The Hubble Tension and Primordial Magnetic Fields

Levon Pogosian

Simon Fraser University

K. Jedamzik and LP, arXiv:2004.09487, Phys. Rev. Lett.
LP, G.-B. Zhao, K. Jedamzik, arXiv:2009.08455, Ap.J.Lett
K. Jedamzik, LP, G.-B. Zhao, arXiv:2010.04158, Comm. Physics
S. Galli, LP, K. Jedamzik, L. Balkenhol, arXiv:2109.03816, Phys. Rev. D

The Hubble Tension

CMB (Planck):

$H_0 = 67.36 \pm 0.54$ km/s/Mpc

Cepheid-calibrated SNIa (SH0ES):

$H_0 = 73 \pm 1$ km/s/Mpc

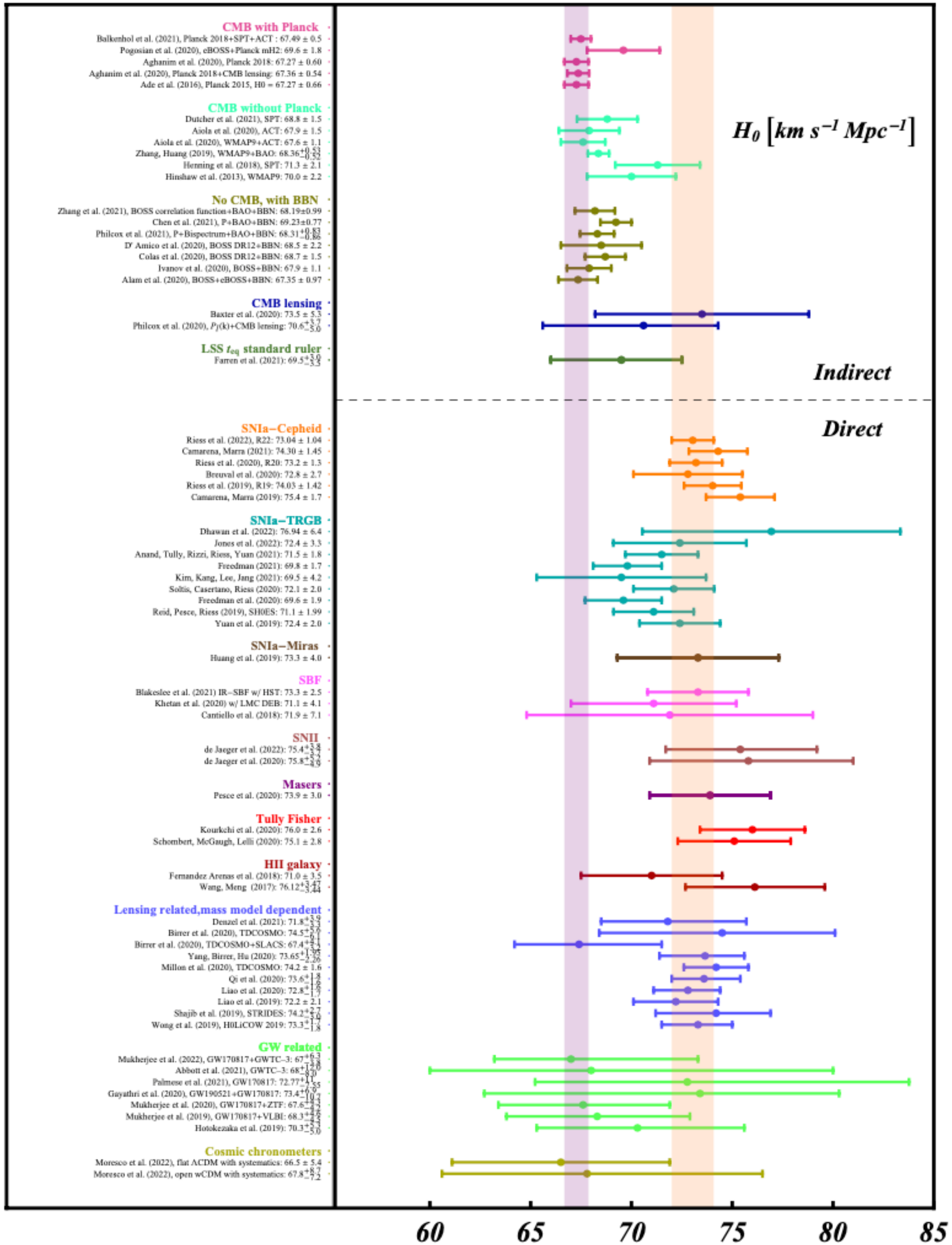
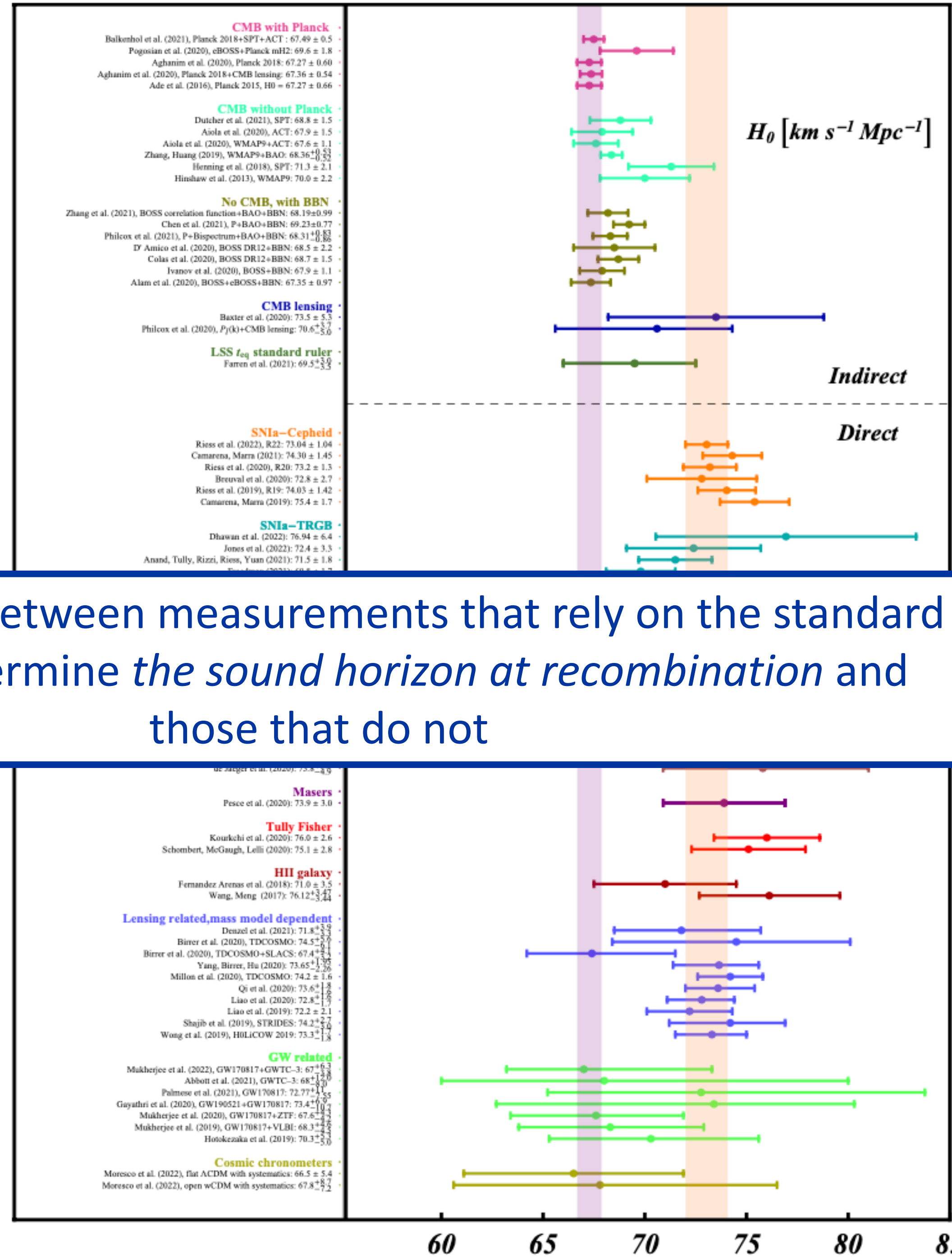


Table from arXiv:2203.06142

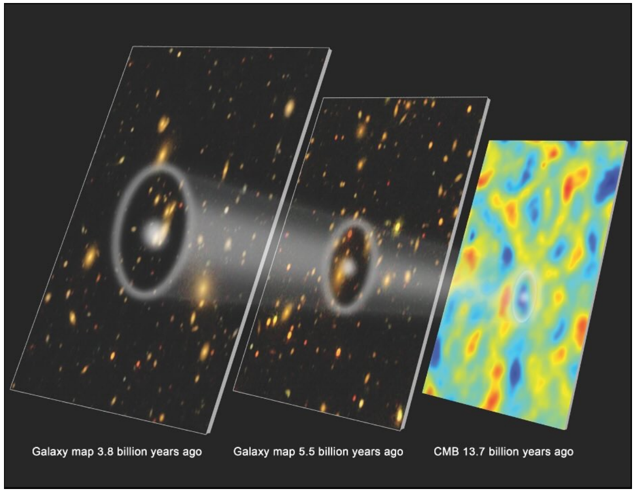
The Hubble Tension

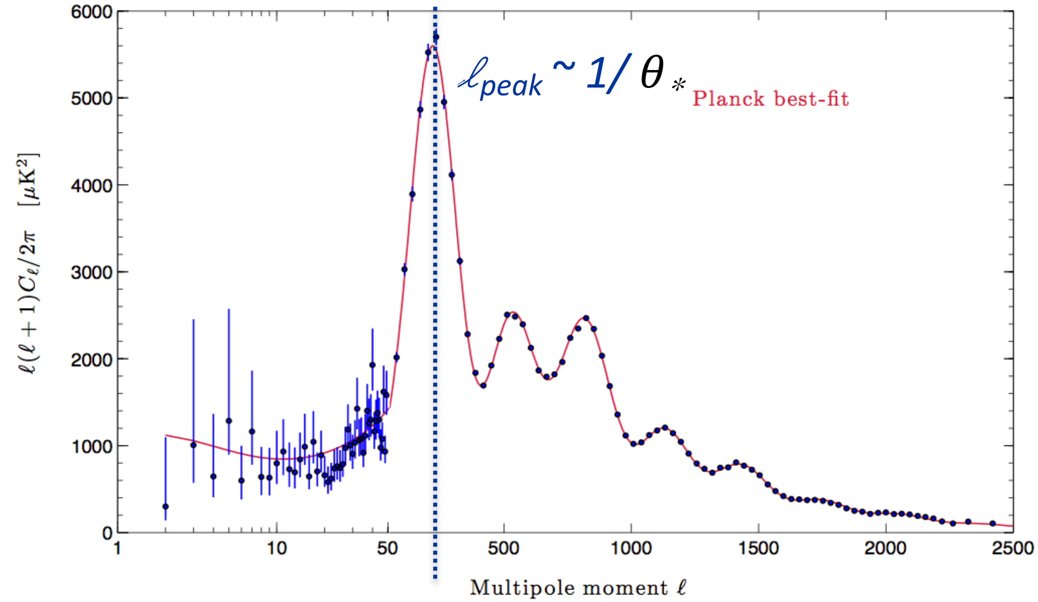


The tension is between measurements that rely on the standard model to determine *the sound horizon at recombination* and those that do not

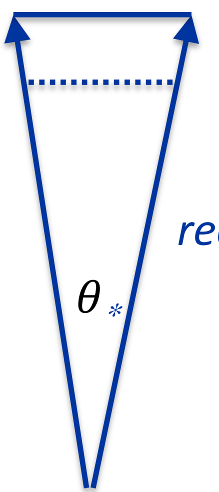
Table from arXiv:2203.06142

H_0 from CMB (and BAO)

