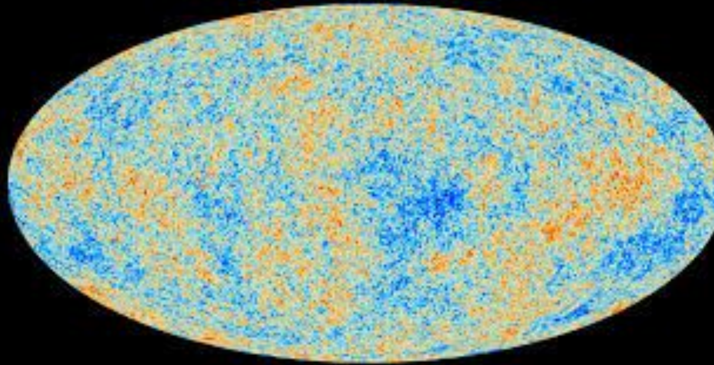
Lemaitre: Getting Hubble into trouble

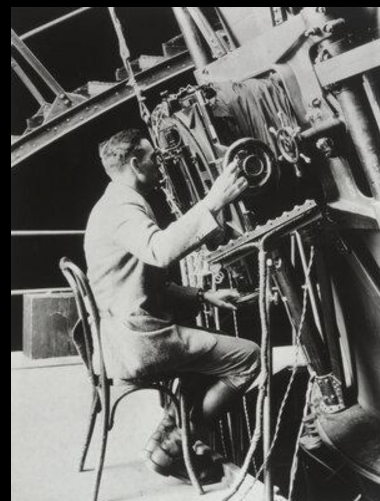


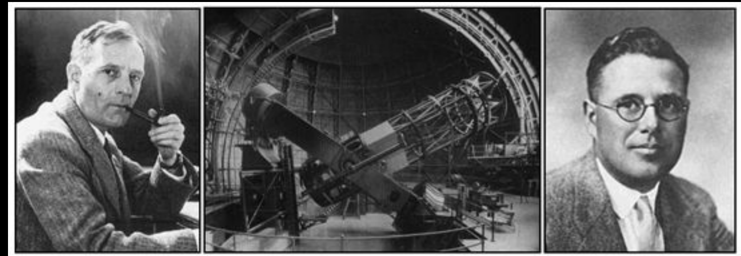
Licia Verde
ICREA & ICCUB

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

The universe is expanding

- Since 1929





Edwin Hubble 1889 – 1953 | 100 inch Mt Wilson Telescope | Milton Humason 1891 – 1972

1927 Lemaitre solution of GR and predicts a distance–redshift relation

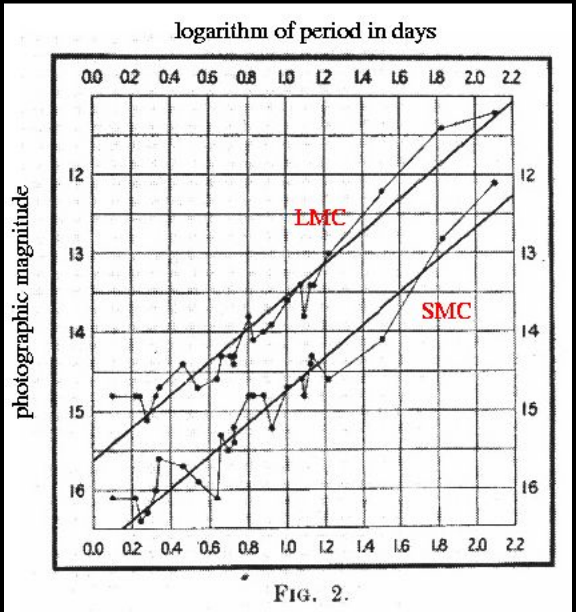
The Hubble-Lemaitre law $$v = H_0 d$$

The Hubble “constant”

Measuring (recession) velocities is easy, but measuring distances is hard

Getting Hubble into trouble…

Cepheids and Henrietta Swan Leavitt



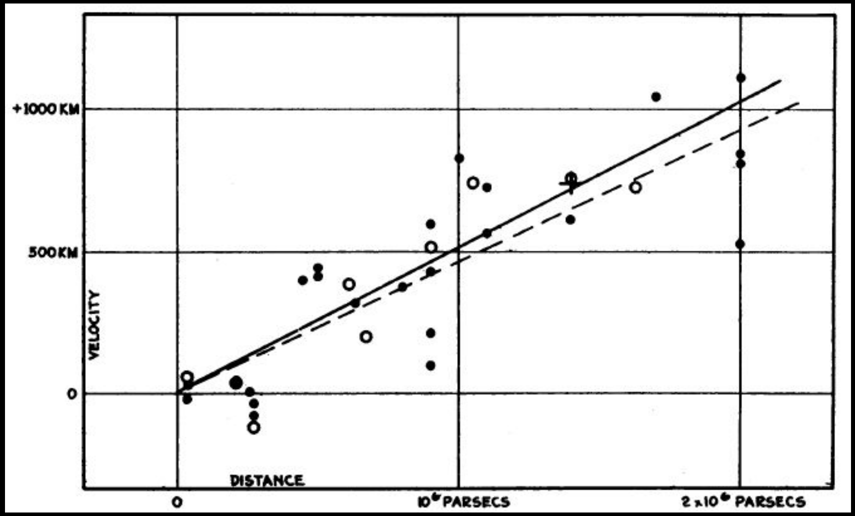
1912

Paper signed by Edward Pickering, but in the first sentence… "prepared by Miss Leavitt".

Period luminosity relation

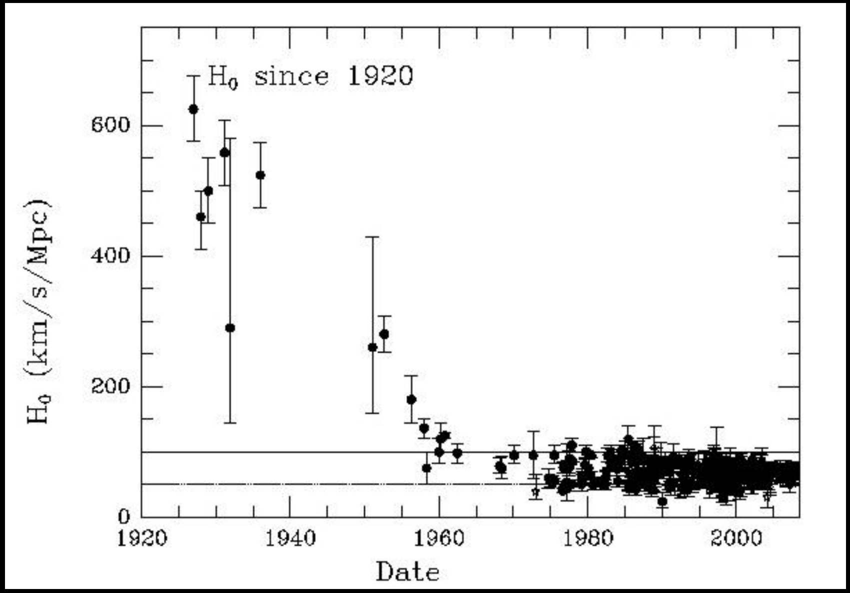
Hubble's plate

The expanding Universe



$$v = H_0 d$$

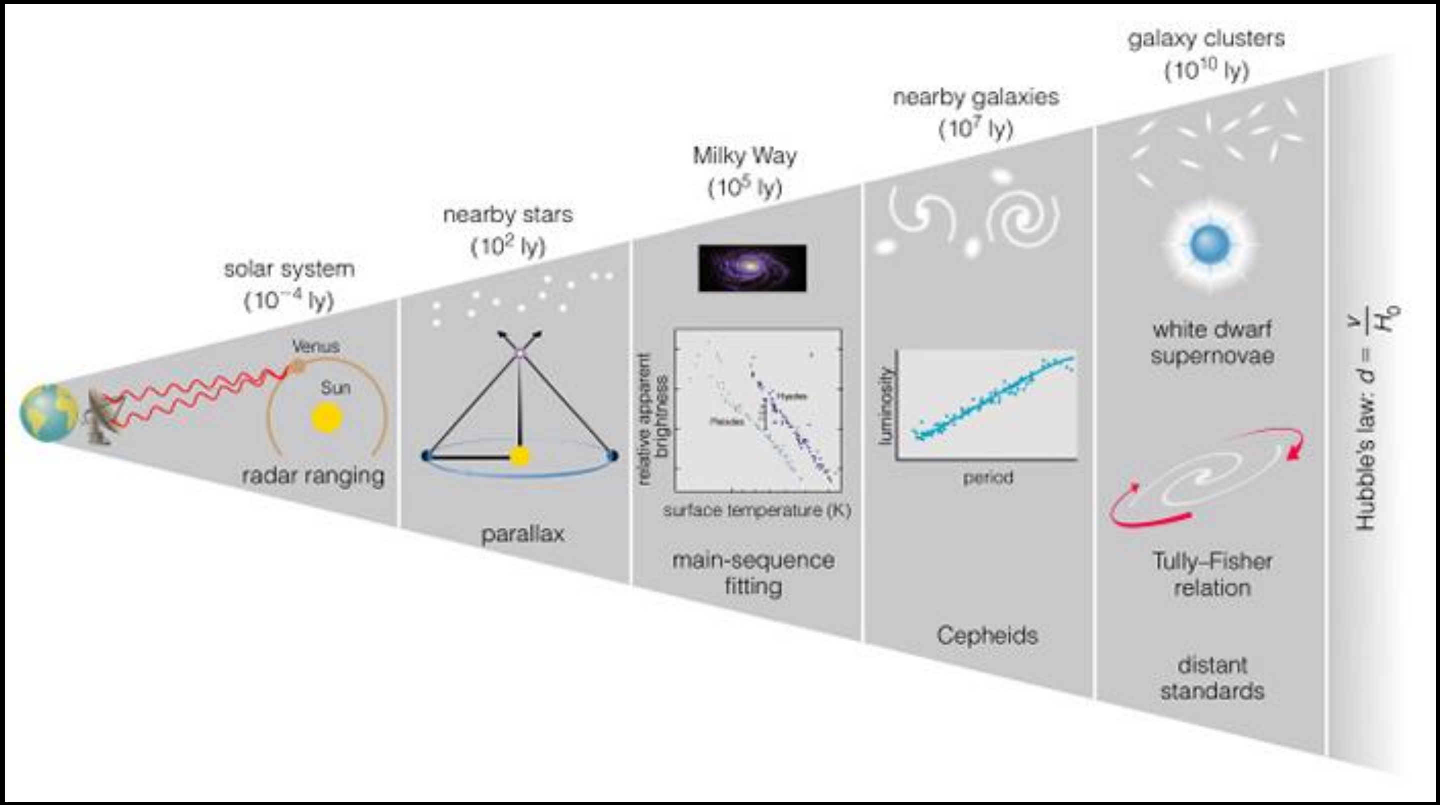
However



Get H this way

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

A cosmic distance ladder



Talks by W. Freedman and A. Riess


"I have read your article.
Your calculations are correct,
but your physics is abominable"

Friedmann
(who scooped Lemaitre) equations

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

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

GR+ cosmological principle

Leap of faith here…

FLRW

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 -

the “cosmology race”

- Since then the development of cosmology

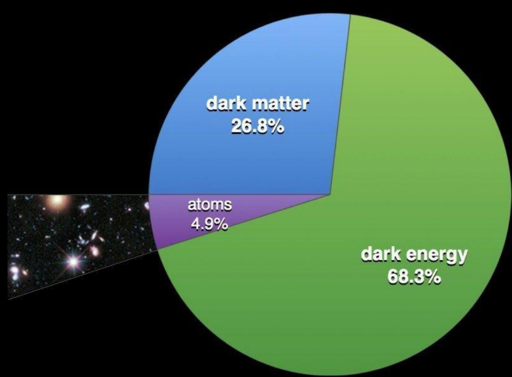
could be summarized by the efforts to constrain cosmological parameters

The standard model of cosmology

The ΛCDM model (see M. Turner talk)

few cosmological parameters: “Just 6 numbers”….

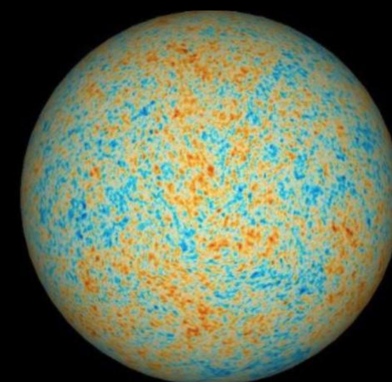
Composition, background evolution



@AstroKatie/Planck13

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

perturbations

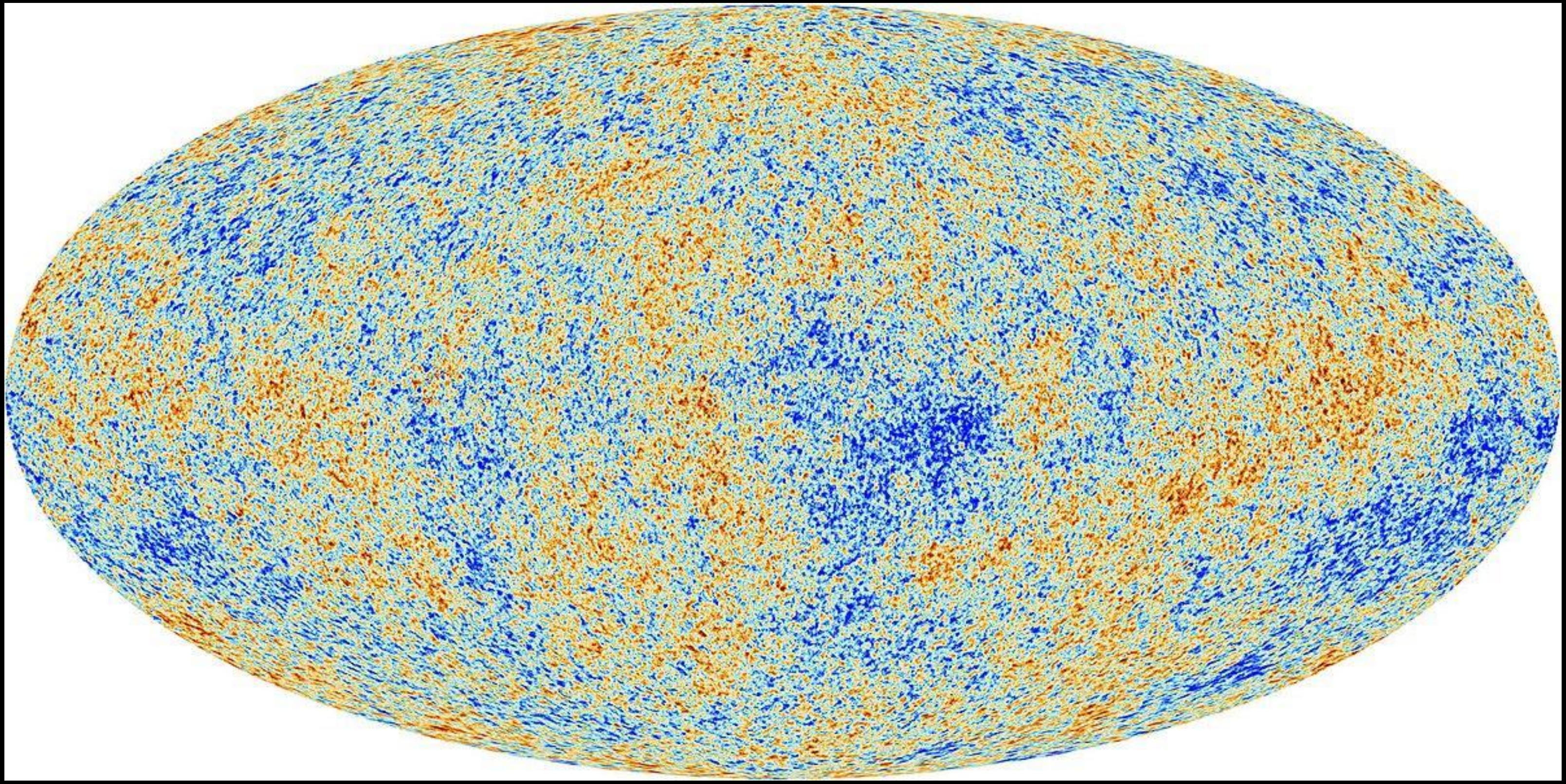


τ, As ns

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

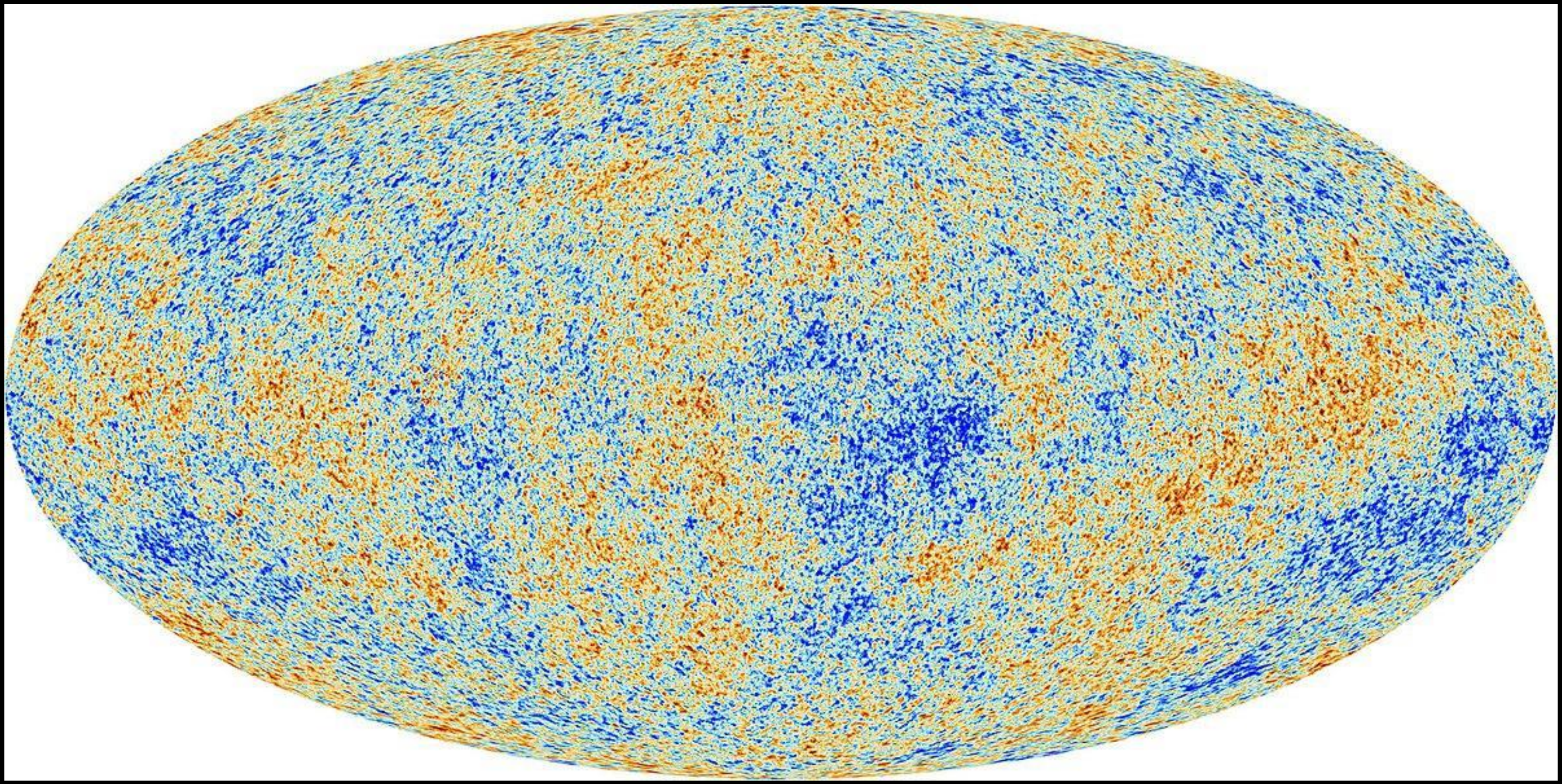
The model’s parameters are now determined with % accuracy: Precision cosmology!

