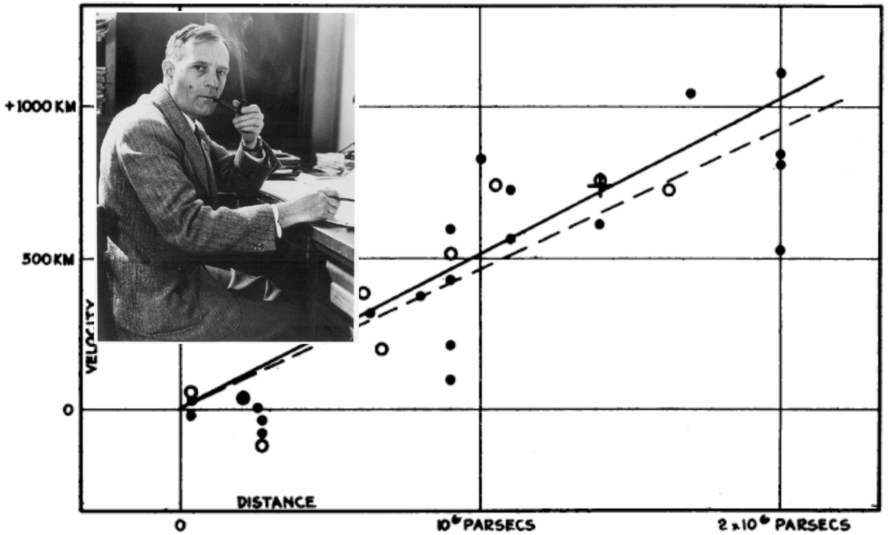
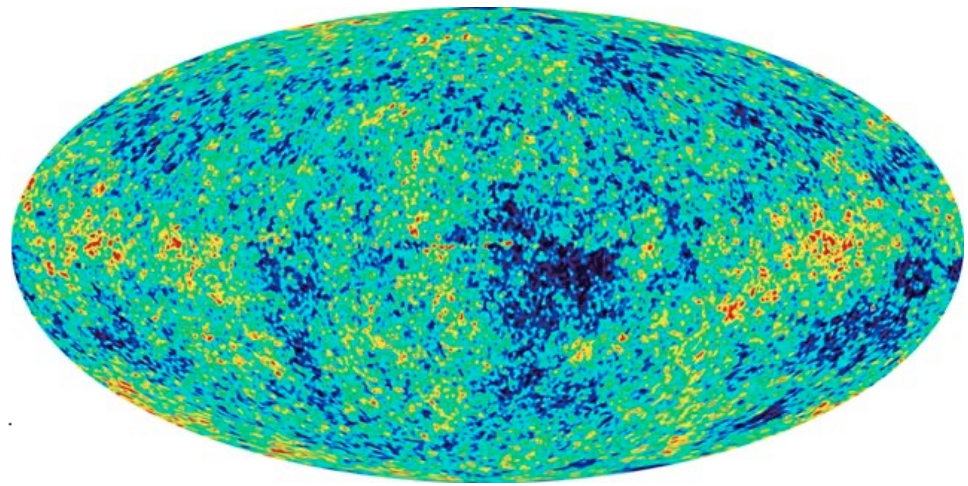


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.



A Theorist's Perspective on The Hubble Tension

Levon Pogosian (SFU)

SFU

Plan of the lectures

I. The Hubble tension
- Edwin Hubble and the expanding universe
- Luminosity and Angular Diameter distances
- The cosmic distance ladder: H_0 with Cepheids and TRGB
- H_0 from megamasers
- H_0 from time delay for lensed quasars
- H_0 from Cosmic Microwave Background
- H_0 from Baryon Acoustic Oscillations
- The S_8 tension

II. Why is it so challenging to fix?
- Challenges for the “early universe” solutions
- Challenges for the “late universe” solutions

III. Theoretical proposals to ease the tension
- Extra relativistic species
- Early Dark Energy
- Other proposals
- Primordial magnetic fields

The Expanding Universe

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

By Edwin Hubble

Mount Wilson Observatory, Carnegie Institution of Washington

Communicated January 17, 1929

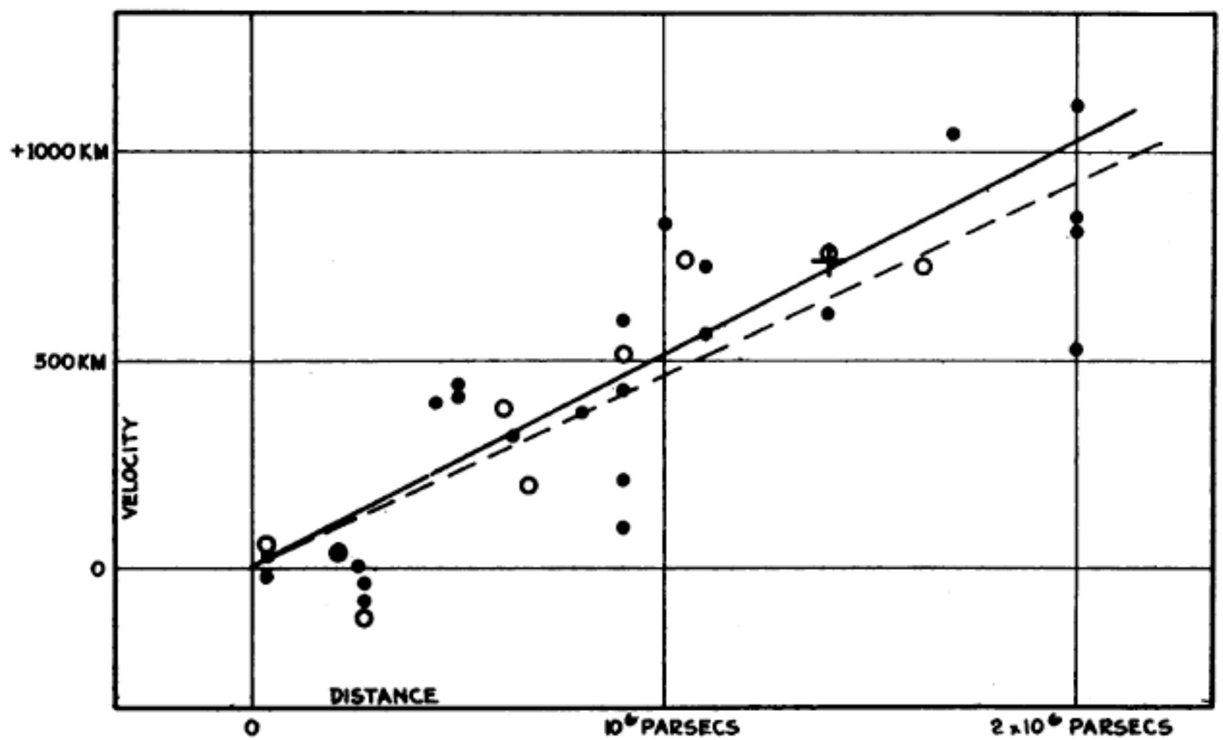


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Measuring the expansion rate

$$v = H_0 \, d$$

Measuring the expansion rate

The redshift

$$1 + z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} = \frac{a_{\rm now}}{a_{\rm then}}$$
$$= \gamma(1 + v/c)$$

Spectrometry
Photometry

$$v = H_0 \, d$$

Measuring the expansion rate

The redshift

$$1 + z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} = \frac{a_{\rm now}}{a_{\rm then}} = \gamma(1 + v/c)$$

$$v = H_0 d$$

Distance to something, e.g. a supernova in a galaxy far, far away

Spectrometry
Photometry

Standard candles (supernovae Ia),
Standard rulers, standard sirens

$$d_L \equiv \sqrt{\frac{\text{Known Intrinsic Luminosity}}{\text{Observed Flux Density}}} = \sqrt{\frac{L_s}{F}}$$

$$d_A \equiv \frac{\text{Known Physical Length}}{\text{Observed Angular Size}} = \frac{\ell}{\theta}$$

$[H_0]$ = [velocity/distance] = [1/time] = km/s/Mpc (1 pc is around 3 light years)

It's a bit more complicated…

H is not a constant

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left(\frac{\Omega_\gamma + \Omega_\nu}{a^4} + \frac{\Omega_{\rm cdm} + \Omega_b}{a^3} + \frac{\Omega_k}{a^2} + \Omega_\Lambda\right)$$

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2(z) = H_0^2\left[\Omega_{\rm r}(1+z)^4 + \Omega_{\rm M}(1+z)^3 + \Omega_{\rm k}(1+z)^2 + \Omega_{\rm DE}\right]$$

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -dt^2 + a^2(t)d\mathbf{x}^2$$

Comoving distance to redshift z:

$$\chi(a) = \int_{t(a)}^{\rm today}\frac{dt'}{a(t')} = \int_a^1 \frac{da'}{a'^2 H(a')} = \int_0^z \frac{dz'}{H(z')}$$

It's a bit more complicated…

H is not a constant

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2(z) = H_0^2\left[\Omega_{\rm r}(1+z)^4 + \Omega_{\rm M}(1+z)^3 + \Omega_{\rm k}(1+z)^2 + \Omega_{\rm DE}\right]$$

$$\Omega_{\rm r} + \Omega_{\rm M} + \Omega_{\rm k} + \Omega_{\rm DE} = 1$$

In an expanding universe distances depend on H(z):

$$\sqrt{\frac{L_s}{F}} \equiv d_L(z) = (1+z)\int_0^z \frac{c\,dz'}{H(z')}$$

$$\frac{\ell}{\theta} \equiv d_A(z) = \frac{1}{(1+z)}\int_0^z \frac{c\,dz'}{H(z')}$$

It's a bit more complicated…

H is not a constant

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2(z) = H_0^2\left[\Omega_{\rm r}(1+z)^4 + \Omega_{\rm M}(1+z)^3 + \Omega_{\rm k}(1+z)^2 + \Omega_{\rm DE}\right]$$

$$\Omega_{\rm r} + \Omega_{\rm M} + \Omega_{\rm k} + \Omega_{\rm DE} = 1$$

Distances depend on H(z), but reduce to the Hubble law for small z:

$$\sqrt{\frac{L_s}{F}} \equiv d_L(z) = (1+z)\int_0^z \frac{c\, dz'}{H(z')} \xrightarrow{z\ll 1} cH_0^{-1} z \approx H_0^{-1} v$$

$$\frac{\ell}{\theta} \equiv d_A(z) = \frac{1}{(1+z)}\int_0^z \frac{c\, dz'}{H(z')} \xrightarrow{z\ll 1} cH_0^{-1} z \approx H_0^{-1} v$$

$$H_0 = 100\ h\ \mathrm{km/s/Mpc}\ , \quad cH_0^{-1} = 2998\ h^{-1}\ \mathrm{Mpc}$$

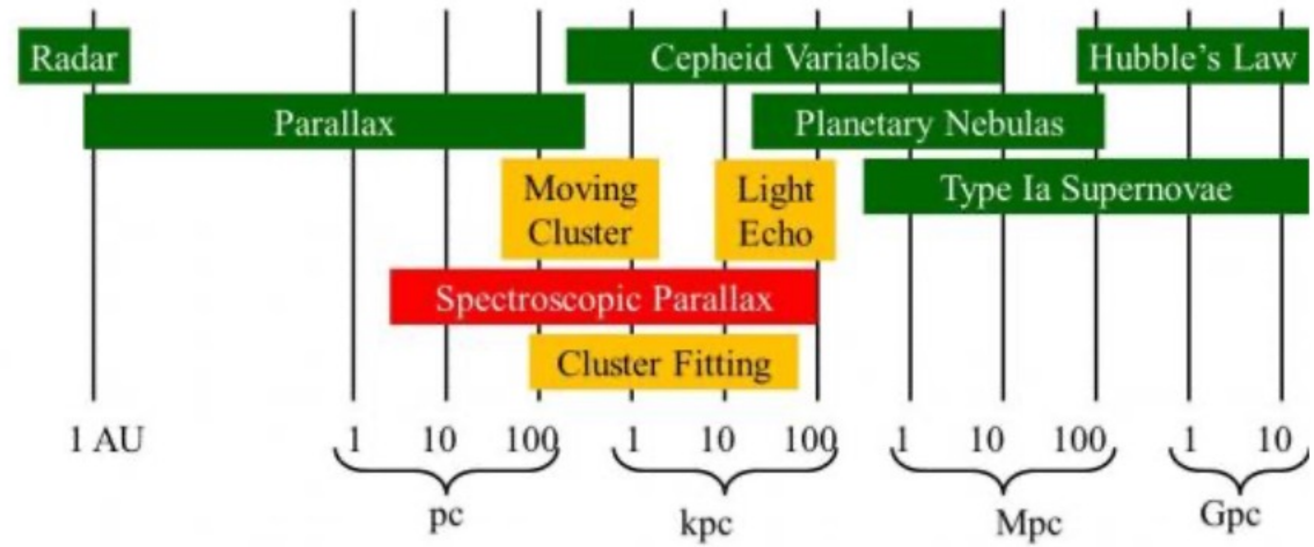
The takeaway message:

- The simple Hubble law works at very small redshifts
- It can provide a measurement of H_0 that is independent of the cosmological model
- At higher redshifts, one has to assume a model

Next:

- Probes of H_0 that do not strongly depend on the cosmological model

The cosmic distance ladder

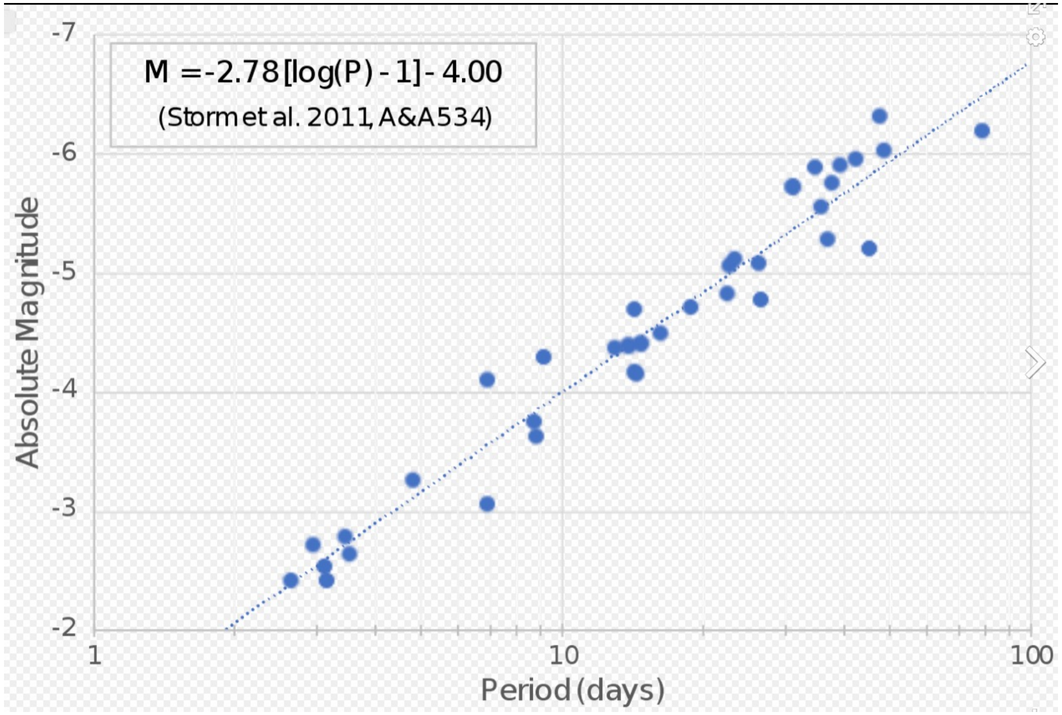


https://www.universetoday.com

SNIa are good standard candles, and they are very bright (hence seen at higher redshifts), but we do not know their intrinsic luminosity from the SNIa data alone

If we find galaxies which, in addition to SNIa, contain other (better understood) standard candles, we can use that to determine the SNIa intrinsic luminosity

Cepheid stars



The true luminosity of Cepheid stars is known from their pulsation period

Observed brightness (magnitude) allows us to find the distance to the host galaxy

If the same galaxy contains a SNIa, we can deduce its intrinsic luminosity from the observed magnitude and the known distance

Deducing H_0 from the cosmic ladder

For historical reasons, astronomers work with $m = M + 25 + 5\log_{10} d_L$

Separate the H_0 dependence from the z-dependence in $d_L(z)$:

$$d_L(z) = \frac{c}{H_0}(1+z)\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + X(z')}} \equiv \frac{c}{H_0}\hat{d}_L(z)$$

Parameterize the dimensionless distance as an expansion in small z :

$$\hat{d}_L(z) \approx z\left[1 + (1-q_0)\frac{z}{2} - (1 - q_0 - 3q_0^2 + j_0)\frac{z^2}{6}\right]$$

Fit $m = M + 25 - 5\log_{10} H_0 + 5\log_{10} c\hat{d}_L$ to data, *m(z) vs z,* and find the intercept (as well as q_0 and j_0)

Use *M* determined from the cosmic ladder (Cepheids, TRGB) to deduce H_0

A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km s^{-1} Mpc^{-1} Uncertainty from the *Hubble Space Telescope* and the SH0ES Team

Adam G. Riess,[1,2] Wenlong Yuan,[2] Lucas M. Macri,[3] Dan Scolnic,[4] Dillon Brout,[5] Stefano Casertano,[1] David O. Jones,[6] Yukei Murakami,[2] Louise Breuval,[2] Thomas G. Brink,[7] Alexei V. Filippenko,[7,8] Samantha Hoffmann,[1] Saurabh W. Jha,[9] W. D'arcy Kenworthy,[2] John Mackenty,[1] Benjamin E. Stahl,[7] and Weikang Zheng[7]

[1] *Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*

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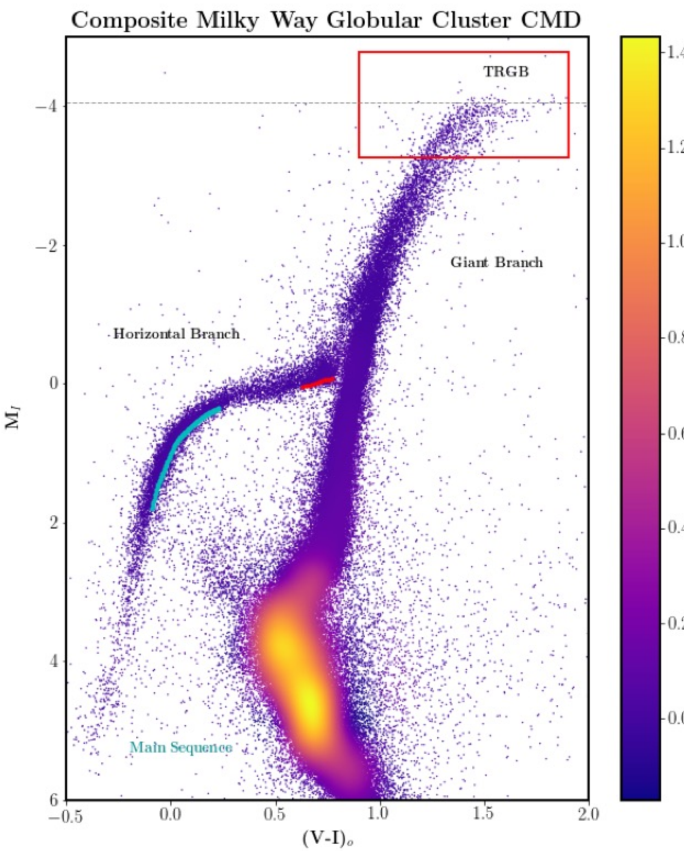
[9] *Department of Physics and Astronomy, Rutgers, the State University of New Jersey, Piscataway, NJ 08854, USA*

ABSTRACT

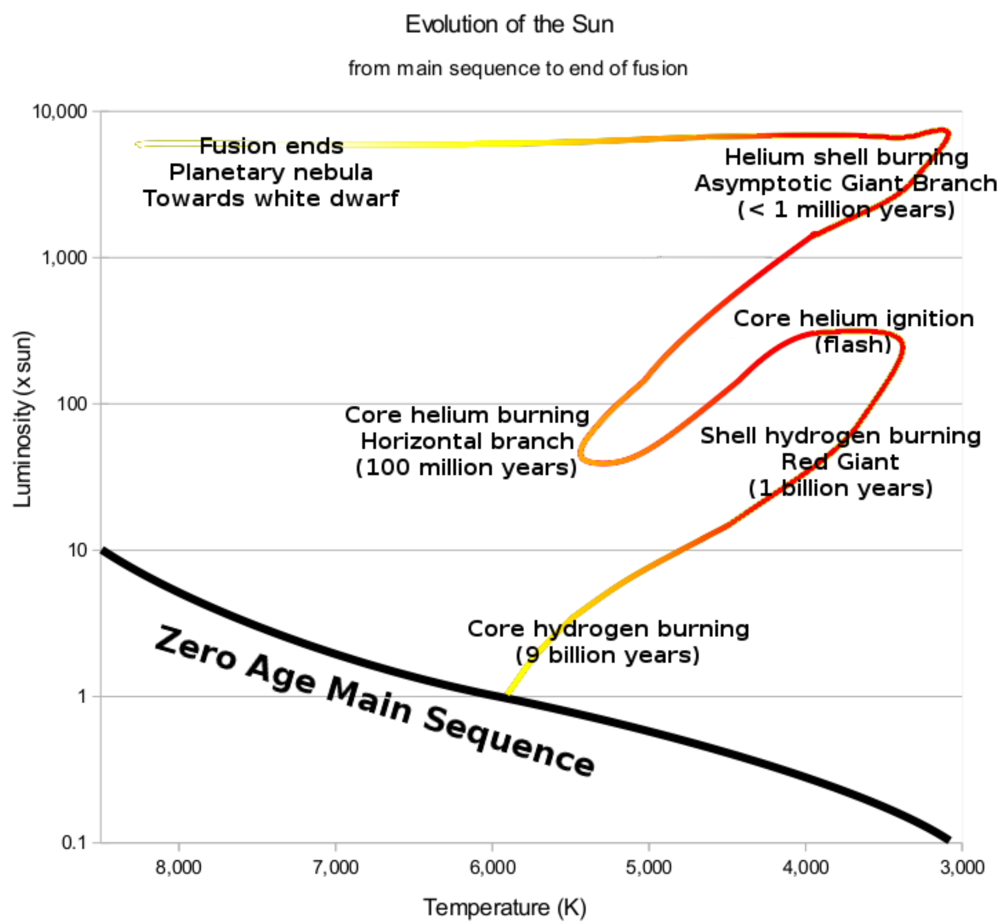
Our baseline result from the Cepheid–SN Ia sample is $H_0 = 73.04 \pm 1.04$ km s^{-1} Mpc^{-1}, which includes systematic uncertainties and lies near the median of all analysis variants. We demonstrate consistency with measures from *HST* of the TRGB between SN Ia hosts and NGC 4258, and include them *simultaneously* to yield 72.53 ± 0.99 km s^{-1} Mpc^{-1}. The inclusion of high-redshift SNe Ia yields $H_0 = 73.30 \pm 1.04$ km s^{-1} Mpc^{-1} and $q_0 = -0.51 \pm 0.024$. We find a 5σ difference with the prediction of H_0 from *Planck* CMB observations under ΛCDM, with no indication that the discrepancy arises from measurement uncertainties or analysis variations considered to date. The source of this now long-standing discrepancy between direct and cosmological routes to determining the Hubble constant remains unknown.

arXiv:2112.04510

Tip of the Red Giant Branch

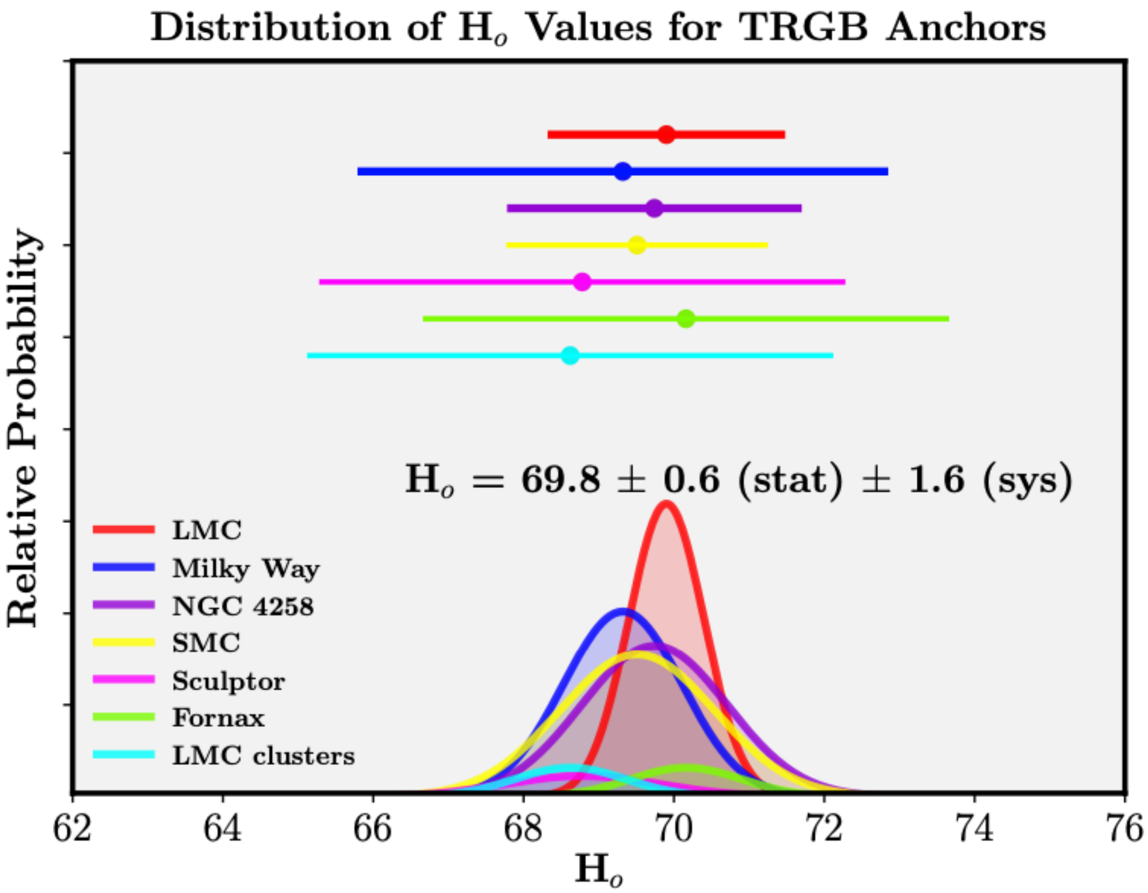


form Freedman, arXiv:2106.15656, ApJ



Stars at the Tip of the Red Giant Branch (TRGB) of the Hertzsprung-Russel diagram are good standard candles with known luminosity

