Precision cosmology and the stiff-amplified gravitational-wave background from inflation:

NANOGrav, Advanced LIGO/Virgo and the Hubble tension

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Based on: Li & Shapiro 2021 JCAP
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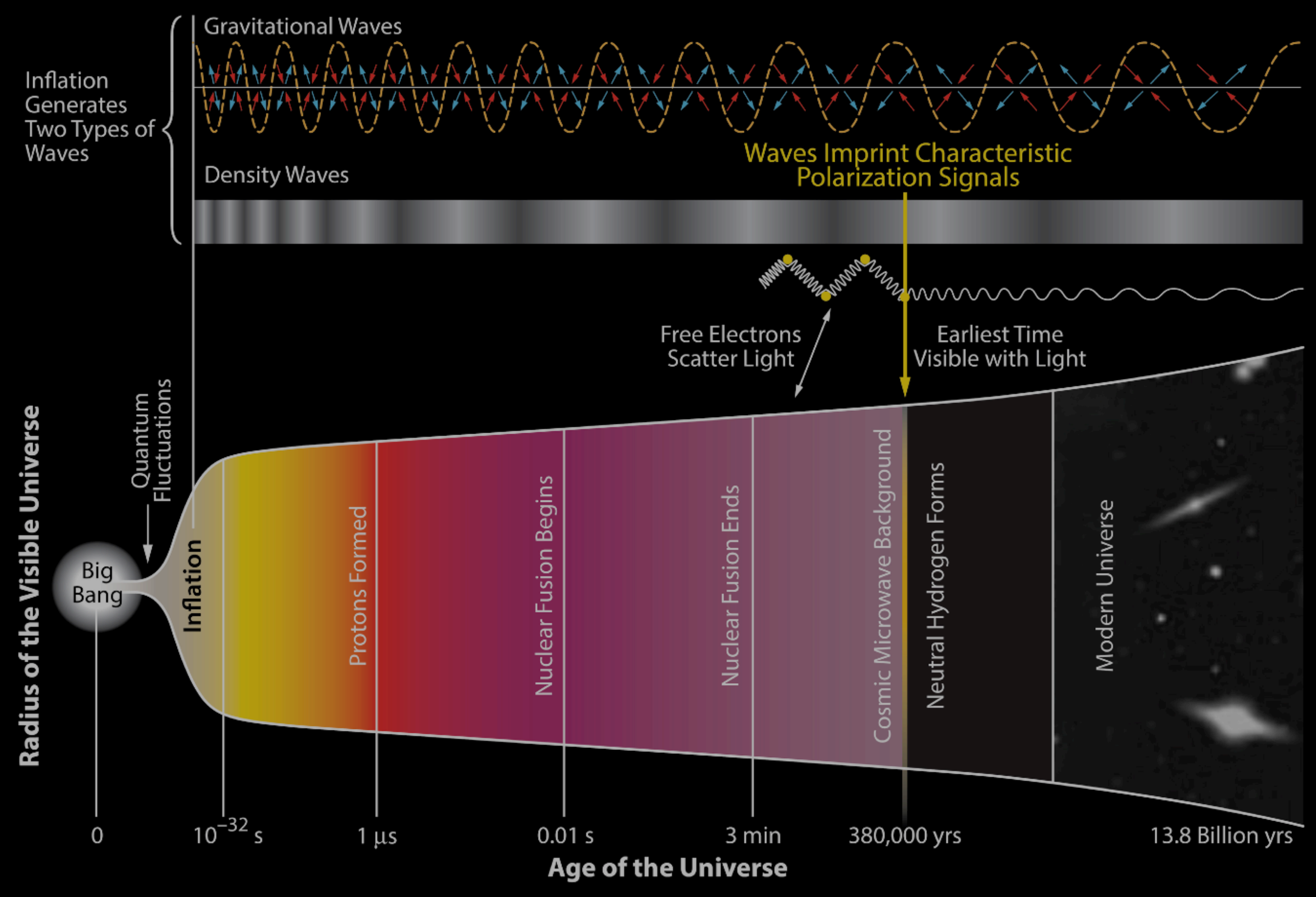


TeVPA meeting 2021/10/29

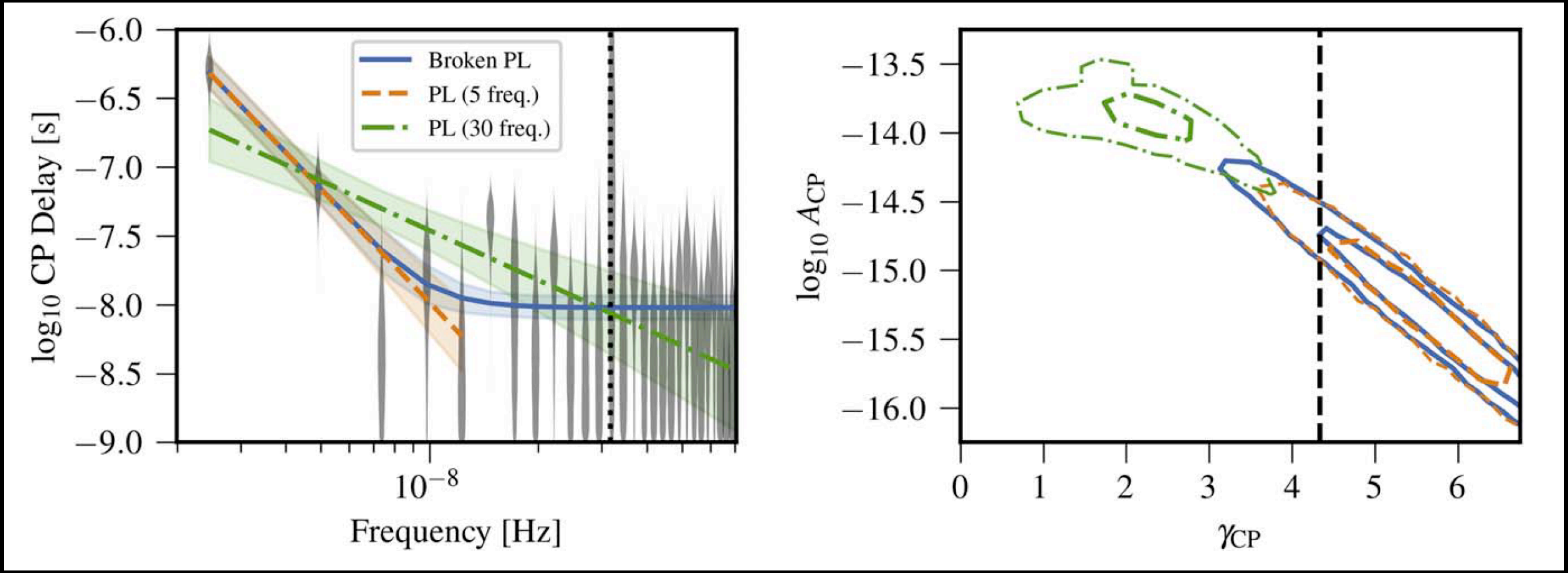
Image credit: BICEP/Keck

Outline

- **Motivation:** **1.** NANOGrav 12.5 yr results **2.** Hubble tension
- **The effect: Stiff amplification** of the primordial gravitational waves (GWs)
- **Our model:** Accounting for the backreation from GWs on cosmic expansion for the sake of **precision cosmology**
- **Results and summary**

Motivation #1

Common process in NANOGrav 12.5 yr data set



Arzoumanian+ 2020
NANOGrav

Primordial Stochastic Gravitational-Wave Background (SGWB)
Tensor fluctuations from inflation

