Relieving the Hubble Tension with Primordial Magnetic Fields

Levon Pogosian

Simon Fraser University
Burnaby, BC, Canada

in collaboration with Karsten Jedamzik (LUPM)

arXiv:2004.09487

SFU


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You can't blame us for being excited about this

- Primordial Magnetic Fields have long been studied as a possible seed for the observed fields in galaxies and clusters, and because they are predicted to originate in the early universe (not a question of if, but how much)

- If there were magnetic fields in the plasma prior to recombination, they would induce baryon inhomogeneities (clumping) on very small scales, speeding up the recombination [*Jedamzik and Abel, JCAP (2013), Jedamzik and Saveliev, PRL (2019)*]

- A faster recombination means a smaller sound horizon at decoupling, potentially solving the tension between the values of H_0 measured by CMB and SNIa

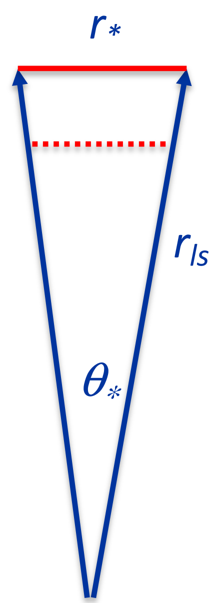
- And indeed, our study finds a 4-sigma detection of the clumping effect, relieving the Hubble tension and, as a byproduct, eliminating the tension between the clustering amplitude S_8 predicted by CMB and that measured by LSS surveys

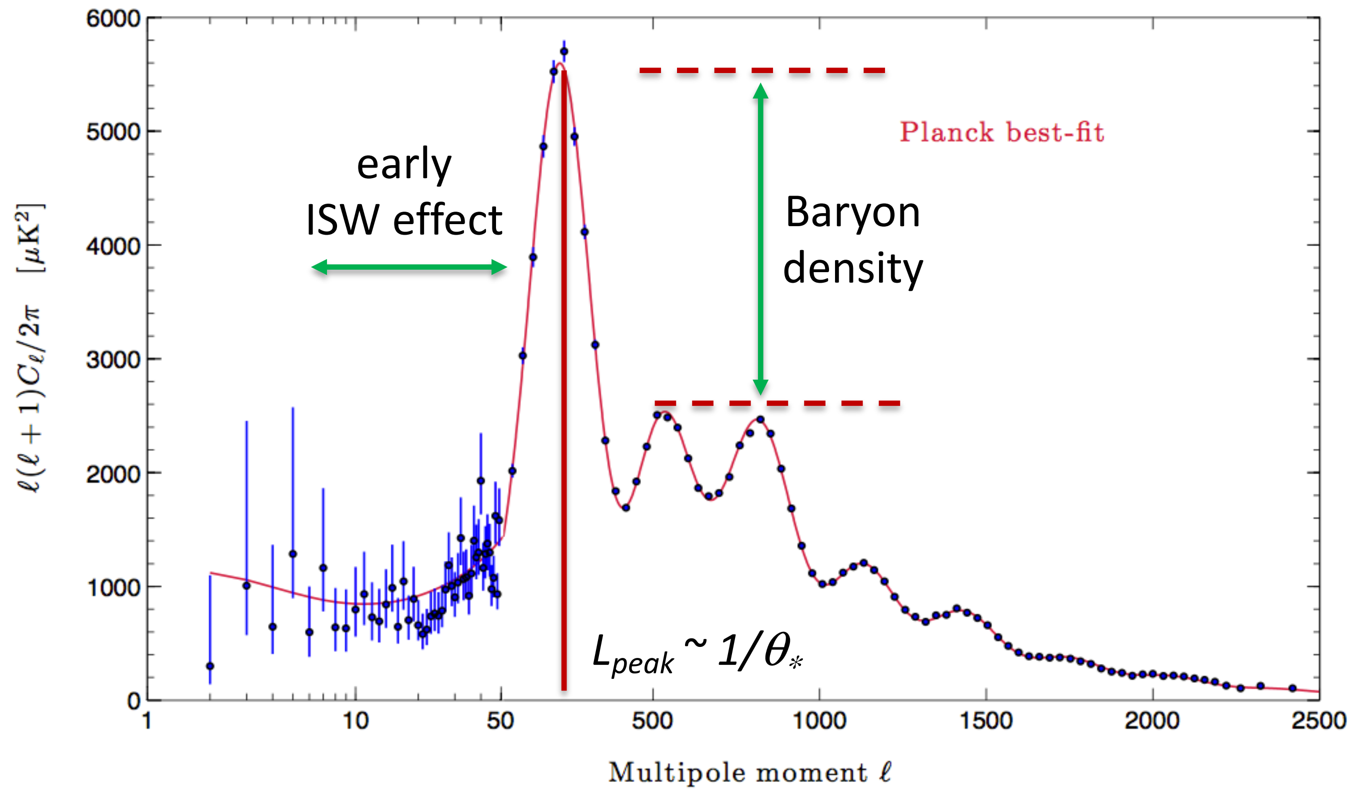
- Our findings provide strong motivation for further detailed studies of magnetic fields in the pre-recombination plasma and provide clear targets for future experiments

Plan of the talk

- A brief review of the H_0 and the S_8-Ω_m tensions
- A brief introduction into primordial magnetic fields
- The baryon clumping effect
- Results
- Implications

How does CMB constrain H0?

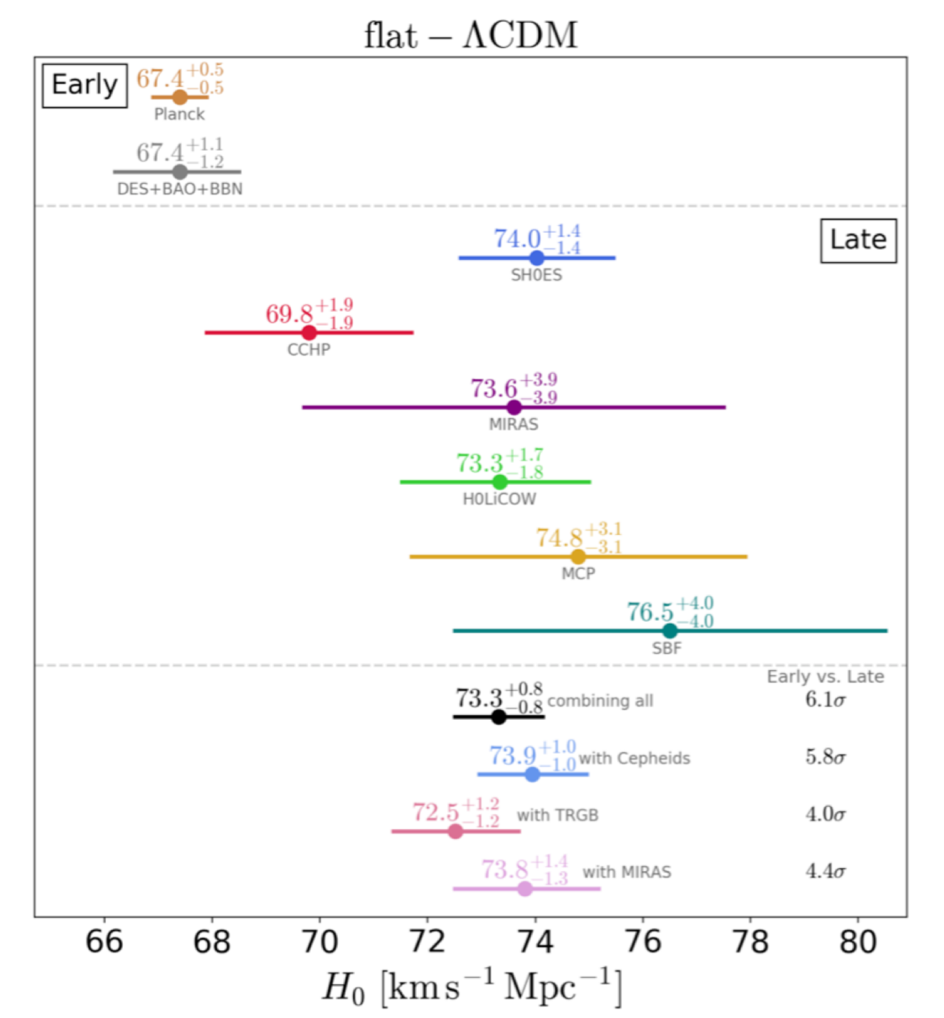




Sound horizon at Last Scattering: $r_* = r_*(h, \Omega_r h^2, \Omega_b, \Omega_m)$

