Gravitational Waves, CMB Polarization, and Hubble Tension

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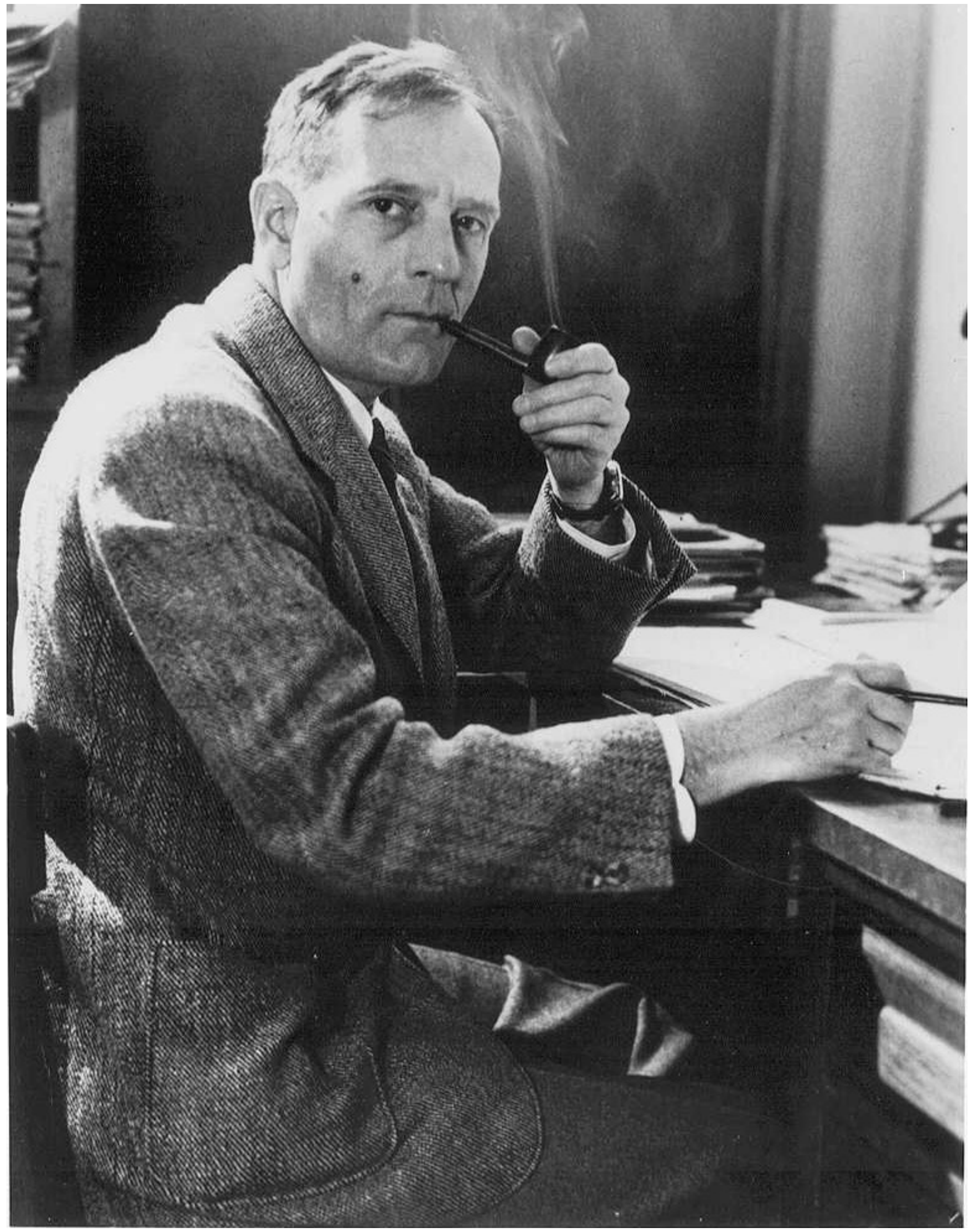
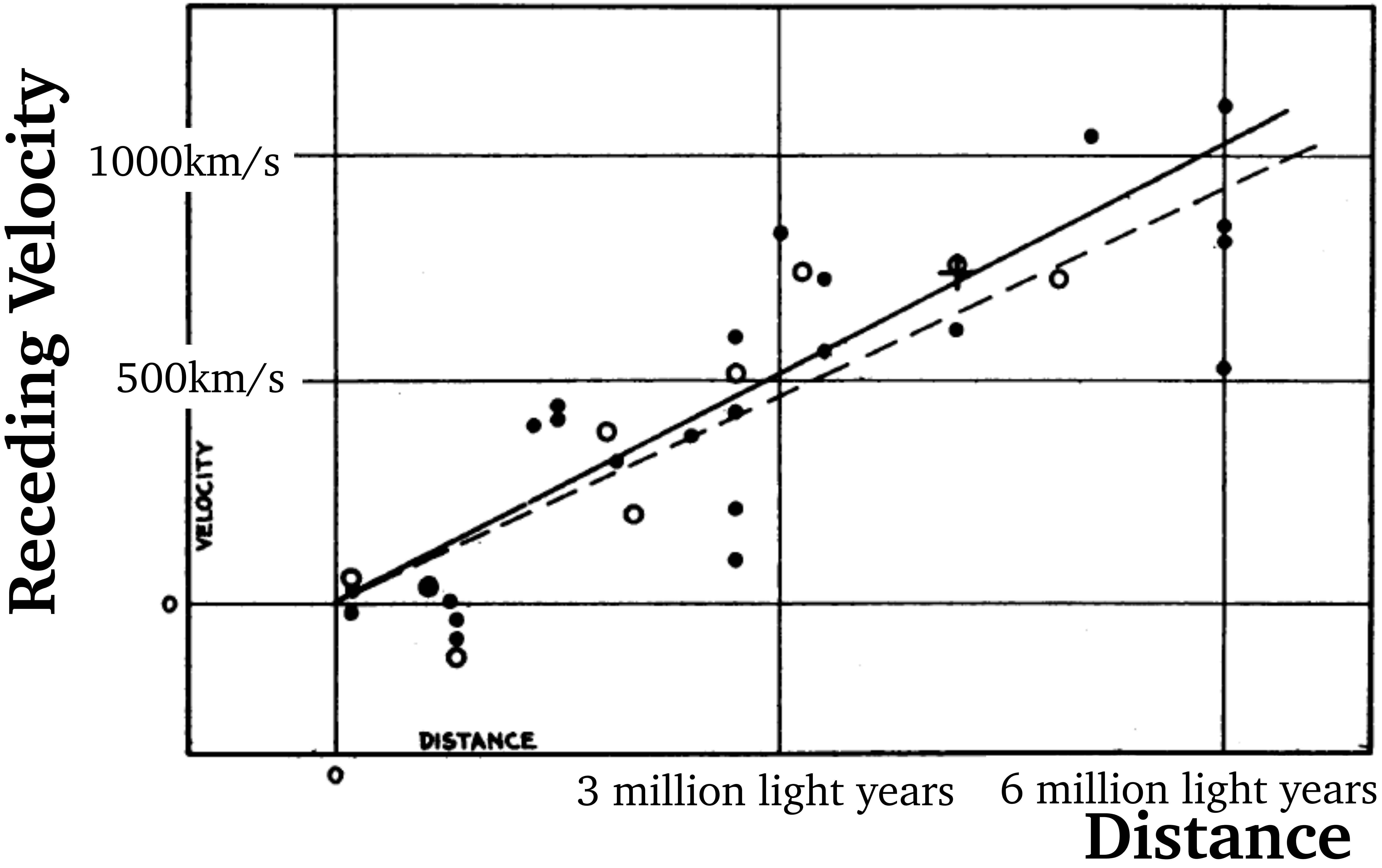
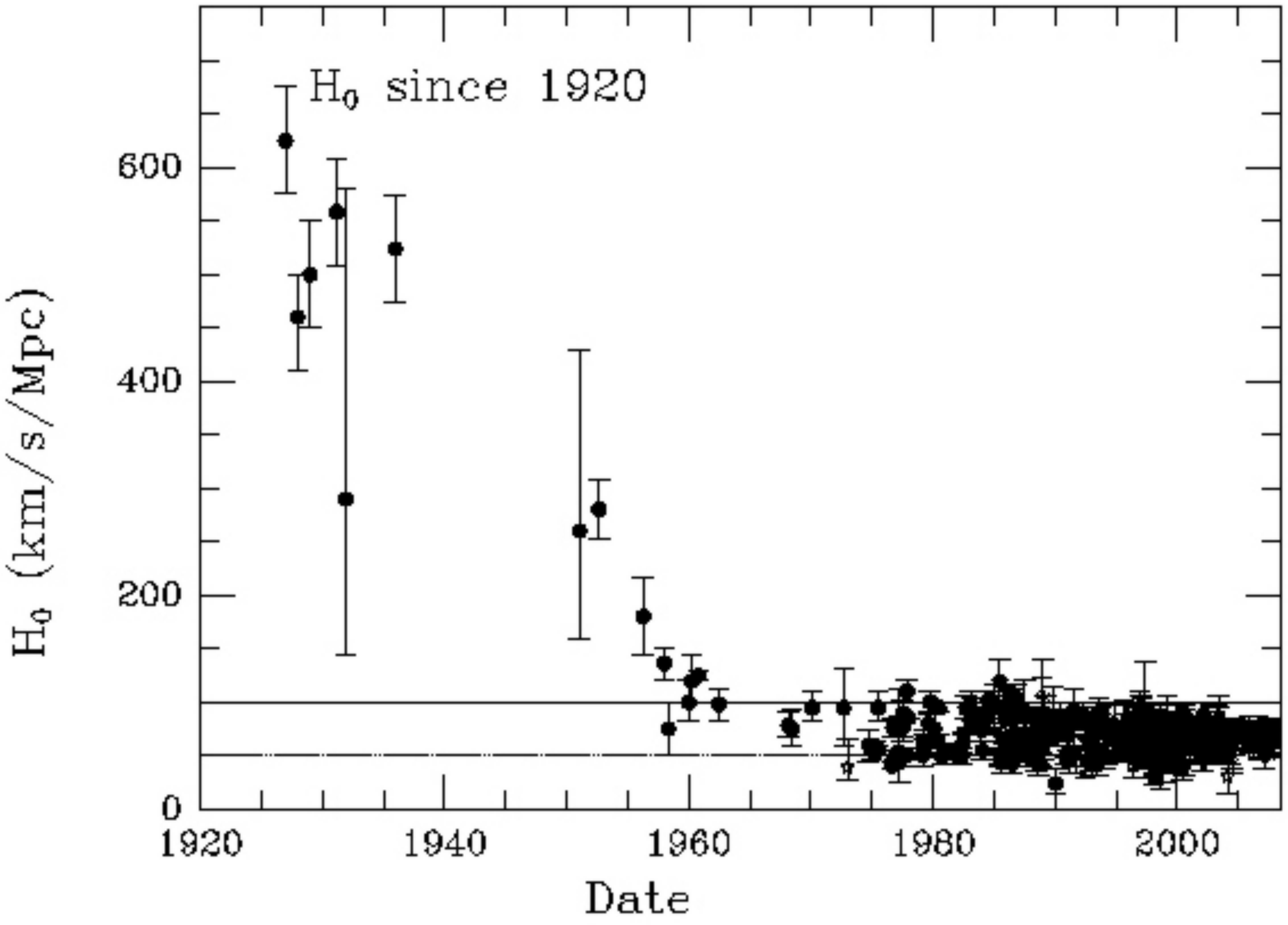
H_0 from Hubble



the first **Hubble diagram** Hubble (1929)



H_0 since 1920s



https://www.cfa.harvard.edu/~dfabricant/huchra/hubble/

H_0 from 1920s

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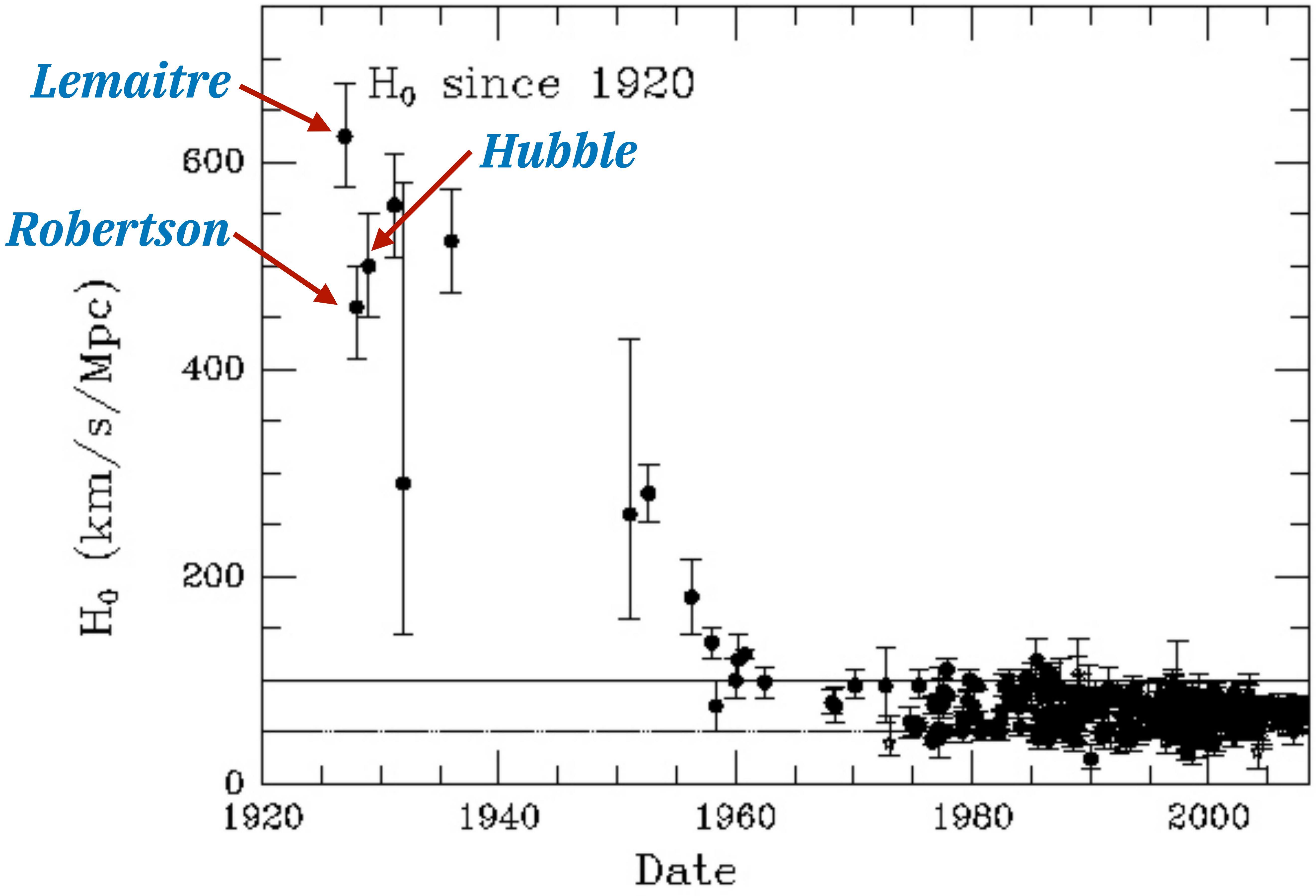

