Two science cases with the CMB B-mode polarization: Hubble tension and LQC prediction

Donghui Jeong, and Marc Kamionkowski
Gravitational waves, CMB polarization, and the Hubble tension
2020, PRL 124, 041301 [arXiv:1908.06100]

Abhay Ashtekar, Brajesh Gupt, **Donghui Jeong**, and V. Sreenath
Alleviating the tension in CMB using Planck-scale Physics
2020, PRL 125, 051302 [arXiv:2001.11689]

Donghui Jeong

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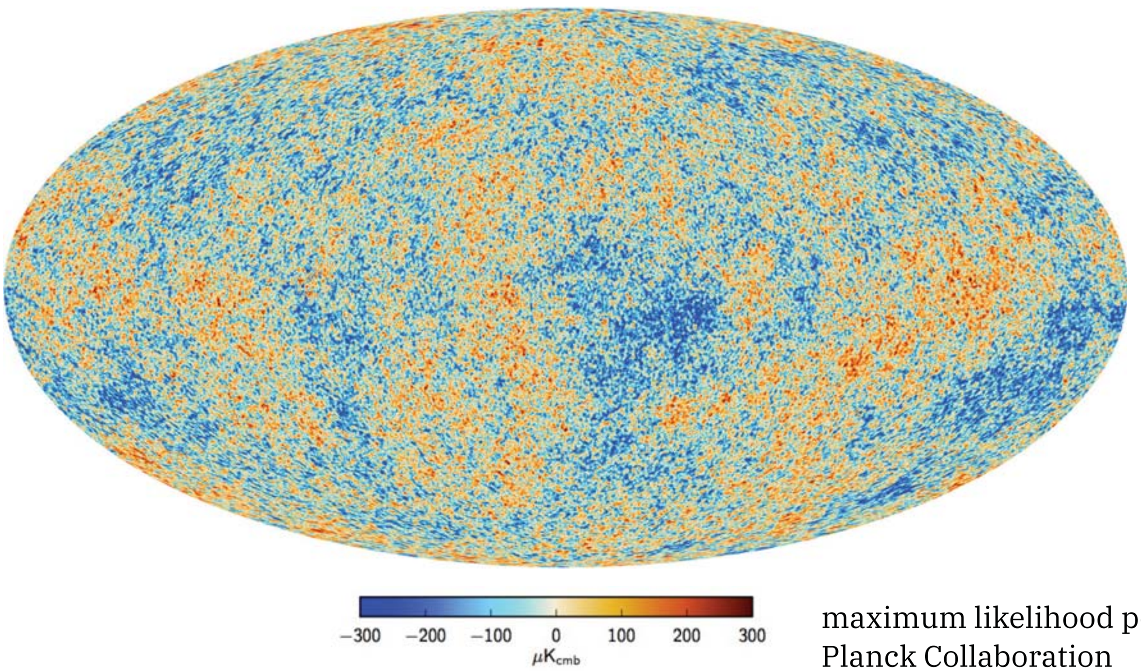
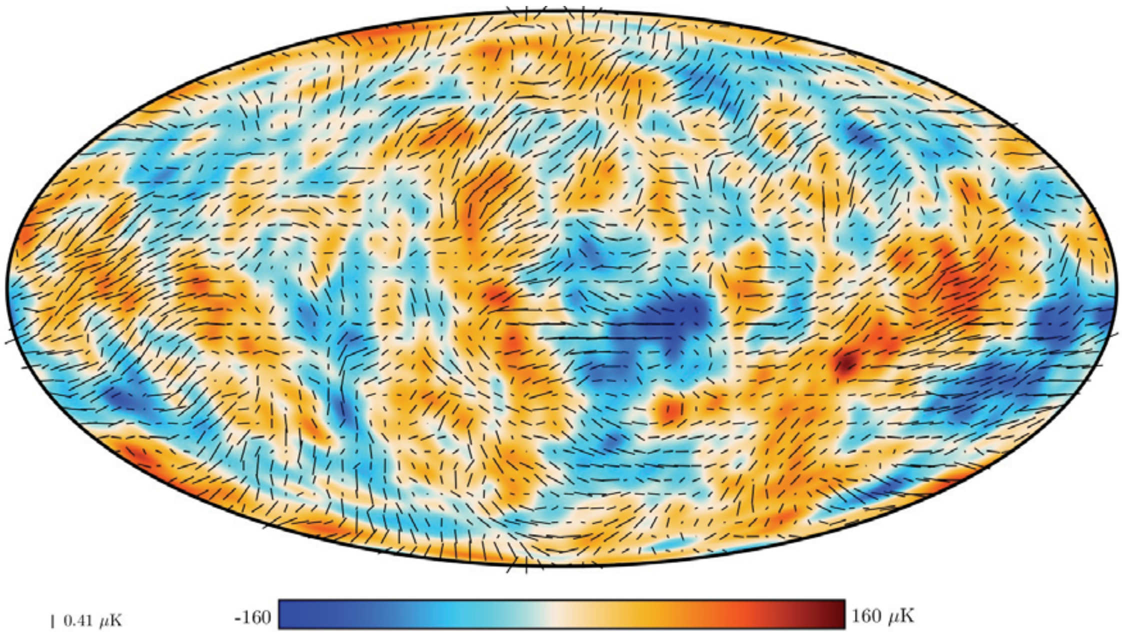
SGC2020 workshop, 20 November 2020

Temperature map of the CMB



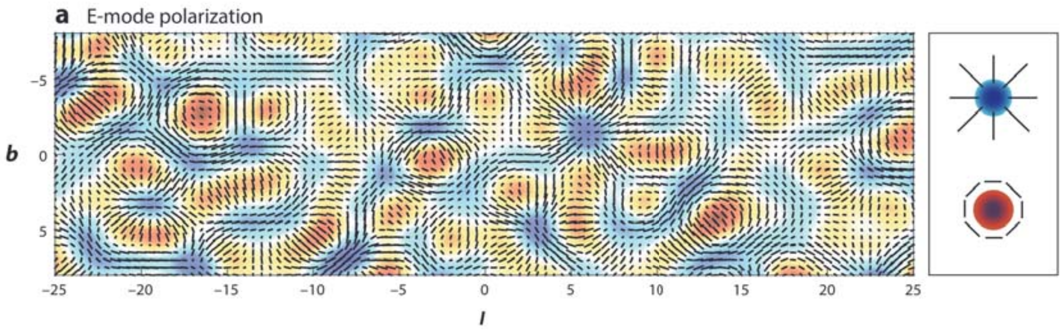
maximum likelihood posterior map
Planck Collaboration

Polarization map of the CMB



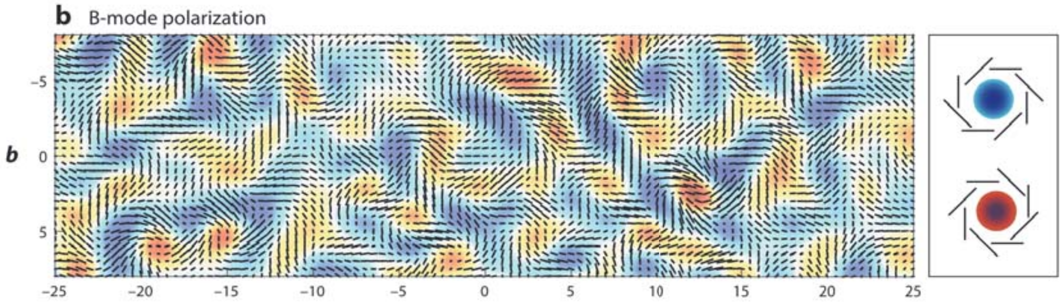
Planck map smoothed with 5° filter

E-mode and B-mode



Even parity

Can be generated from
scalar (density),
vector (vorticity),
tensor (gravitational waves)

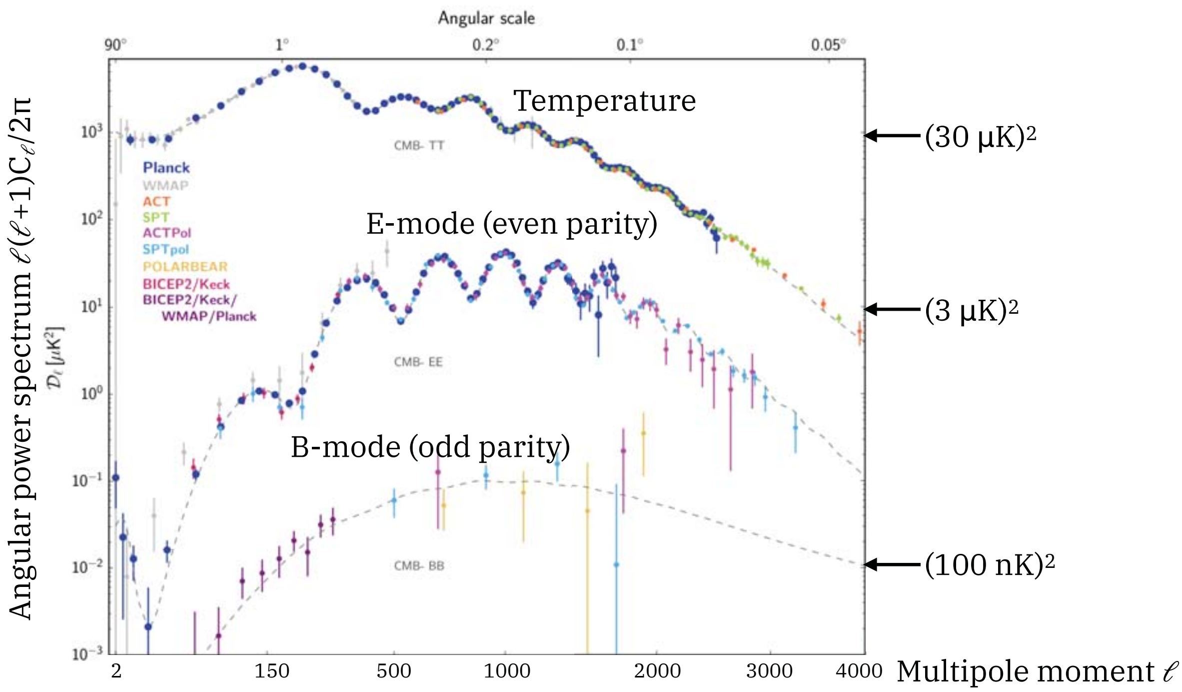


Odd parity

Can be generated from
vector (vorticity),
tensor (gravitational waves)

