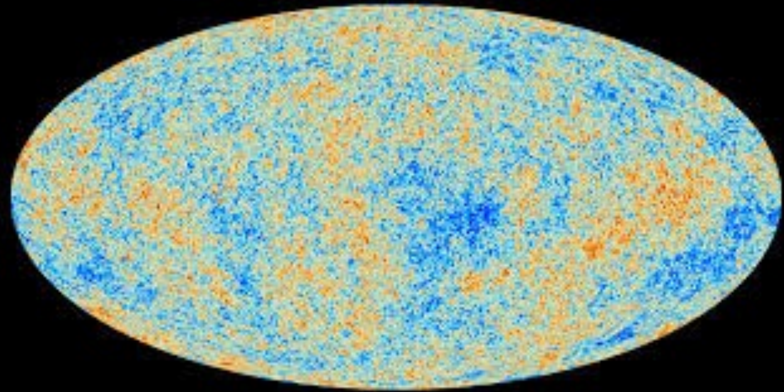
How many h are there?
And what do they mean?



Licia Verde
ICREA & ICCUB

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

When did we accept dark energy?

Flatness…. -- at least 1980

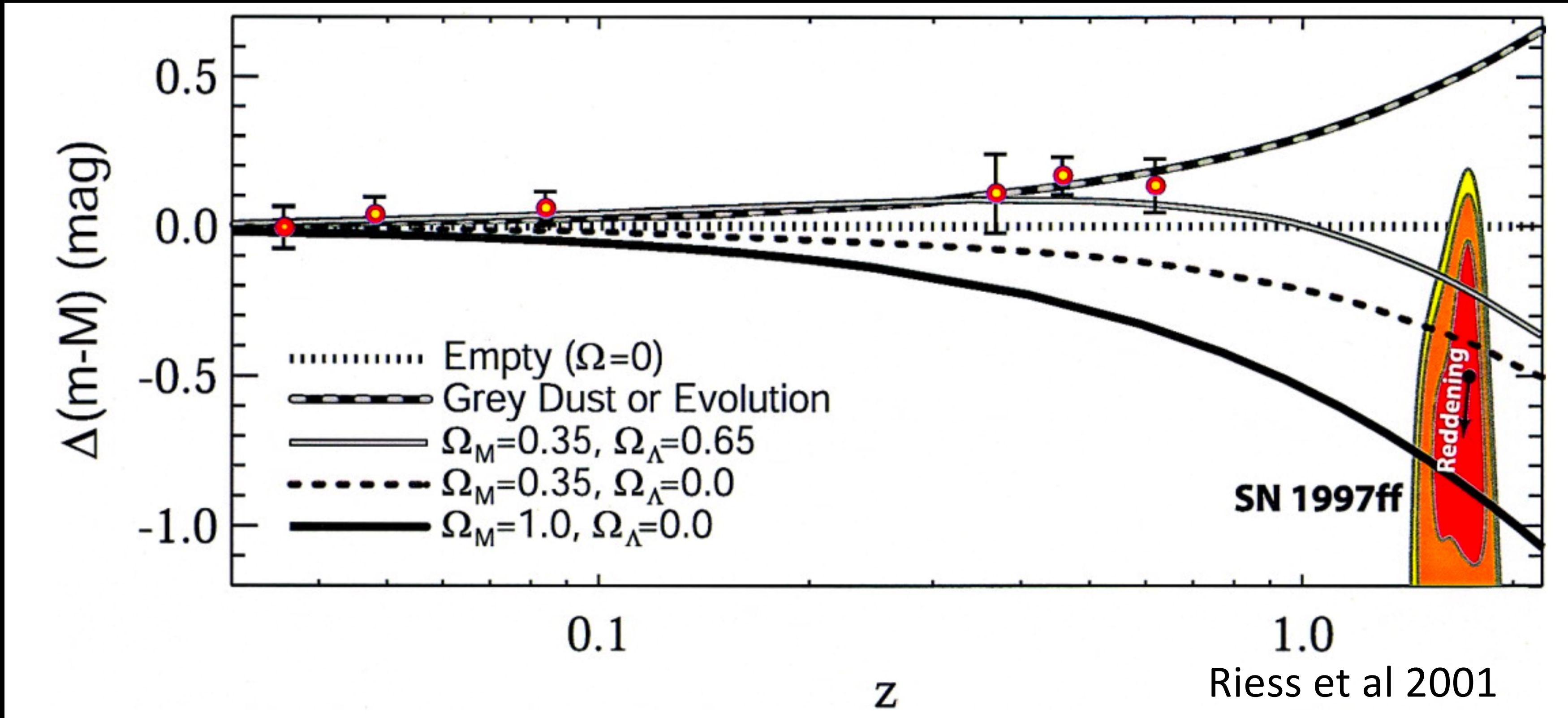
CMB first peak. Nebulous until 2001 but geometric degeneracy

Low matter density. Lots of evidences but focus with COBE (1992, clustering mid 90)

Age of the Universe. Old objects both at low and high redshift (eary to mid 1990's)

And a lot hinged on the value of H0

Negative deceleration parameter from Sne (1998), + 1997ff (deceleration period, 2001)

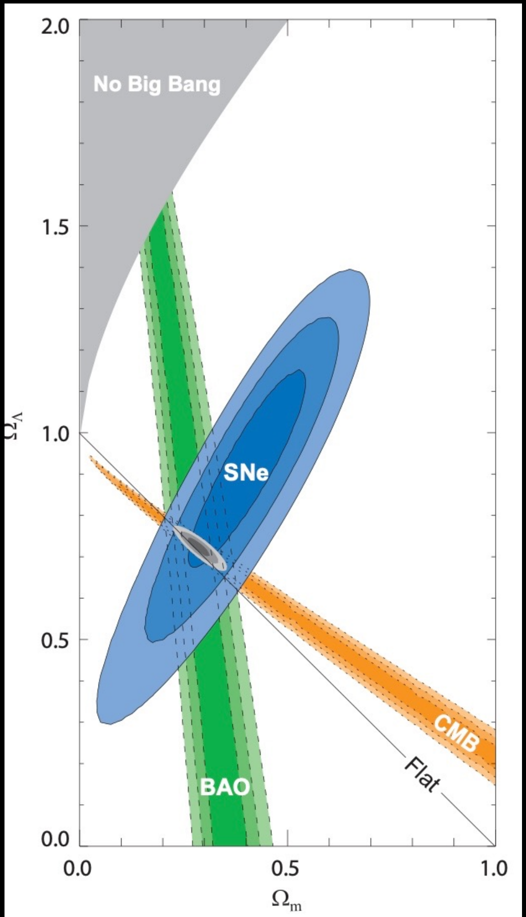


It was a qualitatively different result than parameter fitting

Yet it took another decade for the Nobel committee to recognize
…the accelerating Universe

Yet it took another decade for the Nobel committee to recognize
…the accelerating Universe

By 2010 cosmology had a standard model, with 6 parameters

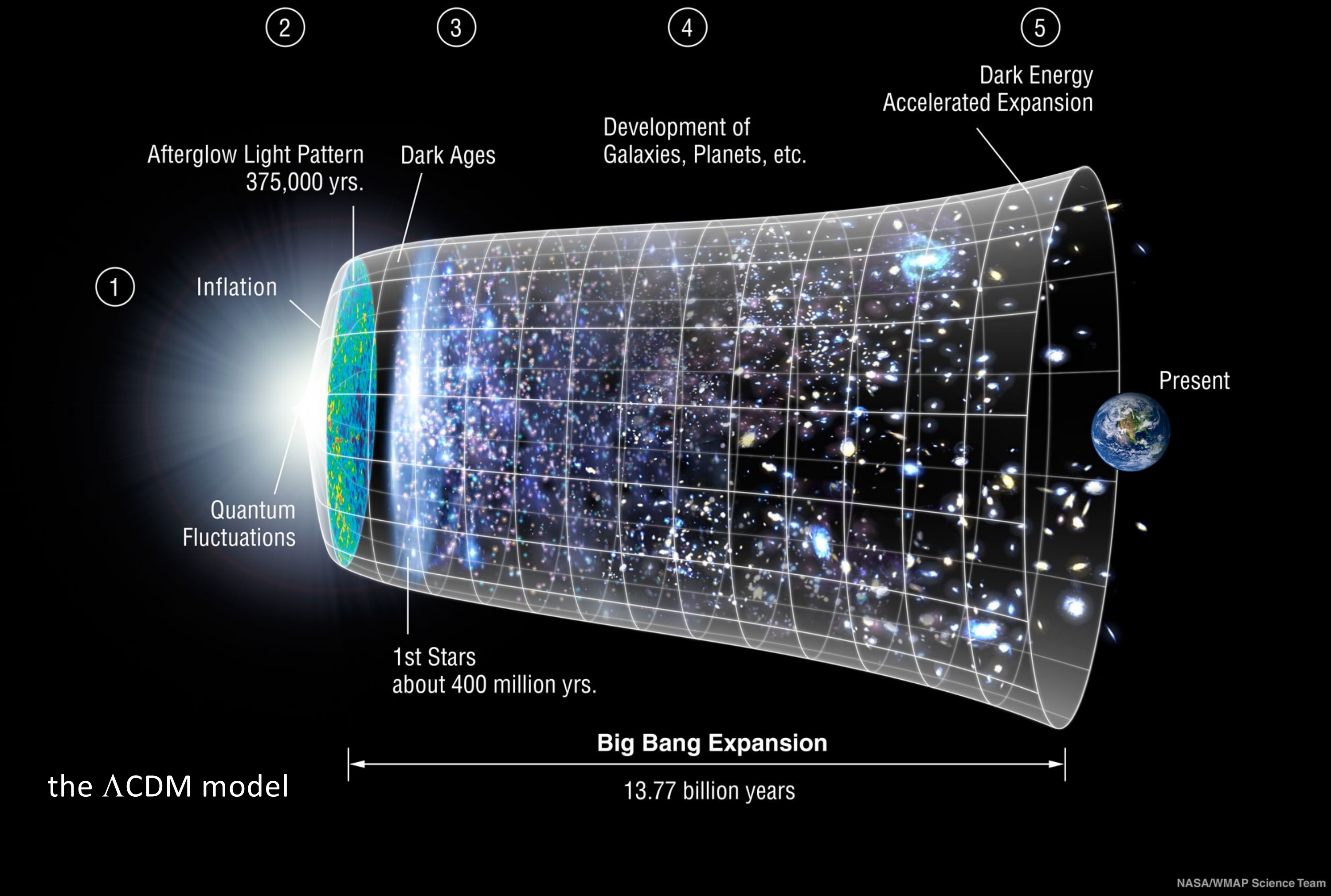


	WMAP5 alone	WMAP5 + BAO + SN
$\Omega_b h^2$	0.0227 ± 0.0006	0.0227 ± 0.0006
$\Omega_{cdm} h^2$	0.110 ± 0.006	0.113 ± 0.003
Ω_Λ	0.74 ± 0.03	0.726 ± 0.015
n	$0.963^{+0.014}_{-0.015}$	0.960 ± 0.013
τ	0.087 ± 0.017	0.084 ± 0.016
$\Delta^2_{\mathcal{R}} \times 10^9$	2.41 ± 0.11	2.44 ± 0.10
h	0.72 ± 0.03	0.705 ± 0.013
σ_8	0.80 ± 0.04	0.81 ± 0.03
$\Omega_m h^2$	0.133 ± 0.006	0.136 ± 0.004

Kowalski et al 2008

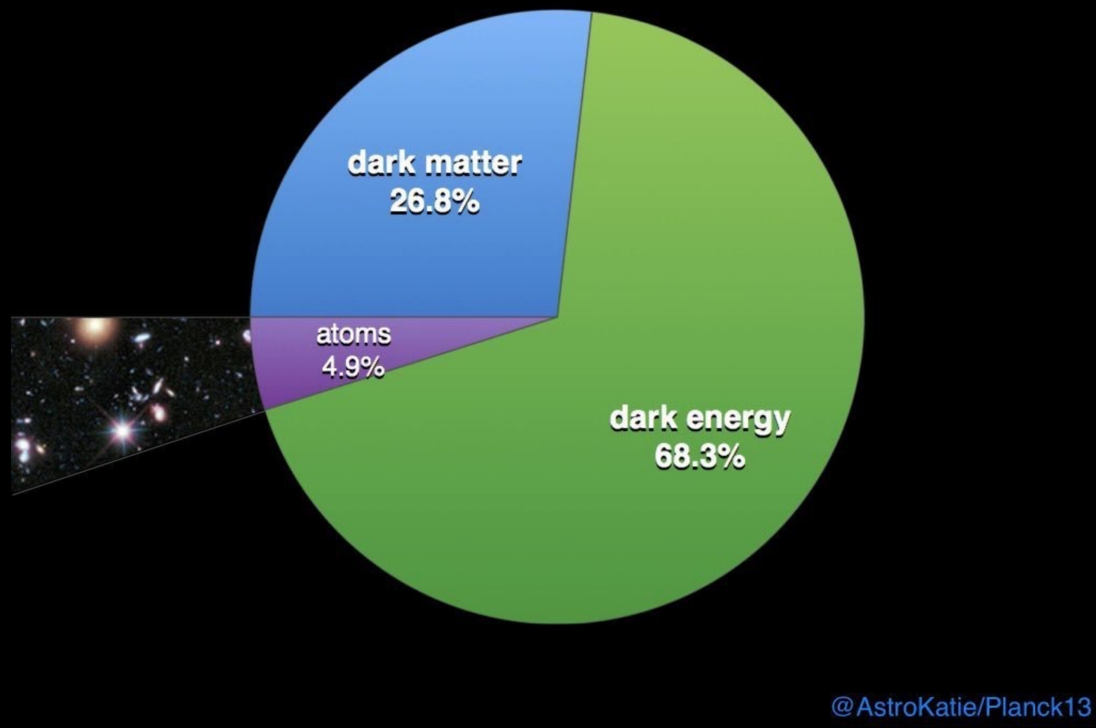
From Review of Particle Physics by particle data group 2010

The extremely successful standard cosmological model



the ΛCDM model

Never mind that the model is weird



Cosmology is special

We can't make experiments, only observations

We have to use the entire Universe as a detector: the detector is given, we can't tinker with it. (Jim Peebles)

A mixed blessing

The curse of cosmology

We only have one observable universe

We can only make observations (and only of the observable Universe) not experiments: we fit models (i.e. constrain numerical values of parameters) to the observations: (Almost) <u>any statement is model dependent</u>

