The background image shows a scenic landscape with snow-capped mountains in the distance, a large body of water, and a town nestled in a valley. A red vertical bar is visible on the left side of the slide.

A sound-horizon-agnostic look at the Hubble tension (and its connection to primordial magnetic fields)

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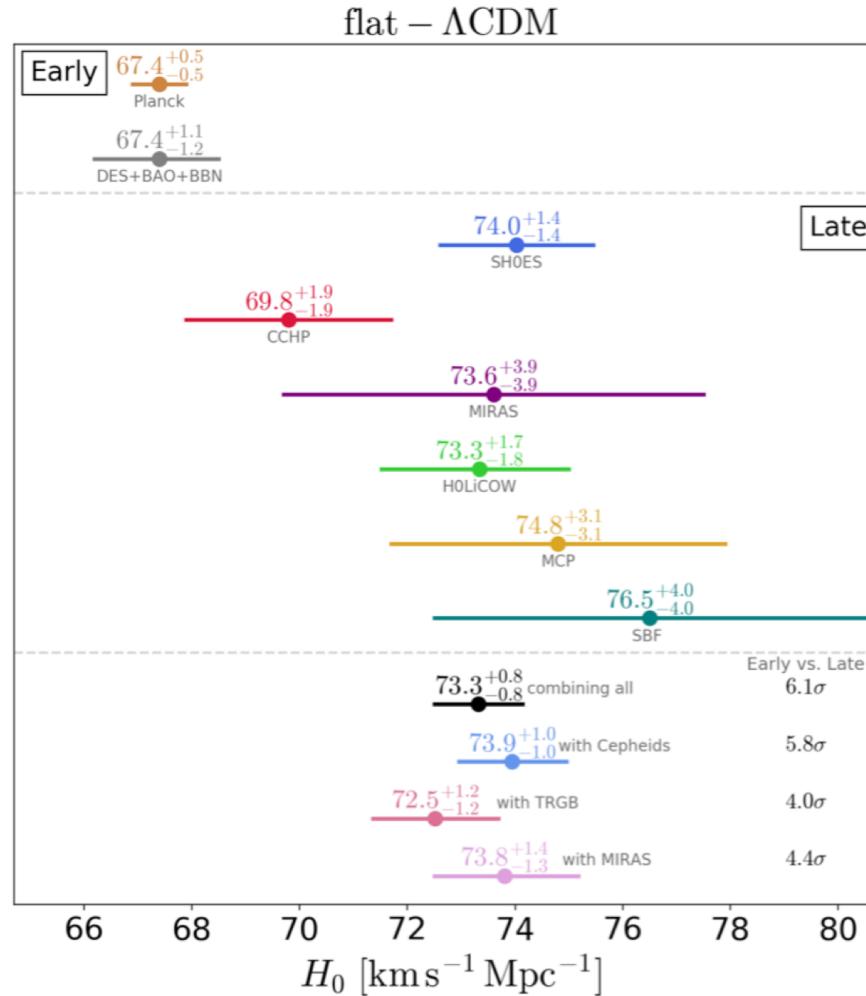
in collaboration with Karsten Jedamzik (LUPM, Montpellier) and Gong-Bo Zhao (NAOC, Beijing)

KJ, LP, GZ, arXiv:2010.04158

LP, GZ, KJ, arXiv:2009.08455, Ap. J. Lett

KJ and LP, arXiv:2004.09487, Phys. Rev. Lett.

The Hubble tension

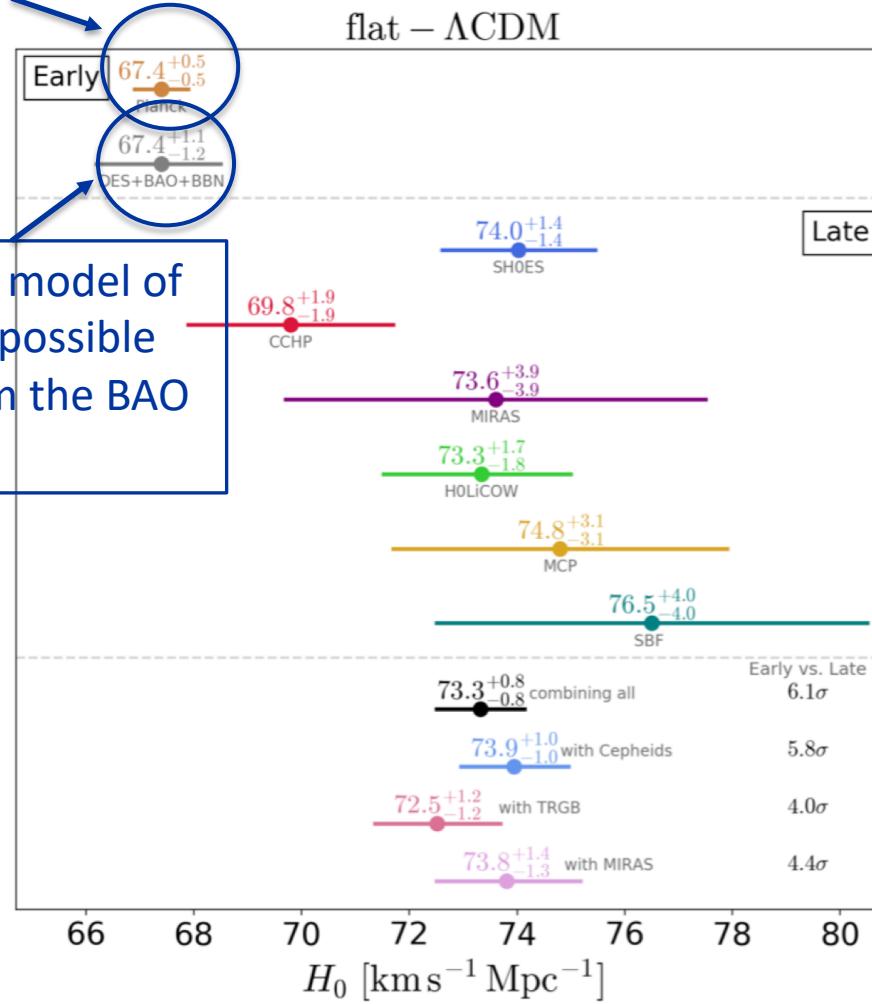


*Tensions between the
Early and the Late
Universe*
L. Verde, T. Treu, A. Riess,
arXiv:1907.10625

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

Requires a model of recombination,
can't do much about it ...

This analysis assumes a model of
recombination, but it's possible
to learn something from the BAO
without it.



