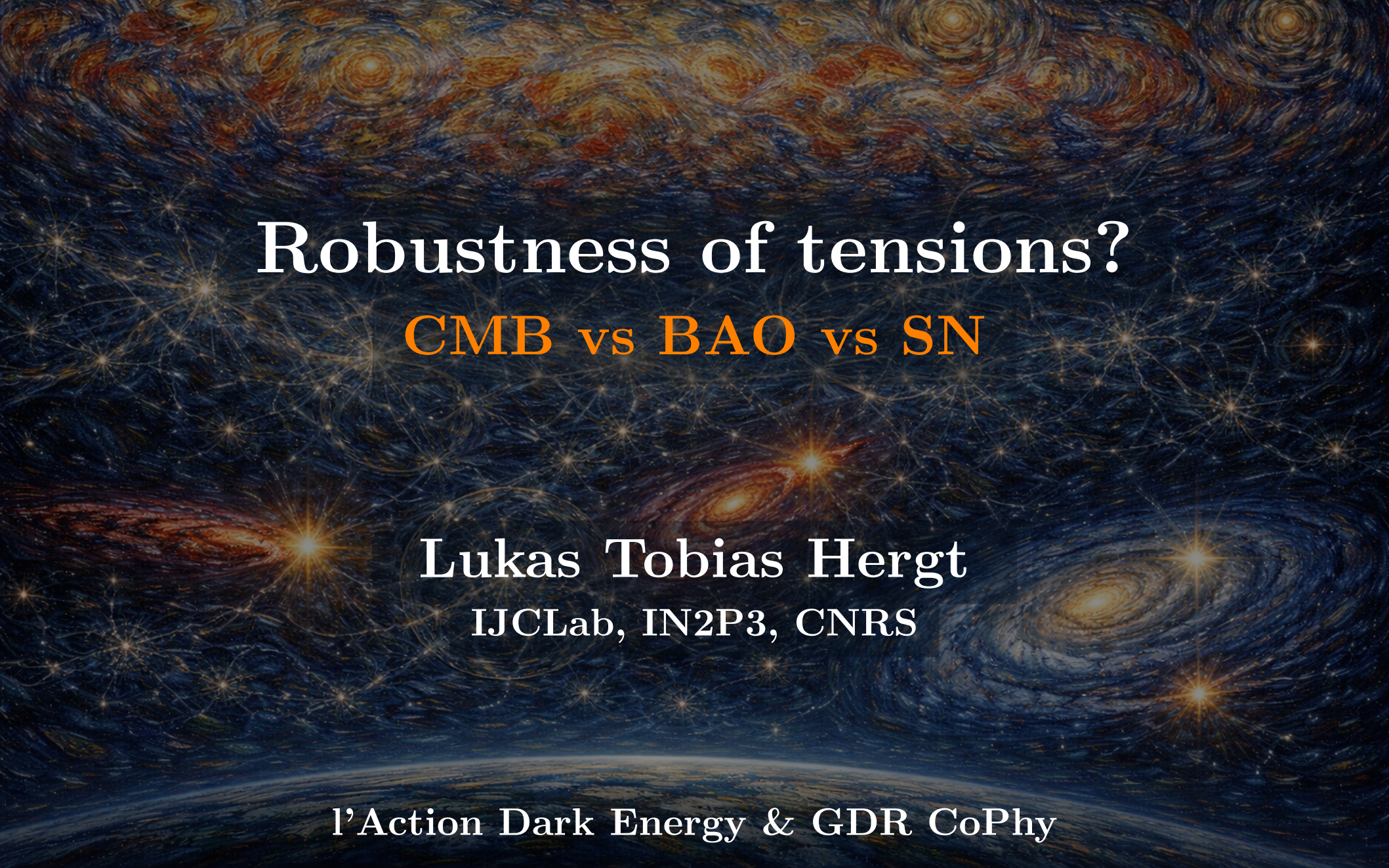

Robustness of tensions?

CMB vs BAO vs SN

Lukas Tobias Hergt

IJCLab, IN2P3, CNRS

l'Action Dark Energy & GDR CoPhy

How robust are tension claims in cosmology?

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 5 Feb 2026]

Consistency of standard cosmologies using Bayesian model comparison and tension quantification

Lukas Tobias Hergt, Sophie Henrot-Versillé, Matthieu Tristram, Douglas Scott

We present a unified Bayesian assessment of model comparison and data-set consistency for LCDM (cold dark matter plus a cosmological constant) and minimal extensions (neutrino mass, spatial curvature, constant or evolving dark energy) using cosmic microwave background (CMB), baryon acoustic oscillation (BAO), and type Ia supernova (SN) data. The major results are summarized in the first three figures. We quantify model preference with Bayesian evidence and assess consistency with complementary evidence- and likelihood-based diagnostics applied uniformly across data-set combinations. For the models considered, updated Planck processing systematically improves internal CMB consistency (low-ℓ versus high-ℓ, and primary CMB versus CMB lensing). The preference for a closed geometry and an associated ``curvature tension'' with BAO and/or CMB lensing are largely confined to earlier Planck likelihood implementations and weaken substantially when using updated CMB processing and more recent BAO measurements. Apparent evidence for evolving dark energy in CMB+BAO+SN combinations depends sensitively on the specific pairing of CMB and SN likelihoods: plausible alternatives shift inferred tensions by more than $1\,\sigma$ and can completely reverse the preferred model. Allowing a free neutrino mass tends to absorb residual shifts without introducing new inconsistencies, and we do not find robust evidence for a standalone τ-driven discrepancy once the full likelihood context is accounted for. We conclude that claims of a required update of our standard cosmological model from LCDM to w_0w_a CDM are premature.

Comments: 22 pages, 16 figures, 2 tables; to be submitted to PRD; data made available at this http URL

Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; Astrophysics of Galaxies (astro-ph.GA); General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Theory (hep-th)

Cite as: arXiv:2602.06115 **[astro-ph.CO]**

(or arXiv:2602.06115v1 **[astro-ph.CO]** for this version)

https://doi.org/10.48550/arXiv.2602.06115

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5) **New high-ℓ likelihoods ACT & SPT**
6) **Conclusion**

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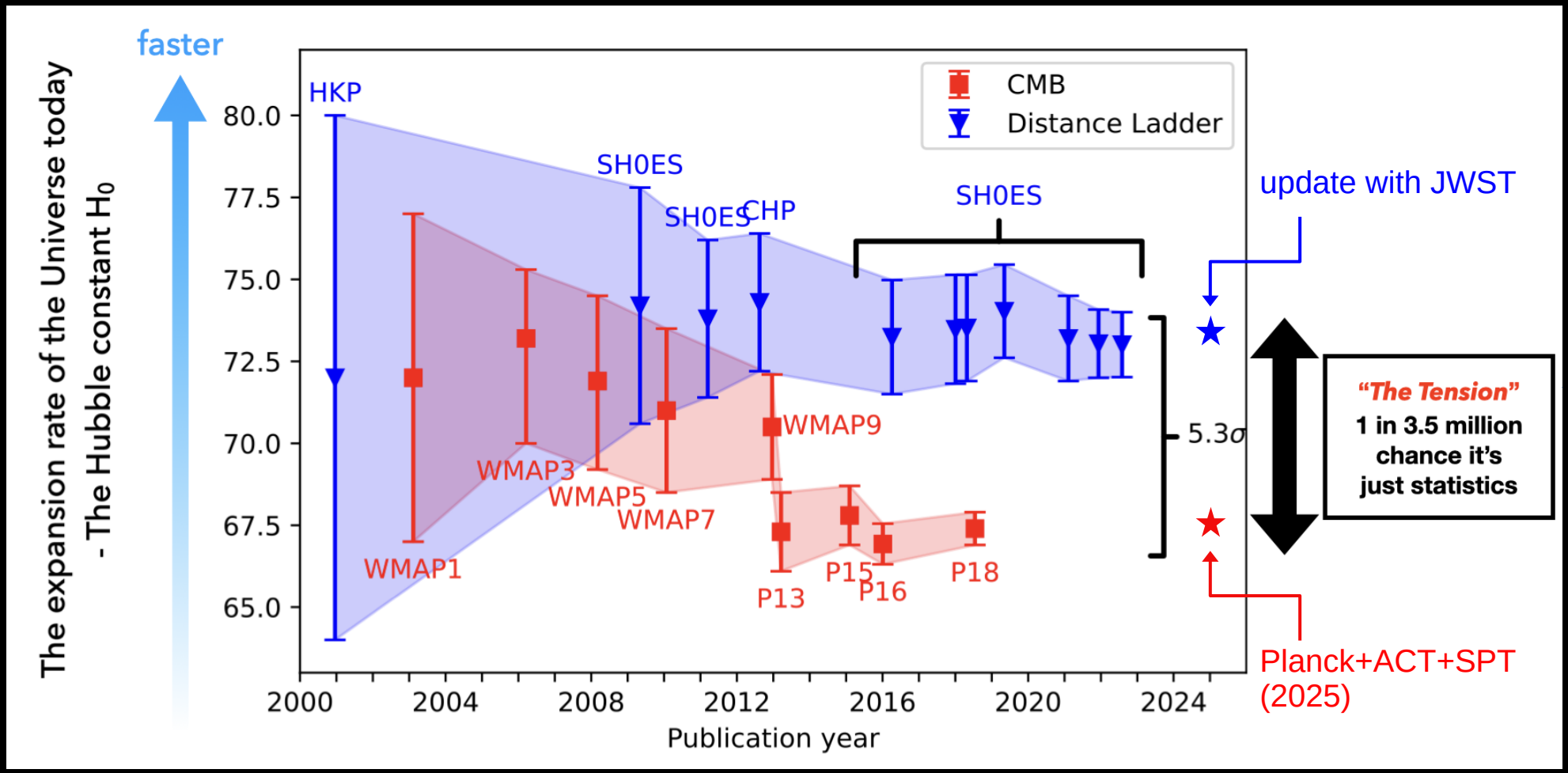
The "Hubble Tension" (a.k.a. H_0 tension)



Credit: D'arcy Kenworthy

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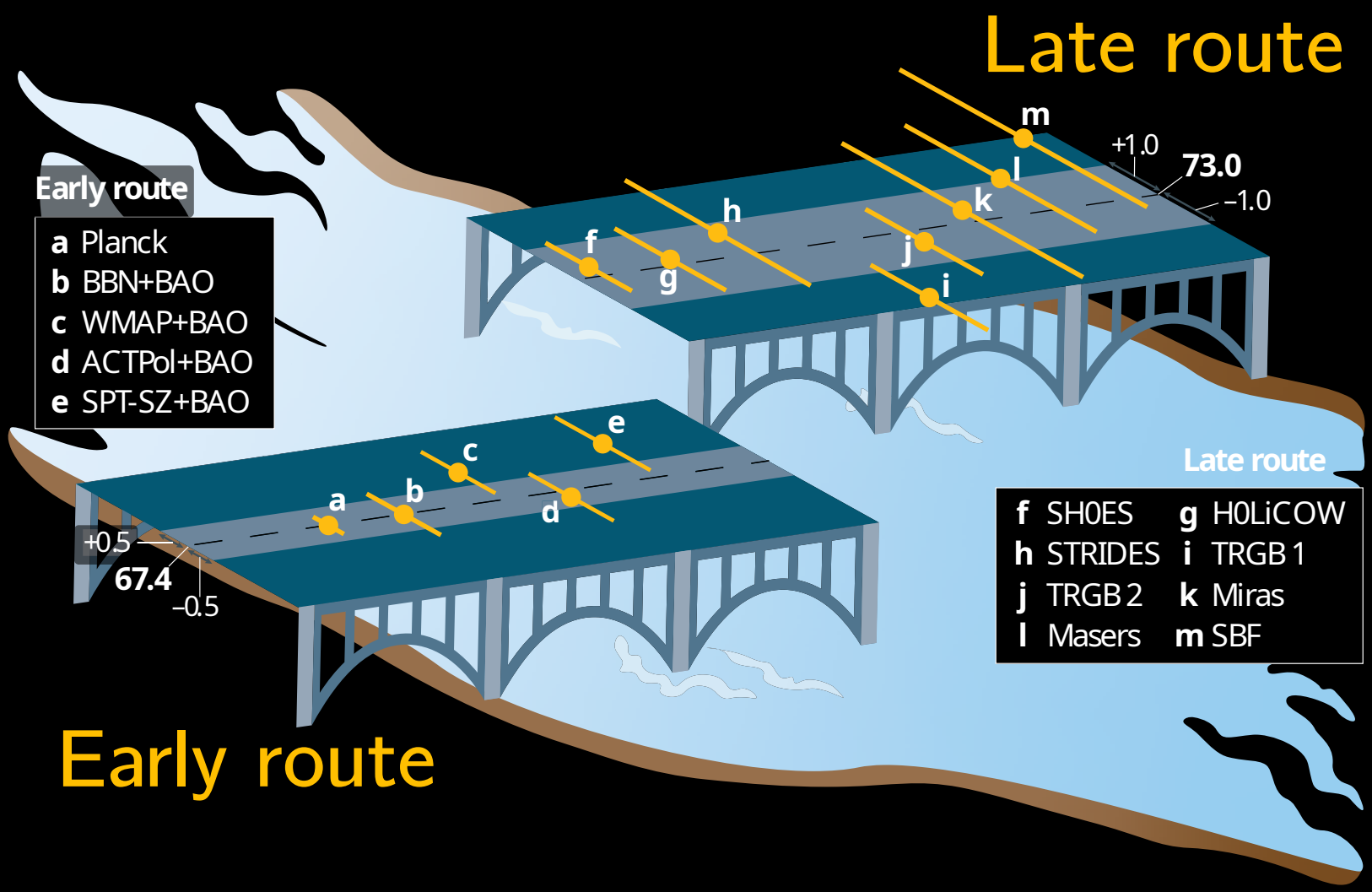


Credit: Adam G. Riess, Nature Rev. Phys. (2020)

The "Clustering Tension" (a.k.a. σ_8 or S_8 tension):
Weak Lensing (WL) vs Cosmic Microwave Background (CMB)

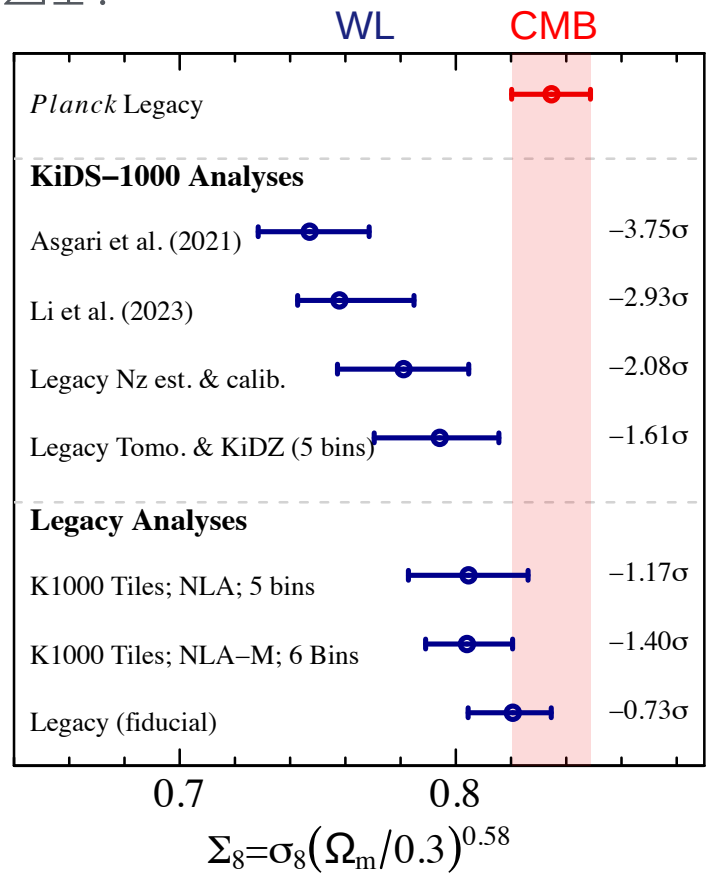
What changed since 2021?