*"Gastrophysics"** and non-linearities get in the way

….And the Blessing

We can observe all there is to see

** Not a typo, means complex astrophysics that is poorly understood/hard to model*

….And the Blessing

We can observe all there is to see

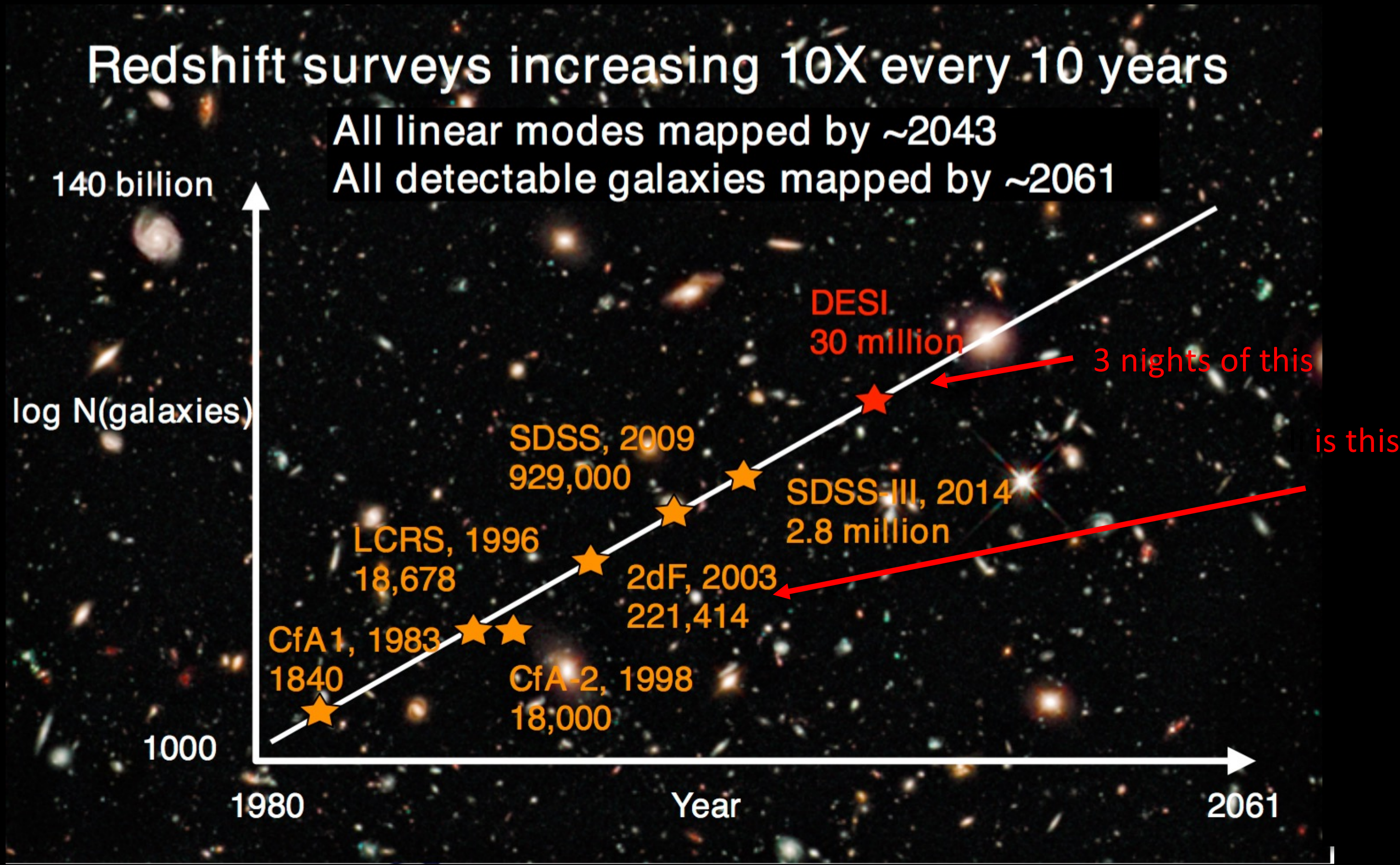
And almost do

Ultimate survey

This has driven a massive experimental effort

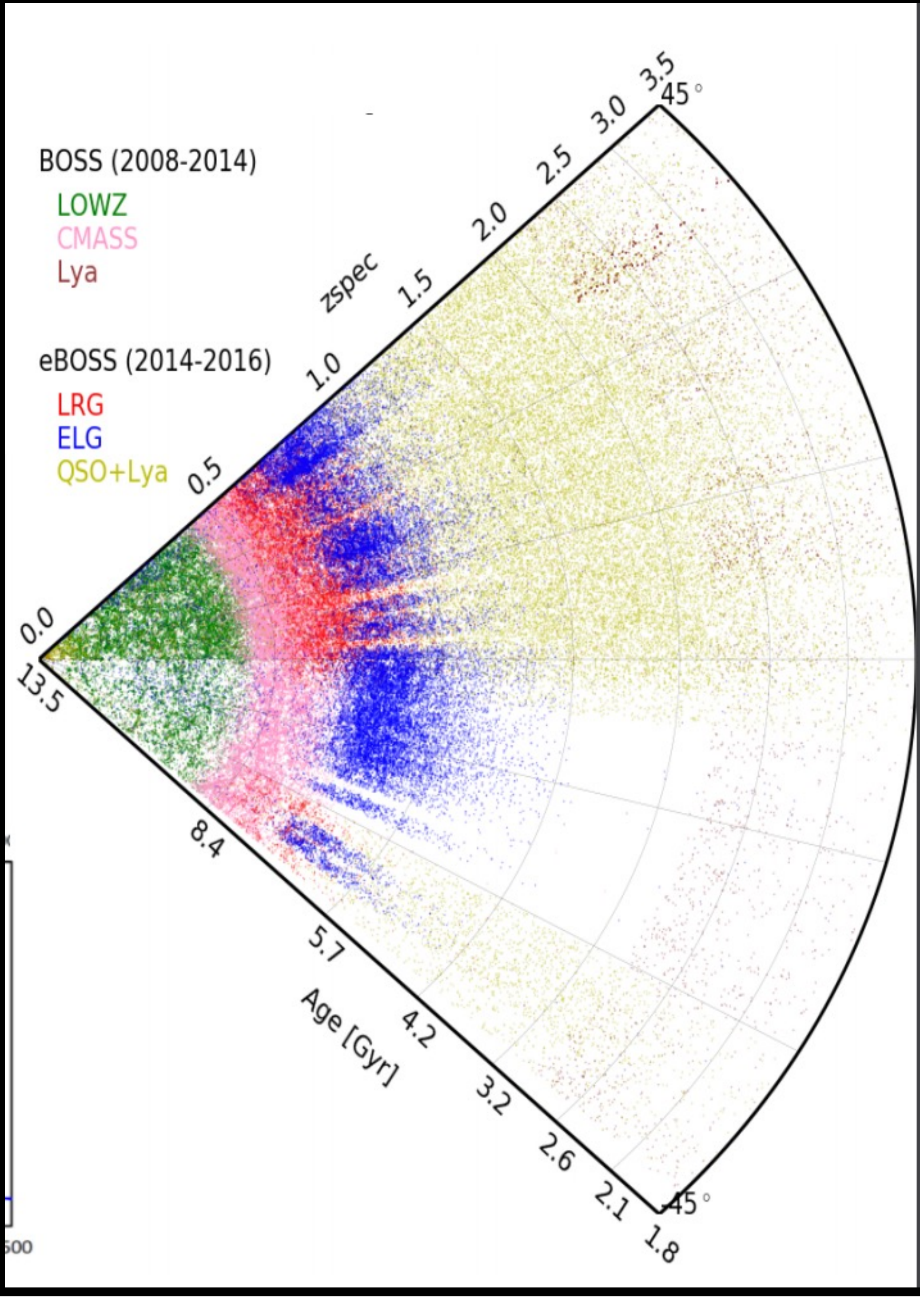
- Observe as much as possible of the Universe.

Golden age or Gold rush?



Courtesy of D. Schlegel

Spectroscopic Galaxy surveys

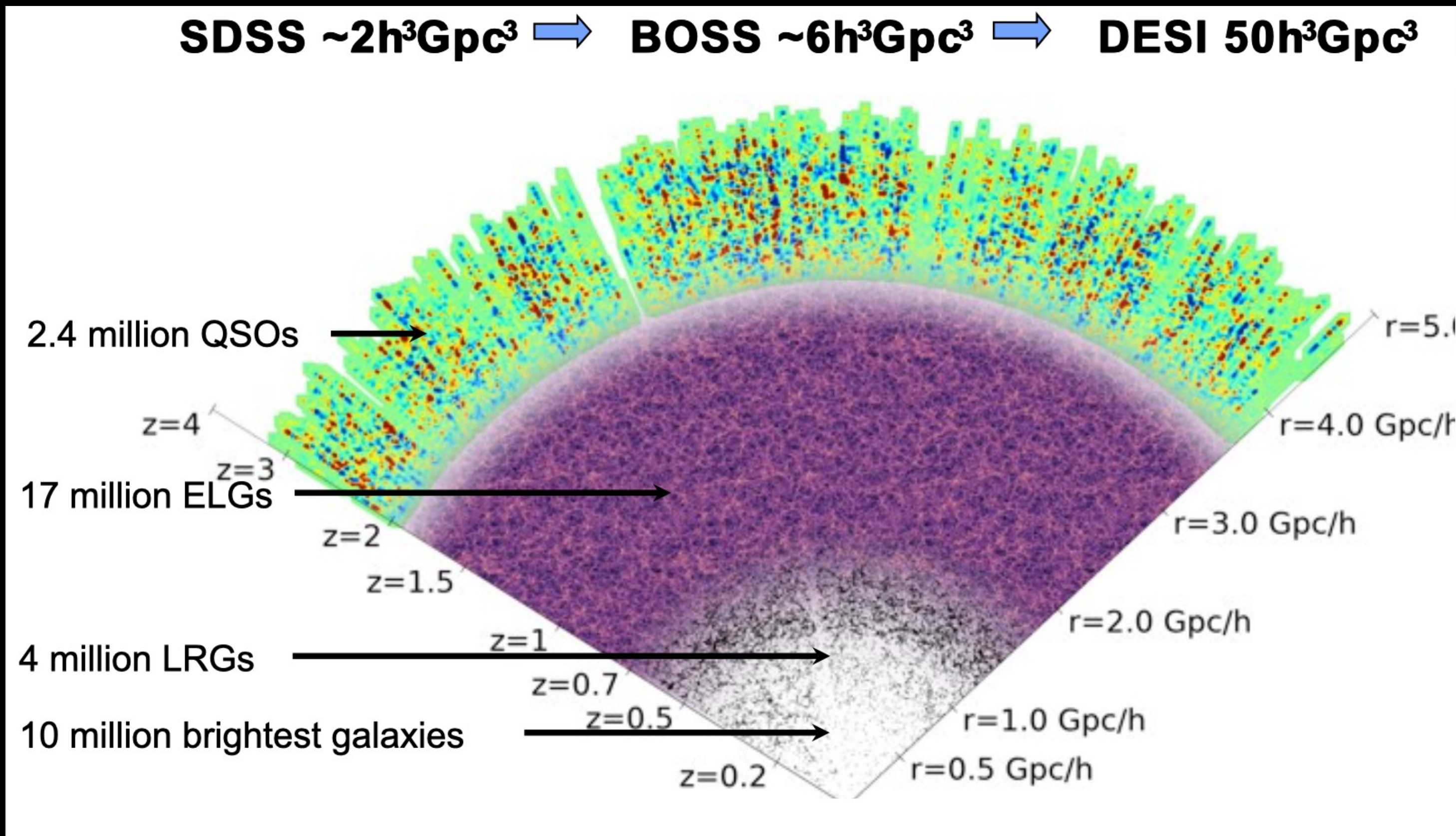


Latest results are from the e-BOSS collaboration
before BOSS DR12, next DESI

DESI: Dark Energy Spectroscopic Instrument, Survey

desi.lbl.gov

- Mayall 4m telescope at Kitt Peak
- Stage IV dark energy measurement
- Baryon acoustic oscillations (but also much more)
- ~30 M spectra over 11 billion years of cosmic history
- 14K deg^2; Galaxies up to z=1.7 and QSOs 2.1<z<3.5



“We can’t live in a state of perpetual doubt, so we make up the best story possible and we live as if the story were true.”

Daniel Kahneman about theories

GR, big bang, choice of metric, nucelosynthesis, etc etc…

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?

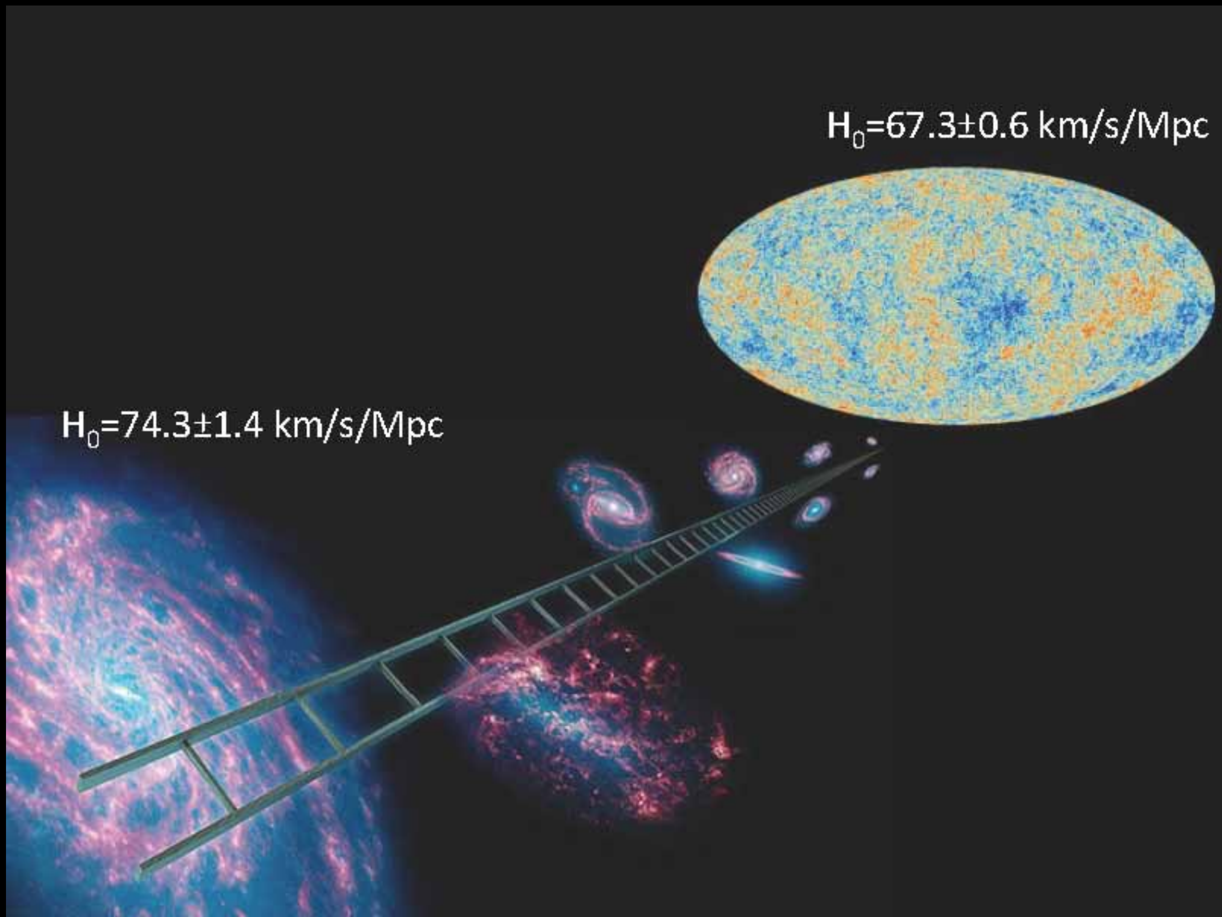
Can you do without?

Precision cosmology

- Parameter fitting (in a ΛCDM model or parametric deviations)
- This does not really ensure that the model is ”correct”
- $\boxed{\text{Redundancy/reproducibility/different probes....}}$
- precision without accuracy is meaningless if not dangerous

....Maybe we shouold try to test the model at some point…

And there is this nagging "little" issue…



Measuring velocities is easy, but measuring distances is hard

$$v = H_0 d$$

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

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

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

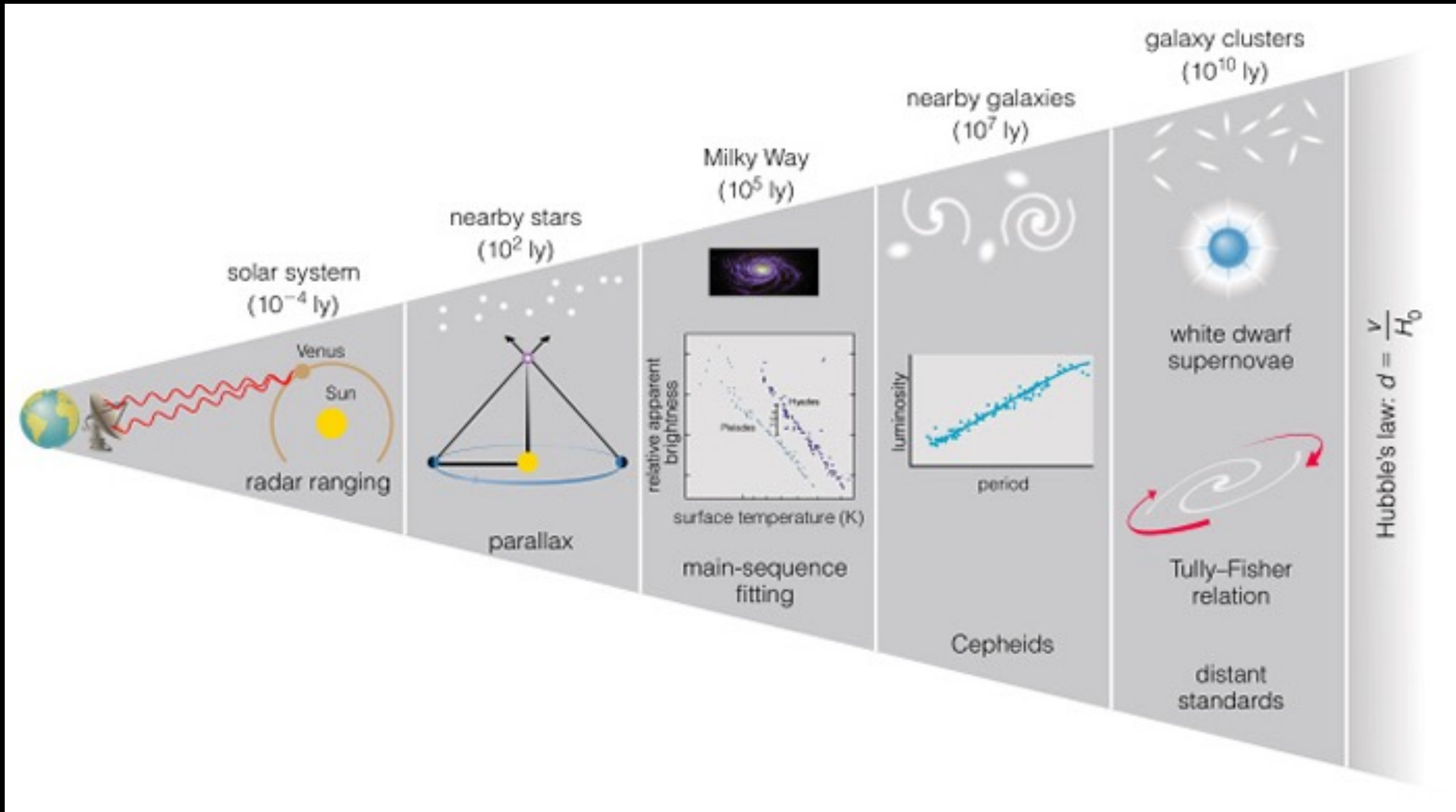
The cosmological parameters have appeared!

