AST 1430

Cosmology

Week Index	Dates	Topics
Week 1	Jan 11, 13	logistics, introduction, basic observations
Week 2	Jan 18, 20	Basic GR, RW metric, Distances, coordinates, Friedmann equations, cosmological models
Week 3	Jan 25, 27	Consistency with observations, Early Hot Universe, BBN
Week 4	Feb 1, 3	Inflation, Perturbations & Structure pre-recombination
Week 5	Feb 8, 10	CMB: basics, polarization, secondaries
Week 6	Feb 15 (2h)	Early-Universe Presentations
Reading Week – No Class		
Week 7	Mar 1, 3	Post-recombination growth of structure, formation of dark matter halos, halo mass function
Week 8	Mar 8, 10	The relation between dark matter halos and galaxies
Week 9	Mar 15, 17	Probing the cosmic density field / clustering
Week 10	Mar 22, 24	Late Universe Presentations; lcosmological observations: BAO, supernovae, weak lensing, etc.
Week 11	Mar 29, 31	H0 controversy: how fast exactly is the Universe expanding today?
Week 12	Apr 5	Review

Keith

Jo

asst1

asst2

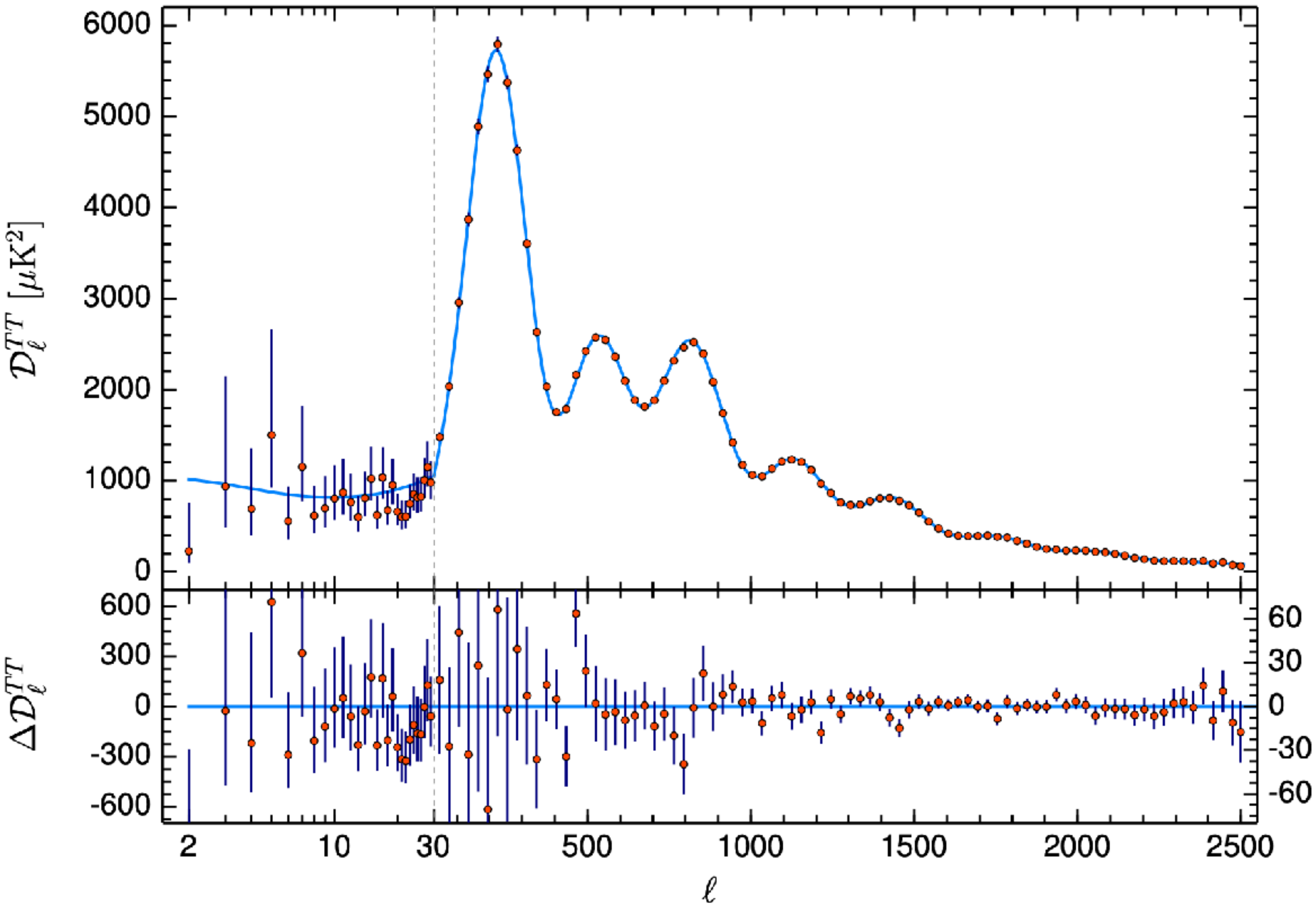
asst3

Late-time cosmological observations

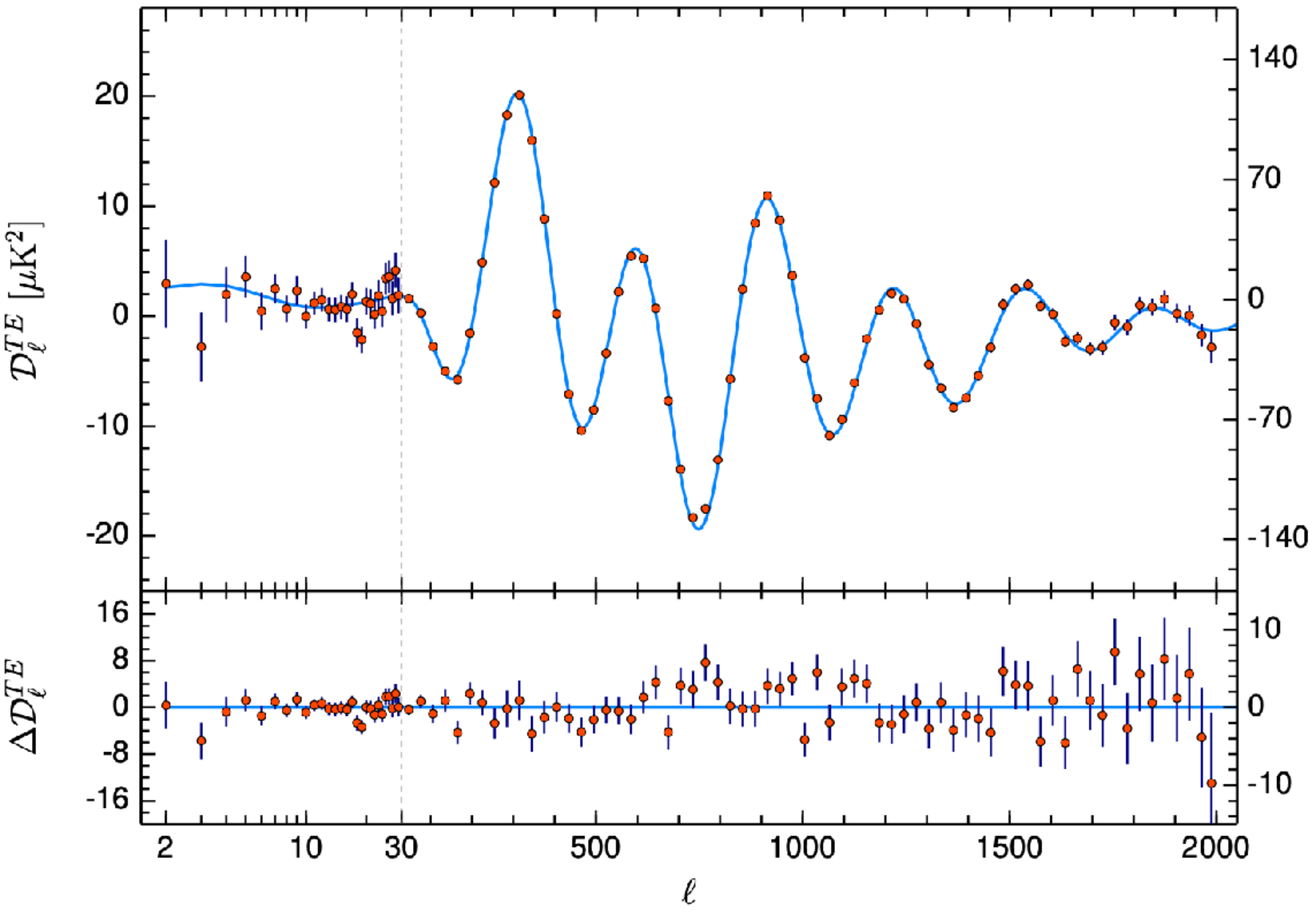
Why late-time cosmological observations?

- CMB measured in exquisite detail, with highly precise and accurate constraints on cosmological parameters
- So what do we need late-time constraints for?
  - Without assuming flatness, CMB alone cannot determine cosmological parameters well (i.e., need to assume Ω_k, or H_0, or similar)
  - Extensions to the basic flat LCDM model:
    - Dark-energy with non-trivial equation of state (CMB not really sensitive to DE at all)
    - Effective number of neutrino species
    - Neutrino masses
    - Non-standard dark matter

The CMB



Planck 2018 VI (2020)



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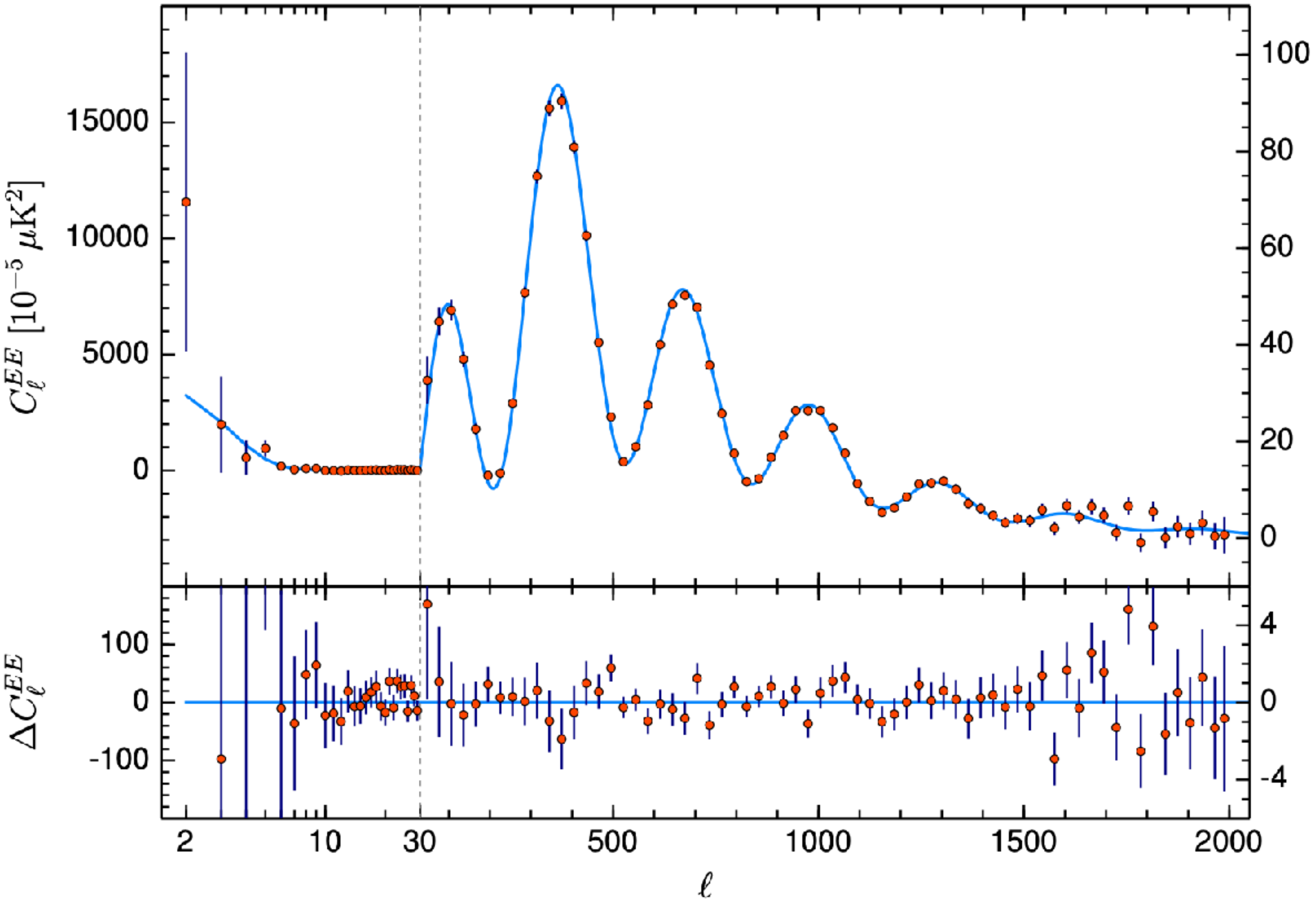

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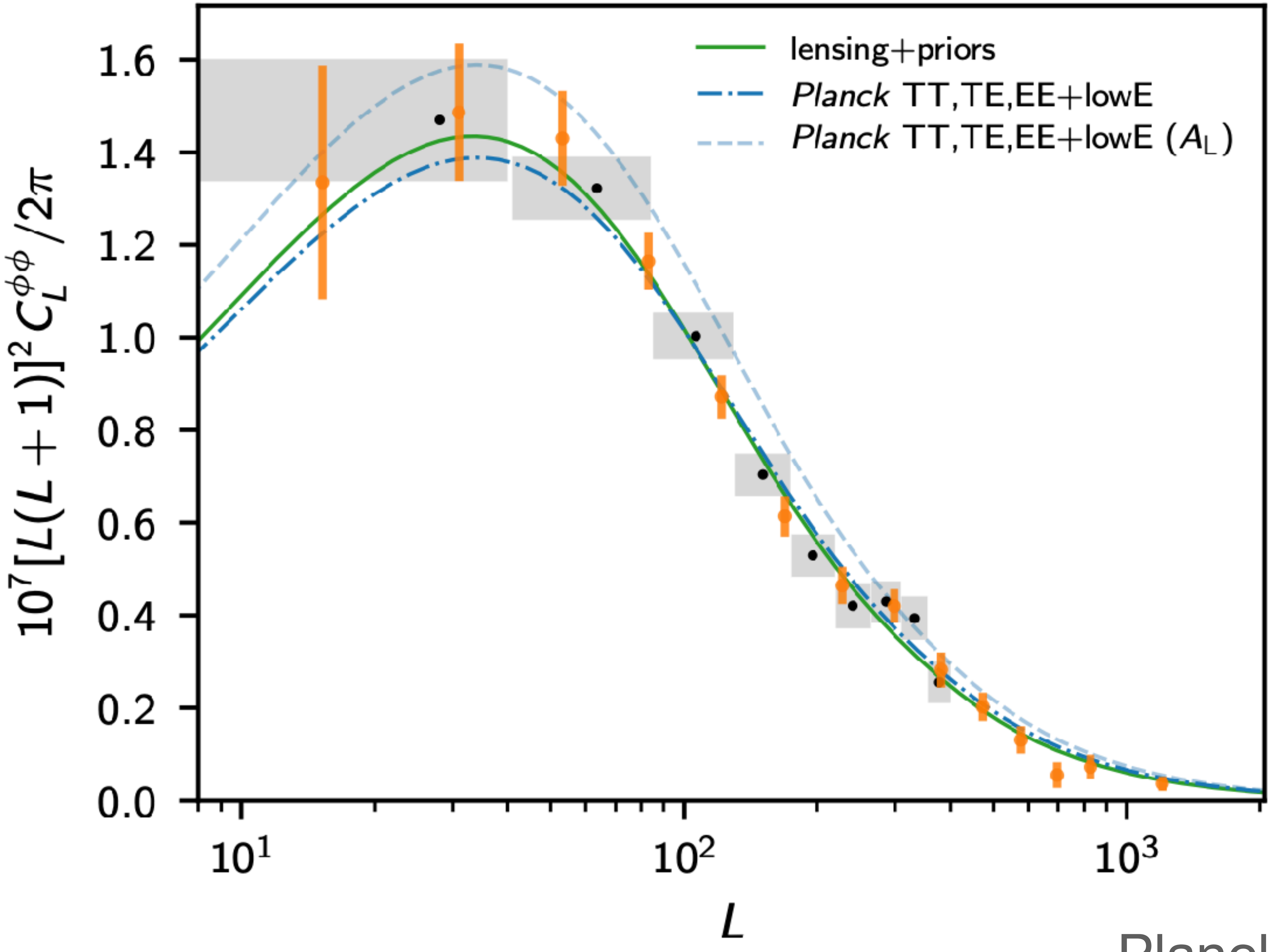

