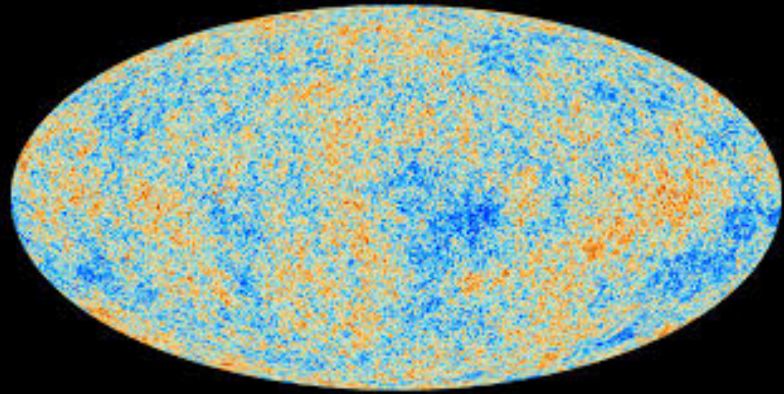
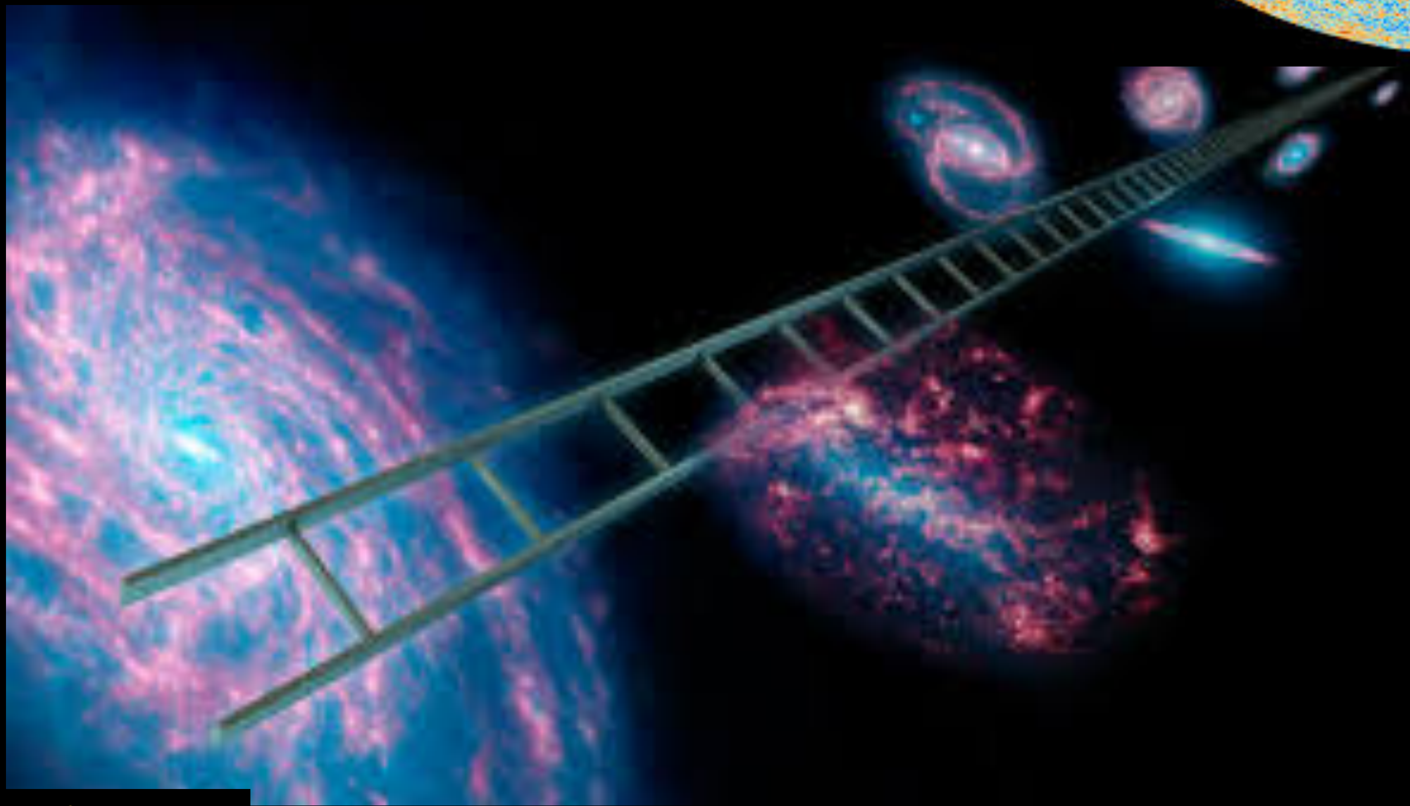
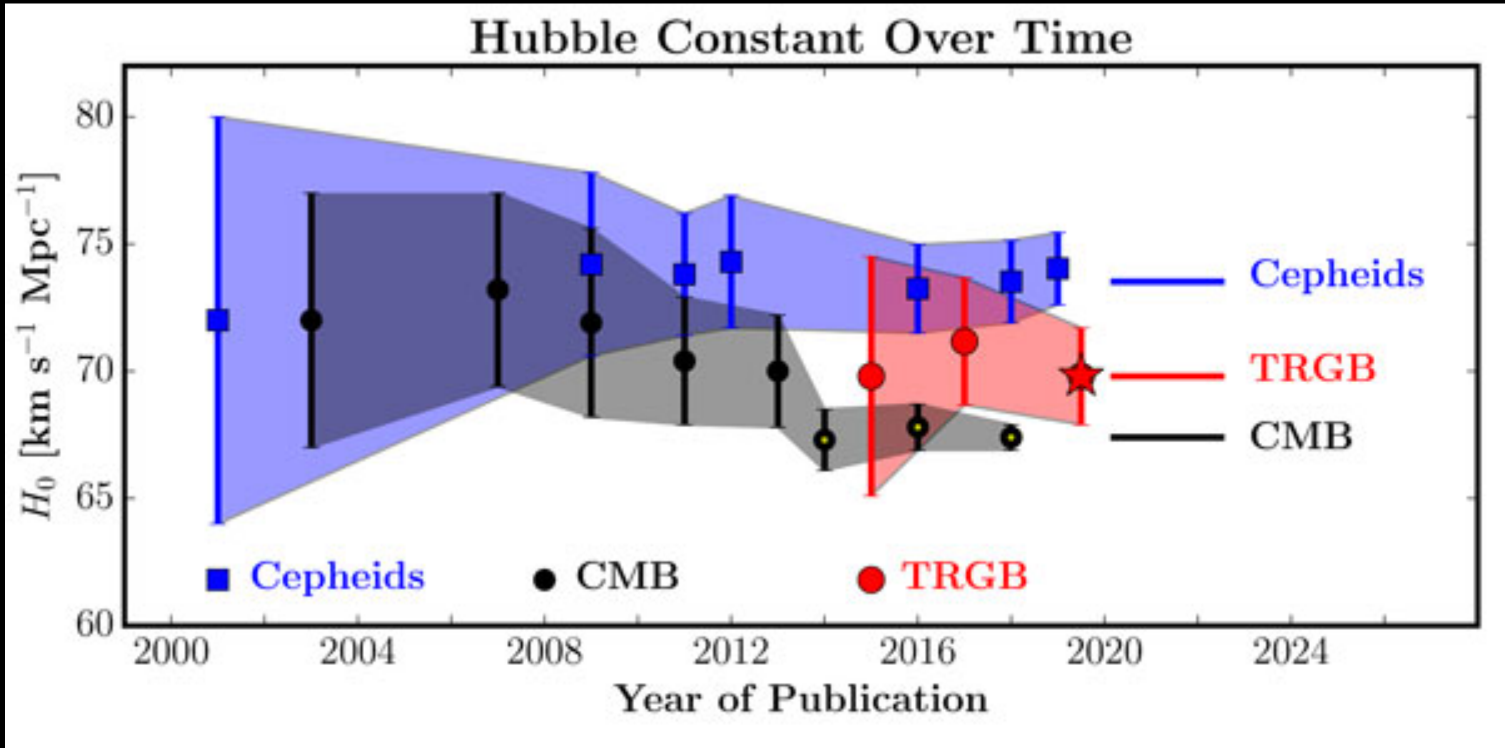
Hubble troubles





Licia Verde
ICREA & ICCUB

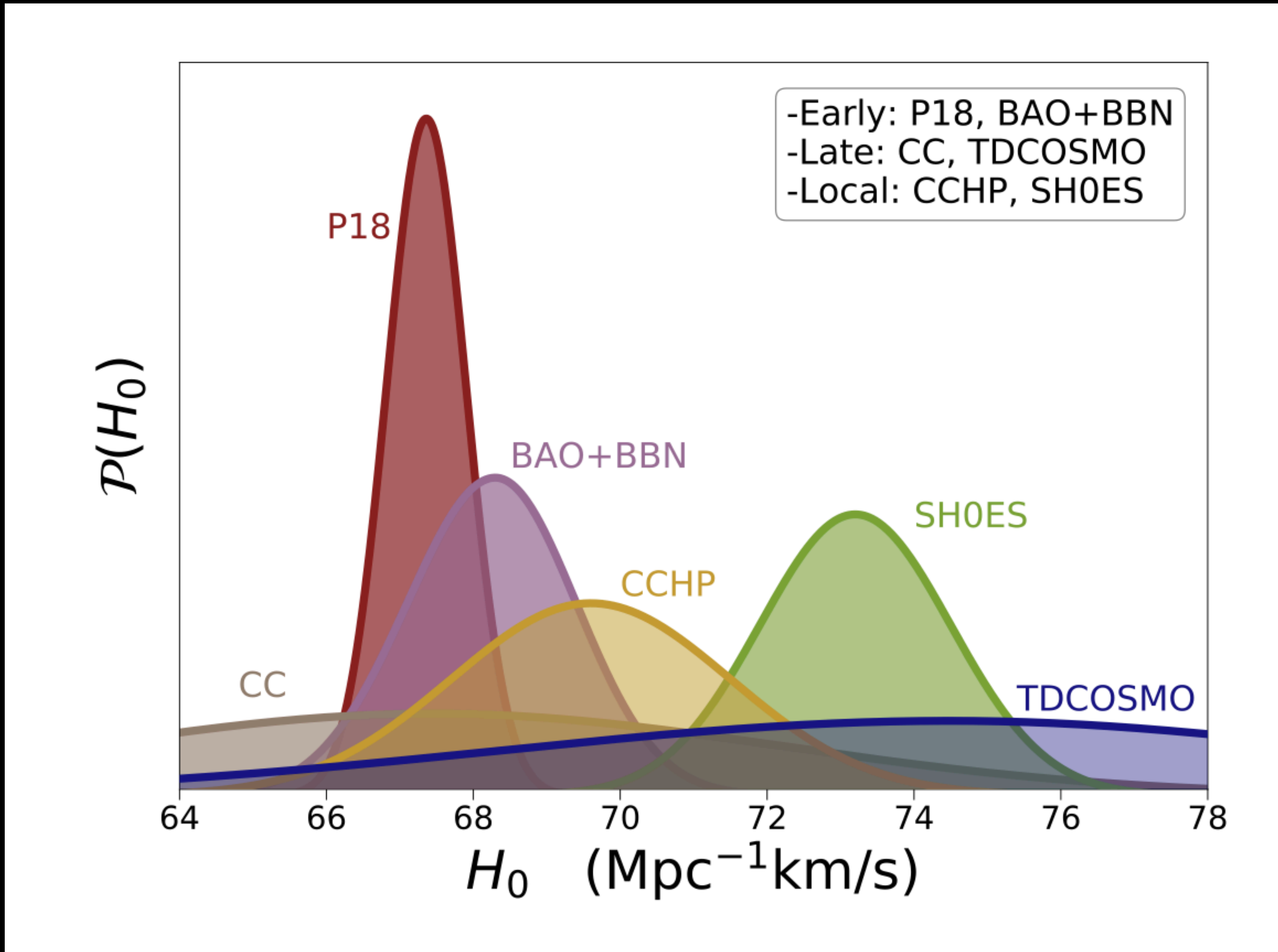
Constant not constant



“The SHoE(S) that fits one pinches another"