Kamionkowski, Kovetz (2015)

C_ℓ = fluctuation amplitude



Three puzzles in the CMB

- Hubble tension
- Lack of CMB clustering on large angular scales
- “Crisis for cosmology”: A_L (lensing amplitude) anomaly

Three puzzles in the CMB

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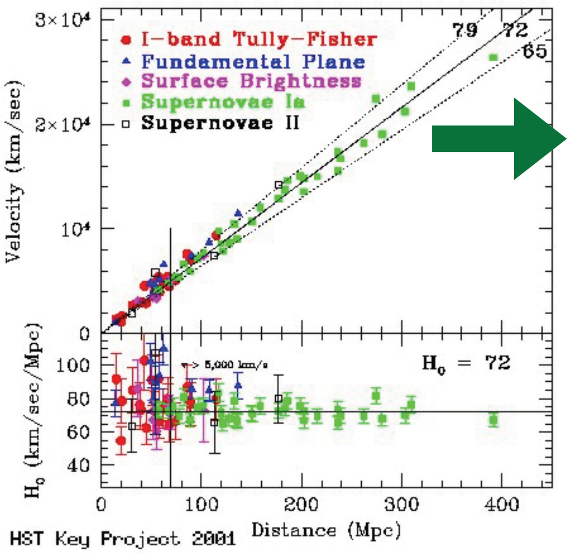
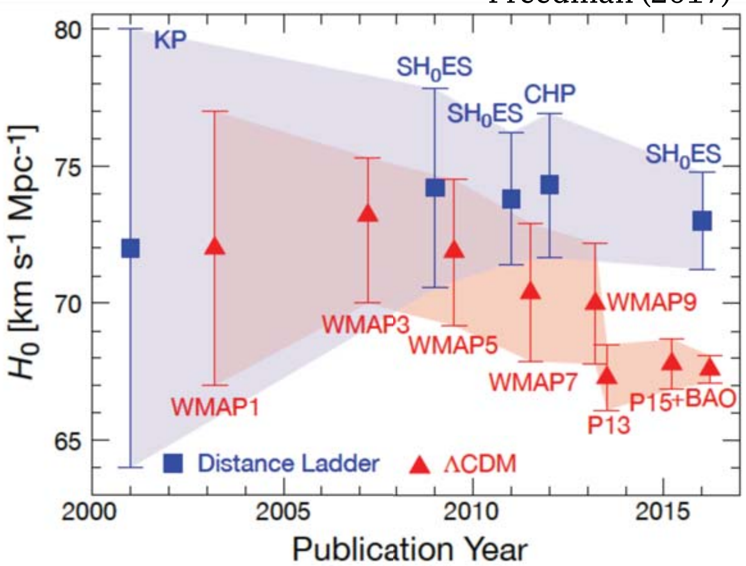
H_0 from the HST Key Project

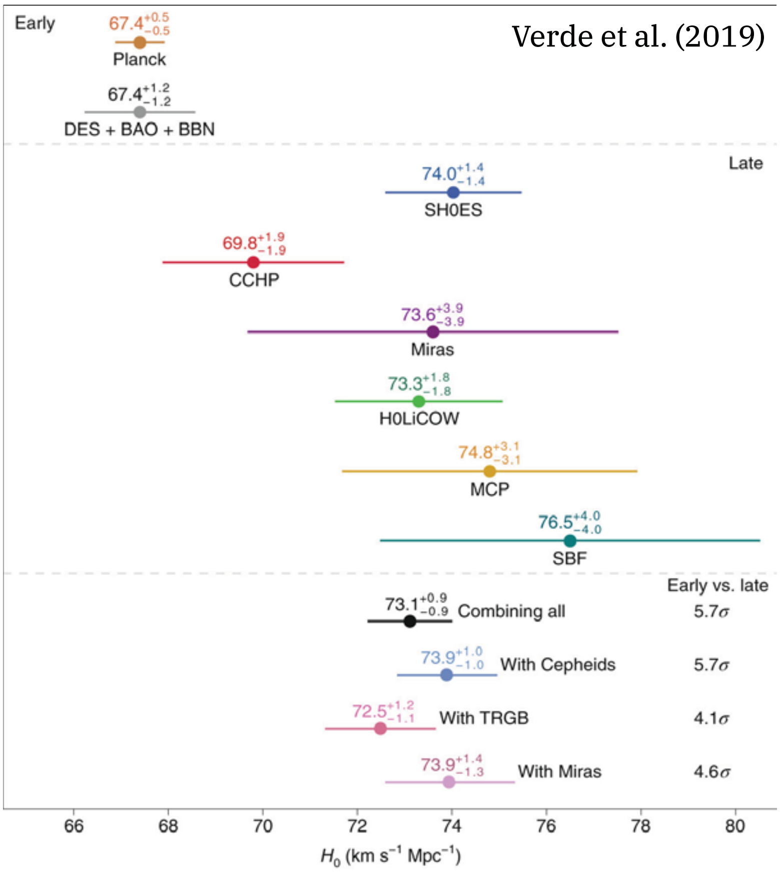


H_0 = slope of this line
= 100h km/s/Mpc

H_0 since HST Key Project

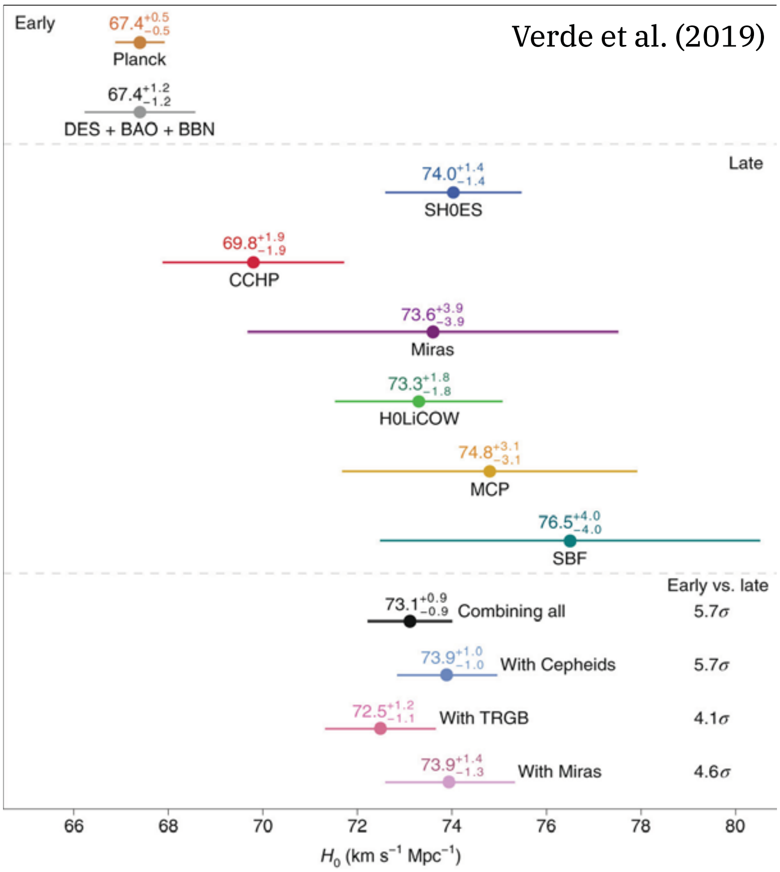
Freedman (2017)





H_0 tension now

- Planck (CMB)
- DES + BAO + BBN
- Variable stars + SN: SH0ES (Cepheid), Miras (Mira)
- TRGB + SN (CCHP)
- Strong lensing (H0LiCOW)
- Megamaser (MCP)
- Surface-brightness fluc. (SBF)

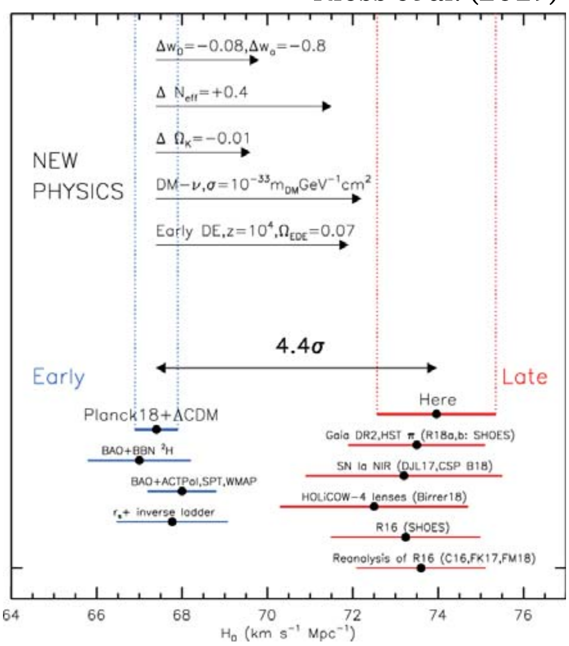


"Sound Discordant"

- It is the discrepancy between
  - Late:
    Standard distance ladder
  - Early:
    Cosmological sound horizon (at photon/baryon decoupling) in ΛCDM model

