This talk is mainly based on Lin, Chen and Mack (2021), accepted by ApJ, arXiv: 2102.05701

UNCALIBRATED COSMIC STANDARDS (UCS) & EARLY-PHYSICS INSENSITIVE H_0 DETERMINATIONS

Weikang Lin

(Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Tsung-Dao Lee Prize Postdoctoral Fellow)

Collaborators: Xingang Chen (Harvard), Katie Mack (NC State)

Copernicus Webinar and Seminar Series
10/22/2021

OUTLINES

- Introduction
  - Why we need early-universe physics independent constraints?
  - Matter density fraction Ω_m is as important as H_0.
- Uncalibrated Cosmic Standards (UCS)
  - Standard rulers without 'calibrated by early physics' and SNe Ia without calibration.
  - Robust constraints on Ω_m.
- Pre-recombination-physics insensitive H_0 results.
  - Results and assumption list.

Why we need early-physics independent methods?

- To verify early-time resolutions to tensions, e.g., the Hubble tension.
  (Note H0 tension refers to that between Planck and Cepheid-based measurements)
- To better understand the underlying assumptions of each probe/result.
- Release strong assumptions; Robustness is more important than precession.
- To test late-time models independent of early-time physics/systematics.
- Many situations need early-time physics independent constraints.

Brief review: early-physics (pre-recombination) resolutions to H_0 tension

Baryon or photons interacting with Dark matters
(Dvorkin et al 2013, Boddy etal 2018)

$$\theta_* = \frac{r_s}{d_{ls}} = \frac{\int_{z_*}^{\infty} dz\, c_s(z)/E(z)}{\int_0^{z_*} dz/E(z)}$$

Increase early expansion:

- ❑ Energy injection
  – Early Dark Energy (Poulin et al 2019)
- ❑ Radiation
  – Interacting Neutrinos (Kreisch et al 2019)

Nonstandard recombination:

Chiang and Slosar (2018)
But see Liu et al (2019) arXiv:1912.00190

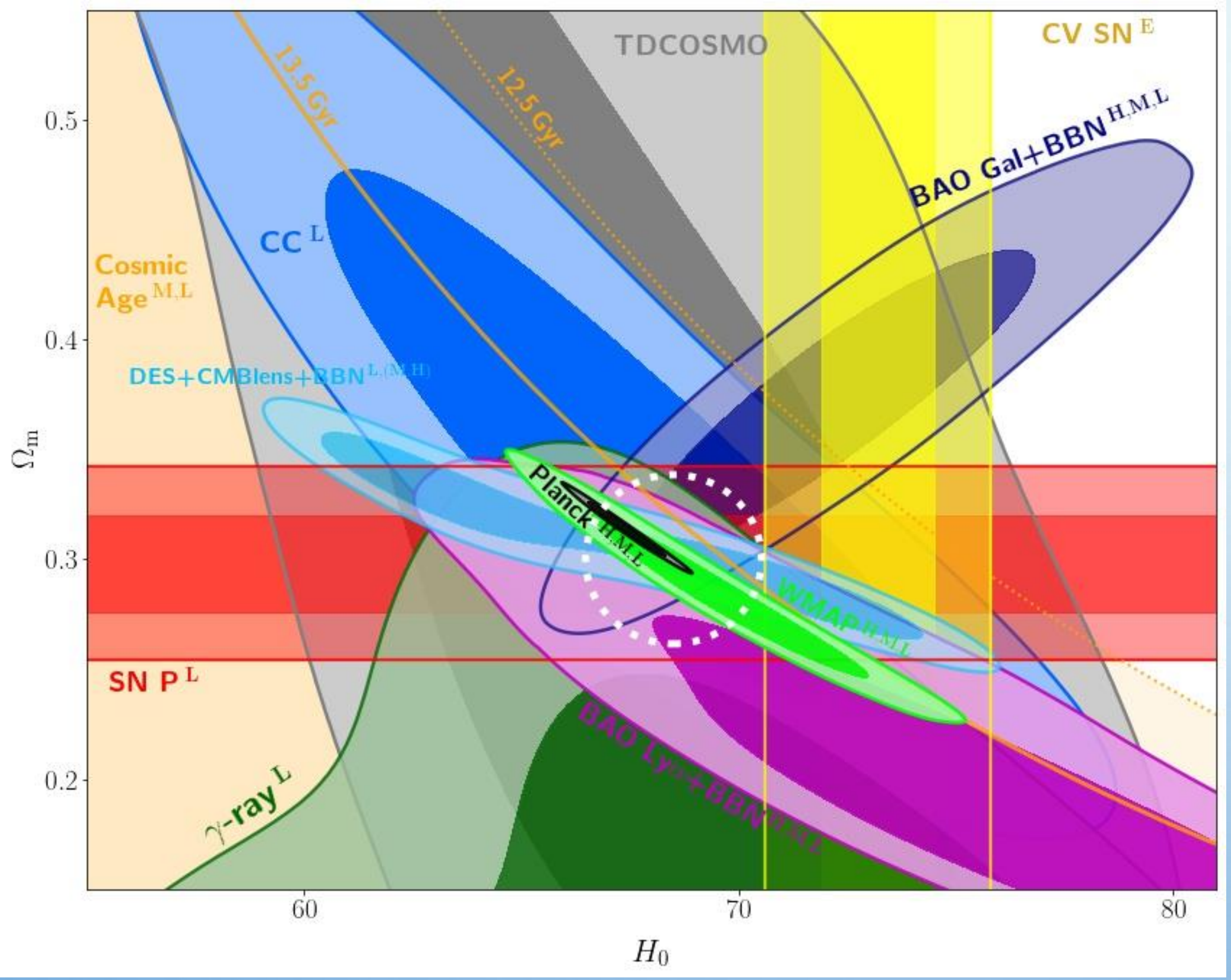
A universal prediction for pre-recombination resolutions

