The trouble with H_0 (and beyond)

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Johns Hopkins University

with Licia Verde, Marc Kamionkowski, Raul Jimenez, David Valcin, Tristan Smith, Kimberly Boddy, Adam Riess, …

KICP
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JOHNS HOPKINS
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Introduction

- Precision cosmology: CMB, clustering & BAO, lensing, SNeIa, GWs, …

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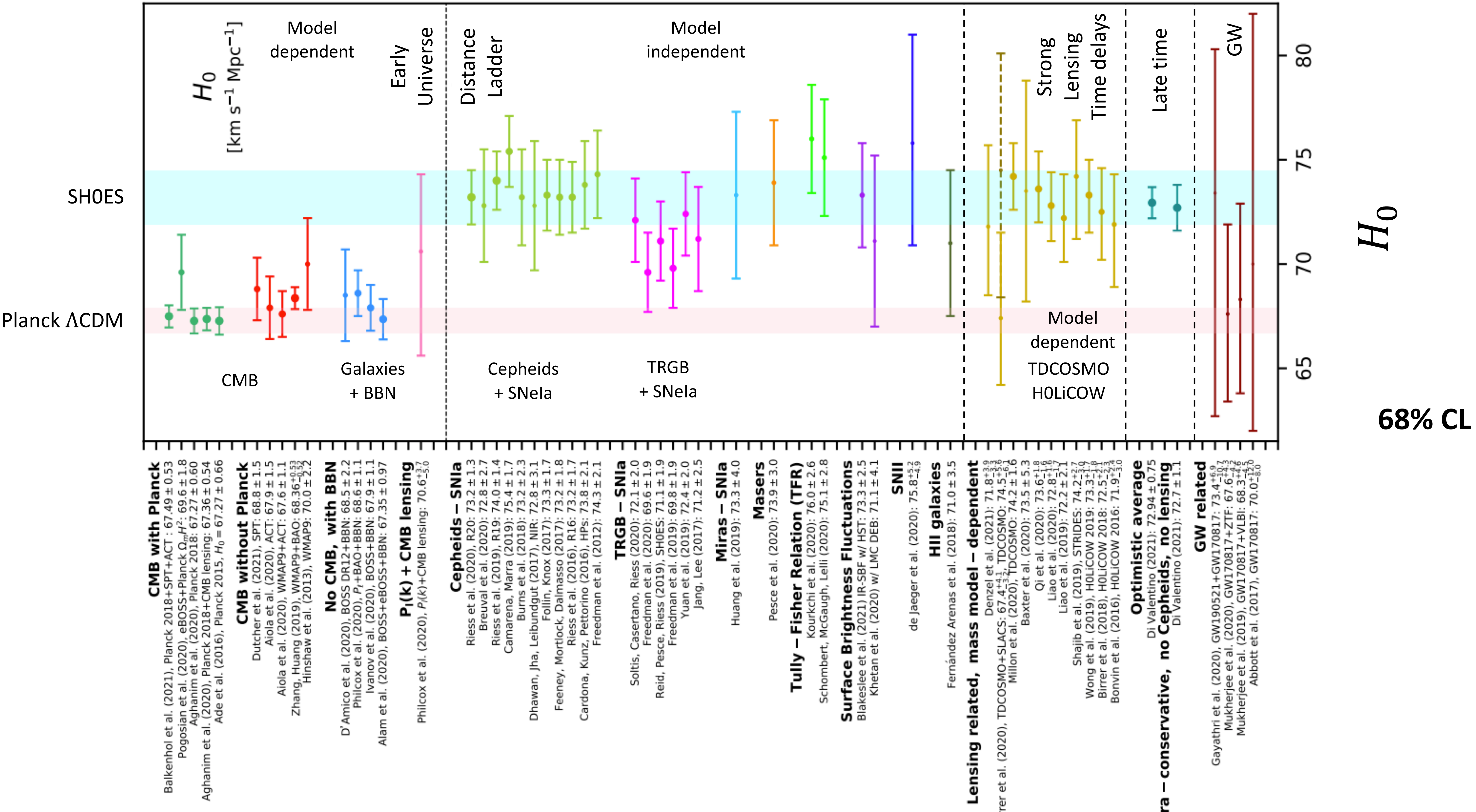
- Standard cosmological model: ΛCDM
- Excellent reproduction of the observations, but…
    - Phenomenological model: nature of DM and DE? Primordial Universe?
    - Persistent discrepancies between different cosmological probes (high-z vs low-z?): H_0, $\sigma_8\Omega_M^{0.5}$

Introduction

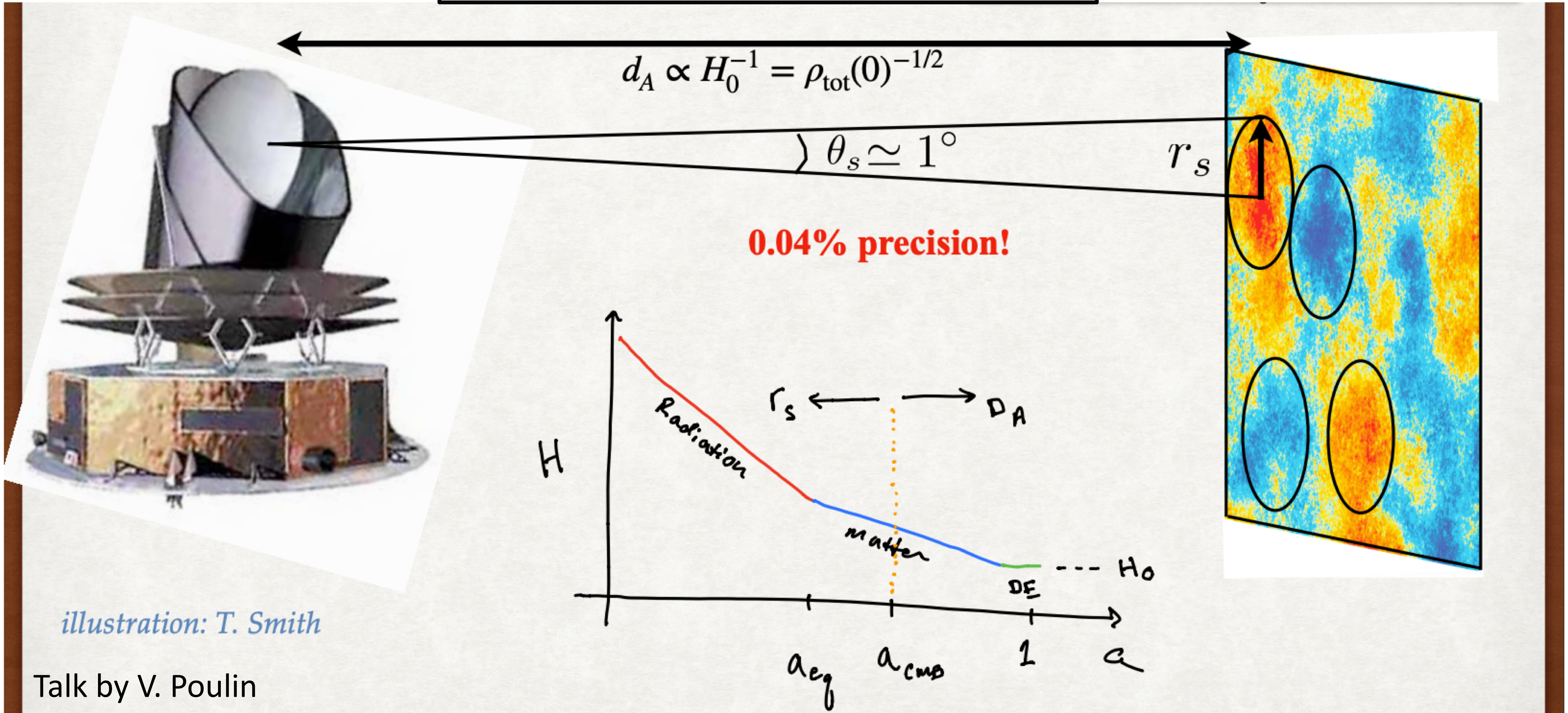
- Precision cosmology: CMB, clustering & BAO, lensing, SNeIa, …
- Standard cosmological model: ΛCDM
- Excellent reproduction of the observations, but…
- Improvement of observations, new cosmological probes, new models, …



Adapted from di Valentino+ 2021

Inferring H_0 from CMB

$$\theta_s \sim \frac{r_s(z_*)}{D_M(z_*)} = \frac{\int_{\infty}^{z_*} c_s(z)dz/H(z)}{\int_{z_*}^{0} c(z)dz/H(z)}$$



Talk by V. Poulin

Inferring H_0 from CMB

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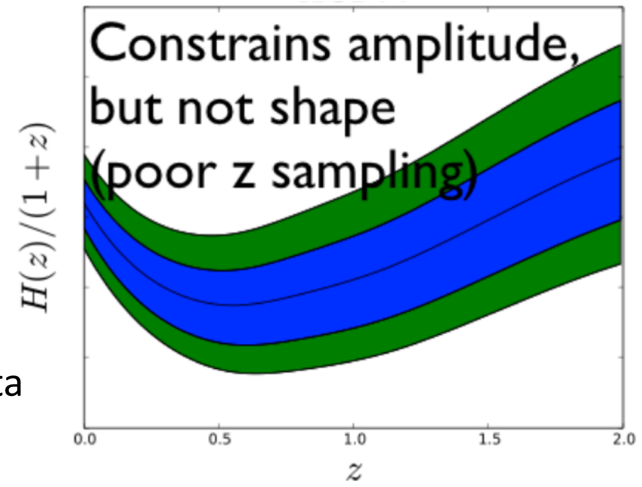
With a high H_0…

- Pre-recombination mods: (change r_s to compensate)
  - Change z_*
  - Change c_s
  - Change $H(z)$
- Post-recombination mods: (keep $D_M(z_*)$ unchanged)
  - Change $H(z)$

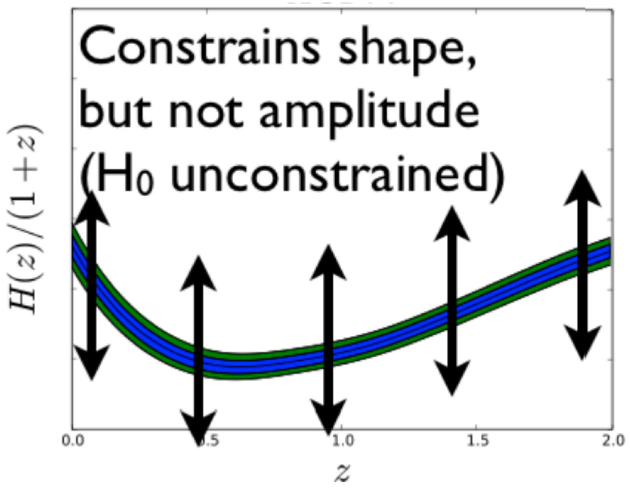
Check Hubble Hunter's guide (Knox & Millea 2019)

Cosmic distance ladder(s)

BAO



SNeIA



A. J. Cuesta

Exploiting BAO

- BAO feature frozen in matter overdensities after recombination

Standard ruler!

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- LSS observations: z → distances (fiducial cosmology needed)

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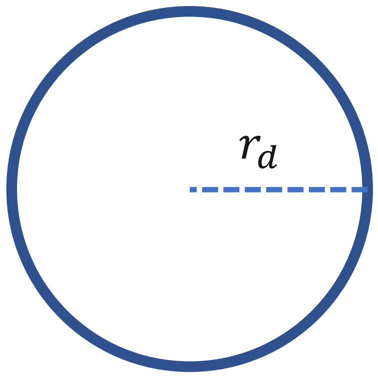
BAO: recognizable feature in $P(k)$

$$x_\perp = D_M(z)\theta$$

$$x_\parallel = \frac{c\delta z}{H(z)}$$



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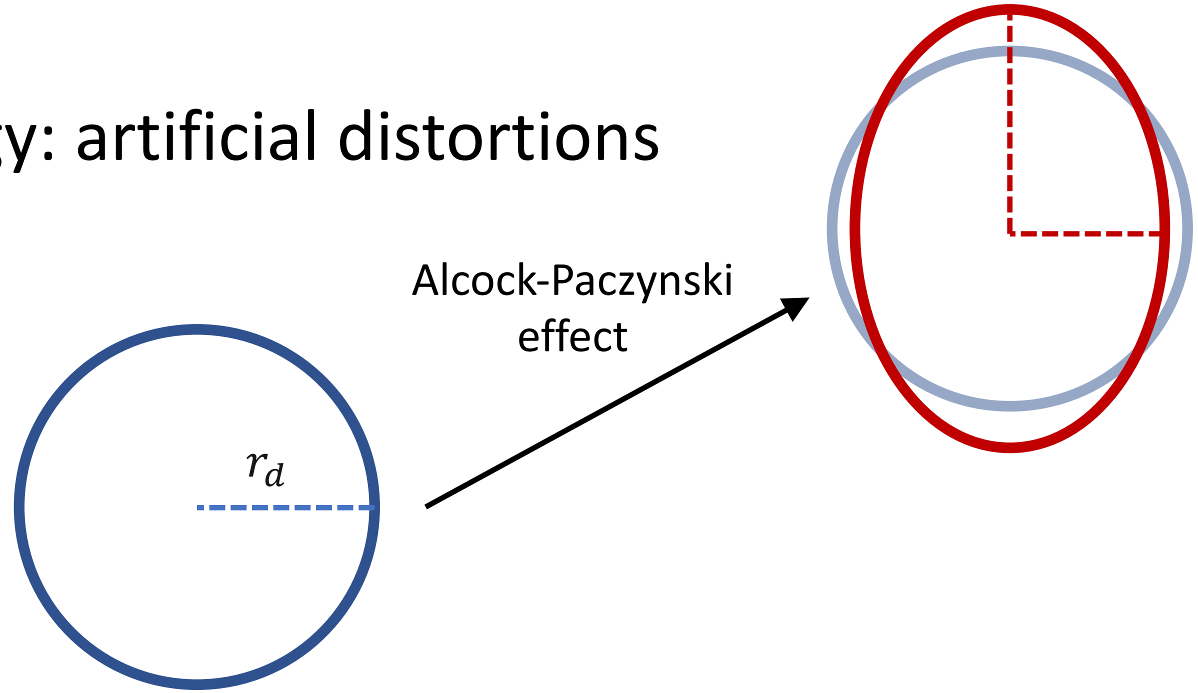

