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# Probing Physics Beyond the Standard Model: Limits from BBN and the CMB Independently and Combined

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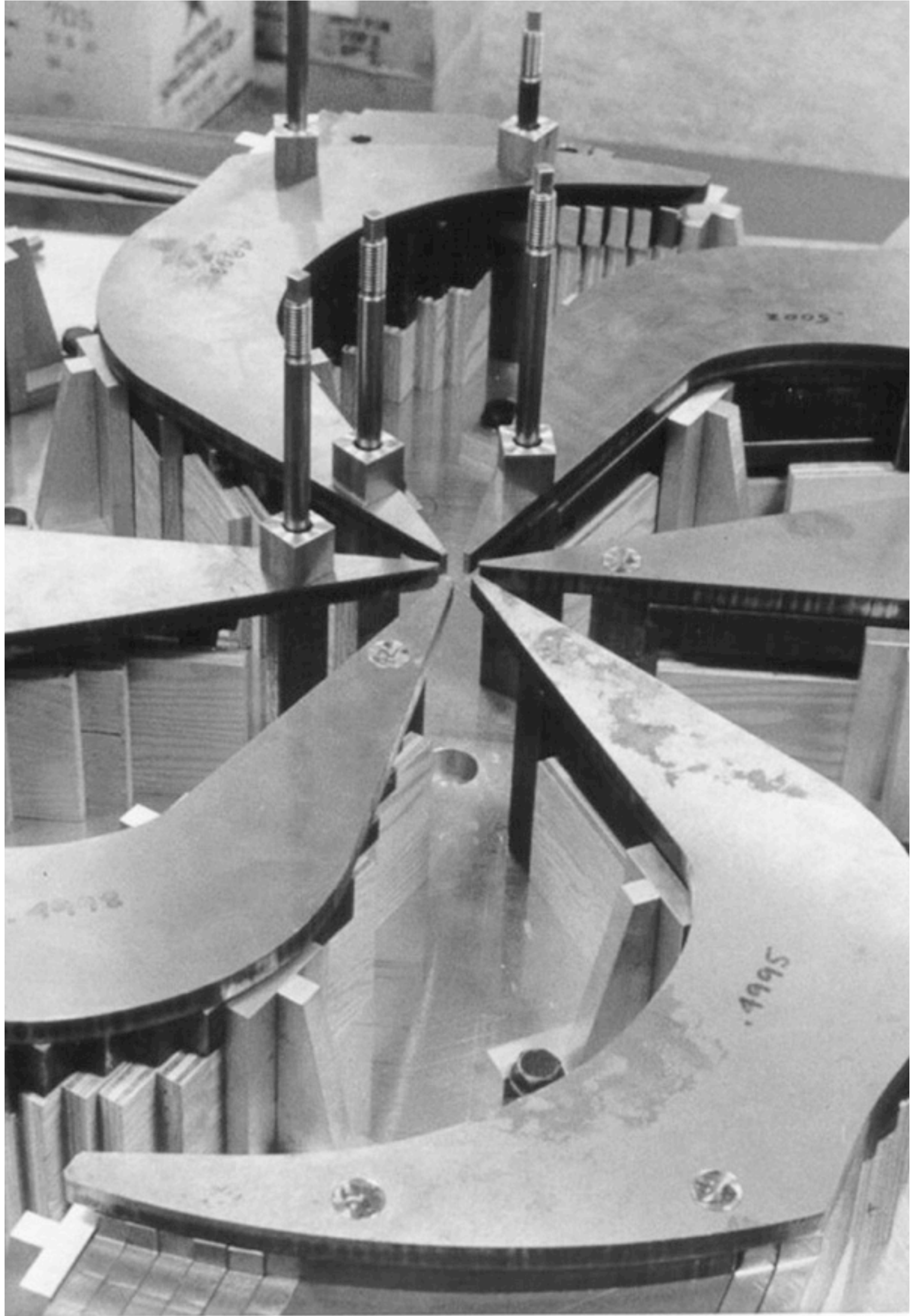
2023 CAP Congress
(PPD) R1-1 DM / Neutrino 5
June 22, 2023

arXiv: 2207.13133
co-authors: Jessie Shelton (UIUC), Keith Olive (UMN),
Brian Fields (UIUC)

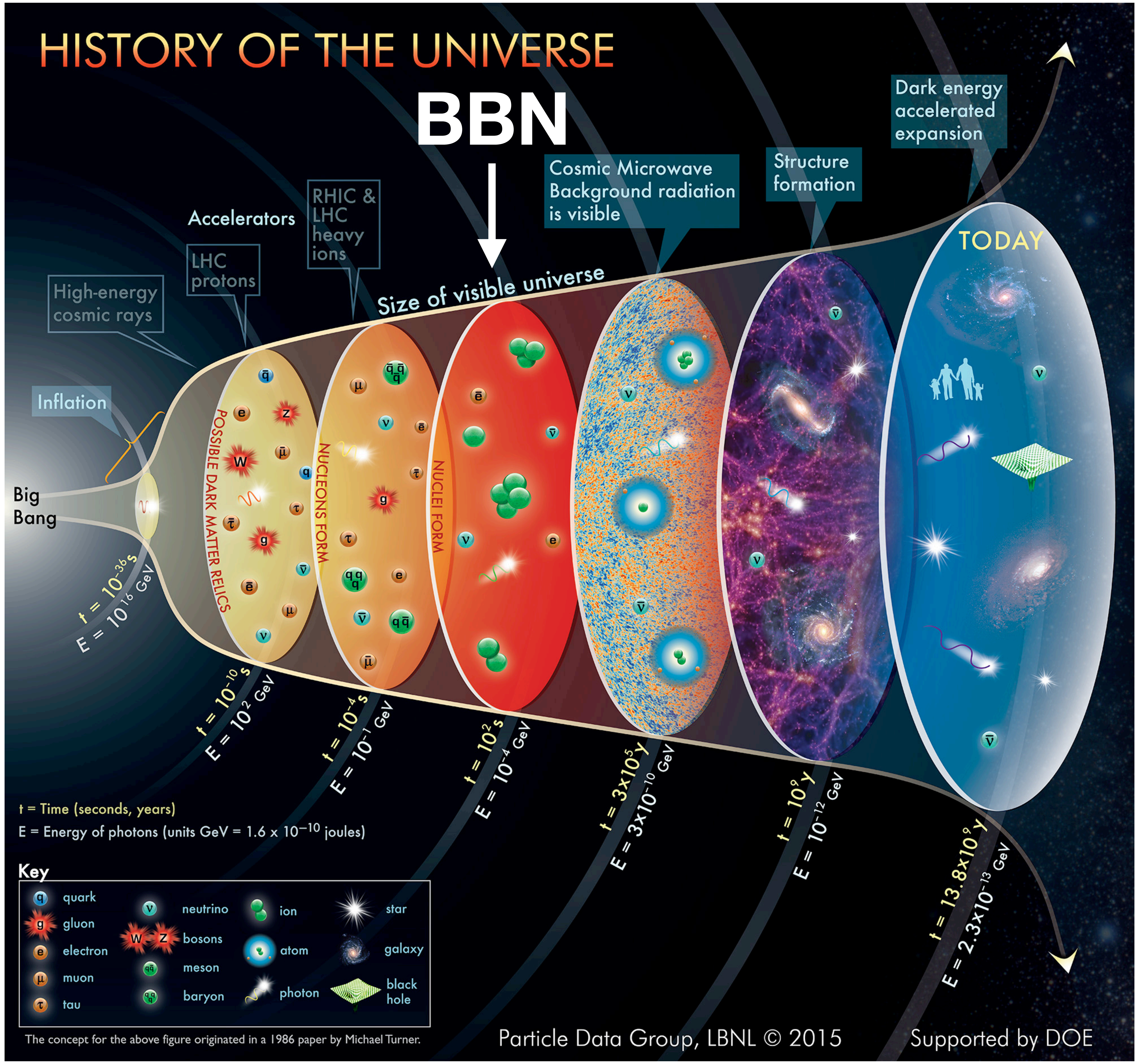


Discovery, accelerated

# Big Bang Nucleosynthesis



- the very first nucleosynthesis
  - lasting from ~1 sec to ~10 mins after the big bang
- the cosmic origin of light elements
  - almost all neutrons → $^4$He
  - trace amounts of d, $^3$He, and $^7$Li
- BBN predictions v.s. astro observations
  - probing the early universe physics

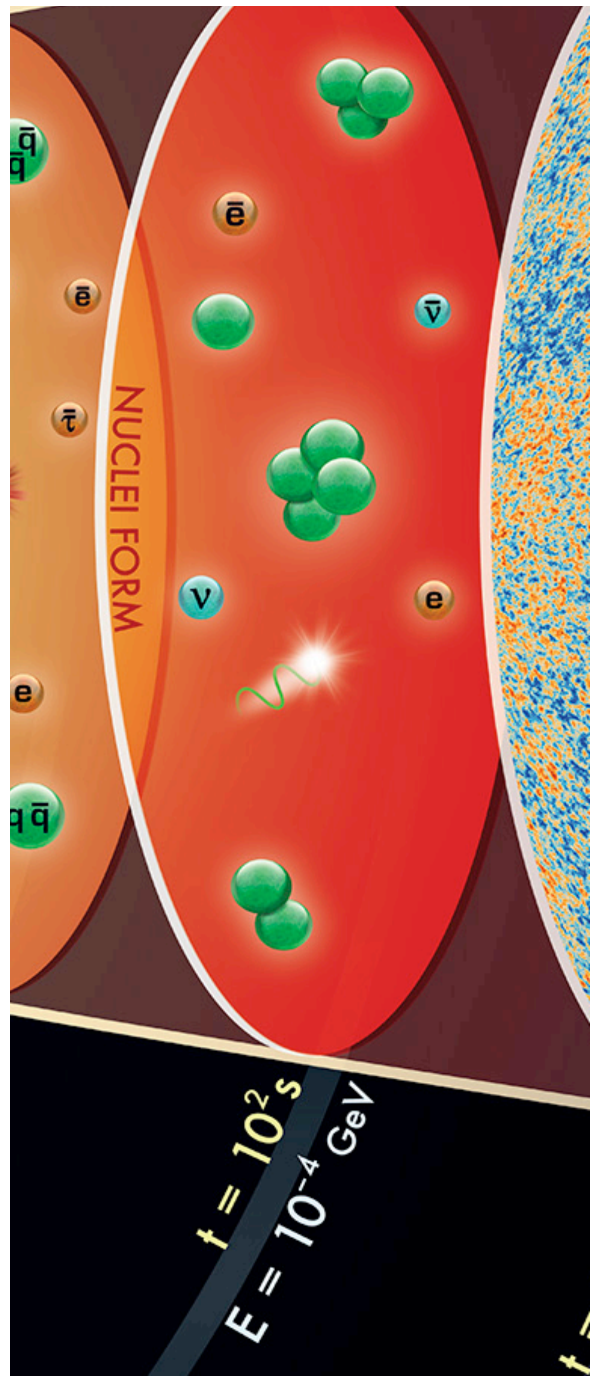


# Standard BBN (SBBN)



ΛCDM cosmology + Standard Model of particle/nuclear physics

- radiation-dominated universe by $\gamma$, $e^{\pm}$, $\nu_i$ and $\bar{\nu}_i$ , where $i = e,\ \mu,\ \tau$
- the cosmic expansion rate (the Hubble parameter): $H^2 = \dfrac{8\pi G_N}{3}\rho_{\rm rad}$



