The CMB-BAO Tension and Implications for Inflation

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Thanks To My Collaborators

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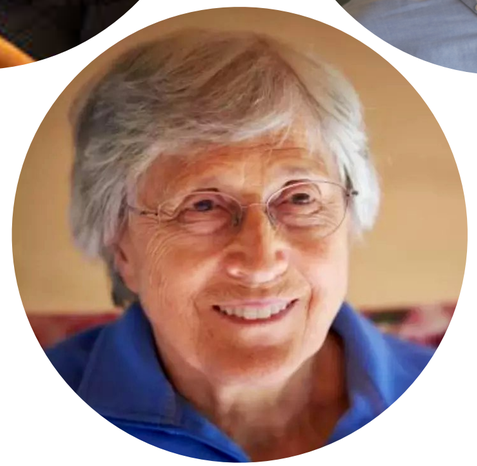

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The BAO-CMB Tension and Implications for Inflation

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The scalar spectral index n_s is a powerful test of inflationary models. The tightest constraint on n_s to date derives from the combination of cosmic microwave background (CMB) data with baryon acoustic oscillation (BAO) data. The resulting n_s constraint is shifted significantly upward relative to the constraint from CMB alone, with the consequence that previously preferred inflationary models are seemingly disfavored by $\gtrsim 2\sigma$. Here we show that this shift in n_s is the combined effect of a degeneracy between n_s and BAO parameters exhibited by CMB data and the tension between CMB datasets and DESI BAO data under the assumption of the standard cosmological model. Given the crucial role of n_s in discriminating between inflationary models, we urge caution in interpreting CMB+BAO constraints on n_s until the BAO-CMB tension is resolved.

CONTENTS

I. INTRODUCTION

Cosmic inflation is a leading candidate to describe the very early universe. Inflation has passed many tests [1], starting with the observation of the acoustic peaks of the cosmic microwave background (CMB), which excluded then-competitor cosmic strings as the origin of structure [2–8], and subsequently by the WMAP [9] and *Planck* [10] experiments' inference of a primordial power spectrum of scalar perturbations that is adiabatic, Gaussian, and nearly-scale invariant, in agreement with the simplest models of inflation.

While ongoing and upcoming experiments [e.g. 11–15] pursue, as a primary science goal, constraints on primordial gravitational waves via their imprint in the B-mode polarization of the CMB (the "Holy Grail" [16] of inflation[1]), the spectral index n_s remains a powerful discriminator of inflationary models. For example, many models of inflation, such as racetrack inflation, D3/D7 inflation, and inflection point inflation, that were compatible with WMAP can be excluded by *Planck* on the basis of n_s alone [1, 18].

Recent works by the ACT [19] and SPT [20] collaborations report joint constraints on n_s from CMB and BAO data that are shifted upward from those reported by Planck. The combined data set of *Planck* and ACT (including CMB lensing), and BAO from the Dark Energy Spectroscopic Instrument (DESI) DR1, gives the "P-ACT-LB" constraint $n_s = 0.9739 \pm 0.0034$ [19], which is nearly identical to the constraint from the combination of SPT with Planck and ACT ("SPA") and DESI DR2 BAO, the latter given by $n_s = 0.9728 \pm 0.0027$ [20], both in ΛCDM. If confirmed, this will have important implications for inflation: the *Planck* preferred inflationary models of Starobinsky [21], Higgs inflation [22, 23], and many (though not all) α-attractors [24], are disfavored at $\gtrsim 2\sigma$. This has led to a flurry of activity to reconcile these inflationary models with the latest CMB data or to extend the already existing models matching the latest CMB data [25–58].

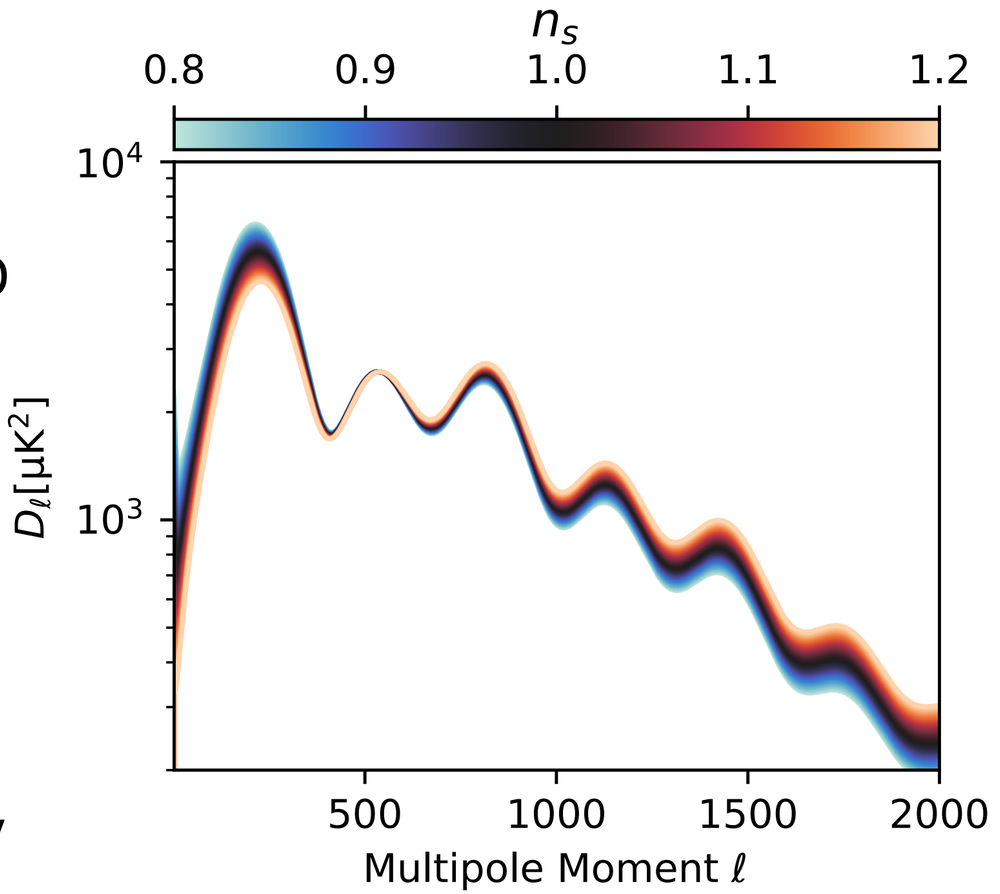
To understand this sudden interest, one may take a look at Fig. 2 in [59], which shows only three targets of the B-mode search by CMB-S4 and LiteBIRD: the Starobinsky model, Higgs inflation, and α-attractors. It does not show any viable targets with $n_s \gtrsim 0.97$.

