Can sterile neutrinos explain the VHE photons from GRB221009A?

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What is and why the GRB221009A

- An unprecedented bright gamma-ray burst was observed by BAT on Swift satellite, and later confirmed by Fermi-GBM as GRB. The generated very high energy photons have been captured by LHAASO.

- In particular, the KM2A detector on LHAASO has reported an observation of ~ 5000 very high energy photons, with E_γ up to $18\ \mathrm{TeV}$, in a ~ 2000 s time window.

- High energy photon would inevitably scatter with extragalactic background photon, i.e. $\gamma + \gamma_{\mathrm{EBL}} \to e^+ + e^-$, on their propagation. For instance, $P \simeq 10^{-7}$ for the $18\ \mathrm{TeV}$ photon traveling from $z \simeq 0.15$ to Earth.

Ways to explain the GRB221009A

- Dark photons
  M. M. Gonzalez, D. A. Rojas, A. Pratts and et al, Astrophys. J. 944, 178 (2023)

- Axion-like particles
  W. Lin and T. T. Yanagida, arXiv:2210.08841.
  S. Nakagawa, F. Takahashi, M. Yamada, and W. Yin, Phys. Lett. B 839, 137824 (2023).
  G. Zhang and B.-Q. Ma, Chin. Phys. Lett. 40, 011401 (2023).
  L. Wang and B.-Q. Ma, arXiv:2304.01819.
  ……

- Invisible neutrino decay
  J. Huang, Y. Wang, B. Yu, and S. Zhou, J. Cosmol. Astropart. Phys. 04 (2023) 056.

- Light scalar decay
  S. Balaji, M. E. Ramirez-Quezada, J. Silk, and Y. Zhang, Phys. Rev. D 107, 083038 (2023).

- Lorentz invariance violation
  A. Baktash, D. Horns, and M. Meyer, arXiv:2210.07172.
  H. Li and B.-Q. Ma, Eur. Phys. J. C 83, 192 (2023).
  V. Vardanyan, V. Takhistov, M. Ata, and K. Murase, arXiv:2212.02436.

The sterile neutrino scenario

- The SM active neutrinos are associated produced with photons in the GRB.

- $\nu_\alpha \to N$ arises through mixing $U_{\alpha 4}$, if there exist sterile partner of SM neutrino; sterile neutrino propagates until it decays:

$N \to 3\nu$

$N \to \nu\gamma$

$$\Gamma_N^{(3,U_{\mu 4})} \approx \frac{G_F^2 m_N^5}{64\pi^3} |U_{\mu 4}|^2 ,$$

$$\Gamma_N^{(2,U_{\mu 4})} \approx \frac{9\alpha G_F^2 m_N^5}{512\pi^4} |U_{\mu 4}|^2 ,$$