https://www.cfa.harvard.edu/~dfabricant/huchra/hubble/

H_0: pre-Hubble Key Project

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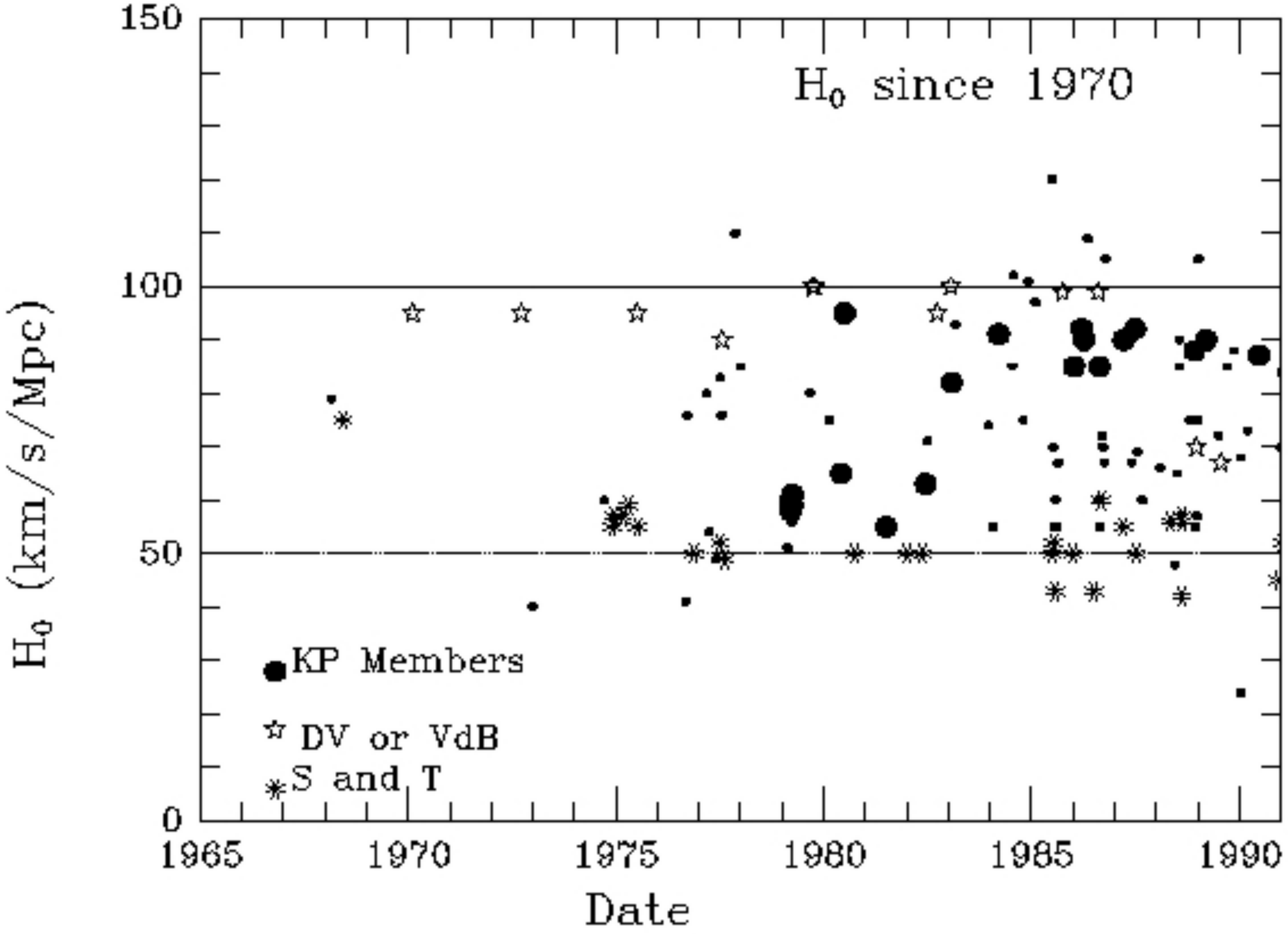
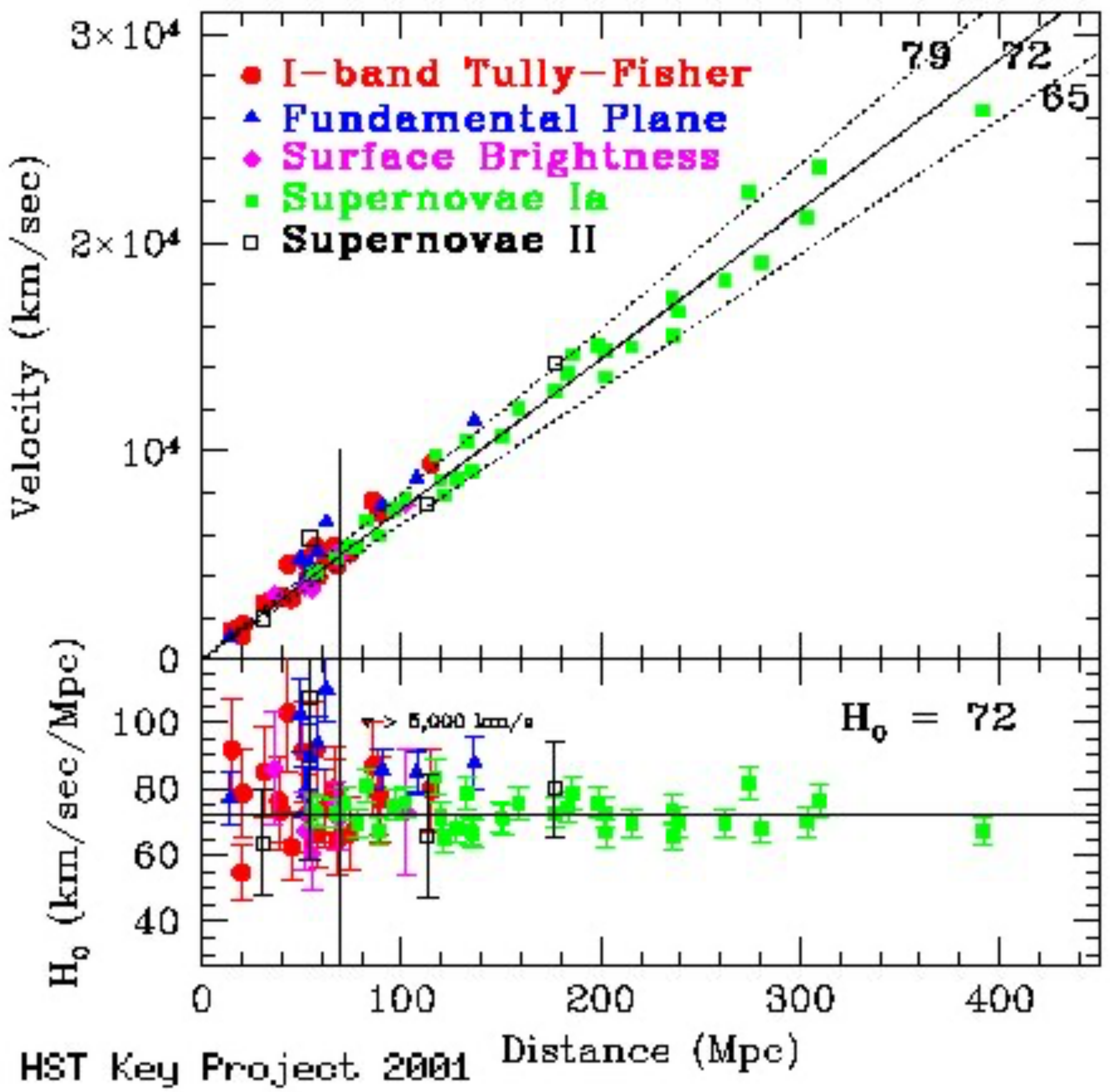


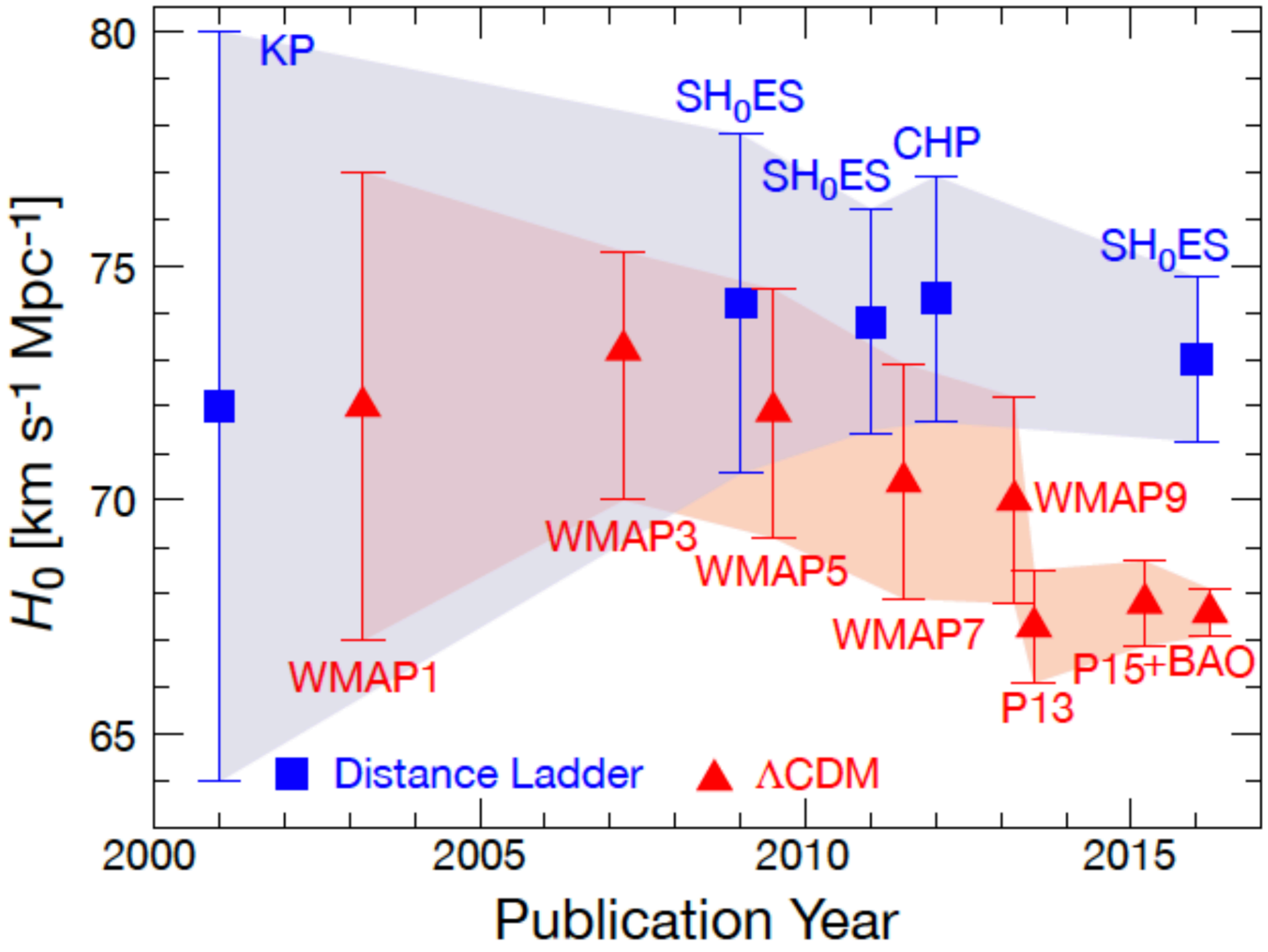
https://www.cfa.harvard.edu/~dfabricant/huchra/hubble/