H_0 from TRGB calibrated SNIa (CCHP)



form Freedman, arXiv:2106.15656, ApJ

Cosmic distances from masers

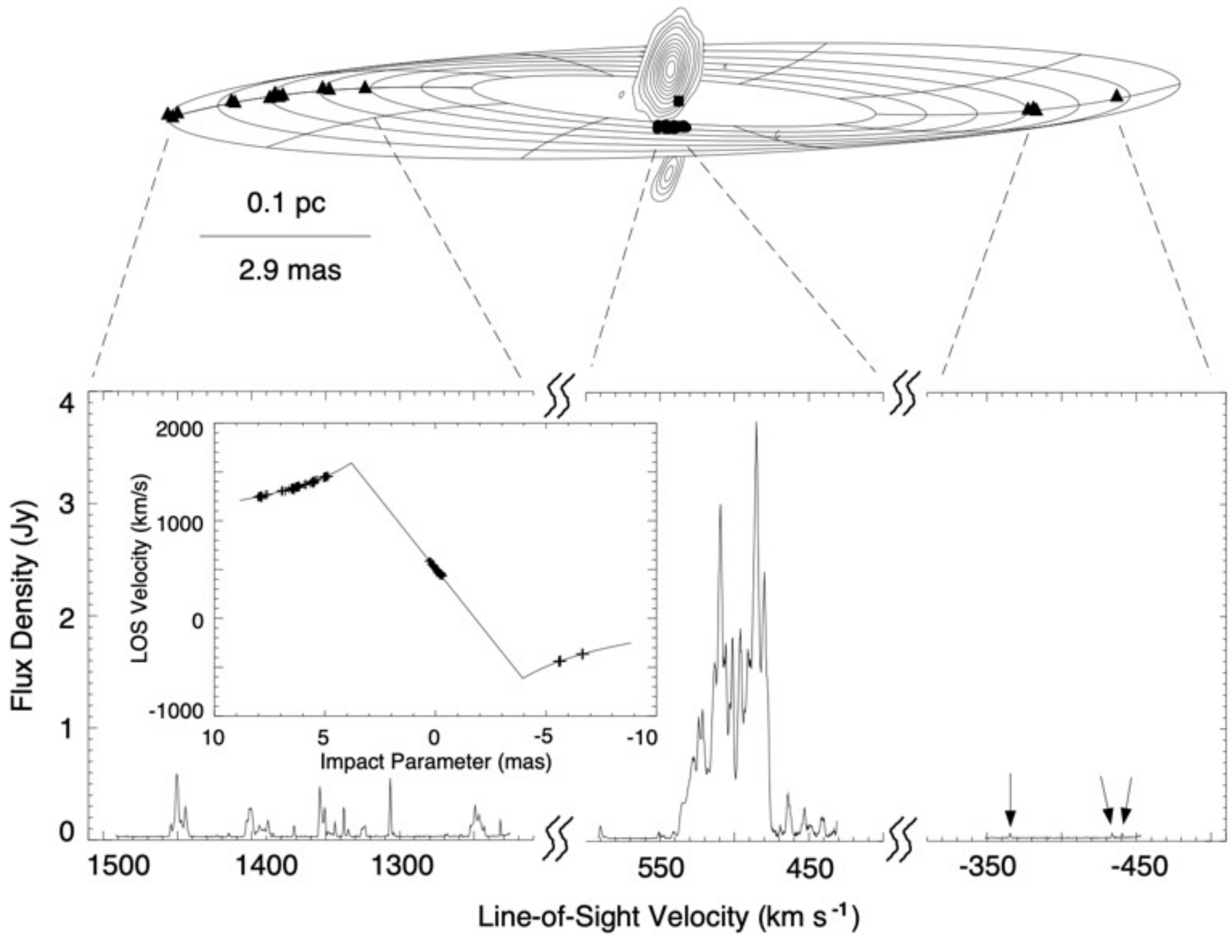
Measure

- redshift of the host galaxy
- angular size θ,
- velocity V
- centripetal acceleration A

Then

$D=r/\theta$
$A=V^2/r$

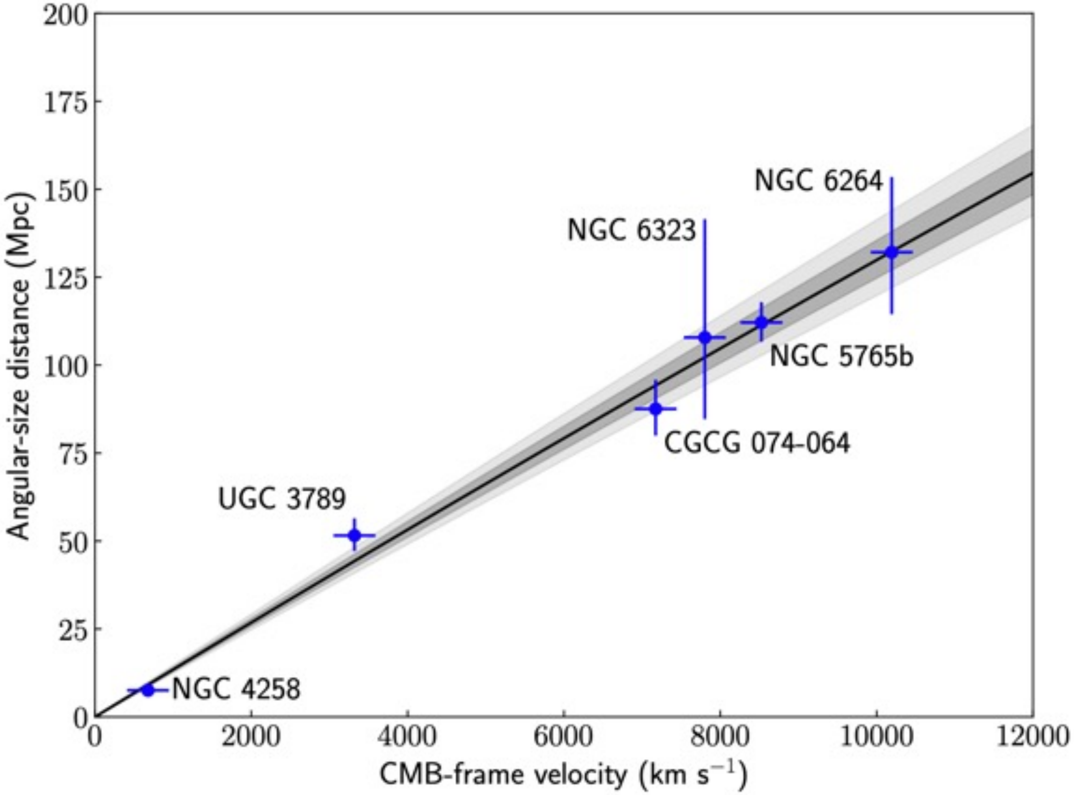
Hence, $D=V^2/A\theta$



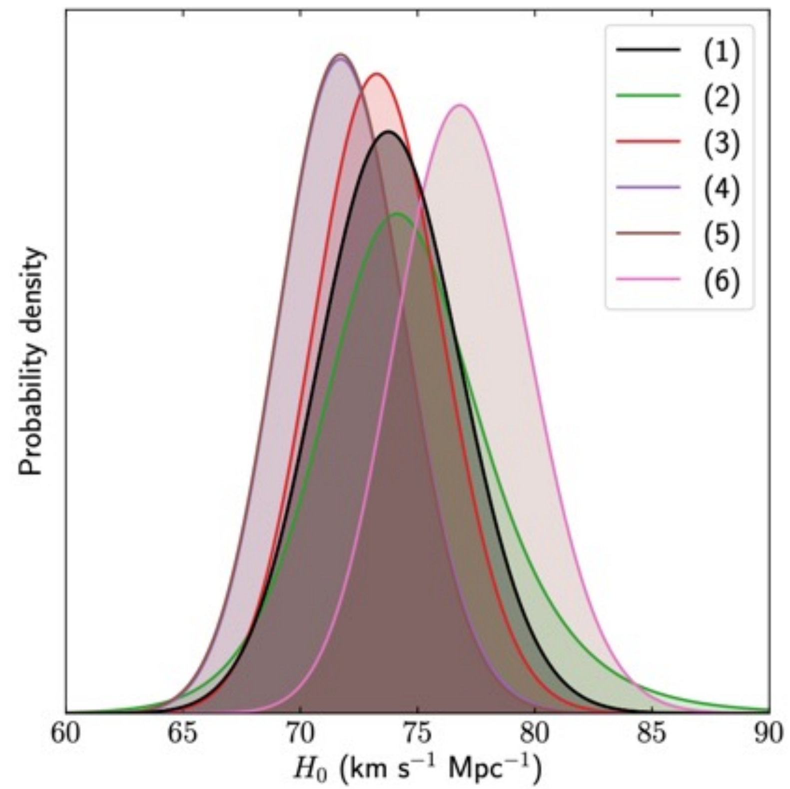
from Herrnstein et al, astro-ph/9907013, Nature

“MASER” = microwave amplification by stimulated emission of radiation

H_0 from the Megamaser Cosmology Project (MCP)

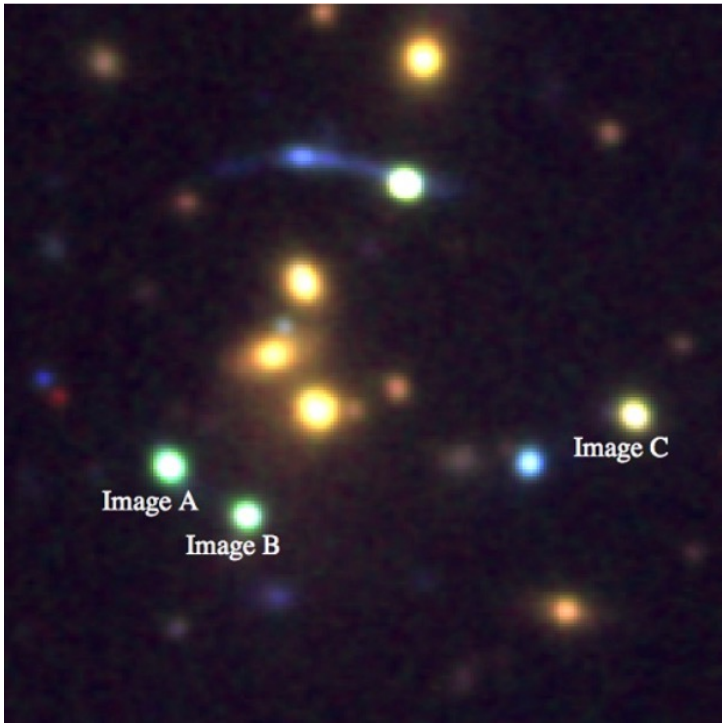


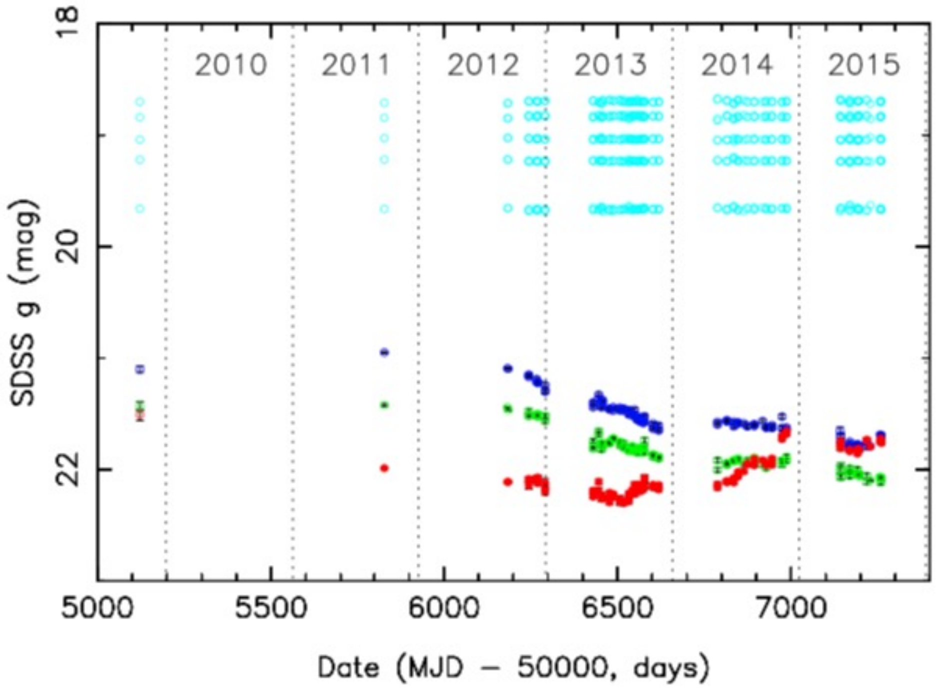
H_0=73.9 ± 3.0 km/s/Mpc



Pesce et al, arXiv:2001.09213, Ap J Lett

Time delays of lensed quasars





Quasar SDSS J2222+2745
https://www.gemini.edu/node/12442

H. Dahle et al, arXiv:1505.06187, Ap J

H_0 from the time delays of lensed quasars

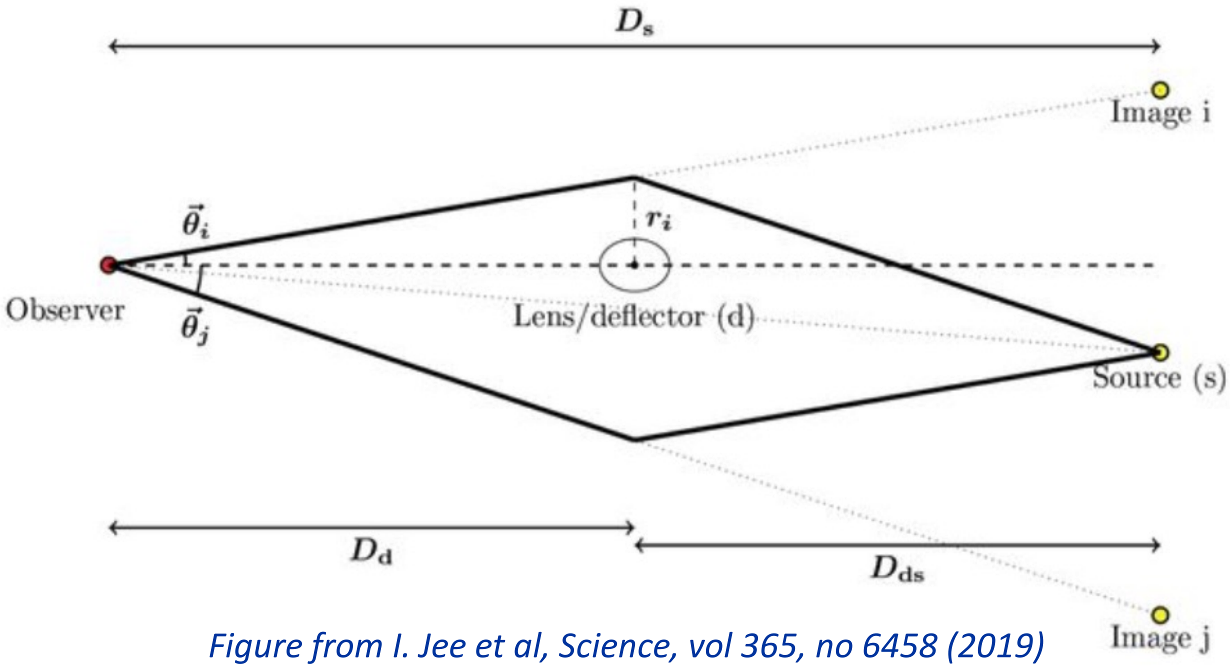


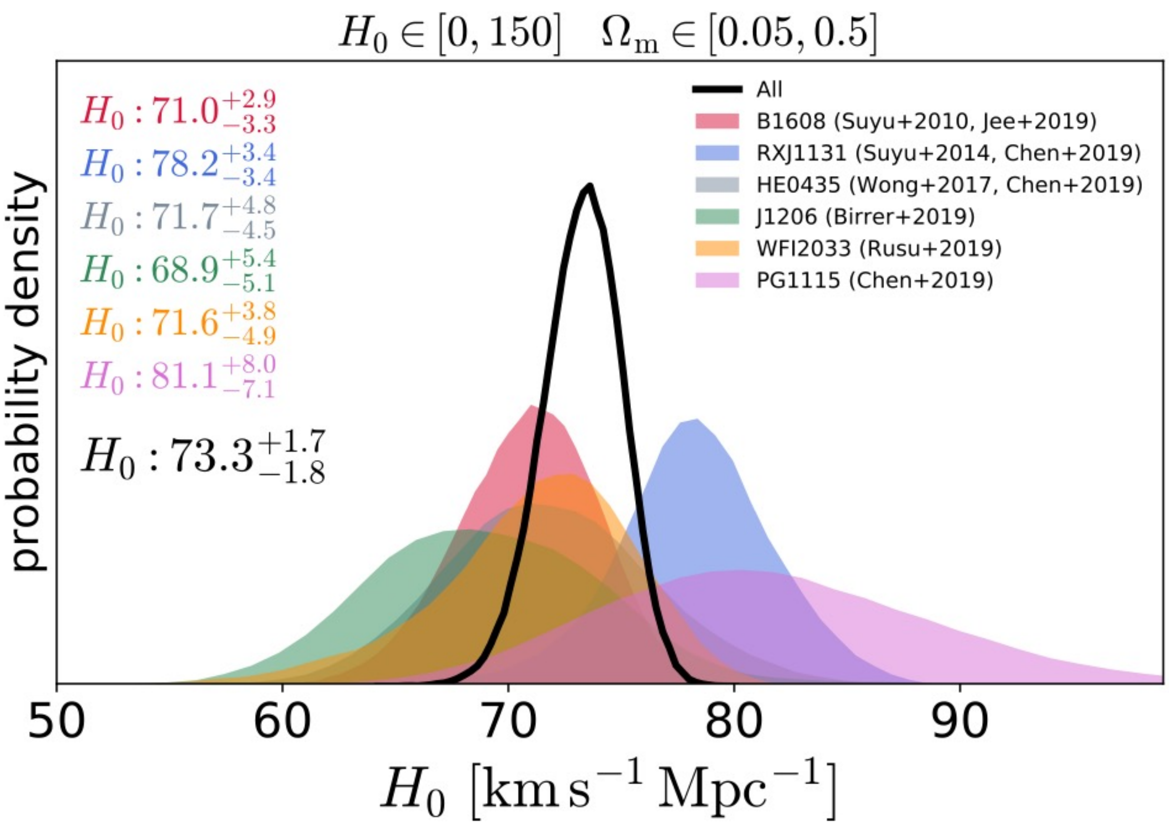
Figure from I. Jee et al, Science, vol 365, no 6458 (2019)

$$c\Delta t = \underbrace{(1+z_d)\frac{D_d D_s}{D_{ds}}}_{\text{time delay distance}} \Delta\phi$$

Given a mass model that predicts $\Delta\phi$, and a measurement of Δt, find the “time delay distance”, which is primarily determined by H_0

H0LiCOW

(The H0 Lenses in COSMOGRAIL's Wellspring)

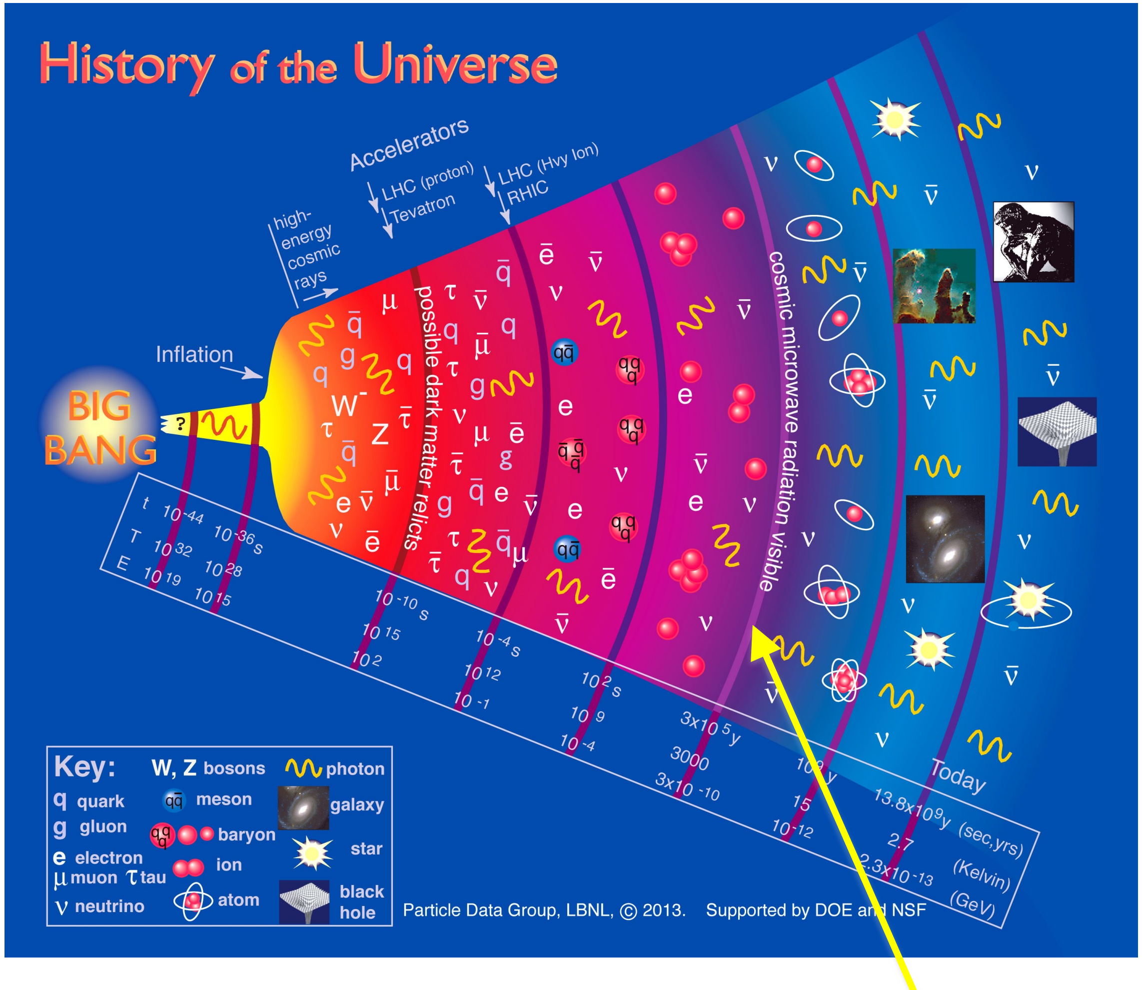


Wong et al, arXiv:1907.04869, MNRAS

(Strongly) LCDM-dependent probes

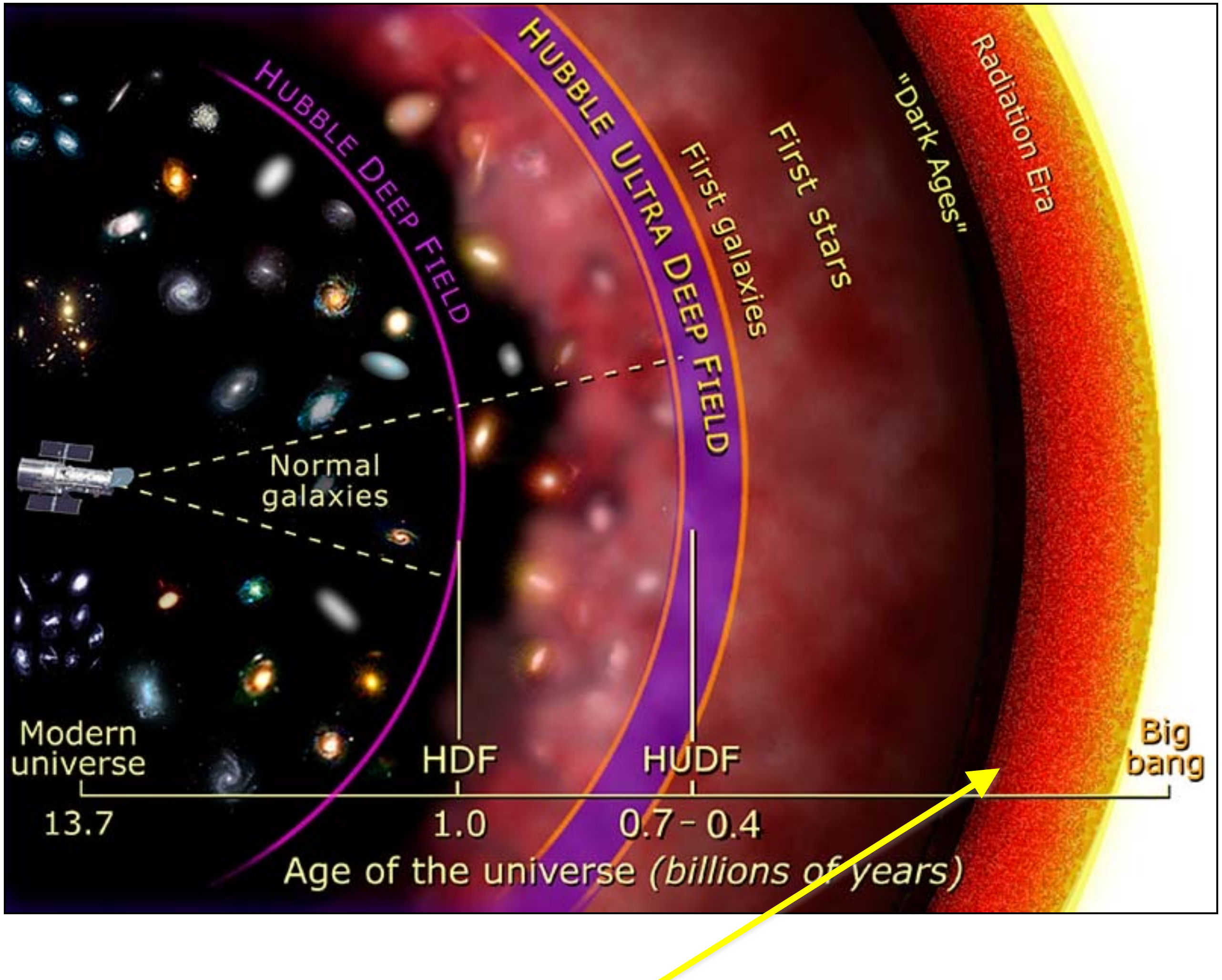
Cosmic Microwave Background
Baryon Acoustic Oscillations

A poster in a typical physics department



Protons and electrons combine to form neutral hydrogen

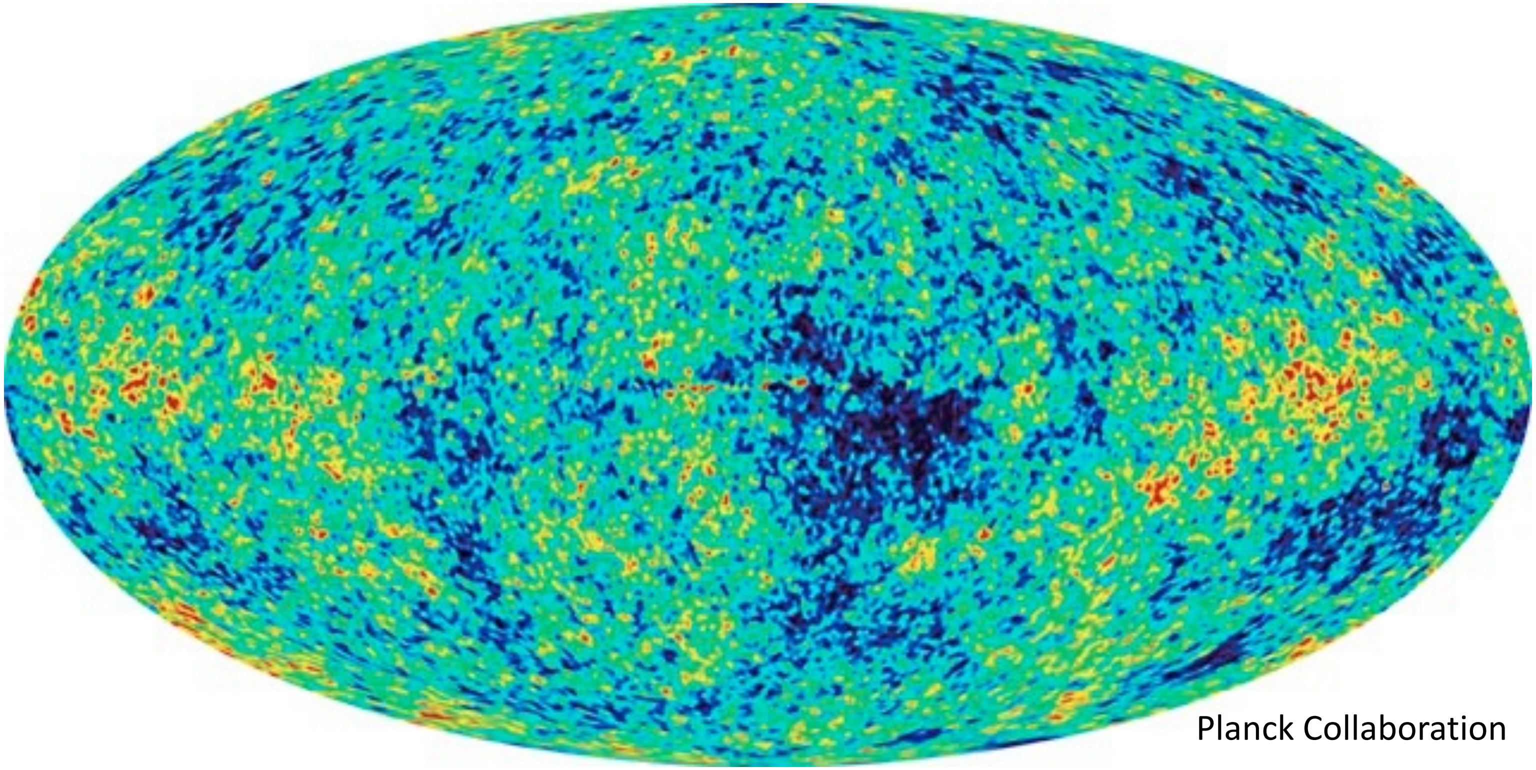
A poster in a typical astronomy department



