Cosmological Constraints on First-Order Phase Transitions

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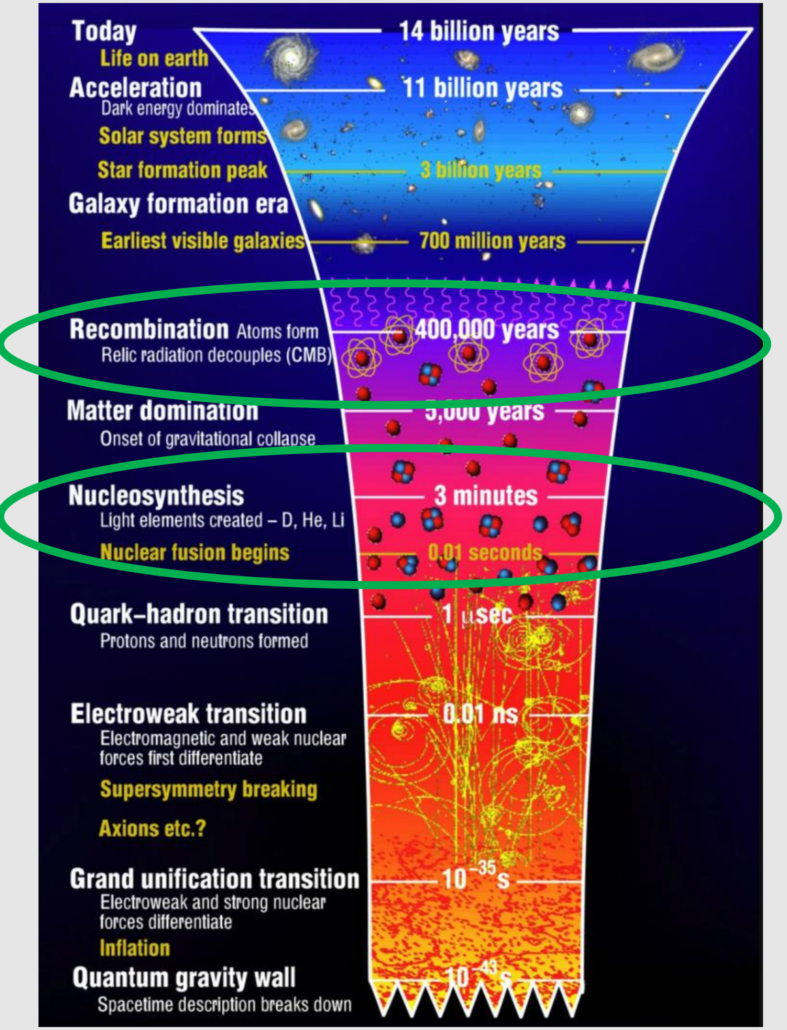
Based on 2109.14765 with Yang Bai

Cosmological Constraints : BBN and CMB

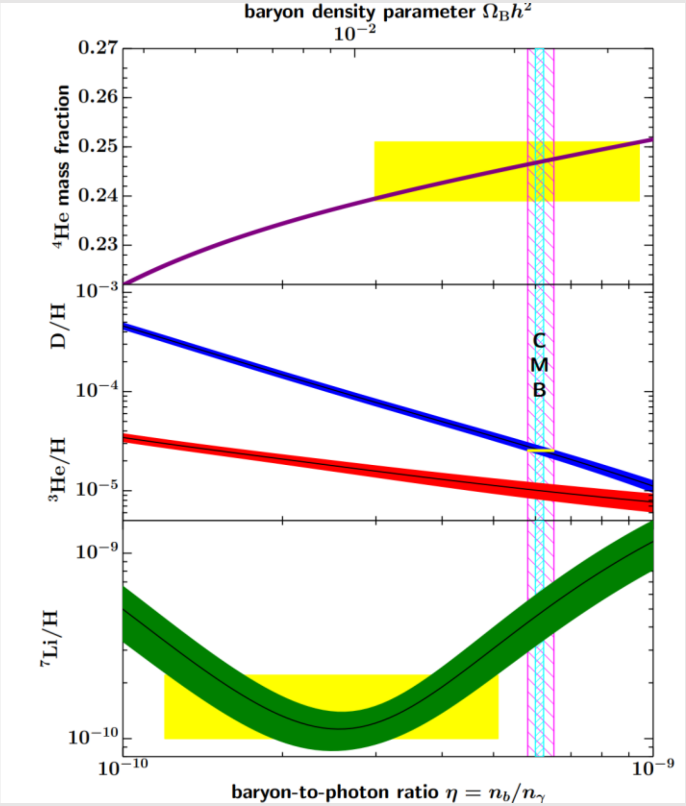


(http://www.ctc.cam.ac.uk/)

- History of universe - BBN is earliest observational probe available
- BBN well understood (except lithium problem)
- N_{eff} constraints from CMB