Distance to Last Scattering: $r_{ls} = r_{ls}(h, \Omega_r, \Omega_m)$

The Hubble tension

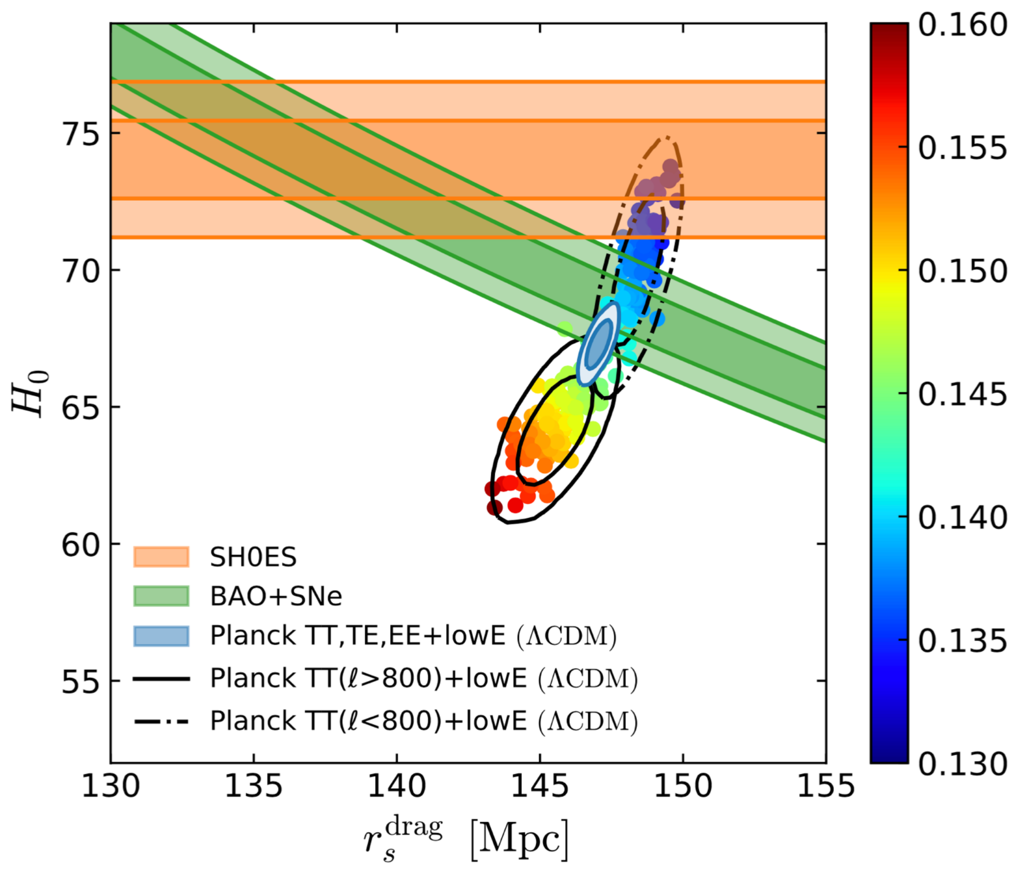


Tensions between the Early and the Late Universe

L. Verde, T. Treu, A. Riess, arXiv:1907.10625

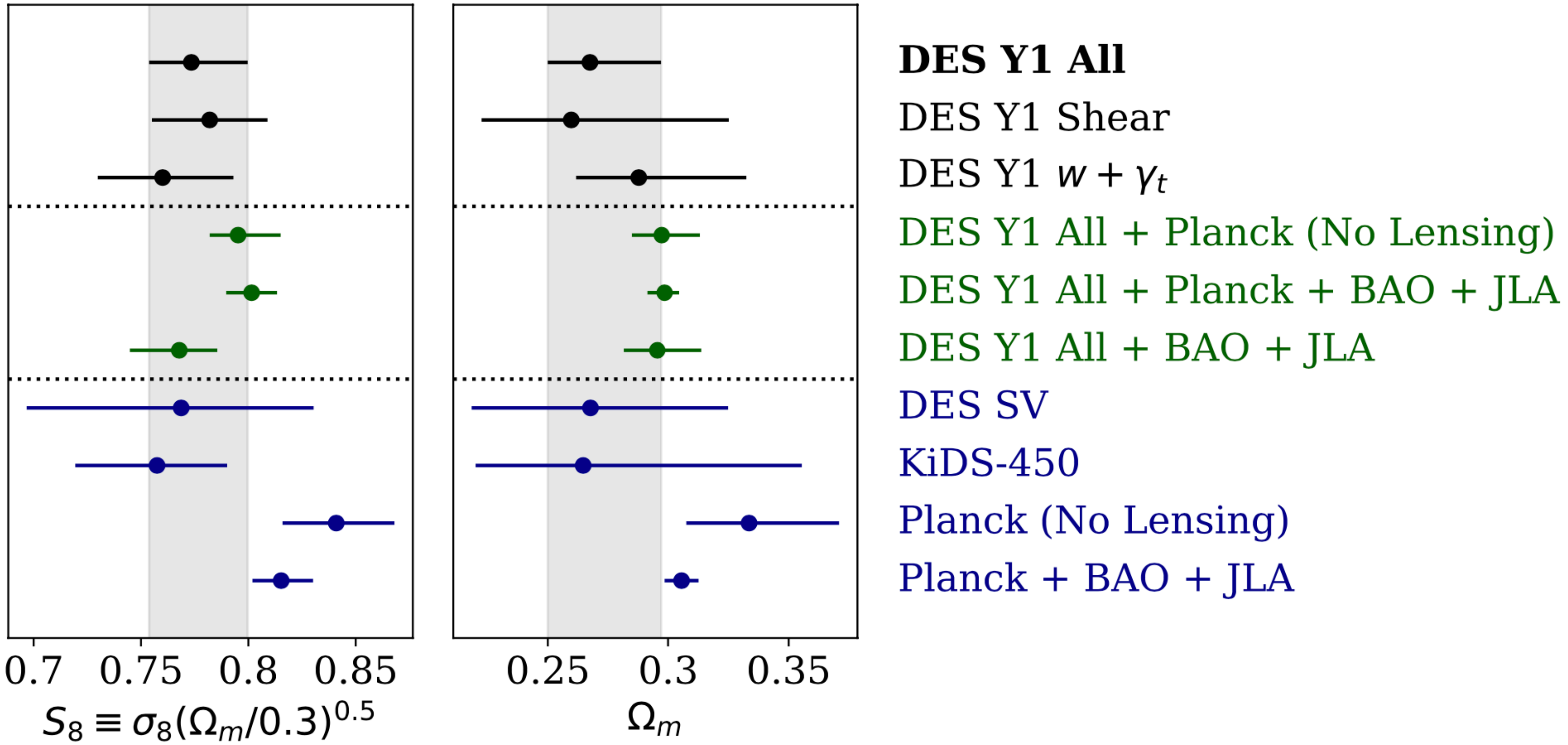
The tension is between the measurements that require calculating r_* and r_{drag} and those that do not

Baryon Acoustic Oscillations



The Hubble Hunter's Guide, L. Knox and M. Millea, arXiv:1908.03663

The S_8-Ω_m tension



DES Y1 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing, arXiv:1708.01530

Cosmic Magnetic Fields

- Origin of 1-10 μG fields in galaxies and clusters
  - mostly astrophysical? (dynamo, SN, …)
  - mostly primordial? (need 0.01-0.1 nG)
  - some combination of the two?

