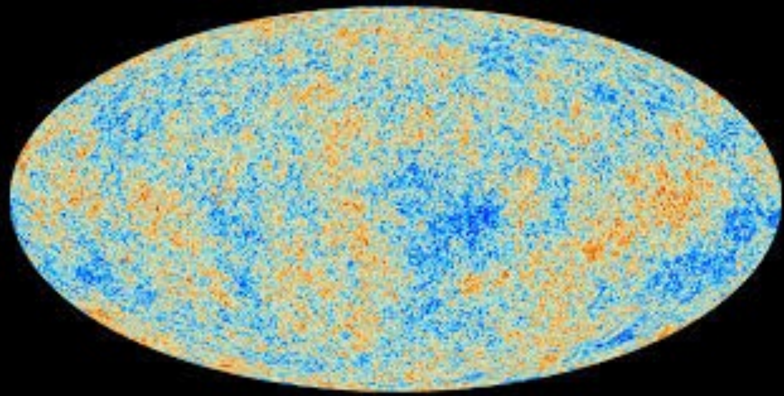
How many h are there? And what do they mean?



Licia Verde
ICREA & ICCUB

ICREA ICCUB EXCELENCIA MARÍA DE MAEZTU
UNIVERSITAT DE BARCELONA
GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD
erc

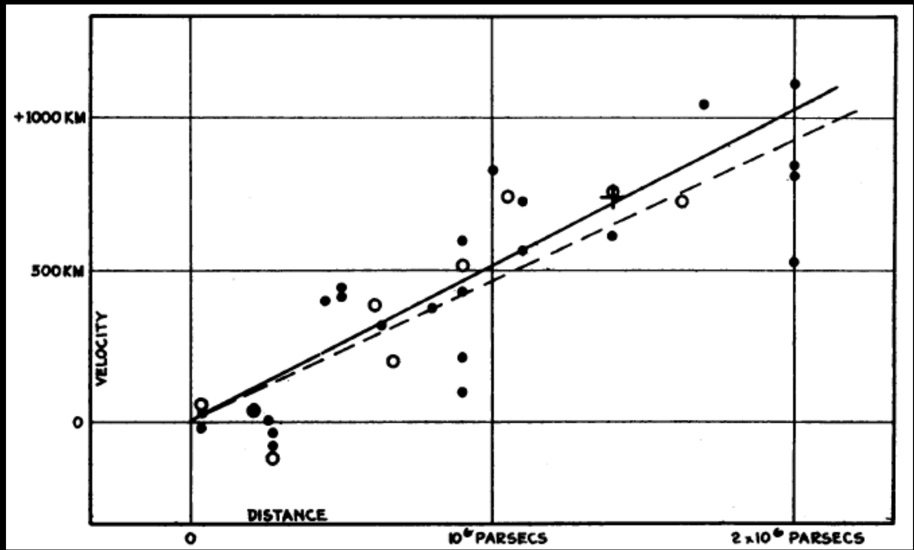
Those who do the real work

- Samuel Brieden
- Hector Gil-Marin

more recently: Nils Schoneberg

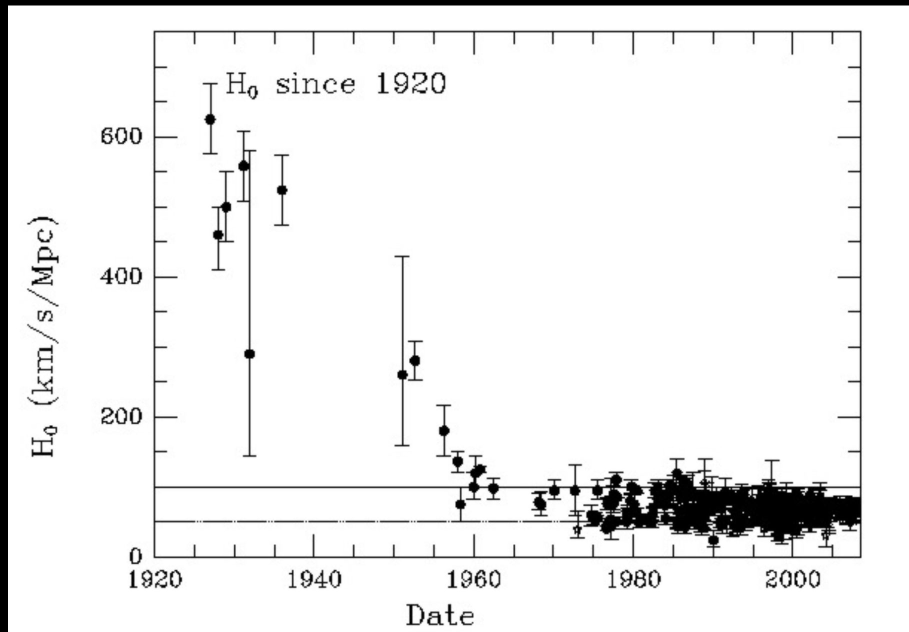
Measuring velocities is easy, but measuring distances is hard

The expanding Universe



$$v = H_0 d$$

However



Friedmann equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

Pillars:
GR+ cosmological principle

Friedmann equations

$$\frac{H^2}{H_0^2} = \Omega_{0,\mathrm{R}} a^{-4} + \Omega_{0,\mathrm{M}} a^{-3} + \Omega_{0,k} a^{-2} + \Omega_{0,\Lambda}.$$

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

The cosmological parameters have appeared!

Friedmann equations

$$\frac{H^2}{H_0^2} = \Omega_{0,\mathrm{R}} a^{-4} + \Omega_{0,\mathrm{M}} a^{-3} + \Omega_{0,k} a^{-2} + \Omega_{0,\Lambda}$$

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

The cosmological parameters have appeared!

> SPACETIME TELLS MATTER HOW TO MOVE;
> MATTER TELLS SPACETIME HOW TO CURVE.
>
> - JOHN ARCHIBALD WHEELER -

H is always on the LHS…

the “cosmo race”

- Since then the development of cosmology

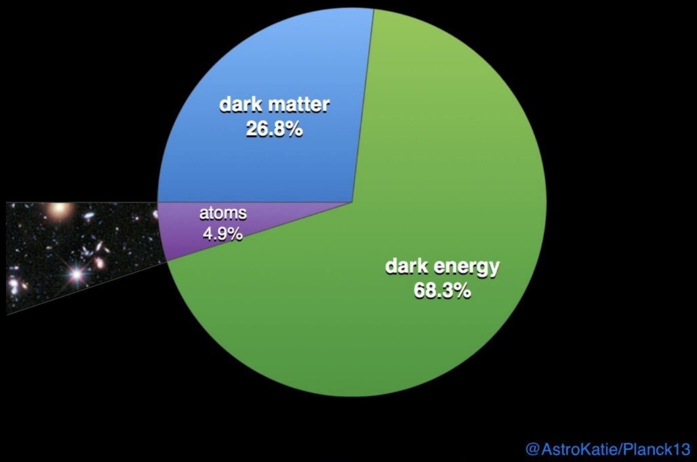
could be summarized by the efforts to constrain cosmological parameters

The standard model of cosmology

The ΛCDM model

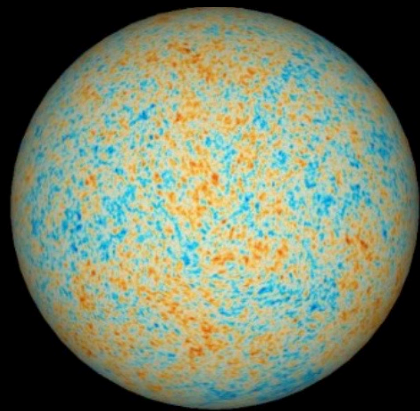
few cosmological parameters: “Just 6 numbers”….

Composition,
background evolution



$\Omega_b, \Omega_c, \Omega_\Lambda, H_0$;

perturbations



τ, As ns

….describe observations of the Universe
across some 14 billion years of evolution

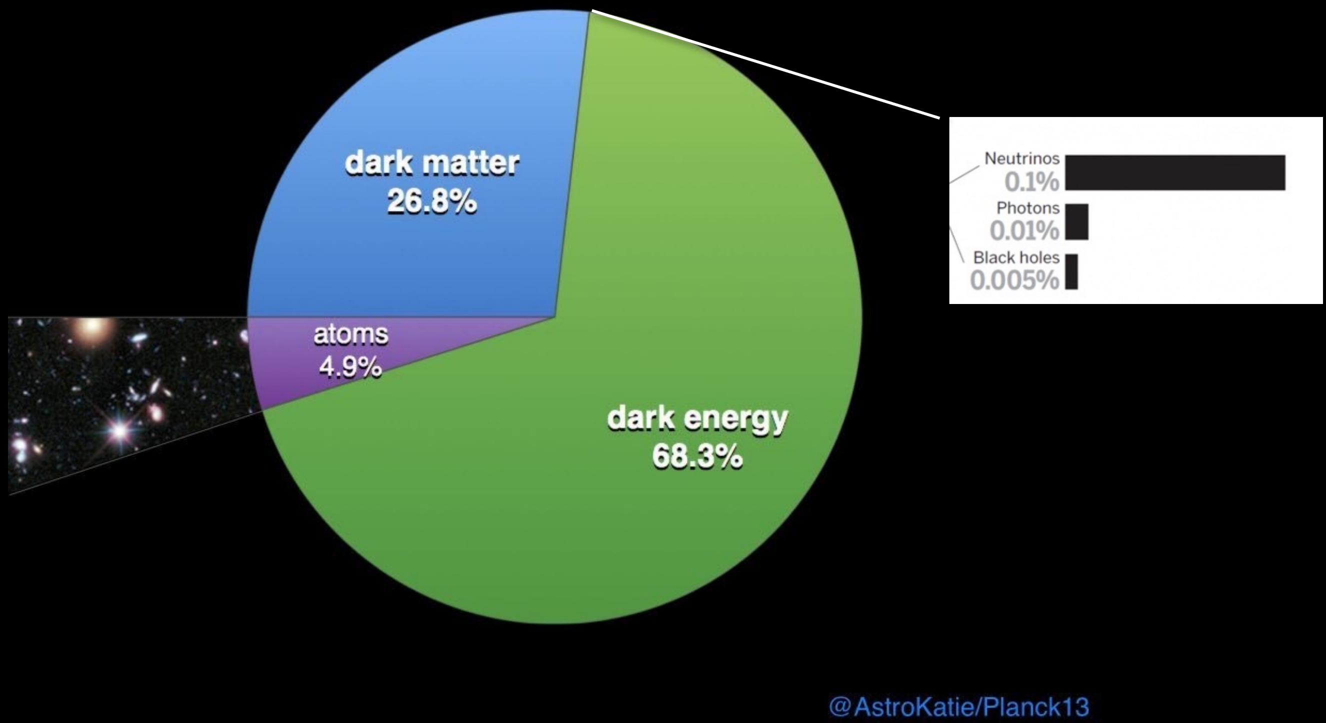
The model’s parameters are now determined with % accuracy

Precision cosmology!

Precision cosmology

More has been discovered about the large-scale structure and history of the visible cosmos in the last 20 years than in the whole of prior human history. (Tim Maudlin)

Never mind that the model is weird



Friedmann equations

$$\frac{H^2}{H_0^2} = \Omega_{0,\mathrm{R}} a^{-4} + \Omega_{0,\mathrm{M}} a^{-3} + \Omega_{0,k} a^{-2} + \Omega_{0,\Lambda}$$

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

The cosmological parameters have appeared!

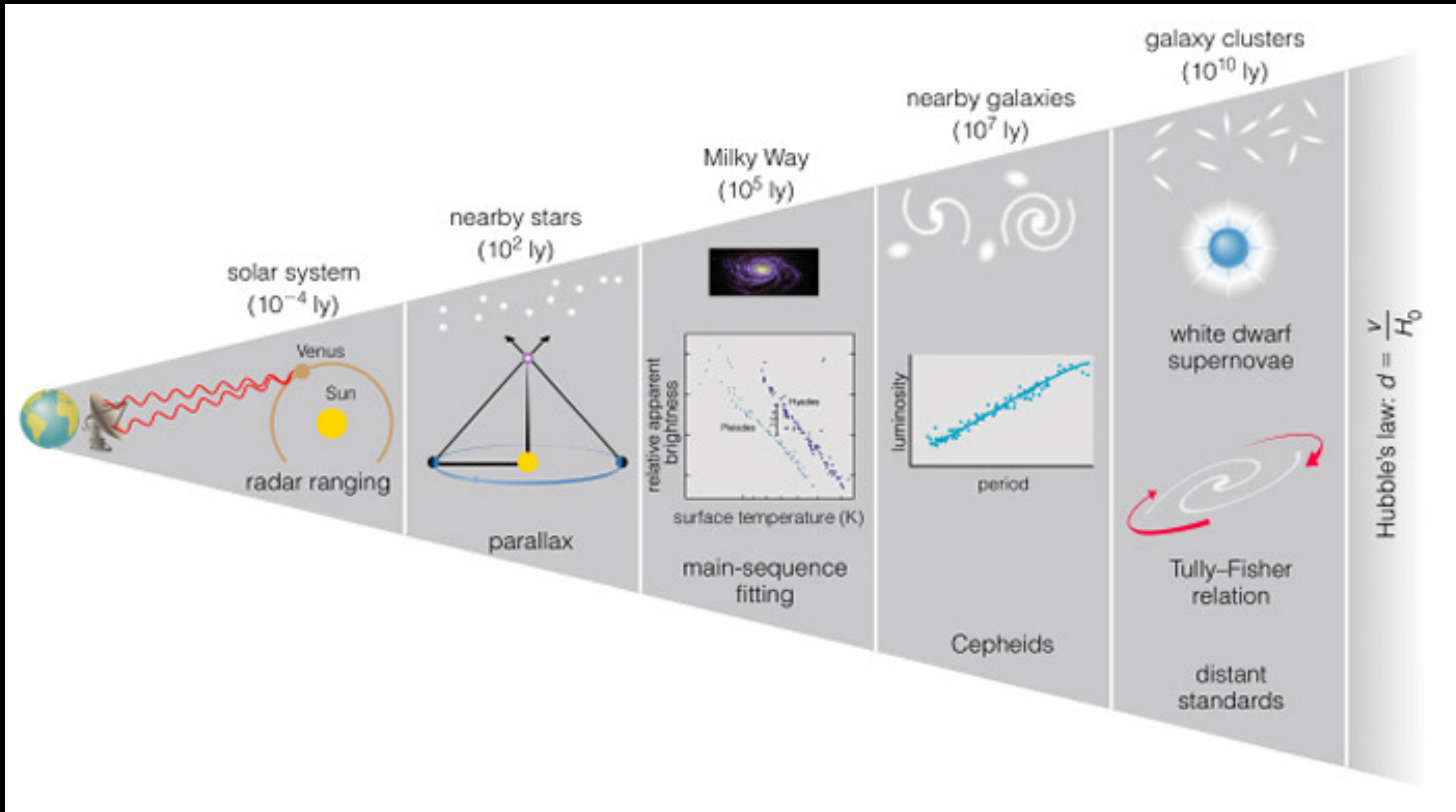
SPACETIME TELLS MATTER HOW TO MOVE;
MATTER TELLS SPACETIME HOW TO CURVE.

- JOHN ARCHIBALD WHEELER -

H is always on the LHS…

Get H this way

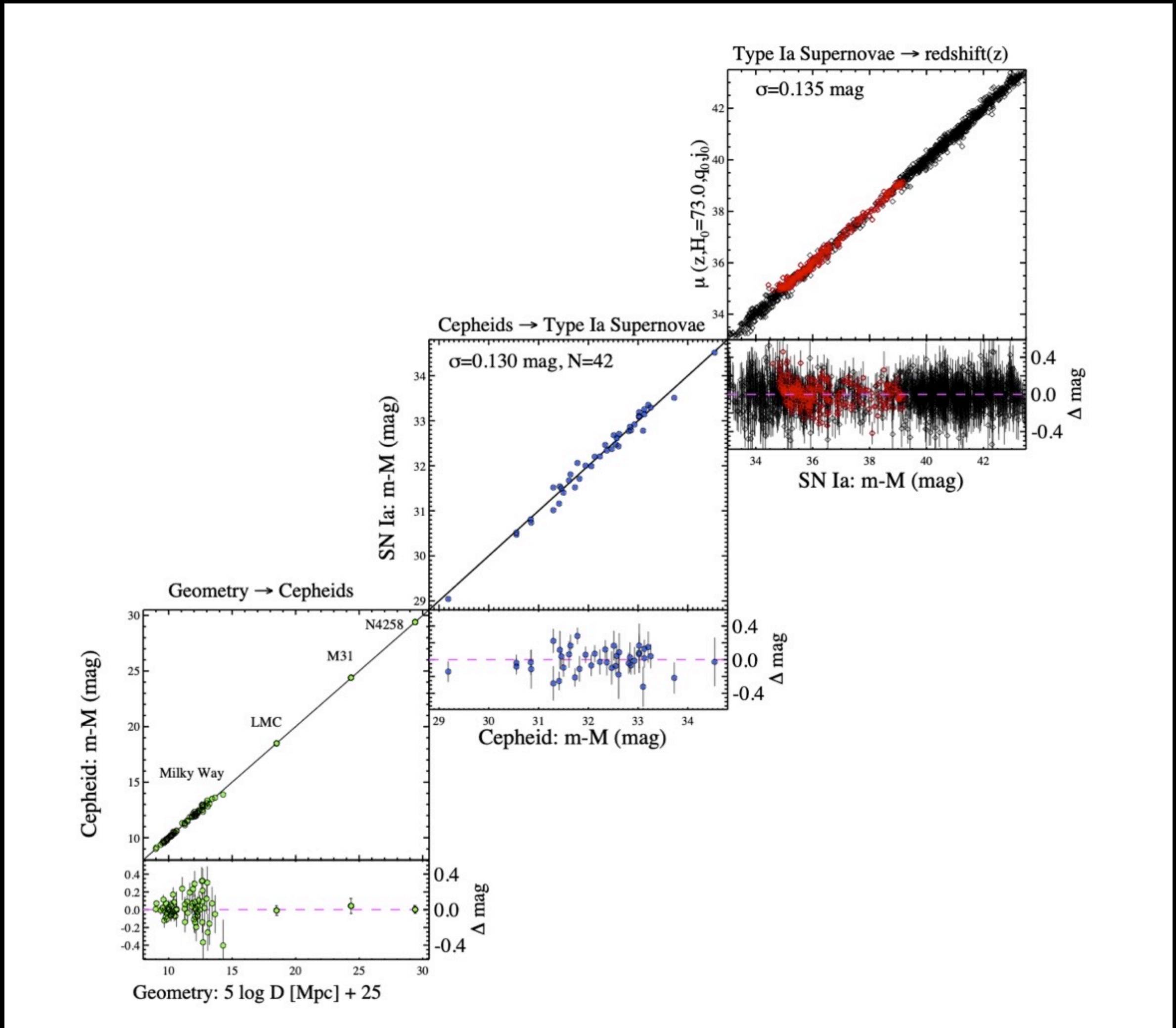
- Do what it says on the can: distances vs redshifts



Three key rungs and 2 key steps: geometry to cepheids and cepheids to supernovae

Get H this way

- Do what it says on the can: distances vs redshifts

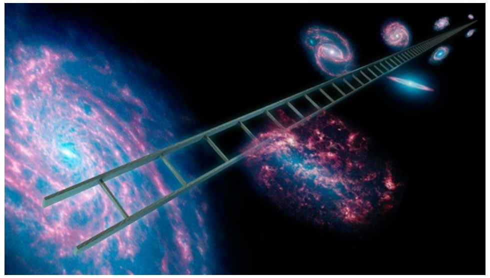


Riess et al. 2021

H_0 is everywhere….. and very special

- We measure (mostly) redshifts and angles, we think in distances….
- We even invented units of h. H_0=100h km/s/Mpc
- H_0 is a KEY cosmological parameter

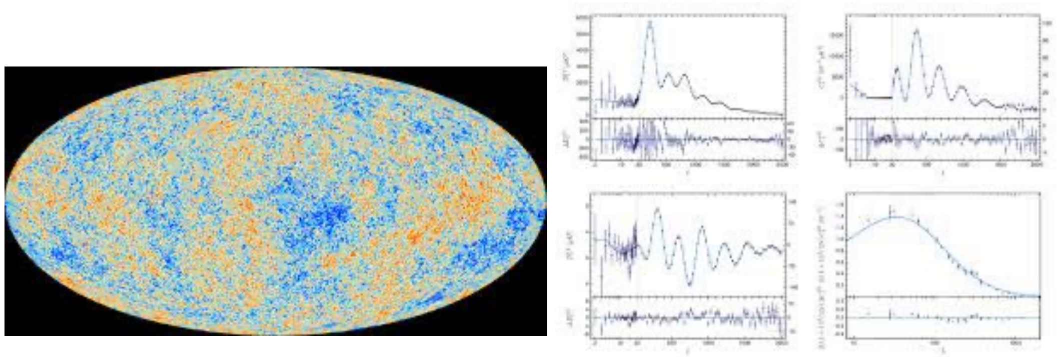
($z \lesssim 0.1$)
Present day expansion rate of the Universe
Recession velocity → distance.



Parallaxes
Cepheids
SNe
TRGB
SBF
Masers
Etc…

Cosmic distance ladder

Global , cosmological parameter of a model



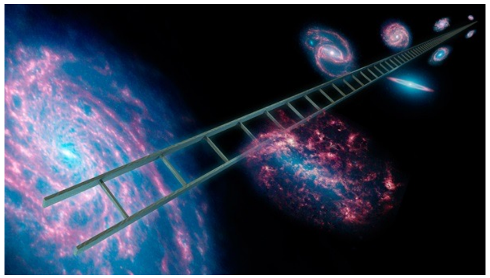
Calibrated on early-time physics

Two cosmic speedometers

H_0 is everywhere….. and very special

- We measure (mostly) redshifts and angles, we think in distances….
- We even invented units of h. H_0=100h km/s/Mpc
- H_0 is a KEY cosmological parameter

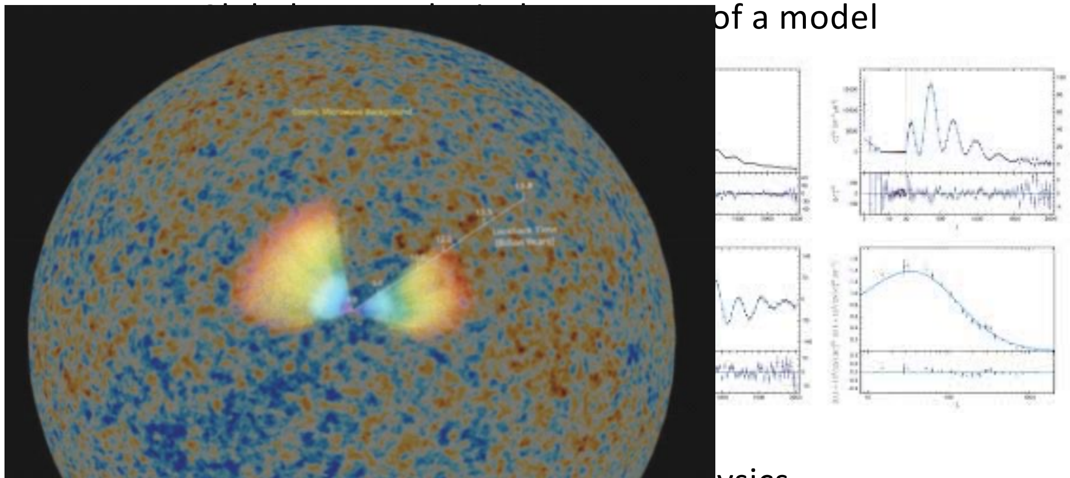
$(z \lesssim 0.1)$
Present day expansion rate of the Universe
Recession velocity → distance.



Parallaxes
Cepheids
SNe
TRGB
SBF
Masers
Etc…

Cosmic distance ladder

of a model



Calibrated on early-time physics

Two cosmic speedometers

A tale of two H's

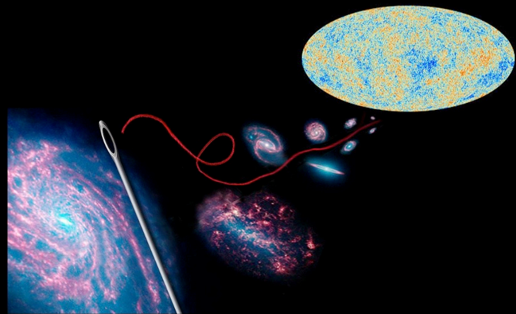
$(z \lesssim 0.1)$
Present day expansion rate of the Universe
Recession velocity → distance.

Parallaxes
Cepheids
SNe
TRGB
SBF
Masers
Etc…

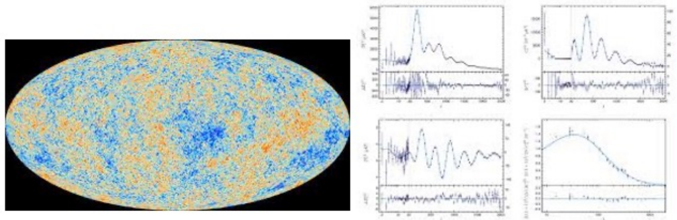
Cosmic distance ladder

A priori, these two numbers do not have to coincide.

