Title: Cosmic Recombination with Primordial Magnetic Fields and the Hubble Tension.

Speakers: Levon Pogosian

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

Date: March 25, 2025 - 11:00 AM

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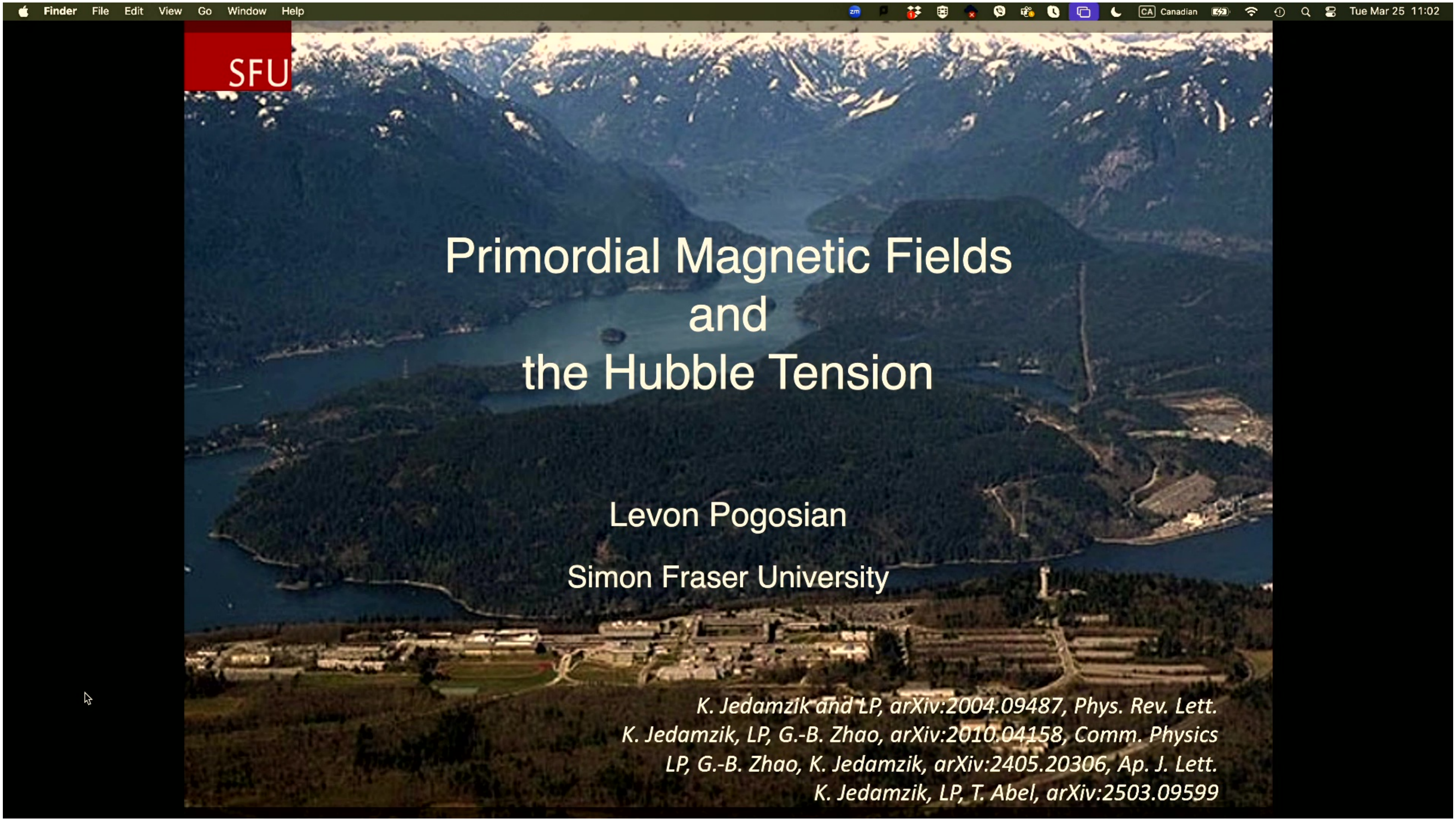
Abstract:

Primordial Magnetic Fields (PMFs), long studied as potential relics of the early Universe, can accelerate recombination and have been proposed as a possible solution to the Hubble tension. In this seminar, I will present the latest observational evidence supporting this idea, based on comprehensive magnetohydrodynamic (MHD) simulations of recombination in the presence of PMFs. Current Cosmic Microwave Background (CMB) and Baryon Acoustic Oscillation (BAO) data exhibit a mild preference for PMFs while predicting a higher Hubble constant. Notably, the inferred field strengths align with those required to explain galaxy cluster magnetic fields purely from primordial origins, eliminating the need for additional dynamo amplification or stellar contributions. Future high-resolution CMB temperature and polarization measurements will be crucial in confirming or further constraining the role of PMFs during recombination.



Primordial Magnetic Fields
and
the Hubble Tension

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

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

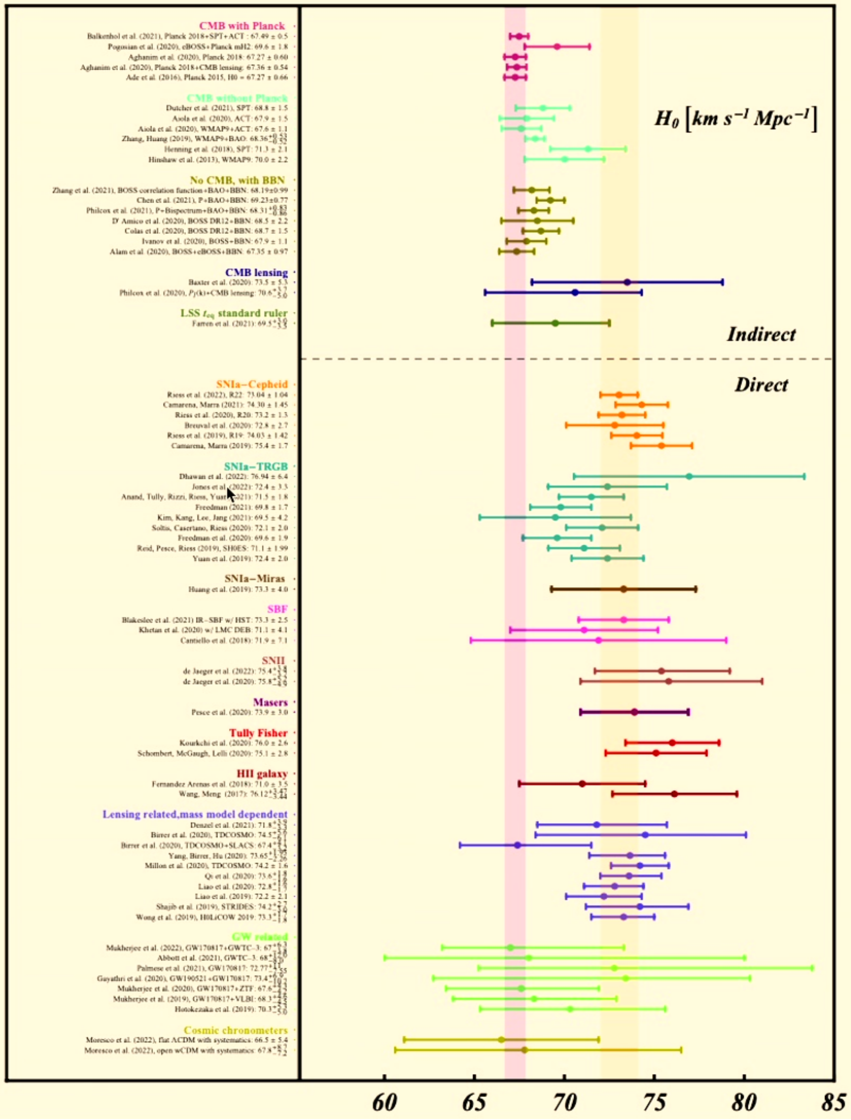
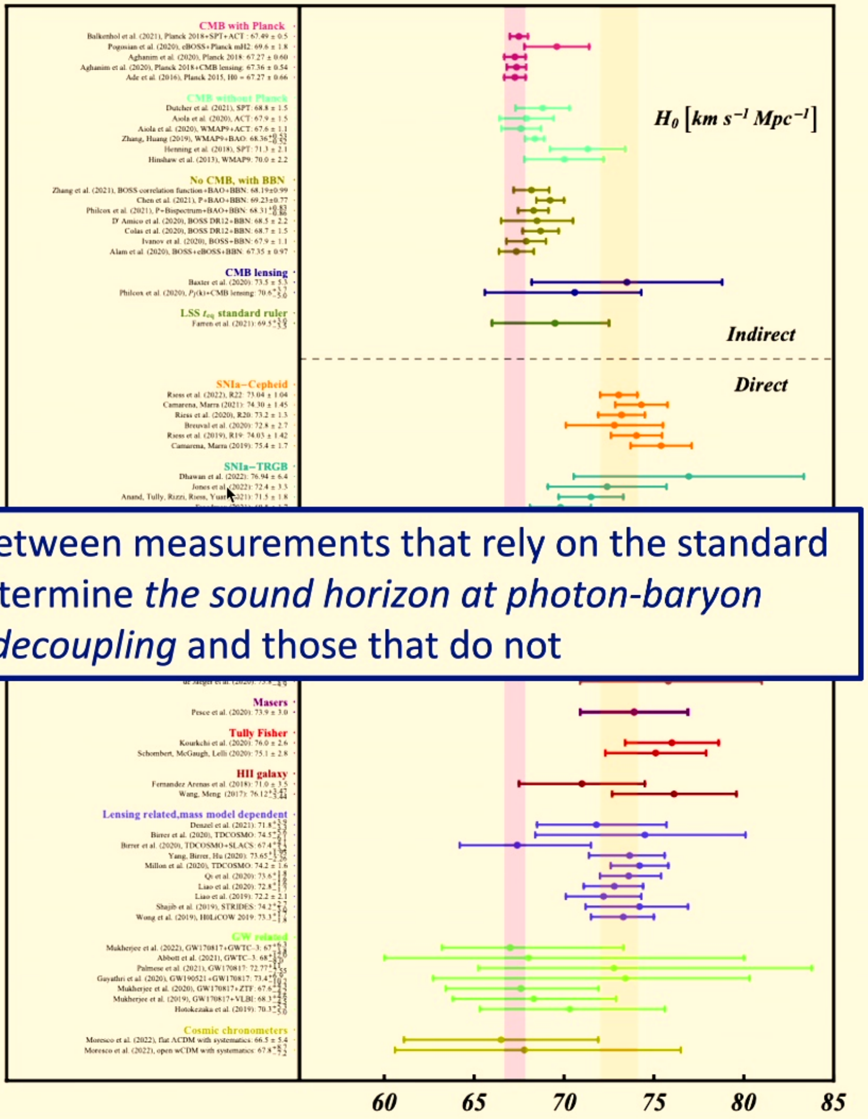


Table from arXiv:2203.06142

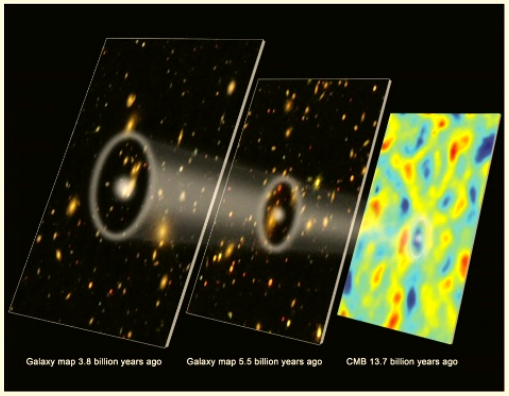
The Hubble Tension



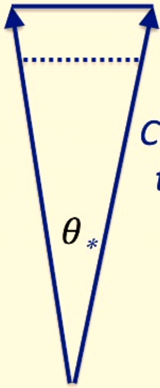
The tension is between measurements that rely on the standard model to determine *the sound horizon at photon-baryon decoupling* and those that do not

