Title: Relieving the Hubble tension with primordial magnetic fields

Speakers: Levon Pogosian

Series: Cosmology & Gravitation

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Abstract: The standard cosmological model determined from the accurate cosmic microwave background measurements made by the Planck satellite implies a value of the Hubble constant H0 that is 4.2 standard deviations lower than the one determined from Type Ia supernovae. The Planck best fit model also predicts lower values of the matter density fraction Om and clustering amplitude S8 compared to those obtained from the Dark Energy Survey Year 1 data. We show that accounting for the enhanced recombination rate due to additional inhomogeneities in the baryon density can solve both the H0 and the S8-Om tensions. The additional baryon inhomogeneities can be induced by primordial magnetic fields present in the plasma prior to recombination. The required field strength to solve the Hubble tension is just what is needed to explain the existence of galactic, cluster, and extragalactic magnetic fields without relying on dynamo amplification. Our results show clear evidence for this effect and motivate further detailed studies of primordial magnetic fields, setting several well-defined targets for future observations.


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

We are quite excited about this

- Primordial magnetic fields have long been studied as possible seeds for the observed fields in galaxies, clusters and intergalactic space, and because they are expected to be produced in the early universe

- Magnetic fields induce baryon inhomogeneities (clumping) on very small scales, speeding up the recombination [*Jedamzik and Abel, JCAP (2013), Jedamzik and Saveliev, PRL (2019)*]. Faster recombination means a smaller sound horizon at decoupling, making the value of H_0 measured by CMB larger

- There is a 4.2σ discrepancy between the value of the Hubble constant inferred from CMB and that measured more directly using SNIa. We find that accounting for magnetic fields in the plasma prior to recombination can relieve the Hubble tension. It also eliminates a minor tension between the clustering amplitude S_8 predicted by CMB and that measured by LSS surveys

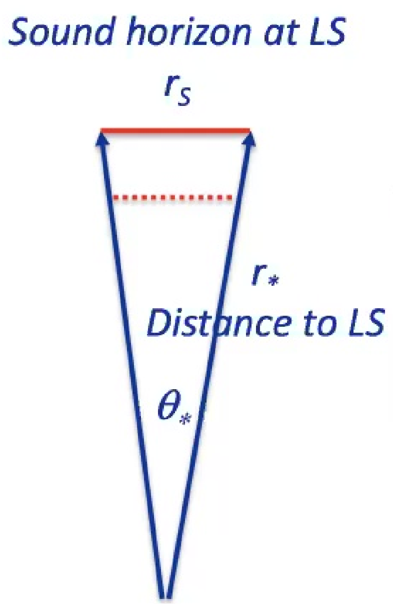
- We find a clear detection of the clumping effect. The corresponding magnetic field strength is of the right order to explain the galactic, cluster and intergalactic fields

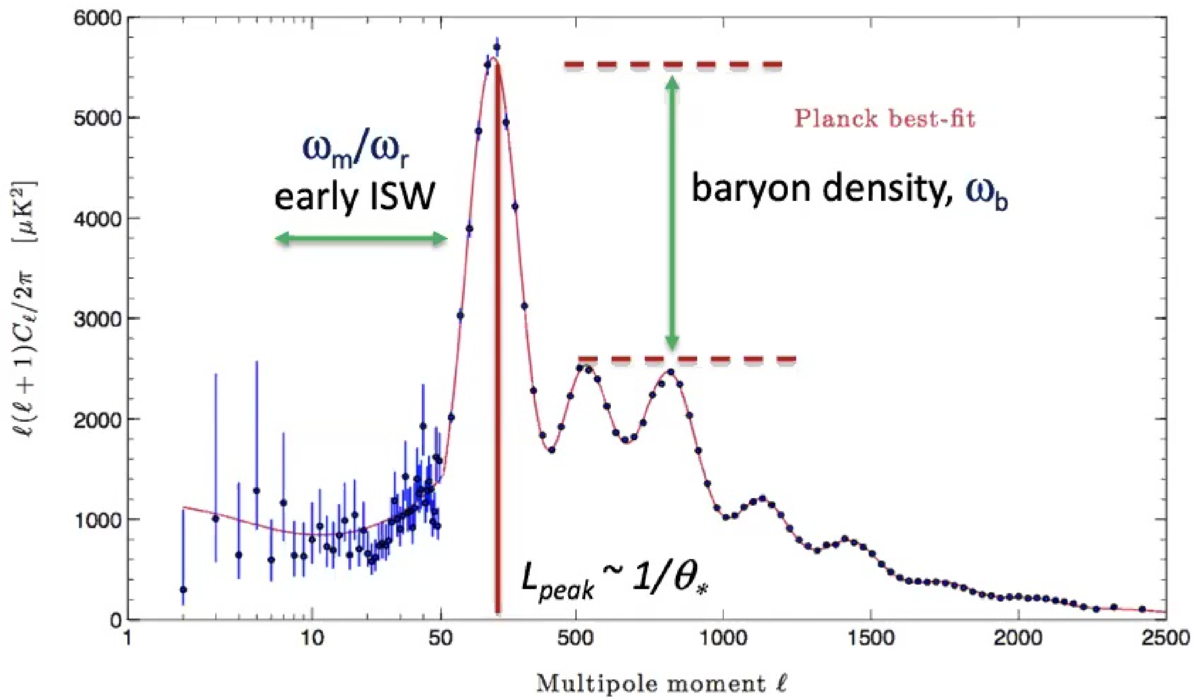
- Our findings motivate further detailed studies of primordial magnetic fields and provide targets for future experiments

Plan of the talk

- The H_0 and the S_8-Ω_m tensions
- Primordial magnetic fields
- The baryon clumping effect
- Results
- Implications

How does CMB constrain H_0?





$$r_* = \int_0^{z_*} \frac{c\,dz}{H(z)} = \int_0^{z_*} \frac{2998\ \mathrm{Mpc}\ dz}{\sqrt{\omega_r[(1+z)^4-1]+\omega_m[(1+z)^3-1]+h^2}}$$

