Early- and late-time consistency tests of ΛCDM and implications for the Hubble tension

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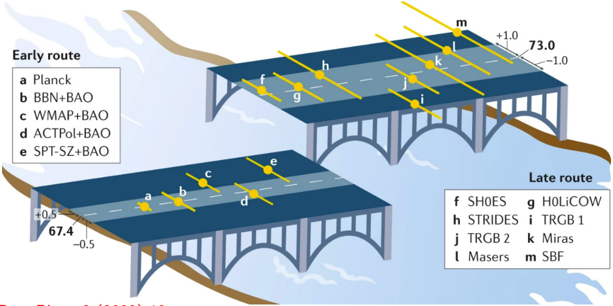
Cosmology from Home 2021, 5-16 July 2021

Looking at the Hubble tension ocean with different eyes



Credits: Riess, Nat. Rev. Phys. 2 (2020) 10

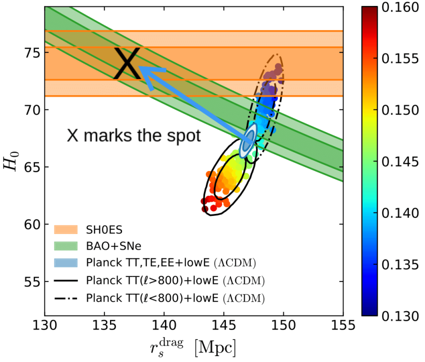
Why does ΛCDM fit data so well? Do we really need new physics? If so, at what time(s), and with what ingredients?

Early times: early ISW effect	$\Longleftrightarrow$	*Consistency tests of ΛCDM*	$\Longleftrightarrow$	*Late times: ages of old objects*

The Hubble tension and new physics

Hubble tension *appears* to call for (substantial) early-time new physics...

Increasing $H(z)$ just prior to $z_\star$: "least unlikely" proposal?



Credits: Knox & Millea, PRD 101 (2020) 043533

Example: early dark energy (some debate as to how much it works)

Featured in Physics | Editors' Suggestion

Early Dark Energy can Resolve the Hubble Tension

Vivian Poulin, Tristan L. Smith, Tanvi Karwal, and Marc Kamionkowski
Phys. Rev. Lett. **122**, 221301 – Published 4 June 2019

Editors' Suggestion

Early dark energy does not restore cosmological concordance

J. Colin Hill, Evan McDonough, Michael W. Toomey, and Stephon Alexander
Phys. Rev. D **102**, 043507 – Published 5 August 2020

Need $\approx$ 12% (!!!) EDE around $z_{\rm eq}$ $\Downarrow$

Why is there no ***clear*** *sign of new physics in CMB data alone?*

Early-time consistency tests of ΛCDM

Why is there no clear sign of early-time new physics in CMB data alone?

↓

Why does ΛCDM fit CMB data so well?

↓

(Early-time) Consistency tests of ΛCDM

The early ISW (eISW) effect

Around recombination: Universe not fully matter dominated $\implies$ residual decay of gravitational potentials $\implies$ eISW effect sources anisotropies

$$\Theta = \int_0^{\eta_0} d\eta \left[\underbrace{\propto g(\Theta_0 + \Psi)}_{\text{Sachs-Wolfe}} + \underbrace{\propto g v_b \frac{d}{d\eta}}_{\text{Doppler}} + \underbrace{\propto e^{-\tau}(\dot{\Psi} - \dot{\Phi})}_{\text{ISW}} + \underbrace{\propto (g\Pi + [g\ddot{\Pi}])}_{\text{Polarization}} \right] j_\ell(k\Delta\eta)$$

$$\Theta_\ell^{\text{ISW}}(k) = \underbrace{\int_0^{\eta_m} d\eta \, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi} \right) j_\ell(k\Delta\eta)}_{\text{early ISW}} + \underbrace{\int_{\eta_m}^{\eta_0} d\eta \, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi} \right) j_\ell(k\Delta\eta)}_{\text{late ISW}}$$

(A substantial amount of) New physics increasing $H(z)$ around $z_{\rm eq}/z_\star$ *should* leave an imprint on the eISW effect!