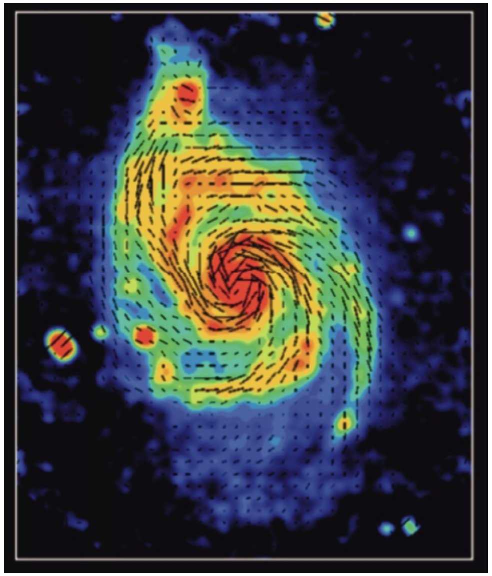


Image courtesy of NRAO/AUI

- Evidence of magnetic fields in voids?
  - missing GeV γ-ray halos around TeV blazars

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

- A distinct signature in CMB could prove their primordial origin

Stochastic Primordial Magnetic Field

- Frozen in the plasma on large scales, amplitude decays as $B(a)=B_0/a^2$
- Magnetic field power spectrum:

$$\langle b_i(\mathbf{k}) b_j(\mathbf{k}')\rangle = (2\pi)^3 \delta^{(3)}(\mathbf{k}+\mathbf{k}')[(\delta_{ij} - \hat{k}_i \hat{k}_j) S(k) + i\varepsilon_{ijl} \hat{k}_l A(k)]$$

$$S(k) \propto k^n, \quad 0 < k < k_{\rm diss}$$

- Common measures of cosmological magnetic fields:

$$B_\lambda^2 \equiv \int_0^\infty \frac{k^2 dk}{2\pi^2} S(k)\, e^{-\lambda^2 k^2} \qquad B_{\rm eff} \equiv \sqrt{8\pi\epsilon_B}$$

- Fields generated in phase transitions have n=2 on CMB scales
  (Durrer and Caprini, 2003; Jedamzik and Sigl, 2010)
- Inflationary mechanisms predict nearly scale-invariant PMFs, n=-3
  (Turner & Widrow, 1988; Ratra. 1992)

Magnetic field effects on CMB

- Gravitational coupling

$$T_0^0 \propto -B^2$$
$$T_j^i \propto B^2\delta_j^i - 2B^iB_j$$

  - ➢ scalar (curvature), vector (vorticity), tensor (gravitational waves) modes
  - ➢ B_{1Mpc}< 1.2 nG at 95% CL for a scale-invariant PMF from Planck+SPT B-modes

- Electromagnetic coupling

  - ➢ Magnetic energy dissipates, dumps energy into the plasma
  - ➢ Faraday Rotation rotates polarization, converting E-modes into B-modes

➡ Induces compressional modes in baryon density on scales below the photon mean free path – the clumping effect

Crossing the nano-Gauss barrier

- Magnetic stress-energy is quadratic in B

$$T^0_0 \propto -B^2$$
$$T^i_j \propto B^2\delta^i_j - 2B^iB_j$$

- Thus, $C_L \sim B^4$

- Bounds based on magnetic contributions to CMB anisotropy will always remain at O(nG)

- Faraday Rotation is linear in B and is only limited by foregrounds, can probe up to ~0.1 nG.

- Much stronger bounds (~0.01-0.05 nG) claimed by Jedamzik & Abel (2011, 2013), Jedamzik & Saveliev (2018) from modified recombination history due to magnetically induced baryon clumping

Magnetic field induced baryon inhomogeneities

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

$$\frac{d\rho}{dt} + \nabla(\rho\mathbf{v}) = 0$$

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

Magnetic field induced baryon inhomogeneities

$$\alpha \sim 1/l_\gamma$$

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

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

$L < l_\gamma$ viscous compressible baryon gas

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

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$L < l_\gamma$ 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

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

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

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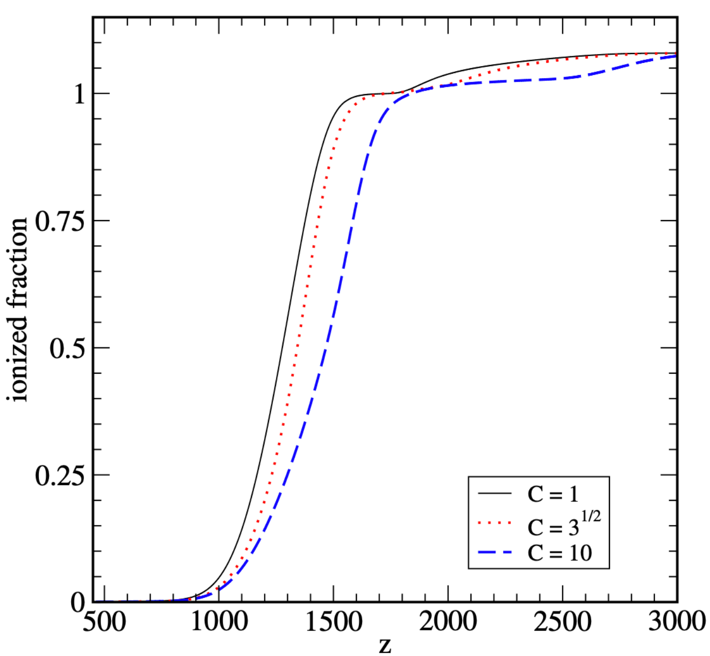
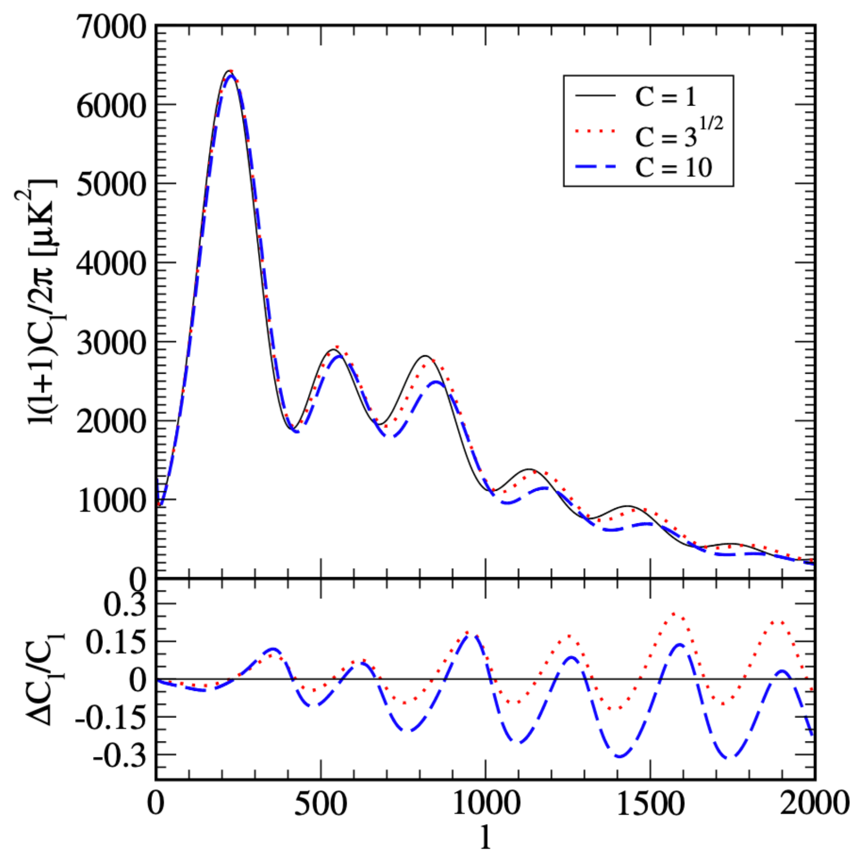




Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

Implementation

Make RECFAST calculate evolution of the ionized fraction in three different zones, with randomly drawn baryon density PDF, and take the average

We compare results for two different models

- 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)

