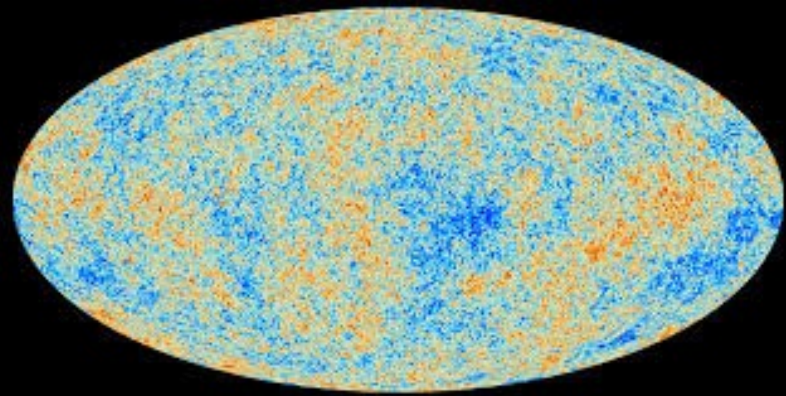
Hubble troubles

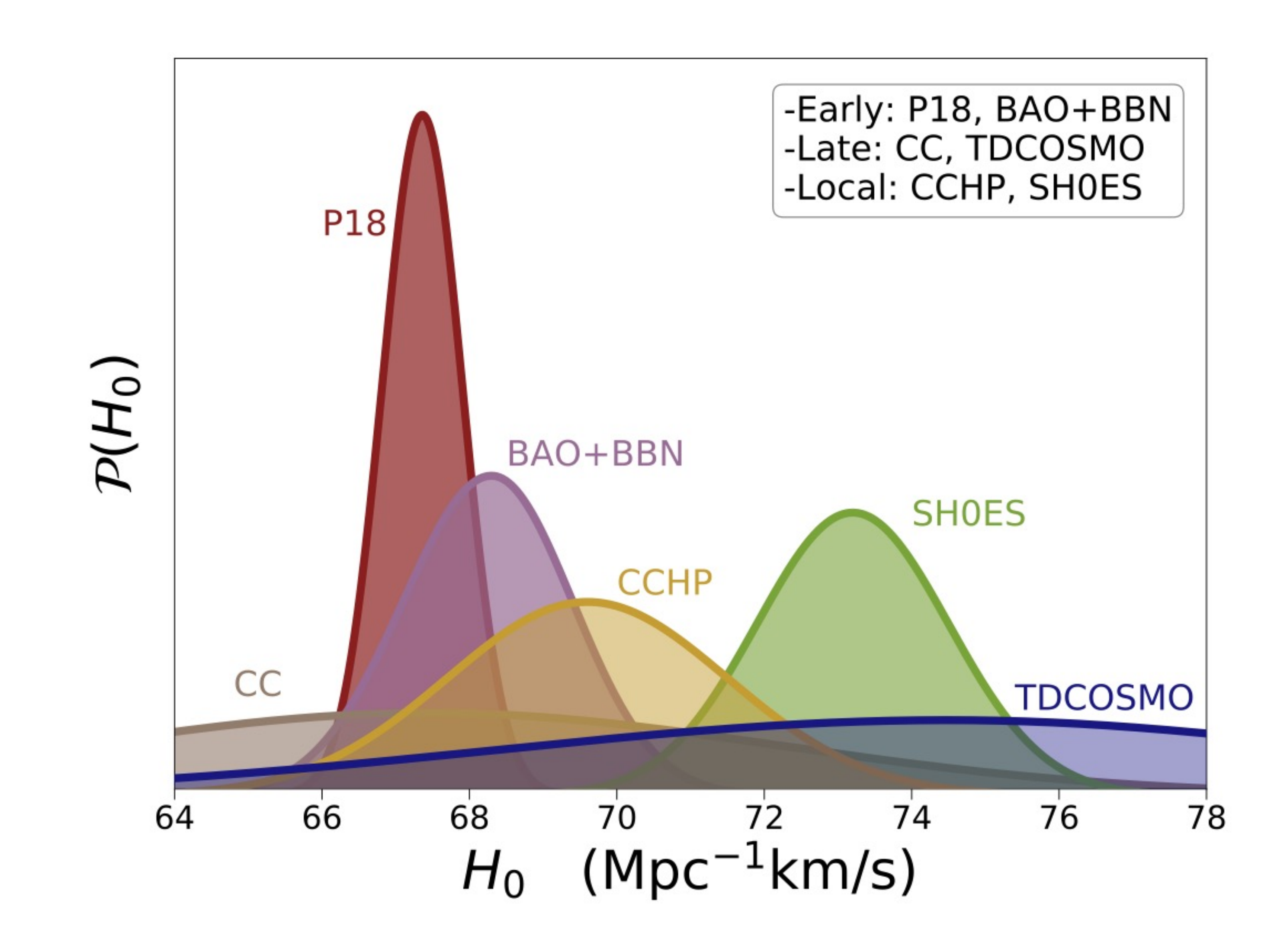


Licia Verde
ICREA & ICCUB

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

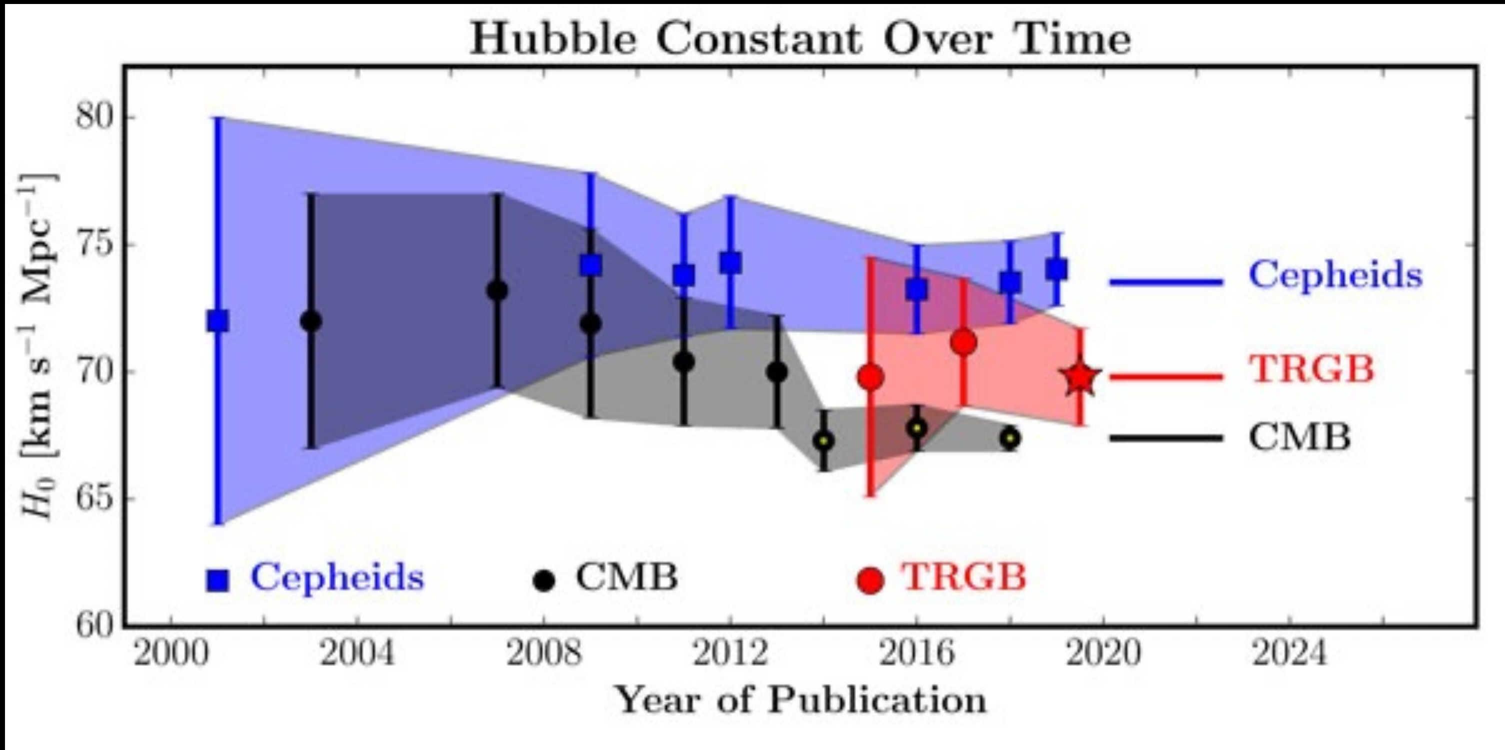
Quote adapted from Carl Jung

Model dependent vs model independent



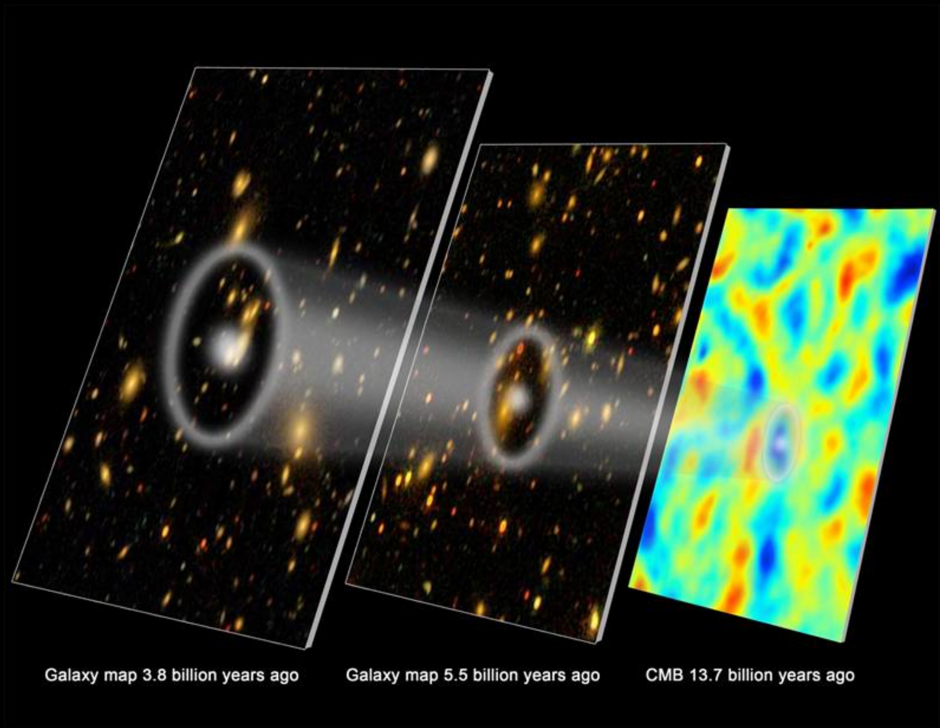
Bernal et al. 2102.05066

Constant not constant



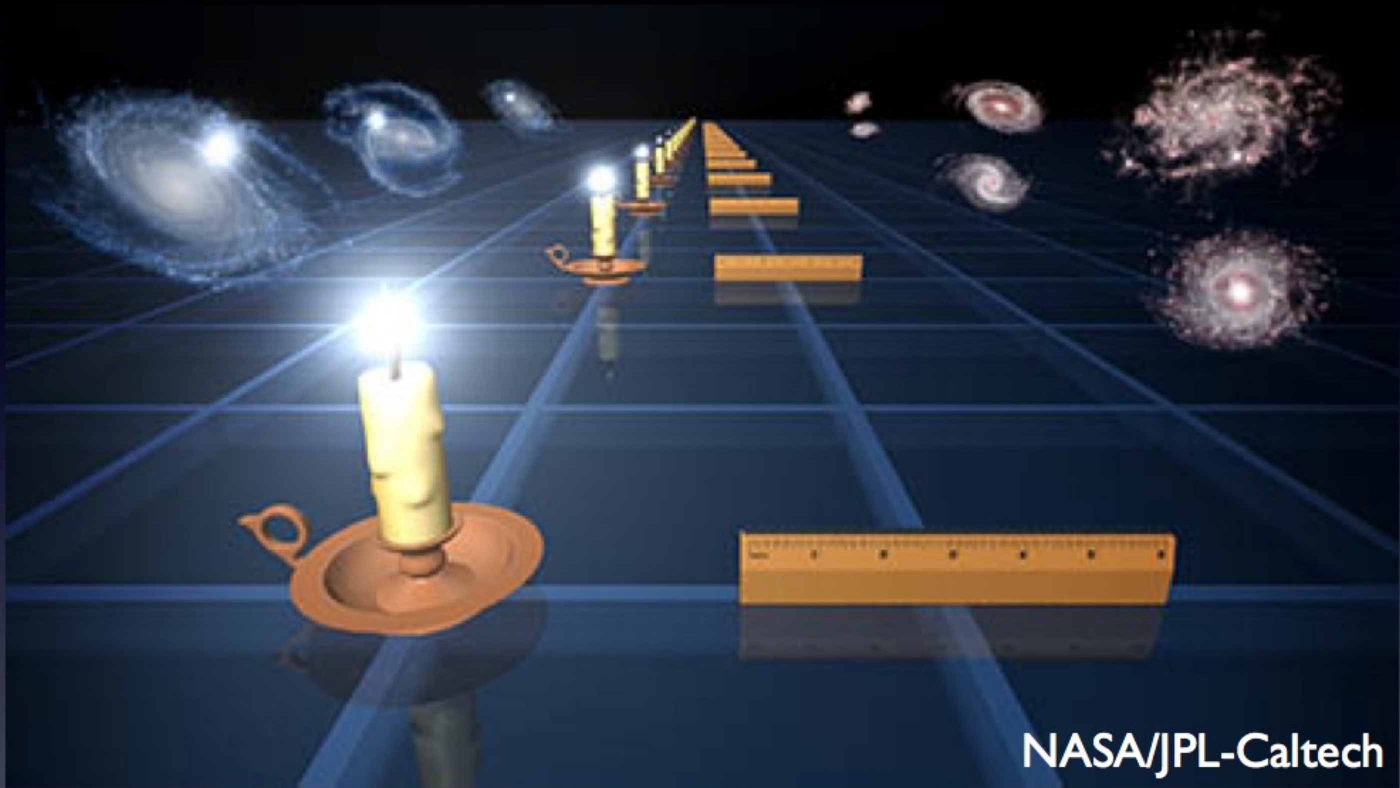
Baryon acoustic oscillations (BAO)
as a Standard ruler

- 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



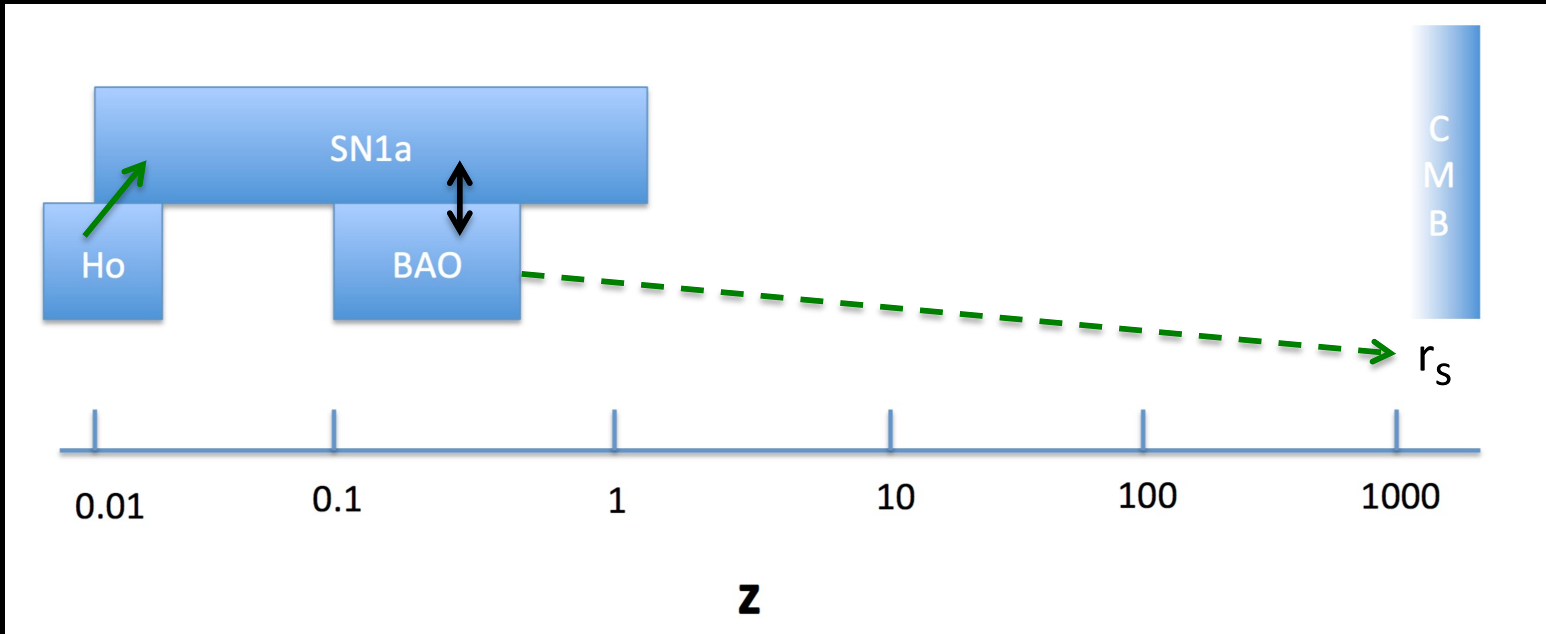
Type-Ia SNe measure
relative distances,
since there is large uncertainty
on the absolute magnitude M
of a fiducial SN

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

- Cuesta et al 2015, Auborg et al 2015
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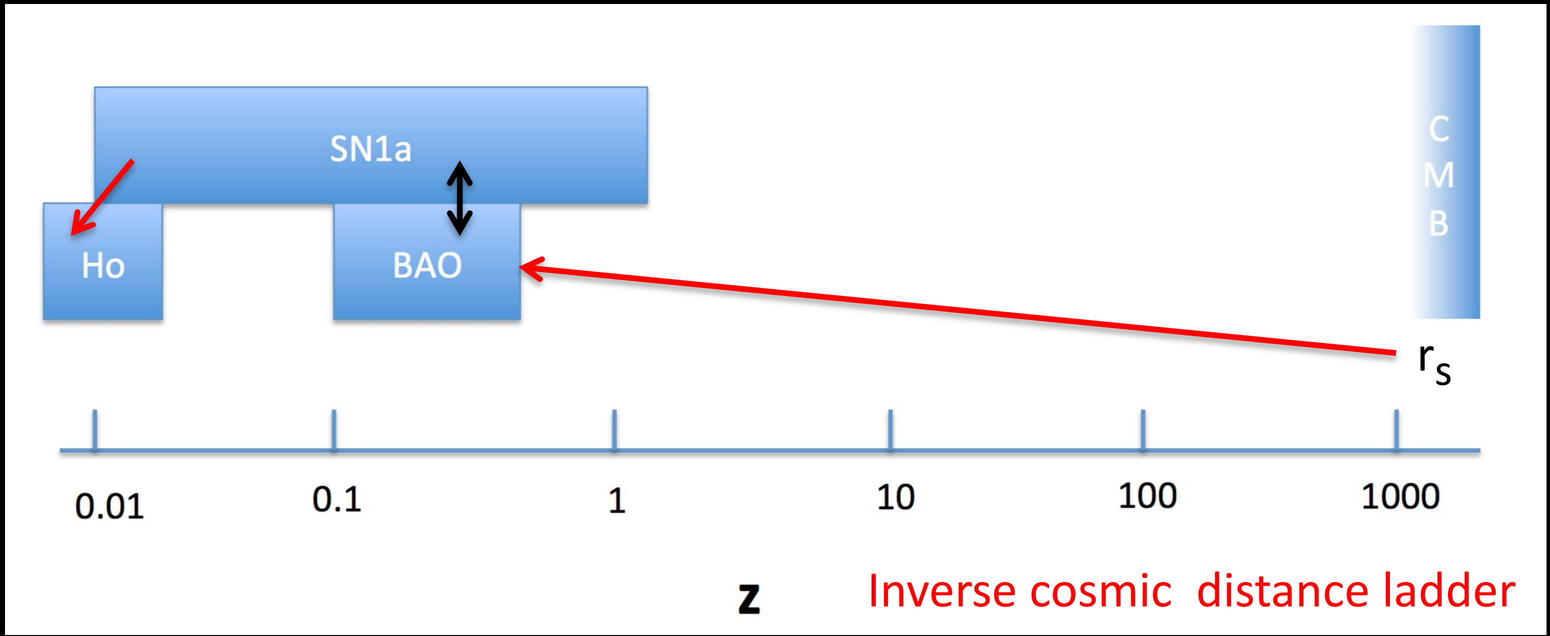
Direct cosmic distance ladder



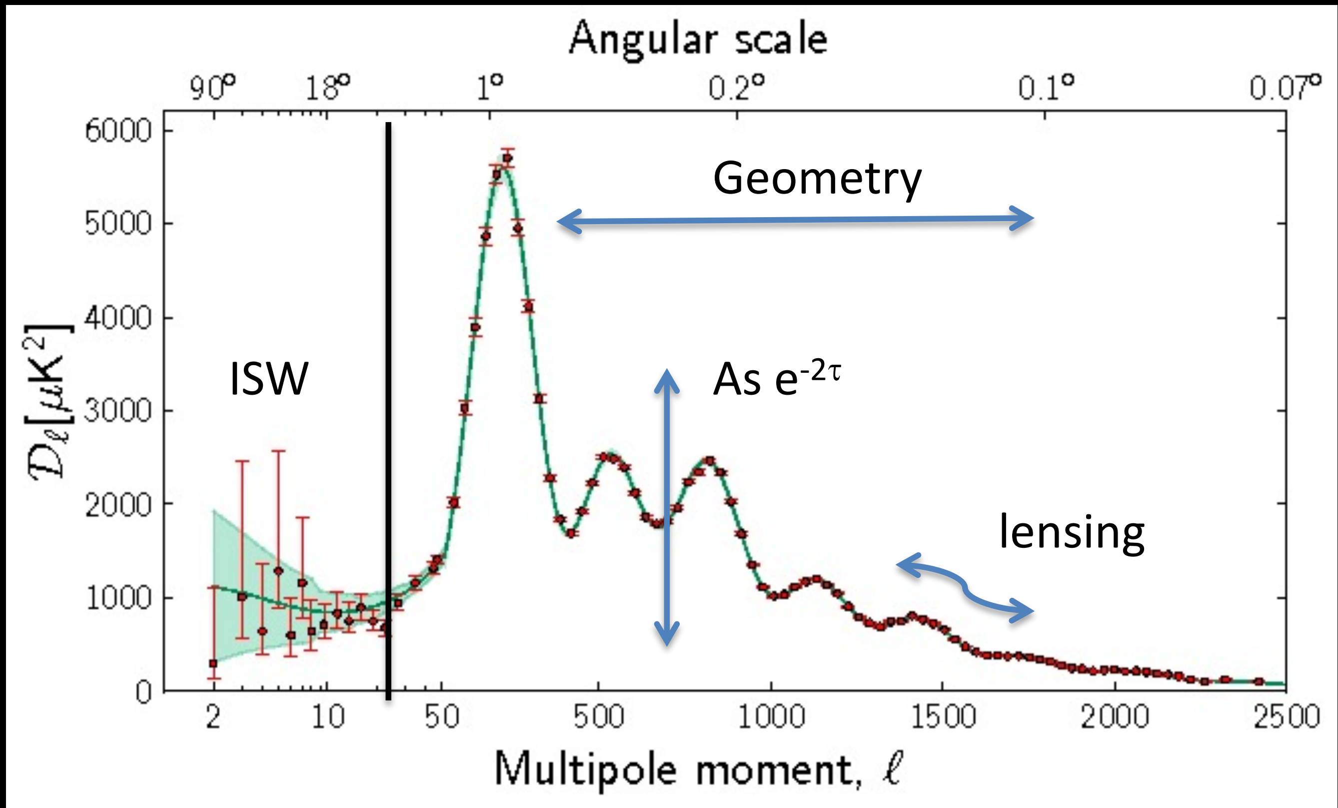
Here is where in ΛCDM or its simple variations the two ladders do not match

r_s from CMB independent from late time physics?

aside Early cosmology constrained (Verde, Bellini, Pigozzo et al 2017)

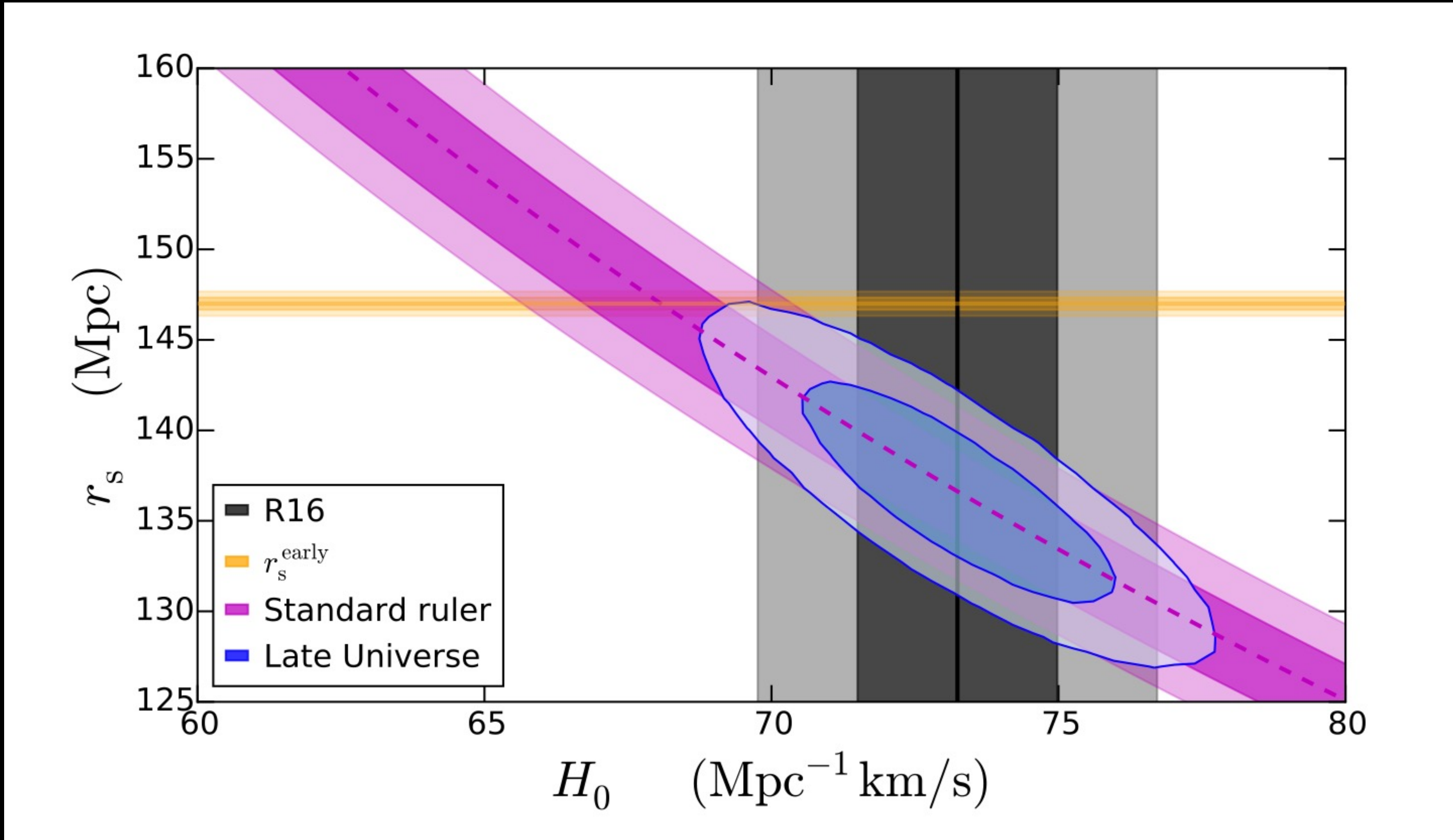
Based on Audren et al 2012

Late time effects in the CMB, combined with early time effects



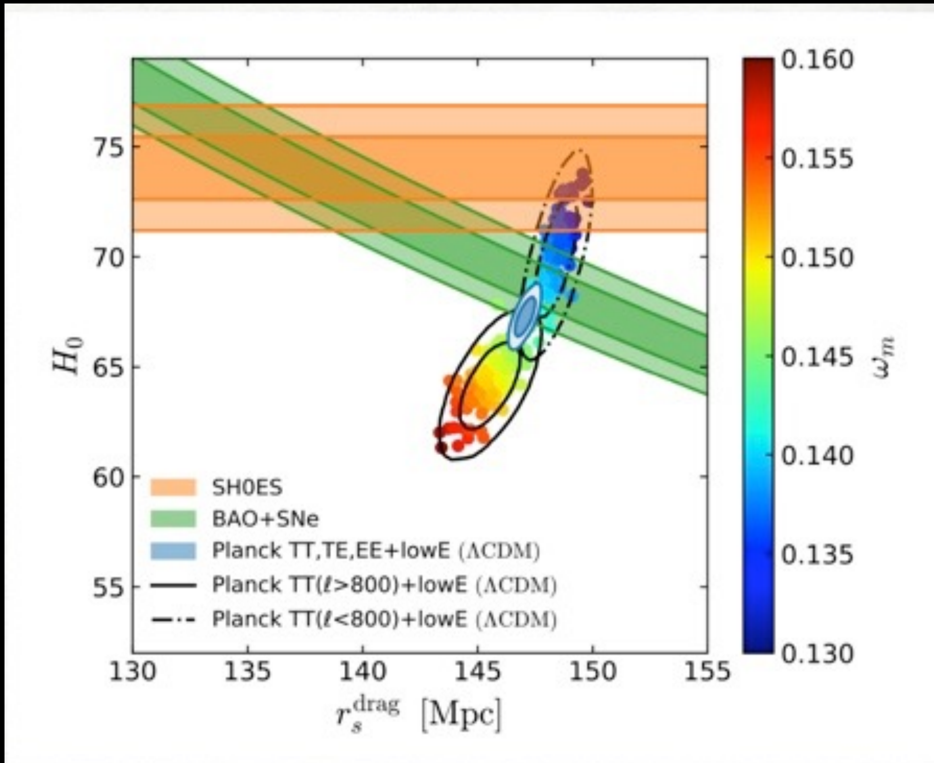
The answer is yes: 147.0pm 0.34 Mpc (assume standard early time physics)

