2020/12/16
CGP internal workshop

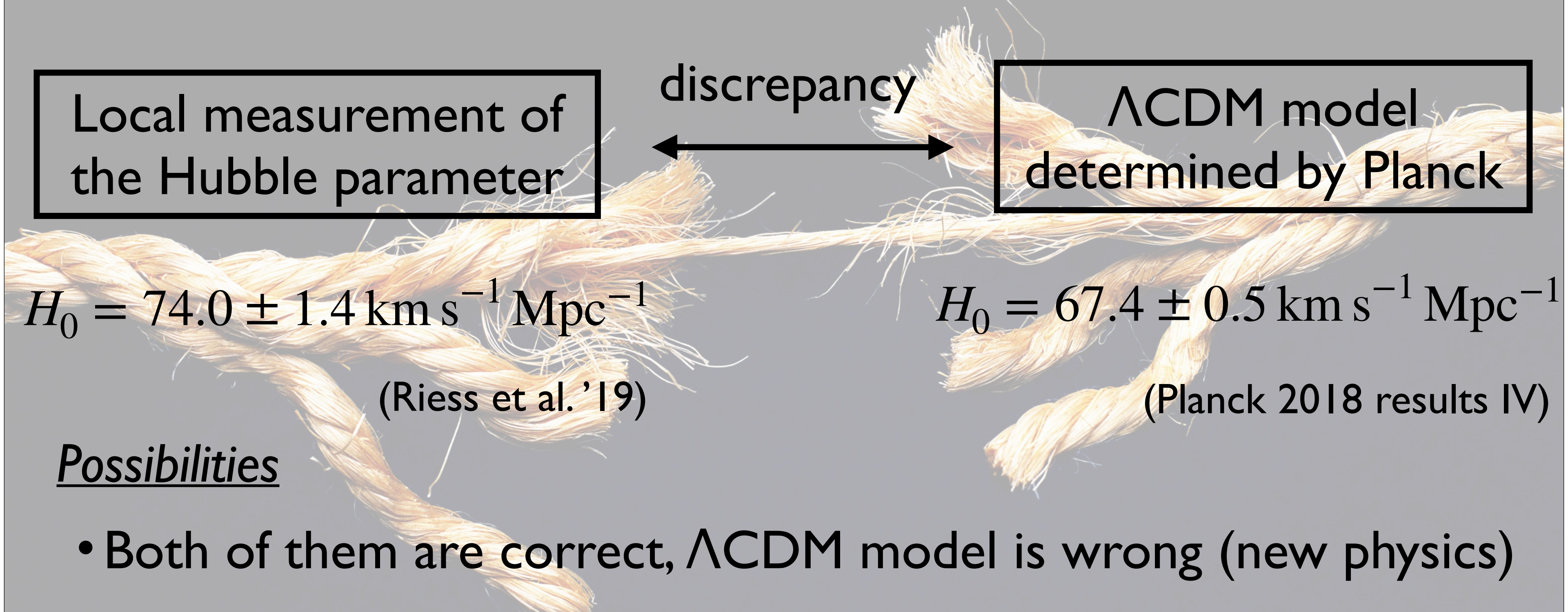
Cosmic tension:

Headache in Planck ΛCDM cosmology

Atsushi Taruya

Plan of talk

Review of H_0 tension



Local measurement of the Hubble parameter

discrepancy ⟷

ΛCDM model determined by Planck

$H_0 = 74.0 \pm 1.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

(Riess et al. ’19)

$H_0 = 67.4 \pm 0.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

(Planck 2018 results IV)

Possibilities

- Both of them are correct, ΛCDM model is wrong (new physics)

  but, some (most?) of the proposed scenarios has some troubles

- Either of them is wrong

  due to unknown systematics

- Or both are wrong

Hubble parameter

Fundamental quantity characterizing the expansion of the Universe

$$H(t) \equiv \frac{\dot{a}(t)}{a(t)}$$

$a(t)$: Scale factor of the Universe

Friedmann equation

$$3H^2(t) = 8\pi G \left\{ \underbrace{\rho_{\mathrm{m}}(t)}_{\text{matter}} + \underbrace{\rho_{\mathrm{DE}}(t)}_{\text{dark energy}} \right\} - \underbrace{\frac{K}{a^2}}_{\text{curvature}}$$

In particular, Hubble parameter at the present time is called

$$H_0$$

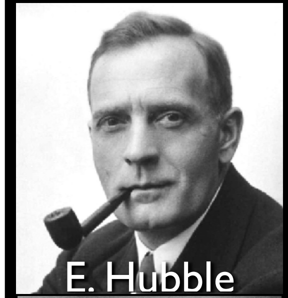
A precision determination of H_0 is important in cosmology, and is a basis to clarify the nature of dark energy or cosmic acceleration

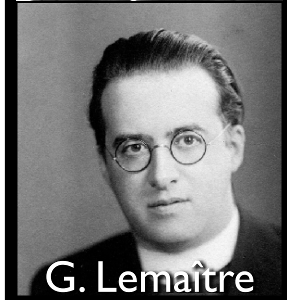
(Local) measurement of H_0

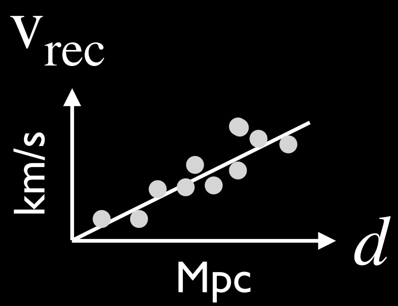
Hubble-Lemaître law

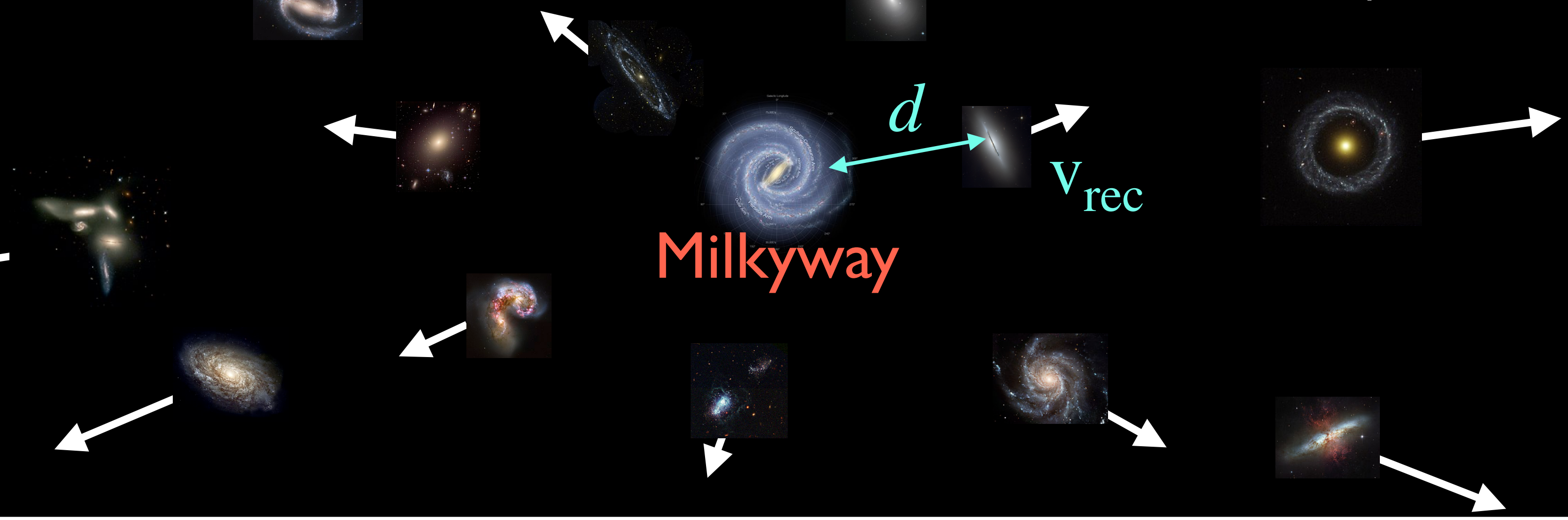
Recession velocity of galaxies is linearly proportional to distance:

$$v_{rec} = H_0\, d$$


E. Hubble


G. Lemaître





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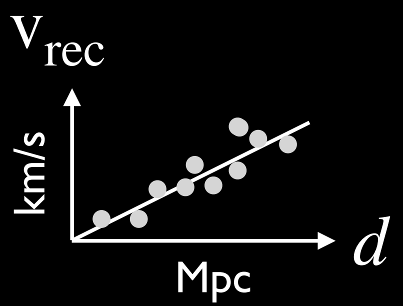
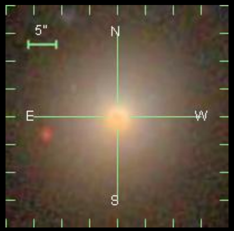


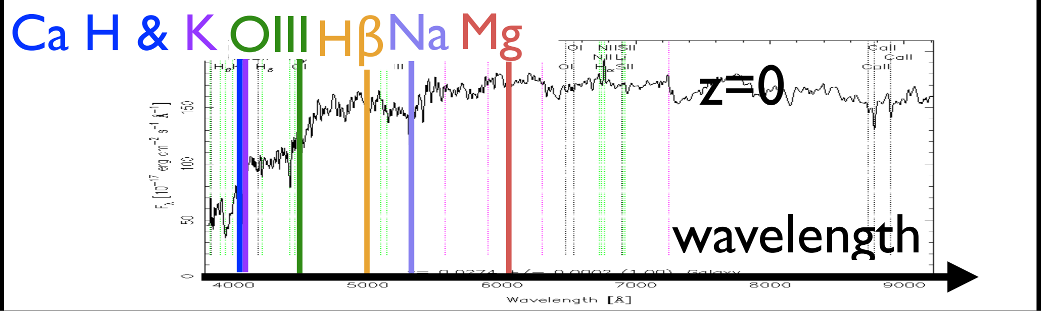
Cosmological redshift

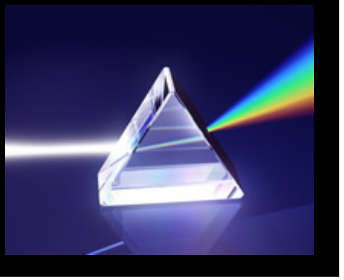
$$z \equiv \frac{\Delta\lambda}{\lambda} = \frac{v_{\rm rec}}{c}$$

Spectroscopic measurement



Nearby galaxy





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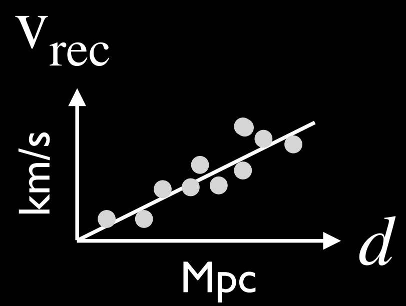

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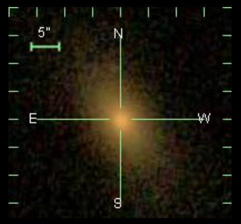
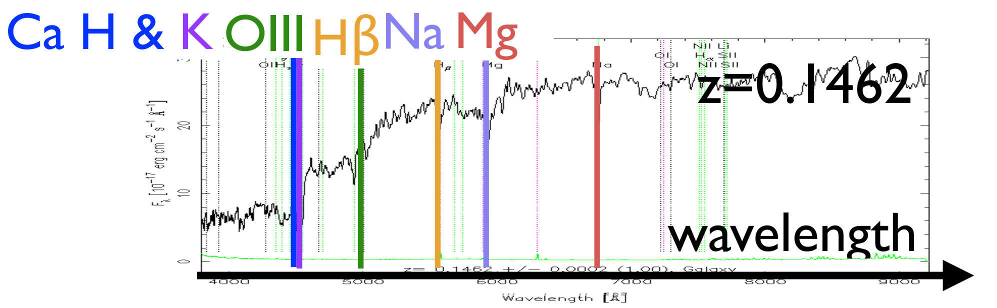
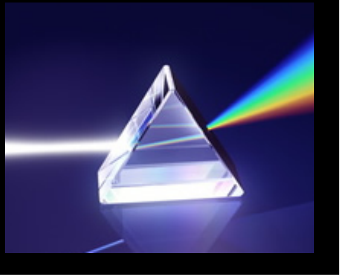


Distant galaxy





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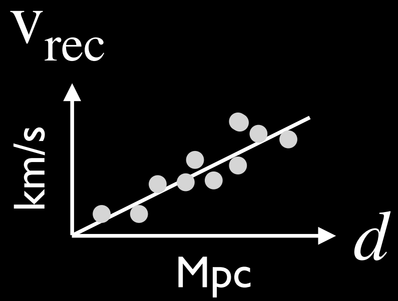
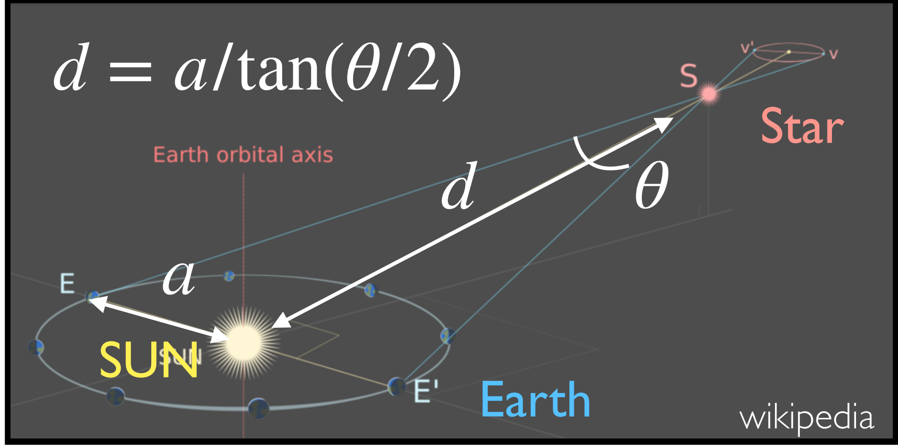


