Knocking at the Door of the Cosmic Microwave Background

Quarks-2026

Adeela Afzal

Bogoliubov Laboratory of Theoretical Physics (BLTP)

22-05-2026

Joint Institute of Nuclear Research

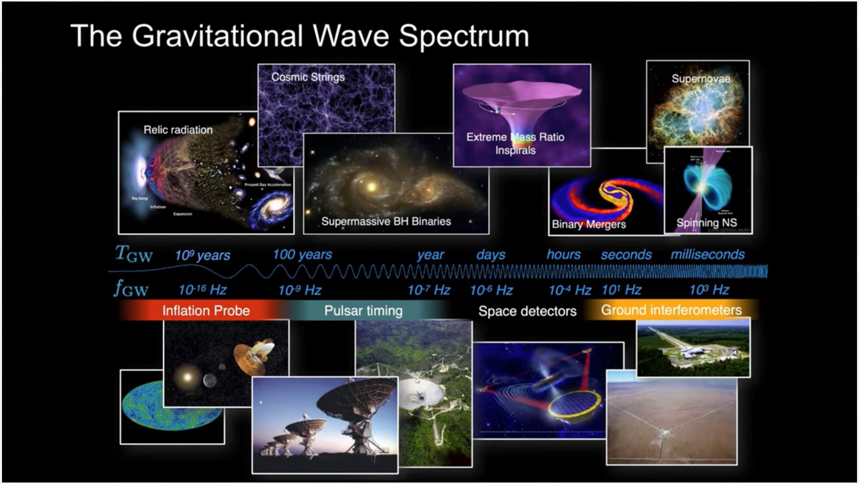
Outline

- Introduction
- Investigation and Results
- Conclusions

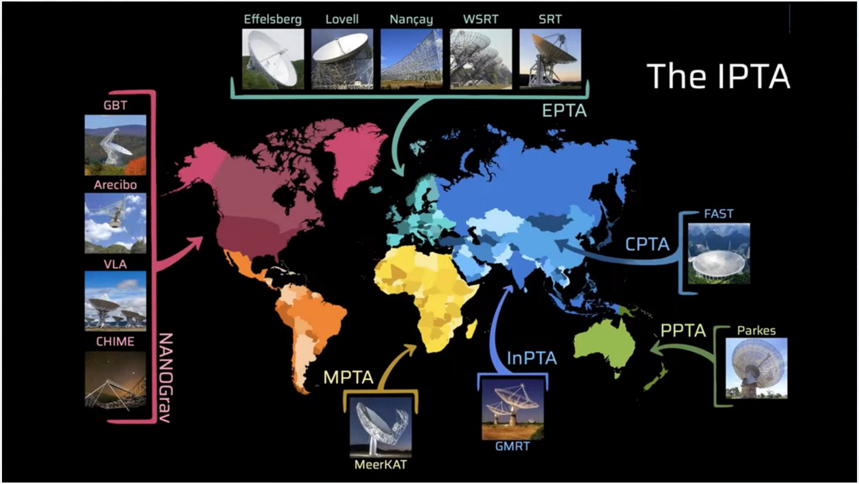
Introduction

- Gravitational Wave Spectrum
- IPTA
- NANOGrav 12.5-year Dataset
- Early Universe

