Primordial Magnetic Fields - a short review

A A quick summary of magnetic field observations

B Magnetogenesis ultra-brief summary

C Primer on magnetic field evolution in the early Universe

I spare you details, mention only the main conclusions, but all statements are verified by full numerical MHD simulations

D Primordial Magnetic Fields, the CMB, and the Hubble constant

E Towards the full computation of recombination in the presence of primordial magnetic fields

Karsten Jedamzik, LUPM, Montpellier

Magnetic fields are observed almost anywhere throughout the local Universe

in local galaxies with strength ~1-10 muGauss

in higher redshift galaxies with strength ~1-10 muGauss

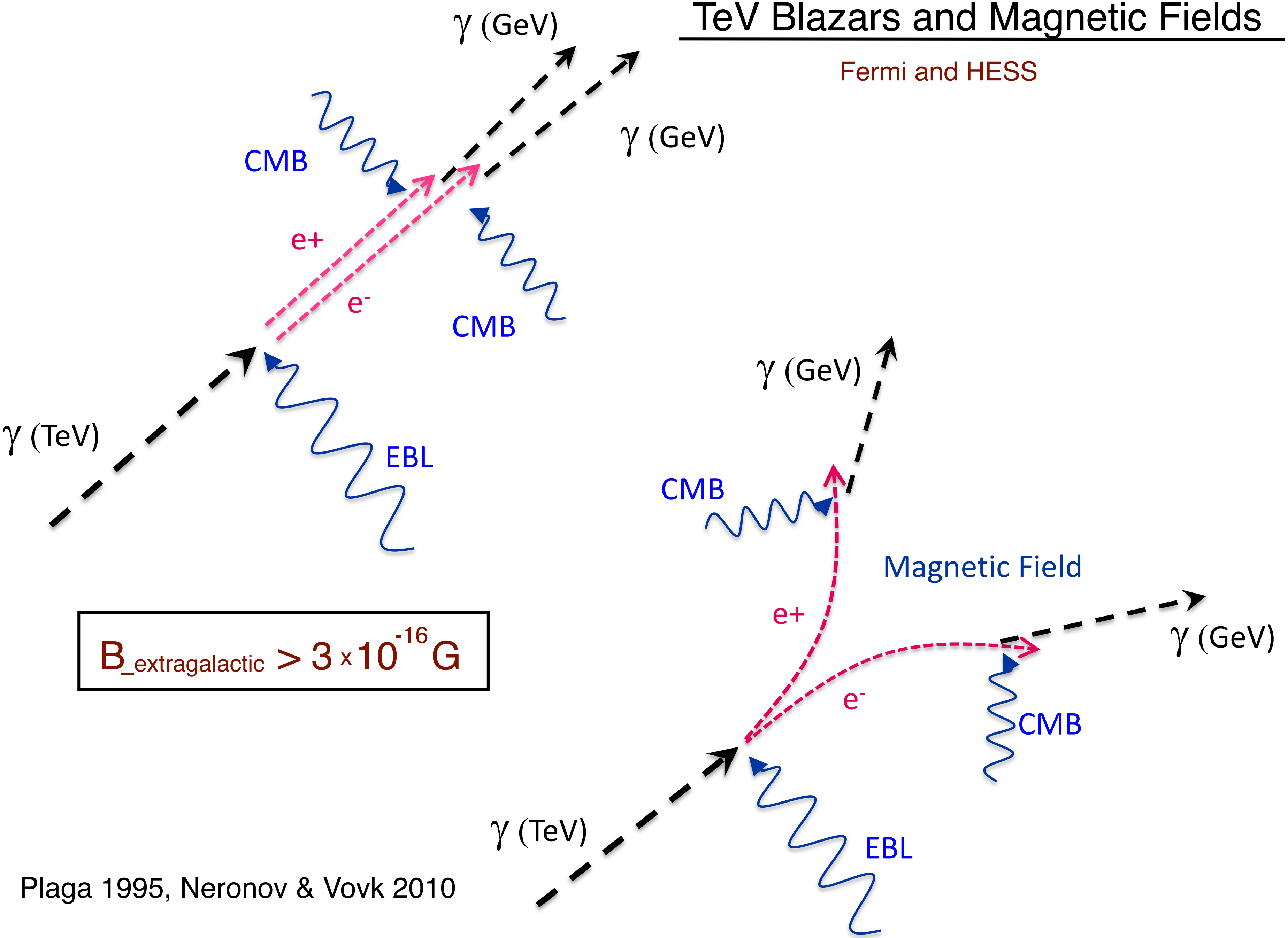
in clusters of galaxies with strength ~1-10 muGauss

in the extra-galactic medium with high volume filling factor, lower limit 10^{-9} muGauss

The question is not if, but how much, magnetic field survived from the early Universe

TeV Blazars and Magnetic Fields

Fermi and HESS



$$\boxed{B_{\text{\_extragalactic}} > 3 \times 10^{-16}\,\mathrm{G}}$$

Plaga 1995, Neronov & Vovk 2010

Magnetogenesis generalities:

phase transition produced magnetic fields: $B(L) \sim (L/L_0)^{5/2}$

Durrer & Caprini 2003

e.g. electroweak phase transition

- helicity is important

Vachaspati 1991

inflationary produced fields: $B(L) \sim (L/L_0)^{0}$

Widrow & Turner 88, Ratra 91

scale invariance difficult to achieve

Generalities of the EVOLUTION of cosmic magnetic fields in the early Universe

After an epoch of magneto-genesis fields decay freely, no active source

magnetic field energy is not conserved, the quantity which is conserved during the evolution is magnetic helicity

for most part MHD evolution is incompressible due to the large speed of sound, however …

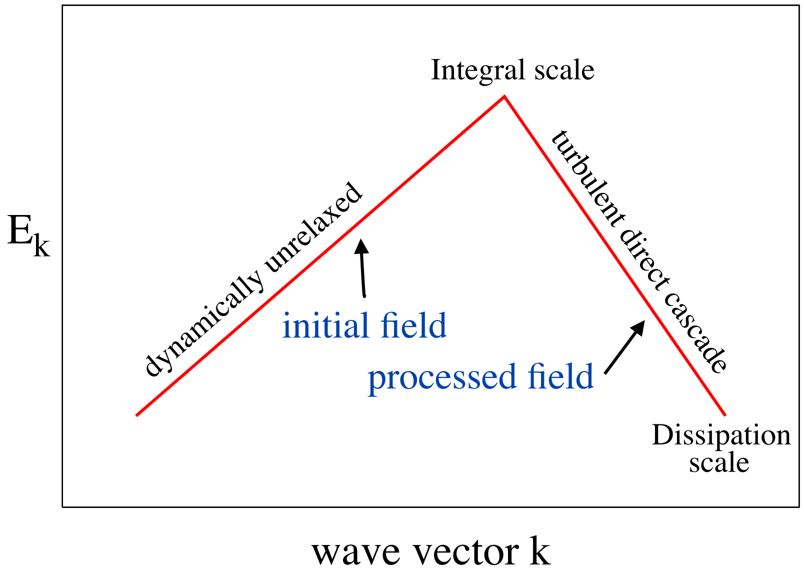
epochs where the viscosity is large and MHD is not turbulent but viscous

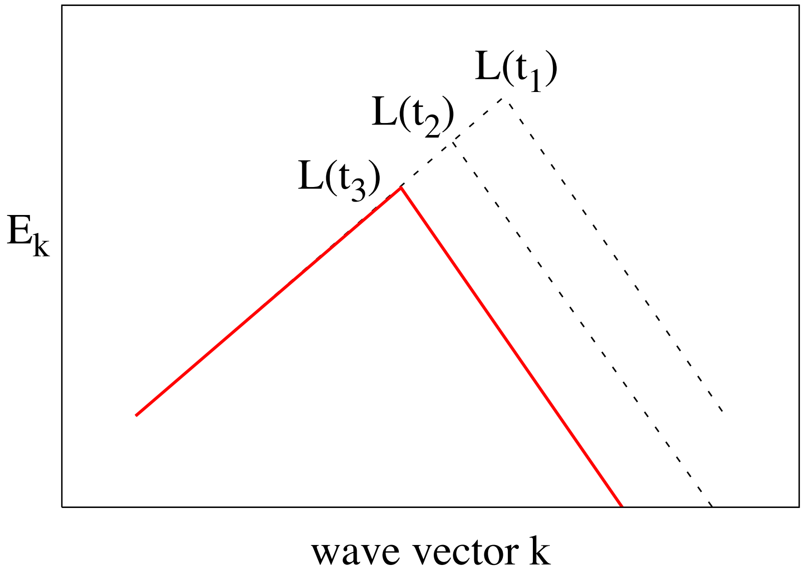
Only the smallest fraction of initial magnetic energy density at very high temperatures may survive to the present

for phase transition produced fields

Freely decaying magnetic fields

- magnetic field excite rotational fluid motions, eddies
- these eddies break up into ever smaller eddies
- at the dissipation scale the energy gets dissipated into heat





Time evolution of magnetic spectra

Condition for magnetic energy dissipation:

$$t_{\text{eddy}} \approx \frac{L_p(T)}{v(L)} \approx \frac{1}{H(T)} \approx t_H$$

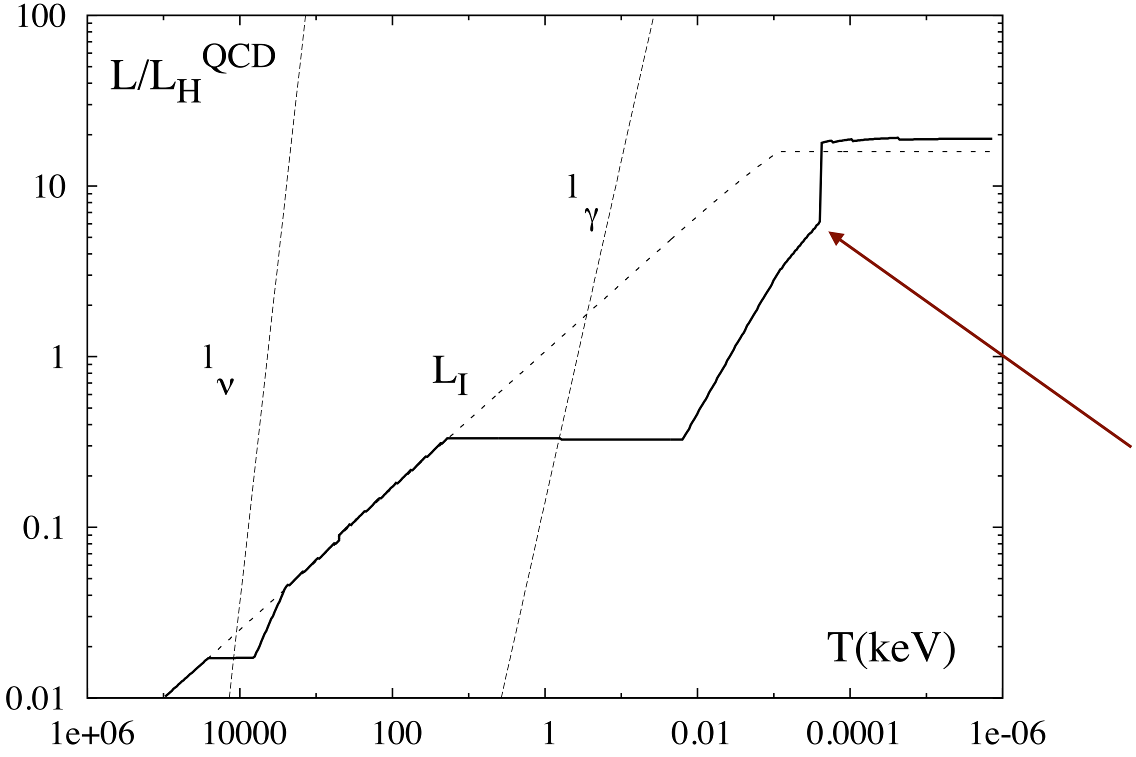
$v(L) \approx v_{\mathsf{A}}(L)\,;$ **when turbulent**

in viscous MHD different

Banerjee and Jedamzik 2004, Campanelli 2007,2014

Evolution of the magnetic coherence lengths in the early Universe

coherence length growth equals dissipation of magnetic energy



coherence length

recombination

cosmic temperature

When the photon mean free path becomes large, magnetic field evolution stops temporarily

Magnetic fields survive Silk damping

Banerjee & KJ 04

A present day correlation for primordial cosmic magnetic fields:

(pre gravitational collapse)

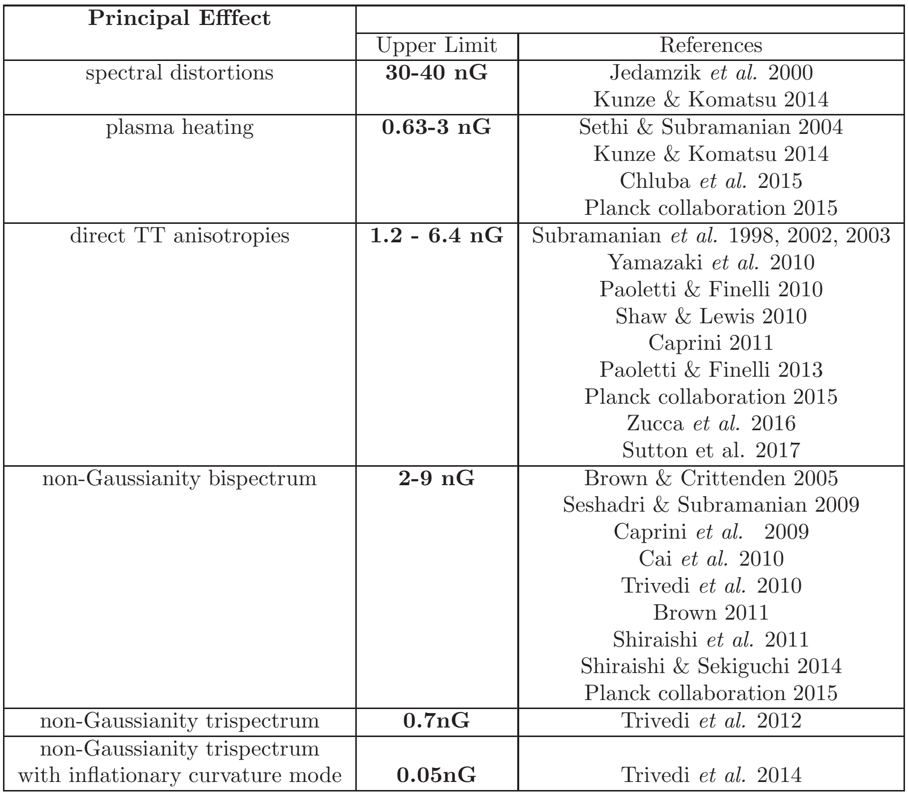
$$B_0 = 5 \times 10^{-12} \text{ Gauss} \left(\frac{L_c}{\text{kpc}} \right)$$

- Fields on smaller scales are dissipated

- this is the primordial field strength necessary to explain observed fields without dynamo

Banerjee and Jedamzik 2004

Primordial Magnetic Fields and the CMBR:



Principal Efffect		
	Upper Limit	References
spectral distortions	**30-40 nG**	Jedamzik *et al.* 2000 Kunze & Komatsu 2014
plasma heating	**0.63-3 nG**	Sethi & Subramanian 2004 Kunze & Komatsu 2014 Chluba *et al.* 2015 Planck collaboration 2015
direct TT anisotropies	**1.2 - 6.4 nG**	Subramanian *et al.* 1998, 2002, 2003 Yamazaki *et al.* 2010 Paoletti & Finelli 2010 Shaw & Lewis 2010 Caprini 2011 Paoletti & Finelli 2013 Planck collaboration 2015 Zucca *et al.* 2016 Sutton et al. 2017
non-Gaussianity bispectrum	**2-9 nG**	Brown & Crittenden 2005 Seshadri & Subramanian 2009 Caprini *et al.* 2009 Cai *et al.* 2010 Trivedi *et al.* 2010 Brown 2011 Shiraishi *et al.* 2011 Shiraishi & Sekiguchi 2014 Planck collaboration 2015
non-Gaussianity trispectrum	**0.7nG**	Trivedi *et al.* 2012
non-Gaussianity trispectrum with inflationary curvature mode	**0.05nG**	Trivedi *et al.* 2014