Ho problem can be seen as an rs problem



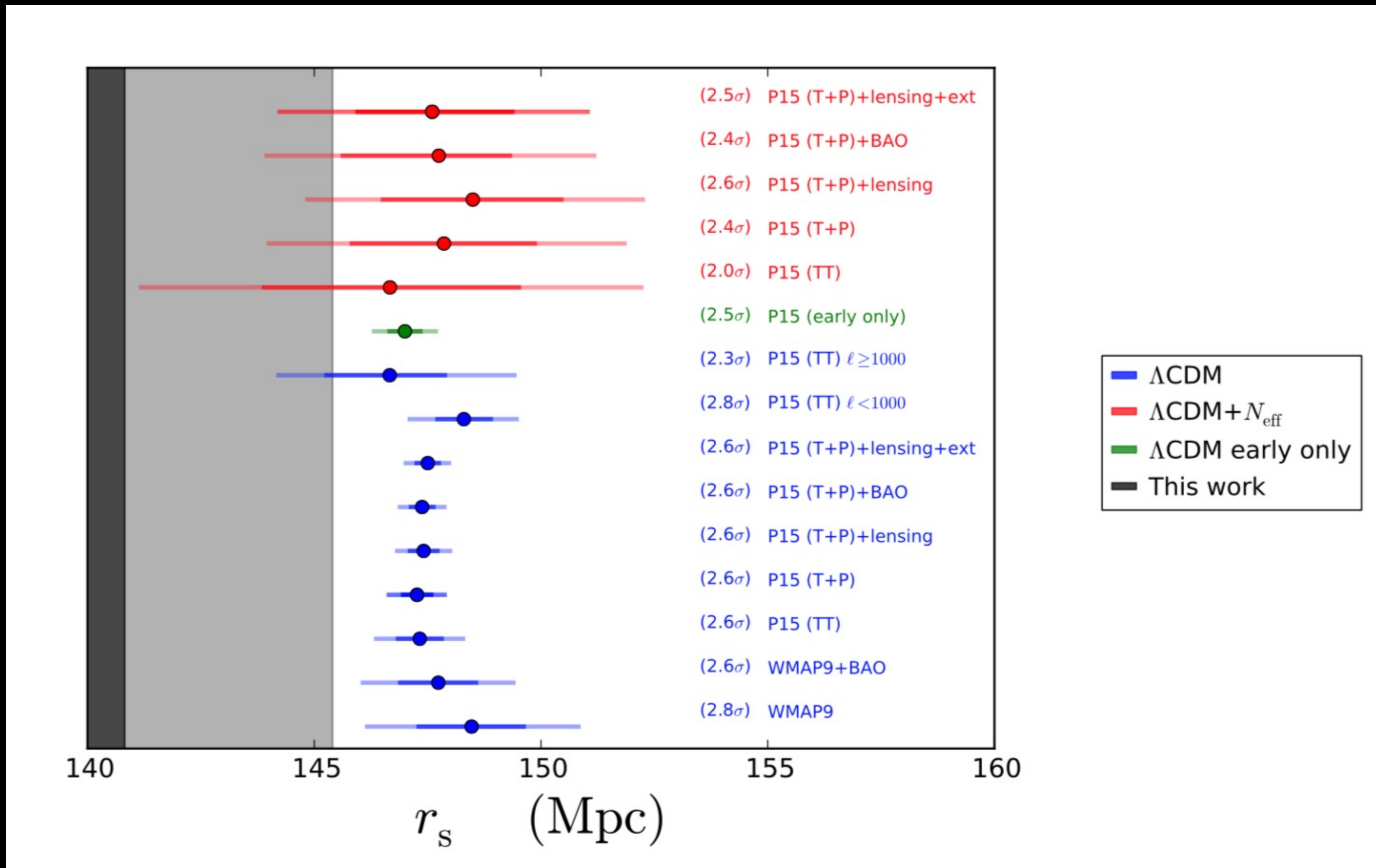
Bernal et al 2016

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



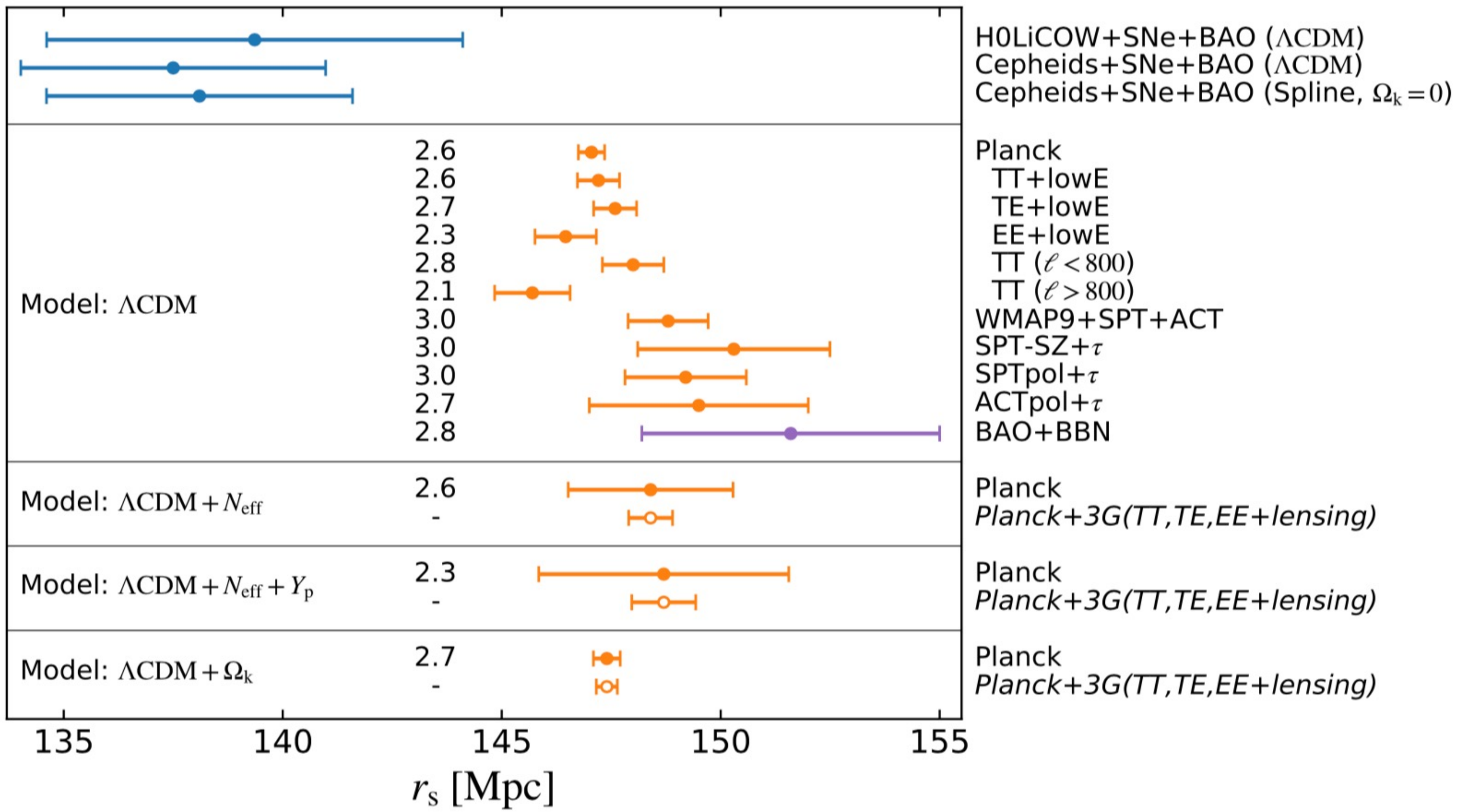
Knox&Milllea 1908.03663

Ho problem can be seen as an rs problem



Bernal et al 2016

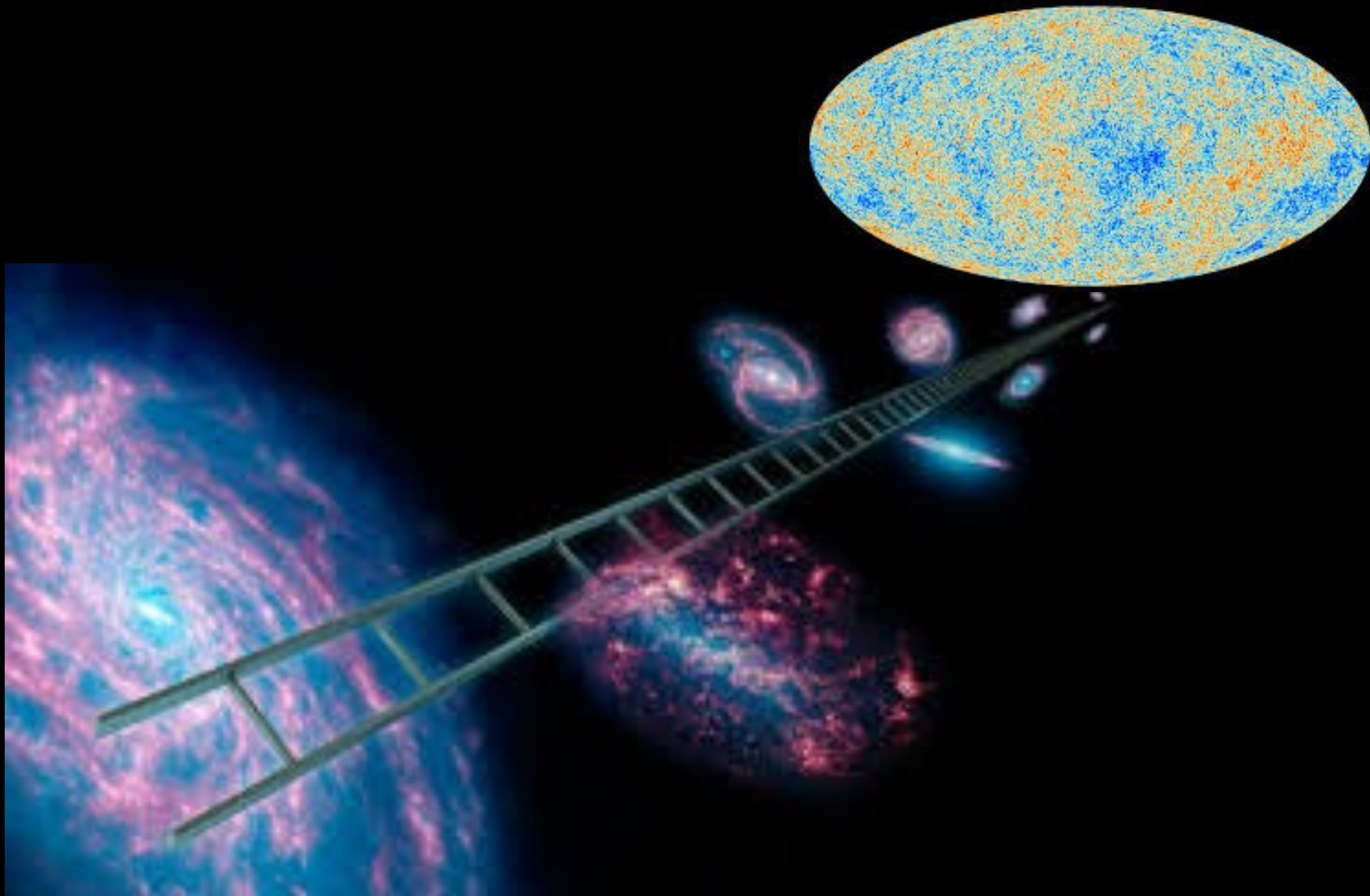
“Sounds discordant”



Ailor et al 2019

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.

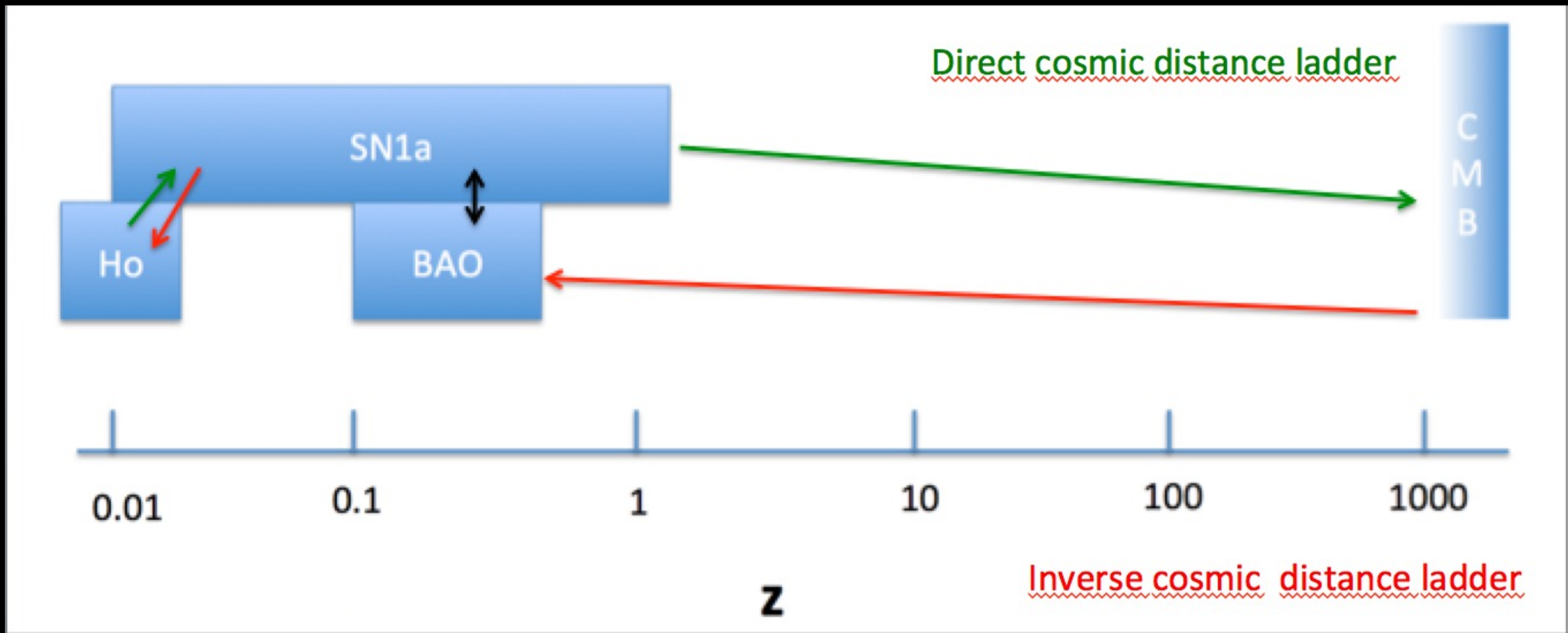
How much of a problem is cosmological-model dependent

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

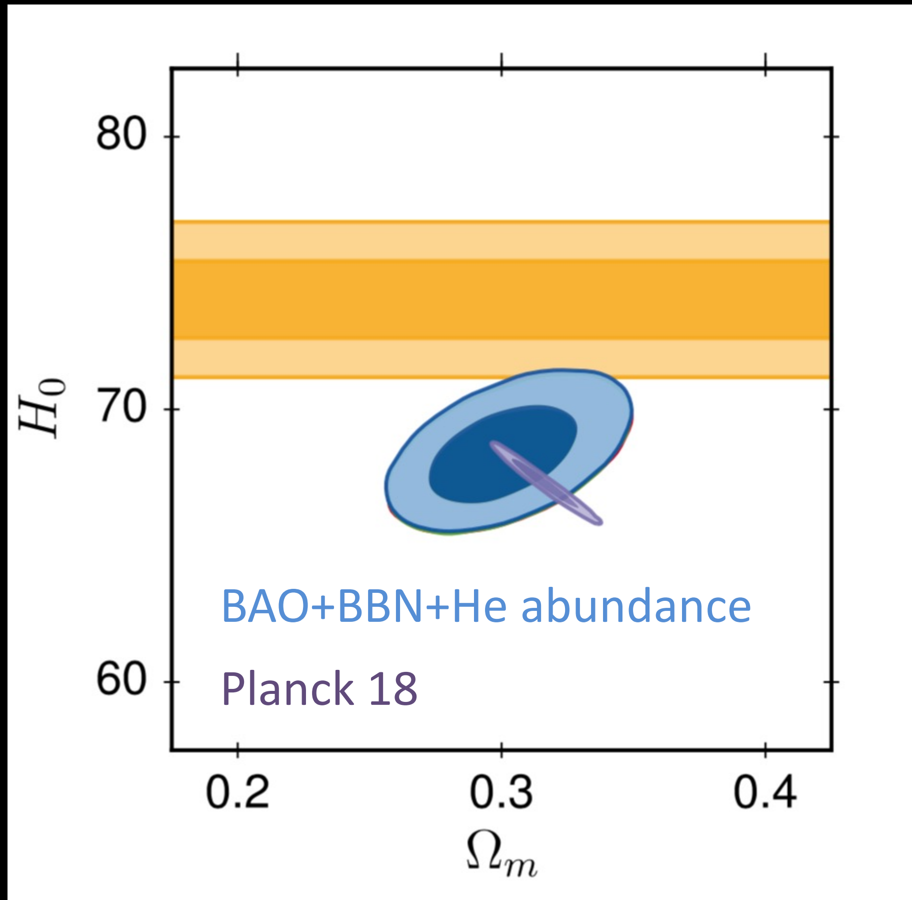
Where is the problem?

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

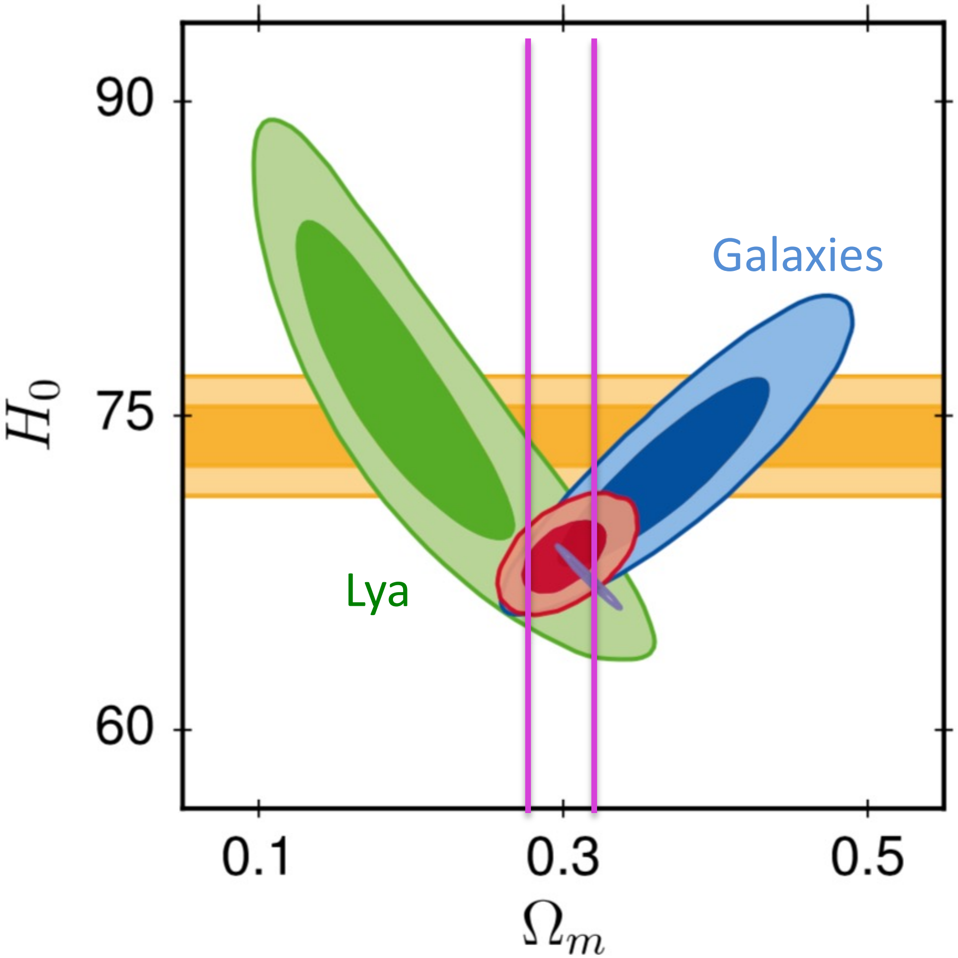
Early: For a while some people put the blame on Planck….

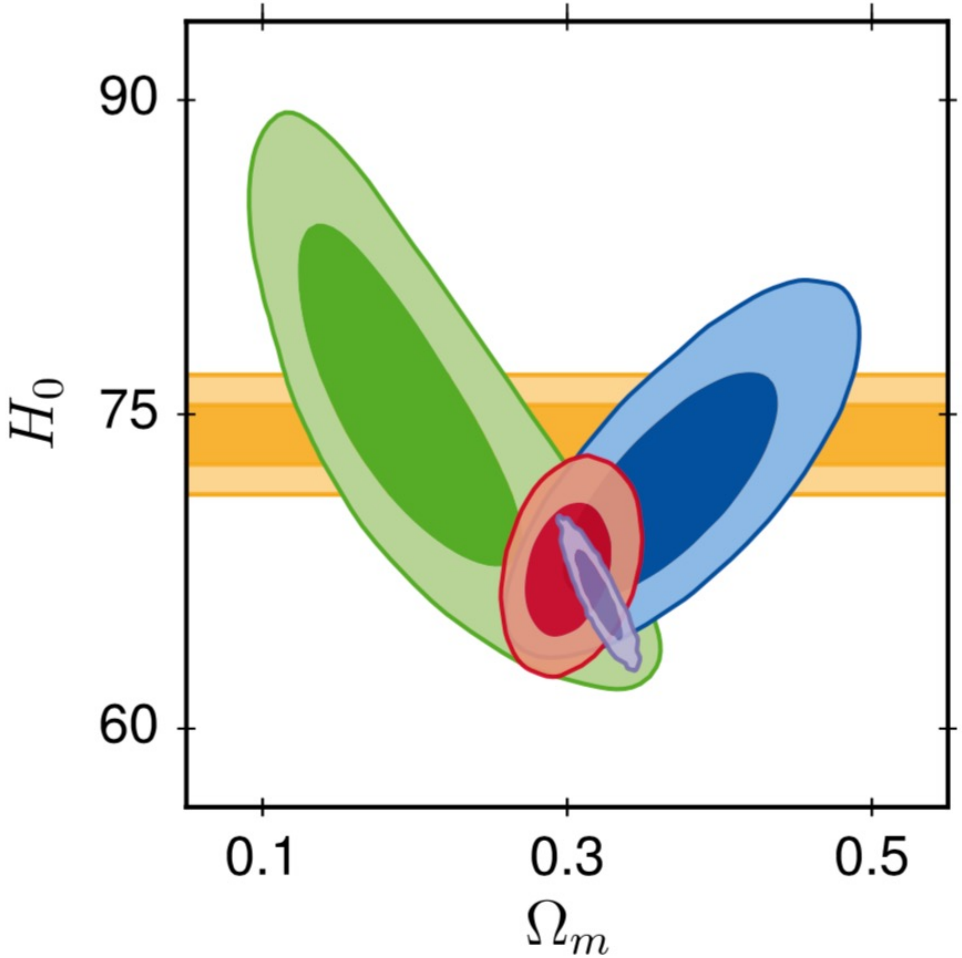
BUT H0(Early) does not budge if you take Planck (or CMB data) out completely (even for Neff-extended models Shonenberg et al 2019)

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



Aside: if not Lya BAO, use SNe



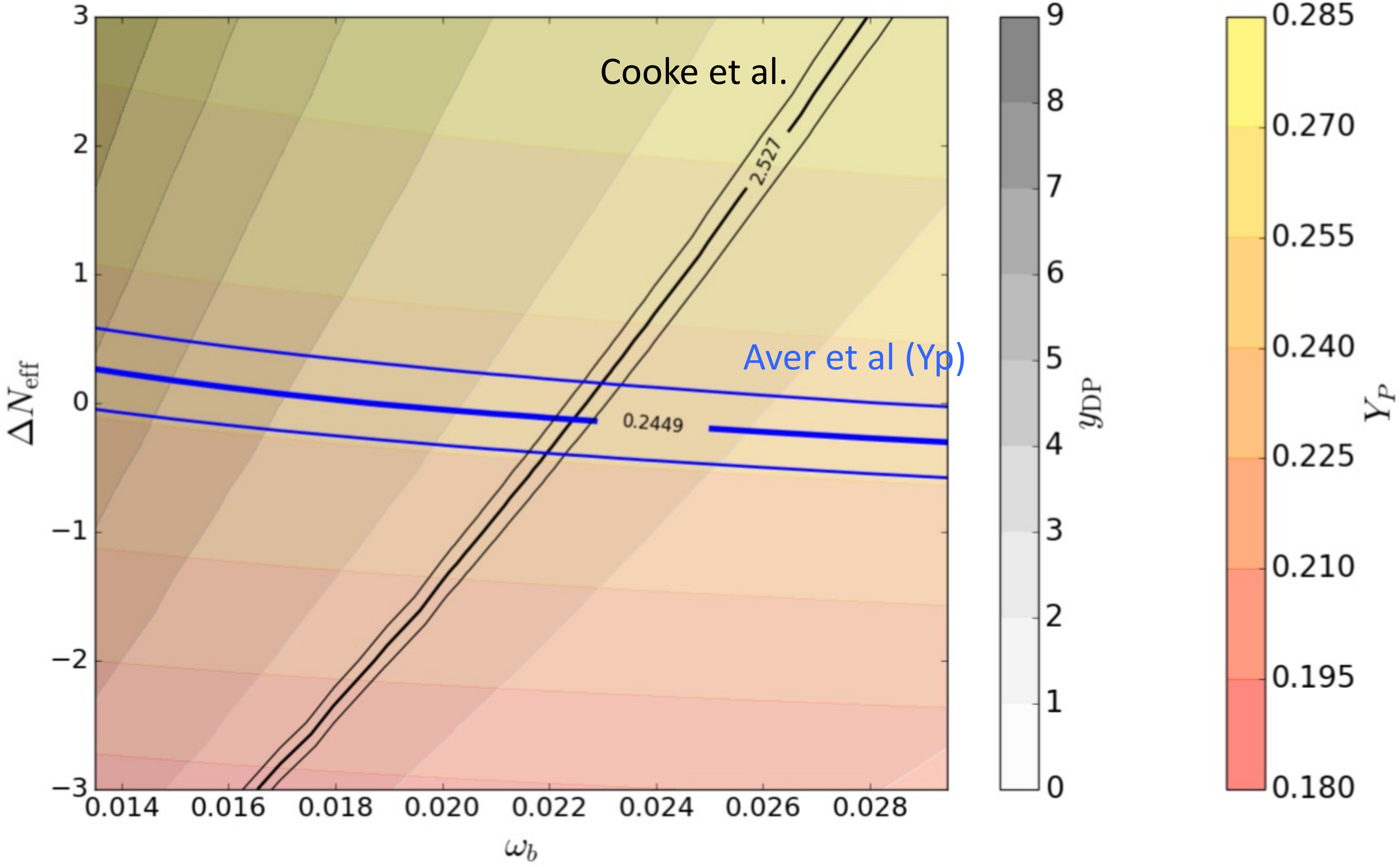


ΛCDM

Shonenberg et al 2019

Neff free

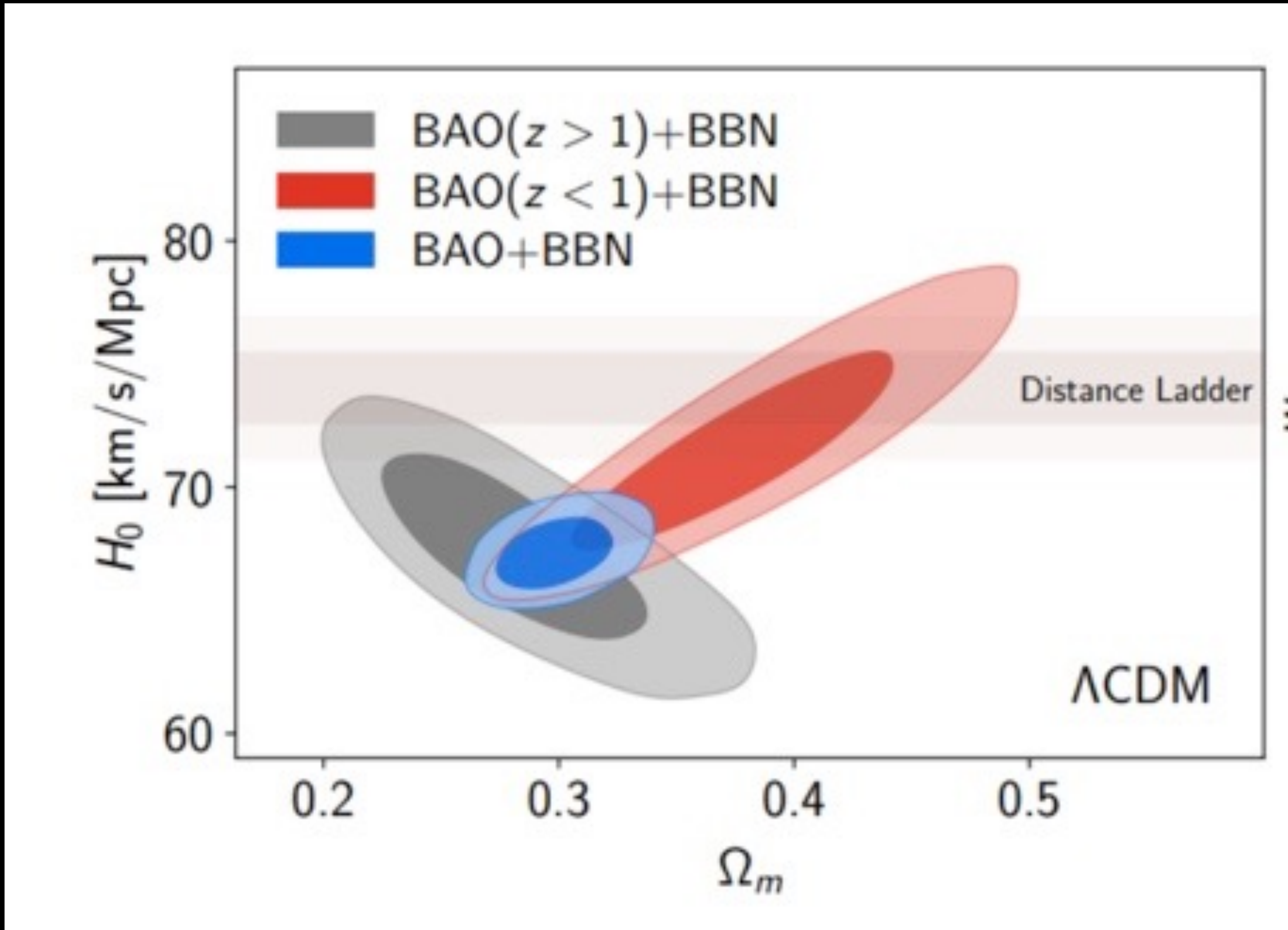
The length of the standard ruler is dictated by early time physics (BBN)



Deuterium

Helium

And again



e-BOSS DR16 2020

Where is the problem?

