SFU

The Hubble Tension
and
Primordial Magnetic Fields

Levon Pogosian

Simon Fraser University

K. Jedamzik and LP, arXiv:2004.09487, Phys. Rev. Lett.
K. Jedamzik, LP, G.-B. Zhao, arXiv:2010.04158, Comm. Physics
LP, G.-B. Zhao, K. Jedamzik, arXiv:2405.20306, Ap. J. Lett.
S.H.Mirpoorian, K. Jedamzik, LP, arXiv:2411.16678, Phys. Rev. D
K. Jedamzik, LP, T. Abel, arXiv:2503.09599
S.H.Mirpoorian, K. Jedamzik, LP, arXiv:2504.15274

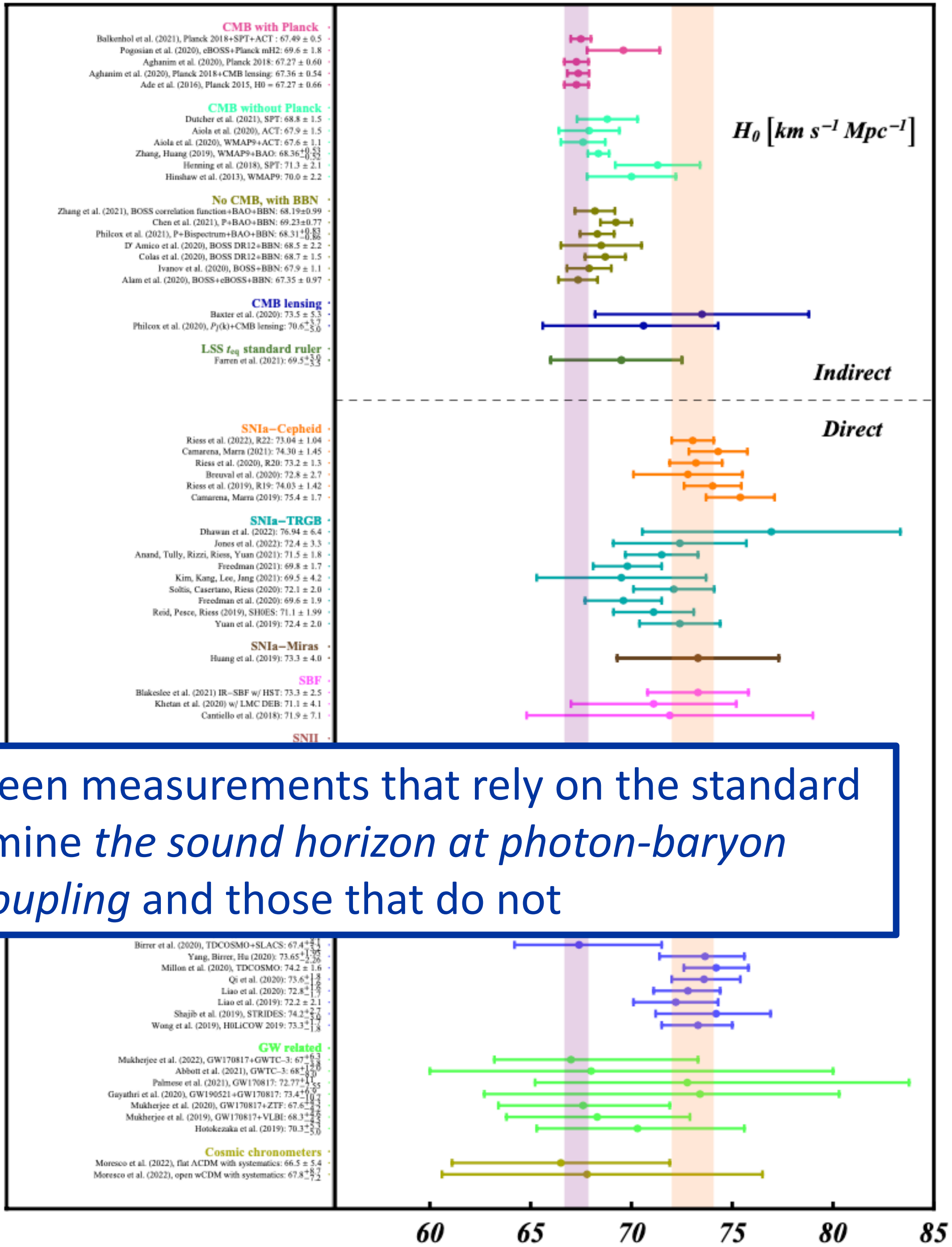
The Hubble Tension

CMB (Planck):

$H_0 = 67.22 \pm 0.47$ km/s/Mpc

Cepheid-calibrated SNIa (SH0ES):

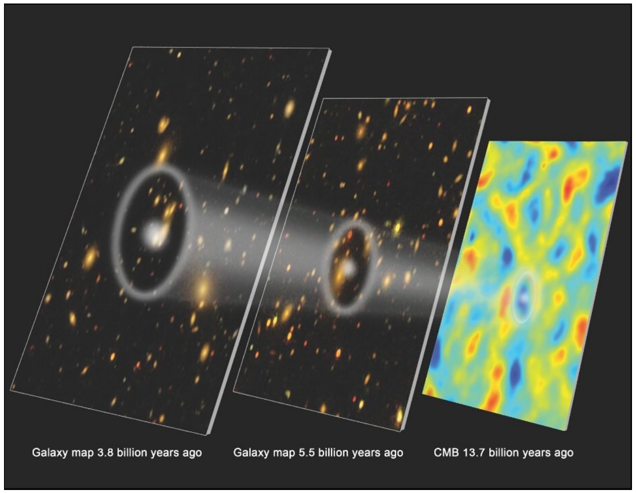
$H_0 = 73 \pm 1$ km/s/Mpc



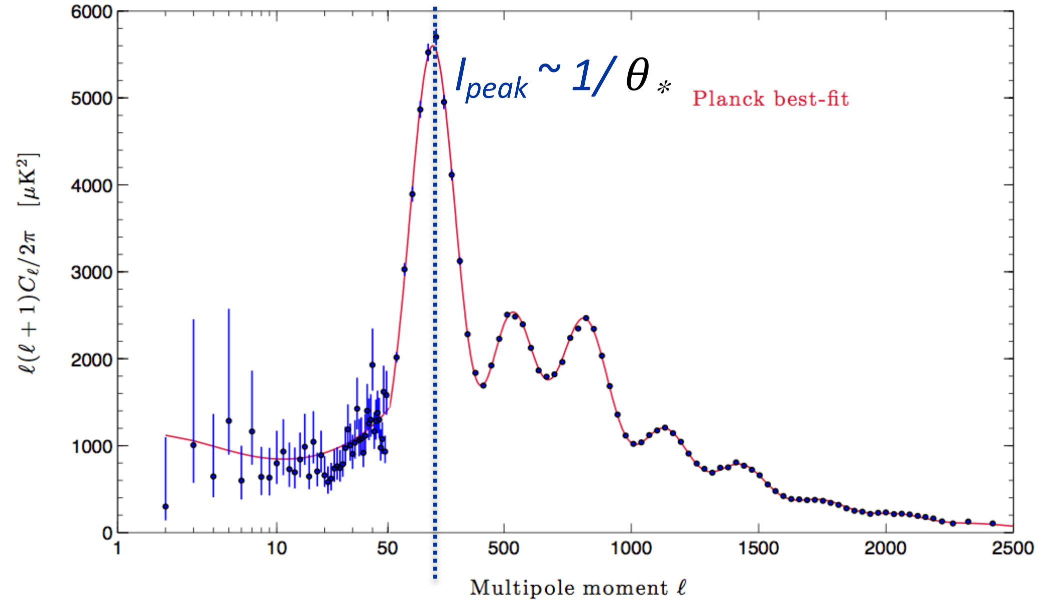
The tension is between measurements that rely on the standard model to determine *the sound horizon at photon-baryon decoupling* and those that do not

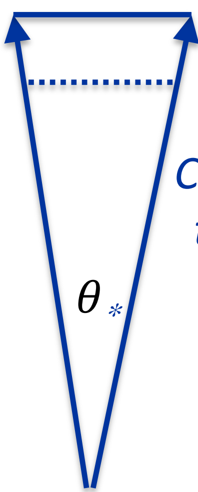
Table from arXiv:2203.06142

H_0 from CMB (and BAO)

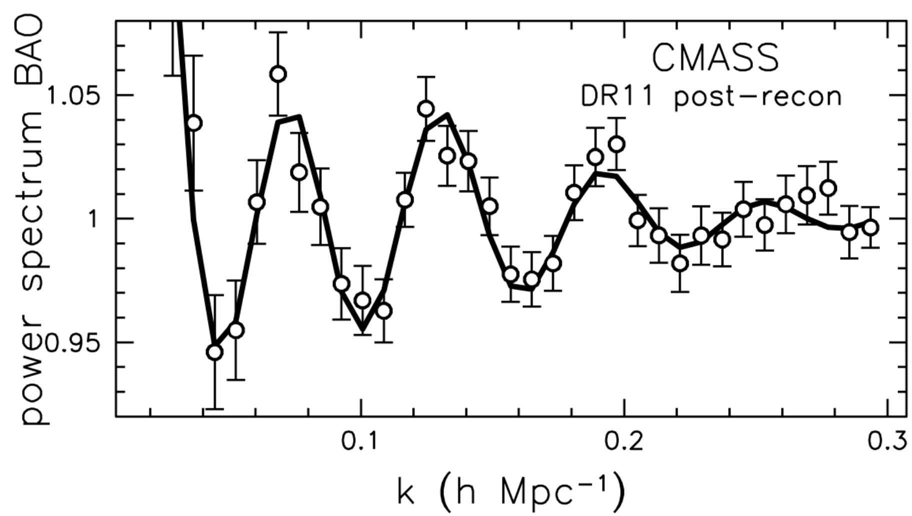


Comoving sound horizon at decoupling, r_*





Comoving distance to decoupling, d_*



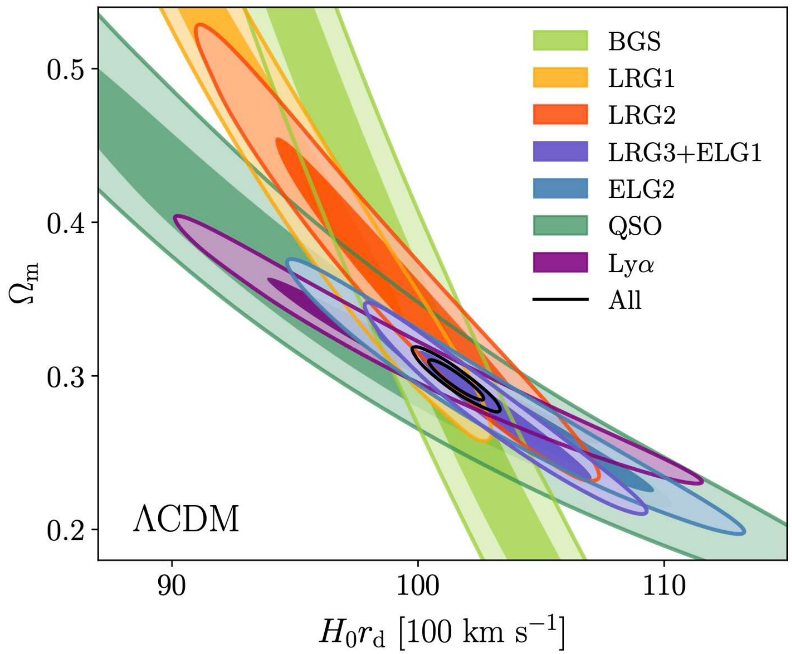
Smaller r_* => smaller d_* => larger H_0

H_0 from BAO?

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

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

By itself, BAO only constrain $r_d h$ and Ω_m



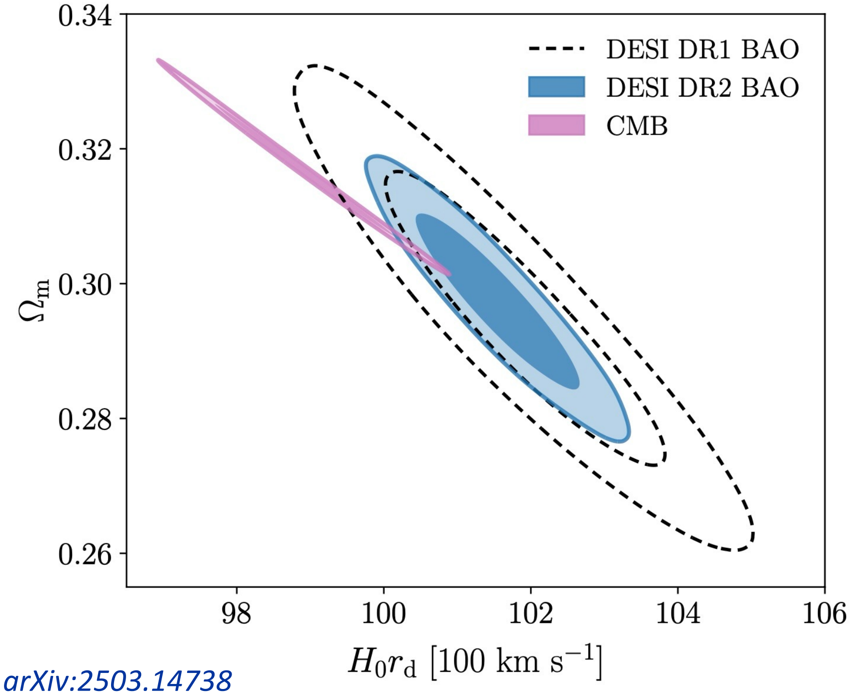
DESI DR2 Results II: Measurements of BAO and Cosmological Constraints, arXiv:2503.14738

CMB-BAO tension?