21 cm and galaxy formation Katz et al 2021

small-scale baryon inhomogeneities set the strongest limit :

~0.01nG (phase transiton) 0.1nG (inflation)

K.J. & Saveliev

-> potential for discovery

Why baryon inhomogeneities on small ~ kpc scales ?

photons are free-streaming on these scales i.e. cs = c/sqrt(3) -> cb

Viscous MHD evolution with free-streaming photon drag:

$$\frac{d\mathbf{v}}{dt} + (\mathbf{v}\cdot\nabla)\cdot\mathbf{v} + c_s^2\frac{\nabla\varrho}{\varrho} = -\alpha\mathbf{v} - \frac{1}{4\pi\varrho}\left(\frac{1}{2}\nabla\mathbf{B}^2 - \mathbf{B}\cdot\nabla\mathbf{B}\right)$$

$$\frac{d\varrho}{dt} + \nabla(\varrho\mathbf{v}) = 0$$

the three important terms

back of the envelope estimate:

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

Jedamzik and Abel 2011

It doesn't take much field:

$$c_s = 6.33 \frac{\mathrm{km}}{\mathrm{s}}$$

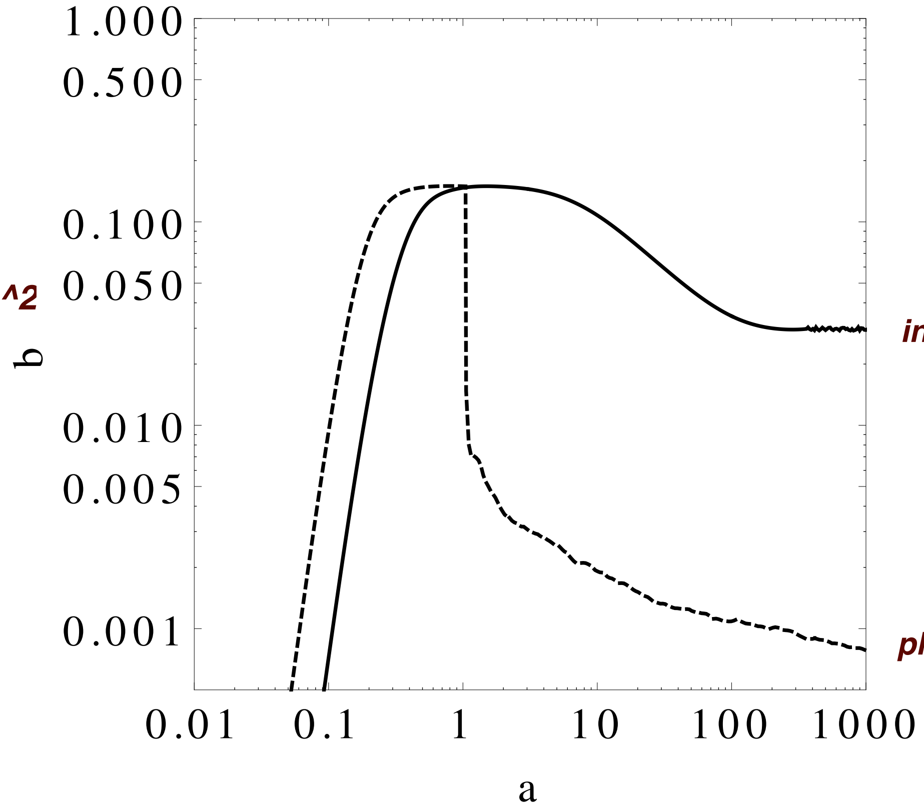
isothermal speed of sound

$$v_A = \frac{B}{\sqrt{4\pi\varrho}} = 5.79 \frac{\mathrm{km}}{\mathrm{s}} \left(\frac{B}{0.04\mathrm{nG}} \right)$$

Full MHD simulations:

clumping factor:

b = <rho^2-<rho>^2>/<rho>^2



inflationary produced fields

phase transition produced fields

final field 10 pG

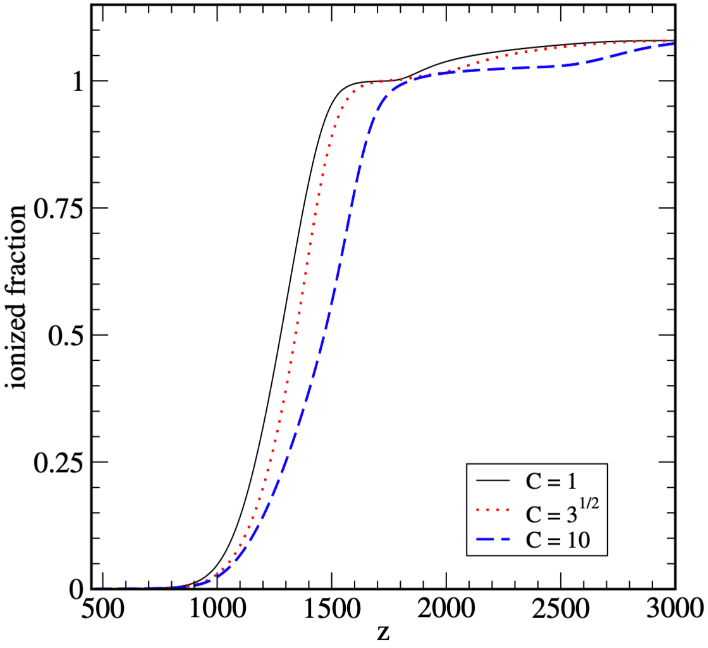
scale factor (a=1 at recombination)

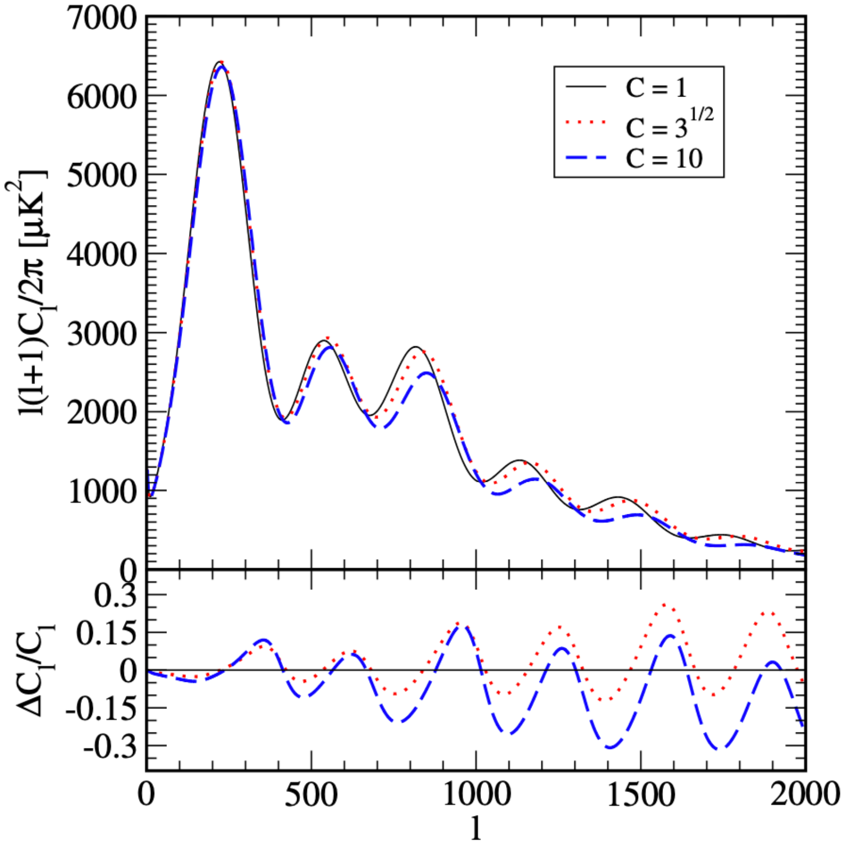
Jedamzik and Saveliev 2018

Inhomogeneities enhance the recombination rate

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

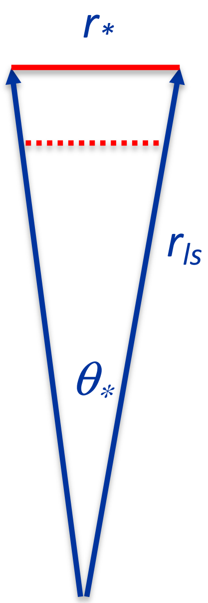
$$\langle n_e^2\rangle \;>\; \langle n_e\rangle^2$$

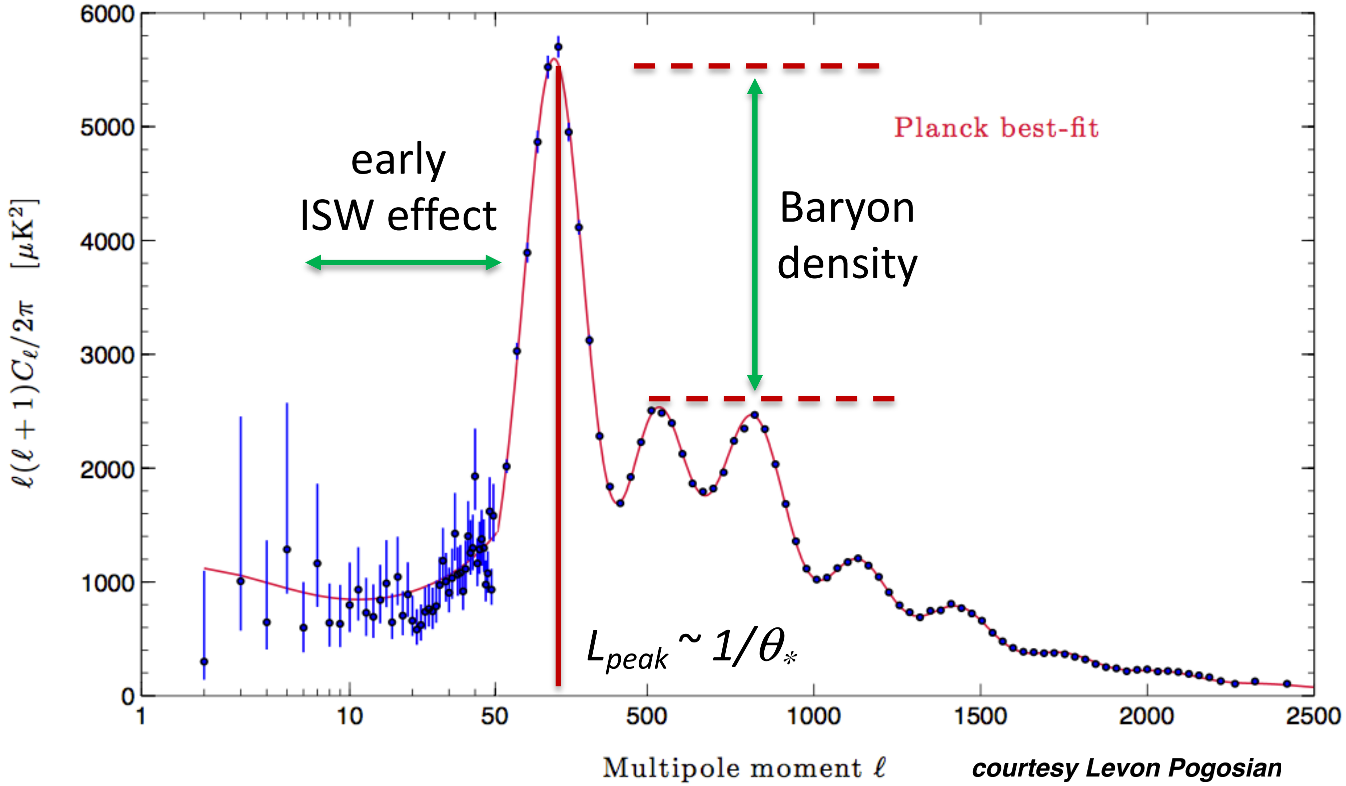




Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

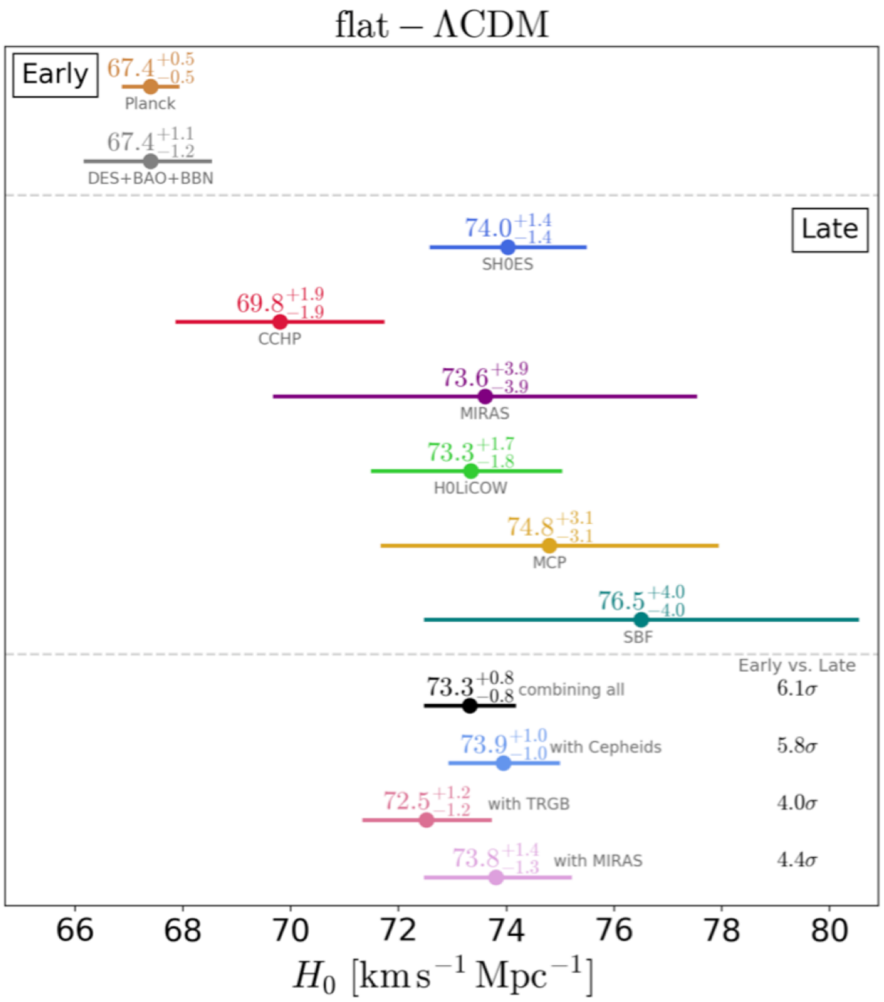
How does CMB constrain H0?





courtesy Levon Pogosian

The Hubble tension



Tensions between the Early and the Late Universe

L. Verde, T. Treu, A. Riess, arXiv:1907.10625

The tension is between the measurements that require calculating r_* and r_{drag} and those that do not

Can baryon clumping before recombination due to primordial magnetic fields help the tension ?

three zone toy model M1 and M2, missing:

⟶ adhoc baryon probability

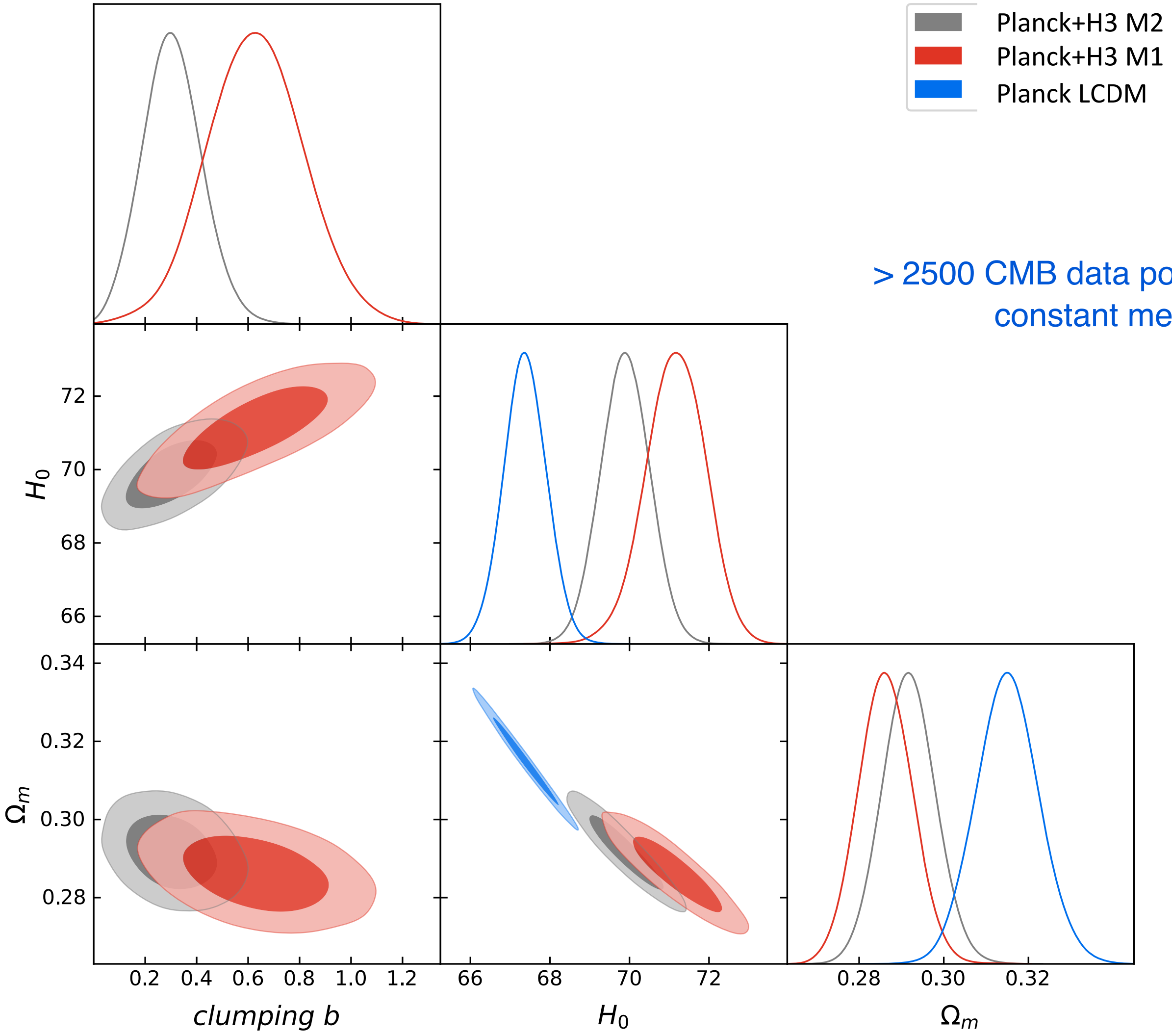
⟶ no evolution

⟶ no velocity gradients

⟶ no Lyman-alpha transport

K.J & Saveliev 19, K.J. & Pogosian 20, Thiele et al 21, Galli et al 21, Rashkovetskyi et al 21

LCDM + clumping: Fitting Planck and 3 Hubble determinations

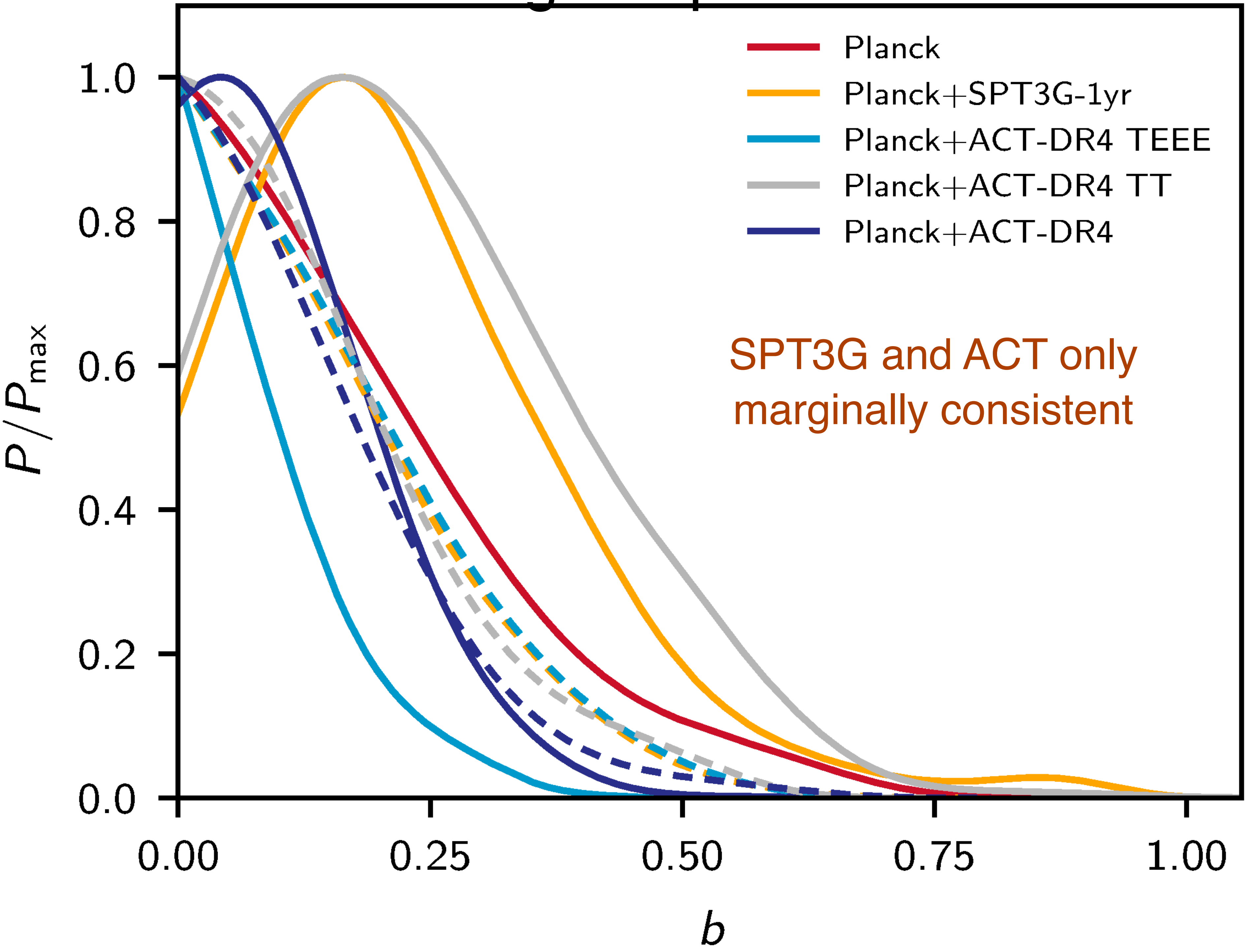


> 2500 CMB data points + only 3 Hubble constant measurements

a clear detection of clumping!

at almost 4 sigma for M1

with high ell polarization



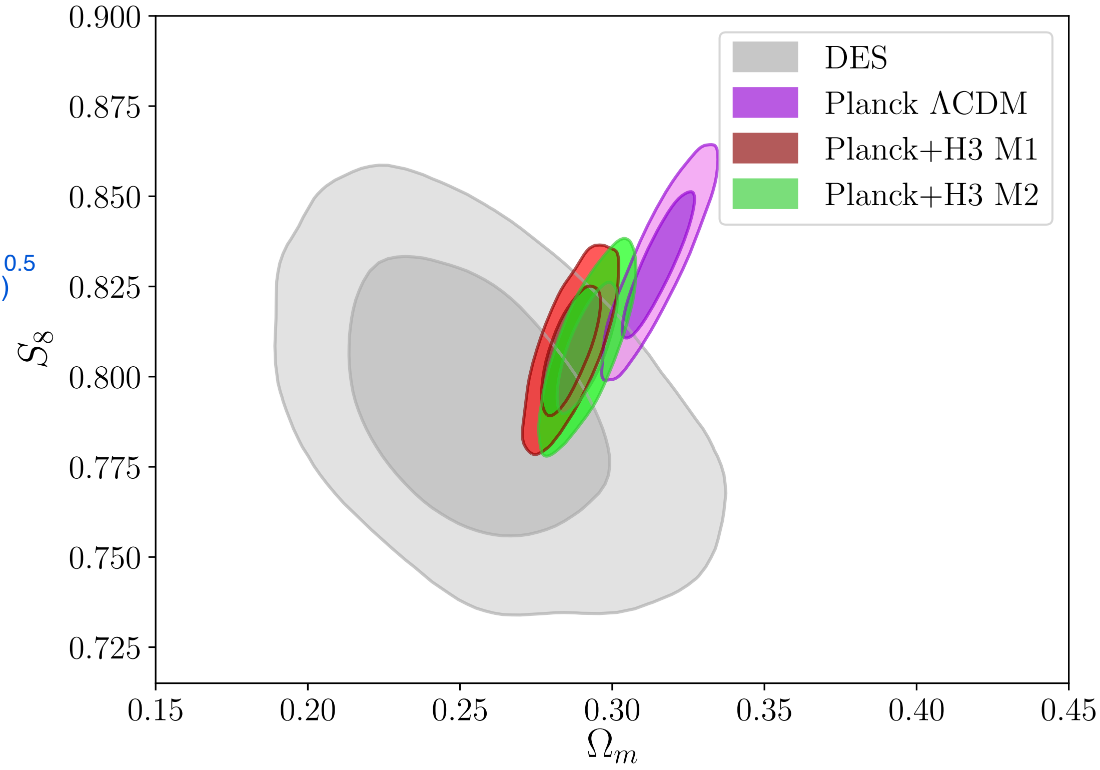
SPT3G and ACT only marginally consistent

Galli et al. 21 **Thiele et al 21**

Relieving the S_8-Ω_m tension

S8 = sigma8 (Omega_m/0.3)$^{0.5}$

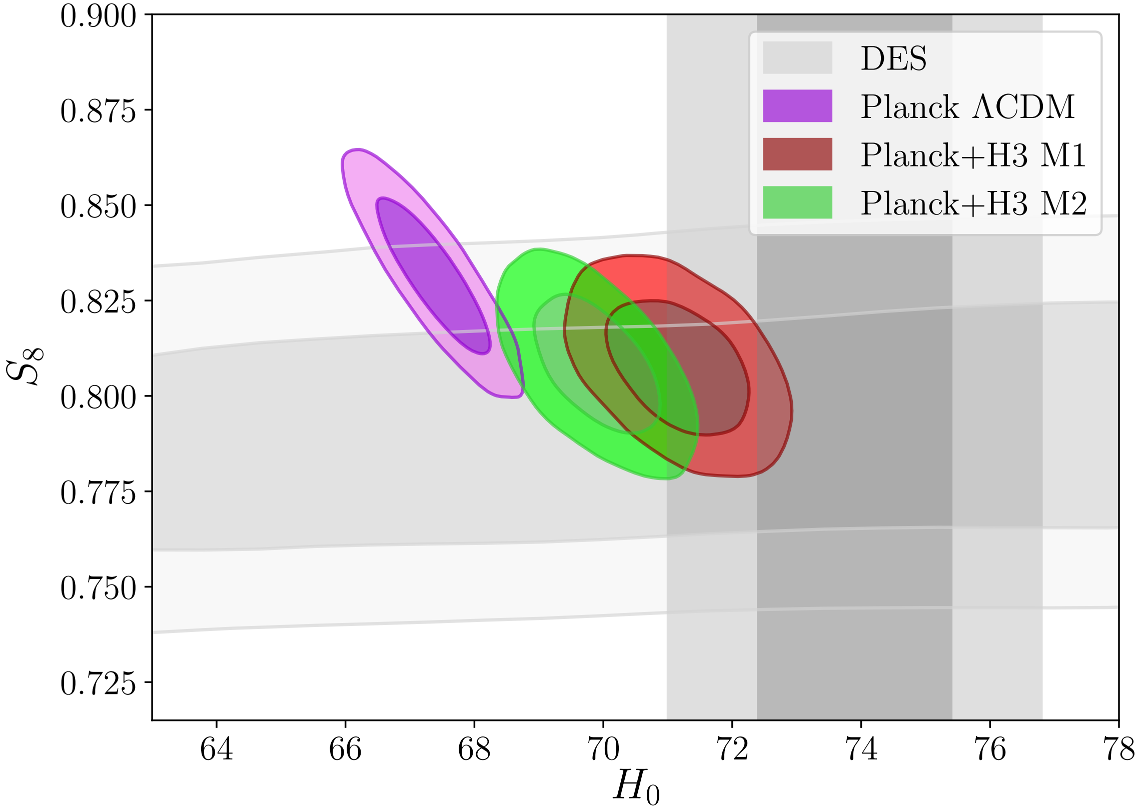
sigma8 = drho/rho at
8Mpc h^-1



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

K. Jedamzik and L. Pogosian, arXiv:2004.09487

Relieving both tension in one plot



K. Jedamzik and L. Pogosian, arXiv:2004.09487

Alternative sources of small-scale baryon clumping:

Enhanced small-scale adiabatic fluctuations do not survive Silk-damping

Extra baryon isocurvature fluctuations violate BBN constraints

B-balls or quark nuggets evaporating before recombination also violate BBN constraints

Baryon inhomogeneities produced by cosmic strings may not reach high volume filling factors

Implications:

Primordial magnetic fields induce clumping before recombination which may relieve the Hubble tension

Clear predictions for this essentially one-parameter family of non-exotic amendement of LCDM can be made

More detailed theoretical calculations on their impact on the CMB have to be performed

Interestingly, the approximately required field strength to relieve the Hubble tension would explain cosmic magnetic fields in the current Universe

The PMF scenario is testable by future CMB and gamma ray observations

However, PMFs can not be a full resolution of the Hubble tension,may only reach values of H around 70

What is needed:

A complete calculation of PMFs influencing recombination

Cosmic Recombination - a Quick Summary

$$e + H^{+} \rightarrow H^{0} + \gamma$$

$$e + He^{+} \rightarrow He^{0} + \gamma$$

- direct recombination into the ground state, immediately ionizes elsewhere -> no net recombination
- ionization into excited states, produces a casade of resonance photons, with the last often a Lyman-alpha photon (i.e. 2p->1s transition). This Lya photon excites a neutral atom elsewhere, The excited 2p atom will to the highest probability be photo-ionized by CMB photons ->no net recombination
- frequent attemps of recombining drives the Lya occupation number to super-thermal values, such that n2p/n1s is out of equilibrium
- there is only one way to have a net recombination, loss of Lya resonance photons, for hydrogen there are two possibilities:
    - a slow two-gamma transition from 2s->1s + 2gamma
    - redshifting of Lya photons out of resonance by Hubble expansion

