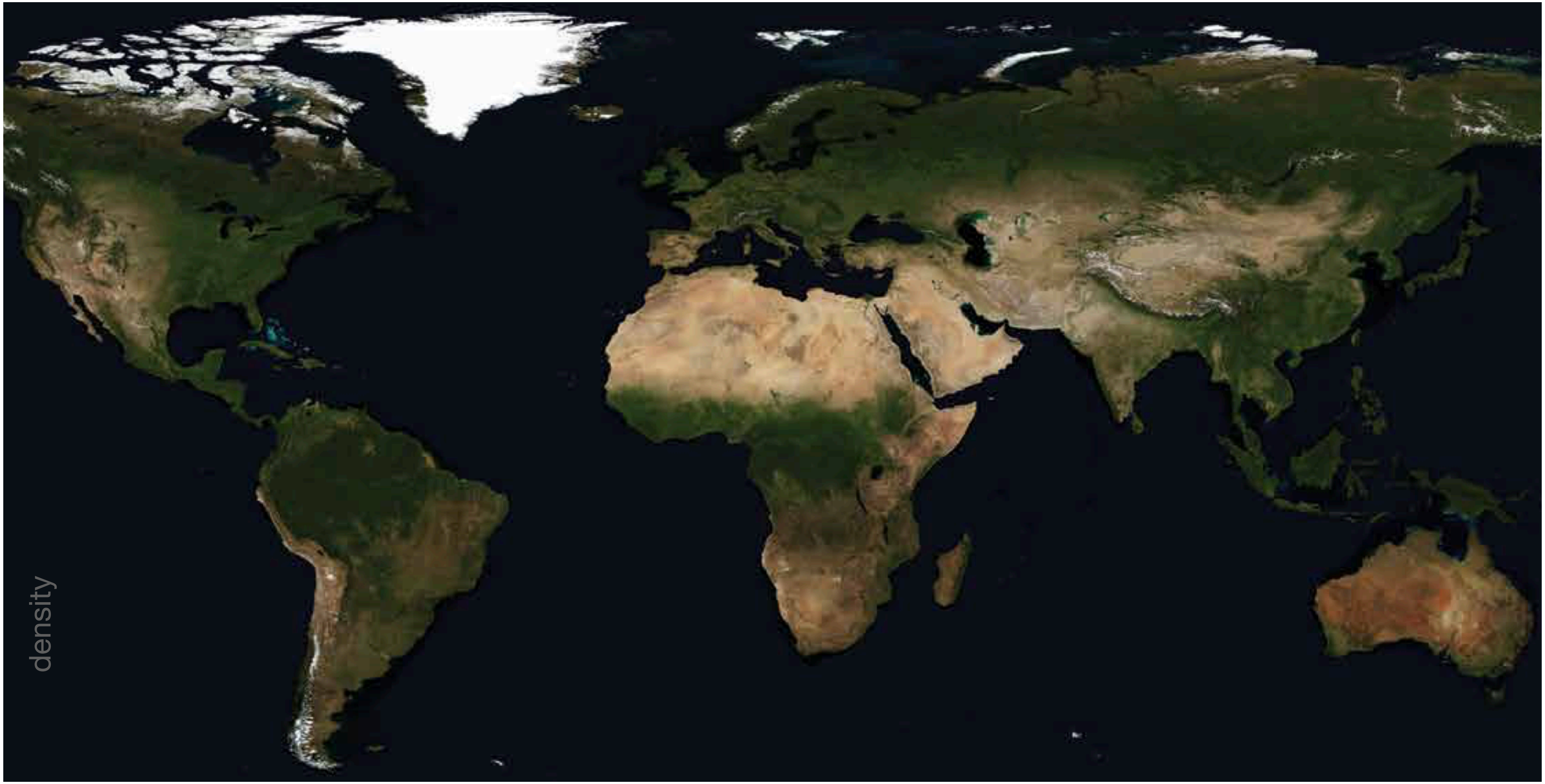
Hikage et al. (2019)

Credit: Takahiro Nishimichi

Is it a real tension or due to systematics in cosmological analyses?

Why measuring σ_8 is hard?

We want to measure mass distribution like this…



Credit: NASA

This is all we can see…

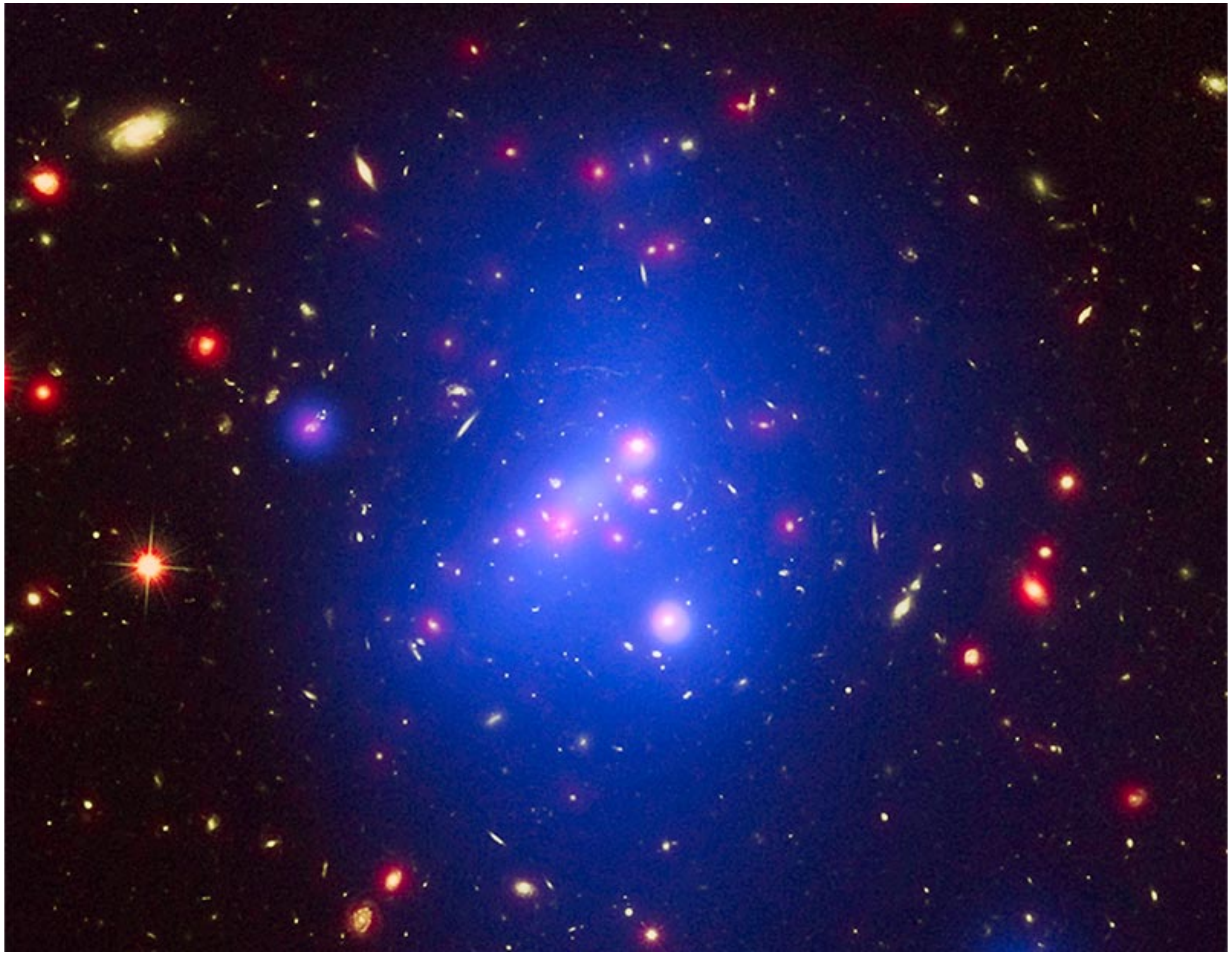
Light from galaxies: galaxies are a biased tracer of DM

Credit: NASA

Optical Cluster Cosmology

Galaxy Clusters

The most massive self-gravitationally bound object



Credit: NASA/CXC/U. Missouri/STScI/JPL/CalTech

- Mass~$10^{14} - 10^{15} \mathrm{M}_{\odot}/h$
- Size~a few Mpc/h

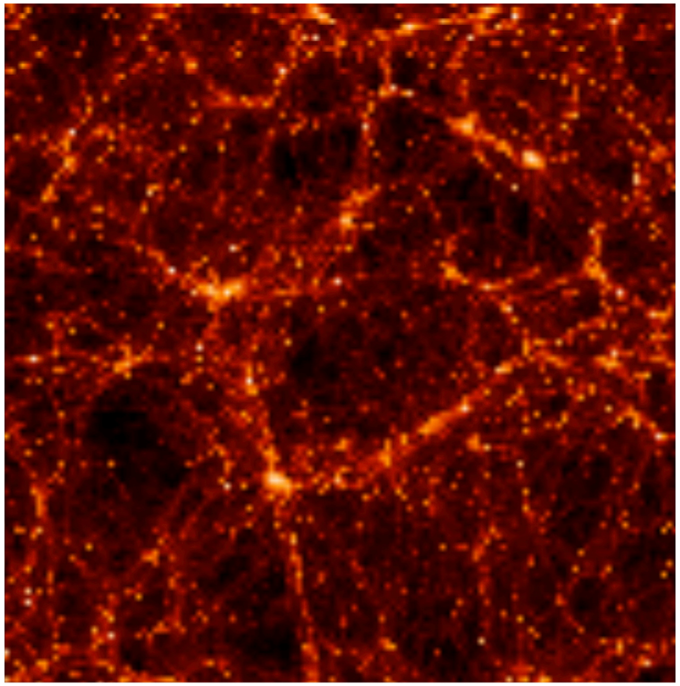
(Mpc=3×10^{19}km)

- "Optical": identified from imaging (photometric) data by finding over-dense regions of galaxies

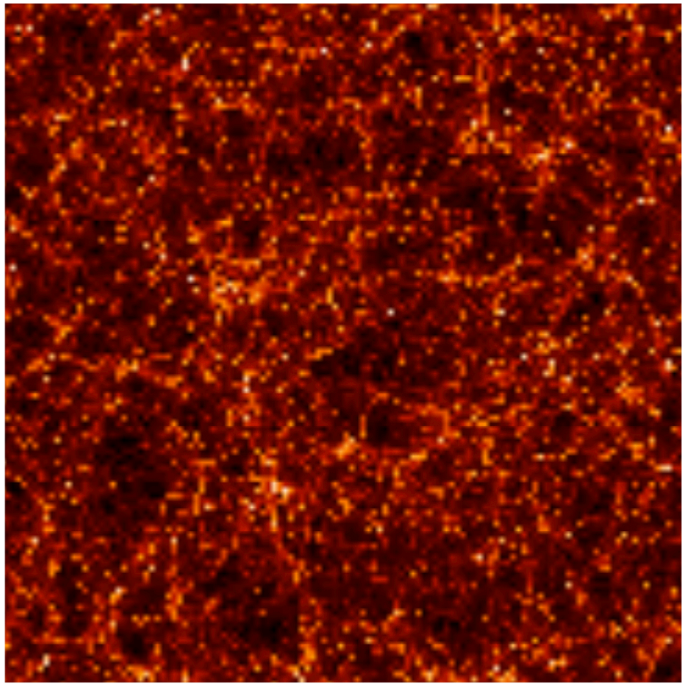
Clusters as a cosmological probe

- Count the number of clusters (as a function of cluster mass)

With Dark Energy



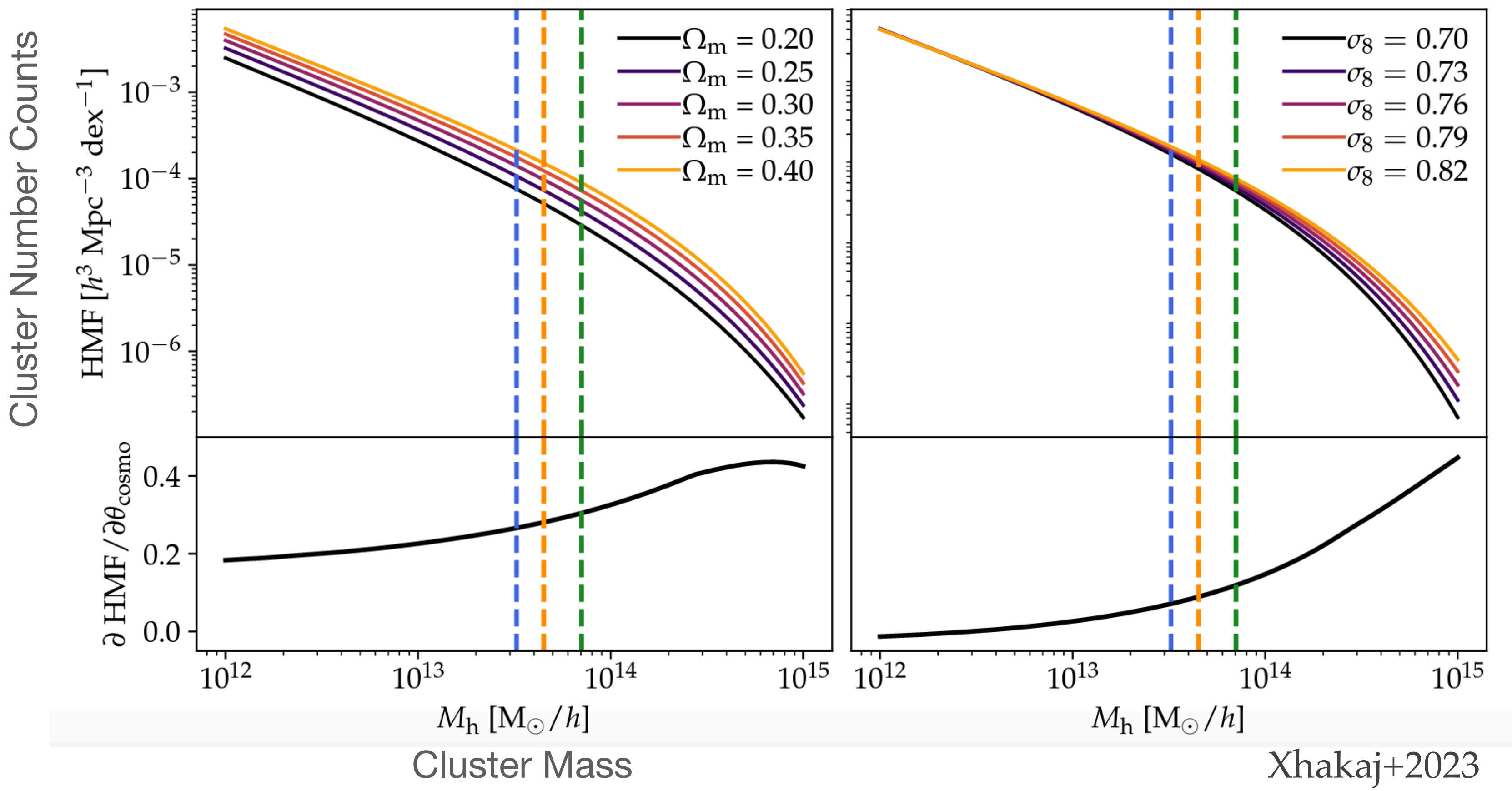
Without Dark Energy



Virgo consortium

Clusters as a cosmological probe

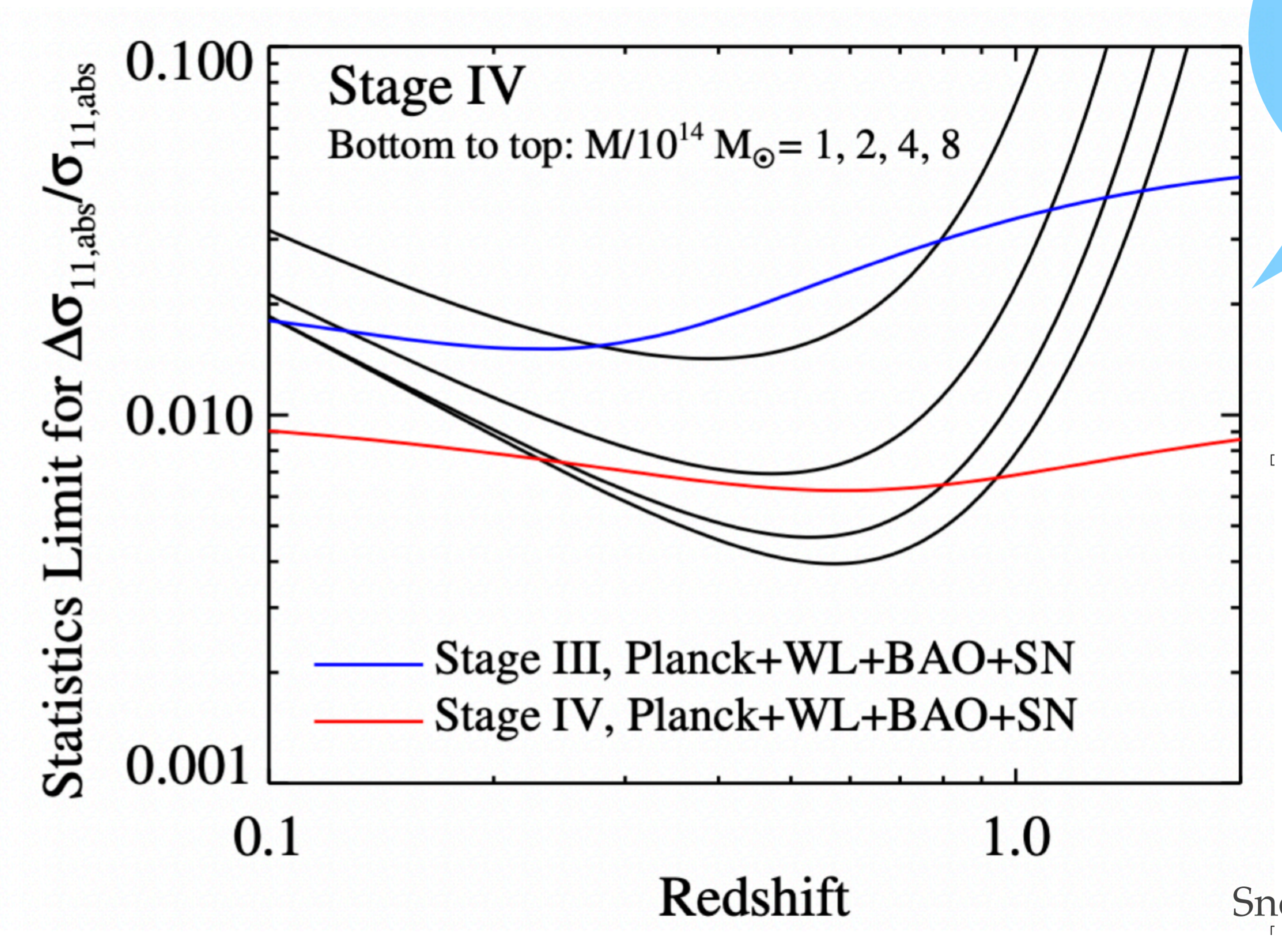
- Background cosmology (i.e., Ω_m) impacts the number density
- Clusters form from the highest density peaks in the initial density field
- σ_8 (="clumpiness"): higher σ_8 → more high-density peaks → more massive clusters



