Cosmology on the edge of Λ-Cold Dark Matter

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Introduction

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

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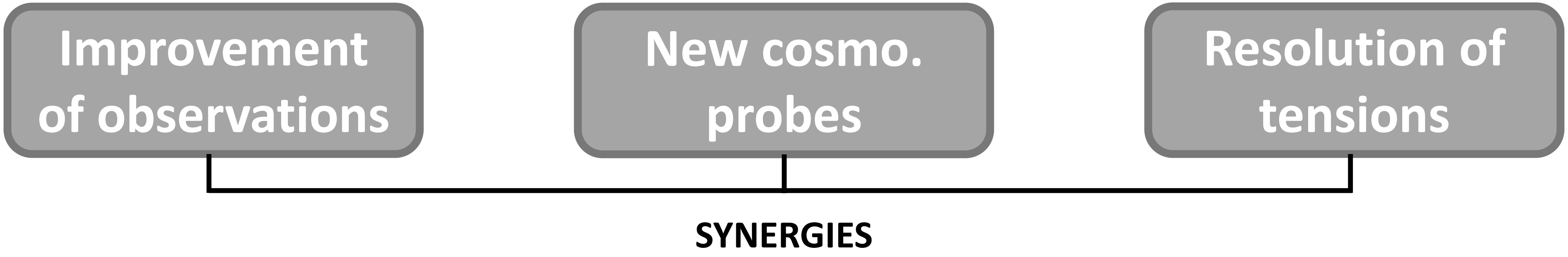
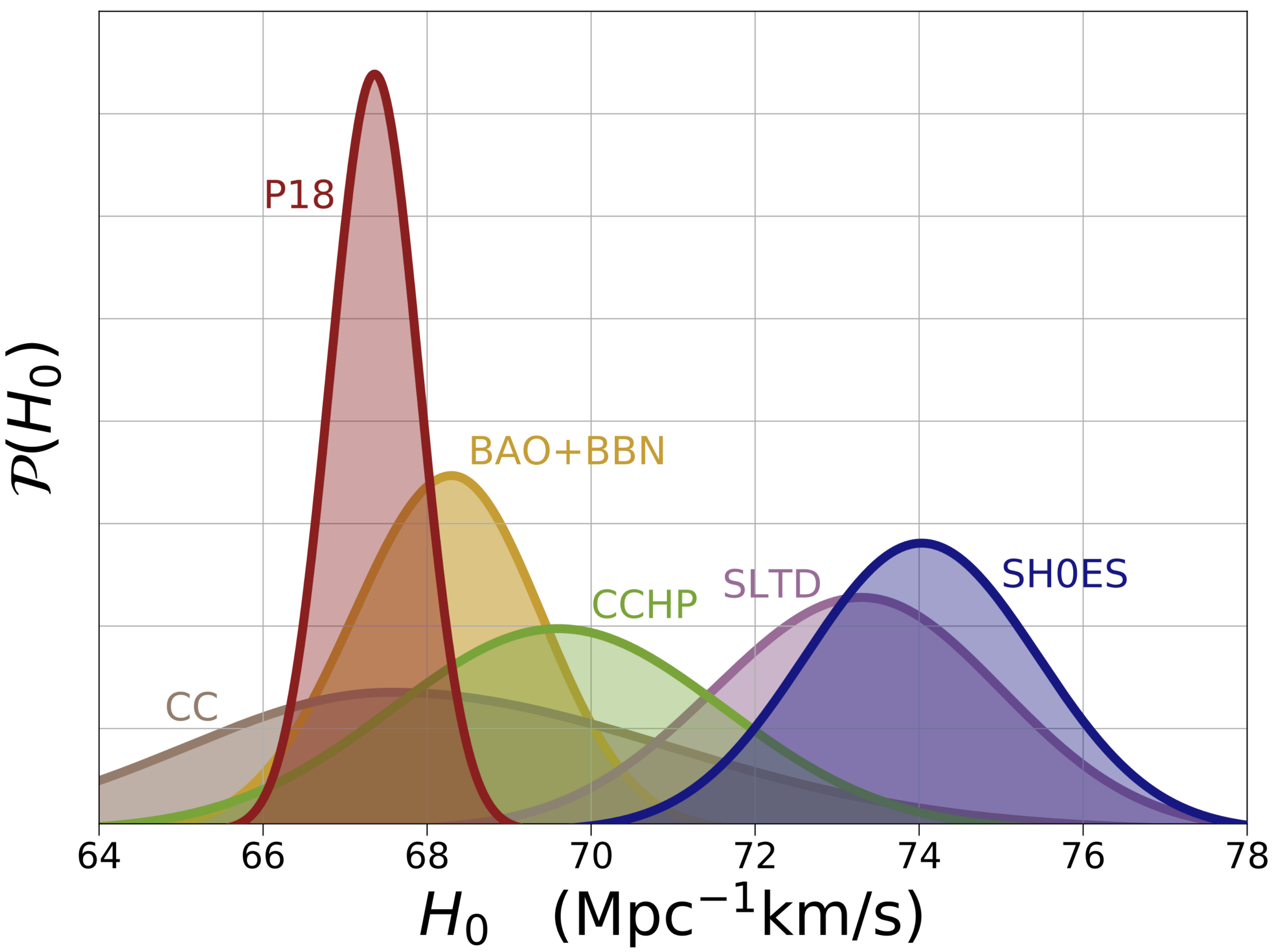
- Standard cosmological model: ΛCDM
- Excellent reproduction of the observations, but…
    - Phenomenological model: nature of DM and DE? Primordial Universe?
    - Persistent discrepancies between different cosmological probes (high-z vs low-z?): H_0, $\sigma_8\Omega_M^{0.5}$

Introduction

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



H_0 Tension

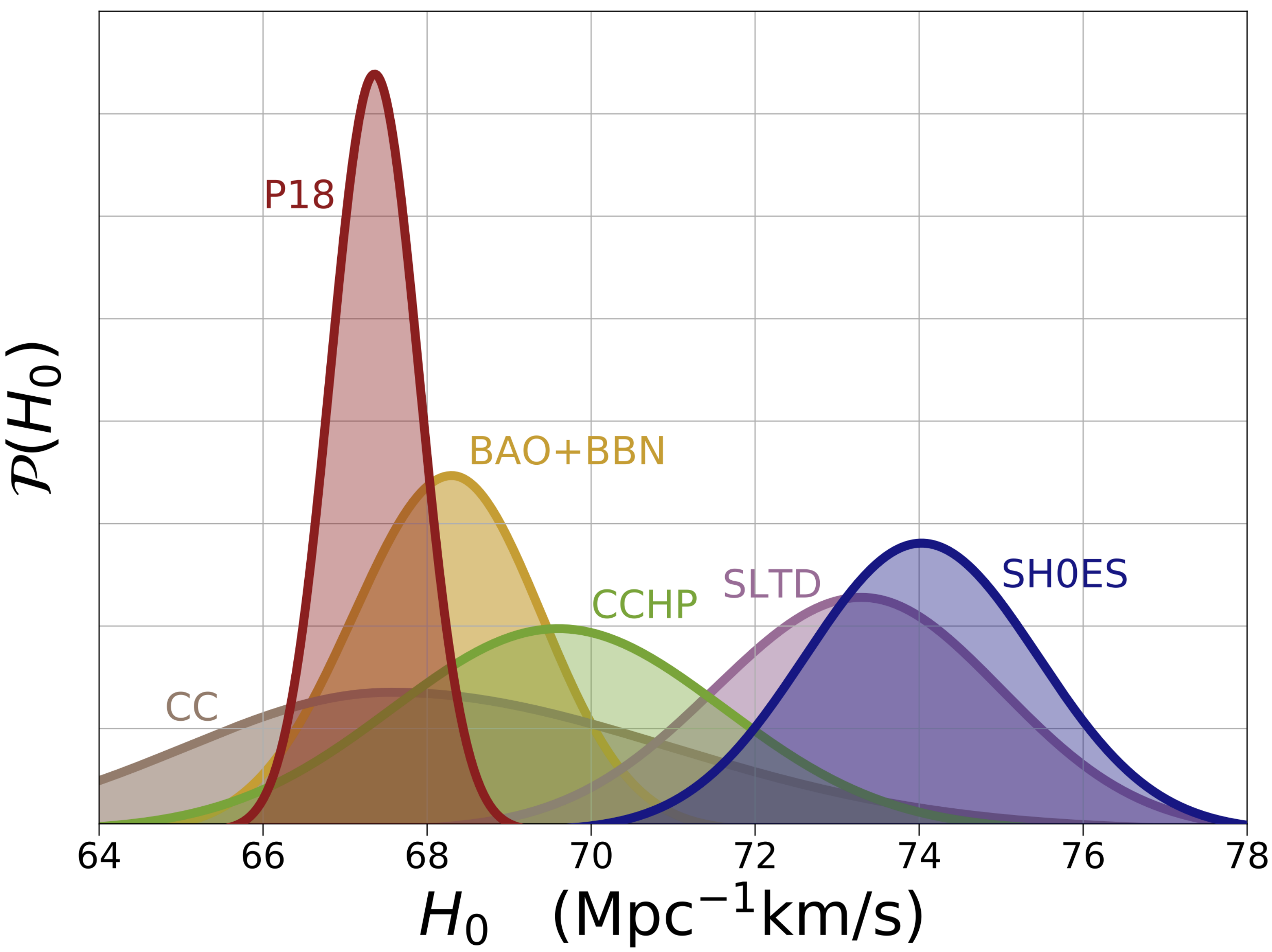


- Model dependent tension
- Coincident results & several cross-checks

Confirmed high-z vs low-z tension

To combine observations in tension in a conservative way accounting for systematics: BACCUS (JLB & Peacock, 2018)

H_0 Tension



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Confirmed
high-z vs low-z
tension

Zoo of posible solutions

ΛCDM $+ N_{eff}$
ruled out as a solution

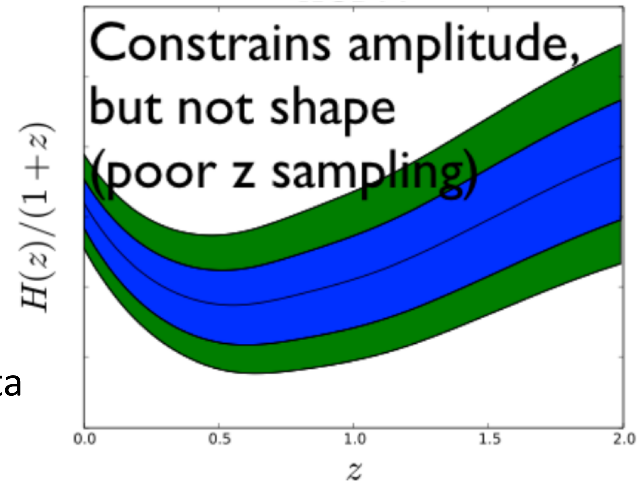
(Not even with theory motivated priors such as hot QCD axions)

D'Eramo, Ferreira, Notari, JLB, 2018

Cosmic distance ladder(s)

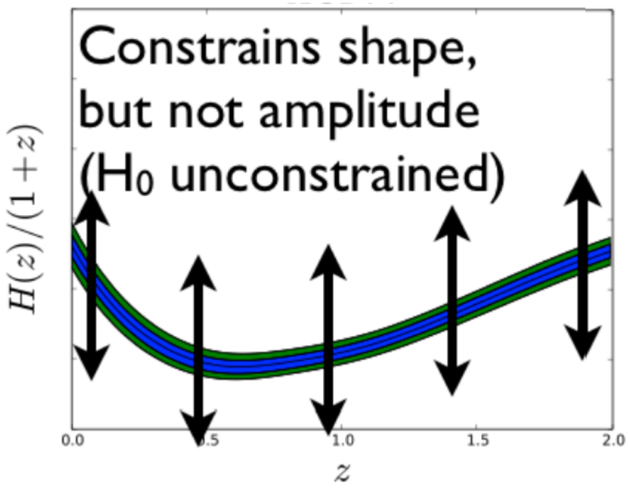
Agnostic approach: Model independent analysis of low-z observations

