SFU

# The Hubble Tension
# and
# Primordial Magnetic Fields

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*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

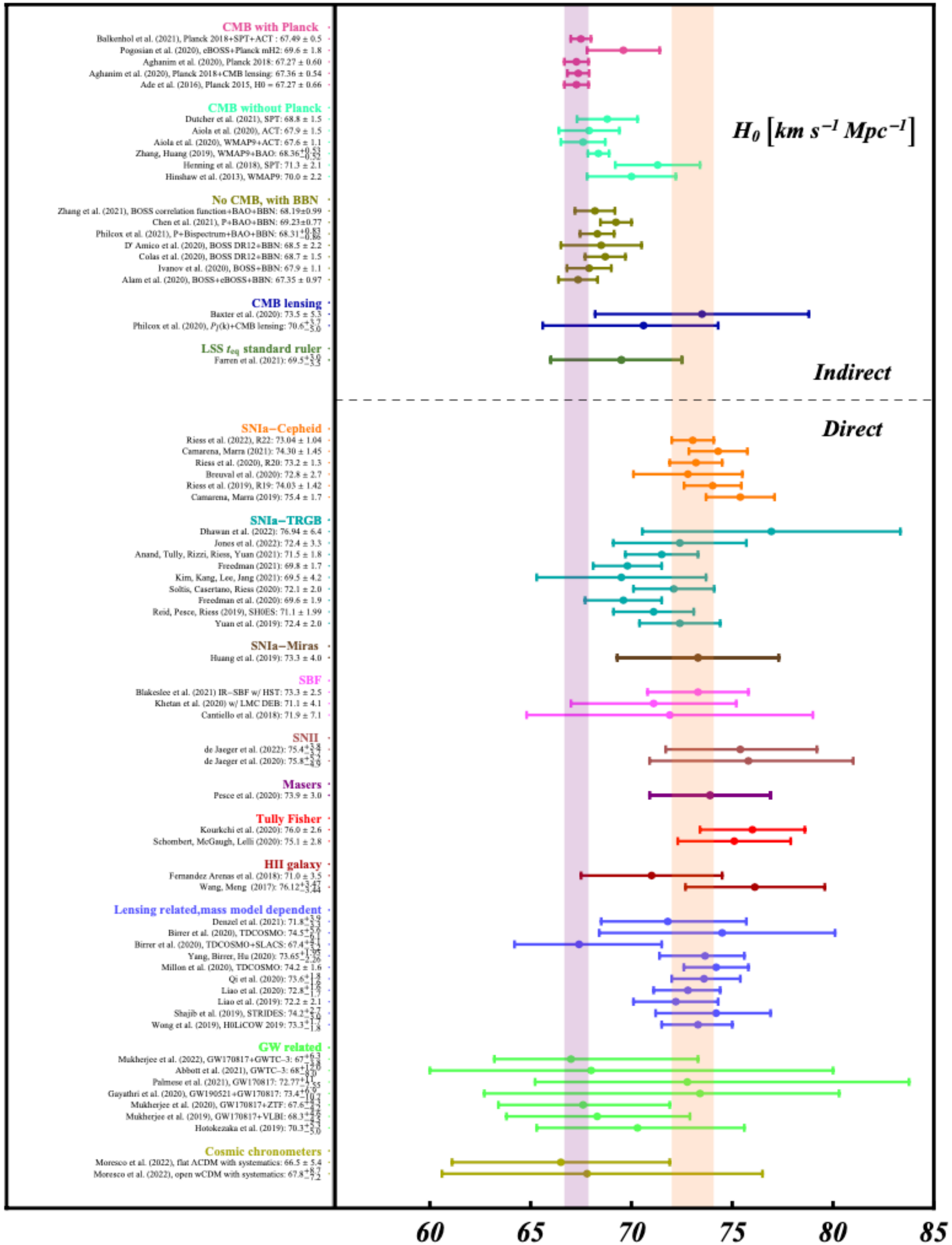
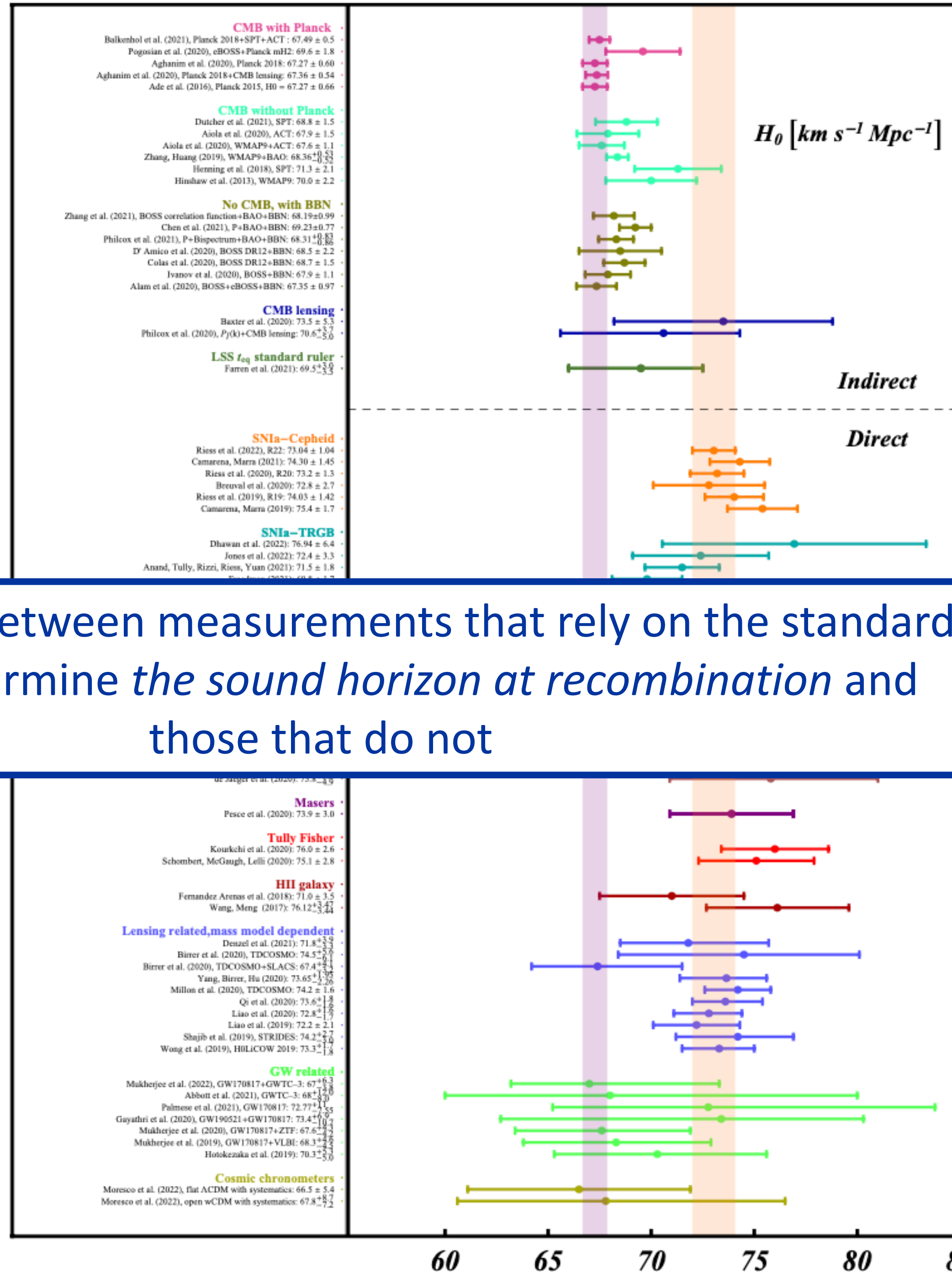



