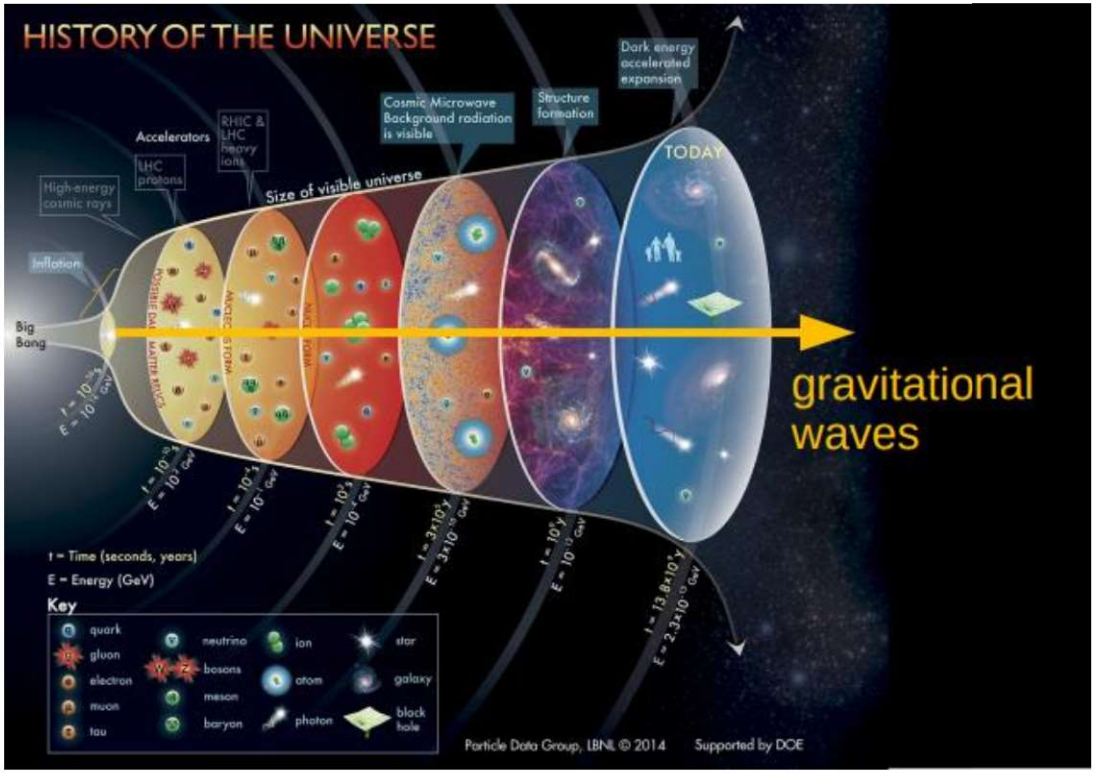
AAPCOS-2023

Probing low scale leptogenesis with inflationary blue tiled Gravitational waves



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In collaboration with
Rome Samanta(CEICO, Prague)

Based on

1. JHEP 11 (2022)159, 2208.09949 [hep-ph]

Baryogenesis via Leptogenesis

- $\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim \frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$
- Asymmetry should develop dynamically after inflation ➡ **Baryogenesis**
- Necessary requirements(**Sakharov's Conditions**) A.D. Sakharov, JETP Lett. 5(1967)24
  - Baryon Number Violation
  - C and CP violation
  - Departure from thermal equilibrium
- Need physics beyond the Standard Model
- **Leptogenesis:** Minimal ext. of SM with RHN facilitating ϑ-mass and lepton asymmetry(spans a wide range $M_N \in [10^{15} - 10^{-3}]$GeV). Later on lepton asymmetry gets converted to baryon asymmetry by (B+L) violating Sphalerons

  M. Fukugita & T. Yanagida PLB 174(1986)45

Low-Scale-Leptogenesis & Scalar era

EW naturalness prefers $M_i \leq 10^7$ GeV

F. Vissani , PRD 57(1997) 7027

Upcoming LHC can probe up to $M_i \sim O(TeV)$

TeV scale Low-scale-leptogenesis

low scale symmetry breaking($v_{B-L} \sim 10^7$ GeV)

$v_{B-L} \sim 10^{13}$ GeV

$M_i \sim y\, v_{B-L}$

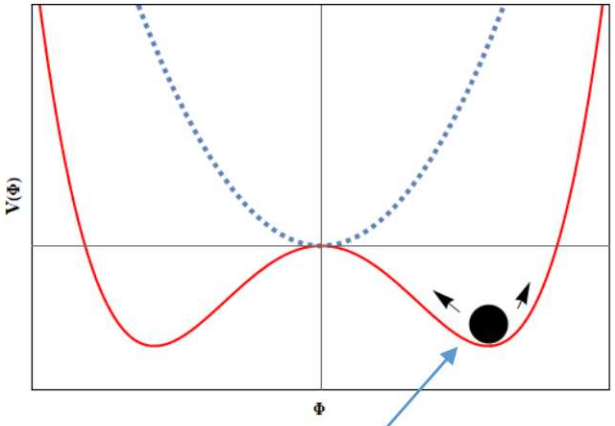
Very small Yukawa

S.Blasi, V.Brdar & K.Schmitz PRR 2(2020) 043321

Life time of scalar, $\tau_\Phi \sim \frac{1}{\Gamma(\Phi \to NN)}$ Very large

After Phase transition scalar field coherently oscillates and produces matter domination