Table from arXiv:2203.06142

H_0 from CMB (and BAO)

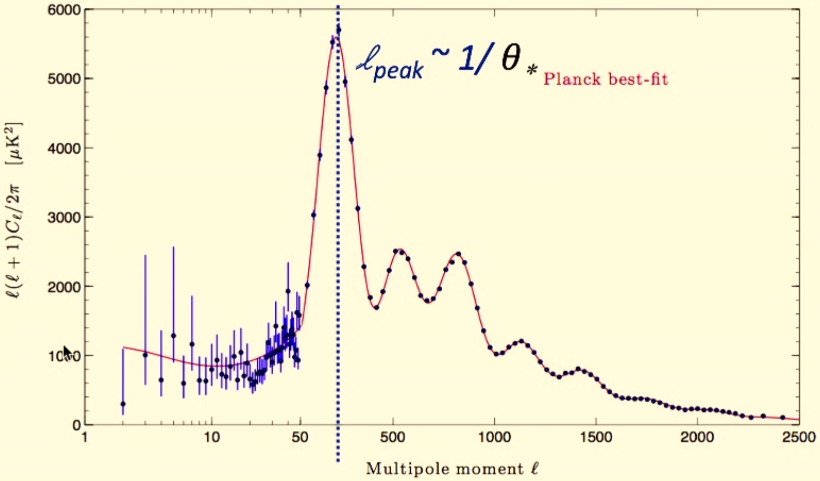


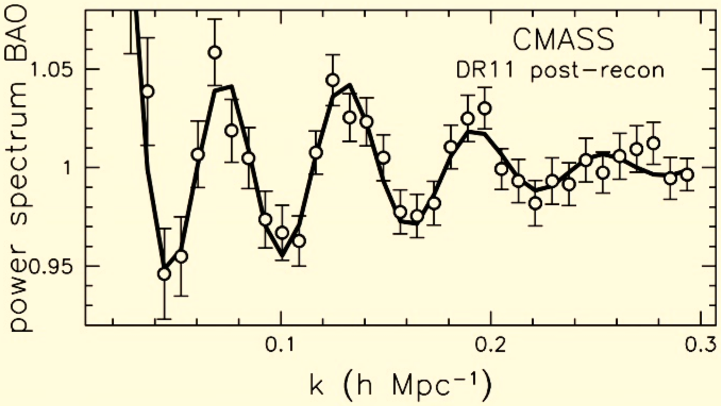
Comoving sound horizon at decoupling, r_*



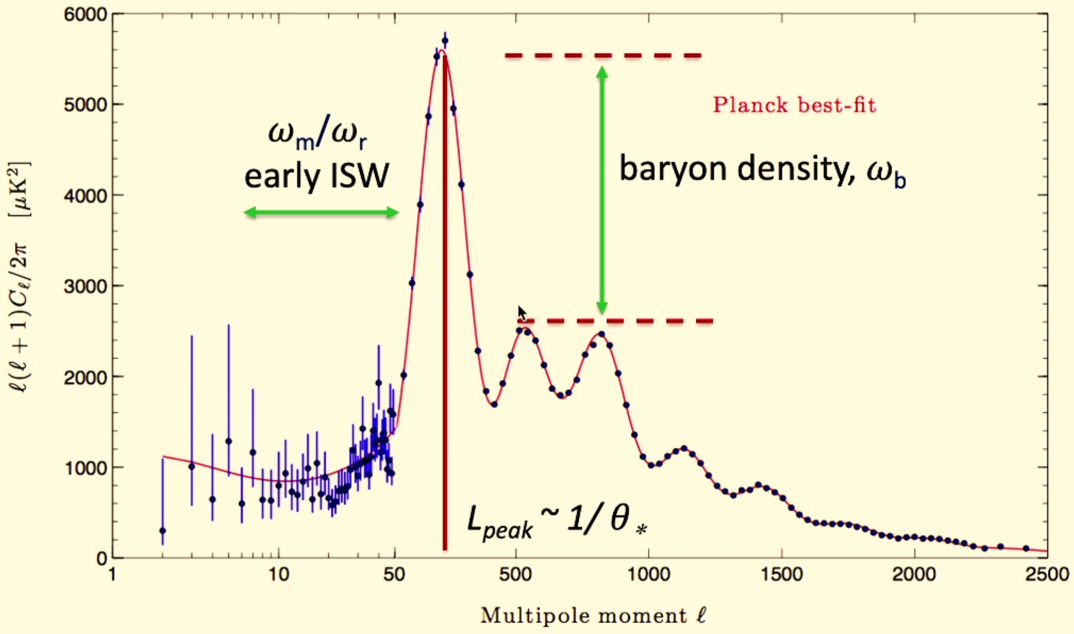
Comoving distance to decoupling, d_*

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





H_0 from CMB (in flat LCDM)

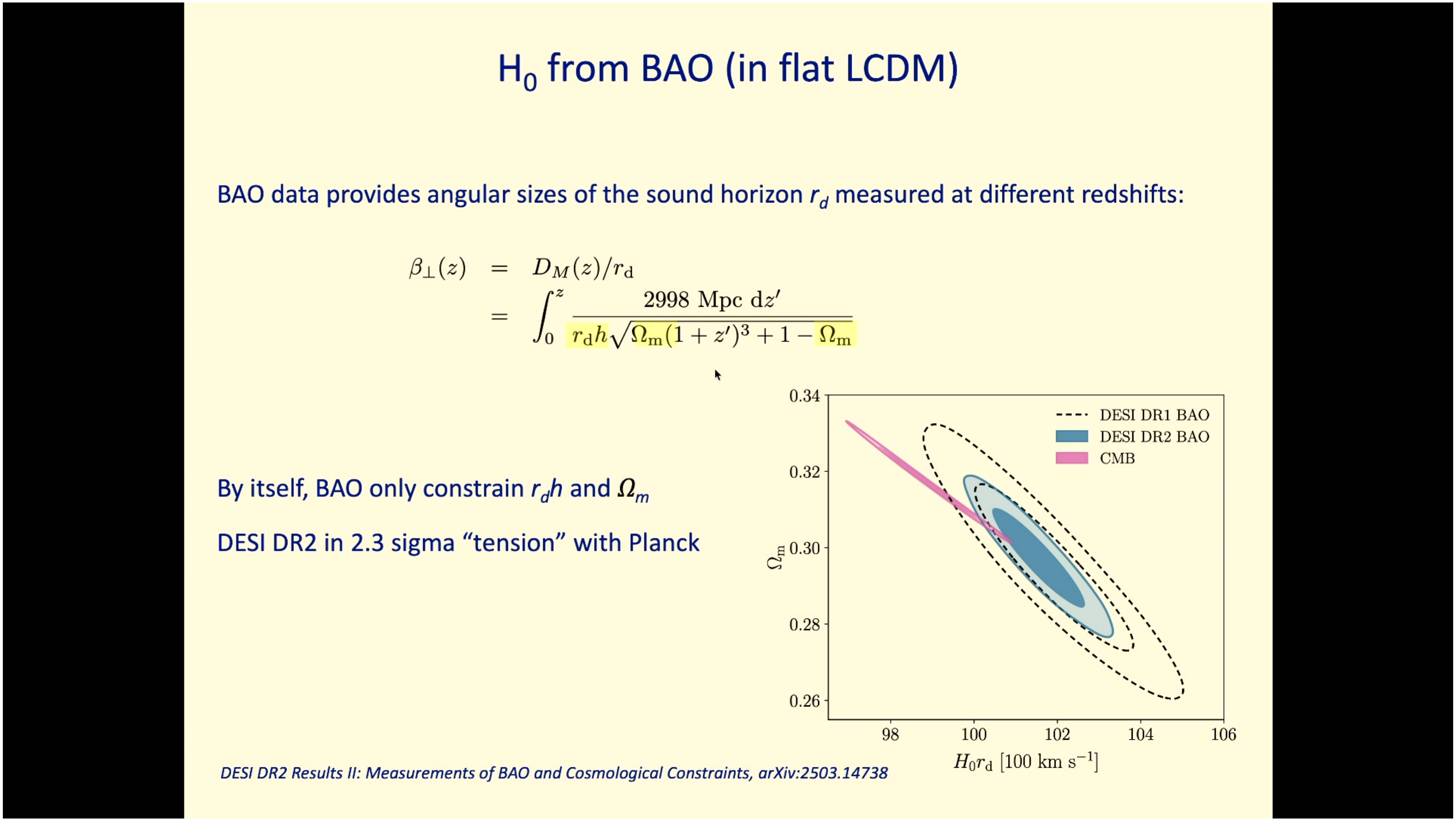


$$r_* = \int_{z_*}^{\infty} \frac{c_S(z)\,dz}{H(z)}$$

4 key parameters: ω_r, ω_m, ω_b, h

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

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



H_0 from BAO (in flat LCDM)

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

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

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

DESI DR2 in 2.3 sigma “tension” with Planck

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

H_0 from BAO

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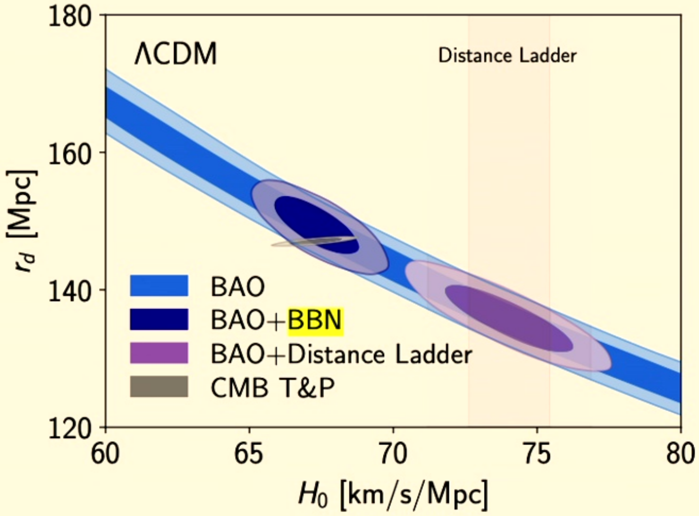
By itself, BAO data constrains $r_d h$ and Ω_m

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.
- use external information on $\omega_m = \Omega_m h^2$ to break the r_d-h degeneracy, e.g. weak lensing



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

DESI Year 1 BAO vs Planck CMB

Use the Planck Gaussian prior $\omega_m = \Omega_m h^2 = 0.142 \pm 0.001$ with BAO to test consistency of BAO vs CMB within flat LCDM, in <u>a recombination-independent way</u>:

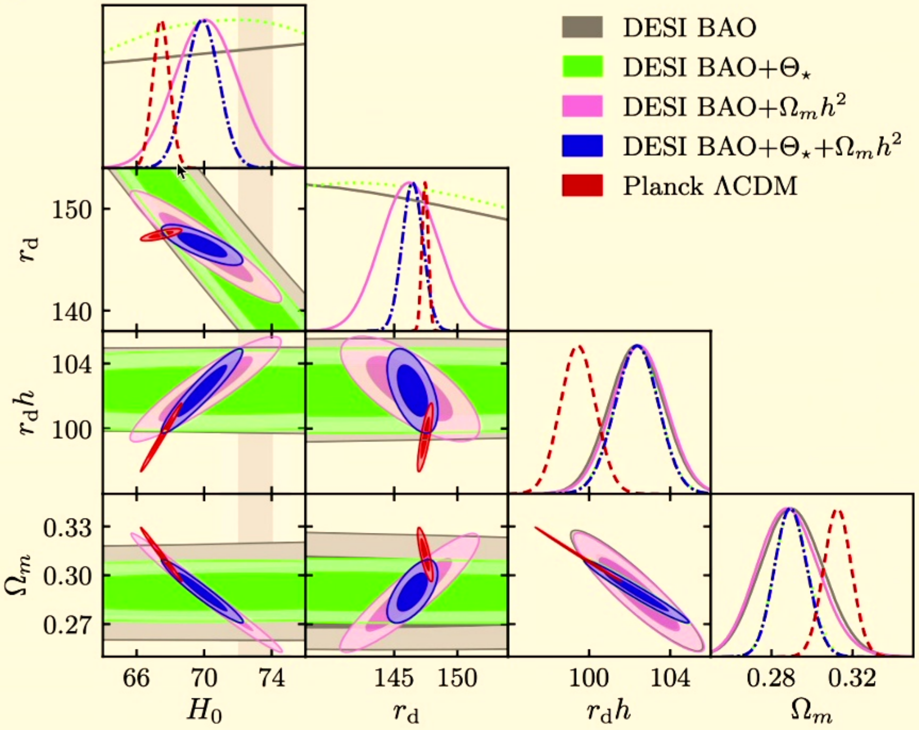
- the sound horizon r_d is a free parameter

<u>DESI Y1 + CMB Theta + ω_m</u>

H_0 = 69.48 ± 0.94 km/s/Mpc

<u>Planck LCDM</u>

H_0 = 67.44 ± 0.47 km/s/Mpc



LP, K. Jedamzik, G.-B. Zhao, Astrophys.J.Lett. 973 (2024) 1, L13 arXiv: 2405.20306

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DESI Y1 + CMB Theta + ω_m

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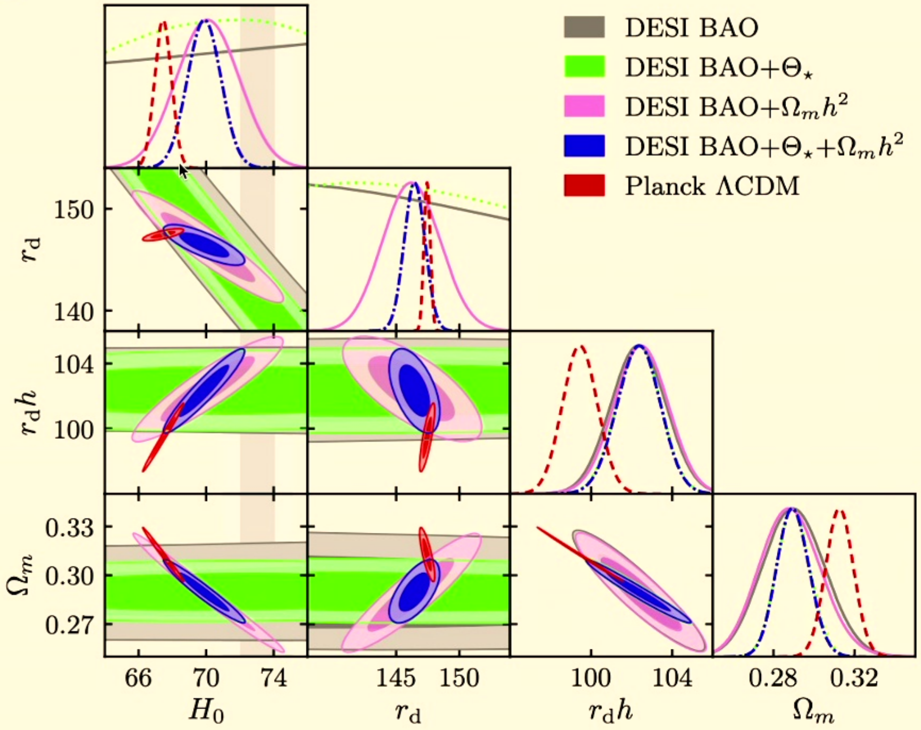


LP, K. Jedamzik, G.-B. Zhao, Astrophys.J.Lett. 973 (2024) 1, L13 arXiv: 2405.20306

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

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

CMB and BAO provide measurements of this at multiple redshifts z

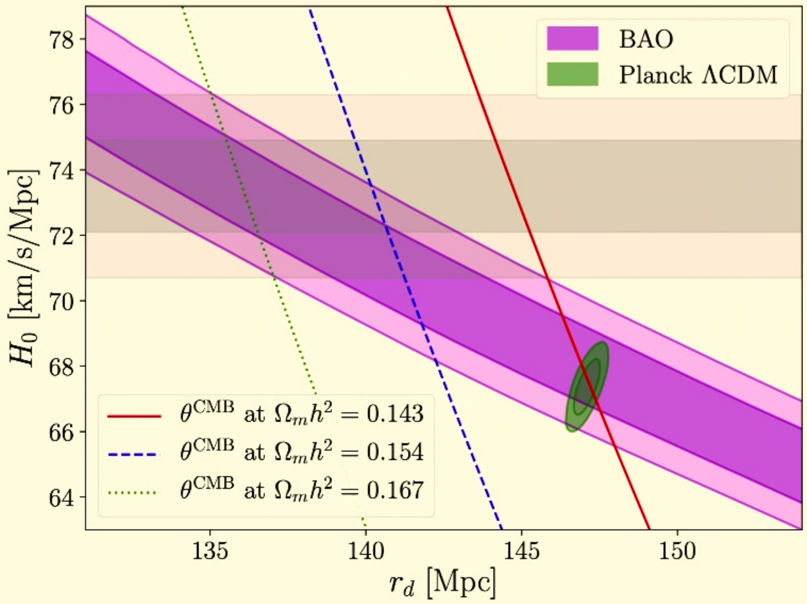
Treat r_d as free parameter

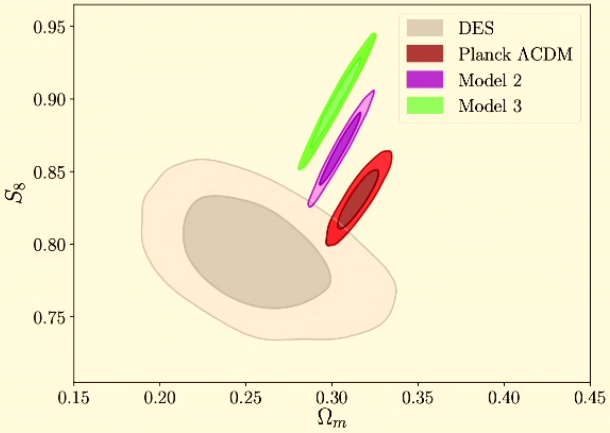
For a given $\omega_m = \Omega_m h^2$, each measured $\theta(z)$ defines a line in the $r_d - h$ plane

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

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

- To make the CMB line pass through the BAO/SH0ES overlap region one needs to increase ω_m
- A larger ω_m increases S_8, worsening the tension with 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

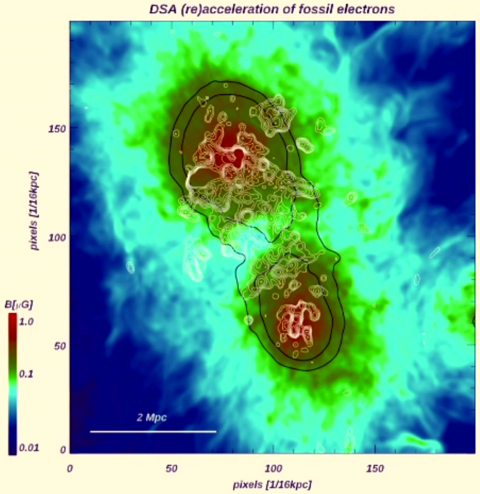
What kind of new physics can help reduce the sound horizon?

- Many models proposed with the aim of solving the Hubble tension (early dark energy, modified gravity, strongly interacting neutrinos,…)
- Primordial Magnetic Fields

Cosmic Magnetic Fields

○ Micro-Gauss (μG) fields in galaxies
  - produced astrophysically via dynamo?
  - primordial origin?

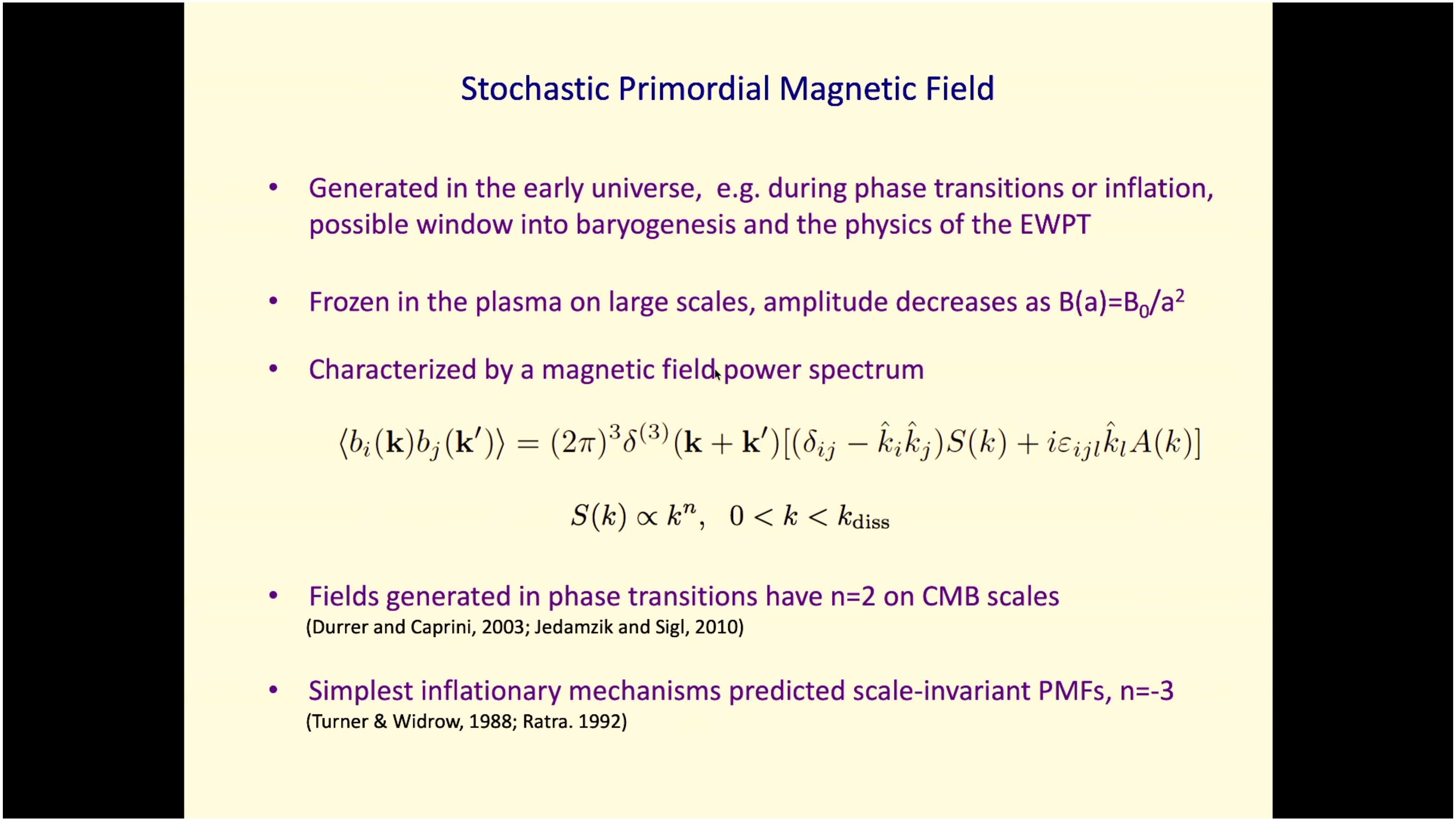
○ Magnetic fields in filaments
  - 3-10 Mpc radio emission ridge connecting two merging clusters suggests ~0.1-0.3 μG fields
    F. Govoni et al, arXiv:1906.07584, Science (2019)
  - Faraday Rotation Measures from filaments suggest ~0.01-0.1 μG fields
    E. Carretti et al, arXiv:2210.06220, MNRAS (2022)