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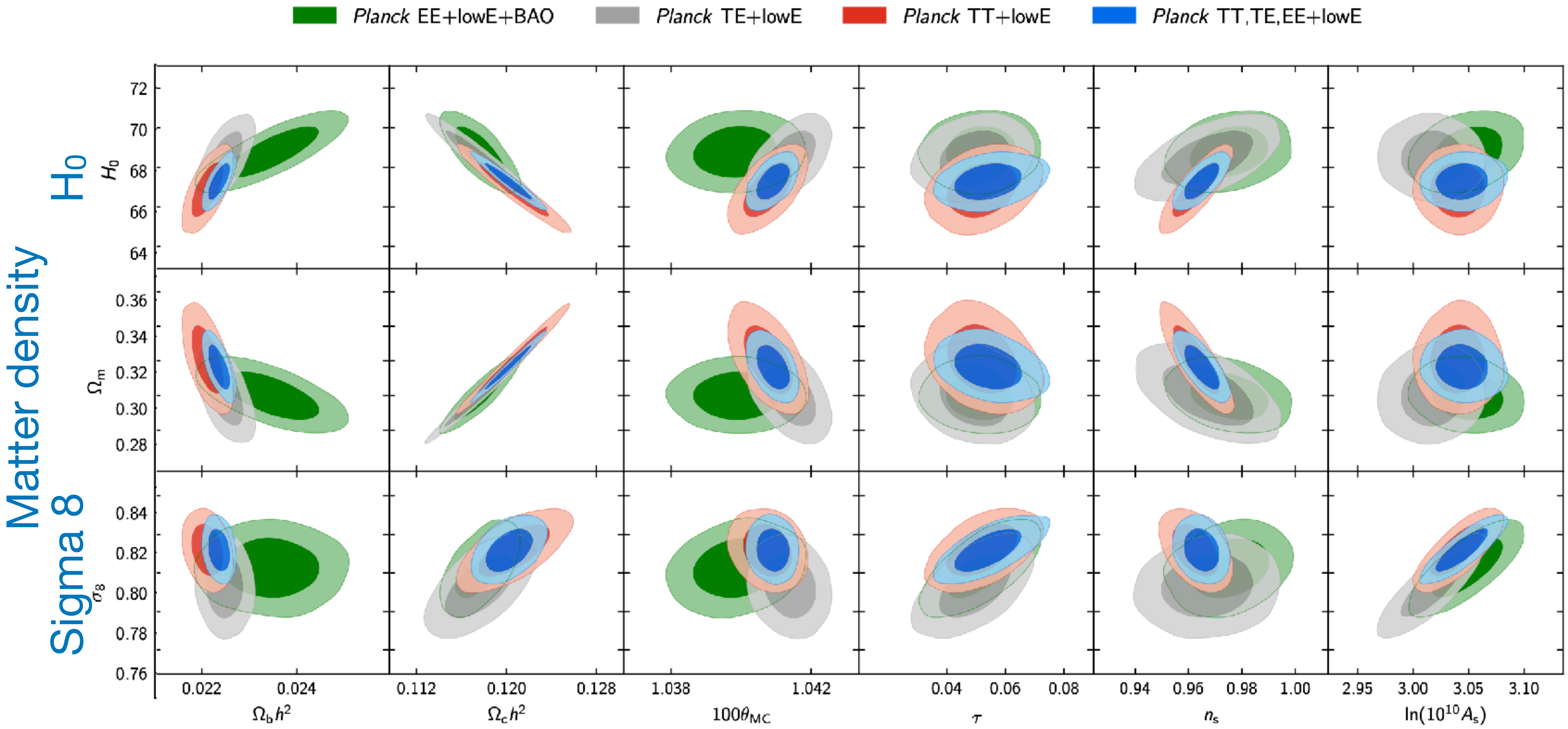


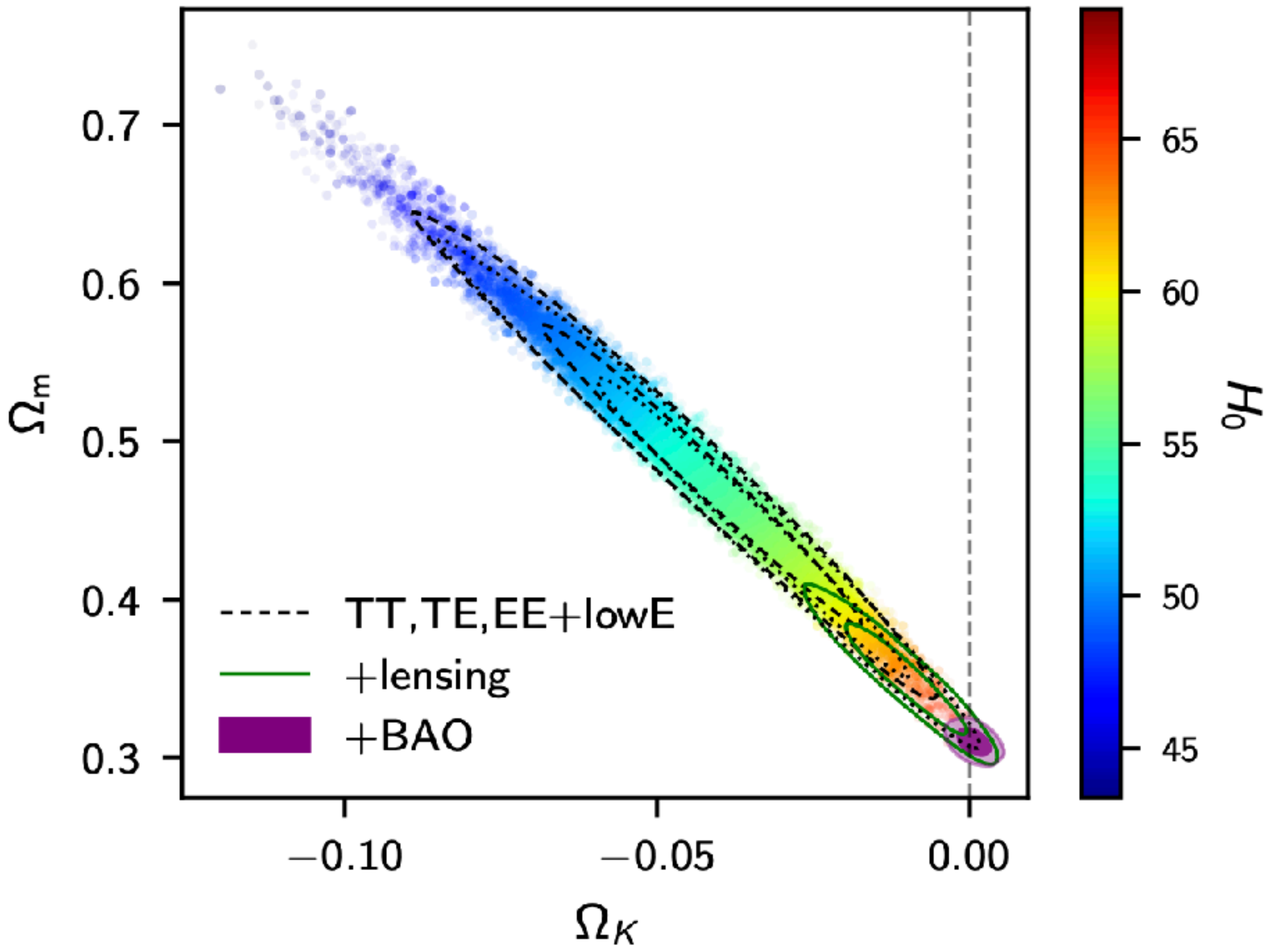
Physical density parameters

Optical depth reionization

Acoustic scale

Initial fluctuation spectrum

CMB degeneracy with flatness / H_0



Planck 2018 VI (2020)

CMB constraints

- Geometry vs. Growth-of-structure
- Geometry:
    - Physical baryon and dark-matter density: $\Omega_b h^2$ and $\Omega_c h^2$
    - Angular acoustic scale
    - Angular diameter distance to last scattering: $D_M(z=1090)/r_d$
- Growth-of-structure:
    - Amplitude and shape of the initial curvature power spectrum: n_s, A_s
    - Optical depth to reionization

Supernovae

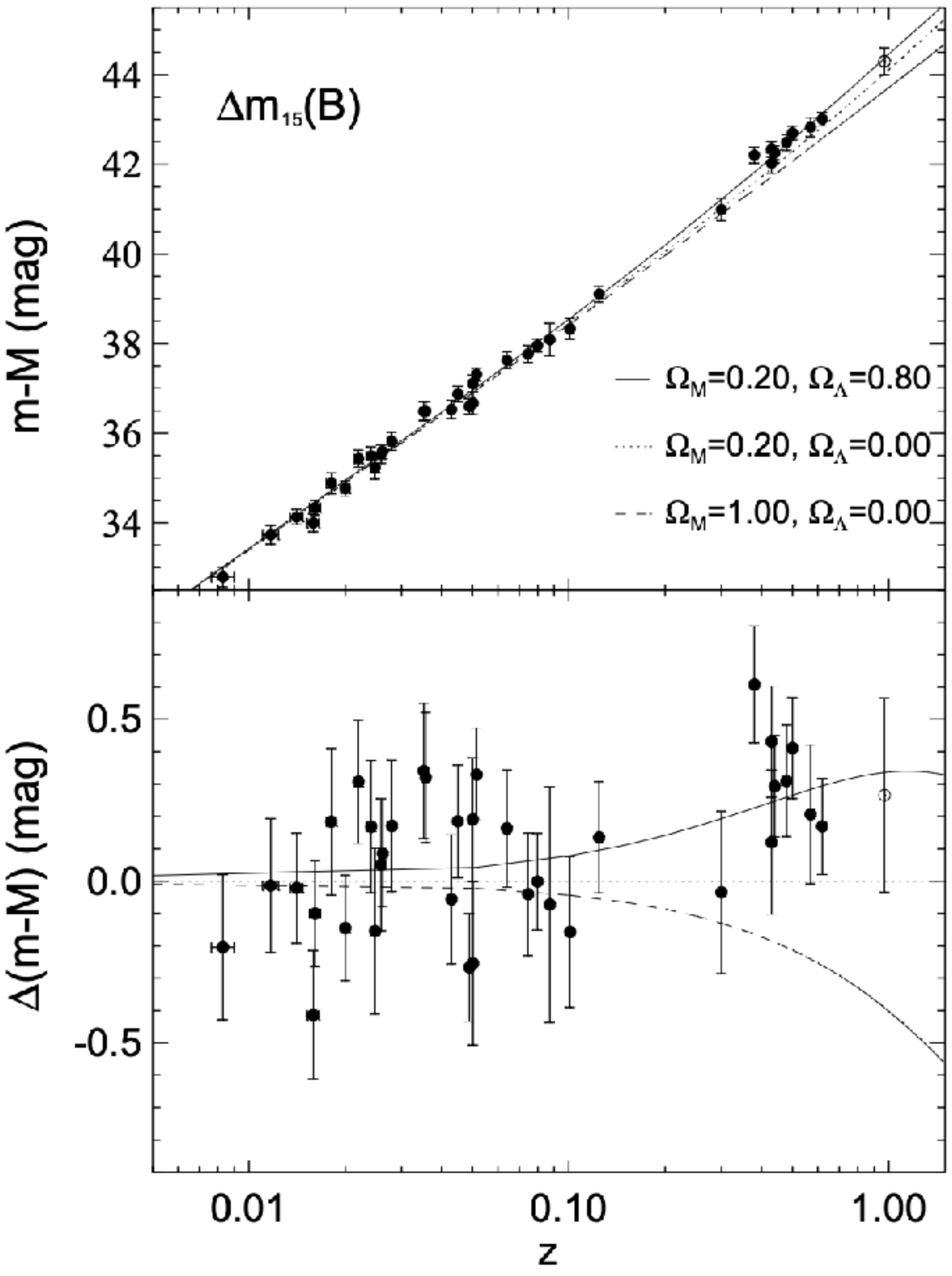
Supernova constraints

- Supernovae allow measurements of absolute distance —> constrain distance-redshift relation

- Distance derived from standardizable luminosity —> measure luminosity distance $d_L(z)$

$$d_L(z) = (1+z)c\int_0^z \frac{dz'}{H(z')},$$

- Two uses:
    - Measure H_0 (requires absolute calibration)
    - Measure redshift derivatives of H(z) (does *not* require absolute calibration)



Riess et al. (1996)

Supernovae and the accelerating Universe

- Expansion of the luminosity distance at low redshift

$$d_L(z) \approx \frac{c}{H_0}\left[z + z^2\left(\frac{1-q_0}{2}\right) + \mathcal{O}(z^3)\right]$$