Xhakaj+2023

Clusters can be powerful…

- Cosmic Visions Report (2016): " The number of massive galaxy clusters could emerge as the most powerful cosmological probe…"

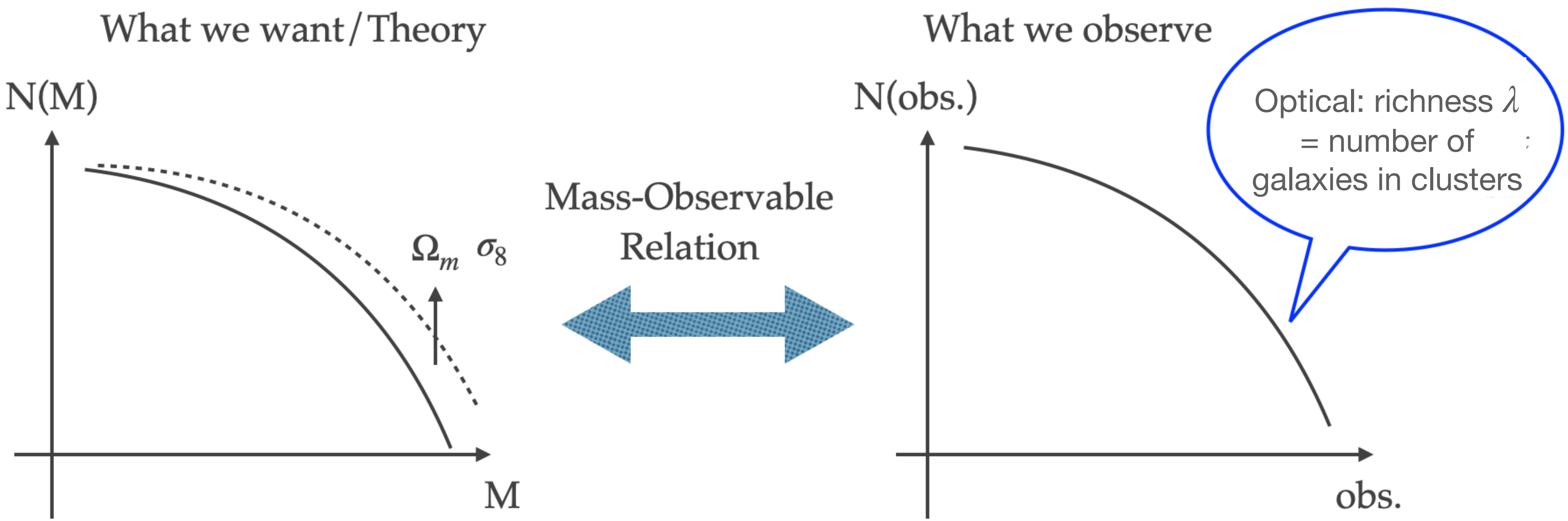


Optical clusters can be identified up to z~1 with the minimum mass of $10^{14}M_{\odot}/h$

Snowmass2013; Huterer et al.

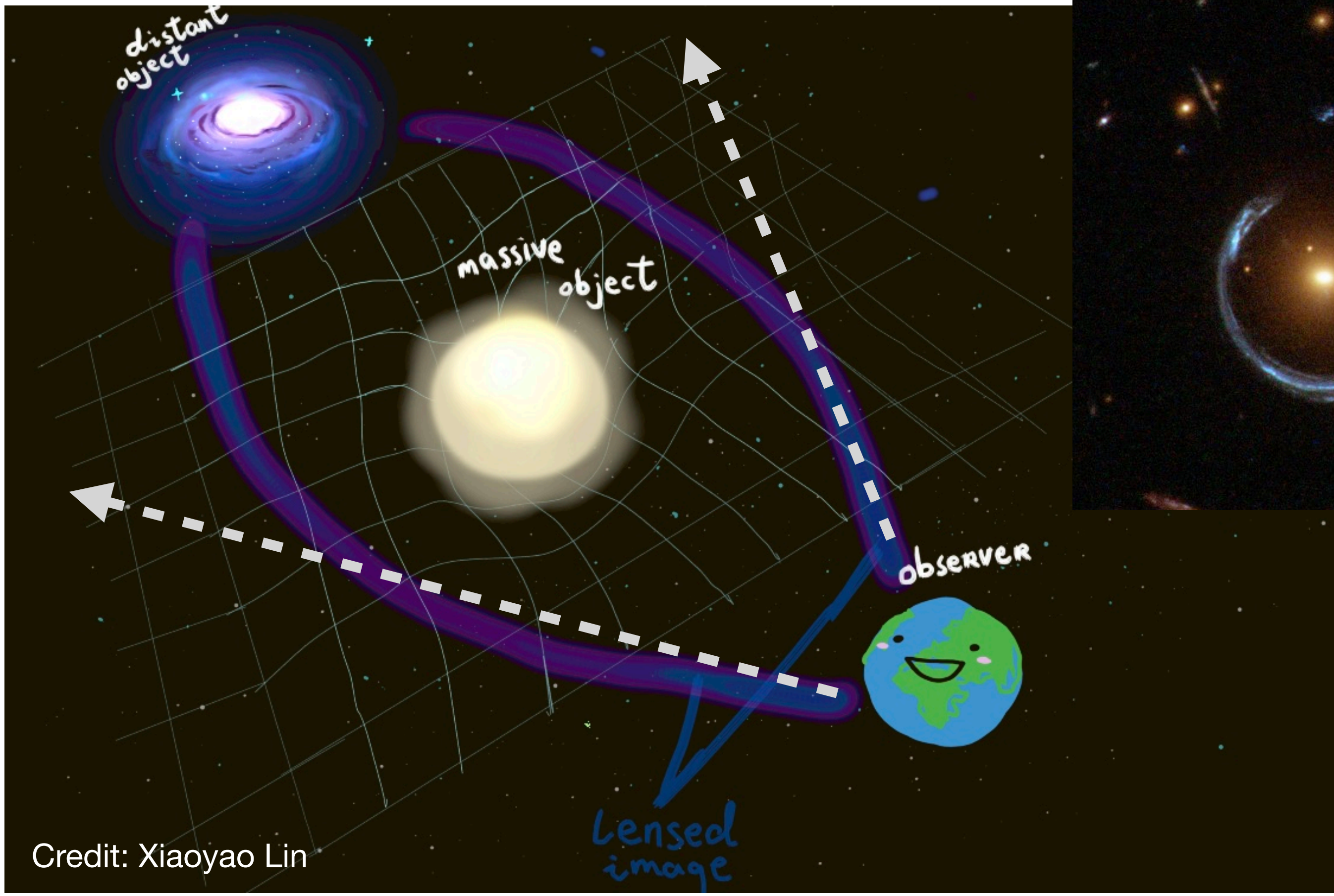
Challenge in Cluster Cosmology

- Cosmic Visions Report (2016): " The number of massive galaxy clusters could emerge as the most powerful cosmological probe if the masses of the clusters can be accurately measured."
- Cluster mass is not a direct observable

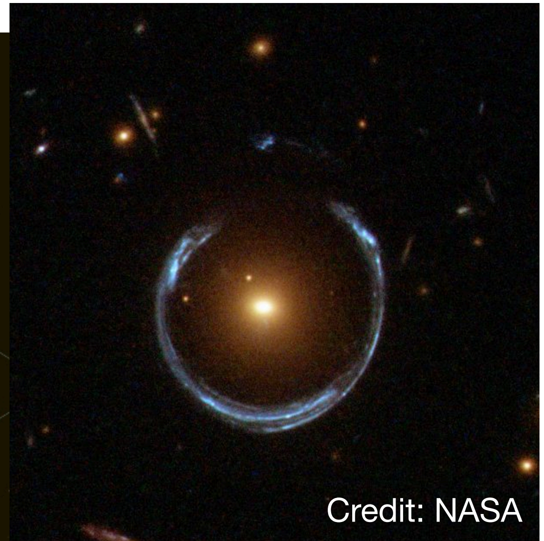


Gravitational Lensing

- When massive objects in the Universe distort spacetime, the path of light around it is bent, as if by a lens.
- Create multiple images of the same objects or distort the image of galaxies (strong lensing)



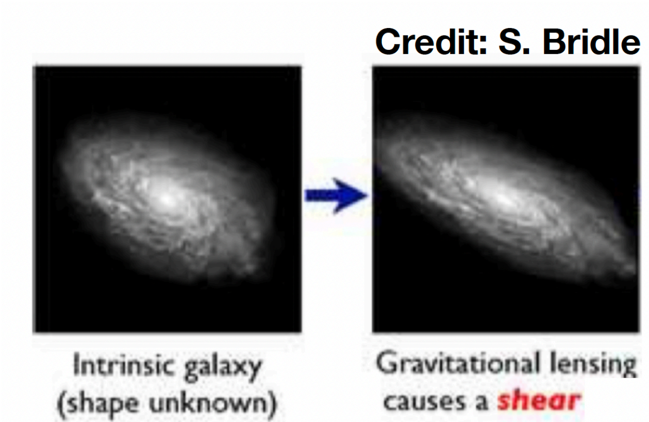
Credit: Xiaoyao Lin

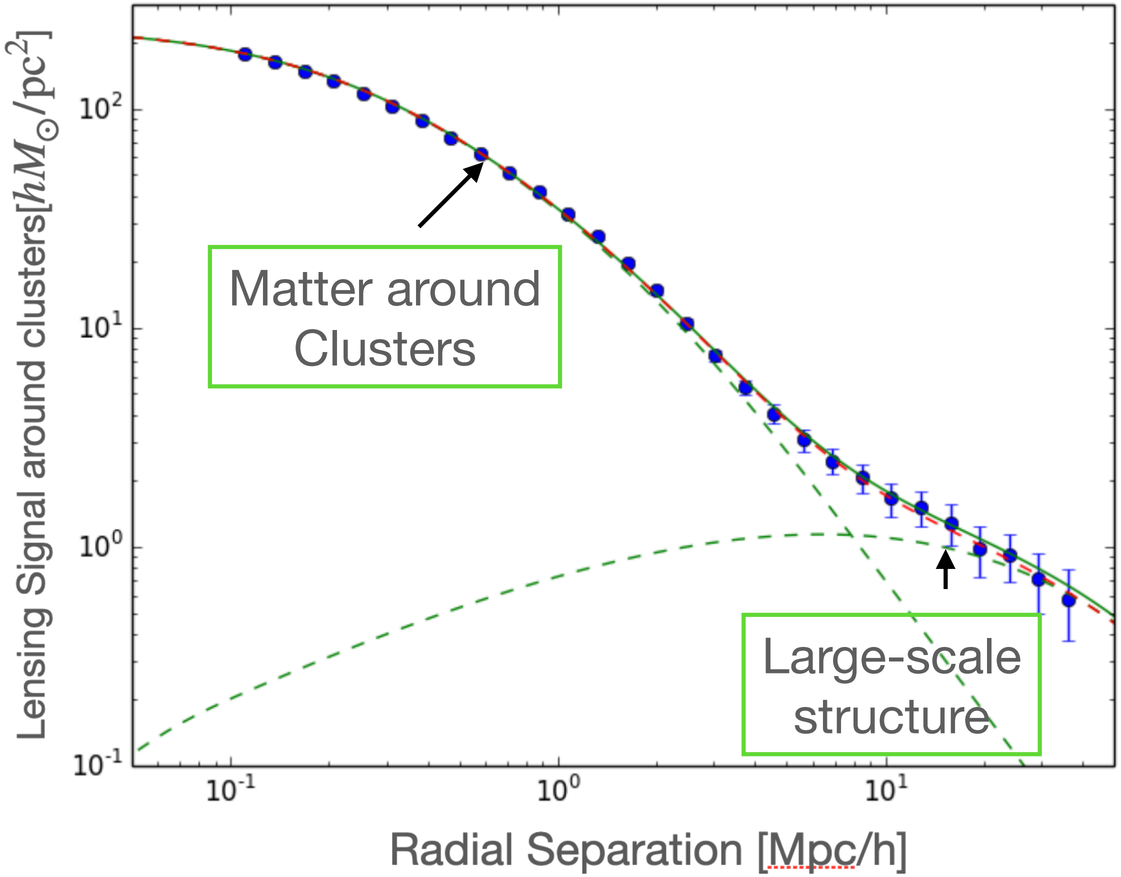

Credit: NASA

Weak Gravitational Lensing

Can measure halo mass of clusters

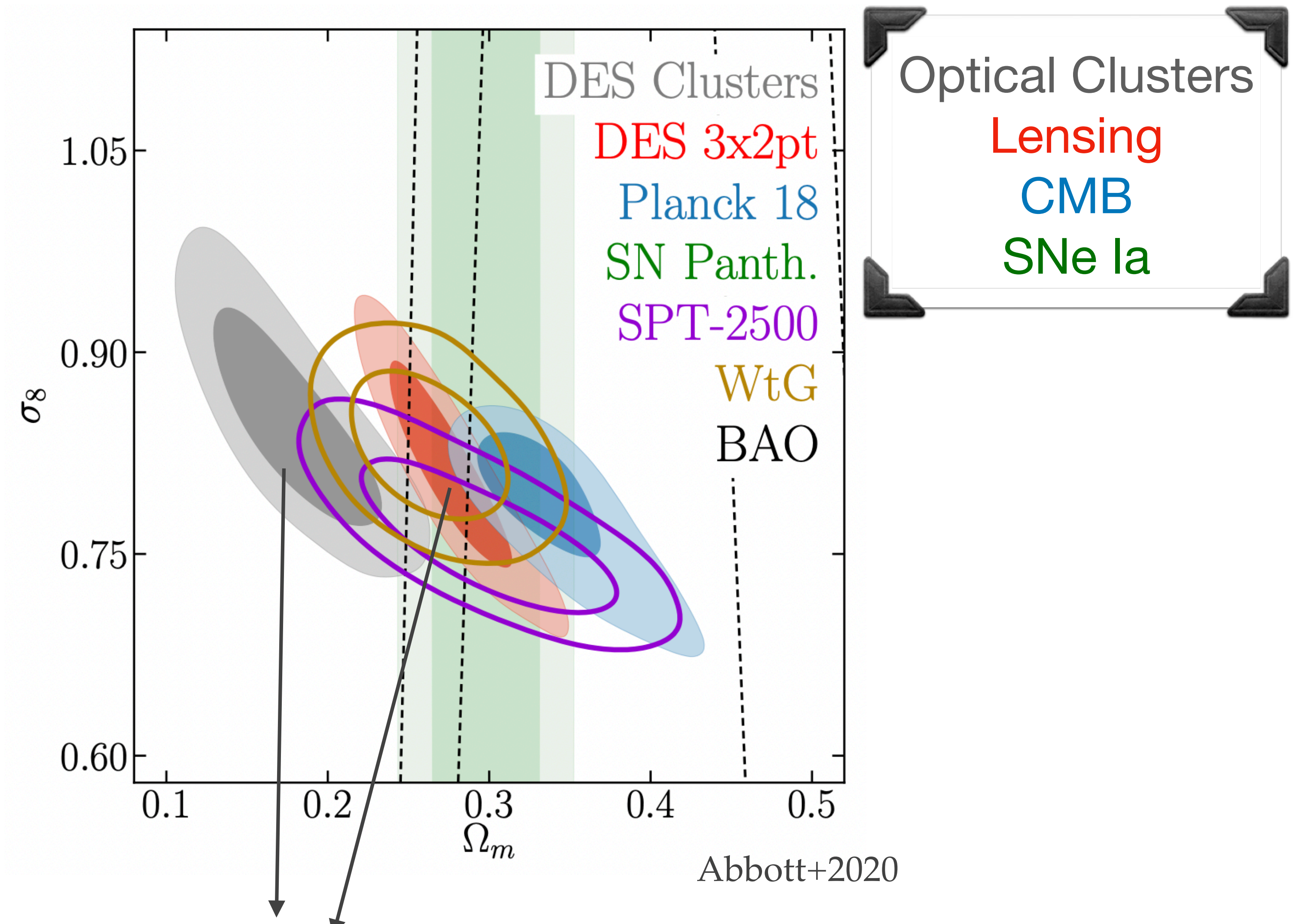
- Coherent distortion of galaxy shapes ("shear") is ~1% effect
- Required many galaxy images!