‘*Fiat Lux*’: Observations that gave us precision cosmology



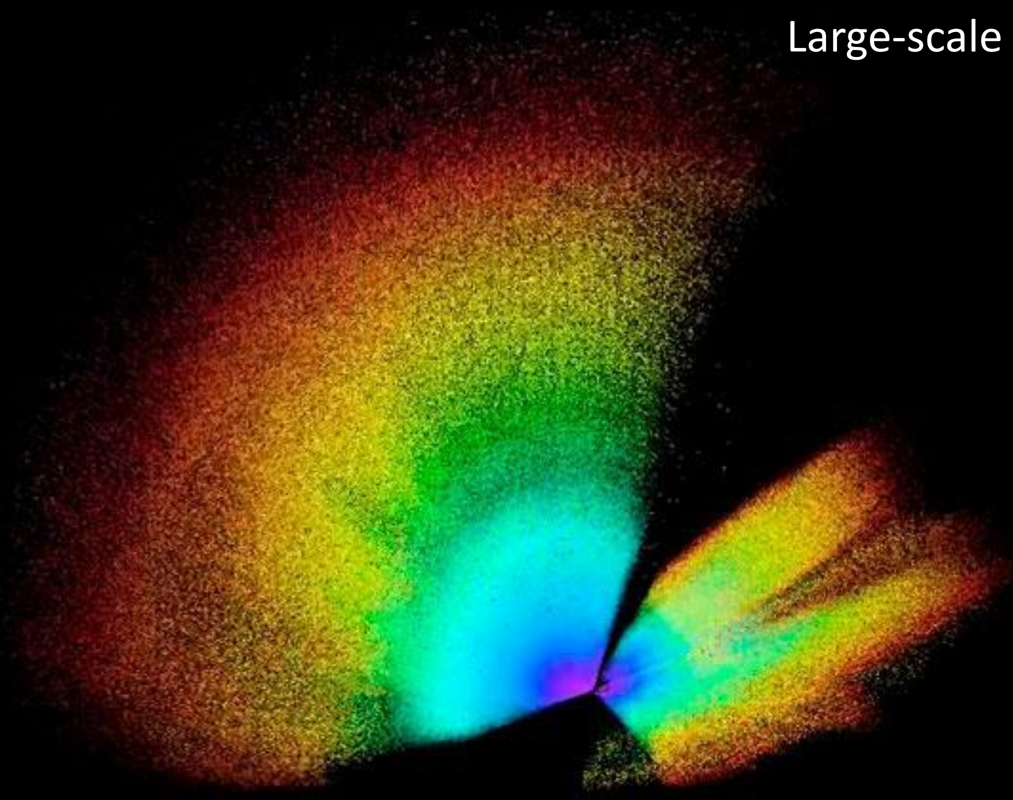
Planck CMB temperature map
This light is also polarized

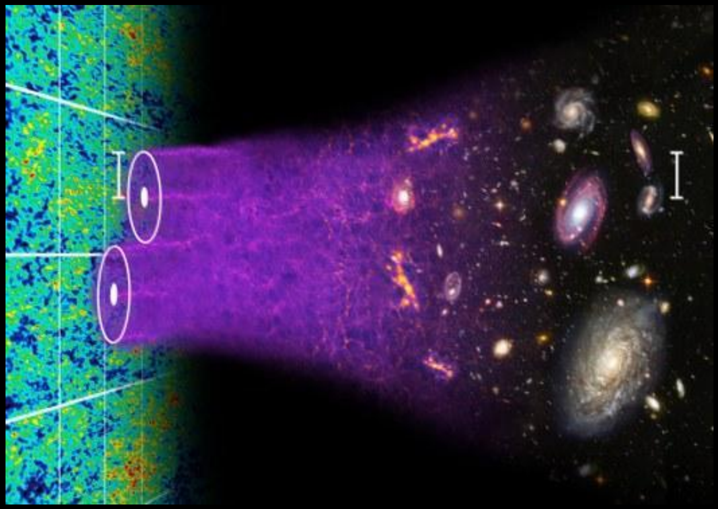
“L’atom primitif”

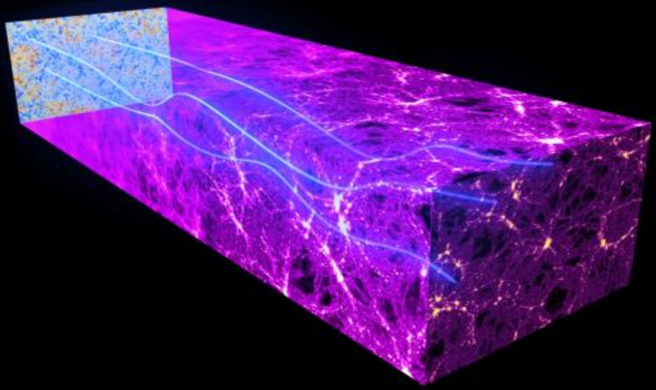


Planck CMB temperature map
This light is also polarized

Large-scale structure (Galaxy surveys)



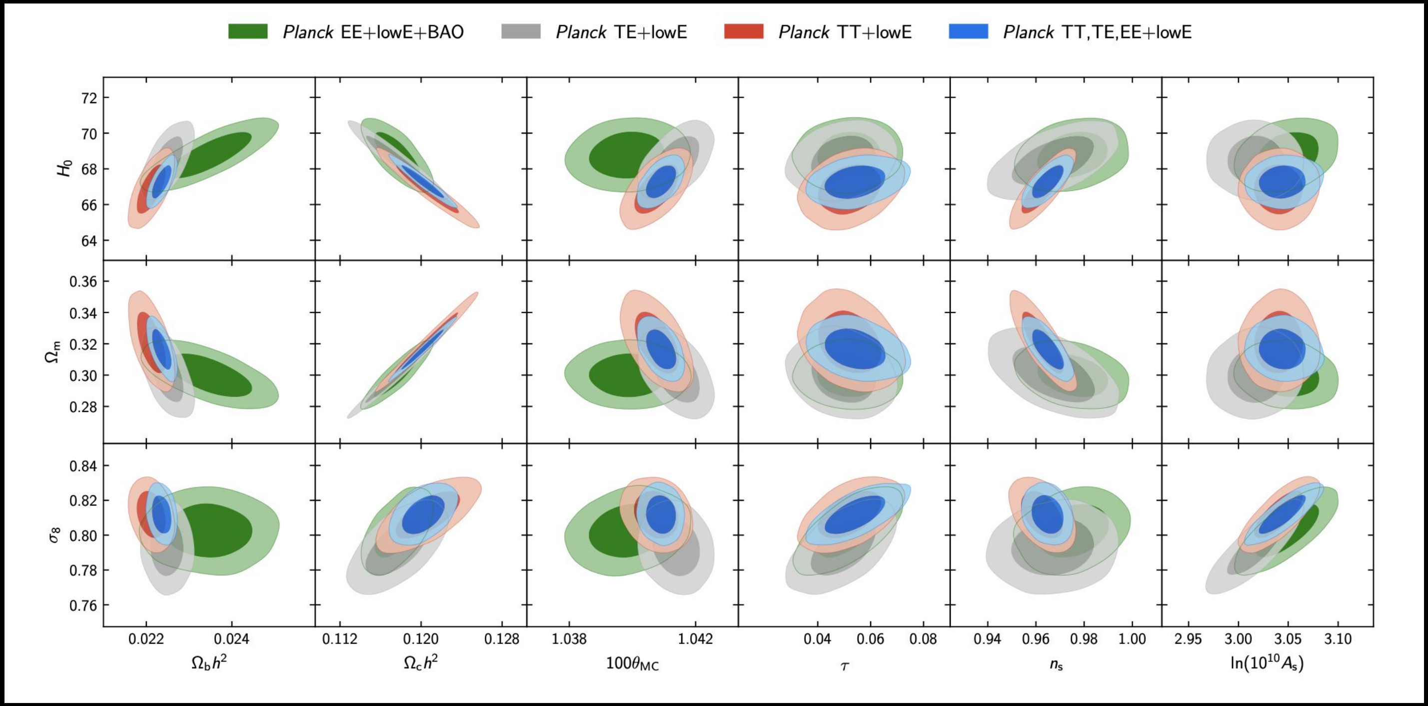




Precision cosmology

- Cosmology over the past three decades has moved from a *data-starved science* to a *data-driven science*
- Cosmology has entered the era of precision: precision cosmology
- As a result, Cosmology has a *standard model.* The *standard cosmological model* only needs few parameters to describe origin composition and evolution of the Universe
- Parameters values are measured with ~% precision

Precision cosmology

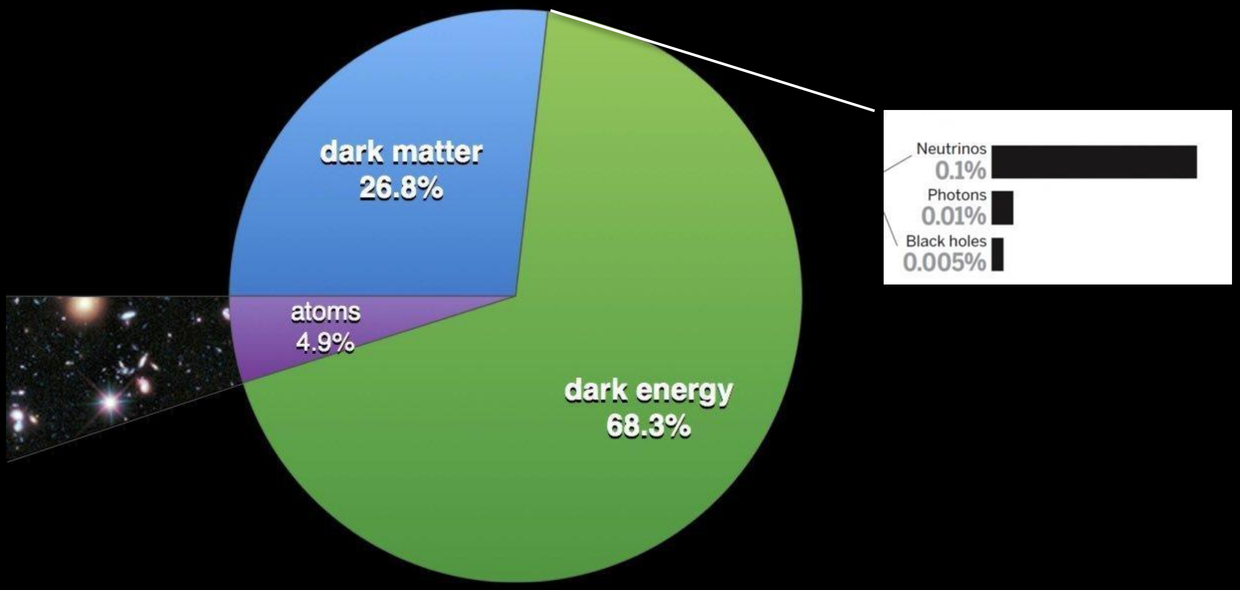


Planck 2018, and tight constraints on popular extensions to this model

CMB+DESI .. I'll spare you the dreaded triangle plots

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



Ad hoc components?

Friedmann equations

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

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

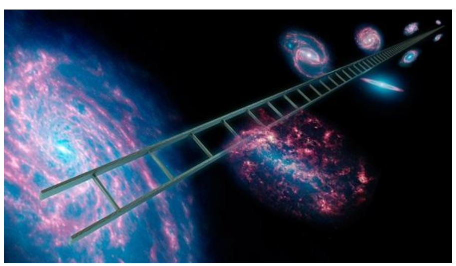
The cosmological parameters have appeared!

H is everywhere!

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

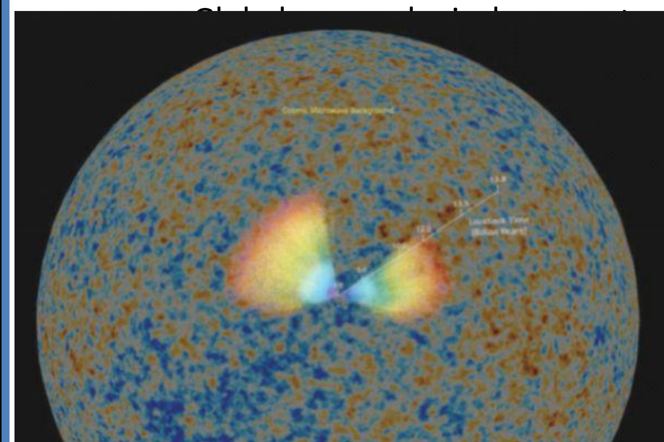
$(z \lesssim 0.1)$
Present day expansion rate of the Universe
Recession velocity ⟶ distance.

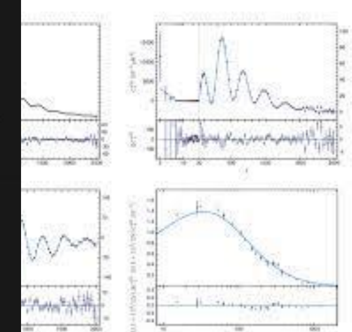


Parallaxes
Cepheids
SNe
TRGB
SBF
Masers
Etc…

Cosmic distance ladder

of a model





Calibrated on early-time physics

Two cosmic speedometers

A tale of two H's

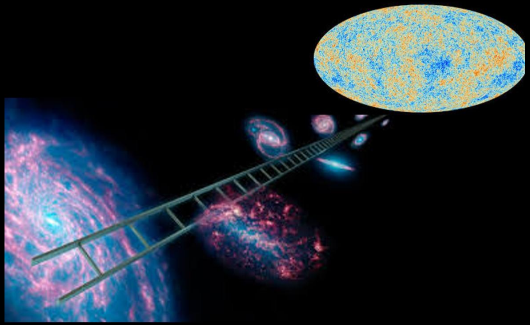
$(z \lesssim 0.1)$
Present day expansion rate of the Universe
Recession velocity → distance.