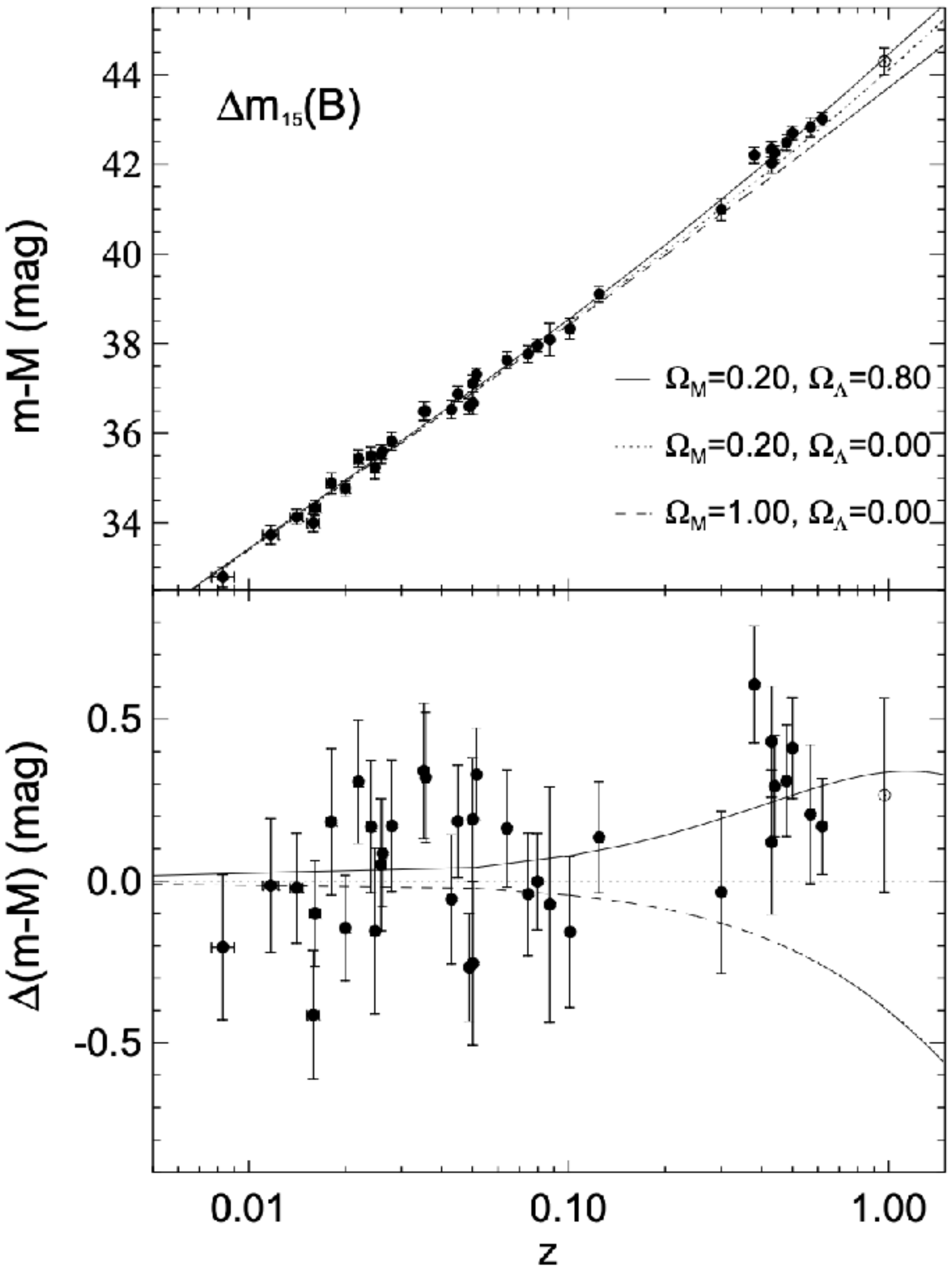
- q_0 is the *deceleration parameter*, given by

$$q_0 = -\frac{\ddot{a}\,a}{\dot{a}^2} = \frac{1}{2}\sum_i \Omega_i\ (1 + 3\,w_i)$$

where (Ω_i,w_i) are the density equation-of-state parameter of component i (e.g., w_i = 0 for matter, w_i = -1 for a cosmological constant)

- E.g., LCDM

$$q_0 = \frac{1}{2}\,\Omega_m - \Omega_\Lambda$$



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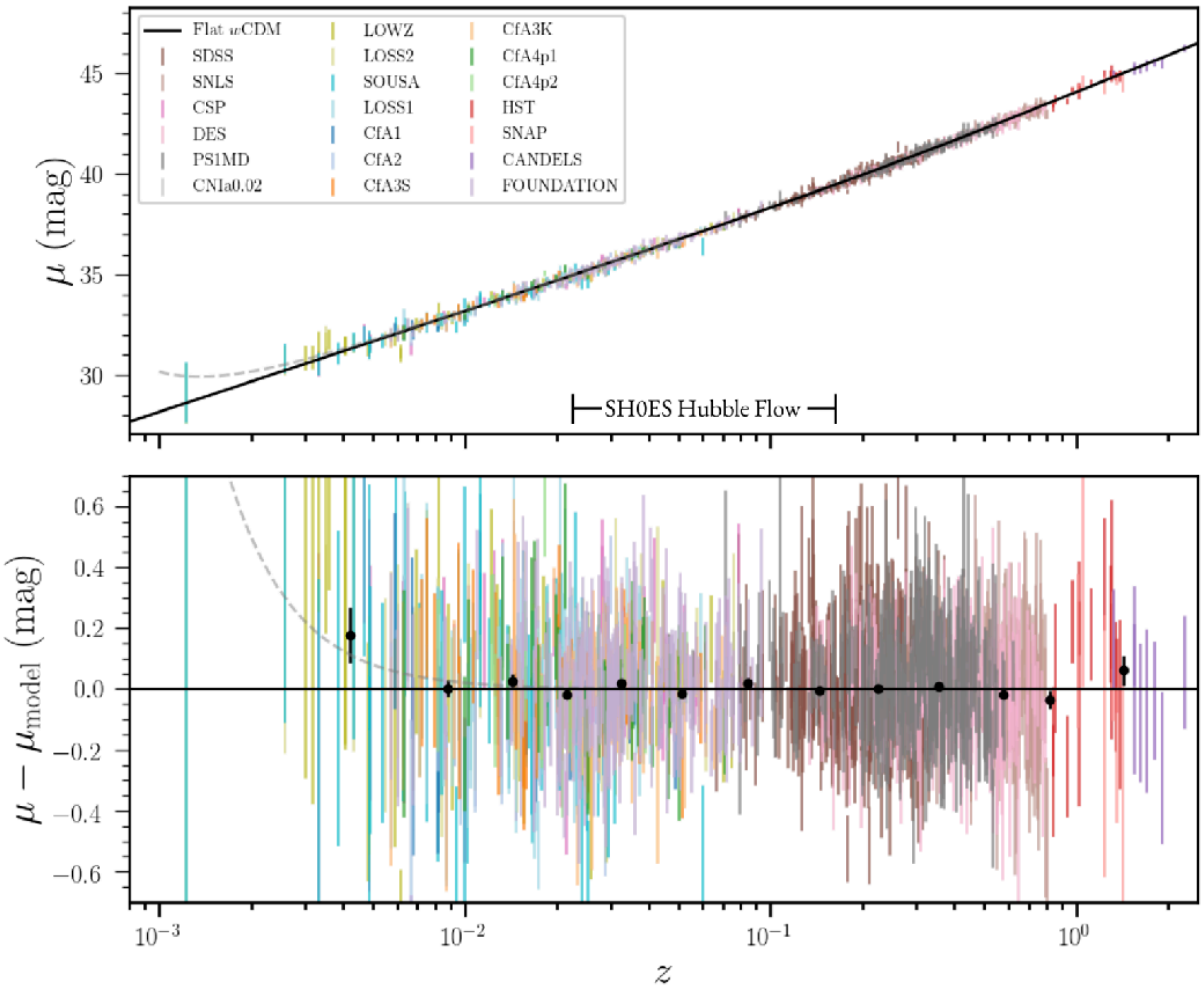
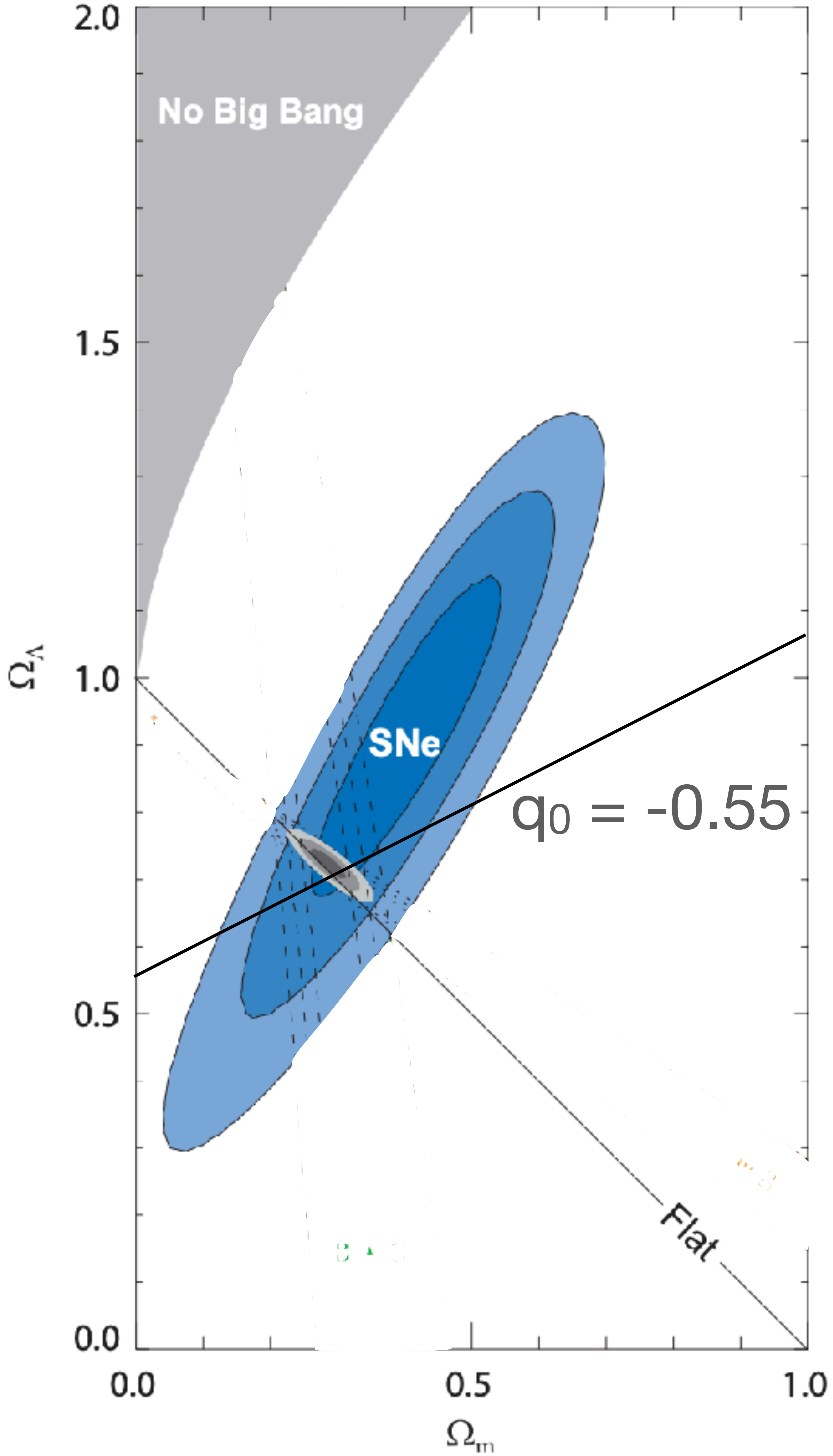


Brout et al. (2022: Pantheon+)

Cosmological constraints from supernovae

$$q_0 = \frac{1}{2}\Omega_m - \Omega_\Lambda$$

- Measurement q_0 =~ -0.55
- Contours tilted with respect to the q_0 = constant line, because measurements are not at z=0

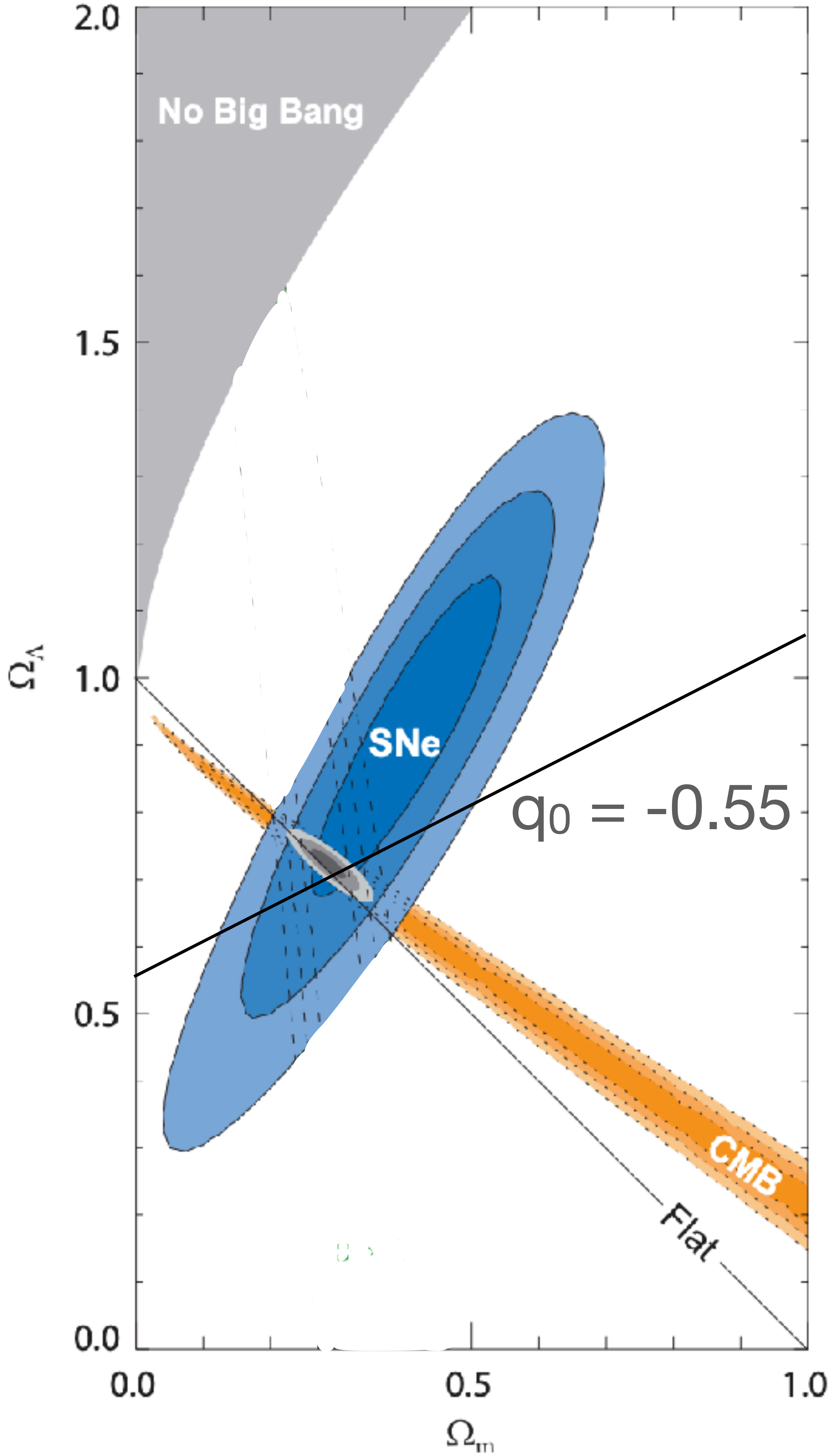


Kowalski et al. (2008)

Cosmological constraints from supernovae

$$q_0 = \frac{1}{2}\Omega_m - \Omega_\Lambda$$

- Measurement q_0 =~ -0.55
- Contours tilted with respect to the q_0 = constant line, because measurements are not at z=0
- Combining with CMB shows that the Universe is flat
- Supernovae constraints are pure geometry, no growth of structure