If pre-recombination physics alone can fully resolve the Hubble tension.

→

All post-recombination determinations of H_0 [km/s/Mpc] using post-recombination ΛCDM are closer to ~73 than to ~68.

Probes that measure the background



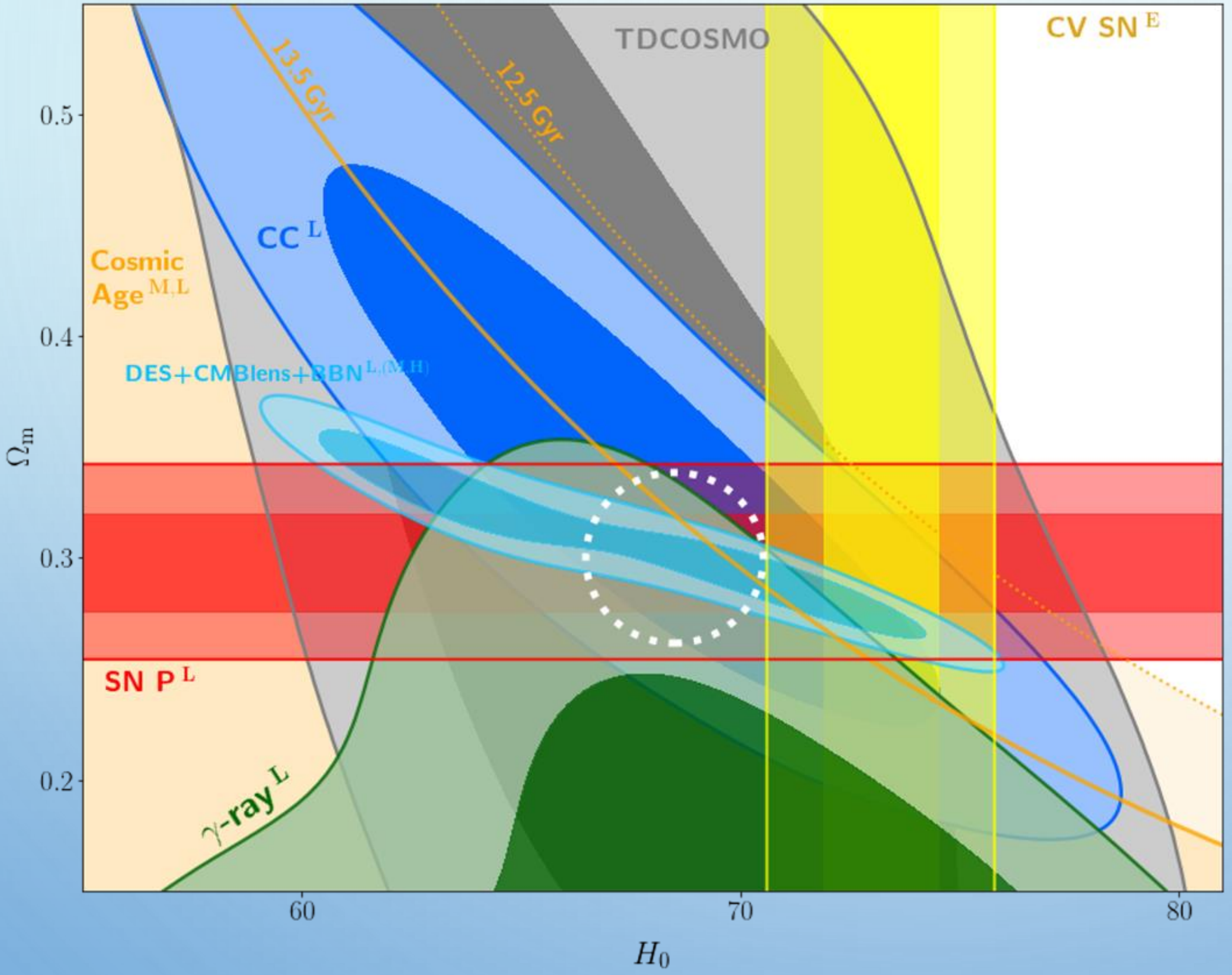
Take-home message 1:

Do not ignore Ω_m

- RESULTS ARE PRESENTED INDEPENDENTLY.
- EFFECTIVELY SEE THE MODEL DEPENDENCES.
- CONSISTENCY IS MORE ROBUST.

-- W. Lin et al, ApJL (2020), 1910.02978 [Plot here is updated]

Taking out CMB and BAOs



But what about CMB and BAO?

-- W. Lin, K. Mack and L. Hou, ApJL (2020), 1910.02978 [Plot updated here]

Analyzing CMB and BAO in an early-physics insensitive way

- Uncalibrated BAO is well-known:

$$\theta_d(z) = \frac{r_\mathrm{d} H_0}{f(z;\, \Omega_\mathrm{m})}$$

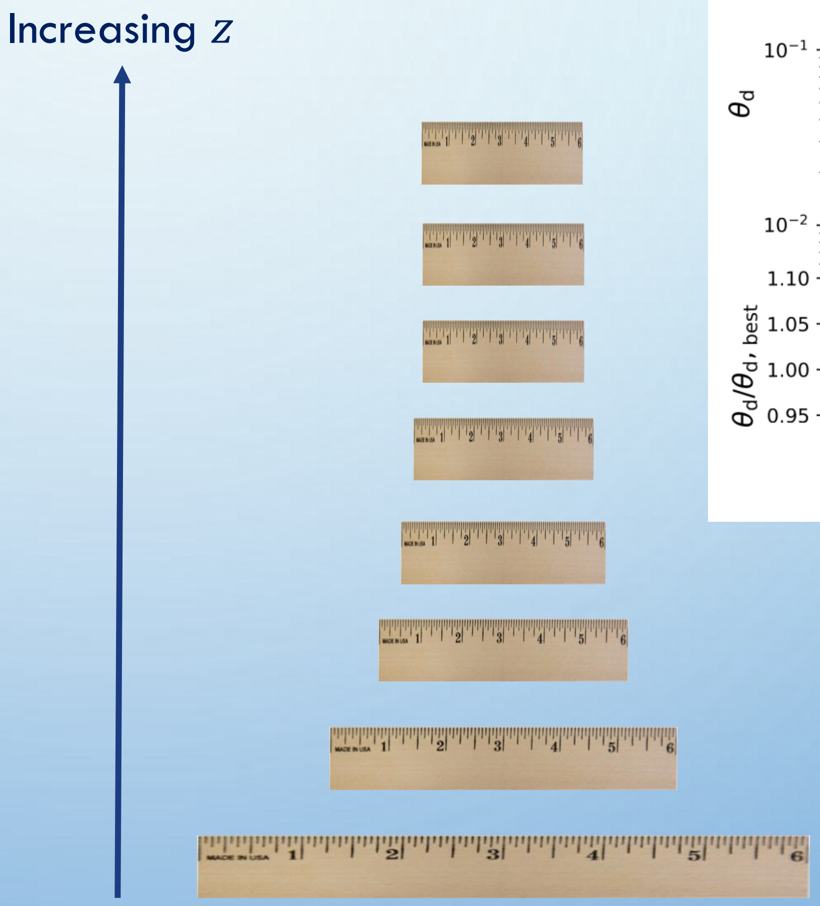
- We add to it the Uncalibrated horizon for CMB:

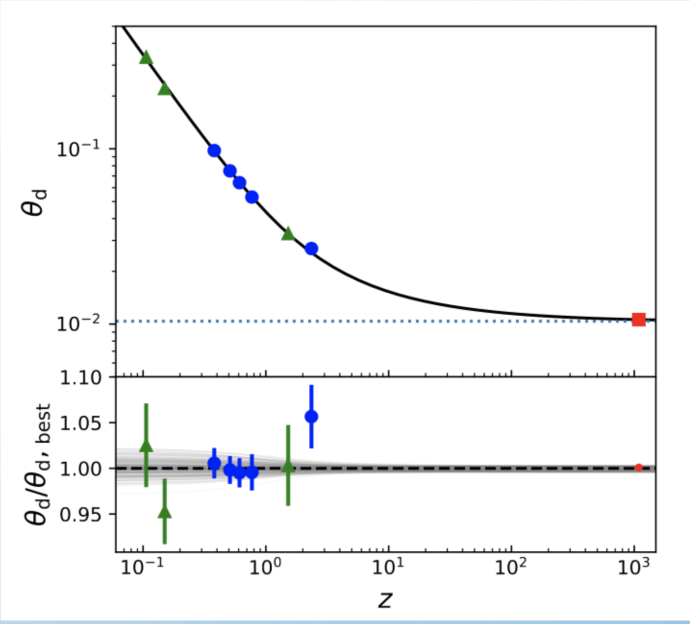
$$\theta_* = \frac{r_* H_0}{f(z_*;\, \Omega_\mathrm{m})}$$

- Linking the two horizon:

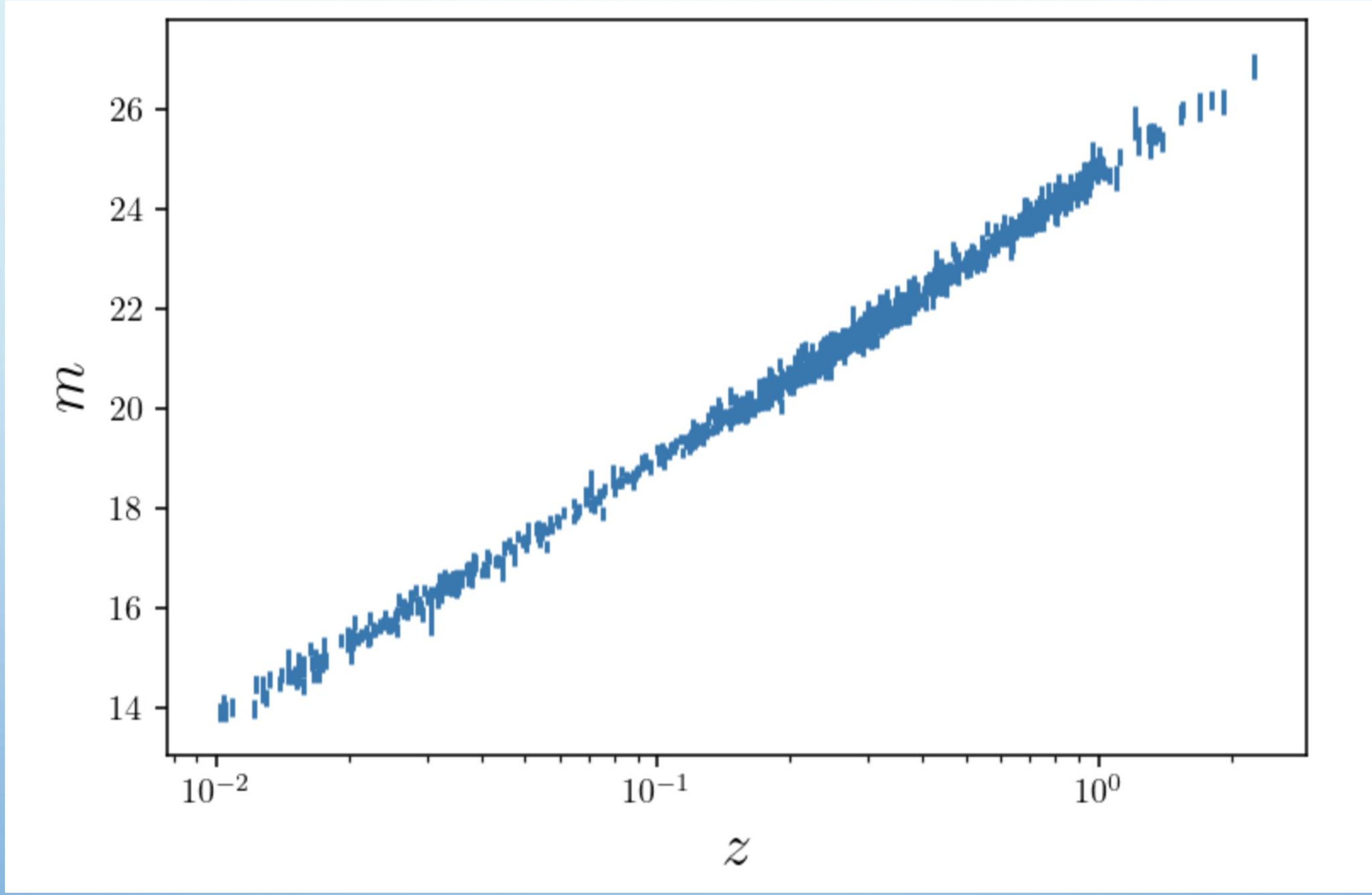
$$r_\mathrm{d} H_0 - r_* H_0 = \int_{z_d}^{z_*} \frac{c_\mathrm{s}(z)}{E(z)} dz$$