$\Delta N_{eff} < 0.51$	Planck 18
$\Delta N_{eff} < 0.03$	CMB-S4

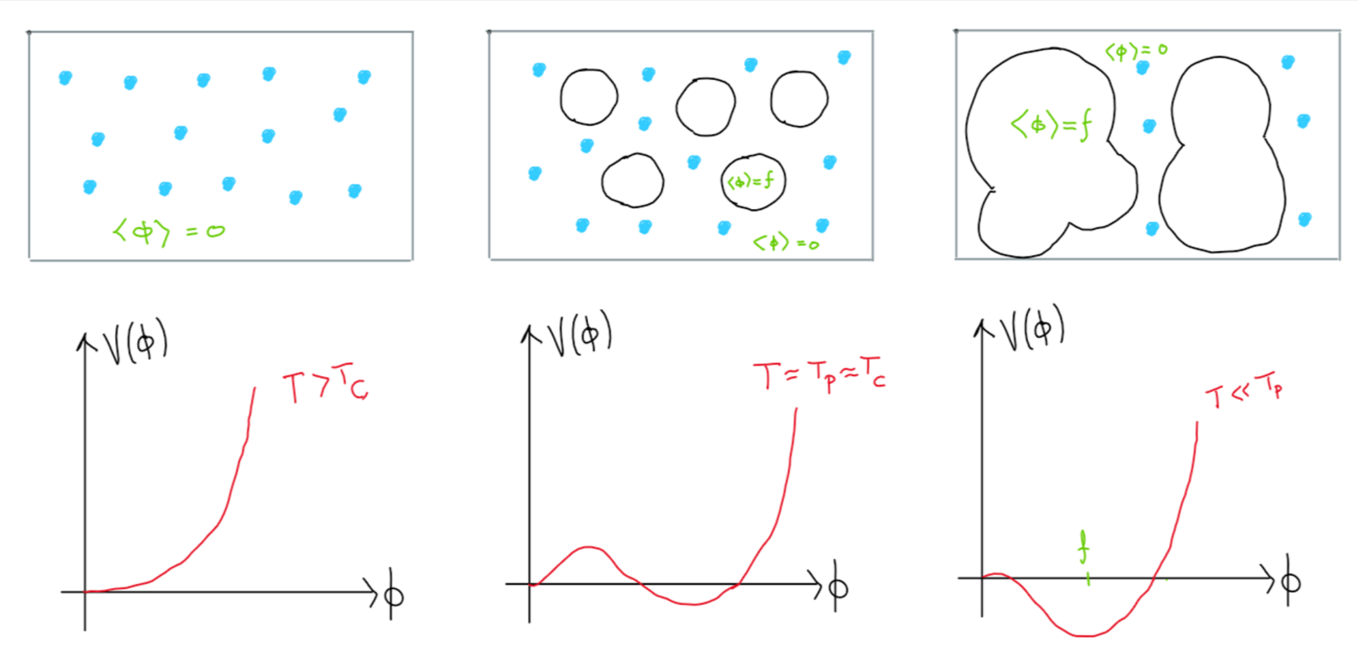
- Energy dump at few MeV can be constrained by BBN and CMB



(pdg 2021)

First-order PT : SGWB and heat release

- PT examples in everyday life and early universe
- FOPT by bubble nucleation
- Relics of FOPT:
  - SGWB
  - Latent heat released
- Model parameters to describe FOPT:



- Strength of PT $\alpha_* \approx \frac{\Delta V}{\rho_R(T_p)}$
- Percolation Temperature T_p
- Bubble nucleation rate $\beta/H(T_p)$
- Wall Velocity v_w

SGWB and NANOGrav Signal

- Frequency and amplitude of GW spectrum

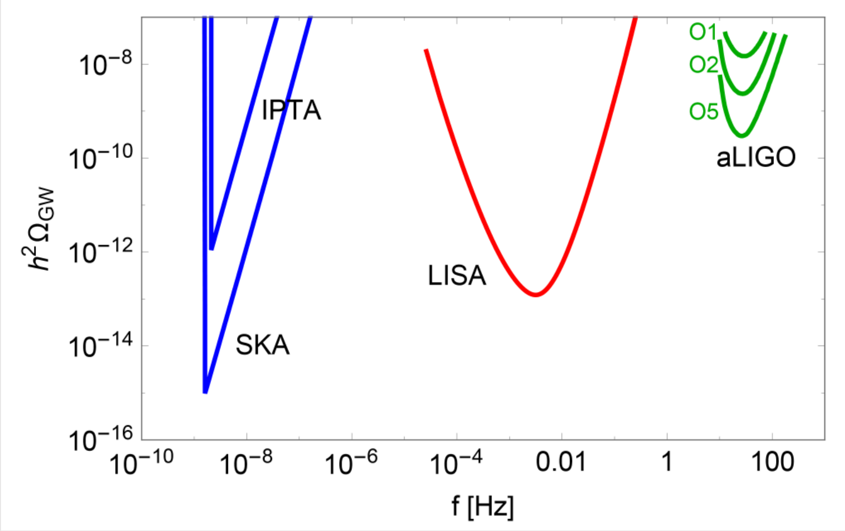
$$f_0 \approx 10^{-10}\,\mathrm{Hz}\left(\frac{f_*}{\beta}\right)\left(\frac{\beta}{H(t_p)}\right)\left(\frac{T_{\rm p}}{\rm MeV}\right)\left(\frac{g_*(T_{\rm p})}{10.75}\right)^{1/6}$$

$$\Omega_{\rm GW,0}h^2 \approx 10^{-5}\left(\frac{10}{g_*(T_p)}\right)^{1/3}\left(\frac{H(t_p)}{\beta}\right)^{q}\left(\frac{\kappa\alpha_*}{1+\alpha_*}\right)^2 \mathcal{S}(f/f_*)$$