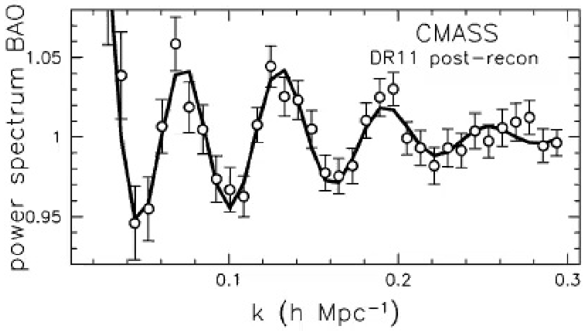
$$r_S = \int_{z_*}^{\infty} \frac{c_S(z)\,dz}{H(z)} \approx \int_{z_*}^{\infty} \frac{2998\ \mathrm{Mpc}\ dz/(1+z)^2}{\sqrt{[1+\omega_b/(\omega_\gamma(1+z))][\omega_r+\omega_m/(1+z)]}}$$

$$z_* = z_*(\omega_r, \omega_b, \omega_m); \quad \omega_i \equiv \Omega_i h^2; \quad \Omega_\Lambda = 1 - \Omega_m - \Omega_r$$

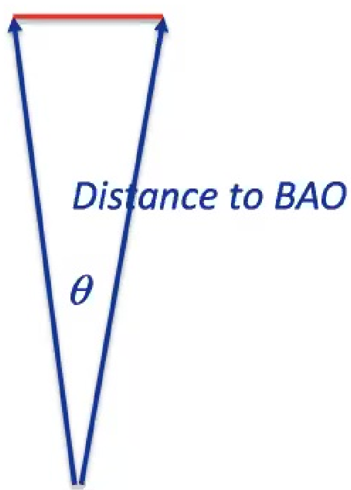
3 pieces of information:
θ_*, eISW, peak heights