$$\Gamma_N^{(2,d_\mu)} \approx \frac{|d_\mu|^2 m_N^3}{4\pi} .$$

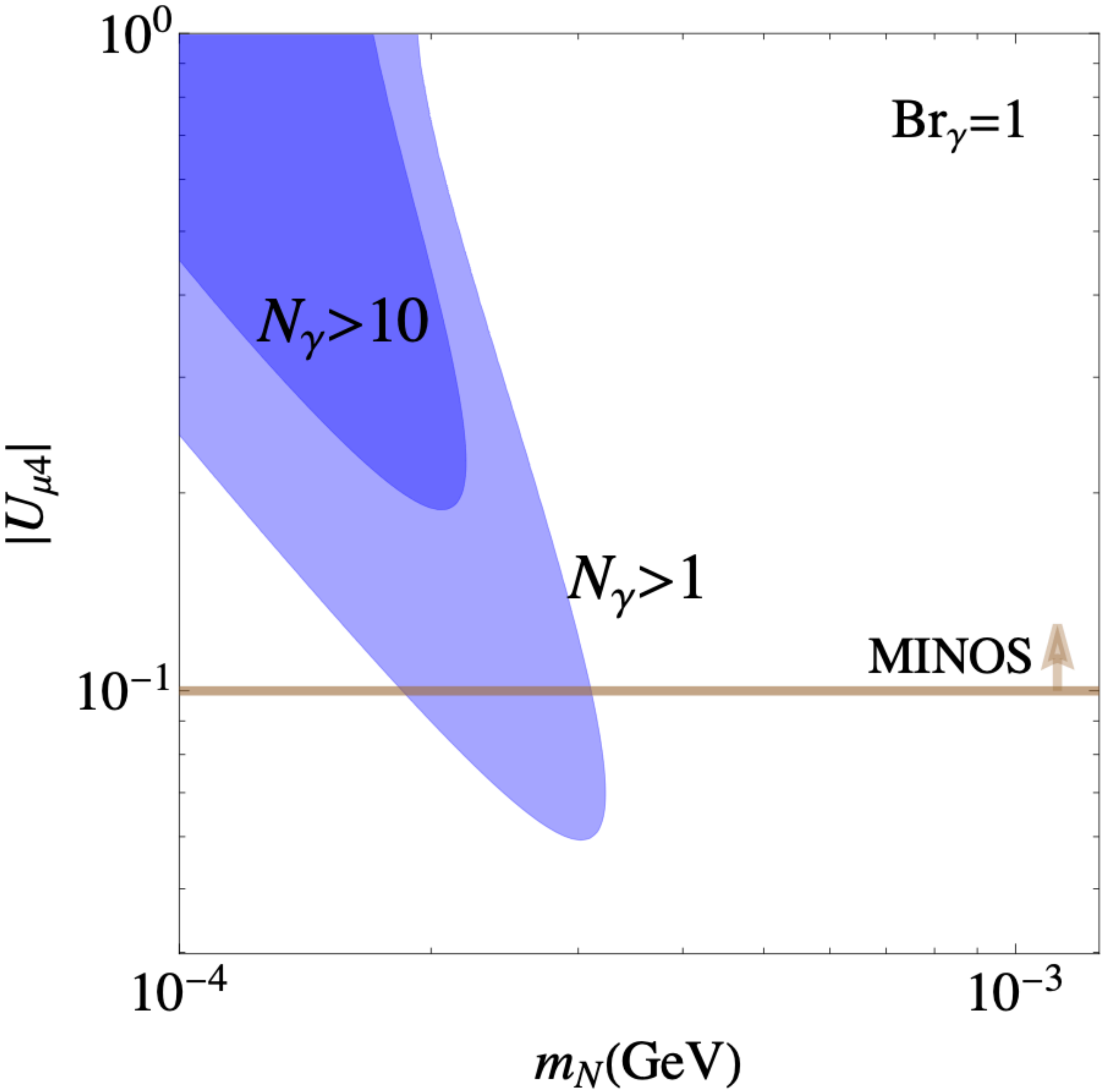
Mixing: $U_{\mu 4}$

Dipole: $d_\mu \overline{\nu_{\mu L}} \sigma_{\beta\gamma} F^{\beta\gamma} N$

- Two choices: mixing(production)+mixing/dipole(decay)