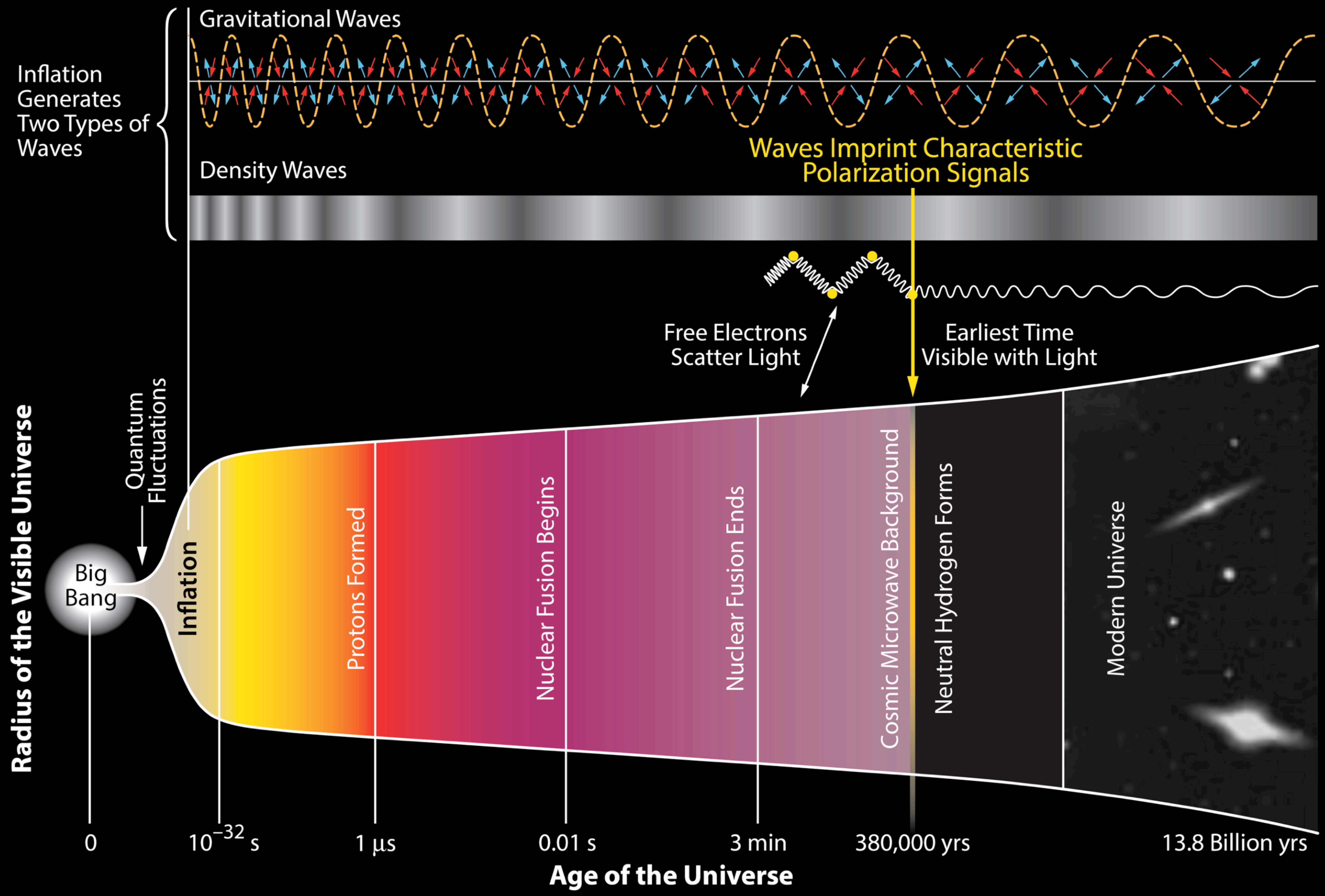
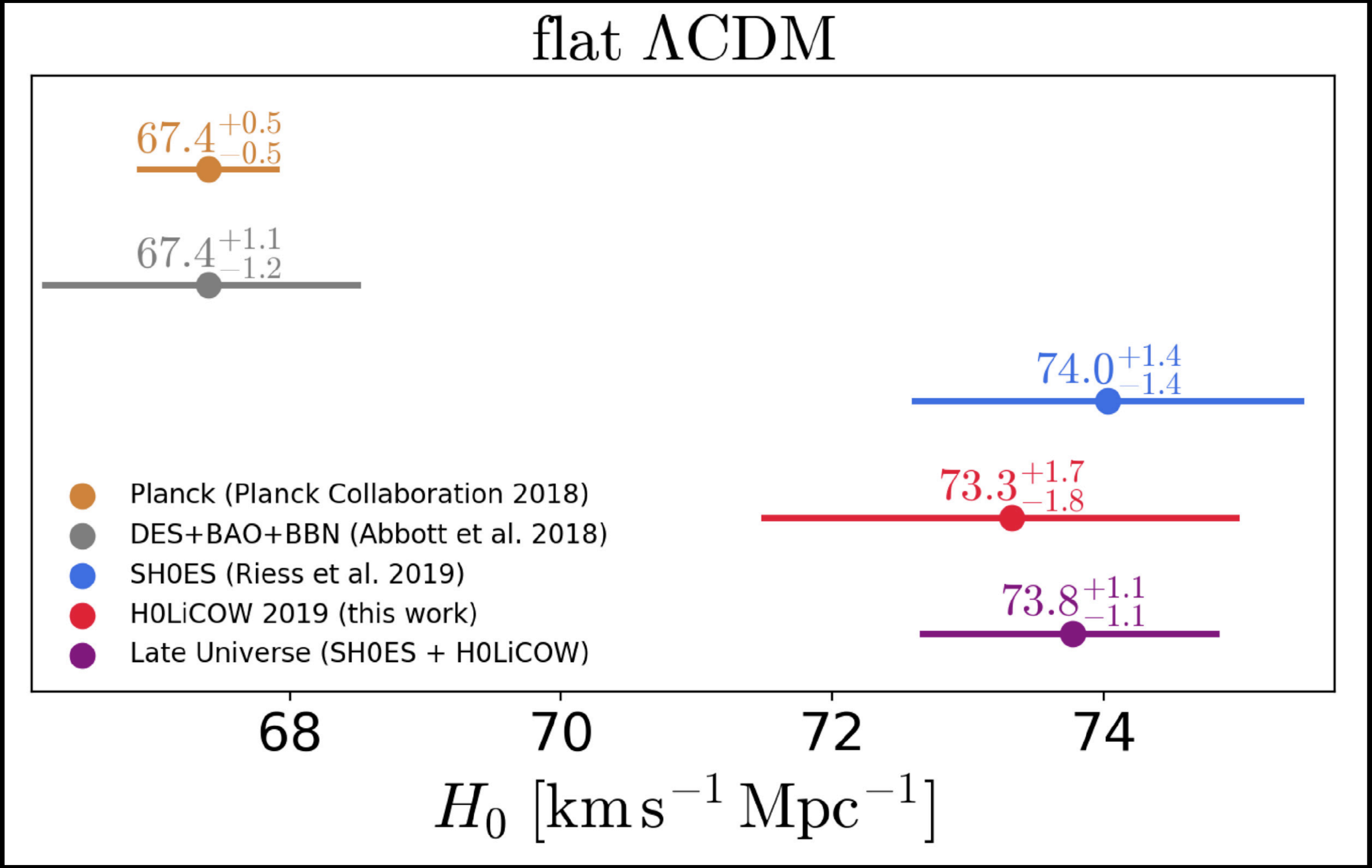


Image credit: BICEP/Keck

Motivation #2

Hubble tension: >4 sigma discrepancy in the measurements of H_0



Wong+ 2020
H0LiCOW

Primordial SGWB: Parametric amplification

From (tensor) quantum fluctuations to macroscopic GWs

- A special expansion history is needed: Modes of interest can *exit* the horizon and later *reenter*

Inflation!

