Perspectives

Colin Hill

Columbia University

Flatiron Institute - Center for Computational Astrophysics

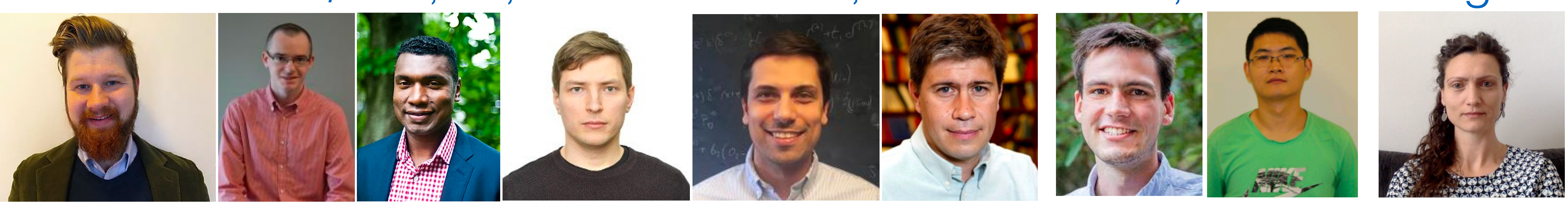
Cosmology Intertwined Mini-Workshop

19 November 2021

2105.03003 w/ L. Thiele, Y. Guan, A. Kosowsky, D. Spergel

2003.07355 w/ E. McDonough, M. Toomey, S. Alexander

2006.11235 w/ EM,MT,SA + M. Ivanov, M. Simonovic, M. Zaldarriaga



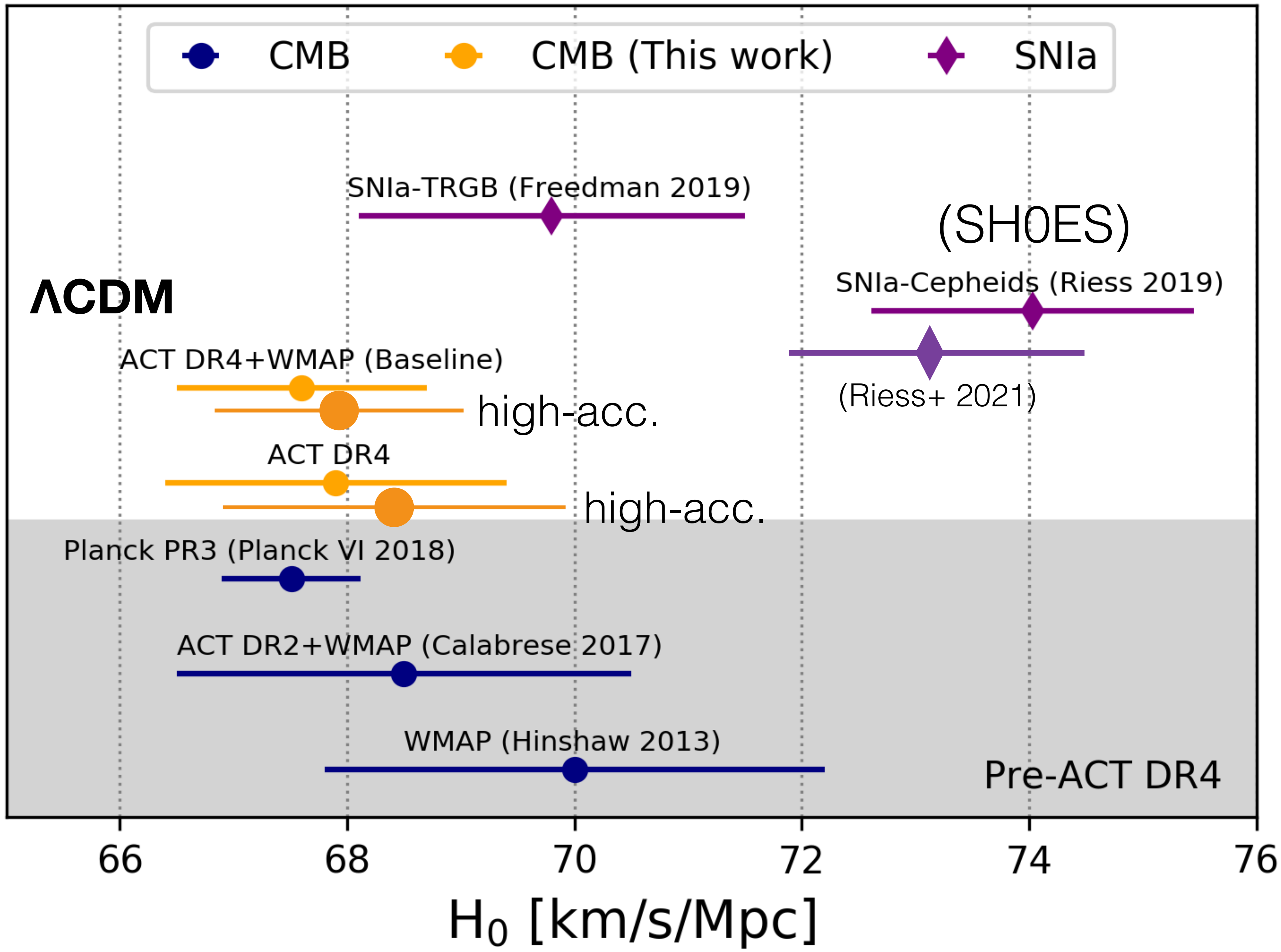
2007.07288 + 2007.07289 + 2109.04451 w/ ACT Collaboration

Data

The Hubble Situation

Colin Hill
Columbia/CCA

My personal view: observational situation remains unclear



~3.1σ difference between ACT+WMAP (high-acc., ΛCDM) and Cepheid-calibrated SNIa (SH0ES 2021)

Agreement within ~1σ between ACT+WMAP and TRGB-calibrated SNIa

Aiola et al. (2020); JCH et al. (2021)

N.B. not an exhaustive compilation!

The Hubble Situation

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A few well-motivated combinations of independent data sets (h/t Adam R.)

ΛCDM

Planck18 + Philcox20 (BOSS-EFT + BBN)

67.6 +/- 0.5

ACT+WMAP + Philcox20 (BOSS-EFT + BBN)

68.3 +/- 0.8

SPT-3G + Philcox20 (BOSS-EFT + BBN)

68.7 +/- 0.9

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ΛCDM	**Direct**
Planck18 + Philcox20 (BOSS-EFT + BBN) 67.6 +/- 0.5	SH0ES21 + SBF_TRGB21 + Boruah21 (maser) + TDCOSMO20 72.3 +/- 1.1
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Differences range from 0.9σ — 4.3σ

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Differences range from 0.9σ — 4.3σ

But combined σ only ranges from 1.2 to 1.6 km/s/Mpc

(Rare) fluctuations around the truth? Or systematics lurking?

The S_8 Situation

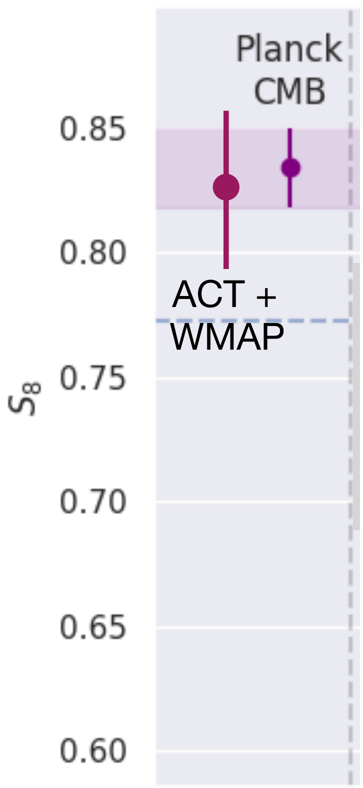
My personal view: observational situation remains unclear

Planck: 0.834 ± 0.016

ACT+WMAP: 0.825 ± 0.031

$$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$$

Indirect



Primary CMB

z~1100

Figure credit: M. Madhavacheril

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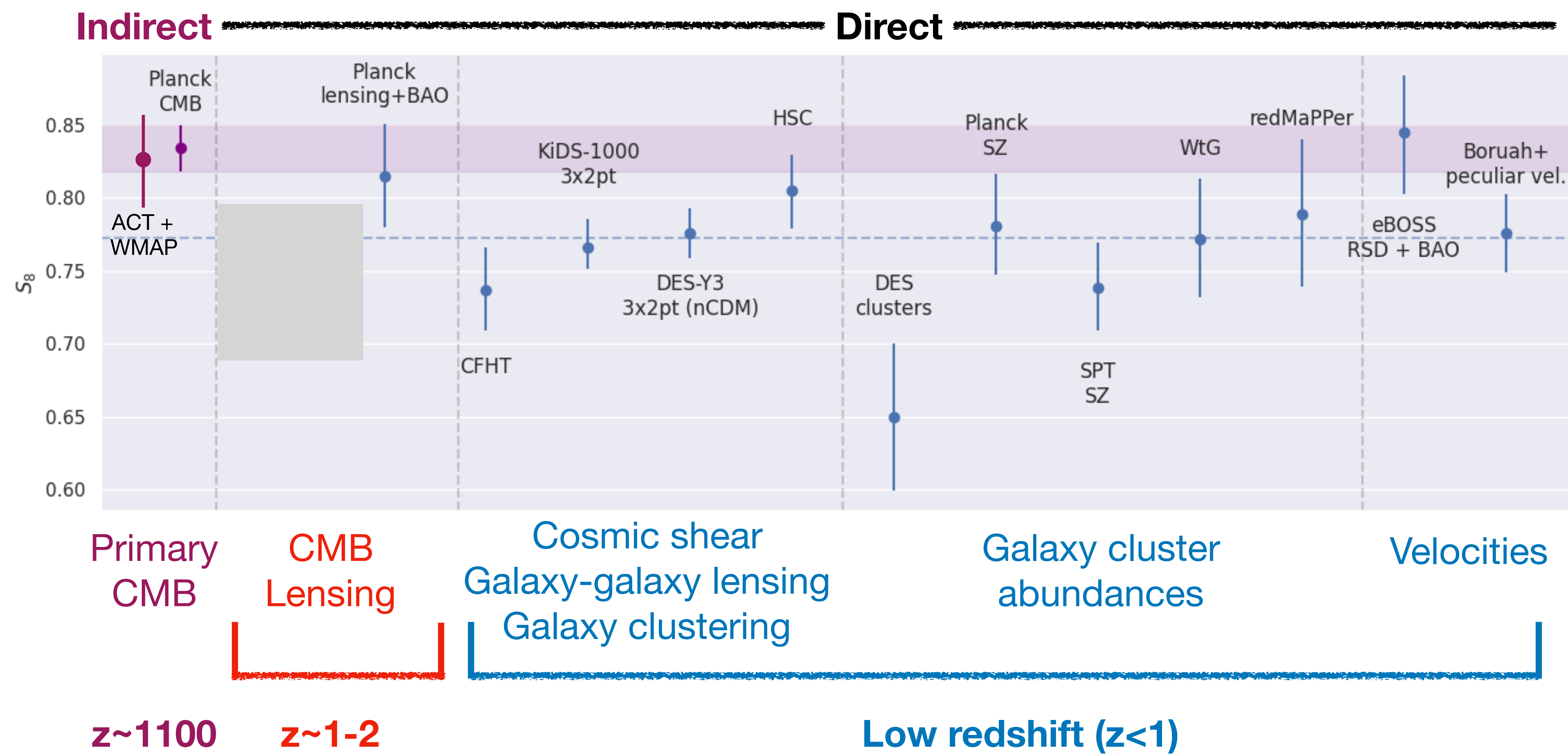