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

It is not in CMB data

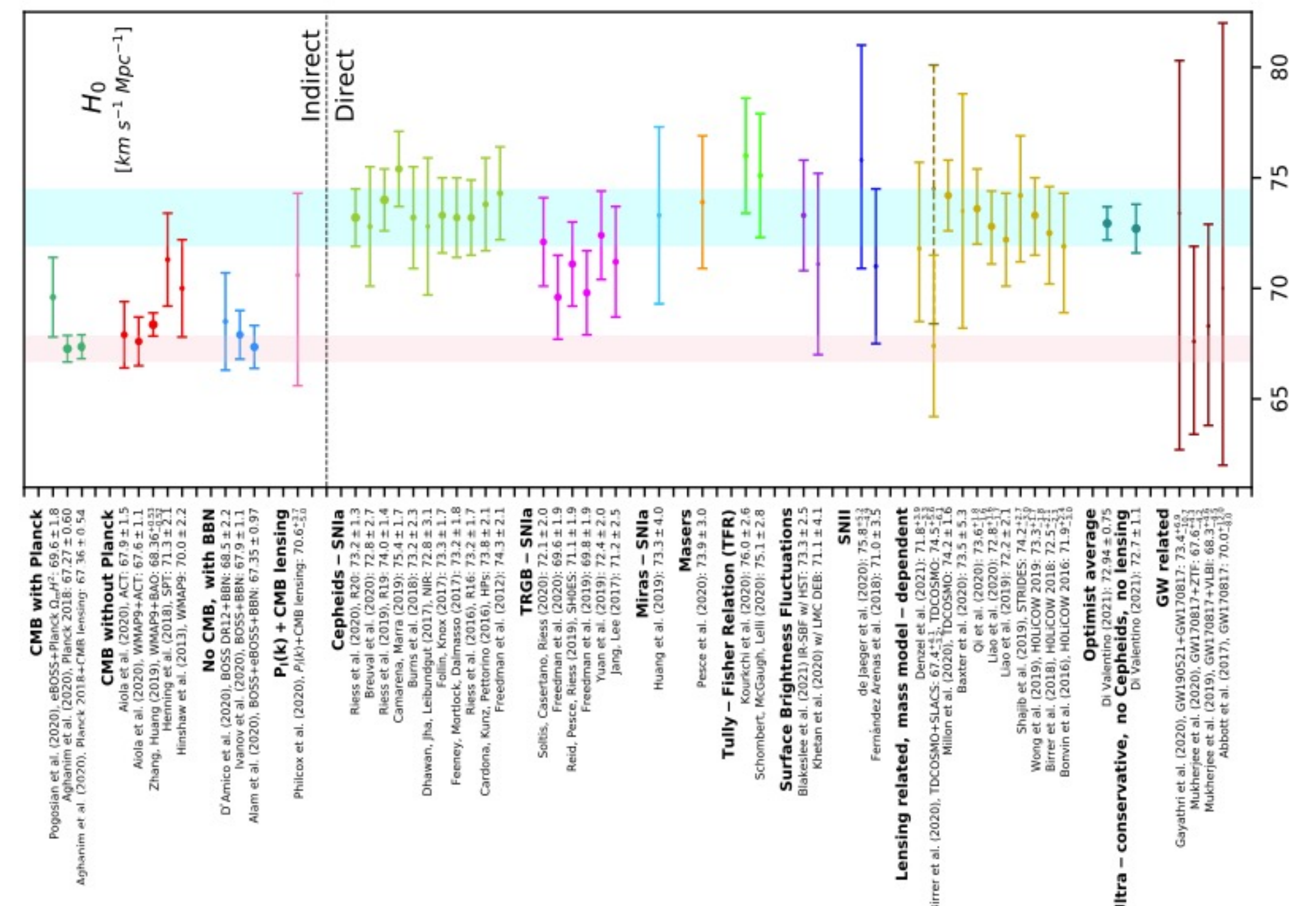
All early-Universe based determinations hoover well below 70km/s/Mpc

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

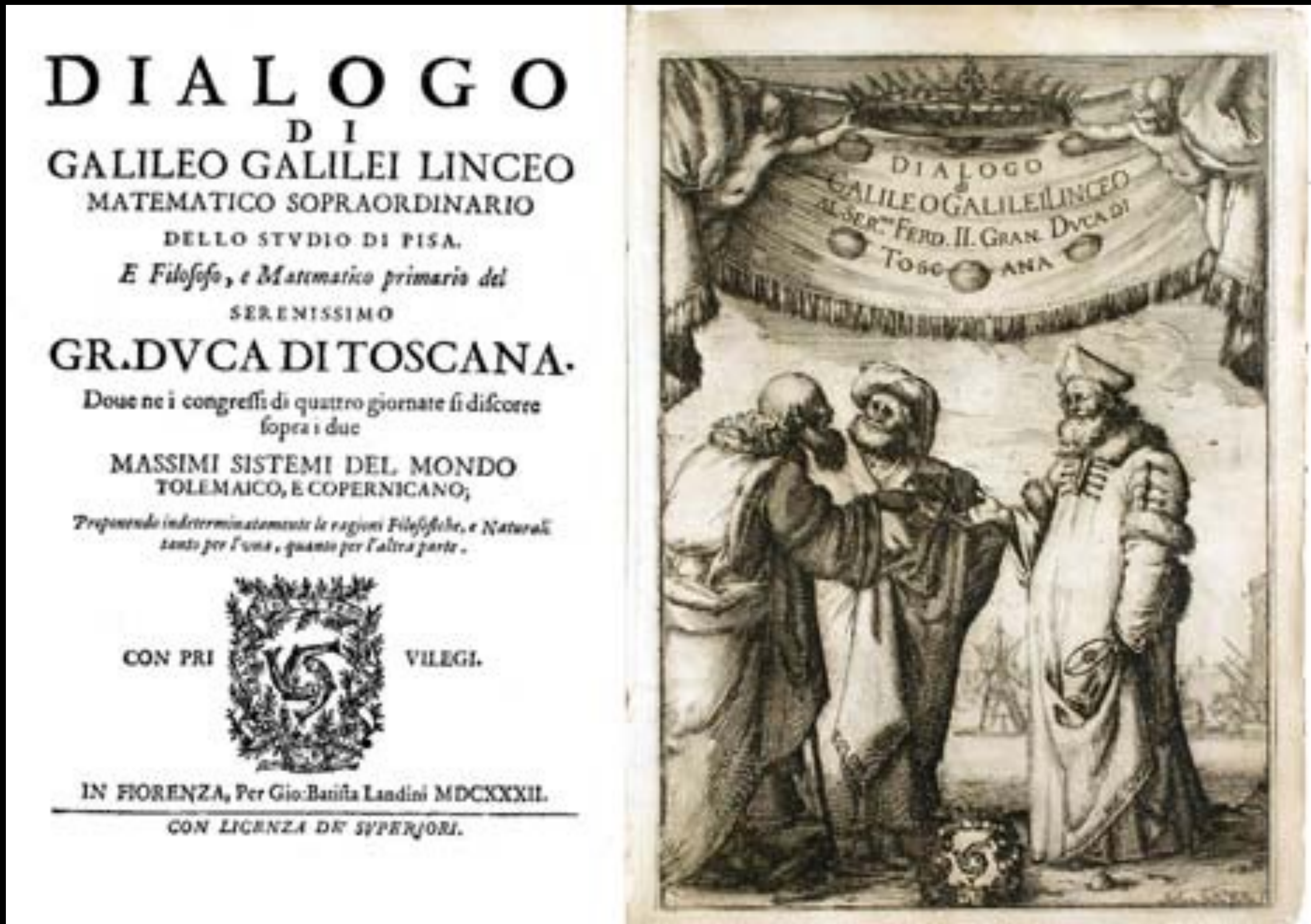
Is it in any specific data set?



Di Valentino et al 21

Where is the problem?

If not in the data then in the model…?


DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filosofo, e Matematico primario del
SERENISSIMO
GR.DVCA DI TOSCANA.
Doue ne i congressi di quattro giornate si discorre
sopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;
Proponendo indeterminatamente le ragioni Filosofiche, e Naturali
tanto per l'una, quanto per l'altra parte.
CON PRI VILEGI.
IN FIORENZA, Per Gio: Batista Landini MDCXXXII.
CON LICENZA DE' SVPERIORI.

Where is the problem?

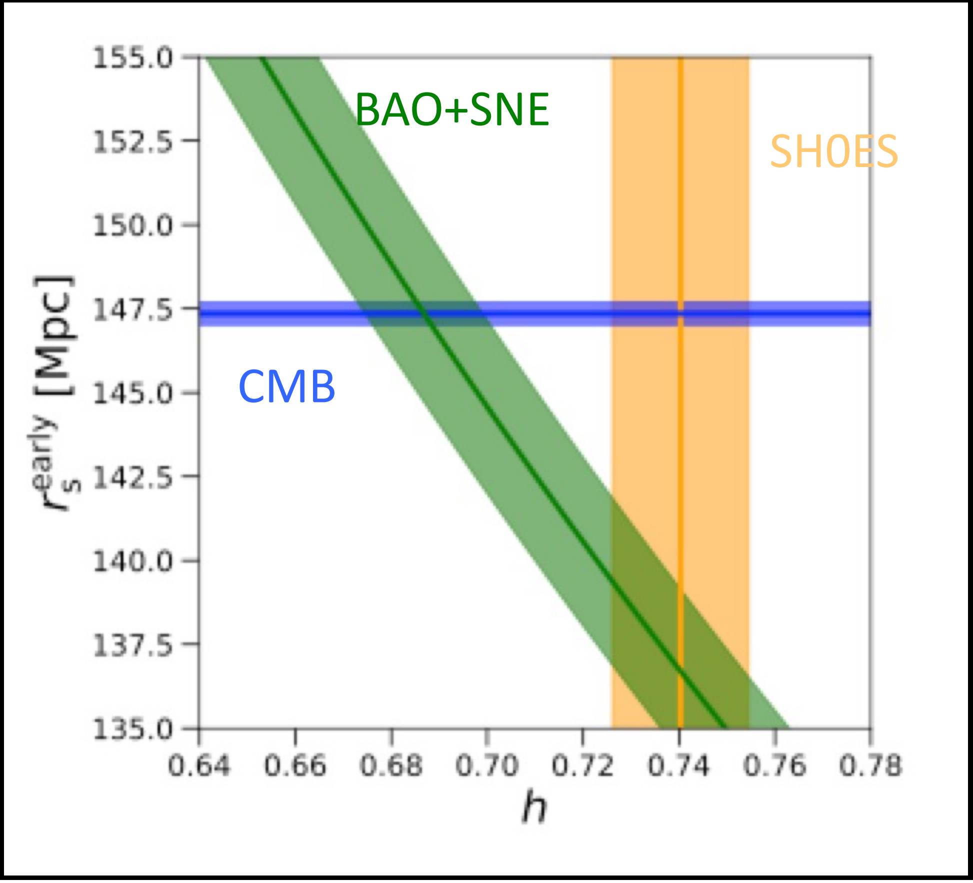
If not in the data then in the model…?

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

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

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

z ~0 measurements "do not do" assumptions about cosmology



Shall we look
pre or after recombination?

Fig.J.L. Bernal

pre-recombination solutions

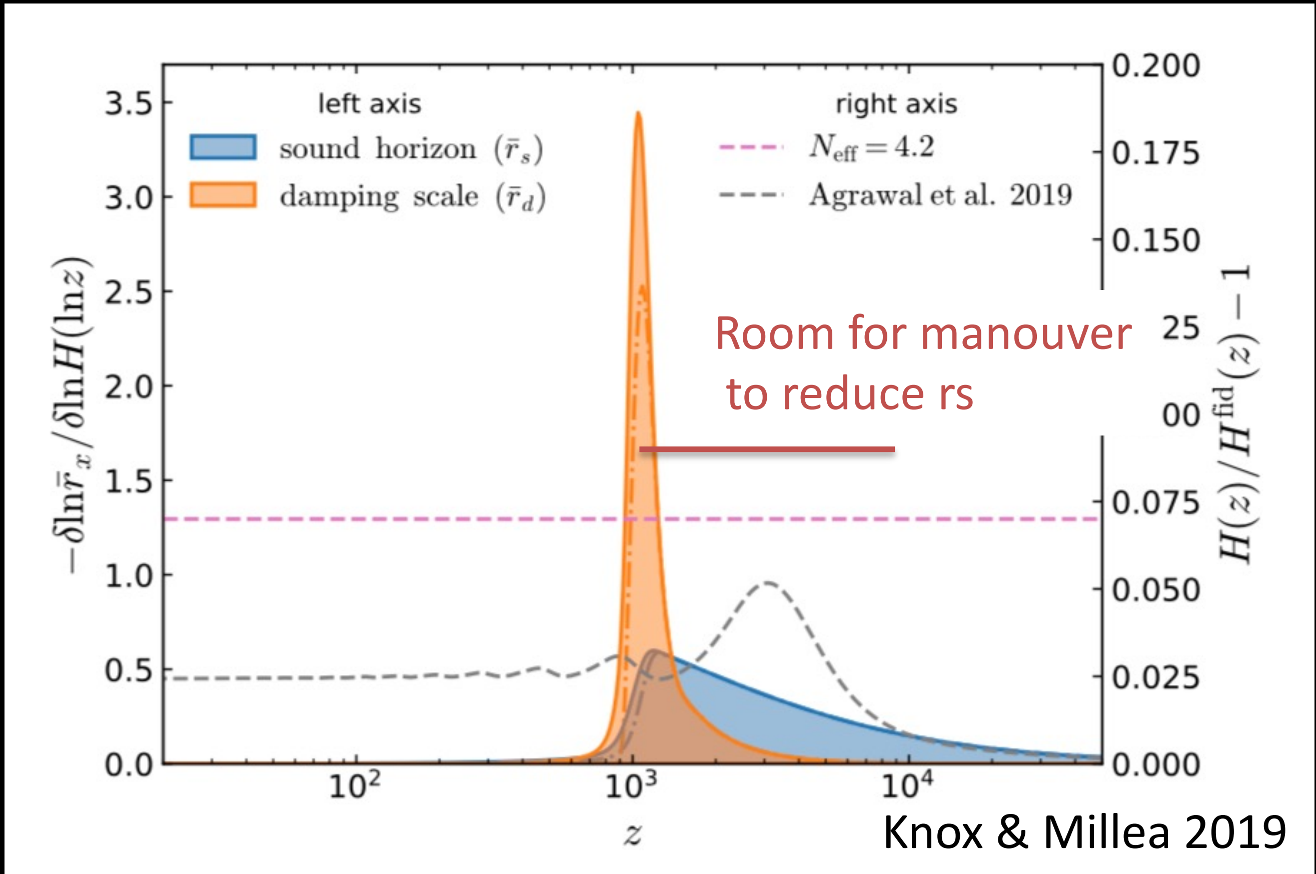
Modify the model right where we most like it

Decrease the sound horizon, by 7%

$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

without wreaking havoc on damping tail… and everything else

A tall order



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

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

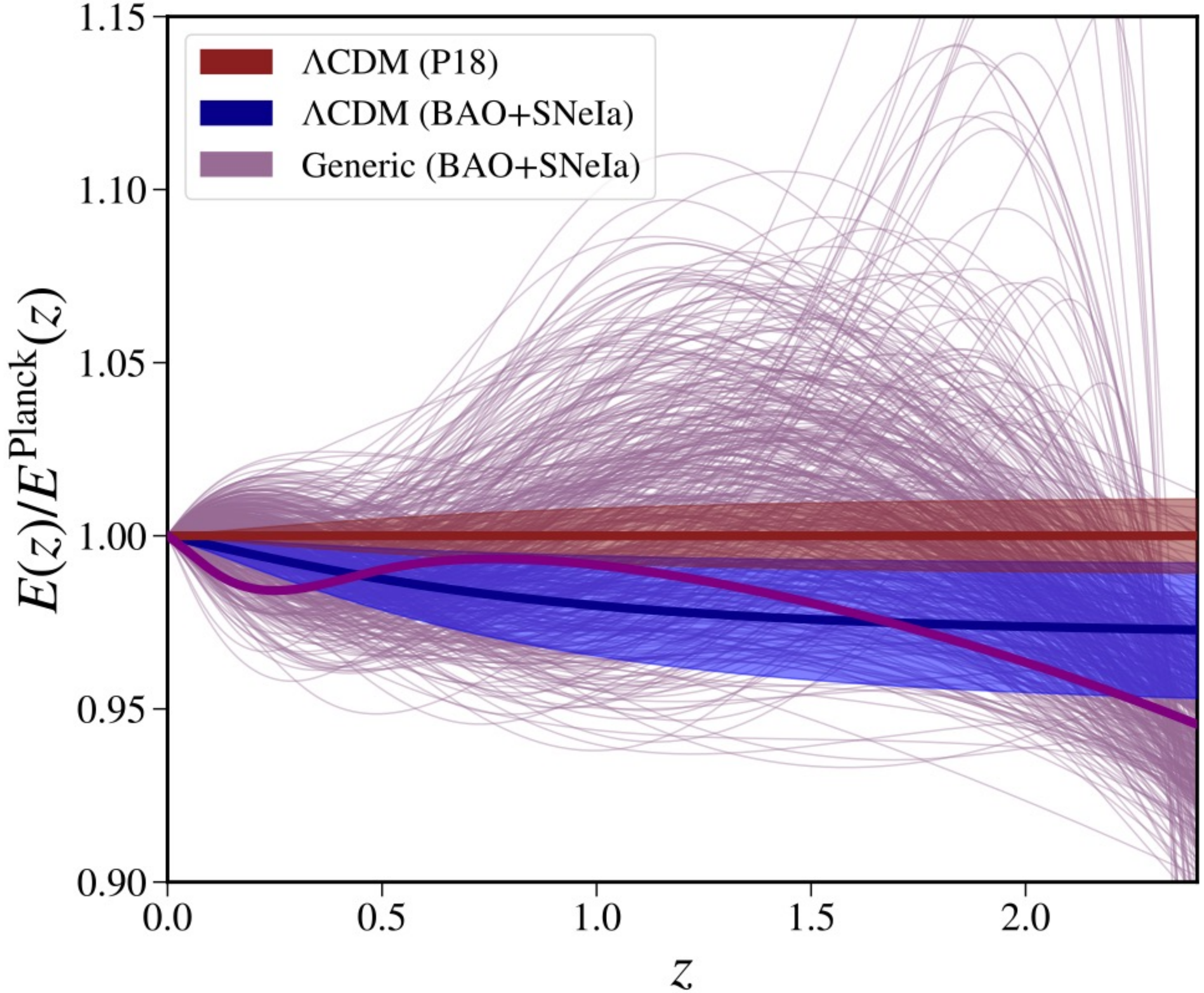
BAO+SNe

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

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

Generic reconstruction

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



Bernal et al. 2102.05066

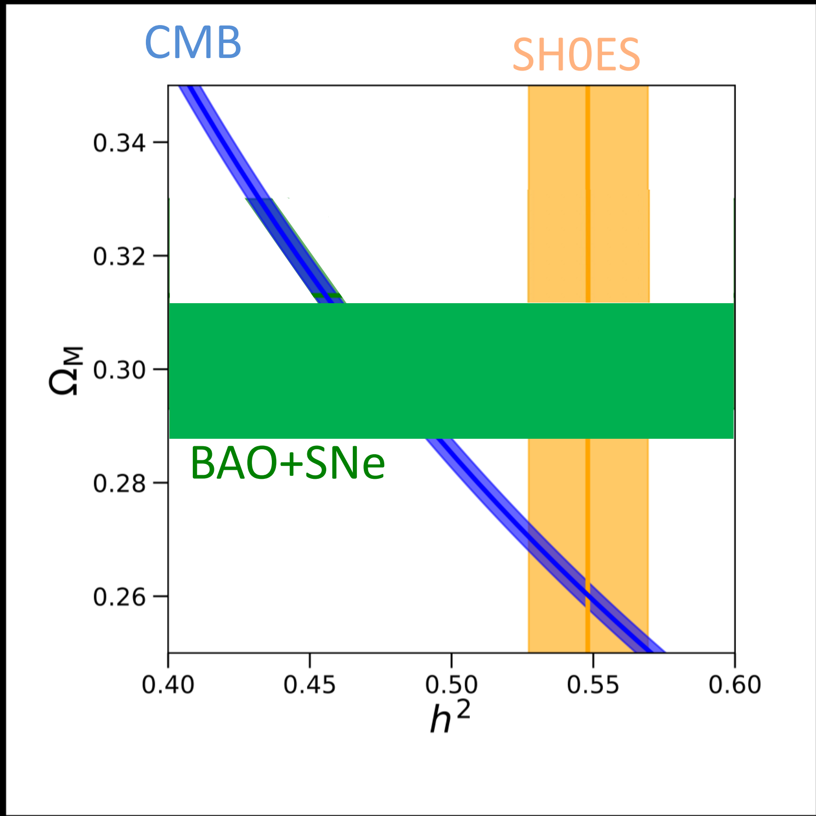
Beyond H0

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

It is a Ω_m problem too

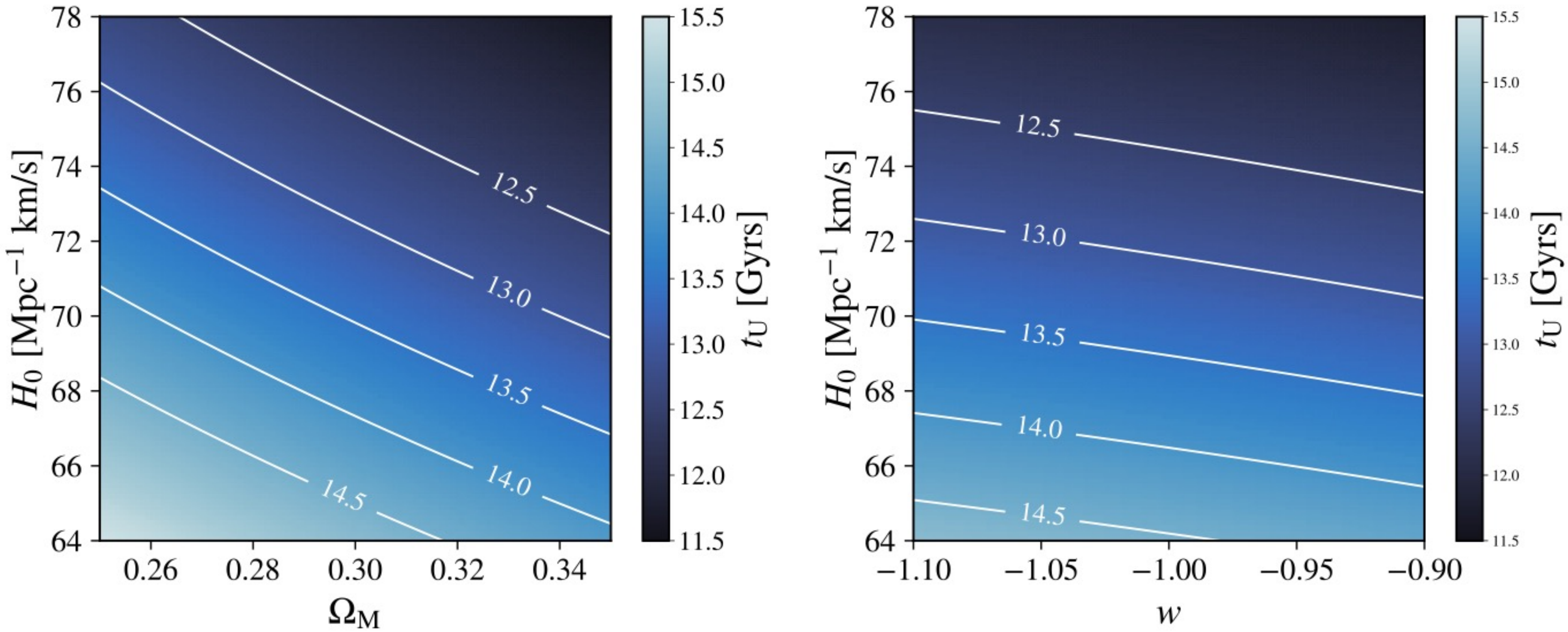
...And an age problem too

ΛCDM assumed



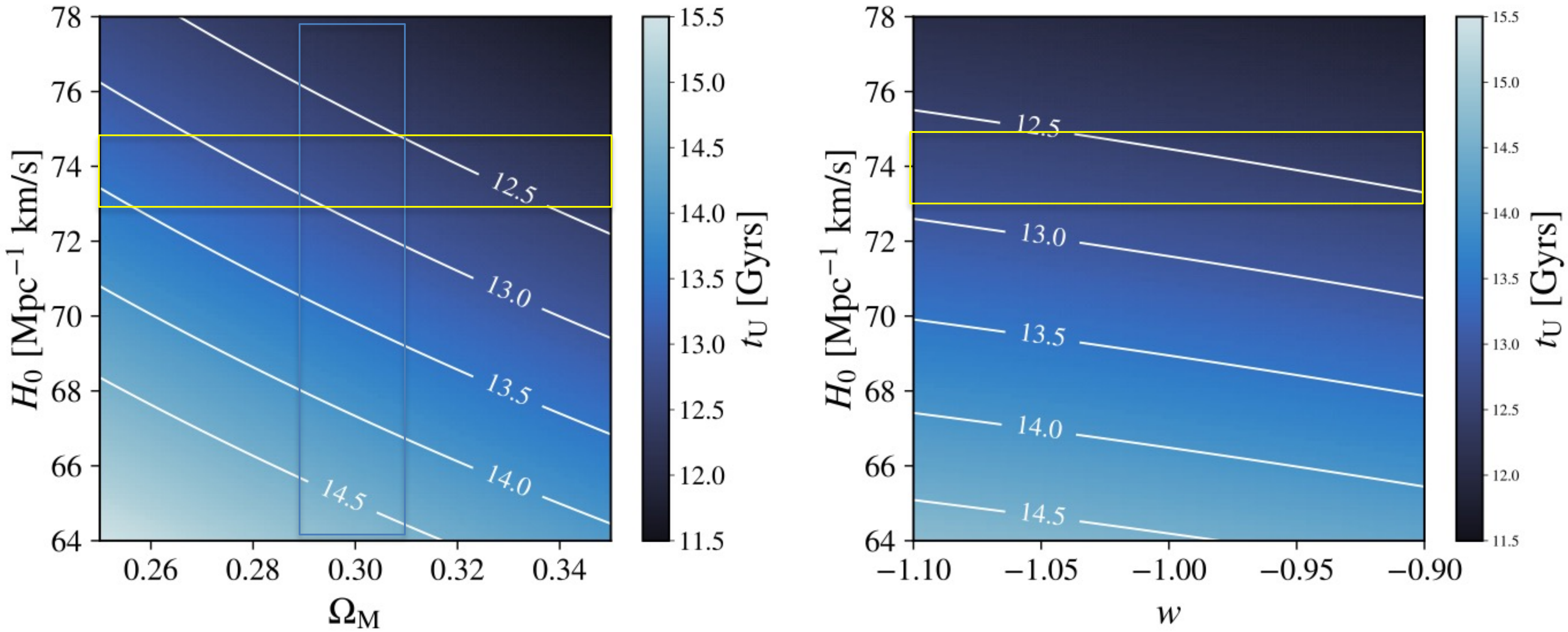
Bernal et al . 2102.05066

Beyond H_0



78
76
74
72
70
68
66
64
H_0 [Mpc^{-1} km/s]
0.26
0.28
0.30
0.32
0.34
Ω_M
12.5
13.0
13.5
14.0
14.5
15.5
15.0
14.5
14.0
13.5
13.0
12.5
12.0
11.5
t_U [Gyrs]
−1.10
−1.05
−1.00
−0.95
−0.90
w

