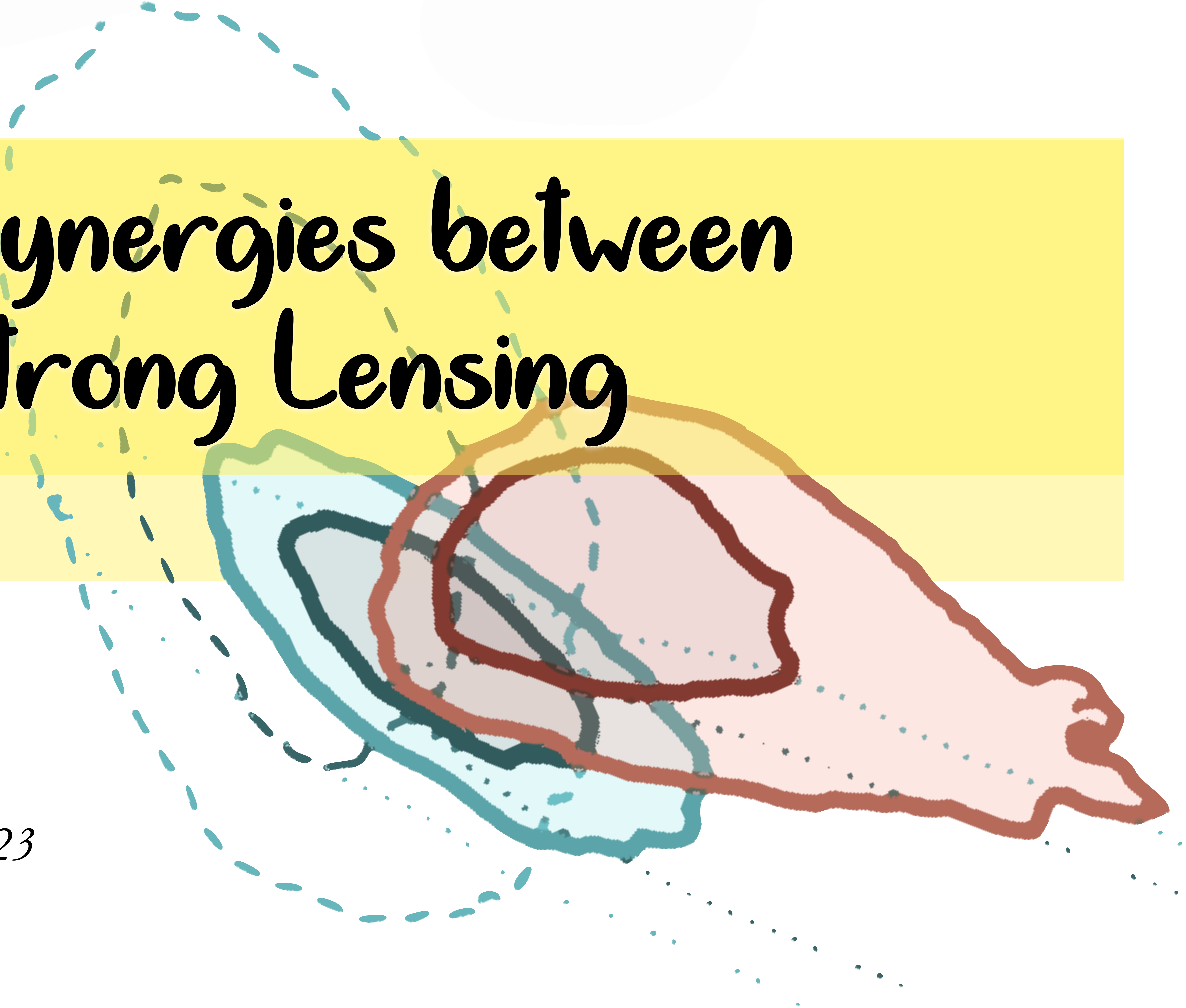
Cosmology synergies between Weak and Strong Lensing



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KICP workshop July 2023

ΛCDM model under discussion

ΛCDM adds **2 new components** to the Standard Model of physics, neither of which has 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 real, systematics, or statistical fluctuations?

Is **dark energy** really not **evolving with time**? We only know that to the current statistical precision.

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.

Stress-testing ΛCDM

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

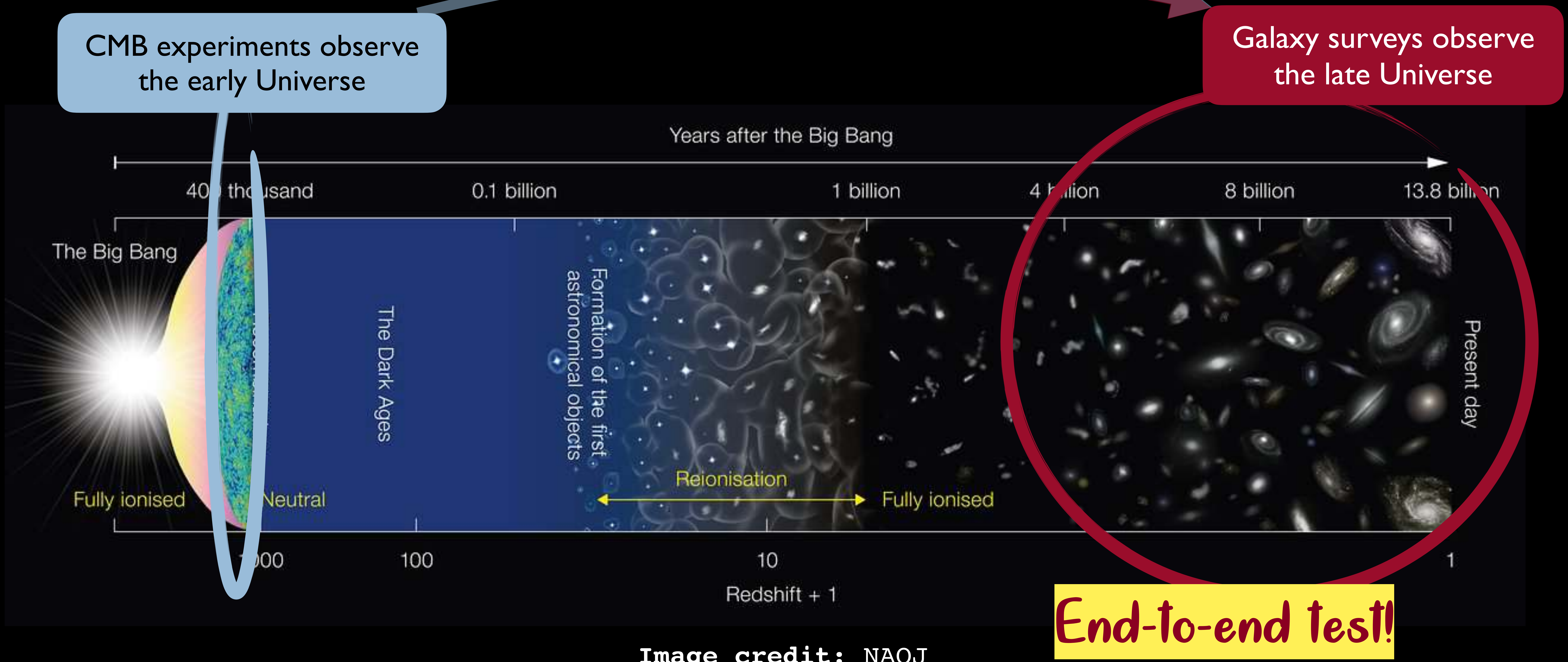

Image credit: NAOJ

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.

$$\sigma_8^2 = \frac{1}{2\pi^2}\int k^2 P(k)\left[\frac{3j_1(kR)}{kR}\right]^2 dk$$

$\longleftrightarrow$

4) Do they agree?