eISW consistency test

Consistency tests of ΛCDM from the early ISW effect: implications for early-time new physics and the Hubble tension

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Introduce scaling amplitude/fudge factor $A_{\rm eISW}$ SV, arXiv:2105.10425

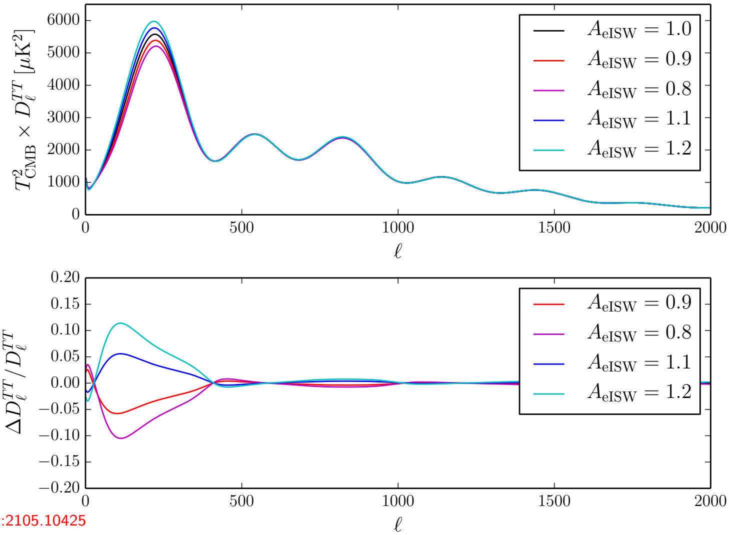
$$\Theta_\ell^{\rm eISW}(k) = A_{\rm eISW} \int_0^{\eta_m} d\eta \, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi} \right) j_\ell(k \Delta \eta)$$

Consistency check: within ΛCDM, is the data consistent with $A_{\rm eISW} = 1$?

Looks familiar? It should remind you of $A_{\rm lens}$ Calabrese *et al.*, PRD 77 (2008) 123531

$$C_\ell^{\phi\phi} \to A_{\rm lens} C_\ell^{\phi\phi}$$

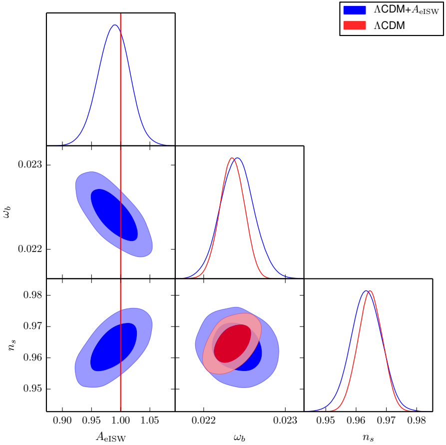
eISW consistency test



SV, arXiv:2105.10425

eISW consistency test

Is the data consistent with $A_{\rm eISW} = 1$? (7-parameter ΛCDM+$A_{\rm eISW}$)



SV, arXiv:2105.10425

Yes!

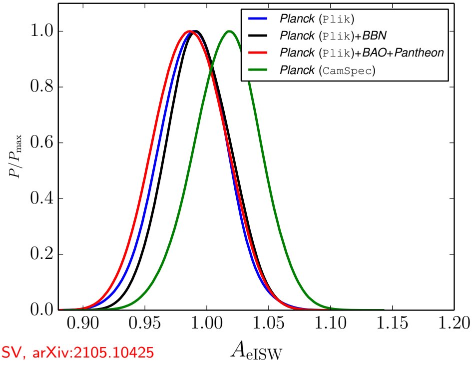
Parameter	*Planck* ΛCDM	*Planck* ΛCDM+$A_{\rm eISW}$
$100\omega_b$	2.235 ± 0.015	2.241 ± 0.020
ω_c	0.1202 ± 0.0013	0.1203 ± 0.0014
θ_s	1.0409 ± 0.0003	1.0409 ± 0.0003
τ	0.0544 ± 0.0078	0.0541 ± 0.0078
$\ln(10^{10} A_s)$	3.045 ± 0.016	3.046 ± 0.016
n_s	0.965 ± 0.004	0.963 ± 0.005
$A_{\rm eISW}$	1.0	0.988 ± 0.027
H_0 [km/s/Mpc]	67.26 ± 0.57	67.28 ± 0.62
Ω_m	0.317 ± 0.008	0.317 ± 0.009