The transition from transparent to opaque

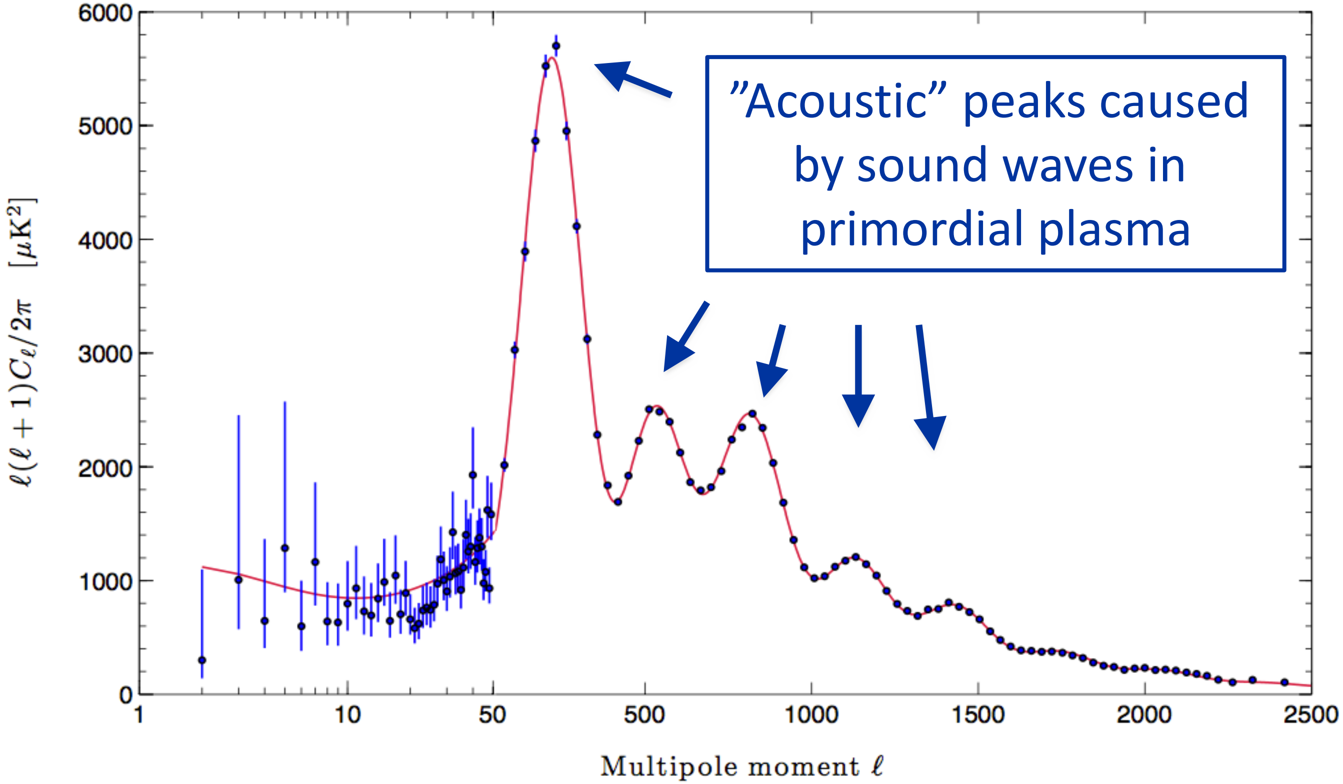
We observe it as the Cosmic Microwave Background (CMB)

CMB temperature fluctuations



Nearly perfect black body with temperature fluctuations of order 1/100,000

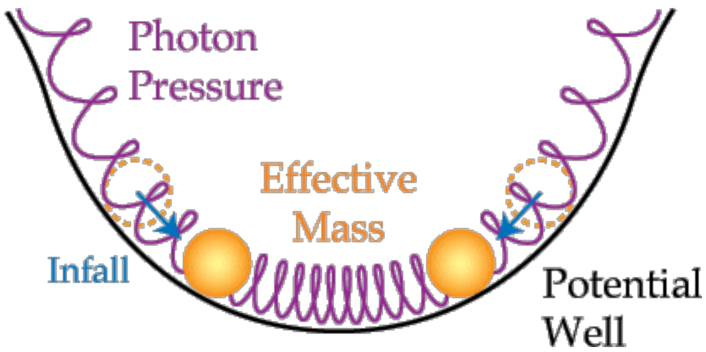
The power spectrum of CMB temperature fluctuations

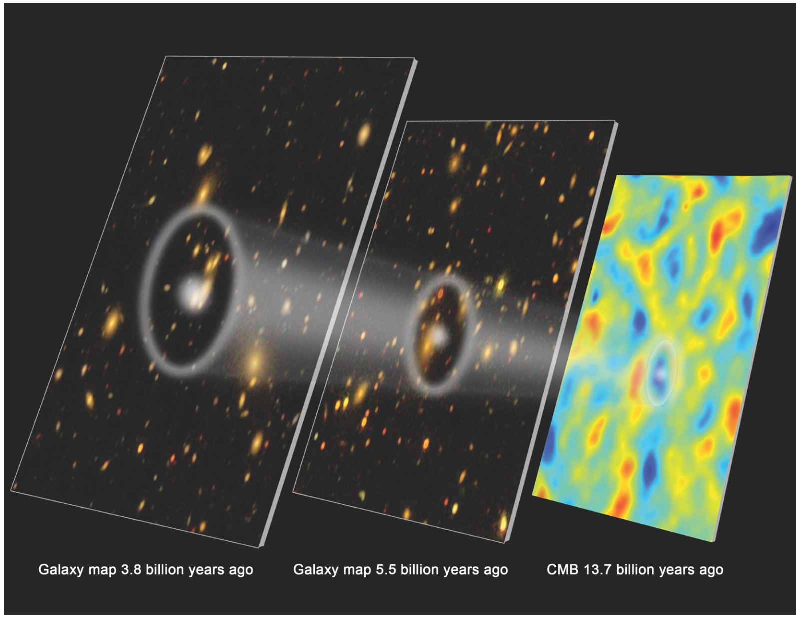


Well-fit by the Lambda Cold Dark Matter (LCDM) model

("Baryon") Acoustic Oscillations
(also known as "Sakharov Oscillations")

A. D. Sakharov, Sov. Phys. JETP 49, 345 (1965)

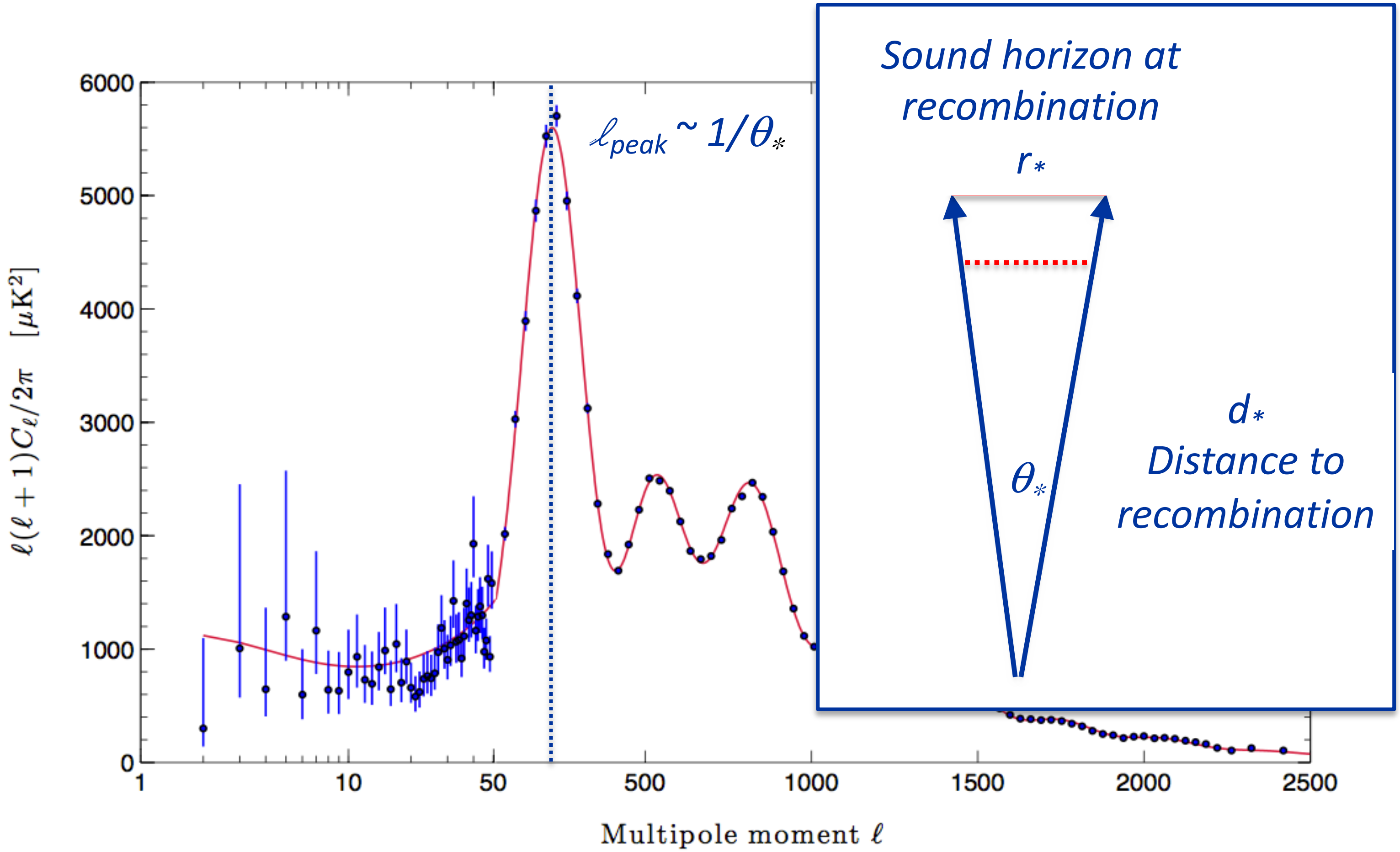




Before recombination:

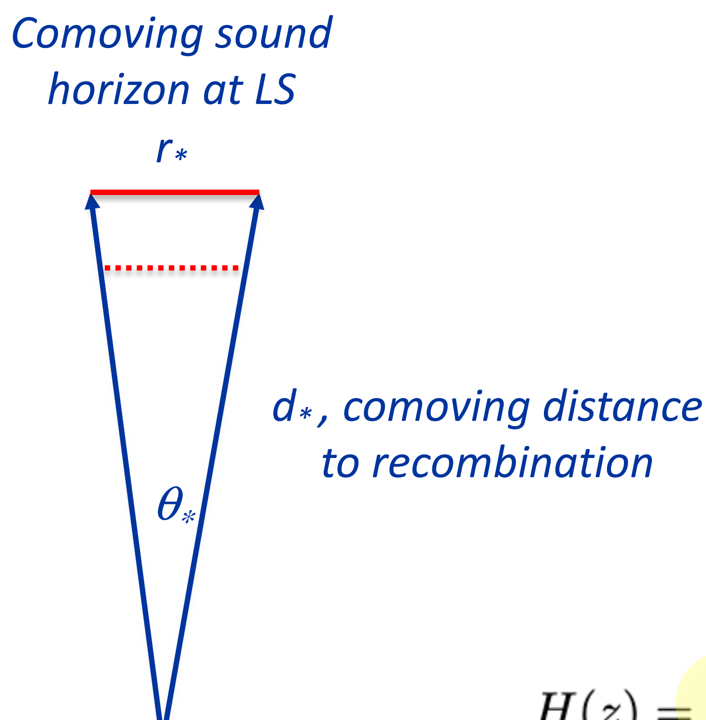
- Protons, electrons and photons are a single tightly coupled fluid
- The fluid gets compressed in the gravitational potentials, but the compression is opposed by the fluid pressure. This sets up sound waves
- Oscillations of given frequency are triggered at the same time in different parts of the universe, hence they are in phase –> coherence

How does CMB constrain H_0?



- Positions of the acoustic peaks tell us the angular size of the sound horizon r_* at recombination, $\theta_* = r_*/d_*$. Given r_* predicted from theory, we can infer the distance to the redshift of recombination d_* (and, hence, derive H_0)
- A smaller sound horizon r_* would imply a shorter distance to the redshift of recombination d_* (implying a larger H_0)

How does CMB constrain H_0?



$$r_* = \int_{z_*}^{\infty} \frac{c_S(z)\ dz}{H(z)}$$

$$d_* = \int_0^{z_*} \frac{c\ dz}{H(z)}$$

$$c_S^2(z) = \frac{1}{3(1+R)}\ , \quad R = \frac{3}{4}\frac{\rho_b}{\rho_\gamma} = \frac{3}{4}\frac{\omega_b}{\omega_\gamma(1+z)}$$

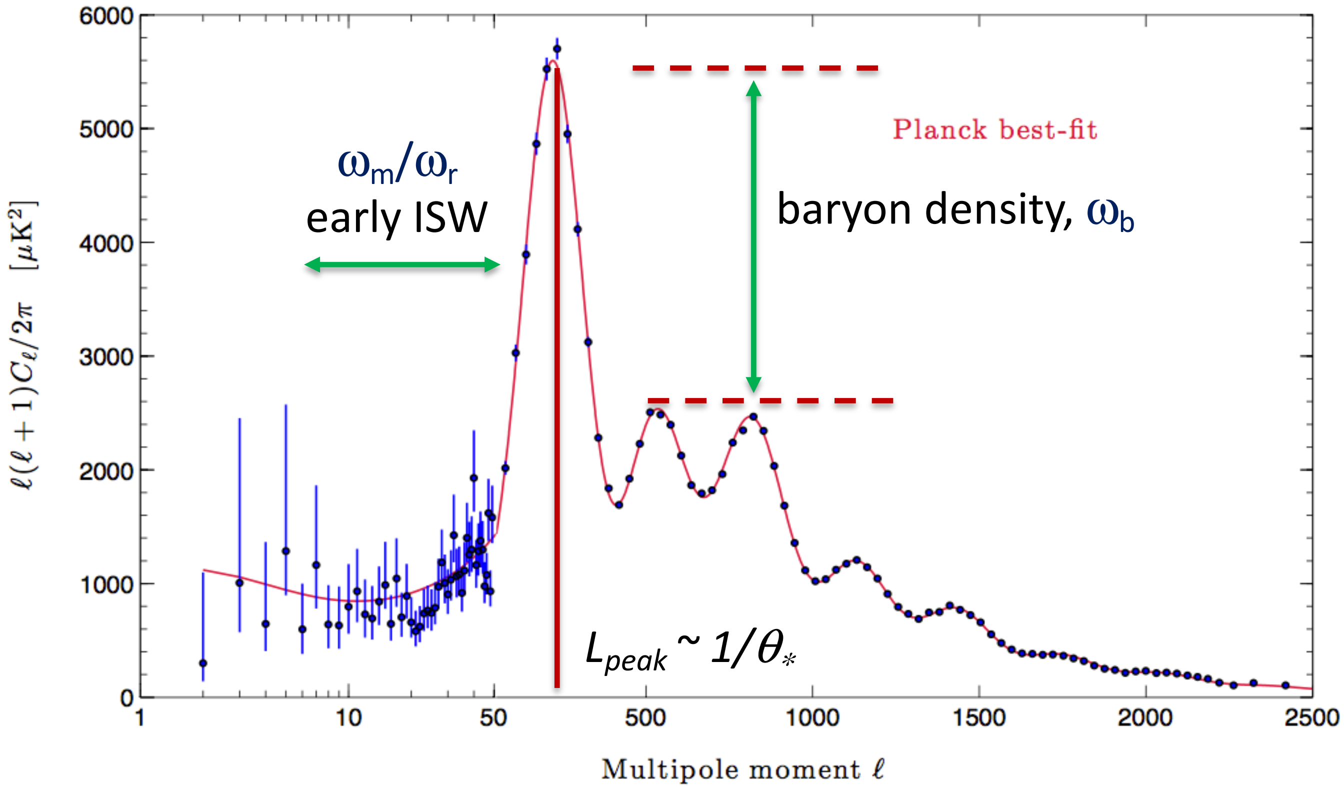
$$z_* = z_*(\omega_r, \omega_b, \omega_m)$$

$$H(z) = H_0\sqrt{\Omega_r(1+z)^4 + \Omega_\mathrm{m}(1+z)^3 + 1 - \Omega_\mathrm{m} - \Omega_r}$$

$$h(z) = \sqrt{\omega_r(1+z)^4 + \omega_m(1+z)^3 + h^2 - \omega_m - \omega_r}$$

H_0 is only one of several key parameters!

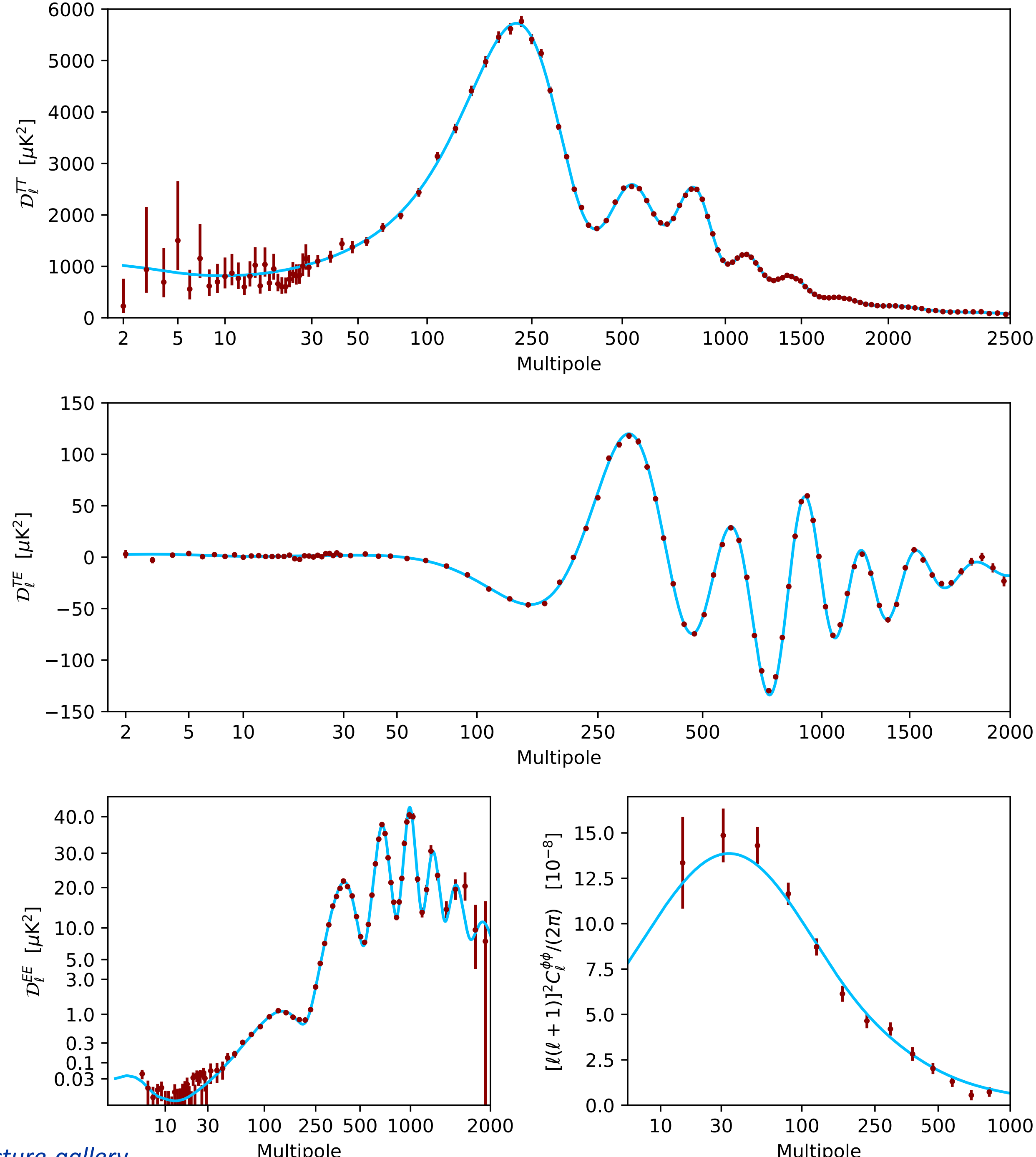
How does CMB constrain H_0?



4 key parameters: ω_γ, ω_m, ω_b, h

4 key pieces of information: T_{CMB}, eISW, peak heights, θ_*

In addition to CMB temperature (TT), we also have CMB polarization (TE and EE), and CMB lensing spectra, which further help to constrain the parameters



https://www.cosmos.esa.int/web/planck/picture-gallery

Summary of H_0 deduced from CMB (within LCDM)

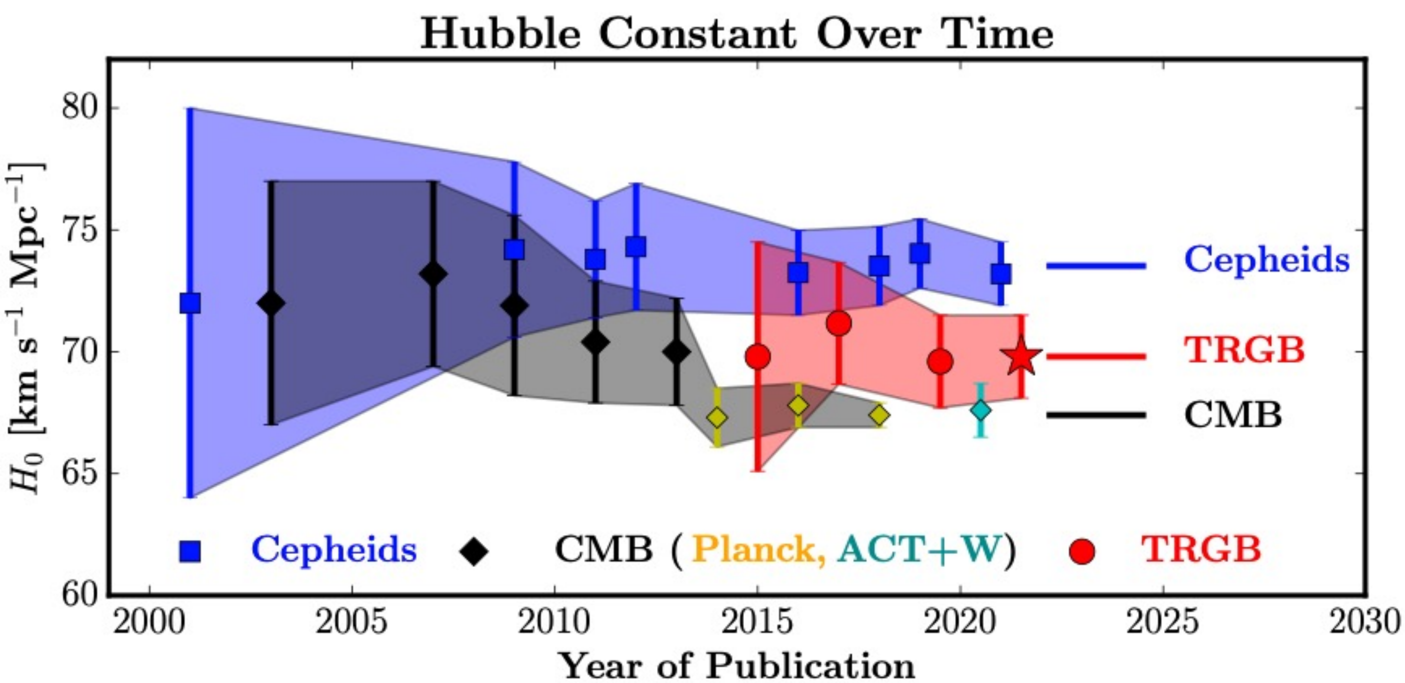
WMAP9: H_0 = 70.0 ± 2.2 km/s/Mpc

Planck 2018: H_0 = 67.36 ± 0.54 km/s/Mpc

ACT-DR4: H_0 = 67.9 ± 1.5 km/s/Mpc

SPT-3G Y1: H_0= 68.8 ± 1.5 km/s/Mpc

The Road to the Hubble Tension

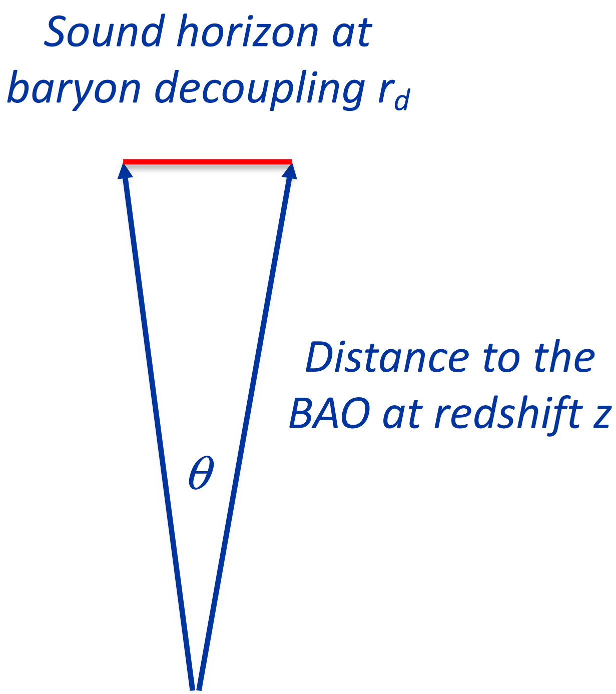


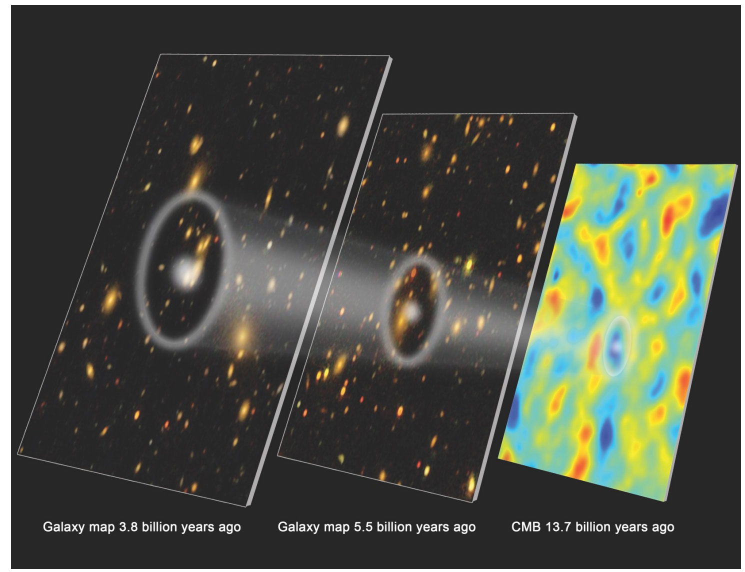
form Freedman, arXiv:2106.15656, ApJ

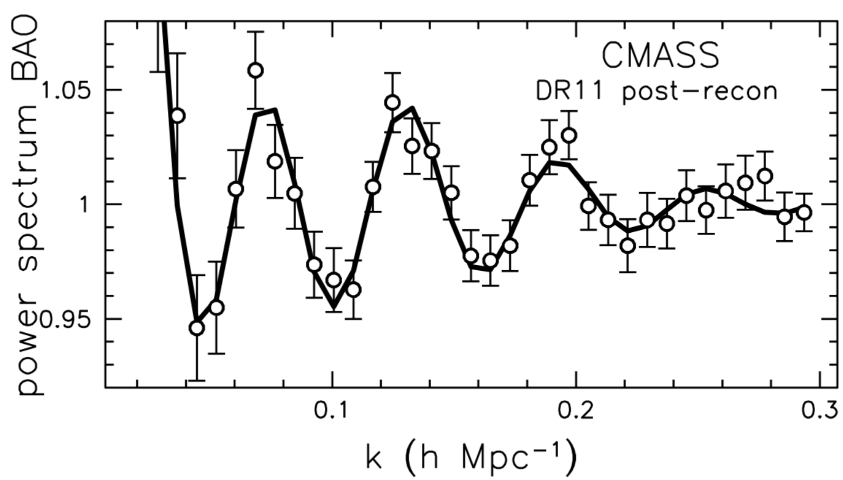
CMB (Planck): H_0 = 67.36 ± 0.54 km/s/Mpc

Cepheid calibrated SNIa (SH0ES): H_0 = 73.04 ± 1.04 km/s/Mpc

Baryon Acoustic Oscillations







How does the BAO data constrain H_0?