Figure credit: M. Madhavacheril

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The S_8 Situation

Possible clarification very soon with ACT DR6 CMB lensing (~50-60σ)

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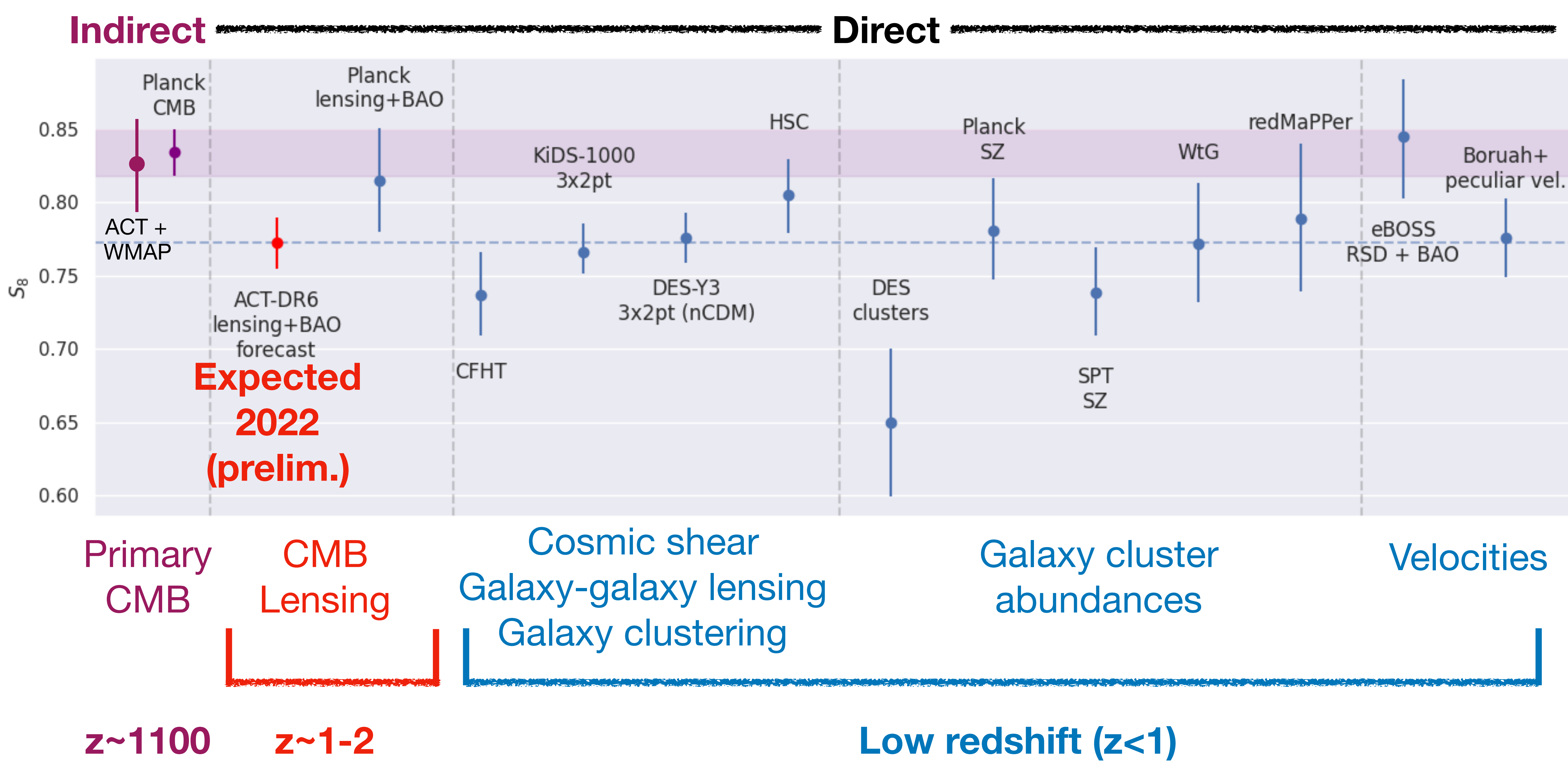
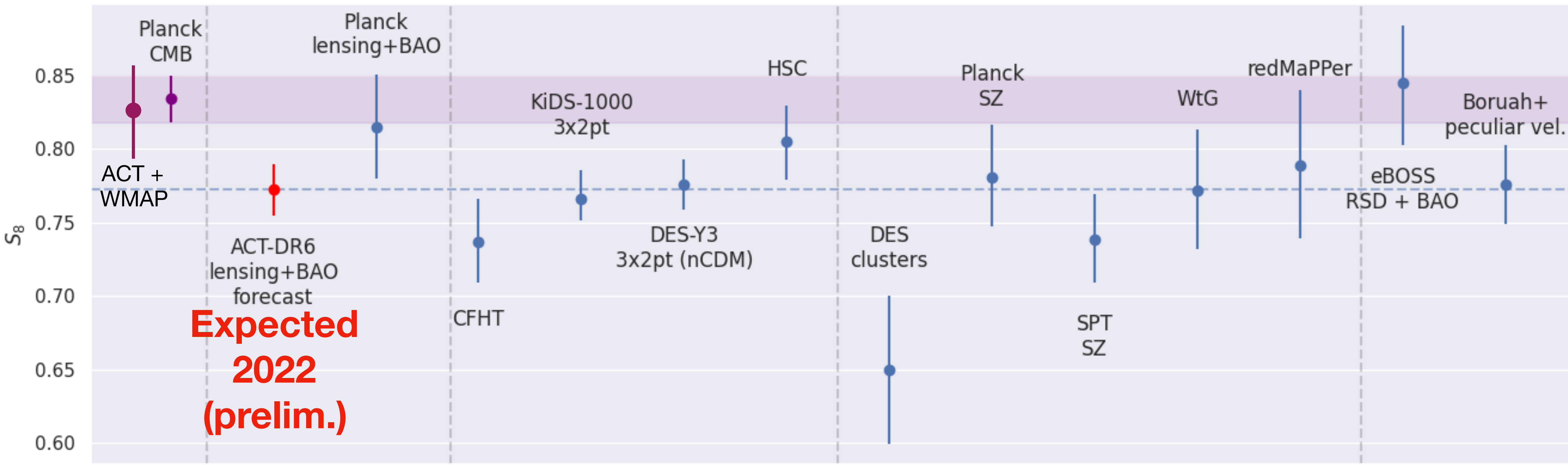


Figure credit: M. Madhavacheril

The S_8 Situation

Significance of the discrepancy between CMB and any individual low-z measurement is at most 2.7σ (Planck vs. KiDS-1000)

Difficult to naively combine the low-z measurements (overlap on the sky, shared methods/ data/systematics, etc.) — dedicated study required



Primary CMB | CMB Lensing | Cosmic shear, Galaxy-galaxy lensing, Galaxy clustering | Galaxy cluster abundances | Velocities

z~1100 | **z~1-2** | **Low redshift (z<1)**

Figure credit: M. Madhavacheril

Discordance

My personal view: observational situation remains unclear

Regardless, the situation has motivated us to think about many types of new physics in the cosmos that we otherwise (likely) would not have

↓

How can we increase H_0 (and, ideally, decrease S_8) inferred from the CMB and large-scale structure?

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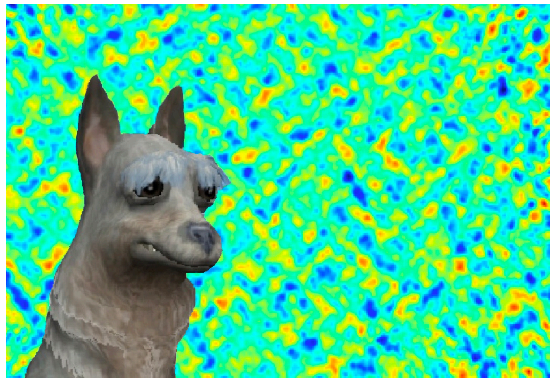
→ **Generic consequence: new signals in the cosmic microwave background**



Theory

H_0 Olympics

Very useful systematically organized global study
(N.B. no S_8 data considered, apart from CMB lensing)

	Model	ΔN_{param}	M_B	Gaussian Tension	Q_{DMAP} Tension		$\Delta\chi^2$	ΔAIC		Finalist
	ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗
early universe	ΔN_{ur}	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗
	SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓ (3)
	mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-8.83	-4.83	✗	✗
	DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	-8.92	-4.92	✗	✗
	SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	-4.98	1.02	✗	✗
	Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓ (2)
	primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	✗	-11.42	-9.42	✓	✓ (3)
	varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓ (1)
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	EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓ (2)
	NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓ (2)
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	DM $\rightarrow$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗
	DM $\rightarrow$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗

Schoenberg+21

H_0 Olympics

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Schoenberg+21

H_0 Olympics

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2) Should we demand more from our theory? (e.g., naturalness)