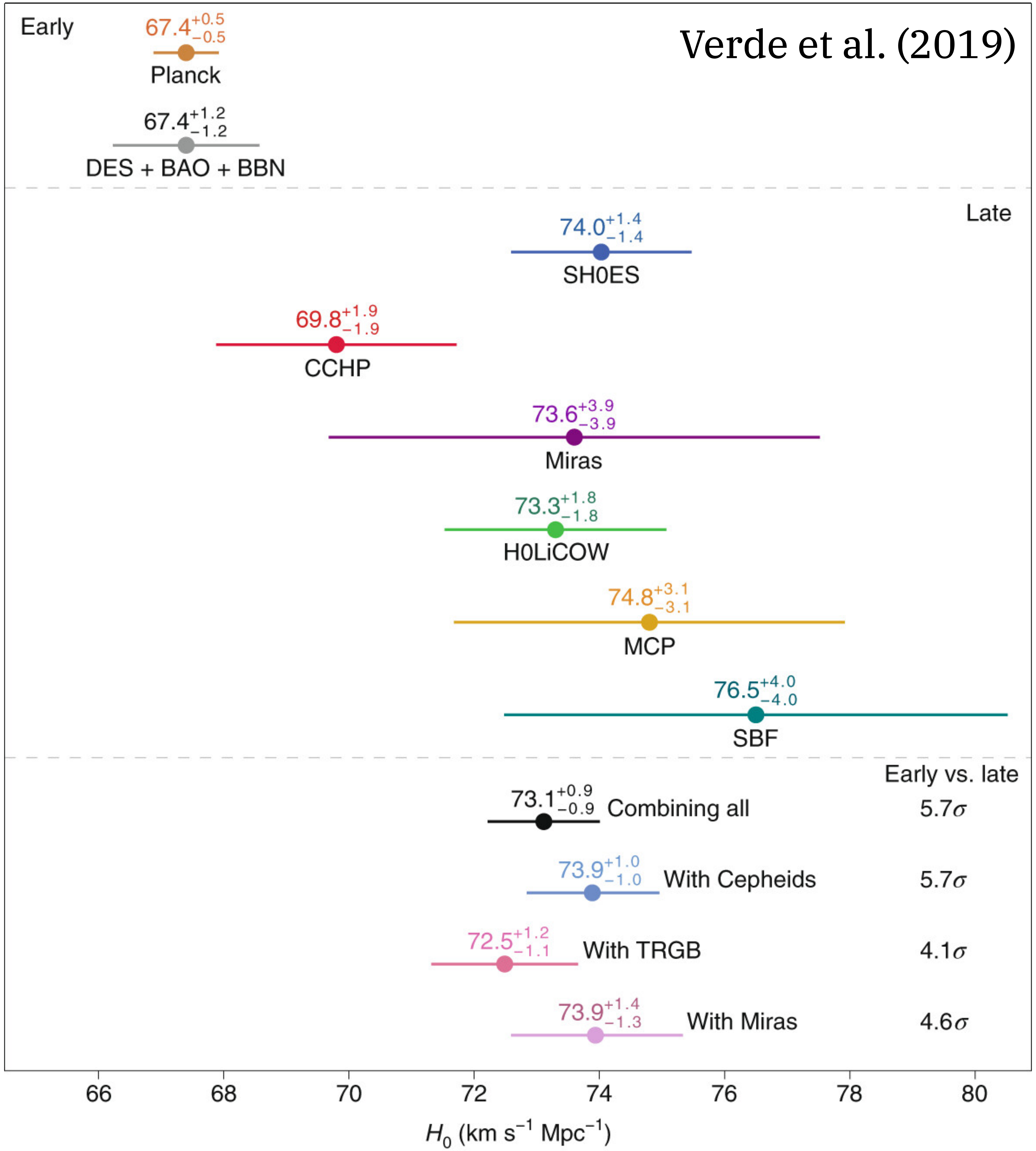
H_0 from Hubble Key Project



H_0 since Hubble Key Project

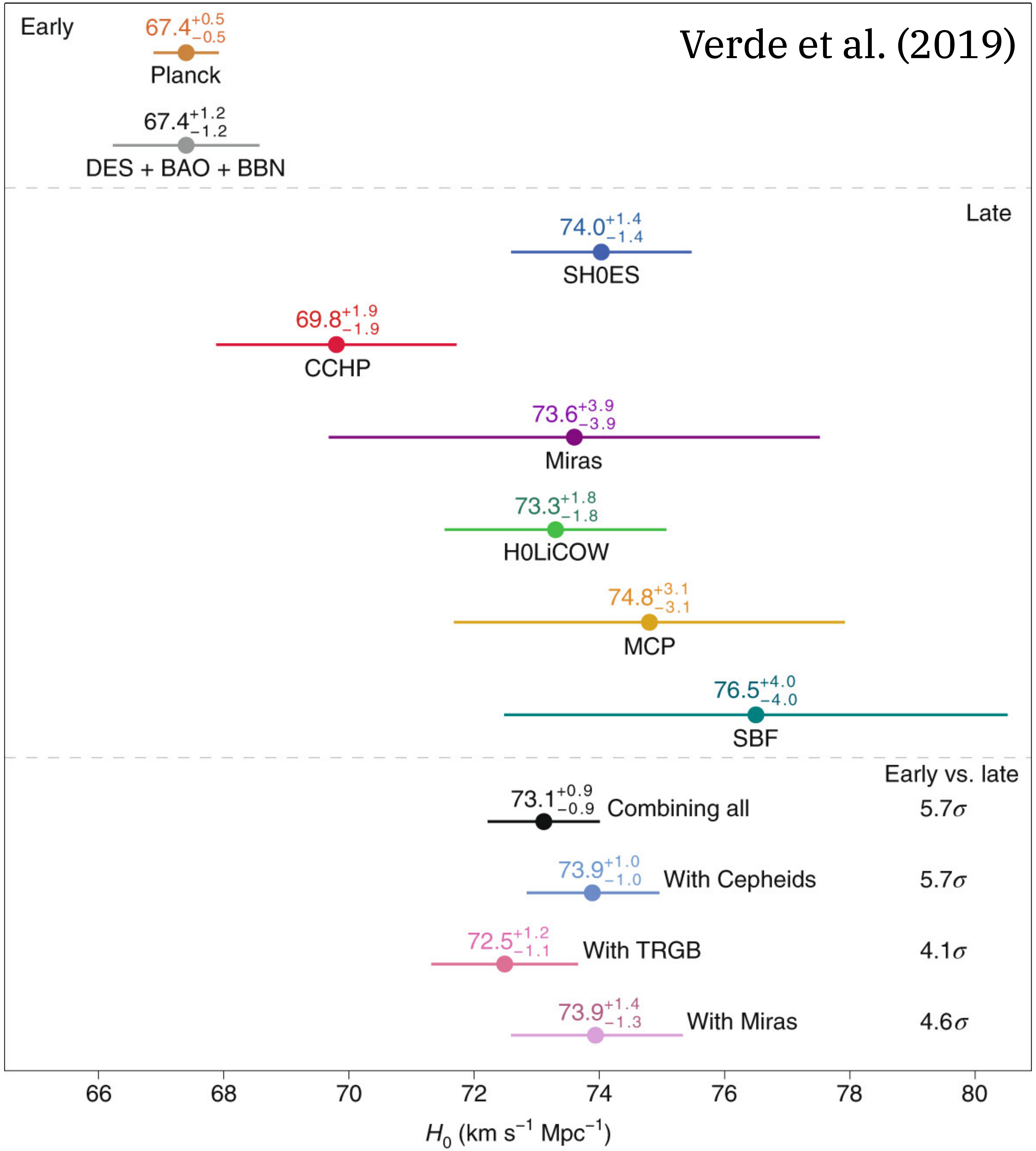
Freedman (2017)





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)

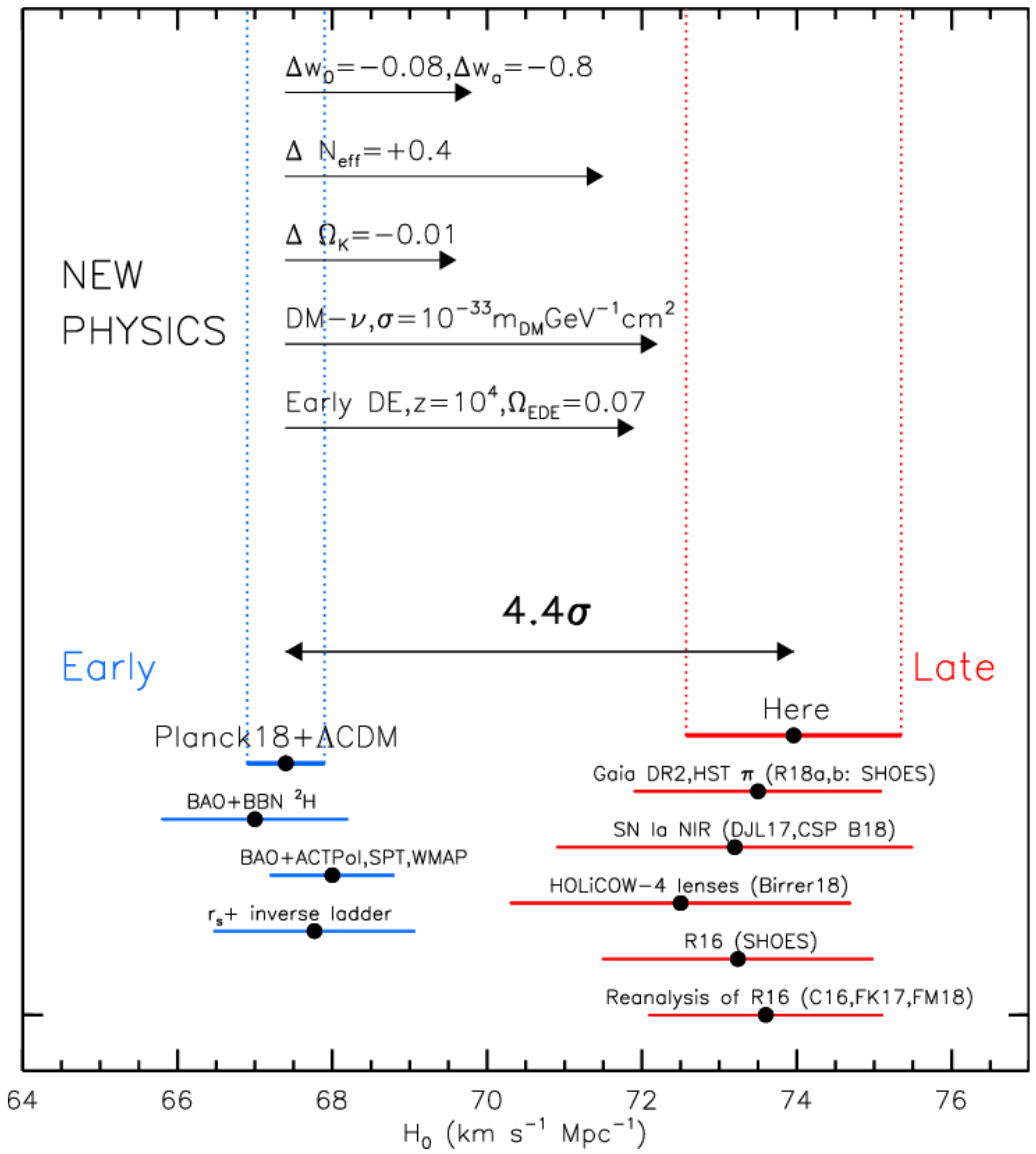


"Sound Discordant"

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

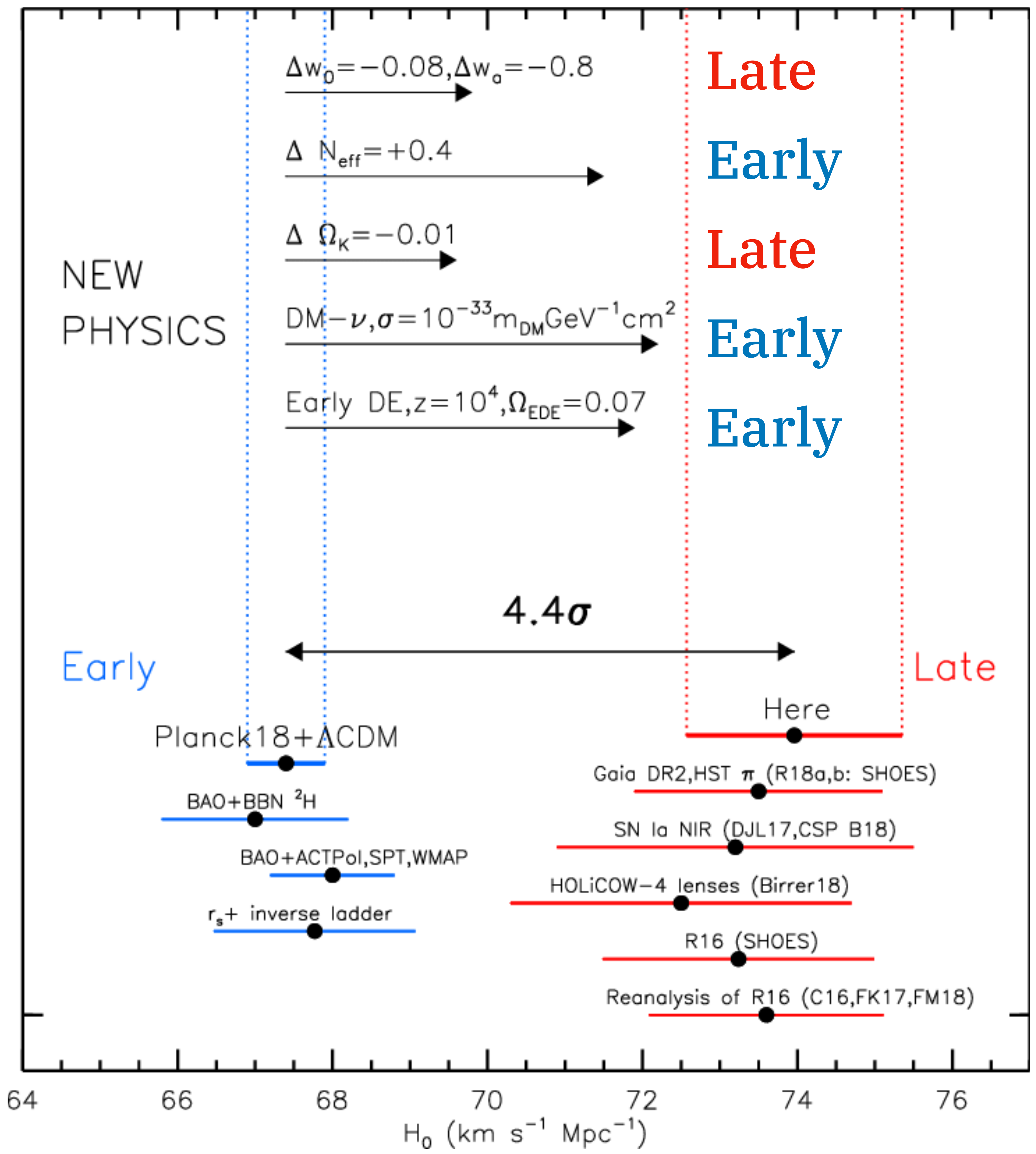
Possible solutions

Riess et al. (2019)

