The Hubble Tension
and
the Magnetic Universe

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with Karsten Jedamzik (LUPM, Montpellier),
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arXiv:2004.09487, Phys. Rev. Lett.
arXiv:2109.03816, submitted to PRD

SFU

This Talk

The Hubble Tension: how fast is the universe expanding today?

Primordial Magnetic Fields

How magnetic fields help to relieve the H_0 tension

Further tests

The Hubble Constant

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

By Edwin Hubble

Mount Wilson Observatory, Carnegie Institution of Washington

Communicated January 17, 1929

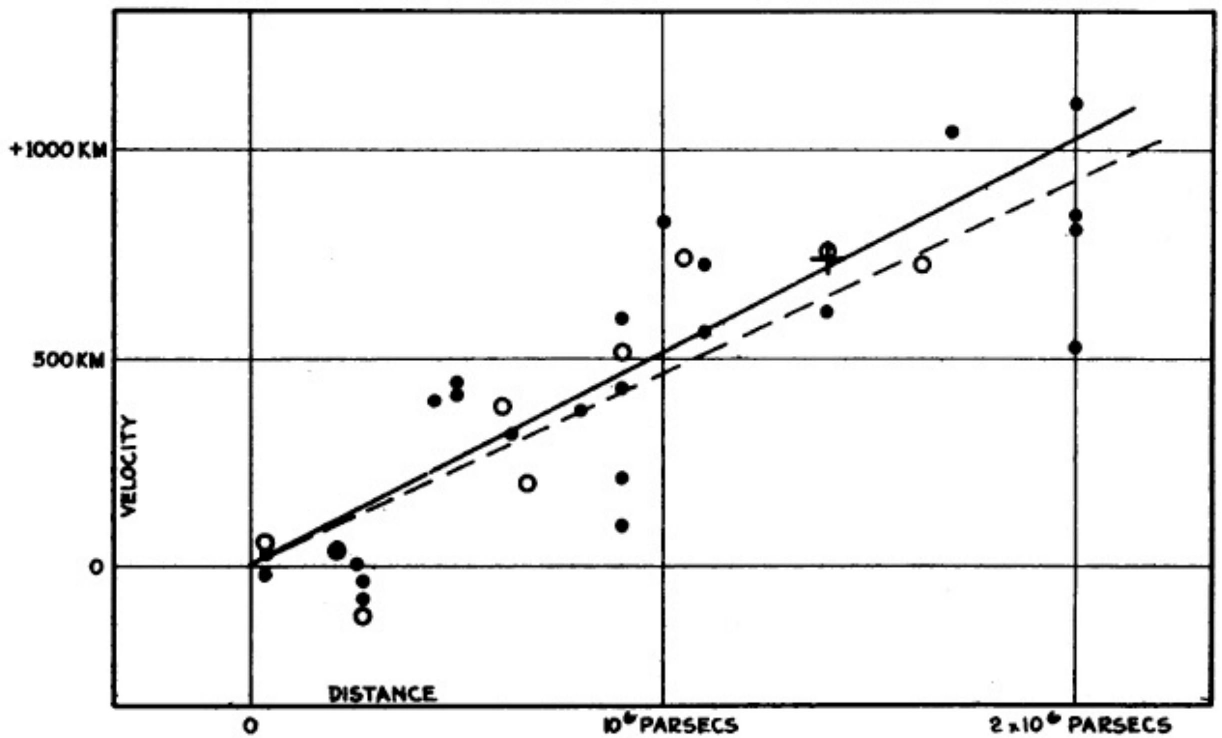

FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Measuring the expansion rate *a la* Hubble

The redshift

$$1+z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} = \frac{a_{\rm now}}{a_{\rm then}}$$
$$= \gamma(1+v/c)$$

$$v = H_0 d$$

Distance to something, e.g. a supernova in a galaxy far, far away

Spectrometry
Photometry

Standard candles (supernovae Ia),
Standard rulers, standard sirens

$$\text{Observed Luminosity} = \frac{\text{Intrinsic Luminosity}}{4\pi\ \text{Distance}^2} = \frac{L}{4\pi d_L^2}$$

$$d_A = \frac{\text{Known Physical Length}}{\text{Observed Angular Size}} = \frac{S}{\theta}$$

$[H_0]$ = [velocity/distance] = [1/time] = km/s/Mpc

It's a bit more complicated…

H is not a constant

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2(z) = H_0^2\left[\Omega_{\rm r}(1+z)^4 + \Omega_{\rm M}(1+z)^3 + \Omega_{\rm k}(1+z)^2 + \Omega_{\rm DE}\right]$$

$$\Omega_{\rm r} + \Omega_{\rm M} + \Omega_{\rm k} + \Omega_{\rm DE} = 1$$

Distances depend on H(z)

$$d_L(z) = (1+z)\int_0^z \frac{c\,dz'}{H(z')}$$

$$d_A(z) = \frac{1}{(1+z)}\int_0^z \frac{c\,dz'}{H(z')}$$

It’s a bit more complicated…

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$$\Omega_{\mathrm{r}} + \Omega_{\mathrm{M}} + \Omega_{\mathrm{k}} + \Omega_{\mathrm{DE}} = 1$$

Distances depend on H(z)

$$d_L(z) = (1+z)\int_0^z \frac{c\,dz'}{H(z')} \xrightarrow{z\ll 1} cH_0^{-1}z \approx H_0^{-1}v$$

$$d_A(z) = \frac{1}{(1+z)}\int_0^z \frac{c\,dz'}{H(z')} \xrightarrow{z\ll 1} cH_0^{-1}z \approx H_0^{-1}v$$

The Astrophysical Journal, 876:85 (13pp), 2019 May 1 https://doi.org/10.3847/1538-4357/ab1422

Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics beyond ΛCDM

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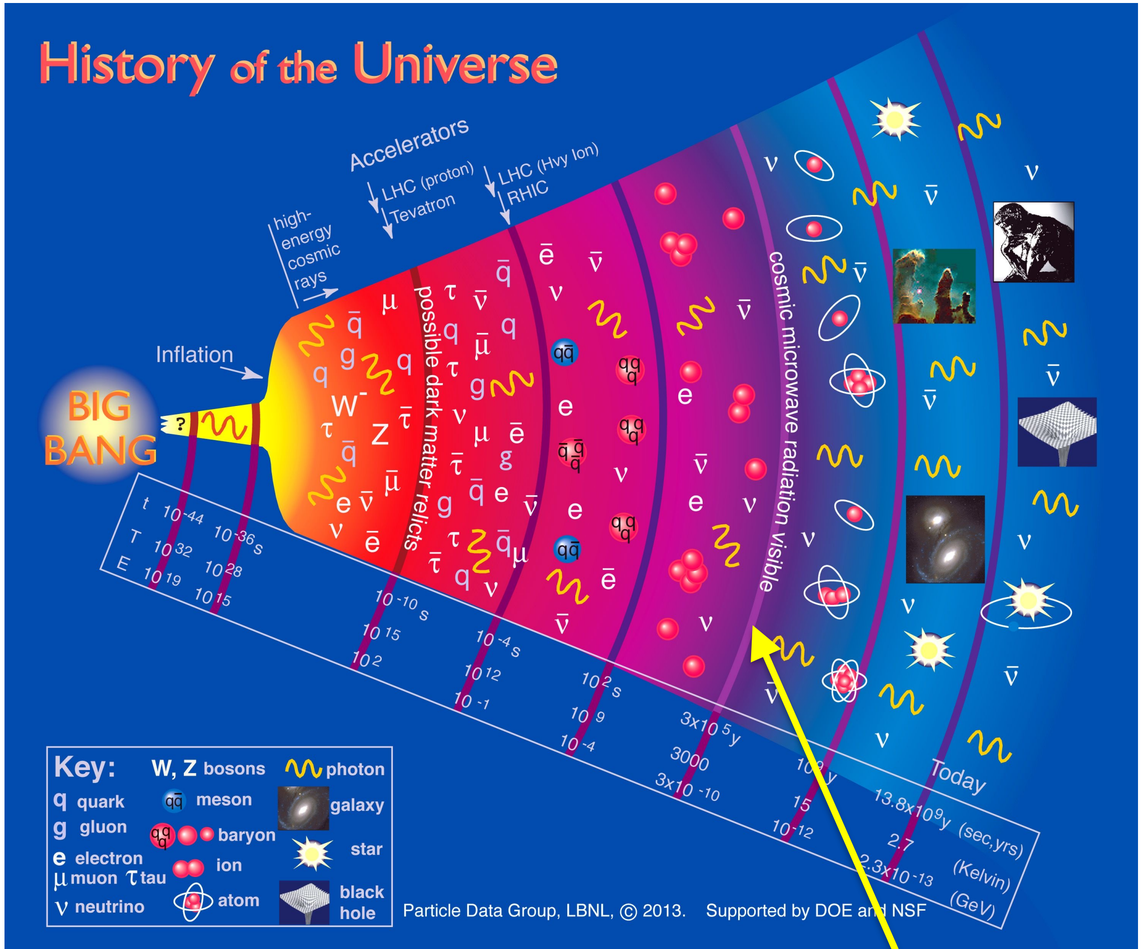
Abstract

We present an improved determination of the Hubble constant from *Hubble Space Telescope (HST)* observations of 70 long-period Cepheids in the Large Magellanic Cloud (LMC). These were obtained with the same WFC3 photometric system used to measure extragalactic Cepheids in the hosts of SNe Ia. Gyroscopic control of *HST* was employed to reduce overheads while collecting a large sample of widely separated Cepheids. The Cepheid period–luminosity relation provides a zero-point-independent link with 0.4% precision between the new 1.2% geometric distance to the LMC from detached eclipsing binaries (DEBs) measured by Pietrzyński et al. and the luminosity of SNe Ia. Measurements and analysis of the LMC Cepheids were completed prior to knowledge of the new DEB LMC distance. Combined with a refined calibration of the count-rate linearity of WFC3-IR with 0.1% precision, these three improved elements together reduce the overall uncertainty in the geometric calibration of the Cepheid distance ladder based on the LMC from 2.5% to 1.3%. Using only the LMC DEBs to calibrate the ladder, we find $H_0 = 74.22 \pm 1.82\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ including systematic uncertainties, 3% higher than before for this particular anchor. Combining the LMC DEBs, masers in NGC 4258, and Milky Way parallaxes yields our best estimate: $H_0 = 74.03 \pm 1.42\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, including systematics, an uncertainty of 1.91%–15% lower than our best previous result. Removing any one of these anchors changes H_0 by less than 0.7%. The difference between H_0 measured locally and the value inferred from Planck CMB and ΛCDM is $6.6 \pm 1.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ or 4.4σ ($P = 99.999\%$ for Gaussian errors) in significance, raising the discrepancy beyond a plausible level of chance. We summarize independent tests showing that this discrepancy is not attributable to an error in any one source or measurement, increasing the odds that it results from a cosmological feature beyond ΛCDM.