PDG, LBNL @ 2015

SBBN + precise nuclear inputs measured from experiments

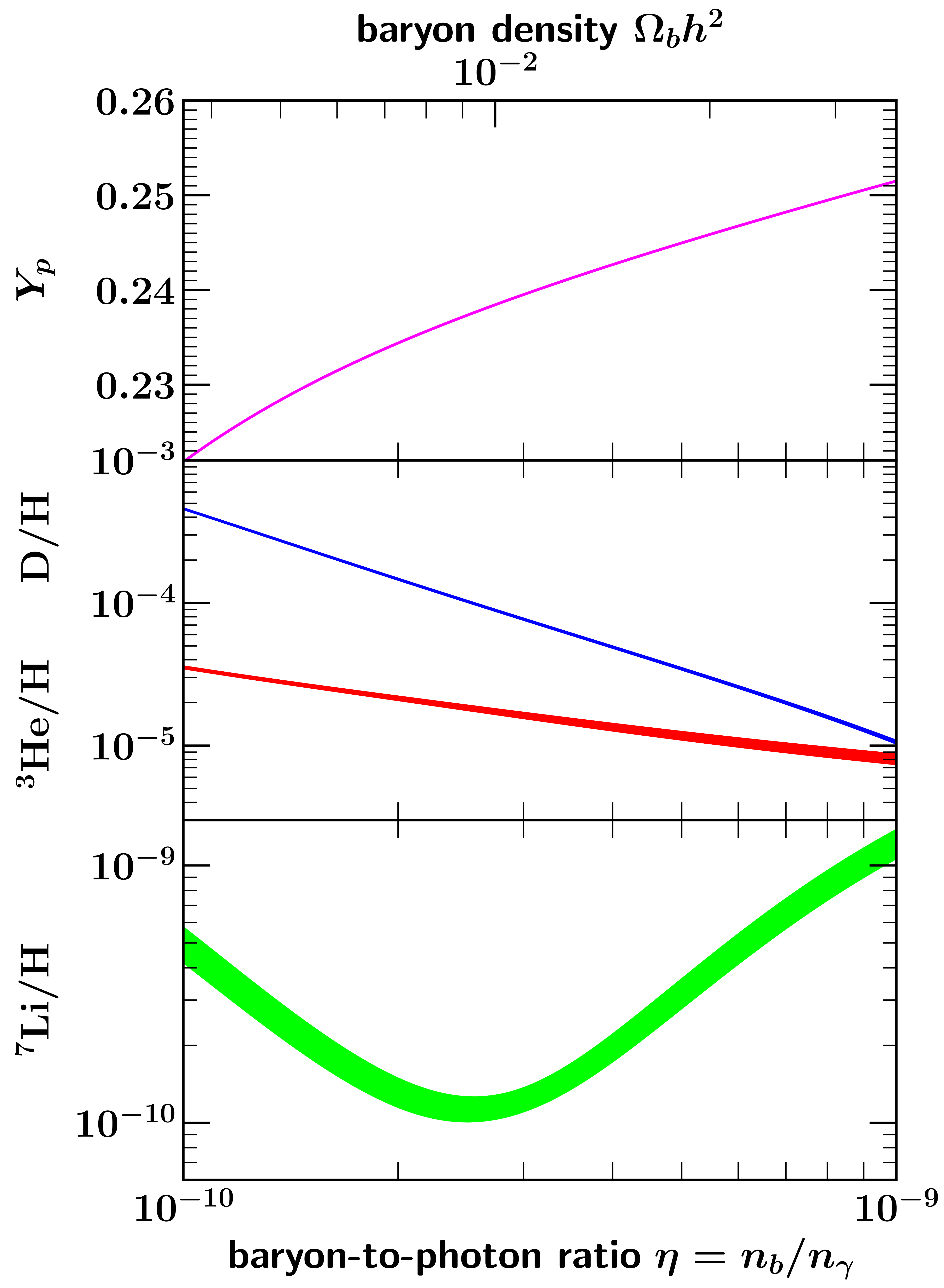
*e.g.*, neutron mean lifetime, recent updates for $d(p,\gamma)^3$He, $d(d,n)^3$He & $d(d,p)^3$t

⇒ single parameter: baryon-to-photon ratio $\eta = \dfrac{n_b}{n_\gamma}$

# The Schramm Plot



- classic tool to show abundances as functions of baryon-to-photon ratio $\eta$
- mass fraction $Y_p$ for $^4$He; abundance ratio to hydrogen for other elements
- widths determined from Monte Carlo runs on nuclear rates



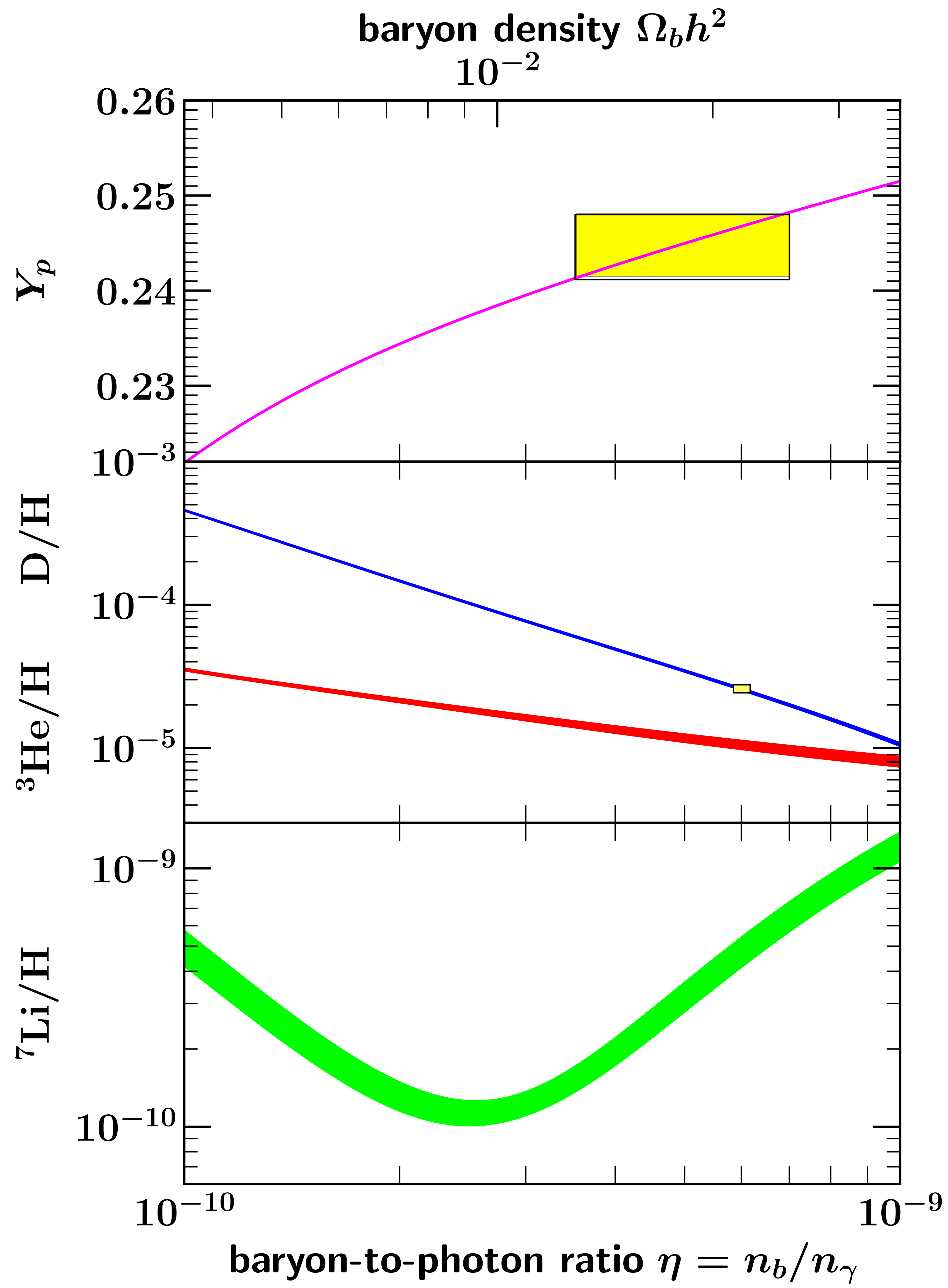
# Schramm Plot + Observations



- $^4$He and D primordial abundances (yellow boxes)

| | mean | $\sigma$ | reference |
|---|---|---|---|
| $Y_p$ ($^4$He) | 0.2448 | 0.0033 | Aver+ (2022) |
| D/H x $10^5$ | 2.527 | 0.030 | Cooke+ (2018) |

- each one selects a range of $\eta$




**Yeh,** Shelton, Olive, & Fields (2022) arXiv: 2207.13133

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- each one selects a range of $\eta$

- SBBN+D is an excellent baryometer!

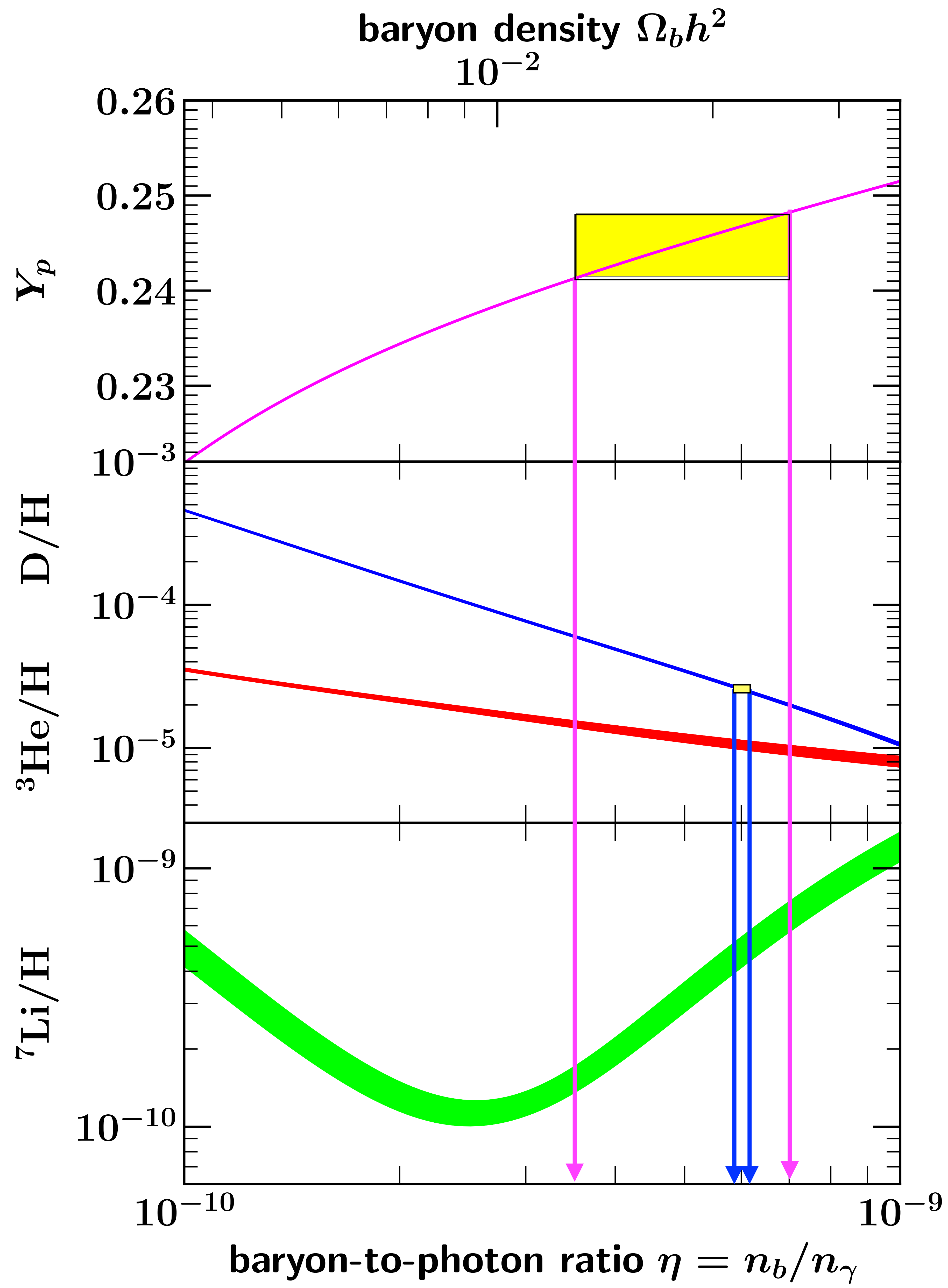
$$\eta_{BBN+D} = (6.042 \pm 0.118) \times 10^{-10}$$

