Imprint of inflationary gravitational waves and WIMP dark matter in pulsar timing array data

SUSY 2024

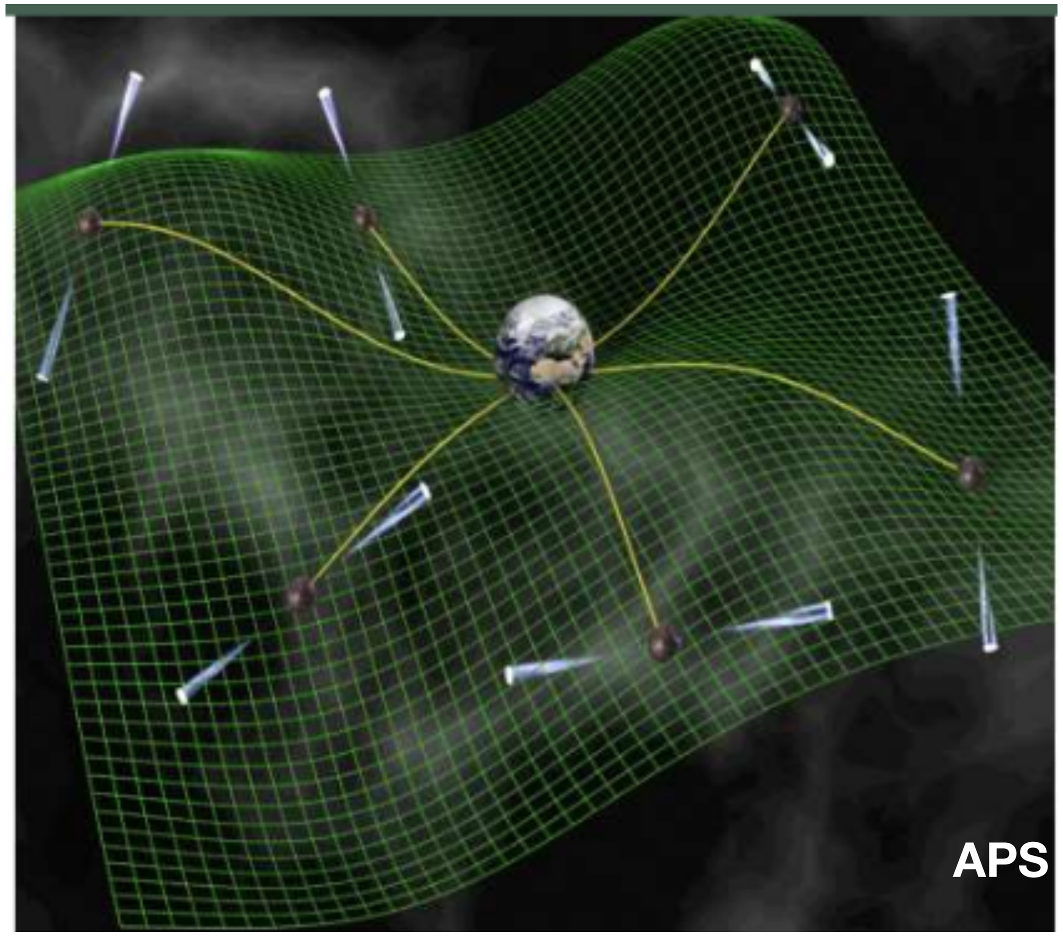
Theory meets Experiment

Suruj Jyoti Das

Institute for Basic Science

Based on: PRD (2022), JCAP(2024)

Collaborators: D. Borah, A.K. Saha, R. Samanta



The era of gravitational wave astronomy…….

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The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background

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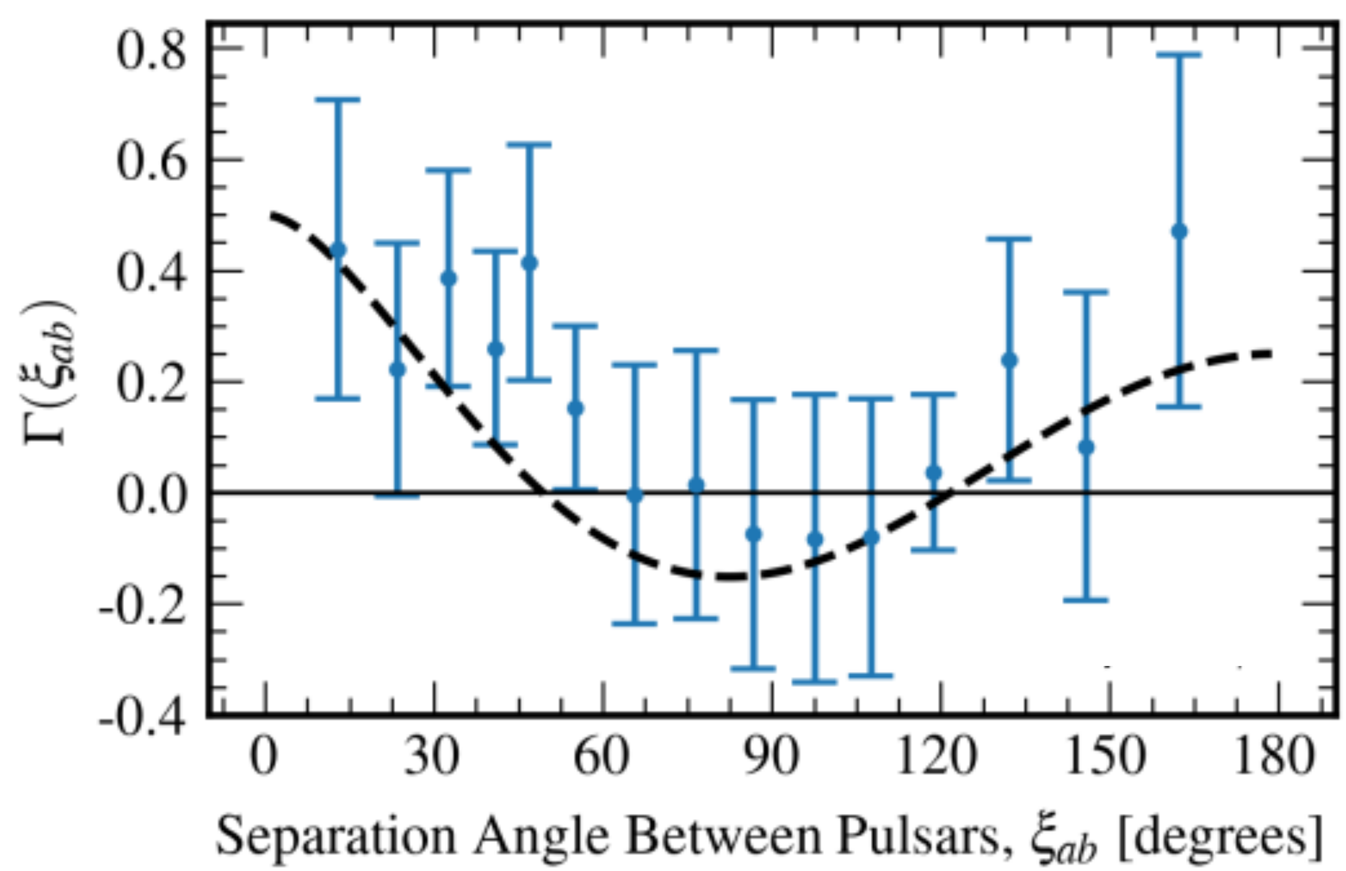

