Testing cosmological models with galaxy surveys

NORDITA
The Nordic Institute for Theoretical Physics

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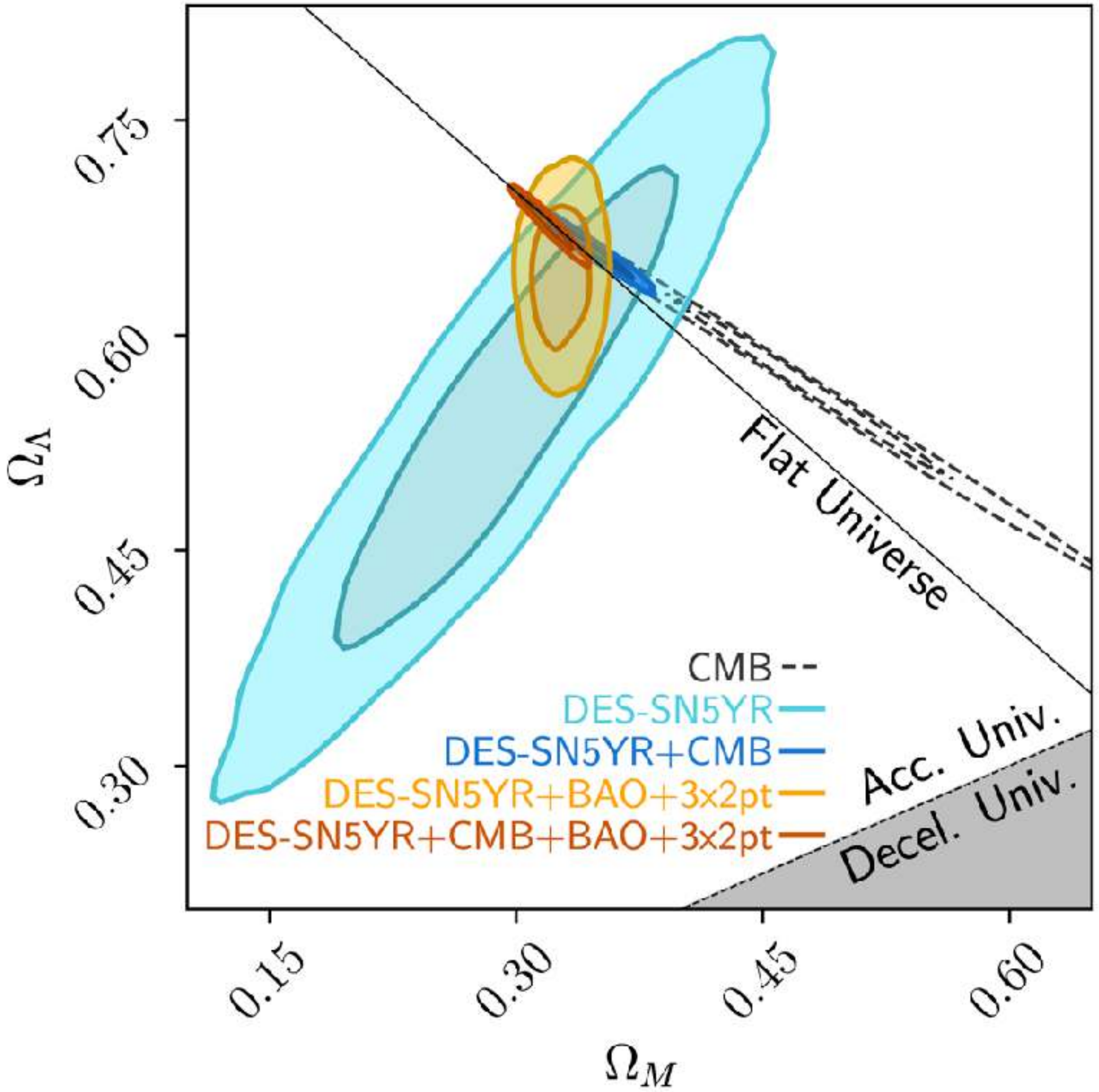
A flat and accelerating Universe

- We have known for some time that the Universe is pretty flat from the combination of CMB, SN Type Ia & LSS measurements.
- Supernovae measurements discovered the acceleration of the expansion Universe a couple of decades ago —> There is a dark energy component.

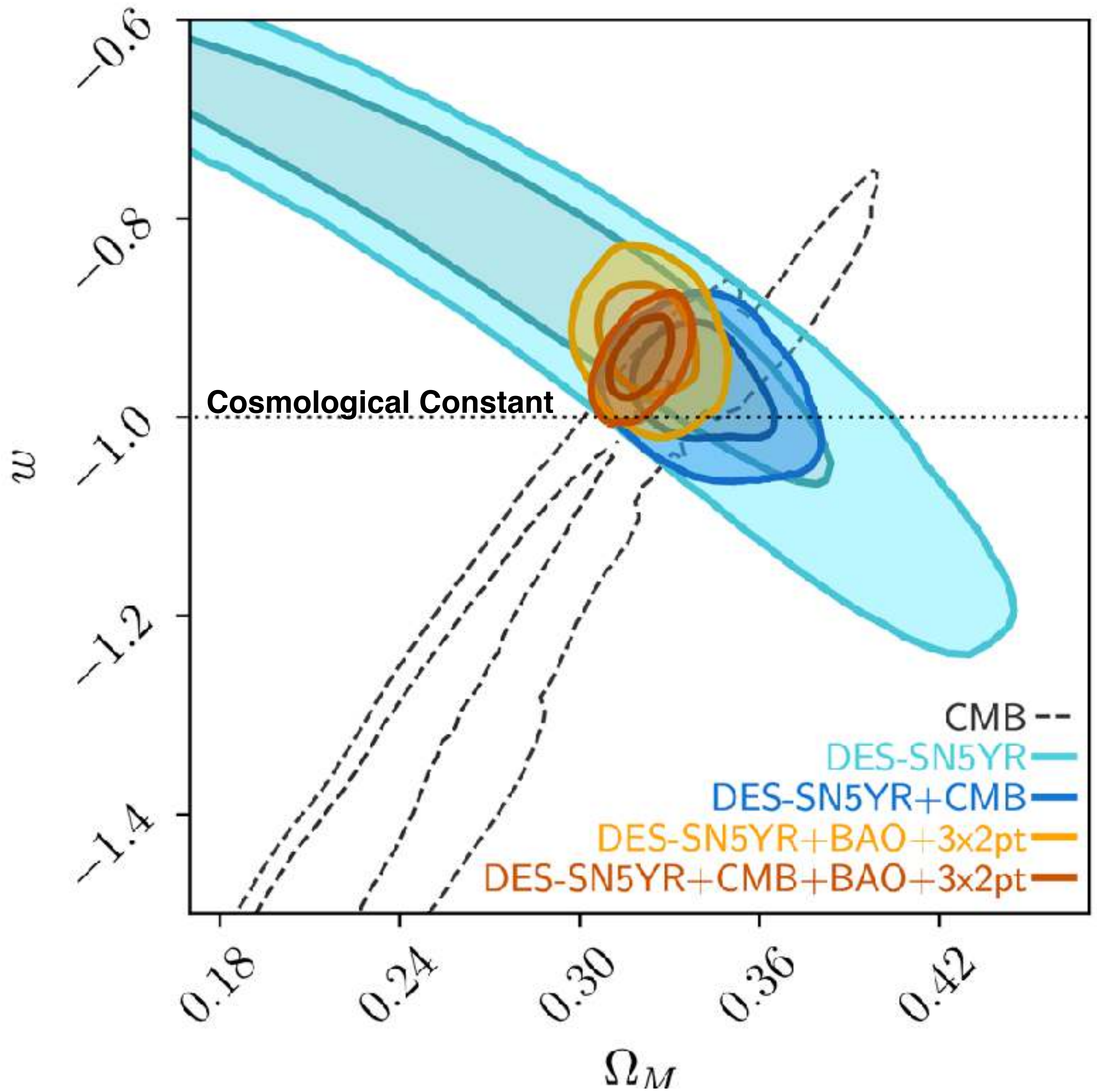
arXiv: 2401.02929 (2024)



Is Dark Energy a cosmological constant?

- Dark Energy seems to be compatible with a **cosmological constant** with the most recent observations —> *w*, the parameter describing the evolution of dark energy with time is compatible with -1 given the current uncertainties.

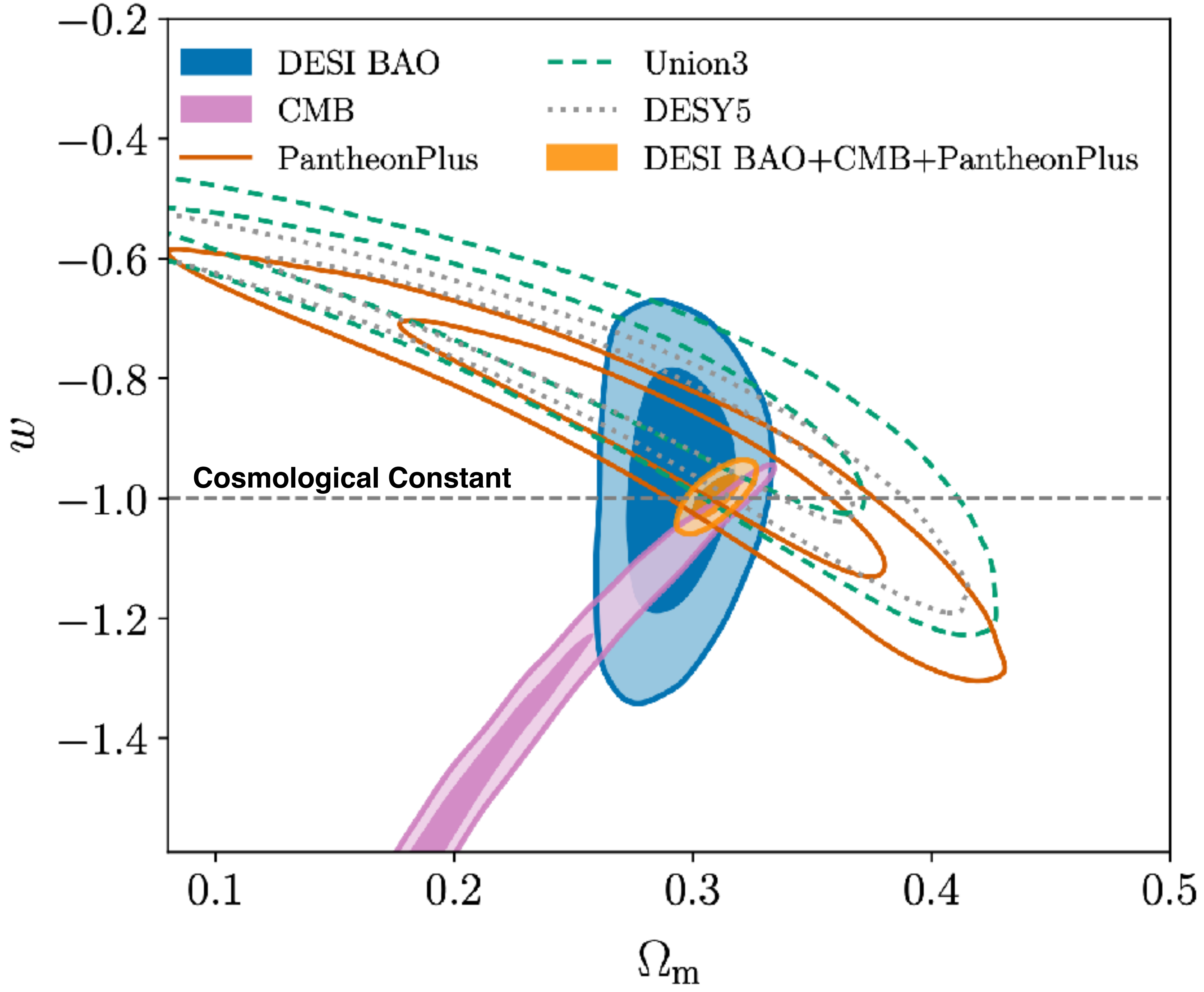
arXiv: 2401.02929 (2024)



Is Dark Energy a cosmological constant?

- DESI new recent results are also compatible with w = -1 in the wCDM model.

DESI Collaboration: arXiv: 2404.03002

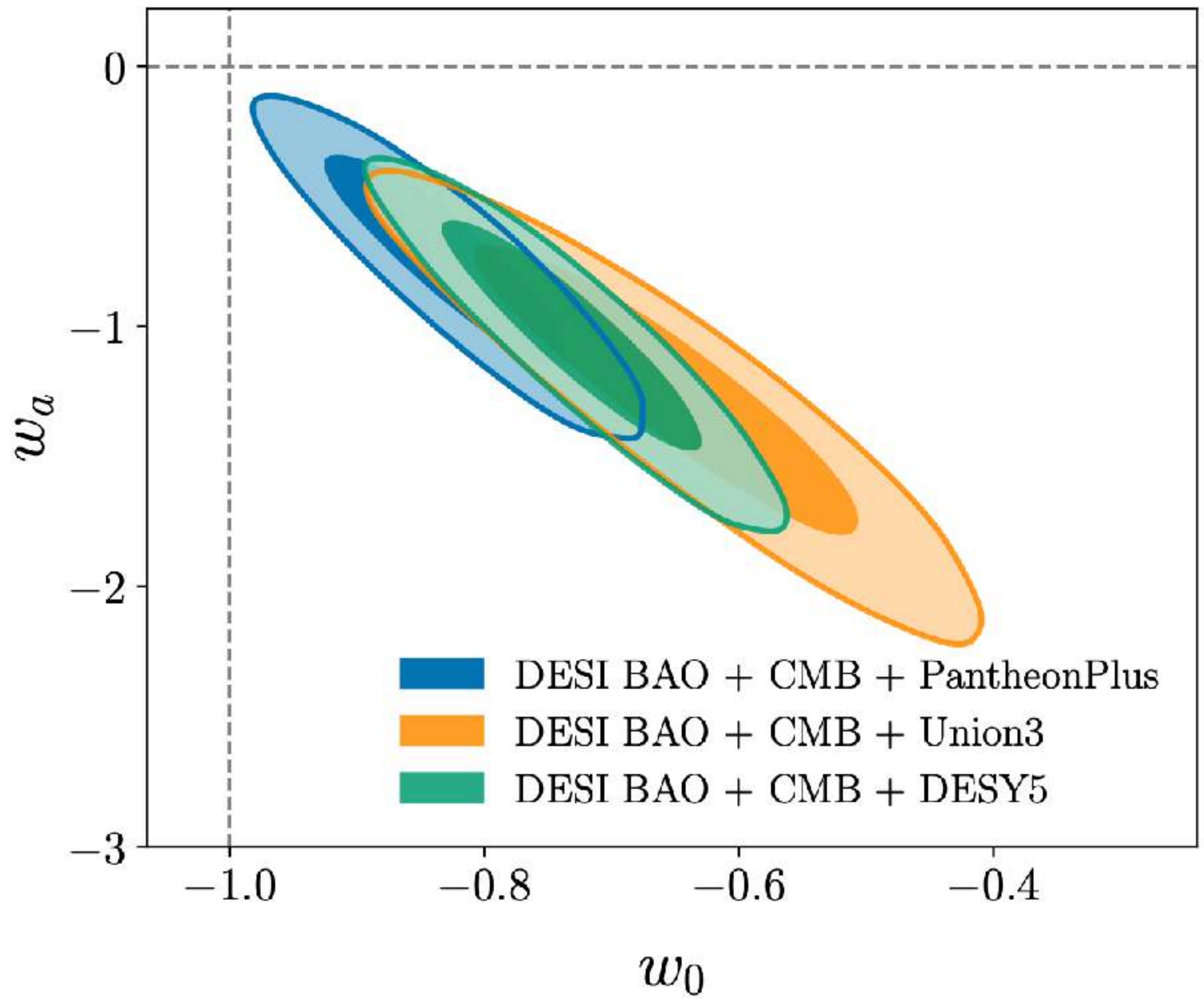


Is Dark Energy a cosmological constant?