If they coincide then……



Global , cosmological parameter of a model

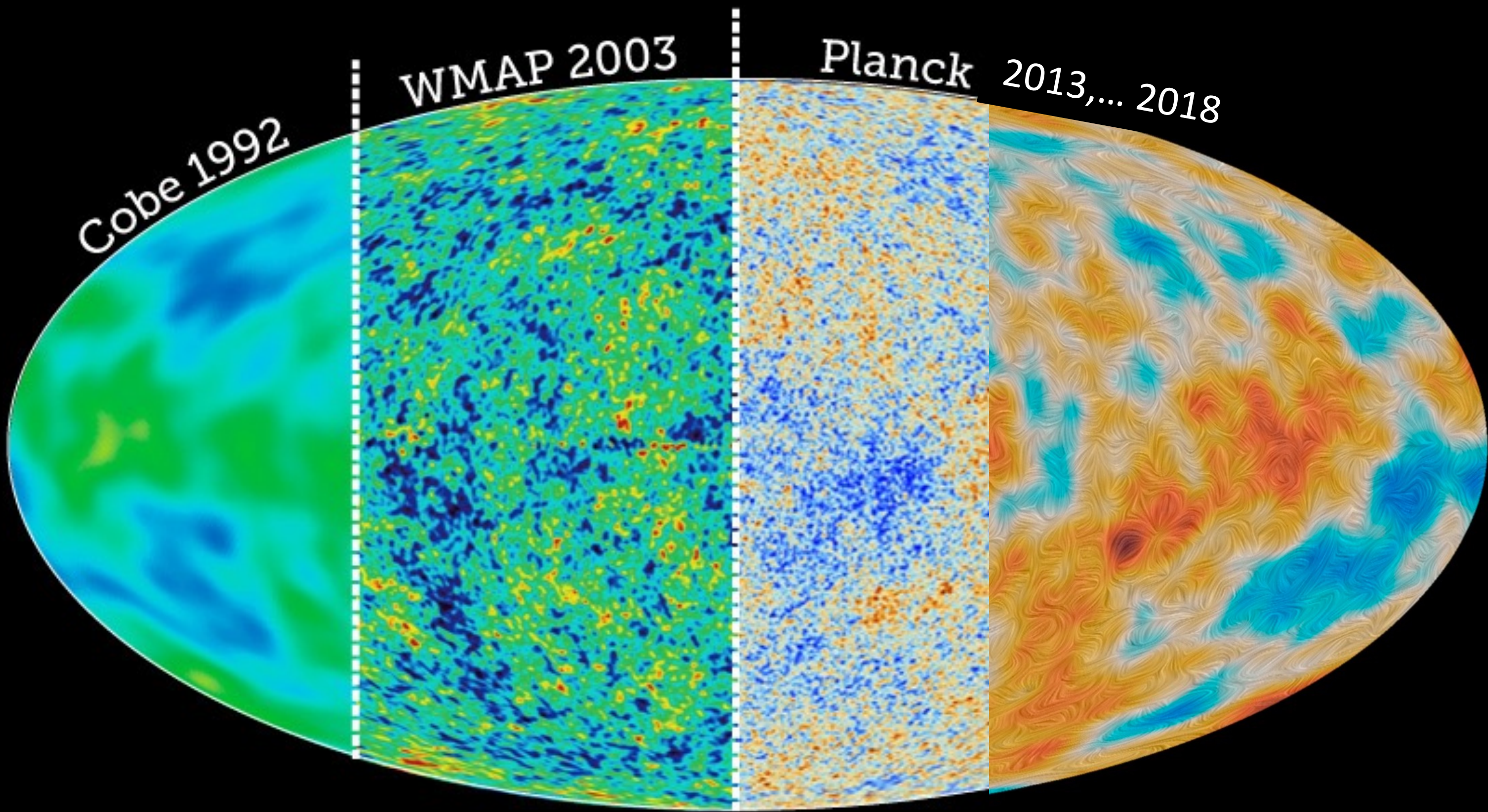


…the adopted cosmological model survives an extremely stringent test

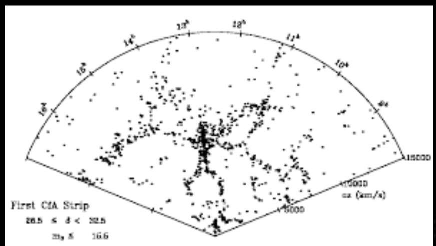
For almost 2 decades these two H's agreed

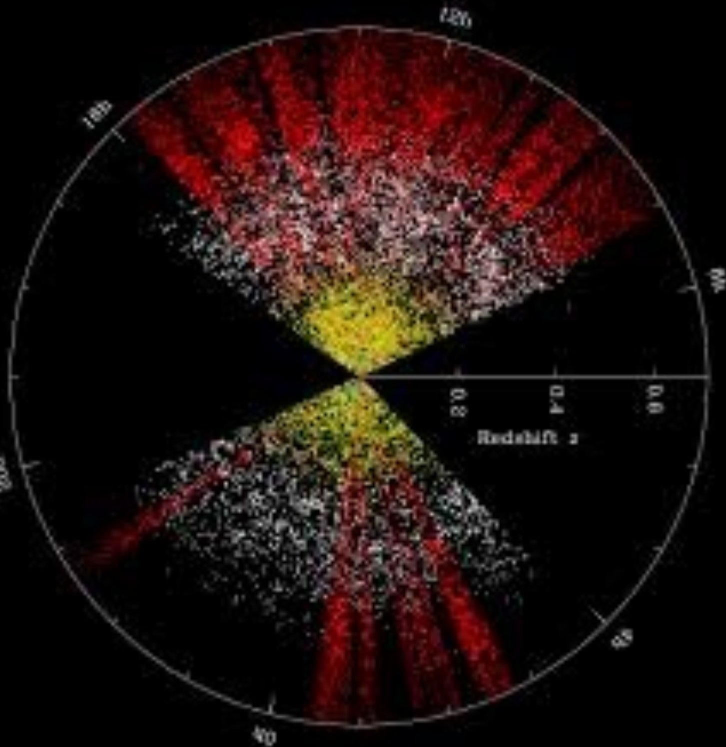
What happened in these 2 decades?

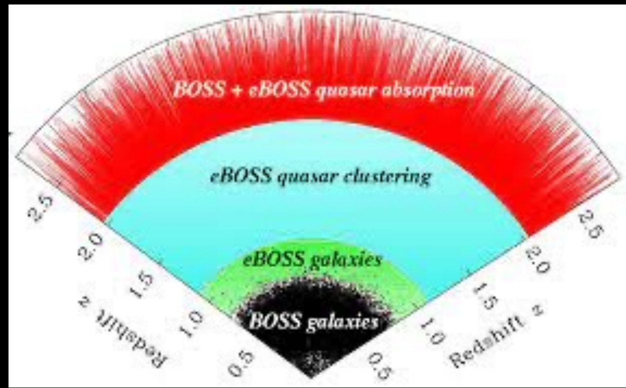
The ΛCDM model has survived unscathed an avalanche of data

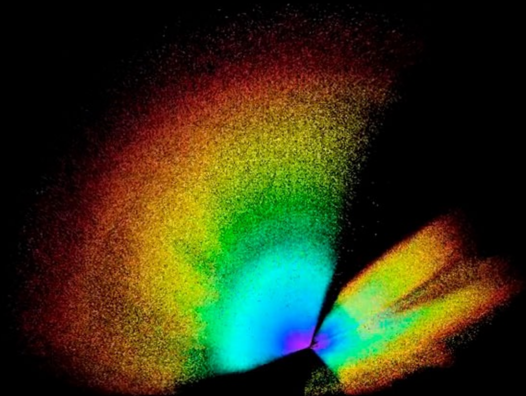


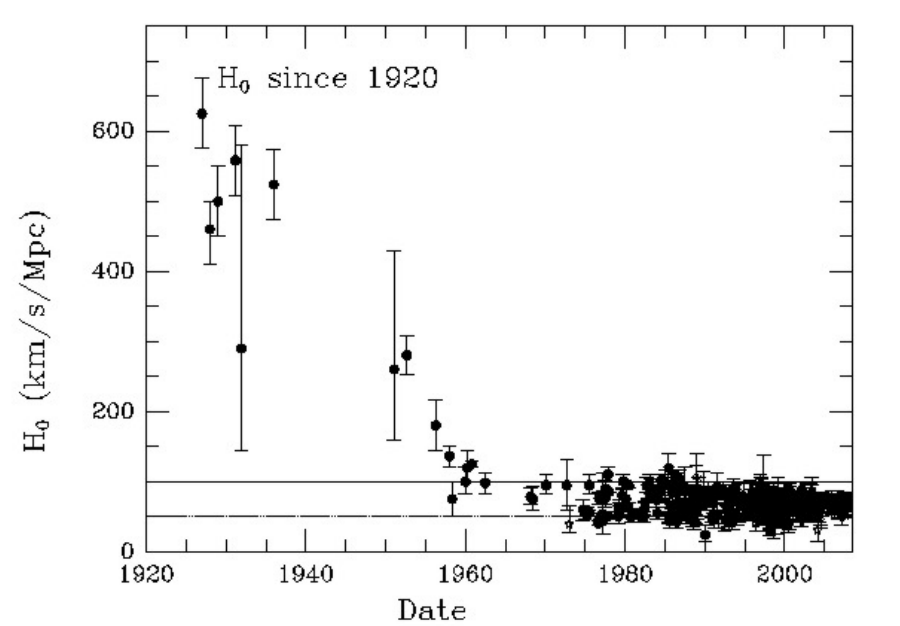
The ΛCDM model has survived unscathed an avalanche of data









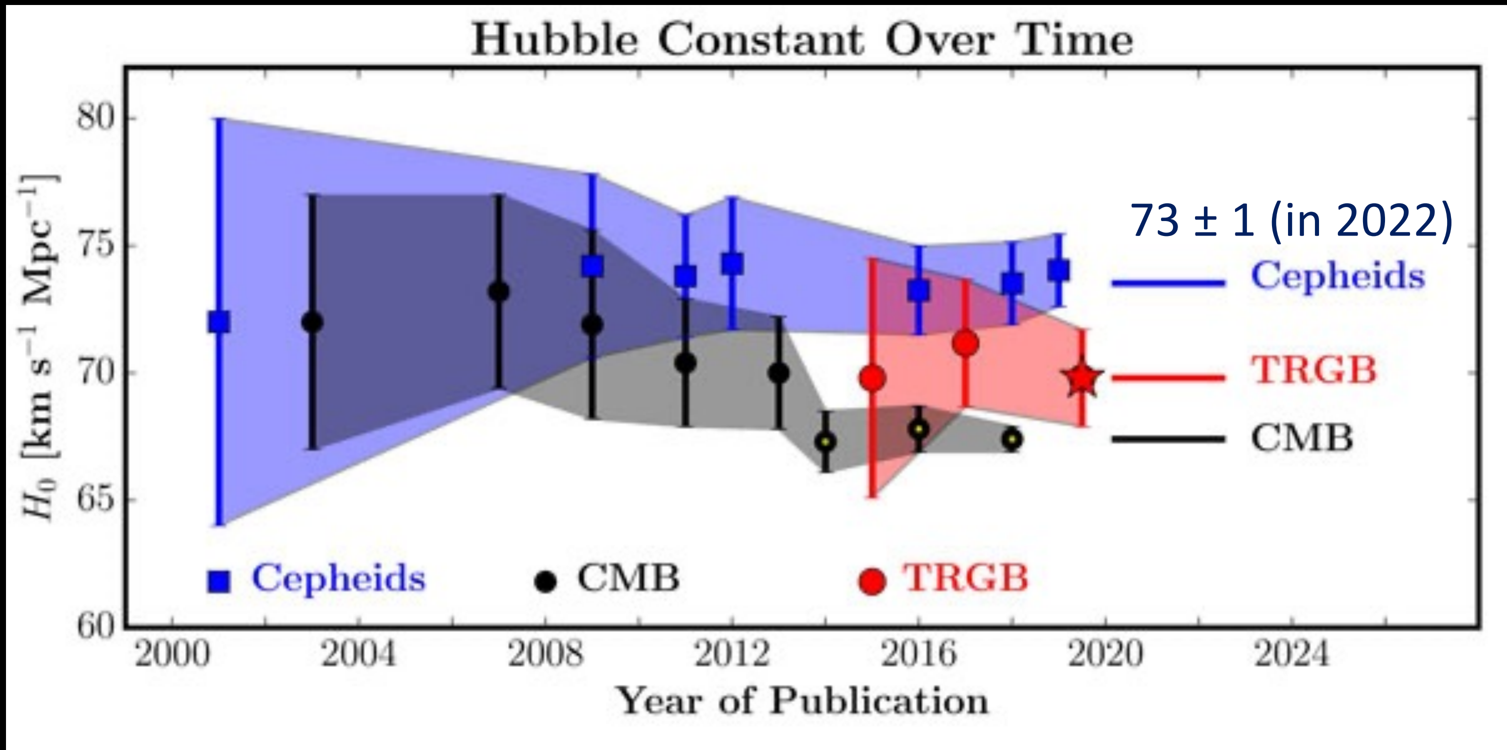


H0 since 1920
H0 (km/s/Mpc)
600
400
200
0
1920
1940
1960
1980
2000
Date

Then something happened....

73 ± 1 (in 2022)

Constant not constant



A tale of two H’s

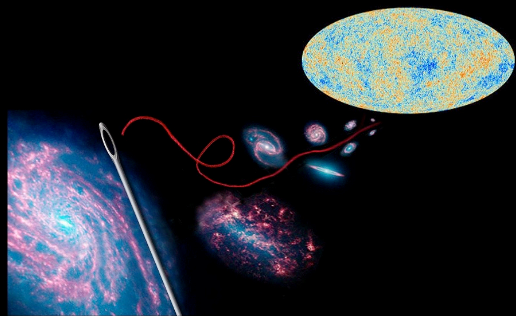
($z \lesssim 0.1$)
Present day expansion rate of the Universe
Recession velocity → distance.

Parallaxes
Cepheids
SNe
TRGB
SBF
Masers
Etc…

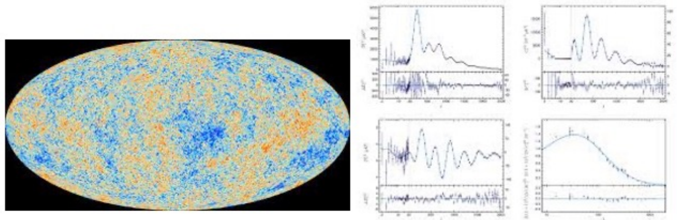
Cosmic distance ladder

A priori, these two numbers do not have to coincide.

If they coincide then……



Global , cosmological parameter of a model



…the adopted cosmological model survives an extremely stringent test

…..And if these two numbers do not coincide?

Errors in the data

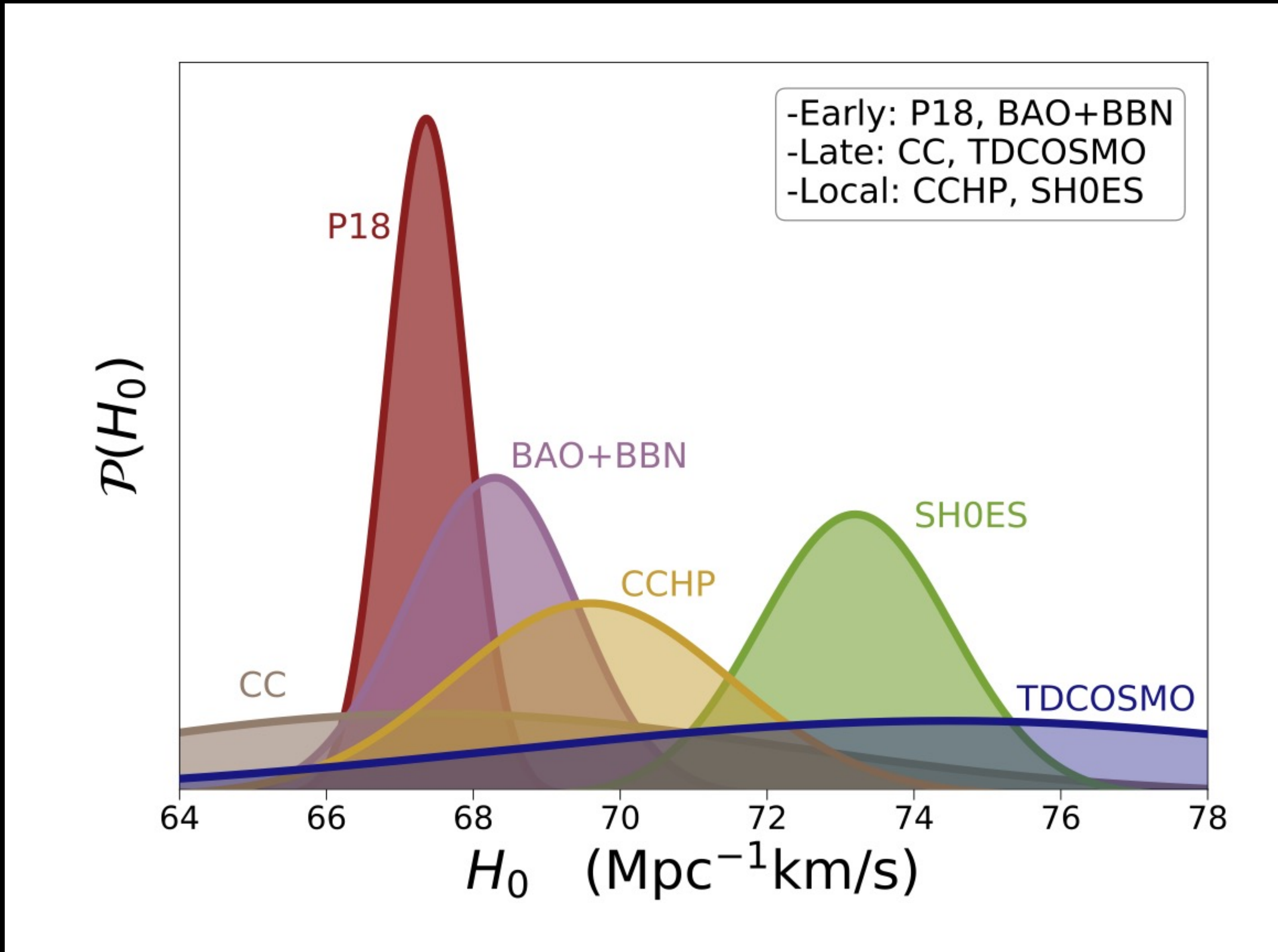
Errors in the analysis

Errors in the model

There are many H_0

Not all measurements measure directly the current expansion rate

Model dependent vs model independent



Will be updated during this conference… just illustrative

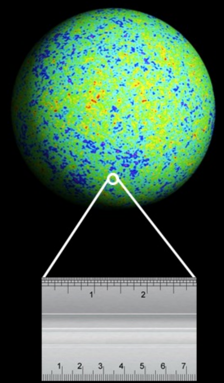
Bernal et al. 2102.05066

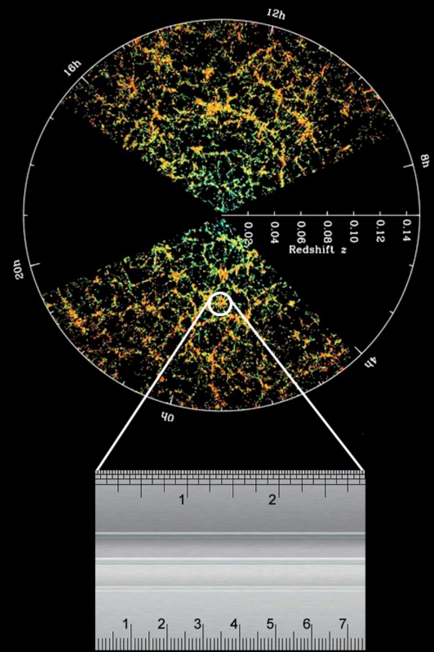
BAOs

Baryon acoustic oscillations

Physics of the early Universe gives a standard ruler

well… in 3d a standard bubble….





a) calibrate ruler on early Universe (physics and/or observations)

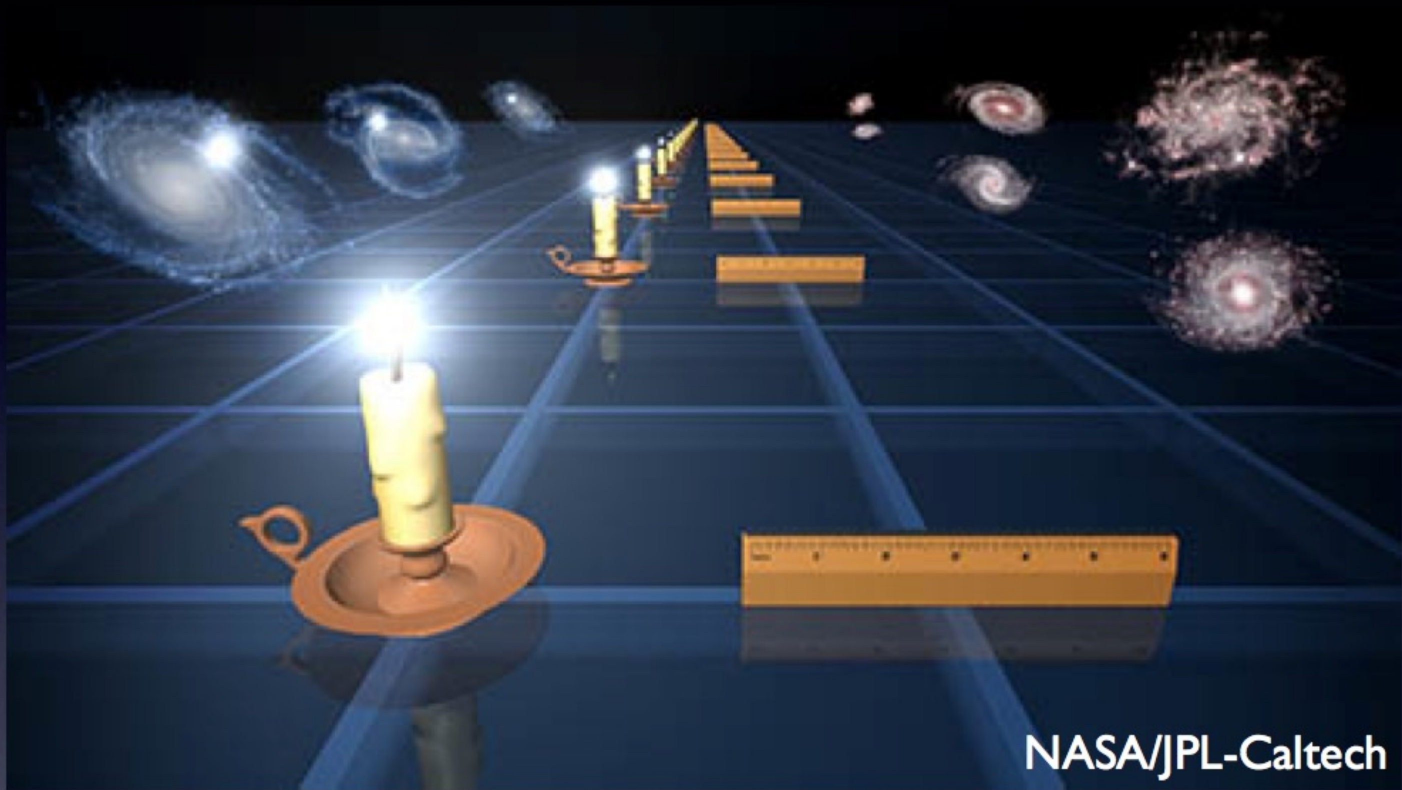
b) say there is a standard ruler, same at all z, but of unknown length

c) use isotropy only (ie. the ruler could change with z)

Effect is a “classic” AP

The ruler is the sound horizon at recombination (CMB), at radiation drag (LSS) but it is the same ruler. Symbols: r_s or r_d

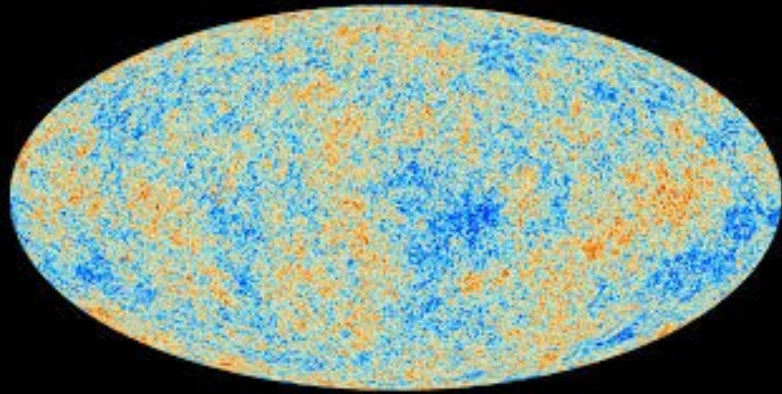
Standard candles & Standard rulers



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}

A truly Cosmological ladder

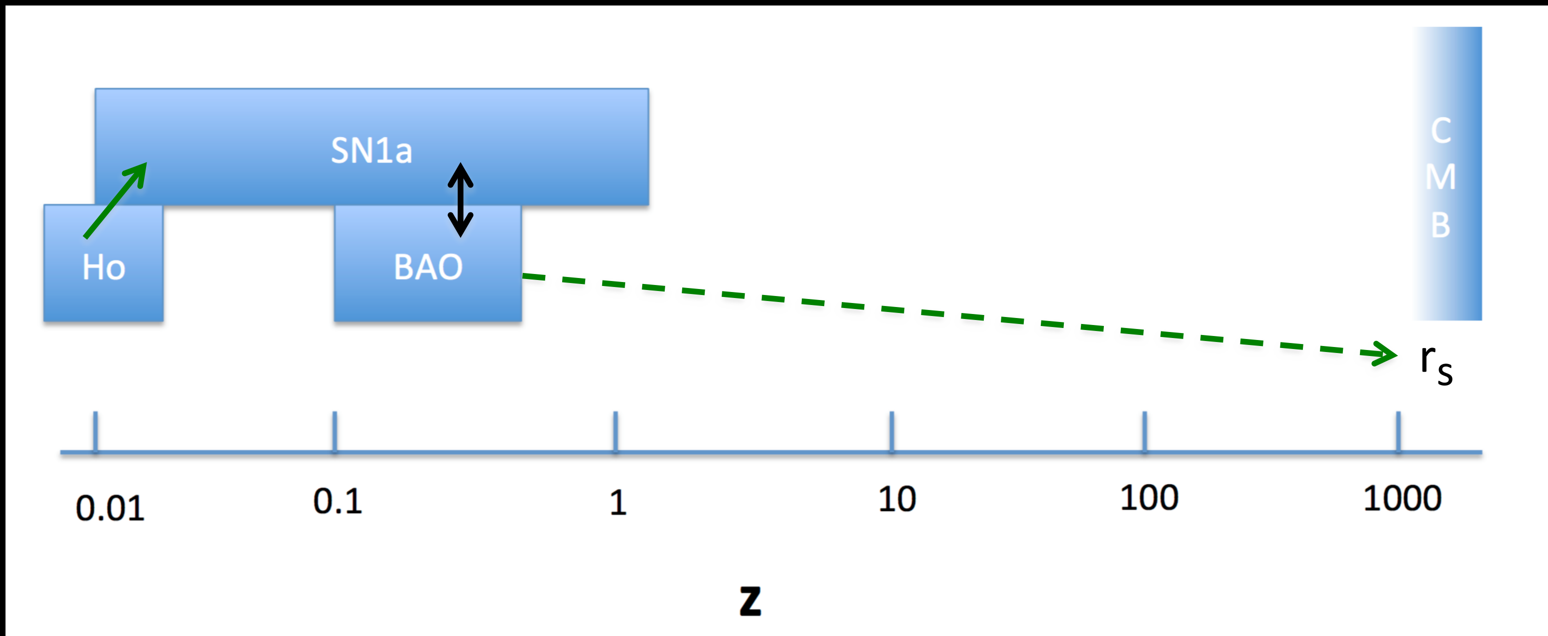


… Since about 2015

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).