- All modes exit during inflation but can reenter during different eras
- In standard cosmology, there must be a radiation-dominated era
  → the "plateau" in GW spectrum

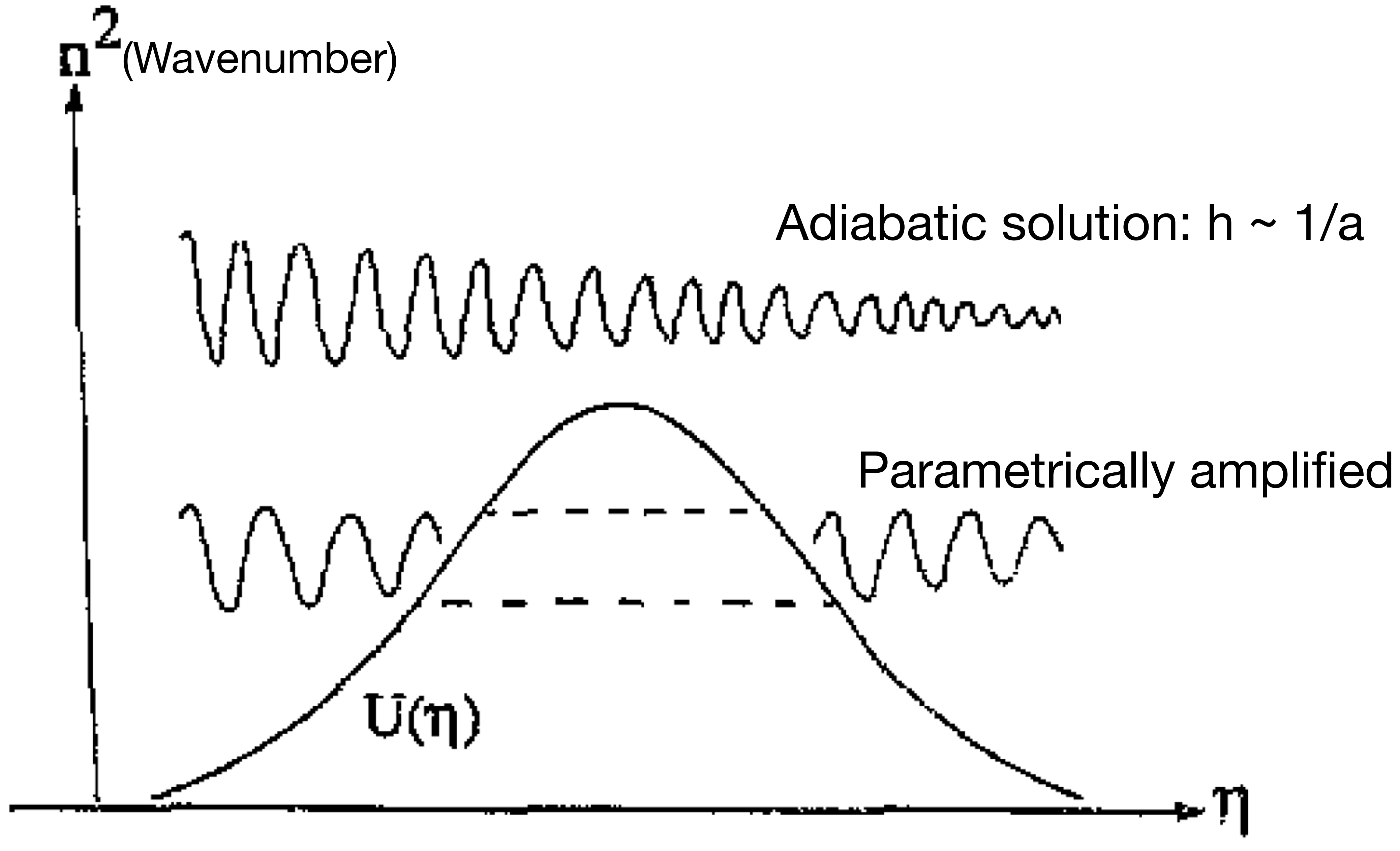
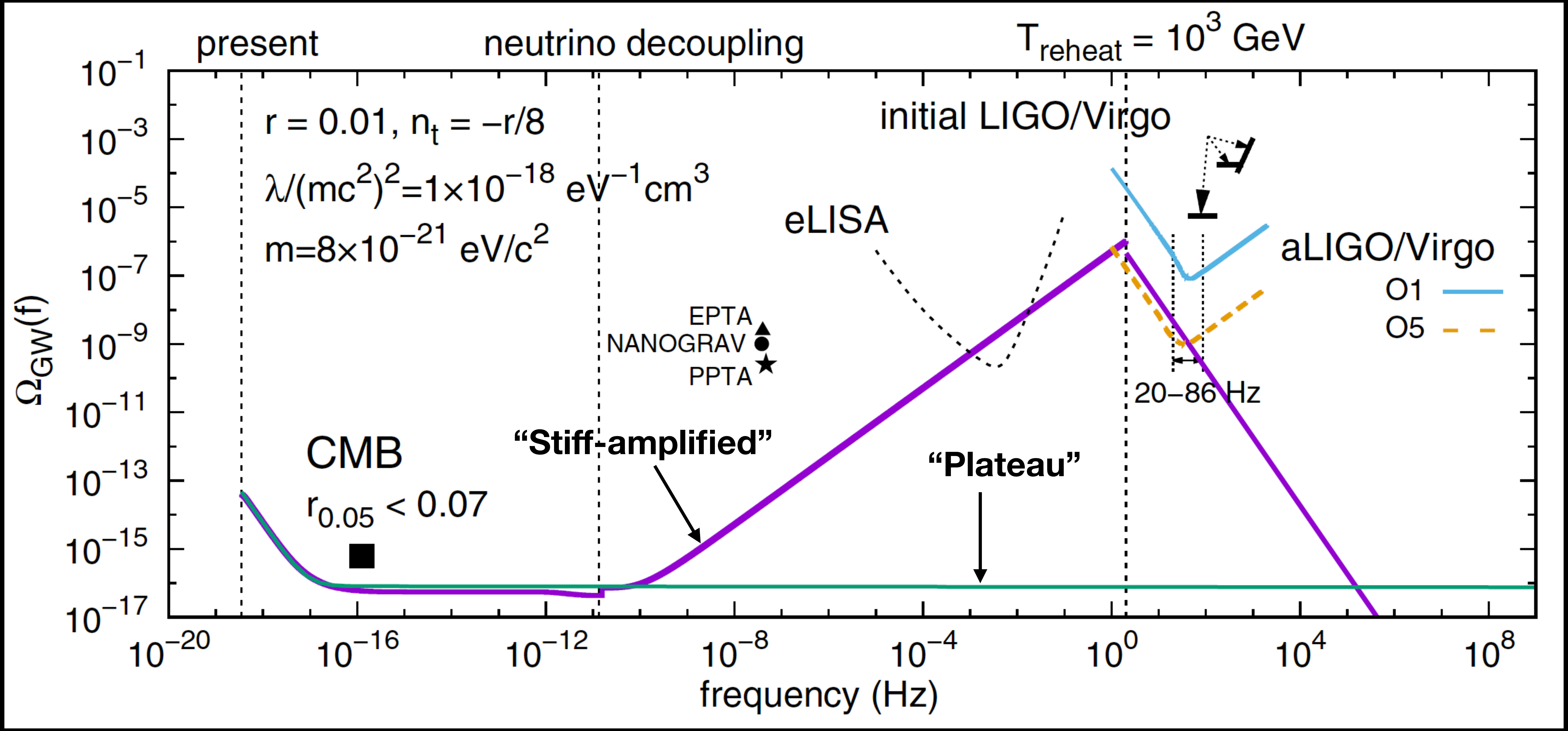


Figure 2. Parametric (superadiabatic) amplification of waves.