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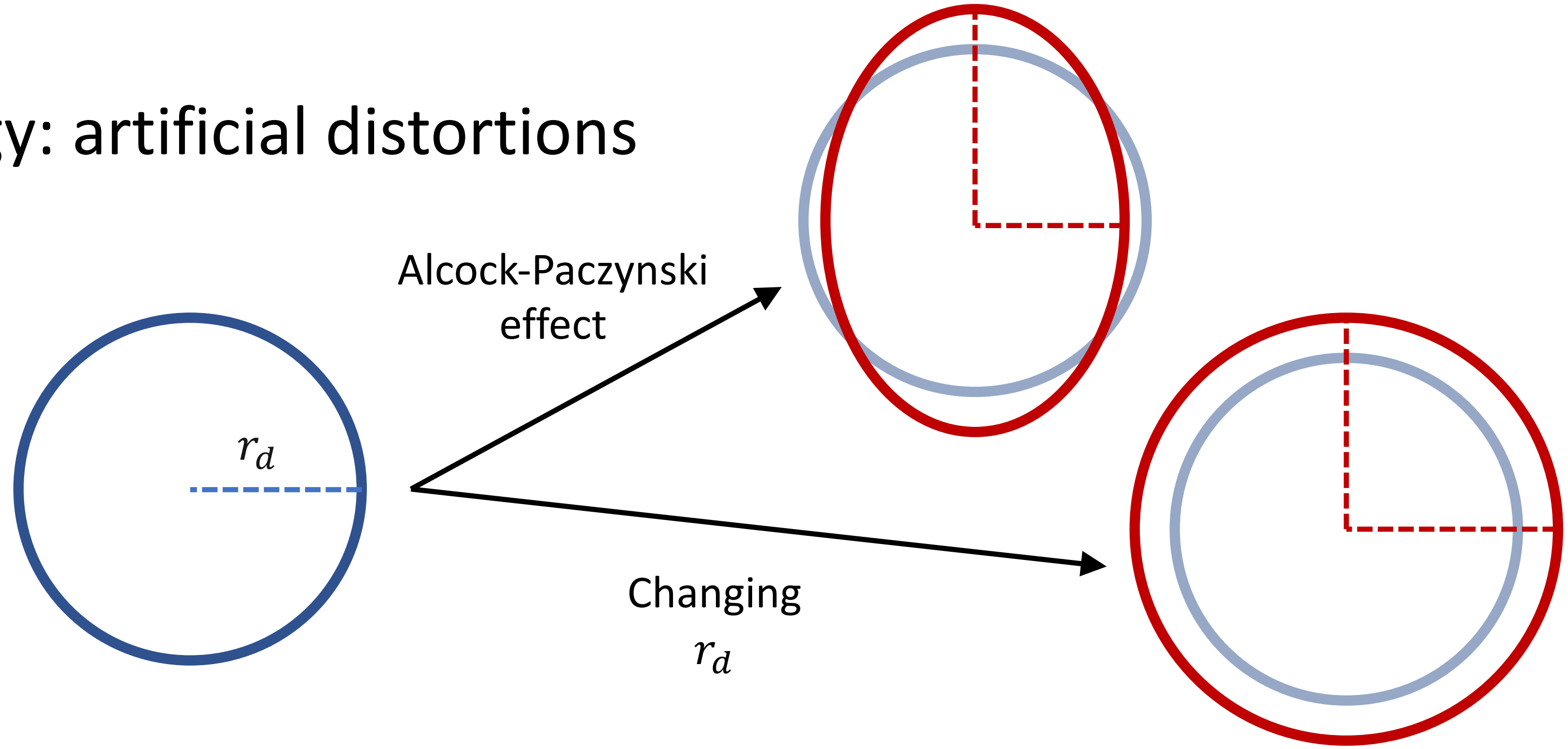

Exploiting BAO

- BAO feature frozen in matter overdensities after recombination
- LSS observations: z → distances (fiducial cosmology needed)
- Wrong cosmology: artificial distortions → $k_{\parallel}^{meas} = k_{\parallel}^{true}\alpha_{\parallel}; \;\; k_{\perp}^{meas} = k_{\perp}^{true}\alpha_{\perp}$
- Measurement: template + rescaling + broadband marginalization

$$\alpha_{\perp} = \frac{D_M(z)/r_d}{(D_M(z)/r_d)^{fid}}$$

$$P(\vec{k}^{meas}) \propto P(k_{\parallel}^{true}\alpha_{\parallel}, k_{\perp}^{true}\alpha_{\perp}) + A(\vec{k}^{meas}, \vec{\eta})$$

Isolating BAO feature

Broadband marginalization

$$\alpha_{\parallel} = \frac{(H(z)r_d)^{fid}}{H(z)r_d}$$

Exploiting BAO

- BAO featu … on
- LSS observ
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BAO provide model independent information of the expansion history of the Universe

Normalization: $r_d \times H_0$

- Measurement: template + rescaling + broadband marginalization

$$P(\vec{k}^{meas}) \propto P\left(k_\parallel^{true}\alpha_\parallel, k_\perp^{true}\alpha_\perp\right) + A(\vec{k}^{meas}, \vec{\eta})$$

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Broadband marginalization

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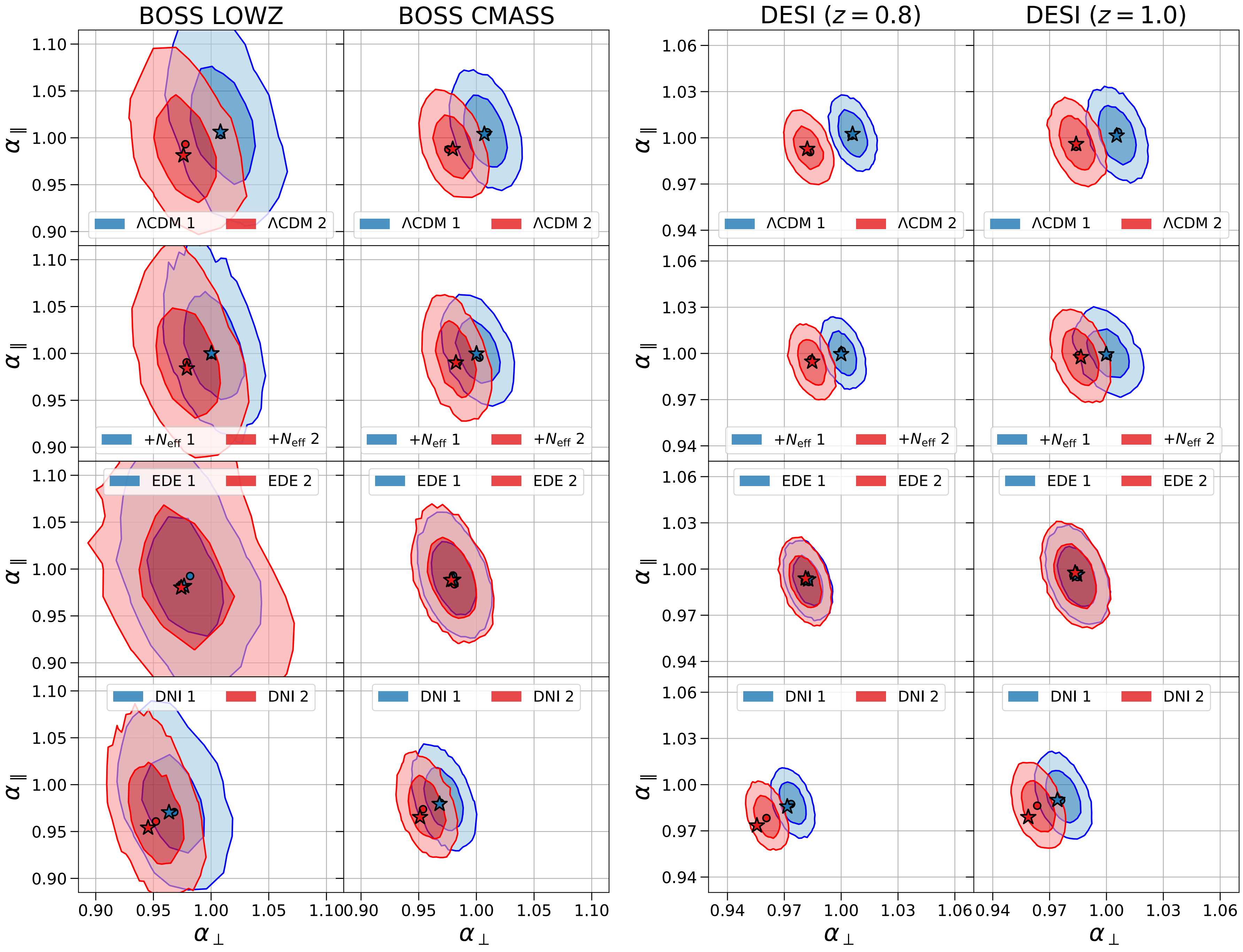
Bernal+ 2020



Check on synthetic $P(k)$:

Fit different models with a template computed assuming Planck's ΛCDM best fit

- ● Maximum posterior values
- ★ True values
- ■ Good fit to Planck
- ■ Bad fit to Planck

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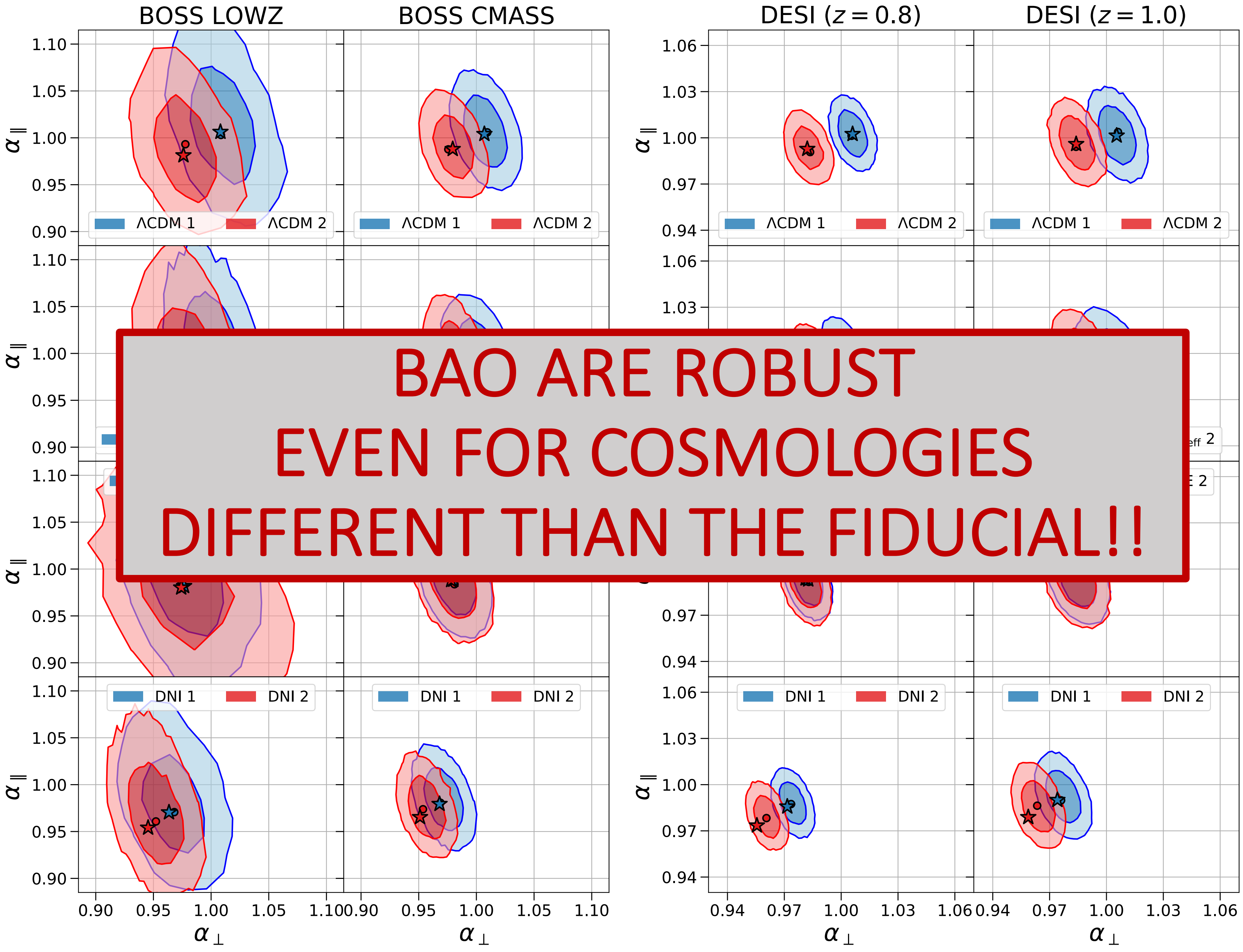

BAO ARE ROBUST EVEN FOR COSMOLOGIES DIFFERENT THAN THE FIDUCIAL!!

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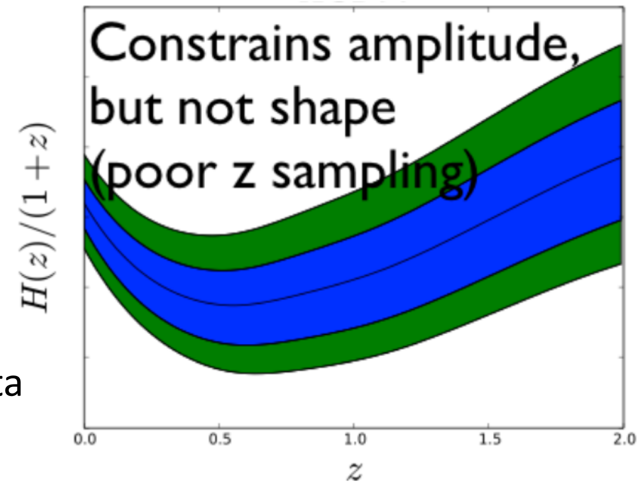
Cosmic distance ladder(s)

Agnostic approach: Model independent analysis of low-z observations

BAO



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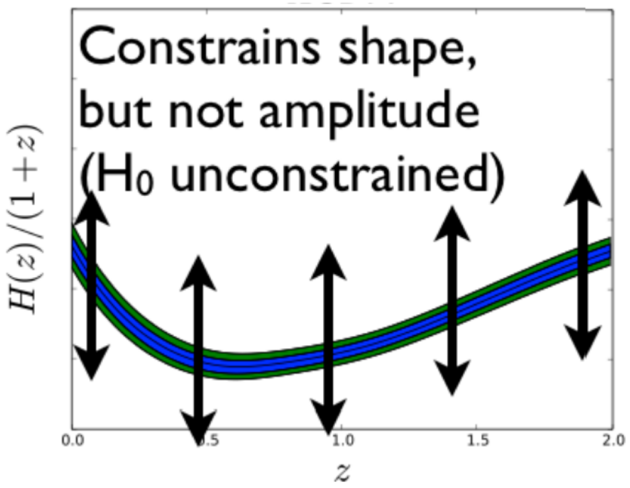
SNeIA



BAO normalization $\propto r_d \times H_0$

BAO: *actually*
model independent! (JLB+, 2020)

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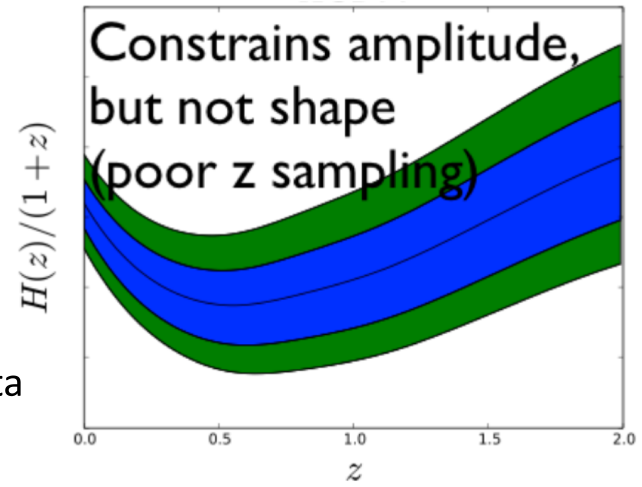