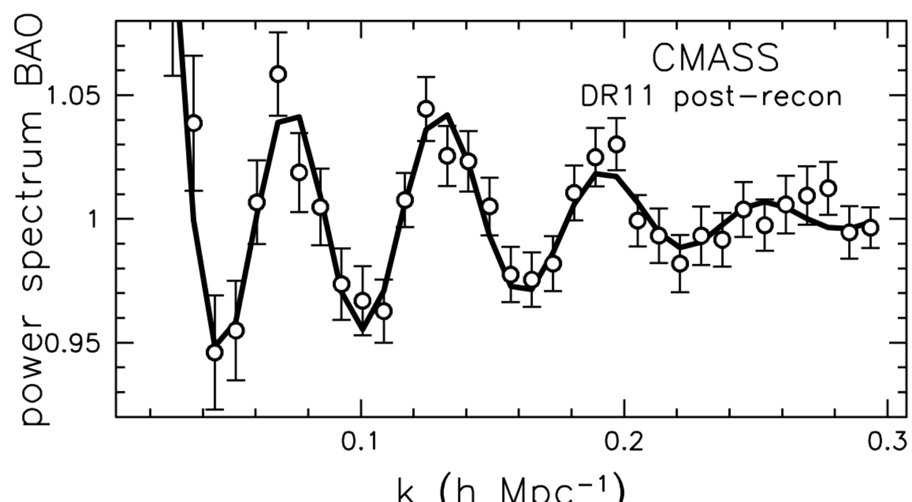




Sound horizon
at recombination, r_*



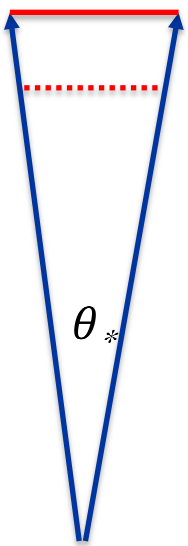
Distance to recombination, d_*



Smaller r_* => smaller d_* => larger H_0

H_0 from CMB

Comoving sound horizon at LS
r_*



d_*, comoving distance to recombination

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

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

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

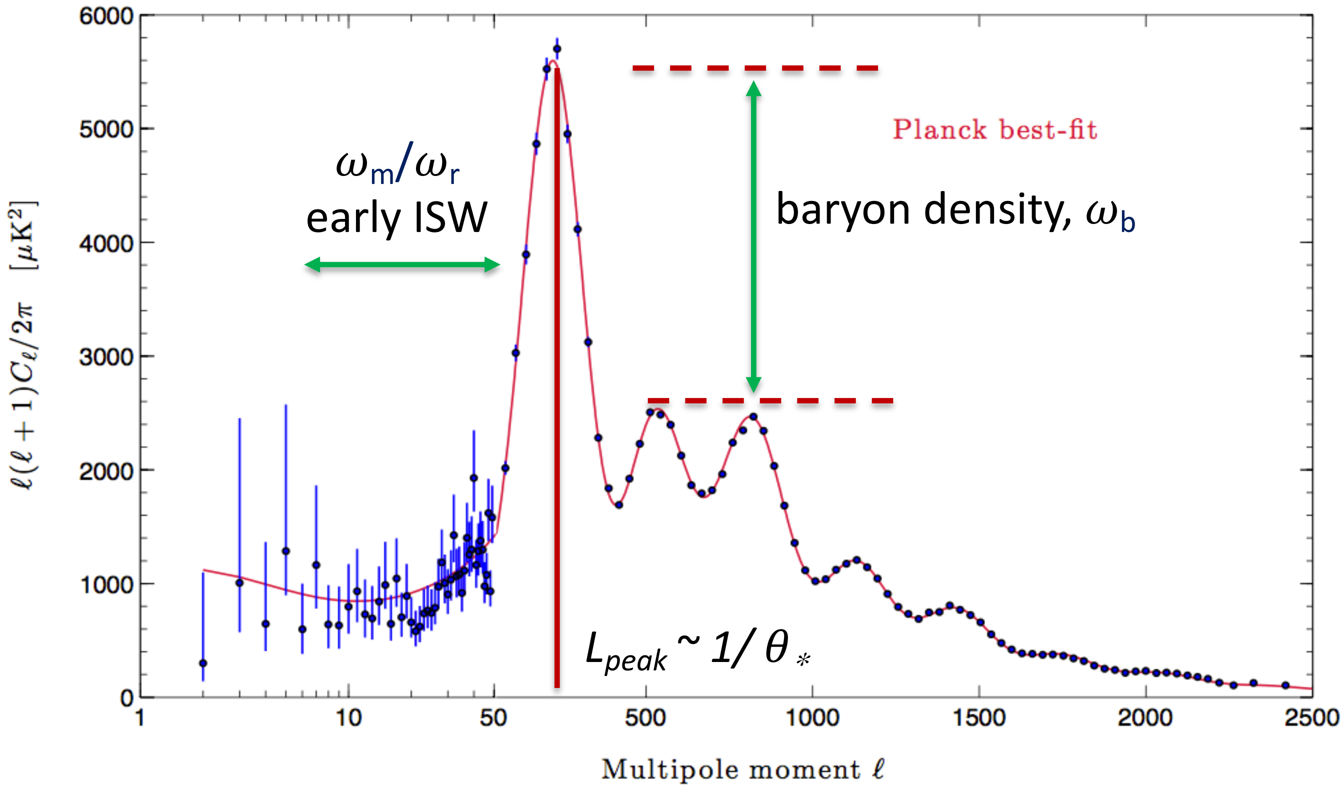
$\omega = \Omega h^2$, $h = H_0 / (100$ Mpc/km/s)

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

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

$z_* = z_*(\omega_r, \omega_b, \omega_m)$ is computed using a recombination model to get r_*

H_0 from CMB



4 key parameters: ω_r, ω_m, ω_b, h

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

Using the BAO data to constrain H_0

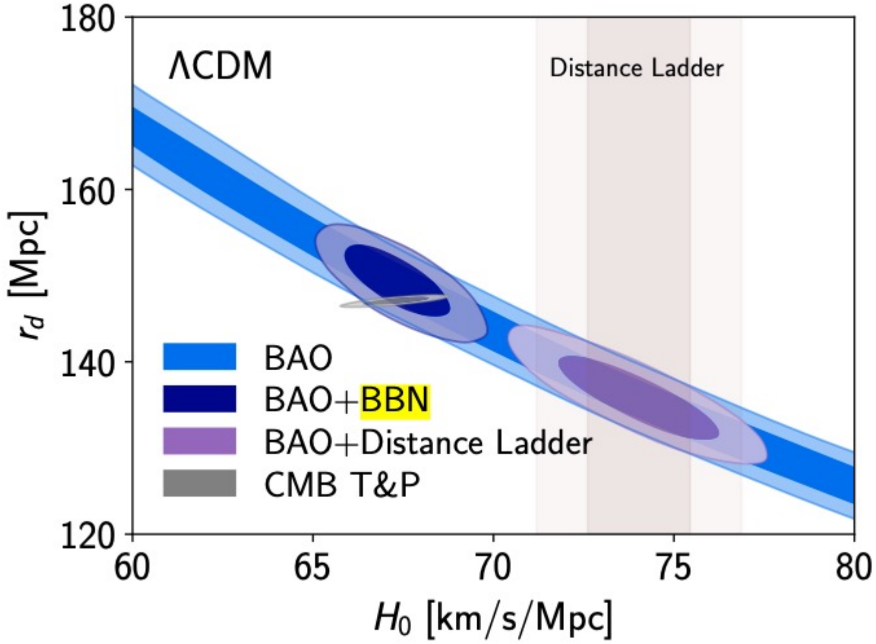
BAO data provides angular sizes of the sound horizon r_d measured at different redshifts

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

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 standard recombination model. This gives:
  H_0 = 67.35 ± 0.97 km/s/Mpc (SDSS+)
  H_0 = 68.53 ± 0.80 km/s/Mpc (DESI Y1)
- use external information on $\omega_m = \Omega_m h^2$ to break the r_d-h degeneracy



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

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

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

CMB and BAO provide measurements of this at multiple redshifts z

Treat r_d as free parameter

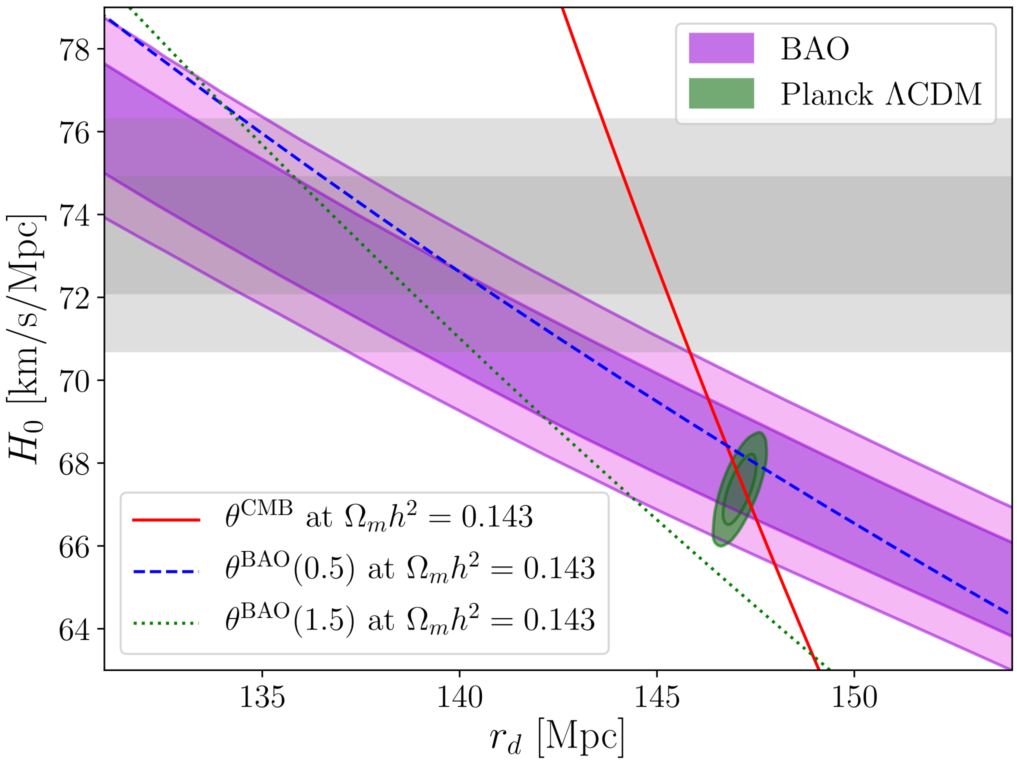
For a given matter density parameter $\omega_m = \Omega_m h^2$, each $\theta(z)$ defines a line in the $r_d - h$ plane

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

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

For a given matter density parameter $\omega_m = \Omega_m h^2$, each $\theta(z)$ defines a line in the $r_d - h$ plane

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



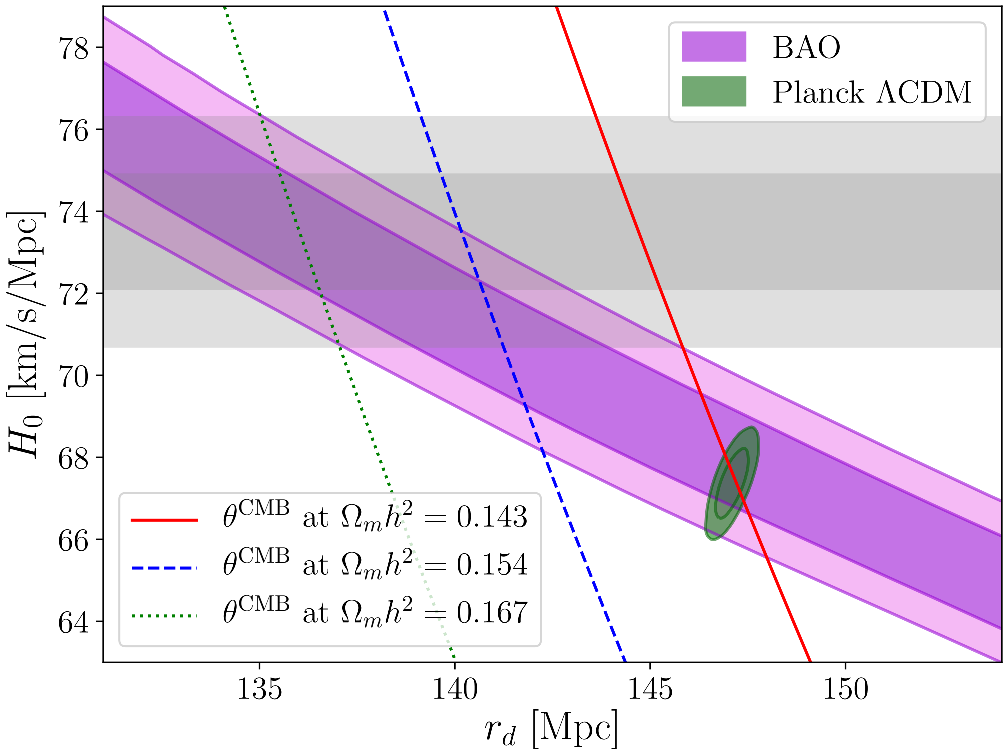
We can make the CMB best fit H_0 larger by making r_d smaller and moving up the red line

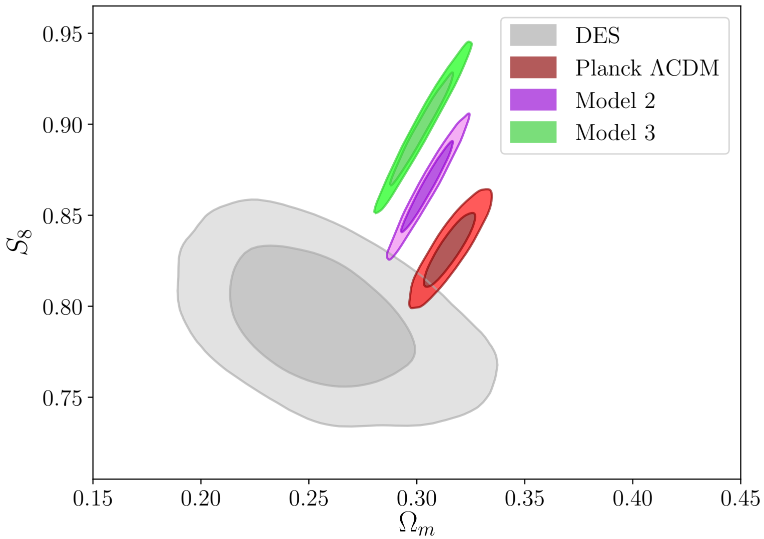
But that creates a tension with the BAO constraint

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, by making the S_8 larger



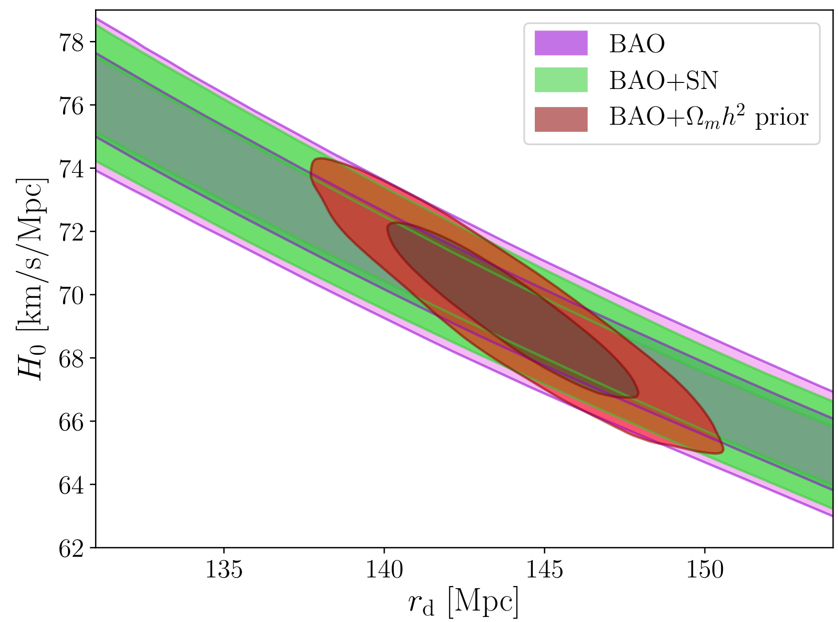


K. Jedamzik, LP, G.-B. Zhao, arXiv:2010.04158

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

- Treat r_d as an independent parameter
- Providing $\omega_m = \Omega_m h^2$ breaks the r_d-h degeneracy
- Combine BAO with CMB and galaxy weak lensing
- Or, <u>combine BAO with a prior on $\Omega_m h^2$</u>, e.g. use the value of $\Omega_m h^2$, as measured by Planck, thus testing consistency of BAO with CMB withing LCDM