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

Ω_m	Amount of matter today
$\sigma_8^2 = \frac{1}{2\pi^2}\int k^2 P(k)\left[\frac{3j_1(kR)}{kR}\right]^2 dk$	
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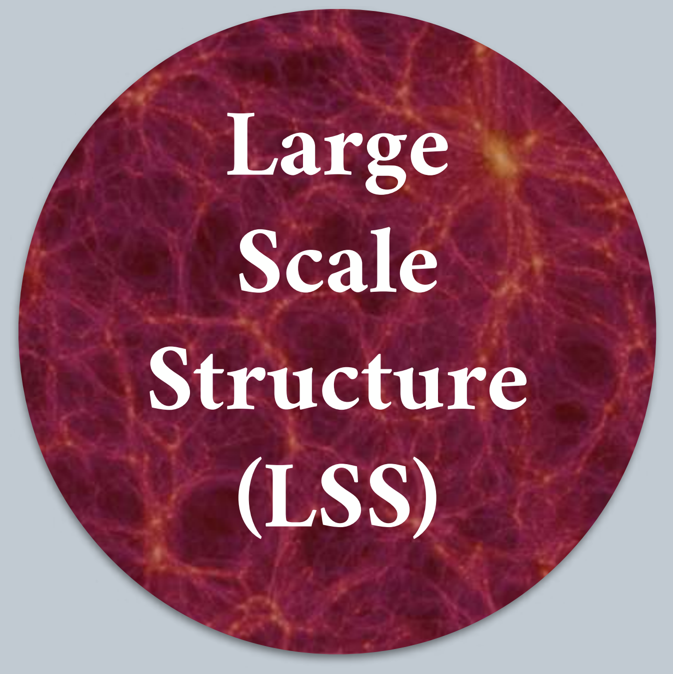
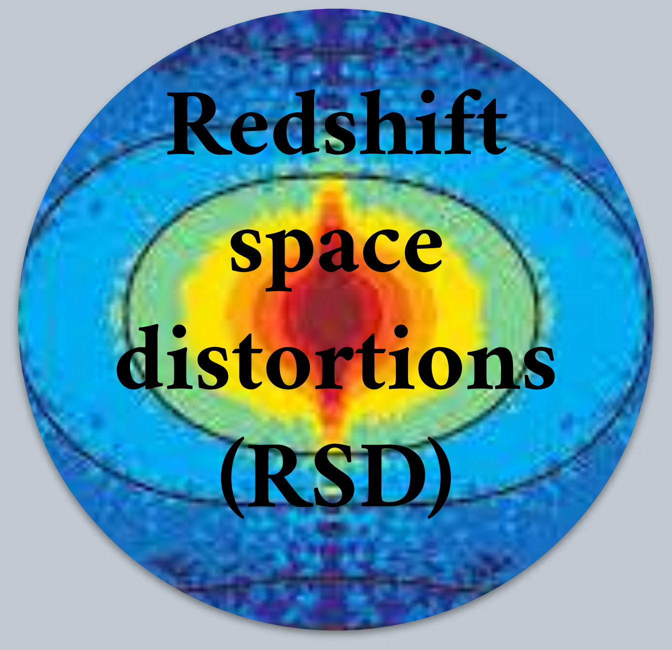
Probes to measure cosmological parameters