Driving Factors

- New spectroscopic sample for $N(z)$ estimation
- Updated $N(z)$ calibration and estimation methods
- New imaging, new area

Further changes

- Revised scale cut
- New IA modelling
- New tomography
- New $P(k)$ emulation
- New sampler
- New analysis pipelines

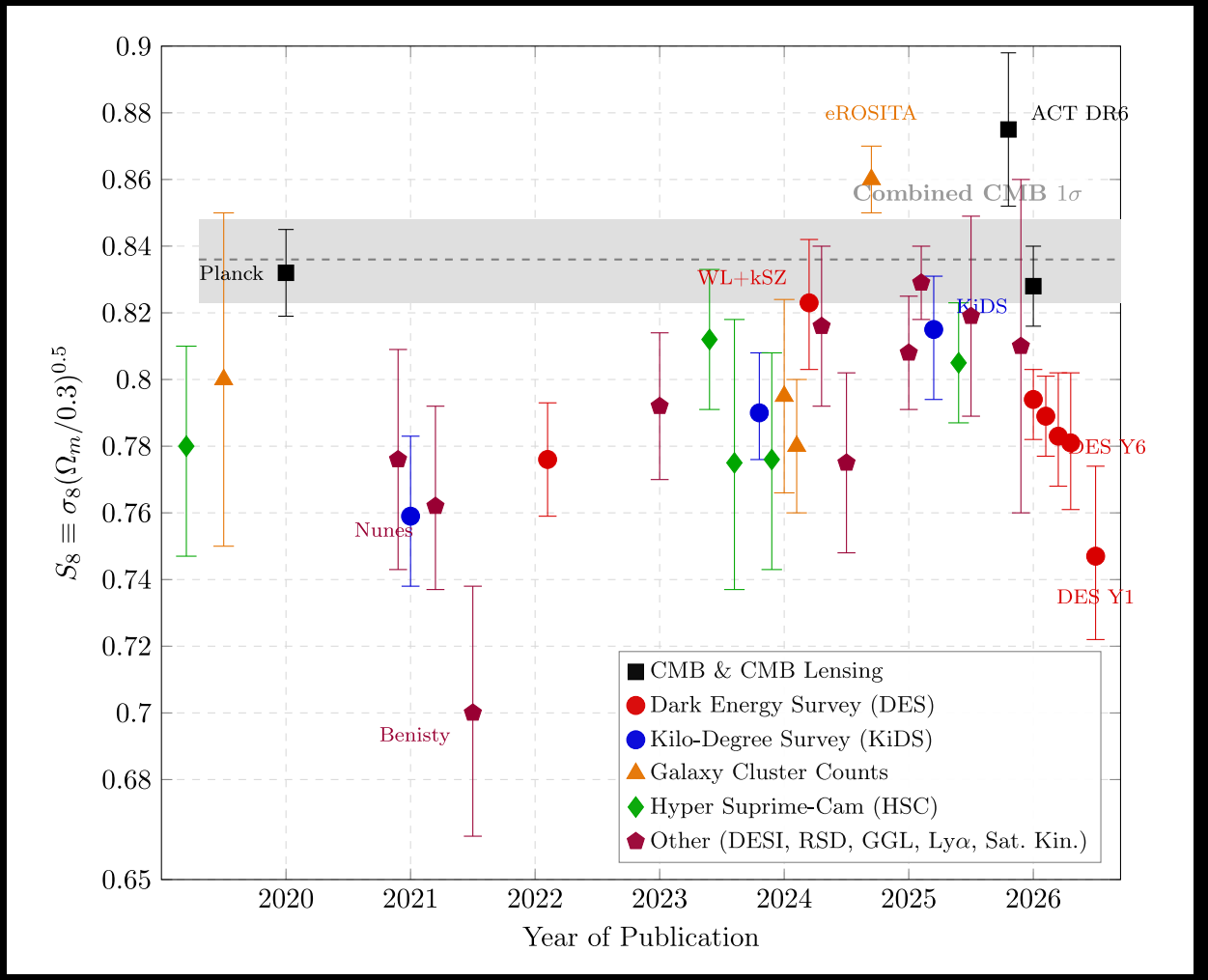


Wright et al. (2025b)

Credit: Angus Wright, CMB France 2025

The "Clustering Tension" (a.k.a. σ_8 or S_8 tension):
Weak Lensing (WL) vs Cosmic Microwave Background (CMB)

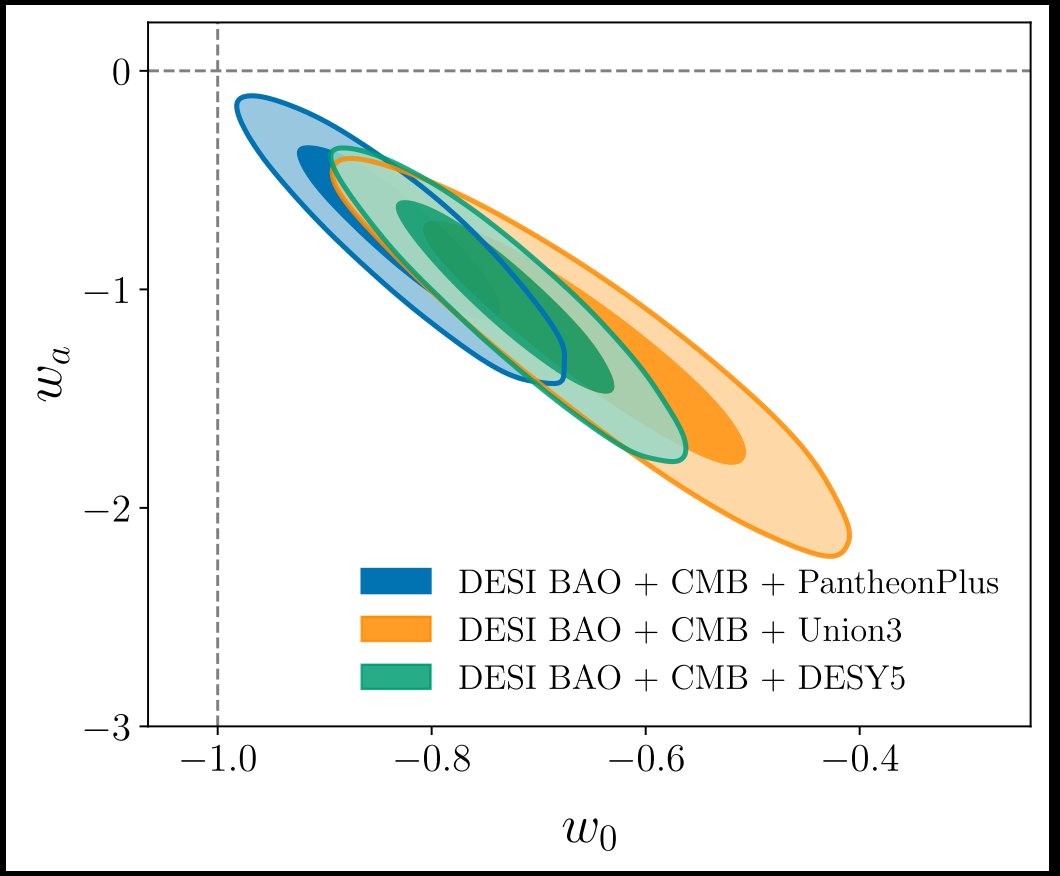
- σ_8: amplitude of matter density fluctuations
- ~ 2017: Discrepancy emerged between CMB and WL
- Trend:
  - until 2026: trend towards consistency
  - since this year: renewed tension?



Credit: Pantos & Perivolaropoulos Phys. Dark Univ. 52 (2026)

Cosmological Constant Tension ?

- Standard model of Cosmology:
  - ΛCDM with cosmological constant Λ
  - Corresponding equation-of-state parameters of Dark Energy:
    - → $w_0 = -1$
    - → $w_a = 0$
    - → $w(a) = w_0 + w_a\,(1 - a)$
- CMB + BAO + SN:
  Preference for $w_0 w_a$CDM?



Credit: DESI Collaboration (2025)

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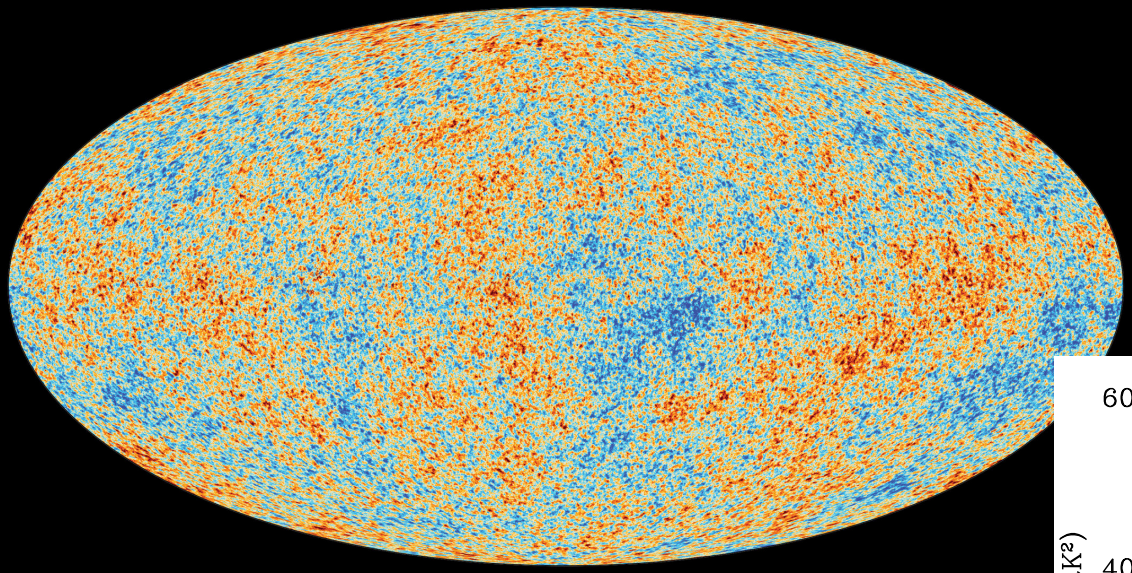
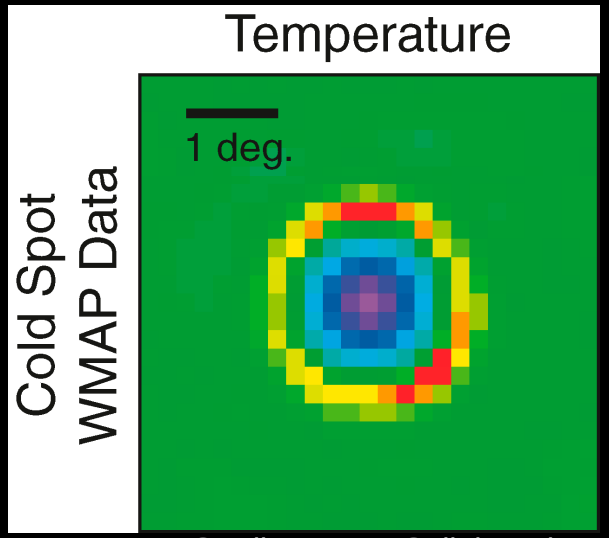
The Cosmic Microwave Background (CMB)

CMB = snapshot of anisotropies at recombination



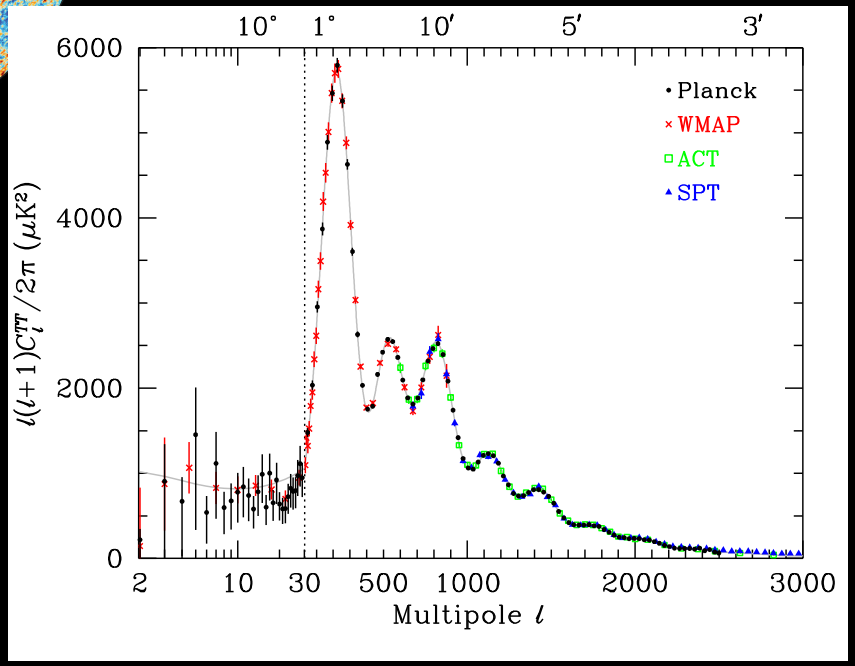
Credit: ESA and Planck Collaboration

Stacking on Cold Spots



Credit: WMAP Collaboration

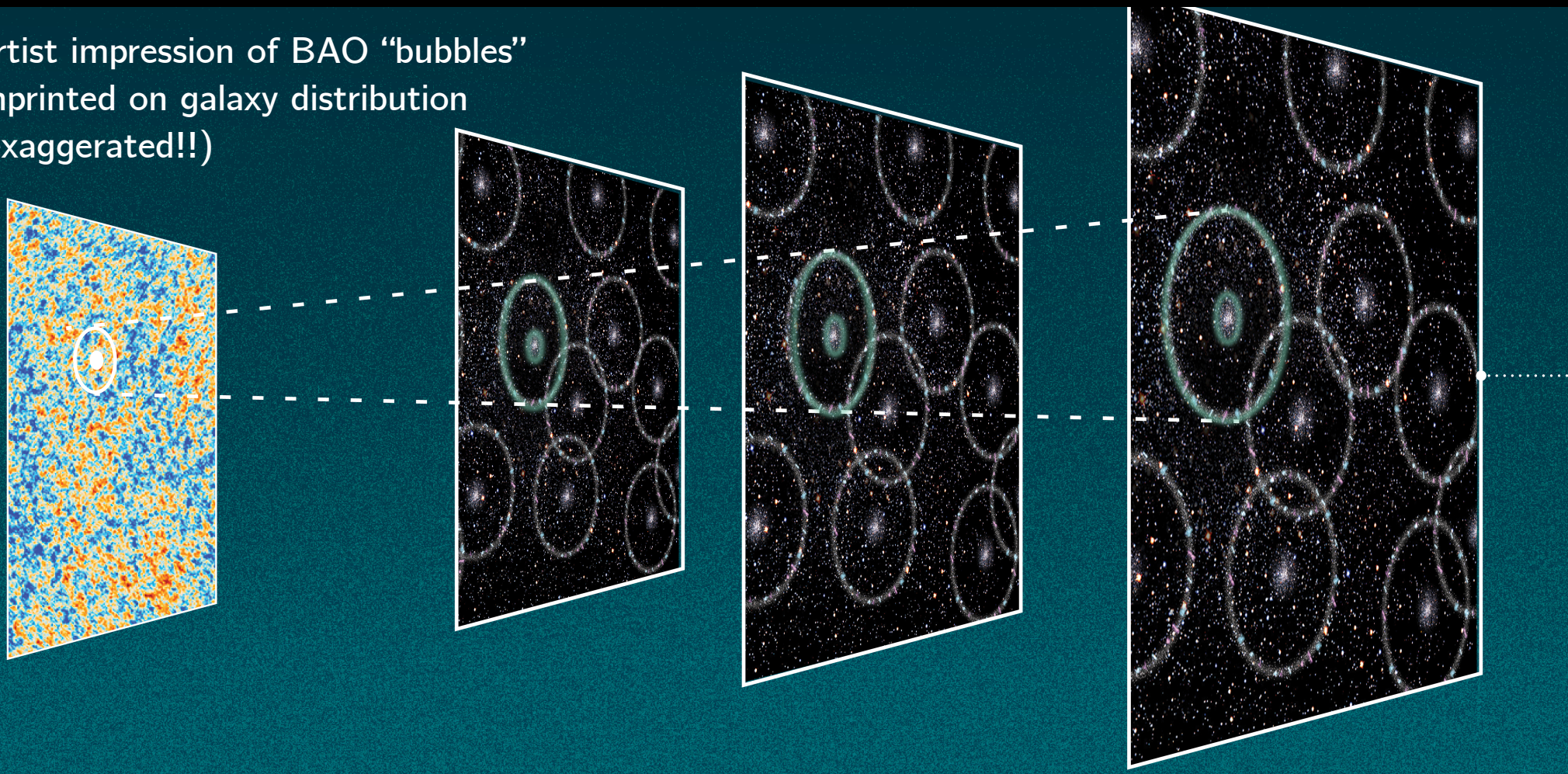
Angular Power Spectrum ("Fourier Transform" of 2-point correlation function)



Credit: Particle Data Group

Baryon Acoustic Oscillations (BAO)