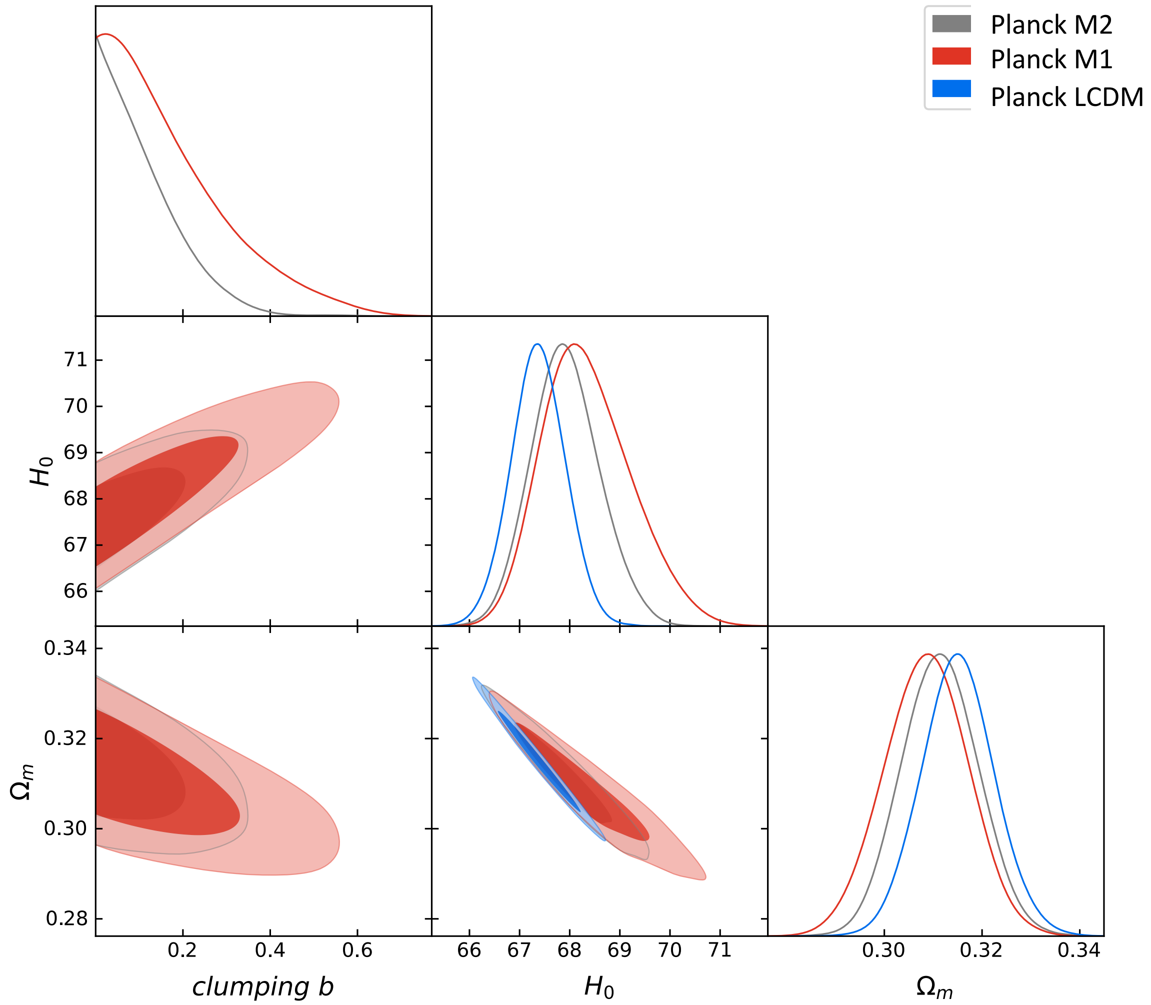
An additional baryon clumping parameter: $b = (\langle n_b^2 \rangle - \langle n_b \rangle^2)/\langle n_b \rangle^2$

Implemented in CAMB and the latest CosmoMC

Datasets considered in this work:

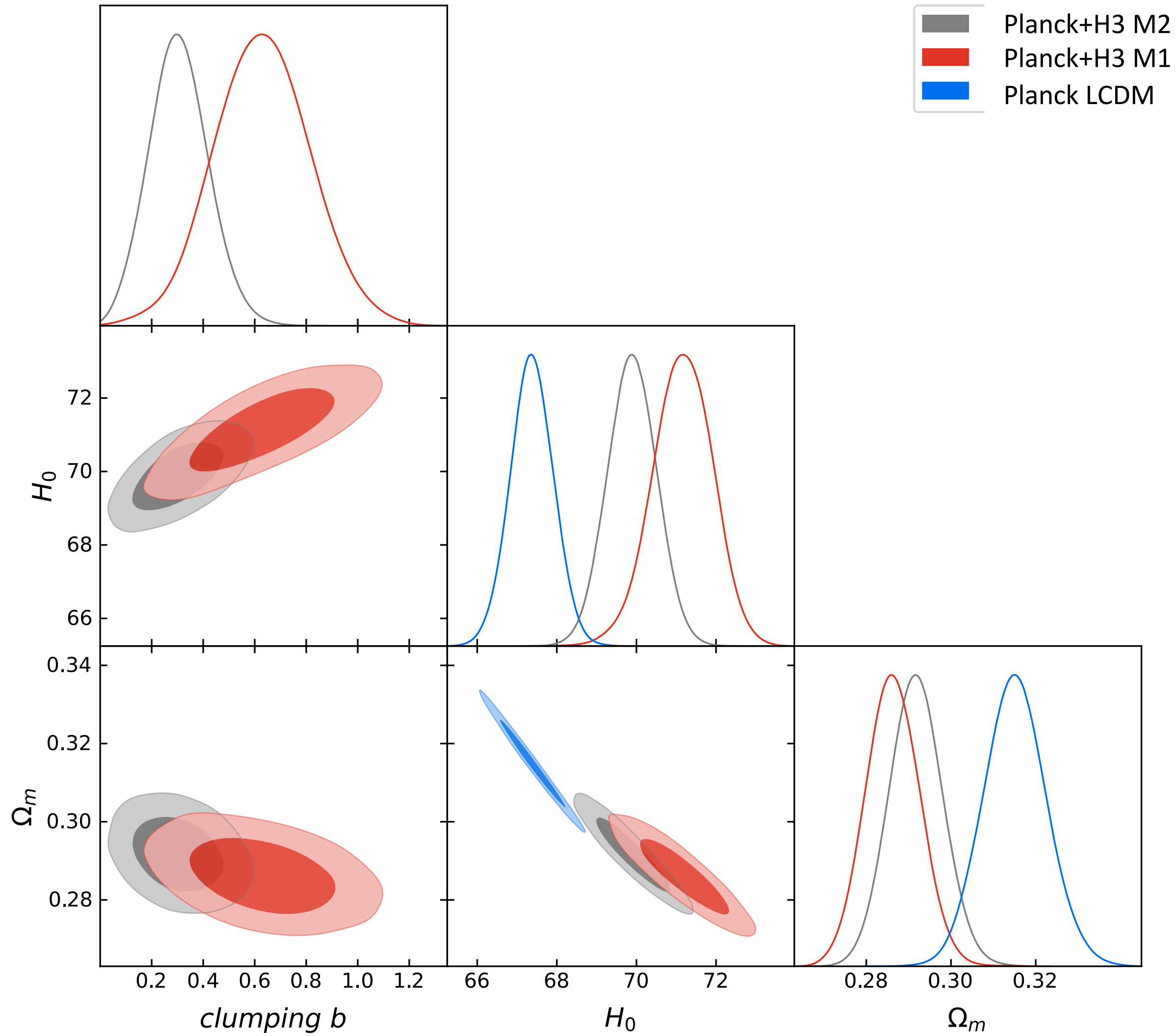
- Planck 2018 TT, TE, EE + lowE + lensing (Planck)
- SH0ES, H0LiCOW and MCP determinations of H_0 (H3)
- Dark Energy Survey Year 1 galaxy clustering and weak lensing (DES)