Parallaxes
Cepheids
SNe
TRGB
SBF
Masers
Etc…

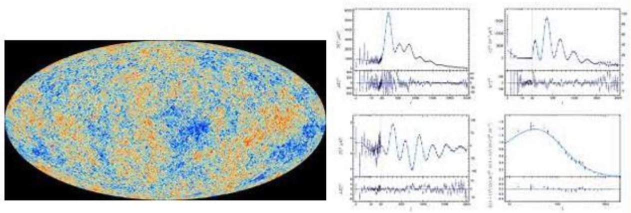
Cosmic distance ladder

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

If they coincide then……



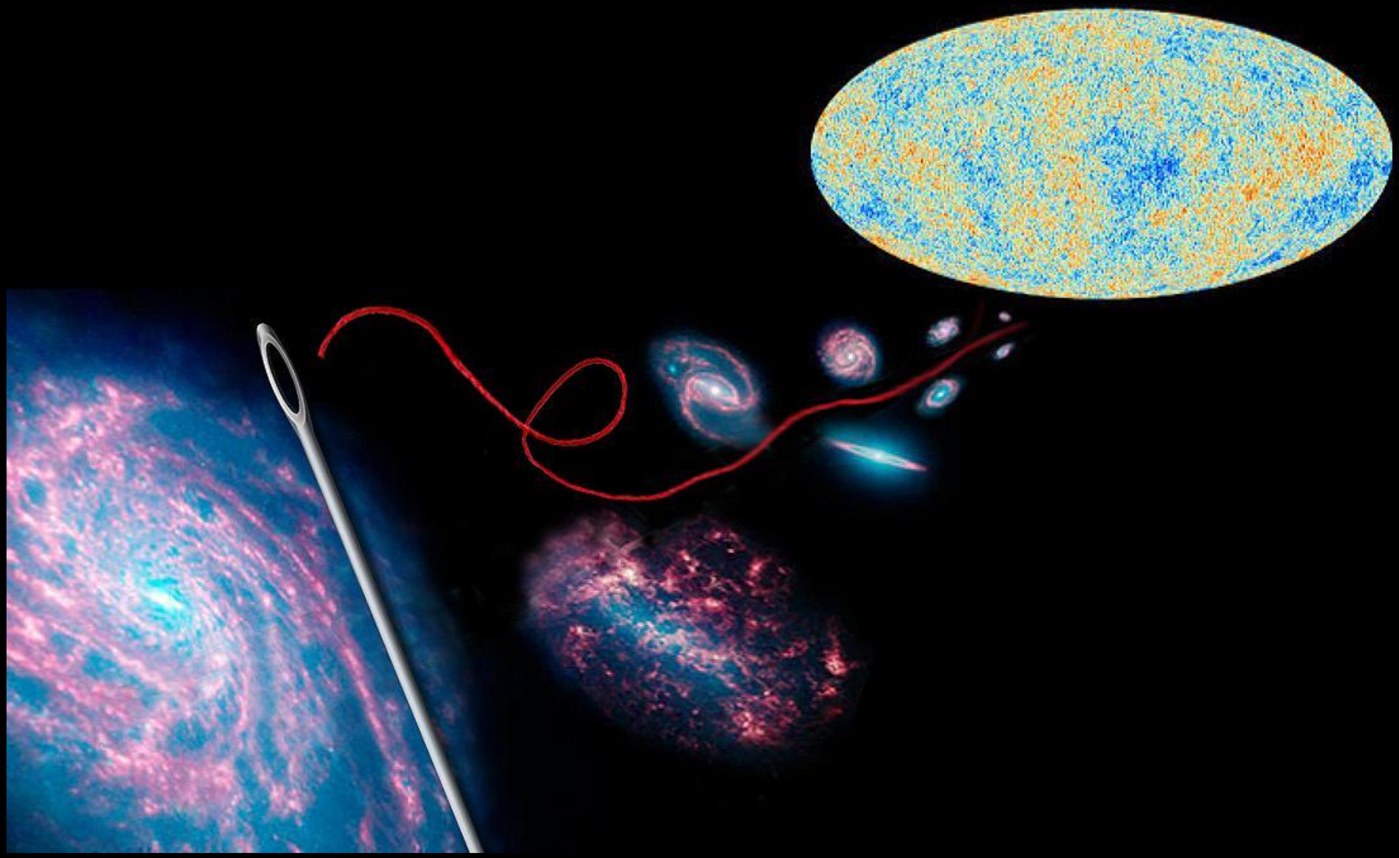
Global , cosmological parameter of a model



…the adopted cosmological model survives an extremely stringent test

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

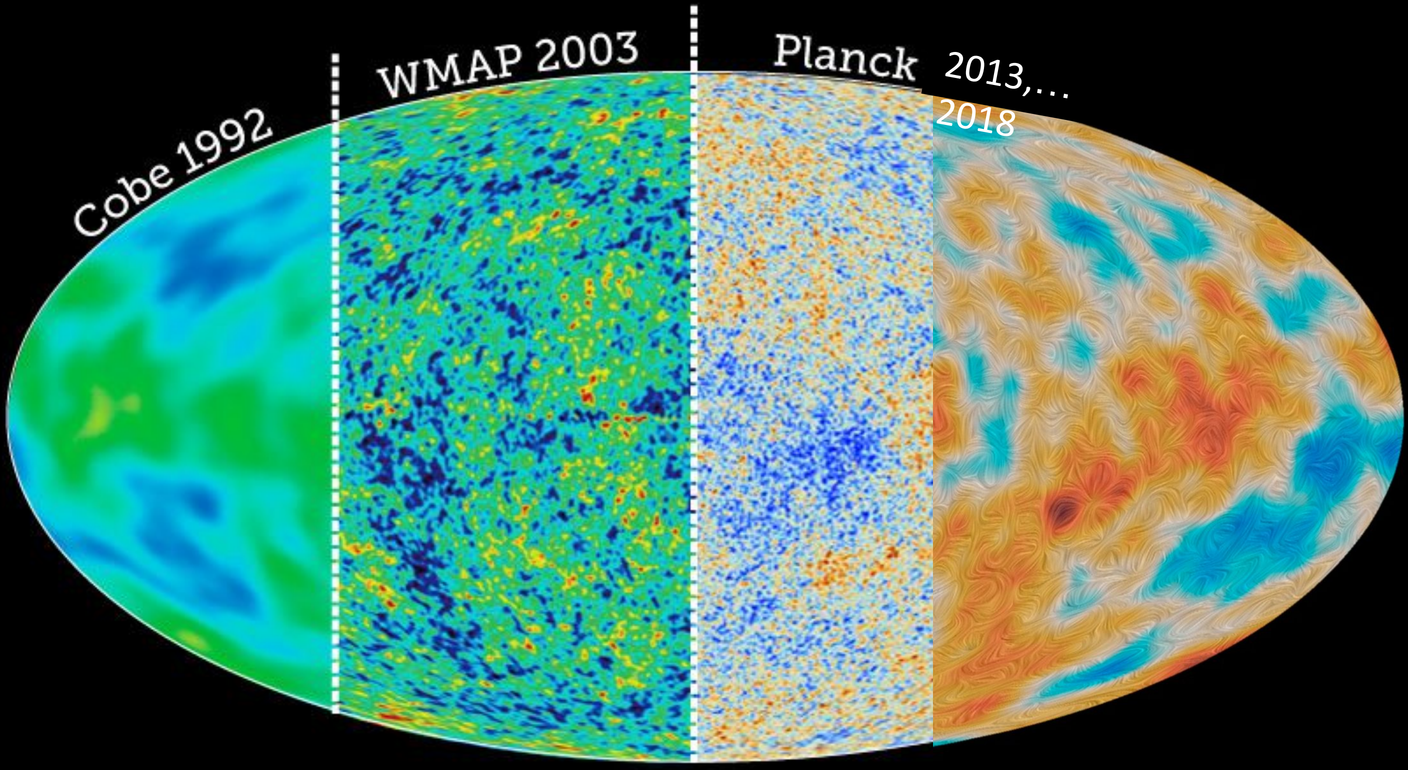
(quote by Adam Riess)



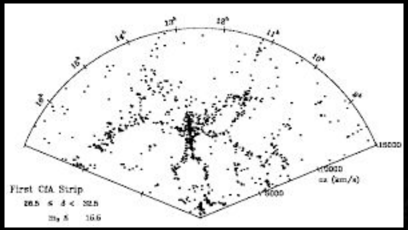
For almost 2 decades these two H's agreed

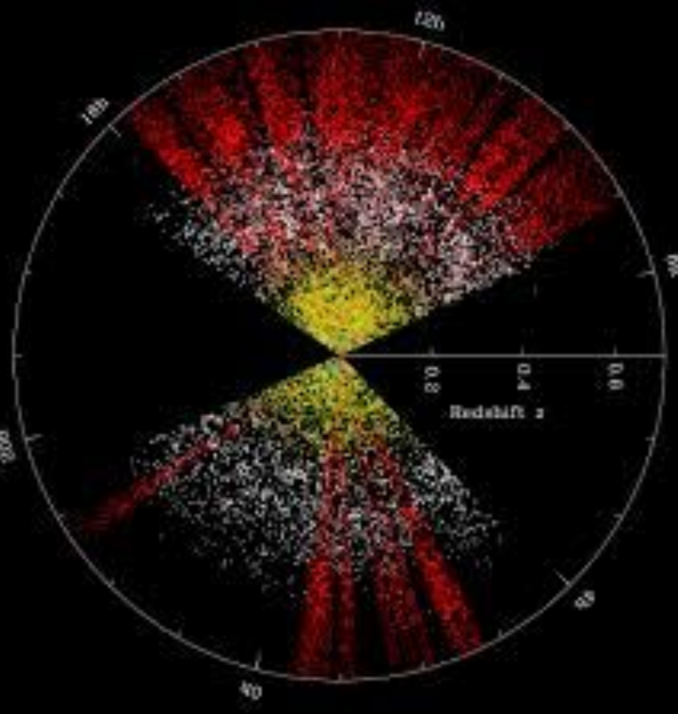
What happened in these 2 decades?

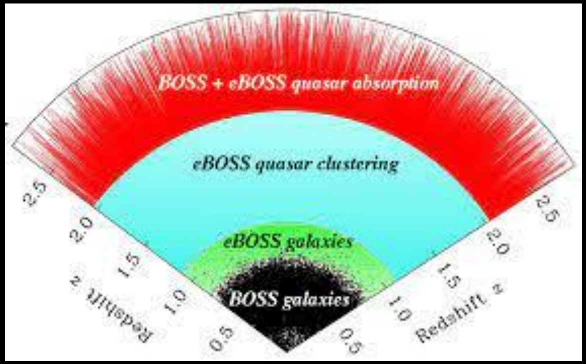
The ΛCDM model has survived unscathed an avalanche of data

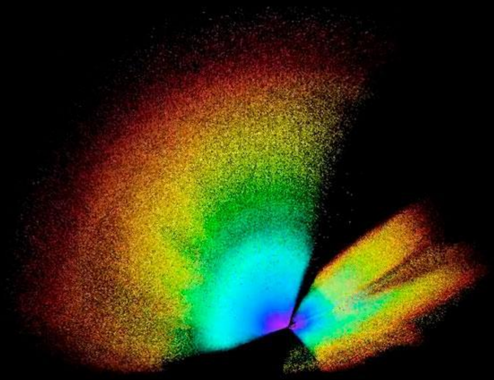


The ΛCDM model has survived unscathed an avalanche of data

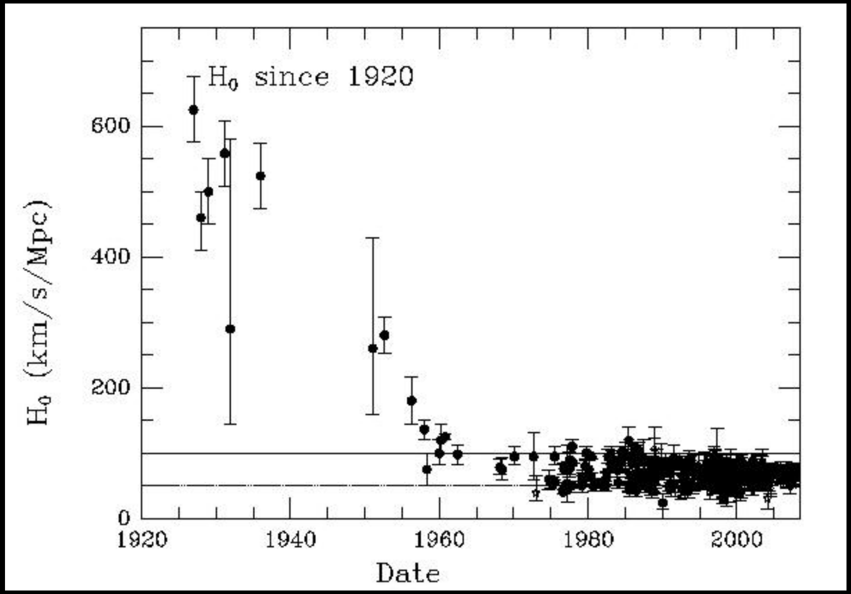




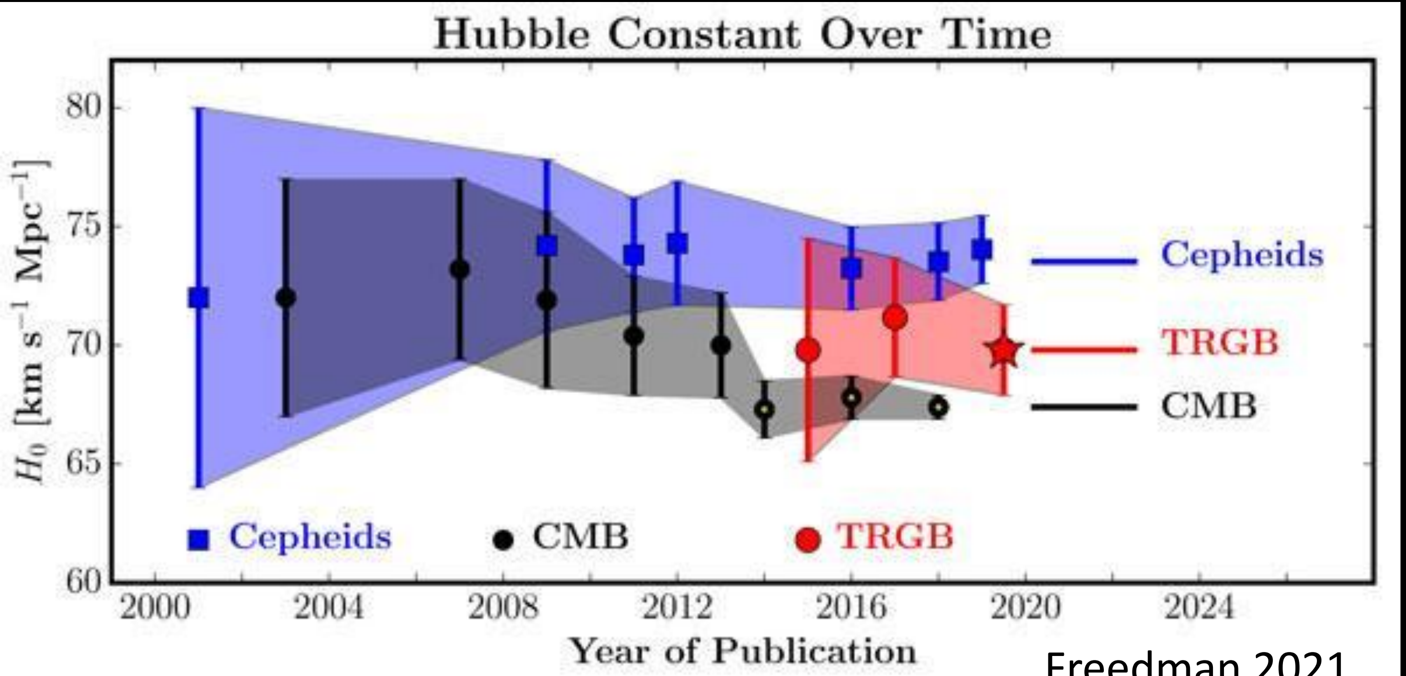




Then something happened….

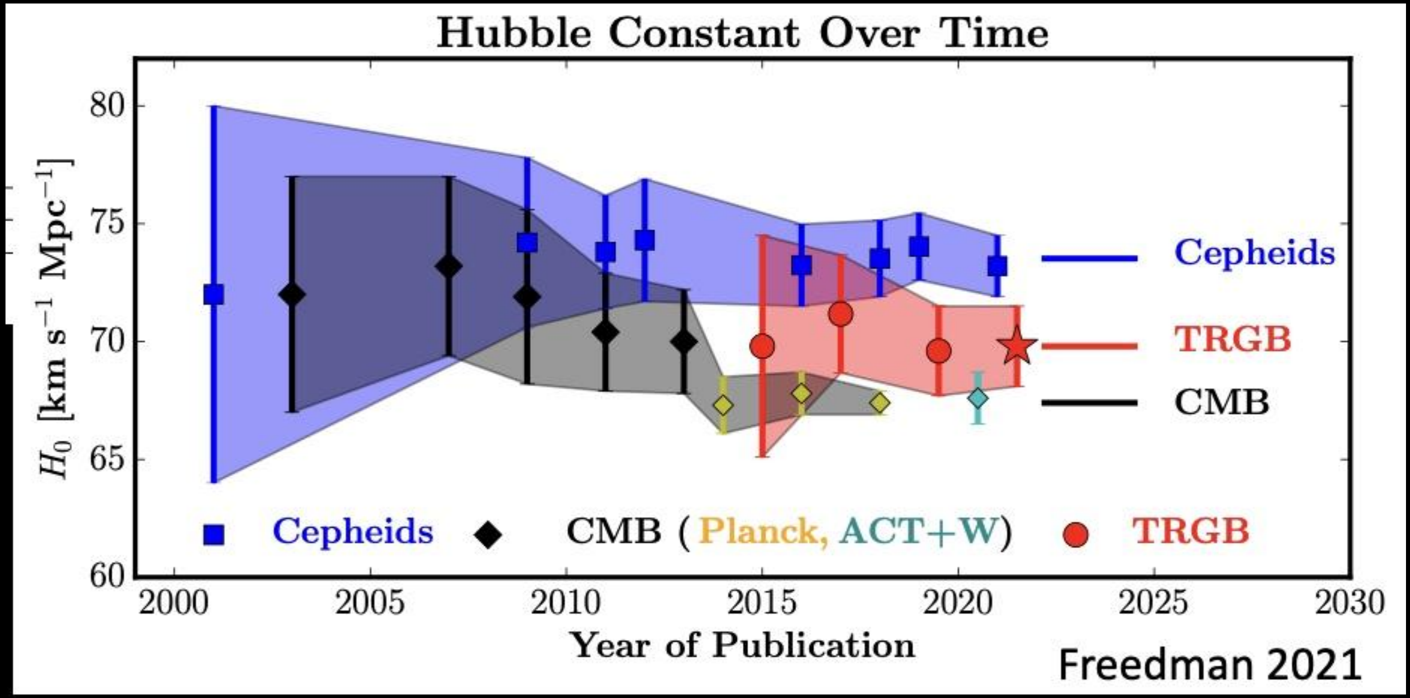


Constant not constant



Freedman 2021

Constant not constant



What’s going on?

There is no consensus

And in science consensus is the **starting point**

not Thatcher “consensus”...

Has persisted for almost a decade

Likely important and insightful

"It's foggy out there" (M. Turner)

A tale of two H's

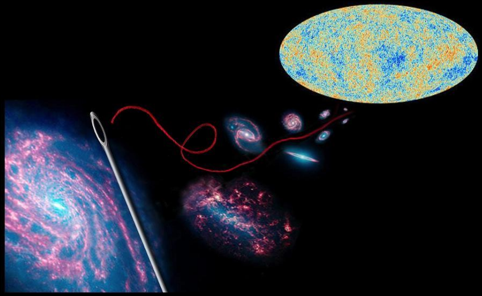
($z \lesssim 0.1$)
Present day expansion rate of the Universe
Recession velocity → distance.