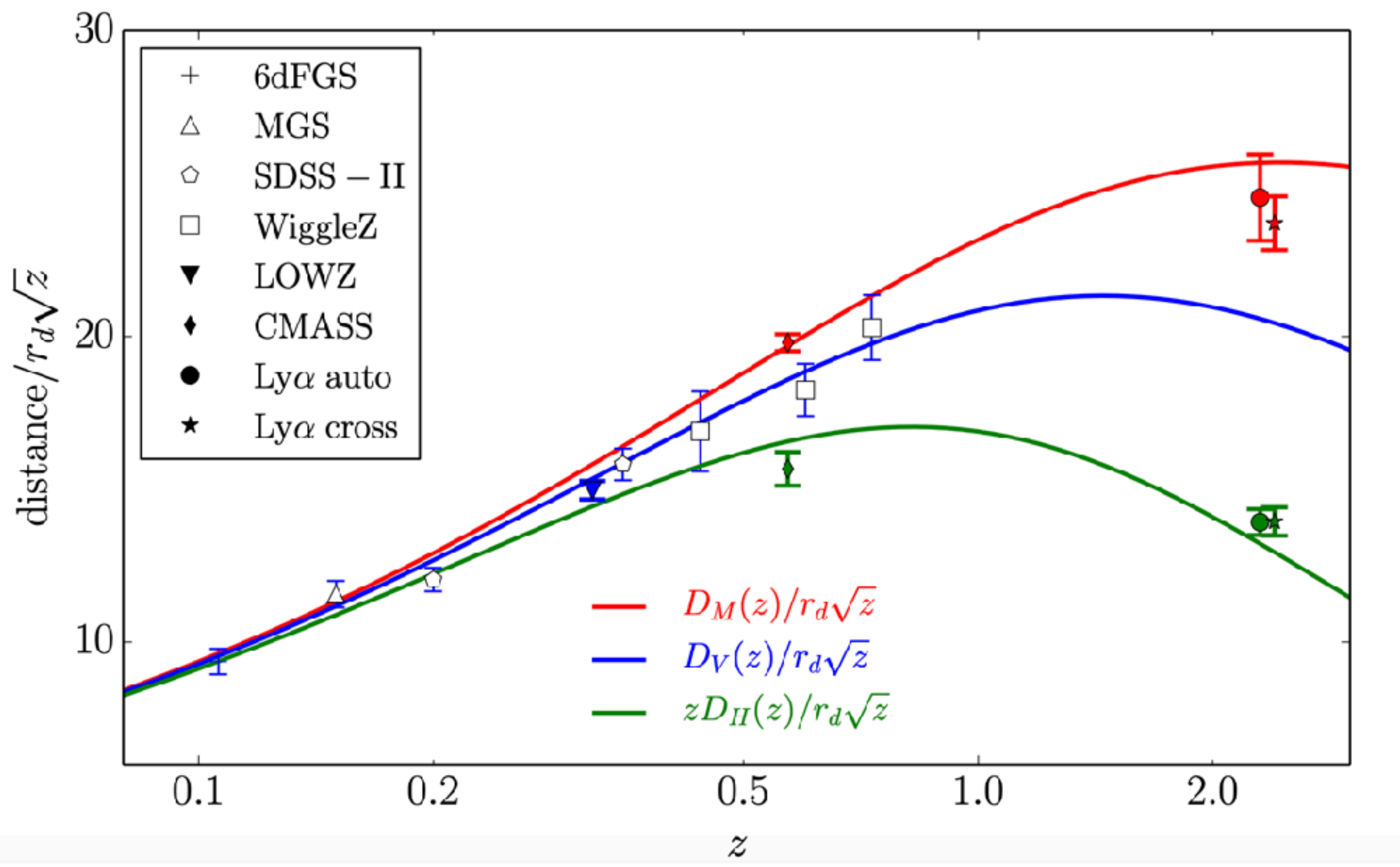
Kowalski et al. (2008)

Baryon acoustic oscillations

BAO constraints

- BAO measurements determine Hubble function $H(z)/r_d$ and co-moving angular diameter distance $D_M(z)/r_d$ at the median redshift of a survey

- CMB measurements of $\Omega_b h^2$ and $\Omega_c h^2$ calibrate the BAO ruler r_d, so turn BAO measurements into absolute distance measurements



Aubourg et al. (2015)

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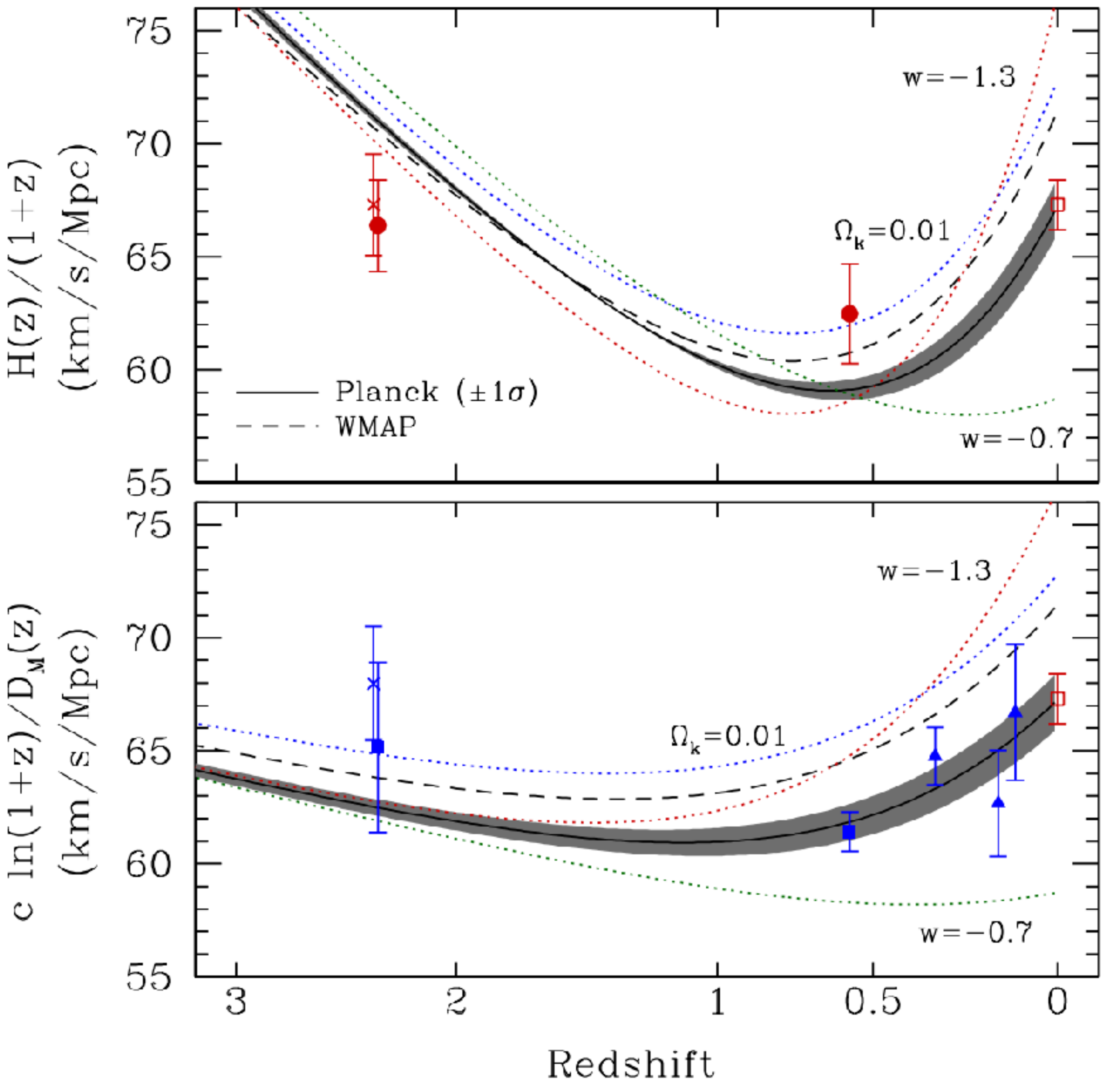

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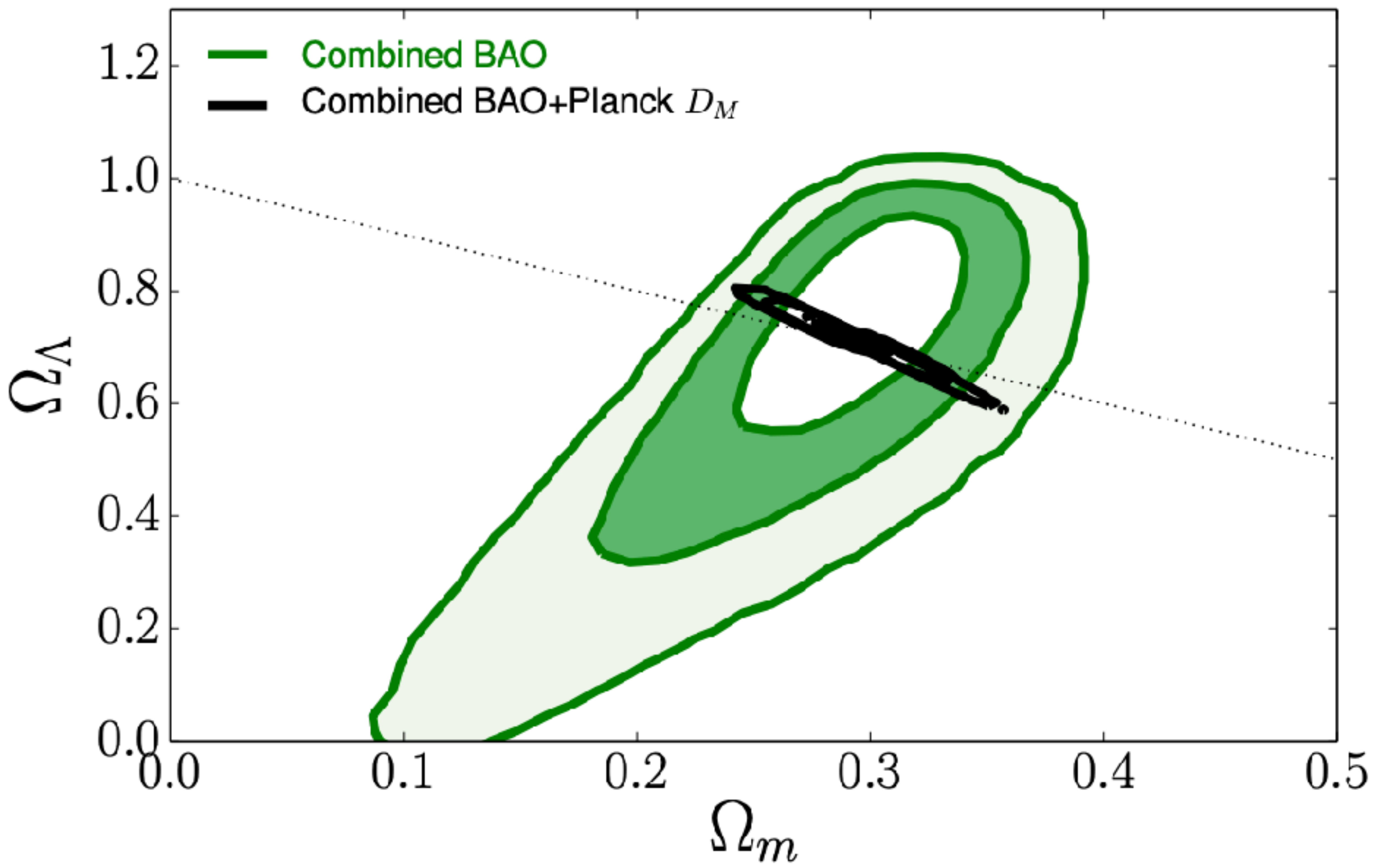

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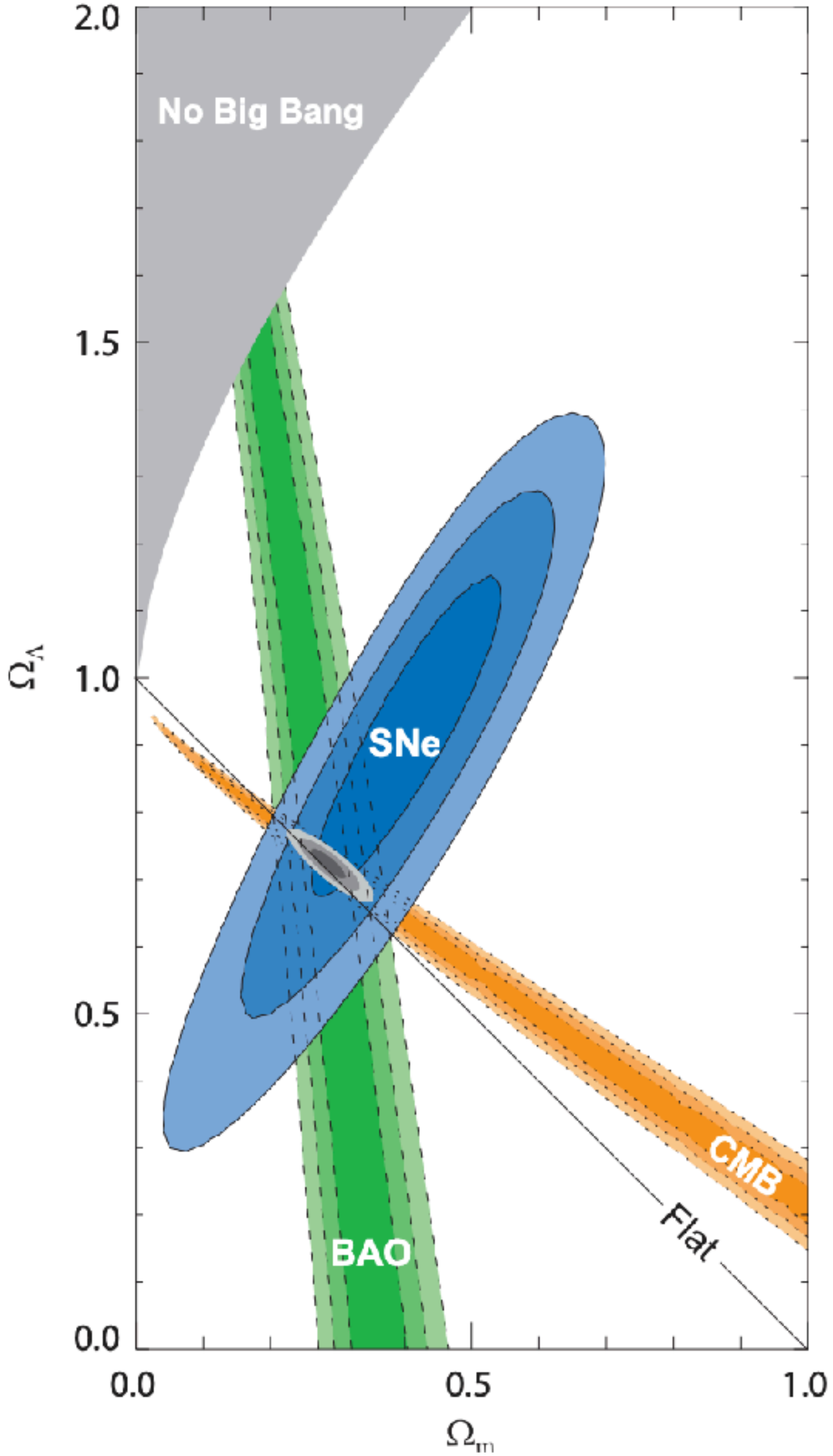