Inhomogeneous Recombination due to Primordial Magnetic Fields

in preparation with Tom Abel

physical effects to be considered:

- → clumping of baryons
- → evolution of this clumping
- → Lyman-alpha photon transport
- → locally varying speed of sound of fluid
- → locally varying photon drag on fluid
- → loss of Lya photons due to peculilar motions

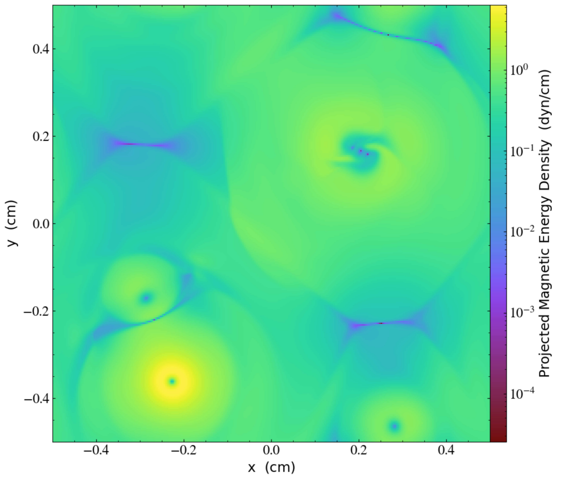
we combined:

- → MHD fluid code ENZO Greg Bryan et al 2014
  (note: three other codes failed)
- → new cosmic recombination code
- → proper Monte-Carlo simulations of Lya loss

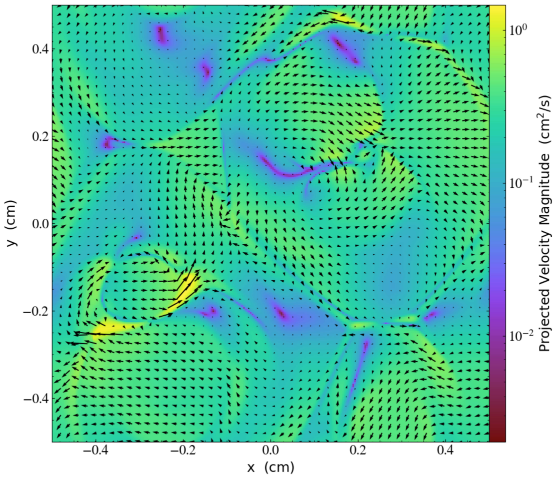
we are not aware of any missing physics

First 2D results: Box 3 kpc, vA = 3 cS

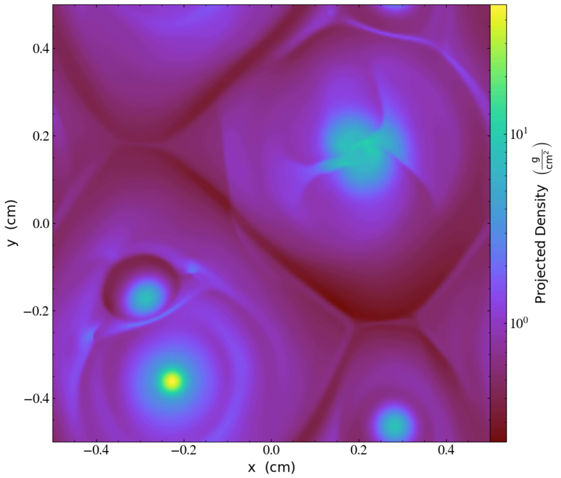
Magnetic energy density



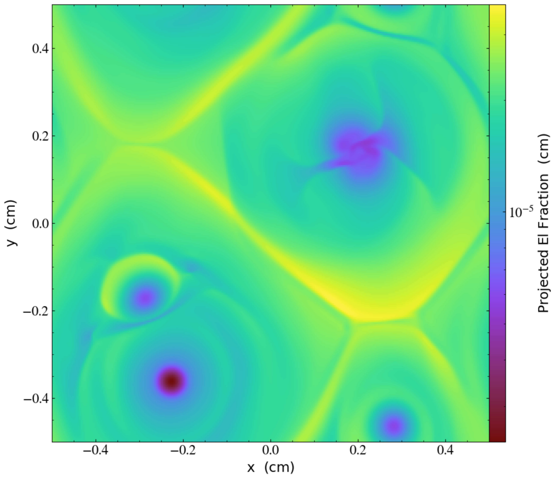
Fluid velocities



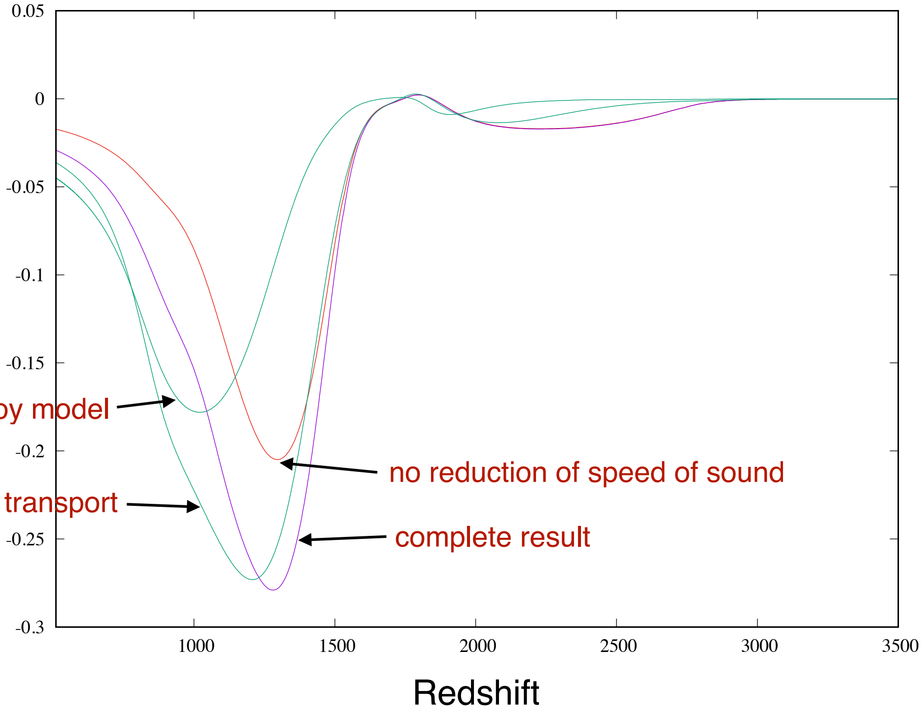
Baryon density



Ionization fraction



Relative change to LCDM ionization fraction Xe

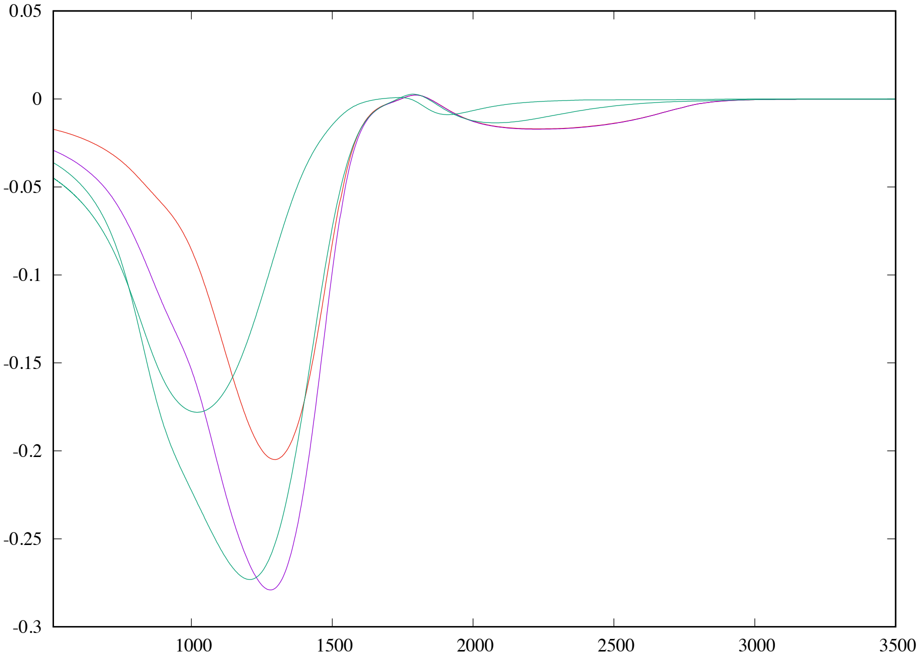


comparison 3 zone toy model

no Lyman-alpha transport

no reduction of speed of sound

complete result


0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
1000
1500
2000
2500
3000
3500

Why is it difficult to solve the Hubble tension ?

with Levon Pogosian and Gong-Bo Zhao

CMBR Doppler peak at angle:

$$\theta_\star = \frac{r_\star}{D_A(z_\star)} = \frac{\int_{z_\star}^{\infty} c_s(z)\mathrm{d}z/H(z)}{\int_0^{z_\star} c\,\mathrm{d}z/H(z)}$$

$$\mathrm{Planck\,LCDM} \rightarrow H_0 = 67.36 \pm 0.54\,\mathrm{km/s/Mpc}$$

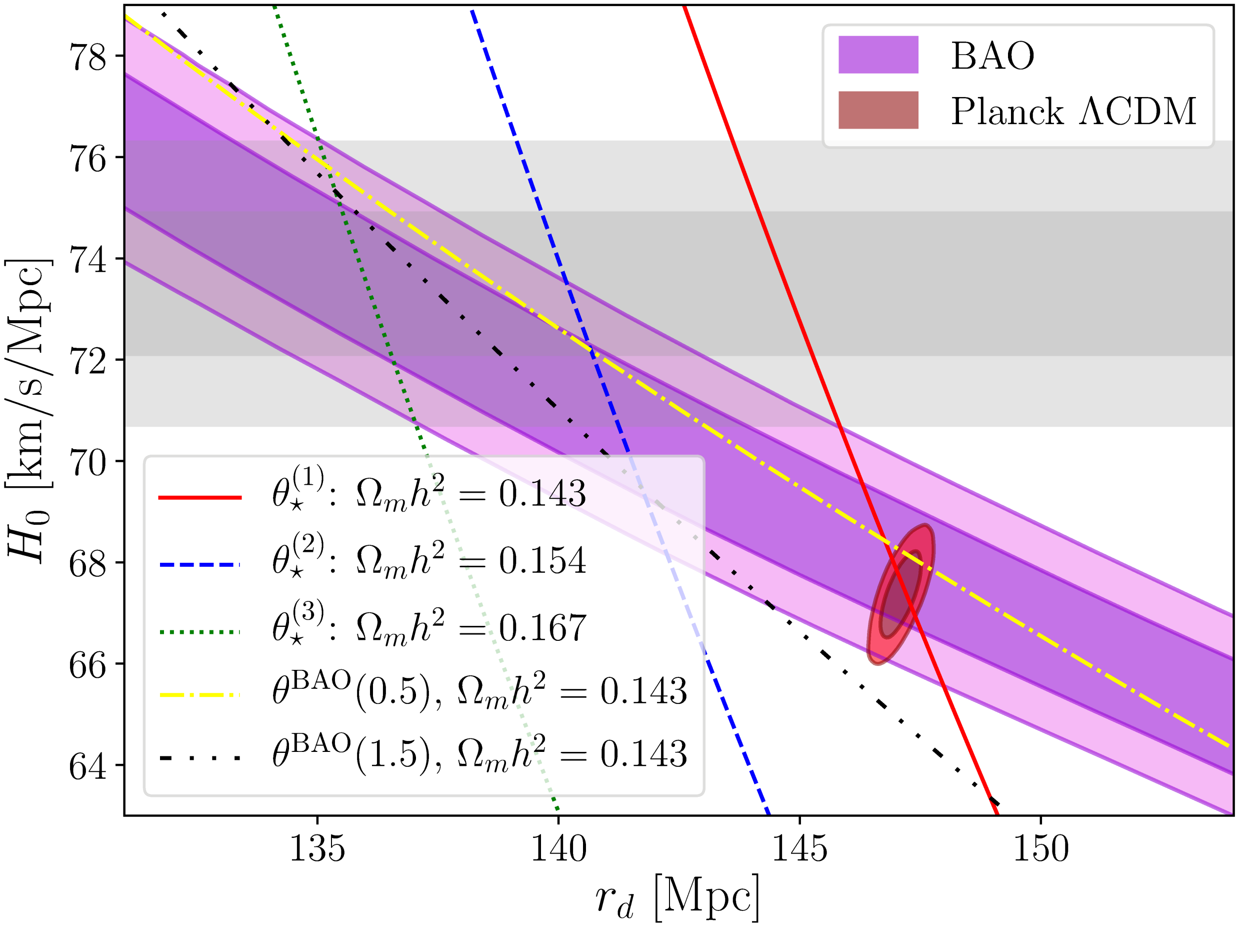
$$\mathrm{local\,measurements,\,i.e.SH0ES} \rightarrow H_0 = 73.5 \pm 1.4\,\mathrm{km/s/Mpc}$$

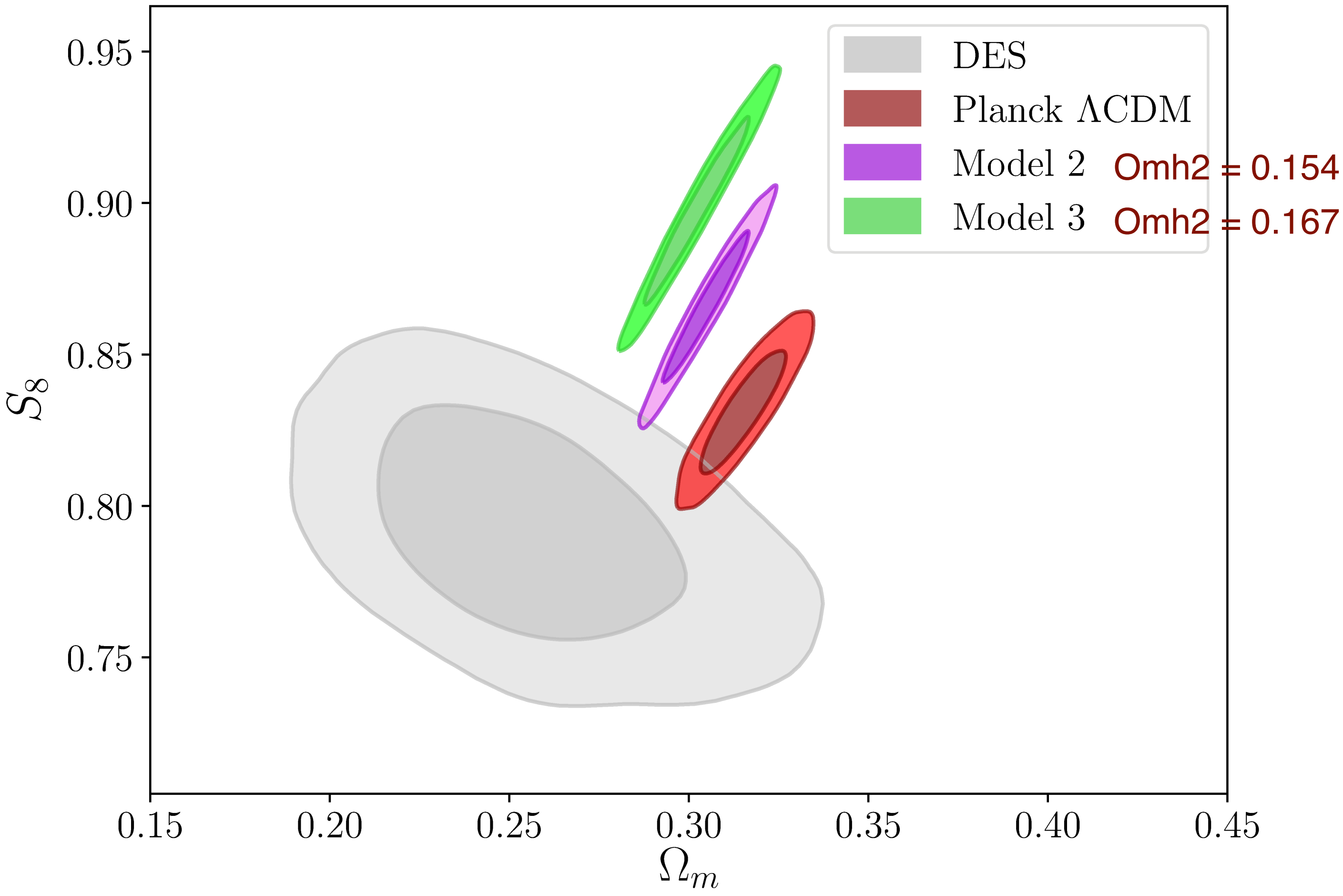
treat $r_\star$ as a free parameter

$$r_\star = \theta_\star \int_0^{z_\star} \frac{2998\,\mathrm{Mpc}\,\mathrm{d}z}{\omega_m^{1/2}\sqrt{(1+z)^3 + h^2/\omega_m - 1}}$$