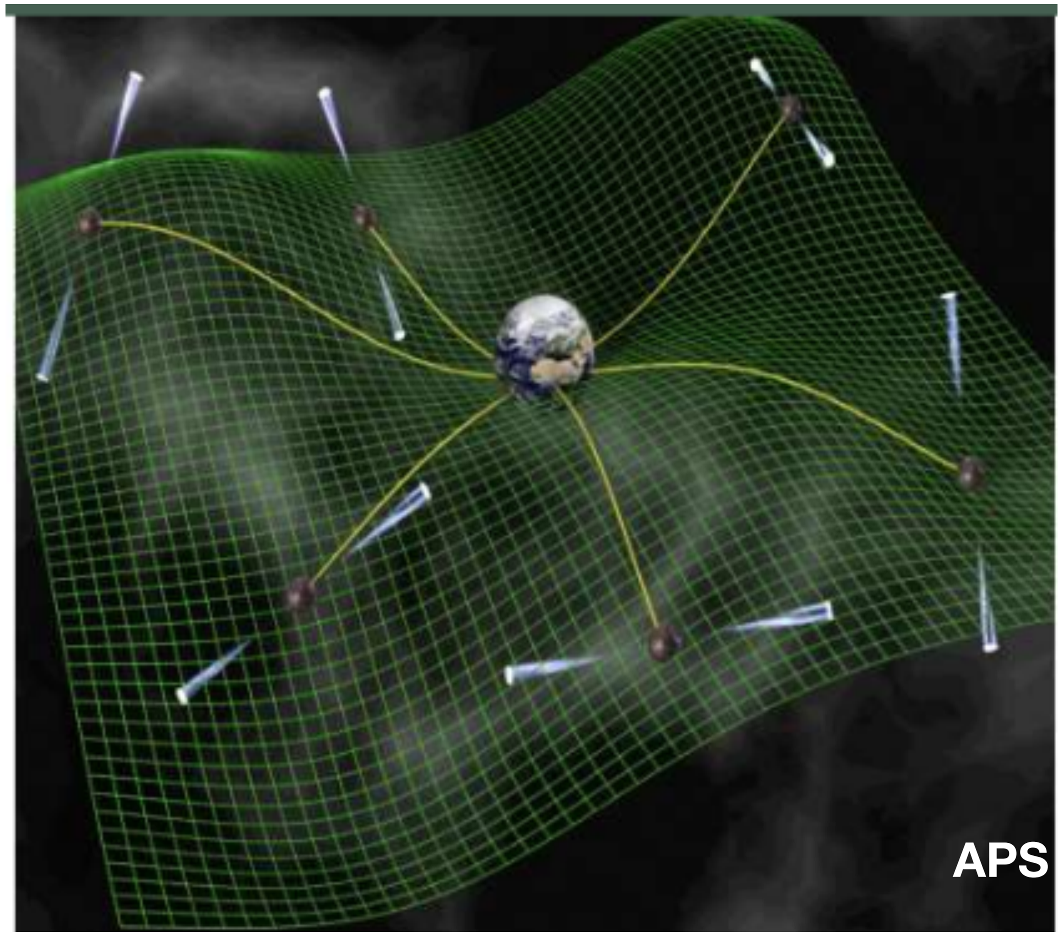

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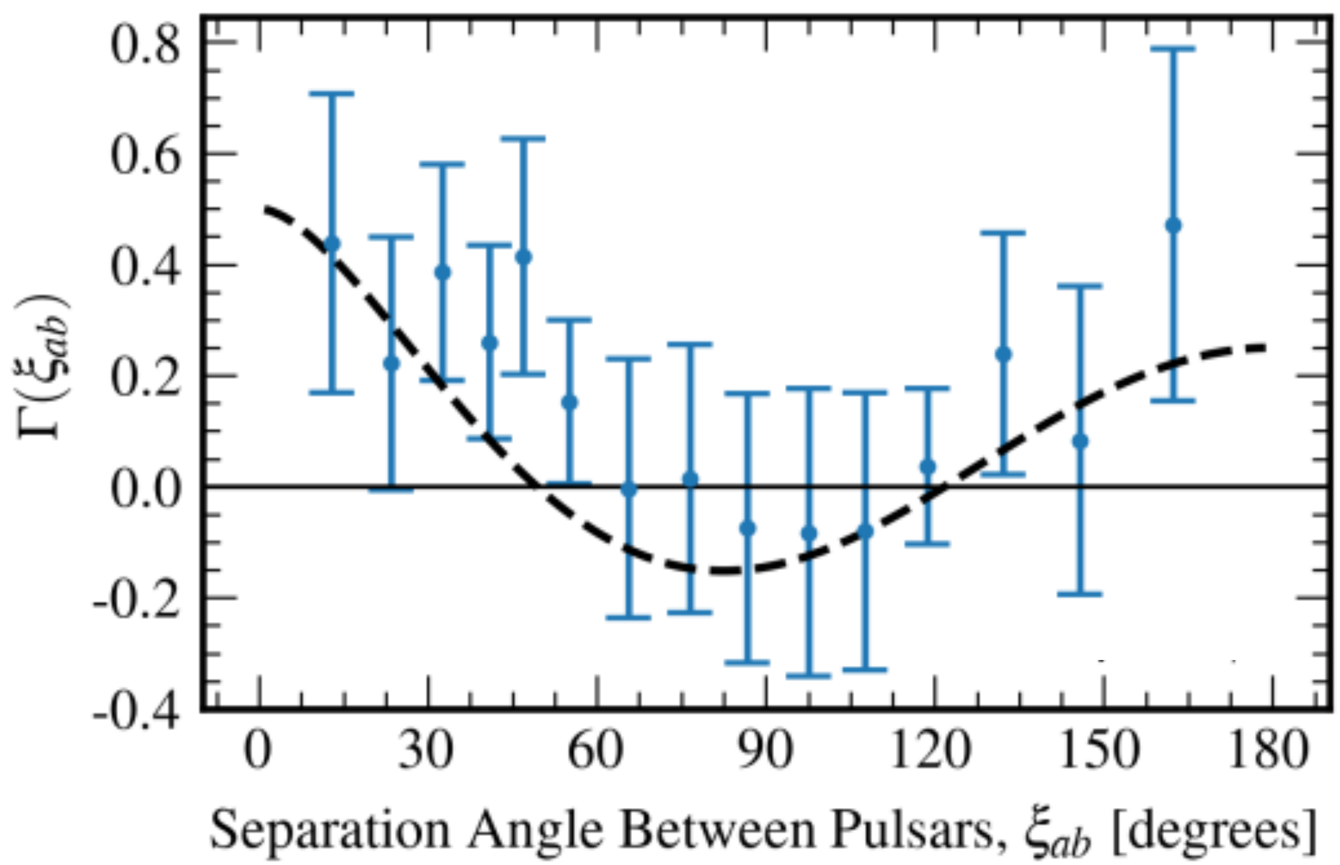
NANOGrav Physics Frontiers Center

EPTA

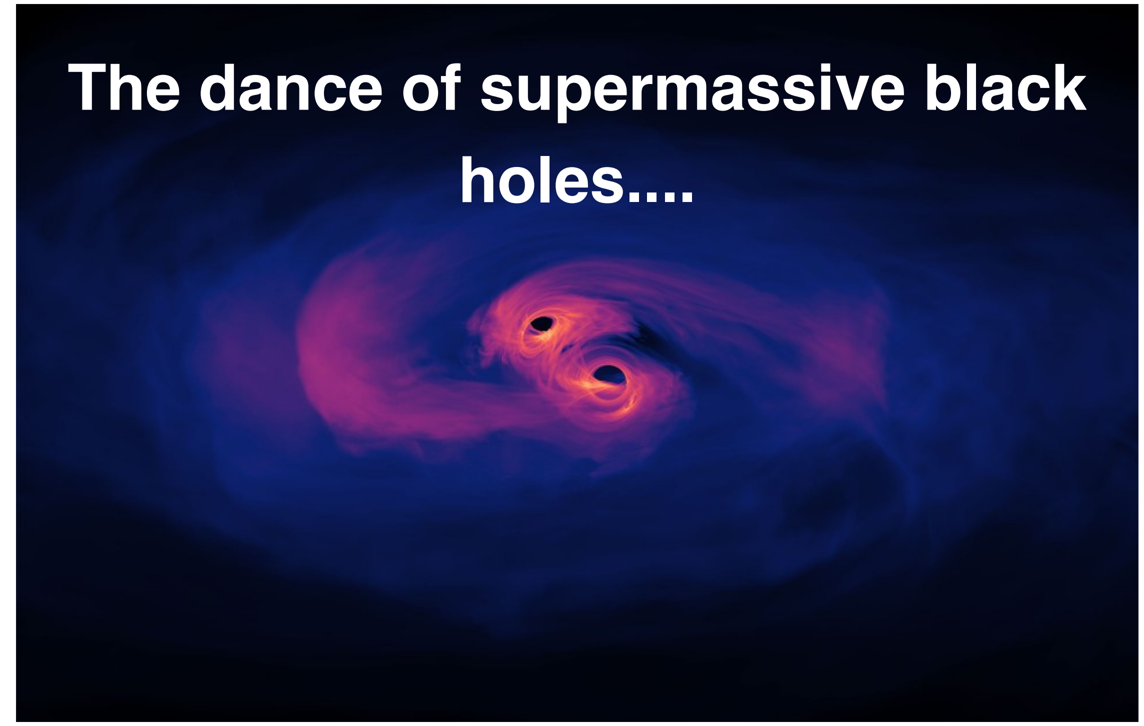
PPTA

InPTA Indian Pulsar Timing Array

Source?