Dependences on early physics cancel out





Also well known: uncalibrated Type Ia Supernovae measures Ω_m

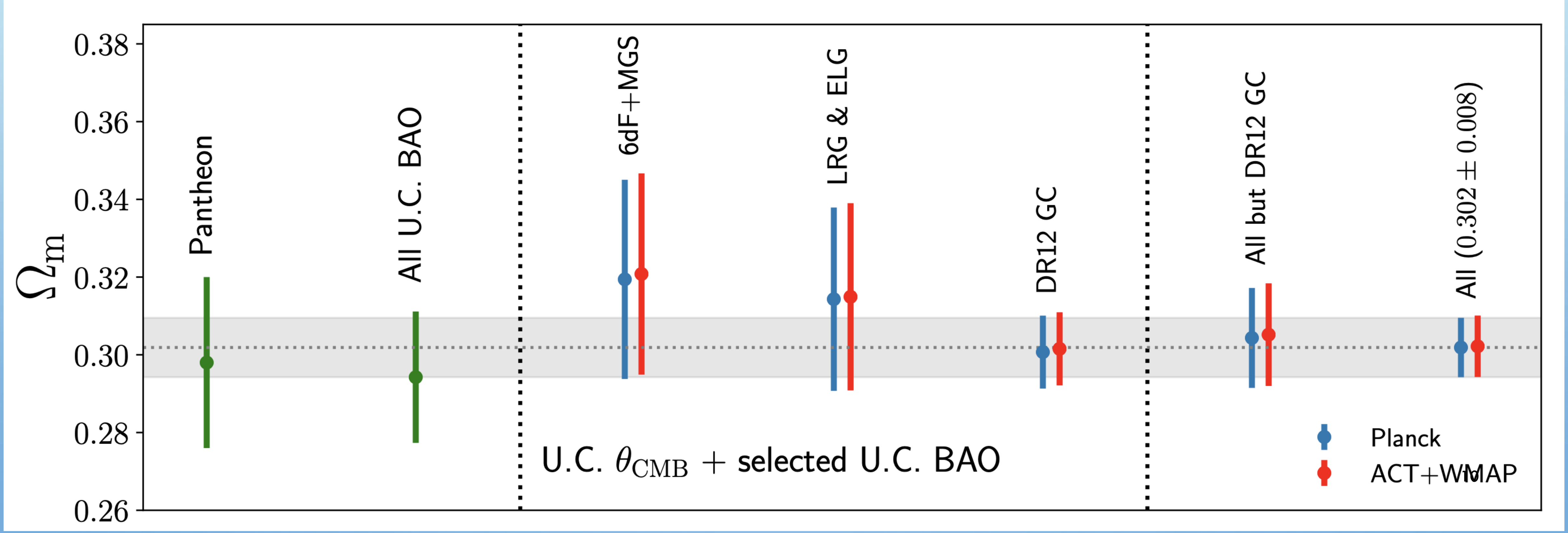


$$\ln l = -2\ln\left[(1+z)f_{\mathrm{M}}(z;\,\Omega_{\mathrm{m}},\cdots)\right] + \ln(LH_0^2/4\pi)$$

Take-home message 2: a strong and robust constraint constraint on Ω_m, nearly independent of early-physics

$$\Omega_{\mathrm{m}} = 0.302 \pm 0.008$$