SV, arXiv:2105.10425

Other parameter constraints very stable, no more than $\approx 0.3\sigma$ shifts

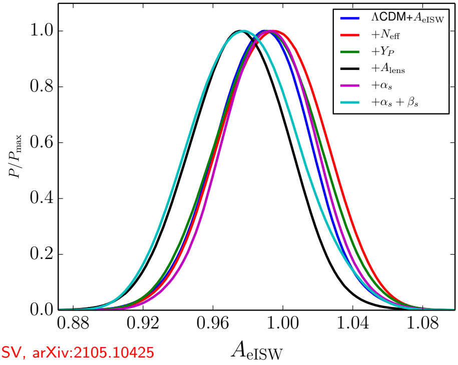
eISW consistency test: robustness of results

External data/different likelihoods



SV, arXiv:2105.10425

Extended parameter space(s)



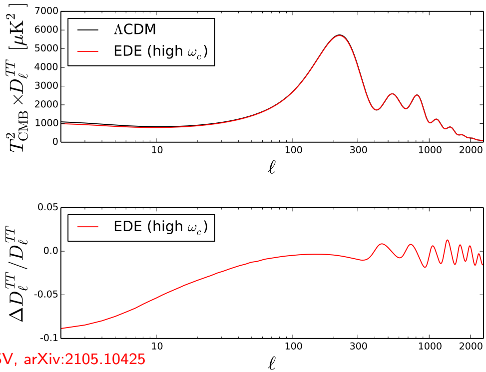
SV, arXiv:2105.10425

Take-away message: ΛCDM (robustly) aces the eISW consistency test!

Implications for early-time new physics: EDE case study

High H_0 EDE fit to CMB at the cost of increase in ω_c $\rightarrow$ worsens tension with WL/LSS data? Hill *et al.*, PRD 102 (2020) 043507; Ivanov *et al.*, PRD 102 (2020) 103502; D'Amico *et al.*, JCAP 2105 (2021) 072; see partial rebuttals in: Murgia *et al.*, PRD 103 (2021) 063502; Smith *et al.*, arXiv:2009.10740

Parameter	ΛCDM	EDE (high ω_c)	EDE (low ω_c)
$100\omega_b$	2.253	2.253	2.253
ω_c	0.1177	0.1322	0.1177
H_0 [km/s/Mpc]	68.21	72.19	72.19
τ	0.085	0.072	0.072
$\ln(10^{10}A_s)$	3.0983	3.0978	3.0978
n_s	0.9686	0.9889	0.9889
$f_{\rm EDE}$	–	0.122	0.122
$\log_{10} z_c$	–	3.562	3.562
θ_i	–	2.83	2.83
n	–	3	3

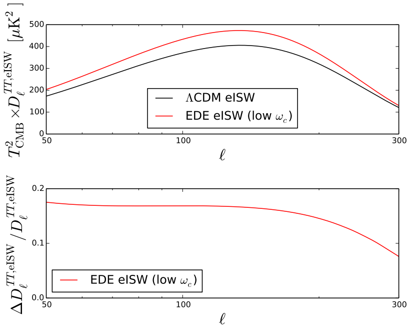


SV, arXiv:2105.10425

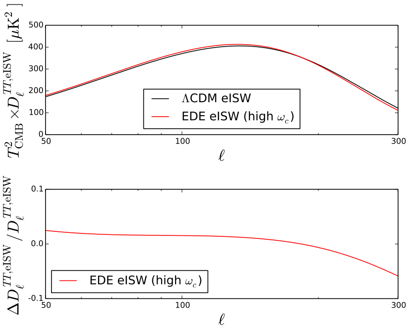
Implications for early-time new physics: EDE case study

Let's extract only the eISW contribution to temperature anisotropies...

Low ω_c



High ω_c



Almost 20% eISW excess!