- In $w_0 w_a$CDM model there are hints of evolving dark energy at the 2-3 sigma level.

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

DESI Collaboration: arXiv: 2404.03002



Notes on $w_0 w_a$ as good parametrization of the dark energy evolution

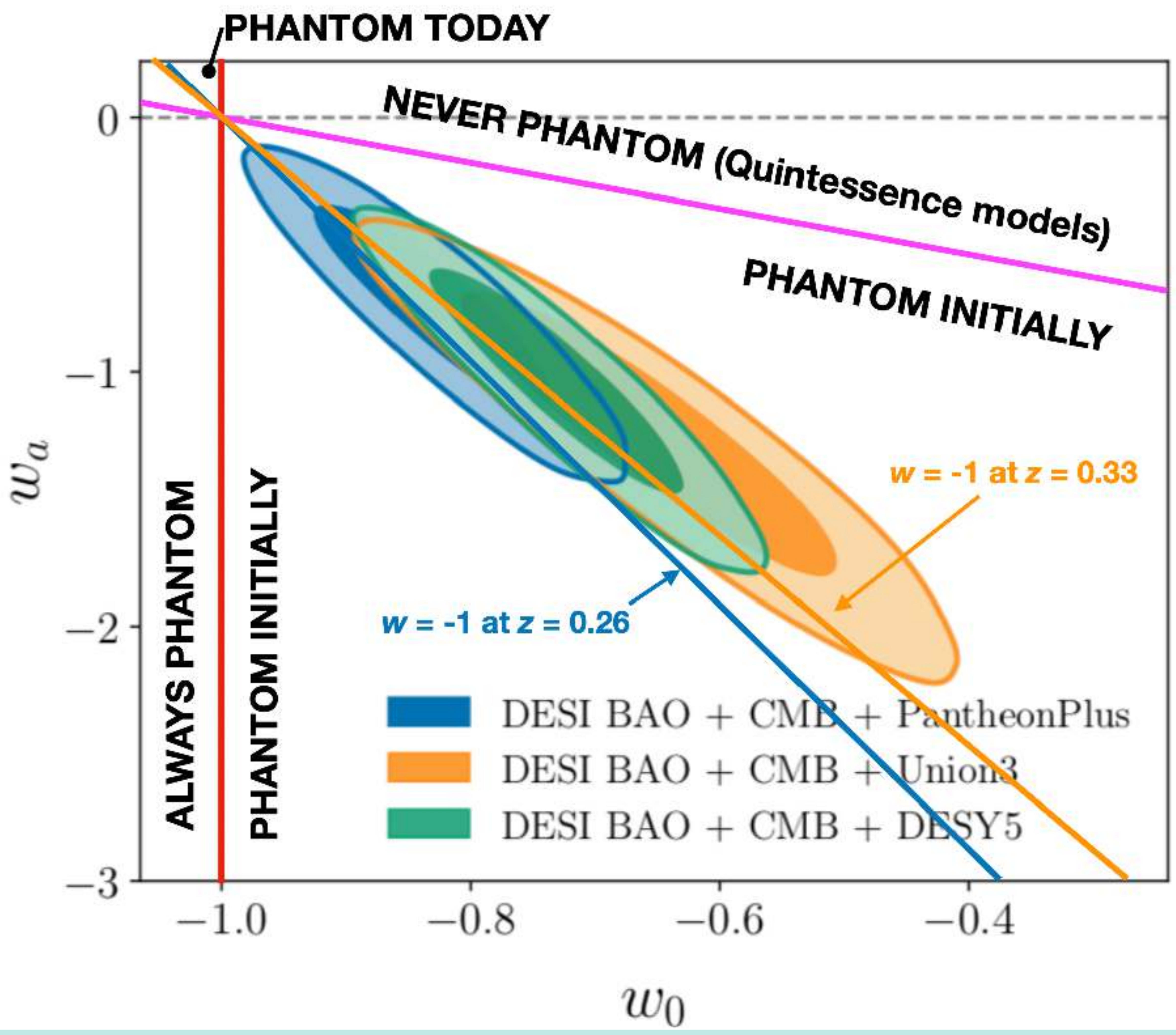
- $w < -1$ is called *phantom* regime due to its difficulties in coming up with physically motivated models for it.

- Models that cross between phantom and non-phantom are even more hard due to singularities in the perturbation equations.

- The $w_0 w_a$CDM parametrization was popularized by the Dark Energy Task Force Report of Albrecht et al., used to define a Figure of Merit.

- If we were to choose a different evolving model that is more theoretically motivating in the quintessence regime, the discrepancy from ΛCDM might change.

Cortês & Liddle: arXiv: 2404.08056




Where does that leave us?

The Standard Cosmological model is still standing: ΛCDM

Flat Universe with Dark Energy in the form of a cosmological constant Λ + Cold Dark Matter, assuming general Relativity.

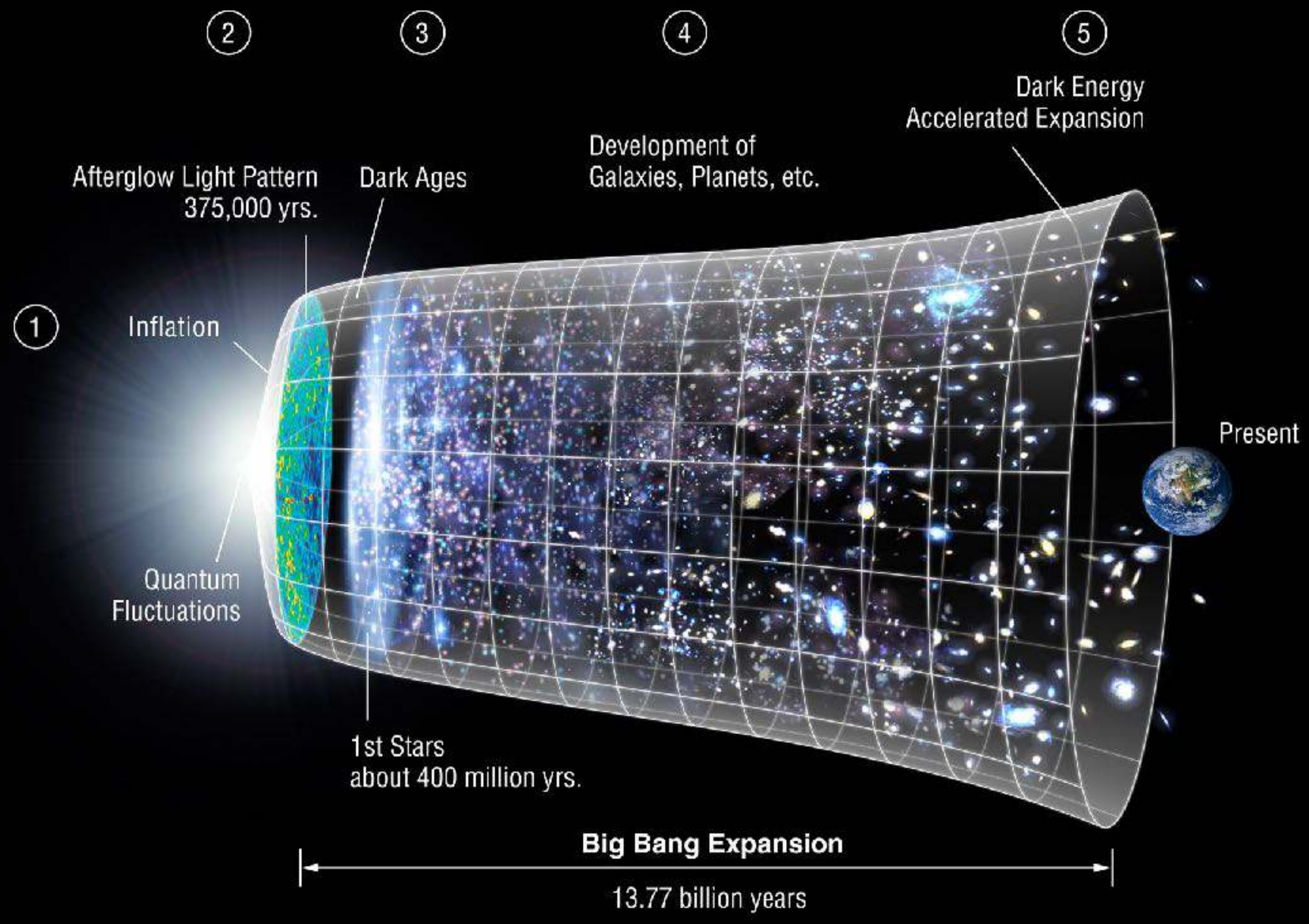


Image Credit: NASA / LAMBDA Archive / WMAP Science Team

However there are a few open questions

ΛCDM model under discussion

ΛCDM adds **2 new components** to the Standard Model of physics, neither of which have been observed in a laboratory.

The cosmological constant interpreted as the vacuum energy is ~**120 orders of magnitude lower** than the naive prediction coming from particle physics.

Some **tensions** are arising between cosmological probes. Are they a hint of new physics, systematics, or statistical fluctuations?

Is **dark energy evolving with time**?

General Relativity may not be valid at the largest scales. This could make us think that the expansion of the Universe is accelerating when it is actually not.

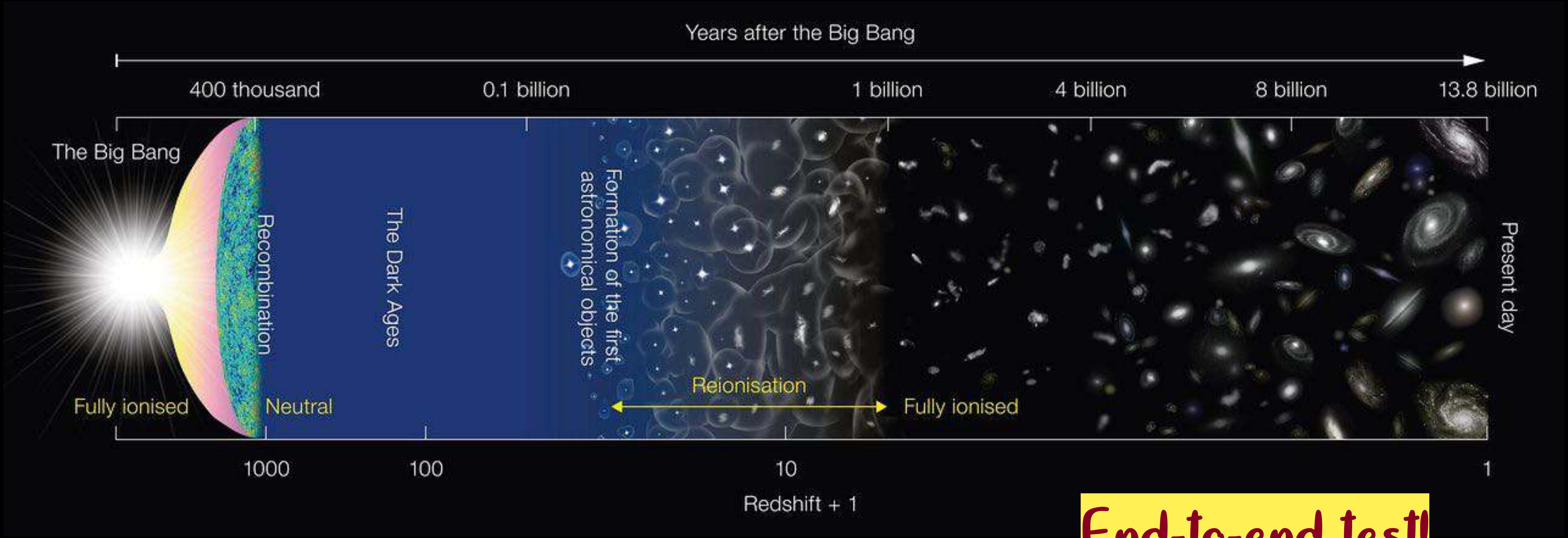
Some paths forward

ΛCDM model under discussion

- Stress-testing ΛCDM.
- Testing if extensions of ΛCDM are preferred. Model comparison.

Stress-testing ΛCDM

Is the late time Universe compatible with the ΛCDM prediction assuming initial conditions from the CMB?