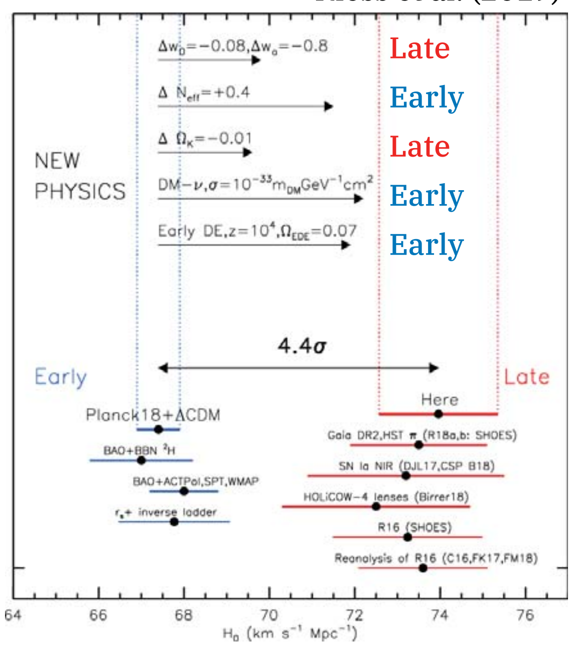
Possible solutions

Riess et al. (2019)

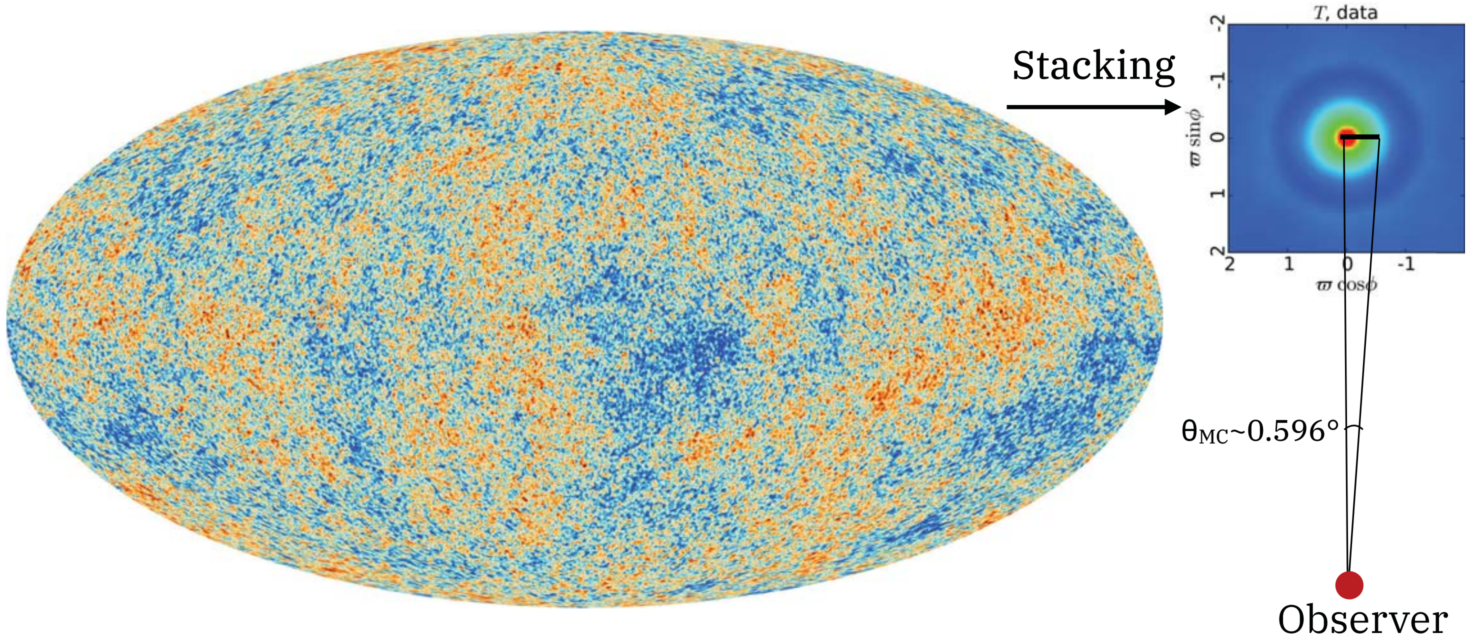


Possible solutions

Riess et al. (2019)



Acoustic scale at θ~0.6°



Physics of acoustic scale

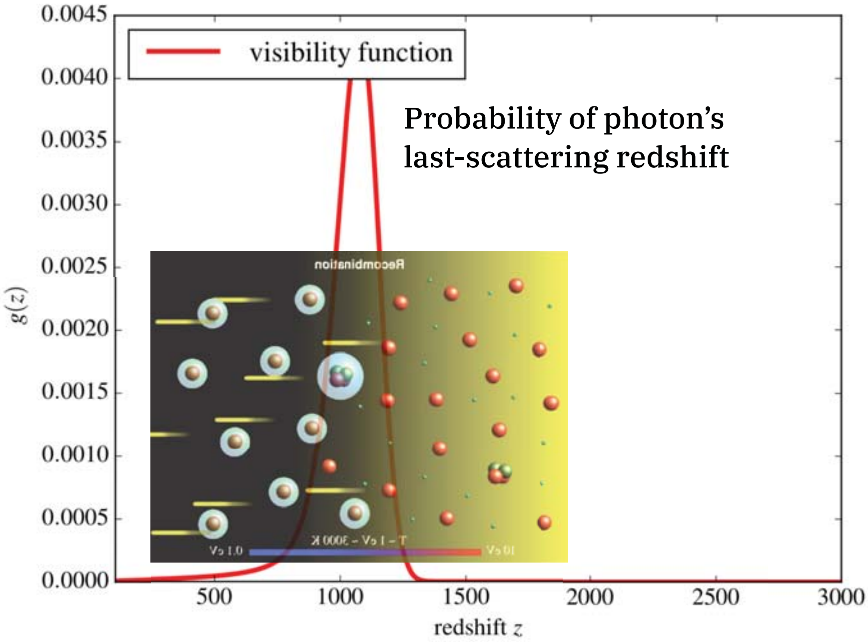
- ***Acoustic oscillation***: Tightly coupled baryon-photon plasma evolves as the pressure wave in the external gravitational field provided by dark matter
- The comoving sound horizon scale is given as

$$r_s = \int_0^{t_{\rm dec}} c_s(t) \frac{dt}{a(t)} = \int_0^{a_{\rm dec}} c_s(a) \frac{da}{a^2 H(a)}$$

$$c_s = \frac{c}{\sqrt{3(1+3\bar{\rho}_{\rm b}/4\bar{\rho}_\gamma)}}$$

$$3H^2 = 8\pi G\left(\bar{\rho}_{\rm r} + \bar{\rho}_{\rm m}\right)$$

Decoupling epoch



- The decoupling epoch (a_{dec}) also depends on
  - **baryon density**:
    how many hydrogen to break
  - **matter density**:
    how fast the photons loose energy

Calculating acoustic scale

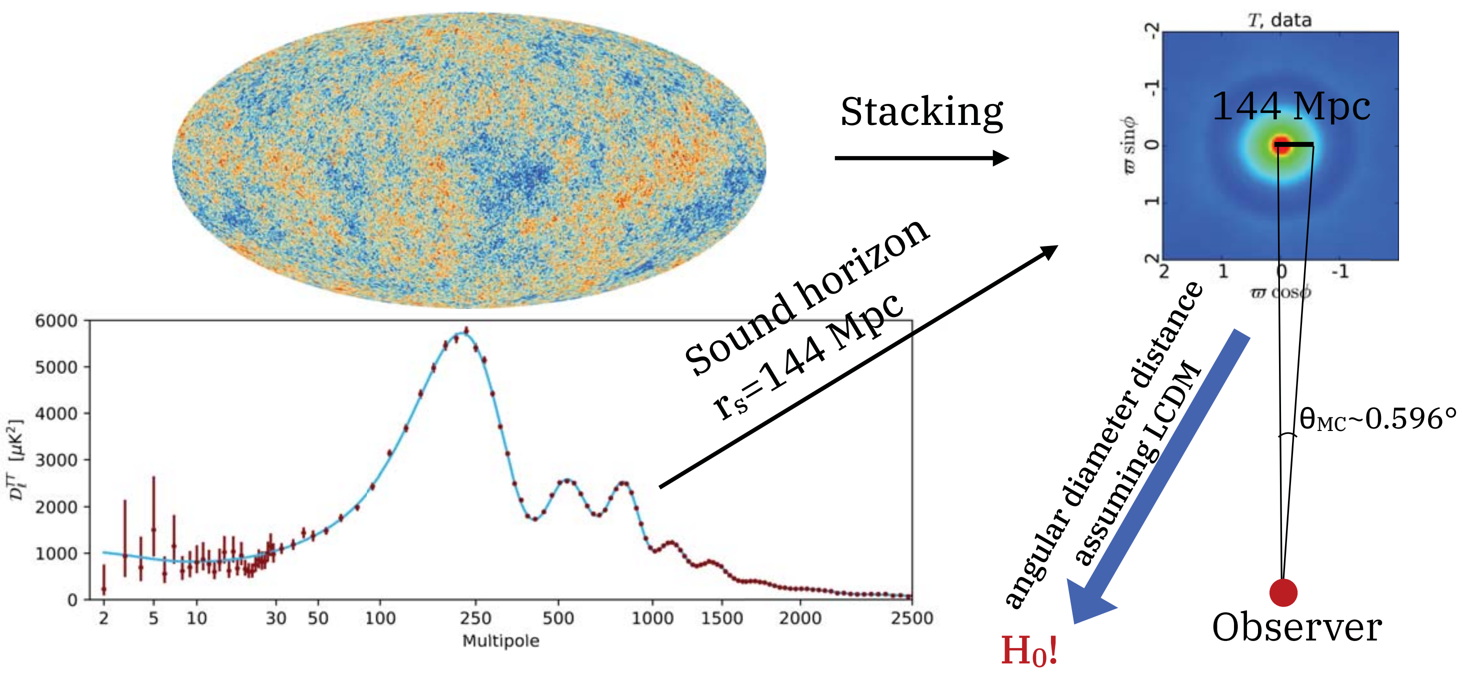
- Given ρ_m, ρ_b, ρ_γ, ρ_ν, we can determine the acoustic scale!
  - ρ_m, ρ_b : from the relative heights of CMB power spectrum
  - ρ_γ : from T_{cmb} (CMB is very good black body)
  - ρ_ν : from N_{eff} (T_ν = 0.714 T_{cmb}, and neutrinos are fermions)
  - Note: r_s is independent from H_0!