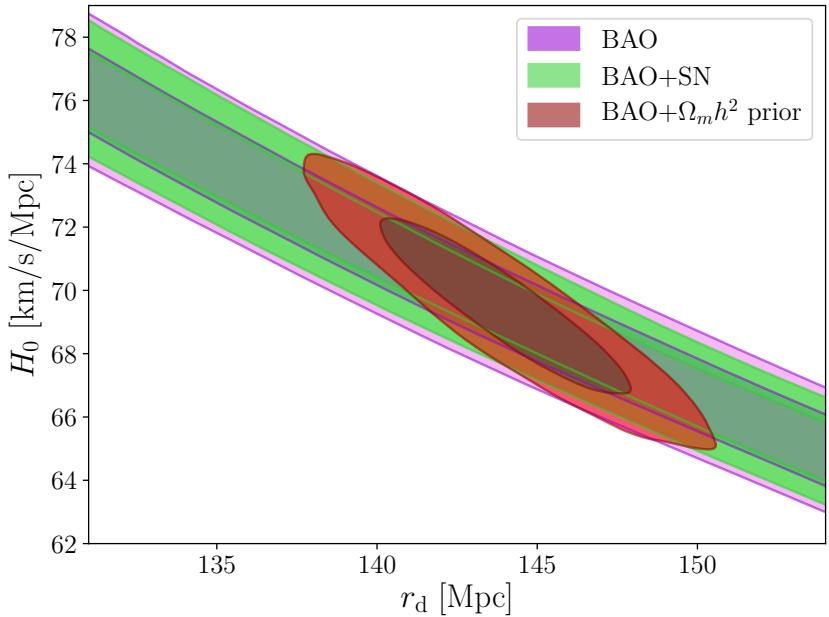
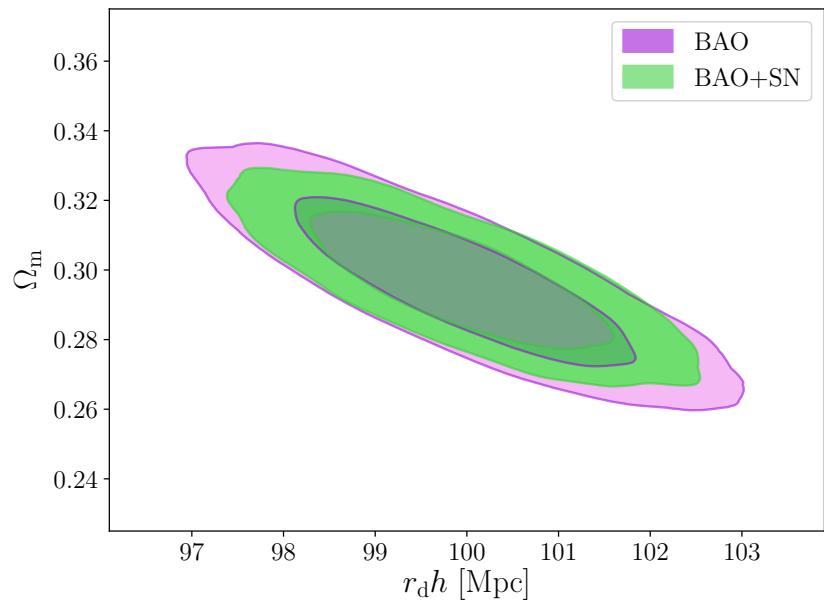
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The tension is between measurements that rely on a model
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BAO with r_d as a free parameter

- Treat the sound horizon at decoupling, r_d , as a free parameter
- By itself, BAO data constrains $r_d h$ and Ω_m
- Knowledge of $\omega_m = \Omega_m h^2$ breaks the r_d - h degeneracy

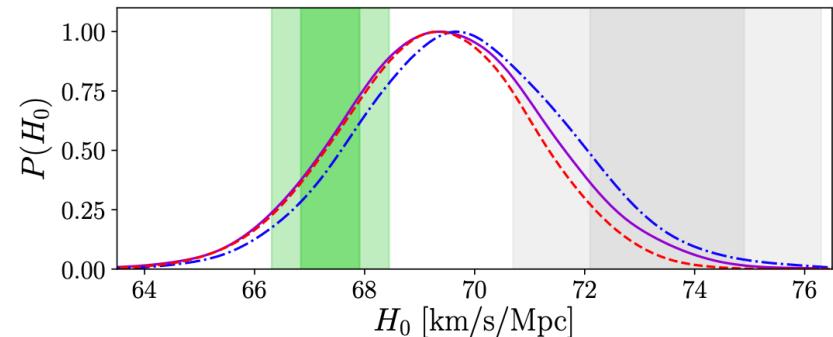
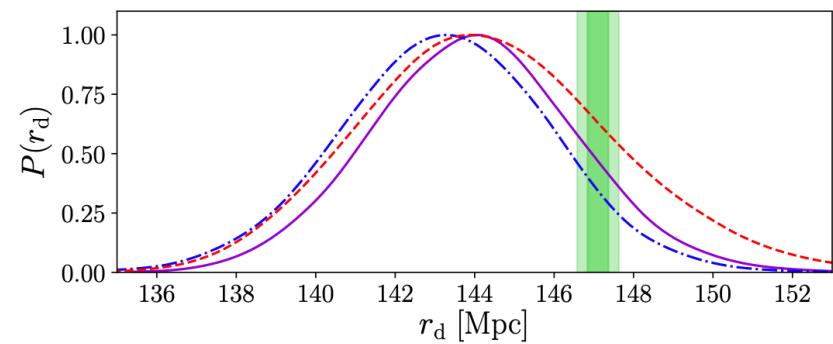
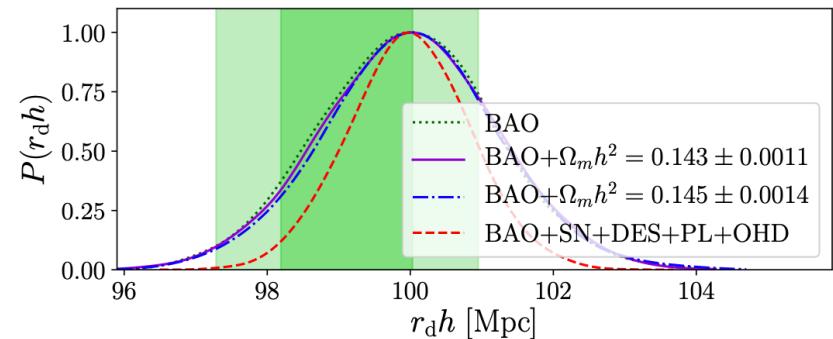
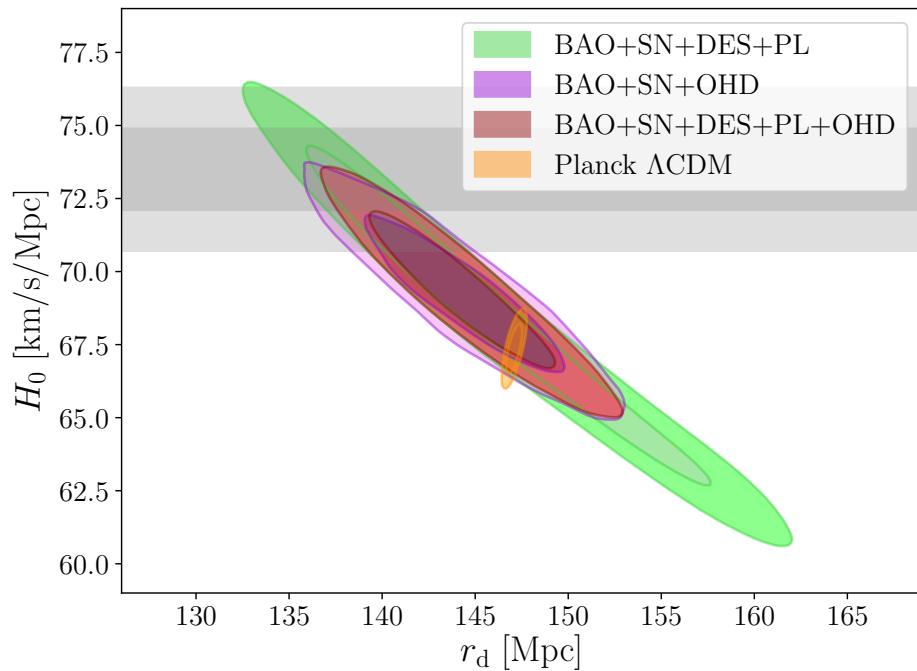
$$\begin{aligned}\beta_{\perp}(z) &= D_M(z)/r_d \\ &= \int_0^z \frac{2998 \text{ Mpc } dz'}{r_d h \sqrt{\Omega_m(1+z')^3 + 1 - \Omega_m}} \\ &= \int_0^z \frac{2998 \text{ Mpc } dz'}{r_d \omega_m^{1/2} \sqrt{(1+z')^3 + h^2/\omega_m - 1}}\end{aligned}$$