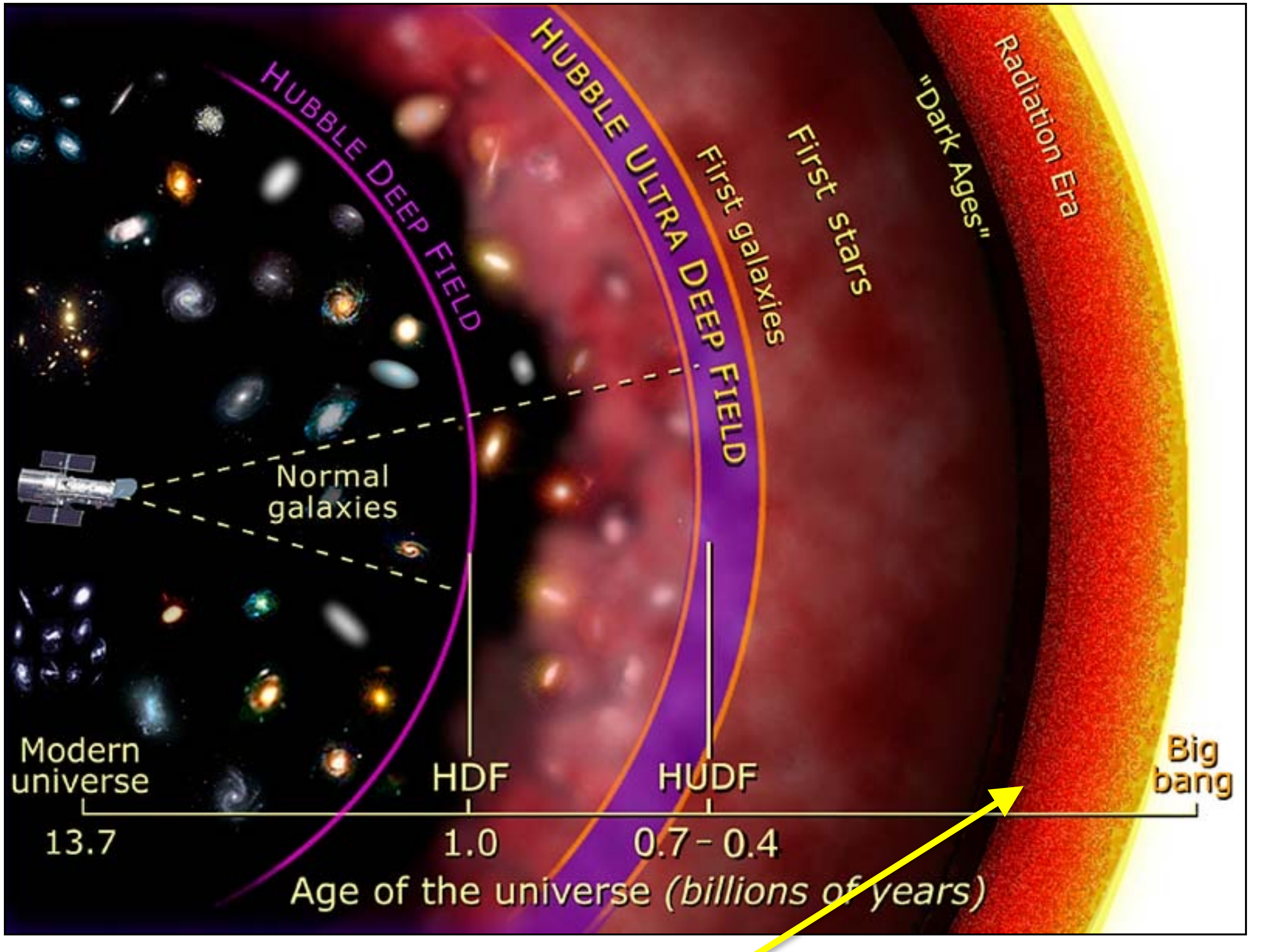
How does Cosmic Microwave Background (CMB) determine H_0?

A poster in a typical physics department



The epoch of “recombination”

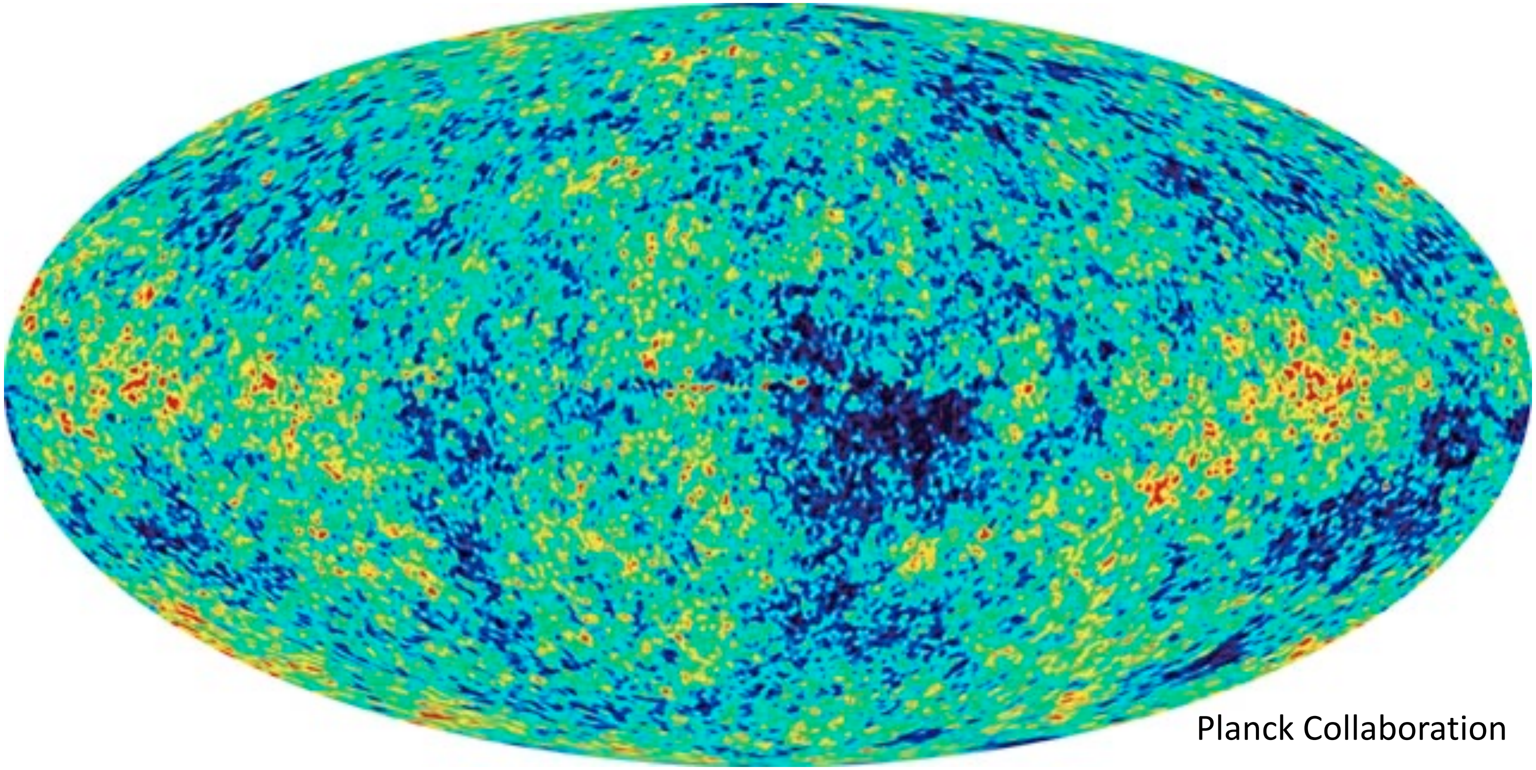
A poster in a typical astronomy department



The transition from transparent to opaque

We observe it as Cosmic Microwave Background (CMB)

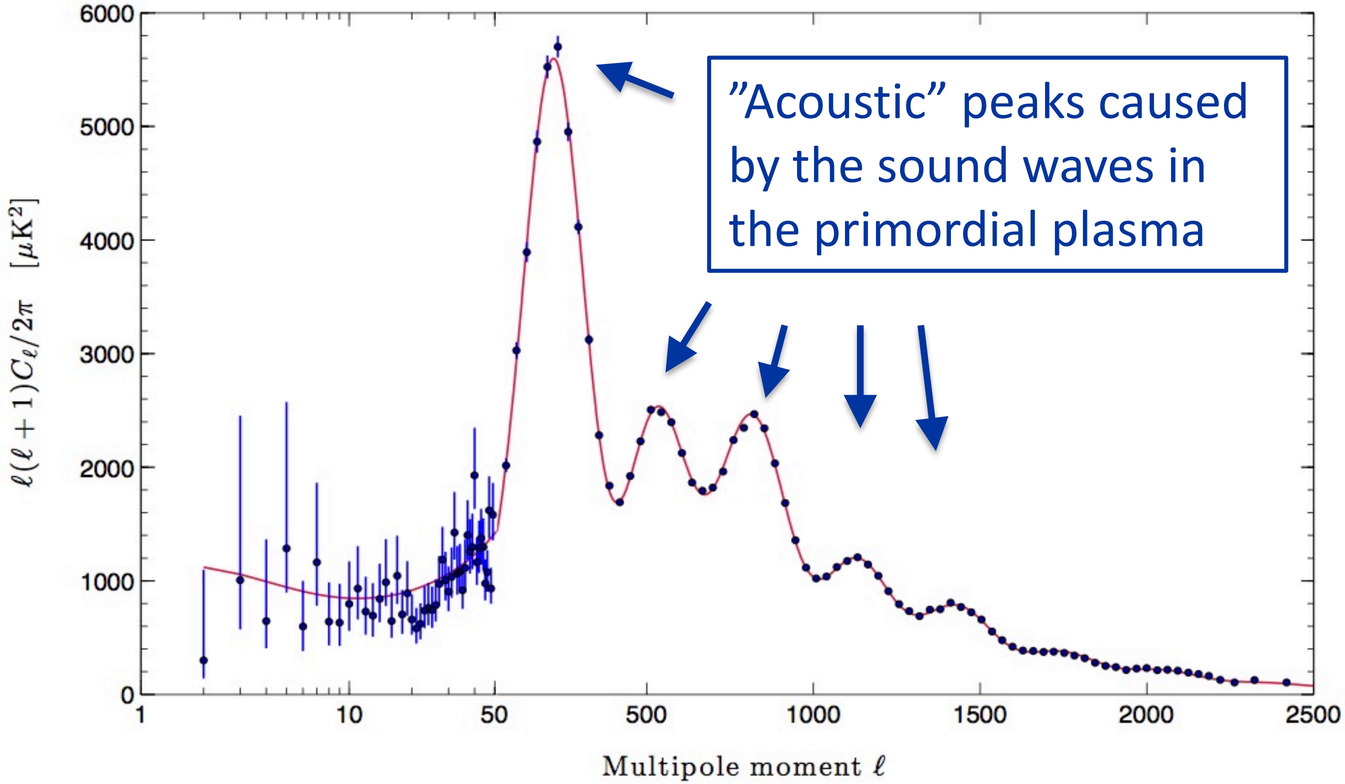
CMB temperature fluctuations



Planck Collaboration

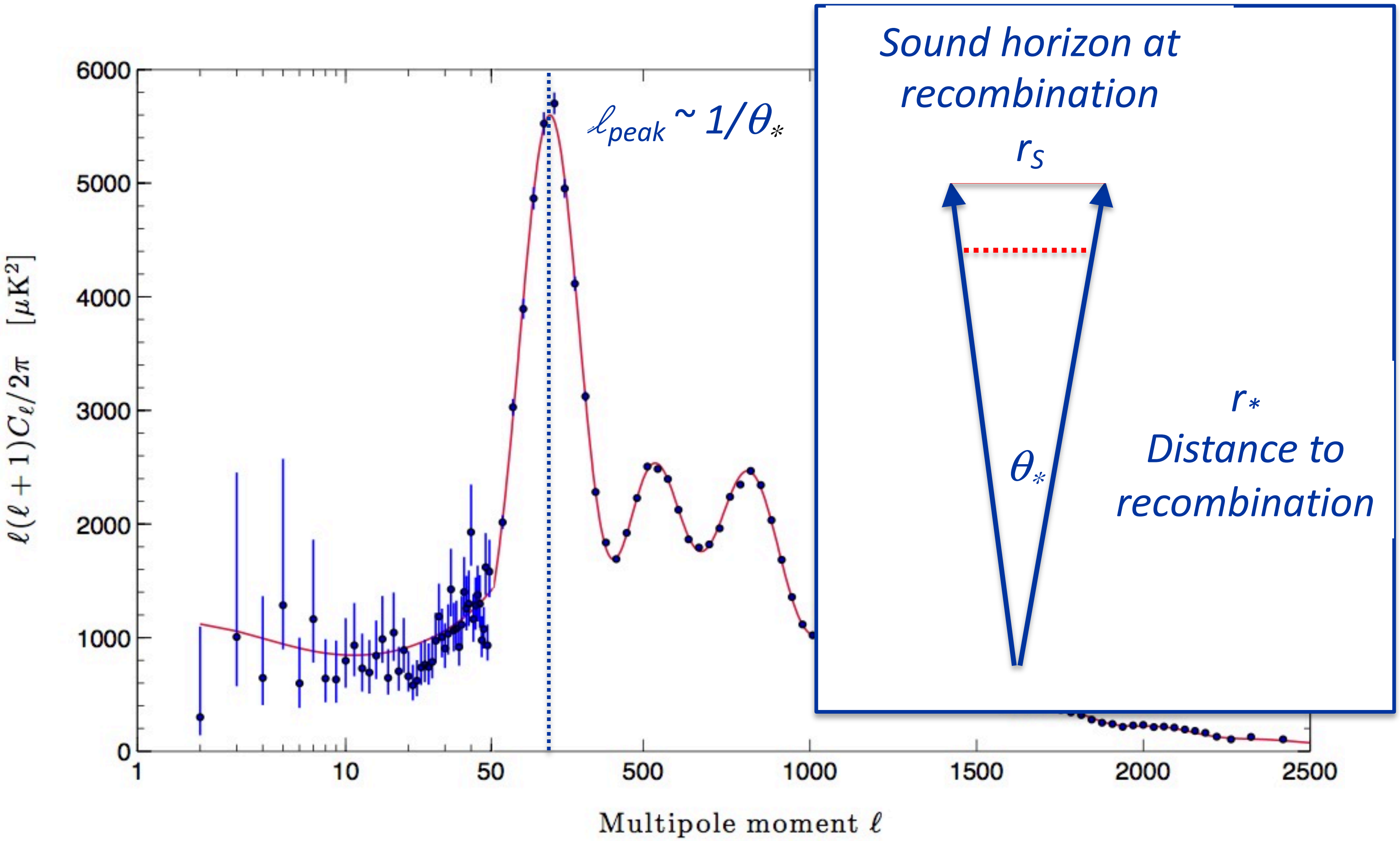
- Nearly perfect black body radiation with average T=2.7K
- Temperature fluctuations of order 1/100,000