Grishchuk 1993

Primordial SGWB: Stiff amplification

Amplitudes dependent on the expansion history at mode reentry



Li Bohua, Shapiro & Rindler-Daller 2017 PRD

Primordial SGWB: Stiff amplification

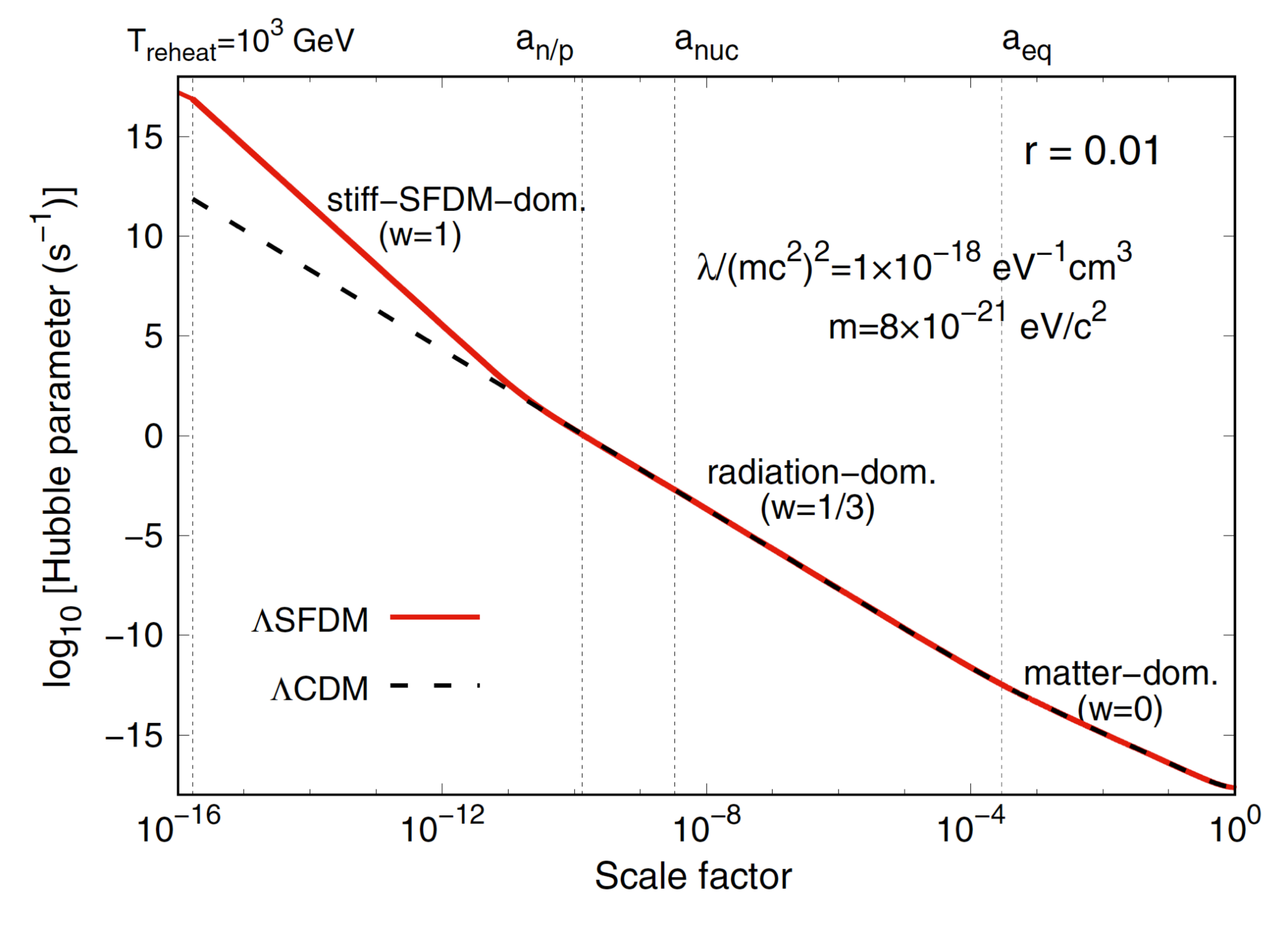
Blue-tilt in the subhorizon amplitudes

- Caused by an early equation of state stiffer than radiation

$$(w \equiv p/\rho > 1/3)$$

- Example: an early **stiff era** resulted from **ultralight scalar field dark matter (SFDM)** in its *stiff phase*

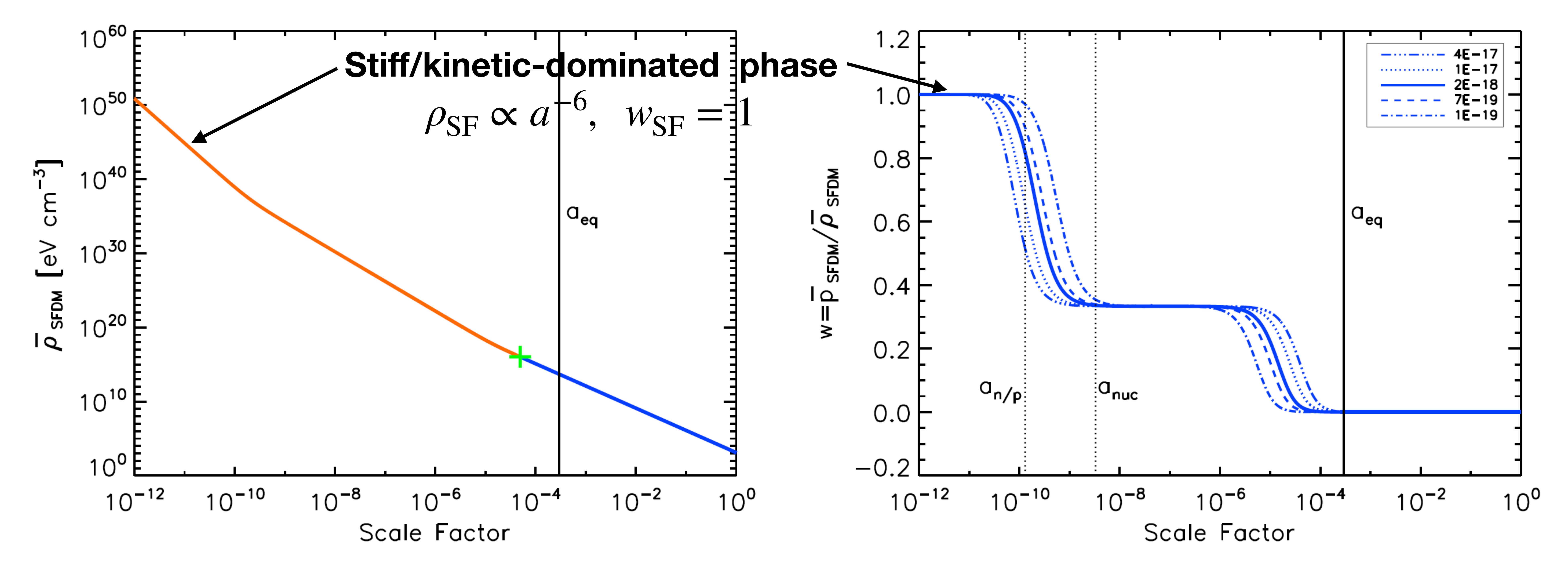
$$(w = 1)$$



Li Bohua, Shapiro & Rindler-Dalller 2017 PRD

Ultralight scalar field dark matter (SFDM)
and its early stiff phase

$$\mathcal{L} = \frac{\hbar^2}{2m}|\partial_\mu \psi|^2 - V(|\psi|), \qquad V(|\psi|) = \frac{1}{2}mc^2|\psi|^2 + \frac{\lambda}{2}|\psi|^4. \qquad m \sim 10^{-22}\ \mathrm{eV}$$