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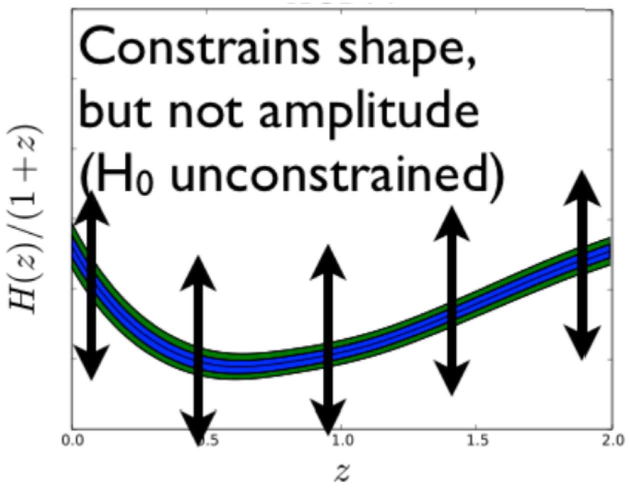

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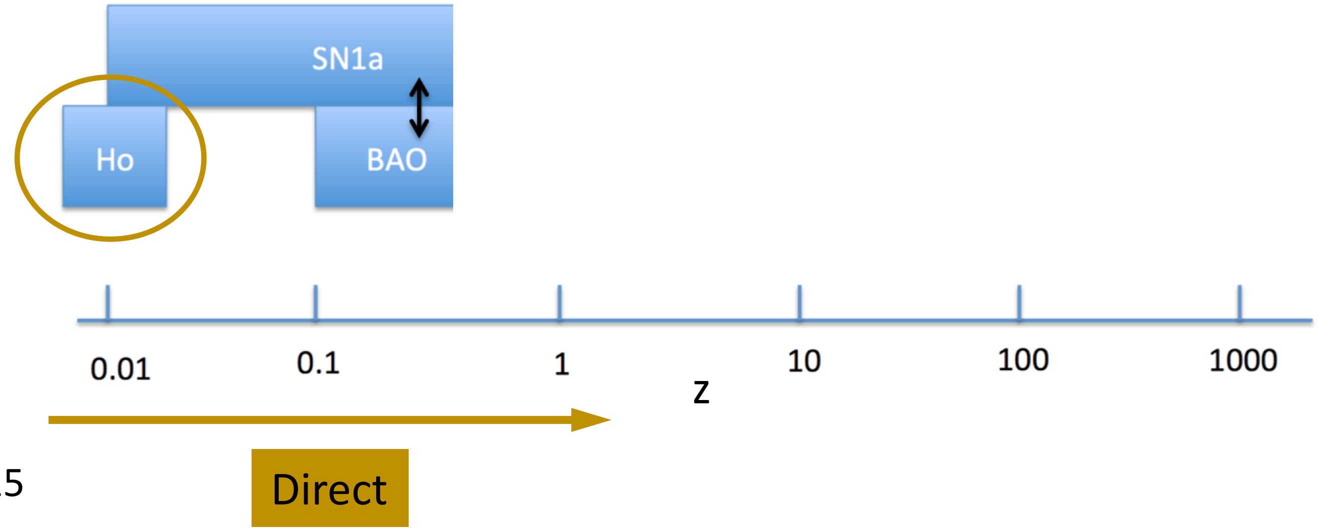

Cuesta+2015

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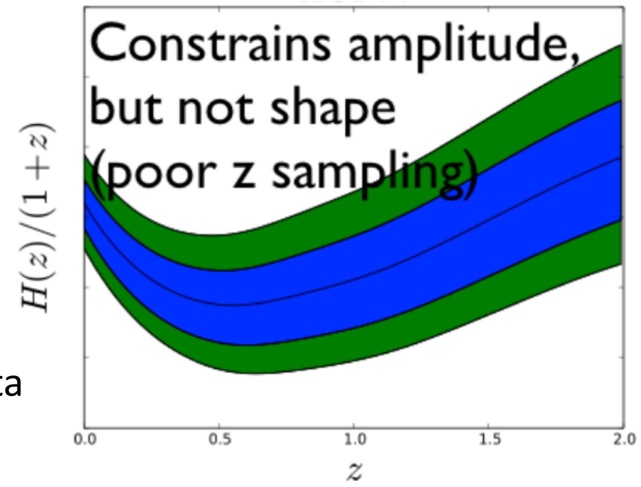

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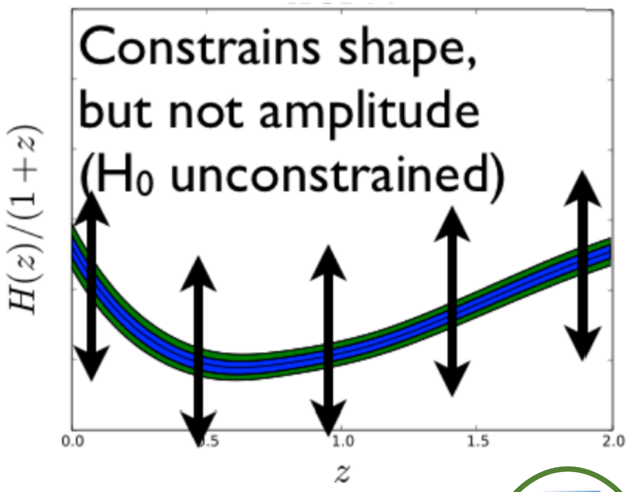

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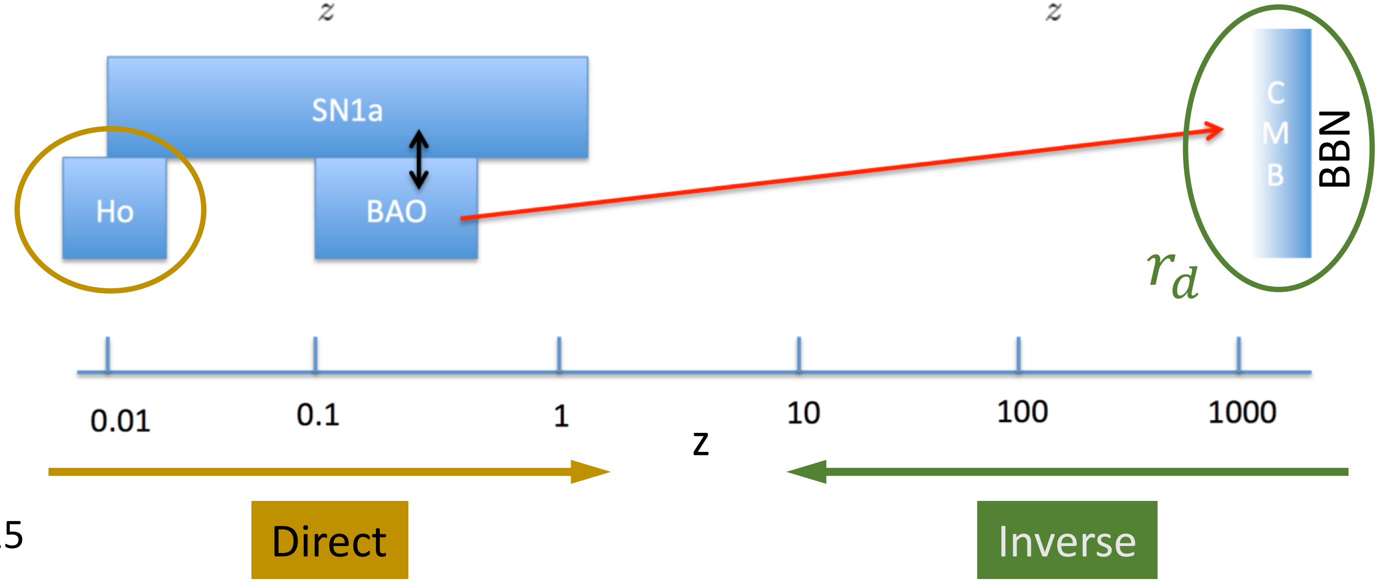
BAO calibrating SNeIA
(inverse distance ladder)



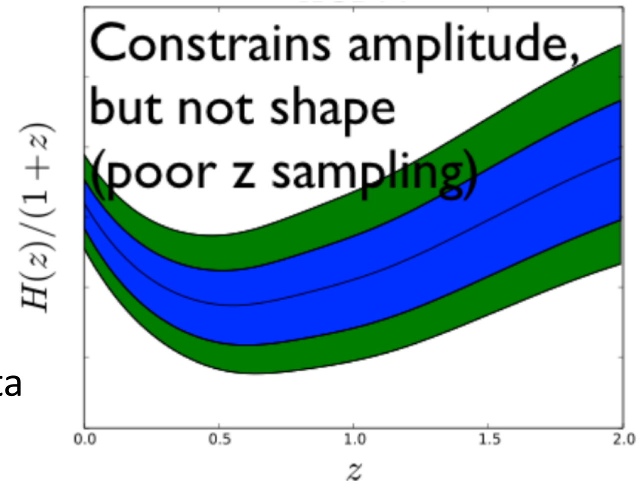
Two anchors of the cosmic distance ladder

Cuesta+2015

Cosmic distance ladder(s)

Agnostic approach: Model independent analysis of low-z observations

BAO



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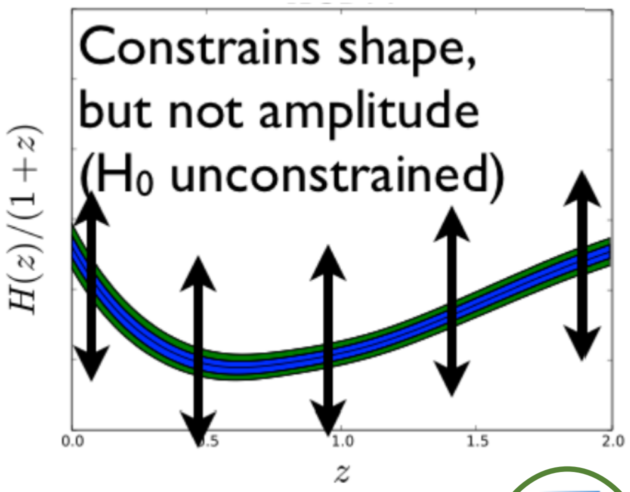

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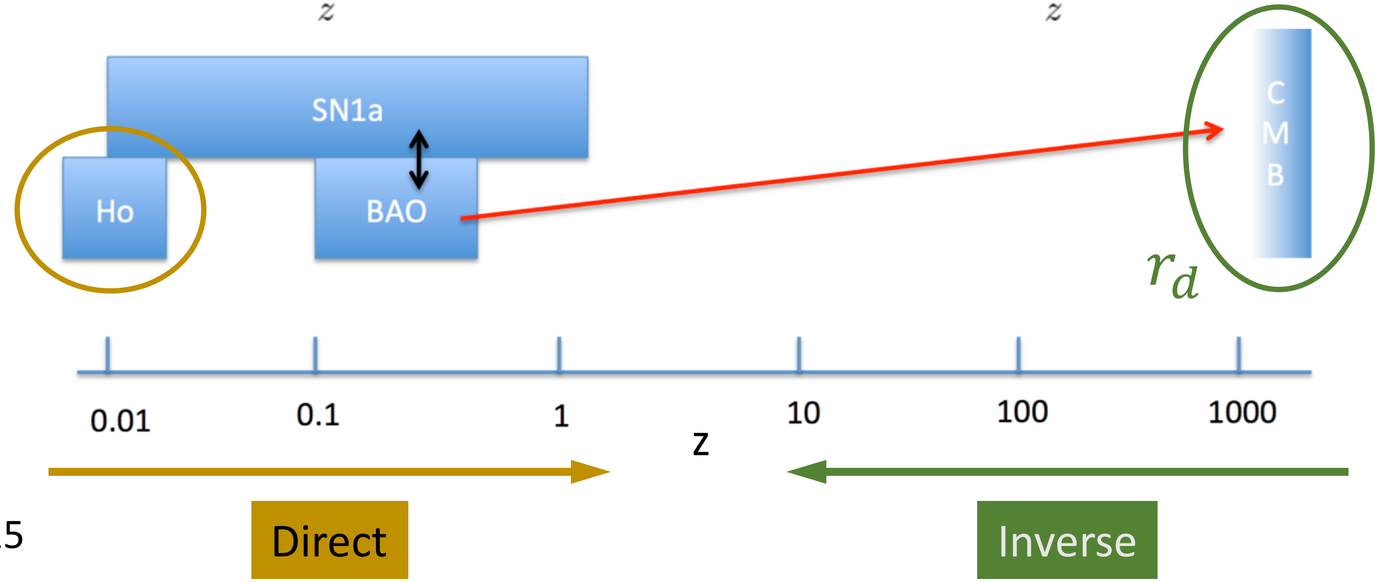

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Two anchors of the
cosmic distance ladder

Free the anchors

Low-z standard ruler

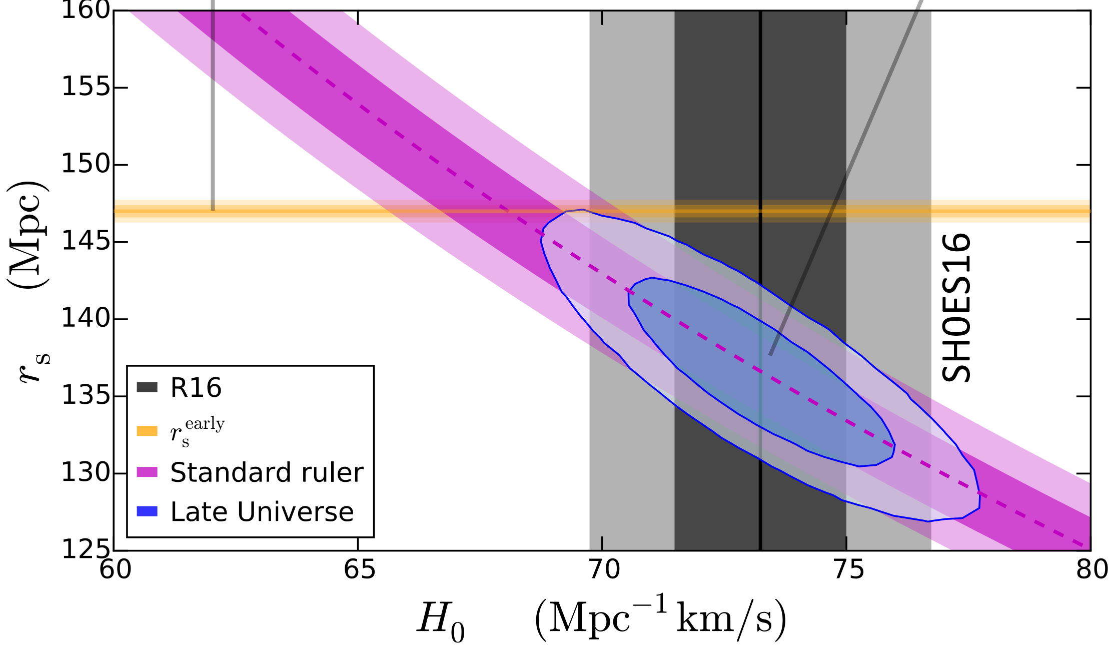
$r_d \times H_0$

Verde, JLB+ 2017

High-z vs low-z

Planck 2015 (only early Universe)
Verde+ 2017

BAO (free r_d)+SN+
SH0ES16



- BAO+SN constrain:
  - Expansion to be ΛCDM-like (dev. < 5%)
  - $r_d \times H_0$ below 2% precision (Verde, JLB+ 2017)