$$r_s = \int_0^{t_{\rm dec}} c_s(t) \frac{dt}{a(t)} = \int_0^{a_{\rm dec}} c_s(a) \frac{da}{a^2 H(a)}$$

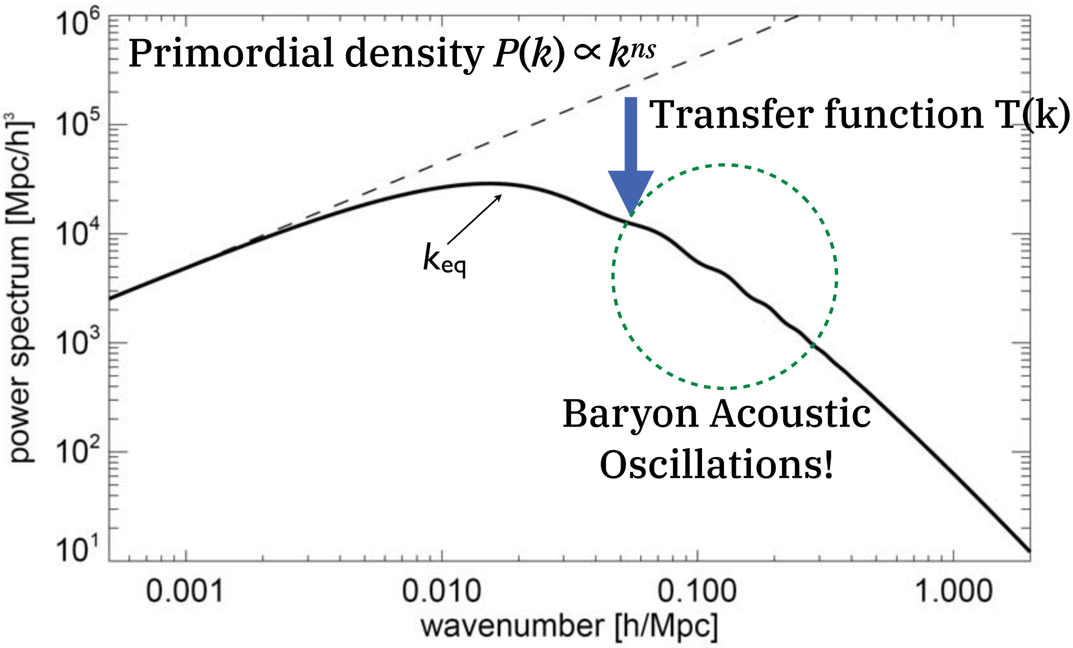
$$c_s = \frac{c}{\sqrt{3(1 + 3\bar{\rho}_{\rm b}/4\bar{\rho}_\gamma)}}$$

$$3H^2 = 8\pi G \left(\bar{\rho}_{\rm r} + \bar{\rho}_{\rm m}\right)$$

CMB power spectrum



The BAO in the galaxy $P(k)$



Dark energy with BAO

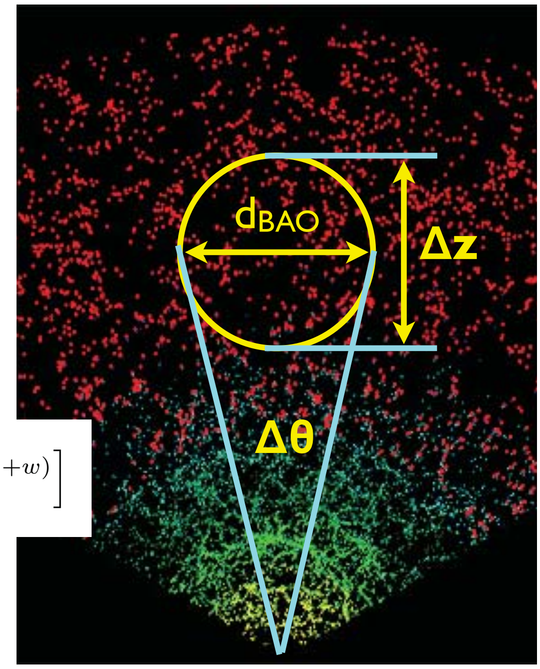
- d_{BAO} is given by CMB, slightly larger than r_s.
- We can measure the angular diameter distance, $d_A(z)$ and Hubble parameter, H(z):

$$d_{\rm BAO} = d_A(z)\Delta\theta = c\Delta z/H(z)$$

- $d_A(z)$, $H(z)$ depend on H_0 (assuming ΛCDM)!

$$H^2(z) = \boxed{H_0^2}\left[\Omega_m(1+z)^3 + \Omega_K(1+z)^2 + \Omega_{\rm DE}(1+z)^{3(1+w)}\right]$$

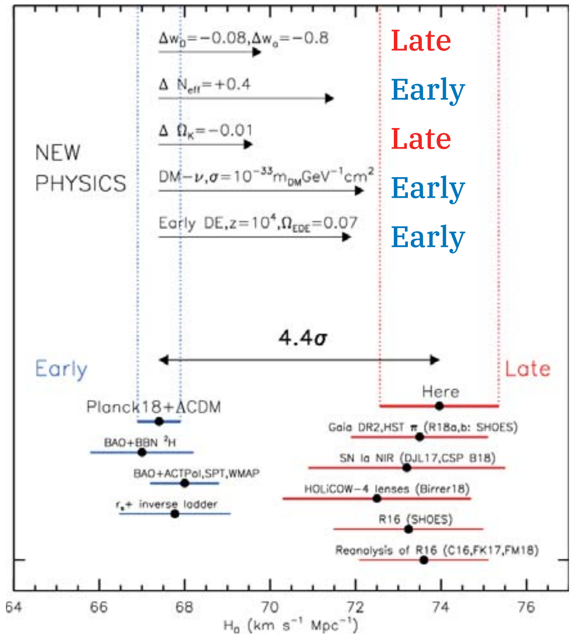
$$d_A(z) = \frac{\chi(z)}{1+z}\left[1 - \frac{k}{6}\frac{\chi^2(z)}{R^2}\right] \quad \chi(z) = c\int \frac{dz}{H(z)}$$



Early time

Mission H_0 : reduce r_s by 9%!

Riess et al. (2019)



- Direct observable = $\theta \sim 0.6° = r_s/d_A(a_{dec}) \sim H_0 r_s$.
- If somehow we over-estimate for r_s by 9%, CMB measurement of H_0 would be lower than the true value by 9%.
- How? Faster expansion at early time:
  - Increase N_{eff}
  - Add exotica (early DE) for that job
- But, CMB does not allow full 9%!

Can we confirm/rule out?

- ***Yes***, if we have another distance in the early universe!
- Where do we have that distance?
  In the *B-mode polarization from primordial gravitational waves!*

$$r_s = \int_0^{t_{\rm dec}} c_s(t)\frac{dt}{a(t)} = \int_0^{a_{\rm dec}} c_s(a)\frac{da}{a^2 H(a)} \qquad c_s = \frac{c}{\sqrt{3(1+3\bar{\rho}_{\rm b}/4\bar{\rho}_\gamma)}}$$

$$\boxed{r_t = \int_0^{t_{\rm dec}} c\frac{dt}{a(t)} = \int_0^{a_{\rm dec}} c\frac{da}{a^2 H(a)}} \qquad 3H^2 = 8\pi G\left(\bar{\rho}_{\rm r} + \bar{\rho}_{\rm m}\right)$$

Gravitational Waves (GW)

- are the traceless and transverse (tensor) components of the metric perturbations: [with Einstein convention, Greeks=0-4, Latin=1-3]

$$ds^2 = a^2(\eta)\left[-d\eta^2 + \{\delta_{ij} + h_{ij}(\eta, \boldsymbol{x})\}\, dx^i dx^j\right]$$

$$\text{Traceless :} \quad \text{Tr}[h_{ij}] = h^i_i = g^{ij} h_{ij} = 0$$

$$\text{Transverse :} \quad \nabla_i h_{ij} = 0$$

- There are 6 (symmetric 3-by-3 matrix) - 3 (transverse) - 1 (traceless) = 2 degrees of freedom ($h_\times$, h_+)

Primordial GW (PGW)

- de Sitter spacetime generates stochastic gravitational waves with amplitude of (here, $m_{pl} = \sqrt{G_N}$):

$$\Delta_h^2(k) = \frac{k^3 P_T(k)}{2\pi^2} = \frac{64\pi}{m_{\rm pl}^2}\left(\frac{H}{2\pi}\right)^2\Bigg|_{k=aH}$$

+ Friedmann equation: $3H^2 \sim 8\pi G\rho$

- ***PGW = energy scale*** of inflation: $E \sim (r/0.01)^{1/4} 10^{16}$GeV!
- ***PGW = expansion rate*** during inflation: can prove inflation!