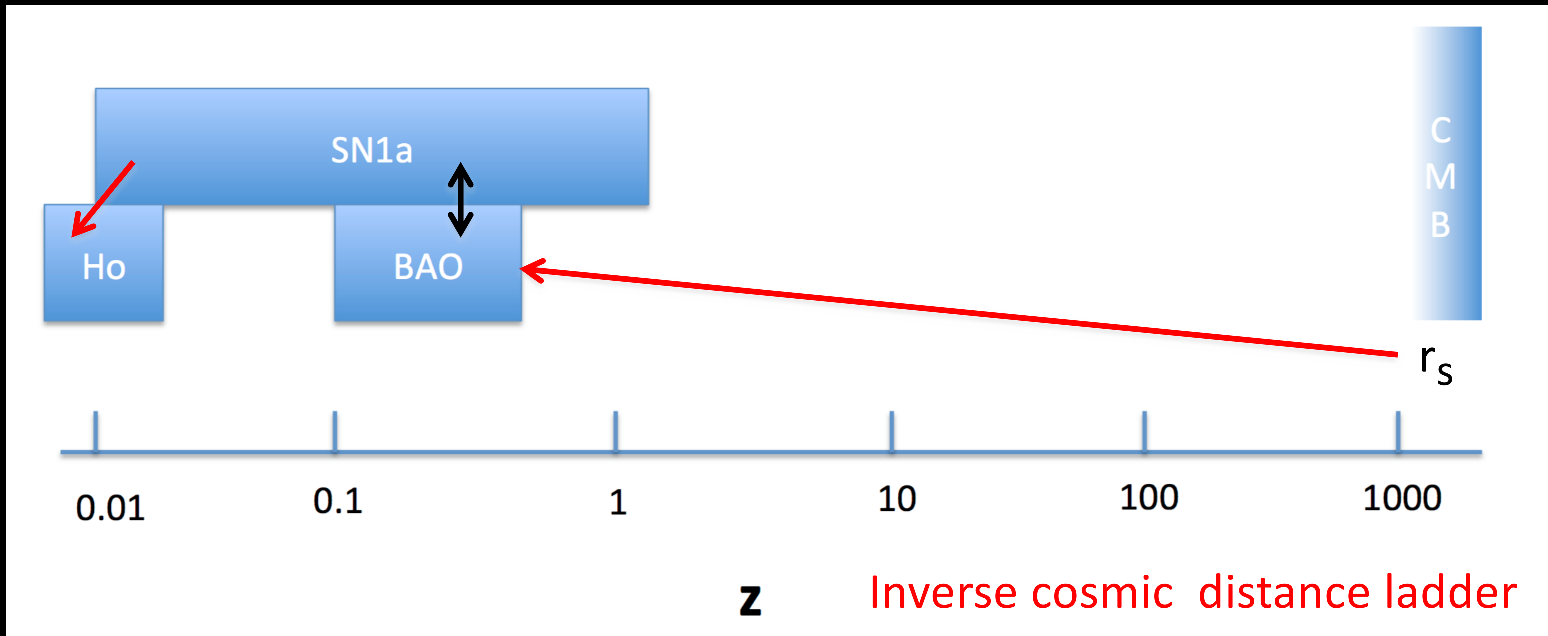
Direct cosmic distance ladder



Direct and inverse cosmic distance ladder

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

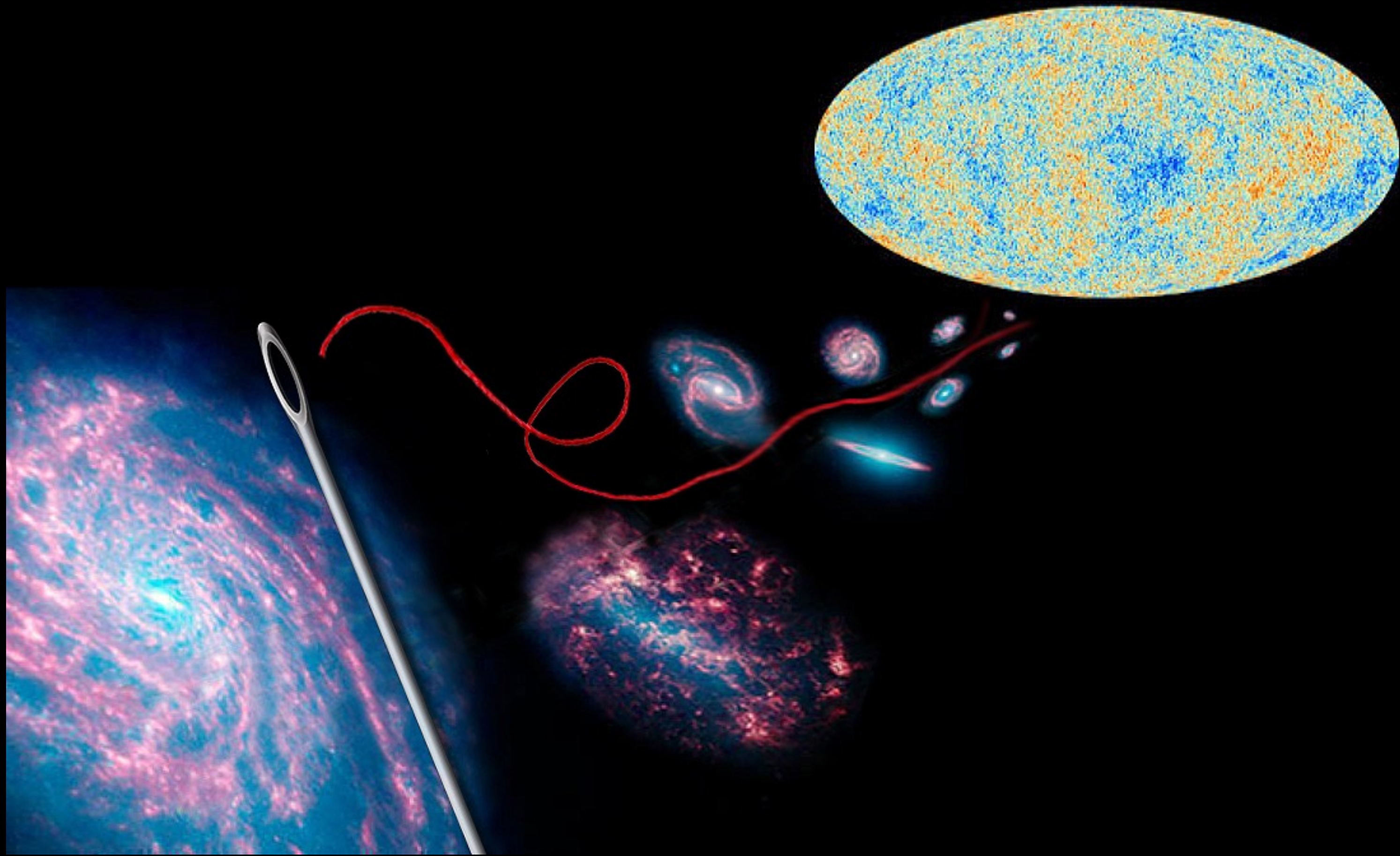
Direct cosmic distance ladder



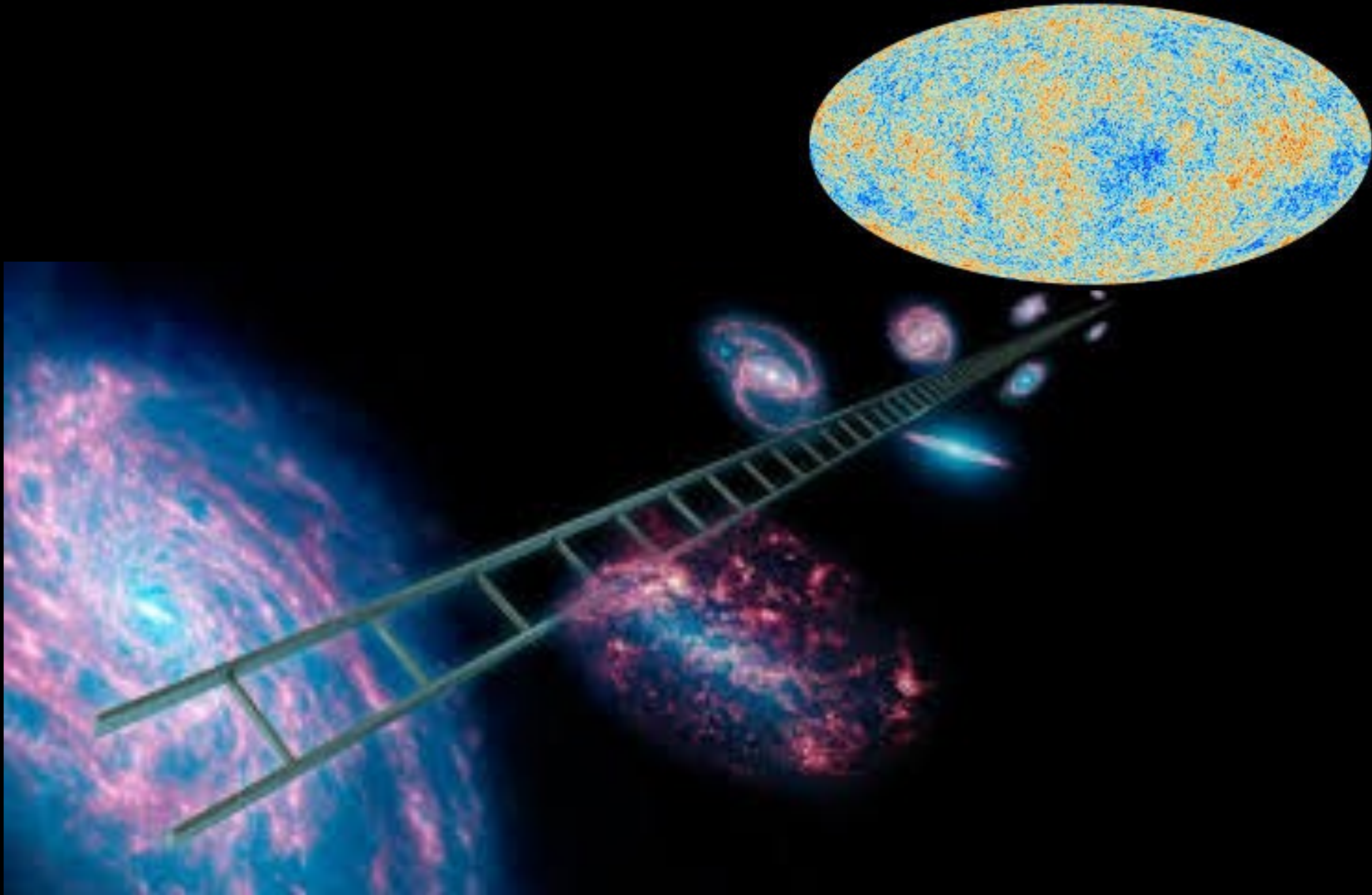
Here is where in ΛCDM or its simple variations the two ladders do not seem match

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

(quote by Adam Riess)



The H0 game: E2E test

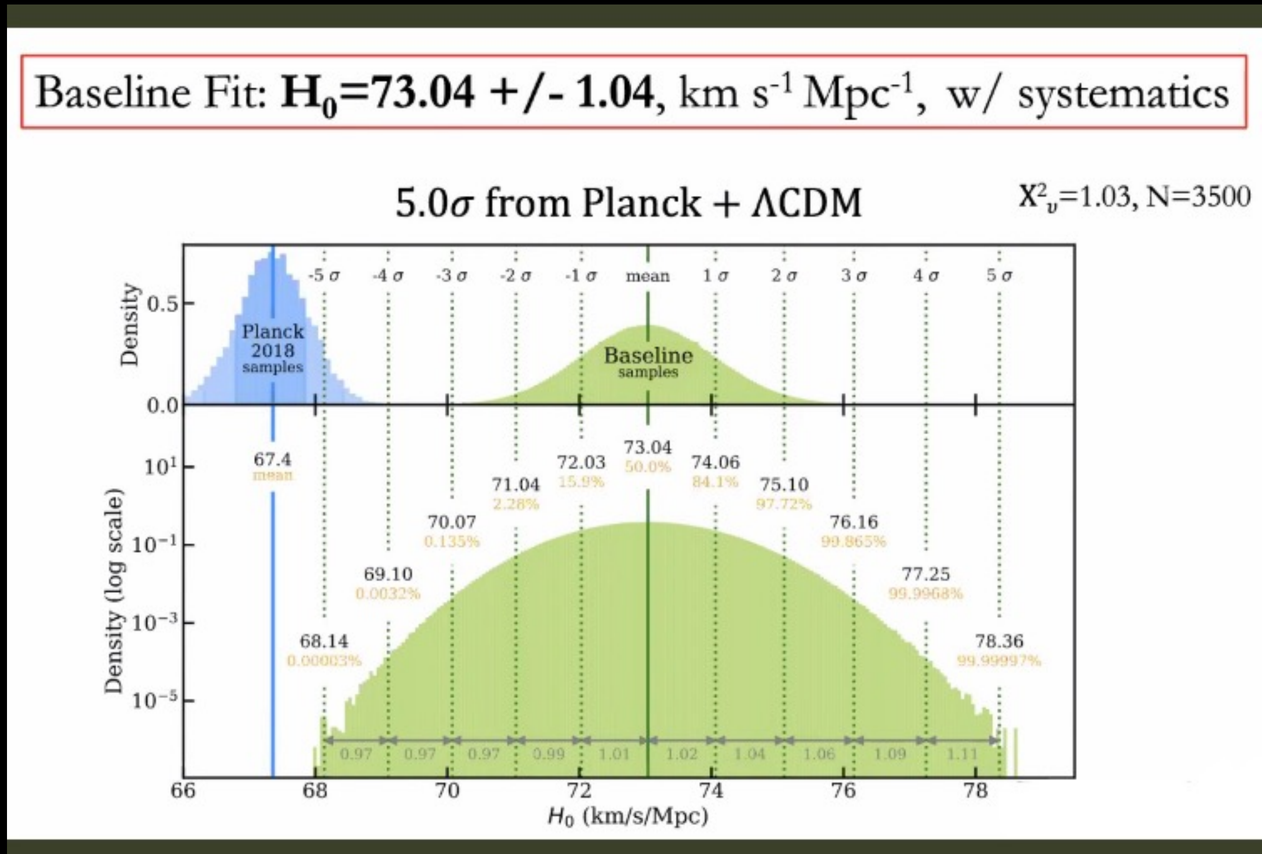


Is there a problem?

Is there a problem?

Whatever it is, it is too large to ignore

Latest SHOES results



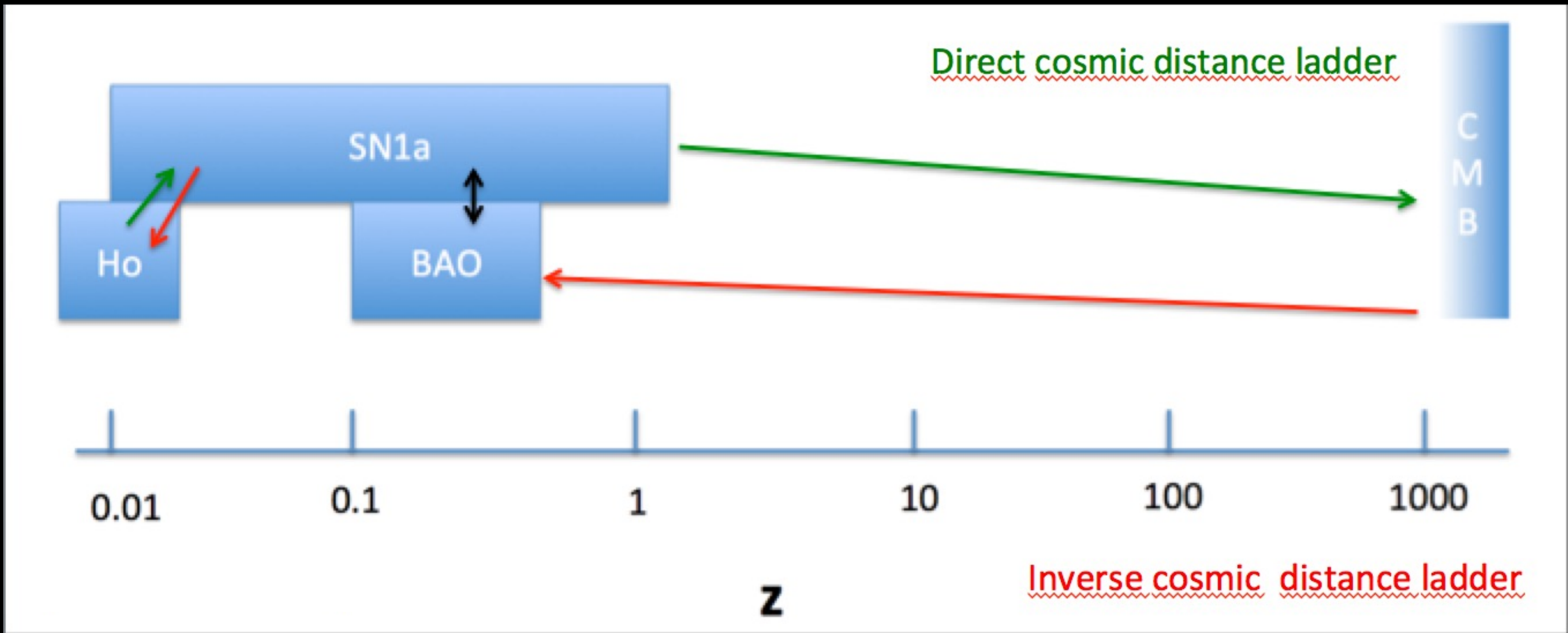
arXiv:2112.04510

This is precision cosmology!

…This tension is fierce… ….the stakes are high…

- Jury is still out
- SH0ES has several calibrators*, cepheids is the best one
- Maybe treat TRGB as another calibrator and average out
- There are now TRGB and cepheids distance measurements to the same object omega cen
- See talks by Scolnic, Riess, Freedman etc.

Working hypothesis: early vs late



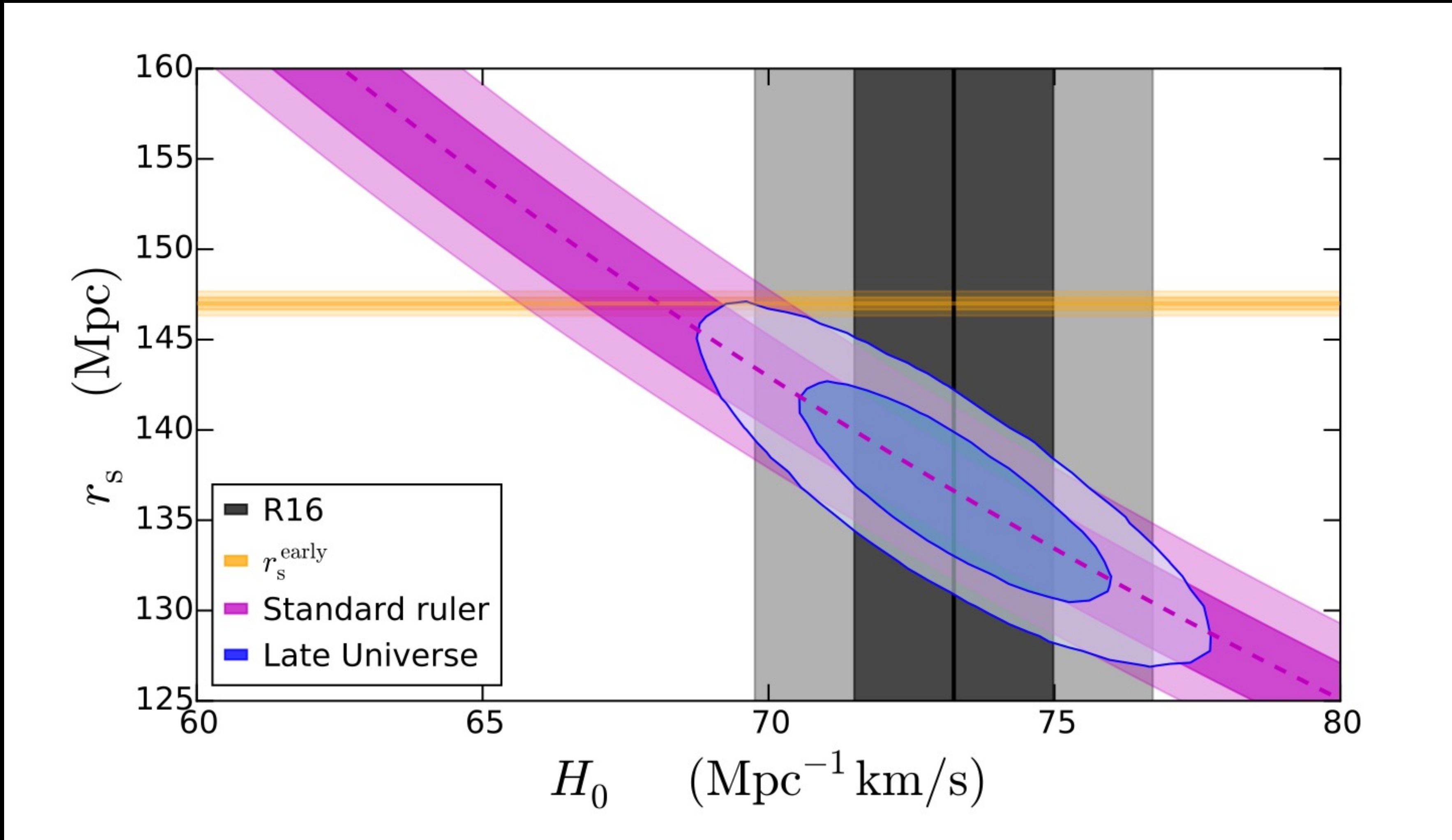
H0

rs

But there is not much wiggle room in the middle!

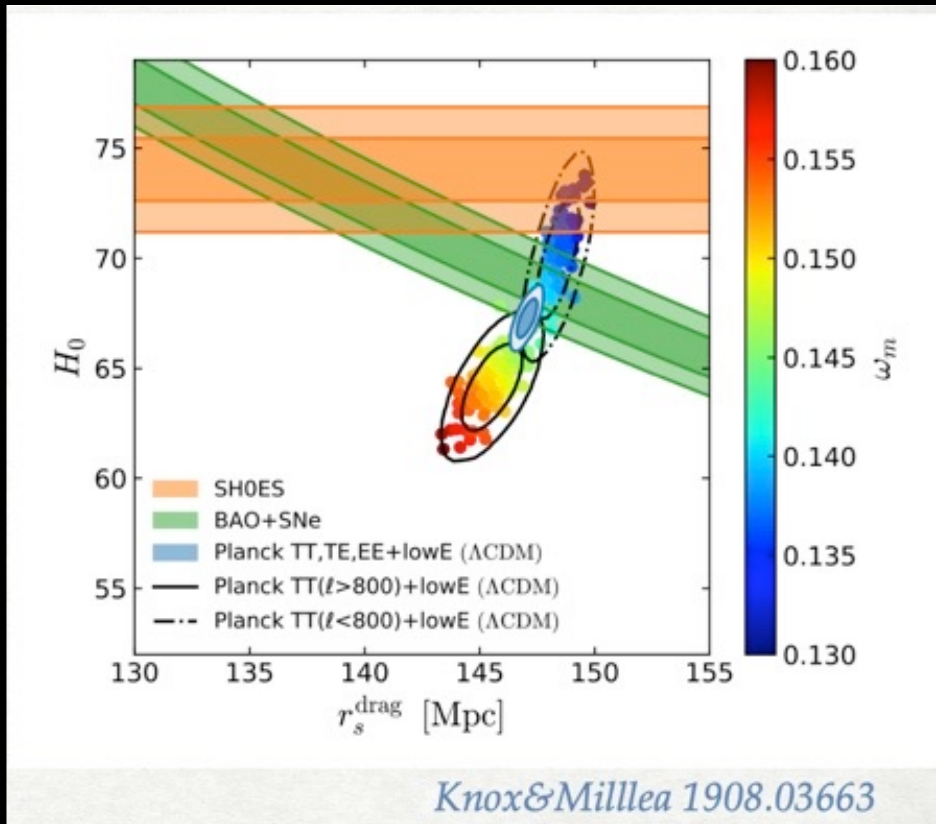
Bernal et al 2016, Aylor et al 2017

Ho problem can be seen as an r_s problem



Bernal et al 2016

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



You can get rs in (at least) 2 ways

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

- From CMB observations (given a cosmological model)
- Using (again) the equation above, a model for early Universe and a constraint on baryon density (e.g.,BBN** & light elements abundance). BAO give matter density (in LCDM).

Where is the problem?

Systematics!

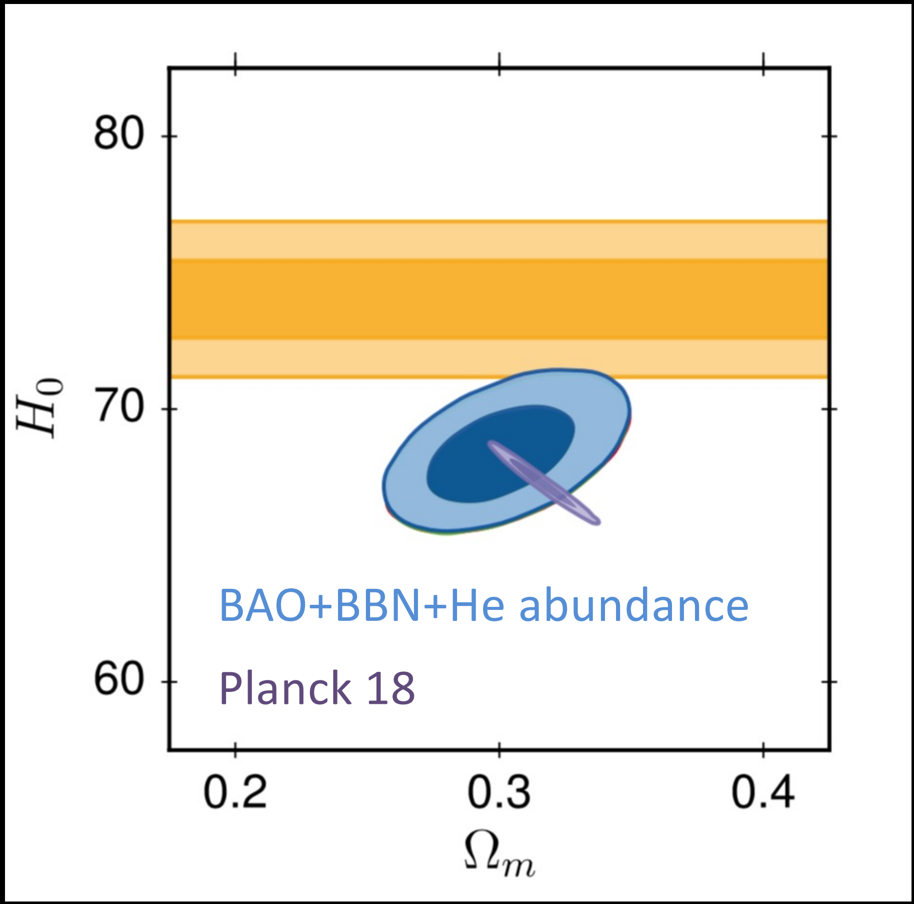
Increasingly unlikely

Where is the problem?