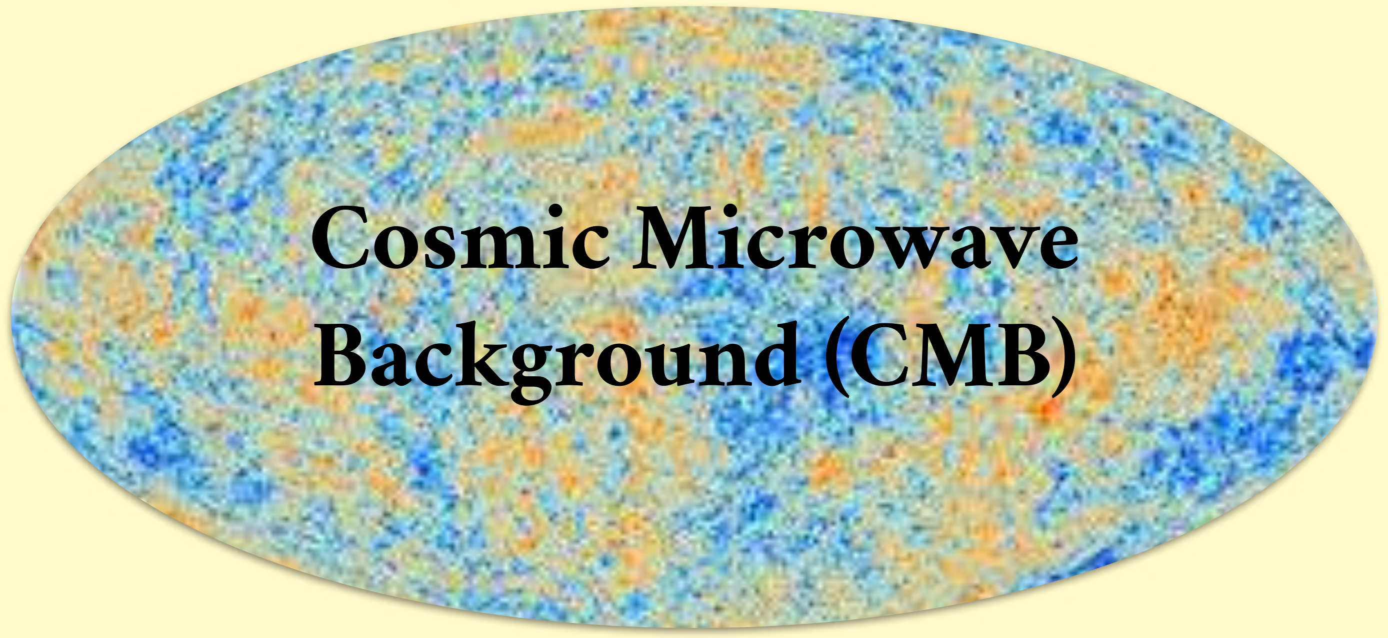
History of Expansion

More Growth, but also a bit of expansion





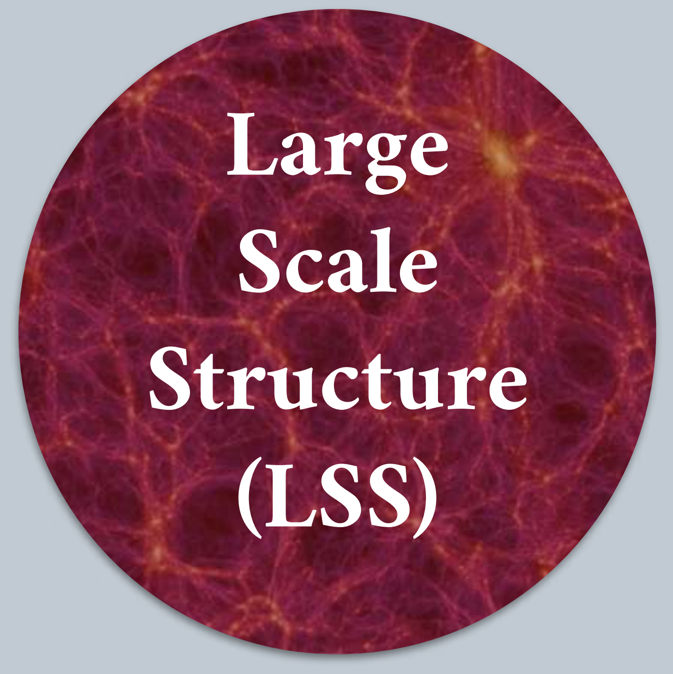
Growth and Expansion

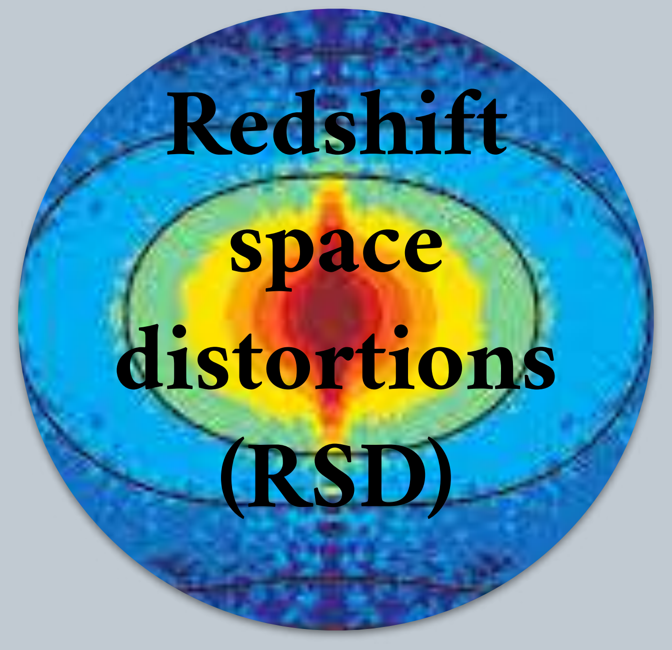


Probes to measure cosmological parameters

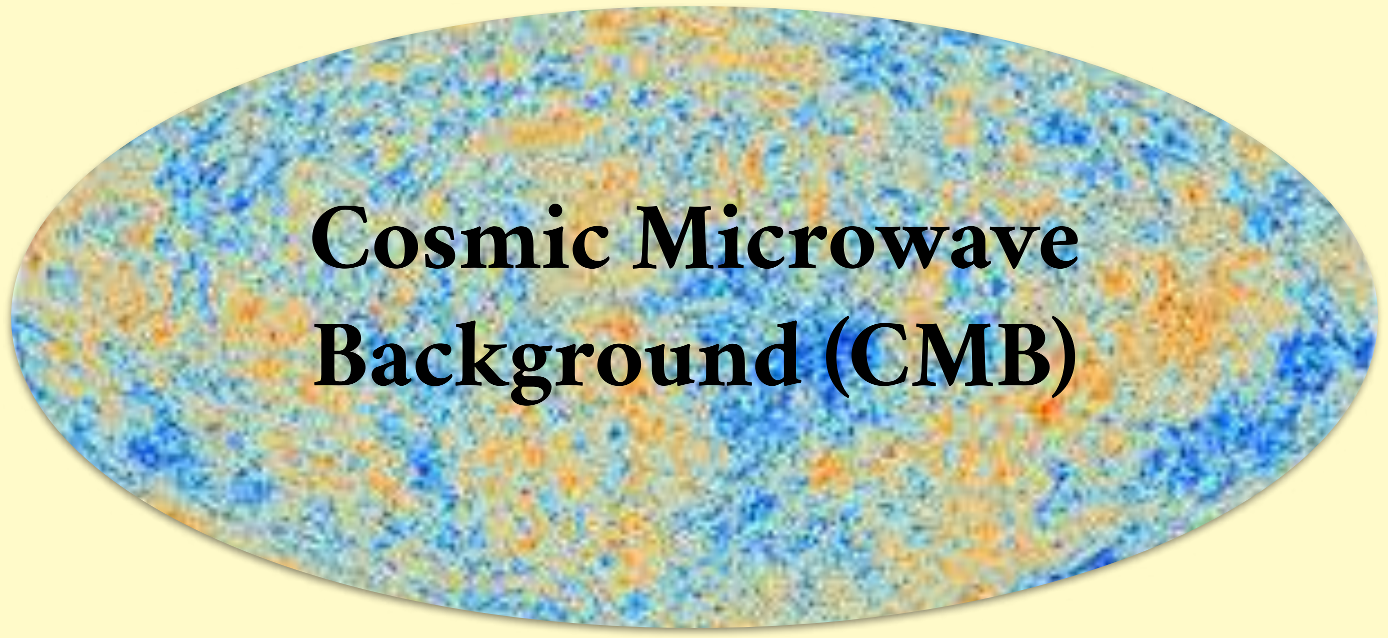
History of Expansion H(z)

More Growth, but also a bit of expansion Ω_{m}, σ_8





Growth and Expansion



$$H^2(z) = H_0^2\left[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda\right]$$

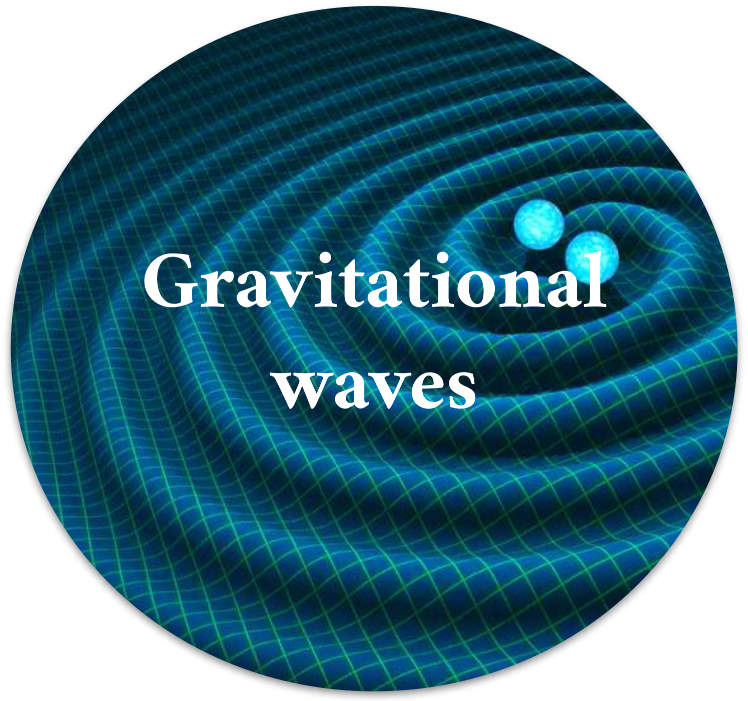
Let's be more detailed

$H(z)/H_0$

(when marginalizing over absolute magnitude)