Breaking the r_d - H_0 degeneracy in a recombination-independent way

Combine BAO with CMB lensing and galaxy weak lensing, and cosmic chronometers (OHD)

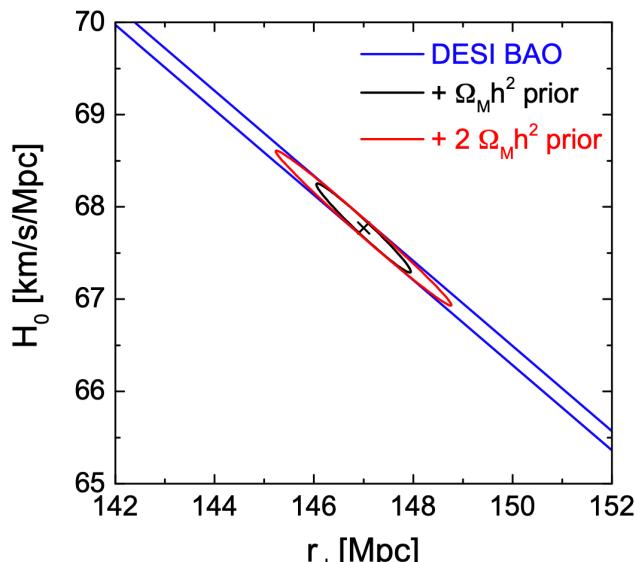
Or impose a prior on $\omega_m = \Omega_m h^2$



Recombination-independent constraints on r_d and H_0

	$r_d h$ [Mpc]	Ω_m	r_d [Mpc]	H_0 [km/s/Mpc]
BAO	99.95 ± 1.2	$0.297^{+0.014}_{-0.016}$	-	-
BAO+SN	99.9 ± 1.0	0.297 ± 0.013	-	-
BAO+SN+OHD	99.9 ± 1.0	0.298 ± 0.013	144.4 ± 3.4	69.2 ± 1.7
BAO+SN+DES+PL	99.9 ± 1.0	0.297 ± 0.012	$145.9^{+5.0}_{-8.3}$	$68.6^{+4.1}_{-3.2}$
BAO+SN+DES+SL	100.2 ± 1.0	$0.292^{+0.011}_{-0.014}$	$142.1^{+4.0}_{-7.3}$	$70.7^{+4.0}_{-2.7}$
BAO+SN+DES+PL+OHD	99.99 ± 0.84	0.2961 ± 0.0083	$144.4^{+2.8}_{-3.4}$	69.3 ± 1.7
BAO+SN+DES+SL+OHD	99.96 ± 0.85	0.2960 ± 0.0083	$143.6^{+2.8}_{-3.3}$	69.6 ± 1.7
BAO+prior $\Omega_m h^2 = 0.143 \pm 0.0011$	100.0 ± 1.2	$0.294^{+0.014}_{-0.016}$	143.8 ± 2.6	69.6 ± 1.9
BAO+prior $\Omega_m h^2 = 0.143 \pm 0.0022$	99.99 ± 1.2	$0.294^{+0.014}_{-0.016}$	143.7 ± 2.7	69.6 ± 1.8
BAO+prior $\Omega_m h^2 = 0.145 \pm 0.0014$	100.0 ± 1.2	$0.294^{+0.015}_{-0.017}$	142.9 ± 2.6	70.0 ± 1.9
BAO+prior $\Omega_m h^2 = 0.145 \pm 0.0028$	100.0 ± 1.2	$0.294^{+0.014}_{-0.016}$	142.7 ± 2.8	70.1 ± 1.9

PL=Planck Lensing; SL = SPTPol Lensing; OHD=Cosmic Chronometers



DESI BAO forecast

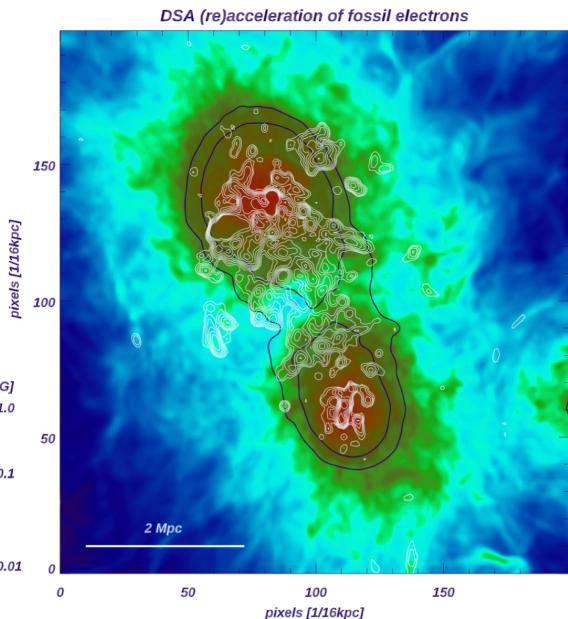
Parameter	BGS	LRG	ELG	ALL	$+ \sigma(\omega_m)$	$+ 2\sigma(\omega_m)$
$\sigma(r_d h)$	0.192	0.464	0.380	0.105	-	-
$\sigma(\Omega_m)$	0.0066	0.0065	0.0047	0.0017	-	-
$\sigma(r_d)$	-	-	-	-	0.636	1.179
$\sigma(H_0)$	-	-	-	-	0.323	0.560

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

- Many models proposed with the aim of solving the Hubble tension
- Primordial Magnetic Fields

Cosmic Magnetic Fields

- Micro-Gauss (μ G) fields in galaxies and clusters
 - produced during galaxy formation via dynamo?
 - primordial origin? (need 0.01-0.1 nano-Gauss)
 - μ G 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 μ G 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



How do magnetic fields help to reduce the sound horizon and, hence, relieve the Hubble tension?

In two sentences:

- Magnetic fields present in the plasma prior to recombination induce baryon inhomogeneities (clumping) on very small ($\sim 1\text{kpc}$) 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)

Magnetic fields induce density inhomogeneities on scales below the photon mean free path

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

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

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

Viscosity 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)