Beyond H0



H_0 [Mpc^{-1} km/s]
Ω_M
t_U [Gyrs]
12.5
13.0
13.5
14.0
14.5
78
76
74
72
70
68
66
64
0.26
0.28
0.30
0.32
0.34
15.5
15.0
14.5
14.0
13.5
13.0
12.5
12.0
11.5
w
−1.10
−1.05
−1.00
−0.95
−0.90

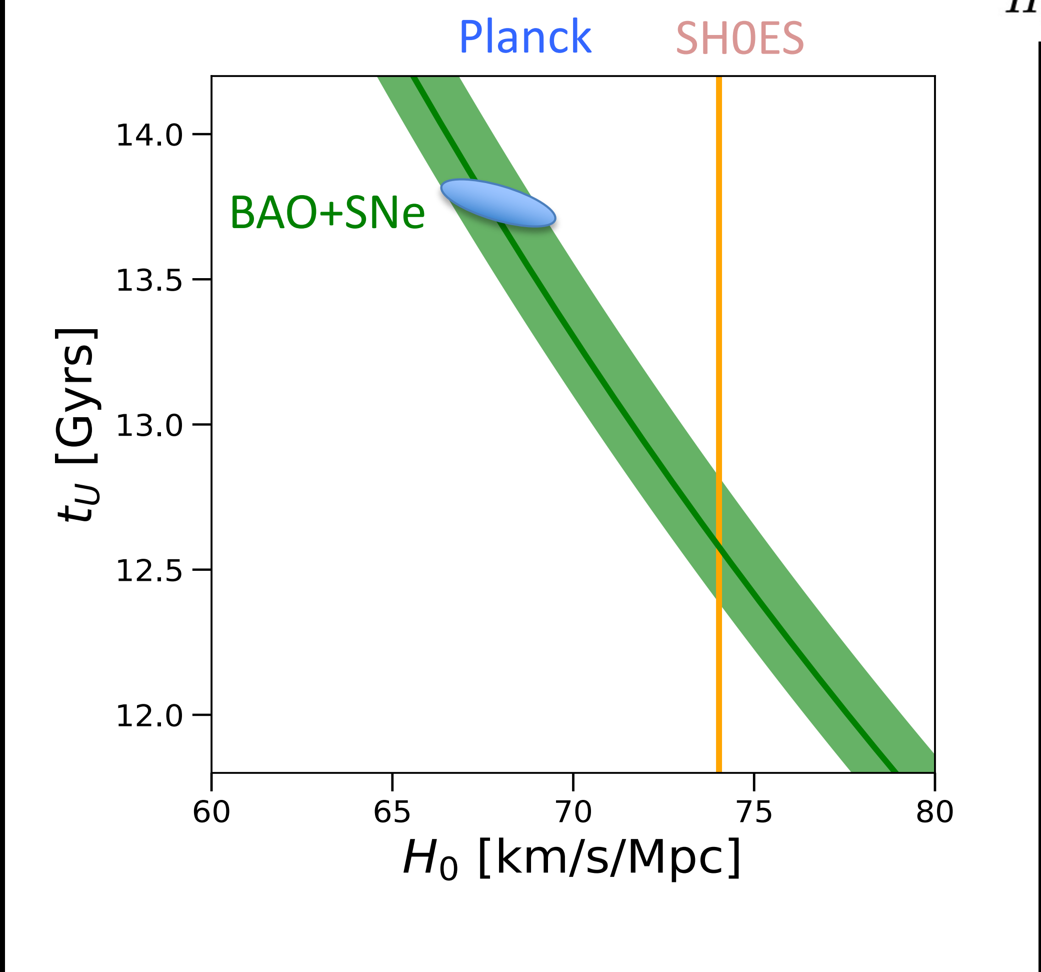
How old is the Universe anyway?

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

Early : high t_0

Late: low t_0

?



D. Valcin

Stellar ages: a tool to measure the expansion rate

- Absolute stellar ages (clocks) at z=0 provide an estimate of the current expansion rate.

$$H_0 = \frac{A}{t}\int_0^{z_t} \frac{1}{1+z}\left[\Omega_{m,0}(1+z)^3 + (1-\Omega_{m,0})(1+z)^{3(1+w)}\right]^{-1/2} dz$$

Relies on knowing other background cosmological parameters
(or the expansion history "shape")

"The local and distant Universe, stellar ages and H0"
JCAP 2019 ,Jimenez, Cimatti, Verde, Moresco, Wandelt

Absolute stellar ages at z=0 provide an estimate of the current expansion rate.

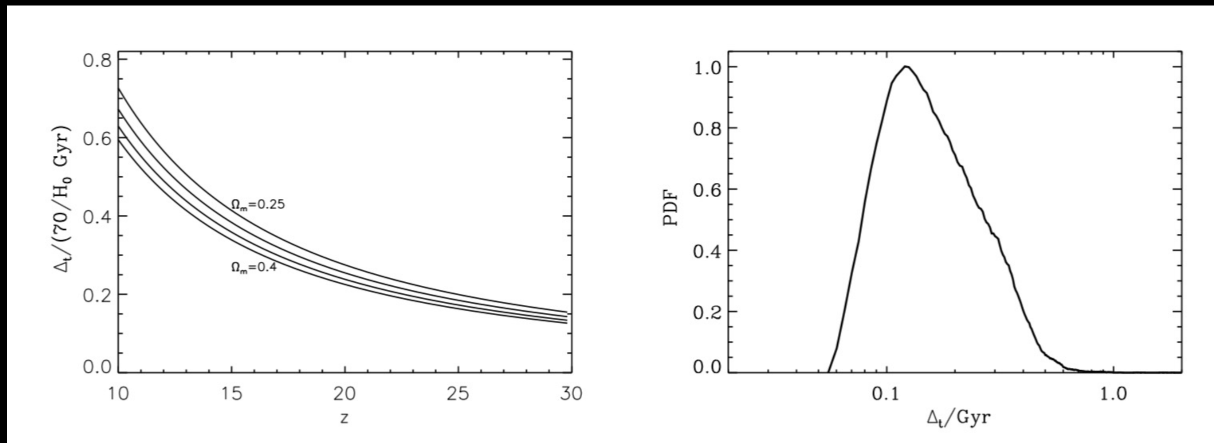
$$H_0 = \frac{A}{t}\int_0^{z_t} \frac{1}{1+z}\left[\Omega_{m,0}(1+z)^3 + (1-\Omega_{m,0})(1+z)^{3(1+w)}\right]^{-1/2} dz$$

Relies on knowing other background cosmological parameters (or the expansion history “shape”)

Use zf=11 but using zf=8 does not change the results

Need also a way to connect t to t_U

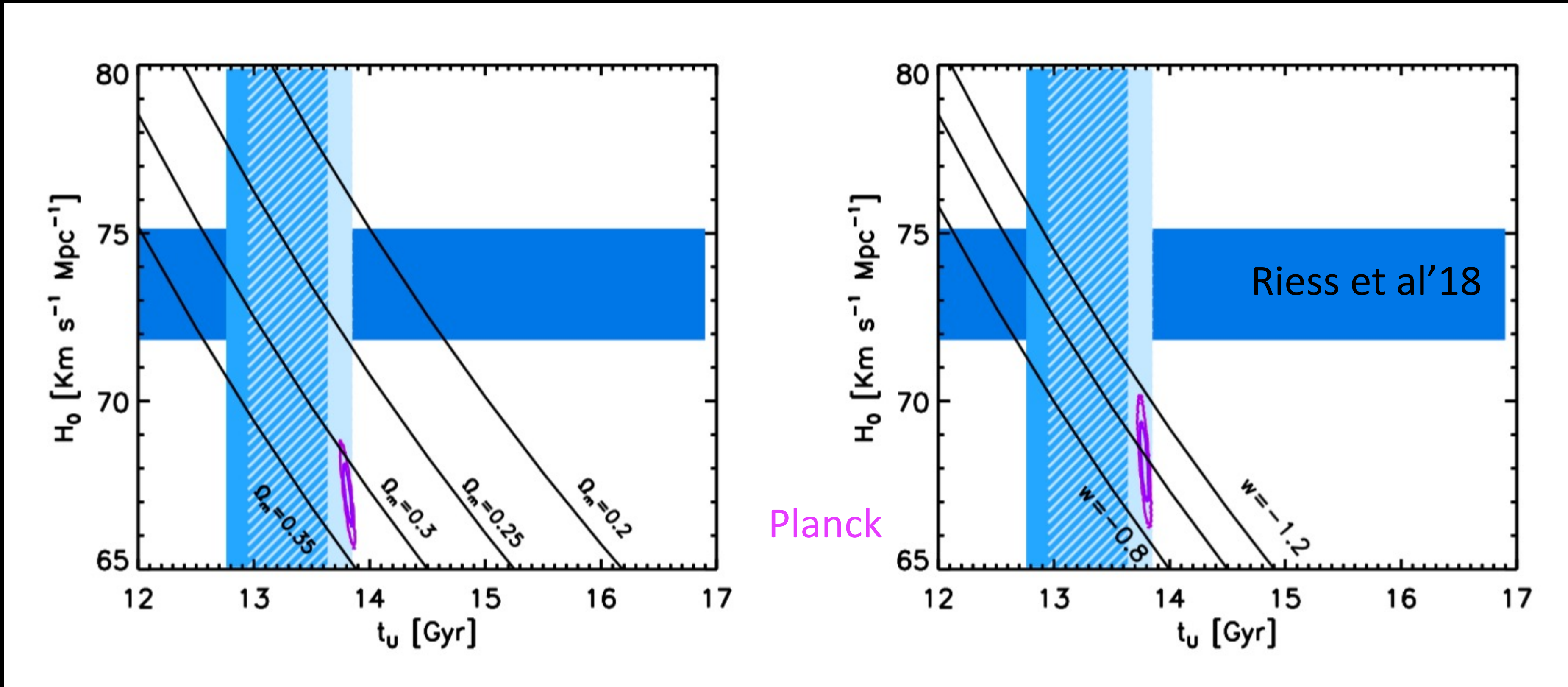
(the second step is not needed for H_0 but for comparing with t_U from CMB)



“The local and distant Universe, stellar ages and H0”
JCAP 2019 ,Jimenez, Cimatti, Verde, Moresco, Wandelt

Age of oldest stars observed locally --> age of the Universe

Proof of principle:



very-low-metallicity stars

HD140283 (Bond et al 2013)

J18082002-5104378 A (Schlaufman et al 2018)

O'Malley et al '18 22 GC

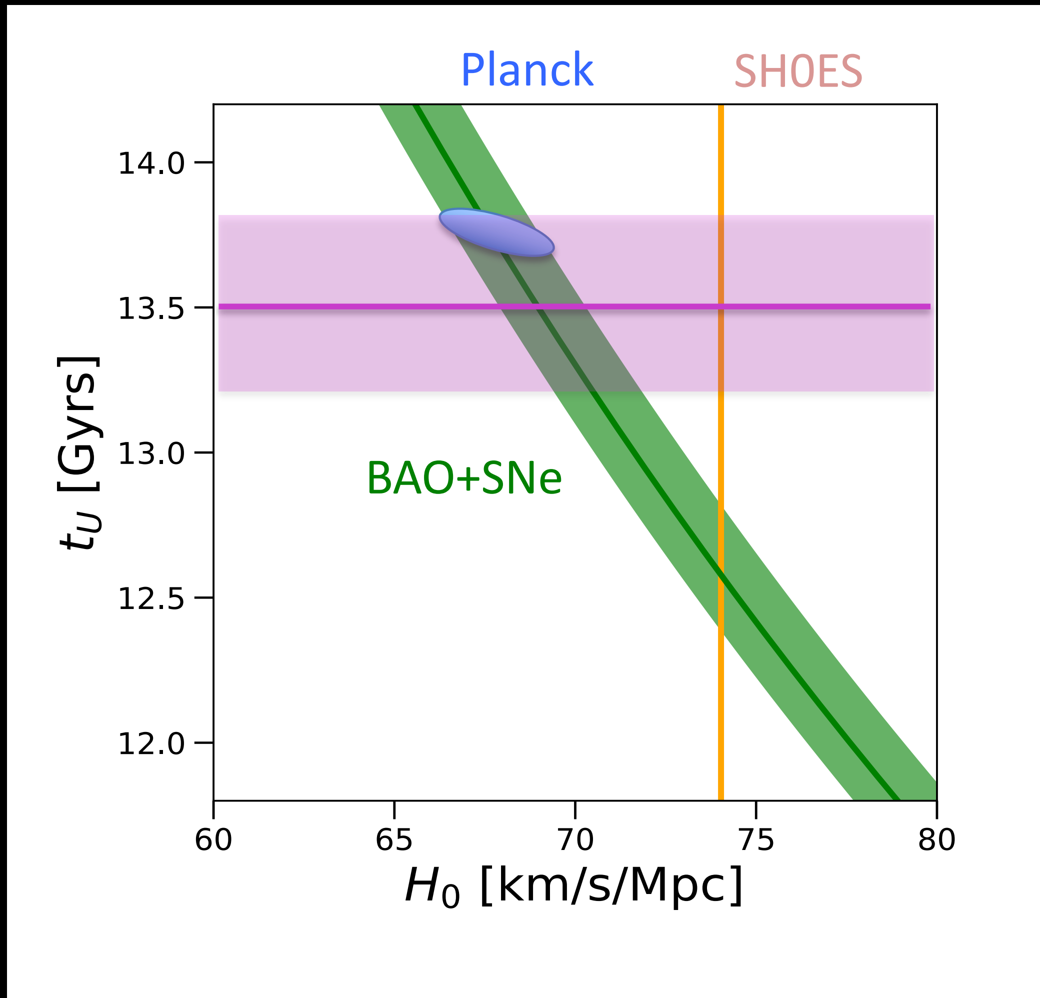
Jimenez et al 2019

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

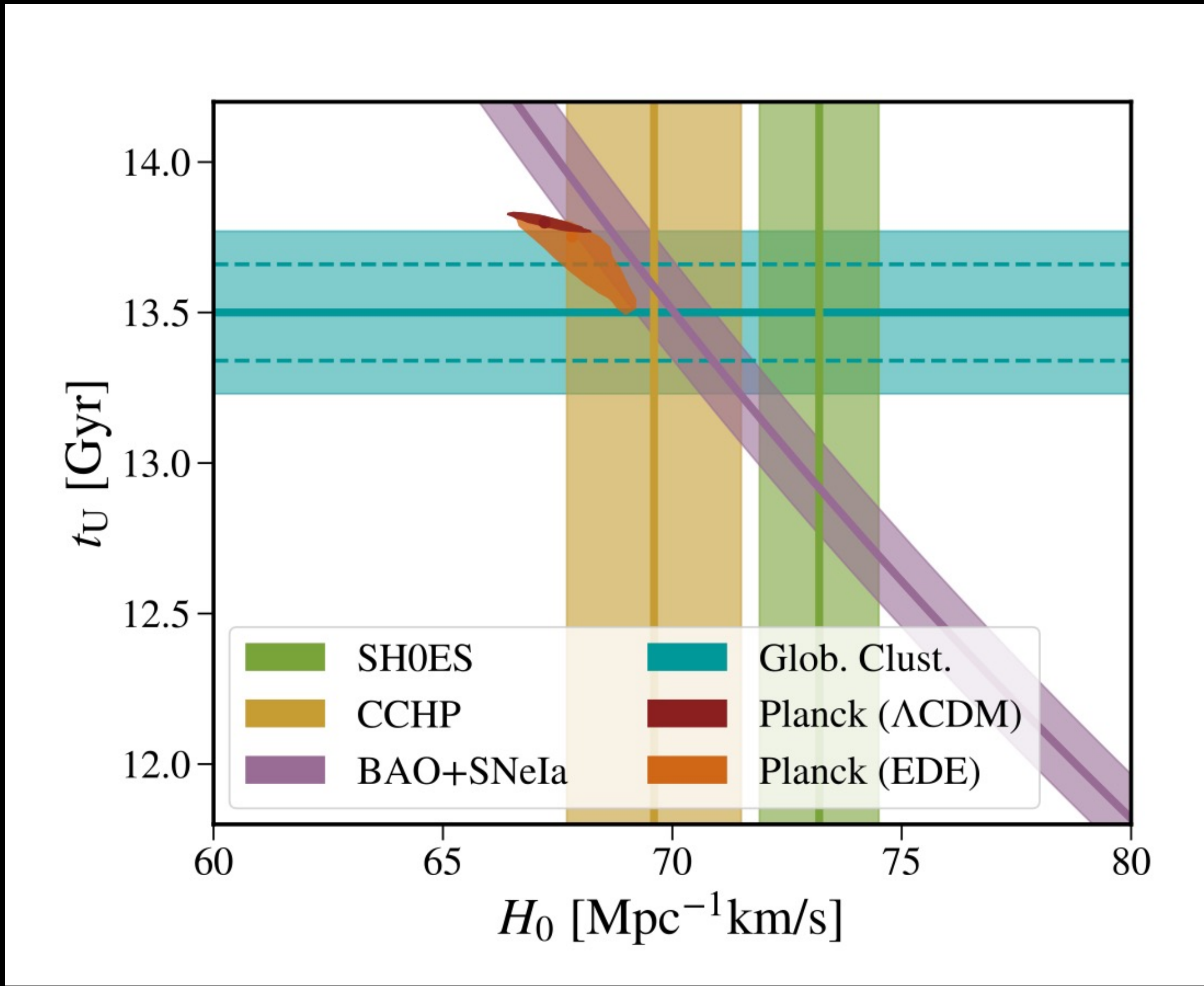
Valcin et al. 2102.04486

Looking for Cinderella….

Looking for Cinderella

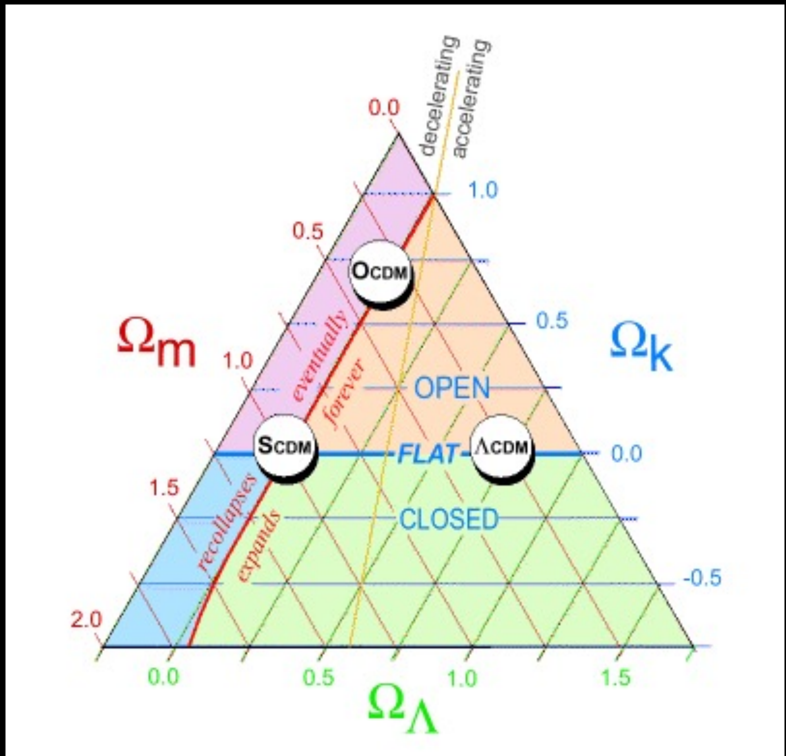
- The bad: $w<-1$, decaying dark matter,
- The ugly: neutrino interactions at early time, early dark energy-ish
- The good:….?

Looking for Cinderella….



Bernal et al 2102.05066

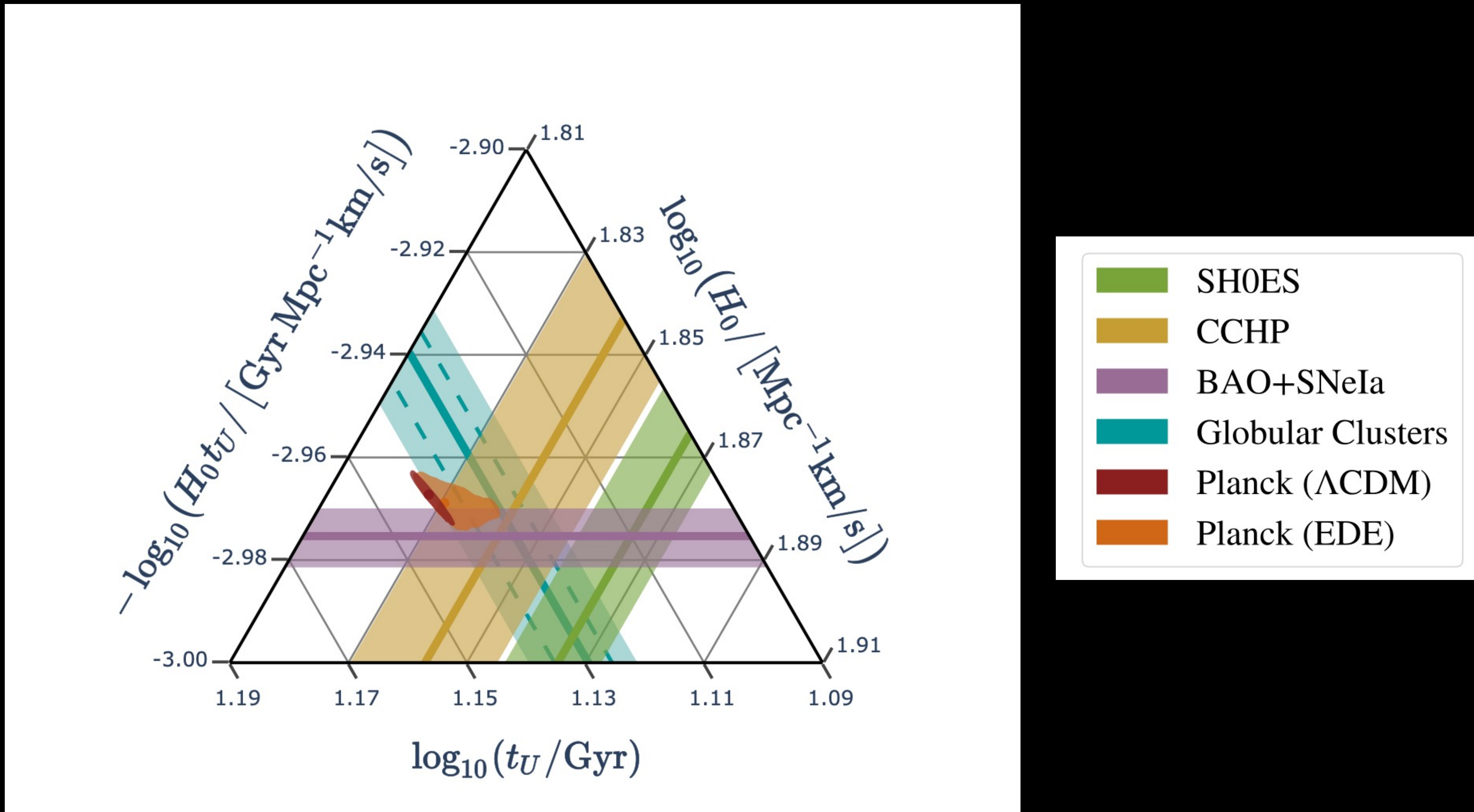
The original Cosmic triangle



Science Bahcall et al 1999

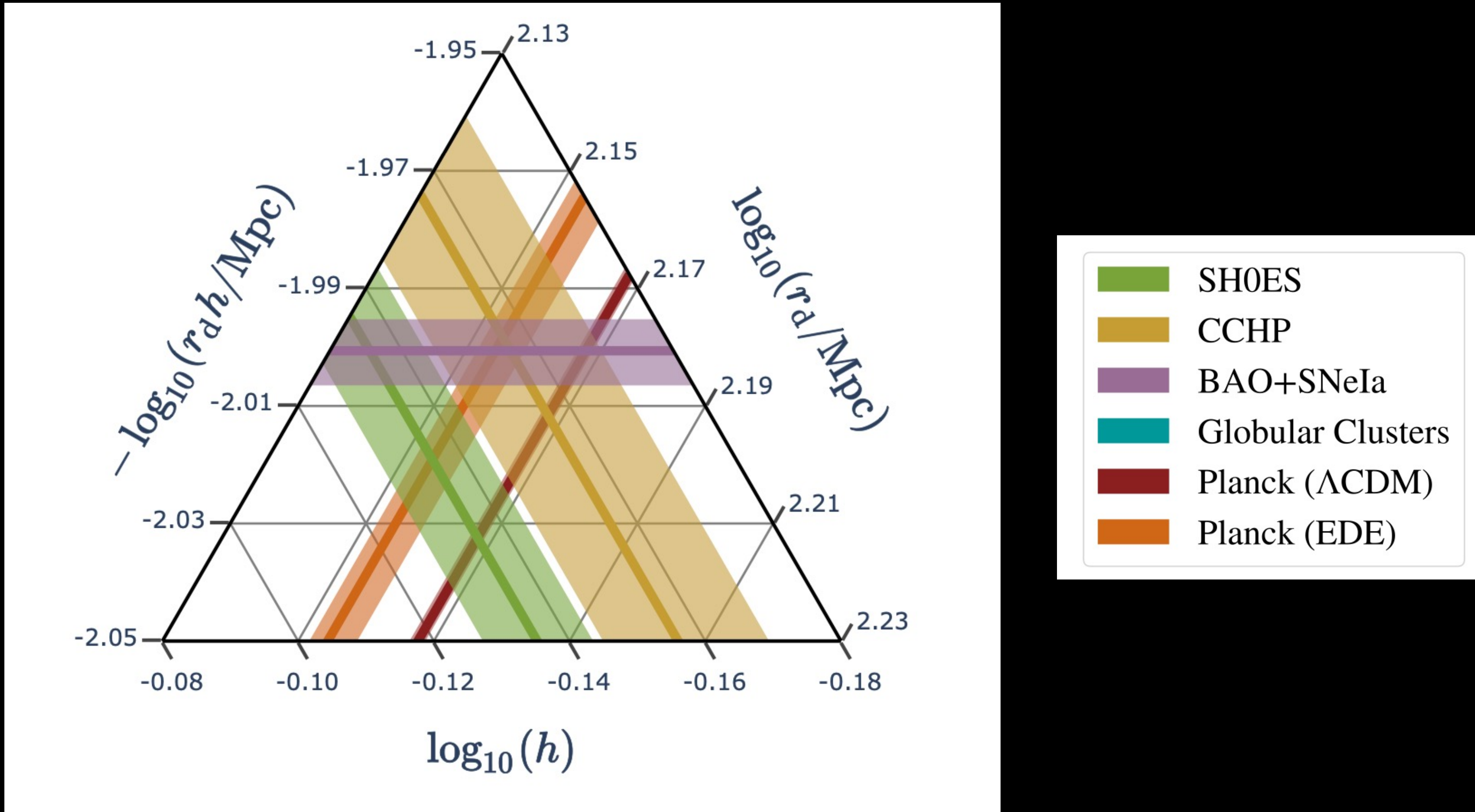
Now.. 22 years later… Back to the future…