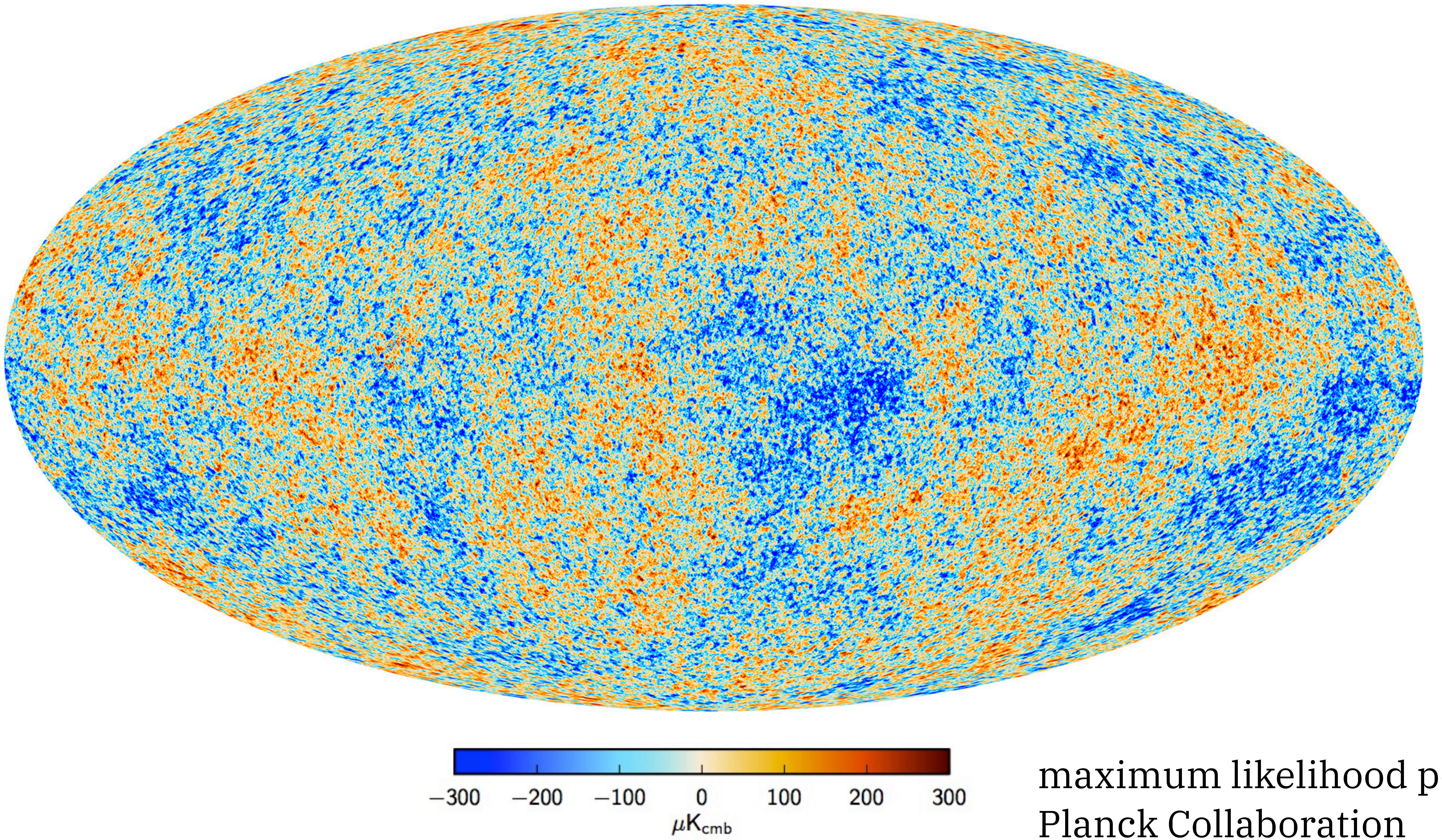


Possible solutions

Riess et al. (2019)

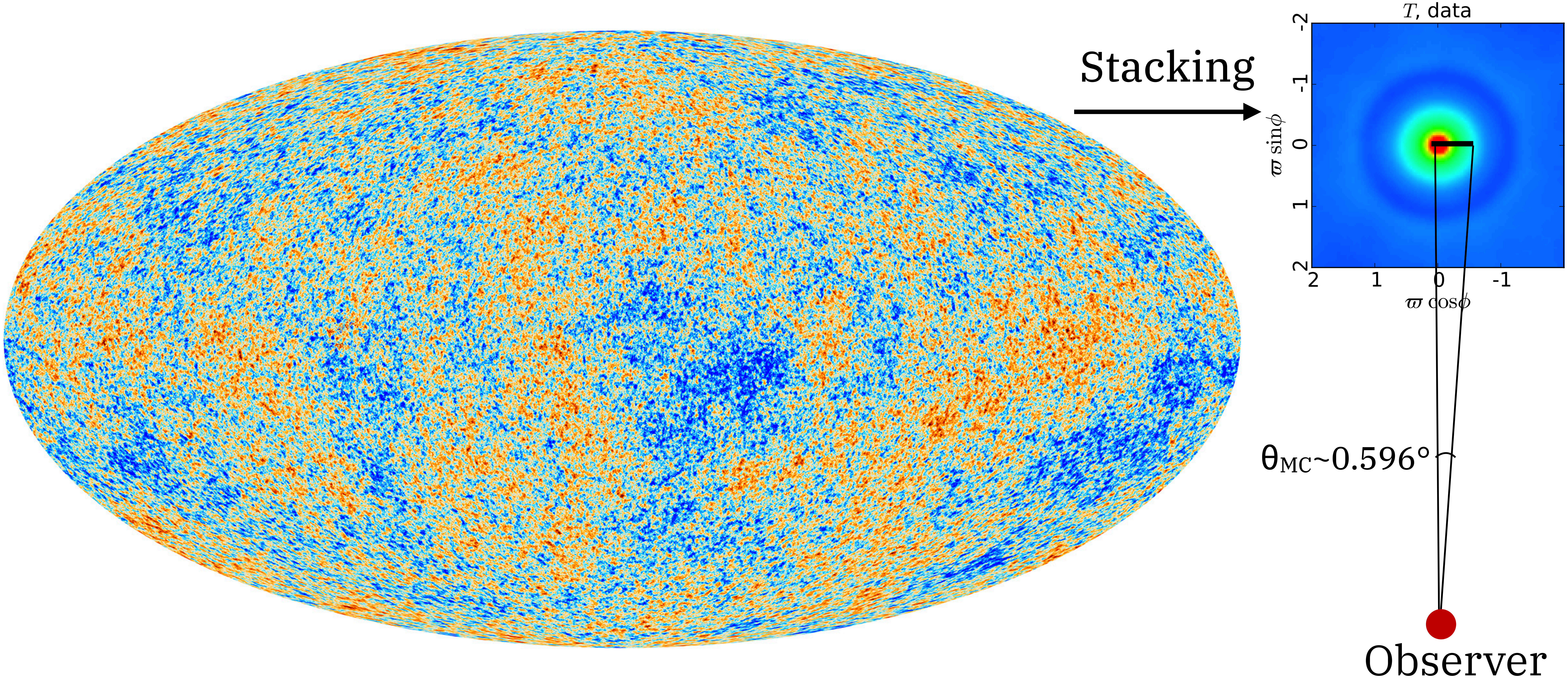


Temperature map of CMB



maximum likelihood posterior map
Planck Collaboration

Acoustic scale at θ~0.6°



Physics of acoustic scale

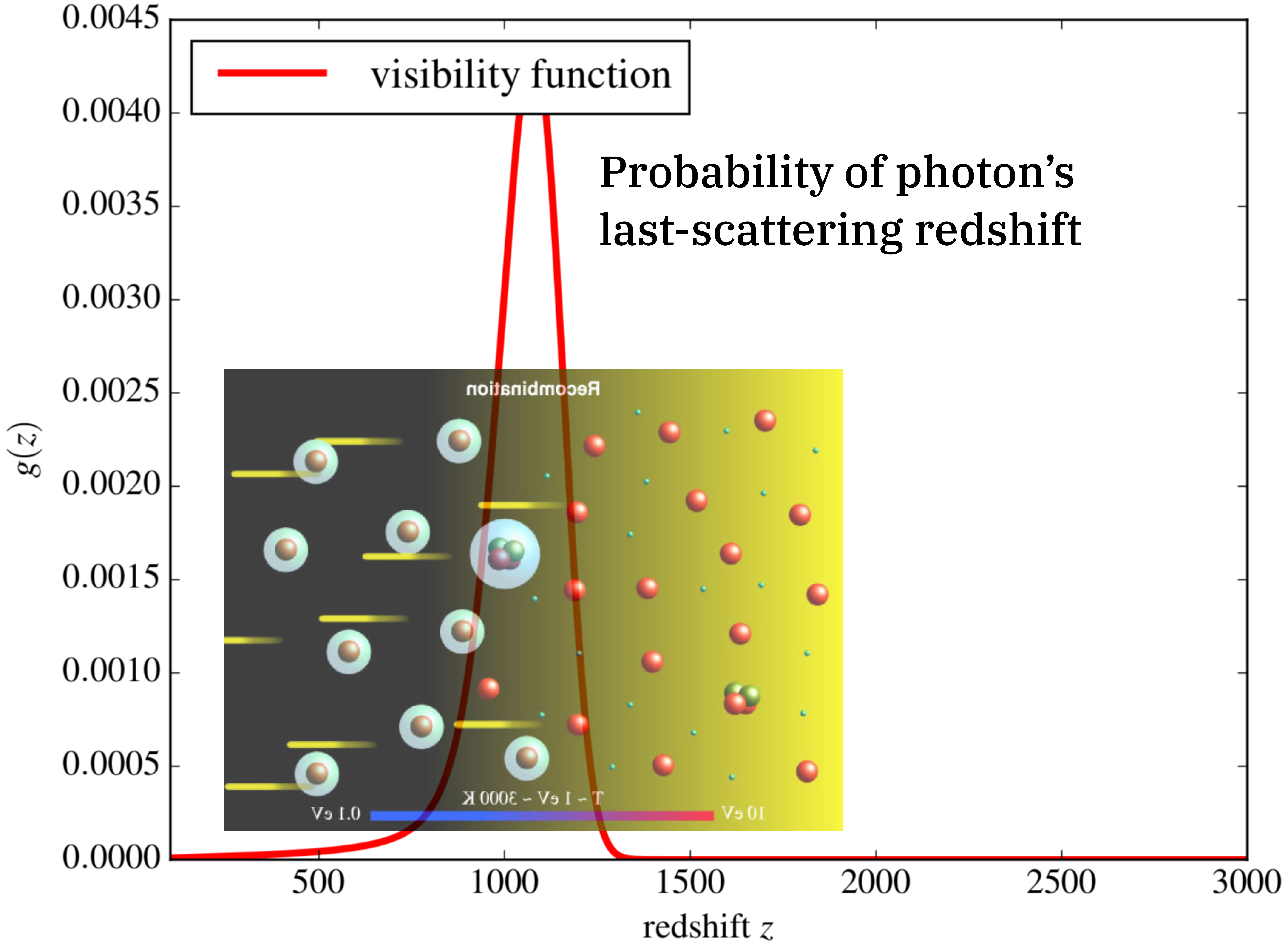
- ***Acoustic oscillation***: Tightly coupled baryon-photon plasma evolves as the pressure wave in the external gravitational field provided by dark matter
- The comoving sound horizon scale is given as