Evolution of GW

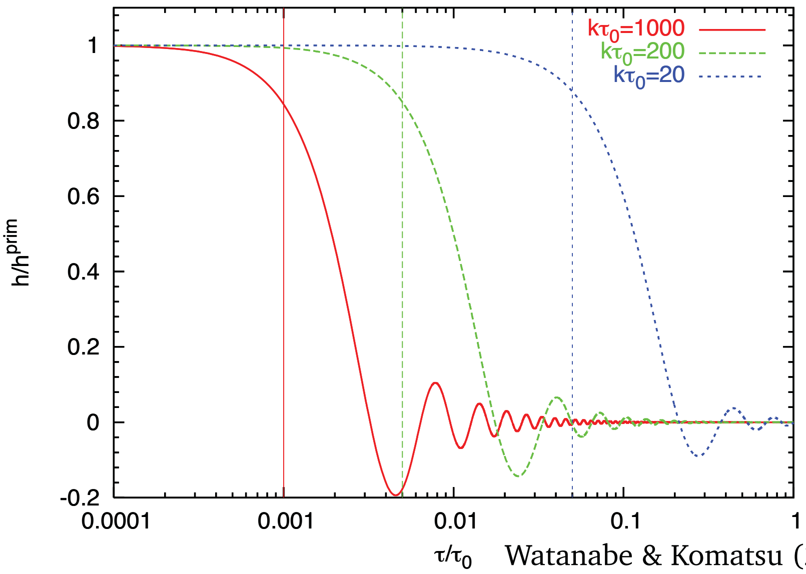
- Evolution of GW amplitudes ($h_\times$, h_+) is governed by Klein-Gordon equation sourced by anisotropic stress Π_p
  ($\mathscr{H}$ =a'/a and ' = d/dη):

$$-h_{ij;\nu}{}^{;\nu} = h_p''(\boldsymbol{k}) + 2\mathcal{H}h_p'(\boldsymbol{k}) + k^2 h_p(\boldsymbol{k}) = 16\pi G a^2 \Pi_p(\boldsymbol{k})$$

Hubble damping

Evolution of PGW w/o sources

$$-\Box h_{ij} = h_p''(\boldsymbol{k}) + 2\mathcal{H}h_p'(\boldsymbol{k}) + k^2 h_p(\boldsymbol{k}) = 0$$

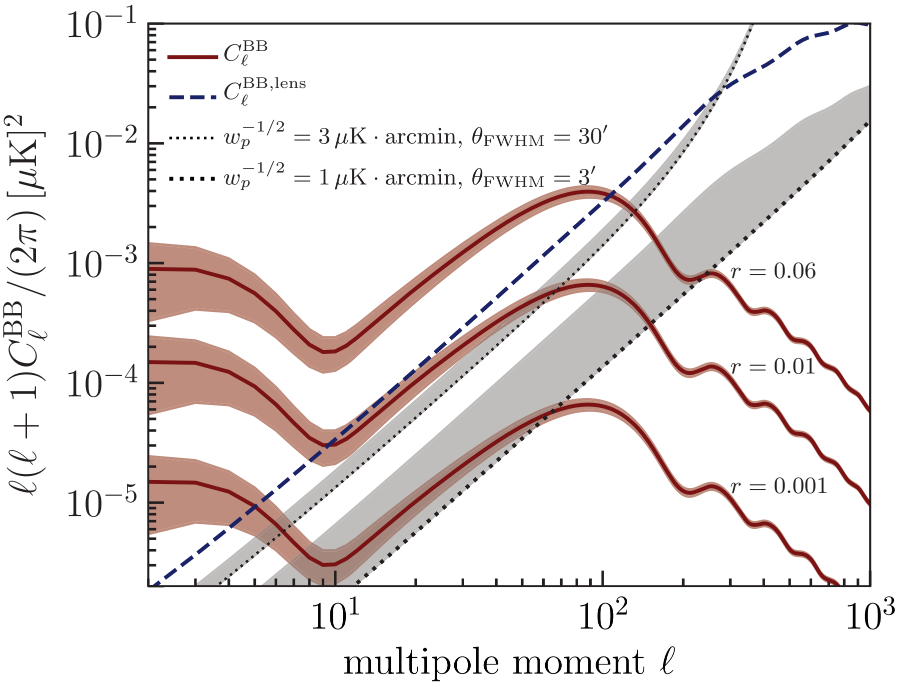


Watanabe & Komatsu (2006)

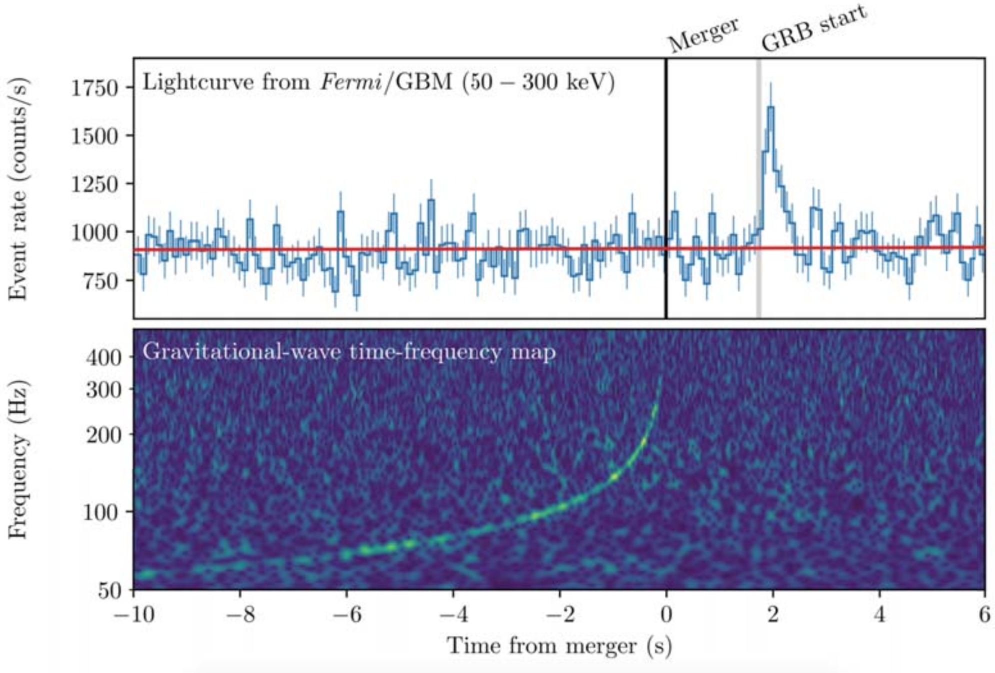
- PGW stays constant outside of horizon, but decays once the mode enters the horizon.
- *cf.* scalar perturbations grow inside of horizon.

Jeong & Kamionkowski (2019)

B-mode power spectrum



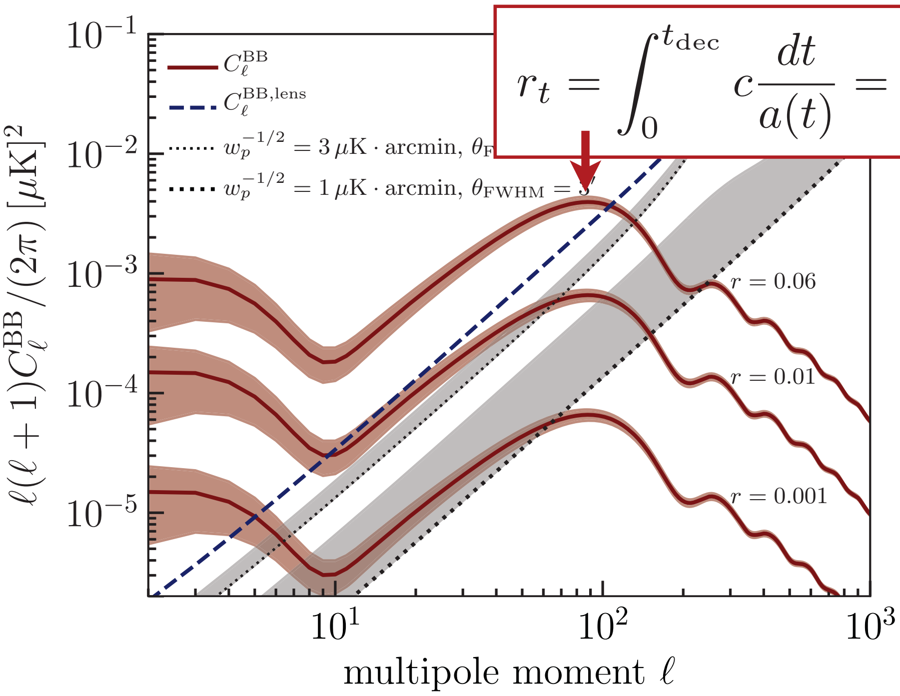
GW170817 and GRB 170817A



Jeong & Kamionkowski (2019)

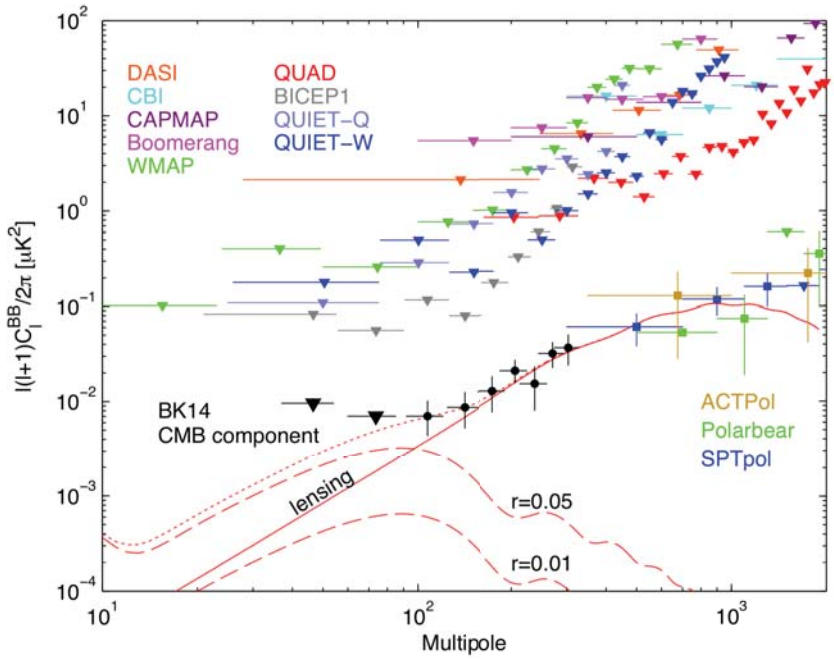
Turn-over scale r_t

$$r_t = \int_0^{t_{\rm dec}} c\frac{dt}{a(t)} = \int_0^{a_{\rm dec}} c\frac{da}{a^2 H(a)}$$