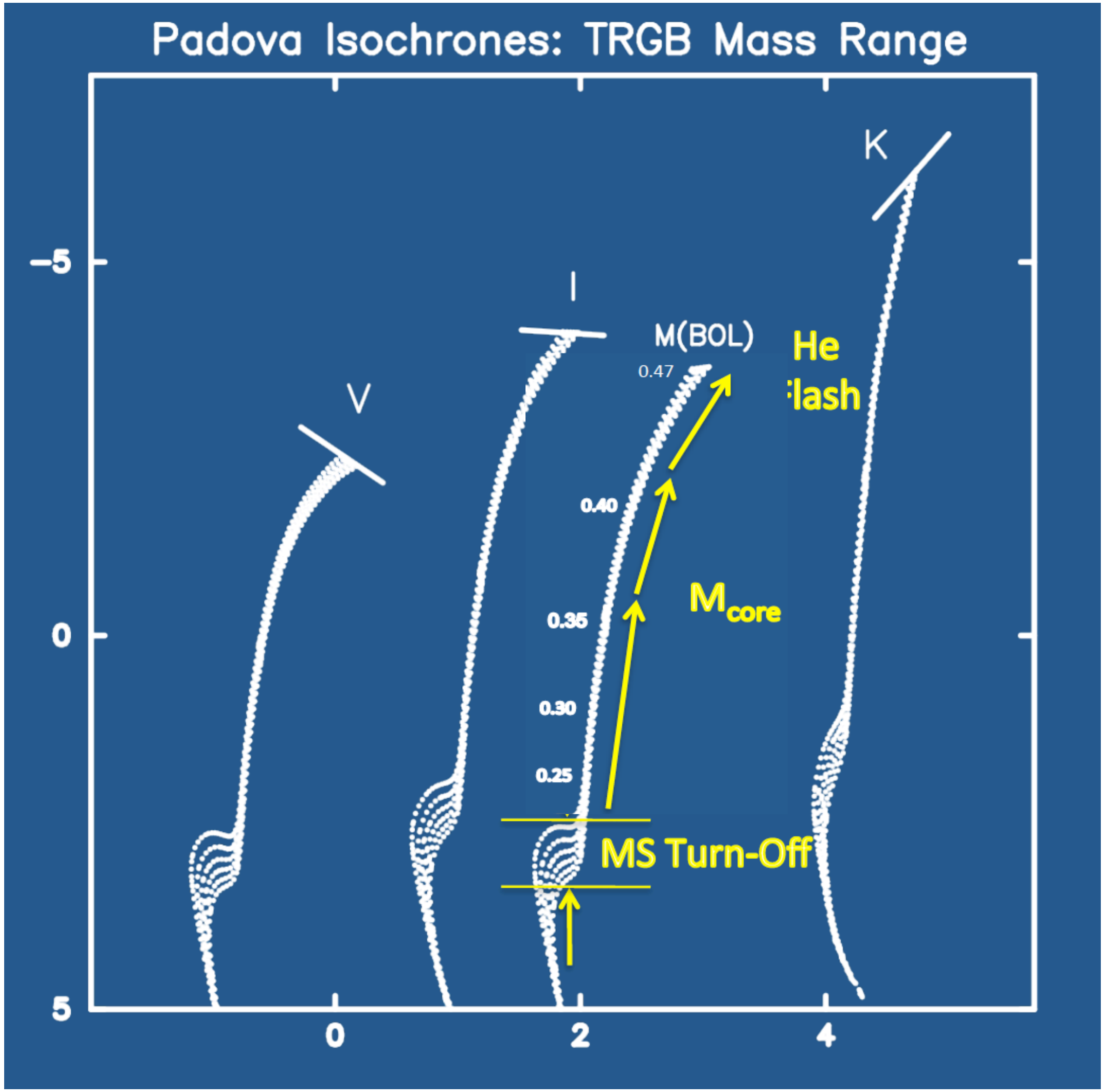
Quote adapted from Carl Jung

Model dependent vs model independent



Bernal et al. 2102.05066

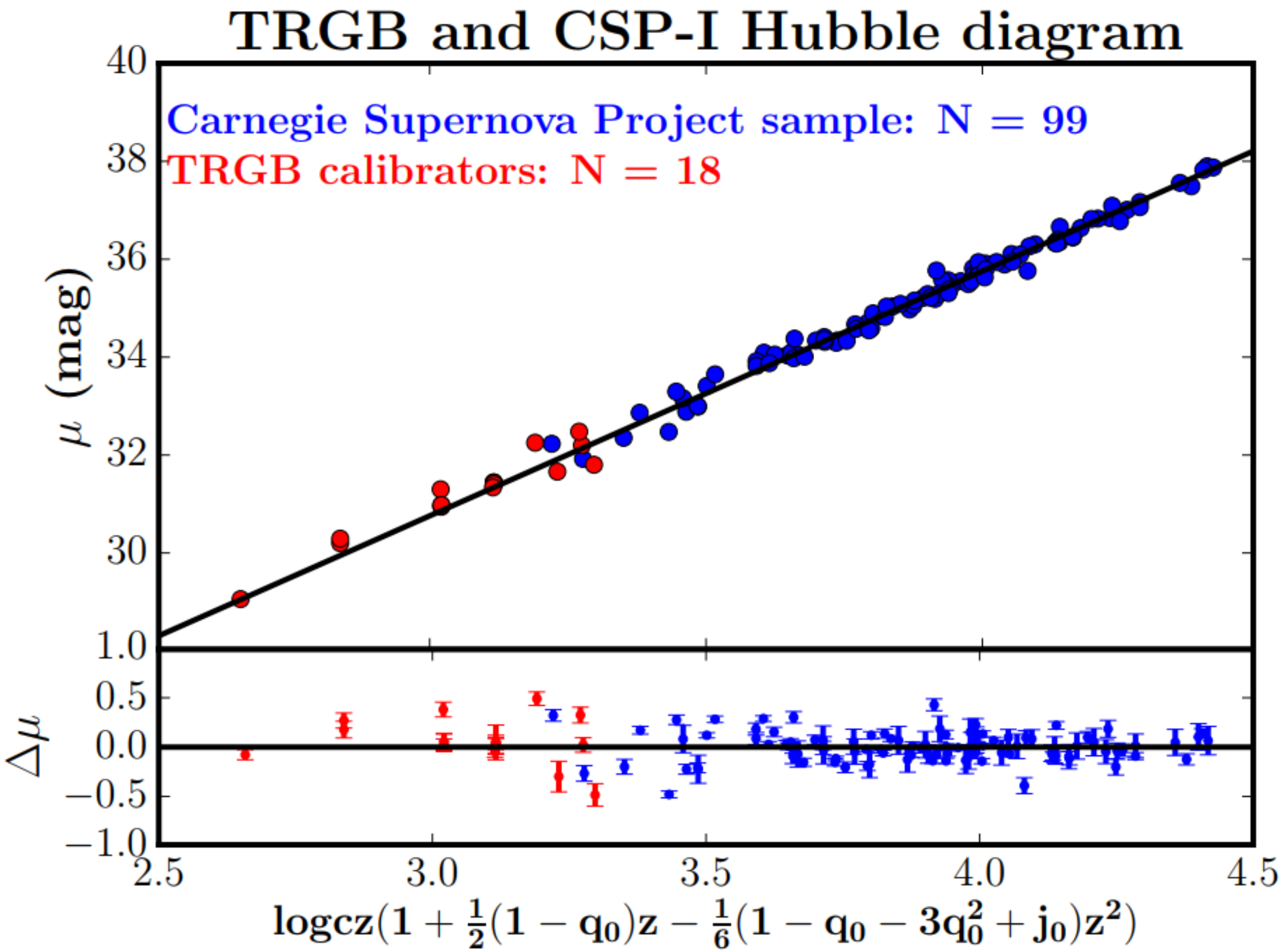
Tip of the red giant branch



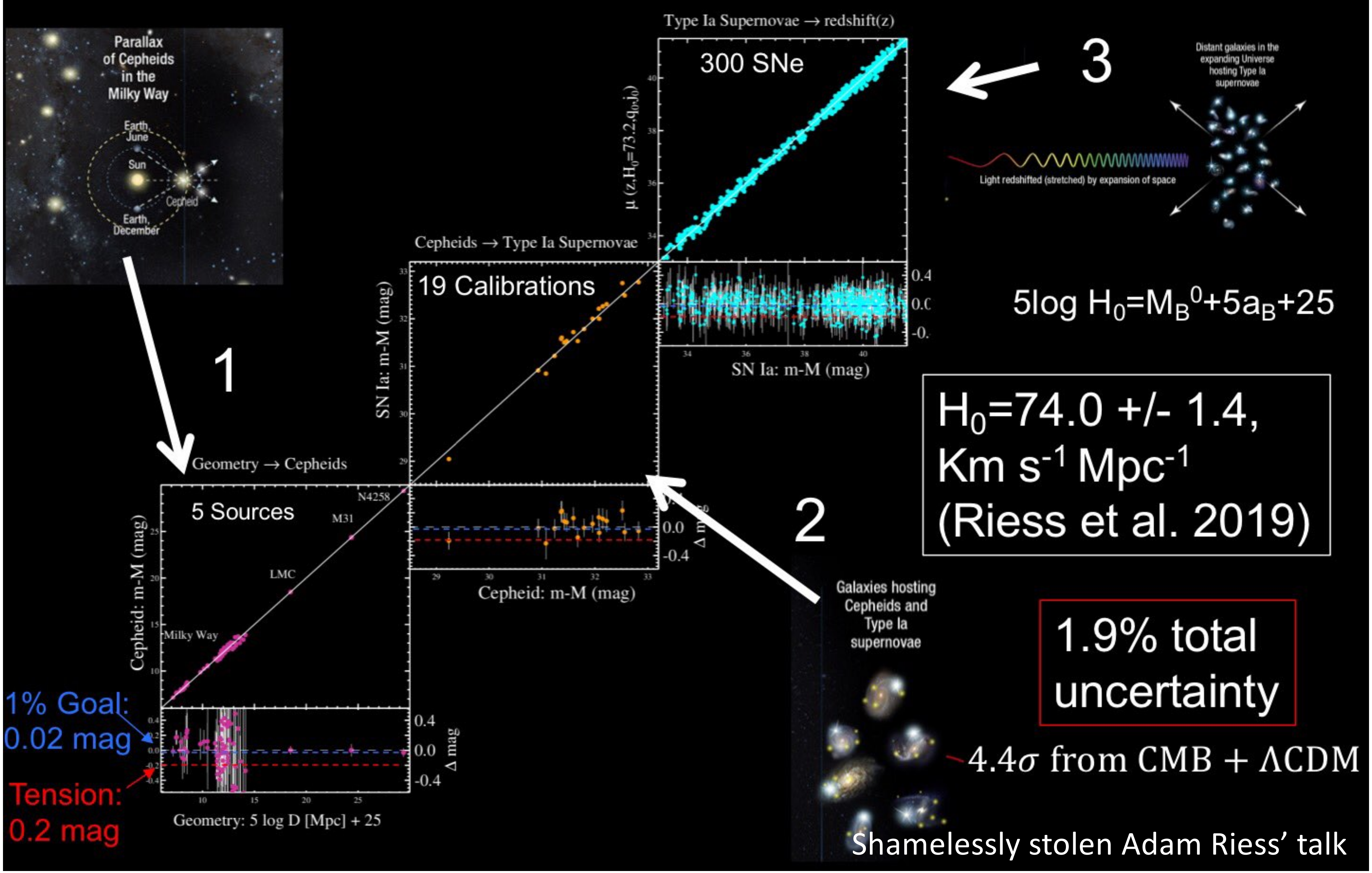
Electron-Degenerate Helium Core Mass-Luminosity Relation