However, as detailed by the SPT collaboration in Ref. [20], DESI DR2 data is in tension with CMB data under the assumption of ΛCDM. The tension with ACT

[1] See [17] for an alternative view.

CMB Constraints

- **<u>B-mode polarisation sensitive to r</u>**
  - Most sensitive data by BICEP/Keck: $r < 0.036$
  - In 2030s expect $\sigma(r) = 10^{-3}$ from SPO/SO/LiteBIRD
- **<u>Temperature, E-mode polarisation sensitive to n_s</u>**
  - Balance of large to small scale power
  - **Planck, ACT, SPT constraints are consistent**, combination yields $n_s = 0.9684 \pm 0.0030$
  - **CMB data consistent across scales, temperature/ polarisation**



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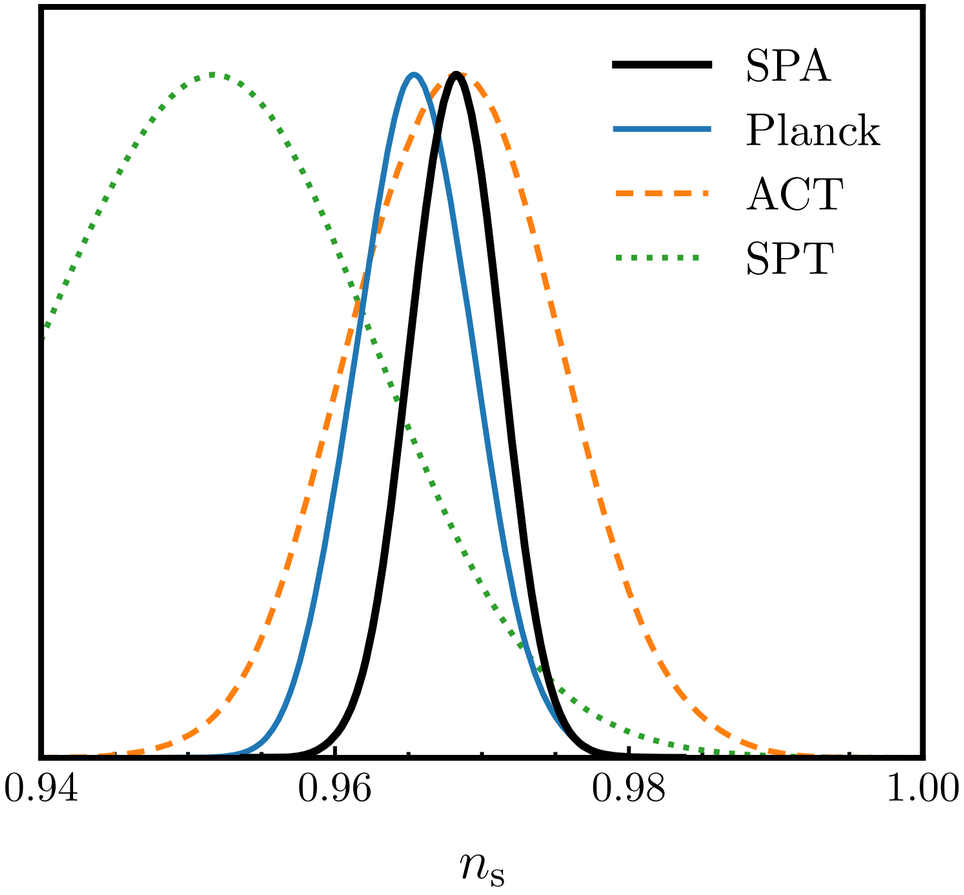
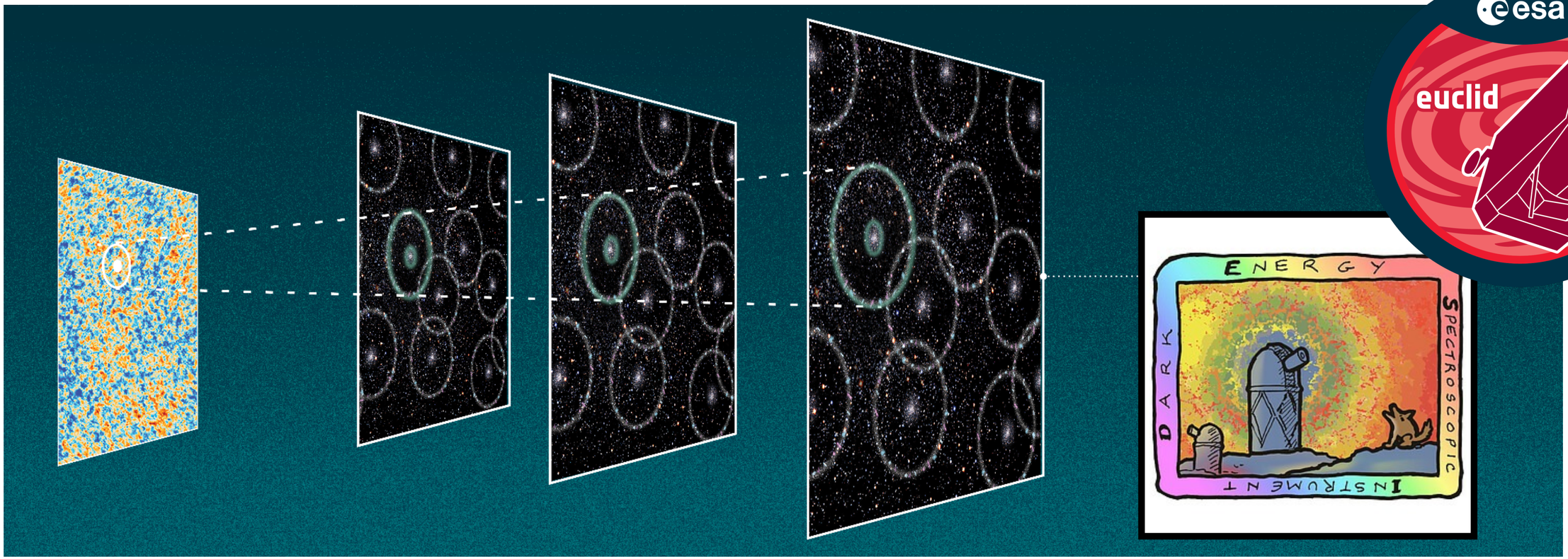