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

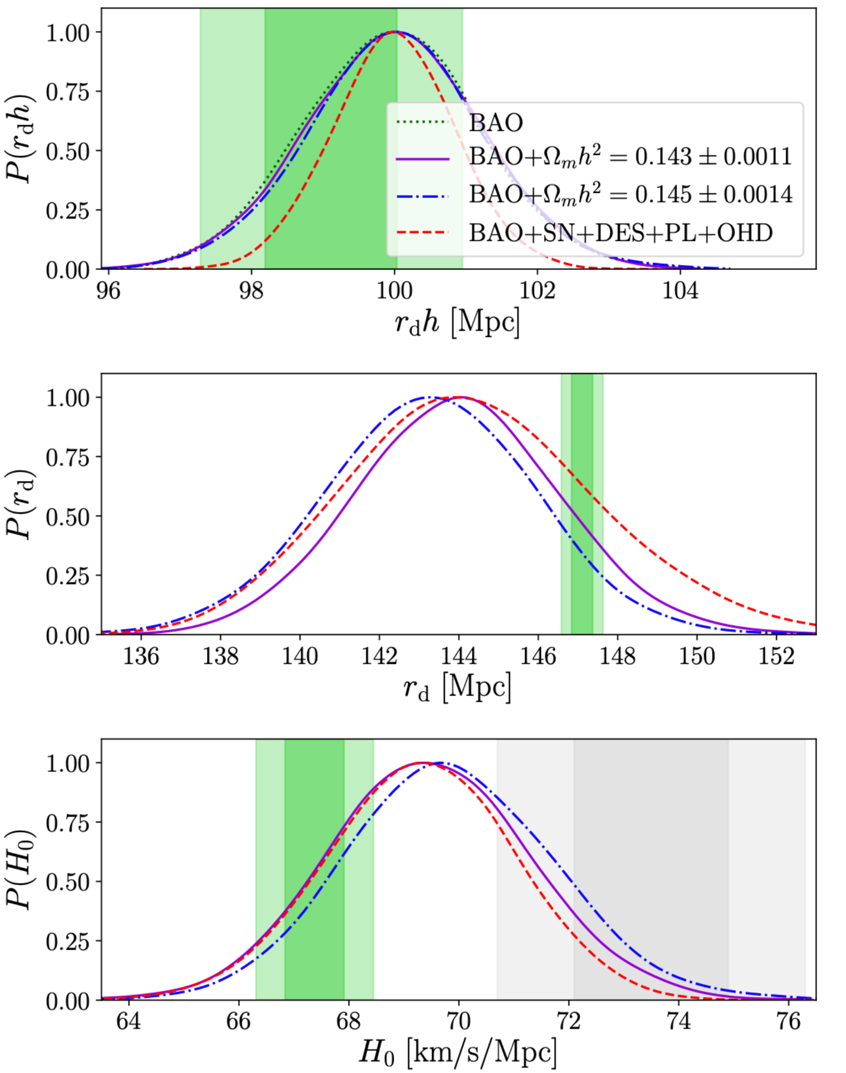


LP, G.-B. Zhao, K. Jedamzik, arXiv:2009.08455, Ap. J. Lett

Testing consistency of BAO with CMB in a recombination-independent way

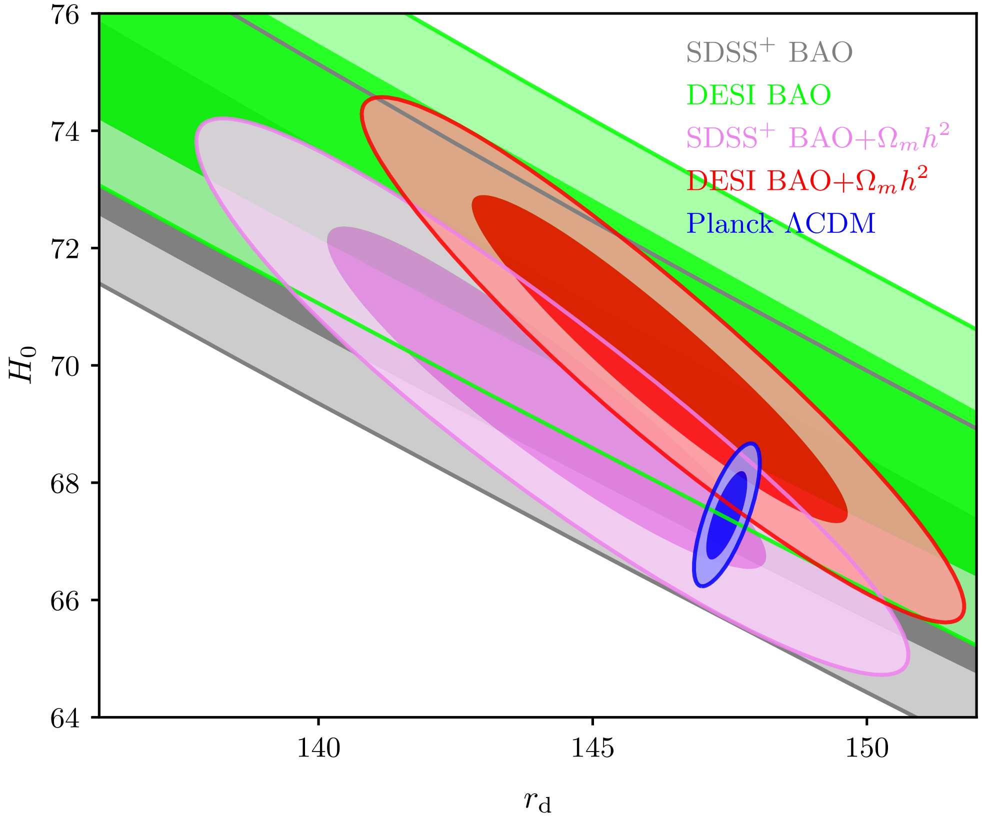
- Treat r_d as a free parameter
- Combine BAO with with a prior on ω_m
- Check if the values of H_0 and r_d are consistent with those in Planck LCDM

Shown are are results for SDSS+ BAO (pre-DESI Year 1)



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

DESI Year 1 update



DESI Y1 prefers a higher value for the product $r_d h$:

$r_d h = 102.33 \pm 1.27$ for DESI

vs

$r_d h = 99.98 \pm 1.21$ for SDSS+

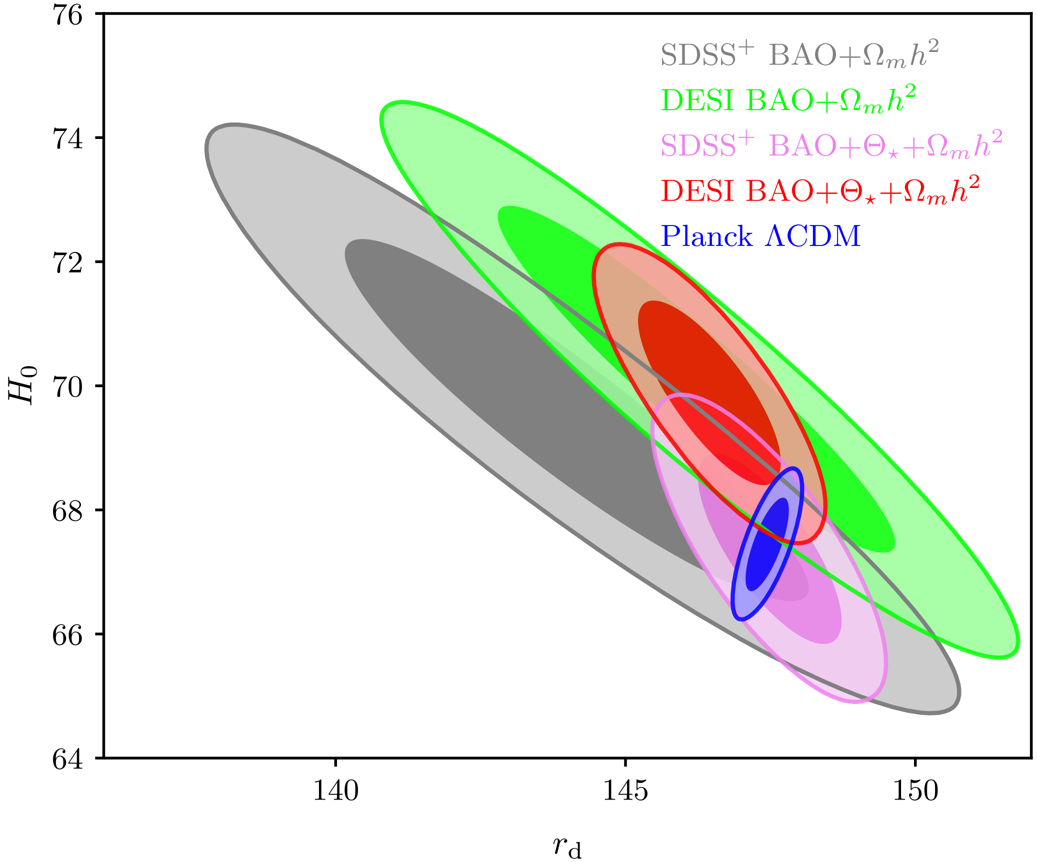
Gaussian prior from Planck LCDM: $\Omega_m h^2 = 0.142 \pm 0.001$

LP, K. Jedamzik, G.-B. Zhao, in preparation

Adding the CMB "BAO" point

Treat CMB peaks as another BAO point

$$\beta_\perp^\star = \frac{r_\star}{\theta_\star r_\mathrm{d}}$$



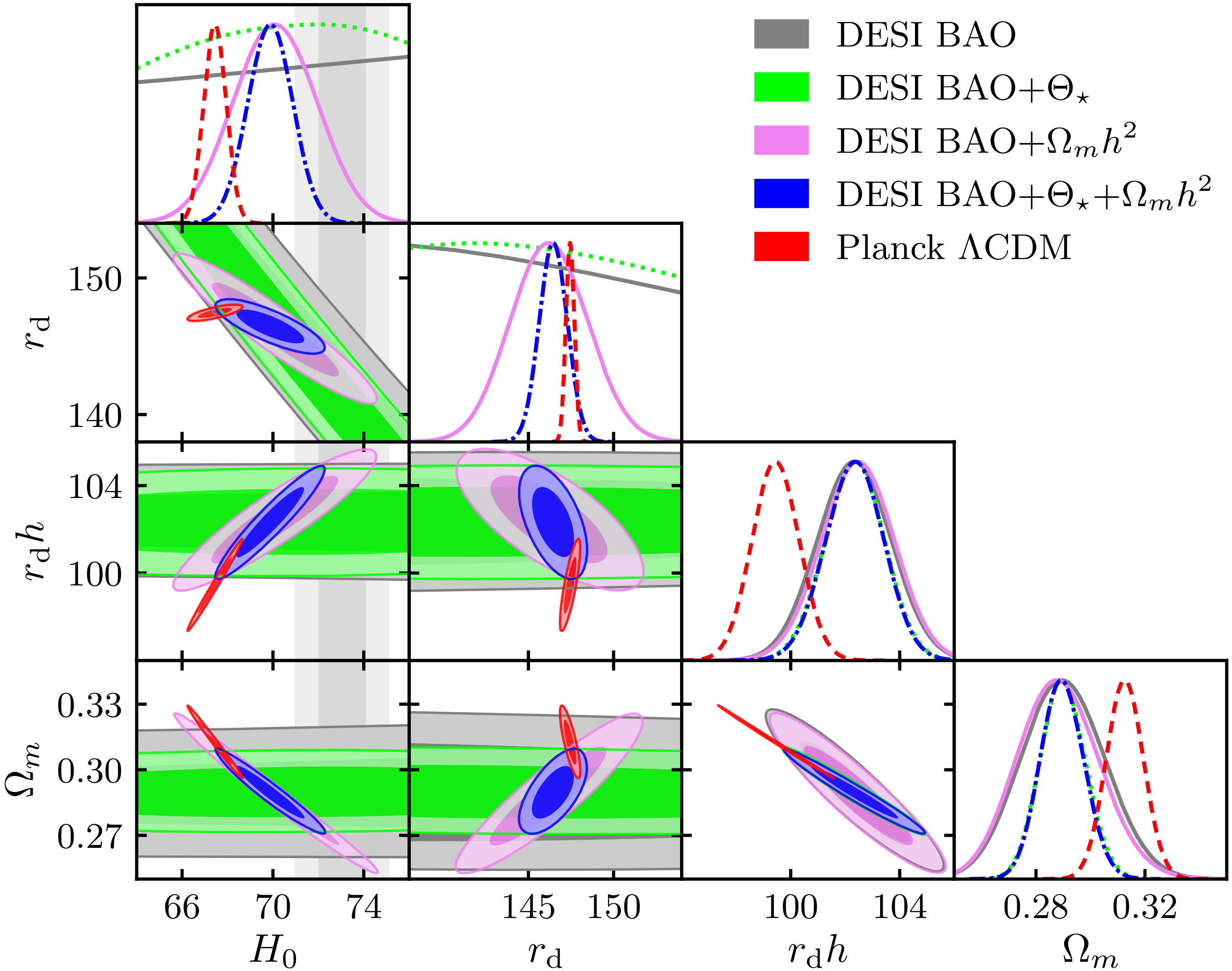
r_* - sound horizon at photon decoupling (peak of the visibility function)

r_d – sound horizon at baryon decoupling

The ratio, r_*/r_d, is the same across different models, use the LCDM value

LP, K. Jedamzik, G.-B. Zhao, in preparation

DESI Year 1 BAO vs CMB



LP, K. Jedamzik, G.-B. Zhao, in preparation

DESI Year 1 update

	$\Omega_m h^2$	$r_d h$ [Mpc]	Ω_m	r_d [Mpc]	H_0 [km/s/Mpc]
Planck LCDM	0.142 ± 0.001	99.44 ± 0.82	0.3126 ± 0.0064	147.44 ± 0.23	67.44 ± 0.47
SDSS$^+$BAO	-	99.98 ± 1.21	0.295 ± 0.016	-	-
SDSS$^+$BAO + Θ_{CMB}	-	99.28 ± 1.08	0.312 ± 0.009	-	-
SDSS$^+$BAO + $\Omega_m h^2$	Planck prior	100.01 ± 1.21	0.294 ± 0.015	144.1 ± 2.5	69.4 ± 1.8
SDSS$^+$BAO + Θ_{CMB} + $\Omega_m h^2$	Planck prior	99.35 ± 1.07	0.312 ± 0.009	147.5 ± 0.8	67.37 ± 0.96
DESI Y1 BAO	-	102.33 ± 1.27	0.290 ± 0.014	-	-
DESI Y1 BAO + Θ_{CMB}	-	102.34 ± 1.03	0.290 ± 0.008	-	-
DESI Y1 BAO + $\Omega_m h^2$	Planck prior	102.46 ± 1.25	0.288 ± 0.014	146.2 ± 2.1	70.1 ± 1.7
DESI Y1 BAO + Θ_{CMB} + $\Omega_m h^2$	Planck prior	102.3 ± 1.0	0.290 ± 0.008	146.5 ± 0.8	69.88 ± 0.93