Distance measurement is the most difficult part :



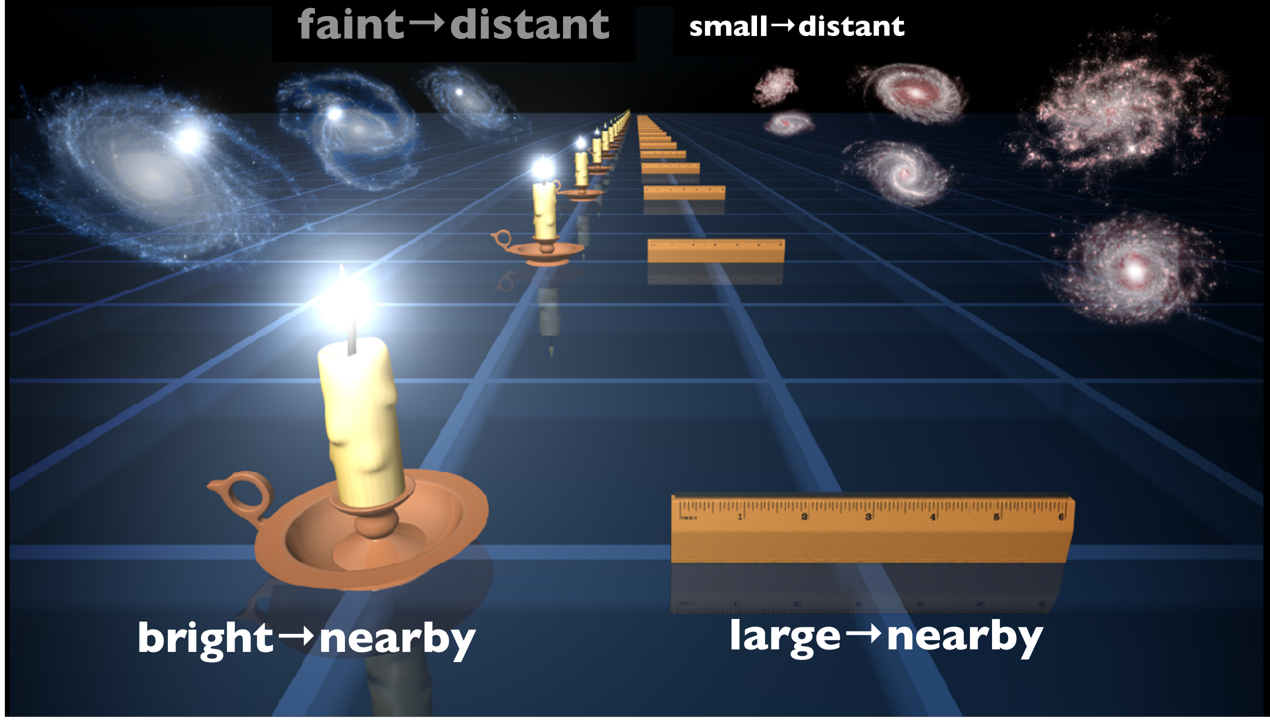
For closer objects (<10^4 light years),

an accurate measurement can be made by using parallax method (e.g., Gaia, HST)

Distance measurements

For much farther objects (d>10^4 light years),

the distance measurement can be still made if we *a priori* know the size or luminosity of the objects



Such a object is called

Standard candle

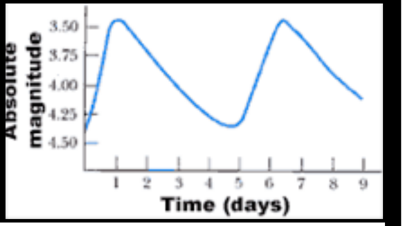
Or

Standard ruler

Note—.

There recently appears *standard siren*

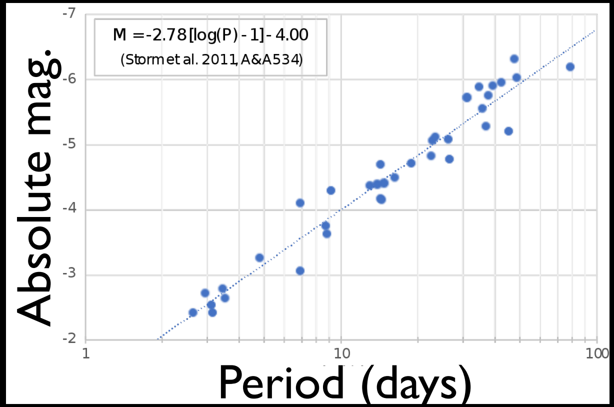
Standard(izable) candles



Cepheid variable

Pulsating stars that periodically gets bright & faint

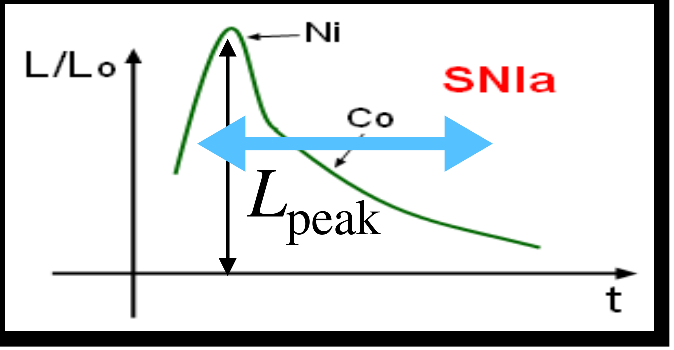
(Empirical) period-luminosity relation



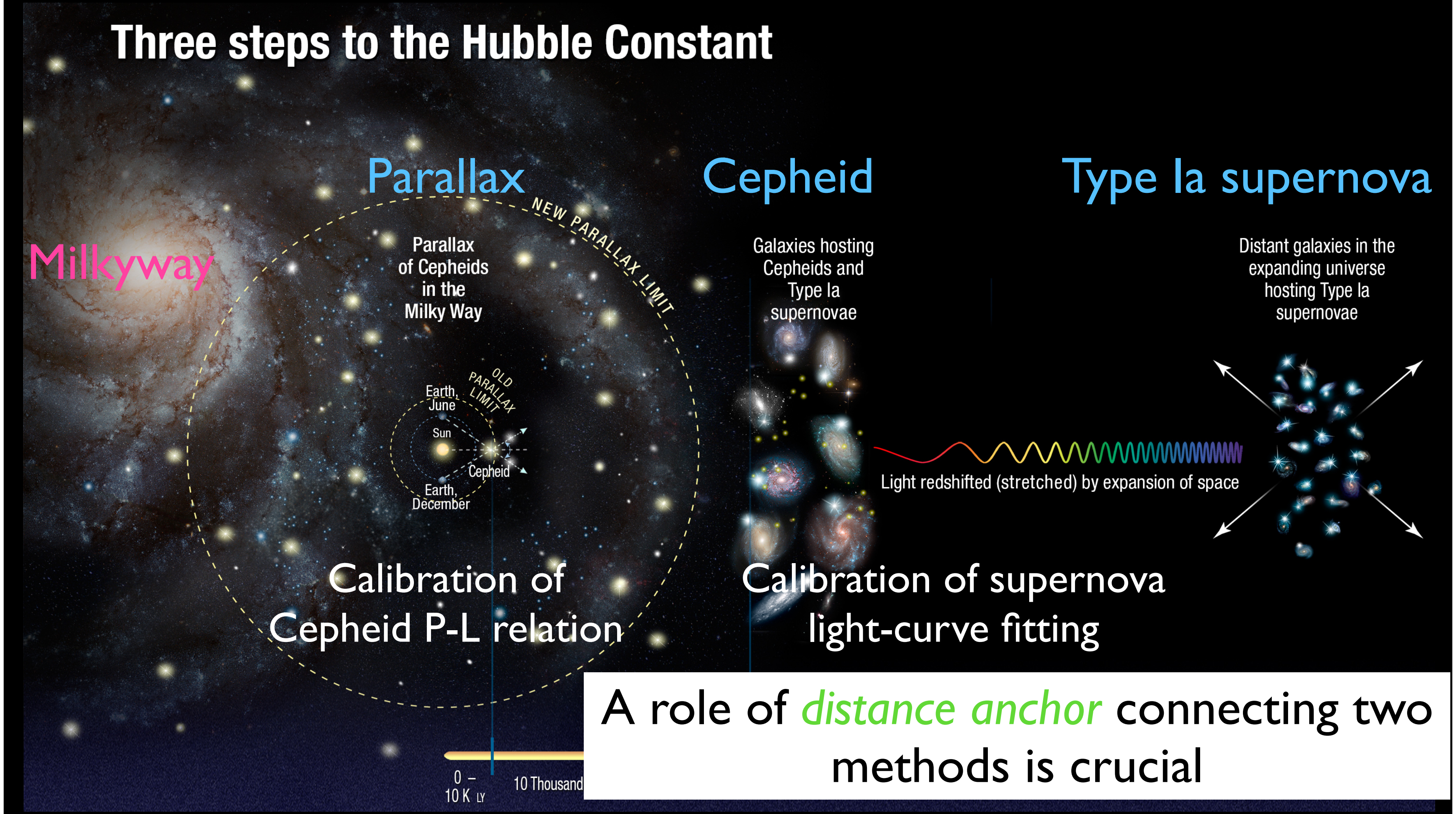
Type-Ia Supernova

A type of supernova that occurs in binary systems

Tight relation between peak luminosity & decay time scale



Distance ladder



Milkyway

Parallax

Cepheid

Type Ia supernova

Calibration of Cepheid P-L relation

Calibration of supernova light-curve fitting

A role of *distance anchor* connecting two methods is crucial

https://en.wikipedia.org/wiki/Cosmic_distance_ladder#/media/File:Cosmic_distance_ladder.jpg

(2011 Nobel Laureate)

SH$_0$ES

(SNe, H$_0$, for the Equation of State of dark energy)

A precision local measurement of H$_0$ using Hubble space telescope (photometric obs. of Cepheid & SNe Ia)

Distance anchors to calibrate Cepheid P-L relation:

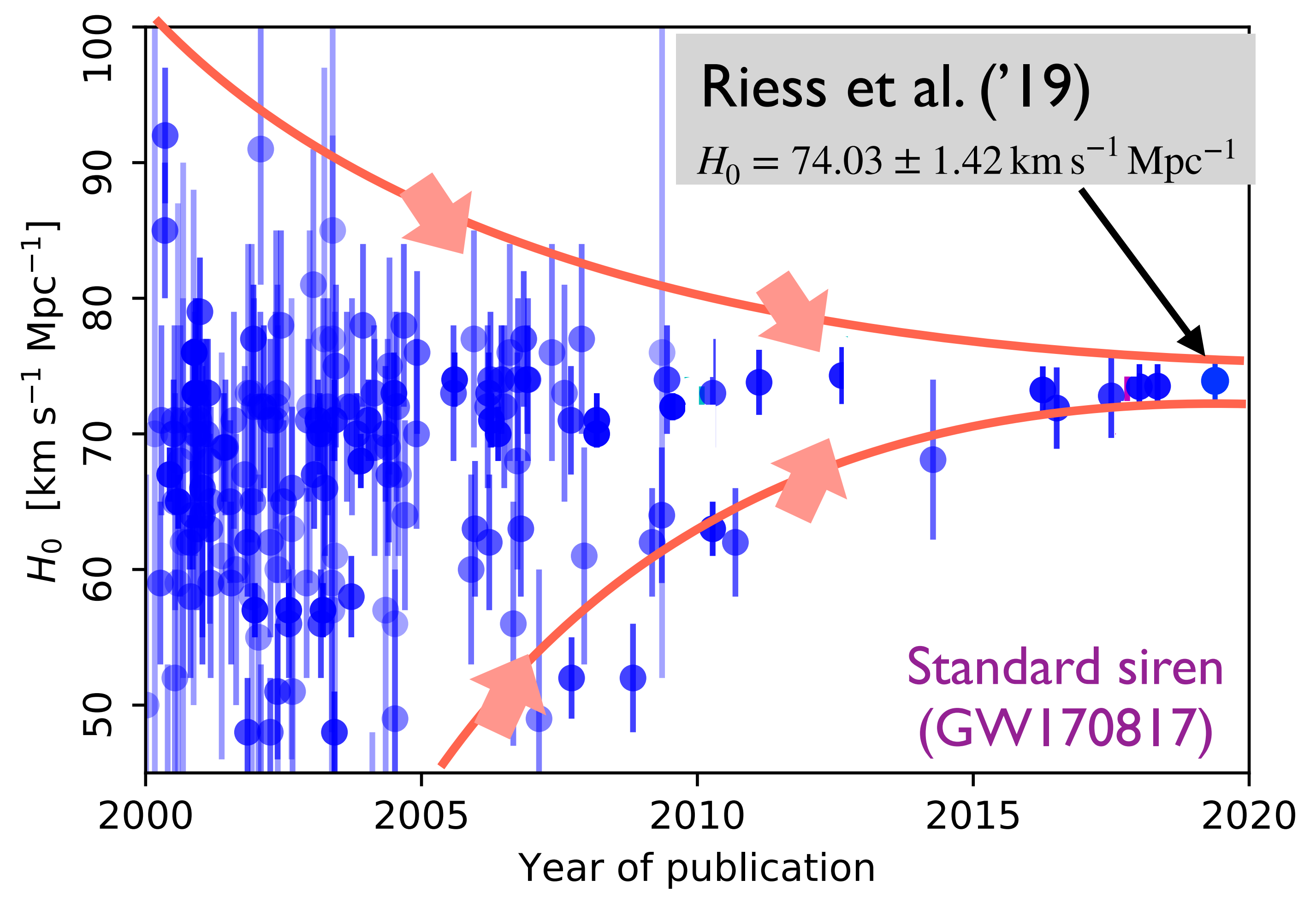
- Parallaxes → Milkyway Cepheids
- 20 Detached eclipsing binaries → LMC Cepheid (Large Magellanic Cepheid)
- VLBI obs. of water masers → NGC4258 Cepheid