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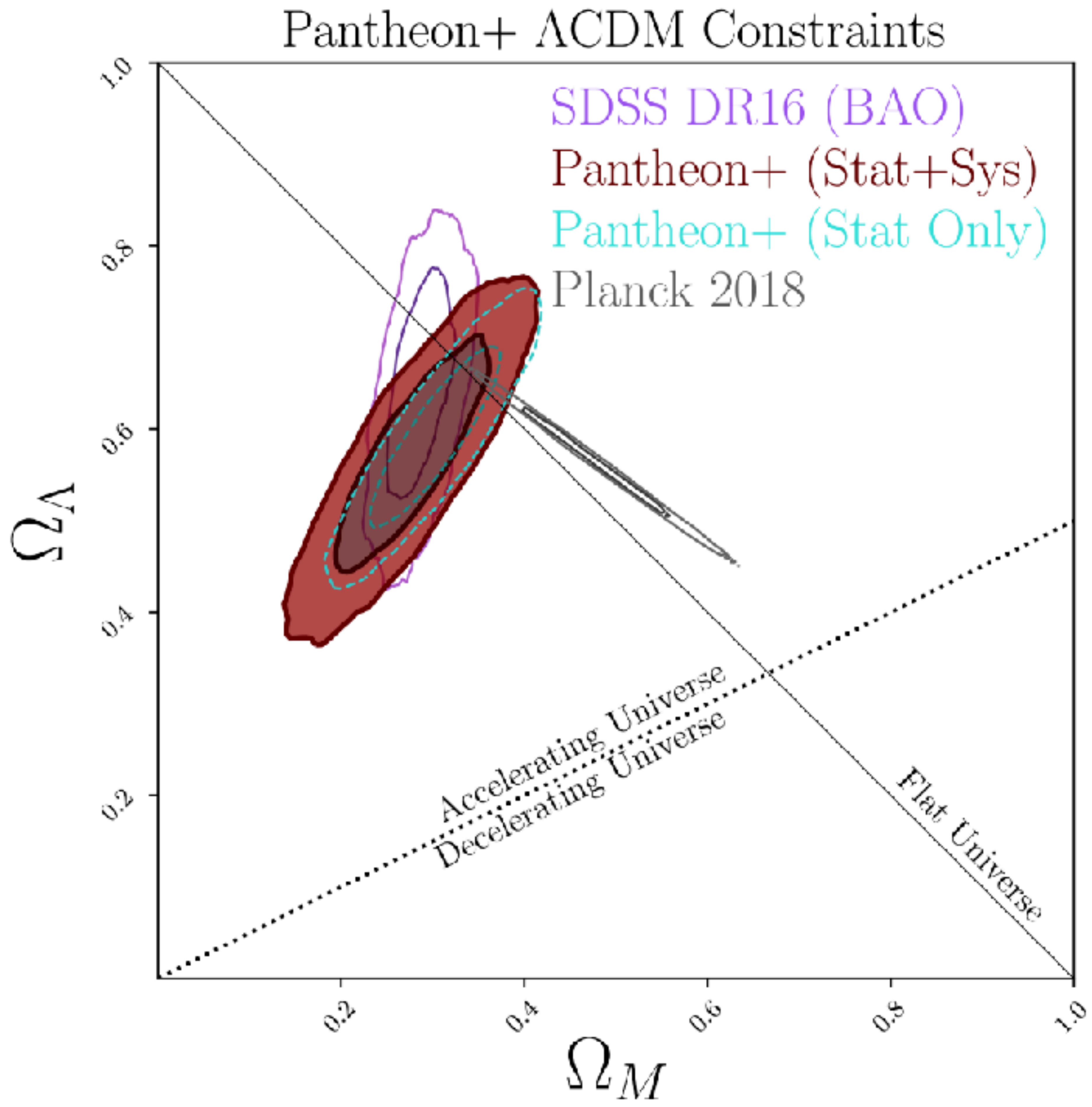


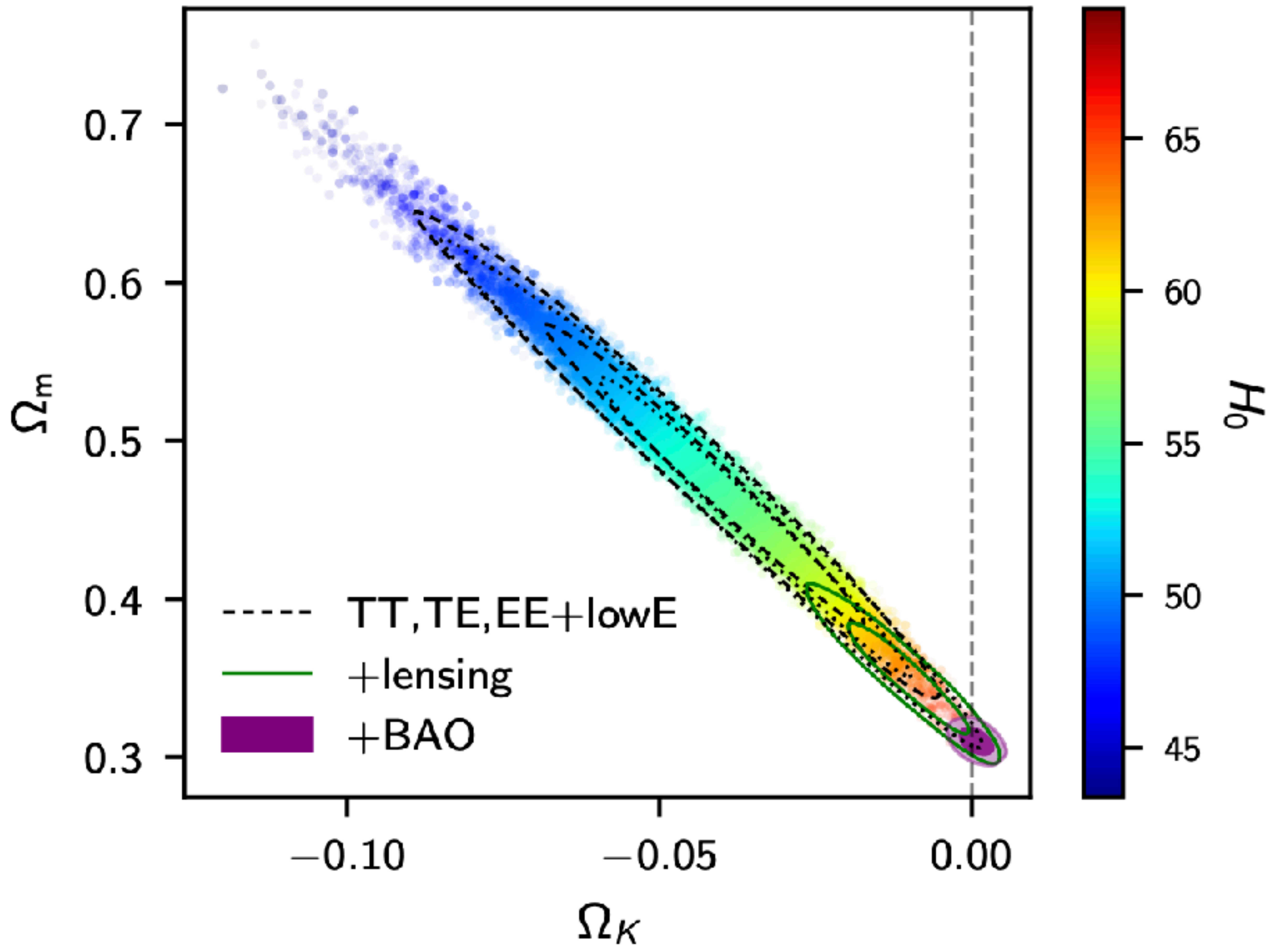
Brout et al. (2022: Pantheon+)

Combined constraints

Flatness

- Combination of CMB + SNe or BAO strongly constrains curvature parameter Ω_k

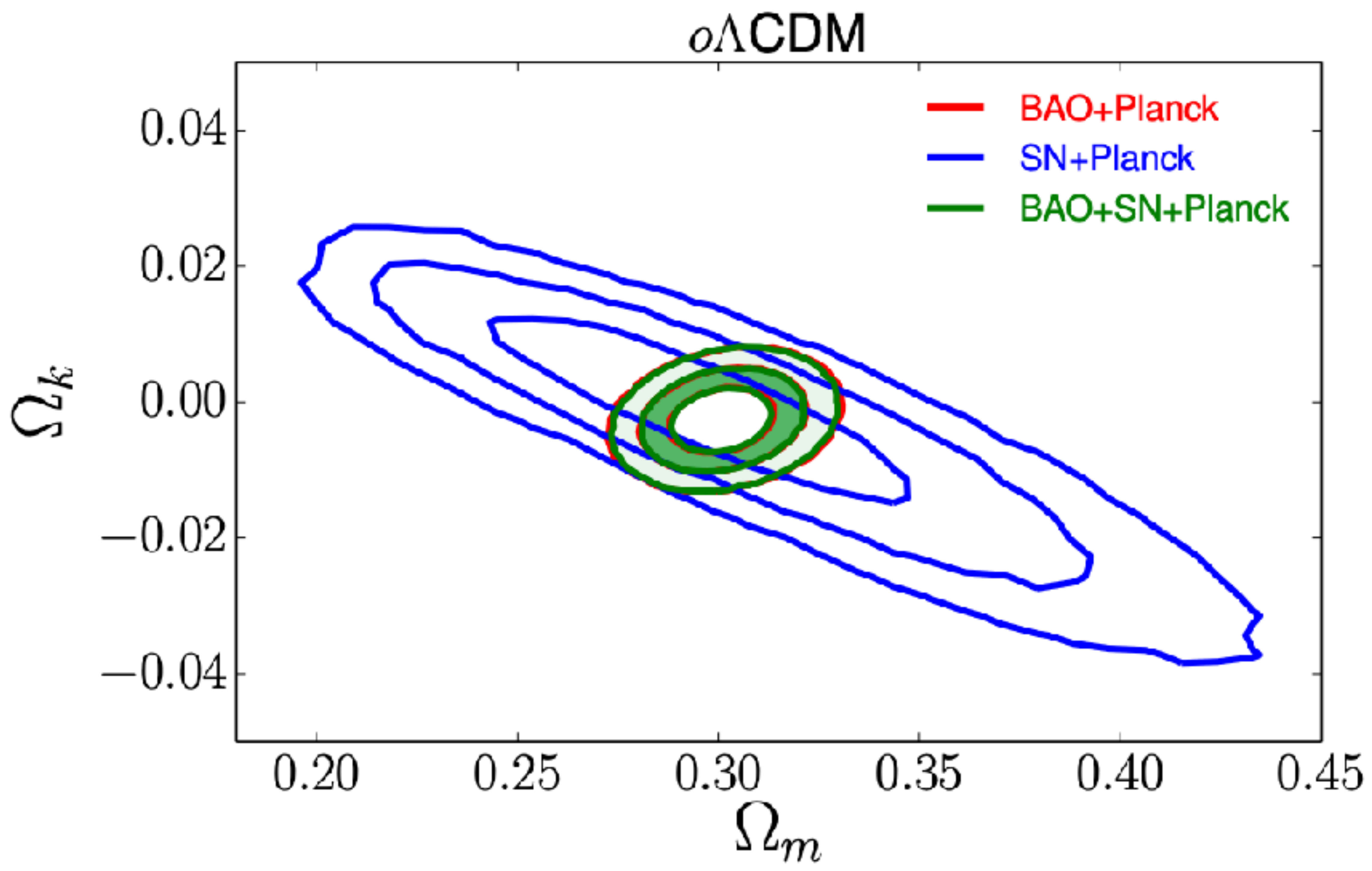
- Planck 2018 + BAO:
  $\Omega_k = 0.0007^{+0.0037}_{-0.0037}$



Planck 2018 VI (2020)

Flatness

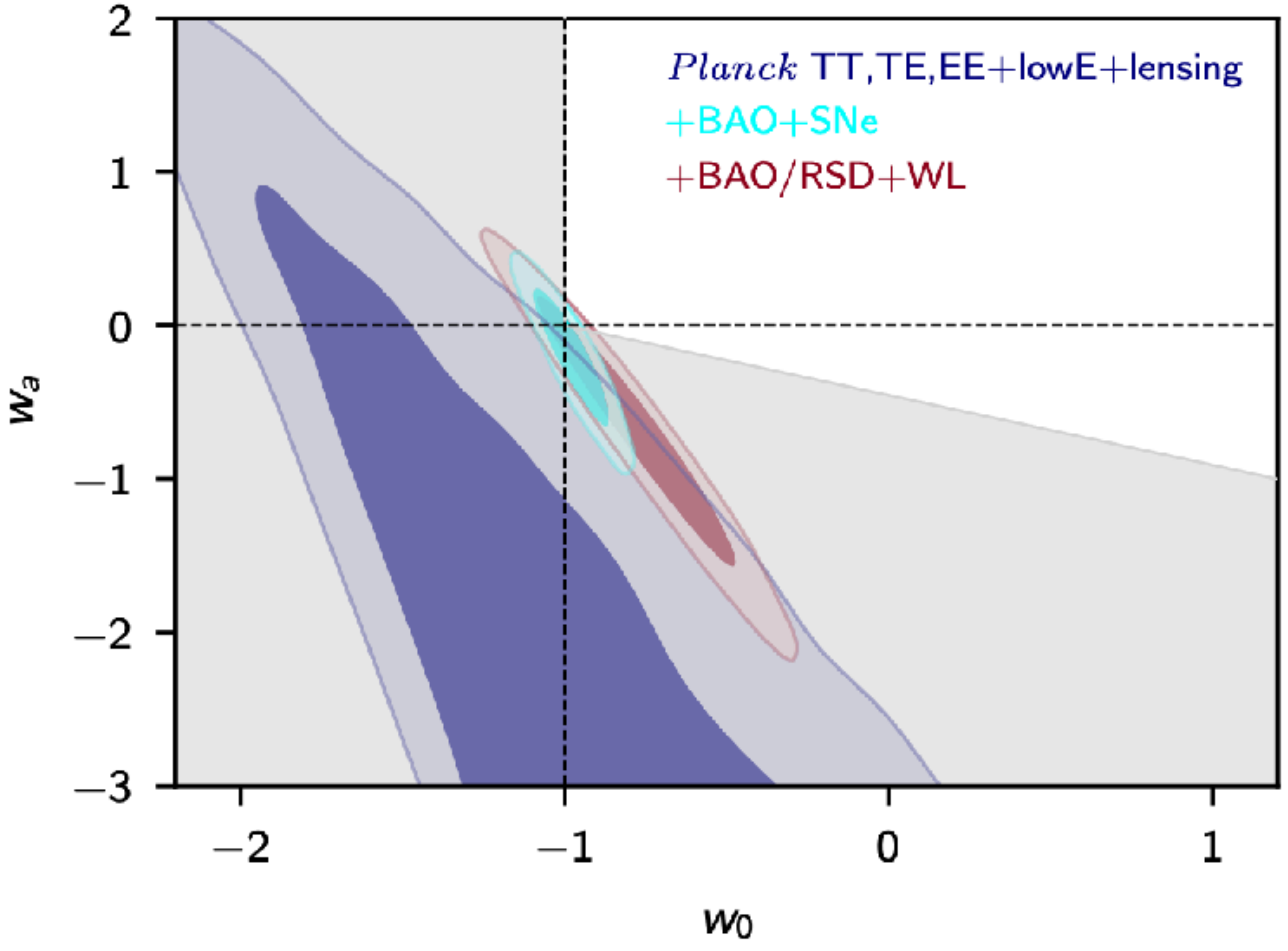
- Combination of CMB + SNe or BAO strongly constrains curvature parameter Ω_k
- Planck 2018 + BAO: $\Omega_k = 0.0007^{+0.0037}_{-0.0037}$
- Supernovae don't add much



Aubourg et al. (2015)

Dark energy that is not a cosmological constant

- Simplest model has DE equation of state: p = w ρ with constant w (w=-1 —> cosmological constant)
- Little constraint from Planck alone