BAO data provides angular sizes of the sound horizon r_d measured at different redshifts

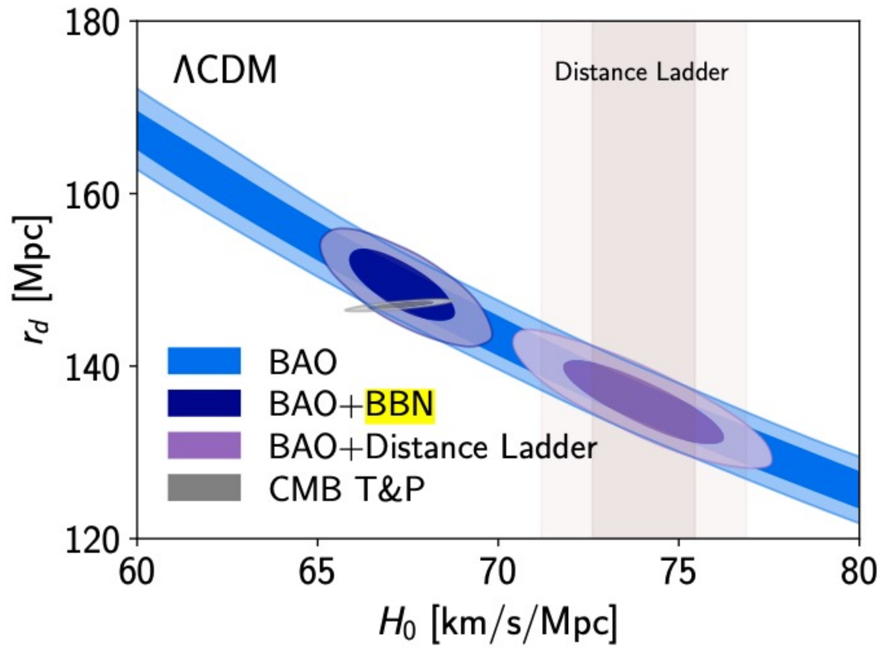
$$\beta_\perp(z) = D_M(z)/r_d = \int_0^z \frac{2998 \text{ Mpc } dz'}{r_d h \sqrt{\Omega_m (1+z')^3 + 1 - \Omega_m}}$$

By itself, BAO data constrains $r_d h$ and Ω_m

To get H_0 from BAO:

- use r_d from the LCDM fit to CMB
- use the BBN value of ω_b and compute r_d assuming the recombination model. This gives $H_0 = 67.35 \pm 0.97$ km/s/Mpc

The H_0 tension can be rephrased as a r_d tension

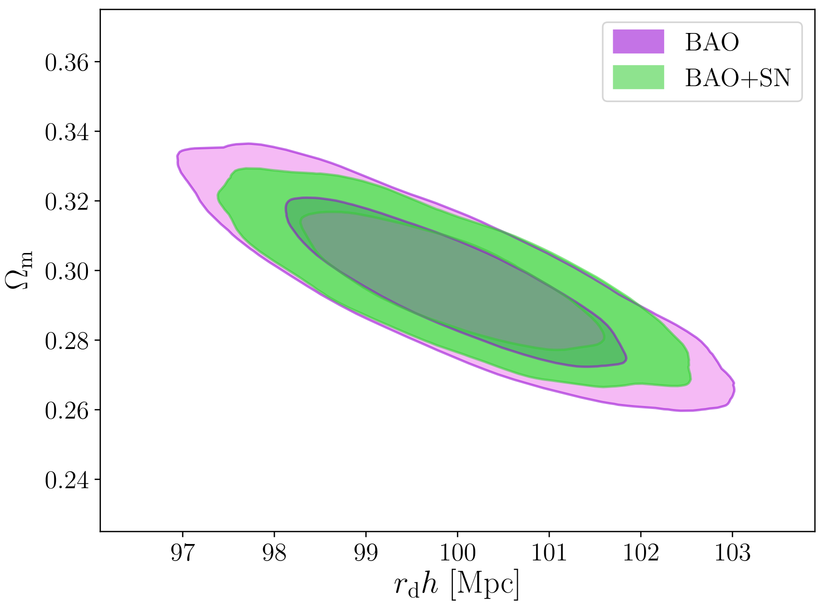


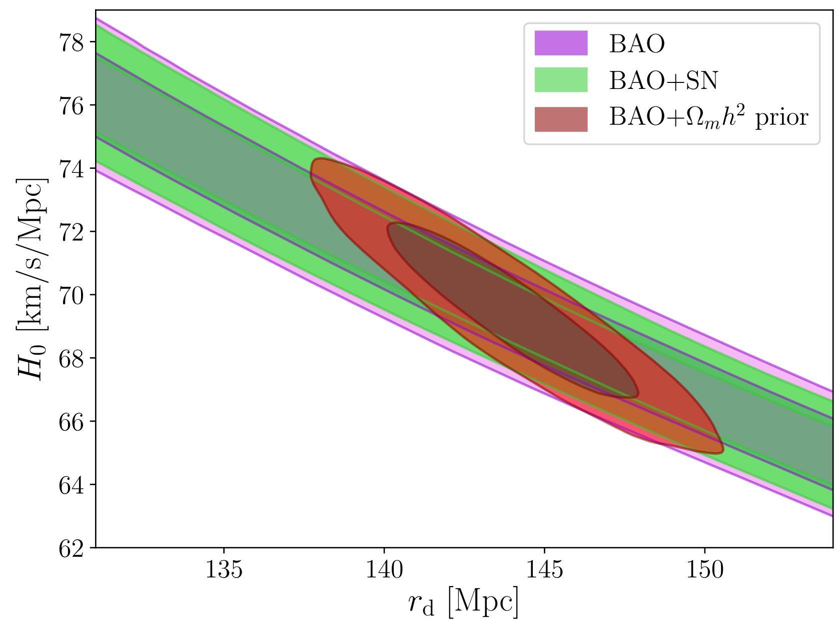
eBOSS Collaboration, Alam et al, arXiv:2007.08991, Phys. Rev. D

The sound horizon and H_0 determined from BAO in a recombination-independent way

- Treat r_d as an independent parameter
- By itself, BAO data constrains $r_d h$ and Ω_m
- Providing ω_m breaks the r_d-h degeneracy

$$\begin{aligned}\beta_\perp(z) &= D_M(z)/r_\mathrm{d} \\ &= \int_0^z \frac{2998\ \mathrm{Mpc}\ \mathrm{d}z'}{r_\mathrm{d} h \sqrt{\Omega_\mathrm{m}(1+z')^3 + 1 - \Omega_\mathrm{m}}} \\ &= \int_0^z \frac{2998\ \mathrm{Mpc}\ \mathrm{d}z'}{r_\mathrm{d} \omega_m^{1/2} \sqrt{(1+z')^3 + h^2/\omega_m - 1}}\end{aligned}$$



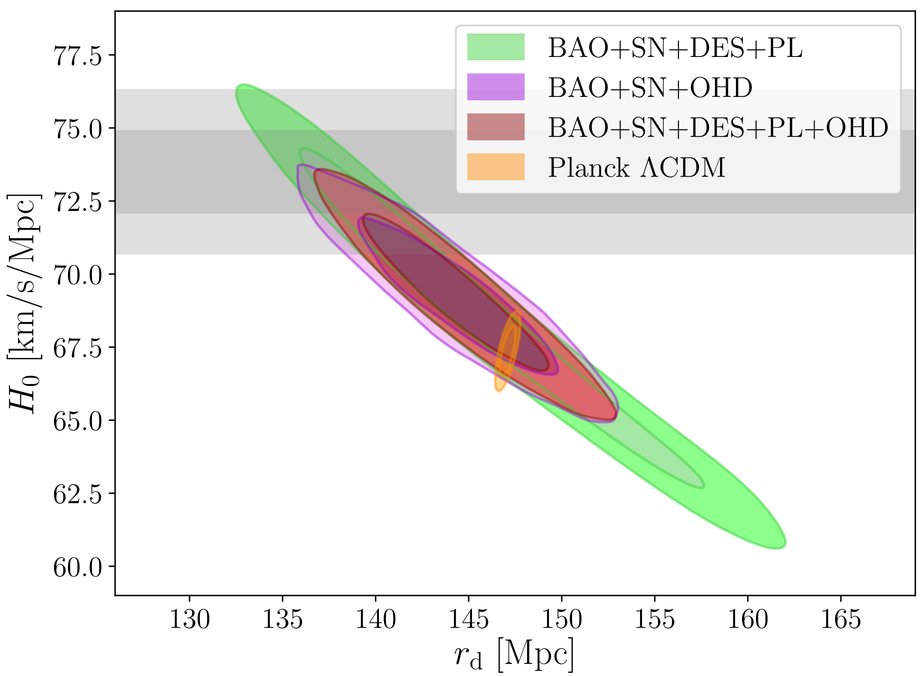


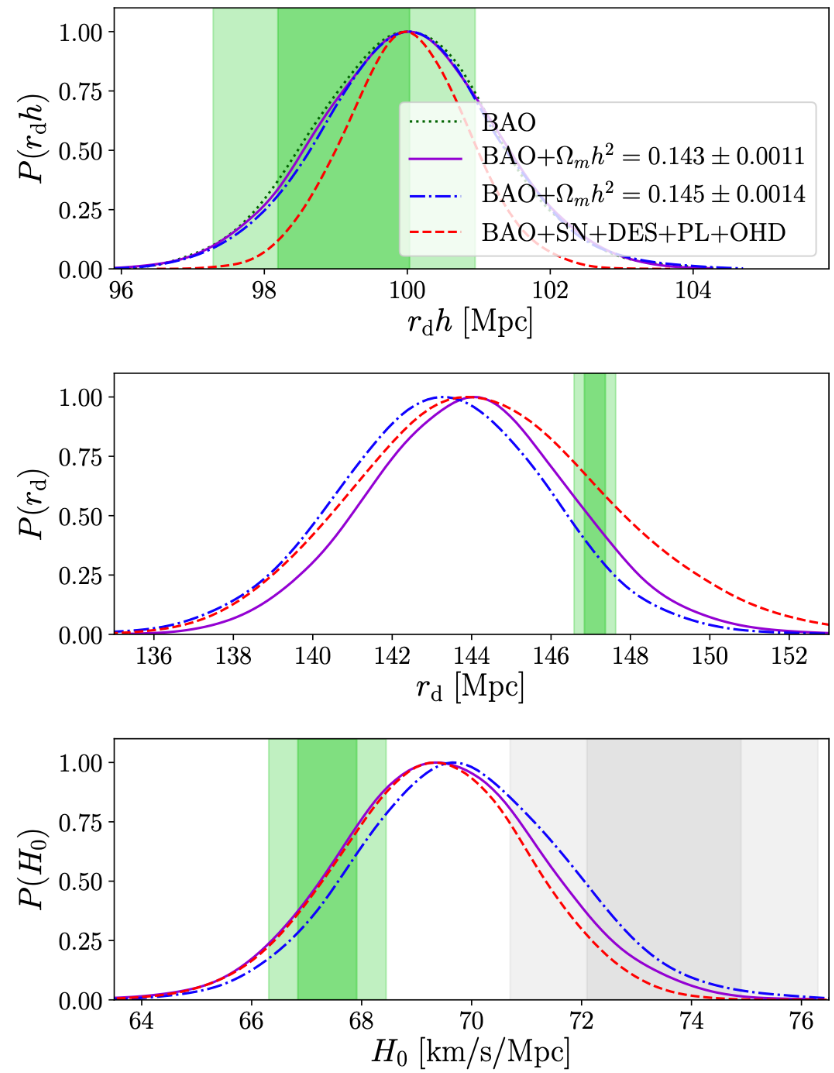
LP, G.-B. Zhao, K. Jedamzik, arXiv:2009.08455, Ap. J. Lett

The sound horizon and H_0 determined from BAO in a recombination-independent way

Treat r_d as a free parameter

Combine BAO with CMB lensing and galaxy weak lensing, and cosmic chronometers, or impose a prior on ω_m

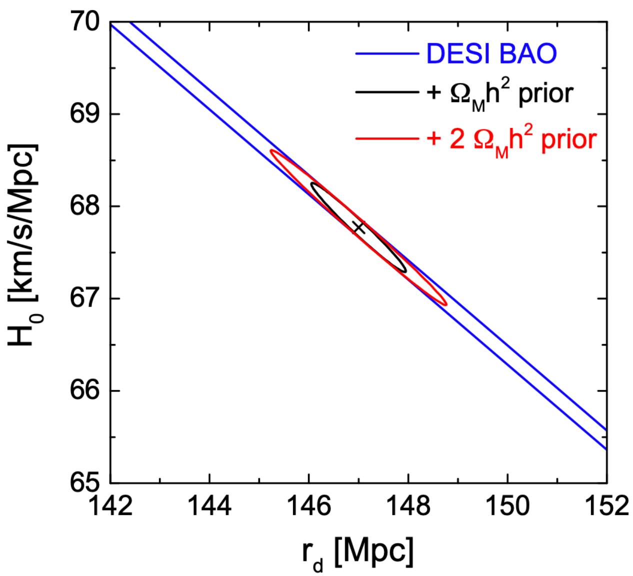




LP, G.-B. Zhao, K. Jedamzik, arXiv:2009.08455, Ap. J. Lett

An upcoming stringent consistency test

Forecast: combining DASI BAO with a Gaussian prior on $\Omega_m h^2$
($\Omega_m h^2$ = *0.143 +/- 0.0011* and *0.143 +/- 0.0022*)



Parameter	BGS	LRG	ELG	ALL	$+\sigma(\omega_m)$	$+2\sigma(\omega_m)$
$\sigma(r_\mathrm{d}h)$	0.192	0.464	0.380	0.105	-	-
$\sigma(\Omega_\mathrm{m})$	0.0066	0.0065	0.0047	0.0017	-	-
$\sigma(r_\mathrm{d})$	-	-	-	-	0.636	1.179
$\sigma(H_0)$	-	-	-	-	0.323	0.560

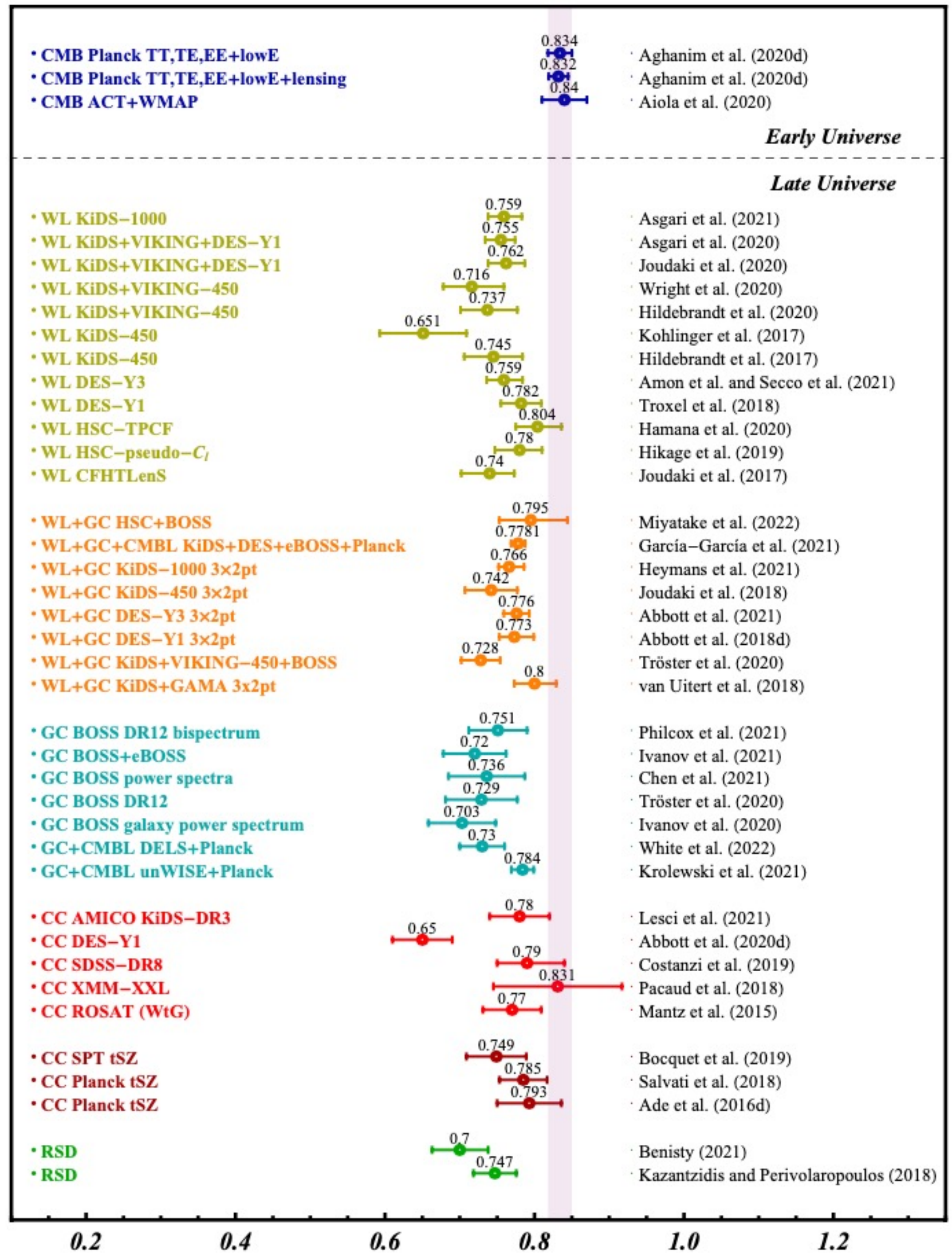
DESI BAO will offer a tight consistency test against the Planck best fit LCDM

LP, G.-B. Zhao, K. Jedamzik, arXiv:2009.08455, Ap. J. Lett

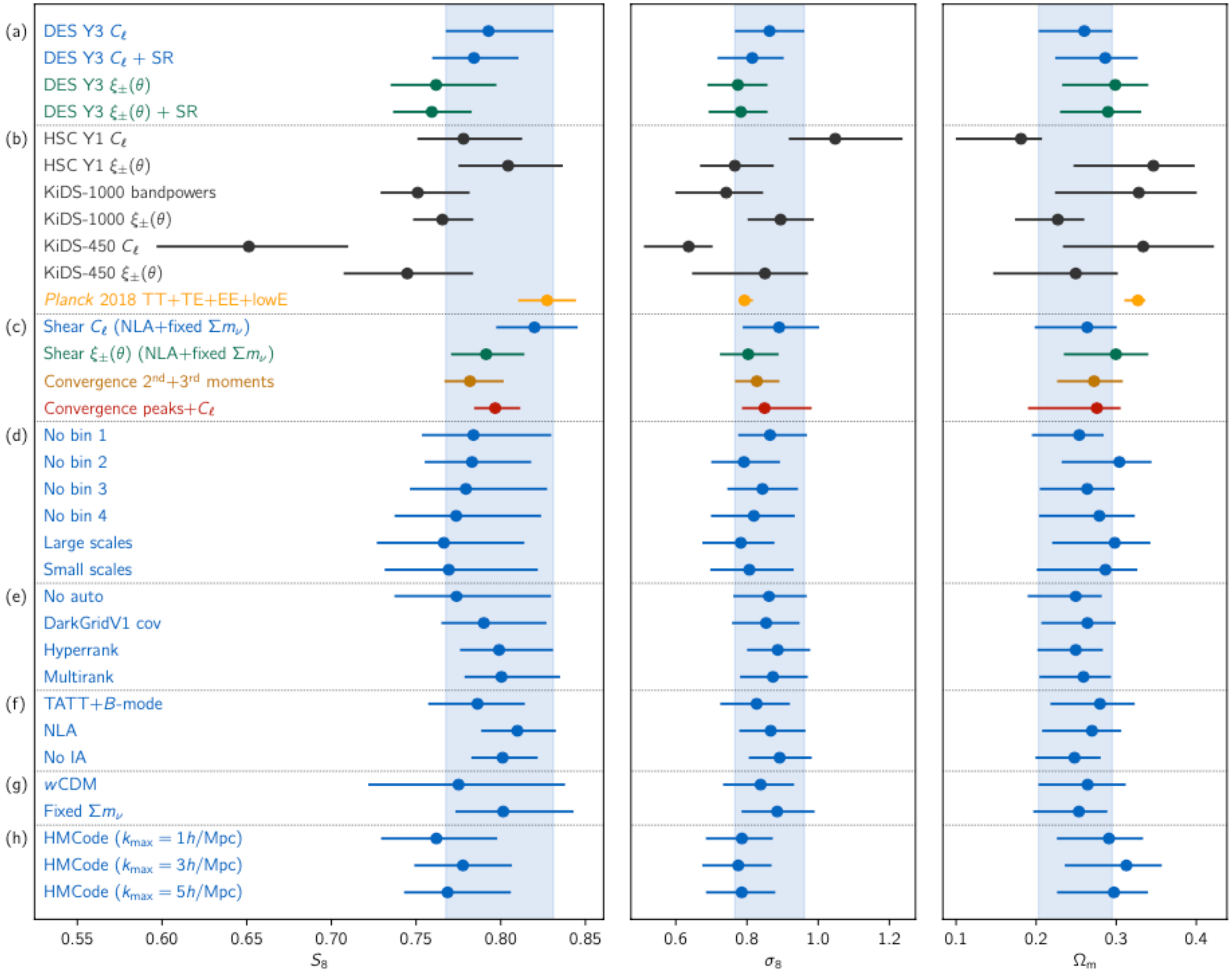
The other tension

$$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$$

$$\sigma_R^2 = \frac{1}{2\pi^2}\int dk\ k^2\ P(k)\ |W(kR)|^2\ ;\quad R = 8\ \mathrm{Mpc/h}$$

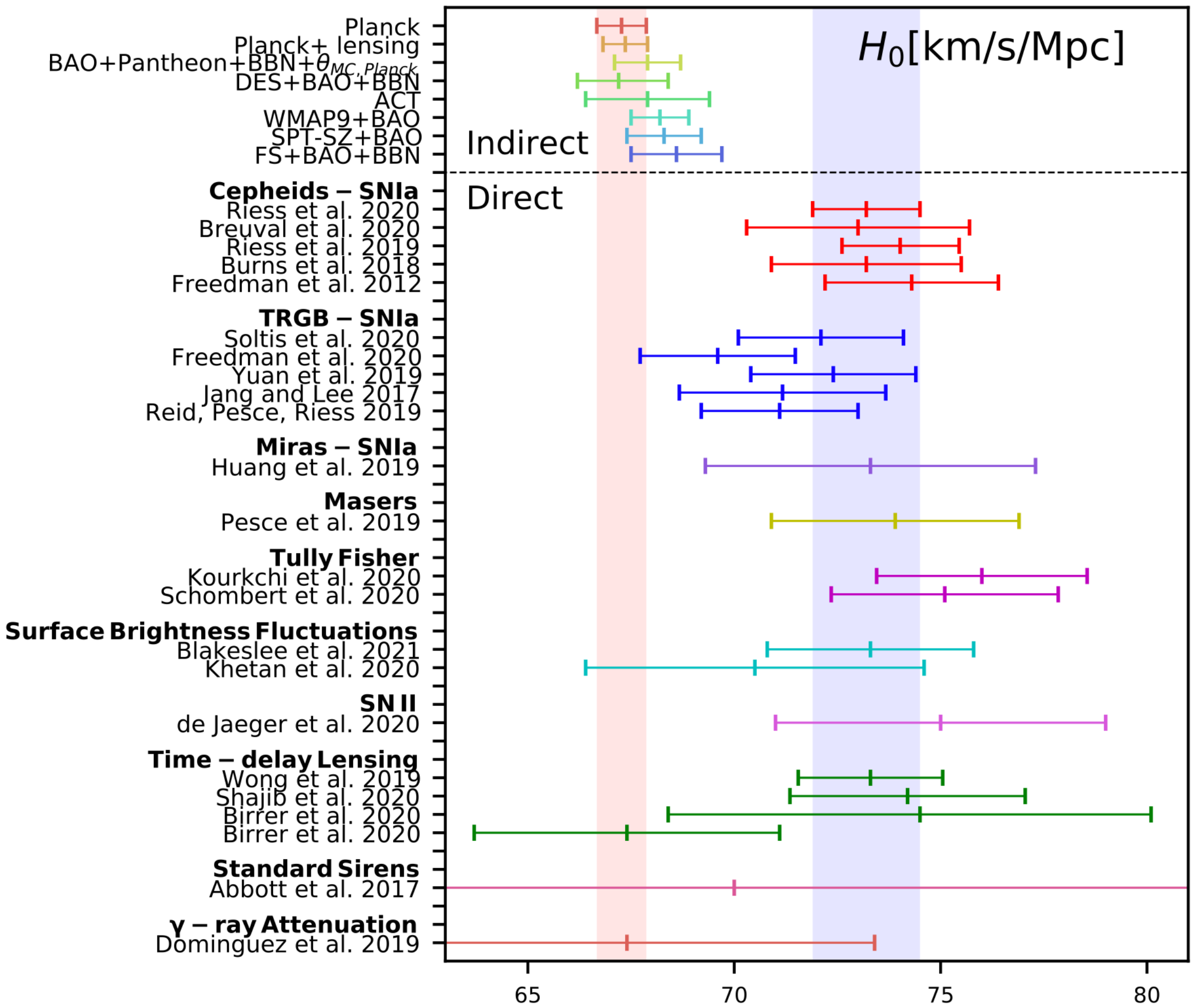


arXiv:2203.06142



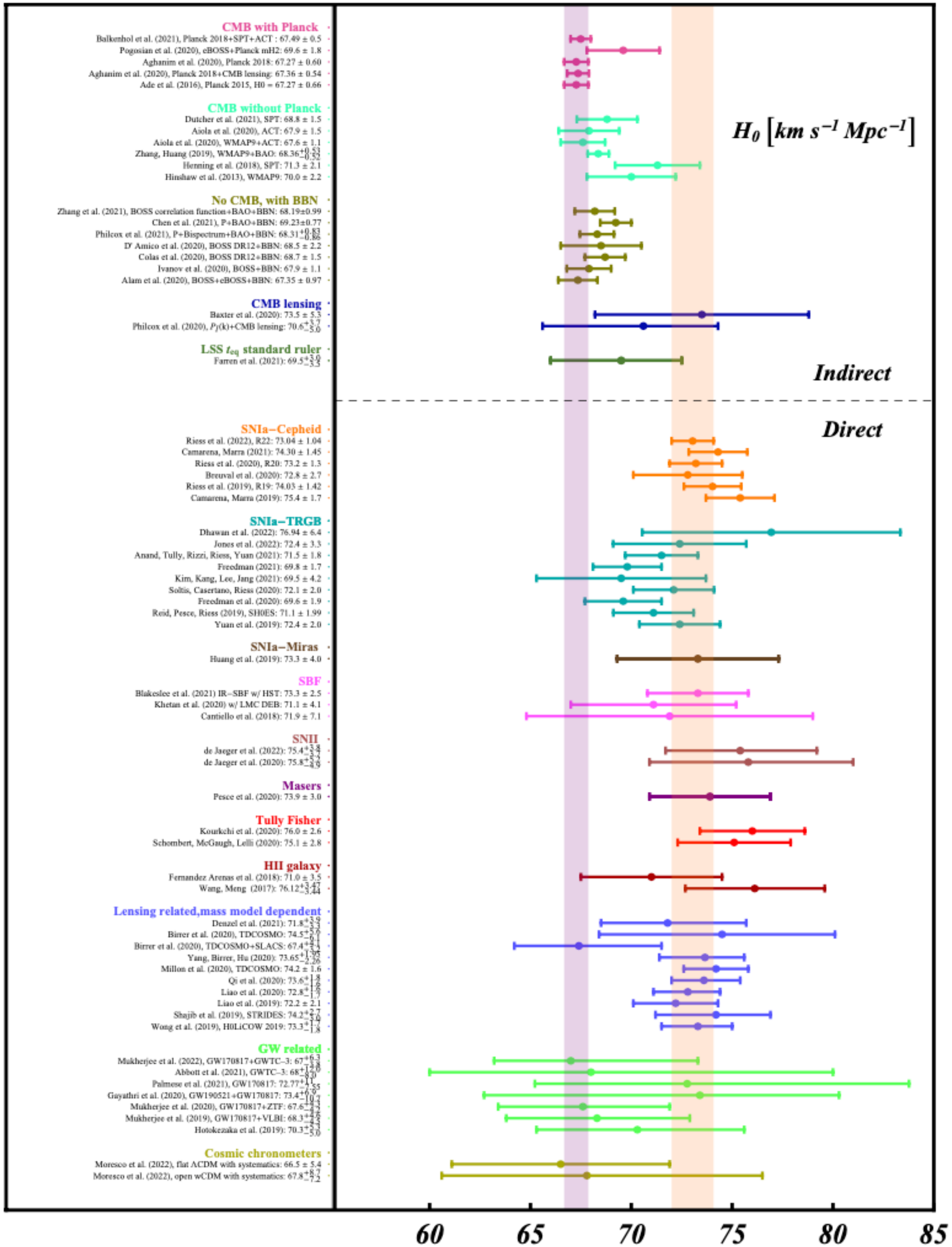
Dark Energy Survey Year 3 results: cosmological constraints from the analysis of cosmic shear in harmonic space
C. Doux et al, arXiv:2203.07128