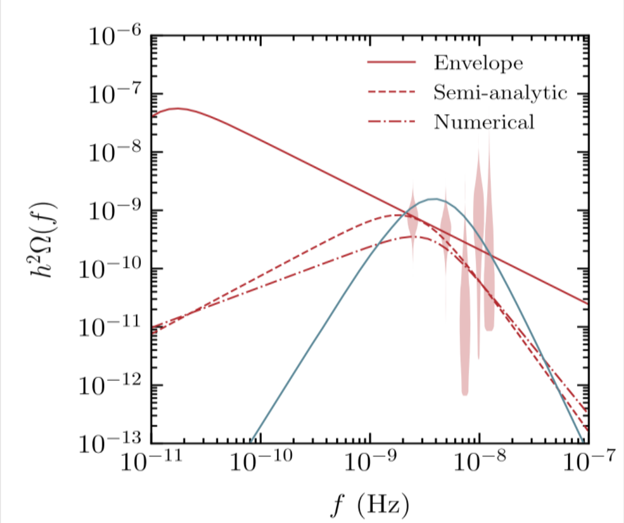
- MeV scale PT give rise to Nano-Hz frequency, probed by pulsar timing array experiments

- Signal in NANOGrav 12.5 yrs data?

MeV scale FOPT can be probed by PTA experiments and cosmological observables in BBN and CMB



(caprini, Figueroa 1801.04268)



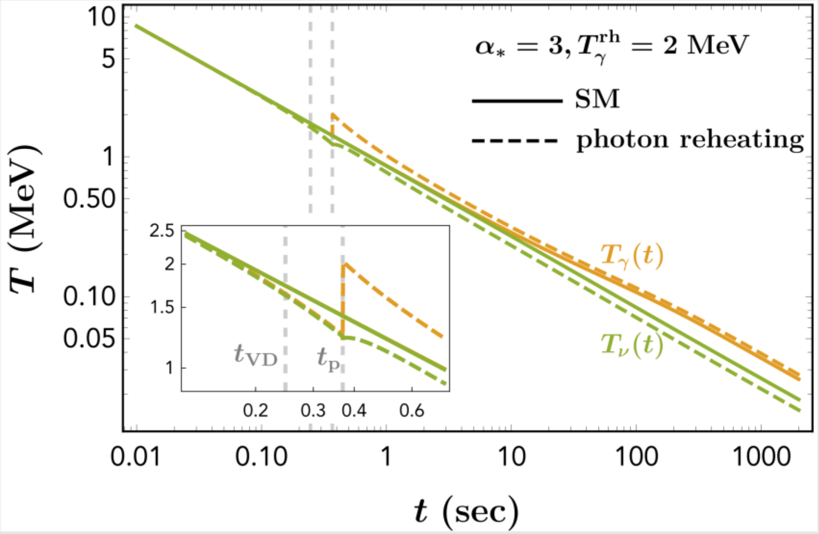
(NANOGrav 2104.13930)

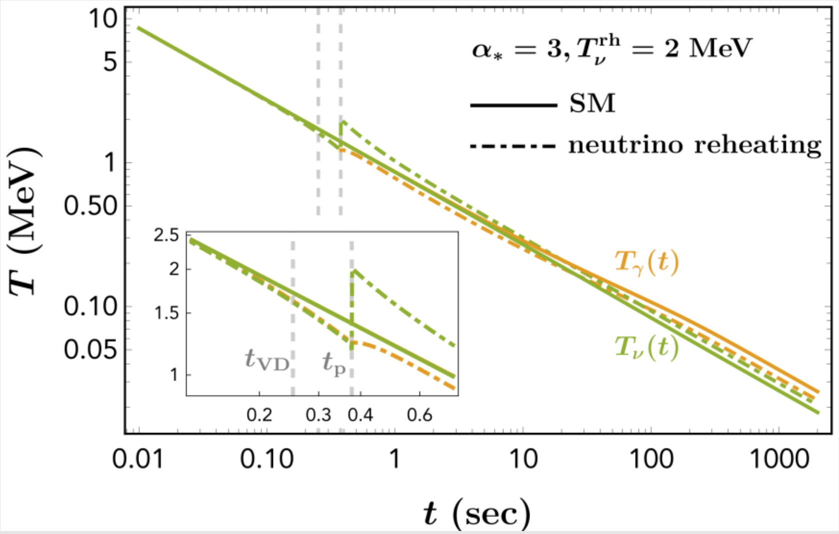
Reheating plasma and Temperature evolution