- Mismatch between the two anchors of the cosmic distance ladder (r_d & H_0)

JLB+ 2016

High-z vs low-z

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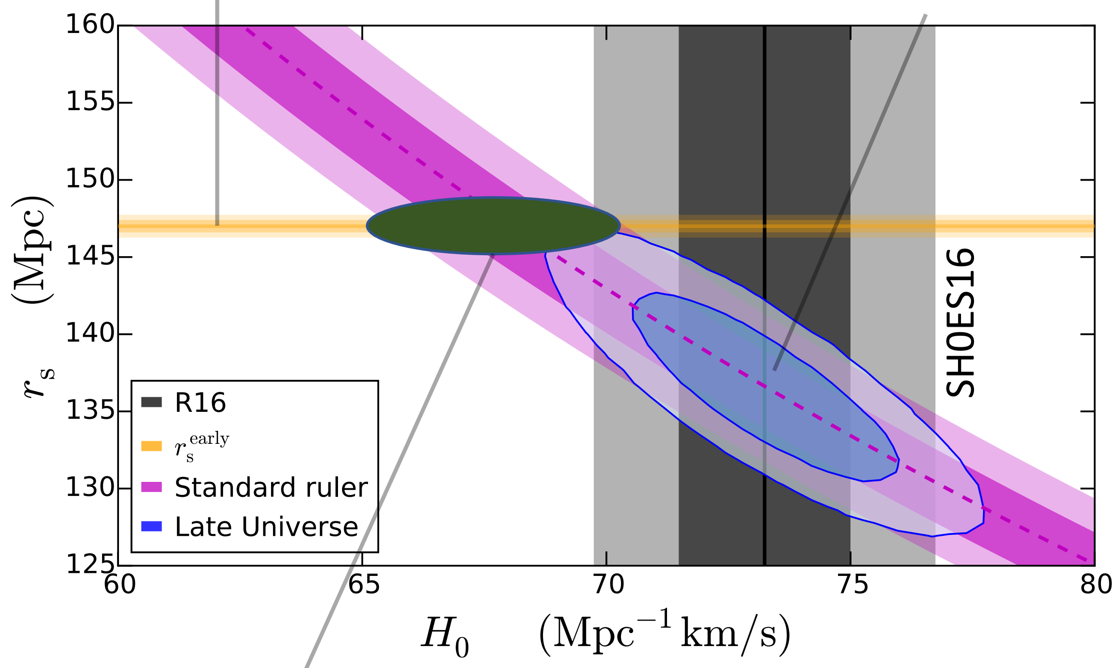

BAO+SN+
Planck 2015 (only early Universe)

Independent measurements

- BAO+SN constrain:
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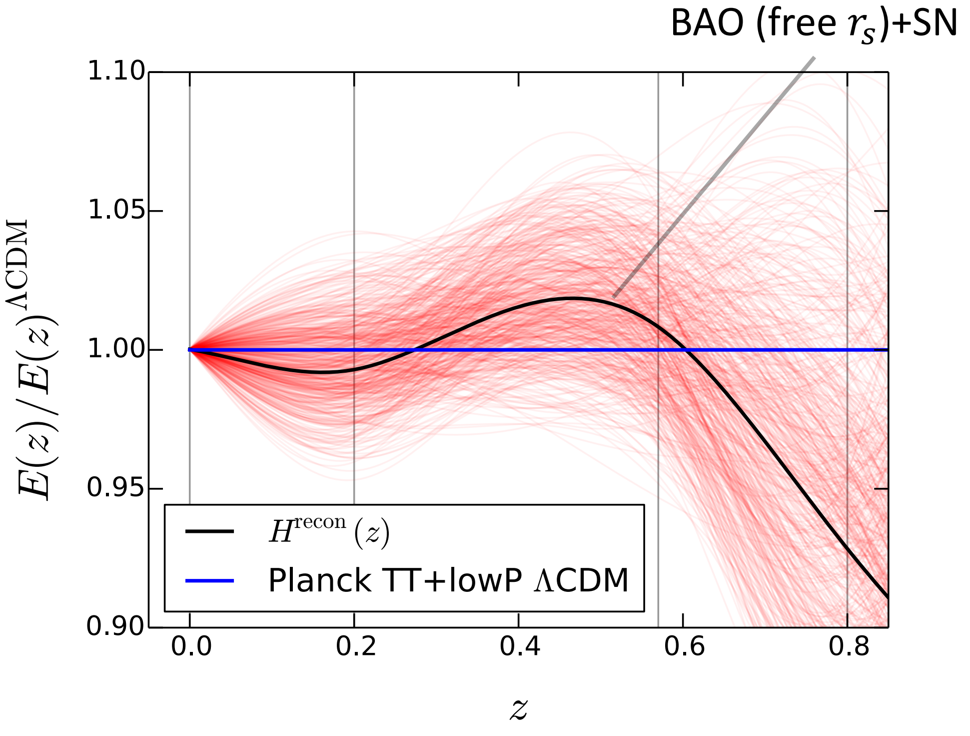
r_d needs to be smaller to match a larger H_0

JLB+ 2016

High-z vs low-z



$E(z) \equiv H(z)/H_0$
(shape of expansion history)

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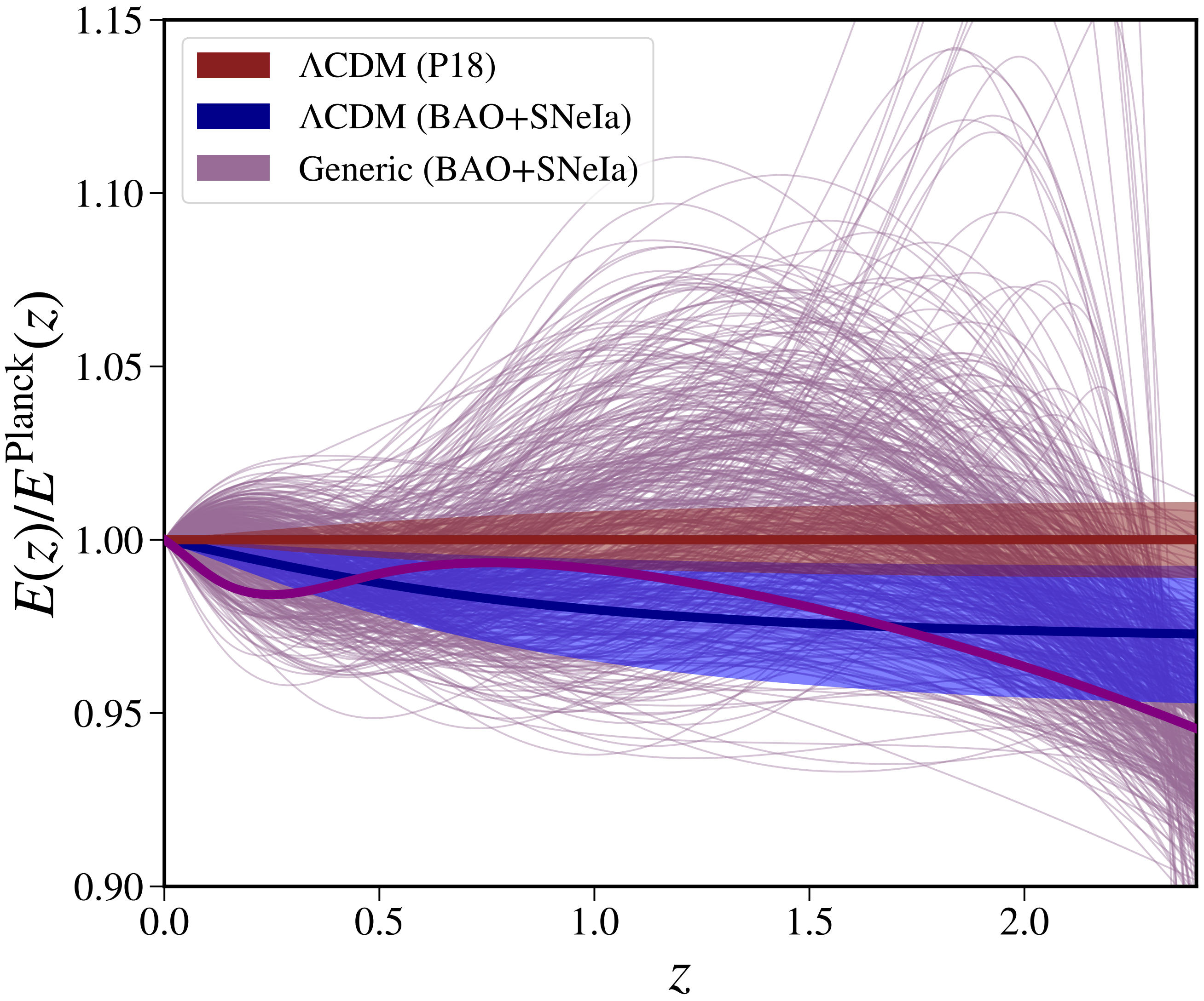
Not a lot of freedom in expansion history at $z \lesssim 0.6$ to alleviate the tension

JLB+ 2021

High-z vs low-z

Done using MABEL



- Planck 18 (ΛCDM):
  - $r_d h = 99.1 \pm 0.9$ Mpc
  - $\Omega_M = 0.3153 \pm 0.0073$
- BAO + SNeIa (ΛCDM):
  - $r_d h = 100.6 \pm 1.1$ Mpc
  - $\Omega_M = 0.297 \pm 0.013$

JLB+ 2021

High-z vs low-z

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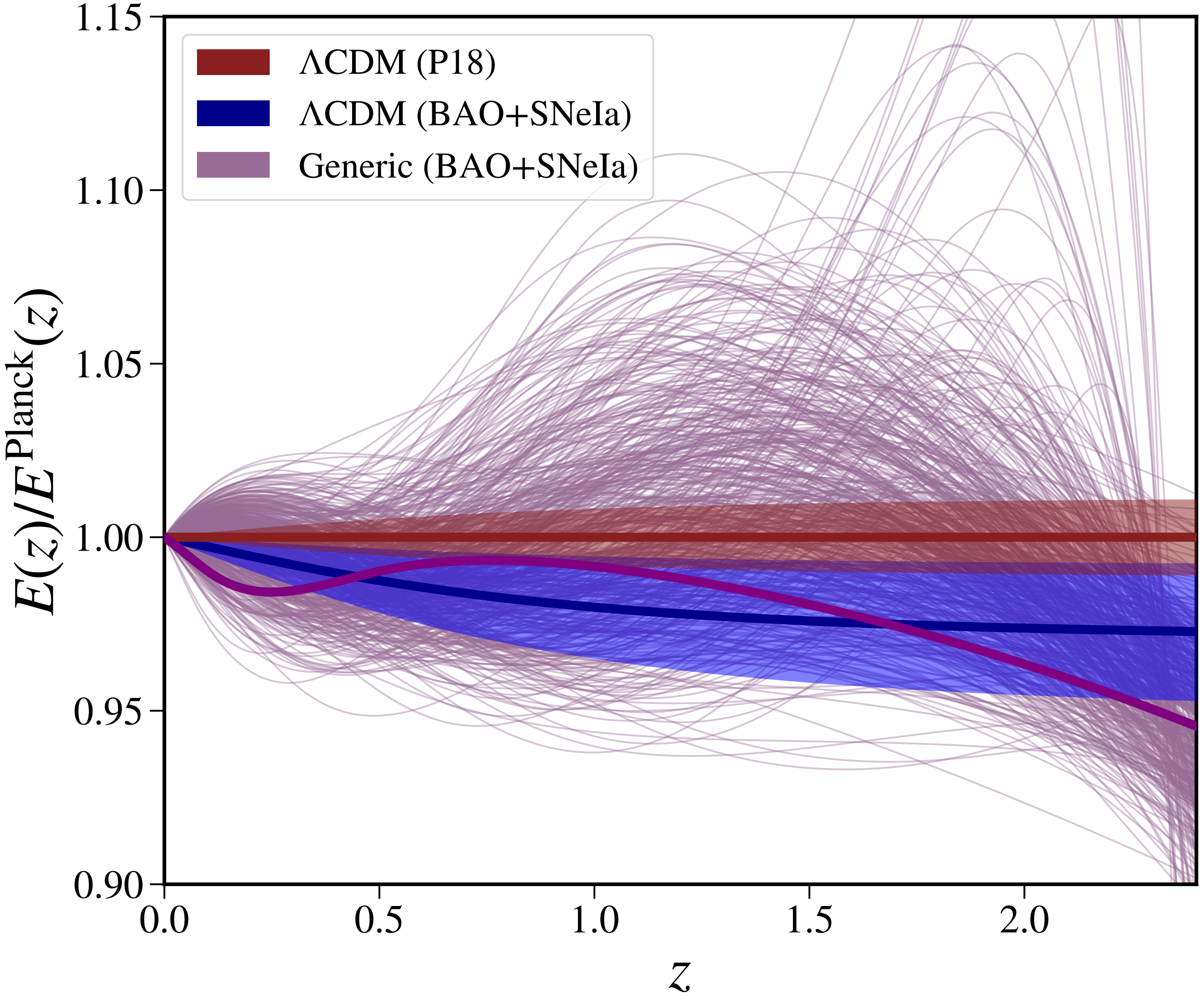