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

H is always on the LHS…

Get H this way

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

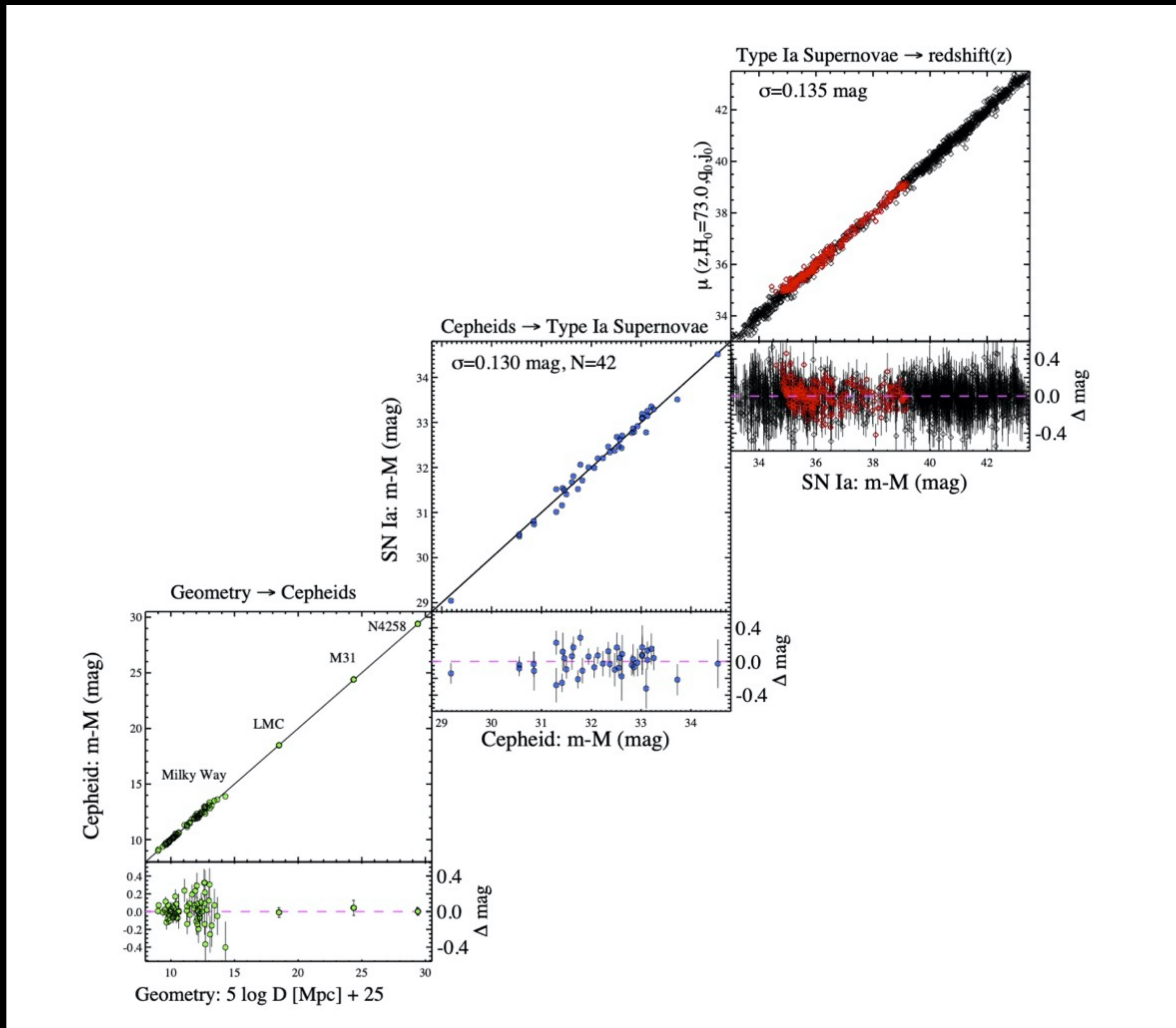


Three key rungs and 2 key steps: geometry to cepheids and cepheids to supernovae

The cosmic distance ladder

Get H this way

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

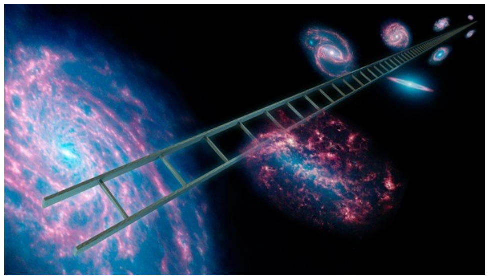


Riess et al. 2021

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

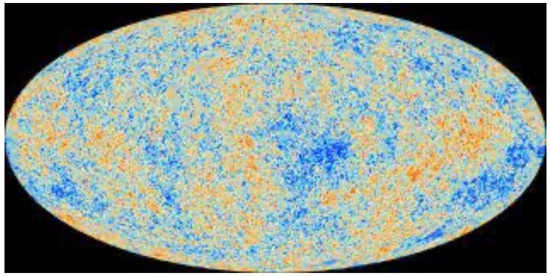
($z \lesssim 0.1$)
Present day expansion rate of the Universe
Recession velocity → distance.

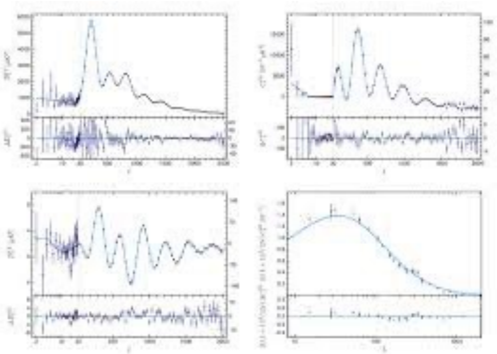


Parallaxes
Cepheids
SNe
TRGB
SBF
Masers
Etc…

Cosmic distance ladder

Global , cosmological parameter of a model





Calibrated on early-time physics

Two cosmic speedometers

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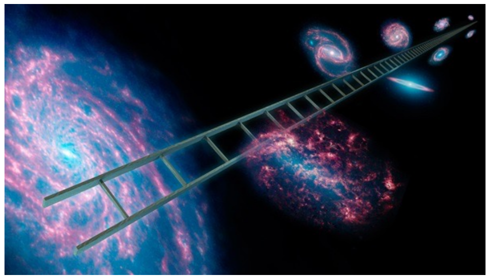

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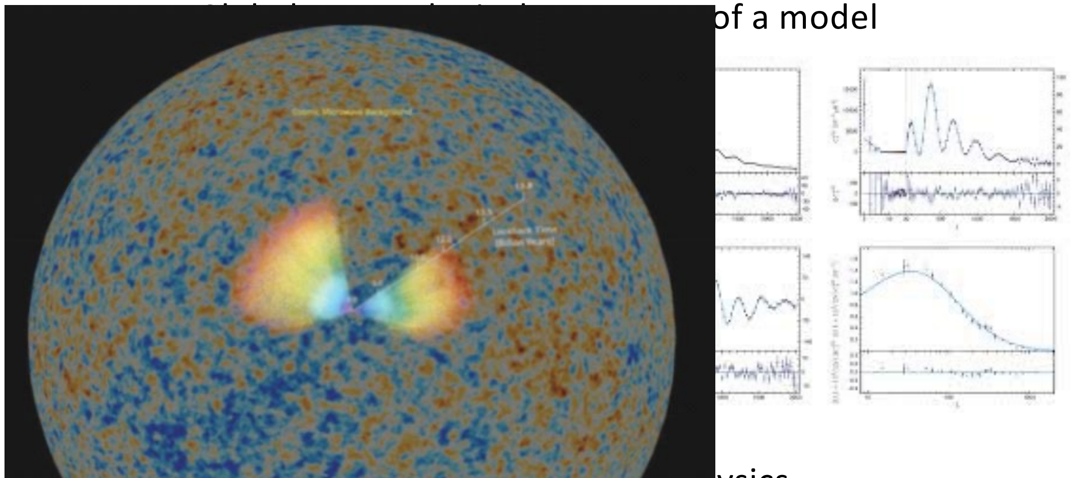
Cosmic distance ladder

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
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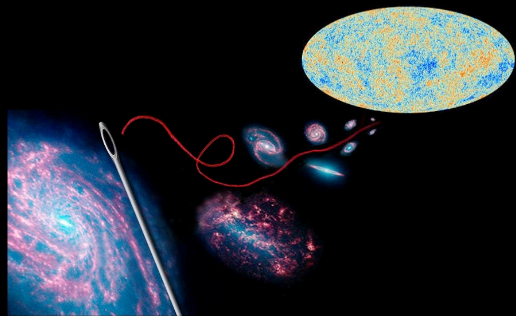
Etc…

Cosmic distance ladder

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

If they coincide then……



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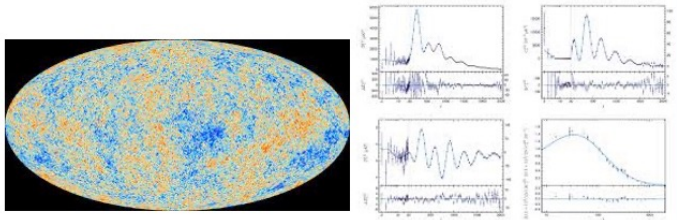


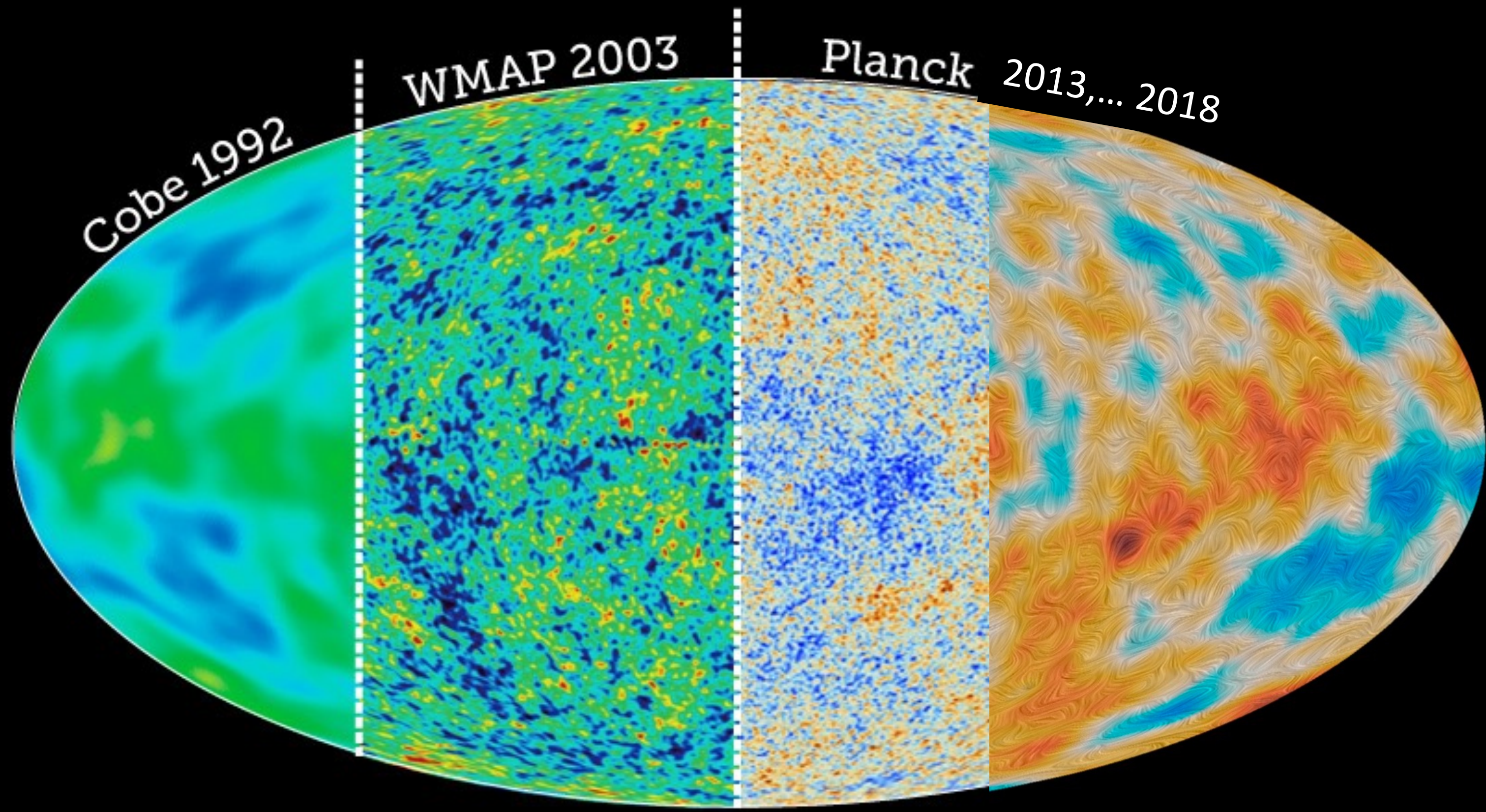
…the adopted cosmological model survives an extremely stringent test

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



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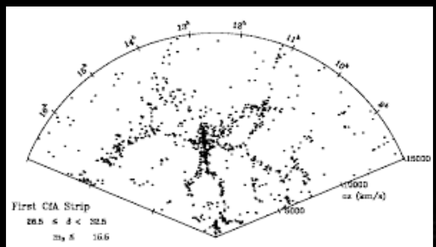
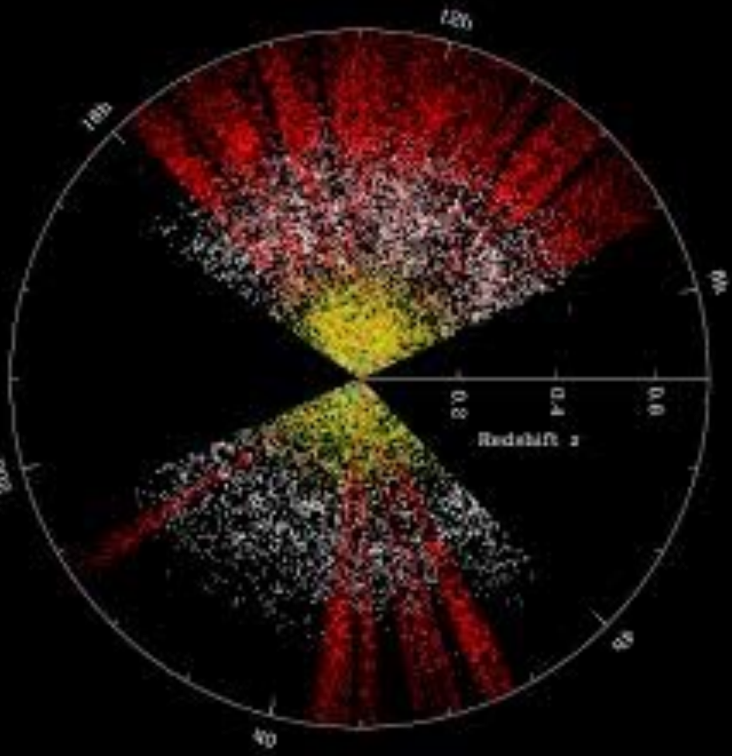
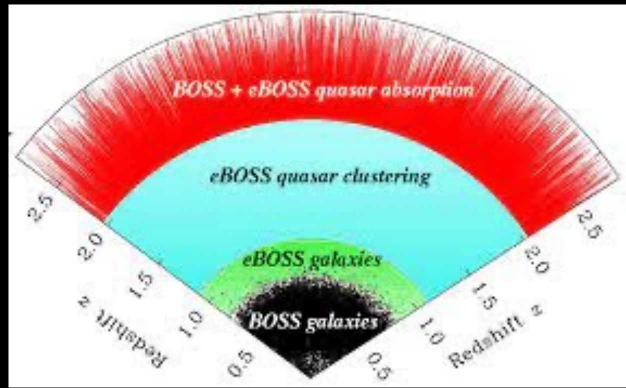
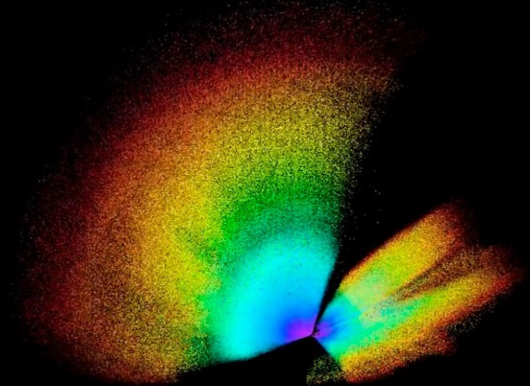
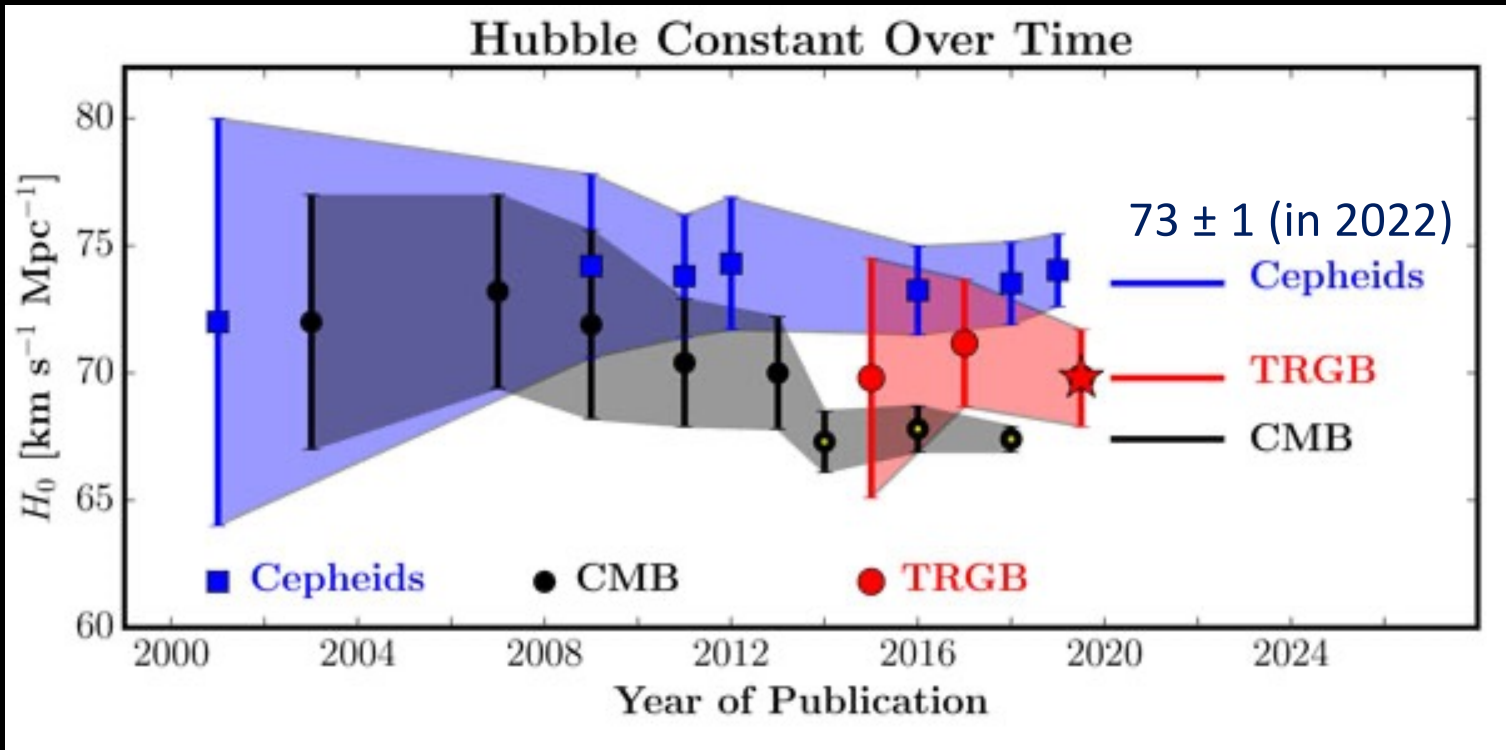








Until the didn't…



A tale of two H's

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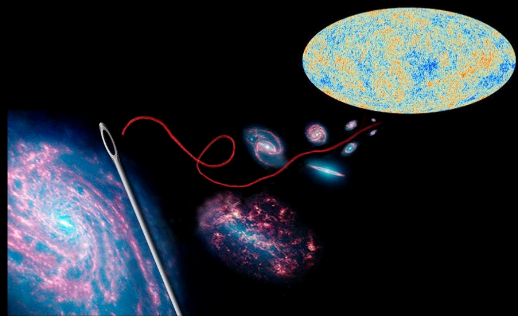