Fitting to Planck only



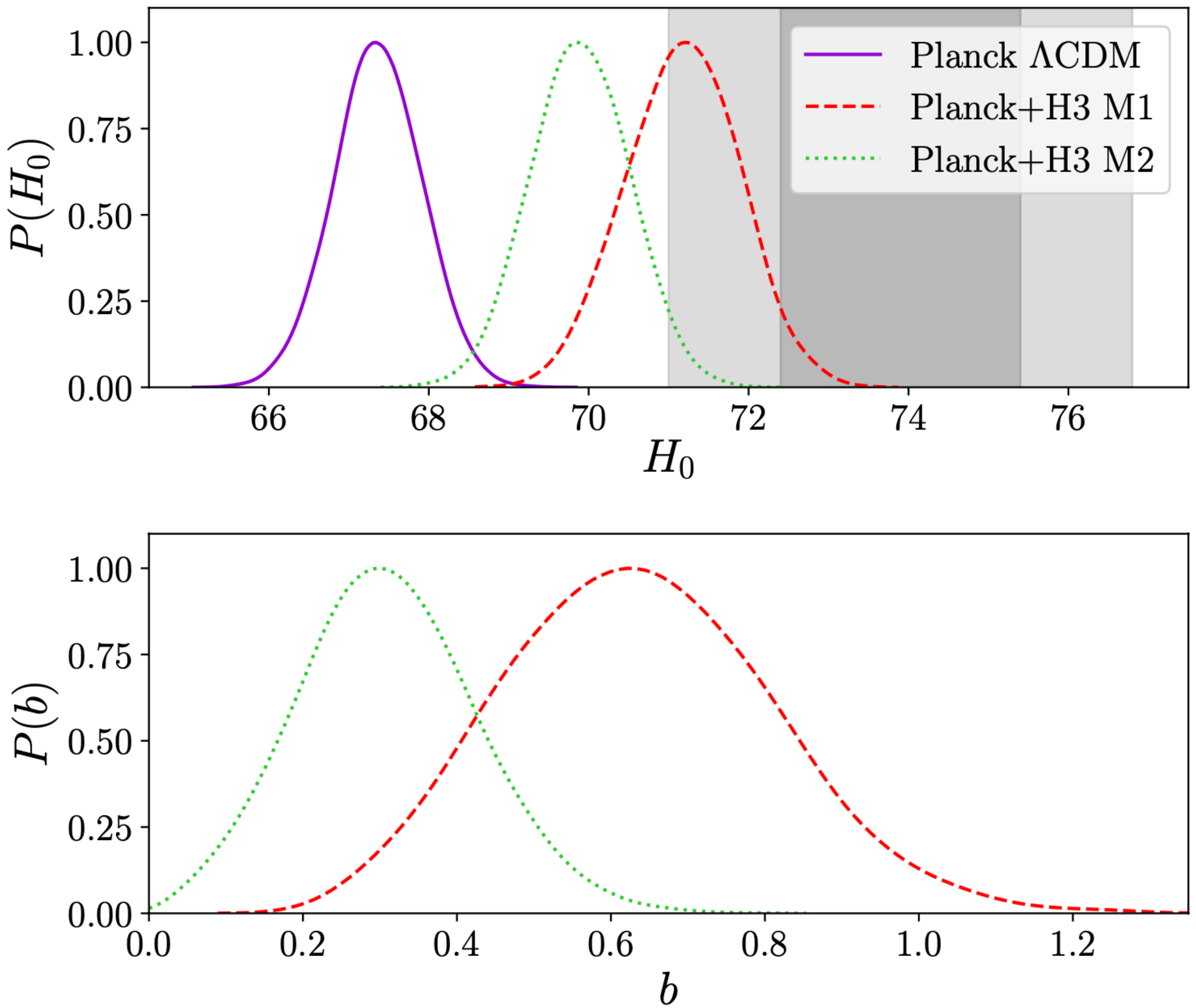
- Strong degeneracy between the clumping parameter b and H_0
- No preference for a non-zero value of b

Fitting to Planck + H3



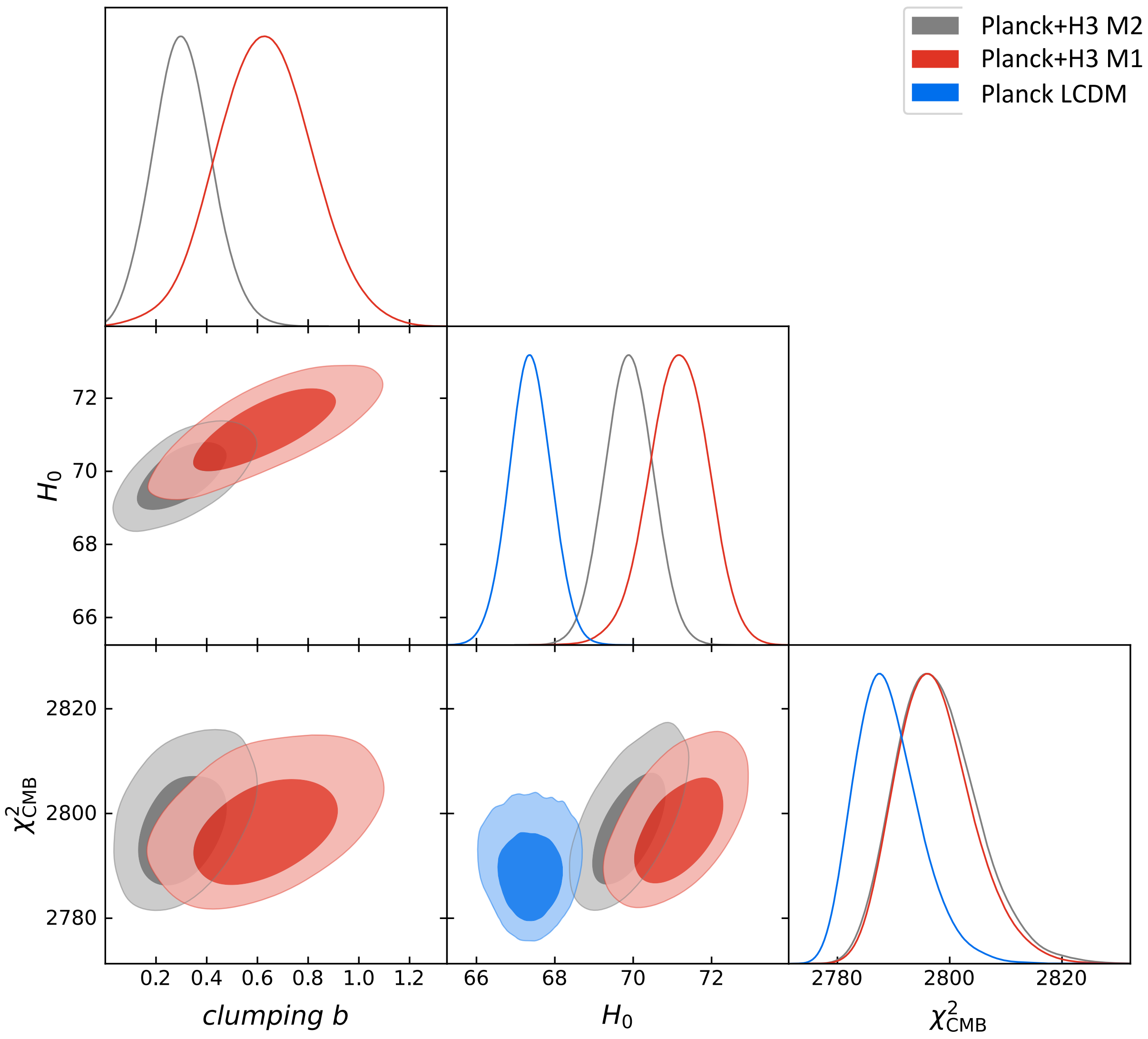
a clear detection of clumping!