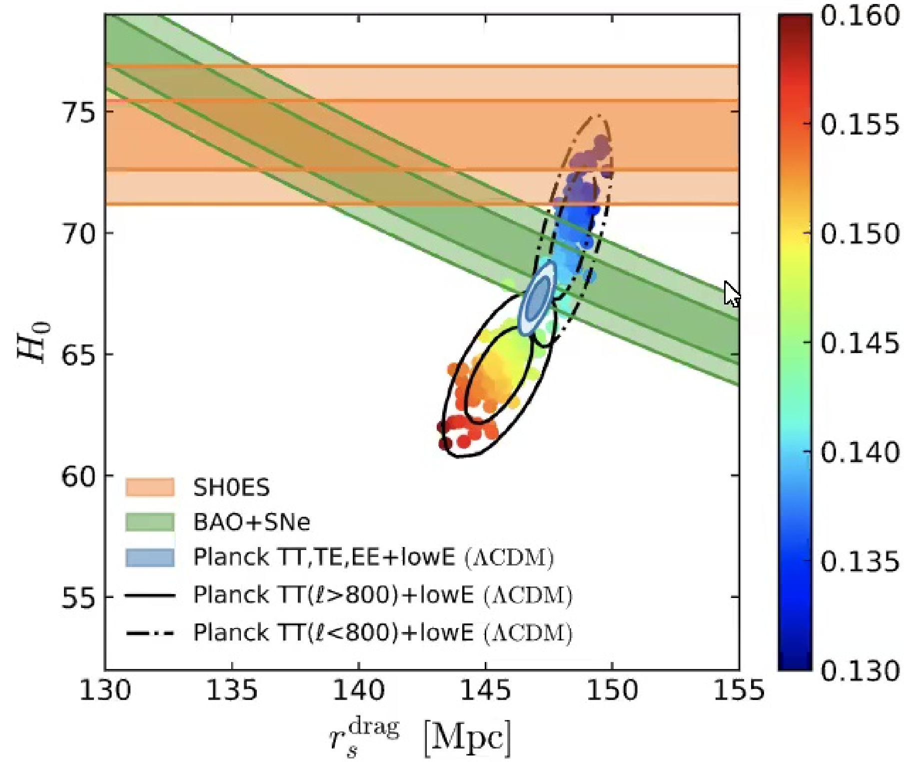
3 unknowns (within LCDM):
ω_m, ω_b, h

Baryon Acoustic Oscillations



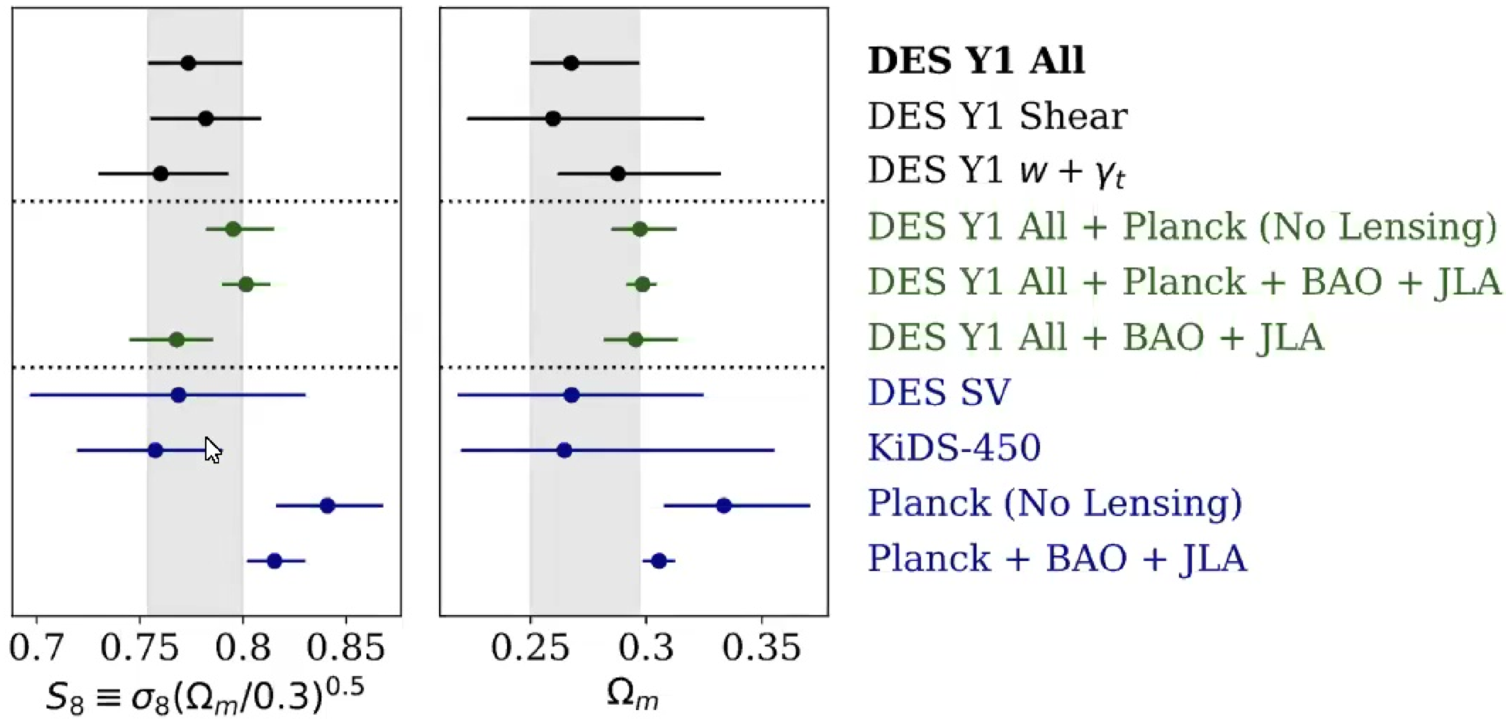
Sound horizon at baryon decoupling





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

Science 2 April 2010:
Vol. 328 no. 5974 pp. 73–75
DOI: 10.1126/science.1184192

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REPORT

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

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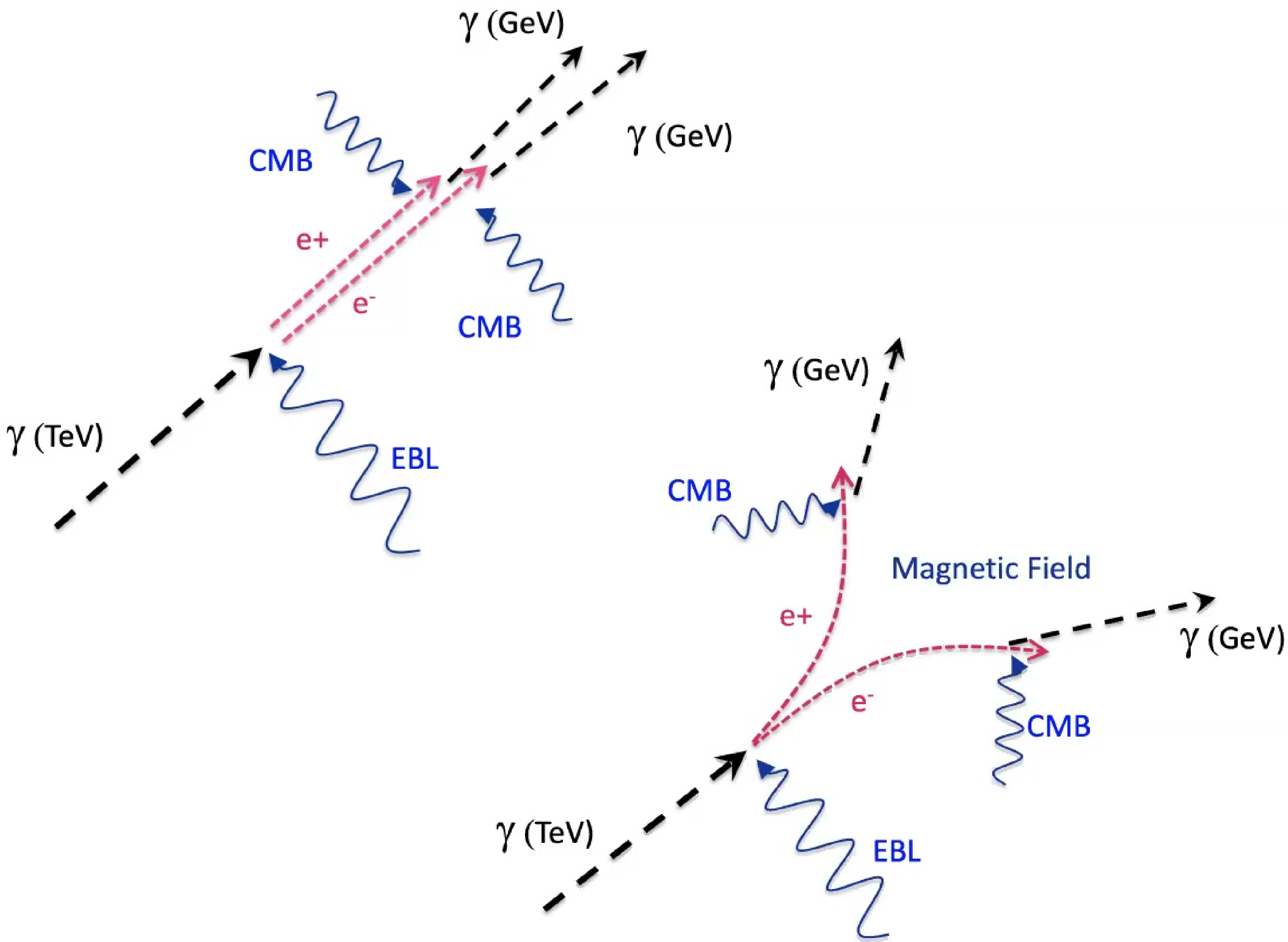
ABSTRACT

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.


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

Search for GeV γ-Ray Pair Halos Around Low Redshift Blazars

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Department of Physics and McDonnell Center for the Space Sciences, Washington University in St. Louis, St. Louis, Missouri 63130, USA

(Received 28 October 2014; revised manuscript received 15 October 2015; published 16 November 2015)

We report on the results of a search for γ-ray pair halos with a stacking analysis of low redshift blazars using data from the Fermi Large Area Telescope. For this analysis we used a number of *a priori* selection criteria, including the spatial and spectral properties of the Fermi sources. The angular distribution of $\sim$1 GeV photons around 24 stacked isolated high-synchrotron-peaked BL Lacs with redshift $z < 0.5$ shows an excess over that of pointlike sources. A frequentist test yields a p value of $p \sim 0.01$ for the extended emission against the point-source hypothesis. A Bayesian estimation provides Bayes factors $\log_{10} B_{10} > 2$, consistent with expectations for pair halos produced in the intergalactic magnetic fields with strength $B_{\mathrm{IGMF}} \sim 10^{-17}$–$10^{-15}$ G.