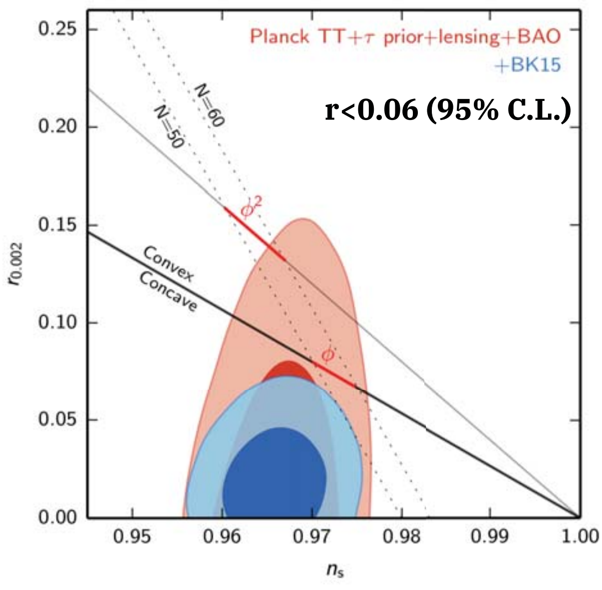


BICEP/Keck Collaboration (2016, 2018)

B-mode polarization, status

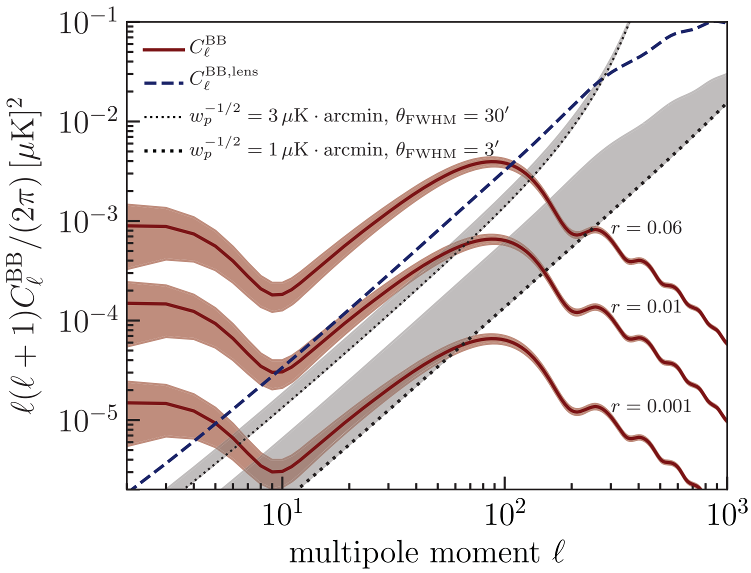


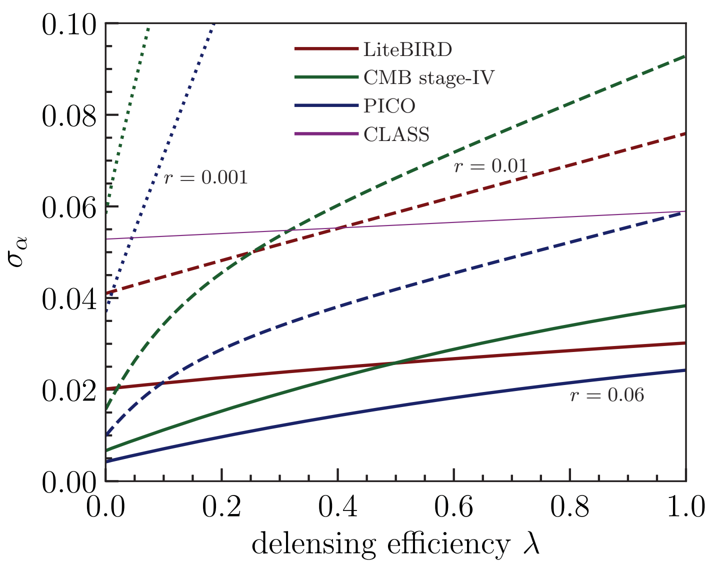
r=(GW)²/(density)²



Jeong & Kamionkowski (2019)

We can measure r_t, if r>0.001!



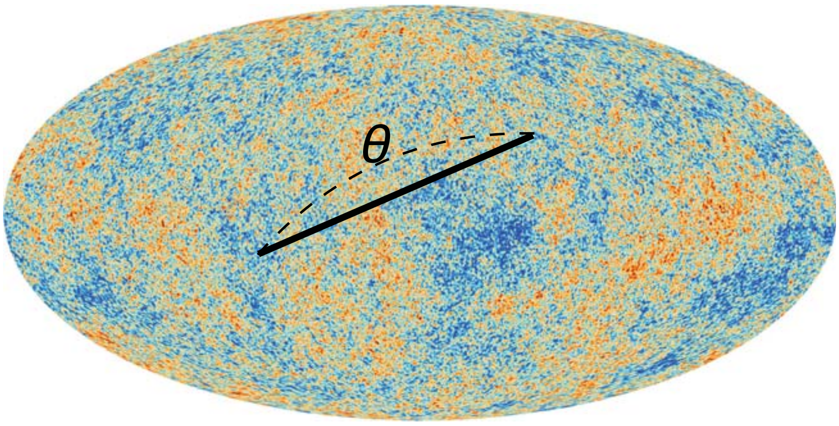


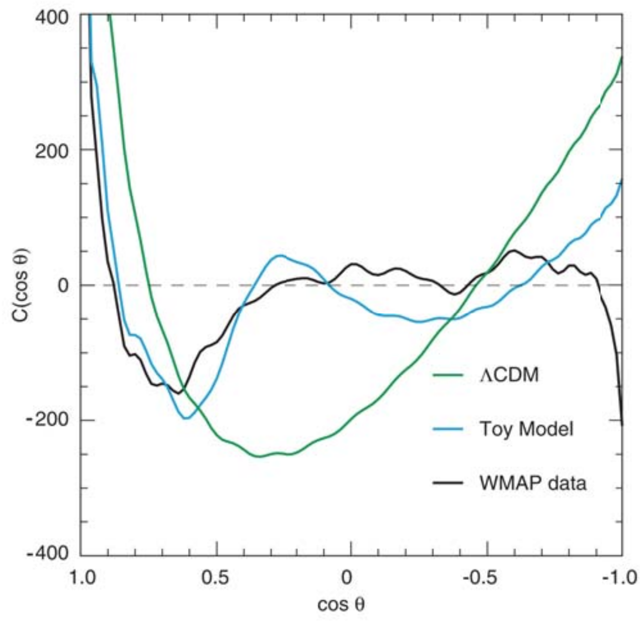
Three puzzles in the CMB

- Hubble tension
- Lack of CMB clustering on large angular scales
- “Crisis for cosmology”: A_L (lensing amplitude) anomaly

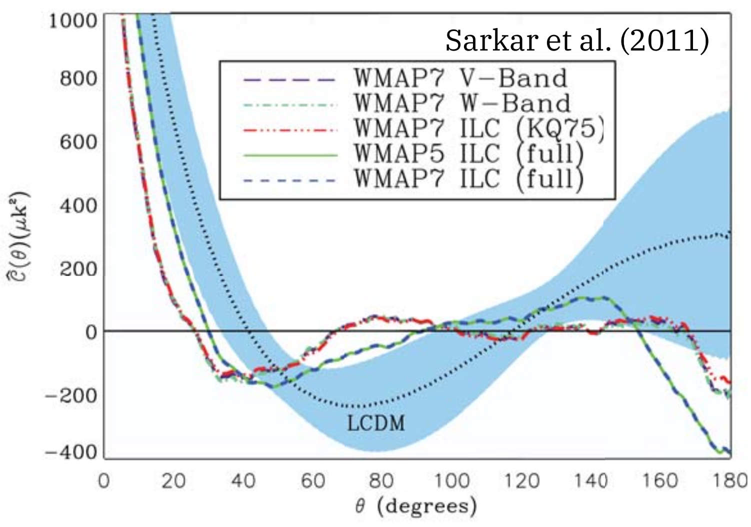
WMAP1, Spergel et al. (2003)

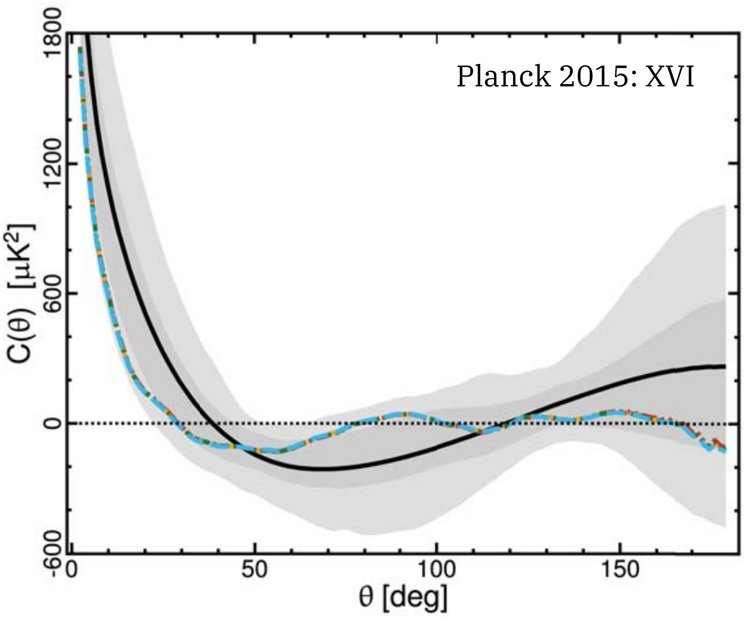
“Intriguing discrepancy”





C(θ) after WMAP1





The $S_{1/2}$ parameter

$$S_{1/2} \equiv \int_{-1}^{1/2} \mathrm{d}(\cos\theta)\,[C(\theta)]^2$$

Table 11. Values for the $S^{XY}_{1/2} \equiv S^{XY}(60°, 180°)$ statistic (in units of μK^4) for the *Planck* 2018 data with resolution parameter $N_{\rm side} = 64$.