○ 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

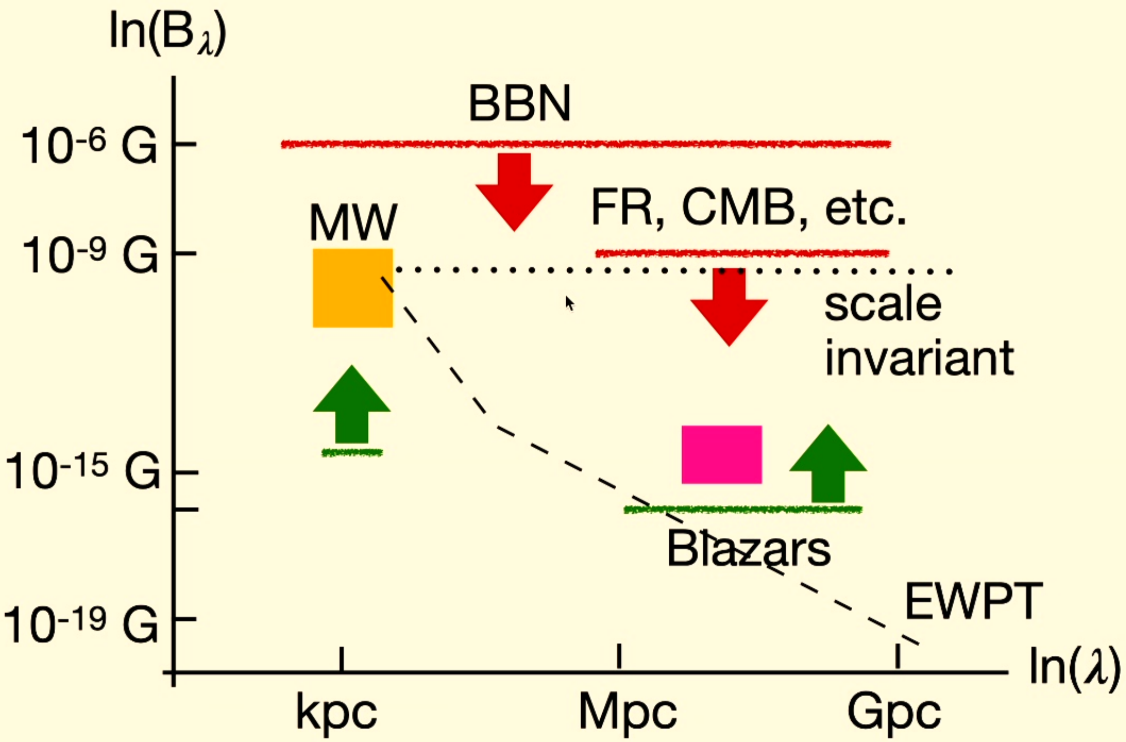
- Generated in the early universe, e.g. during phase transitions or inflation, possible window into baryogenesis and the physics of the EWPT
- Frozen in the plasma on large scales, amplitude decreases as $B(a)=B_0/a^2$
- Characterized by a magnetic field power spectrum

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

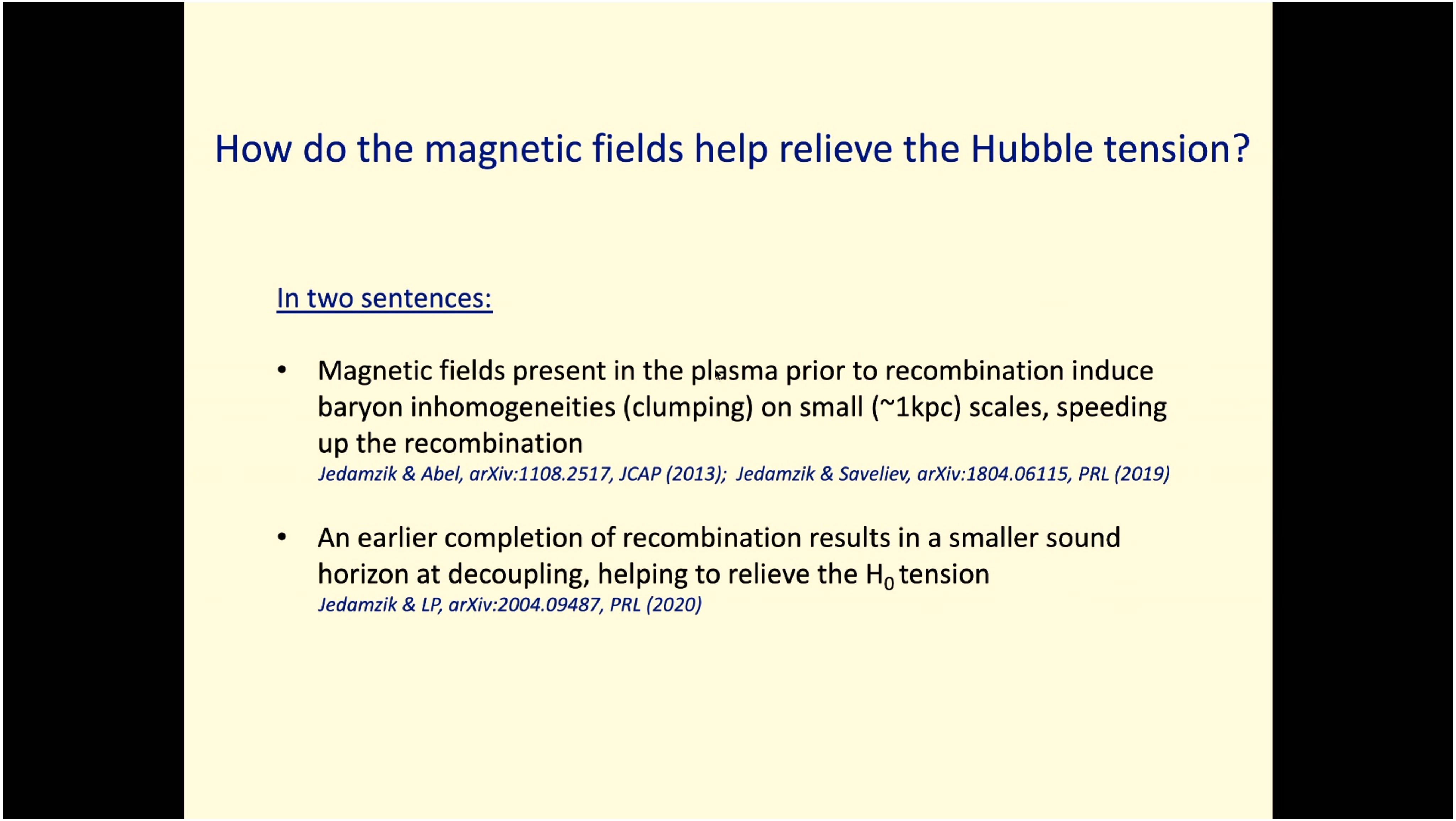
$$S(k) \propto k^n, \quad 0 < k < k_{\rm diss}$$

- 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



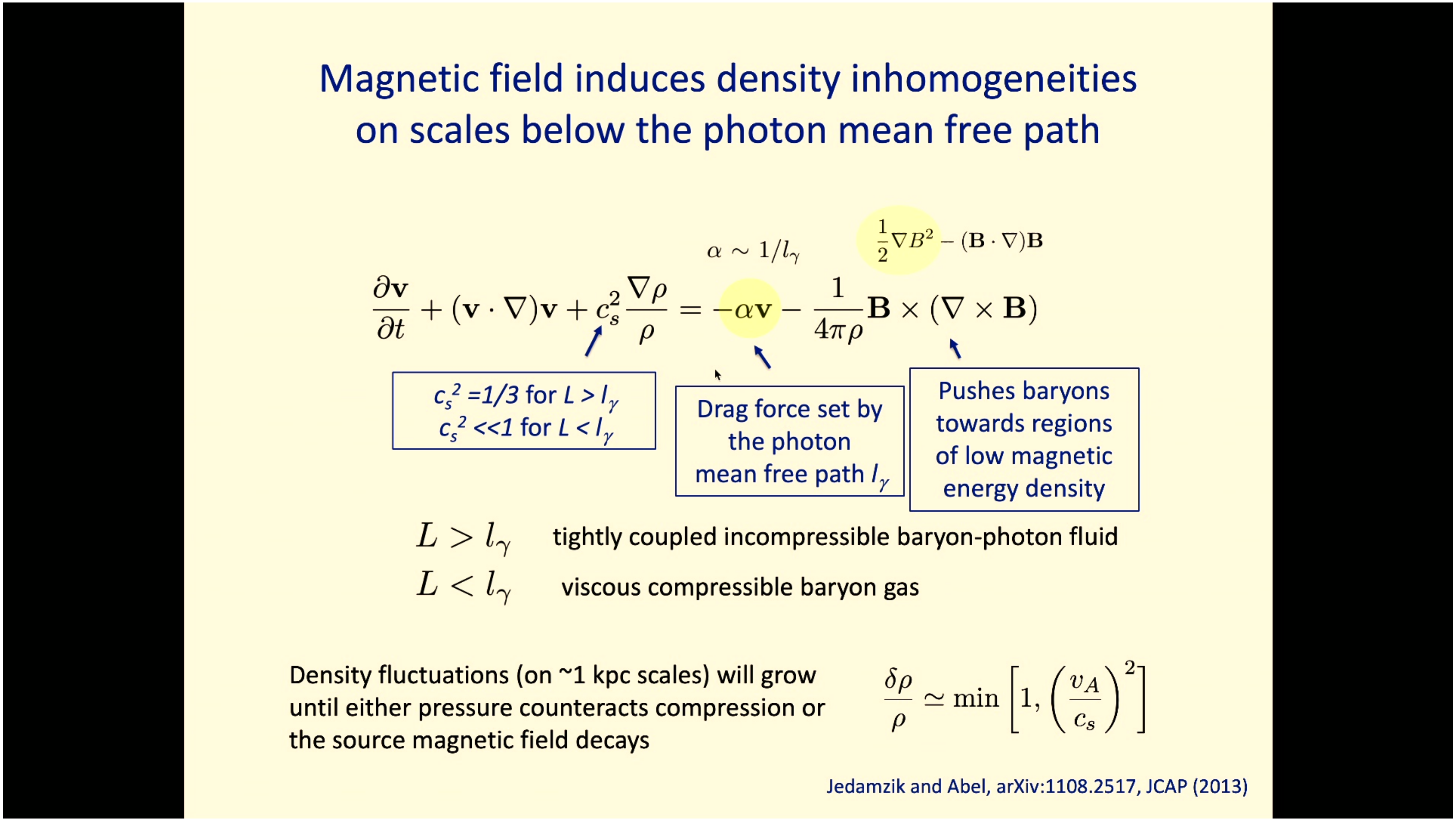
Plot from T. Vachaspati, arXiv:2010.10525