Inhomogeneities enhance the recombination rate

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

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

Inhomogeneities enhance the recombination rate

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

Inhomogeneities enhance the recombination rate

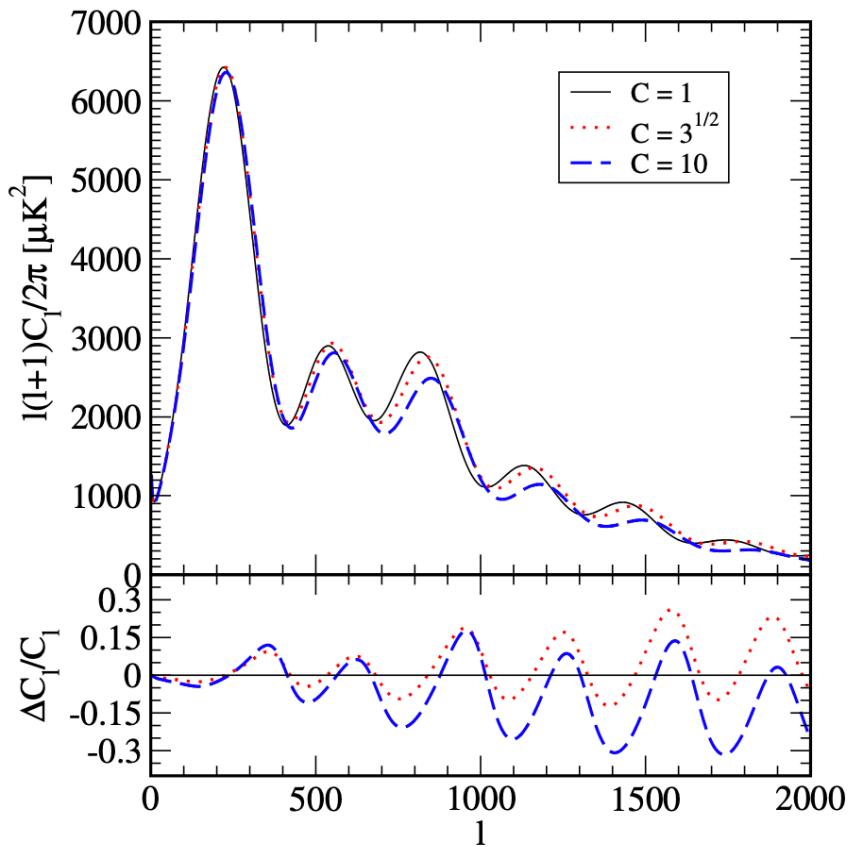
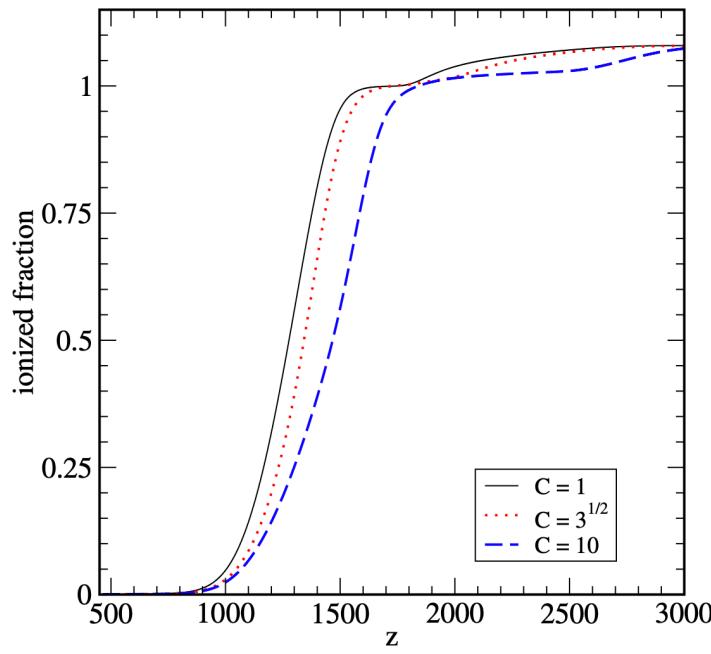
$$\left\langle \frac{dn_e}{dt} + 3Hn_e = -C \left(\alpha_e n_e^2 - \beta_e n_{H^0} e^{-h\nu_\alpha/T} \right) \right\rangle$$

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

Inhomogeneities enhance the recombination rate

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

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



Implementation

An additional baryon clumping parameter:

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

Considered two different models of baryon density distribution

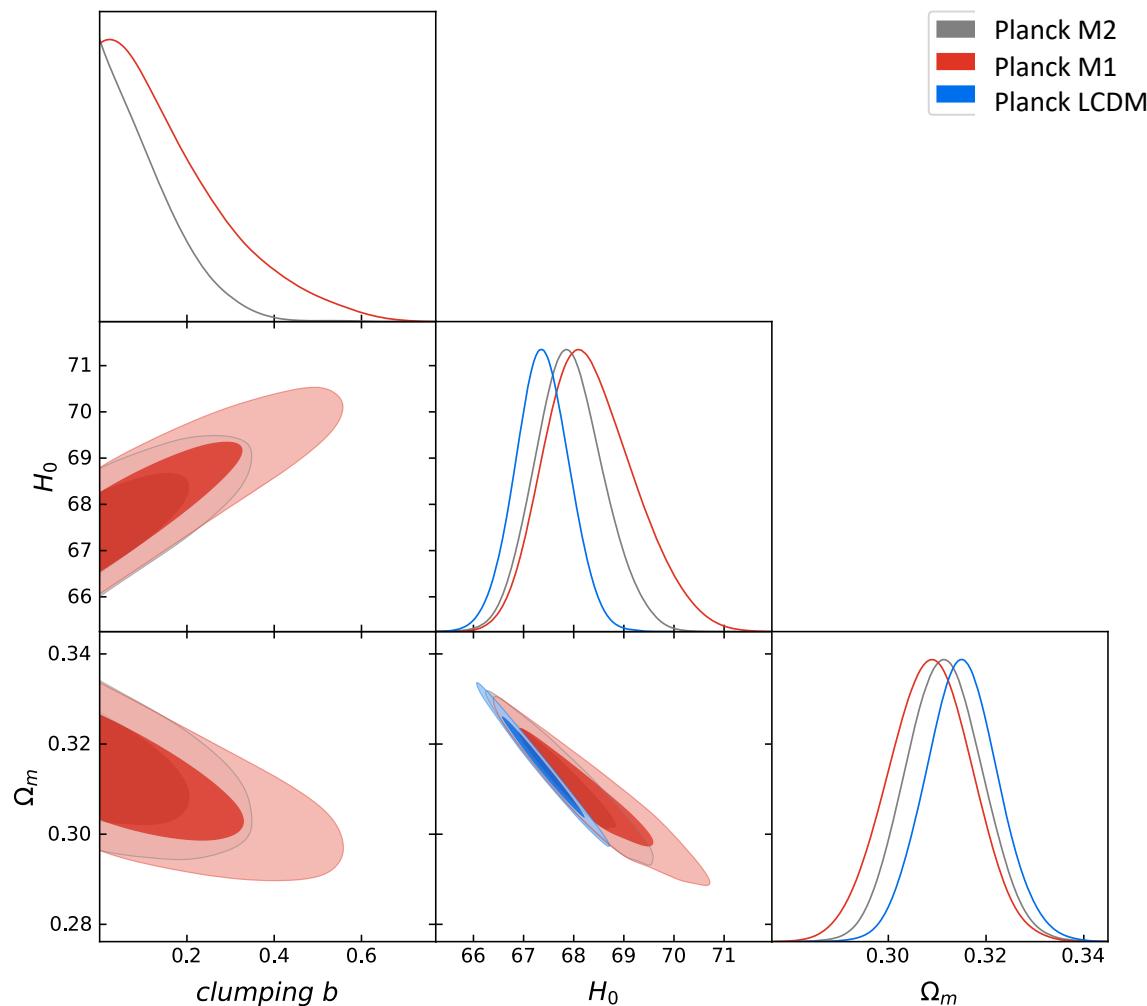
- M1, with the same baryon density PDF as in Jedamzik and Abel (2013)
- M2, using a different PDF

(The exact PDF determination from MHD simulations is in progress)

Datasets considered in this work:

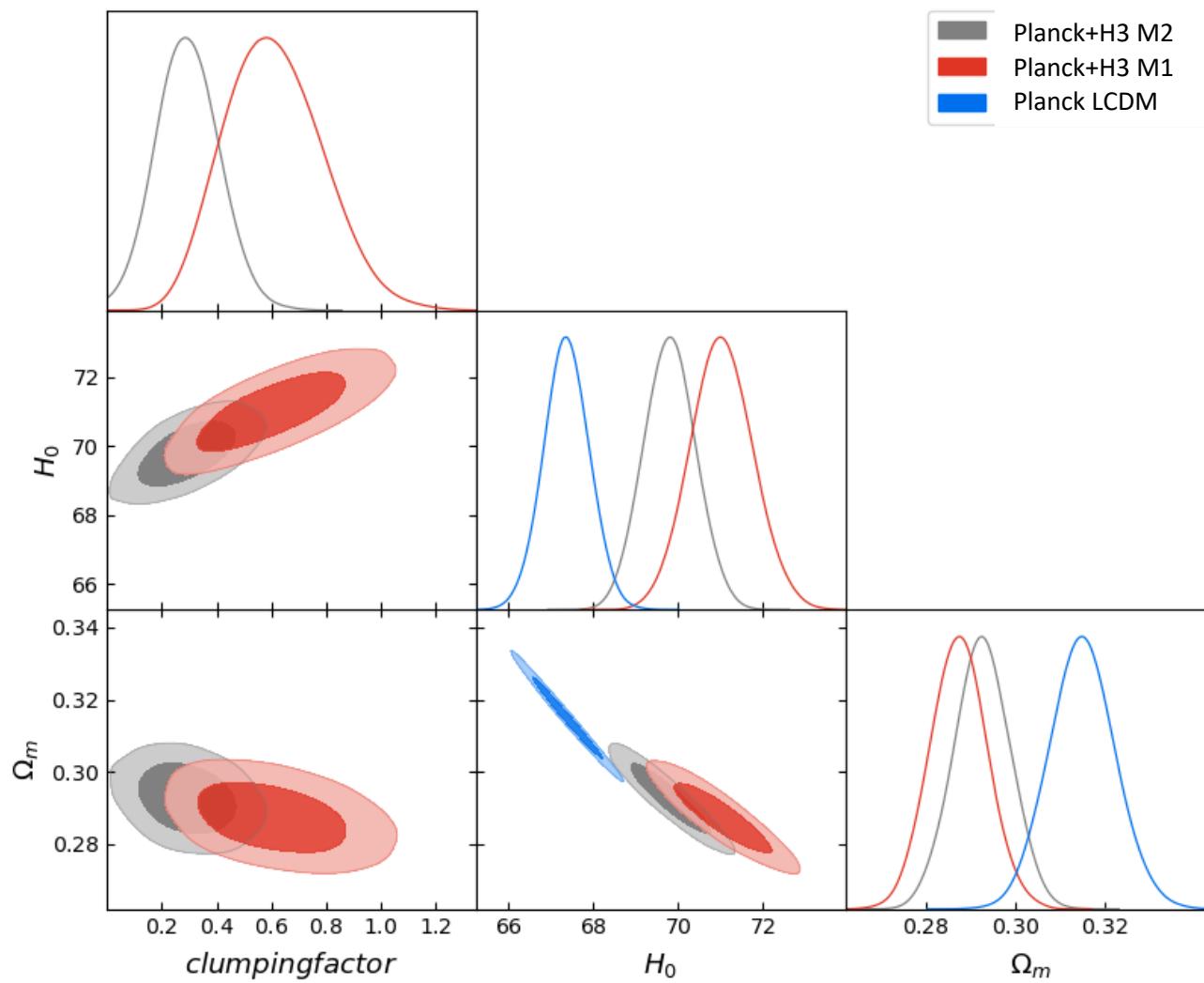
- CMB temperature and polarization from Planck 2018
- SHOES, HOLICOW and MCP determinations of H_0 (H3)
- Other publicly available datasets

Fitting to CMB only



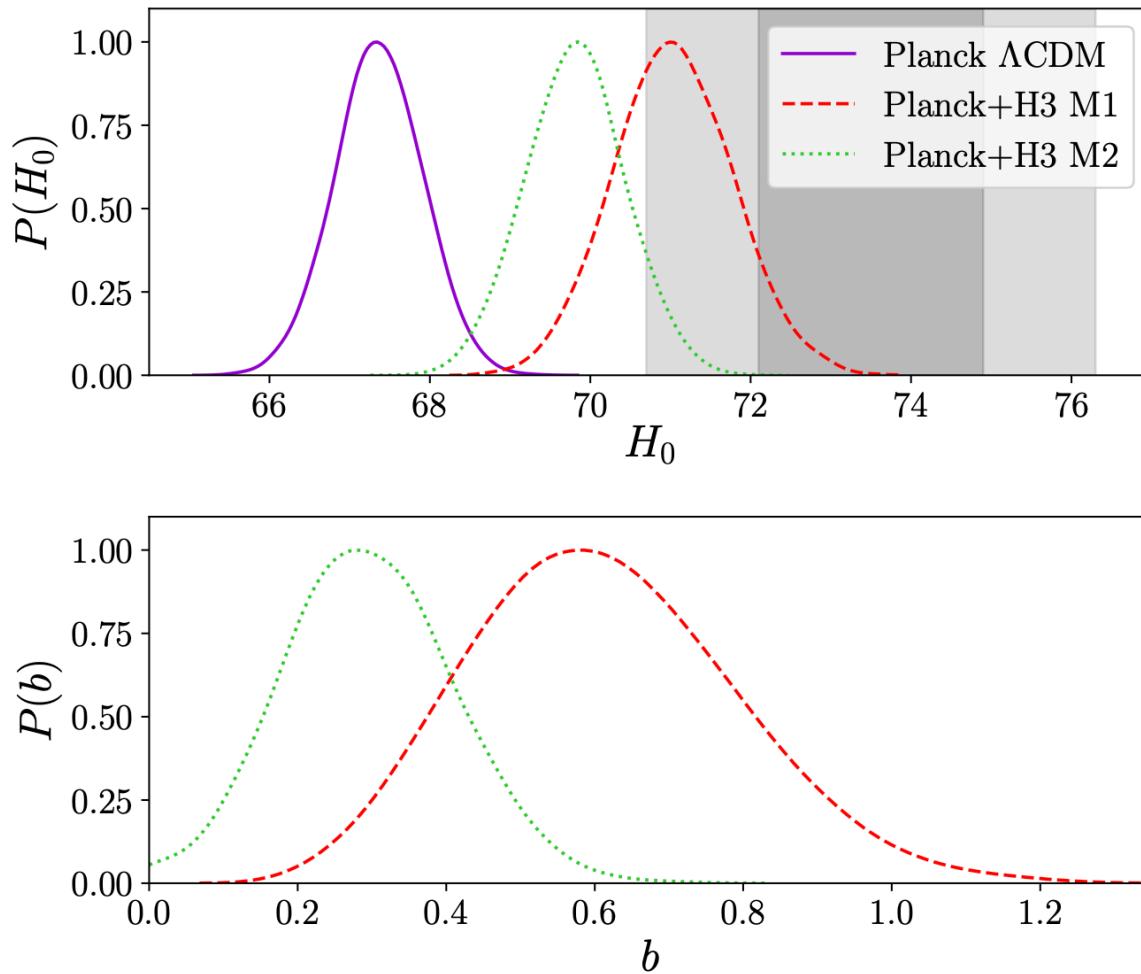
- Strong degeneracy between the clumping parameter b and H_0
- No preference for a non-zero value of b