- Planck 2018*: (arXiv:1807.06209)

$$\eta_{CMB} = (6.104 \pm 0.055) \times 10^{-10}$$

$$\text{i.e., } \Omega_b h^2 = 0.02230 \pm 0.0002$$

* the base_yhe_plikHM_TTTEEE_lowl_lowE_post_lensing MCMC chains

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# Probing Big Bang Light Relics with Non-Standard BBN



- many BSM models predict extra radiation:

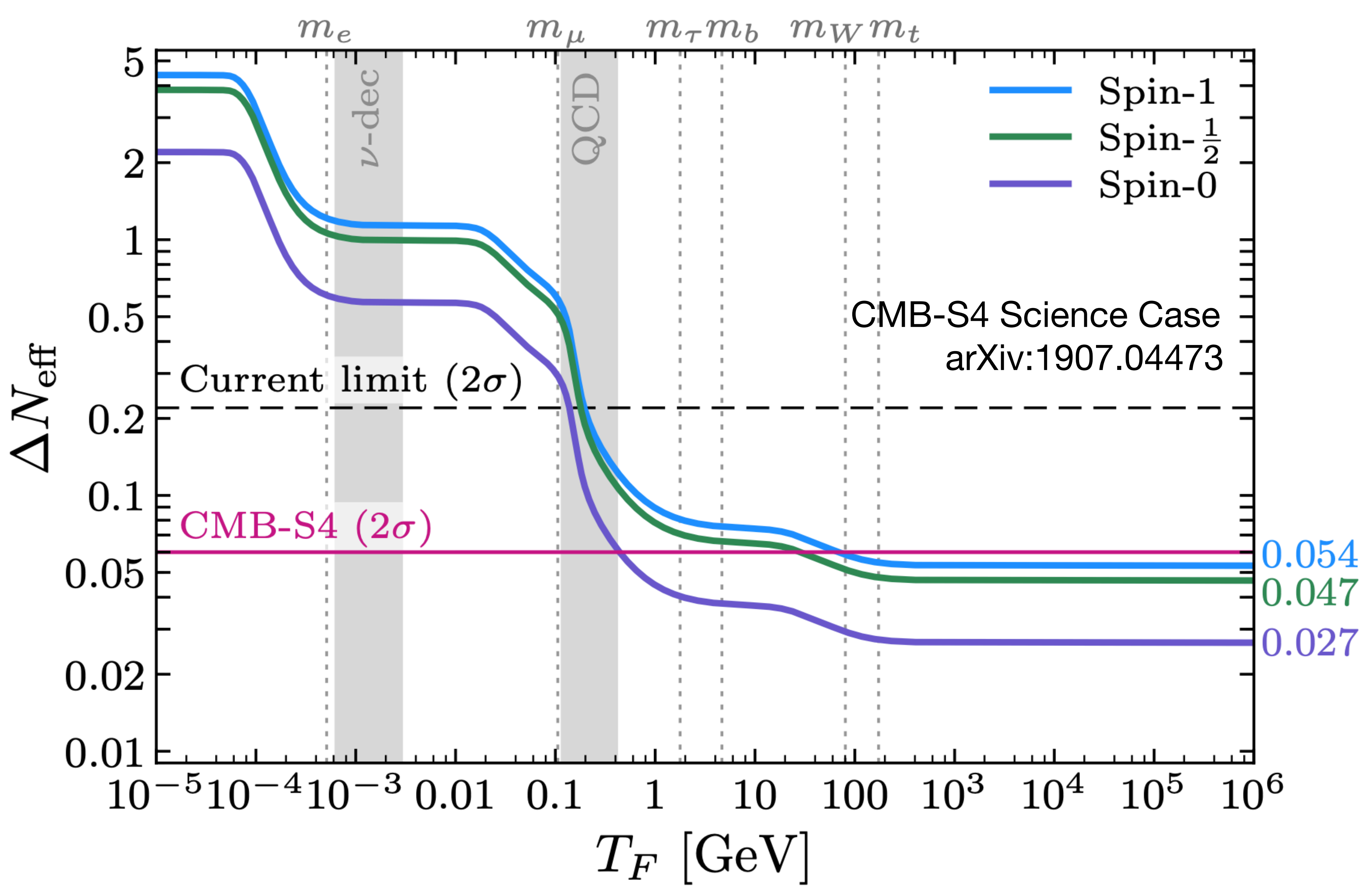
$$H^2 = \frac{8\pi G}{3}(\rho_{\rm rad}^{\rm SM} + \rho_{\rm rad}^{\rm BSM})$$

- parameterize effects of light relics in terms of effective species of SM thermal neutrinos

$$\Delta N_{\rm eff} \equiv \frac{\rho_{\rm rad}^{\rm BSM}}{\rho_{1\nu}^{\rm SM}}, \text{ where } \rho_{1\nu}^{\rm SM} = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4$$

-> total $N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}$, where $N_{\rm eff}^{\rm SM} = 3.044$

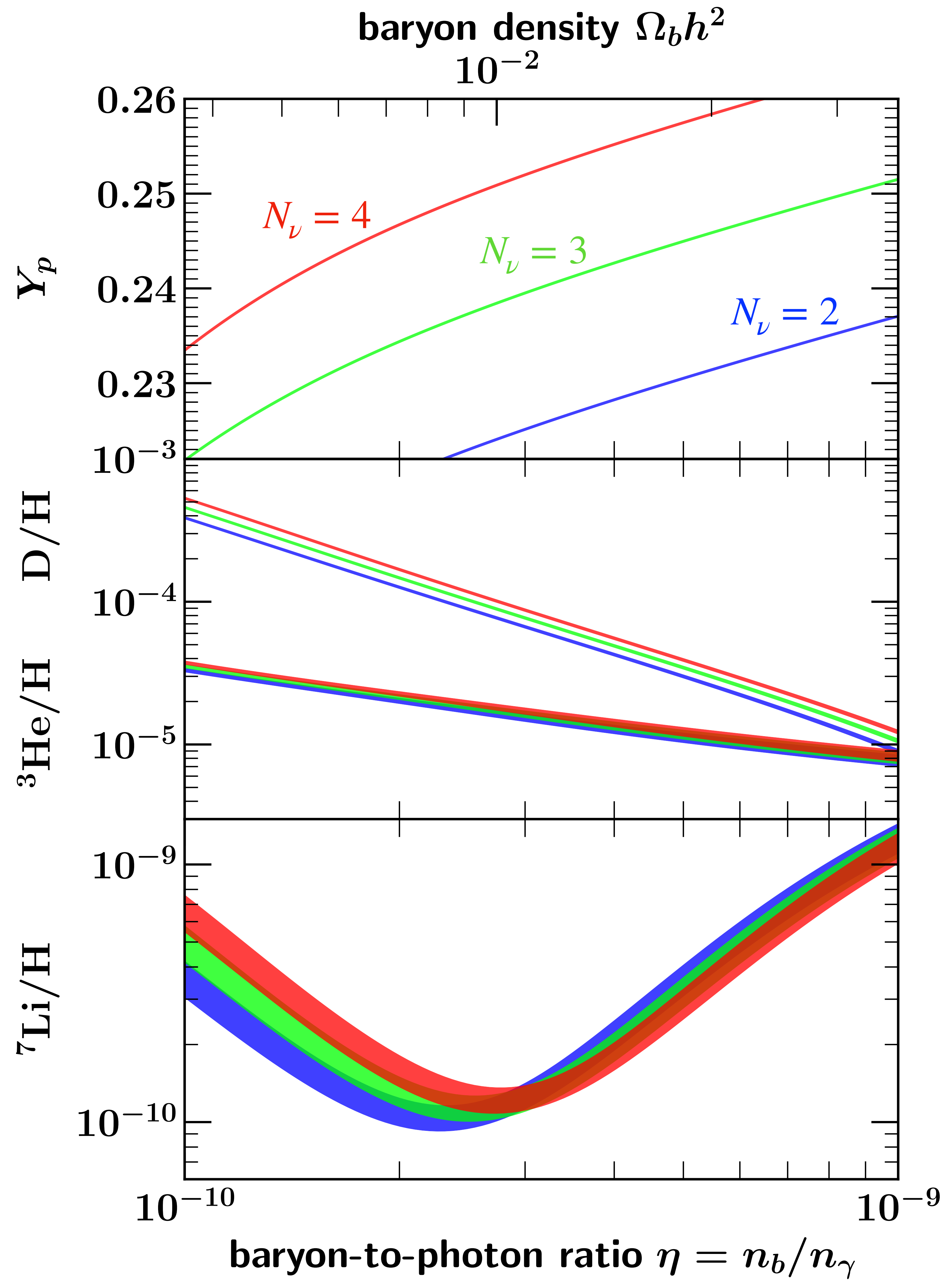
(the extra 0.044 from the heating effect of $e^{\pm}$ annihilation predicted by standard physics)



# Probing Big Bang Light Relics with Non-Standard BBN



- Non-Standard BBN for light relics scenario:
  allow neutrino flavor $N_\nu \neq N_\nu^{\rm SM}$ ($N_\nu^{\rm SM} = 3 \leftrightarrow N_{\rm eff}^{\rm SM} = 3.044$)
  e.g., $N_\nu \uparrow \Rightarrow H \uparrow \Rightarrow$ cosmic $T \downarrow$ faster $\Rightarrow$ n for BBN $\uparrow$
  -> 2 parameters $(\eta, N_\nu)$ v.s. 2 observables $(^4\mathrm{He}, \mathrm{D})$