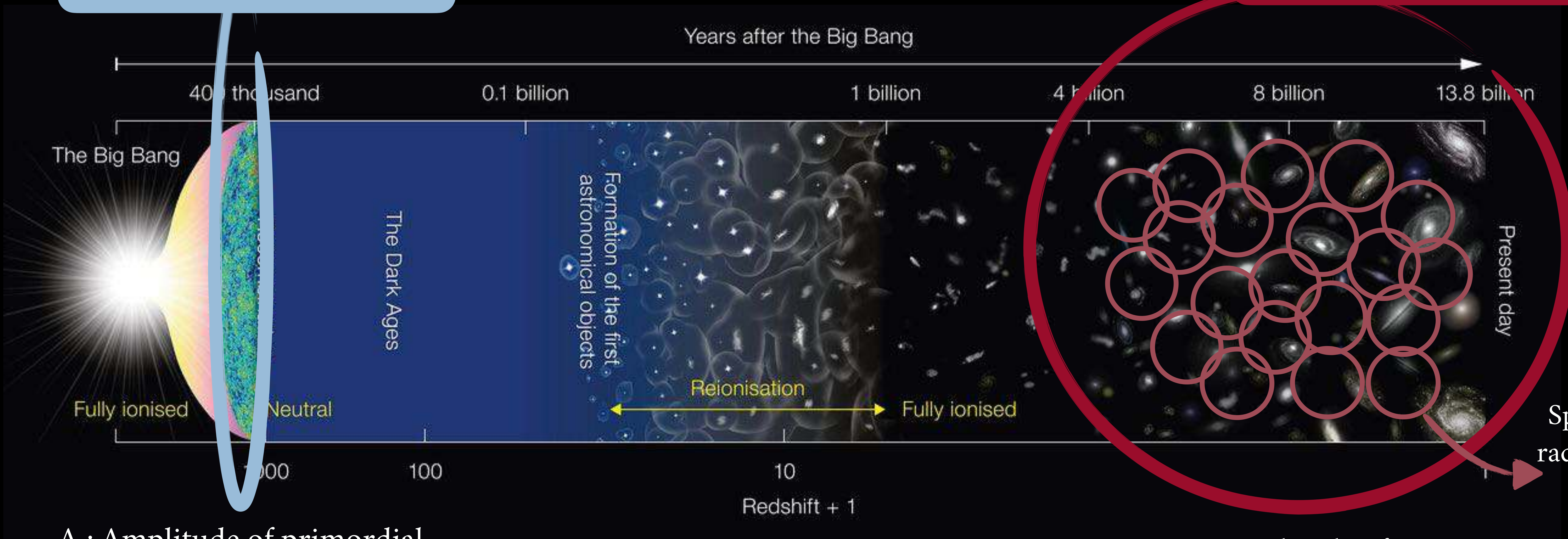
End-to-end test!

Stress-testing ΛCDM

Is the late time Universe compatible with the ΛCDM prediction assuming initial conditions from the CMB?

CMB experiments observe the early Universe

Galaxy surveys observe the late Universe



Spheres with radius 8Mpc/h

A_s: Amplitude of primordial scalar density fluctuations.

Image credit: NAOJ

σ_8: Amplitude of mass fluctuations today.

4 steps to test ΛCDM

1) We measure the ΛCDM cosmological parameters from a CMB experiment.

Ω_m	Amount of matter today
A_s	Amplitude of primordial scalar density perturbations
n_s	Spectral index of primordial scalar density perturbations
Ω_b	Amount of baryons today
h	Expansion rate
$\Omega_\nu h^2$	Amount of neutrinos

2) Then, we can predict how much matter, dark energy, etc there will be in the late time Universe.

RMS amplitude of mass fluctuations on scales of 8Mpc/h in linear theory at z=0.

4) Do they agree?

3) We measure the ΛCDM cosmological parameters from a late-time Universe experiment.

Ω_m	Amount of matter today
$\sigma_8^2 = \frac{1}{2\pi^2}\int k^2 P(k)\left[\frac{3j_1(kR)}{kR}\right]^2 dk$	
n_s	Spectral index of primordial scalar density perturbations
Ω_b	Amount of baryons today
h	Expansion rate
$\Omega_\nu h^2$	Amount of neutrinos

How can we measure these cosmological parameters?

How can we measure cosmological parameters?

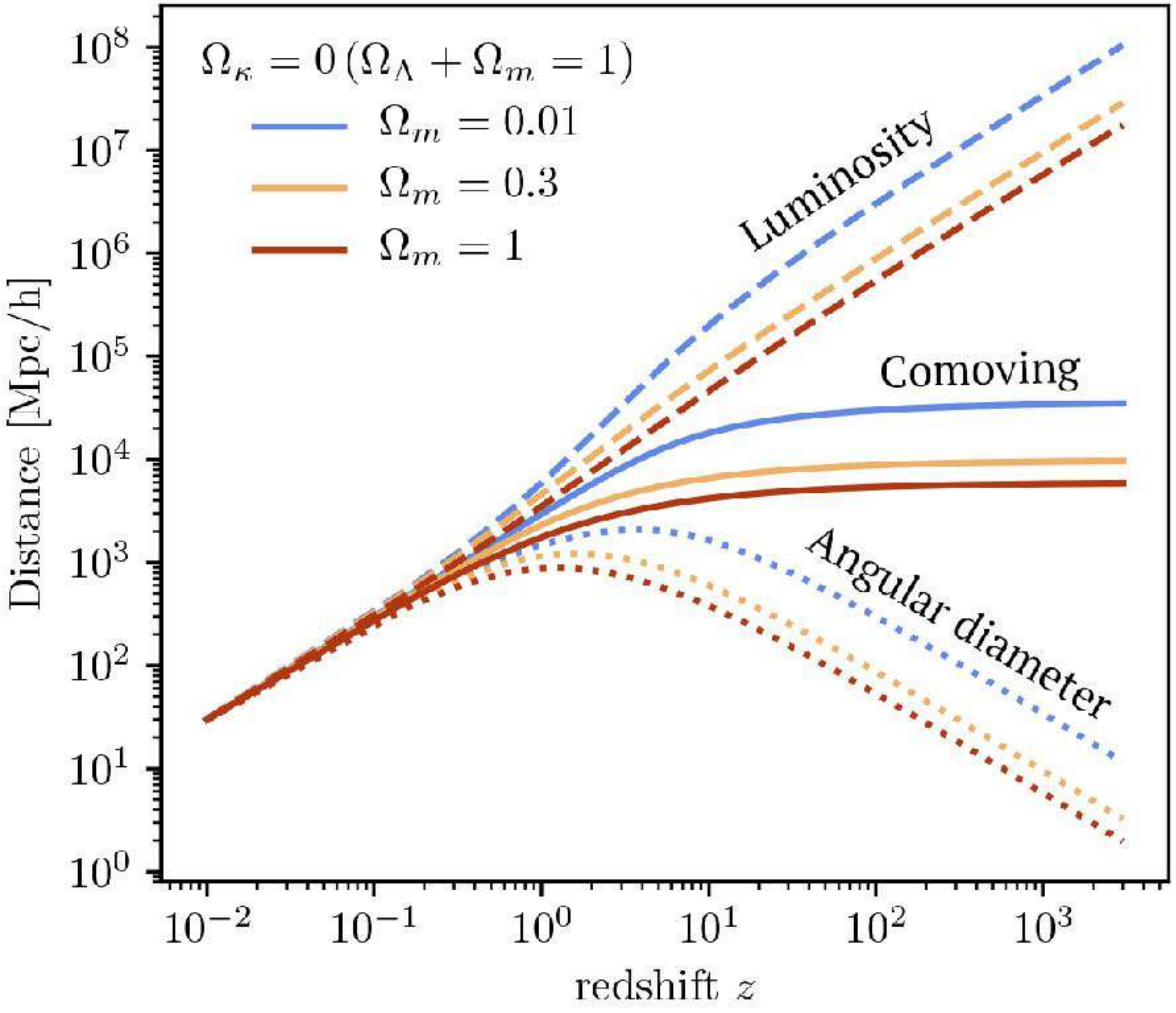
We can probe a cosmological model by studying:

(i) The history of **expansion** of the Universe (kinematics probe).

$$\chi(z) = c\int_0^{z_e} \frac{dz}{H(z)}$$

Via the first Friedmann equation:

$$H^2(z) = H_0^2\left[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_{de}(1+z)^{3(1+w)}\right]$$



How can we measure cosmological parameters?

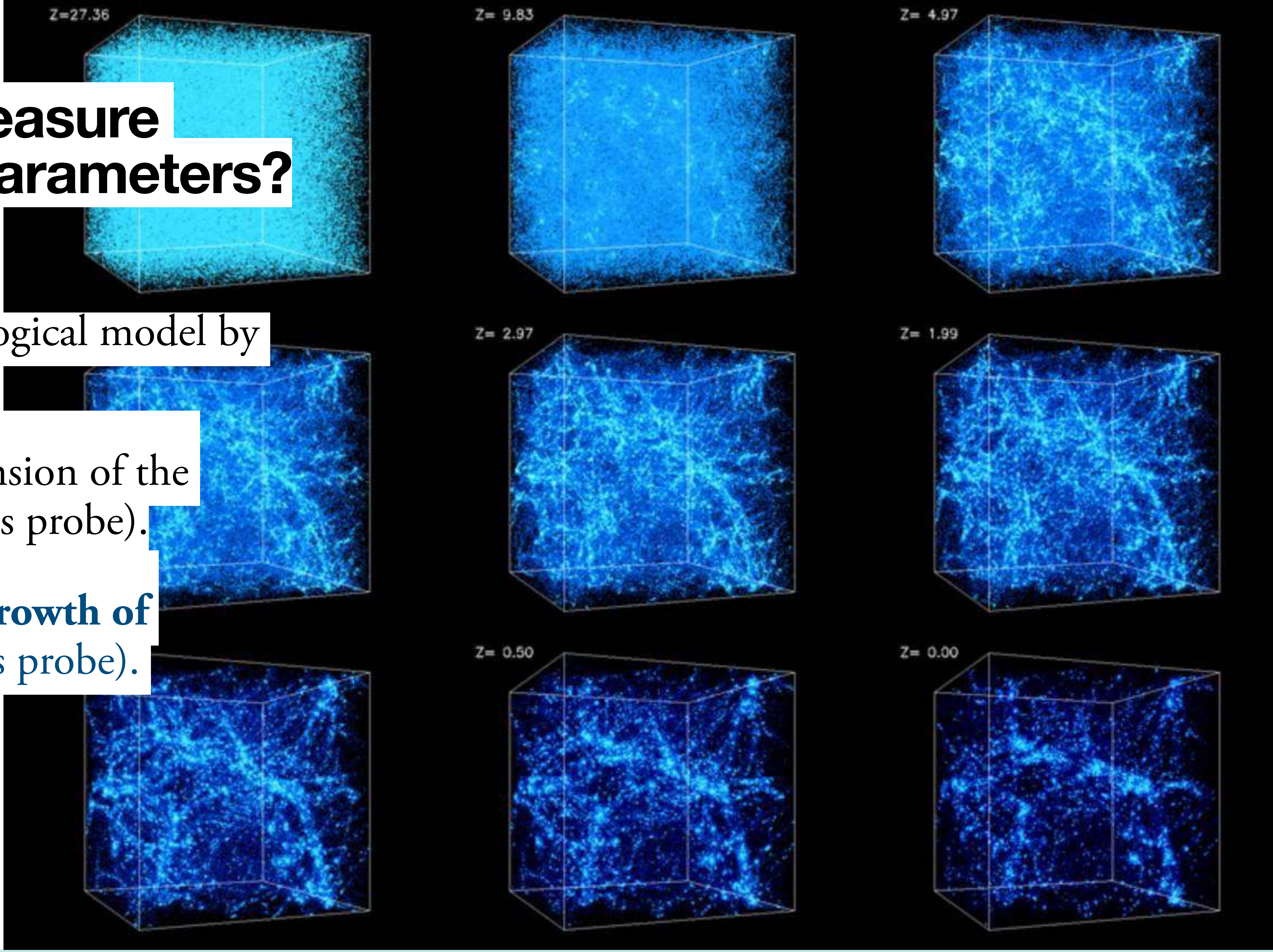
We can probe a cosmological model by studying:

(i) The history of expansion of the Universe (kinematics probe).

(ii) The history of the **growth of structure** (dynamics probe).

Via the Poisson equation:

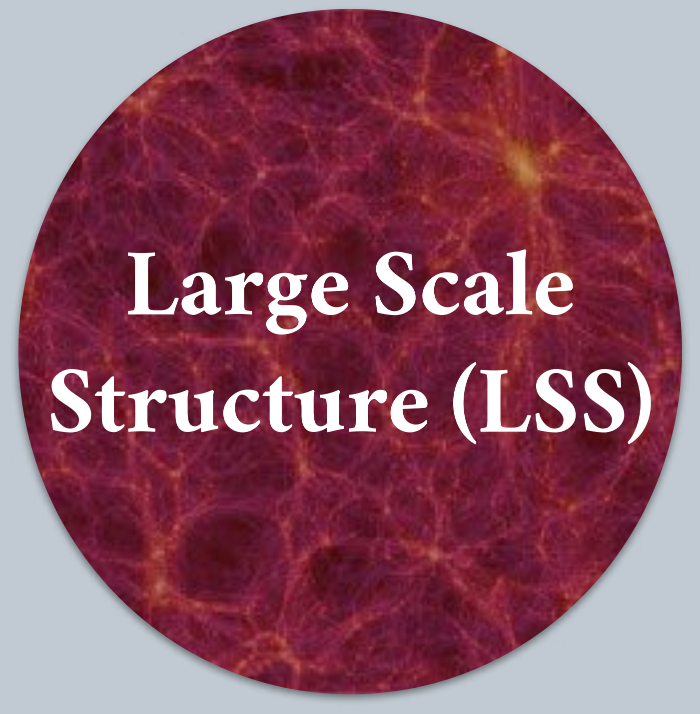
$$\nabla_r^2 \Phi(t, \boldsymbol{r}) = \frac{3\Omega_m H_0^2}{2a(t)} \delta(t, \boldsymbol{r})$$