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

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

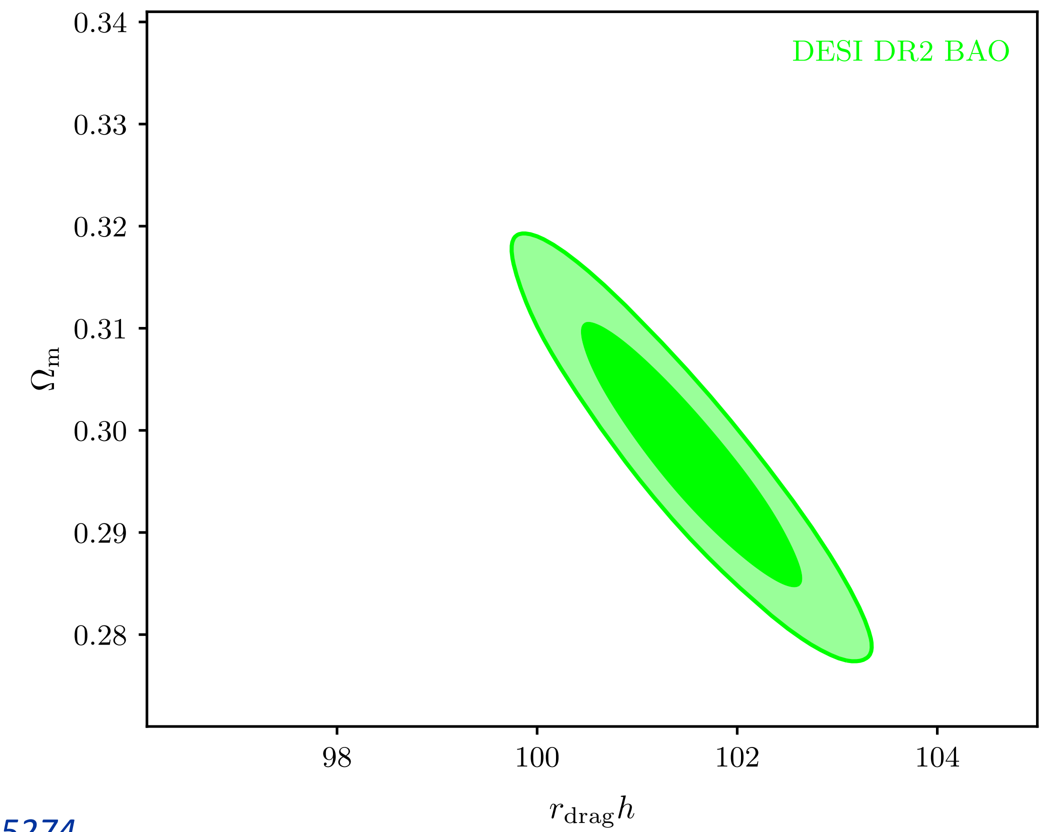
DESI DR2 in 2.3 sigma “tension” with Planck



DESI DR2 Results II: Measurements of BAO and Cosmological Constraints, arXiv:2503.14738

What aspect of LCDM is in tension?

Is it the late-time expansion history or the sound horizon physics?

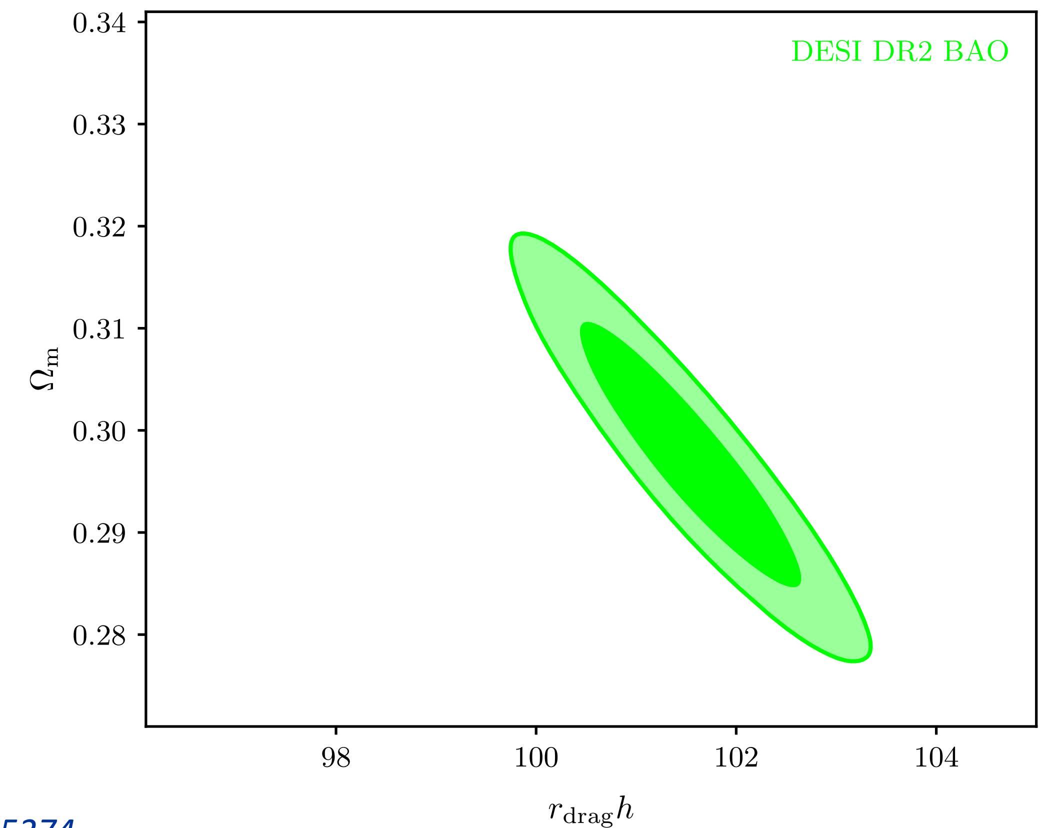


S.H.Mirpoorian, K. Jedamzik, LP, arXiv:2504.15274

What aspect of LCDM is in tension?

Is it the late-time expansion history or the sound horizon physics?

Treat the CMB acoustic scale θ_* as another BAO point at *z_*=1090* and let r_d be a free parameter*



*assume that $r_d = 1.02\, r_*$ holds

S.H.Mirpoorian, K. Jedamzik, LP, arXiv:2504.15274

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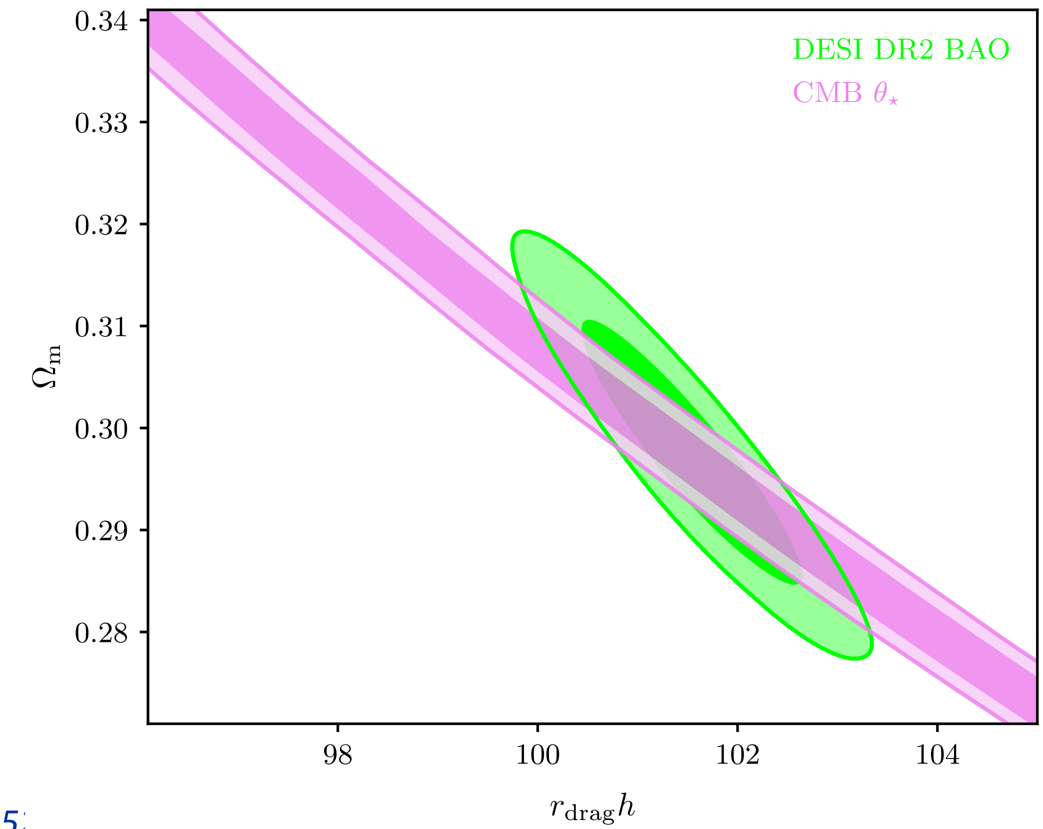
Treat the CMB acoustic scale θ_* as another BAO point at $z_*=1090$ and <u>let r_d be a free parameter</u>*



*assume that r_d = 1.02 r_* holds

S.H.Mirpoorian, K. Jedamzik, LP, arXiv:2504.152

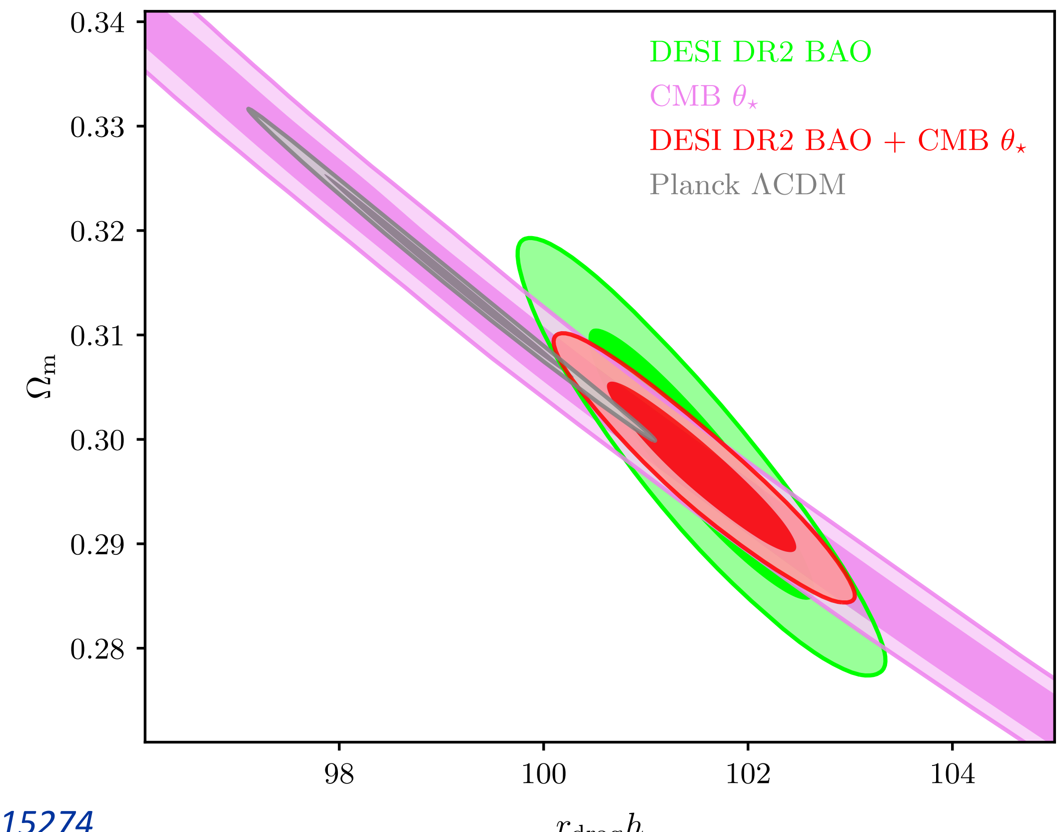
What aspect of LCDM is in tension?