- SDSS+ BAO is more consistent with the Planck LCDM model with standard recombination, but in slight tension with the CMB acoustic peaks if no recombination model assumed

- **DESI Y1 is less consistent** with Planck LCDM **with standard recombination**, but in perfect agreement with the CMB acoustic peaks if no recombination model assumed

LP, K. Jedamzik, G.-B. Zhao, in preparation

- A smaller sound horizon at decoupling appears to be a necessary (but not necessarily sufficient) ingredient to relieve the Hubble tension

- Many models proposed with the aim of solving the Hubble tension by reducing the sound horizon

  Early dark energy, interacting neutrinos, modified gravity, …

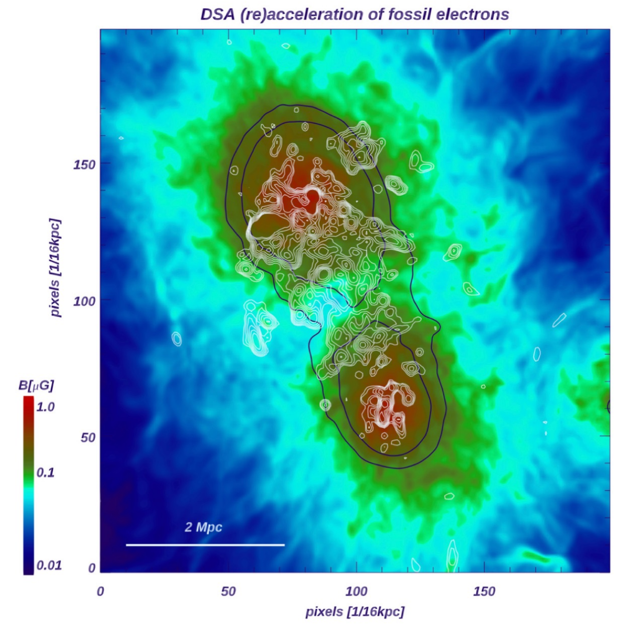
- Primordial Magnetic Fields may help relieve the tension

Cosmic Magnetic Fields

- Micro-Gauss (μG) fields in galaxies
  - produced astrophysically via dynamo?
  - μG fields seen in very high-z galaxies
  - primordial origin? (need 0.01-0.1 nano-Gauss)
- Magnetic fields in filaments
  - 3-10 Mpc radio emission ridge connecting two merging clusters suggests ~0.1-0.3 μG fields

    F. Govoni et al, arXiv:1906.07584, Science (2019)
  - Faraday Rotation Measures from filaments suggest ~0.01-0.1 μG fields

    E. Carretti et al, arXiv:2210.06220, MNRAS (2022)

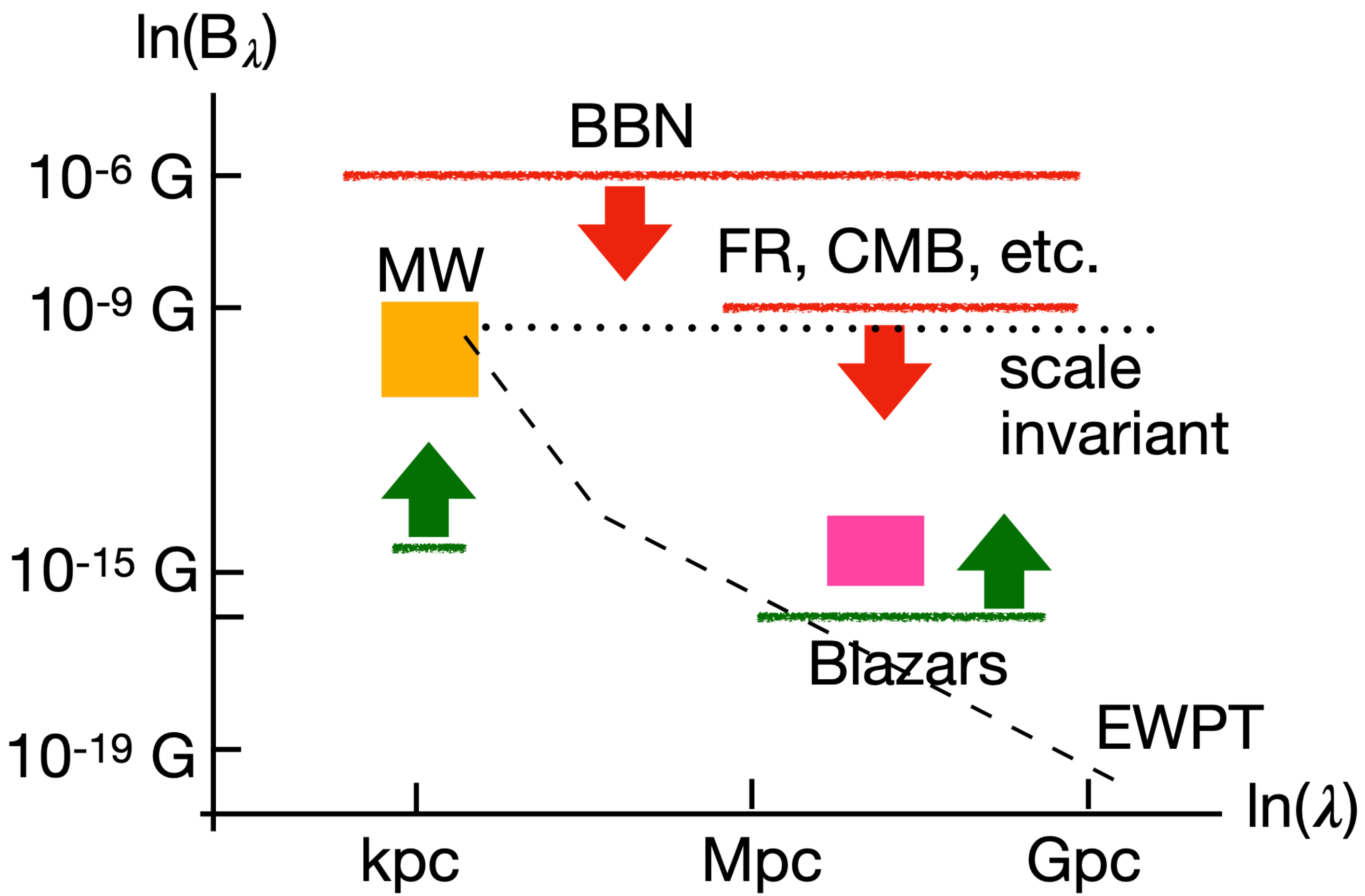


- Magnetic fields in voids?
  - missing GeV γ-ray halos around TeV blazars

    A. Neronov and I. Vovk, arXiv:1006.3504, Science (2010)
- Generated in the early universe? Not "if", but "how much"
  - phase transitions
  - inflationary mechanisms

Durrer & Neronov, arXiv:1303.7121
Vachaspati, arXiv:2010.10525

Bounds on 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 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)

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 $L > l_\gamma$
$c_s^2 << 1$ for $L < l_\gamma$

Drag force 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)

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

$\frac{1}{2}\nabla B^2 - (\mathbf{B}\cdot\nabla)\mathbf{B}$

$\alpha \sim 1/l_\gamma$

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

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

Drag force 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

Density fluctuations (on ~1 kpc scales) will grow until either pressure counteracts compression or the source magnetic field decays

$$\frac{\delta\rho}{\rho} \simeq \min\left[1, \left(\frac{v_A}{c_s}\right)^2\right]$$

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

Inhomogeneities enhance the recombination rate

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

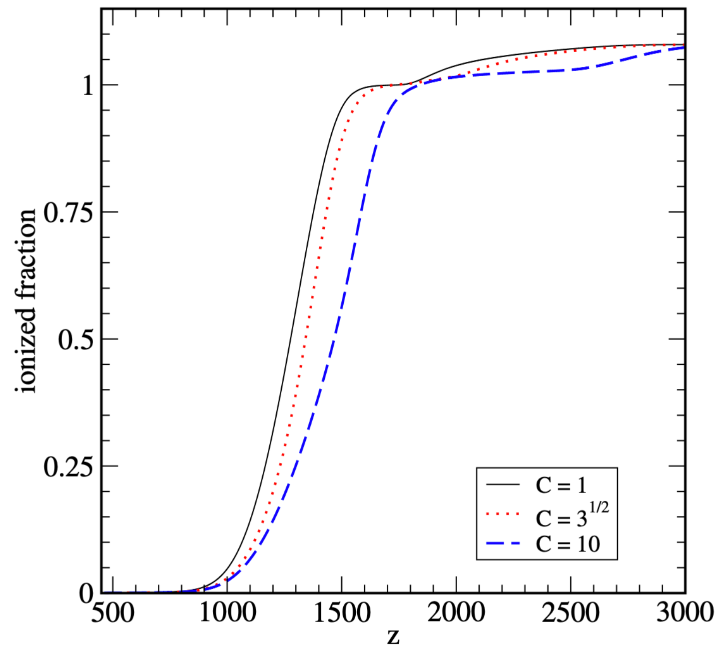
$$n_e = \langle n_e \rangle + \delta n_e \quad \rightarrow \quad \langle n_e^2 \rangle \; > \; \langle n_e \rangle^2$$

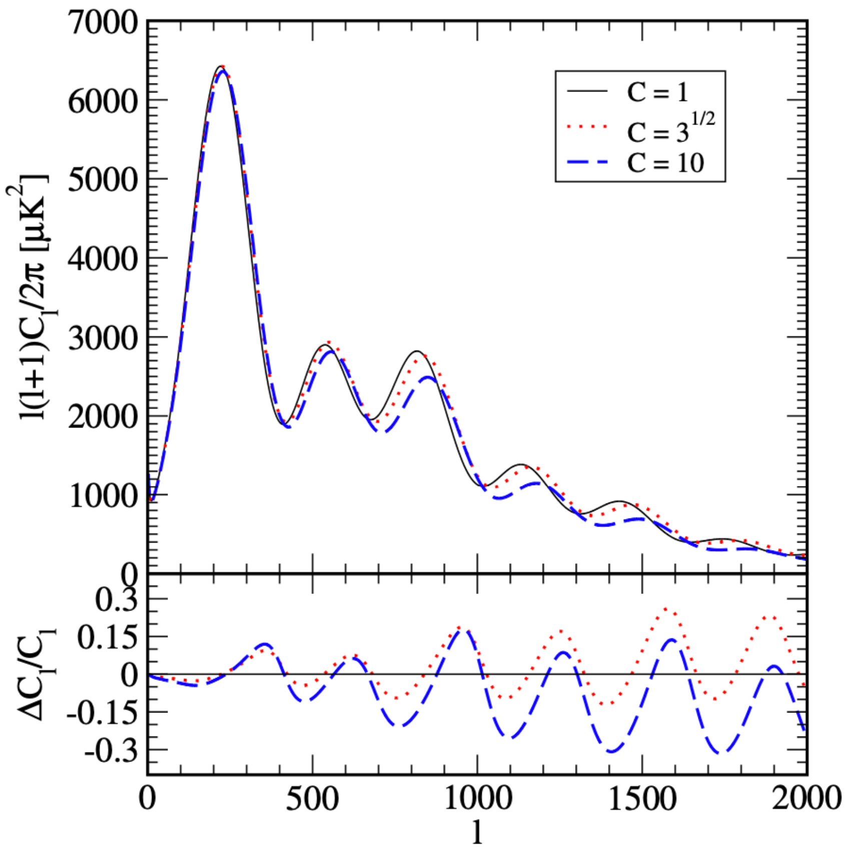
Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

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)

The toy-model implementation*

The 3–zone model (M1) for the baryon density PDF from Jedamzik & Abel (2013)