Compared to 0.006~0.007 in Planck full ΛCDM analysis



Robustness of UCS to early-universe physics

Key: the fact that $r_* \sim r_d$ is insensitive to pre-recombination physics.

10% change in $\Delta r H_0$ only make 0.36% change in Ω_m

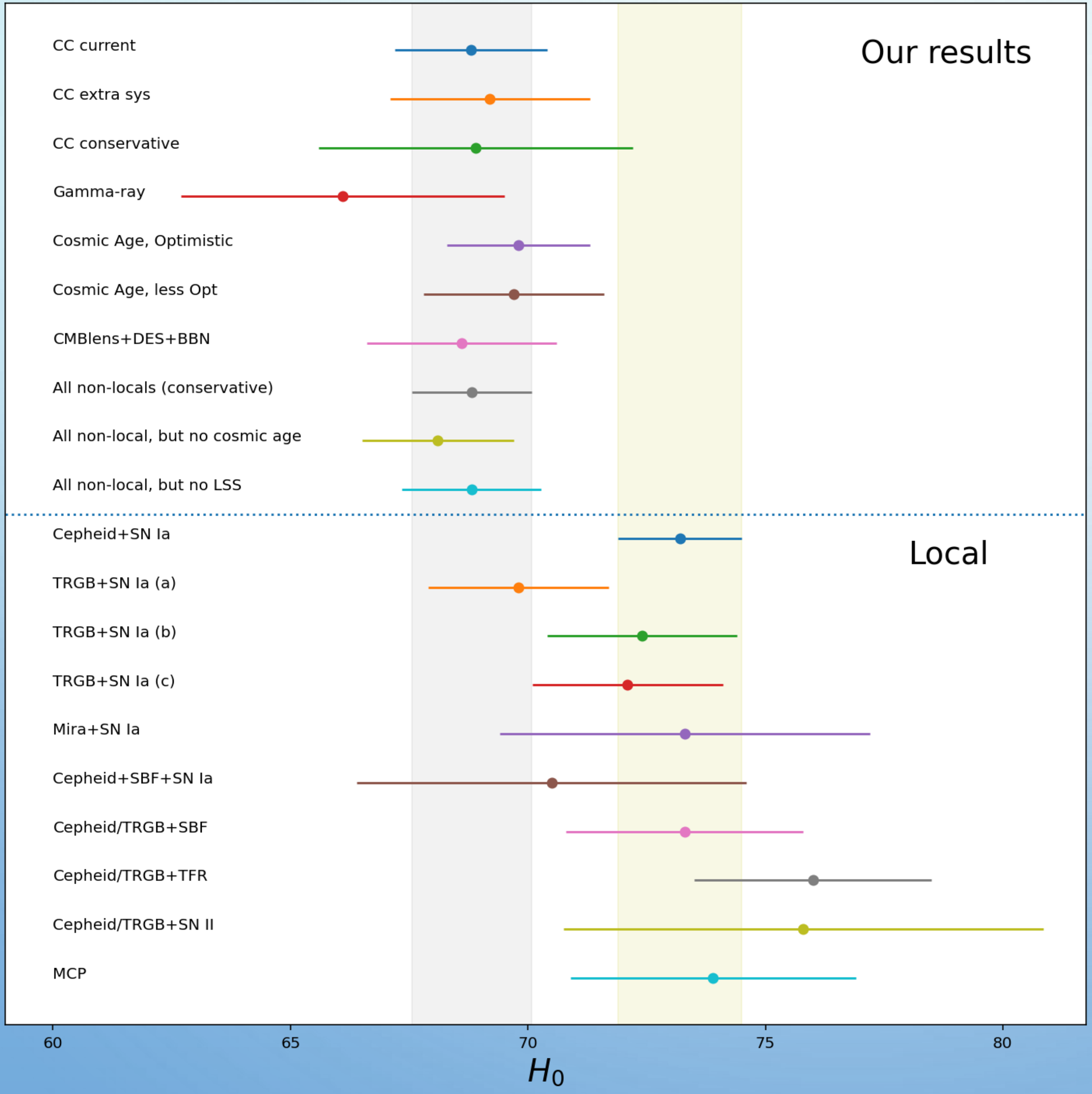
$$r_\mathrm{d} H_0 - r_* H_0 = \int_{z_\mathrm{d}}^{z_*} \frac{c_\mathrm{s}(z)}{E(z)} dz$$