Is it the late-time expansion history or the sound horizon physics?

Treat the CMB acoustic scale θ_* as another BAO point at $z_*=1090$ and let r_d be a free parameter*

The CMB acoustic scale is in perfect agreement with the DESI BAO measurements within a flat LCDM

The expansion history does not seem to be the problem



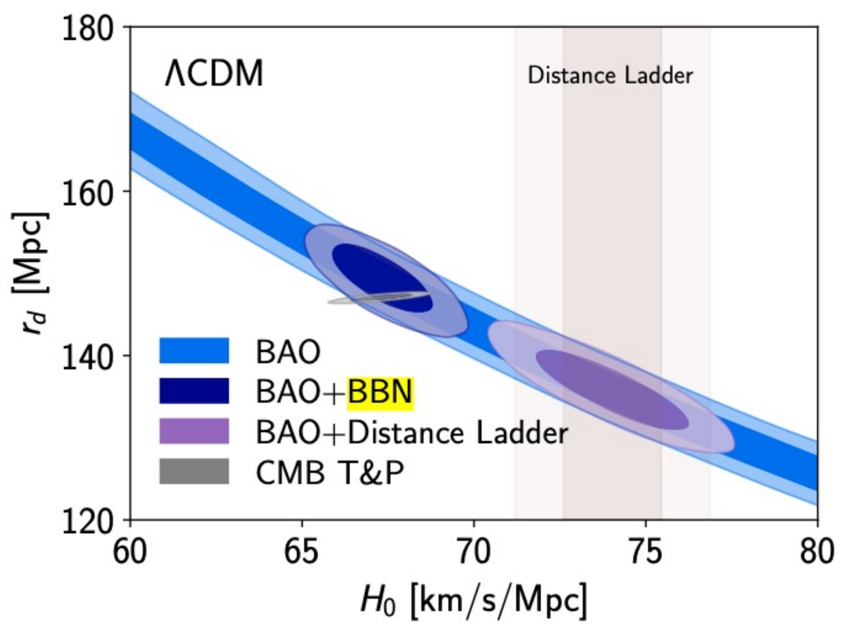
*assume that $r_d = 1.02\, r_*$ holds

S.H.Mirpoorian, K. Jedamzik, LP, arXiv:2504.15274

H_0 from BAO

By itself, BAO data only constrains $r_d h$ and Ω_m. To get H_0 from BAO, one can:

- use r_d from the LCDM fit to CMB (computed assuming the standard recombination model)
- use the BBN value of ω_b and compute r_d (assuming the standard recombination model)
- use external information on $\omega_m = \Omega_m h^2$ to break the r_d-h degeneracy, e.g. CMB Lensing, WITHOUT assuming a recombination model



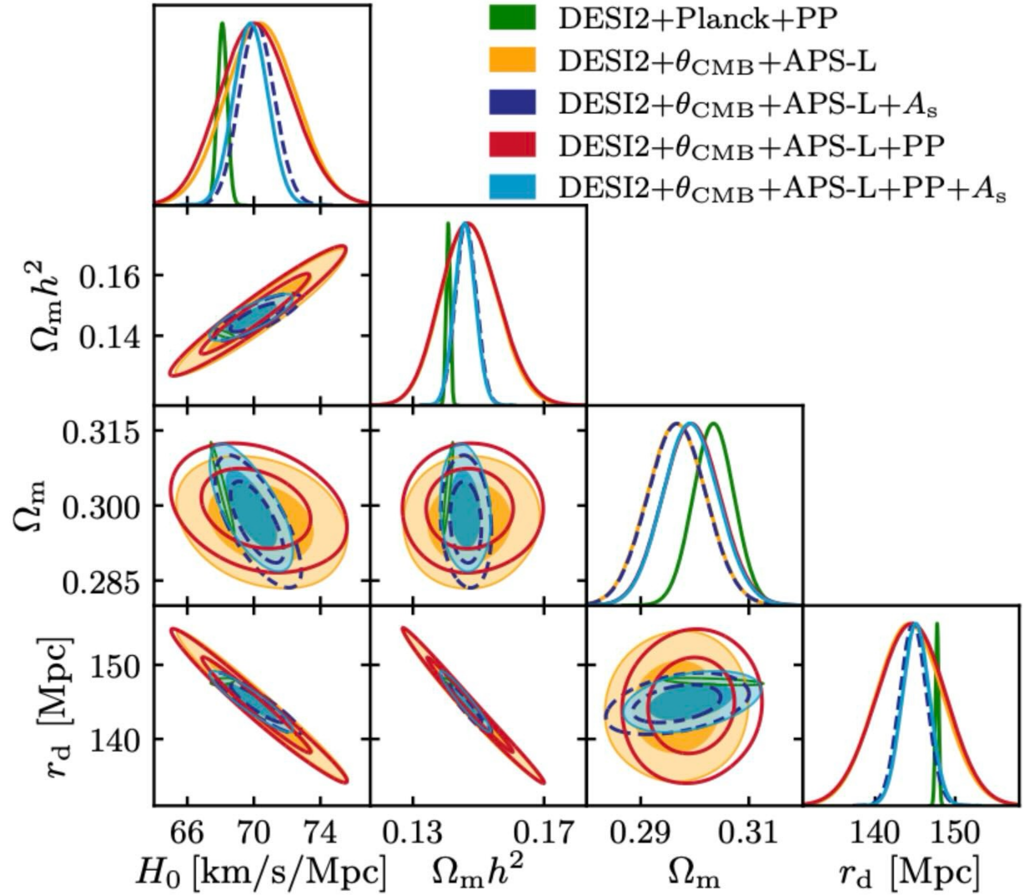
eBOSS Coll, Alam et al, arXiv:2007.08991, Phys. Rev. D

Calibration-independent H_0 from BAO and CMB Lensing

A way to measure H_0 from BAO in a calibration-independent way, with r_d as a free parameter:

DESI BAO + θ_* + CMB Lensing (Planck+ACT+SPT) + prior on A_s

H_0 = 70.02 ± 1.0 km/s/Mpc

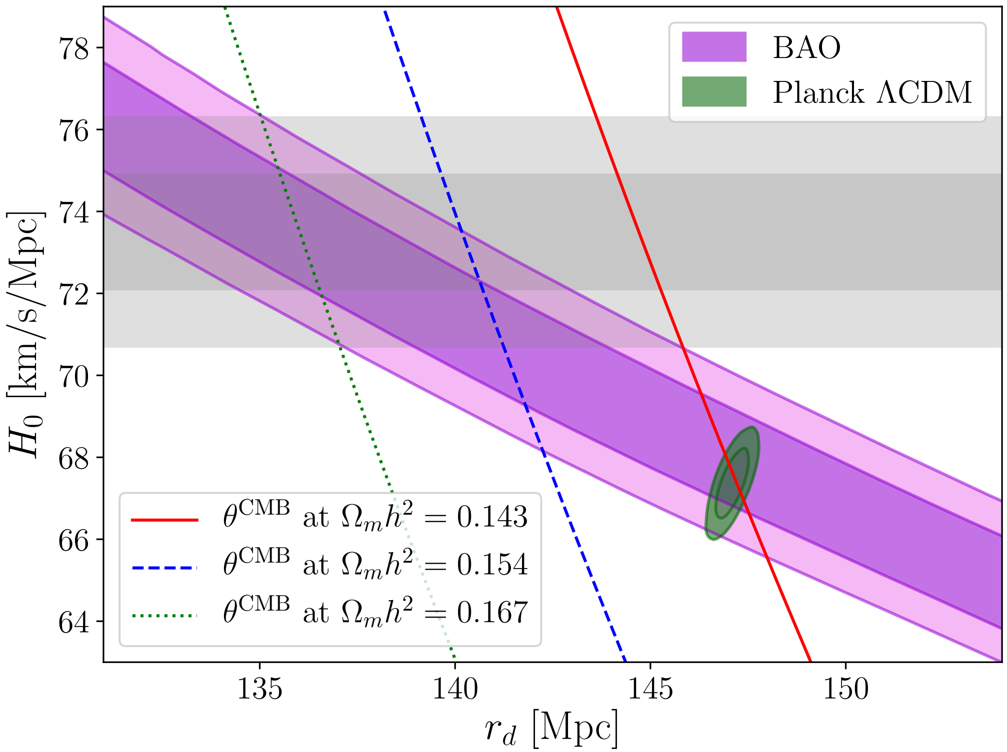


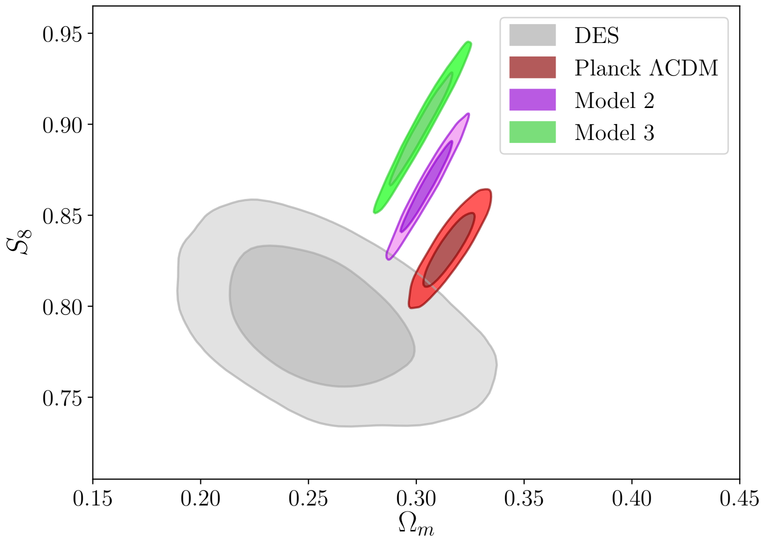
H.G. Escudero, S.H. Mirpoorian, LP, in preparation
LP, G.-B. Zhao, K. Jedamzik, arXiv:2009.08455, Ap. J. Lett.

Data DESI2+	H_0 [km/s/Mpc]	$100\ \Omega_m h^2$	Ω_m	r_d [Mpc]	$\ln(10^{10}A_s)$	n_s	S_8
Planck+PP	68.11 ± 0.28	14.08 ± 0.06	0.304 ± 0.004	147.8 ± 0.18	3.047 ± 0.014	0.968 ± 0.003	0.811 ± 0.008
$\theta_{\rm CMB}$+APS-L	70.4 ± 2.0	$14.73^{+0.74}_{-0.86}$	0.297 ± 0.005	144.3 ± 3.9	3.041 ± 0.073	0.963 ± 0.020	0.830 ± 0.011
$\theta_{\rm CMB}$+APS-L+A_s	70.2 ± 1.0	14.62 ± 0.30	0.297 ± 0.005	144.8 ± 1.6	3.049 ± 0.019	0.964 ± 0.015	0.830 ± 0.011
$\theta_{\rm CMB}$+APS-L+PP	$70.1^{+1.9}_{-2.2}$	$14.74^{+0.72}_{-0.92}$	0.299 ± 0.005	144.5 ± 4.0	3.037 ± 0.074	0.963 ± 0.020	0.833 ± 0.011
$\theta_{\rm CMB}$+APS-L+PP+A_s	69.82 ± 0.97	14.59 ± 0.30	0.299 ± 0.005	145.1 ± 1.6	3.049 ± 0.020	0.965 ± 0.015	0.832 ± 0.011

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

- For a given matter density parameter $\omega_m = \Omega_m h^2$, the CMB θ_* defines a line in the $r_d - h$ plane
- To make the CMB line pass through the BAO/SH0ES overlap region one needs to increase $\omega_{\rm m}$
- A larger $\omega_{\rm m}$ increases S_8, worsening the fit to galaxy weak lensing





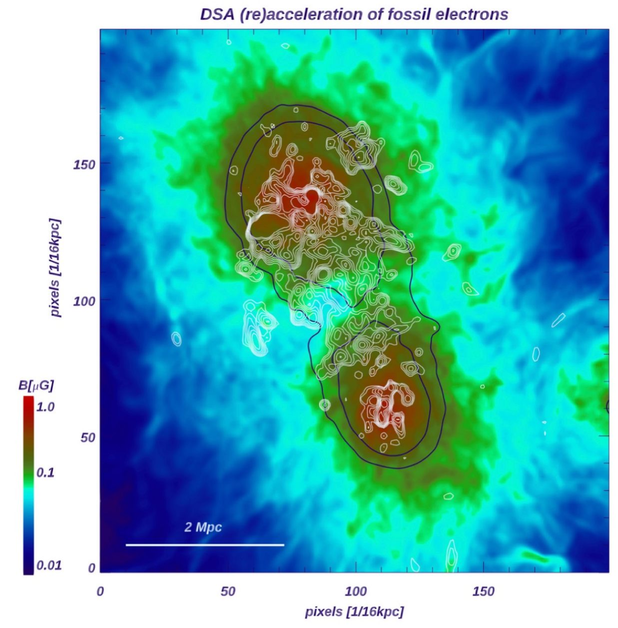
K. Jedamzik, LP, G.-B. Zhao, arXiv:2010.04158