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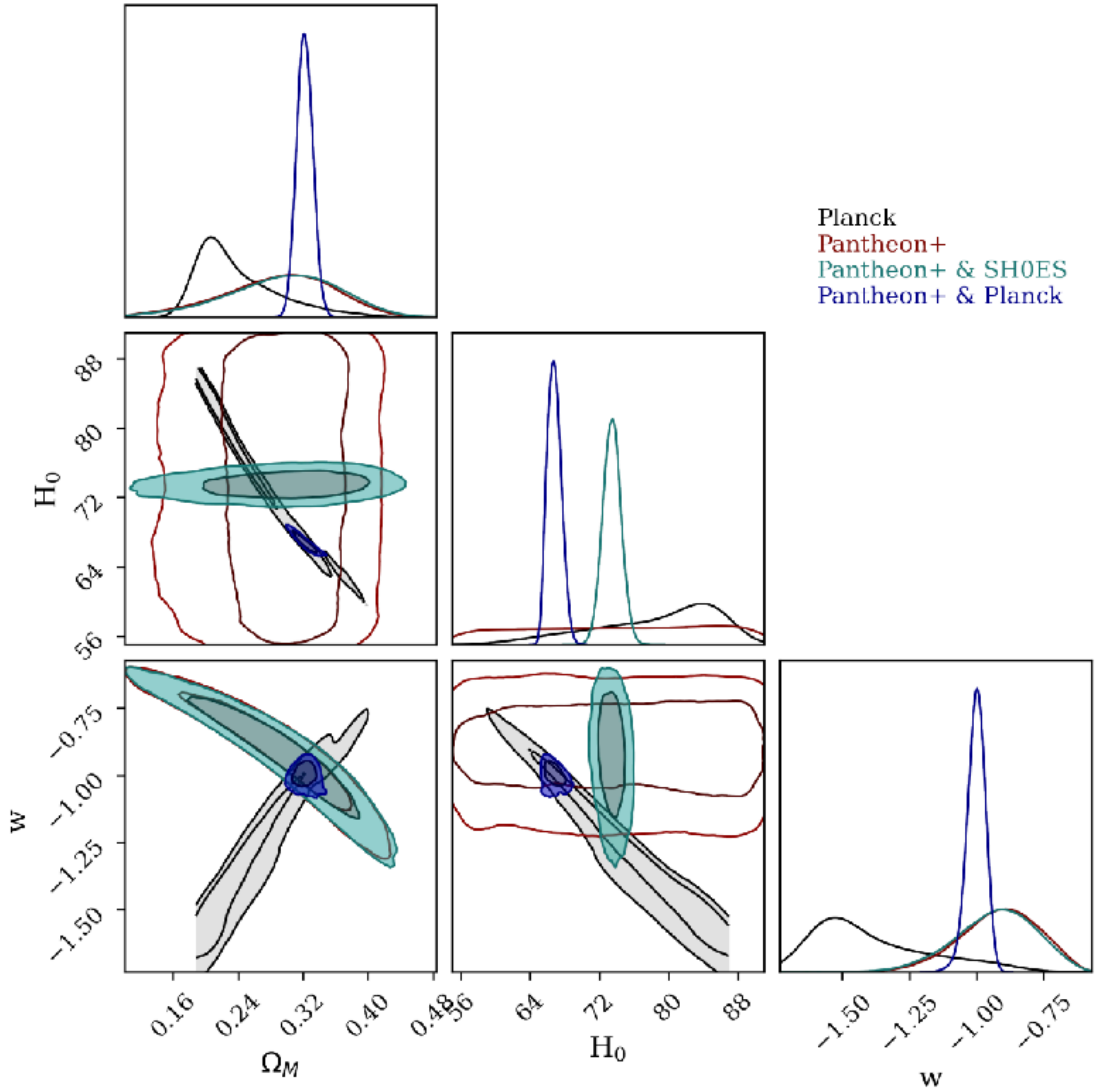
w = $-0.982^{+0.022}_{-0.038}$



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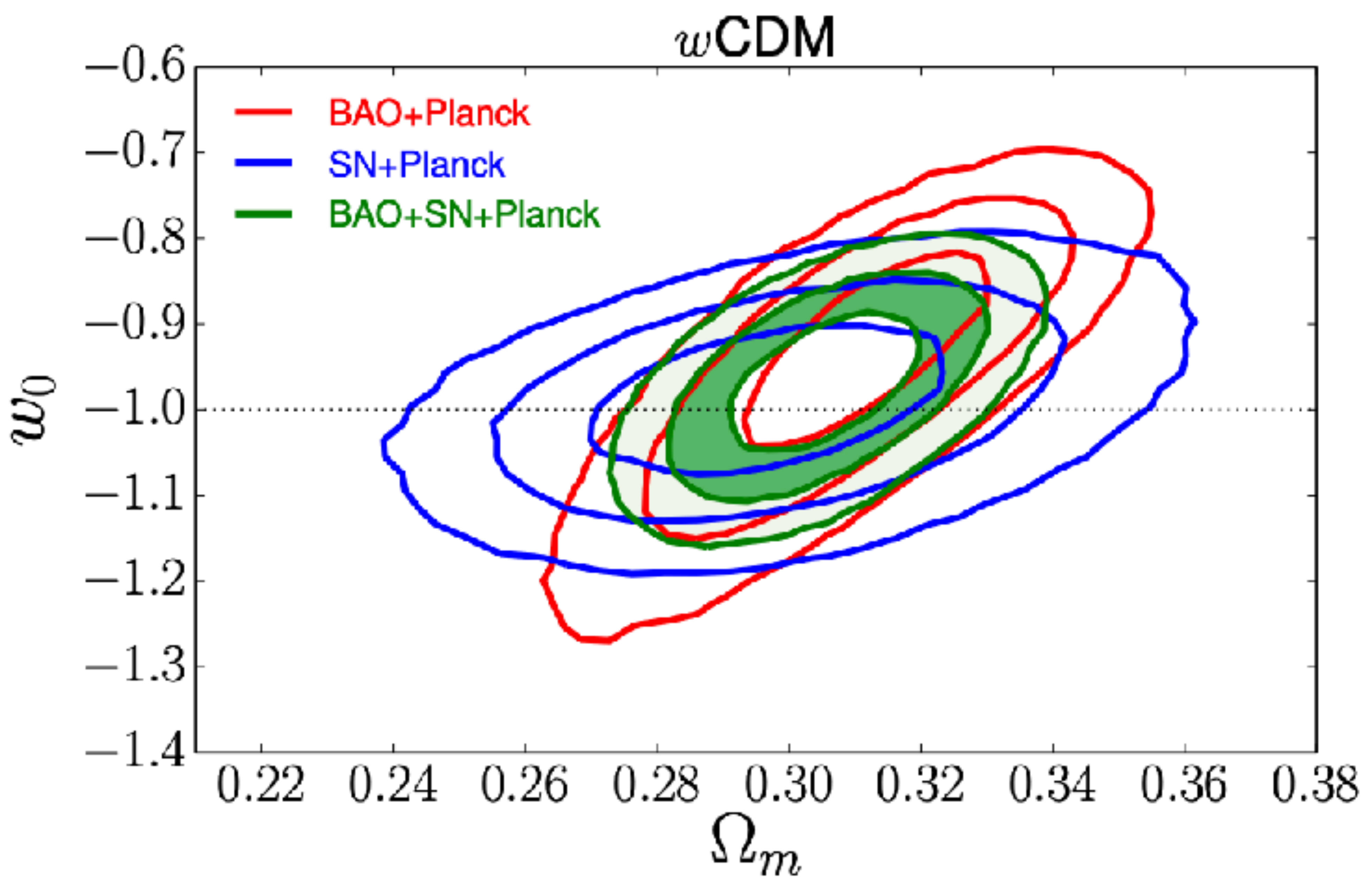
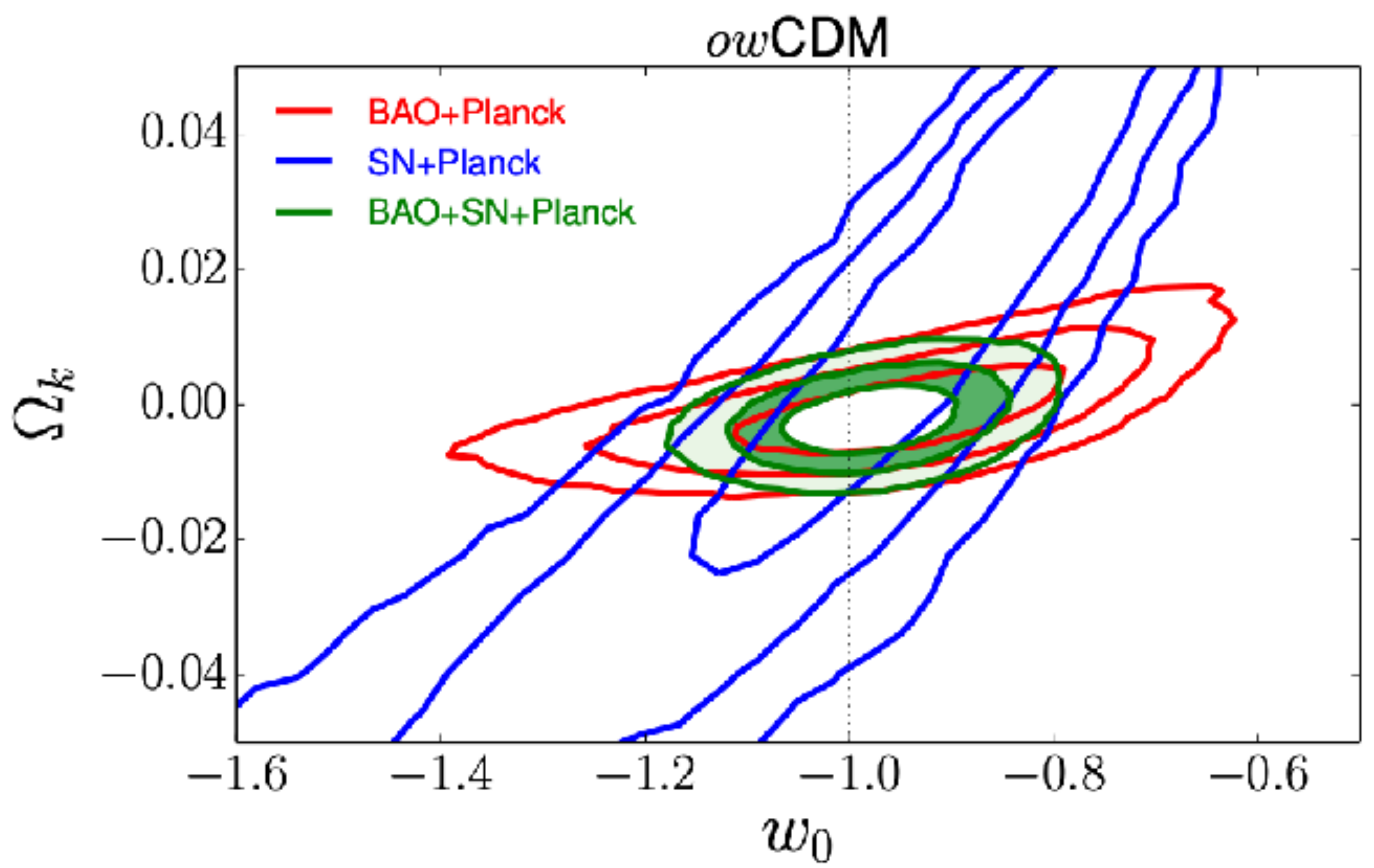
- BAO helps a bit, especially when considering non-flat models





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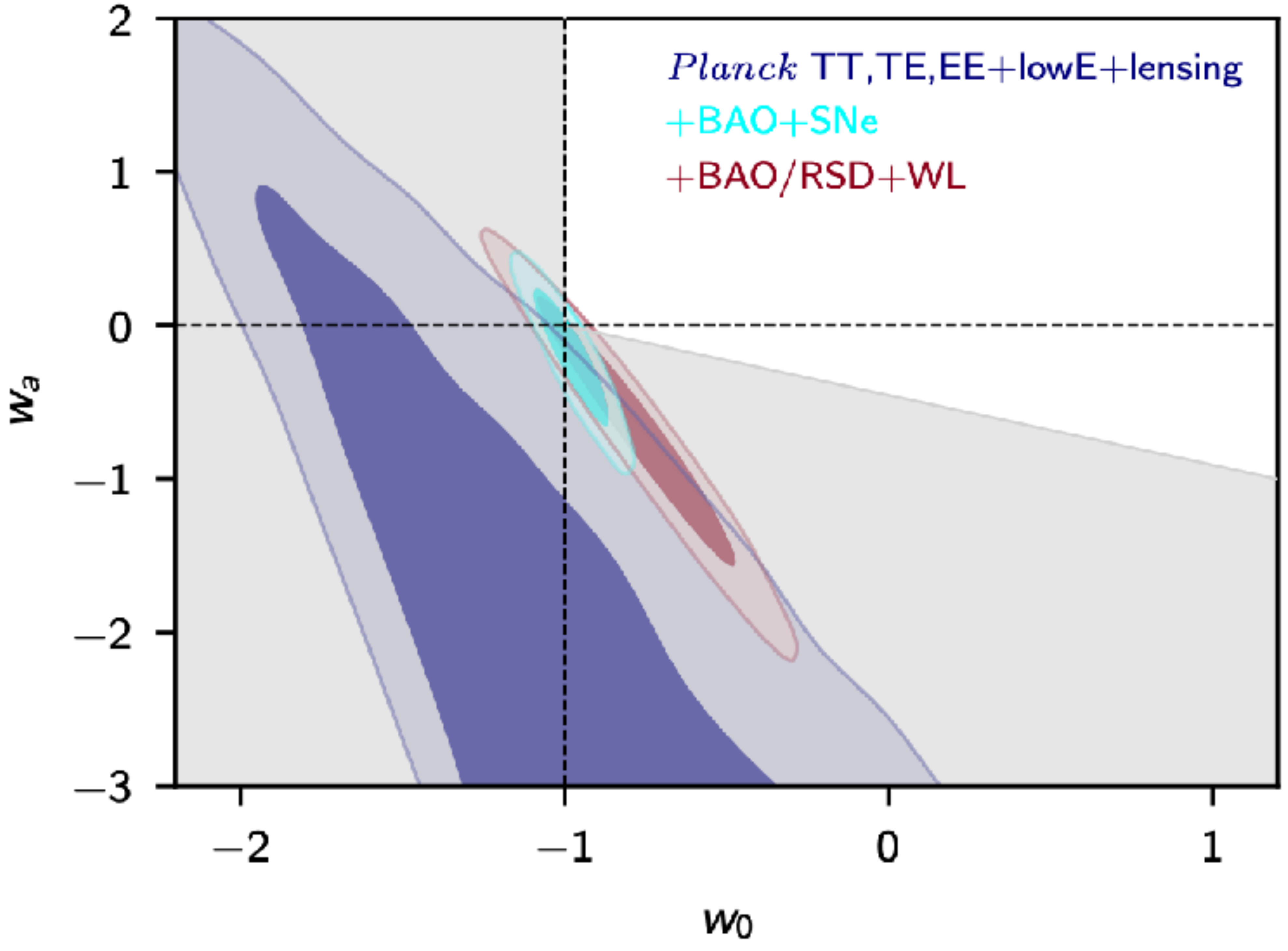
Dark energy that is not a cosmological constant

- Second simplest model has DE equation of state: $p = w\ \rho$ with $w = w_0 + w_a\ (1\text{-}a)$
- Little constraint from Planck alone



Planck 2018 VI (2020)