mixing+mixing: not viable

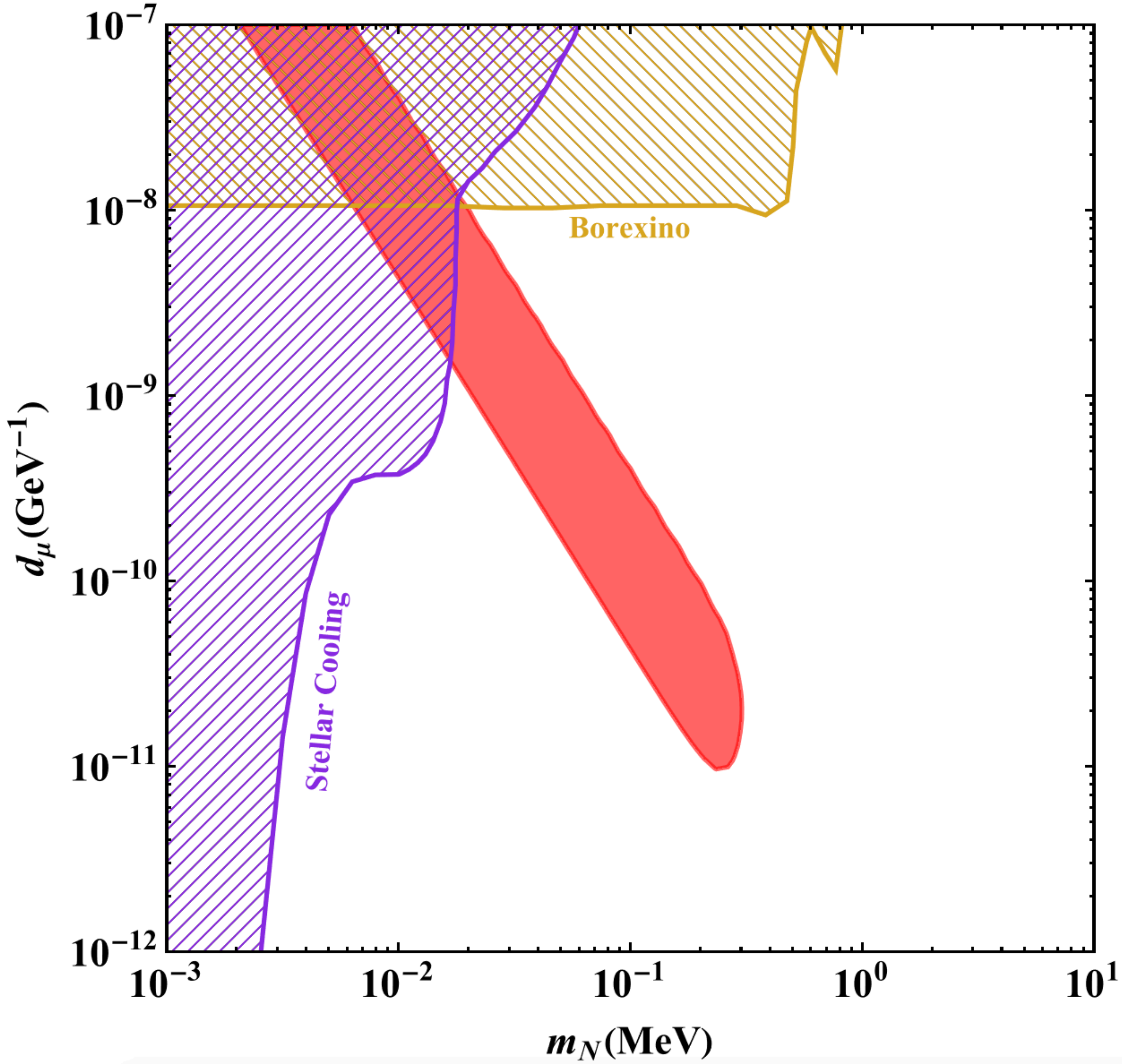
V. Brdar and Y.-Y. Li, Phys. Lett. B 839, 137763 (2023).



- Overoptimistic $\mathrm{Br}_\gamma = 1$, actually at $\mathcal{O}(10^{-3})$.
- Oscillation constraint from MINOS gives $|U_{\mu 4}| < 0.1$.

$$\frac{dN_{\nu_\mu}}{dE} |U_{\mu 4}|^2 \mathrm{Br}_\gamma \frac{\mathrm{d}/\tau}{\gamma/\Gamma - \mathrm{d}/\tau} \left(\exp\left[-\frac{\mathrm{d}\Gamma}{\gamma} \right] - \exp(-\tau) \right)$$ (Observed photon flux)

mixing+dipole



- $\mathrm{Br}_\gamma \approx 1$ achievable.
- Red shaded region indicates $N_\gamma > 1$ on LHAASO for $|U_{\mu 4}| = 0.1$.
- Survived after imposing dipole constraints from νe scattering and stellar cooling.

$$\frac{dN_{\nu_\mu}}{dE} |U_{\mu 4}|^2 \mathrm{Br}_\gamma \frac{\mathrm{d}/\tau}{\gamma/\Gamma - \mathrm{d}/\tau} \left(\exp\left[-\frac{\mathrm{d}\Gamma}{\gamma}\right] - \exp(-\tau) \right)$$

(Observed photon flux)

Constraints from cosmology

- The sterile neutrino may contribute to $N_{\rm eff}$:

$$\rho_R = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{T_\nu^0}{T_\gamma}\right)^4 N_{\rm eff}\right]$$

the energy density of neutrino plasma:

$$\rho_{\nu:N} = \rho_\gamma \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 \left[N_\nu + \frac{g_N}{2} I(y_N)\right].$$