1. **Energy dump to dark radiation:** ΔN_{eff} constraints can bound the PT parameters

$$\Delta N_{\rm eff} \approx \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{g_{*,s}^{4/3}(t_{\rm CMB})}{2 g_*^{1/3}(t_p)} \alpha_* \xrightarrow{\text{Planck 18}} \boxed{\alpha_* < 0.08}$$

2. **Energy dump to SM plasma:** We can have energy dump into **photon plasma** or **neutrinos**. The temperature of heated sector is $\boldsymbol{T_\gamma^{rh}}$ or $\boldsymbol{T_\nu^{rh}}$.





(Escudero 1812.05605)

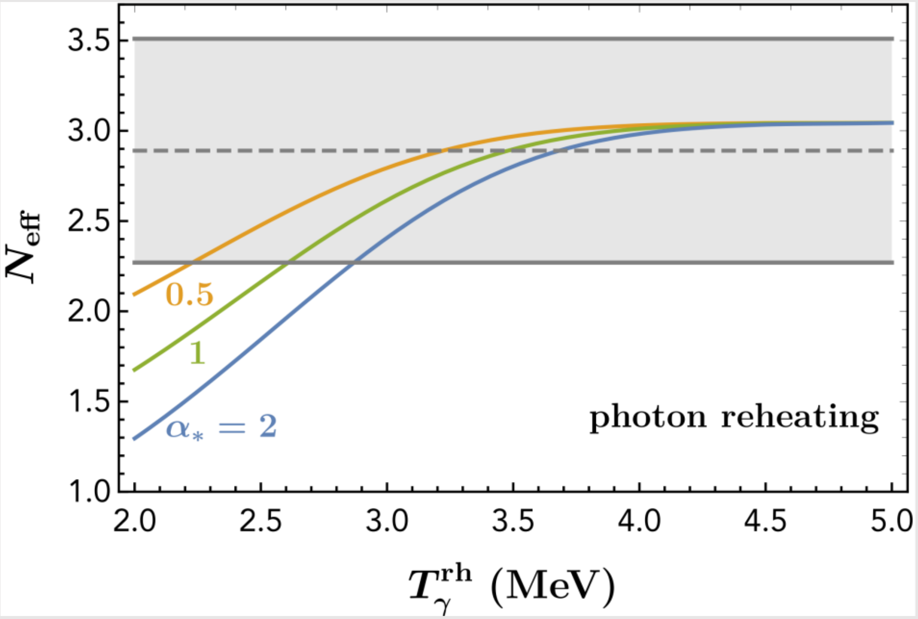
Effects on N_{eff}

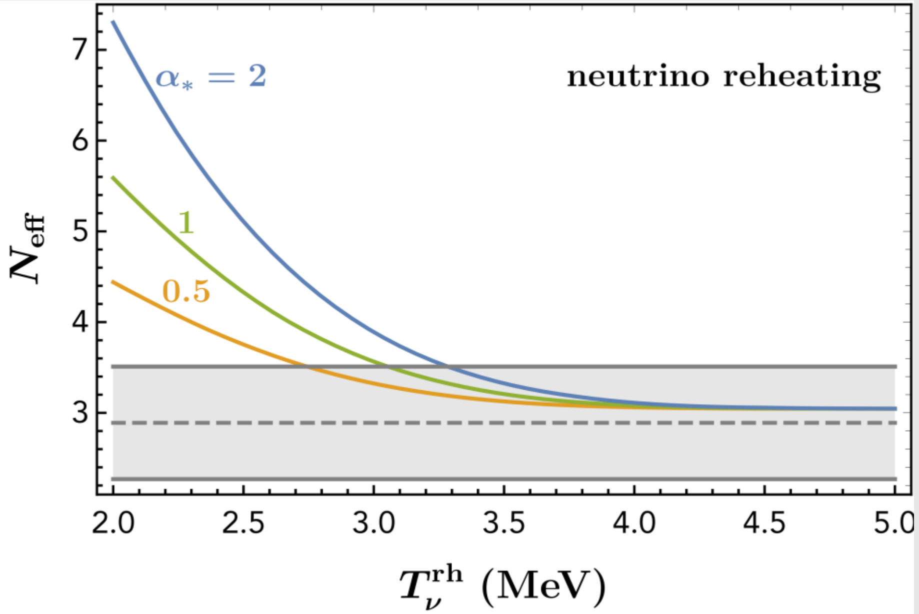
- Energy dump into photon plasma or neutrinos can modify N_{eff}

$$N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma} = 3\left(\frac{11}{4}\right)^{4/3} \times \frac{T_\nu^4(\text{today})}{T_\gamma^4(\text{today})}$$