Statistic	$S^{XY}_{1/2}$ [μK^4]			
	Comm.	NILC	SEVEM	SMICA
TT	1209.2	1156.6	1146.2	1142.4
$Q_r Q_r$	8.3×10^{-5}	8.6×10^{-5}	0.00019	4.9×10^{-5}
$U_r U_r$	3.9×10^{-5}	4.8×10^{-5}	5.9×10^{-5}	1.6×10^{-5}
TQ_r	0.26	0.13	0.45	0.13
TU_r	0.065	0.044	0.2	0.081
$Q_r U_r$	6.4×10^{-6}	3.6×10^{-5}	7.1×10^{-6}	2.1×10^{-6}

Planck 2018 VII. Isotropy and statistics of the CMB

Table 12. Probabilities of obtaining values for the $S^{XY}_{1/2}$ statistic for the *Planck* fiducial ΛCDM model at least as large as the observed values of the statistic for the *Planck* 2018 CMB maps with resolution parameter $N_{\rm side} = 64$, estimated using the `Commander`, `NILC`, `SEVEM`, and `SMICA` maps.

Statistic	Probability [%]			
	Comm.	NILC	SEVEM	SMICA
TT	>99.9	>99.9	>99.9	>99.9
TT (no quadr.) ...	96.0	96.1	96.1	96.2
$Q_r Q_r$	42.8	50.5	30.3	57.0
$U_r U_r$	74.5	71.7	68.9	89.0
TQ_r	83.5	94.0	74.6	94.8
TU_r	94.5	97.8	79.1	88.6
$Q_r U_r$	88.8	59.7	94.4	97.7

Notes. The second row shows results for each temperature map after removing the corresponding best-fit quadrupole. In this table high probabilities would correspond to anomalously low $S^{XY}_{1/2}$ values.

Three puzzles in the CMB

- Hubble tension
- Lack of CMB clustering on large angular scales
- “Crisis for cosmology”: A_L (lensing amplitude) anomaly

  Di Valentino, Melchiorri, Silk
  “Planck evidence for a closed Universe and a possible crisis for cosmology”
  Nature Astronomy (2019), arXiv:1911.02087

Planck 2018 VI. Cosmological parameters

A_L =(lensing amplitude)/(best-fitting ΛCDM)

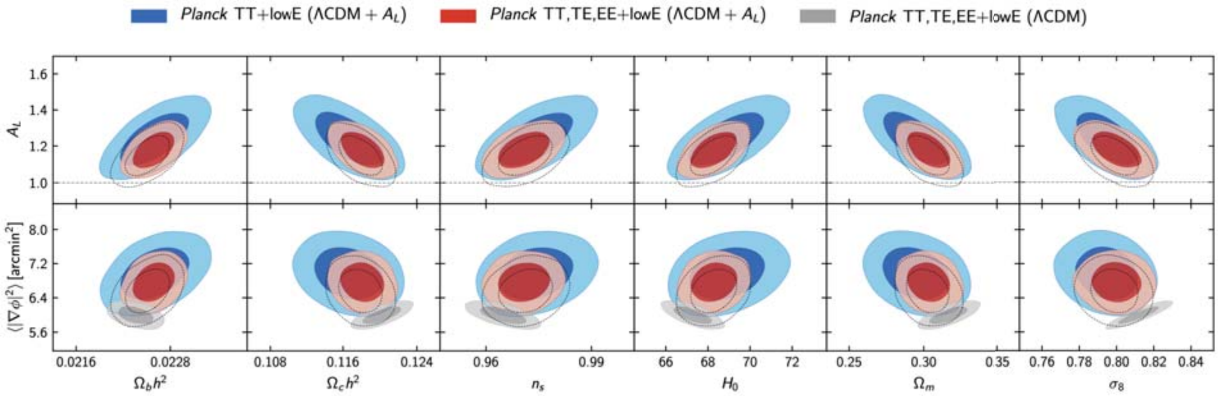
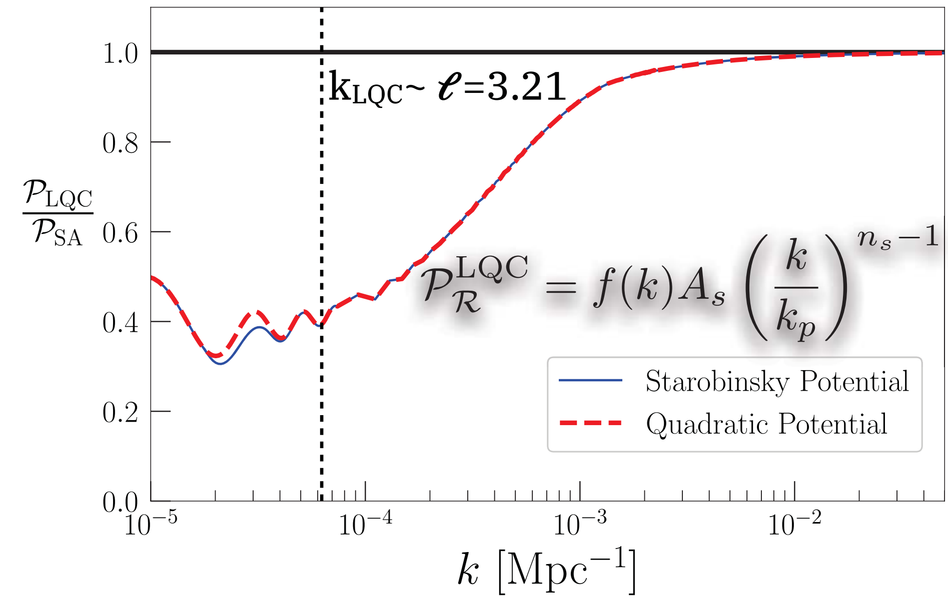


Fig. 25. Marginalized 68 % and 95 % parameter constraint contours when adding A_L as a single-parameter extension to the base-ΛCDM model, with (red) and without (blue) small-scale polarization, compared to the constraints in the base-ΛCDM model (grey). The dashed contours show equivalent results for *Planck* TT,TE,EE+lowE when using the CamSpec likelihood, which gives results with A_L nearer unity and with slightly larger errors. The second row of subplots show, on the left axis, the predicted lensing deflection angle variance (from lensing multipoles $2 \leq L \leq 2000$), which is a measure of the amount of actual lensing: the TT,TE,EE+lowE likelihood prefers about 10 % more actual lensing power (associated with lensing smoothing), but in the (unphysical) varying-A_L case this can be achieved using cosmological parameters that predict less lensing than in ΛCDM but substantially larger A_L, giving a preference for $A_L \approx 1.2$.

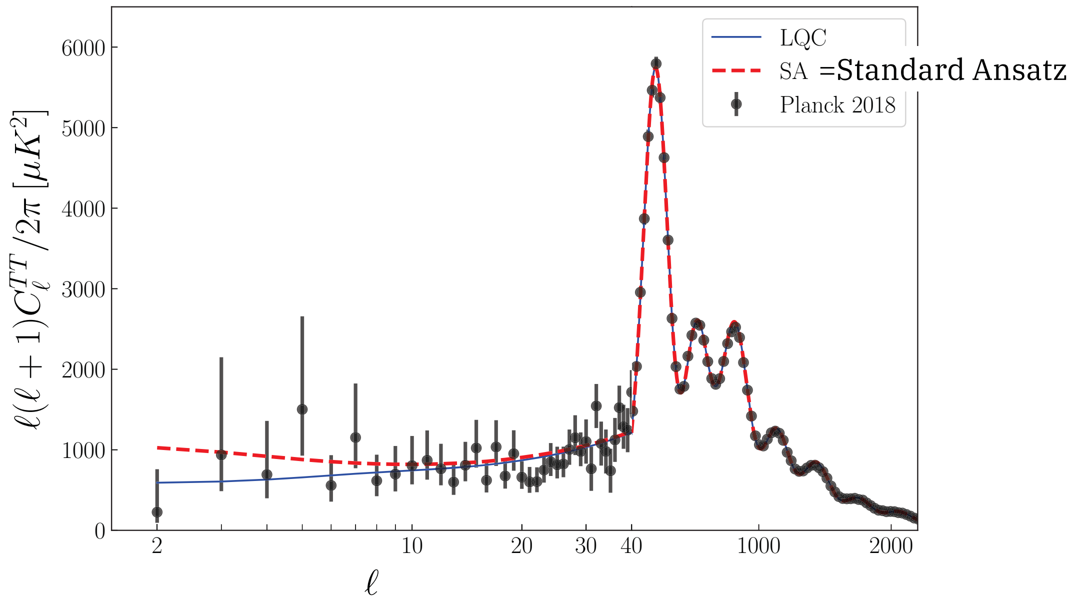
Initial P(k) from LQC

- Loop-Quantum Cosmology provides an initial condition of inflation
- Quantum correction yields the "bounce" at which $R_{max} \sim 62$ (Planck unit).
- The "LQC scale" is given by $k_{LQC} = (R_{max}/6)^{1/2} \sim 3.21$ (Planck unit).
- Fourier modes $k < k_{LQC}$ are *not* in the Bunch-Davies vacuum; that leads to the large-scale suppression.
- Equating the CMB horizon size with the "unit spacetime quanta" at the bounce, we can equate $k_{LQC}^{(co\text{-}moving)} \sim 3.6 \times 10^{-4}\ \mathrm{Mpc}^{-1}$.