Scalar Era



(B-L) phase transition

Temperature dependent effective potential,

$$V(\Phi, T) = \frac{\lambda}{4}\Phi^4 + D(T^2 - T_0^2)\Phi^2 - ET\Phi^3$$

Where,

$$D = \frac{3g'^2 + 4\lambda}{24}, \quad E = \frac{3g'^3 + g'\lambda + 3\lambda^{3/2}}{24\pi}, \quad T_0 = \frac{\sqrt{12\lambda}v_\Phi}{\sqrt{3g'^2 + 4\lambda}}$$

The phase transition parameters

$$T_c = T_0 \frac{\sqrt{\lambda D}}{\sqrt{\lambda D - E^2}}, \quad \Phi_c = \sqrt{\frac{4D}{\lambda}(T_c^2 - T_0^2)}.$$

- For ${}^{\Phi_c}/_{T_c} \ll 1$ ⇒ a very weak FOPT

↓

Smooth rolling of field from $\Phi = 0$ to $\Phi = v_\Phi$

↓

Necessary condition to realize a scalar era

Scalar era controlled by LSL

- We assume $\lambda \sim (g')^3$ and $g' \leq 10^{-2}$ for which $\Phi_c/T_c \leq 0.08$

$m_\Phi \sim \sqrt{2\lambda} v_{B-L} \ll 2M_{Z'} \longrightarrow \Phi \to Z'Z'$ is not allowed from kinematic consideration

$$\Gamma(\Phi \to f\bar{f}V) \sim 10^{-8}\lambda(g')^4 m_\Phi$$

$$\Gamma(\Phi \to N_i N_i) \sim \frac{y^2}{10\pi} m_\Phi \sim \frac{\boldsymbol{M_N^2}}{10\pi v_{B-L}^2} m_\Phi$$

LSL parameter controlling the scalar dynamics

$$\Gamma(\Phi \to N_i N_i) > \Gamma(\Phi \to f\bar{f}V)$$

$$(g')^7 \lesssim \frac{10^7 M_N^2}{\pi v_{B-L}^2}$$

LSL controls the scalar era

Scalar dynamics & Entropy production

Energy densities evolves according to these BEs

$$\frac{d\rho_R}{dz}+\frac{4}{z}\rho_R=0,\quad \frac{d\rho_\Phi}{dz}+\frac{3}{z}\frac{H}{\tilde{H}}\rho_\Phi+\Gamma_N^\Phi\frac{1}{z\tilde{H}}\rho_\Phi=0,$$

Amount of entropy production can be calculated from

$$\frac{da}{dz}=\left(1+\Gamma_N^\Phi\frac{\rho_\Phi}{4\rho_R\tilde{H}}\right)\frac{a}{z}$$

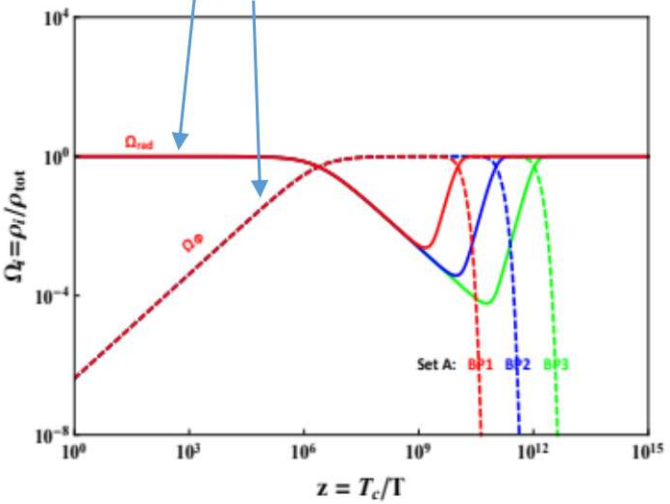
An analytical expression for entropy dump i.e. S_{after}/S_{before}

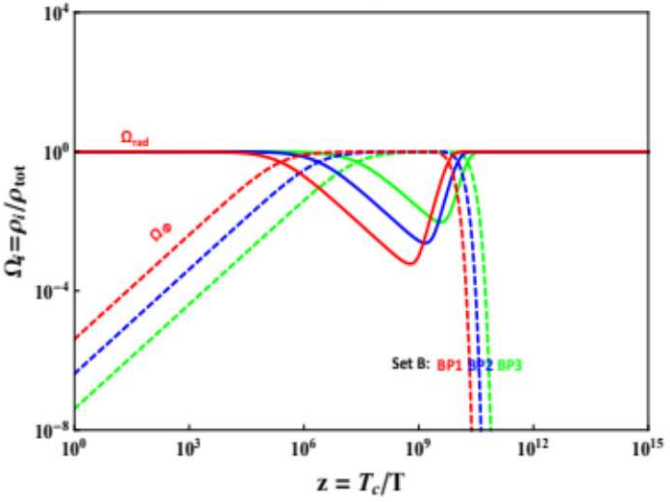
$$\kappa^{-1}\simeq\frac{\left(\frac{90}{\pi^2 g_*}\right)^{1/4}\rho_R\left(T_c\right)\sqrt{\Gamma_N^\Phi\tilde{M}_{Pl}}}{\rho_\Phi\left(T_c\right)T_c}\simeq\frac{3^{1/4}\left(\frac{30}{\pi^2 g_*}\right)^{-3/4}T_c^3\sqrt{\Gamma_N^\Phi\tilde{M}_{Pl}}}{V_{\rm eff}\left(0,T_c\right)},$$