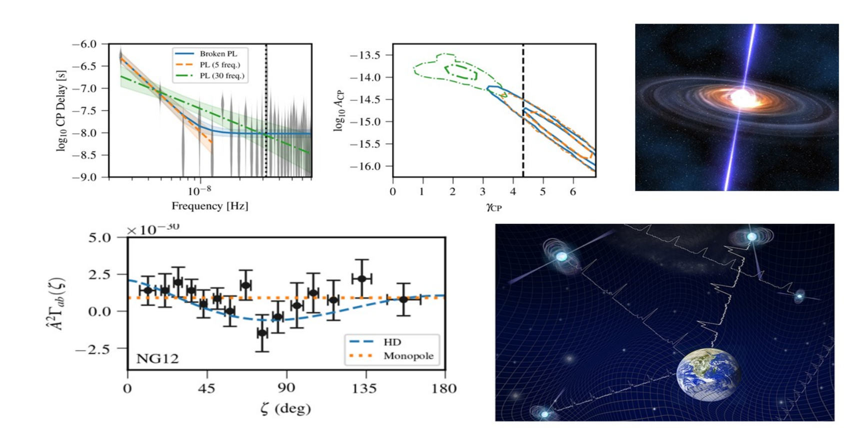
Gravitational Wave Spectrum



International Pulsar Timing Array



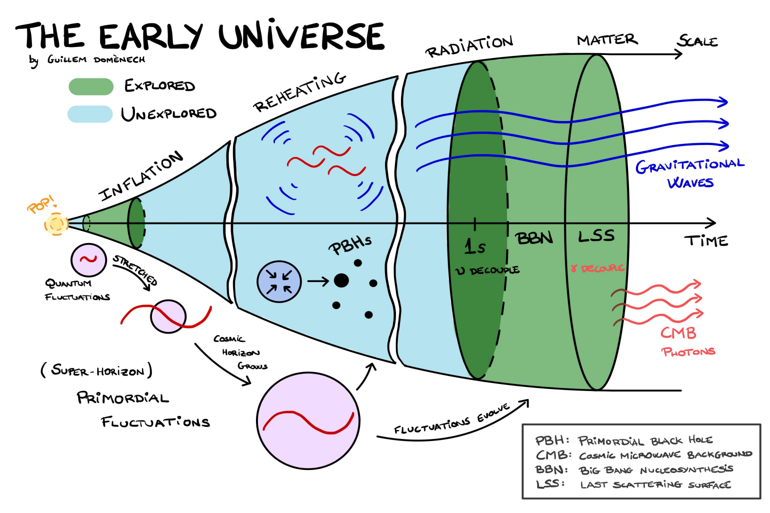
NANOGrav 12.5-year Dataset



Arxiv: 2009.04496

This dataset shows evidence of a common stochastic signal; however, there is not yet evidence for the spatial correlations characteristic of the GWB.

Knocking at the Door of CMB



https://domenechcosmo.netlify.app/post/induced-gws/

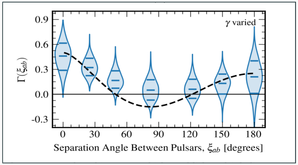
Investigation and Results ($\hbar = c = k_B = 1$ Natural Units)

- NANOGrav 15-year dataset [2306.16219; APJ Lett.]
  1. Scalar Induced Gravitational Waves
  2. Metastable CSs
- Super-heavy Metastable Current-carrying Cosmic Strings [2311.05564; PLB]
- Gravitational Waves from Type-I Strings in a Neutrino Mass Model [2509.11107 ,Phys.Dark Univ.]

DR2 and the IPTA Summery

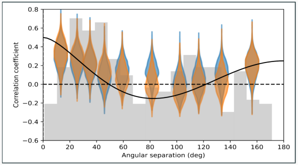
Major announcment on June 29: compelling evidence for HD correlations

2306.16213: NANOGrav



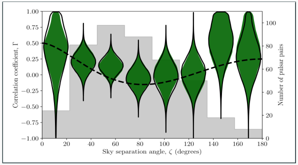
68 pulsars, 16 yr of data, HD at $\sim 3 \cdots 4\,\sigma$

2306.16214: EPTA+InPTA



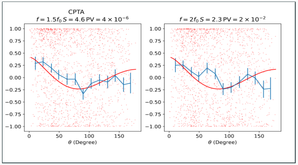
25 pulsars, 25 yr of data, HD at $\sim 3\,\sigma$