Ways to change $\Delta r H_0$	**In order to change $\Delta r H_0$ by 10%**
1. Change sound speed	e.g. >50% change in $\Omega_b h^2$
2. E(z)	20% change in the energy content
3. Δz	10% change in Δz, different from the standard case by 6σ
4. z_*	The required change to z_* is too large! (>100)
5. θ_* itself?	θ_* is almost a direct measurement, using θ from Planck or ACT is consistent

UCS only provides a strong prior on Ω_m. To determine H_0, we need other information

- Cosmic chronometer (Moresco et al. 2016; Moresco & Marulli 2017; Moresco et al. 2020)
- γ-ray optical depth (Gould & Schre´der 1966; Ackermann et al. 2012; H.E.S.S. Collaboration & others 2013; Biteau & Williams 2015; Dom´inguez et al. 2019)
- Age of the universe (Jimenez et al. 2019; Bernal et al. 2021; Boylan-Kolchin & Weisz 2021; Valcin et al. 2021)
- Large-scale-structure + BBN (Lin & Ishak 2017; Baxter & Sherwin (2020); Philcox et al. (2021); Pogosian et al. 2020; CMB LENSING + DES YEAR 1)

Methods	H_0 (km/s/Mpc)		n-σ from R21	
UCS+individual non-local observation	Without $\theta_{\rm cmb}$	**With $\theta_{\rm cmb}$**	Without $\theta_{\rm cmb}$	**With $\theta_{\rm cmb}$**
Cosmic Chronometers				
Current public data	69.1 ± 1.7	$\mathbf{68.8 \pm 1.6}$	1.9σ	$\mathbf{2.1\sigma}$
Extra systematic	69.4 ± 2.3	$\mathbf{69.2 \pm 2.1}$	1.4σ	$\mathbf{1.6\sigma}$
Extra systematic, conservative	69.3 ± 3.4	$\mathbf{68.9 \pm 3.3}$	1.1σ	$\mathbf{1.2\sigma}$
γ-ray optical depth	66.2 ± 3.5	$\mathbf{66.1 \pm 3.4}$	1.9σ	$\mathbf{2.0\sigma}$
Cosmic Age				
$t_{\rm U} = 13.5 \pm 0.27\,{\rm Gyr}$	70.2 ± 1.7	$\mathbf{69.8 \pm 1.5}$	1.4σ	$\mathbf{1.7\sigma}$
$t_{\rm U} = 13.5 \pm 0.33\,{\rm Gyr}$	70.3 ± 2.1	$\mathbf{69.8 \pm 1.9}$	1.2σ	$\mathbf{1.5\sigma}$
CMBlens+DES+BBN	68.8 ± 2.4	$\mathbf{68.6 \pm 2.0}$	1.6σ	$\mathbf{1.9\sigma}$
UCS+joint non-local observations [a]				
All non-local observations	69.1 ± 1.5	$\mathbf{68.8 \pm 1.3}$	2.0σ	$\mathbf{2.4\sigma}$
Non-local observations without cosmic age	68.3 ± 1.9	$\mathbf{68.1 \pm 1.6}$	2.1σ	$\mathbf{2.5\sigma}$
Non-local observations without LSS	69.1 ± 1.6	$\mathbf{68.8 \pm 1.5}$	2.0σ	$\mathbf{2.2\sigma}$
Time-delay strong-lensing [b]				
TDCOSMO (Millon et al. 2020)		74.2 ± 1.6		
TDCOSMO+SLACS (Birrer, S. et al. 2020)		$67.4^{+4.1}_{-3.2}$		
Local measurements [c] **(distance ladder)**				
Cepheid+SN Ia (Riess et al. 2021)		73.2 ± 1.3		
TRGB+SN Ia (a) (Freedman et al. 2020)		69.8 ± 1.9		
TRGB+SN Ia (b) (Yuan et al. 2019)		72.4 ± 2.0		
TRGB+SN Ia (c) (Soltis et al. 2021)		72.1 ± 2.0		
Mira+SN Ia (Huang et al. 2020)		73.3 ± 3.9		
Cepheid+SBF+SN Ia (Khetan et al. 2021)		70.5 ± 4.1		
Cepheid/TRGB+SBF (Blakeslee et al. 2021)		73.3 ± 2.5		
Cepheid/TRGB+TFR (Kourkchi et al. 2020; Schombert et al. 2020)		76.0 ± 2.5		
Cepheid/TRGB+SN II (de Jaeger et al. 2020)		$75.8^{+5.2}_{-4.9}$		
Local measurements (non-distance ladder)				
Megamaser Cosmology Project (Pesce et al. 2020)		73.9 ± 3.0		
Standard siren multi-messenger (The LIGO Scientific Collaboration et al. 2021)		69^{+16}_{-8}		



Several results with reduced sensitivity to early physics consistently favor lower value of H_0.

There appears to be a tension between nonlocal versus local H_0 determinations

Take-home message 3: Several H_0 results with reduced sensitivity to early physics still favor lower value.

A universal prediction for pre-recombination resolutions

If pre-recombination physics alone can fully resolve the Hubble tension. ⇒ All post-recombination determinations of H_0 [km/s/Mpc] using post-recombination ΛCDM are closer to ~73 than to ~68.

Disfavored ⇐ Disfavored

The analysis here is complementary to and agree with Jedamzik, Pogosian and Zhao (2021): Early-universe resolutions tend to worsen the σ_8 tension.

Underlying assumptions of our results

Results	Assumptions
Ω_m	1. Post-recombination ΛCDM
	2. Standard rulers/candles have some time-independent features
	3. Physics during the small redshift gap (z_* to z_d) not too different from the standard
H_0	(a) All above
Type 1 (UCS+Astro)	(b1) The treatments of the corresponding astrophysical effects
Type 2 (UCS+LSS)	Raised sensitivity to early physics (but still reduced to a large extent and not relying on sound horizon)
	(c1) The dependence of the matter power on $\Omega_m h$; horizon scale at radiation-matter equality
	(c2) BBN constraint on $\Omega_b h^2$ (but weak dependence)

See 2102.05701 and references wherein for detailed discussions

Use UCS as test to late-time models

ADVANTAGES:

- Free from biases due to possible early-time nonstandard physics or systematic errors in the CMB;

- Minimal assumptions with remained constraining power.

Beyond the Hubble tension

- There are many situations that require to know Ω_m, e.g., large scale structure and the σ_8 tension;

    -- Recall that cosmology was called “a search of two numbers”.

- Whenever you need an early-universe-physics insensitive prior of Ω_m using UCS!

Now $\Omega_m = 0.302 \pm 0.008$

SUMMARY

UCS only gets more & more important

- Take-home 1-- Don't ignore Ω_m:
  Important to look at Ω_m and H_0 simultaneously.

- Take-home 2 – UCS robustly tells us Ω_m:
  Releases r_s and use UCS in data, $\Omega_m = 0.302 \pm 0.008$.

- Take-home 3 -- Early-time physics cannot fully resolve H_0 tension:
  The tension appears to be between nonlocal versus local, instead of the often quoted pre-recombination vs post-recombination.