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)



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_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

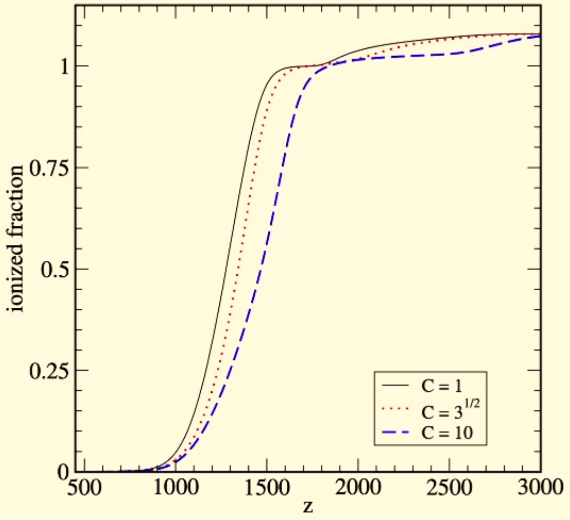
$$\frac{\delta\rho}{\rho} \simeq \min\left[1, \left(\frac{v_A}{c_s}\right)^2\right]$$

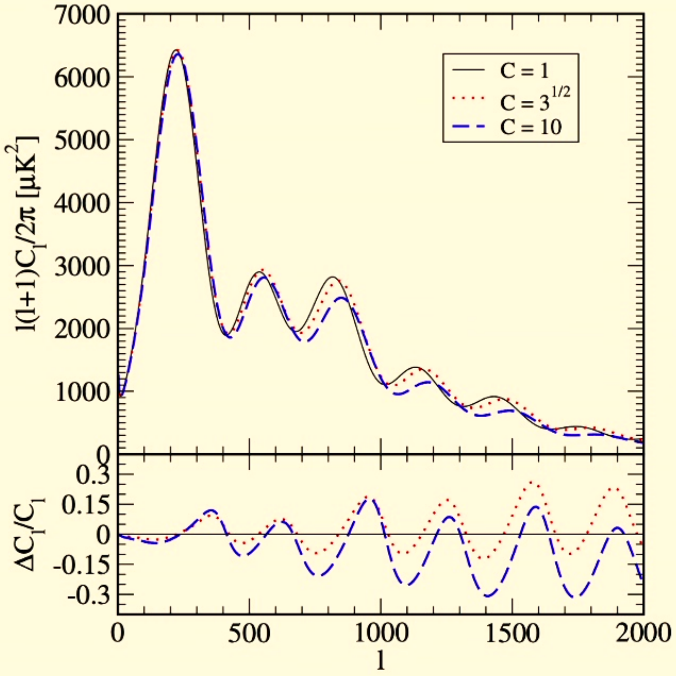
Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

Inhomogeneities enhance the recombination rate

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

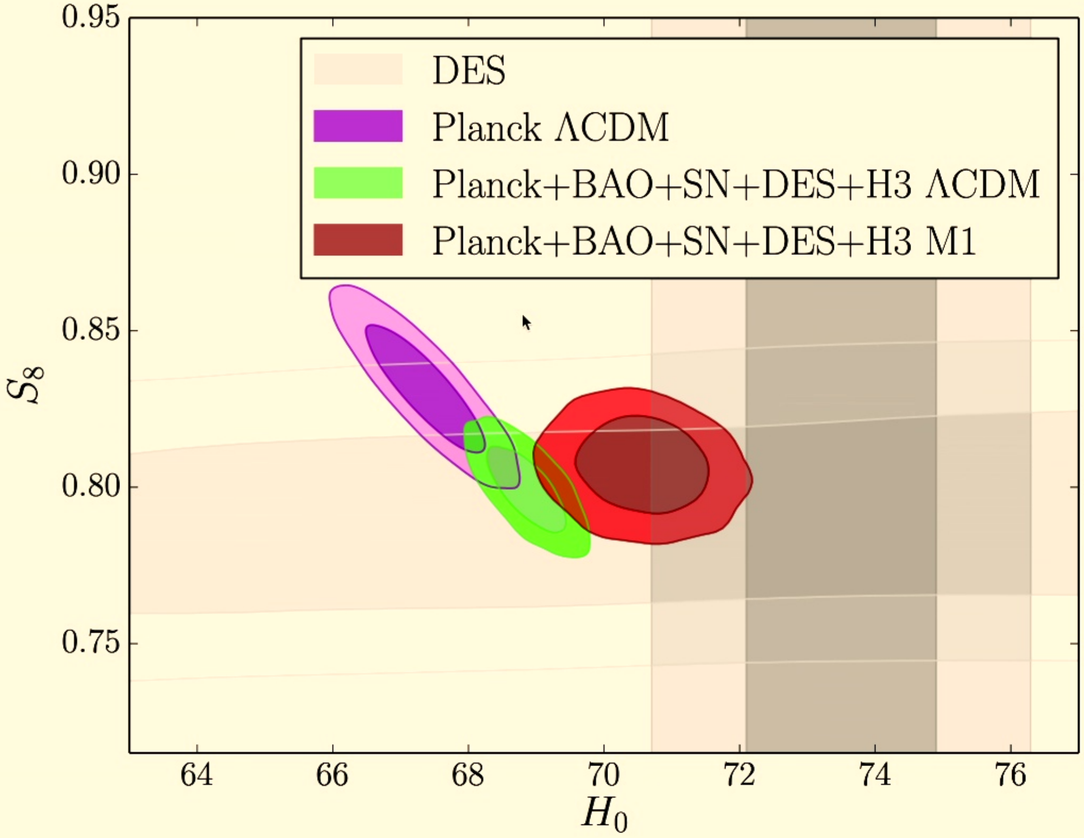
$$\langle n_e^2\rangle \ > \ \langle n_e\rangle^2$$



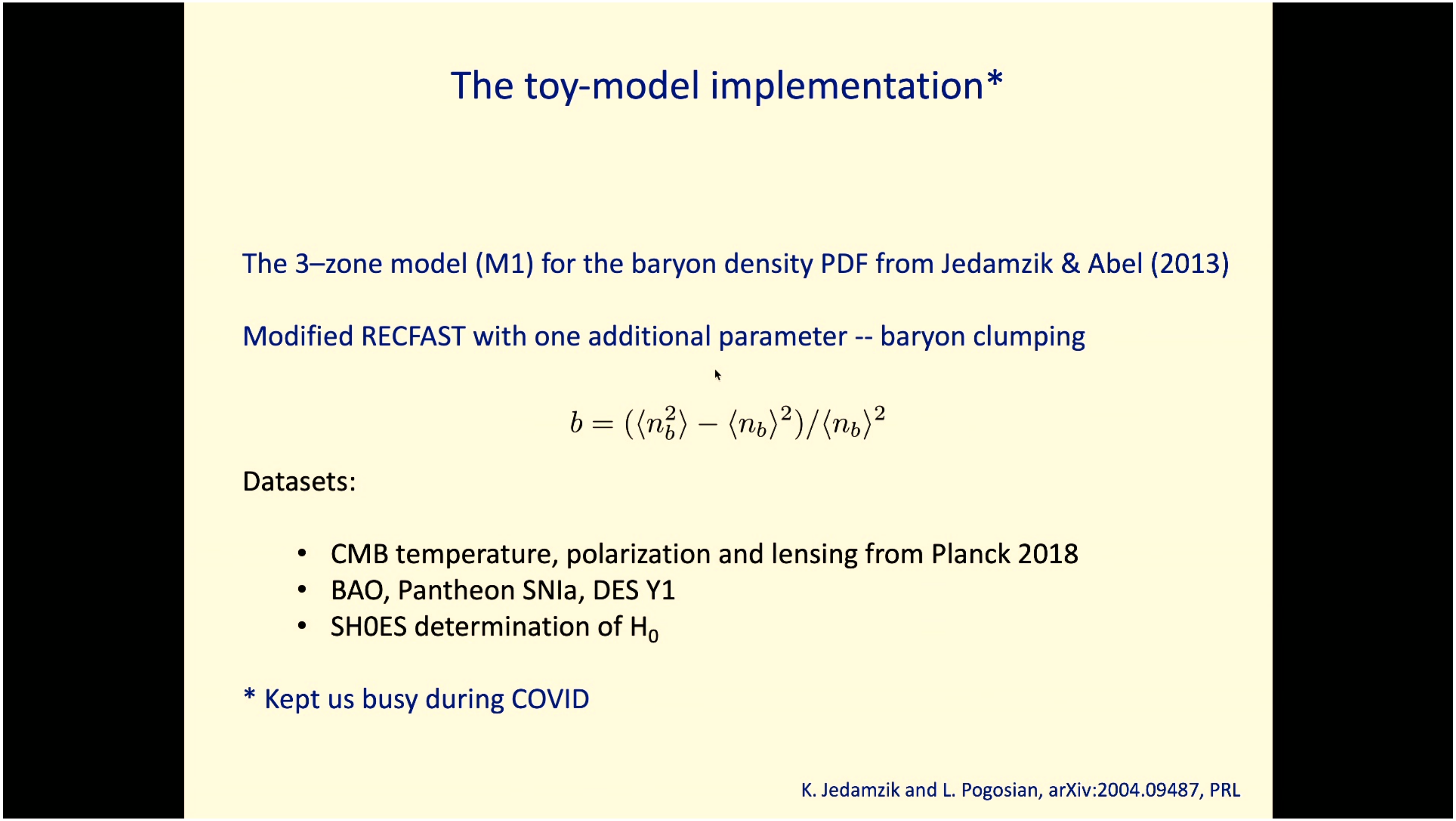


Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

Fitting the M1 model to all data



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



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

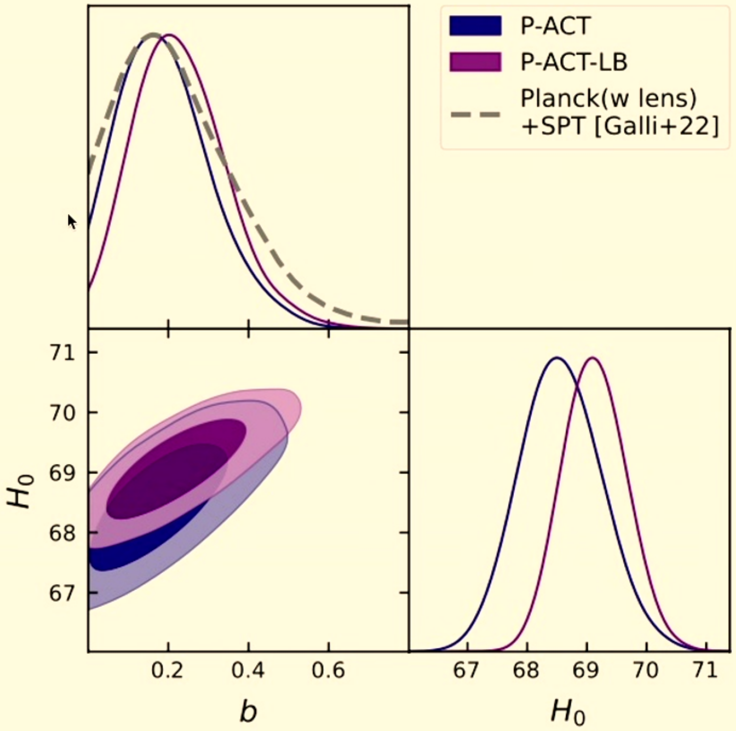
ACT DR6 (+ Planck + DESI Y1) constraints on the M1 model