Set A: $v_\Phi=10^{13}$GeV, $m_\Phi=4.47\times10^8$GeV					
Parameters	g'	Γ_N^Φ/GeV	T_c/GeV	M_i/GeV	$H(T_c)$/GeV
BP1	10^{-3}	1.3×10^{-14}	6.3×10^{11}	300	5.9×10^5
BP2	10^{-3}	1.3×10^{-16}	6.3×10^{11}	30	5.9×10^5
BP3	10^{-3}	1.3×10^{-18}	6.3×10^{11}	3	5.9×10^5
Set B: $v_\Phi=10^{13}$GeV, $M_i=300$GeV					
Parameters	g'	Γ_N^Φ/GeV	T_c/GeV	m_Φ/GeV	$H(T_c)$/GeV
BP1	10^{-2}	4.05×10^{-13}	2×10^{12}	1.4×10^{10}	5.9×10^6
BP2	10^{-3}	1.3×10^{-14}	6.3×10^{11}	4.47×10^8	5.9×10^5
BP3	10^{-4}	4.05×10^{-16}	2×10^{11}	1.4×10^7	5.9×10^4

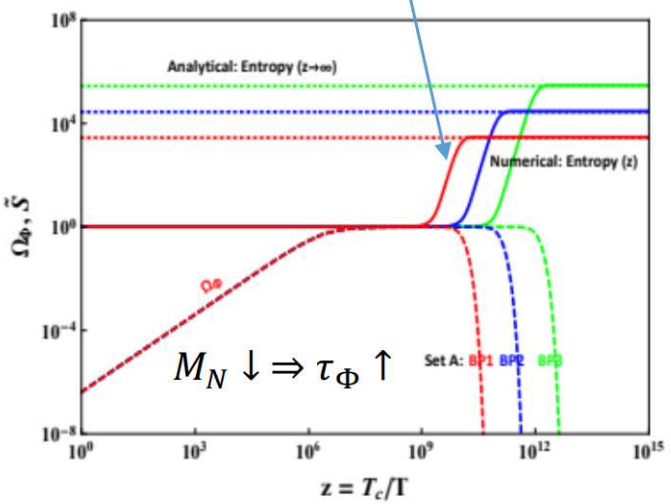
Scalar dynamics & Entropy production

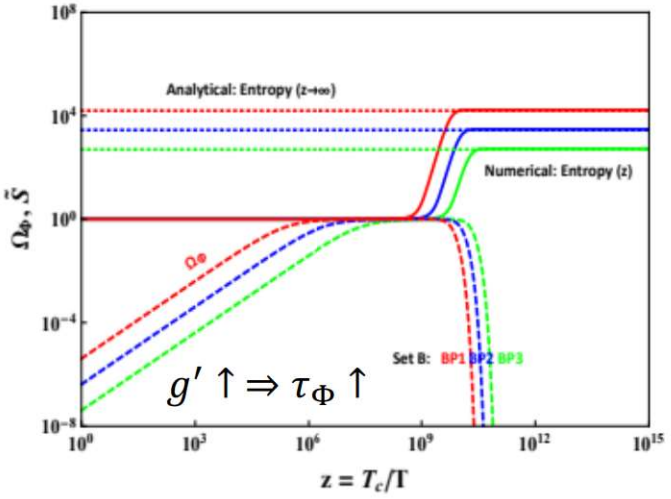
Evolution of normalised energy densities