Parallaxes
Cepheids
SNe
TRGB
SBF
Masers
Etc...

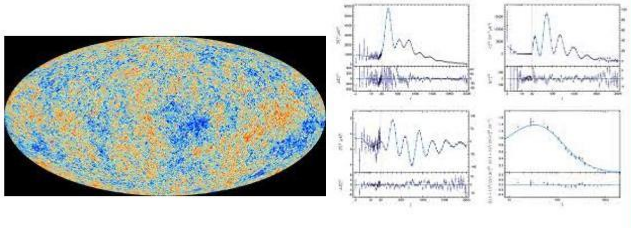
Cosmic distance ladder

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

We have been dwelling on this for a decade now

"Do you believe in the Hubble tension/crisis?"

"cannot swipe it under the carpet"

If there is a significant tension ….

observations should provide guardrails towards a

If there is no tension…

Observations provide an "envelope" around LCDM which enclose the

Standard Model for Cosmology 2.0

It is illustrative to consider the possibility that there is a tension (as lack of it sets an upper limit)

There are many H_0

Not all measurements measure directly the current expansion rate

Model dependent vs model independent

4 “families”

Direct distance ladder(s). W. Freedman Talk, A. Riess Talk.

No ladder: single step Lensing time delays, standard sirens, Masers

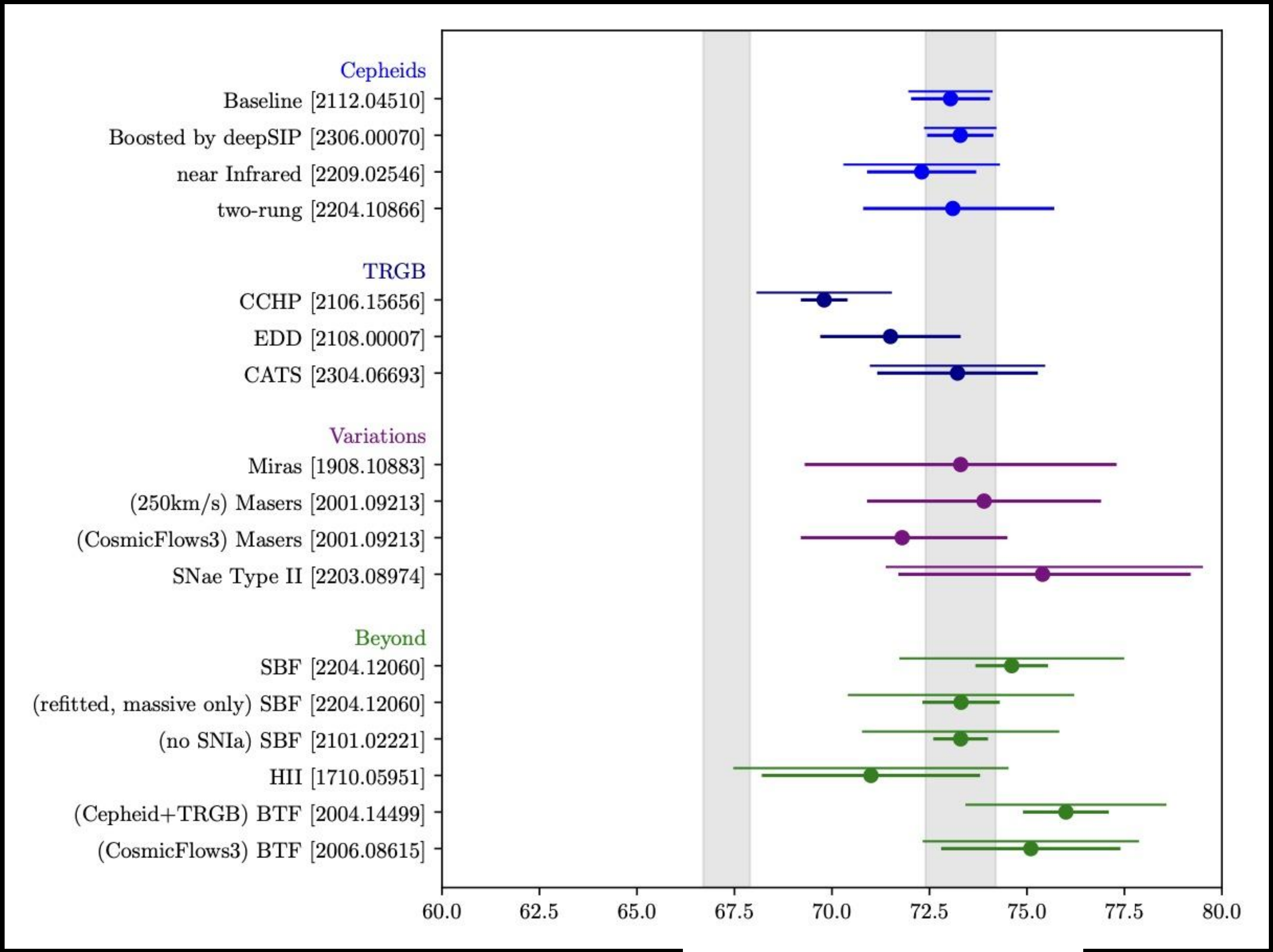
Global parameter of the model/inverse distance ladder

Ages of cosmic objects (lookback time)

Each family has many H_0 determinations (internal consistency checks)

Verde, Schoneberg, Gil-Marin et al. 2311.13305, ARAA 2024

Zooming into the first family

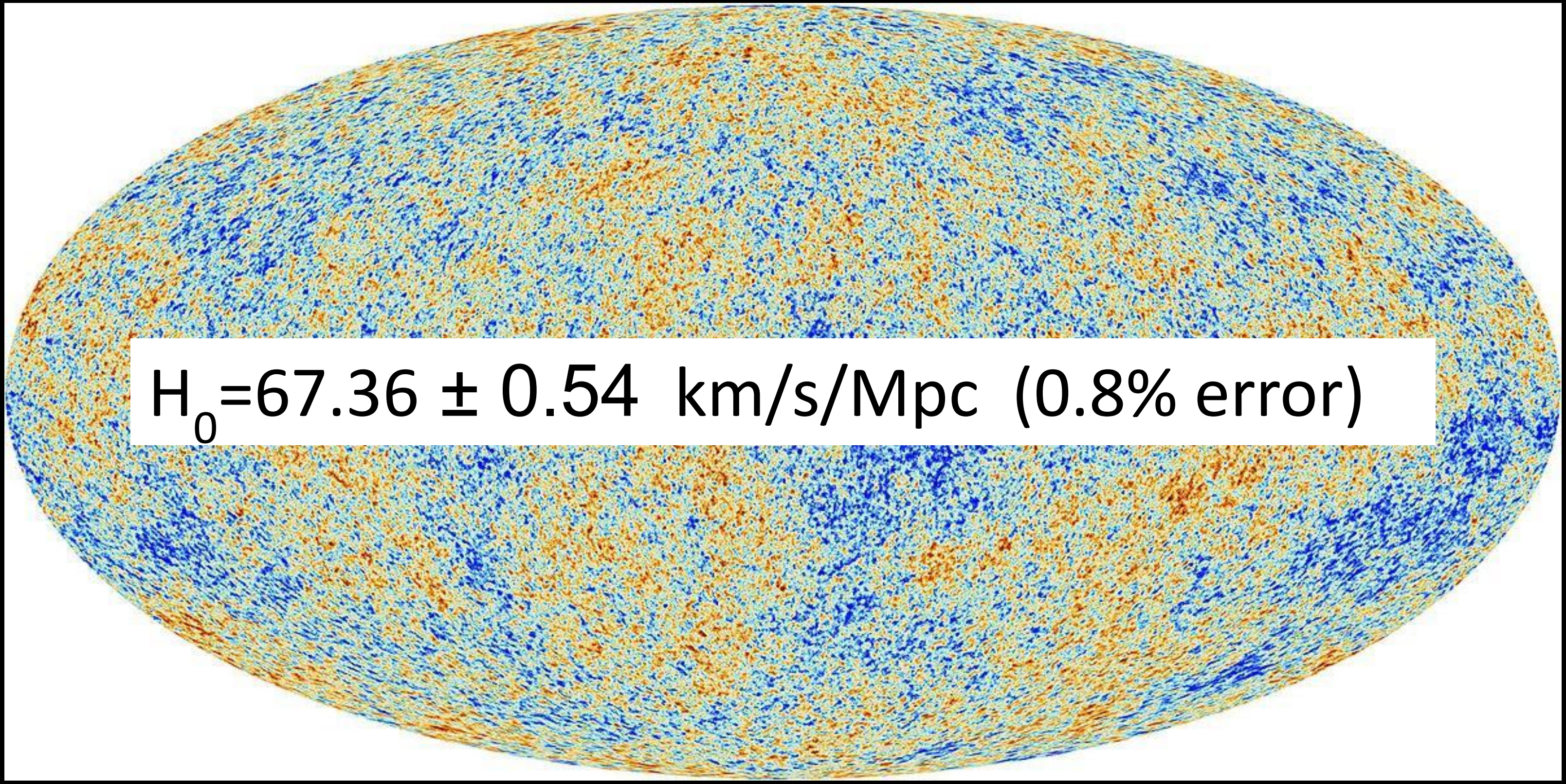


H_0 km/s/Mpc

Non exhaustive

Verde, Schoneberg, Gil-Marin et al. 2311.13305, ARAA 2024

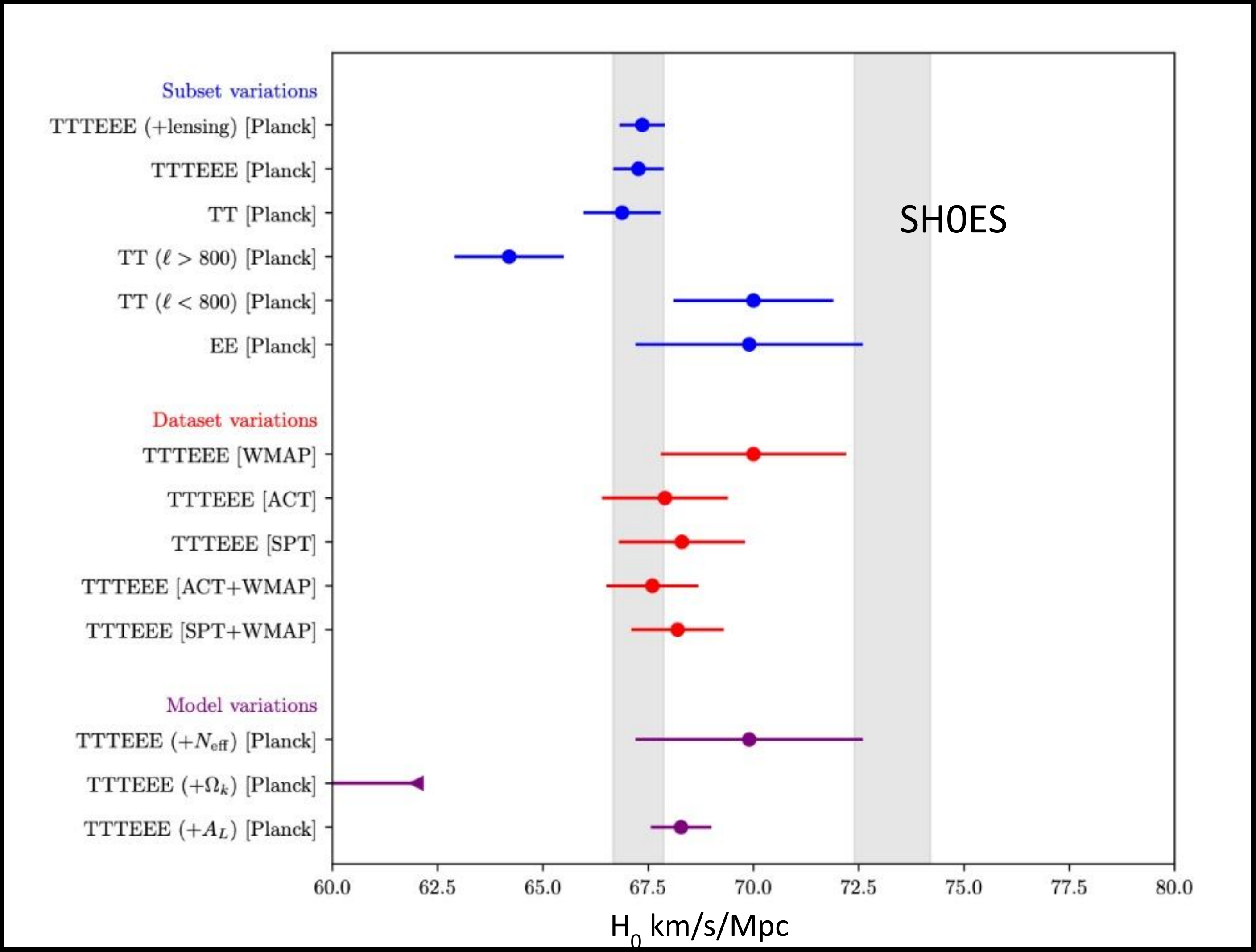
The echo of the bang of the “primeval atom”



Planck CMB temperature map
This light is also polarized

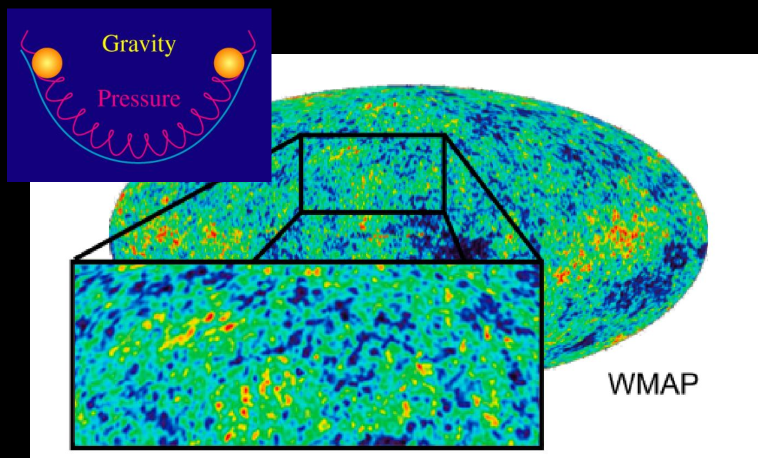
Fit model’s parameters…. Get H_0

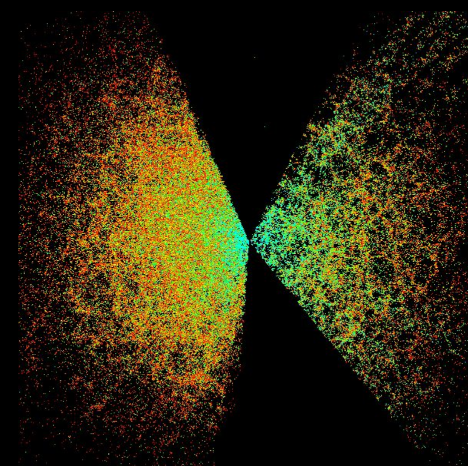
Dissecting CMB-only H_0



Verde, Schoneberg, Gil-Marin et al. 2311.13305, ARAA 2024

BAOs
Baryon acoustic oscillations





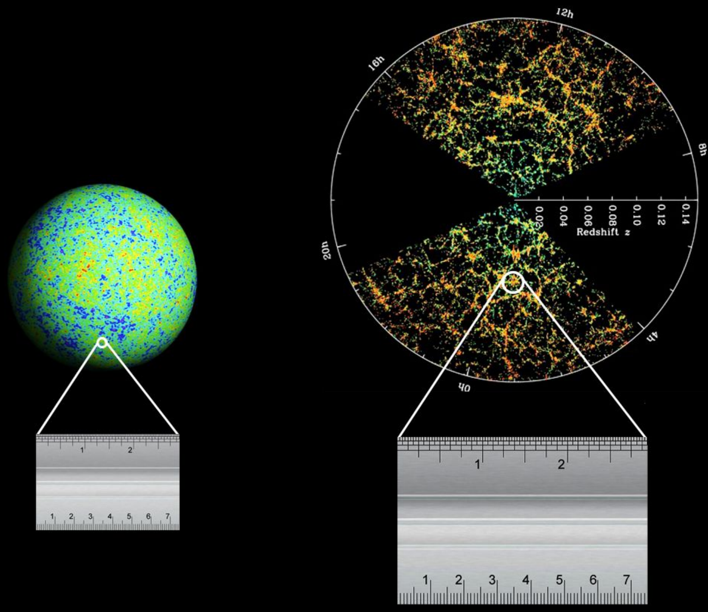
Observe photons

Photons coupled to baryons

“See” dark matter

AS baryons are ~1/6 of the dark matter these baryonic oscillations leave some imprint in the dark matter distribution
(gravity is the coupling)

A standard ruler
(well… in 3d a standard bubble.. But ok)

