Tensions in cosmology

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IFCA
CSIC
Consejo Superior de Investigaciones Científicas
UC
Ministerio de Ciencia, Innovación y Universidades
Agencia Estatal de Investigación

Outline

- Introduction
- Measuring the local expansion rate
- Inferring H_0 from the CMB
- BAO role and nature of the tension
- H_0 beyond H_0
- Final touches about features for theoretical models
- DESI BAO and low-z expansion rate
- Conclusions

Introduction

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

Introduction

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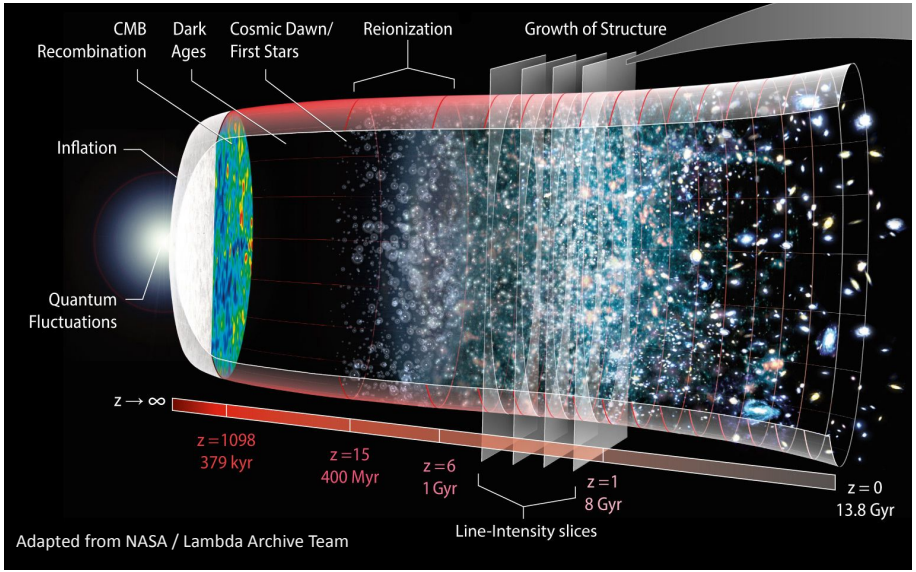
- Standard/consensus cosmological model: ΛCDM
- Excellent reproduction of observations

$$\{H_0,\ \Omega_b,\ \Omega_m,\ A_s,\ n_s,\ \tau_{\rm reio}\}$$

contents of Universe — Primordial Universe — Astro

$$ds^2 = -dt^2 + a^2(t)dx^i dx_i$$



Introduction

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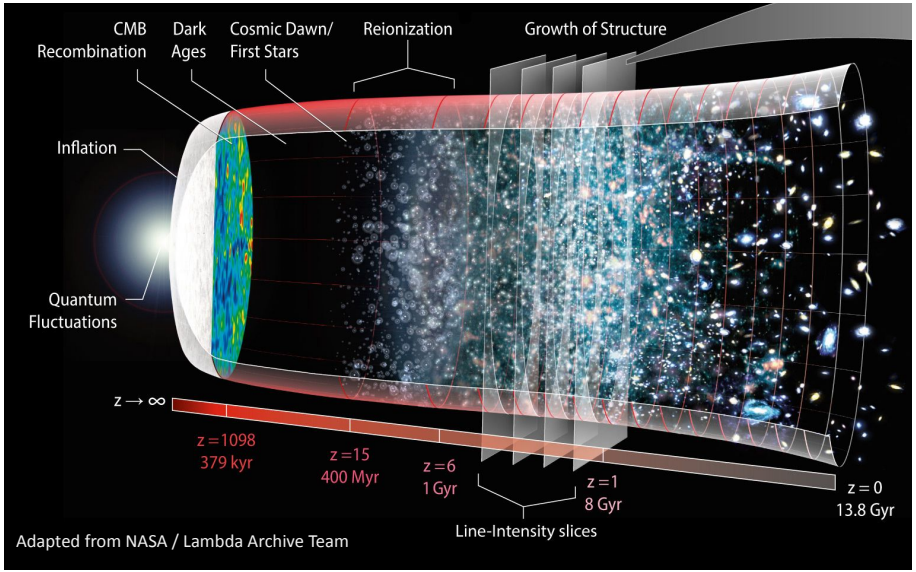
- Standard/consensus cosmological model: ΛCDM

- Excellent reproduction of observations,
  - Persistent **discrepancies** between diff. probes (high vs low *z*?)
  - **Phenomenological** model
  - **Lots of unknowns**
    galaxy formation, reionization, …

$$ds^2 = -dt^2 + a^2(t)dx^i dx_i$$

$$H = \dot{a}/a \qquad H_0 = H(z=0)$$



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- Standard/consensus cosmological model: ΛCDM

- Excellent reproduction of observations, but…
  - Persistent **discrepancies** between diff. cosmological probes
  - **Phenomenological** model
  - **Lots of unknowns** regarding first stars, galaxy formation, reionization, …

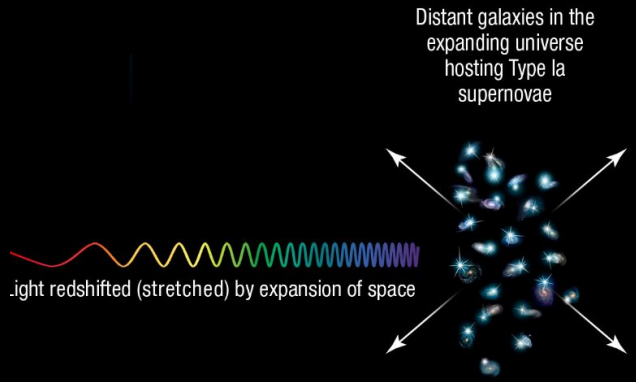
- 3 avenues to tackle this challenge:

  1): **Improve** observations and modeling of traditional probes; cross-correlations