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

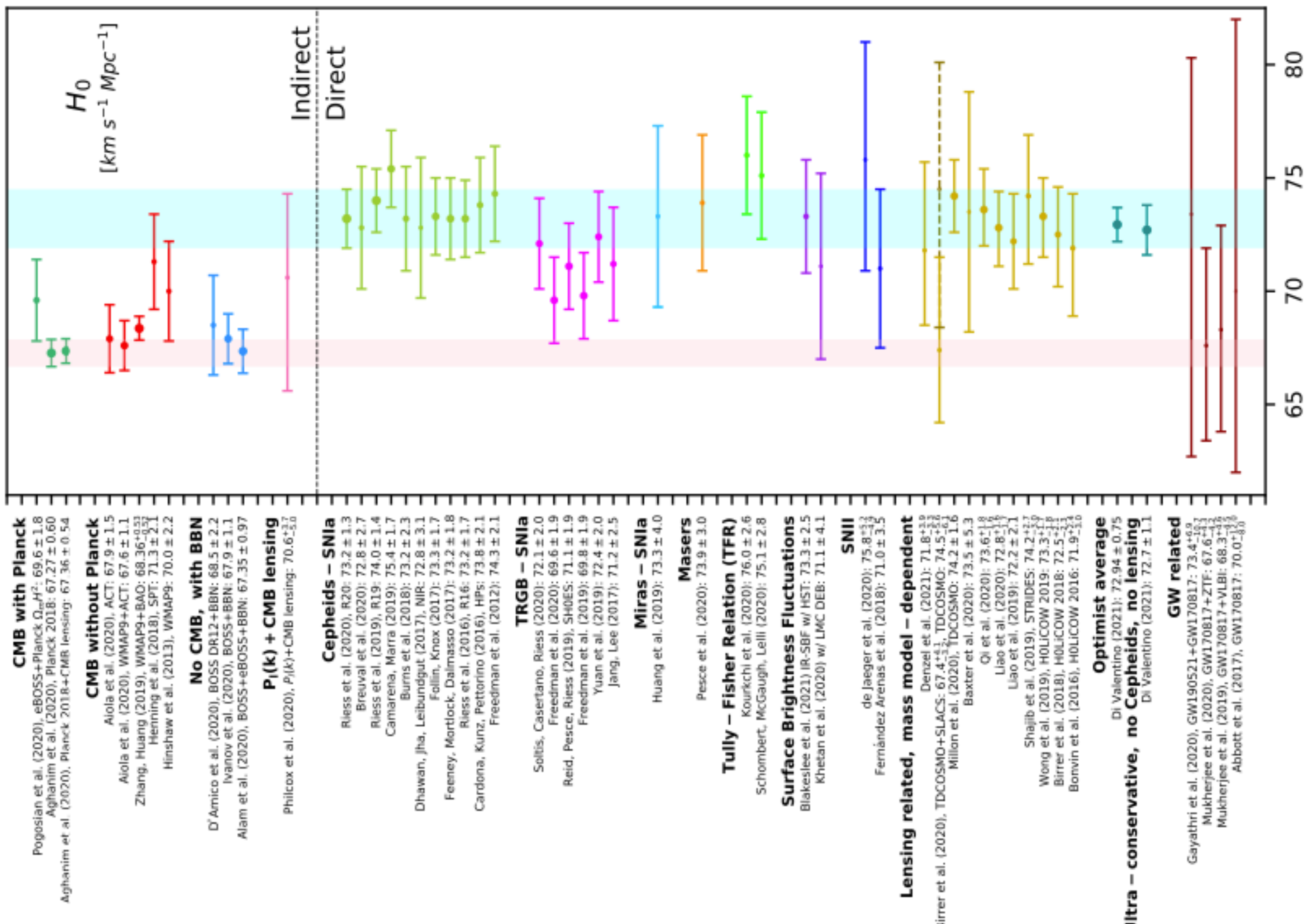
Early: For a while some people put the blame on Planck….

BUT H_0(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.

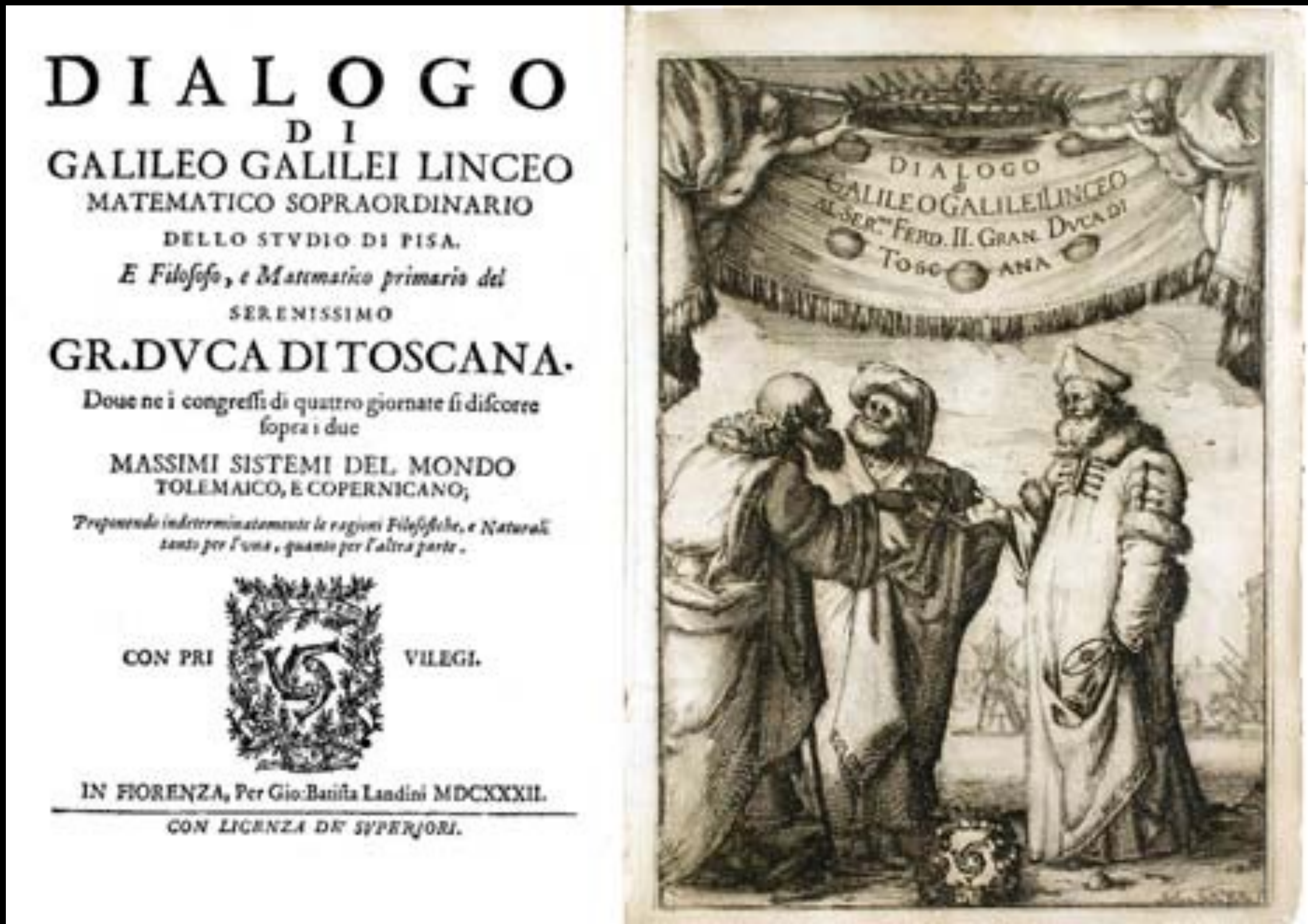
Is it in any specific data set?



Di Valentino et al 21

Where is the problem?

If not in the data then in the model…?



My personal very partial view, happy to discuss

The Ho Olympics

Model	ΔN_{param}	M_B	Gaussian Tension	Q_{DMAP} Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗
ΔN_{ur}	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓ (3)
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-8.83	-4.83	✗	✗
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	-8.92	-4.92	✗	✗
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	-4.98	1.02	✗	✗
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓ (2)
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	✗	-11.42	-9.42	✓	✓ (3)
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓ (1)
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓ (1)
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓ (2)
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓ (2)
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓ (2)
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	✗	-4.94	-0.94	✗	✗
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	✗	✗
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	✗	-0.45	1.55	✗	✗
DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗

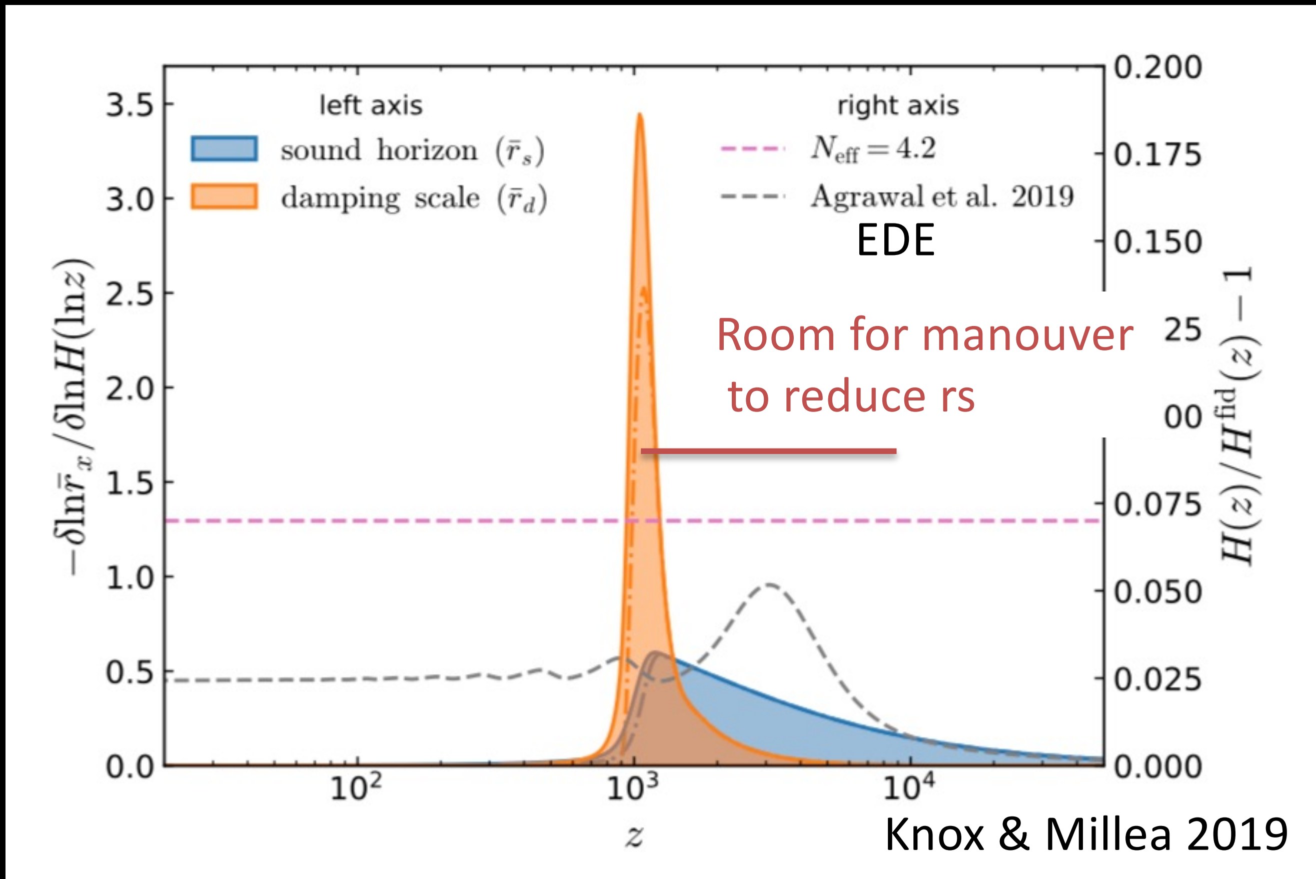
Shoneberg et al. arXiv:2107.10291.

pre-recombination solutions

Modify the model right where we most like it

Decrease the sound horizon, by 7% $r_s = \int_0^{t_\mathrm{d}} c_\mathrm{s} dt/a = \int_0^{a_\mathrm{d}} c_\mathrm{s} \frac{da}{a^2 H(a)}$
without wreaking havoc on damping tail… and everything else

A tall order



Reminds me of fine tuning

Ailor et al 2019

Cosmology tends to rely heavily on models (both for “signal” and “noise”)

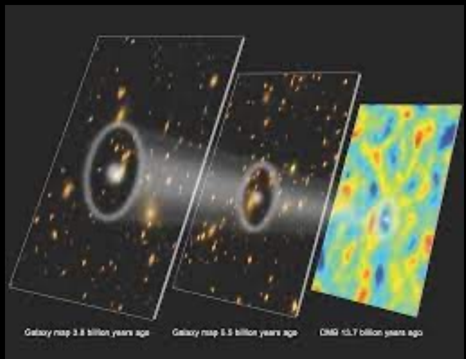
Essentially, all models are wrong , but some are useful
(Box and Draper 1987)

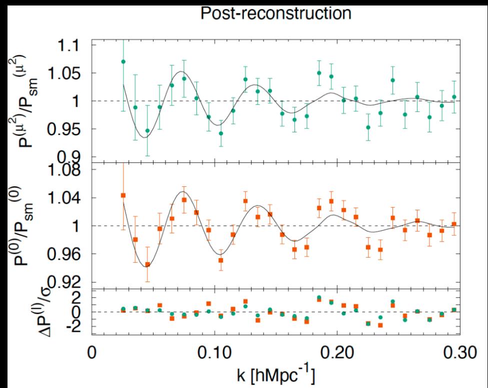
This is in the back of my mind....

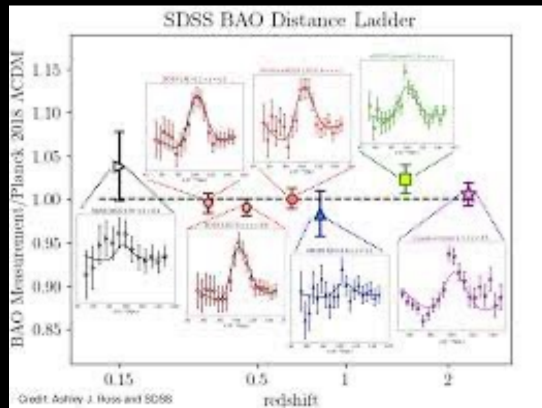
How do you test the model?

Can you do without?

Two philosophies to constrain cosmology:
1: BAO; BAO +RSD (compression)







BAO is a standard ruler: early time physics sets it “rs”; galaxy clustering then measures rs Da(z) and rs/H(z)
Signal is the angular “location” of the BAO (not its amplitude)

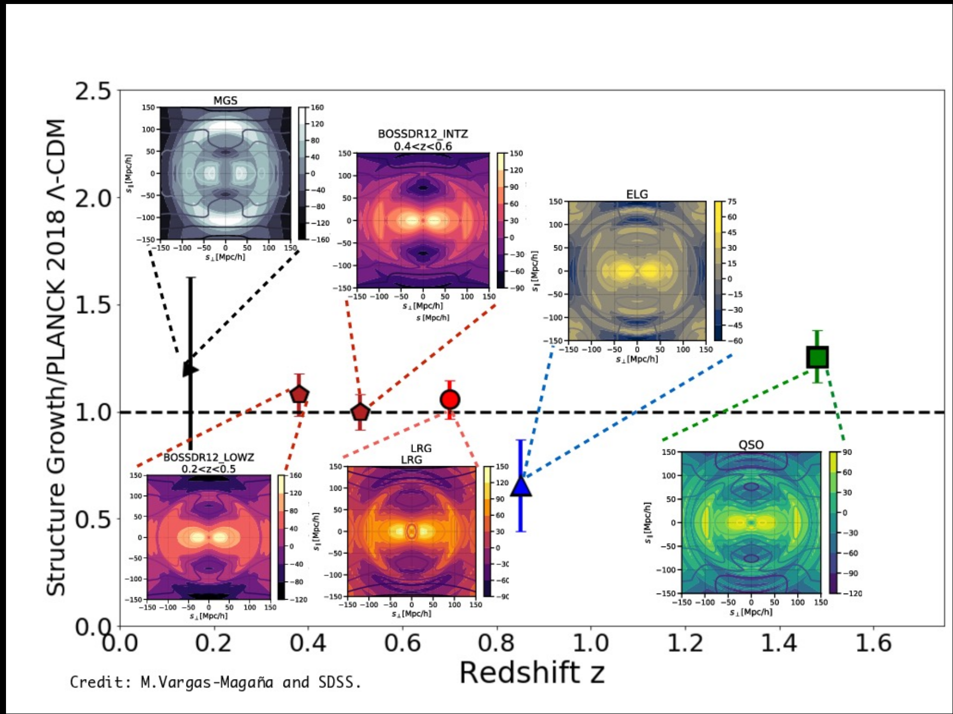
- → Expansion history, but not its normalization (i.e. not H0 b/c measuring angles!).
- → Only early-time physics information (and data) give the length of the standard ruler

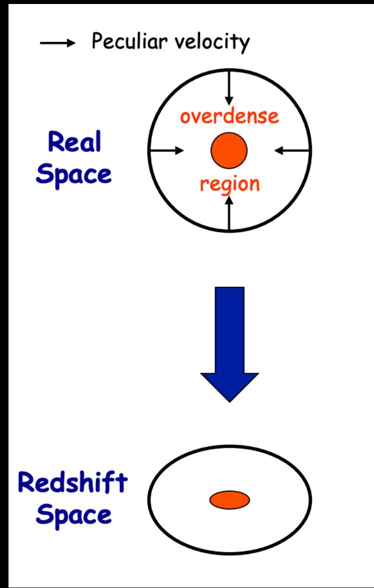
Without calibration this gives the shape of the expansion history in a model-agnostic way

This is a data compression

Two philosophies to constrain cosmology:
1: BAO; BAO +RSD (compression)

Redshift space distortions: peculiar velocities are sourced by gravitational pull of the inhomogeneities
measure growth of structure i.e. f $\sigma 8$



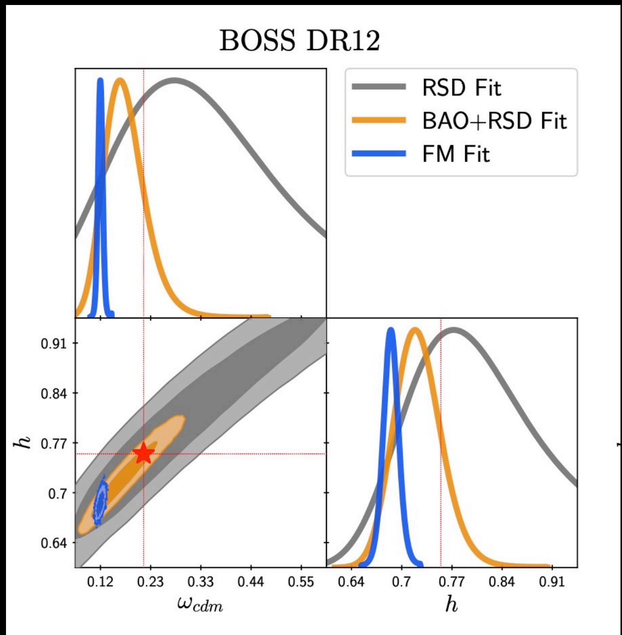


One measures a “squashing”(physical signal), which can help constrain models

Two philosophies to constrain cosmology:
2: do like for CMB

Pick a model and fit the anisotropic power spectrum

Approach 1 is said to be more model-independent; constrain physical quantities not parameters of a model
Approach 2 is more computationally expensive and obviosuly more model dependent but gives better constraints



Approach 1

Approach 2

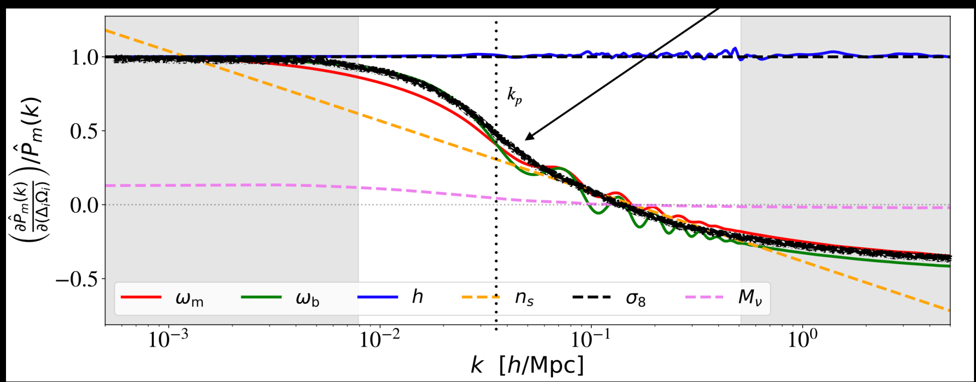
What's the star?

Brieden et al arXiv:2106.07641

Two philosophies to constrain cosmology:
2: do like for CMB

Pick a model and fit the anisotropic power spectrum

Approach 1 is said to be more model-independent; constrain physical quantities not parameters of a model
Approach 2 is more computationally expensive and obviosuly more model dependent but gives better constraints



Turns out (Brieden, Gil-Marin, LV 2021) that the difference in information content between 1 and 2 is
* mostly the behaviour of the matter transfer function "turn around"
    i.e. details of expansion history around matter-radiation equality
* to a smaller extent the amplitude of the BAO

ShapeFit

Brieden et al., arXiv: arXiv: 2106.11931,   Brieden et al arXiv:2106.07641

$$m = \frac{d}{dk}\left(\ln \left[\frac{P^{\rm lin}_{\rm no-wiggle}\left(\frac{k_p}{s}, \mathbf{\Omega}\right)/\mathcal{P}_{\mathcal{R}}\left(\frac{k_p}{s}, \mathbf{\Omega}\right)}{P^{\rm lin}_{\rm no-wiggle}\left(k_p, \mathbf{\Omega}^{\rm ref}\right)/\mathcal{P}_{\mathcal{R}}\left(k_p, \mathbf{\Omega}^{\rm ref}\right)} \right] \right) \Bigg|_{k=k_p}$$

$$m = \frac{d}{dk}\left(\ln \left[\frac{\left(\frac{r_{\rm d}^{\rm fid}}{r_{\rm d}}\right)^3 \cdot T^2_{\rm nw}\left(\left(\frac{r_{\rm d}^{\rm fid}}{r_{\rm d}}\right)\cdot k\right)}{T^{\rm fid\,2}_{\rm nw}(k)} \right] \right) \Bigg|_{k=k_p}$$

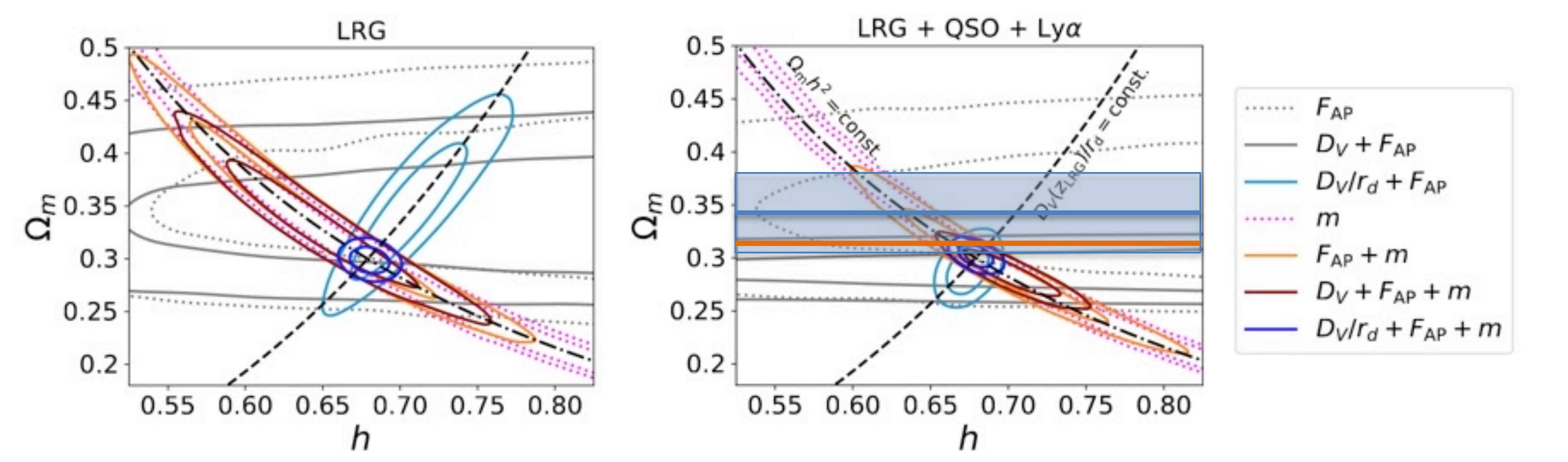
One extra effective parameter to the “usual” compressed variables (physical parameters).

Quite generic: mops up things like fnl, neutrino masses, dark radiation, any expansion history, generic growth histories etc.

Use (isotropic) slope feature) as standar (ruler)

See talk by Hector Gil-Marin for details

Yet another h…



$h \pm 68\%$ CL	LRG	LRG + QSO + Lyα
$F_{AP} + m$	$0.639^{+0.047}_{-0.064}$	$0.695^{+0.042}_{-0.051}$
$D_V + F_{AP} + m$	$0.645^{+0.035}_{-0.045}$	$0.702^{+0.019}_{-0.021}$
$D_V/r_d + F_{AP}$	$0.708^{+0.022}_{-0.028}$	$0.6742^{+0.0088}_{-0.0094}$
$D_V/r_d + F_{AP} + m$	$0.6799^{+0.0083}_{-0.0085}$	$0.6790^{+0.0076}_{-0.0075}$

Unpublished: w/ Brieden & Gil-Marin

- This is similar and complementary to Tristan Smith and collaborators work, E.g., arXiv:2208.12992: pick a model, marginalize over rs
- Extract the physical signal. Interpret in the context of the strictly necessary aspects of a model. Consistency reduces model's "freedom".