BAO



A. J. Cuesta

SNeIA

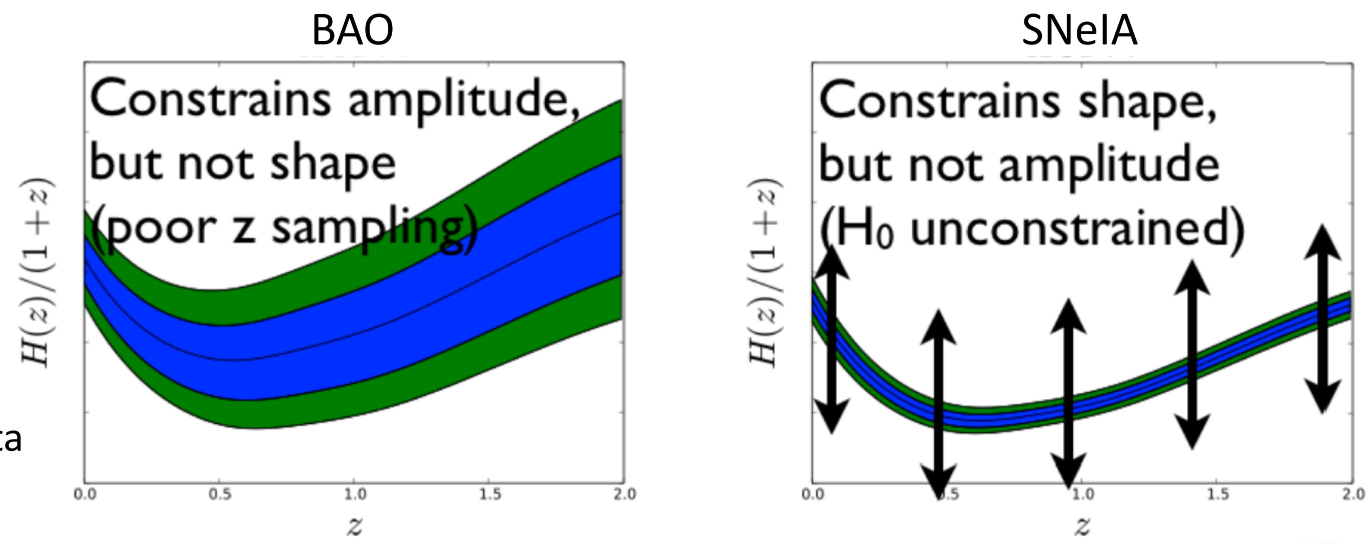


BAO normalization $\propto r_s \times H_0$

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

Cosmic distance ladder(s)

Agnostic approach: Model independent analysis of low-z observations



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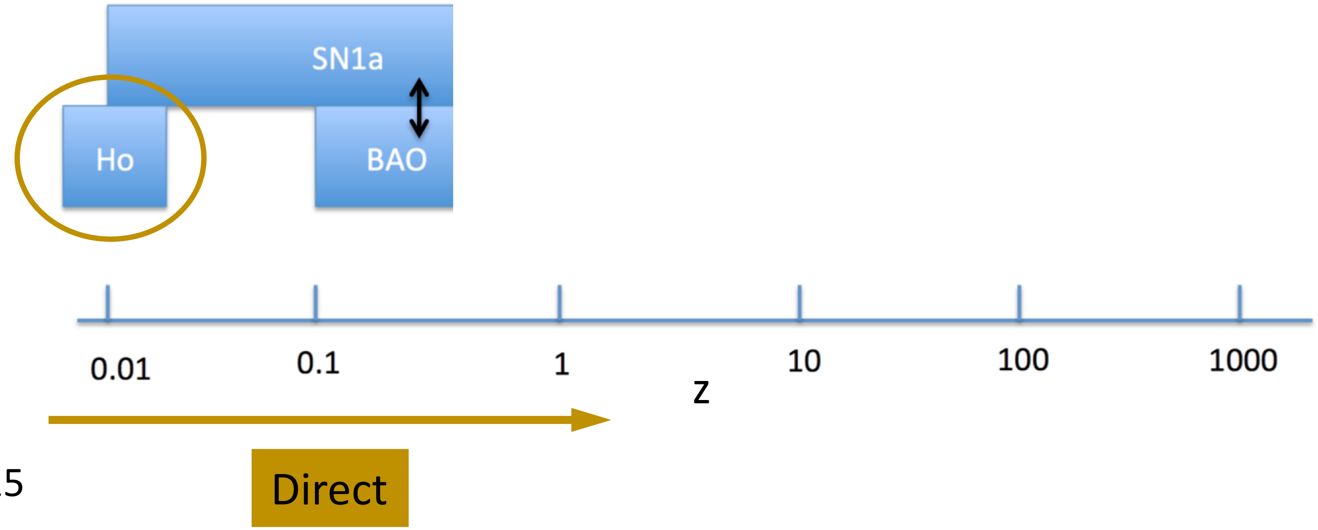

Cuesta+2015

Cosmic distance ladder(s)

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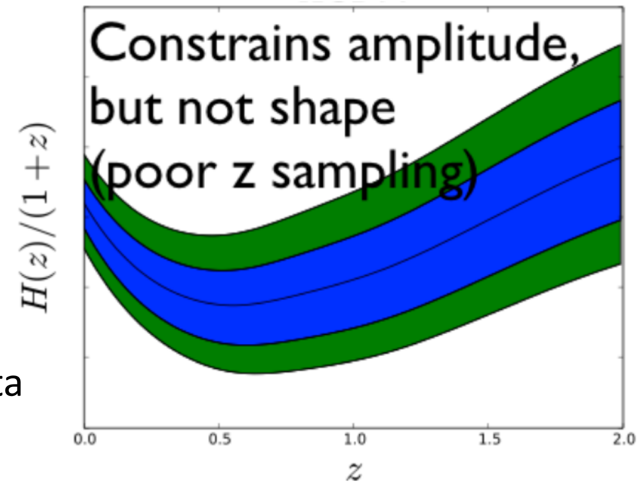
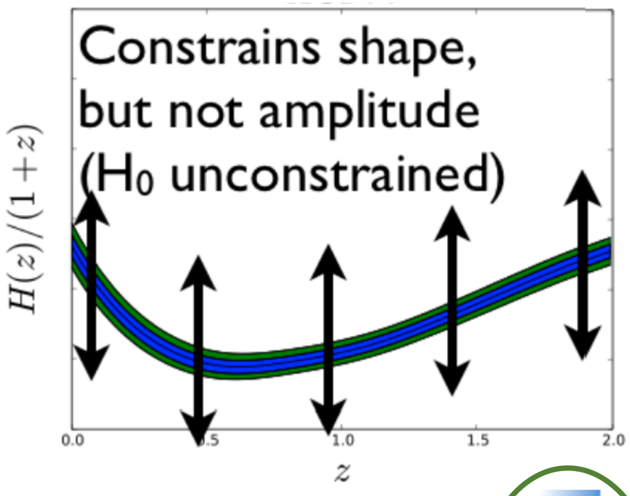


SNeIA



A. J. Cuesta

BAO normalization $\propto r_s \times H_0$

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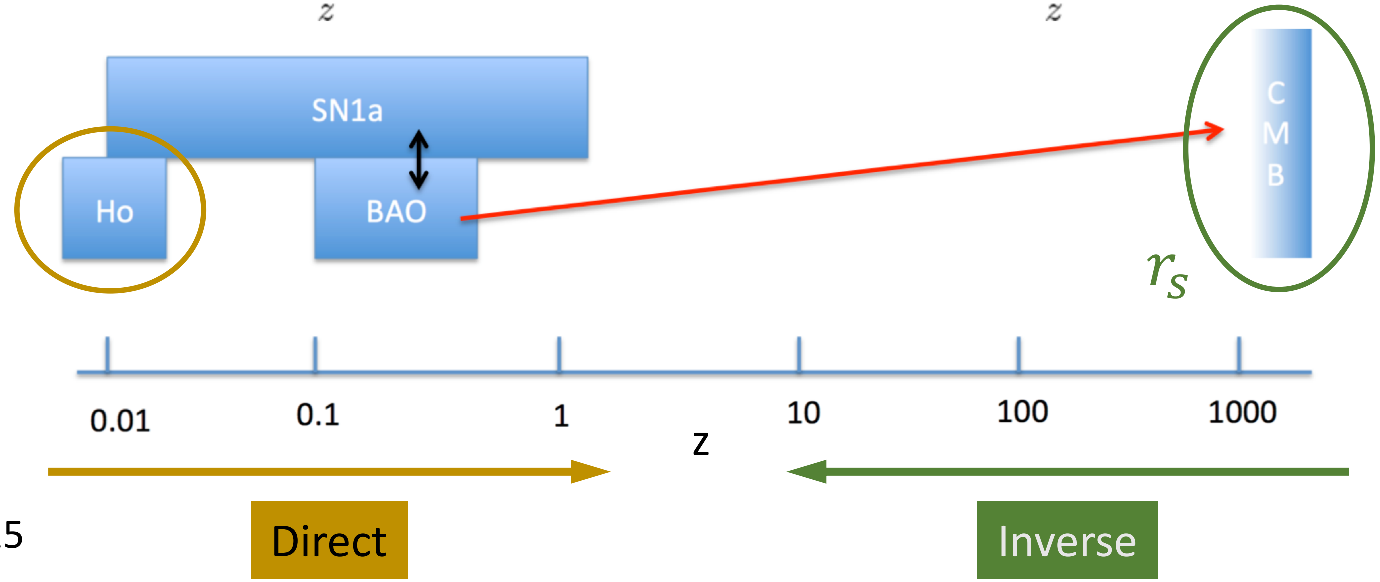
BAO calibrating SNeIA
(inverse distance ladder)

Two anchors of the
cosmic distance ladder



Cuesta+2015

Cosmic distance ladder(s)

Agnostic approach: Model independent analysis of low-z observations

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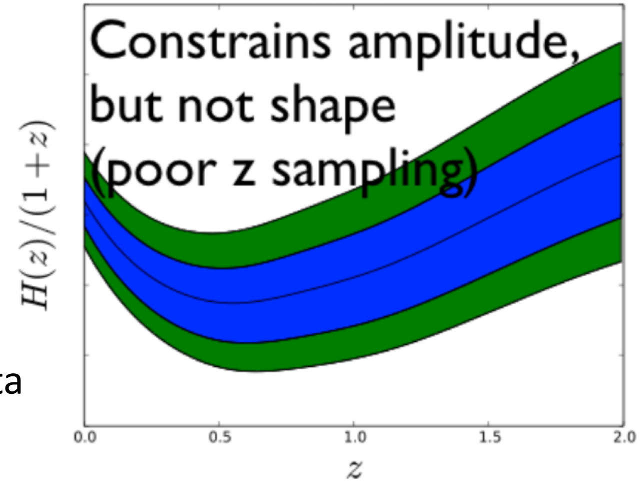

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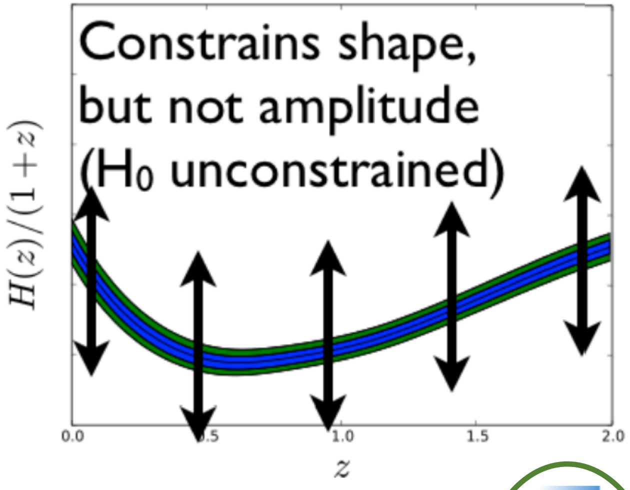
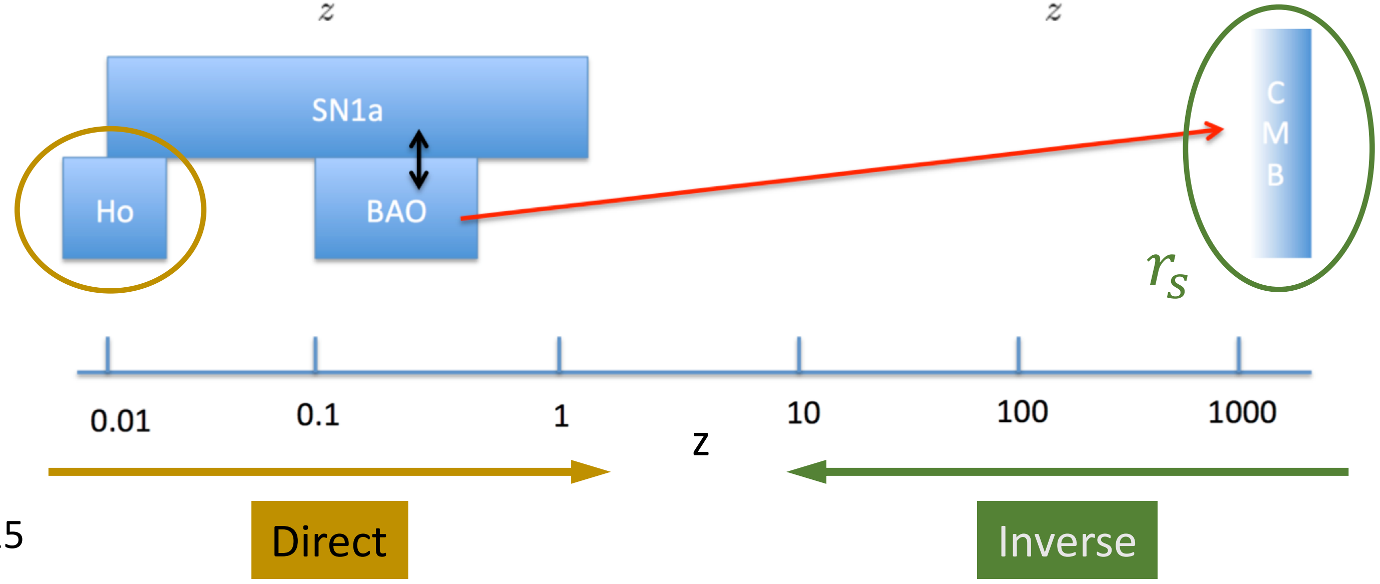
SNeIA