No more than $\lesssim$ 3-5% eISW excess

Generic to models increasing pre-recombination $H(z)$, not just EDE

Recap: eISW effect and early-time new physics

- Early-time new physics *should* leave an imprint on eISW effect
- Consistency test: in ΛCDM, *Planck* highly consistent with $A_{\rm eISW} \approx 1$
- Challenge for early-time new physics, need to match this prediction
- Example: EDE compensates extra eISW with increase in ω_c
- Generic problem for models increasing pre-recombination $H(z)$
  $\Longrightarrow$ need extra ingredients?
  $\Longrightarrow$ relation to S_8 discrepancy?
  $\Longrightarrow$ can't go beyond $H_0 \sim 70$ with early-time new physics?
  $\Longrightarrow$ related: H_0 from BOSS DR12 $P(k)$ inferred from $k_{\rm eq}$ and r_s consistent: no evidence for non-standard pre-recombination physics?

Philcox *et al.*, PRD 103 (2021) 023538

Why aren't there clear signs of substantial early-time new physics solving the Hubble tension?

Late-time consistency tests of ΛCDM

Is ΛCDM really all there is at late times?

↓

(Try to) Test ΛCDM making no assumptions about early-time physics

↓

Learn something about H_0 in the process?

Old astrophysical objects at high redshift

Historically (1960s-1998) high-z OAO provided the first hints for the existence of dark energy ($\Omega \neq 1$, $\Omega_\Lambda > 0$)

A 3.5-Gyr-old galaxy at redshift 1.55

James Dunlop, John Peacock, Hyron Spinrad, Arjun Dey, Raul Jimenez, Daniel Stern & Rogier Windhorst

Nature **381**, 581–584 (1996) | Cite this article

Conflict over the age of the Universe

M. Bolte & C. J. Hogan

Nature **376**, 399–402 (1995) | Cite this article

The observational case for a low-density Universe with a non-zero cosmological constant

J. P. Ostriker & Paul J. Steinhardt

Nature **377**, 600–602 (1995) | Cite this article

What can OAO do for cosmology in the 2020s?

Cosmology with old astrophysical objects

Implications for the Hubble tension from the ages of the oldest astrophysical objects

Sunny Vagnozzi,[1,*] Fabio Pacucci,[2,3,†] and Abraham Loeb[2,3,‡]
[1]*Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*
[2]*Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA*
[3]*Black Hole Initiative, Harvard University, Cambridge, MA 02138, USA*

$$t_U(z) = \int_z^\infty \frac{dz'}{(1+z')H(z')} \propto \frac{1}{H_0}$$

Pros and cons:

- OAO cannot be older than the Universe $\rightarrow$ **upper limit on $\mathbf{H_0}$**
- $t_U(z)$ integral insensitive to early-time cosmology
- $\Longrightarrow$ **late-time consistency test for ΛCDM independent of the early-time expansion**!
- Ages of astrophysical objects at $z > 0$ hard to estimate robustly ⚠

Old astrophysical objects and the Hubble tension

Usefulness in relation to the Hubble tension:

- Reliable high t_U measurement(s) would disfavor models with high H_0 and standard post-recombination physics
- OAO cannot be older than the Universe $\rightarrow$ **upper limit on $\mathbf{H_0}$**
- Contradiction between OAO upper limit on H_0 and local H_0 measurements could indicate the need for non-standard late-time ($z \lesssim 10$) physics, or non-standard local physics
- Conclusions completely independent of pre-recombination physics

Role of age of the Universe *today* $t_U(z=0)$ recently appreciated in the Hubble tension context Jiménez *et al.*, JCAP 1903 (2019) 043; Bernal *et al.*, PRD 103 (2021) 103533

The local and distant Universe: stellar ages and H_0

Raul Jimenez[1,2], Andrea Cimatti[3,4], Licia Verde[1,2], Michele Moresco[3,5] and Benjamin Wandelt[6,7,8]

Published 28 March 2019 • © 2019 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2019, March 2019