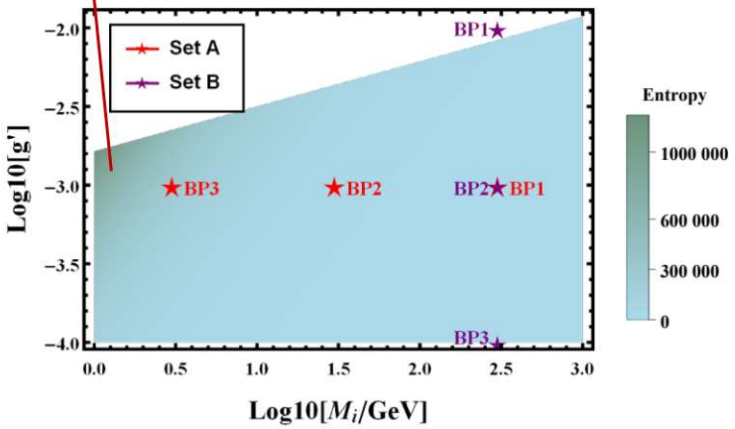


Evolution of entropy densities





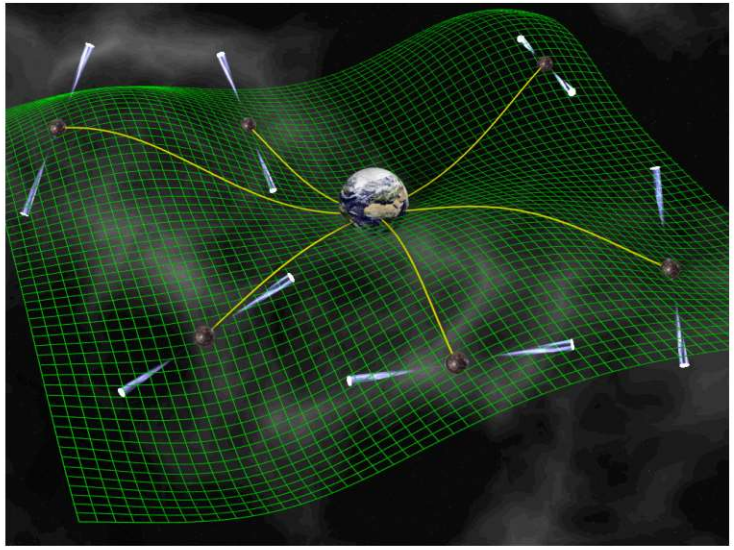
Max entropy production with smaller M_N and a high g'



Stochastic GW alike process at PTAs

- Pulser timing arrays which typically work with high amplitude GWs recently coming into news claiming **Stochastic common spectrum process at NANOGrav 12.5**

  Z. Arzoumanian et al.



- Till date the data set **does not show** any evidence for quadrupolar spatial correlation described by the **Hellings-Downs curve**(characteristic for GW)

  R.W.Hellings & G.S. Downs, AJL 265(1983)L39

- Recent data release by **PPTA, EPTA, IPTA is in agreement** with NANOGrav result

  arXiv:2107.12112 [astro-ph.HE]

- If the detection is genuine opens up a luring possibility to test and constrain **particle physics** and **cosmological** models

GW from inflation

Gravitational waves are described with the perturbed FLRW line element:

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

Transverse and traceless part of the of the 3X3 symmetric matrix h_{ij} represents GW

GW propagation equation in the Fourier space

$$\ddot{h}_k + 2\frac{\dot{a}}{a}\dot{h}_k + k^2 h_k = 0,$$

GW amplitude,

$$\Omega_{GW}(k) = \frac{1}{12H_0^2}\left(\frac{k}{a_0}\right)^2 T_T^2(\tau_0, k)P_T(k),$$

Where,

$$T_T^2(\tau_0, k) = F(k)T_1^2(\zeta_{\rm eq})T_2^2(\zeta_\Phi)T_3^2(\zeta_{\Phi R})T_2^2(\zeta_R),$$

Primordial Power spectrum $P_T(k) = rA_s(k_*)\left(\frac{k}{k_*}\right)^{n_T}$ → Connection to inflation model