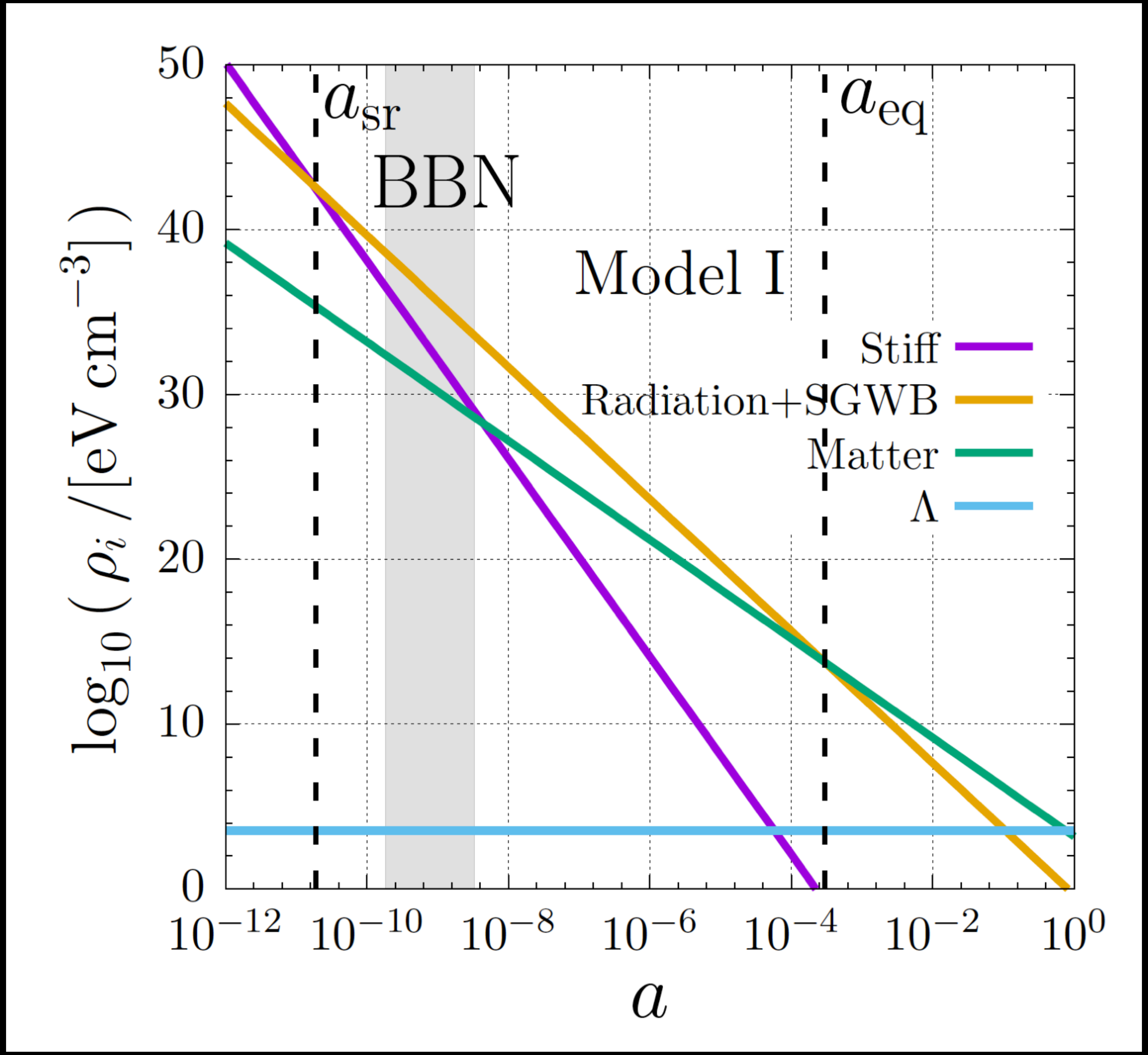


Li Bohua, Rinder-Daller & Shapiro 2014 PRD

Stiff-amplified primordial SGWB: Our model

- Three inflation/early Universe parameters

- **Tensor-to-scalar ratio:** r
- **Reheating temperature:** $T_{\rm re}$
- **Temperature of stiff-radiation equality:** $T_{\rm sr}$



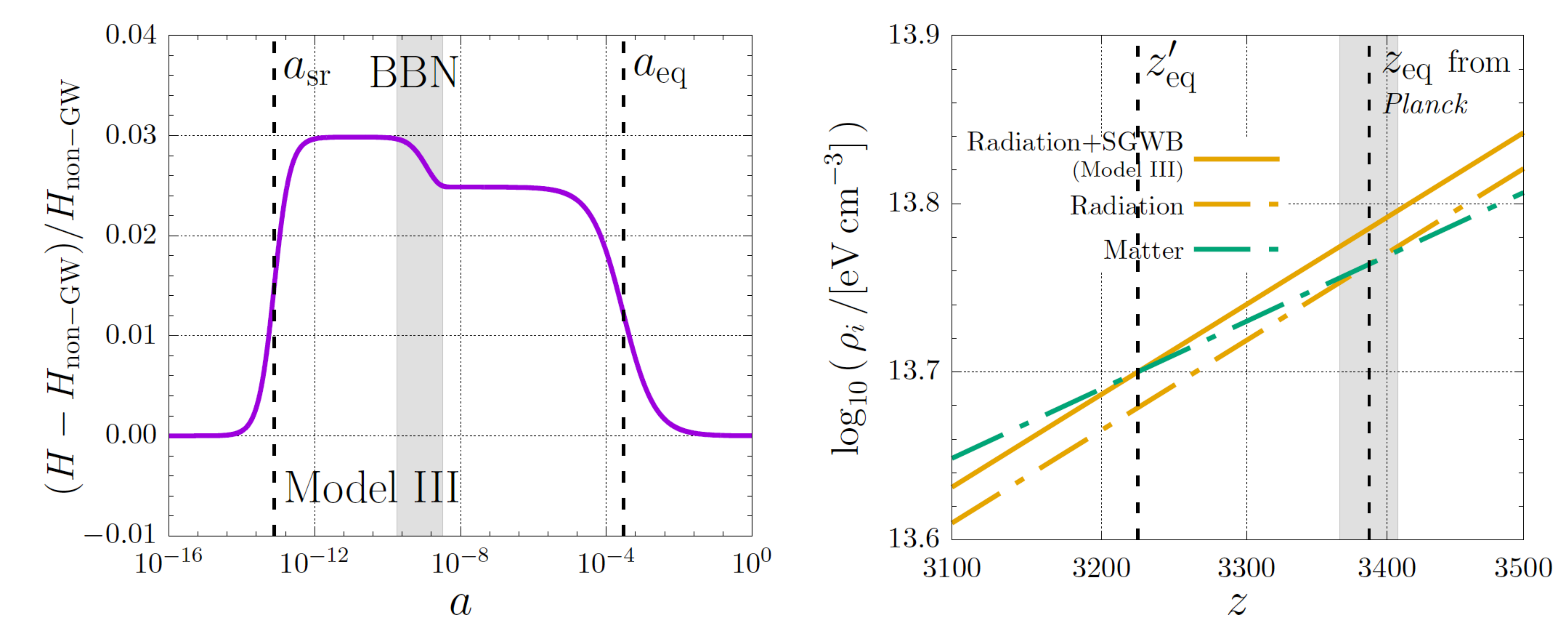
Li Bohua & Shapiro 2021 JCAP

Backreaction from the stiff-amplified primordial SGWB

Self-consistent expansion history as required by precision cosmology

$$H^2 = H_0^2\left(\frac{\Omega_s}{a^6}+\frac{\Omega_r}{a^4}+\frac{\Omega_m}{a^3}+\Omega_\Lambda\right)+\boxed{\frac{8\pi G}{3c^2}\rho_{GW}}$$