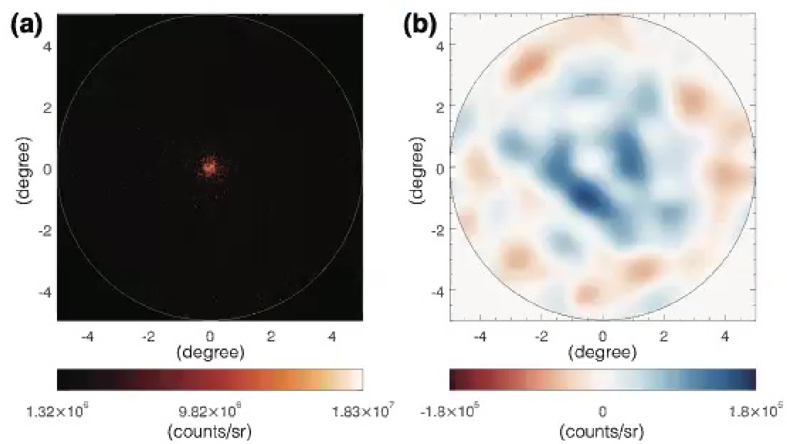

FIG. 7. γ-ray counts maps of the stacked sources in the 1GeV-1.58GeV energy bin. The large circles show the outer edge of the detection region. (a) Counts map of the stacked BL Lacs. (b) Smoothed counts difference between the stacked BL Lacs and the center-normalized stacked FSRQs. Positive values indicate the BL Lacs' counts are greater than the normalized counts of the FSRQs in that angular region

Cosmic Magnetic Fields

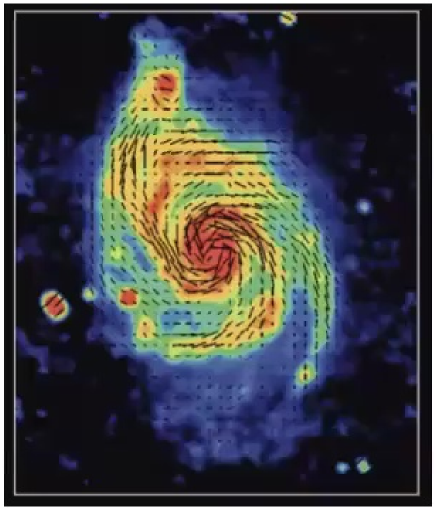

Image courtesy of NRAO/AUI

- Origin of micro-Gauss fields in galaxies and clusters
  - mostly astrophysical? (dynamo, SN, …)
  - mostly primordial? (need 0.01-0.1 nano-Gauss)
  - μG fields in galaxies at z>2
- Evidence of magnetic fields in voids
  - missing GeV γ-ray halos around TeV blazars
- 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

Stochastic Primordial Magnetic Field

- Generated in the early universe, e.g. during phase transitions or inflation
- Frozen in the plasma on large scales, amplitude decreases as $B(a)=B_0/a^2$
- Characterized by a magnetic field power spectrum

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

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

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

Magneto-Hydro-Dynamics (MHD)

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

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

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

MHD at Recombination

$-\alpha v$

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

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

Magnetic field induced baryon inhomogeneities

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

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

$L > l_\gamma$ 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)

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Magneto-Hydro-Dynamics (MHD)

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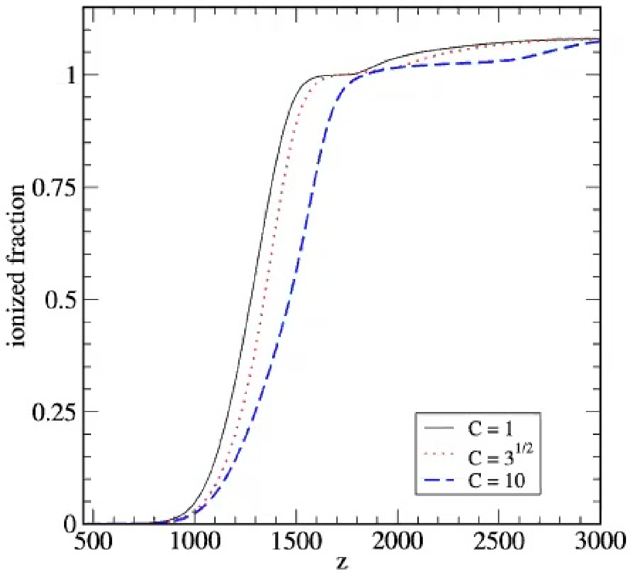
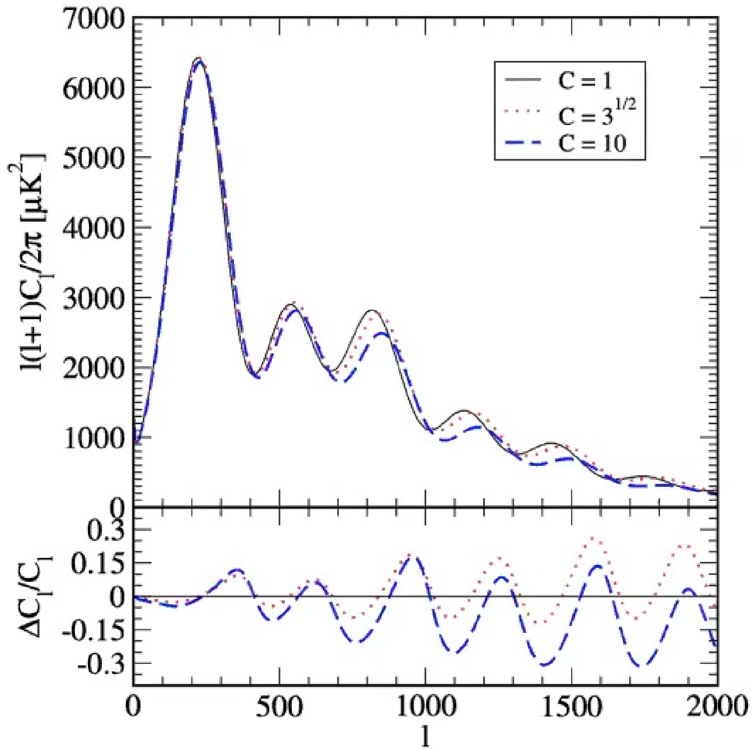
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