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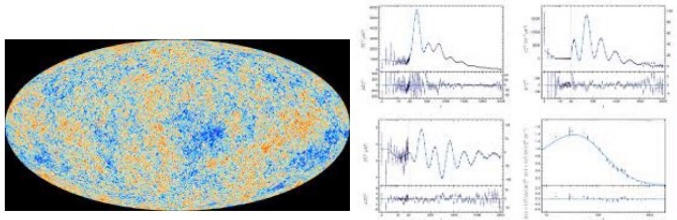


…the adopted cosmological model survives an extremely stringent test

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

Errors in the data

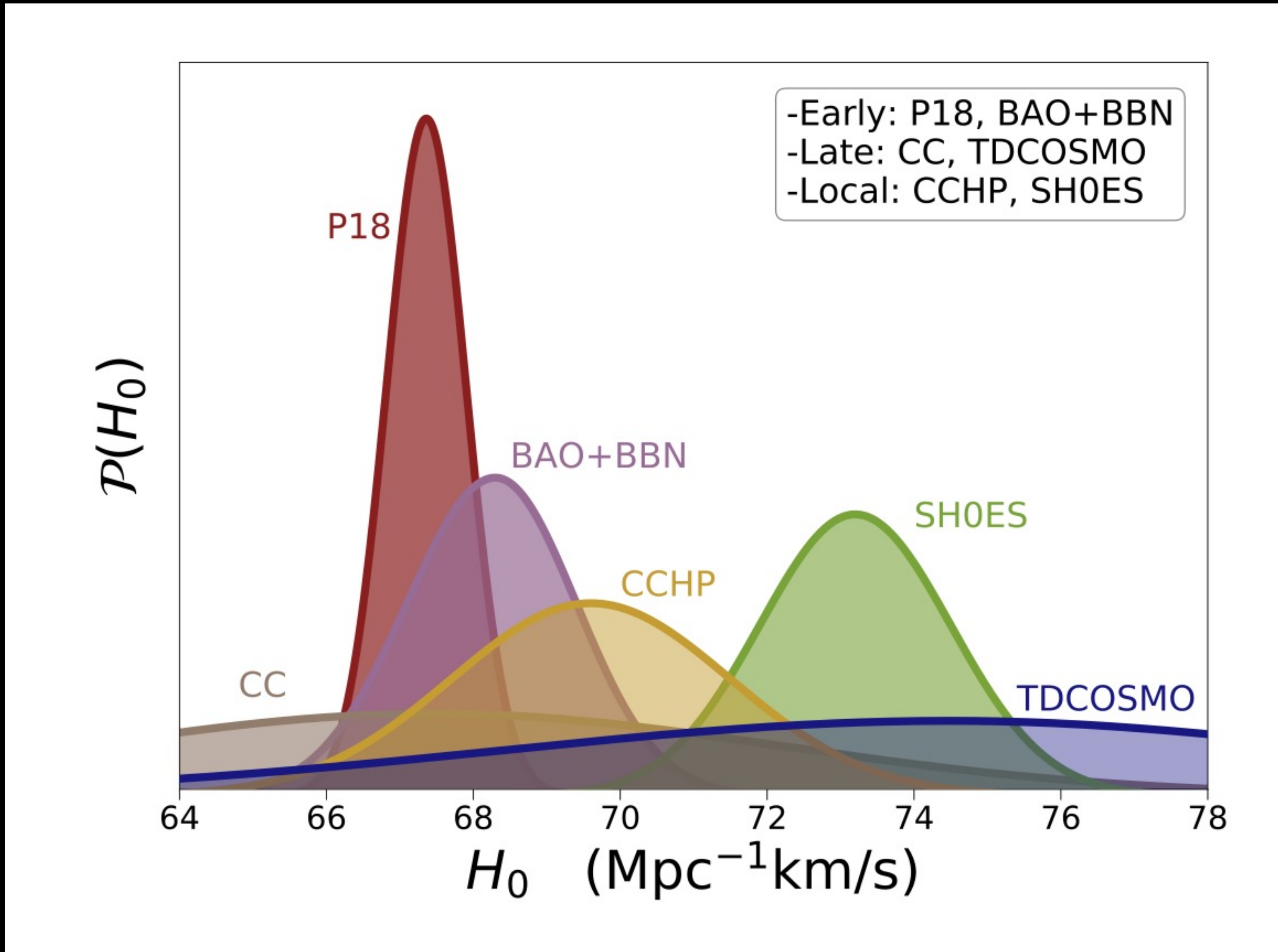
Errors in the analysis

Errors in the model

There are many H_0

Not all measurements measure directly the current expansion rate

Model dependent vs model independent



Frequently updated … just illustrative

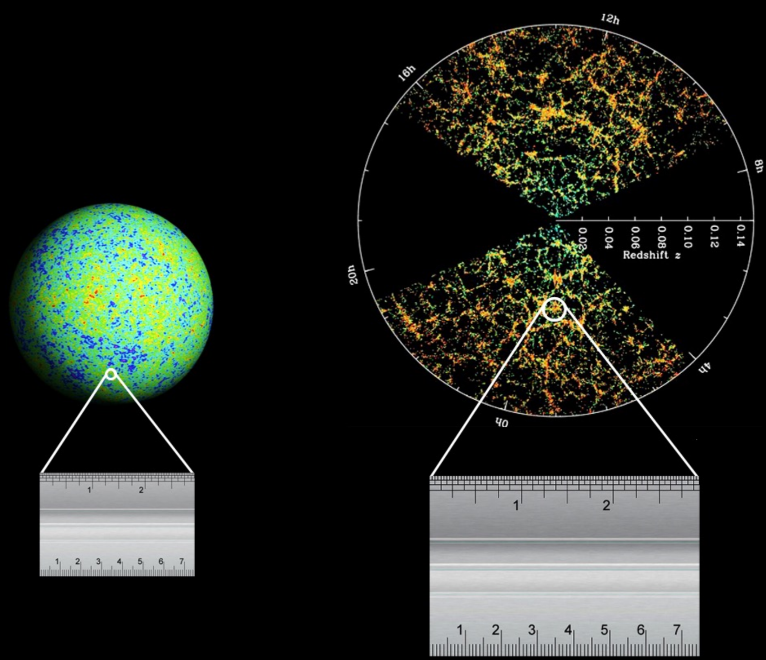
Bernal et al. 2102.05066

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)

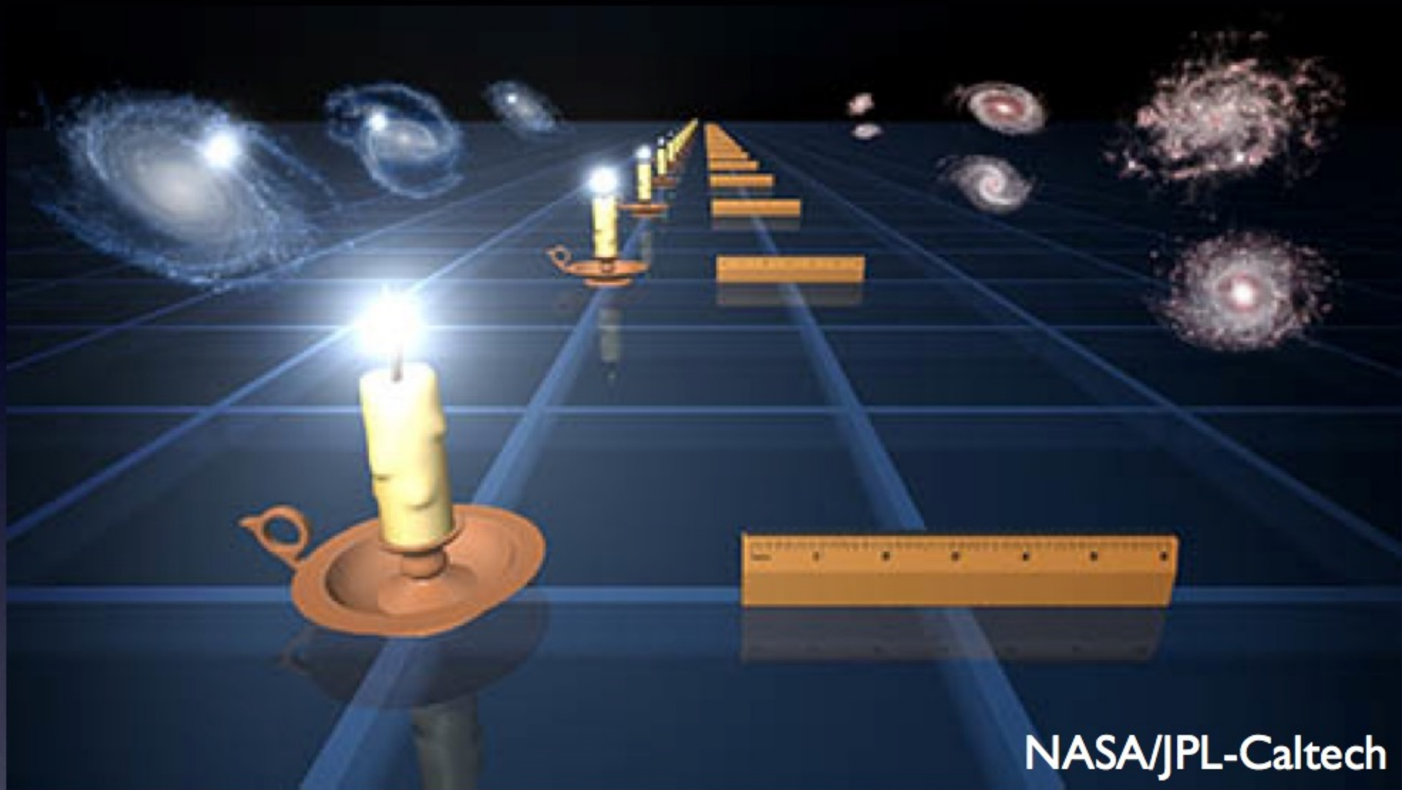
b) say there is a standard ruler, same at all z, but of unknown length

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

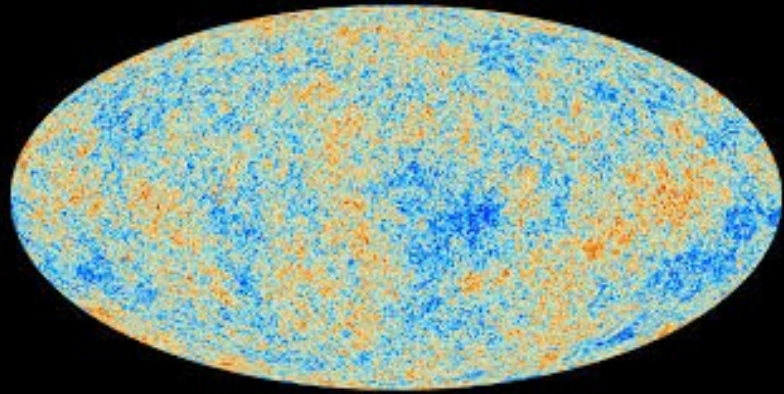
Standard candles & Standard rulers



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

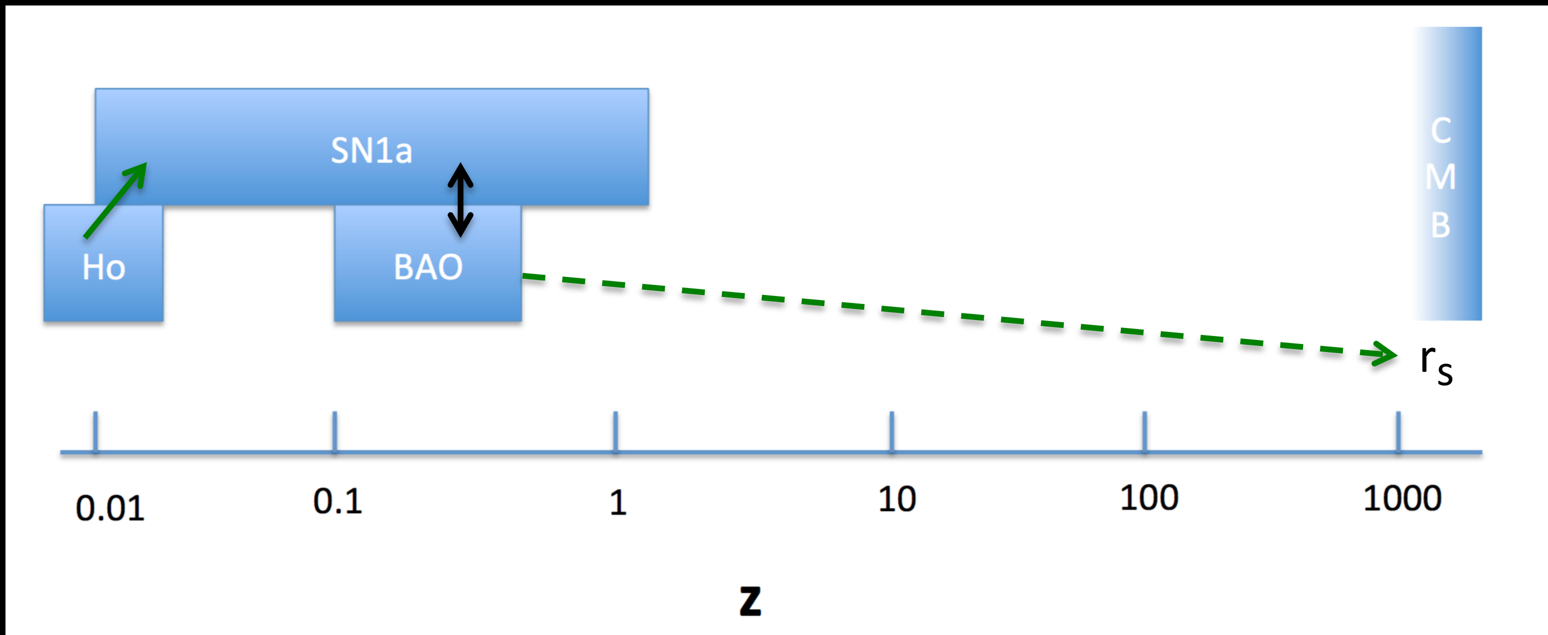


… Since about 2015

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



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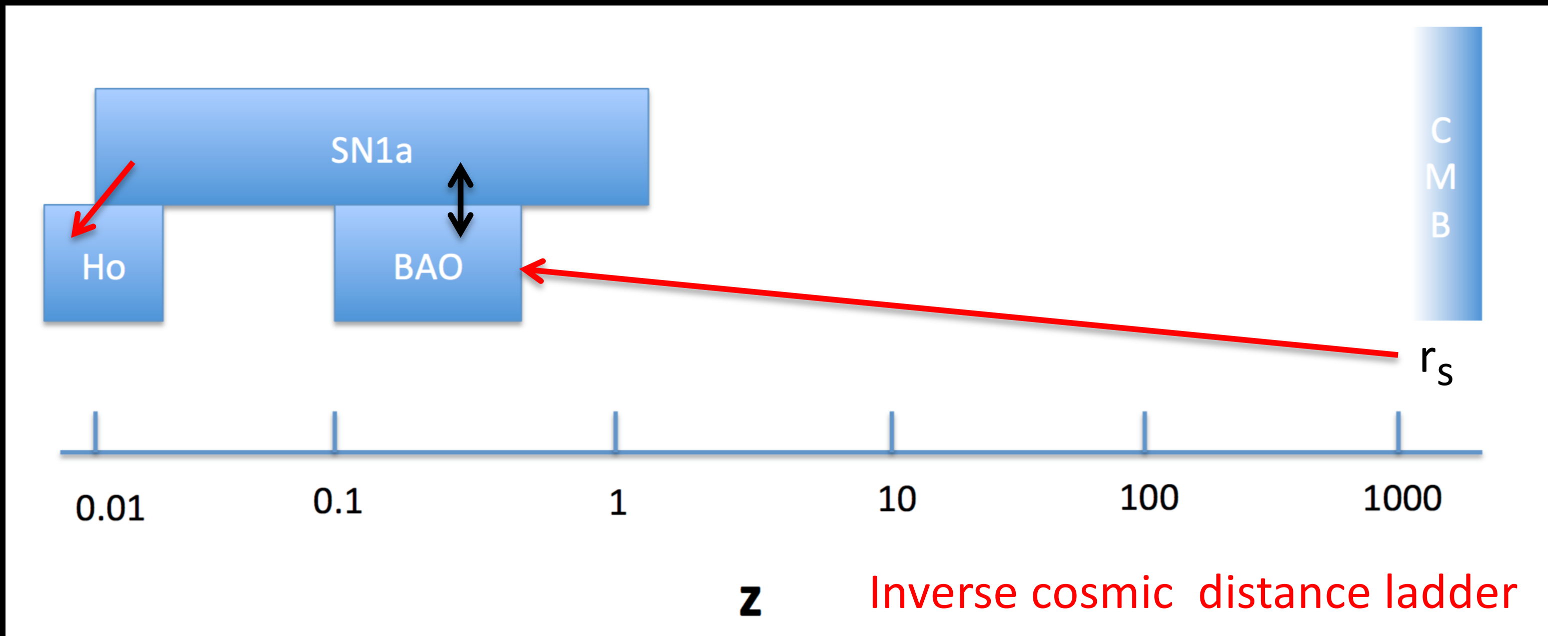
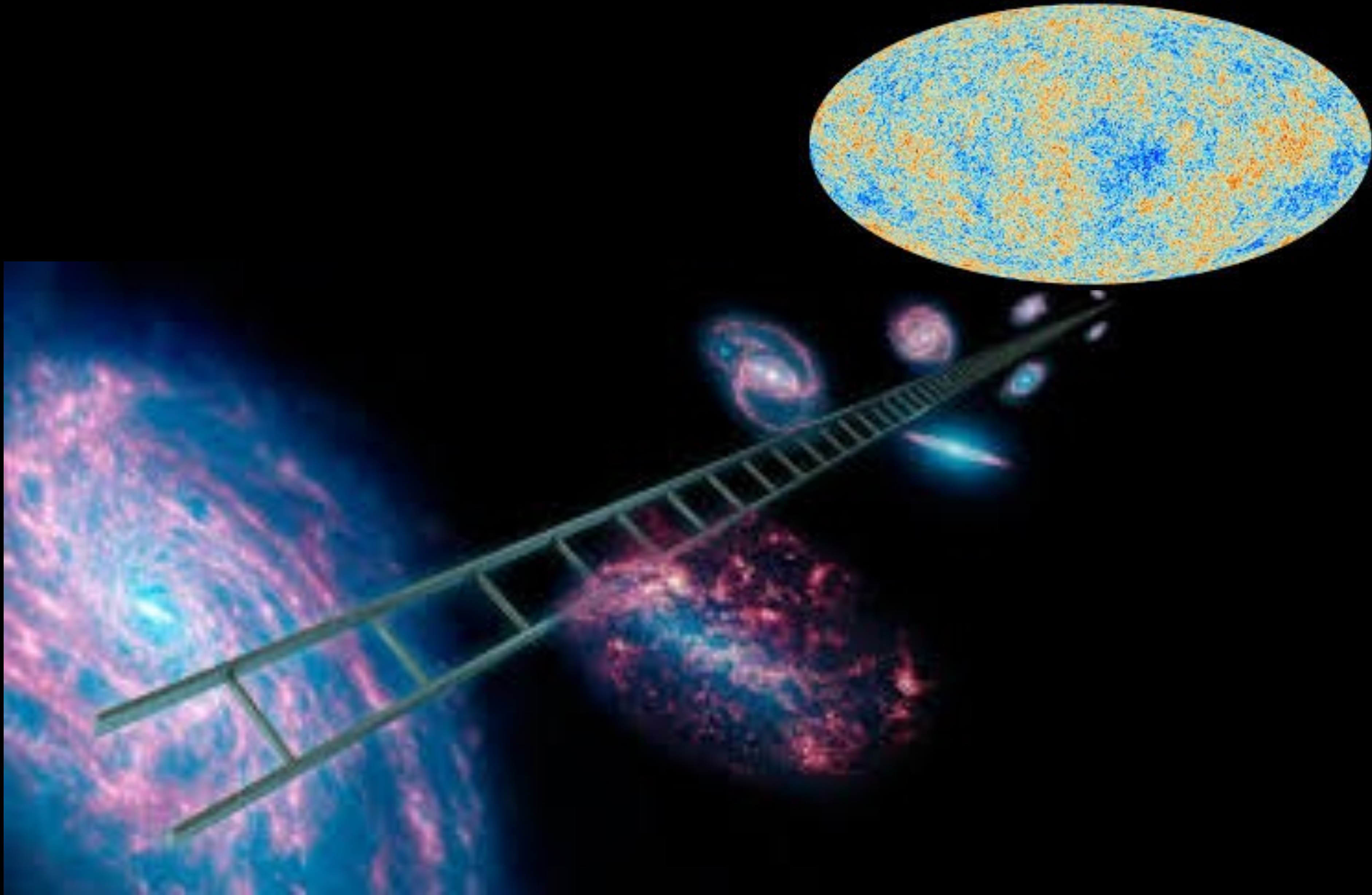