Clusters are a powerful cosmological probe, and cluster mass can be accurately determined by weak lensing

Result: the most precise result to-date

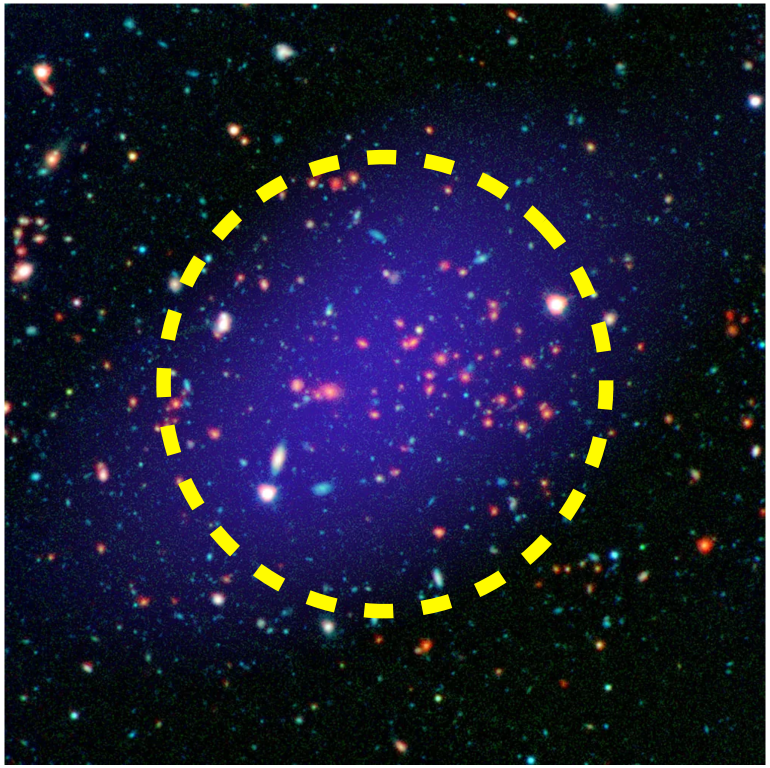


Same data sets = same area and redshift

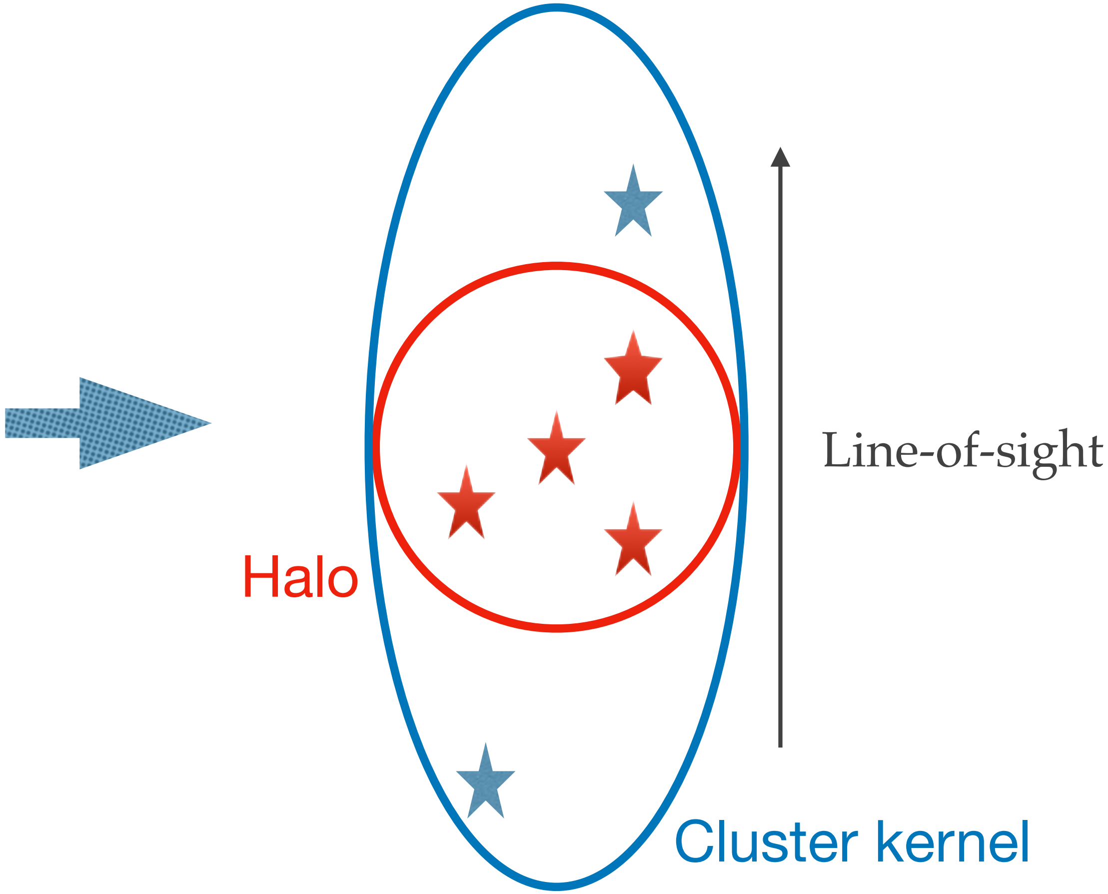
My cluster results

Projection Effects

- Misidentification of member galaxies along the line-of-sight



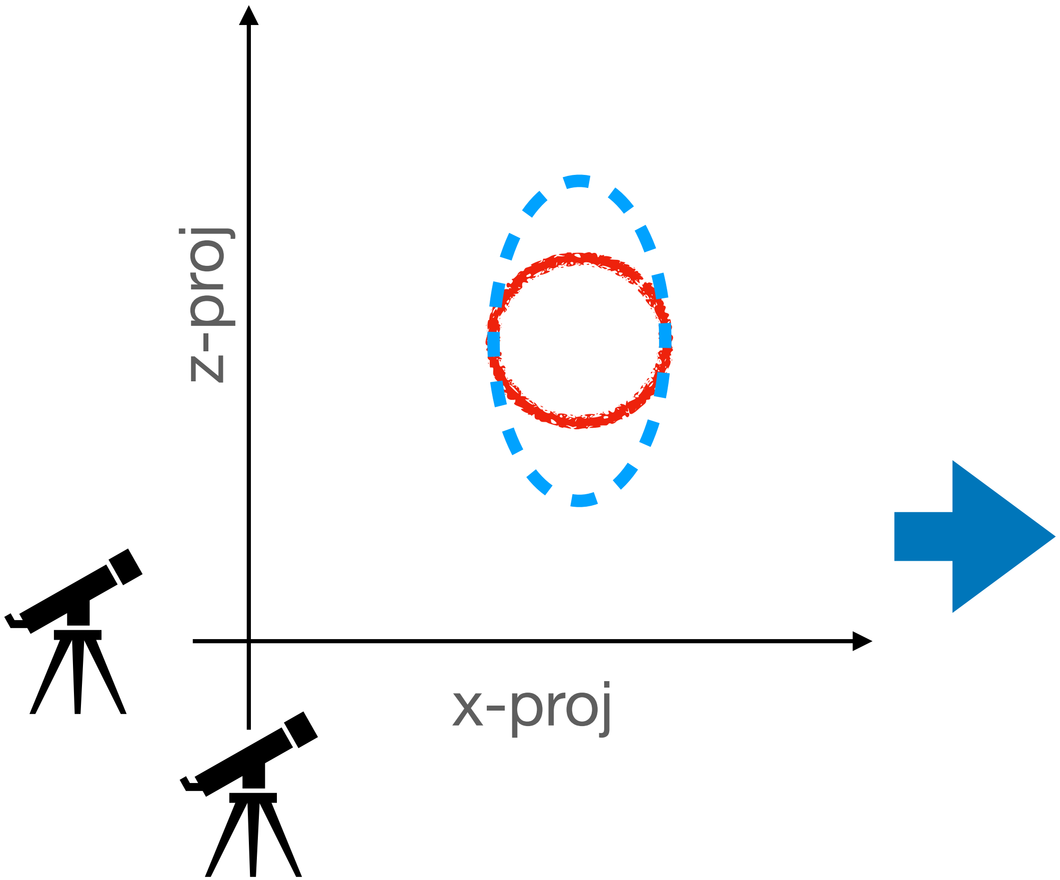
WISE/Spitzer

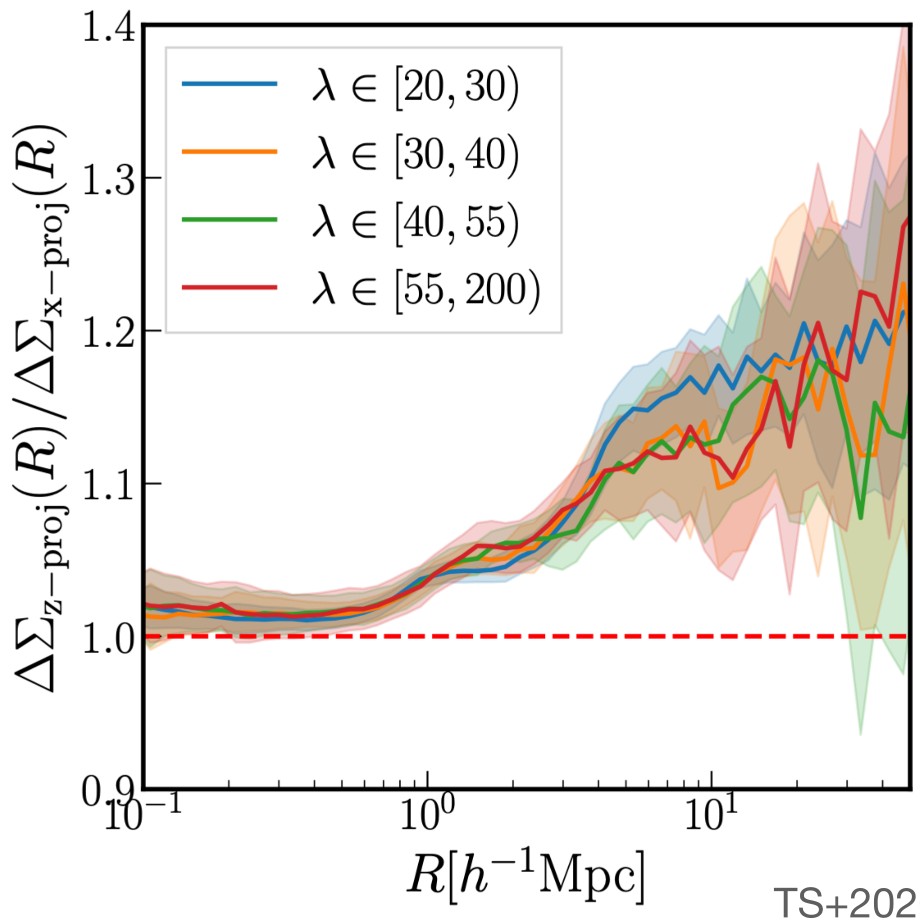


Projection effects contaminate the membership estimation

Projection effects correlate with large-scale structure

- We can measure lensing signals around clusters from two different directions

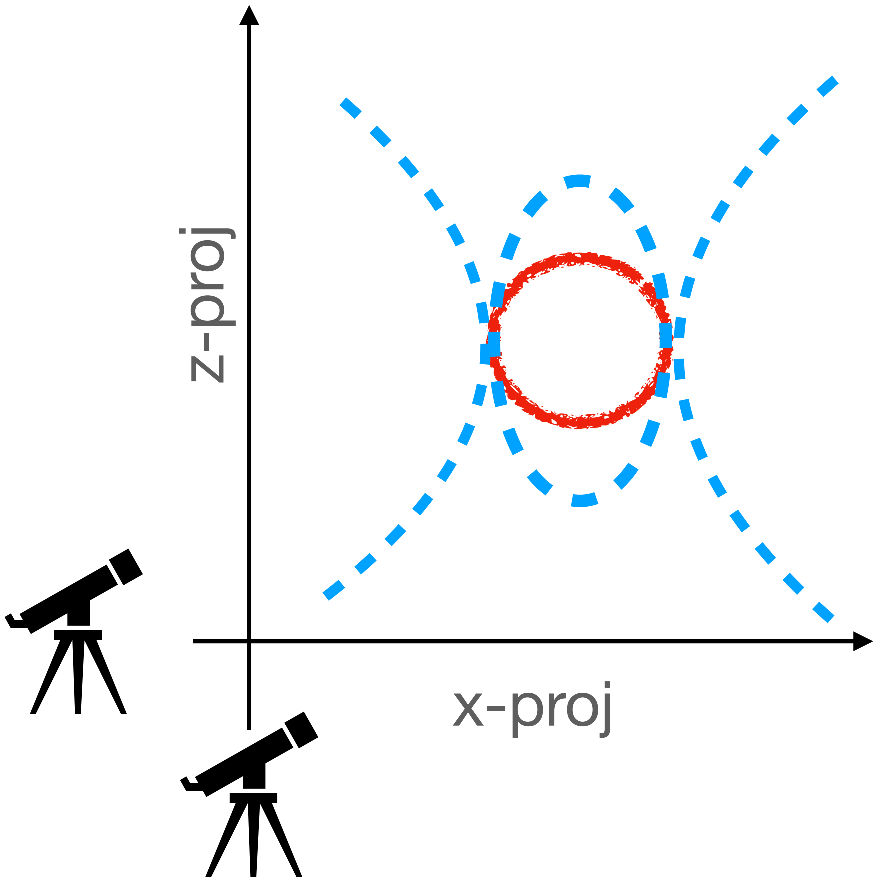


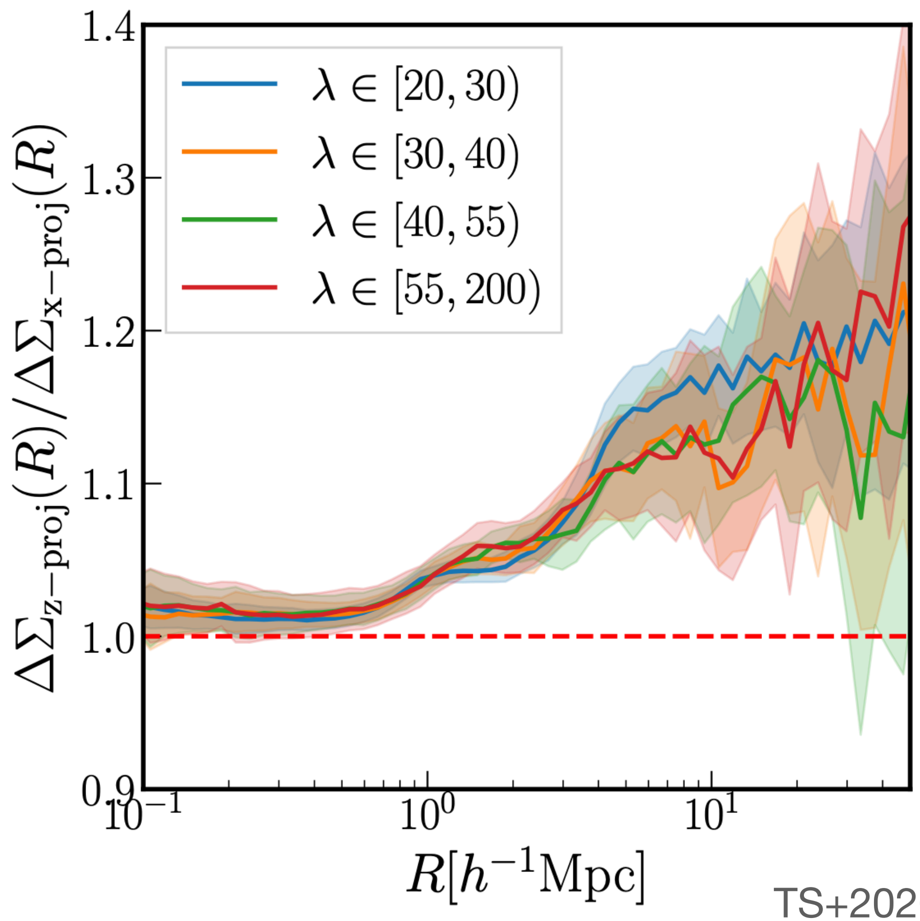


TS+2020

Measure lensing signals from different direction

- We can measure lensing signals around clusters from two different directions



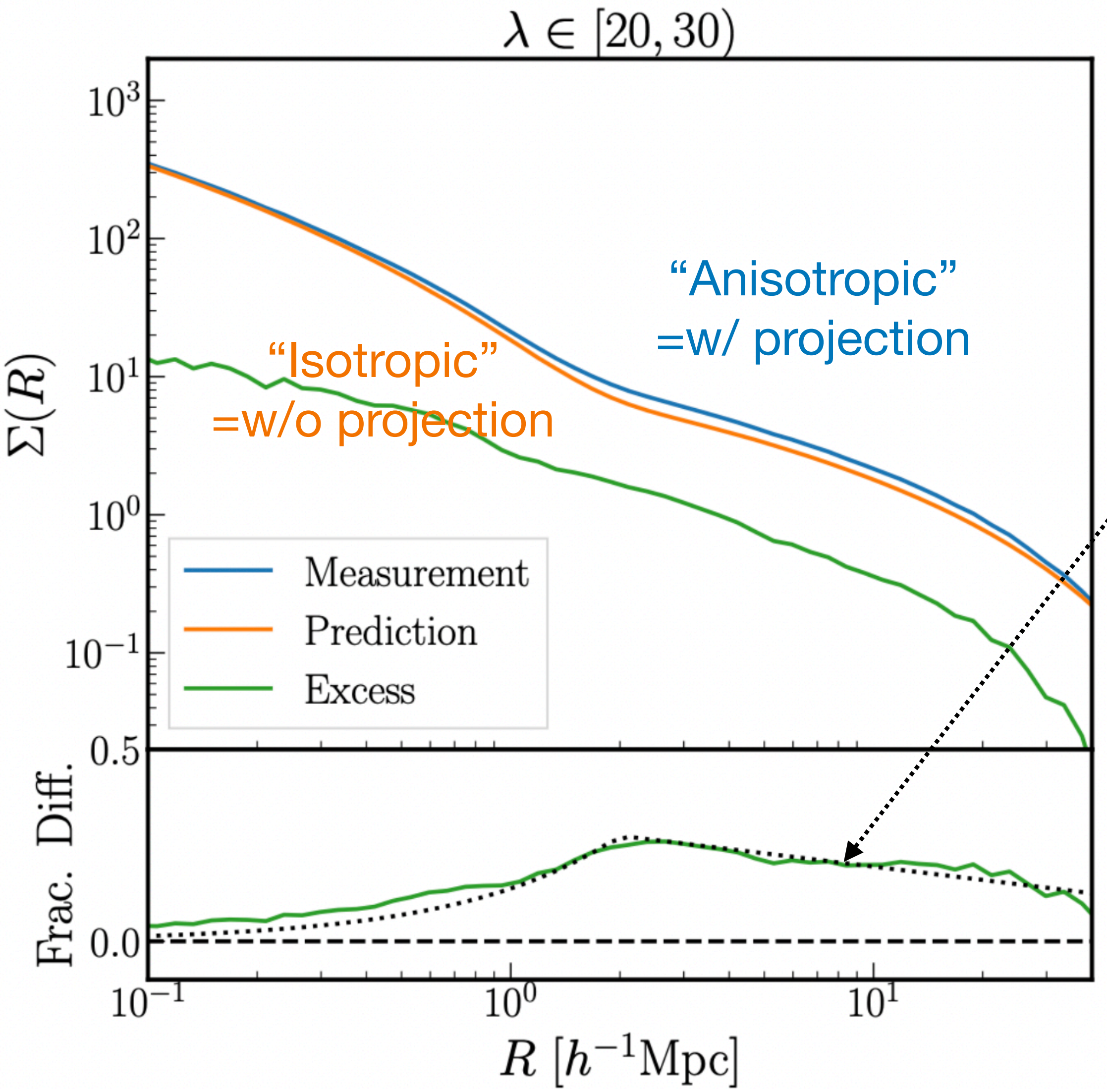


TS+2020

Distribution of optical clusters is anisotropic!