Fitting to Planck + H3

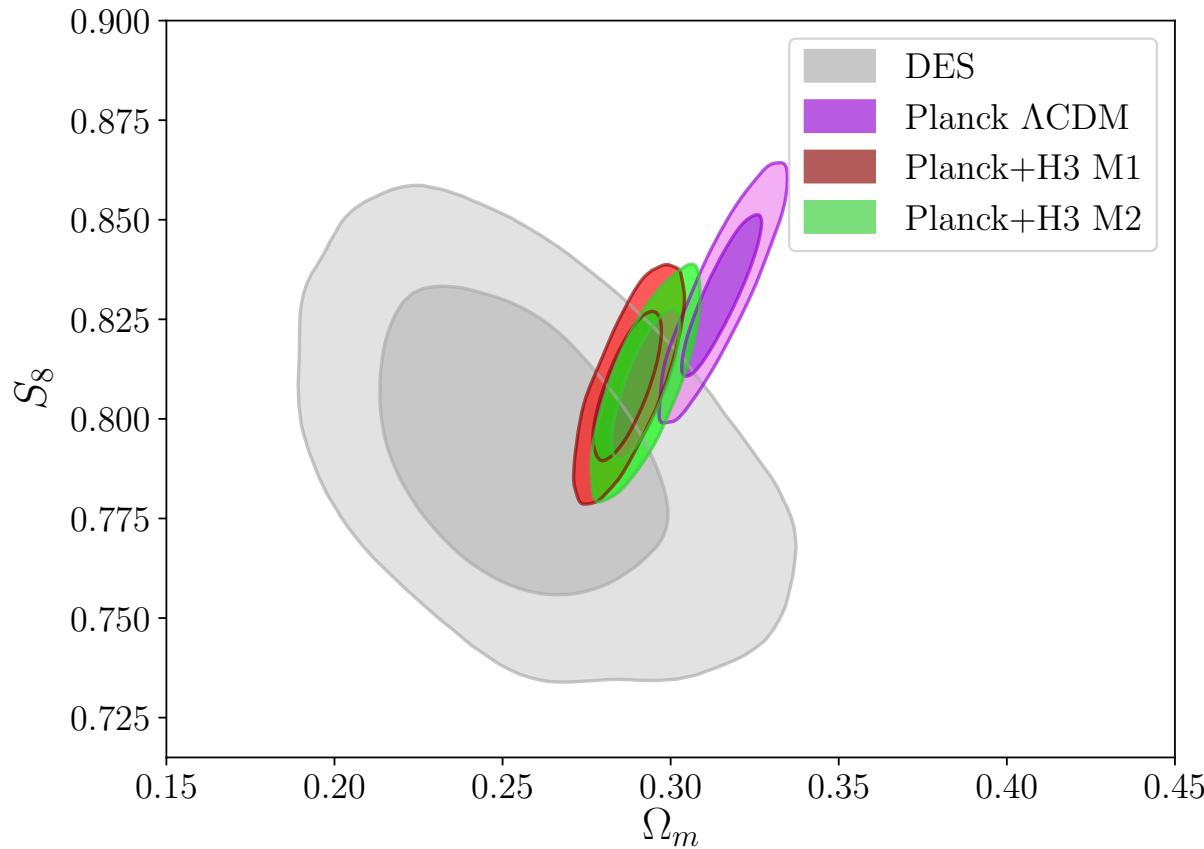


a clear detection of clumping

Relieving the Hubble tension

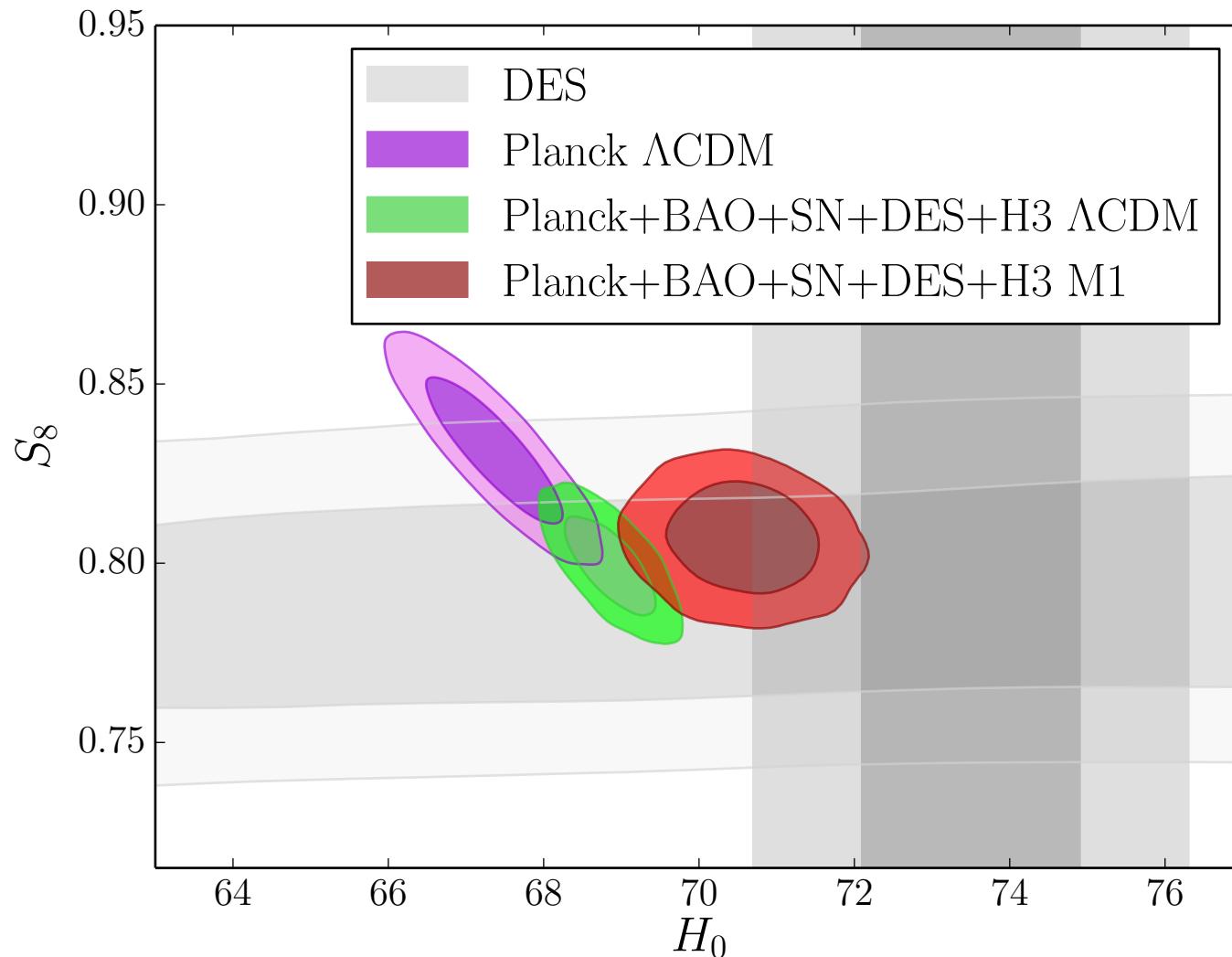


Relieving the S_8 - Ω_m tension



As a byproduct, clumping models also relieve the S_8 - Ω_m tension

Fitting to all data



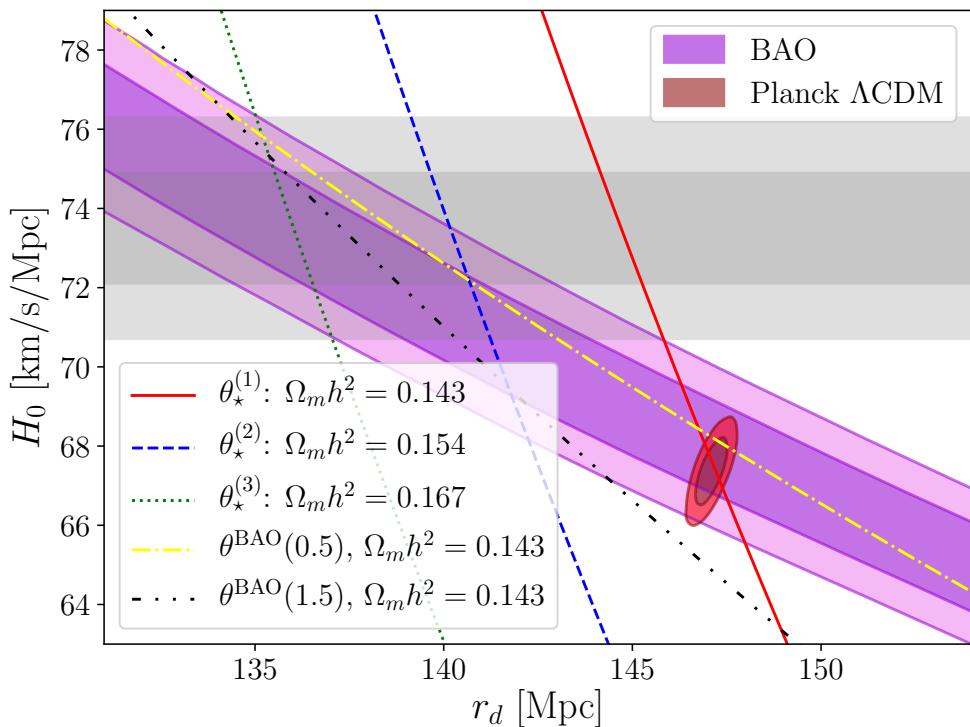
Implications

- The amount of clumping needed to relieve the Hubble tension corresponds to $\sim 0.05\text{-}0.1$ nano-Gauss pre-recombination magnetic field
- This is of the right order of magnitude to explain the observed galactic, cluster and intergalactic magnetic fields

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