Planck* + ACT DR6 + DESI Y1:

$H_0 = 69.1 \pm 0.5$ km/s/Mpc

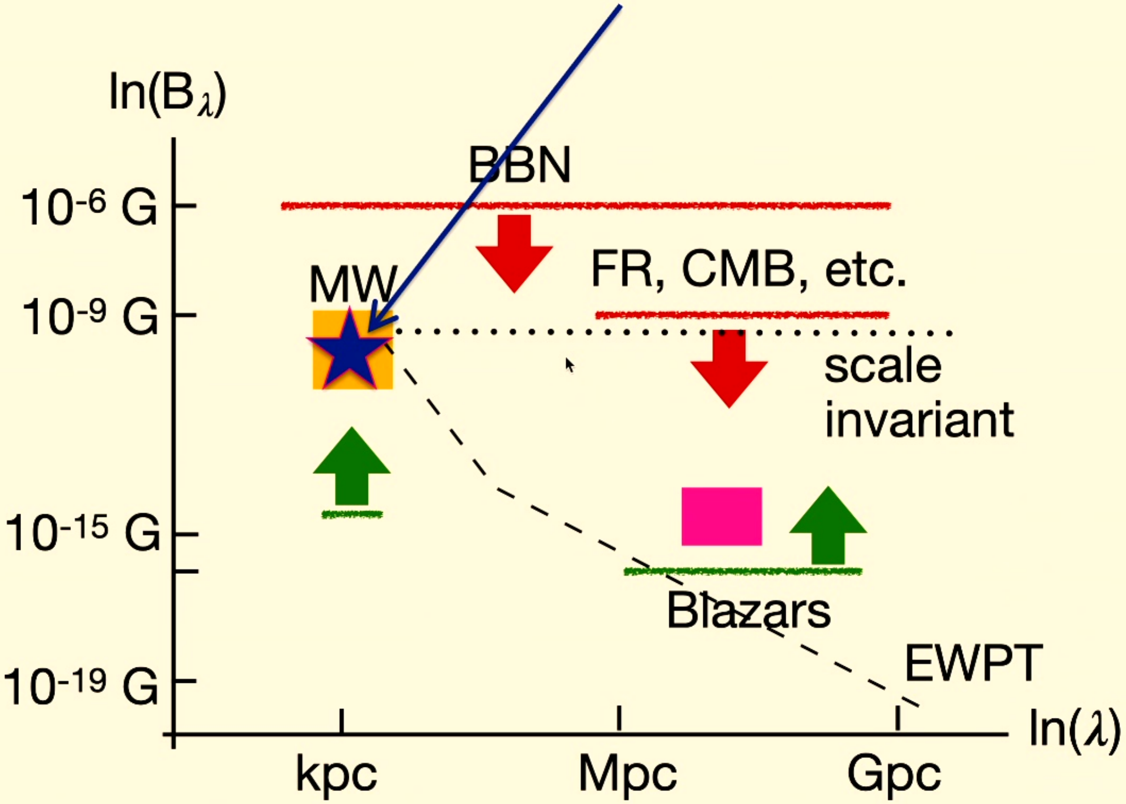
(no "SH0ES prior")

*truncated Planck data



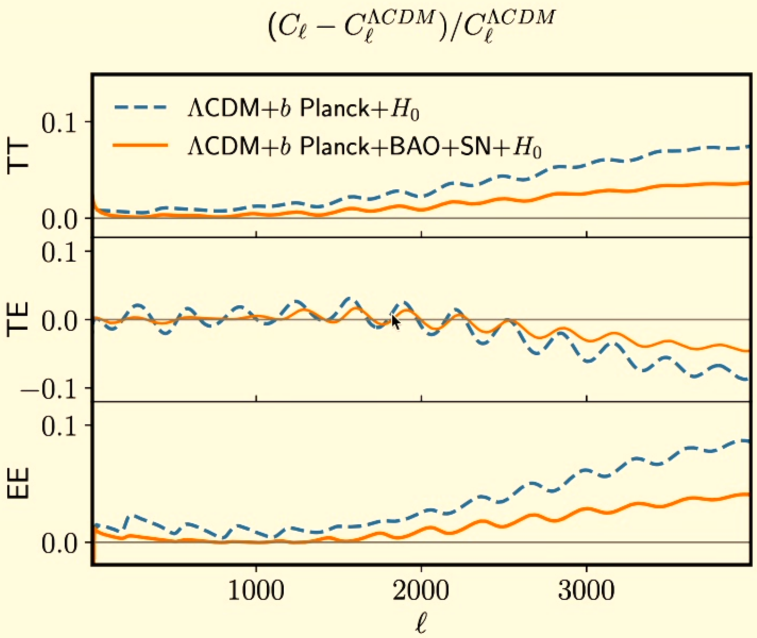
The Atacama Cosmology Telescope: DR6 Constraints on Extended Cosmological Models, arXiv:2503.14454

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

Planck* + ACT DR6 + DESI Y1:

$H_0 = 69.1 \pm 0.5$ km/s/Mpc

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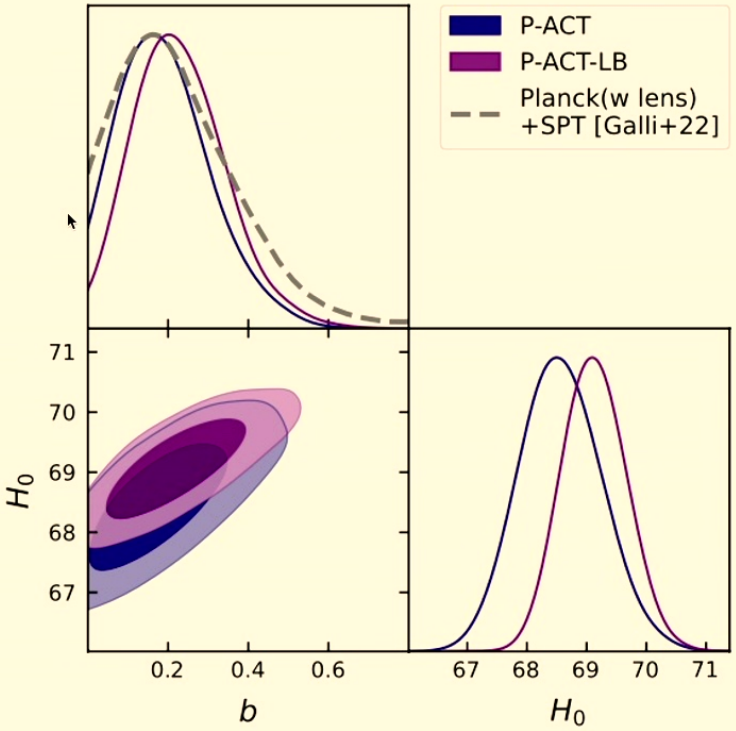
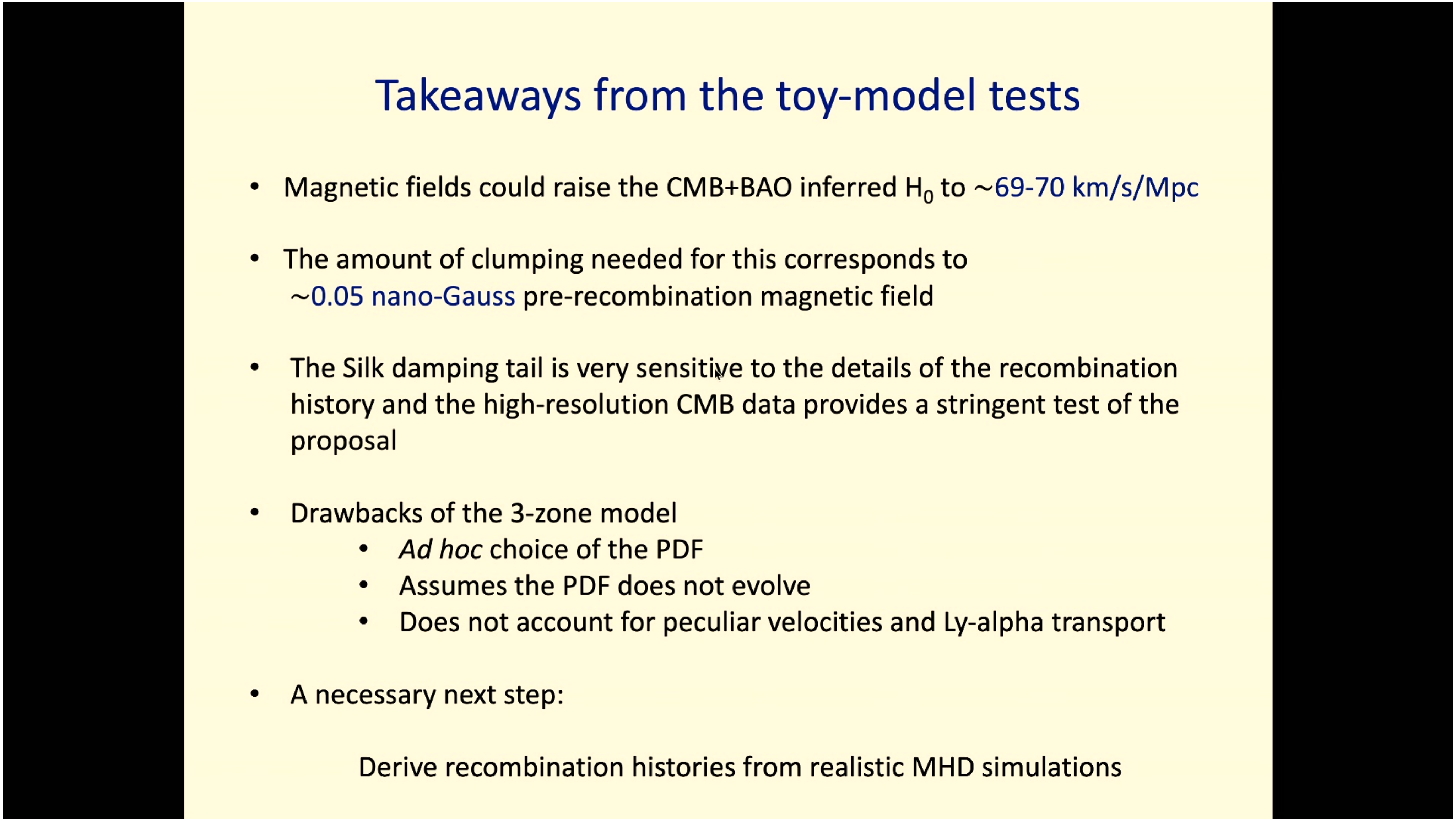


The Atacama Cosmology Telescope: DR6 Constraints on Extended Cosmological Models, arXiv:2503.14454



Takeaways from the toy-model tests

- Magnetic fields could raise the CMB+BAO inferred H_0 to ~69-70 km/s/Mpc

- The amount of clumping needed for this corresponds to ~0.05 nano-Gauss pre-recombination magnetic field

- The Silk damping tail is very sensitive to the details of the recombination history and the high-resolution CMB data provides 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 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” (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