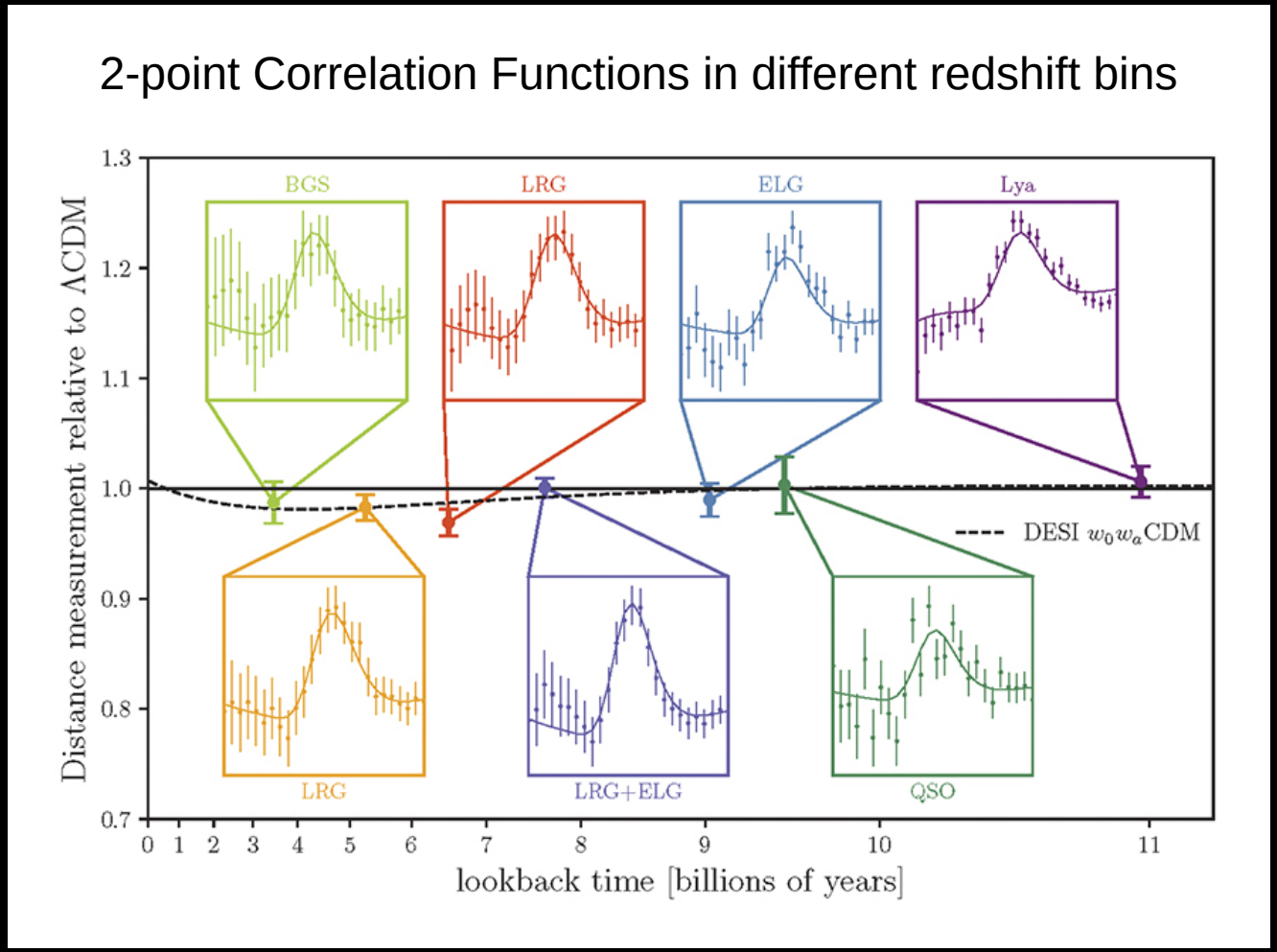
Artist impression of BAO “bubbles” imprinted on galaxy distribution (exaggerated!!)



Source: ESA and the Planck Collaboration / Gabriela Secara / Perimeter Institute

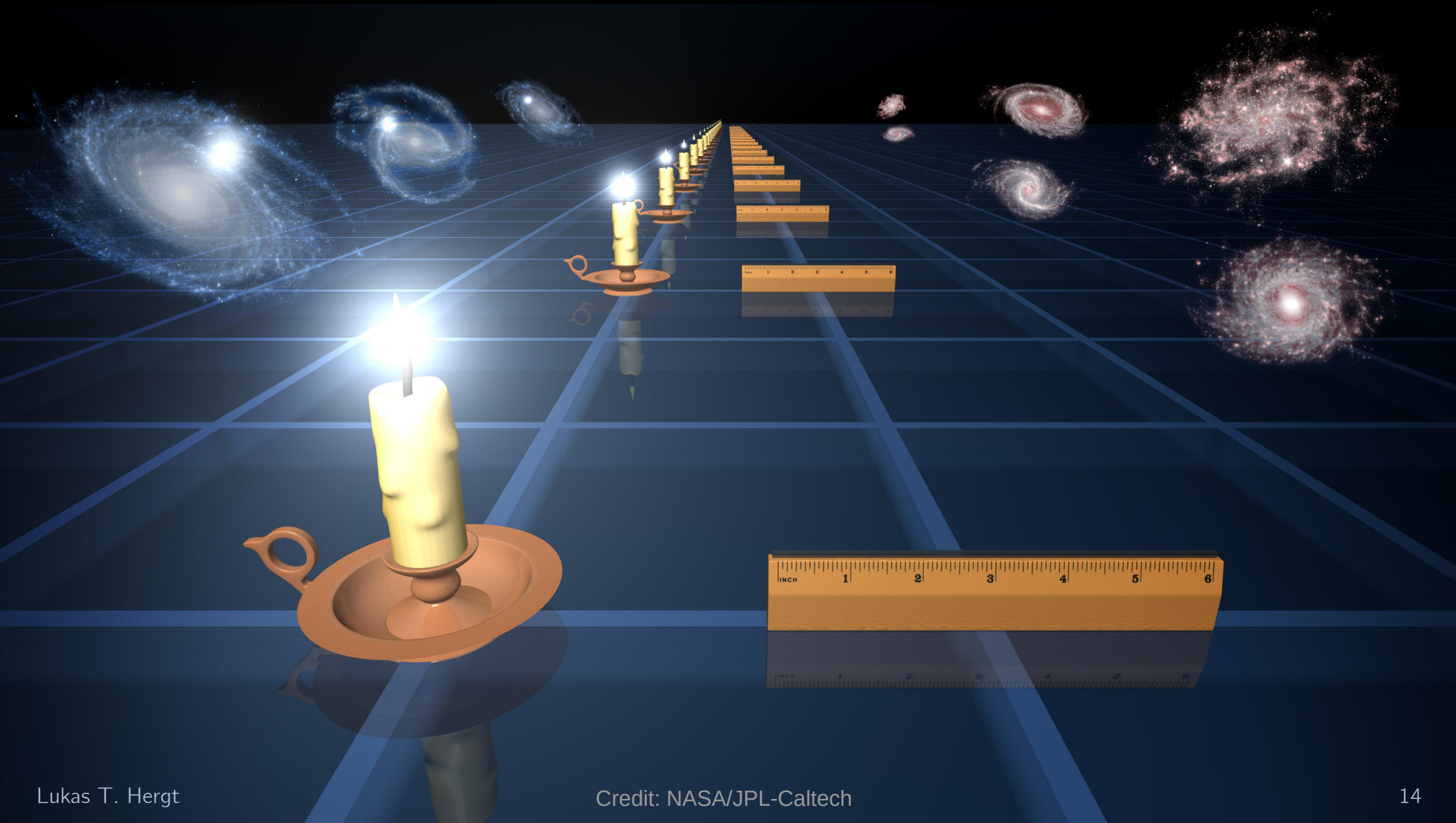
Baryon Acoustic Oscillations (BAO)

- Interplay between gravity and photon-baryon-pressure in the early Universe
  - → overdensities propagate as sound waves
- Waves freeze when Universe becomes neutral (at recombination)
  - → characteristic length scale: sound horizon
  - → Standard Ruler

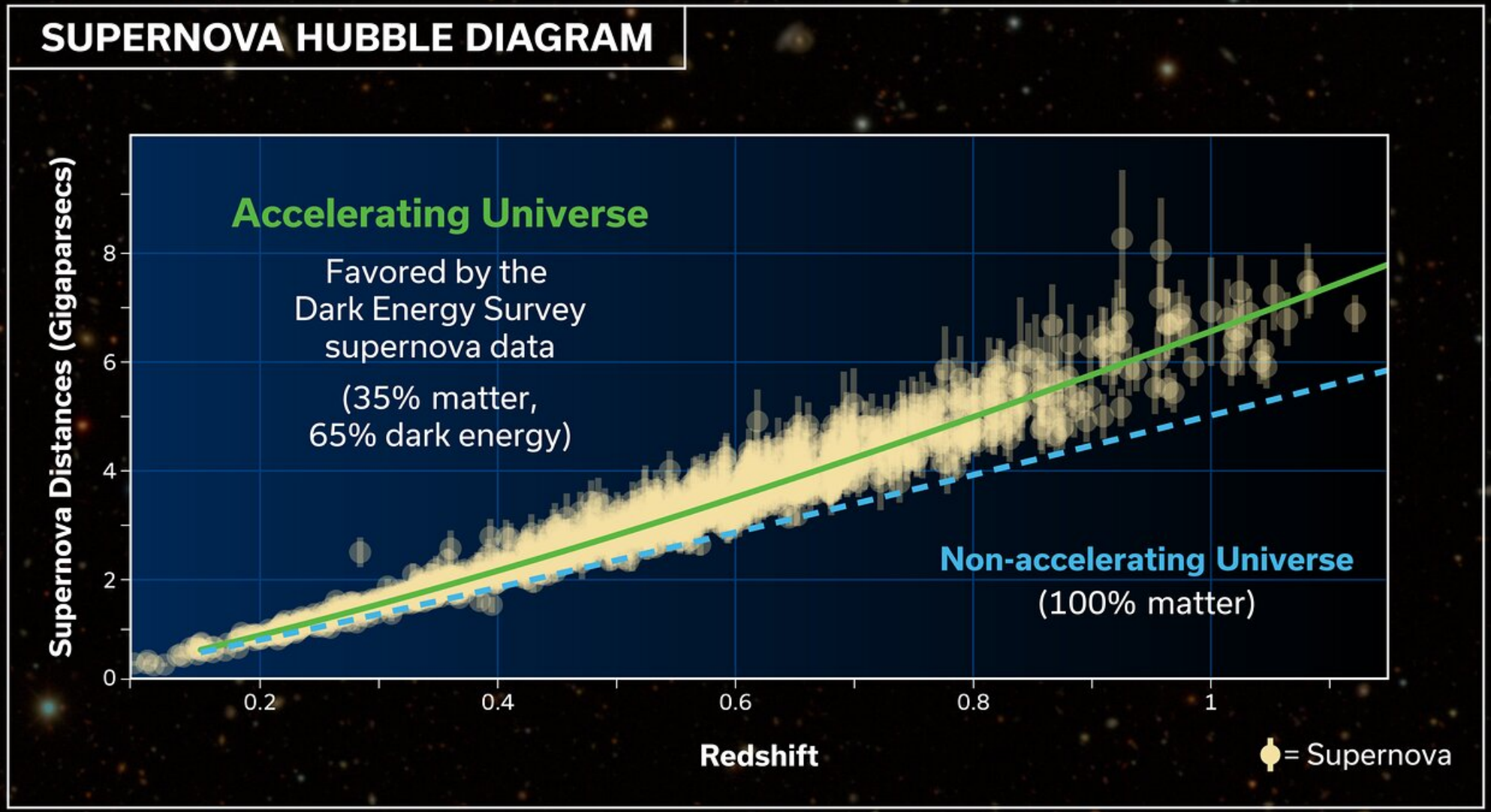


Credit: DESI Collaboration (2024)

Supernovae as Standard Candles — BAOs as Standard Rulers



Credit: NASA/JPL-Caltech



Credit: DES Collaboration

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Variations on Bayes Theorem

- Traditional form:

$$\underbrace{P(\theta|D,M)}_{\text{posterior } \mathcal{P}(\theta)} = \frac{\overbrace{P(D|\theta,M)}^{\text{likelihood } \mathcal{L}(\theta)} \times \overbrace{P(\theta|M)}^{\text{prior } \Pi(\theta)}}{\underbrace{P(D|M)}_{\text{Bayesian evidence } \mathcal{Z}}}$$

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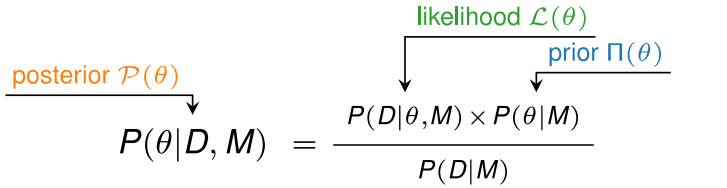

- In computing:
  (e.g. MCMC or nested sampling)

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$$\underbrace{\mathcal{P}(\theta)}_{\text{Output}} \times \mathcal{Z} = \underbrace{\mathcal{L}(\theta)}_{\text{Input}} \times \Pi(\theta)$$

- Parameter estimation:
  (neglect $\mathcal{Z}$ as normalisation const.)

$$\mathcal{P}(\theta) \propto \mathcal{L}(\theta) \times \Pi(\theta)$$

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- Generalised Occam equation:
  (solve for $\mathcal{Z}$ and take logarithm)

$$\log \mathcal{Z} = \log \mathcal{L}(\theta) - \log\left(\frac{\mathcal{P}(\theta)}{\Pi(\theta)}\right)$$

- (Special) Occam equation:
  (take posterior average)

$$\log \mathcal{Z} = \langle \log \mathcal{L} \rangle_{\mathcal{P}} - \underbrace{\mathcal{D}_{\mathrm{KL}}}_{\text{Kullback–Leibler divergence}}$$

Variations on Bayes Theorem

- Traditional form:

$$P(\theta|D,M) = \frac{P(D|\theta,M) \times P(\theta|M)}{P(D|M)}$$

posterior $\mathcal{P}(\theta)$; likelihood $\mathcal{L}(\theta)$; prior $\Pi(\theta)$; Bayesian evidence $\mathcal{Z}$

- In computing:
  (e.g. MCMC or nested sampling)

$$\mathcal{P}(\theta) \times \mathcal{Z} = \mathcal{L}(\theta) \times \Pi(\theta)$$

Output; Input

- Parameter estimation:
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Kullback–Leibler divergence

- Occam equation for tension quantification:

$$\log \mathcal{R} = \log \mathcal{S} - \mathcal{I}$$

a.k.a. Suspiciousness

The 3 Pillars of Bayesian Inference

Parameter Estimation

What do the data tell us about the parameters of a model?
(e.g. the size or age of a ΛCDM universe)

Bayes' Theorem:

$$P(\theta|D,M) = \frac{P(D|\theta,M)\times P(\theta|M)}{P(D|M)}$$

$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{evidence}}$$

$$\mathcal{P}(\theta) = \frac{\mathcal{L}(\theta)\times\Pi(\theta)}{\mathcal{Z}} \propto \mathcal{L}(\theta)\times\Pi(\theta)$$

Model Comparison

How much does the data support one model compared to another?
(e.g. cosmology with a cosmological constant vs with a dynamic dark energy)

$$\frac{P(M_1|D)}{P(M_2|D)} = \frac{P(D|M_1)\times P(M_1)}{P(D|M_2)\times P(M_2)} = \frac{\mathcal{Z}_{M_1}}{\mathcal{Z}_{M_2}} \times \frac{P(M_1)}{P(M_2)}$$

$$\text{posterior odds} = \text{evidence ratio} \times \text{prior odds}$$

Occam's razor:

$$\log\mathcal{Z} = \langle\log\mathcal{L}\rangle_{\mathcal{P}} - \mathcal{D}_{\mathrm{KL}}$$

$$\text{log-evidence} = \text{fit} - \text{Occam penalty}$$

Dataset Consistency

Do different datasets *A* and *B* make consistent predictions for the same model?
(e.g. CMB vs BAO data)

H_0: datasets described by the same parameters

H_1: datasets described by distinct parameters

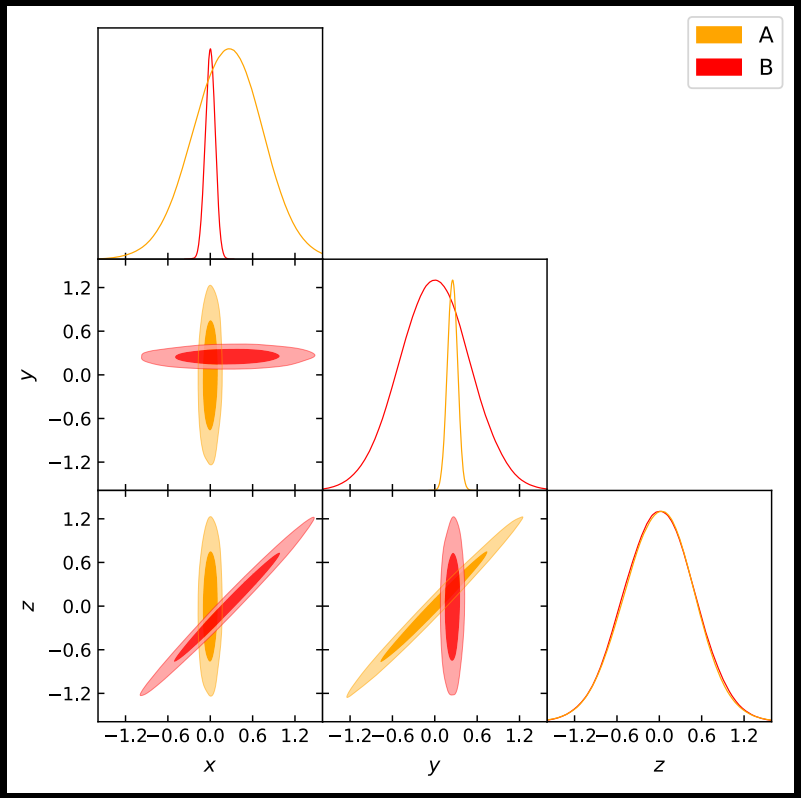
$$\mathcal{R} = \frac{\mathcal{Z}_{AB}}{\mathcal{Z}_A\mathcal{Z}_B},$$