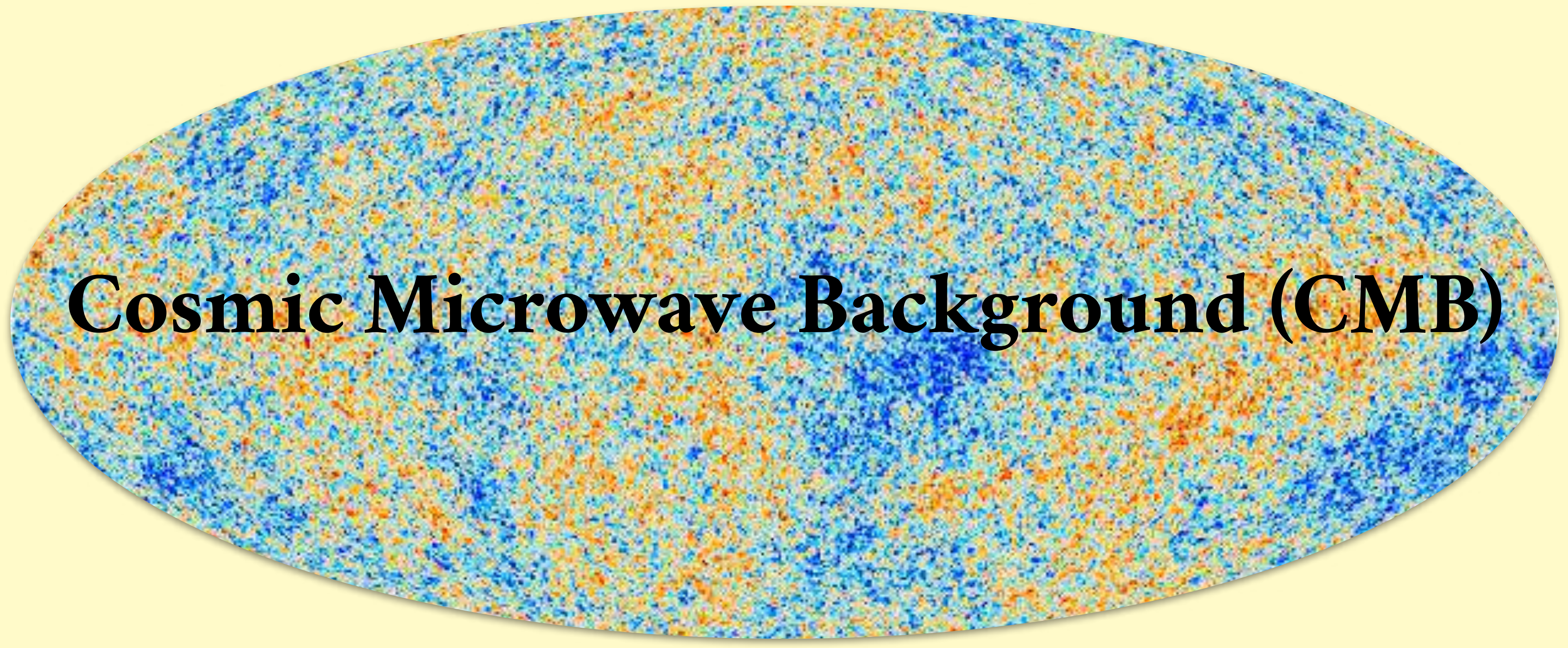
Probes to measure cosmological parameters

History of Expansion

More Growth, but also a bit of expansion

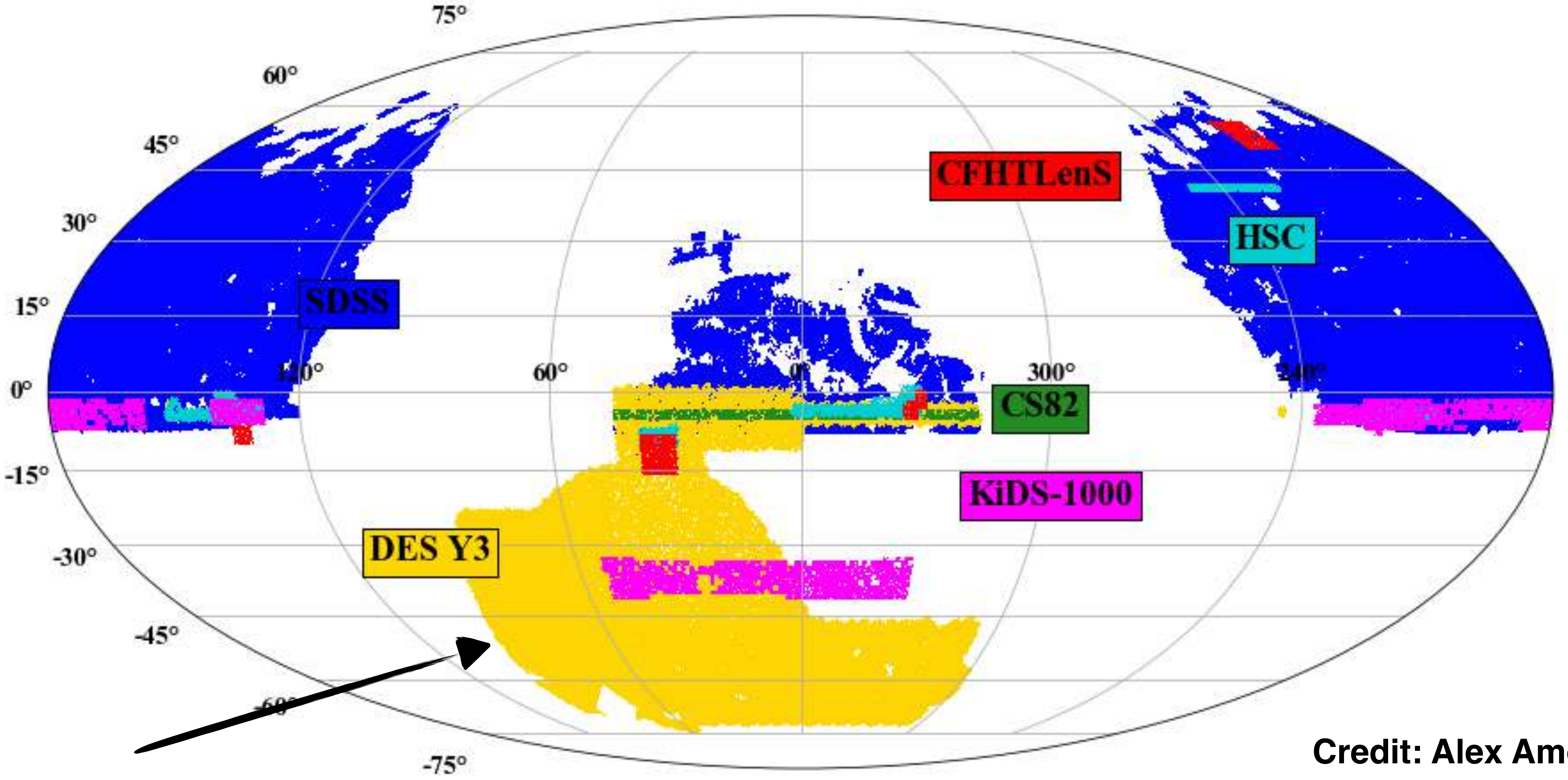


Growth and Expansion



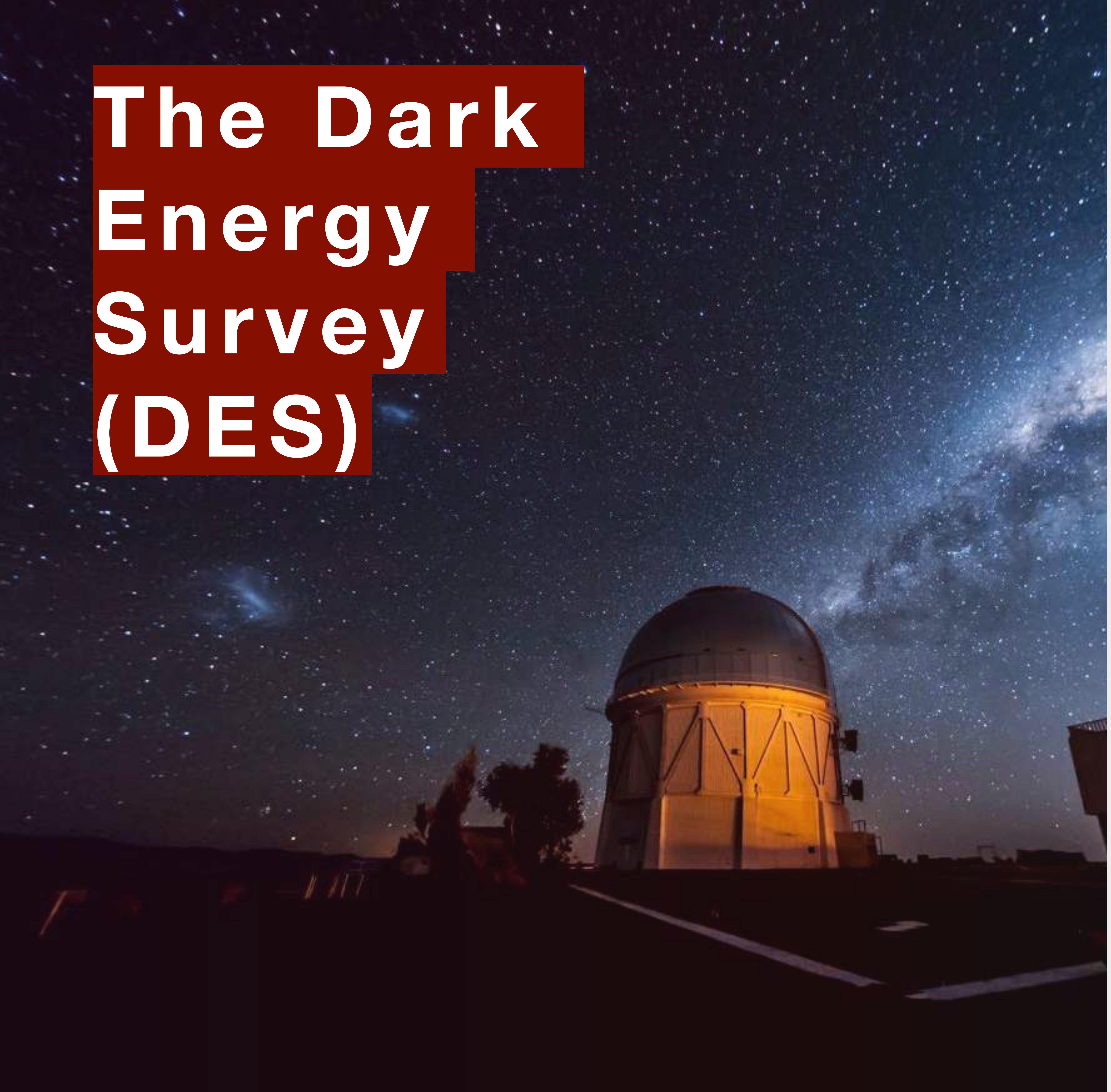
Galaxy surveys: Photometric surveys for WL

Mapping the Universe



Credit: Alex Amon

The Dark Energy Survey (DES)