Credit: ESA

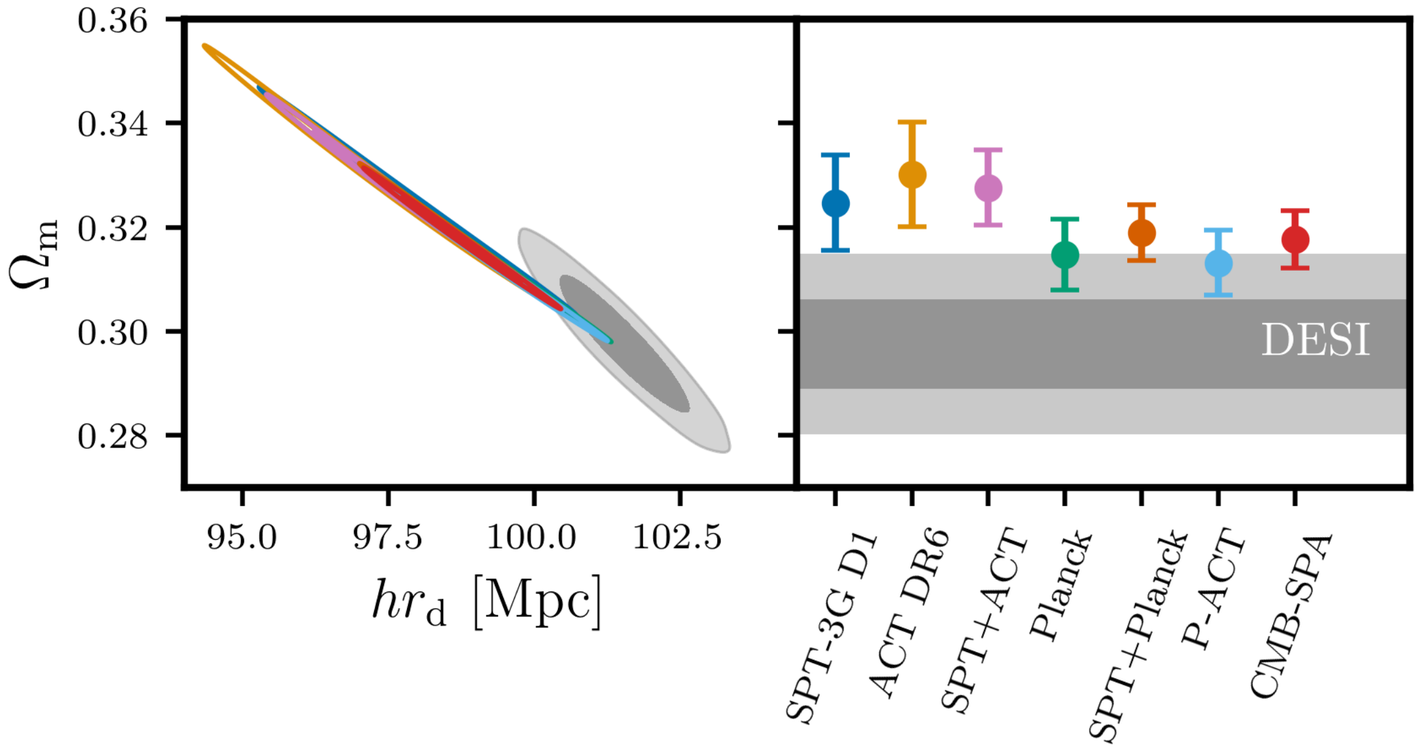
Baryon Acoustic Oscillations



- BAO trace matter distribution throughout cosmic history
- Constrain Ω_m and hr_d, highly complementary to CMB
- State-of-the-art: DESI DR2

CMB-BAO Tension(?)