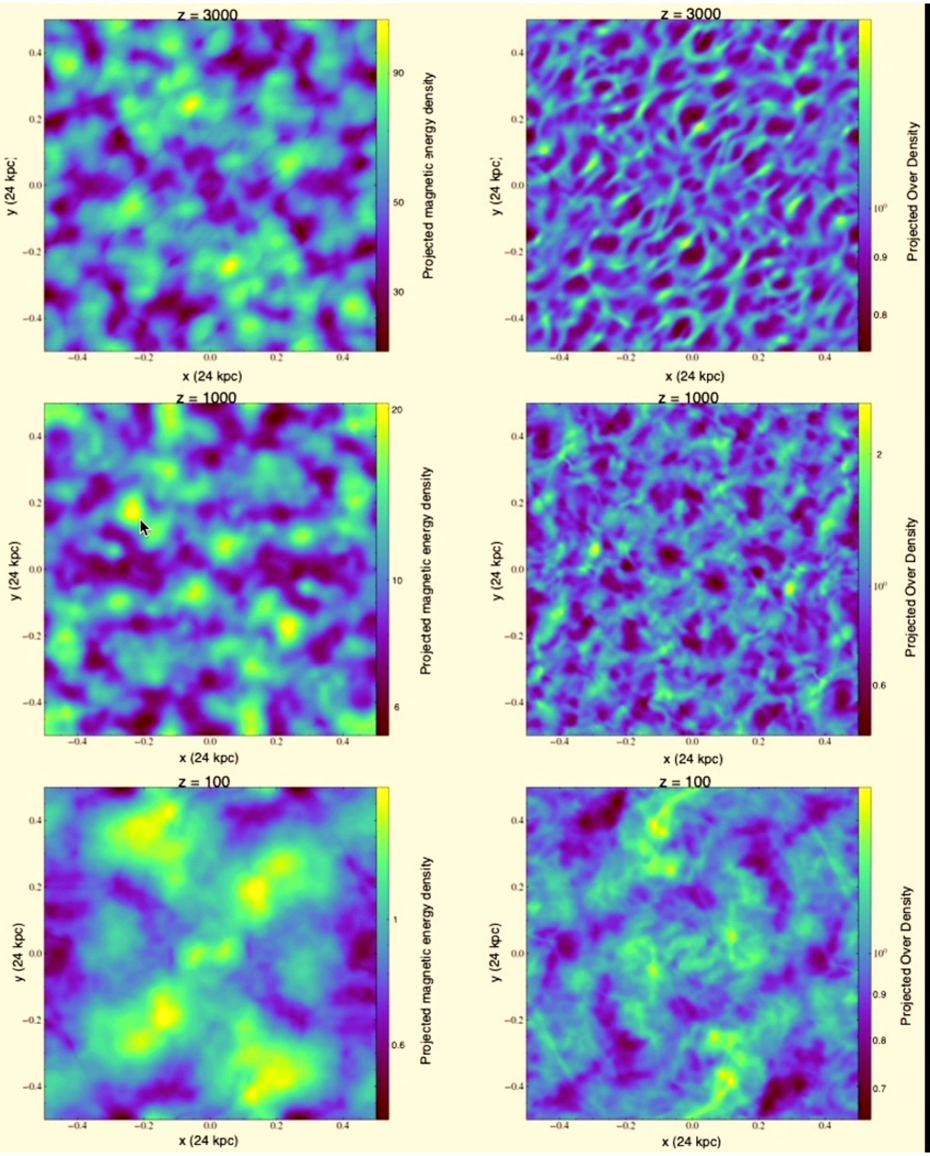
Four PMF scenarios to be considered:

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

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

Magnetically induced baryon clumping

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

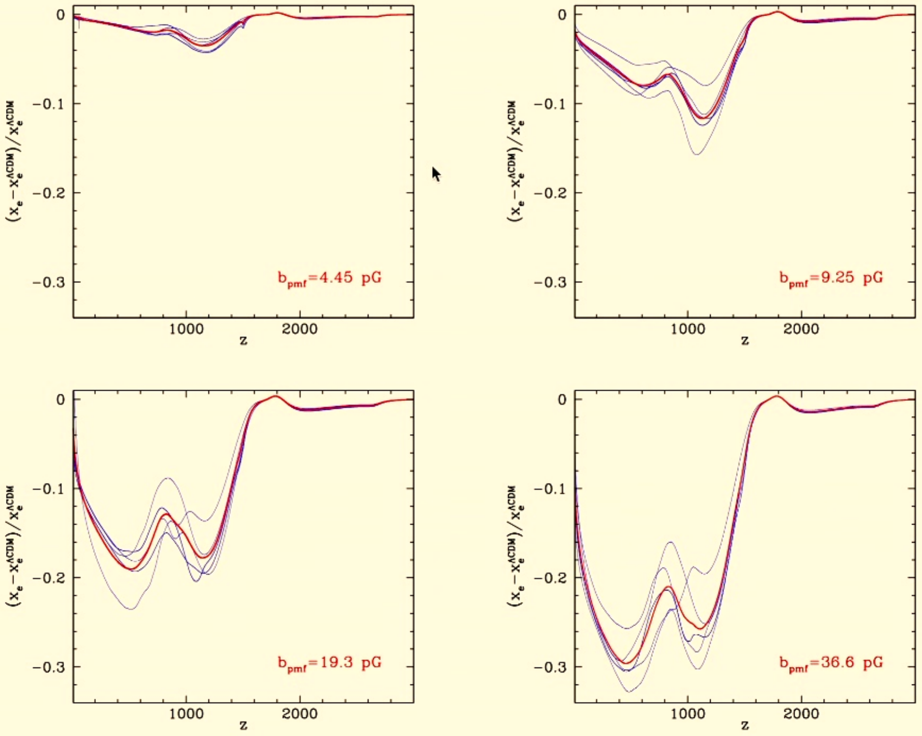


K. Jedamzik, T. Abel and Y. Ali-Haımoud,
arXiv:2312.11448

MHD-derived ionization histories

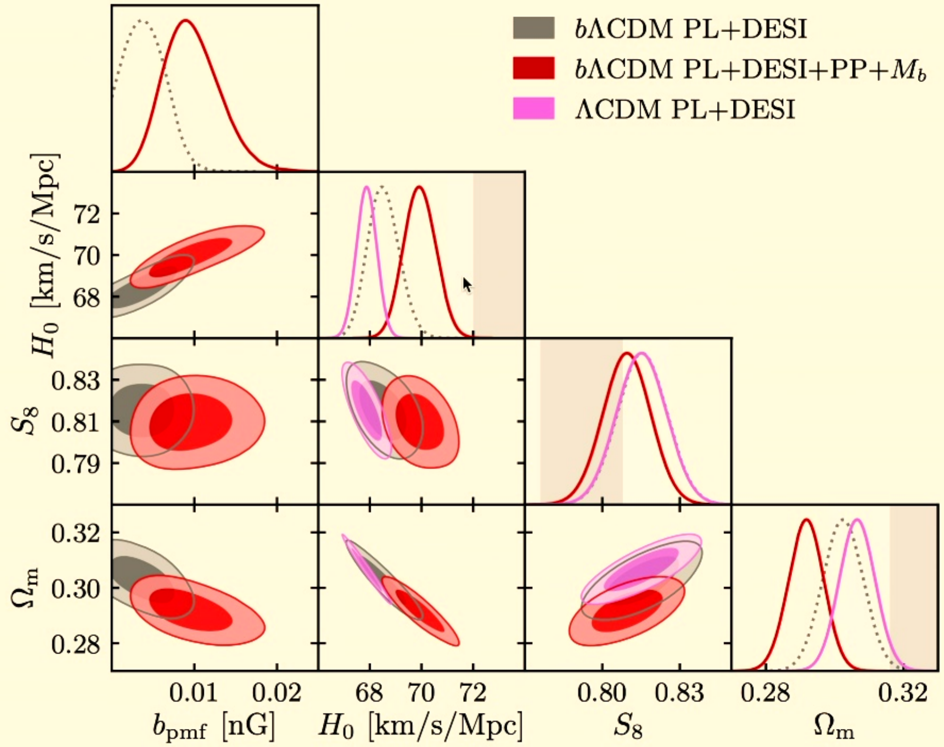
non-helical PMF with n=2 (Batchelor spectrum)

b_{pmf} is the “total” comoving field strength at *z=10*



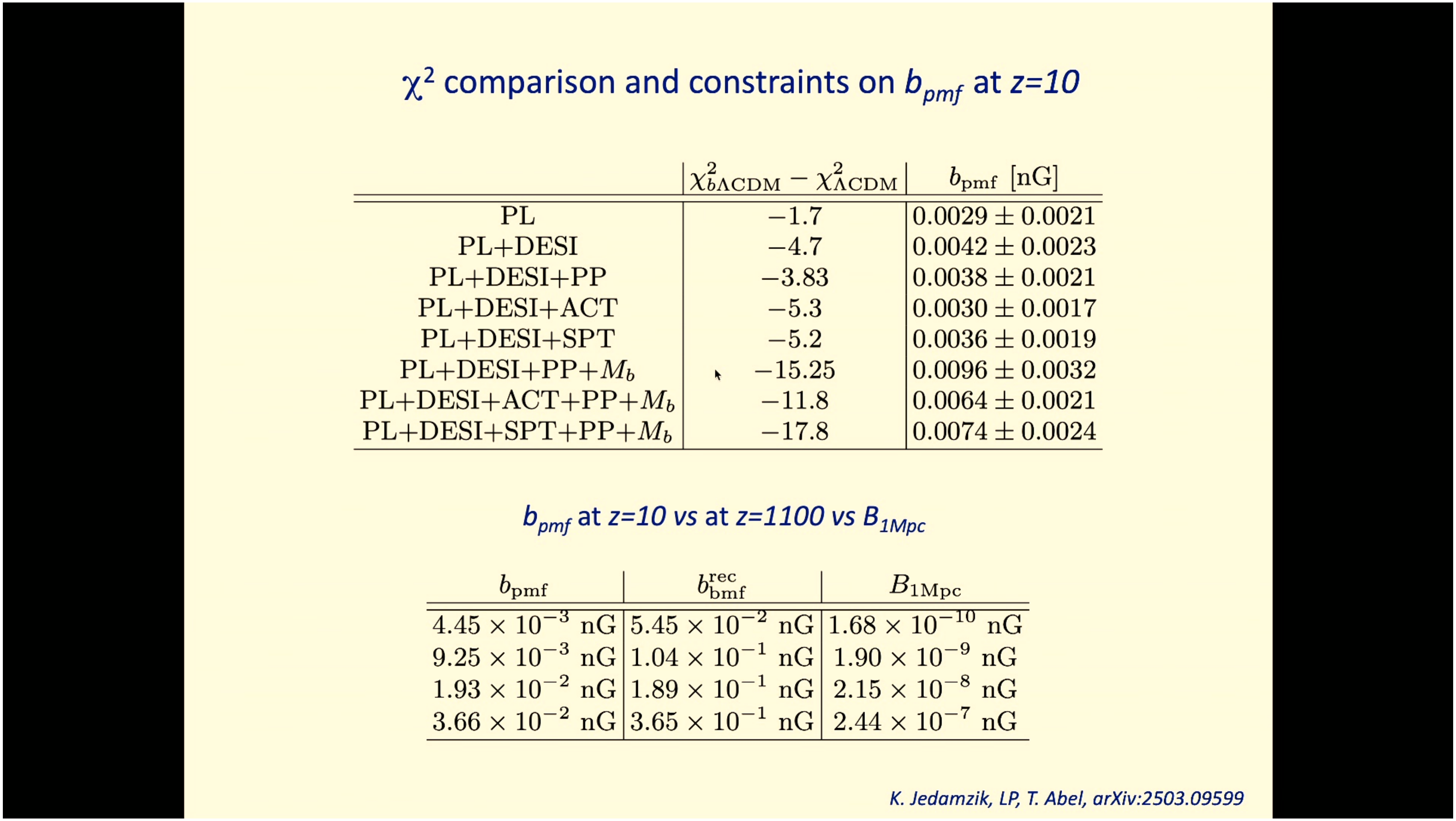
K. Jedamzik, LP, T. Abel, arXiv:2503.09599