2306.16215: PPTA



32 pulsars, 18 yr of data, HD at $\sim 2\,\sigma$

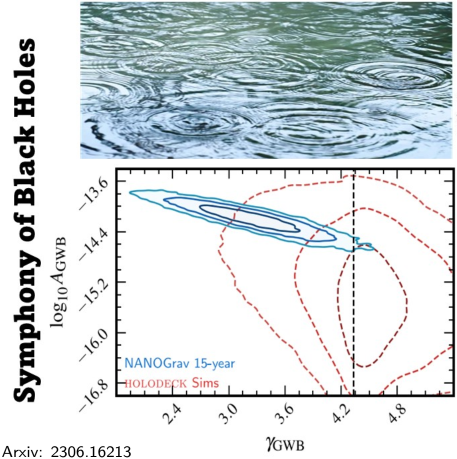
2306.16216: CPTA

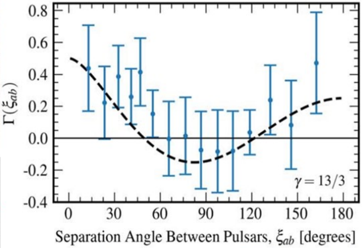


57 pulsars, 3.5 yr of data, HD at $\sim 4.6\,\sigma$

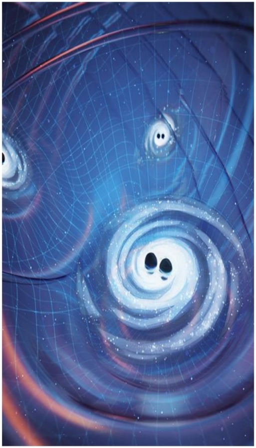
Credit: Kai Schmitz

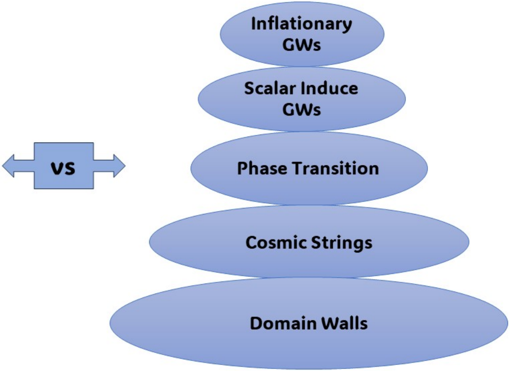
NANOGrav 15-year Dataset

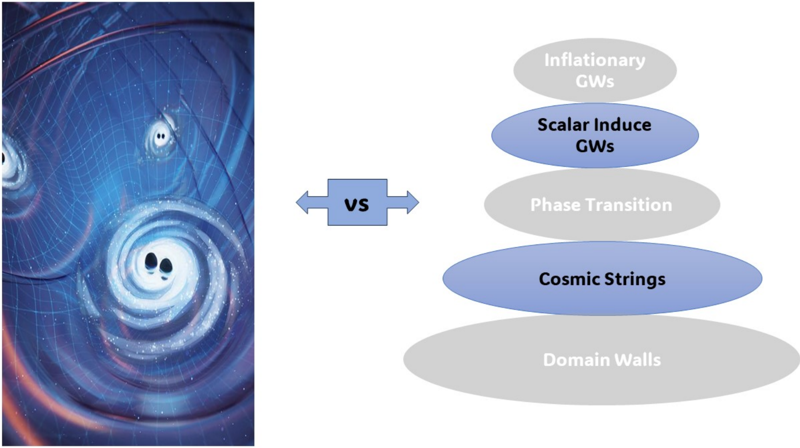




Arxiv: 2306.16213

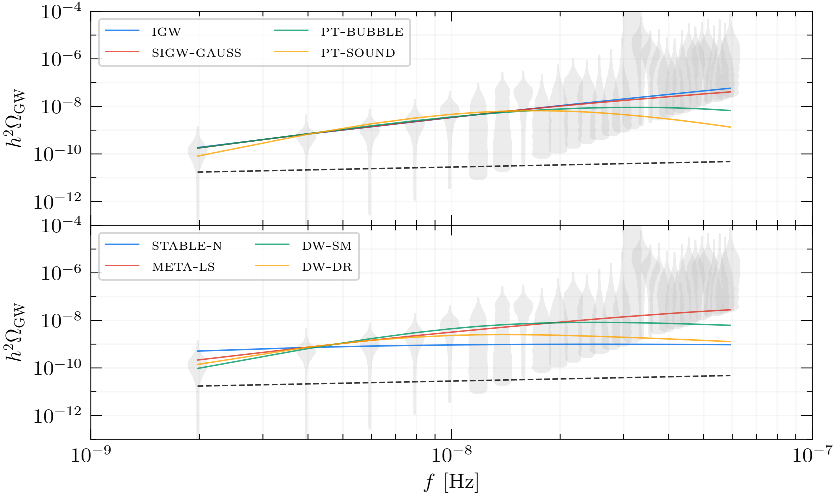



VS
Inflationary GWs
Scalar Induce GWs
Phase Transition
Cosmic Strings