Here is where in ΛCDM or its simple variations the two ladders do not seem match

The H0 game: E2E test

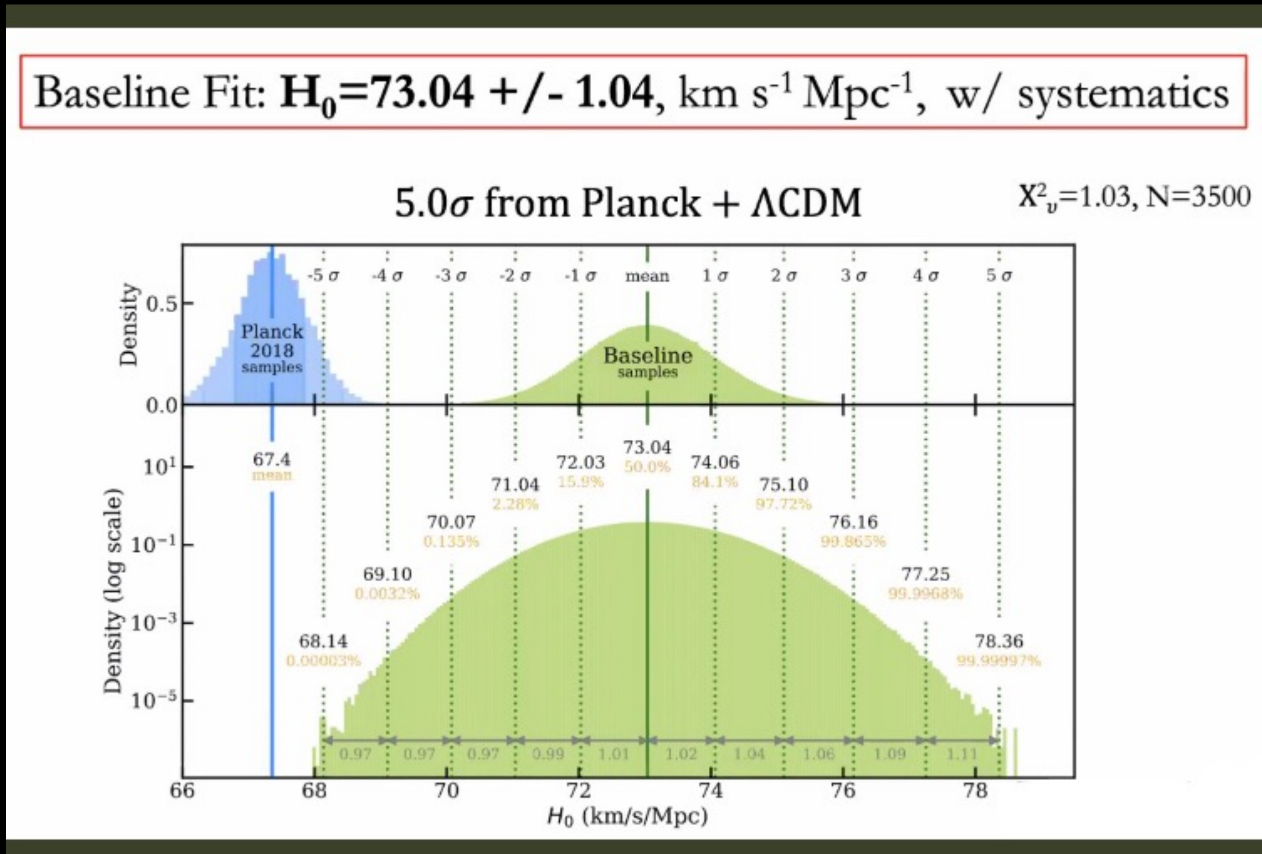


Is there a problem?

Is there a problem?

Whatever it is, it is too large to ignore

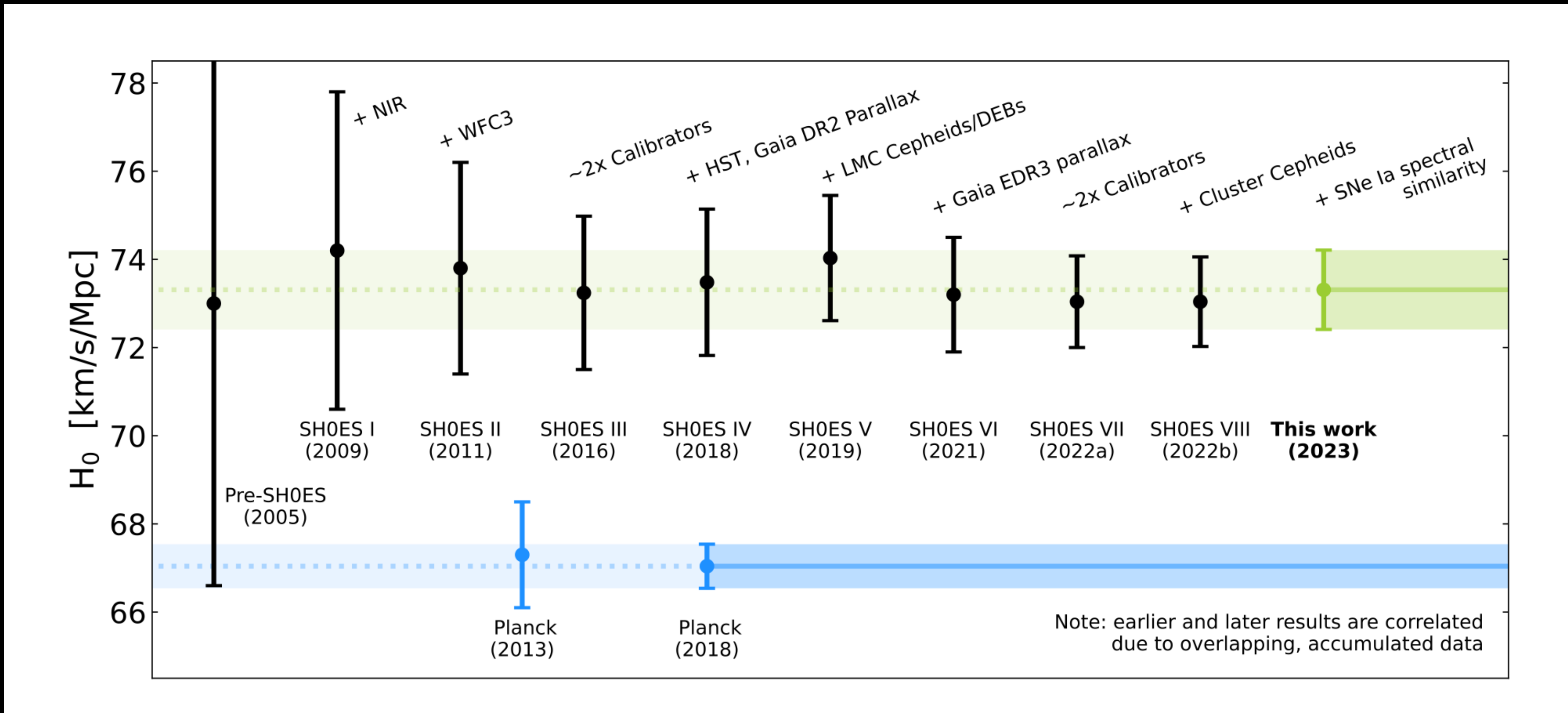
Latest SHOES results



arXiv:2112.04510

This is precision cosmology!

No, sorry…Latest SH0ES results



5.7 σ

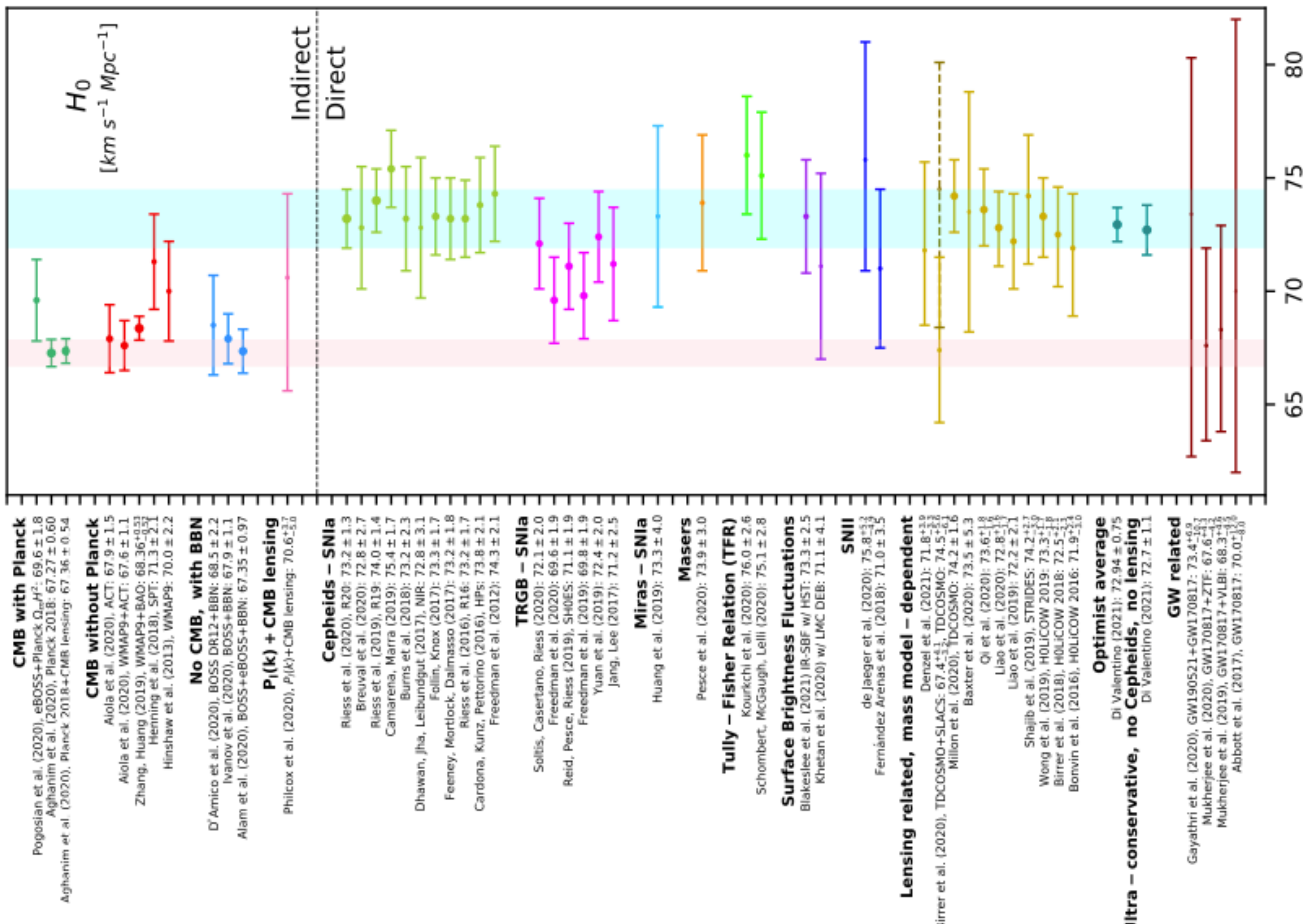
Murakami et al JCAP special 20 years anniversary issue

…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 objects

Where is the problem?

Is it in any specific data set?



Di Valentino et al 21

Is there wiggle room in the middle?