Where, $r \leq 0.06$, $k_* = 0.01Mpc^{-1}$, $A_s \sim 2 \times 10^{-9}$

GW from inflationary Blue-Tilt

With slow-roll approximation

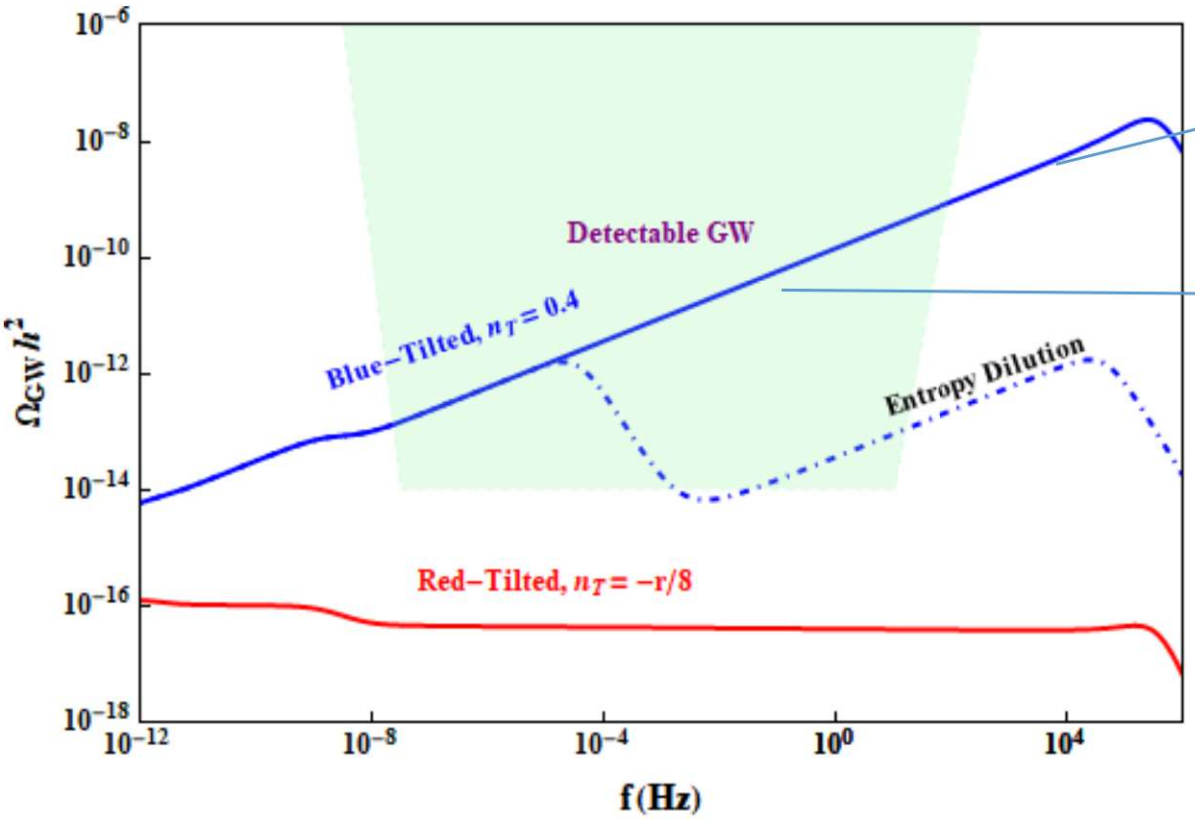
$$n_T = -r/8$$

Mild Red-tilt

$$n_T \lesssim 0$$

We treat the n_T as a constant and blue-tilted, i.e. $n_T > 0$

S. Vagnozzi, MNRAS 502(2021)L11



Many inflationary models predict BGWs

BGWs are possible sources of GW finding at PTA

GW from cosmic strings

The GW energy density/ amplitude

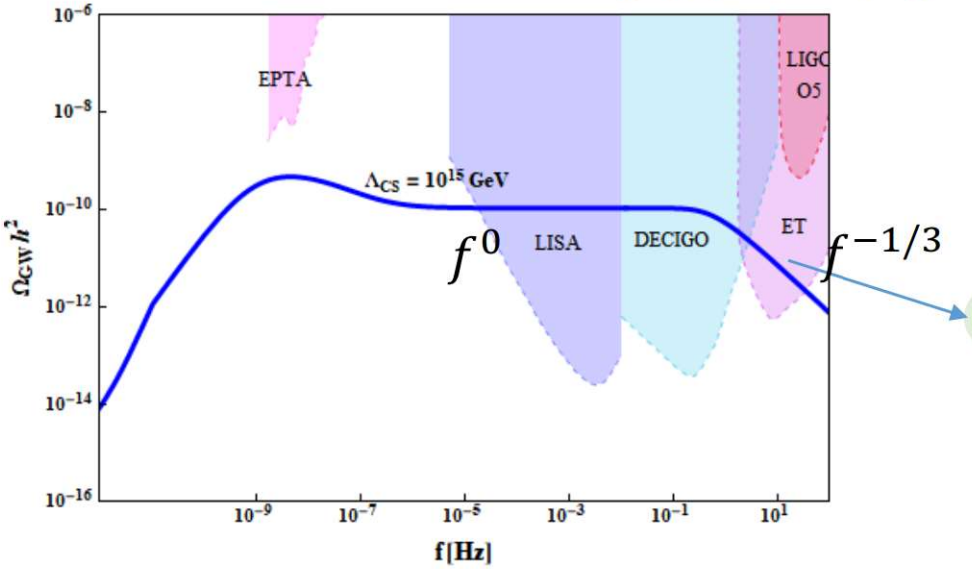
$$\Omega_{GW}(t_0, f) \equiv f\rho_c^{-1} d\rho_{GW}/df = \sum_k \Omega_{GW}^{(k)}(t_0, f)$$

Where,

$$\Omega_{GW}^{(k)}(f) = \frac{2kG\mu^2\Gamma_k}{f\rho_c} \int_{t_{osc}}^{t_0} \left[\frac{a(\tilde{t})}{a(t_0)}\right]^5 n\left(\tilde{t}, l_k\right) d\tilde{t}.$$

For a general e.o.s, the loop number density

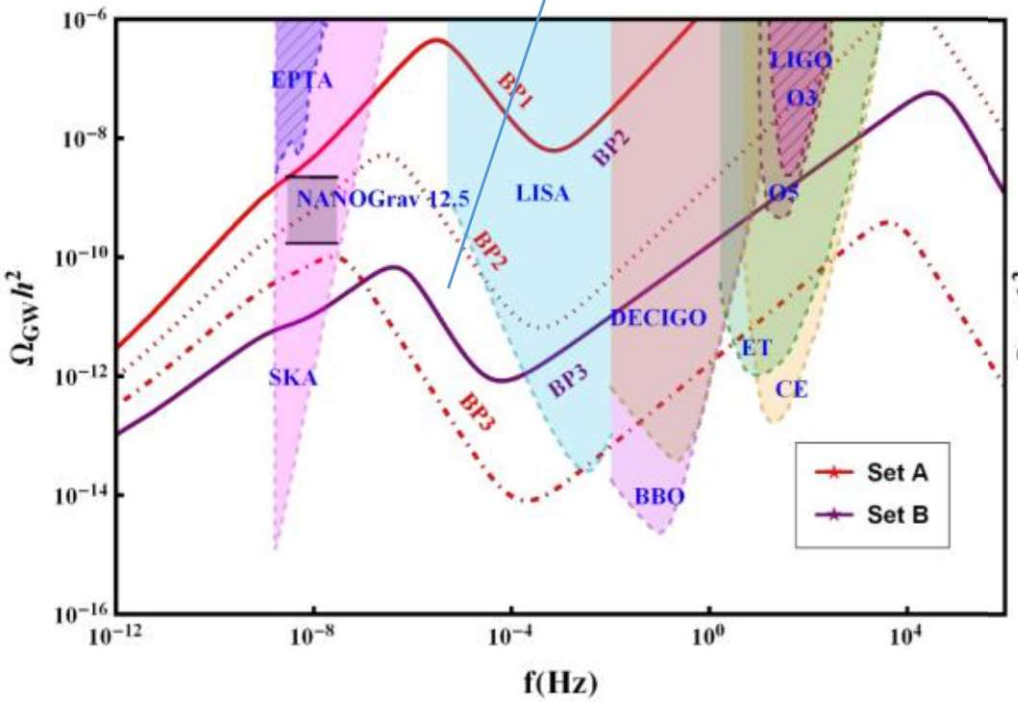
$$n_\omega(\tilde{t}, l_k(\tilde{t})) = \frac{A_\beta}{\alpha} \frac{(\alpha + \Gamma G\mu)^{3(1-\beta)}}{\left[l_k(\tilde{t}) + \Gamma G\mu\tilde{t}\right]^{4-3\beta}\, \tilde{t}^{3\beta}} \qquad \beta = 2/3(1+\omega)$$