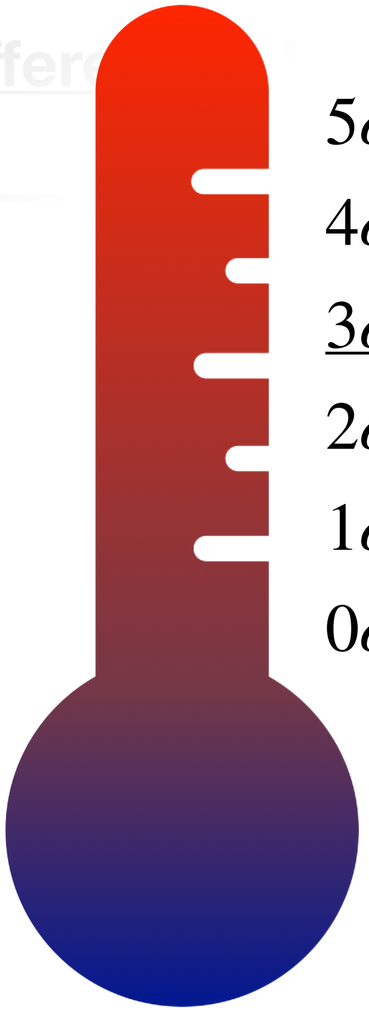
Differences between CMB and BAO data at the 2-4σ level



SPT-3G D1 vs. DESI:	$2.5\,\sigma$
ACT DR6 vs. DESI:	$3.1\,\sigma$
SPT+ACT vs. DESI:	$3.7\,\sigma$
Planck vs. DESI:	$2.0\,\sigma$
SPT+Planck vs. DESI:	$3.0\,\sigma$
P-ACT vs. DESI:	$2.0\,\sigma$
CMB-SPA vs. DESI:	$2.8\,\sigma$

Planck+SPT+ACT vs. DESI

CMB-BAO Tension(?)