  2): **Explore** models beyond ΛCDM to reconcile tension and explain unknowns

  3): **Develop** new cosmological probes

Measuring H_0 : 3 rung ladder

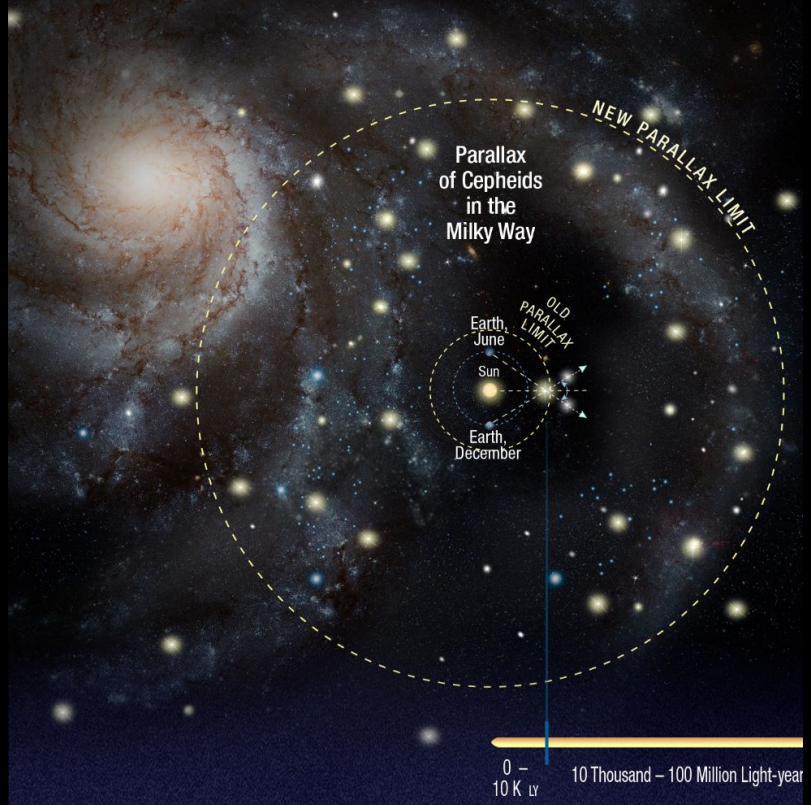


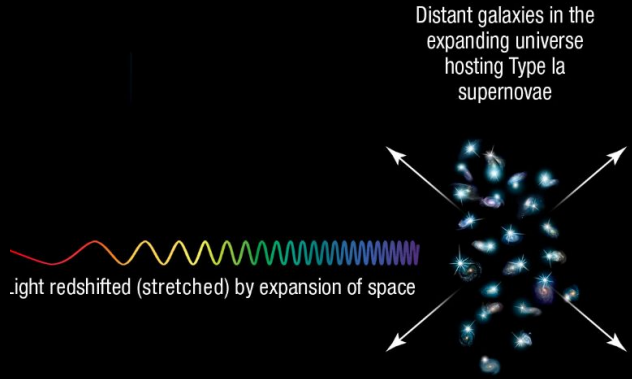
$$H_0 = dv_{\mathrm{rec}}$$

ESO

Measuring H_0 : 3 rung ladder

Change cepheids for your favorite calibrator:
TRGB, JAGB, MIRAS, …





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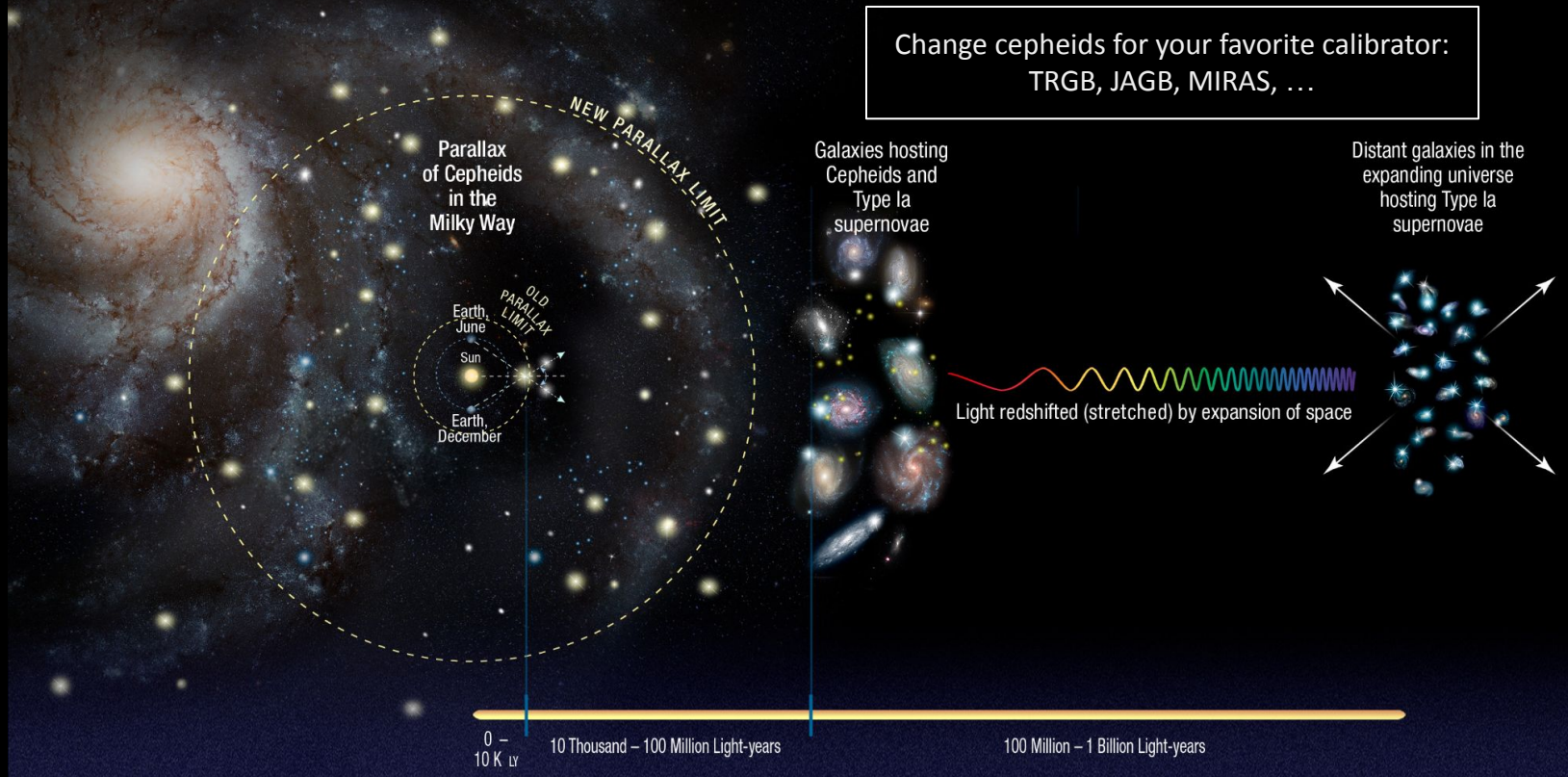
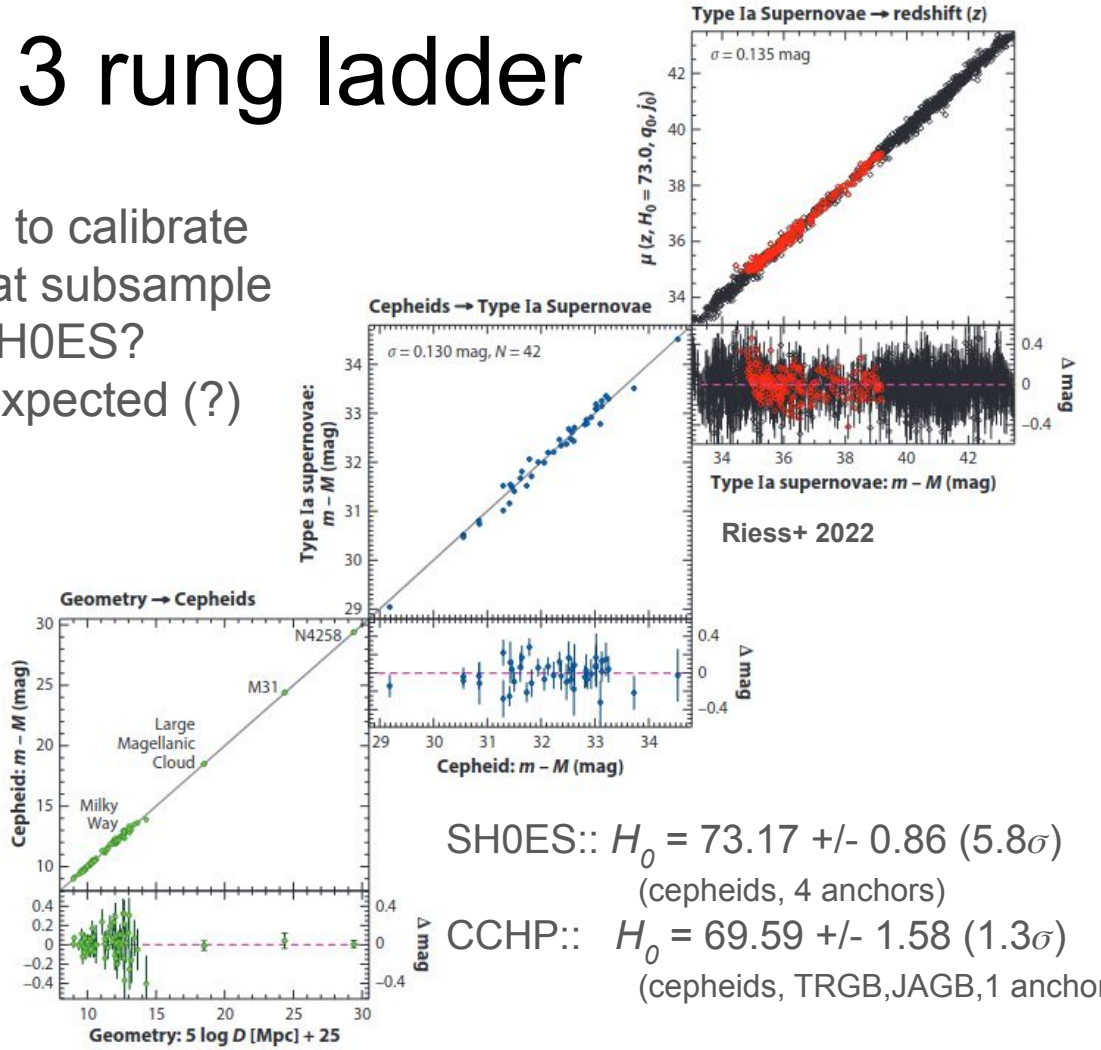


ESO

$$H_0 = dv_{\mathrm{rec}}$$

Measuring H_0 : 3 rung ladder

- Precision limited by *N* SN hosts to calibrate
- H_0 result depends largely on that subsample
  - Diff. between CCHP and SH0ES?
  - Recent *JWST* results are expected (?)



SH0ES:: H_0 = 73.17 +/- 0.86 (5.8σ)
(cepheids, 4 anchors)

CCHP:: H_0 = 69.59 +/- 1.58 (1.3σ)
(cepheids, TRGB,JAGB,1 anchor)

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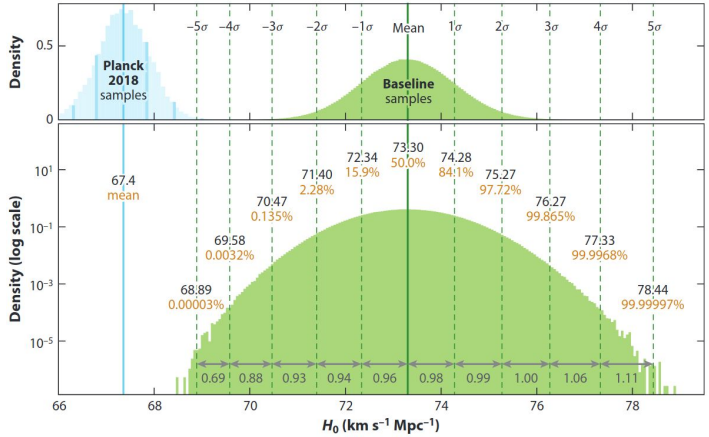
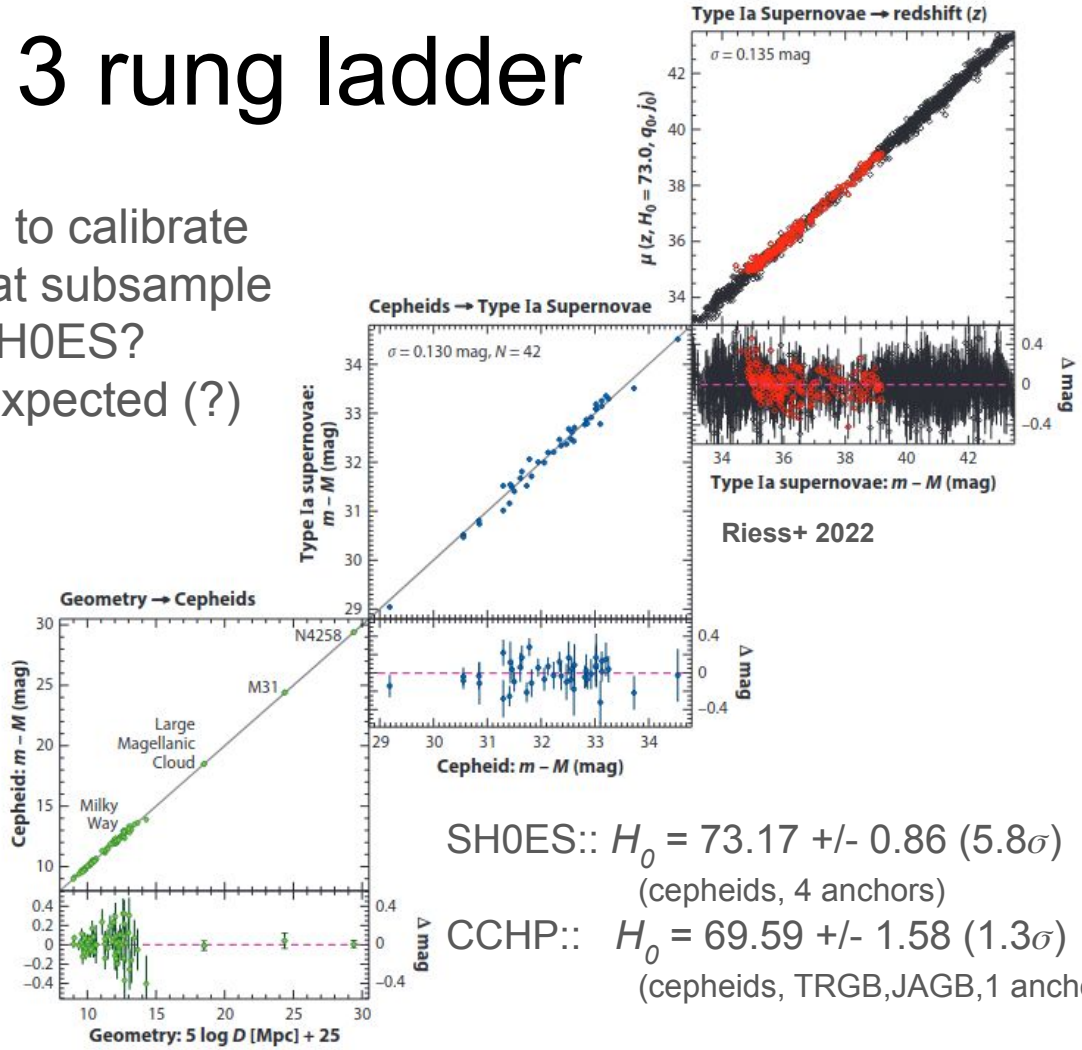


Kamionkowski & Riess 2023



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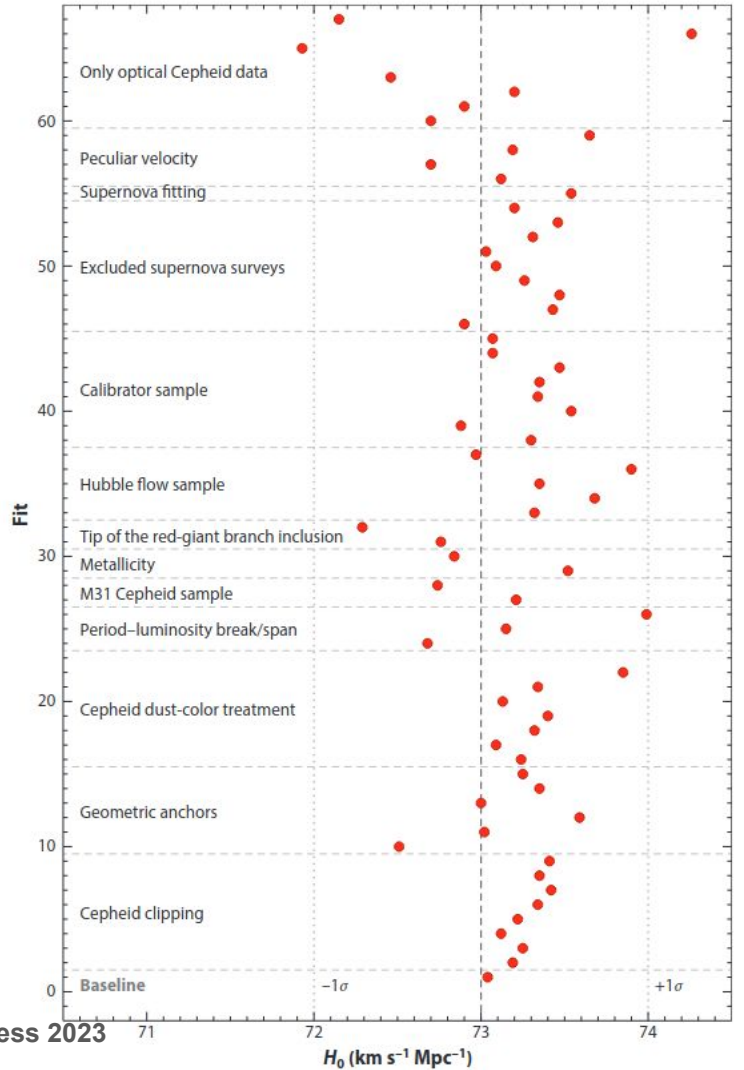
Measuring H_0 : 3 rung la

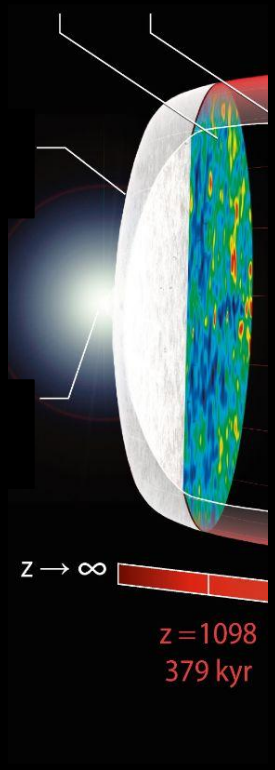
- Systematics?
  - Calibrators? (*)
  - Dust?
  - Cepheid crowding?
  - Peculiar velocity correction?
  - Metallicity correction?
  - Gaia parallaxes?
  - SNeIa populations?
  - Issues in the CMB?