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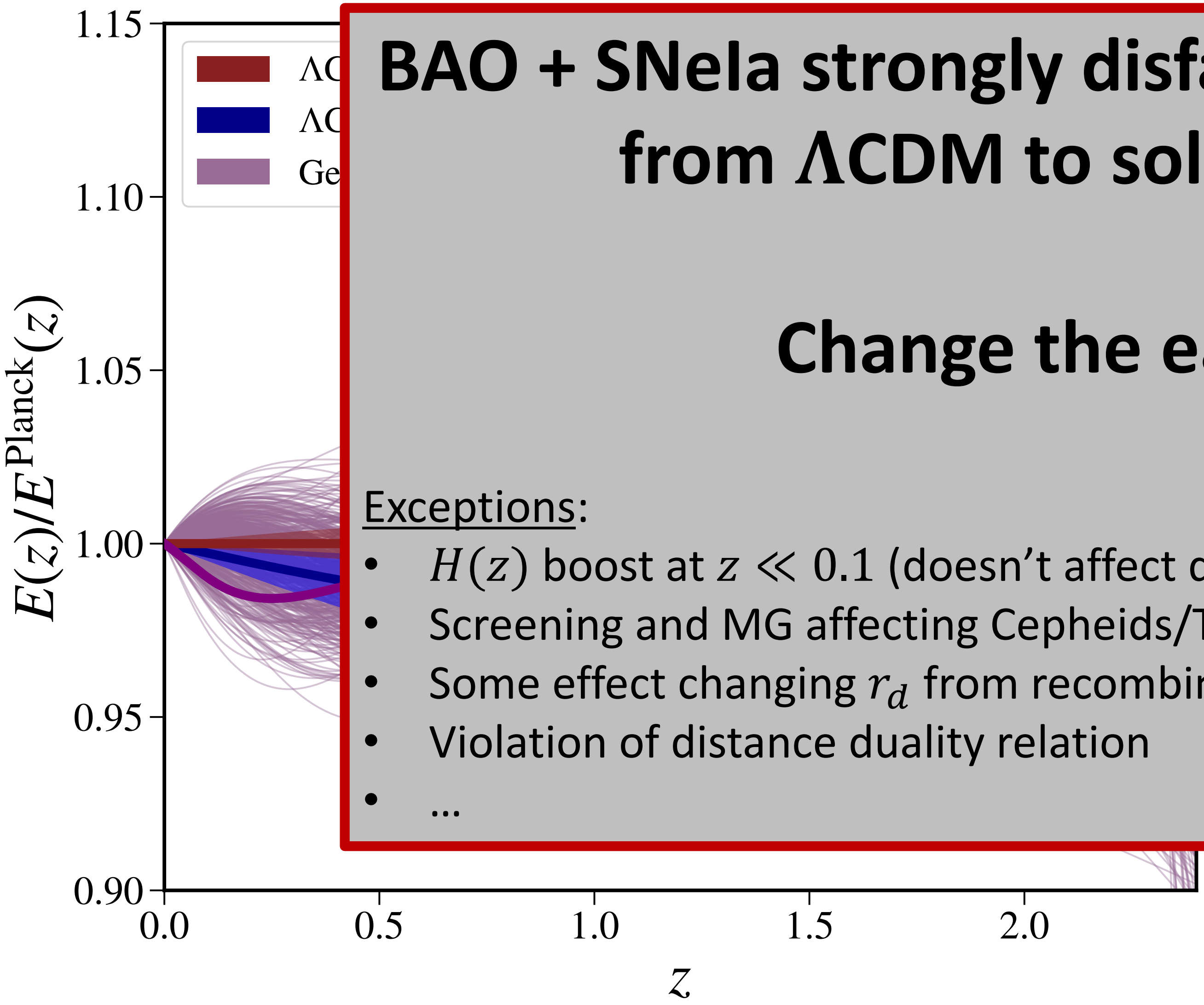
- BAO + SNeIa (flexknot):
  - $r_d h = 100.2 \pm 1.2$ Mpc
  - $\Omega_K = -0.02 \pm 0.10$

High-z vs low-z

Done using MABEL



BAO + SNeIa strongly disfavors any low z deviation from ΛCDM to solve the H_0 tension

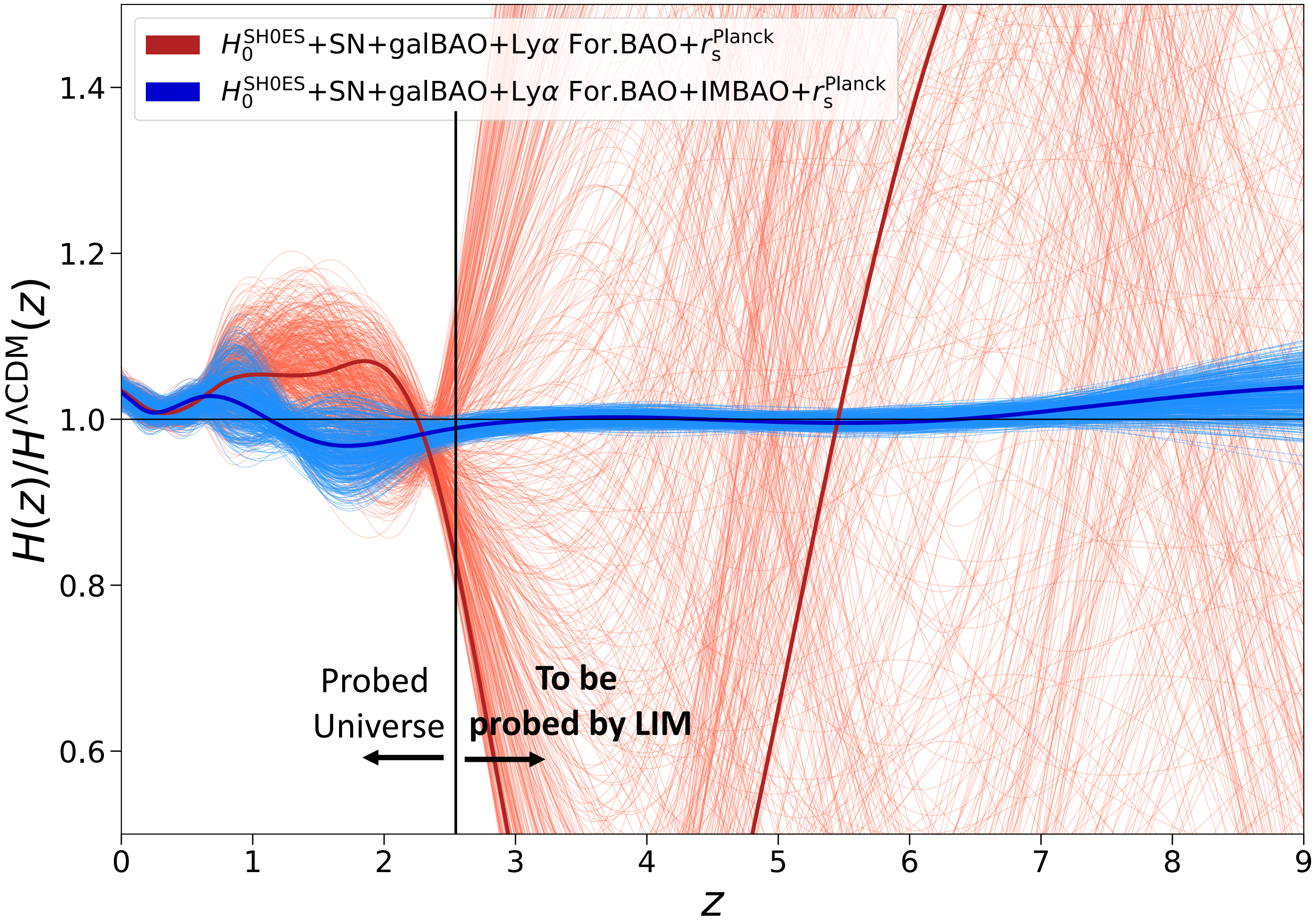
Change the early Universe

<u>Exceptions</u>:

- $H(z)$ boost at $z \ll 0.1$ (doesn't affect distances): Raveri 2019, Benevento+2020
- Screening and MG affecting Cepheids/TRGB calibration (Desmond+2019,2020)
- Some effect changing r_d from recombination to BAO measurements (?)
- Violation of distance duality relation
- …

$H(z)$ beyond the reach of galaxy surveys

Model independent $H(z)$ reconstructed with cubic splines



Bridge early and late Universe to probe post-recombination solutions

Current constraints using galaxy surveys (and H_0 and r_s) and **ADDING LIM BAO**

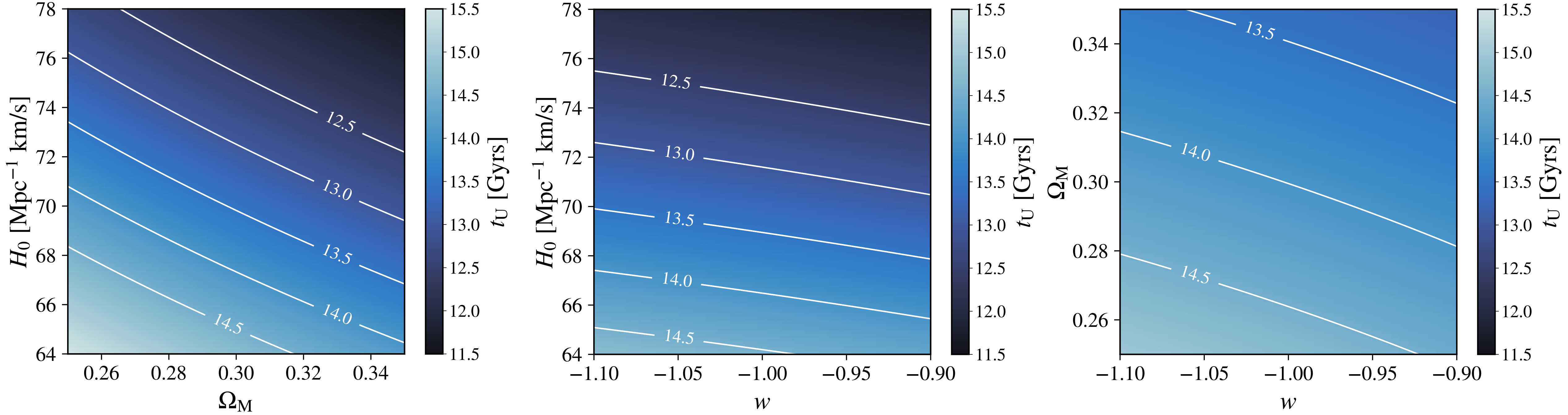
JLB+2019a
JLB+2019b

Beyond H_0

- H_0 affects distances AND times

$$t(z) = \frac{977.8}{H_0} \int_0^z \frac{dz'}{(1+z')E(z')} \text{ Gyr}$$

- $t_U \equiv t(\infty)$, but dominated by $z \lesssim 30$



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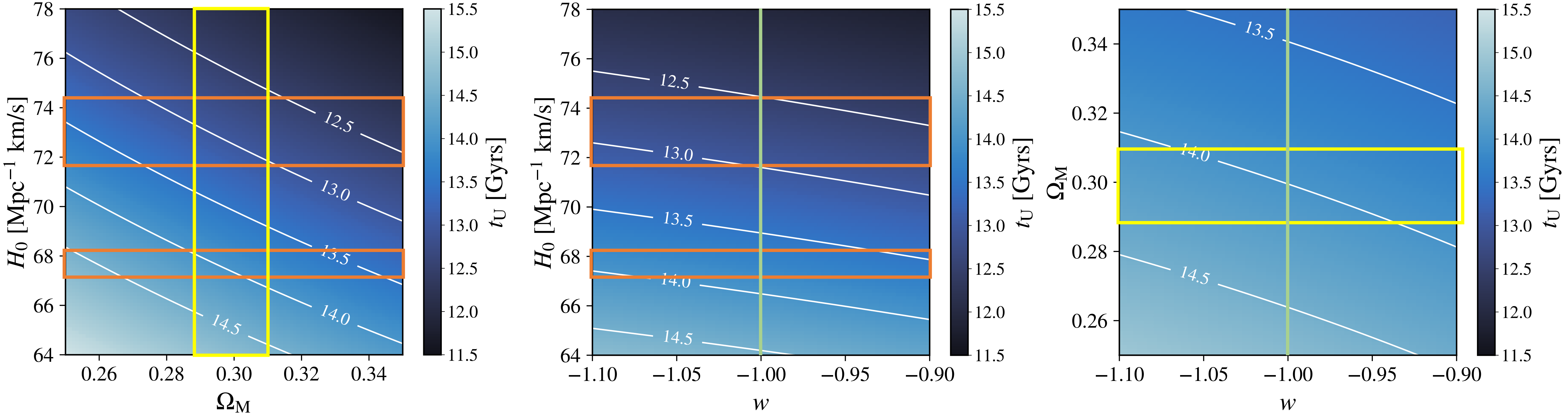
- $t_U \equiv t(\infty)$, but dominated by $z \lesssim 30$: No dependence on the early Universe



Inferring t_U

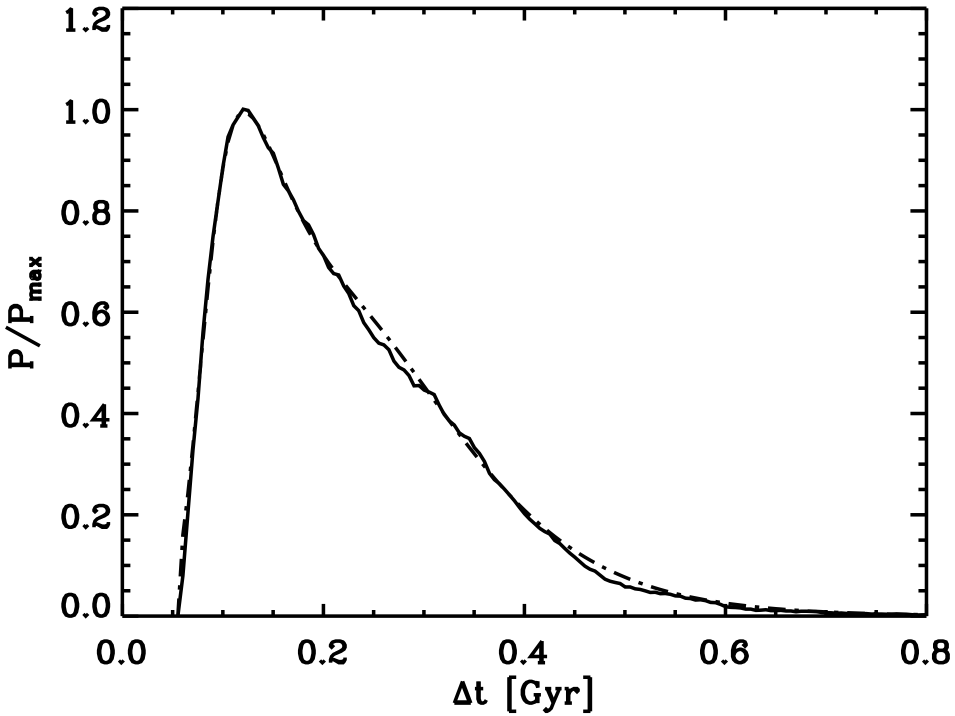
- From CMB (or other combination) assuming a cosmological model
- BAO+SNeIa: get $H_0 t_U$ from Ω_M when assuming ΛCDM
- Can we be more model-independent?