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

Implemented in CAMB and CosmoMC

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

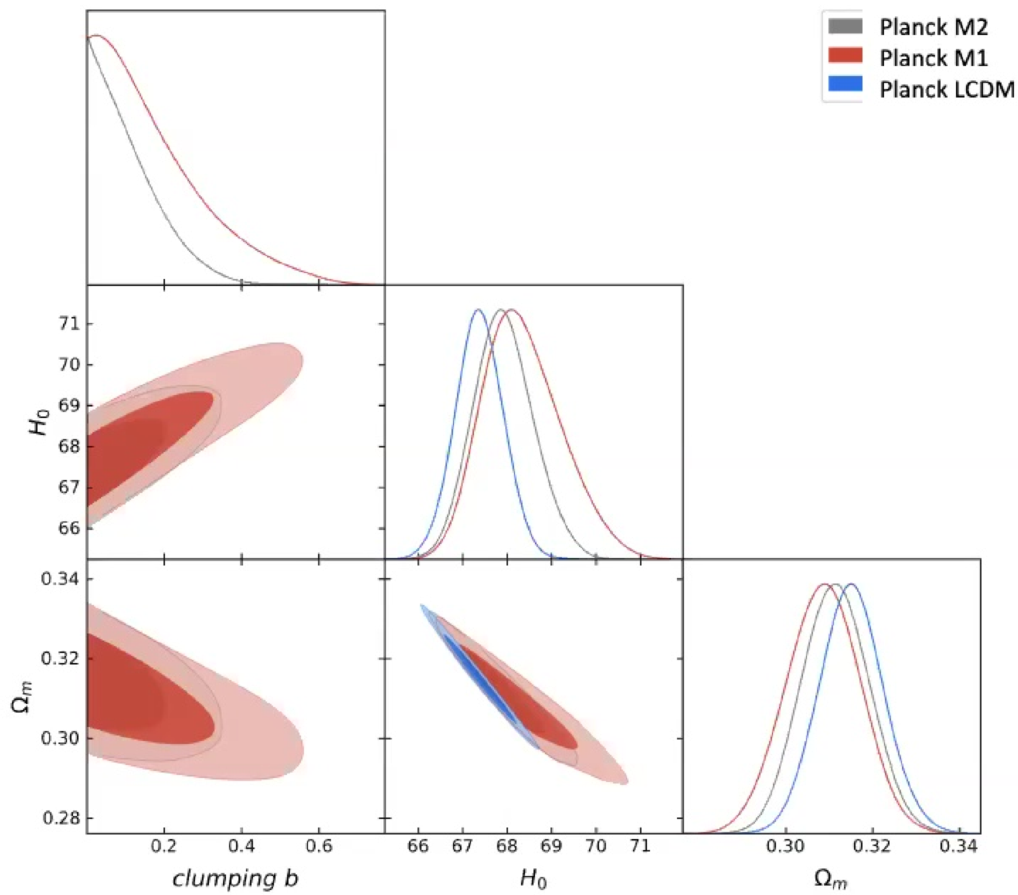
(The exact PDF determination from MHD simulations is in progress)

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

Datasets considered in this work:

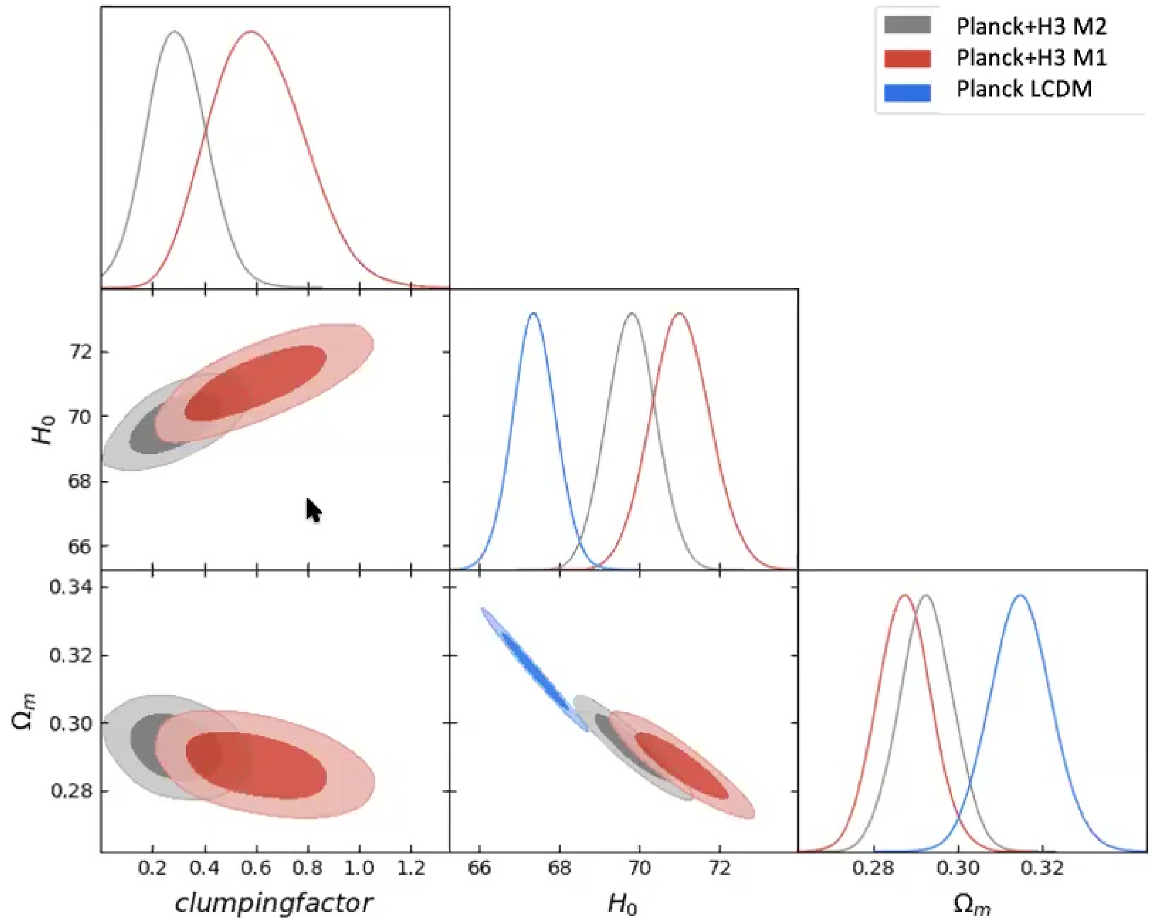
- Planck 2018 TT, TE, EE + lowE + lensing (Planck)
- SH0ES, H0LiCOW and MCP determinations of H_0 (H3)
- Other publicly available datasets in CosmoMC: SN, BAO, DES