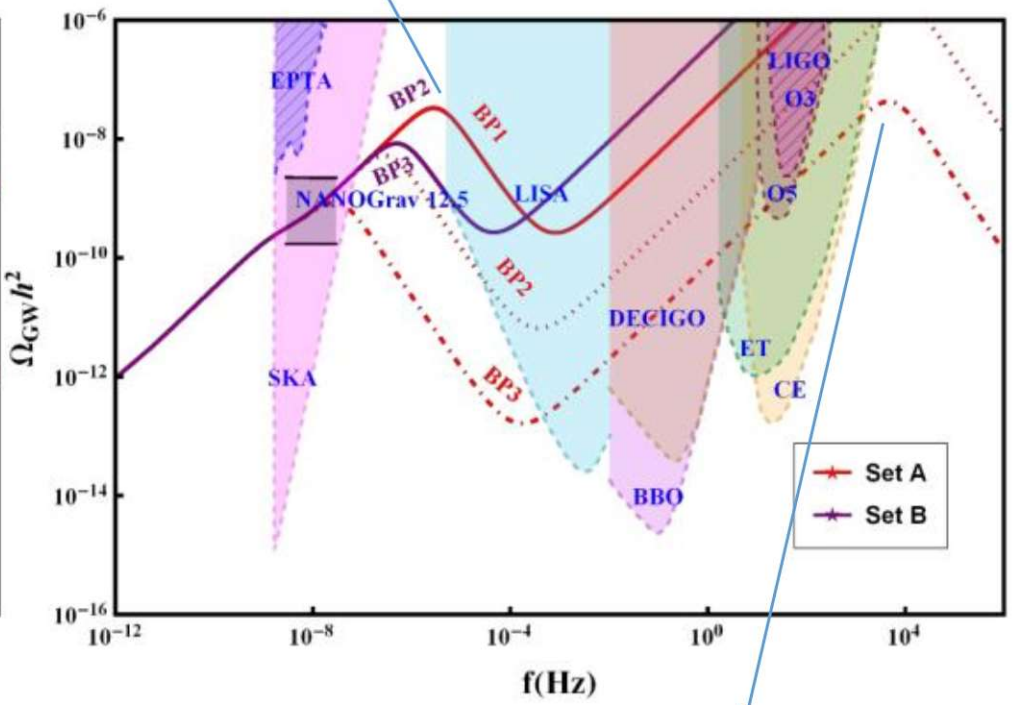
Due to modified **loop number density** and **redshifting** of GW