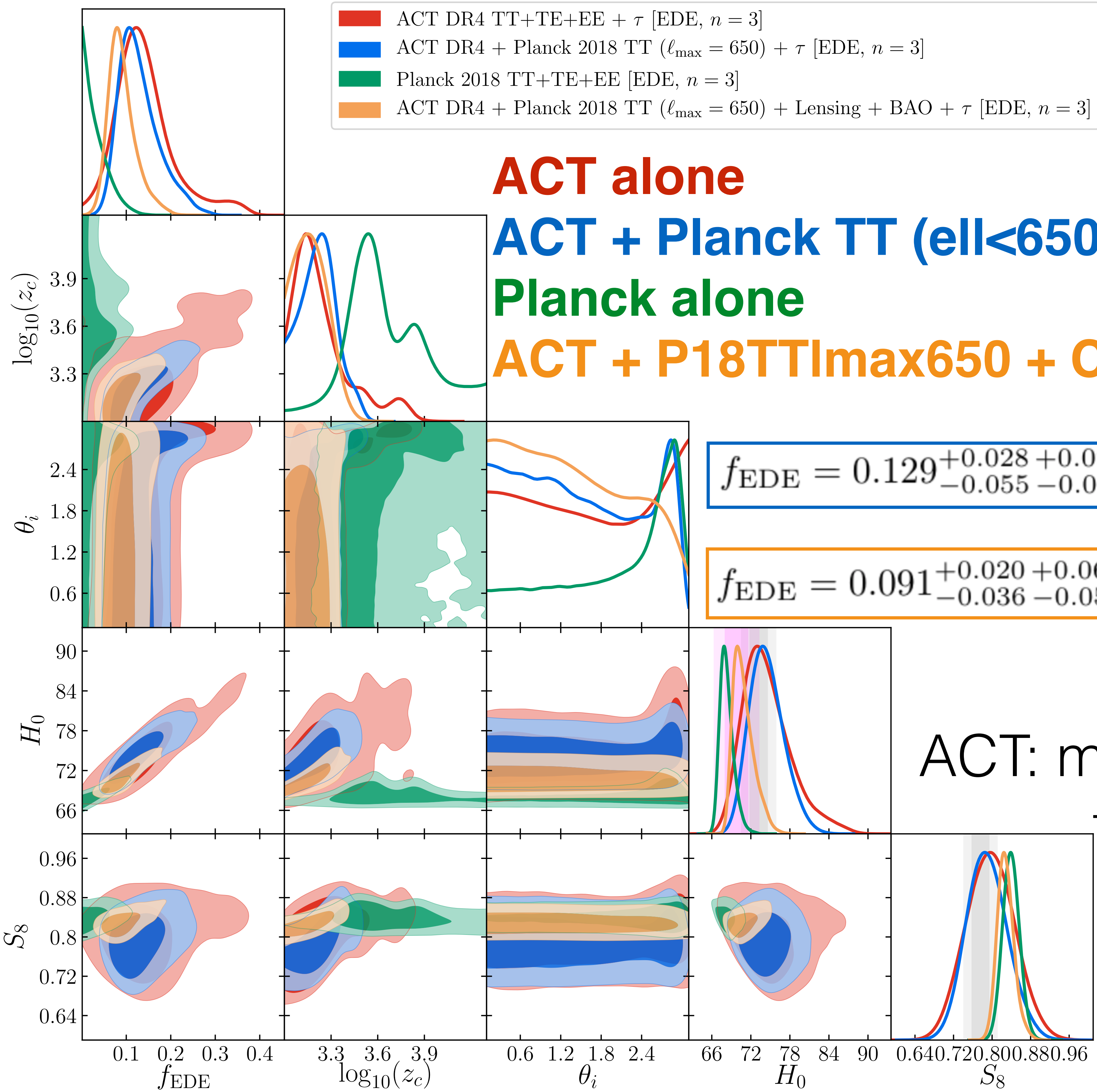
Schoenberg+21

H_0 Post-Olympics: New Data

The Atacama Cosmology Telescope: Constraints on Pre-Recombination Early Dark Energy

JCH+21

H_0 Post-Olympics: New Data



ACT alone

ACT + Planck TT (ell<650)

Planck alone

ACT + P18TTlmax650 + CMB Lensing + BAO

$$f_{\rm EDE} = 0.129^{+0.028\,+0.099\,+0.14}_{-0.055\,-0.076\,-0.084} \quad (68\%/95\%/99.7\%\ {\rm CL})$$

$$f_{\rm EDE} = 0.091^{+0.020\,+0.069\,+0.11}_{-0.036\,-0.056\,-0.063} \quad (68\%/95\%/99.7\%\ {\rm CL})$$

$$H_0 = 70.9^{+1.0}_{-2.0}\ {\rm km/s/Mpc}$$

ACT: moderate preference for EDE over ΛCDM (~3σ in MAP comparison)

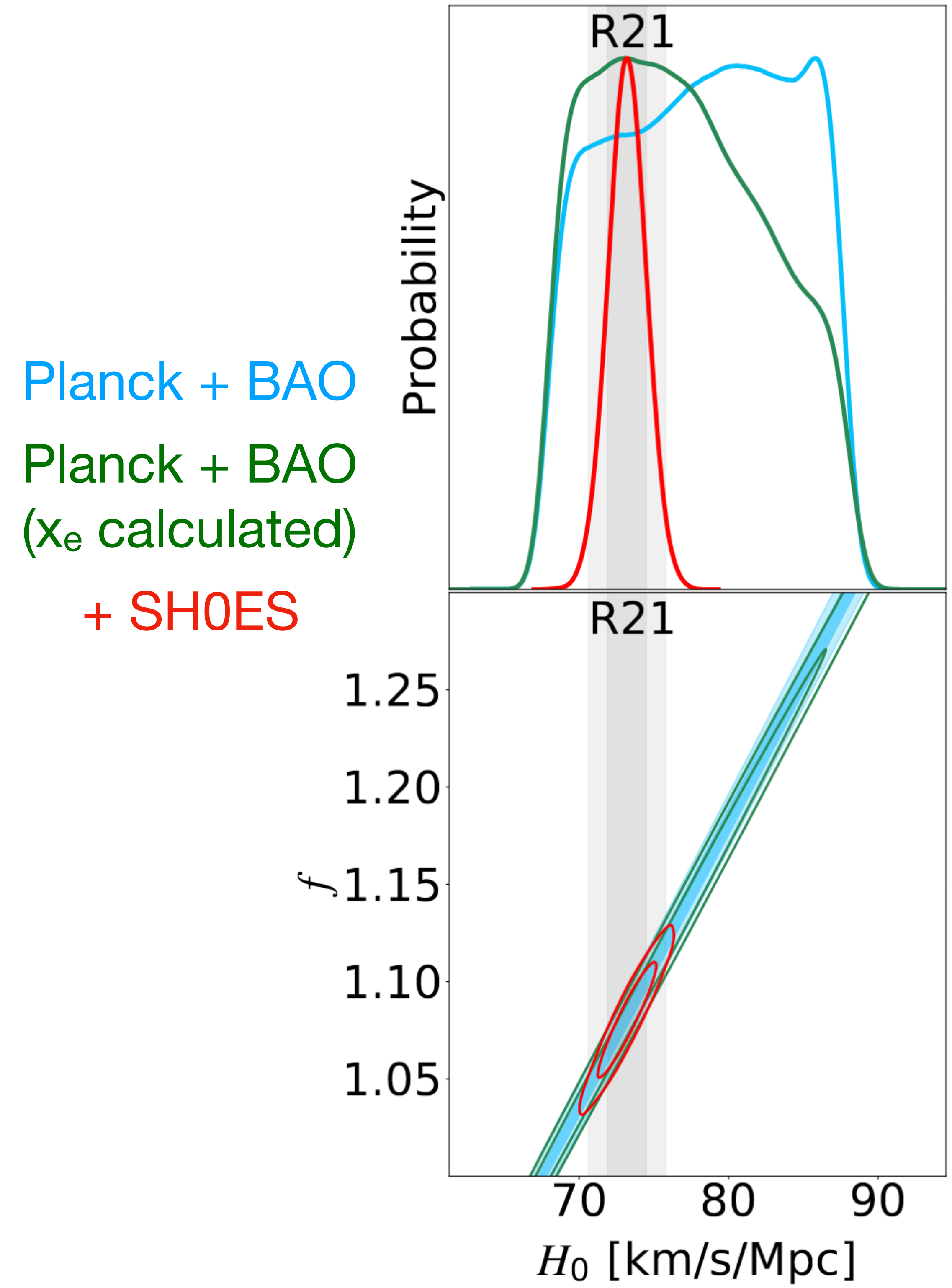
JCH+21; see also Poulin+21

H_0 Post-Olympics: New Theory

A Symmetry of Cosmological Observables, and a High Hubble Constant as an Indicator of a Mirror World Dark Sector

Scaling symmetry of background and linear perturbation theory:

$$\sqrt{G\rho_i(a)} \to f\sqrt{G\rho_i(a)}, \quad \sigma_{\rm T} n_e(a) \to f\sigma_{\rm T} n_e(a)$$
$$\text{and} \quad A_{\rm s} \to A_{\rm s}/f^{(n_{\rm s}-1)}.$$