Inferring t_U

- From CMB (or other combination) assuming a cosmological model

- Can we be more model-independent? YES!
- Infer the age of the oldest globular clusters and estimate the gap

Jimenez+ 2019



Valcin, JLB+ 2020

- $t_{GC} \equiv t(z_f)$

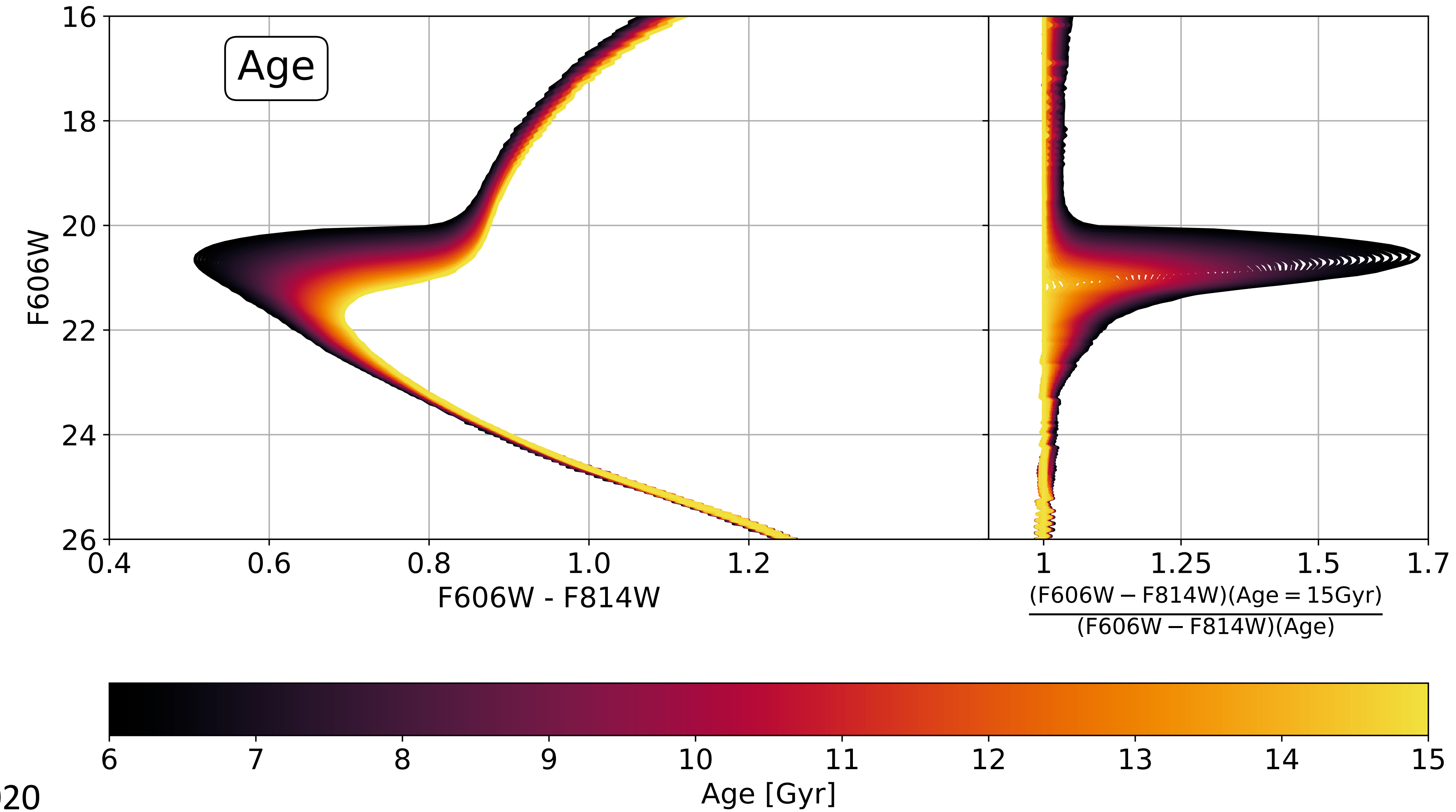
$z_f \in [11,30]$

- $t_U = t_{GC} + \Delta t$

$$\Delta t = \frac{977.8}{H_0} \int_{z_f}^{\infty} \frac{dz'}{(1+z')E(z')} \text{ Gyr}$$

Marginalizing over cosmo parameters and z_f

Age of the oldest GCs



Valcin, JLB+ 2020

Valcin, Jimenez, Verde, JLB+ 2021

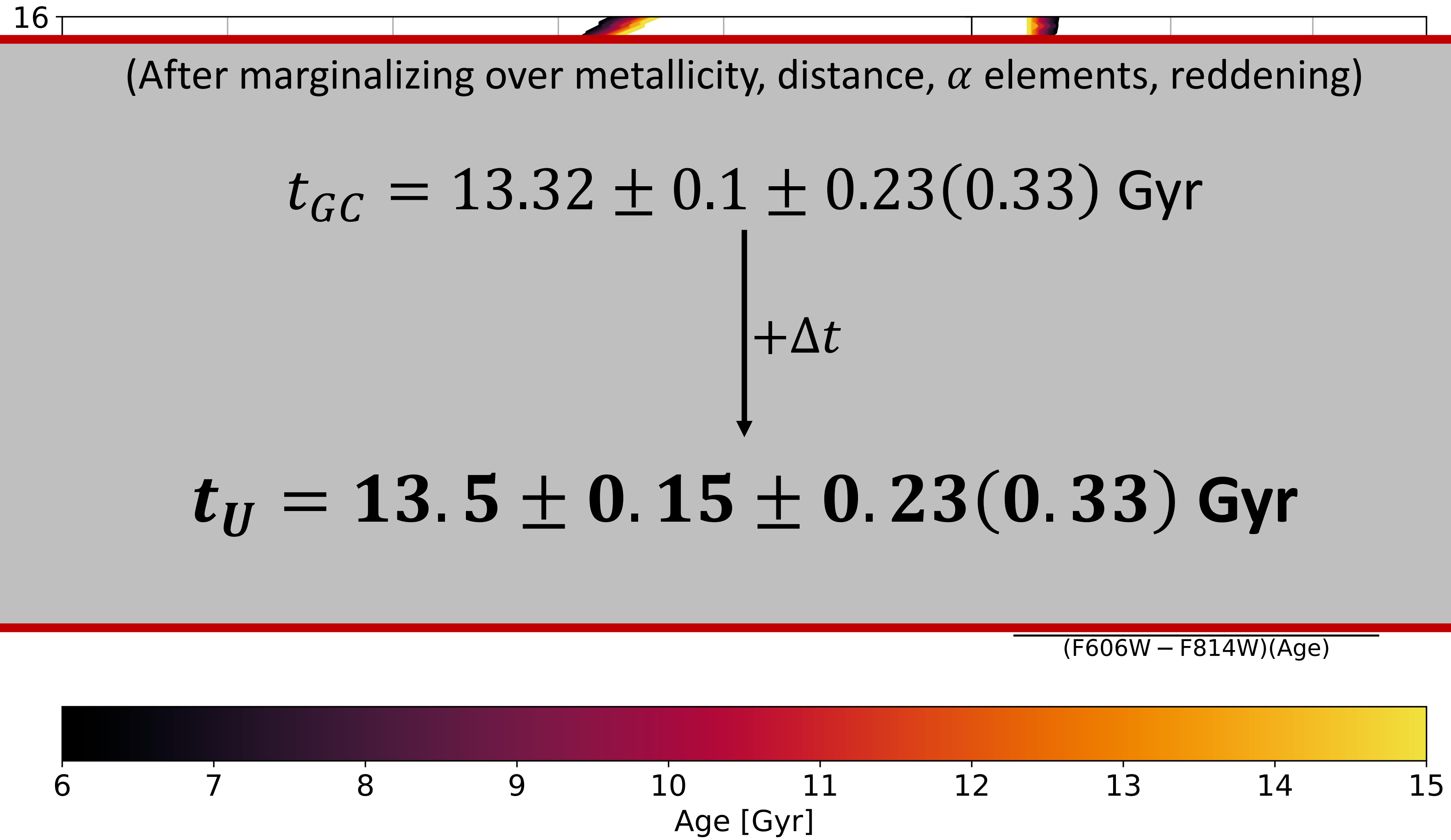
Age of the oldest GCs

(After marginalizing over metallicity, distance, α elements, reddening)

$$t_{GC} = 13.32 \pm 0.1 \pm 0.23(0.33) \text{ Gyr}$$

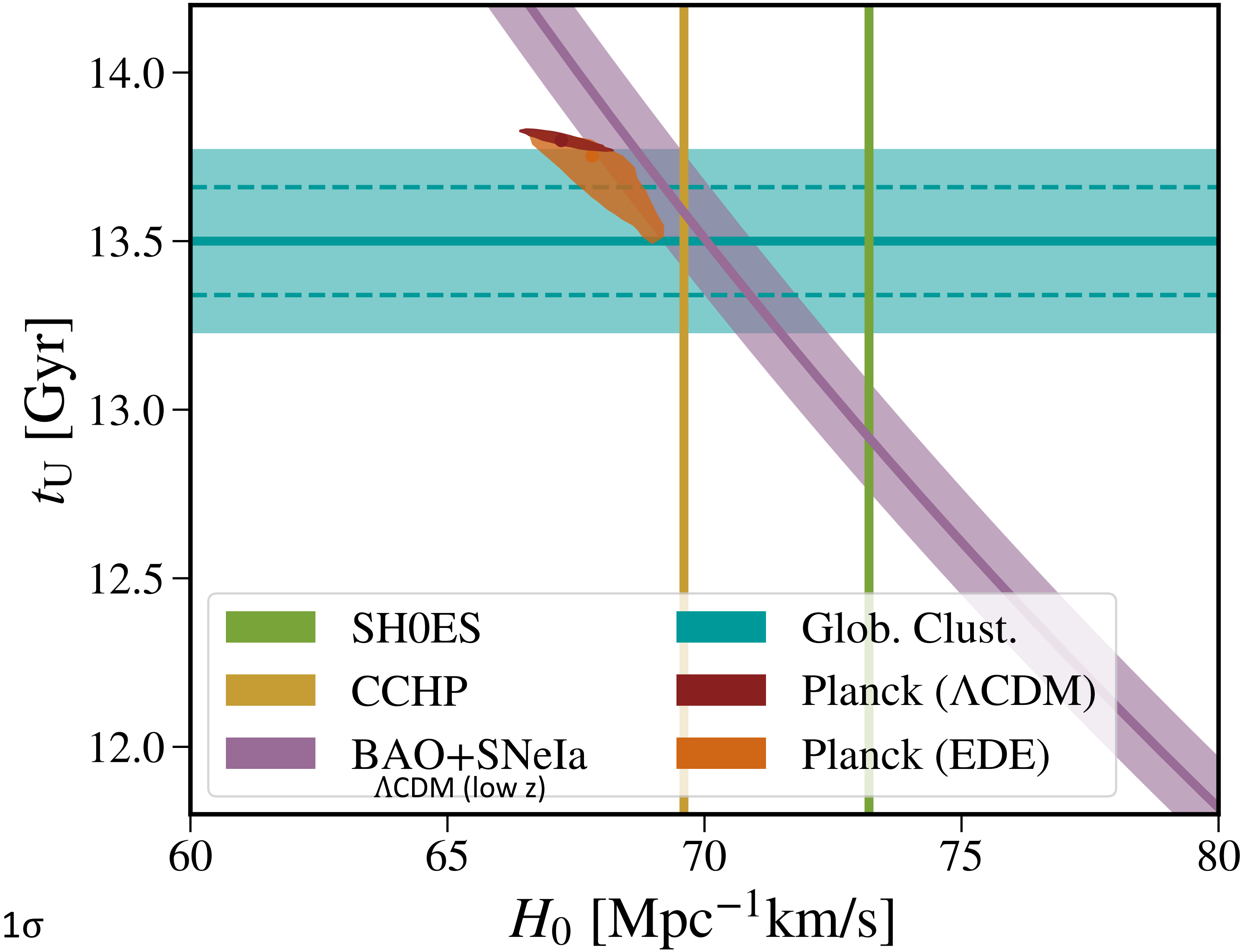
$$\downarrow +\Delta t$$

$$\mathbf{t_U = 13.5 \pm 0.15 \pm 0.23(0.33)} \textbf{ Gyr}$$



Valcin, JLB+ 2020
Valcin, Jimenez, Verde, JLB+ 2021

Implications of t_U

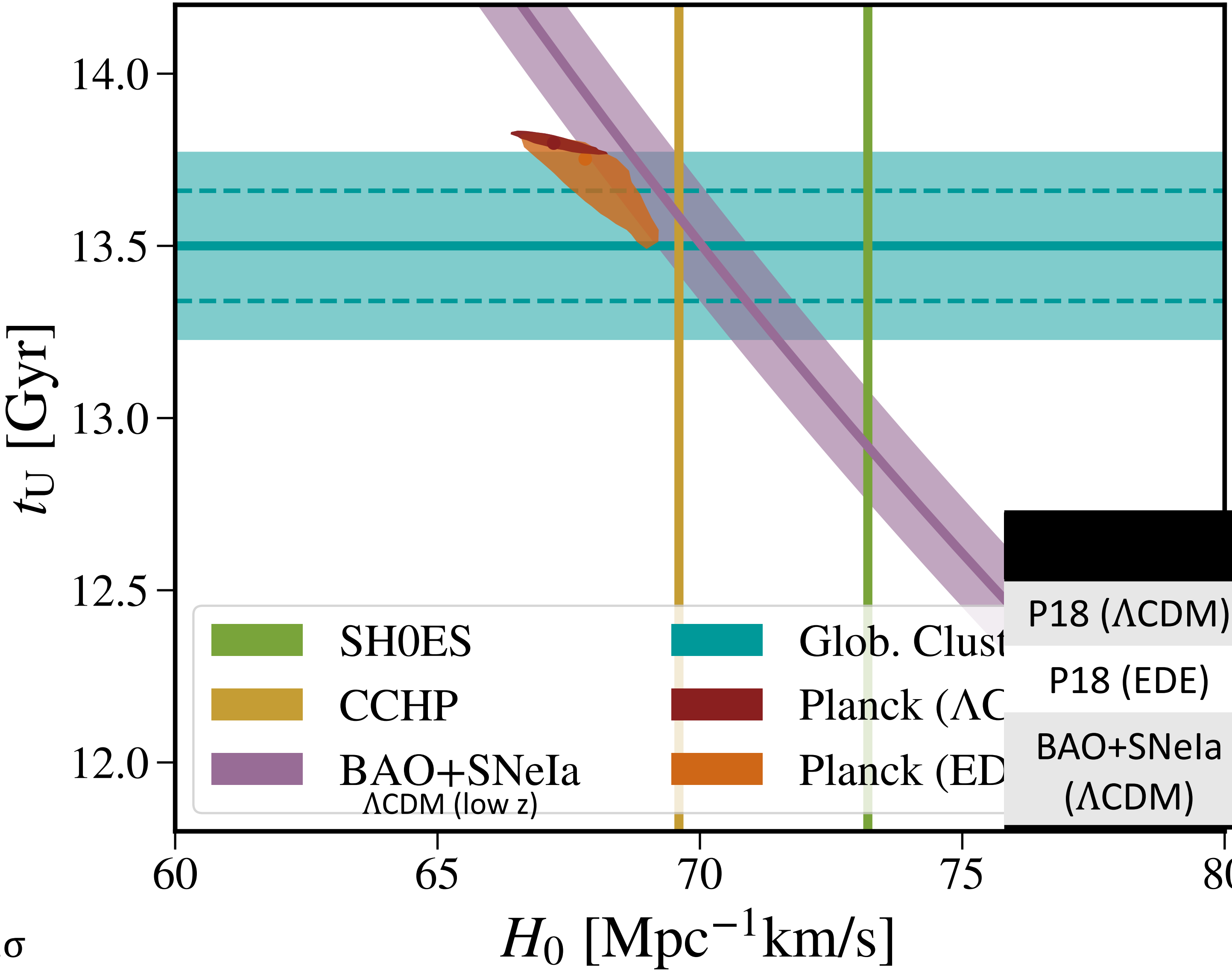


1σ

- More problems!!
- Ω_M fixed by BAO+SNeIa
- Pre-recombination solutions DON'T change t_U directly: same as if it was ΛCDM