Table from arXiv:2203.06142

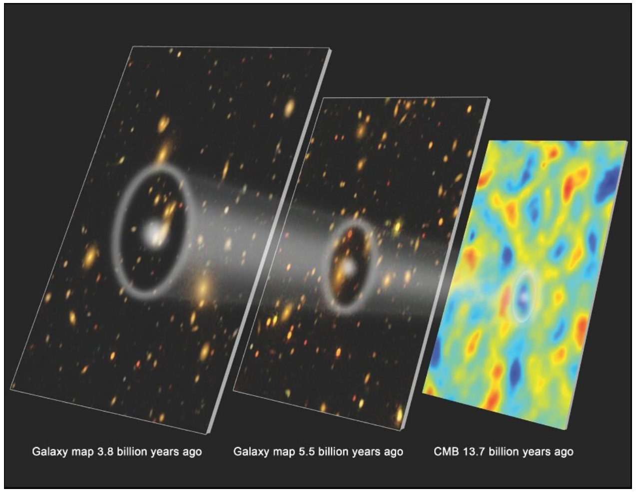
# The Hubble Tension

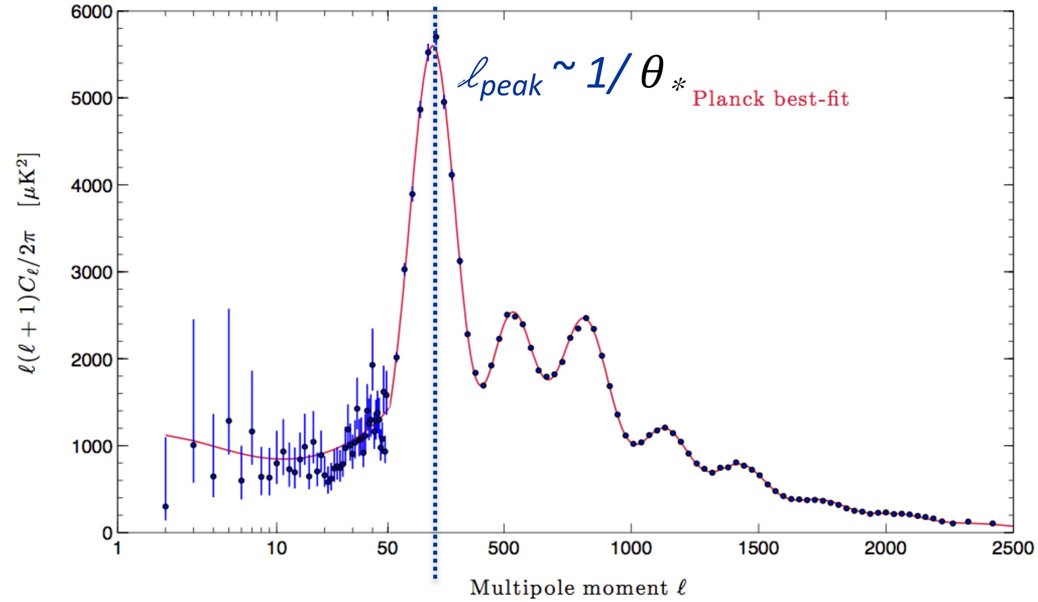



The tension is between measurements that rely on the standard model to determine *the sound horizon at recombination* and those that do not

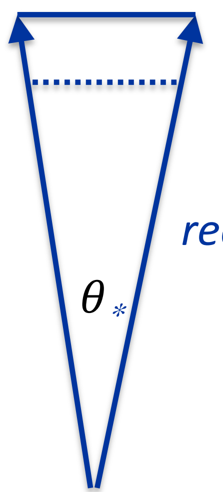
Table from arXiv:2203.06142

# $H_0$ from CMB (and BAO)

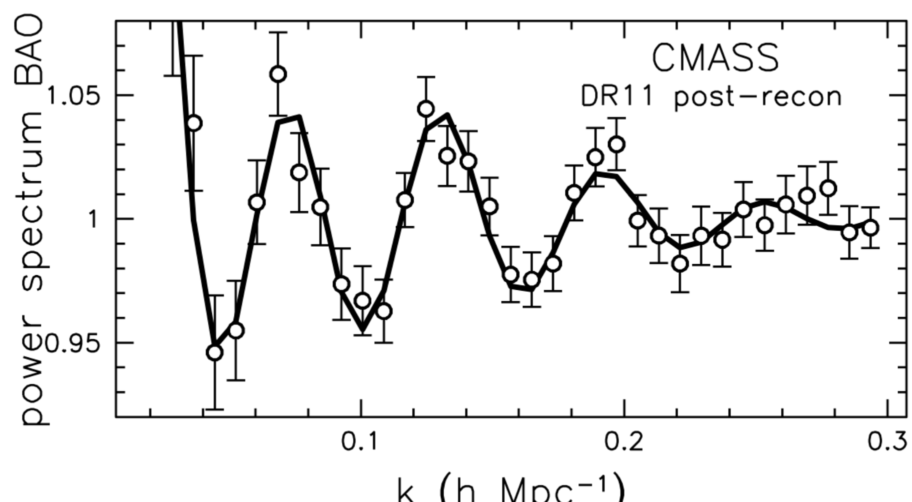



*Sound horizon at recombination, $r_*$*




*Distance to recombination, $d_*$*




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

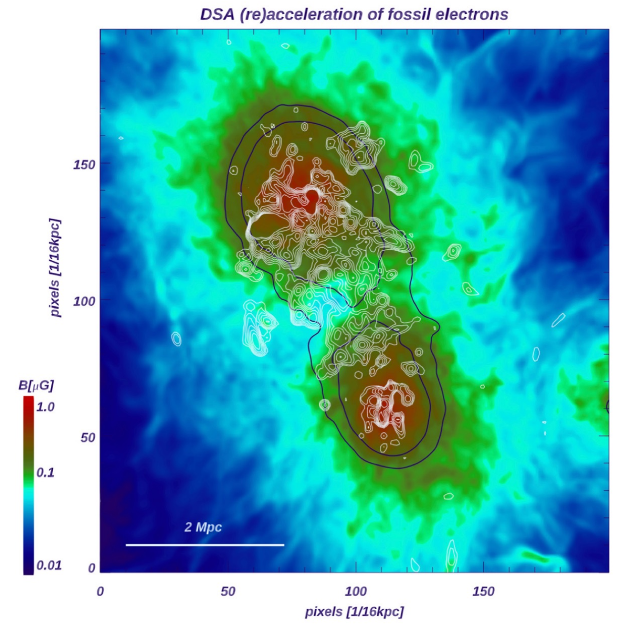
- A smaller sound horizon at decoupling appears to be a necessary ingredient to relieve the Hubble tension

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

  Early dark energy, interacting neutrinos, varying electron mass, modified gravity, etc

- Primordial Magnetic Fields may help relieve the tension

# Cosmic Magnetic Fields




- Micro-Gauss ($\mu$G) fields in galaxies
  - produced astrophysically via dynamo?
  - primordial origin? (need 0.01-0.1 nano-Gauss)