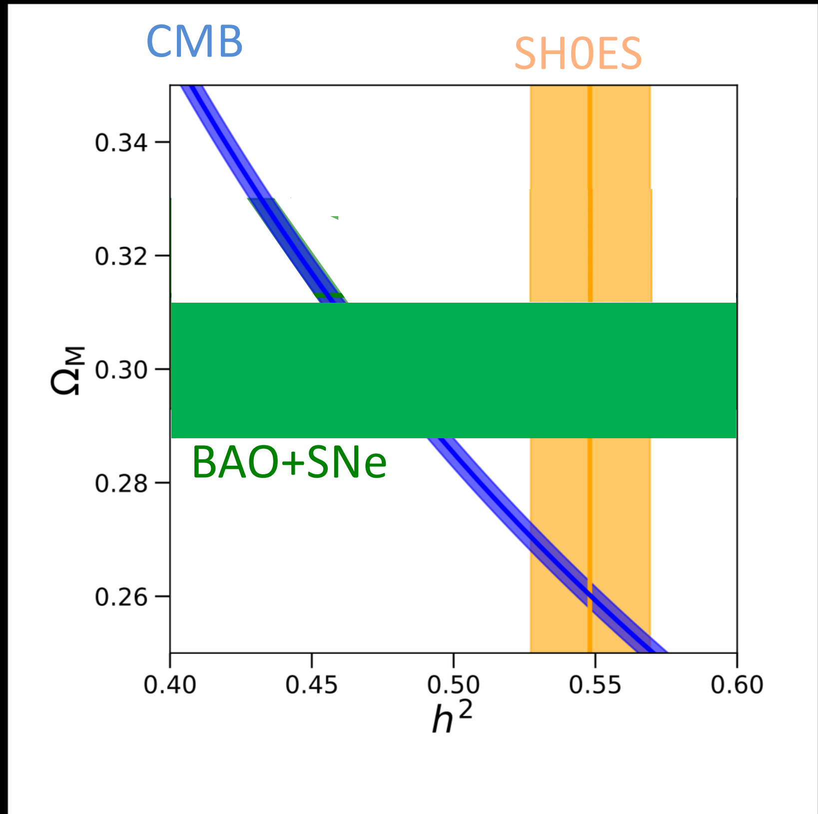
Beyond H0

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

Being in a tight spot

- Observations are VERY constraining
- Even within variations on the ΛCDM model we have several overconstrained systems

Ω_m, H_0, $\Omega_m h^2$

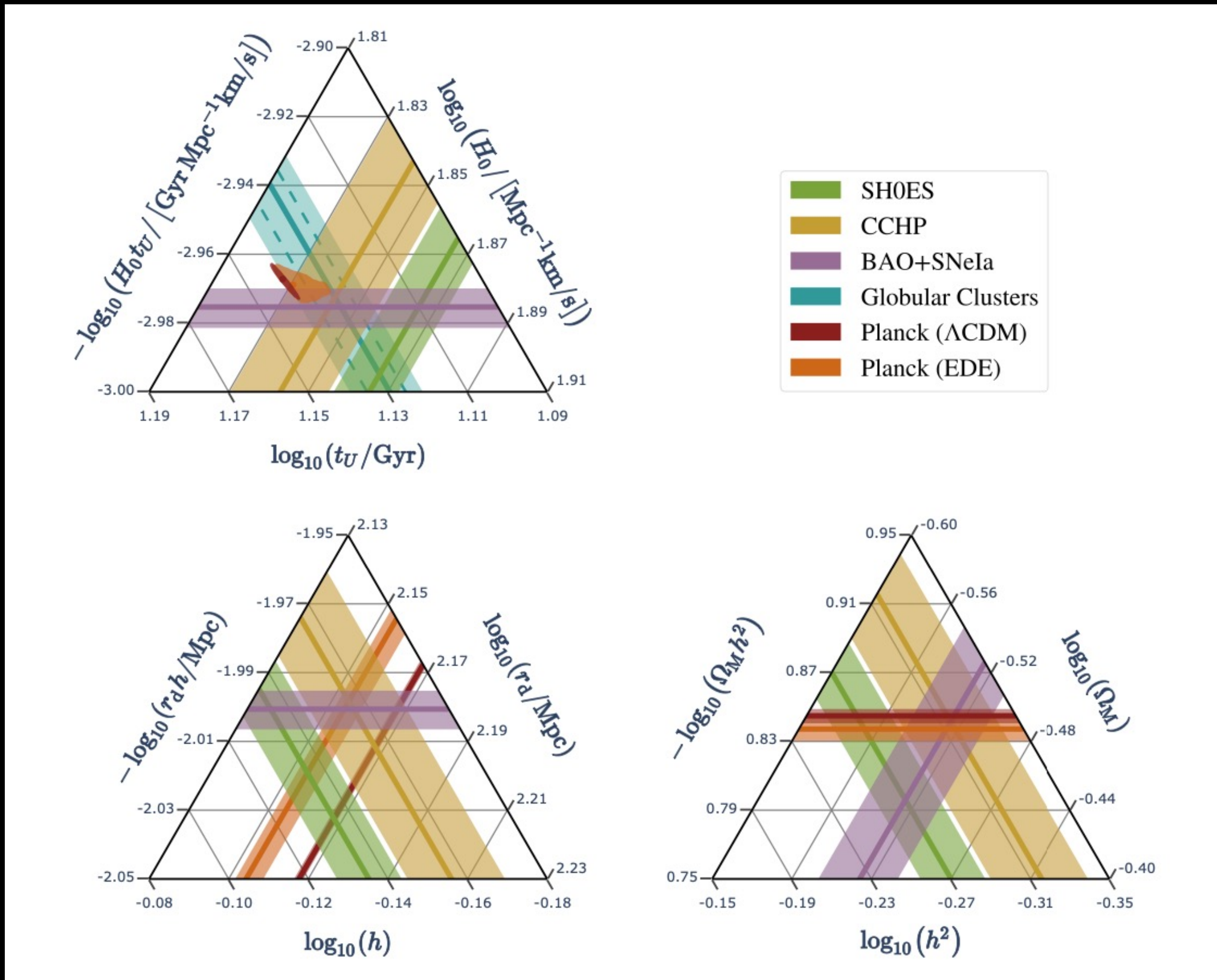
H_0, r_d h, r_d

Age, H_0, Age h

Equality scale, $\Omega_m h^2$, H_0

With each, we test different observations and different aspects of the model.

Cosmic triangles



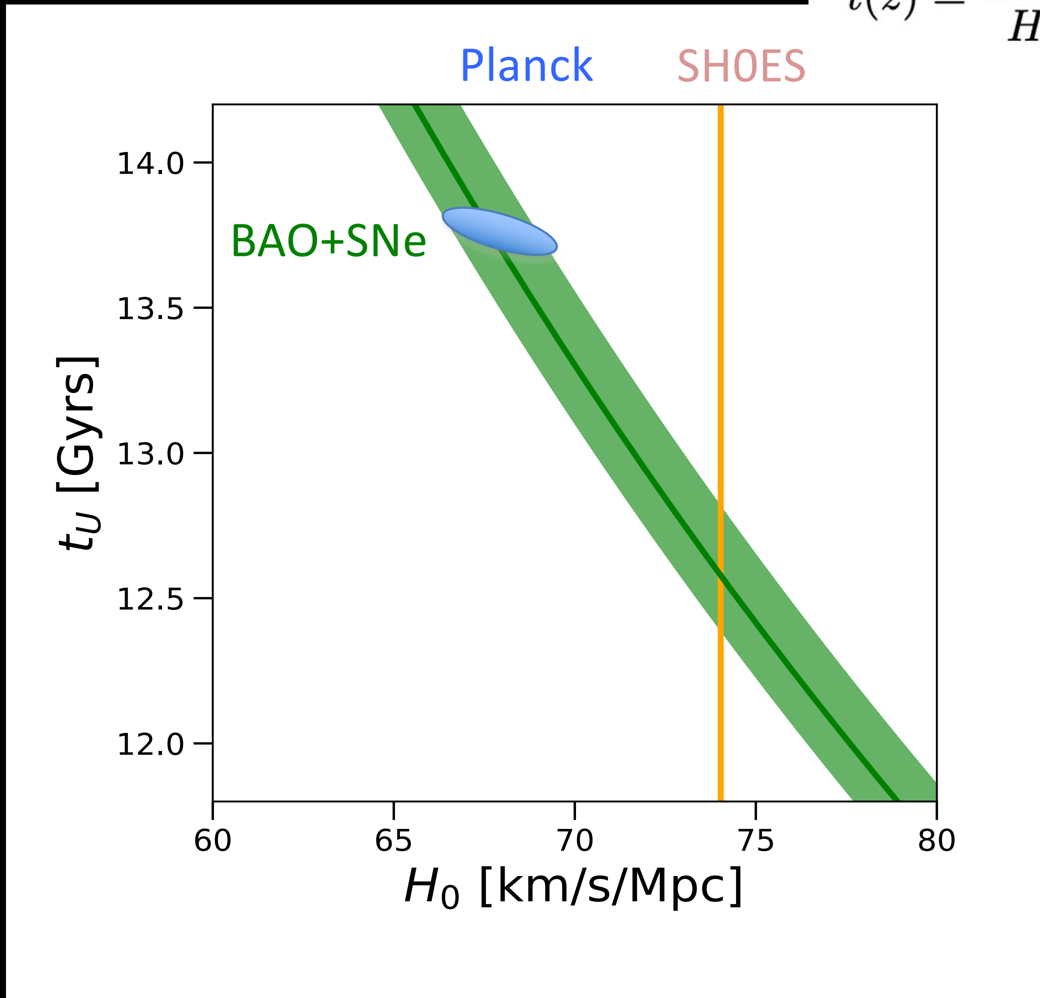
Bernal et al. 2021

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

?

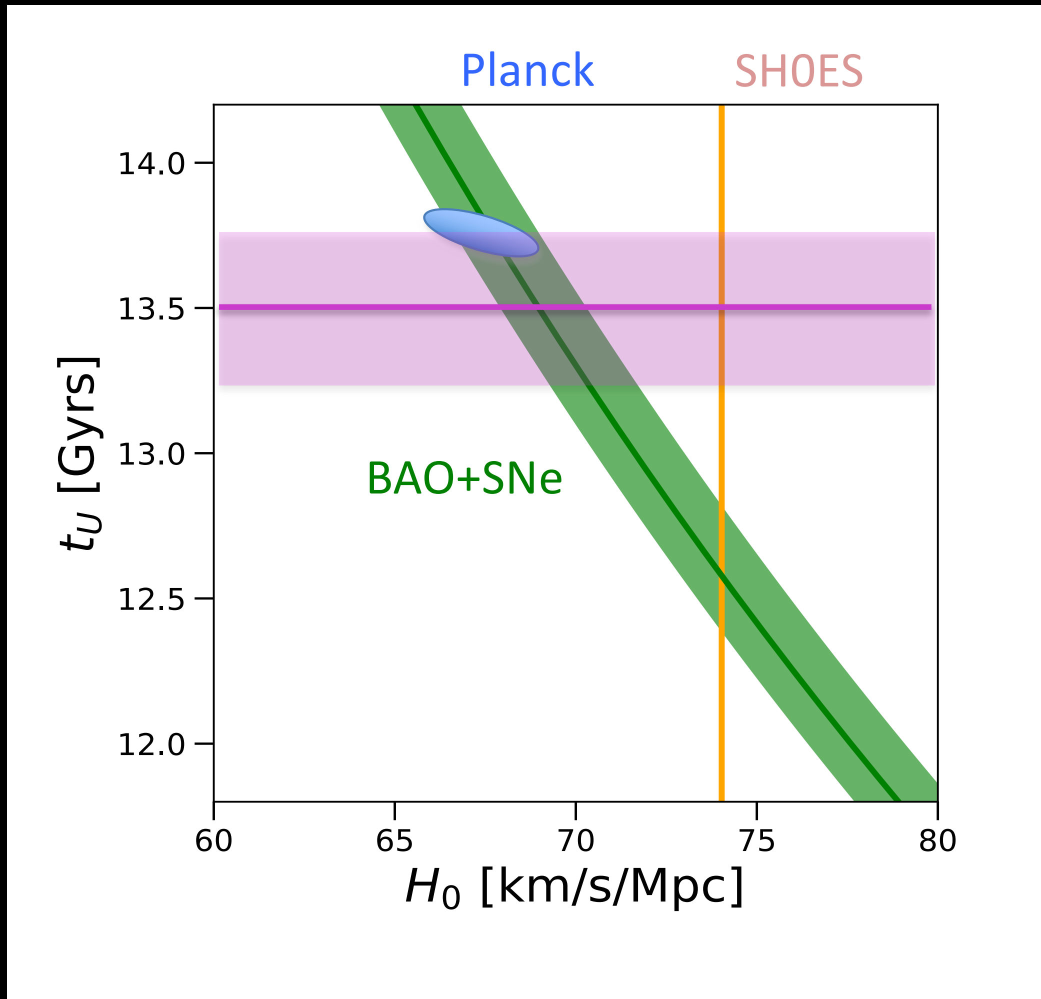


D. Valcin

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

Large-scale structure give more than one h

BAO give AP (minimal) an uncalibrated expansion history, (hence Ωm) or an early-Universe calibrated H0. (CMB-data or BBN-inspired prior)

Growth of structure give fs8 i.e. for more than one z Ωm (in GR)

But the large-scales shape of the LSS power spectrum can also be used:
Information about matter-radiation equality
→ Self consisteny as function of z
→ another scale as standard ruler different early time physics

another over constrained system

Large-scale structure take on h-σ8

BAO give AP (minimal) an uncalibrated expansion history, (hence Ωm) or
an early-Universe calibrated H0. (CMB-data or BBN-inspired prior)

Growth of structure give fσ8 i.e., for more than one z, Ωm

But if you use the Ωm above….

Theoretical solutions….

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

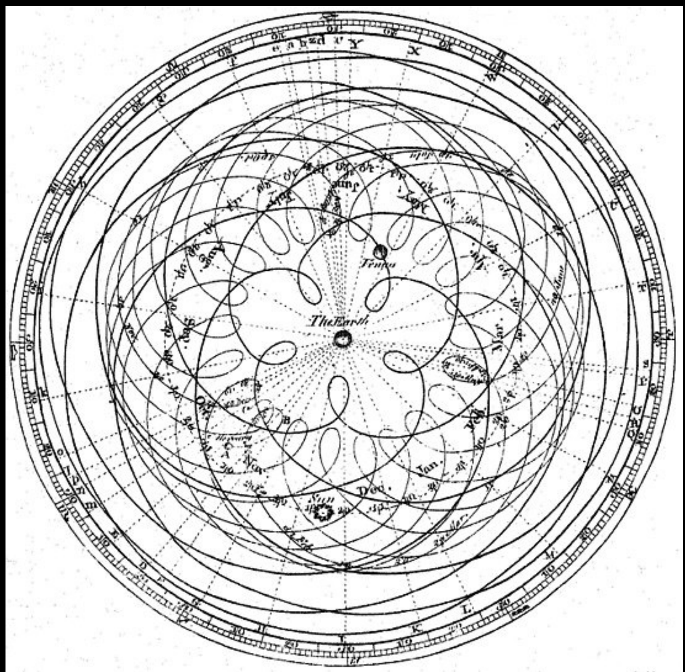
Should improve (or not worsen) other tensions, e.g. $\sigma 8$

We should quantify improvement vs predictability (degrees of freedom)

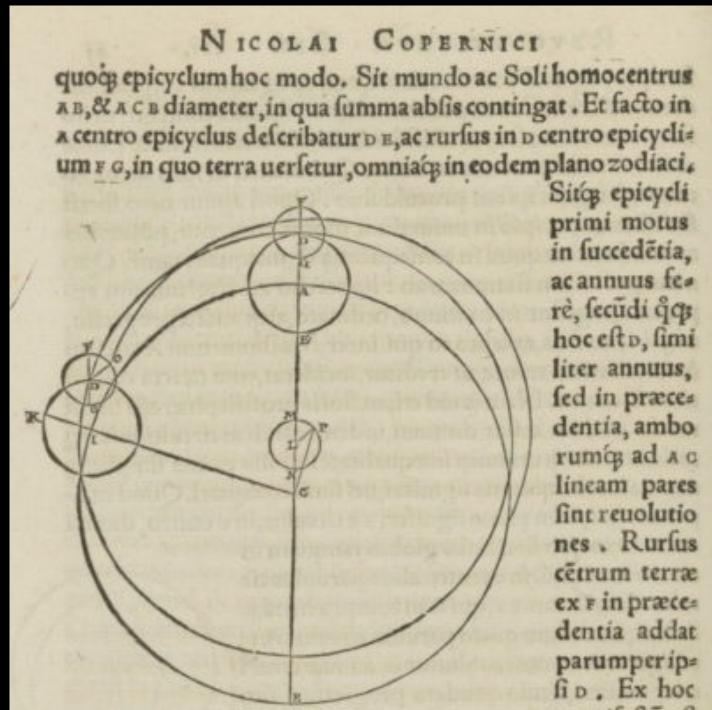
Parallelism with Λ…..

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 epicyclium FG, in quo terra uersetur, omniaq; in eodem plano zodiaci. Sitq; epicycli primi motus in succedētia, ac annuus ferè, secūdi q̊q; hoc est D, simi liter annuus, sed in præce dentia, ambo rumq; ad AC lineam pares sint reuolutio nes. Rursus cētrum terræ ex F in præce dentia addat parumper ip si D. Ex hoc

summary

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-
but beware of more than one ladder

Low redshift solutions→ very limited wiggle room

AND the troubles go well beyond H_0 and distance ladders-→ Matter density and age
equality scale and sound horizon

Looking for Cinderella….

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.
If shape measurements confirmed then reduced wiggle room to change early-time physics

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.
If shape measurements confirmed then reduced wiggle room to change early-time physics

Two possible scenarios : local and global

Local:
affect very local H_0 measurements
(astrophysical or cosmological
e.g., screening, stellar properties)
leaving all else unchanged
(including LOS integral as seen in BAO)

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.
If shape measurements confirmed then reduced wiggle room to change early-time physics

Two possible scenarios : local and global

Local:
affect very local H_0 measurements
(astrophysical or cosmological
e.g., screening, stellar properties)
leaving all else unchanged
(including LOS integral as seen in BAO)

Global:
New physics affecting entire history both early and late. Little wiggle room.
Impacts quantities well beyond H_0.
Will show up in new cosmological observations, over constrained systems!
We are narrowing down on what to tinker with wrt LCDM

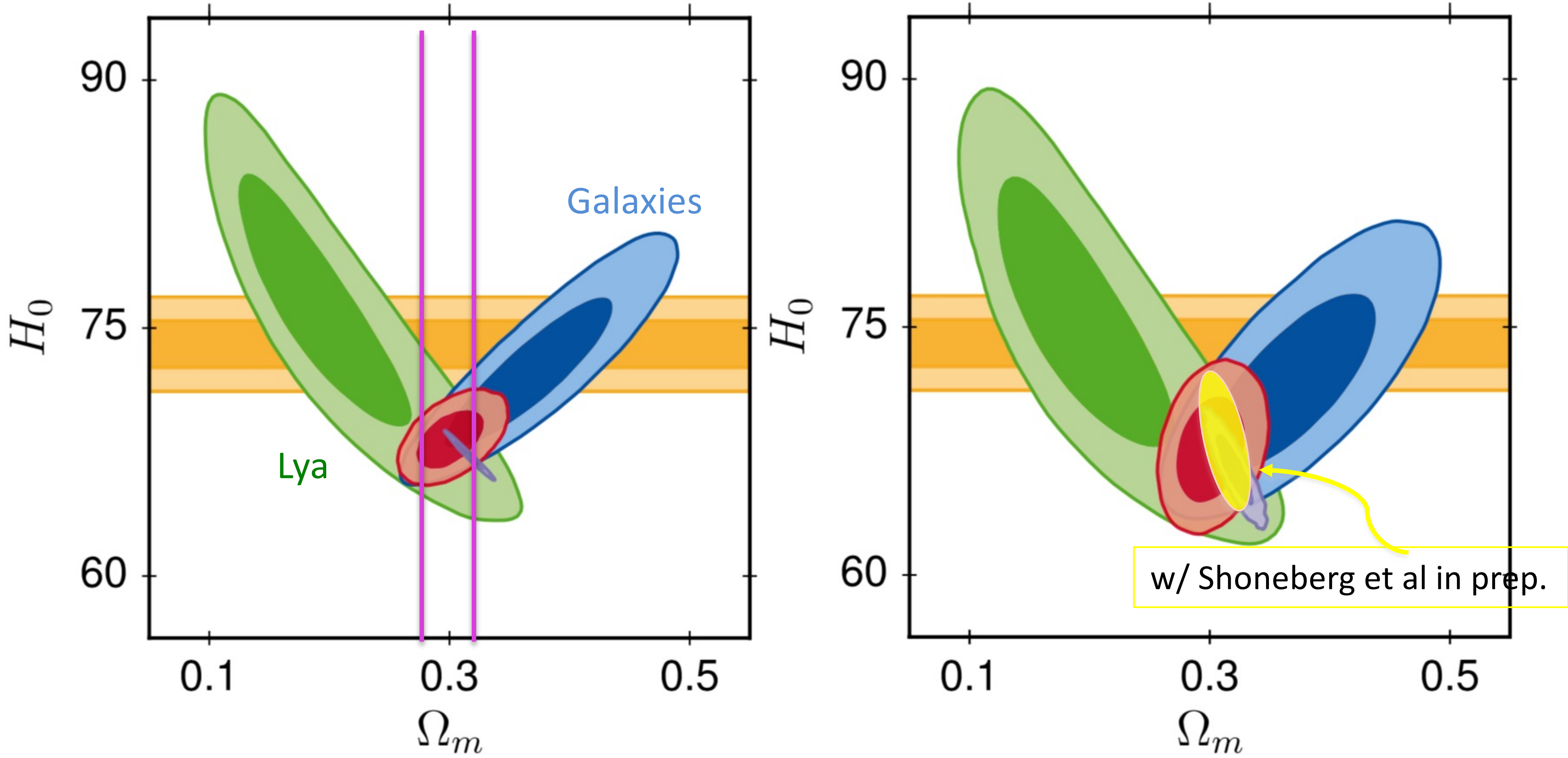
END

[redacted]

[redacted]

[redacted]

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)

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

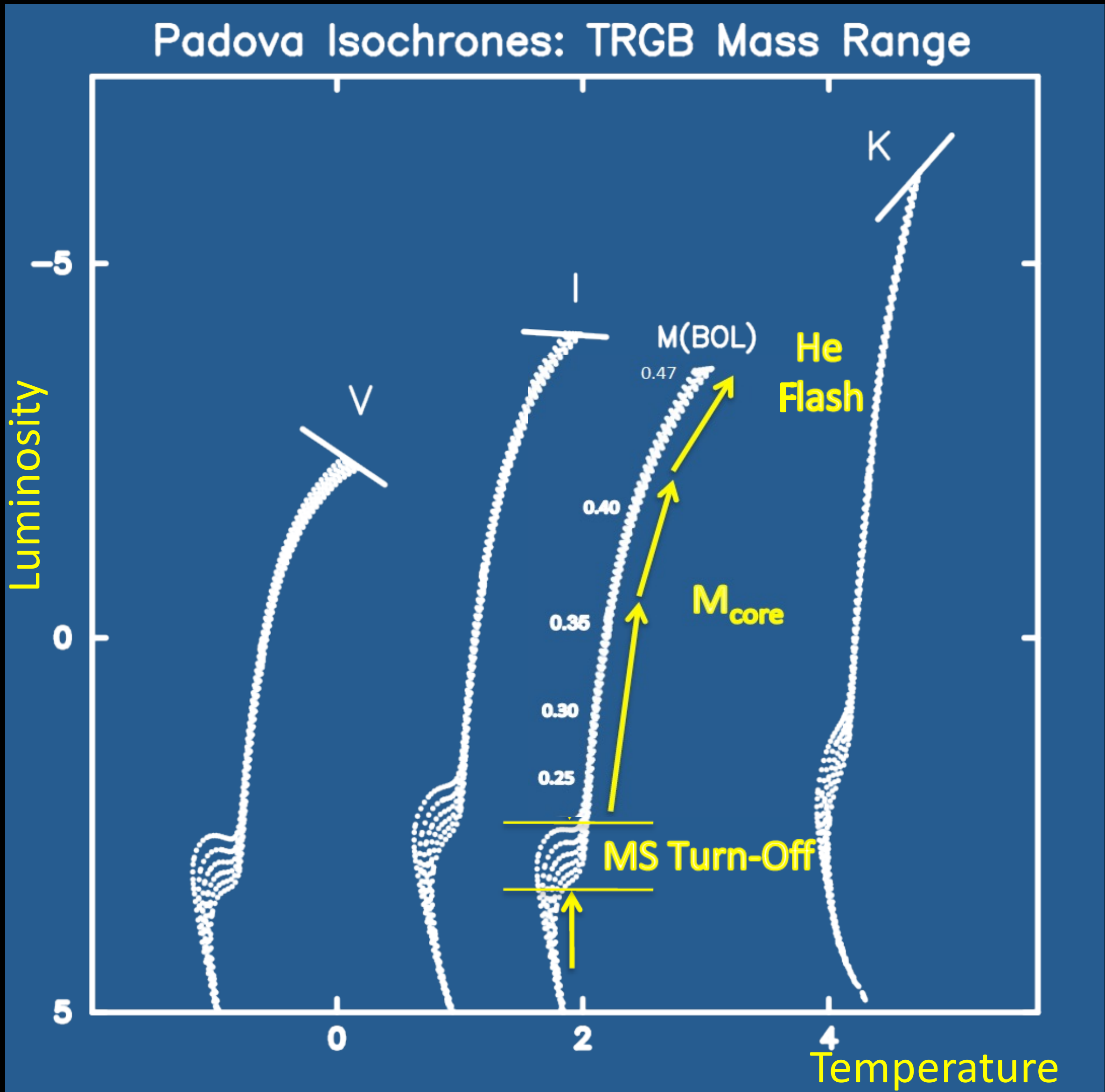
Many groups reanalized SHoES data…

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

As time goes on seems less and less likely

* Not all, see TRGB

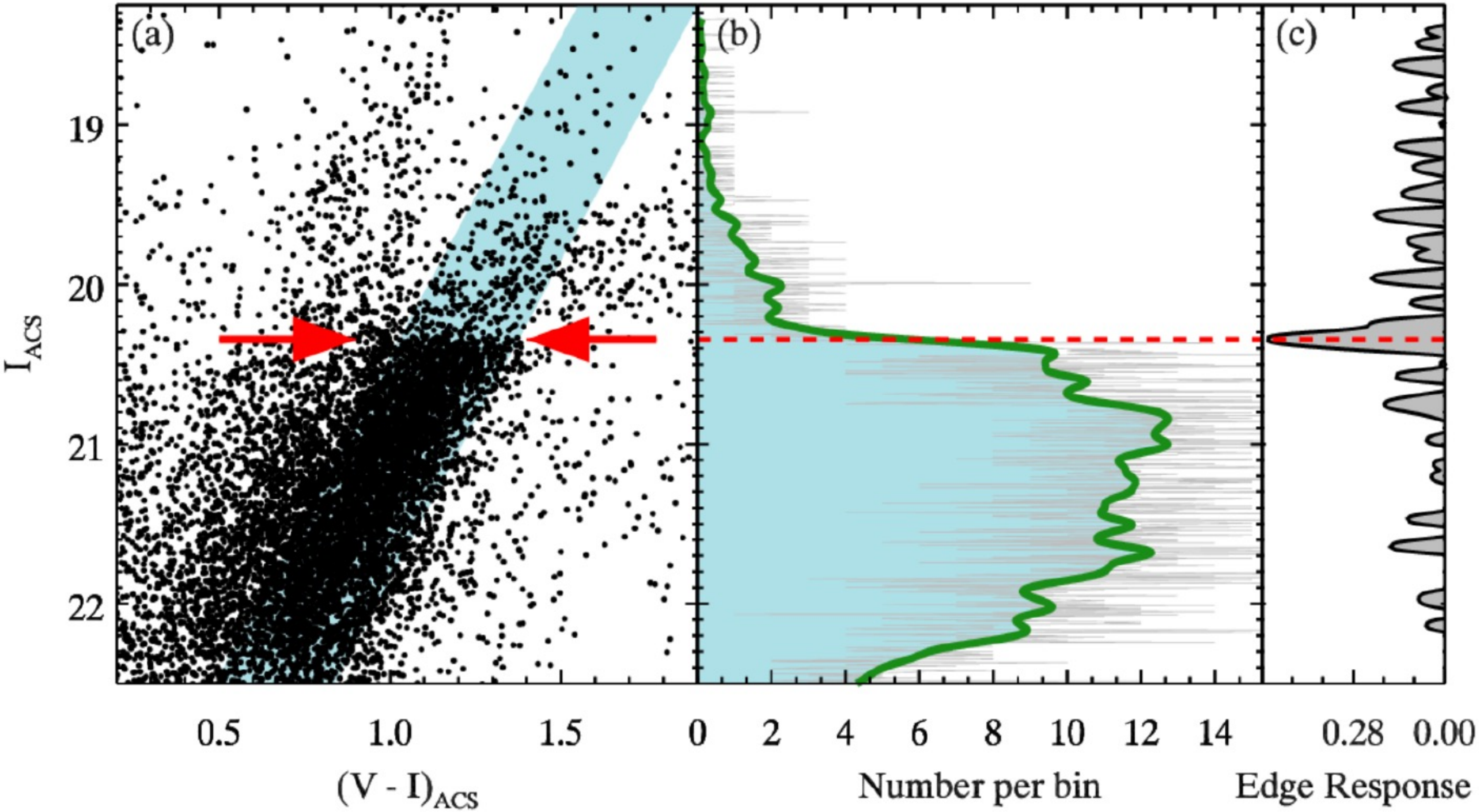
Tip of the red giant branch



Electron-Degenerate Helium Core Mass-Luminosity Relation

From B. Madoore

Tip of the red giant branch



Hatt et al. 2017

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 damping 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,

Increase the freedom of H(z); come up with designer models…
The price is high:
many extra degrees of freedom (epicycles?) and 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