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

ΛCDM

CMB

$r_d h = 99.1 \pm 0.9$ Mpc

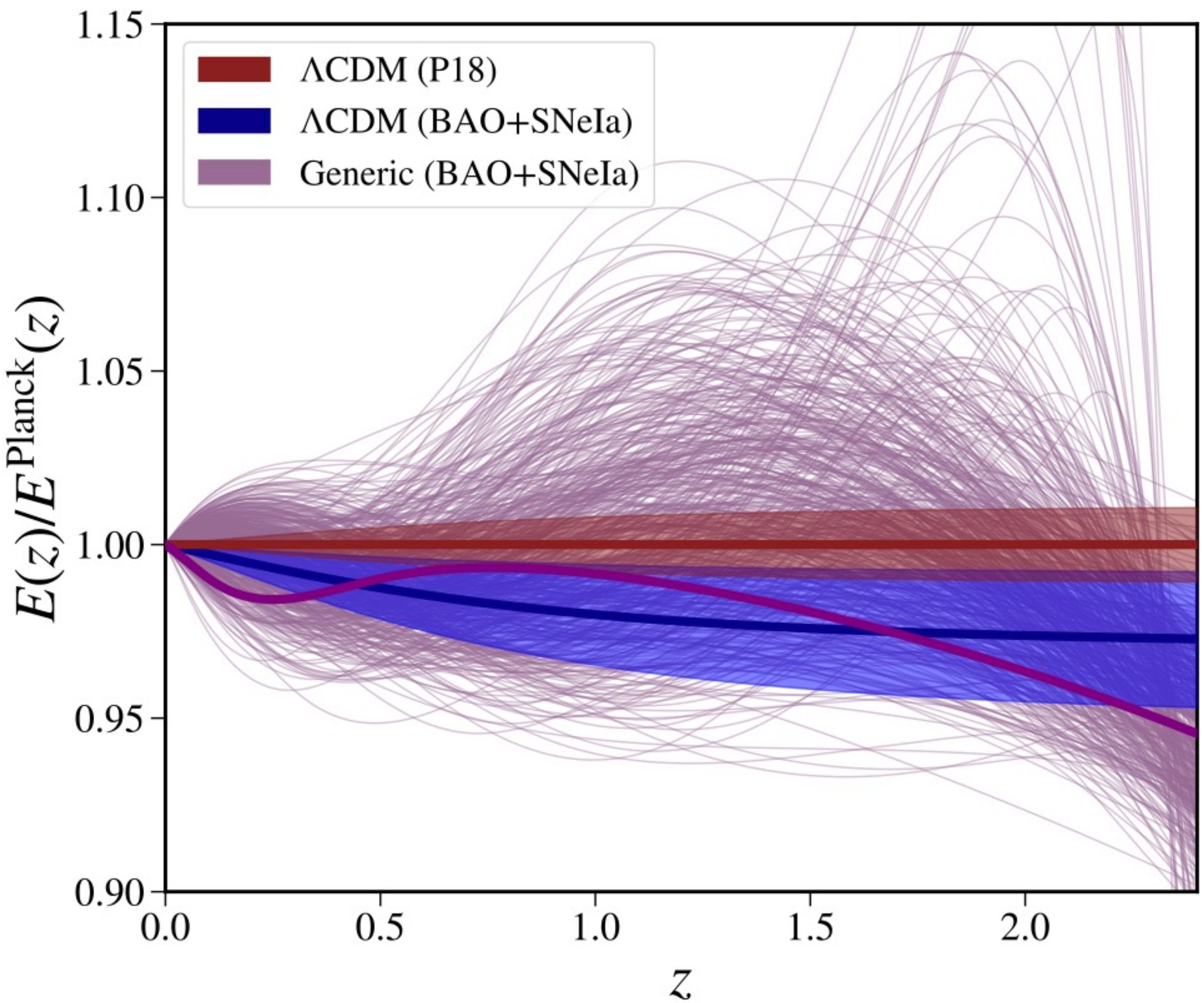
BAO+SNe

$\Omega_M = 0.297 \pm 0.013$

$r_d h = 100.6 \pm 1.1$ Mpc

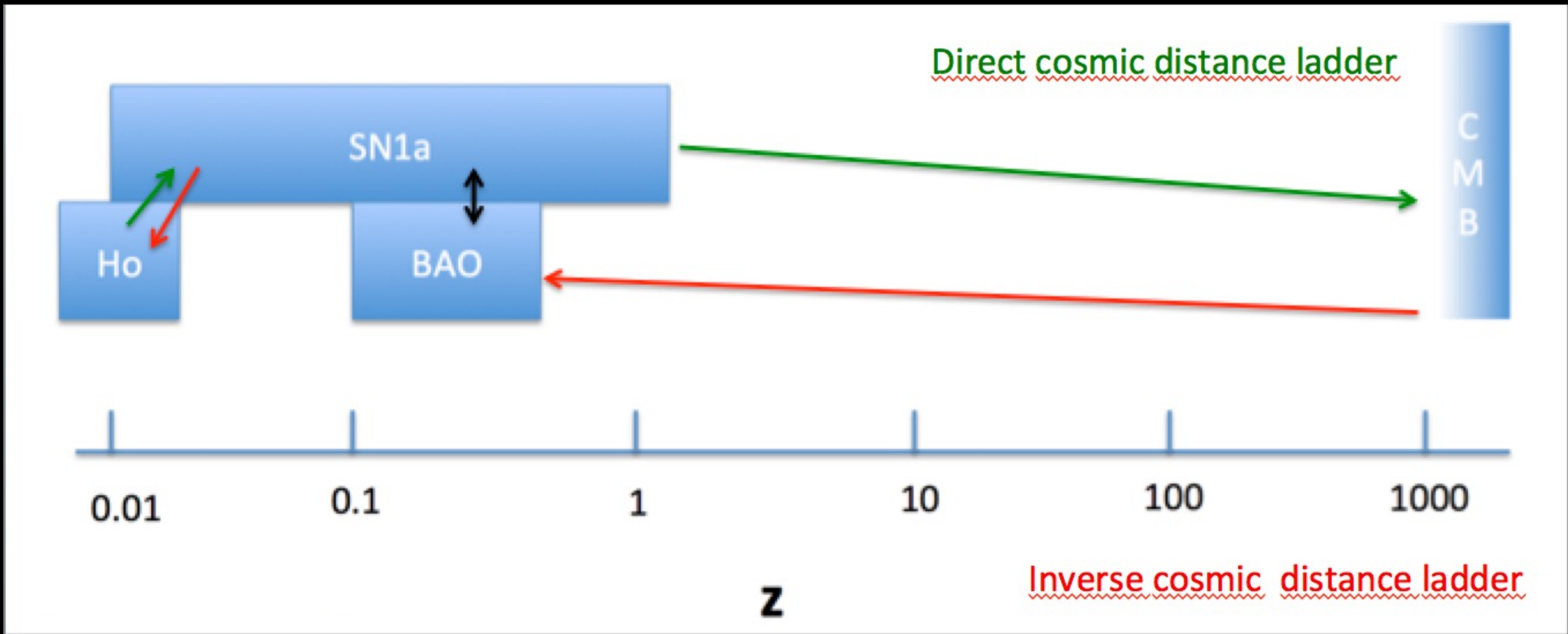
Generic reconstruction

$r_d h = 100.2 \pm 1.2$ Mpc



Bernal et al. 2102.05066

Working hypothesis: early vs late



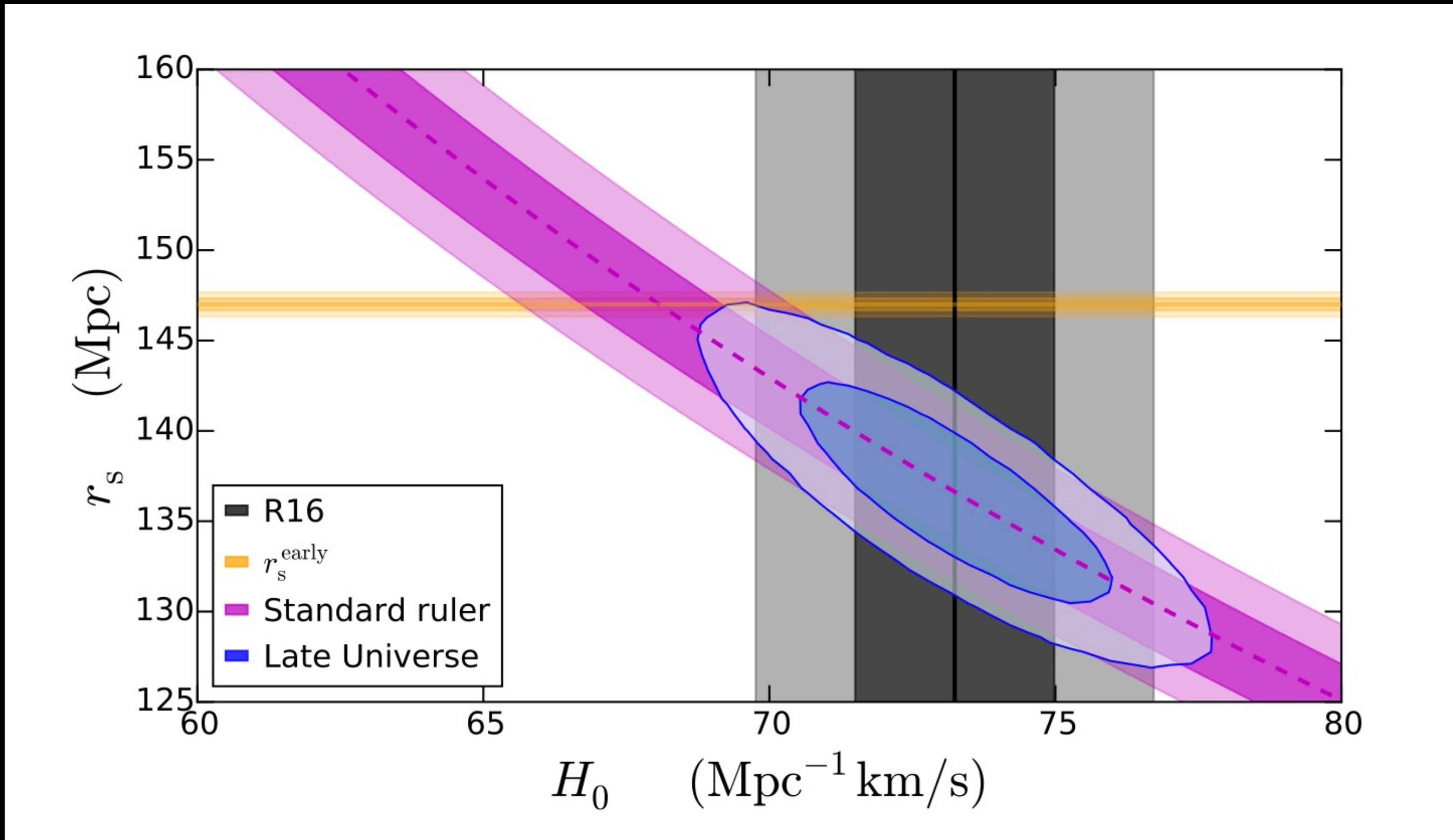
H0

rs

there is not much wiggle room in the middle!

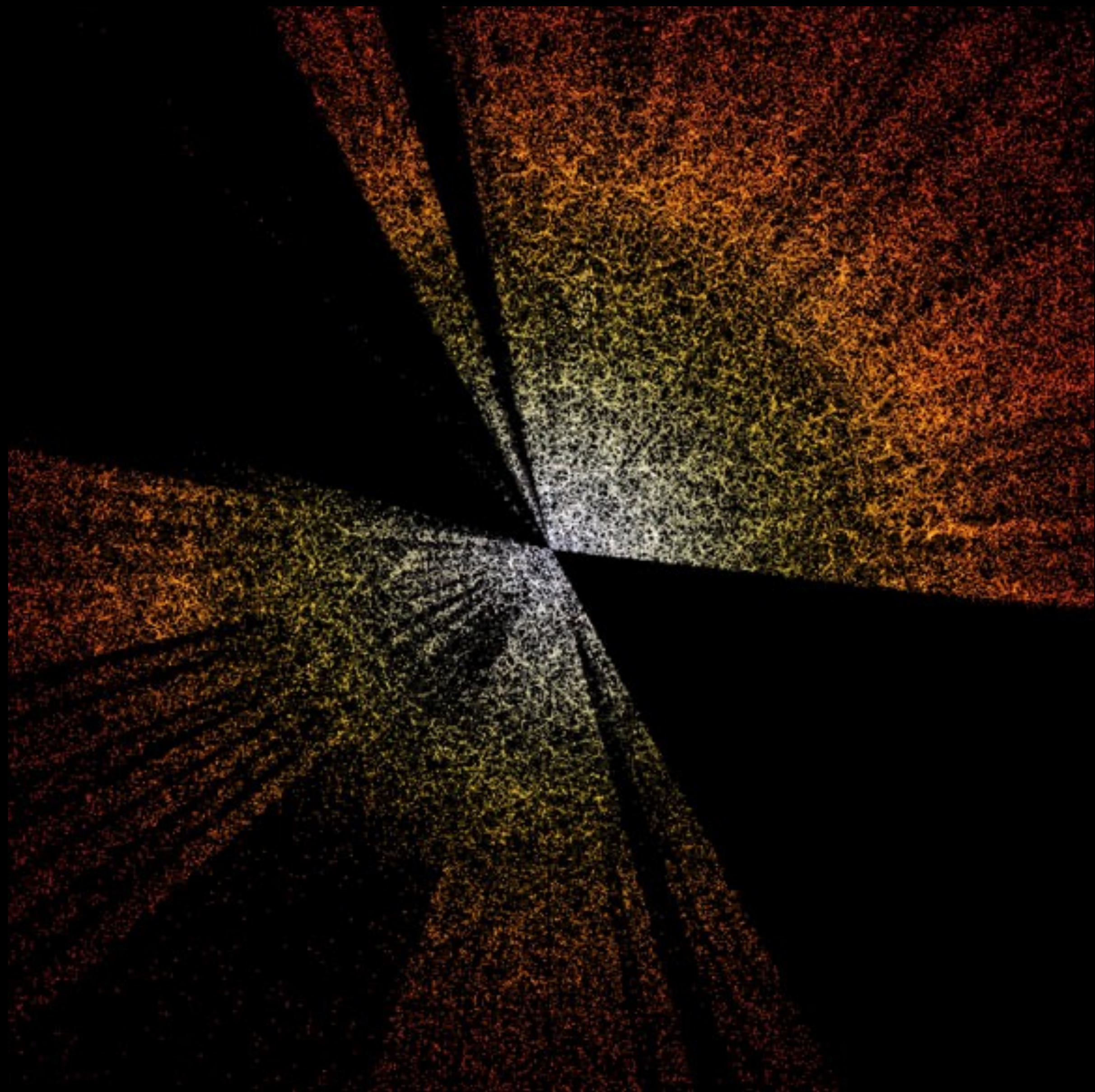
Bernal et al 2016, Aylor et al 2017

Ho problem (late time) can be seen as an r_s problem (early time)



Bernal et al 2016

How can galaxy redshift surveys help?



For galaxy redshift surveys

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

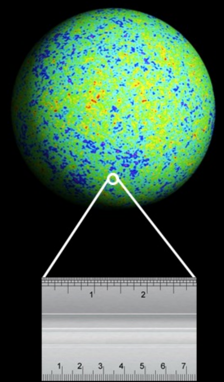
- We measure (mostly) redshifts and angles, we think in distances….
- Theory is in distances so we pick a model (z→ distances) even before we start…

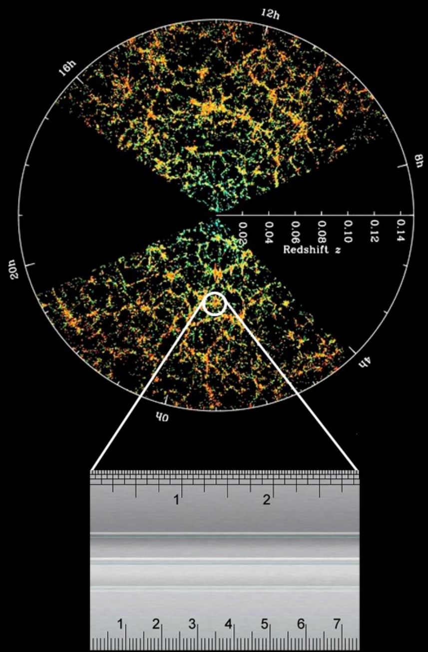
BAOs

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)

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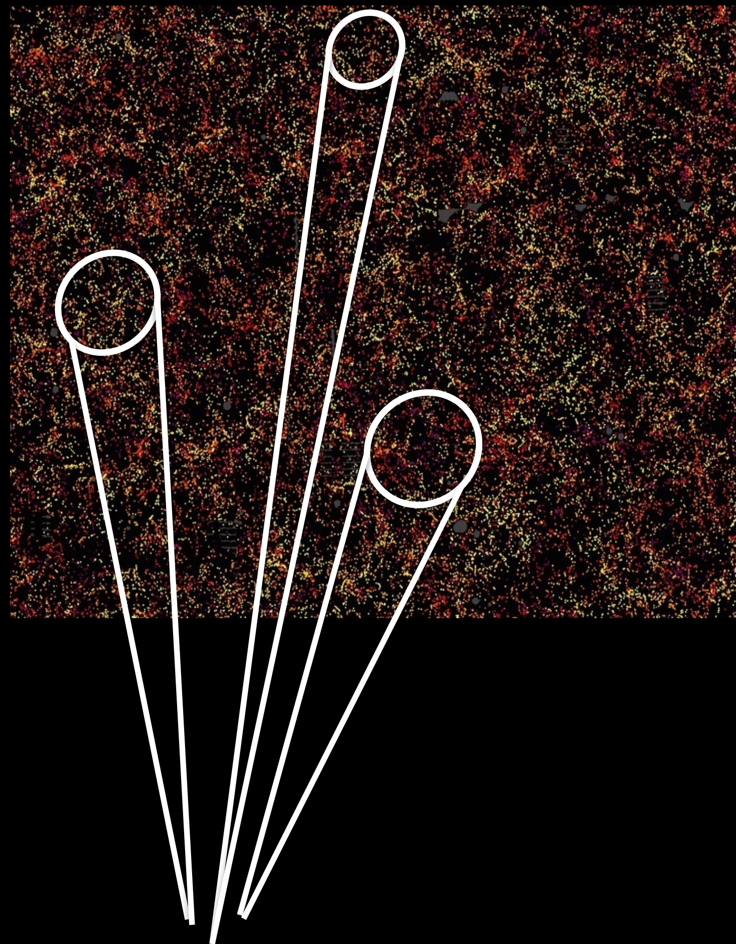
Effect is a “classic” AP

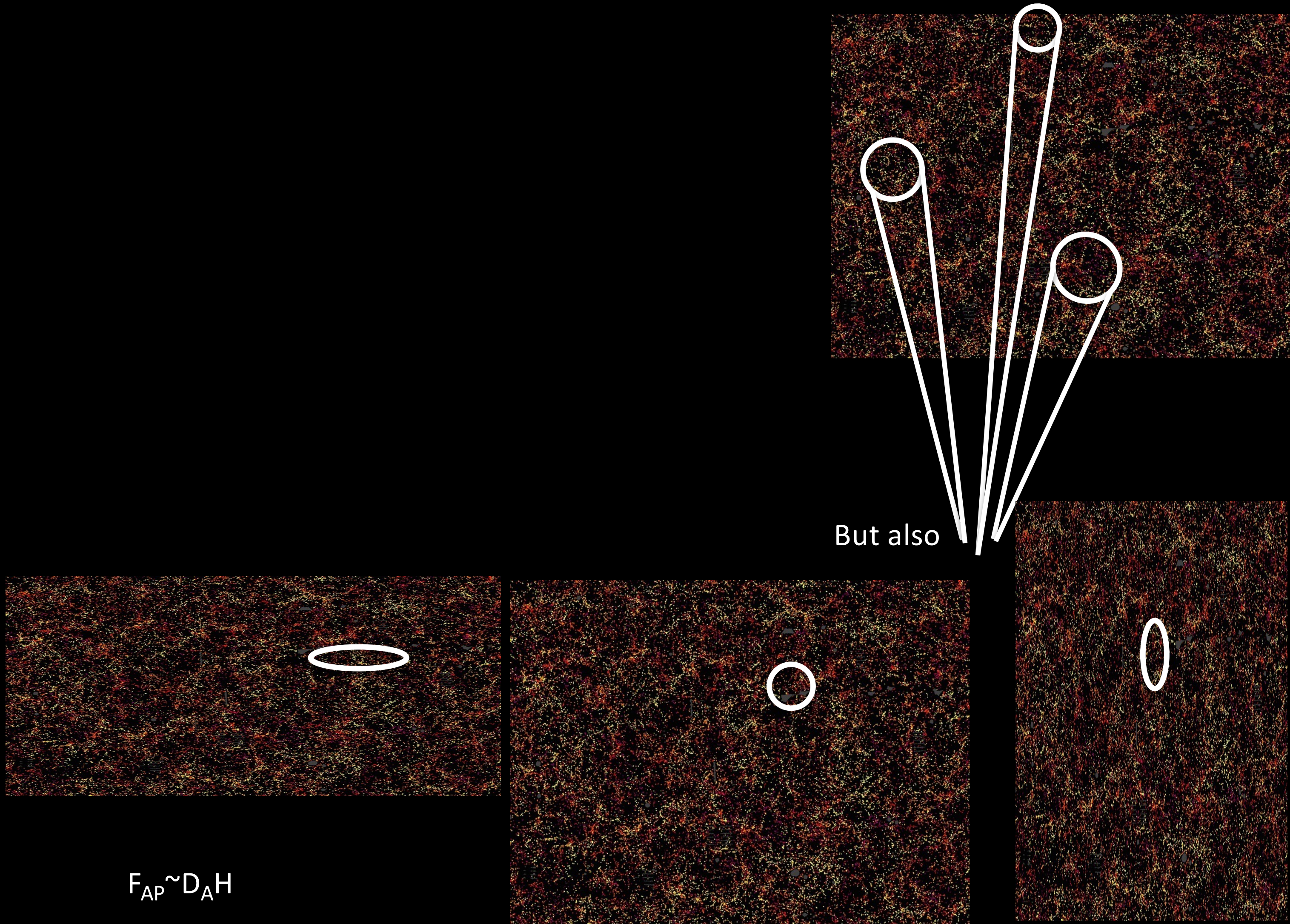
The ruler is the sound horizon at recombination (CMB), at radiation drag (LSS) but it is the same ruler. Symbols: r_s or r_d

Options…

1) known r_d
2) I insist I know the expression of r_d (but I am wrong)
3) r_d is not the LCDM one….