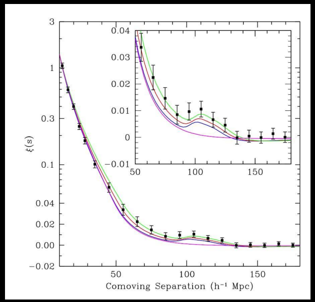


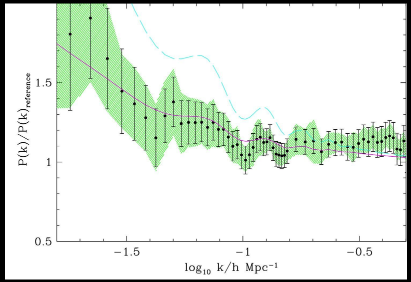
Effect is a “classic” AP

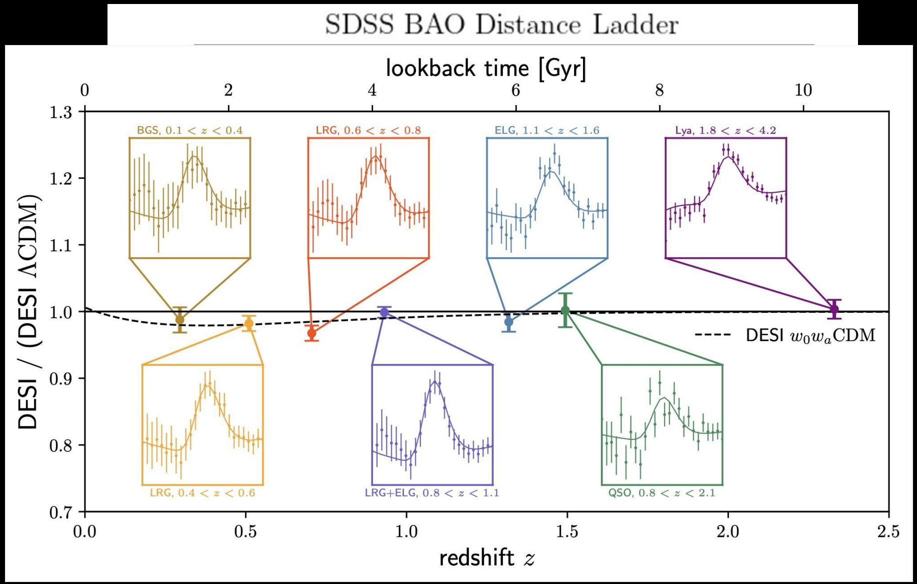
The ruler is the sound horizon at recombination (CMB), at radiation drag (LSS) but it is the same ruler. Symbols: r_s or r_d

From detection to precision cosmology

- Detection in 2005 by SDSS and 2dFGRS



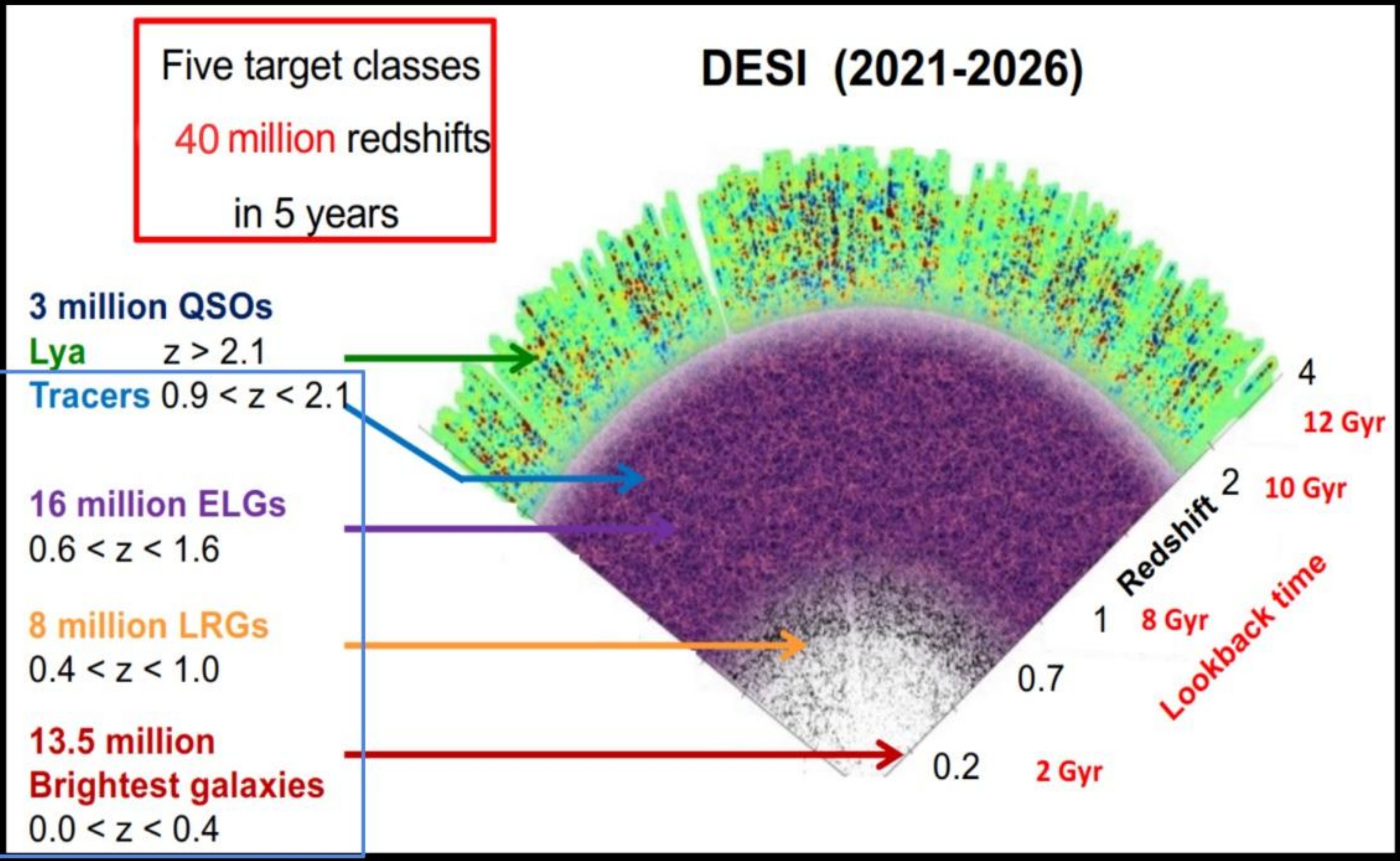




DESI 2024

Dark Energy Spectroscopic Instrument

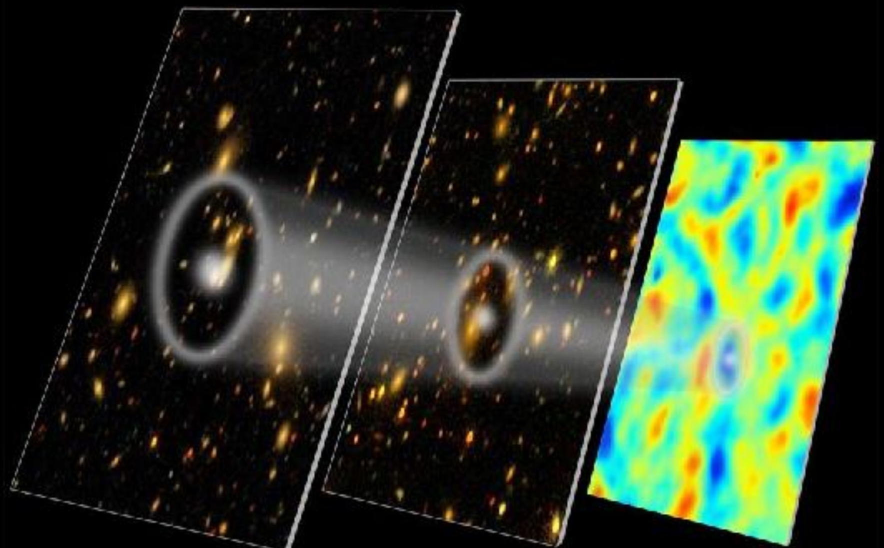
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science



2024 data release: aggregate distance precision 0.52%. Cf all SDSS galaxy BAO (20 years) 0.64%

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. (sound horizon)
- Useful for:
  - Expansion history of the Universe
  - early Universe physics (well known) sets it



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

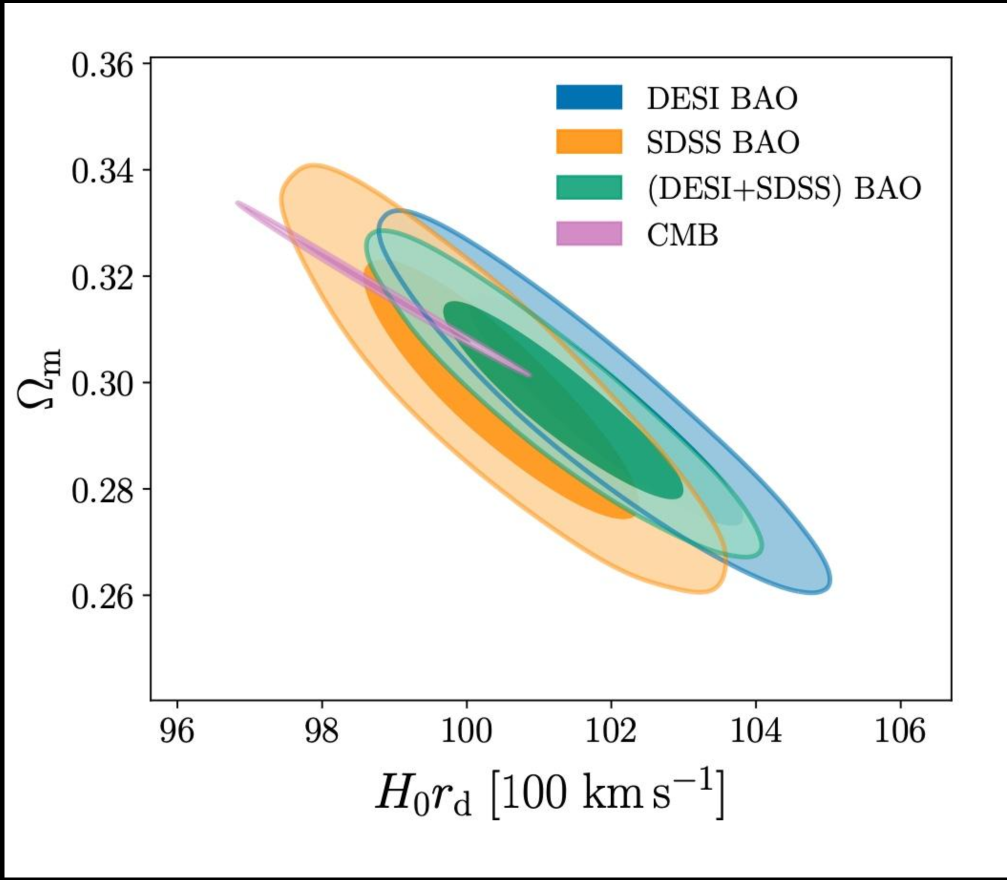
It should be evident that…

Since one measures only angles and redshfts…

If the standard ruler length is not known → get expansion history $H/H0=E(z)$ ~Ωm

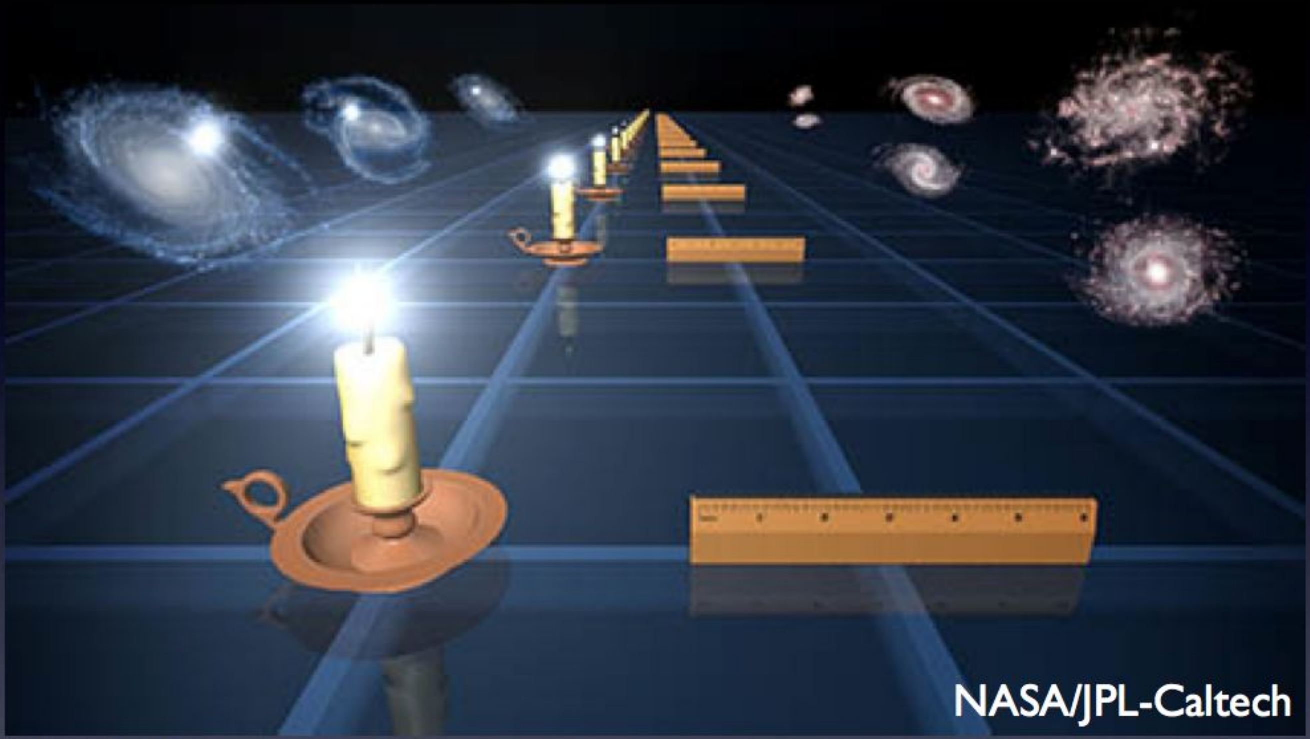
By marginalizing over the expansion history → get hr_d (the standard ruler in combination w/ h)

Without knowing the length of the standard ruler…



DESI collab. 2024, 2404.03002

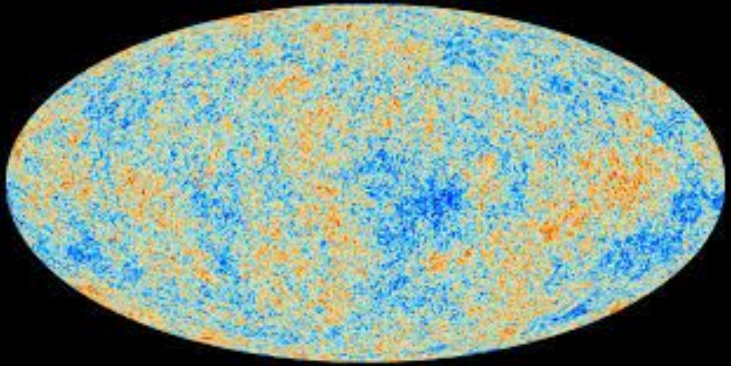
Standard candles & Standard rulers



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

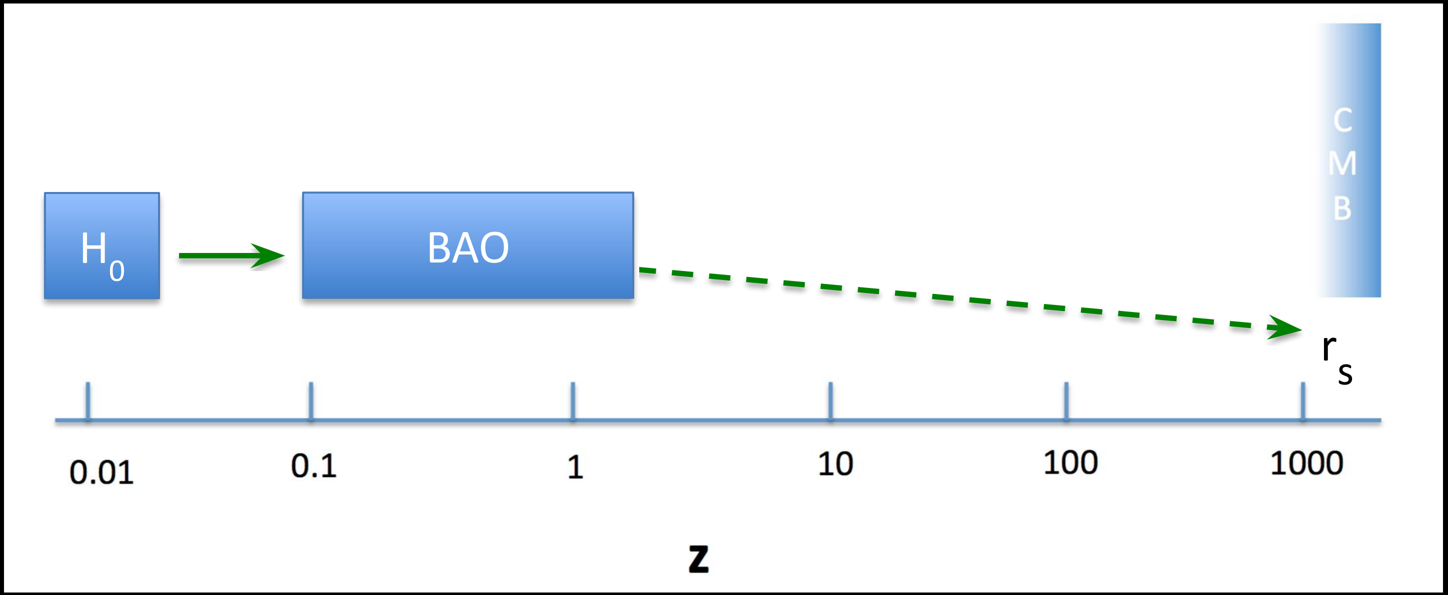


… Since about 2015

Direct and inverse cosmic distance ladder

- Cuesta et al 2015, Auborg et al 2015

Direct cosmic distance ladder

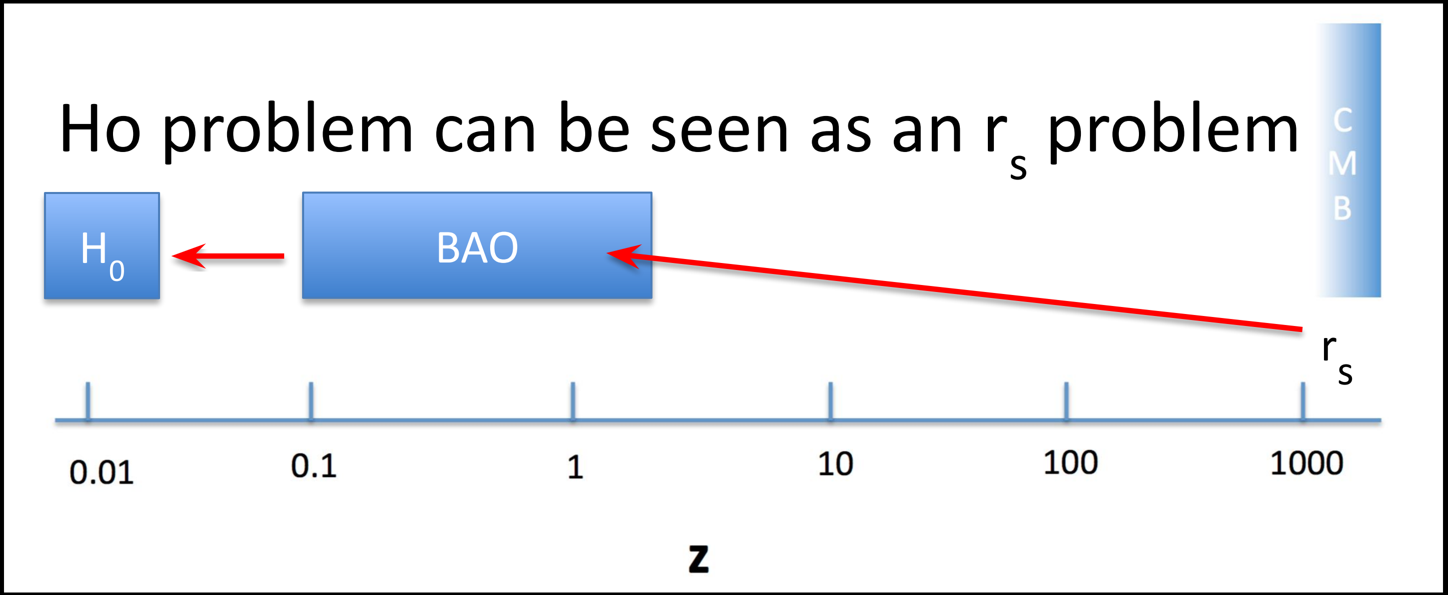


Direct and inverse cosmic distance ladder

- Cuesta et al 2015, Auborg et al 2015

Inverse cosmic distance ladder

DESI 2024+CMB (Planck +lensing+ACT): H0= 67.97 ± 0.38 km/s/Mpc (0.55% error)