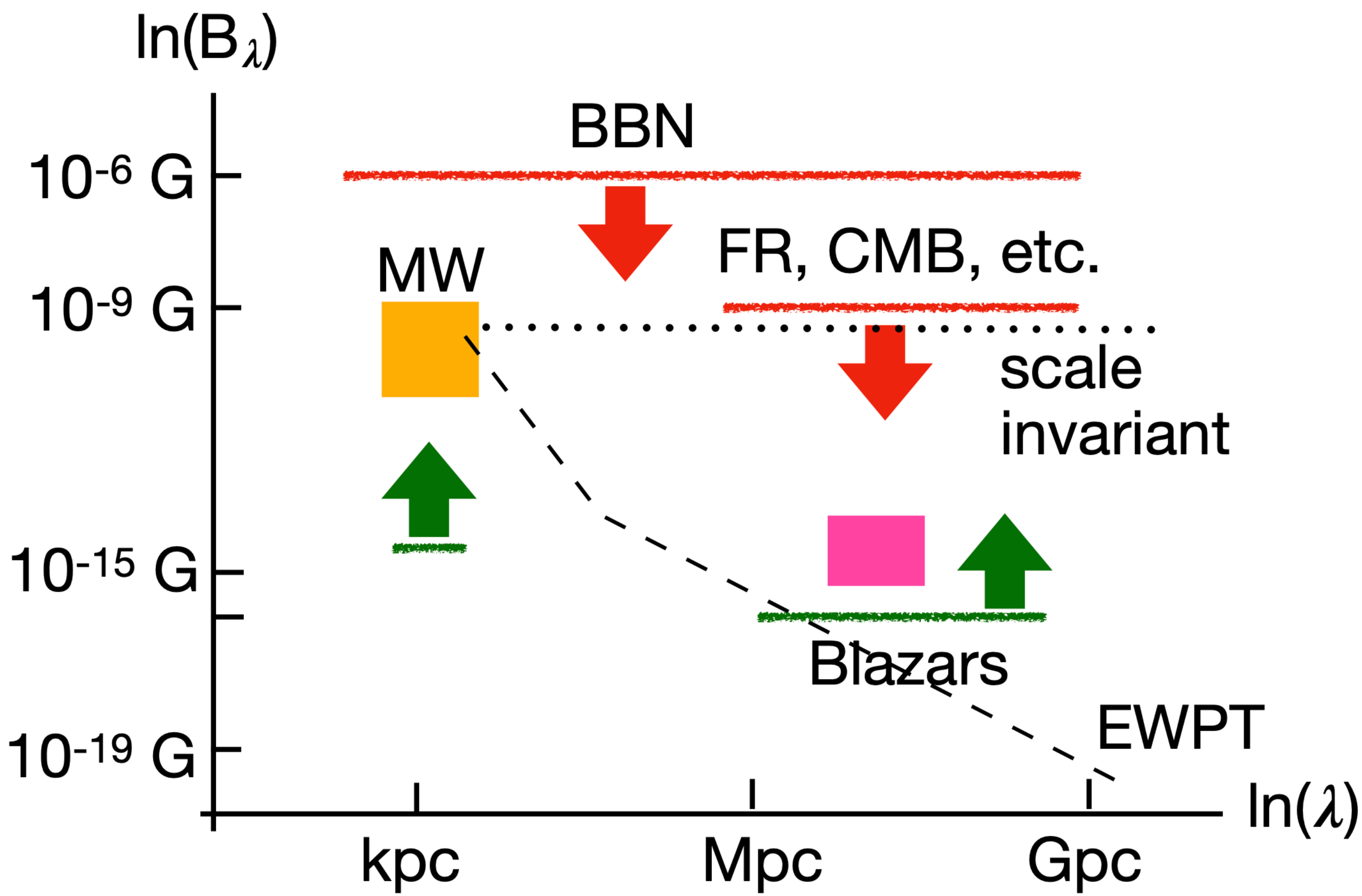
- Magnetic fields in filaments
  - 3-10 Mpc radio emission ridge connecting two merging clusters suggests ~0.1-0.3 μG fields
    *F. Govoni et al, arXiv:1906.07584, Science (2019)*
  - Faraday Rotation Measures from filaments suggest ~0.01-0.1 μG fields
    *E. Carretti et al, arXiv:2210.06220, MNRAS (2022)*

- Magnetic fields in voids?
  - missing GeV $\gamma$-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

# Stochastic Primordial Magnetic Field

- Generated in the early universe, e.g. during the electroweak phase transition (EWPT) 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)