1.9% precision

$$H_0 = 74.03 \pm 1.42\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Riess et al. ('19)

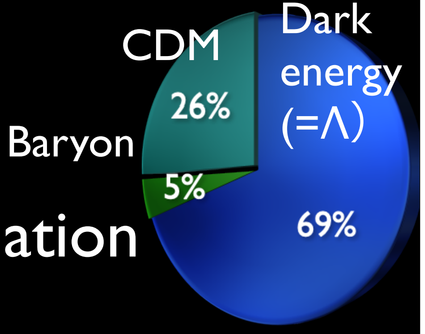
Time evolution of H_0 measurement



Planck 2018 results I, modified

Alternative method

We can rely on the standard cosmological model



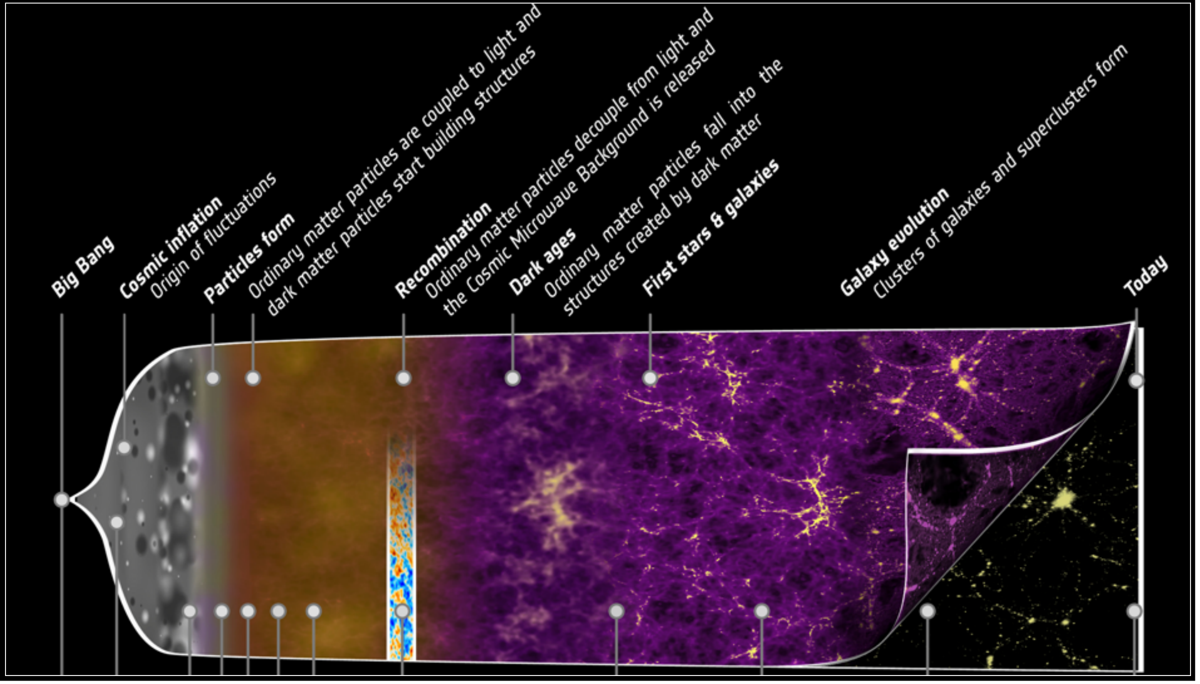
Lambda Cold Dark Matter (ΛCDM) model

describes both cosmic expansion & structure formation
(with parameters including H_0)

Based on the theory of structure formation,

H_0 can be inferred from the observations of high-redshift universe

(*Inverse distance ladder*)



http://www.esa.int/spaceinimages/Images/

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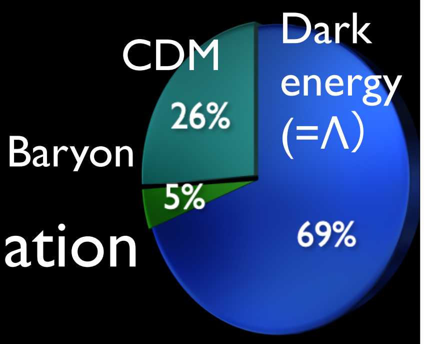

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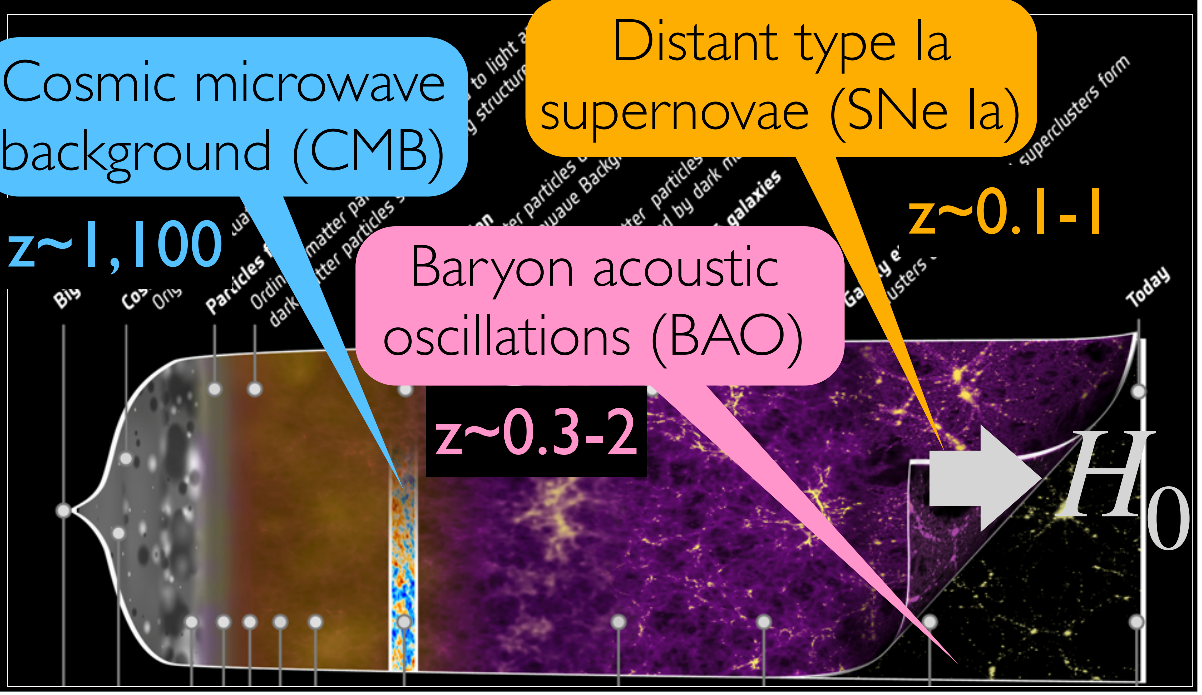


Cosmic microwave background (CMB)

z~1,100

Distant type Ia supernovae (SNe Ia)

z~0.1-1

Baryon acoustic oscillations (BAO)

z~0.3-2

http://www.esa.int/spaceinimages/Images/

Cosmic microwave background (CMB)

‘Relic’ radiation emitted at 380,000 years after Big-Bang

Tiny anisotropies offers a powerful cosmological probe

➡ Standard cosmological model

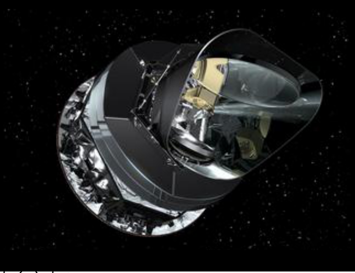
Planck satellite (ESA) provides high-precision data of

- temperature
- polarization
- gravitational lensing

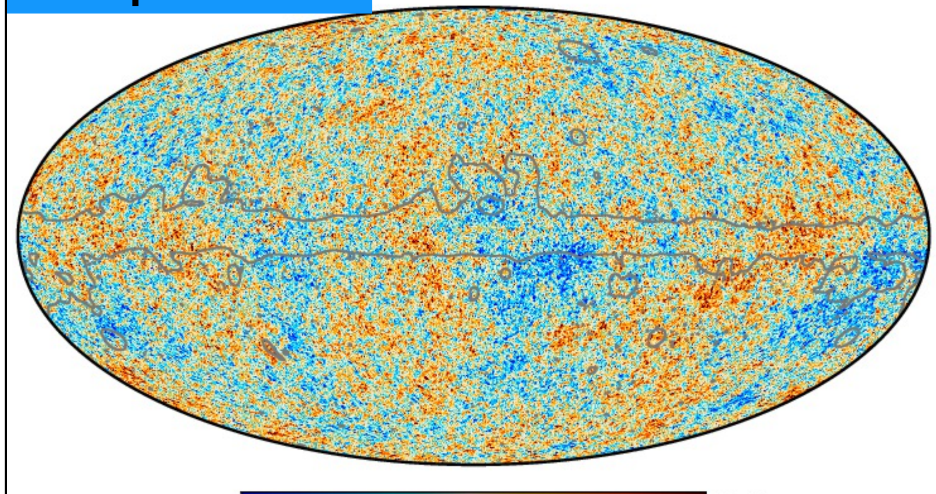
Help tightening cosmological constraints

Planck (2009-2013)