→cluster mass measurement is biased

Modeling Projection Effects

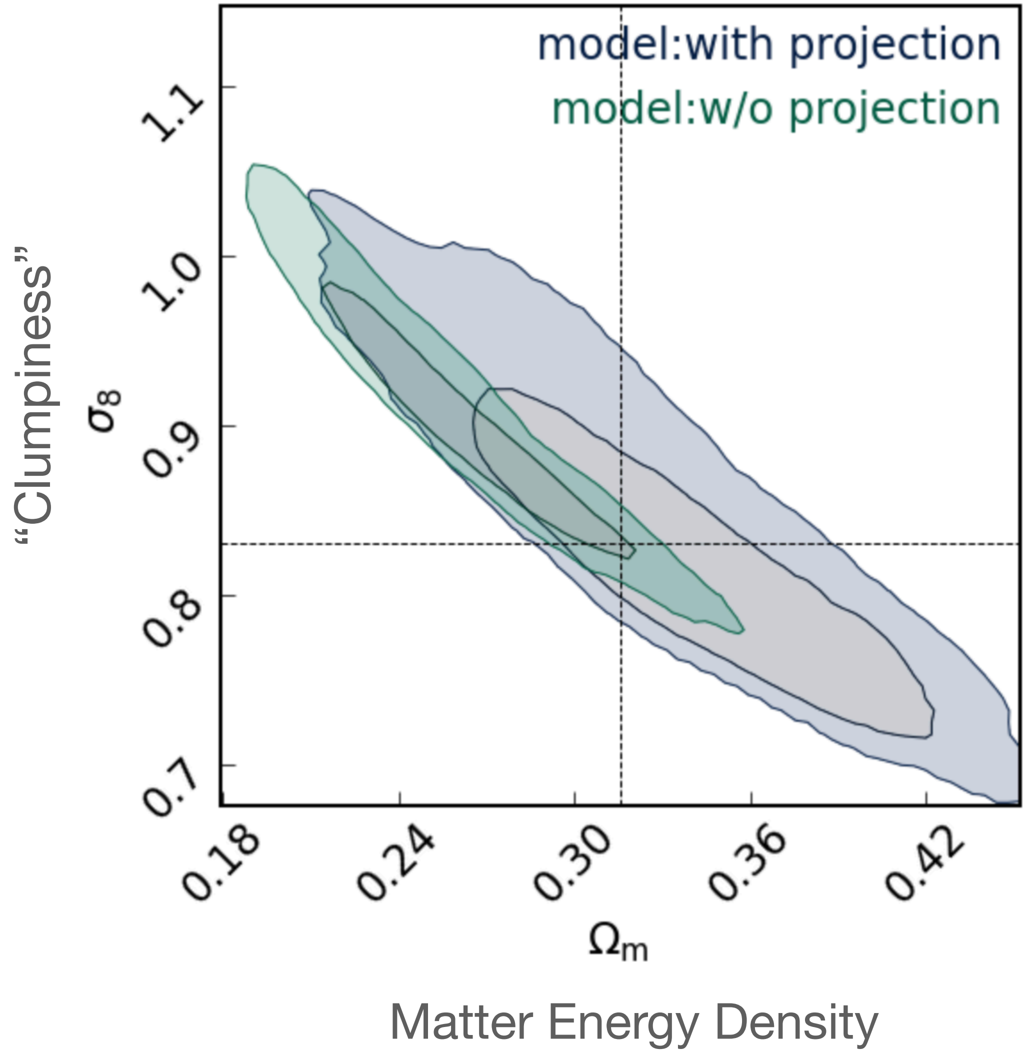


Park, TS+2022

We solved it with a simple model! Ask me later if you are interested in details

Including projection effects fixes the problem!

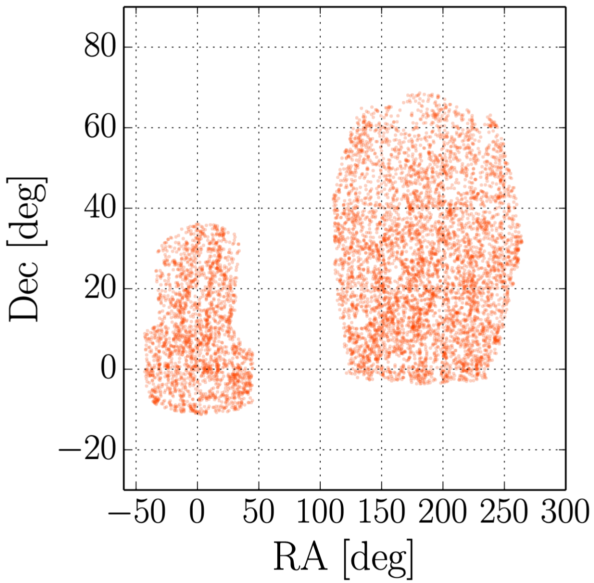
Ignoring the projection effects can bias the constraints on cosmological parameters



SDSS redMaPPer clusters x HSC WL Measurement

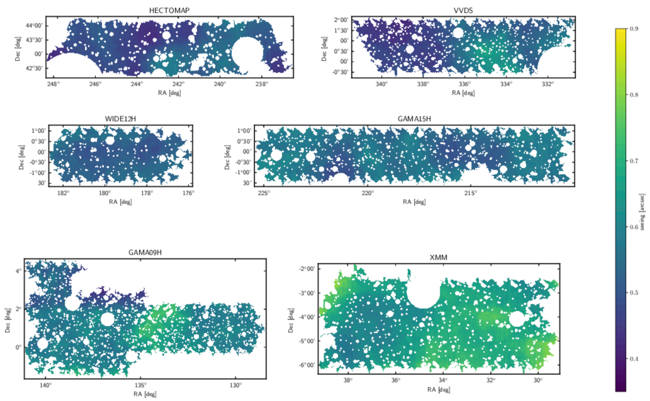
SDSS redMaPPer cluster sample

- Area ~ 8300 deg²
- z = [0.1, 0.33]
- λ = [20,30],[30,40],[40,55],[55,200]
- In total, ~8000 clusters
- Based on SDSS DR8 photometry



HSC-Y3 shape catalog

- Area ~ 433 deg² in total
- <z>~1.2.
- $n_s \sim 16 \mathrm{arcmin}^{-2}$



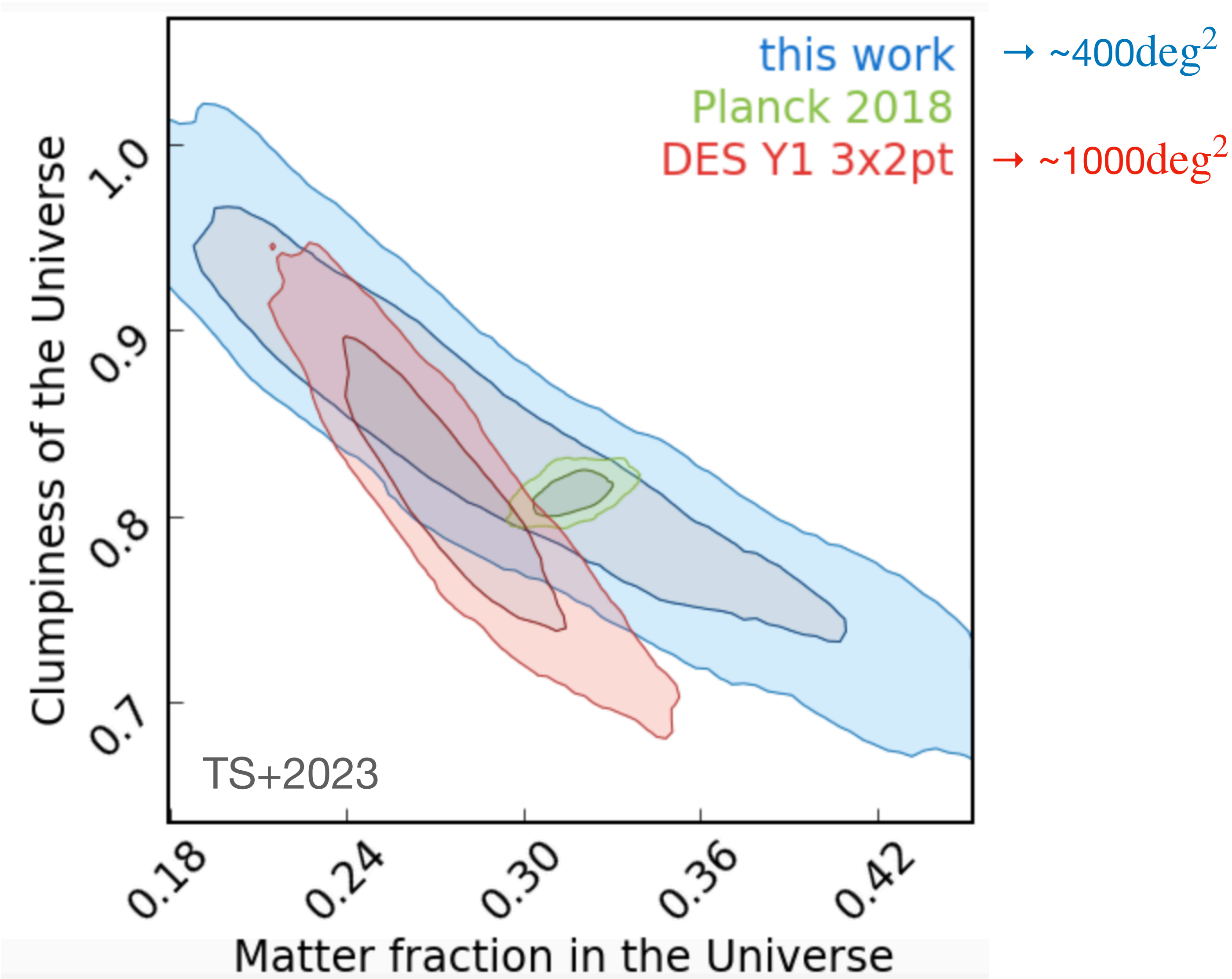
Cluster lensing signal

Cluster abundance

Cluster clustering signal

Optical Cluster Cosmology Constraints from HSC-Y3

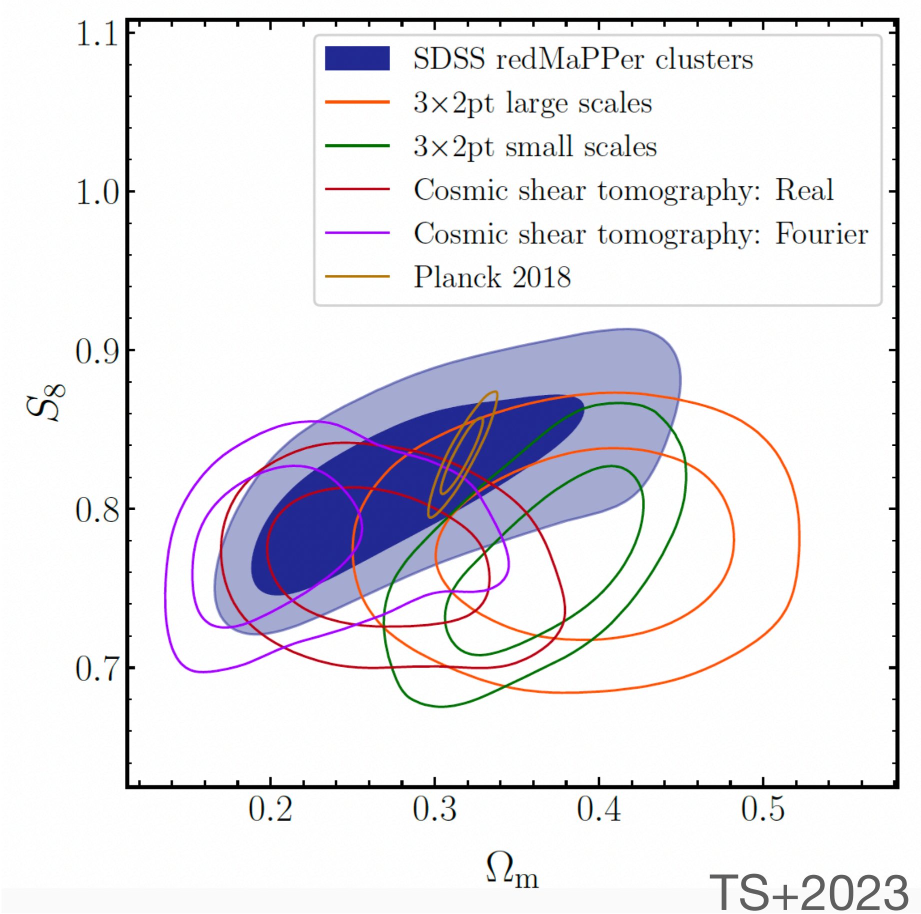
My result is consistent with other cosmology analyses from DES Y1 lensing (3x2pt) and Planck CMB measurements



Comparing to other HSC-Y3 lensing constraints…

My result is consistent with other HSC-Y3 lensing analyses at the level of 1-sigma on S_8