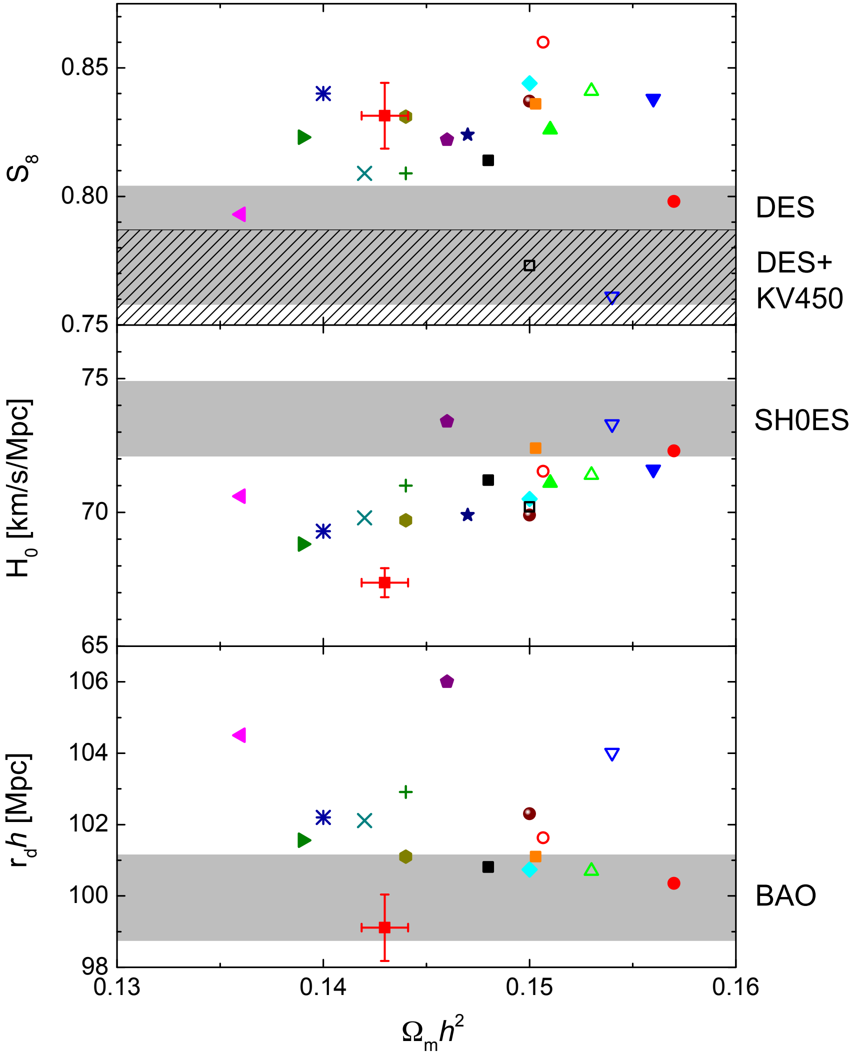
$$\omega_m = \Omega_m \mathrm{h}^2$$

very similar relationship from baryon accoustic oscillations !


🟪 BAO
🟥 Planck ΛCDM
$\theta_\star^{(1)}$: $\Omega_m h^2 = 0.143$
$\theta_\star^{(2)}$: $\Omega_m h^2 = 0.154$
$\theta_\star^{(3)}$: $\Omega_m h^2 = 0.167$
$\theta^{\mathrm{BAO}}(0.5)$, $\Omega_m h^2 = 0.143$
$\theta^{\mathrm{BAO}}(1.5)$, $\Omega_m h^2 = 0.143$
H_0 [km/s/Mpc]
78
76
74
72
70
68
66
64
135
140
145
150
r_d [Mpc]

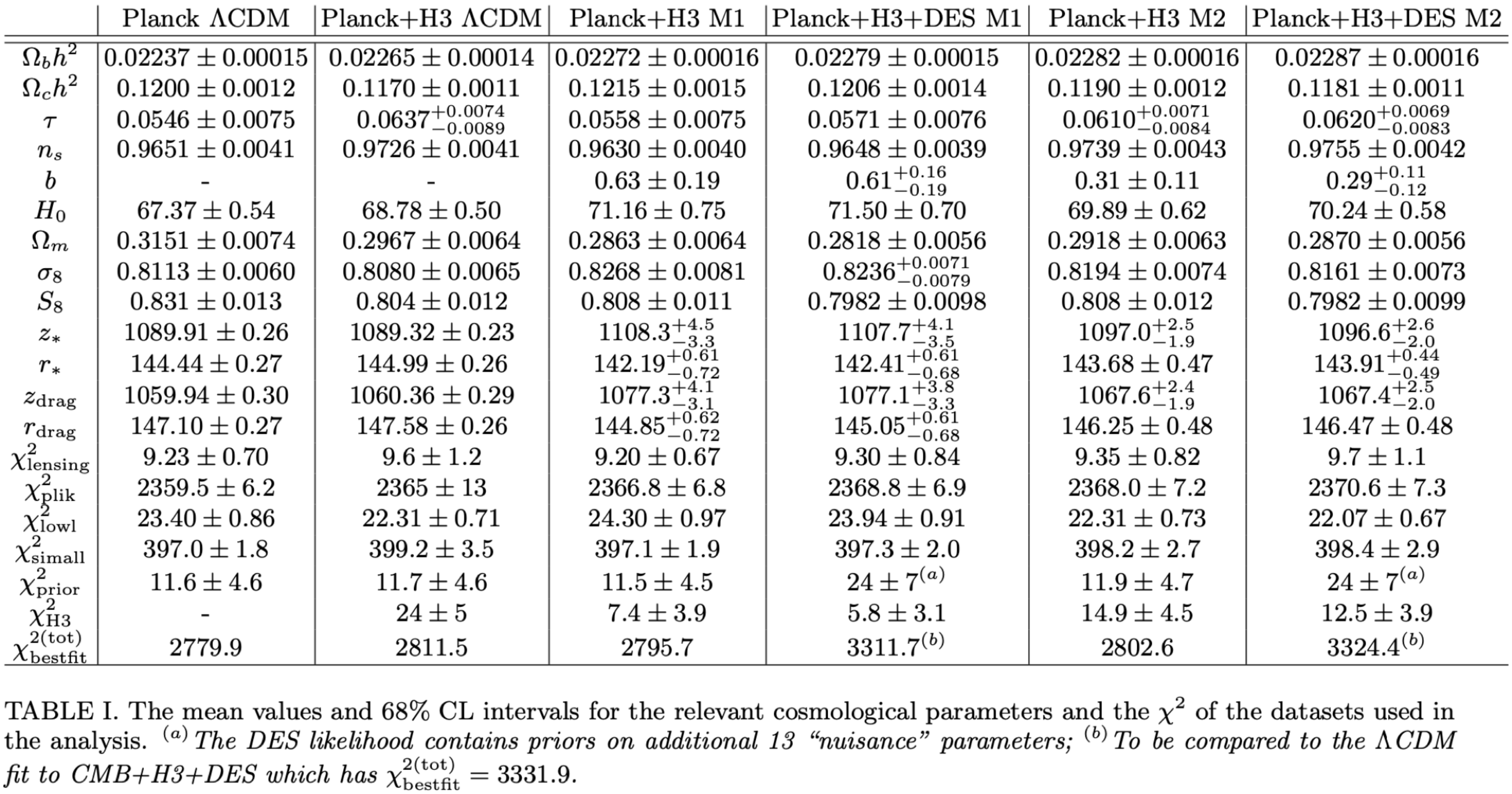


-> when only changing the sound horizon impossible to reconcile CMB peak positions, SH0ES, BAO, and DES


S_8
0.85
0.80
0.75
DES
DES+
KV450
H_0 [km/s/Mpc]
75
70
65
SH0ES
r_d h [Mpc]
106
104
102
100
98
BAO
0.13
0.14
0.15
0.16
Ω_m h^2

■ 1902.00534 (Kreisch et al 2019; moderately interacting)
● 1902.00534 (Kreisch et al 2019; strongly interacting)
▲ 1811.04083 (Poulin et al 2018; EDE model 1)
▼ 1811.04083 (Poulin et al 2018; EDE model 2)
◆ 1904.01016 (Agrawal et al 2019A)
◀ 1902.10636 (Pandey et al 2019; decaying DM; PLC+R18)
▶ 1902.10636 (Pandey et al 2019; decaying DM; Planck+JLA+BAO+R18)
⬢ 1904.01016 (Agrawal et al 2019A; Neff)
★ 2006.13959 (Gonzalez et al 2020; ultralight scalar decay)
⬟ 1811.03624 (Chiang et al 2018; non-standard recombination 1)
● 1811.03624 (Chiang et al 2018; non-standard recombination 2)
+ 2004.09487 (Jedamzik & Pogosian 2020; PMF model 1)
× 2004.09487 (Jedamzik & Pogosian 2020; PMF model 2)
✳ 1906.08261 (Agrawal et al 2019B; swampland & fading dark matter)
■ 2007.03381 (Sekiguchi et al 2020; early recombination)
■ ΛCDM
□ 1507.04351 (Lesgourgues et al 2015; DM-dark interaction)
○ 1909.04044 (Escudero & Witte 2019; Neutrino sector - extra radiation)
△ 2009.00006 (Niedermann & Sloth 2020; new EDE)
▽ 1803.10229 (Kumar et al 2018; dark-matter photon interactions;
massive neutrinos, Neff > 3.04)

The effect on other parameters



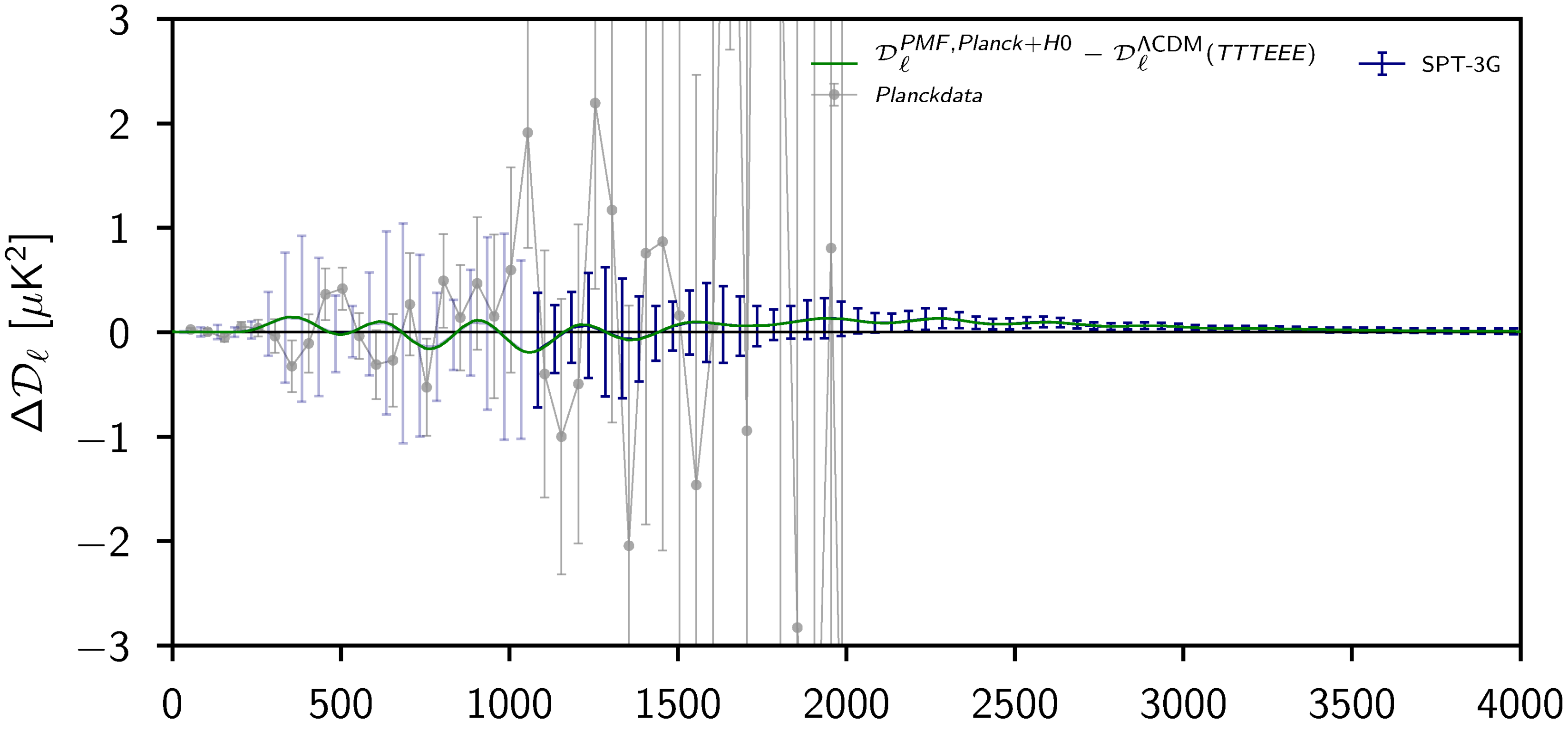
	Planck ΛCDM	Planck+H3 ΛCDM	Planck+H3 M1	Planck+H3+DES M1	Planck+H3 M2	Planck+H3+DES M2
$\Omega_b h^2$	0.02237 ± 0.00015	0.02265 ± 0.00014	0.02272 ± 0.00016	0.02279 ± 0.00015	0.02282 ± 0.00016	0.02287 ± 0.00016
$\Omega_c h^2$	0.1200 ± 0.0012	0.1170 ± 0.0011	0.1215 ± 0.0015	0.1206 ± 0.0014	0.1190 ± 0.0012	0.1181 ± 0.0011
τ	0.0546 ± 0.0075	$0.0637^{+0.0074}_{-0.0089}$	0.0558 ± 0.0075	0.0571 ± 0.0076	$0.0610^{+0.0071}_{-0.0084}$	$0.0620^{+0.0069}_{-0.0083}$
n_s	0.9651 ± 0.0041	0.9726 ± 0.0041	0.9630 ± 0.0040	0.9648 ± 0.0039	0.9739 ± 0.0043	0.9755 ± 0.0042
b	-	-	0.63 ± 0.19	$0.61^{+0.16}_{-0.19}$	0.31 ± 0.11	$0.29^{+0.11}_{-0.12}$
H_0	67.37 ± 0.54	68.78 ± 0.50	71.16 ± 0.75	71.50 ± 0.70	69.89 ± 0.62	70.24 ± 0.58
Ω_m	0.3151 ± 0.0074	0.2967 ± 0.0064	0.2863 ± 0.0064	0.2818 ± 0.0056	0.2918 ± 0.0063	0.2870 ± 0.0056
σ_8	0.8113 ± 0.0060	0.8080 ± 0.0065	0.8268 ± 0.0081	$0.8236^{+0.0071}_{-0.0079}$	0.8194 ± 0.0074	0.8161 ± 0.0073
S_8	0.831 ± 0.013	0.804 ± 0.012	0.808 ± 0.011	0.7982 ± 0.0098	0.808 ± 0.012	0.7982 ± 0.0099
z_*	1089.91 ± 0.26	1089.32 ± 0.23	$1108.3^{+4.5}_{-3.3}$	$1107.7^{+4.1}_{-3.5}$	$1097.0^{+2.5}_{-1.9}$	$1096.6^{+2.6}_{-2.0}$
r_*	144.44 ± 0.27	144.99 ± 0.26	$142.19^{+0.61}_{-0.72}$	$142.41^{+0.61}_{-0.68}$	143.68 ± 0.47	$143.91^{+0.44}_{-0.49}$
$z_{\rm drag}$	1059.94 ± 0.30	1060.36 ± 0.29	$1077.3^{+4.1}_{-3.1}$	$1077.1^{+3.8}_{-3.3}$	$1067.6^{+2.4}_{-1.9}$	$1067.4^{+2.5}_{-2.0}$
$r_{\rm drag}$	147.10 ± 0.27	147.58 ± 0.26	$144.85^{+0.62}_{-0.72}$	$145.05^{+0.61}_{-0.68}$	146.25 ± 0.48	146.47 ± 0.48
$\chi^2_{\rm lensing}$	9.23 ± 0.70	9.6 ± 1.2	9.20 ± 0.67	9.30 ± 0.84	9.35 ± 0.82	9.7 ± 1.1
$\chi^2_{\rm plik}$	2359.5 ± 6.2	2365 ± 13	2366.8 ± 6.8	2368.8 ± 6.9	2368.0 ± 7.2	2370.6 ± 7.3
$\chi^2_{\rm lowl}$	23.40 ± 0.86	22.31 ± 0.71	24.30 ± 0.97	23.94 ± 0.91	22.31 ± 0.73	22.07 ± 0.67
$\chi^2_{\rm simall}$	397.0 ± 1.8	399.2 ± 3.5	397.1 ± 1.9	397.3 ± 2.0	398.2 ± 2.7	398.4 ± 2.9
$\chi^2_{\rm prior}$	11.6 ± 4.6	11.7 ± 4.6	11.5 ± 4.5	$24 \pm 7^{(a)}$	11.9 ± 4.7	$24 \pm 7^{(a)}$
$\chi^2_{\rm H3}$	-	24 ± 5	7.4 ± 3.9	5.8 ± 3.1	14.9 ± 4.5	12.5 ± 3.9
$\chi^{2({\rm tot})}_{\rm bestfit}$	2779.9	2811.5	2795.7	$3311.7^{(b)}$	2802.6	$3324.4^{(b)}$