JLB+2021

Implications of t_U



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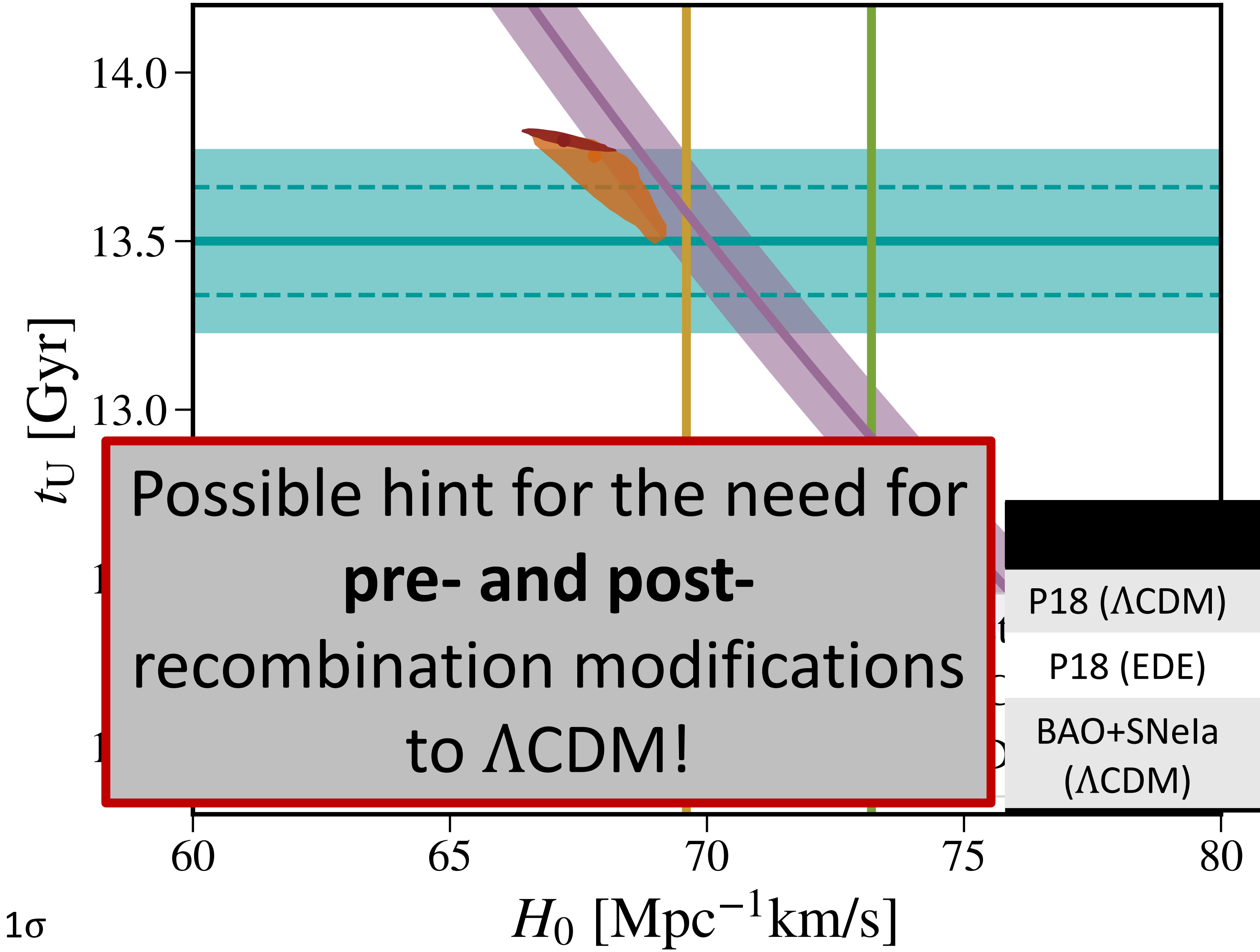
	$H_0 t_U$ (Gyr km/s/Mpc)	t_U (Gyr)
P18 (ΛCDM)	928 ± 7	13.80 ± 0.02
P18 (EDE)	932 ± 7	$13.76^{+0.06}_{-0.16}$
BAO+SNeIa (ΛCDM)	945 ± 11	12.93 ± 0.29 (+SH0ES) 13.62 ± 0.42 (+CCHP)

1σ

JLB+2021

Implications of t_U



- More problems!!
- Ω_M fixed by BAO+SNeIa
- Pre-recombination solutions DON'T change t_U directly (only through H_0)

Possible hint for the need for **pre- and post-** recombination modifications to ΛCDM!

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JLB+2021

Cosmic triangles

- Over-constrained triads:

$$r_d \times h = r_d h; \qquad H_0 \times t_U = H_0 t_U; \qquad \Omega_M \times h^2 = \Omega_M h^2$$

■ CMB (early Universe)

■ BAO+SNeIa (late Universe)

■ SH0ES/TRGB (local Universe)

■ GCs (local Universe)

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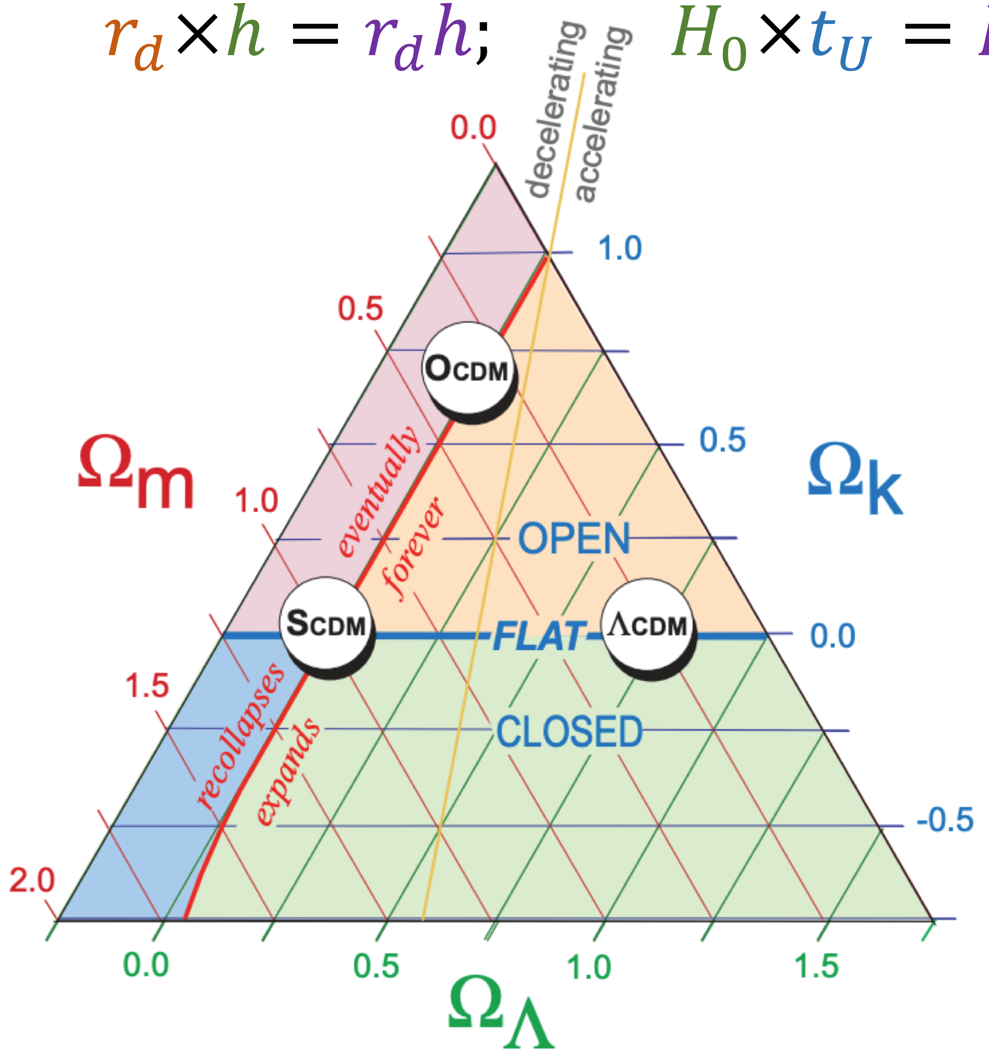


$$\Omega_M + \Omega_\Lambda + \Omega_k = 1$$

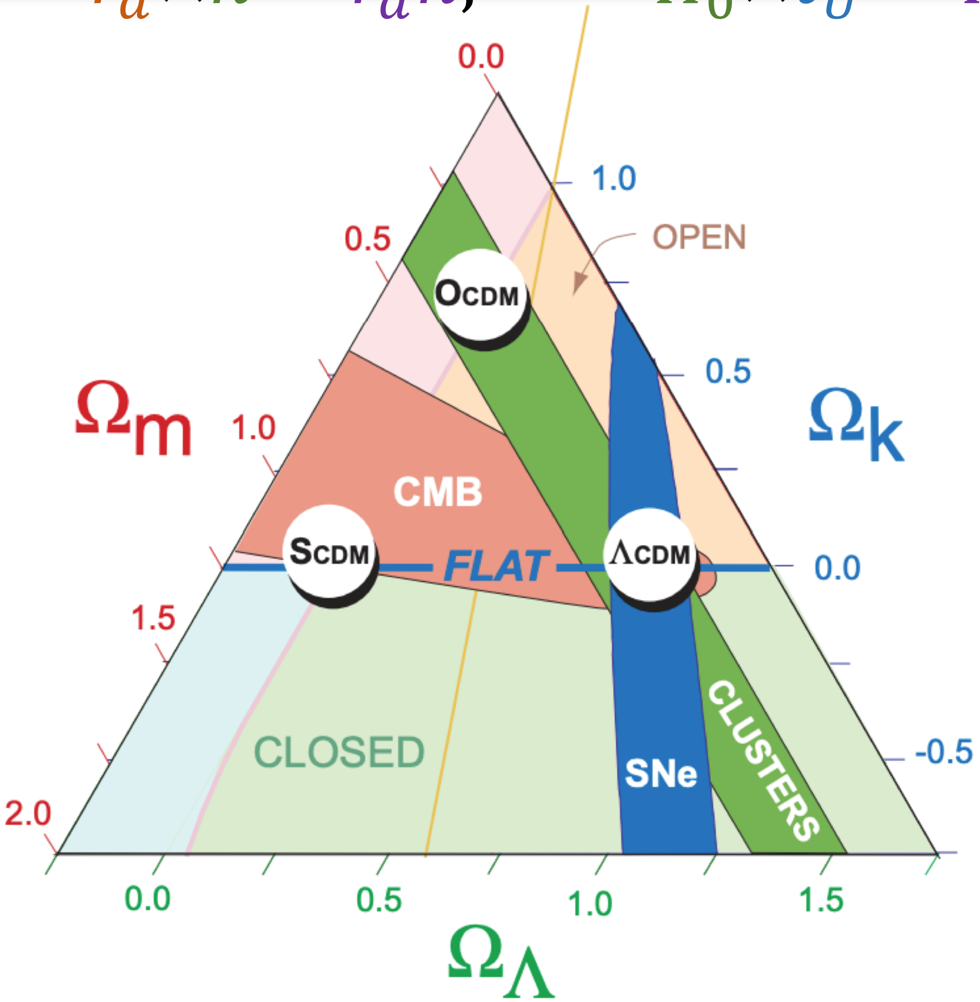
Original cosmic triangle
(Bahcall+ 99)

Plot over-constrained systems in ternary plots to find consistency and preferred values

Cosmic triangles

- Over-constrained triads:

$$r_d \times h = r_d h; \qquad H_0 \times t_U = H_0 t_U; \qquad \Omega_M \times h^2 = \Omega_M h^2$$

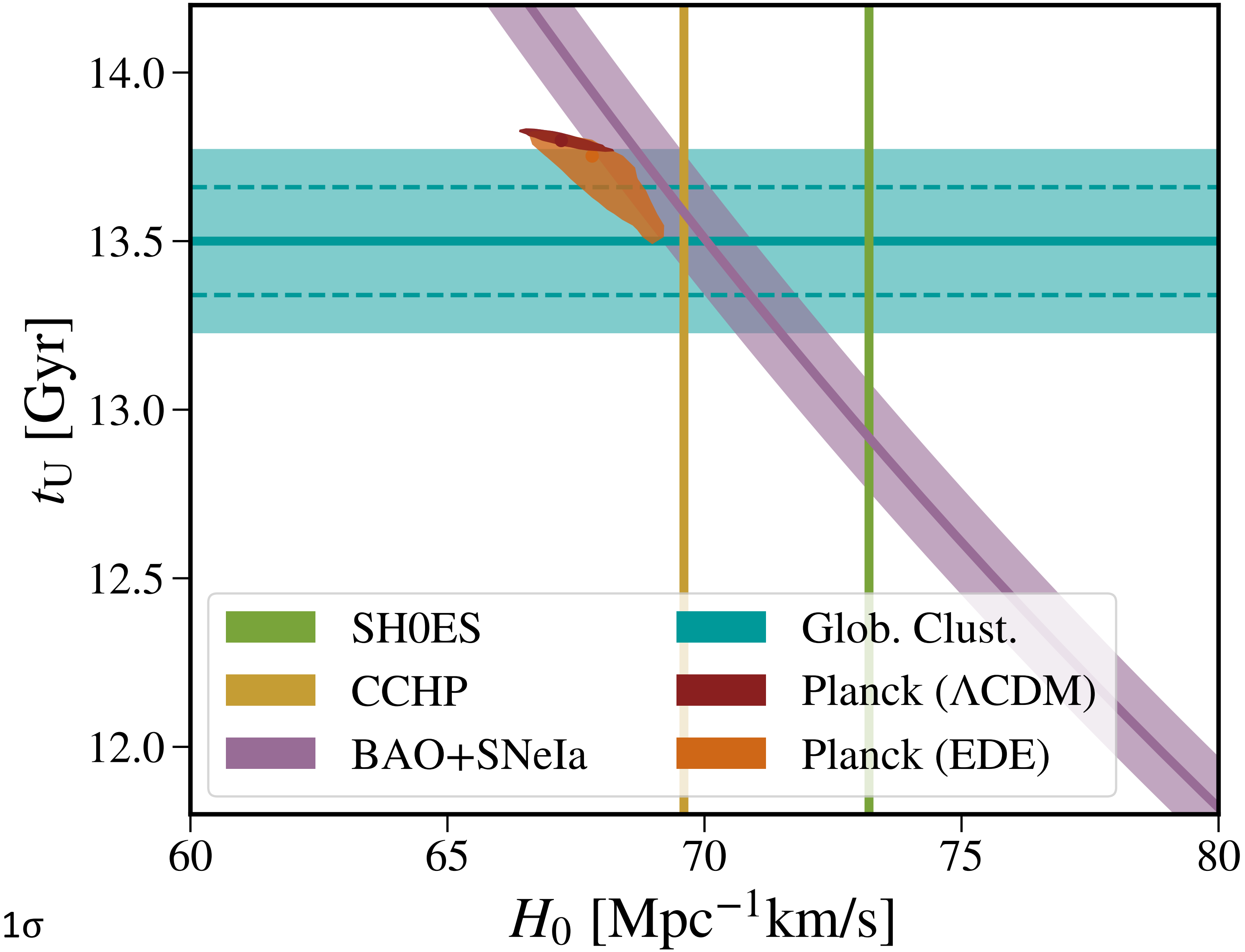


$$\Omega_M + \Omega_\Lambda + \Omega_k = 1$$

Original cosmic triangle
(Bahcall+ 99)

Plot over-constrained systems in ternary plots to find consistency and preferred values