Cyr-Racine, Ge, & Knox 21

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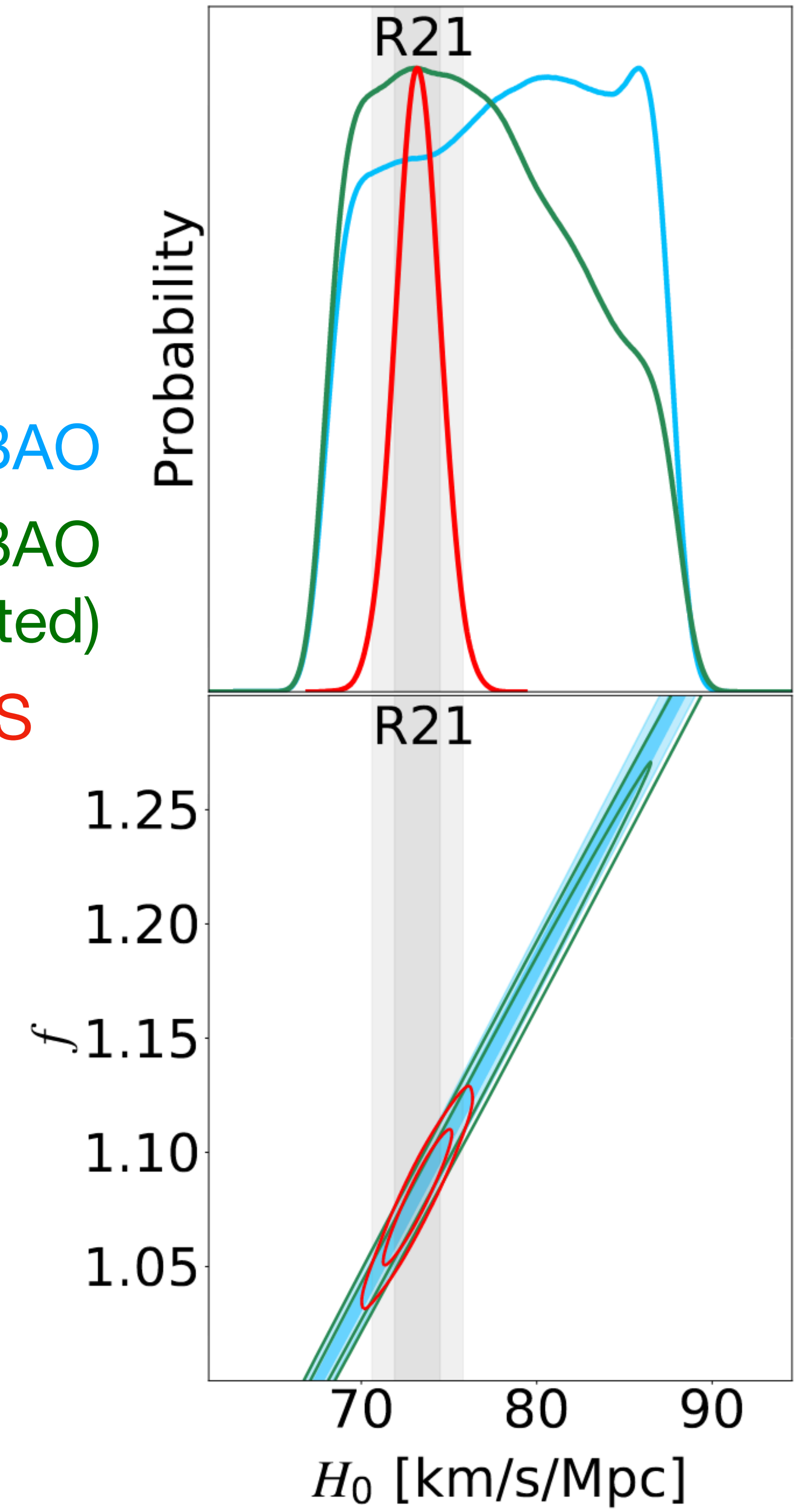
Planck + BAO

Planck + BAO (x_e calculated)

+ SH0ES



Challenges: how to modify the photon scattering rate in a physical way?

Varying Y_P leads to 3σ tension with BBN

Realization in a particle physics model?

Cyr-Racine, Ge, & Knox 21

H_0 Post-Olympics: New Theory

A Step in Understanding the Hubble Tension

Consider strongly coupled dark radiation, mediated by a (heavier) boson that becomes non-relativistic in the epoch prior to recombination

Mediator deposits its entropy into the light species, thus increasing its relative energy density

$$\mathcal{L}_{\rm WZ} = \lambda\,\phi\,\psi^2 + \lambda^2\,(\phi^*\phi)^2$$

integrate out ϕ → $\lambda^2\psi^4/m_\phi^2$

Aloni+ 21

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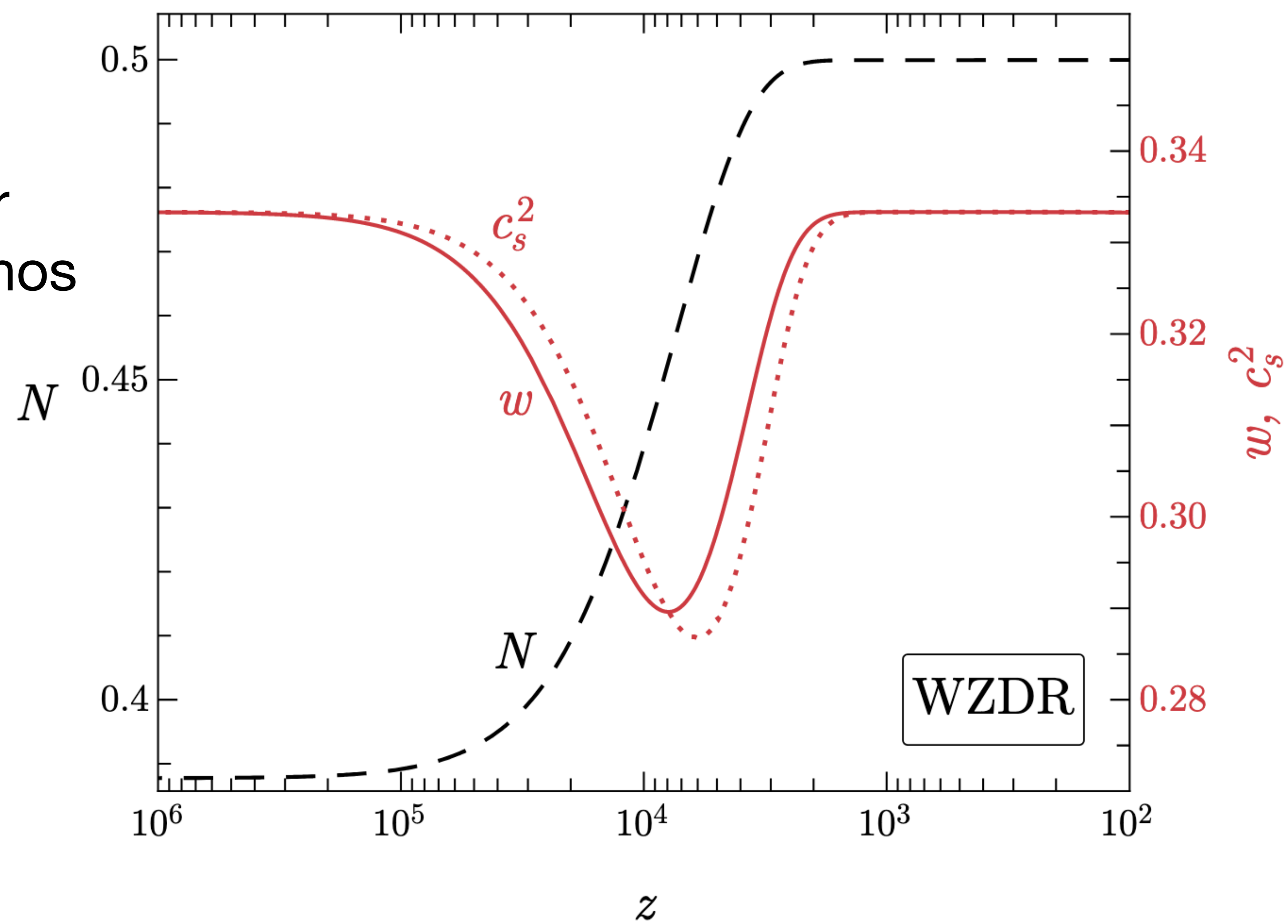
Effective number of additional neutrinos



Aloni+ 21

H_0 Post-Olympics: New Theory

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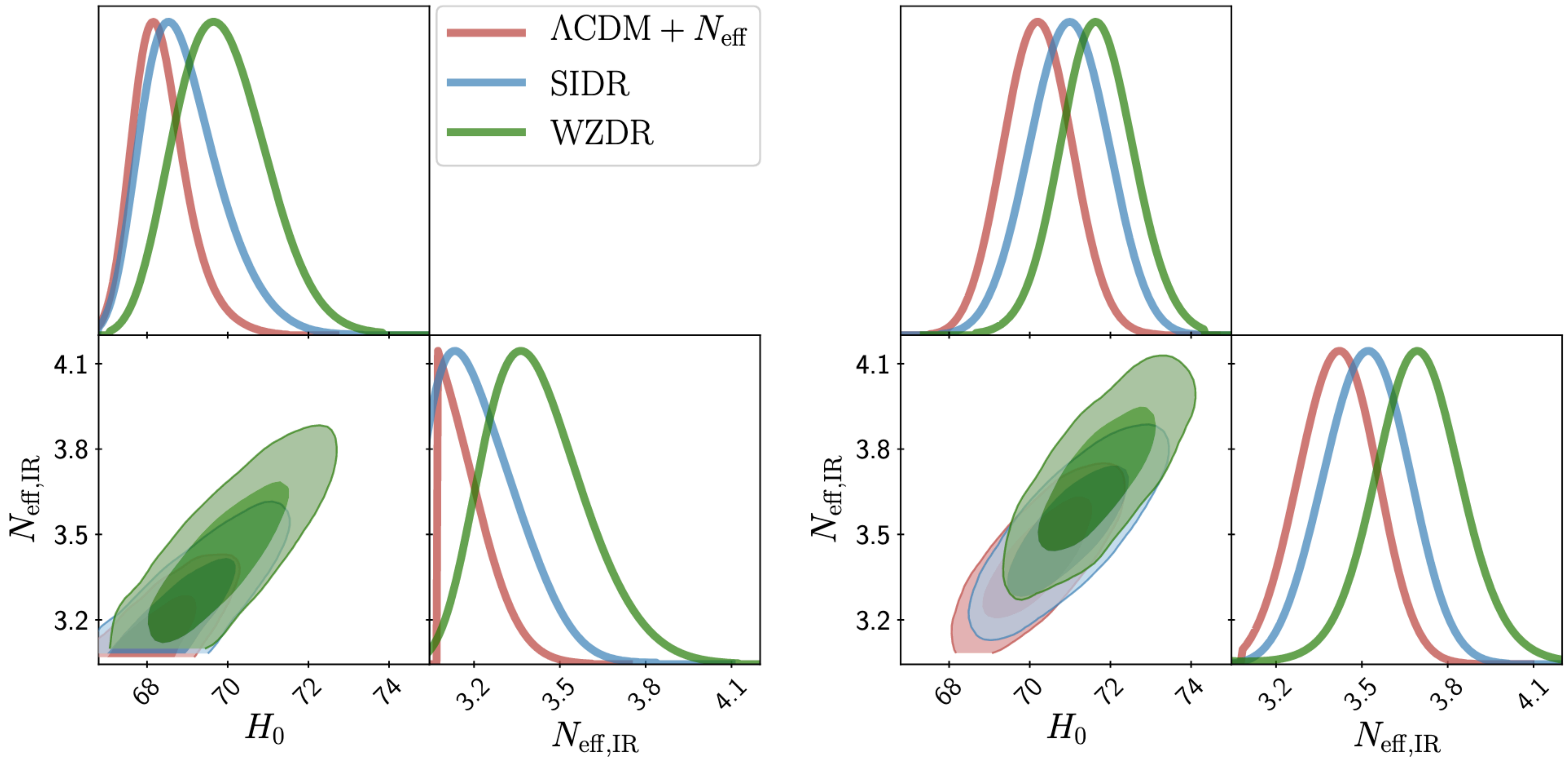