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

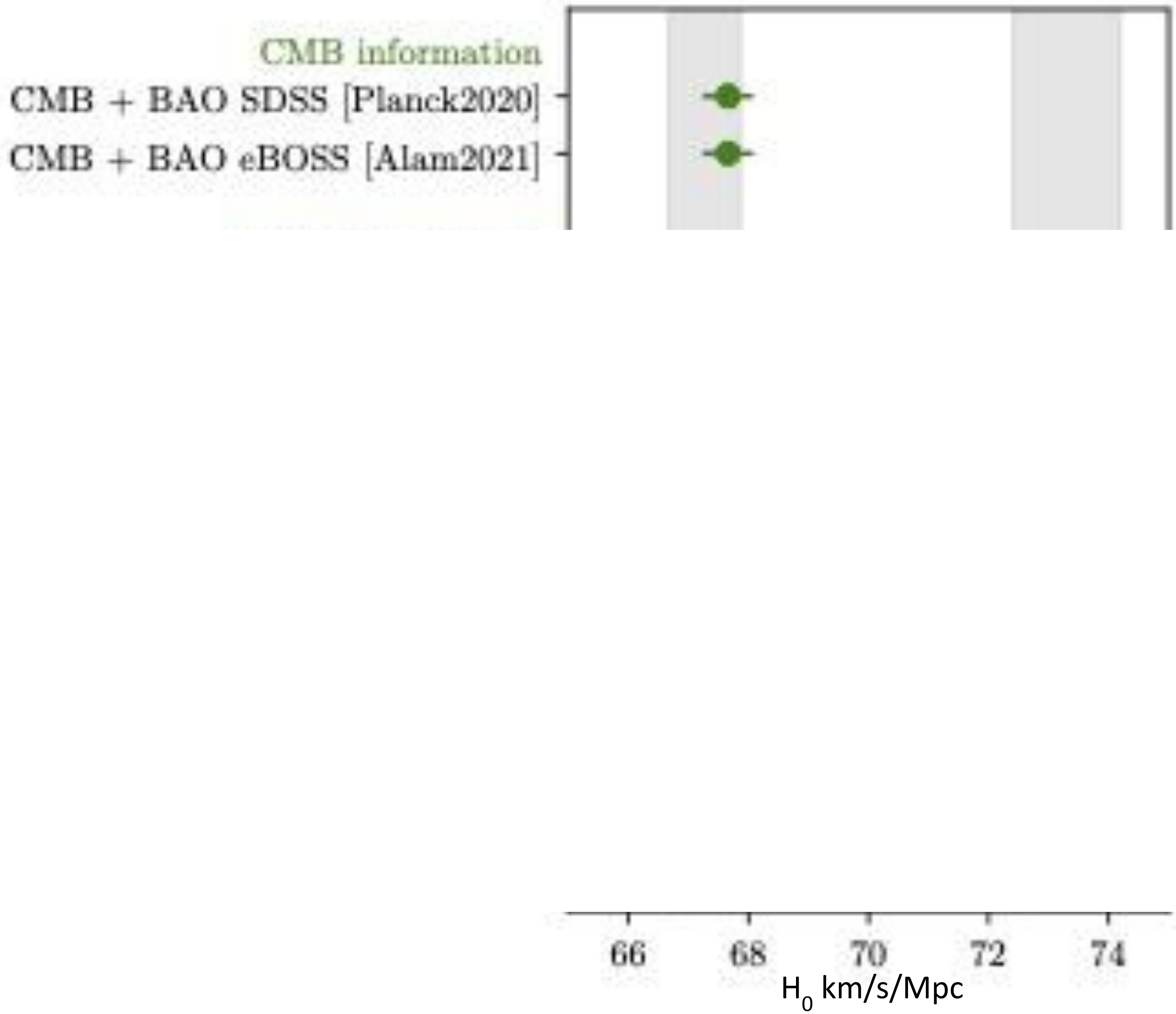
You can get $r_s(r_d)$ in (at least) 2 ways

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

- From CMB observations (given a cosmological model)

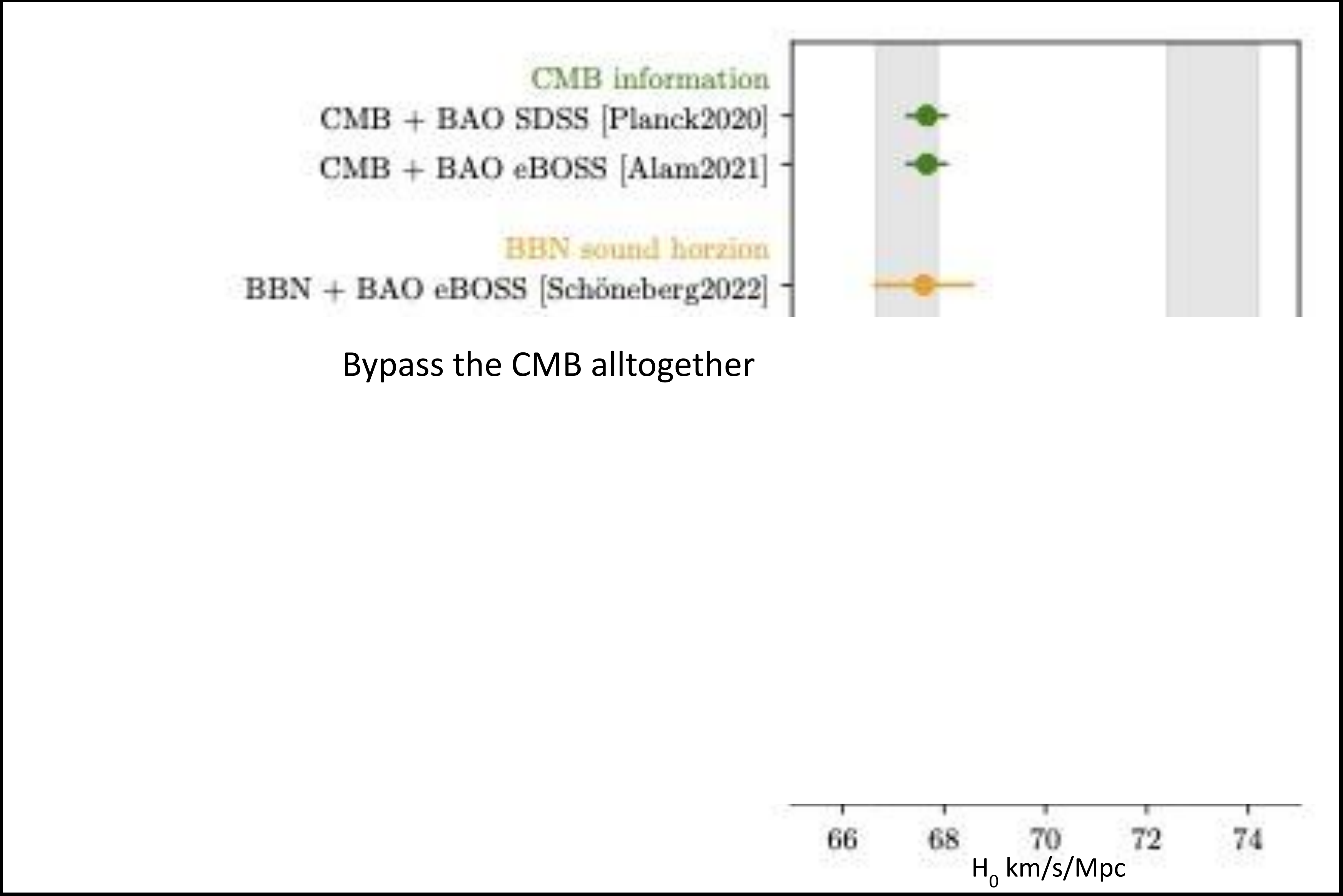
- Using (again) the equation above, a model for early Universe and a constraint on baryon density (e.g.,BBN & light elements abundance). BAO give matter density (in LCDM).

The inverse distance ladder



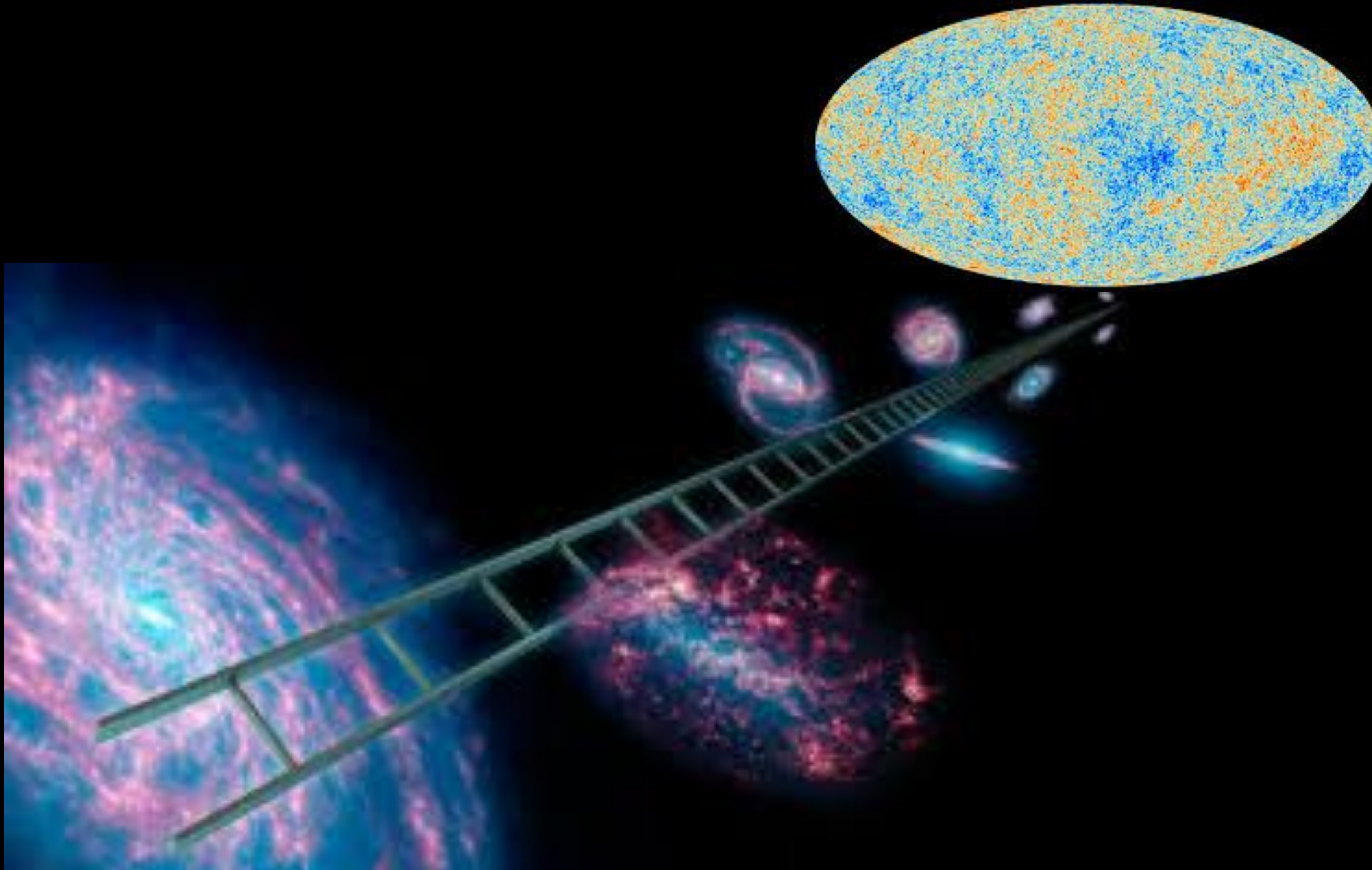
Verde, Schoneberg, Gil-Marin et al. 2311.13305, ARAA 2024

The inverse distance ladder



Verde, Schoneberg, Gil-Marin et al. 2311.13305, ARAA 2024

The H0 game: E2E test



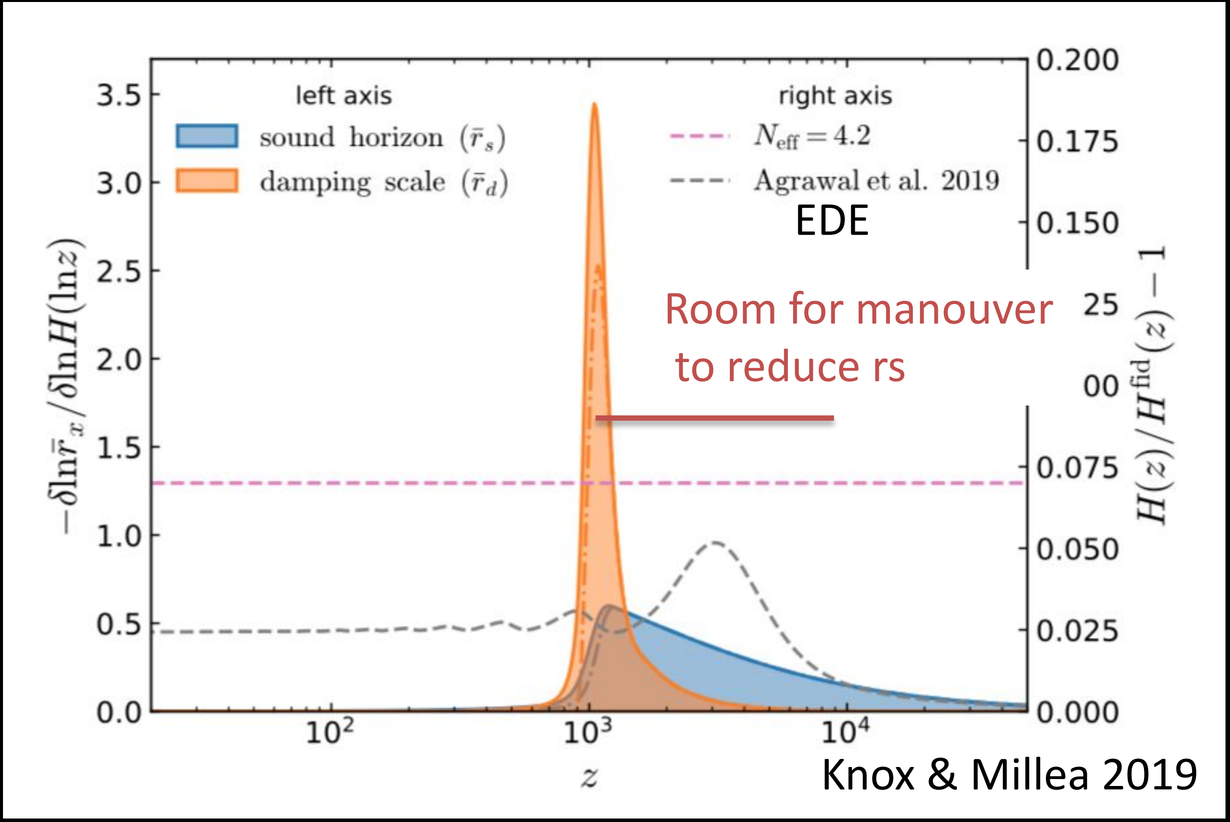
Good ladders need 2 good anchor points

pre-recombination physics

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



Knox & Millea 2019

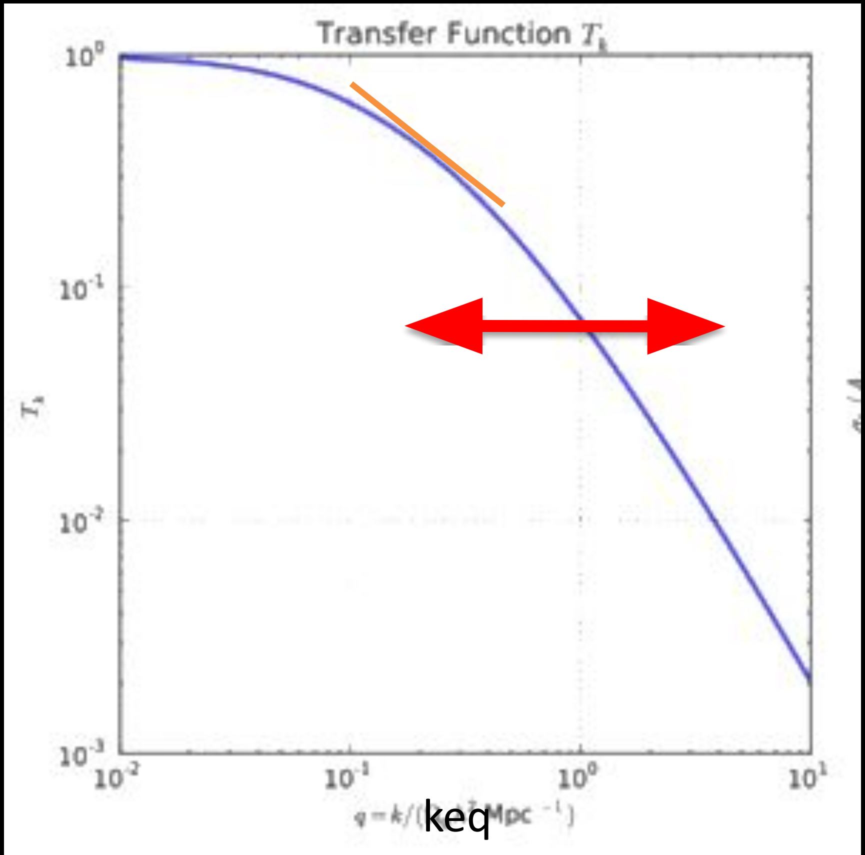
Ailor et al 2019

We effectively have one standard ruler for early-times "rs"