I measure an angle: D_V/r_d





$F_{AP} \sim D_A H$

It should be evident that…

Since one measures only angles and redshfts…

If the standar ruler length is not known -→ expansion history $H/H0=E(z) \sim \Omega m$

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

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)

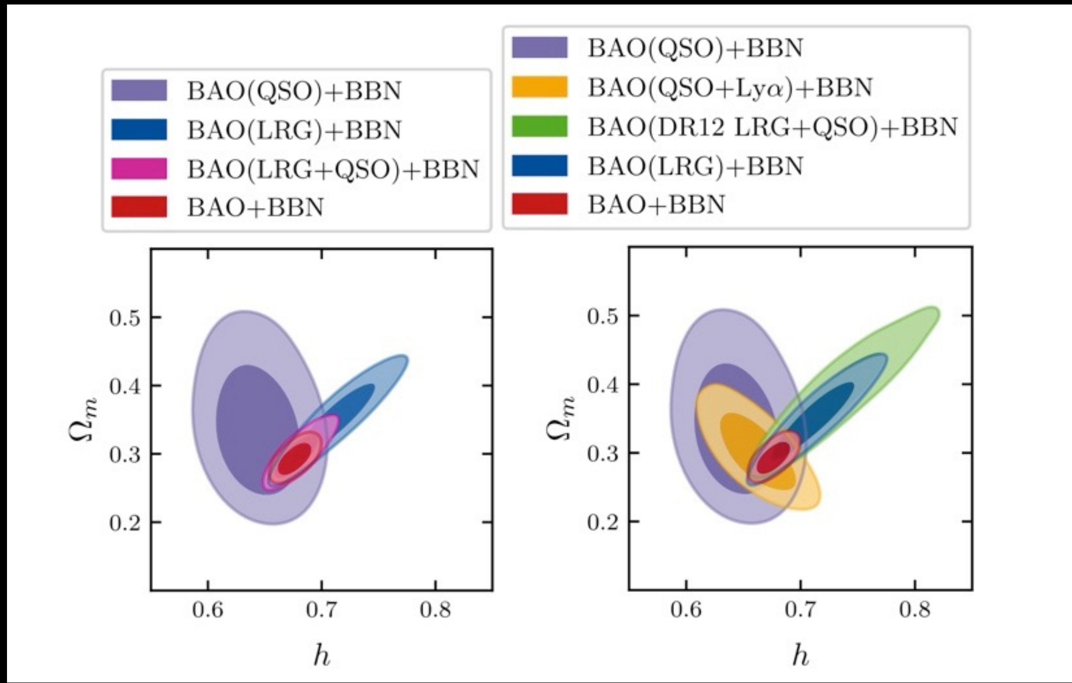
- Using (again) the equation above, a model for early Universe and a constraint on baryon density (e.g.,BBN & light elements abundance). BAO give matter density (in LCDM).

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, 2022



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

NOT in CMB data

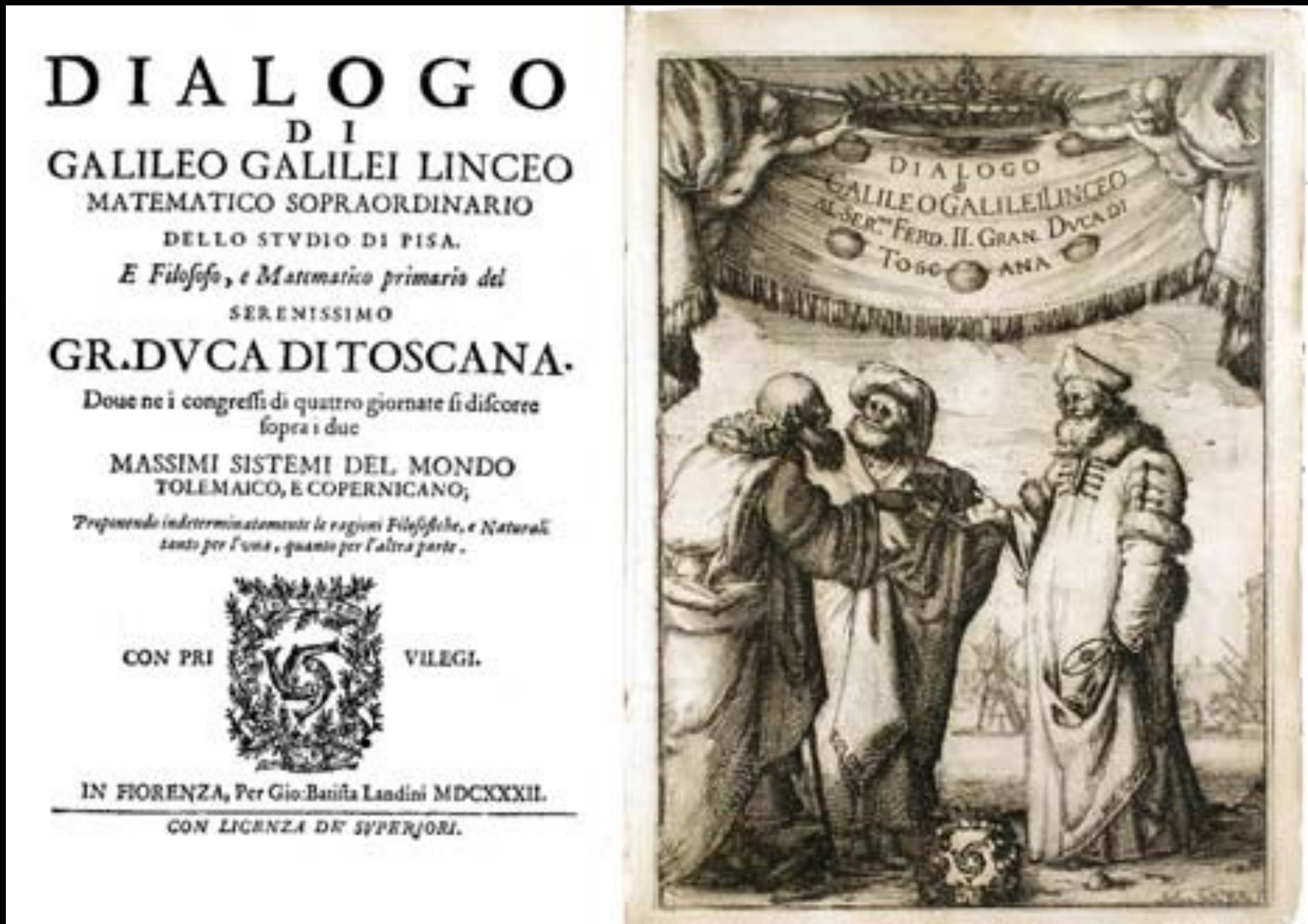
Early Universe physics yields stubbornly H0 in the 68km/s/Mpc camp

Systematics!

Increasingly unlikely

Where is the problem?

If not in the data then in the model…?



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 $m_e+\Omega_k$	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 $\rightarrow$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗
DM $\rightarrow$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗

Shoneberg et al. arXiv:2107.10291.

Early-time pre recombination solutions are preferred

Late-time post-recombination solutions do not appear to be viable (read: heavily disfavored by the data).

pre-recombination solutions

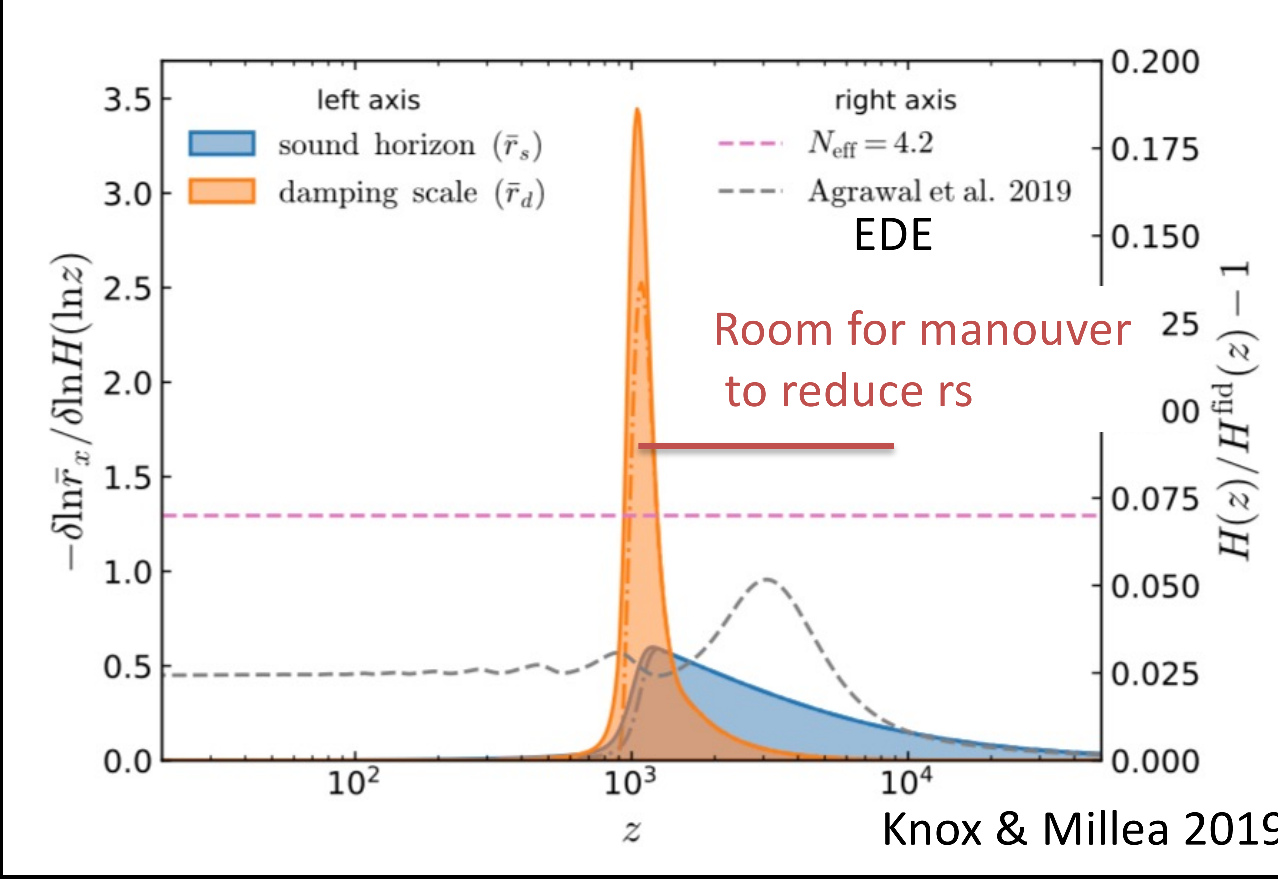
Modify the model right where we most like it

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



Knox & Millea 2019

Reminds me of fine tuning

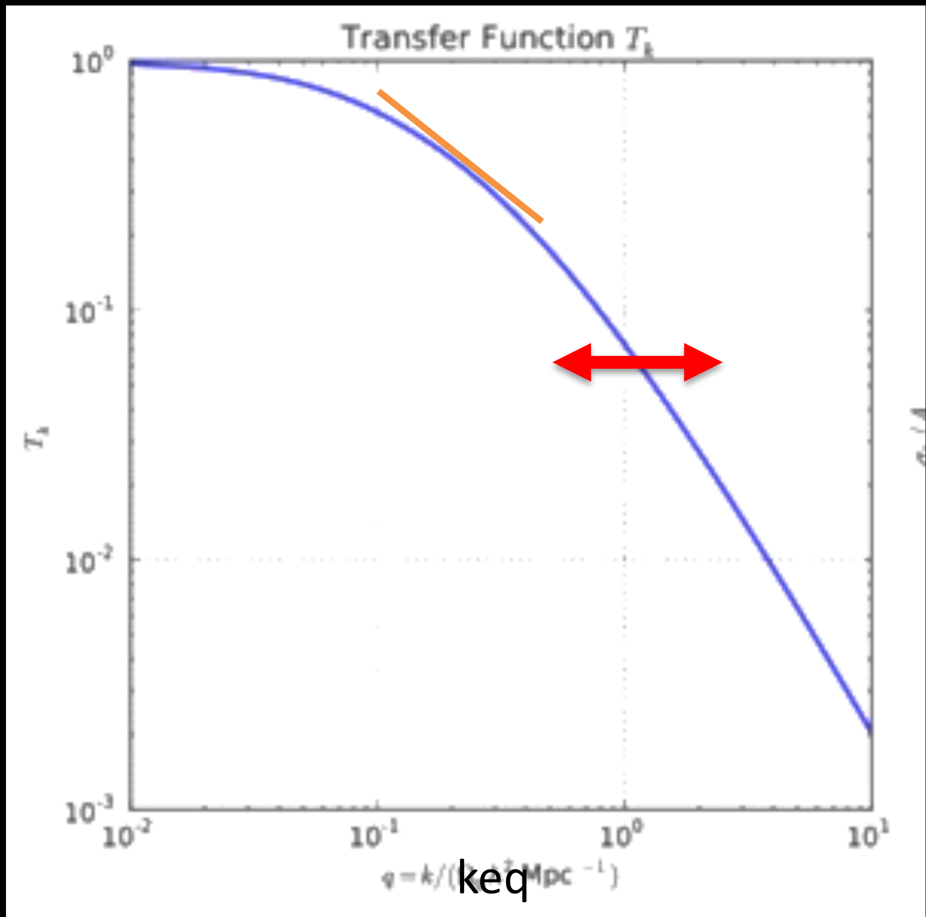
Ailor et al 2019

We effectively have one standard ruler for early-times “rs”

It would be good to get more…

Down memory lane….
(not quite)

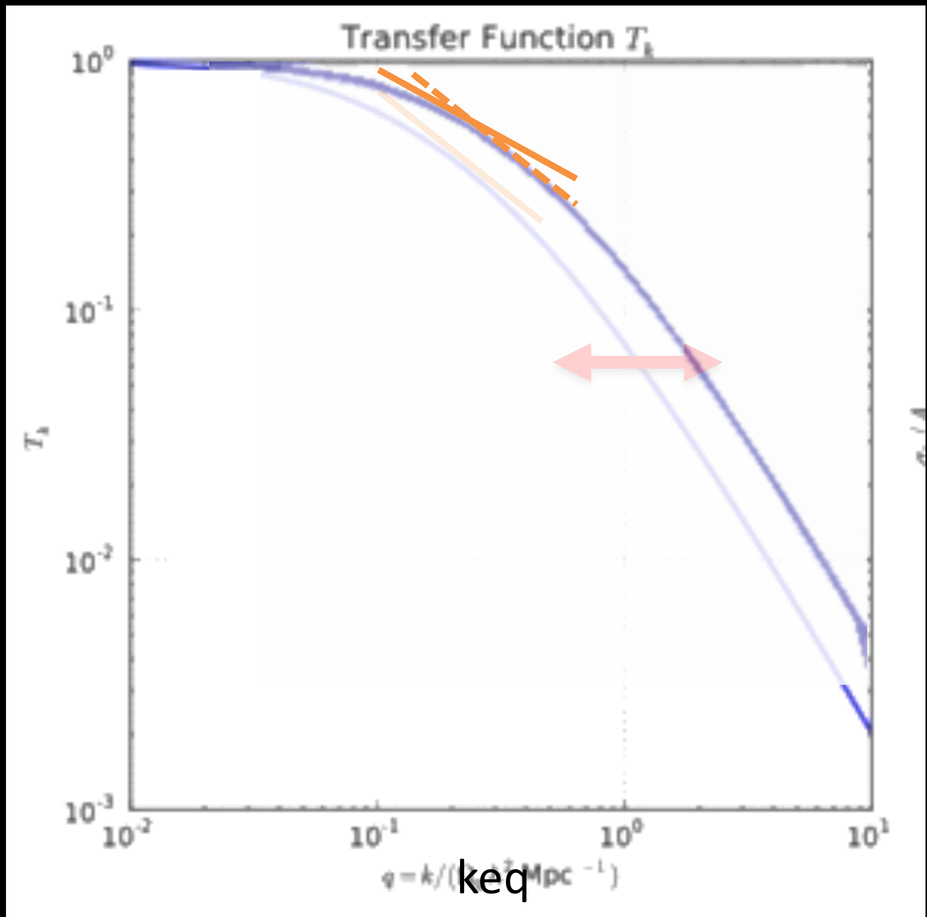
$$P(k)=T^2(k)(k/k_p)^{ns}$$



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

Down memory lane....
(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 $\Omega\gamma\ h^{2.}$ and $\Omega b\ h^2$

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

h

Large-scale structure give more than one h

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

D_V/rd Use the expression for r_d, using BBN Ωm, h, (Ω_b)

$\mathcal{D}_V$ Relative BAO, no assumption obout r_d (except that one exists) Ωm

AP distorion wrt line of sight Ωm

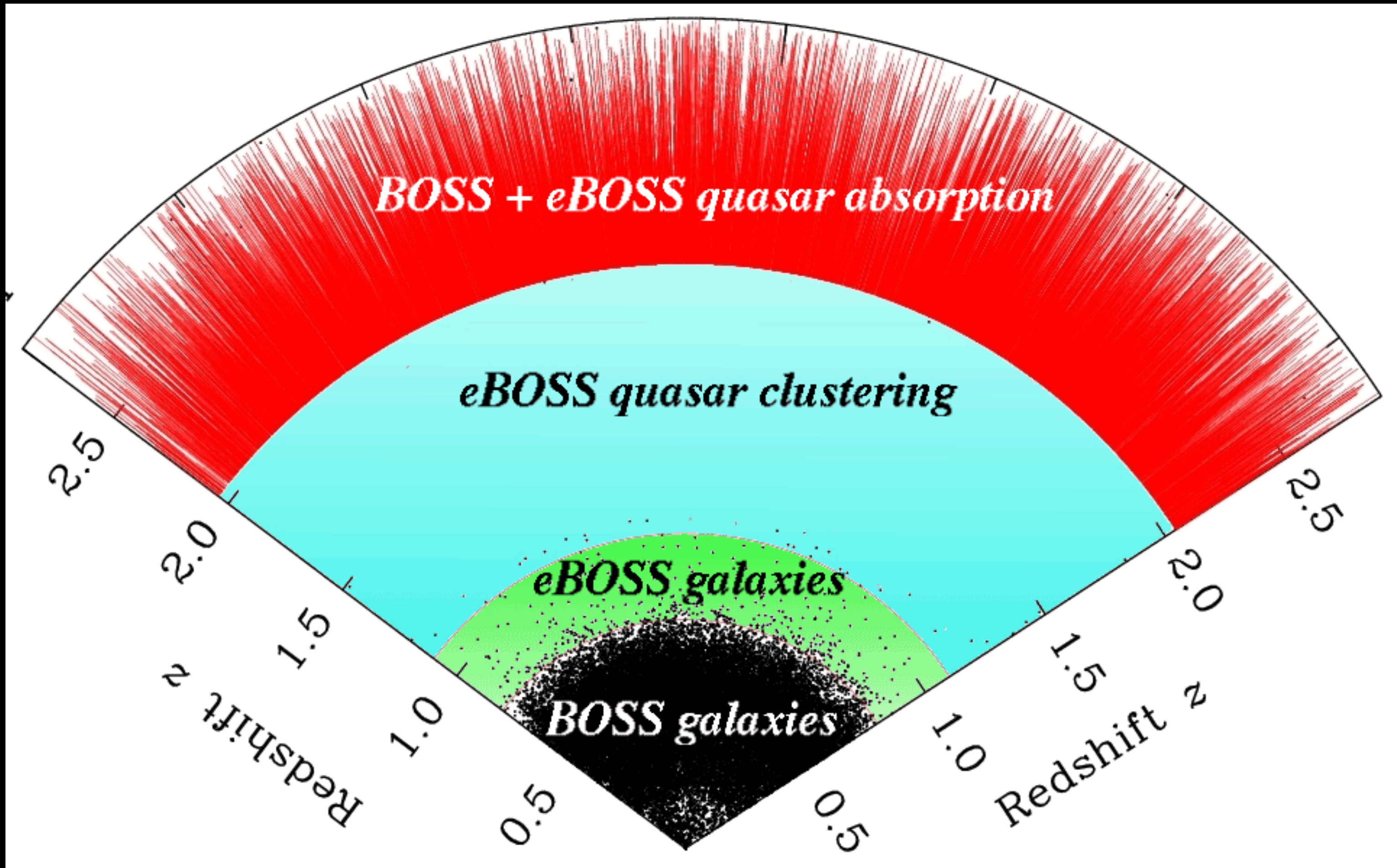
Growth of structure give Ωm

But the large-scales shape of the LSS power spectrum can also be used:
Information about matter-radiation equality. → $\Omega m\ h^2$

(assuming a BBN prior on baryon abundance and ns)

Let’s play this game!