Planck + BAO + Pantheon

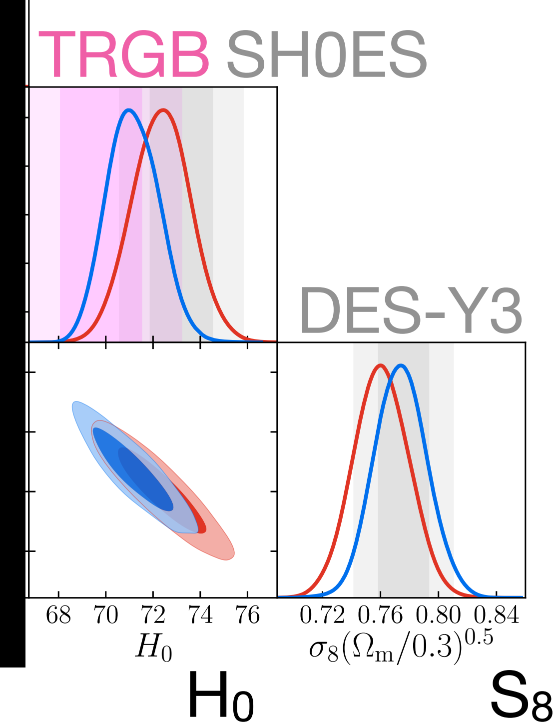
+ SH0ES

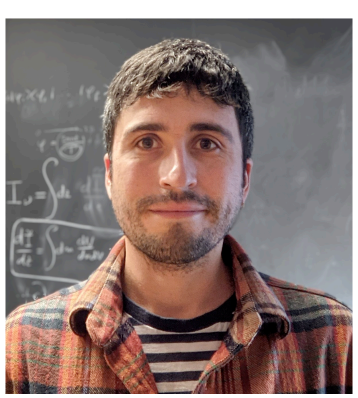
Aloni+ 21

H_0 Post-Olympics: New Theory

Evidently there is promising model space left to be uncovered

[redacted]





JCH & Bolliet (in prep)

Cosmology Intertwined: S_8 + H_0 Olympics?

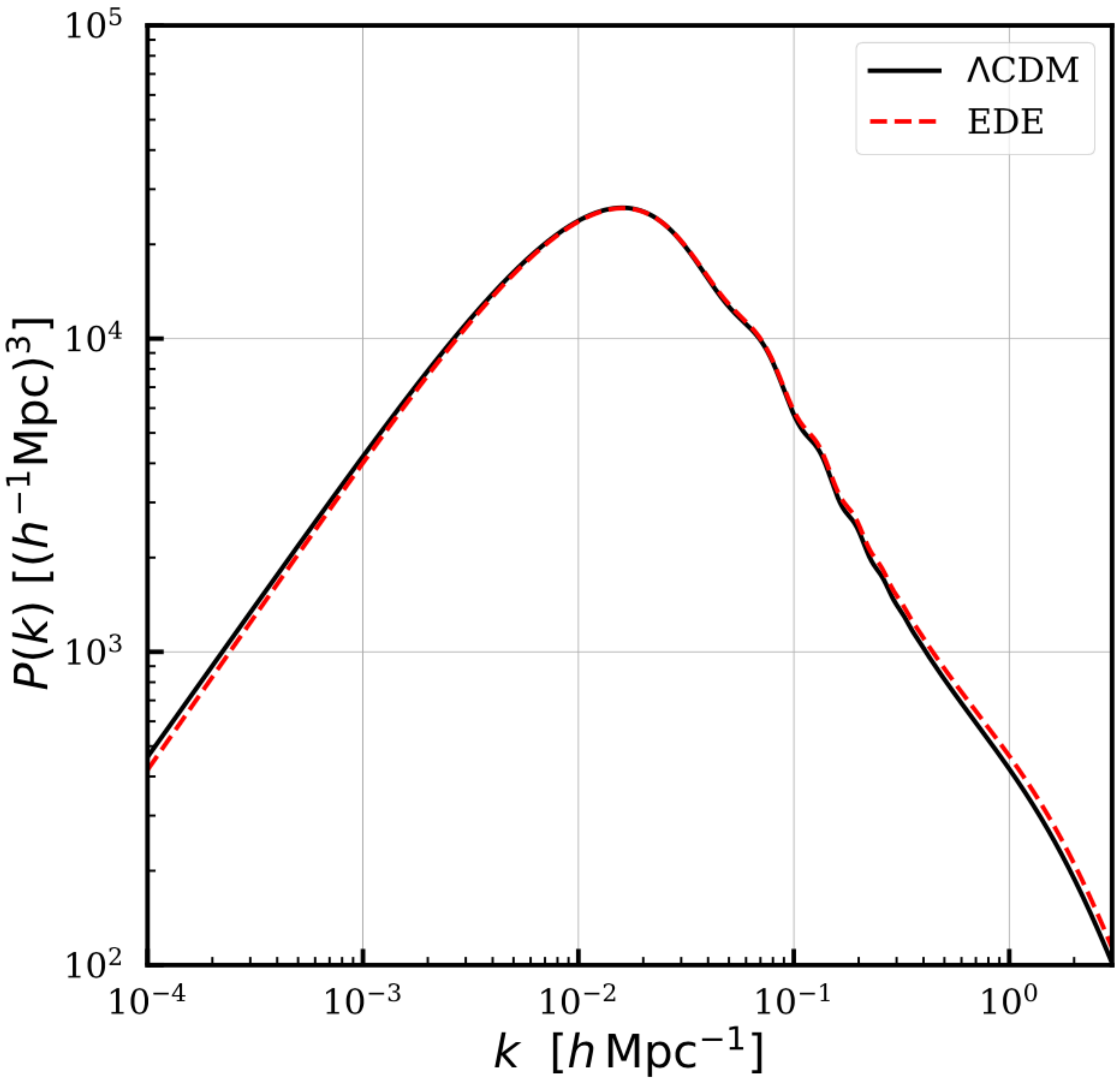
example: large-scale structure in early dark energy models

JCH+20

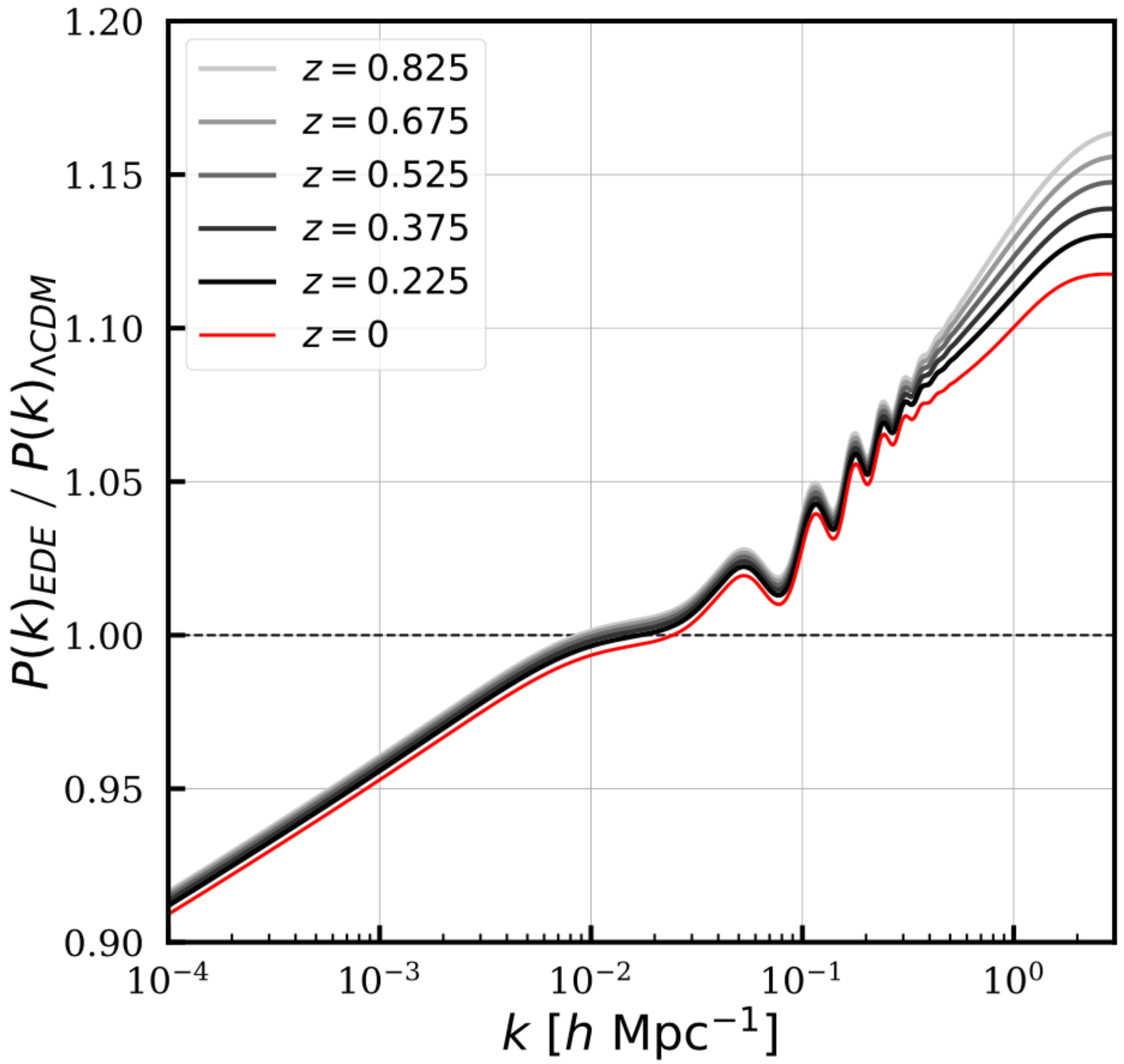
Cosmology Intertwined: S_8 + H_0 Olympics?