Modified RECFAST with one additional parameter -- baryon clumping

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

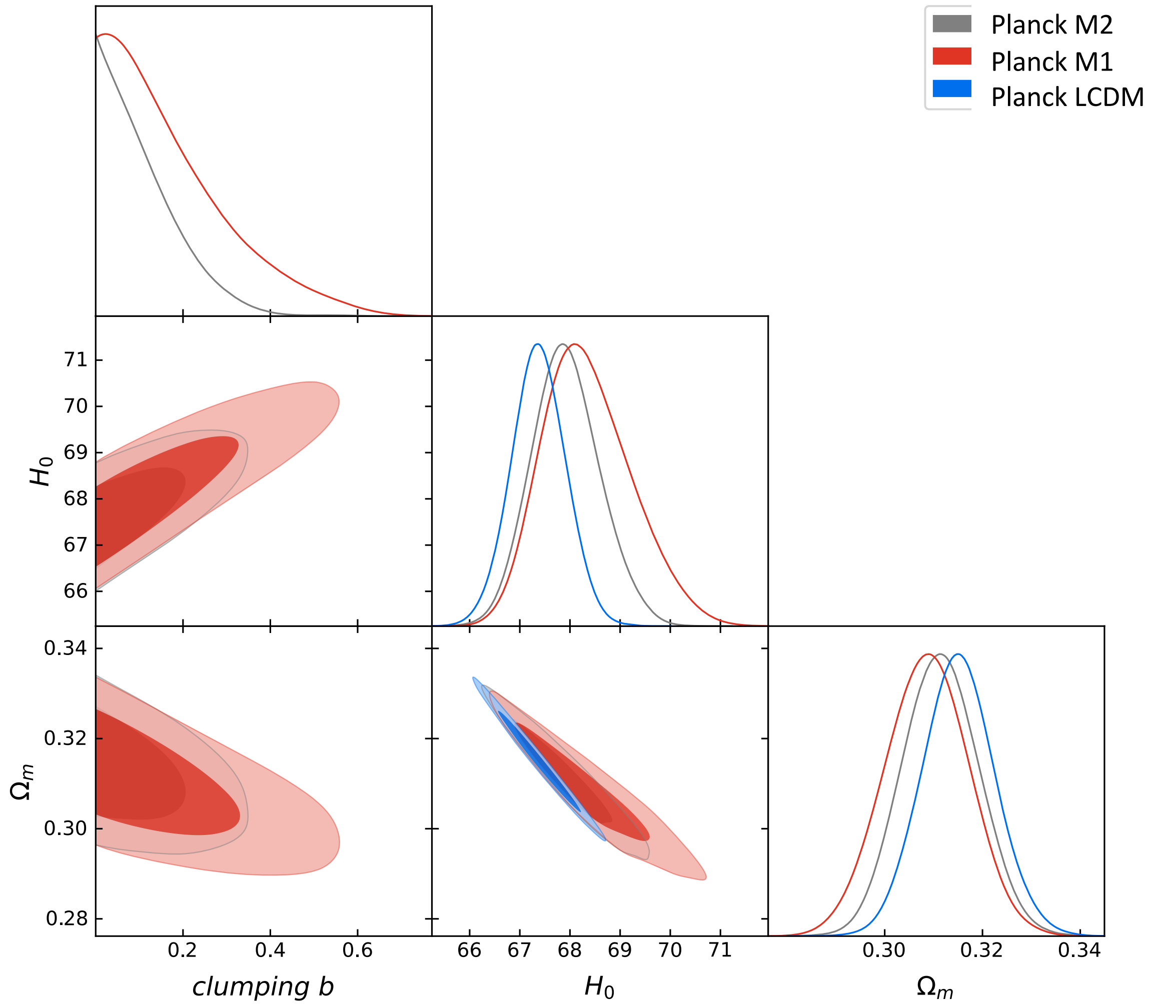
Datasets:

- CMB temperature, polarization and lensing from Planck 2018
- BAO, Pantheon SNIa, DES Y1
- SH0ES determination of H_0

* Kept us busy during COVID

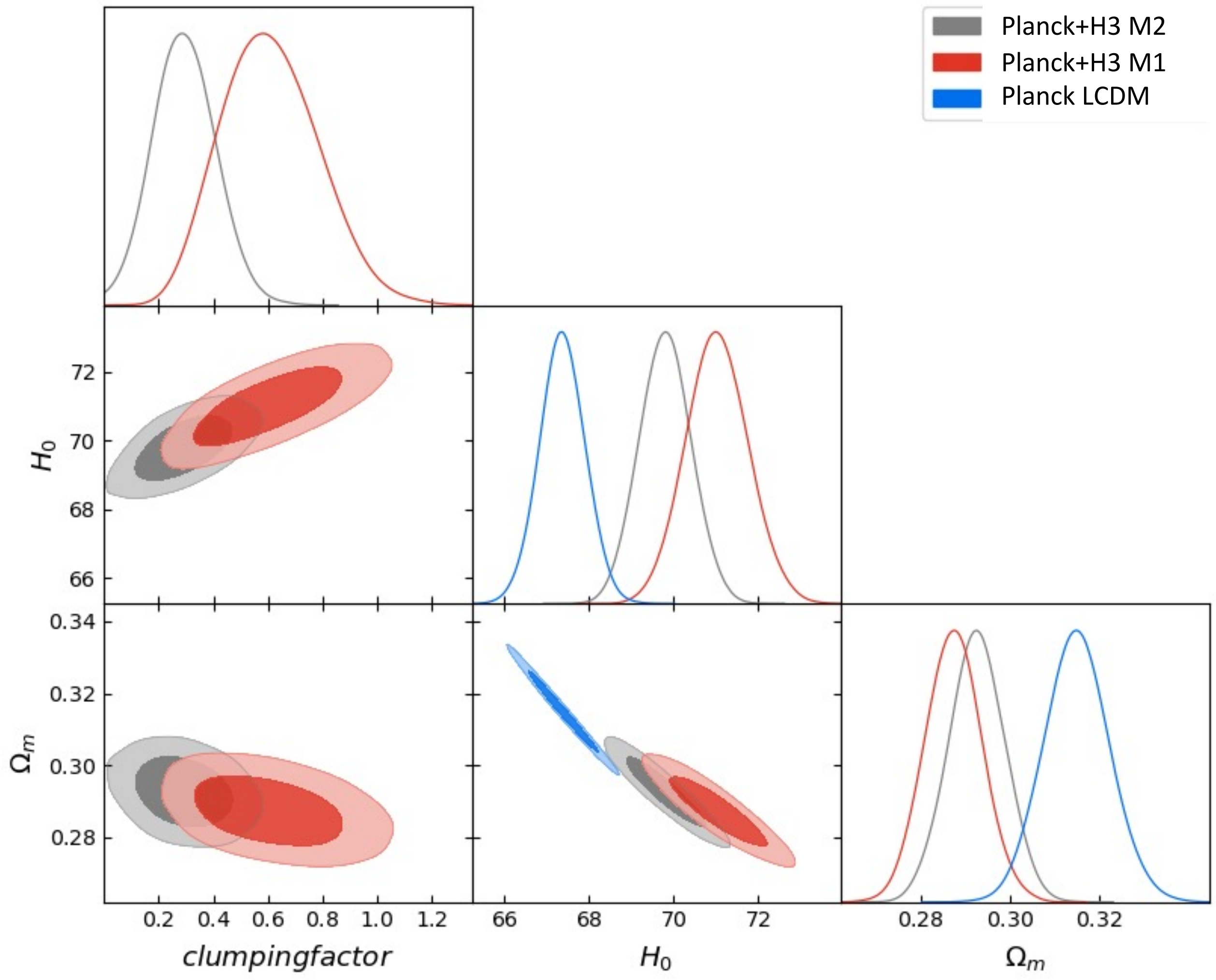
K. Jedamzik and L. Pogosian, arXiv:2004.09487, PRL

Fitting the M1 model to Planck only



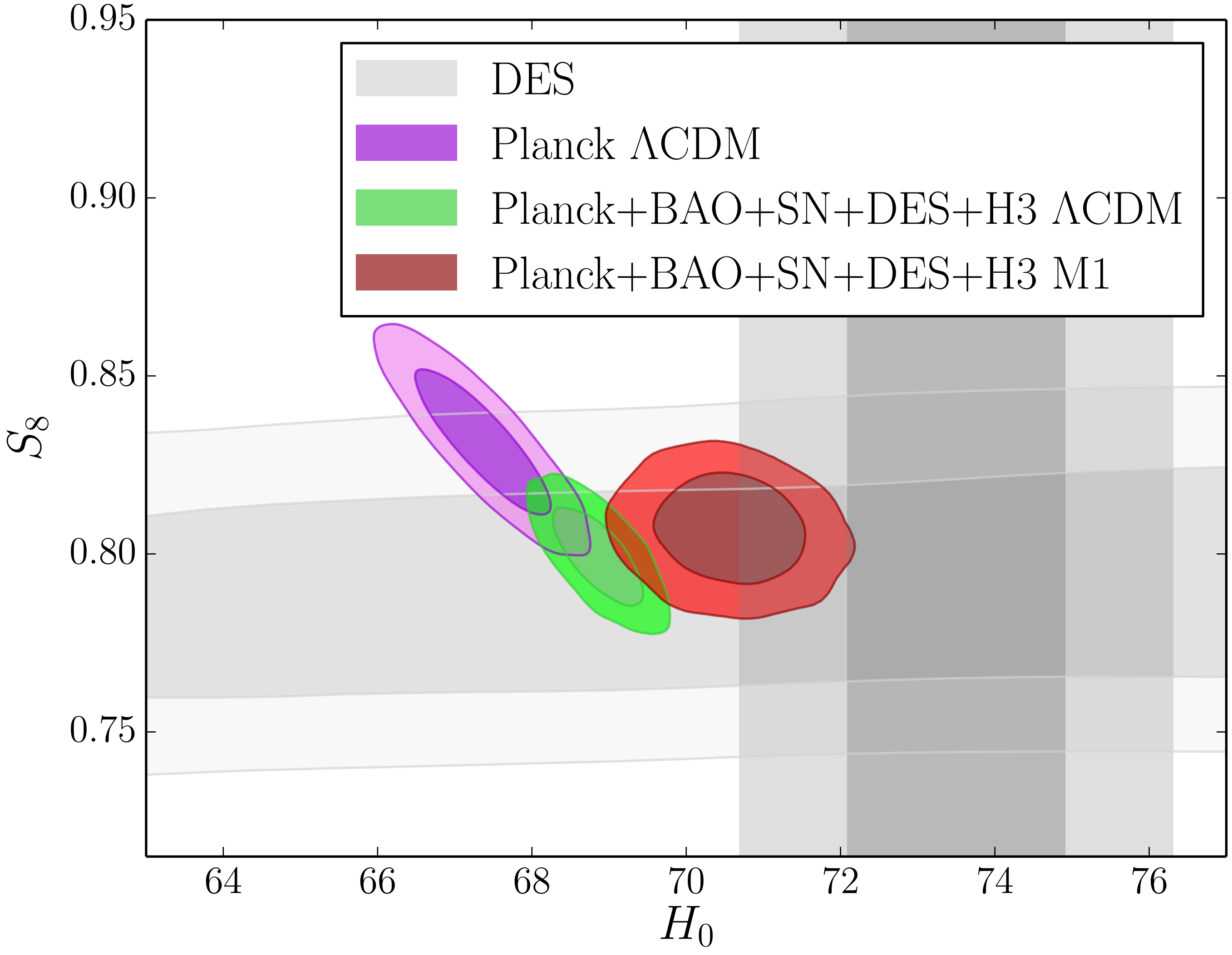
- Strong degeneracy between the clumping parameter b and H_0
- No preference for a non-zero value of b