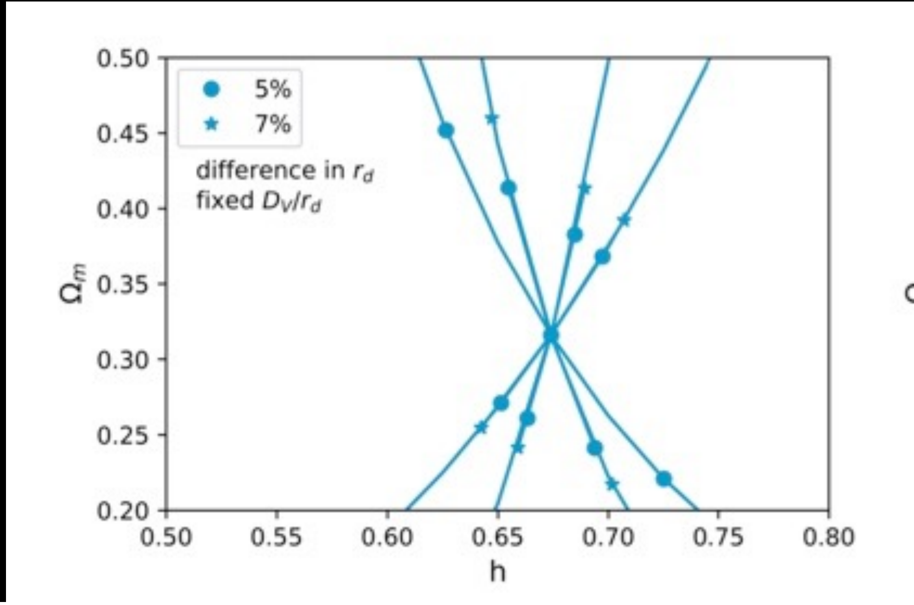
Brieden et al 2022 arXiv:221204522



Use two bins BOSS LRG, one bin eBOSS LRG, eBOSS quasars (+ lyalpha for BAO)

Planck calibrated ΛCDM predictions vs measurements

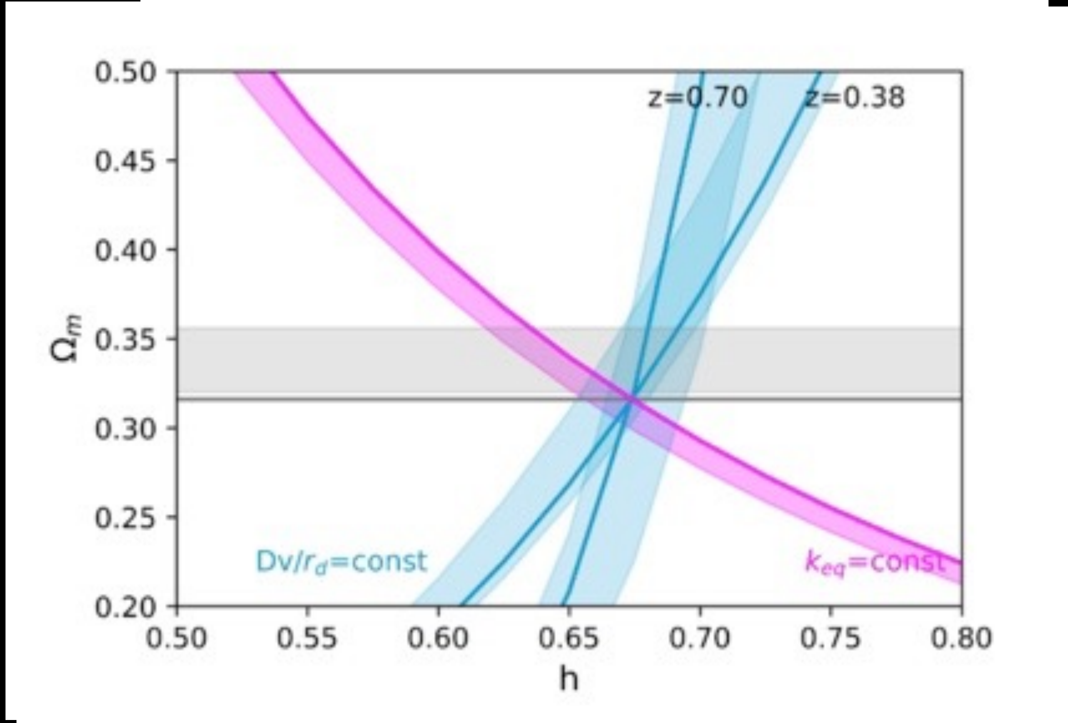
$$r_{\rm d} = \int_{\infty}^{z_d} \frac{c_s(z)}{H(z)} dz \simeq|_{\Lambda\rm CDM} \frac{147.05}{\rm Mpc} \left(\frac{\Omega_m h^2}{0.1432}\right)^{-0.23} \left(\frac{N_{\rm eff}}{3.04}\right)^{-0.1} \left(\frac{\Omega_{\rm b} h^2}{0.02236}\right)^{-0.13}$$



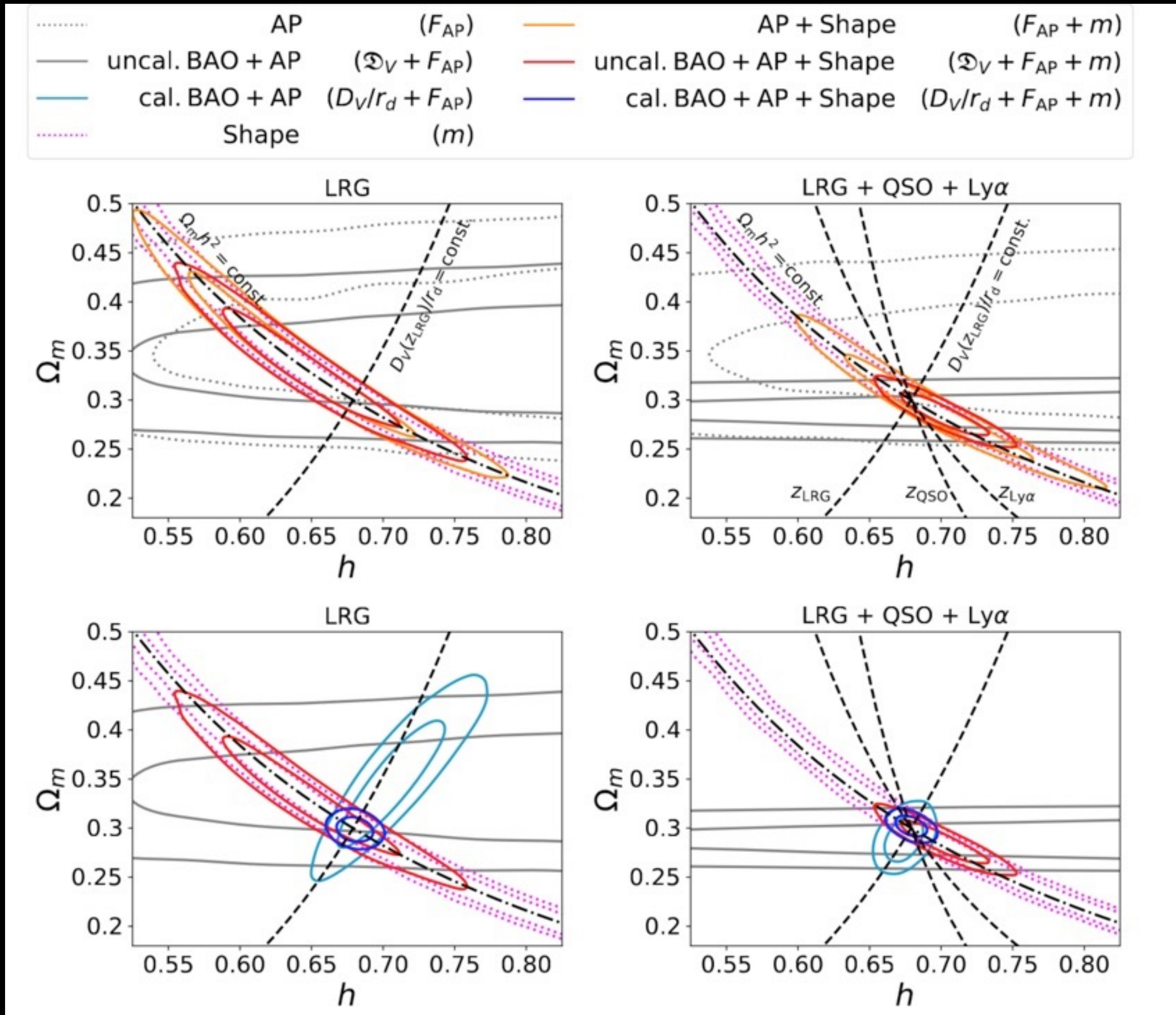
$$\frac{D_V(z=0.38)}{r_{\rm d}} \simeq |_{\Lambda\rm CDM}\, 10.04 \left(\frac{\Omega_m}{0.316}\right)^{0.12} \left(\frac{h}{0.674}\right)^{-0.54};$$
$$\frac{D_V(z=0.70)}{r_{\rm d}} \simeq |_{\Lambda\rm CDM}\, 16.15 \left(\frac{\Omega_m}{0.316}\right)^{0.047} \left(\frac{h}{0.674}\right)^{-0.54};$$
$$\frac{D_V(z=1.48)}{r_{\rm d}} \simeq |_{\Lambda\rm CDM}\, 25.90 \left(\frac{\Omega_m}{0.316}\right)^{-0.058} \left(\frac{h}{0.674}\right)^{-0.54};$$
$$\frac{D_V(z=2.4)}{r_{\rm d}} \simeq |_{\Lambda\rm CDM}\, 31.30 \left(\frac{\Omega_m}{0.316}\right)^{-0.11} \left(\frac{h}{0.674}\right)^{-0.54}.$$

$$\frac{k_{\rm eq}}{k_{\rm eq}^{\rm fid}} = 0.77m^4 + 0.80m^3 + 0.96m^2 + 1.16m + 1\,.$$

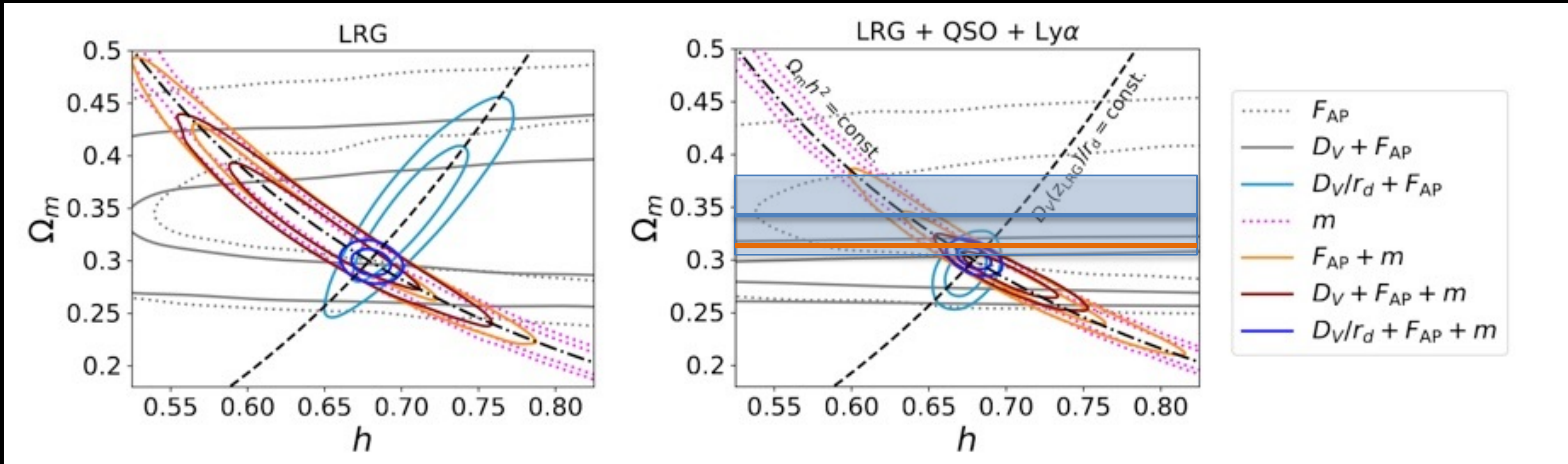
$$k_{\rm eq}\,[{\rm Mpc}^{-1}] \simeq|_{\Lambda\rm CDM}\, 0.010398 \frac{\Omega_m h^2}{0.1432} \left(\frac{2.379\times 10^4}{\Omega_{\rm rad} h^2}\right)^{1/2}$$



With all the bells and whistles of mcmc's



Yet another h…



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

With Brieden & Gil-Marin

Accelerating Universe and H0

Relation between redshifts (velocties) and distances

Cosmc distance ladder

Standard rurels, standard candles and “anchors”

Good ladders need 2 good anchor points

But more is even better

Large-scale structure give more than one anchor and thus 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→ key to gude us towards…

Theoretical solutions….

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

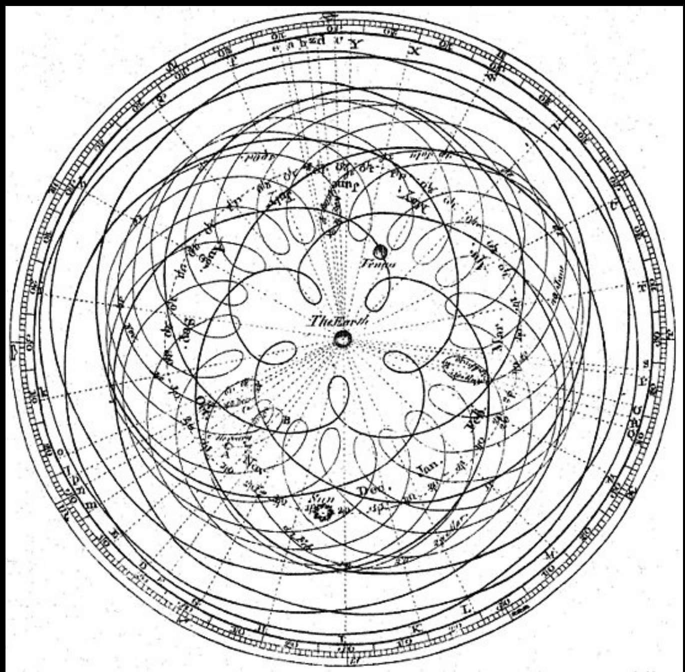
Should improve (or not worsen) other tensions, e.g. $\sigma 8$

We should quantify improvement vs predictability (degrees of freedom)

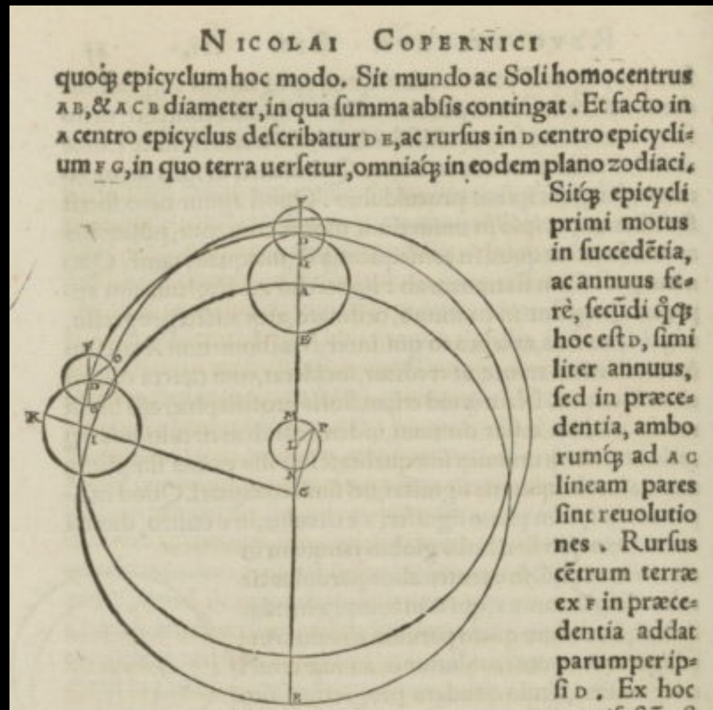
Parallelism with Λ…..

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

Looking for Cinderella….