example: large-scale structure in early dark energy models

matter power spectrum



ratio



What drives these differences? Shifts in other ΛCDM parameters that are required to preserve the CMB fit in EDE by compensating early ISW (increase in ω_{cdm} and n_s), leading to increase in S_8

JCH+20

Generalization to Other Sound-Horizon-Reducing Models

“tension trading”

leads to conflict with either BAO or WL constraints via ω_m

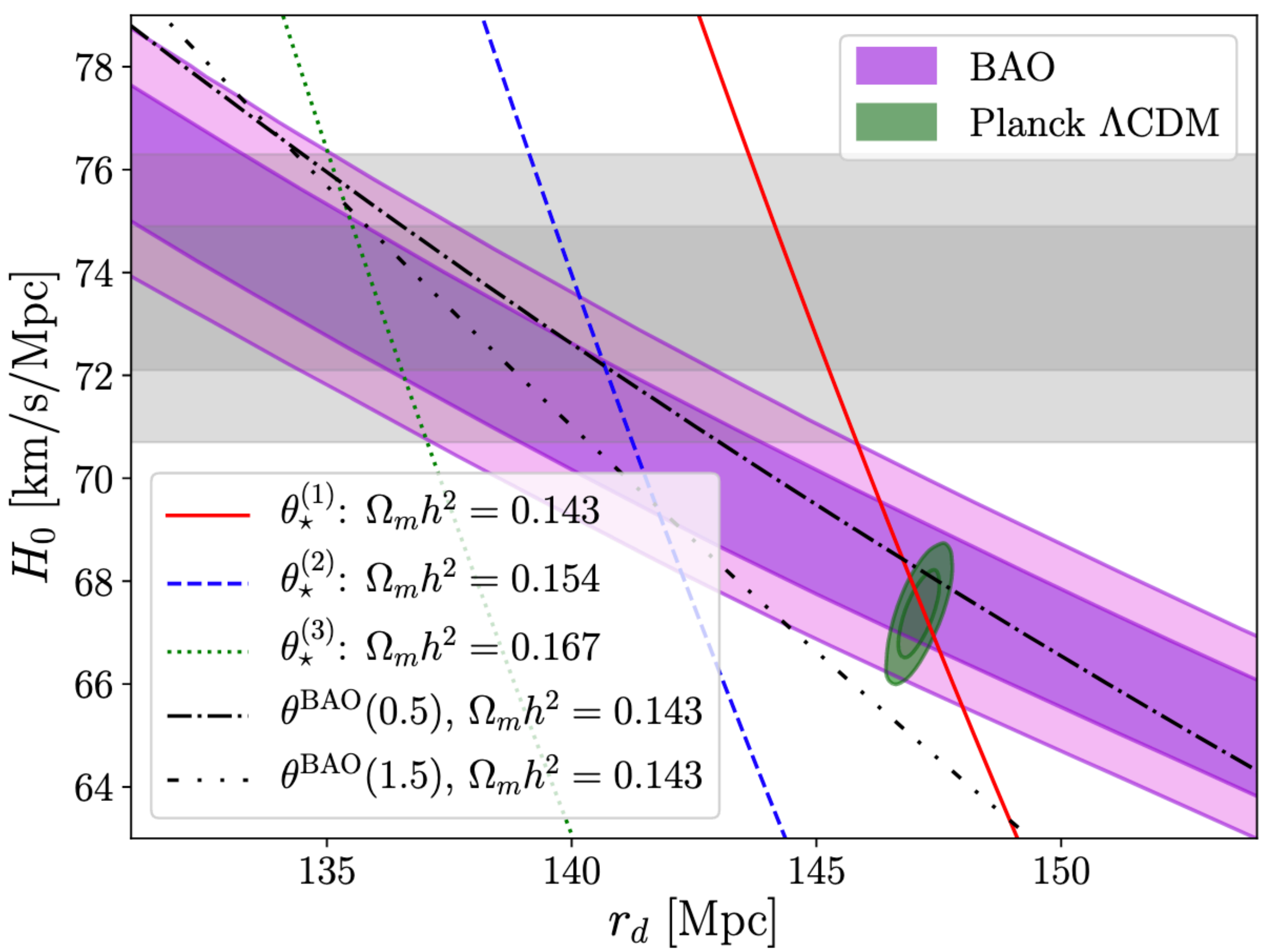
Jedamzik, Pogosian, & Zhao (2021)

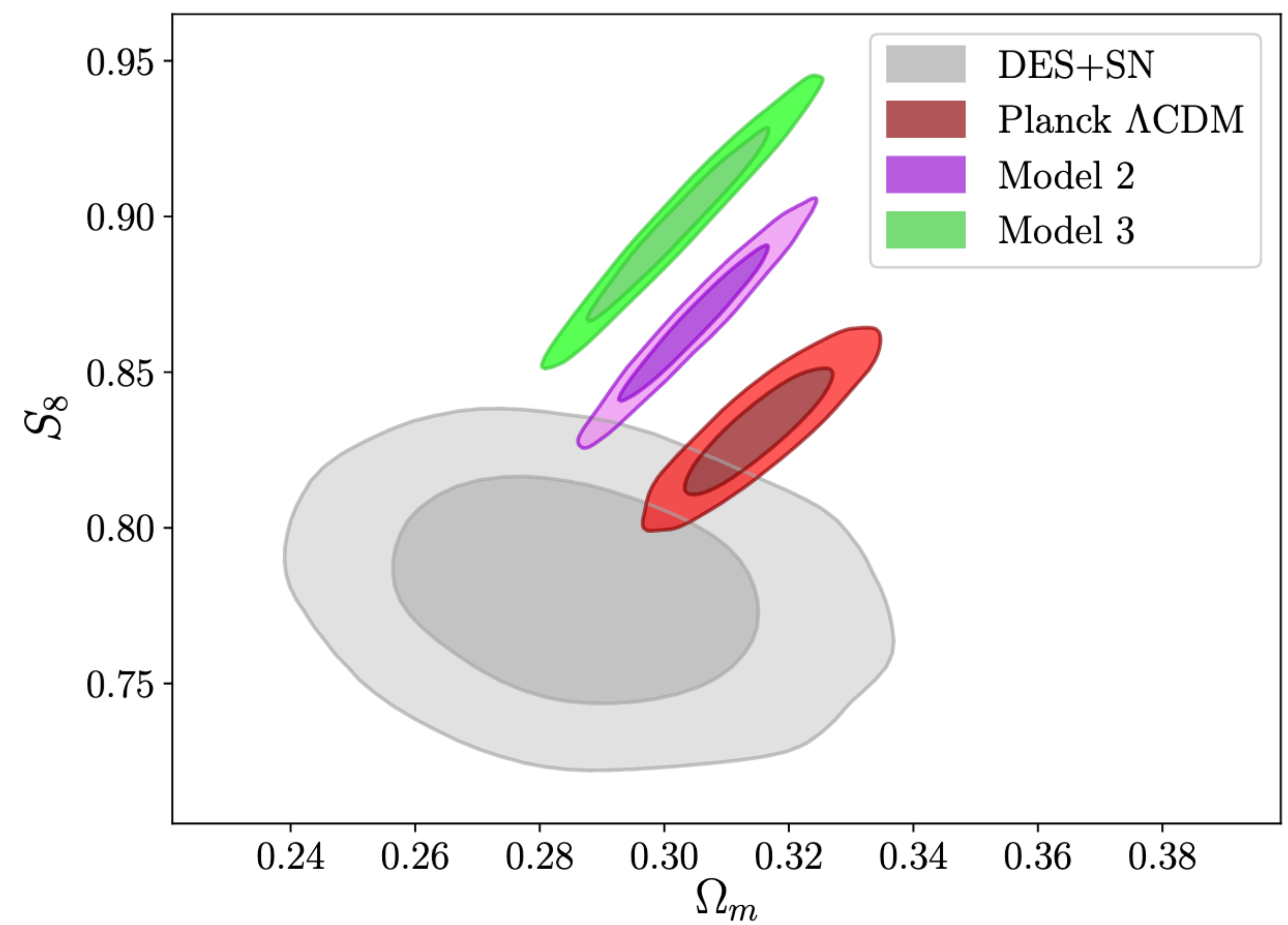
see also Lin, Chen, & Mack (2021)

Generalization to Other Sound-Horizon-Reducing Models

"tension trading"

leads to conflict with either BAO or WL constraints via ω_m





caveat: r* is not actually a free (input) parameter of our physical models

Jedamzik, Pogosian, & Zhao (2021)

see also Lin, Chen, & Mack (2021)

Cosmology Intertwined: S_8 + H_0 Olympics?

Are multiple modifications necessary? (personal view: not yet)