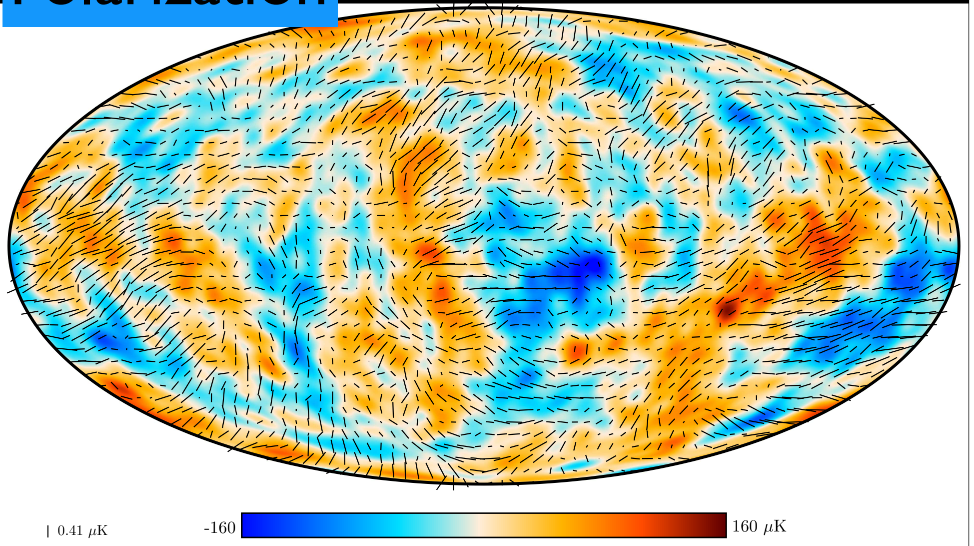
Planck 2018



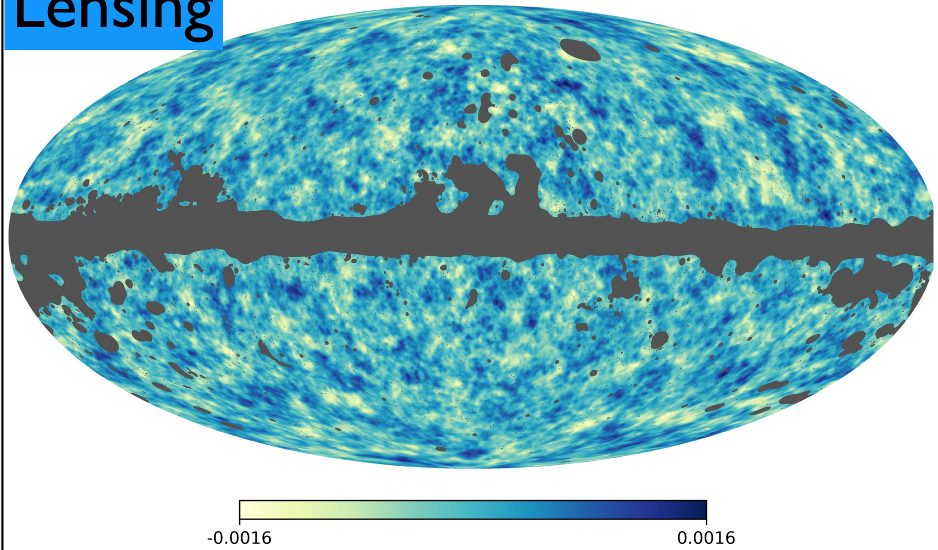
Temperature



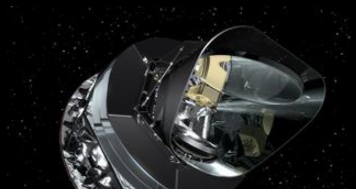
Polarization

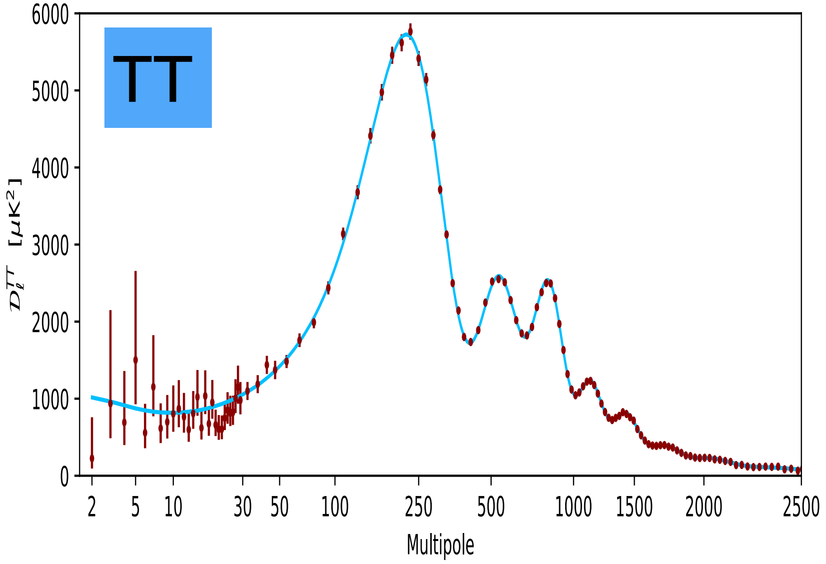


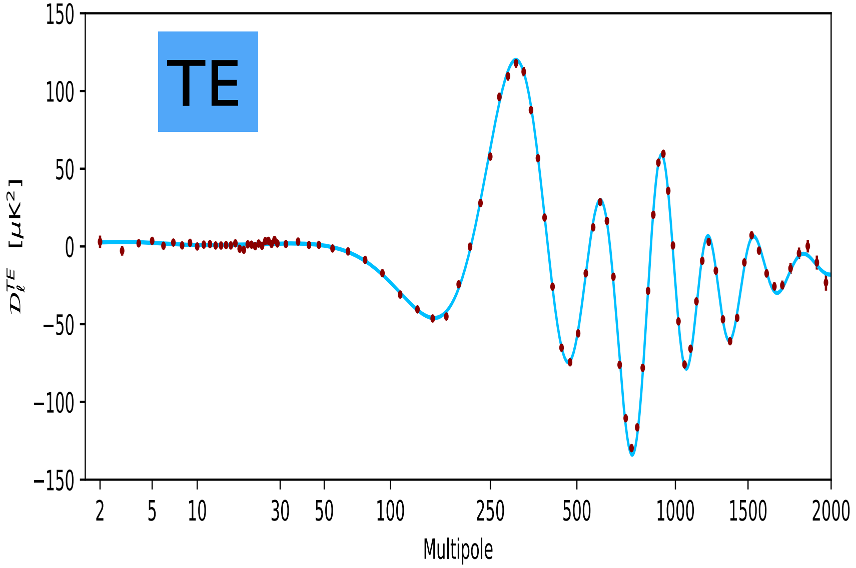
Lensing

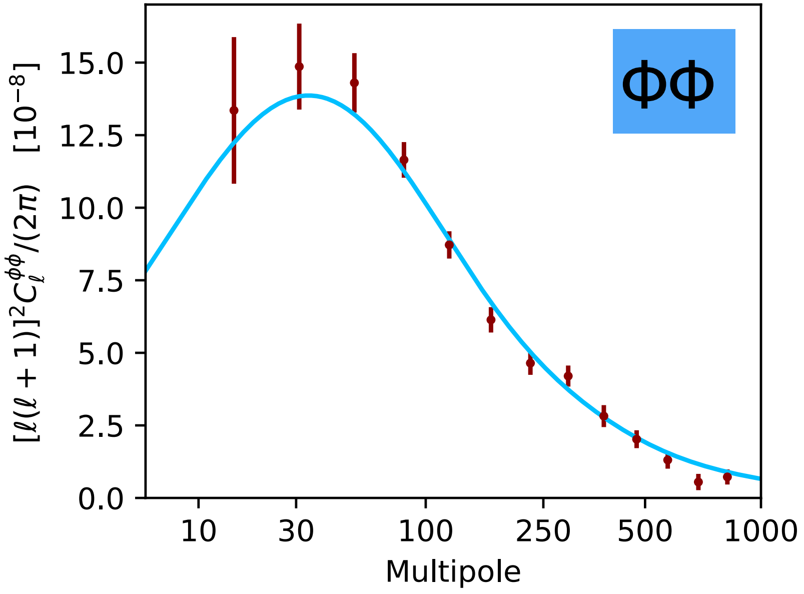


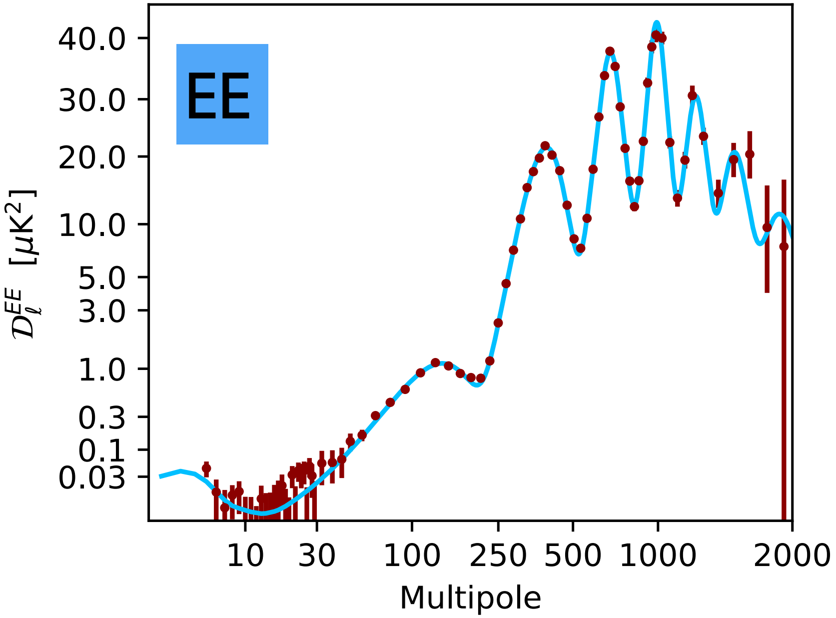
Planck 2018



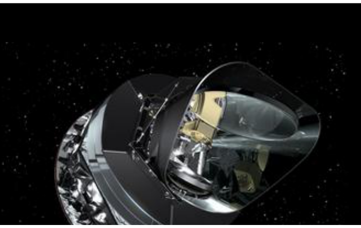

TT
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
2
5
10
30
50
100
250
500
1000
1500
2000
2500
Multipole


TE
150
100
50
0
−50
−100
−150
$\mathcal{D}_\ell^{TE}$ [μK^2]
2
5
10
30
50
100
250
500
1000
1500
2000
Multipole


ΦΦ
15.0
12.5
10.0
7.5
5.0
2.5
0.0
$[\ell(\ell+1)]^2 C_\ell^{\phi\phi}/(2\pi)$ [10^{-8}]
10
30
100
250
500
1000
Multipole


EE
40.0
30.0
20.0
10.0
5.0
3.0
1.0
0.3
0.1
0.03
$\mathcal{D}_\ell^{EE}$ [μK^2]
10
30
100
250
500
1000
2000
Multipole

Planck 2018

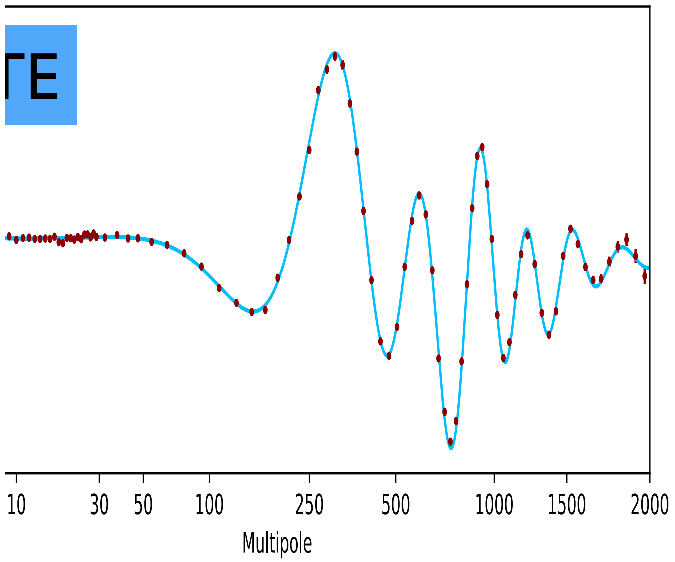


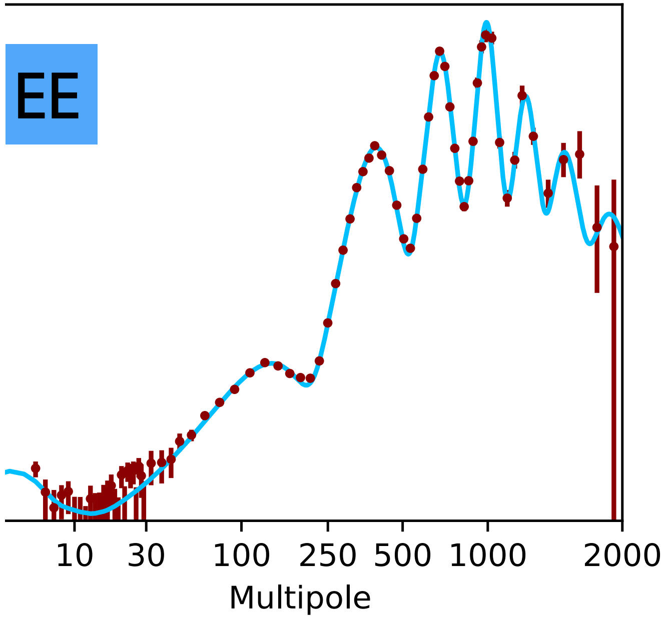
Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
Ω_m	0.3153 ± 0.0073
$\Omega_m h^2$	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00030
σ_8	0.8111 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013
z_{re}	7.67 ± 0.73
Age[Gyr]	13.797 ± 0.023
r_*[Mpc]	144.43 ± 0.26
$100\theta_*$	1.04110 ± 0.00031
r_{drag}[Mpc]	147.09 ± 0.26
z_{eq}	3402 ± 26
$k_{eq}[\mathrm{Mpc}^{-1}]$	0.010384 ± 0.000081