It would be good to get more…

Down memory lane…BBKS (not quite)

$P(k)=T^2(k)(k/k_p)^{ns}$



+ a wiggle (rd)
and suppression (Ωb)
part

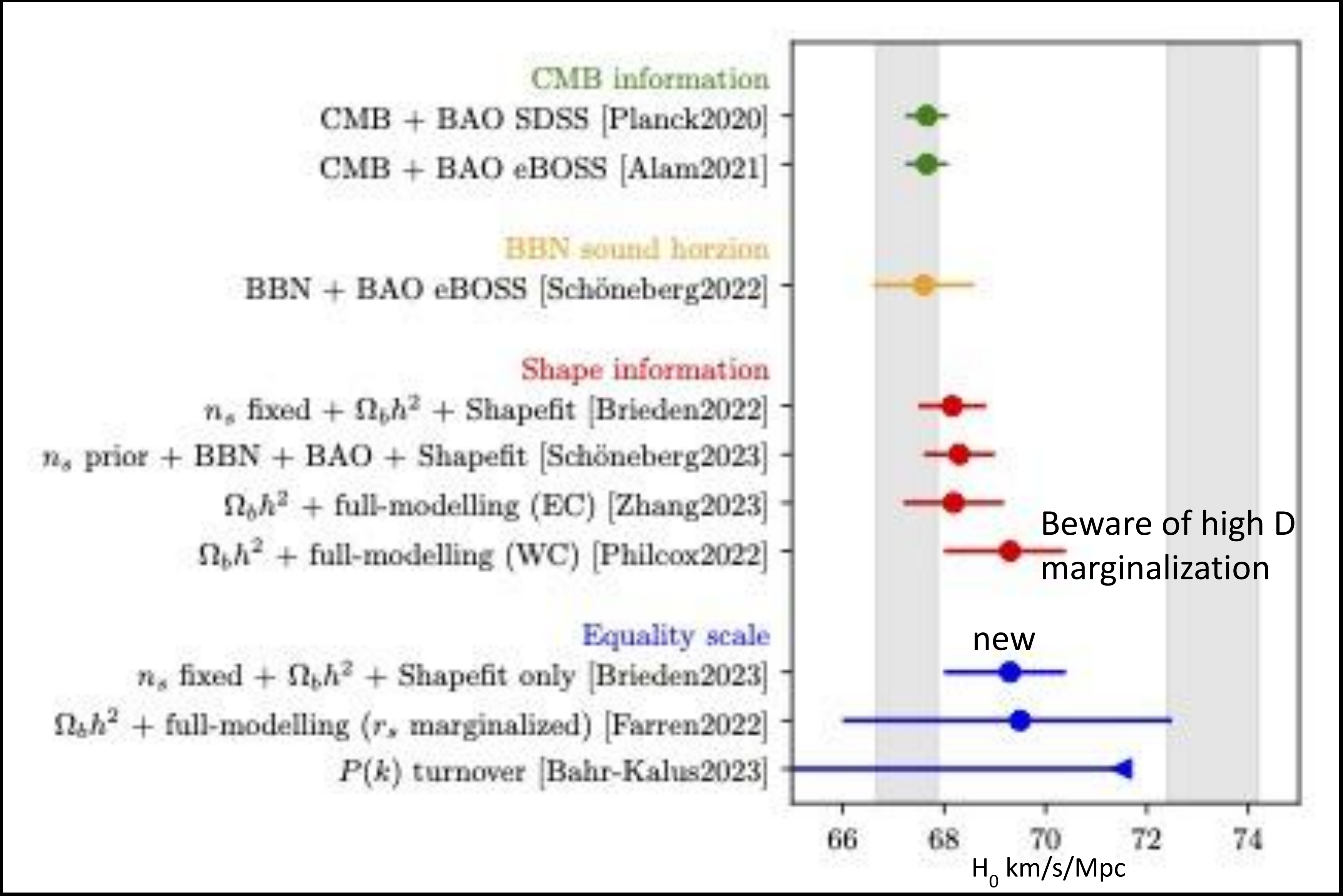
A speedometer at matter-radiation equality

Driven by $\Omega m\ h^2$ And $\Omega\gamma\ h^{2\cdot}$ and $\Omega b\ h^2$

But BAO (uncalibrated and rs-free) give me Ωm

h

The inverse distance ladder



Verde, Schoneberg, Gil-Marin et al. 2311.13305, ARAA 2024

pre-recombination physics

Modify the model right where we most like it

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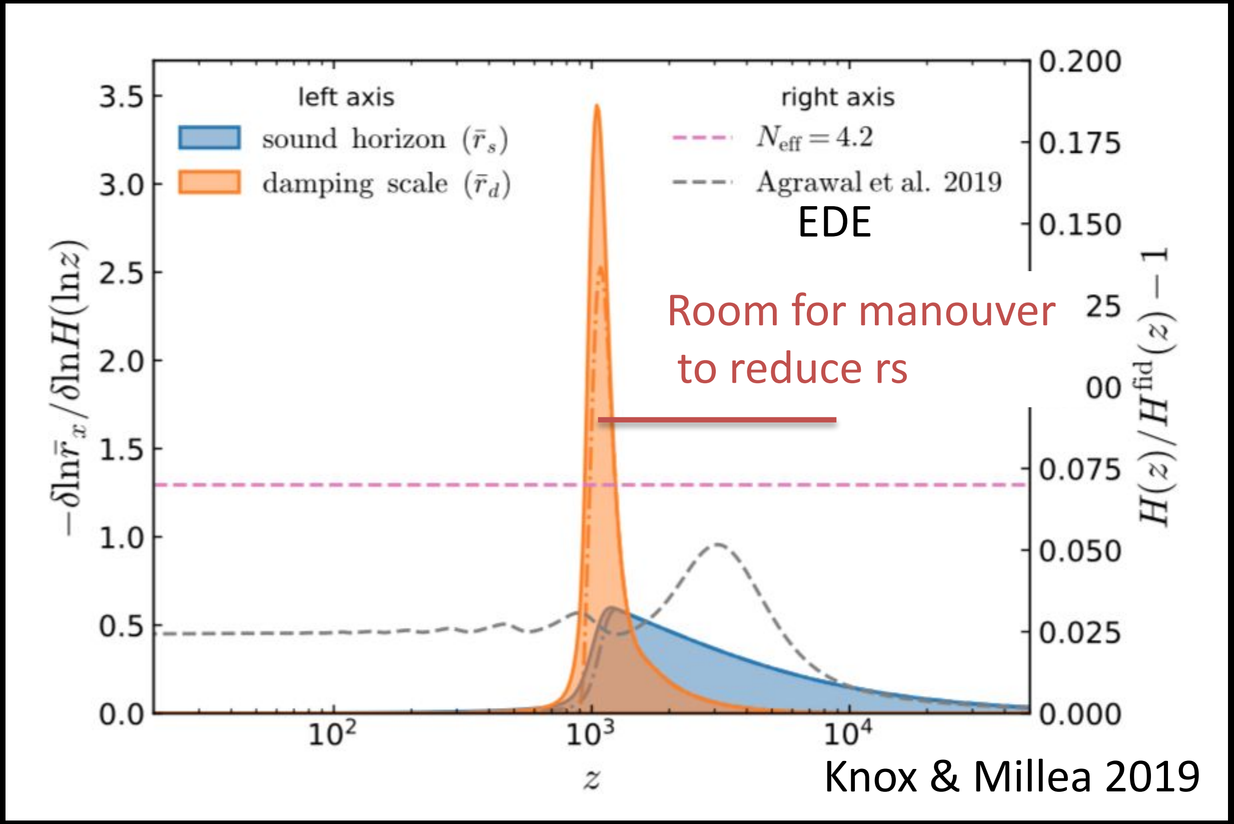


Ailor et al 2019

Early Universe physics yields stubbornly H0 in the 68km/s/Mpc camp

There is more than one “early” H_0

Systematics!

Increasingly unlikely

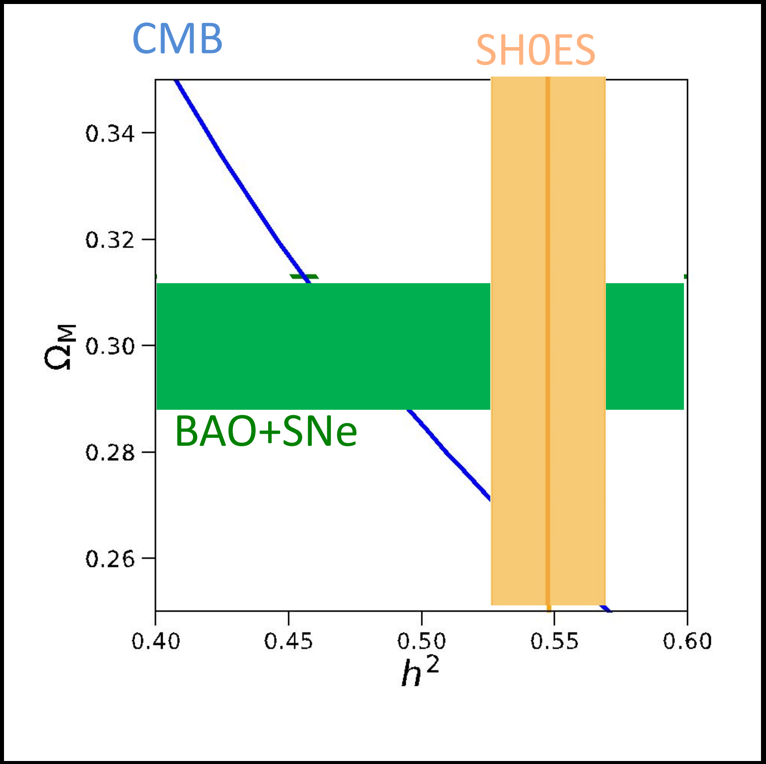
Beyond H0

ΛCDM assumed

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



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

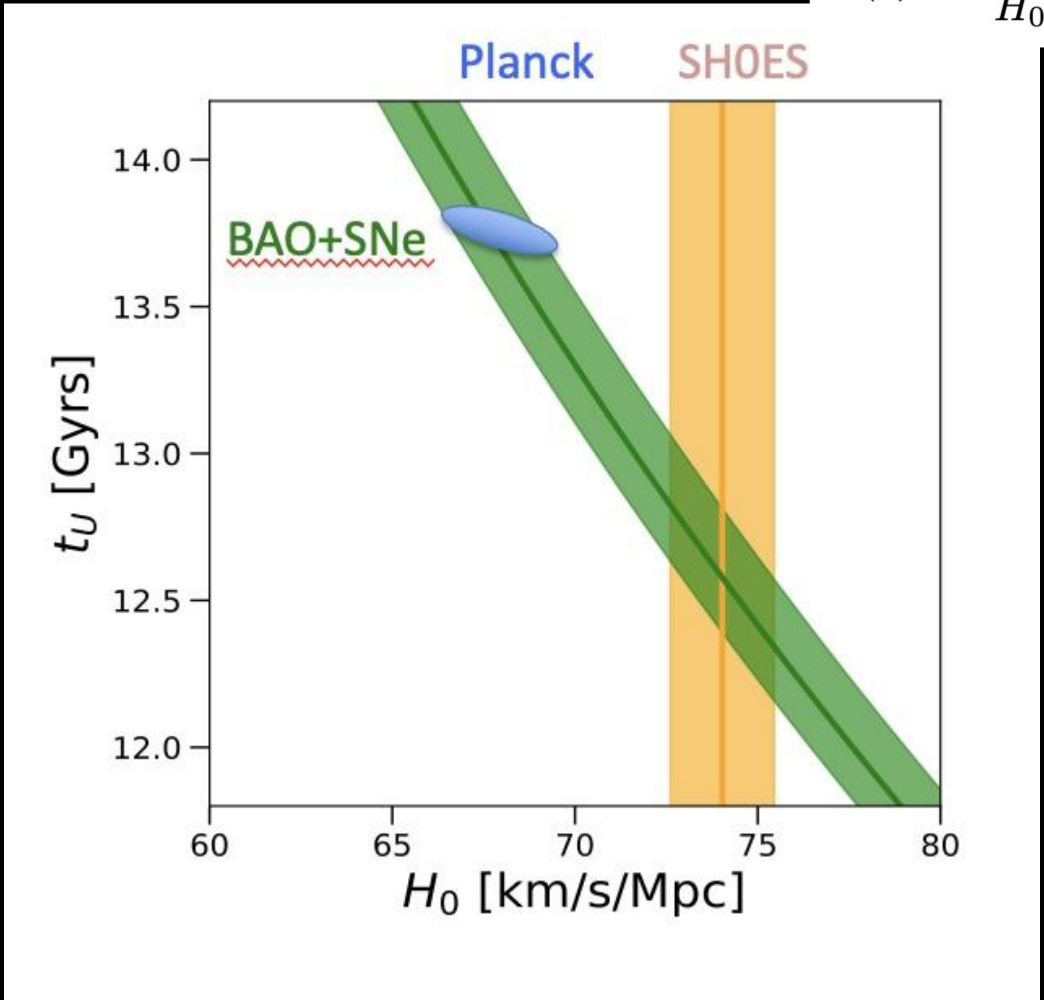
With each we test different observations and different aspects of the model.

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 and tu for the oldest objects adding in formation time.

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

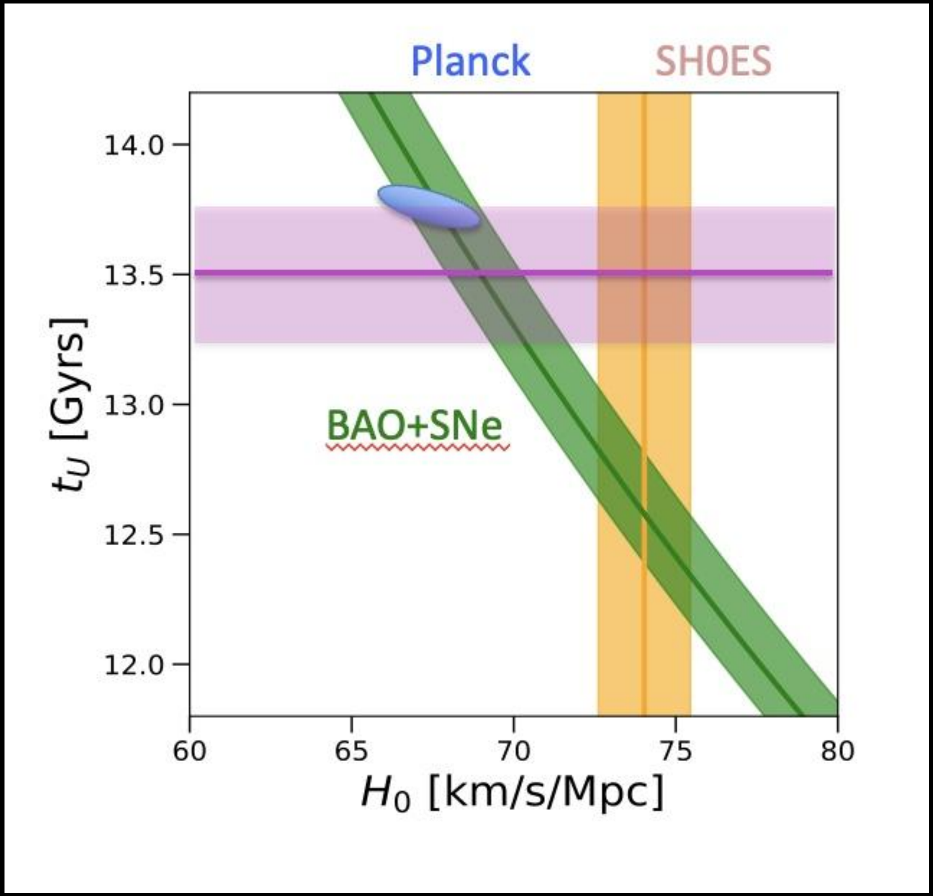
Relies on knowing other background cosmological parameters
(or the expansion history "shape")