Decreases for PR
Increases for NR

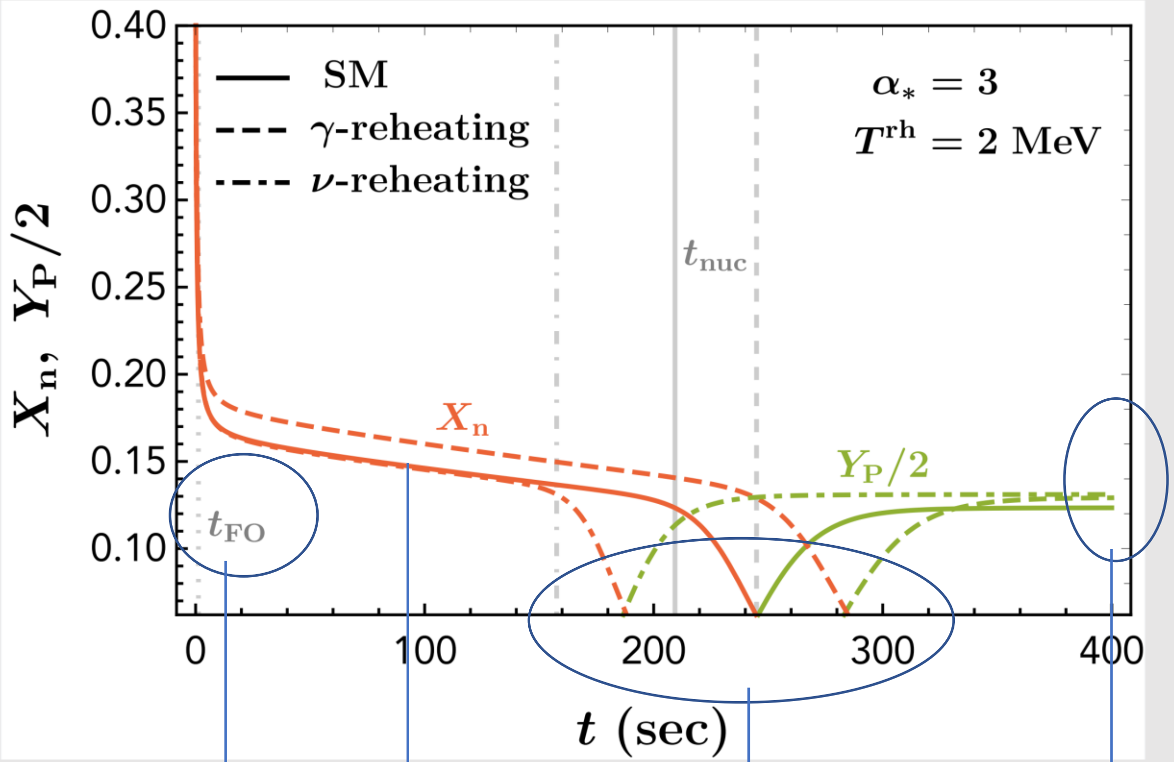
- Effects are enhanced for larger α_* and for smaller $T^{rh}_{\gamma/\nu}$