The Hubble tension



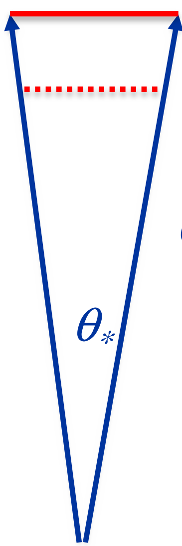
from E. Di Valentino, arXiv:2011.00246

The tension is between measurements that rely on a model to determine *the sound horizon at recombination* and those that do not



arXiv:2203.06142

How to modify LCDM to relieve the tension?



$$r_* = \int_{z_*}^{\infty} \frac{c_S(z)\ dz}{H(z)}$$

$$d_* = \int_0^{z_*} \frac{c\ dz}{H(z)} :$$

CMB fixes $\theta_* = r_*/d_*$

<u>"Early" solutions</u>: smaller r_* requires smaller d_*, and smaller d_* means larger h (no need to modify LCDM at late times)

Ways to make r_* smaller:

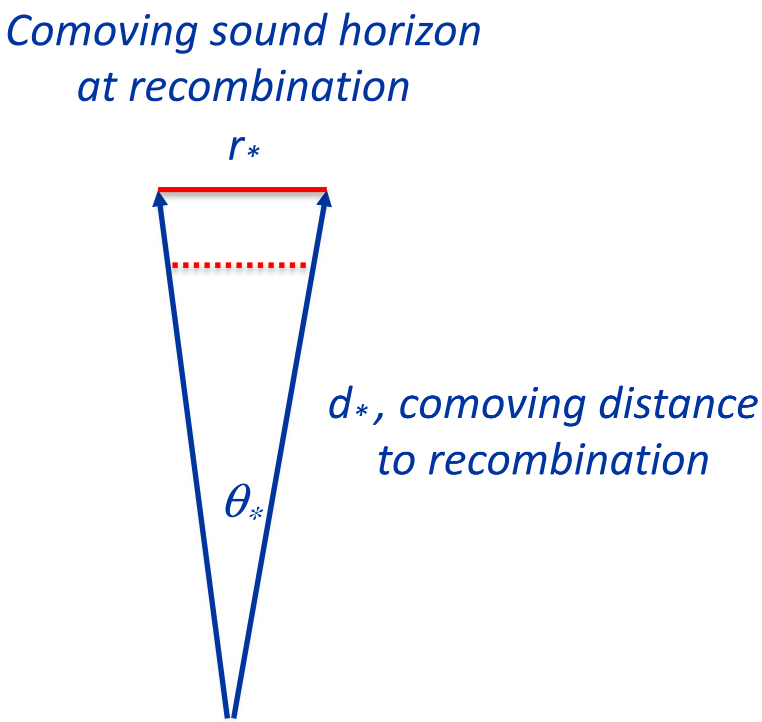
$$r_* = \int_{z_*}^{\infty} \frac{c_S(z)\ dz}{H(z)}$$

Modified recombination: make recombination complete faster

Early Dark Energy: increase the energy density just before recombination

$$H(z) \propto \sqrt{\rho(z)}$$

How to modify LCDM to relieve the tension?



$$r_* = \int_{z_*}^{\infty} \frac{c_S(z)\, dz}{H(z)}$$

$$d_* = \int_0^{z_*} \frac{c\, dz}{H(z)}$$

CMB fixes $\theta_* = r_*/d_*$

<u>"Late" solutions</u>: keep r_* and d_* unchanged, but modify $\rho(z)$ at late times so that H_0 is larger

$$H^2(z) \approx H_0^2 \left[\Omega_{\rm M}(1+z)^3 + X(z)\right]$$

Dark Energy,
Modified Gravity,
Interacting Dark Matter
Decaying Dark Matter, ...

Why it is challenging to (fully) relieve the Hubble tension by reducing the sound horizon

$$\theta^{-1}(z) = \frac{D(z)}{r_d} = \int_0^z \frac{2998\ \mathrm{Mpc}\ \mathrm{d}z'}{r_d h \sqrt{\Omega_m (1+z')^3 + 1 - \Omega_m}} = \int_0^z \frac{2998\ \mathrm{Mpc}\ \mathrm{d}z'}{r_d \omega_m^{1/2} \sqrt{(1+z')^3 + h^2/\omega_m - 1}}$$

CMB and BAO provide measurements of this at multiple redshifts z

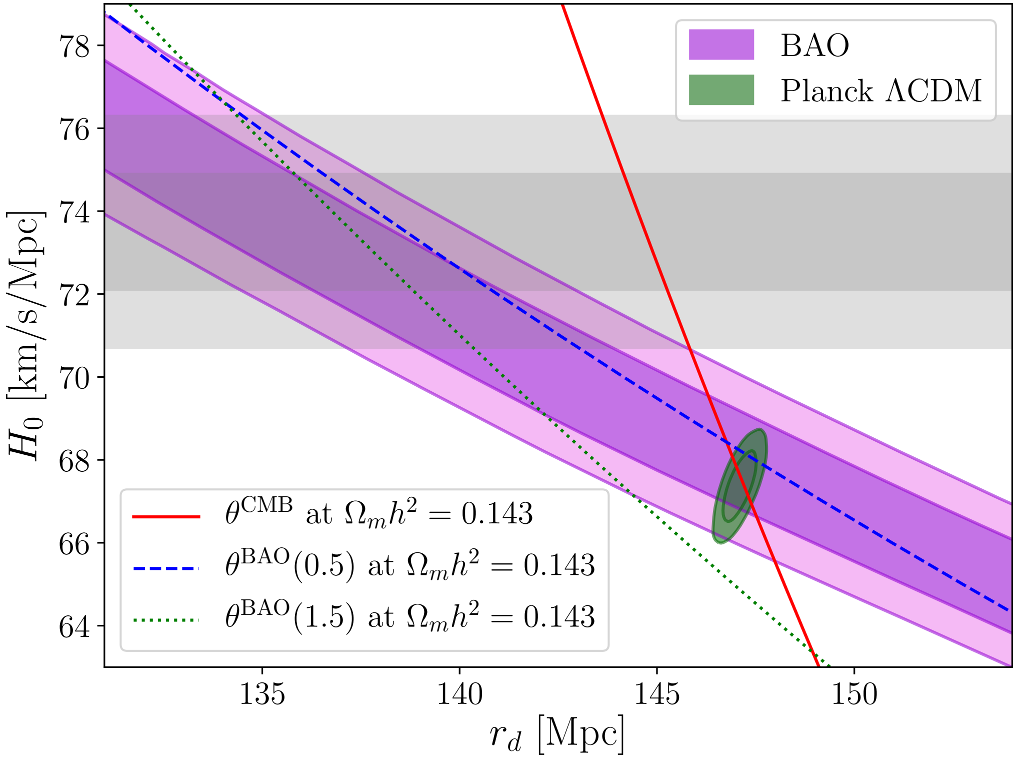
For a given matter density parameter ω_m, each $\theta(z)$ defines a line in the $r_d - h$ plane

$$r_d(h)\Big|_{\omega_m, z} = \theta(z) \int_0^z \frac{2998\ \mathrm{Mpc}\ \mathrm{d}z'}{\omega_m^{1/2} \sqrt{(1+z')^3 + h^2/\omega_m - 1}} \quad \Rightarrow \quad h = h(r_d)\Big|_{\omega_m, z}$$

Why it is challenging to (fully) relieve the Hubble tension by reducing the sound horizon

For a given matter density parameter ω_m, each $\theta(z)$ defines a line in the $r_d - h$ plane

$$r_d(h)\Big|_{\omega_m,z} = \theta(z)\int_0^z \frac{2998\ \mathrm{Mpc}\ \mathrm{d}z'}{\omega_m^{1/2}\sqrt{(1+z')^3 + h^2/\omega_m - 1}} \Rightarrow h = h(r_d)\Big|_{\omega_m,z}$$



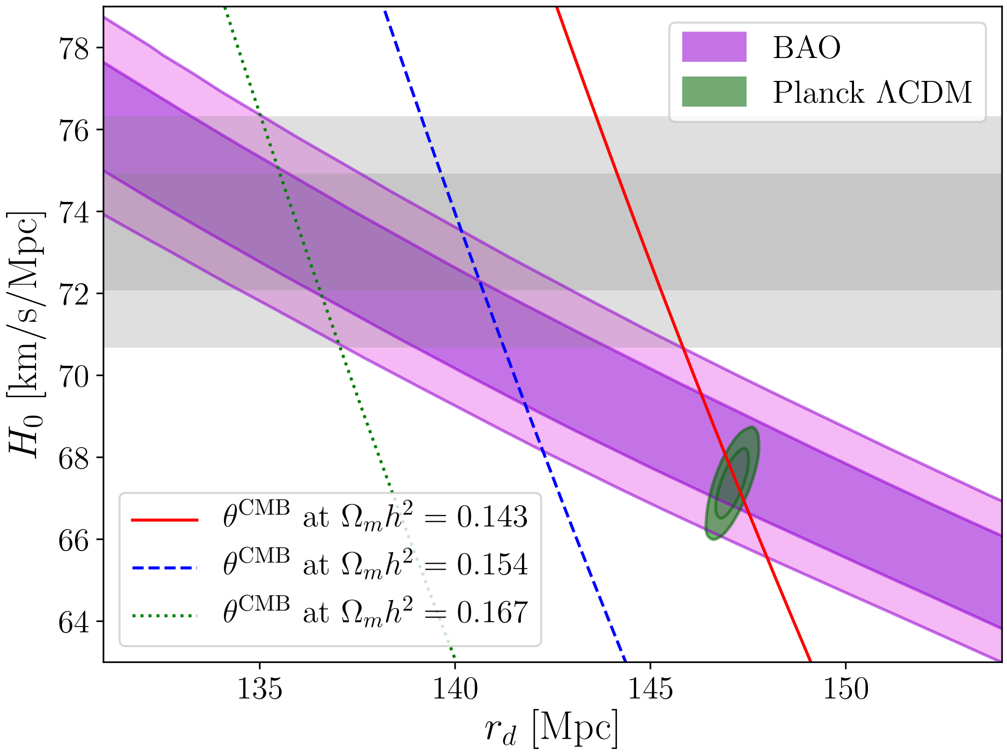
We can make the CMB best fit H_0 larger by making r_d smaller and moving up the red line

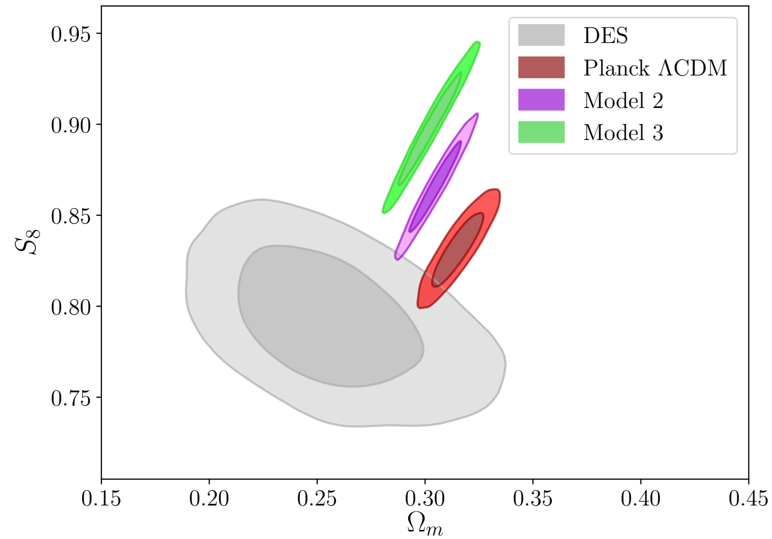
But that creates a tension with the BAO constraint

K. Jedamzik, LP, G.-B. Zhao, arXiv:2010.04158

Why it is challenging to (fully) relieve the Hubble tension by reducing the sound horizon

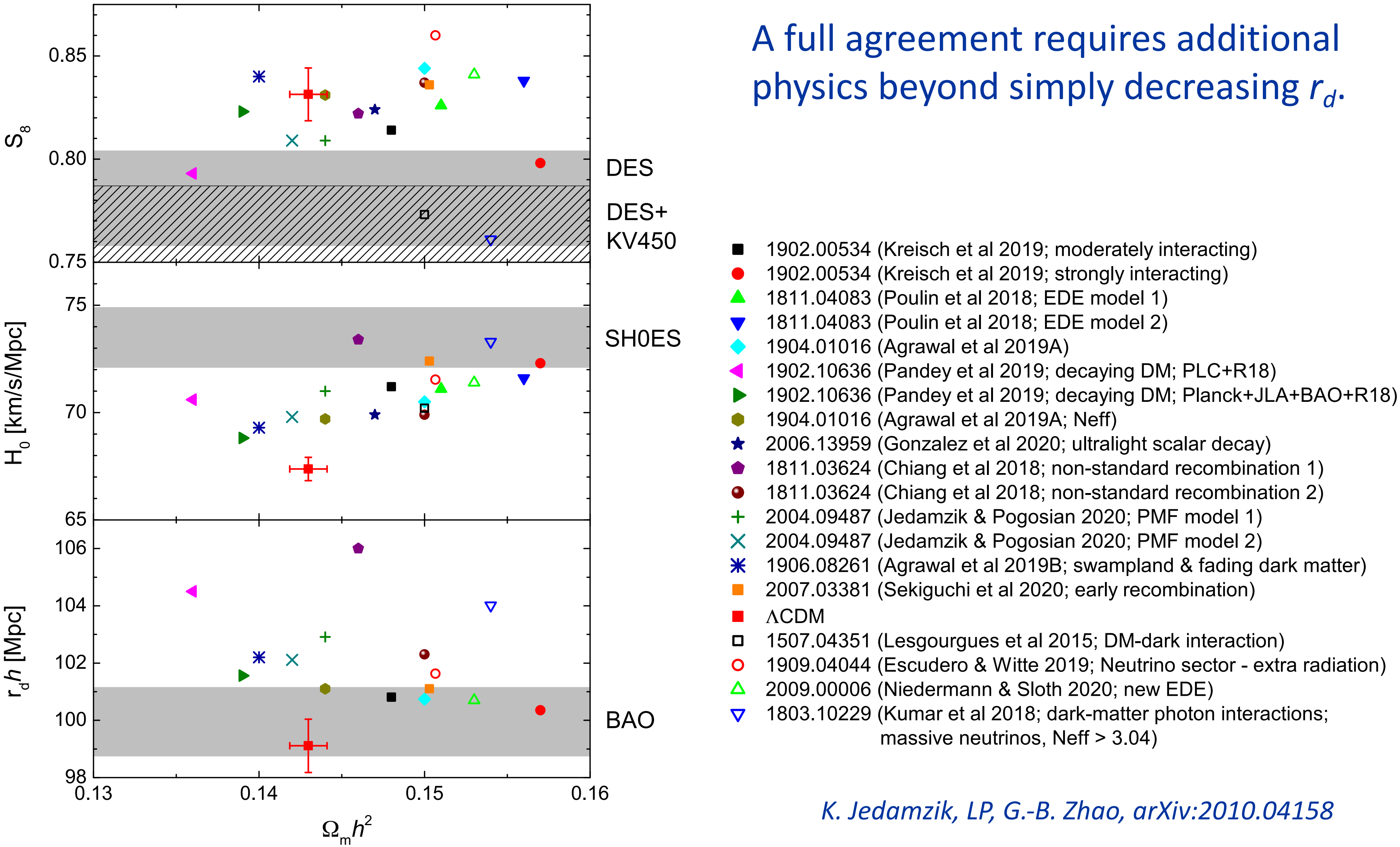
- To make the CMB line pass through the BAO/SH0ES overlap region one needs to increase ω_m
- A larger ω_m creates tension with weak lensing data, e.g. DES and KiDS, making the S_8 tension worse





K. Jedamzik, LP, G.-B. Zhao, arXiv:2010.04158

Reduced sound horizon models vs BAO, SH0ES and WL



A full agreement requires additional physics beyond simply decreasing r_d.

K. Jedamzik, LP, G.-B. Zhao, arXiv:2010.04158

Difficulty with late time-solutions

The intrinsic SNIa magnitude measured by SH0ES

$$\sqrt{\frac{L_s}{F}} \equiv d_L(z) = (1+z)\int_0^z \frac{c\,dz'}{H(z')}$$

Pantheon SNIa data: the observed SNIa magnitudes at many redshifts

The sound horizon predicted by the CMB best fit model

$$\frac{\ell}{\theta} \equiv d_A(z) = \frac{1}{(1+z)}\int_0^z \frac{c\,dz'}{H(z')}$$

BAO data: the angular size of the sound horizon at many redshifts

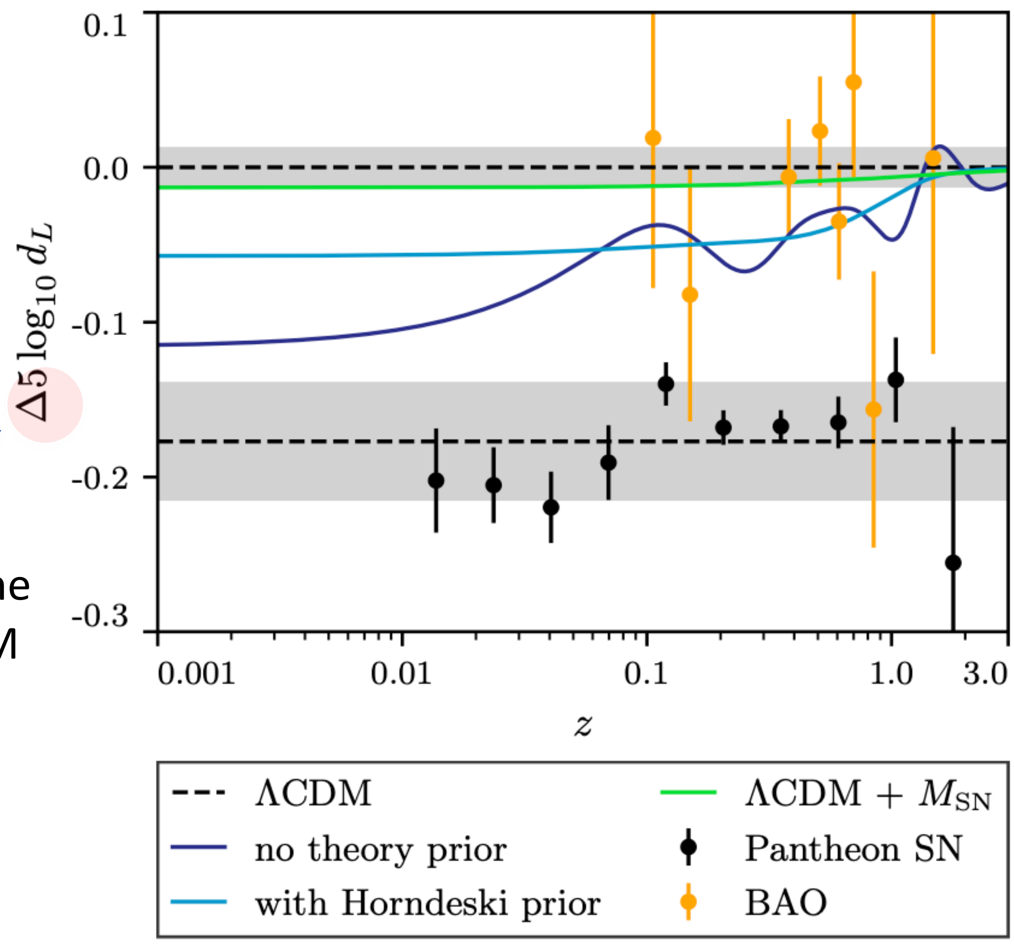
Can express all data in $d_L(z)$:

$$d_L(z) = (1+z)^2 d_A(z)$$

For historical reasons, astronomers work with $m = M + 25 + 5\log_{10} d_L$

Difficulty with late time-solutions

from Raveri et al, arXiv:2107.12992



Note, we plot the difference from the CMB best fit LCDM

It is challenging to come up with a model that can pass through both the BAO and the SNIa data without altering the sound horizon r_d

What kind of new physics can help reduce the sound horizon?

Neutrinos/dark radiation

Early Dark Energy

Varying constants

Primordial Magnetic Fields

Additional relativistic particles

There are good reasons to consider this possibility!

- Our understanding of the neutrino sector is incomplete
- If Dark Matter is real, then the dark sector could include radiation
- A lot of effort has been invested in studying constraints on extra relativistic species with current and future CMB experiments (regardless of the Hubble tension)

The h - N_{eff} degeneracy

Fixing the fractional densities, Ω, keeps the acoustic scale θ_* fixed:

$$\theta_* = \frac{r_*}{d_*} = \frac{\int_{z*}^{\infty} \frac{c_S\ \mathrm{d}z'}{H(z')}}{\int_0^z \frac{c\ \mathrm{d}z'}{H(z')}} = \frac{\int_{z*}^{\infty} \frac{c_S\ \mathrm{d}z'}{\sqrt{\Omega_r(1+z')^4+\Omega_m(1+z')^3+\Omega_\Lambda}}}{\int_0^z \frac{c\ \mathrm{d}z'}{\sqrt{\Omega_r(1+z')^4+\Omega_m(1+z')^3+\Omega_\Lambda}}}$$

One can increase h and N_{eff} simultaneously, while keeping Ω_r fixed:

$$\Omega_r = 4.18 \cdot 10^{-5} h^{-2} \left(\frac{T_0}{2.7255\mathrm{K}}\right)^4 \left(\frac{1+\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}}{1+\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} 3.044}\right)$$

$$H_0 \simeq \left(67.5 + 6.2\,\Delta N_{\mathrm{eff}}^{\mathrm{CMB}}\right)\ \mathrm{km/s/Mpc}$$ *(Vagnozzi, arXiv:1907.07569)*

(Note: increasing h increases the physical densities $\omega = \Omega h^2$, reducing r_*)

$$r_* = \int_{z*}^{\infty} \frac{c_S\ \mathrm{d}z'}{H(z')} = \int_0^z \frac{c_S\ \mathrm{d}z'}{\sqrt{\omega_r(1+z')^4 + \omega_m(1+z')^3 + \omega_\Lambda}}$$

Why simply increasing N_{eff} does not work?

- Big Bang Nucleosynthesis (BBN) constrains the allowed number of relativistic species (but one can evade this constraint by producing the extra radiation after the BBN and before CMB)

- Phase shift in the CMB acoustic peaks:
  neutrino perturbations propagate faster than the sound of the photon fluid and generate metric perturbations beyond the acoustic horizon

- Enhanced Silk Damping:
  while θ_* remains the same, the angular scale of diffusion damping θ_d is increased, suppressing CMB anisotropies at lower l

Bashinsky and Seljak, astro-ph/0310198
Hou et al, arXiv:1104.2333
Schoneberg, Lesgourgues, Hooper, arXiv:1907.11594

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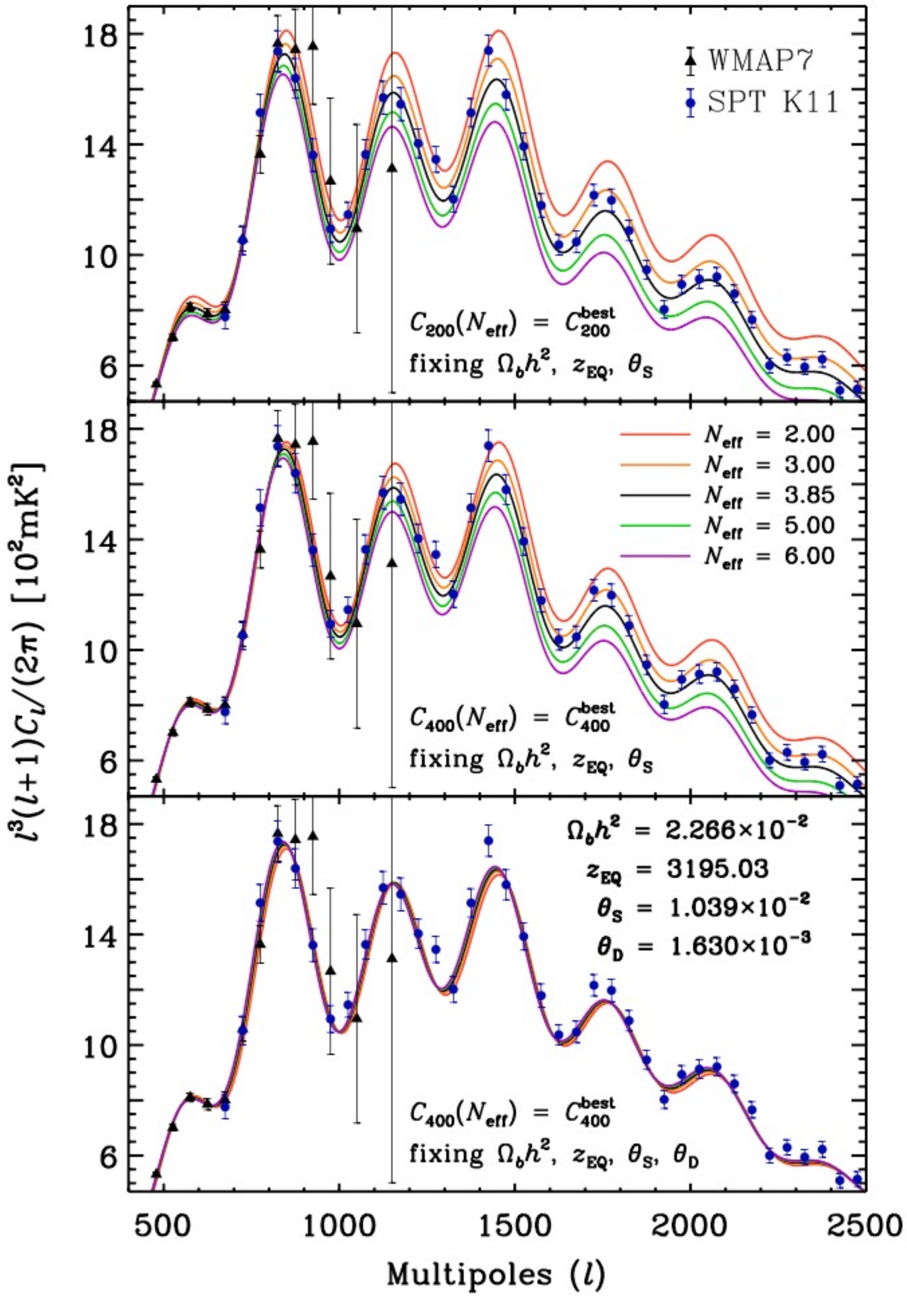
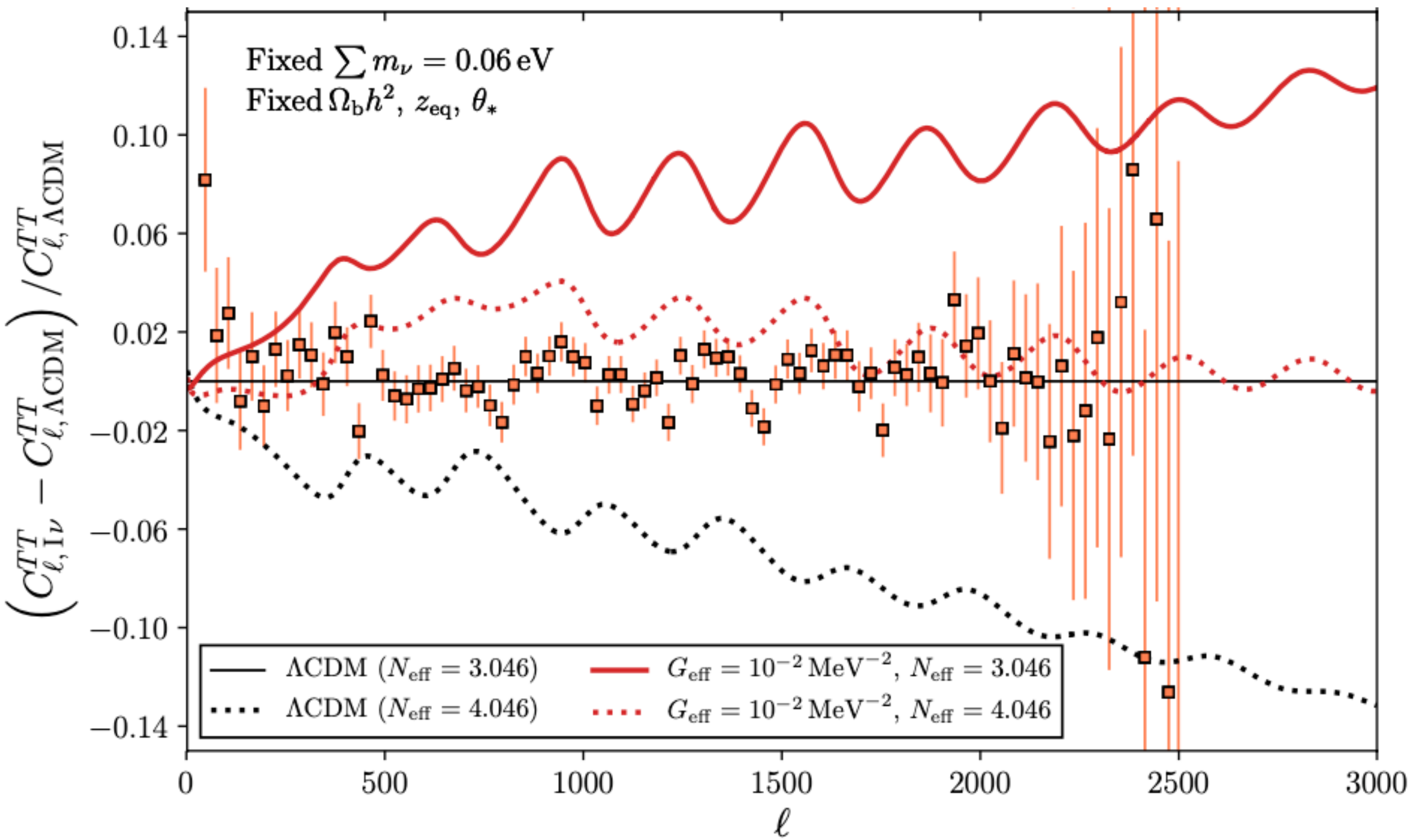


Hou, Keisler, Knox, Millea and Reichardt, arXiv:1104.2333

Interacting neutrinos: a way out?