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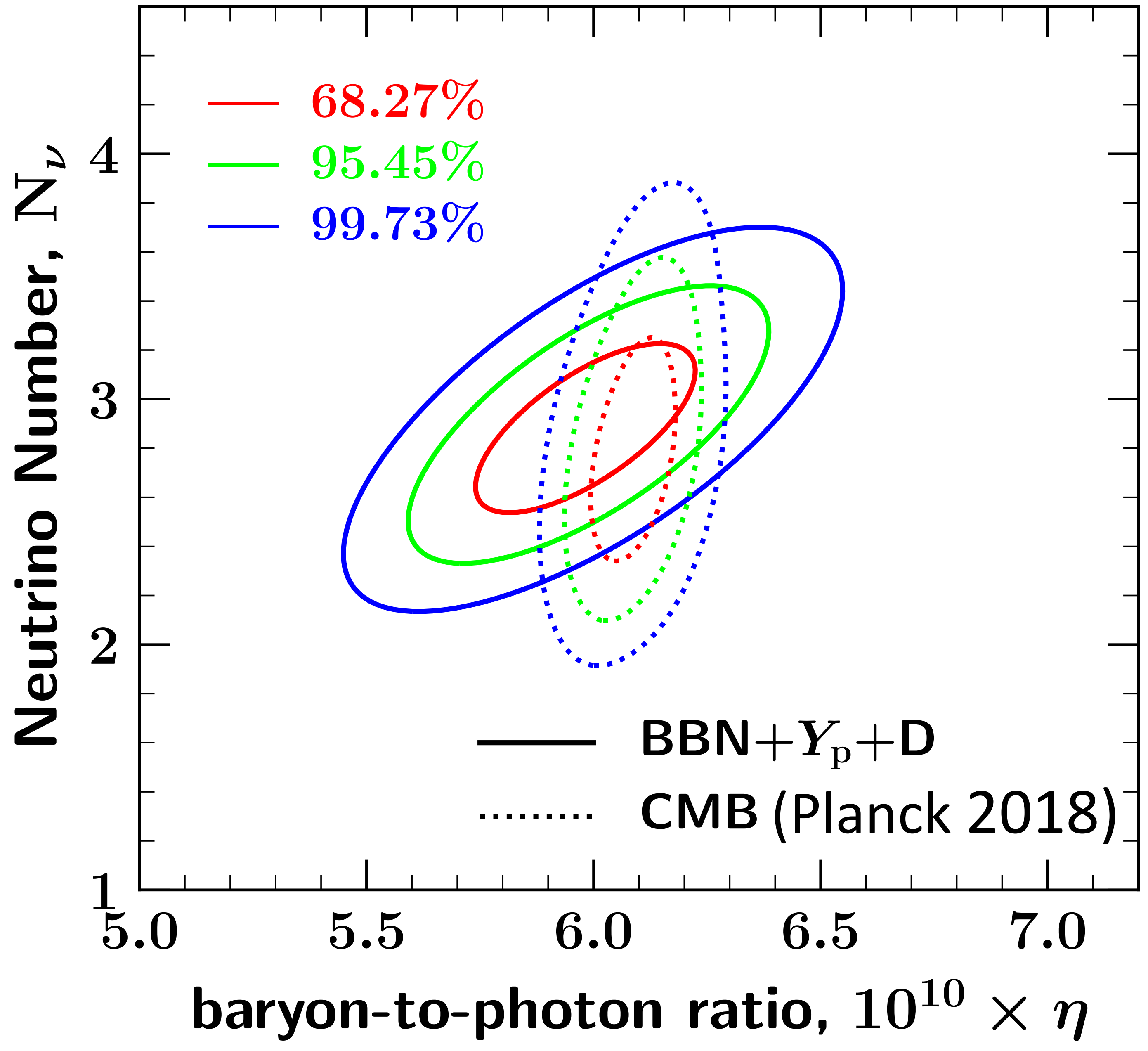
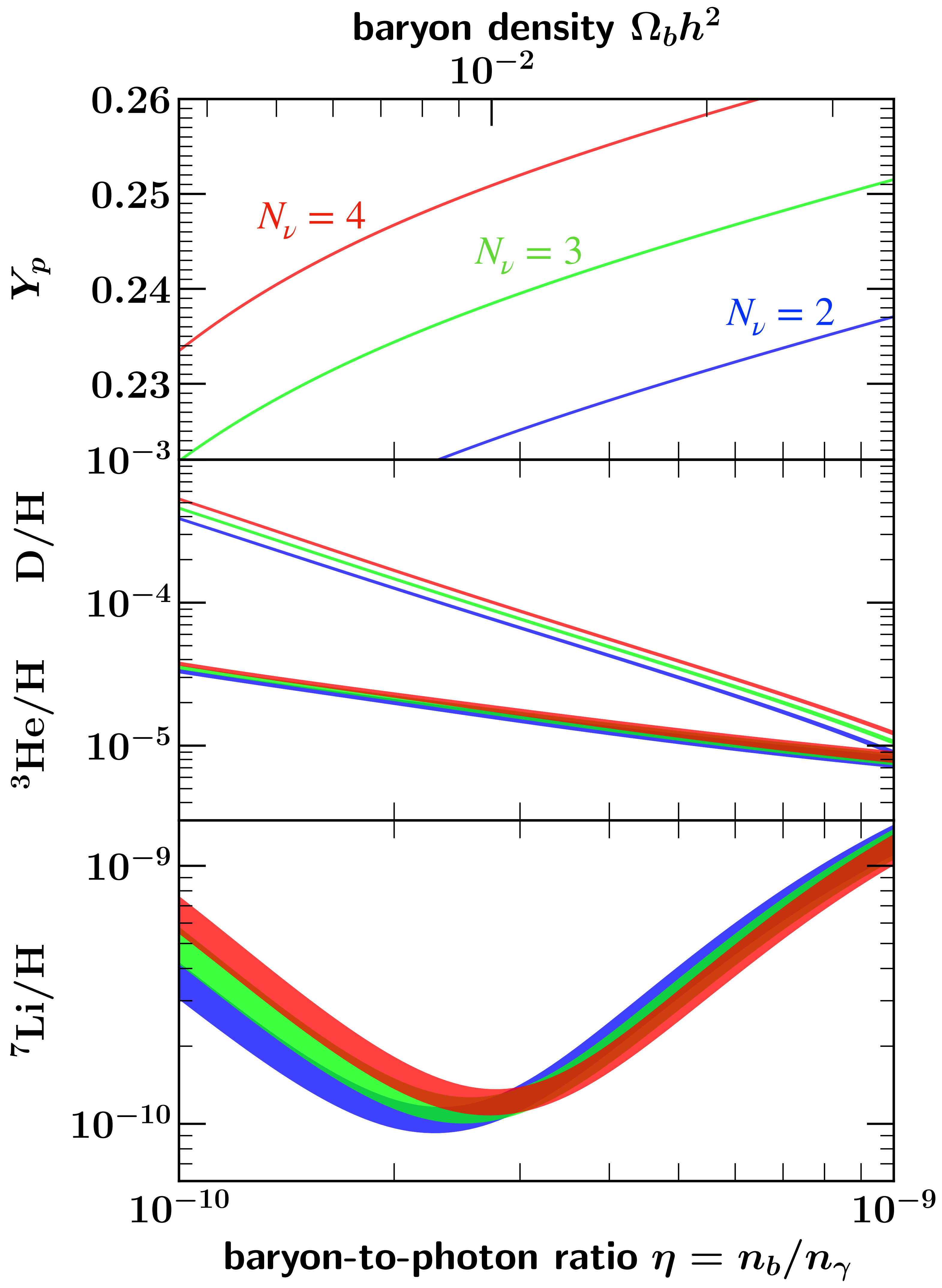
- BBN and Planck 2018*
  in good agreement!

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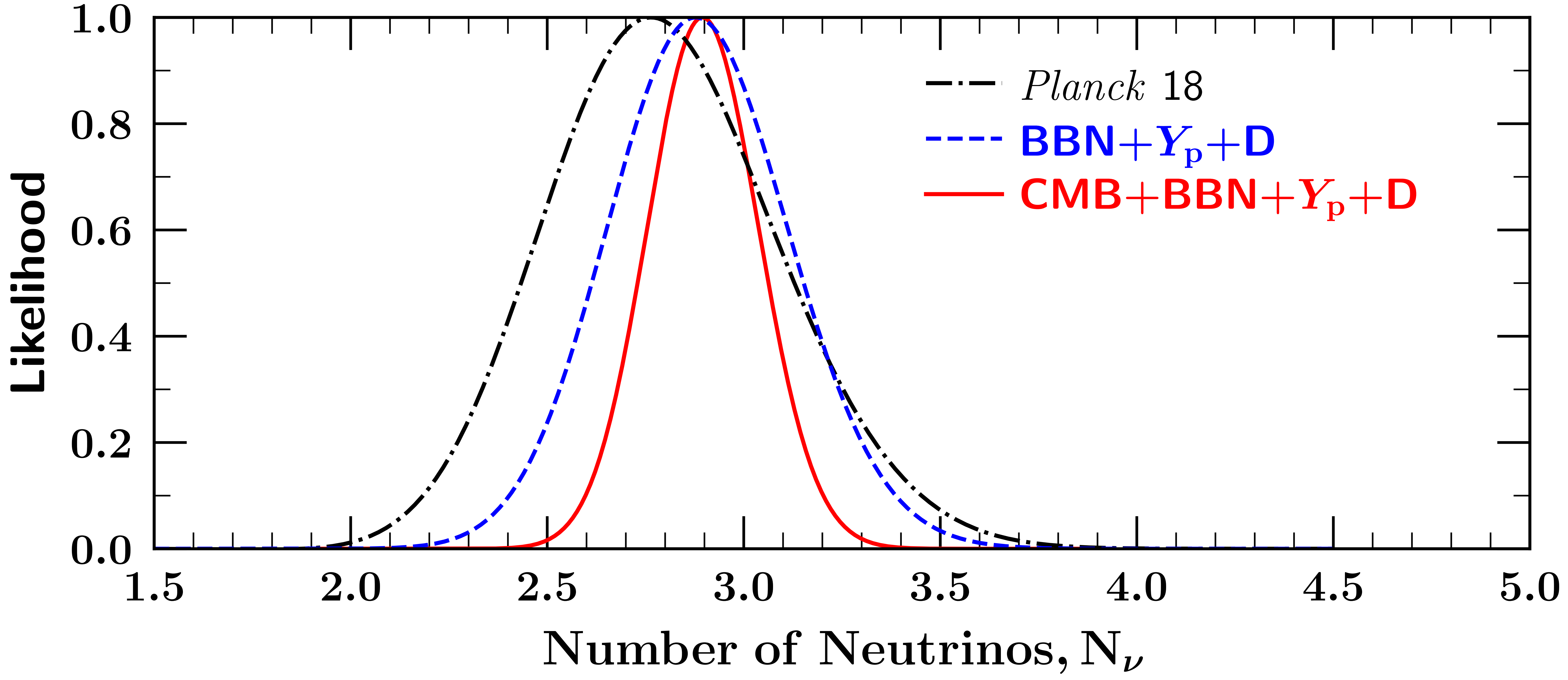
# Limits on Neutrino Flavors $N_\nu$

summary statistics for $N_\nu$

| | mean | $\sigma$ |
|---|---|---|
| Planck 2018 | 2.800 | 0.294 |
| BBN+Obs | 2.889 | 0.229 |
| combined | 2.898 | 0.141 |



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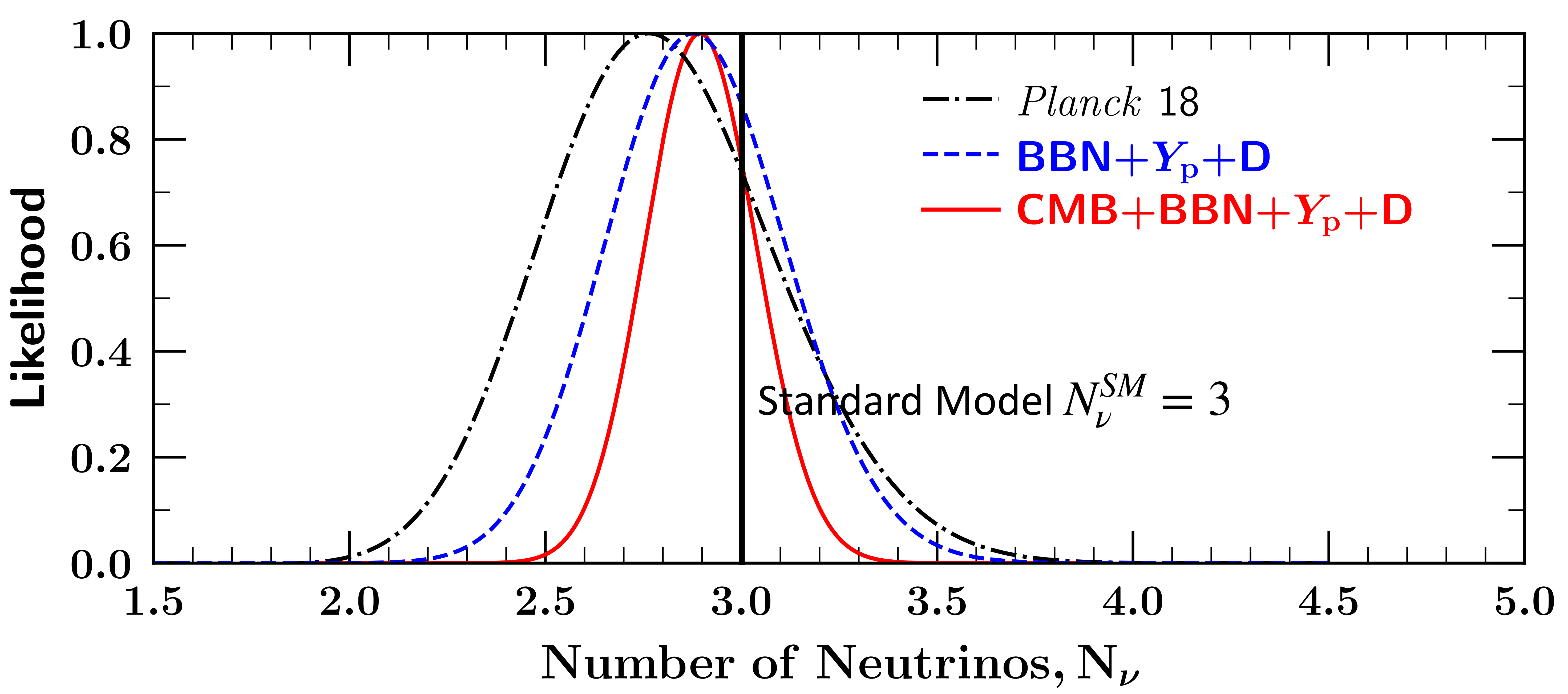
=> 95% upper limit: $N_\nu < 3.18$