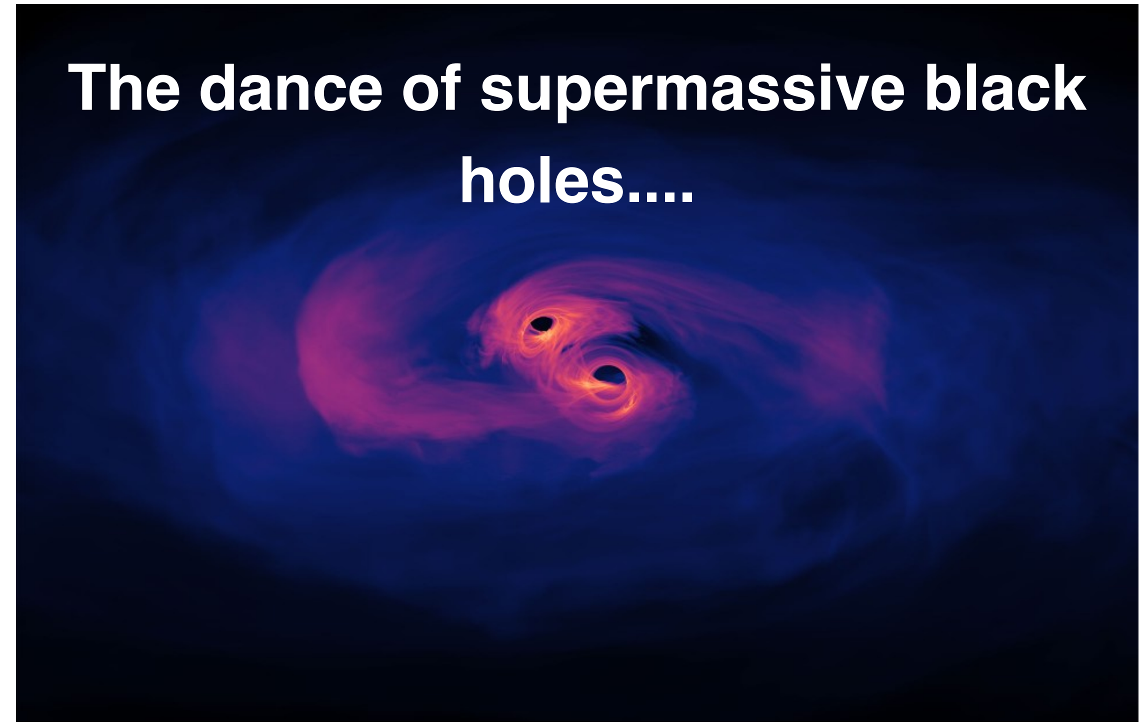


Astrophysical

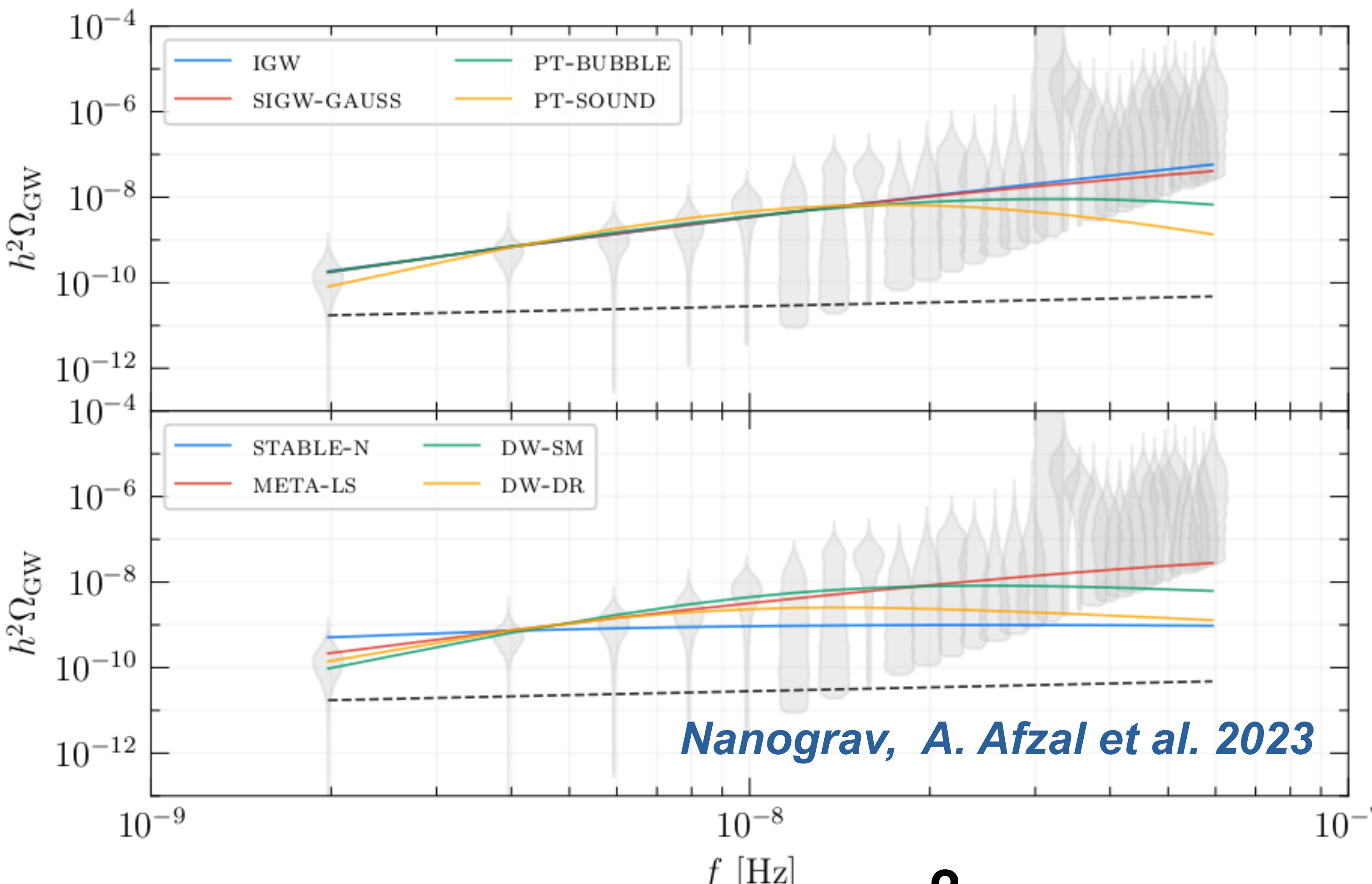


Astrophysical

Cosmological?



Several early Universe physics....



Can be strongly connected with Particle physics...

Gravitational waves from Inflation?

Sourced by tensor perturbations

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

Transfer function

$$P_T(k) = r A_s(k_*) \left(\frac{k}{k_*}\right)^{n_T} \qquad \Omega_{\rm GW}(k) = \frac{1}{12H_0^2}\left(\frac{k}{a_0}\right)^2 T_T^2(\tau_0, k) P_T(k)$$

Constrained from CMB

For single-field slow roll inflation models: $n_T = -r/8$

$$\Omega_{\rm GW} h^2 \sim 10^{-16}$$

(too faint and scale-invariant...)

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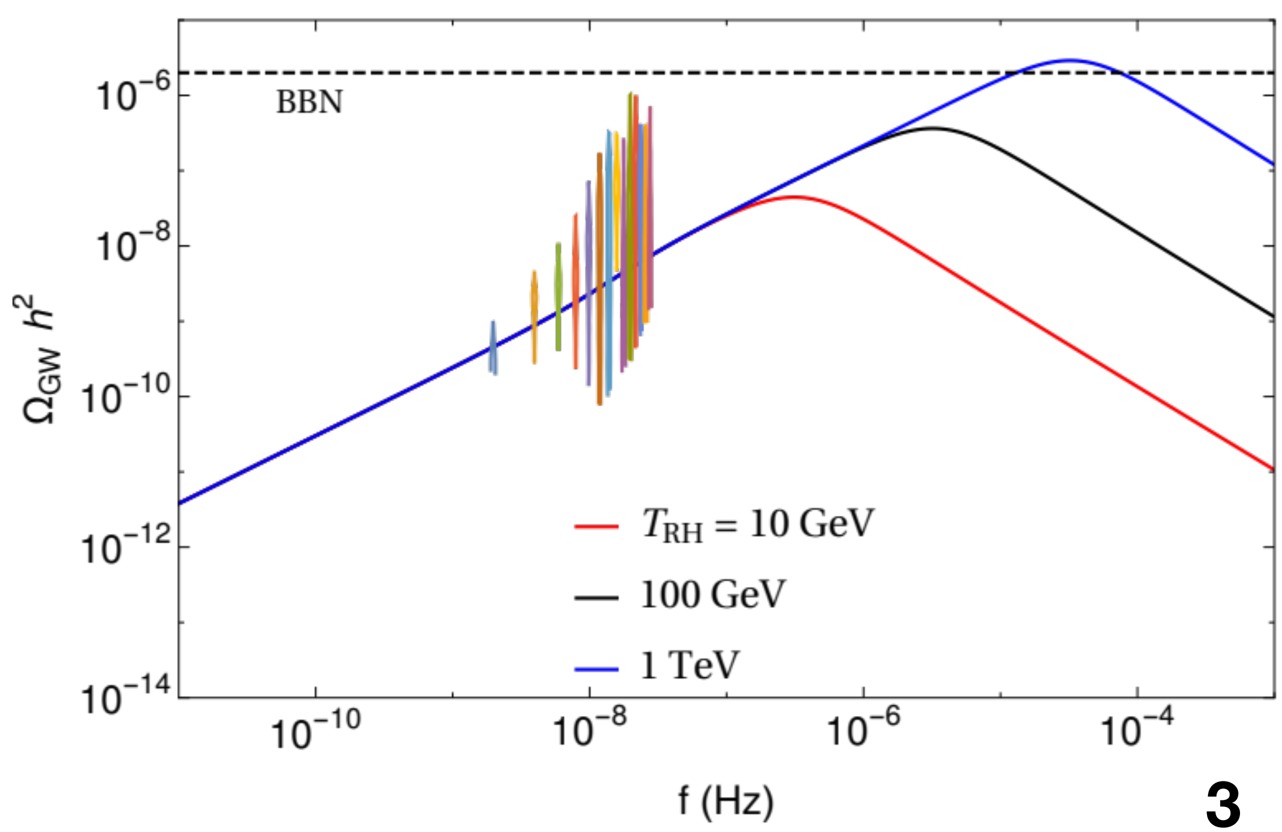
Blue-tilted spectra: $n_T > 0$



Violates BBN bound unless low reheat temperature !

$T_T^2(\tau_0, k)$ **?**

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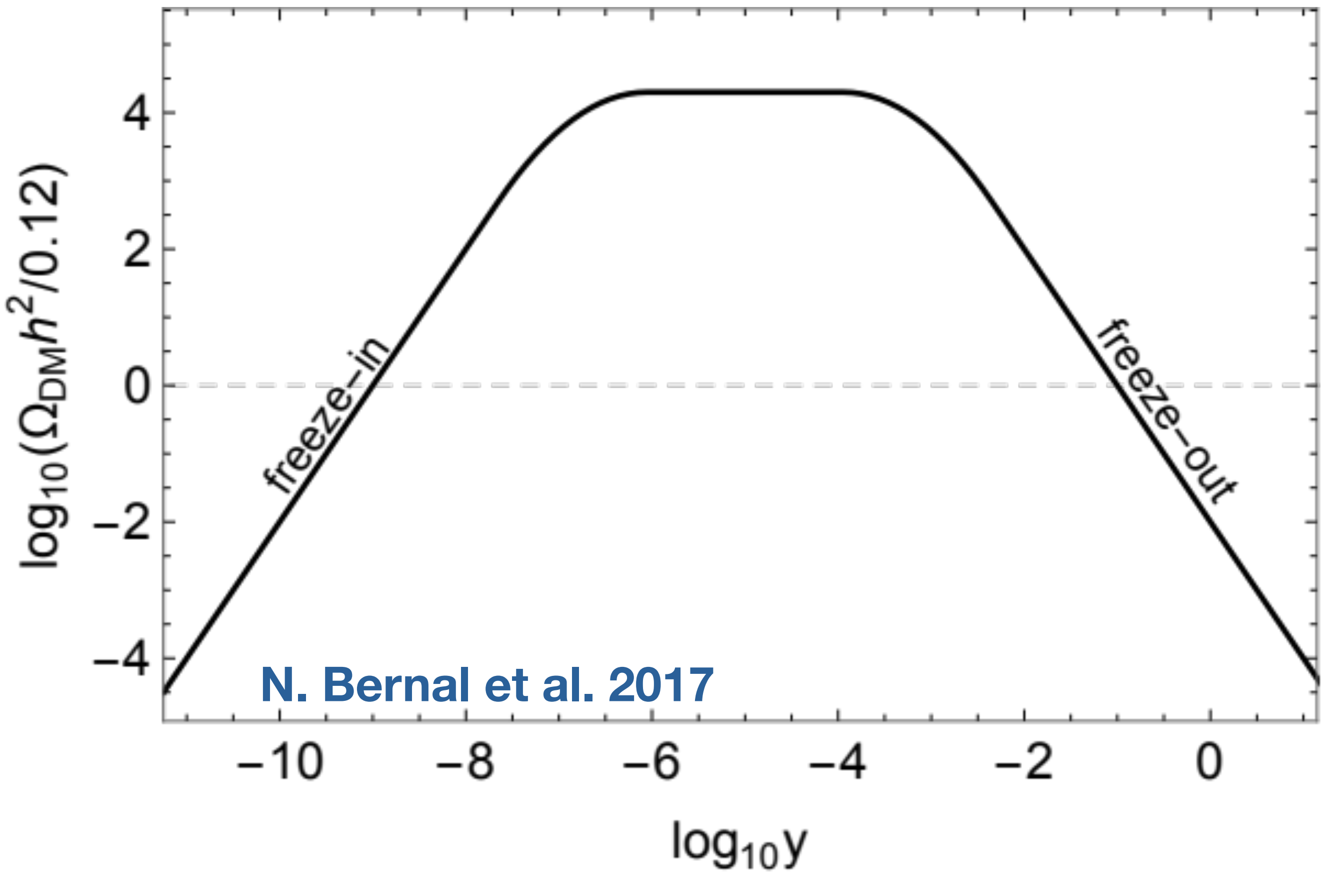
What if DM interaction between typical WIMP and FIMP?

Large enough to keep it in equilibrium, but small for the WIMP criteria.

motivated from null detection at DM experiments...