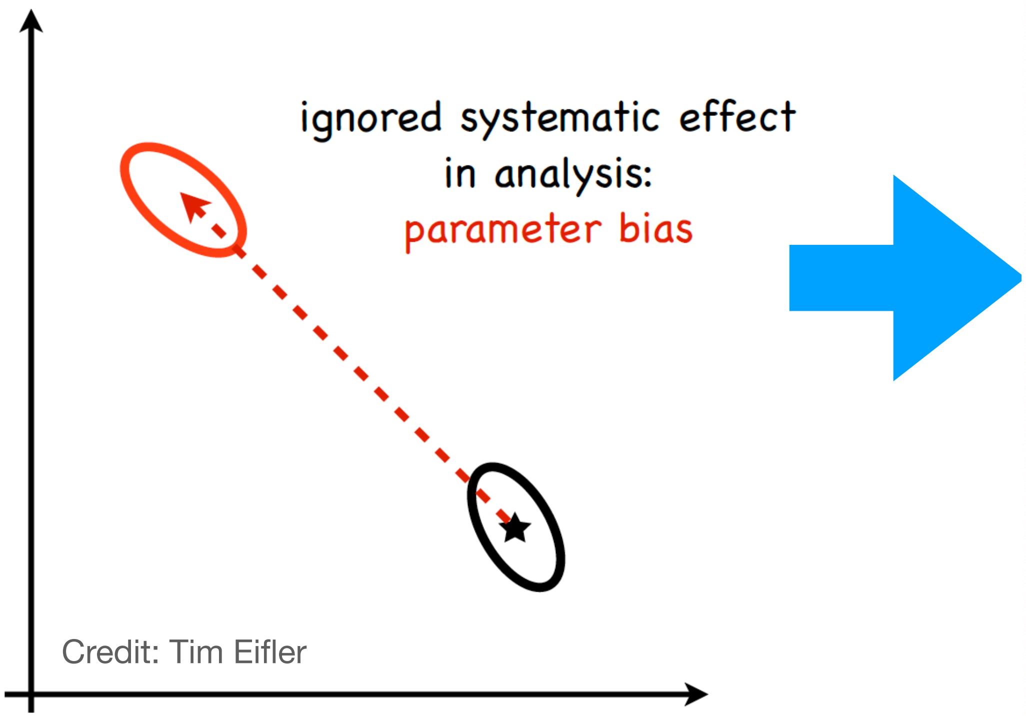
HSC Y3 lensing measurements

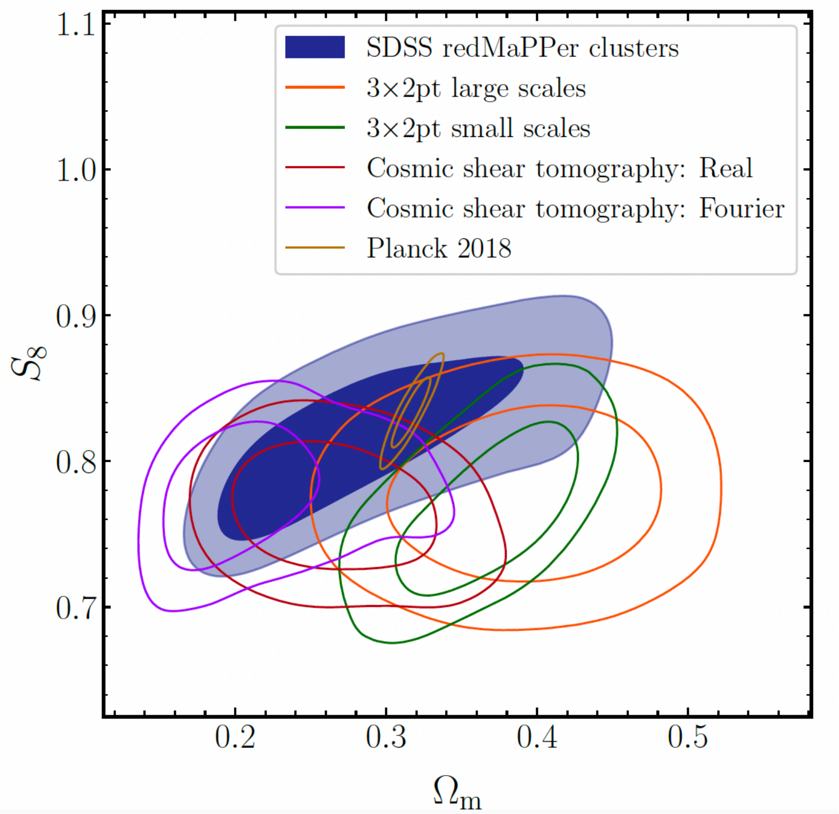


TS+2023

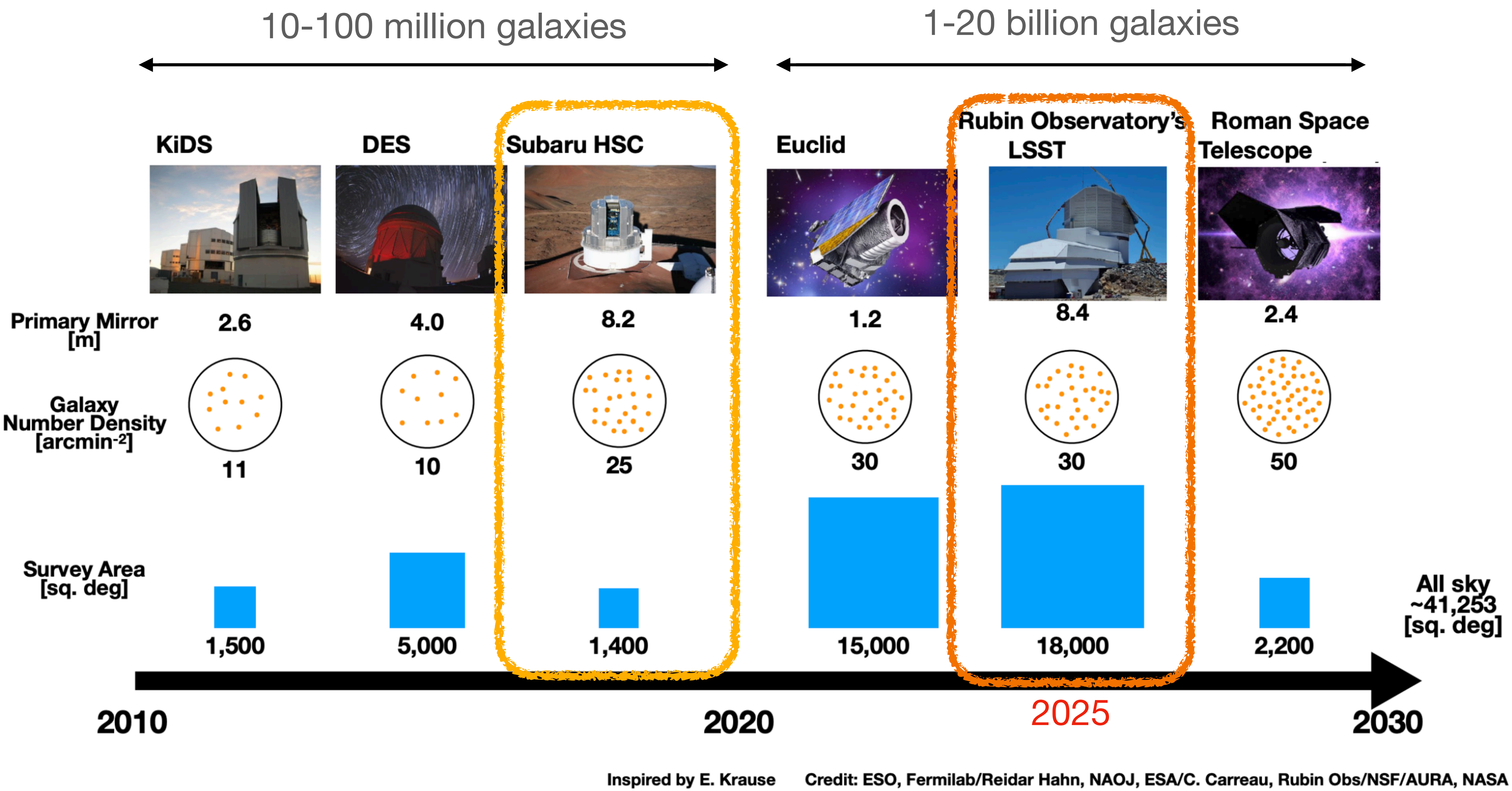
Lessons learned and next…?

- Projection effects make the distribution of optical cluster anisotropic
- Anisotropic distribution of optical clusters affect lensing signals around clusters—bias the cluster mass measurements from lensing
- Modeling projection effects fixed the problem of DES Y1 cluster cosmology analysis!





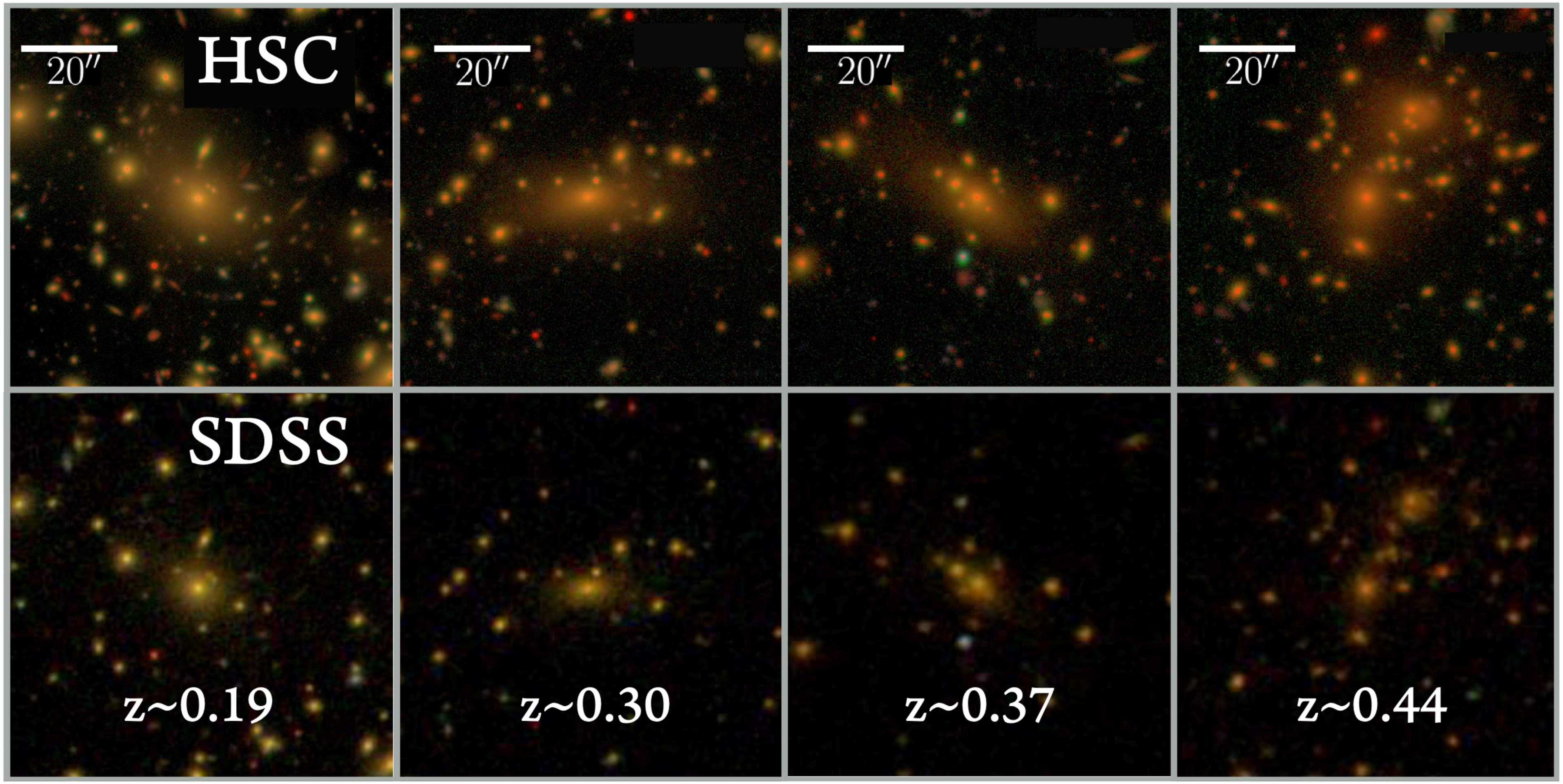
Photometric Surveys: Now and Future



Arai et al (incl. TS),2023

Subaru HSC: Best imaging data before Rubin

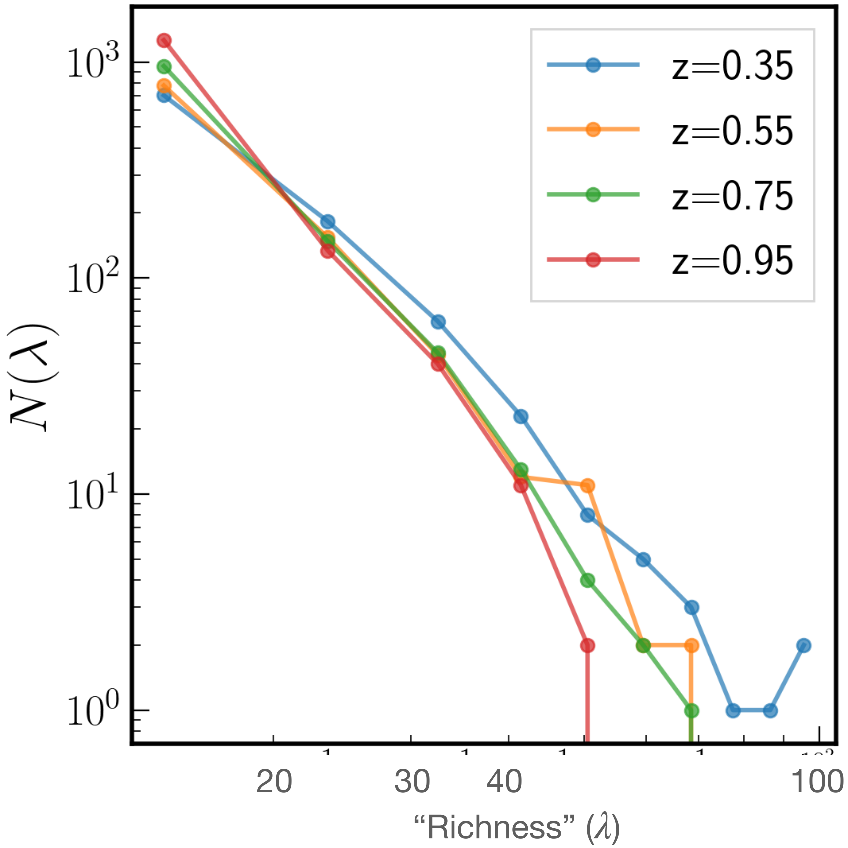
- We are currently preparing the final year data
- Final year data covers 1200 deg^2, which is roughly 3 times larger than HSC Y3 data



Plans for Optical Cluster Cosmology

With Subaru HSC final year data

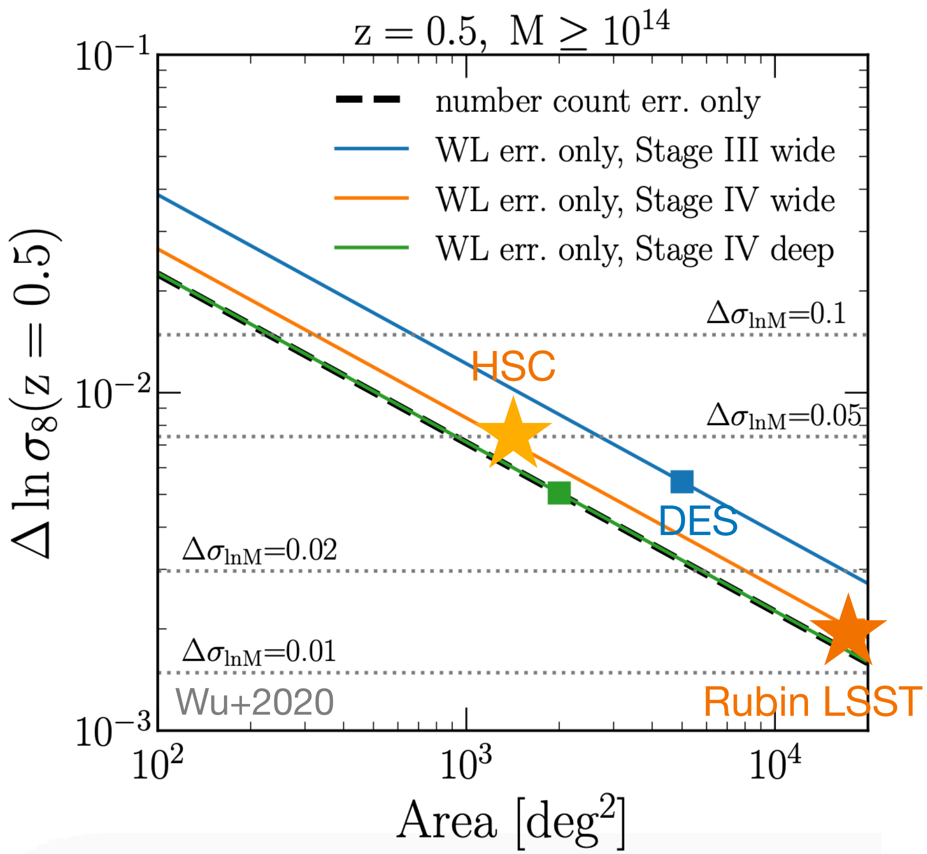
- HSC is almost as deep as Rubin LSST: we can track the evolution of galaxy clusters up to $z \sim 1.2$ → better constraint on Ω_m
- Can test LSST cluster analysis pipeline with HSC data



Rubin Legacy Survey of Space and Time (LSST)

Dark Energy Science Collaboration (DESC)

- Will start taking data in 2025
- ~20TB of raw data each night
- Cover ~18000 deg^2 and will find ~20,000 galaxy clusters up to z~1 (largest cluster catalog ever)
- Rubin LSST cluster cosmology can constrain σ_8 with a sub-percent precision at z~1!
- I am a DESC pipeline scientist for cluster cosmology WG



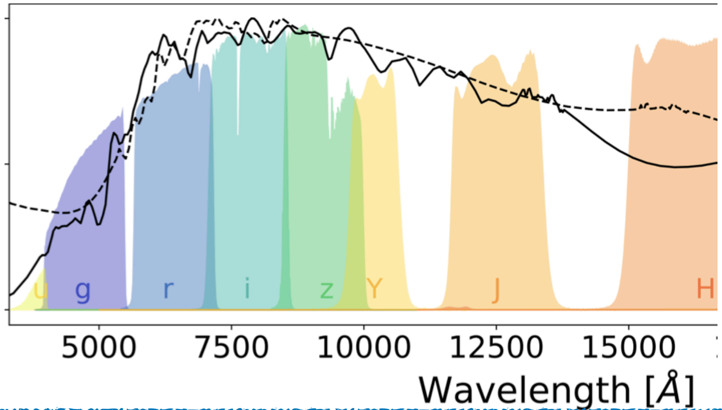
Structure probes and Geometrical probes

Photometric vs. Spectroscopic galaxy surveys

Photometry

- Redshift is estimated from colors (photo-z)
- Redshift uncertainty is large

→ 2D map of galaxy images

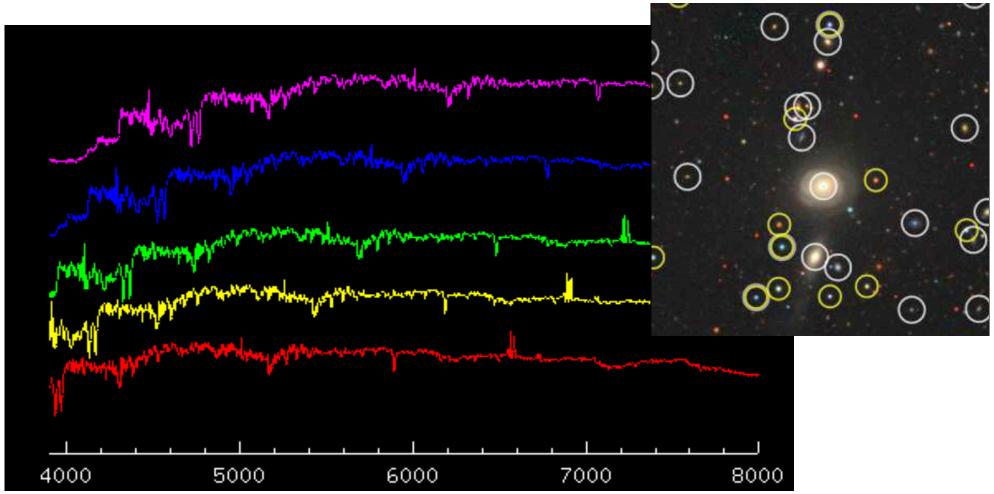


Structure probes: galaxy clusters, galaxy lensing

Spectroscopy

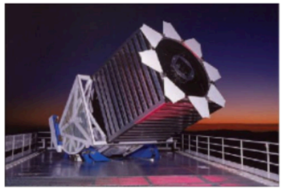
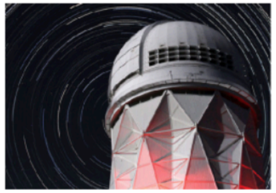
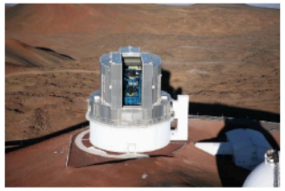
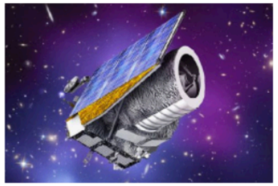
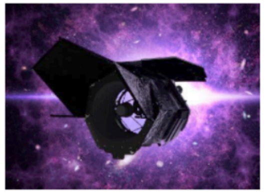
- Need to pre-select galaxies to measure spectra
- Precise redshift

→ 3D map of galaxy positions



Geometrical probes: Baryon Acoustic Oscillation (BAO), SNeIa

Roadmap of Spectroscopic Galaxy Surveys

	BOSS	eBOSS	DESI	Subaru PFS	Euclid	Roman Space Telescope
Primary Mirror [m]	2.5		4.0	8.2	1.2	2.4
Spectrograph	1000 fibers		5000 fibers	2400 fibers	Slitless	Slitless
Redshift	$0.2<z<0.7$	$0.7<z<1.1$	$1.1<z<1.6$	$0.8<z<2.4$	$0.7<z<2.1$	$1.0<z<2.8$
# of galaxies	~1.3M	~550k	~10M	~4M	~50M	~18M
Survey Area [sq. deg]	9,000	9,000	14,000	1,400	15,000	2,200