Fitting to Planck only



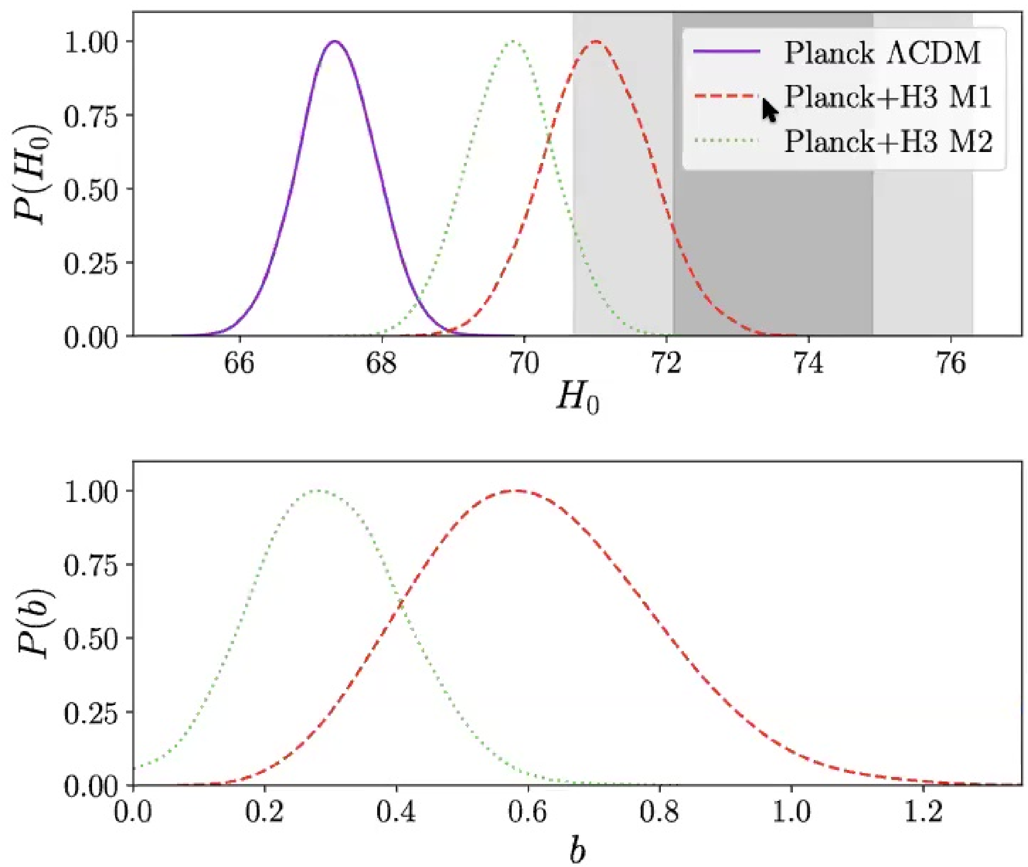
- Strong degeneracy between the clumping parameter b and H_0
- No preference for a non-zero value of b

Fitting to Planck + H3



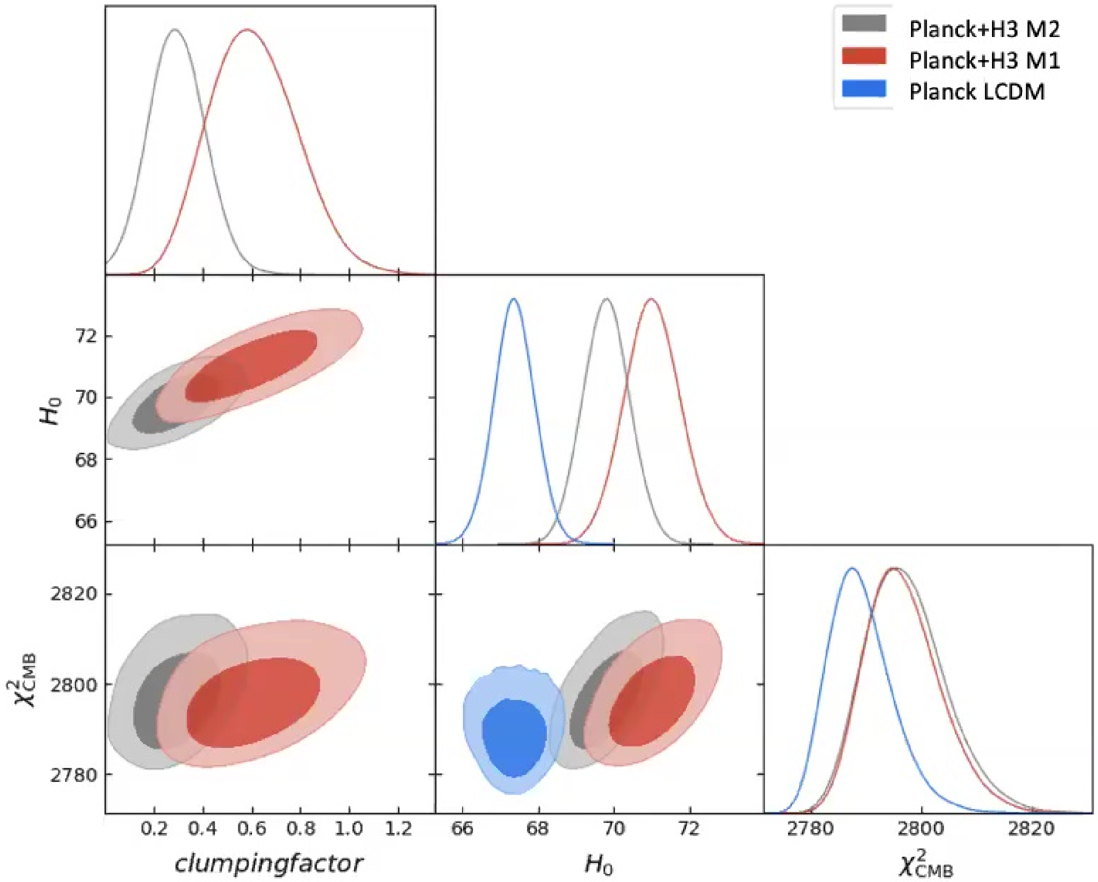
a clear detection of clumping!