Freedman+ 19, Freedman+ 20, Yuan+ 19, Efstathiou+ 20, Soltis+21, Freedman+ 21, Anand+21, Kenworthy+ 22, Rigault+15, Jones+18, Brout+ 20, …

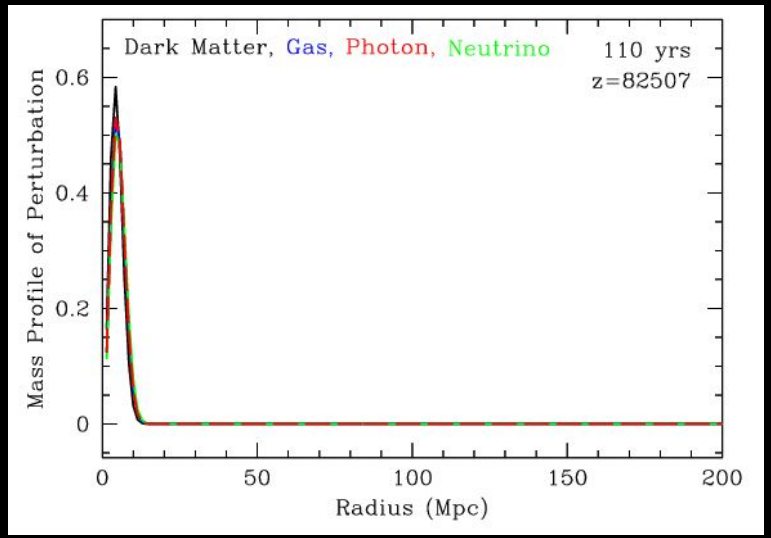


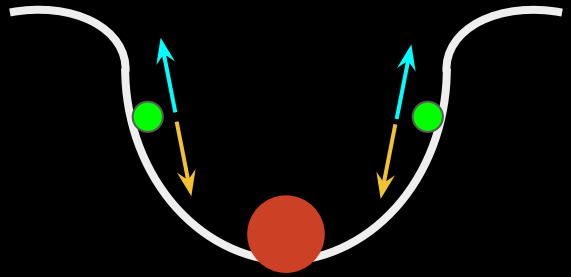
Kamionkowski & Riess 2023

Inferring H_0 from the CMB: standard ruler



Adapted from NASA / Lambda Archive Team





Gravity
vs
Radiation pressure

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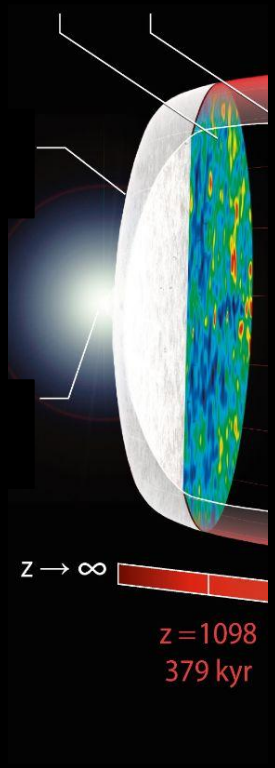

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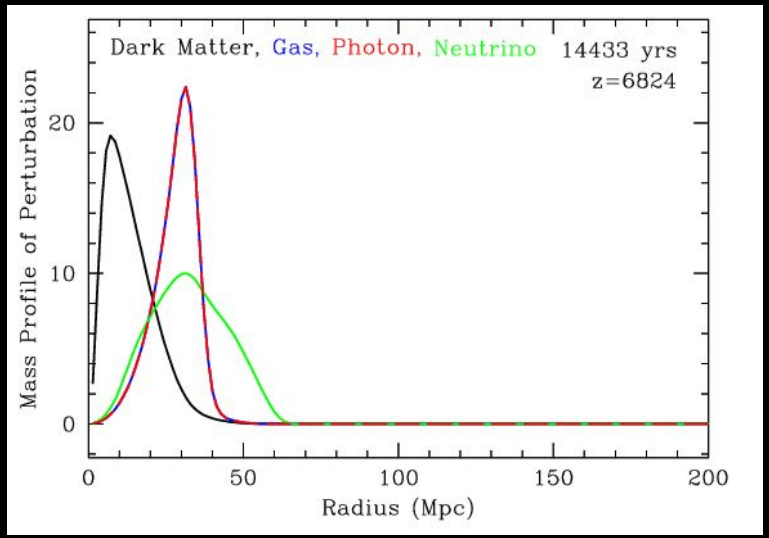

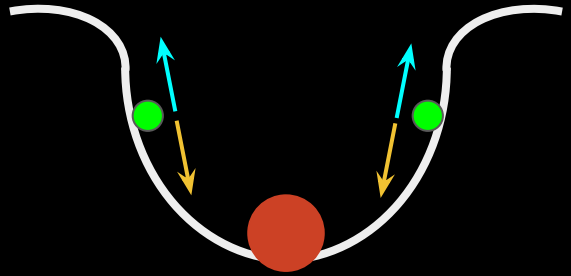

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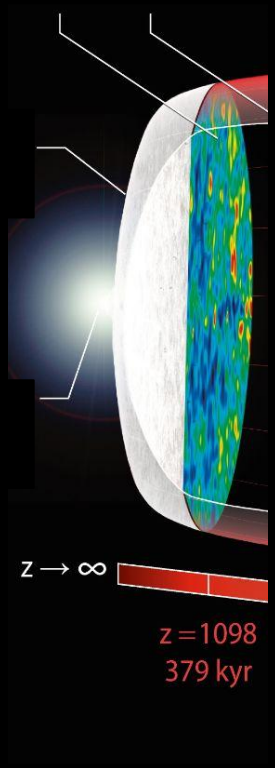

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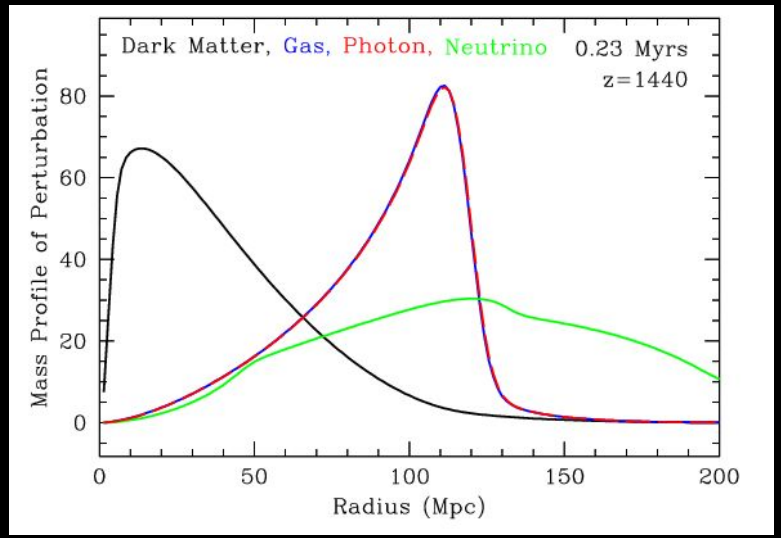

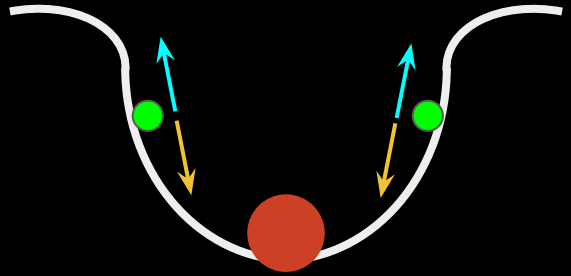

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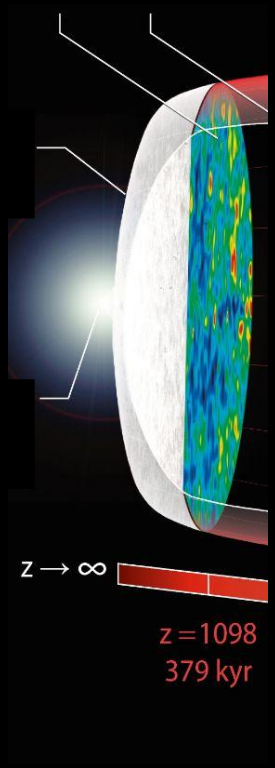

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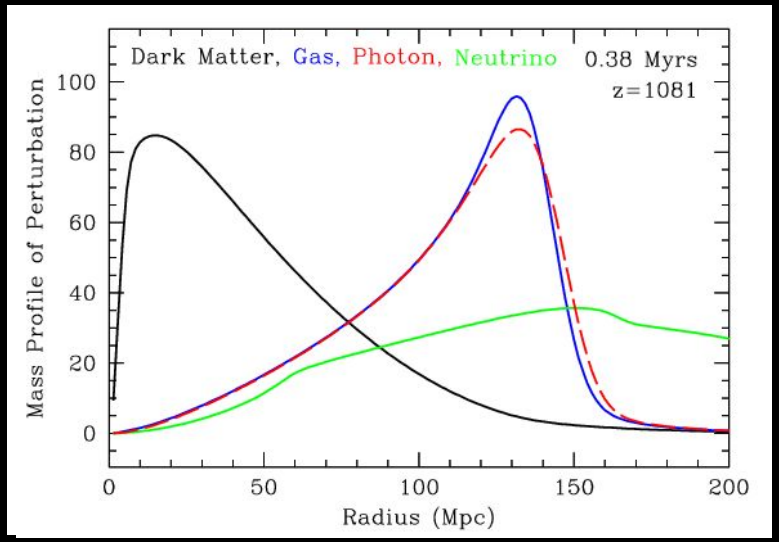

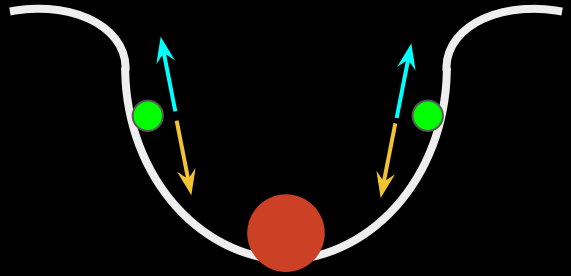

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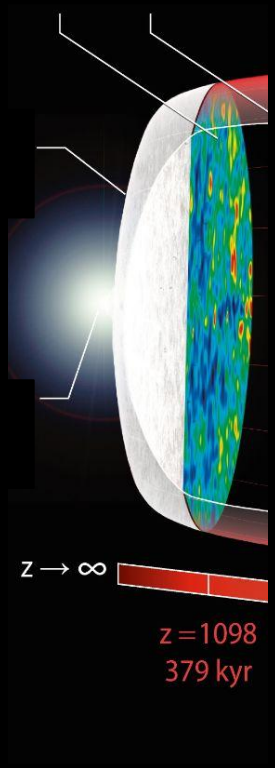

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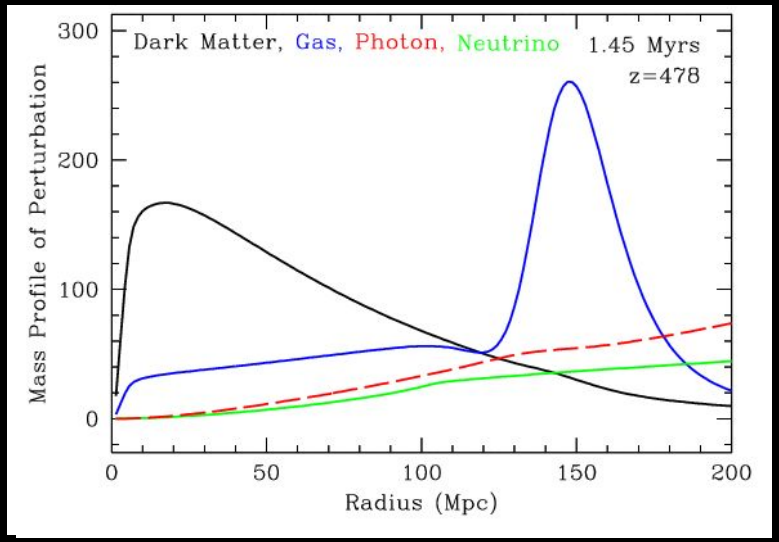