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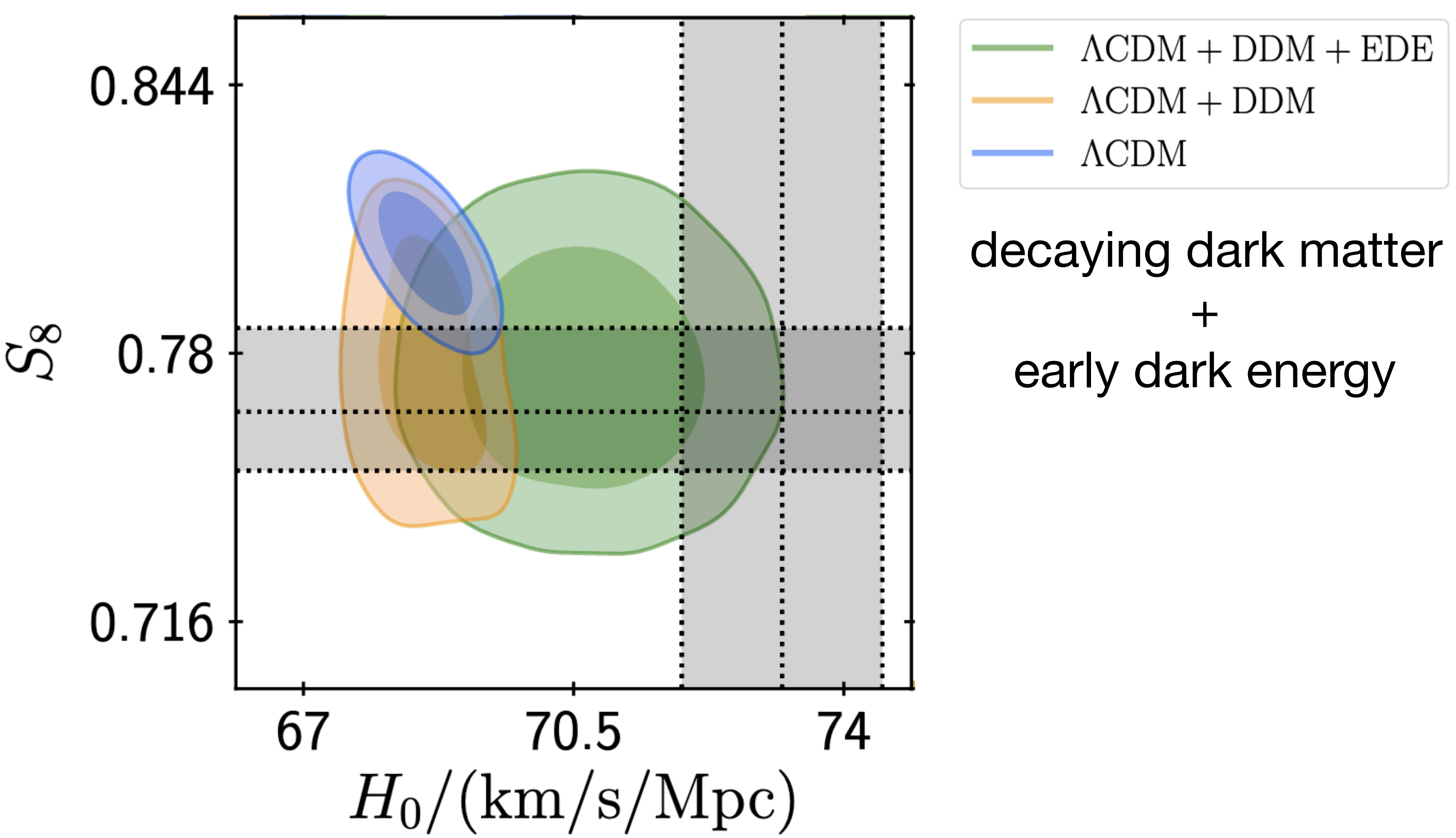
The H_0 and S_8 tensions necessitate early and late time changes to ΛCDM



decaying dark matter
+
early dark energy

Clark+21

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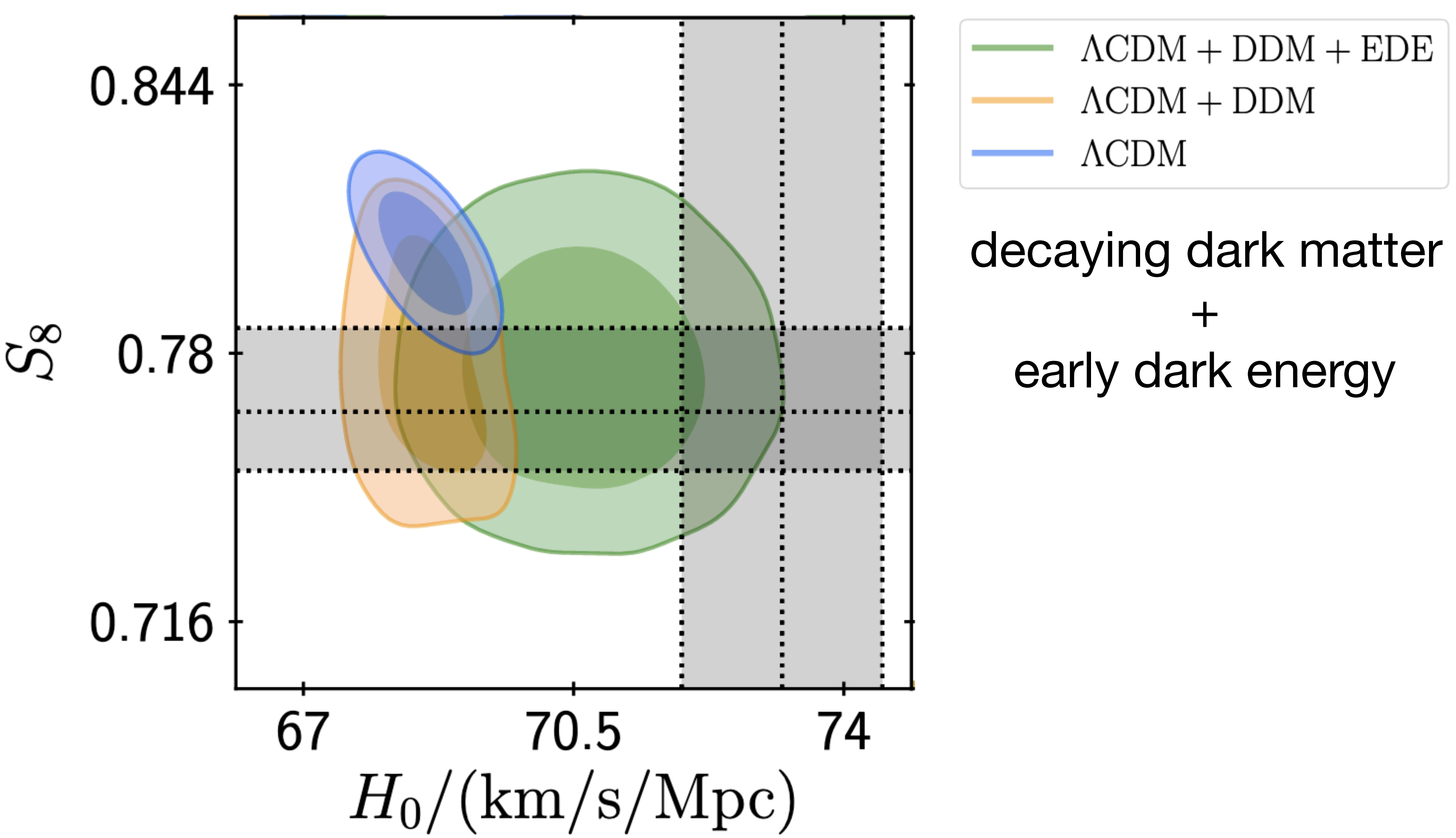

decaying dark matter
+
early dark energy

Can we achieve such phenomenology in a single-component extension of ΛCDM?

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Theory Takeaways

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- Recent results make it clear that there is significant model space left to explore

- "Intertwined": our ultimate goal should be to achieve concordance, rather than tension-trade

- Do we need multiple new components? What would be convincing?
  - My view: finding a new model that conclusively fits CMB data better than ΛCDM (preferred at >>5σ, consistent across experiments) — but yields (high H0+high S8) or (low S8+low H0)

- Open-source: share modified Boltzmann codes to enable community progress

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Observational Outlook

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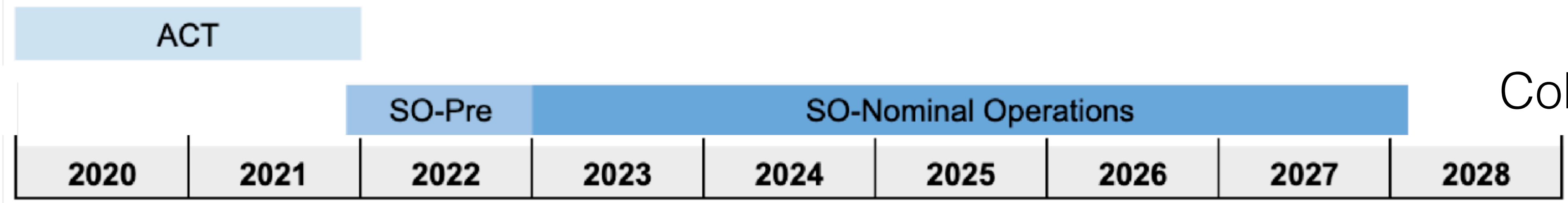
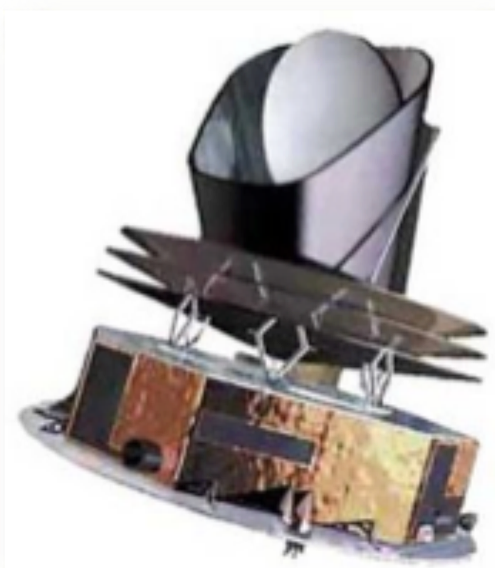


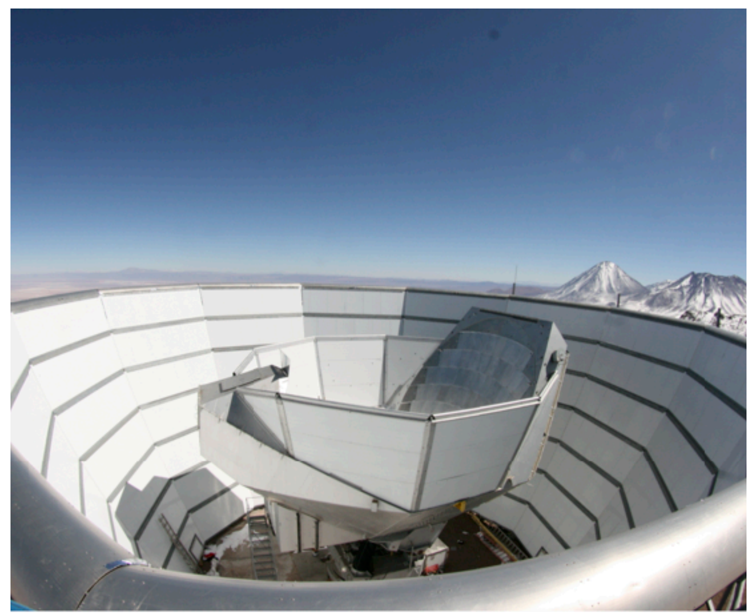
Planck →



Final data 2018
100% sky

0.35 — 10 mm (9 bands)
5 — 33' resolution

Advanced ACT



Observations until 2022
40% sky
Noise ~3 times < Planck
1.4 — 10 mm (5 bands)
1 — 7' resolution

[South Pole Telescope - same timeframe]

ACT DR4 (2020) only comprises data collected through 2016 — we have >4x as much data already on disk, collected through 2021, and we are still going!