5σ Crisis

4σ Problem

3σ **Tension** ←

2σ Curiosity

1σ Consistency

0σ Too good to be true

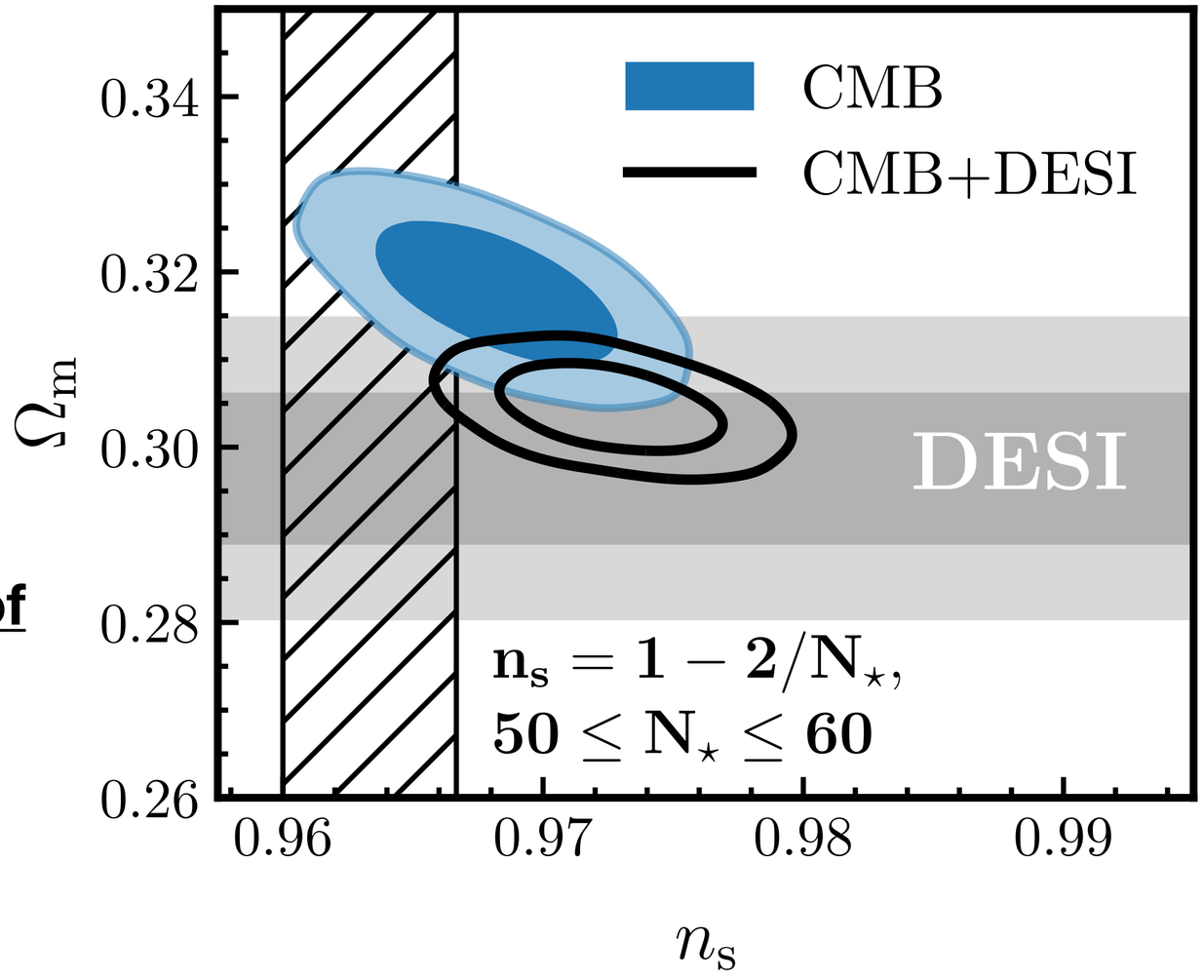
Official Tensiometer of Cosmology™

~ a series of coin flips that gives tails 8 times in a row…

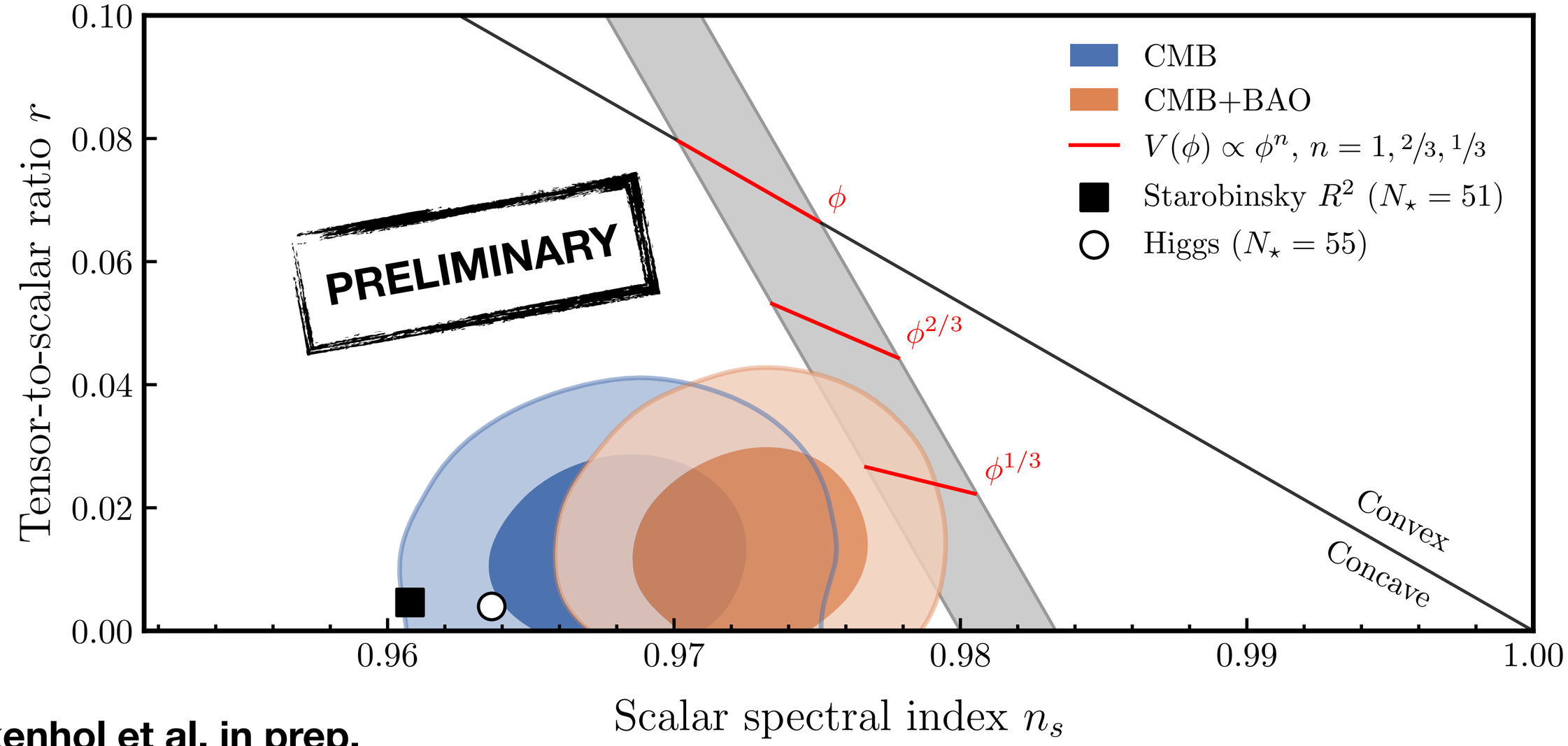
Terminology by Silvia Galli

CMB-BAO Differences Shift n_s High

- **<u>Differences pull n_s high in joint analysis</u>**
  - For CMB data, n_s is (-) correlated with Ω_m and (+) with hr_d
  - Degree of correlation depends on specific data set, but up to 70%
- **<u>CMB+DESI n_s is high w.r.t. predictions of Starobinsky R^2, Higgs, α-attractors</u>**
  - More compatible with monomial potentials



The State of r-n_s Constraints in 2025



Balkenhol et al. in prep.