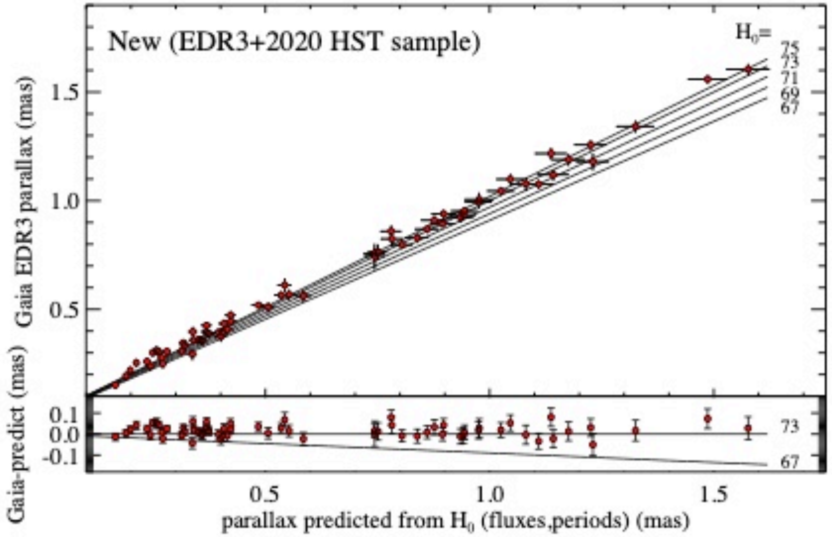
From B. Madoore

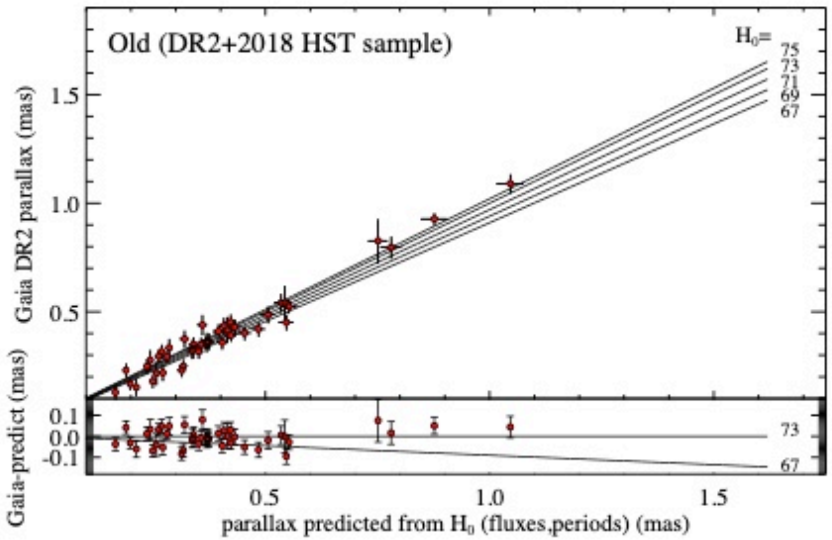
Distance scale



The Hubble Constant in 3 Steps: Present Data



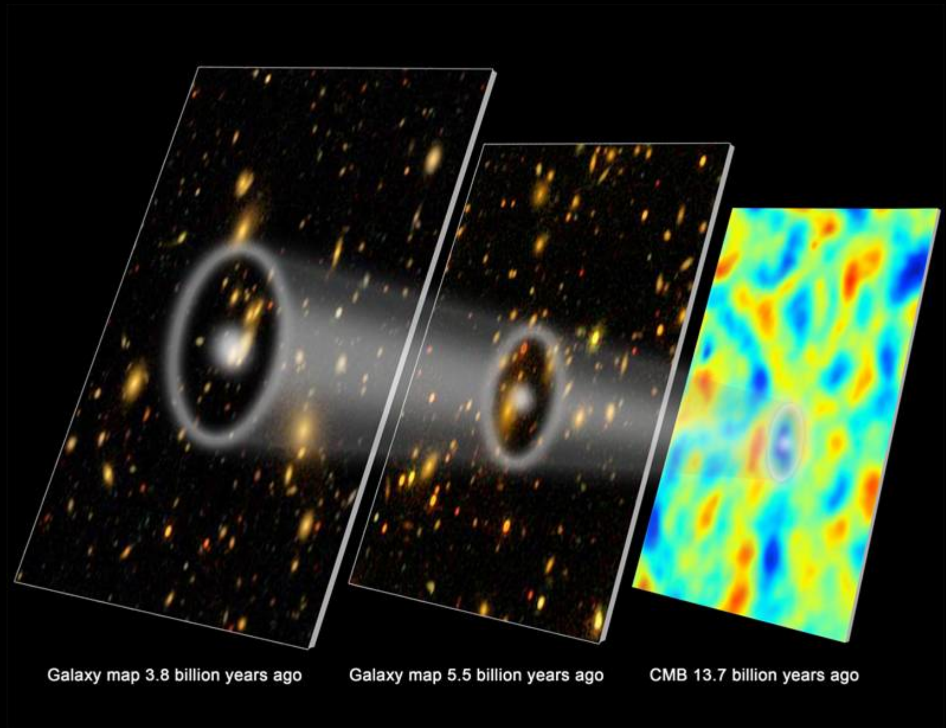




arXiv:2012.08534

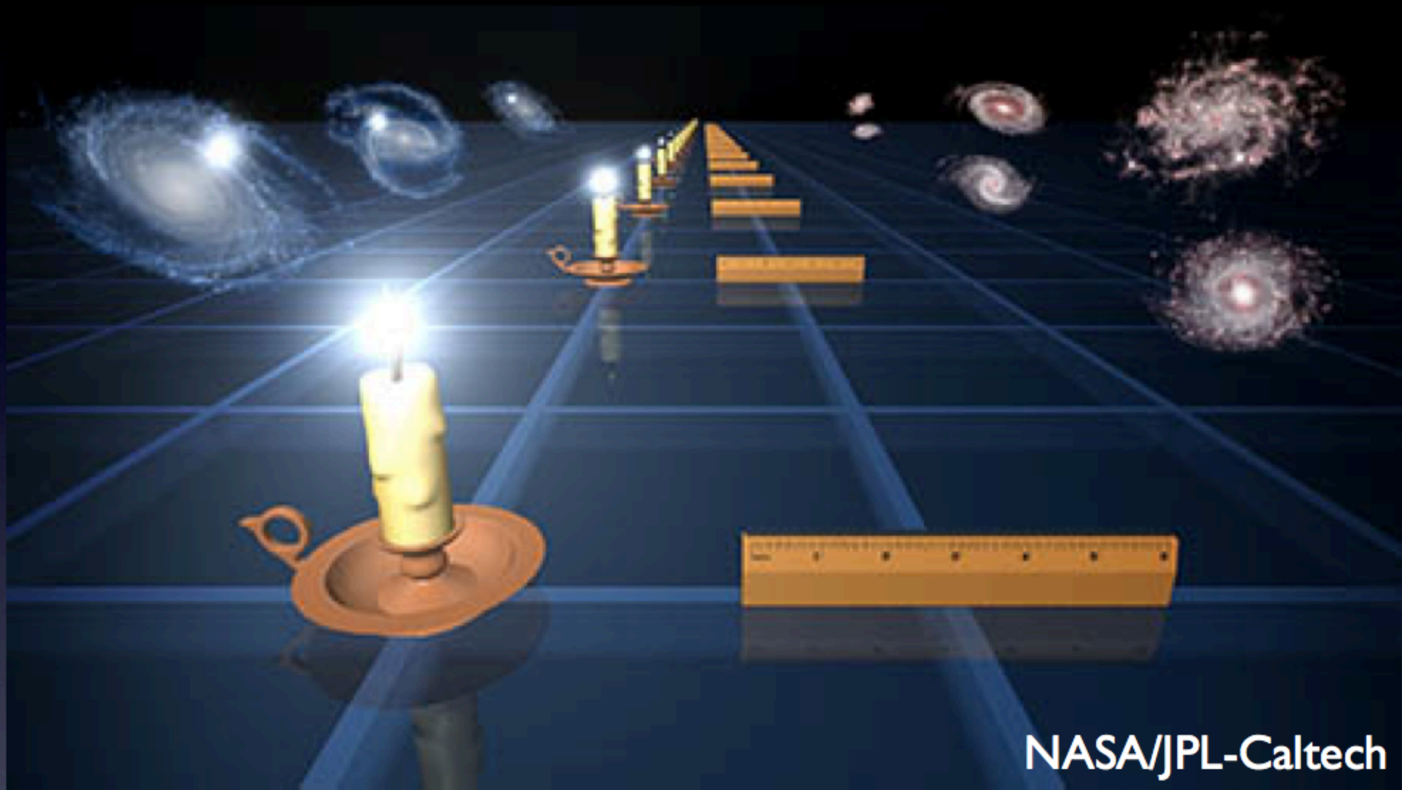
Baryon acoustic oscillations (BAO)
as a Standard ruler

- Physics: sound waves in early Universe propagate until radiation and matter decouple
- Imprints a scale - standard ruler
- Key Observable. rd (sound horizon)
- Useful for:
  - geometry of Universe (Dark Energy equation of state, or modifications to GR)
  - early Universe physics (well known) sets it



CMB and early universe physics in LCDM constrain the standard ruler length to 0.2%

Standard candles & Standard rulers



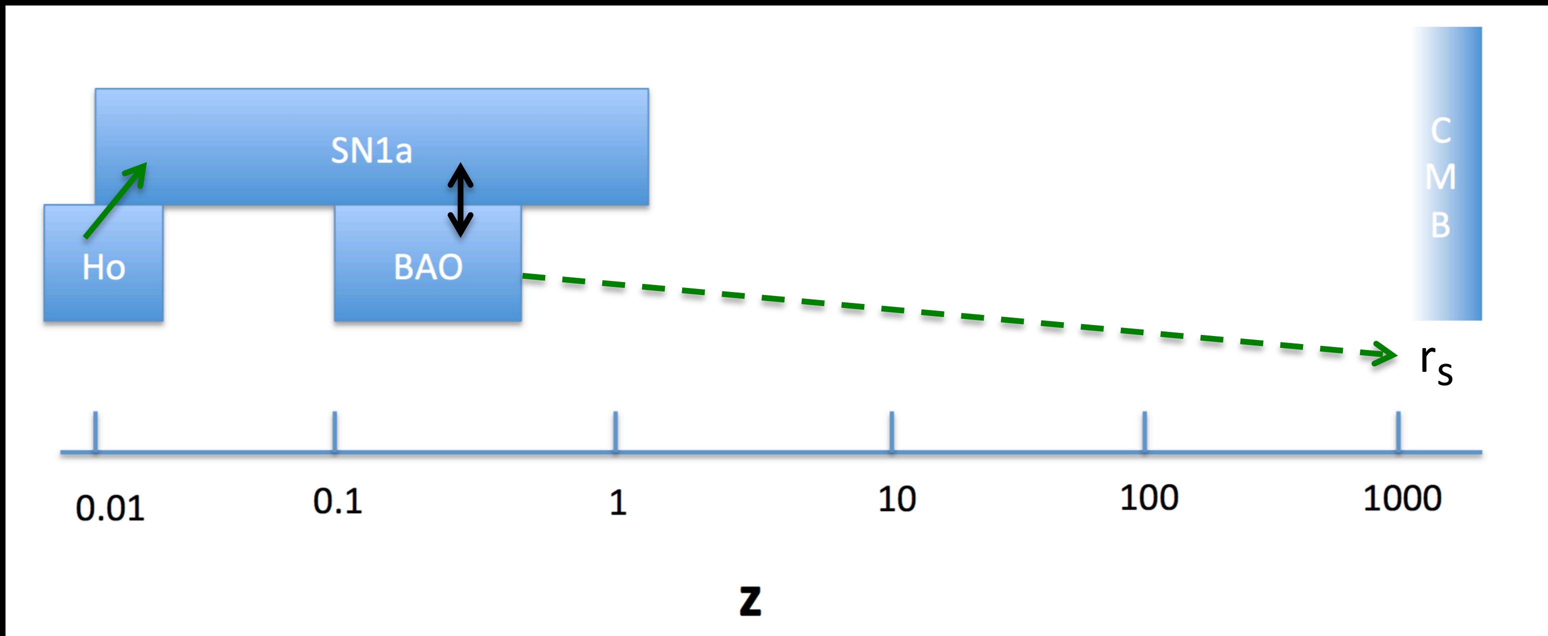
Type-Ia SNe measure
relative distances,
since there is large uncertainty
on the absolute magnitude M
of a fiducial SN

BAOs measure
absolute distances,
but depend on the value of
sound horizon r_{drag}

Direct and inverse cosmic distance ladder

- Cuesta et al 2015, Auborg et al 2015
- Bernal et al 2016/21 Spline reconstruction of the expansion history H(z).

Direct cosmic distance ladder



Direct and inverse cosmic distance ladder

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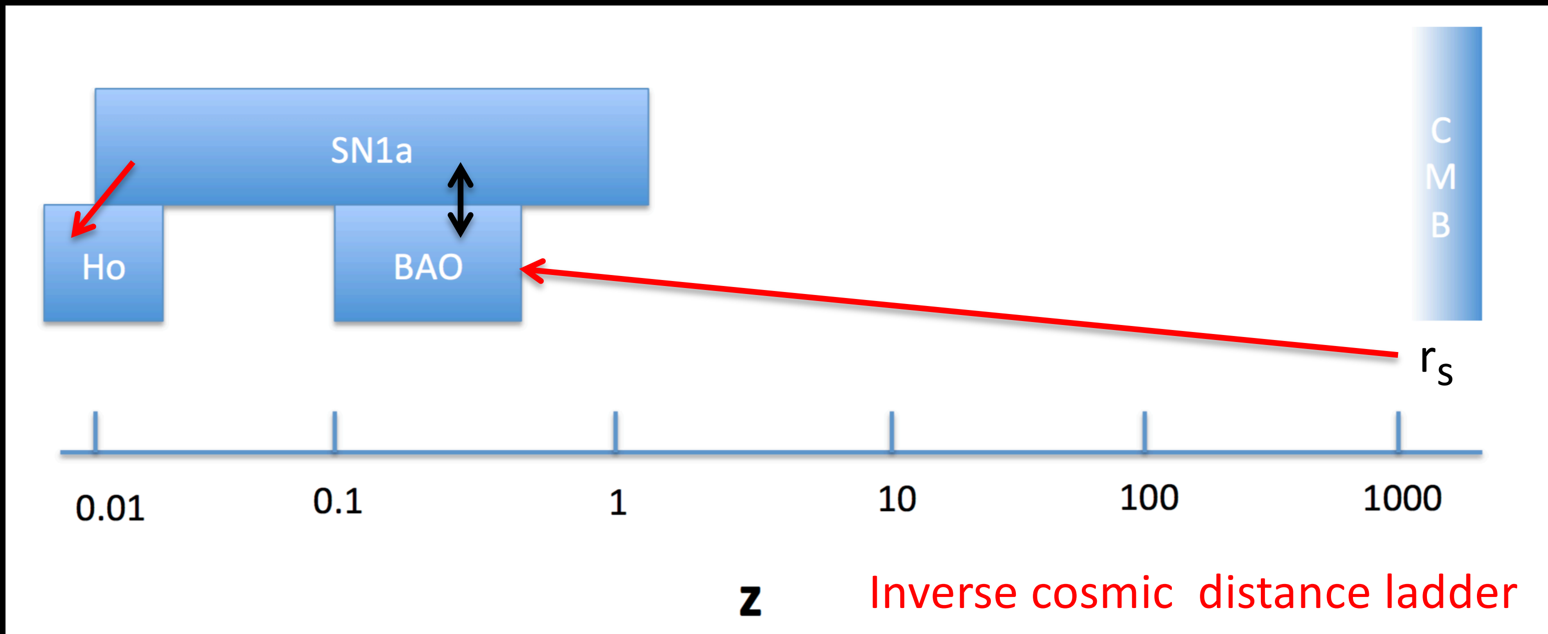
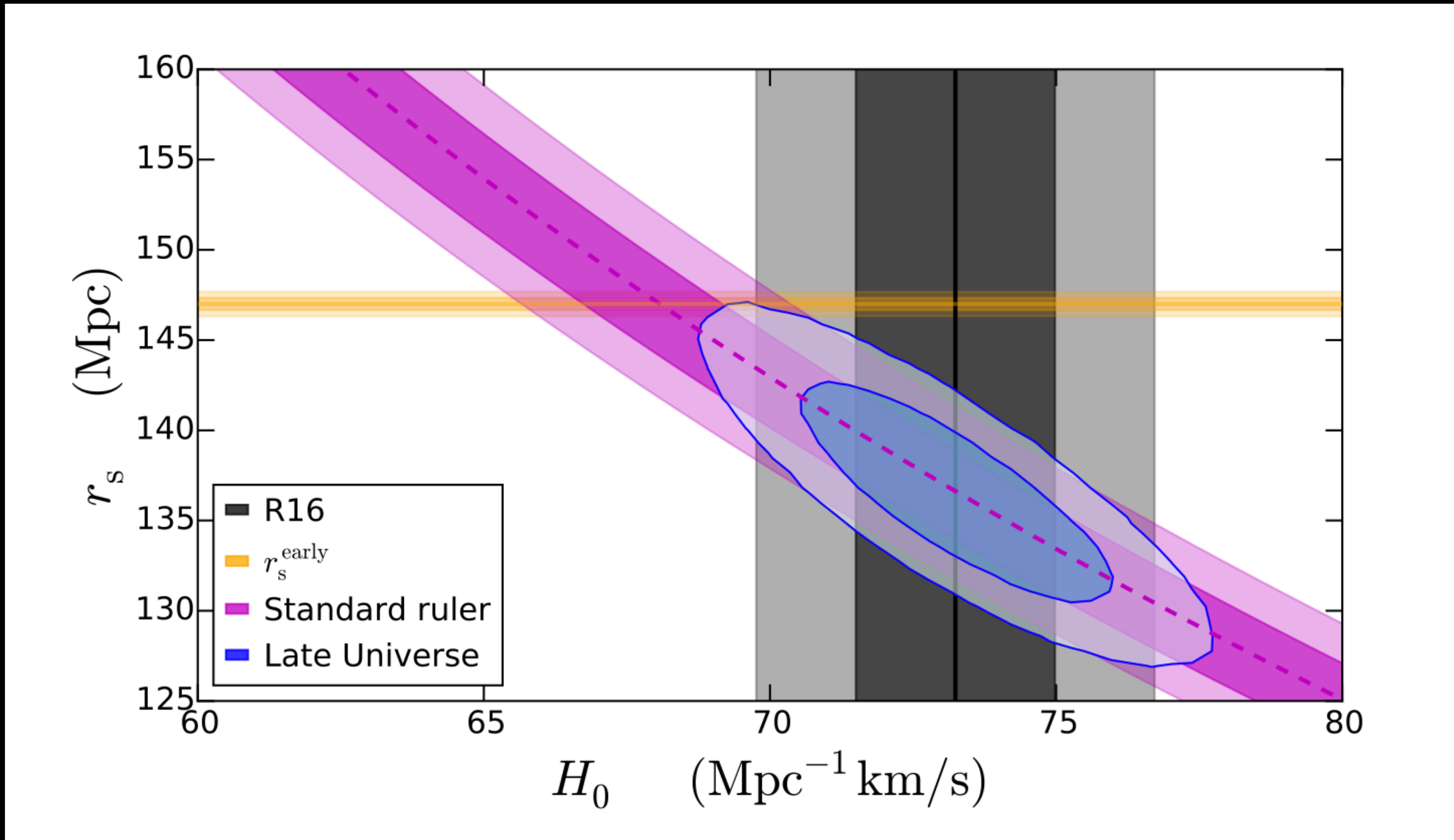
Direct cosmic distance ladder



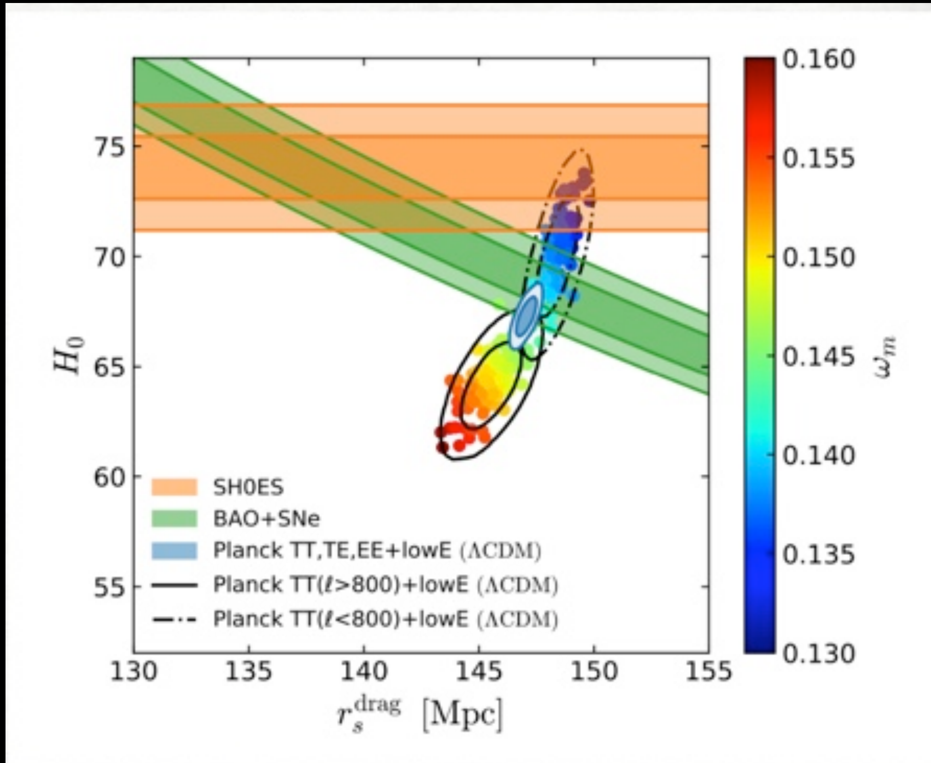
Here is where in ΛCDM or its simple variations the two ladders do not match