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

Drag force set by the photon mean free path $l_\gamma$

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

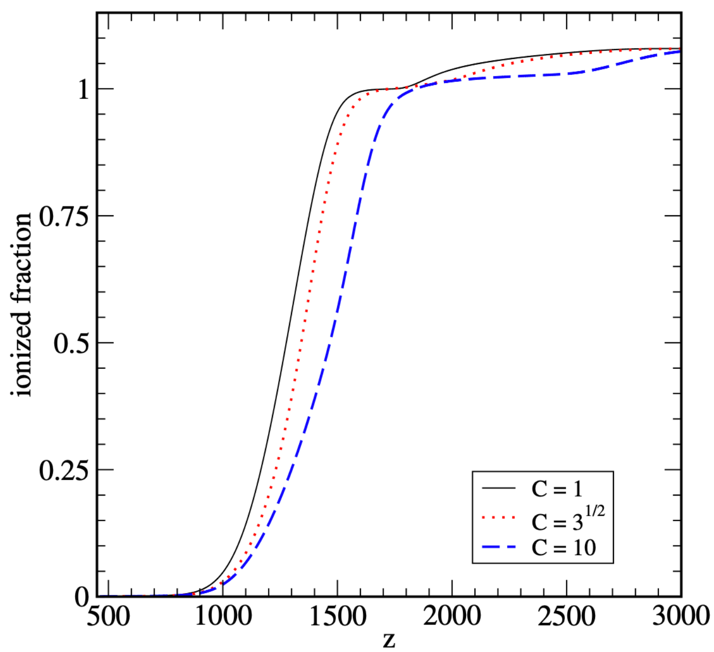
Plasma develops density fluctuations on ~1 kpc scales
(below the photon mean free path)

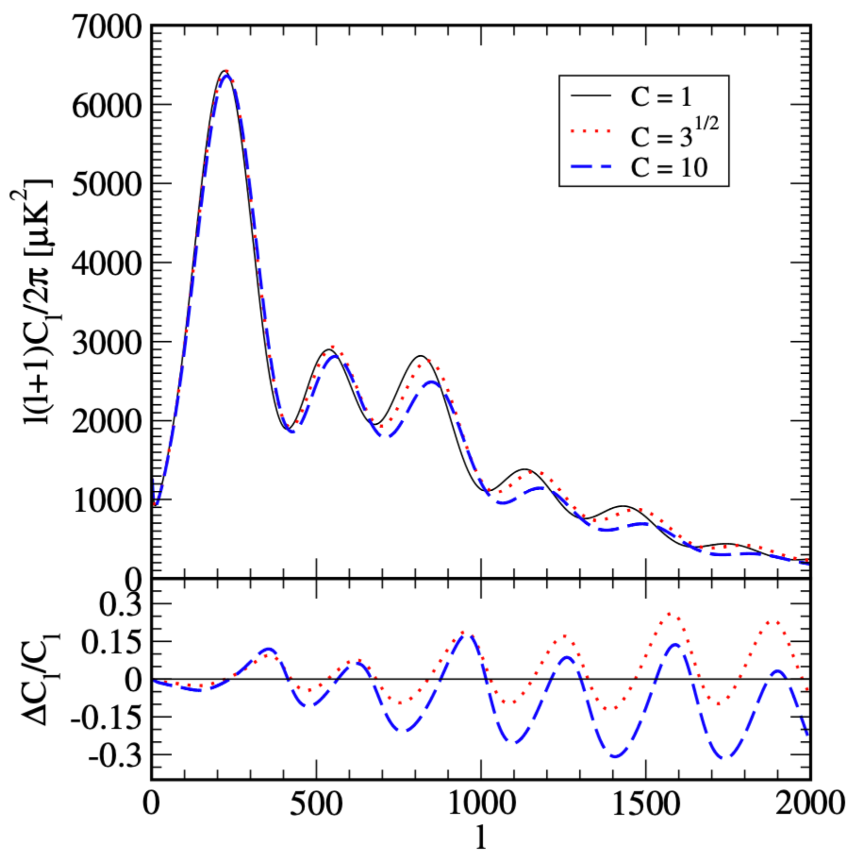
Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