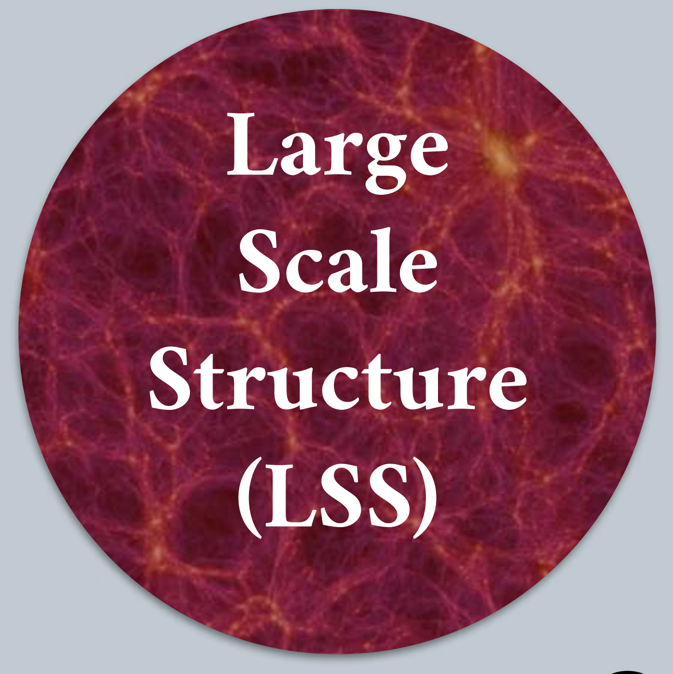
$H(z)$, sound horizon

$H(z)$

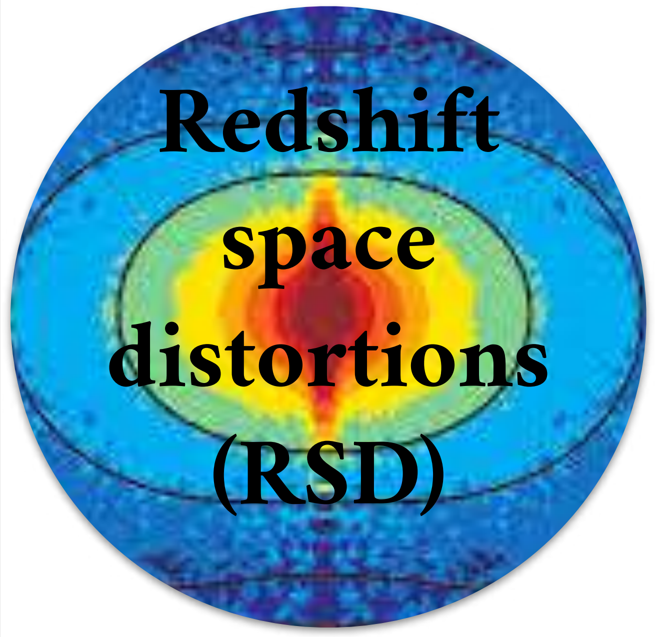


$H(z)$

3x2pt



Ω_m, σ_8



Ω_m, σ_8

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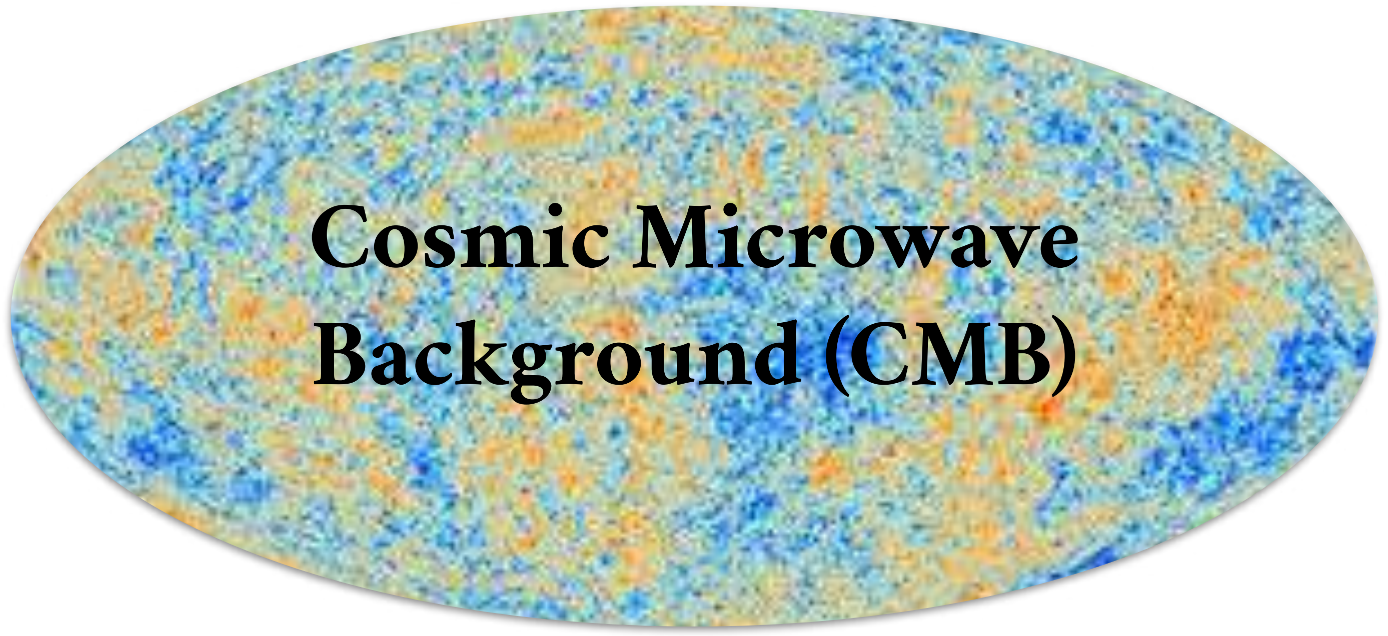
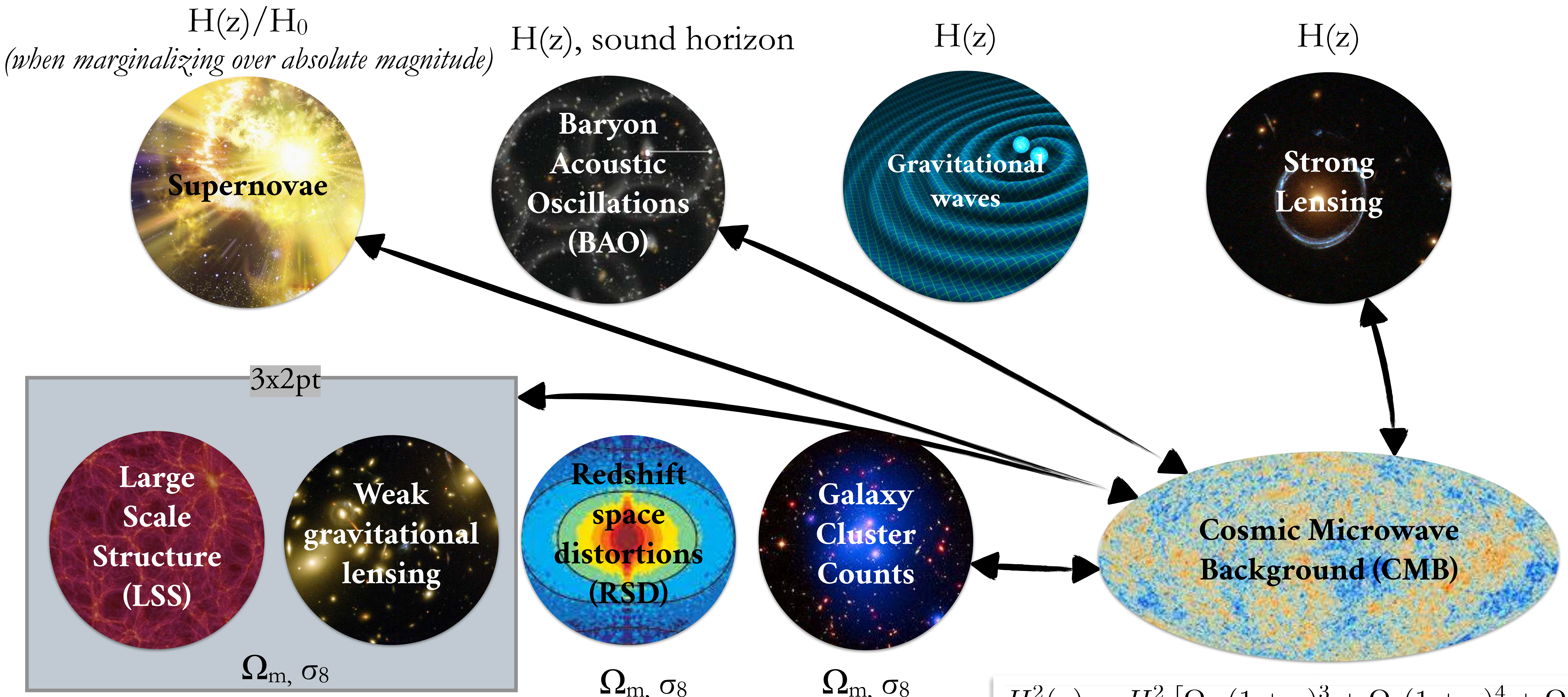


$$H^2(z) = H_0^2 \left[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda\right]$$

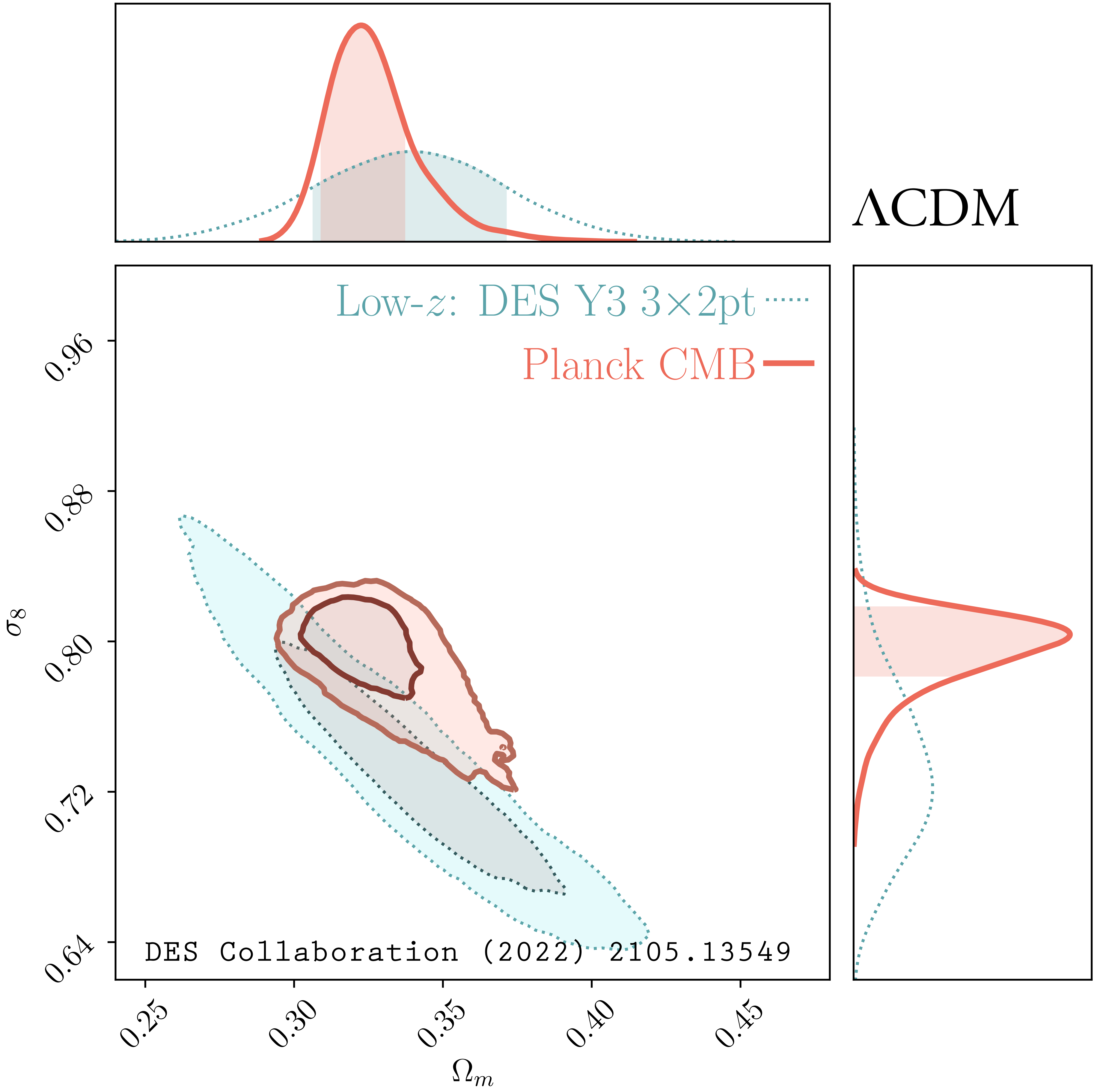
A lot of focus on individual comparisons