Miracle-less WIMP

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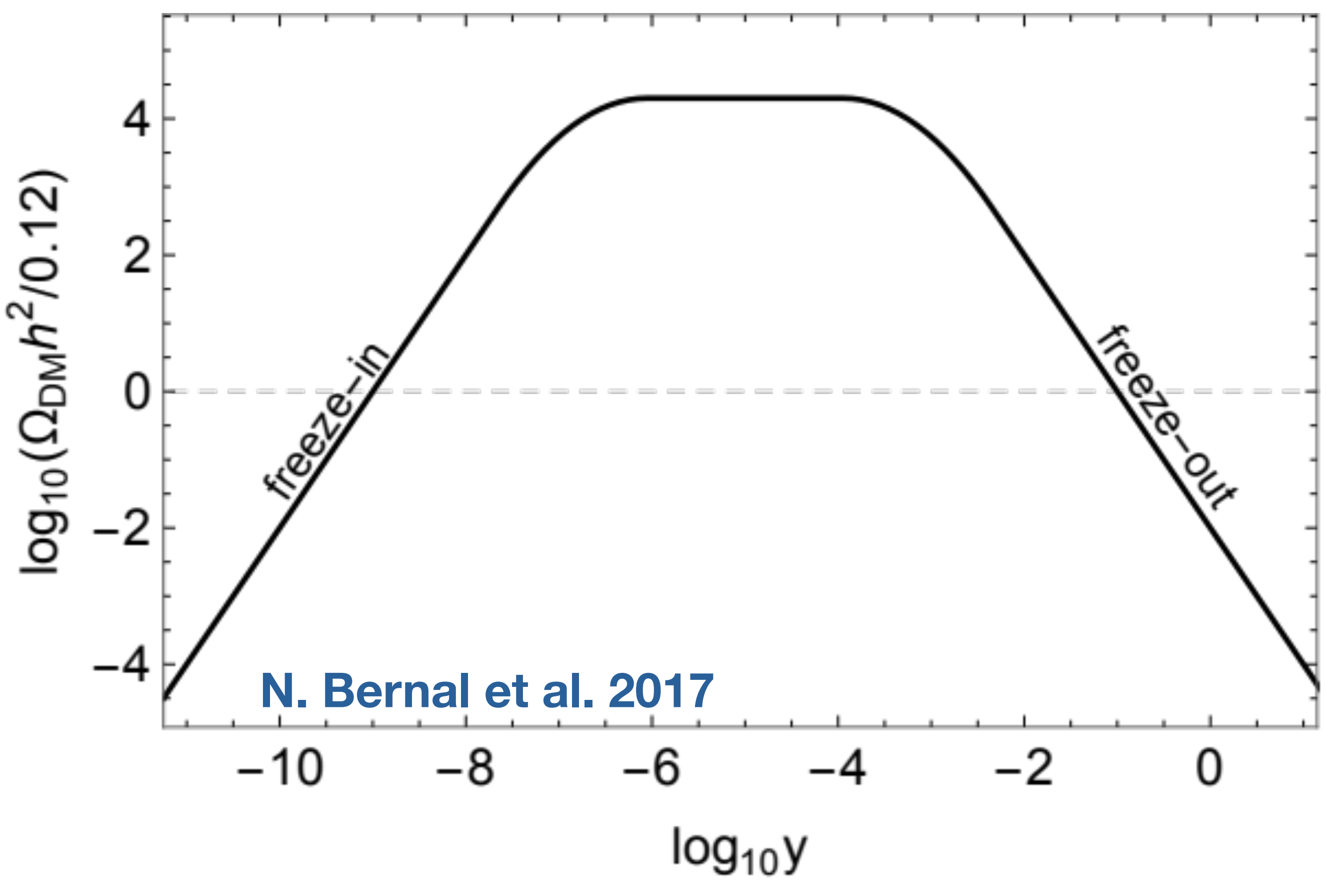

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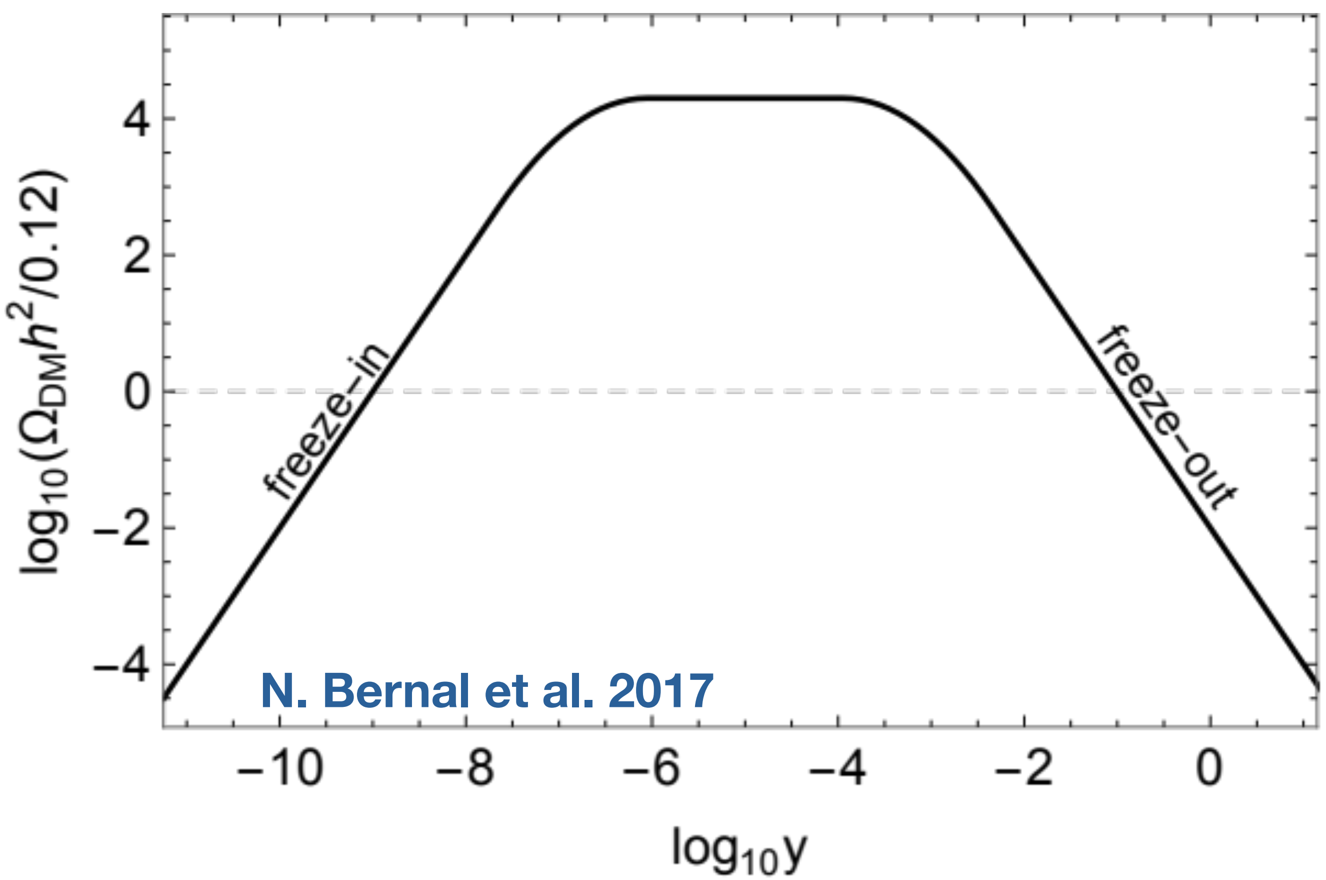
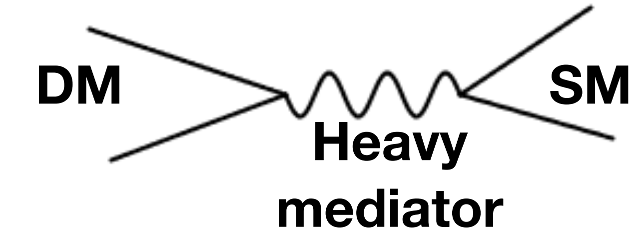


Miracle-less WIMP

Consequence: Thermally overproduced, some additional phenomena ?

Injection of entropy into the thermal bath...

How to realize?



Heavy gauge bosons from a high-scale symmetry breaking

The Framework

- Can be based on any Abelian extension of the SM.

BSM particles	$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
N_{R_1}	$(1, 1, 0, -1)$
N_{R_2}	$(1, 1, 0, -1)$
N_{R_3}	$(1, 1, 0, -1)$
Φ	$(1, 1, 0, 2)$
χ	$(1, 1, 0, q_\chi)$

EMD ← N_{R_1}

Leptogenesis Neutrino mass ← N_{R_2}, N_{R_3}

DM ← χ

$$\mathcal{L}_{\rm DM} = i\overline{\chi}\not{D}(q_\chi)\chi - m_\chi\overline{\chi}\chi.$$

$$\not{D}(q_\chi)\,\chi = \gamma^\mu\left(\partial_\mu + i g_{\rm BL}\, q_\chi\, Z_{{\rm BL}\mu}\right)\chi$$

Boltzmann equations :

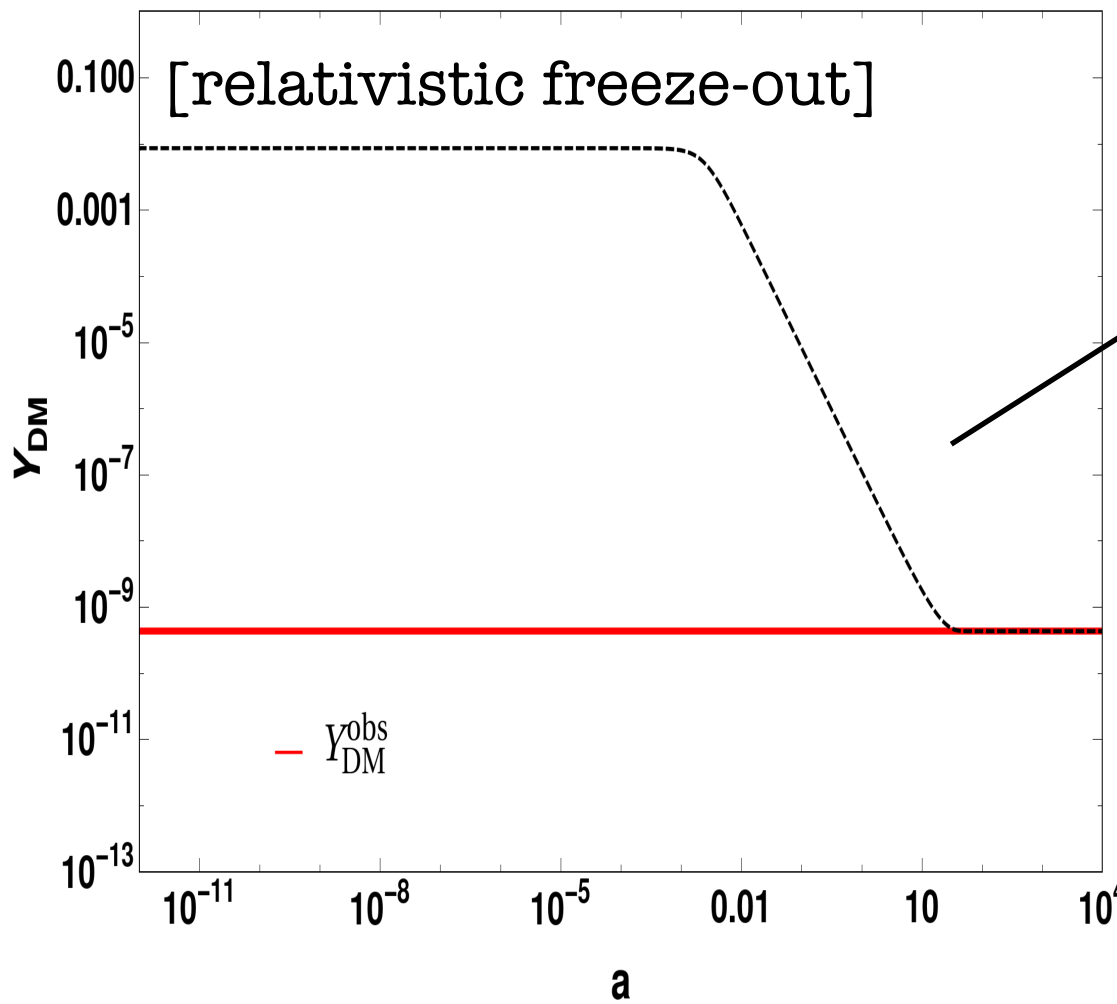
E = n a³

$$\frac{dE_\chi}{da} = \frac{\langle \sigma v \rangle_\chi}{H a^4} \left((E_\chi^{\rm eq})^2 - E_\chi^2 \right) , \quad (1)$$

$$\frac{dE_{N_1}}{da} = \frac{\langle \sigma v \rangle_{N_1}}{H a^4} \left((E_{N_1}^{\rm eq})^2 - E_{N_1}^2 \right) - \frac{\Gamma_{N_1}}{H a} E_{N_1} , \quad (2)$$