Base ΛCDM parameters

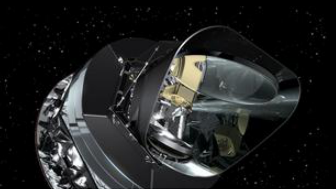
- temperature
- polarization
- lensing

derived parameters





Planck 2018



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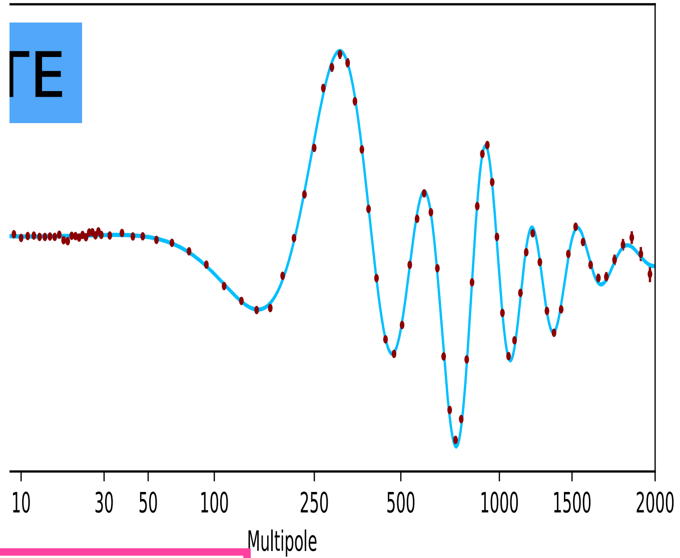
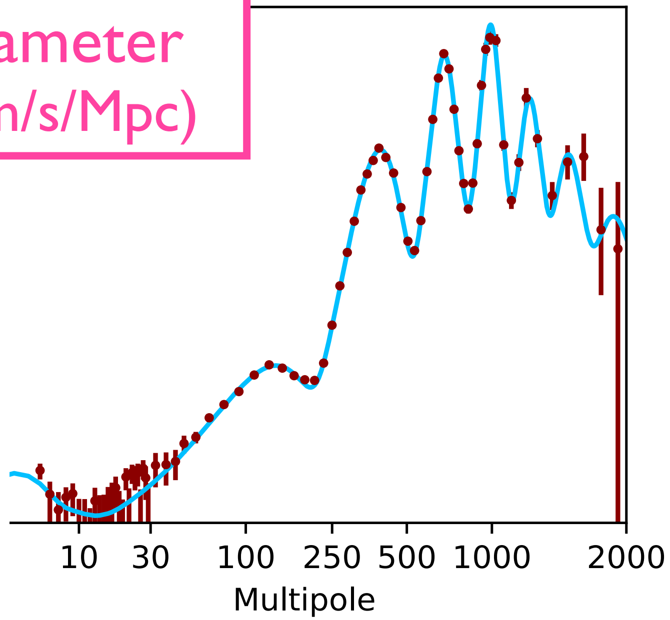
Hubble parameter
(in units of km/s/Mpc)

derived parameters





H_0 tension

Model-independent

Local measurement by SH_0ES
(distance ladder)

VS

Planck CMB measurement
assuming ΛCDM model

$$H_0 = 74.0 \pm 1.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

(Riess et al. '19)

$$H_0 = 67.4 \pm 0.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

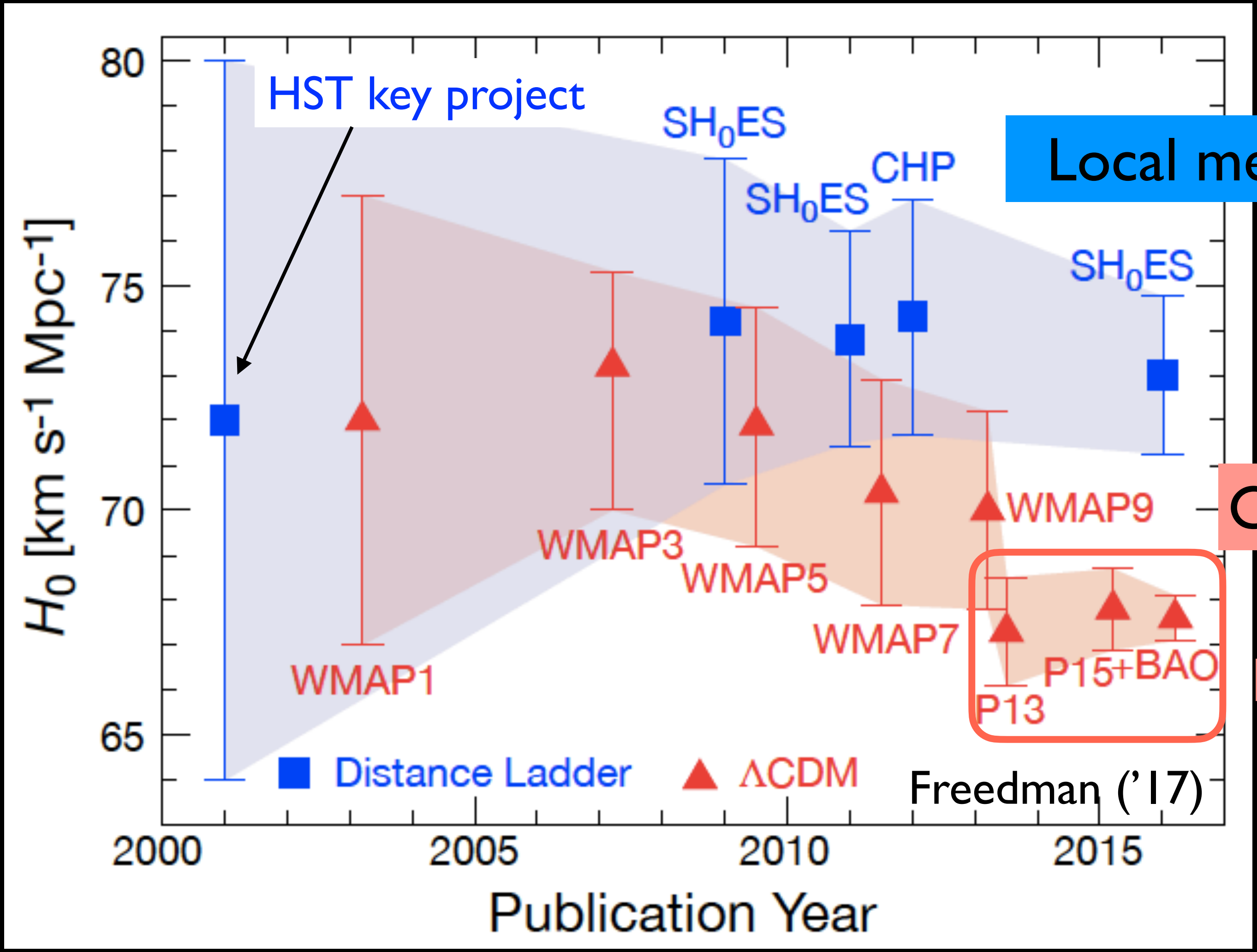
(Planck 2018 results IV)

Deviation of Planck H_0 from local measurement is at 4.4σ level
(99.999% for Gaussian errors)

Discrepancy remains statistically significant even if <u>other parameters</u> are allowed to vary.
(spatial curvature, dark energy EOS, neutrino mass, …)

This is actually not the first to highlight the discrepancy

Time evolution of competing H_0



Freedman ('17)

Local measurement

CMB

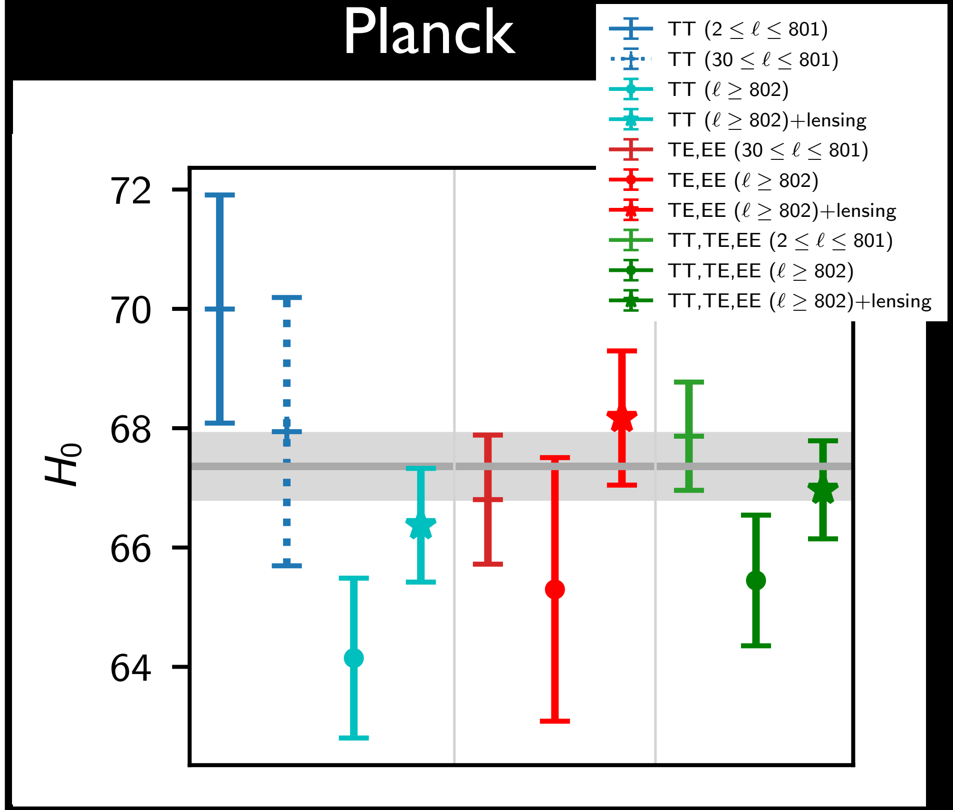
Planck

After WMAP

Local measurements prefer a large H_0, while CMB prefer a small H_0

Systematics ?

Planck



Planck 2018 result IV

SH$_0$ES

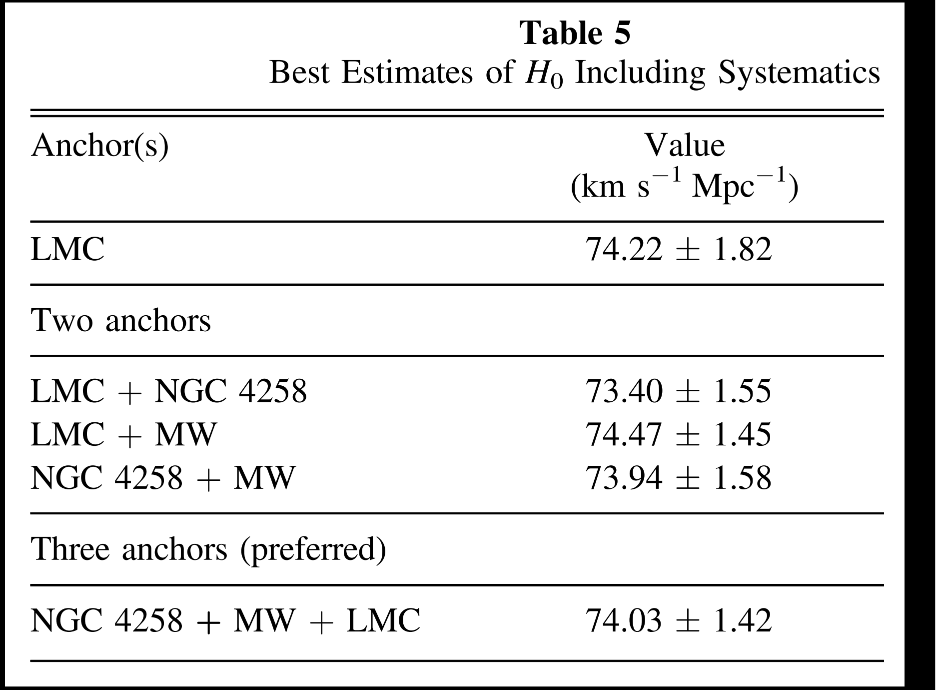


Table 5
Best Estimates of H_0 Including Systematics

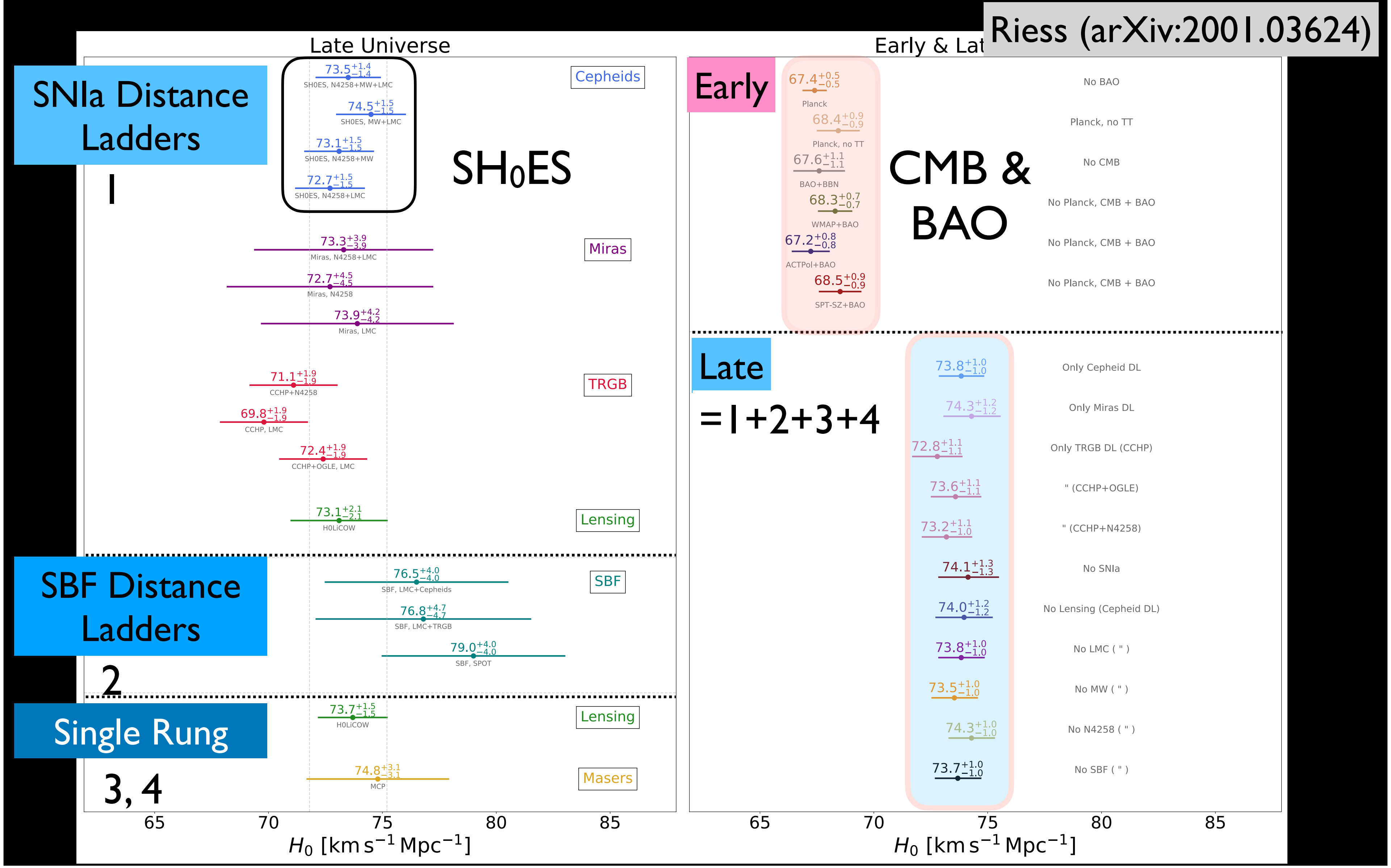
Anchor(s)	Value (km s^{-1} Mpc^{-1})
LMC	74.22 ± 1.82
Two anchors	
LMC + NGC 4258	73.40 ± 1.55
LMC + MW	74.47 ± 1.45
NGC 4258 + MW	73.94 ± 1.58
Three anchors (preferred)	
NGC 4258 + MW + LMC	74.03 ± 1.42