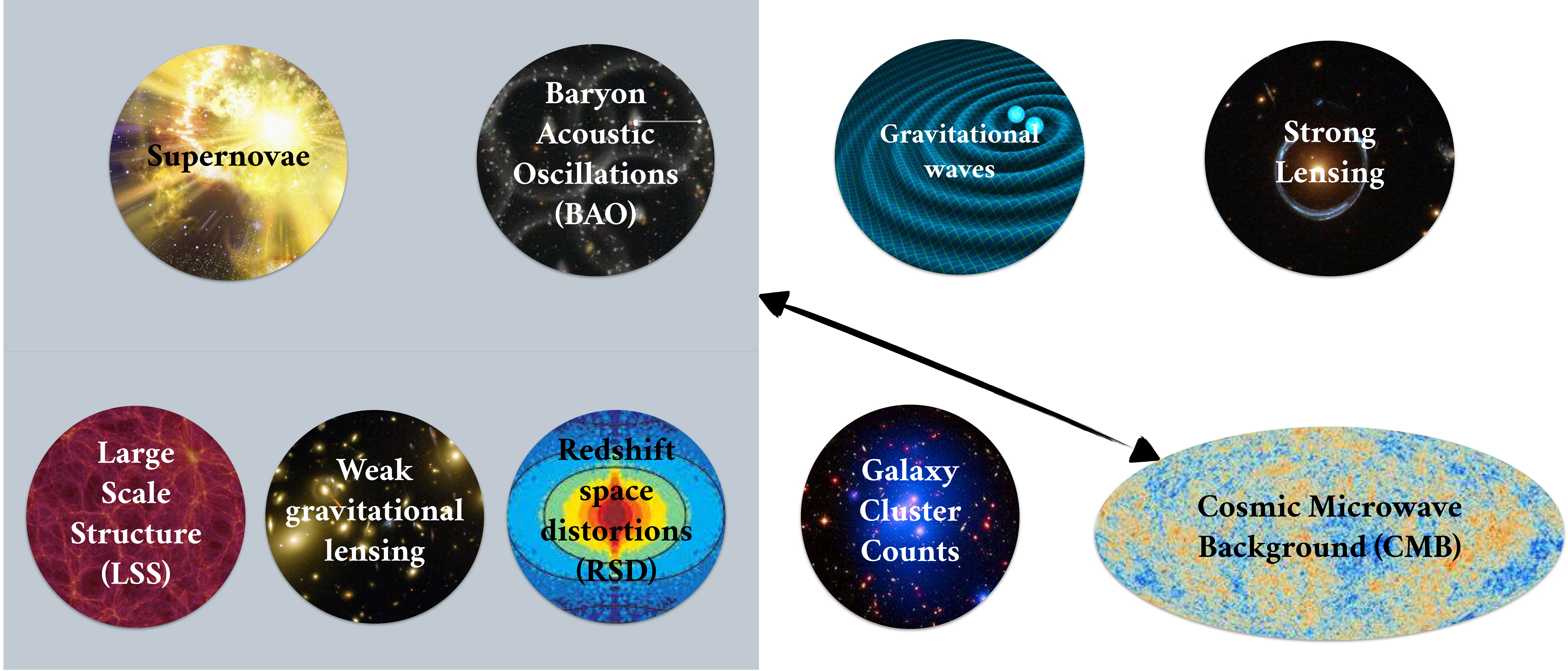
$$H^2(z) = H_0^2 \left[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda\right]$$

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.

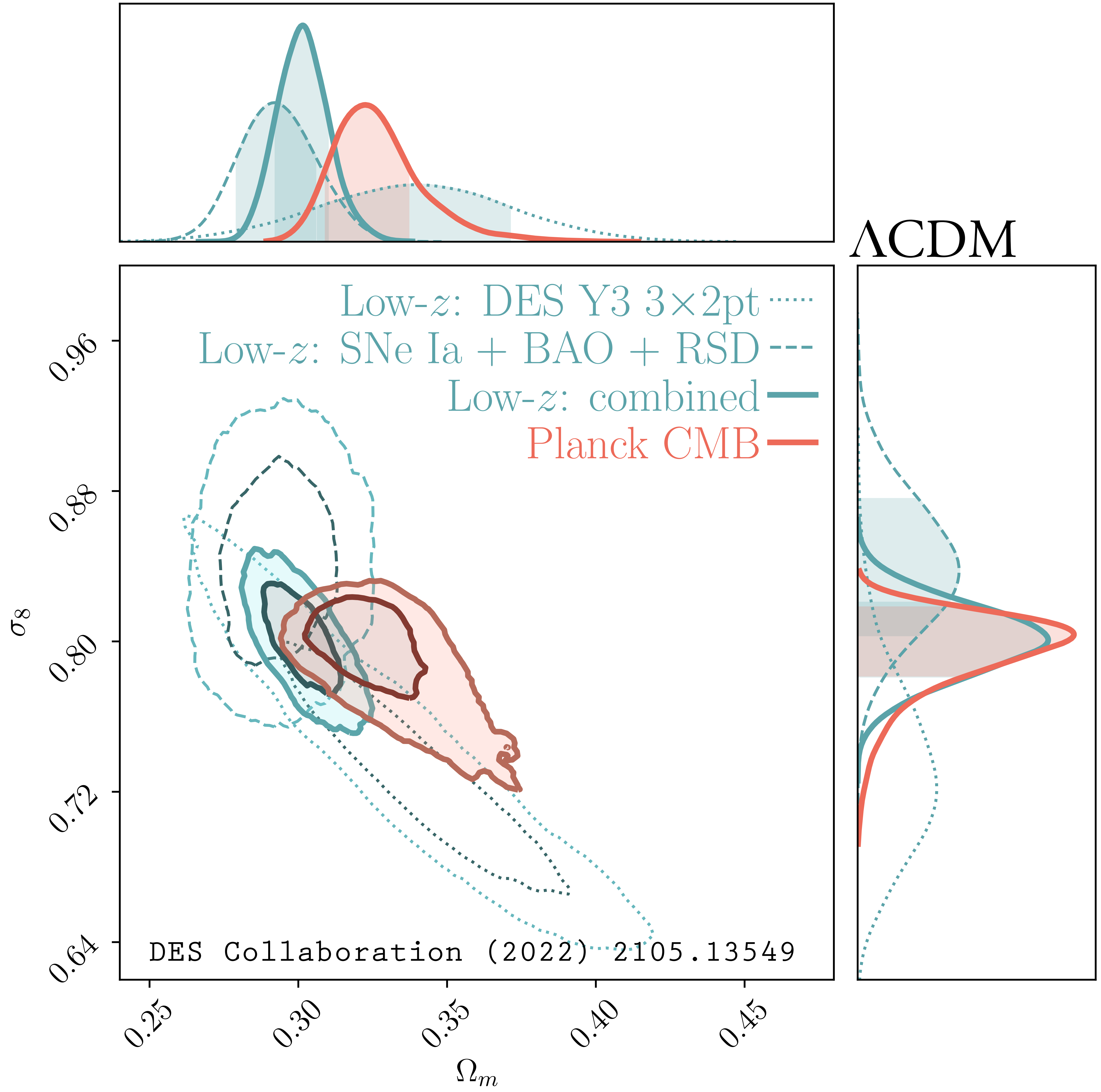


Most constraining comparison so far:



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.