# 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

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

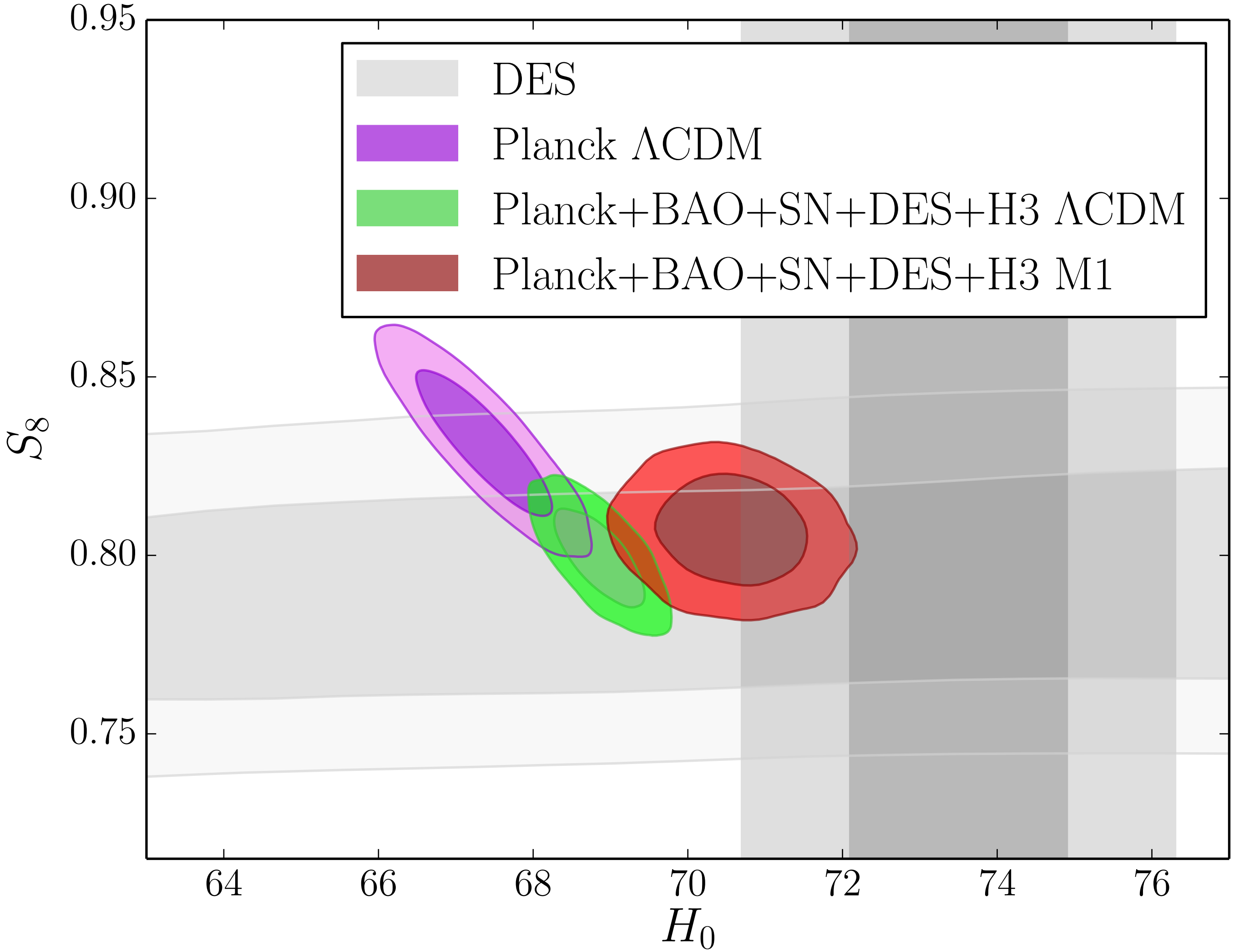
Datasets:

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

* Kept us busy during COVID

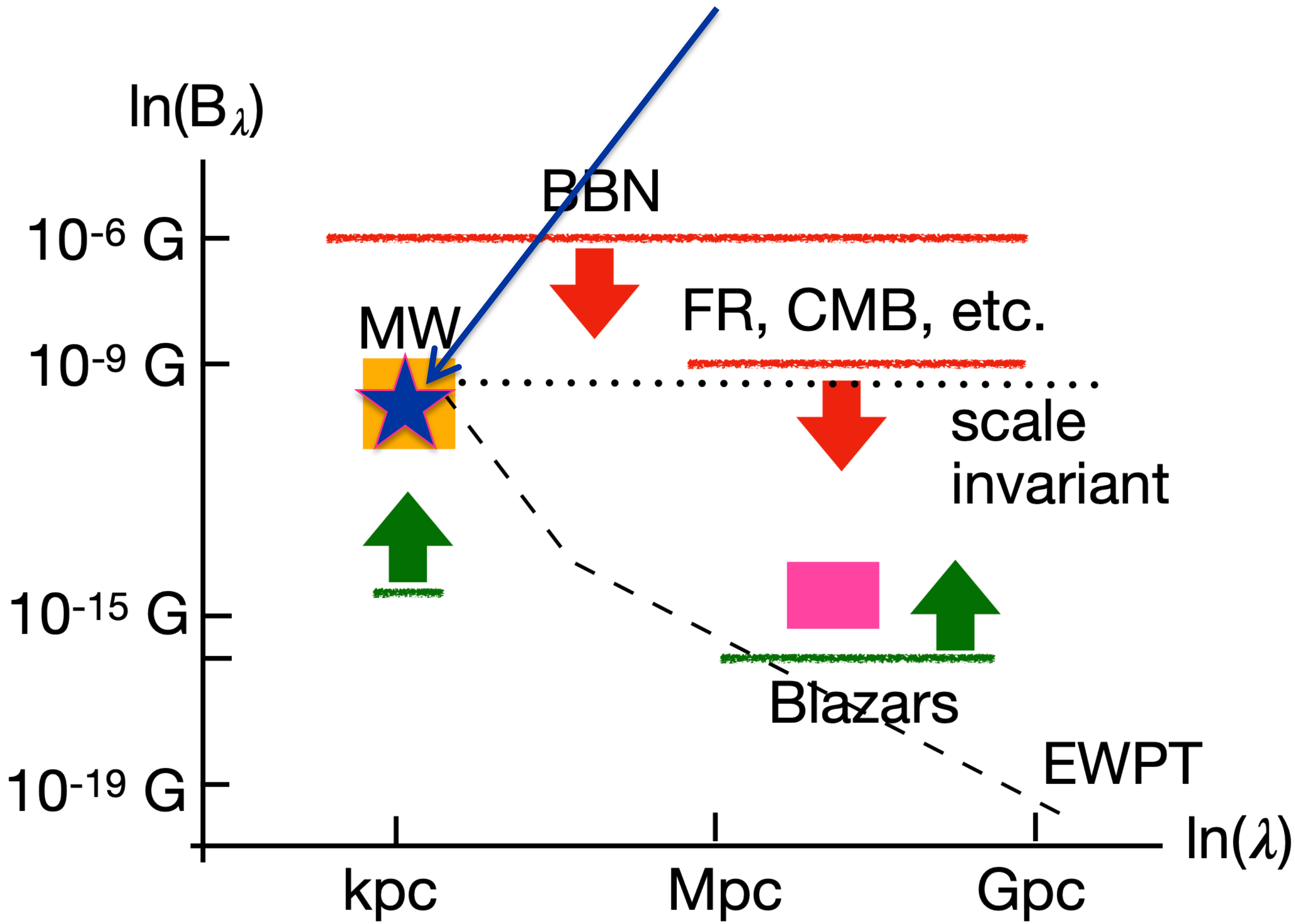
K. Jedamzik and L. Pogosian, arXiv:2004.09487, PRL