The power spectrum of CMB temperature fluctuations



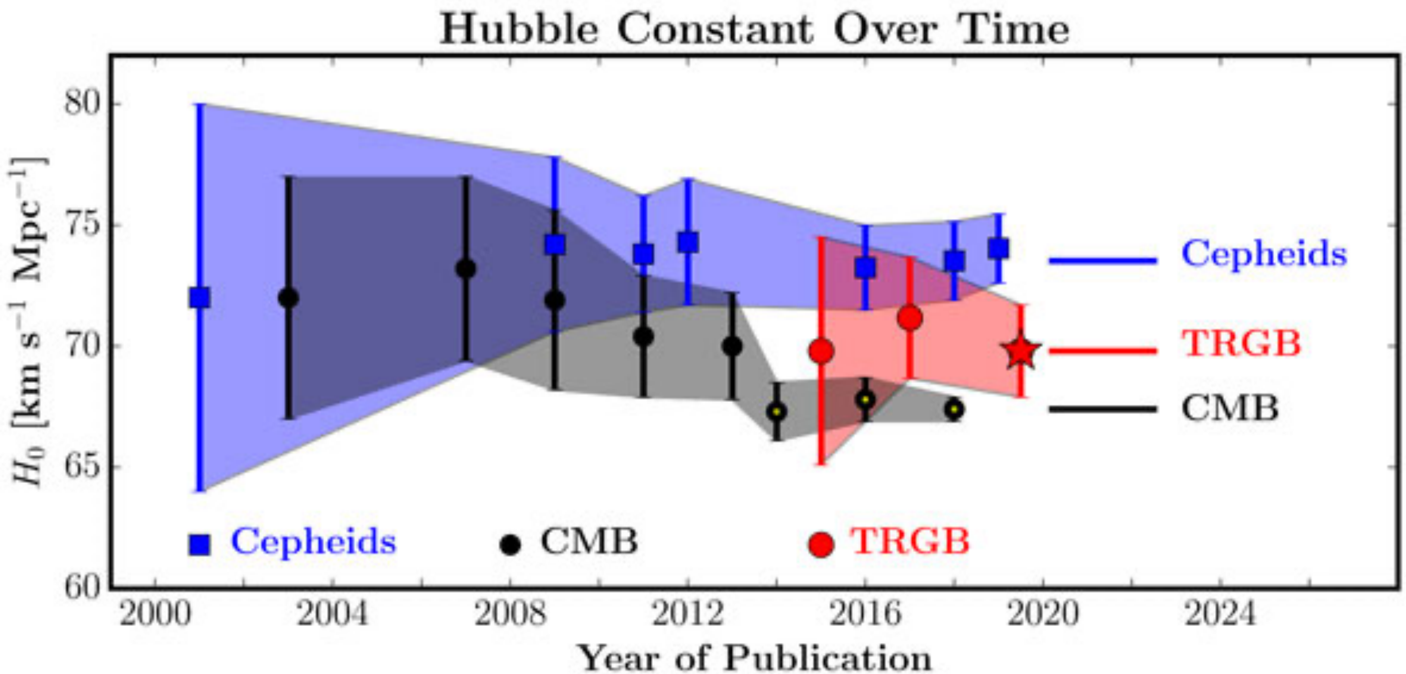
By fitting to the CMB spectrum, one constrains all parameters of the LCDM model, including H_0.

How does CMB constrain H_0?



- Positions of the acoustic peaks tell us the <u>angular size of the sound horizon</u> at recombination, $\theta_* = r_S/r_*$
- A <u>smaller sound horizon</u> r_S would imply a shorter distance to the redshift of recombination r_*, implying a <u>larger H_0</u>

The Road to the Hubble Tension



Freedman et al. / Astrophysical Journal

CMB (Planck): H_0 = 67.36 ± 0.54 km/s/Mpc

Cepheid calibrated SNIa (SH0ES): H_0 = 73.2 ± 1.3 km/s/Mpc

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'Serious gap' in cosmic expansion rate hints at new physics

By Paul Rincon
Science editor, BBC News website, Washington DC

11 January 2018

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Police officer shot dead named as Sgt Matt Ratana
The "much-loved" long-serving officer was originally from New Zealand but moved to

Artwork: The expansion of the Univers

A mathematical discrepancy i "pretty serious", and could pc says a Nobel laureate.

The New York Times

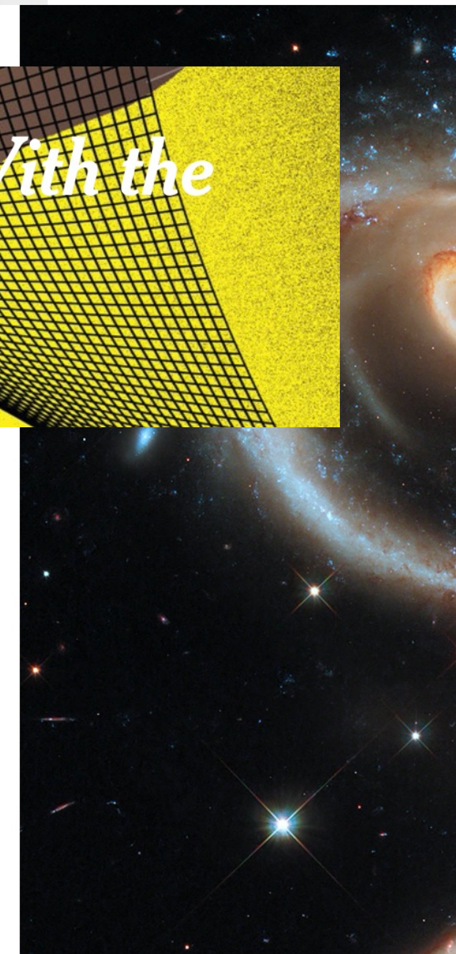
Have Dark Forces Been Messing With the Cosmos?

Axions? Phantom energy? Astrophysicists scramble to patch a hole in the universe, rewriting cosmic history in the process.

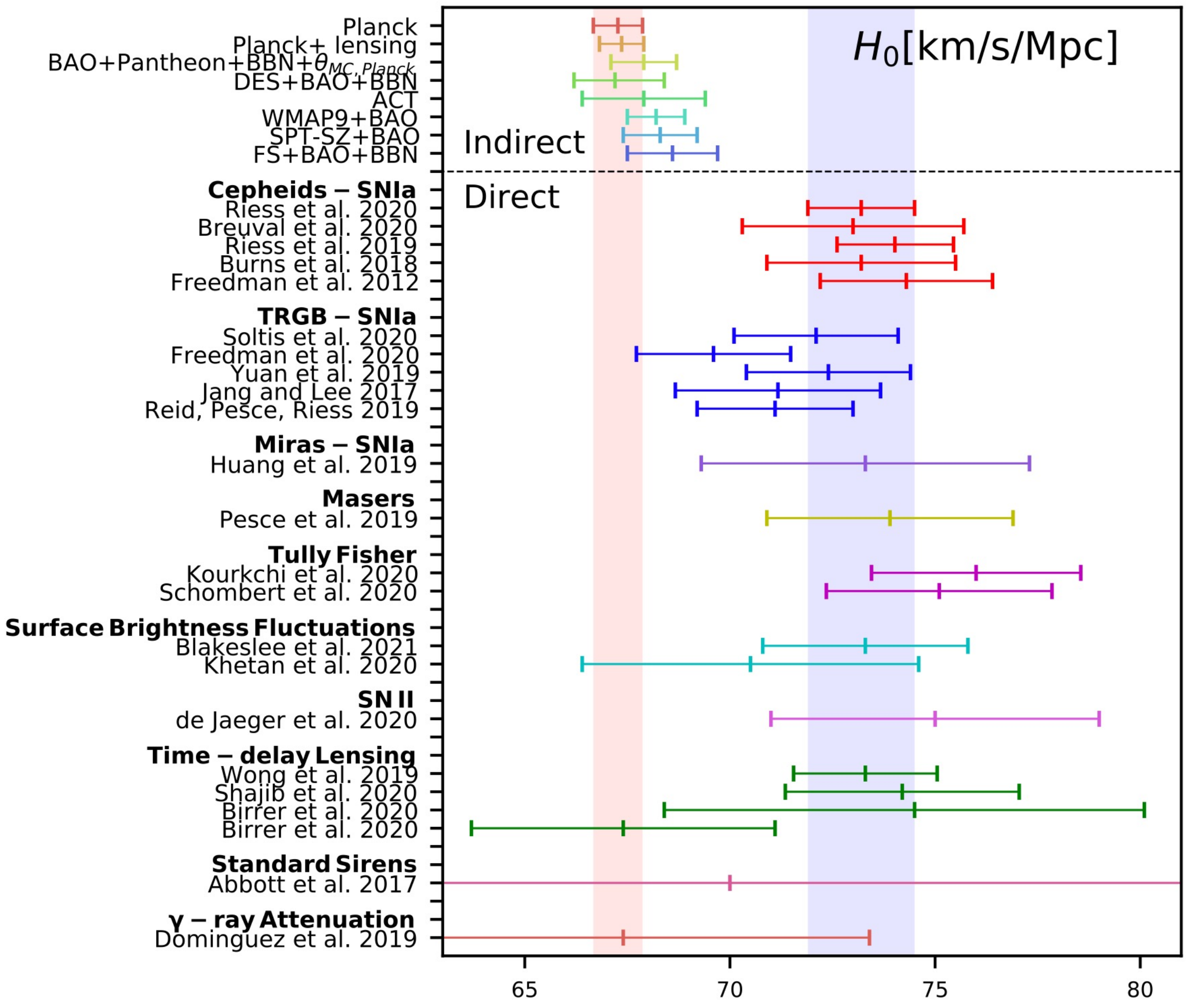
OUT THERE

Cosmos Controversy: The Universe Is Expanding, but How Fast?

A small discrepancy in the value of a long-sought number has fostered a debate about just how well we know the cosmos.