Relieving the Hubble tension



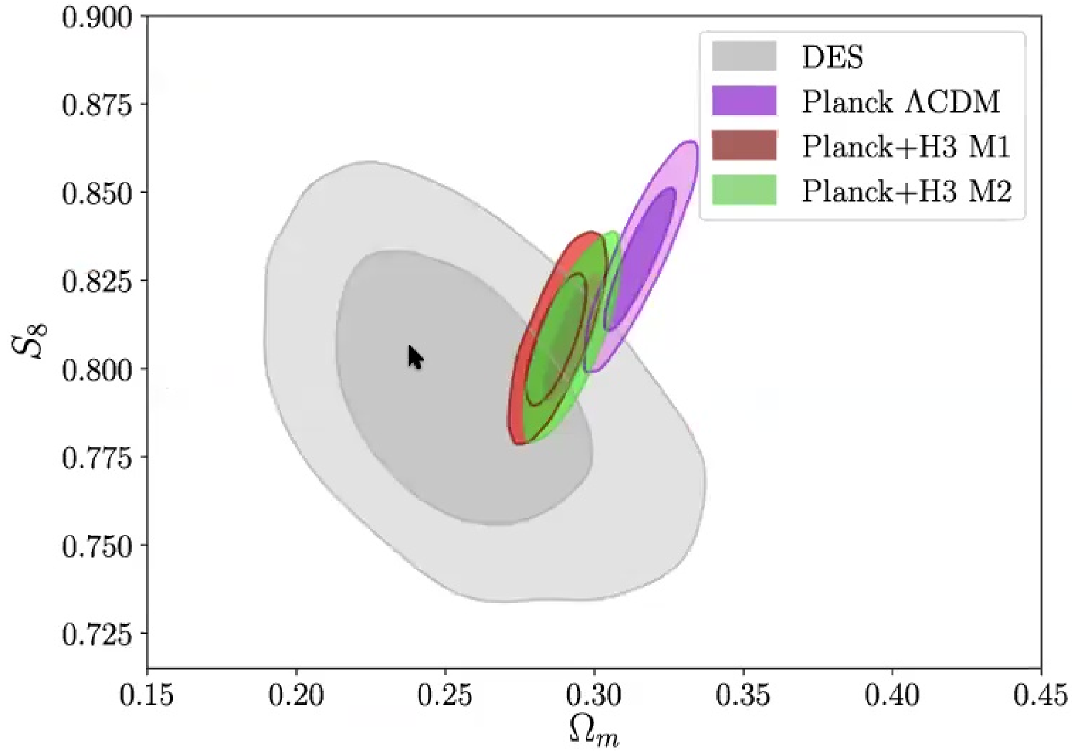
K. Jedamzik and L. Pogosian, arXiv:2004.09487