A smaller sound horizon at decoupling appears to be a necessary (but not necessarily sufficient) ingredient to relieve the Hubble tension, and would remove the (minor) tension between BAO and CMB in LCDM

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

- Many models proposed with the aim of solving the Hubble tension (early dark energy, varying fundamental constants,…)
- Primordial Magnetic Fields

Cosmic Magnetic Fields



- Micro-Gauss (μG) fields in galaxies
  - produced astrophysically via dynamo?
  - primordial origin?
- 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?
  - lower bound on PMF from 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

Stochastic Primordial Magnetic Field

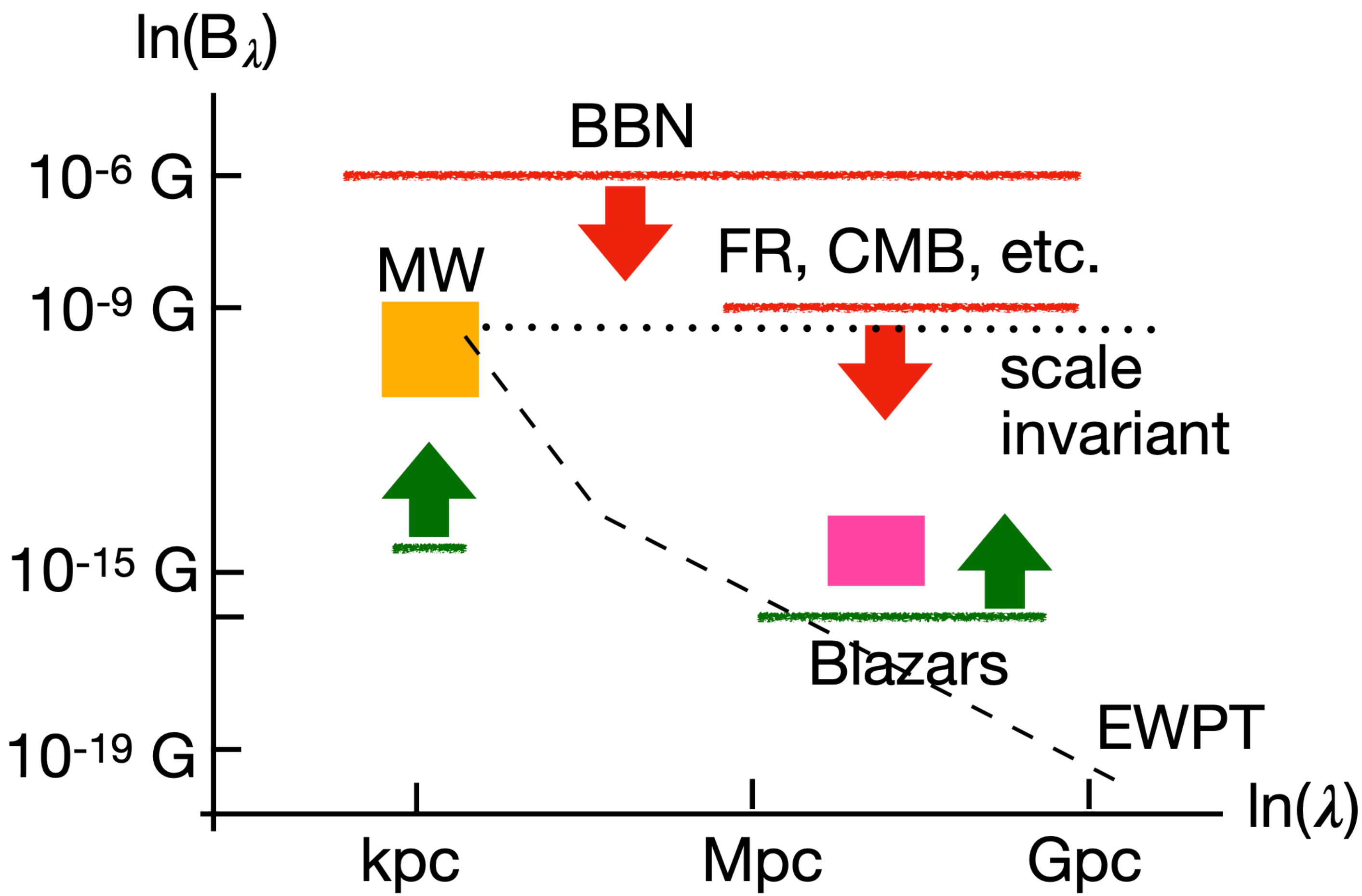
- Generated in the early universe, e.g. during phase transitions or inflation, possible window into baryogenesis and the physics of the EWPT
- Frozen in the plasma on large scales, amplitude decreases as $B(a)=B_0/a^2$
- Characterized by a magnetic field power spectrum

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

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

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

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)

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

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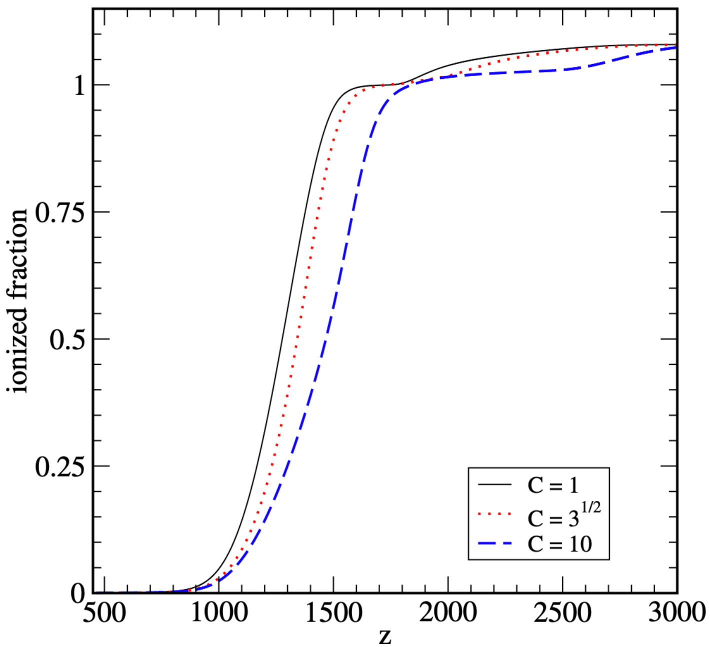
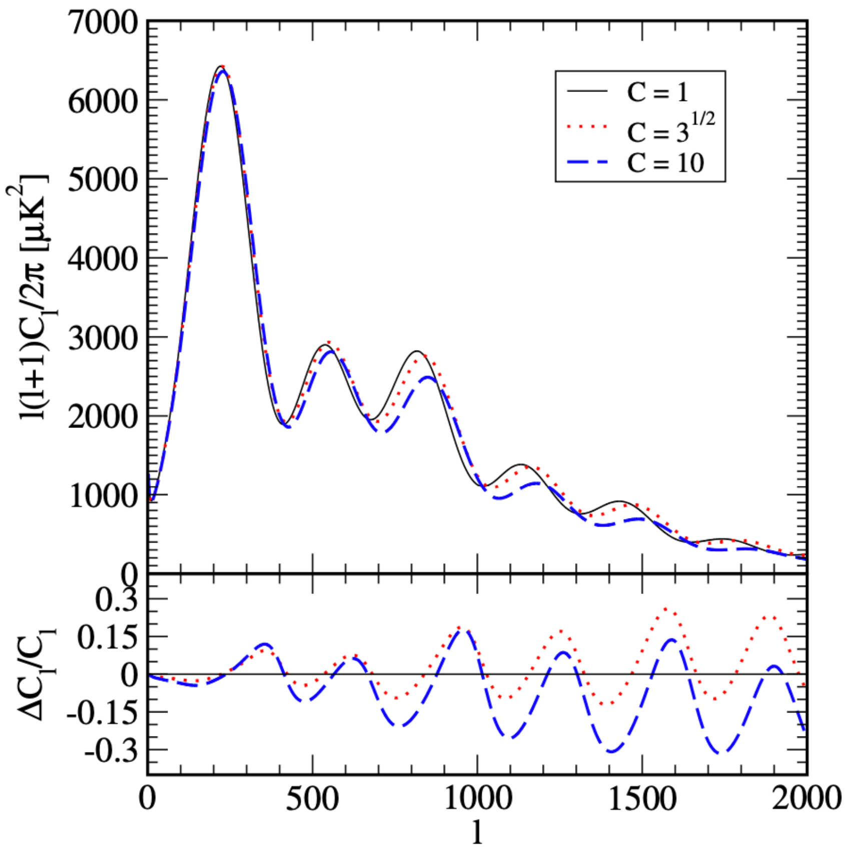




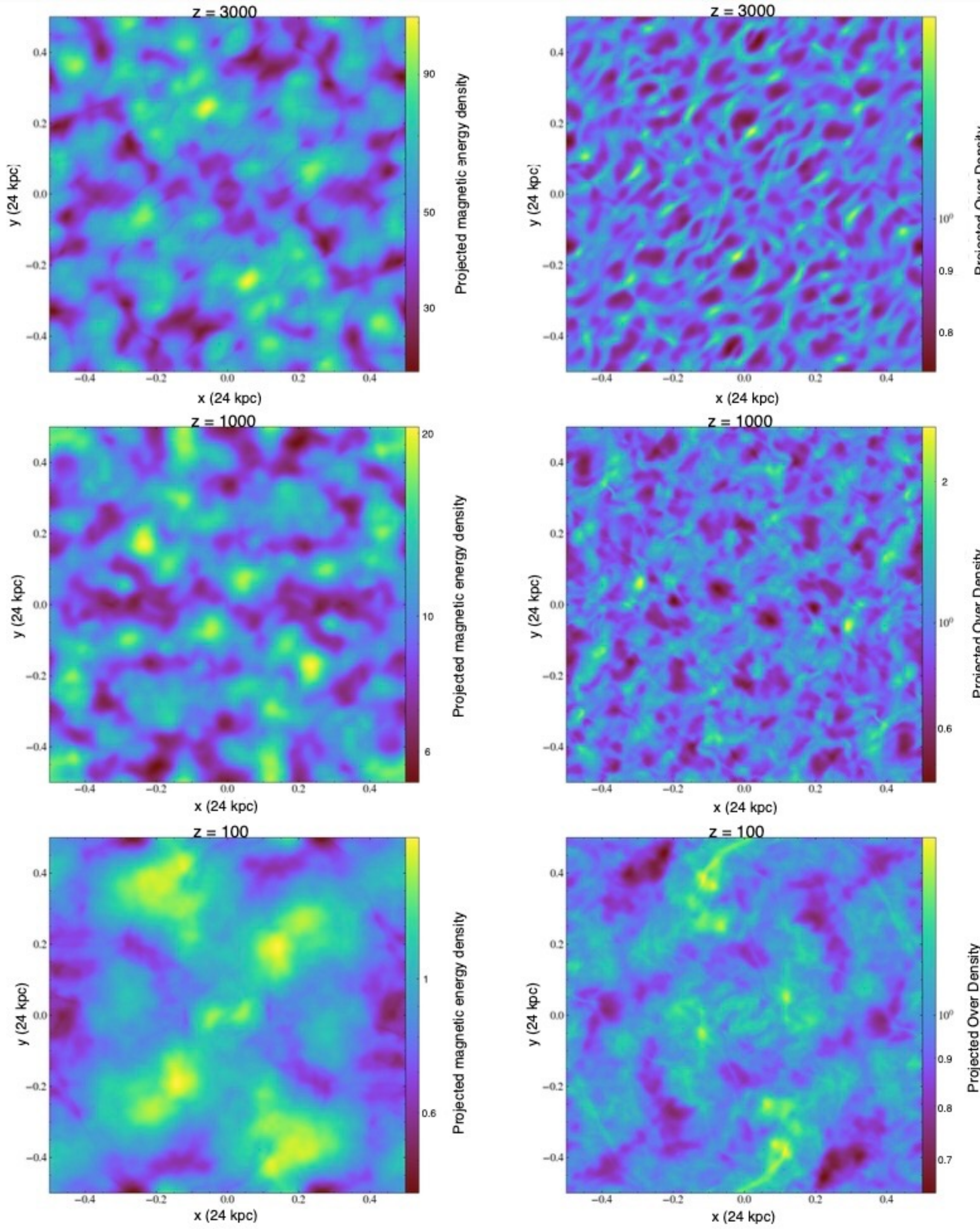
Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

Magnetically induced baryon clumping

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

Four PMF scenarios will eventually be considered:

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

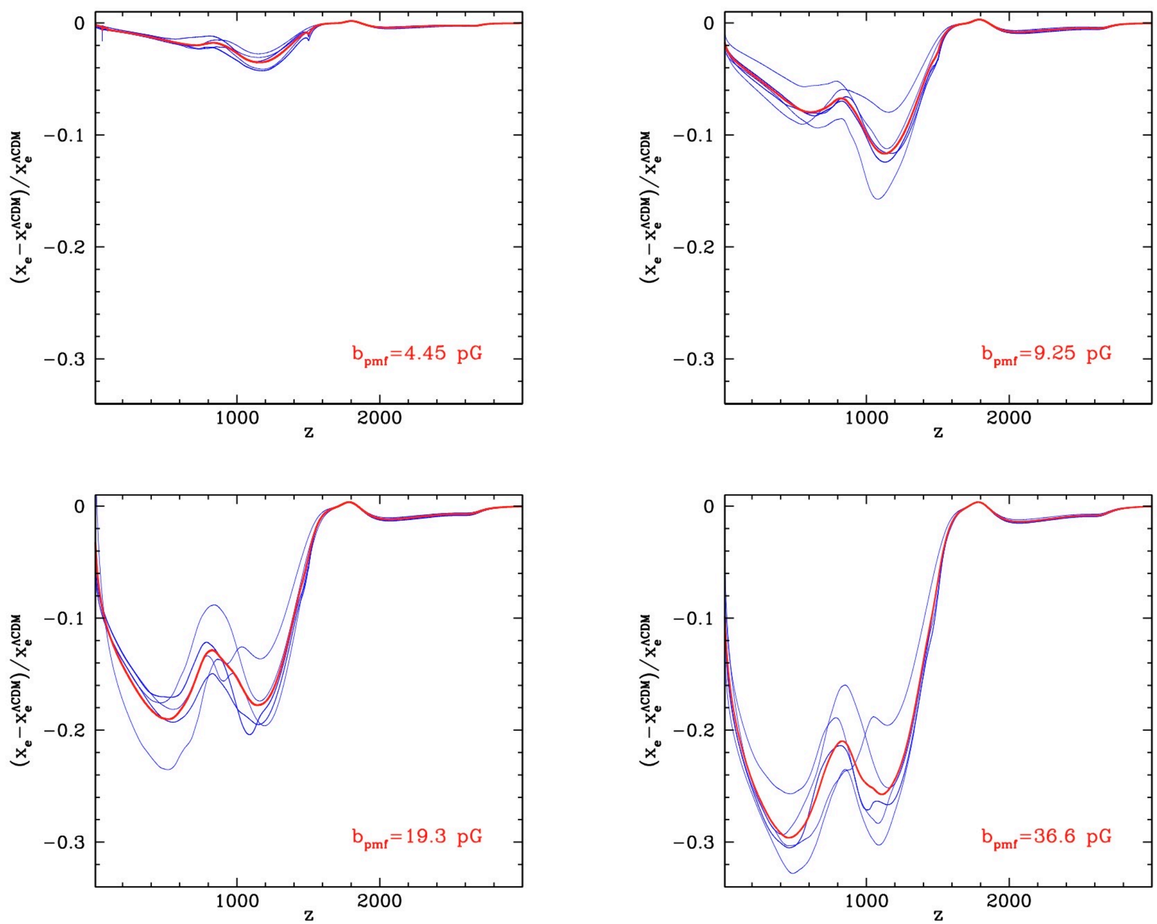


K. Jedamzik, T. Abel and Y. Ali-Haımoud, arXiv:2312.11448

MHD-derived ionization histories

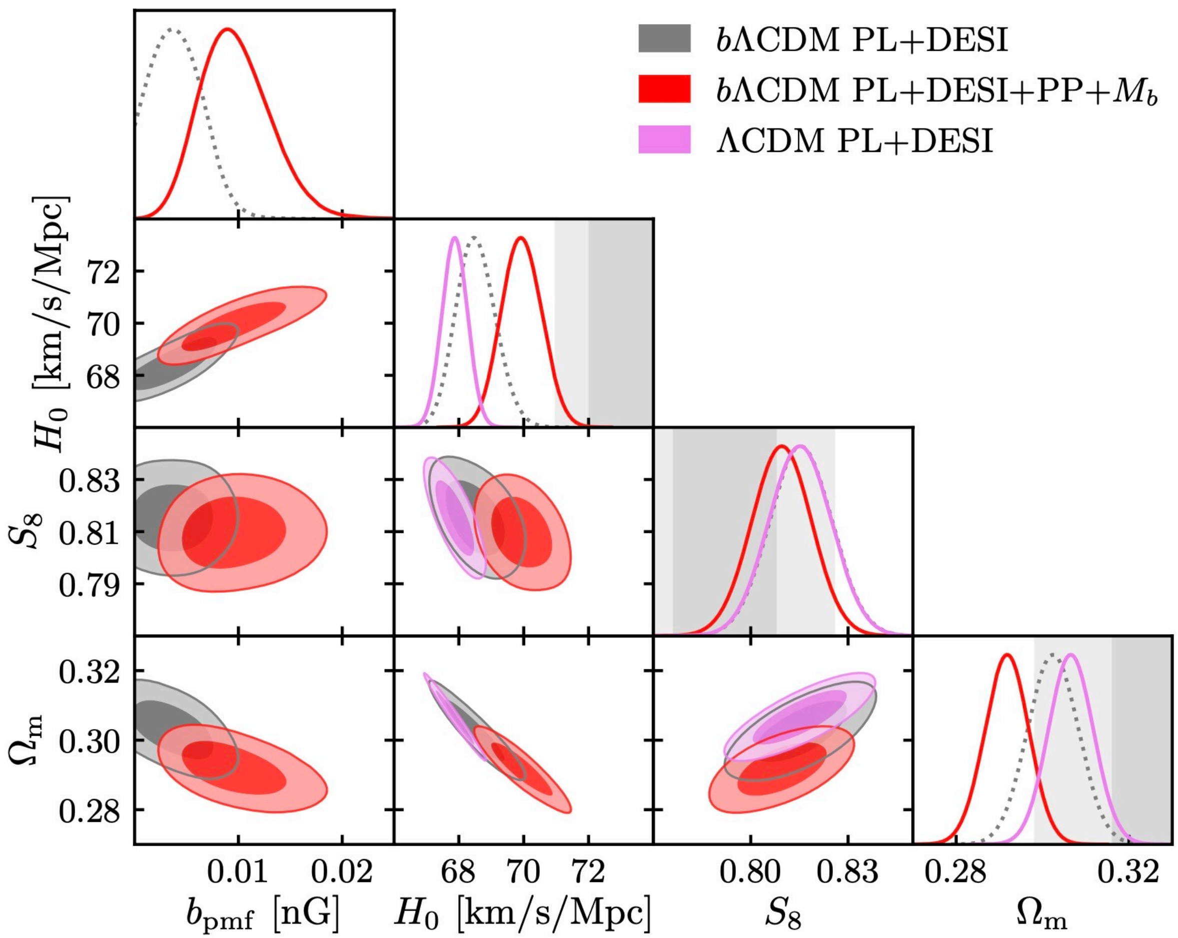
non-helical PMF with n=2 (Batchelor spectrum)

b_{pmf} is the "total" comoving field strength at $z=10$



K. Jedamzik, LP, T. Abel, arXiv:2503.09599

Parameters from Planck + DESI DR1 BAO (+ Pantheon$^+$ + M_b)



b_{pmf} is the "total" comoving field strength at *$z=10$*

K. Jedamzik, LP, T. Abel, arXiv:2503.09599

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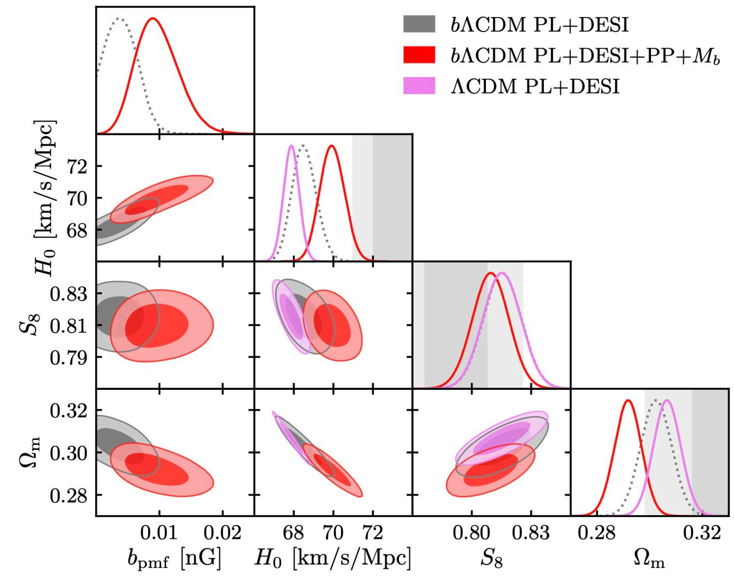
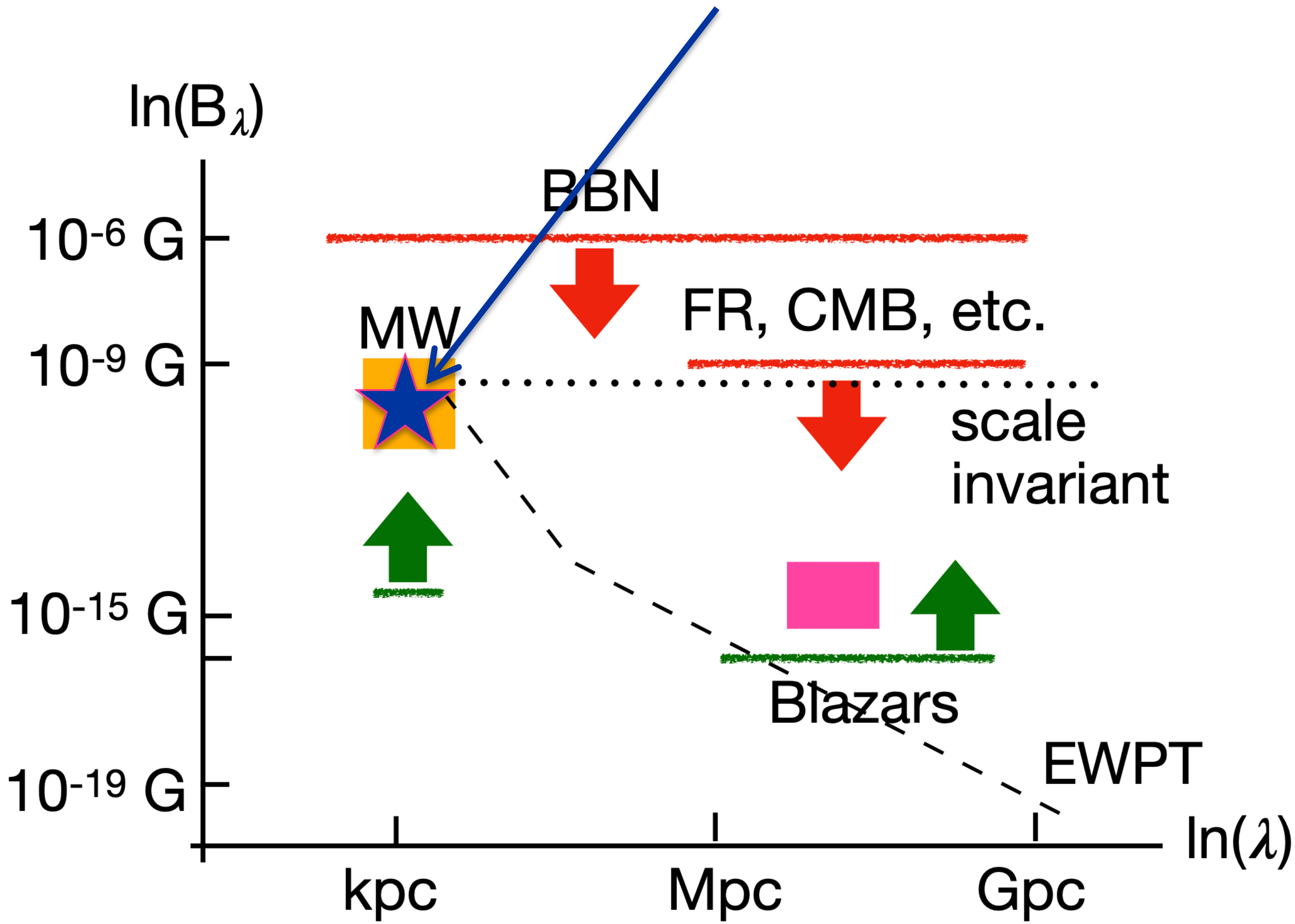