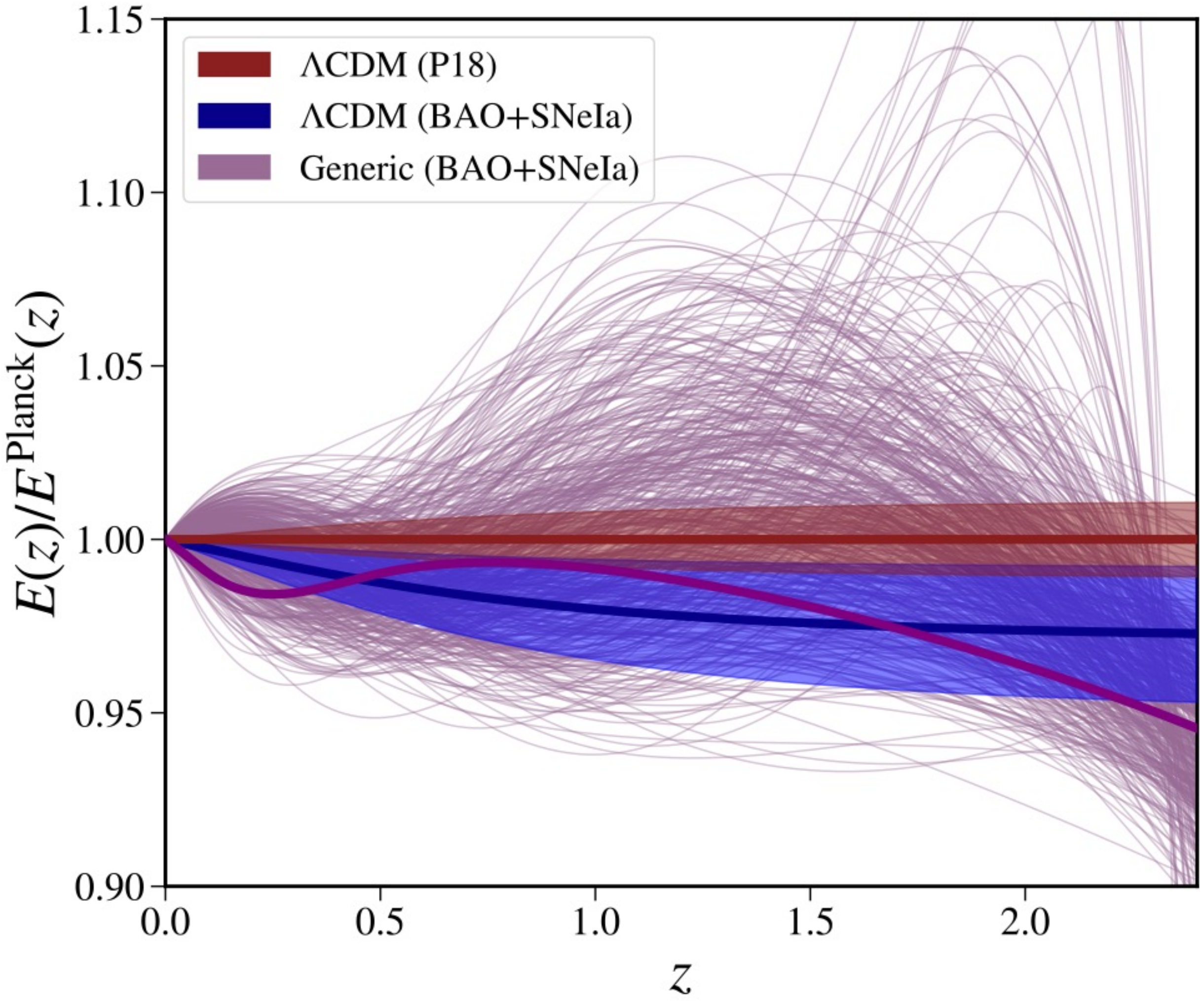
BAO+SNe

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

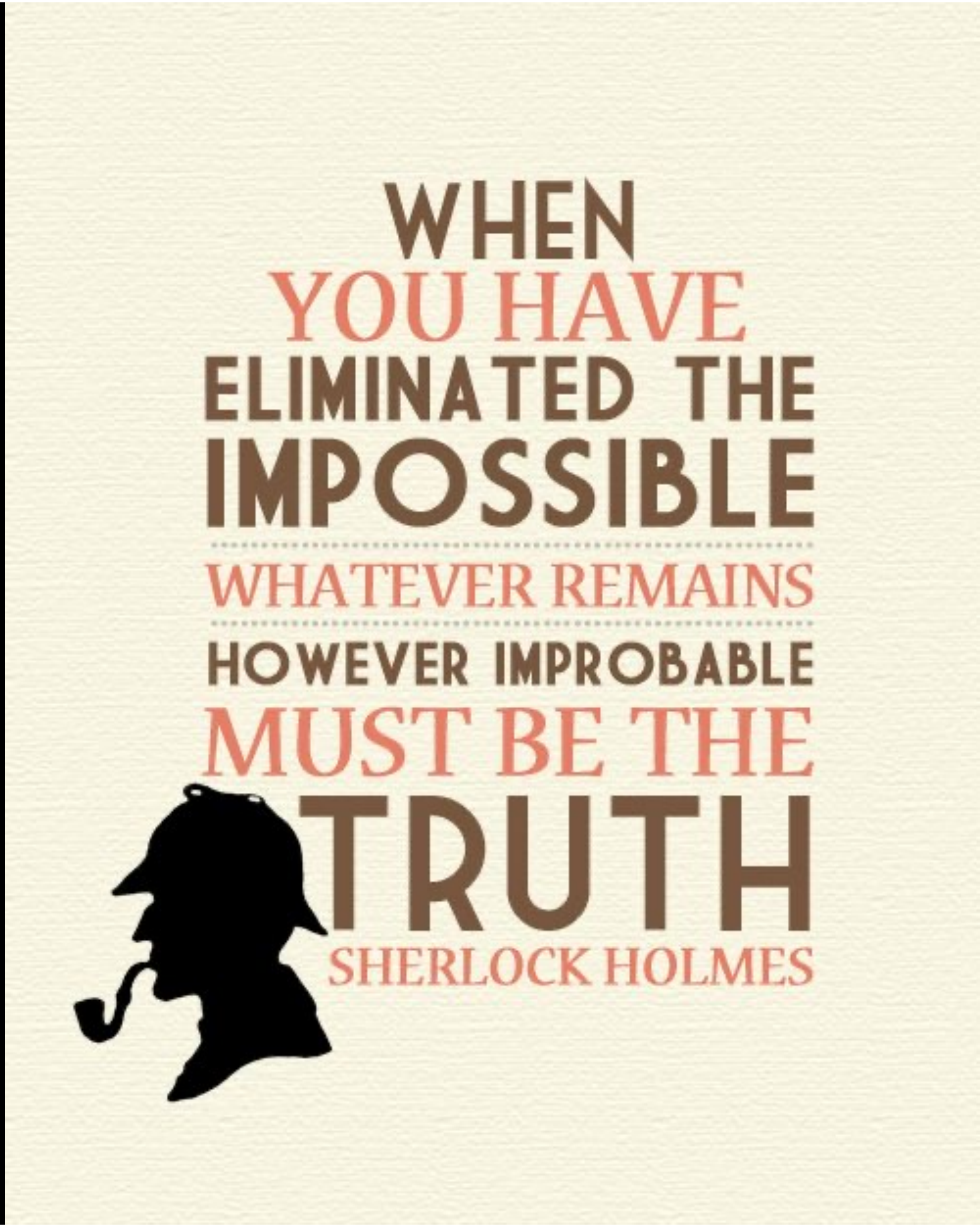
$r_{\rm d}h = 100.6 \pm 1.1$ Mpc

Generic reconstruction

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



Bernal et al. 2102.05066


WHEN
YOU HAVE
ELIMINATED THE
IMPOSSIBLE
WHATEVER REMAINS
HOWEVER IMPROBABLE
MUST BE THE
TRUTH
SHERLOCK HOLMES

Stellar ages: a tool to measure the expansion rate

- Absolute stellar ages (clocks) at z=0 provide an estimate of the current expansion rate and tu for the oldest objects adding in formation time.

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

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

WHEN
YOU HAVE
ELIMINATED THE
IMPOSSIBLE

WHATEVER REMAINS

HOWEVER IMPROBABLE
MUST BE THE
TRUTH

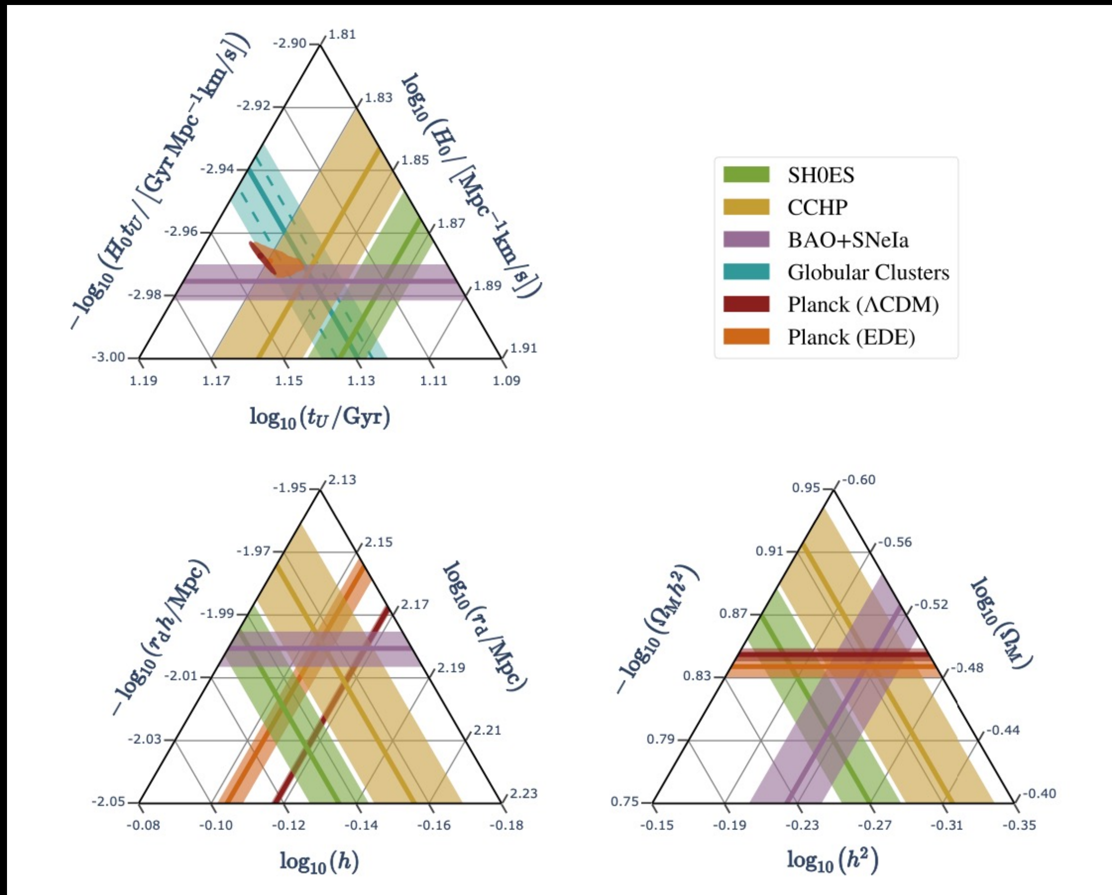
SHERLOCK HOLMES

Selected extra references

- DiValentino et al 2021 arXiv:2103.01183
- DiValentino et al 2020 arXiv:2008.11284
- Shoneberg et al. 2021 arXiv:2107.10291
- Riess et al. 2021 arXiv:2112.04510
- Freedman 2021 arXiv:2106.15656
- Riess 2020 arXiv:2001.03624
- LV et al 2019 arXiv:1907.10625

To conclude

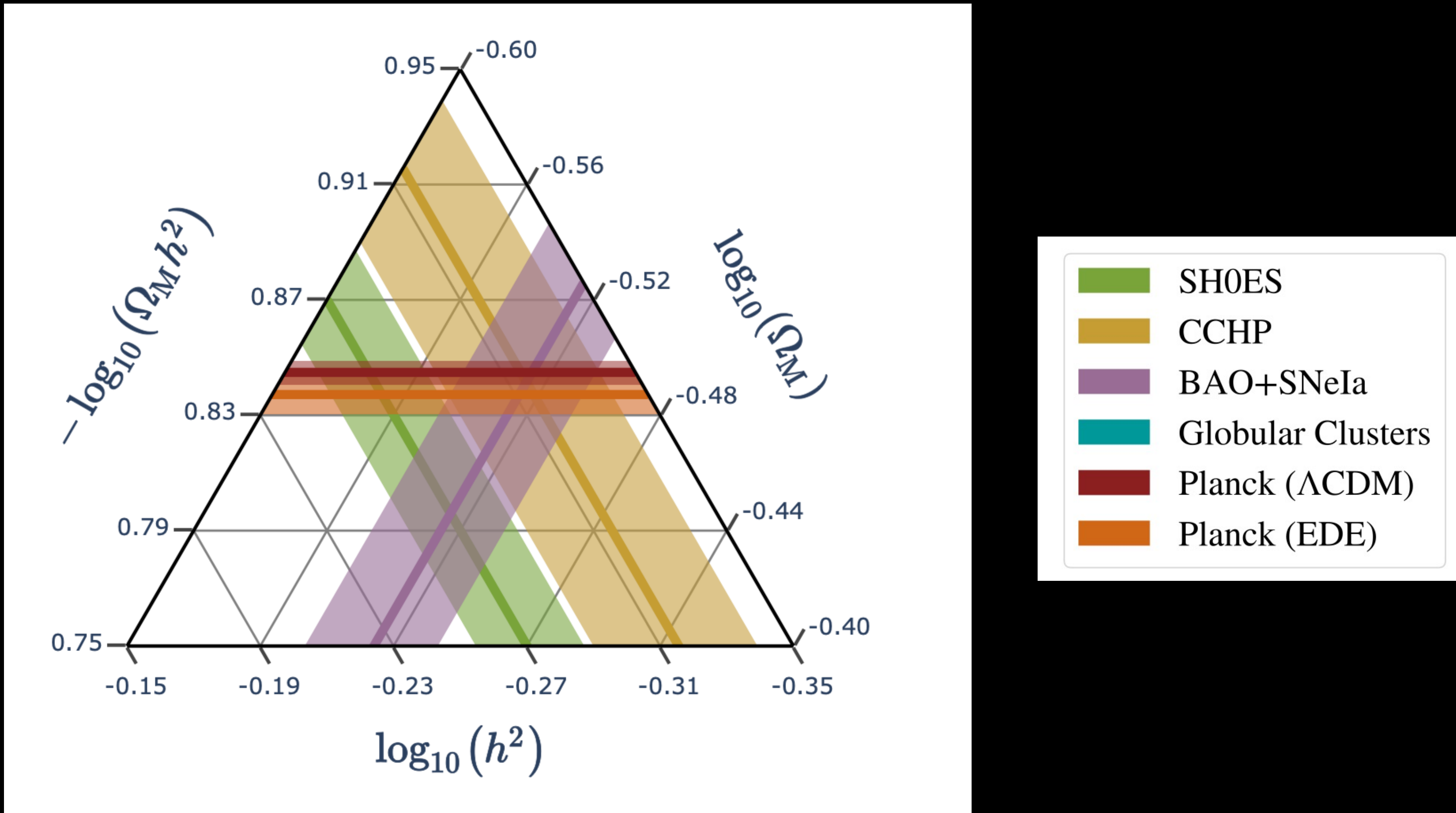
I hope that the new cosmic triangles representation of the observational constraints will help discriminating between the two scenarios and help guide future efforts to find a solution to the Hubble troubles.



Bernal et al 2021

The new cosmic triangles

Ωm, h, Ωm h



Bernal et al 2102.05066

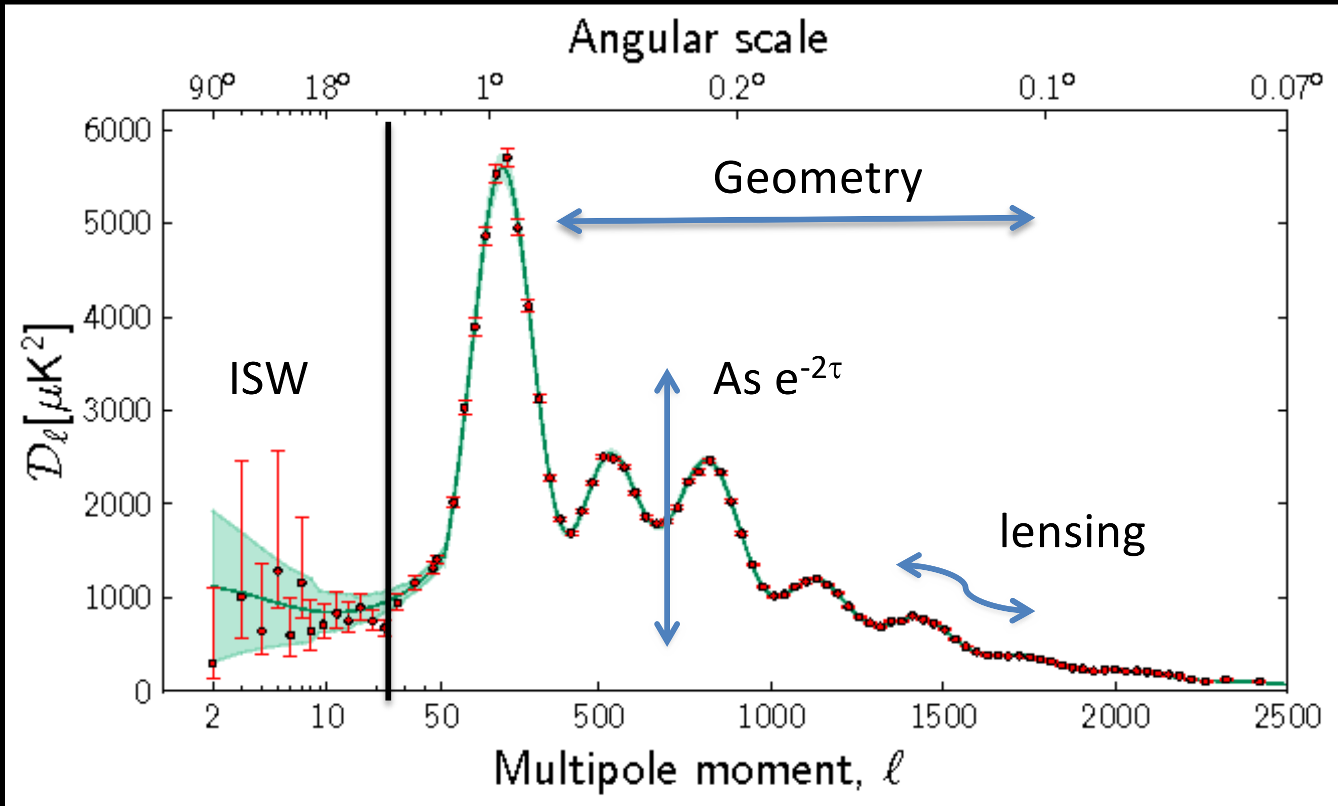
r_s from CMB independent from late time physics?

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

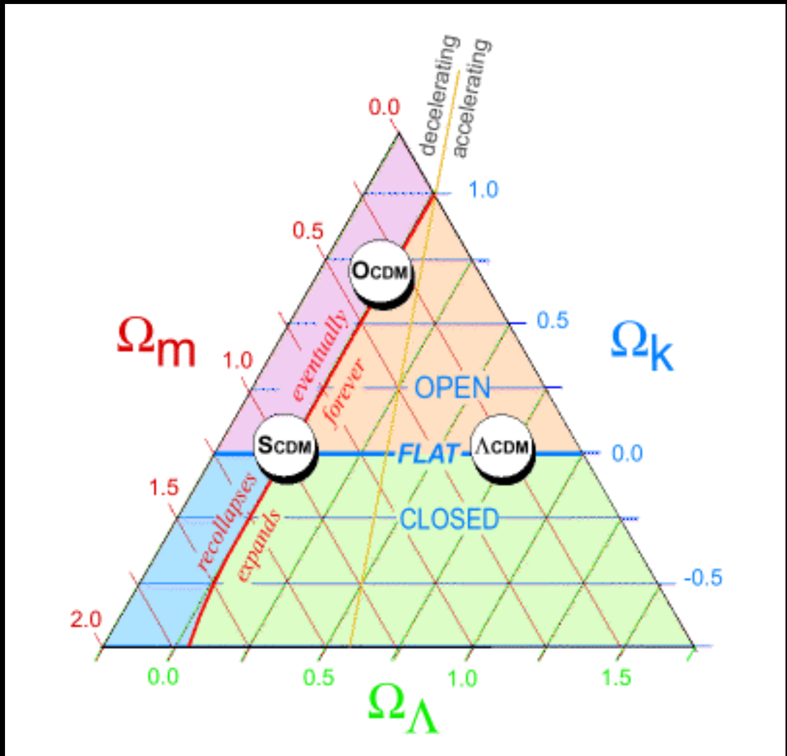


The answer is yes: 147.0pm 0.34 Mpc (assume standard early time physics)