The Hubble tension



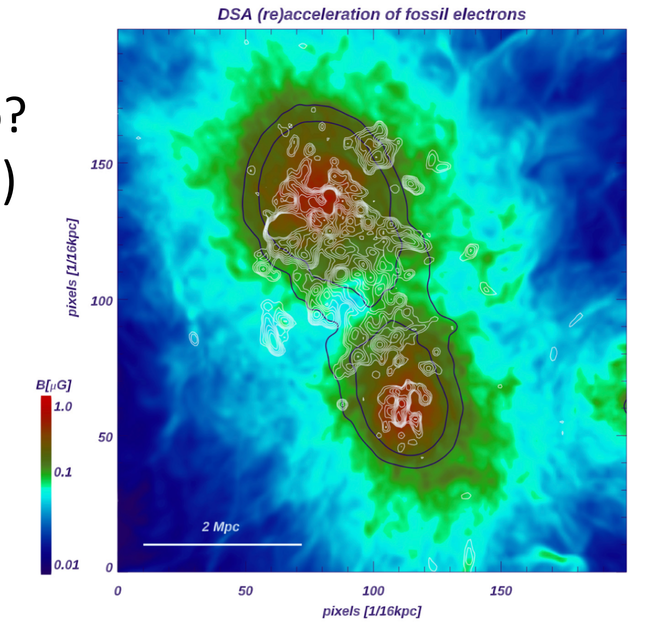
from E. Di Valentino, arXiv:2011.00246

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

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

- Many models proposed with the aim of solving the Hubble tension
- Primordial Magnetic Fields

Cosmic Magnetic Fields



- ○ Micro-Gauss (μG) fields in galaxies and clusters
  - produced during galaxy formation via dynamo?
  - primordial origin? (need 0.01-0.1 nano-Gauss)
  - μG fields seen in proto-galaxies that haven't turned enough times for the dynamo to work!
- ○ Evidence of magnetic fields in voids
  - missing GeV γ-ray halos around TeV blazars

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

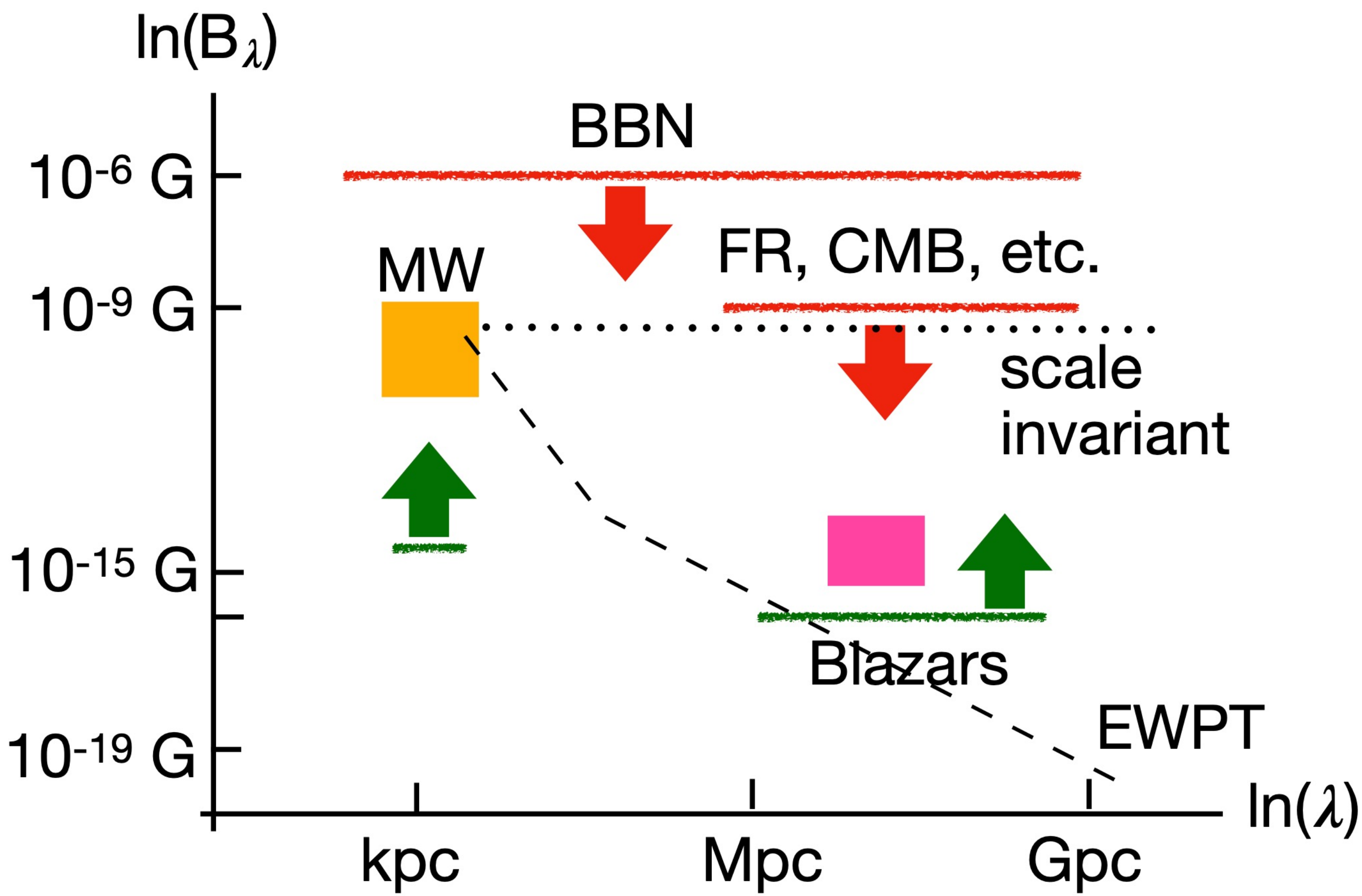
    F. Govoni et al, arXiv:1906.07584, Science (2019)
- ○ Generated in the early universe – not "if", but "how much"
  - phase transitions
  - inflationary mechanisms
  - a window into the early universe

See a recent review by T. Vachaspati, arXiv:2010.10525

Stochastic Primordial Magnetic Field (PMF)

- Generated in the early universe, e.g. during the electroweak phase transitions or inflation
- Frozen in the plasma on large scales, the amplitude decreases with the expansion as $B(a)=B_0/a^2$
- PMF generated in a phase transition would have most of its power on small scales
- The simplest Inflation based models predict a scale-invariant PMF

Cosmological Magnetic Fields



Plot from T. Vachaspati, arXiv:2010.10525

How do magnetic fields help to relieve the Hubble tension?

In two sentences:

- Magnetic fields present in the plasma prior to recombination induce baryon inhomogeneities (clumping) on very 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)

Magneto-Hydro-Dynamics

Pressure = $c_s^2\, \rho$ Gravity Viscosity Lorentz force

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

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

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

MHD at Recombination

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

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

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

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 $L < l_\gamma$

Drug due to photons with 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)

Inhomogeneities enhance the recombination rate

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

The probability of a proton and an electron combining to form H is proportional to $n_p n_e = n_e^2$

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

Inhomogeneities enhance the recombination rate

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

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

Inhomogeneities enhance the recombination rate

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

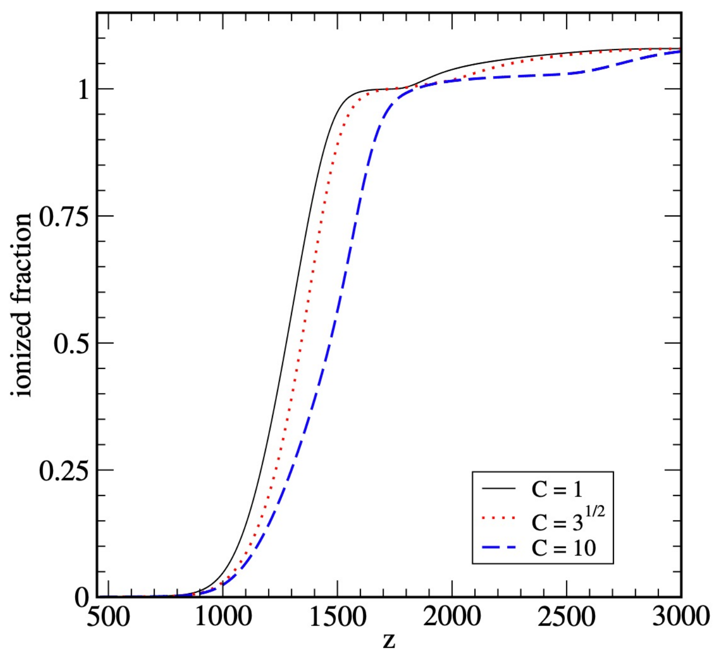
$$n_e = \langle n_e \rangle + \delta n_e \quad \rightarrow \quad \langle n_e^2 \rangle \; > \; \langle n_e \rangle^2$$

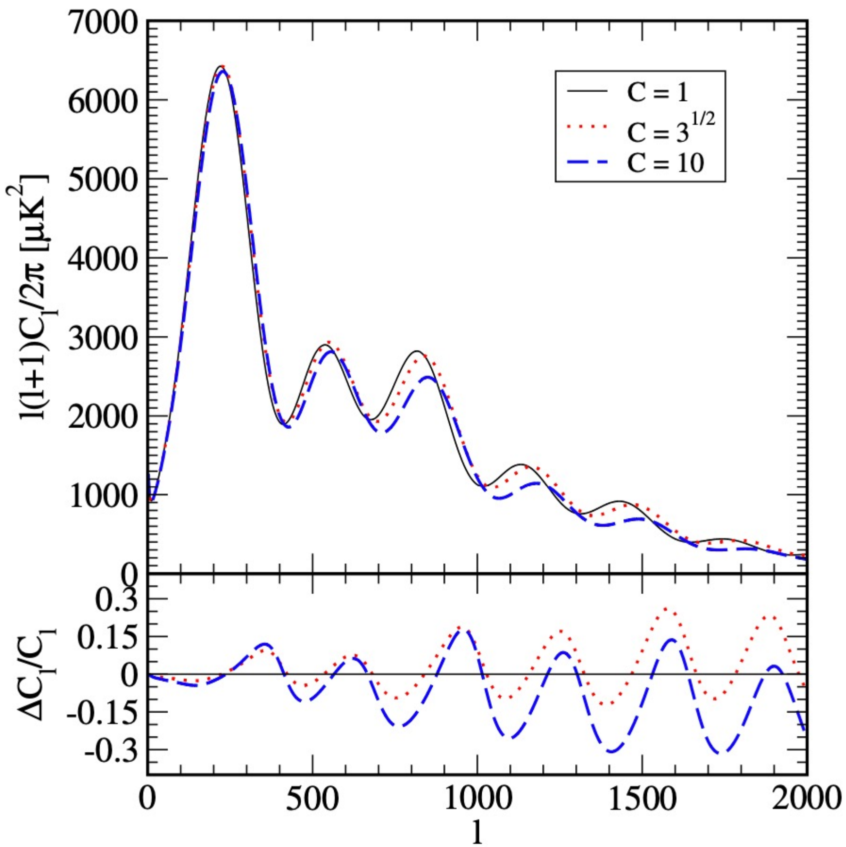
Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

Inhomogeneities enhance the recombination rate

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

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





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

Implementation

An additional baryon clumping parameter:

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

Considered two different models of baryon density distribution

- M1, with the same baryon density PDF as in Jedamzik and Abel (2013)
- M2, using a different PDF

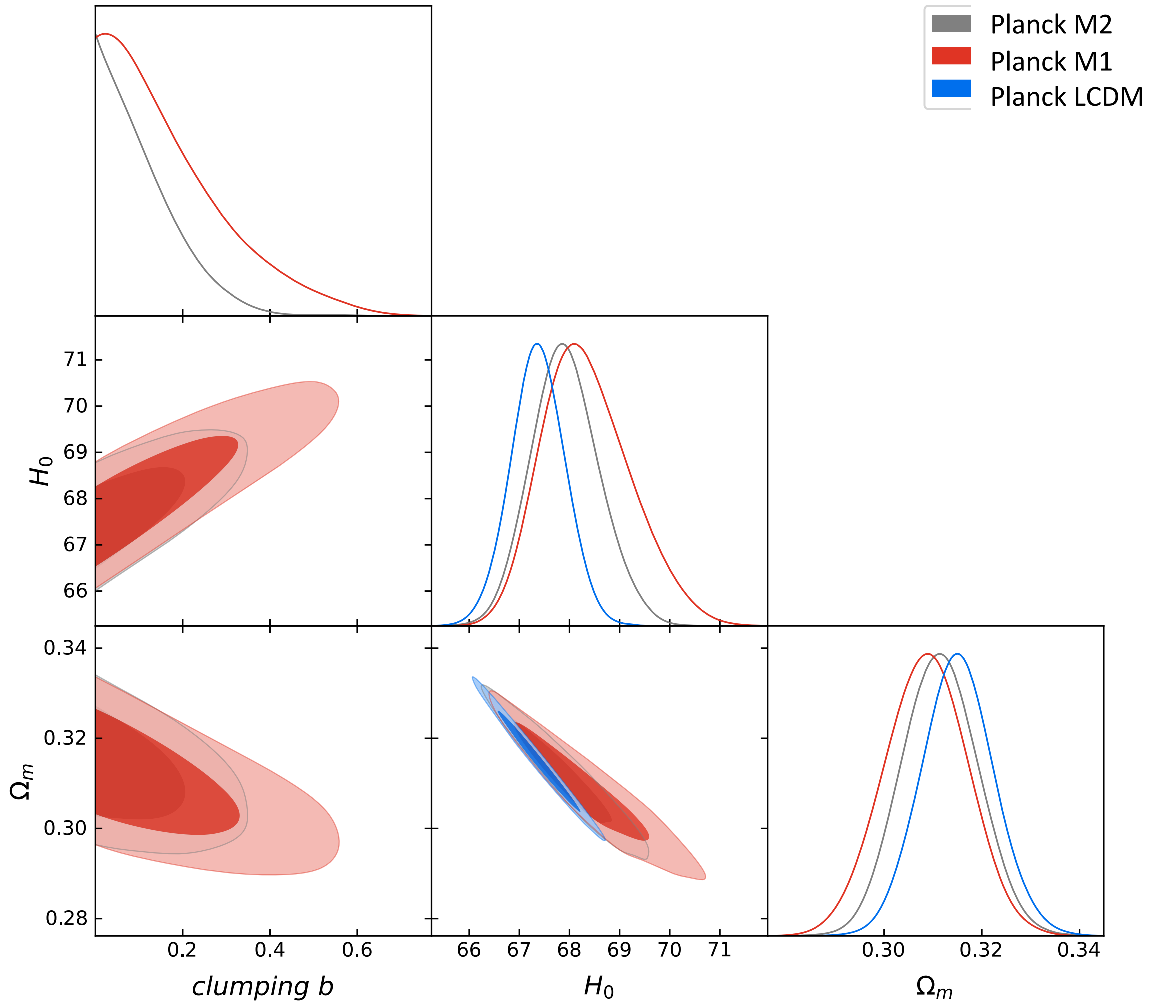
(The exact PDF determination from MHD simulations is in progress)