$I \to 1(0)$ for $m_N/T_\nu \to 0(\infty)$

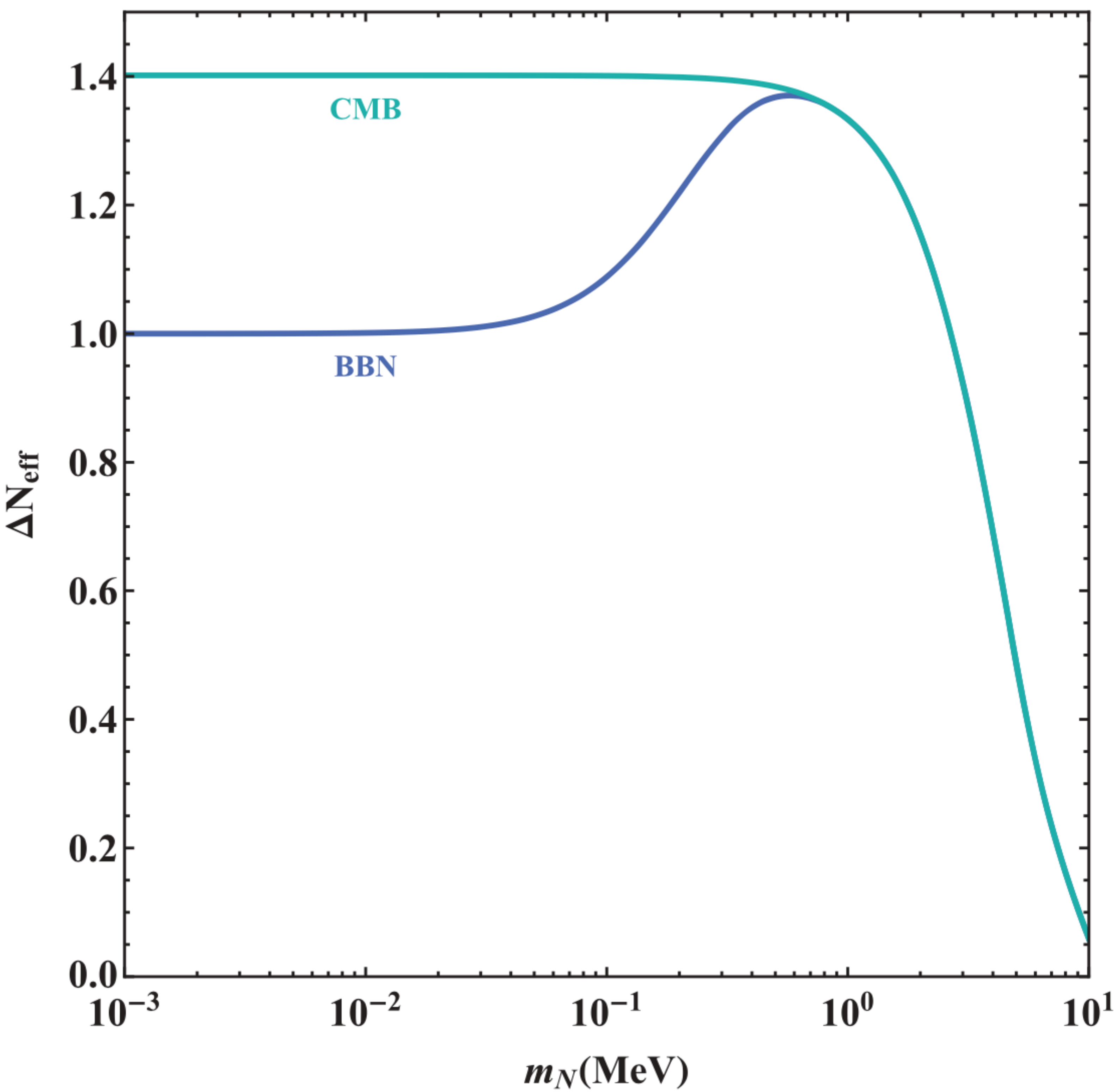
Constraints from cosmology

- Temperature ratio between the neutrino plasma and EM plasma:

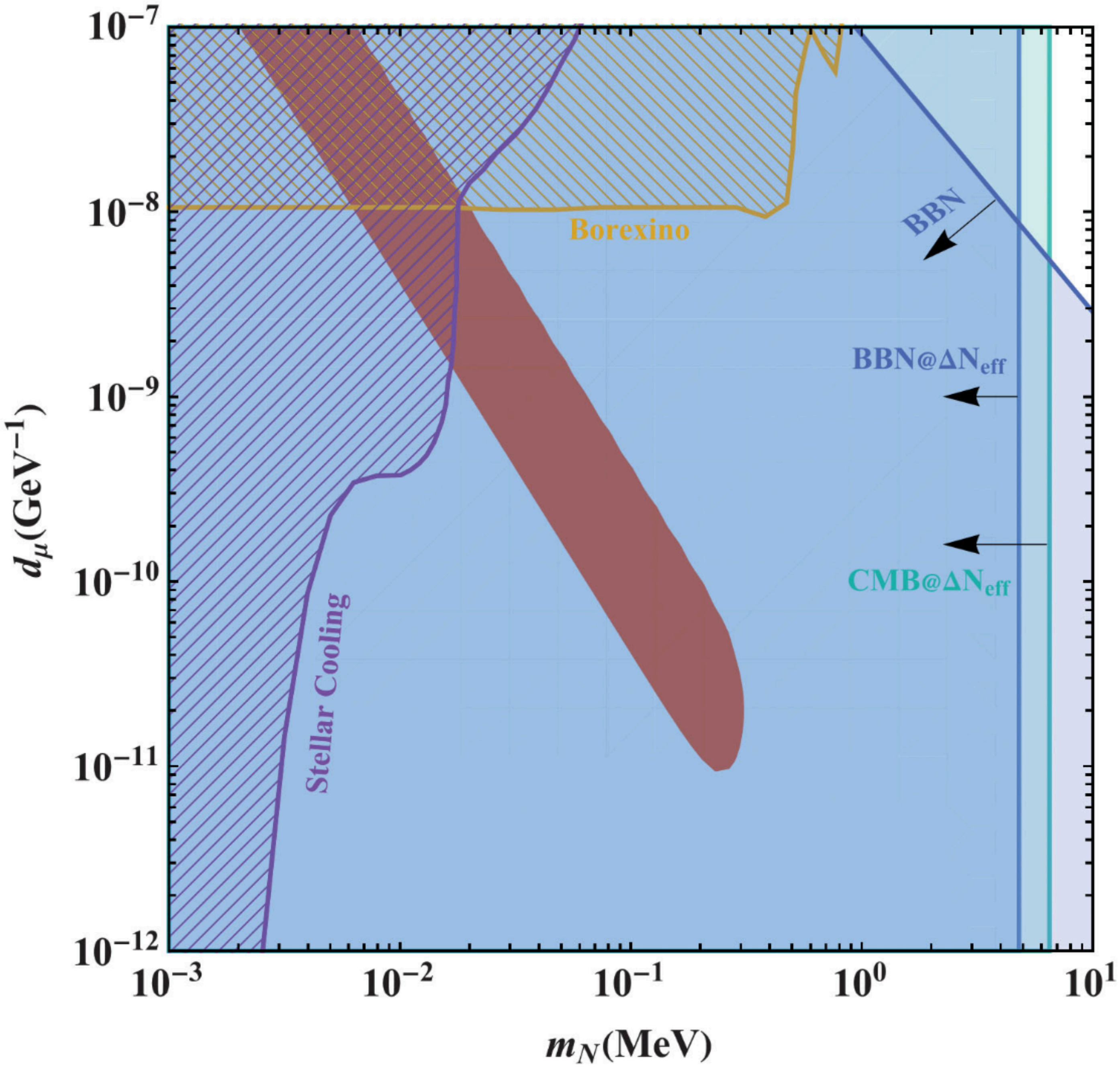
$$\frac{T_\nu}{T_\gamma} = \left(\frac{g_{\star s:\nu}}{g_{\star s:\gamma}}\bigg|_{T_{\rm D}} \frac{g_{\star s:\gamma}}{g_{\star s:\nu}} \right)^{1/3} = \left(\frac{T_\nu^0}{T_\gamma}\right) \left(\frac{g_{\star s:\nu}|_{T_{\rm D}}}{g_{\star s:\nu}} \right)^{1/3}$$

  if sterile neutrinos become non-relativistic after the neutrino plasma decoupling, d.o.f. would decrease, results in larger temperature ratio, similar to the reheating of $e^\pm$ to photon, finally arrive at a larger $N_{\rm eff}$.

Constraints from cosmology



mixing+dipole: not viable



- $\Delta N_{\rm eff} < 0.5(0.28)$ at BBN(CMB), translate into constraints on m_N.
- Additional BBN bound to avoid significant impact on the abundance of light elements.
- Cosmology constraints have excluded all the survived region!

What we've learned

- The LHAASO's observation of very high energy photons from gamma-ray bursts presents a perplexing puzzle. The interaction of these photons with extragalactic background photons makes their appearance on Earth seemingly implausible. To unravel this enigma, we must delve into the realm of new physics and seek a fresh perspective that can offer a plausible explanation.

- The sterile neutrino scenario has been proved unsuitable as a viable explanation. The mixing+mixing case has already been ruled out by oscillation studies. As for the mixing+dipole case, although LHAASO favors a lighter neutrino, it would inevitably leave detectable signatures in cosmological observations. Our analysis, considering constraints from BBN and CMB data, has effectively eliminated the mixing+dipole scenario. Consequently, the sterile neutrino hypothesis does not stand as a feasible explanation for the LHAASO observation.