Fitting the M1 to Planck + H0



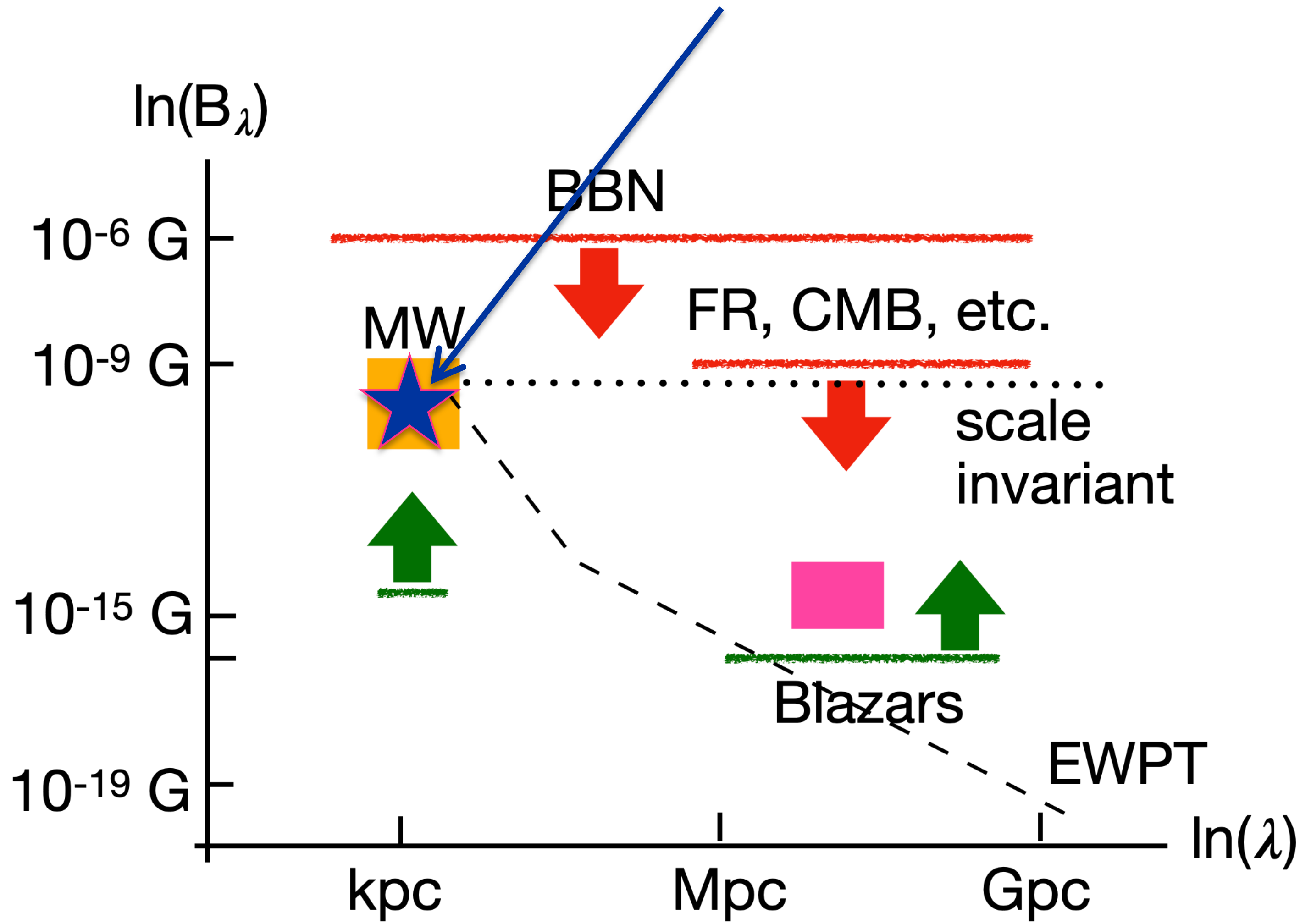
a clear detection of clumping

Fitting the M1 model to all data



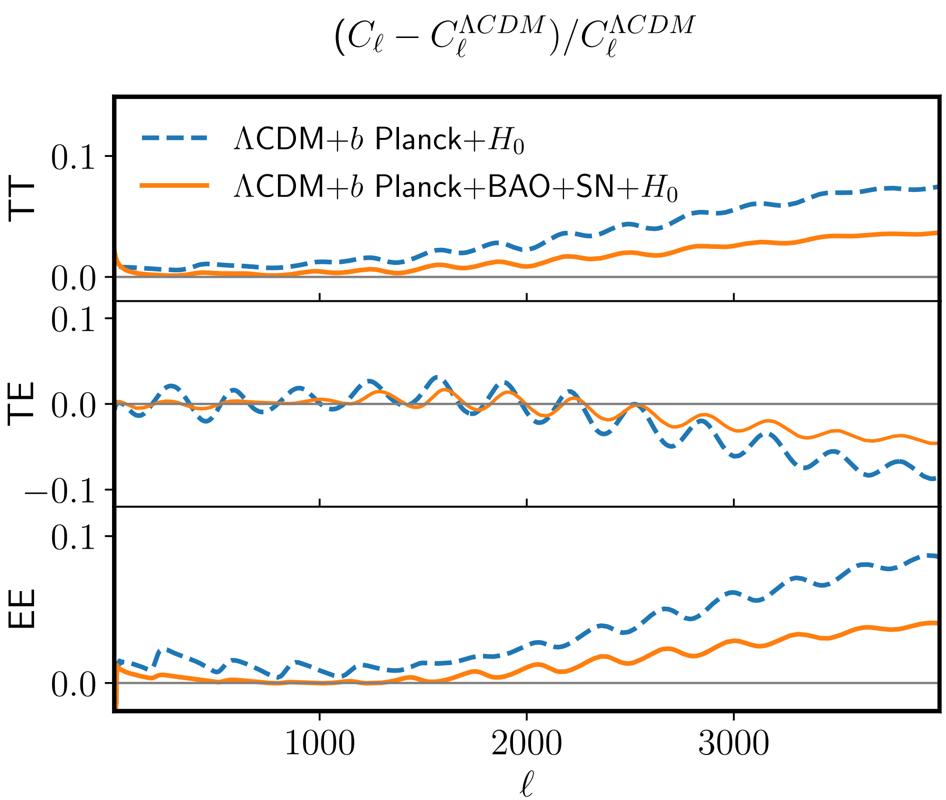
K. Jedamzik and L. Pogosian, arXiv:2004.09487, PRL

Clumping required to relieve the H_0 tension



Plot from T. Vachaspati, arXiv:2010.10525

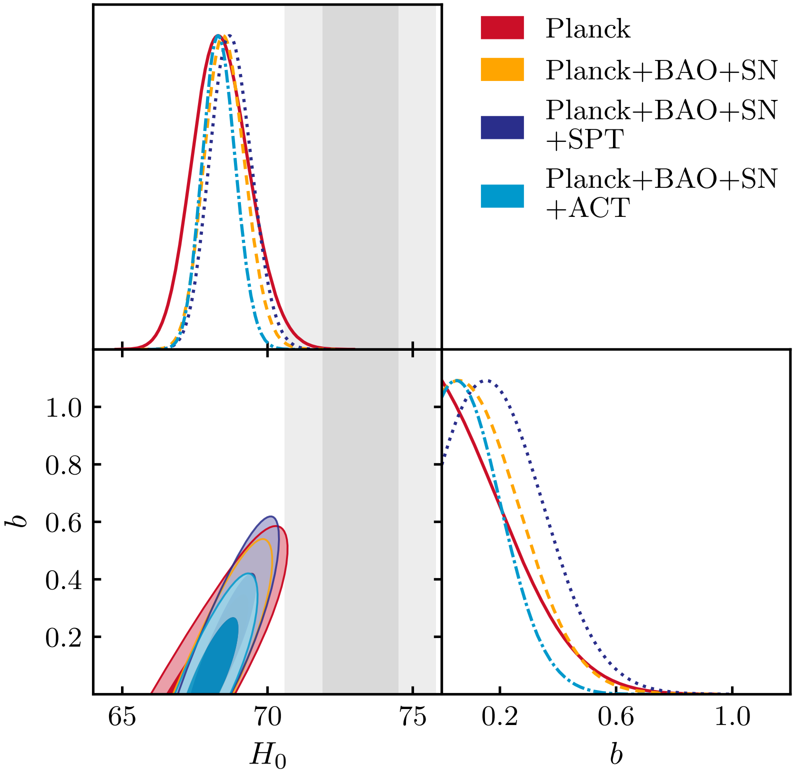
The Silk Damping Tail in M1



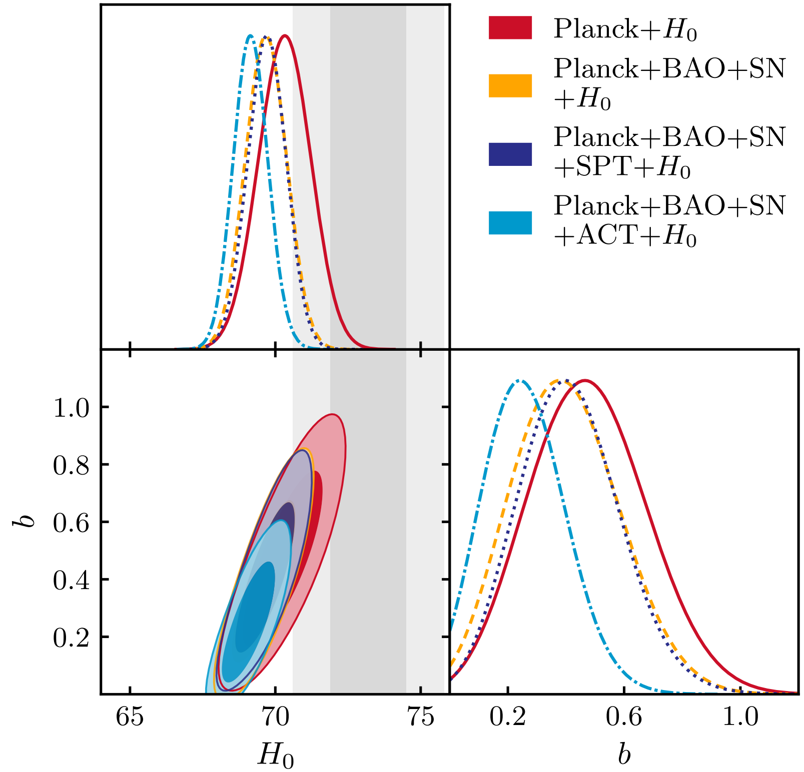
LCDM and M1 make comparable predictions for CMB Temperature (T) and polarization (E) spectra for l<2000, but the differences become large at higher l

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

ACT DR4 and SPT-3G Y1 constraints on the M1 model



without SH0ES



with SH0ES

	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

Takeaways from the M1 toy-model tests

- Magnetic fields could 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
- The Silk damping tail is very sensitive to the details of the baryon PDF and the high-resolution CMB data could provide a stringent test of the proposal
- Drawbacks of the 3-zone model
  - *Ad hoc* choice of the PDF
  - Assumes the PDF does not evolve
  - Does not account for peculiar velocities and Ly-alpha transport
- A necessary next step:

  Derive recombination histories from realistic MHD simulations

MHD simulations

Performed by Karsten Jedamzik and Tom Abel using a modification of ENZO (https://enzo-project.org)

Compressible magneto-hydrodynamics (MHD) in an expanding universe before, during and after recombination, with added photon drag

Coupled with a "chemical solver" (similar to RECFAST) that computes abundances of ionized hydrogen and helium at each time step

Additional modeling of Lyman-alpha photon transport across the simulation volume

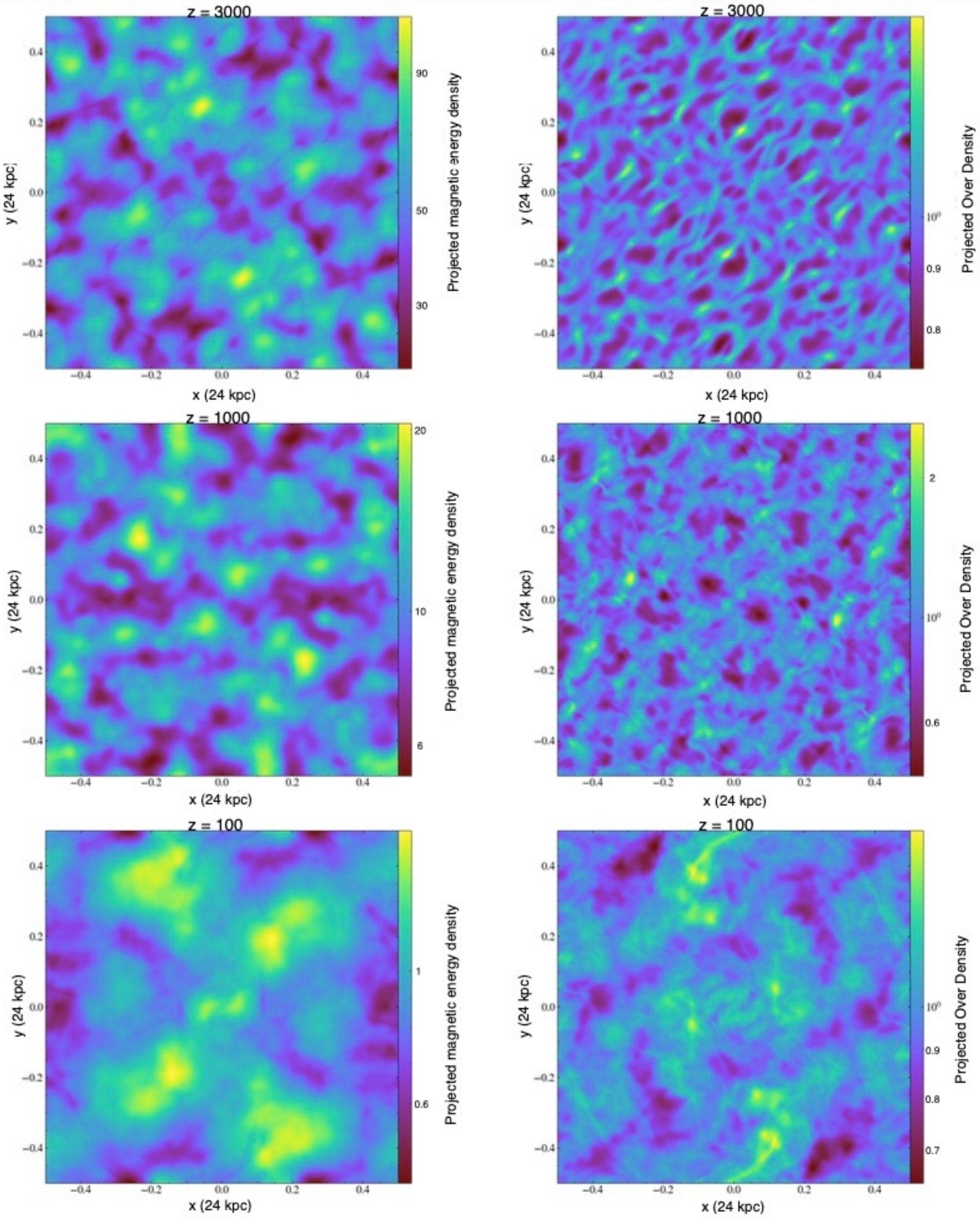
Four PMF scenarios to be considered:

Phase-transition-sourced blue spectrum with and without helicity
Inflation-sourced scale-invariant spectrum with and without helicity

K. Jedamzik and T. Abel, arXiv:2312.11448

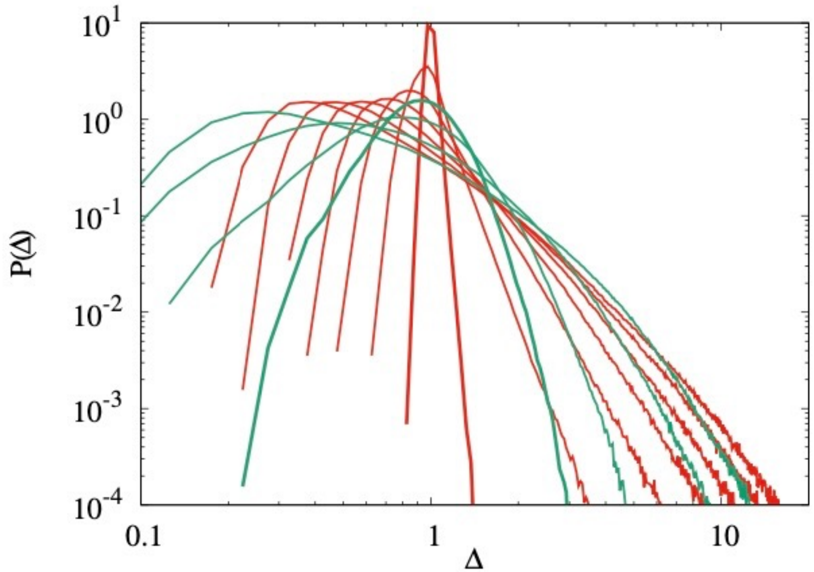
Magnetically induced baryon clumping

Non-helical PMF, blue spectrum,
0.5 nano-Gauss (comoving) strength,
(24 kpc)^3 box