TABLE I. The mean values and 68% CL intervals for the relevant cosmological parameters and the χ^2 of the datasets used in the analysis. $^{(a)}$ *The DES likelihood contains priors on additional 13 "nuisance" parameters;* $^{(b)}$ *To be compared to the ΛCDM fit to CMB+H3+DES which has* $\chi^{2({\rm tot})}_{\rm bestfit} = 3331.9$.

Minor changes in the values and uncertainties of other cosmological parameters
Adding the DES Y1 data pushes the detection of clumping beyond 4σ

K. Jedamzik and L. Pogosian, arXiv:2004.09487

Observations of EE polarization at high multipoles with SPT3G



courtesy Silvia Galli (SPT3G collaboration)

Observations of extended gamma ray emission around energetic blazars such as Mrk501 with CTA:

Korochkin et al: 2007.14331

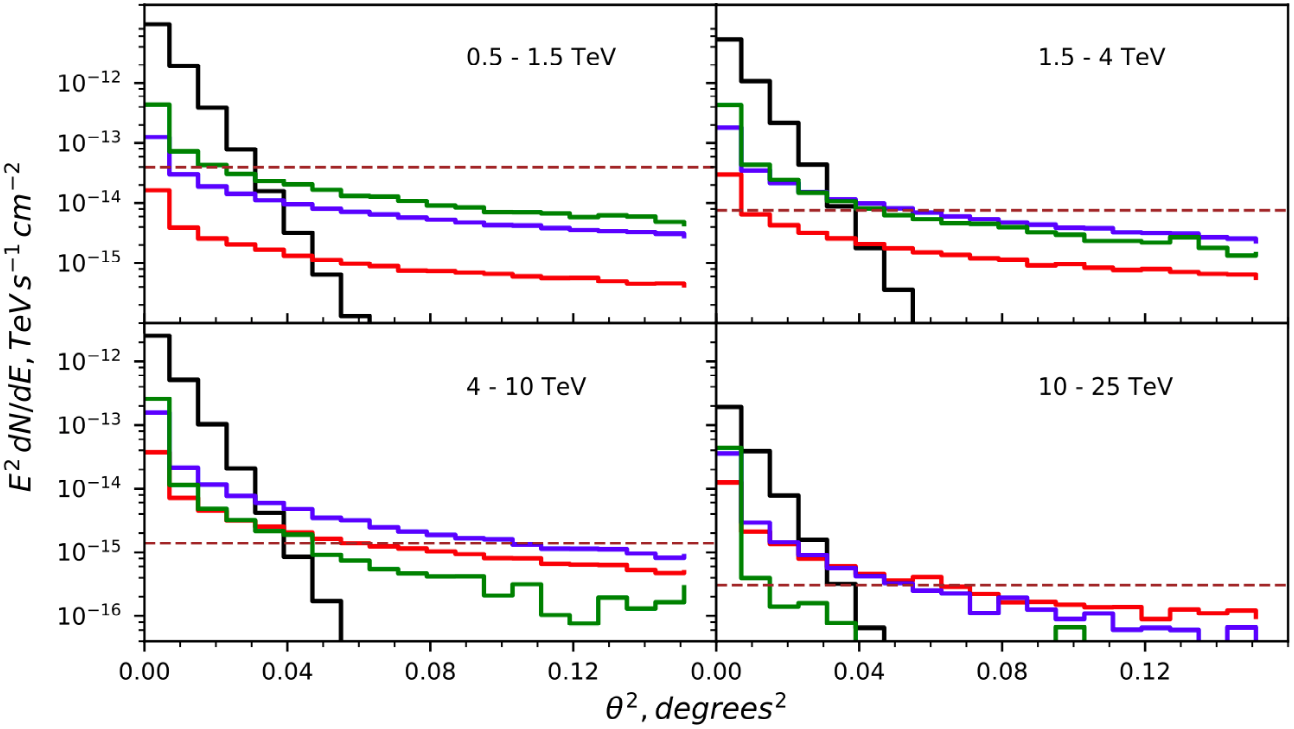
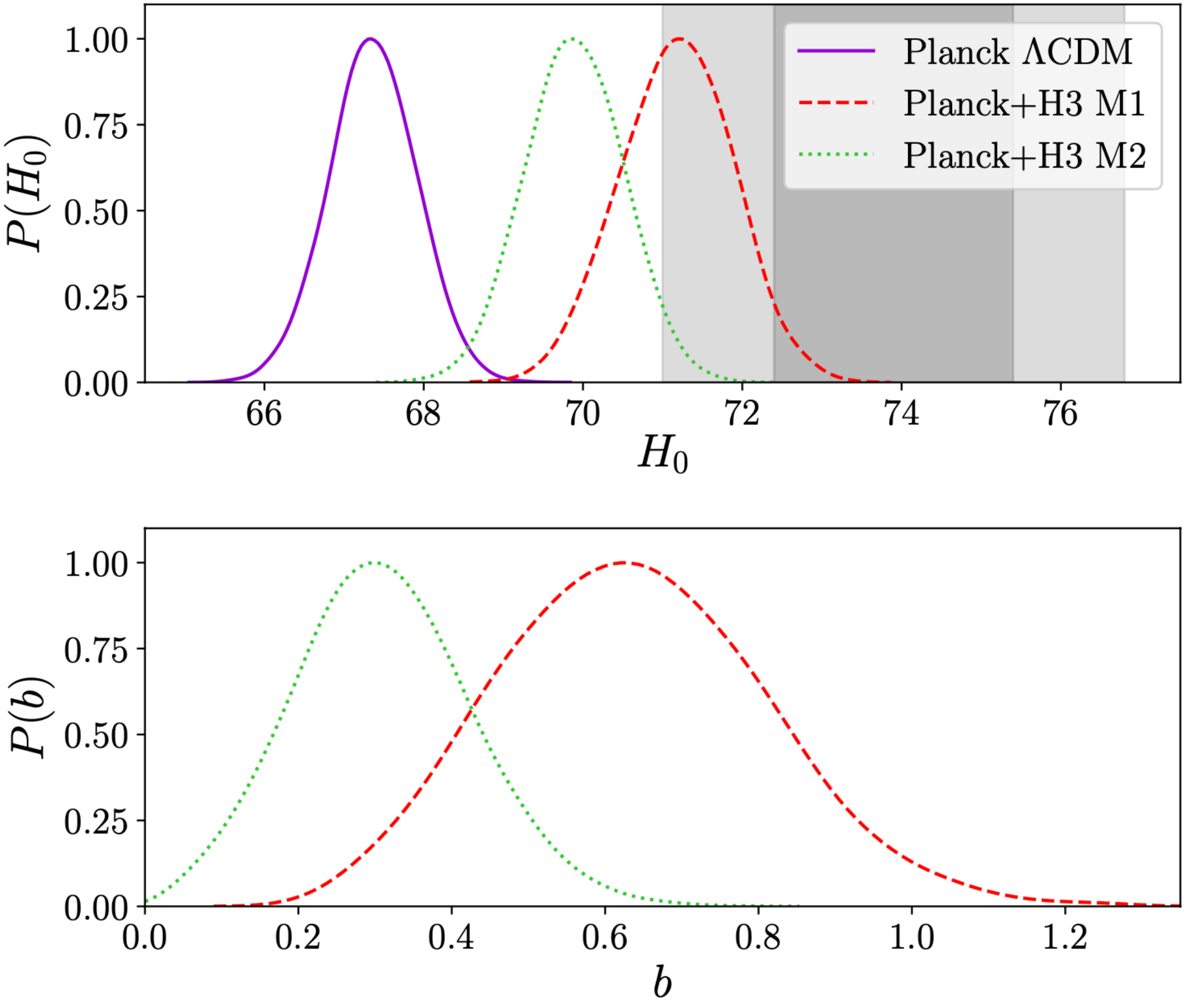


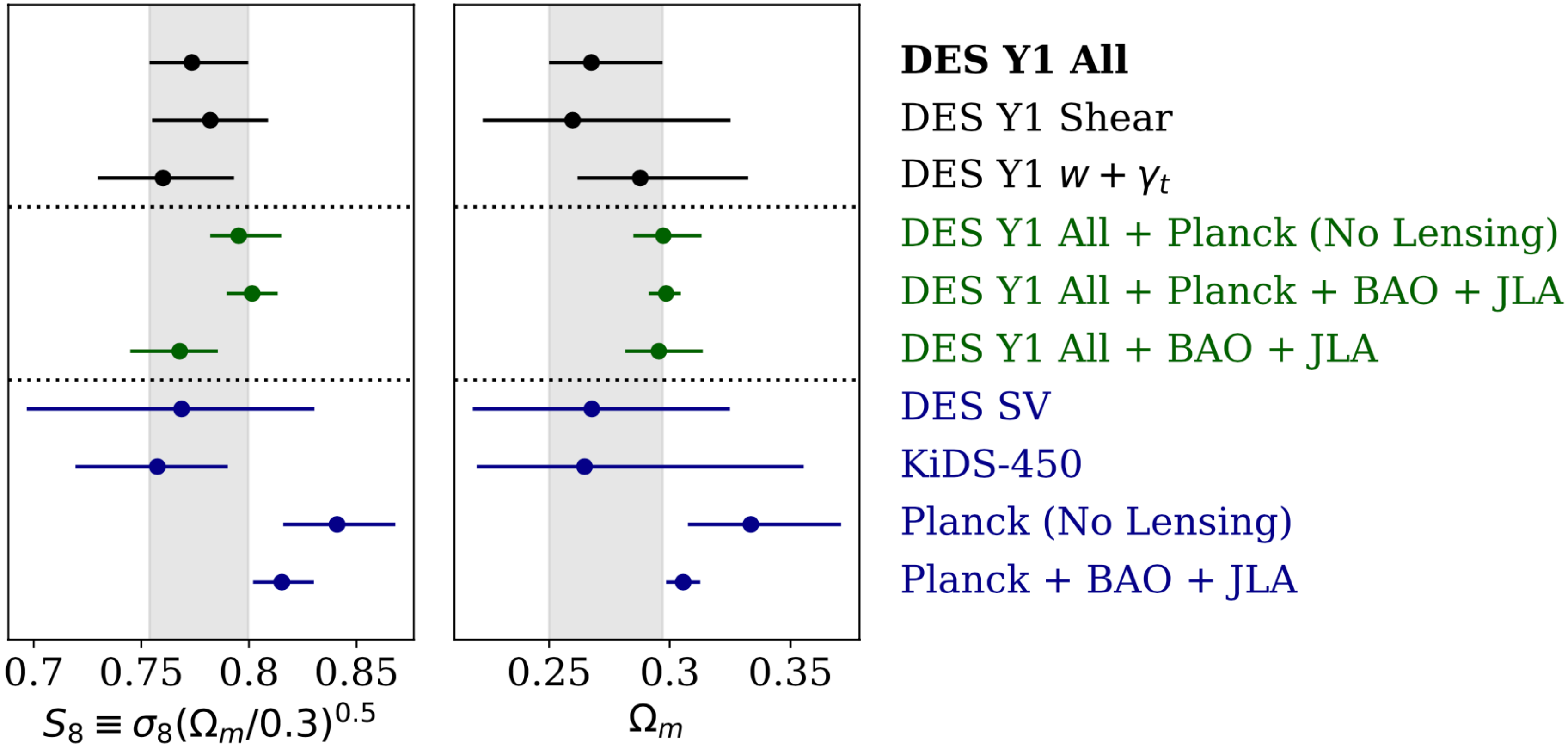
Figure 4. Angular distribution of primary and secondary photons in different energy ranges. Black histograms show the primary point source signal, green, blue and red histograms show the extended emission calculated for different magnetic field strengths: 10^{-12} G, 3×10^{-12} G, 10^{-11} G. Horizontal dashed line shows the level of residual cosmic ray electron background measured by HESS (Kerszberg et al. 2017).