Cuesta+2015

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Two anchors of the cosmic distance ladder

Free the anchors

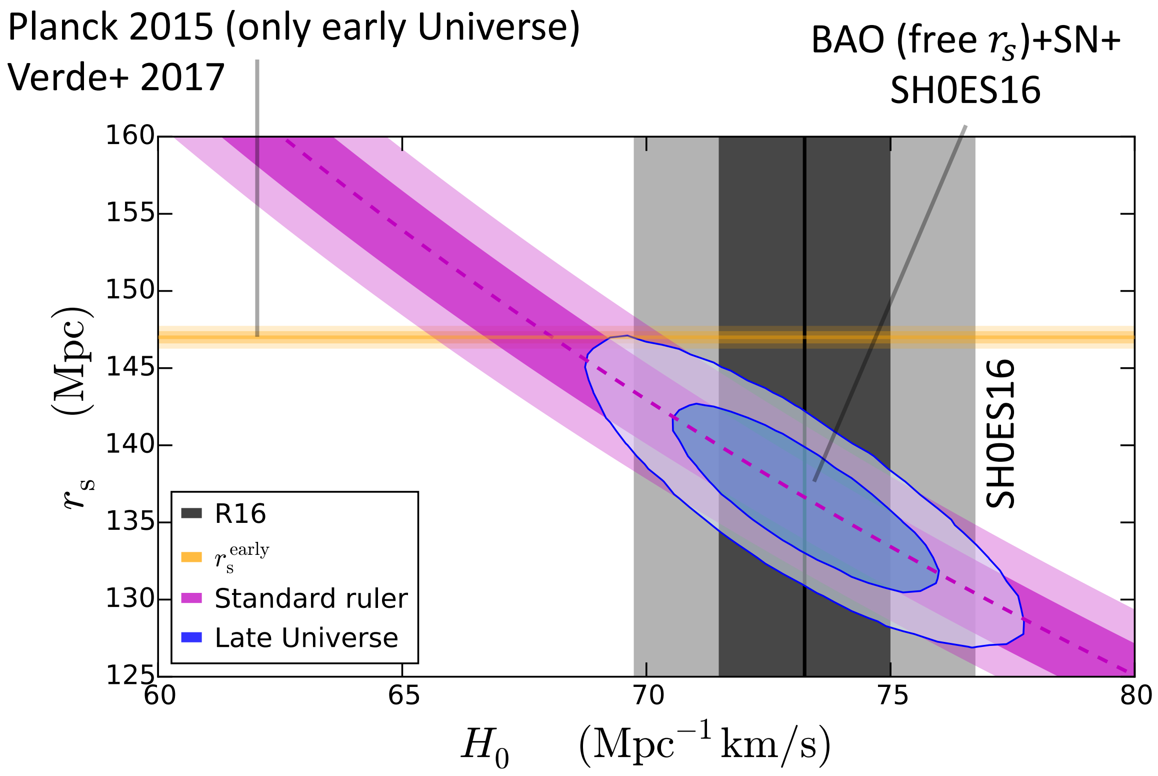
Low-z standard ruler

$r_s \times H_0$

Verde, JLB+ 2017

JLB+ 2016

High-z vs low-z

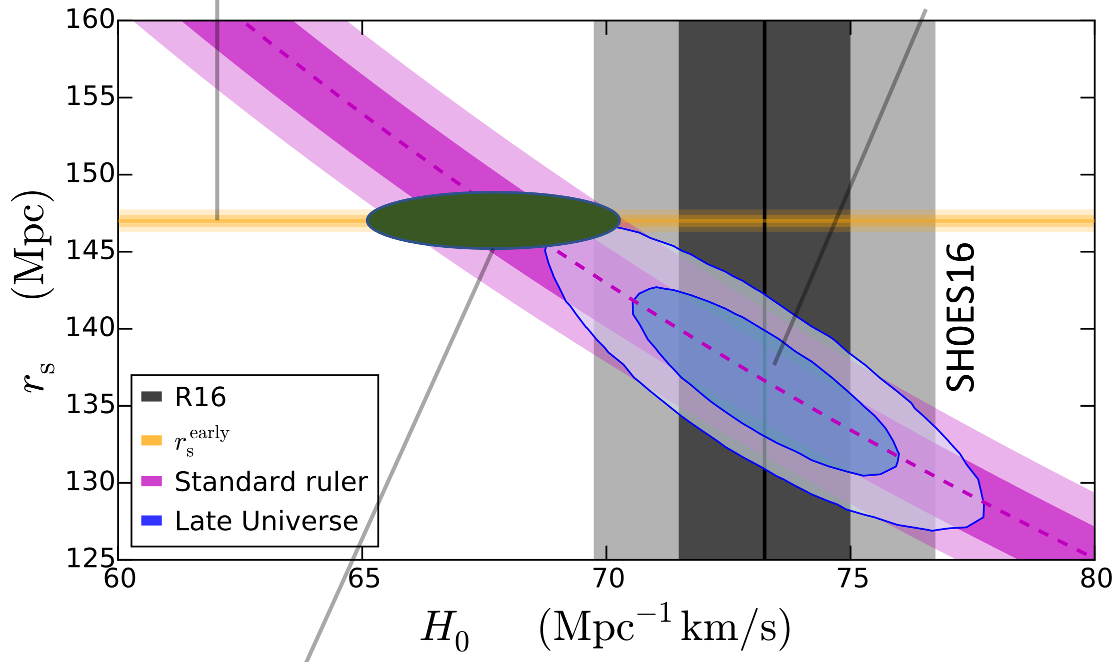


- BAO+SN constrain:
  - Expansion to be ΛCDM-like (dev. < 5%)
  - $r_s \times H_0$ below 2% precision (Verde, JLB+ 2017)
- Mismatch between the two anchors of the cosmic distance ladder (r_s & H_0)

High-z vs low-z

Planck 2015 (only early Universe)
Verde+ 2017

BAO (free r_s)+SN+
SH0ES16



BAO+SN+
Planck 2015 (only early Universe)

Independent measurements

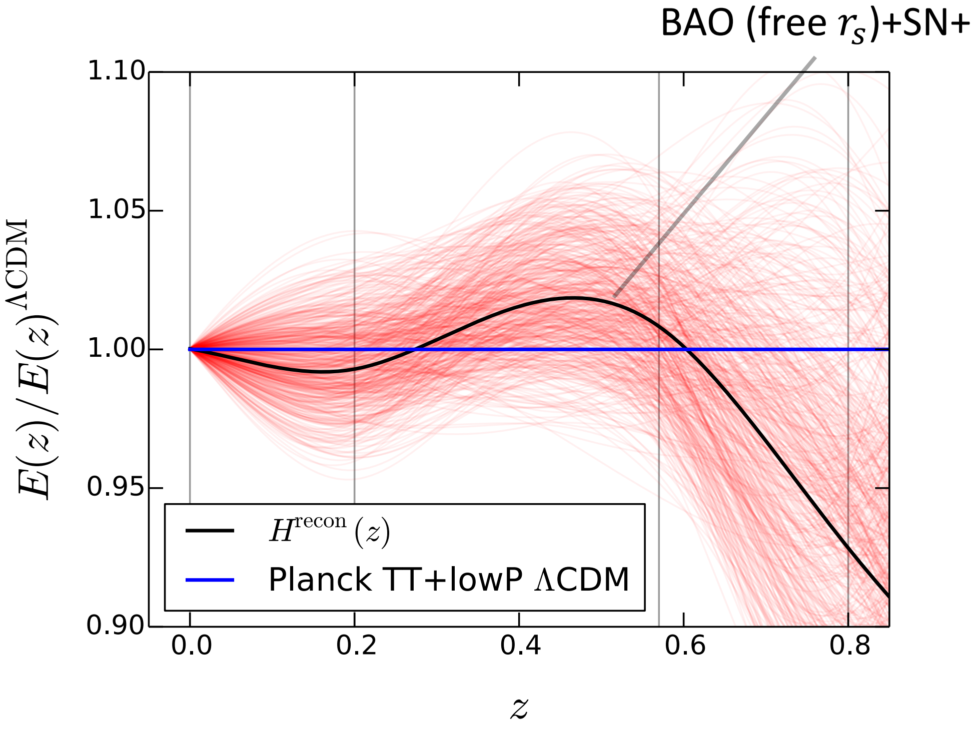
- BAO+SN constrain:
  - Expansion to be ΛCDM-like (dev. < 5%)
  - $r_s \times H_0$ below 2% precision (Verde, JLB+ 2017)

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

r_s needs to be smaller to match a larger H_0

JLB+ 2016

High-z vs low-z



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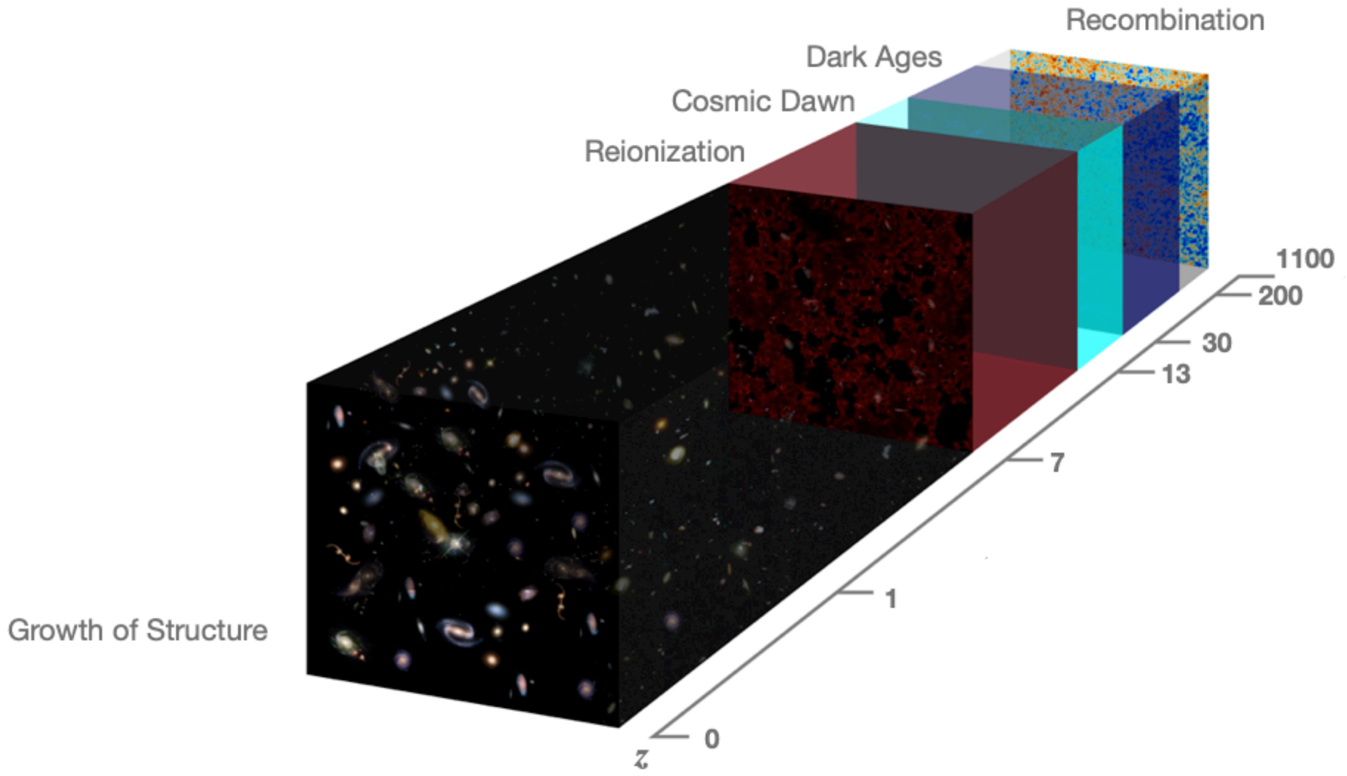
No change in expansion history at $z \lesssim 1$ can alleviate the tension