K. Jedamzik and T. Abel, arXiv:2312.11448

Baryon density distribution



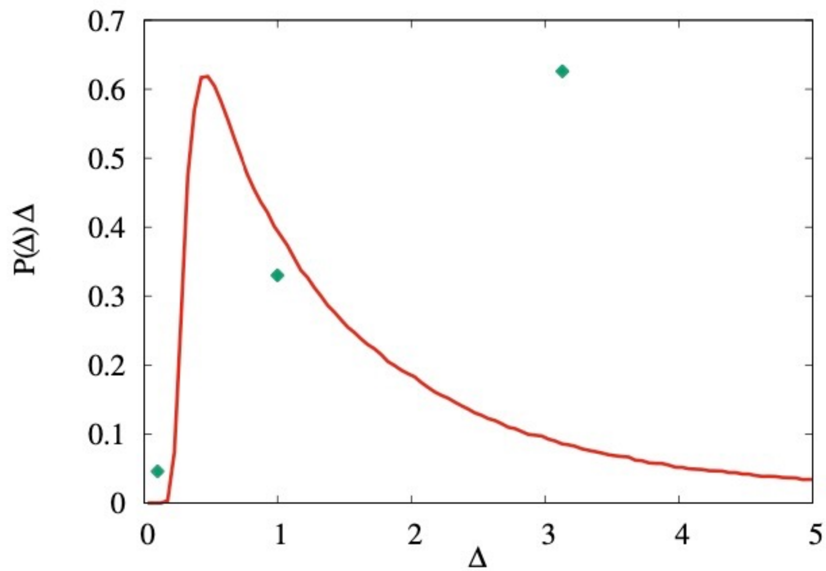
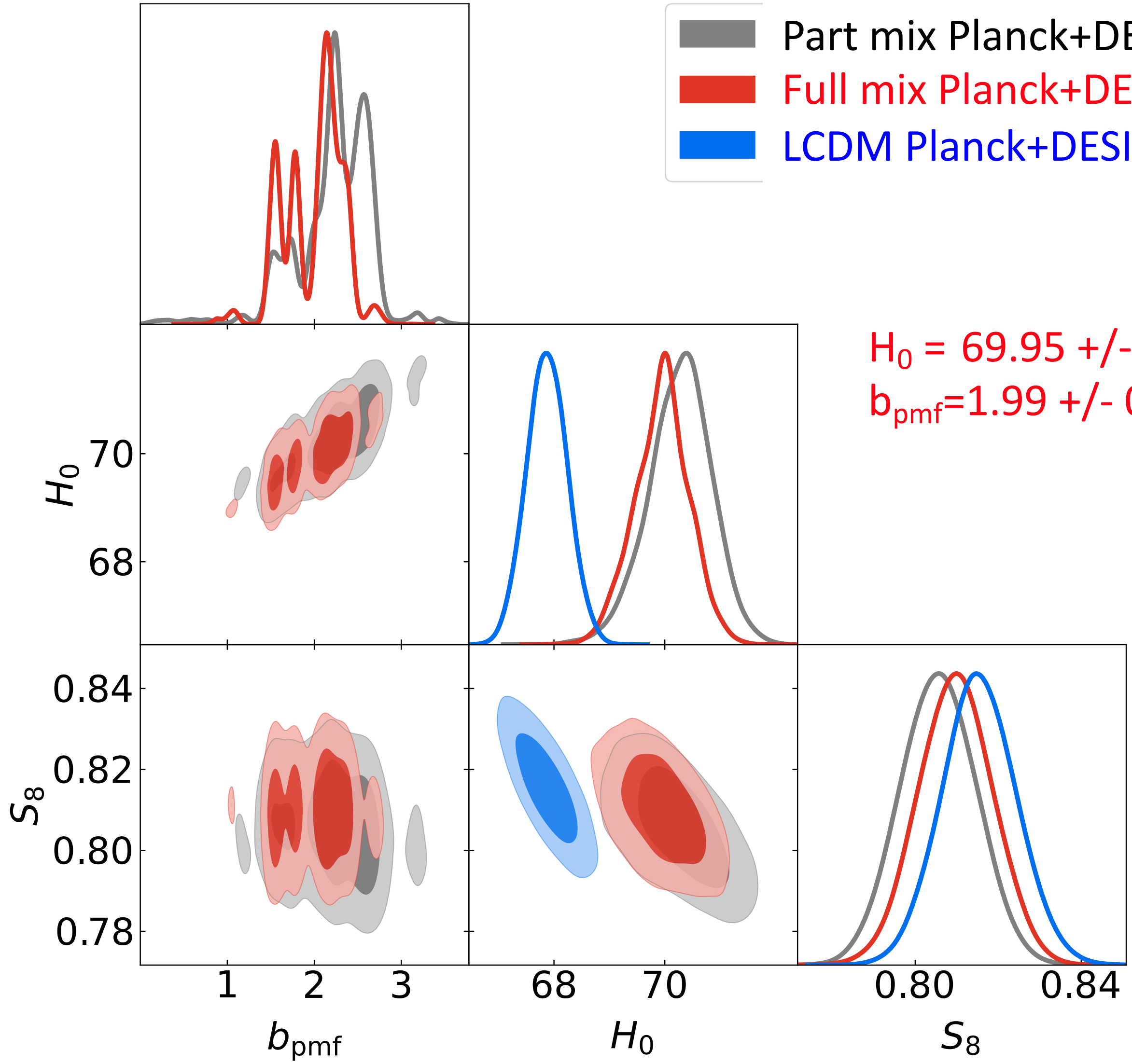


FIG. 4. The baryon probability distribution function (pdf) $P(\Delta)$, for several redshifts for the numerical simulation shown in Fig. 1. $P(\Delta)$ is shown by red (green) lines before (after) the maximum of the clumping factor occurs at $z_{\max} \approx 1250$, respectively. Is is shown for redshifts $z = 4400, 4000, 3500, 3000, 2500, 2000, 1500, 1000, 500, 100$ and 10. The lines for $P(\Delta)$ at redshifts $z = 4400$ and $z = 10$ are slighlty thicker. For $z > z_{\max}$ the maximum moves to lower densities and very high density regions get more and more probable, whereas for lower redshifts $z < z_{\max}$ the maximum moves to higher densities and very high density regions get less and less probable.

FIG. 5. The quantity $P(\Delta)\Delta$, with $P(\Delta)\Delta d\Delta$ giving the probability to find a baryon at overdensity between Δ and $\Delta + d\Delta$, for the simulation shown in Fig. 1 at redshift $z = 1500$. For comparison the analogous quantity for the M1 three-zone model at the same clumping factor $b = 1.28$ is shown (green dots), illustrating that three zone models do not capture the baryon probability function correctly.

K. Jedamzik and T. Abel, arXiv:2312.11448

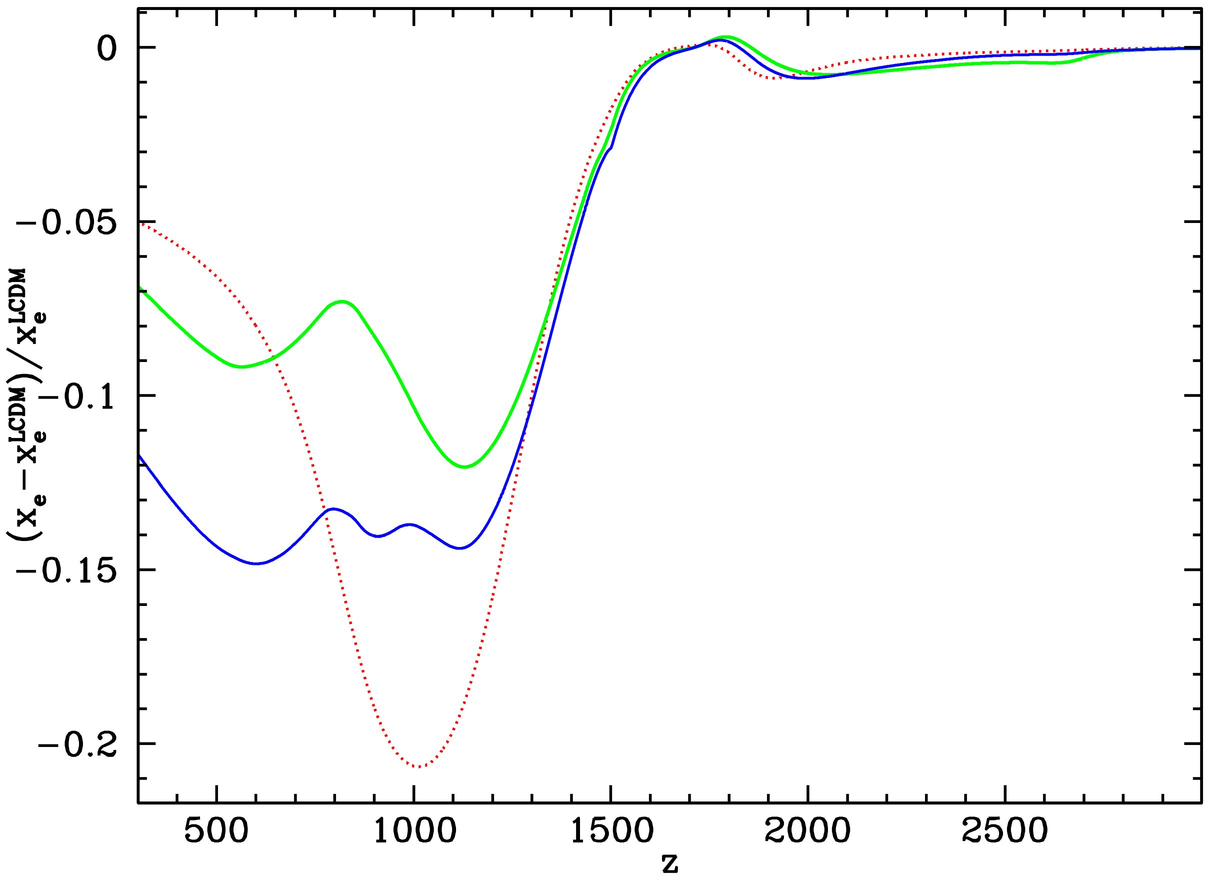
Preliminary results: b_{pmf}, H_0 and S_8