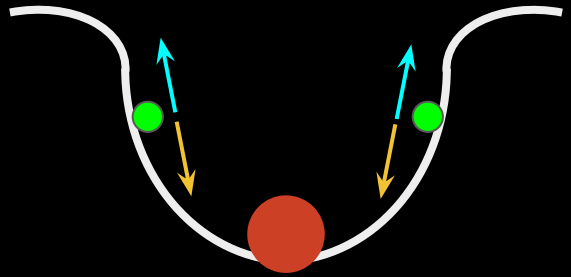

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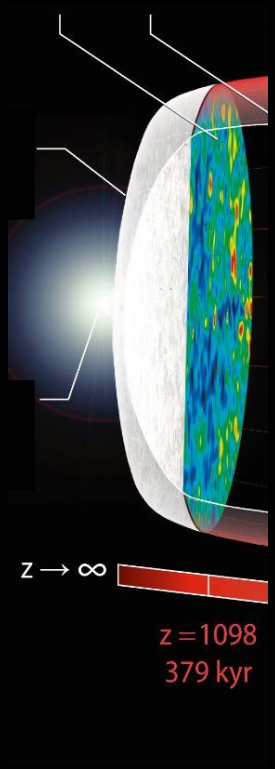

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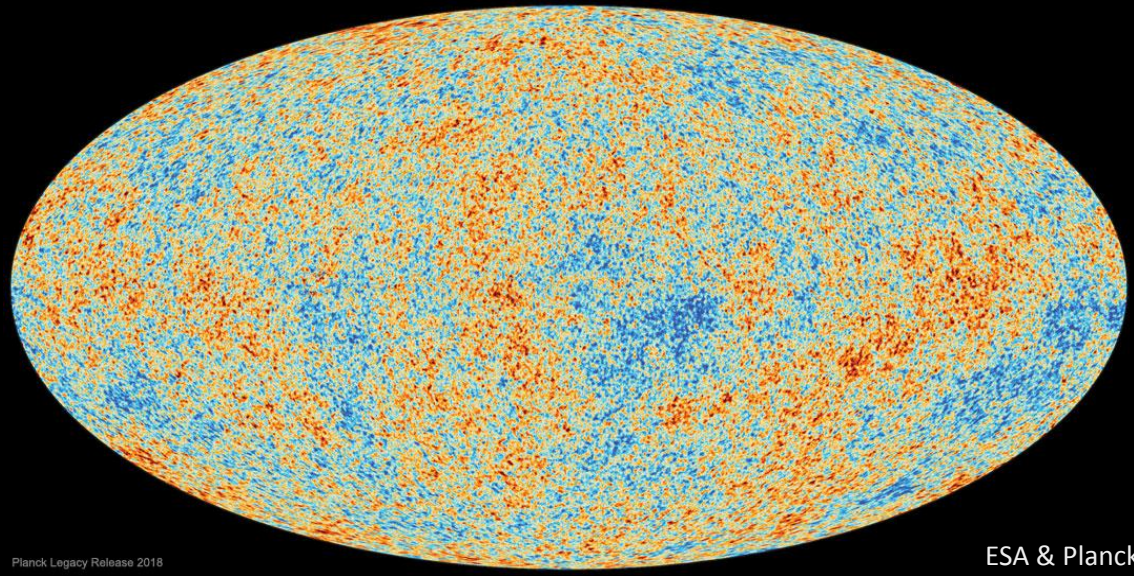
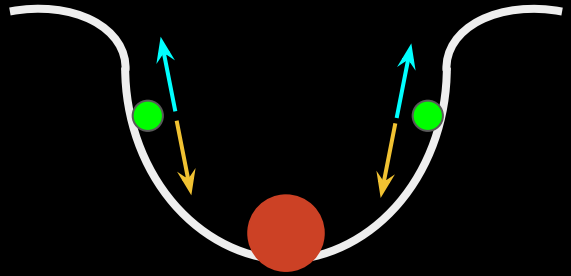


ESA & Planck collaboration



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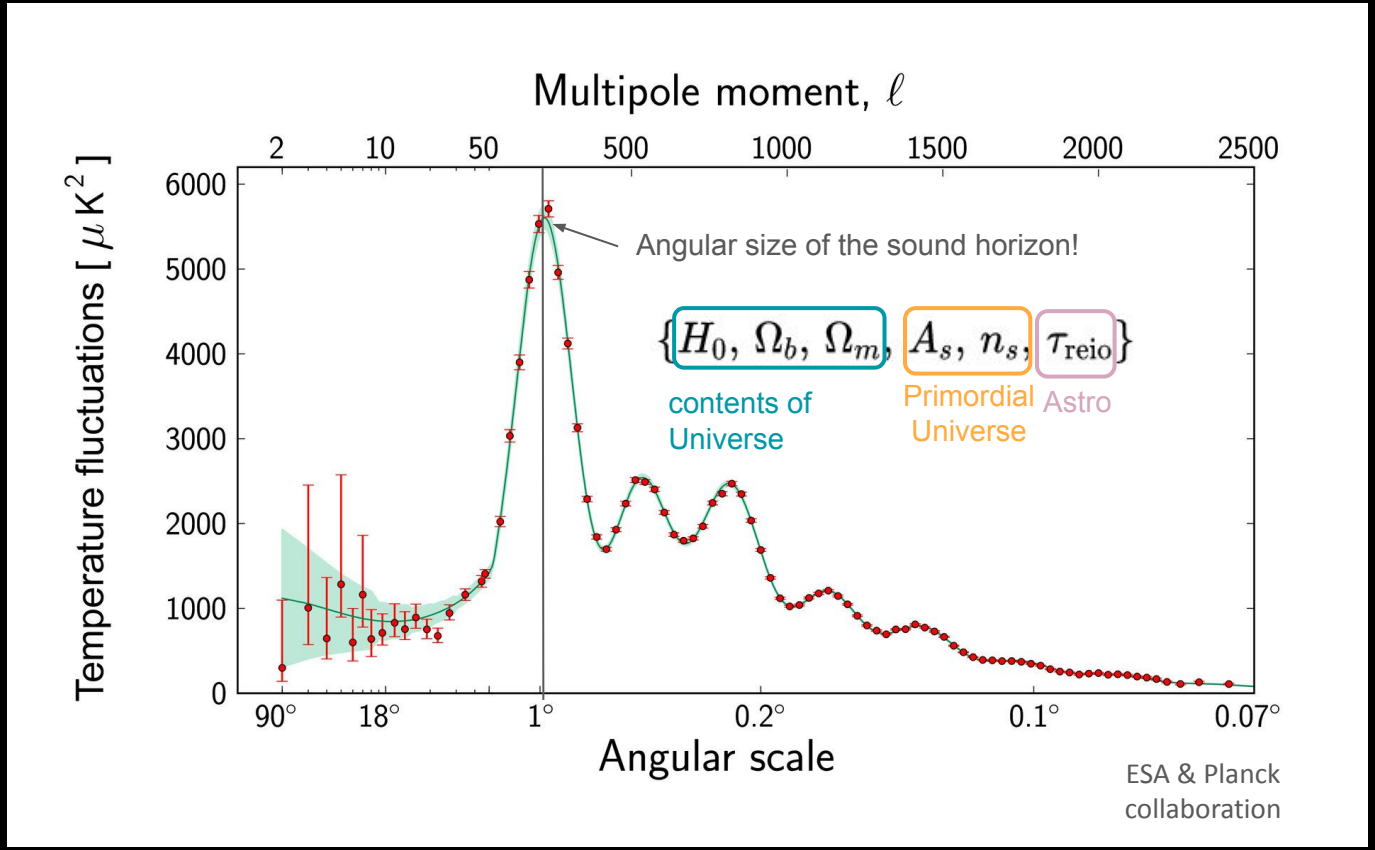
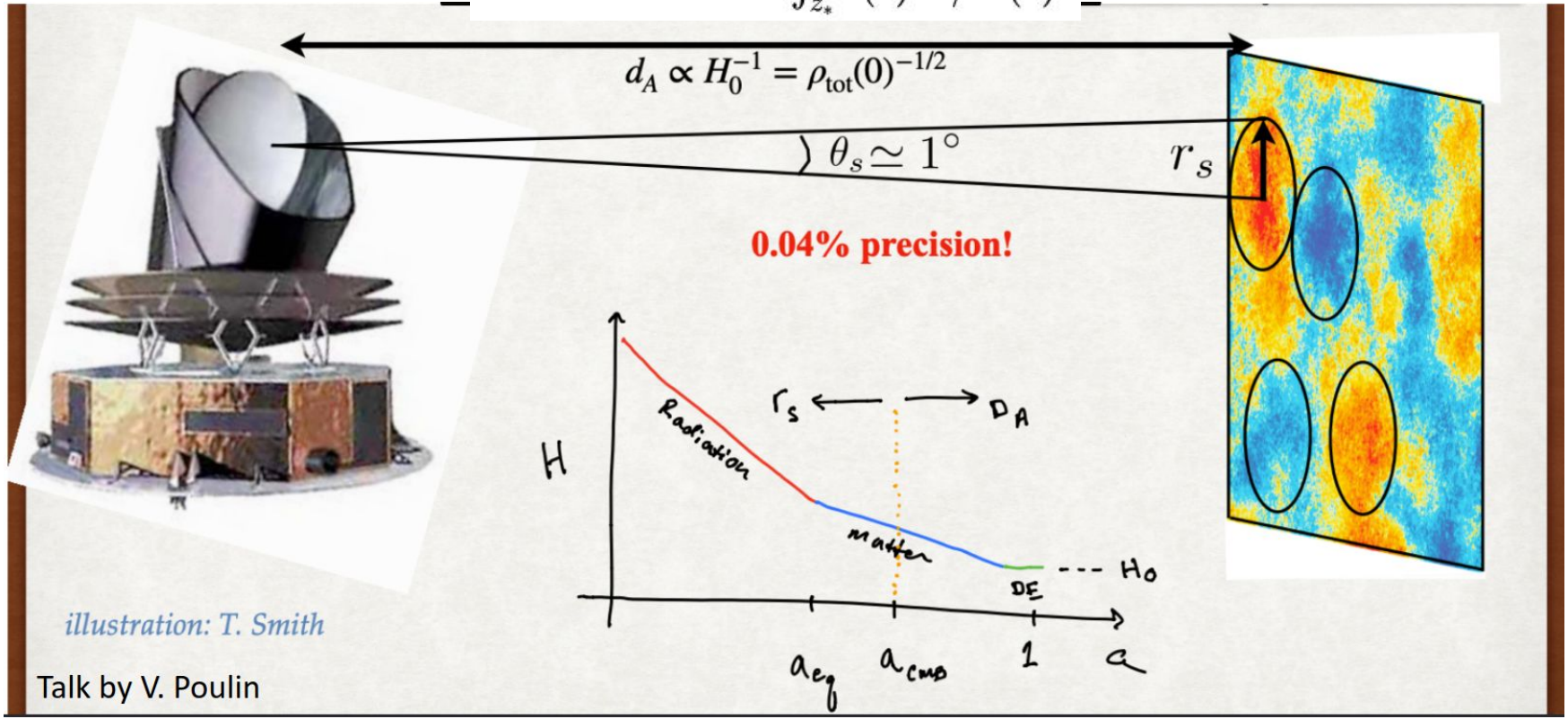


Inferring H_0 from the CMB: standard ruler

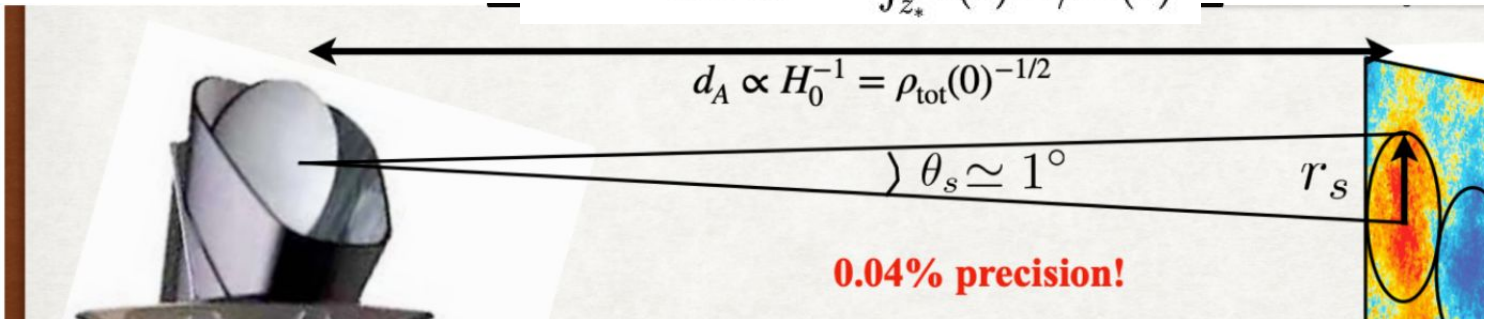
$$\theta_s \sim \frac{r_s(z_*)}{D_M(z_*)} = \frac{\int_\infty^{z_*} c_s(z)dz/H(z)}{\int_{z_*}^0 c(z)dz/H(z)}$$