2010 → 2020

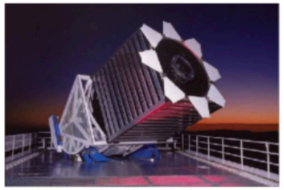
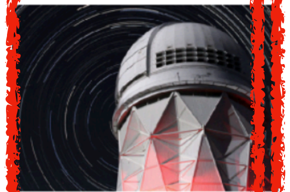
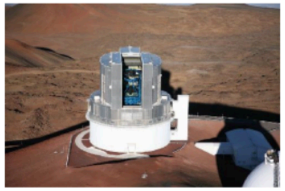
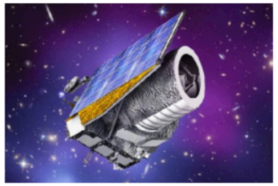
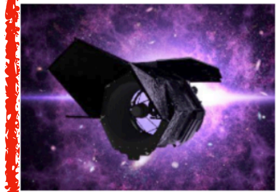
Arai et al (incl. TS),2023

Credit: SDSS, NOIRLab, NAOJ, ESA/C. Carreau, NASA

Stage-III (BOSS, eBOSS)

Stage-IV (DESI, Subaru PFS, Euclid, Roman Space Telescope)

Roadmap of Spectroscopic Galaxy Surveys

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u, NASA

Roman PIT member

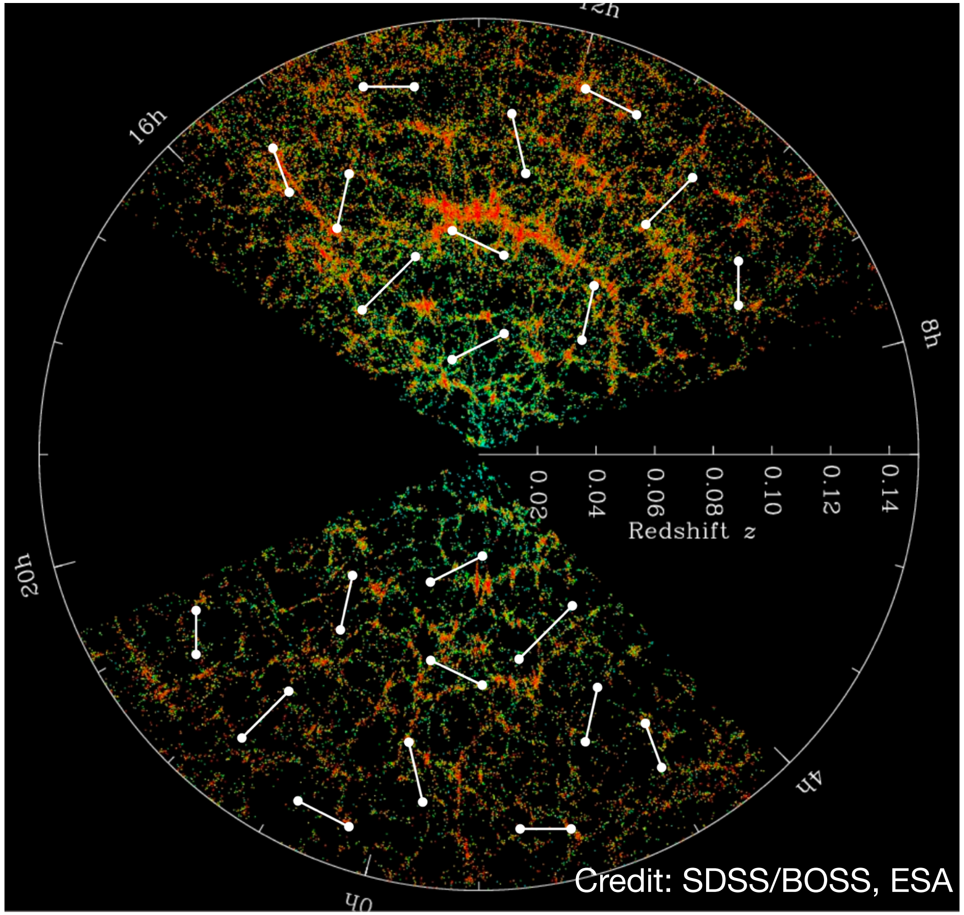
Leader of Cosmology WG

- Shaping science goals
- Optimizing survey design
- Identify/manage tasks to achieve science goals

Statistical tool to quantify galaxy distributions

2-point correlation functions/Power spectrum

- Galaxy correlation functions measure an excess probability (relative to Poisson) of galaxy pairs separated by distance r.



Matter Density Contrast

$$\delta(r) = \frac{n(r,t) - \bar{n}(t)}{\bar{n}(t)}$$

2 point correlation function

$$\xi(r) = \frac{DD(r)}{RR(r)} - 1$$

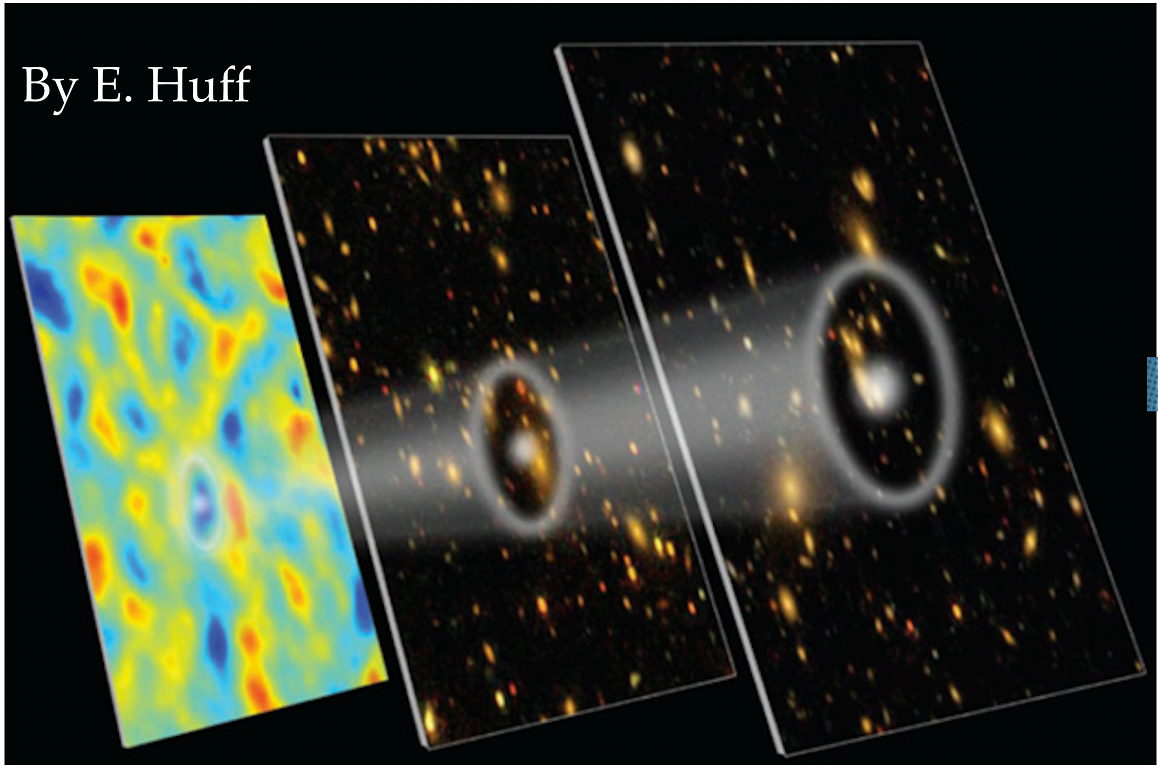
Fourier Transformation

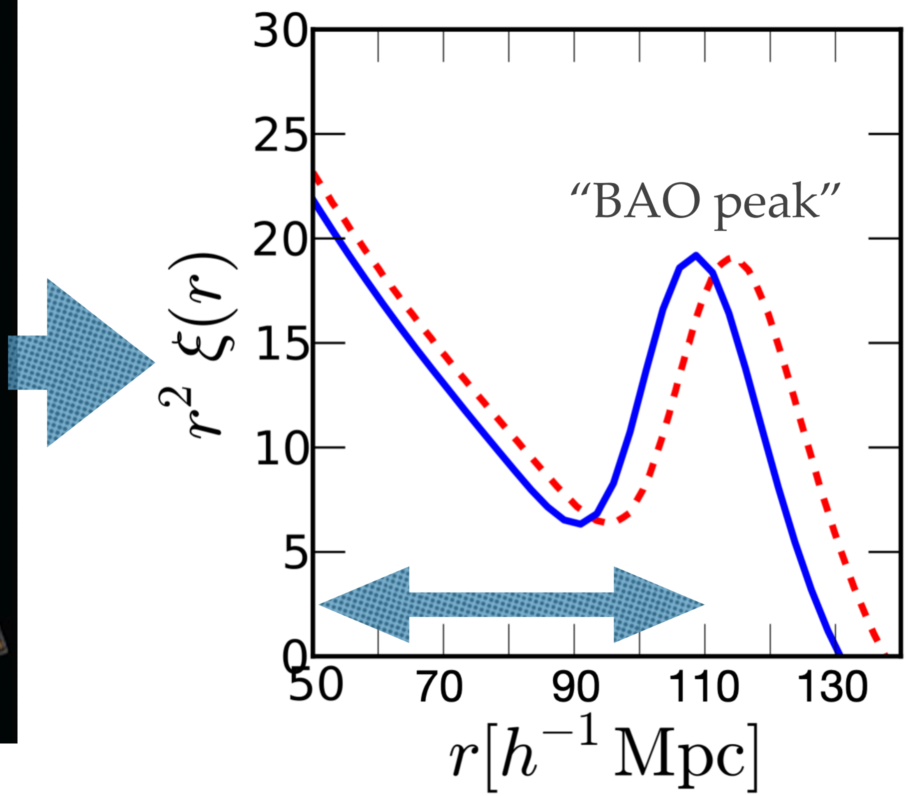
Power spectrum

$$\left\langle \delta(\vec{k})\delta(\vec{k'}) \right\rangle = (2\pi)^3 \delta_D(\vec{k} - \vec{k'})P(k)$$

Baryon Acoustic Oscillations (BAO)

Standard Ruler

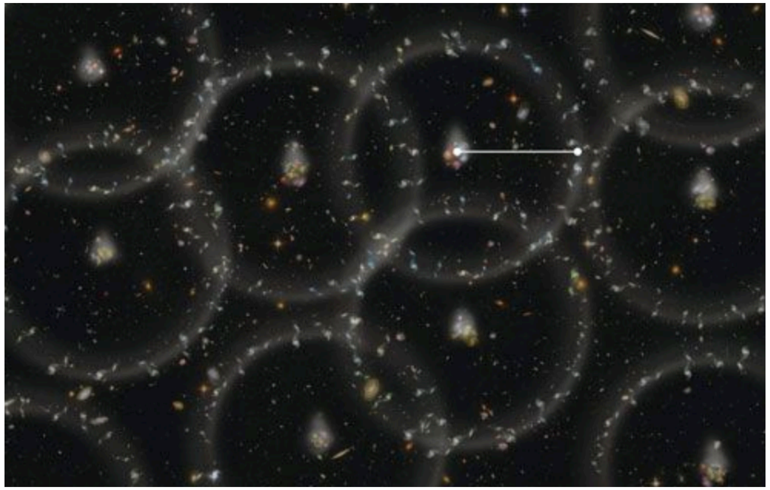


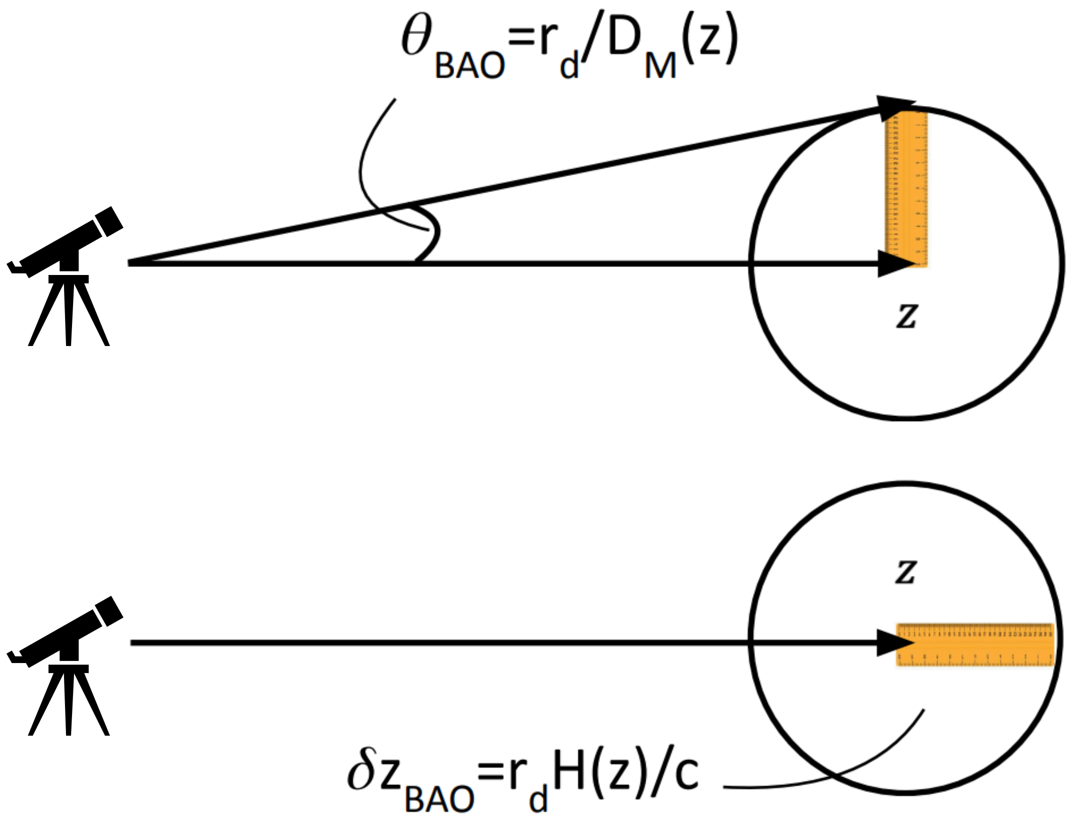


- Imprint of sound waves frozen in the early Universe
- Scale set by sound horizon and does not change in time, but depends on the amount of dark energy

Baryon Acoustic Oscillations (BAO)