Ho problem can be seen as an rs problem



Bernal et al 2016

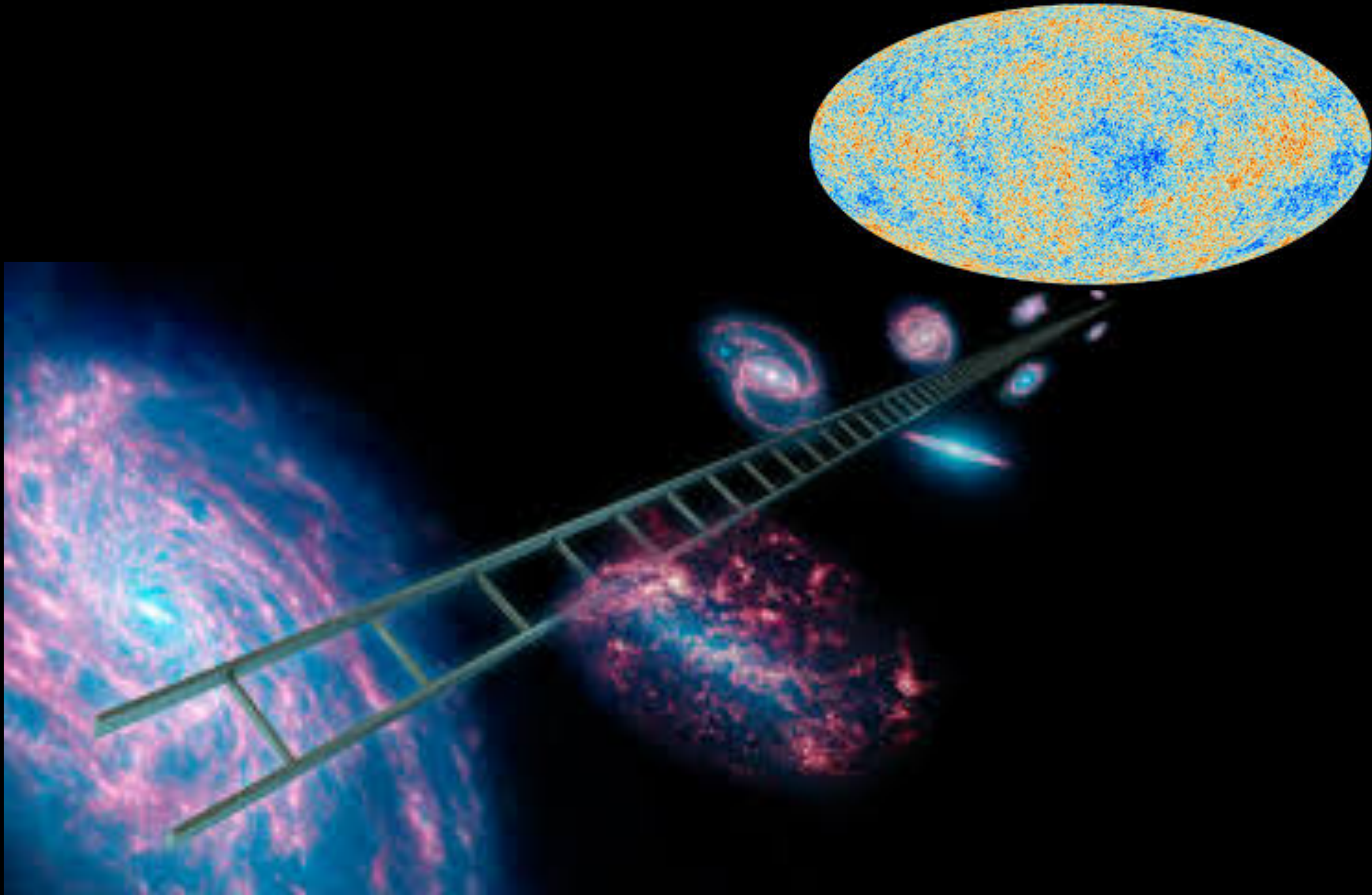
Ho problem can be seen as an rs problem (again)



Knox&Milllea 1908.03663

H0: Threading a needle from the other side of the Universe

(quote by Adam Riess)



Good ladders need 2 good anchor points

Is there a problem?

Yes

Even George E. now agrees.

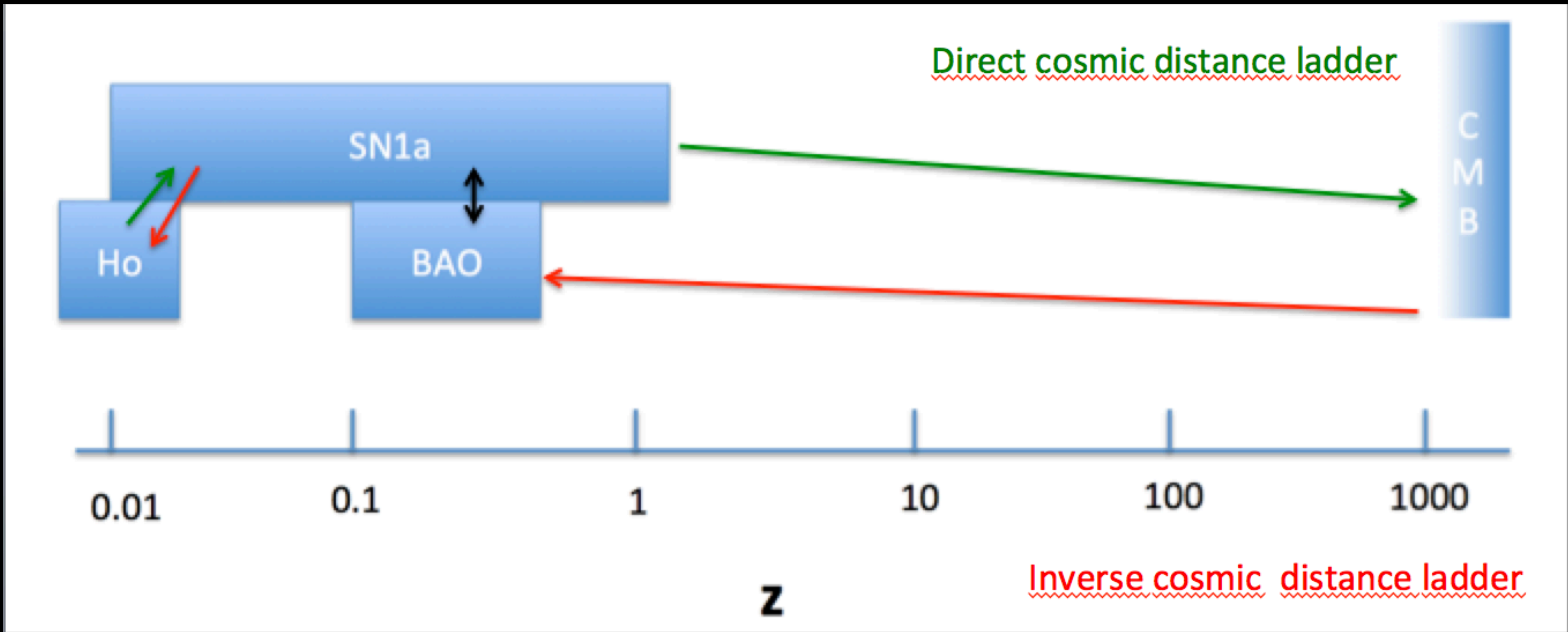
How much of a problem is cosmological-model dependent

Where is the problem?

Systematics!

Increasingly unlikely

Working hypothesis: early vs late



H0

rs

But there is not much wiggle room in the middle!

Bernal e tal 2016, Aylor et al 2017

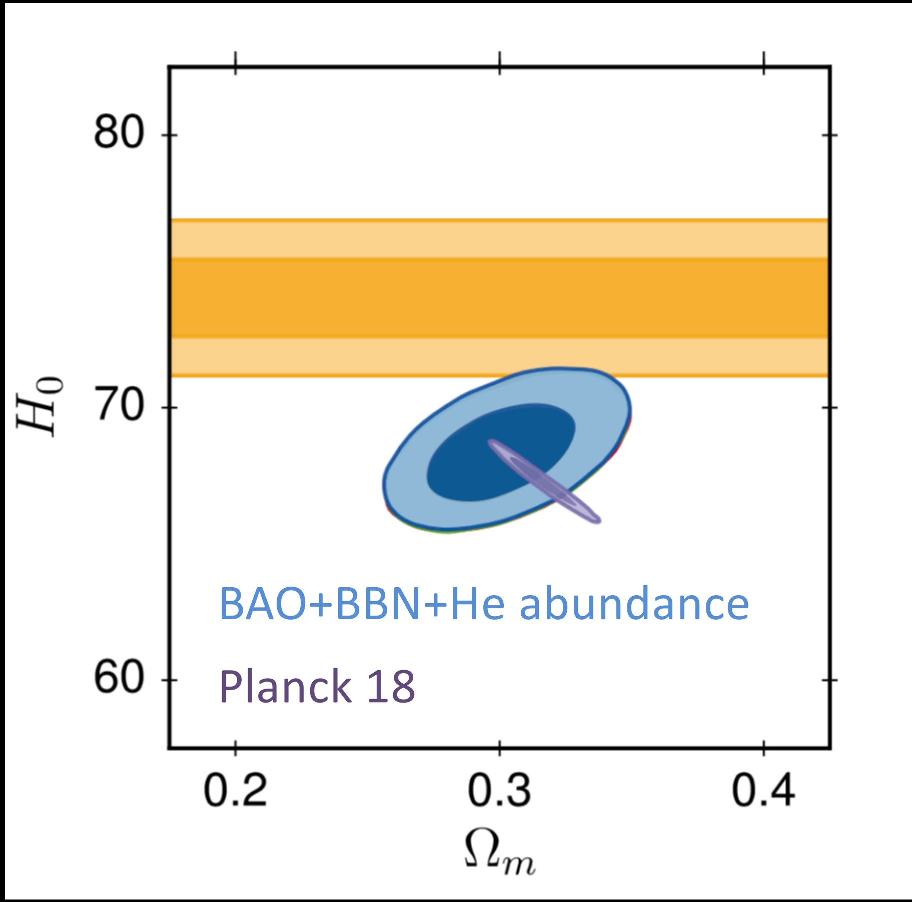
Where is the problem?

Is it in any specific **data** set? (keeping the standard ΛCDM context)

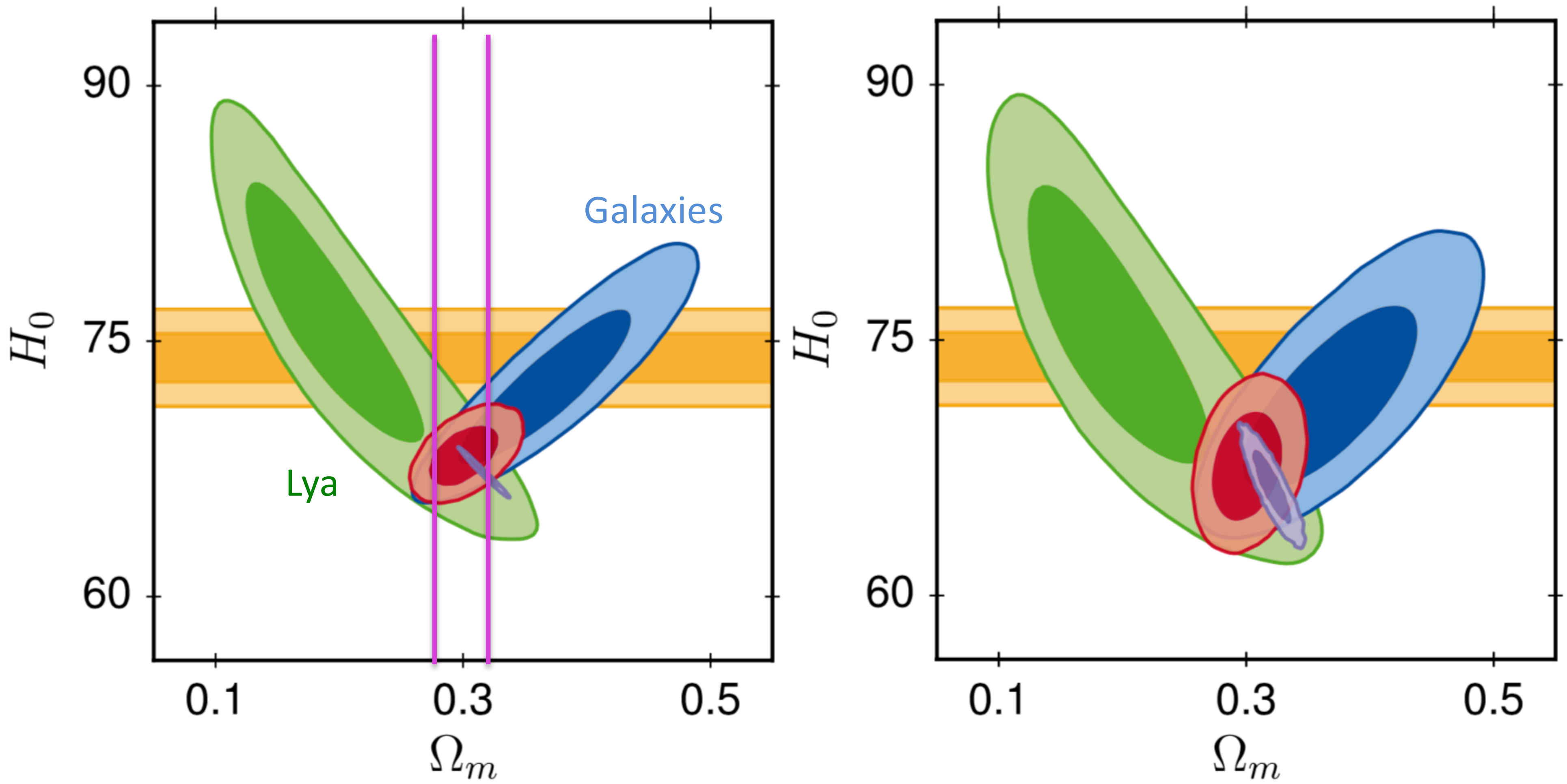
Early: For a while some people put the blame on Planck….

BUT H0(Early) does not budge if you take Planck (or CMB data) out completely (even for Neff-extended models Shonenberg et al 2019)

Before works which dropped Planck used instead WMAP+ACT/SPT.