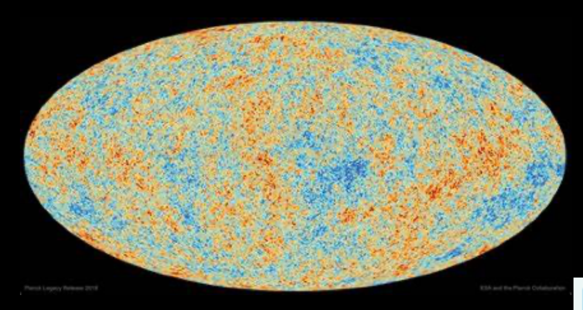
- **Stiff-amplified SGWB** can *boost* the expansion rate up to ~ 3%, thus also shifting **radiation-matter equality**
- Iterative numerical scheme that accounts for ρ_{GW} and also preserves the equality



Li Bohua & Shapiro 2021 JCAP

Constrain the stiff-amplified primordial SGWB

Multi-frequency probes and the joint analysis

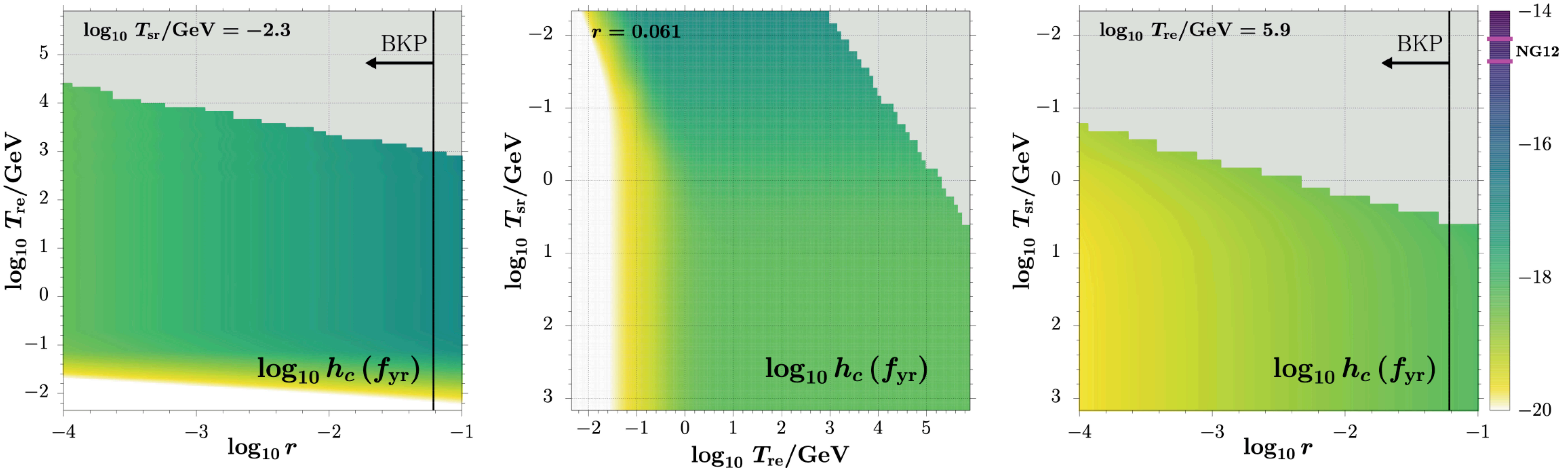


- CMB temperature and polarization
- Pulsar-timing arrays
- Laser interferometers
- Integral bounds
  - Early-Universe cosmology: big bang nucleosynthesis (BBN)
  - Late-Universe cosmology: radiation-matter equality and the CMB damping tail

Li Bohua & Shapiro 2021 JCAP

Result: Implication for NANOGrav 12.5 yr data

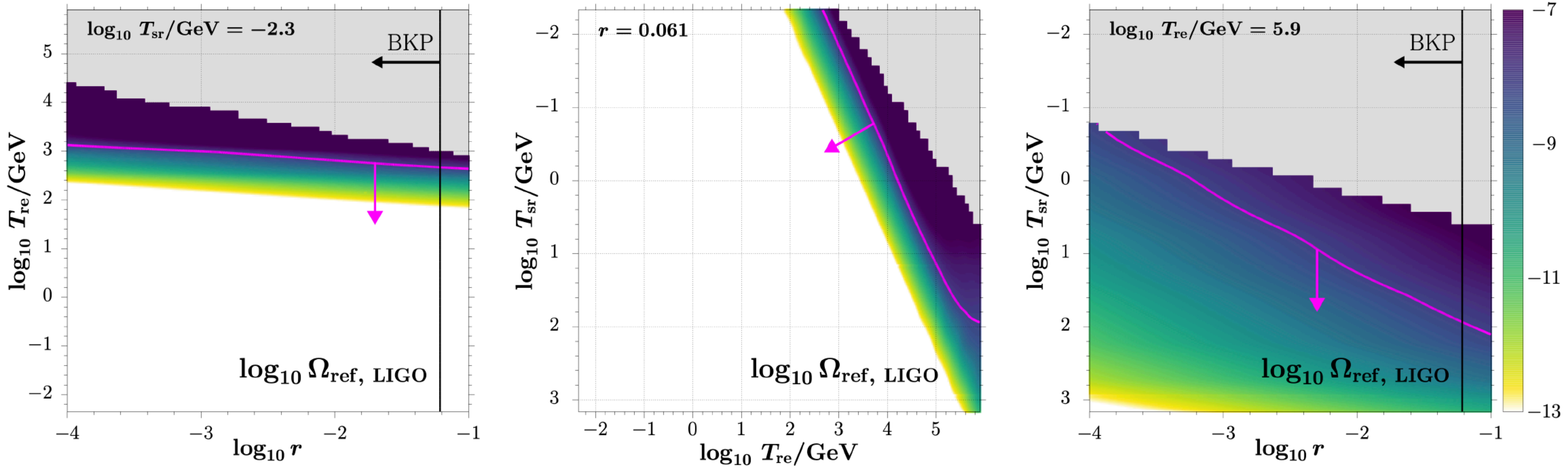
Three-view parameter space $(r, T_{\rm re}, T_{\rm sr})$