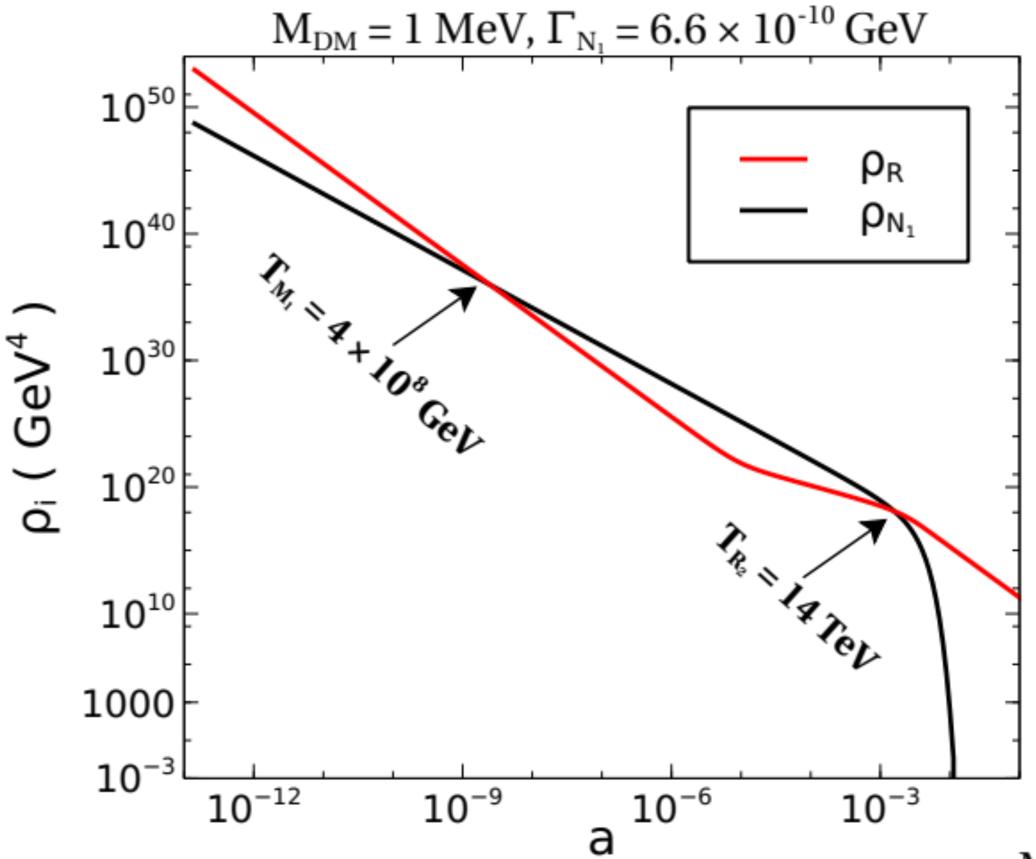
$$\frac{dT}{da} = \left(1 + \frac{T}{3 g_{*s}} \frac{d g_{*s}}{dT} \right)^{-1} \left[- \frac{T}{a} + \frac{\Gamma_{N_1} M_{N_1}}{3 H \ s \ a^4} E_{N_1} \right] . \quad (3)$$

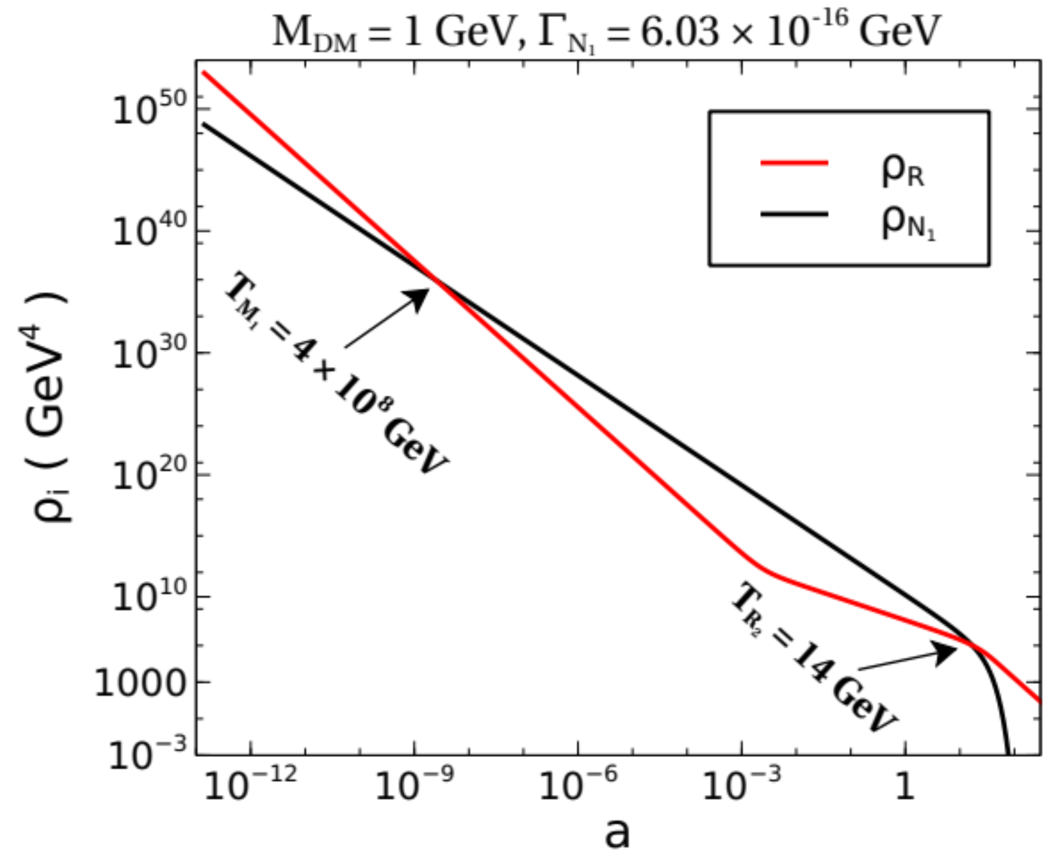
Evolution of DM:

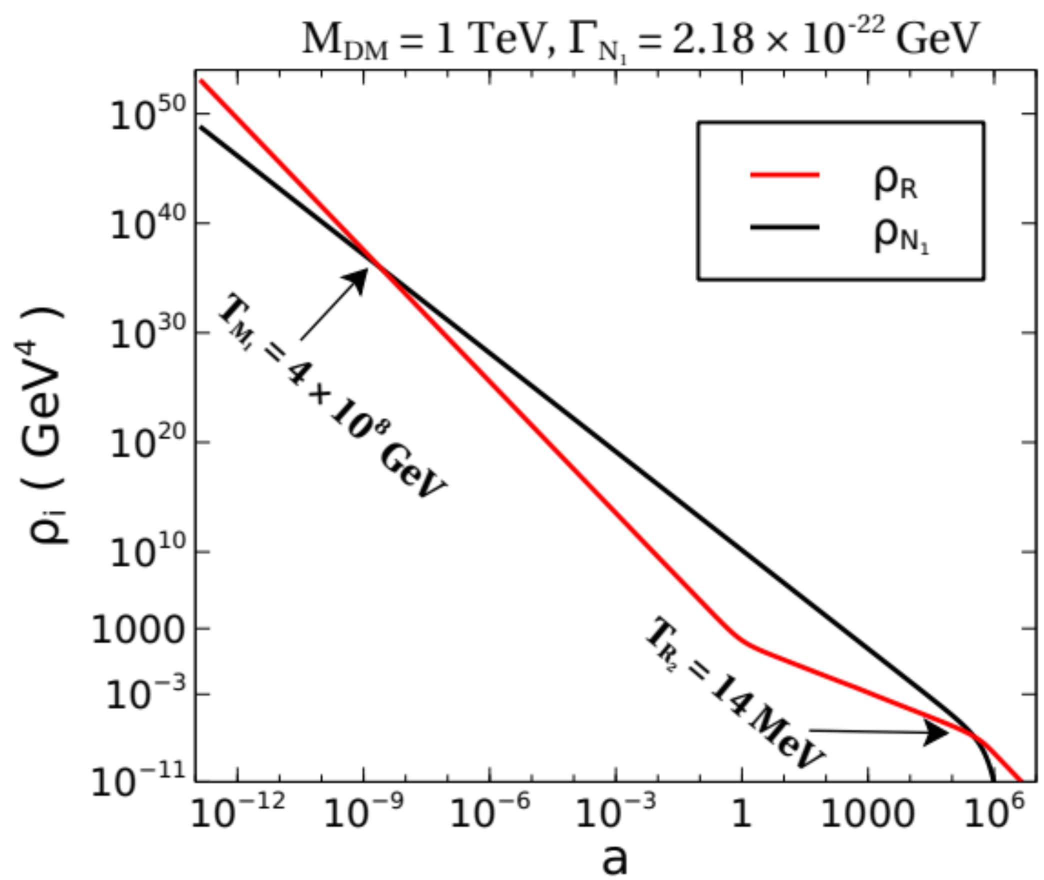


Entropy injection

Evolution of the background:







DM phenomenology

- DM relic : [relativistic freeze-out]

$$\Omega_\chi h^2 = 2.745 \times 10^8 \times m_\chi \times \frac{0.278}{g_{*s}(x_f)} \times \frac{3\, g_\chi}{4}.$$