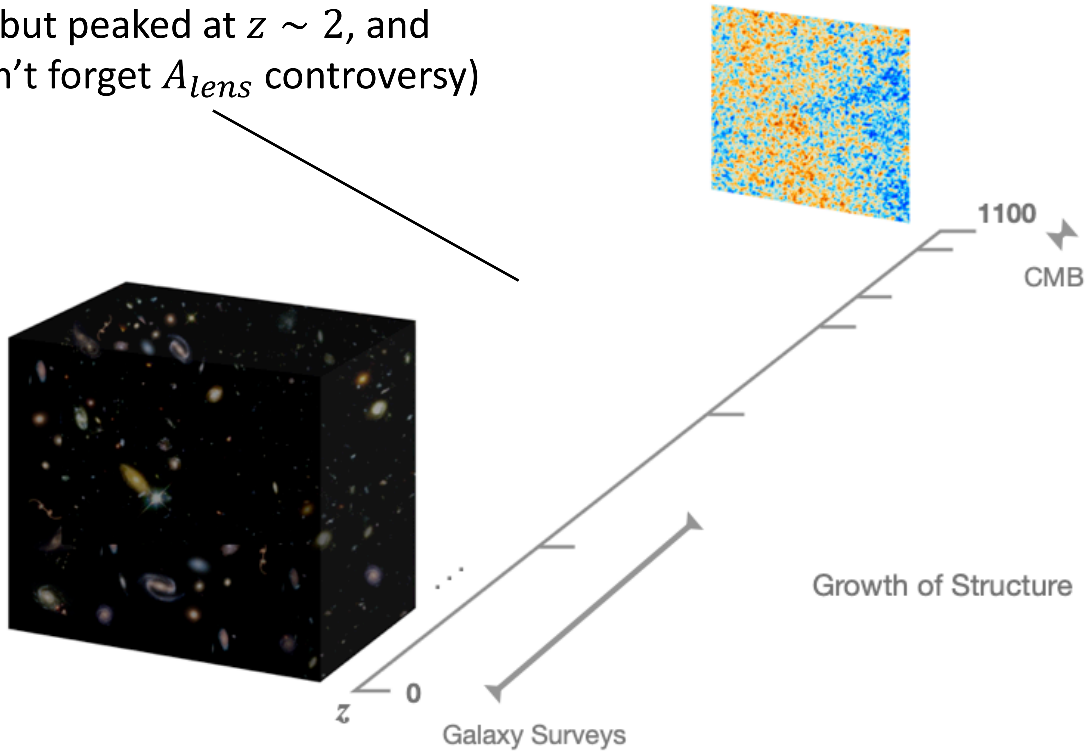
Probing the Universe

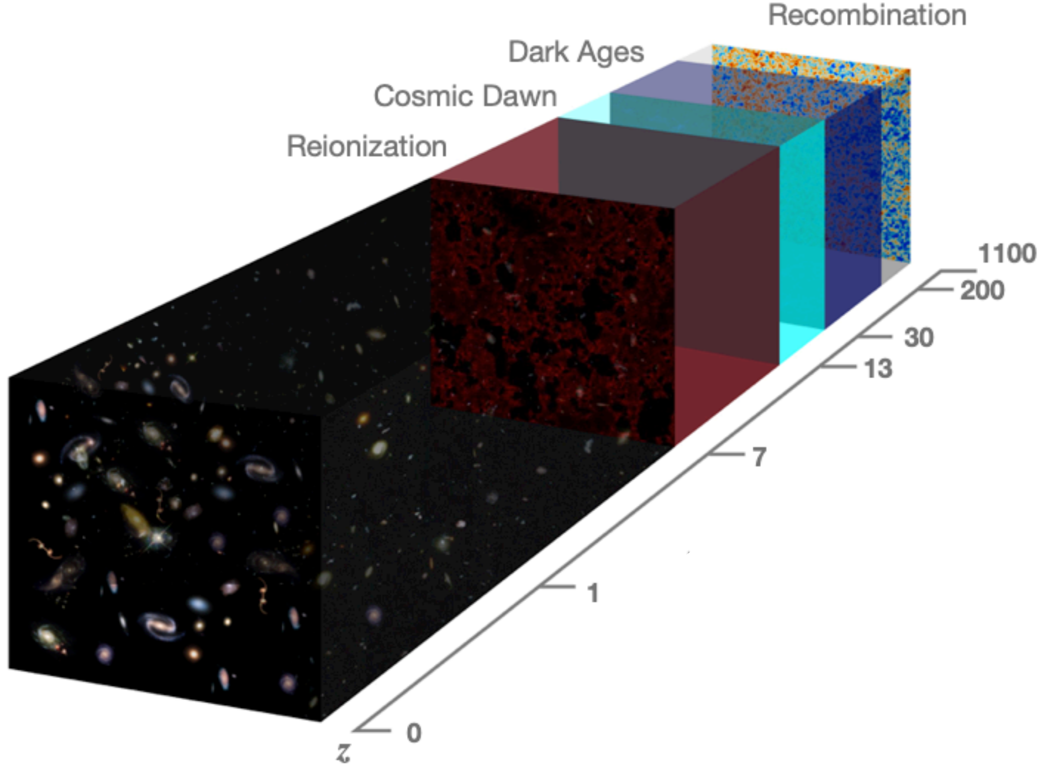


E. D. Kovetz

Probing the Universe

Indirect measurements with CMB lensing
(but peaked at $z \sim 2$, and
don't forget A_{lens} controversy)





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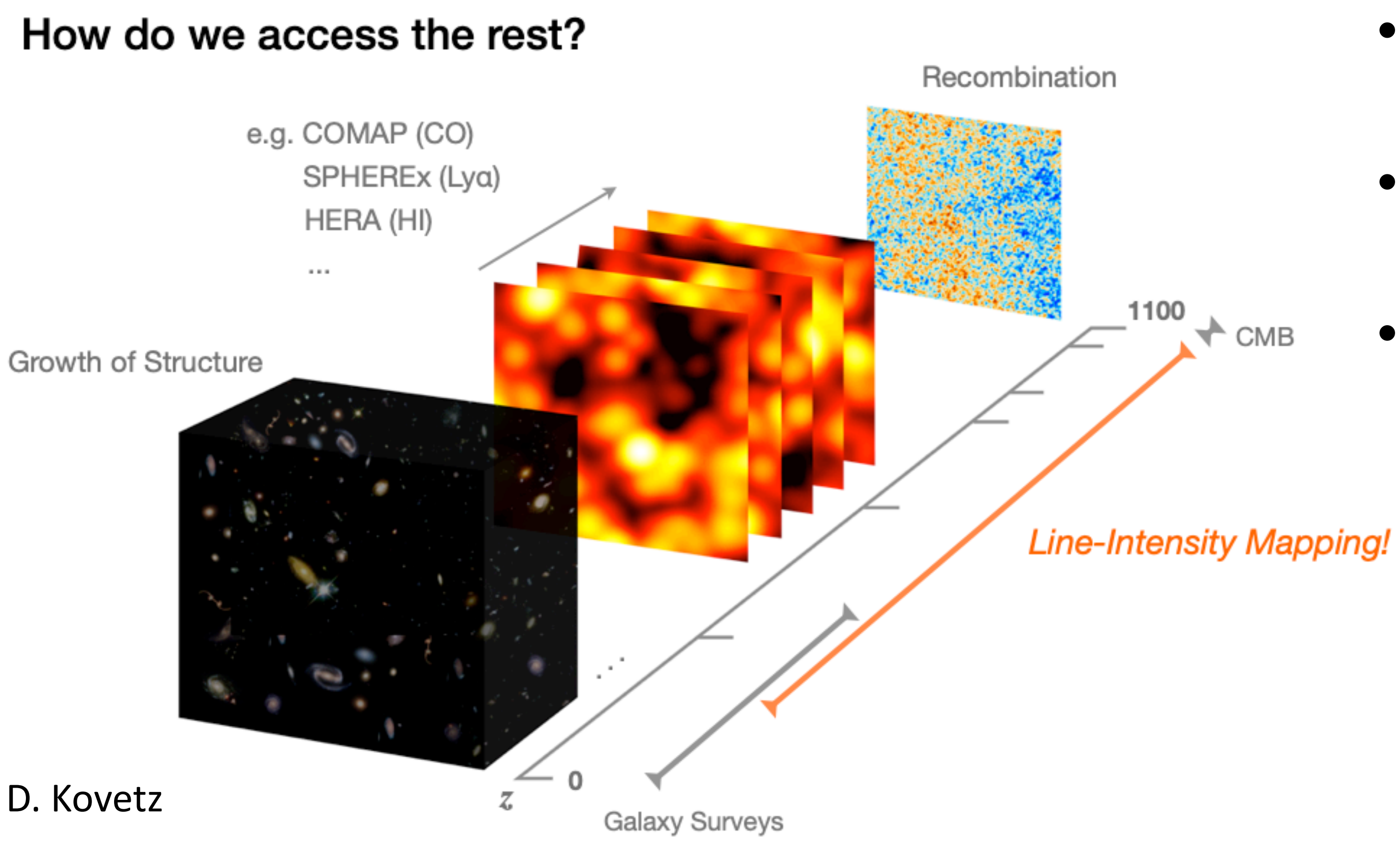
Probed Universe

LIM fills the gap



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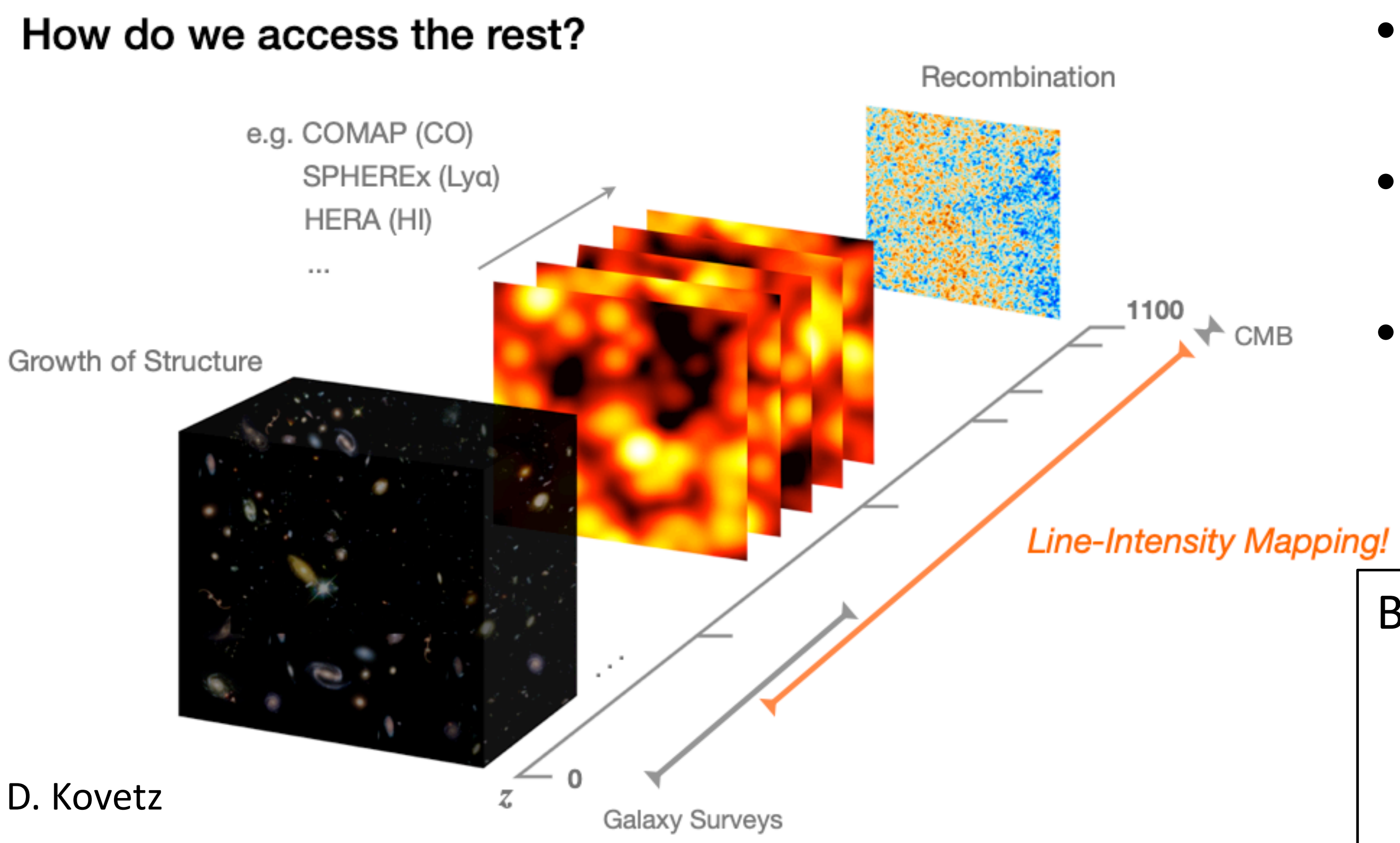
Optimistic experimental status

- Different stages of evolution across time
- But we have only exploited a small part
- LIM: integrated signal from ALL sources

LIM fills the gap



E. D. Kovetz

Optimistic experimental status

- Different stages of evolution across time
- But we have only exploited a small part
- LIM: integrated signal from ALL sources