Datasets considered in this work:

- CMB temperature and polarization from Planck 2018
- SH0ES, H0LiCOW and MCP determinations of H_0 (H3)
- Baryon Acoustic Oscillations (BAO) and supernovae (SN) data

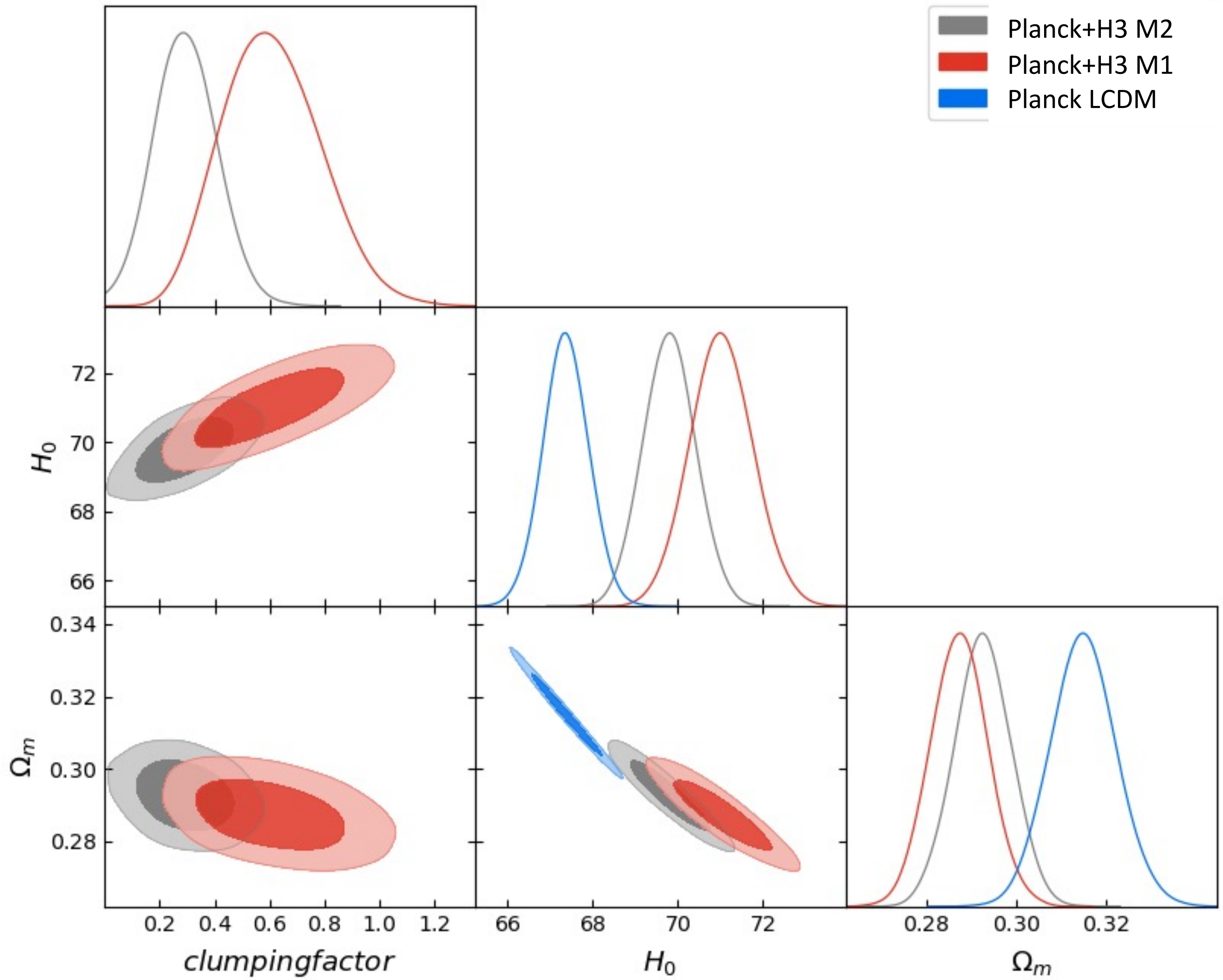
K. Jedamzik and L. Pogosian, arXiv:2004.09487, PRL

Fitting to Planck CMB only



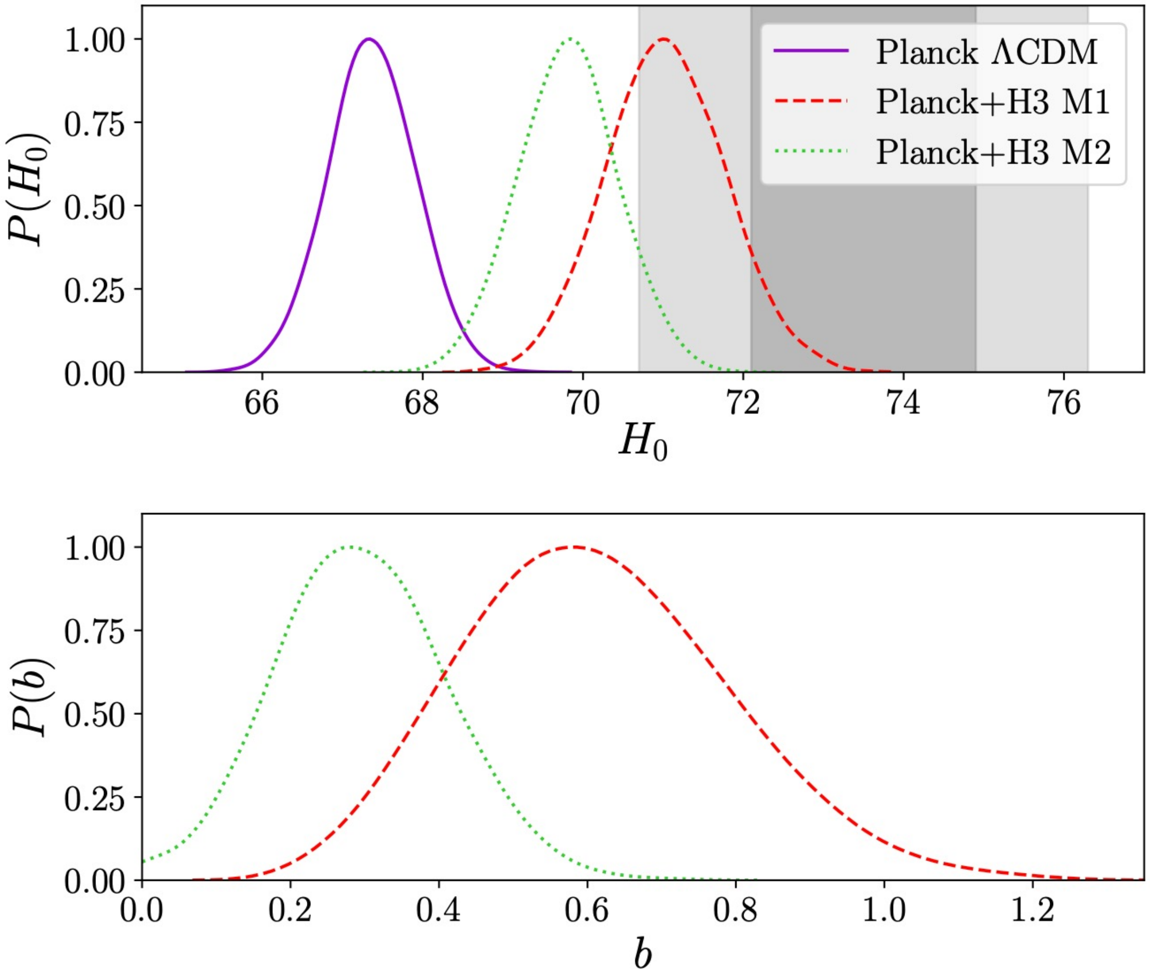
- Strong degeneracy between the clumping parameter b and H_0
- No preference for a non-zero value of b