Relieving the Hubble tension



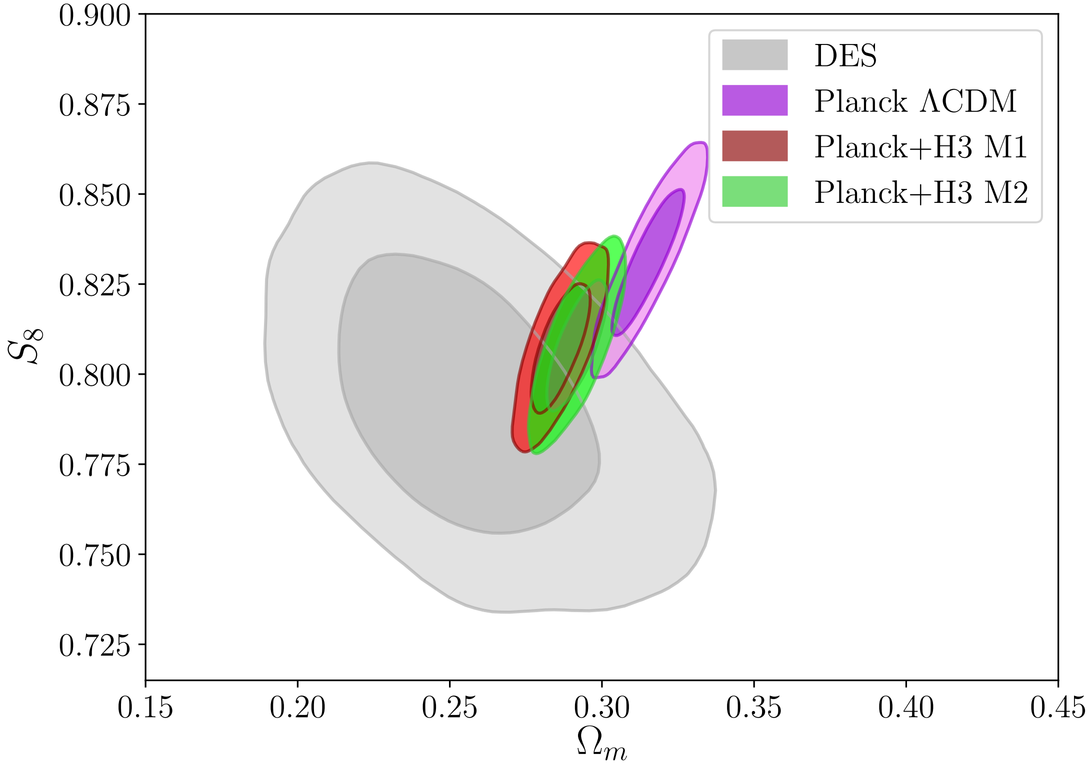
K. Jedamzik and L. Pogosian, arXiv:2004.09487

Does the fit to CMB get worse?



The LCDM model and the clumping models give comparable fits

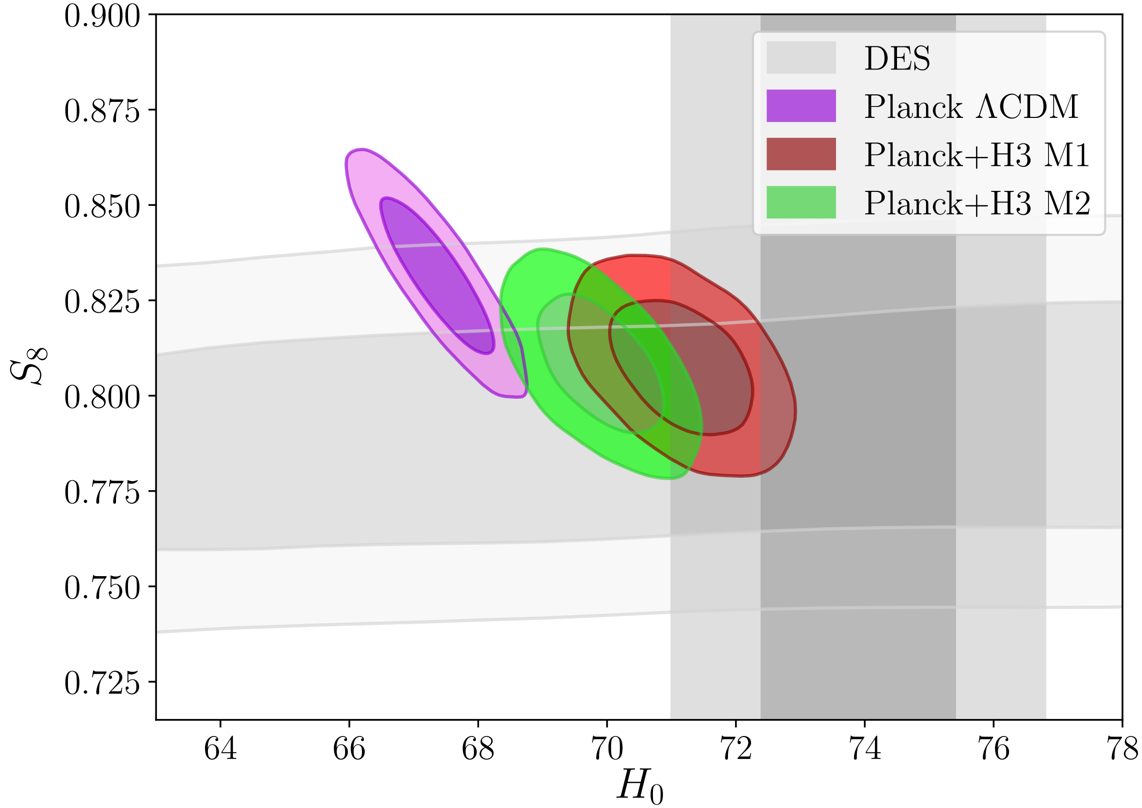
Relieving the S_8-Ω_m tension



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

K. Jedamzik and L. Pogosian, arXiv:2004.09487

Relieving both tension in one plot



K. Jedamzik and L. Pogosian, arXiv:2004.09487

The effect on other parameters

	Planck ΛCDM	Planck+H3 ΛCDM	Planck+H3 M1	Planck+H3+DES M1	Planck+H3 M2	Planck+H3+DES M2
$\Omega_b h^2$	0.02237 ± 0.00015	0.02265 ± 0.00014	0.02272 ± 0.00016	0.02279 ± 0.00015	0.02282 ± 0.00016	0.02287 ± 0.00016
$\Omega_c h^2$	0.1200 ± 0.0012	0.1170 ± 0.0011	0.1215 ± 0.0015	0.1206 ± 0.0014	0.1190 ± 0.0012	0.1181 ± 0.0011
τ	0.0546 ± 0.0075	$0.0637^{+0.0074}_{-0.0089}$	0.0558 ± 0.0075	0.0571 ± 0.0076	$0.0610^{+0.0071}_{-0.0084}$	$0.0620^{+0.0069}_{-0.0083}$
n_s	0.9651 ± 0.0041	0.9726 ± 0.0041	0.9630 ± 0.0040	0.9648 ± 0.0039	0.9739 ± 0.0043	0.9755 ± 0.0042
b	-	-	0.63 ± 0.19	$0.61^{+0.16}_{-0.19}$	0.31 ± 0.11	$0.29^{+0.11}_{-0.12}$
H_0	67.37 ± 0.54	68.78 ± 0.50	71.16 ± 0.75	71.50 ± 0.70	69.89 ± 0.62	70.24 ± 0.58
Ω_m	0.3151 ± 0.0074	0.2967 ± 0.0064	0.2863 ± 0.0064	0.2818 ± 0.0056	0.2918 ± 0.0063	0.2870 ± 0.0056
σ_8	0.8113 ± 0.0060	0.8080 ± 0.0065	0.8268 ± 0.0081	$0.8236^{+0.0071}_{-0.0079}$	0.8194 ± 0.0074	0.8161 ± 0.0073
S_8	0.831 ± 0.013	0.804 ± 0.012	0.808 ± 0.011	0.7982 ± 0.0098	0.808 ± 0.012	0.7982 ± 0.0099
z_*	1089.91 ± 0.26	1089.32 ± 0.23	$1108.3^{+4.5}_{-3.3}$	$1107.7^{+4.1}_{-3.5}$	$1097.0^{+2.5}_{-1.9}$	$1096.6^{+2.6}_{-2.0}$
r_*	144.44 ± 0.27	144.99 ± 0.26	$142.19^{+0.61}_{-0.72}$	$142.41^{+0.61}_{-0.68}$	143.68 ± 0.47	$143.91^{+0.44}_{-0.49}$
$z_{\rm drag}$	1059.94 ± 0.30	1060.36 ± 0.29	$1077.3^{+4.1}_{-3.1}$	$1077.1^{+3.8}_{-3.3}$	$1067.6^{+2.4}_{-1.9}$	$1067.4^{+2.5}_{-2.0}$
$r_{\rm drag}$	147.10 ± 0.27	147.58 ± 0.26	$144.85^{+0.62}_{-0.72}$	$145.05^{+0.61}_{-0.68}$	146.25 ± 0.48	146.47 ± 0.48
$\chi^2_{\rm lensing}$	9.23 ± 0.70	9.6 ± 1.2	9.20 ± 0.67	9.30 ± 0.84	9.35 ± 0.82	9.7 ± 1.1
$\chi^2_{\rm plik}$	2359.5 ± 6.2	2365 ± 13	2366.8 ± 6.8	2368.8 ± 6.9	2368.0 ± 7.2	2370.6 ± 7.3
$\chi^2_{\rm lowl}$	23.40 ± 0.86	22.31 ± 0.71	24.30 ± 0.97	23.94 ± 0.91	22.31 ± 0.73	22.07 ± 0.67
$\chi^2_{\rm simall}$	397.0 ± 1.8	399.2 ± 3.5	397.1 ± 1.9	397.3 ± 2.0	398.2 ± 2.7	398.4 ± 2.9
$\chi^2_{\rm prior}$	11.6 ± 4.6	11.7 ± 4.6	11.5 ± 4.5	$24 \pm 7^{(a)}$	11.9 ± 4.7	$24 \pm 7^{(a)}$
$\chi^2_{\rm H3}$	-	24 ± 5	7.4 ± 3.9	5.8 ± 3.1	14.9 ± 4.5	12.5 ± 3.9
$\chi^{2({\rm tot})}_{\rm bestfit}$	2779.9	2811.5	2795.7	$3311.7^{(b)}$	2802.6	$3324.4^{(b)}$