Cosmic triangles



$H_0 \times t_U = H_0 t_U$

1σ

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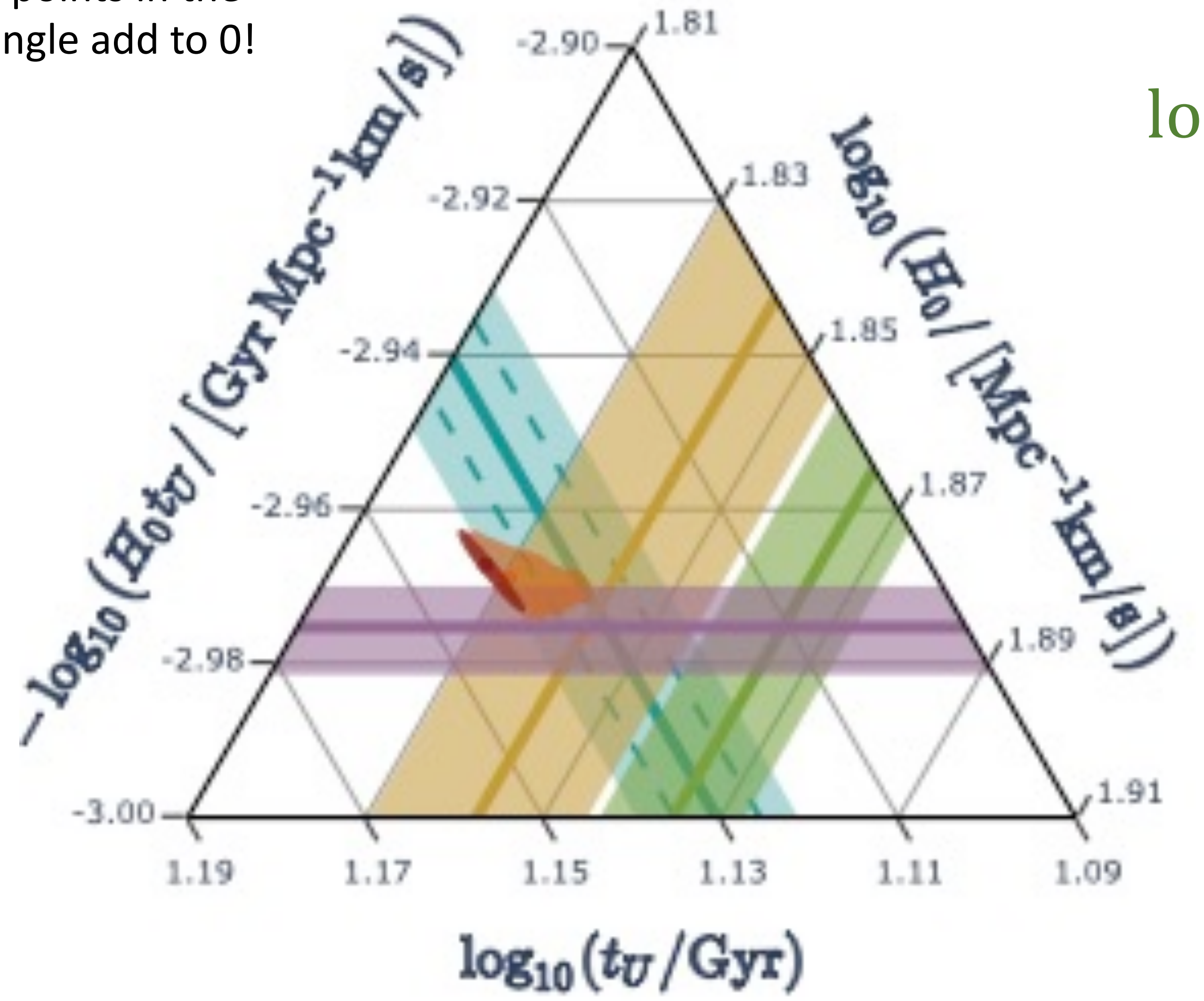
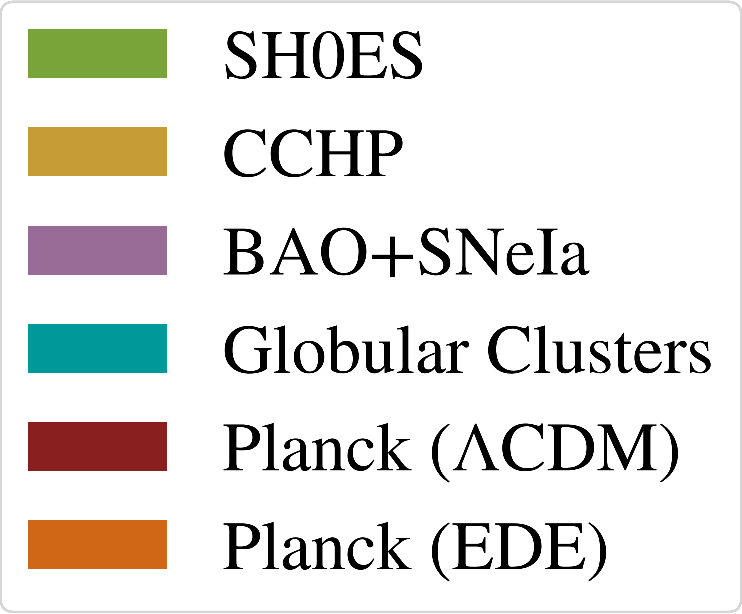
Cosmic triangles

All points in the triangle add to 0!

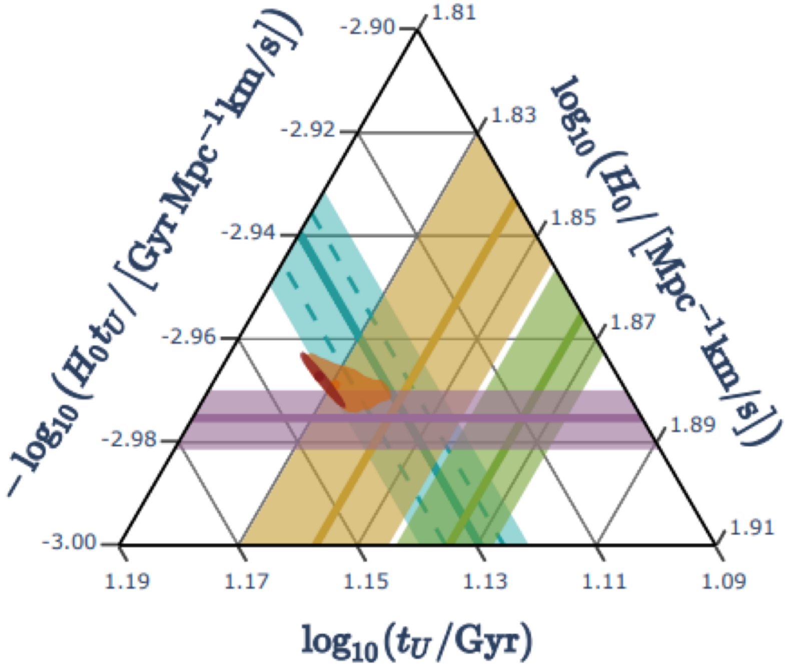


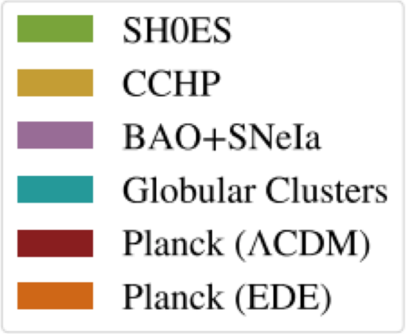
$$\log_{10} H_0 + \log_{10} t_U - \log_{10}(H_0 t_U) = 0$$



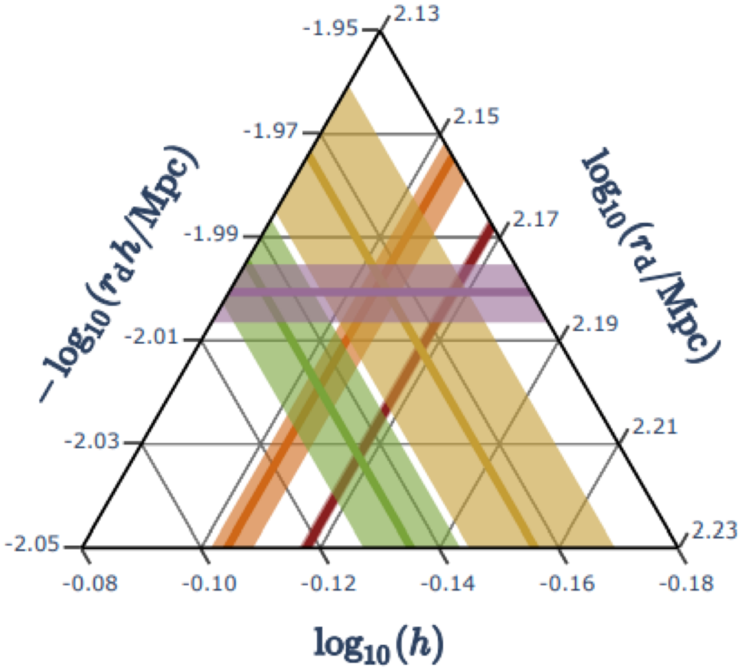
1σ

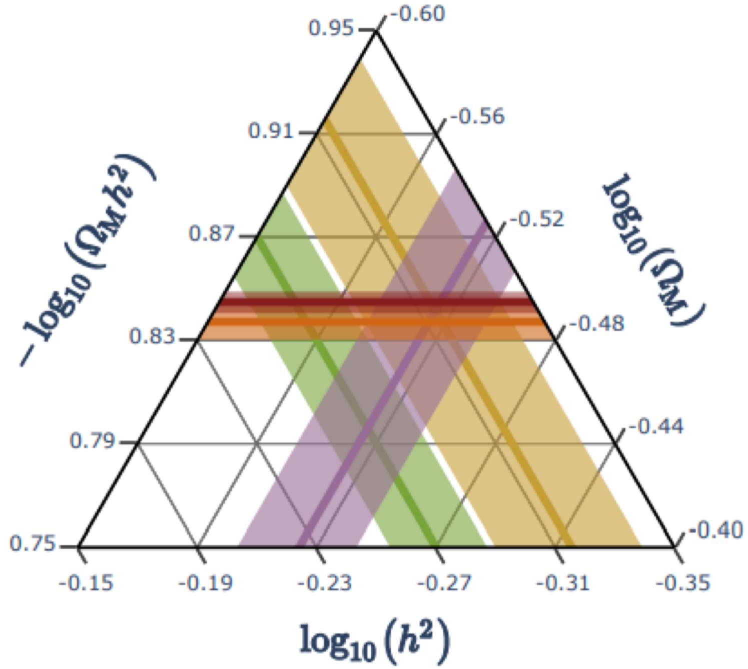
JLB+2021





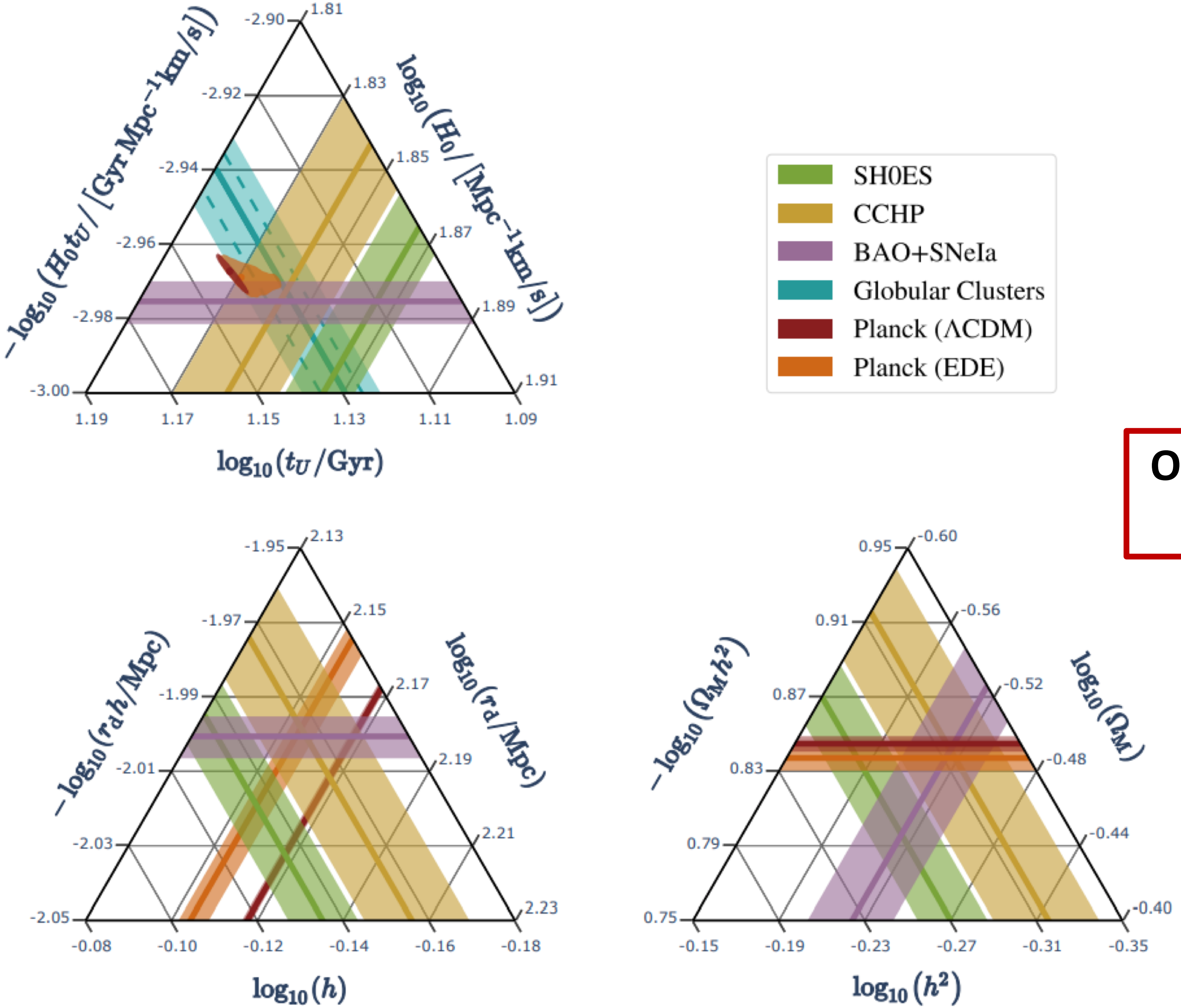
Cosmic triangles





1σ

JLB+2021



1σ

Out with the standard ruler,
In with the 📐.

Nick Kokron

JLB+2021

Conclusions

- Importance of model-independent approaches to highlight requirements
- Early-late Universe tension? Mismatch in the anchors of the distance ladder.
  - But also beyond H_0: t_U and Ω_M are also affected.
- No room for big changes at low redshift.
  - Pre-recombination changes (boost in $H(z)$?) are required, but likely not enough.
- Reconcile ALL measurements, at least not worsen other agreements and tensions
- LIM will grant access to unprobed stages of the Universe
- Use of new cosmic triangles