Fitting to Planck + H3



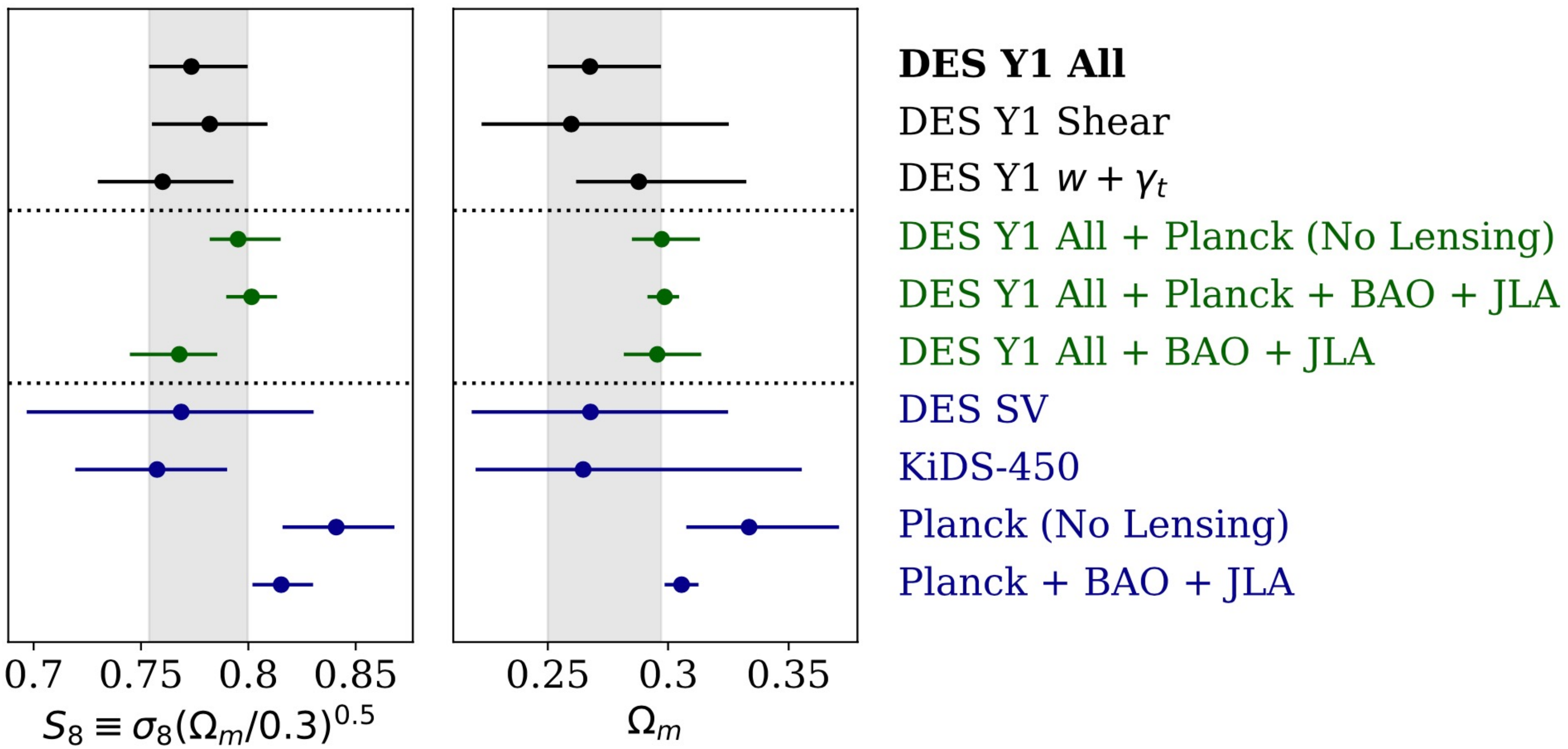
a clear detection of clumping

Relieving the Hubble tension



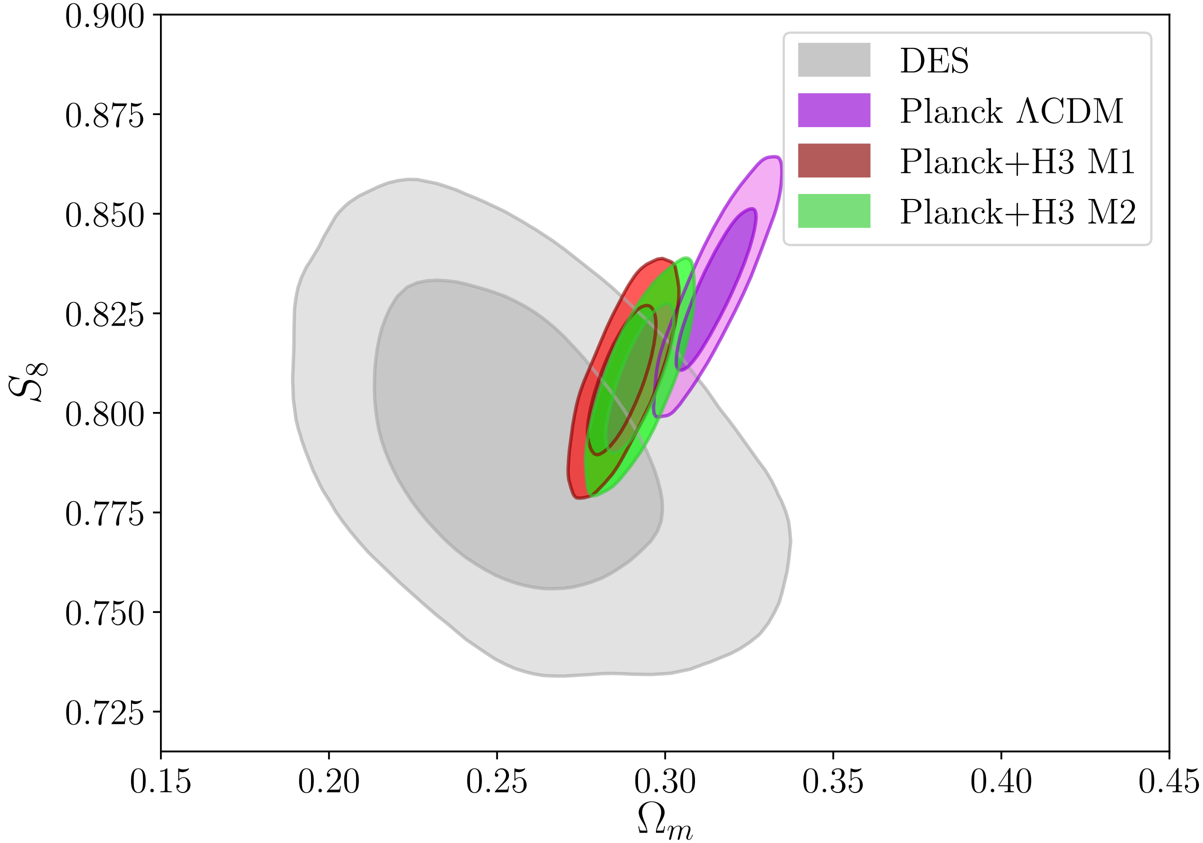
K. Jedamzik and L. Pogosian, arXiv:2004.09487, PRL

Another (milder) tension, cosmic matter is less clustered than predicted



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

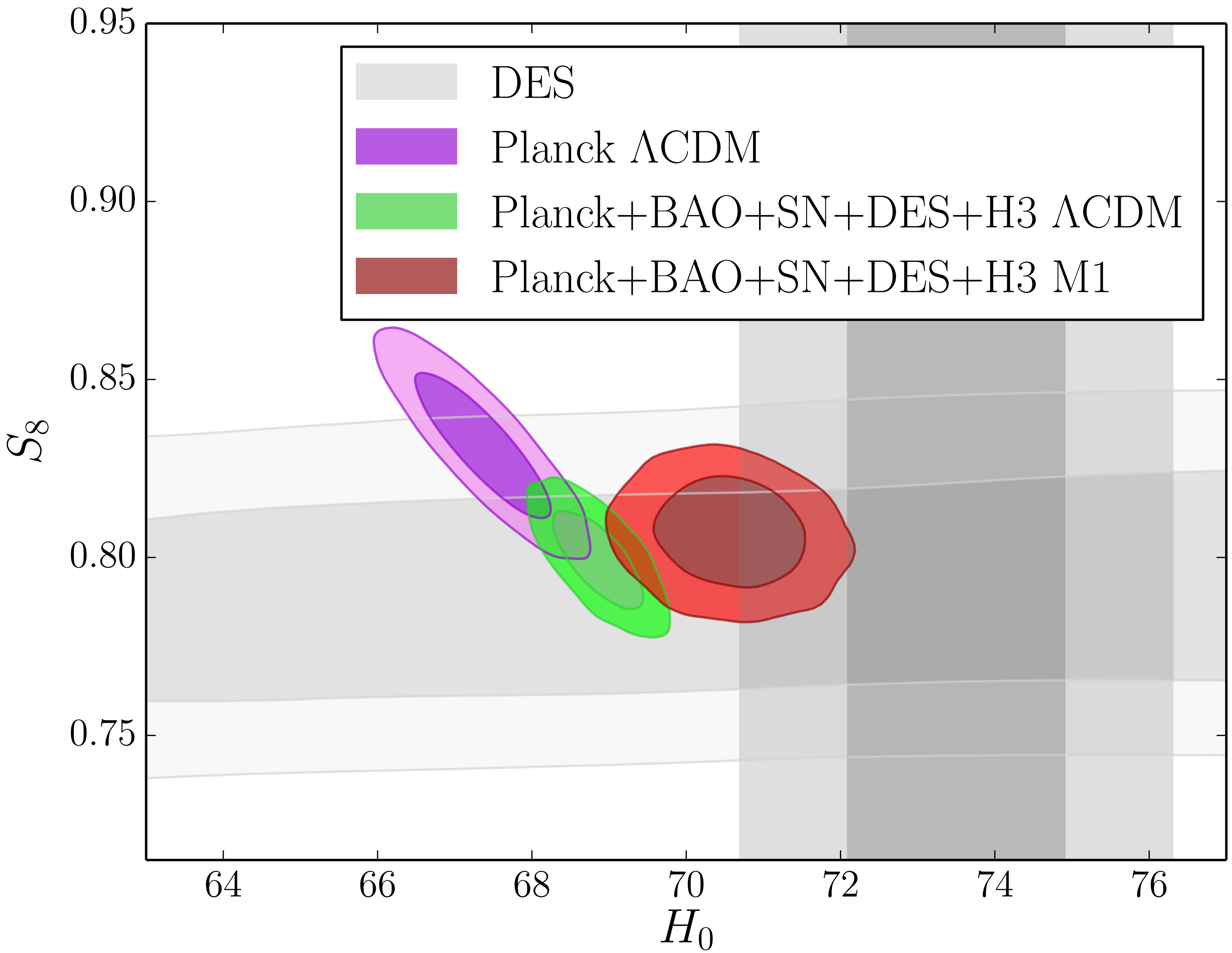
Relieving the S_8-Ω_m tension



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

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

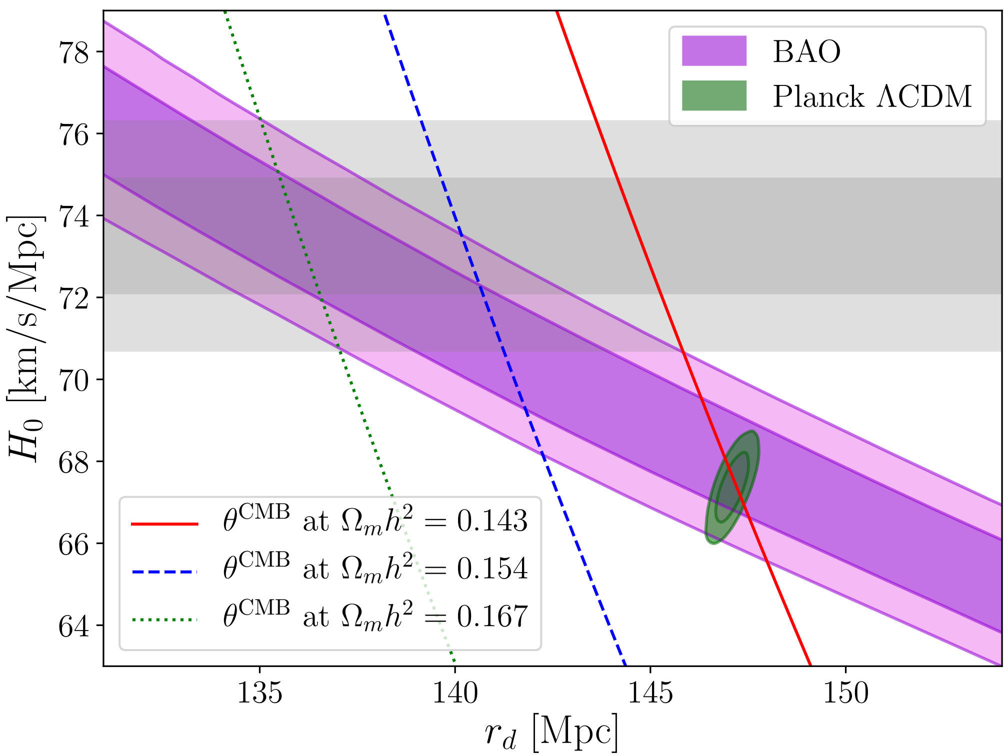
Fitting to all data

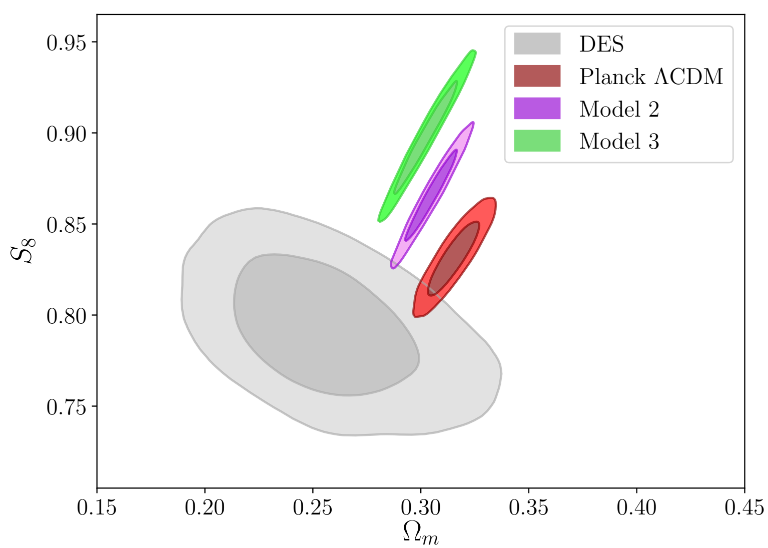


K. Jedamzik and L. Pogosian, arXiv:2004.09487, PRL

Why reducing the sound horizon cannot (by itself) <u>fully</u> relieve the Hubble tension

- The relevant parameters are the sound horizon at decoupling, r_d, h and $\Omega_m h^2$
- To simultaneously fit the CMB, Baryon Acoustic Oscillations (BAO) and SH0ES data one needs to increase $\Omega_m h^2$
- A larger $\Omega_m h^2$ creates tension with weak lensing data, e.g. DES and KiDS