Talk by V. Poulin

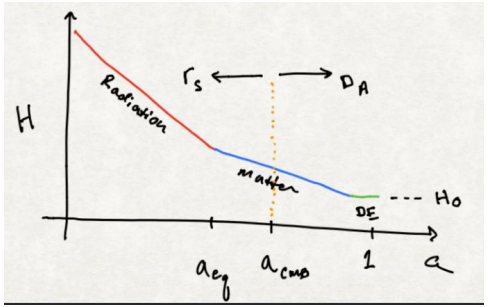
Tension in the Hubble constant

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



Decrease r_s

Keep $D_M(z)$ unchanged correcting with $E(z)$



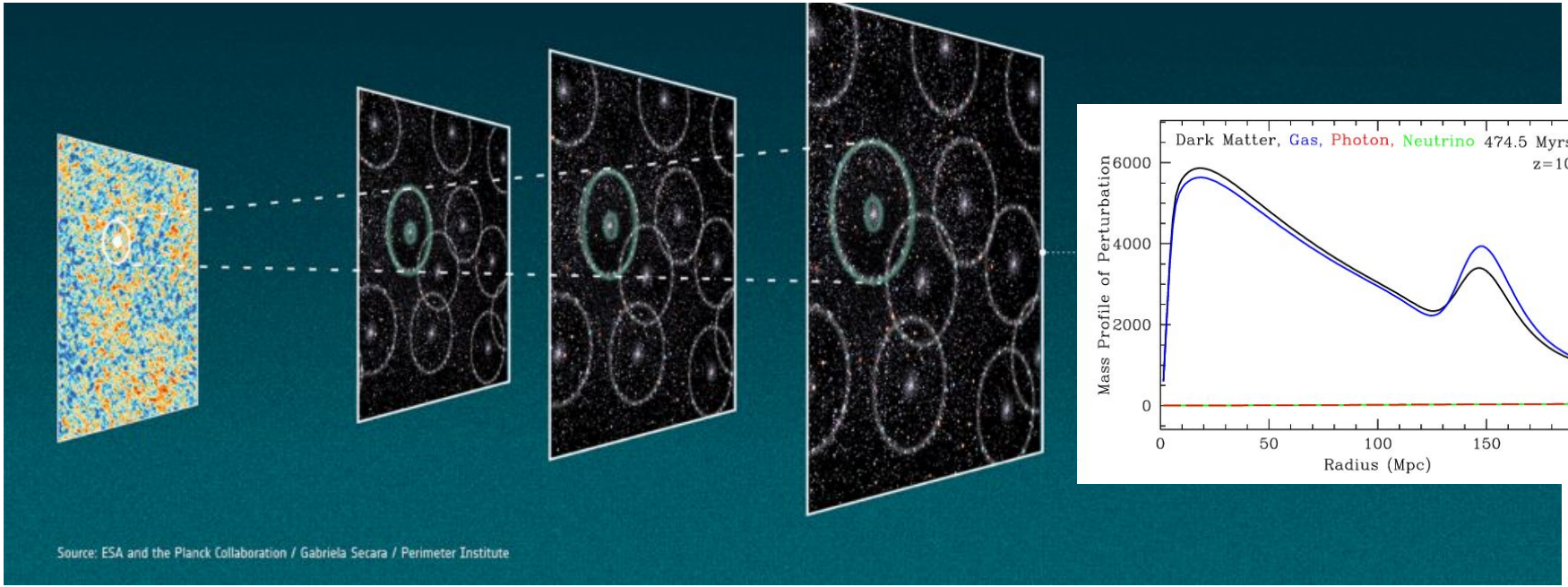
For a higher H_o…

- Low-*z* changes to keep the distance unchanged?
  (CMB alone allows for it: complementary probes needed!)
- High-*z* changes to correct in the standard ruler?

Cosmic distance ladder(s)

- SNeIa and BAO provide uncalibrated distance measurements
- BAO feature frozen in matter overdensities => imprinted in galaxy distribution!

  r_s becomes a “statistical” standard ruler. But it’s **model dependent**!



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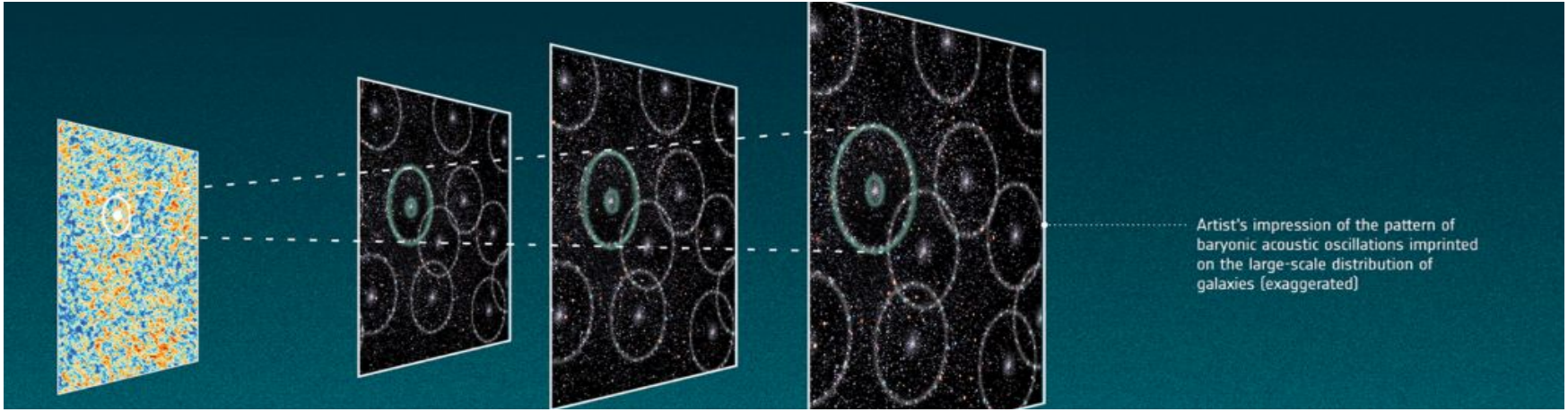
  - Wrong cosmology? Artificial distortions



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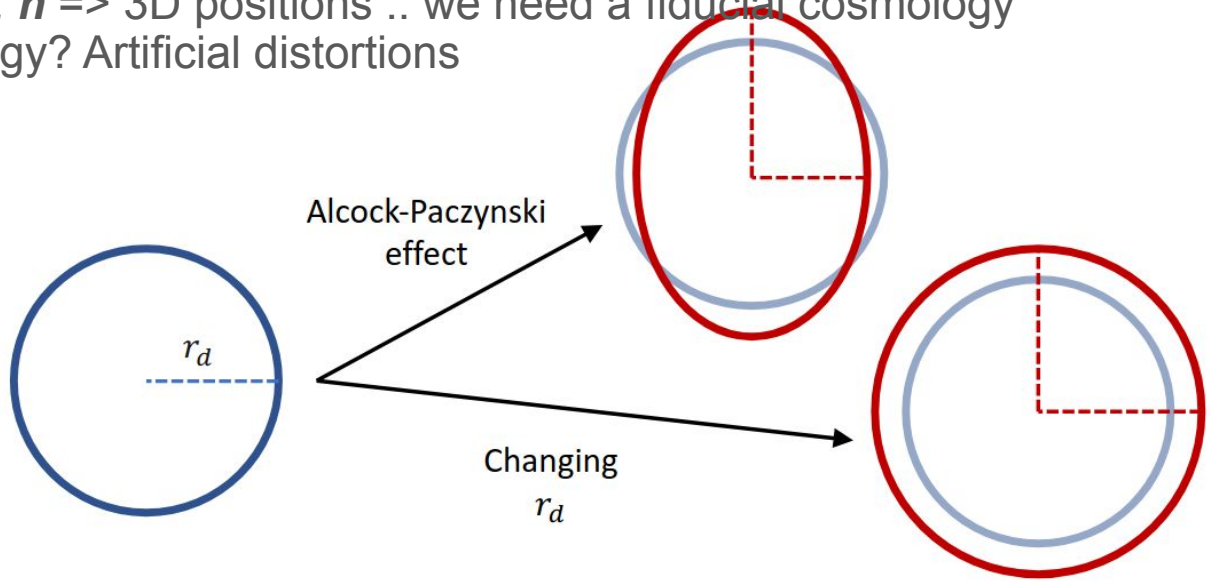
BAO: recognizable feature in $P(k)$

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

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



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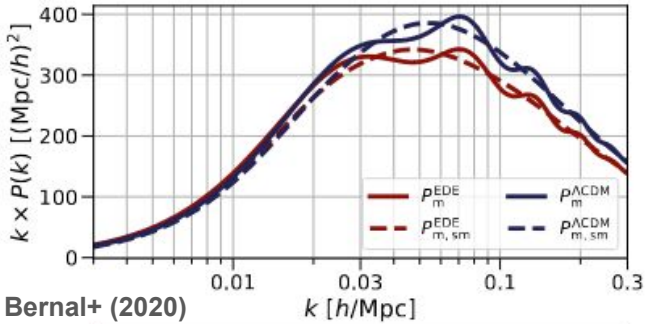

Bernal+ (2020)

- BAO analysis: **template** + **rescaling** + **broadband marginalization**

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

Isolating BAO feature

Broadband marginalization

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

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

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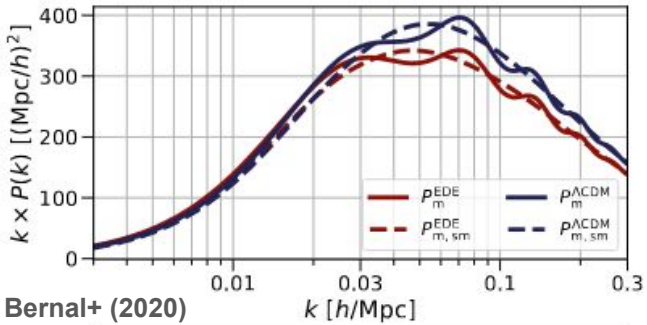

Bernal+ (2020)

model-independent expansion-history measurement
Normalized to $r_s H_0$ product!

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Isolating BAO feature

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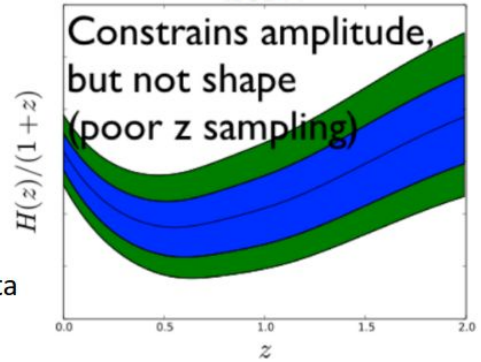
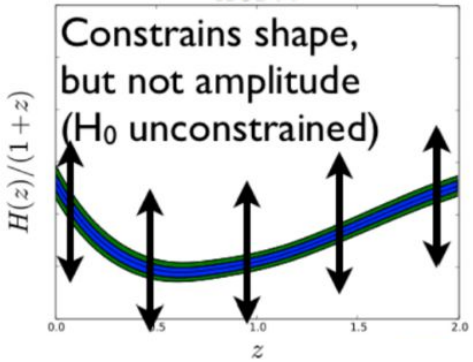


SNeIA



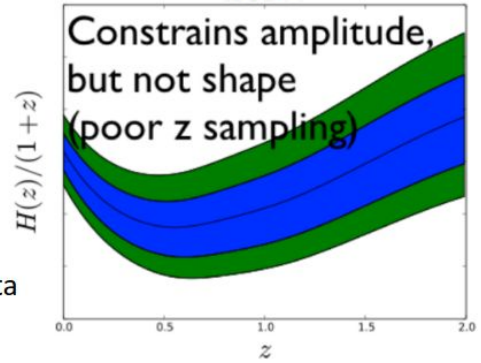
A. J. Cuesta

BAO normalization $\propto r_d \times H_0$

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

Cosmic distance ladder(s)

BAO



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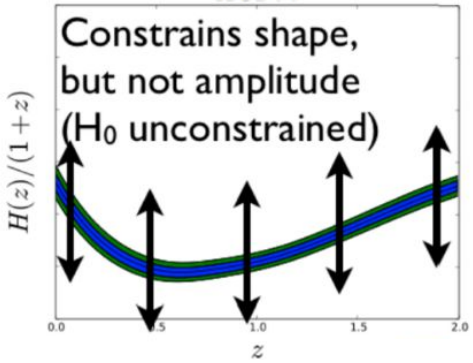