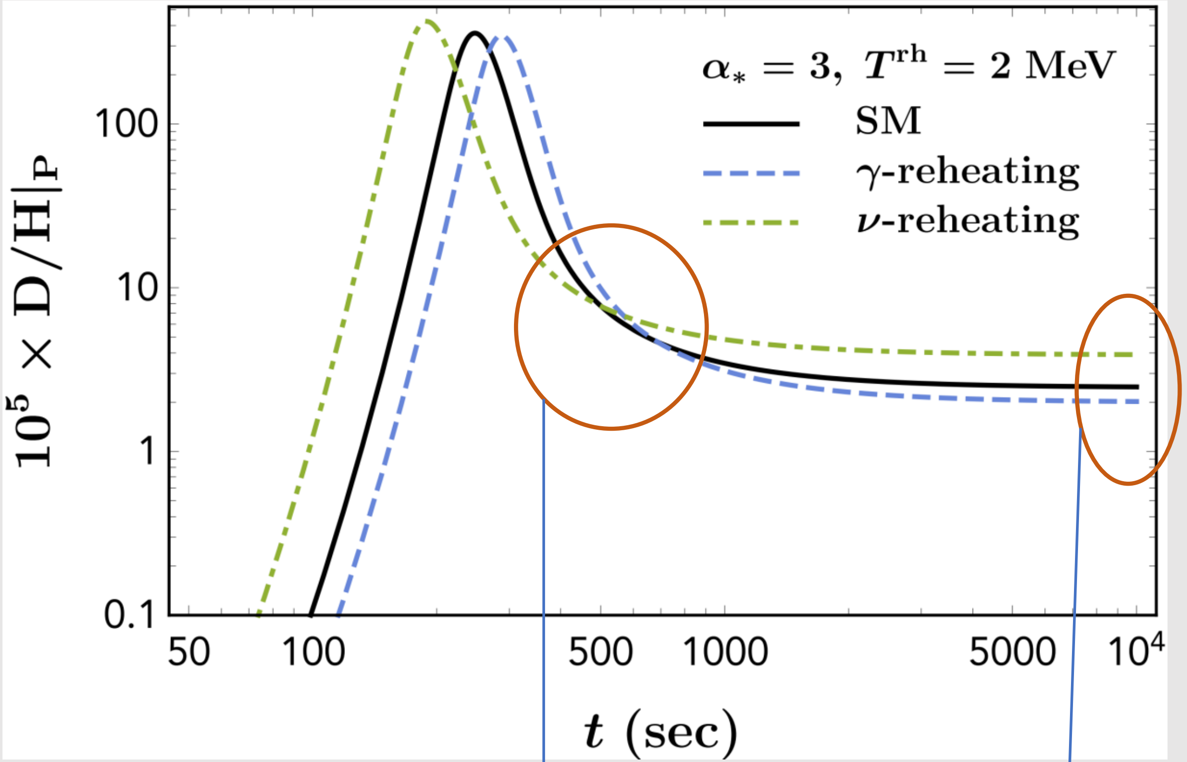




(Bai, **MK** 2109.14765)

Effects on helium and deuterium abundance





$\Gamma_{np} = H$

$X_n(t) \approx X_n(t_{\rm FO}) \exp(-t/\tau_n)$

$Y_P \approx 2X_n(t_{\rm nuc})$

Y_P increases for both cases

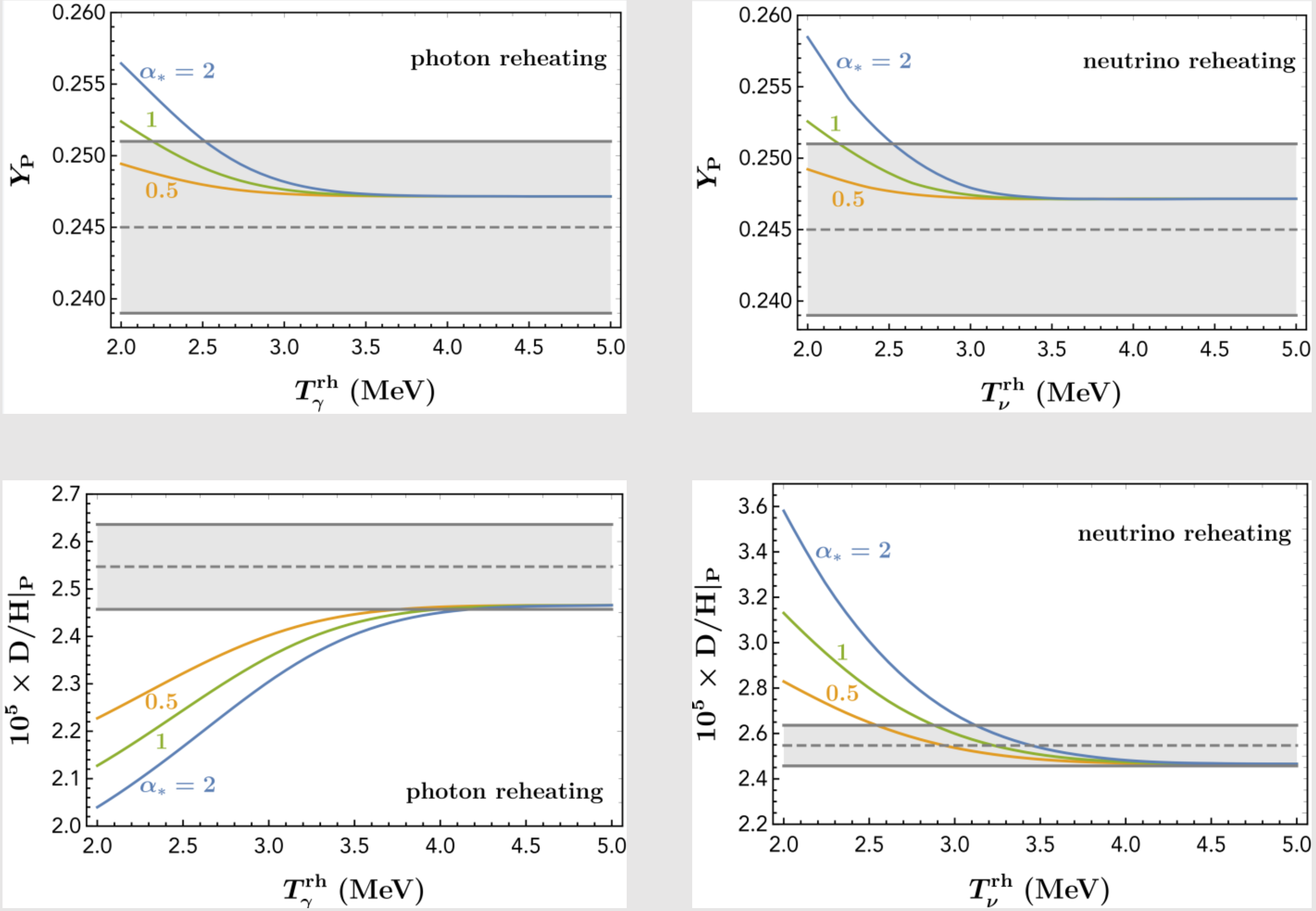
Deuterium abundance freeze-out at earlier time for higher N_{eff} as higher Hubble rate