Cosmic archaeology with LSL & BGW

Red tilt due to entropy production



Low - f peak explaining
NANOGrav data with $n_T \sim 0.8$



Complementary high- f signal
to be detected

Cosmic archaeology with LSL & BGW

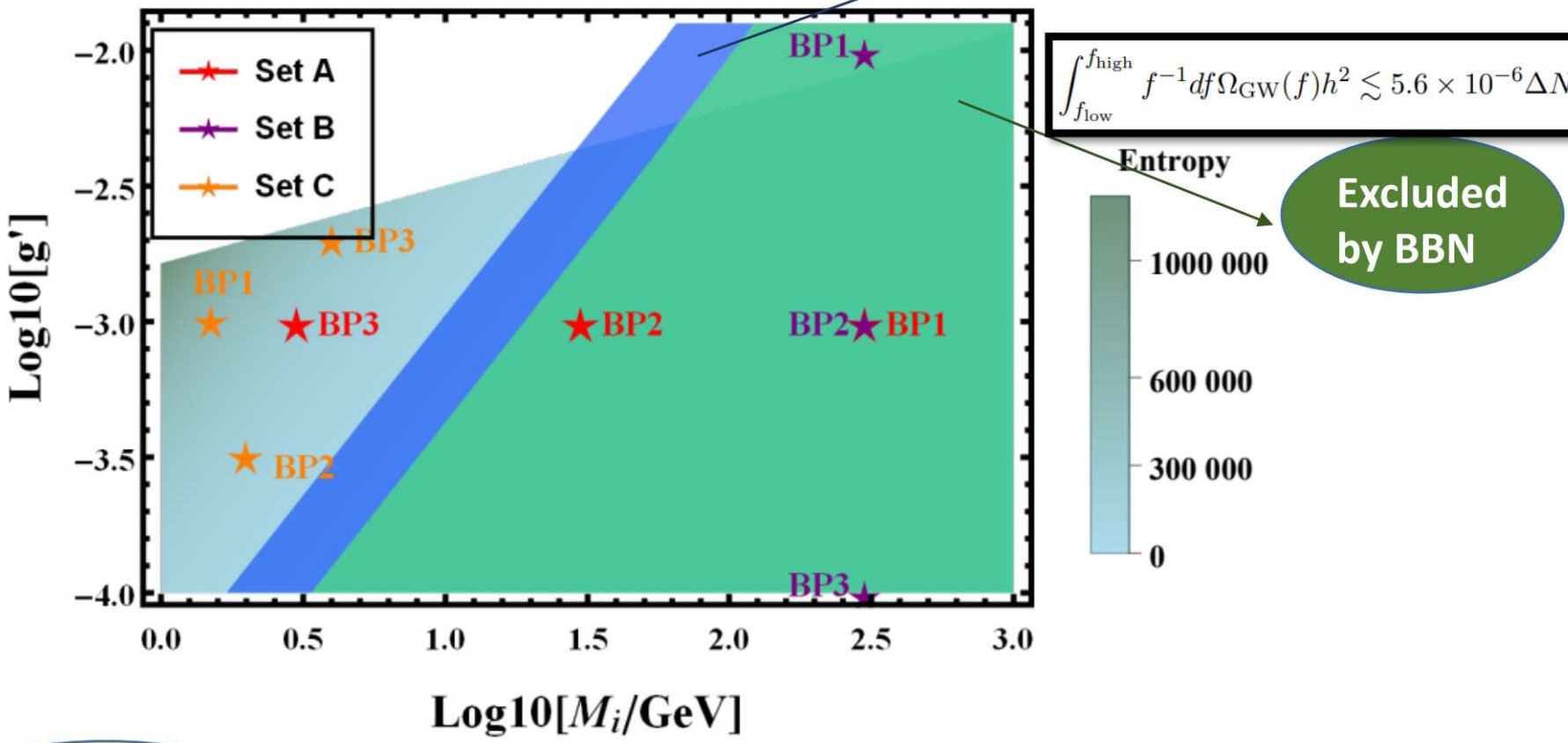
n_T = 0.8 → Best-fit by **NANOGrav**

$\Omega_{\rm GW}(25{\rm Hz})\ h^2 \lesssim 2.2 \times 10^{-9}$

Excluded by LIGO O3

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

Excluded by BBN



If NANOGrav result is due to BGWs → Future interferometers constrain LSL for $M_i < 30 \pm \delta M_i$ GeV

Cosmic strings Complementarity

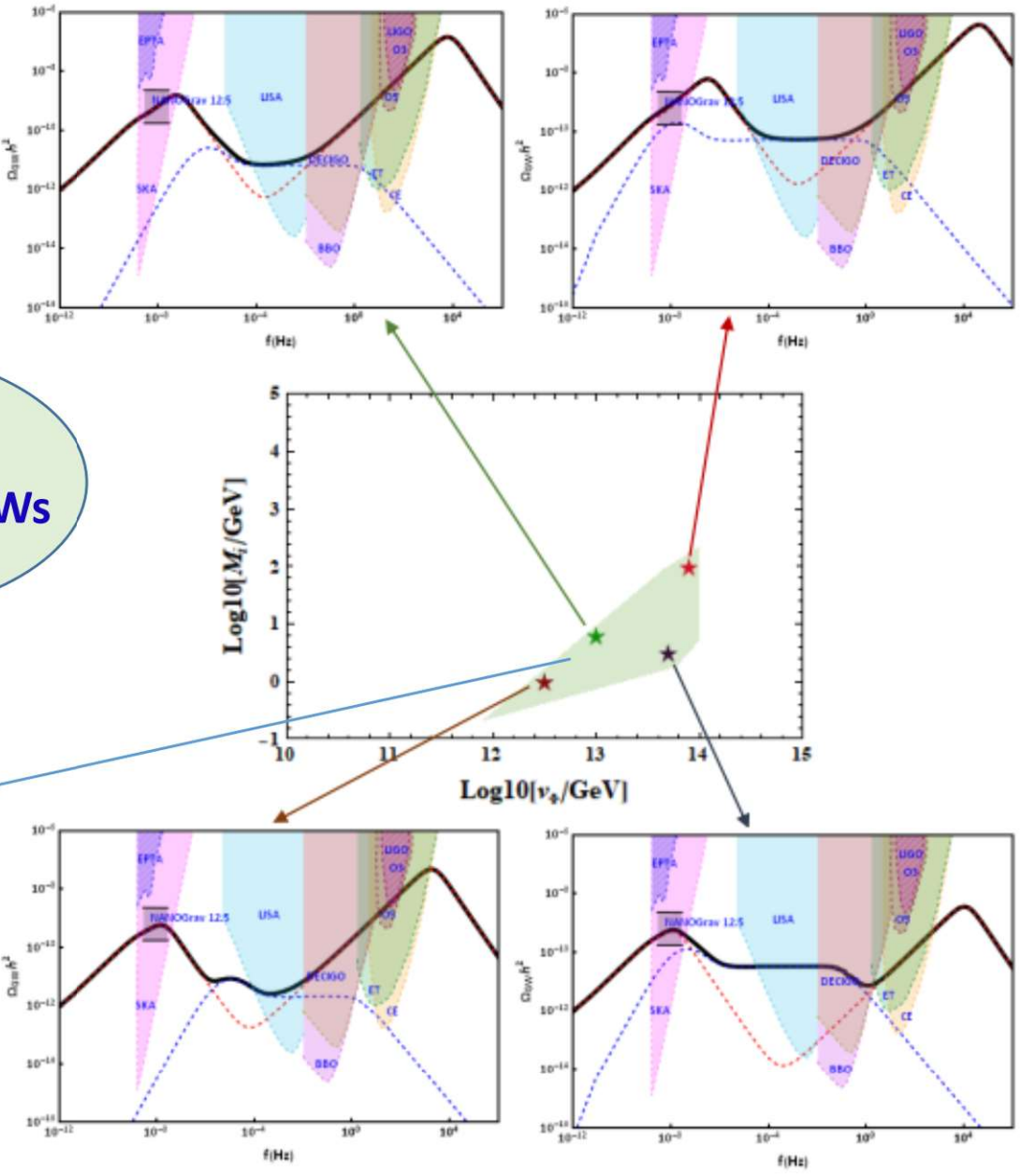
How to discriminate LSL from any other intermediate matter domination scenarios??