Proceed With Caution

- **<u>With current data, joint CMB+BAO constraints are volatile</u>**
  - Differences between CMB and BAO borderline significant at $2\text{-}4\sigma$
  - All constraints assume ΛCDM, can project onto extensions and change n_s
  - Caveat of unknown systematics
- **<u>If tension is real, one of these has to go:</u>**
  - Higgs, Starobinsky, α-attractor Inflation
  - ΛCDM

<u>More data is needed for a stronger judgement</u>

Conclusions

- CMB data are highly consistent
- Differences between CMB and DESI data are borderline statistically significant
  - Differences project onto n_s, shifting favour towards monomial potentials
- Robust n_s inference is crucial to confirm/reject inflation models
- **Joint CMB+DESI constraints should be interpreted with caution**

New CMB and LSS data are coming
and may confirm or rule out a “CMB-BAO tension”
(South Pole Telescope, Simons Observatory, Euclid, DESI)

BACKUP

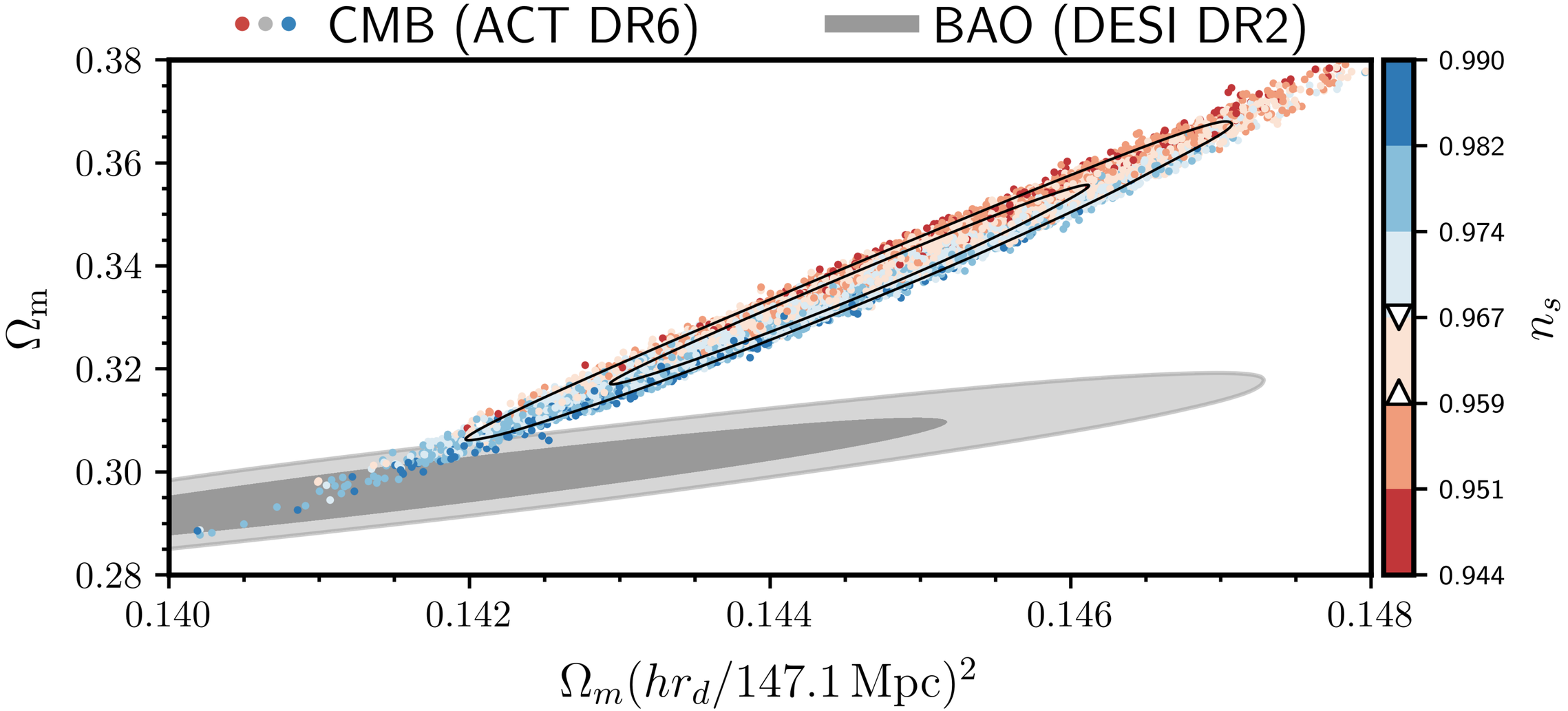
Correlation of ns with BAO parameters

- $\Omega_m h^2$ imprints on CMB through radiation driving
  - Smooth amplitude boost over wide range of angular scales - similar to n_s
- $\Omega_m h^3$ can be inferred precisely
  - From the angular size of the sound horizon θ
- These two constraints are combined, but at the price of correlating Ω_m with n_s
- Degree of correlation depends on the specific data set (angular scales, T vs E, lensing)