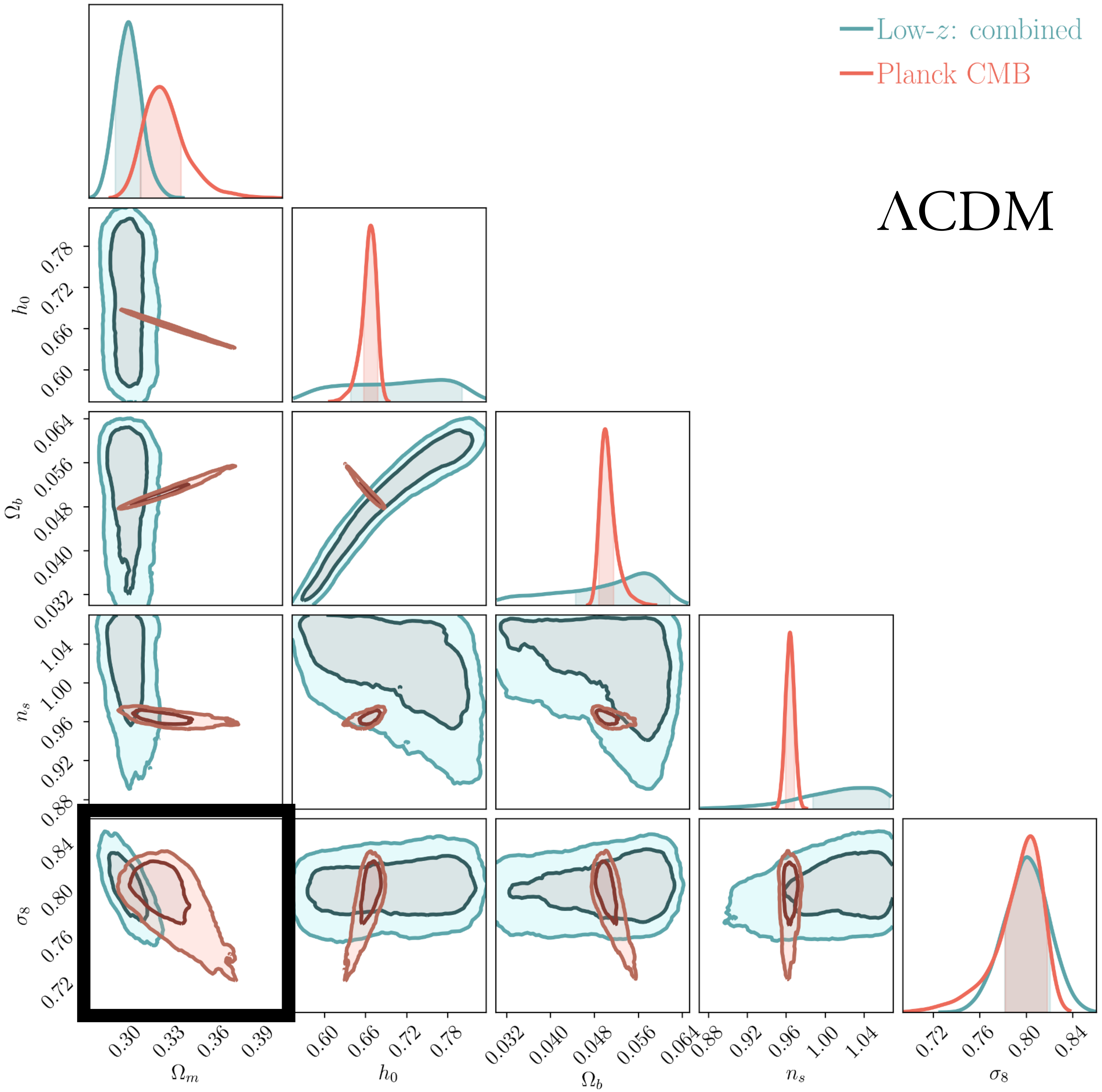
The real power in the late-time Universe comes when combining different probes!!

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.
- More work needed to allow an even more compelling test.

DES Collaboration (2022) 2105.13549



What else can we do?

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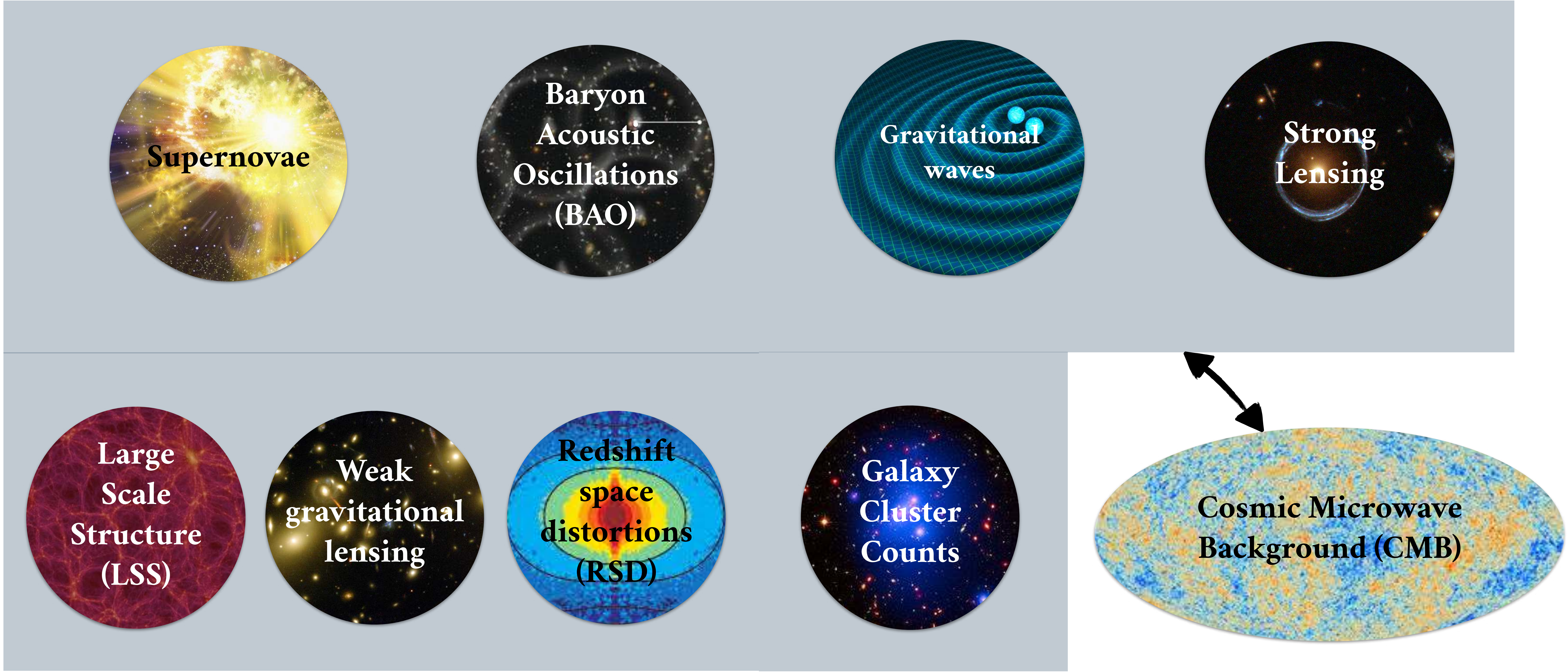