Dark energy that is not a cosmological constant

- Second simplest model has DE equation of state: $p = w\,\rho$ with $w = w_0 + w_a\,(1-a)$

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- SNe + Planck: tight constraint

  $w_0 = -0.851^{+0.092}_{-0.099}$, $w_a = -0.70^{+0.49}_{-0.51}$

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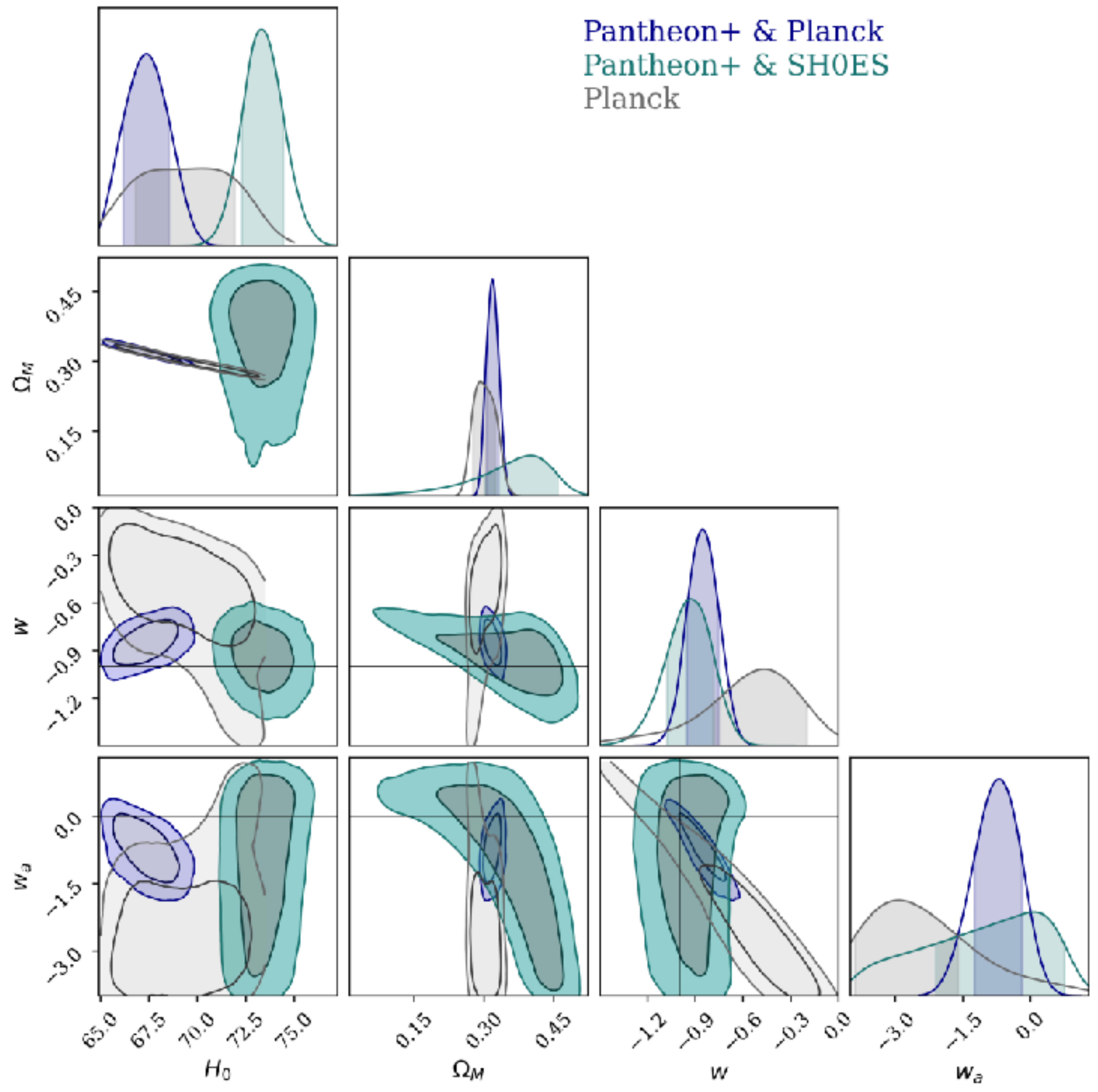

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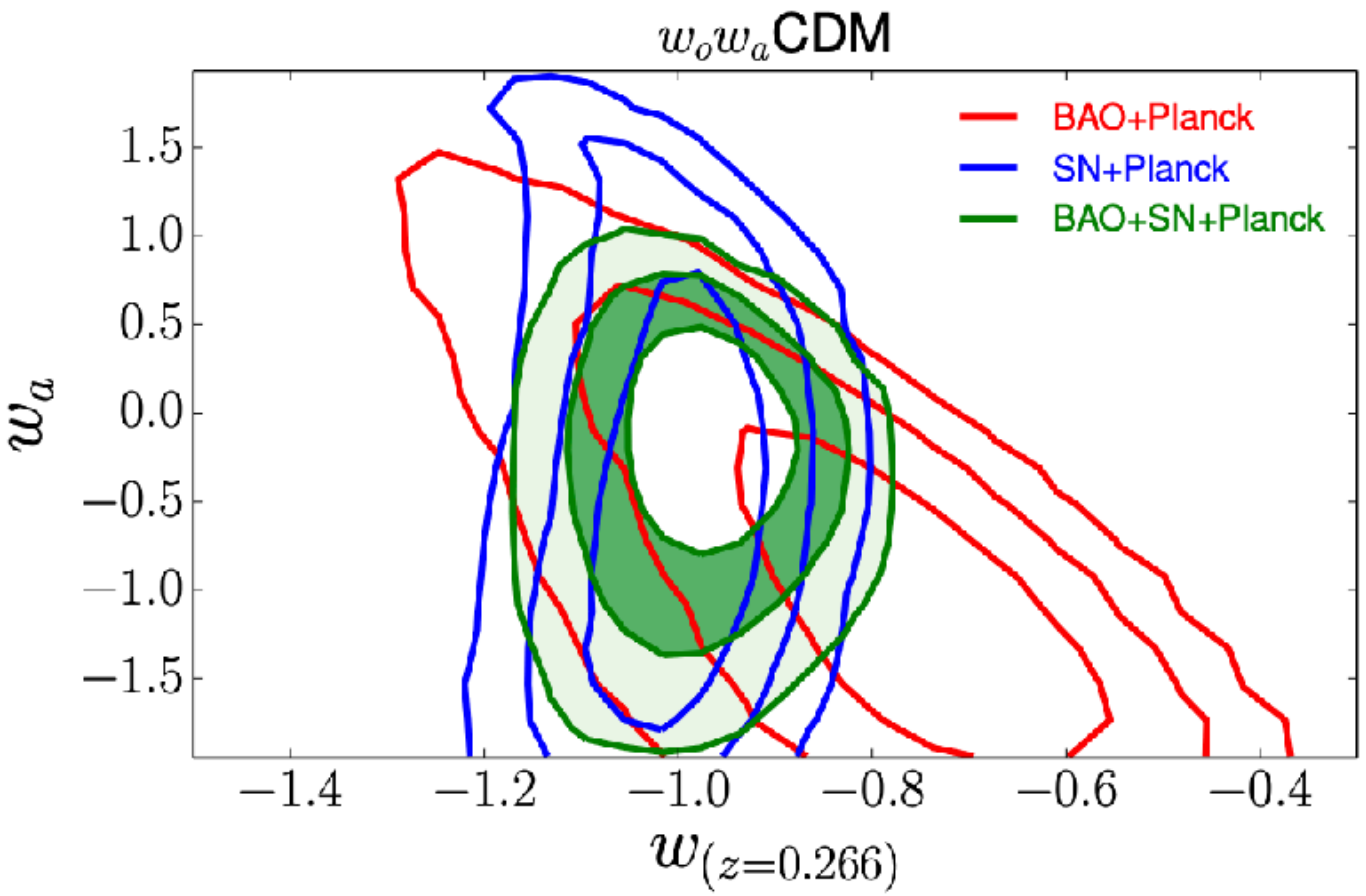
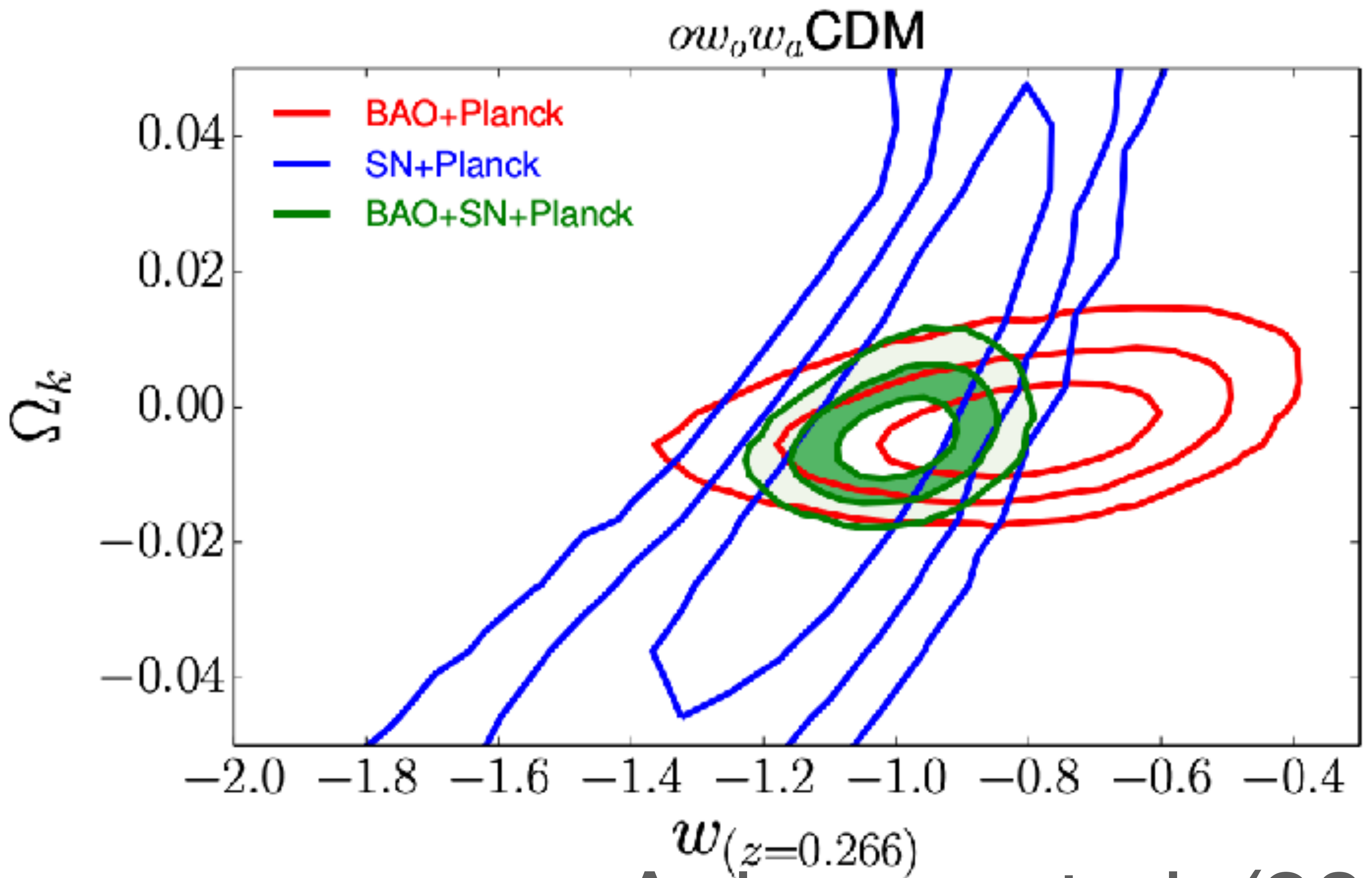




Aubourg et al. (2015)

Other extensions

Spoiler: it's LCDM everywhere!

Parameter	TT+lowE	TT, TE, EE+lowE	TT, TE, EE+lowE+lensing	TT, TE, EE+lowE+lensing+BAO
Ω_K	$-0.056^{+0.044}_{-0.050}$	$-0.044^{+0.033}_{-0.034}$	$-0.011^{+0.013}_{-0.012}$	$0.0007^{+0.0037}_{-0.0037}$
Σm_ν [eV]	< 0.537	< 0.257	< 0.241	< 0.120
$N_{\rm eff}$	$3.00^{+0.57}_{-0.53}$	$2.92^{+0.36}_{-0.37}$	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$Y_{\rm P}$	$0.246^{+0.039}_{-0.041}$	$0.240^{+0.024}_{-0.025}$	$0.239^{+0.024}_{-0.025}$	$0.242^{+0.023}_{-0.024}$
$dn_s/d\ln k$	$-0.004^{+0.015}_{-0.015}$	$-0.006^{+0.013}_{-0.013}$	$-0.005^{+0.013}_{-0.013}$	$-0.004^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.102	< 0.107	< 0.101	< 0.106
w_0	$-1.56^{+0.60}_{-0.48}$	$-1.58^{+0.52}_{-0.41}$	$-1.57^{+0.50}_{-0.40}$	$-1.04^{+0.10}_{-0.10}$

Planck 2018 VI (2020)

Growth of structure constraints

Growth of structure constraints

- Constraints shown so far largely only use geometric constraints on the expansion history (+ CMB)
- Growth-of-structure constraints can add valuable additional info, generally on combination of Ω_m and σ_8:
  - RSD: f x σ_8 ~ $(\Omega_m)^{0.55}$ x σ_8 as well as b x σ_8
  - Lensing: $(\Omega_m)^{0.5}$ x σ_8, possibly b and σ_8 separately
  - Abundance of galaxy clusters: $(\Omega_m)^a$ x σ_8 with a ~ 0.2, exact form set by how cluster masses are obtained (X-ray, SZ, …)

Weak lensing

Extremely brief overview of cosmological weak lensing

Cosmic shear

- Galaxies have a range of intrinsic shapes projected randomly on the sky
- Averaged over enough galaxies, average shape should be constant across the sky
- Lensing of background galaxies by the foreground matter distribution systematically distorts the shape —> cosmic shear (~1% effect)
- Lensing is determined by the gravitational potential

$$\delta(\mathbf{k}, a) = -\frac{2}{3}\frac{k^2 a}{\Omega_{0,m} H_0^2}\,\Phi(\mathbf{k}, a)\,,$$