The new cosmic triangles



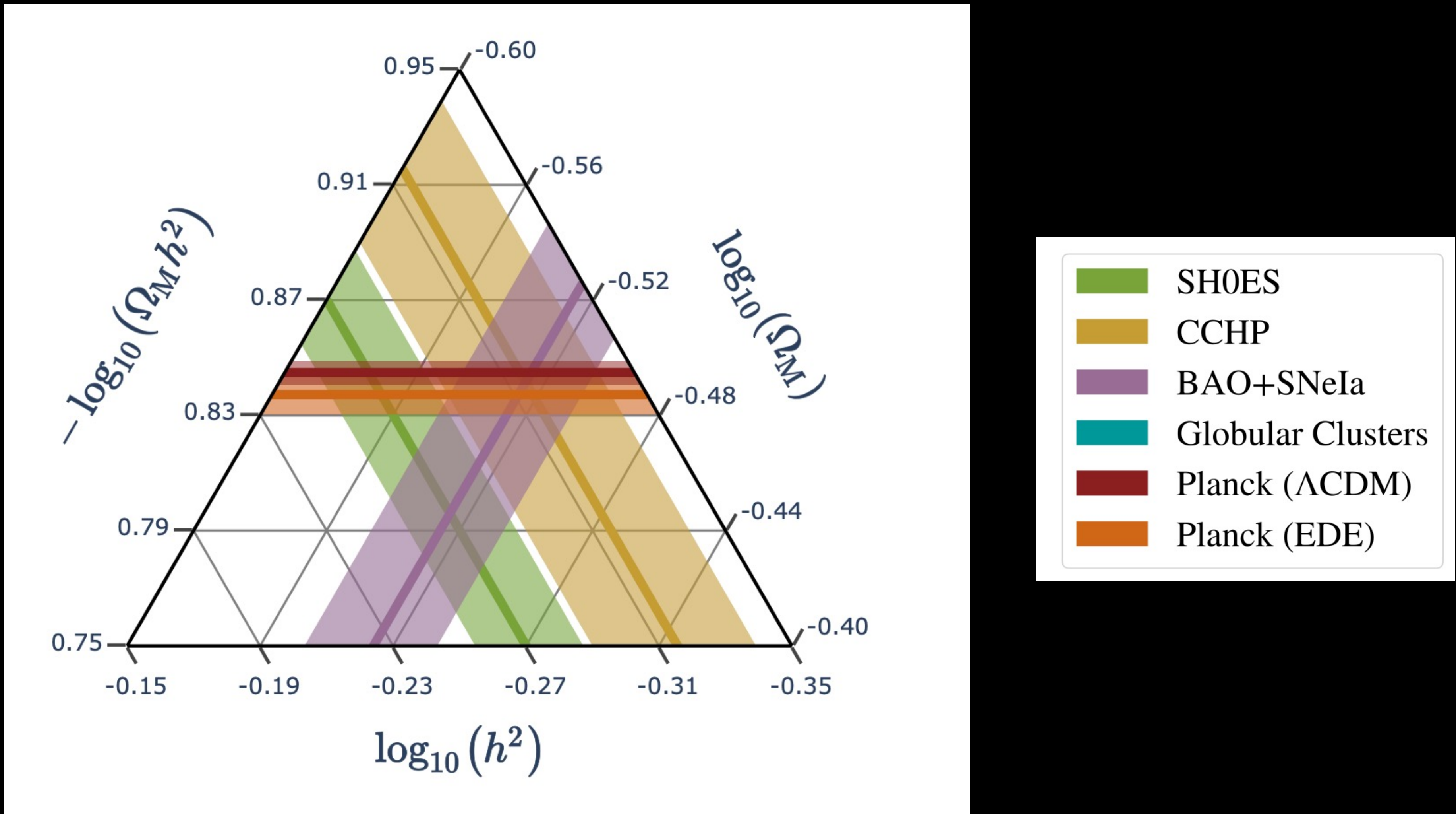
Bernal et al 2102.05066

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

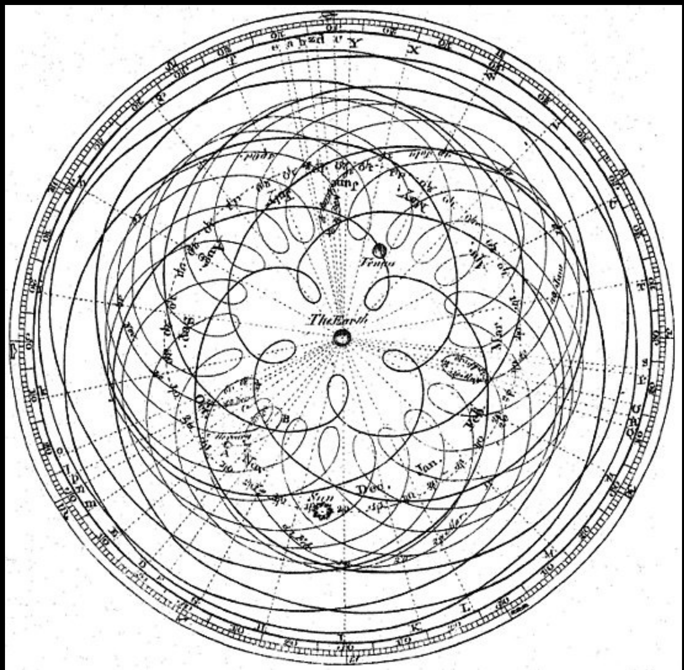
Should improve (or not worsen) other tensions

We should quantify improvement vs predictability (degrees of freedom)

Parallelism with Λ…..

Model-dependent vs model independent approaches

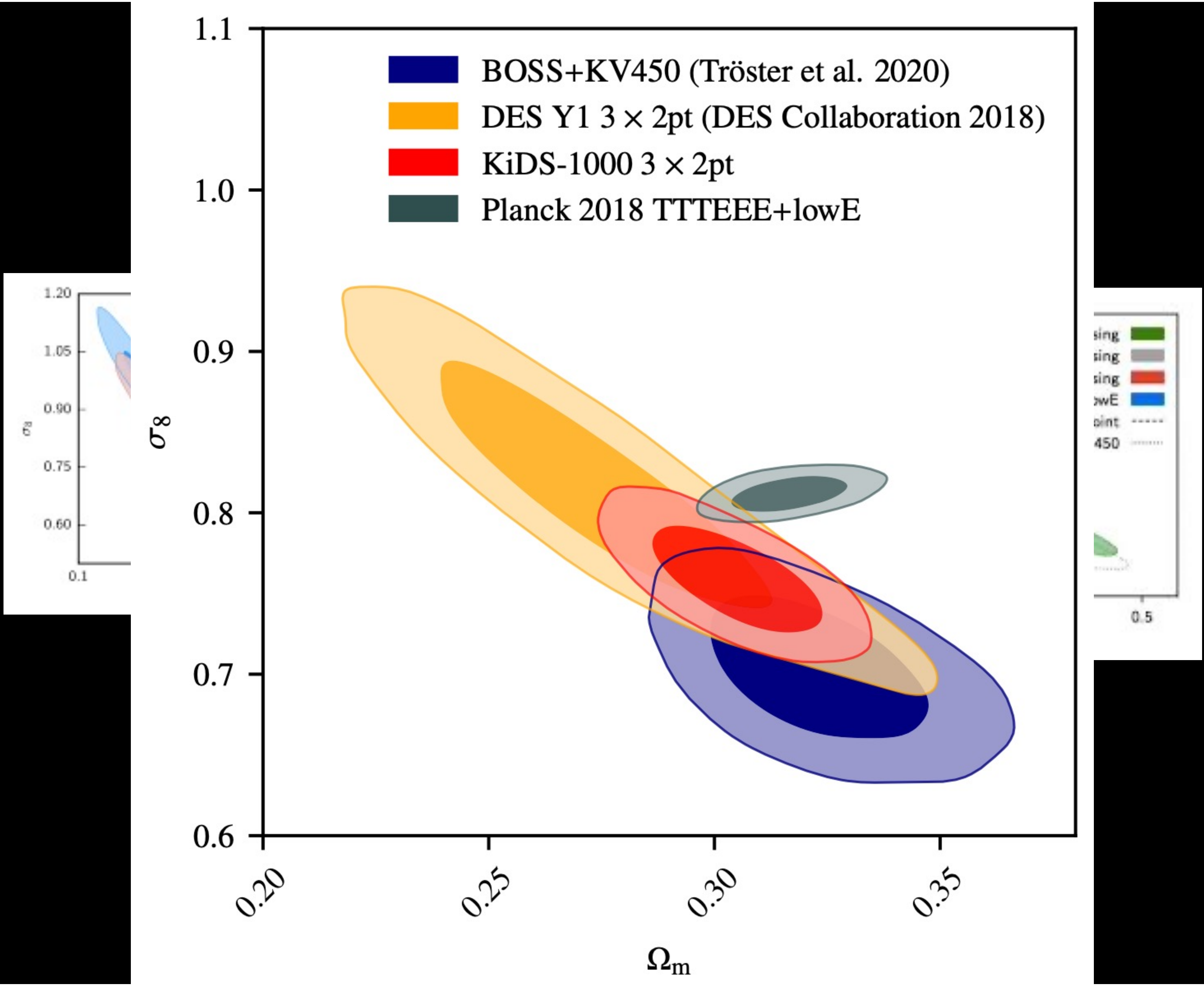
At what point are we adding epicycles?



Cassini

Nicolai Copernici

quocꝫ 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 epicyclium FG, in quo terra uersetur, omniaꝗ in eodem plano zodiaci. Sitꝗ epicycli primi motus in succedētia, ac annuus ferè, secūdi ꝗꝗ hoc est D, similiter annuus, sed in præcedentia, amborumꝗ ad AC lineam pares sint reuolutiones. Rursus cētrum terræ ex F in præcedentia addat parumper ipsi D. Ex hoc



BOSS+KV450 (Tröster et al. 2020)
DES Y1 3 × 2pt (DES Collaboration 2018)
KiDS-1000 3 × 2pt
Planck 2018 TTTEEE+lowE
σ_8
Ω_m
1.1
1.0
0.9
0.8
0.7
0.6
0.20
0.25
0.30
0.35
1.20
1.05
0.90
0.75
0.60
0.1
0.5

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.

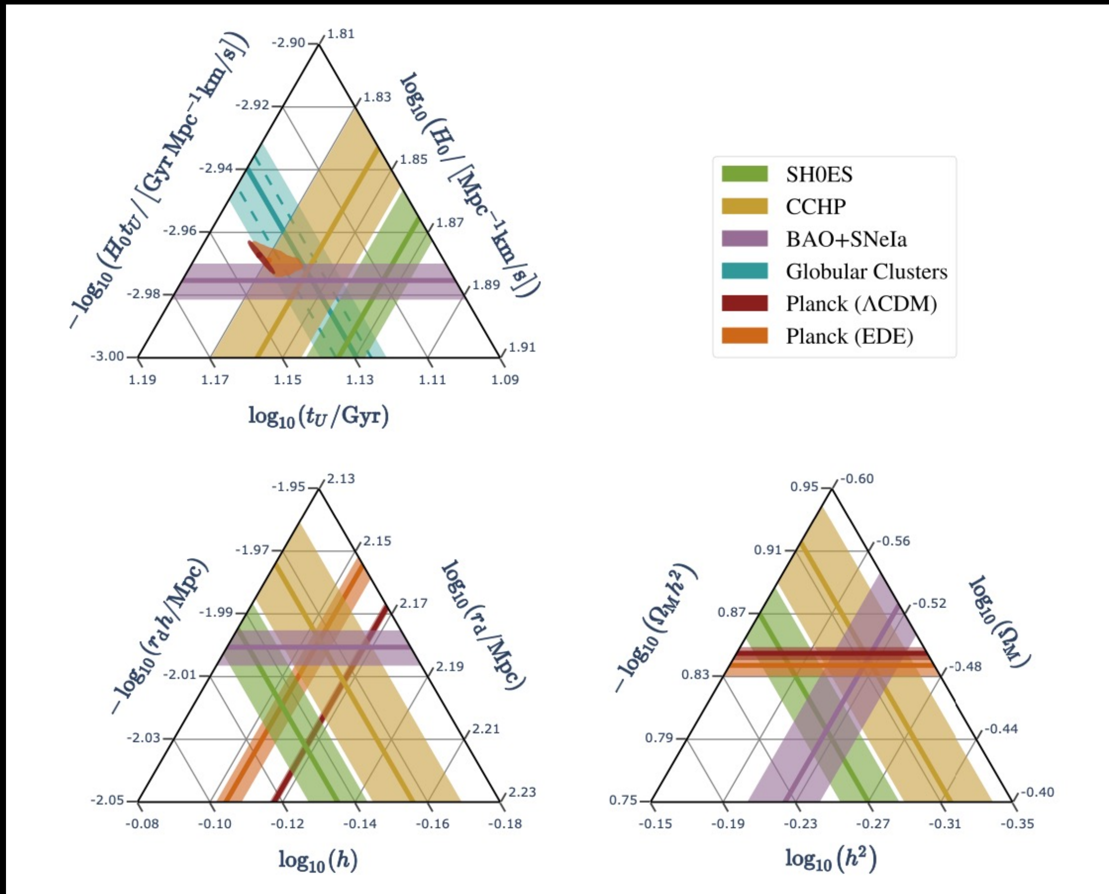
Two possible scenarios : local and global

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 !

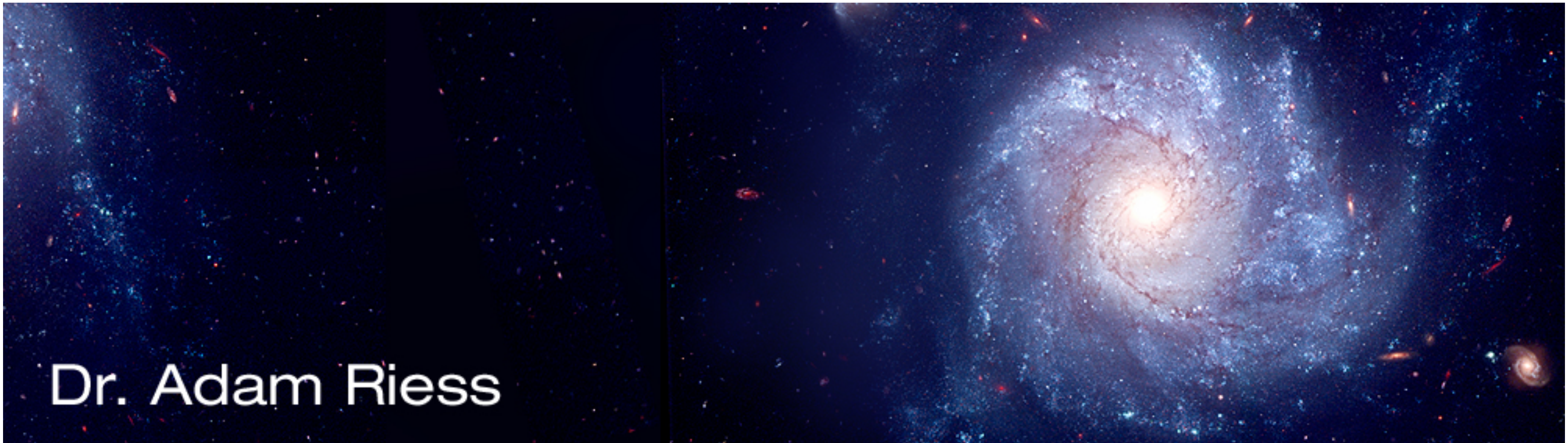
To conclude

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



Johns Hopkins University
Space Telescope Science Institute

New Determination of the Hubble constant with Gaia EDR3, Further evidence of excess expansion

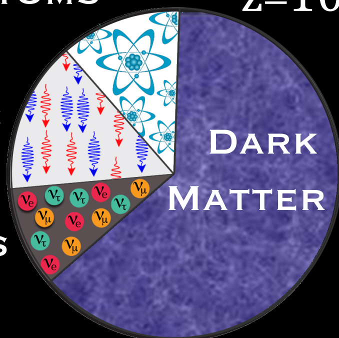
SH_0ES Team

Riess et al. 2021, ApJ Letters, 908, 6

Ultimate "End-to-end" test for ΛCDM, Predict and Measure H_0

Standard Model: (Vanilla) ΛCDM, 6 parameters + ansatz (w, N_{eff}, Ω_K, etc)

z=1000

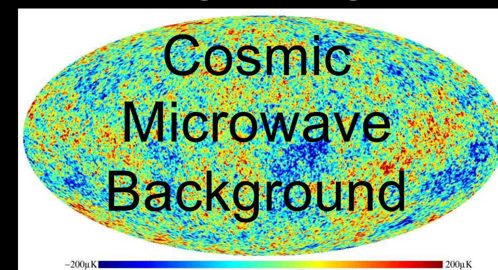


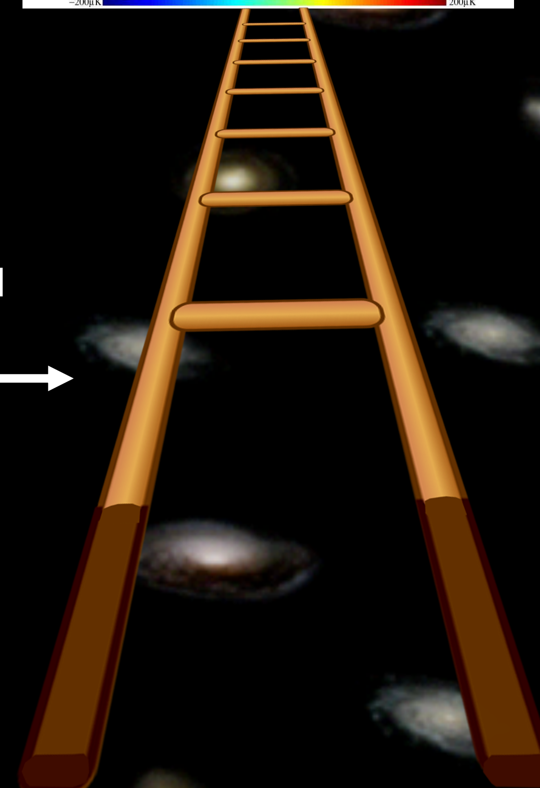
Predict physical size fluctuations, r_s, Ω_B →

← Measure angular fluctuations (or Ω_B)

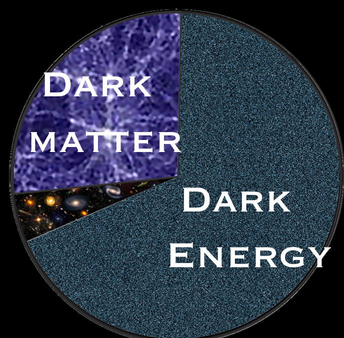
Calibrate ΛCDM …

Big Bang

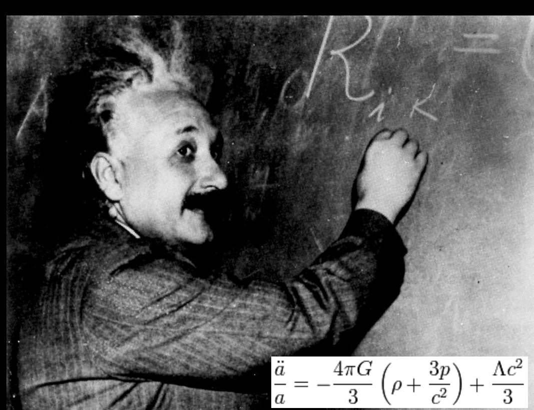




Now



Expansion history predicted
("guard rails", BAO, SNe) →



Planck Predicted, H_0=67.4+/-0.5 km/s/Mpc

A Direct, Local Measurement of H_0 to percent precision

The SH_0ES Project (2005)

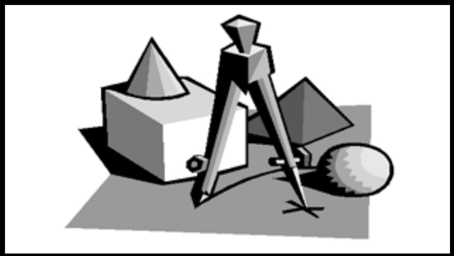
(Supernovae, H_0 for the dark energy Equation of State)

A. Riess, L. Macri, D. Scolnic, S. Casertano, A. Filippenko, W. Yuan, S. Hoffman, +

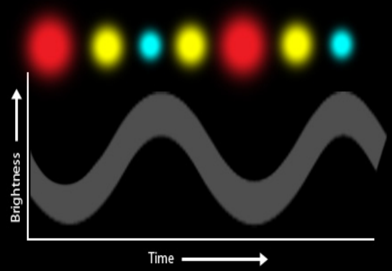
Measure H_0 to percent precision empirically by:

"Gold Standard" tools: Geometry→Cepheids→ SNe Ia

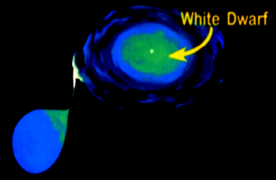
Multiple ways



Pulsating Stars, 10^5 $L_\odot$, P-L relation



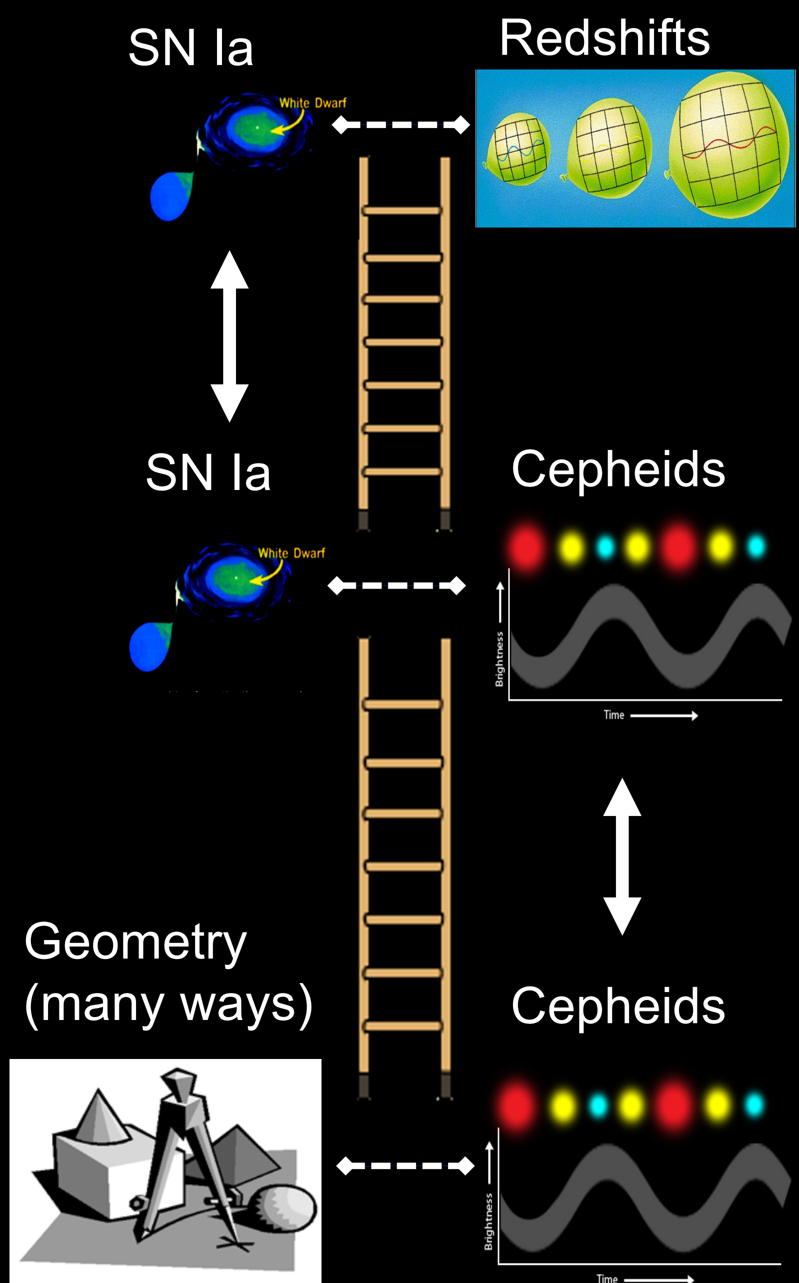
Exploding Stars, 10^9 $L_\odot$, σ~ 5%



An explosion resulting from the thermonuclear detonation of a White Dwarf Star.

--Reduce systematics w/ consistent data along ladder and NIR
--Thorough propagation of statistical and systematic
--HST Cycle 11-28, 17 competed GO proposals,~1000 orbits

Distance Ladders: Empirical & Model-free, Must be Consistent



Hubble Flow:
D~Gpc, z~0.1

Cross-calibrate:
D~10-40 Mpc

Anchors:
D~Kpc or Mpc

Nutrition Facts

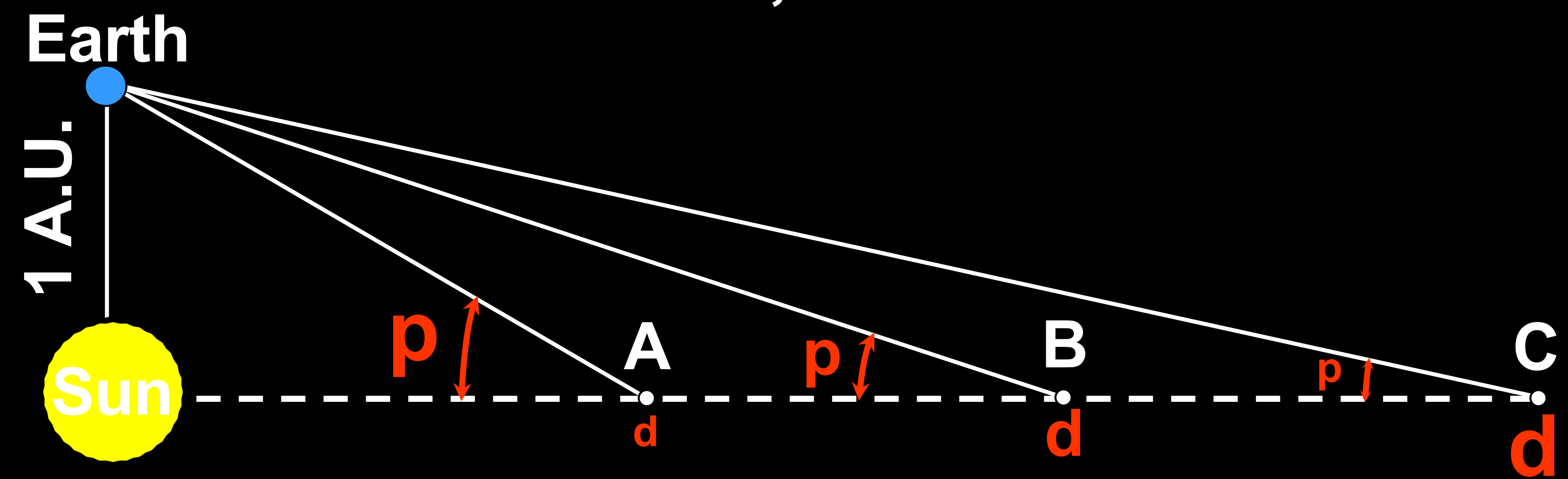
Serving size	1 potato (148g/5.2oz)
Amount per serving	
Calories	**73**
	% Daily Value*
Astrophysical modeling	0%
General Relativity	<1%
LCDM	<1%

WARNING

Same object types on different rungs must be standardized and measured consistently!