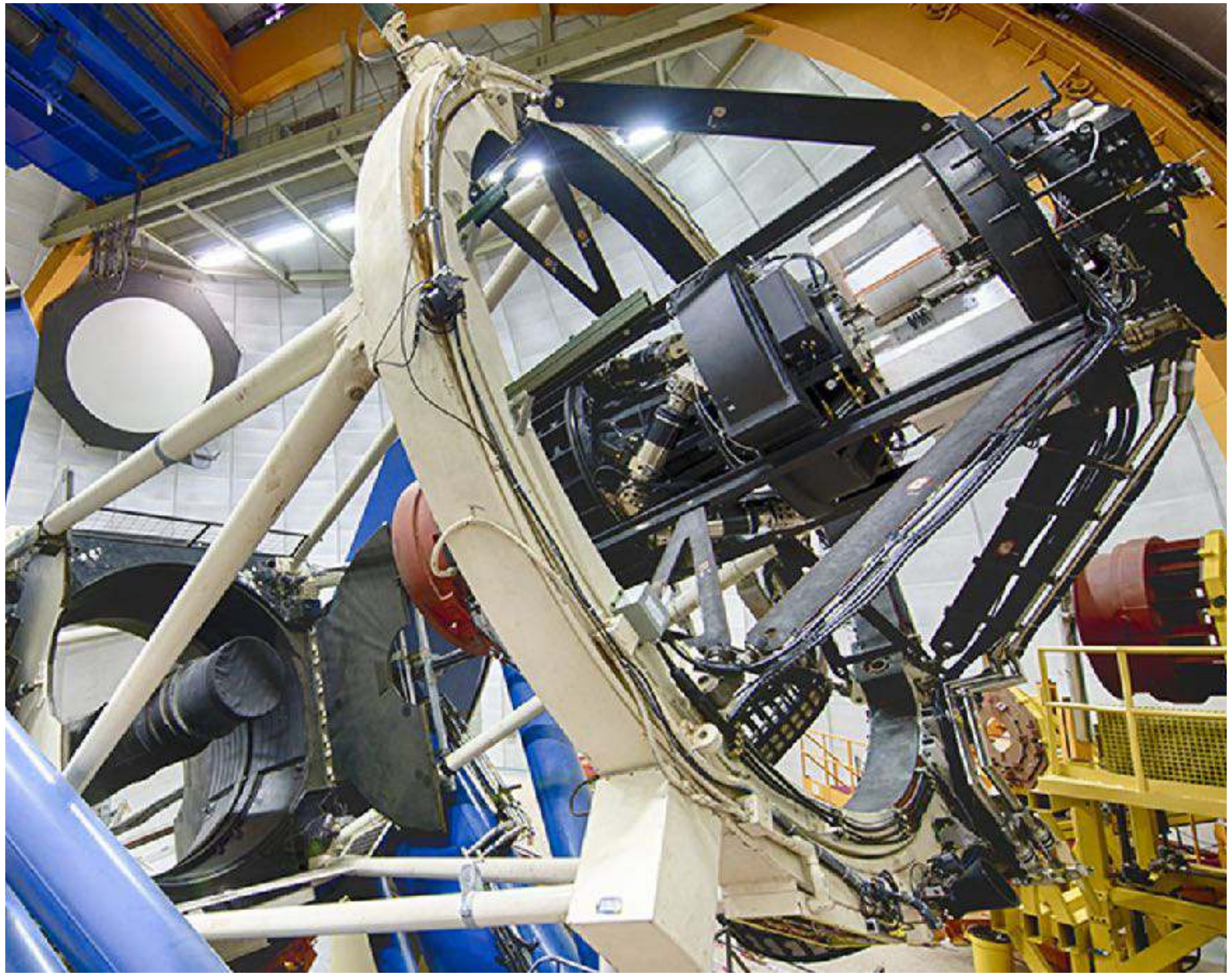


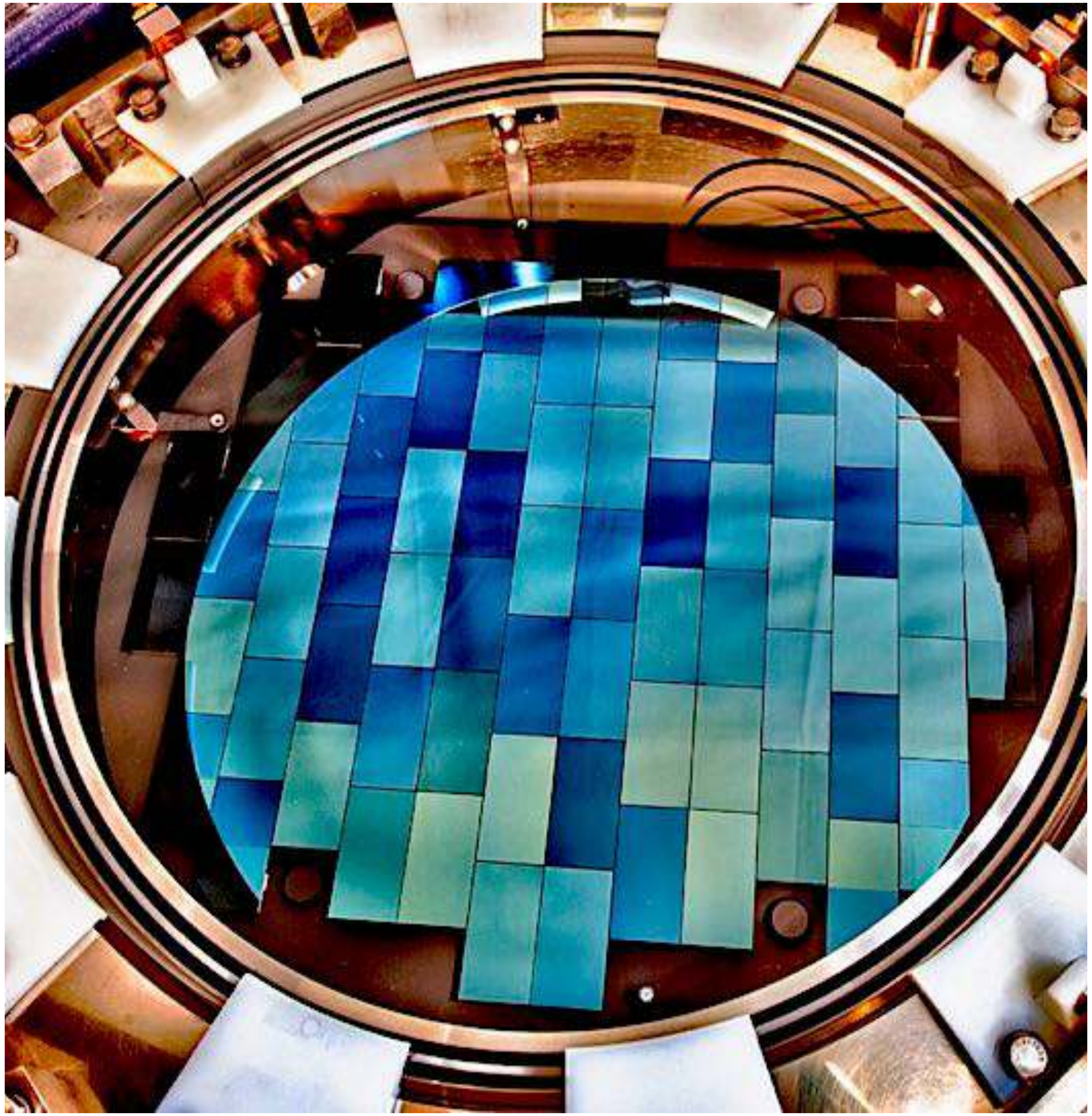
- Imaging galaxy survey.
- 5000 sq. deg. after 6 years (2013-2019)
- 570-Megapixel digital camera, DECam, mounted on the Blanco 4-meter telescope at Cerro Tololo Inter-American Observatory (Chile).
- Five filters are used (grizY) with a nominal limiting magnitude $i_{AB} \simeq 24$ and with a typical exposure time of 90 sec for griz and 45 sec for Y.

The Dark Energy Telescope

Blanco & DECam

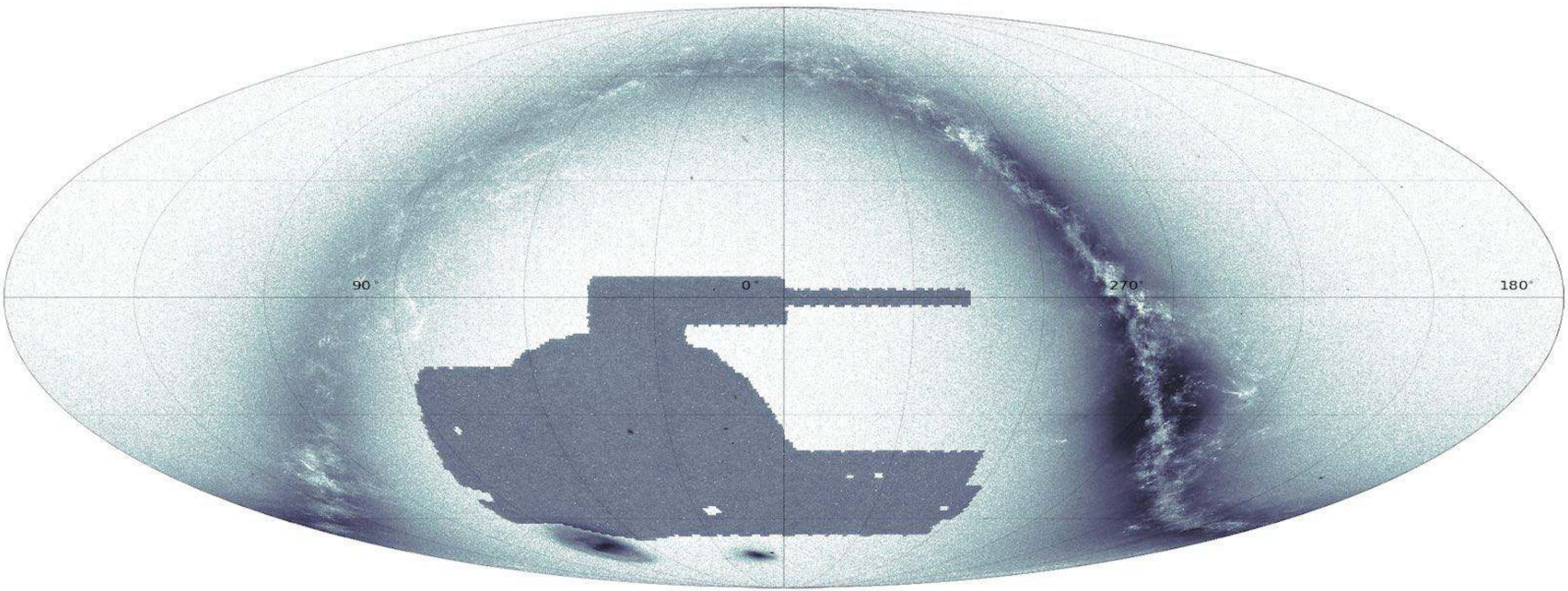
Telescope & Camera



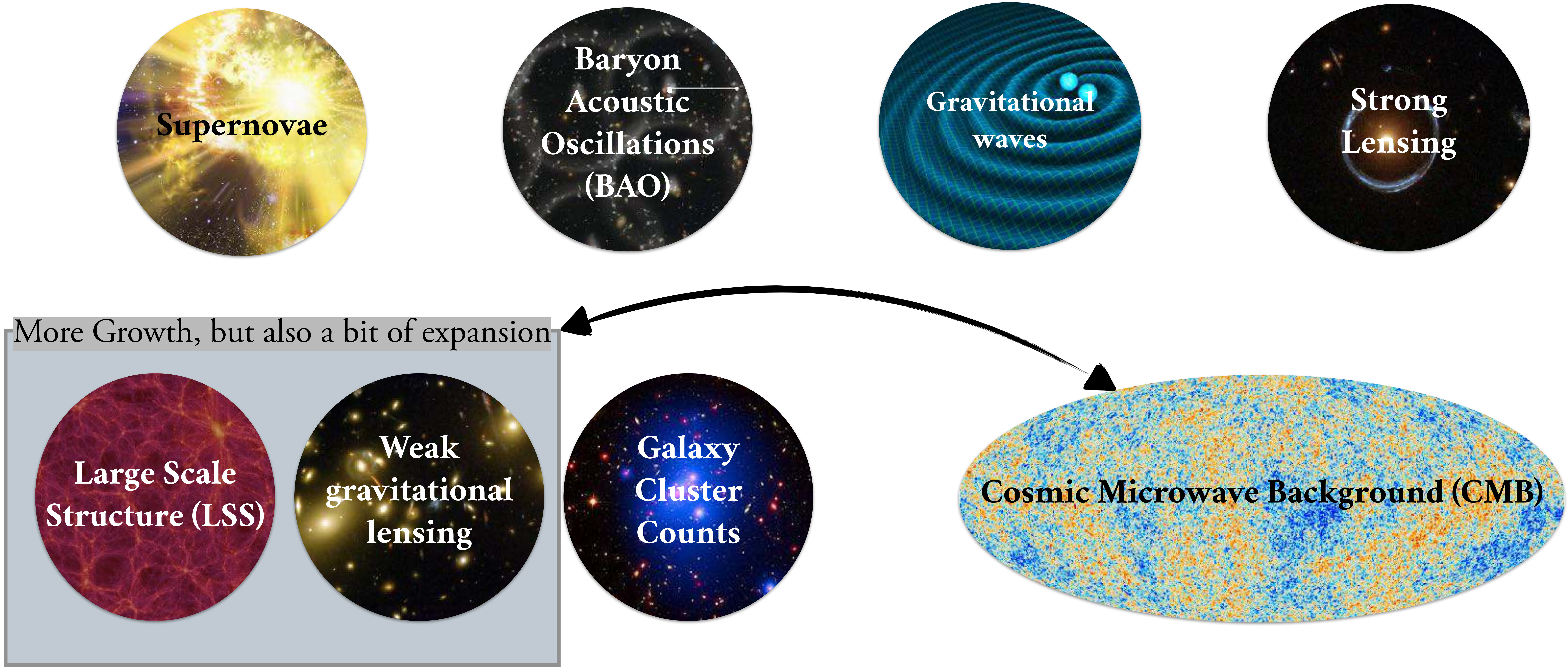


Dark Energy Survey Collaboration

The Dark Energy Survey (DES)



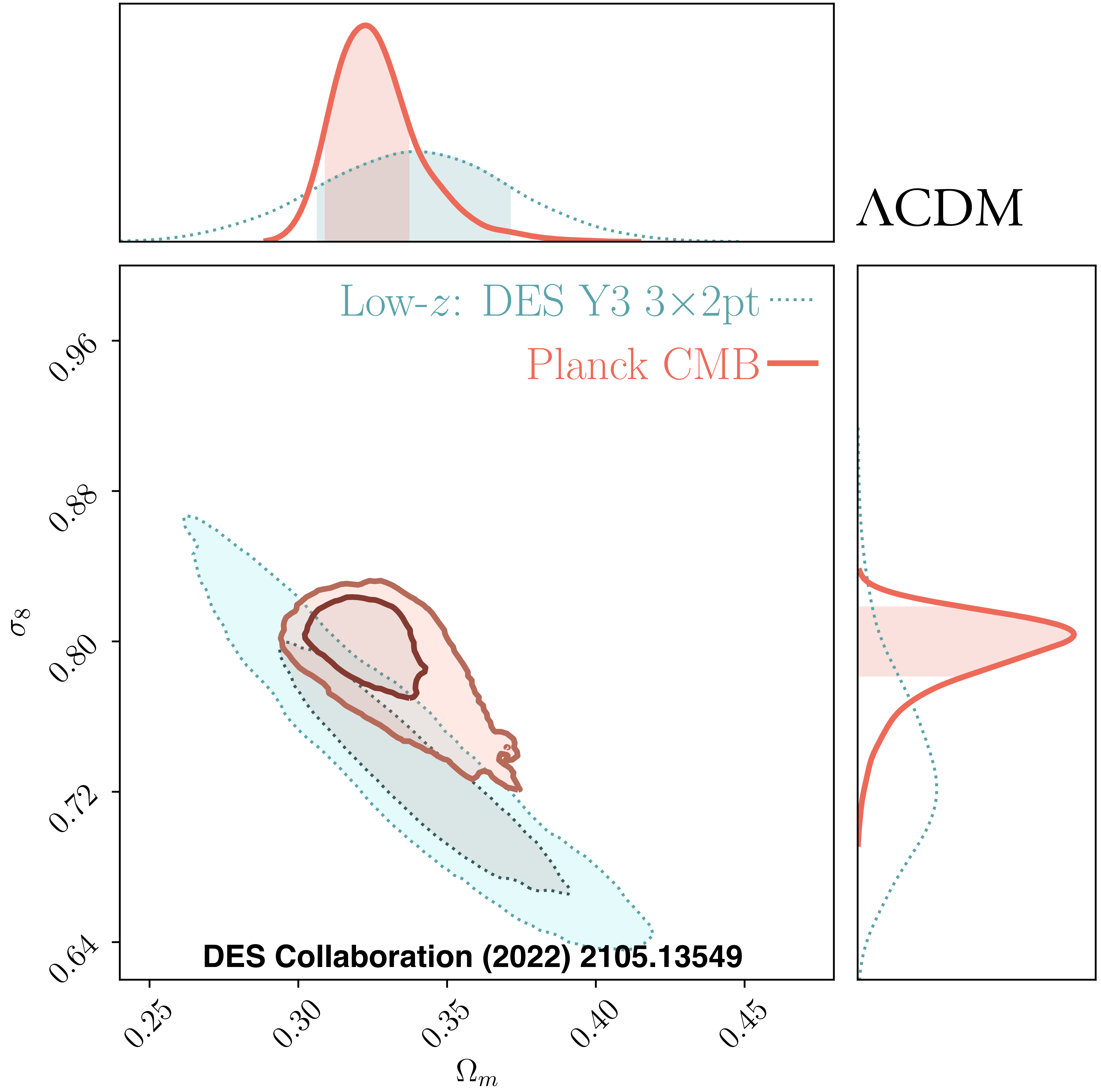
LSS + WL: 3x2pt



Supernovae
Baryon Acoustic Oscillations (BAO)
Gravitational waves
Strong Lensing
More Growth, but also a bit of expansion
Large Scale Structure (LSS)
Weak gravitational lensing
Galaxy Cluster Counts
Cosmic Microwave Background (CMB)