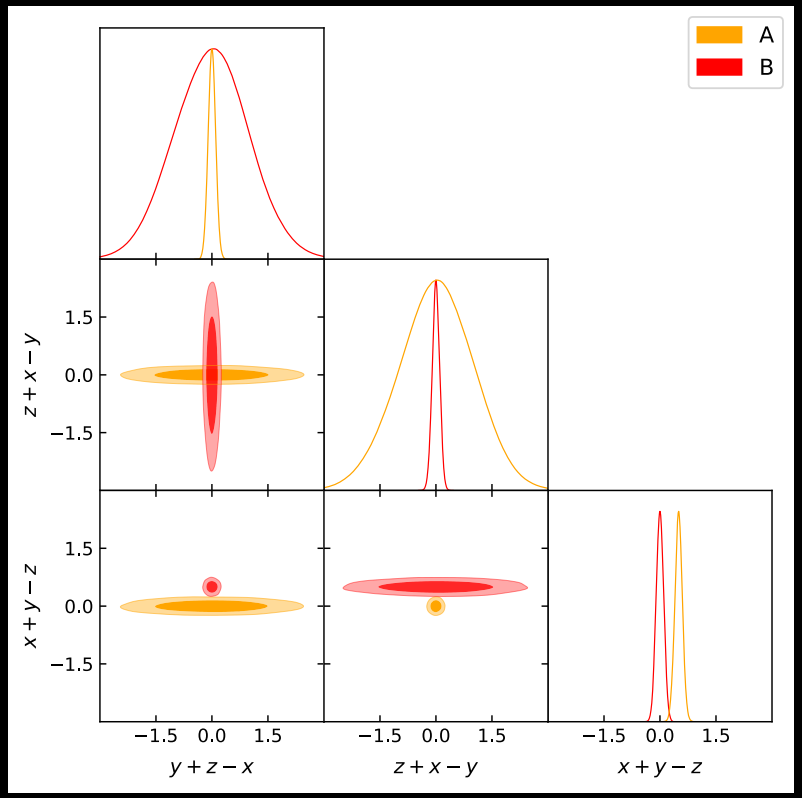
$$\mathcal{R} = \log\mathcal{S} - \mathcal{I},$$

$$\log\mathcal{S} = \langle\log\mathcal{L}_{AB}\rangle_{\mathcal{P}_{AB}} - \langle\log\mathcal{L}_A\rangle_{\mathcal{P}_A} - \langle\log\mathcal{L}_B\rangle_{\mathcal{P}_B}$$

$$d - 2\log\mathcal{S} \sim \chi^2_d$$

Tensions can be hidden in 1D and 2D projections

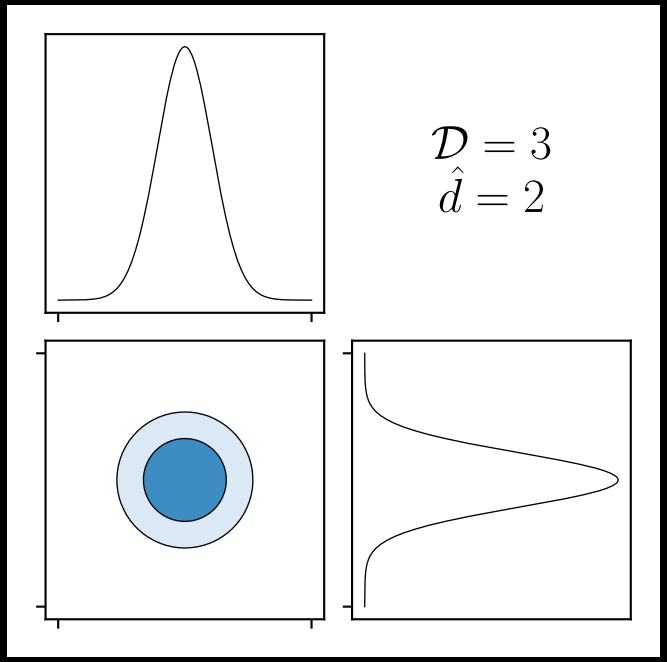


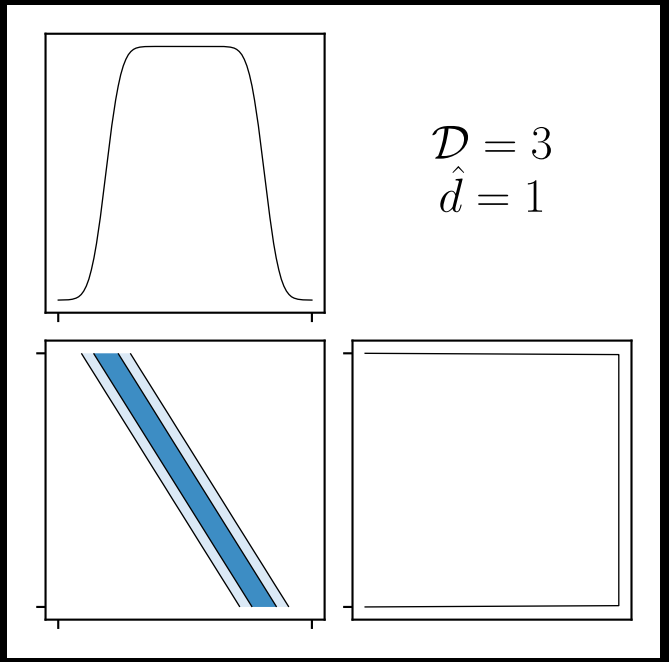


Credit: Handley & Lemos, Phys. Rev. D 100 (2019)

- Projections can be misleading. → Can miss tensions after marginalisation.
- Evidence ratio, R, and likelihood ratio or "suspiciousness", S, take full dimensionality into account (estimated by the Bayesian Model Dimensionality d).

Bayesian Model Dimensionality





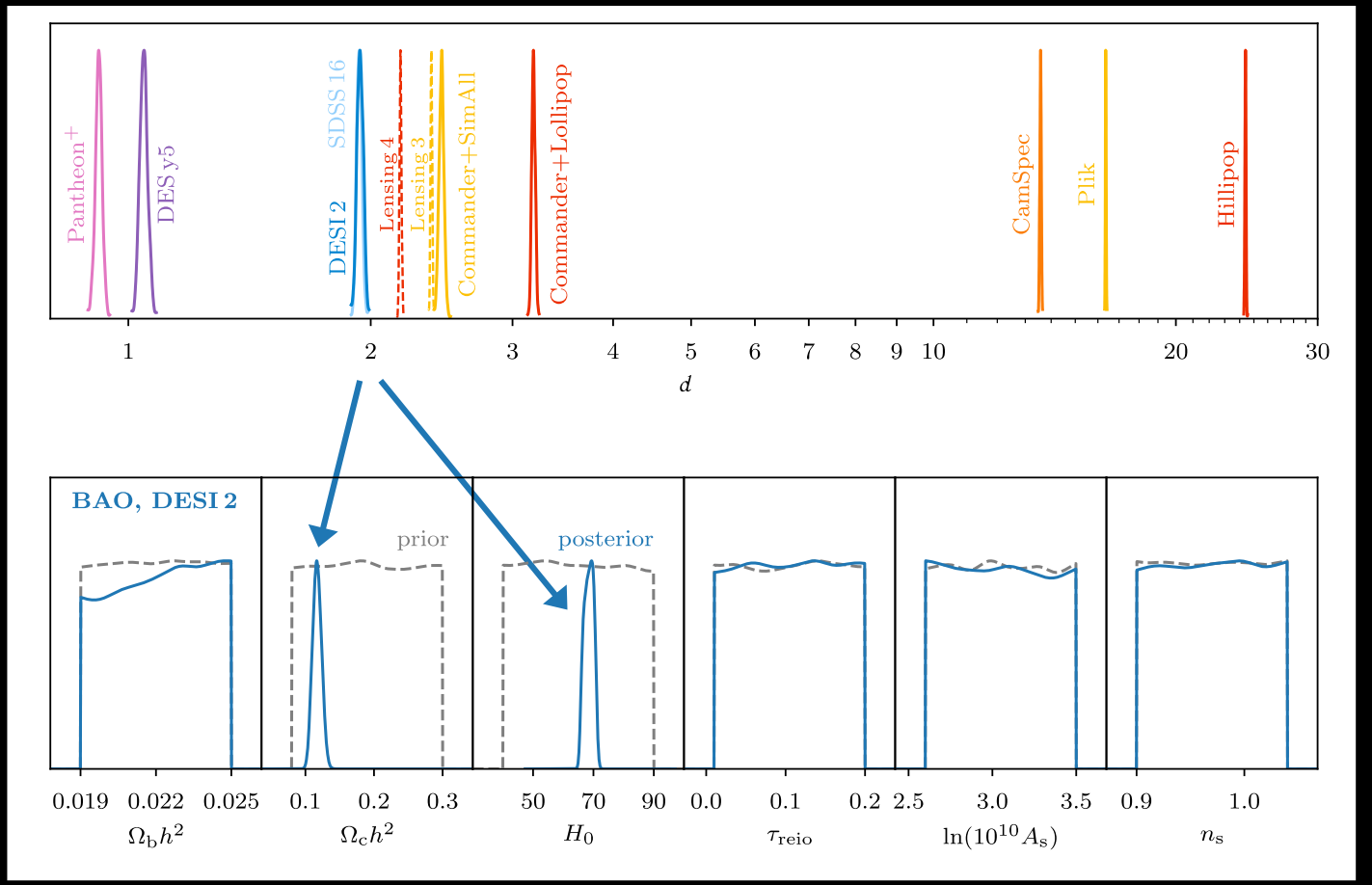
Credit: Handley & Lemos, Phys. Rev. D 100 (2019)

- **Same** number (i.e. 2) of sampling parameters.
- **Same** Kullback–Leibler divergence D (i.e. same prior to posterior compression).
- **Different** dimensionality d (i.e. different number of *constrained* parameters).

Bayesian Model Dimensionality in action

- Estimated from the log-likelihood (or χ^2) of the full sampling chain.
- Unconstrained parameters do not contribute!

$$d / 2 = \langle (\ln L)^2 \rangle - \langle \ln L \rangle^2$$



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Slightly overwhelming overview

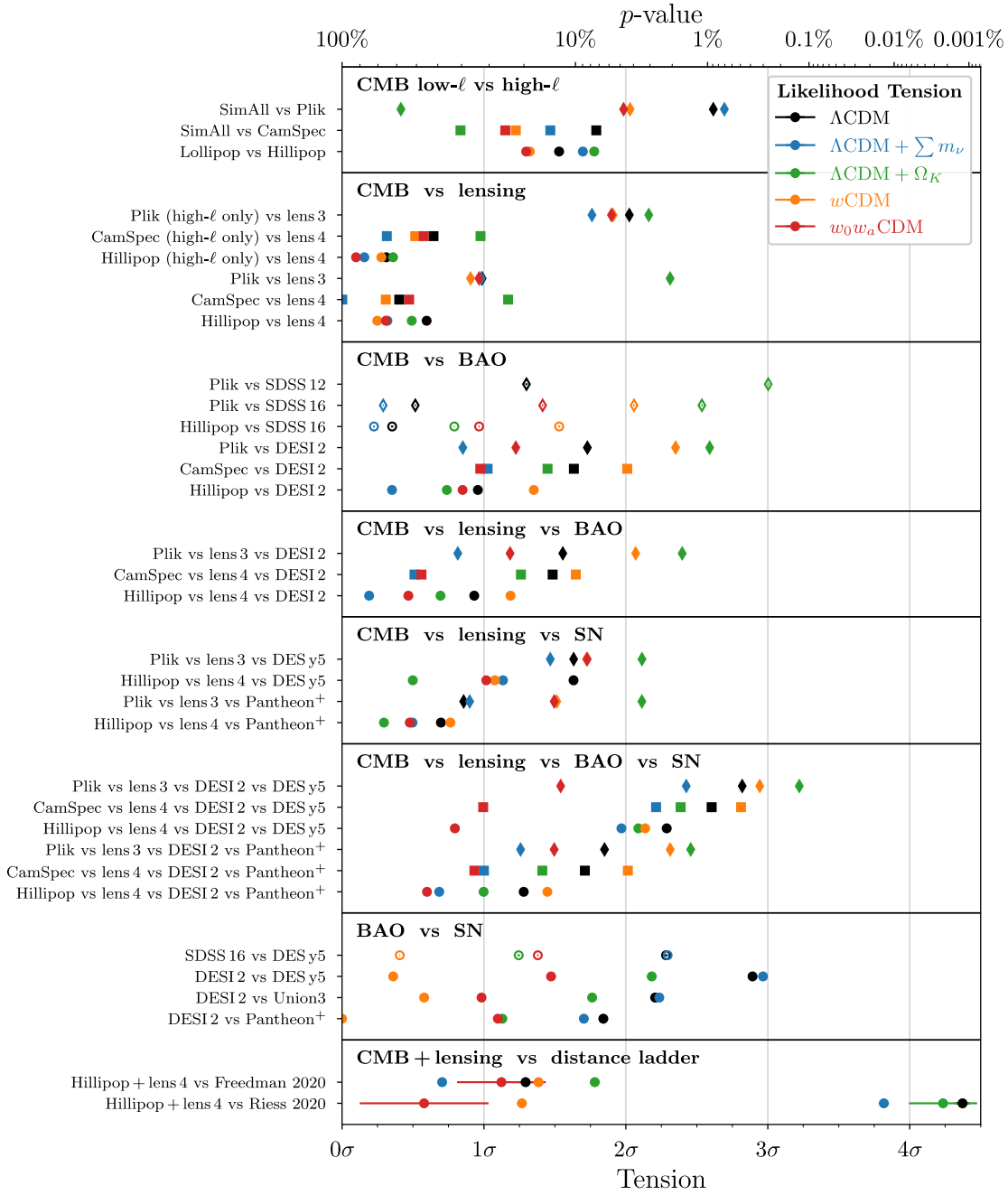
Range of dataset combinations

- **CMB:** Planck PR3 and PR4
  - low-ℓ: SimAll, Lollipop
  - high-ℓ: Plik, CamSpec, Hillipop
- **CMB lensing:**
  - Planck PR3 and PR4
- **BAO:**
  - SDSS DR12 and DR16
  - DESI DR2
- **SN:**
  - Pantheon+
  - DES year-5

Range of models

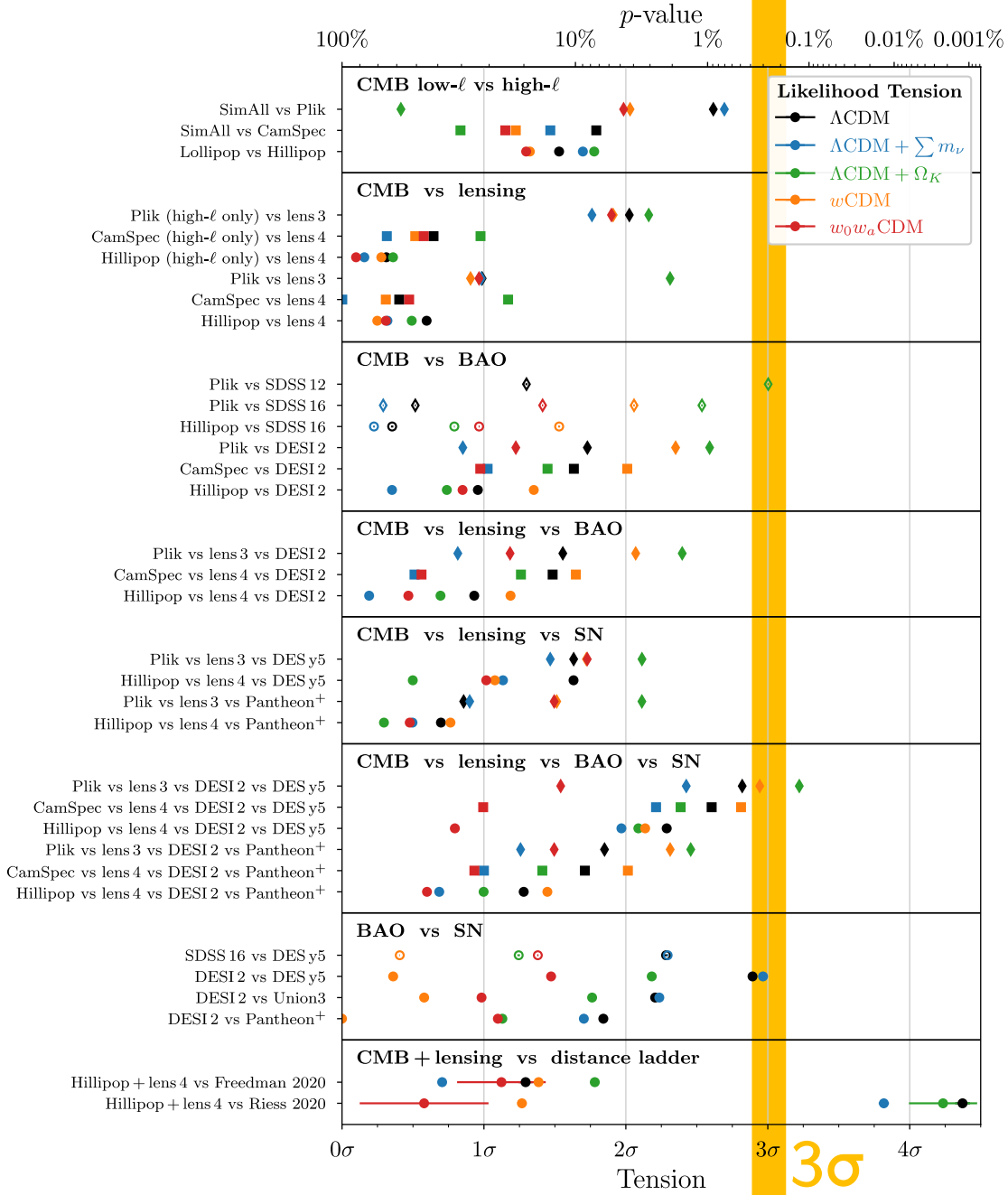
- **ΛCDM:** dominated by cold dark matter and cosmological constant Λ
- **ΛCDM+Σm$_\nu$:** 3 massive neutrinos (instead of just one)
- **ΛCDM+Ω$_K$:** non-zero curvature
- **wCDM:** constant equation of state w of dark energy
- **w$_0$w$_a$CDM:** evolving equation of state w(a) of dark energy