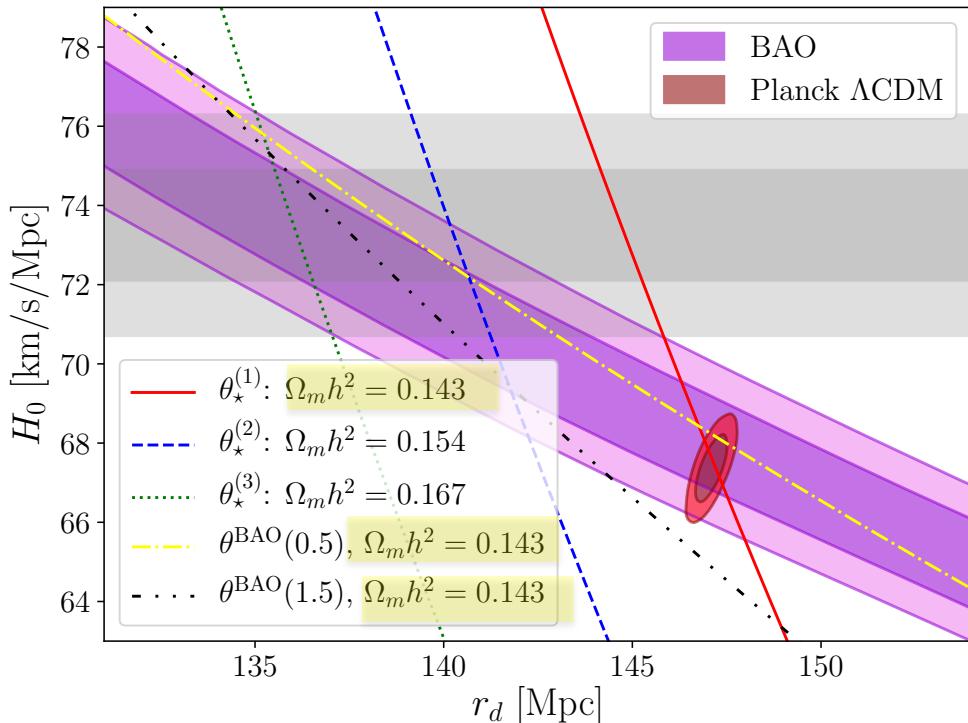
- This is a highly falsifiable proposal -- future observations can rule it out or lend further support
- Lines of investigation:
 - (!) Detailed MHD simulations of PMFs during recombination
 - How could fields of this strength originate in the early universe?
 - Other observations that can confirm magnetic fields at recombination

Why reducing the sound horizon cannot (by itself) fully relieve the Hubble tension



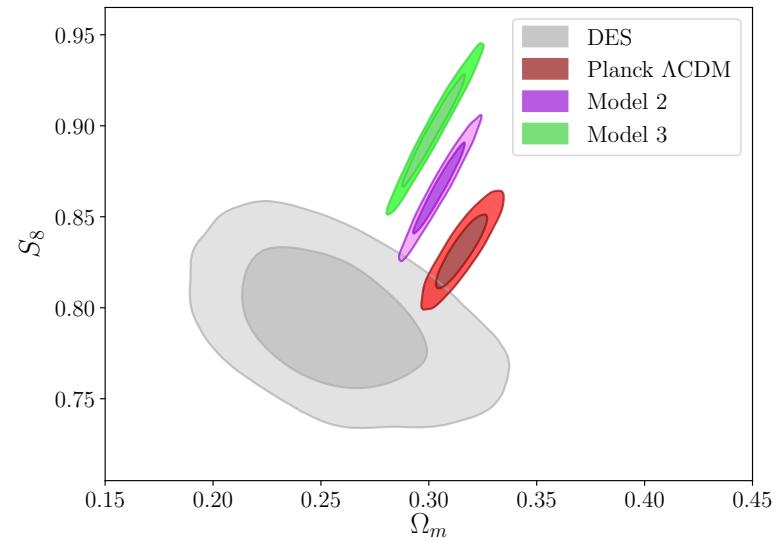
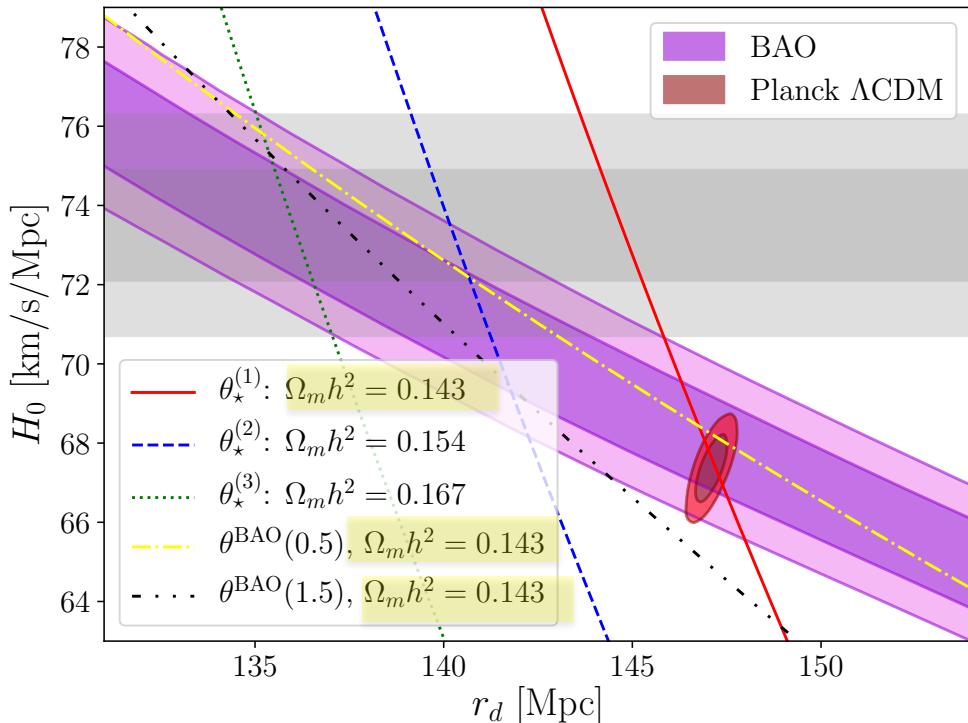
Why reducing the sound horizon cannot (by itself) fully relieve the Hubble tension