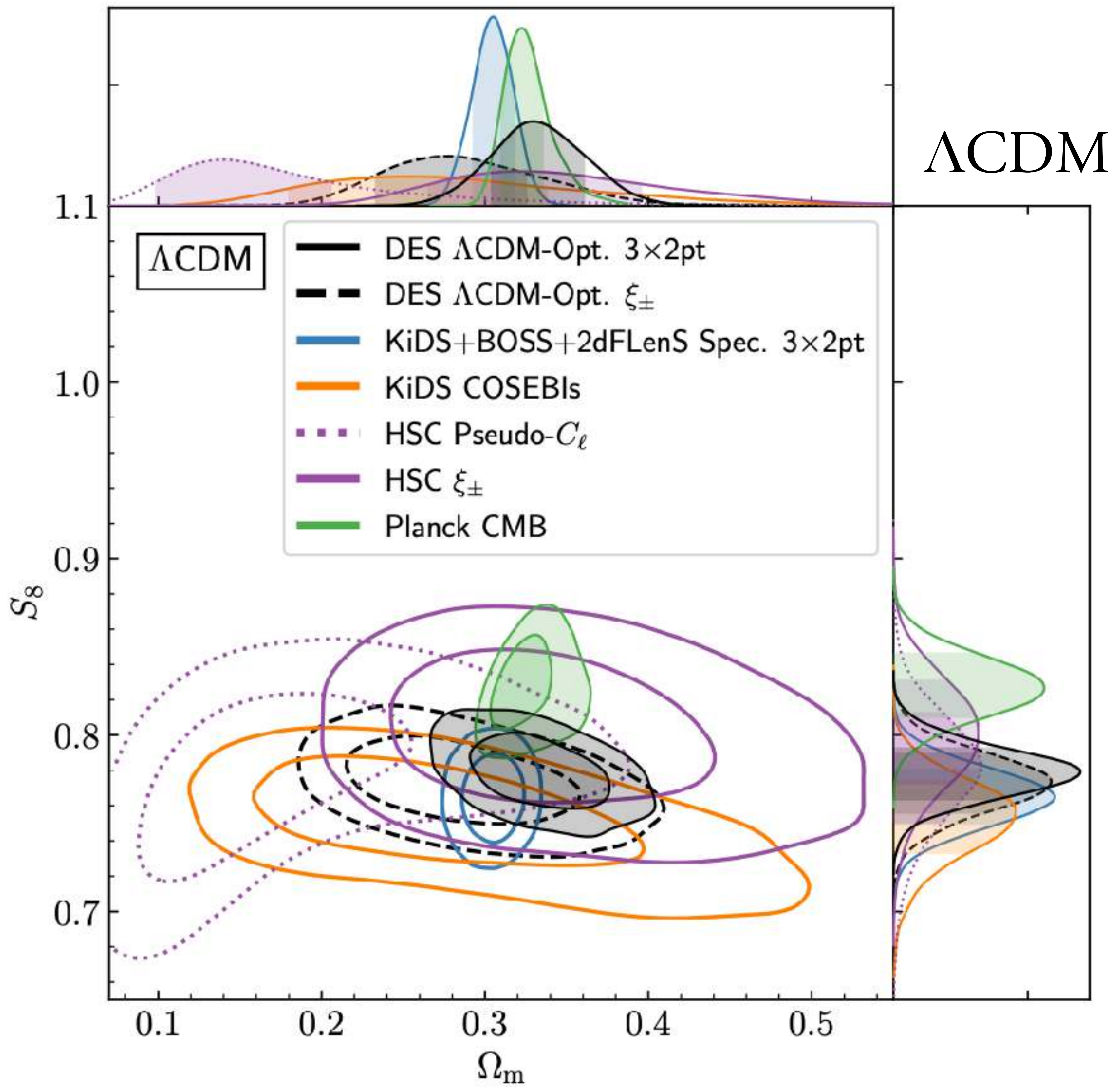
Stress testing ΛCDM:
early vs late Universe

- Planck and DES Y3 are consistent assuming the ΛCDM model (1.5σ), although the clustering amplitude is lower for DES Y3 than Planck.



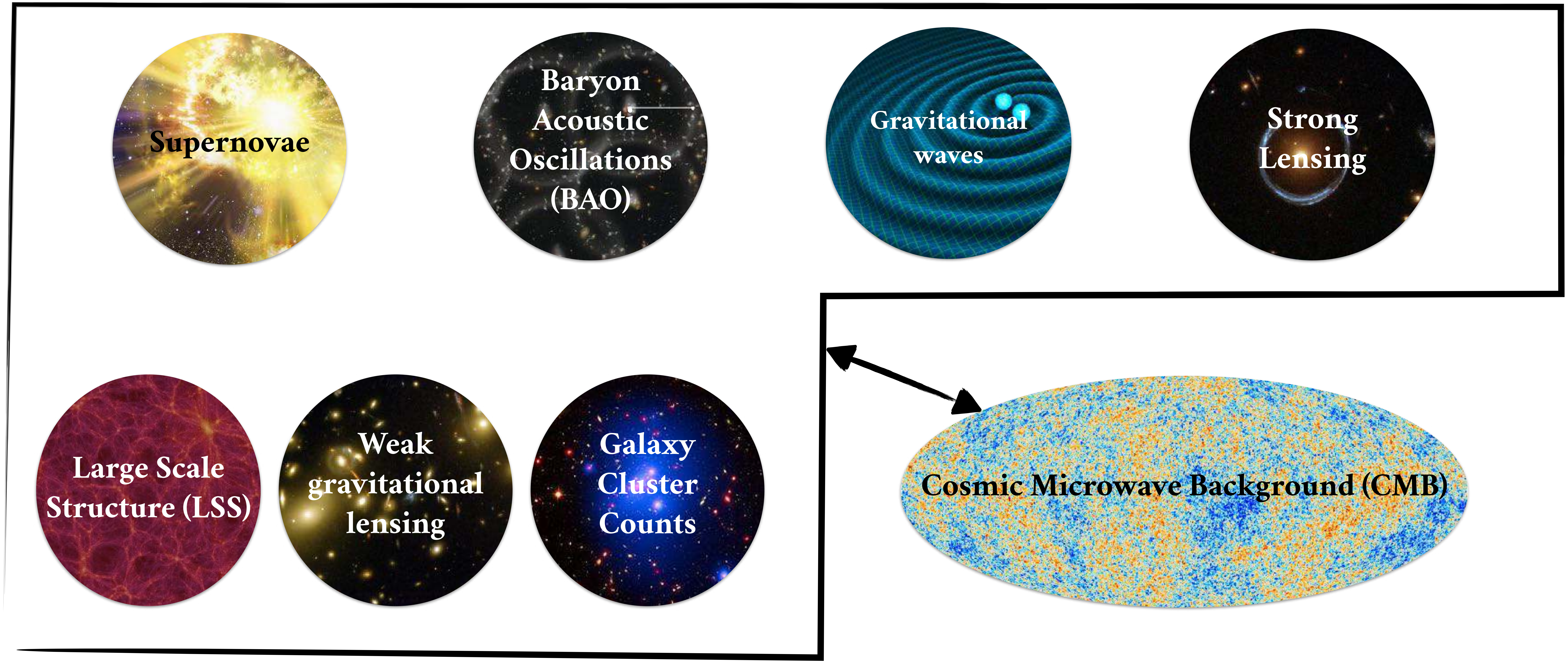
However many late-time Universe observations have shown lower S_8 values

- Cosmic shear measurements in DES Y3 are 2.3σ away from Planck.
- All the other cosmic shear and 3x2pt measurements are also below Planck.



DES Collaboration (2022) 2105.13549

Then I will discuss synergies between late-time Universe probes

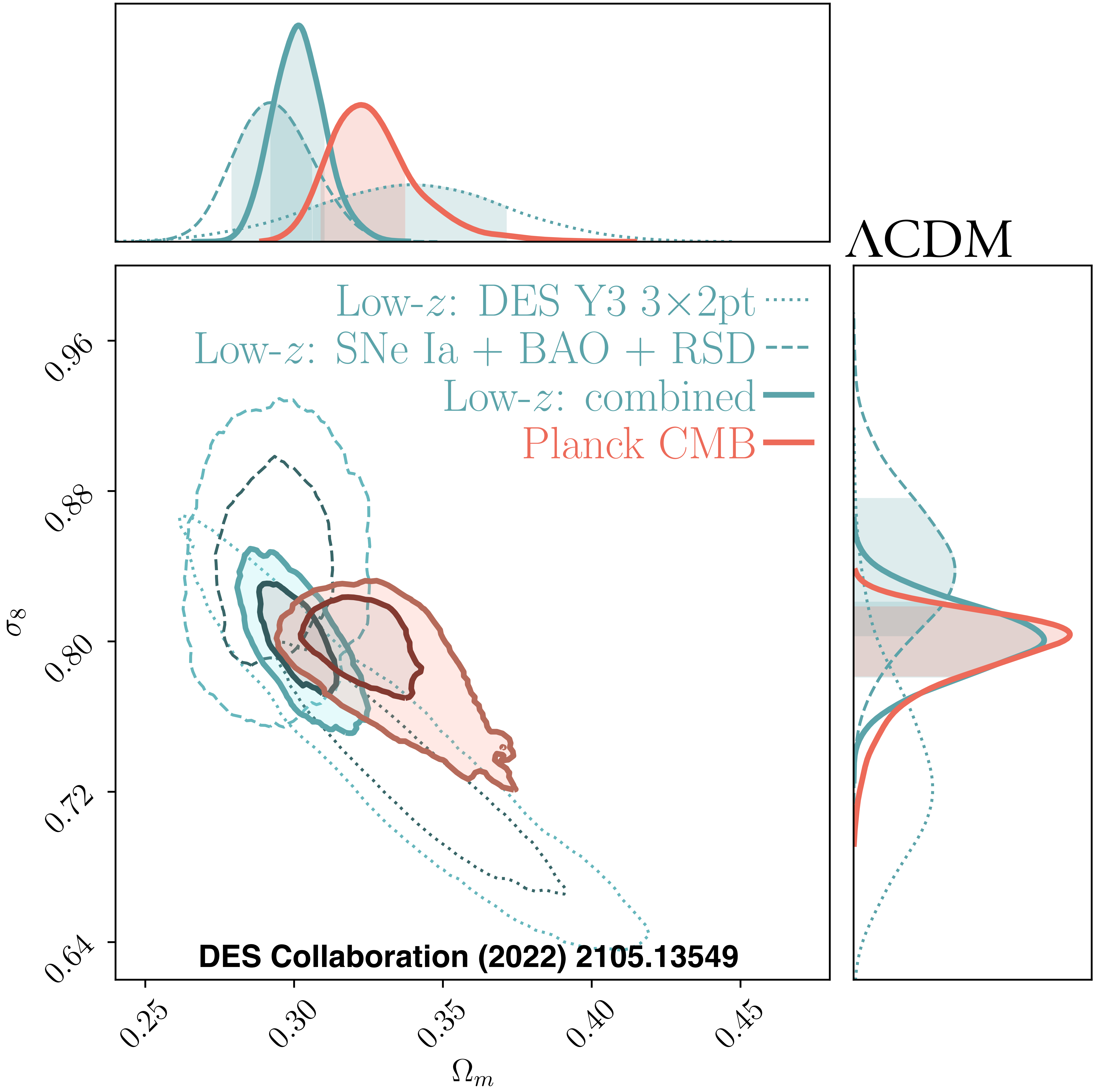


Stress testing ΛCDM:

early vs late Universe

- When combined with other external redshift probes (*Pantheon SNe IA, BOSS BAO, BOSS RSD*), they are also consistent (0.9σ), with smaller uncertainties.

The real power comes when combining different probes!!