Next cosmology release: ACT DR6

$\sigma(H_0) \sim 0.5$ km/s/Mpc in ΛCDM

Ex.: Discovering EDE in the CMB

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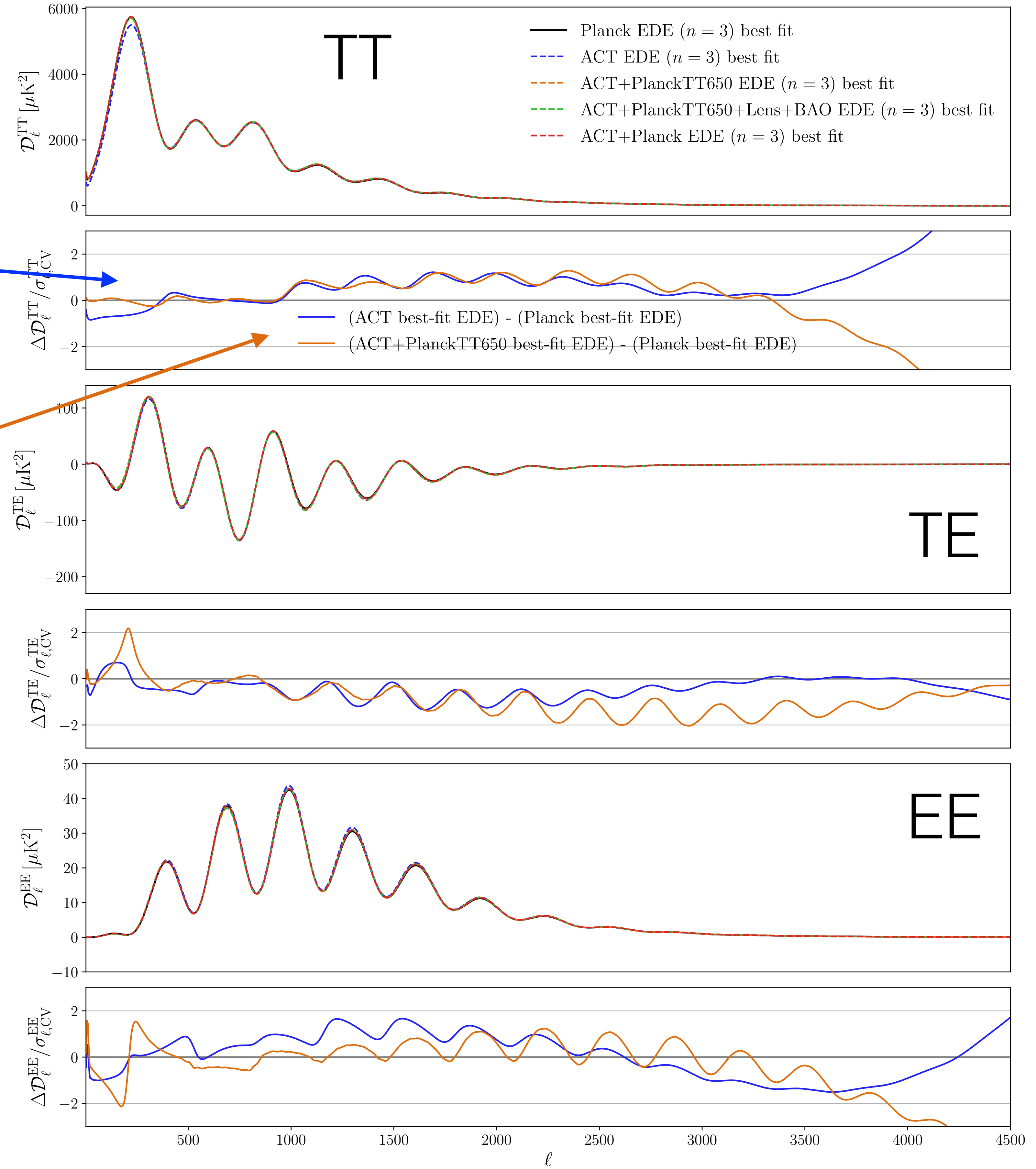
Columbia/CCA

ACT best-fit EDE - Planck EDE

(ACT+low-ell TT) EDE - Planck EDE

Imminent potential discovery with upcoming ACT DR6 (~2022): the models shown here can be distinguished at ~20σ (with DR4: currently ~3σ)



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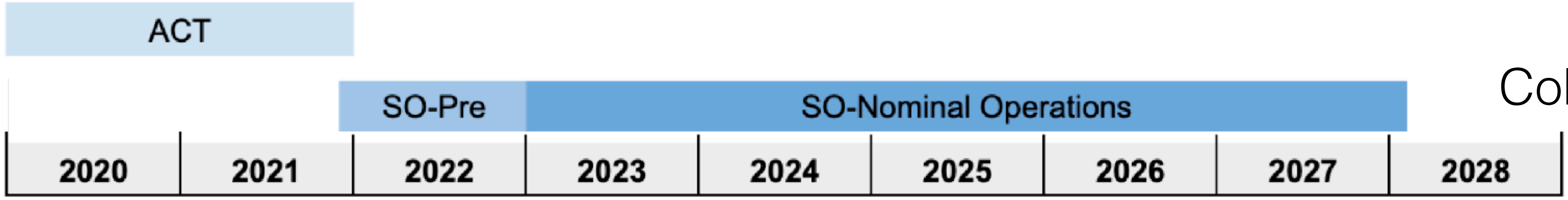
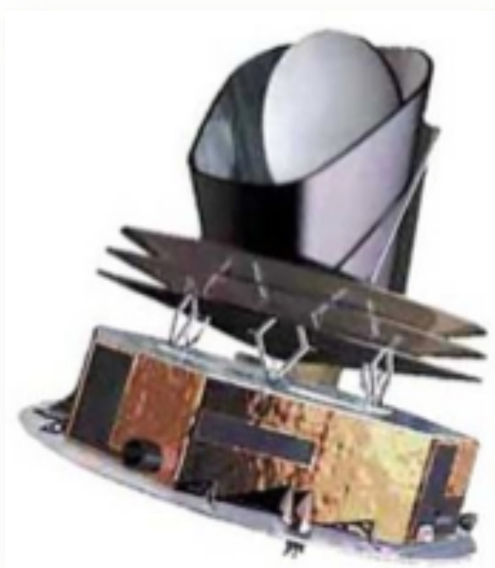
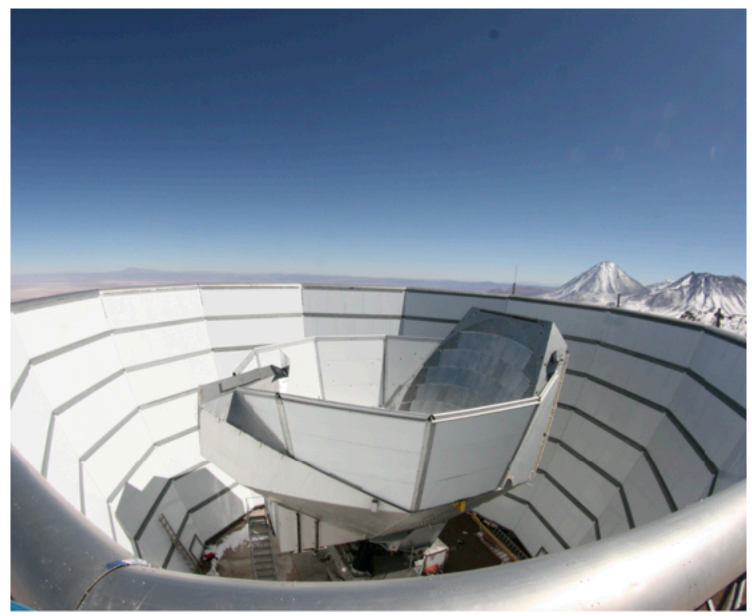
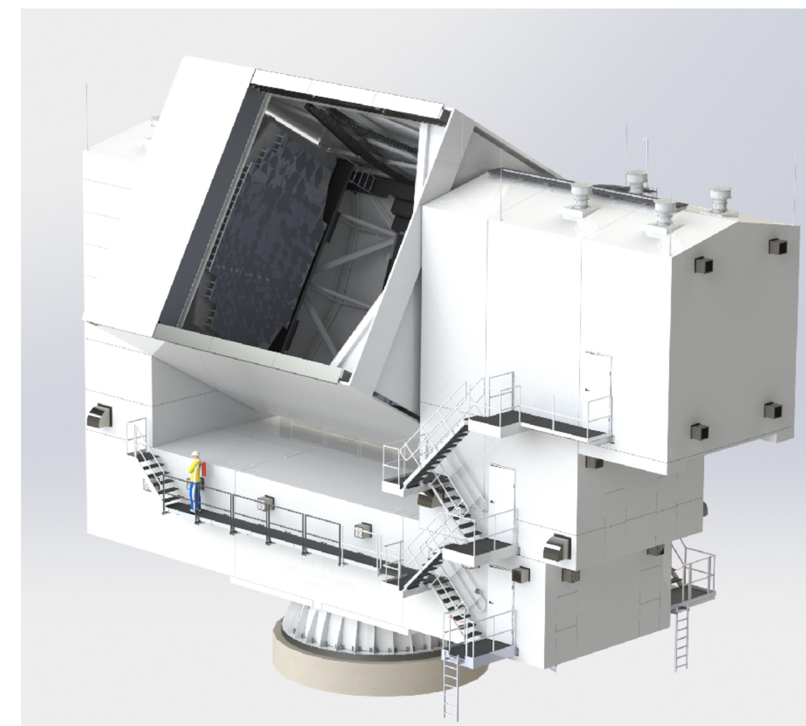


Planck → ACT → SO Large Aperture Telescope







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[South Pole Telescope - same timeframe]

SO Large Aperture Telescope

Observations ~2023-28
40% sky
Noise ~3 times < ACT
1 — 10 mm (6 bands)
1 — 7' resolution

[CMB-S4 would start observing after this, with multiple telescopes]

The Future Is Bright

1) ΛCDM H_0 is secure; *if* local measurements robustly agree on a higher value via multiple probes, new physics likely
2) Significant model space for altering pre-recombination universe remains to be explored — or even re-explored
3) Early-universe H_0 resolutions predict clear deviations from ΛCDM in the CMB — imminently testable with ACT+SPT (now), SO (2024), and Astro2020-endorsed CMB-S4 (2029)

Photo: D. Kellner

Thanks!