=> $\Delta N_\nu = N_\nu - 3 < 0.18$

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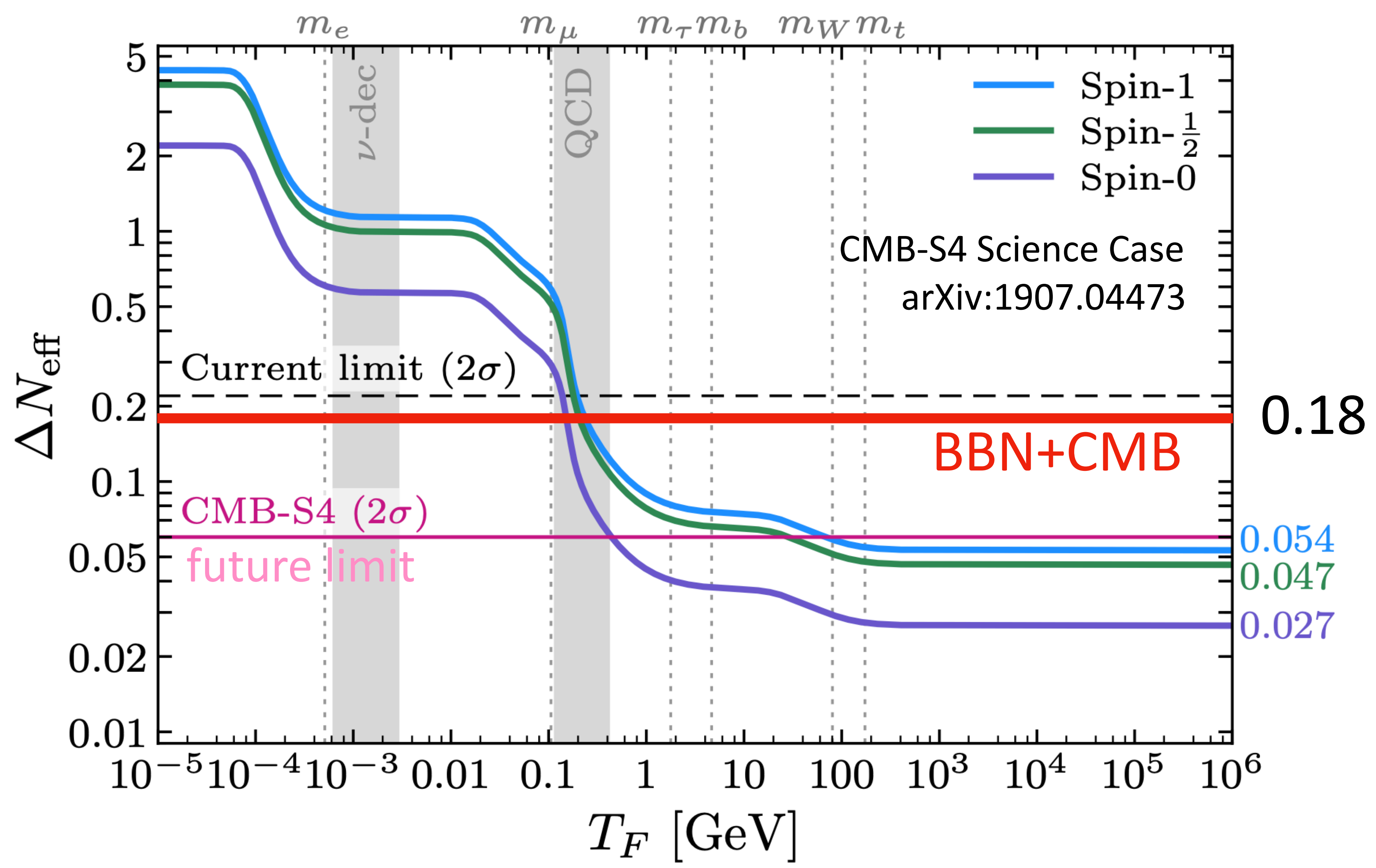


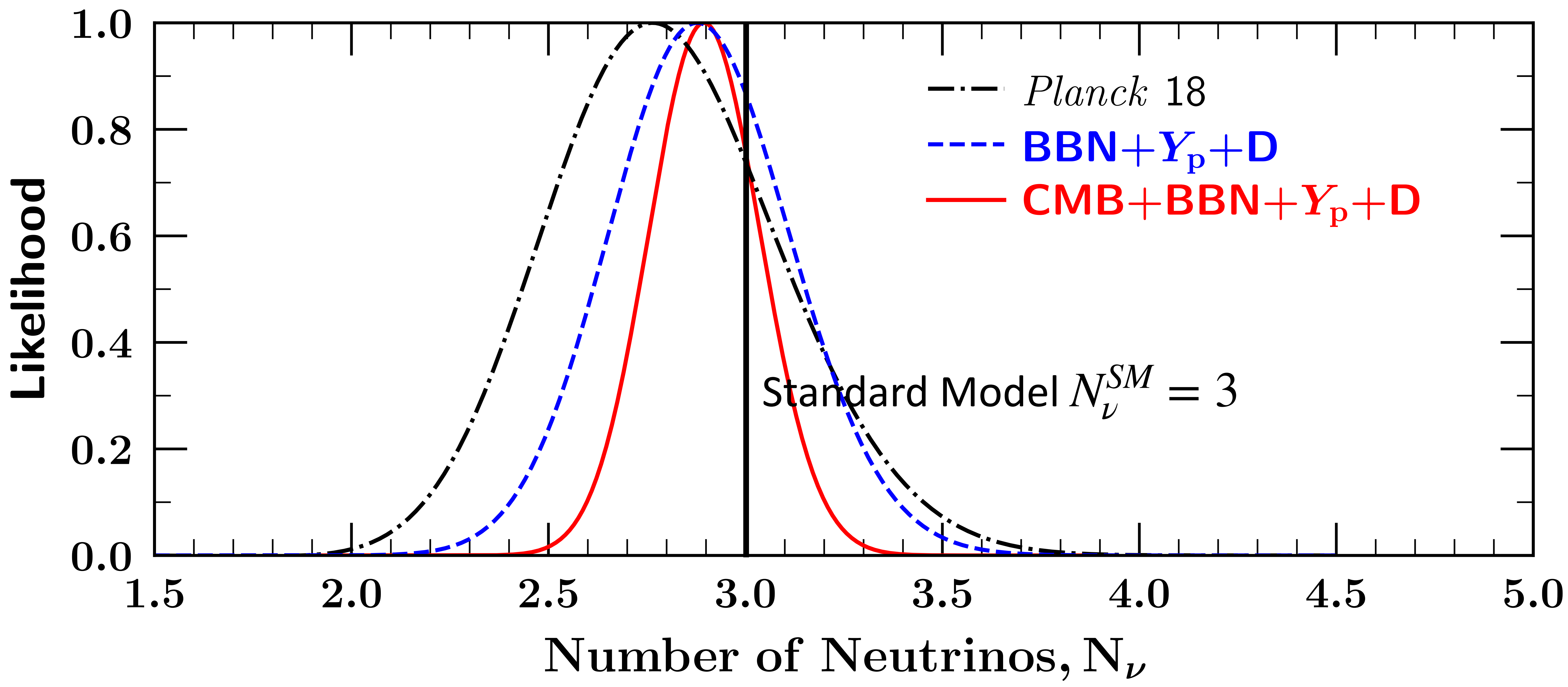


=> new species must be:

1. thermally decoupled before QCD transition (w/ different $T_{\rm new}$)
2. produced with non-thermal distribution

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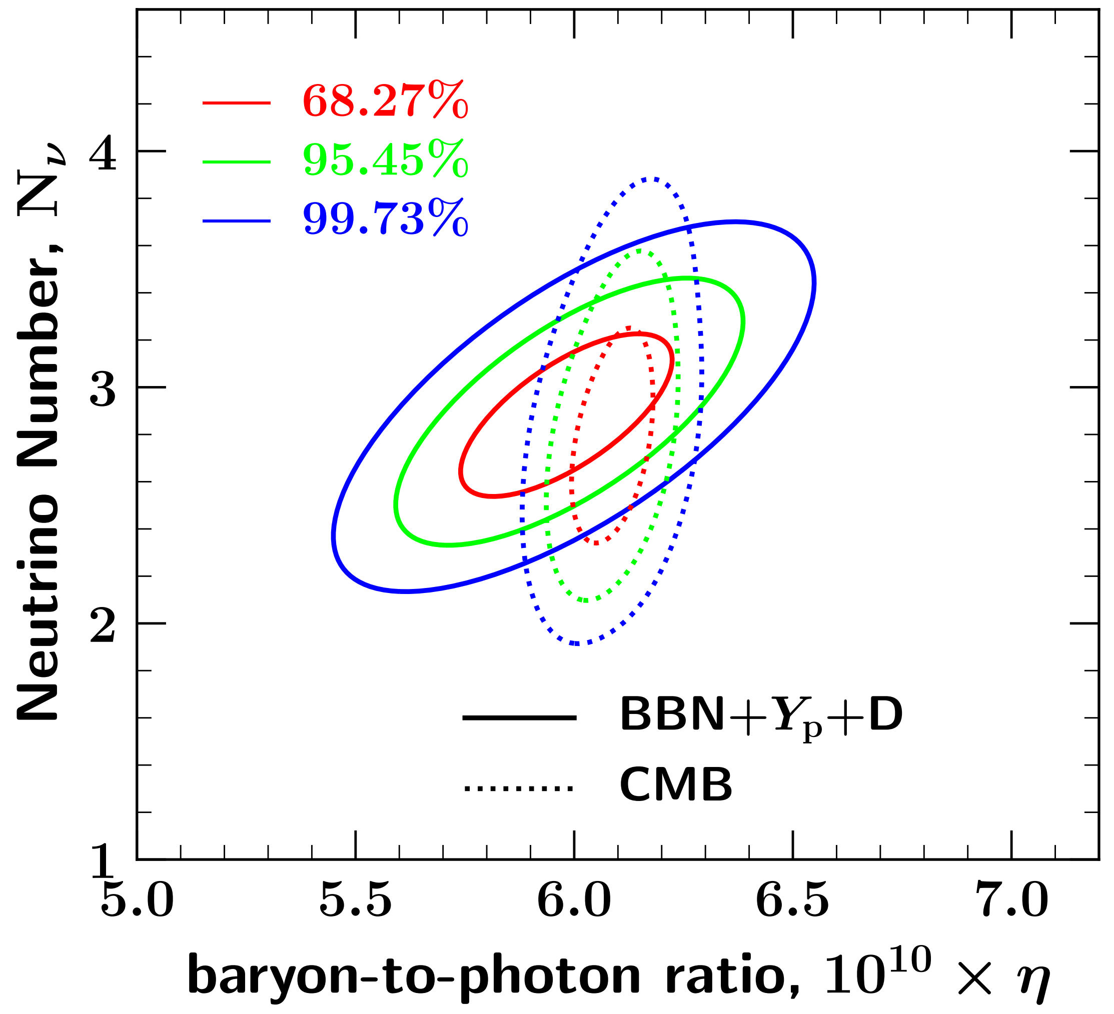
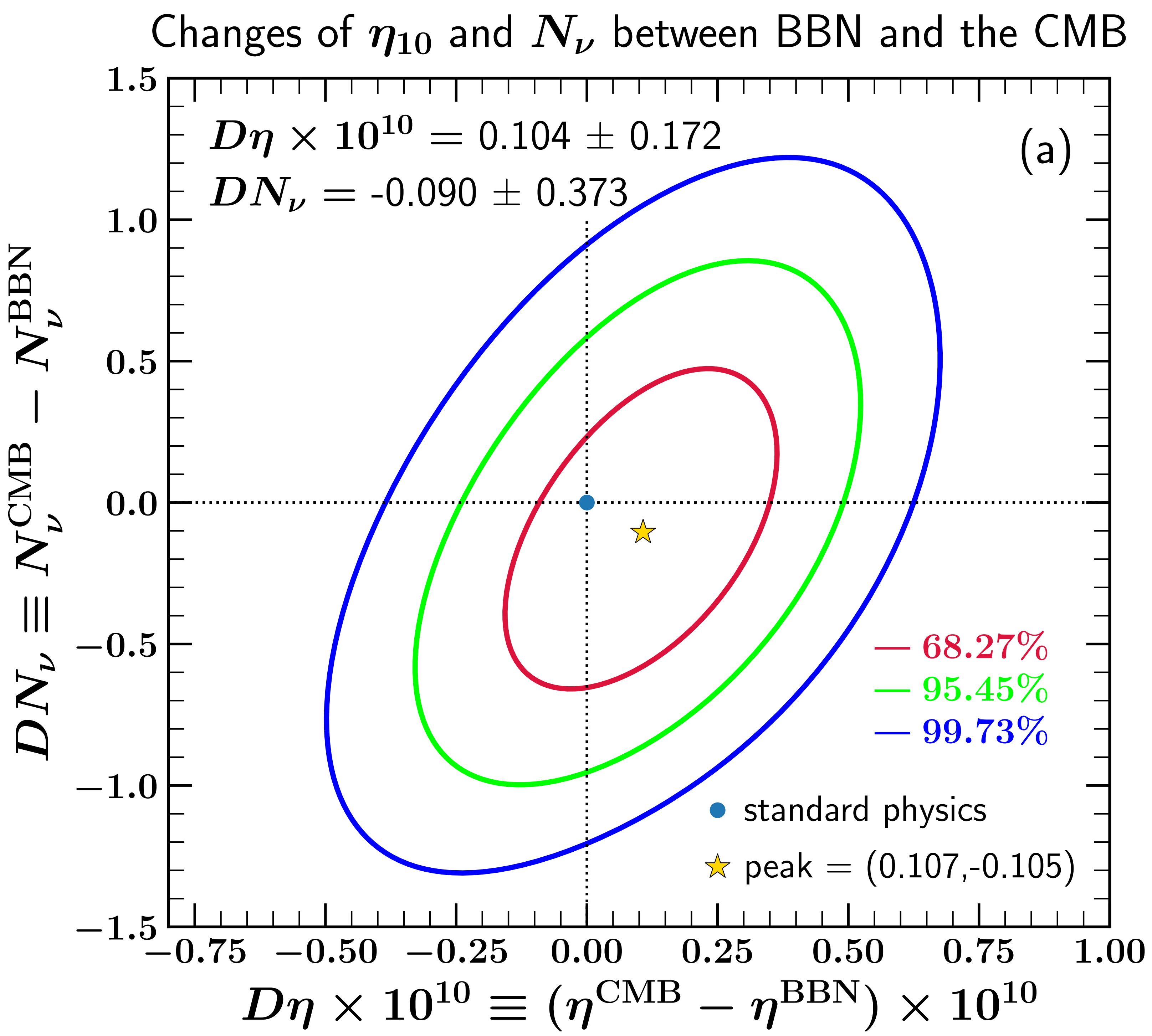
# Changes in $\eta$ and $N_\nu$ between BBN and CMB Eras