Riess et al. ('19)

Depending on how they combine the data set, the tension may be alleviated, but it seems difficult to completely resolve the tension

Other H_0 measurements

Riess (arXiv:2001.03624)



SNIa Distance Ladders

1

SH0ES

SBF Distance Ladders

2

Single Rung

3, 4

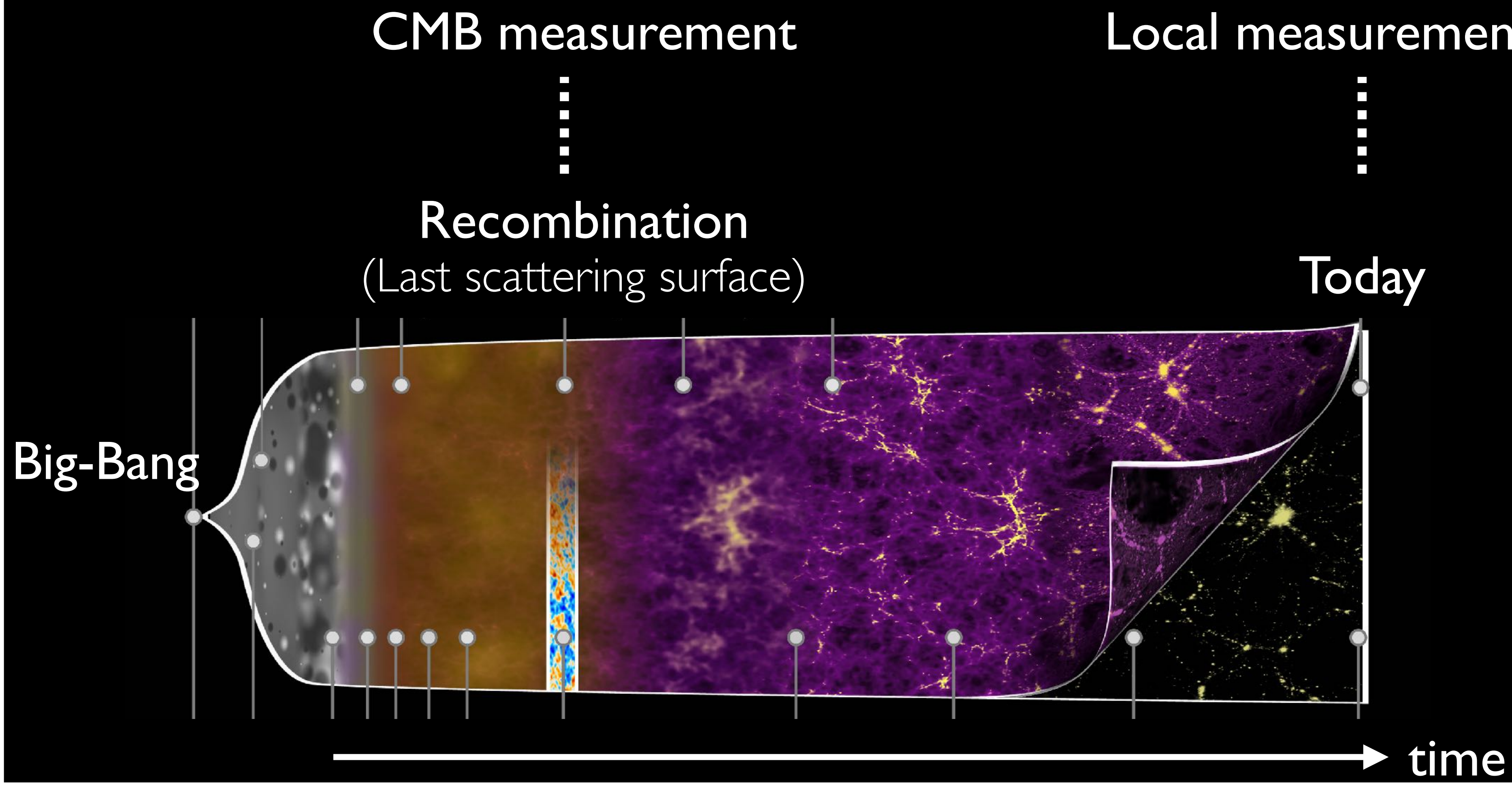
Early

CMB & BAO

Late

=1+2+3+4

Relieving H_0 tension by ‘*new*’ physics



CMB measurement

Local measurement

Recombination
(Last scattering surface)

Today

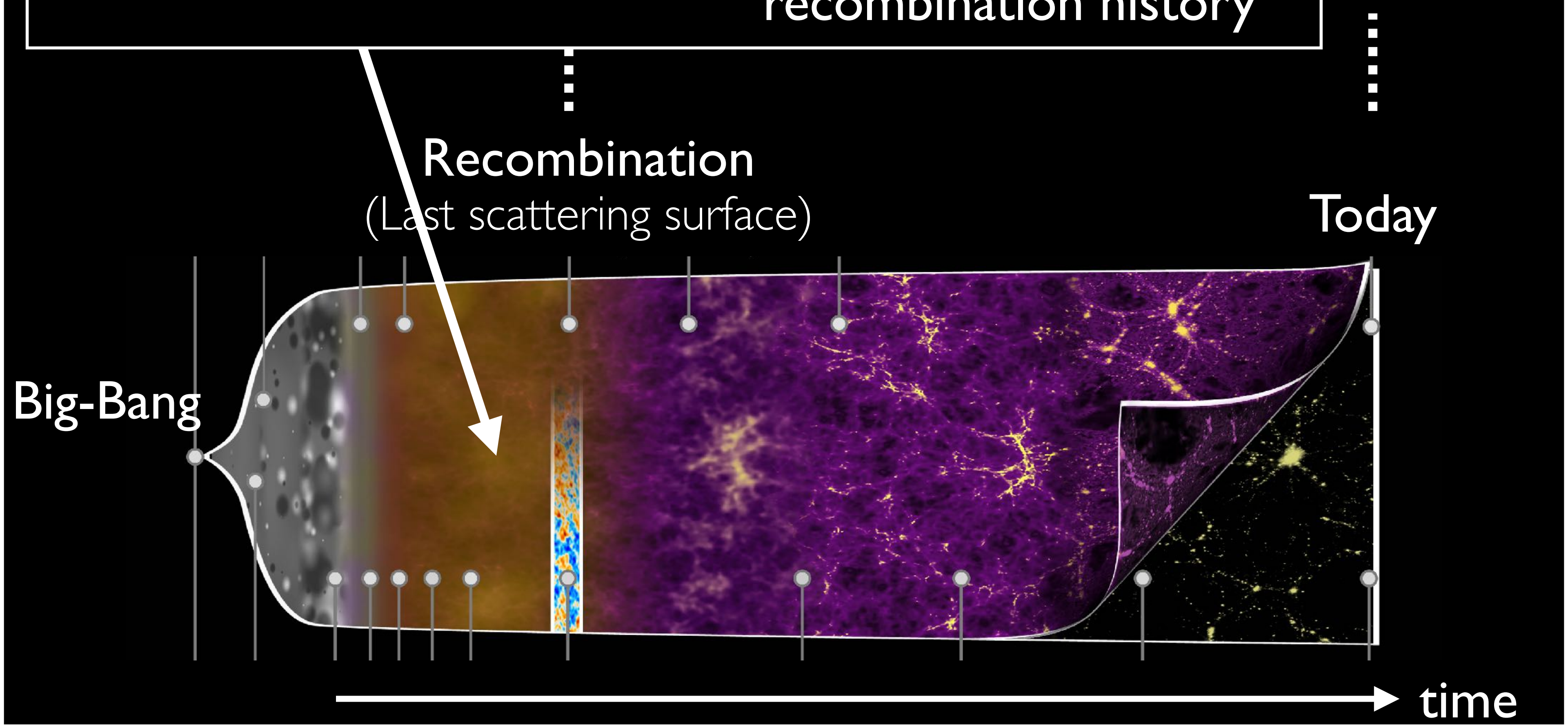
Big-Bang

time

Relieving H_0 tension by ‘*new*’ physics

Early-time solution

change cosmic expansion before recombination or recombination history



asurement

Recombination
(Last scattering surface)

Today

Big-Bang

time

Relieving H_0 tension by ‘*new*’ physics

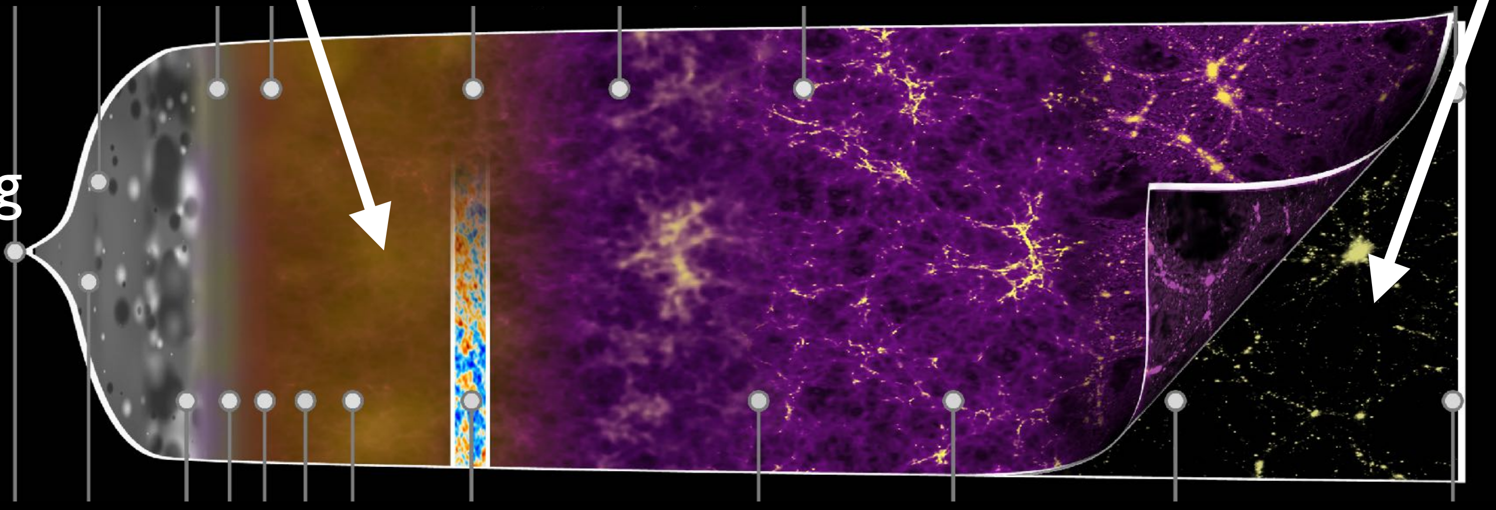
Early-time solution

change cosmic expansion before recombination or recombination history

asurement

Late-time solution

change cosmic expansion in the nearby universe



Incomplete

Proposed scenarios

Early-time or Late-time solution

- Early dark energy @ rad-matter equality

Poulin, Smith, Karwal & Kamionkowski ('19)

- Strongly self-interacting neutrinos with N_{eff}~4

Kreisch, Cyr-Rachine & Doré ('19)

- Early-time modification of gravity

Braglia et al. ('20)

- Nonlinear small-scale fluctuations by primordial magnetic field

Jedamzik & Pogosian ('20)

- Change of background CMB temperature

Ivanov, Ali-Haimoud & Lesgourgues ('20); Bose & Lombrizer ('20)