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



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

	$\chi^2_{b\Lambda\mathrm{CDM}} - \chi^2_{\Lambda\mathrm{CDM}}$	b_{pmf} [nG]
PL	-1.7	0.0029 ± 0.0021
PL+DESI	-4.7	0.0042 ± 0.0023
PL+DESI+PP	-3.83	0.0038 ± 0.0021
PL+DESI+ACT	-5.3	0.0030 ± 0.0017
PL+DESI+SPT	-5.2	0.0036 ± 0.0019
PL+DESI+PP+M_b	-15.25	0.0096 ± 0.0032
PL+DESI+ACT+PP+M_b	-11.8	0.0064 ± 0.0021
PL+DESI+SPT+PP+M_b	-17.8	0.0074 ± 0.0024

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

b_{pmf}	$b^{\mathrm{rec}}_{\mathrm{bmf}}$	B_{1Mpc}
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

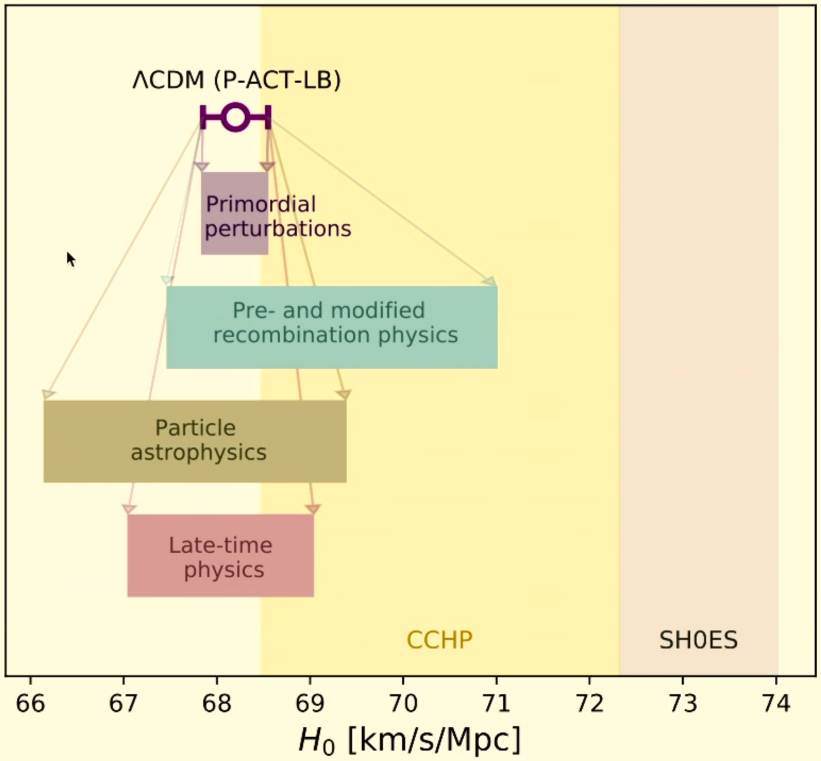
Outlook: PMF and the Hubble Tension

The PMF proposal is still alive, which was not trivial

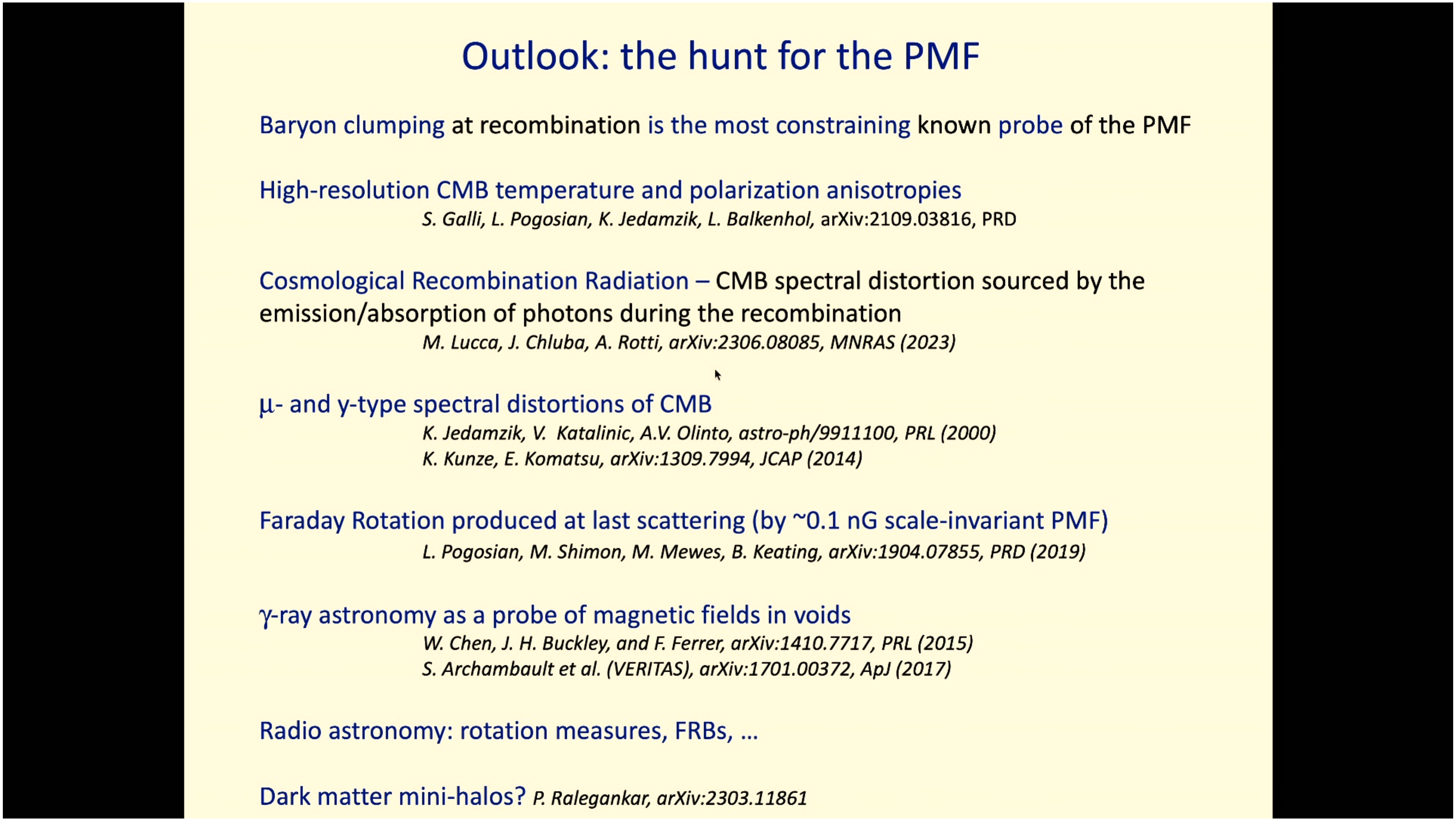
We are just starting:

- More 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)

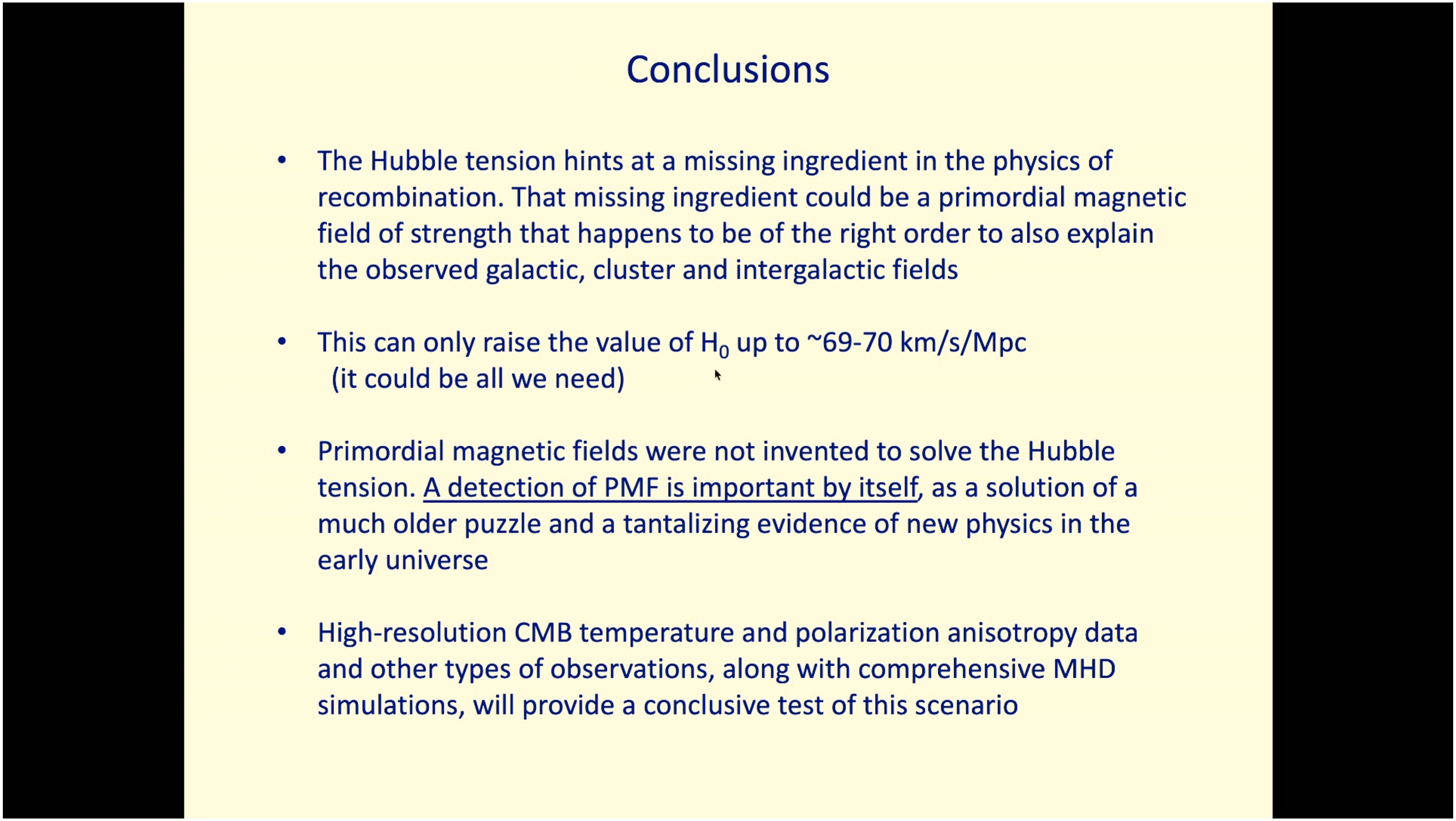
L. Pogosian, M. Shimon, M. Mewes, B. Keating, arXiv:1904.07855, PRD (2019)

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