D/H increases for NR and decreases for PR

(Pitrou et al. 1801.08023 – PRIMAT code)
(Mukhanov 0303073)
(Bai, **MK** 2109.14765)

Effects on helium and deuterium abundance

	N_{eff}	Y_P	$D/H\|_P$
Photon Reheating	Decreases	Increases	Decreases
Neutrino Reheating	Increases	Increases	Increases



- Effects are enhanced for larger α_* and for smaller $T^{rh}_{\gamma/\nu}$
- Deuterium abundance provides strongest constraints from BBN because of better measurements

(Bai, **MK** 2109.14765)

Constraints on FOPT

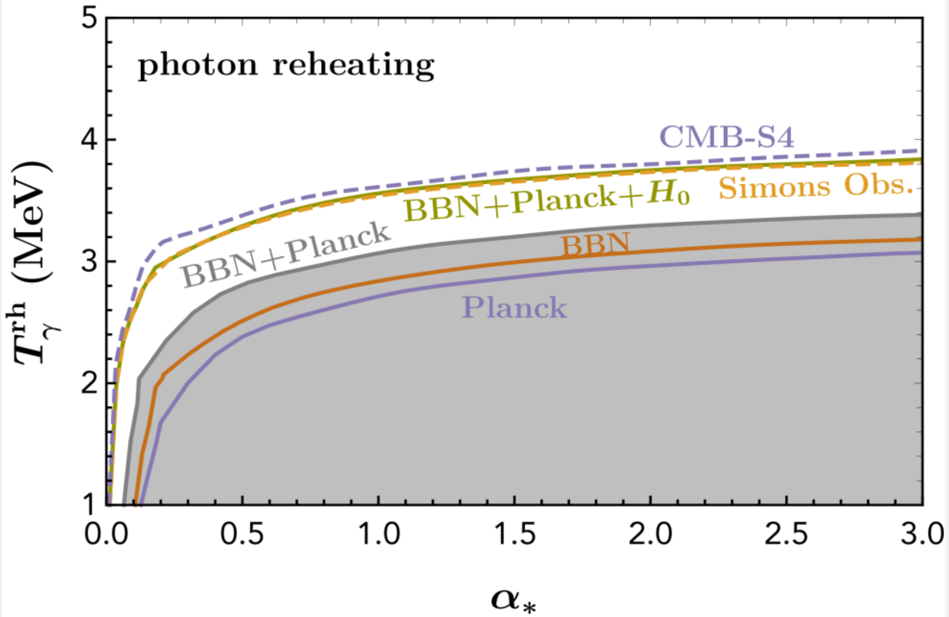
Datasets:

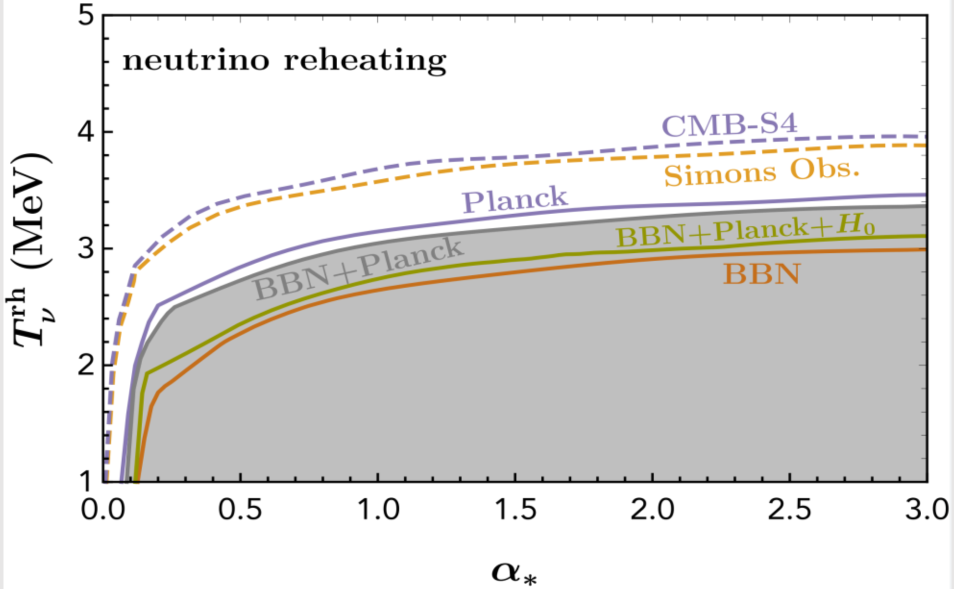
1. BBN: Y_P and $D/H|_P$

2. CMB and local H_0: $\Omega_b h^2$, N_{eff} and Y_P
   with $\Omega_b h^2$ marginalized

3. BBN + CMB (H_0)

4. Future CMB experiments: Simons observatory and CMB-S4





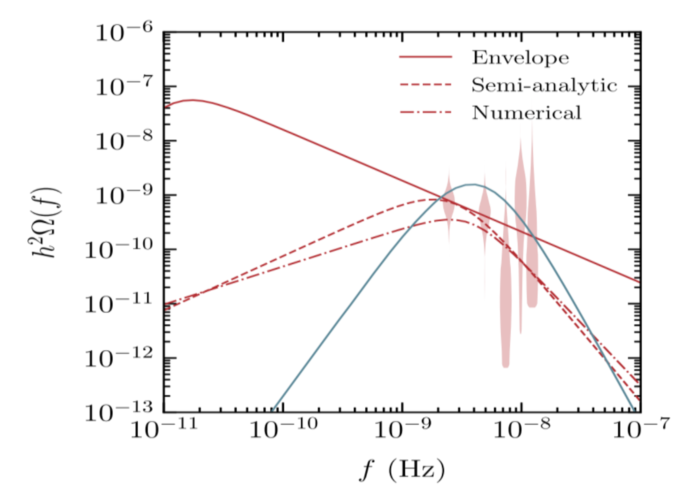
(PDG 2021)
(Sabti et al. 1910.01649)
(Bai, **MK** 2109.14765)

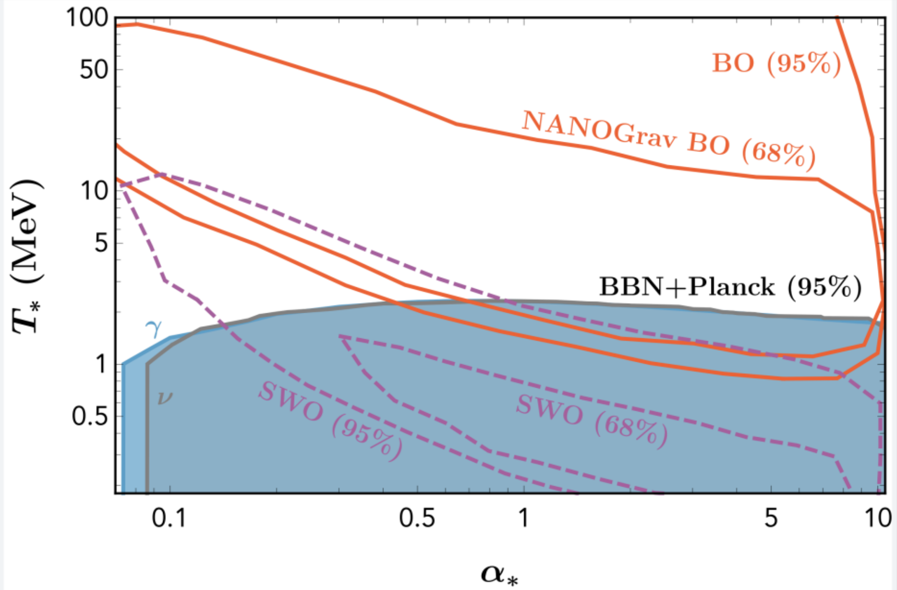
Implications for NANOGrav

- Signal in NANOGrav 12.5 yrs dataset. The signal can be explained with SMBHB and FOPT.

- Contours from NANOGrav results
  SWO - Sound wave contribution
  BO - Bubble collision contribution

- SWO case well probed by BBN + Planck constraints





(NANOGrav 2009.04496, 2104.13930)
(Bai, **MK** 2109.14765)

Summary

- MeV scale FOPT can be probed by PTA experiments and cosmological observables in BBN and CMB

- For strong FOPT, phase transition temperature should be above 2-3 MeV

- For Weak FOPT and phase transition below MeV, strength of PT (α_*) should be less than 0.1

- Improvements with future CMB experiments.

- Implications for NANOGrav results – can distinguish between FOPT and other explanations for the signal.

Thank You!

Questions?

Appendix

Model for photon and neutrino couplings

- **Photon Reheating Case**

$$\mathcal{O}_5^\gamma = \frac{\alpha}{4\pi\,\Lambda}\,\Phi\, F^{\mu\nu} F_{\mu\nu}$$

For this case to have a decay into photons at MeV scale we need $\Lambda < 8$ TeV. Current constraints are around $\Lambda >$ few 100 GeV.

(Marciano et al. 1607.01022)

$$O_5^e = \frac{\Phi\, H\, \overline{L}_L e_R}{\Lambda}$$

For this case to have decay into electrons at MeV scale we need $\Lambda < 10^{12}$ GeV. Constraints are $\Lambda > 10^9$ GeV.

(Liu et al. 1605.04612)

- **Neutrino Reheating Case**

$$\mathcal{O}_6^\nu = \frac{\Phi (H L_L)^2}{\Lambda^2}$$

For this case to have decay to neutrinos at MeV scale we need $\Lambda < 10^6$ GeV. Constraints are $\Lambda > 10^4$ GeV.

(Blinov et al. 1905.02727)