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

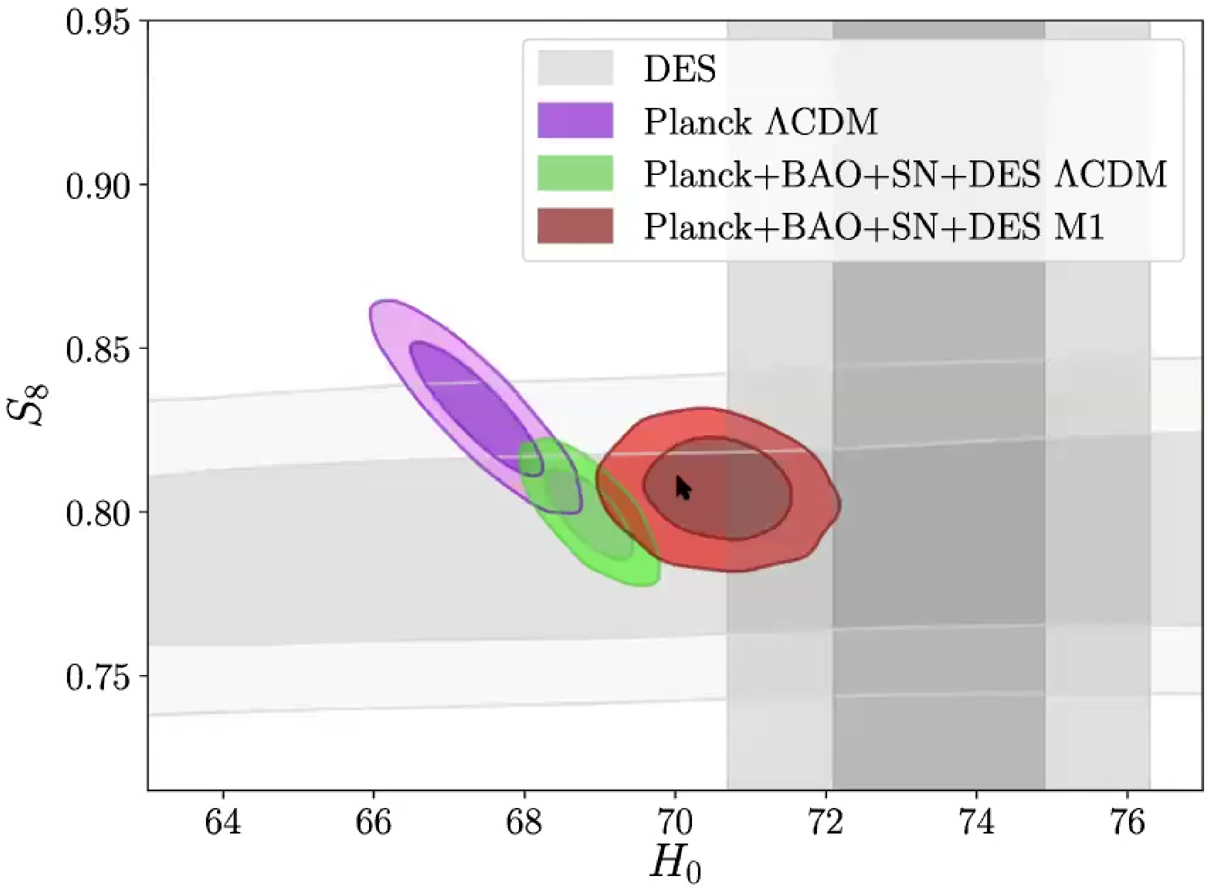
The effect on other parameters

	Planck ΛCDM	Planck+H3 ΛCDM	Planck+H3 M1	Planck+H3 M2
$\Omega_b h^2$	0.02237 ± 0.00015	0.02263 ± 0.00014	$0.02270^{+0.00014}_{-0.00016}$	0.02280 ± 0.00016
$\Omega_c h^2$	0.1200 ± 0.0012	0.1172 ± 0.0011	0.1216 ± 0.0014	0.1191 ± 0.0012
τ	0.0546 ± 0.0075	$0.0629^{+0.0075}_{-0.0087}$	0.0555 ± 0.0073	$0.0607^{+0.0071}_{-0.0085}$
n_s	0.9651 ± 0.0041	0.9721 ± 0.0040	0.9628 ± 0.0040	0.9734 ± 0.0042
$b^{(a)}$	-	-	$0.61^{+0.16(0.35)(0.57)}_{-0.20(0.33)(0.42)}$	$0.30 \pm 0.11(0.22)(0.34)$
H_0	67.37 ± 0.54	68.70 ± 0.50	71.03 ± 0.74	69.81 ± 0.62
Ω_m	0.3151 ± 0.0074	0.2977 ± 0.0064	0.2873 ± 0.0064	0.2926 ± 0.0064
σ_8	0.8113 ± 0.0060	0.8080 ± 0.0064	0.8265 ± 0.0079	0.8192 ± 0.0075
S_8	0.831 ± 0.013	0.805 ± 0.012	0.809 ± 0.012	0.8192 ± 0.0075
z_*	1089.91 ± 0.26	1089.35 ± 0.24	$1107.9^{+4.2}_{-3.6}$	$1096.8^{+2.6}_{-2.0}$
r_*	144.44 ± 0.27	144.96 ± 0.25	142.22 ± 0.65	143.69 ± 0.48
$z_{\rm drag}$	1059.94 ± 0.30	1060.33 ± 0.29	$1076.9^{+3.8}_{-3.4}$	$1067.4^{+2.4}_{-2.0}$
$r_{\rm drag}$	147.10 ± 0.27	147.55 ± 0.25	144.89 ± 0.64	146.28 ± 0.49
$r_{\rm drag} h$	99.11 ± 0.93	101.36 ± 0.87	102.91 ± 0.92	102.11 ± 0.89
$\chi^2_{\rm lensing}$	9.23 ± 0.70 (8.73)	9.6 ± 1.2 (8.74)	9.20 ± 0.66 (8.80)	9.33 ± 0.80 (9.39)
$\chi^2_{\rm plik}$	2359.5 ± 6.2 (2347.6)	2364.0 ± 6.6 (2350.93)	2366.2 ± 6.7 (2356.7)	2367.4 ± 7.1 (2359.2)
$\chi^2_{\rm lowl}$	23.40 ± 0.86 (23.18)	22.36 ± 0.72 (22.76)	24.30 ± 0.97 (24.9)	22.37 ± 0.72 (21.9)
$\chi^2_{\rm simall}$	397.0 ± 1.8 (396.0)	399.0 ± 3.3 (397.2)	397.0 ± 1.7 (395.7)	398.2 ± 2.7 (396.3)
$\chi^2_{\rm prior}$	11.6 ± 4.6 (4.46)	11.6 ± 4.6 (4.38)	11.6 ± 4.5 (2.93)	11.9 ± 4.6 (3.42)
$\chi^2_{\rm CMB}$	2789.1 ± 6.4 (2775.5)	2794.9 ± 7.2 (2779.7)	2796.8 ± 6.9 (2786.1)	2797.3 ± 7.3 (2786.8)
$\chi^2_{\rm H3}$	-	22 ± 4 (24.92)	6.1 ± 3.4 (4.14)	12.9 ± 4.2 (9.62)
$\chi^{2({\rm tot})}_{\rm bestfit}$	2779.9	2809.0	2793.2	2799.9

Minor changes in the values and uncertainties of other cosmological parameters

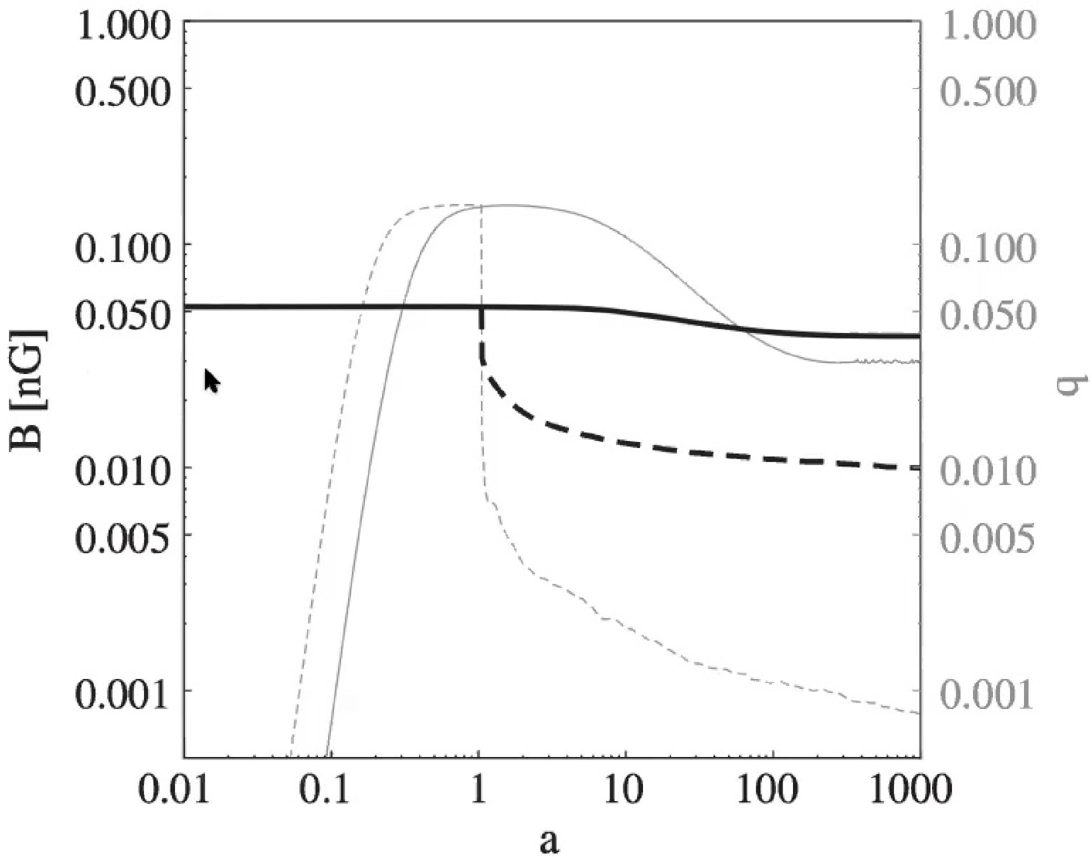
K. Jedamzik and L. Pogosian, arXiv:2004.09487

Comparing the global fits



K. Jedamzik and L. Pogosian, arXiv:2004.09487

Magnetic field evolution through recombination



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

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
- Rich phenomenology to explore in both cases!
- Lines of investigation:
  - Detailed MHD simulations 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)

γ-ray astronomy is a promising probe of magnetic fields in voids

A. Neronov and I. Vovk, arXiv:1006.3504, Science (2010)
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

Radio astronomy with LOFAR, SKA,…

Summary

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

The combination of Planck, 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-rays will be in position to probe PMFs of this strength