- many BSM models predict extra radiation injections in the early universe; e.g. heavy relics decay

- improved BBN and CMB errors make it possible to probe such evolution in $N_\nu$
  - rooms for new physics, but SM still good fit
  - future precision measurements, like CMB-S4, will sharpen these limits

- caveat for this approach:
  sophisticated calculation needed if new physics alters BBN beyond simply adding extra radiation

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# Could We Further Improve the Current Constraints?

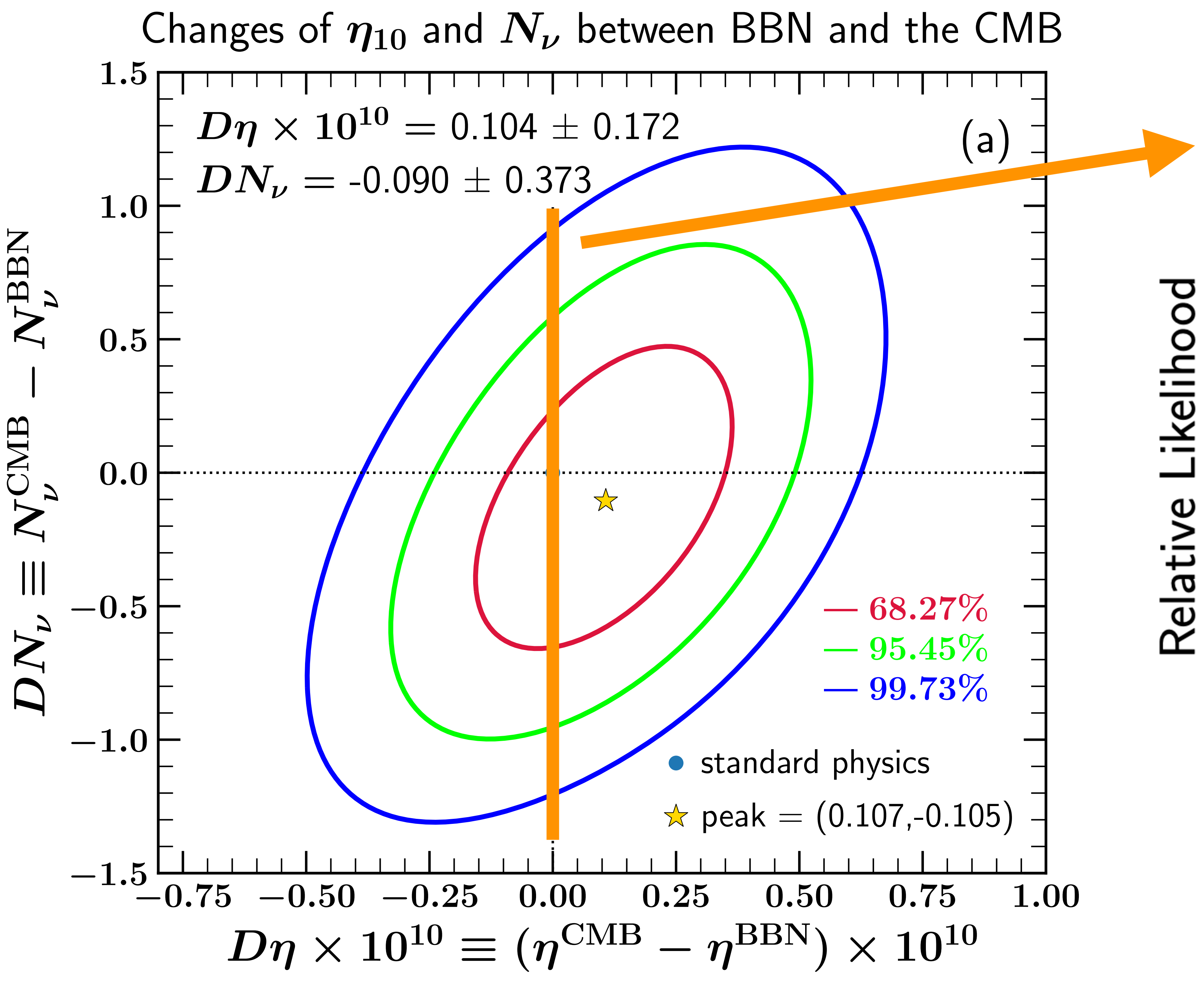


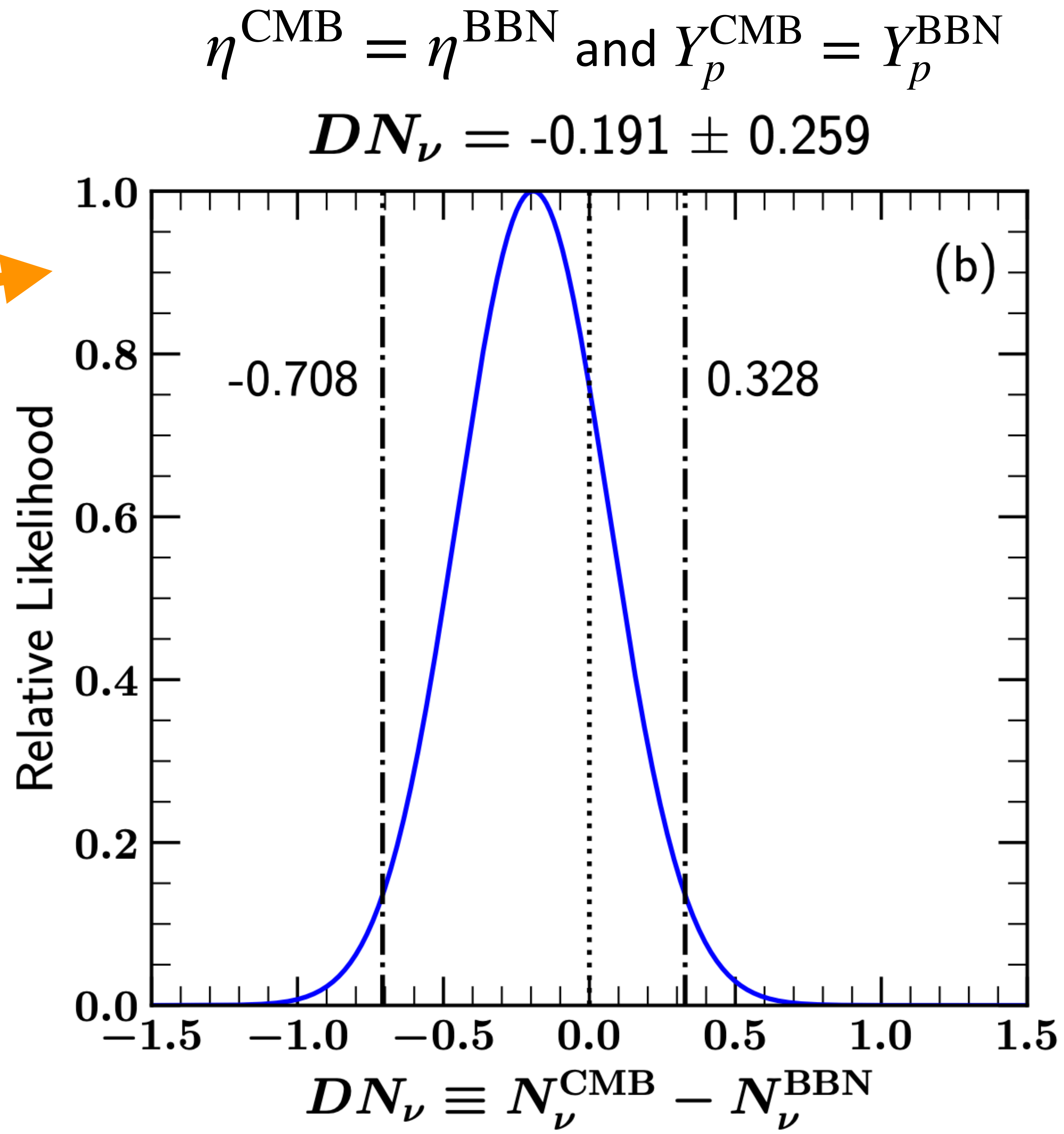
- If new physics does NOT change the baryon to photo ratio and helium mass fraction

  => $\eta^{\rm CMB} = \eta^{\rm BBN}$ ($D\eta = 0$ slice) and $Y_p^{\rm CMB} = Y_p^{\rm BBN}$