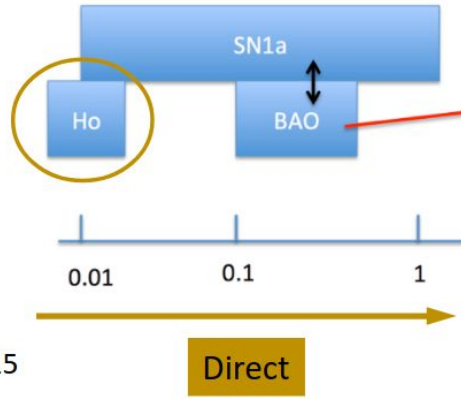

Cuesta+2015

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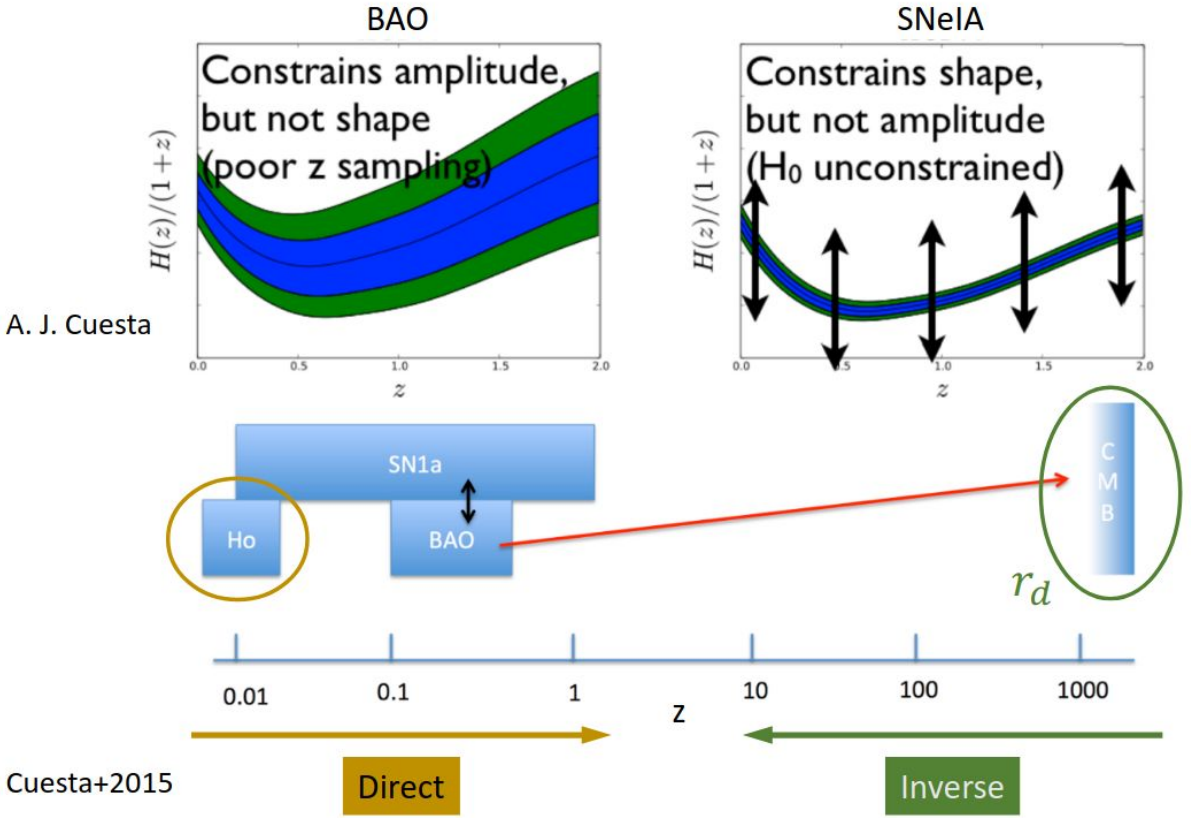
model independent! (JLB+, 2020)

Cosmic distance ladder(s)



BAO normalization $\propto r_d \times H_0$

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

BAO calibrating SNeIA
(inverse distance ladder)

Two anchors of the cosmic distance ladder

Free the anchors

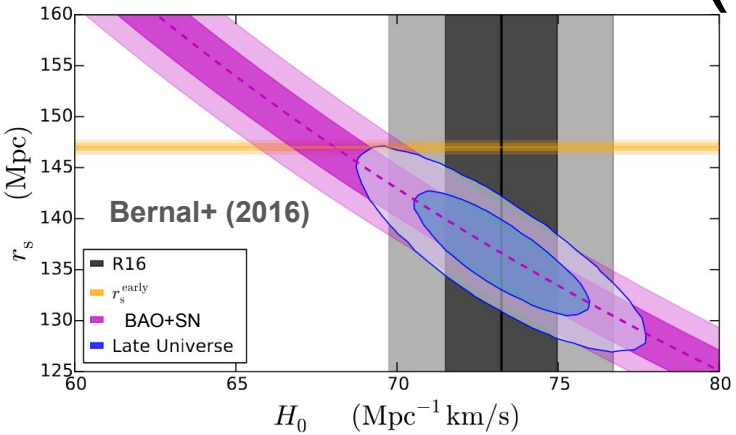
Low-z standard ruler

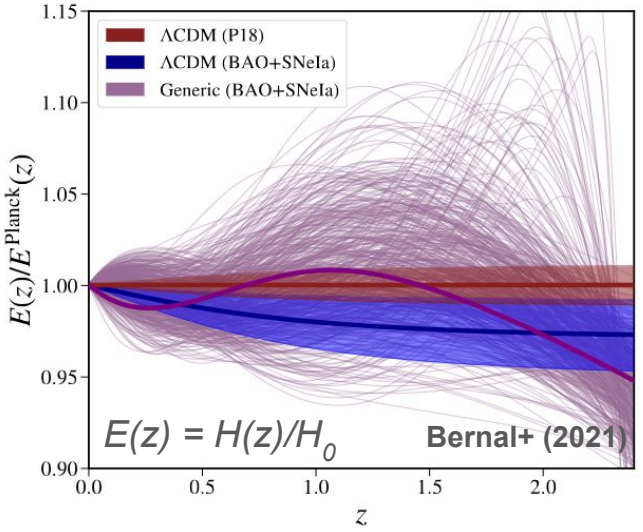
$r_d \times H_0$

Verde, JLB+ 2017

Cosmic distance ladder(s)

Need smaller r_s to allow for higher H_0

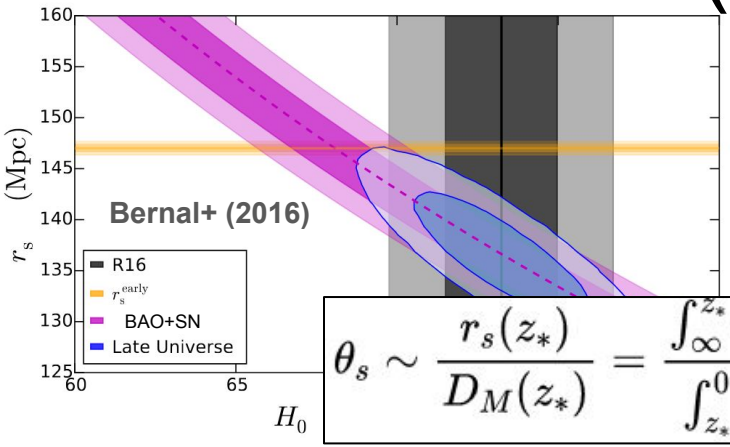


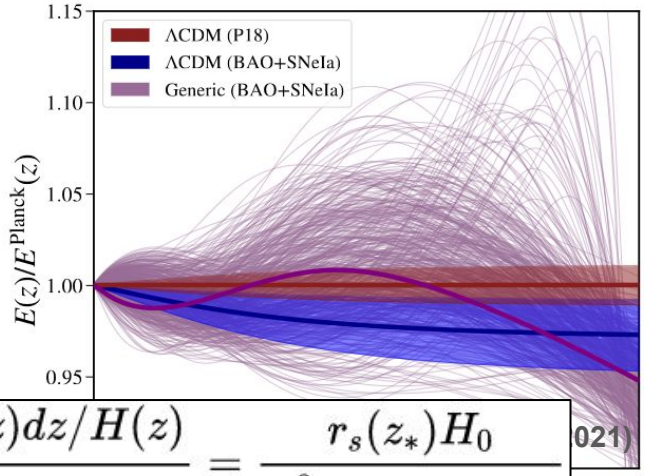


- **Mismatch between the anchors** of the cosmic distance ladder
  - $r_s H_0$ measured at < 1% precision

Cosmic distance ladder(s)

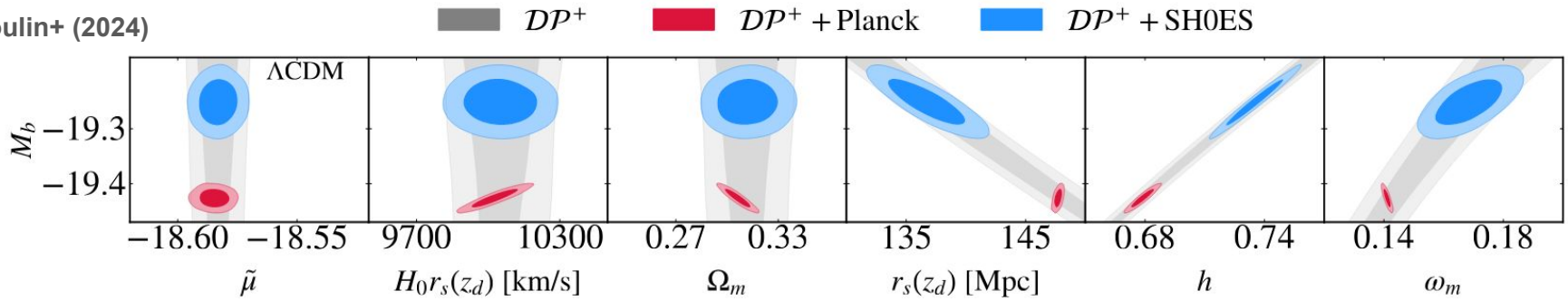
Need smaller r_s to allow for higher H_0





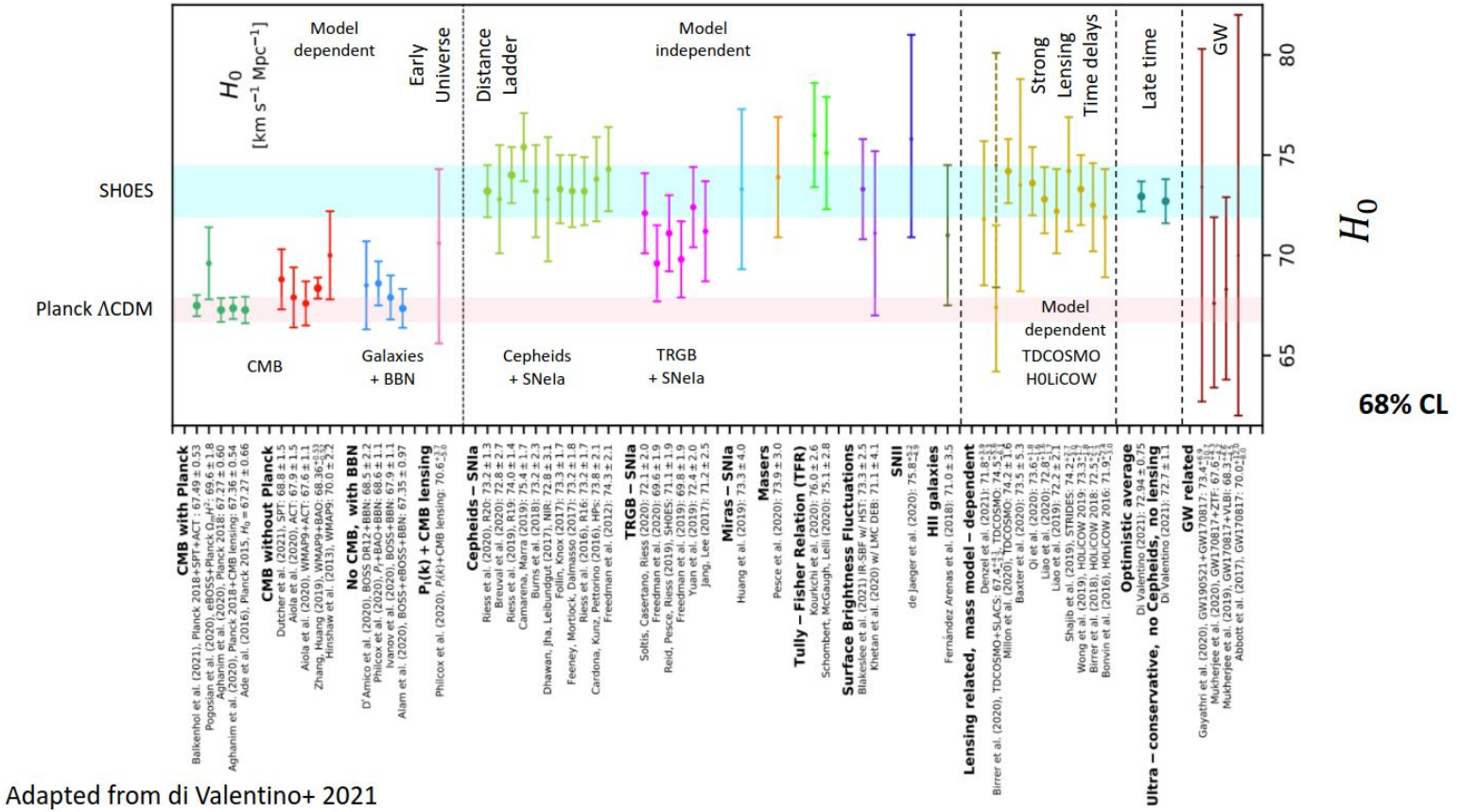
$$\theta_s \sim \frac{r_s(z_*)}{D_M(z_*)} = \frac{\int_\infty^{z_*} c_s(z)dz/H(z)}{\int_{z_*}^0 c(z)dz/H(z)} = \frac{r_s(z_*)H_0}{\int_{z_*}^0 c(z)dz/E(z)}$$