- Required entropy injection

$$S = \frac{\Omega_\chi h^2}{0.12}$$

Diluter properties

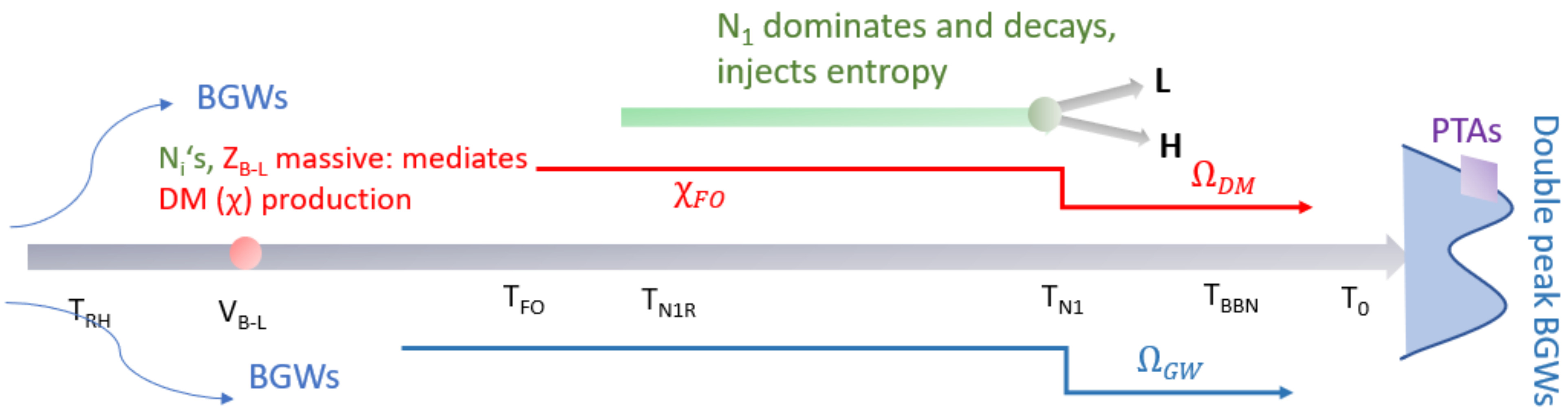
$$S \simeq \left[2.95 \times \left(\frac{2\pi^2 g_* \quad (T_{N_1})}{45} \right)^{1/3} \overbrace{\frac{(r M_{N_1})^{4/3}}{(\Gamma_{N_1} M_P)^{2/3}}} \right]^{3/4}.$$

- Assuming instantaneous decay of N_1 $(\Gamma_{N_1} = H)$:

$$T_{N_1} \simeq 3.104 \times 10^{-10} \left(\frac{M_{N_1}}{m_\chi} \right) \simeq T_{R_2}.$$

Connected with DM phenomenology

Impact on inflationary GW?



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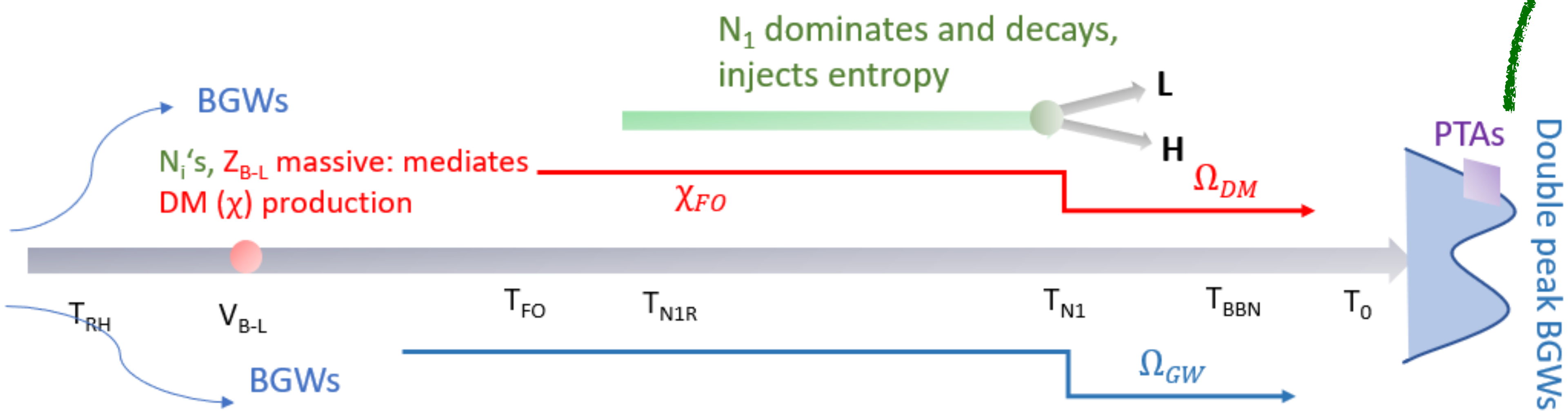

Peaks related to DM phenomenology

- **1st peak:** T_{RH}
- **Dip:** T_{N1R}
- **2nd peak:** T_{N1}

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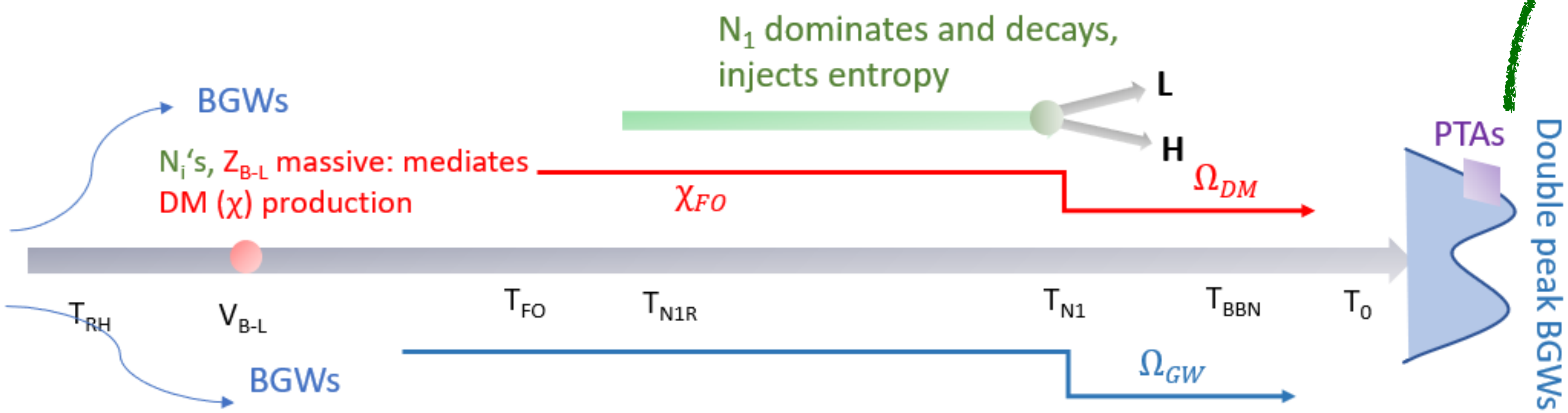


Peaks related to DM phenomenology

- **1st peak:** T_{RH}
- **Dip:** T_{N1R}
- **2nd peak:** T_{N1}

$$T_T^2(\tau_0,k) = F(k)T_1^2(\zeta_{\rm eq})T_2^2(\zeta_{N_1})T_3^2(\zeta_{N_1R})T_2^2(\zeta_R), \quad \zeta_i \equiv k/k_i$$

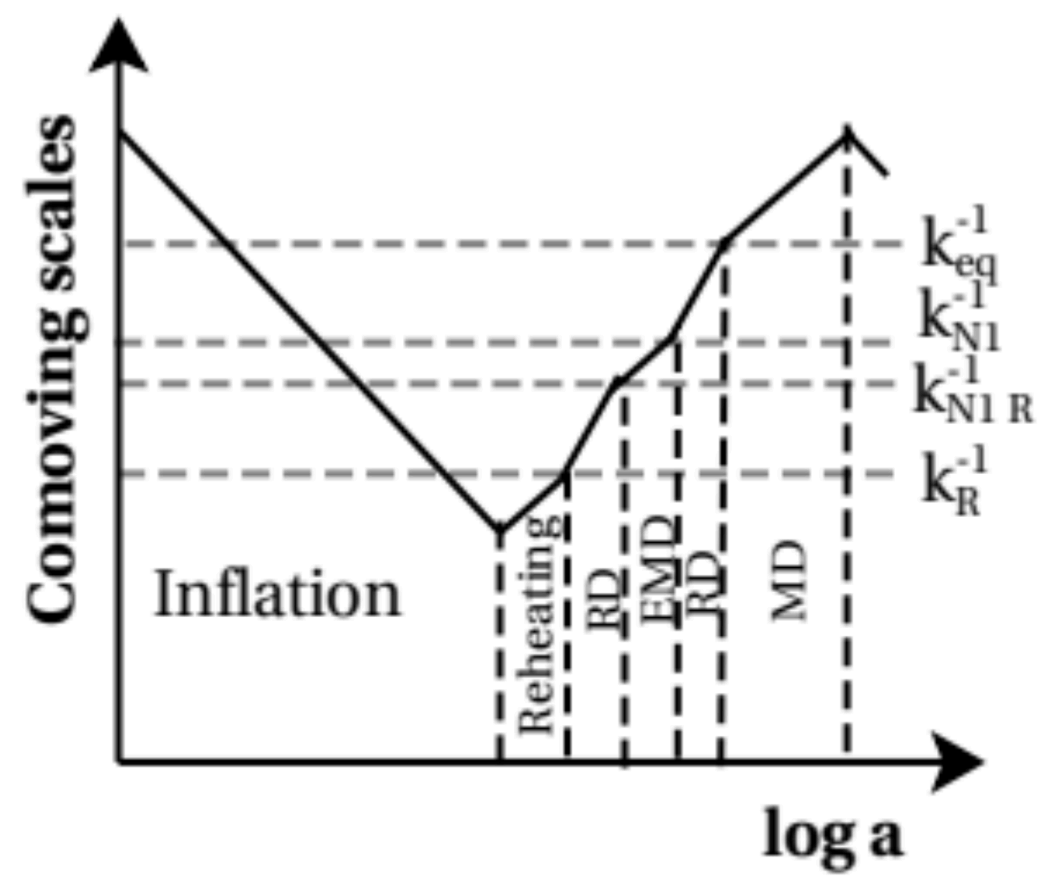
S: *Entropy dilution*

$$k_{\rm eq} = 7.1\times 10^{-2}\Omega_m h^2$$

$$k_{N_1} = 1.7\times 10^{14}\left(\frac{g_{*s}(T_{N_1})}{106.75}\right)^{1/6}\left(\frac{T_{N_1}}{10^7\,{\rm GeV}}\right)$$