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

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

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

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

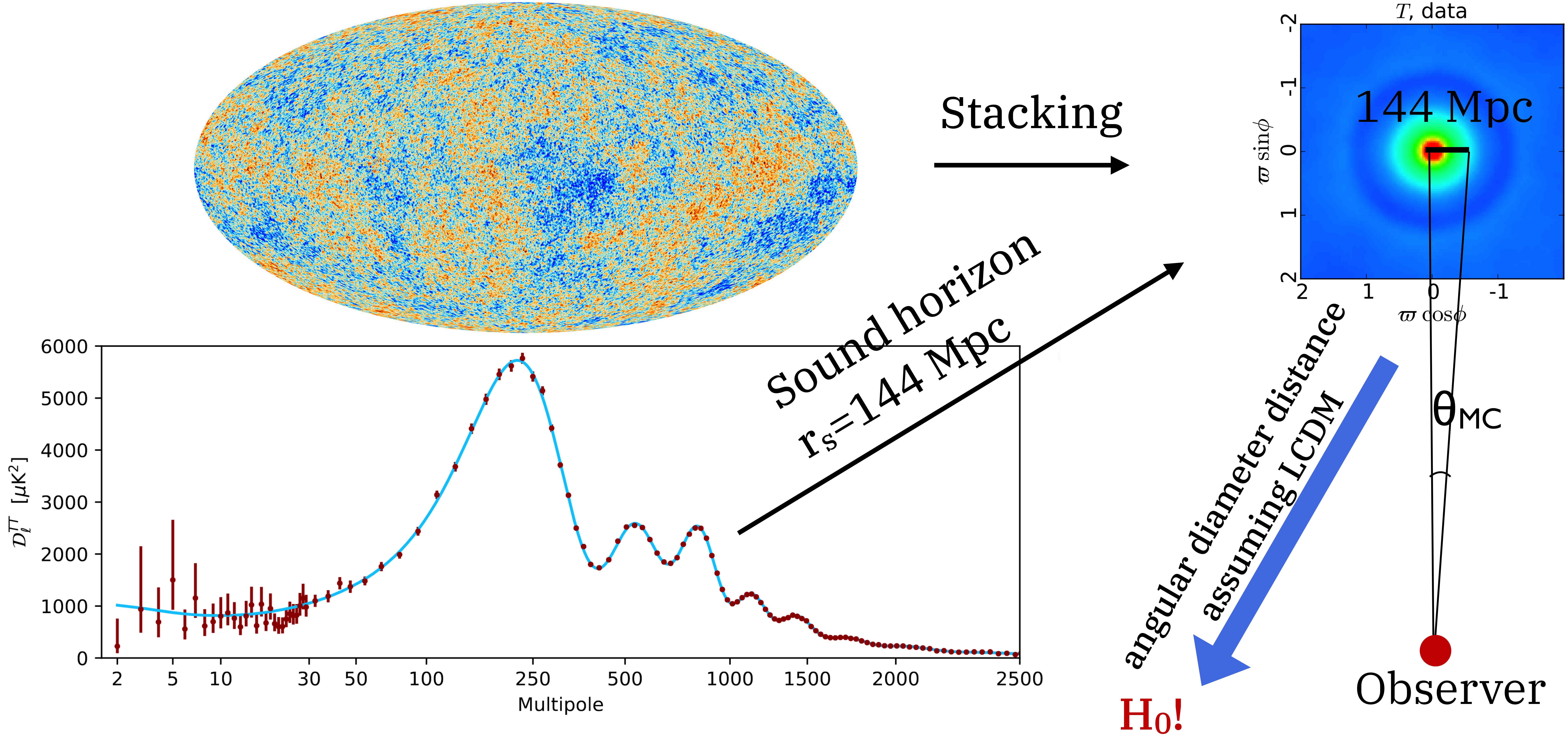
- Given ρ_m, ρ_b, ρ_γ, ρ_ν, we can determine the acoustic scale!
  - ρ_m, ρ_b : from the relative heights of CMB power spectrum
  - ρ_γ : from T_{cmb} (CMB is very good black body)
  - ρ_ν : from N_{eff} (T_ν = 0.714 T_{cmb}, and neutrinos are fermions)
  - Note: r_s is independent from H_0!

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

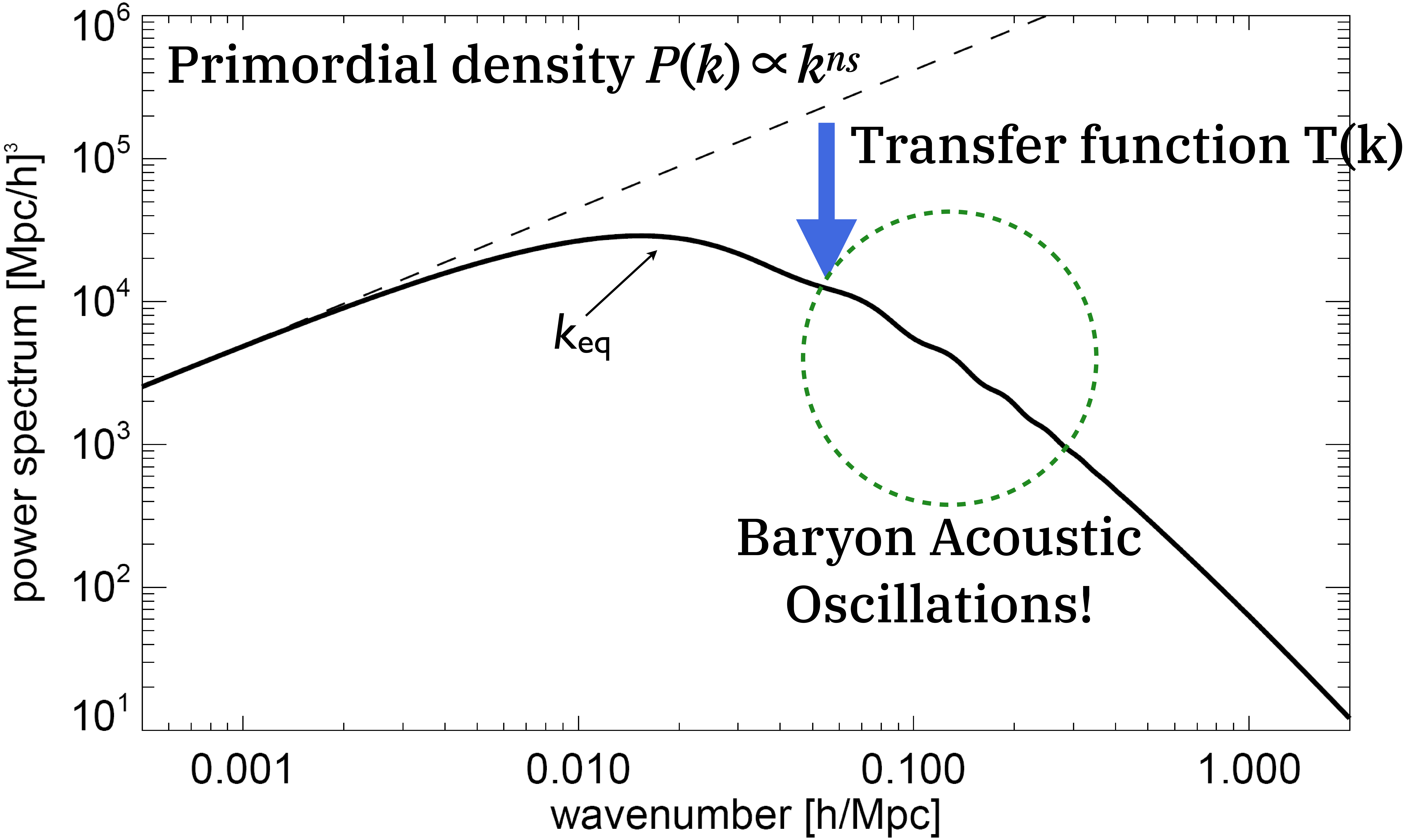
$$r_s = \int_0^{t_\mathrm{dec}} c_s(t)\frac{dt}{a(t)} = \int_0^{a_\mathrm{dec}} c_s(a)\frac{da}{a^2H(a)}$$

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

CMB power spectrum



Same BAO in matter $P(k)$



Dark energy with BAO

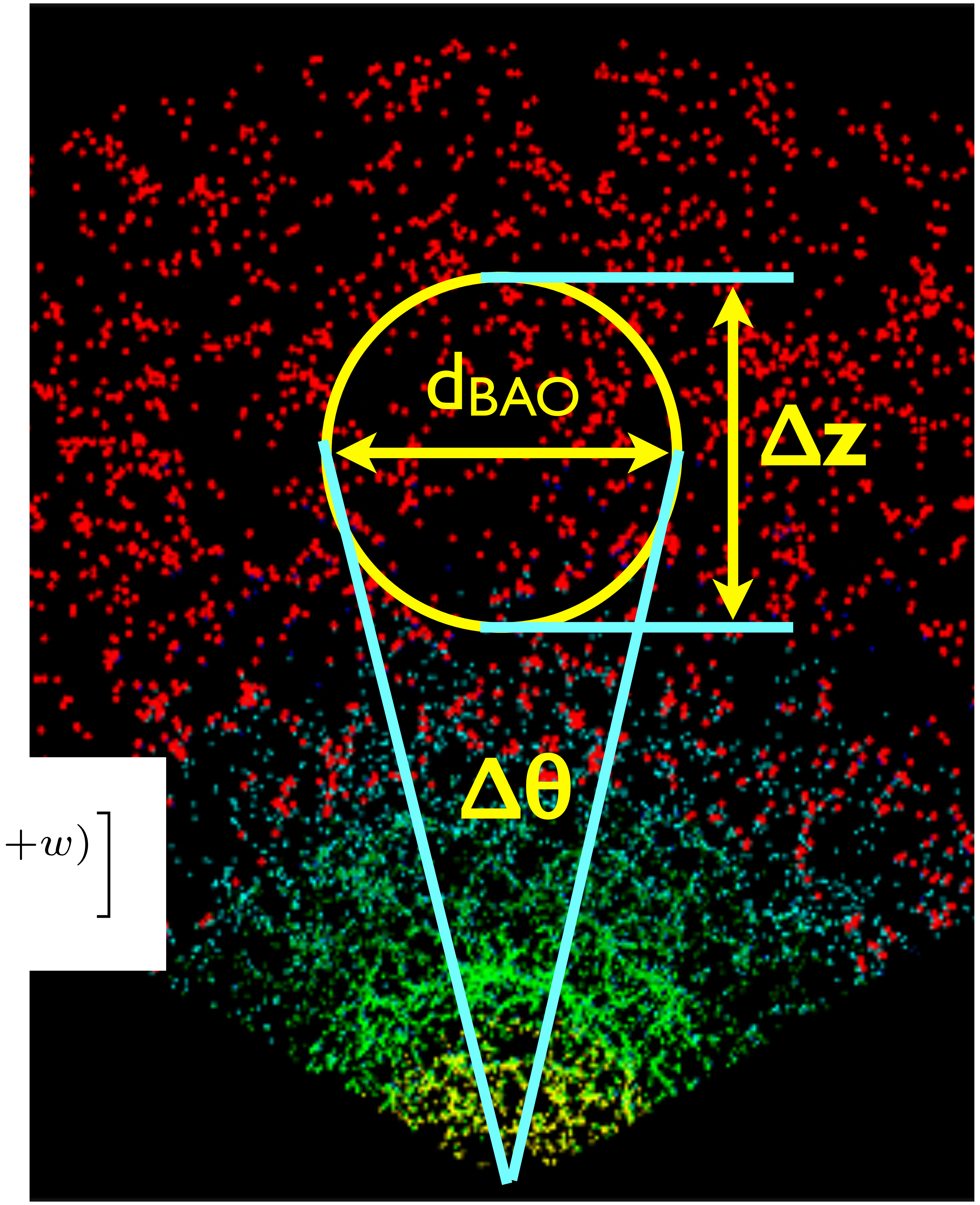
- d_{BAO} is given by CMB, slightly larger than r_s.
- We can measure the angular diameter distance, $d_A(z)$ and Hubble parameter, H(z):

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

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

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

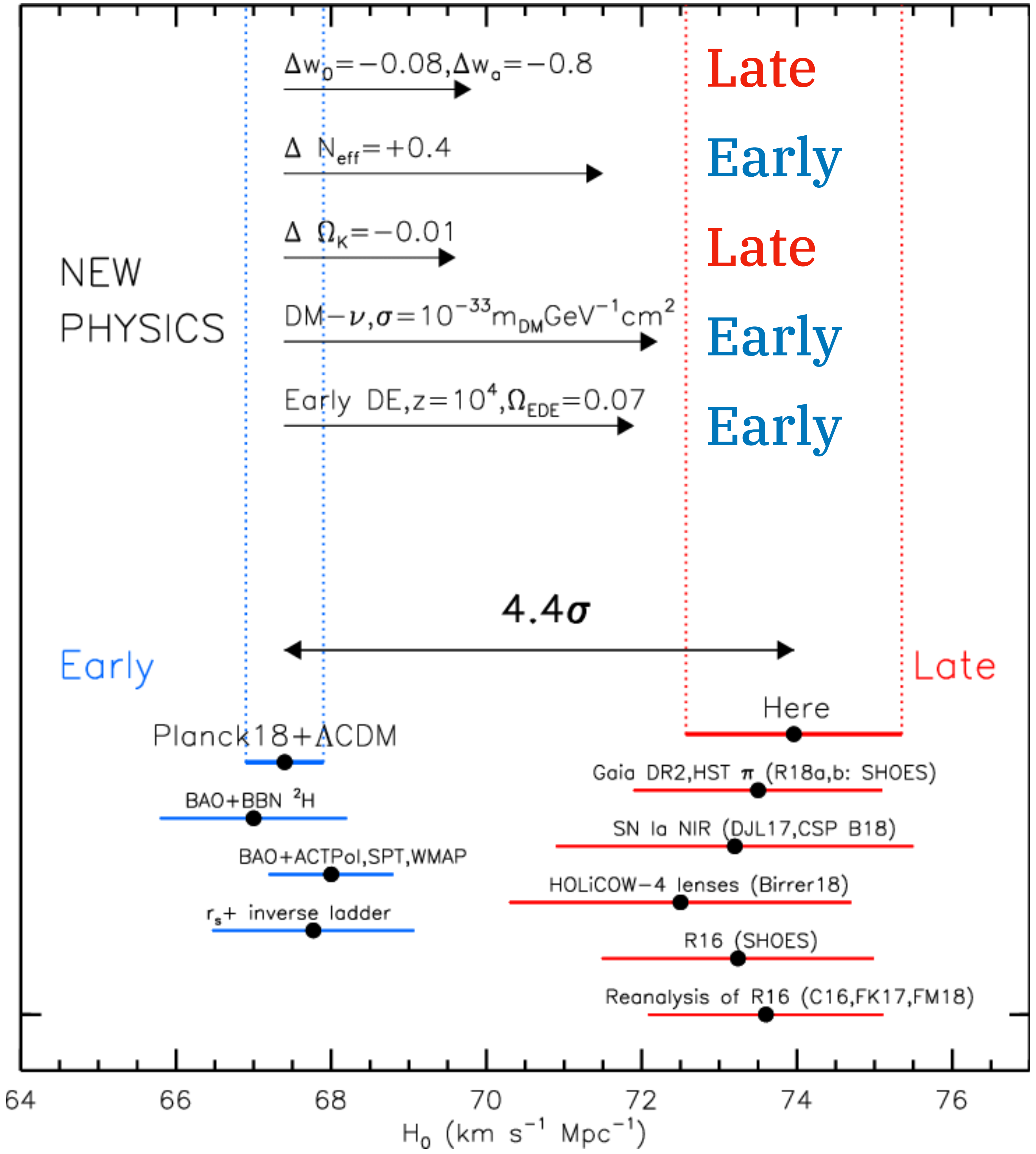
$$d_A(z) = \frac{\chi(z)}{1+z}\left[1 - \frac{k}{6}\frac{\chi^2(z)}{R^2}\right] \quad \chi(z) = c\int \frac{dz}{H(z)}$$



Early time

Mission H_0 : reduce r_s by 9%!