Looking for Cinderella

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

The original Cosmic triangle



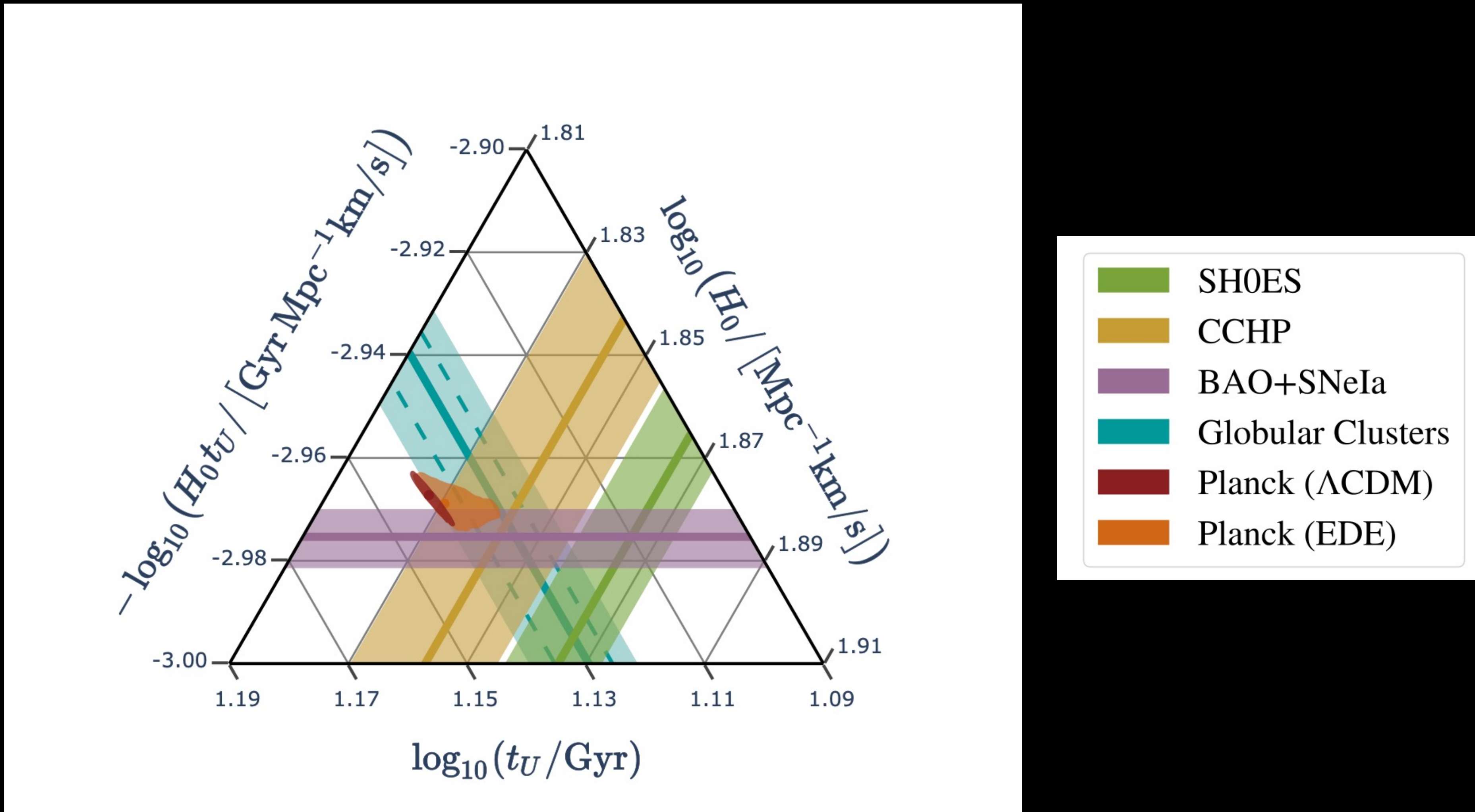
Science Bahcall et al 1999

Measure three parameters
only 2 are independent

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

The new cosmic triangles

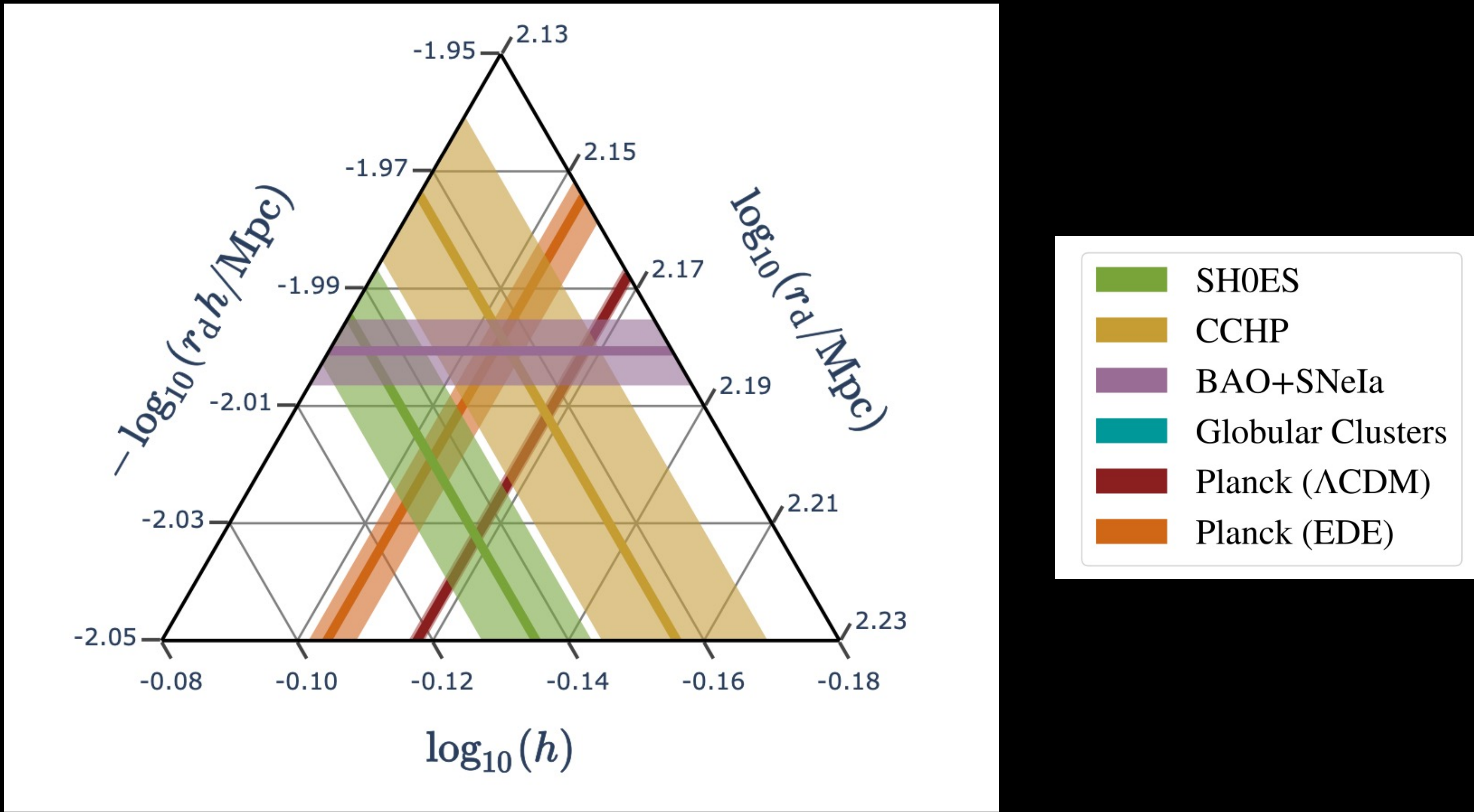
H_0, t_u, ht_u



Bernal et al 2102.05066

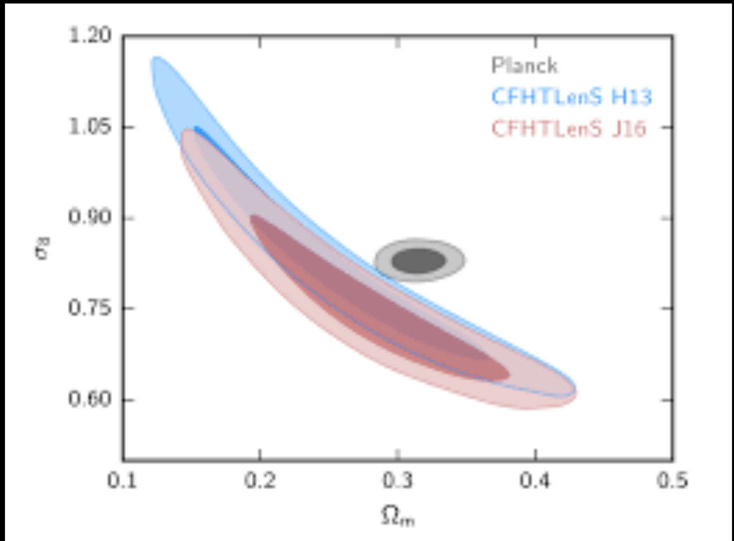
The new cosmic triangles

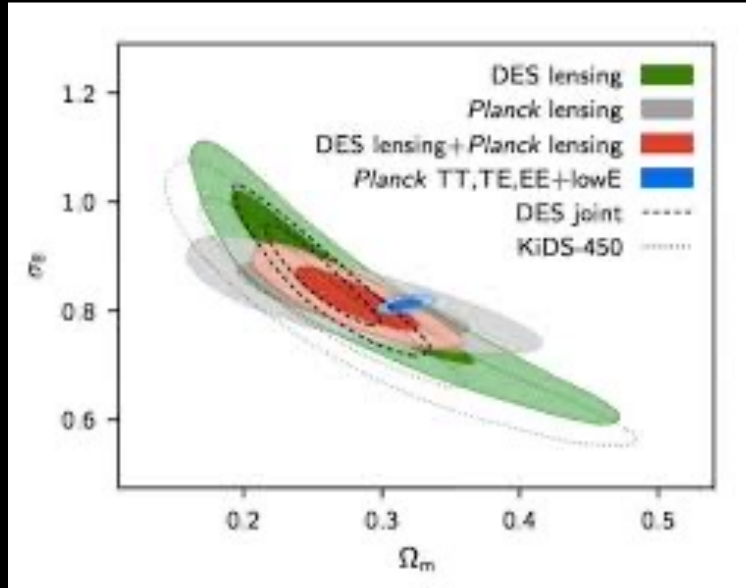
r_d, h, r_dh

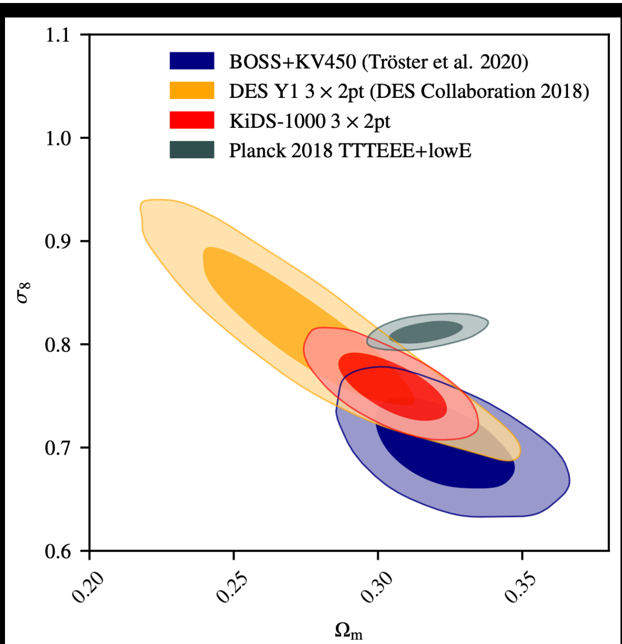


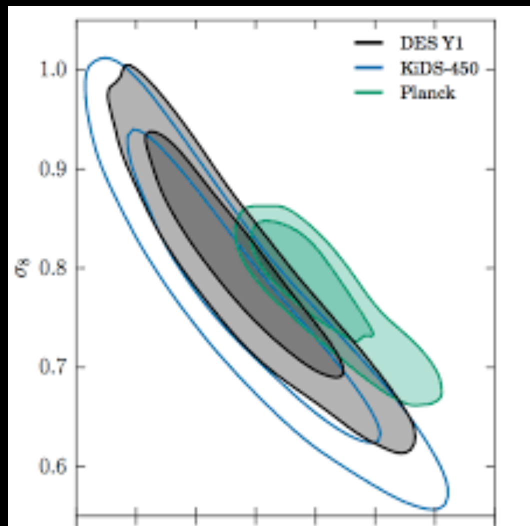
Bernal et al 2102.05066

Should not worsen the other "tension"



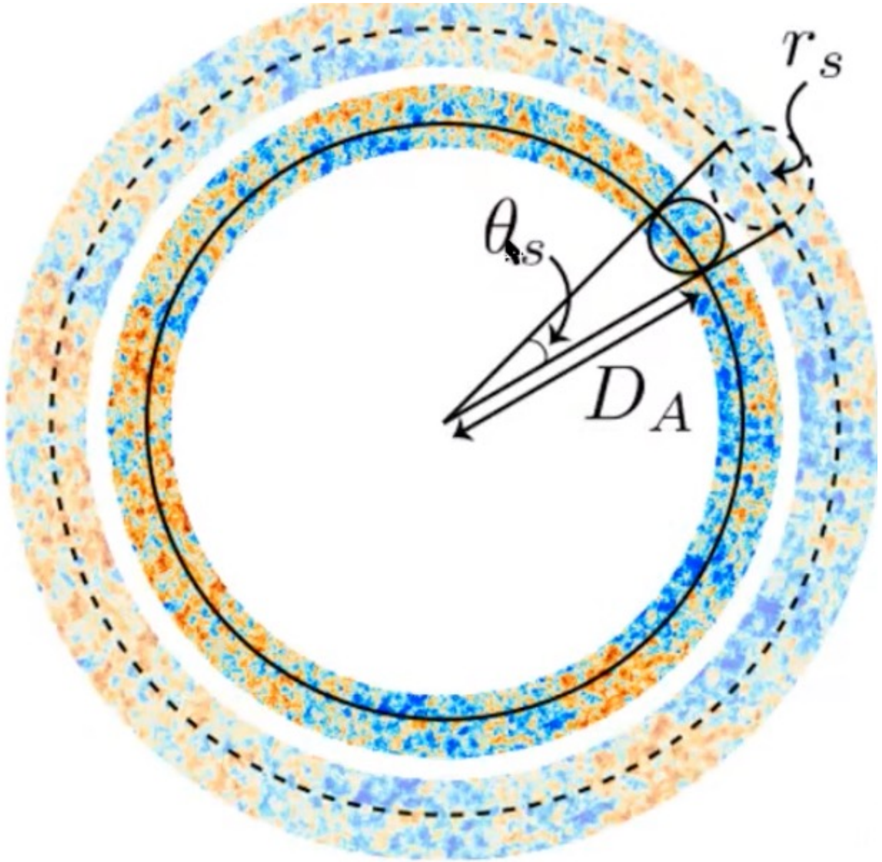






If it ain't broken don't fix it

$$\theta_s = \frac{r_s}{D_A}$$



$$D_A = \frac{c}{H_0} \int_{t_{rec}}^{t_0} \frac{dt/t_0}{[\rho(t)/\rho_0]^{1/2}}$$

$$H_0 = H_{\text{rec}} \frac{\int_{t_{\text{rec}}}^{t_0} \frac{c\,dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\text{rec}}} \frac{c_s(t)\,dt/t_{\text{rec}}}{[\rho(t)/\rho(t_{\text{rec}})]^{1/2}}}$$

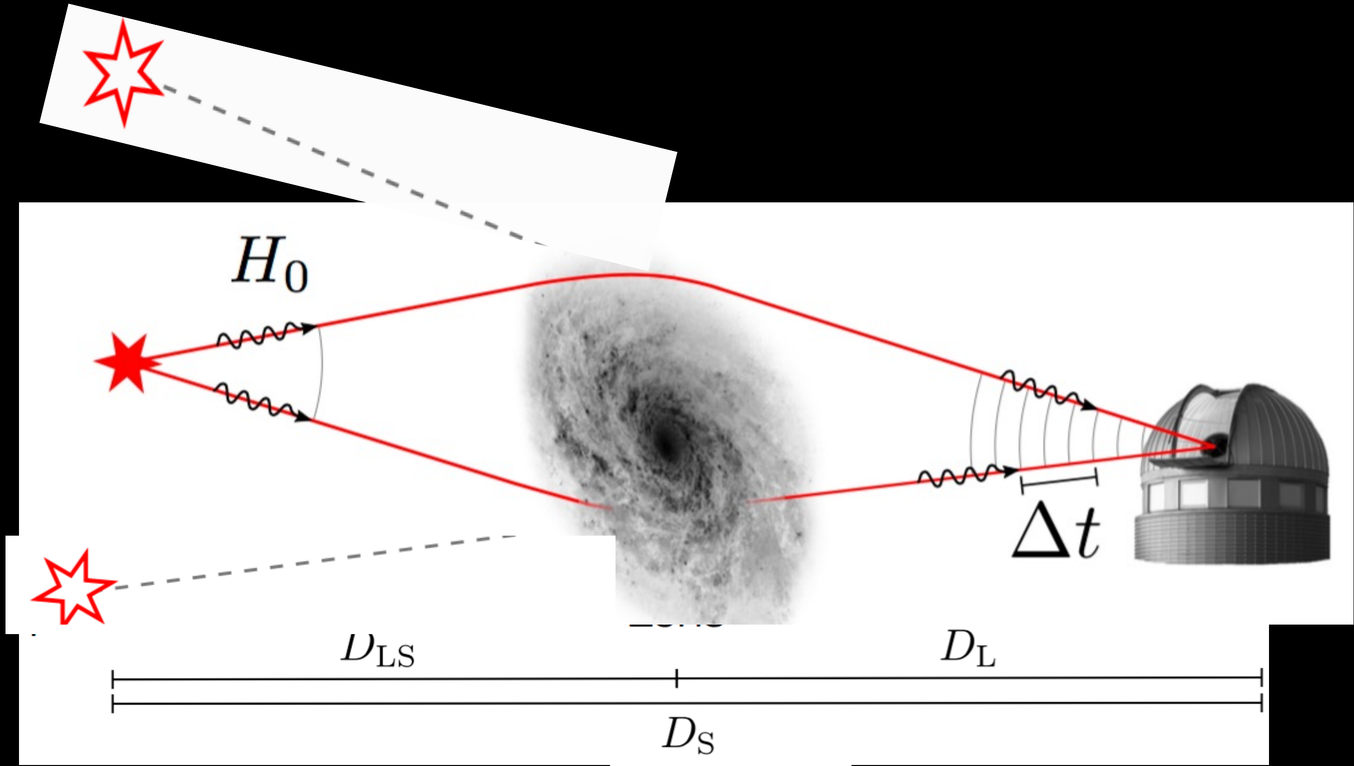
$$r_s = \frac{1}{H_{\text{rec}}} \int_0^{t_{\text{rec}}} \frac{c_s(t)\,dt/t_{\text{rec}}}{[\rho(t)/\rho(t_{\text{rec}})]^{1/2}}$$

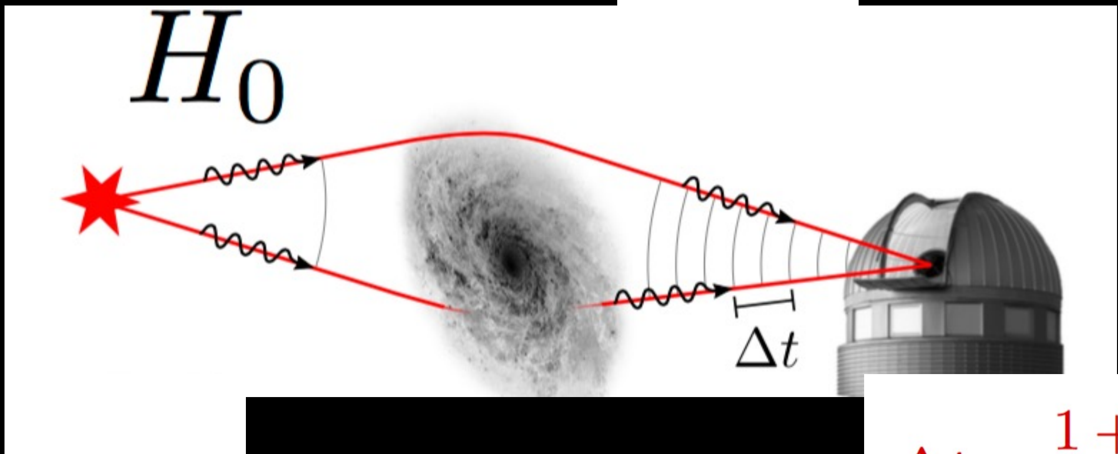
Back to the 90ies

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

Example: old halo stars, globular clusters

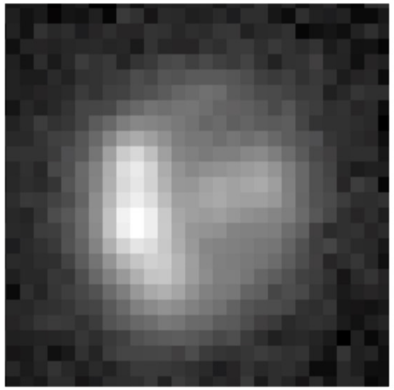
But.. Detemining accurately the absolute age of these objects has his own



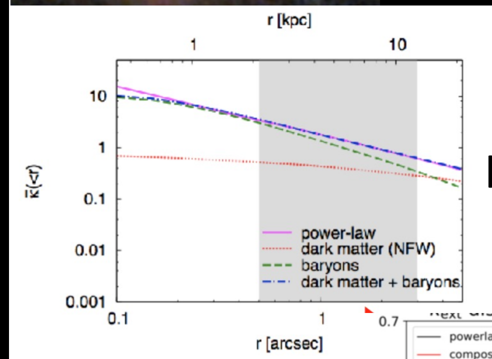


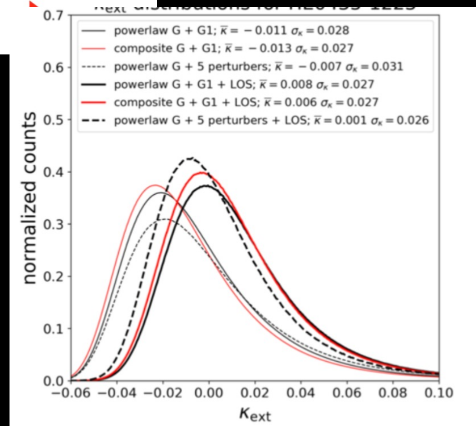
$$\Delta t = \frac{1+z_{\rm L}}{c} \underbrace{\frac{D_{\rm L} D_{\rm S}}{D_{\rm LS}}}_{\propto 1/H_0} \cdot \Delta \left(\frac{1}{2} |\vec{\theta} - \vec{\beta}|^2 - \psi(\vec{\theta}) \right)$$

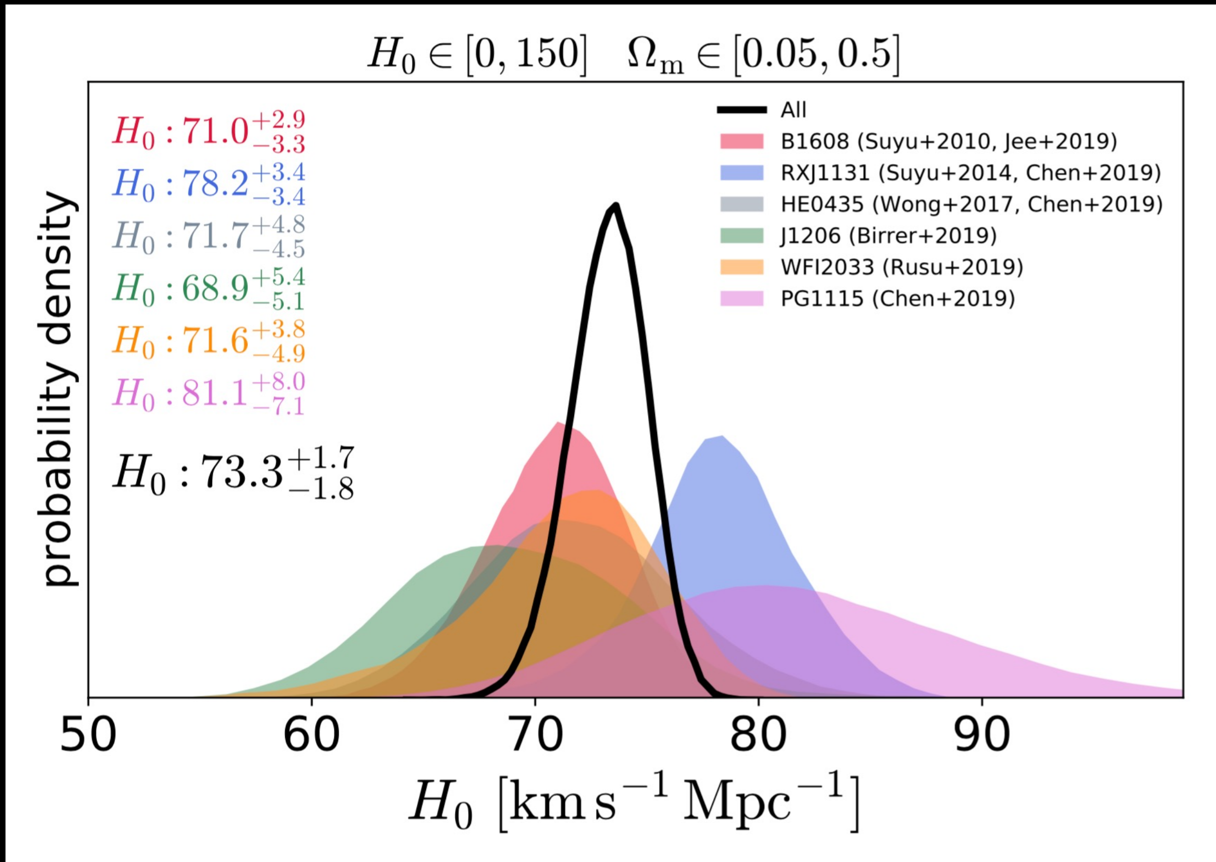
PAST



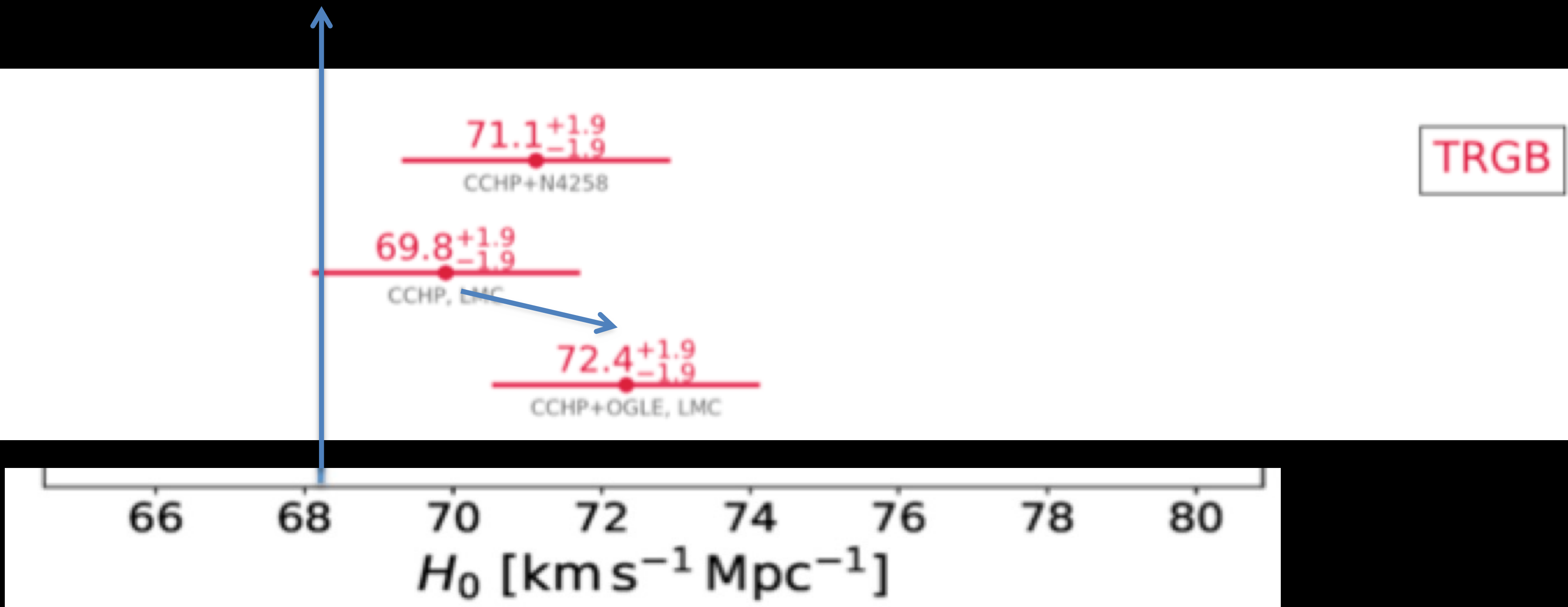
Ground-based seeing-limited



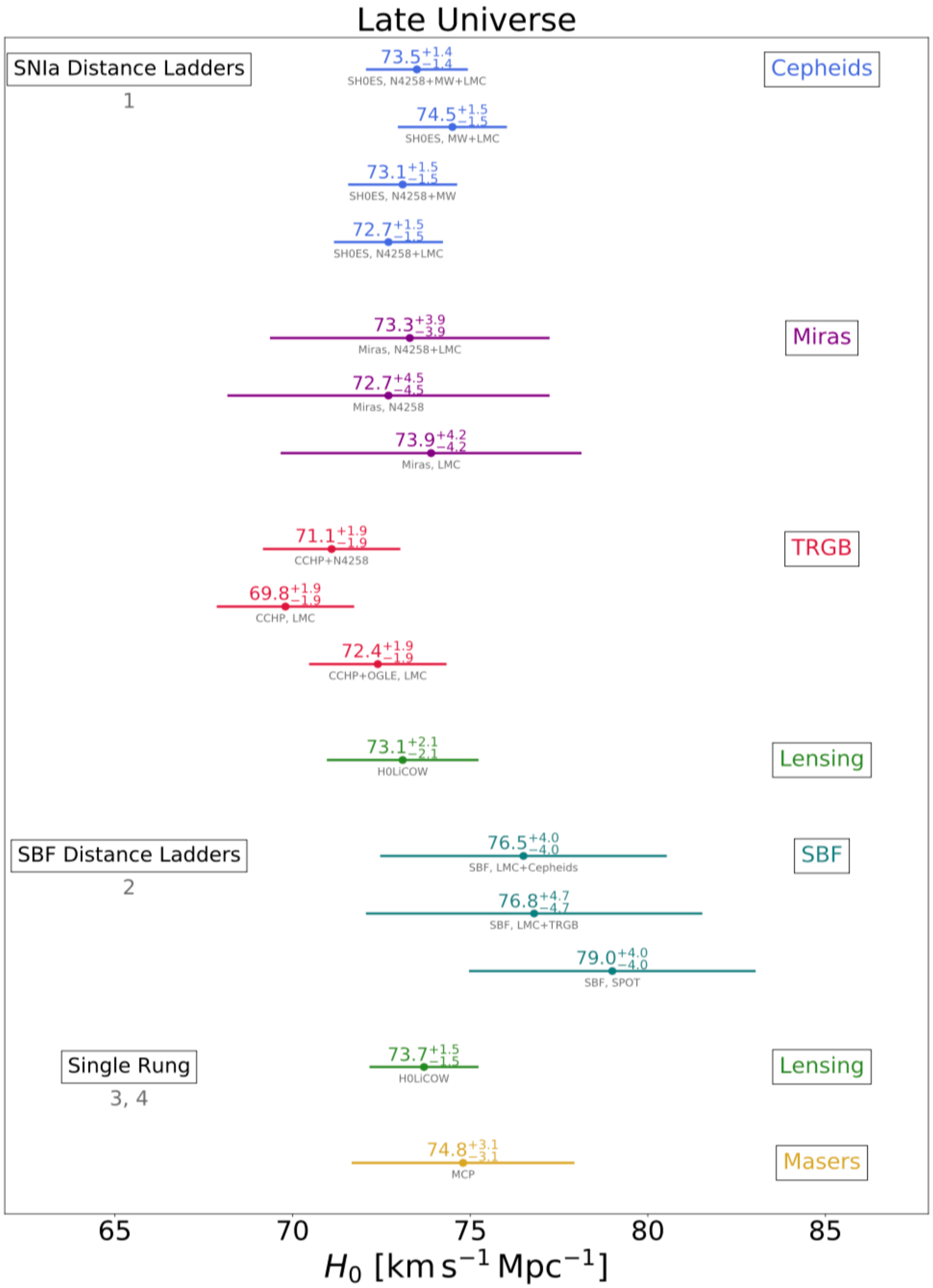




$H_0 \in [0, 150] \quad \Omega_m \in [0.05, 0.5]$
$H_0 : 71.0^{+2.9}_{-3.3}$
$H_0 : 78.2^{+3.4}_{-3.4}$
$H_0 : 71.7^{+4.8}_{-4.5}$
$H_0 : 68.9^{+5.4}_{-5.1}$
$H_0 : 71.6^{+3.8}_{-4.9}$
$H_0 : 81.1^{+8.0}_{-7.1}$
$H_0 : 73.3^{+1.7}_{-1.8}$
All
B1608 (Suyu+2010, Jee+2019)
RXJ1131 (Suyu+2014, Chen+2019)
HE0435 (Wong+2017, Chen+2019)
J1206 (Birrer+2019)
WFI2033 (Rusu+2019)
PG1115 (Chen+2019)
probability density
50
60
70
80
90
$H_0 \ [\mathrm{km\,s^{-1}\,Mpc^{-1}}]$