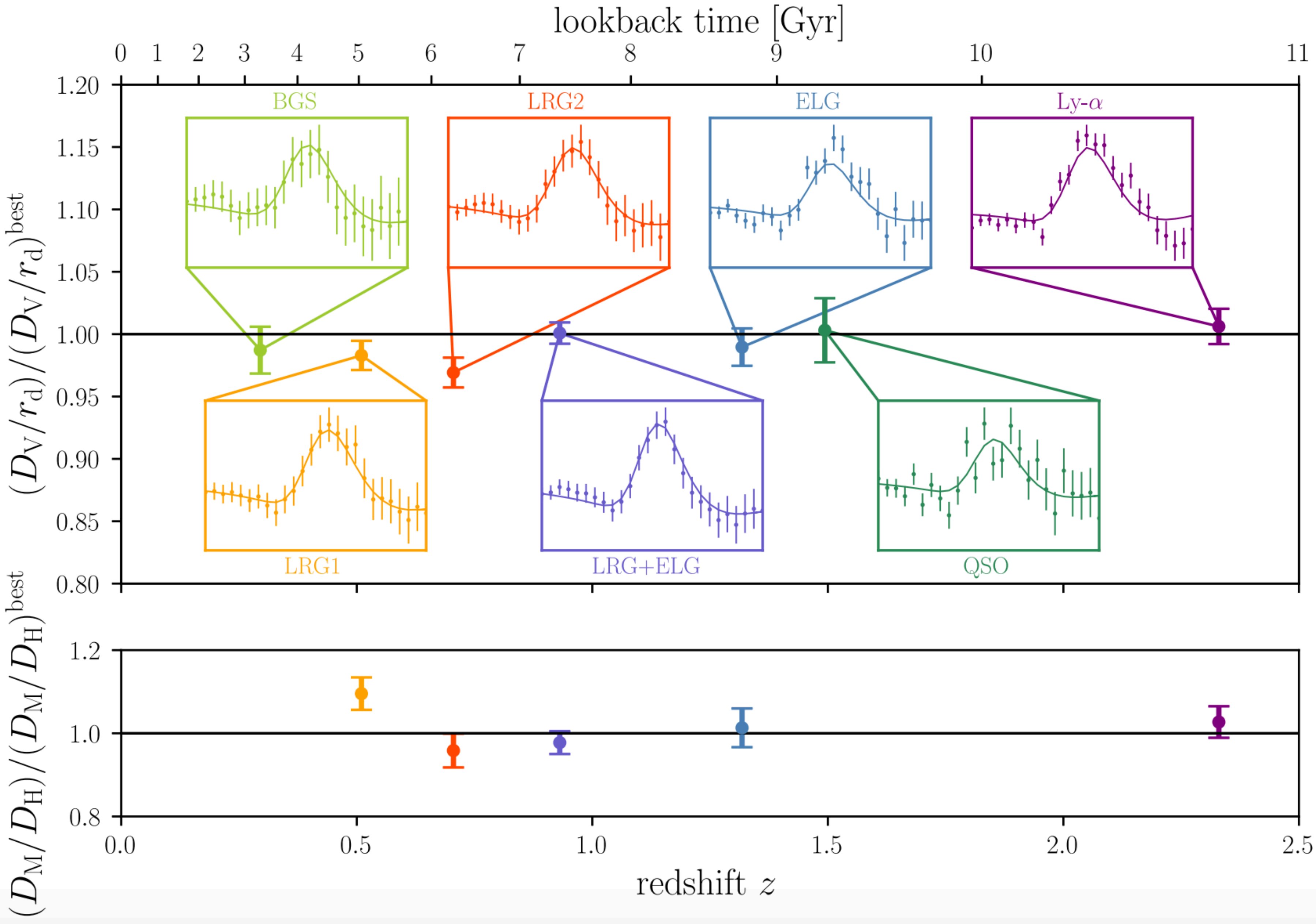
Standard Ruler





$$D_V \propto [D_M^2(z)H^{-1}(z)]^{1/3}$$

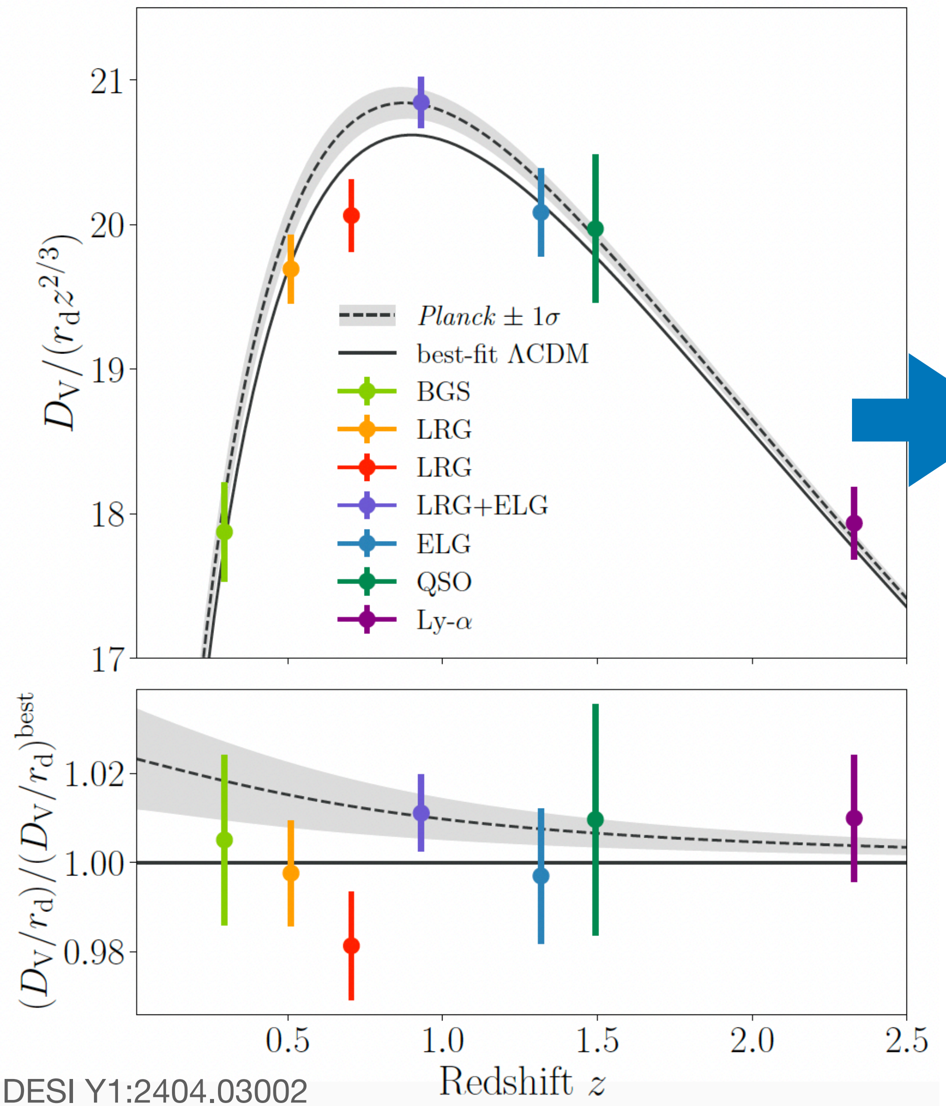
DESI Y1 BAO measurements



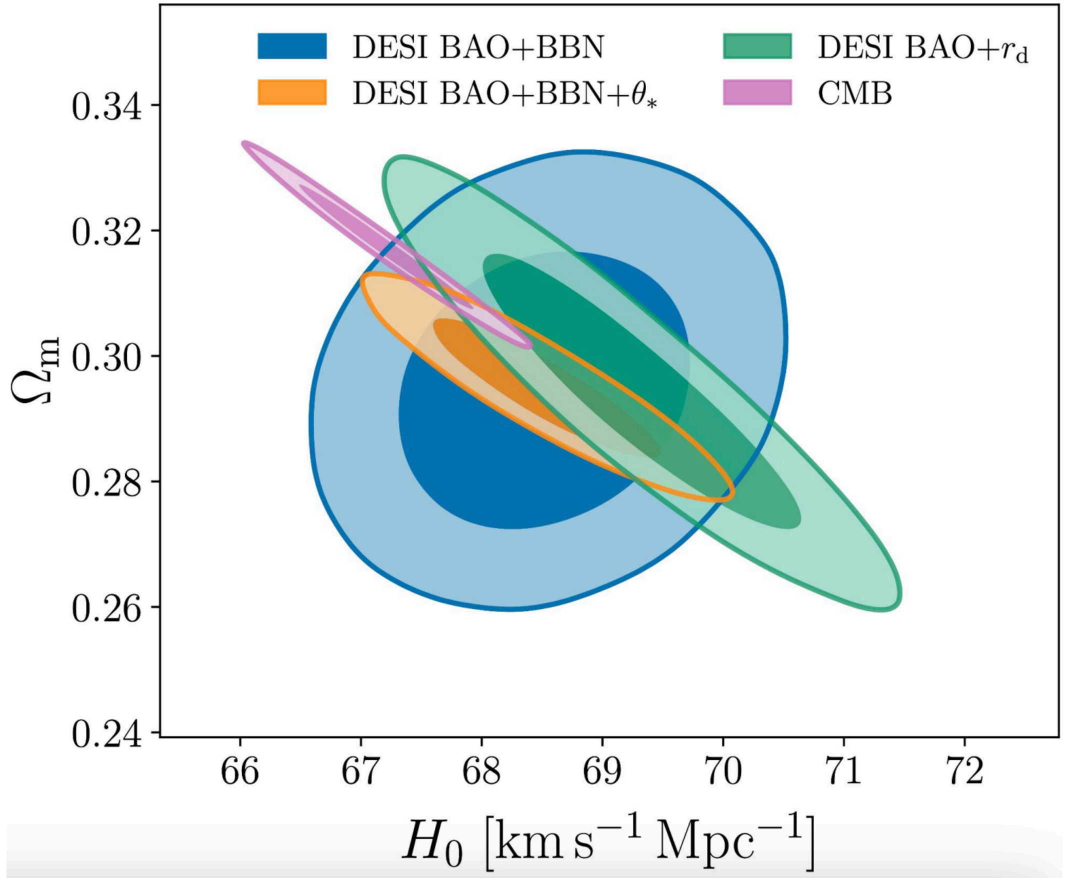
DESI Y1 Cosmology Result

ΛCDM model: consistent with Planck CMB

BAO measurement



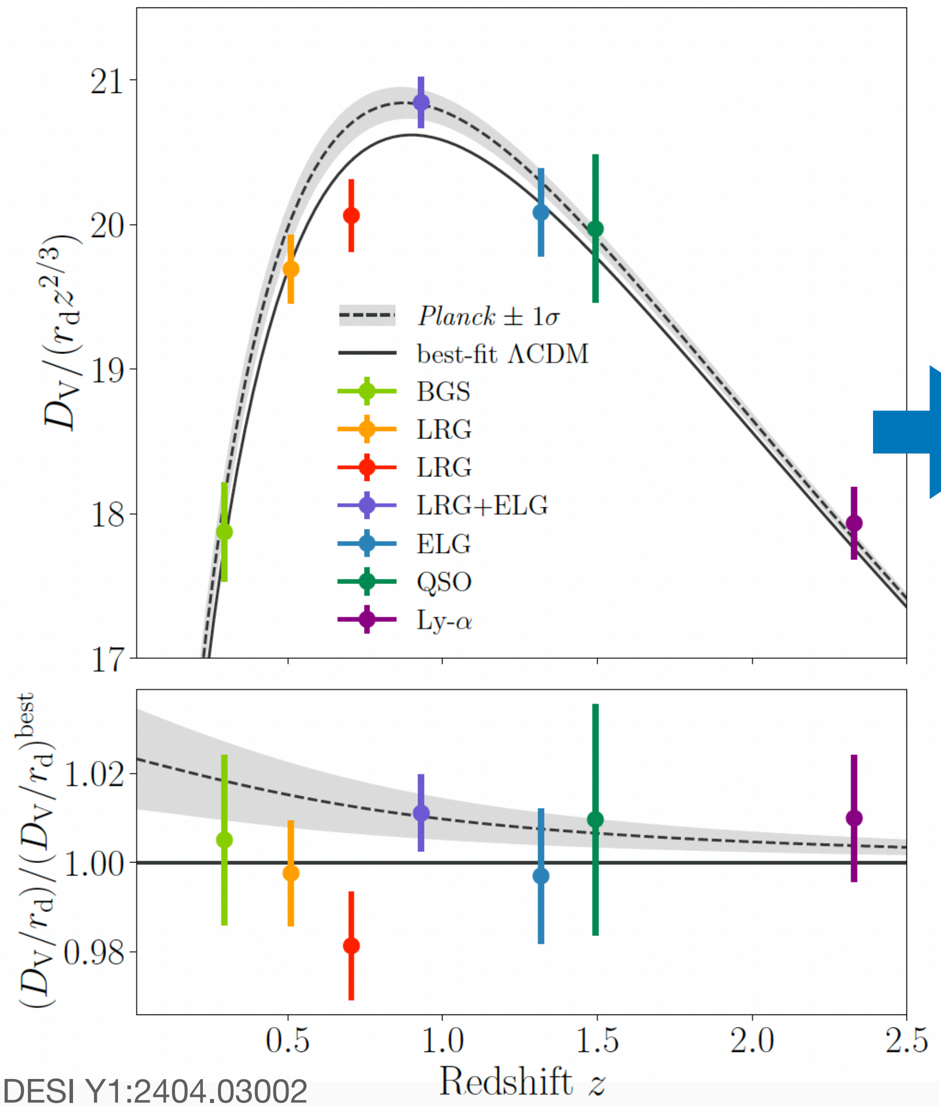
DESI Y1:2404.03002



DESI Y1 Cosmology Result

Potential evidence of time-varying DE?

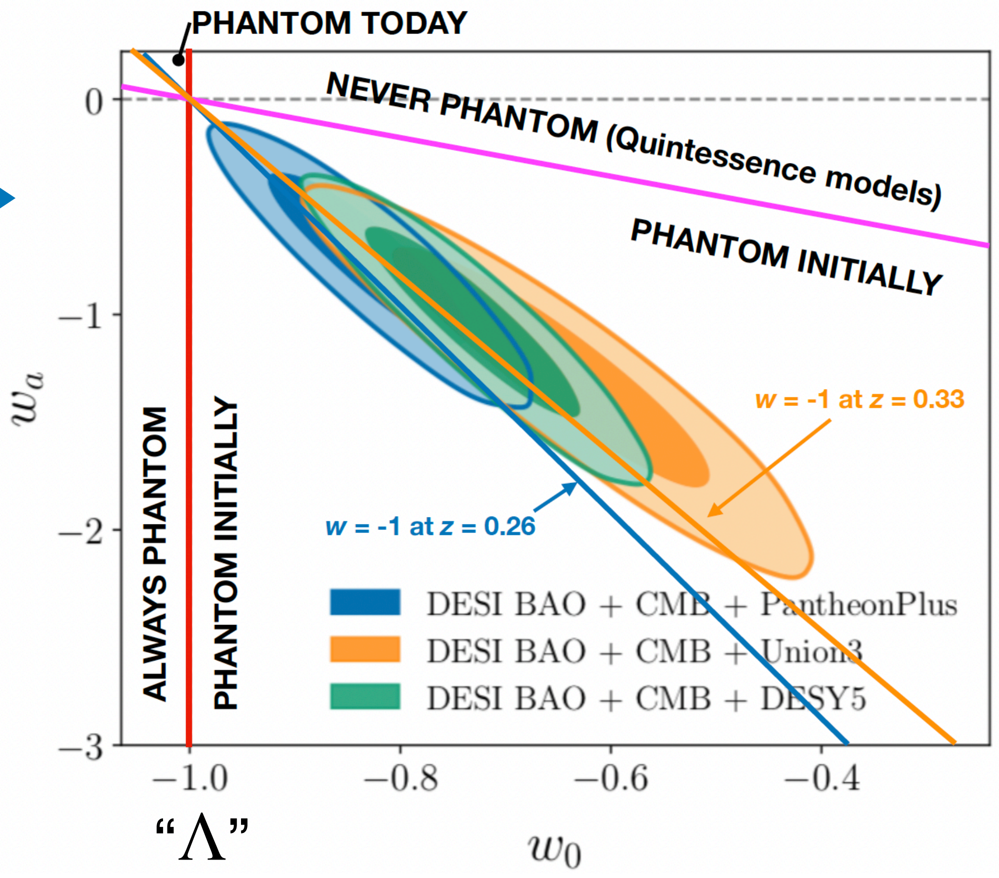
BAO measurement



DESI Y1:2404.03002

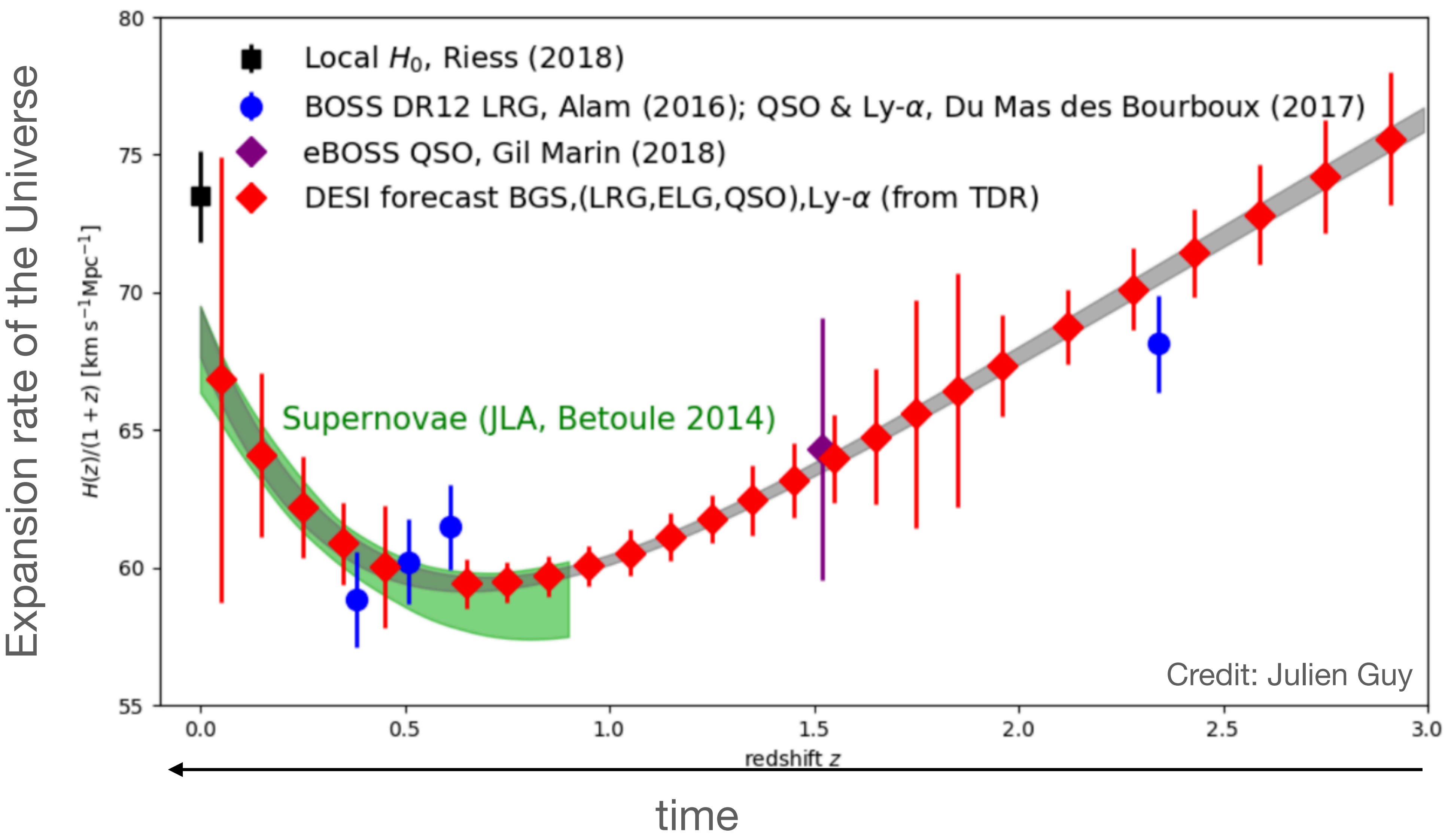
$$\Omega_{DE}(z) = \Omega_{DE,0}\exp\{3\int_0^z \frac{dz}{1+z}[1+w(z)]\}$$

$$w(z) = w_0 + w_a \frac{z}{1+z}$$



DESI will constrain the expansion rate of the Universe with unprecedented precision

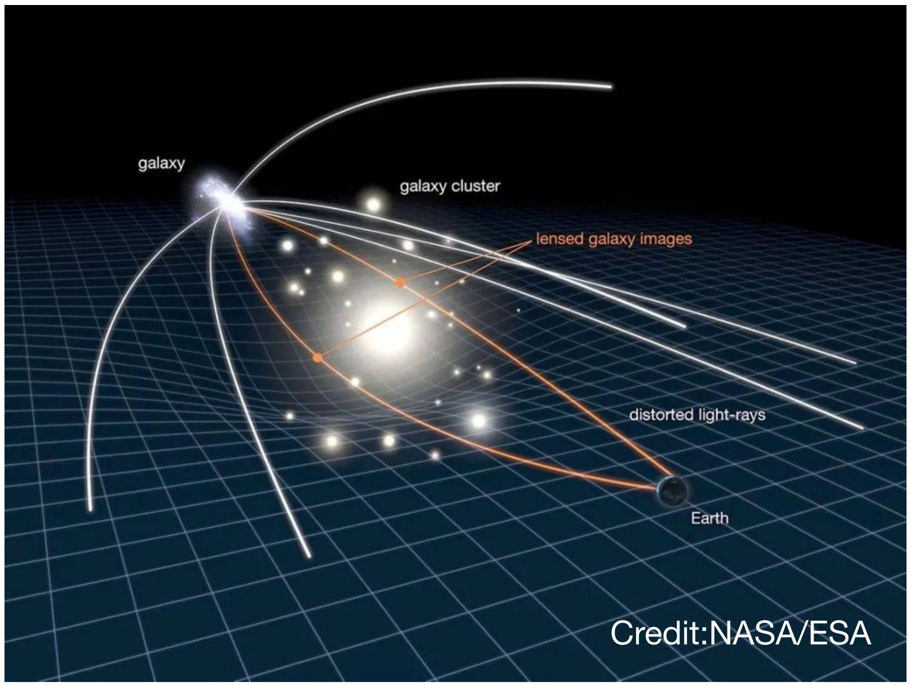
Using Baryon Acoustic Oscillations="Standard Ruler"