- Time varying electron mass

Sekiguchi & Takahashi ('20)

- Late-time modification of gravity
  (Generalized Proca, MTMG)

De Felice, Mukohyama & Pookkillath ('20)
De Felice, Geng, Pookkillath & Yin ('20)

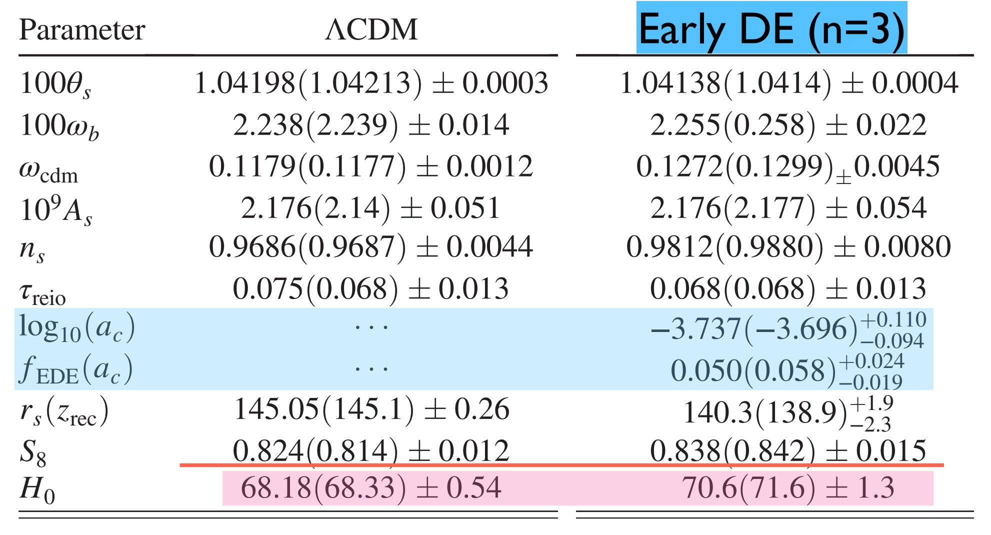
Early dark energy

Adding a tiny amount of dark energy at the time of pre-recombination epoch

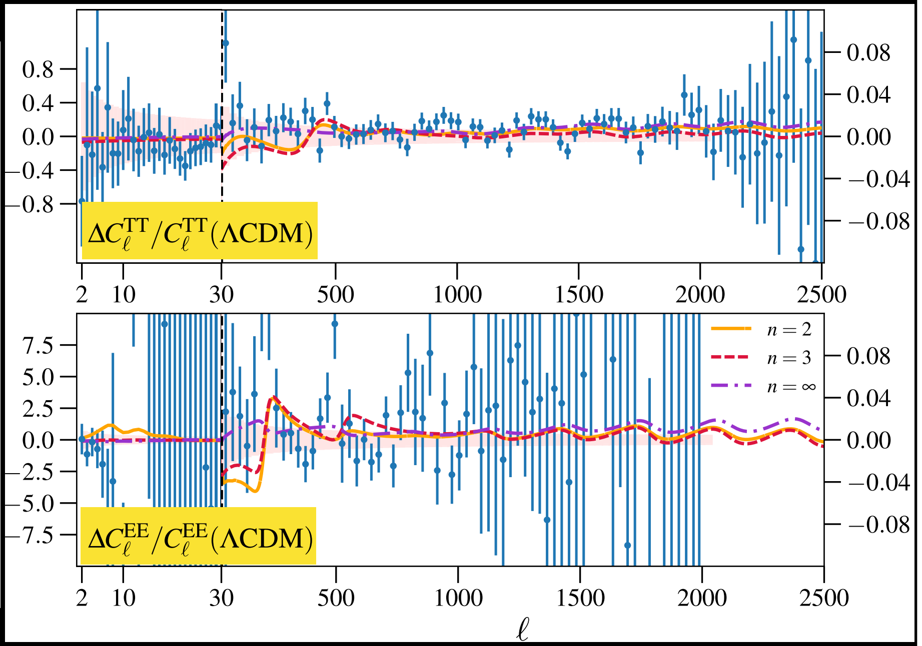
Poulin et al. ('19)

2 parameters: a_c, $f_{\rm EDE}(a_c)$

***a_c*:** scale factor at which DE contribution become maximum



Parameter	ΛCDM	Early DE (n=3)
$100\theta_s$	$1.04198(1.04213) \pm 0.0003$	$1.04138(1.0414) \pm 0.0004$
$100\omega_b$	$2.238(2.239) \pm 0.014$	$2.255(0.258) \pm 0.022$
$\omega_{\rm cdm}$	$0.1179(0.1177) \pm 0.0012$	$0.1272(0.1299)_{\pm}0.0045$
$10^9 A_s$	$2.176(2.14) \pm 0.051$	$2.176(2.177) \pm 0.054$
n_s	$0.9686(0.9687) \pm 0.0044$	$0.9812(0.9880) \pm 0.0080$
$\tau_{\rm reio}$	$0.075(0.068) \pm 0.013$	$0.068(0.068) \pm 0.013$
$\log_{10}(a_c)$	$\cdots$	$-3.737(-3.696)^{+0.110}_{-0.094}$
$f_{\rm EDE}(a_c)$	$\cdots$	$0.050(0.058)^{+0.024}_{-0.019}$
$r_s(z_{\rm rec})$	$145.05(145.1) \pm 0.26$	$140.3(138.9)^{+1.9}_{-2.3}$
S_8	$0.824(0.814) \pm 0.012$	$0.838(0.842) \pm 0.015$
H_0	$68.18(68.33) \pm 0.54$	$70.6(71.6) \pm 1.3$



$$\to \quad z_c \simeq 5{,}000 \ \ \& \ \ f_{\rm EDE}(a_c) \equiv \left.\frac{\rho_{\rm EDE}}{\rho_{\rm tot}}\right|_{a_c} \simeq 0.05$$

- Incompatible with LSS data (Shape of P(k))
- S8 tension remains significant

S_8 tension

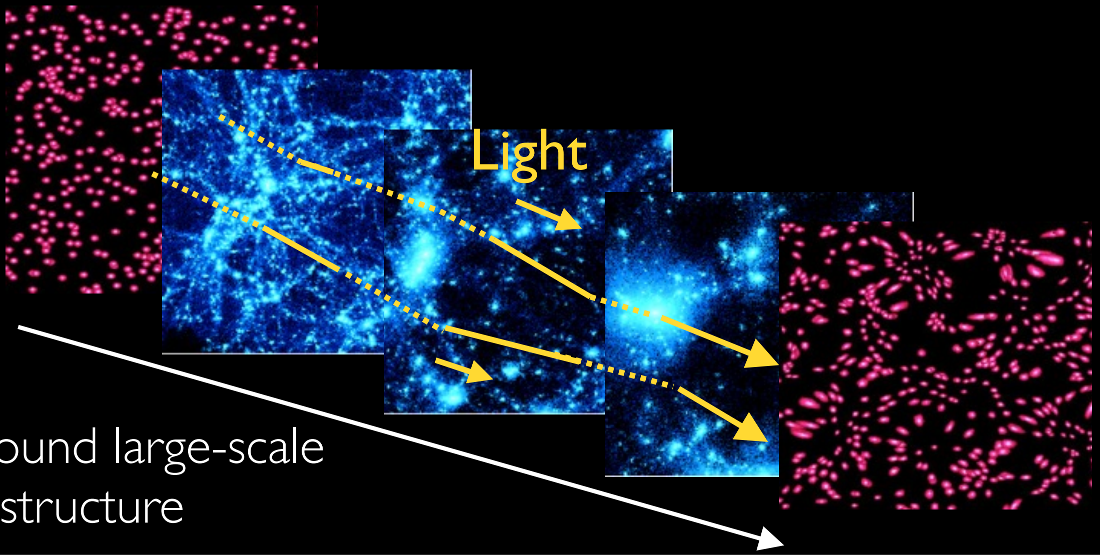
Yet another tension with Planck CMB

$$S_8 \equiv \sigma_8(\Omega_{\rm m}/0.3)^{0.5}$$

RMS fluctuation amplitude at 8 Mpc/h

Density parameter of (non-relativistic) matter

Weak-lensing observations prefer a larger S_8 than that of Planck



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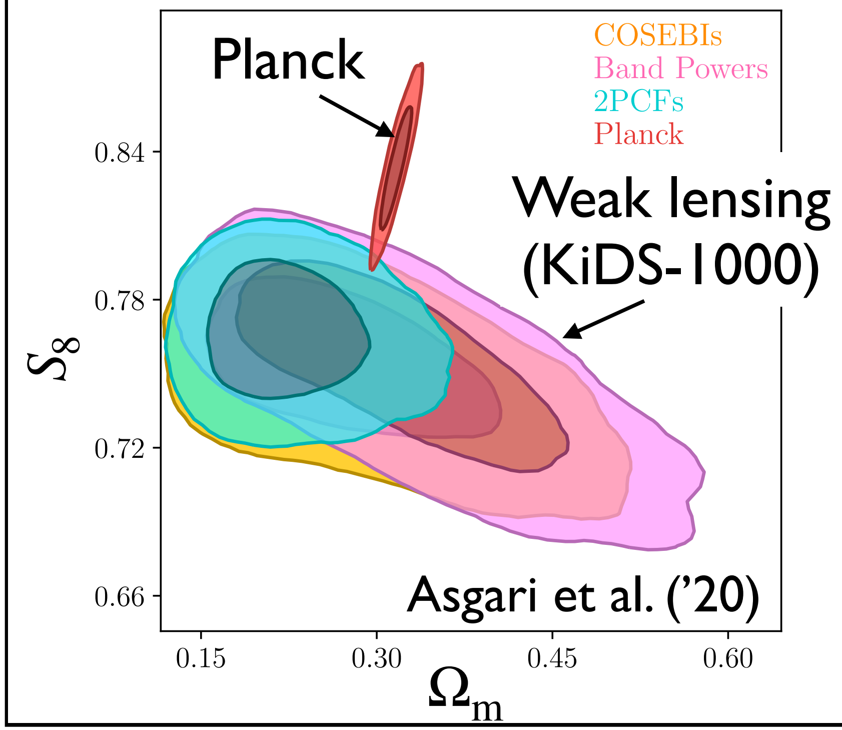