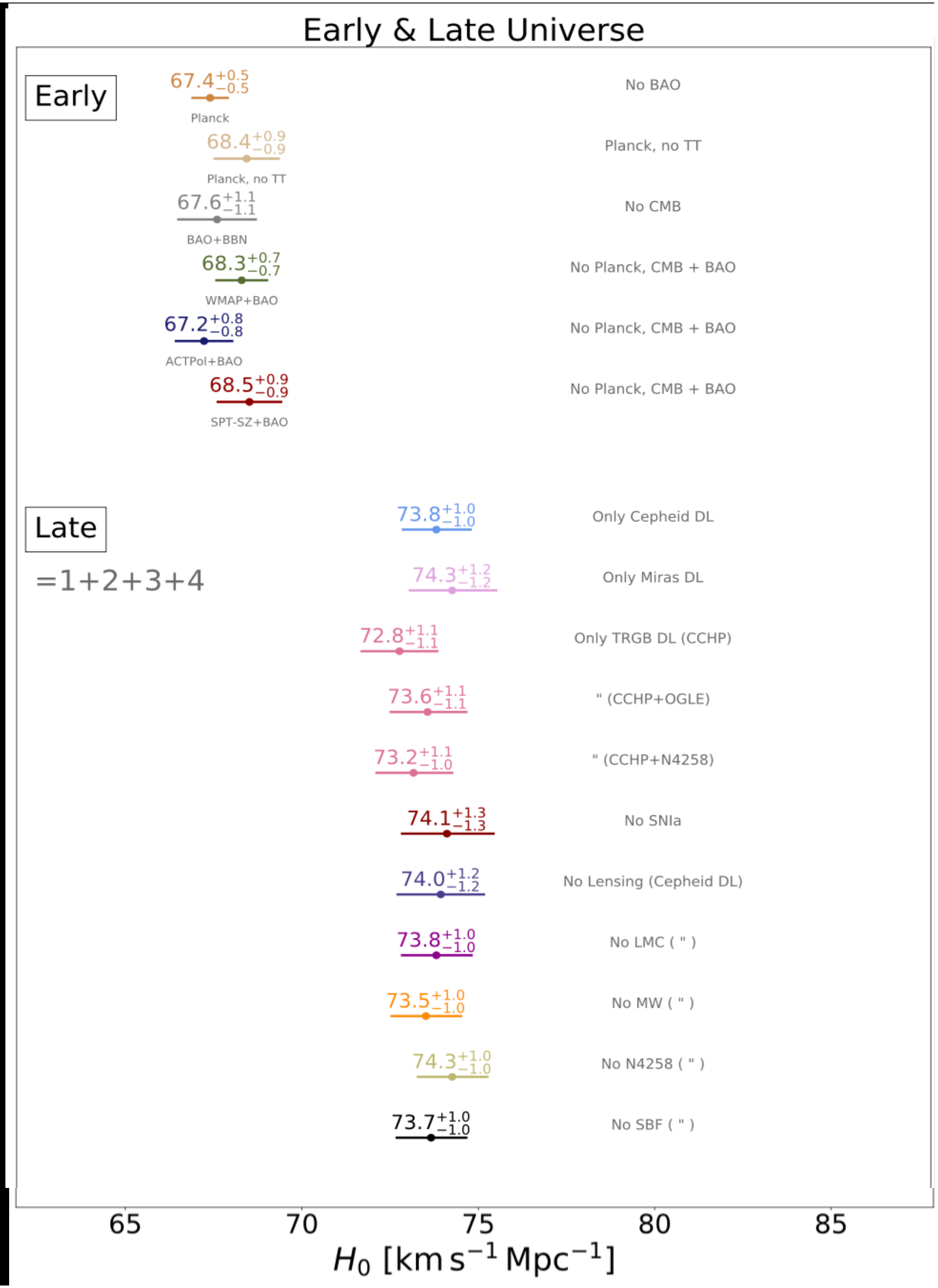


$71.1^{+1.9}_{-1.9}$
CCHP+N4258
$69.8^{+1.9}_{-1.9}$
CCHP, LMC
$72.4^{+1.9}_{-1.9}$
CCHP+OGLE, LMC
TRGB
66
68
70
72
74
76
78
80
H_0 [km s^{-1} Mpc^{-1}]



Late Universe
Prix Fixe Menu

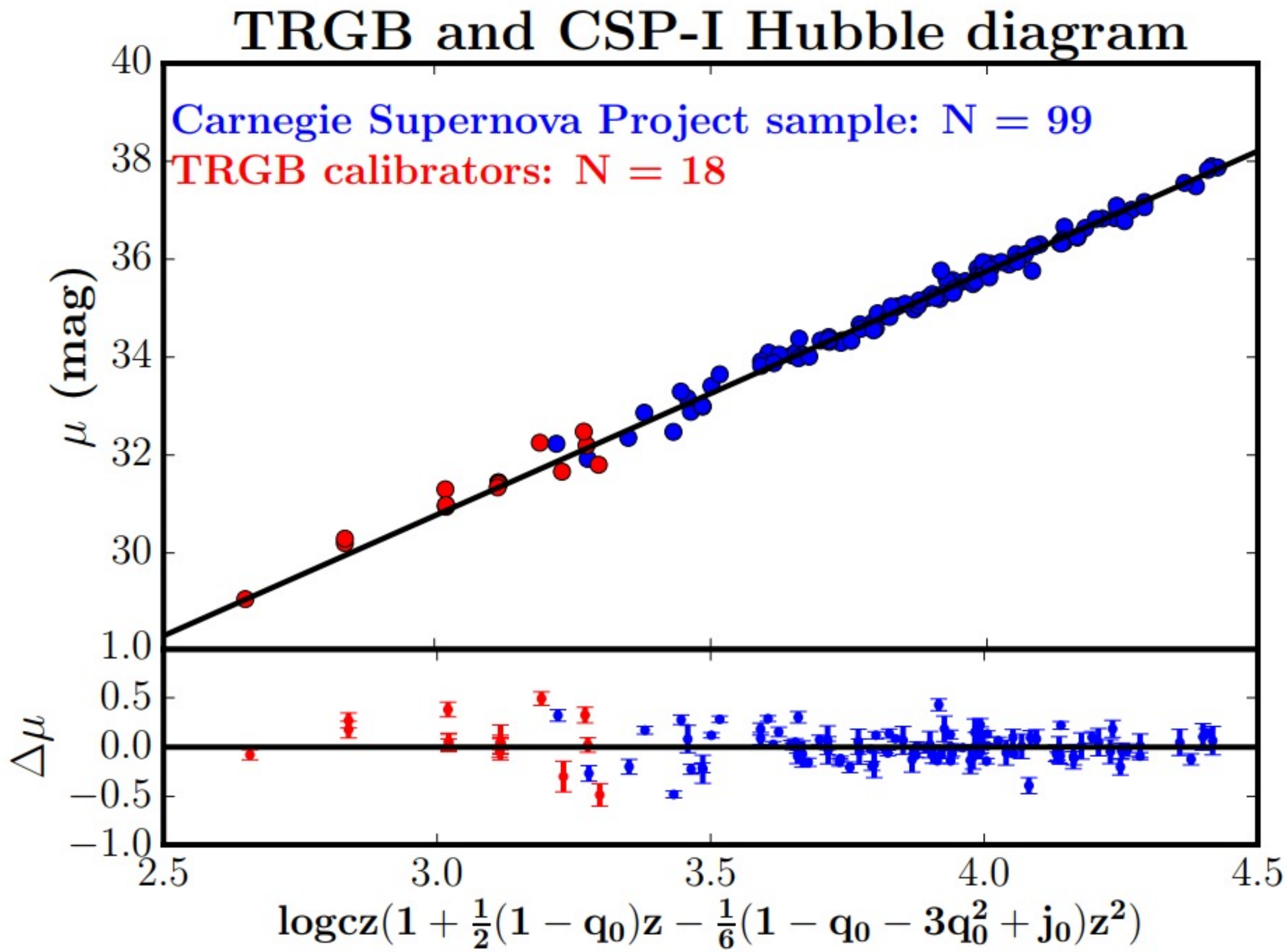
One from 1
+ One from 2
+3
+4
- one peremptory challenge



Late Universe
Prix Fixe Menu

One from 1
+ One from 2
+3
+4
- one peremptory challenge

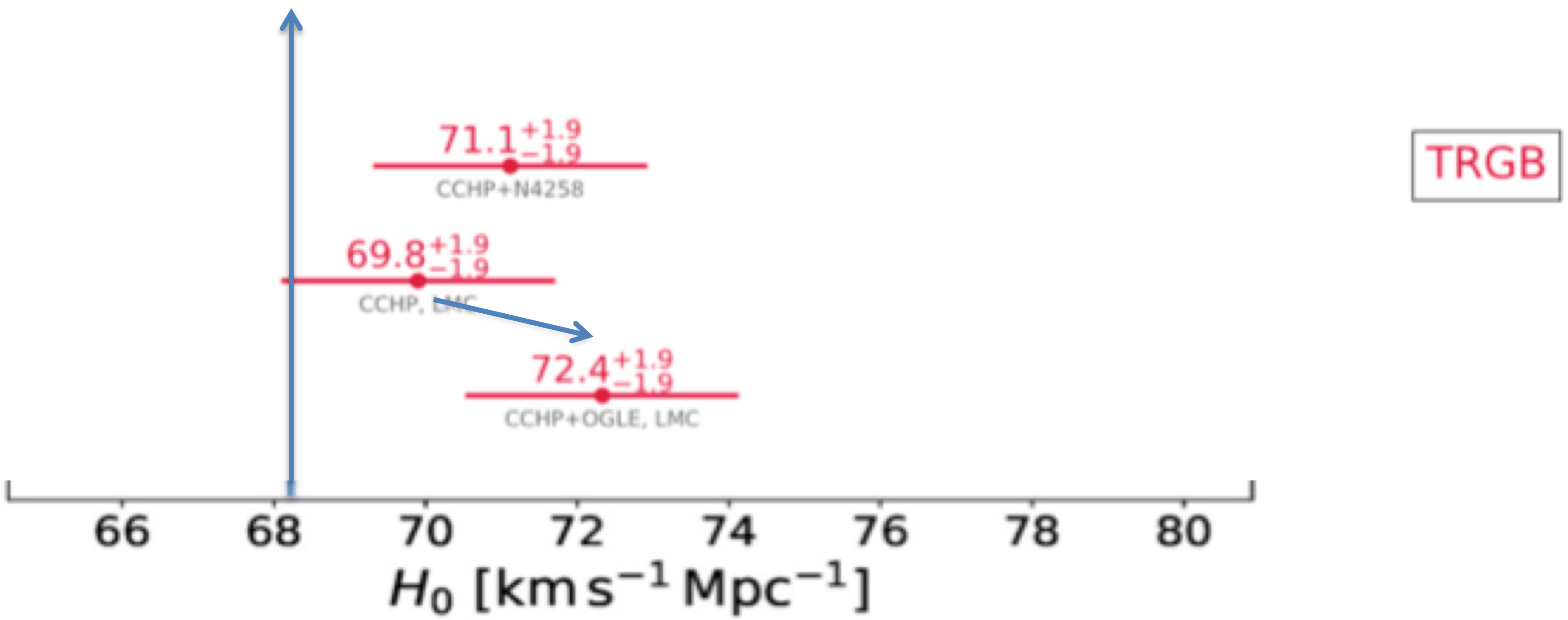
Distance scale



LMC reddening

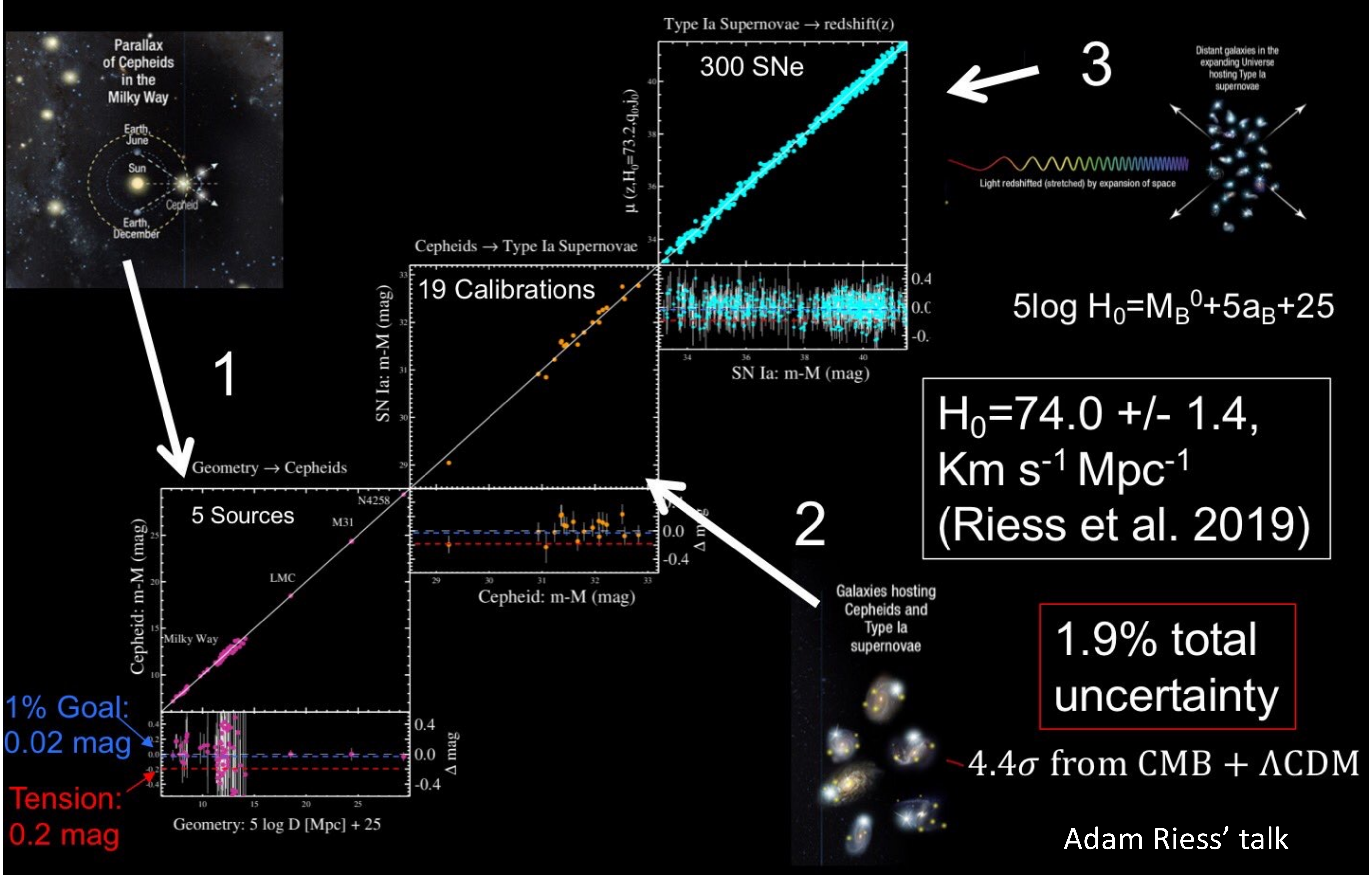
Add OGLE info on this

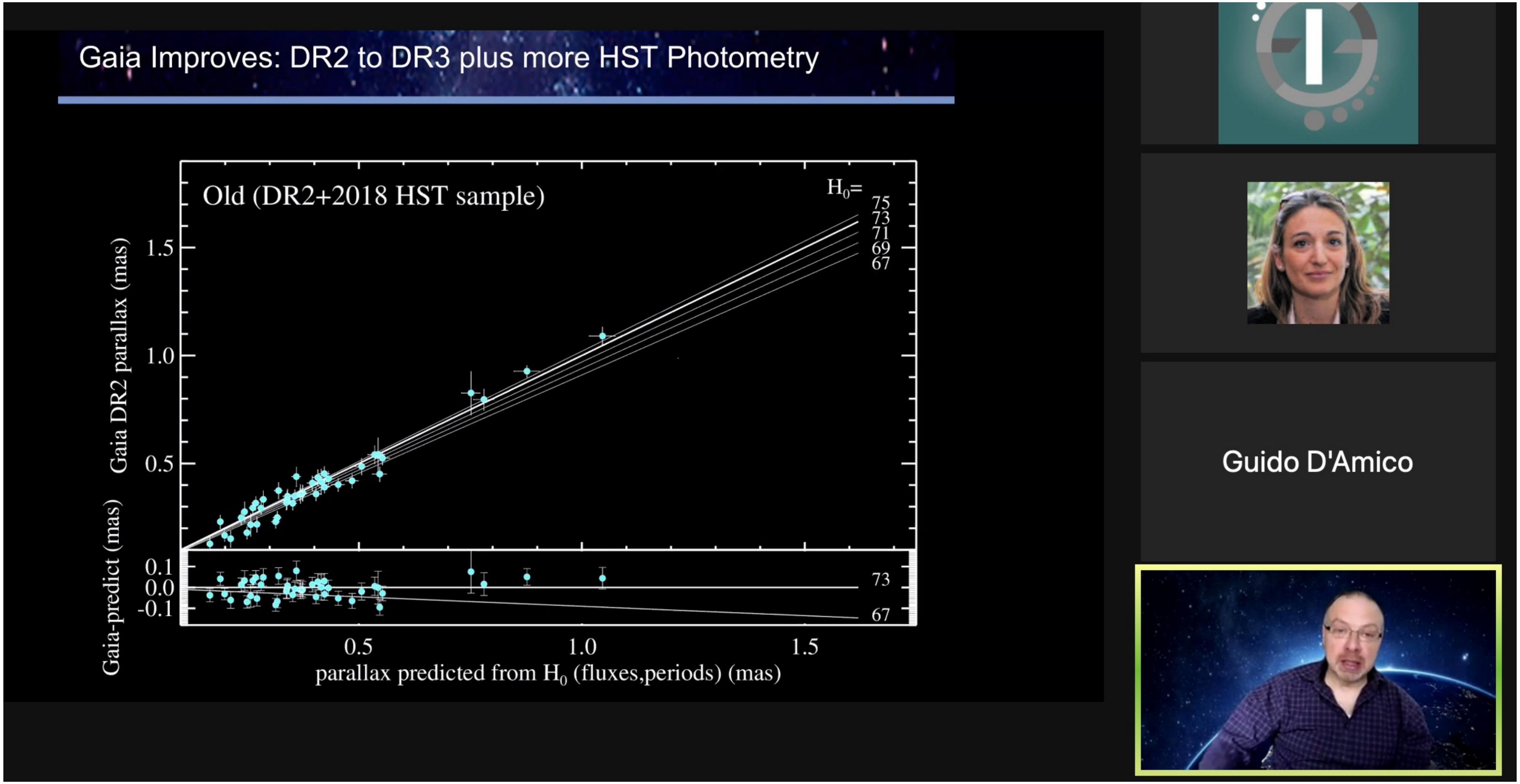
Yuan et al. 2019 TRGB in SN hosts-→ H0=72.4 ± 2 km/s/Mpc

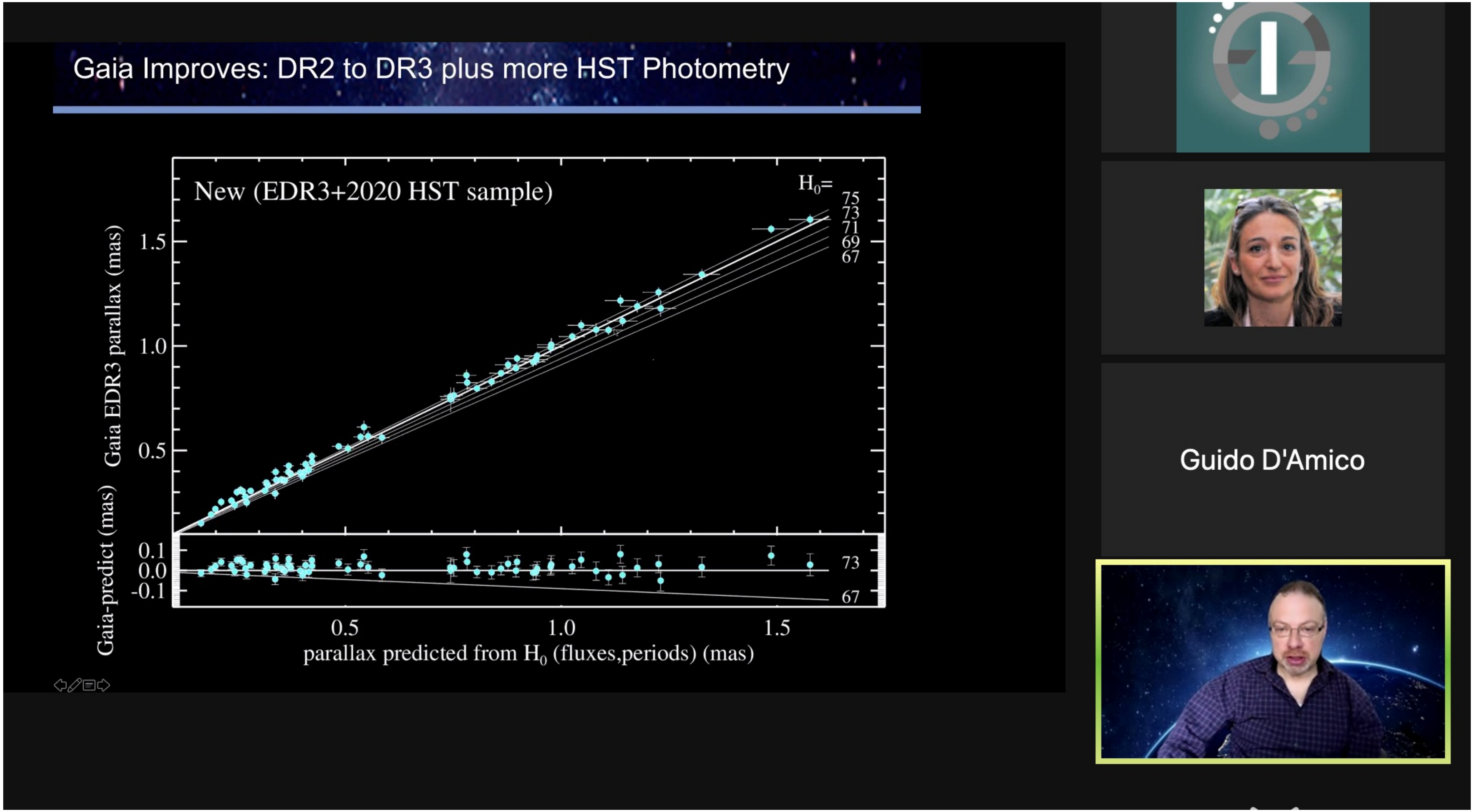


Jury is still out…..

The Hubble Constant in 3 Steps: Present Data



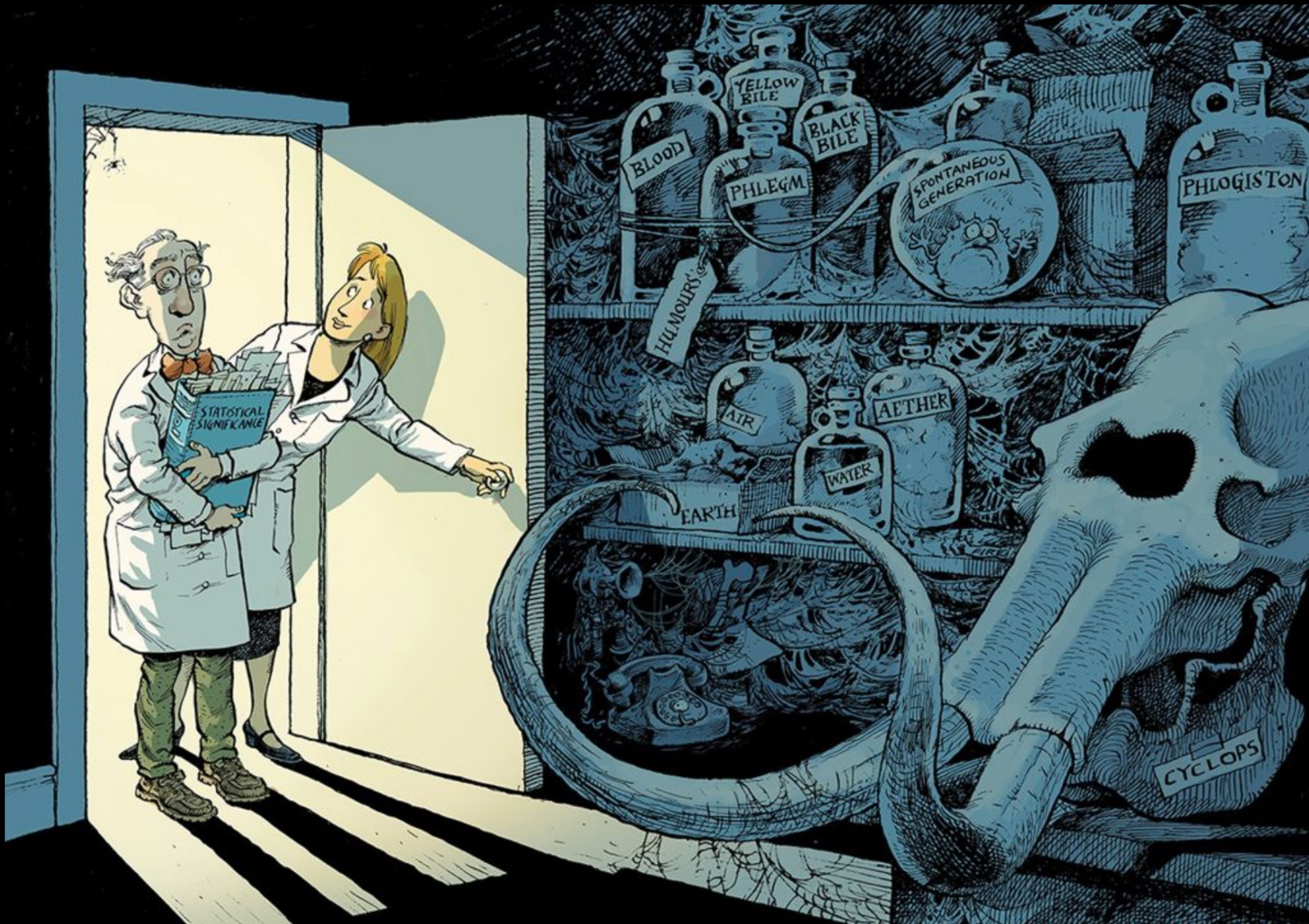

Gaia Improves: DR2 to DR3 plus more HST Photometry
Old (DR2+2018 HST sample)
H0=
75
73
71
69
67
Gaia DR2 parallax (mas)
1.5
1.0
0.5
Gaia-predict (mas)
0.1
0.0
-0.1
73
67
0.5
1.0
1.5
parallax predicted from H0 (fluxes,periods) (mas)
Guido D'Amico



Gaia Improves: DR2 to DR3 plus more HST Photometry
New (EDR3+2020 HST sample)
H0=
75
73
71
69
67
Gaia EDR3 parallax (mas)
1.5
1.0
0.5
Gaia-predict (mas)
0.1
0.0
-0.1
73
67
0.5
1.0
1.5
parallax predicted from H0 (fluxes,periods) (mas)
Guido D'Amico

A word on the meaning of these percentages

Both 5 σ discovery level and BACCUS were motivated by



The Tension Matrix—present difference is 4-6 times the error bars