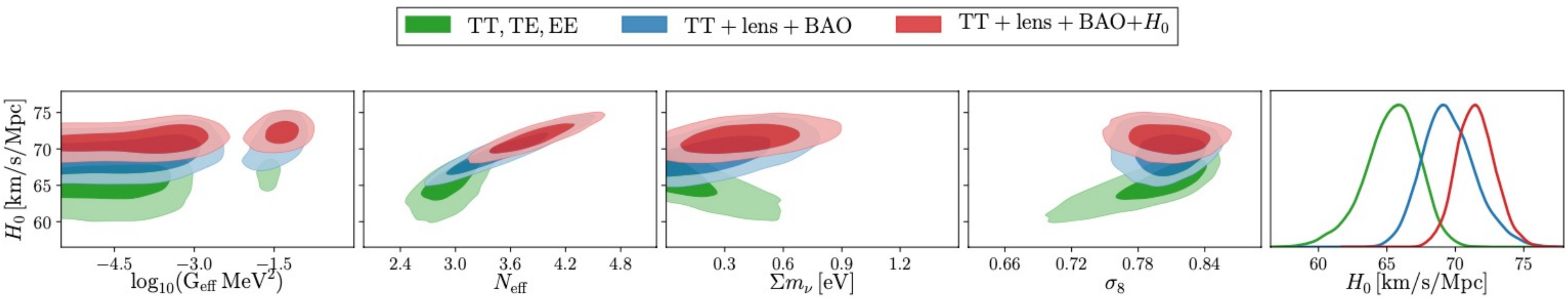
Neutrino interactions would delay the onset of free-streaming and compensate for the excess damping



Kreisch, Cyr-Racine and Dore', arXiv:1902.00534

Interacting neutrinos: a way out?

In addition to adding the interactions, also vary the net neutrino mass

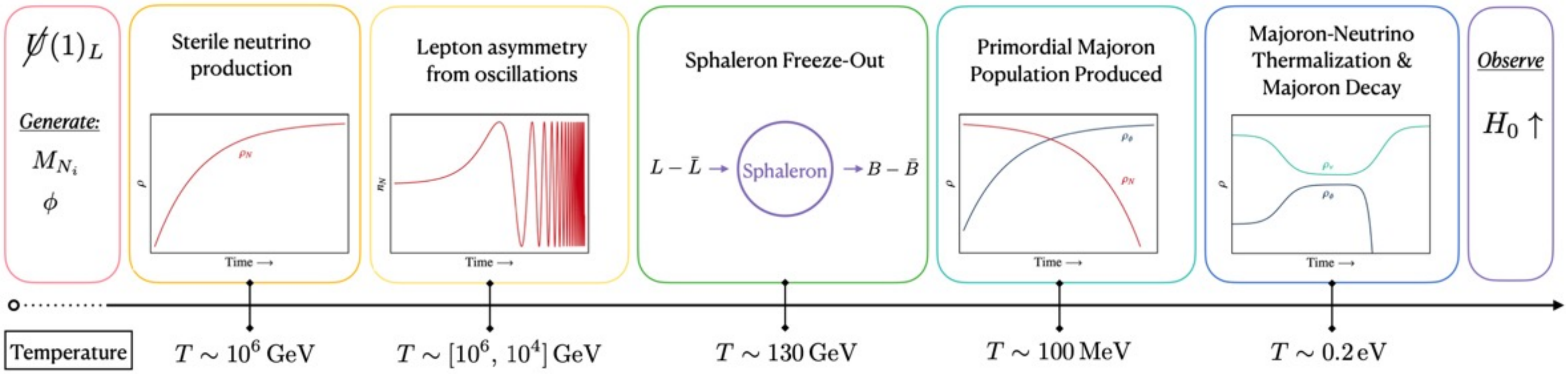


It is challenging to design dark radiation models that fit both CMB temperature and polarization data

(which does not mean it is impossible!)

Kreisch, Cyr-Racine and Dore', arXiv:1902.00534

The Majoron



Simultaneously addresses the origin of neutrino masses, the baryon asymmetry, and the H_0 tension.

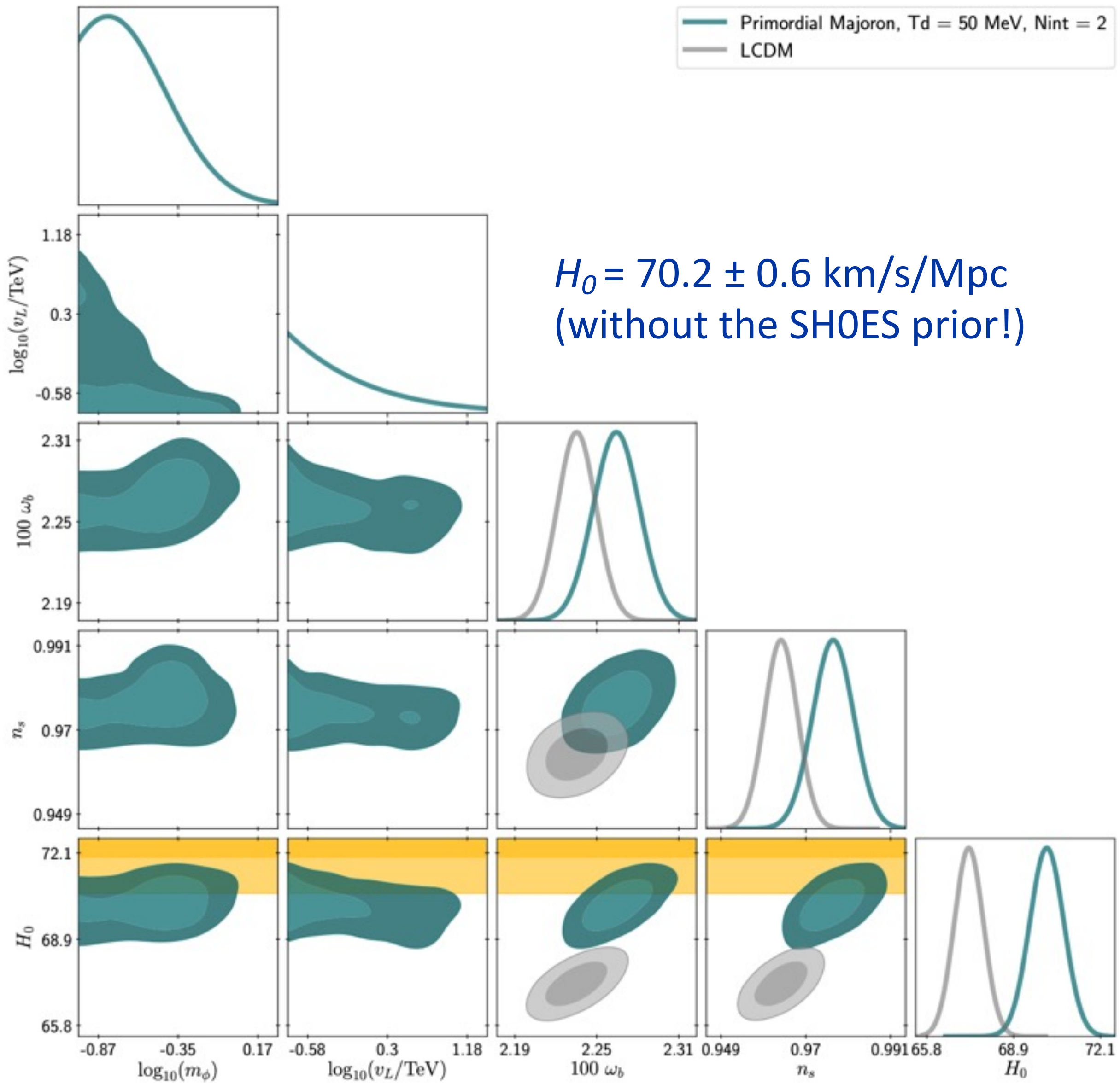
Extra sterile neutrino

Time-varying N_{eff} and neutrino interaction rate

Non-trivial evolution of H(z)

The Hubble Tension as a Hint of Leptogenesis and Neutrino Mass Generation, Escudero and Witte, arXiv:2103.03249

The Majoron



H_0 = 70.2 ± 0.6 km/s/Mpc
(without the SH0ES prior!)

Escudero and Witte, arXiv:2103.03249

Early Dark Energy

$$r_* = \int_{z_*}^{\infty} \frac{c_S(z)\, dz}{H(z)}$$

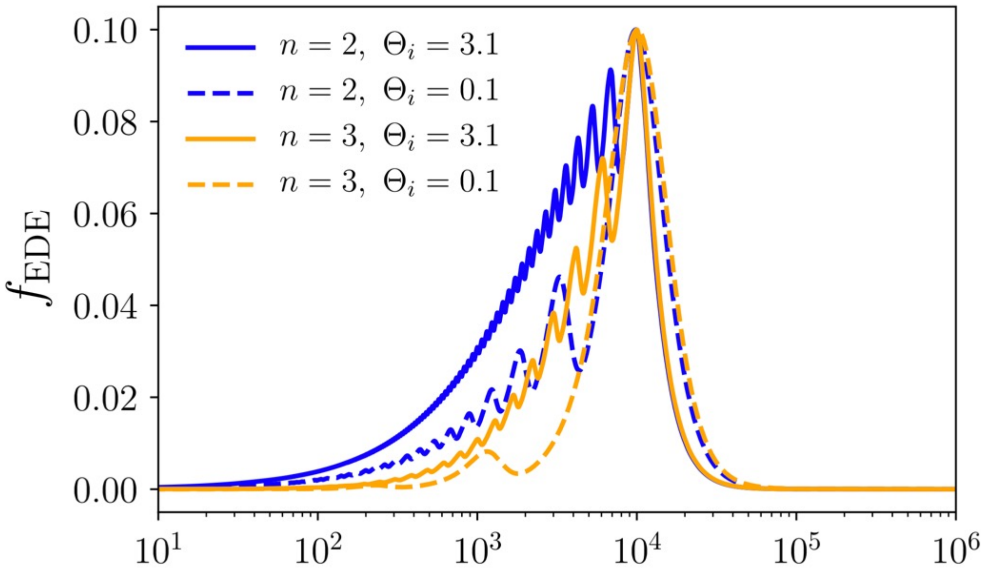
Increase the energy density just before recombination

$$H = H_0 E(a) = H_0 \sqrt{\Omega_m(a) + \Omega_r(a) + \Omega_\Lambda + \Omega_\phi(a)}$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_n(\phi)$$

$$P_\phi = \frac{1}{2}\dot{\phi}^2 - V_n(\phi)$$

$$V_n(\phi) = m^2 f^2 [1 - \cos(\phi/f)]^n$$



Free parameters: z_c, $f_{EDE}(z_c)$, $\theta_i = \phi_i/f$

Karwal and Kamionkowski, arXiv:1608.01309
Smith, Poulin, Amin, arXiv:1908.06995

Is Early Dark Energy always fine-tuned?

Couple EDE to neutrino(s) with mass $\mathcal{O}$(1 eV)

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}{}^2 R(g)}{2} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi)\right] + S_\nu[\tilde{g}_{\mu\nu}],$$

$$\tilde{g}_{\mu\nu} = e^{2\beta\frac{\phi}{M_{\rm pl}}} g_{\mu\nu}$$

Natural coincidence: neutrino temperature at z = 3000 is 0.51 eV, so they turn from relativistic to non-relativistic just before recombination

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \frac{\beta}{M_{\rm pl}}\Theta(\nu)$$

← The trace of the neutrino stress-energy tensor becomes non-zero after neutrinos become non-relativistic

If ϕ is initially at the minimum of *V(*ϕ*)*, the (suddenly) non-zero neutrino trace will kick it up the potential, after which it will slowly roll down and behave like EDE

Sakstein and Trodden, arXiv:1911.117602

Hints of Early Dark Energy in *Planck*, SPT, and ACT data: new physics or systematics?

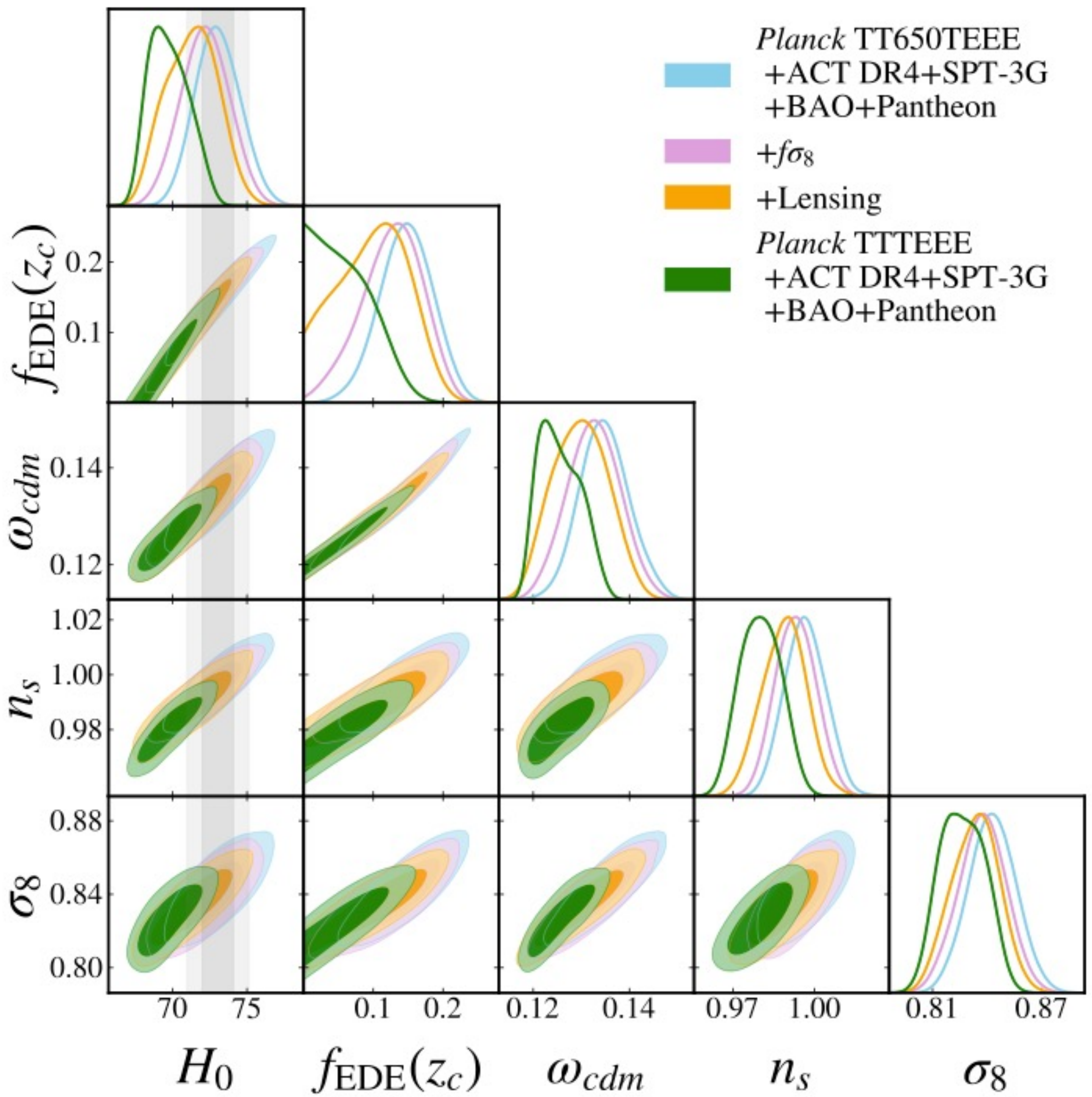
Tristan L. Smith,[1] Matteo Lucca,[2] Vivian Poulin,[3] Guillermo F. Abellan,[3] Lennart Balkenhol,[4] Karim Benabed,[5] Silvia Galli,[5] and Riccardo Murgia[3]

[1] *Department of Physics and Astronomy, Swarthmore College, Swarthmore, PA 19081, USA*
[2] *Service de Physique Théorique, Université Libre de Bruxelles, C.P. 225, B-1050 Brussels, Belgium*
[3] *Laboratoire Univers & Particules de Montpellier (LUPM), CNRS & Université de Montpellier (UMR-5299), Place Eugène Bataillon, F-34095 Montpellier Cedex 05, France*
[4] *School of Physics, University of Melbourne, Parkville, VIC 3010, Australia*
[5] *Sorbonne Université, CNRS, UMR 7095, Institut d'Astrophysique de Paris, 98 bis bd Arago, 75014 Paris, France*

We investigate constraints on early dark energy (EDE) using ACT DR4, SPT-3G 2018, *Planck* polarization, and restricted *Planck* temperature data (at $\ell < 650$), finding a 3.3σ preference ($\Delta\chi^2 = -16.2$ for three additional degrees of freedom) for EDE over ΛCDM. The EDE contributes a maximum fractional energy density of $f_{\rm EDE}(z_c) = 0.163^{+0.047}_{-0.04}$ at a redshift $z_c = 3357 \pm 200$ and leads to a CMB inferred value of the Hubble constant $H_0 = 74.2^{+1.9}_{-2.1}$ km/s/Mpc. We find that *Planck* and ACT DR4 data provide the majority of the improvement in χ^2, and that the inclusion of SPT-3G pulls the posterior of $f_{\rm EDE}(z_c)$ away from ΛCDM. This is the first time that a moderate preference for EDE has been reported for these three combined CMB data sets. We find that including measurements of supernovae luminosity distances and the baryon acoustic oscillation standard ruler only minimally affects the preference (3.0σ), while measurements that probe the clustering of matter at late times – the lensing potential power spectrum from *Planck* and $f\sigma_8$ from BOSS – decrease the significance of the preference to 2.6σ. Conversely, adding a prior on the H_0 value as reported by the SH$_0$ES collaboration increases the preference to the $4-5\sigma$ level. In the absence of this prior, the inclusion of *Planck* TT data at $\ell > 1300$ reduces the preference from 3.0σ to 2.3σ and the constraint on $f_{\rm EDE}(z_c)$ becomes compatible with ΛCDM at 1σ. We explore whether systematic errors in the *Planck* polarization data may affect our conclusions and find that changing the TE polarization efficiencies significantly reduces the *Planck* preference for EDE. More work will

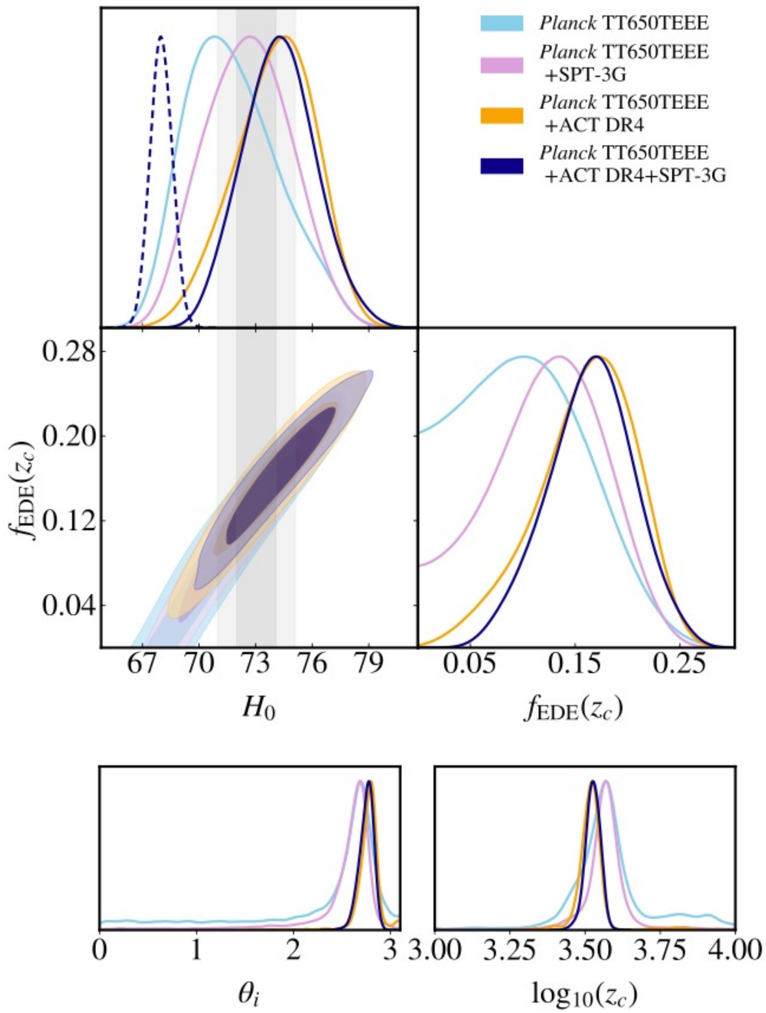
Smith et al, arXiv:2202.09379

Hints of EDE in CMB



Smith et al, arXiv:2202.09379

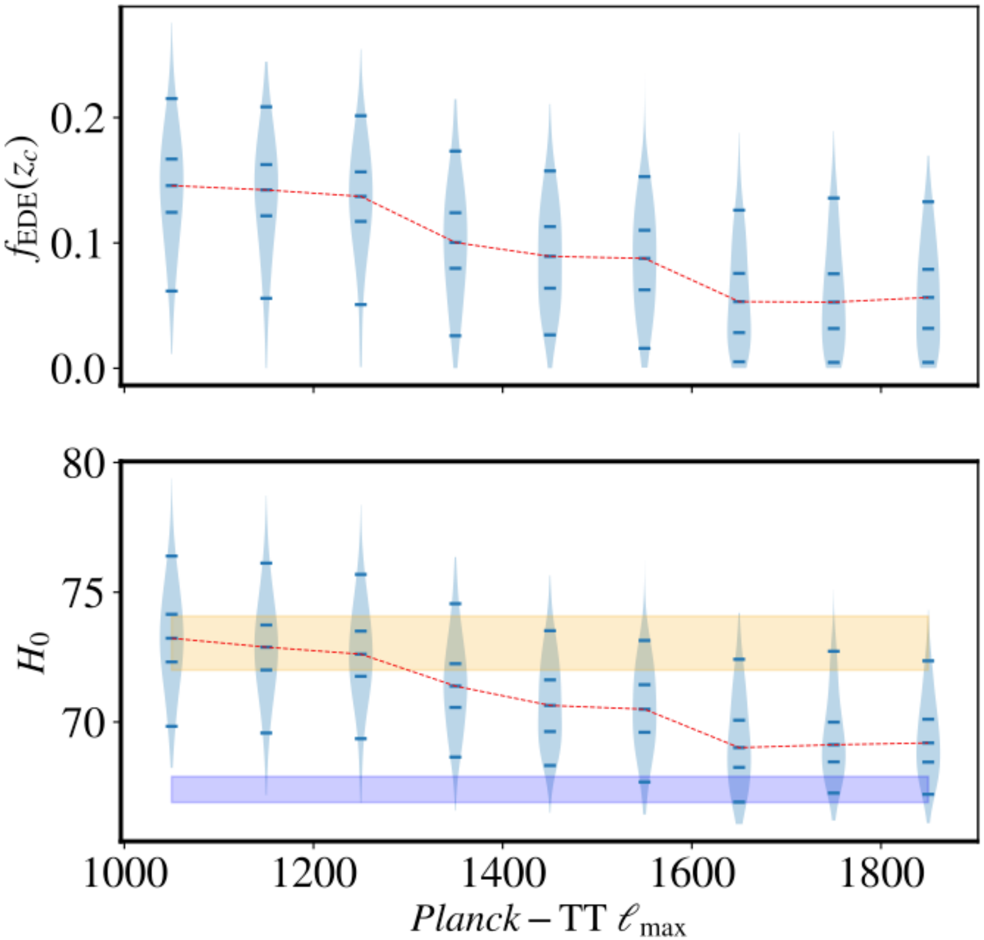
Hints of EDE in CMB



Model	ΛCDM	EDE
$f_{\rm EDE}(z_c)$	–	$0.163(0.179)^{+0.047}_{-0.04}$
$\log_{10}(z_c)$	–	$3.526(3.528)^{+0.028}_{-0.024}$
θ_i	–	$2.784(2.806)^{+0.098}_{-0.093}$
m (eV)	–	$(4.38 \pm 0.49) \times 10^{-28}$
f (Mpl)	–	0.213 ± 0.035
H_0 [km/s/Mpc]	$68.02(67.81)^{+0.64}_{-0.6}$	$74.2(74.83)^{+1.9}_{-2.1}$
$100\ \omega_b$	$2.253(2.249)^{+0.014}_{-0.013}$	$2.279(2.278)^{+0.018}_{-0.02}$
$\omega_{\rm cdm}$	$0.1186(0.1191)^{+0.0014}_{-0.0015}$	$0.1356(0.1372)^{+0.0053}_{-0.0059}$
$10^9 A_s$	$2.088(2.092)^{+0.035}_{-0.033}$	$2.145(2.146)^{+0.041}_{-0.04}$
n_s	$0.9764(0.9747)^{+0.0046}_{-0.0047}$	$1.001(1.003)^{+0.0091}_{-0.0096}$
$\tau_{\rm reio}$	$0.0510(0.0510)^{+0.0087}_{-0.0078}$	$0.0527(0.052)^{+0.0086}_{-0.0084}$
S_8	$0.817(0.821) \pm 0.017$	$0.829(0.829)^{+0.017}_{-0.019}$
Ω_m	$0.307(0.309)^{+0.008}_{-0.009}$	$0.289(0.287) \pm 0.009$
Age [Gyrs]	$13.77(13.78) \pm 0.023$	$12.84(12.75) \pm 0.27$
$\Delta\chi^2_{\rm min}$ (EDE−ΛCDM)	–	-16.2
Preference over ΛCDM	–	99.9% (3.3σ)

Smith et al, arXiv:2202.09379

Hints of EDE in CMB



Including the Planck TT spectrum at l>1300 dilutes the preference for EDE

Smith et al, arXiv:2202.09379

Varying m_e (and Ω_k)

Energy levels of hydrogen ∝ m_e

Increasing the energy gap increases the temperature of photo-dissociation of hydrogen/helium, thus increasing the redshift of recombination