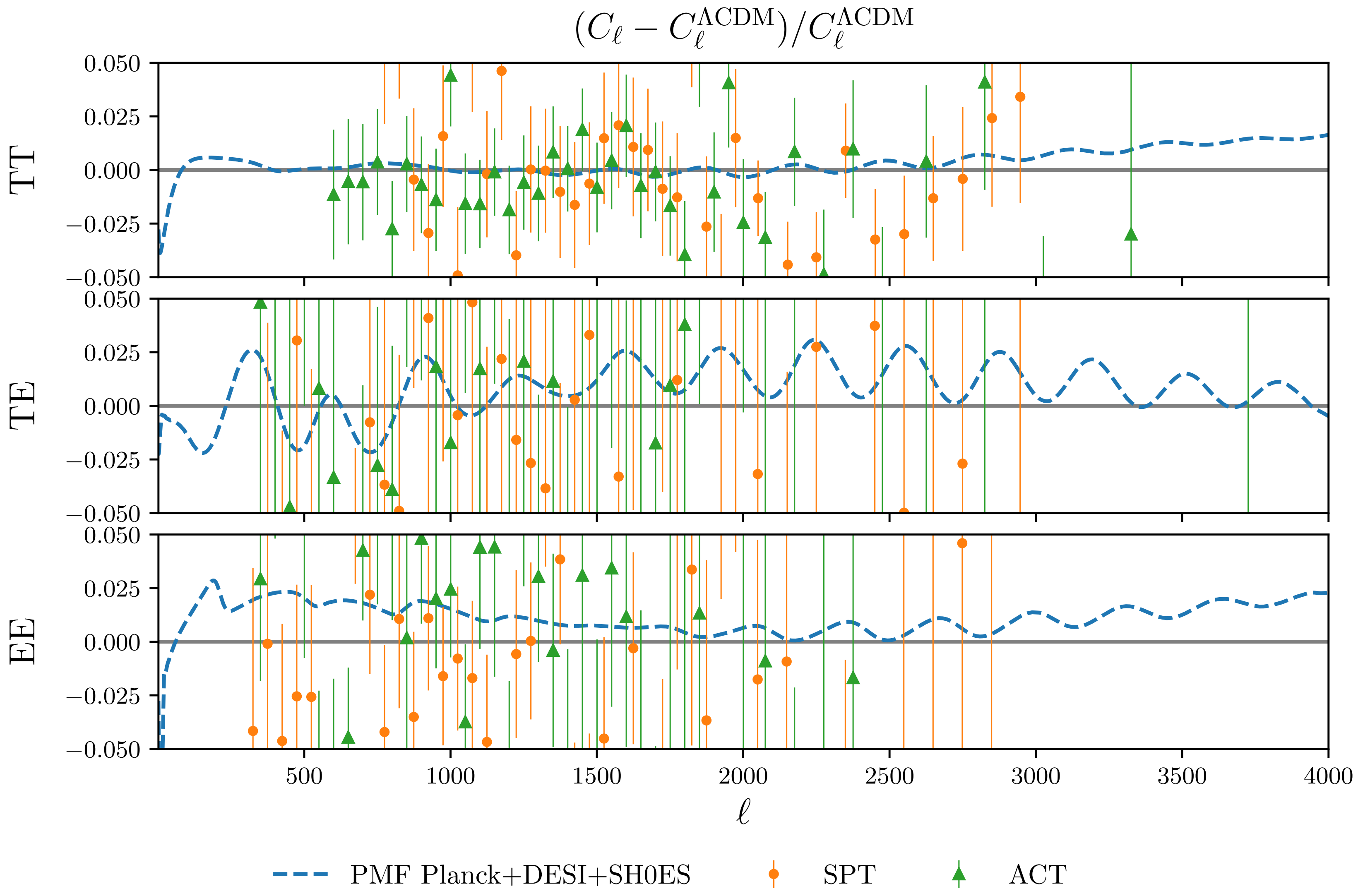
	ΛCDM PL+DESI	$b\Lambda$CDM PL+DESI	$b\Lambda$CDM PL+DESI+PP+M_b
b_{pmf} [nG]	-	$0.0042^{+0.0021}_{-0.0028}$	$0.0096^{+0.0029}_{-0.0036}$
H_0 [km/s/Mpc]	67.88 ± 0.37	$68.52^{+0.54}_{-0.62}$	$69.93^{+0.53}_{-0.66}$
Ω_m	0.3066 ± 0.0049	0.3024 ± 0.0055	0.2917 ± 0.0048
S_8	0.8154 ± 0.0090	0.8154 ± 0.0090	0.8095 ± 0.0087
χ^2_{Planck}	10973.9	10971.6	10977.6
χ^2_{DESI}	16.55	14.0728	12.91
$\chi^2_{\mathrm{Planck+DESI}}$	10990.4	10985.7	10990.5

K. Jedamzik, LP, T. Abel, arXiv:2503.09599

PMF required to relieve the H_0 tension



Relative differences in CMB spectra



K. Jedamzik, LP, T. Abel, arXiv:2503.09599

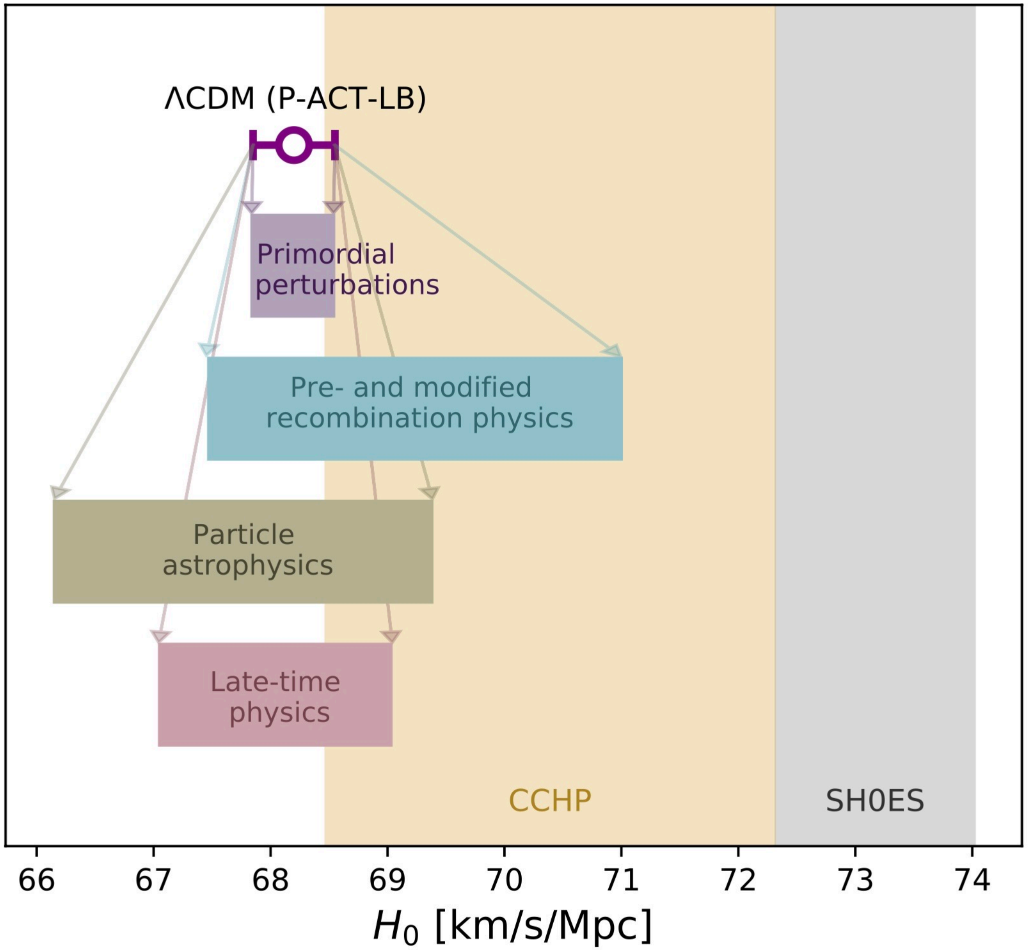
Outlook: PMF and the Hubble Tension

The PMF proposal is still alive, which was not trivial

We are just starting:

- Larger MHD simulations to beat the variance
- Helical PMF simulations and the scale-invariant case
- Code comparisons

The data is evolving too:
DESI, ACT, SPT, JWST, CCHP vs SH0ES



The Atacama Cosmology Telescope: DR6 Constraints on Extended Cosmological Models, arXiv:2503.14454

Outlook: the hunt for the PMF

Baryon clumping at recombination is the most constraining known probe of the PMF

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 ~69-70 km/s/Mpc (it could be all we need)

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

- 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

BAO vs CMB consistency test

Use the BAO data with the Planck LCDM measurement of $\omega_m = \Omega_m h^2$ as a Gaussian prior ($\omega_m = 0.142 \pm 0.001$), treat he sound horizon r_d as a free parameter, and check the consistency between BAO and CMB within a flat LCDM model in a calibration-independent way

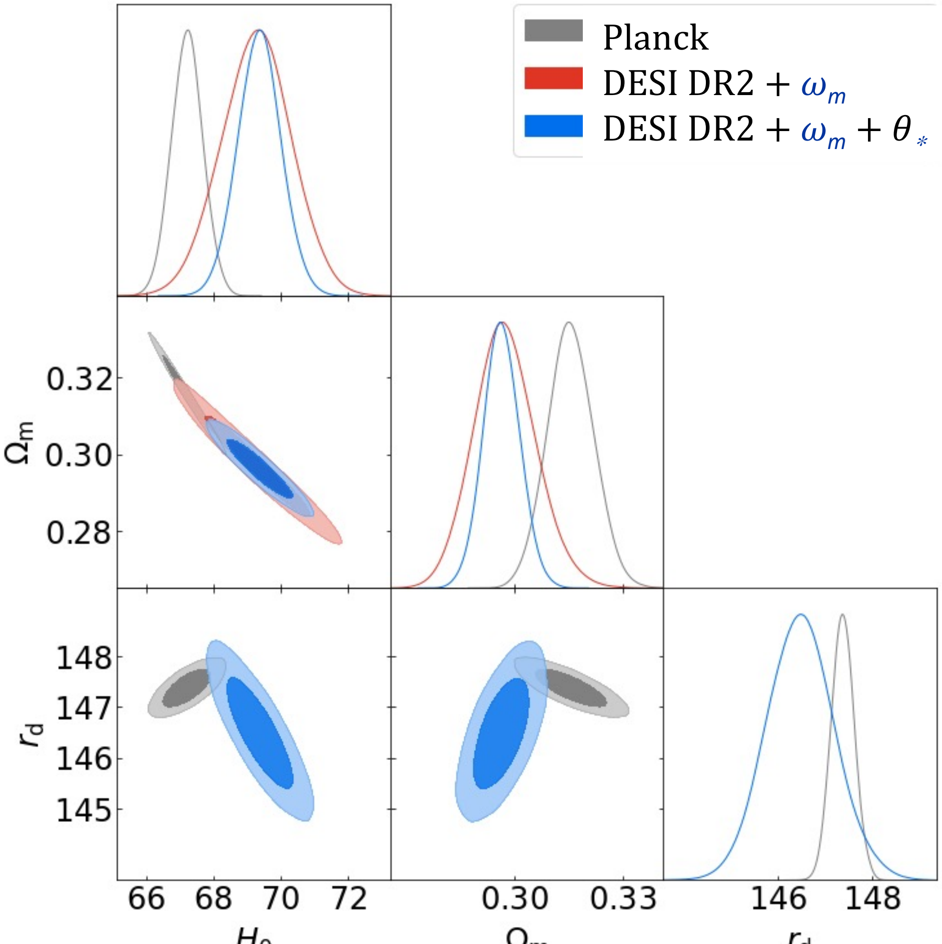
- with r_d as a free parameter:

  DESI DR2 + $\theta_* + \omega_m$

  $H_0 = 69.37 \pm 0.65$ km/s/Mpc

- Planck LCDM (r_d derived from standard recombination)

  $H_0 = 67.22 \pm 0.47$ km/s/Mpc



LP, G.-B. Zhao, K. Jedamzik, arXiv:2009.08455, Ap. J. Lett.
LP, K. Jedamzik, G.-B. Zhao, arXiv: 2405.20306, Ap. J. Lett.