Riess et al. (2019)



- Direct observable = θ~0.6° = $r_s/d_A(a_{\rm dec})$~$H_0 r_s$.
- 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 $N_{\rm eff}$
  - 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?

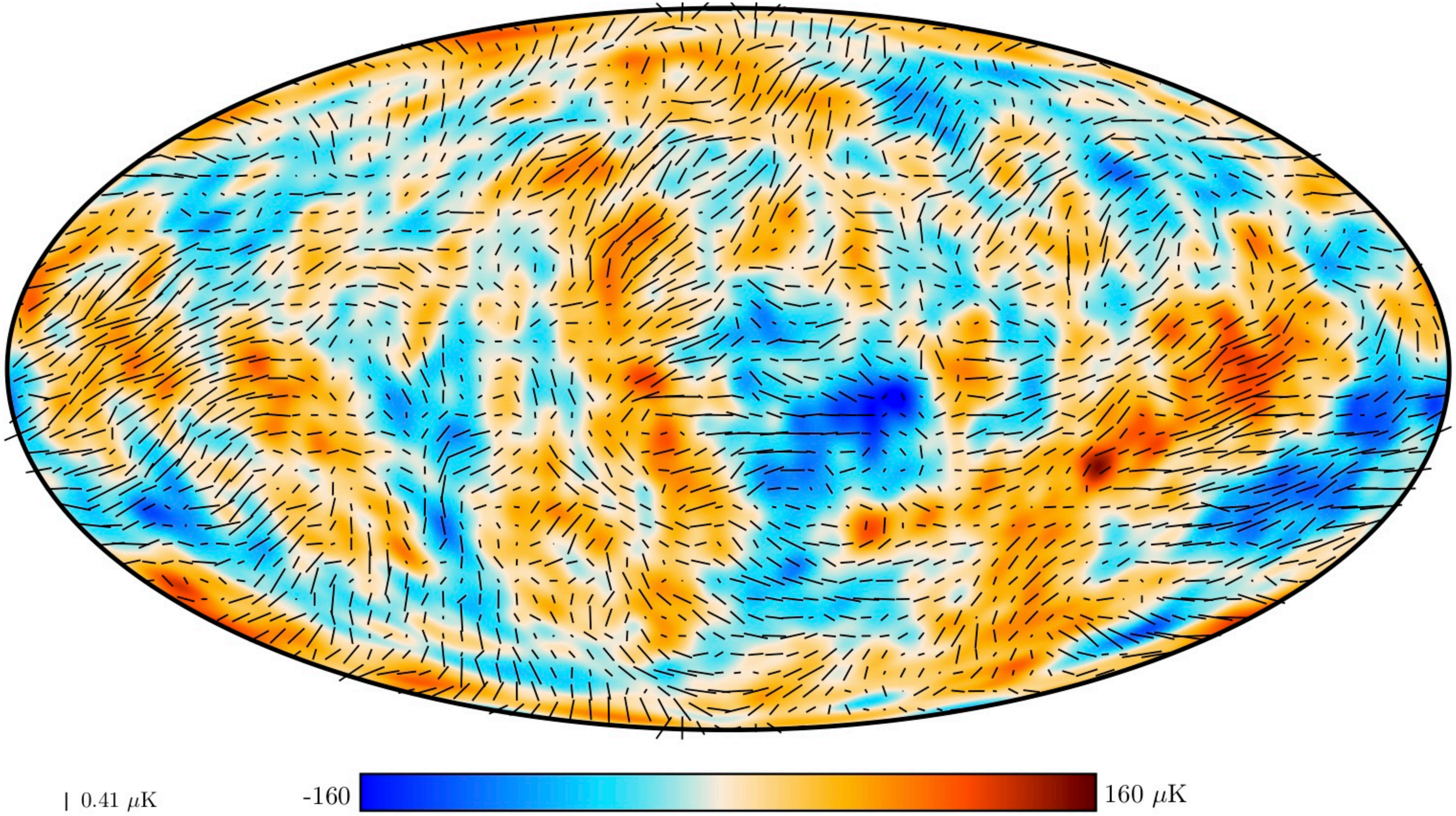
  In the *B-mode polarization from primordial gravitational waves!*

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

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

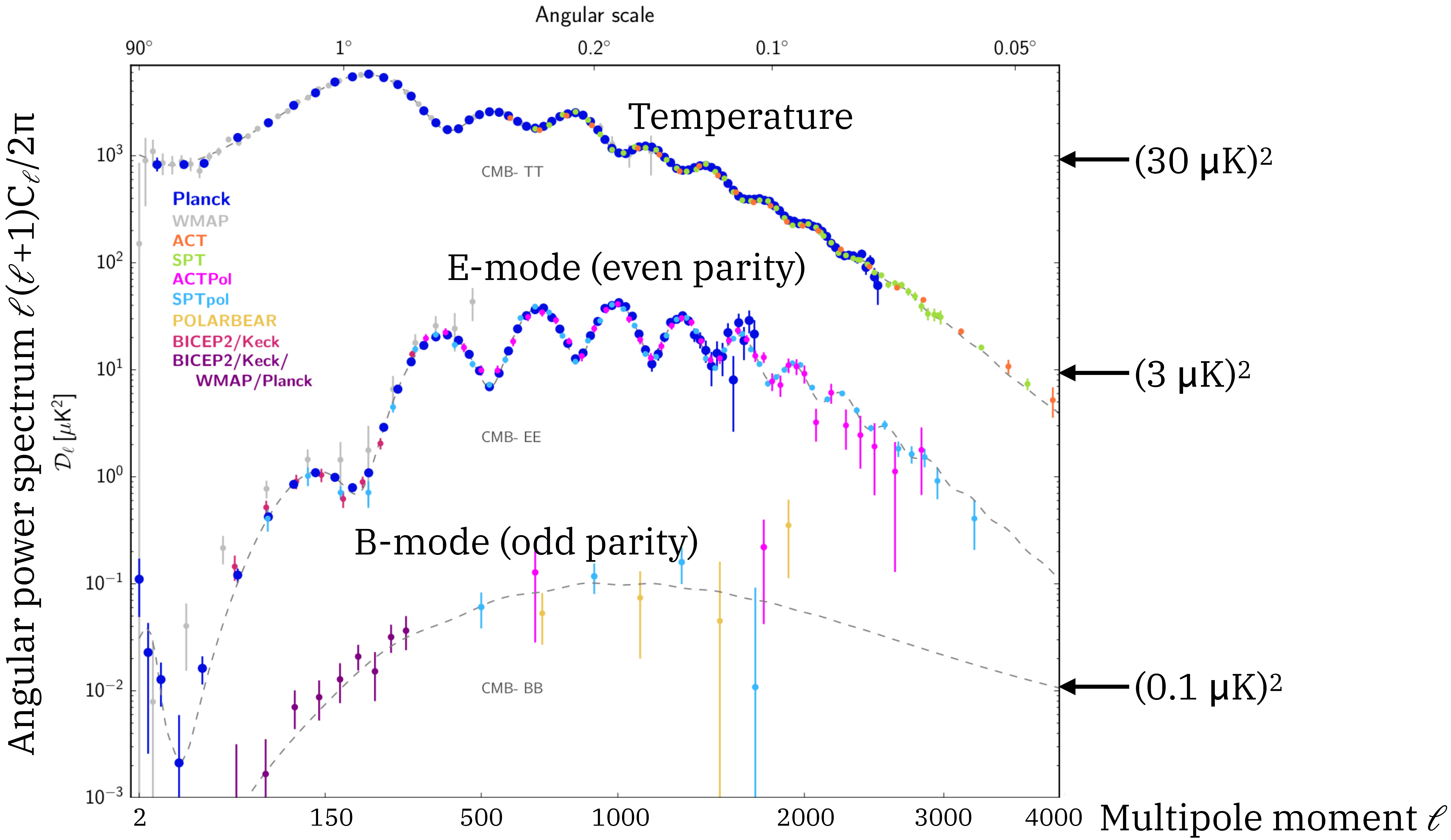
$$3H^2 = 8\pi G\left(\bar{\rho}_{\rm r} + \bar{\rho}_{\rm m}\right)$$

CMB is polarized

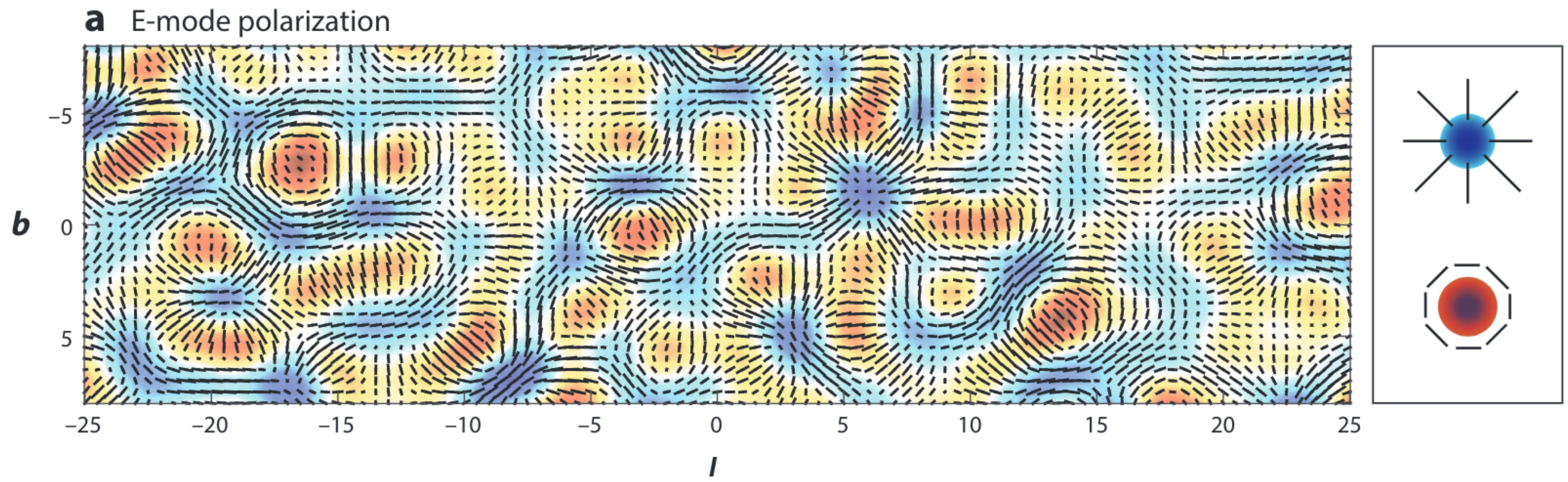


Planck map smoothed with 5° filter

Polarization is small!