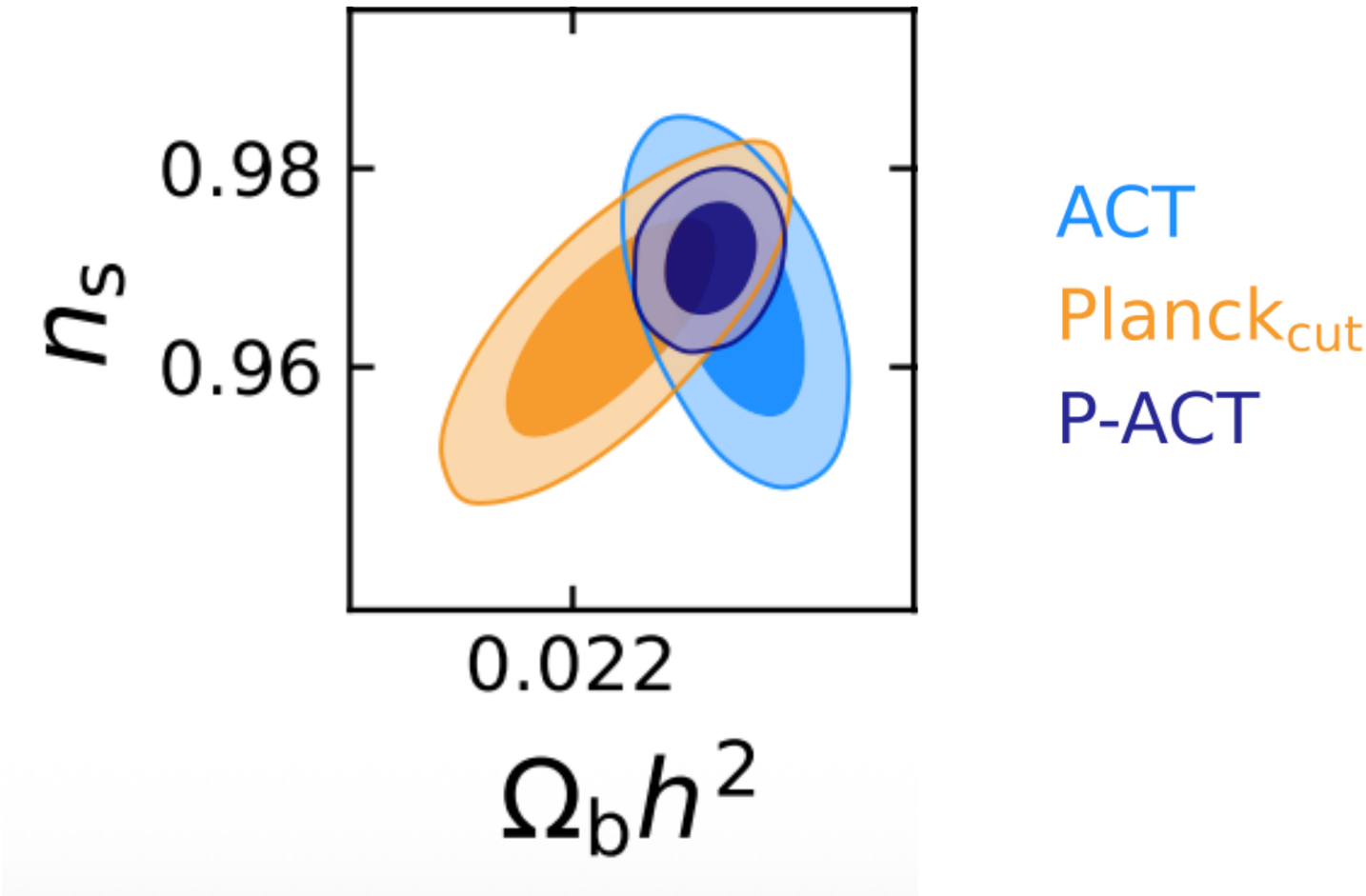
Caveats

- CMB Omega_m, ns determination hinges on tau-prior
  - Tau and ns are correlated - raising tau shifts ns high
  - No evidence for significant systematics in Planck measurement, LiteBIRD, CLASS can re-check
- Model dependence in of BAO analysis?
  - For SDSS data, assuming LCDM can introduce a small bias, but analysis not repeated for DESI data