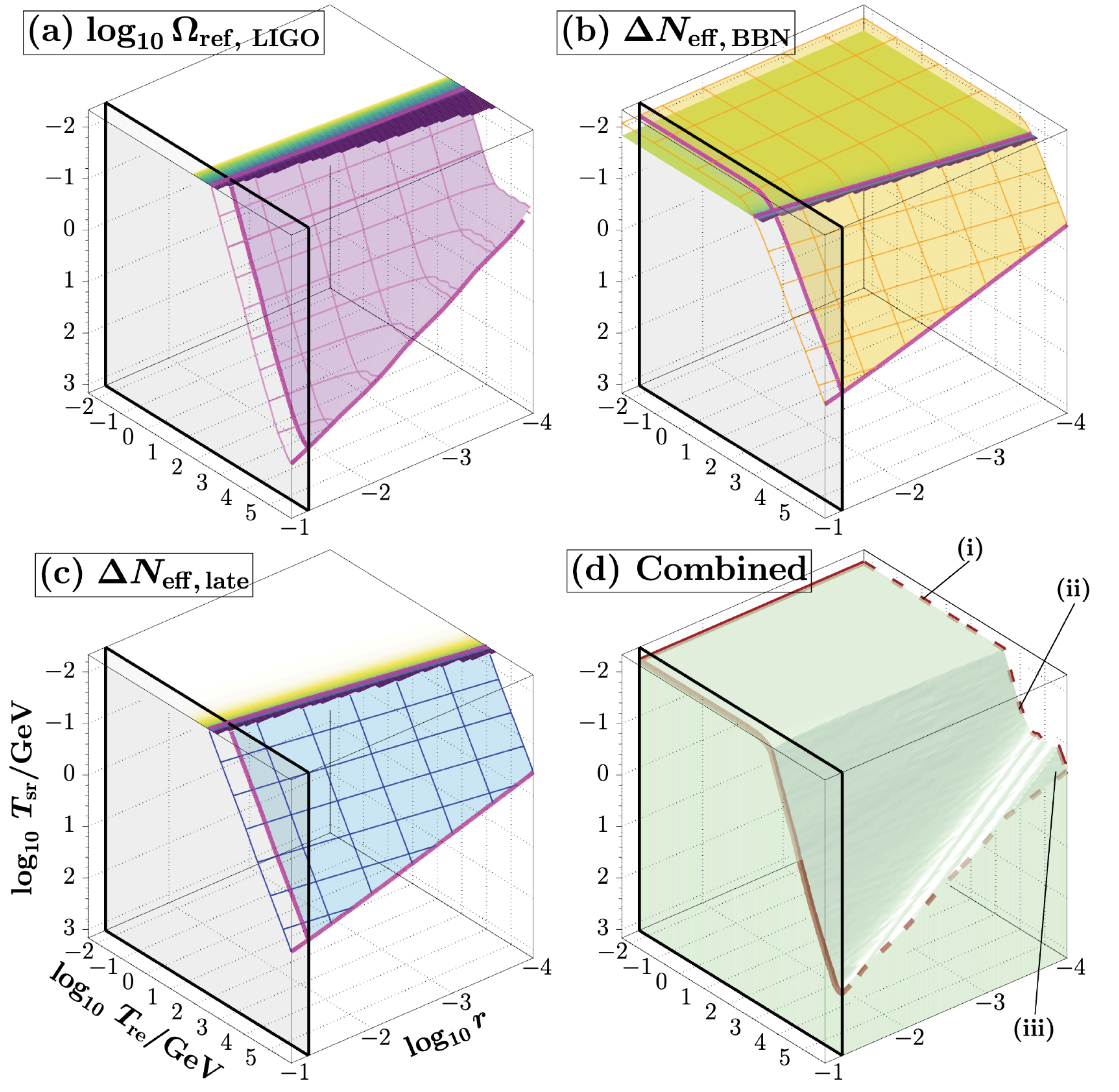


Stiff-amplified primordial SGWB _cannot_ explain the NANOGrav 12.5 yr results (lower by >1 decade)

Result: Constraint from Advanced LIGO/Virgo

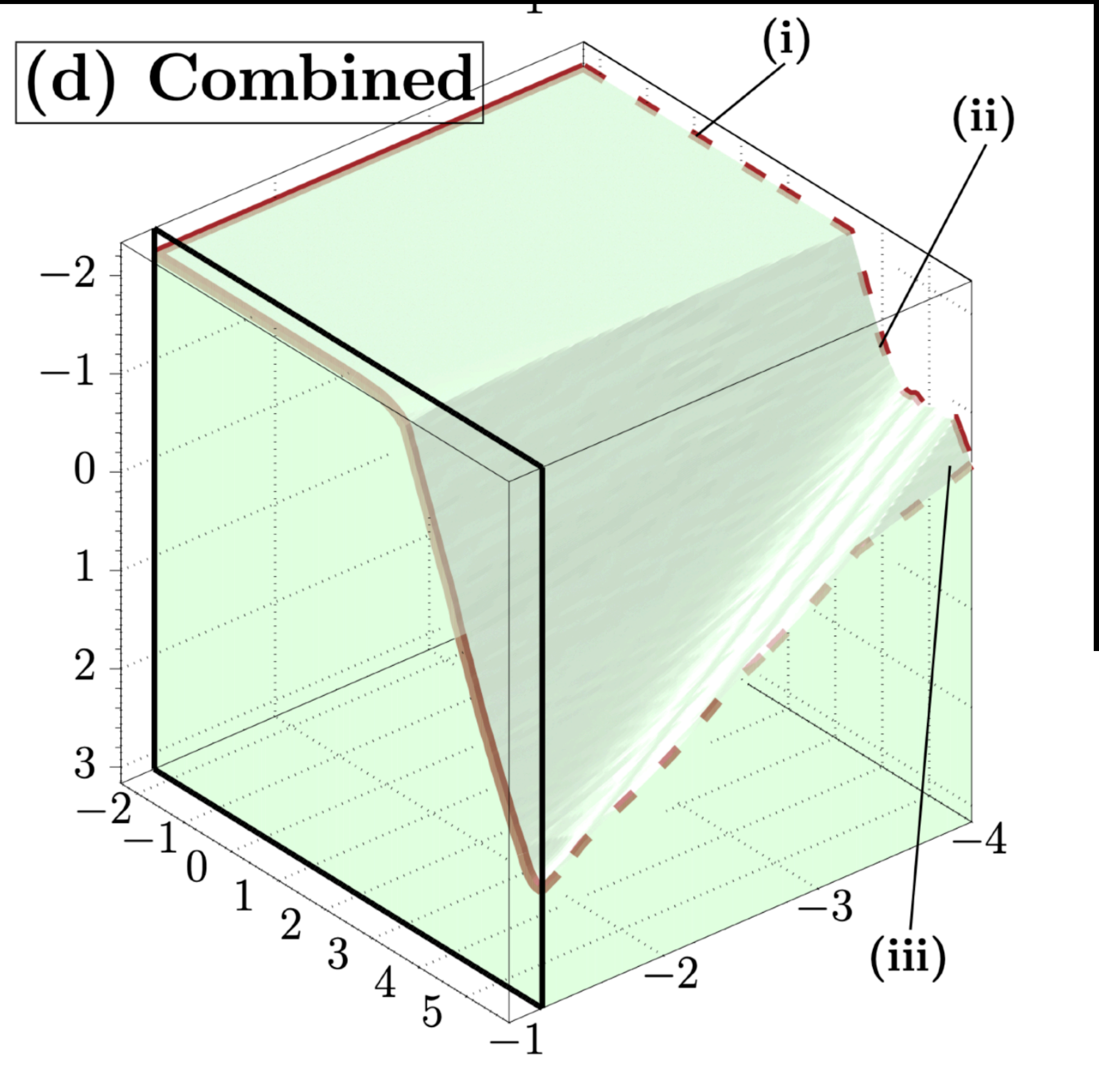
Third observation run data (O3)





Li Bohua & Shapiro 2021 JCAP

For **stiff-amplified primordial SGWB**, ***which probe*** is it most sensitive to, dependent on the reheat temperature?



Regime	Range of $T_{\rm re}$	Lower limit on $T_{\rm sr}$ (95% CL)	Dominant probe
(i)	$4 \times 10^{-3} \lesssim T_{\rm re}/\text{GeV} \lesssim 10^{3}$	$T_{\rm sr} > 8.3 \times 10^{-3}$ GeV	$N_{\rm eff,\,BBN}$
(ii)	$10^{3} \lesssim T_{\rm re}/\text{GeV} \lesssim 10^{6}$	Indicated by the "waterfall" surface in panel (d) of figure 8	$\Omega_{\rm ref,\,LIGO}$
(iii)	$T_{\rm re}/\text{GeV} \gtrsim 10^{6}$	$\log_{10}\frac{T_{\rm sr}}{\text{GeV}} > \frac{1}{2}\log_{10} r + \log_{10}\frac{T_{\rm re}}{\text{GeV}} - 4.4$	$N_{\rm eff,\,late}$