Aside: if not Lya BAO, use SNe



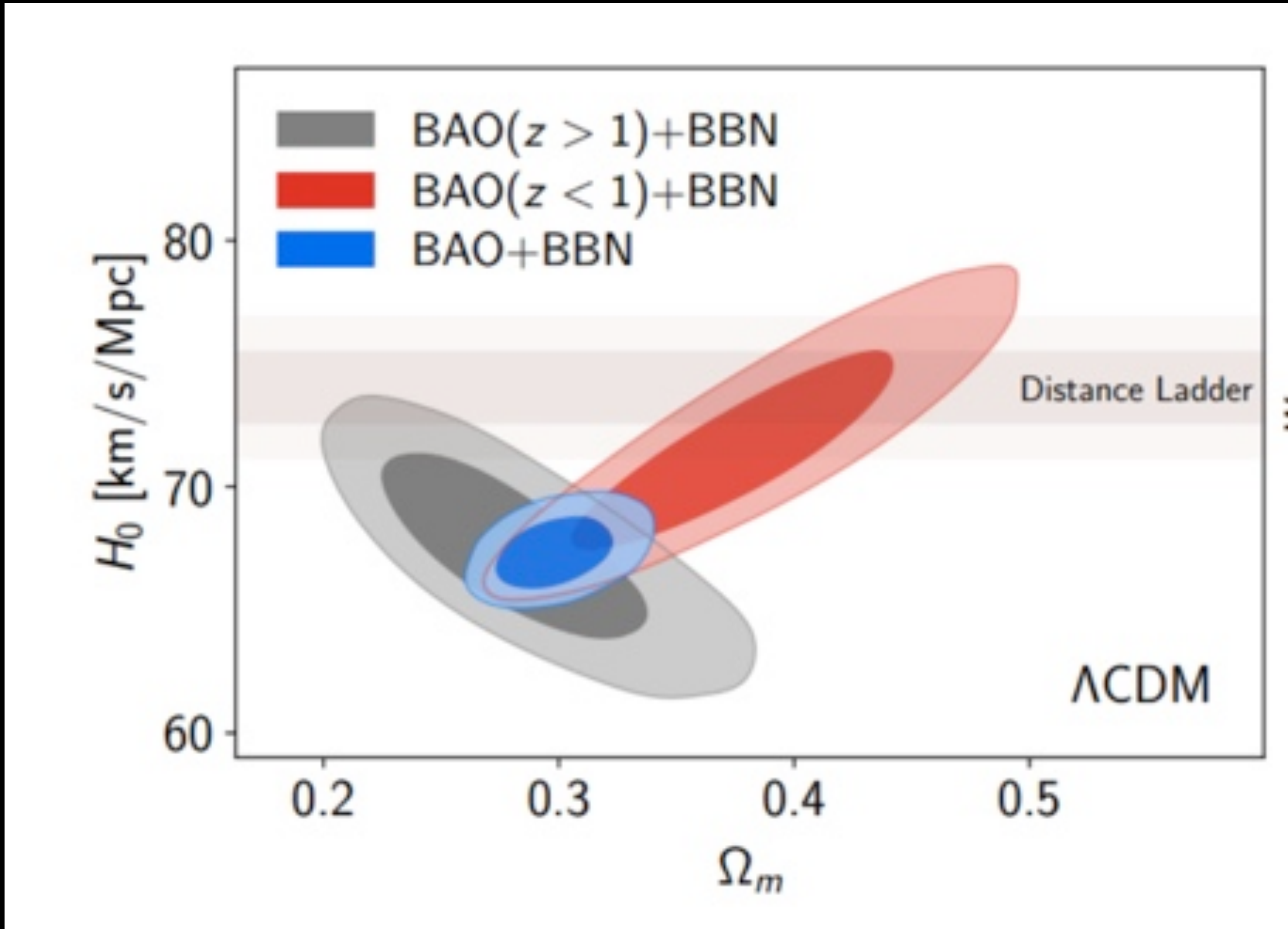
ΛCDM

Shonenberg et al 2019

Neff free

The length of the standard ruler is dictated by early time physics (BBN)

And again



e-BOSS DR16 2020

Where is the problem?

Is it in any specific **data** set?

It is not in CMB data

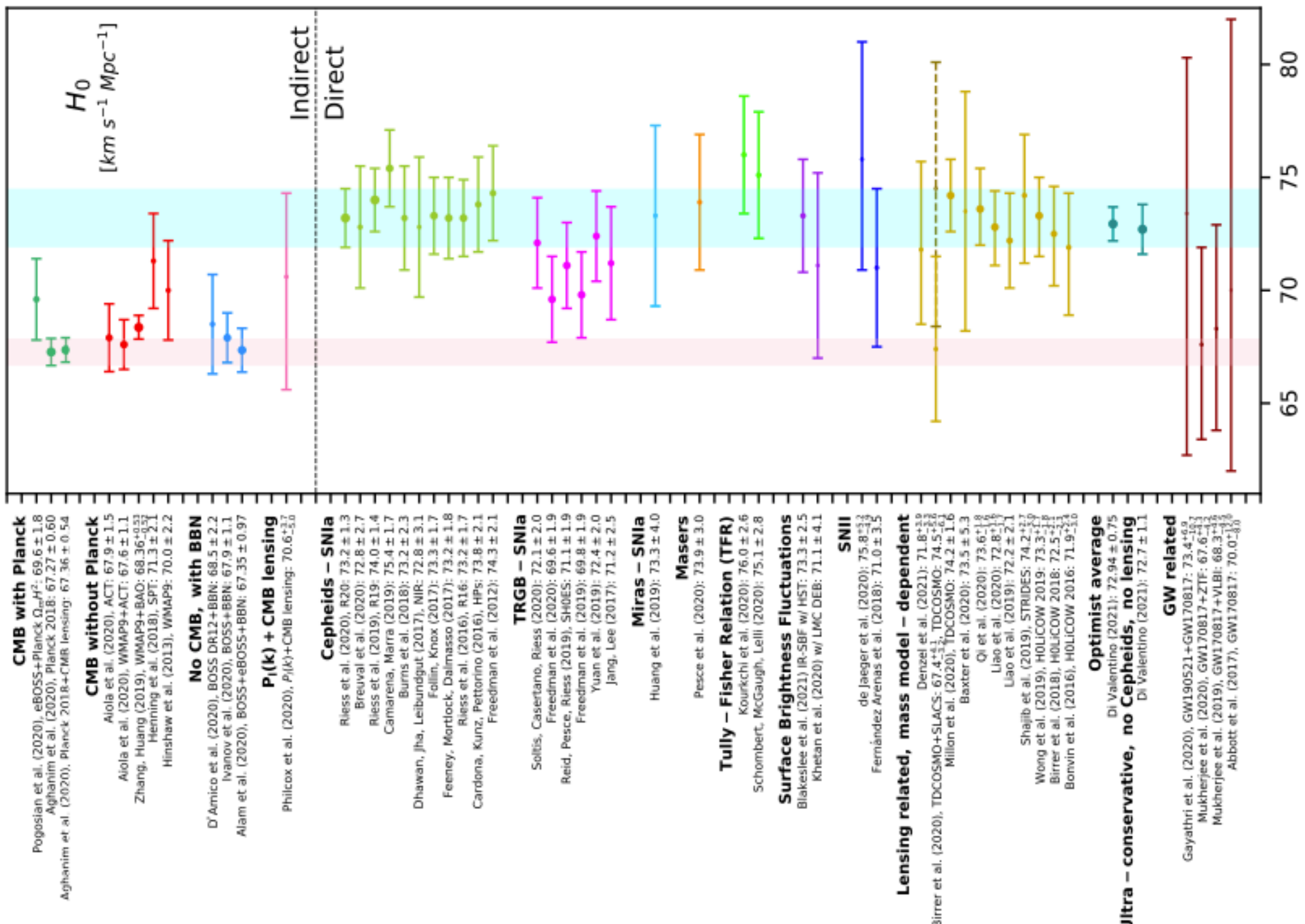
All early-Universe based determinations hoover well below 70km/s/Mpc

Many groups reanalized SHoES data…

Several independent low z determinations hoover above 70 km/s/Mpc

As time goes on seems less and less likely

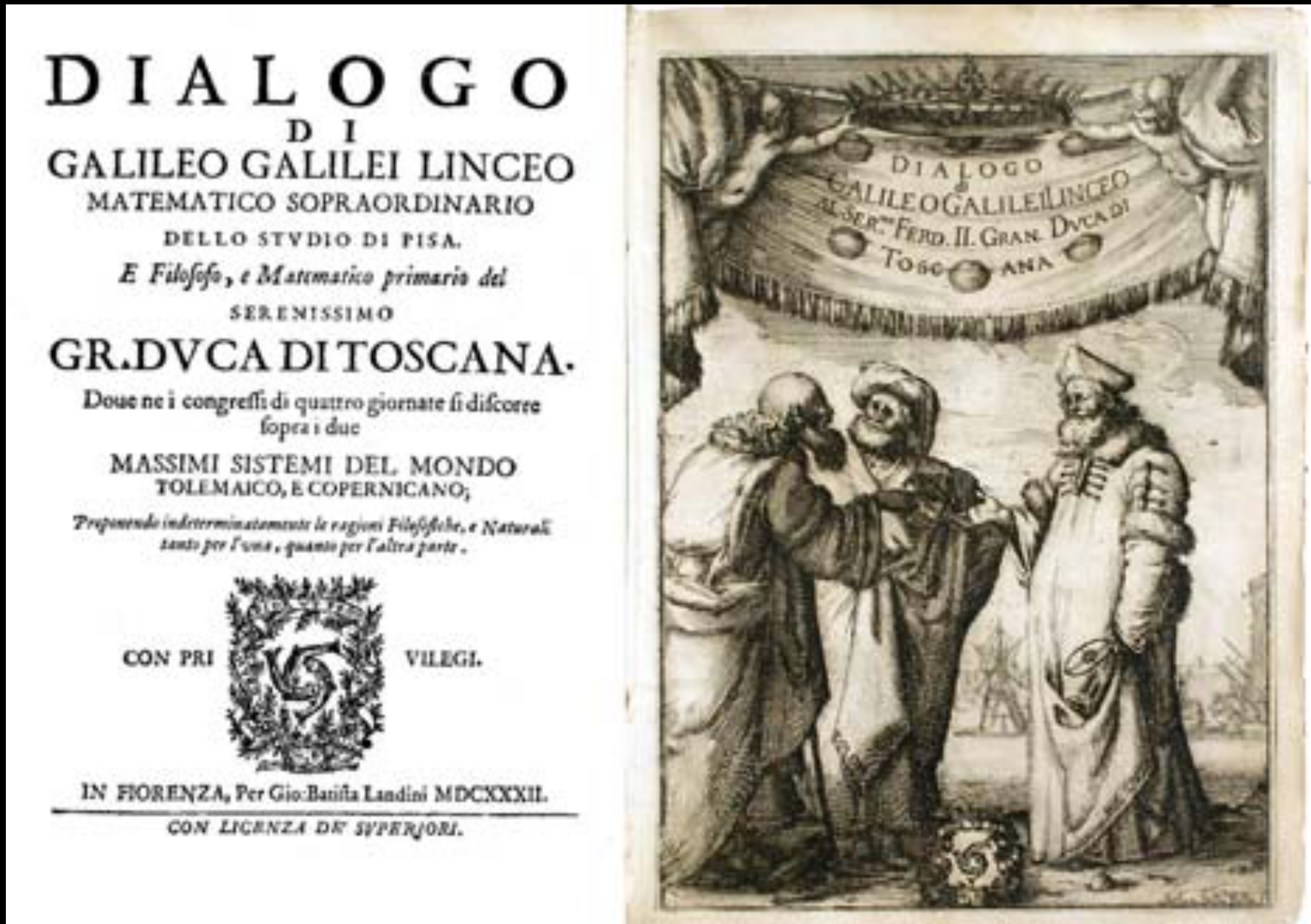
Is it in any specific data set?



Di Valentino et al 21

Where is the problem?

If not in the data then in the model…?



Where is the problem?

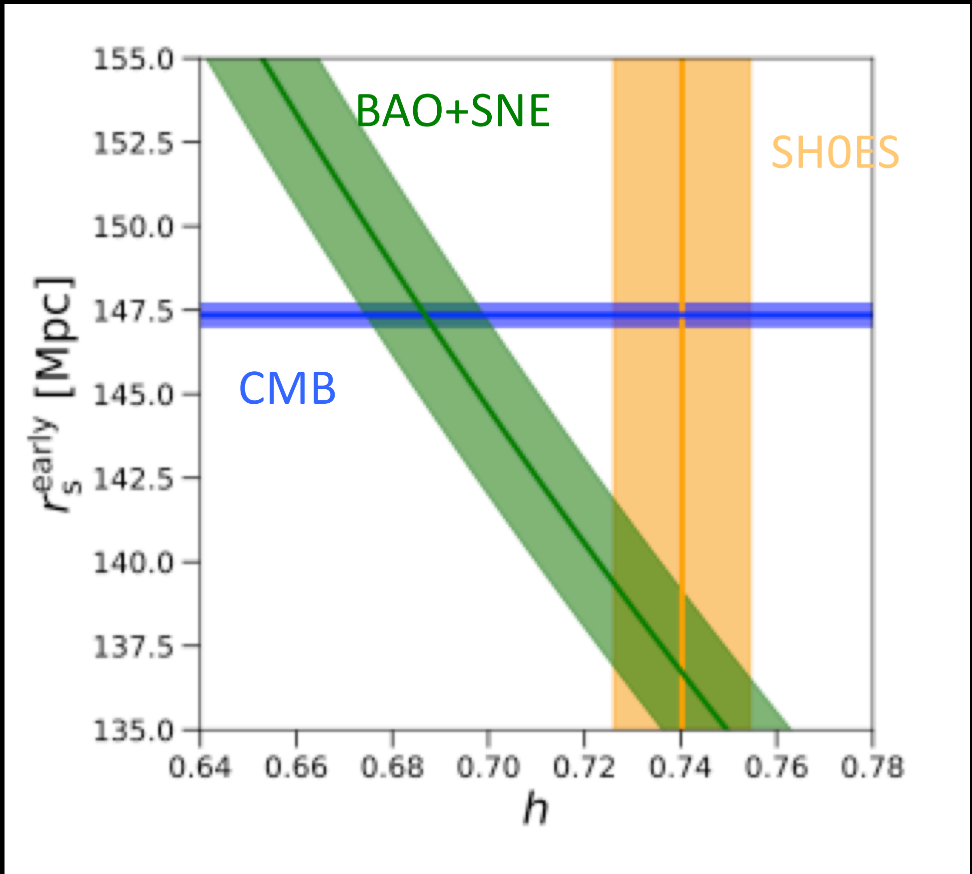
If not in the data then in the model…?

Early-time measurements assume standard ΛCDM.
Effectively this yields rd (the length of the standard ruler)

$$r_s(z_D) = \int_0^{\tau_D} c_s(\tau) d\tau$$

$$= \int_0^{a_\mathrm{d}} c_\mathrm{s} \frac{da}{a^2 H(a)}$$

z ~0 measurements “do not do” assumptions about cosmology



Shall we look
pre or after recombination?