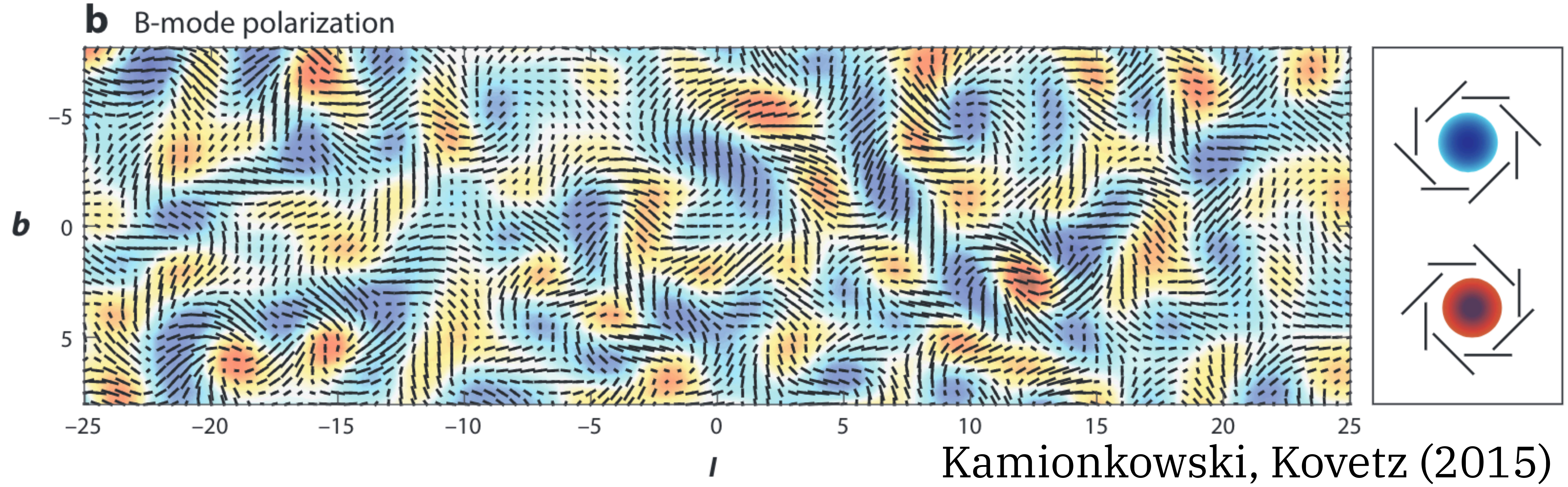


E-mode and B-mode



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)

Gravitational Waves (GW)

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

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

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

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

- 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

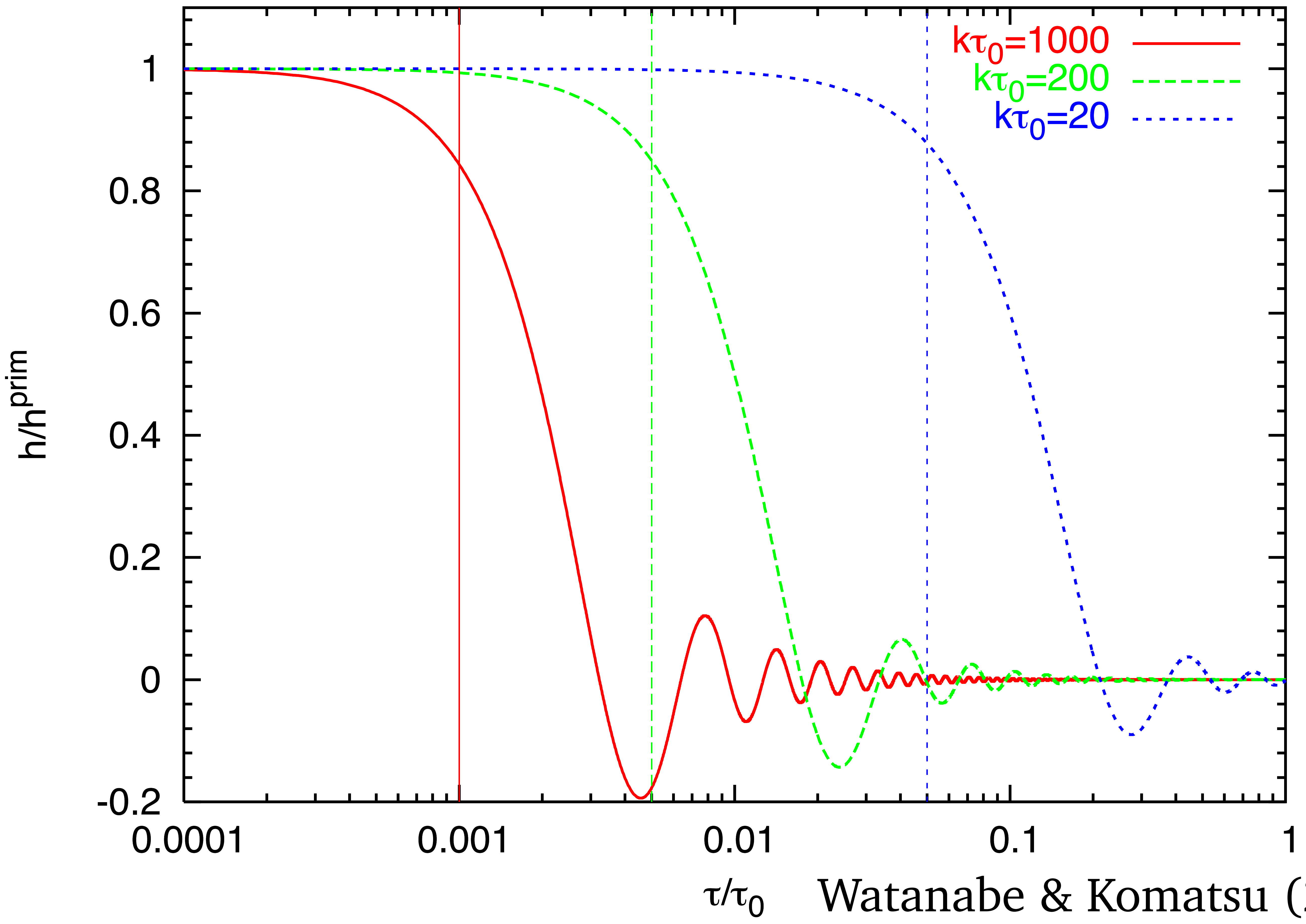
- Evolution of GW amplitudes ($h_\times$, h_+) is governed by Klein-Gordon equation sourced by anisotropic stress Π_p
($\mathscr{H}$=a'/a and ' = d/dη):

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

Hubble damping

Evolution of PGW w/o sources

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

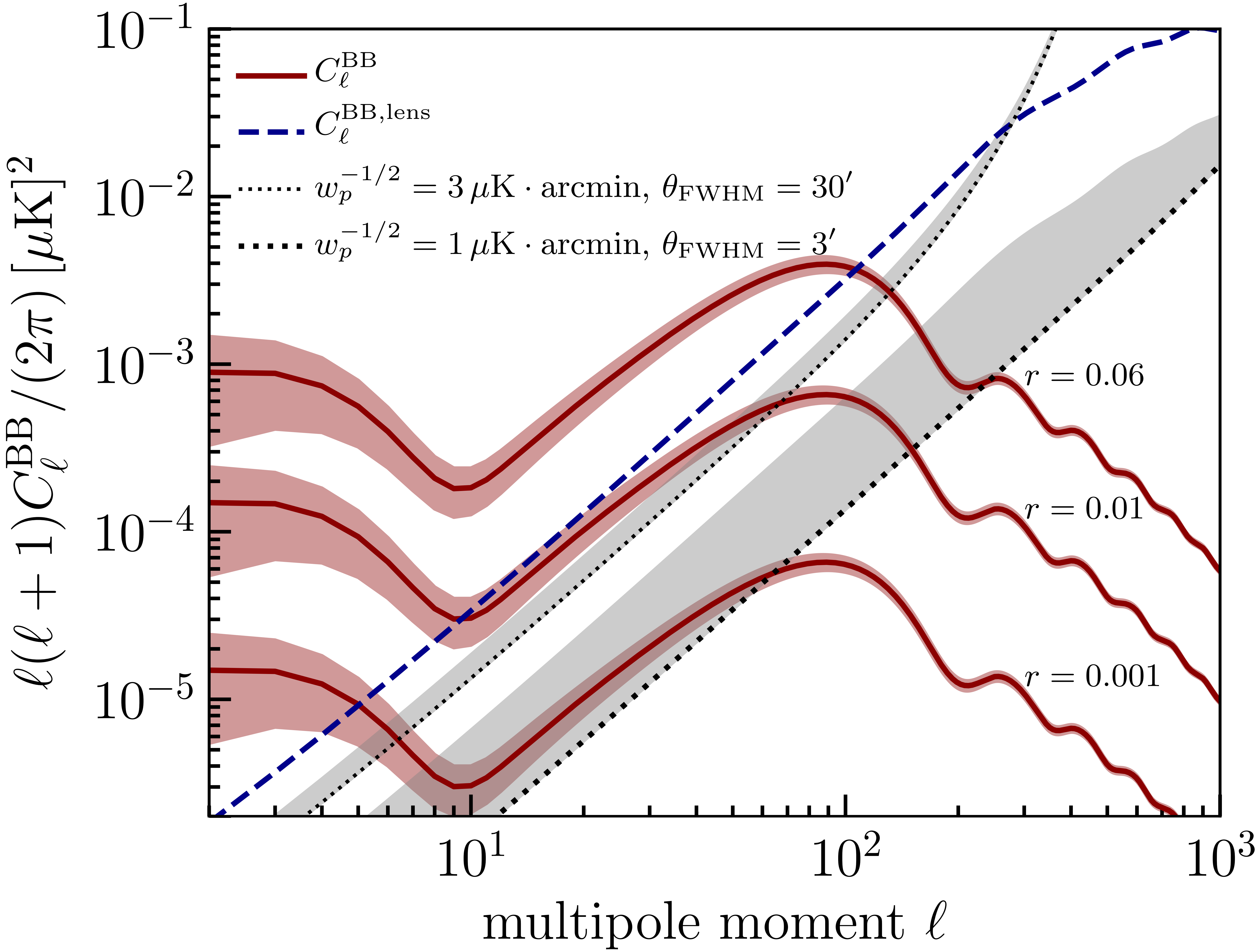


Watanabe & Komatsu (2006)

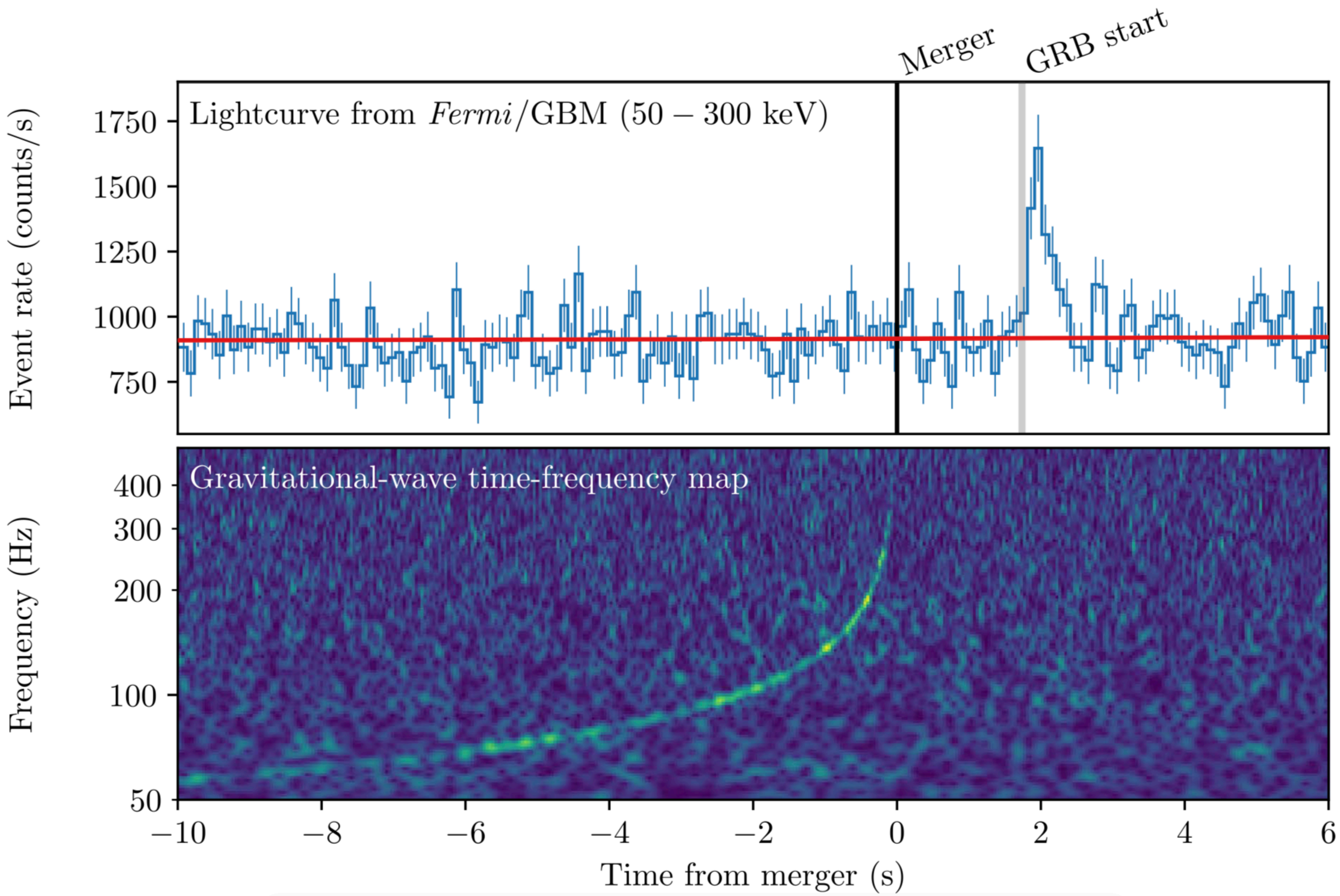
- PGW stays constant outside of horizon, but decays once the mode enters the horizon.
- *cf.* scalar perturbations grow inside of horizon.