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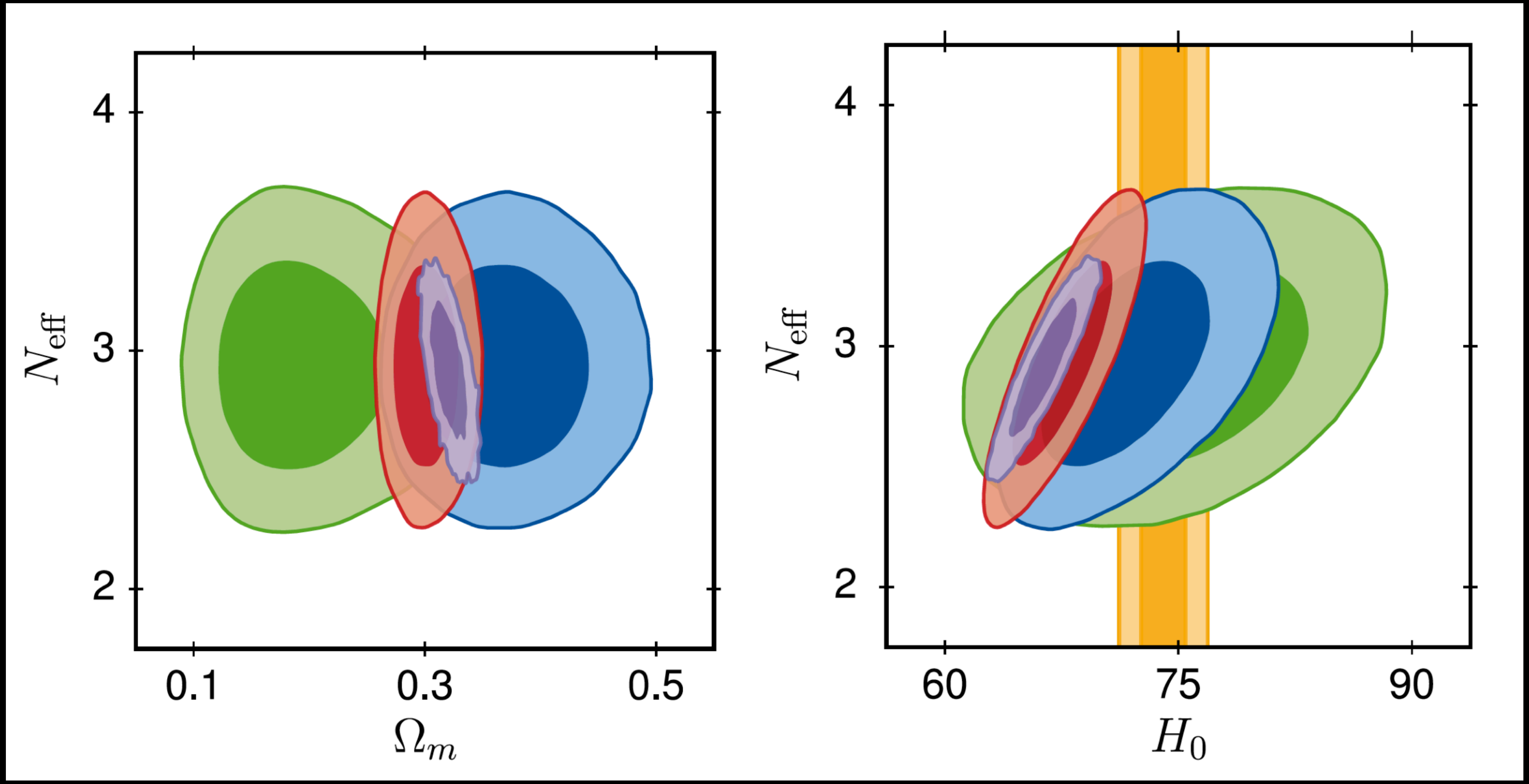
Resolve/alleviate the Hubble tension

$H_0 - N_{\rm eff}$ degeneracy

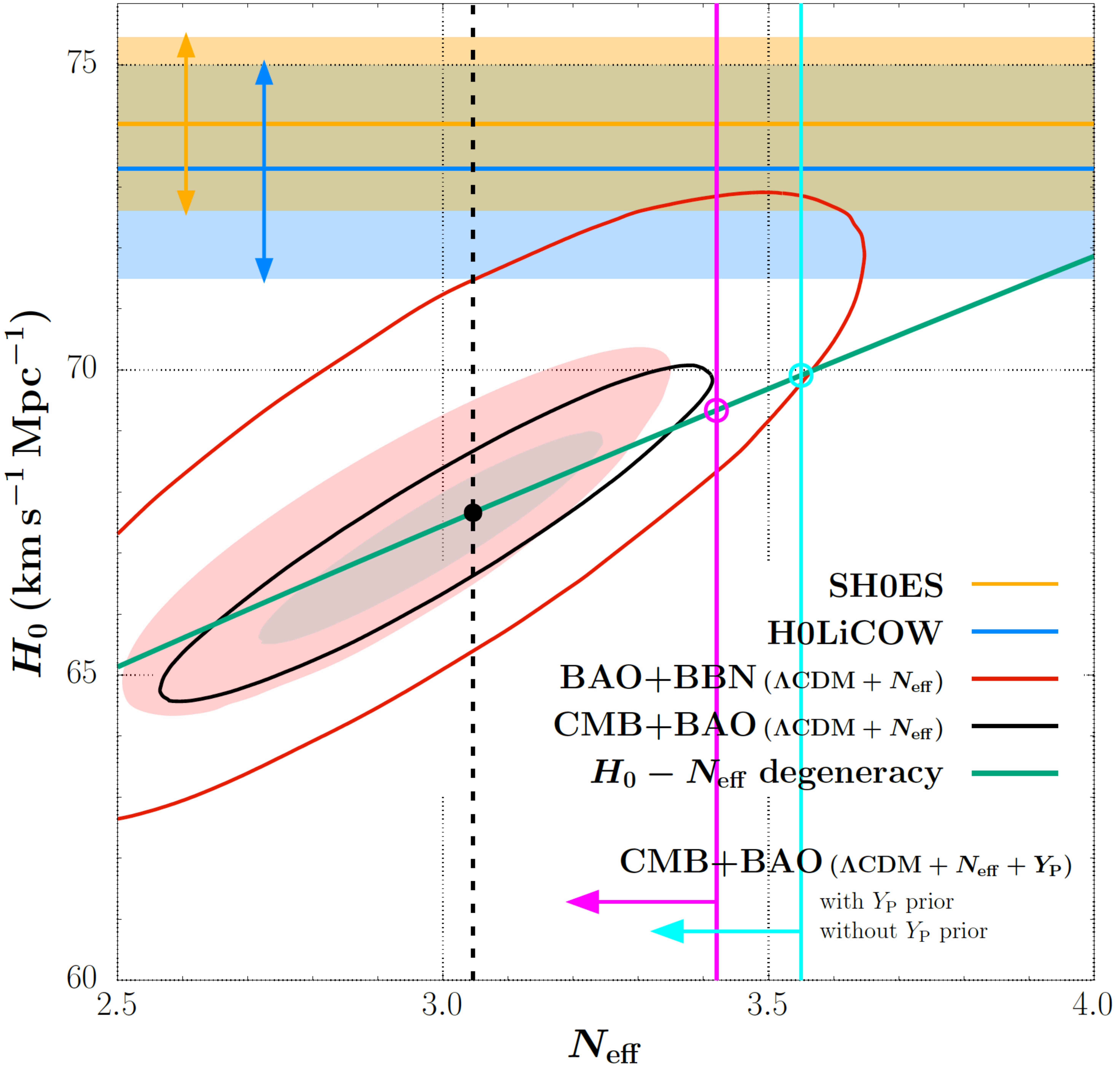


Schoneberg+ 2019

- Extra radiation component contributes to the effective number of relativistic species, $N_{\rm eff}$
- **Primordial SGWB** is a given radiation in **standard inflationary cosmology,** with no need to introduce other exotic radiation.

Result:

Stiff-amplified primordial SGWB can ***partially alleviate*** the Hubble tension



Li Bohua & Shapiro 2021 JCAP

Li **Bohua** & Shapiro 2021 JCAP
arXiv: 2107.12229

Summary

- **Stiff amplification of the primordial SGWB causes a blue-tilt in its energy spectrum today. It should be considered in GW analysis.**
- **Backreaction of the SGWB should be accounted for to retain precision cosmology.**
- **Stiff-amplified primordial SGWB *cannot* explain the NANOGrav 12.5 yr results (lower by >1 decade).**
- **If this GW signal is detected, it can be an *indirect evidence* of ultralight boson.**
- **Stiff-amplified primordial SGWB partly alleviates the Hubble tension.**