CMB-BAO Differences Shift n_s High

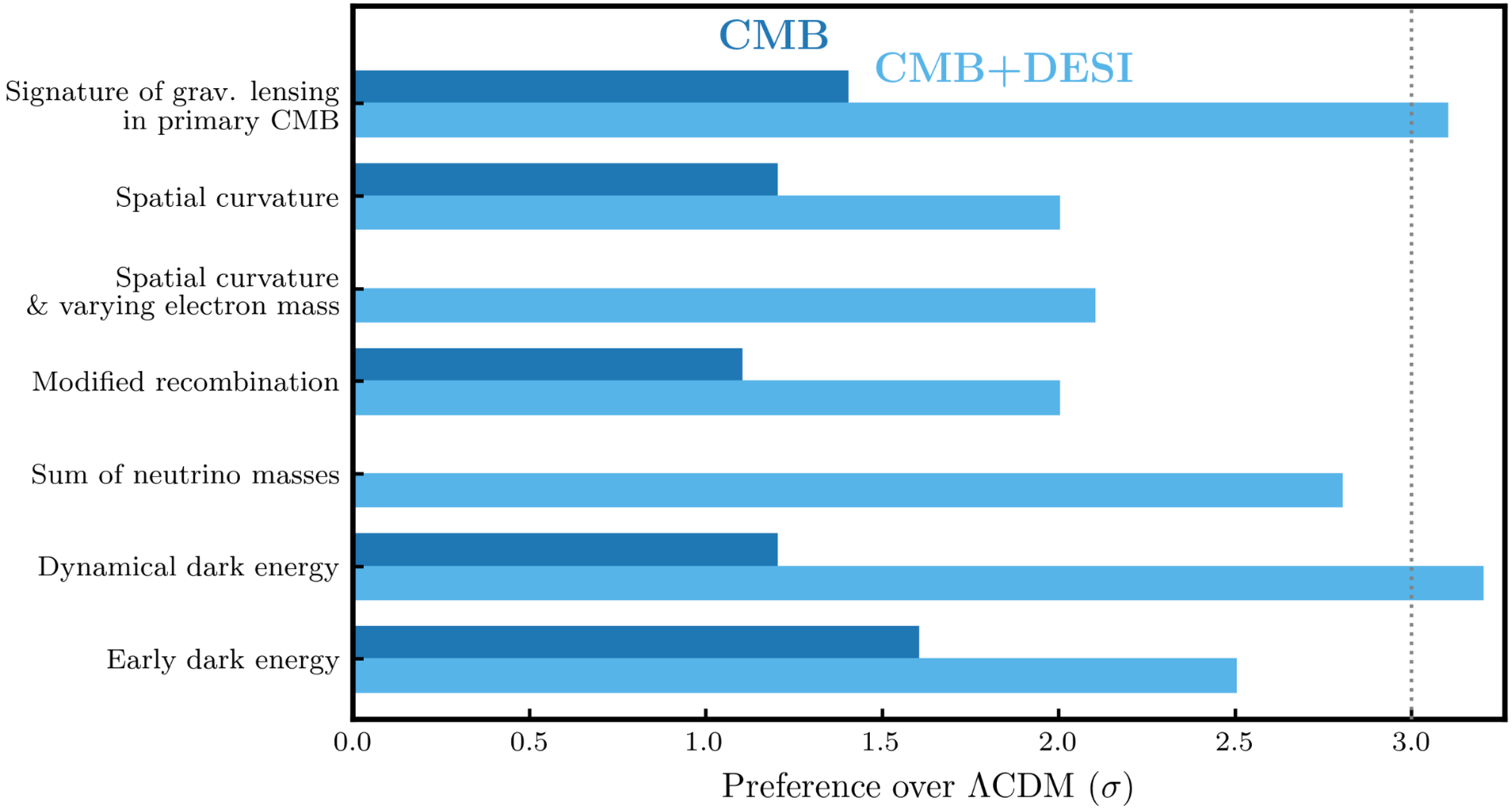


P-ACT ns

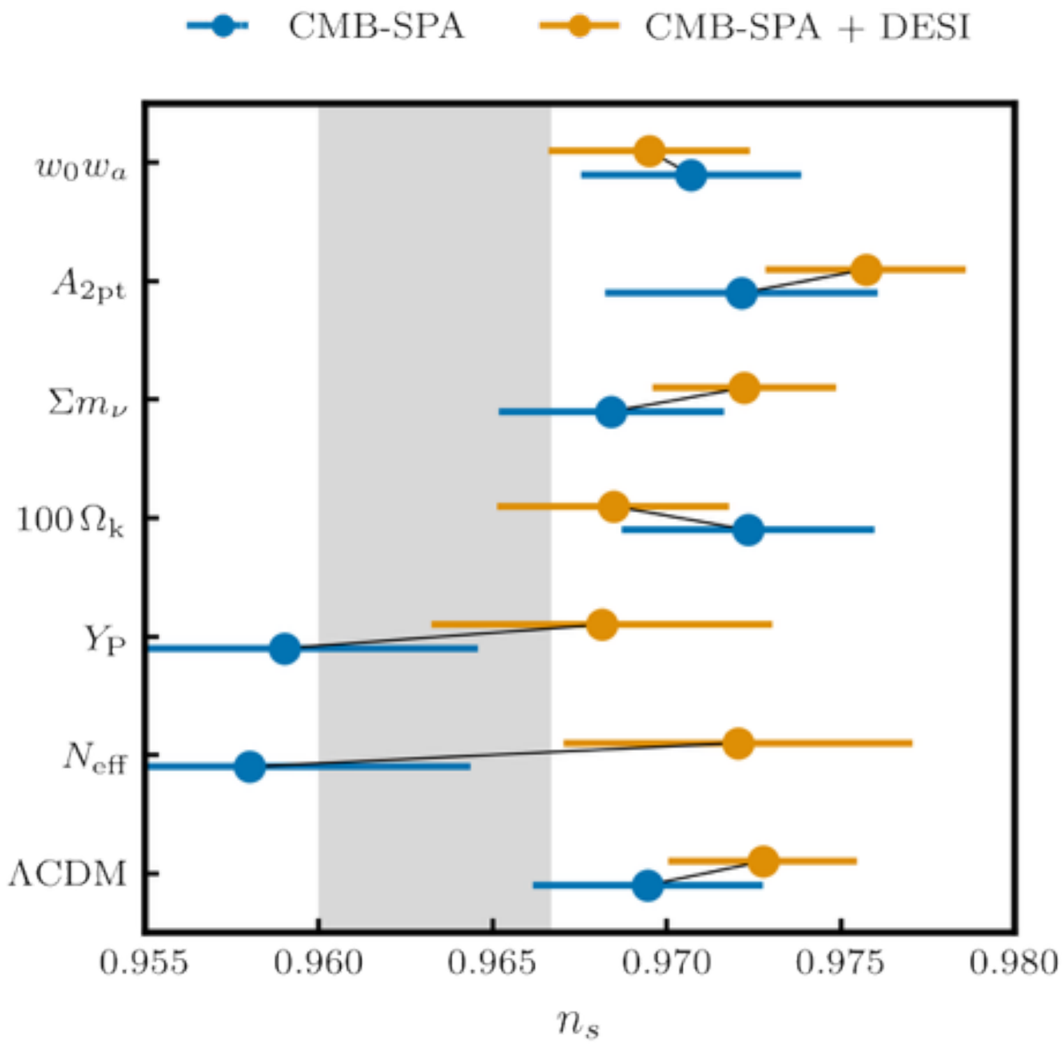


Louis et al. 25

Beyond LCDM


CMB
CMB+DESI
Signature of grav. lensing in primary CMB
Spatial curvature
Spatial curvature & varying electron mass
Modified recombination
Sum of neutrino masses
Dynamical dark energy
Early dark energy
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Preference over ΛCDM (σ)

Beyond LCDM


CMB-SPA
CMB-SPA + DESI
w_0w_a
$A_{2\mathrm{pt}}$
Σm_ν
$100\,\Omega_\mathrm{k}$
Y_P
N_eff
ΛCDM
0.955
0.960
0.965
0.970
0.975
0.980
n_s