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

Age of oldest Globular clusters

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

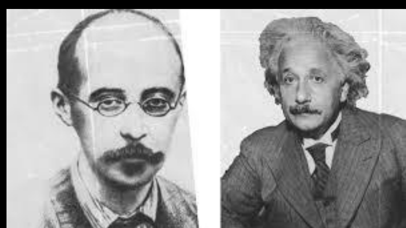
Early : high t_0
Late: low t_0

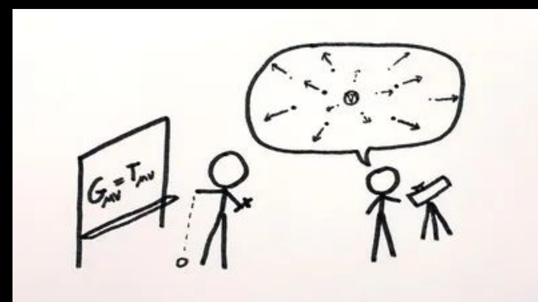


t_U=13.5± 0.3 Gy
22 GC

Valcin et al. 2007.06594
Valcin et al. 2102.04486

Lemaitre: getting Hubble into trouble

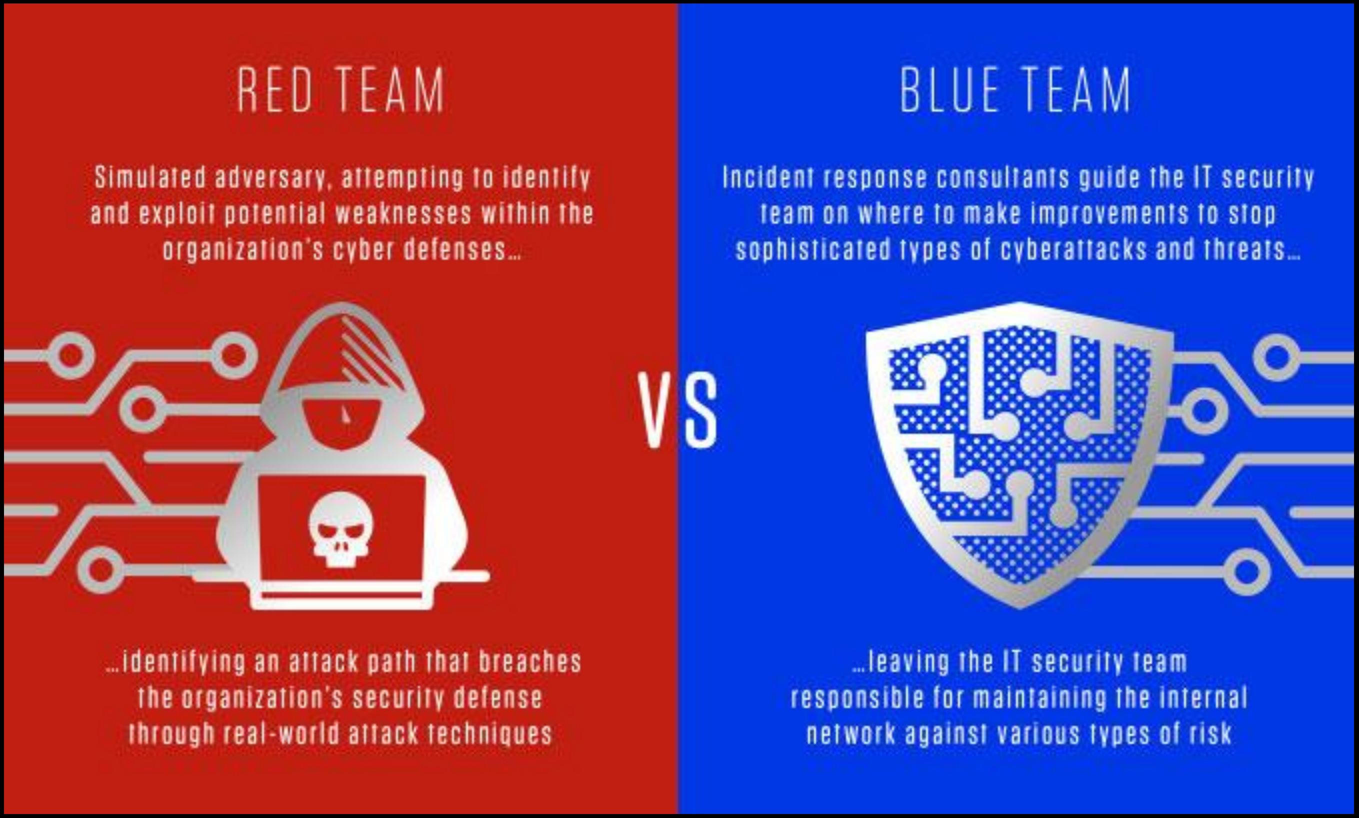




- Identifying the local distance-redshift relation H_0 with the global parameter of a model relies on many assumptions and a model

- The standard model of cosmology is likely an effective model with ad hoc components (dark matter, dark energy); a placeholder for a better model
- Tensions or inconsistencies can offer guardrails toward this better model
- Lack of inconsistencies produce “envelope” around LCDM

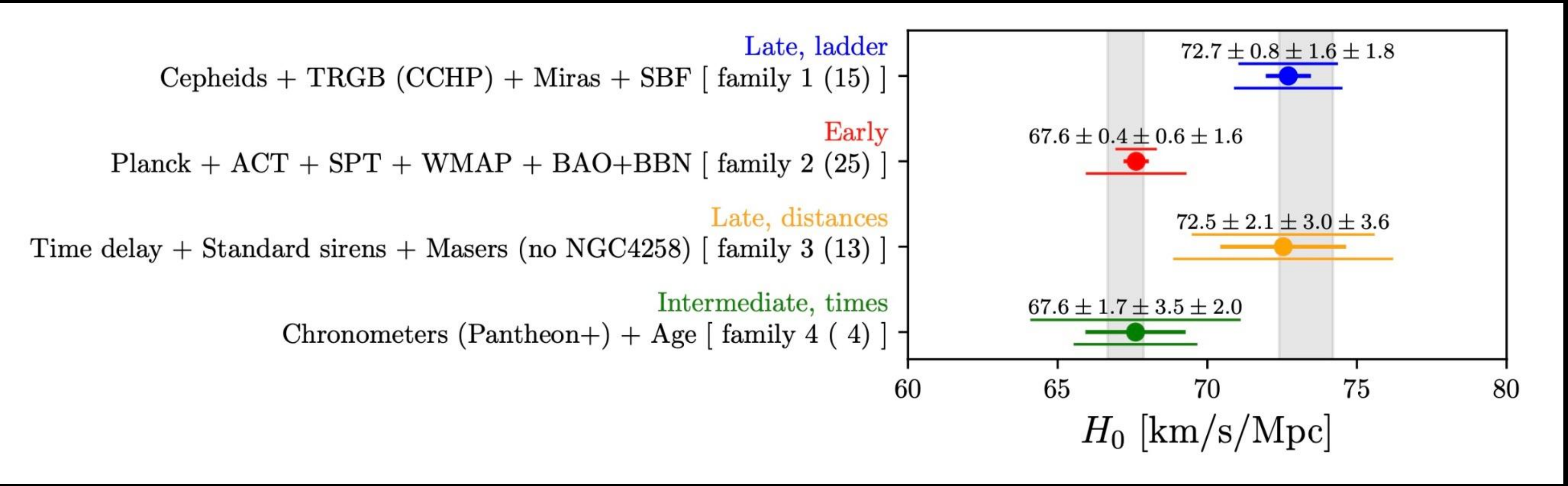
How to achieve consensus?



a comprehensive comparison of step-by-step results, ie a red teaming process, which can increase the community's confidence in all measurements.

The many H_0

Different families rely on different physics



Each family has several internal consistency checks

No consensus within family 1: redteaming!

If consensus can be reached, in combination, they can provide guardrails towards the SM of cosmology 2.0

Verde, Schoneberg, Gil-Marin et al. 2311.13305, ARAA 2024

Large-scale structure give more than one h

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

Growth of structure give Ωm

But the large-scales shape of the LSS power spectrum can also be used: Information about matter-radiation equality

Data are in the can, wait for DESI papers…

Guardrails towards SM of Cosmology 2.0

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

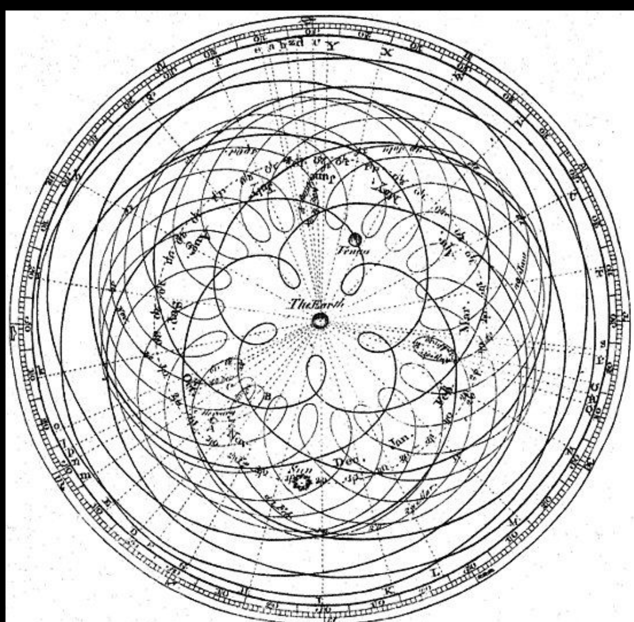
Should improve (or not worsen) other tensions, e.g. $\sigma 8$

Should quantify improvement vs predictability (degrees of freedom)

Parallelism with Λ…..

Model-dependent vs model independent approaches

At what point are we adding epicycles?



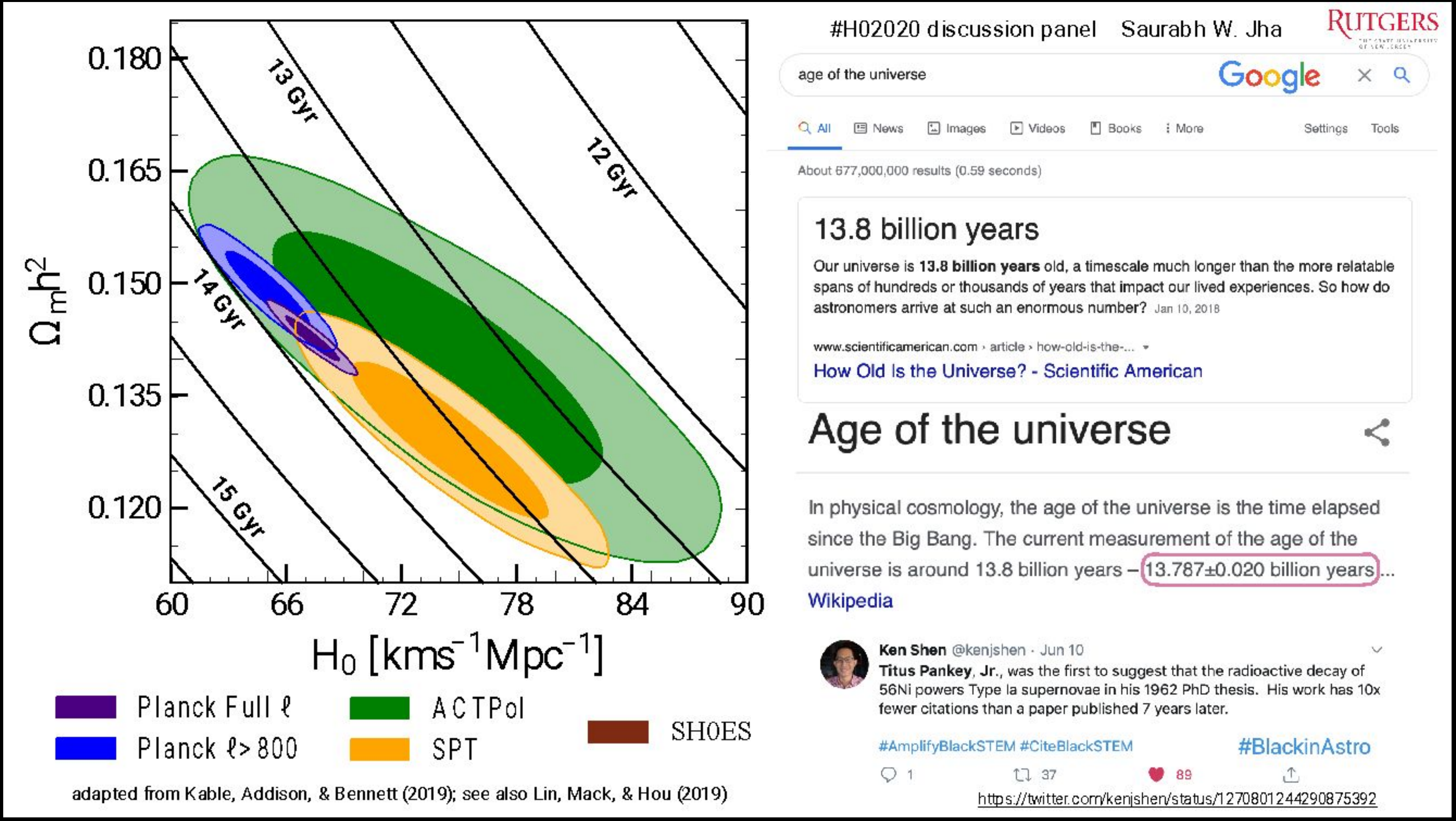
Cassini

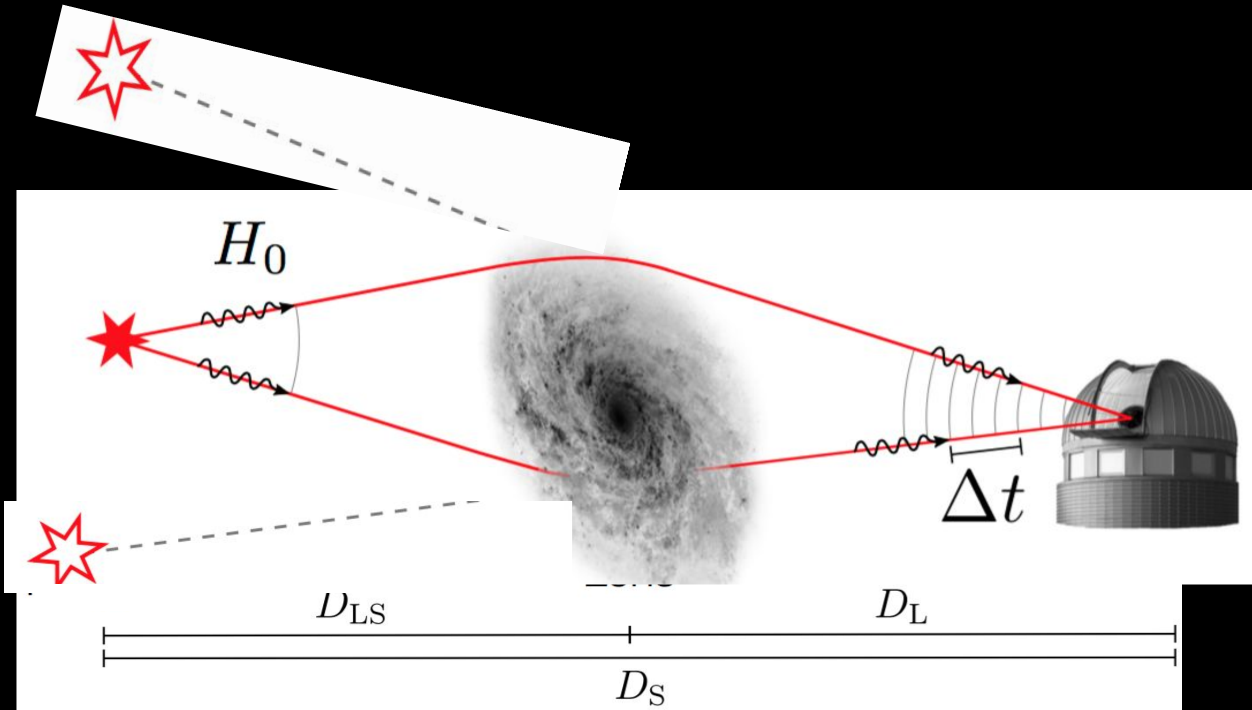
NICOLAI COPERNICI

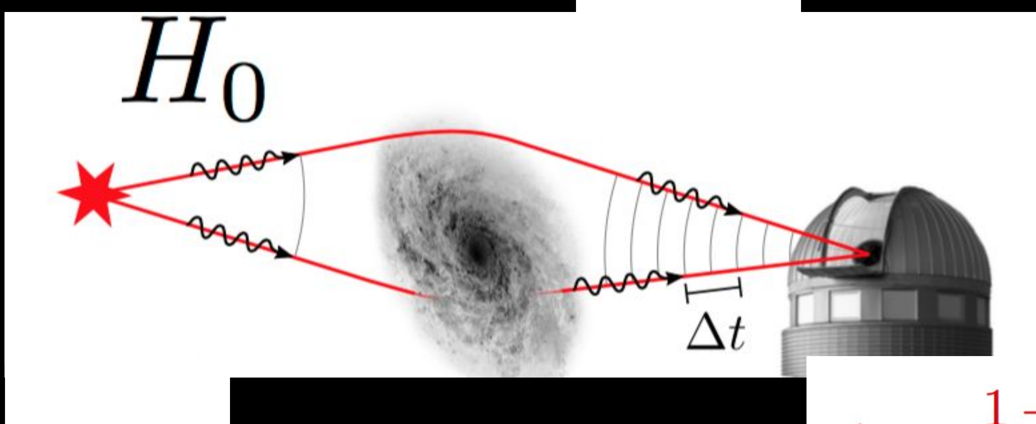
quoq; epicyclum hoc modo. Sit mundo ac Soli homocentrus AB, & ACB diameter, in qua summa absis contingat. Et facto in A centro epicyclus describatur DE, ac rursus in D centro epicyclium FG, in quo terra uersetur, omniaq; in eodem plano zodiaci. Sitq; epicycli primi motus in succedētia, ac annuus ferè, secūdi q̃q; 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

END

The beauty of on-line meetings







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