Lukas T. Hergt



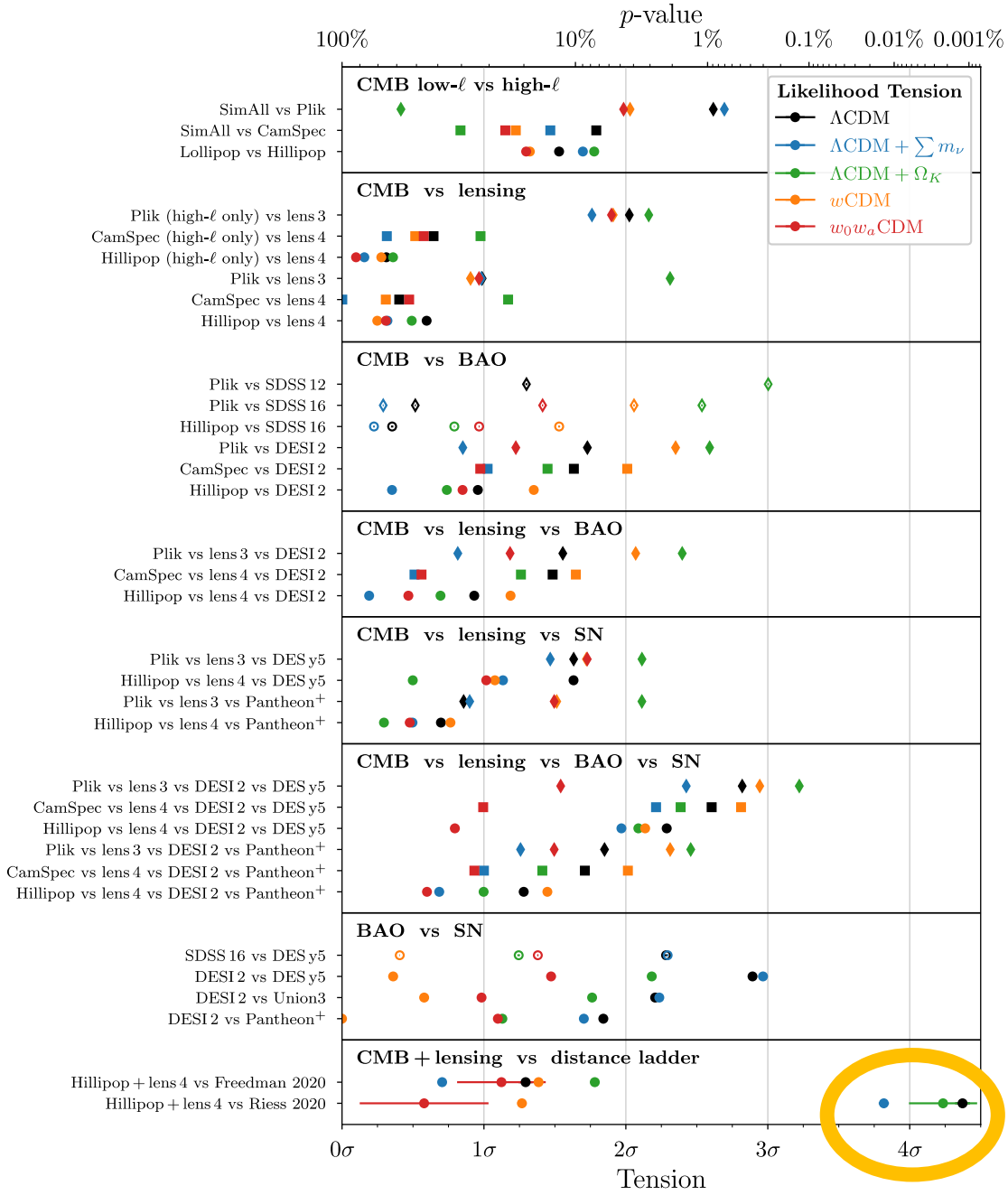
Slightly overwhelming overview

Remark 1:
Allmost all points below 3σ line.



Slightly overwhelming overview

Remark 2:
Hubble Tension clearly strongest.



Slightly overwhelming overview

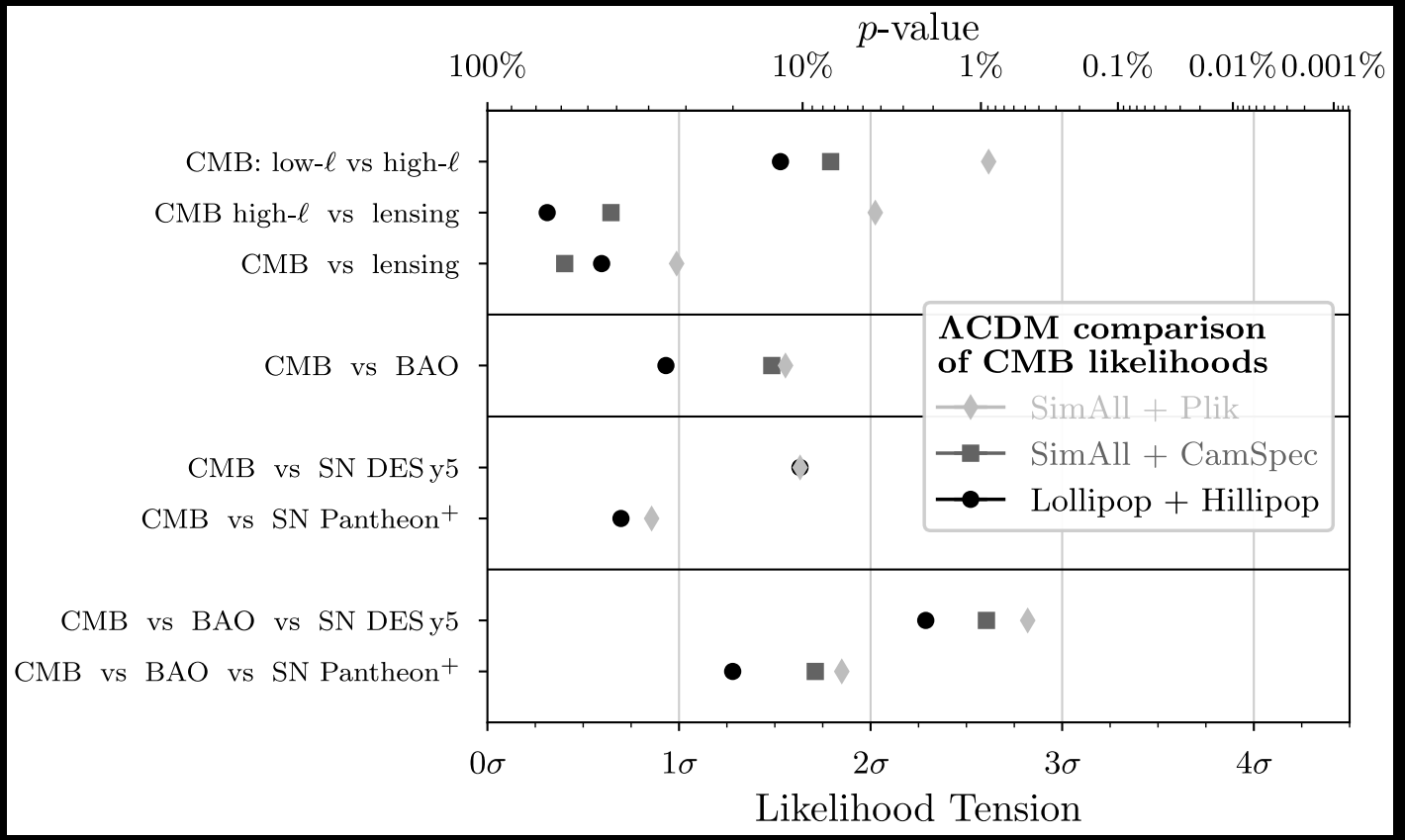
Remark 3:
CMB internal tensions have also reached beyond 2σ in the past.

Slightly overwhelming overview

Remark 4:
Highly variable tension statistics dependent on dataset choices for CMB vs BAO vs SN.
(Independent of theory model!)

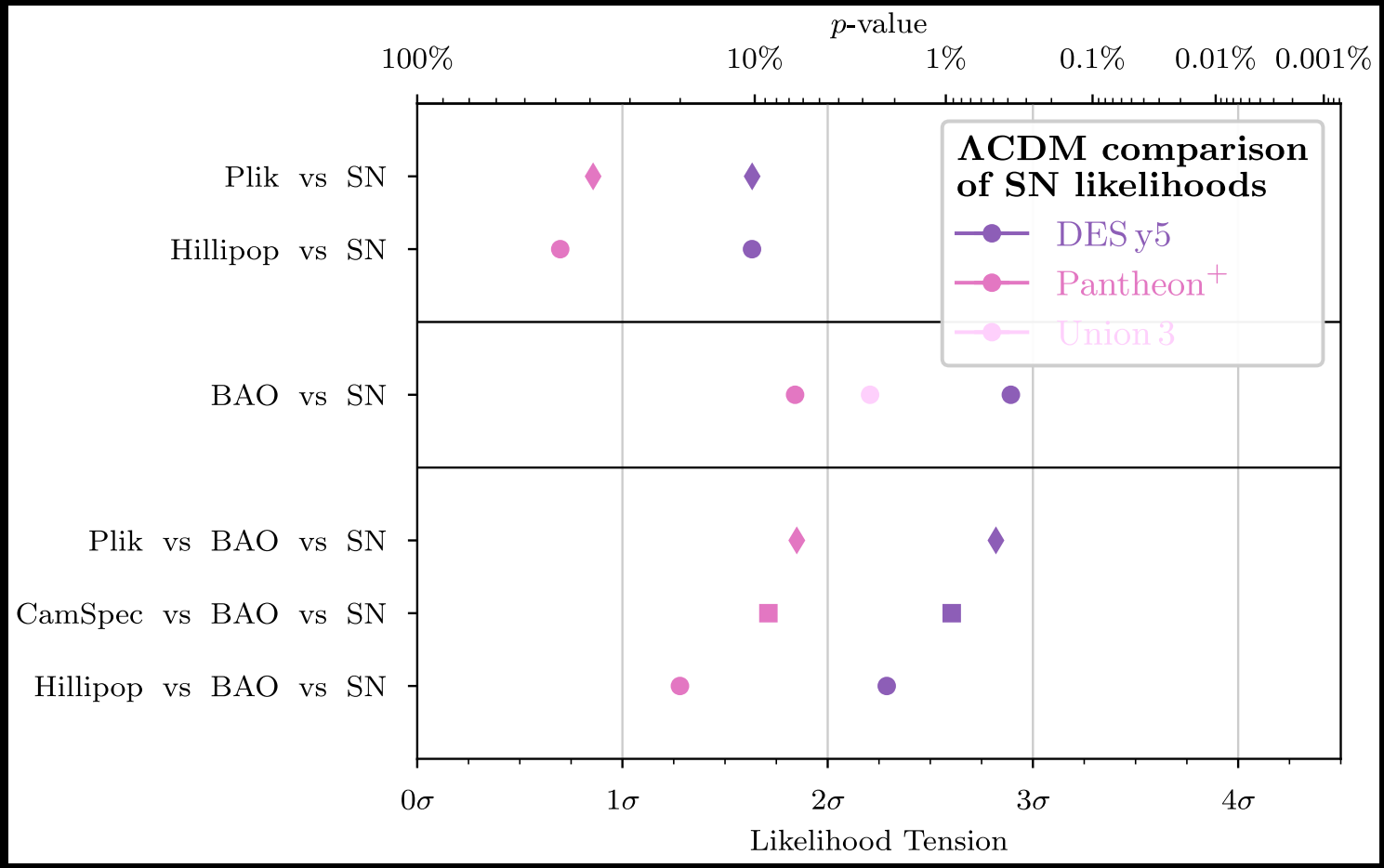
Comparison of Planck Likelihoods

- Plik:
  - Planck PR3 (2018)
- CamSpec:
  - Planck PR4 (2020)
  - pre-cleaning of galactic dust
  - fitting of foreground residuals
- Hillipop:
  - Planck PR4 (2020)
  - fitting of foreground spectra



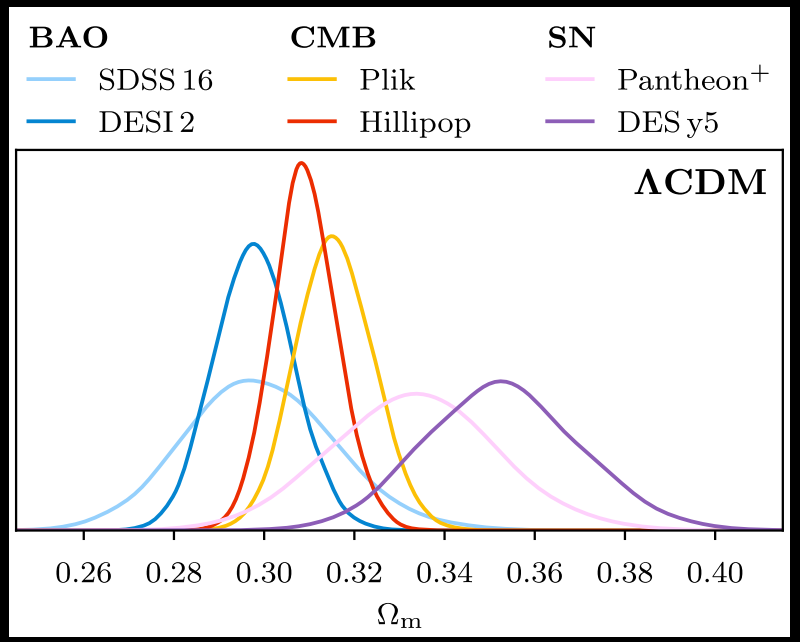
Takeaway:
Big shifts in tension statistics from choice of CMB likelihood pipeline (for the same data!)

Comparison of Supernovae Likelihoods

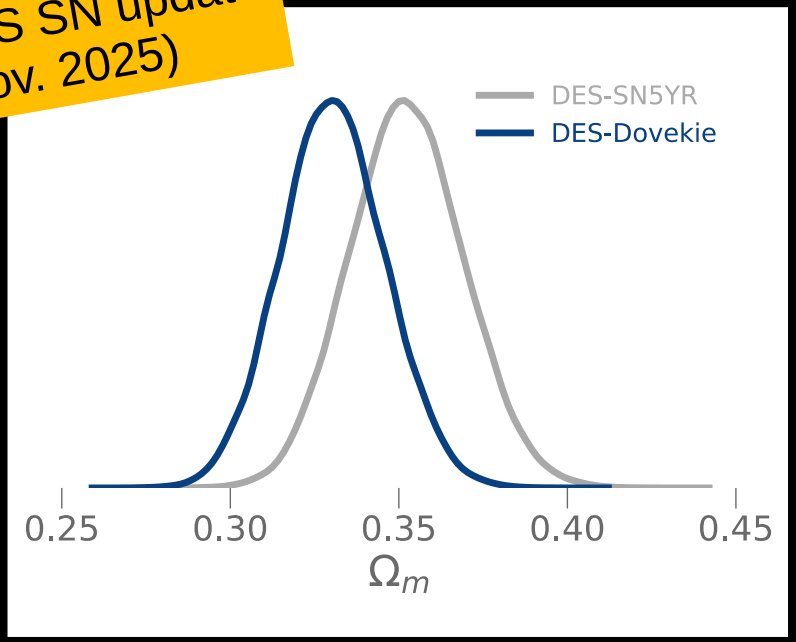


Takeaway:
Big shifts in tension statistics from choice of SN likelihood.