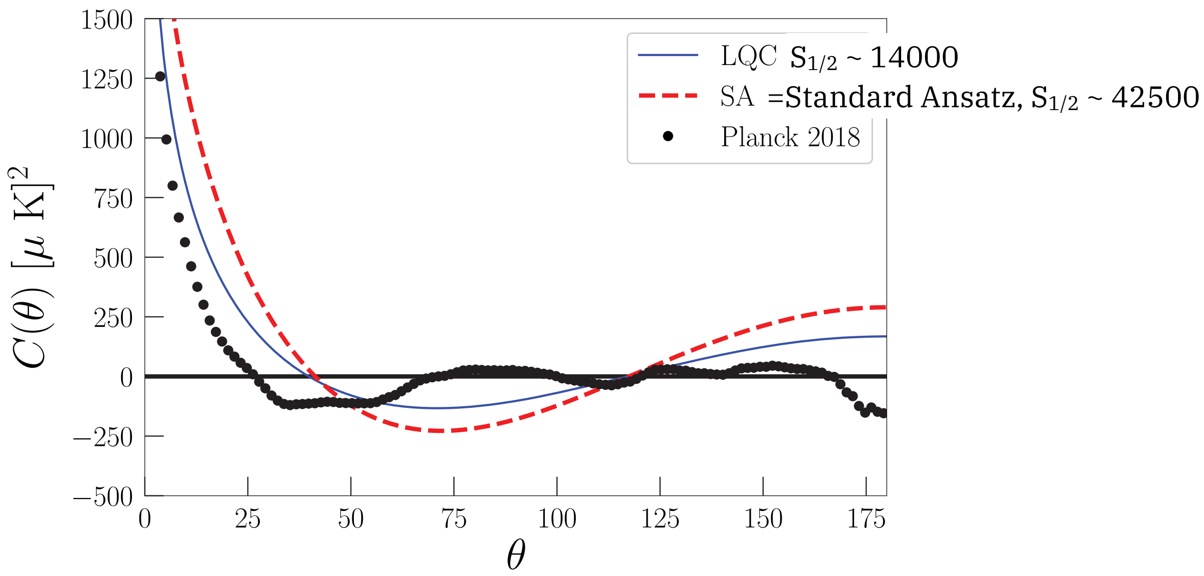
Initial P(k) from LQC



CMB power spectrum with LQC

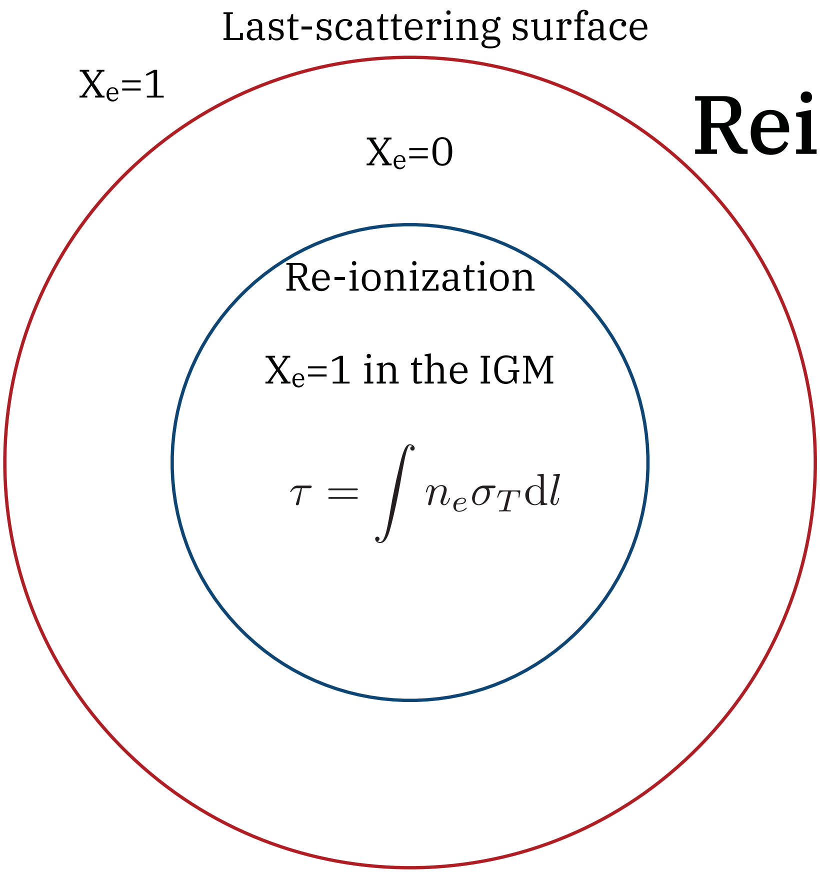


C(θ) with LQC



LQC S1/2 ~ 14000
SA =Standard Ansatz, S1/2 ~ 42500
Planck 2018
C(θ) [μ K]^2
θ
1500
1250
1000
750
500
250
0
−250
−500
0
25
50
75
100
125
150
175

Reionization and CMB



- Reionization Optical depth ~ 0.05 (Planck): 5% scatter
  - Damping the temperature anisotropies on small scales

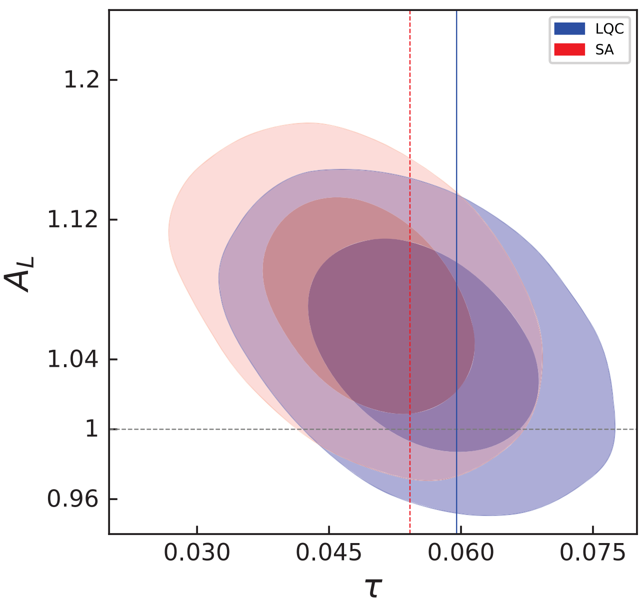
$$(T + \Delta T)^{\mathrm{obs}}$$
$$= (T + \Delta T)^{\mathrm{primordial}} e^{-\tau} + T\left(1 - e^{\tau}\right)$$

$$(\Delta T)^{\mathrm{obs}} = (\Delta T)^{\mathrm{primordial}} e^{-\tau}$$

(For $\ell > \ell_{\mathrm{reionization}}$~40)

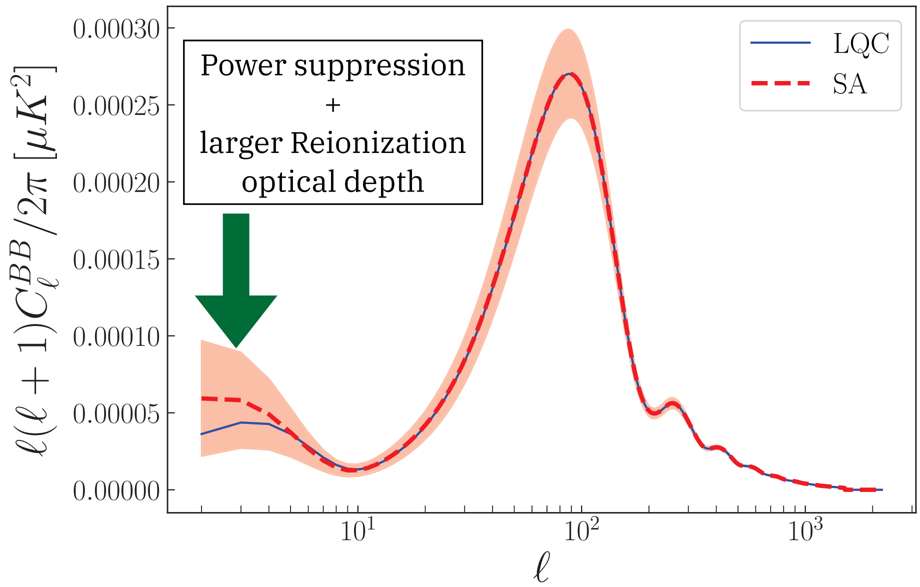
  - Polarization on large scales.

LQC and A_L



- Interplay between large and small scales
- Small scale anisotropy measures = $A_s e^{-2\tau}$
- By increasing the optical depth, we increases the density fluctuation amplitude A_s in the CMB
- The ratio A_L = (lensing amplitude)/A_s drops!
- All of them without screwing the large-scale C_ℓ thanks to the power suppression!

LQC prediction for C_ℓ^{BB}



Conclusion

- C_ℓ^{BB} can test the early-type resolution of the Hubble tension hypothesizing that Universe expanded with a faster rate prior to the decoupling time.
- C_ℓ^{BB} can test the LQC prediction that primordial power spectrum is suppressed on large-scales (k<0.002 Mpc^{-1}).
- Resolving the Hubble tension may require first-principle measurements at low redshifts, such as standard siren from Gravitational Waves.
- Large-scale power suppression can also be probe with full-sky galaxy/21cm surveys in the future.