Domain Walls

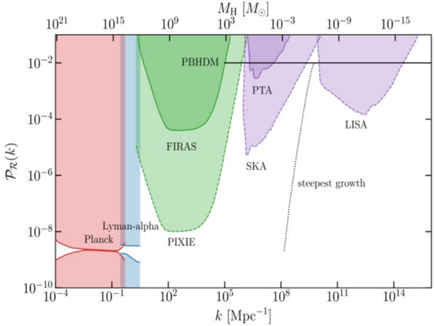

vs
Inflationary GWs
Scalar Induce GWs
Phase Transition
Cosmic Strings
Domain Walls

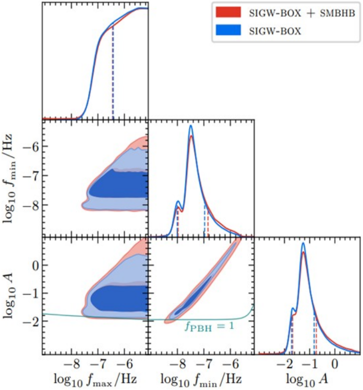
Gravitational Wave Spectra

NANOGrav Collaboration: Adeela Afzal(Munster U. and Quaid-i-Azam U.) et al. e-Print: 2306.16219: APJL



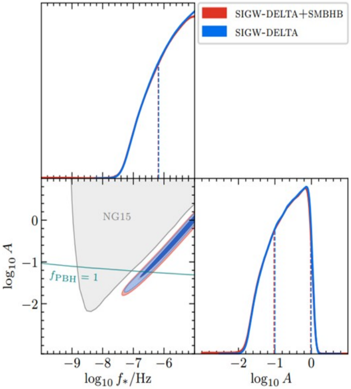
Scalar Induced Gravitational Waves



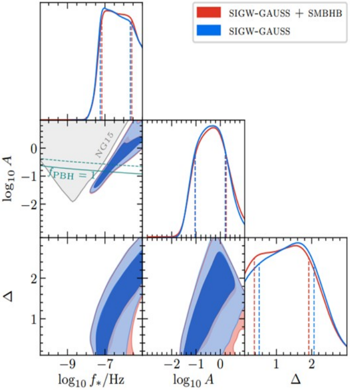


$$\mathcal{P}_\mathcal{R}(k) = A\,\Theta(\ln k_{\rm max} - \ln k)\,\Theta(\ln k - \ln k_{\rm min})$$