TABLE I. The mean values and 68% CL intervals for the relevant cosmological parameters and the χ^2 of the datasets used in the analysis. $^{(a)}$ *The DES likelihood contains priors on additional 13 "nuisance" parameters;* $^{(b)}$ *To be compared to the ΛCDM fit to CMB+H3+DES which has* $\chi^{2({\rm tot})}_{\rm bestfit} = 3331.9$.

Minor changes in the values and uncertainties of other cosmological parameters
Adding the DES Y1 data pushes the detection of clumping beyond 4σ

K. Jedamzik and L. Pogosian, arXiv:2004.09487

Ongoing Business

- Going beyond simple models

  awaiting results of MHD simulations for different types of magnetic fields:
  ”causal” and ”inflationary”, different strengths and helicities
  (in progress by Andrey Saveliev)

- Including the BAO data and other datasets

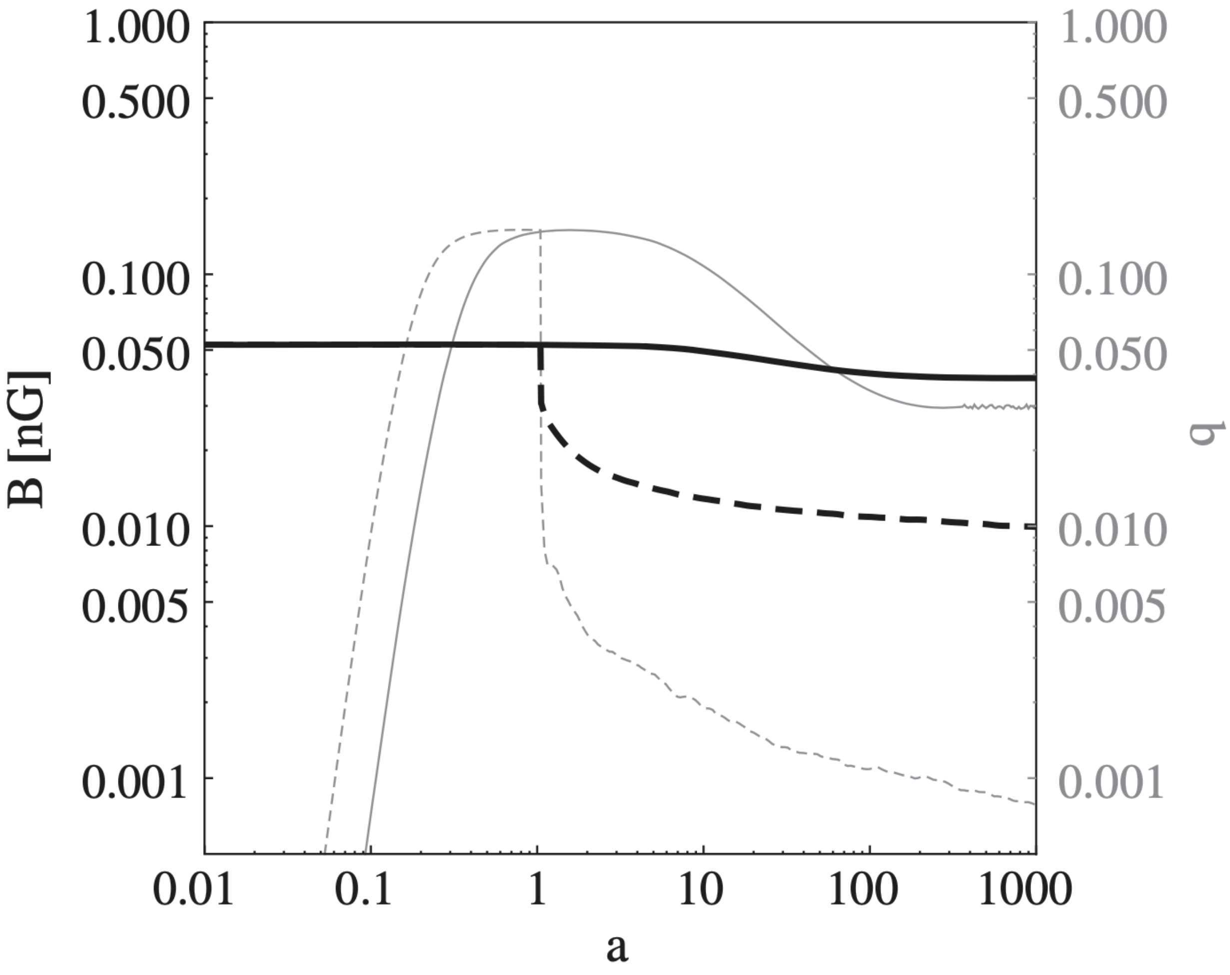
Implications

- The amount of clumping required to solve the Hubble tension corresponds to ~0.05-0.1 nano-Gauss pre-recombination magnetic field

- What happens at lower redshift, depends on the spectrum of the PMF:

    - Scale-invariant (inflationary) fields remain roughly at the same strength
    - Blue spectra (from phase transitions) drop a factor of ~6 in strength

Magnetic field evolution through recombination



Jedamzik and Saveliev, arXiv:1804.06115, PRL (2019)

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  - Scale-invariant (inflationary) fields remain roughly at the same strength
  - Blue spectra (from phase transitions) drop a factor of ~6 in strength

- Rich phenomenology to explore in both cases!