Fig.J.L. Bernal

pre-recombination solutions

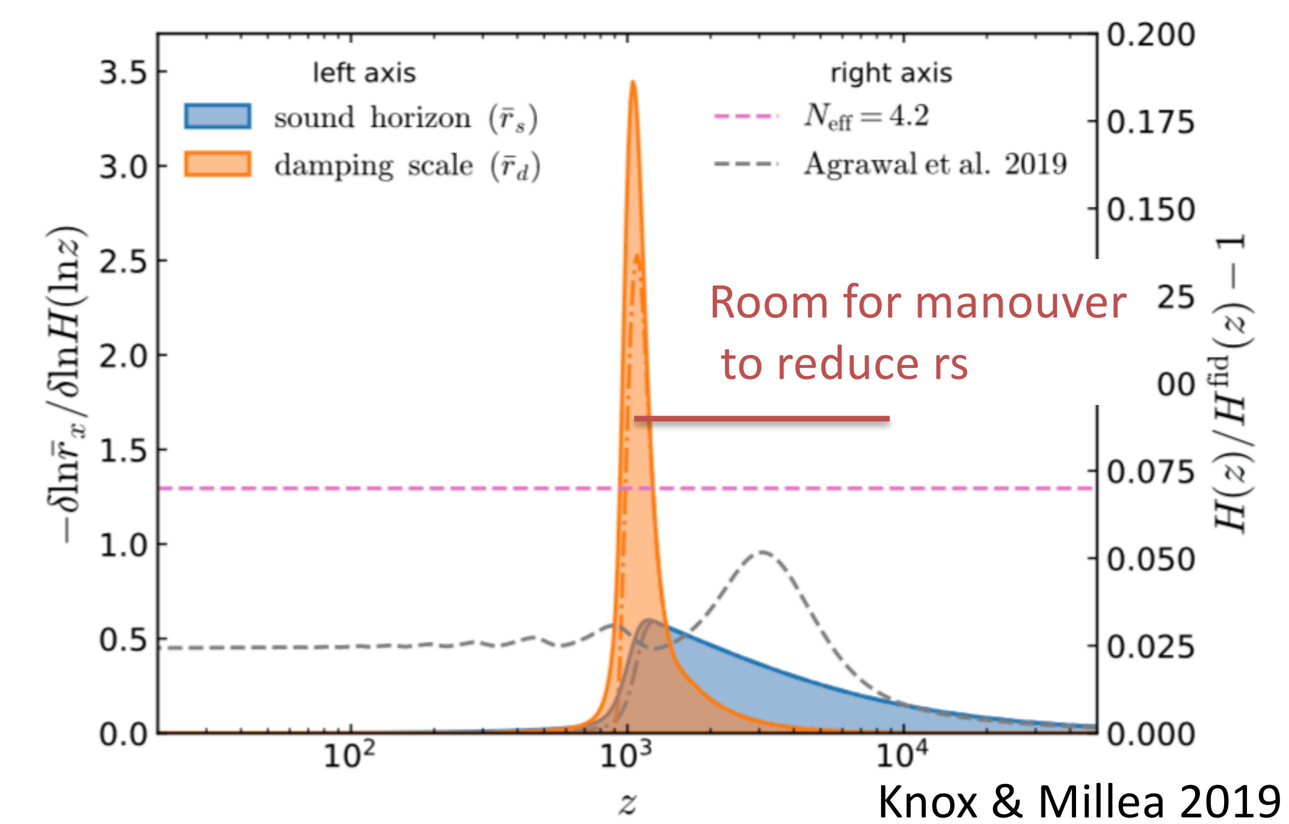
Modify the model right where we most like it

Decrease the sound horizon,   by 7%

$$r_s = \int_0^{t_\mathrm{d}} c_\mathrm{s} dt/a = \int_0^{a_\mathrm{d}} c_\mathrm{s} \frac{da}{a^2 H(a)}$$

A tall order

without wreaking havoc on damping tail… and everything else



Knox & Millea 2019

Reminds me of fine tuning

Ailor et al 2019

pre-recombination solutions

Modify the model right where we most like it

Decrease the sound horizon,   by 7%
without wreaking havoc on damping tail… and everything else

Early dark energy… affects the damplig tail (can look for signatures)

Change initial conditions

Extra components/ Extra interactions/Energy injection (localized!)

High T recombination

Change H(z) → change of inferred wm with scale

These are not all equivalent!

Post recombination?

Including screening and modifications to GR etc.

My take: it's complicated as it would have to affect several different things at once, including time-delay distances

Increase the freedom of H(z); Bernal, Raveri, Joudaki, Keeley…
The price is high:
many extra degrees of freedom (epicycles?) or hide it where there are no data

It is also very hard to change rs by 7% one has to tinker with wb (hard) , wm (by ~20-30%) without changing rs/rd in the CMB… and equality scale

It is also hard to just mess around with the standard ruler *as seen in BAO*

How much wiggle room is there?
H(z)/H0 reconstruction

ΛCDM

CMB

$r_\mathrm{d}h = 99.1 \pm 0.9$ Mpc

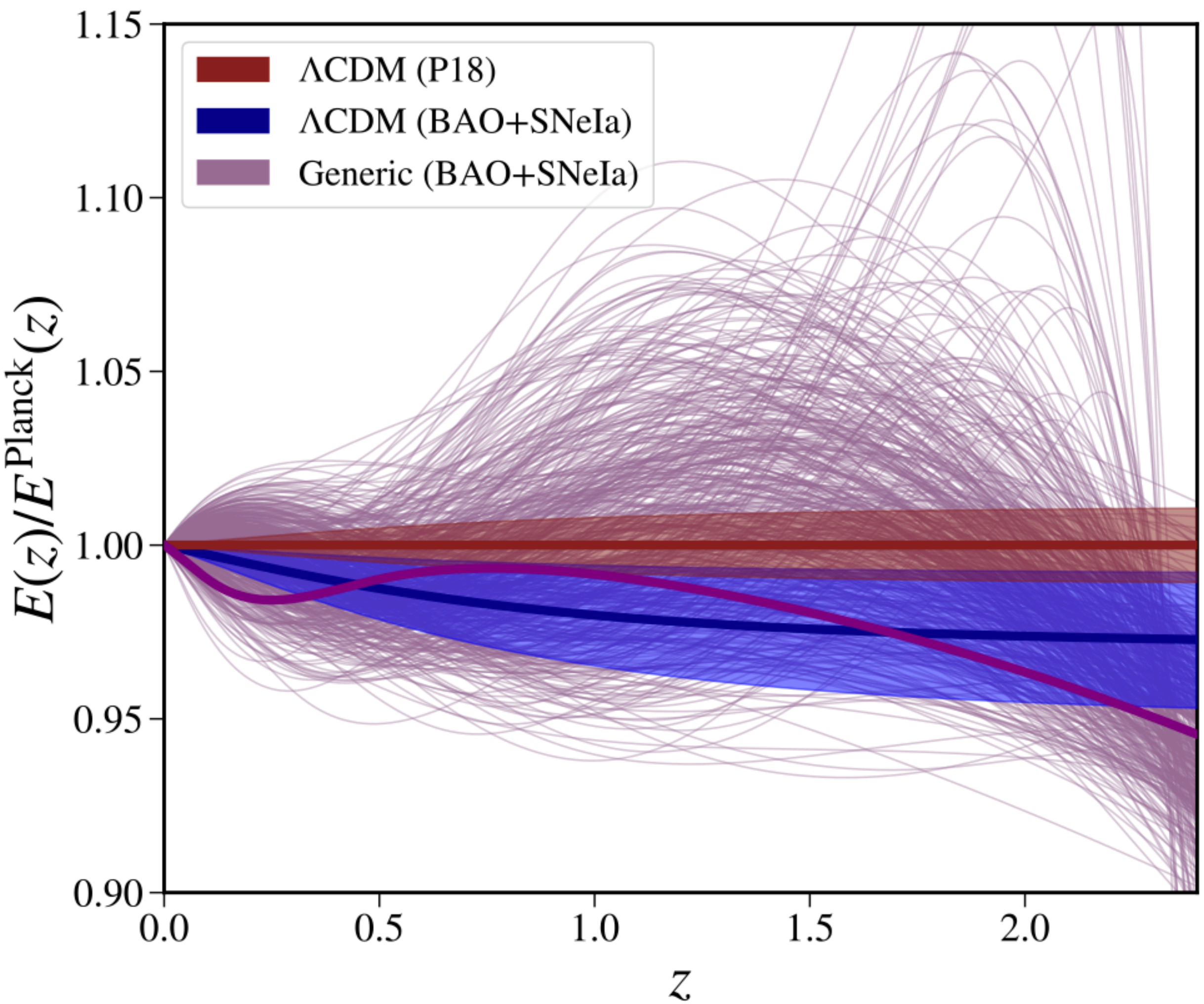
BAO+SNe

$\Omega_\mathrm{M} = 0.297 \pm 0.013$

$r_\mathrm{d}h = 100.6 \pm 1.1$ Mpc

Generic reconstruction

$r_\mathrm{d}h = 100.2 \pm 1.2$ Mpc



Bernal et al. 2102.05066

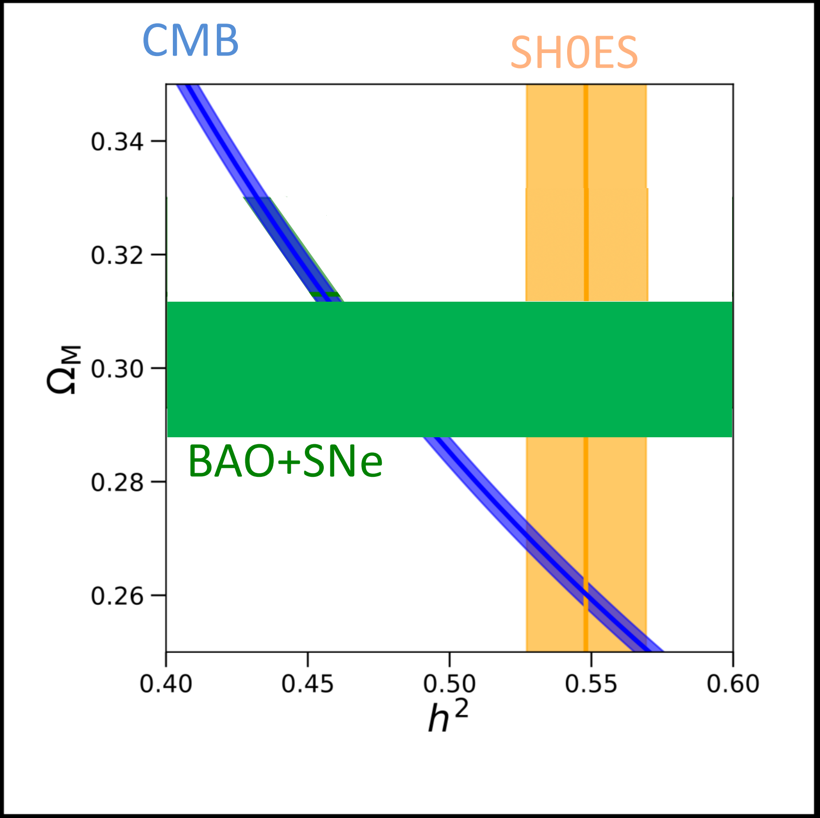
Beyond H0

This is not just a H0 problem or a r_{s}, r_{d} problem.

It is a Ω_{m} problem too

...And an age problem too

ΛCDM assumed



Bernal et al . 2102.05066

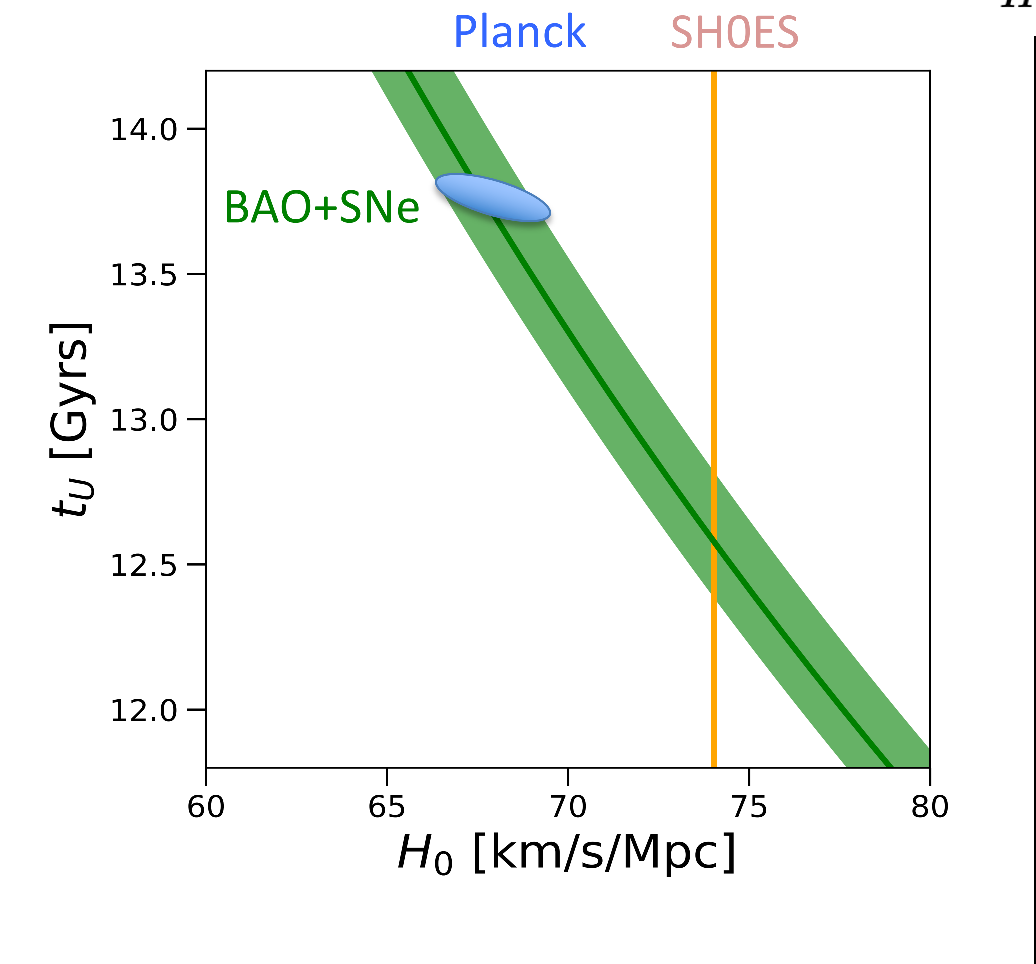
How old is the Universe anyway?

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

Early : high t_0

Late: low t_0

?