Scalar Induced Gravitational Waves

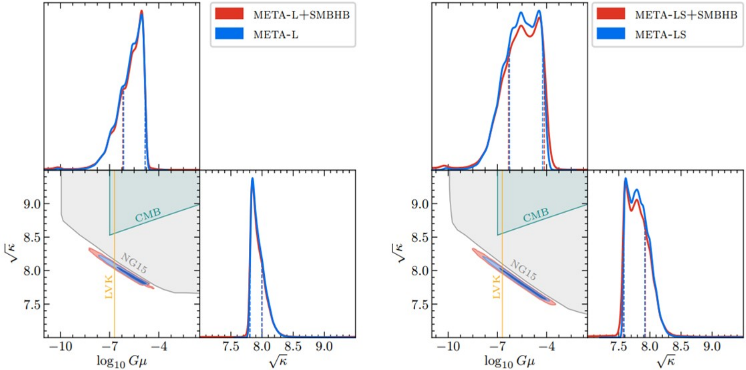


$$\mathcal{P}_{\mathcal{R}}(k) = A\,\delta\left(\ln k - \ln k_*\right)$$

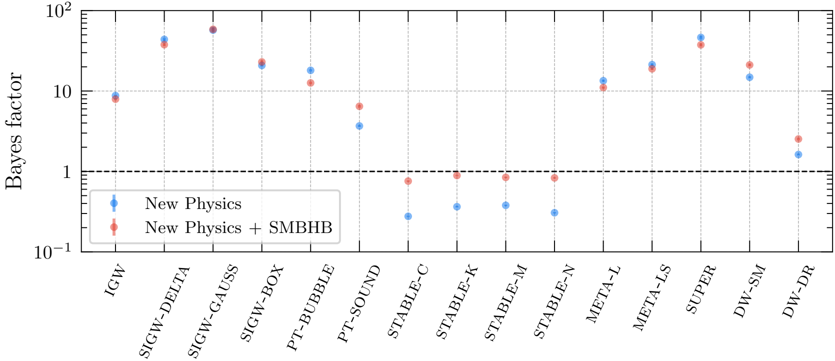


$$\mathcal{P}_{\mathcal{R}}(k) = \frac{A}{\sqrt{2\pi}\,\Delta}\exp\left[-\frac{1}{2}\left(\frac{\ln k - \ln k_*}{\Delta}\right)^2\right]$$

Cosmic Strings

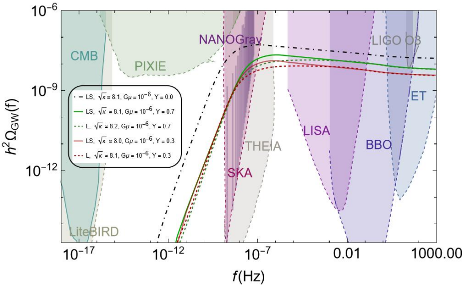


Bayes Factor



BF<1: disfavored, $1-10^{0.5}$: negligibly small, $10^{0.5}-10^{0}$: substantial, $10^{0}-10^{1.5}$: strong, $10^{1.5}-10^{2}$: v. strong, $10^{2}-\infty$: evidence

Super Heavy Metastable Current-carrying Cosmic Strings



$$E_6 \xrightarrow{E_6\ \text{MP}} SO(10) \times U(1)_\psi$$

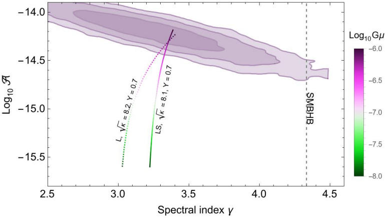
$$\xrightarrow{SO(10)\ \text{MP}} SU(5) \times U(1)_\chi \times U(1)_\psi$$

$$\xrightarrow[\text{Inflation}]{\text{GUT MP}} G_{\text{SM}} \times U(1)_\chi \times U(1)_\psi$$

$$\xrightarrow[\text{CCCS}]{\mathbf{H}^\dagger,\ \text{QN}:\nu_i^c} G_{\text{SM}} \times U(1)_{\psi'}$$

$$\xrightarrow[\text{charged matter fields}]{\text{SCCS: no GW}} G_{\text{SM}}$$

Adeela Afzal(Quaid-i-Azam U.), Qaisar Shafi(Delaware U.), Amit Tiwari(Delaware U.) e-Print: 2311.05564; PLB



Gravitational Waves from Type-I Strings in a Neutrino Mass Model

Adeela Afzal (Dubna, JINR) 2509.11107, PDU

The Neutrino Mass Naturalness Problem

Why are neutrino masses so tiny?