- Lines of investigation:

  - ➢ Detailed simulations of different types of PMFs during recombination
  - ➢ What other observations can confirm magnetic fields at recombination?
  - ➢ How could fields of this strength originate?
  - ➢ Detailed predictions for galactic, cluster and intergalactic fields

Looking for PMF in future data

A probe like PIXIE can detect causally produced PMF via 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)
J. M. Wagstaff, R. Banerjee, arXiv:1508.01683, PRD (2015)

CMB-S4 and PICO can probe 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)

Cosmic ray astronomy, e.g. γ-rays from Fermi satellite, can detect or rule out the magnetic fields in voids

H. Tashiro, W. Chen, F. Ferrer, and T. Vachaspati, arXiv:1310.4826, MNRAS (2014)
W. Chen, J. H. Buckley, and F. Ferrer, arXiv:1410.7717, PRL (2015)
S. Archambault et al. (VERITAS), arXiv:1701.00372, ApJ (2017)
P. Tiede et al, arXiv:1702.02586

Conclusions

Both the H_0 and the S_8-Ω_m tensions can be simultaneously relieved by the baryon inhomogeneities source by primordial magnetic fields during recombination

The combination of Planck, DES, SH0ES, H0LiCOW and MCP data gives a 4σ detection of the baryon clumping effect

The required field strength to solve the Hubble tension, ~0.05 nG, is of just the right order to explain the existence of galactic, cluster, and extragalactic magnetic fields without relying on dynamo amplification

Detailed MHD simulations are underway (with Andrey Saveliev) to help make more definitive predictions for different PMF spectra and helicities

Future observations, such as CMB spectral distortions, Faraday Rotation, and gamma-ray astronomy will be in position to confirm the existence of PMFs of this strength

Science 2 April 2010:
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DOI: 10.1126/science.1184192

REPORT

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

Andrii Neronov*, Ievgen Vovk

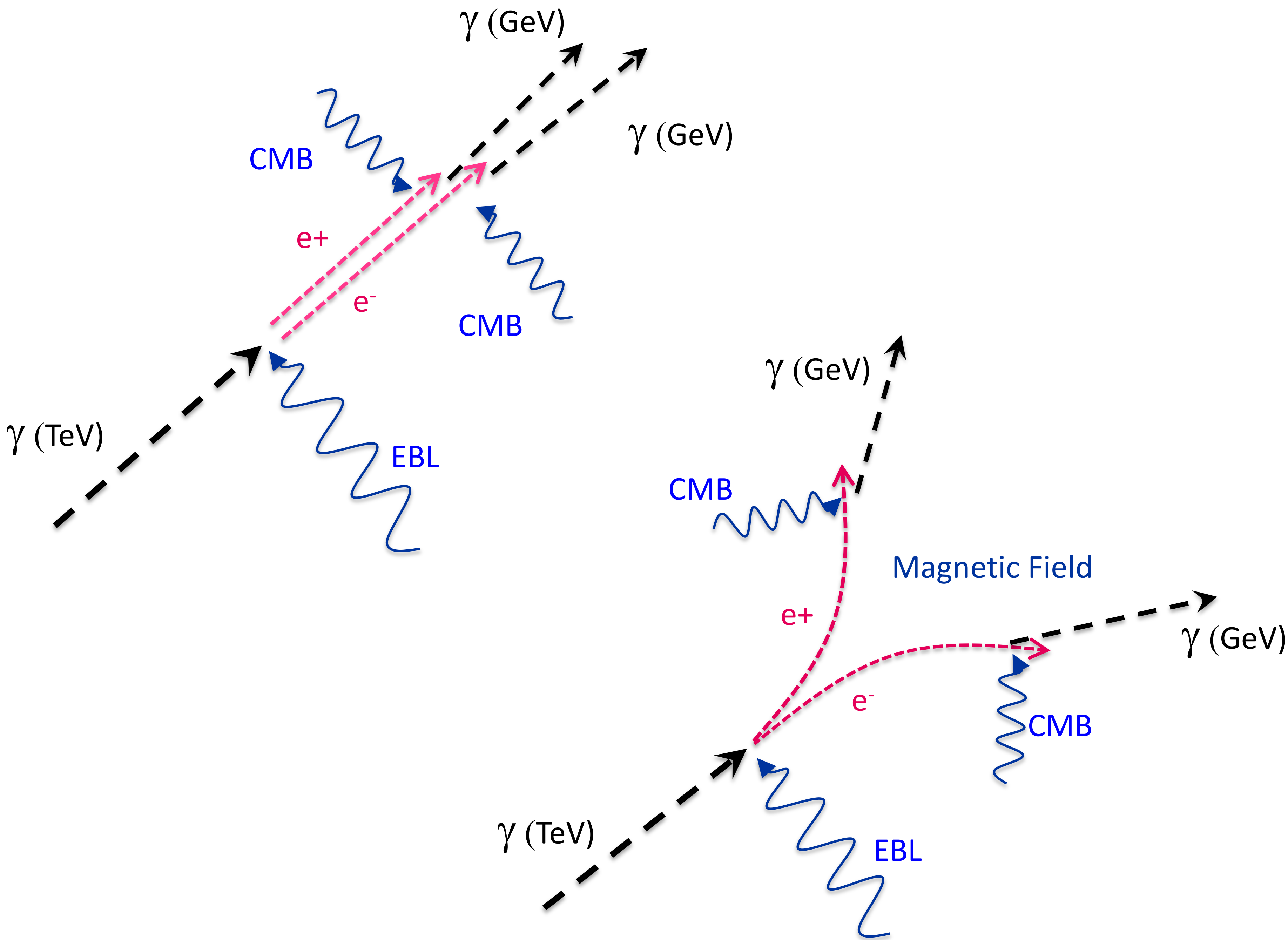
Author Affiliations

ISDC Data Centre for Astrophysics, Geneva Observatory, Ch. d'Ecogia 16, Versoix 1290, Switzerland.

*To whom correspondence should be addressed. E-mail: Andrii.Neronov@unige.ch

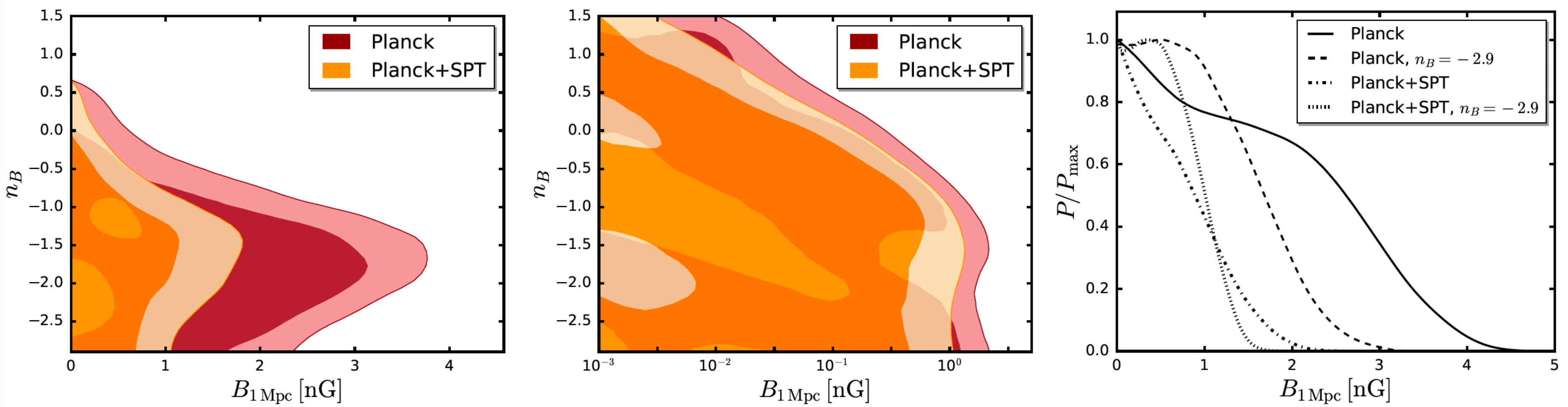
ABSTRACT

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.



γ (GeV)
γ (GeV)
CMB
e+
e-
CMB
γ (TeV)
EBL
γ (GeV)
CMB
Magnetic Field
e+
γ (GeV)
e-
CMB
γ (TeV)
EBL

Bounds from Planck combined with SPT B-modes



- B_{1Mpc}< 1.2 nG at 95% CL for a nearly scale-invariant PMF
- Adding SPT BB reduces the Planck bound on B_{1Mpc} by a factor of 2
- using a uniform prior on B_{1Mpc} can lead to fake bounds on n_B

A. Zucca, Y. Li, LP, 1611.00757, LP & A. Zucca, 1801.08936