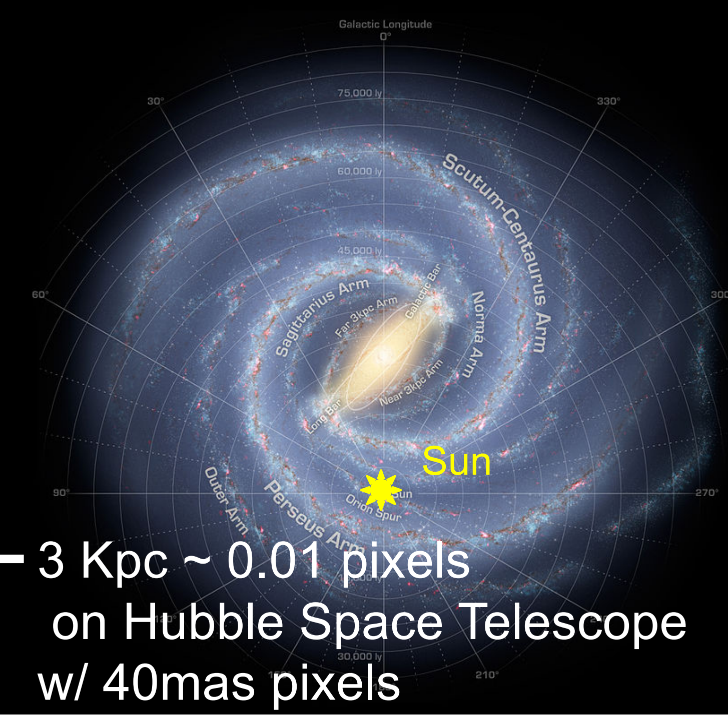
Step 1: Parallax in the Milky Way at Kiloparsec Distances

Stars are far, Parallax is small !



$$d\ (\text{kpc}) = \frac{1}{p\ (\text{milliarcsec})}$$

Nearly all long-period (P>10 days)
MW Cepheids D > kpc (p<mas)



— 3 Kpc ~ 0.01 pixels
on Hubble Space Telescope
w/ 40mas pixels

Extending Parallax with WFC3 Spatial Scanning (~2014)

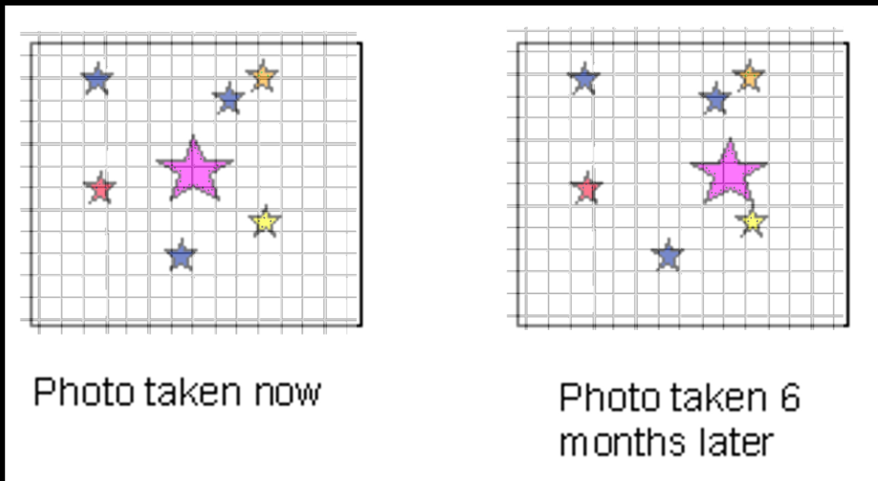
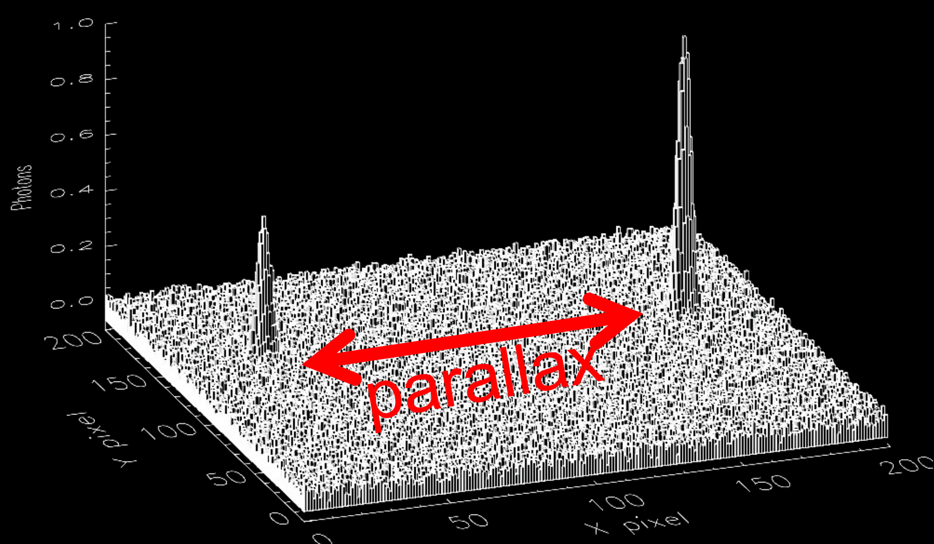


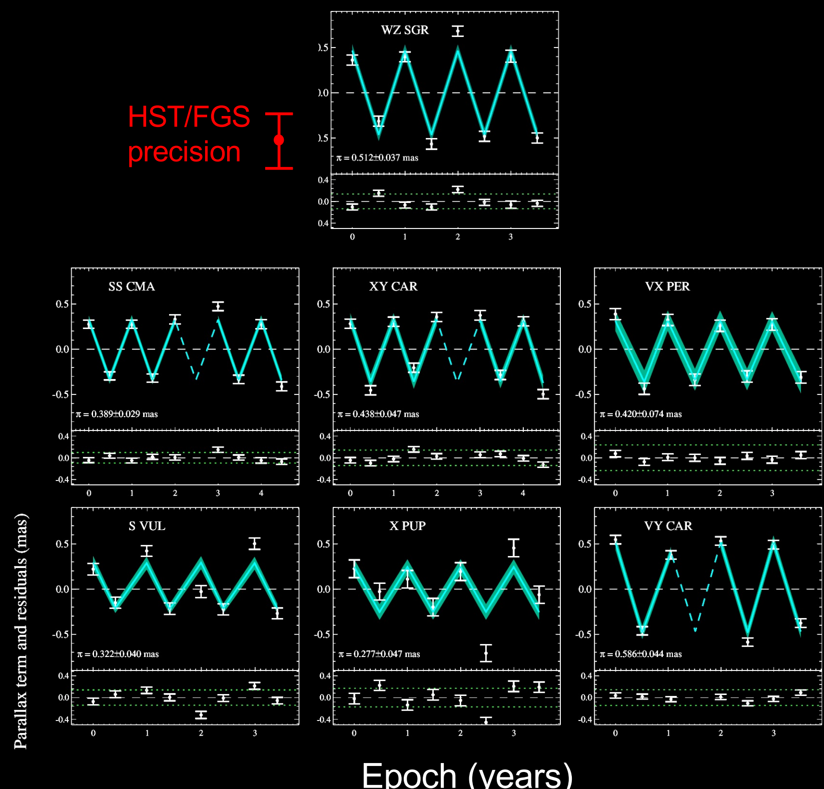
Image centroiding precision: S
~0.01 pix WFC3: ~1σ @ 3 kpc



New Tool: WFC3 Spatial scanning for long range parallaxes, photometry

<u>Approach 1: HST Spatial Scanning</u>

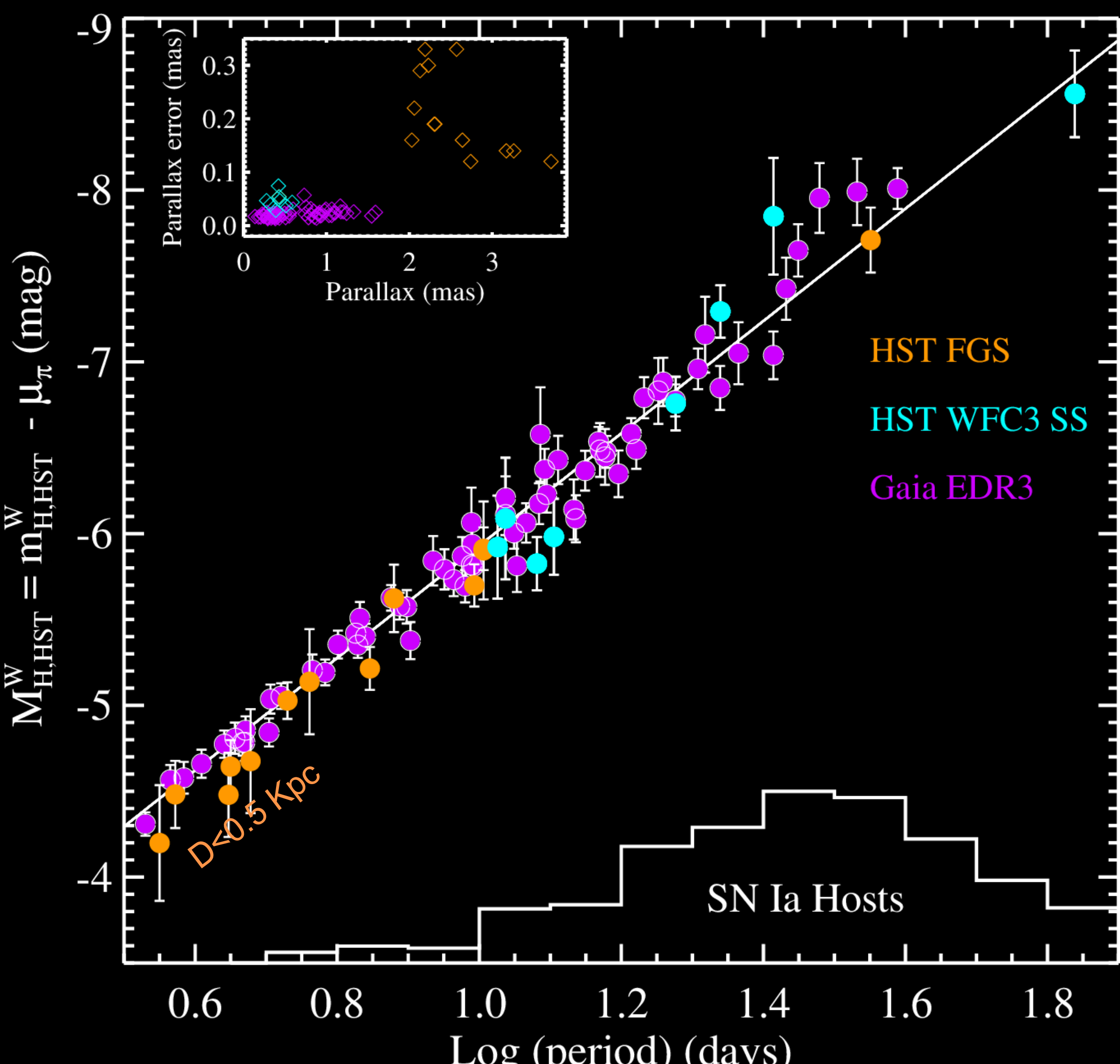
4 Years Later, 8 MW long-P Cepheid Parallaxes, 20-40 μas precision, 1.7<D<3.6 Kpc, error in mean=3.3%



Riess et al. (2018a), ApJ, 855,136

Milky Way Cepheid P-L Relation, Now w/ HST photometry, Gaia EDR3!

Milky Way Cepheid Period-Luminosity Relation



Final Gaia Parallaxes + HST Photometry→ H_0~0.4%!

Two advantages over old HST FGS parallaxes (Benedict+2007)

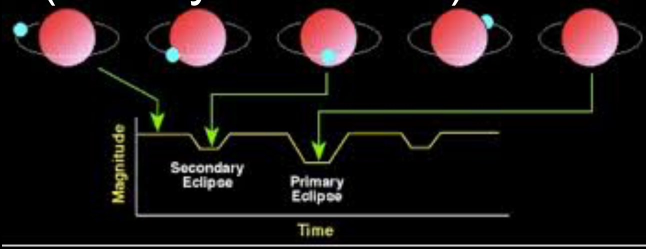
1) Periods > 10 days
2) HST photometry

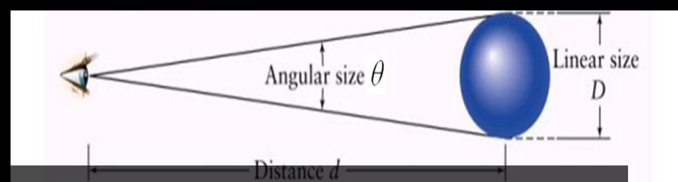
Three Sources of Geometric Distances to Calibrate Cepheids

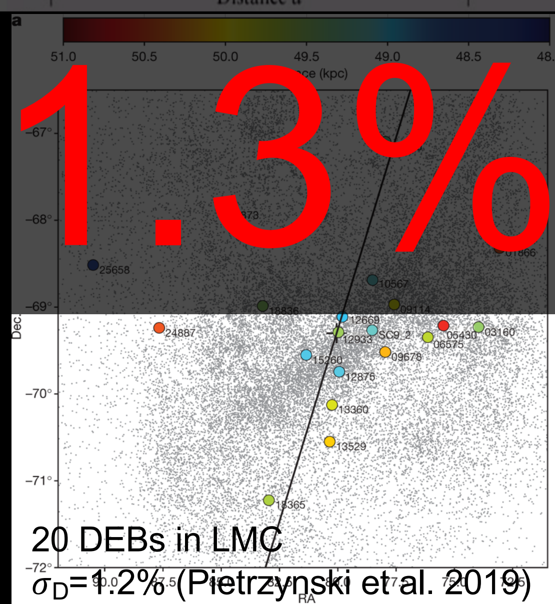
Parallax in Milky Way (WFC3 SS, HST FGS, Gaia)

1.0%

Detached Eclipsing Binaries in LMC (Pietrzynski+2019)







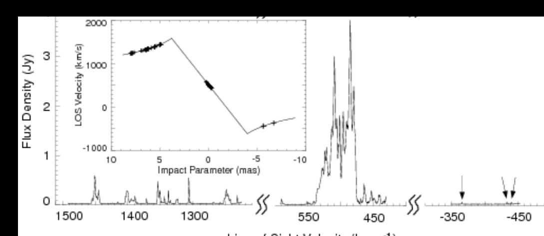
1.3%

20 DEBs in LMC

σ_D=1.2% (Pietrzynski et al. 2019)

Masers in NGC 4258, Keplerian Motion (Reid+2019)

1.5%



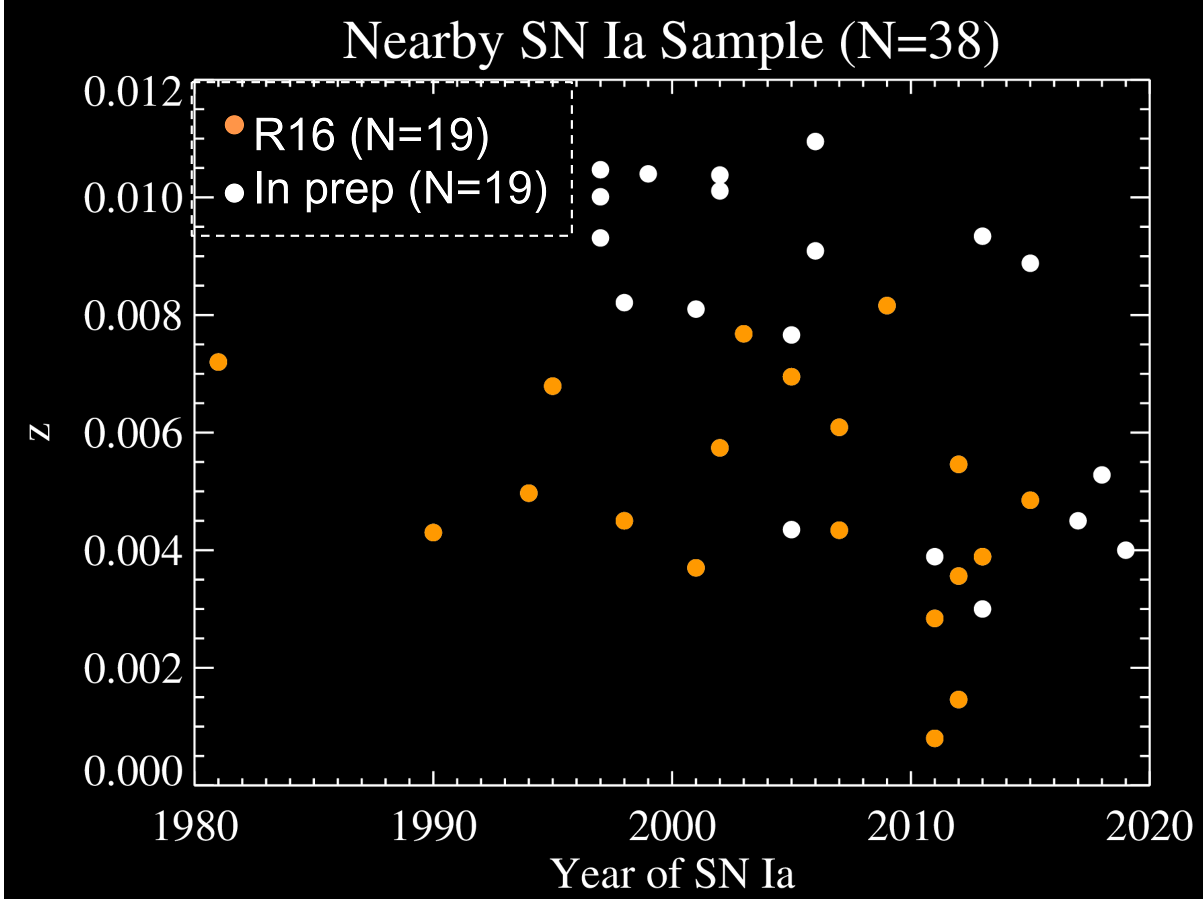
Step 2: Cepheids to Type Ia Supernovae

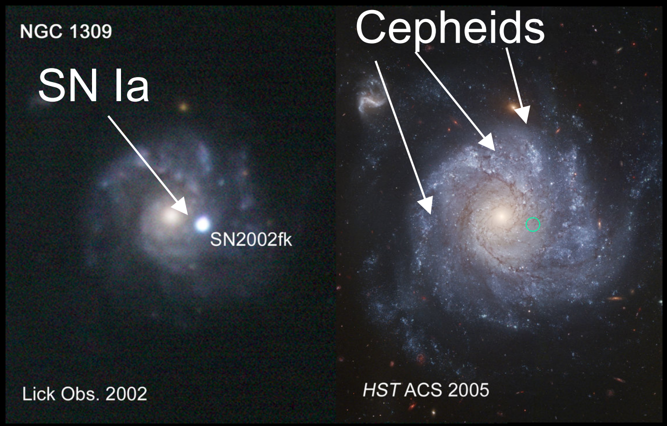
Number nearby SN Ia limits H_0 precision, $\sigma=\frac{6\%}{\sqrt{N}}$

SN Ia Requirements: A_V<0.5, normal, pre-max, digital

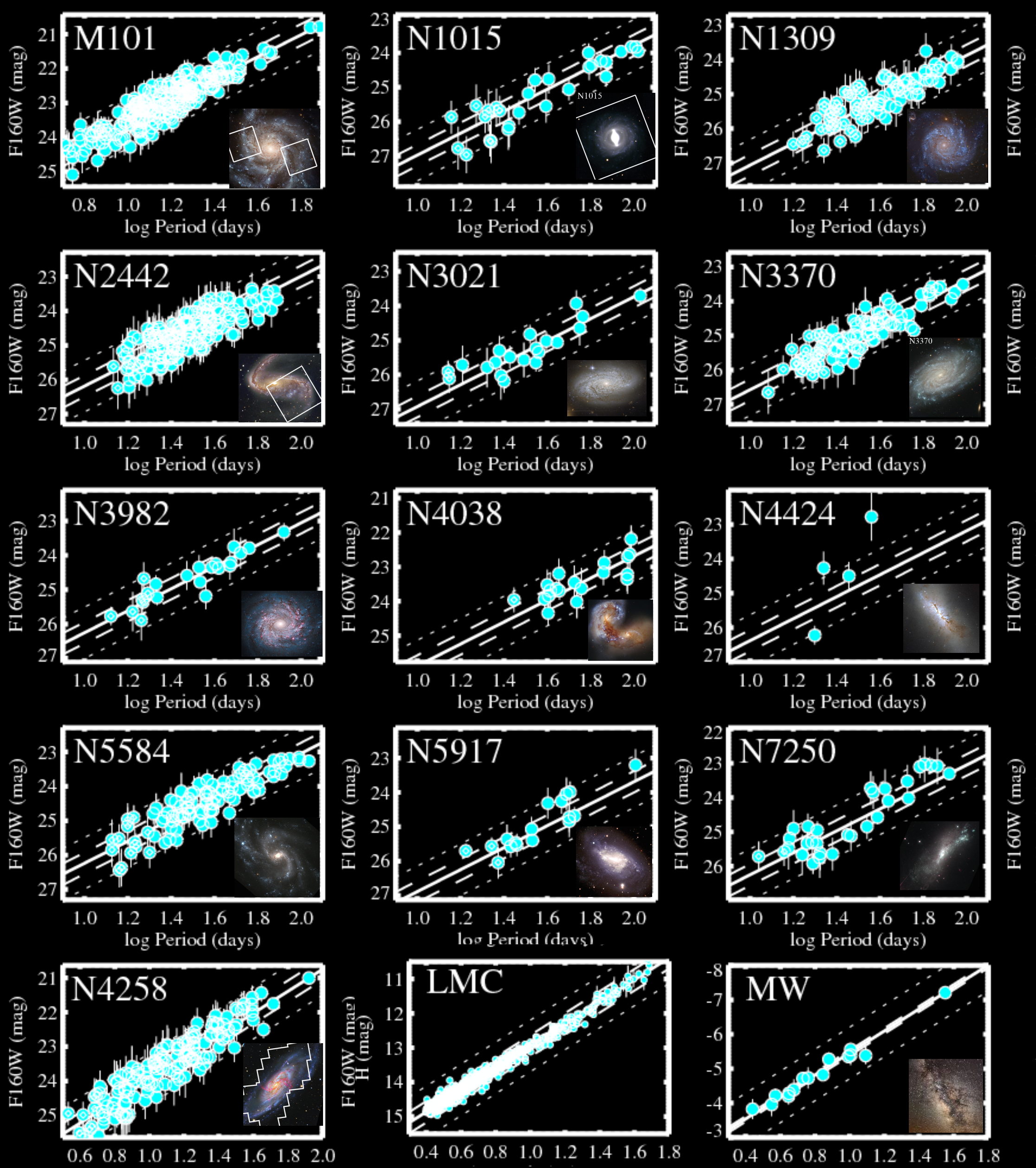
Host Requirements: Late-type, z≤0.01, not-edge on

2020 Complete sample (new ones @ 1.5/yr)





Cepheid V,I,H band Period-Luminosity Relationships: 19 hosts, 3 anchors

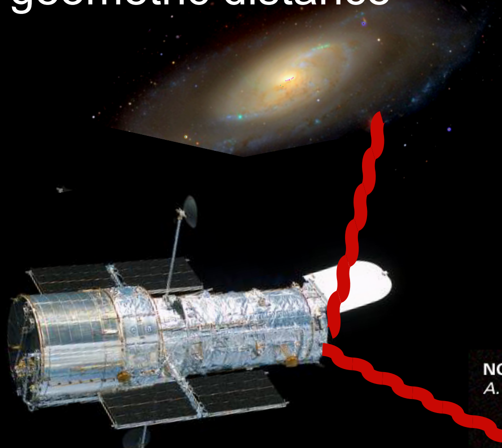


← 3 Anchors

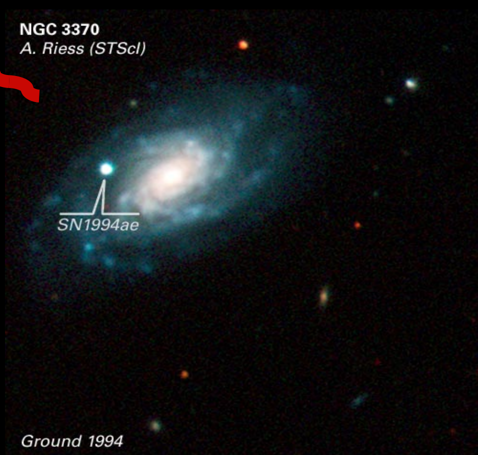
Lower Systematics from *Differential* Flux Measurements

To reduce systematic errors: measure all Cepheids with same instrument, filters, similar metallicity, period range

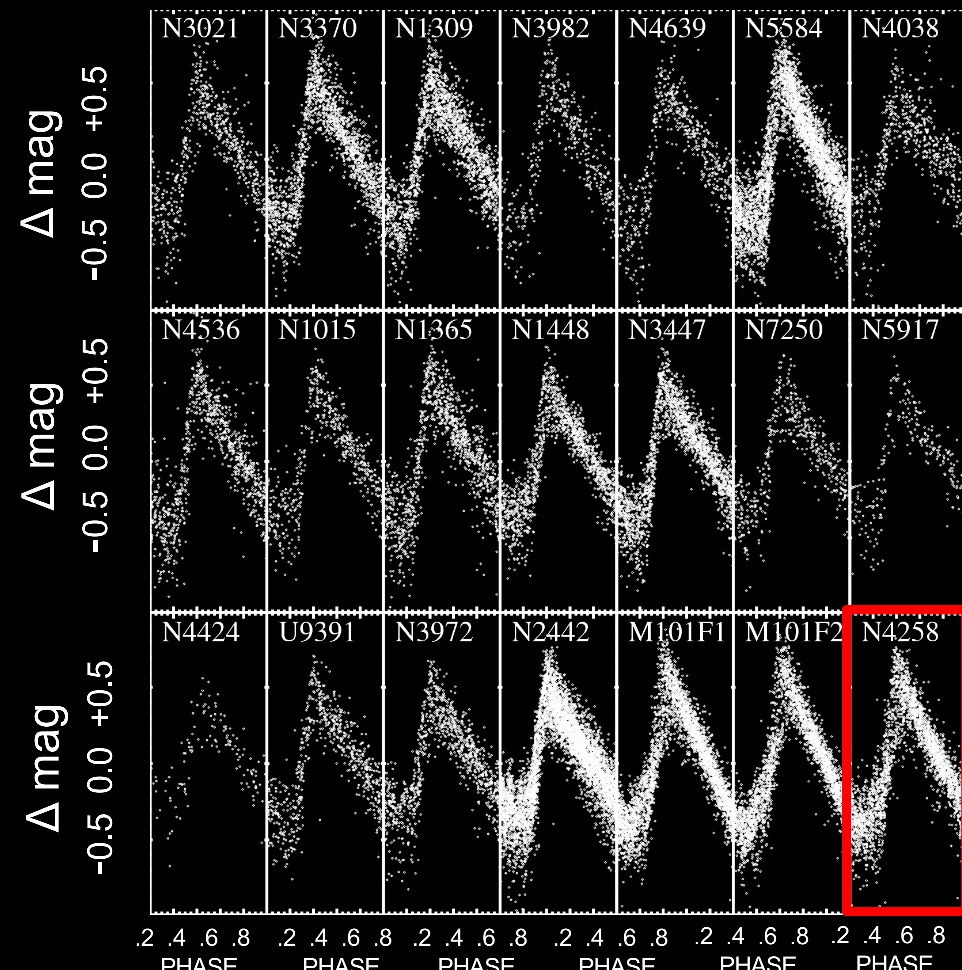
ANCHORS: NGC 4258, MW, & LMC geometric distance



19 SN Ia Hosts



Cepheid composite LC's, >2400

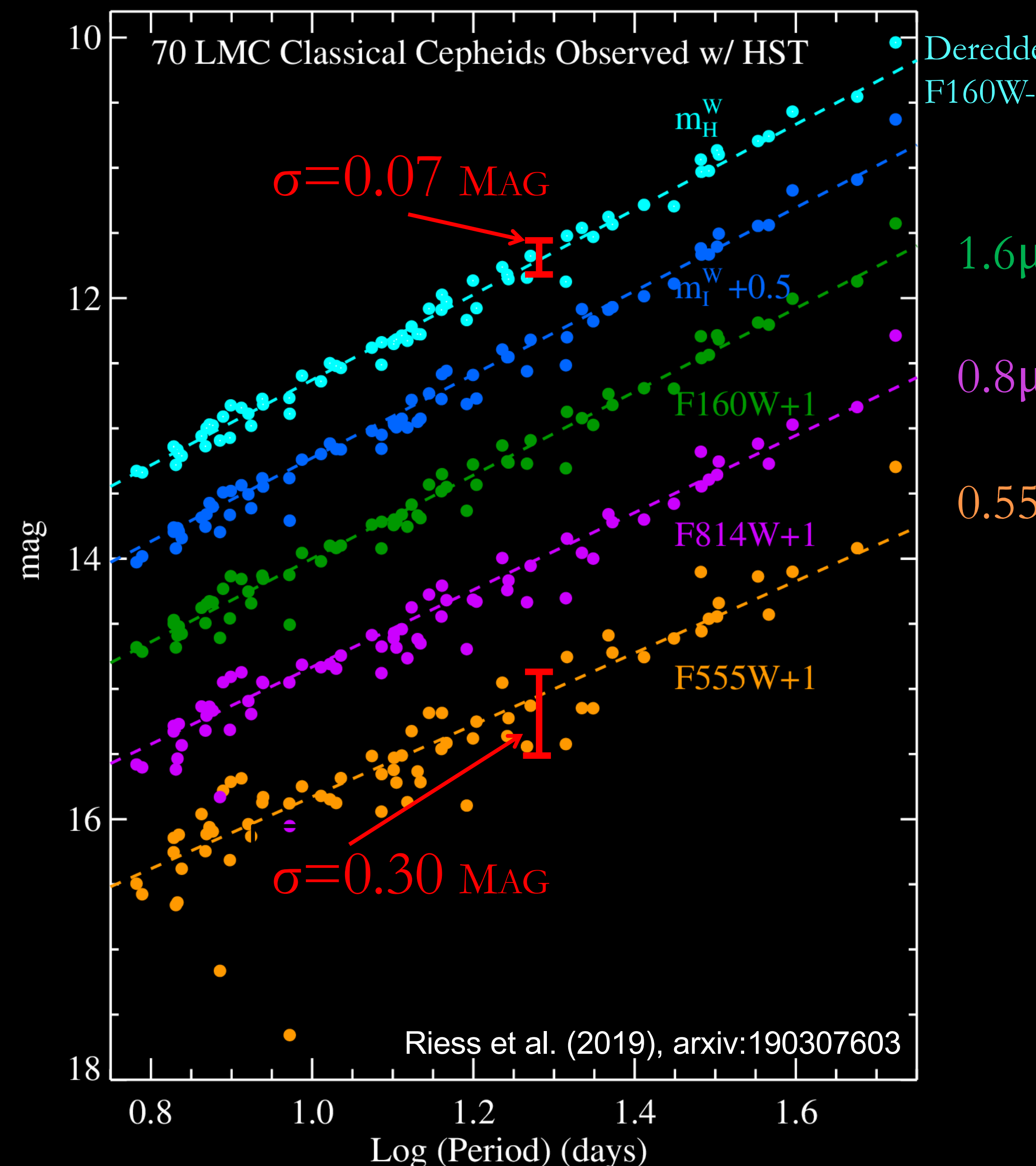


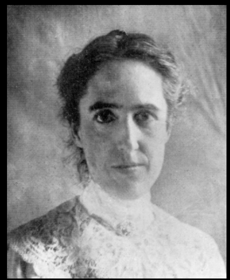
Lowering Systematics: Near-IR Cepheid Observations + HST, Now in LMC!