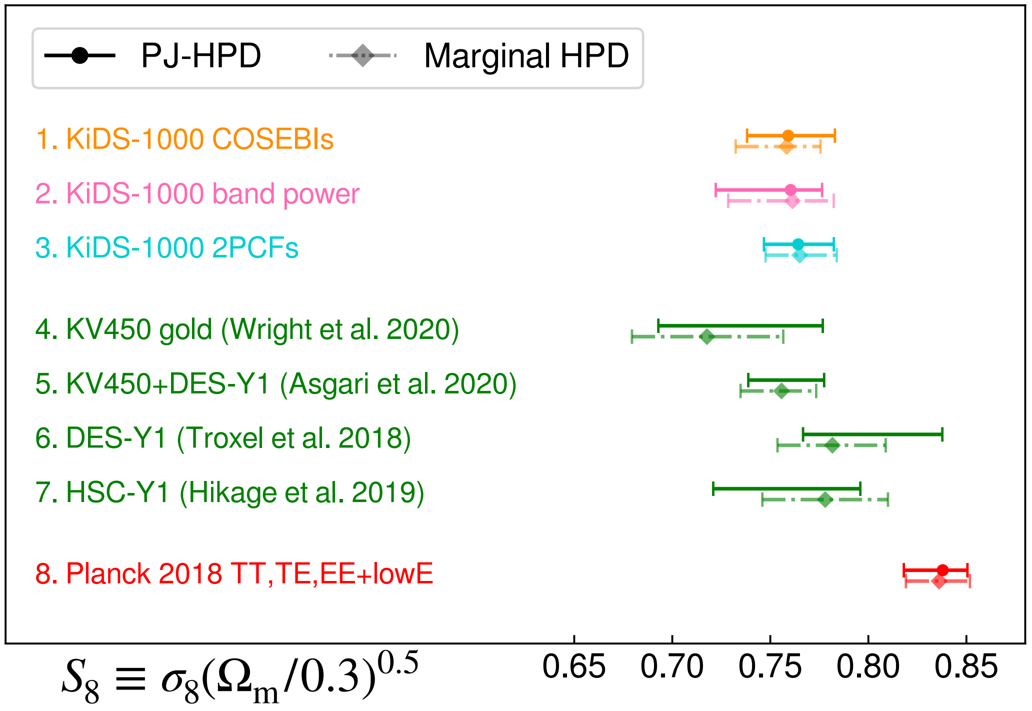

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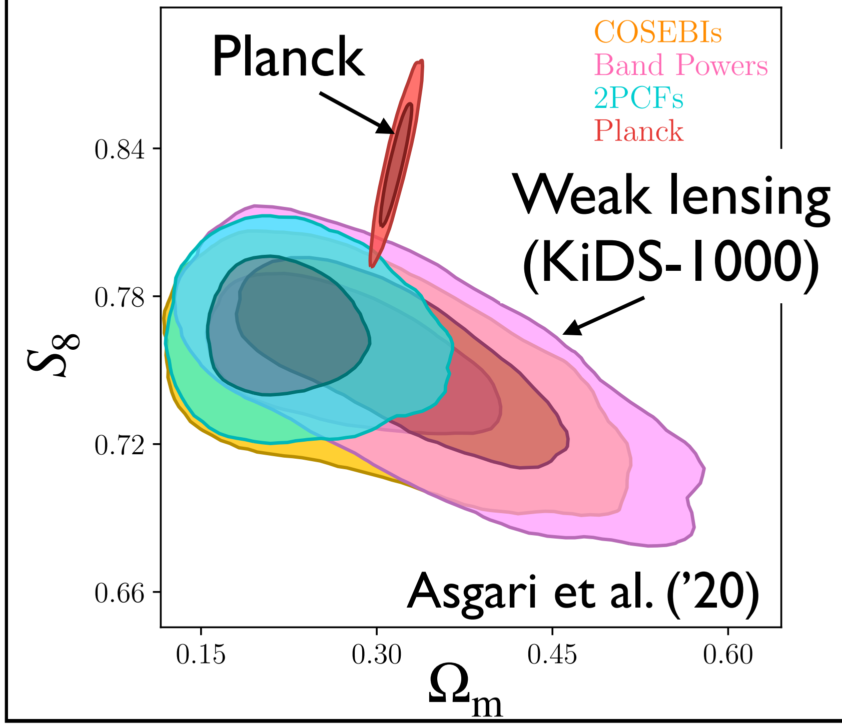
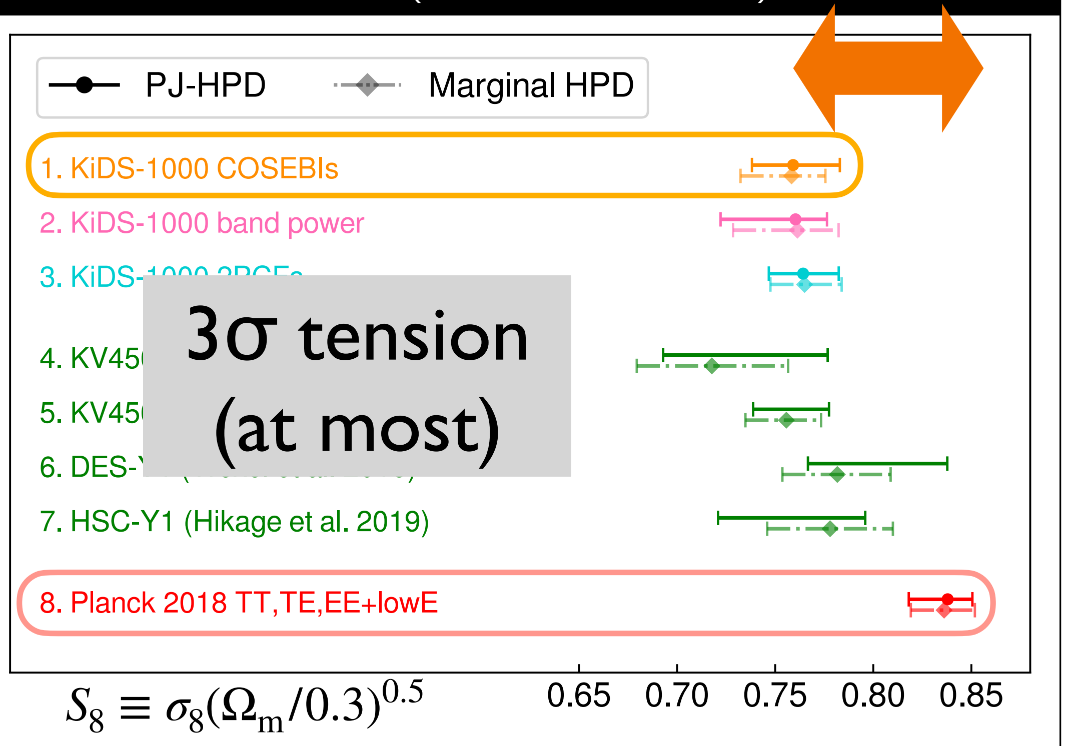


Planck

Weak lensing (KiDS-1000)

Asgari et al. ('20)



3σ tension (at most)

Summary

H_0 tension appears manifest and gets serious since the CMB measurements by Planck

- Low-z measurements prefer higher H_0 *(model-indept. distance ladder)*
- Hi-z measurements prefer lower H_0 *(based on ΛCDM model)*

New physics ? but most of the (early-time) solutions has troubles

Another tension (S_8 tension) is now highlighted
and has to be solved simultaneously (if possible)

Unknown systematics ?

Planck has some internal anomalies

- A_L (lensing) anomaly
- Curvature anomaly

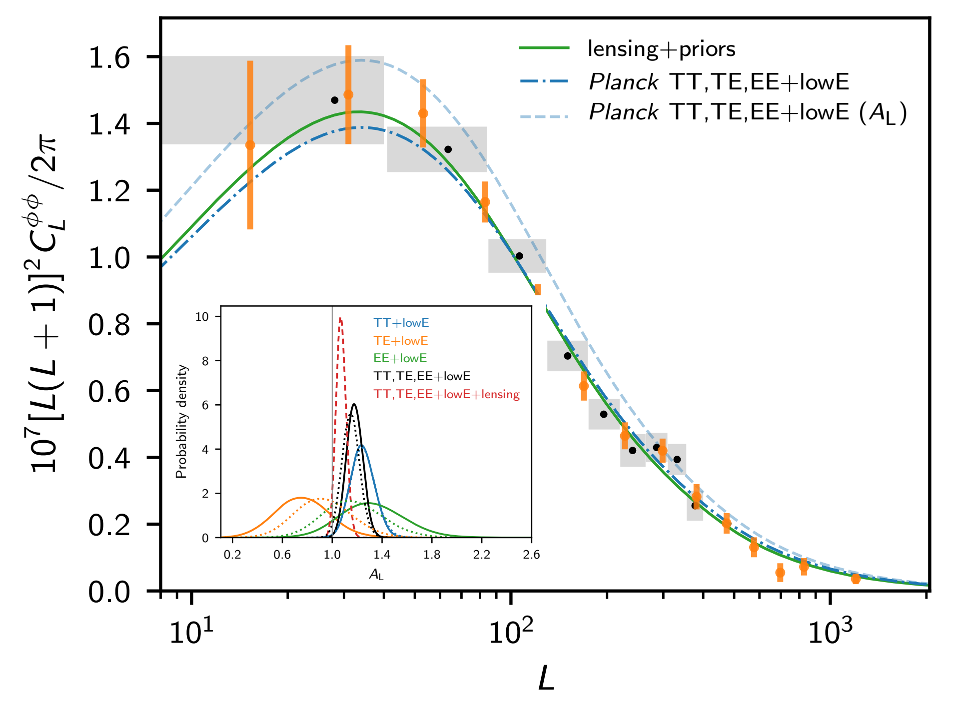
SH0ES internal inconsistencies G. Efstathiou ('20)

Planck internal anomalies

Planck 2018 results VI.

A_L anomaly

Allowing the lensing amplitude to vary gives a larger best-fit value

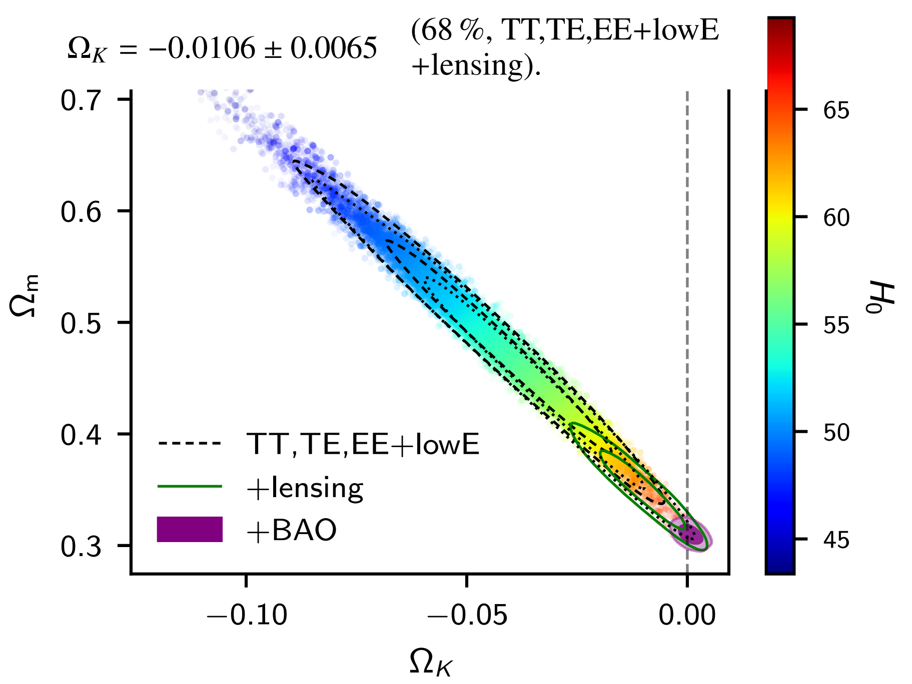


Curvature anomaly

One parameter extension to Λ CDM prefer positive curvature

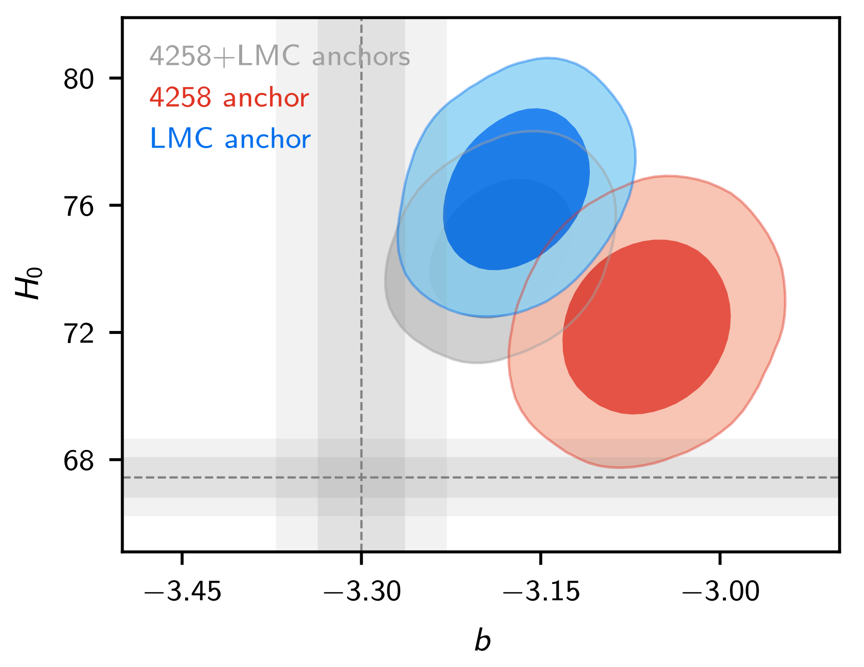
$\Omega_K = -0.044^{+0.018}_{-0.015}$ (68 %, *Planck* TT,TE,EE+lowE),

$\Omega_K = -0.0106 \pm 0.0065$ (68 %, TT,TE,EE+lowE +lensing).

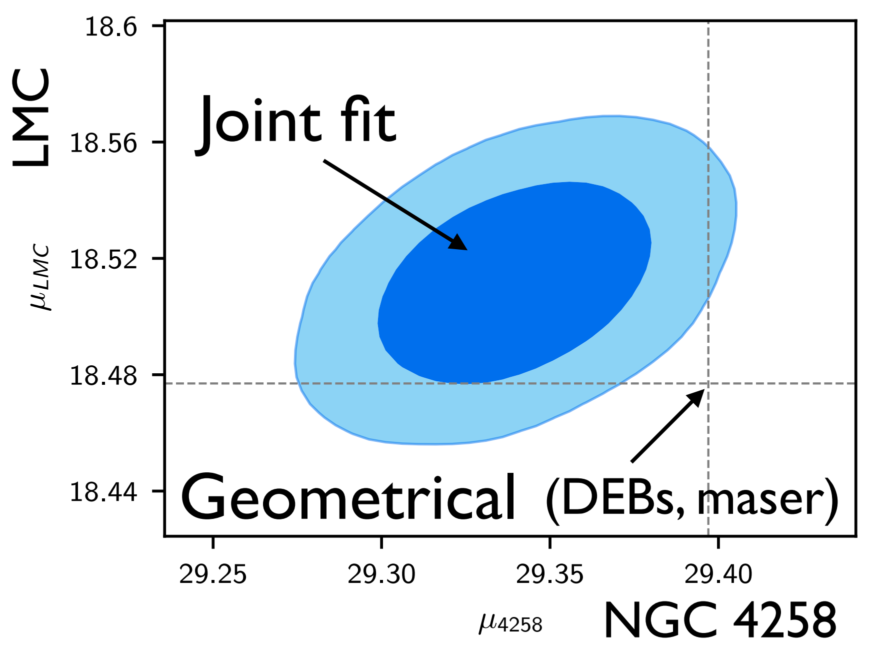


SH$_0$ES internal consistency

No prior on P-L relation



slope of P-L relation



Distance moduli

Efstathiou ('20)