- improving $DN_\nu$ uncertainty,

  $-0.708 < DN_\nu < 0.328$ $(2\sigma)$

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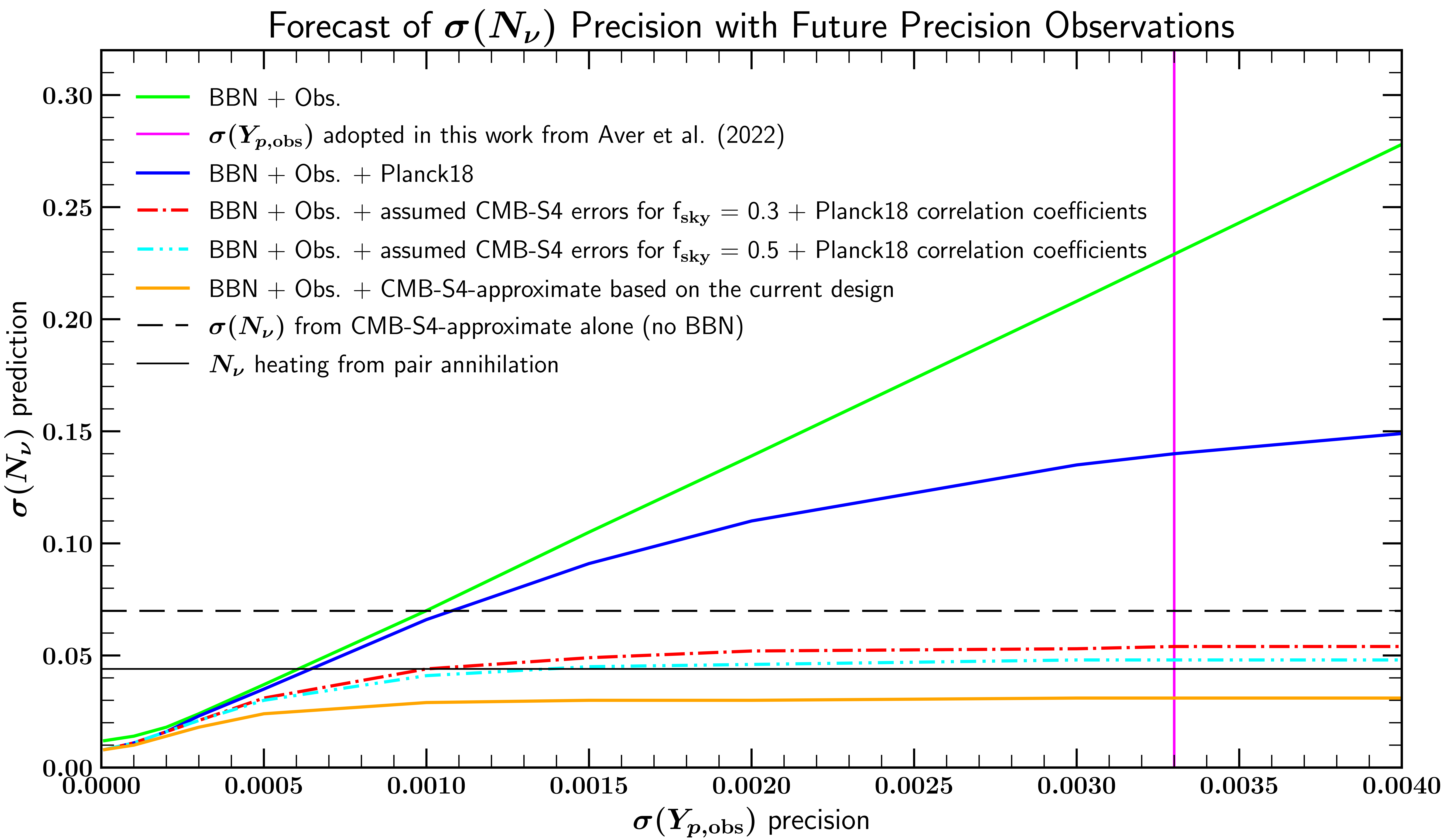
# The Expected Impact of Future Precision Observations



- $\sigma(N_\nu) \sim 0.07$ is expected from future CMB-S4 experiment
- To catch up, BBN needs $\sigma(Y_{p,\mathrm{obs}}) \sim 0.001$
- promising to probe the neutrino heating effect in SM with BBN+CMB-S4

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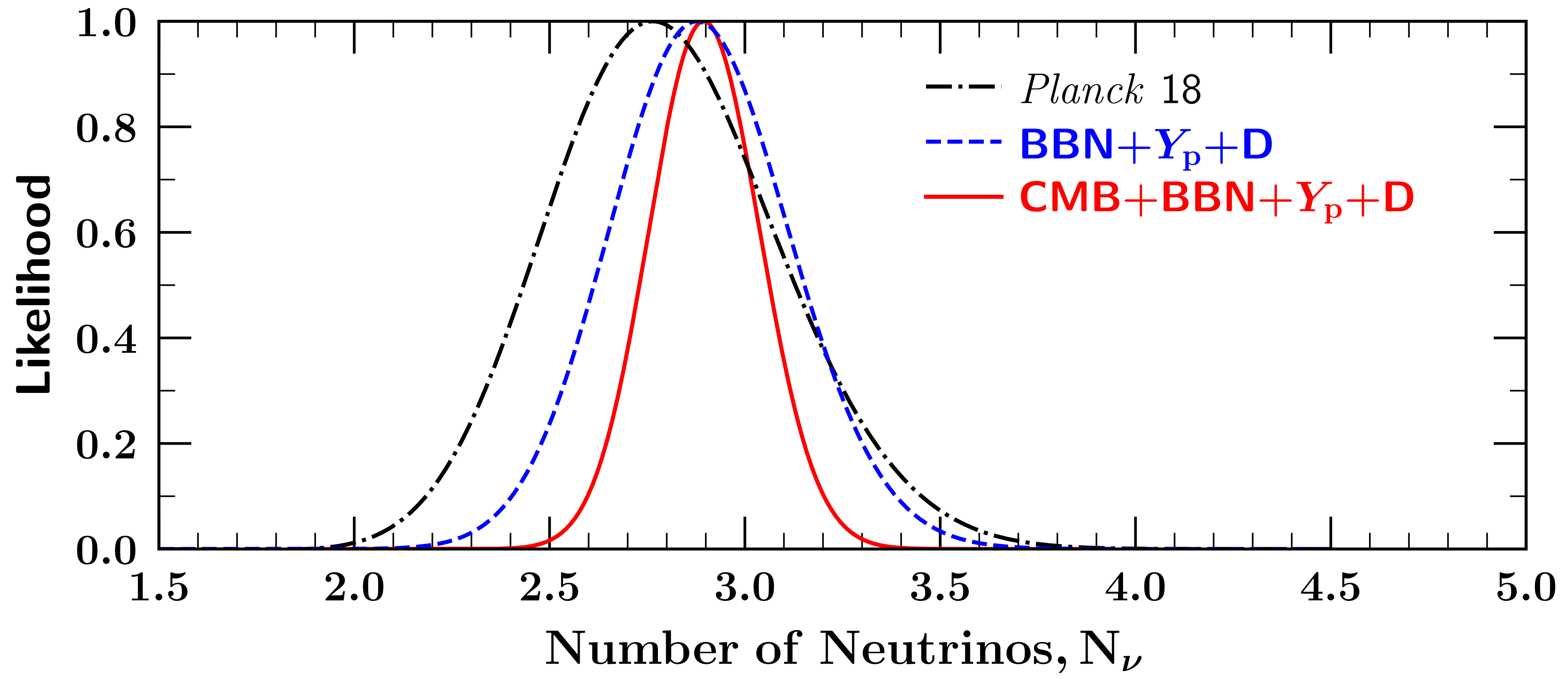
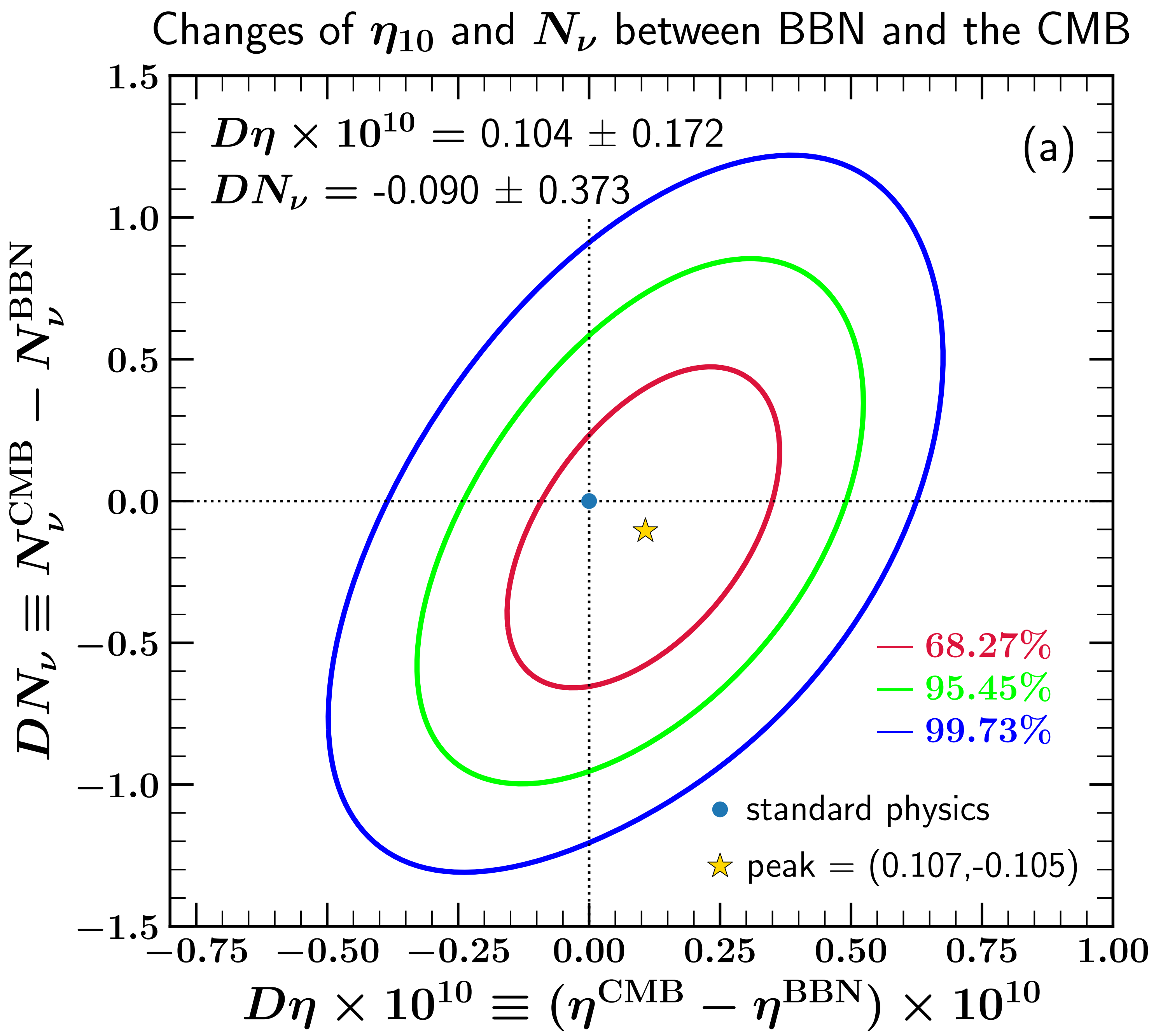
# Summary

- precise nuclear inputs make BBN a reliable and powerful probe to the early universe physics
- given latest nuclear rates and astro observations, SBBN baryon determination agrees the baryon density from Planck 2018 within %-level uncertainties
- Even if $N_\nu \neq 3$, BBN and CMB neutrino numbers are still consistent with $N_\nu^{\mathrm{SM}} = 3$ within uncertainties. Joint BBN+CMB analysis gives $N_\nu = 2.898 \pm 0.141$
- improved BBN and CMB constraints make it possible to probe changes in $\eta$ and/or $N_\nu$ between the two epochs
- future precision observations will sharpen these limits and reveal clues to how cosmic relativistic content evolves