-Dependence on reddening laws 6x smaller than optical

We use F160W-band as primary +F555W,F814W

Key Project used F555W and F814W



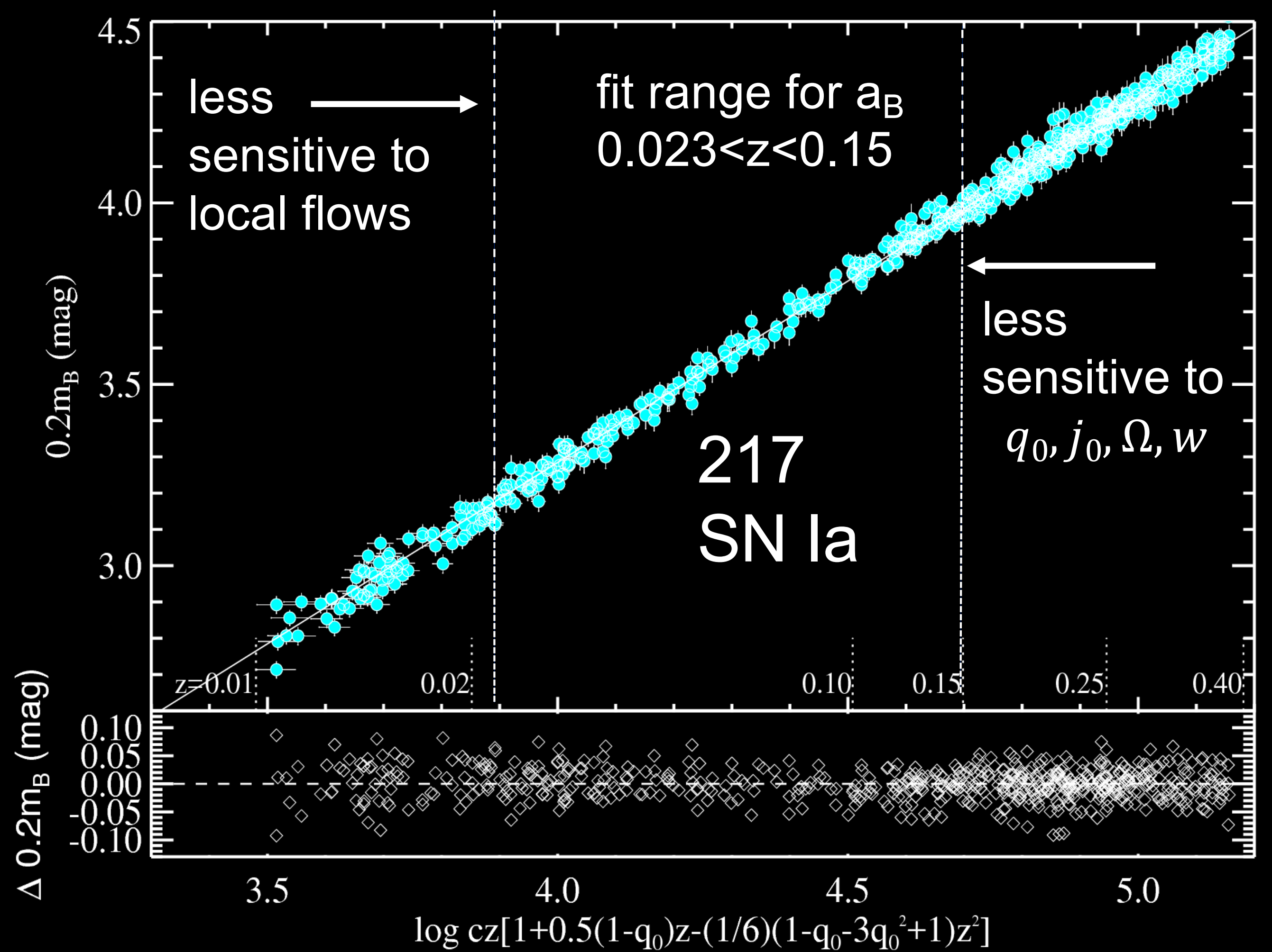


Leavitt

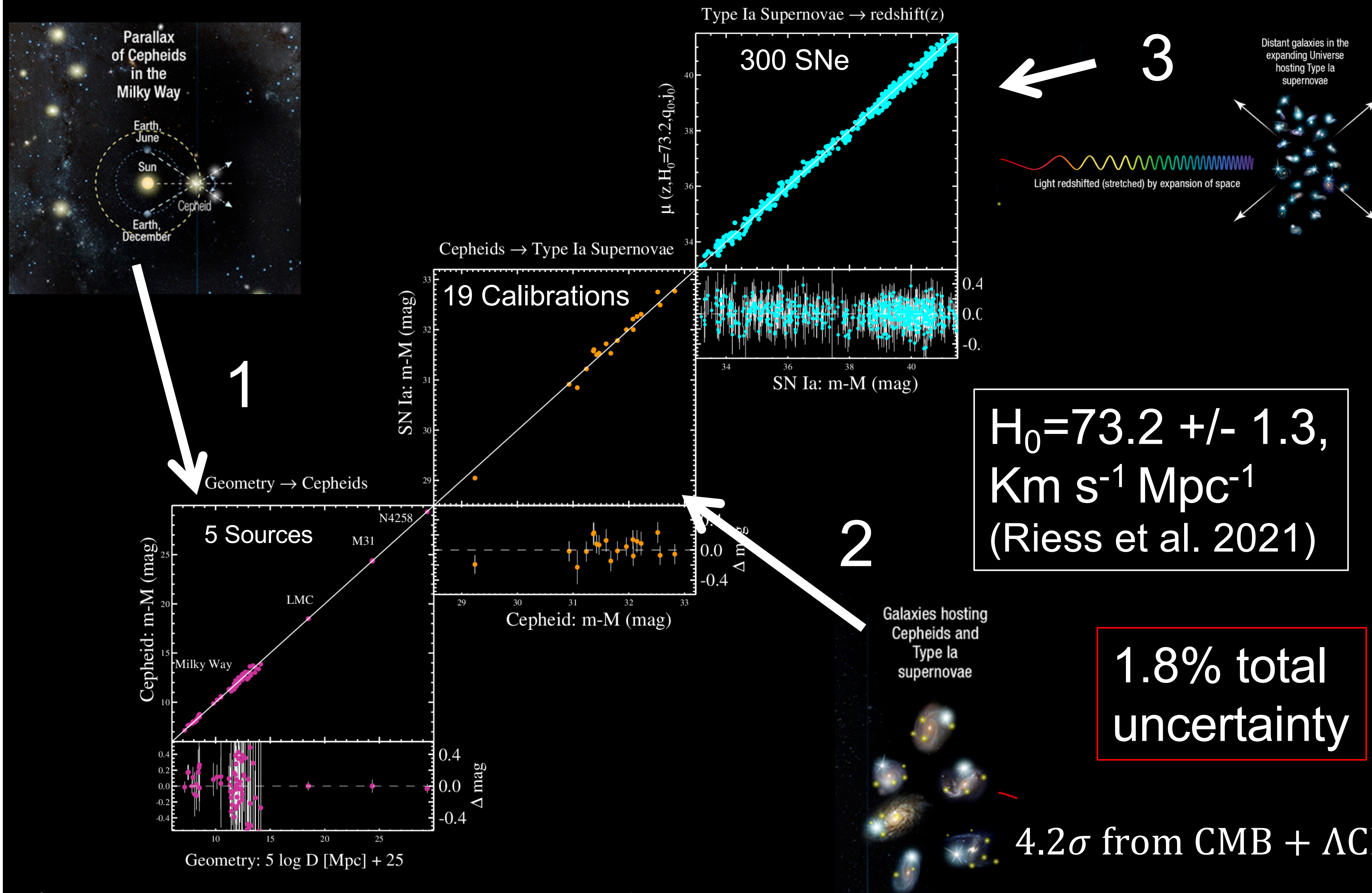
Step 3: Intercept of SN Ia Hubble Diagram: Distance vs Redshift

$$a_B = \log cz \left\{1 + \frac{1}{2}[1 - q_0] z - \frac{1}{6}[1 - q_0 - 3q_0^2 + j_0] z^2 + O(z^3)\right\} - 0.2m^0_B$$

← Kinematic Intercept equation



The Hubble Constant in 3 Steps: Present Data



H_0=73.2 +/- 1.3, Km s^{-1} Mpc^{-1}
(Riess et al. 2021)

1.8% total uncertainty

4.2σ from CMB + ΛCDM !

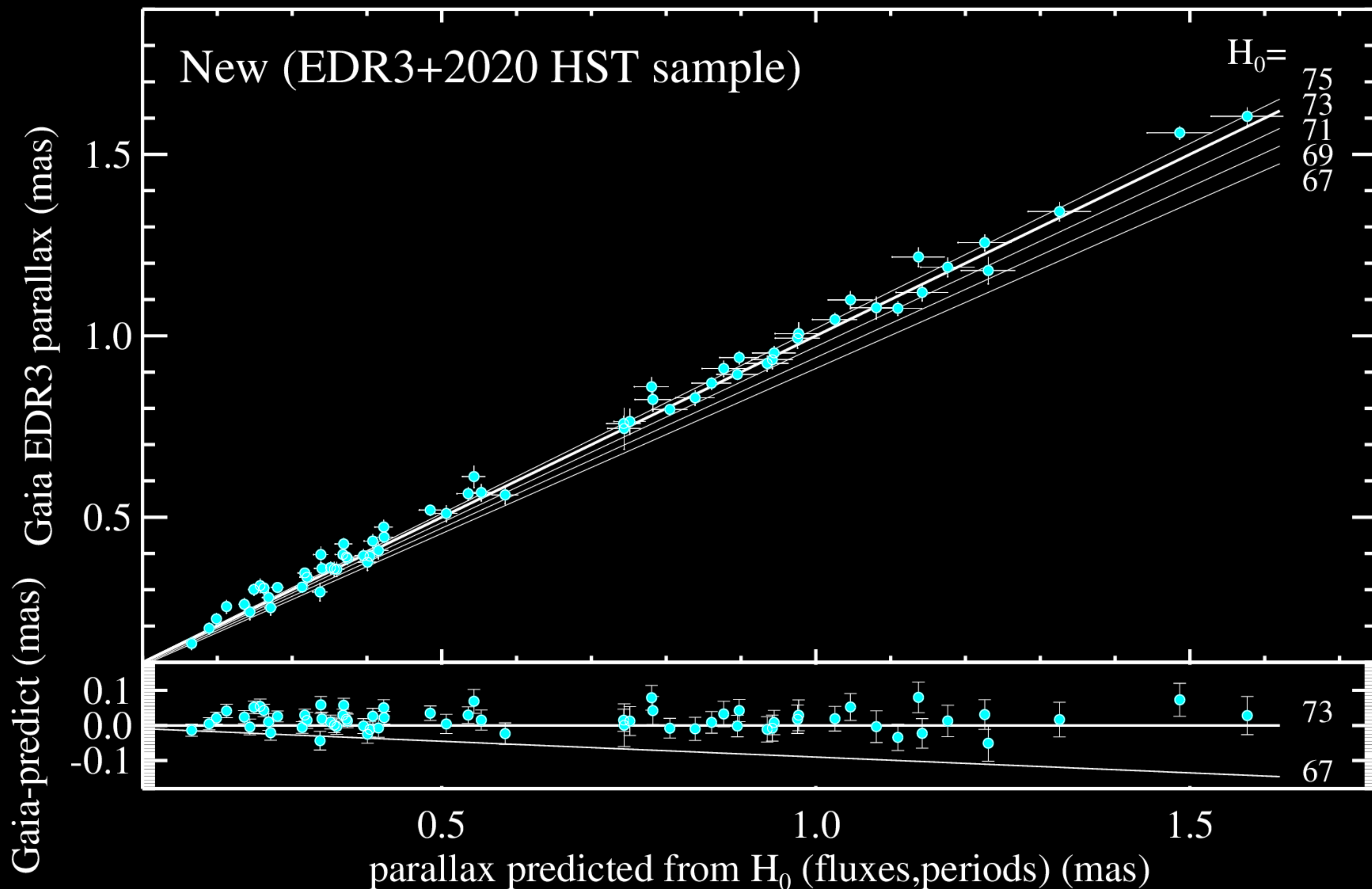
*Simultaneous Fit: Retain interdependence of data and parameters

Robust? Seven Sources of Cepheid Geometric Calibration

	Independent Geometric Source	σ_D	H_0
primary	75 Milky Way Parallaxes Gaia EDR3 par. + HST fluxes Riess+ 2020	1.0%	73.0
primary	NGC 4258 H_20 Masers: Reid, Pesce, Riess 2019	1.5%	72.0
primary	LMC 20 Detached Eclipsing Binaries: Pietzrynski+ 2019 + 70 HST LMC Cepheids: Riess+(2019)	1.3%	74.2
checks	Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess+ 2018	3.3%	75.7
checks	Milky Way 10 HST FGS Short P Parallaxes: Benedict+2007 -- also Hipparcos (Van leeuwen et al 2007)	2.2%	76.2
checks	Milky Way Short P Cepheid Binary Gaia DR2 Companion Parallax: Breuval+20	3.8%	72.7
checks	Milky Way Short P Cepheid Cluster Gaia DR2 Parallax: Breuval+20	3.2%	73.6

Consistent Results ($\leq 2\sigma$), *Independent Systematics*

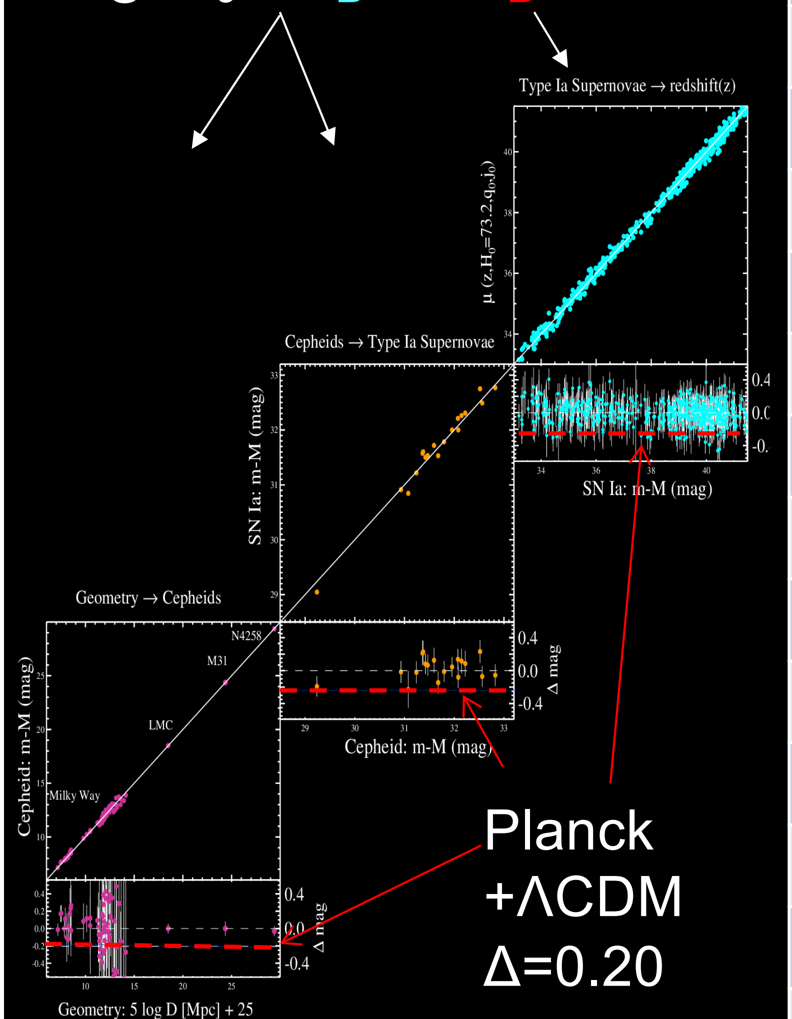
Gaia Improves: DR2 to DR3 plus more HST Photometry



Systematics? 23 Analysis Variants—we propagate variation to error

Best Fit:

$5\log H_0 = M_B^0 + 5a_B + 25$



Planck +ΛCDM Δ=0.20 mag

Analysis Variants	H_0
Best Fit (2021)	73.2
Reddening Law: LMC-like (R_V=2.5, not 3.3)	73.0
Reddening Law: Bulge-like (N15)	73.5
No Cepheid Outlier Rejection (normally 2%)	73.3
No Correction for Cepheid Extinction	74.8
No Truncation for Incomplete Period Range	74.2
Metallicity Gradient: None (normally fit)	73.6
Period-Luminosity: Single Slope	73.5
Period-Luminosity: Restrict to P>10 days	73.2
Period-Luminosity: Restrict to P<60 days	73.8
Supernovae z>0.01 (normally z>0.023)	73.3
Supernova Fitter: MLCS (normally SALT)	75.1
Supernova Hosts: Spiral (usually all types)	73.1
Supernova Hosts: Locally Star Forming	73.4
Optical Cepheid Data only (no NIR)	72.0

Frequently Asked Questions

- Could we live in a giant void (9% in H_0)?
  No, LSS Theory and SN Ia mag-z limit σ~0.6% in H_0

  Odderskov et al. (2016) , Wu & Huterer (2017), Kenworthy, Scolnic, Riess 2019

- Is HST WFC3-IR flux scale linear to 1%?
  Yes, calibrated to σ=0.3% in H_0 across 15 mag

  Riess, Narayan, Calamida 2019

- Does Cepheid crowding compromise accuracy?
  No, amplitude data confirms crowding estimate accuracy ~2%

  Riess, Yuan, Casertano, Macri, Scolnic 2020

- Is there a difference in SN Ia at ends of distance ladder?
  No, correlations of Hubble residuals < σ=0.3% in H_0

  Jones et al 2018

FAQ: Cepheid physics different *locally* vs bit more distant?

"Hertzsprung progression" (1926)—shape vs period (in prep)

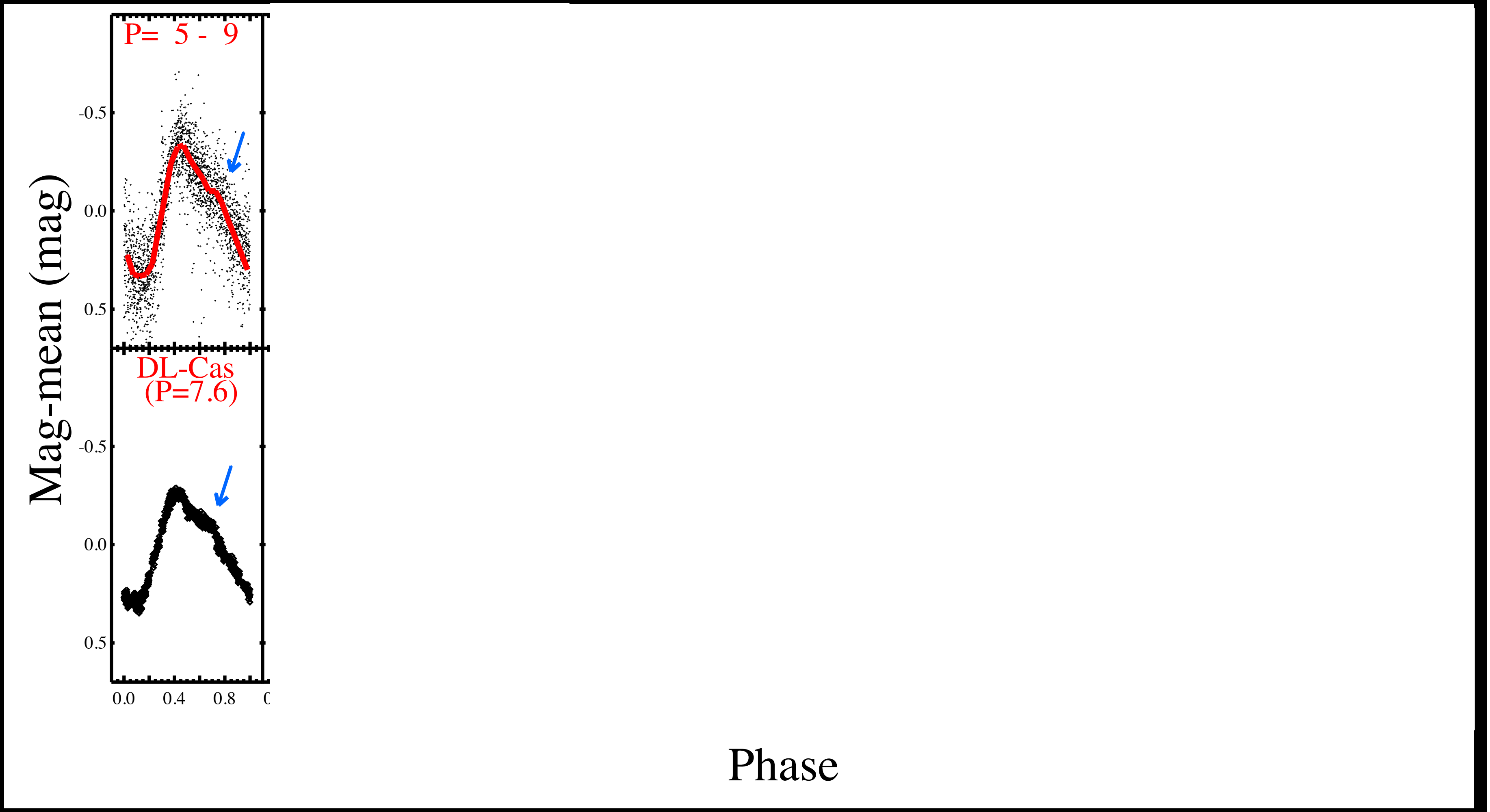
-asymmetry (Fund.), "bump", 2:1 resonance fundamental and 2nd overtone

-high amplitude "saw-tooth", sinusoidal at P>40 days

Bono et al 2000/02

In SN Ia Hosts

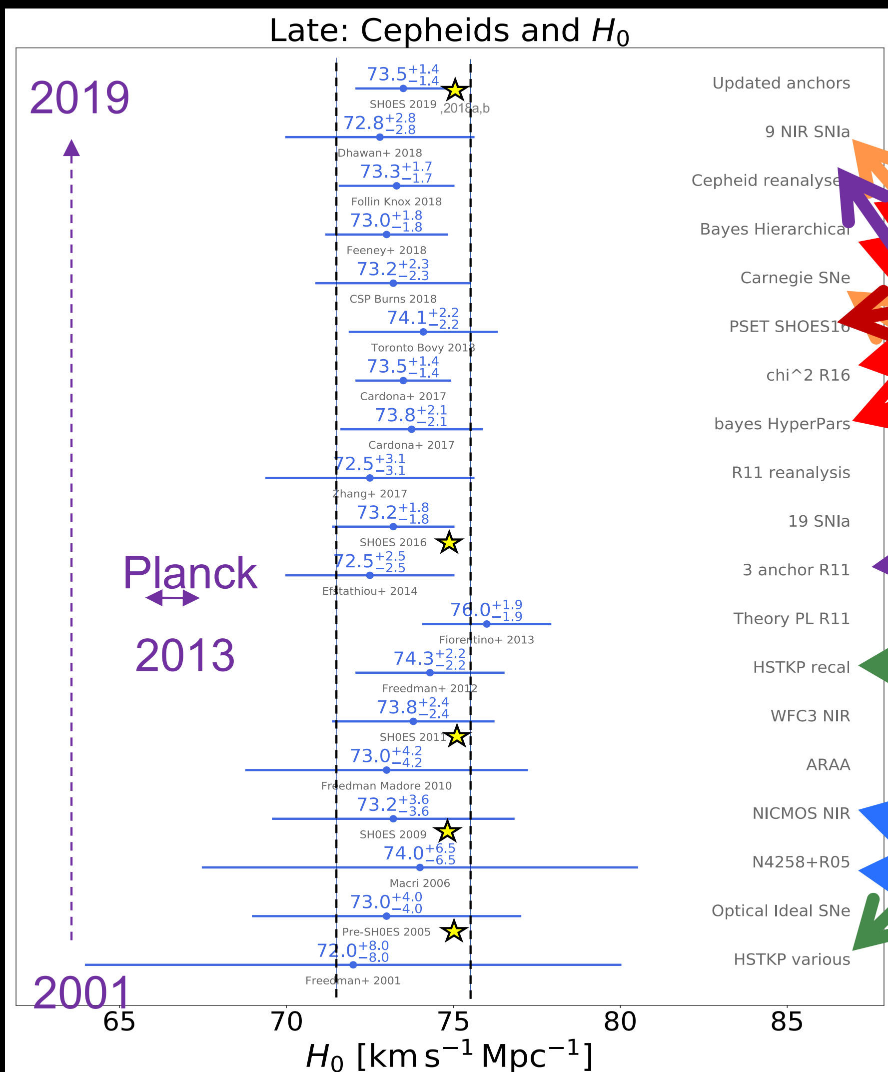
In Milky Way



FAQ: Only us? No, Cepheids+SNIa, widely replicated: 2001-19

Why Cepheids? Advantages: 1) longest-range 2) most calibrations 3) consistent photometry along ladder 4) most tested…

SH_0ES results (★) *cumulative* but compared to present… consistent



grad student problem set! (Toronto)

Different analyses

Different SNe, wavelength

"Planck People"