Poulin+ (2024)



- **Mismatch between the anchors** of the cosmic distance ladder
  - $r_s H_0$ measured at < 1% precision

Tension in the Hubble constant

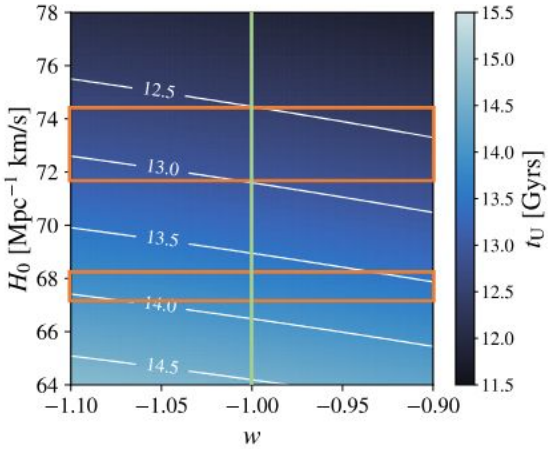


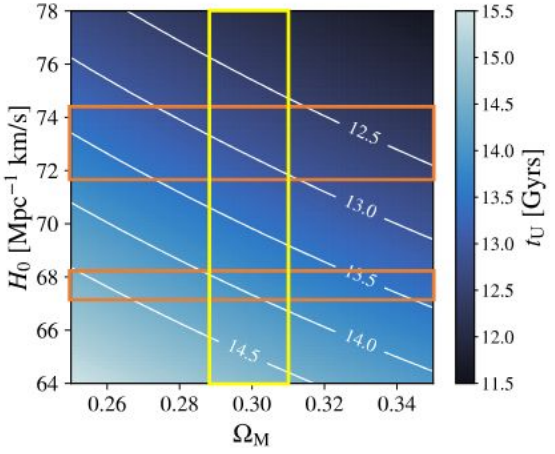
Adapted from di Valentino+ 2021

Beyond H_0…

- H_0 affects distances *and* times: $t(z) = \frac{977.8}{H_0} \int_0^z \frac{dz'}{(1+z')E(z')}$ Gyr

- t_U dominated by z<30: doesn't depend on early Universe
- BAO get expansion history shape $E(z)$: infer $t_U H_0$





Bernal+ (2021)

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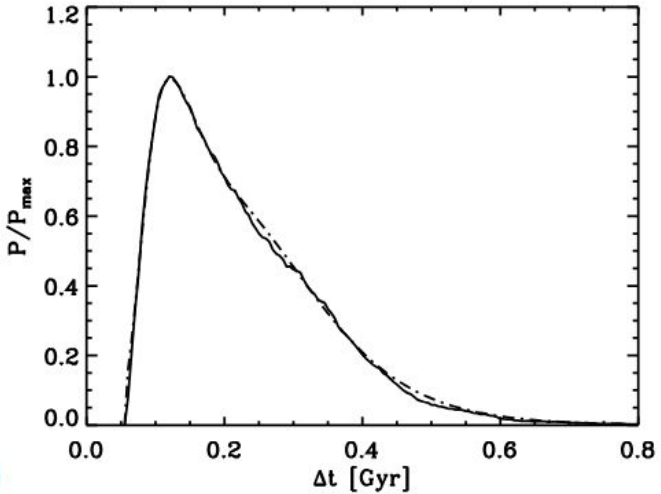
- BAO get expansion history shape $E(z)$: infer $t_U H_0$
- Use the **age of the oldest globular clusters as proxy**! (Jimenez+ 2019)



Valcin, JLB+ 2020

- $t_{GC} \equiv t(z_f)$ $\quad z_f \in [11,30]$
- $t_U = t_{GC} + \Delta t$

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

Marginalizing over cosmo parameters and z_f

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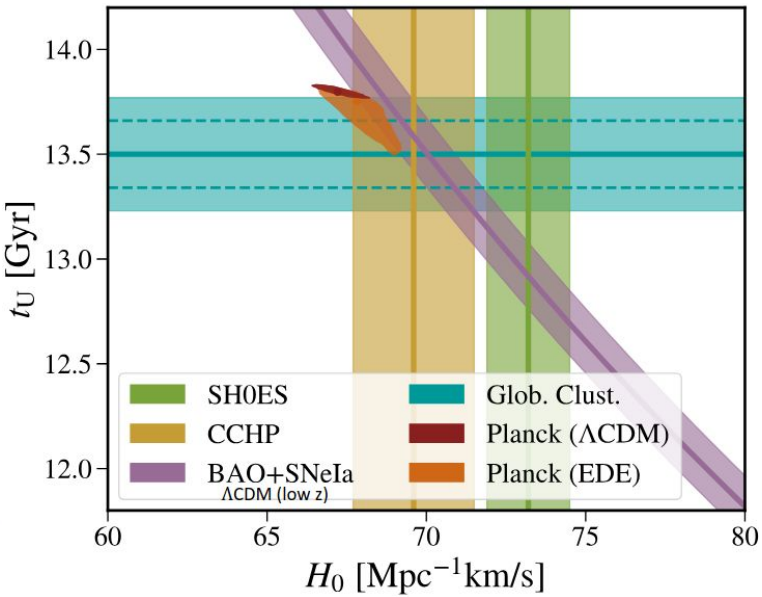

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Marginalizing over cosmo parameters and z_f

Bernal+ (2021)

New cosmic triangles

- Overconstrained 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)

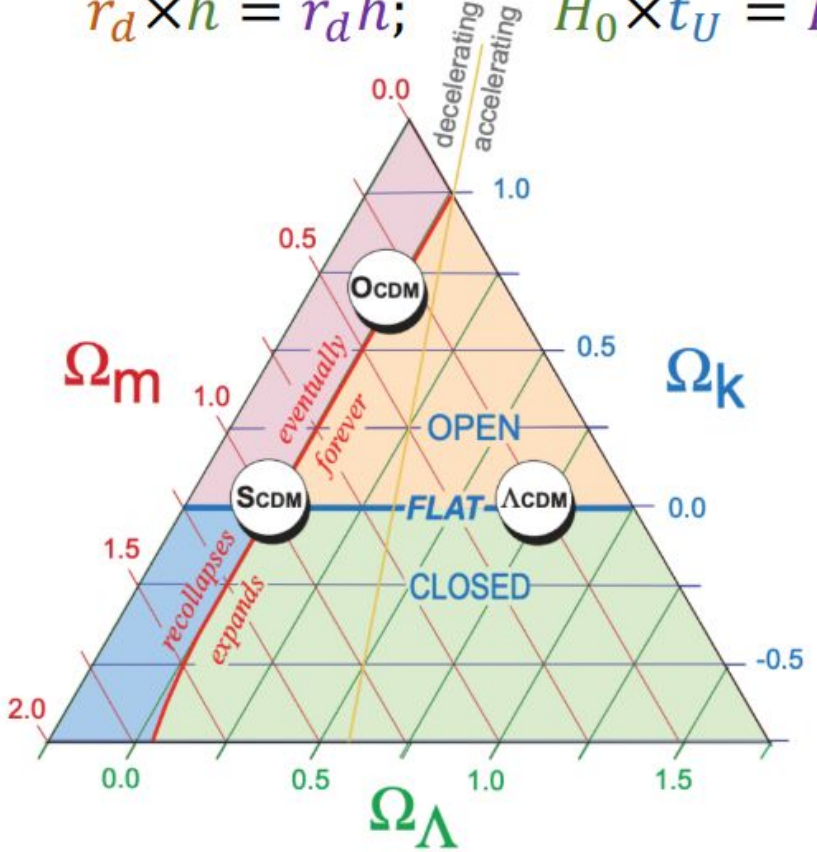
BAO+SNeIa (late Universe)

SH0ES/TRGB (local Universe)

GCs (local Universe)

New cosmic triangles

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



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

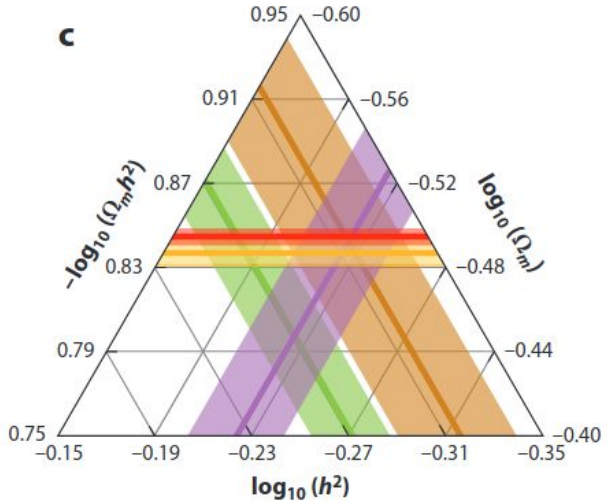
Original cosmic triangle
(Bahcall+ 99)

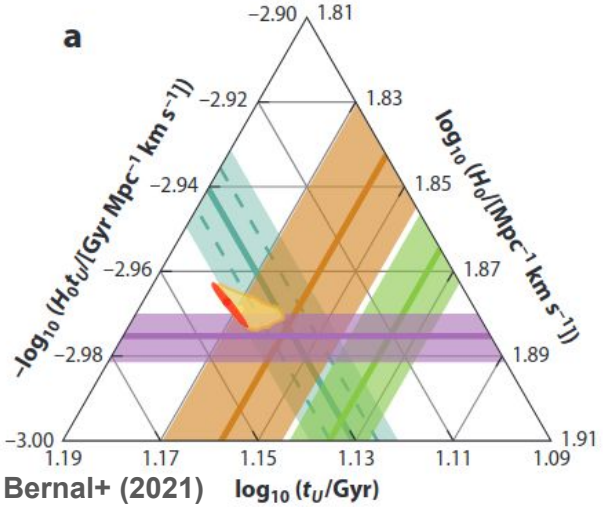
Plot over-constrained systems in ternary plots to find consistency and preferred values

New cosmic triangles

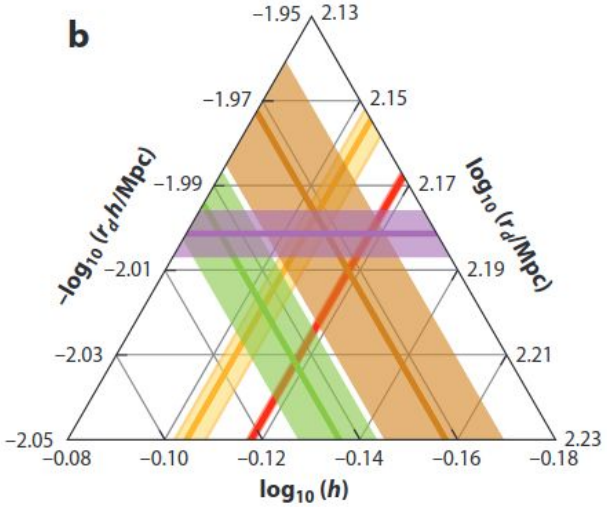
Out with the standard ruler,
In with the 📐.