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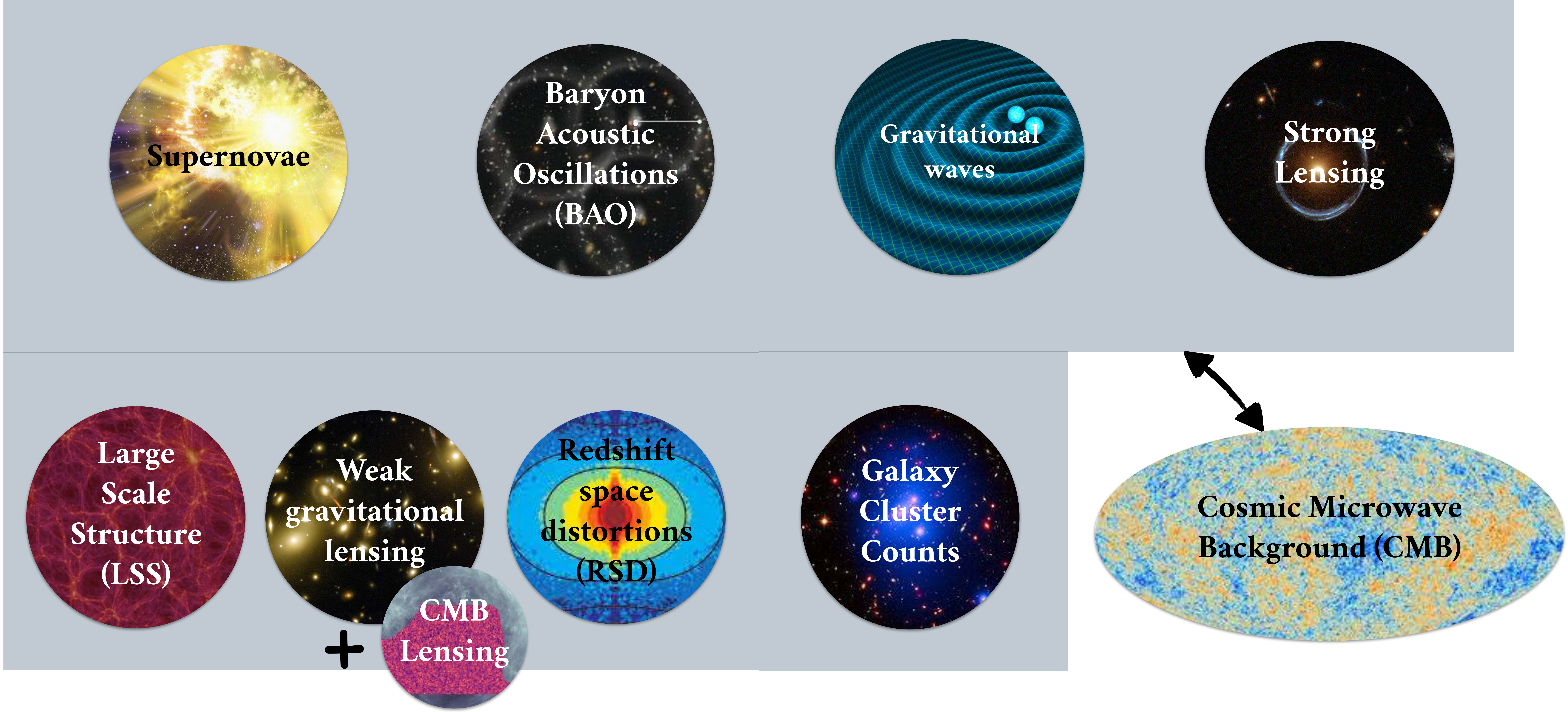
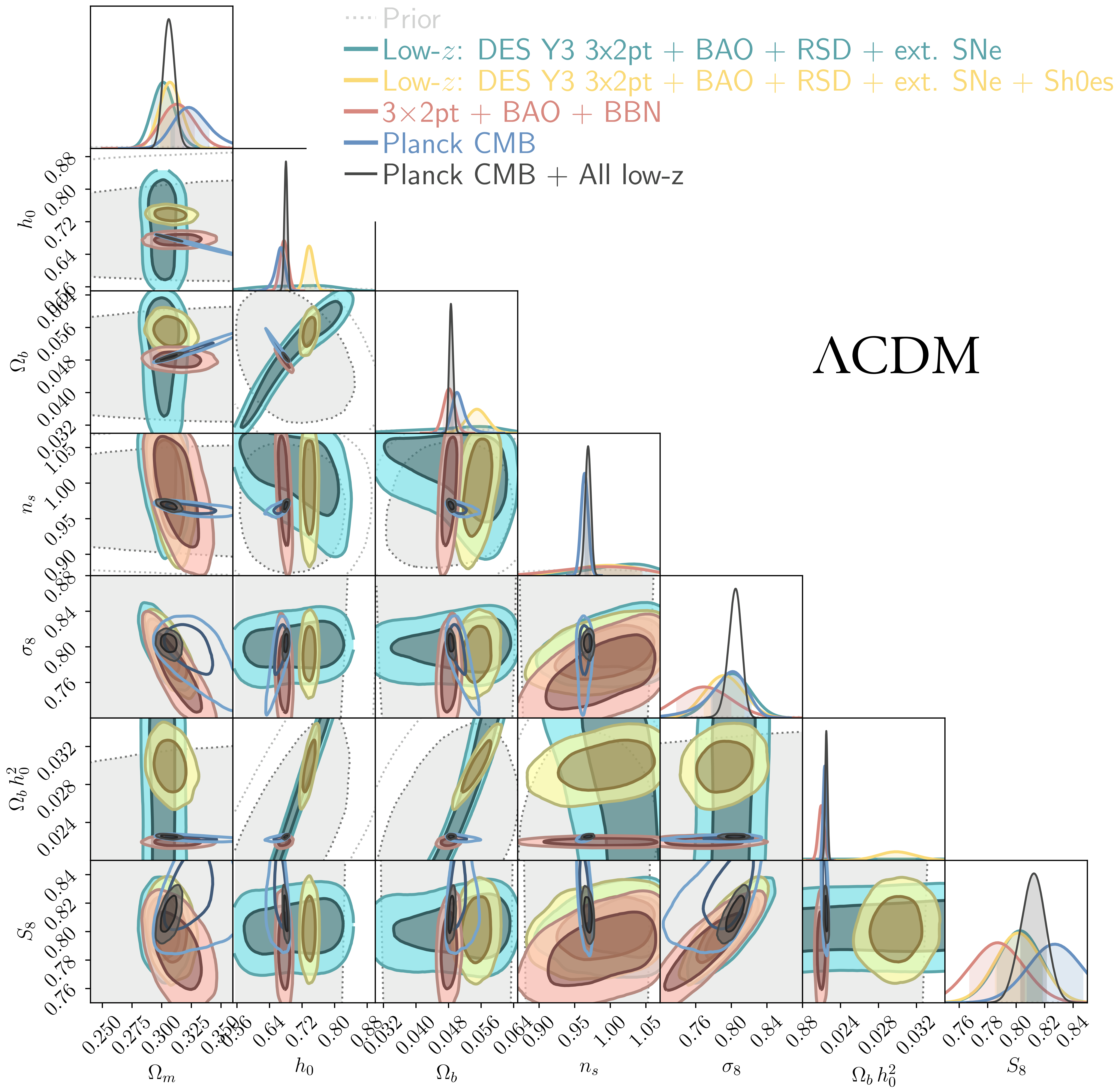


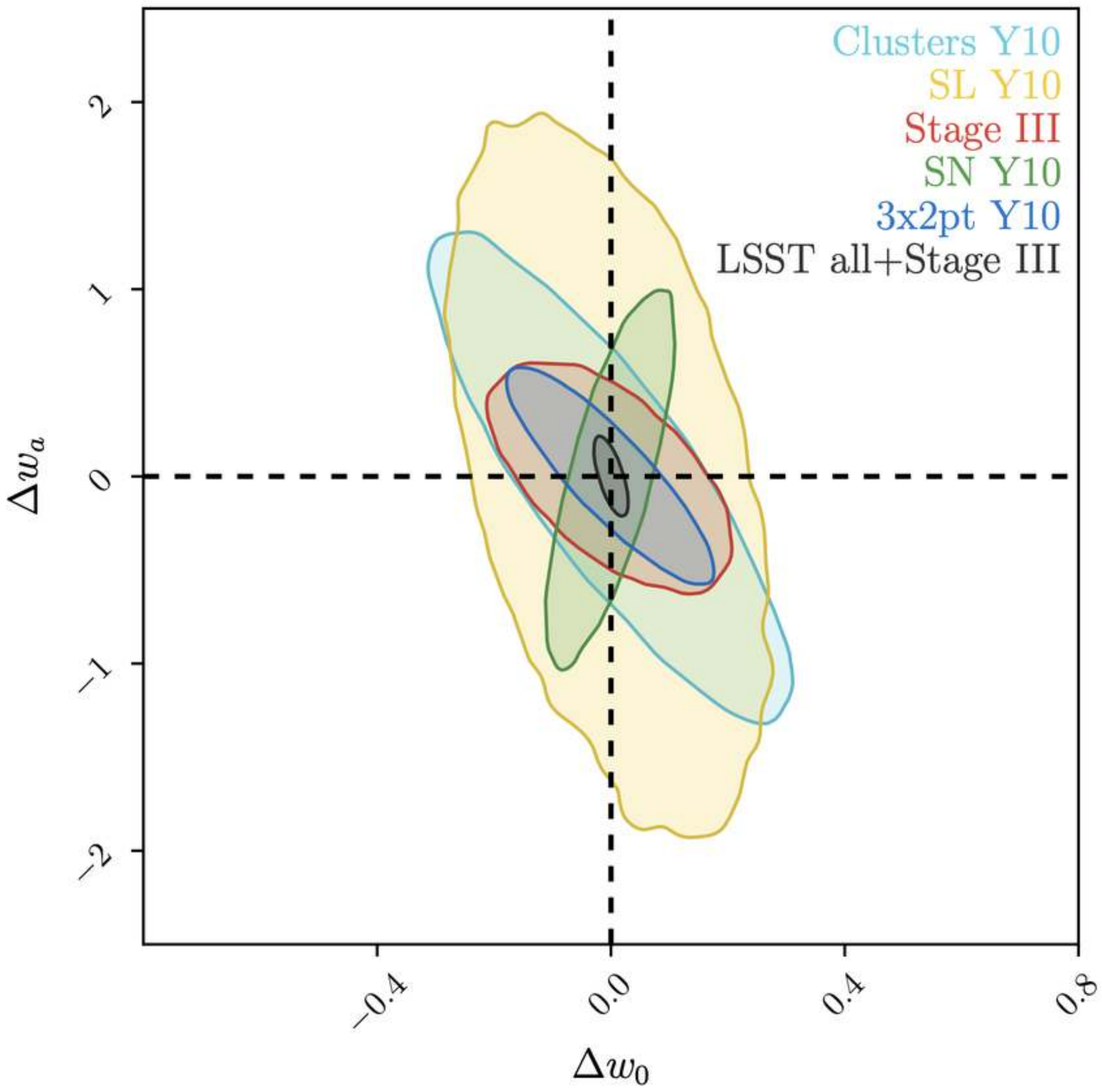
Adding more probes: *Cepheids anchor*

- We can add the SH0ES constraint as an H_0 prior.
- Ideally you would do this properly specifying the SH0ES likelihood that already includes the Pantheon SN data.



Adding more probes: *Strong Lensing?*

- We could add the strong lensing likelihood to the current likelihoods.
- We haven't yet added SL to other low-z probes in Stage-III surveys. However, it is in the plan for LSST.
- We could start using the current surveys as a test bed for this (*has this been done?*)
- Within LCDM, it is sensitive to H(z), H_0, and slightly to Ω_m.
- Also beyond LCDM dependencies.