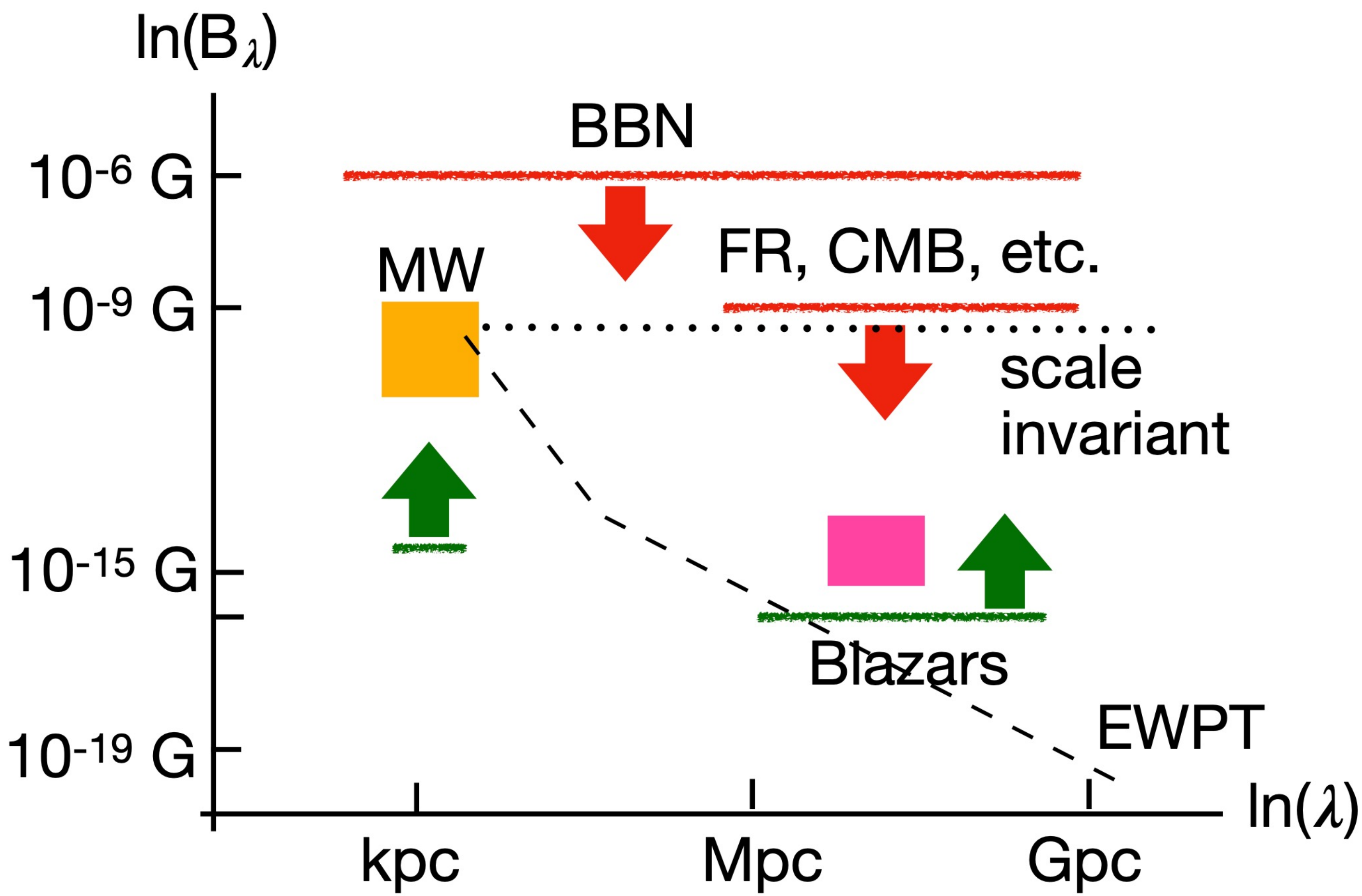
K. Jedamzik, LP, G.-B. Zhao, Physics Communications (Nature) arXiv:2010.04158

Implications

- Magnetic fields can raise the CMB+BAO inferred H_0 to $\sim$70 km/s/Mpc

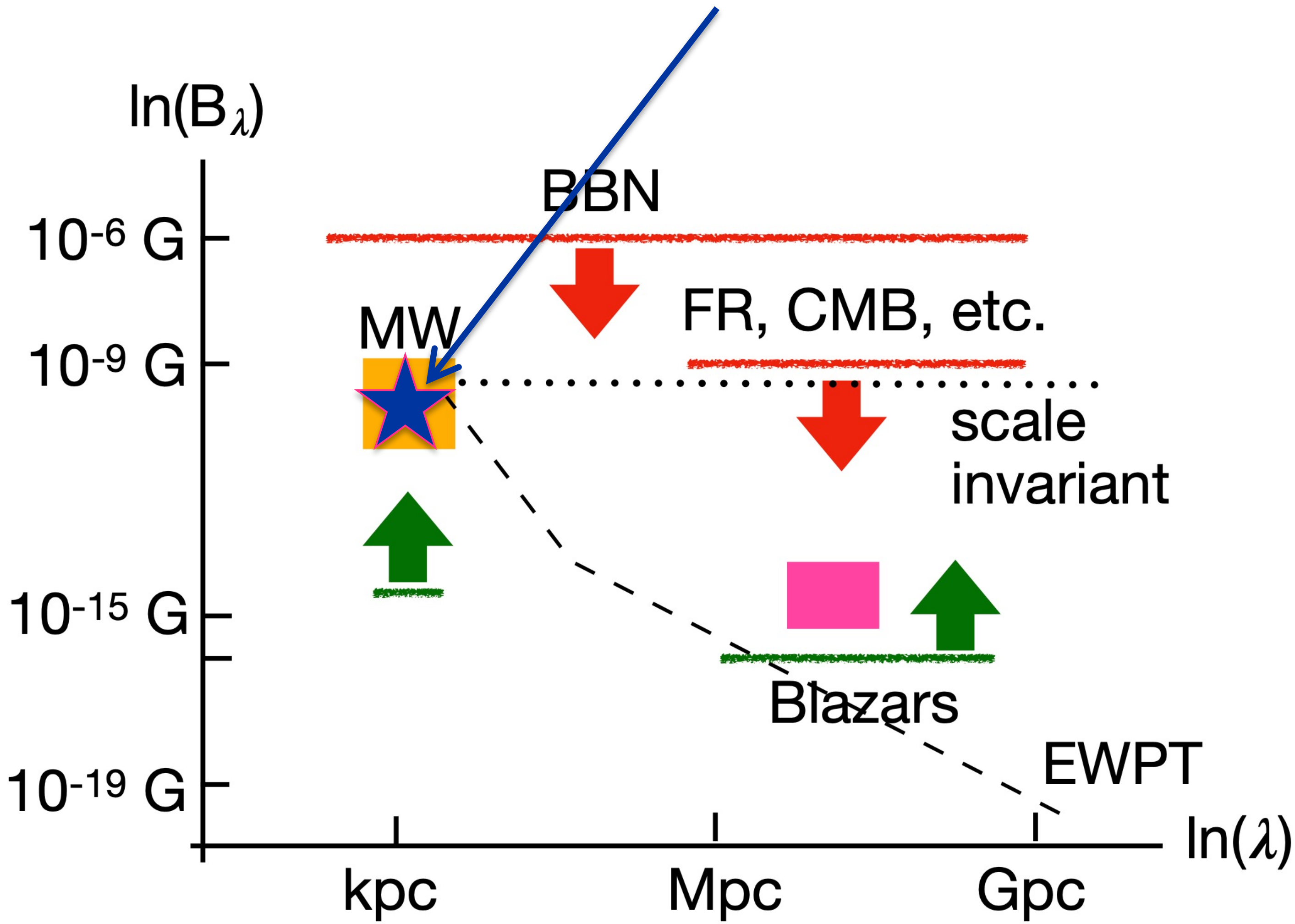
- The amount of clumping needed for this corresponds to $\sim$0.05-0.1 nano-Gauss pre-recombination magnetic field

Cosmological Magnetic Fields



Plot from T. Vachaspati, arXiv:2010.10525

Clumping required to relieve the H_0 tension

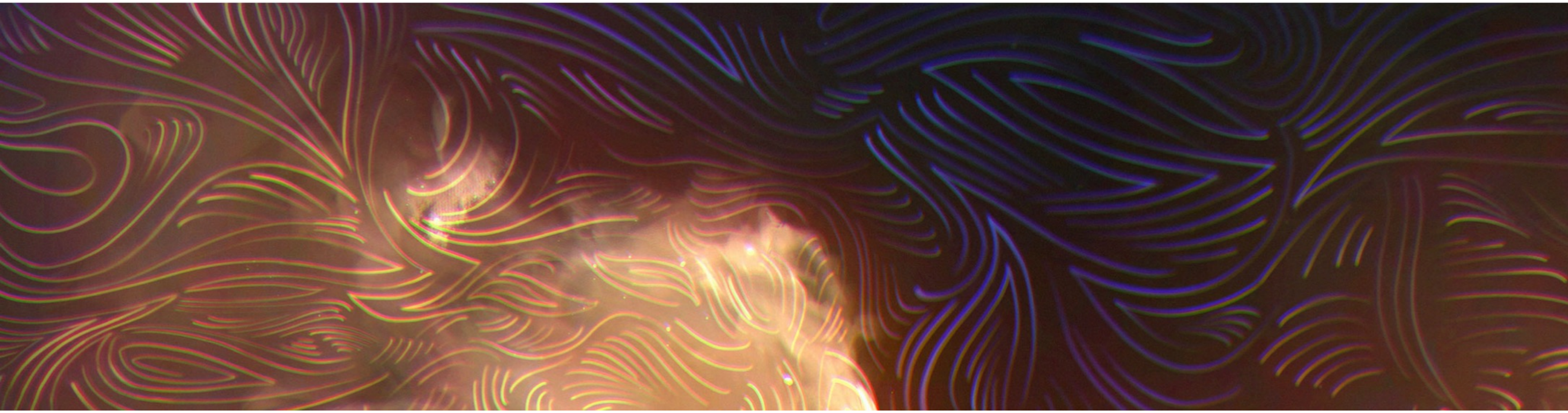


Plot from T. Vachaspati, arXiv:2010.10525

COSMOLOGY

The Hidden Magnetic Universe Begins to Come Into View

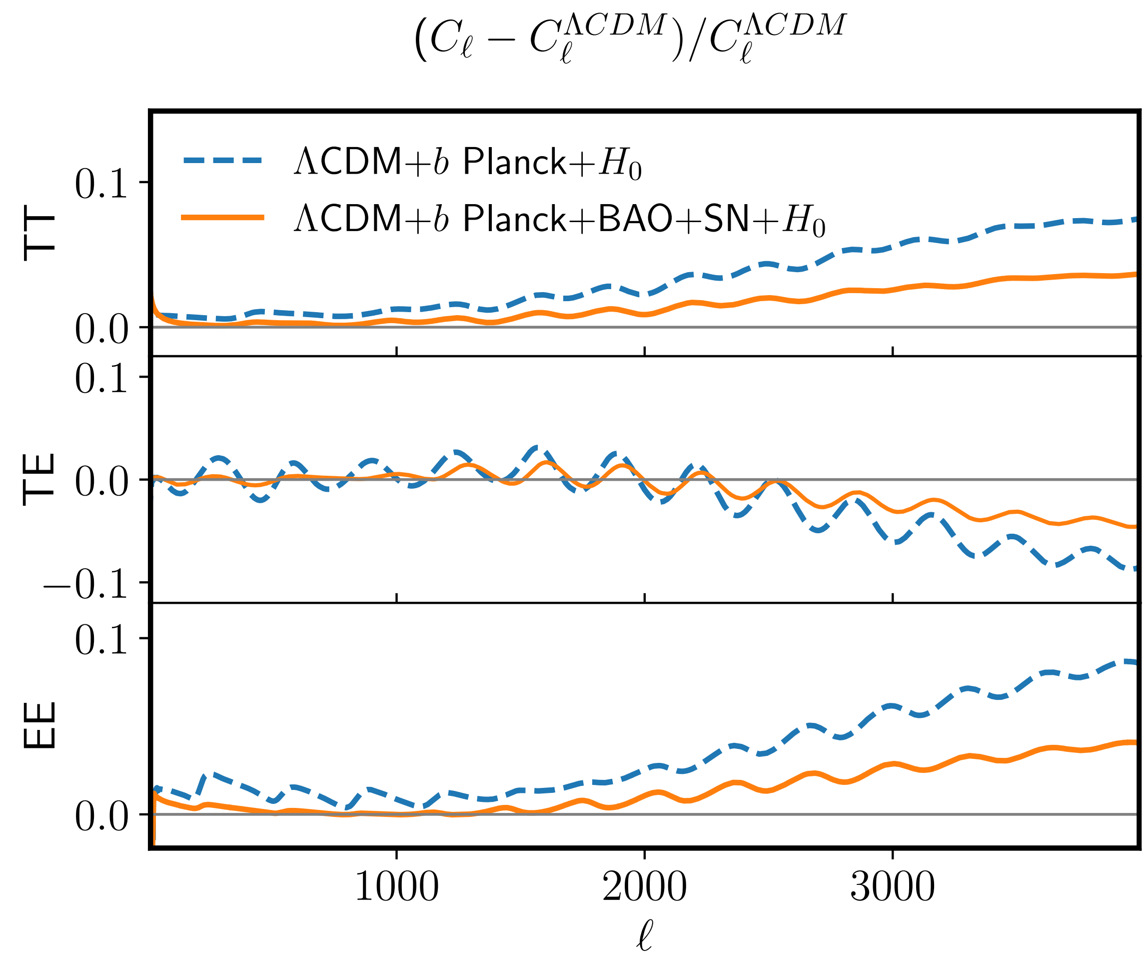
Astronomers are discovering that magnetic fields permeate much of the cosmos. If these fields date back to the Big Bang, they could solve a major cosmological mystery.