- Given the matter density $\Omega_m h^2$, each measurement of the angular acoustic scale θ (from CMB or BAO) defines a line in the r_d - H_0 plane. The slope of the line is different for measurements at different redshifts

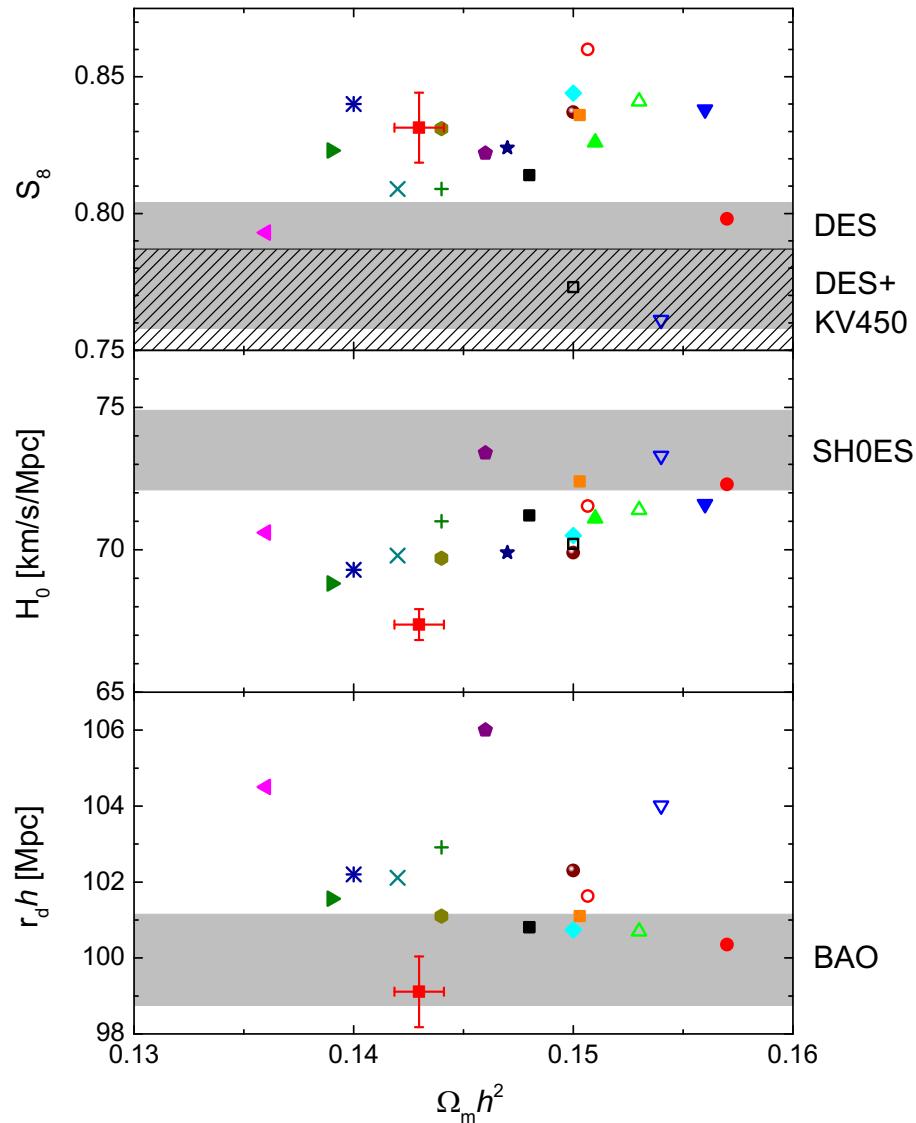


Why reducing the sound horizon cannot (by itself) fully relieve the Hubble tension

- Given the matter density $\Omega_m h^2$, each measurement of the angular acoustic scale θ (from CMB or BAO) defines a line in the r_d - H_0 plane. The slope of the line is different for measurements at different redshifts
- To reconcile the CMB and BAO lines with SHOES one needs a large $\Omega_m h^2$ which creates tension with galaxy weak lensing data, such as DES and KiDS



Modified recombination vs BAO, SHOES and WL



A full agreement requires additional physics beyond simply decreasing r_d .

- 1902.00534 (Kreisch et al 2019; moderately interacting)
- 1902.00534 (Kreisch et al 2019; strongly interacting)
- ▲ 1811.04083 (Poulin et al 2018; EDE model 1)
- ▼ 1811.04083 (Poulin et al 2018; EDE model 2)
- ◆ 1904.01016 (Agrawal et al 2019A)
- ◀ 1902.10636 (Pandey et al 2019; decaying DM; PLC+R18)
- ▶ 1902.10636 (Pandey et al 2019; decaying DM; Planck+JLA+BAO+R18)
- 1904.01016 (Agrawal et al 2019A; Neff)
- ★ 2006.13959 (Gonzalez et al 2020; ultralight scalar decay)
- 1811.03624 (Chiang et al 2018; non-standard recombination 1)
- 1811.03624 (Chiang et al 2018; non-standard recombination 2)
- + 2004.09487 (Jedamzik & Pogosian 2020; PMF model 1)
- × 2004.09487 (Jedamzik & Pogosian 2020; PMF model 2)
- * 1906.08261 (Agrawal et al 2019B; swampland & fading dark matter)
- 2007.03381 (Sekiguchi et al 2020; early recombination)
- Λ CDM
- 1507.04351 (Lesgourgues et al 2015; DM-dark interaction)
- 1909.04044 (Escudero & Witte 2019; Neutrino sector - extra radiation)
- △ 2009.00006 (Niedermann & Sloth 2020; new EDE)
- ▽ 1803.10229 (Kumar et al 2018; dark-matter photon interactions; massive neutrinos, Neff > 3.04)

Conclusions

- The Hubble tension hints at a potentially missing ingredient in the physics of recombination
- That missing ingredient could be primordial magnetic fields of strength that happens to be of the right order to also explain the observed galactic, cluster and intergalactic fields
- While reducing the sound horizon r_d can reduce the Hubble tension from $\sim 4\sigma$ to $\sim 2\sigma$, one cannot bring CMB into a full agreement with SHOES by a reduction of r_d alone without running into trouble with either the BAO or the galaxy weak lensing data