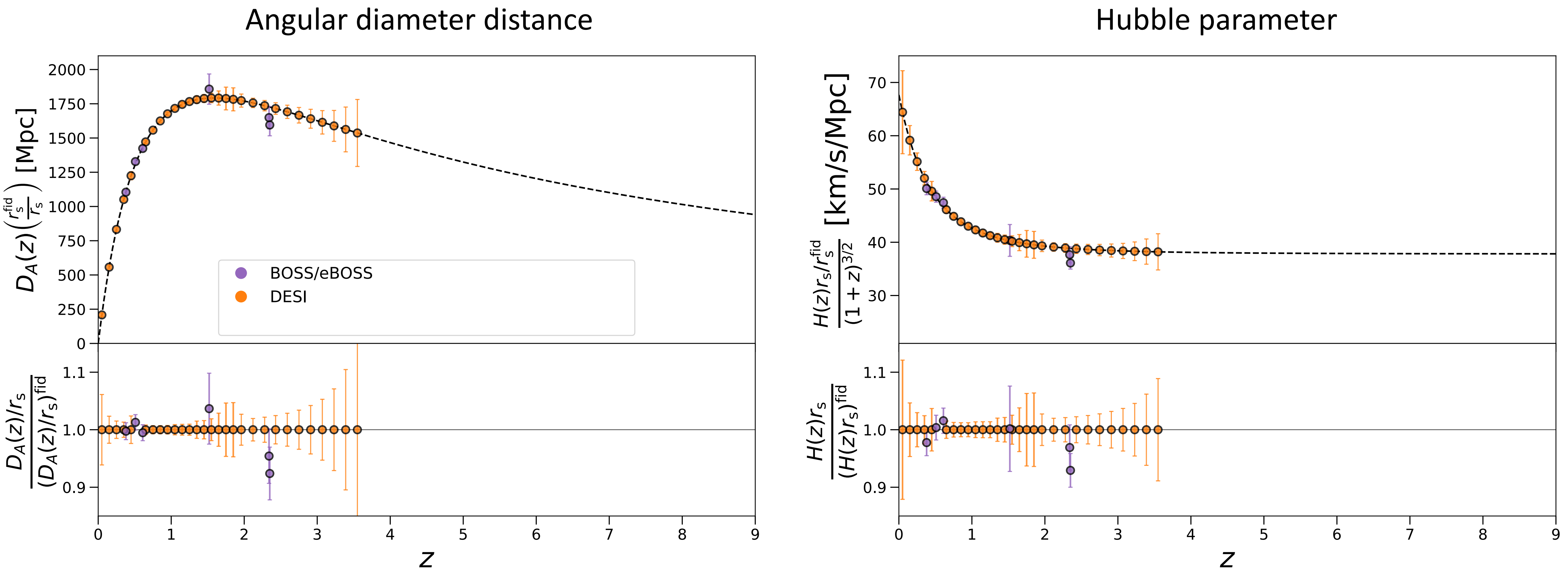
Biased tracer of the density fluctuations

Cosmological information

But degenerate with astrophysics

User's guide:JLB+2019a

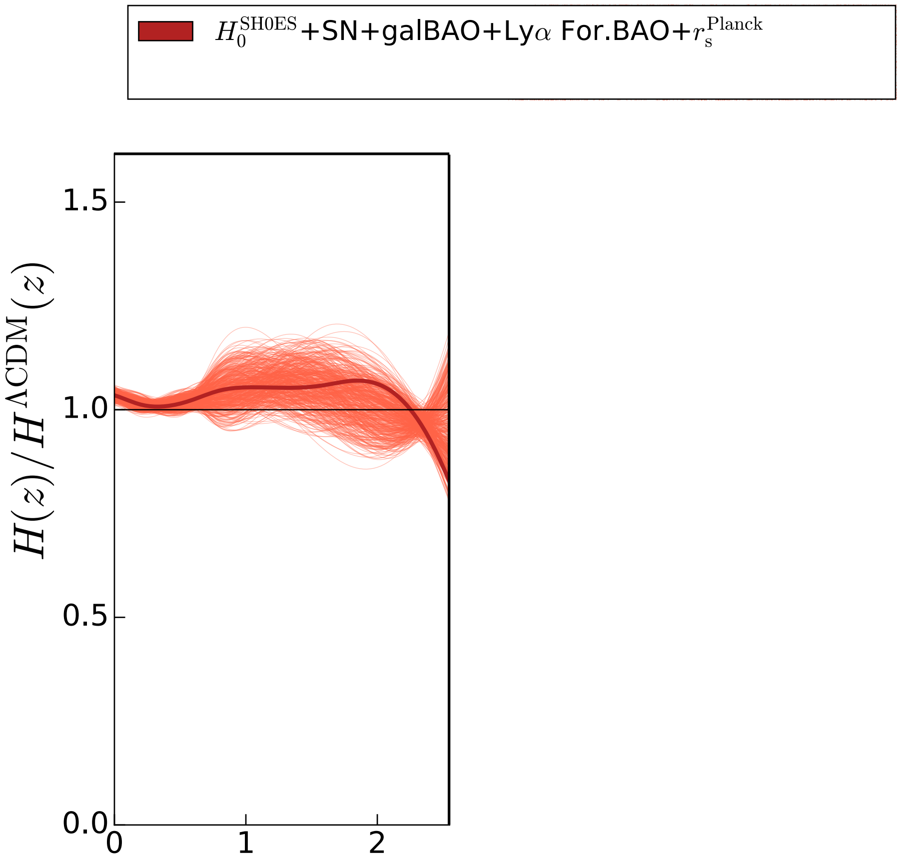
LIM BAO



Current and coming constraints using galaxy surveys

Constraining the expansion history

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

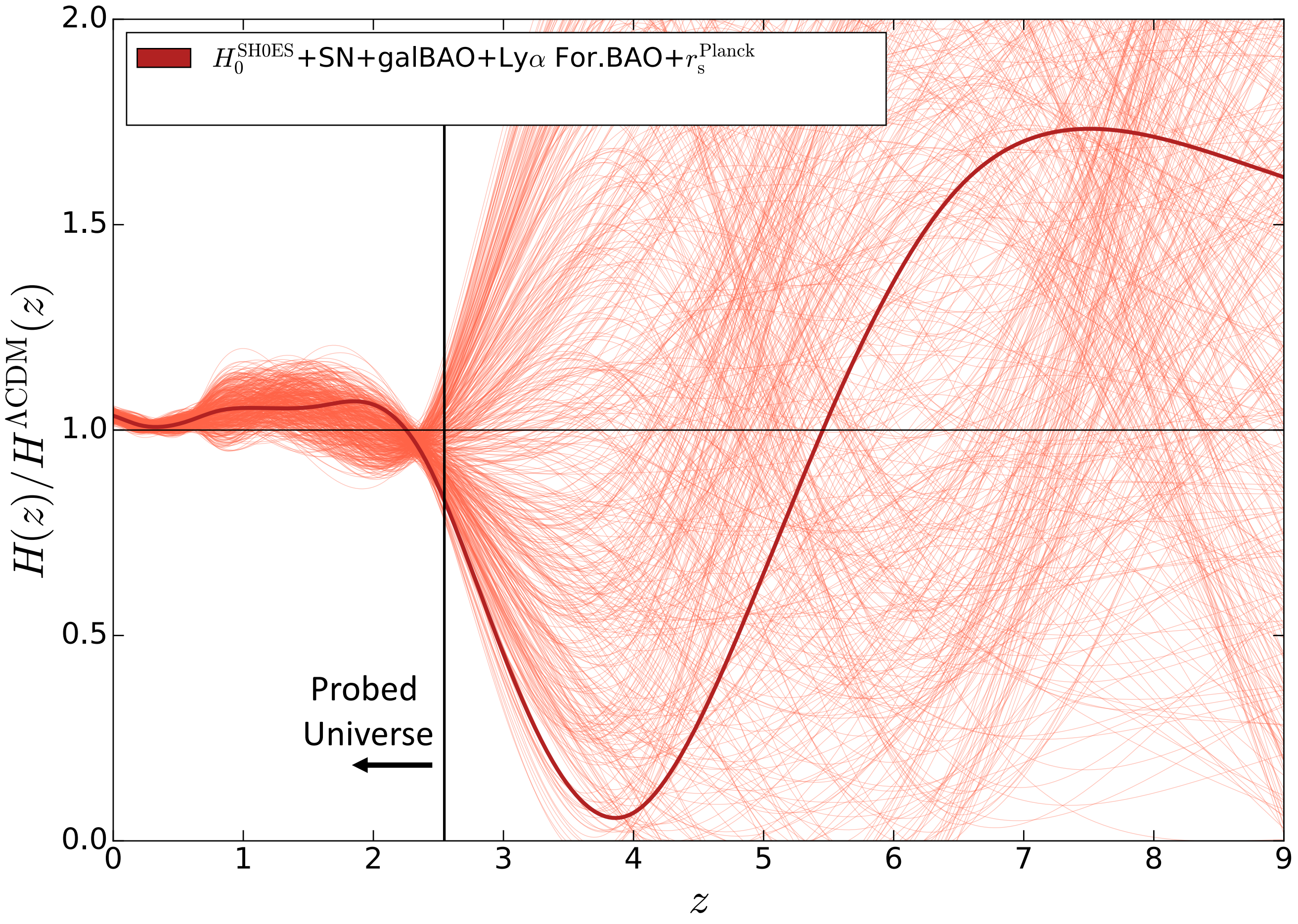


Current constraints using galaxy surveys (and H_0 and r_s)

Constraining the expansion history

JLB+2019b

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



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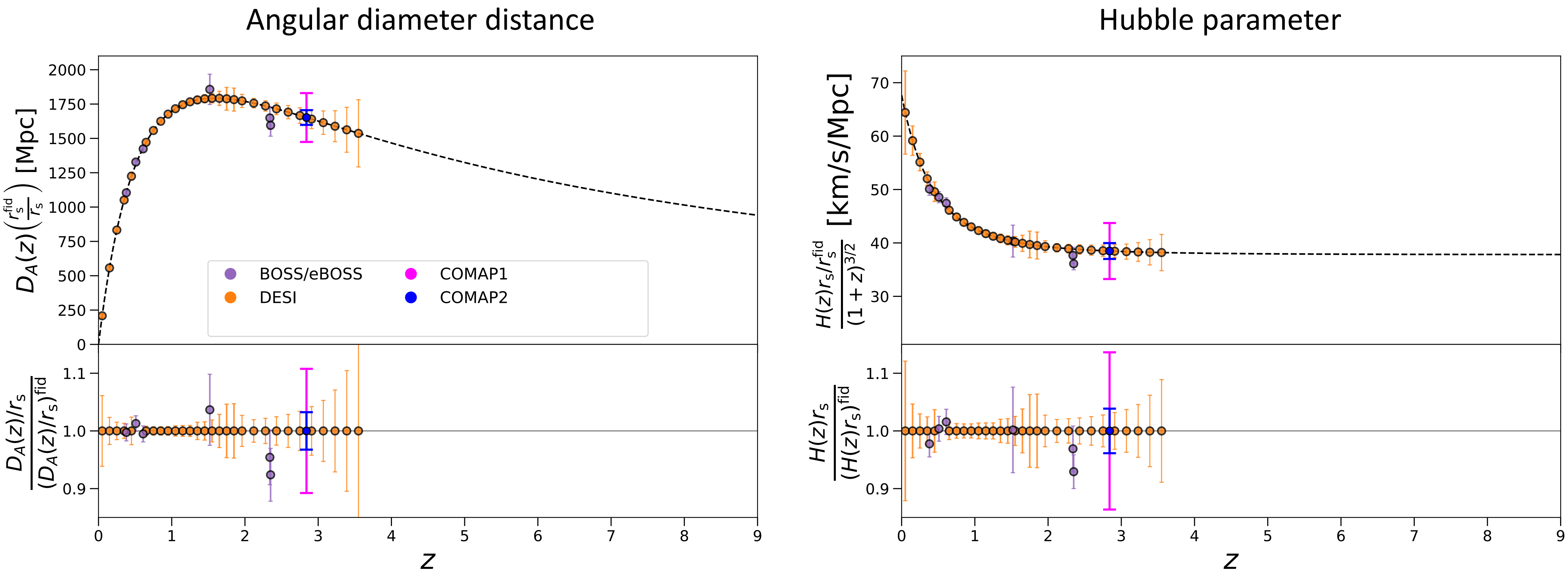
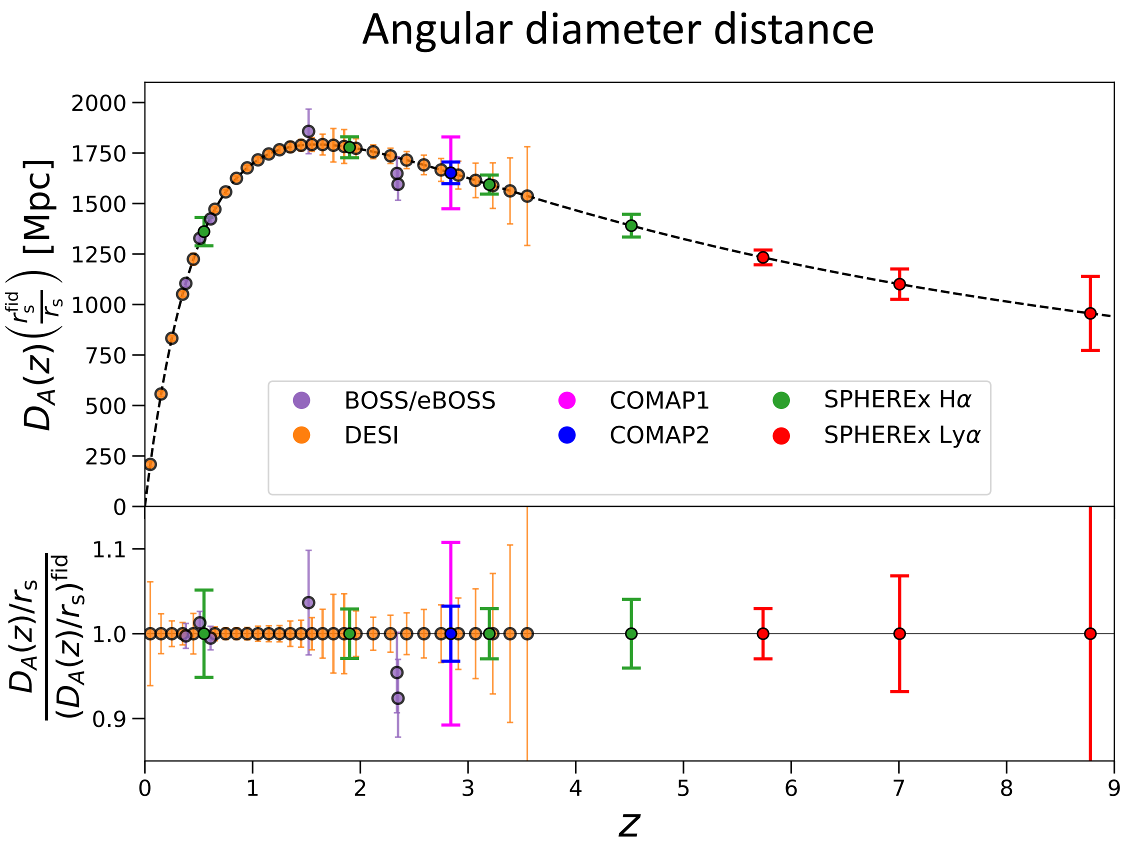