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

$\alpha \sim 1/l_\gamma$

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

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

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

Drag 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

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

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

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

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Pushes baryons towards regions of low magnetic energy density

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

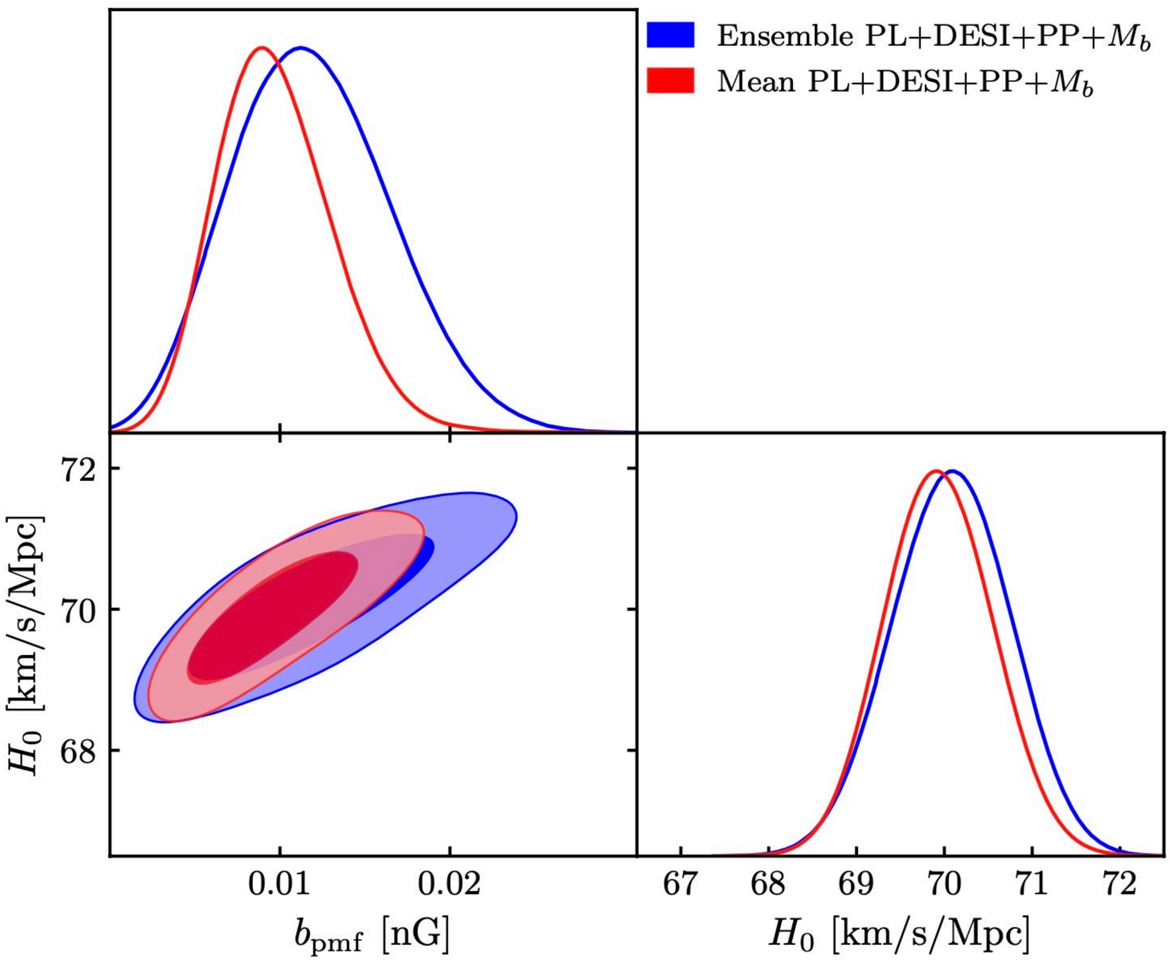
$L < l_\gamma$ viscous compressible baryon gas

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)

Taking sample variance into account



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

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

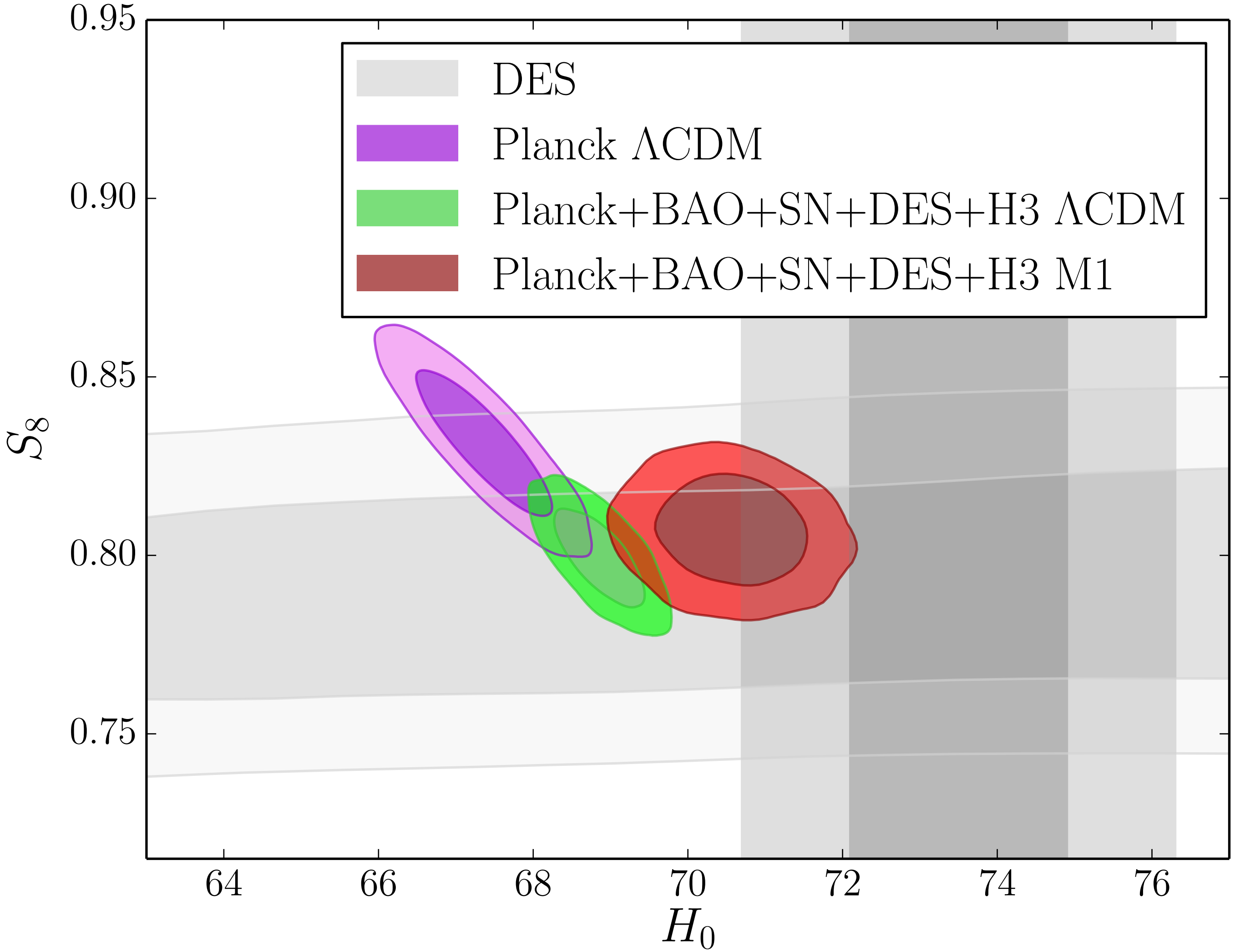
Datasets:

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

* Kept us busy during COVID

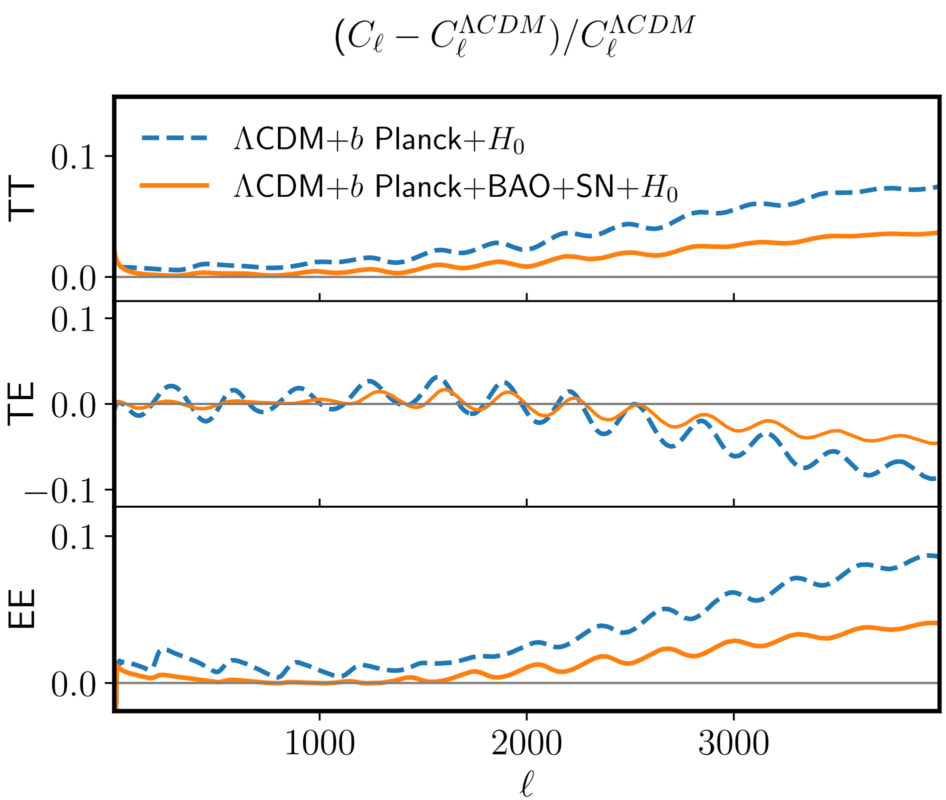
K. Jedamzik and L. Pogosian, arXiv:2004.09487, PRL

Fitting the M1 model to all data



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

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

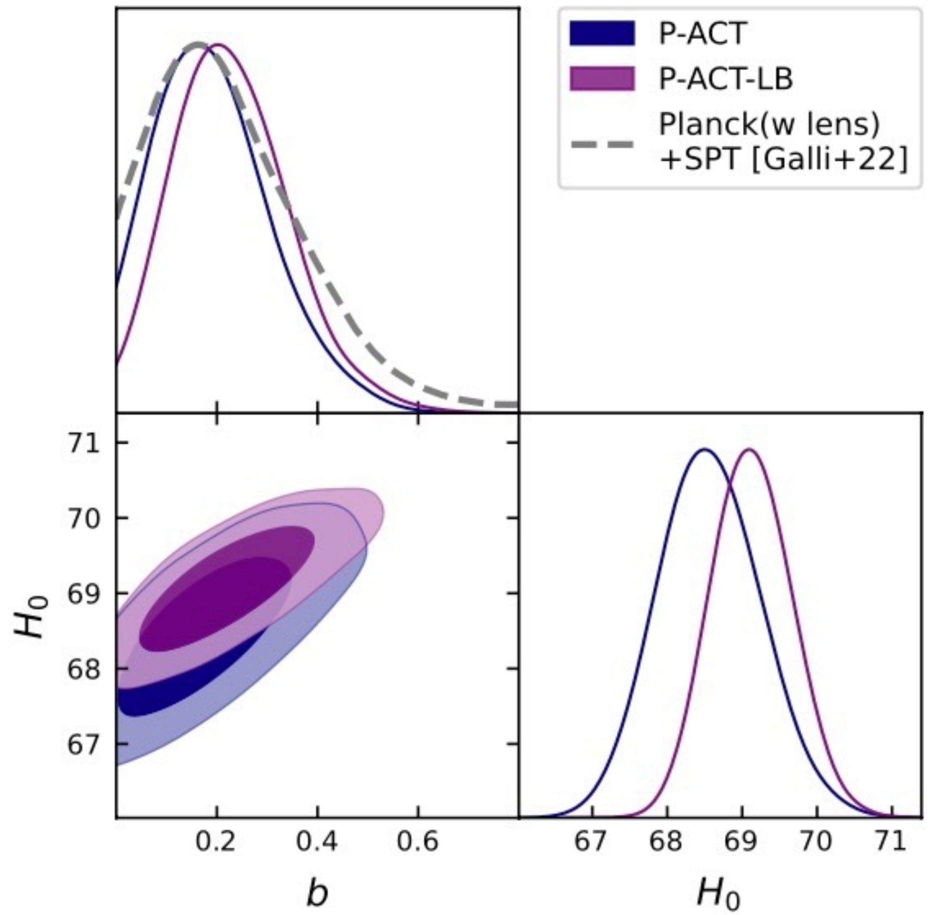
ACT DR6 (+ Planck + DESI Y1) constraints on the M1 model

Planck* + ACT DR6 + DESI Y1:

H_0 = 69.1 ± 0.5 km/s/Mpc

(no “SH0ES prior”)

*truncated Planck data



The Atacama Cosmology Telescope: DR6 Constraints on Extended Cosmological Models, arXiv:2503.14454

MHD simulations

Performed by K. Jedamzik, T. Abel and T. Ali-Haimoud 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” (clone of RECFAST) that computes abundances of ionized hydrogen and helium at each time step