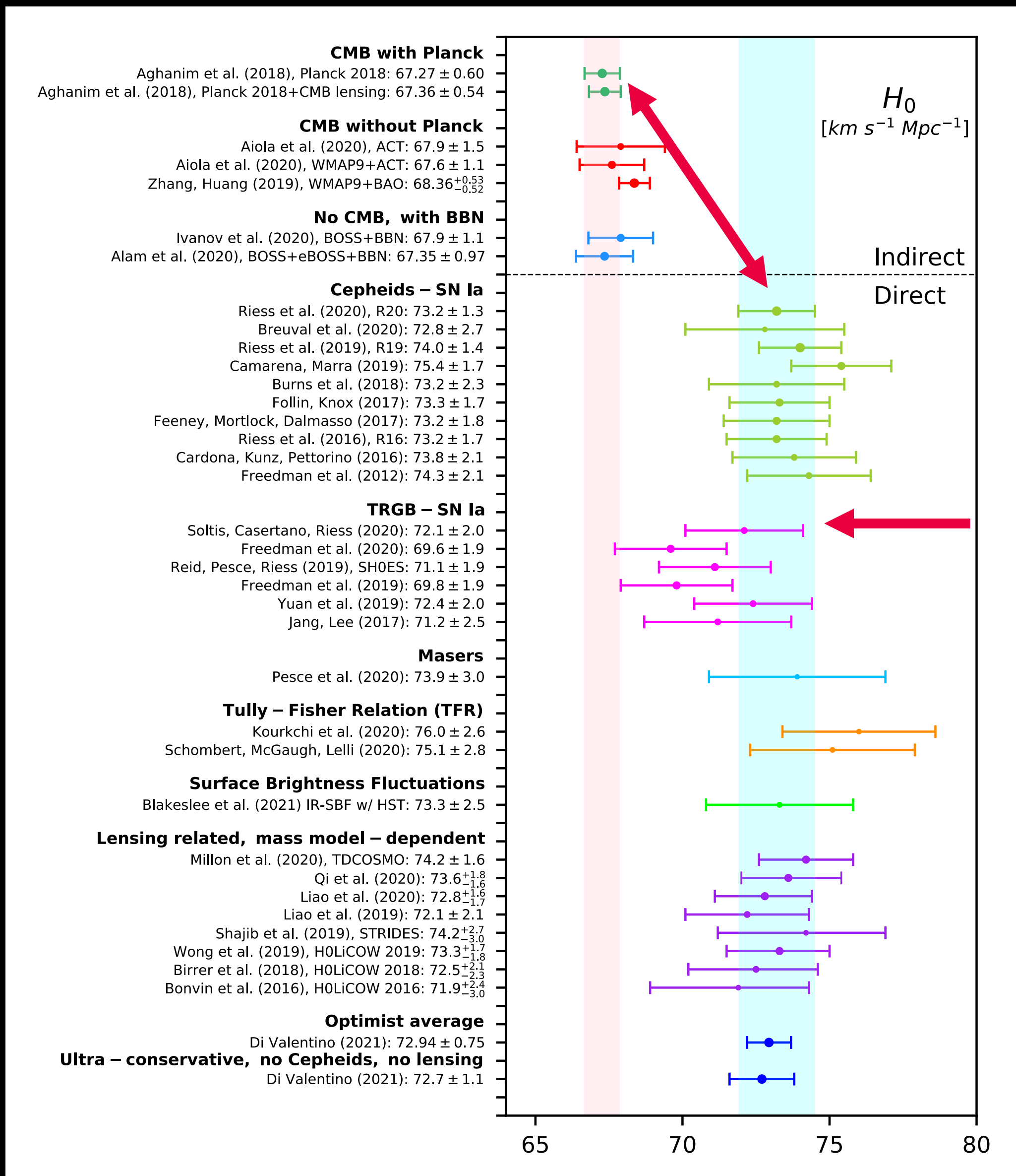
Different Team (KP), photometry, Cepheids, wavelengths

Different HST Instruments

NEW: Reanalysis of SH0ES at pixel level, different methods, 1% agreement Araucauria: Javanmardi et al 2021, ApJ,

Others? The Hubble Constant Tension, Discrepancy, Problem, Crisis

Present Status*



KITP 2019 (Verde, Treu, Riess 2019)

"does not appear to depend on the use of any one method, team or source"

Early:67-68, Late:70-75
No Cepheids: 4.5-5.3σ
No TRGB: 5.7-6.3σ
No lens: 5.0σ
No SN Ia: 4.9σ
No Cepheids or TRGB: 5.3σ
No Planck: 4.4-4.9σ
No CMB: 4.0-4.5σ
(Riess 2019, Nature Reviews)

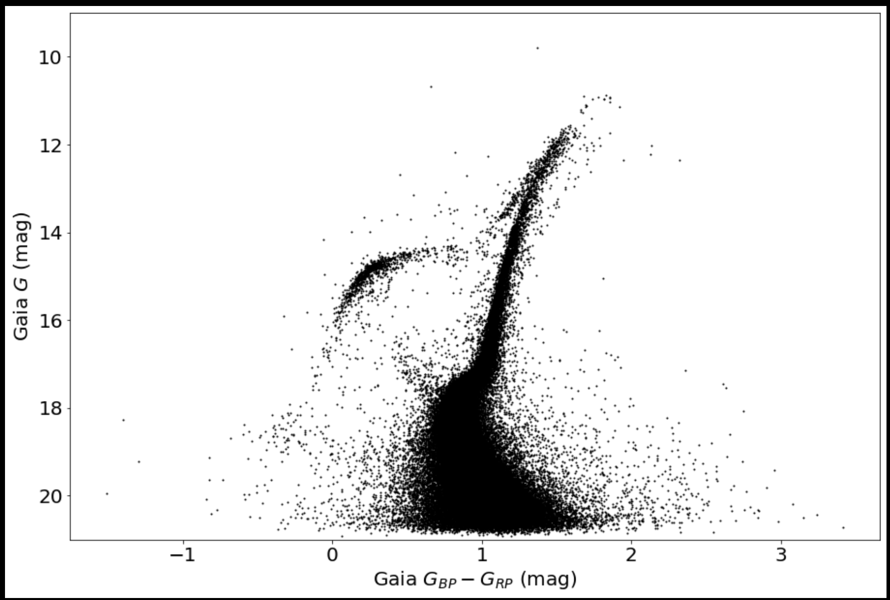
*Compilation: measures w/ σ<4% from Di Valentino et al 2021

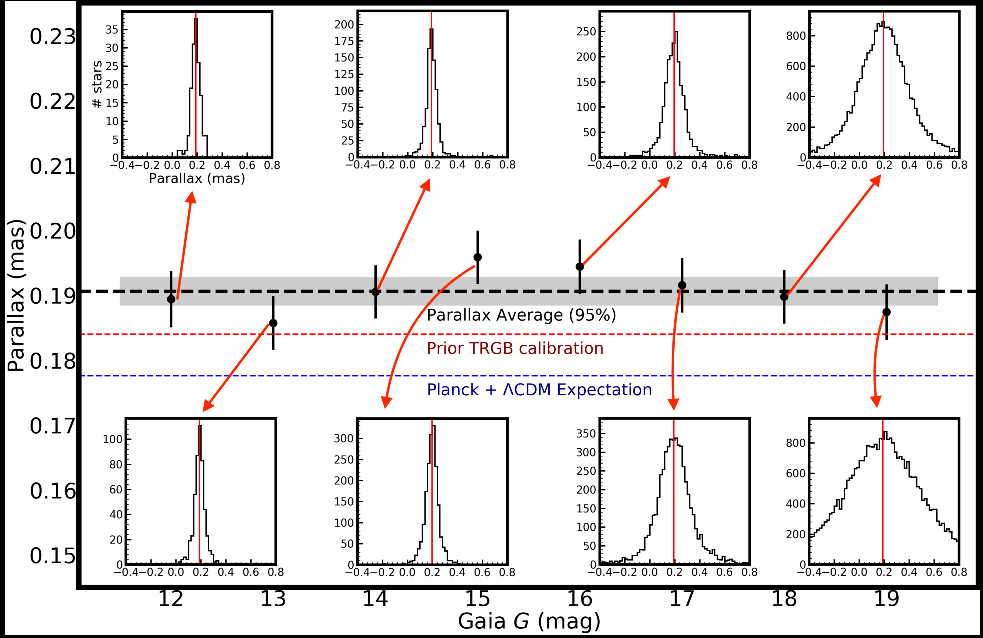
New: Gaia EDR3 Calibrates TRGB w/ Parallax of Omega Centauri

ω Centauri: biggest globular cluster, best *direct* MW TRGB

Soltis, Casertano, AGR, ApJ, 2021, 908, 5

- 67,000 stars w/ tight position, motion locus in EDR3, sharp CMD, parallax independent of mag, color
- $\pi = 0.191 \pm 0.005,$ w/ known apparent tip and MW extinction→ M_I=-3.97 $\pm$ 0.06 mag, H_0=72.1+/- 2.0 km/s/Mpc
- 4 Gaia studies, π good agreement (Maiz-Apellaniz+2021, Baumgardt et al 2019,Vasiliev+21), our σ in middle→ robust

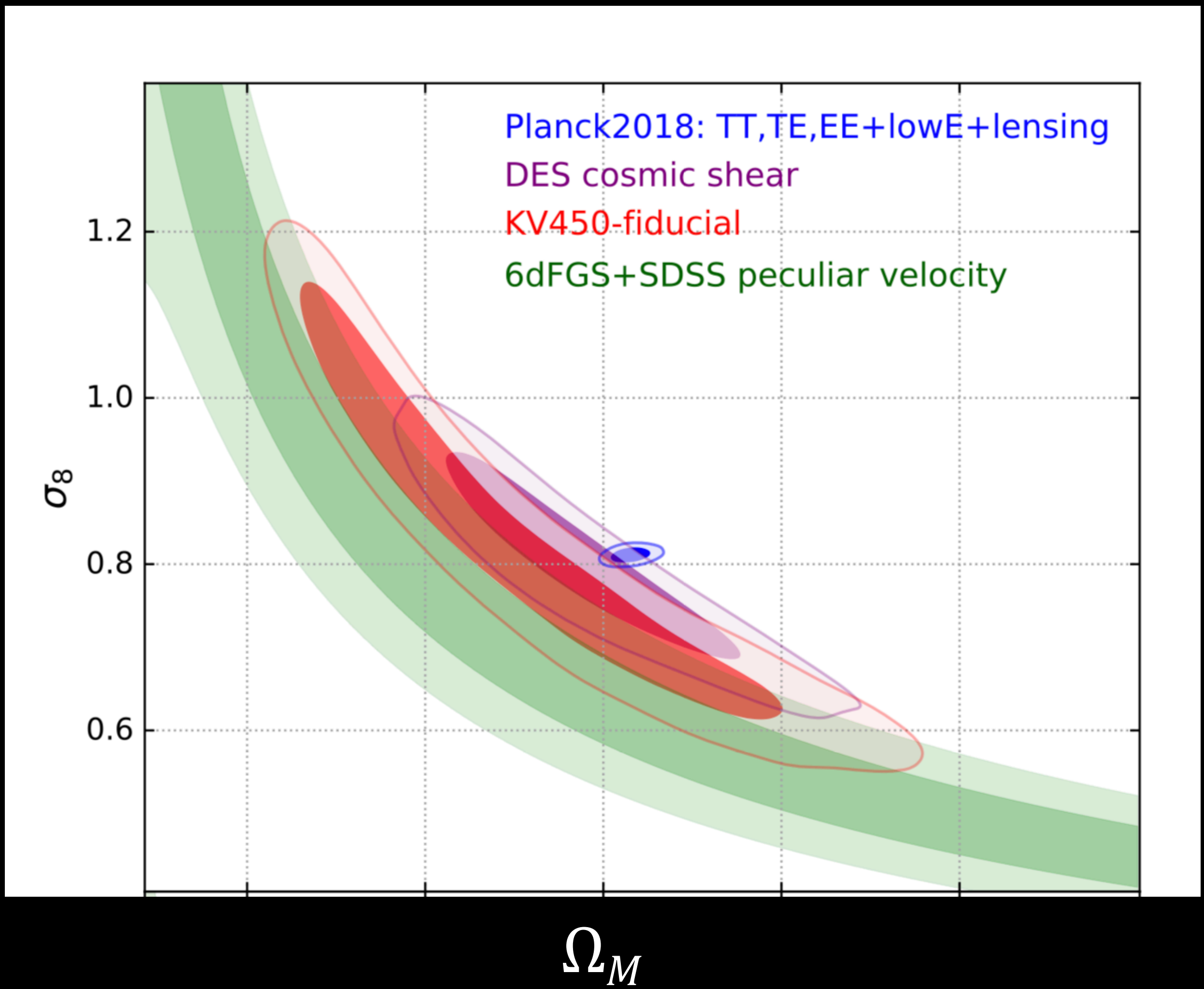




Another Early vs Late Tension? Matter clumpiness, σ_8

RMS matter fluctuation, σ_8, ($r=8\ h^{-1}$ Mpc), 0.8 Early vs late divide

~3 σ from lensing and peculiar velocities, independently



6dFGS+SDSS

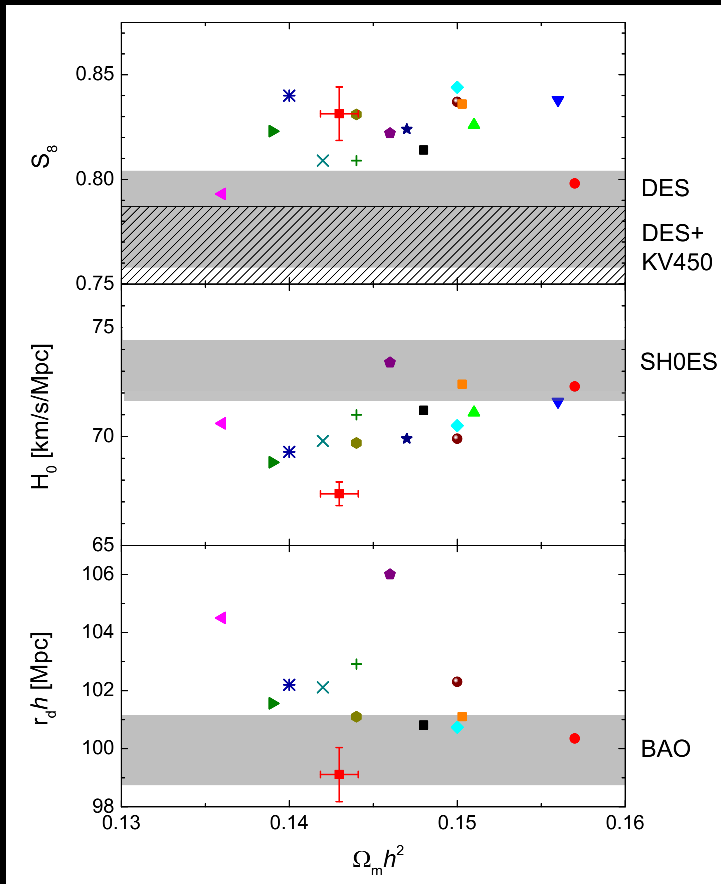
Said, K et al 2020, MNRAS,497, 1275

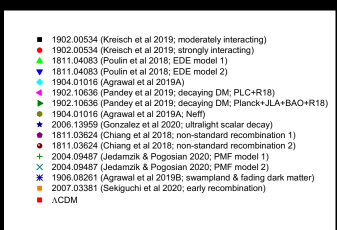
"…deviates by more than 3σ from the latest Planck CMB measurement. Our results favour … a Hubble constant H_0 > 70 km s^{-1} Mpc^{-1} or a fluctuation amplitude σ_8 < 0.8 or some combination of these. "

Cause Early vs Late Difference? New Physics Tempts, “Feign No Hypothesis”

Early dark energy, weird neutrinos, decaying dark matter?

NEW PHYSICS ?





Jedamzik, Pogosian, Zhao,2010.04158
Di Valentino et al (2021) for reviews

Worse: decaying dark matter, w<-1, Swampland

Better: strong neutrino interactions, early dark energy, evolving electron mass, early recombination, PMF

Best: <your idea here>

“The Hubble Hunter’s Guide”, Knox and Millea, 2019: “Most Likely”: Increase Expansion Rate Pre-recombination->reduce sound horizon by 5-8%
Mechanisms: Early DE or sterile (and/or self-interacting) neutrinos
Claims: not worse fit to CMB, should produce new CMB features, future

Believe Measurements Before Understanding Physics?

Don't sweep "problems" under the rug

"Problems" are often clues!

Avoid: "all surprises wrong"

~~Precession of Mercury~~ Solved!

~~Solar Neutrino Problem~~ Solved!

~~Missing Baryon Problem~~ Solved!

Lithium Problem

CMB Cold Spot

Flat rotation curves/
what/where is dark matter?

Accelerating Universe/
why Λ so small?

Can We Believe Explanation without hypothesis (*how*)?

“Its Ne

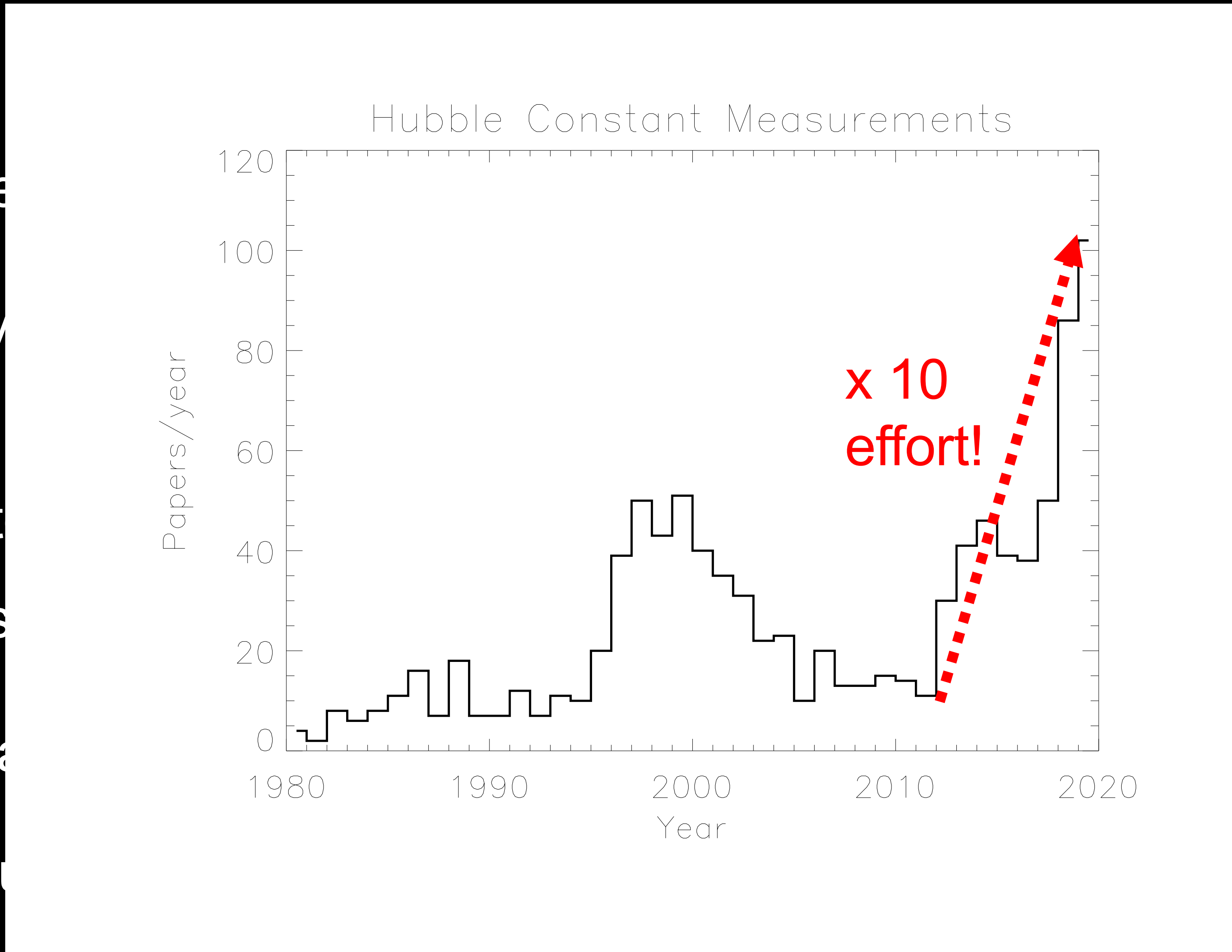
“Its Sy ungs,
dupli

Data t ation

Reasons

New da

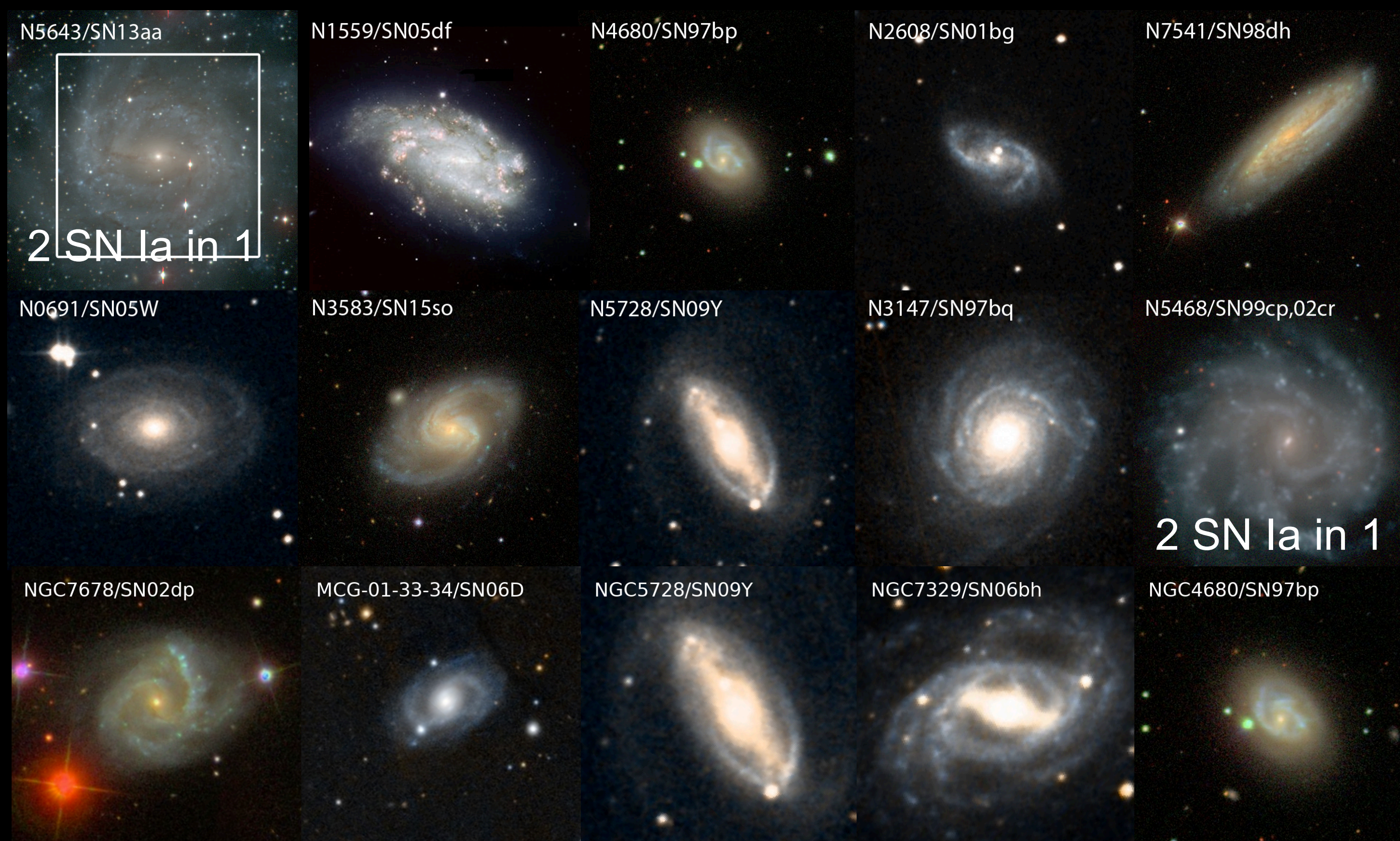
New cl l, BBN?



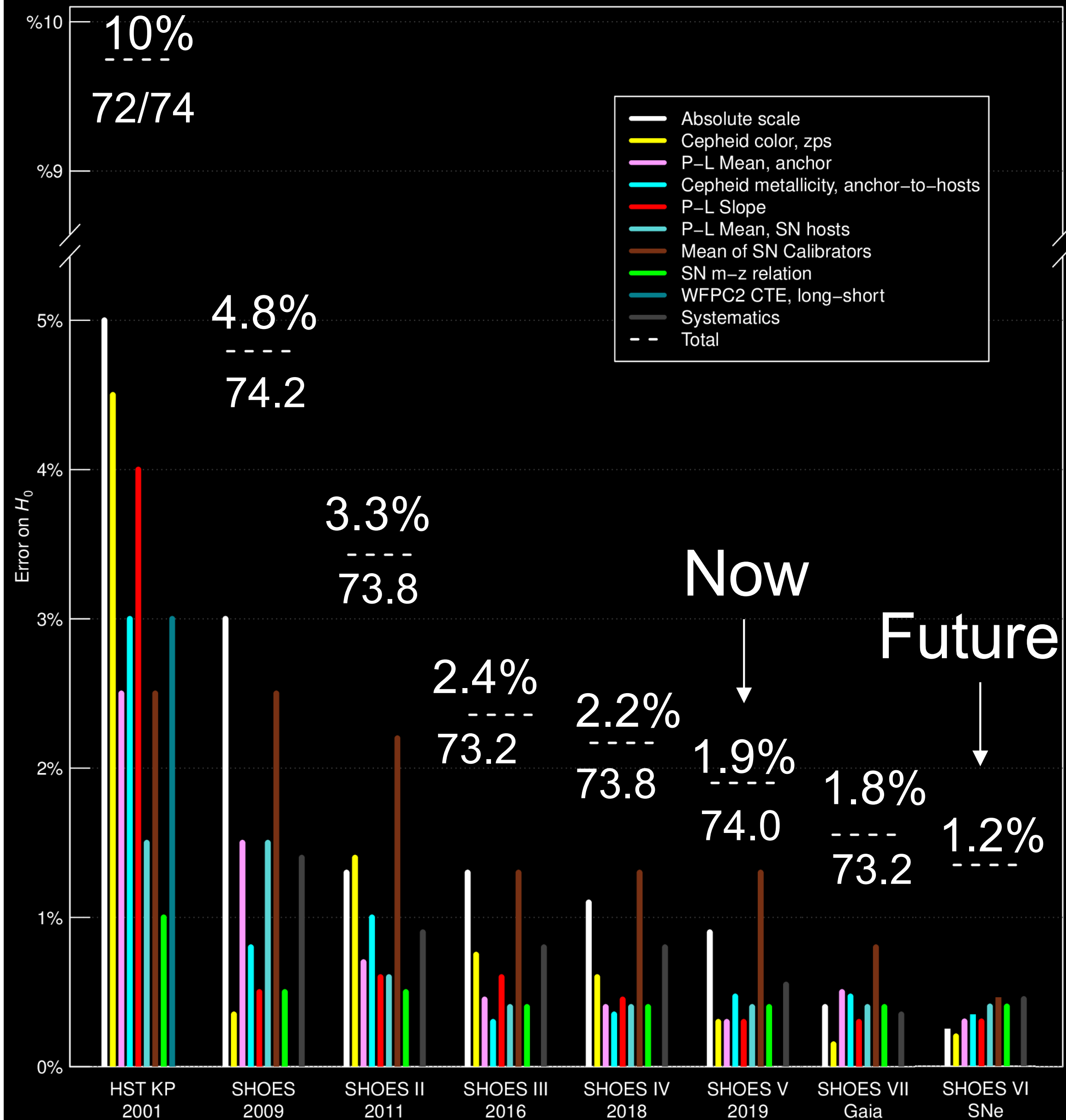
Big Playground: Lambda CDM is 95% dark, quantum gravity

Next Steps: Increasing Number of SN-Cepheid Calibrations

NEW SHOES Large HST Programs, Cycles 25,26,28
24 more Cepheid-SN Ia Calibrators underway,
to reach total=43, + Cepheids to Coma!
more Cepheid calibrations in NGC 4258



Future Prospects…



- **New low-z SN samples**
- **Doubling SN Calibrator sample, 19→40**
- LIGO H_0 (Late Universe)
- DESI,LSST,WFIRST,Euclid →better w(z)
- Next generation CMB: signatures (e.g., EDE)
- Stay tuned…

Final Thoughts

- Discrepancy is ~5σ (4-6) σ (depending on combination)

  No precise Late Universe measurements lower than any Early

- Appears robust, requires <u>multiple</u> catastrophic failures to avoid

- <u>Very interesting!</u> (unless your Bayesian prior on ΛCDM > 5 σ or willing to discard most data)

- Let's follow evidence, find the *how*, hopefully Universe more clever than we are *now*

Di Valentino et al 2021 (σ <4%)