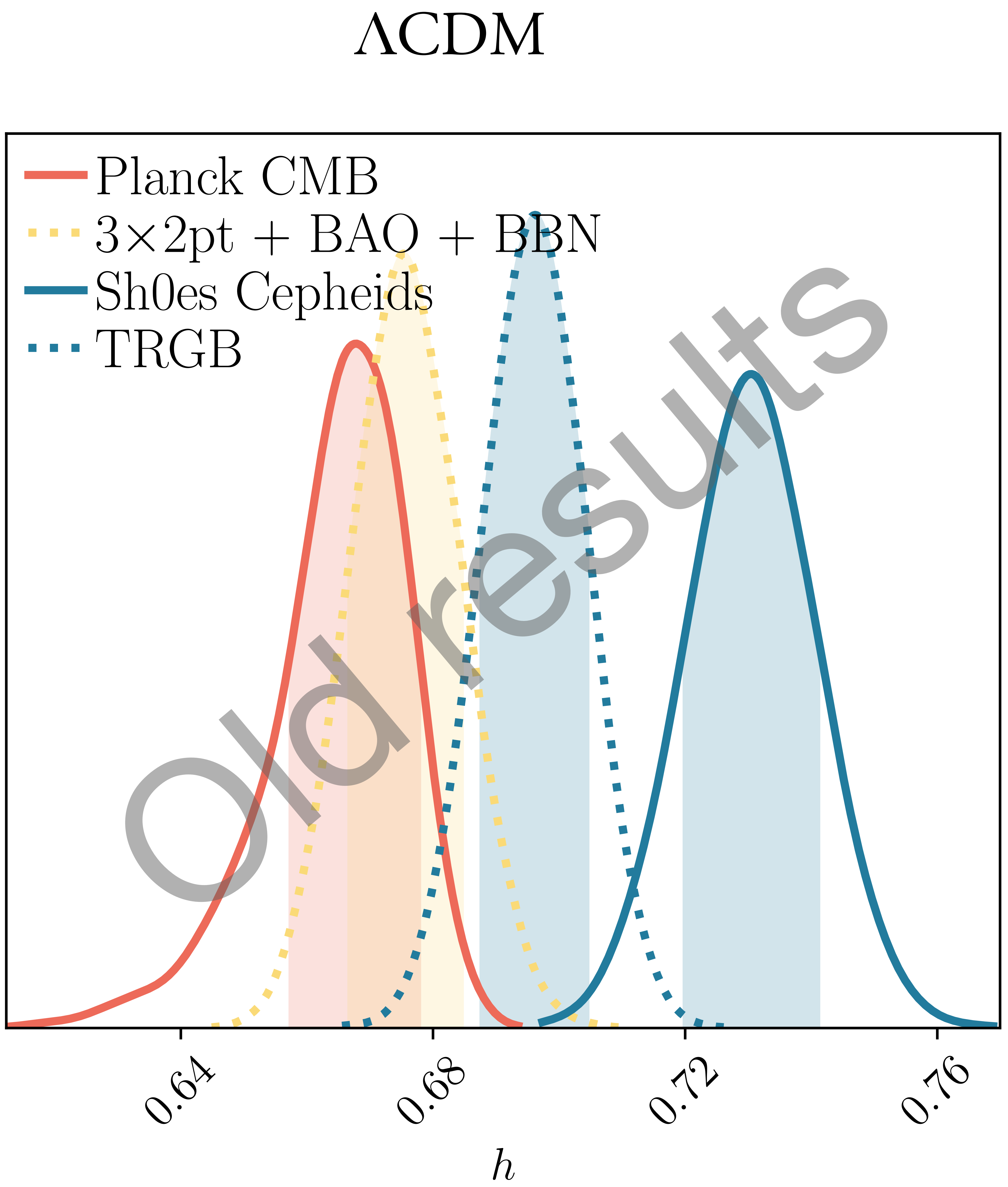
Stress testing ΛCDM:
What about the H0 tension?

- What we learned at the *Challenging the standard cosmological mode*l meeting earlier this week from Wendy Freedman's talk is that new results from her group from combining Cepheids+TRBG+ luminosity function of JAGB/carbon stars yield results consistent with Planck.

- The differences were attributed to:

    - New JWST data.

    - A bug in the calibration which was used in all previous results (also from Sh0es).



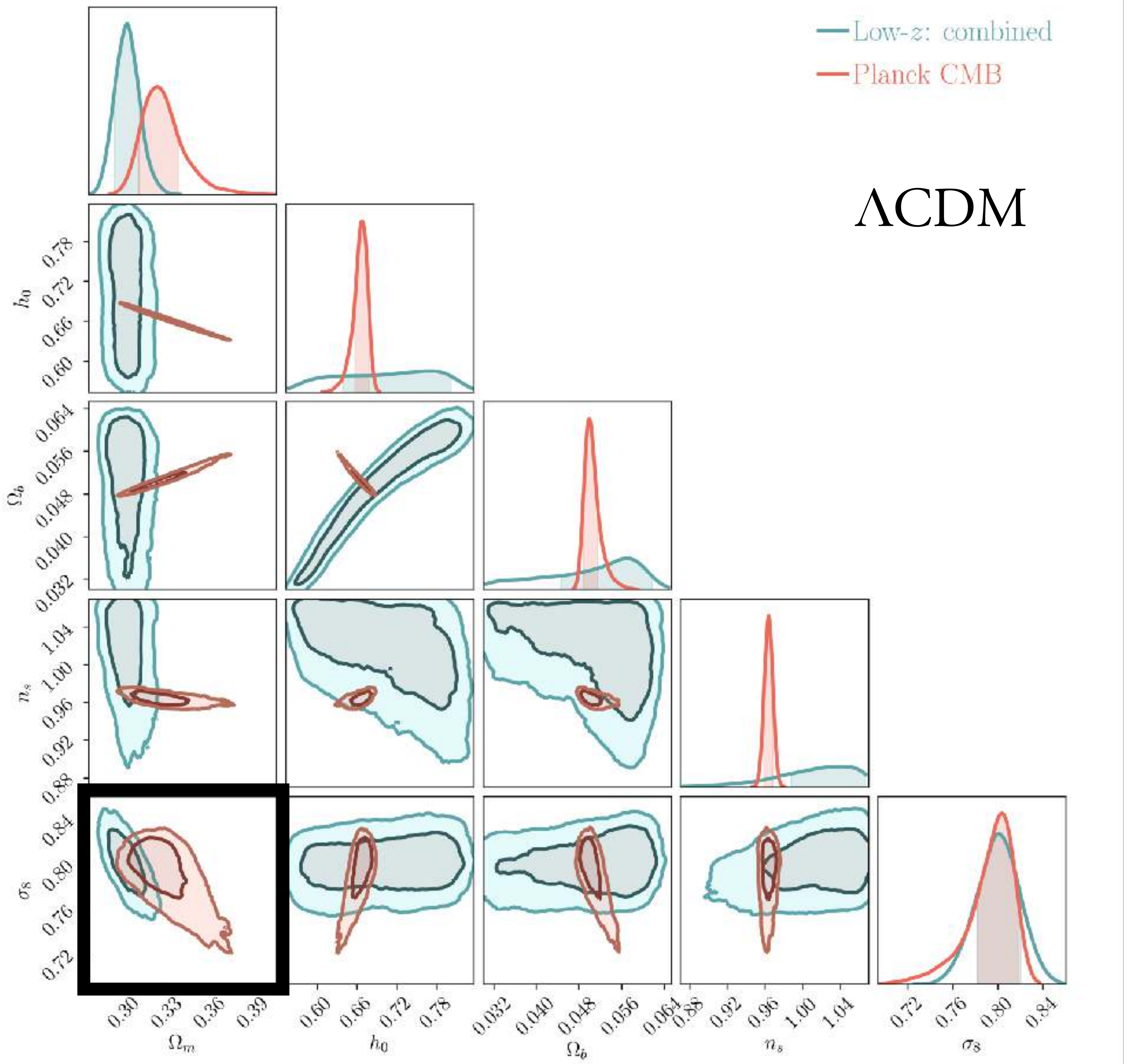
Thoughts on current and future directions

Stress testing ΛCDM:
Looking at the full parameter space

- When we look at the full parameter space we can see that only two parameters are constrained to a similar precision as Planck. —>We still have a long way to go to reach the same precision in the late time Universe.

- We have work to do to be able to do an even more compelling test.

DES Collaboration (2022) 2105.13549



3 ways to move forward:

What am I doing?

How can we get more precise constraints from the late-time Universe?

Combining more probes from the late-time Universe

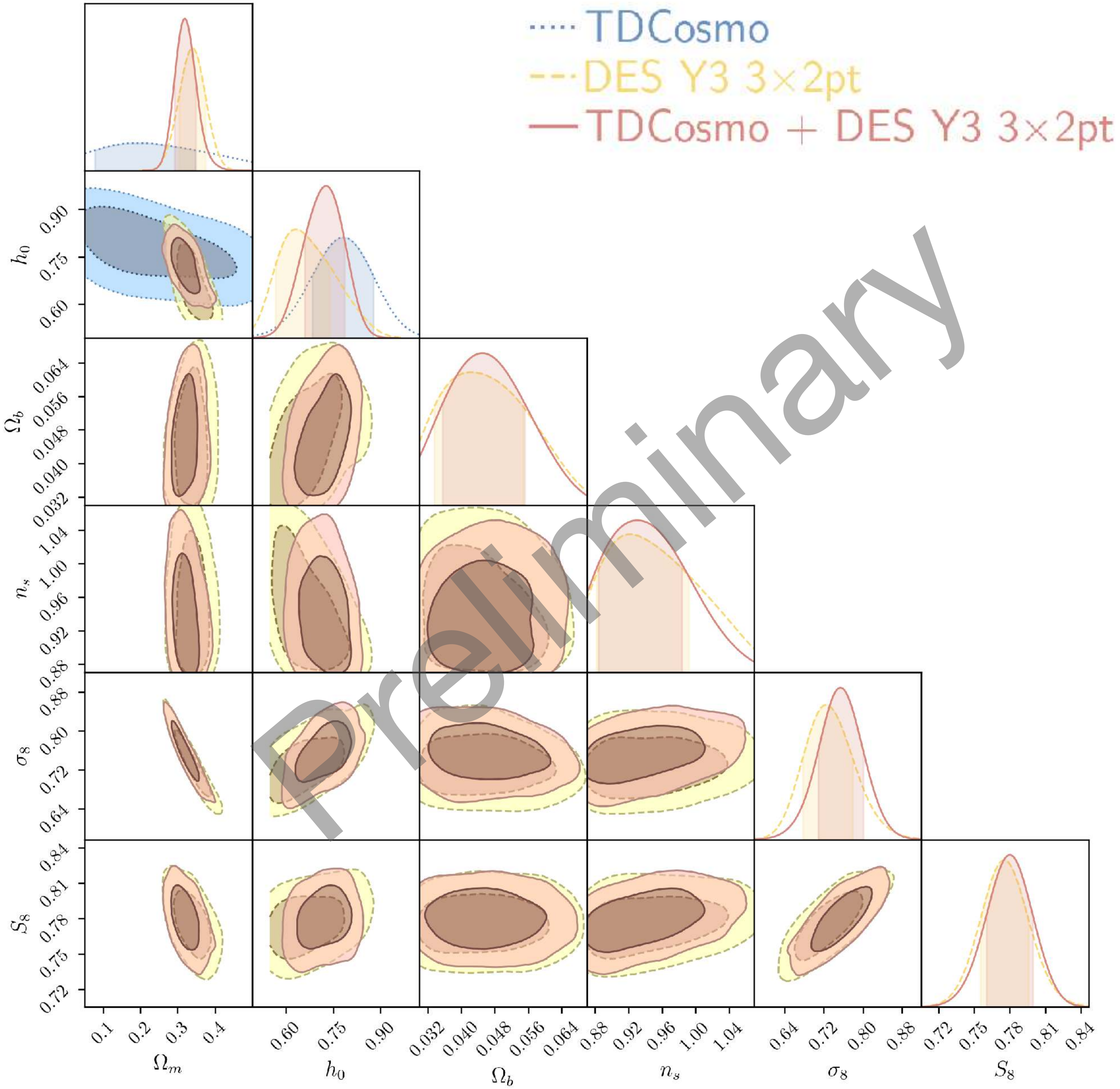
Exploring new combinations of data:
(i) Strong Lensing + Weak Lensing
(ii) Cosmological Constraints from Combining Galaxy Surveys and Gravitational Wave Observatories

Gagnon, Anbajagane, Prat et al. (2023): *2312.16289*

SL + WL constraints

- SL + WL is an example of how we can do better by combing emerging synergetic probes. SL is sensitive to H0, and WL is sensitive to Omega_m + sigma_8.

- The combination yields tighter constraints in all these parameters.



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Extracting more information from the same data

Capture non-gaussian information from the late-time Universe with higher-order statistics:

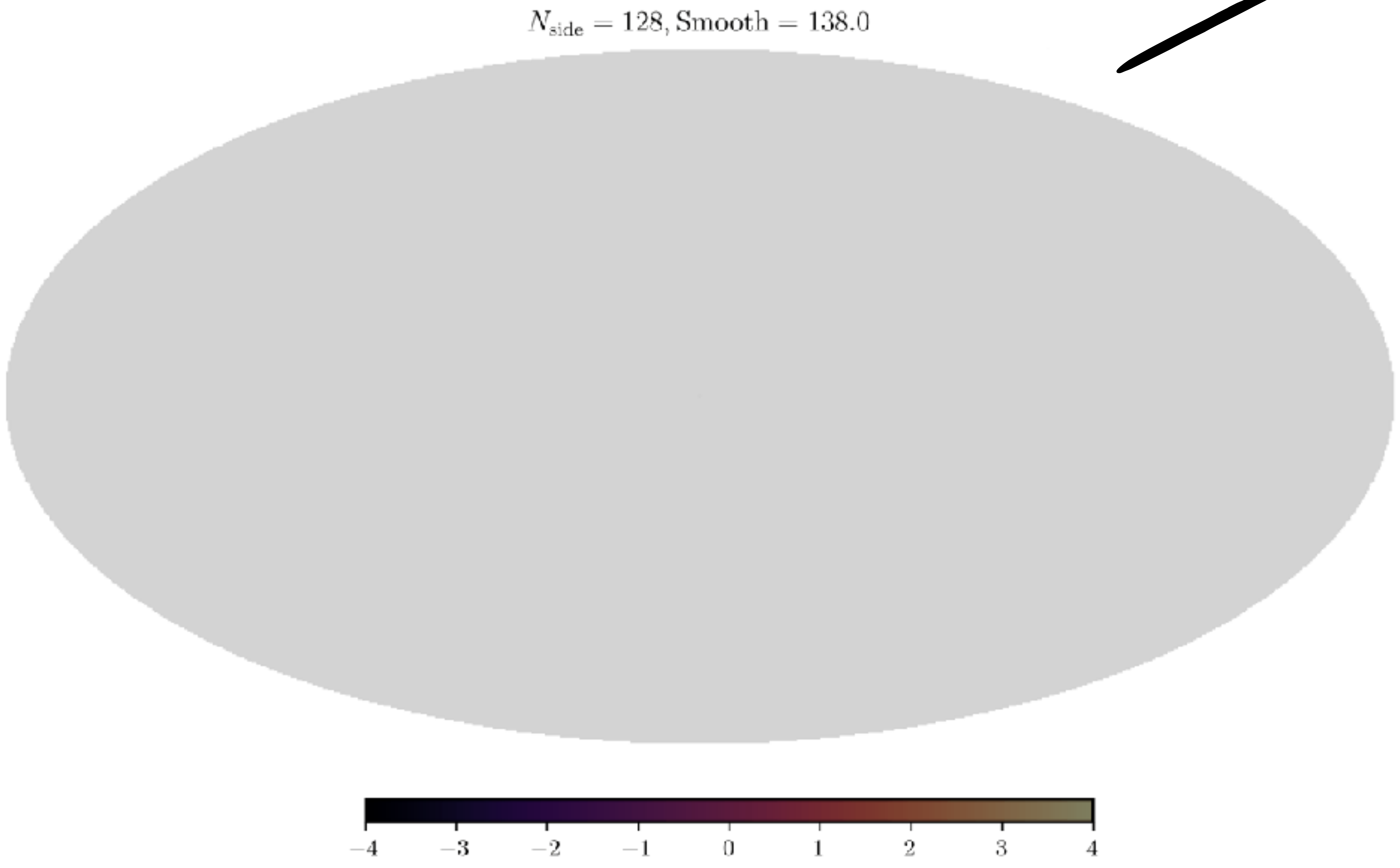
(i) Persistent homology applied to DES Y3 WL mass maps
(ii) Contrastive learning applied to DES Y3 WL mass maps