H_0 = 69.95 +/- 0.50 km/s/Mpc
b_{pmf}=1.99 +/- 0.34

b_{pmf}	pG at z=10
1	4.3
2	9.0
3	20.0
4	37.4
5	70.2
6	136.7

Ionized fraction from simulations vs M1



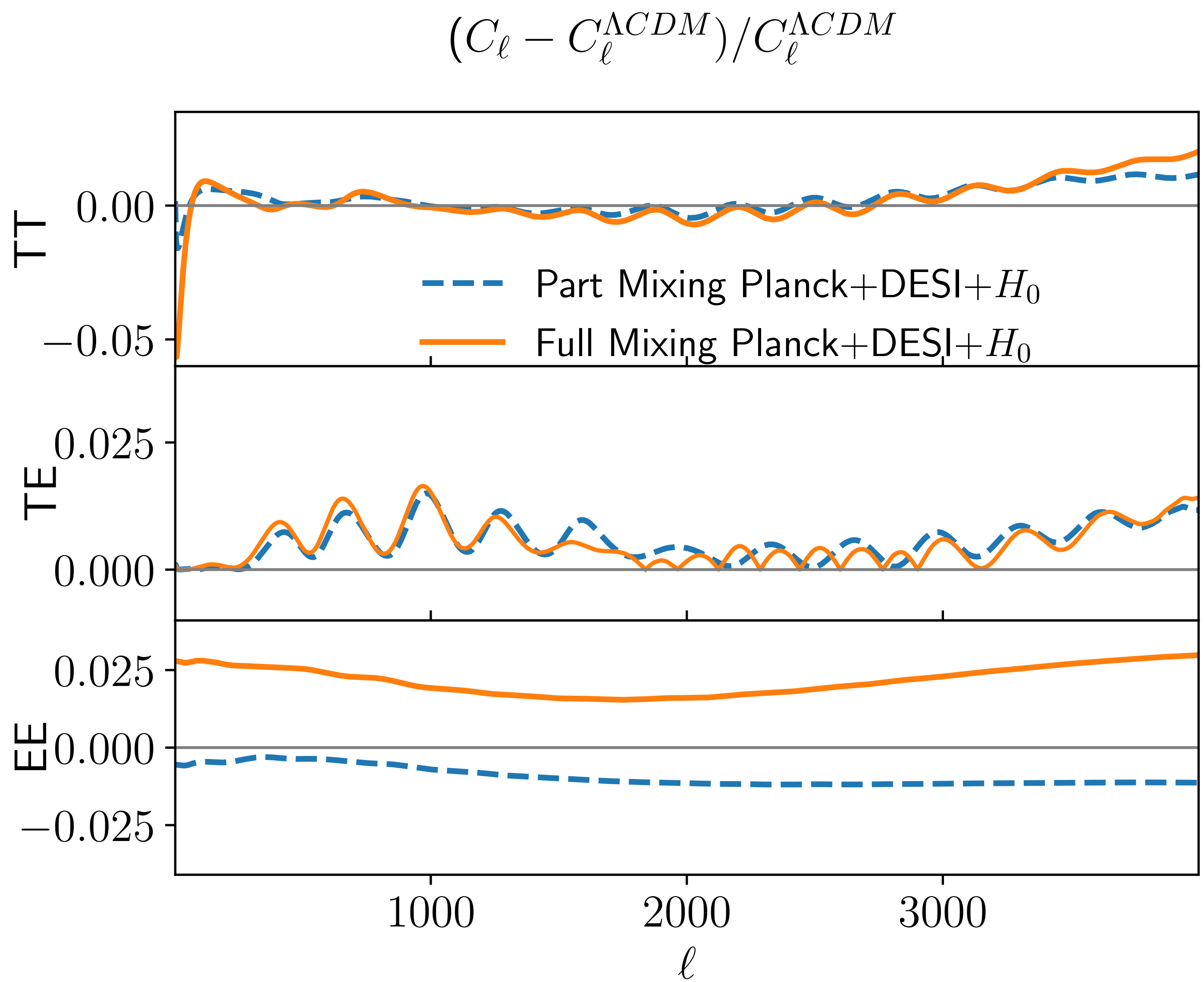
Full mixing b_{pmf} = 2.1

mix=0.25, b_{pmf}=2.46

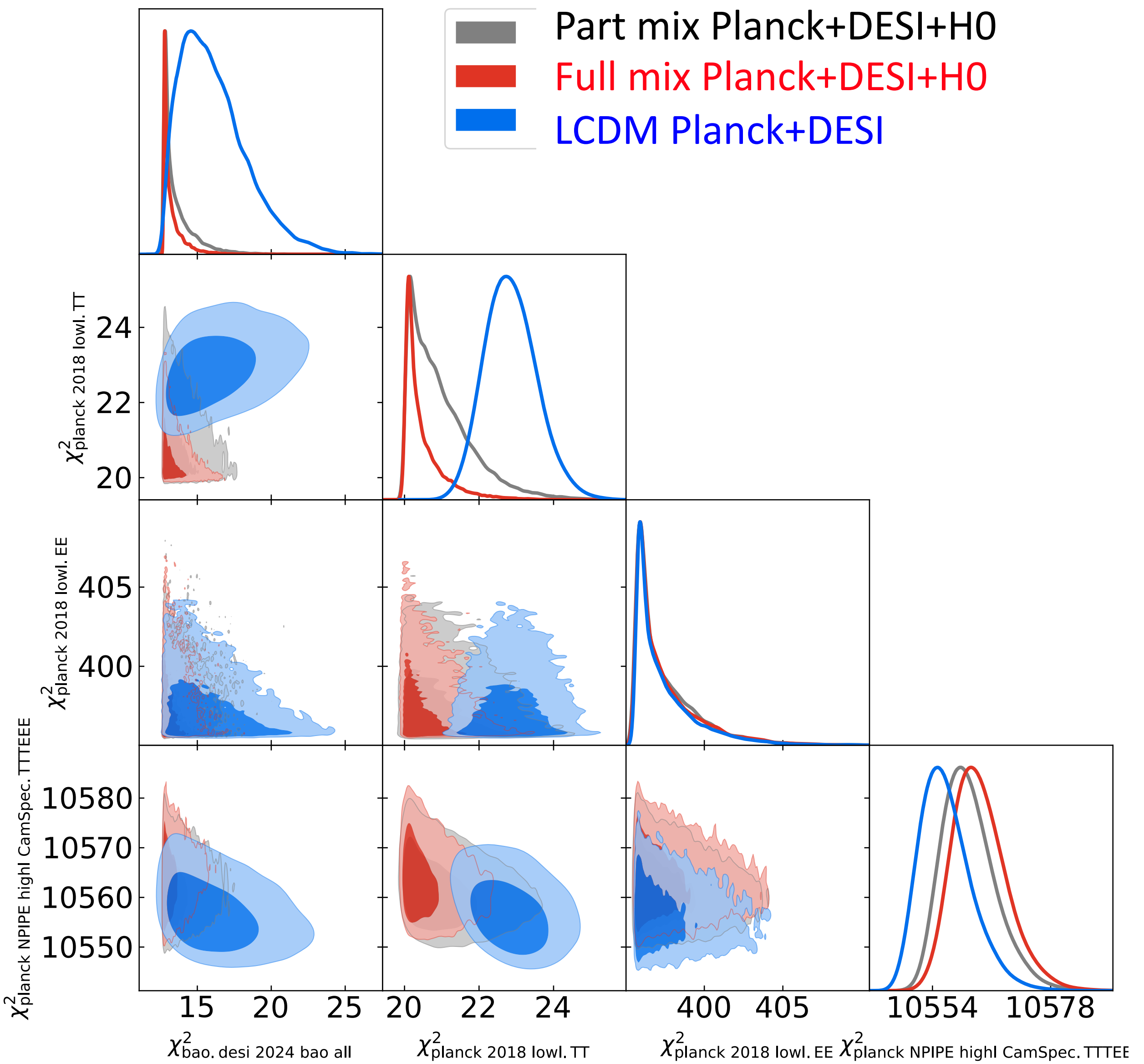
M1 b=0.5

b_{pmf}	pG at z=10
1	4.3
2	9.0
3	20.0
4	37.4
5	70.2
6	136.7

Differences in CMB spectra



Preliminary results: χ^2 comparison



Preliminary results: χ^2 comparison

	LCDM	PMF Full Mix	PMF Part Mix
CamSpec	10545.6	10551.6	10549.6
Low-ell EE	397.02	396.02	395.72
Low-ell TT	22.75	20.60	20.95
DESI BAO	16.55	12.74	13.69
Total	10982	10981	10980

The Outlook

The proposal is still alive, which is not trivial

We are just starting:

- More simulations to beat the variance
- Code comparisons
- Helical PMF simulations, scale-invariant case

The data is evolving too

The Outlook

This is <u>a highly falsifiable proposal</u> (having a well-defined target helps!)

High-resolution CMB temperature and polarization anisotropies

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

Cosmological Recombination Radiation – CMB spectral distortion sourced by the emission/absorption of photons during the recombination

M. Lucca, J. Chluba, A. Rotti, arXiv:2306.08085, MNRAS (2023)

μ- and y-type spectral distortions of CMB

K. Jedamzik, V. Katalinic, A.V. Olinto, astro-ph/9911100, PRL (2000)
K. Kunze, E. Komatsu, arXiv:1309.7994, JCAP (2014)

Faraday Rotation produced at last scattering (by ~0.1 nG scale-invariant PMF)

L. Pogosian, M. Shimon, M. Mewes, B. Keating, arXiv:1904.07855, PRD (2019)

γ-ray astronomy as a probe of magnetic fields in voids

W. Chen, J. H. Buckley, and F. Ferrer, arXiv:1410.7717, PRL (2015)
S. Archambault et al. (VERITAS), arXiv:1701.00372, ApJ (2017)

Radio astronomy: rotation measures, FRBs, …

Dark matter mini-halos? *P. Ralegankar, arXiv:2303.11861*

Conclusions

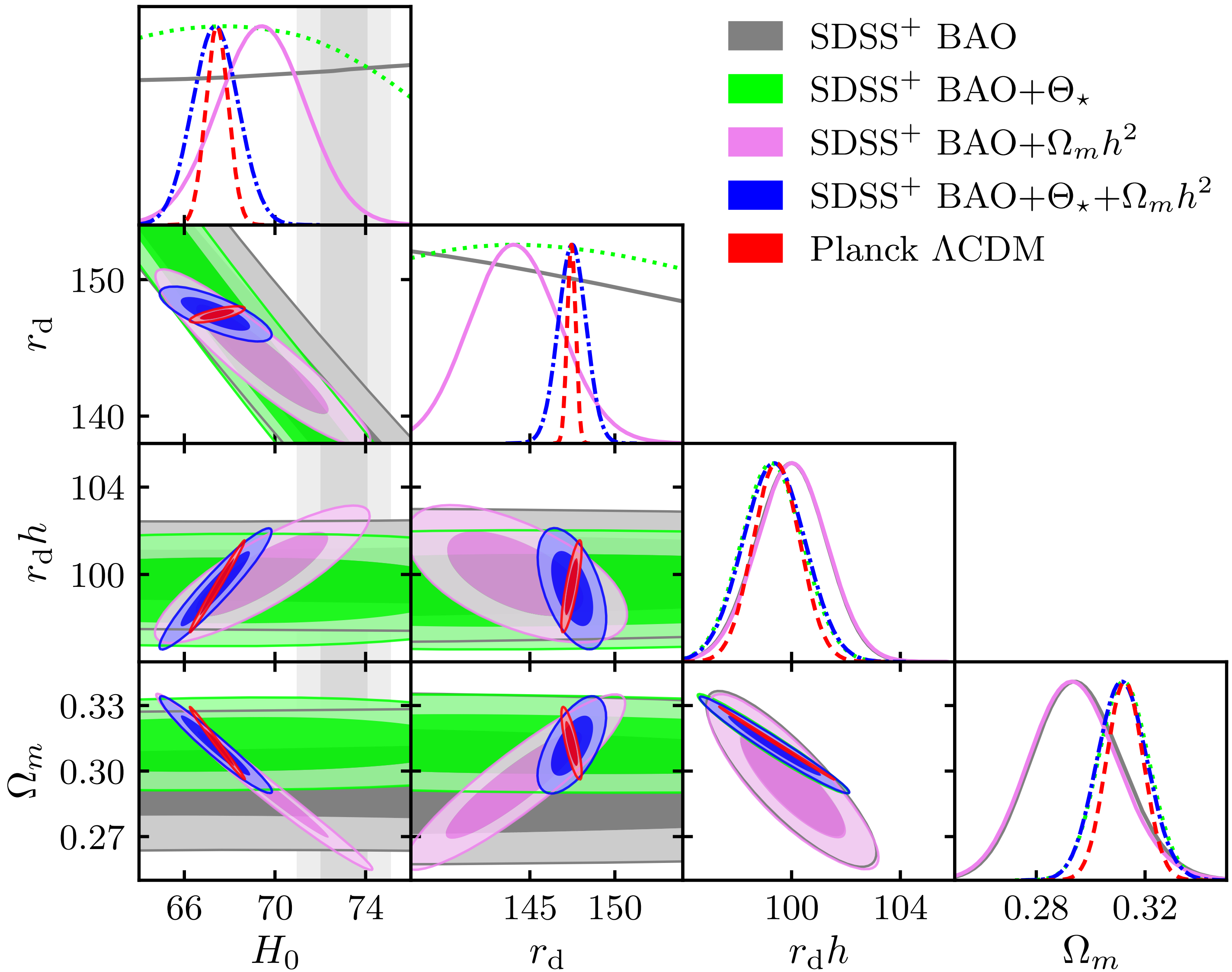
- The Hubble tension hints at a missing ingredient in the physics of recombination. That missing ingredient could be a primordial magnetic field of strength that happens to be of the right order to also explain the observed galactic, cluster and intergalactic fields

- This can only raise the value of H_0 up to 70 km/s/Mpc
  (it could be all we need)

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

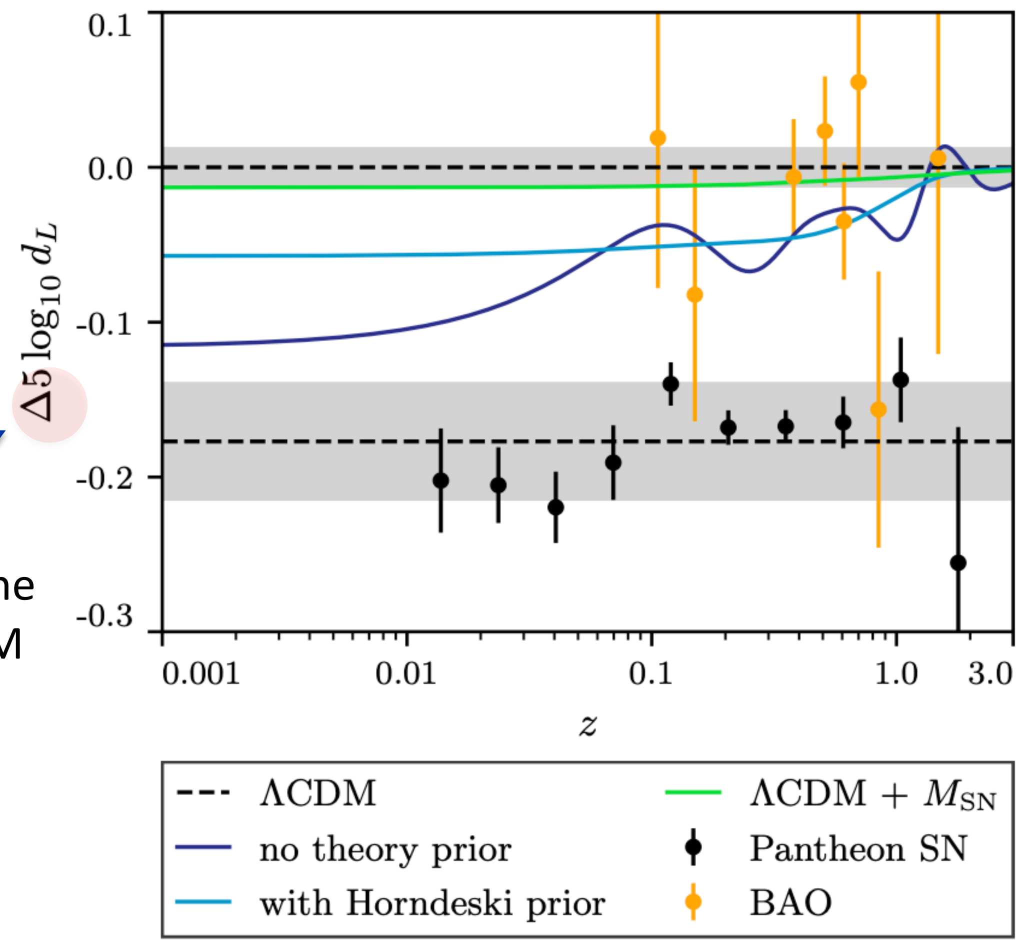
- Future high resolution CMB temperature and polarization anisotropy data and other types of observations, along with comprehensive MHD simulations, will provide a conclusive test of this scenario

SDSS+ BAO vs CMB



LP, K. Jedamzik, G.-B. Zhao, in preparation

Difficulty with late time-solutions



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

Pogosian et al, arXiv:2107.12992, Nature Astronomy