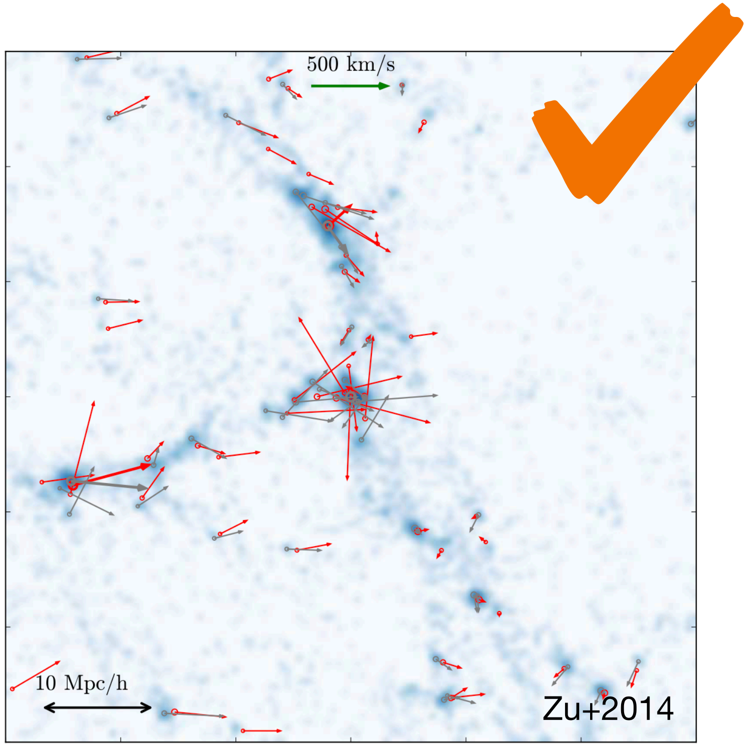


We can probe structure in two ways…

Gravitational lensing and galaxy velocities

- Path of light is bent by gravity (gravitational lensing)
- Similarly, motions of planets, stars, and galaxies are response to gravitational potential



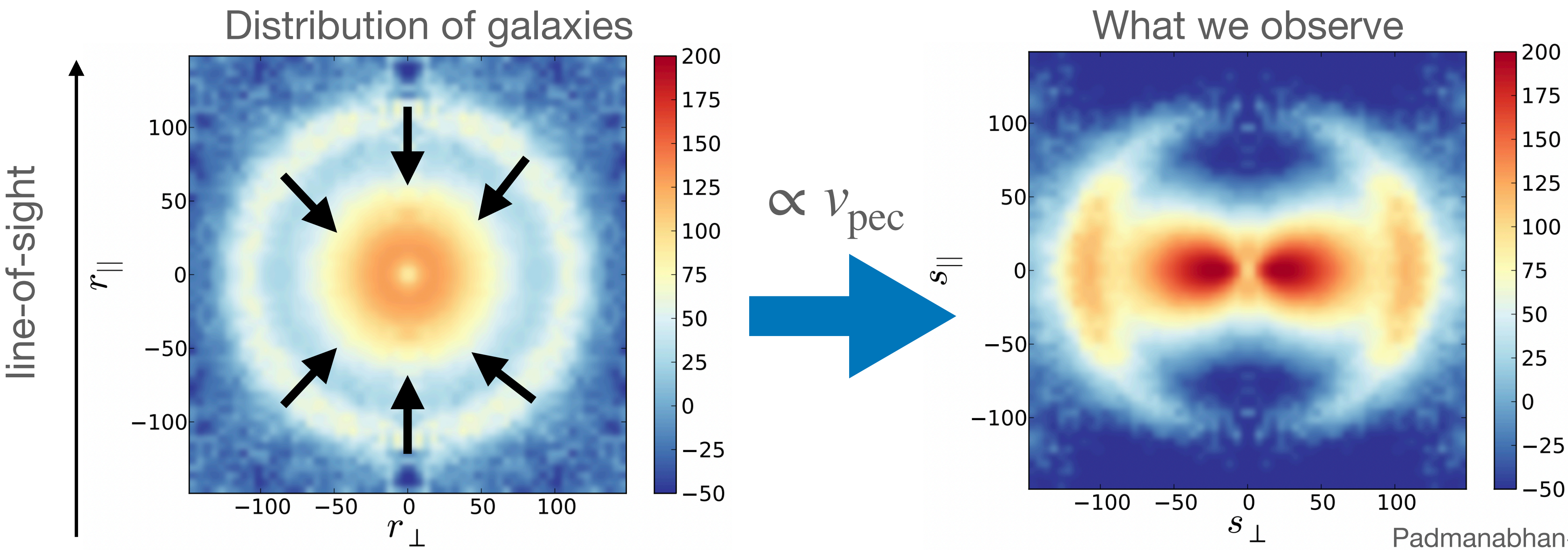


Redshift-Space Distortion (RSD)

- Redshift is a combination of Hubble expansion and peculiar motion of galaxies → isotropic galaxy distribution becomes anisotropic in redshift-space

$$cz = H_0 r + v_{\rm pec}$$

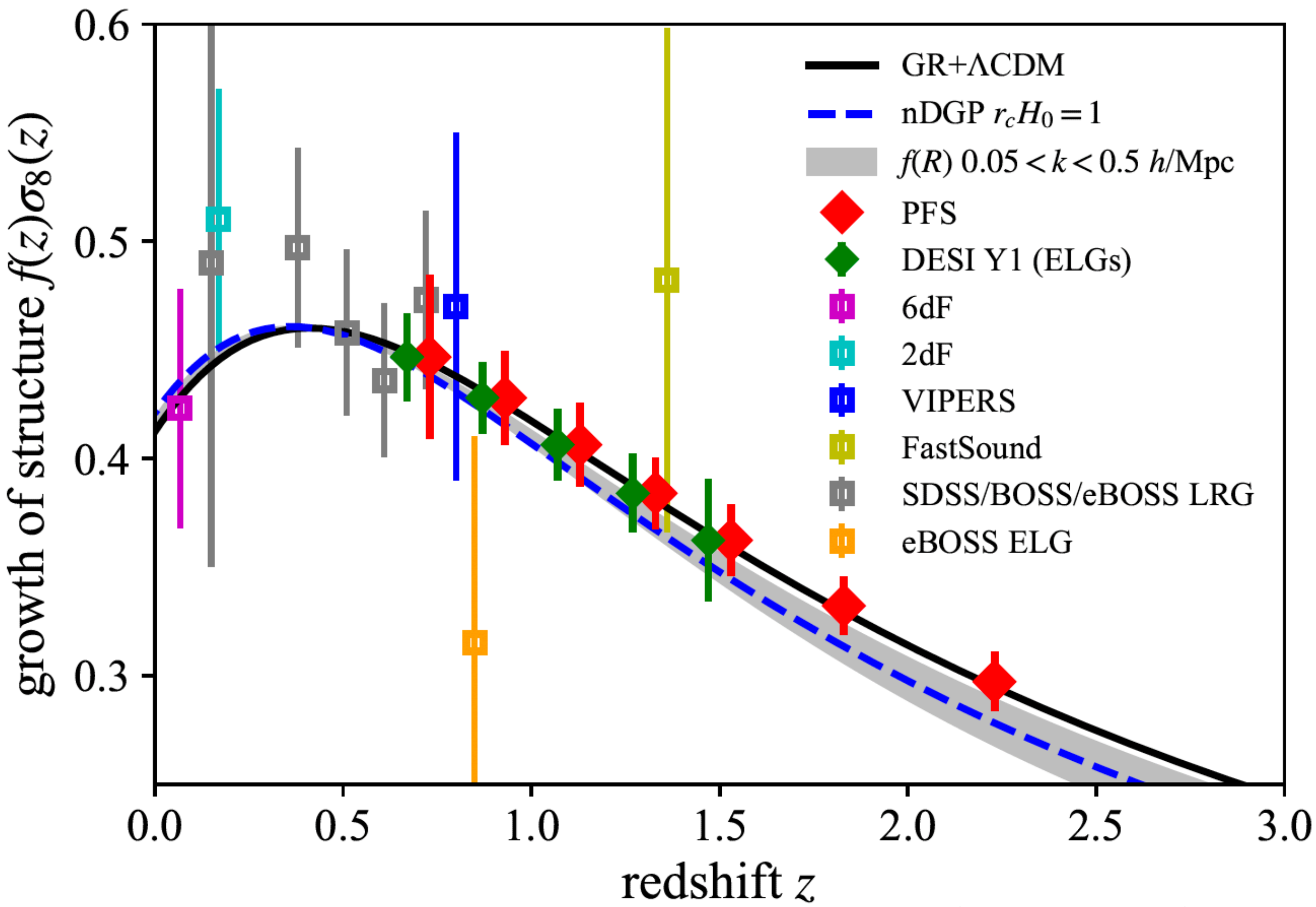
Redshift "What we measure"	Expansion of the Universe	Motion of Galaxies



Padmanabhan+2012

Forecast for DESI Y1 and PFS in a few years

- Can constrain the growth of structure with 6% up to z~2.4



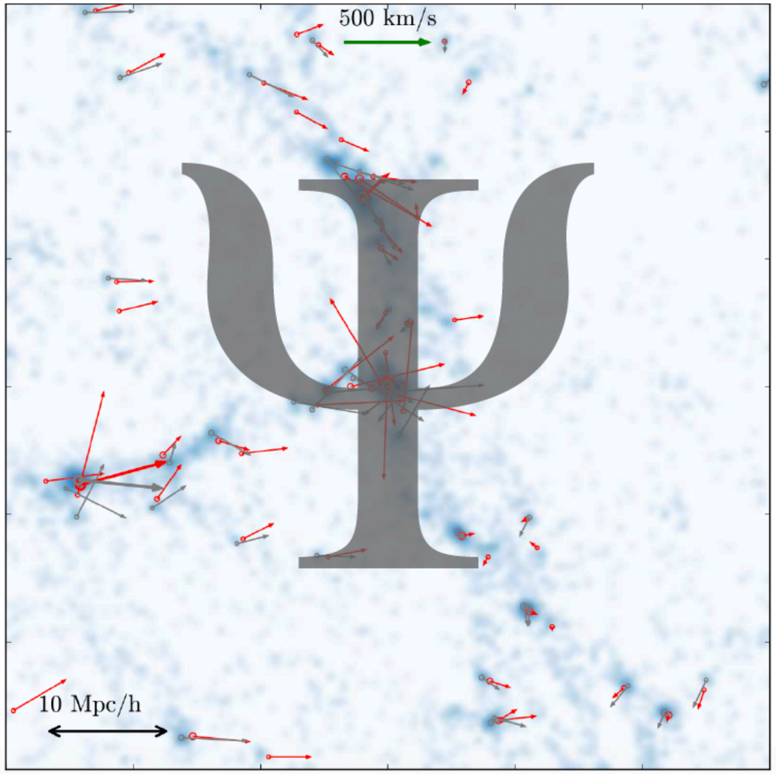
PFS forecast: TS+,in prep.

Testing theory of gravity on cosmological scales

Combining galaxy velocities and lensing

- Photons (light rays for lensing) are sensitive to $\Phi + \Psi$, and galaxies experience the Newtonian potential Ψ

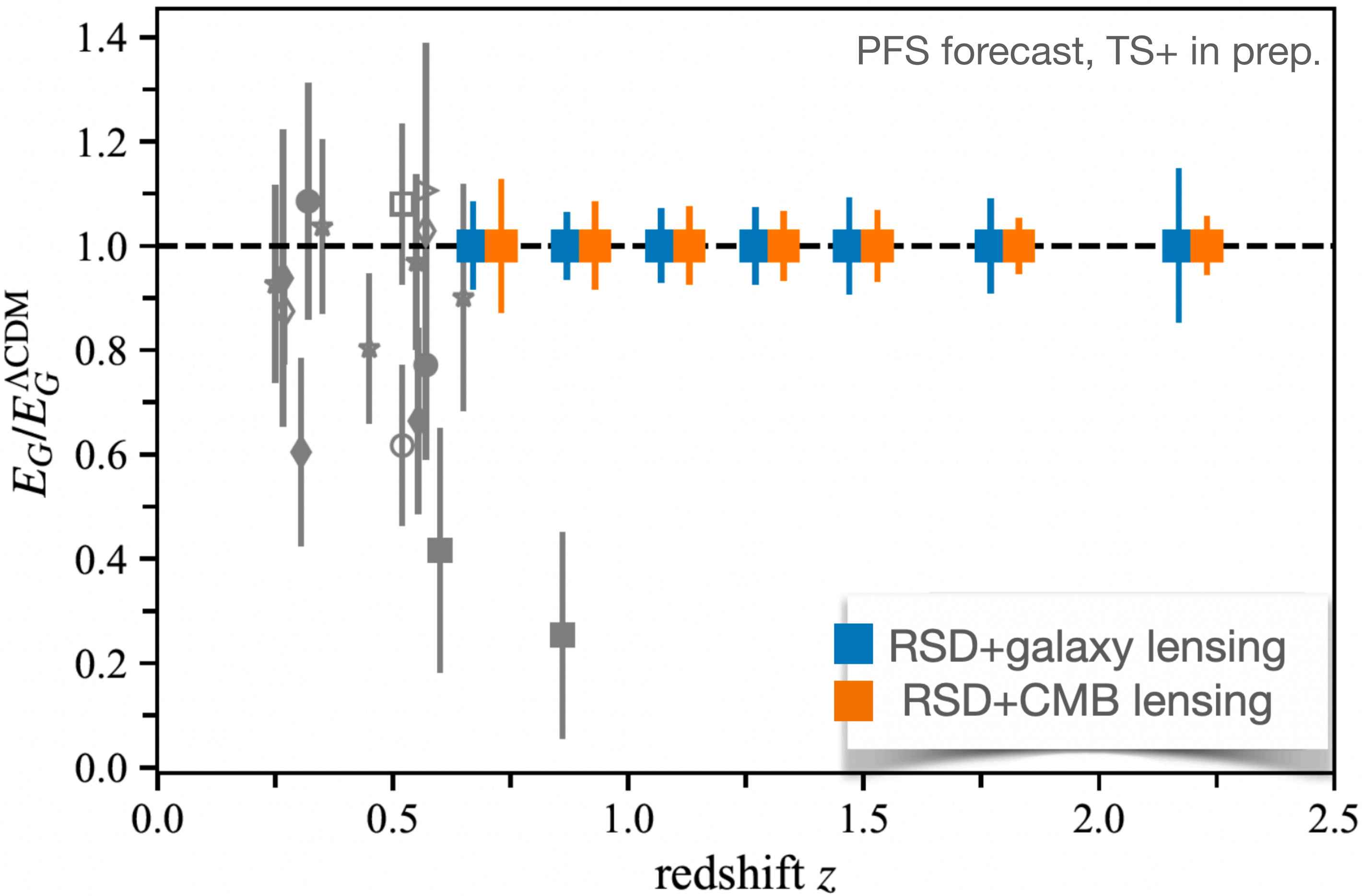
- GR predicts $\Phi = \Psi$



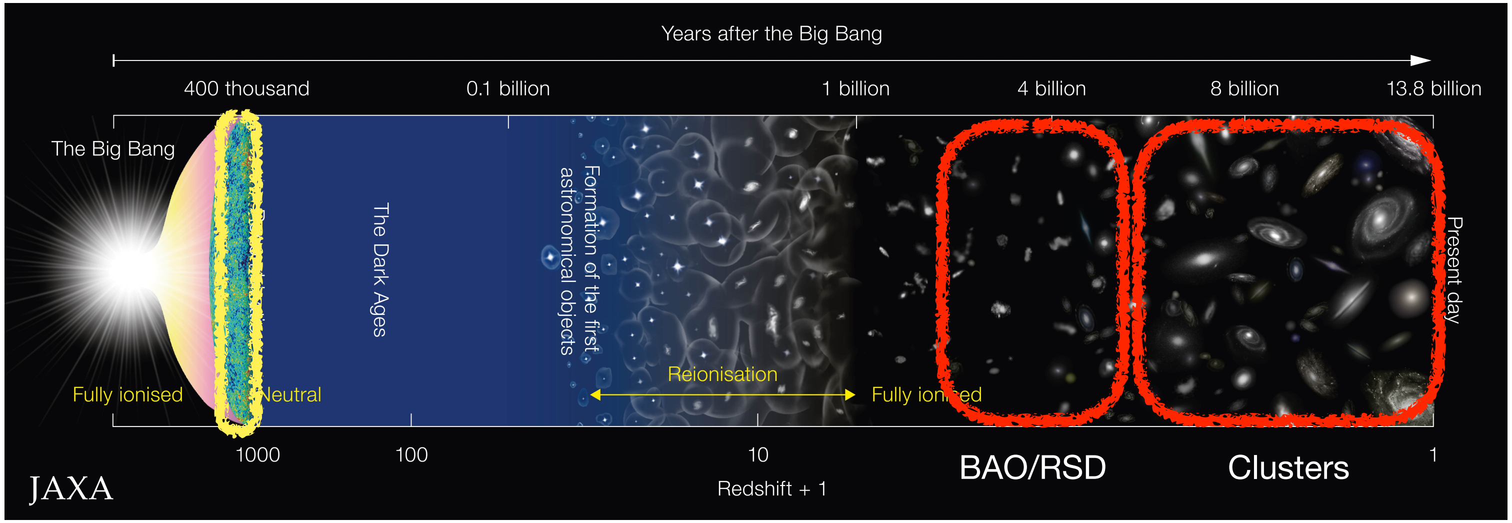
Testing theory of General Relativity

- E_G statistics combines galaxy velocity and lensing
- Spectroscopic data provides galaxy velocity information, and photometric data provides galaxy lensing measurements
- GR predicts $\Phi = \Psi$

Gray points are existed constraints:
Blake+2016: WiggleZ/BOSS+CFHTLen
Pullen+2016: BOSS+Planck
delaTorre+2016: VIPERS+CFHTLenS
Alam+2016: BOSS+CFHTLenS
Amon+2018: GAMA+KiDS/2dFLens
Singh+2019: BOSS+SDSS/Planck
Jullo+2019: BOSS+CFHTLenS
Blake+2020: BOSS+KiDS-1000/2dFLen



Summary



- Optical clusters can be the most powerful cosmological probe at z<1 if we can control systematics robustly
- BAO is the powerful cosmological probe with the least systematics and can measure the expansion rate of the Universe with a sub-percent precision in future
- Using these probes, we can constrain cosmological parameters very precisely and can tell whether the current cosmological tensions are in the early Universe, the later Universe or somewhere in between, more decisively