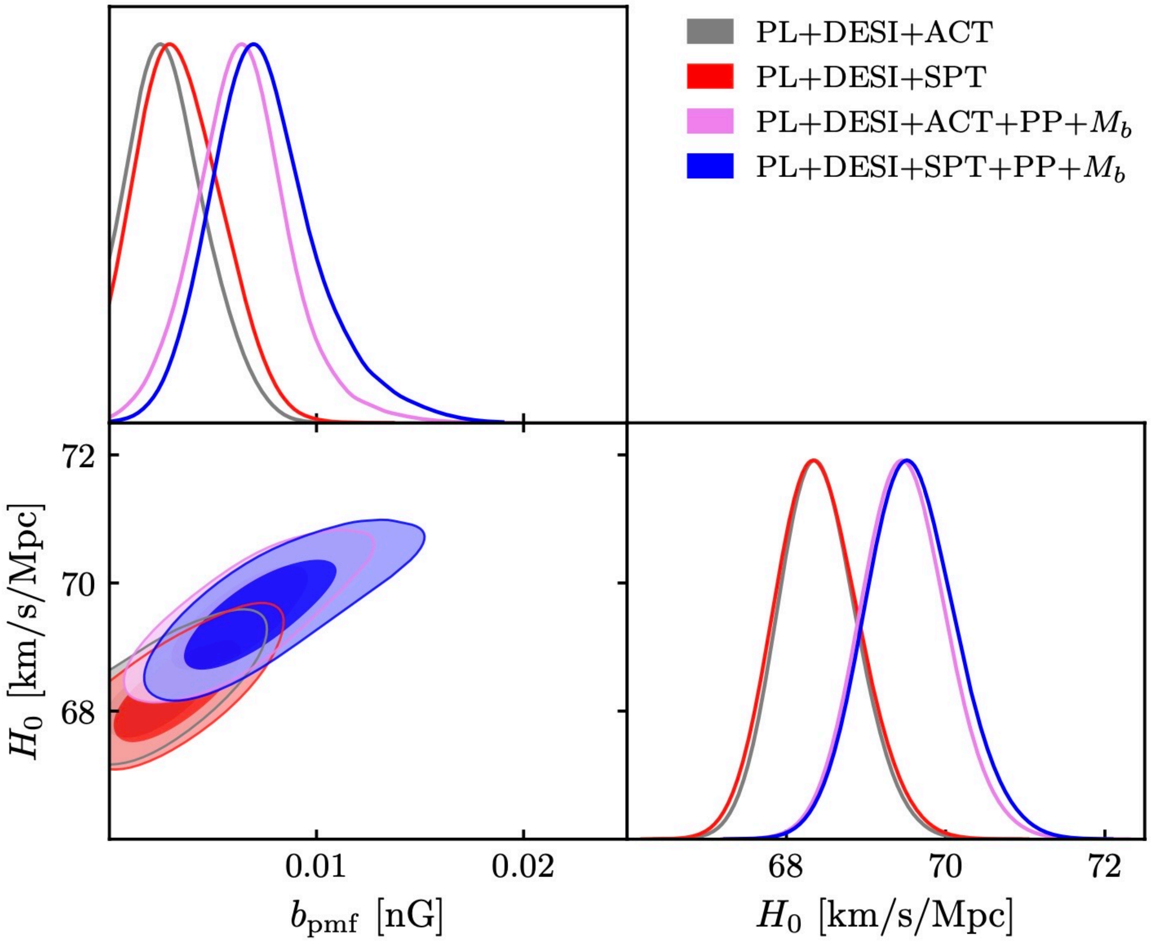
Additional modeling of Lyman-alpha photon transport across the simulation volume

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, T. Abel and Y. Ali-Haımoud, arXiv:2312.11448

Constraints from ACT DR4 and SPT-3G + Planck + DESI DR1 BAO (+ Pantheon$^+$ + M_b)



K. Jedamzik, LP, T. Abel, arXiv:2503.09599

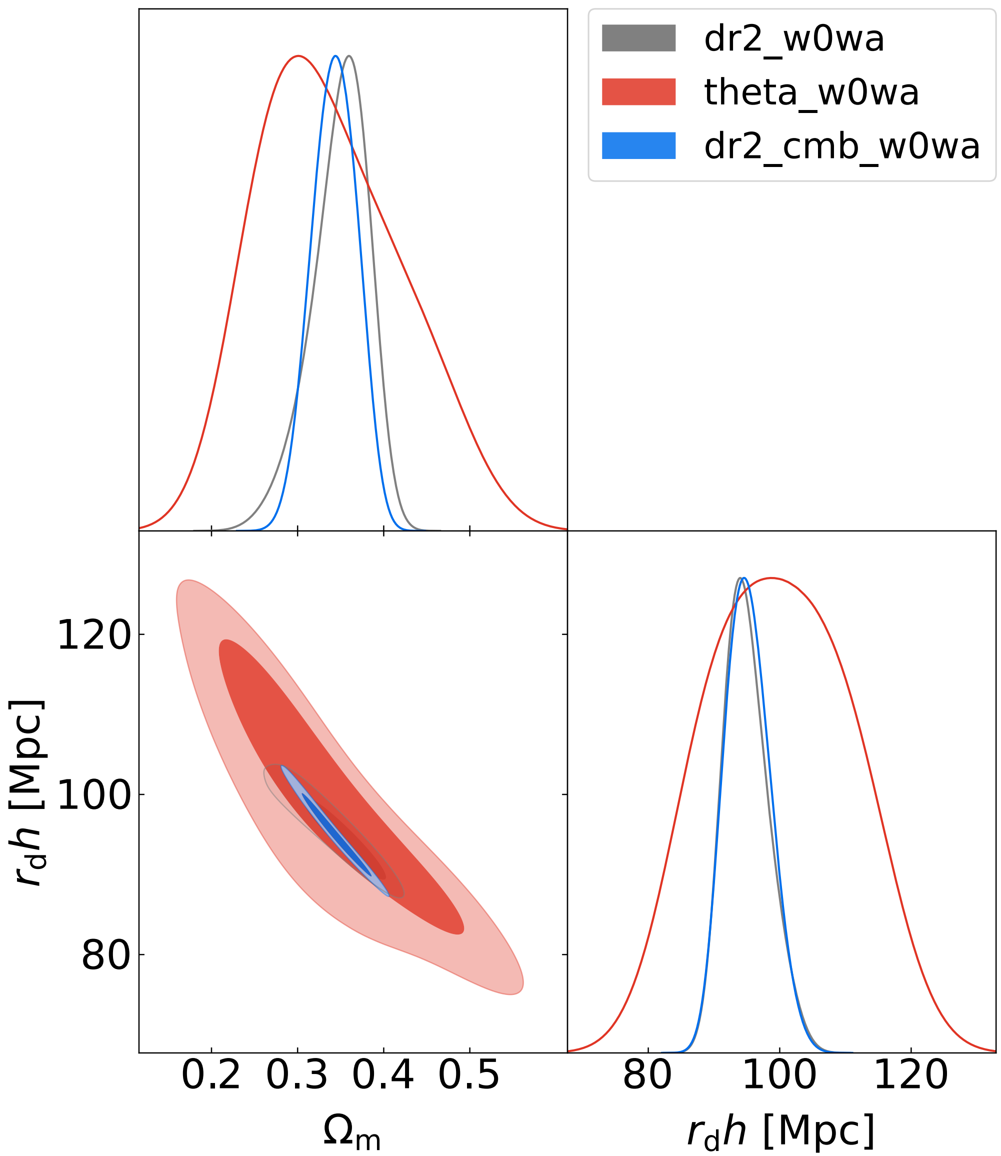
chi^2 comparison and constraints on b_{pmf} at $z=10$

	$\chi^2_{b\Lambda\mathrm{CDM}} - \chi^2_{\Lambda\mathrm{CDM}}$	b_{pmf} [nG] median & 68% CI	95% CI	99.7% CI
PL	-1.7	$0.0023^{+0.0048}_{-0.0022}$	$< 0.0075^{\mathrm{a}}$	< 0.015
PL+DESI	-4.7	$0.0042^{+0.0021}_{-0.0028}$	< 0.0083	< 0.013
PL+DESI+PP	-3.83	$0.0038^{+0.0017}_{-0.0028}$	< 0.0079	< 0.011
PL+DESI+ACT	-5.3	$0.0030^{+0.0012}_{-0.0021}$	< 0.0067	< 0.008
PL+DESI+SPT	-5.2	$0.0036^{+0.0015}_{-0.0023}$	< 0.0075	< 0.010
PL+DESI+PP+M_b	-15.25	$0.0096^{+0.0029}_{-0.0036}$	$[0.0049, 0.016]$	$[0.0024, 0.024]$
PL+DESI+ACT+PP+M_b	-11.8	0.0064 ± 0.0021	$[0.0025, 0.012]$	< 0.016
PL+DESI+SPT+PP+M_b	-17.8	$0.0074^{+0.0018}_{-0.0027}$	$[0.0031, 0.013]$	$[0.0019, 0.016]$

b_{pmf} at $z=10$ vs b_{pmf} at $z=1100$ vs B_{1Mpc}

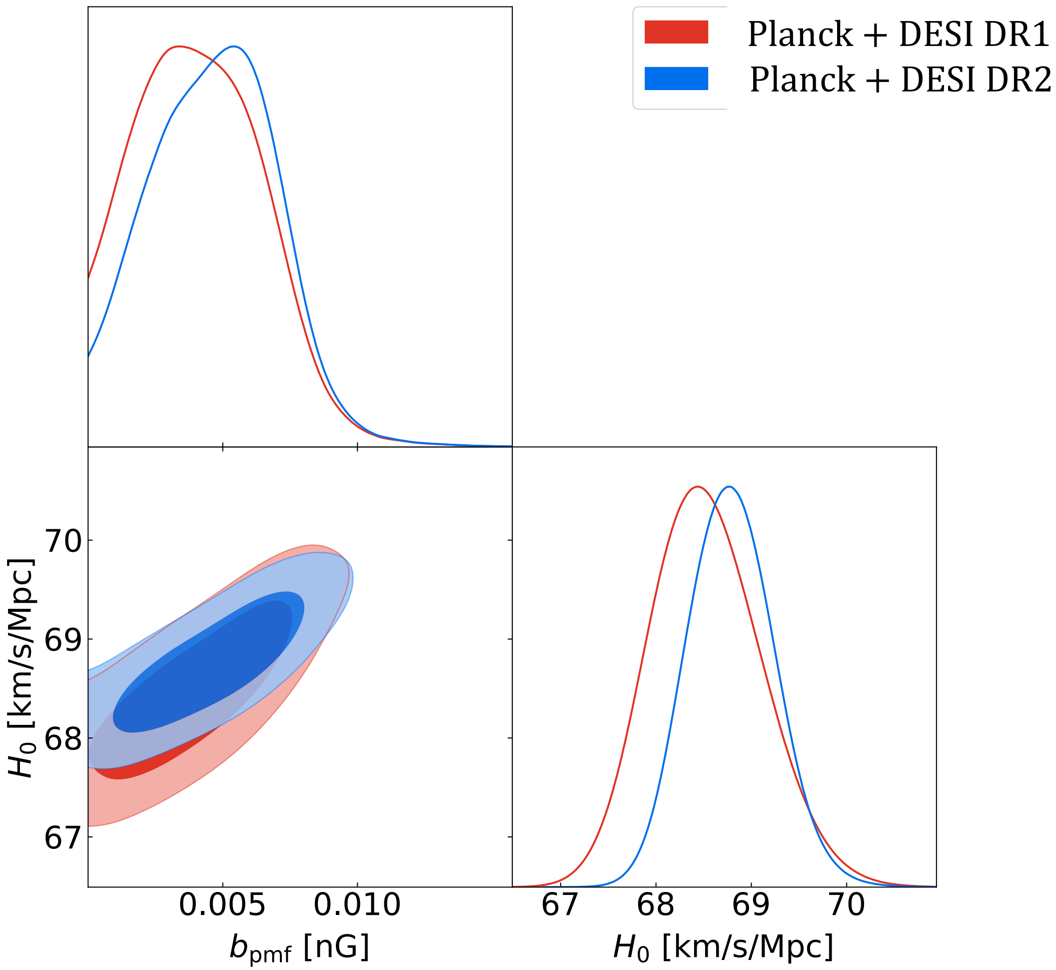
b_{pmf}	$b^{\mathrm{rec}}_{\mathrm{bmf}}$	$B_{1\mathrm{Mpc}}$
4.45×10^{-3} nG	5.45×10^{-2} nG	1.68×10^{-10} nG
9.25×10^{-3} nG	1.04×10^{-1} nG	1.90×10^{-9} nG
1.93×10^{-2} nG	1.89×10^{-1} nG	2.15×10^{-8} nG
3.66×10^{-2} nG	3.65×10^{-1} nG	2.44×10^{-7} nG

K. Jedamzik, LP, T. Abel, arXiv:2503.09599



dr2_w0wa
theta_w0wa
dr2_cmb_w0wa
120
100
80
$r_d h$ [Mpc]
0.2
0.3
0.4
0.5
Ω_m
80
100
120
$r_d h$ [Mpc]

Planck + DESI DR2 vs Planck + DESI DR1



b_{pmf} is the "total" comoving field strength at $z=10$