$U(1)_{B-L}$ breaking

Complementary particle physics expt.

Own source of Cosmic string GWs

peak-plateau-peak signal instead of a peak-dip-peak



Conclusion

- We studied signatures of LSL favoured by **EW naturalness** and upcoming **LHC**
- A long lived scalar field generates small RHN masses and dominates the energy density before BBN resulting a **scalar era**
- RHN masses thus **LSL controls the scalar era** leading to GW-spectral distortions via entropy production
- As a result models with a **sizeable tensor-blue-tilt** become viable even if the reheating temperature is large
- Unravels an opportunity to test LSL via a low frequency and **complimentary high frequency doubly peaked** GW waves
- Taking recent **PTA data** seriously future detectors at the interferometer scales have the potential to test and constrain LSL mechanisms with $\boldsymbol{M_N \lesssim 10^2}$**GeV**
- Finally a **cosmic string** complementarity makes the scenario **unique** than any other matter domination scenarios

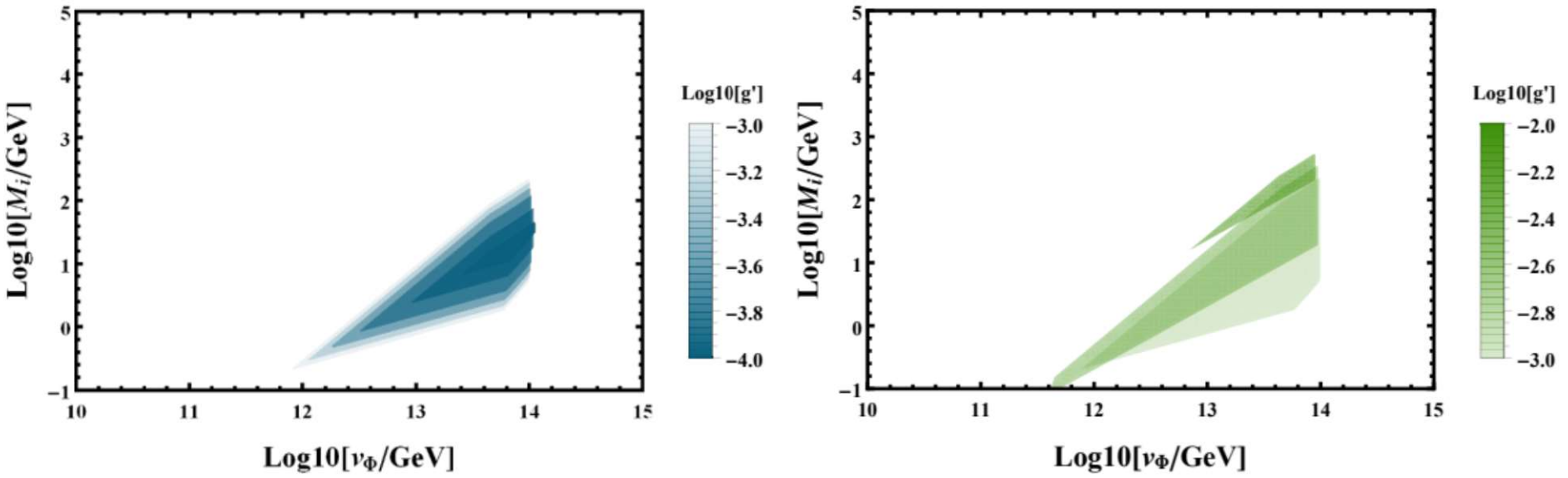
Acknowledgements

I would like to express my special thanks of gratitude to my PhD supervisor Prof. Ambar Ghosal for his guidance and support. I would also like to extend my gratitude to SINP, Theory Division for providing me with all the facility required.

Thank you for your patience

Backup Slides

GW-tomography of LSL for different gauge coupling



$$g' \in [10^{-4} - 5 \times 10^{-3}]$$