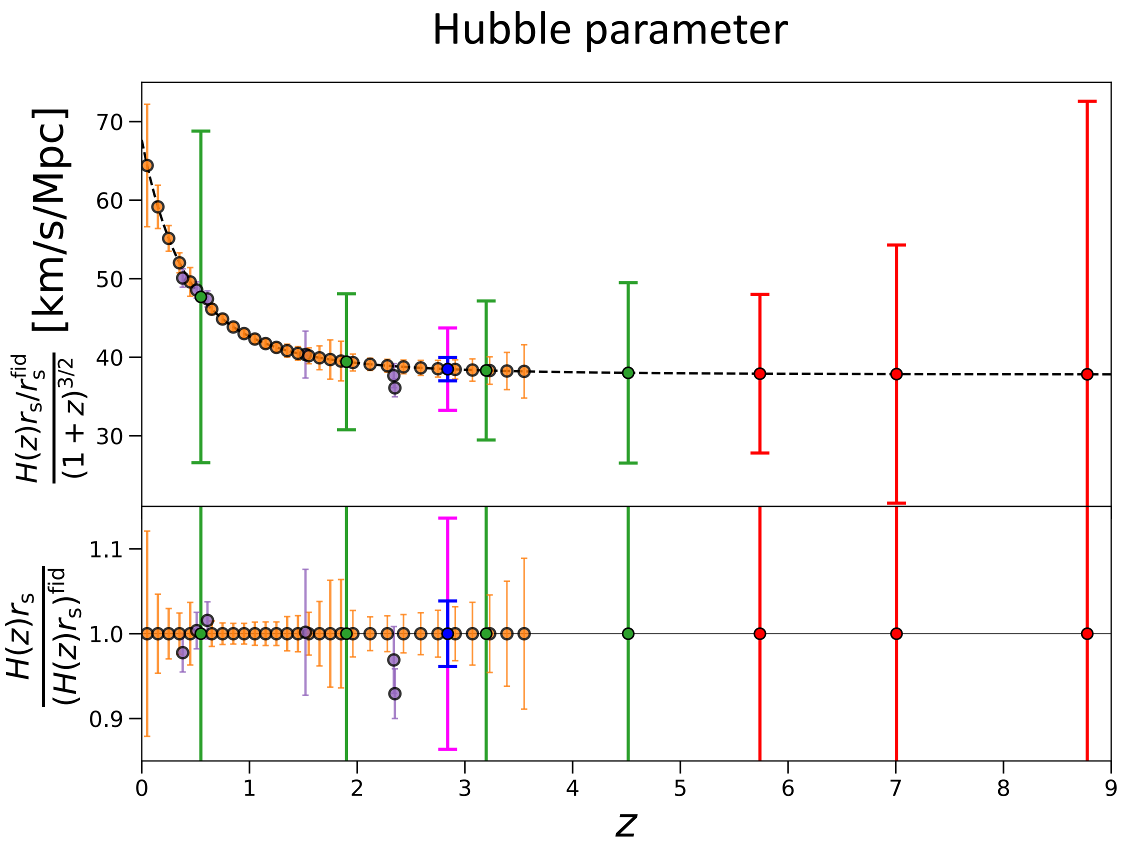
Current and coming constraints using galaxy surveys

+ Star-Formation-related LIM BAO

JLB+2019b

LIM BAO





Current and coming constraints using galaxy surveys

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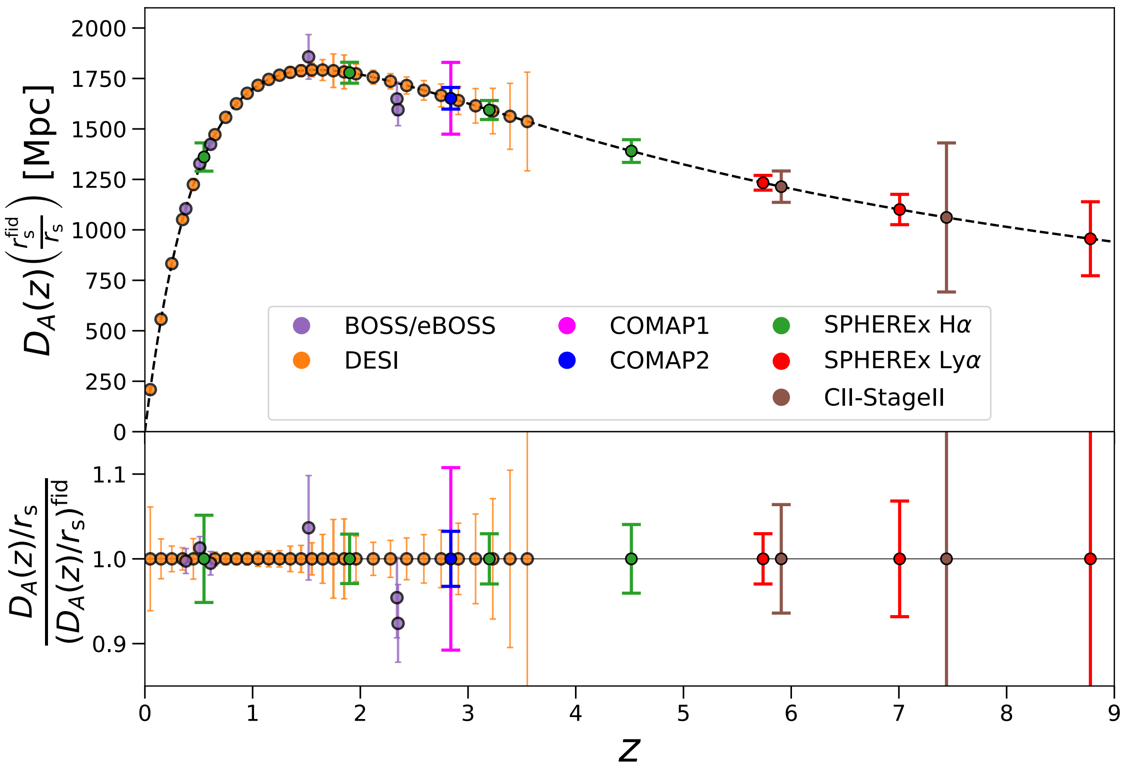
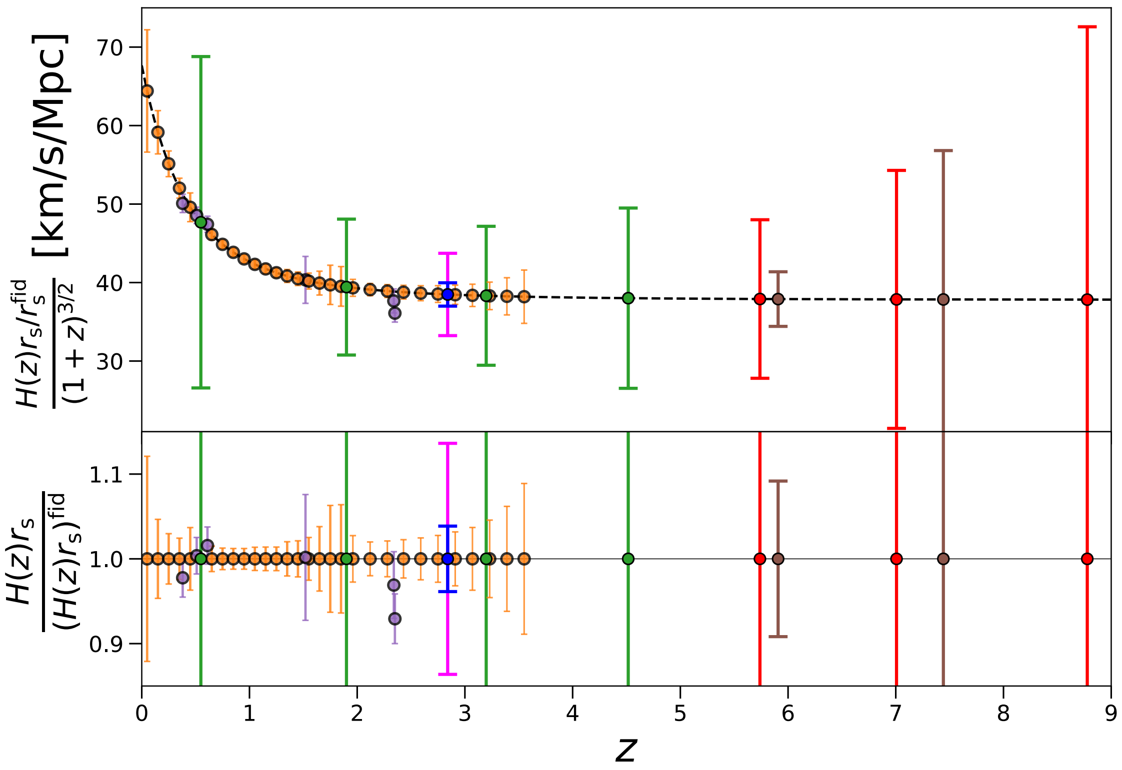
LIM BAO

JLB+2019b

Angular diameter distance



Hubble parameter



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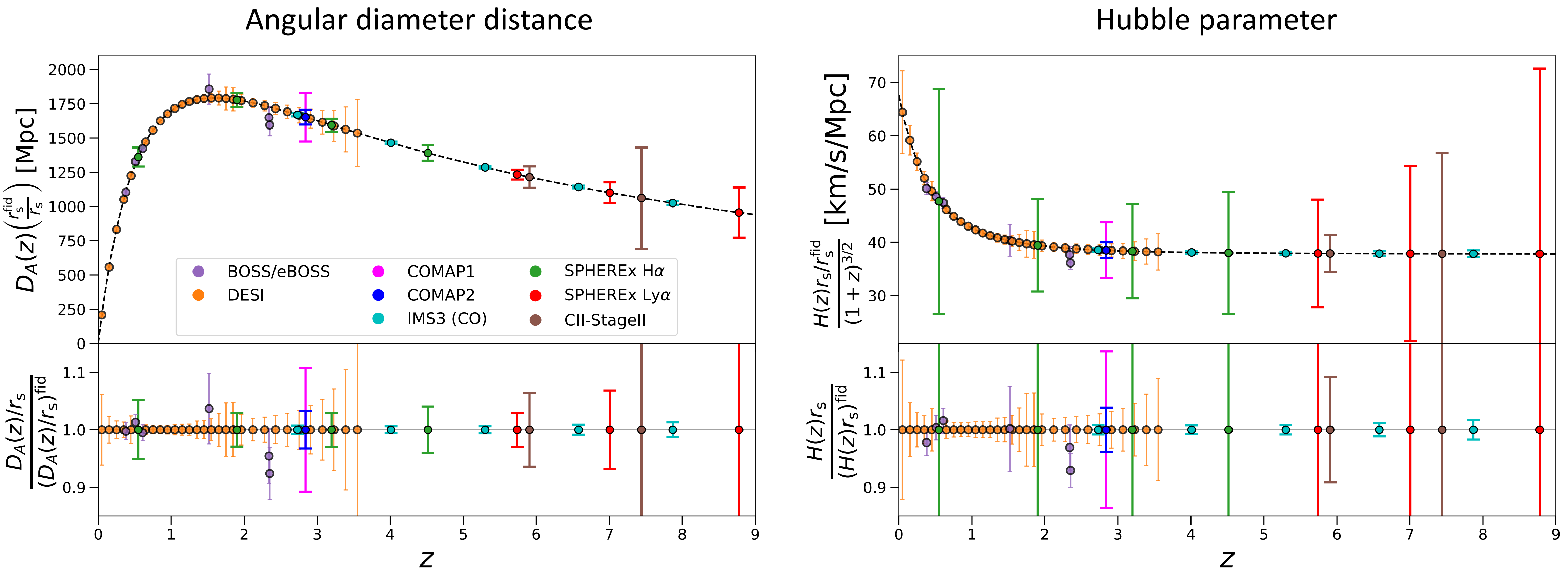
JLB+2019b