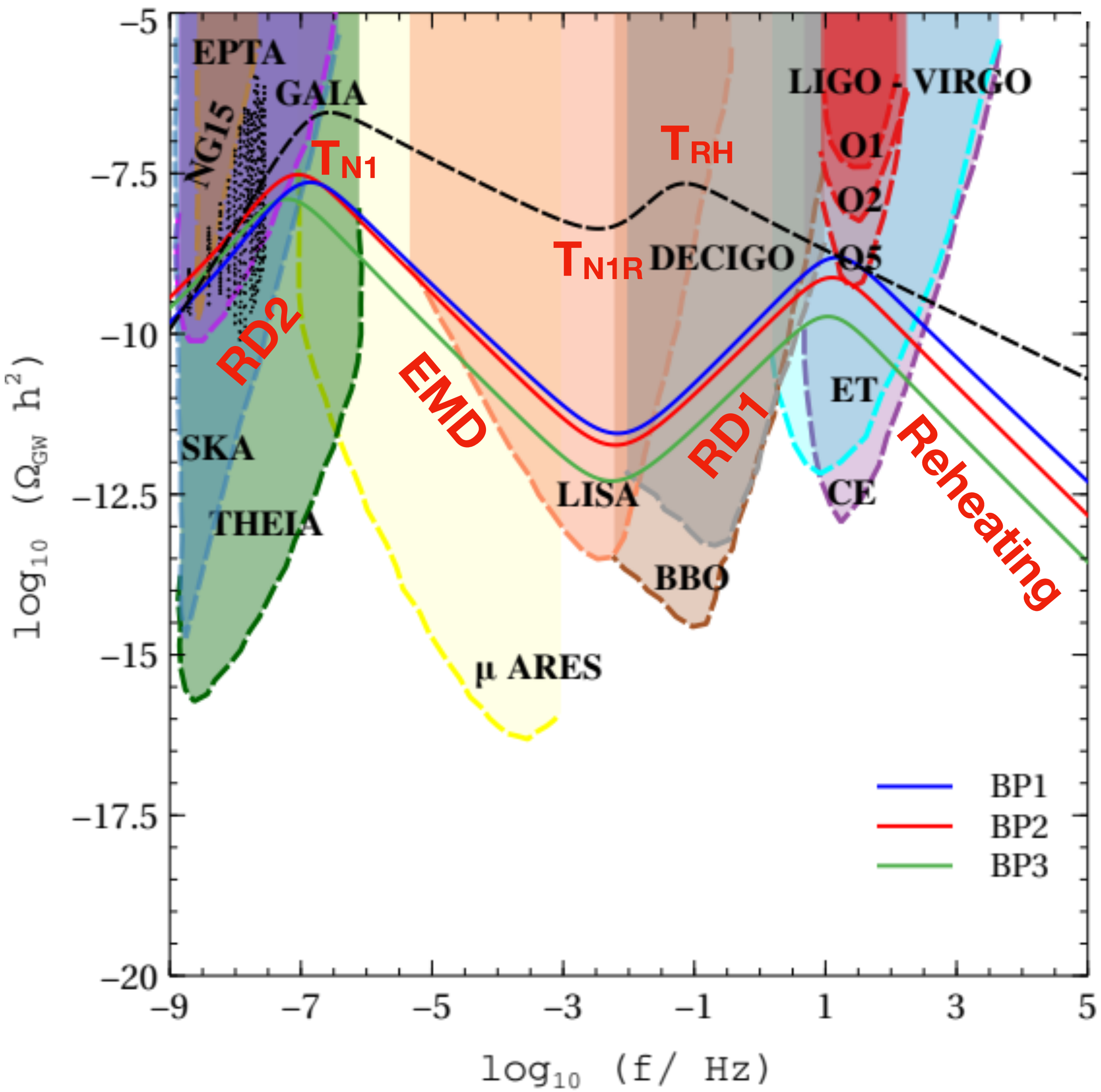
$$k_{N_1R} = 1.7\times 10^{14}S^{2/3}\left(\frac{g_{*s}(T_{N_1})}{106.75}\right)^{1/6}\left(\frac{T_{N_1}}{10^7\,{\rm GeV}}\right)$$

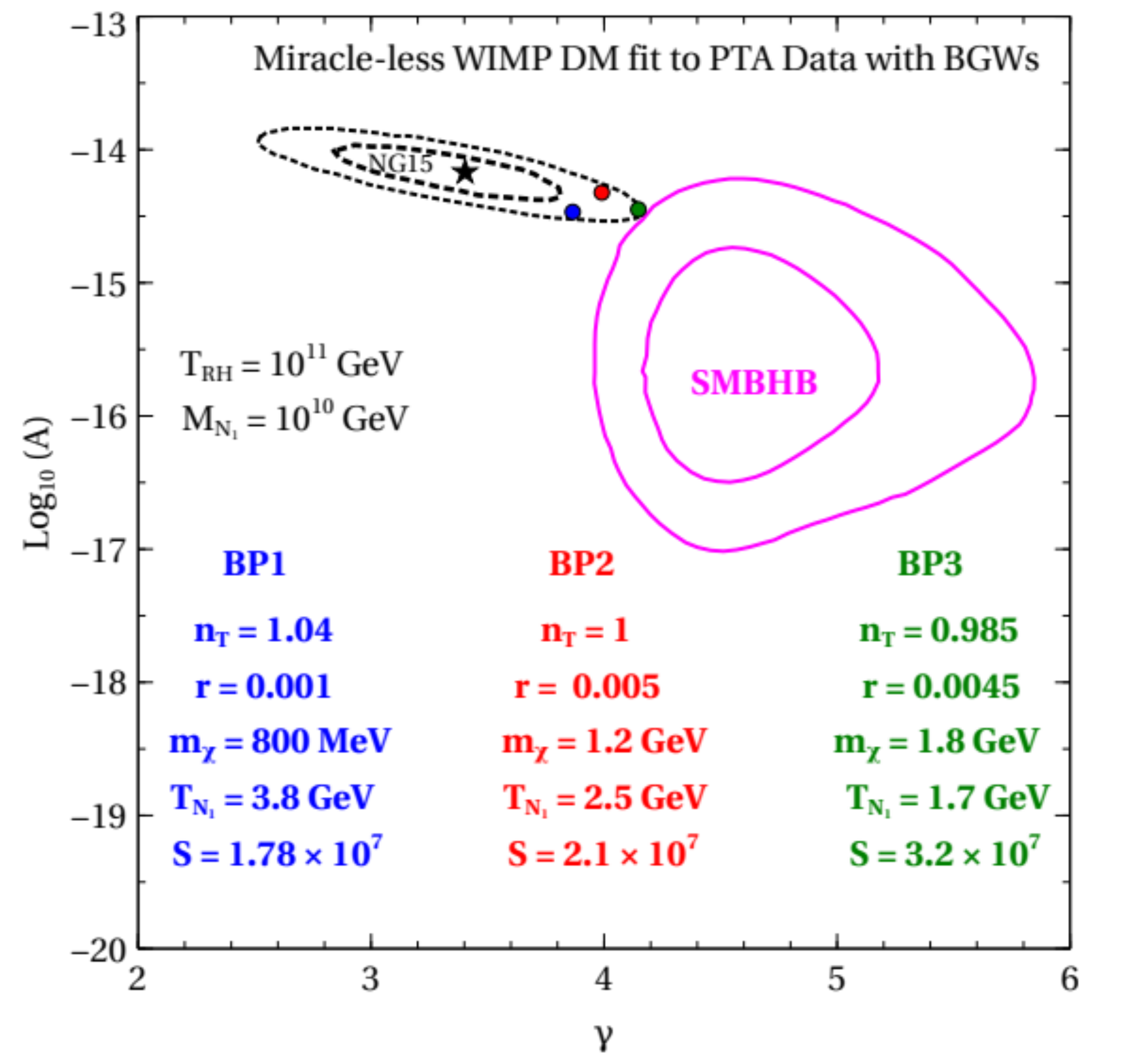
$$k_R = 1.7\times 10^{14}S^{-1/3}\left(\frac{g_{*s}(T_{\rm RH})}{106.75}\right)^{1/6}\left(\frac{T_{\rm RH}}{10^7\,{\rm GeV}}\right)$$

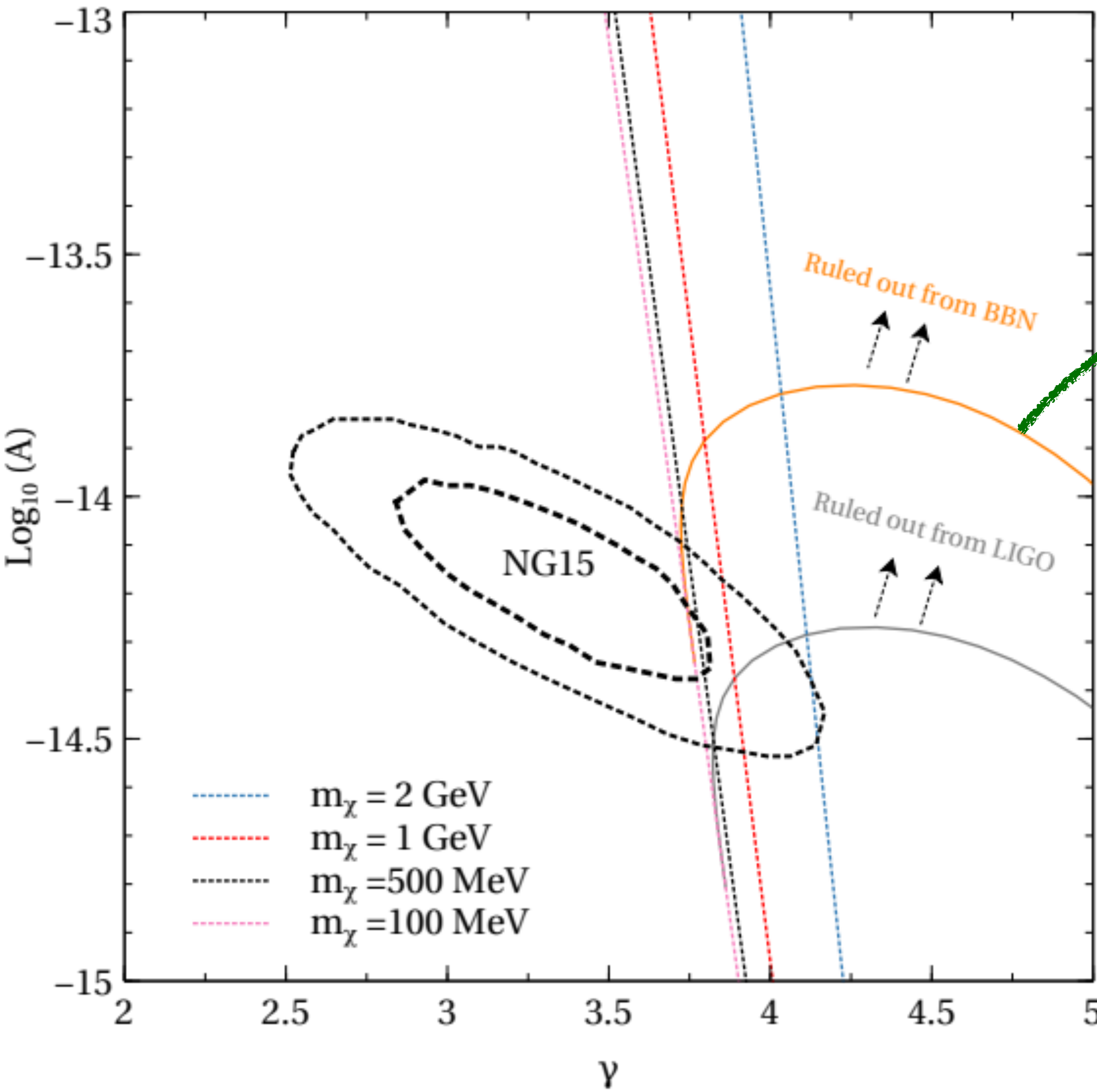


Implications for Nanograv

$$\Omega_{yr}\left(\frac{f}{f_{yr}}\right)^{5-\gamma} \;, \; \Omega_{yr} = \frac{2\pi^2}{3H_0^2}A^2 f_{yr}^2$$