Relieving the Hubble tension



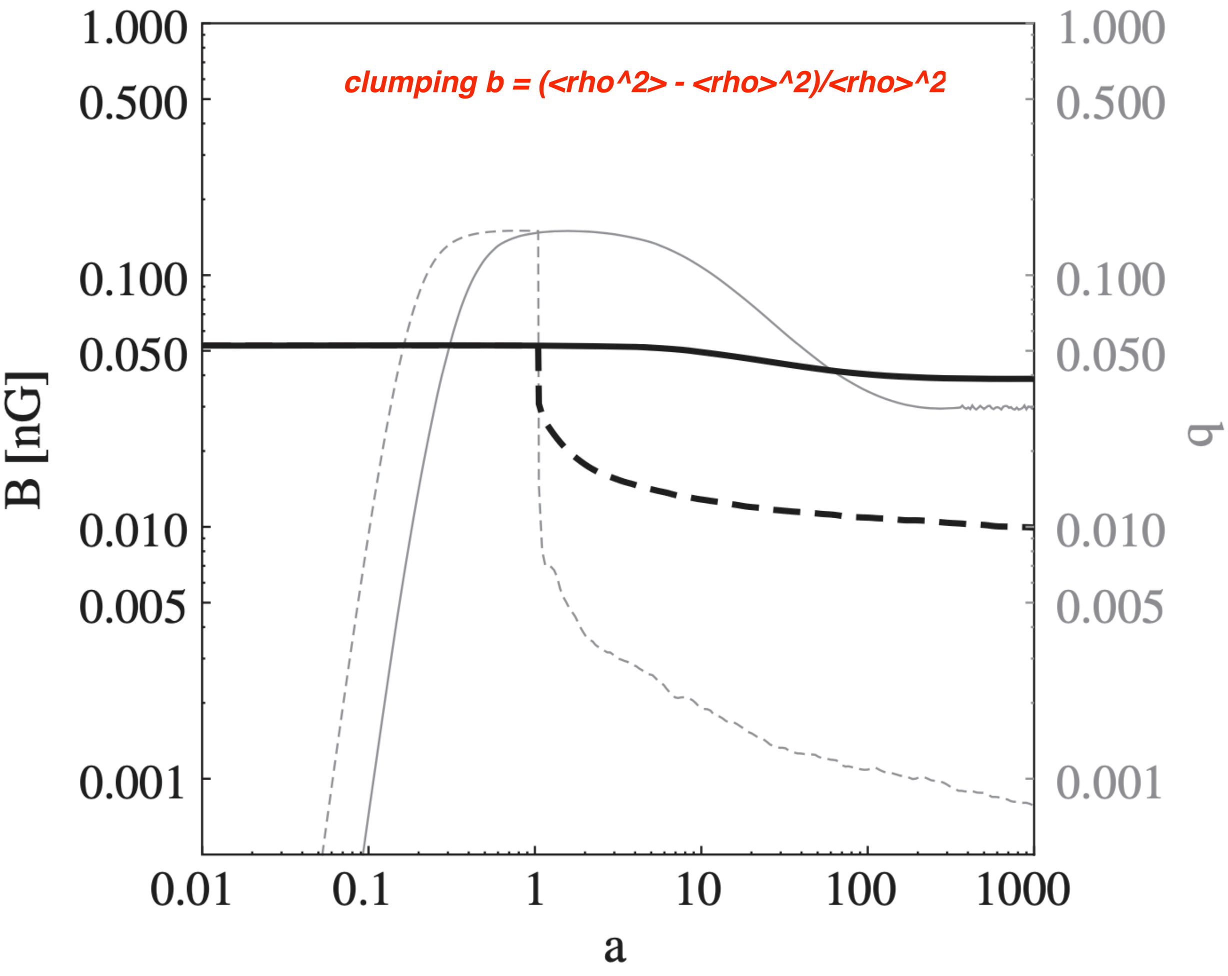
K. Jedamzik and L. Pogosian, arXiv:2004.09487

The S_8-Ω_m tension



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

Magnetic field evolution through recombination



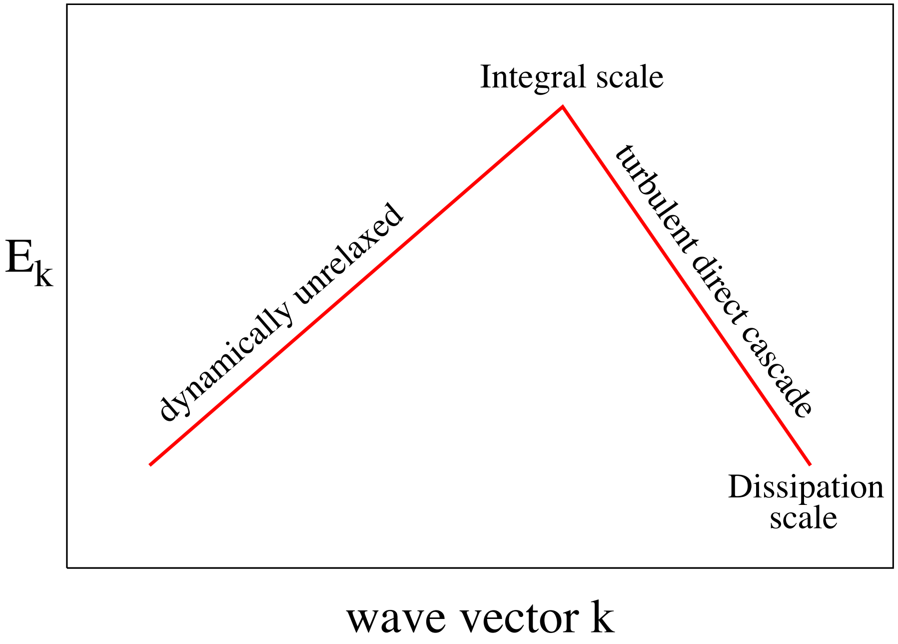
Jedamzik and Saveliev, arXiv:1804.06115, PRL (2019)

MHD Cascades in Fourier Space

$$E_B = \frac{\varrho}{2}\frac{1}{V}\int \mathrm{d}^3x\,\mathbf{v}_{\mathsf{A}}{}^2 = \int \mathrm{d}^3k\langle|v_{A,k}|^2\rangle \equiv \int \mathrm{d}\ln\,k\,E_k\,, \qquad (1)$$

quasi-stationary state (Kolmogoroff, Iroshnikov-Kraichnan)

$$\frac{\mathrm{d}E_k}{\mathrm{d}t} \approx \frac{E_k}{\tau_k} \approx \mathrm{const}(k)\ , \qquad (2)$$

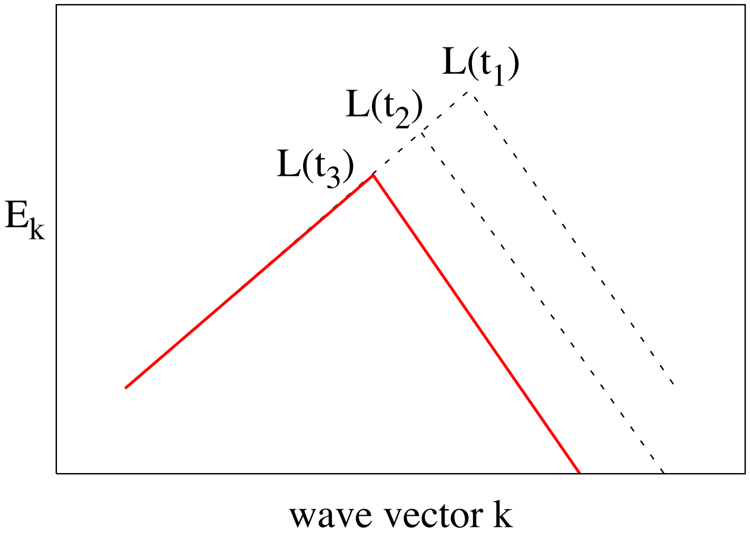


Decay of magnetic energy in MHD

Assume initial small-k spectrum:

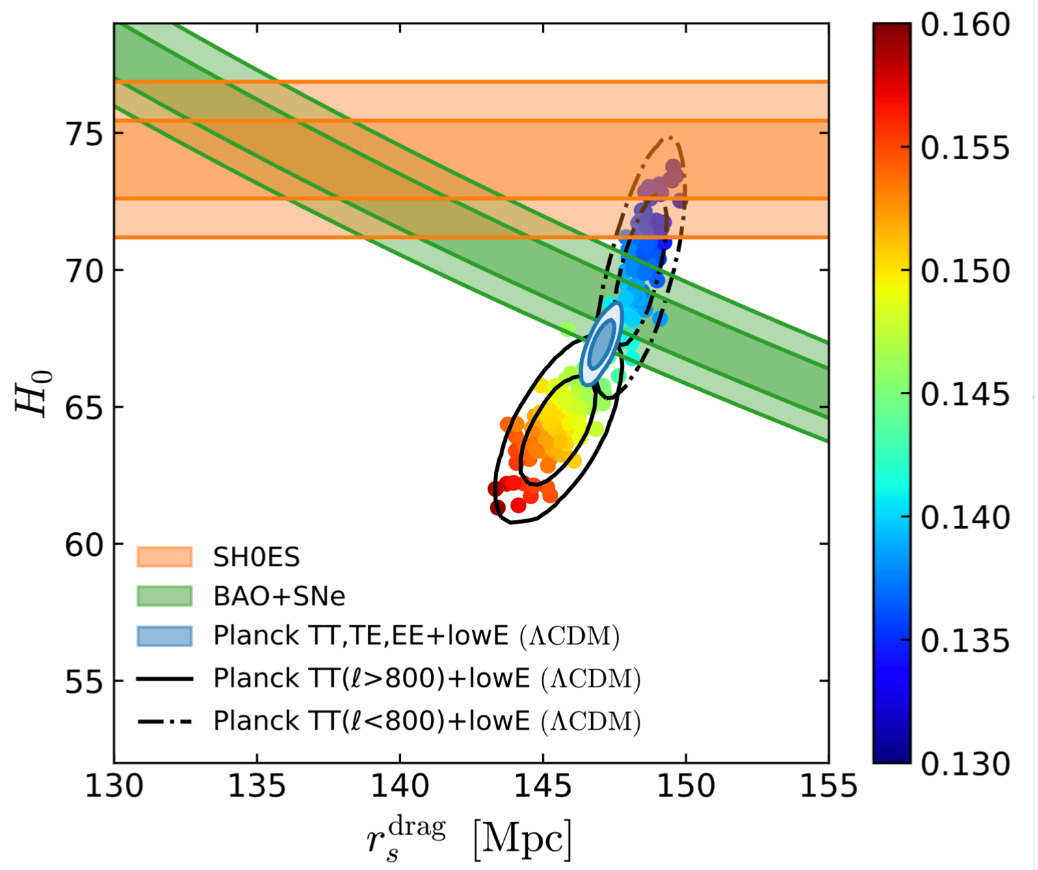
$$E_l(t_0) = E_0 \left(\frac{l}{L_0}\right)^{-n} \quad \text{for}\, l > L_0$$

Processing on Integral Scale by development of fluid eddies and cascade of energy to dissipation scale

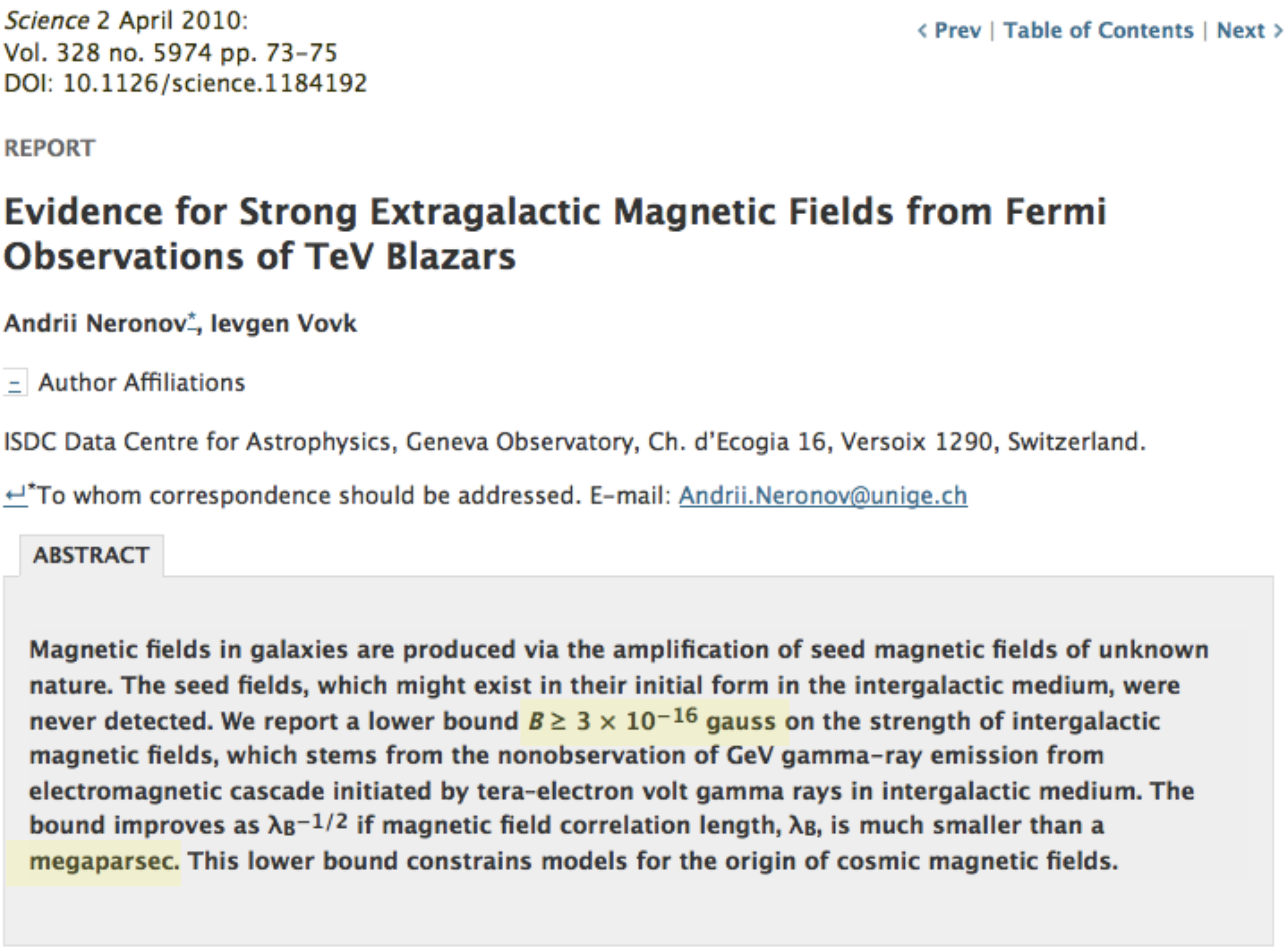


relaxation time: $\tau_L = t \sim L/v_L \sim L/\sqrt{E_L}$

Baryon Acoustic Oscillations



The Hubble Hunter's Guide, L. Knox and M. Millea, arXiv:1908.03663



Science 2 April 2010:
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REPORT

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

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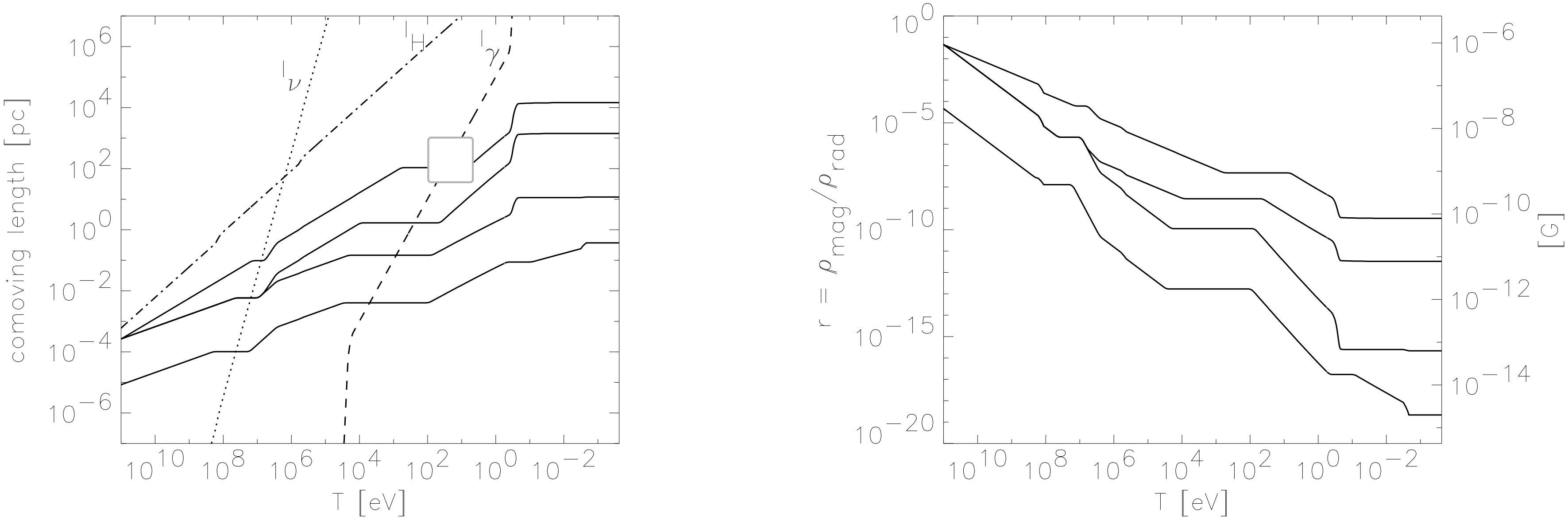
ABSTRACT

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.