D. Valcin

Back to the 90ies

The Universe can’t be younger than the oldest objects it contains

Example: old halo stars, globular clusters

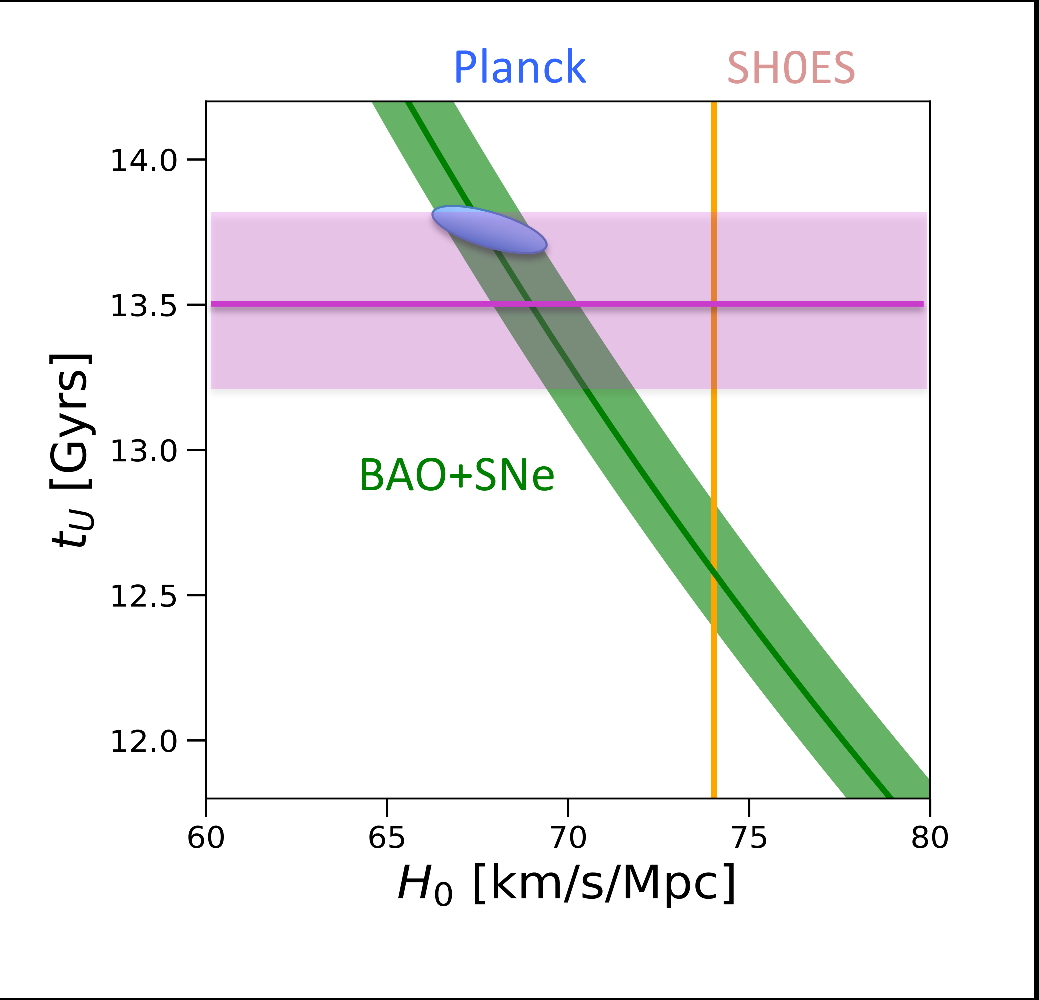
But.. Detemining accurately the absolute age of these objects has his own

Age of oldest Globular clusters

Age of the Universe from re-analysis of Globular clusters ages marginalize over: metalicity, absorption, He fraction, distance, etc.

Early : high t_0

Late: low t_0



t_U=13.5± 0.3 Gy

22 GC

ΛCDM acts its age not its SH0ES size…

Valcin et al. 2007.06594

Valcin et al. 2102.04486

Looking for Cinderella....

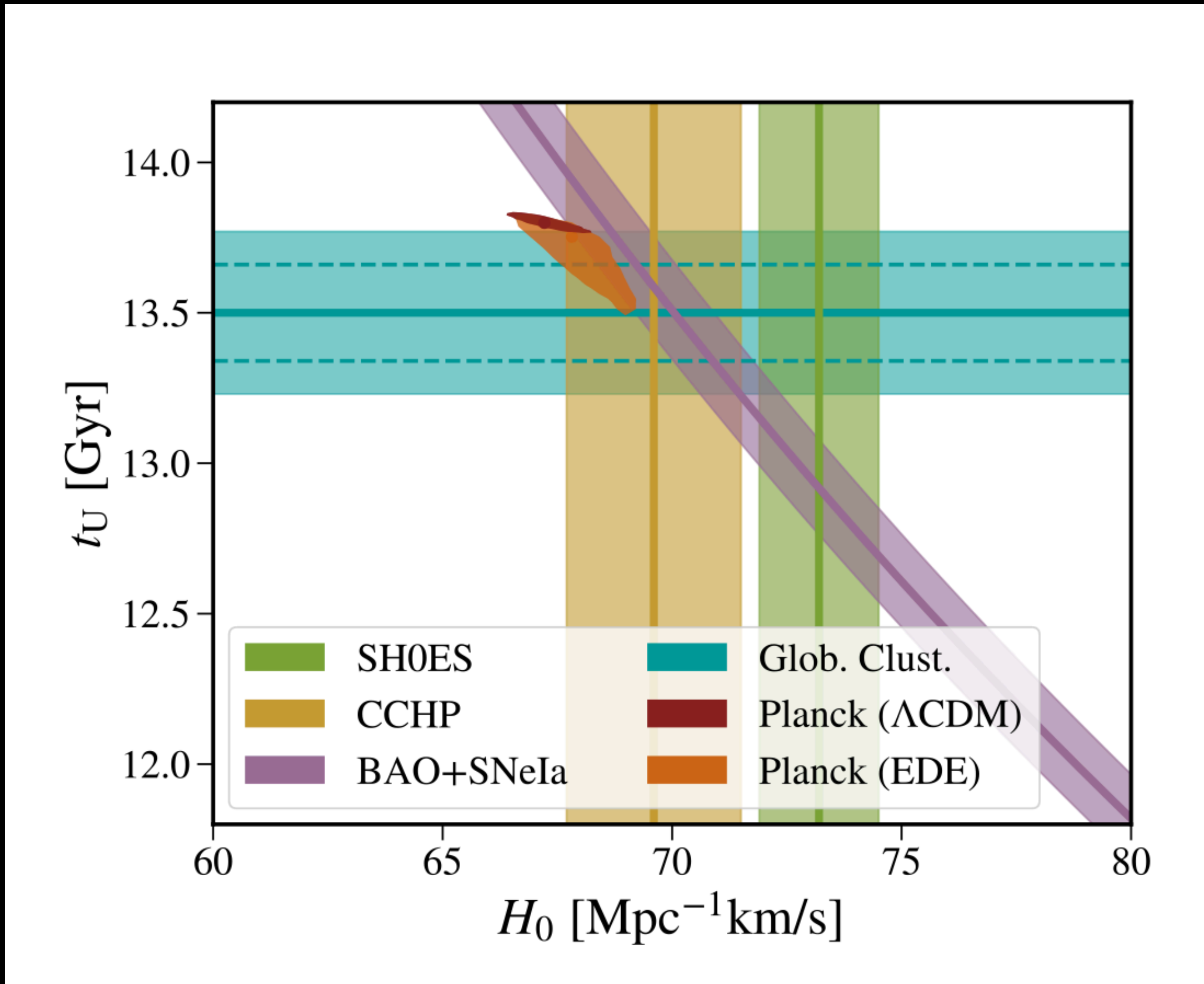
Looking for Cinderella

- The bad: w<-1, decaying dark matter,

- The ugly: neutrino interactions at early time, early dark energy-ish

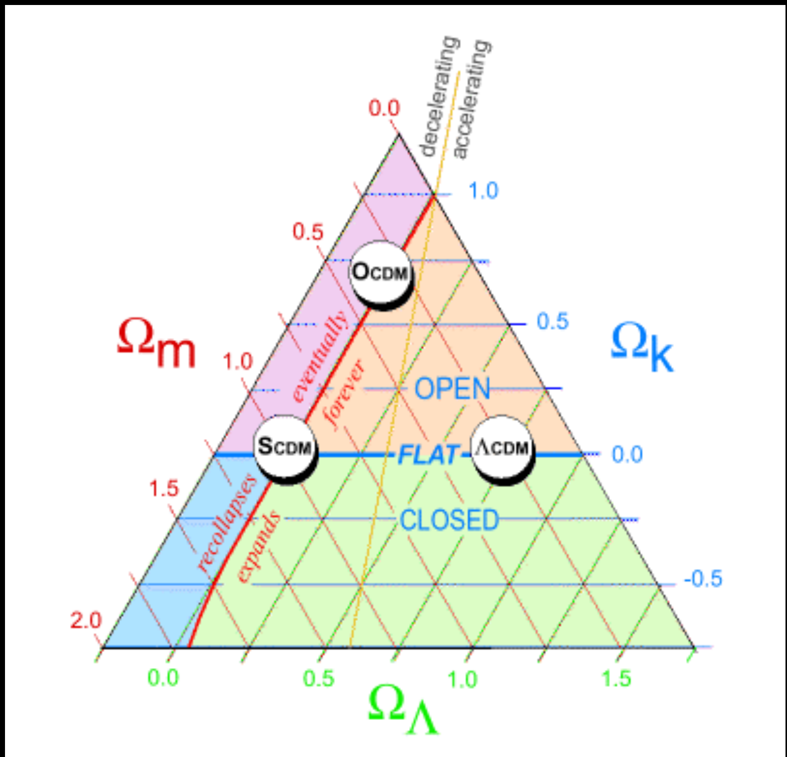
- The good:….?

Looking for Cinderella….



Bernal et al 2102.05066

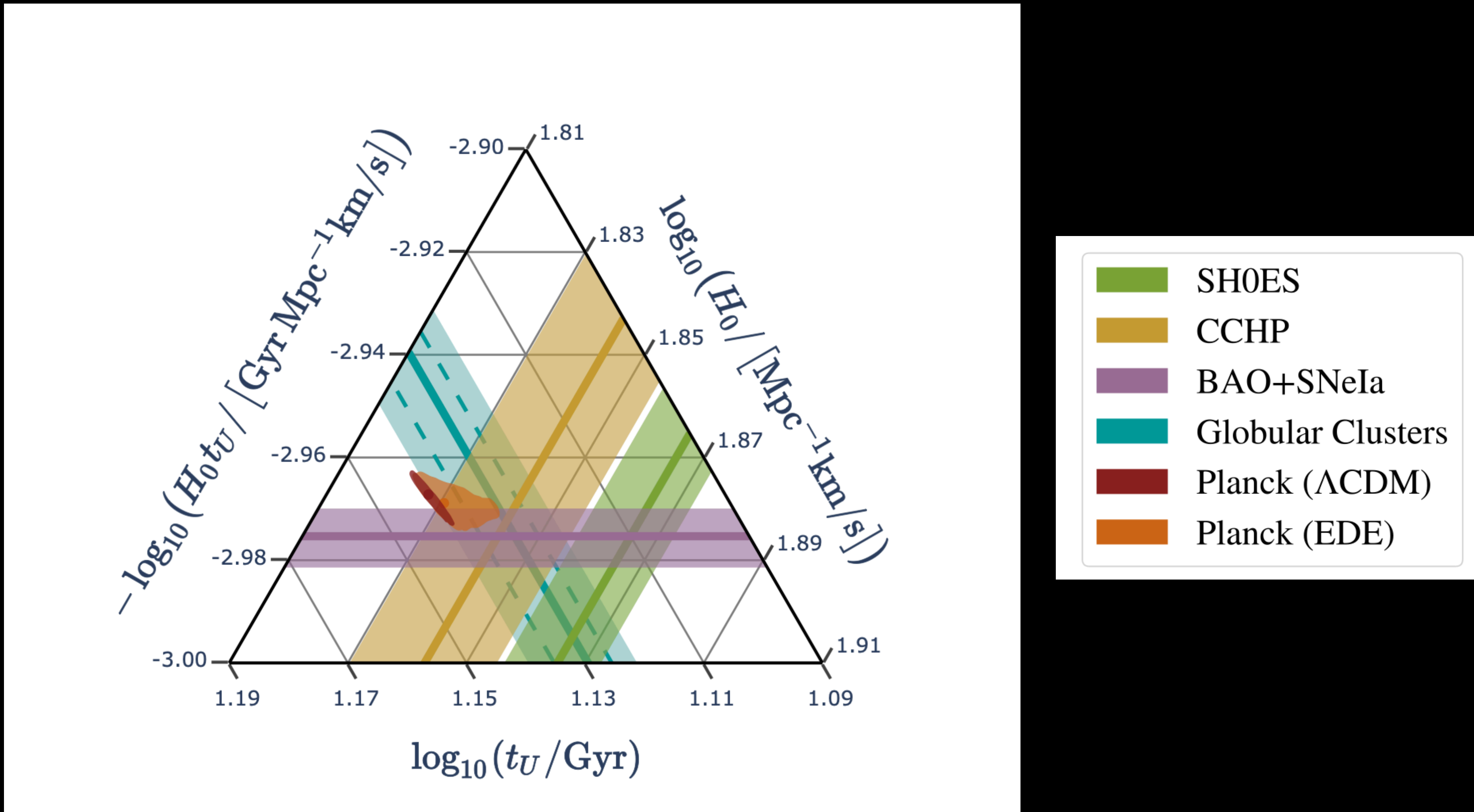
The original Cosmic triangle



Science Bahcall et al 1999

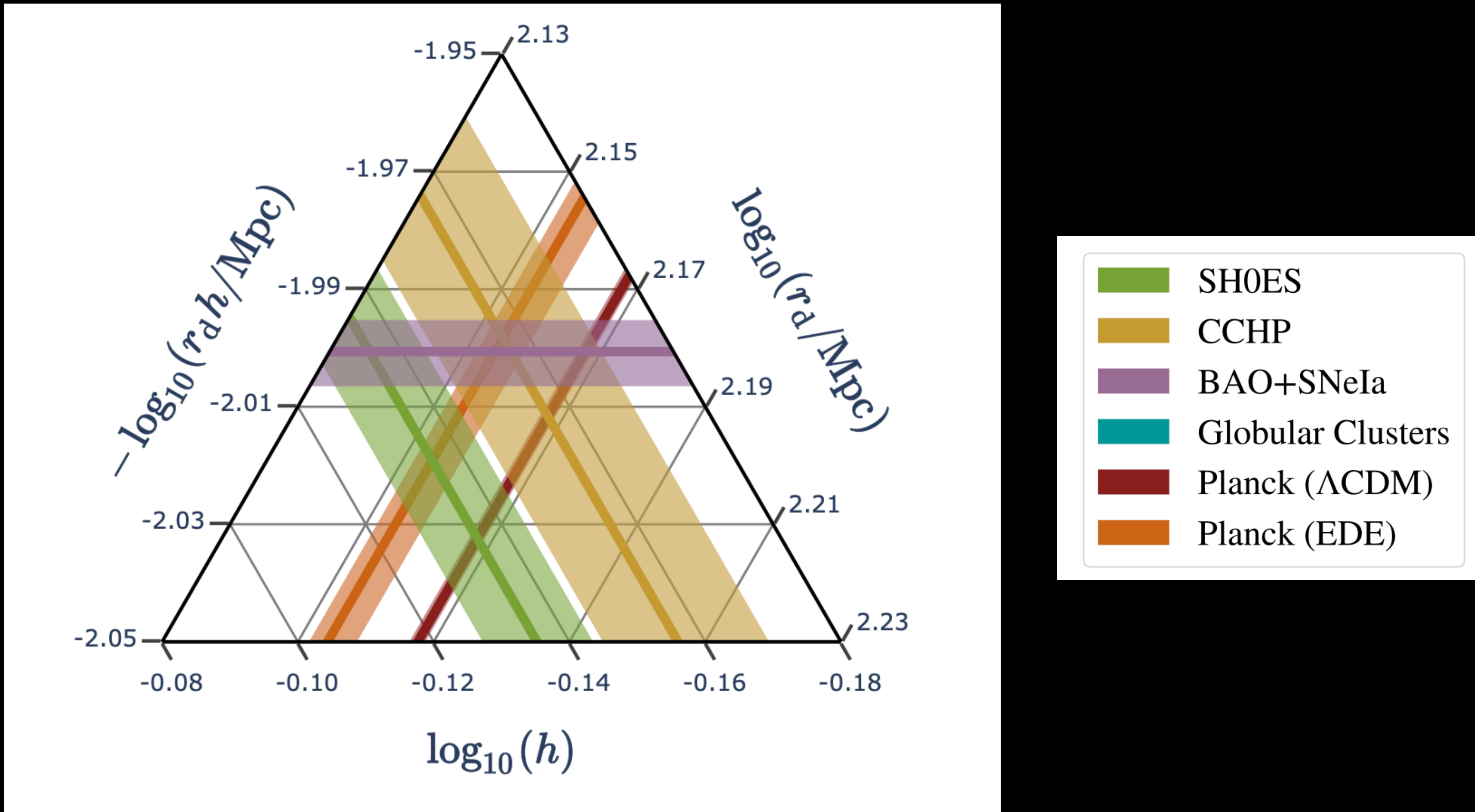
Now.. 22 years later… Back to the future…