Jeong & Kamionkowski (2019)

B-mode power spectrum



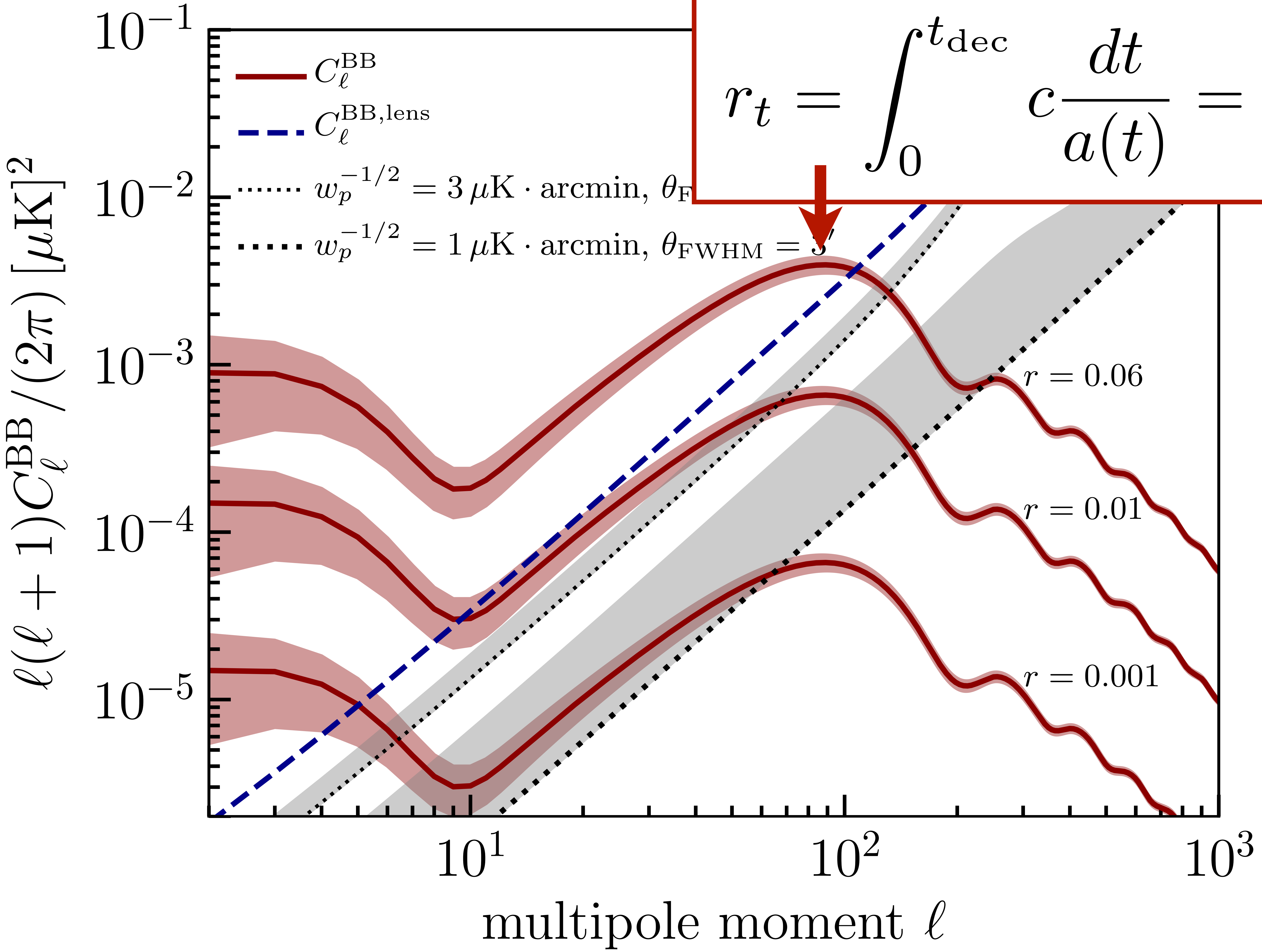
GW170817 and GRB 170817A



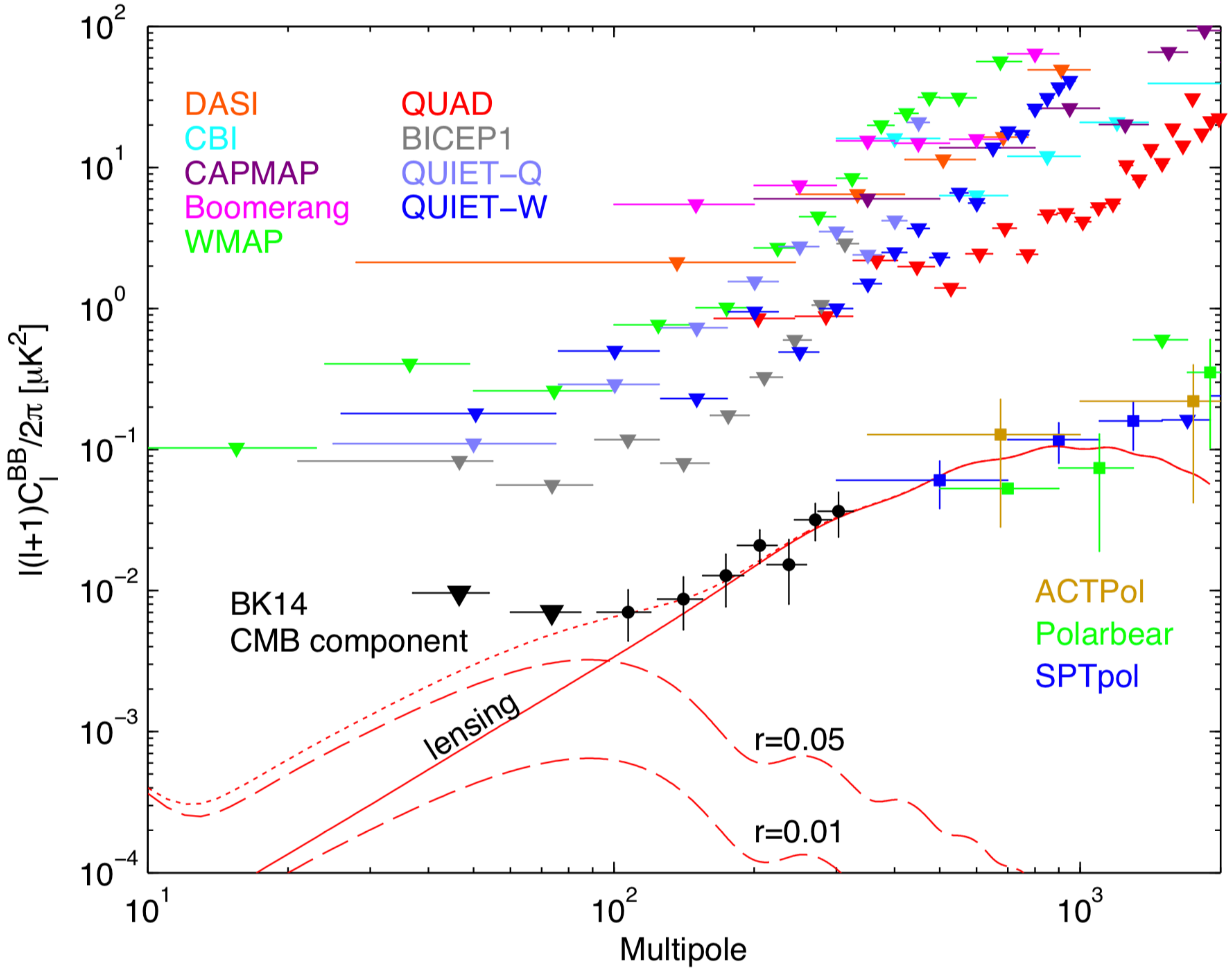
Jeong & Kamionkowski (2019)

Turn-over scale r_t

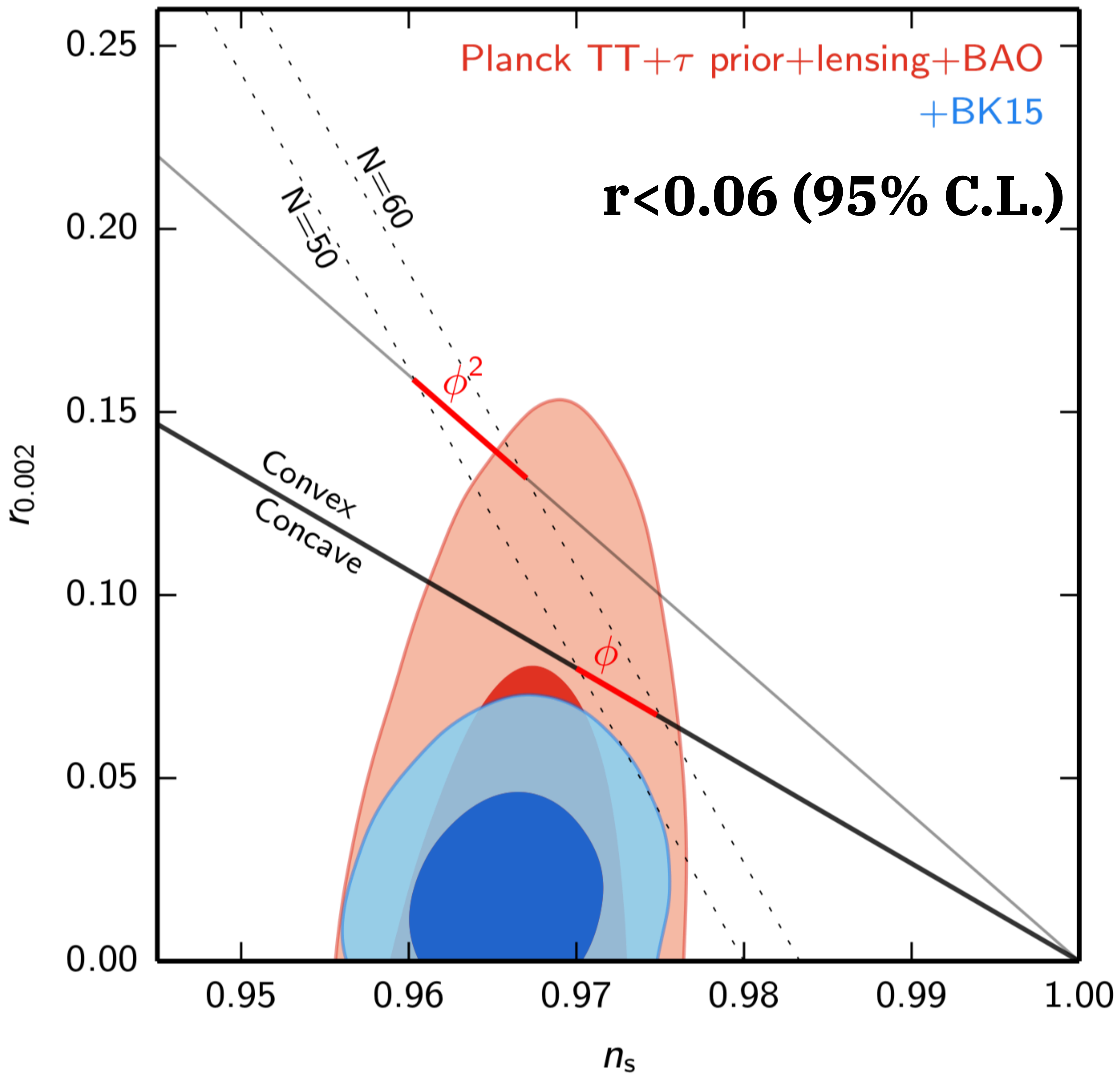
$$r_t = \int_0^{t_{\rm dec}} c\frac{dt}{a(t)} = \int_0^{a_{\rm dec}} c\frac{da}{a^2 H(a)}$$



B-mode polarization, status

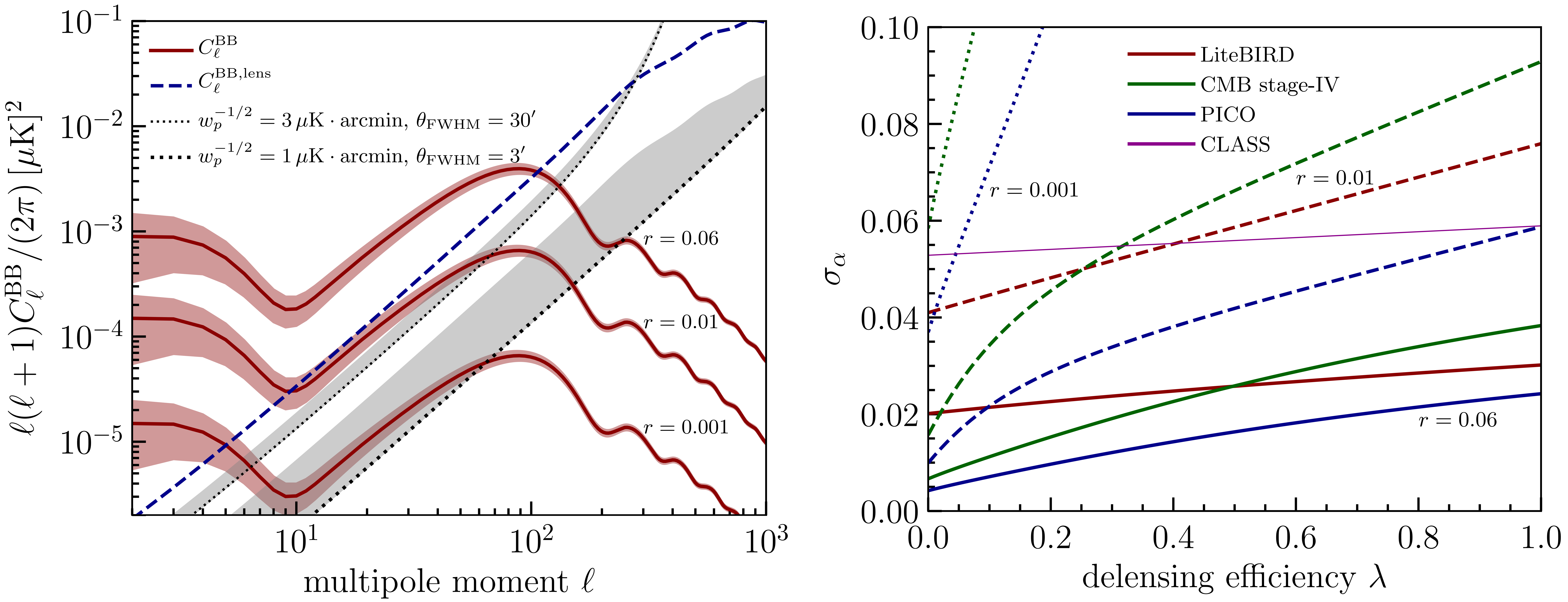


r=(GW)²/(density)²



Jeong & Kamionkowski (2019)

We can measure r_t, if r>0.001!



Conclusion

- Hubble tension can be a problem, or systematics.
- There are early universe solutions that modify the expansion rate prior to the decoupling time.
- If detected, B-mode polarization of the CMB can test the hypothesis.
- Resolving the Hubble tension may require first-principle measurements at low redshifts, such as standard siren from Gravitational Waves.