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# Thank you
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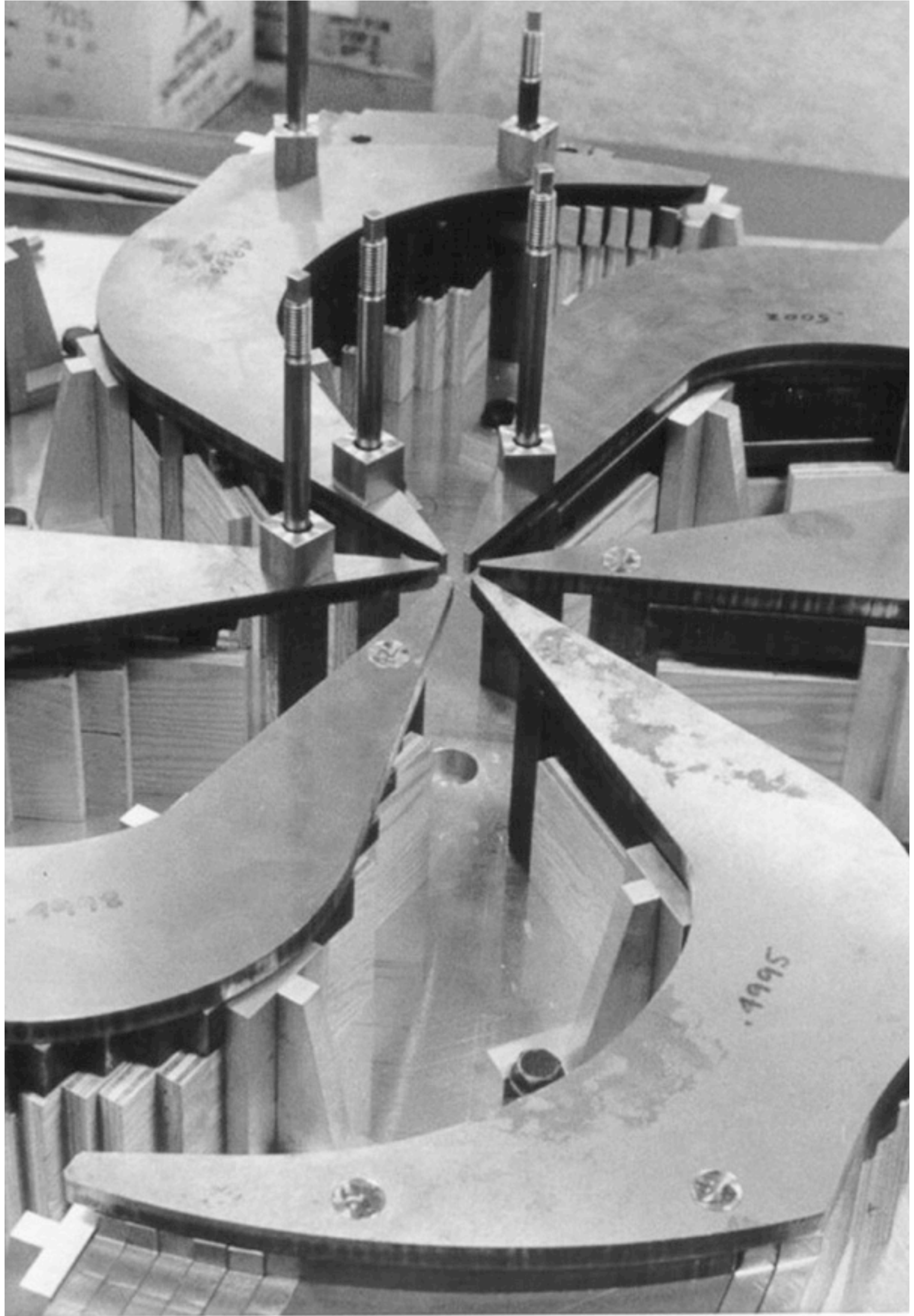


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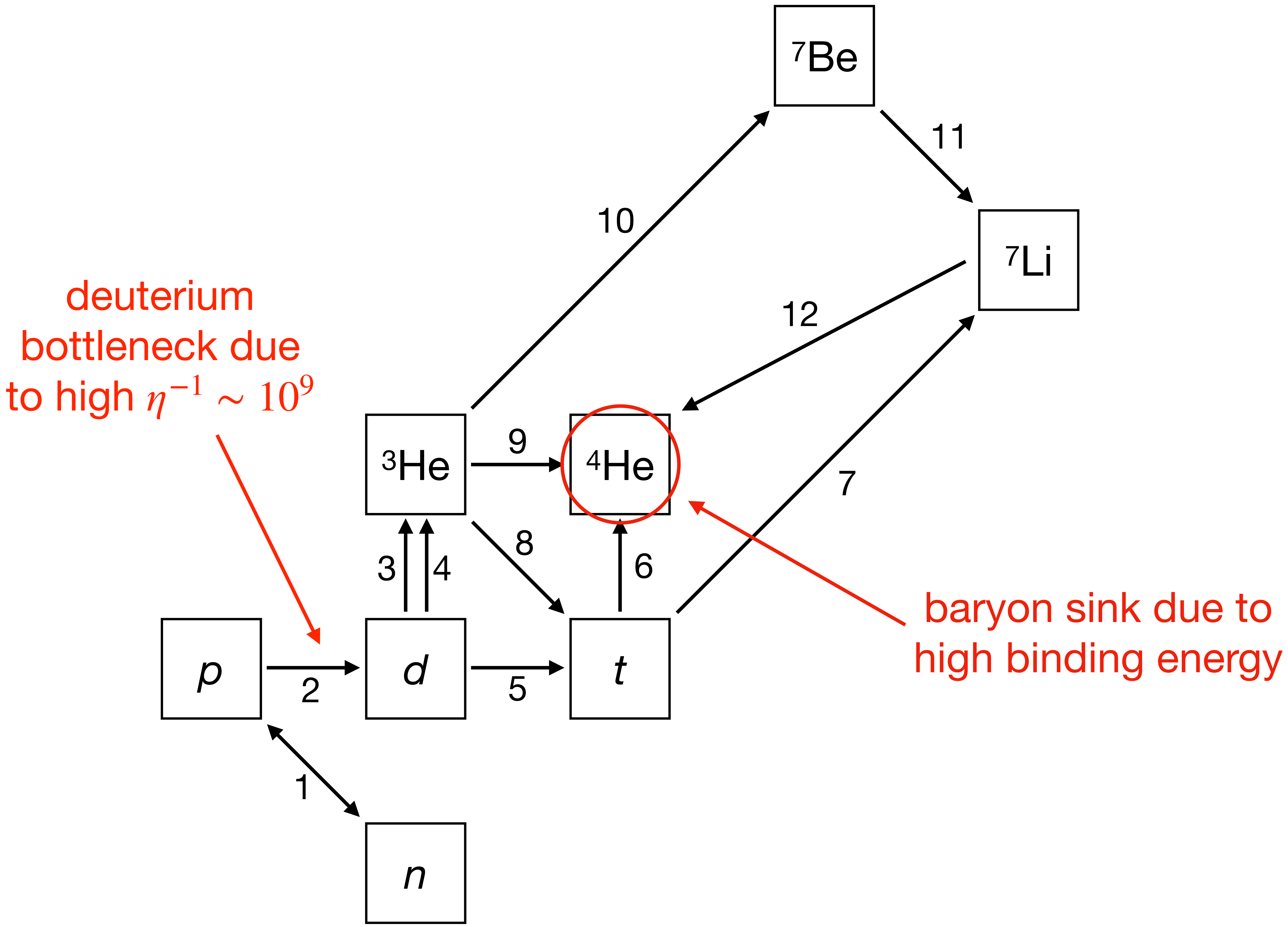
# backup slides

# SBBN Core Network of 12 Dominant reactions



| | Q (MeV) |
|---|---|
| **1.** $n \leftrightarrow p$ | 0.782 |
| **2.** $p(n,\gamma)d$ | 2.225 |
| **3.** $d(p,\gamma)^3\mathrm{He}$ | 5.493 |
| **4.** $d(d,n)^3\mathrm{He}$ | 3.269 |
| **5.** $d(d,p)t$ | 4.033 |
| **6.** $t(d,n)^4\mathrm{He}$ | 17.589 |
| **7.** $t(\alpha,\gamma)^7\mathrm{Li}$ | 2.467 |
| **8.** $^3\mathrm{He}(n,p)t$ | 0.764 |
| **9.** $^3\mathrm{He}(d,p)^4\mathrm{He}$ | 18.353 |
| **10.** $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ | 1.586 |
| **11.** $^7\mathrm{Be}(n,p)^7\mathrm{Li}$ | 1.644 |
| **12.** $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ | 17.347 |



# SBBN Abundance History



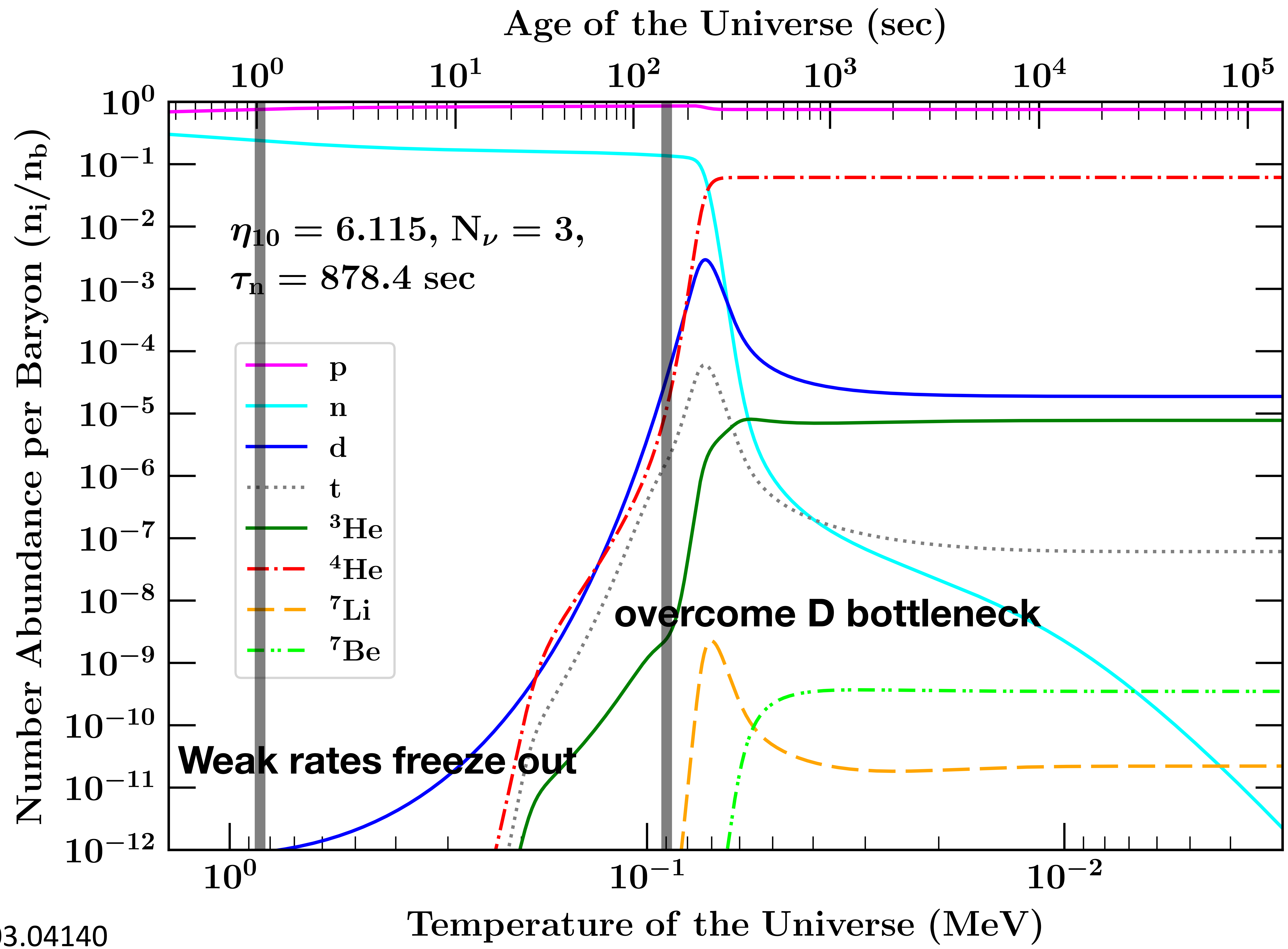
- time-temperature relation:

$$t_{sec} \sim T_{MeV}^{-2}$$

- BBN lasts from

  ~1 MeV to ~30 keV

  i.e. ~1 to ~1000 sec




**Yeh,** Olive, & Fields (2023) arXiv: 2303.04140