(i) *Prat et al. (in prep)*
(ii) Ongoing

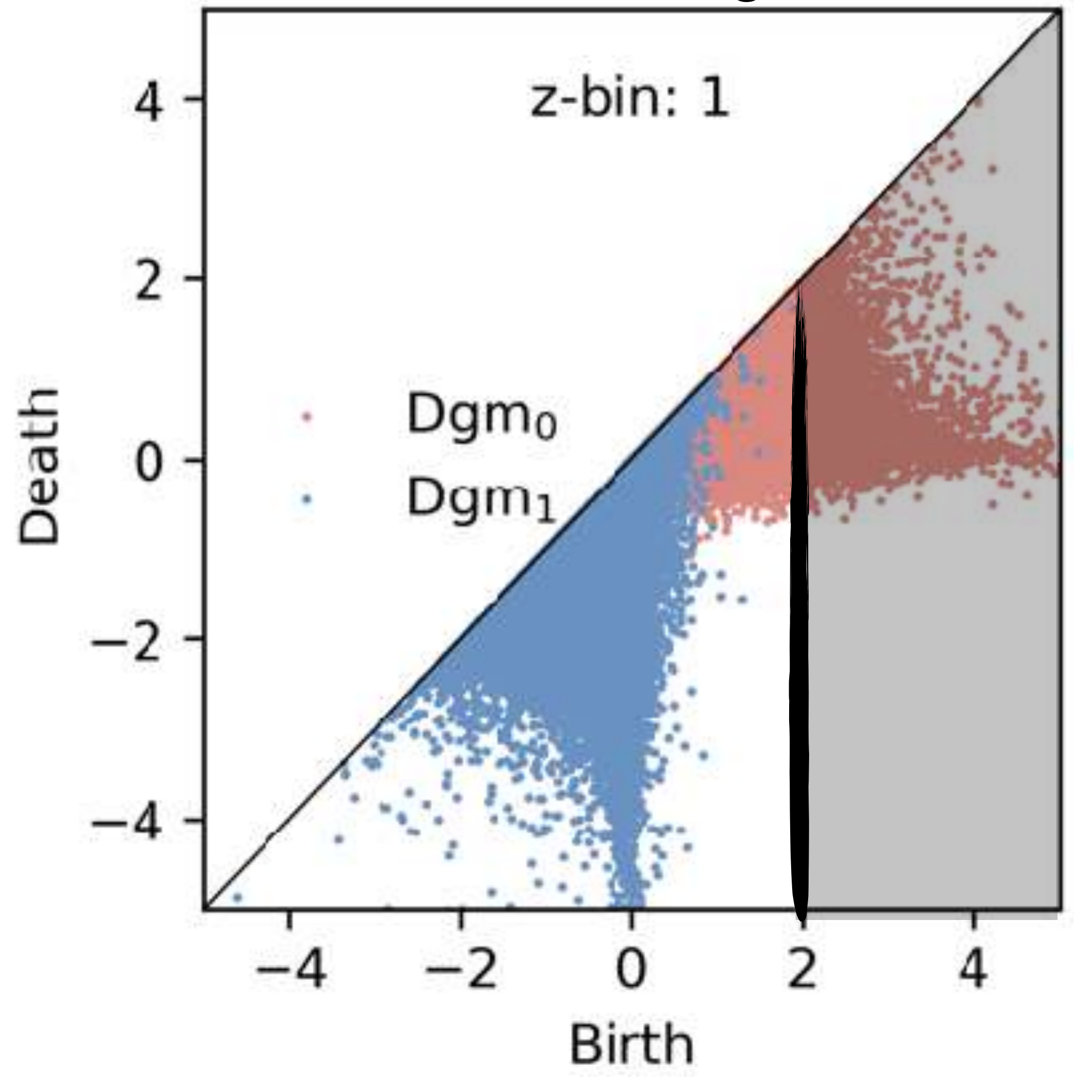
With more data

Persistent homology

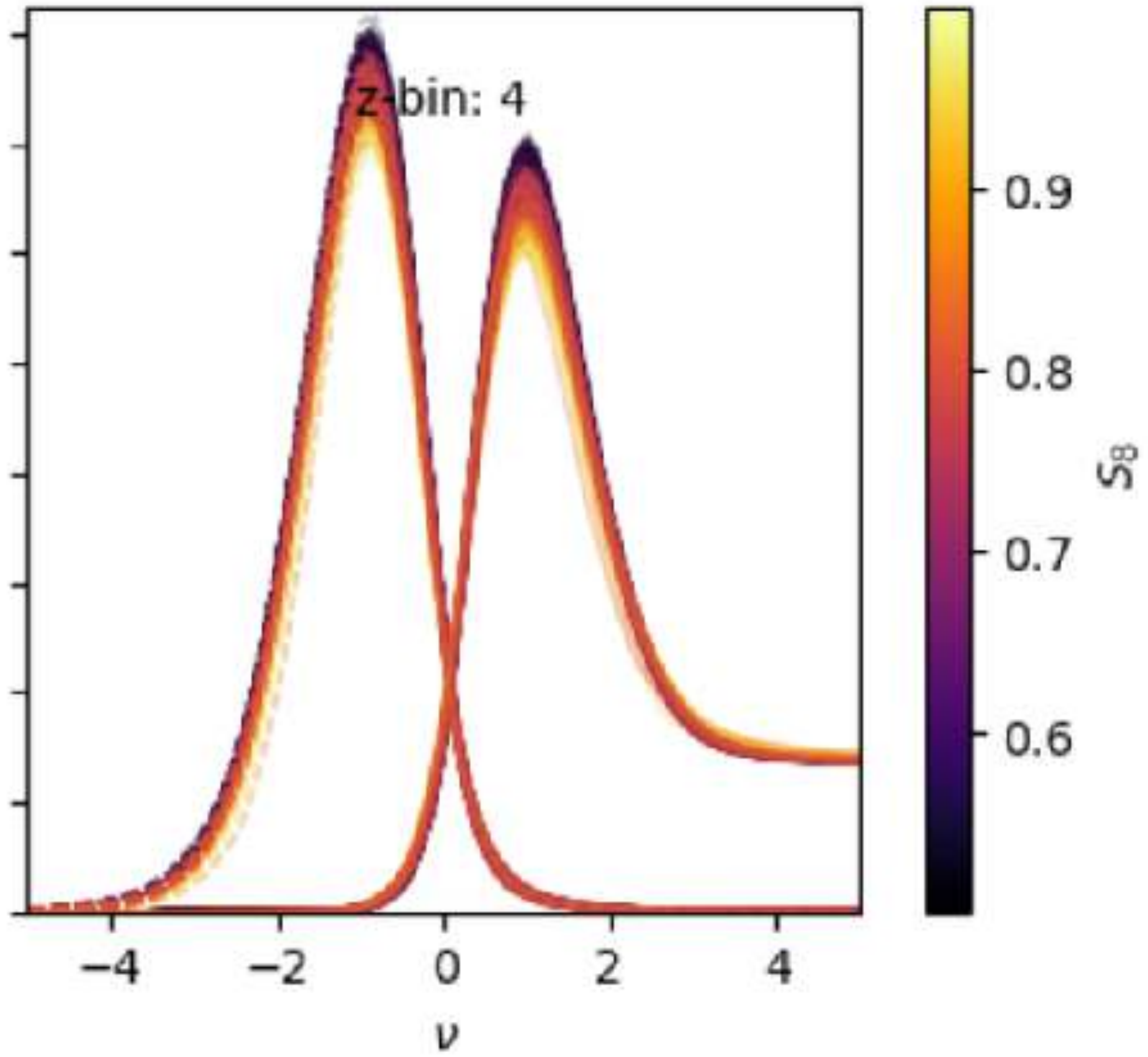
Filtration



Persistent diagram



Betti numbers count the number of **connected components** and **holes** that are present above a given threshold ν_0. These are called the 'Betti numbers' β_0 (for connected components) and β_1 (for holes).



Betti numbers

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(ii) Ongoing

Improve modeling (of small scales especially, galaxy-halo connection):

(i) Galaxy-halo connection from galaxy-galaxy lensing

(ii) Weak Gravitational Lensing around Low Surface Brightness Galaxies

(iii) Cosmic filaments on DES Y3 data

(i) ***Zacharegkas, Chang, Prat et al (2022)*** **+ in prep.**

(ii) ***Chicoine, Prat et al. (in prep)***

(iii) Ongoing

With more data

DES Y6 & Preparing for LSST:

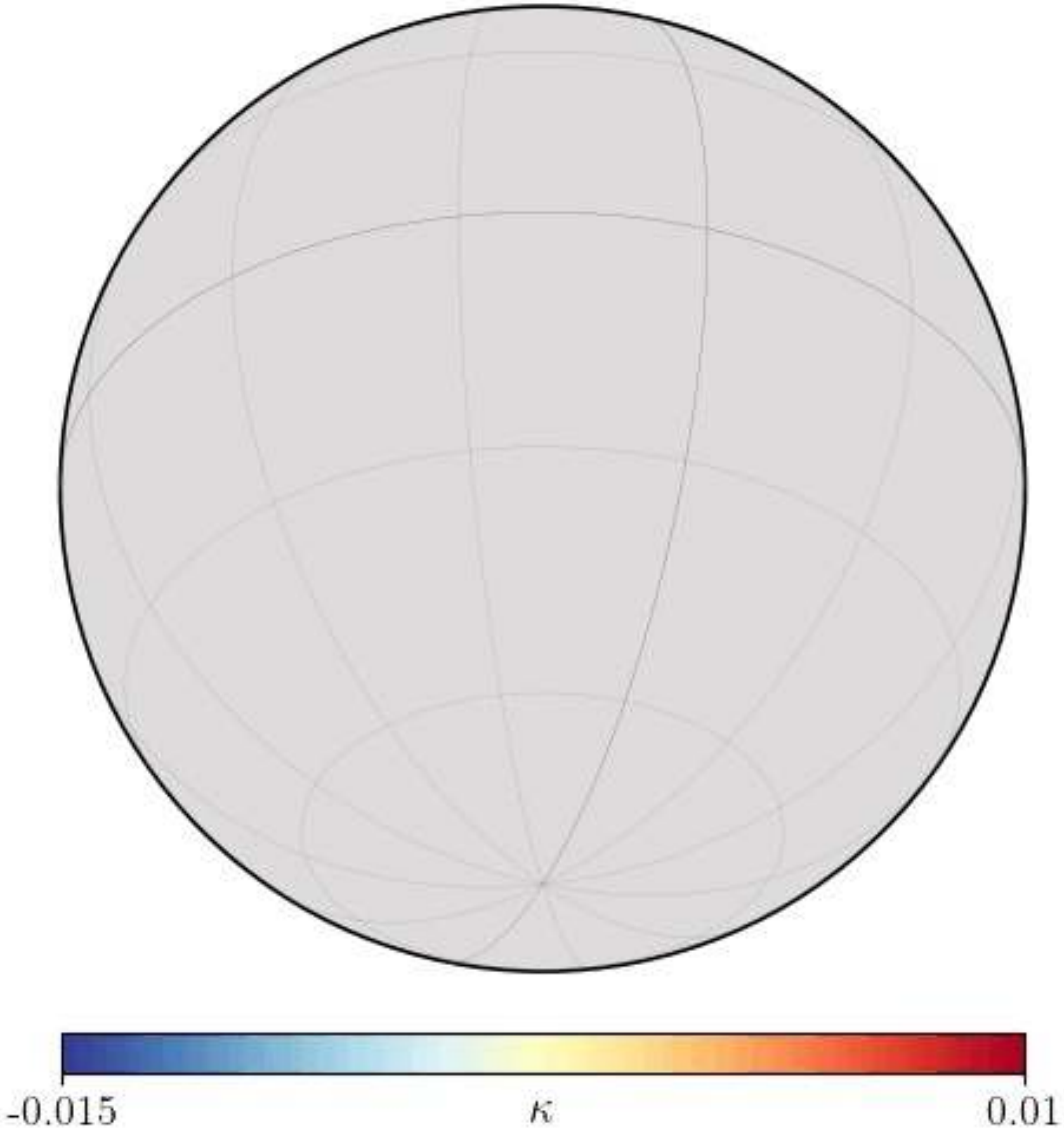
(i) DES Y6 3x2pt

(ii) Developing and validating the framework for LSST-DESC WL+LSS cosmology

(i) Ongoing

(ii) ***Prat, Zuntz et al. (2023):*** *2212.09345*

DES Y6



Credit: Chihway Chang, Marco Gatti and all the DES Y6 shear team!

Conclusions and outlook

- The ΛCDM is still standing but there are hints indicating soon we'll reach enough precision that it might break.
- The late-time DES Y3 3x2pt cosmology results are in agreement with early-Universe predictions assuming the ΛCDM model at the 1.5σ level. This is a very important end-to-end test of ΛCDM. Keep an eye for the DES Y6 results coming this year!
- When combined with the other most constraining low-z probes (BAO and RSD from BOSS DR16, and Type Ia Supernova from Pantheon) the agreement is at the 0.9 sigma level, with smaller uncertainties.
- More stringent testing is needed to determine whether ΛCDM holds or not.
- A new generation of galaxy surveys, using more scales and higher order information and emerging probes (such as GW) and maturing of existing ones (such as strong lensing) will (hopefully) provide the answers.

Thanks!

NORDITA
The Nordic Institute for Theoretical Physics

Judit Prat
London meeting
April 2024