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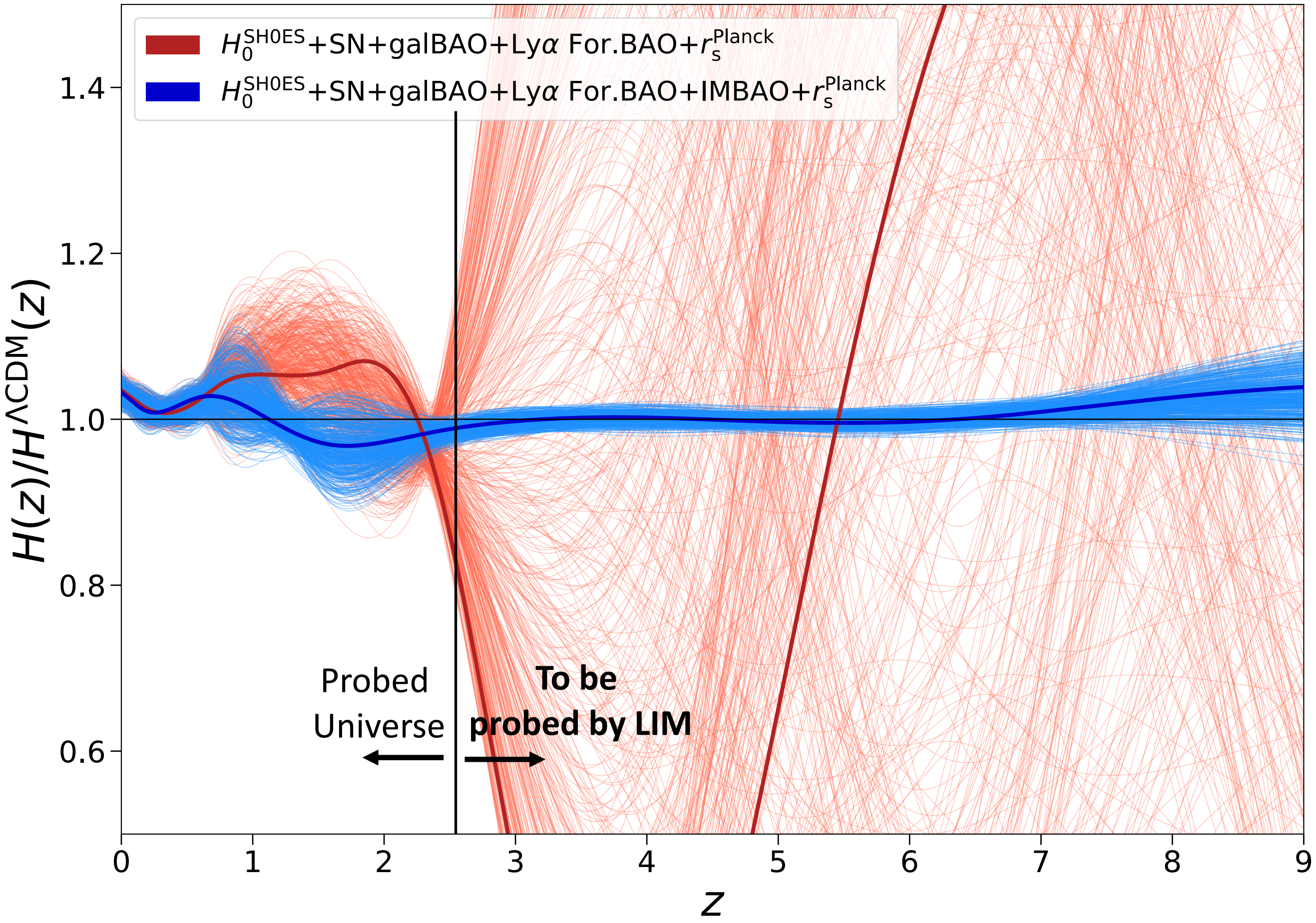


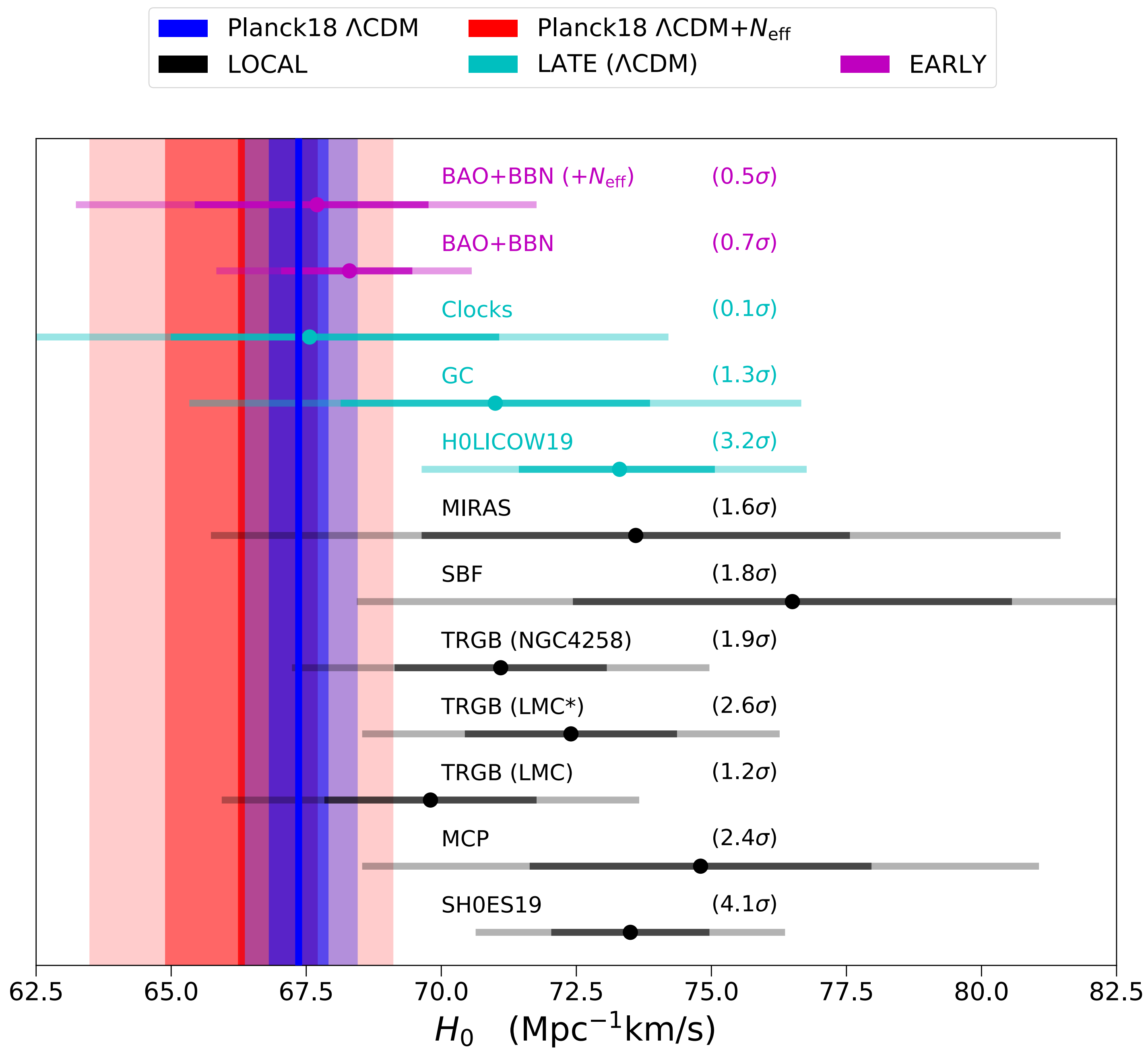
Bridge early and late Universe to probe post-recombination solutions

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

Conclusions

- Early-late Universe tension? Mismatch in the anchors of the distance ladder.
- The tension in H_0 is not related with deviations in the late time expansion history.
- LIM will grant access to unprobed stages of the Universe
- LIM will bridge between late and early Universe and probe $H(z < 7)$ to $\sim 10\%$ in the coming years ($\sim 2\%$ with IMS3) in a model independent way
- Time for blinded analyses to avoid confirmation bias (Brieden, Gil-Marín, Verde, JLB, 2020)

Back up slides



H_0 Tension

Model dependent tension

Coincident results & several cross-checks

Confirmed high-z vs low-z tension

Zoo of posible solutions

Exploiting BAO

- BAO feature frozen in matter overdensities after recombination

Standard ruler!

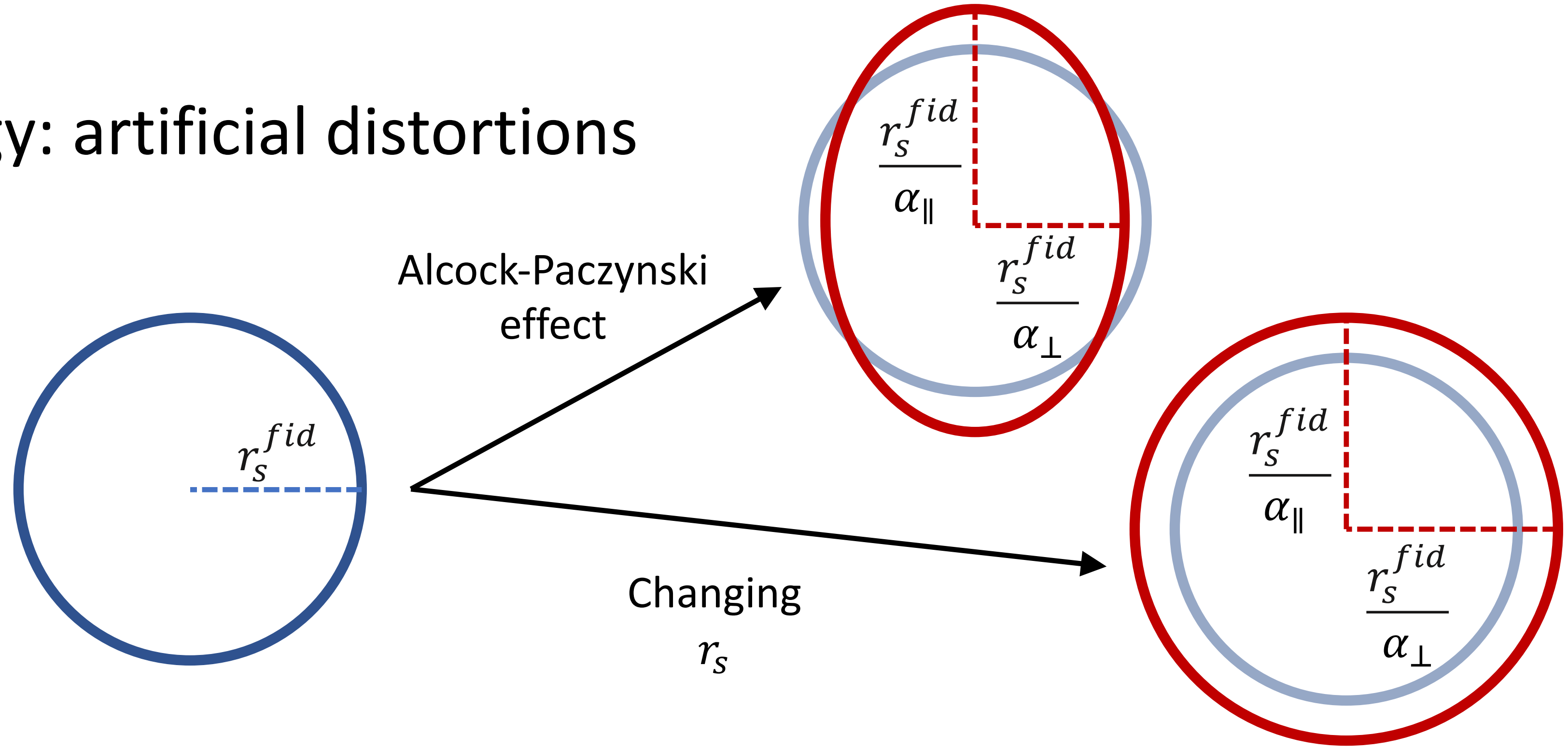
- LLS observations: z → distances (fiducial cosmology needed)