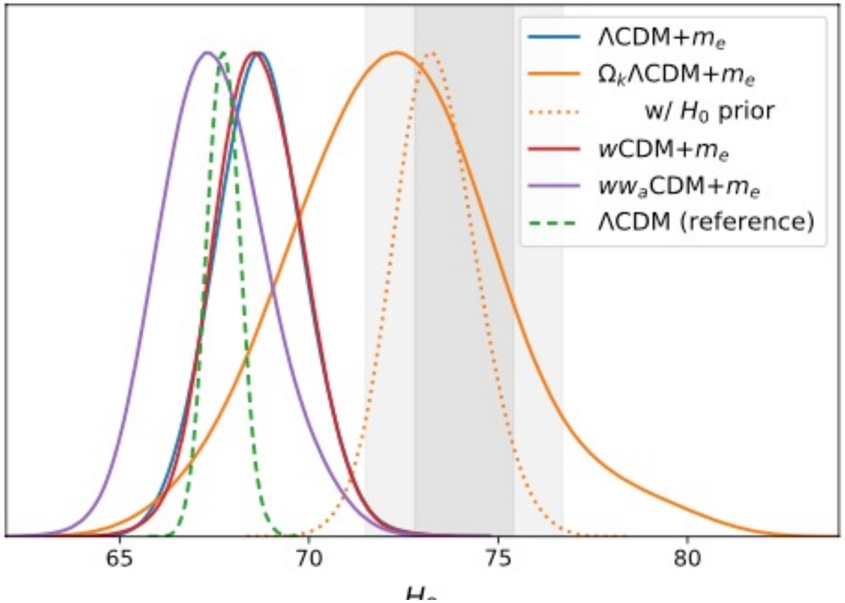
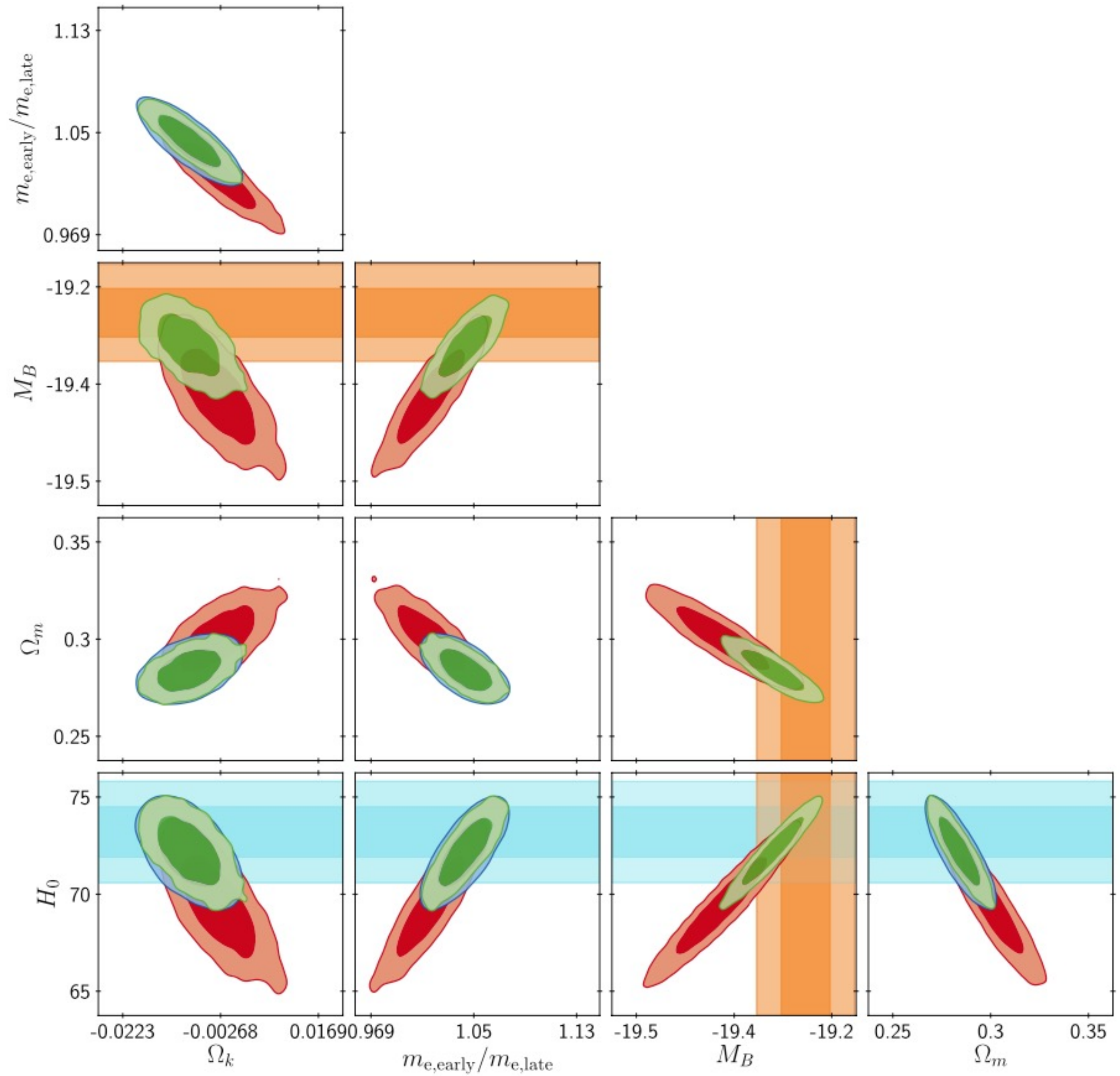


TABLE I: Summary of estimation of H_0 and $\Delta\chi^2_{\rm eff}$.

	varying m_e				constant m_e
	ΛCDM	Ω_kΛCDM	wCDM	ww_aCDM	ΛCDM (reference)
H_0 [km/sec/Mpc] (mean with 68% errors)					
based on CMB+BAO+SNeIa	$68.7^{+1.2}_{-1.2}$	$72.3^{+2.7}_{-2.8}$	$68.7^{+1.1}_{-1.2}$	$67.5^{+1.3}_{-1.6}$	$67.7^{+0.4}_{-0.4}$
based on CMB+BAO+SNeIa+H0	$71.2^{+0.9}_{-0.9}$	$72.9^{+1.0}_{-1.0}$	$71.0^{+1.0}_{-1.0}$	$71.5^{+1.1}_{-0.9}$	$68.4^{+0.4}_{-0.4}$
$\Delta\chi^2_{\rm eff}$ relative to the reference					
based on CMB+BAO+SNeIa+H0	−12.2	−23.5	−12.5	−13.2	0

Sekiguchi and Takahashi, arXiv:2007.03381

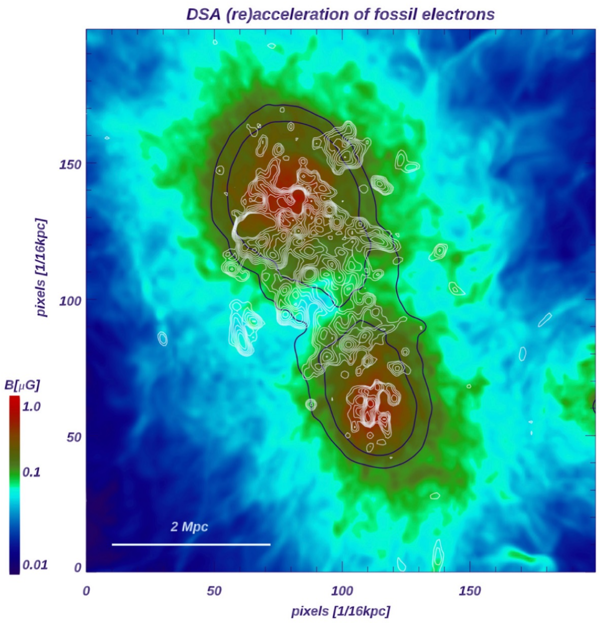
Varying m_e and Ω_k



"The H0 Olympics", Schoneberg et al, arXiv:2107.10291

Cosmic Magnetic Fields

- Micro-Gauss (μG) fields in galaxies and clusters
  - produced during galaxy formation via dynamo?
  - primordial origin? (need 0.01-0.1 nano-Gauss)
  - μG fields seen in proto-galaxies that haven't turned enough times for the dynamo to work!



- Evidence of magnetic fields in voids
  - missing GeV γ-ray halos around TeV blazars
    A. Neronov and I. Vovk, arXiv:1006.3504, Science (2010)

- Magnetic fields in filaments
  - LOFAR observation of a ~3-10 Mpc radio emission ridge connecting two merging galaxy clusters suggests ~0.1-0.3 μG fields in the filament
    F. Govoni et al, arXiv:1906.07584, Science (2019)

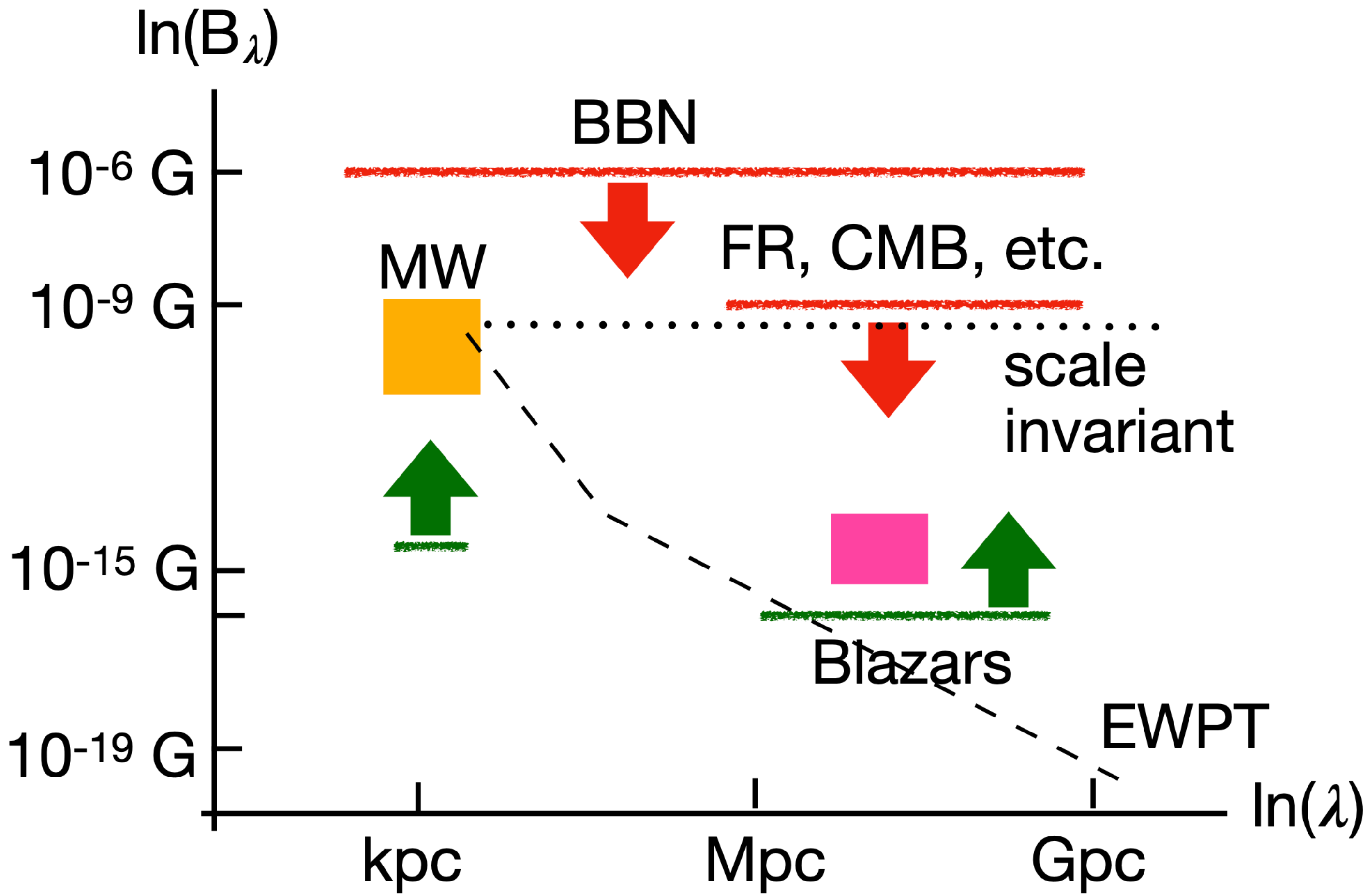
- Generated in the early universe – not "if", but "how much"
  - phase transitions
  - inflationary mechanisms
  - a window into the early universe

See a recent review by T. Vachaspati, arXiv:2010.10525

Stochastic Primordial Magnetic Field (PMF)

- Generated in the early universe, e.g. during the electroweak phase transitions or inflation
- Frozen in the plasma on large scales, the amplitude decreases with the expansion as $B(a)=B_0/a^2$
- PMF generated in a phase transition would have most of its power on small scales
- The simplest Inflation based models predict a scale-invariant PMF

Cosmological Magnetic Fields



Plot from T. Vachaspati, arXiv:2010.10525

How do the magnetic fields help relieve the Hubble tension?

In two sentences:

- Magnetic fields present in the plasma prior to recombination induce baryon inhomogeneities (clumping) on very small (~1kpc) scales, speeding up the recombination
  Jedamzik & Abel, arXiv:1108.2517, JCAP (2013); Jedamzik & Saveliev, arXiv:1804.06115, PRL (2019)

- An earlier completion of recombination results in a smaller sound horizon at decoupling, helping to relieve the H_0 tension
  Jedamzik & LP, arXiv:2004.09487, PRL (2020)

Magneto-Hydro-Dynamics (MHD)

Pressure = $c_s^2\,\rho$ | Gravity | Viscosity | Lorentz force

Navier-Stokes:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + c_s^2 \frac{\nabla \rho}{\rho} + \nabla \Phi = \nu \nabla^2 \mathbf{v} - \frac{1}{4\pi\rho}\mathbf{B} \times (\nabla \times \mathbf{B})$$

Continuity:

$$\frac{\partial \mathbf{v}}{\partial t} + \nabla(\rho \mathbf{v}) = 0$$

Induction:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

MHD at Recombination

-α v

Navier-Stokes: $$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + c_s^2 \frac{\nabla \rho}{\rho} + \nabla \Phi = \nu \nabla^2 \mathbf{v} - \frac{1}{4\pi\rho} \mathbf{B} \times (\nabla \times \mathbf{B})$$

Continuity: $$\frac{\partial \mathbf{v}}{\partial t} + \nabla(\rho \mathbf{v}) = 0$$

Induction: $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Magnetic field induces density inhomogeneities on scales below the photon mean free path

$$\alpha \sim 1/l_\gamma \qquad \frac{1}{2}\nabla B^2 - (\mathbf{B}\cdot\nabla)\mathbf{B}$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} + c_s^2 \frac{\nabla\rho}{\rho} = -\alpha\mathbf{v} - \frac{1}{4\pi\rho}\mathbf{B}\times(\nabla\times\mathbf{B})$$

$c_s^2 = 1/3$ for $L > l_\gamma$
$c_s^2 \ll 1$ for $L < l_\gamma$

Drag set by the photon mean free path l_γ

Pushes baryons towards regions of low magnetic energy density

$L > l_\gamma$ tightly coupled incompressible baryon-photon fluid

$L < l_\gamma$ viscous compressible baryon gas

Plasma develops density fluctuations on small scales (below the photon mean free path)

Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

Inhomogeneities enhance the recombination rate

$$\frac{\mathrm{dn_e}}{\mathrm{d}t} + 3Hn_e = -C\left(\alpha_e n_e^2 - \beta_e n_{H^0} \mathrm{e}^{-h\nu_\alpha/T}\right)$$

The probability of a proton and an electron combining to form H is proportional to $n_p n_e = n_e^2$

Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

Inhomogeneities enhance the recombination rate

$$< \frac{\mathrm{dn_e}}{\mathrm{d}t} + 3Hn_e = -C\left(\alpha_e n_e^2 - \beta_e n_{H^0} \mathrm{e}^{-h\nu_\alpha/T}\right) >$$

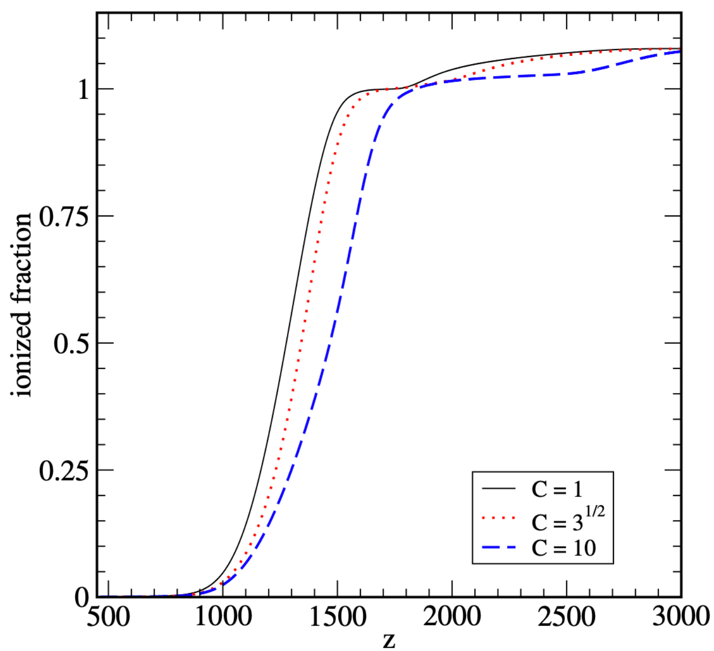
$$n_e = \langle n_e \rangle + \delta n_e \quad \rightarrow \quad \langle n_e^2 \rangle \; > \; \langle n_e \rangle^2$$

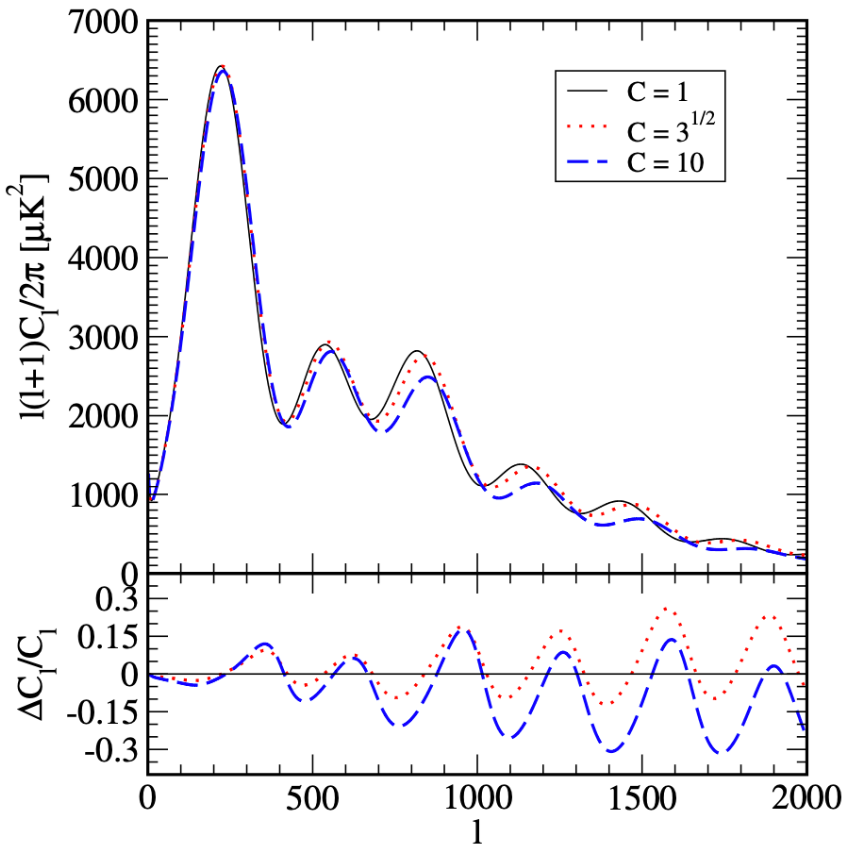
Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

Inhomogeneities enhance the recombination rate

$$< \frac{\mathrm{dn_e}}{\mathrm{d}t} + 3Hn_e = -C\left(\alpha_e n_e^2 - \beta_e n_{H^0} \mathrm{e}^{-h\nu_\alpha/T}\right) >$$

$$\langle n_e^2 \rangle \;>\; \langle n_e \rangle^2$$





Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

Implementation

LCDM with an additional baryon clumping parameter:

$$b = (\langle n_b^2 \rangle - \langle n_b \rangle^2) / \langle n_b \rangle^2$$

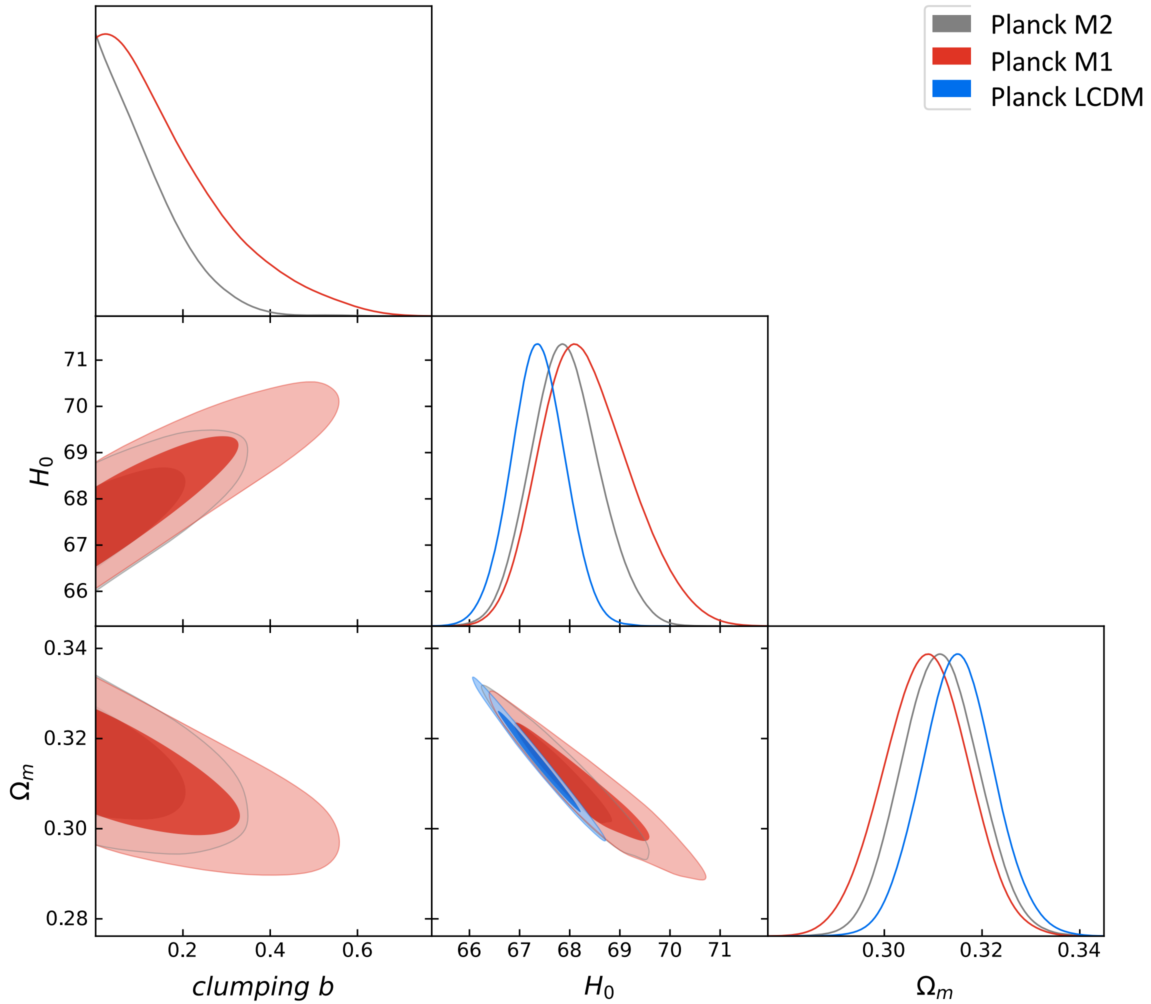
Use the same baryon density PDF model as in Jedamzik and Abel (2013)
(The exact PDF determination from MHD simulations is in progress)

Datasets:

- CMB temperature, polarization and lensing from Planck 2018
- SH0ES, H0LiCOW and MCP determinations of H_0 (H3)
- BAO, Pantheon SNIa, DES Y1

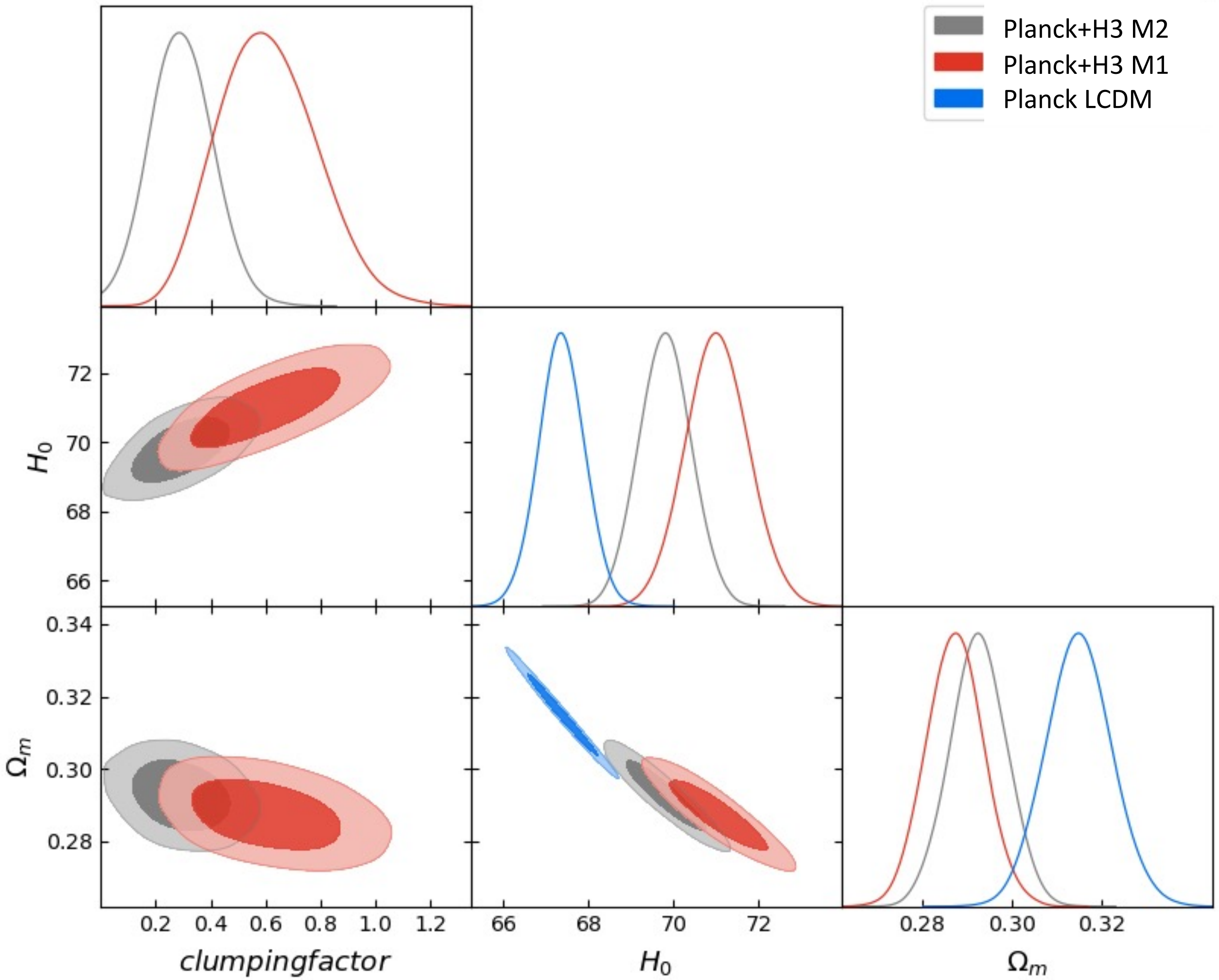
K. Jedamzik and L. Pogosian, arXiv:2004.09487, PRL