Citation Raul Jimenez *et al* JCAP03(2019)043

Editors' Suggestion

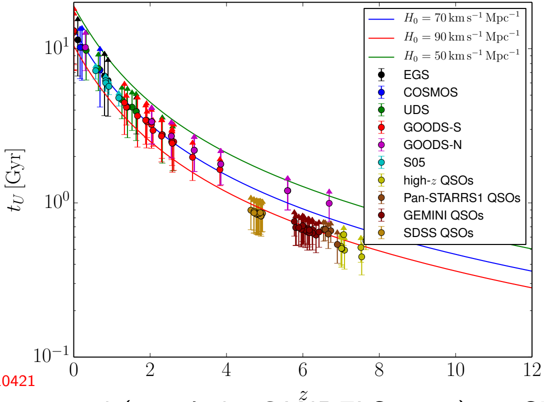
Trouble beyond H_0 and the new cosmic triangles

José Luis Bernal, Licia Verde, Raul Jimenez, Marc Kamionkowski, David Valcin, and Benjamin D. Wandelt

Phys. Rev. D **103**, 103533 – Published 26 May 2021

OAO age-redshift diagram

Age-redshift diagram up to $z \sim 8$



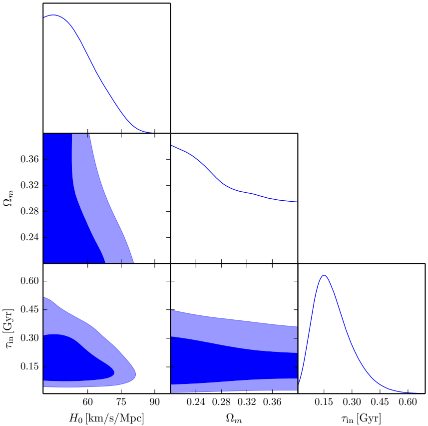
SV *et al.*, arXiv:2105.10421

Galaxy ages estimated (mostly by CANDELS team) via SED fitting, QSOs ages via growth model Pacucci *et al.*, ApJ Lett. 850 (2017) L42

Results

Assume ΛCDM at late times, constrain H_0, Ω_m, and incubation time $\tau_{\rm in}$

Prior for $\tau_{\rm in}$ following Jiménez *et al.*, JCAP 1903 (2019) 043; Valcin *et al.*, JCAP 2012 (2020) 022



- $H_0 < 73.2$ (95% C.L.)
- $\approx 2\sigma$ tension with Cepheid-calibrated SNeIa H_0 measurement
- Tighter (but less robust) results using non-flat prior on Ω_m
- (in principle can also constrain w, Ω_K,...)

SV *et al.*, arXiv:2105.10421

Implications for the Hubble tension

CAVEAT – if the OAO ages are reliable, possible explanations for the previous results include:

- #1: ΛCDM is not the end of the story at $z \lesssim 10$
- #2: Nothing wrong with ΛCDM at $z \lesssim 10$, need local new physics...

  Examples: screened 5th forces (Desmond *et al.*, PRD 100 (2019) 043537; Desmond & Sakstein, PRD 102 (2020) 023007), breakdown of FLRW (Krishnan *et al.*, arXiv:2105.09790; arXiv:2106.02532),++
- #3: A combination of the above
- #4: Just a boring 2σ fluke or systematics?

If #1, maybe the answer to the Hubble tension is a combination of (mostly) pre-plus-post-recombination new physics?
If #2, maybe the Hubble tension is not cosmological, but non-local vs local discrepancy? See hints for this in Lin, Chen & Mack, arXiv:2102.05701

Several other hints that pre-recombination new physics alone not enough to solve Hubble tension Krishnan *et al.*, PRD 102 (2020) 103525; Jedamzik *et al.*, Commun. Phys. 4 (2021) 123; Lin *et al.*, arXiv:2102.05701; Dainotti *et al.*, ApJ 912 (2021) 150

Conclusions

- Hubble tension ocean/model space is too vast: need more general (consistency) tests to identify promising directions
- Early times: no signs of new physics in early ISW effect $\rightarrow A_{\rm eISW} \approx 1$ sets important challenge for early-time new physics (EDE case study)
- Late times: slight discrepancy between ages of oldest astrophysical objects (upper limit on H_0) and local H_0 measurements

Question for everybody:

Do you think early-time new physics **alone** *can solve the Hubble tension?*

Please let me know through this poll: linkto.run/p/Y7MXGGBI