Evolution: The Global Picture



from top to bottom: (a) $h_{\rm g} = 1$, $r_{\rm g} = 0.01$, (b) $h_{\rm g} = 10^{-3}$, $n = 3$, $r_{\rm g} = 0.01$, (c) $h_{\rm g} = 0$, $n = 3$, $r_{\rm g} = 0.01$, (d) $h_{\rm g} = 0$, $n = 3$, $r_{\rm g} = 10^{-5}$

Banerjee and Jedamzik 2004

Cosmic Magnetic Fields

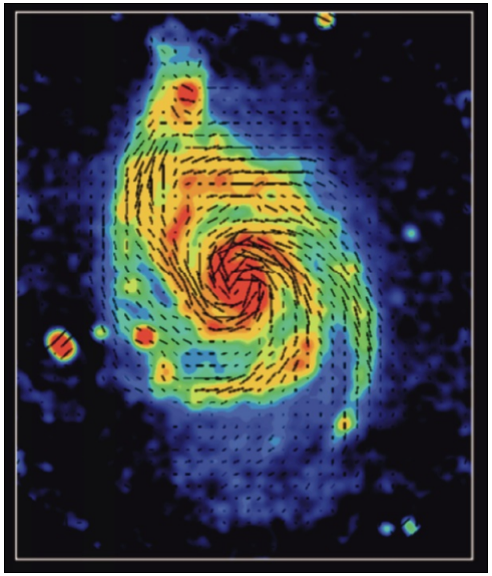
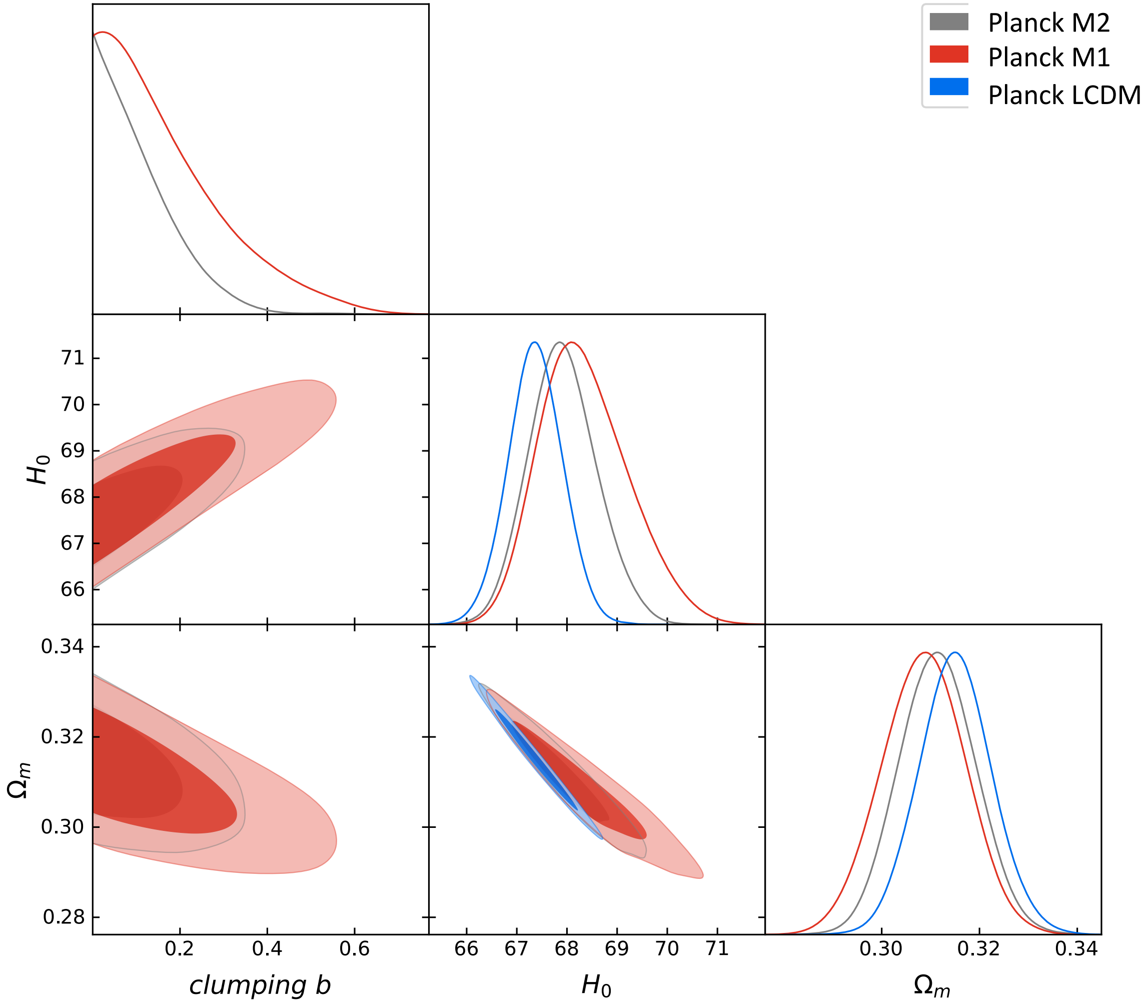


Image courtesy of NRAO/AUI

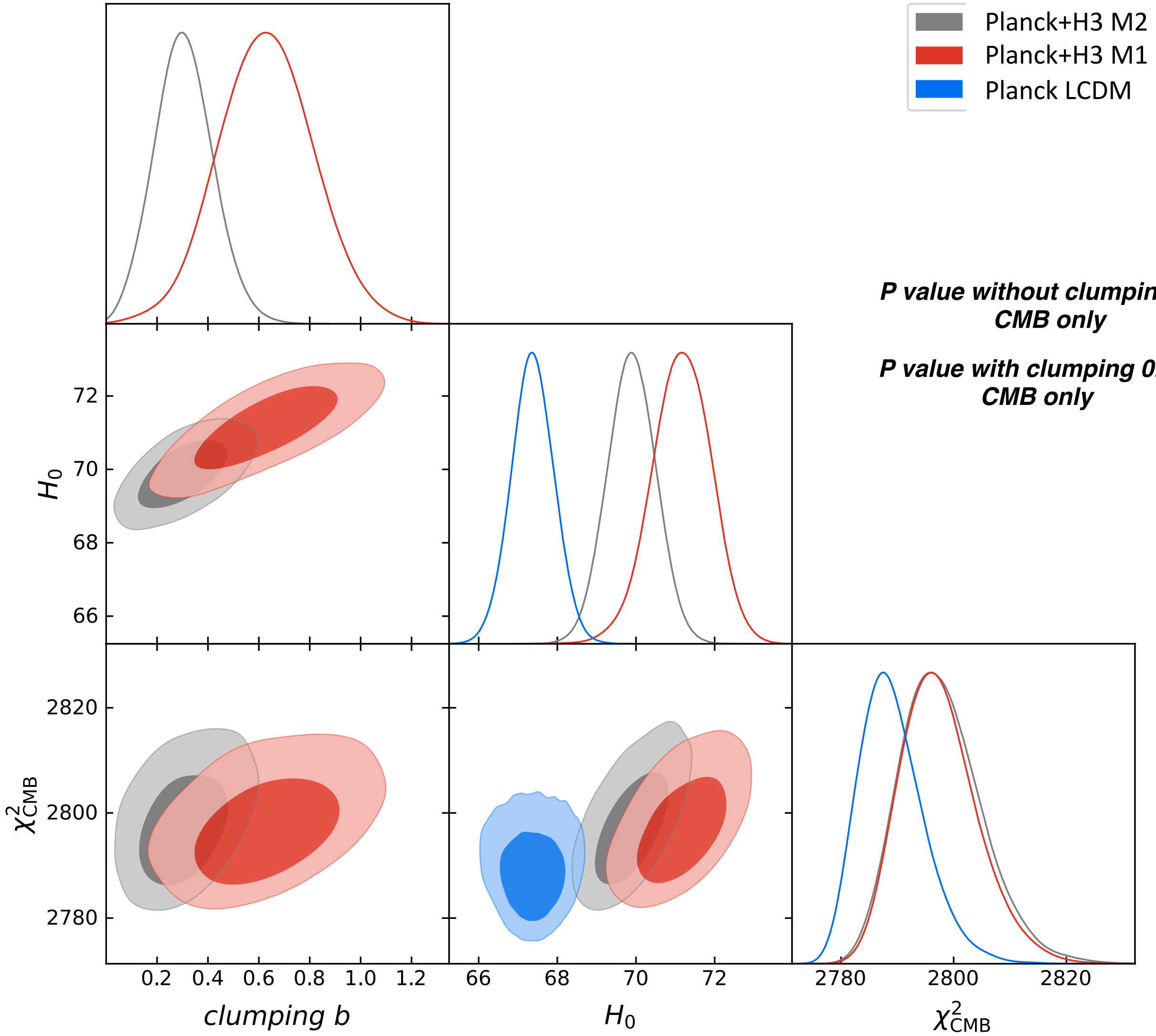
- Origin of 1-10 μG fields in galaxies and clusters
  - mostly astrophysical? (dynamo, SN, …)
  - mostly primordial? (need 0.01-0.1 nG)
  - some combination of the two?
- Evidence of magnetic fields in voids?
  - missing GeV γ-ray halos around TeV blazars
- Generated in the early universe – not “if”, but “how much”
  - phase transitions
  - inflationary mechanisms
  - a window into the early universe
- A distinct signature in CMB could prove their primordial origin

LCDM + clumping: Fitting Planck only



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

Does the fit to CMB get worse?



P value without clumping 0.2, CMB only

best-fit LCDM

P value with clumping 0.17, CMB only

best-fit LCDM + clumping

The LCDM model and the clumping models give comparable fits

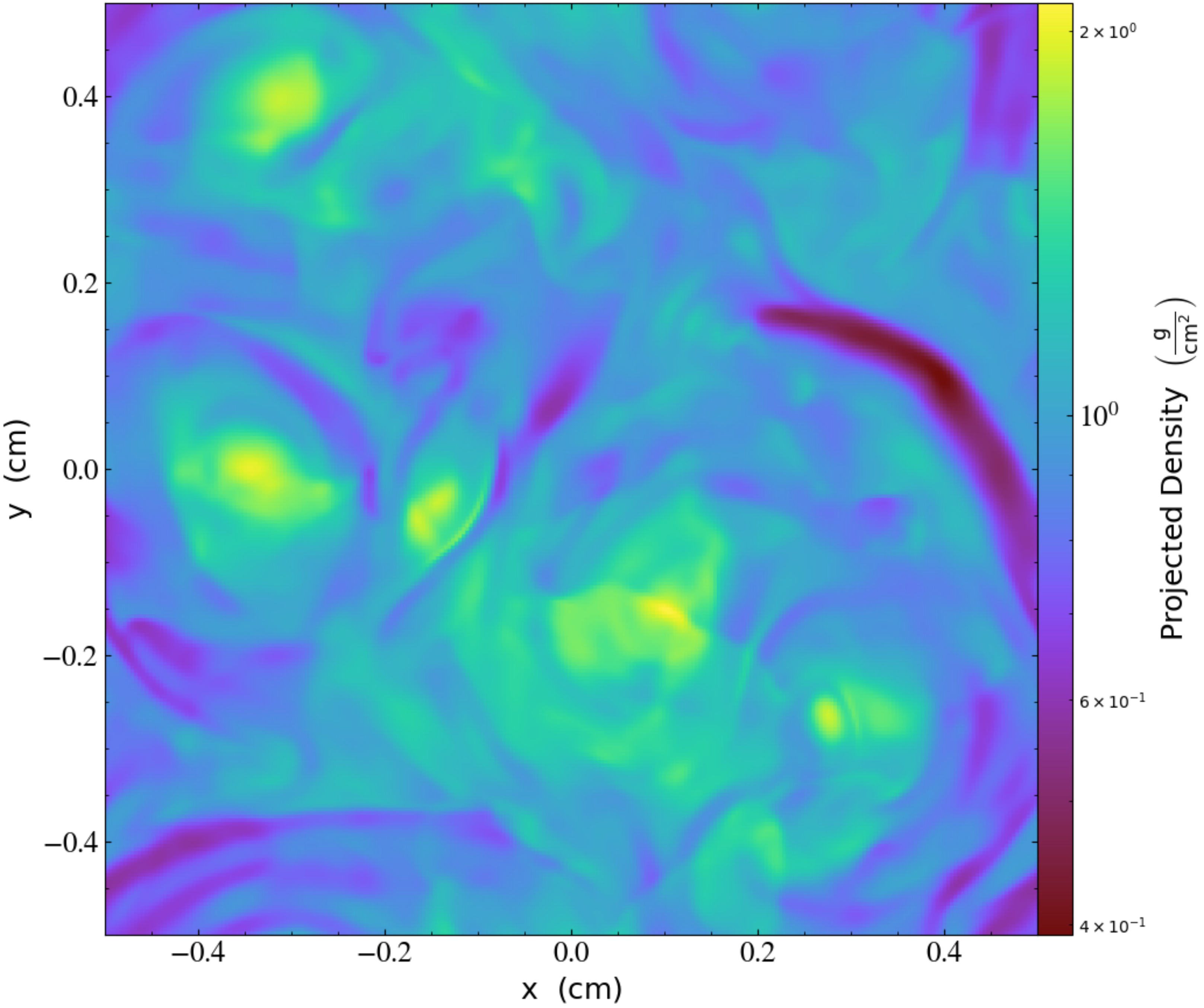
CMBR Doppler peak at angle:

$$\theta_\star = \frac{r_\star}{D_A(z_\star)} = \frac{\int_{z_\star}^{\infty} c_s(z)\mathrm{d}z/H(z)}{\int_0^{z_\star} c\,\mathrm{d}z/H(z)}$$

$$H(z) = 100\mathrm{km/s/Mpc}\sqrt{\Omega_r h^2(1+z)^4 + \Omega_m h^2(1+z)^3 + \Omega_\Lambda h^2}$$

- $\Omega_\gamma h^2$ well know form current CMBR temperature
- $\Omega_\nu h^2$ well known from standard model of particle physics and cosmology
- $\Omega_b h^2$ well known from CMBR and BBN
- $z_\star$ well known from atomic physics
- $\Omega_m h^2$ well know in any particular model from CMBR
- criticality condition: $\Omega_\Lambda + \Omega_m + \Omega_r = 1$

=> Measure Doppler peak angle, assume LCDM, predict the Hubble constant



Jedamzik and Abel, in preparation