Fitting to CMB only



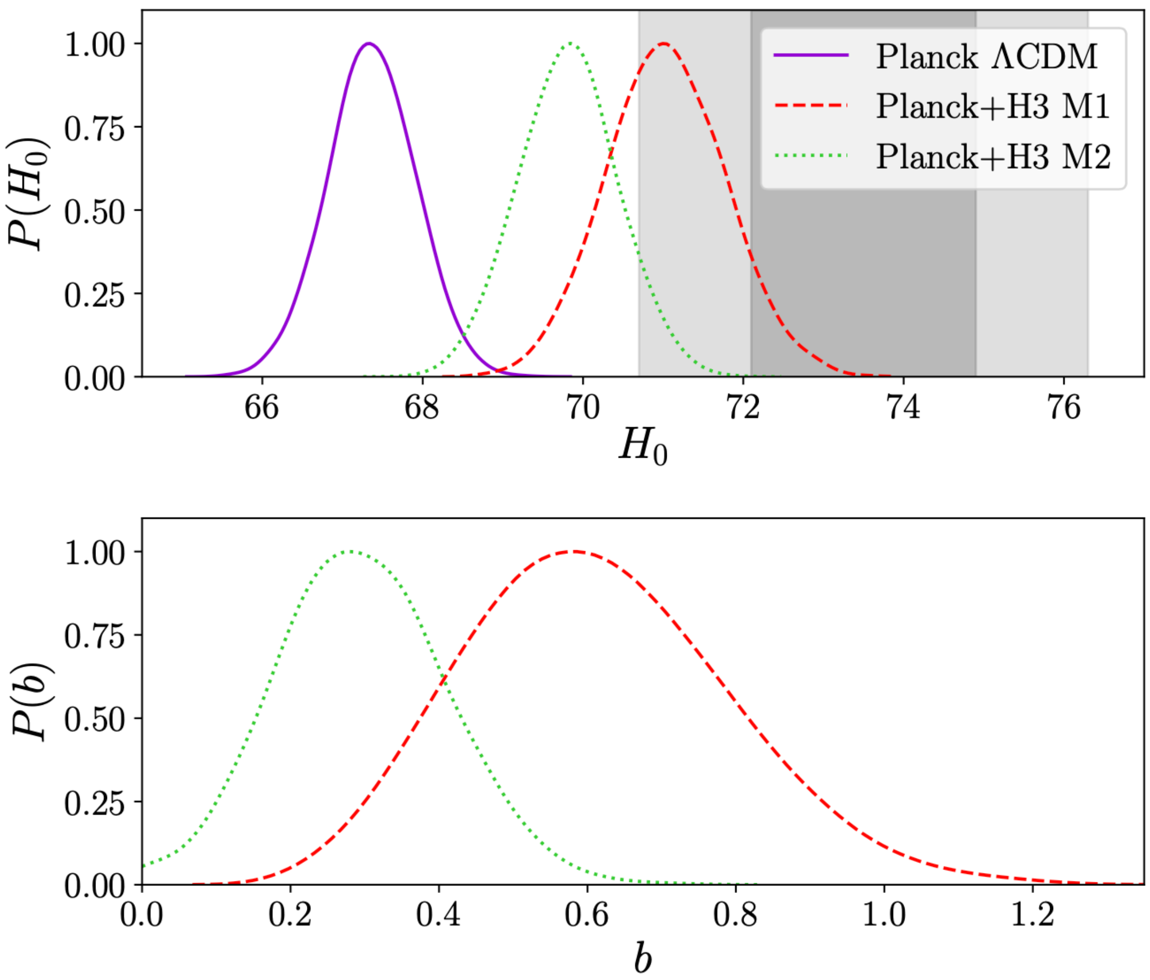
- Strong degeneracy between the clumping parameter b and H_0
- No preference for a non-zero value of b

Fitting to Planck + H3



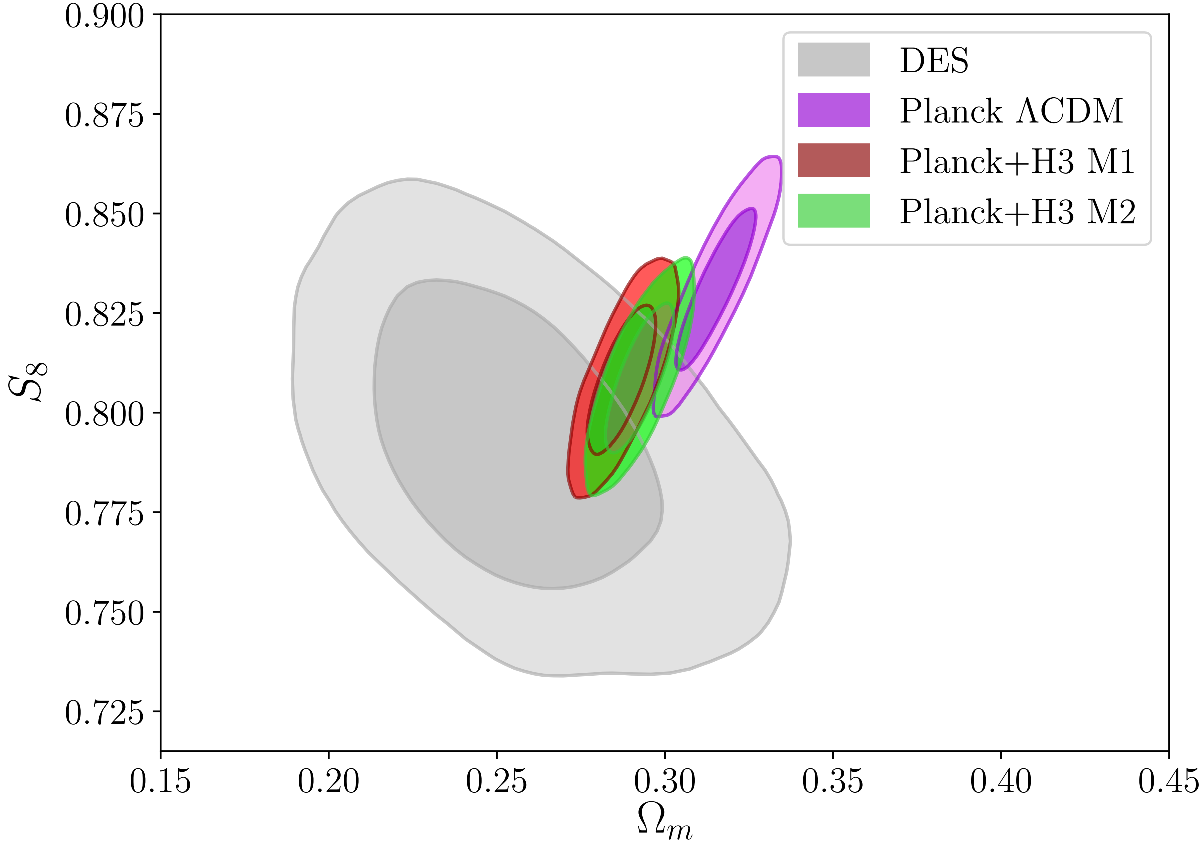
a clear detection of clumping

Relieving the Hubble tension



K. Jedamzik and L. Pogosian, arXiv:2004.09487, PRL

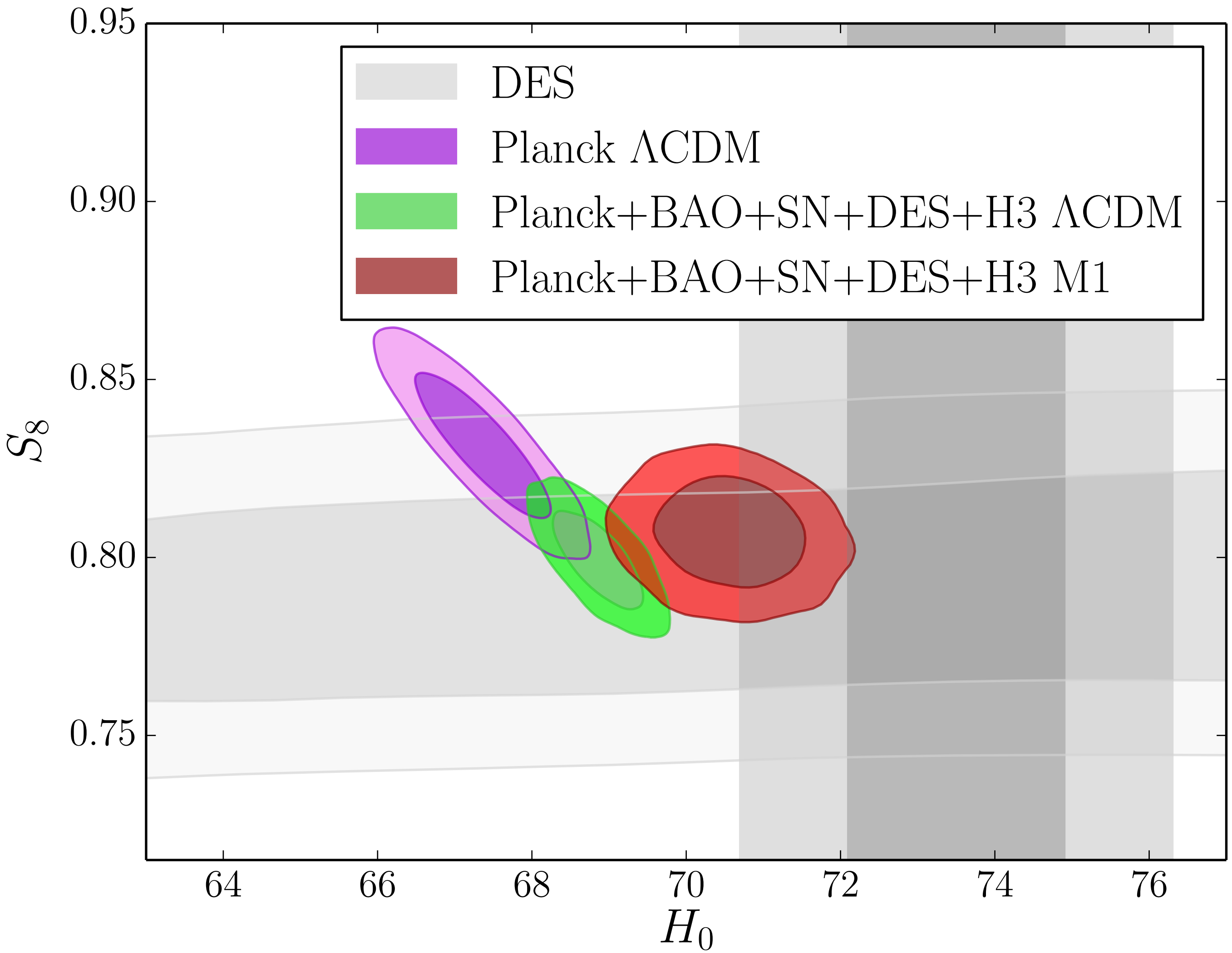
Relieving the S_8-Ω_m tension



As a byproduct, clumping models help with the S_8-Ω_m tension

K. Jedamzik and L. Pogosian, arXiv:2004.09487, PRL

Fitting to all data



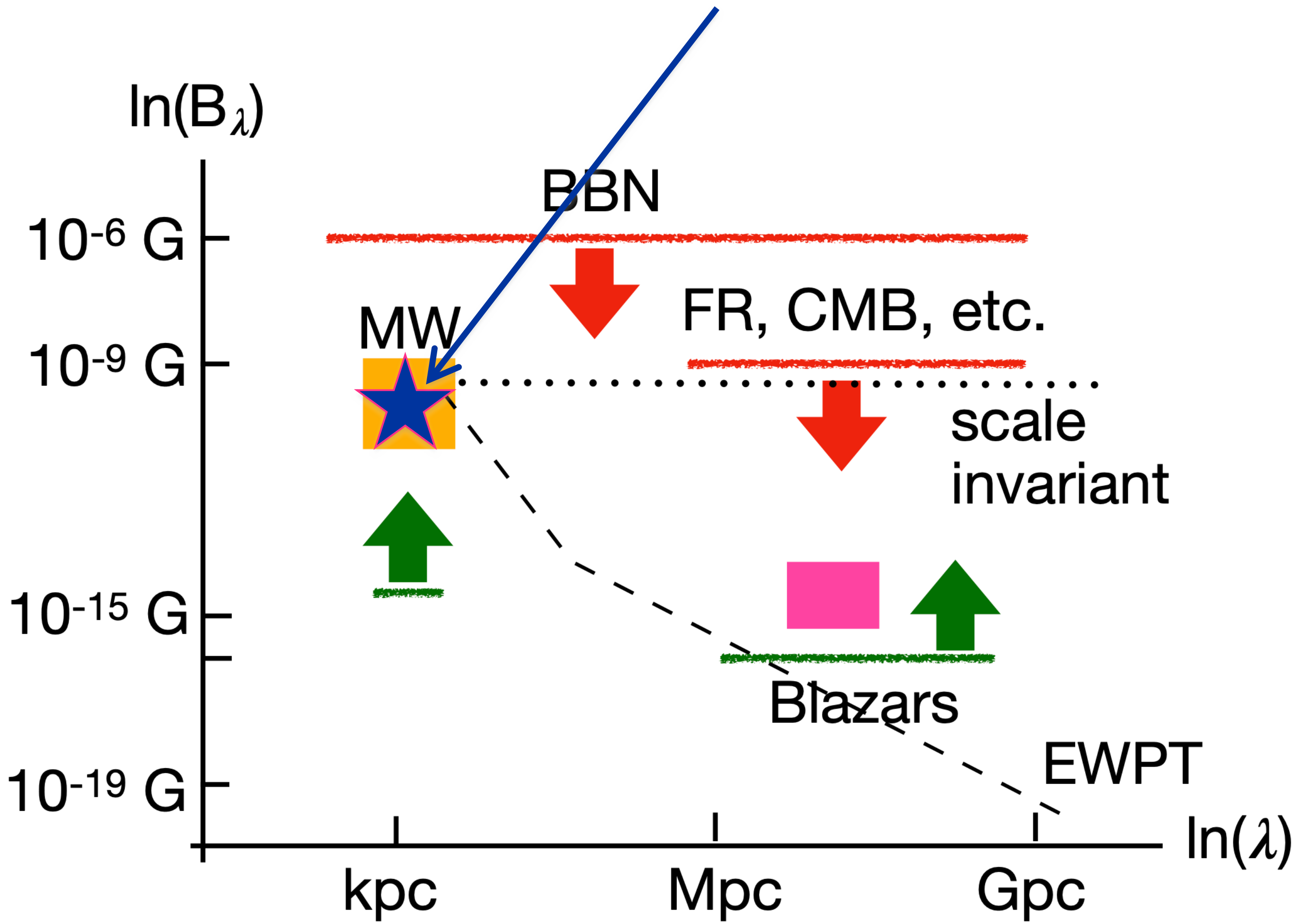
K. Jedamzik and L. Pogosian, arXiv:2004.09487, PRL

Implications

- Magnetic fields can raise the CMB+BAO inferred H_0 to $\sim$70 km/s/Mpc

- The amount of clumping needed for this corresponds to $\sim$0.05-0.1 nano-Gauss pre-recombination magnetic field,

Clumping required to relieve the H_0 tension



Plot from T. Vachaspati, arXiv:2010.10525

Implications

- Magnetic fields can raise the CMB+BAO inferred H_0 to ~70 km/s/Mpc

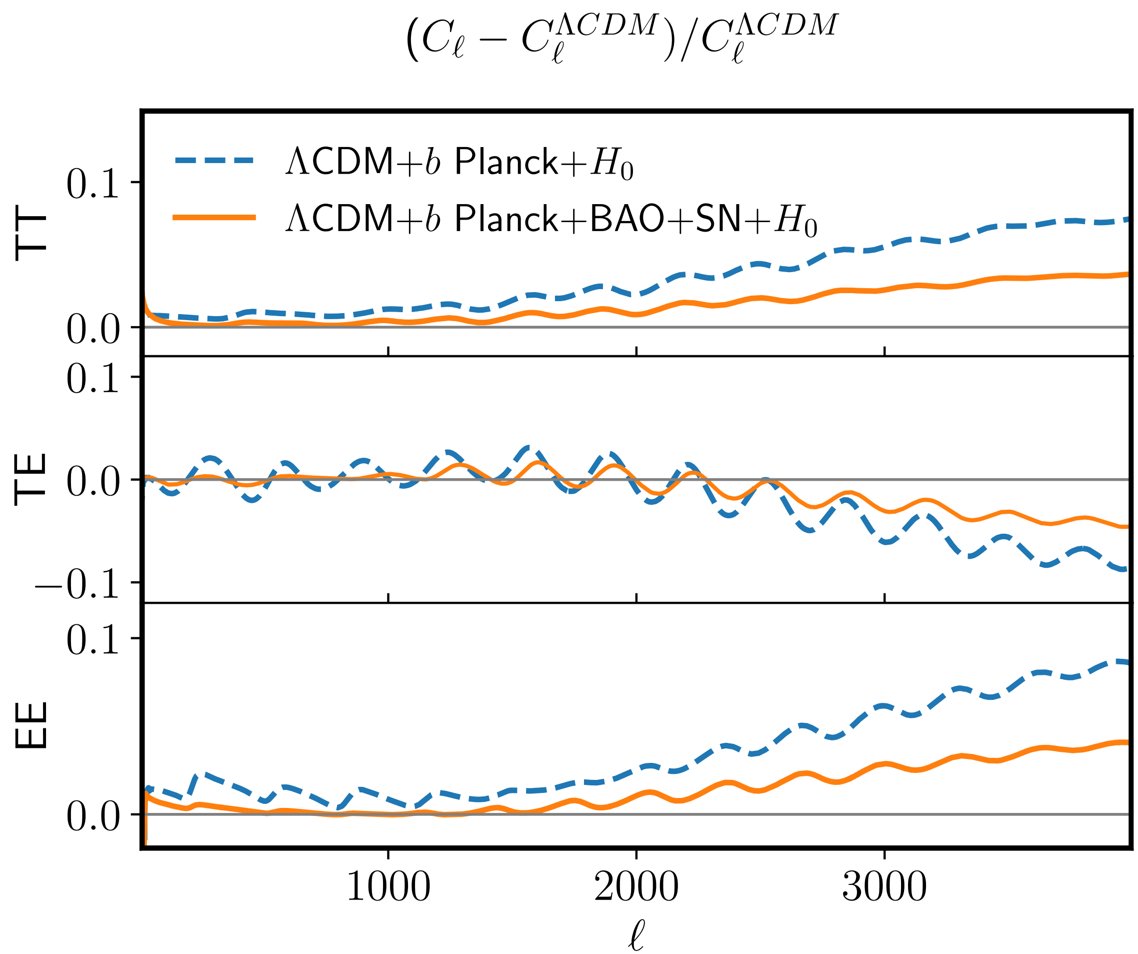
- The amount of clumping needed for this corresponds to ~0.05-0.1 nano-Gauss pre-recombination magnetic field, which is what one would need to explain the observed galactic, cluster and intergalactic fields

- This is a highly falsifiable proposal -- future observations will rule it out or land further support

- Clumping affects the amount of Silk damping that determines the anisotropy power at the high-l end of CMB spectra

- How about the recent high resolution CMB data from ACT and SPT-3G?
  (see also Thiele et al, arXiv:2105.03003, for ACT DR4 constraints on clumping)

The Silk Damping Tail



LCDM and LCDM+b make comparable predictions for CMB Temperature (T)
and polarization (E) spectra for l<2000, but the differences becomes large at higher l

The new data (since Spring 2020)

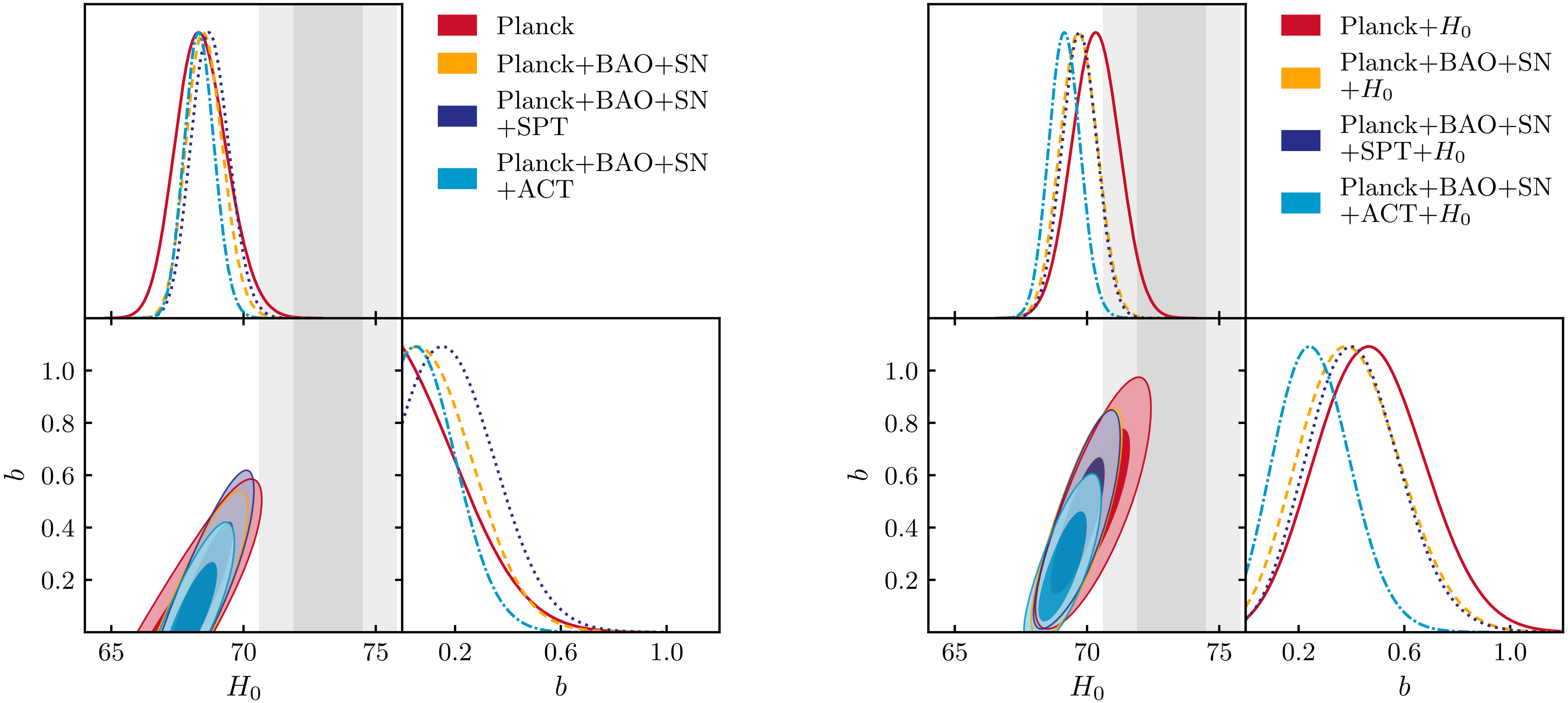
- ACT DR4 TT ($600<l<4000$), TE and EE ($350<l<4000$)

  Choi et al, arXiv:2007.07289

- SPT-3G Year 1, TE and EE ($300<l<3000$)

  Dutcher et al, arXiv:2101.01684

New constraints on clumping



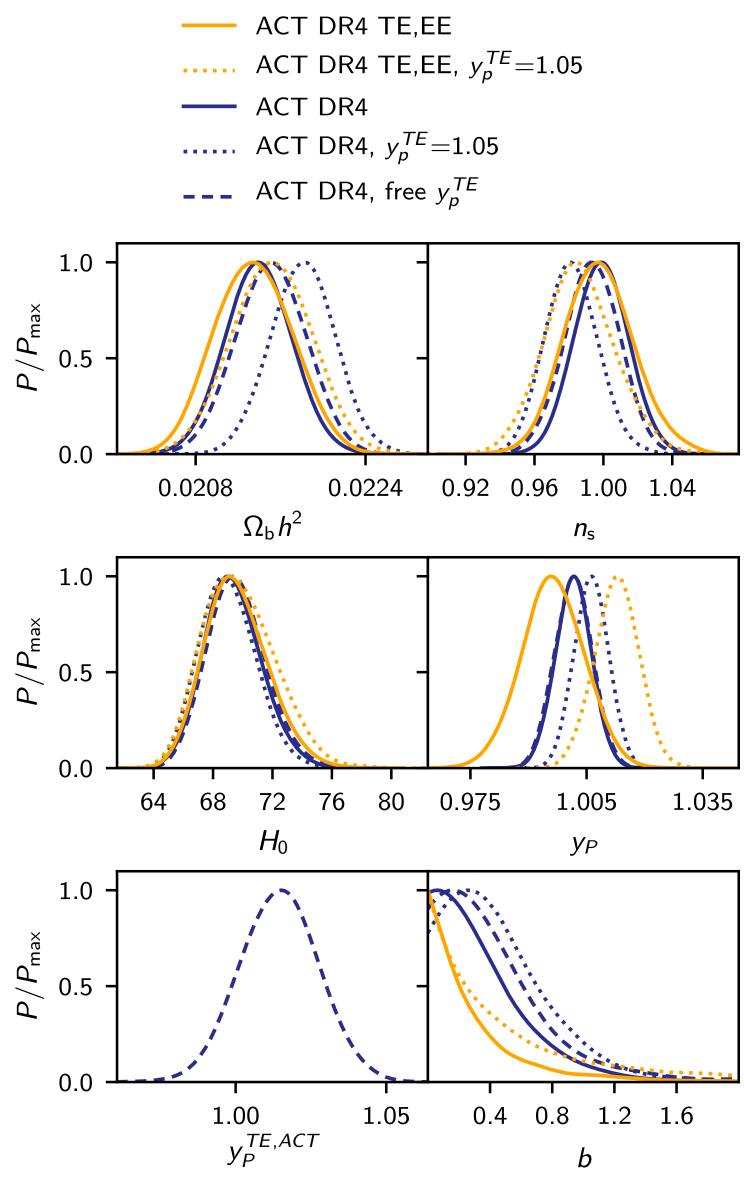
	without SH0ES	with SH0ES
Planck+BAO+SN	b<0.47 (95%CL), H_0=68.57 ± 0.68	b=0.42 ± 0.18, H_0=69.68 ± 0.66
with SPT	b < 0.50 (95%CL), H_0=68.73 ± 0.64	b = 0.43 ± 0.17, H_0=69.74 ± 0.61
with ACT	b < 0.34 (95%CL), H_0=68.30 ± 0.55	b = 0.28 ± 0.14, H_0=69.14 ± 0.56

S. Galli, LP, K. Jedamzik, L. Balkenhol, arXiv:2109.03816, PRD

Why is ACT DR4 so much more constraining compared to SPT-3G Y1?

- Not the 3000<l<4000 band powers
- Not the TT: ACT constraints on b get stronger when TT is removed
- LCDM based mock simulations show that ACT and SPT-3G TE+EE spectra should yield comparable constrains on b, while adding ACT TT should make them tighter
- Stronger than expected constraints coming from ACT DR4 TE+EE
- A 2.7-sigma "tension" between Planck and ACT DR4 in LCDM can be partially resolved by a 5% re-calibration of TE (Y^{TE}_p=1.05, *Aiola et al, arXiv:2007.07288*)
- While there is no apparent physical reason for recalibrating TE, doing so notably relaxes the ACTDR4 constraints on clumping

S. Galli, LP, K. Jedamzik, L. Balkenhol, arXiv:2109.03816, PRD



S. Galli, LP, K. Jedamzik, L. Balkenhol, arXiv:2109.03816, PRD

The current status of the PMF proposal

- Working on comprehensive MHD simulations to provide a conclusive test of this scenario

- Primordial magnetic fields were not invented to solve the Hubble tension. A detection of clumping is important by itself, as a solution of a much older puzzle and a tantalizing evidence of new physics in the early universe

- Future high resolution CMB temperature and polarization anisotropy data (Simons Observatory, CMB-S4), will provide a conclusive test of this scenario

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REPORT

Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars

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ABSTRACT

Magnetic fields in galaxies are produced via the amplification of seed magnetic fields of unknown nature. The seed fields, which might exist in their initial form in the intergalactic medium, were never detected. We report a lower bound $B \geq 3 \times 10^{-16}$ gauss on the strength of intergalactic magnetic fields, which stems from the nonobservation of GeV gamma-ray emission from electromagnetic cascade initiated by tera-electron volt gamma rays in intergalactic medium. The bound improves as $\lambda_B^{-1/2}$ if magnetic field correlation length, λ_B, is much smaller than a megaparsec. This lower bound constrains models for the origin of cosmic magnetic fields.