Extremely brief overview of cosmological weak lensing

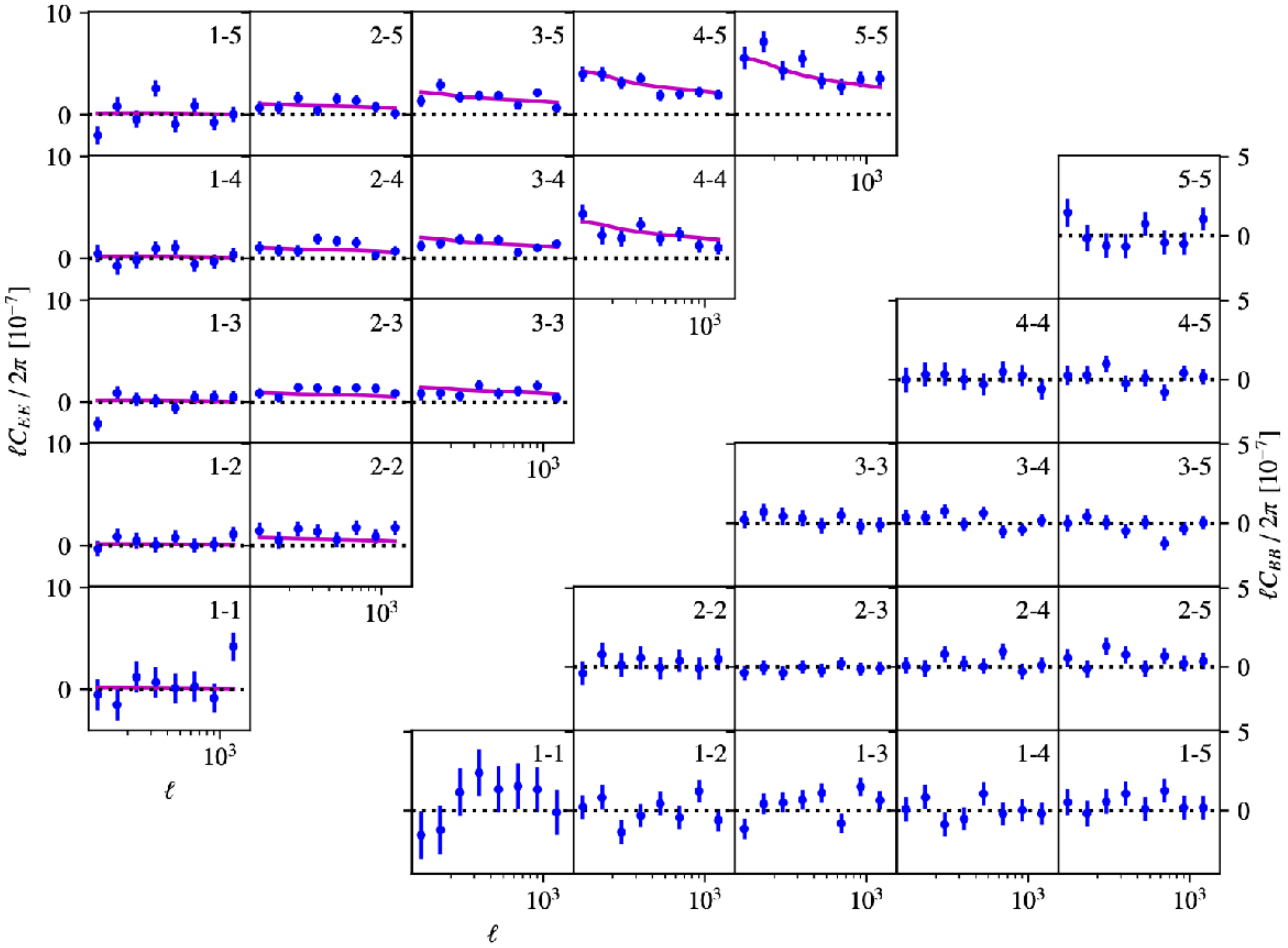
Cosmic shear

- Lensing is determined by the gravitational potential

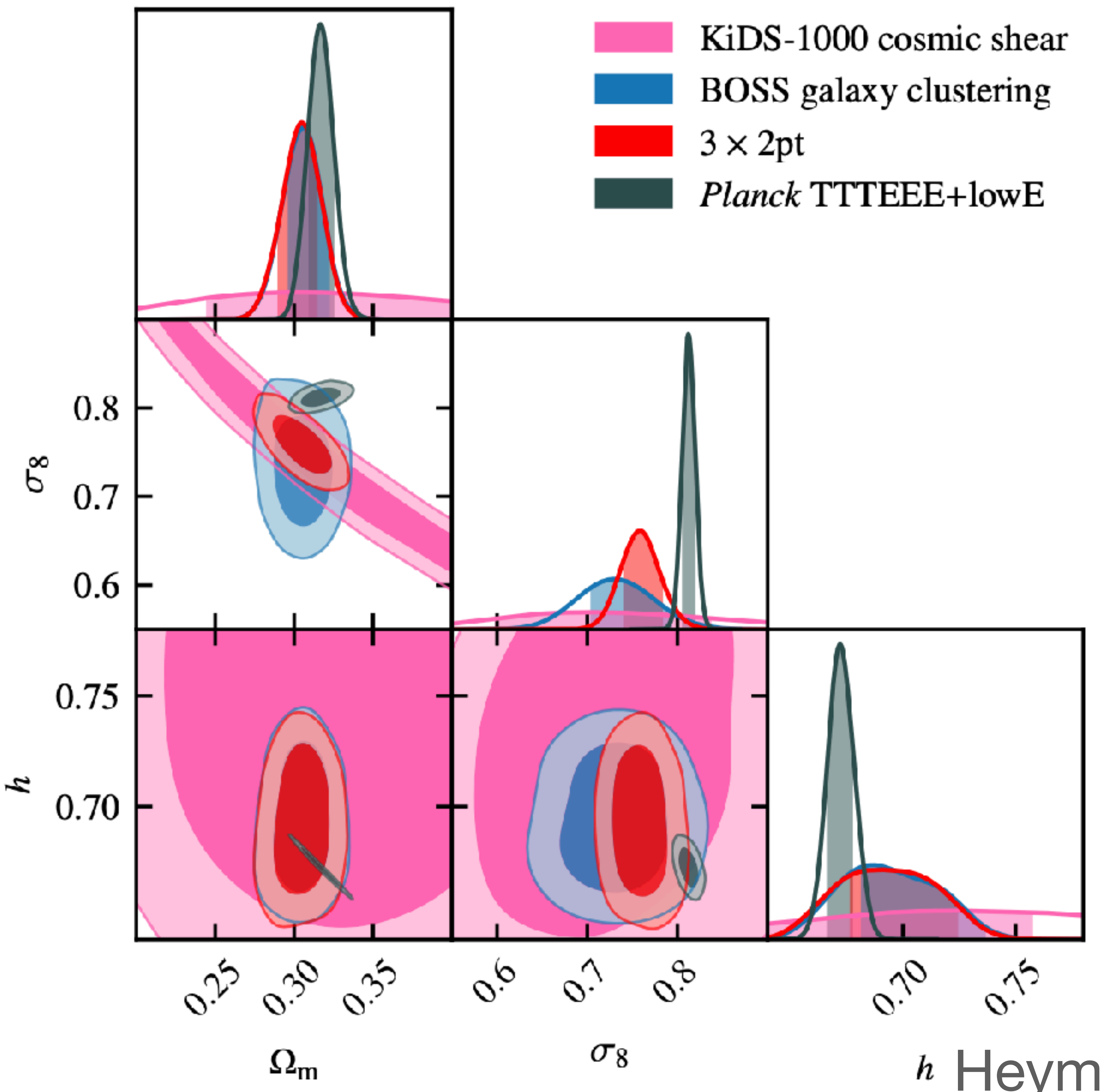
$$\delta(\mathbf{k}, a) = -\frac{2}{3} \frac{k^2 a}{\Omega_{0,m} H_0^2} \Phi(\mathbf{k}, a) \,,$$

- Like galaxies, we can auto- or cross-correlate shears:
    - Auto-correlation gives measurement of the power spectrum of the potential ~ $(\Omega_m)^2$ $P_{\delta\delta}$ —> measure Ω_m x σ_8
    - Cross-correlation with galaxies (galaxy-galaxy lensing): measure $b\Omega_m(\sigma_8)^2$
    - Combination with galaxy clustering (~ b^2 x $[\sigma_8]^2$) —> measure Ω_m x σ_8
- In practice, non-linear effects change these scalings, often constrained combination

$$S_8 = \sigma_8 \sqrt{\Omega_m / 0.3}$$



Heymans et al. (2020; KiDS)



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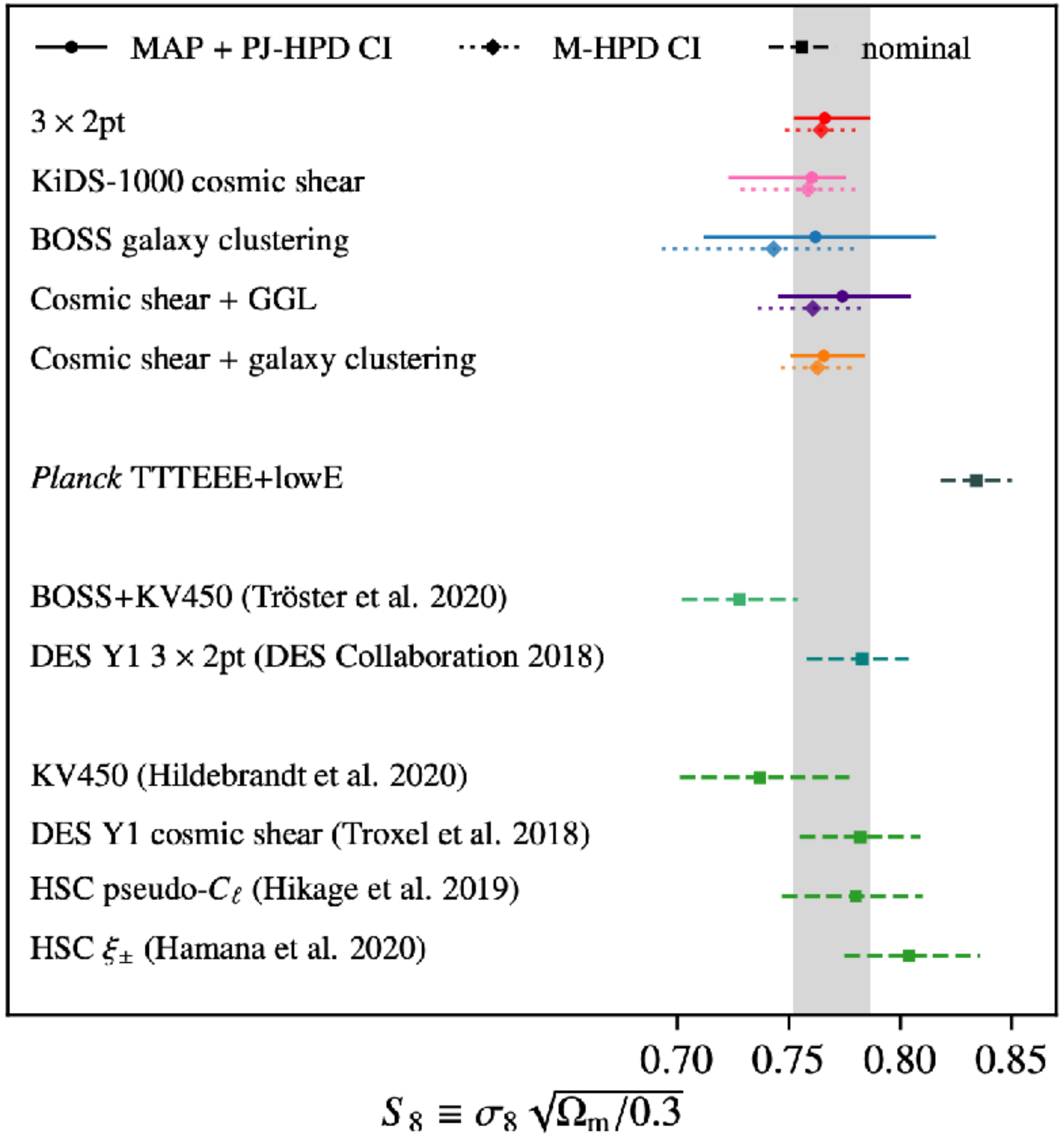
S_8 tension

- Lensing gives lower value of S_8 than Planck



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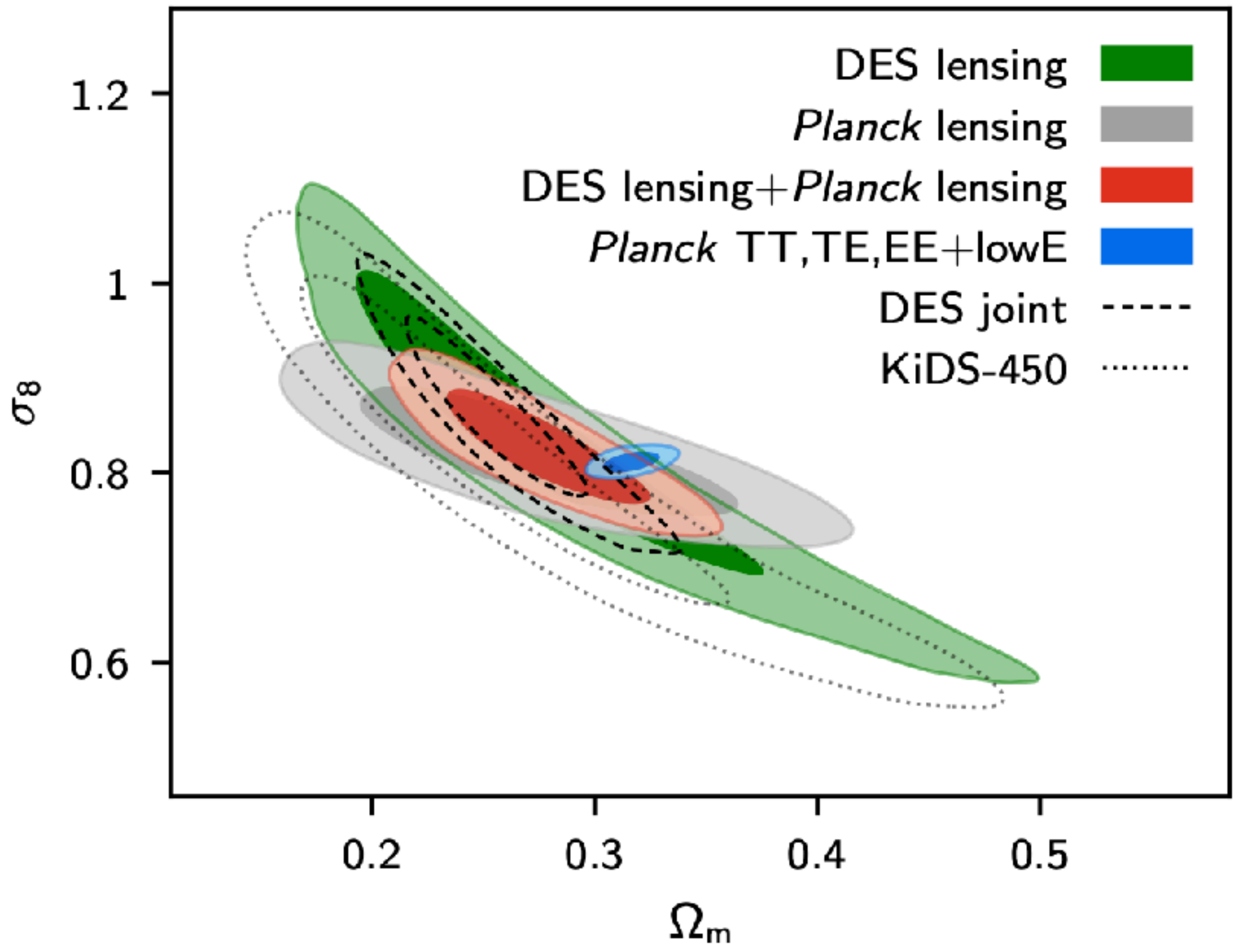

Planck 2018 VI (2020)

Conclusion

- Early+late Universe constraints complementary and highly consistent with simple flat LCDM model (BBN also consistent)
- Late-Universe measurements crucial for obtaining constraints on dark energy and its equation of state
- Some tensions:
    - H_0 tension: H_0 derived from Planck + BAO + uncalibrated SNe 5σ off from locally measured value —> see next lecture
    - S_8 tension
    - Sometimes a data point here or there is a bit off, but nothing that screams an obvious new model