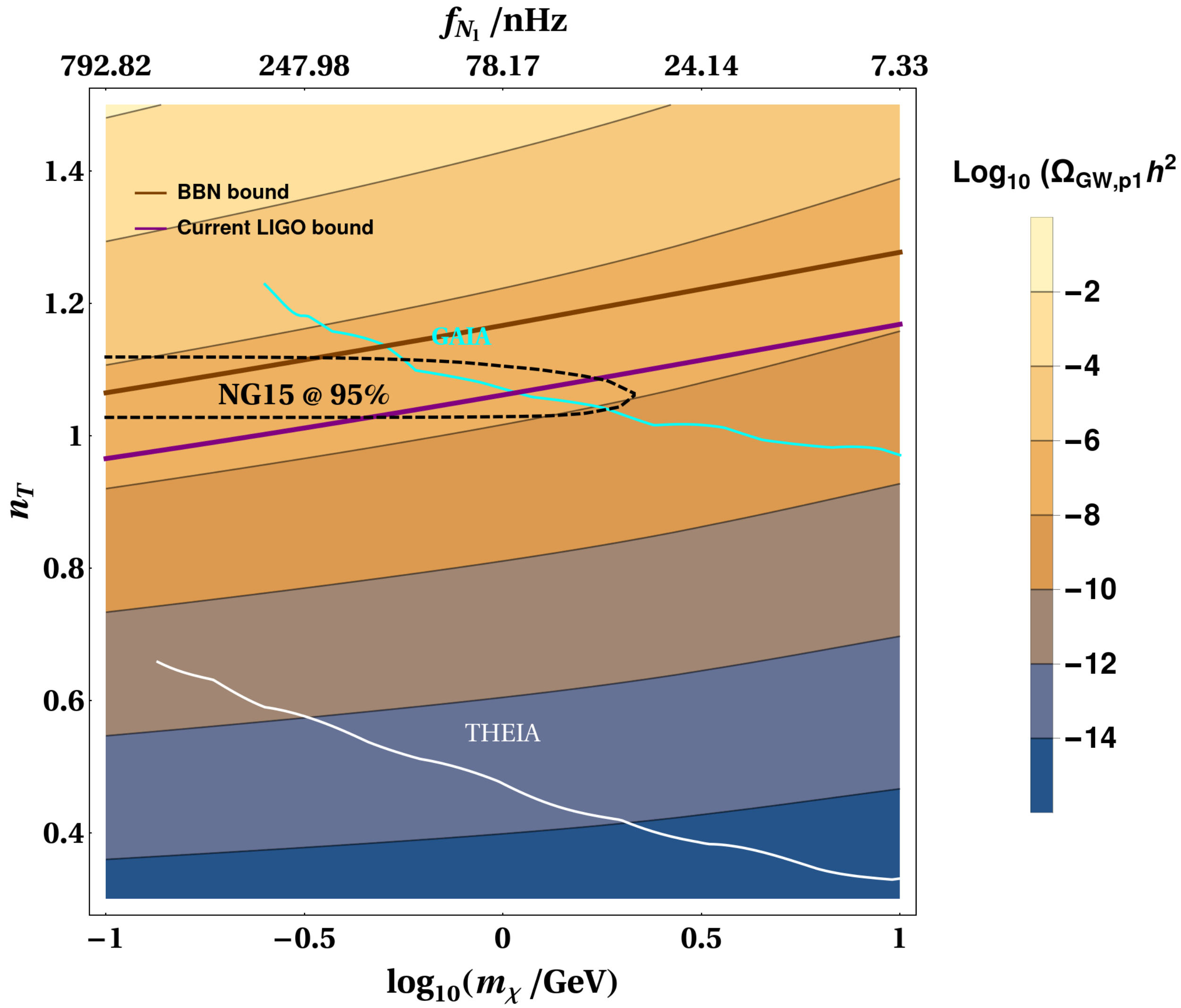


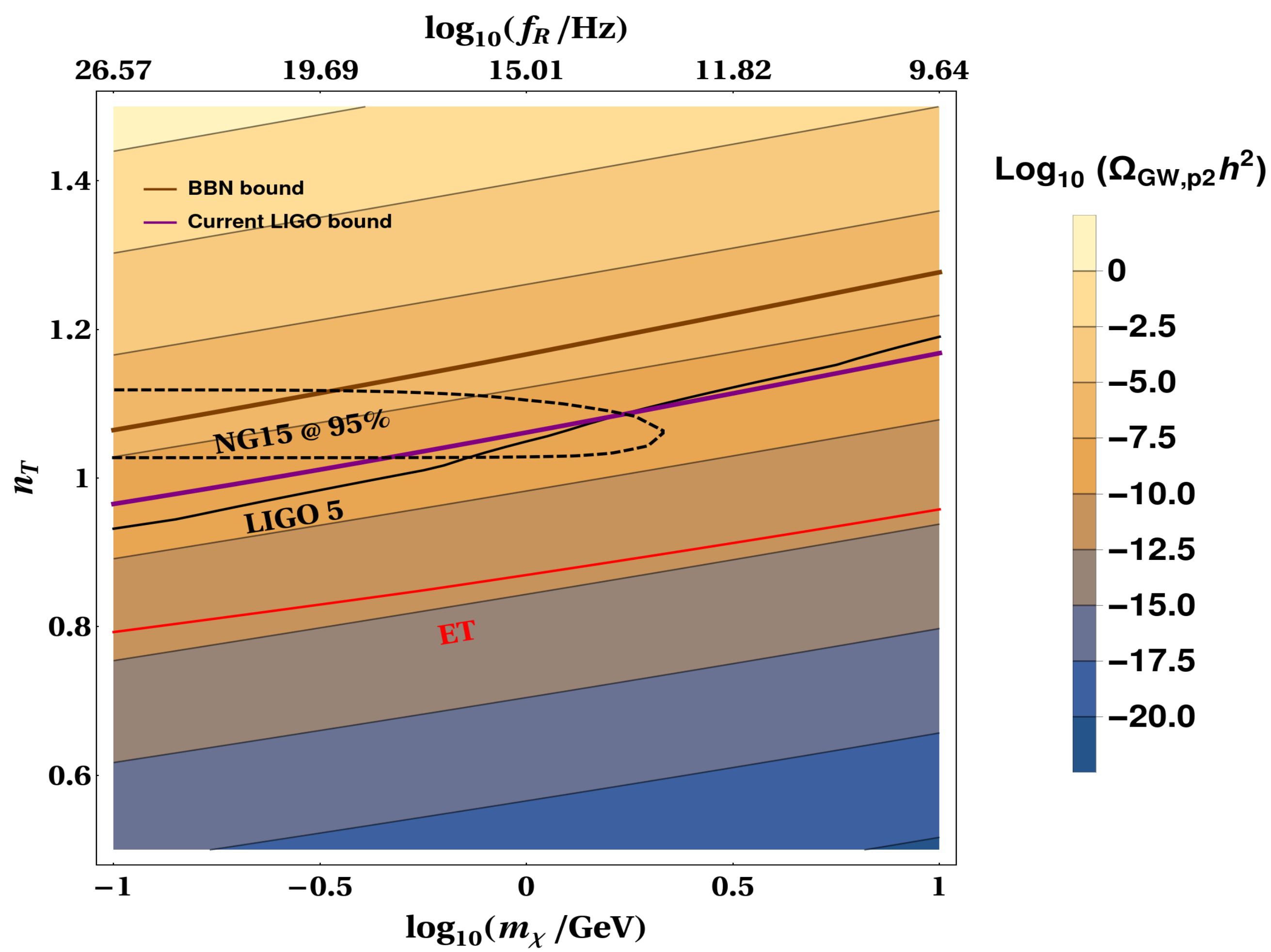


$$\int_{f_{\rm low}}^{f_{\rm high}} f^{-1} df\, \Omega_{\rm GW}(f) h^2 \lesssim 5.6 \times 10^{-6} \Delta N_{\rm eff}$$

$\Delta N_{\rm eff} \lesssim 0.2$

Peak frequencies





- **Frequencies correlated with DM mass.**
- **Tightly constrained from LIGO, BBN bounds.**
- **Offers PTA-LIGO(05) complementarity.**

Conclusion & Outlook

- **Evidence of GW background at nHz frequencies by PTAs.**
- **Possible source: Inflationary GW with a blue tilt.**
- **Low reheat temperature unless different post-inflationary cosmology.**
- **Connection with Dark Matter (or may be some other) particle physics scenarios, with characteristic GW spectra at higher frequencies.**
- **Miracle-less WIMP: naturally leads to such a non-standard post-inflationary epoch, testable at LIGO O5.**
- **Other complementary probes in particle physics experiments: KATRIN, NDBD.**
- **Sub-dominant GW from cosmic strings also present in the setup.**
- **A detailed analysis for astrophysical foregrounds, multiband analysis, anisotropy signatures...**

THANK YOU

GRACIAS!

Questions?

BACK-UP

$$F(k) = \Omega_m^2 \left(\frac{g_*(T_{k,\mathrm{in}})}{g_{*0}} \right) \left(\frac{g_{*s0}}{g_{*s}(T_{k,\mathrm{in}})} \right)^{4/3} \left(\frac{3 j_1(k\tau_0)}{k\tau_0} \right)^2 .$$

$$\begin{aligned} T_1^2(\zeta) &= 1 + 1.57\zeta + 3.42\zeta^2, \\ T_2^2(\zeta) &= \left(1 - 0.22\zeta^{1.5} + 0.65\zeta^2\right)^{-1}, \\ T_3^2(\zeta) &= 1 + 0.59\zeta + 0.65\zeta^2, \end{aligned}$$

$$\rho_{\mathrm{GW}} = \frac{1}{32\pi G} \int \frac{dk}{k} \left(\frac{k}{a} \right)^2 T_T^2(\tau, k) P_T(k),$$