Tension driving parameter: Matter density Ω_m



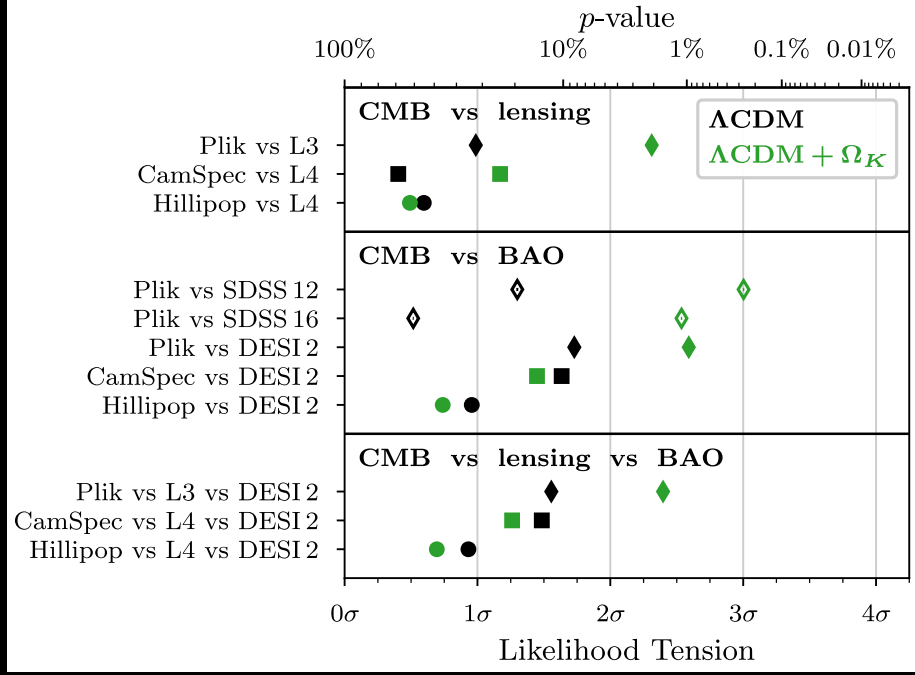
DES SN update (Nov. 2025)

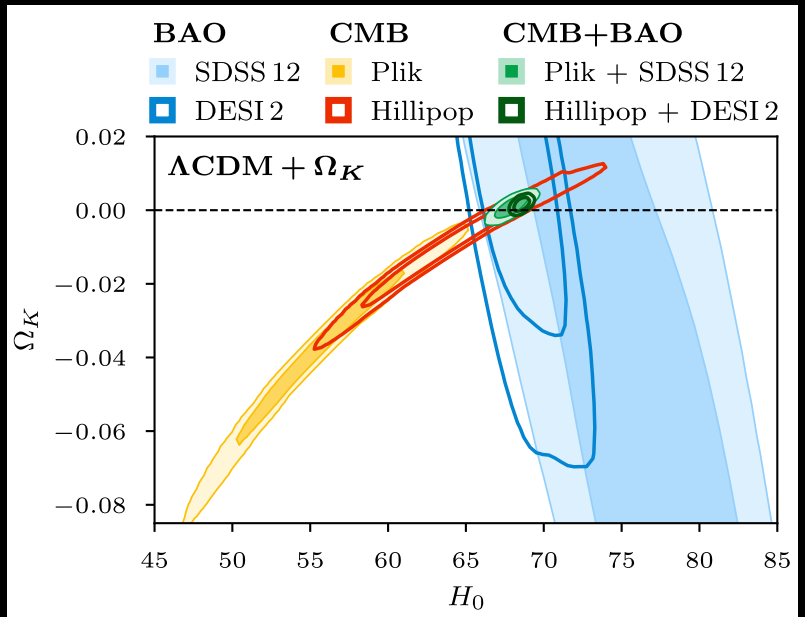


Credit: Popovic et al. (2025)

The "Curvature Tension"

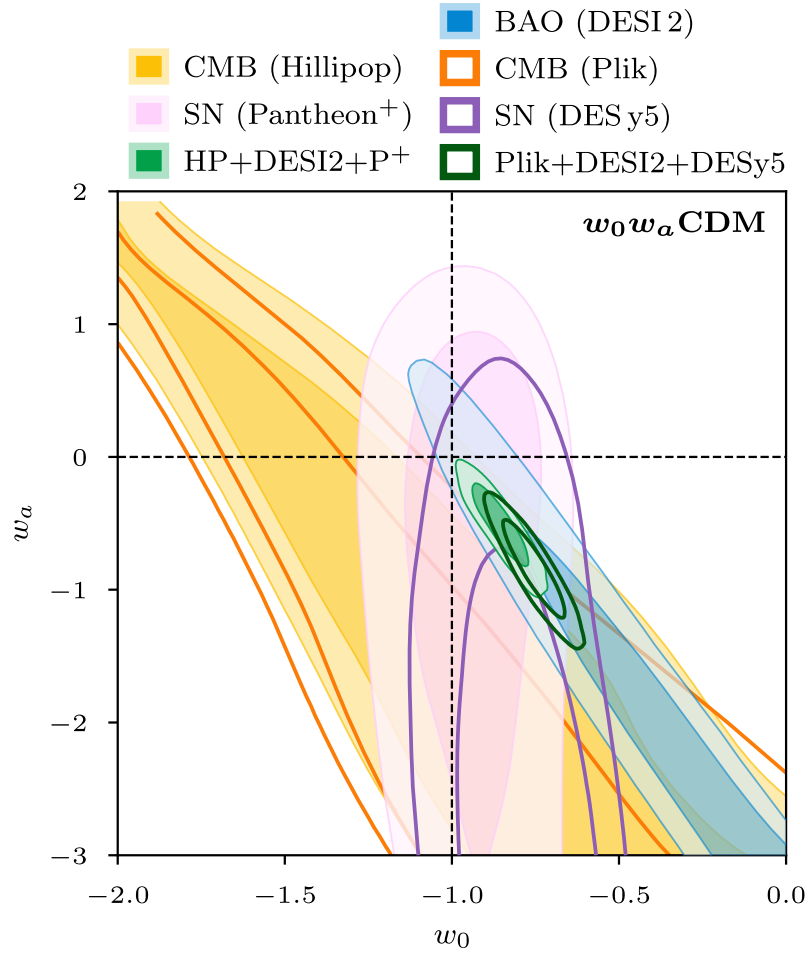
- ΛCDM extension with curvature density parameter Ω_K
- Tension around 2018:
  - 2.3σ between Plik and lensing.
  - 3σ between Plik and SDSS 12.
- BAO update:
  - Reduces to 2.5σ with SDSS 16 or DESI 2.
- CMB update:
  - Goes away with CamSpec or Hillipop.
- Takeaway:
  Tension after *opening* parameter space!

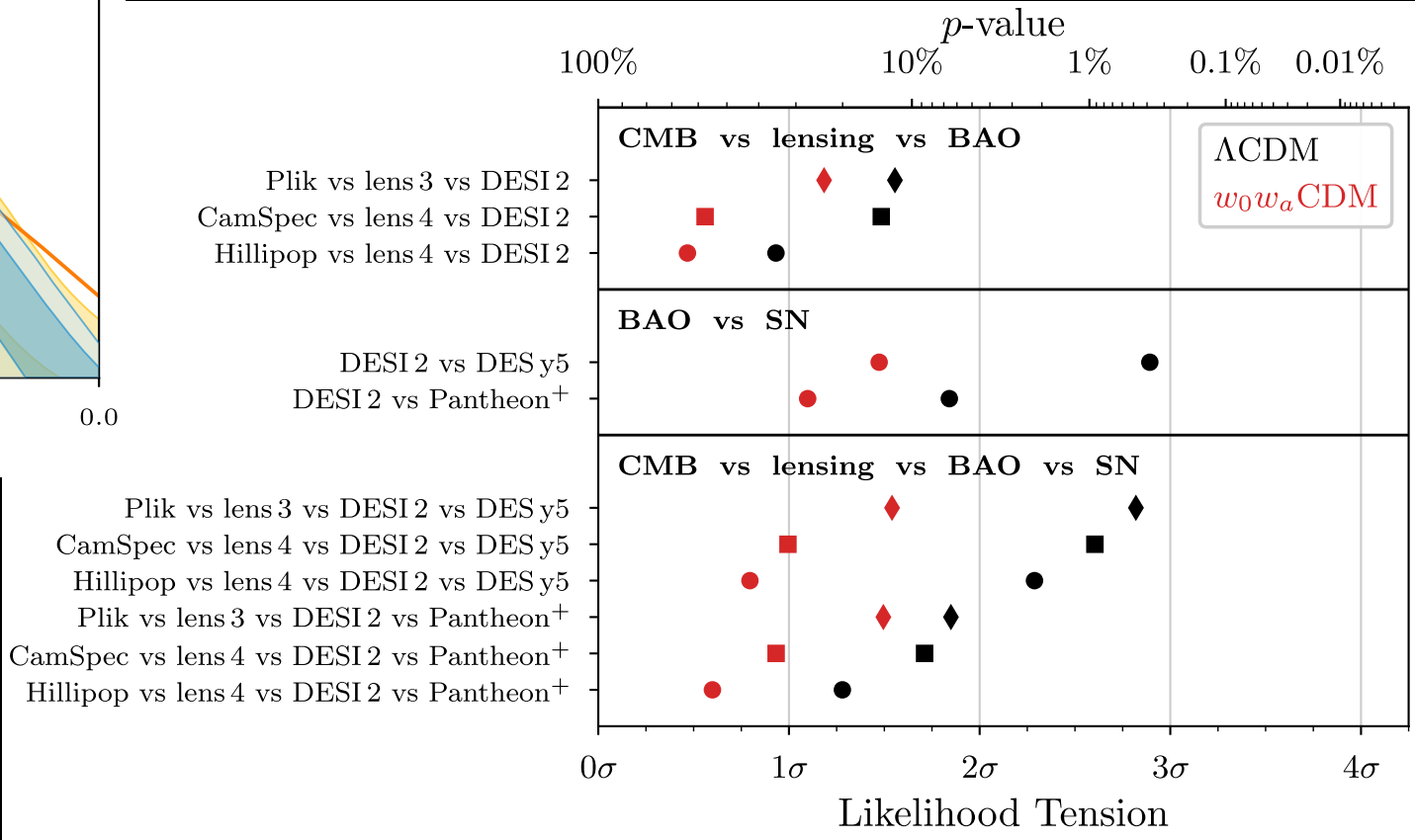




Evolving Dark Energy $w(a)$

Takeaway:
Cosmologic Constant Tension highly dependent on choice of dataset combination.





Tension

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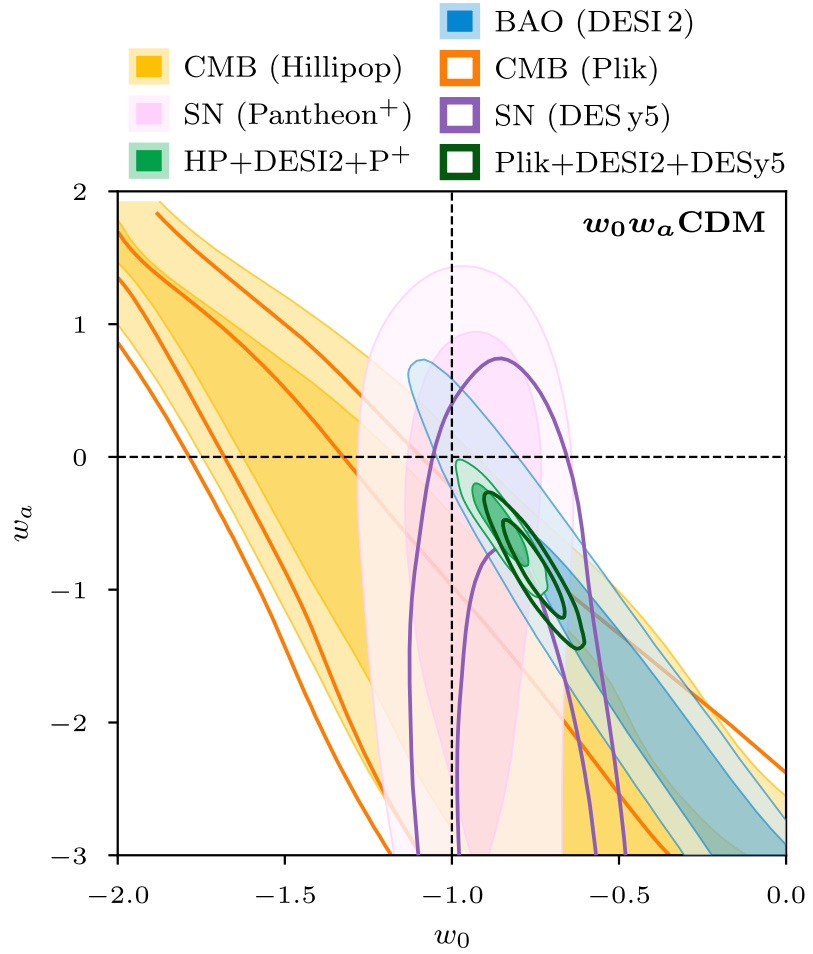
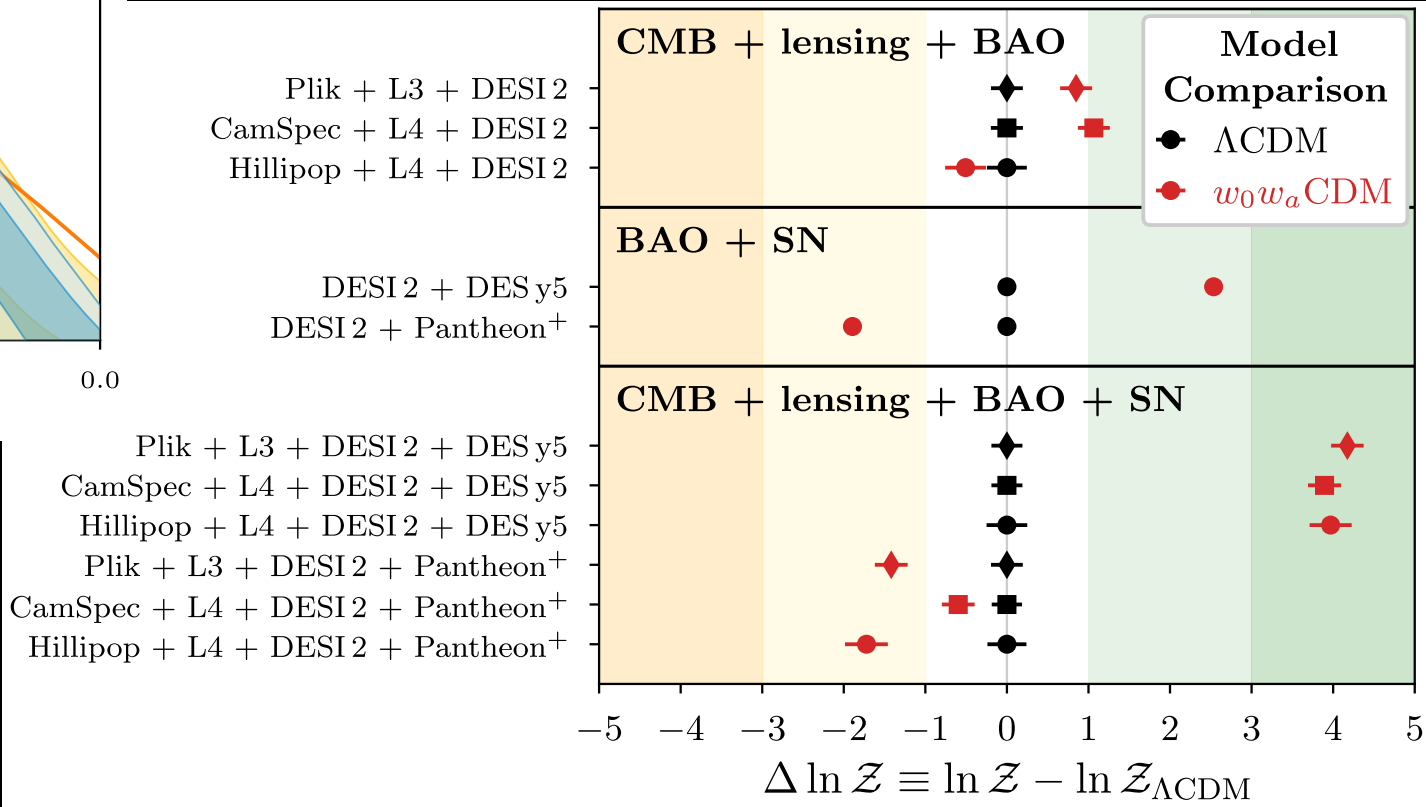
Evolving Dark Energy $w(a)$

Takeaway:
Model preference completely flips with SN likelihood.