The new cosmic triangles



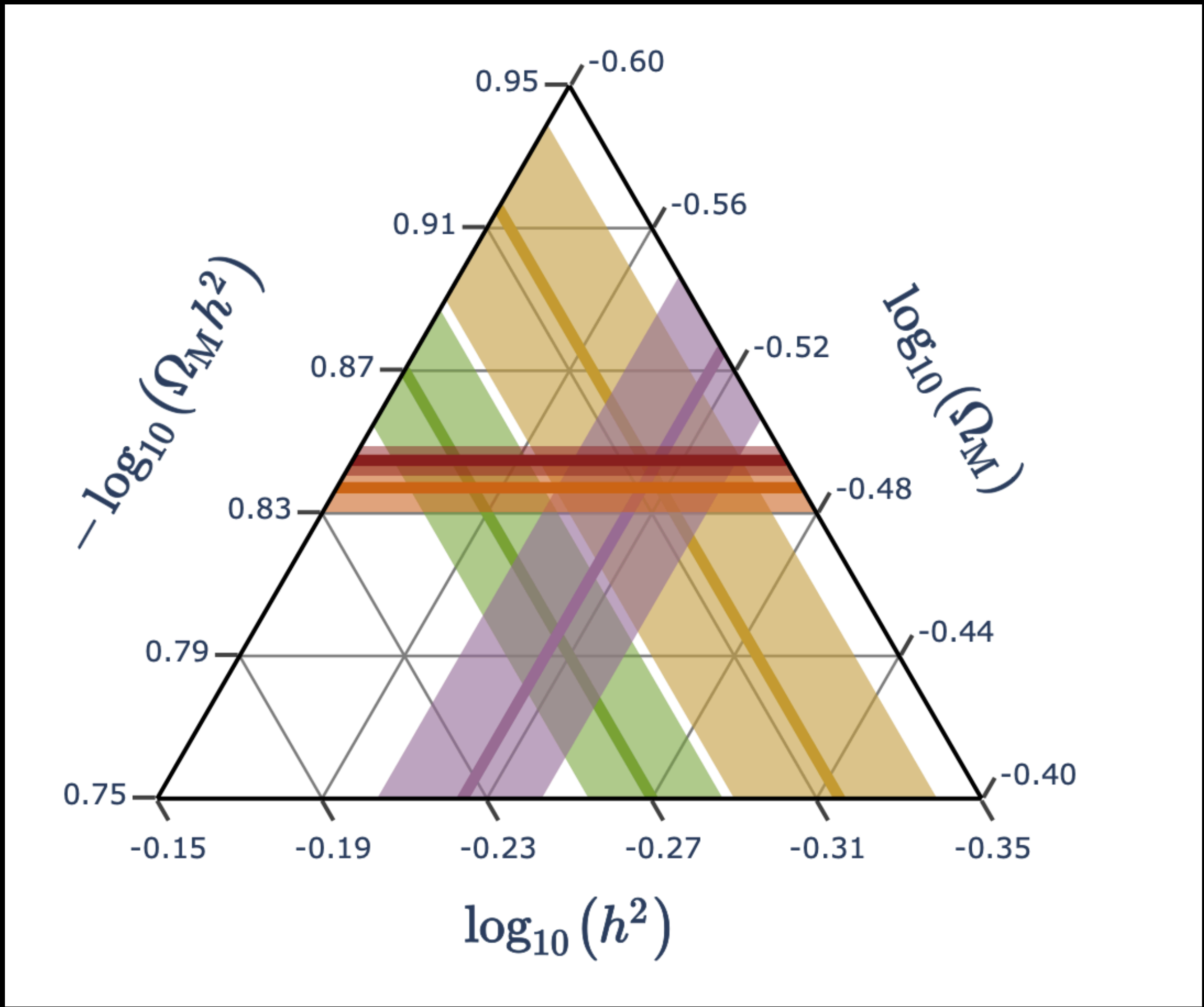
Bernal et al 2102.05066

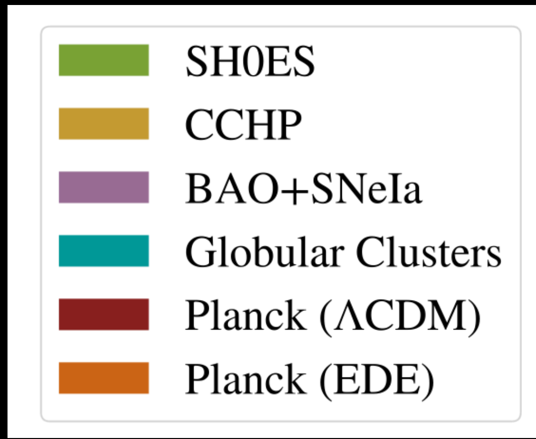
The new cosmic triangles



Bernal et al 2102.05066

The new cosmic triangles





Bernal et al 2102.05066

Theoretical solutions….

Should not break havoc where not needed: preserve the good agreement of LCDM with data

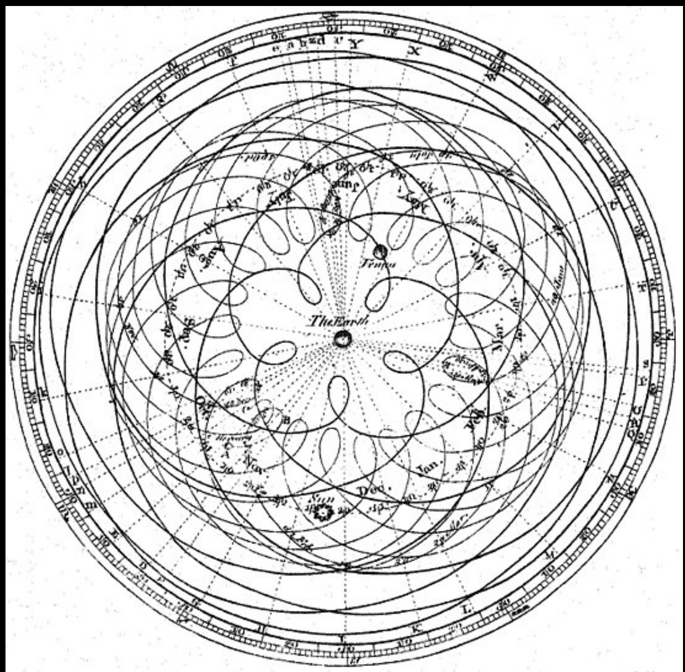
Should improve (or not worsen) other tensions

We should quantify improvement vs predictability (degrees of freedom)

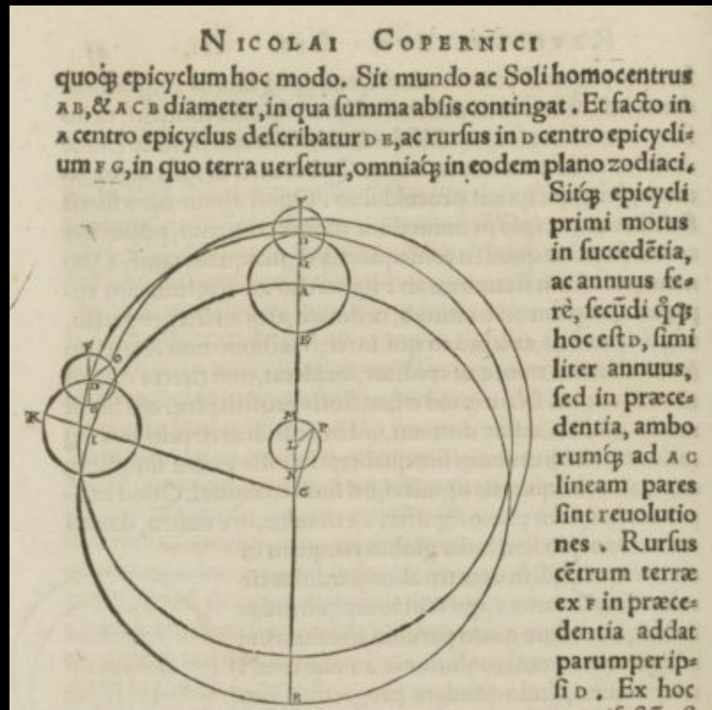
Parallelism with Λ…..

Model-dependent vs model independent approaches

At what point are we adding epicycles?



Cassini



NICOLAI COPERNICI

quoq; epicyclum hoc modo. Sit mundo ac Soli homocentrus AB, & ACB diameter, in qua summa absis contingat. Et facto in A centro epicyclus describatur DE, ac rursus in D centro epicycli-um FG, in quo terra uersetur, omniaq; in eodem plano zodiaci. Sitq; epicycli primi motus in succedētia, ac annuus ferè, secūdi quoq; hoc est D, similiter annuus, sed in præcedentia, amborumq; ad AC lineam pares sint reuolutiones. Rursus cētrum terræ ex F in præcedentia addat parumper ipsi D. Ex hoc

Looking for Cinderella....

Discrepancy between model–dependent and model -independent determinations of H_0

If not in the data.... Then...in the model?

Boost expansion rate before recombination → fixes the ladder
Low redshift solutions→ very limited wiggle room

AND the troubles go well beyond H_0 and distance ladders-→ Matter density and age

Looking for Cinderella....

Age is insensitive to: dimming, screening, deviations from GR, distance measures…

If high t_U is confirmed, models with high H_0 and standard low redshift physics are disfavoured.

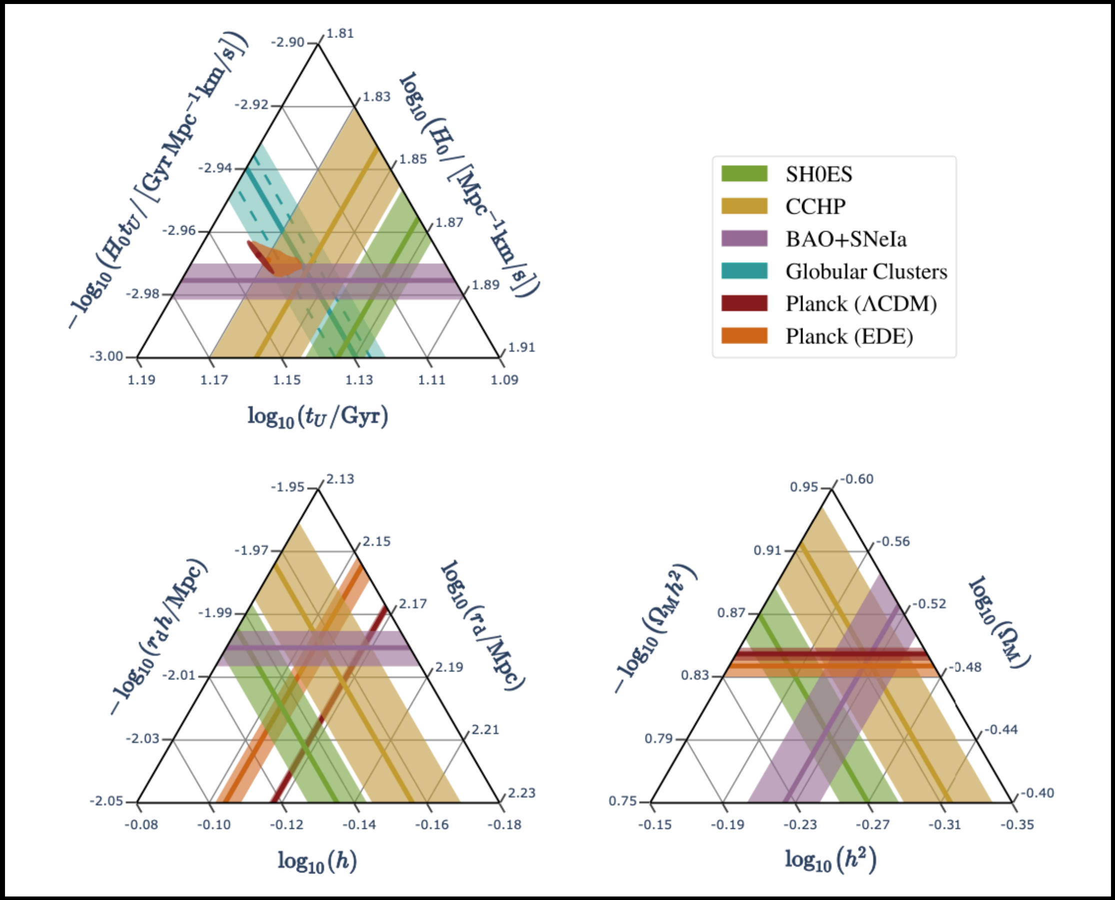
Two possible scenarios : local and global

Local:
affect local H_0 measurements
(astrophysical or cosmological
e.g., screening)
leaving all else unchanged

Global:
New physics affecting entire history
both early and late.
Impacts quantities well beyond $H_{0.}$
Will show up in new cosmological
observations !

To conclude

I hope that the new cosmic triangles representation of the observational constraints will help discriminating between the two scenarios and help guide future efforts to find a solution to the Hubble troubles.



Bernal et al 2021

END