Nick Kokron





Bernal+ (2021)



All points in the triangle add to 0:

log A + log B - log AB = 0

How to reconcile all data?

Need smaller r_s to allow for higher H_0

Match high H_0 to CMB data

- Increase *H(z)* before recombination?
  - EDE, neutrino/ur species physics, interacting dark radiation,...
- Change recombination physics?
  - varying electron mass, primordial magnetic fields, …

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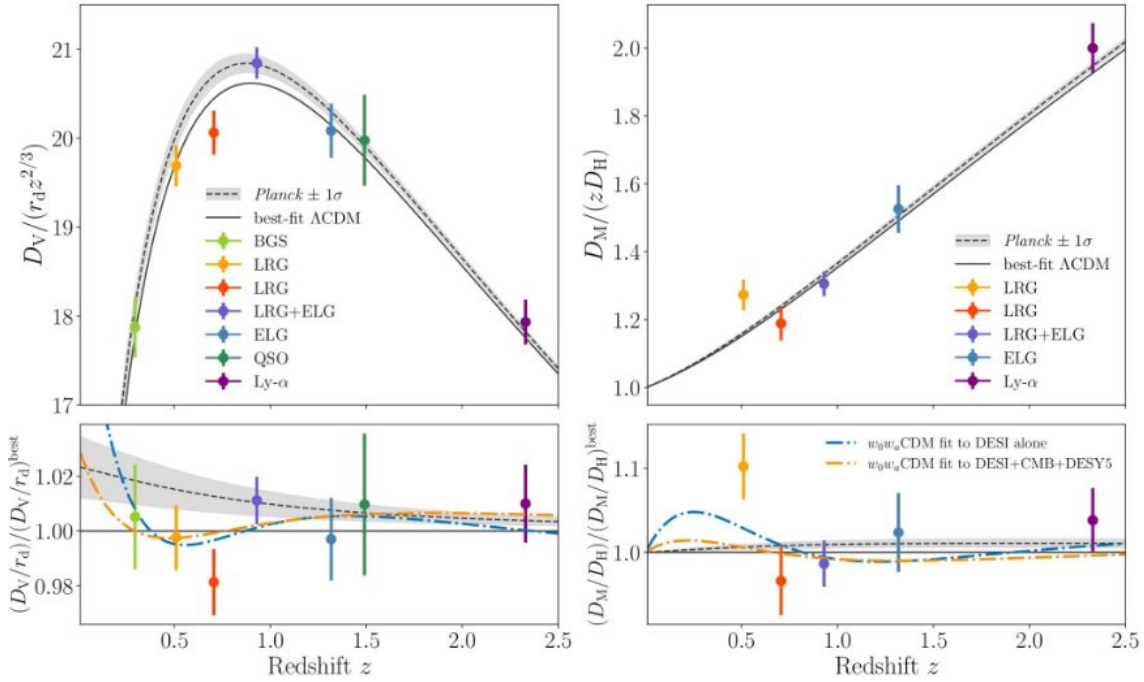
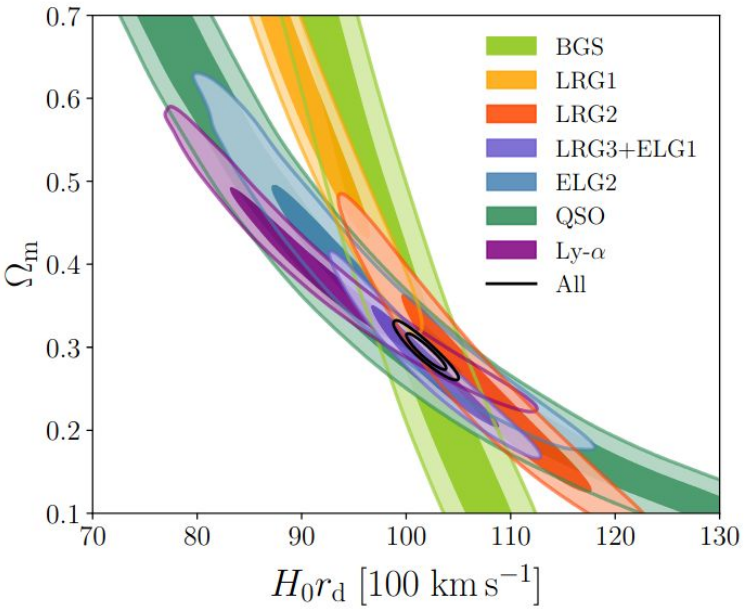
Don't mess up other data: move along degeneracies

Low-z anchors to the data (inverse vs direct distance ladder)

- $r_s H_0$ similarly constrained for any $E(z)$ model (DESI doesn't open many windows…)
- Low-z ΛCDM? changed recombination physics disfavored
- Changed recombination physics? Low-z $H(z)$ must change
- Increased low-z amplitude of perturbations?
- Age of the Universe, tilt of the primordial power spectrum, …

DESI BAO: no cosmological constant?



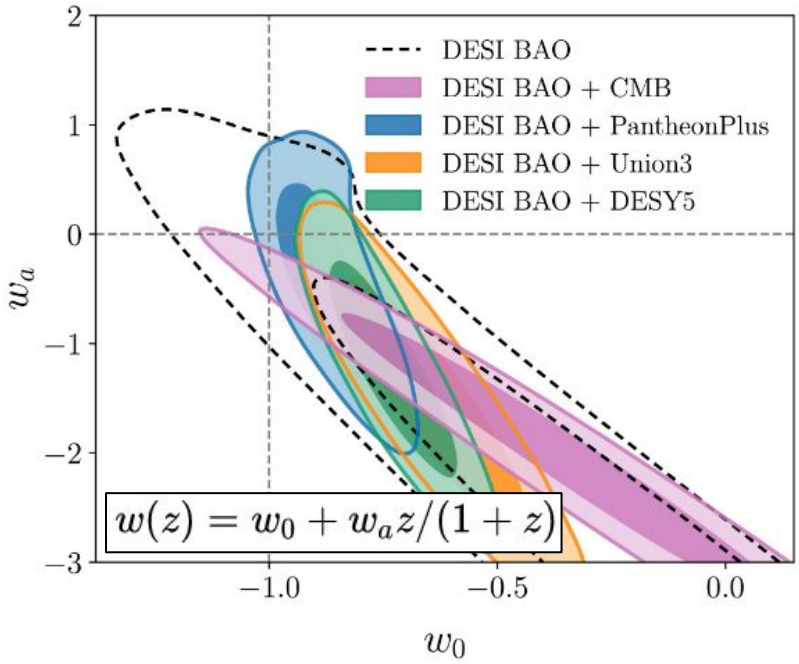


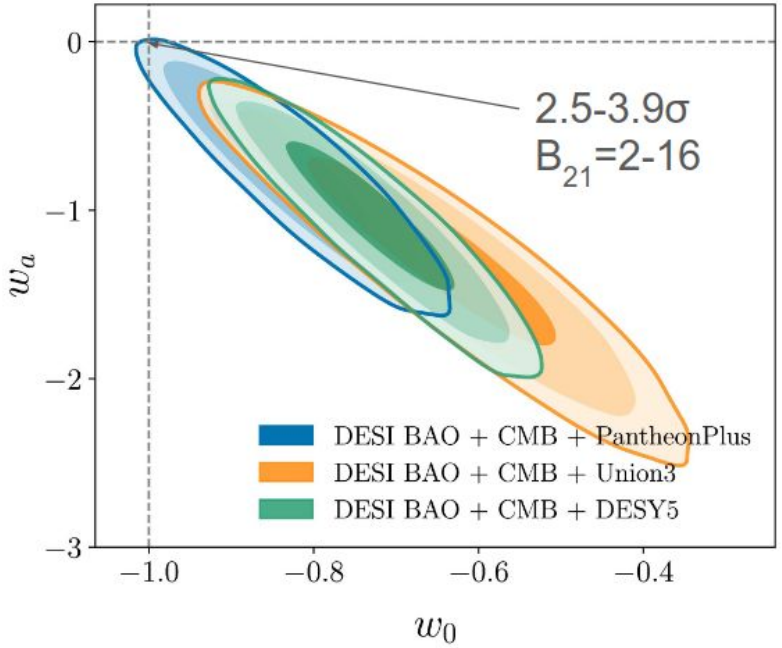
DESI alone, consistent with LCDM, internal consistency between different samples

H_0 tension remains

Blind analysis!

DESI BAO: no cosmological constant?





Add more data, let DE evolve, and hints of tension with LCDM
All probes seem to favor deviations from LCDM of “thawing DE”
Not motivated parametrization… Phantom DE at z>~0.5?

Conclusions

- ΛCDM is a very successful model, but tensions arise: no strong conclusion yet
- Simple explanations (systematics, trivial extensions) don't work out
  - Eucapt rapid response workshop tomorrow 3-5 pm
- Solving H_0 tension: reduce r_s by modifying *at least* the early Universe physics
- DESI Y1+CMB+SN: hint of deviations from a cosmological constant (?)

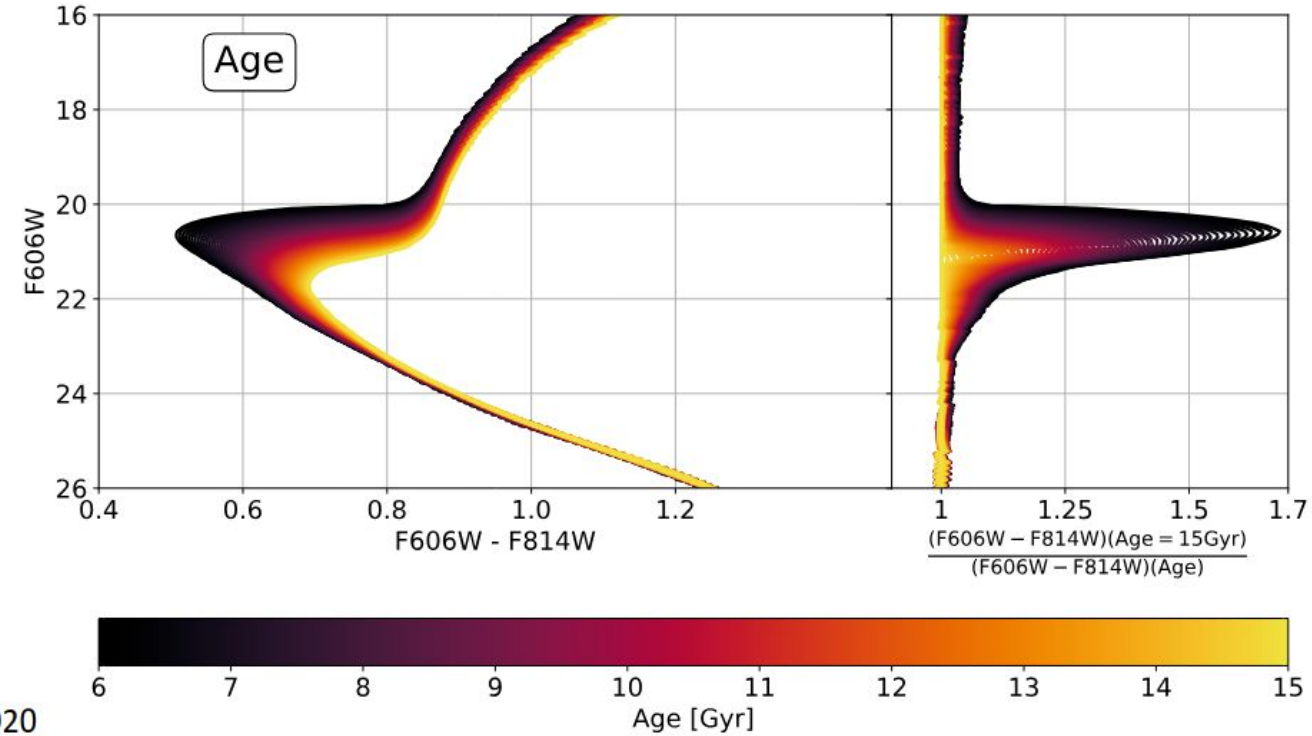
Conclusions

- ΛCDM is a very successful model, but tensions arise: no strong conclusion yet
- Simple explanations (systematics, trivial extensions) don't work out
- Solving H_0 tension: reduce r_s by modifying *at least* the early Universe physics
- DESI Y1+CMB+SN: hint of deviations from a cosmological constant (?)

- Future looks interesting!
  - Forthcoming CMB experiment will discriminate among different flavors of the family of models that can solve the H_0 tension
  - Future LSS/SN data will be key for the survival of the cosmological constant
  - Improved local measurements will refine/cross check H_0 measurements

Back up slides

Age of the oldest GCs



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