Model Comparison

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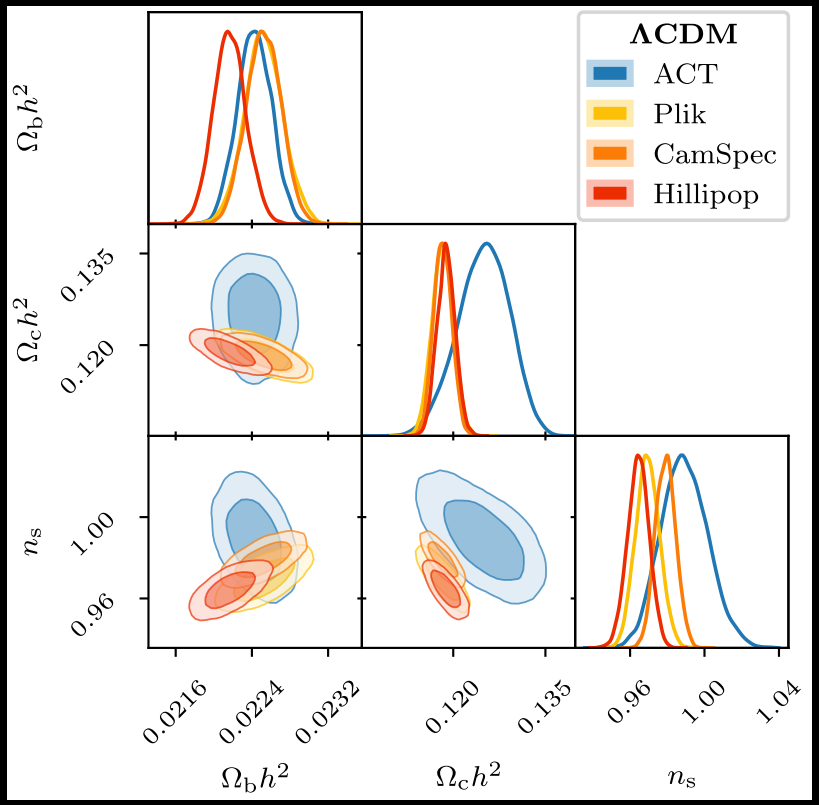
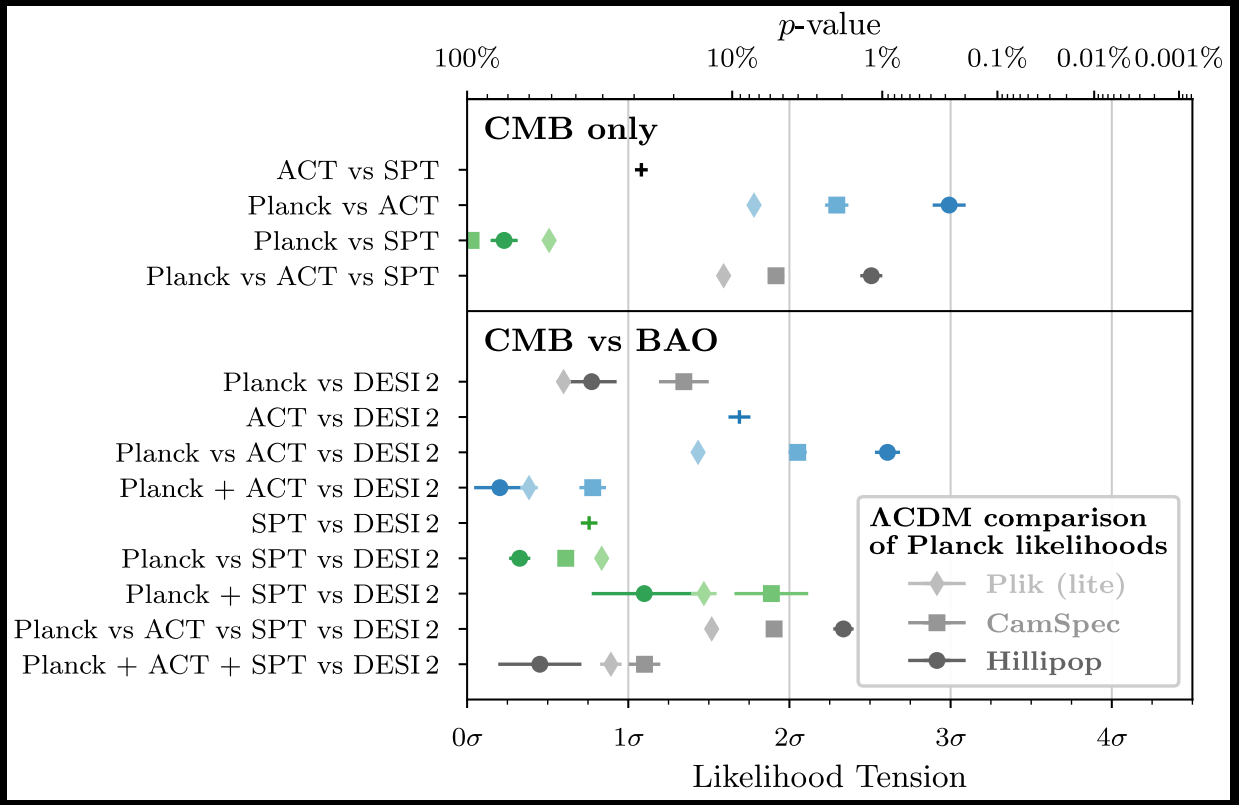
Planck, ACT, SPT

- ACT or SPT on their own: no tension with BAO
- Signs of tension only in combination with low-ℓ from Planck.





Conclusion

- Hubble Tension the only one clearly over 3σ threshold.
  - Still persisting after first JWST updates.
- Tensions vary with choice of CMB likelihood:
  - 0.5σ to 1.5σ.
  - Trend: tensions reduce from Plik → CamSpec → Hillipop
- Tensions vary with choice of SN likelihood:
  - –1σ going from DES-y5 → Pantheon+
  - Model comparison switches from "strongly preferred" to "disfavoured"
- Many tensions have reduced over time with analysis updates:
  - Clustering tension between Weak Lensing and CMB.
  - CMB low-ℓ vs high-ℓ or CMB vs lensing with updates PR3 → PR4.
  - SN update DES-y5 → DES-Dovekie.

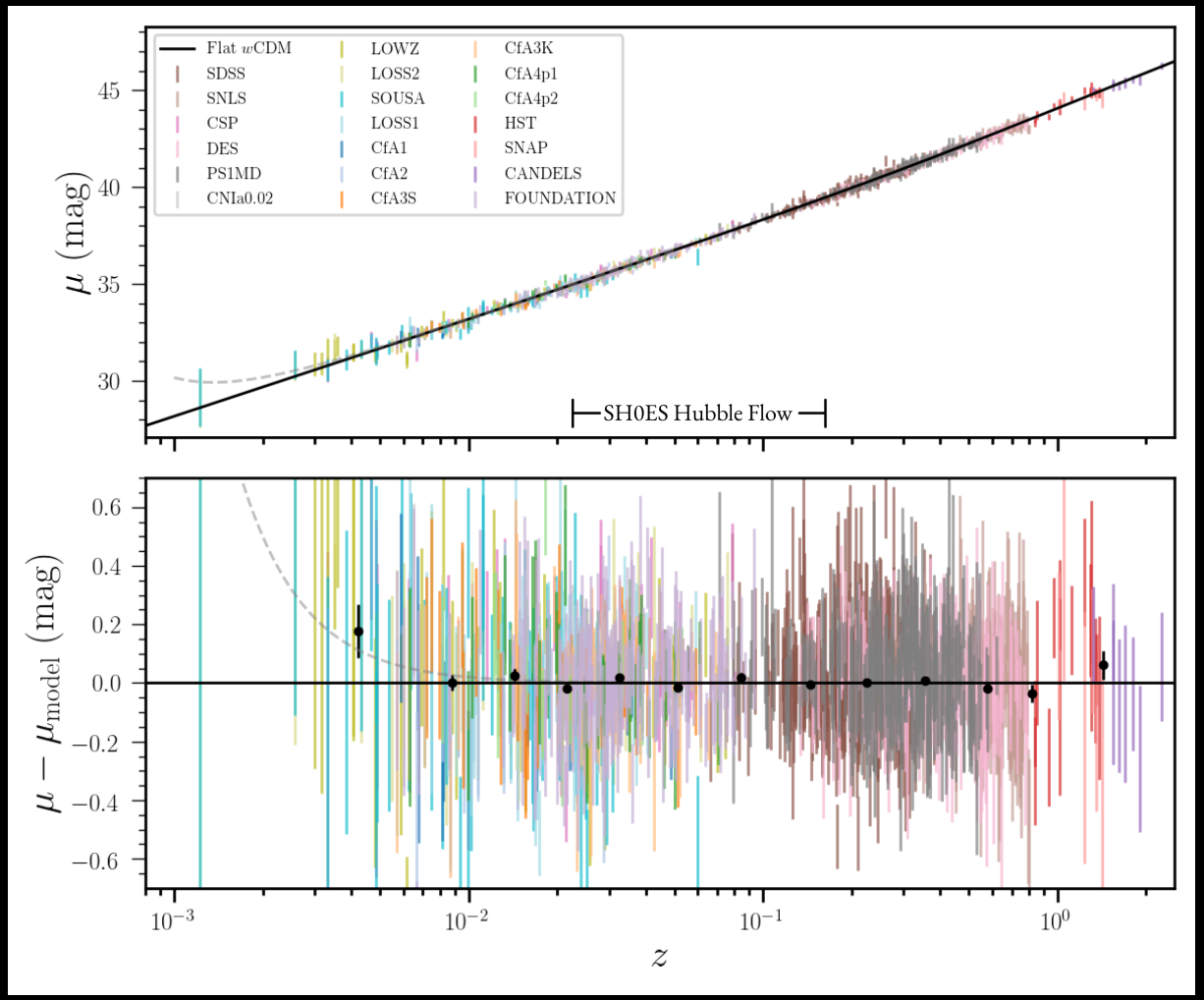
- Curvature tension?
  - Model preference and tension go away with Planck updates
- Cosmological Constant Tension and preference for w_0w_aCDM?
  - Only specifically for Plik + DESI + DES-y5
  - Gone with Hillipop + DESI + Pantheon+

→ Claims for a needed update from ΛCDM to w_0w_aCDM are premature.


Backup slides

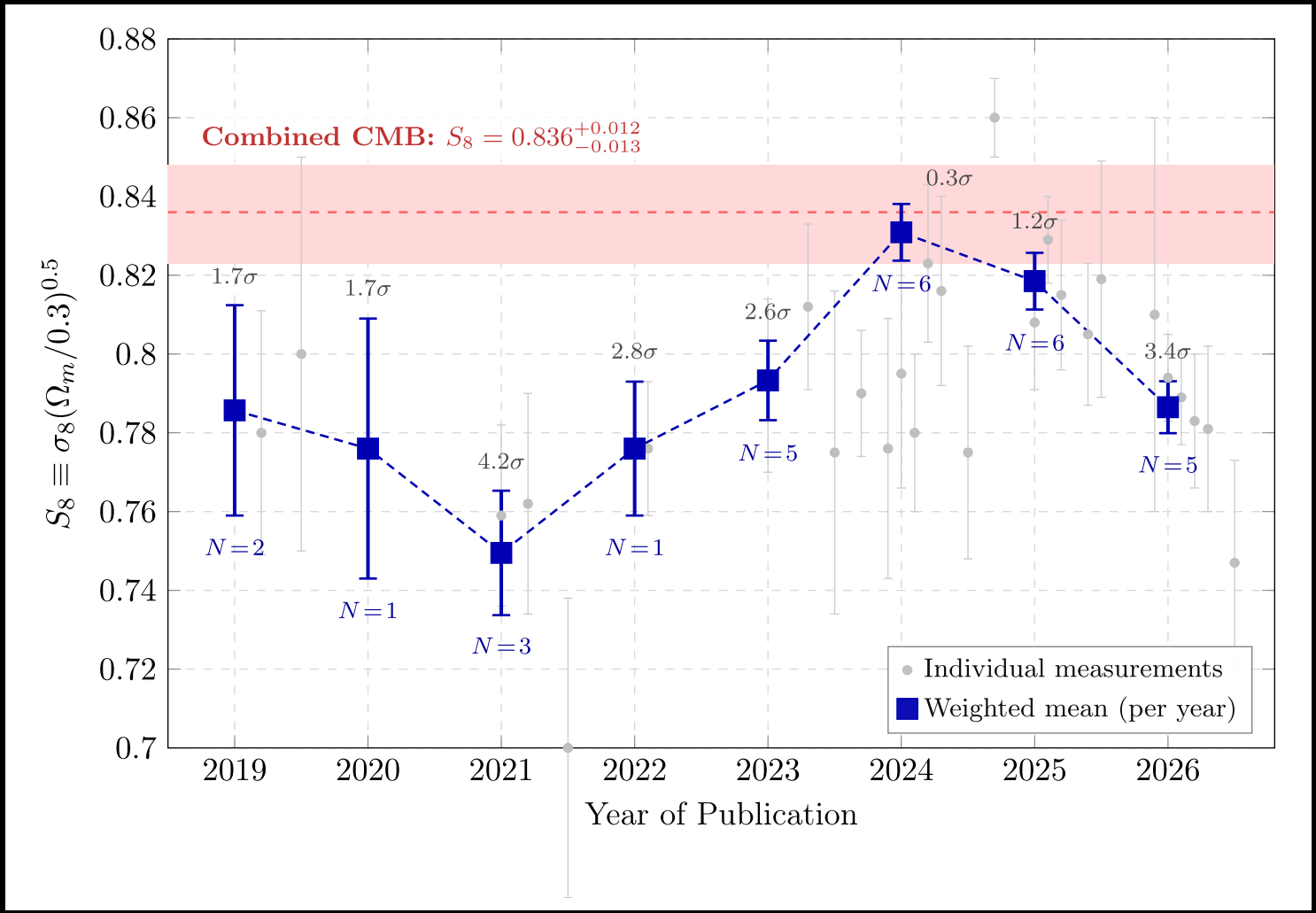
Supernovae Cosmology

"Hubble Diagram"
of Supernovae (Pantheon+)



Credit: Pantheon+ (2022)

The "Clustering Tension" (a.k.a. σ_8 or S_8 tension):
Weak Lensing (WL) vs Cosmic Microwave Background (CMB)

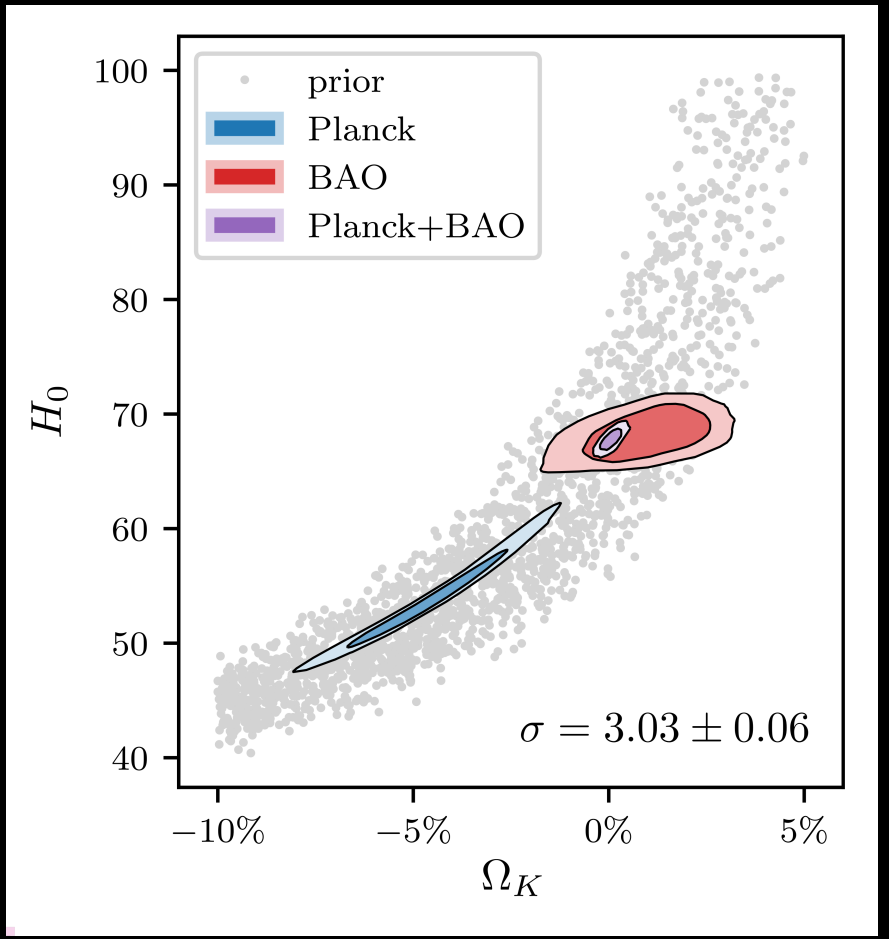


Credit: Pantos & Perivolaropoulos, Phys. Dark Univ. 52 (2026)