Implications

- Magnetic fields can 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, which is what one would need to explain the observed galactic, cluster and intergalactic fields
- This is a highly falsifiable proposal -- future observations will rule it out or land further support
- Clumping affects the amount of Silk damping that determines the anisotropy power at the high-l end of CMB spectra
- How about the recent high resolution CMB data from ACT and SPT-3G?
  (see also Thiele et al, arXiv:2105.03003, for ACT DR4 constraints on clumping)

The Silk Damping Tail



LCDM and LCDM+b make comparable predictions for CMB Temperature (T) and polarization (E) spectra for l<2000, but the differences becomes large at higher l

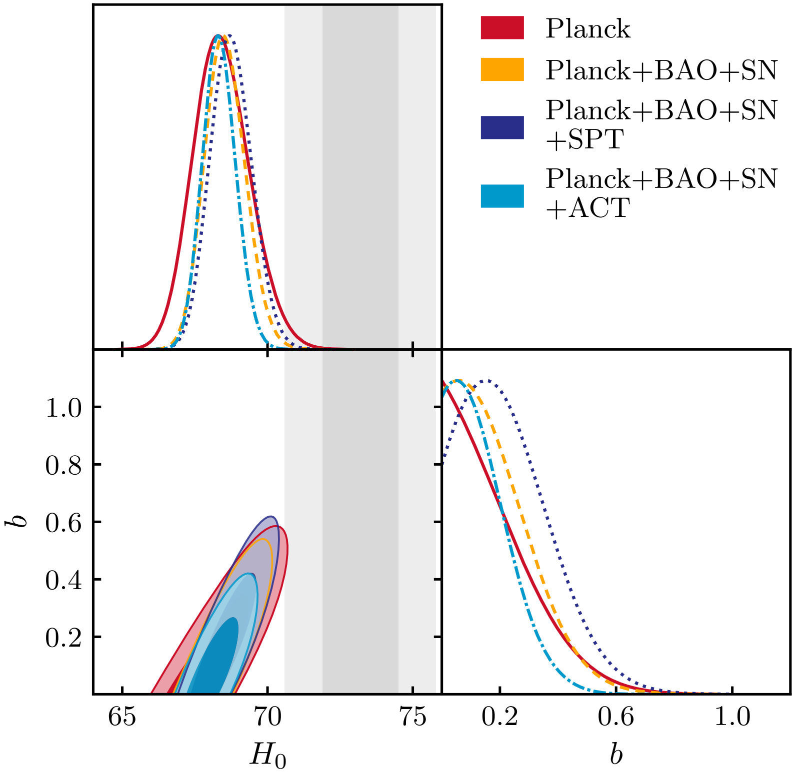
The new data (since Spring 2020)

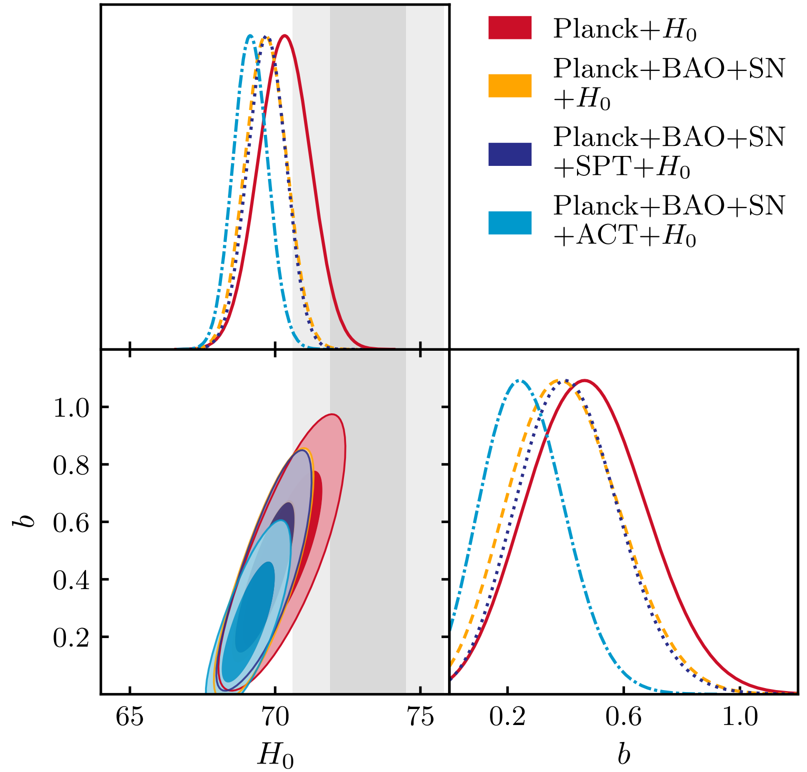
- New BAO from eBOSS DR16
  Alam et al, arXiv:2007.08991
- New SH0ES, H_0=73.2 +/- 1.3 km/s/Mpc
  Riess et al, arXiv:2012.08534

Do not notably change clumping constraints based on DR12 BAO and 2019 SH0ES

- ACT DR4 TT (600<l<4000), TE and EE (350<l<4000)
  Choi et al, arXiv:2007.07289
- SPT-3G Year 1, TE and EE (300<l<3000)
  Dutcher et al, arXiv:2101.01684

New constraints on clumping





	without SH0ES	with SH0ES
Planck+BAO+SN	$b<0.47$ (95%CL), $H_0=68.57 \pm 0.68$	$b=0.42 \pm 0.18$, $H_0=69.68 \pm 0.66$
with SPT	$b < 0.50$ (95%CL), $H_0=68.73 \pm 0.64$	$b = 0.43 \pm 0.17$, $H_0=69.74 \pm 0.61$
with ACT	$b < 0.34$ (95%CL), $H_0=68.30 \pm 0.55$	$b = 0.28 \pm 0.14$, $H_0=69.14 \pm 0.56$

S. Galli, LP, K. Jedamzik, L. Balkenhol, arXiv:2109.03816

Why is ACT DR4 so much more constraining compared to SPT-3G Y1?

- Not the $3000<l<4000$ band powers
- Not the TT: ACT constraints on b get stronger when TT is removed

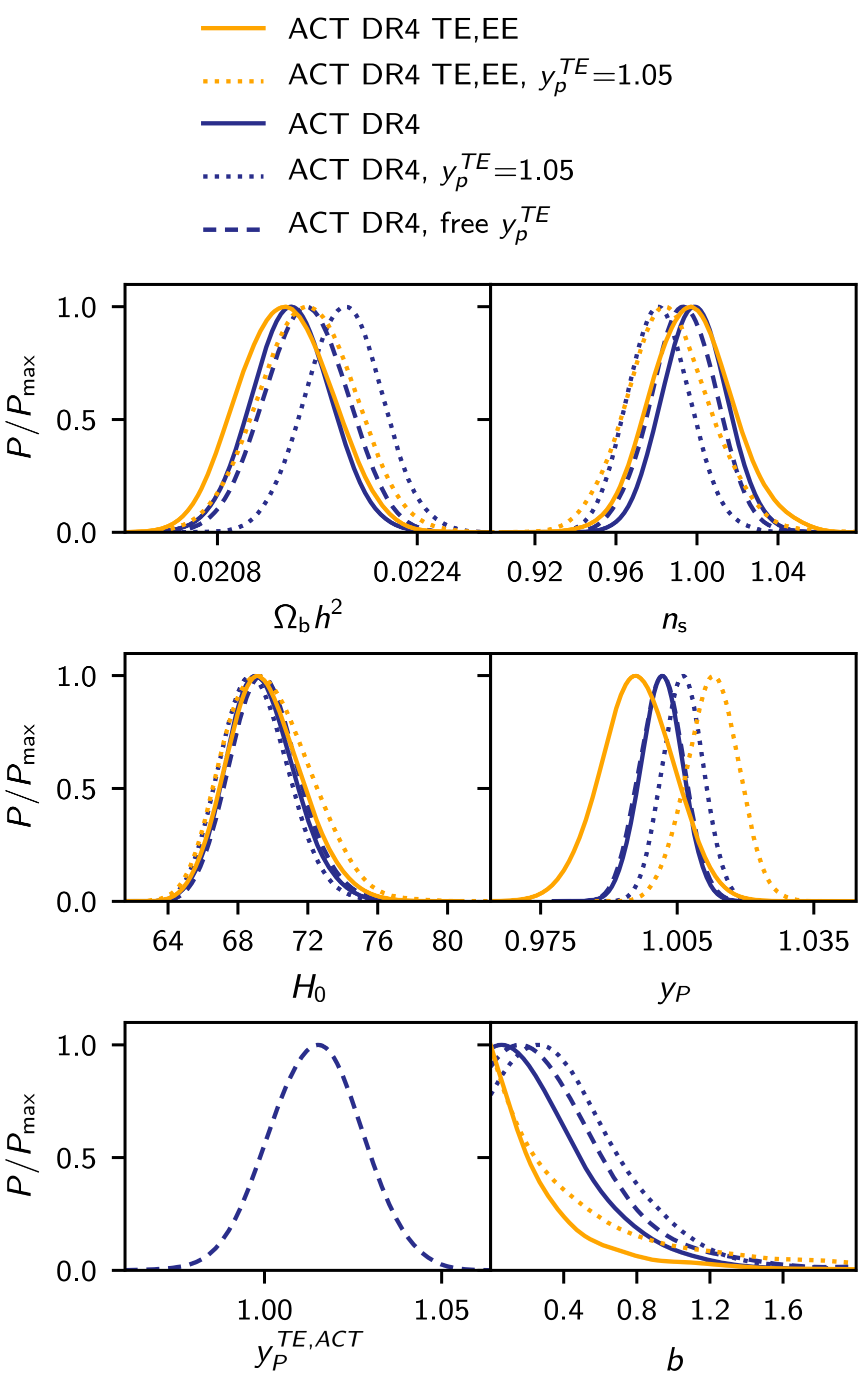
- LCDM based mock simulations show that ACT and SPT-3G TE+EE spectra should yield comparable constrains on b, while adding ACT TT should make them tighter

- Anomalously strong constraints coming from ACTDR4 TE+EE

- A 2.7σ tension between Planck and ACT DR4 in LCDM can be partially resolved by a 5% re-calibration of TE (Y^{TE}_{p}=1.05, *Aiola et al, arXiv:2007.07288*)

- While there is no apparent physical reason for recalibrating TE, doing so significantly relaxes the ACTDR4 constraints on clumping

S. Galli, LP, K. Jedamzik, L. Balkenhol, arXiv:2109.03816



S. Galli, LP, K. Jedamzik, L. Balkenhol, arXiv:2109.03816

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
  (not 73.2, but it could be all we need!)

- Primordial magnetic fields were not invented to solve the Hubble tension. A detection of clumping 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 (Simons Observatory, CMB=S4), along with comprehensive MHD simulations, will provide a conclusive test of this scenario