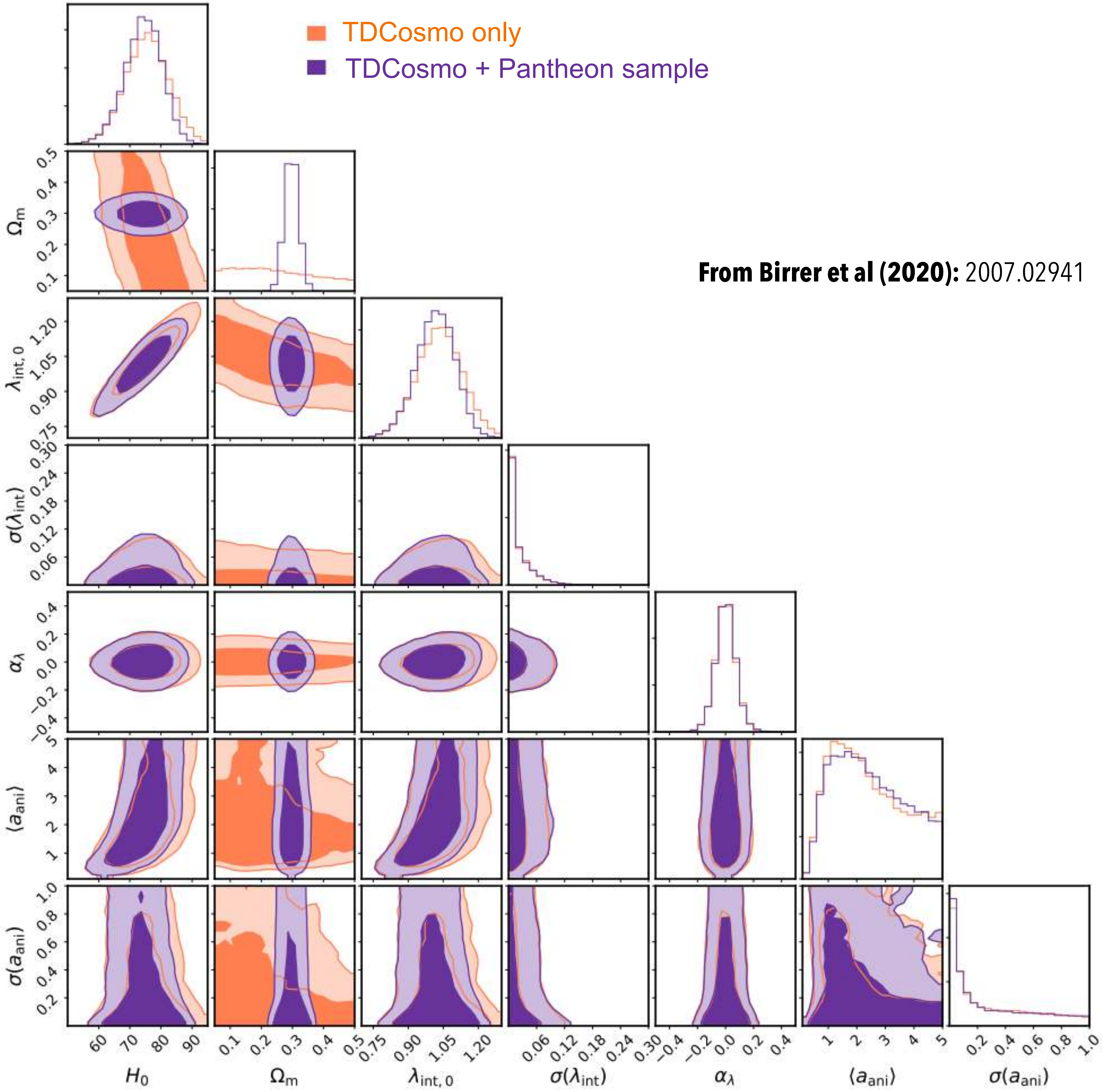


Adding more probes: *Strong Lensing?*

- Which likelihoods exactly?
- As an H_0 prior?
- Time delay distance as the likelihood:

$$D_{\Delta t} \equiv (1 + z_{\rm d}) \frac{D_{\rm d} D_{\rm s}}{D_{\rm ds}}$$

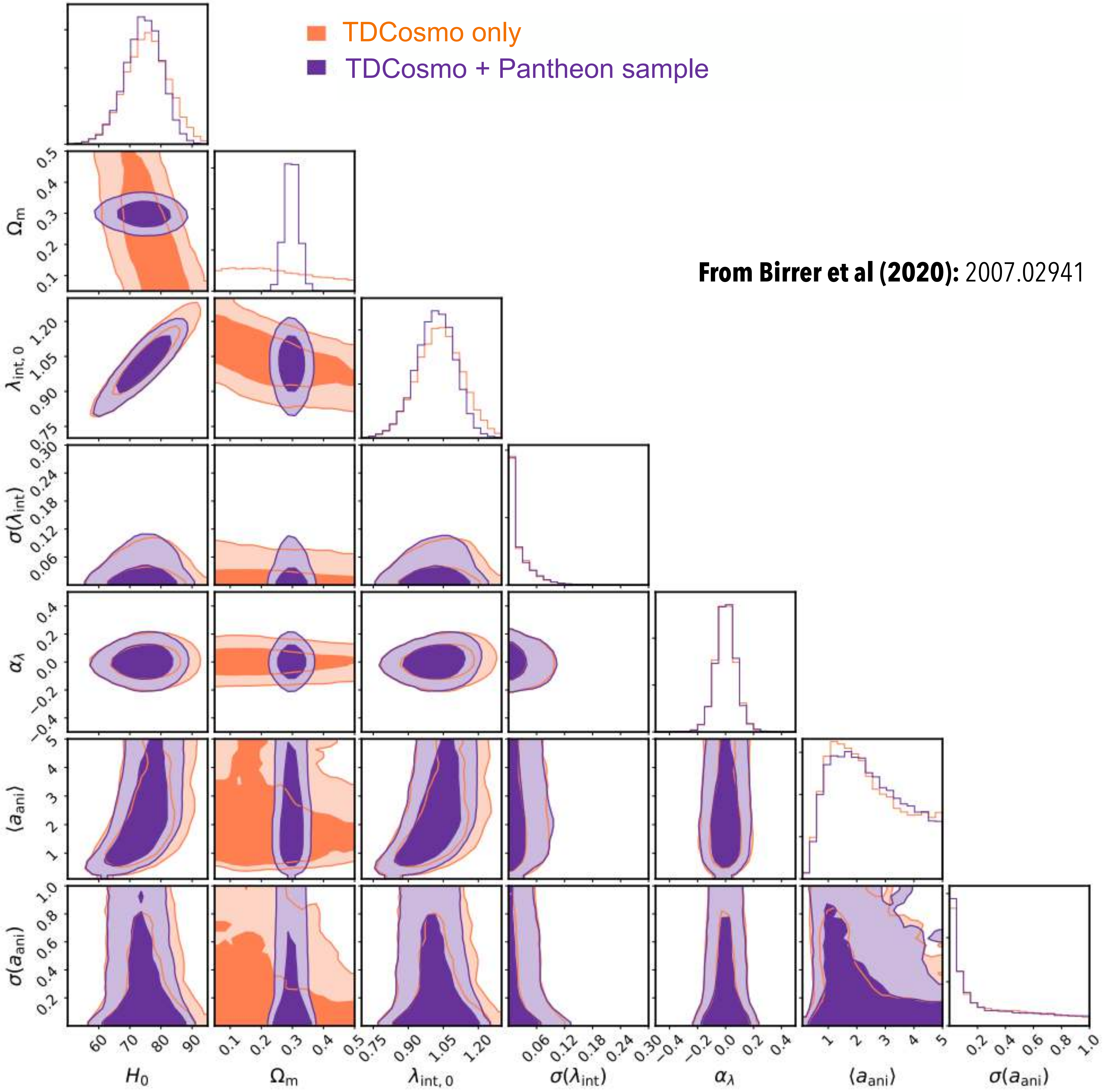
- Going back to the mass-model marginalization?
- Also other likelihoods beyond Time-delay?



From Birrer et al (2020): 2007.02941

Adding more probes:
Strong Lensing?

- **Proposed hack session:** <u>Implement the Strong Lensing likelihood in CosmoSIS.</u> *Which likelihood(s) exactly would be better to implement and which parameters to marginalize over?*



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Constraining other models with WL + SL

- wCDM, w_0-w_aCDM
- *Brainstorming question:* What cosmological models would the WL + SL likelihoods be particularly good at constraining

Thanks!

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WL + SL Workshop 2023