The "Curvature Tension"

ΛCDM extension with
curvature density parameter Ω_K

- $\Omega_K = 0$:
  - flat universe → Euclidean Geometry
- introduces tension between CMB and BAO
  - CMB: Planck (2018)
  - BAO: SDSS DR12 (2016)



Credit: Will Handley, Phys. Rev. D 103 (2021)

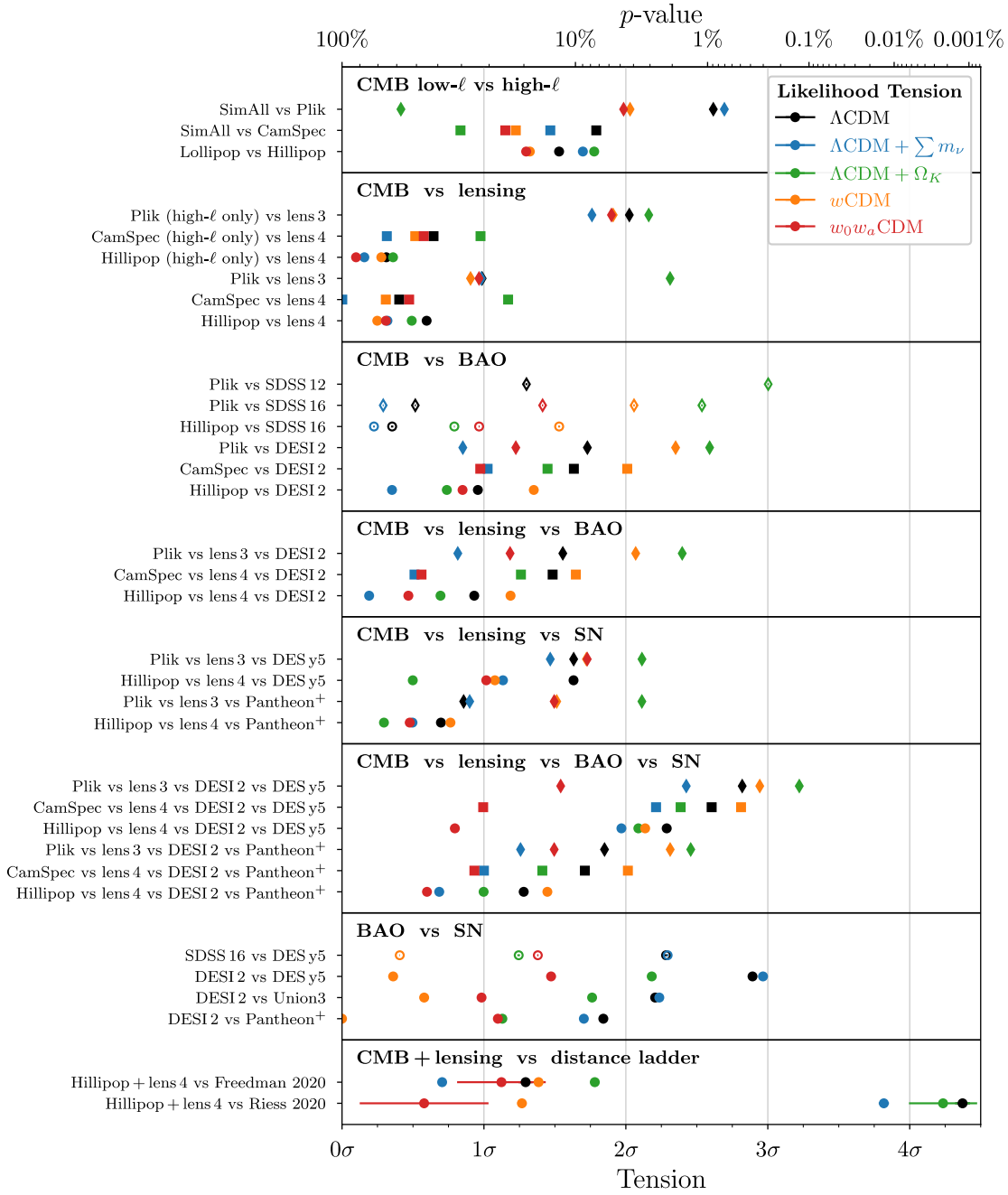
CMB likelihoods

- **Planck**
  - Plik
    - Planck PR3, 2018, “Legacy”
  - CamSpec
    - Planck PR4, 2022, NPIPE
  - Hillipop
    - Planck PR4, 2023, NPIPE
- Since last year (2025):
  - ACT DR6
  - SPT-3G DR1

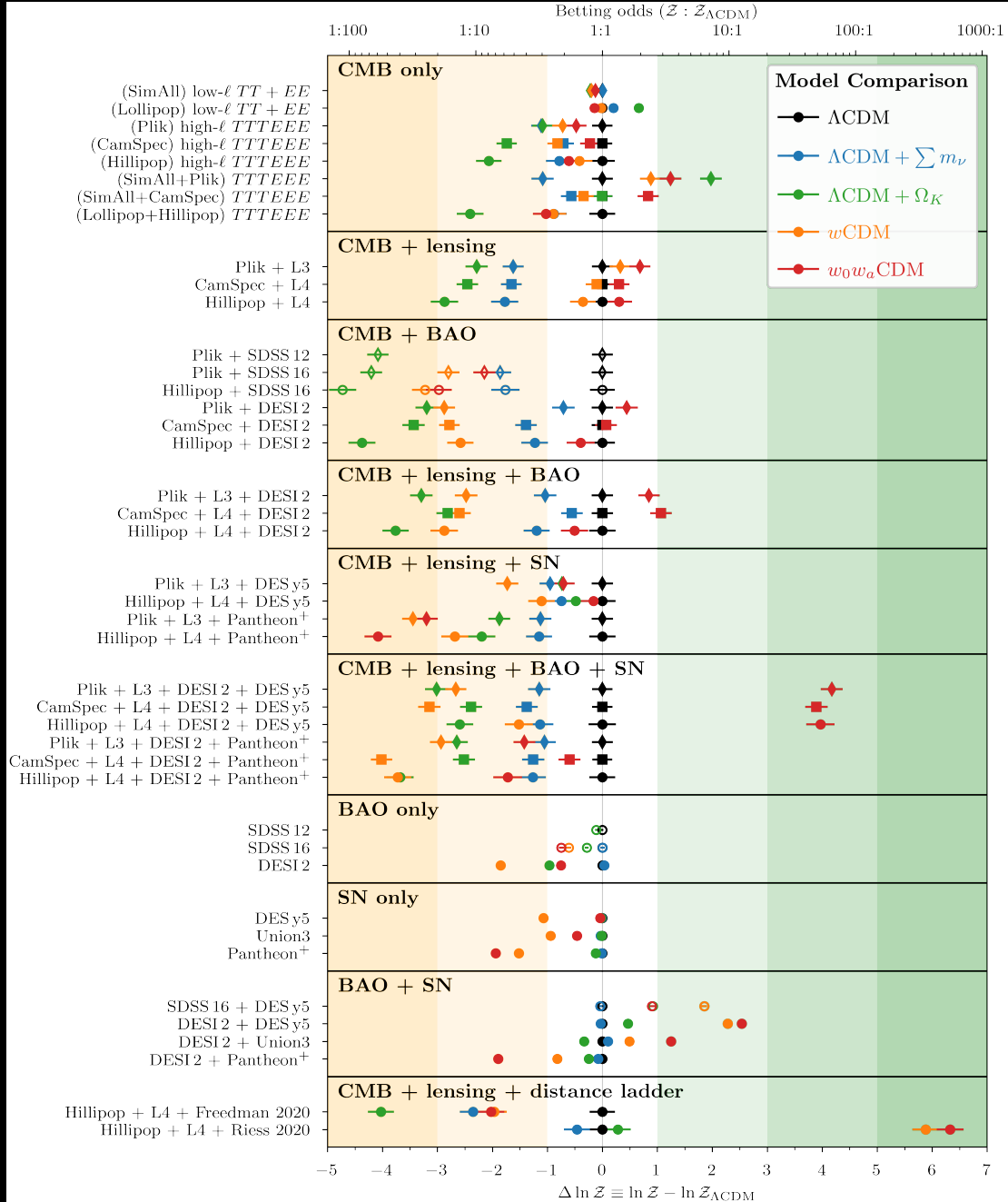
Slightly overwhelming overview

Range of dataset combinations

- **CMB:** Planck PR3 and PR4
  - low-ℓ: SimAll, Lollipop
  - high-ℓ: Plik, CamSpec, Hillipop
- **CMB lensing:**
  - Planck PR3 and PR4
- **BAO:**
  - SDSS DR12 and DR16
  - DESI DR2
- **SN:**
  - Pantheon+
  - DES year-5



Model Comparison



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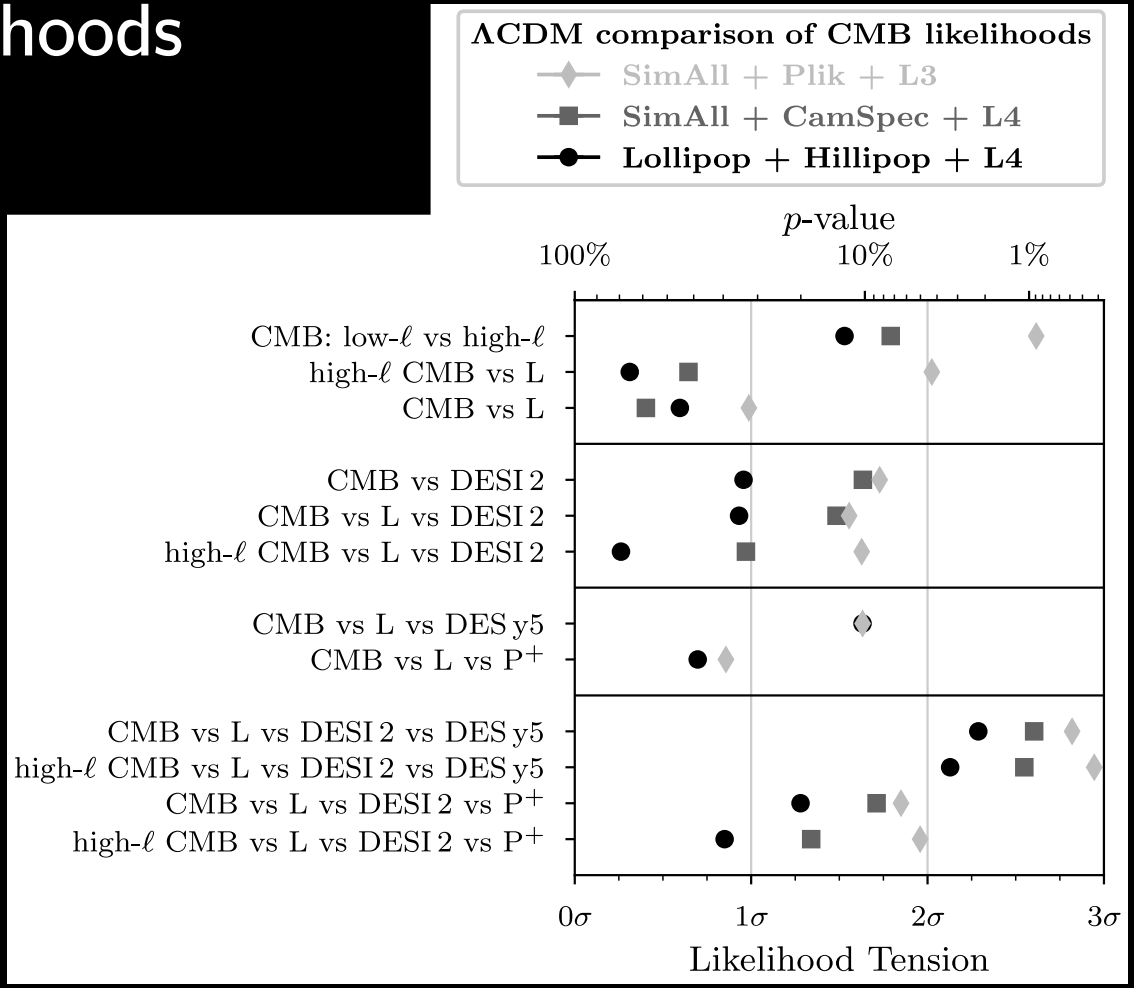
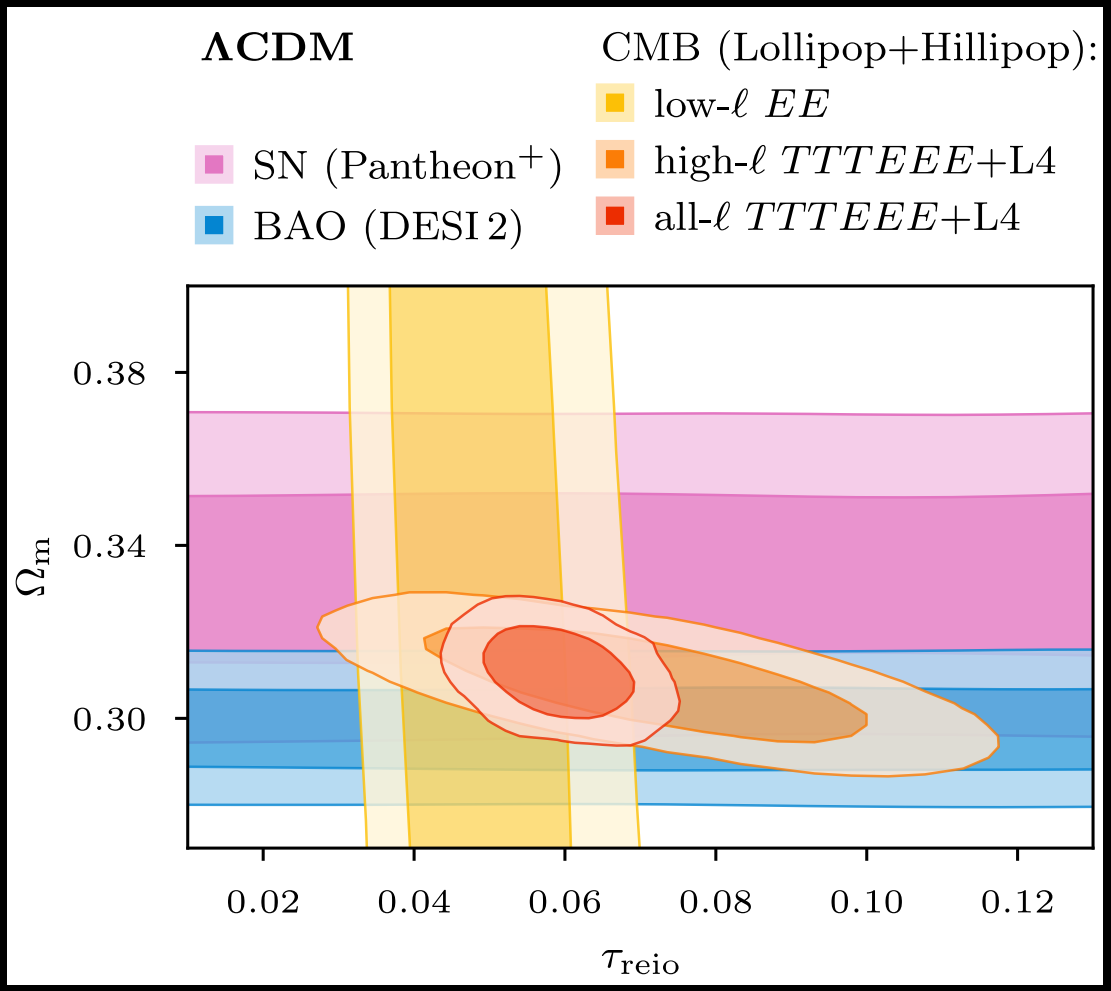
Comparison of Planck Likelihoods

- Plik:
  - Planck PR3 (2018)
- CamSpec:
  - Planck PR4 (2020)
  - pre-cleaning of galactic dust
  - fitting of foreground residuals
- Hillipop:
  - Planck PR4 (2020)
  - fitting of foreground spectra



Takeaway:
Big shifts in tension statistics from choice of CMB likelihood pipeline (for the same data!)

τ – tension?


ΛCDM
CMB (Lollipop+Hillipop):
low-ℓ EE
high-ℓ TTTEEE+L4
all-ℓ TTTEEE+L4
SN (Pantheon+)
BAO (DESI 2)
0.38
0.34
0.30
Ω_m
0.02
0.04
0.06
0.08
0.10
0.12
τ_{reio}