- Wrong cosmology: artificial distortions

BAO: recognizable feature in $P(k)$

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

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



Exploiting BAO

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

BAO: recognizable feature in $P(k)$

$$x_{\perp} = D_A(z)\theta$$

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

Rescaling with respect the fiducial prediction

$$\alpha_{\perp} = \frac{D_A(z)/r_s}{(D_A(z)/r_s)^{fid}}$$

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

Exploiting BAO

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

$$\alpha_{\perp} = \frac{D_A(z)/r_s}{(D_A(z)/r_s)^{fid}}$$

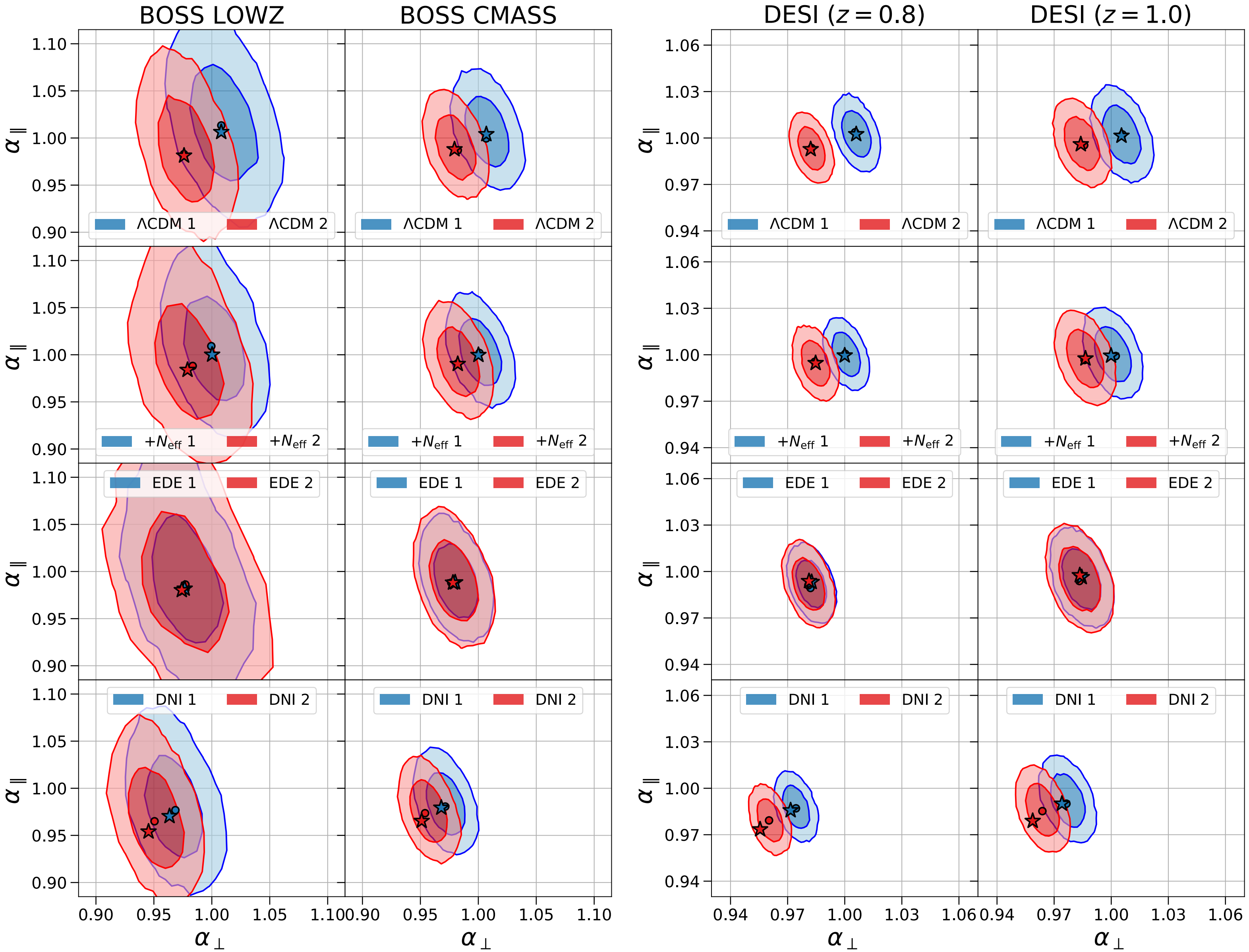
$$P(\vec{k}^{meas}) \propto P(k_{\parallel}^{true}\alpha_{\parallel}, k_{\perp}^{true}\alpha_{\perp}) + A(\vec{k}^{meas}, \vec{\eta})$$

Isolating BAO feature

Broadband marginalization

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

Compressed BAO constraints $(\alpha_\perp; \alpha_\parallel)$ are robust also beyond ΛCDM



Check on synthetic $P(k)$:

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

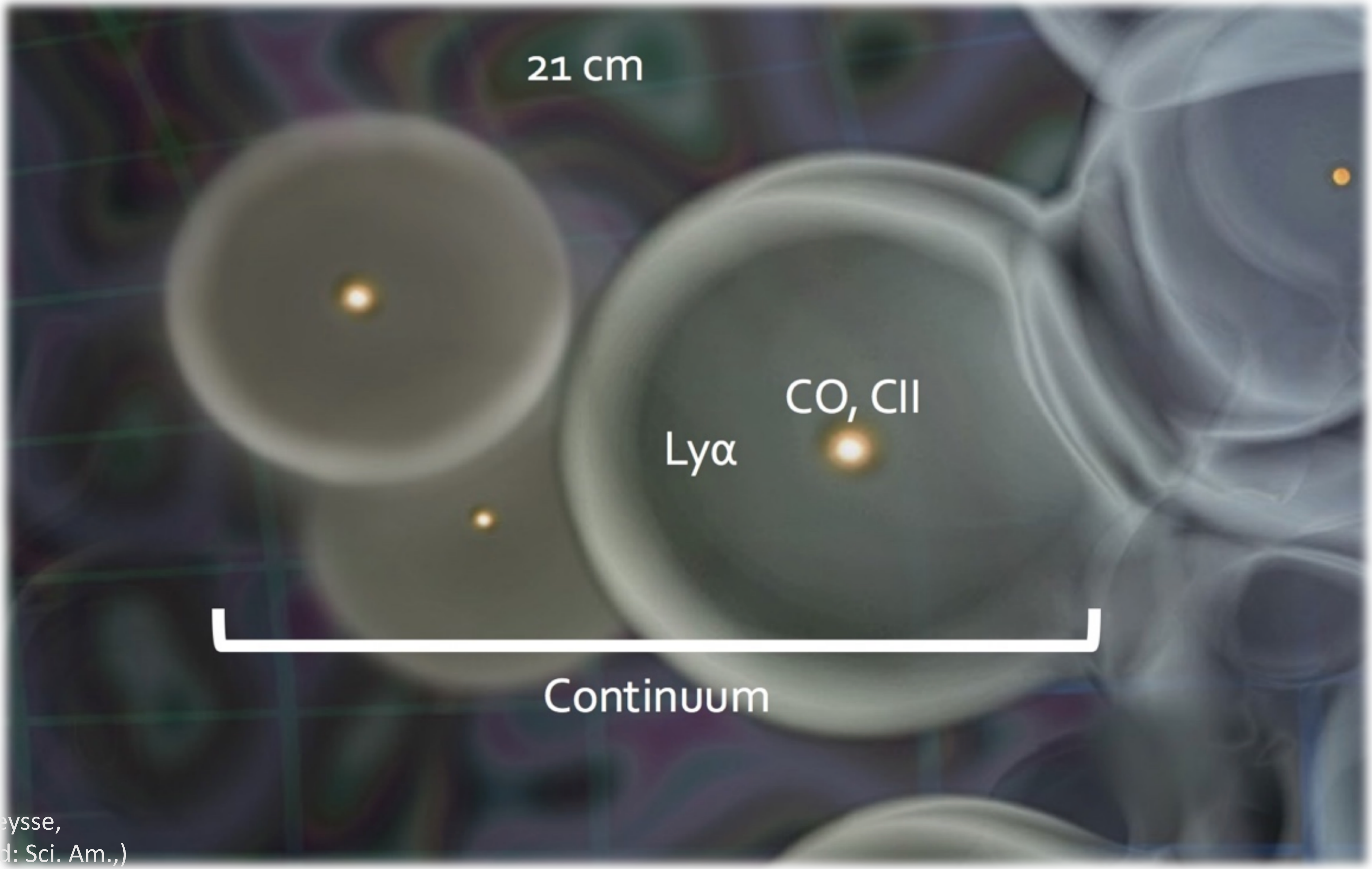
- ● Best fit
- ★ Real values
- Good fit to Planck
- Bad fit to Planck

$$\alpha_\perp = \frac{D_A(z)/r_s}{(D_A(z)/r_s)^{fid}}$$

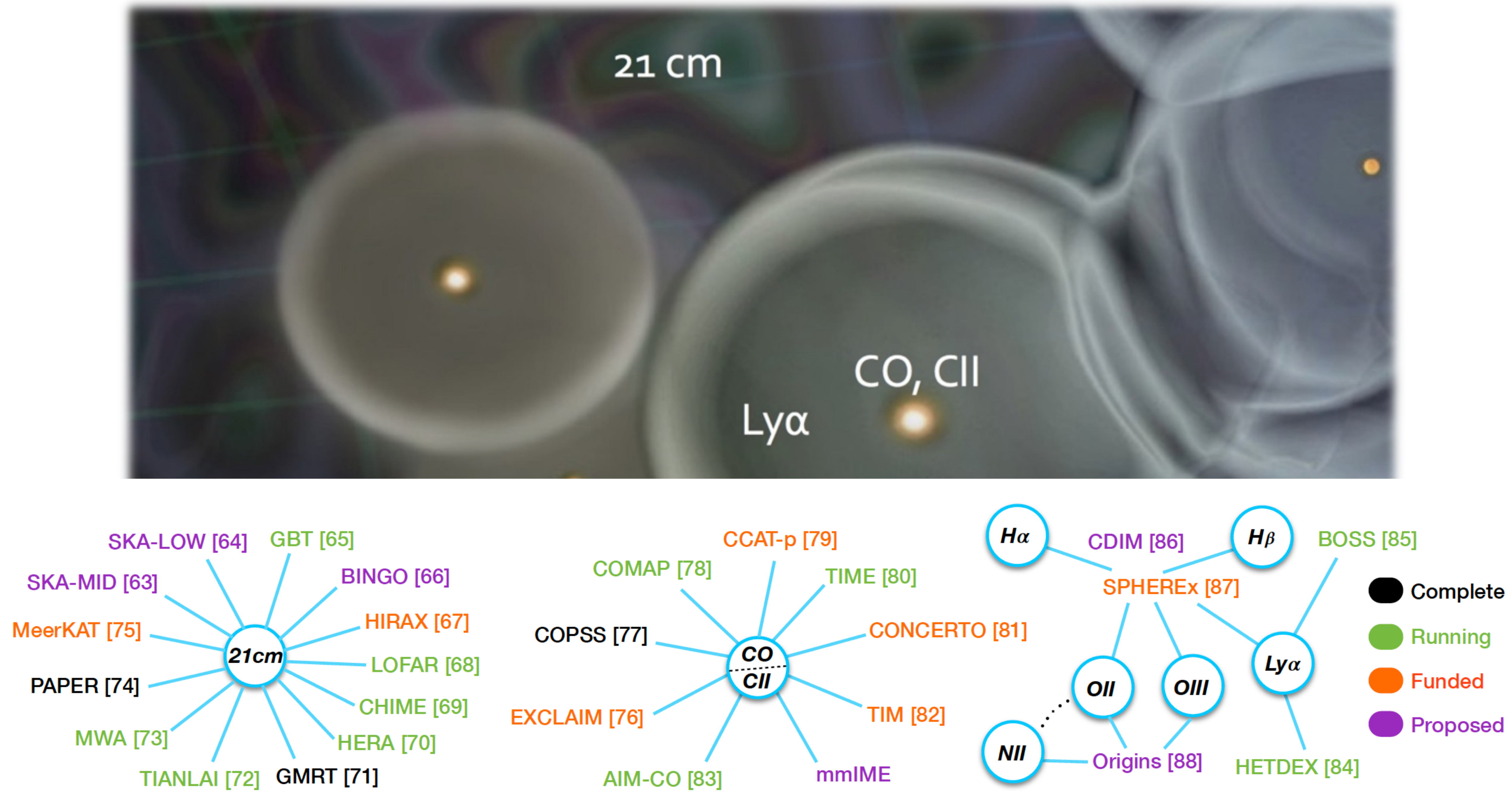
$$\alpha_\parallel = \frac{(H(z)r_s)^{fid}}{H(z)r_s}$$

2004.07263

Bernal et al. (2020)



P. Breysse,
Background: Sci. Am.,)


21 cm
CO, CII
Lyα
SKA-LOW [64]
GBT [65]
SKA-MID [63]
BINGO [66]
MeerKAT [75]
HIRAX [67]
21cm
LOFAR [68]
PAPER [74]
CHIME [69]
MWA [73]
HERA [70]
TIANLAI [72]
GMRT [71]
CCAT-p [79]
COMAP [78]
TIME [80]
COPSS [77]
CONCERTO [81]
CO
CII
EXCLAIM [76]
TIM [82]
AIM-CO [83]
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Hα
CDIM [86]
Hβ
BOSS [85]
SPHEREx [87]
Lyα
OII
OIII
NII
Origins [88]
HETDEX [84]
Complete
Running
Funded
Proposed

E. D. Kovetz