# Fitting the M1 model to all data




K. Jedamzik and L. Pogosian, arXiv:2004.09487, Phys Rev Lett

# Clumping required to relieve the $H_0$ tension




Plot from T. Vachaspati, arXiv:2010.10525

# 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

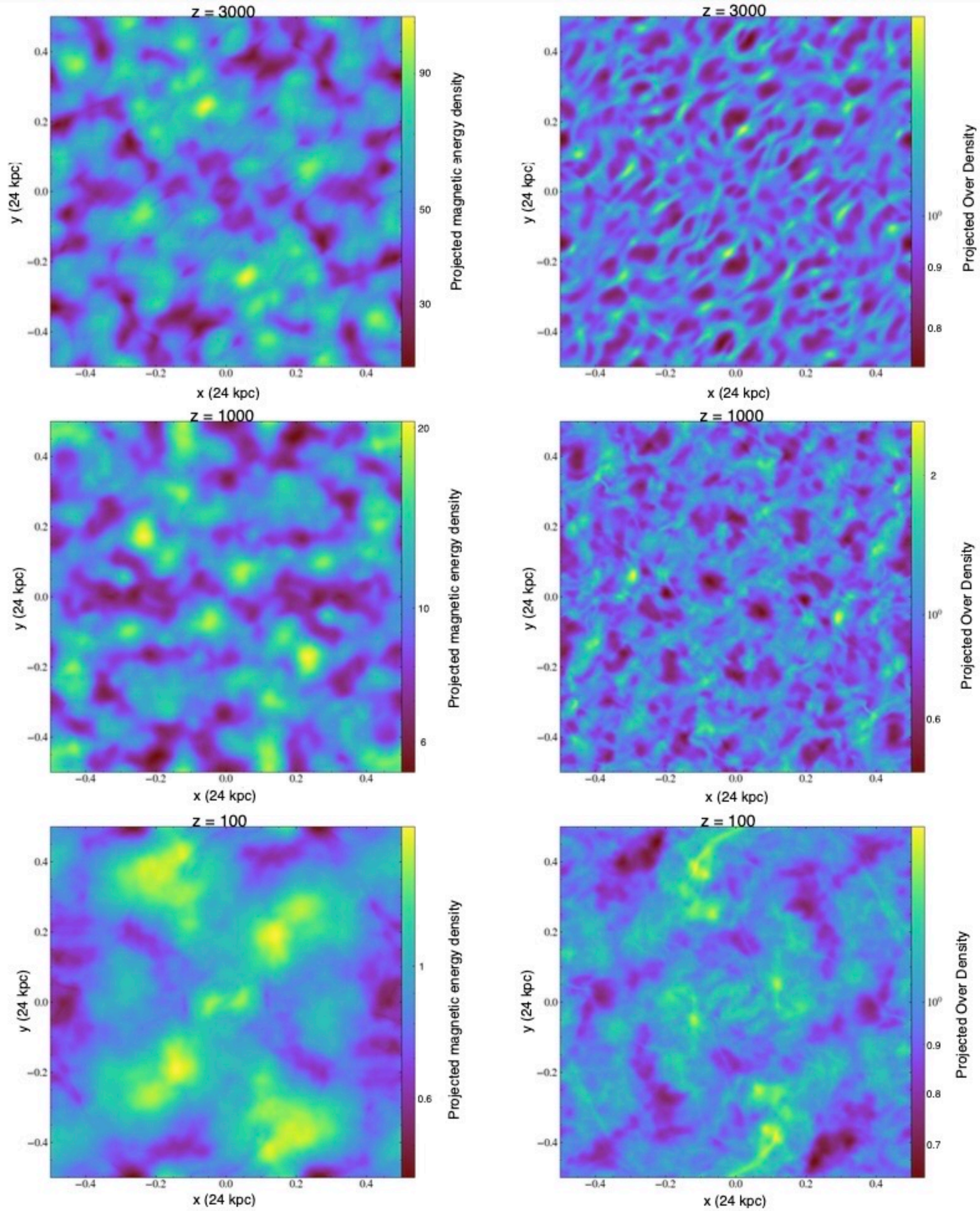
Four PMF scenarios to be considered:

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

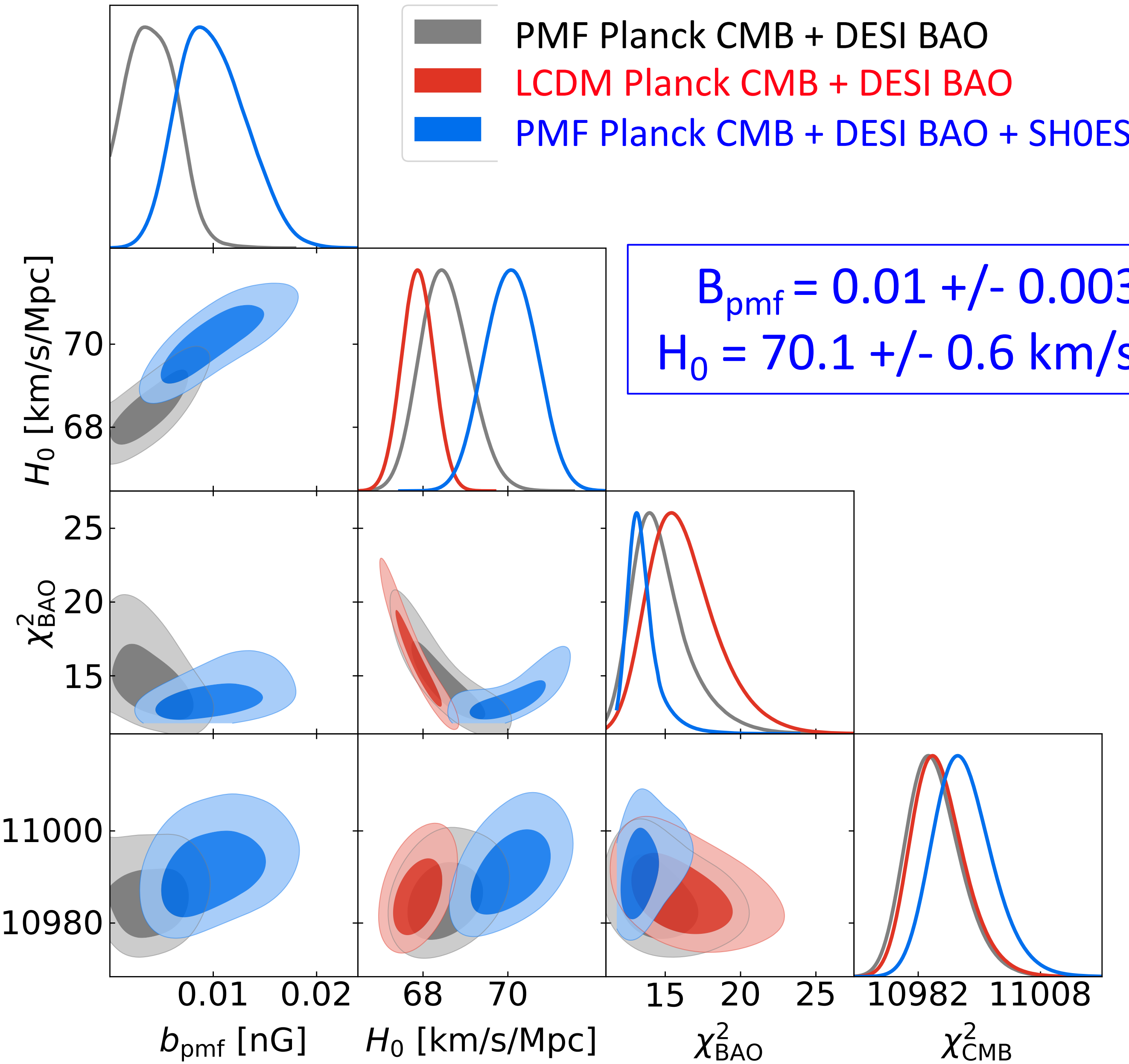
# Magnetically induced baryon clumping

Non-helical PMF, blue spectrum,
0.5 nano-Gauss (comoving) strength,
$(24\ \text{kpc})^3$ box




K. Jedamzik and T. Abel, arXiv:2312.11448

# Preliminary results after MHD: $B_{pmf}$ and $H_0$




$B_{pmf}$ = 0.01 +/- 0.003 nG

$H_0$ = 70.1 +/- 0.6 km/s/Mpc

# 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 a highly falsifiable proposal (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)*

$\mu$- 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)*

$\gamma$-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