$m_\nu \simeq 0.05\,\text{eV}$ **vs** $m_e \simeq 0.5\,\text{MeV}$ $\sim \mathbf{10^{-6}}$

(Atmospheric scale) (Electron mass)

Standard Model predicts $m_\nu \simeq 0$!

Standard Seesaw Issue

$$m_\nu \approx \frac{m_D^2}{M_R}$$

Requires either:

$Y_\nu \sim 10^{-12}$, (unnaturally tiny) $M_R \sim 10^{14}$ GeV (inaccessible scale)

Both look like fine-tuning!

This Paper's Solution

Extra Dimensions!

Geometry → Natural small Y_{eff}

RH neutrinos "far away" in extra dimension

→ Small wavefunction overlap

→ Naturally tiny effective Yukawa

Left Right Symmetric Model (LRSM)

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\langle\Delta_R\rangle} SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$V(\Delta_R) \supset -\mu^2 \,\mathrm{Tr}[\Delta_R^\dagger \Delta_R] + \lambda \left(\mathrm{Tr}[\Delta_R^\dagger \Delta_R]\right)^2$$

Field	Symbol	Representation
LH quark doublet	Q_L	$(\mathbf{3}, \mathbf{2}, \mathbf{1}, +\frac{1}{3})$
RH quark doublet	Q_R	$(\mathbf{3}, \mathbf{1}, \mathbf{2}, +\frac{1}{3})$
LH lepton doublet	L_L	$(\mathbf{1}, \mathbf{2}, \mathbf{1}, -1)$
RH lepton doublet	L_R	$(\mathbf{1}, \mathbf{1}, \mathbf{2}, -1)$
Higgs bidoublet	Φ	$(\mathbf{1}, \mathbf{2}, \mathbf{2}, 0)$
Left Higgs triplet	Δ_L	$(\mathbf{1}, \mathbf{3}, \mathbf{1}, +2)$
Right Higgs triplet	Δ_R	$(\mathbf{1}, \mathbf{1}, \mathbf{3}, +2)$

$$\mathcal{M} = \frac{SU(2)_R \times U(1)_{B-L}}{U(1)_Y} \to \pi_1(\mathcal{M}) = \mathbb{Z}$$

Give rise to the formation of topologically stable CSs!

Split seesaw in the Brane-world

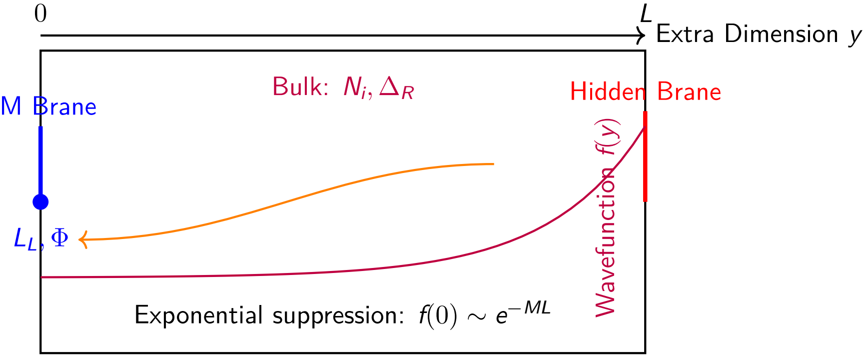


Figure: Brane-world setup for split seesaw mechanism

Split Seesaw

The 5D wavefunction of the i-th RH neutrino and the bulk field Δ_R, localized near the brane at $y = L$, takes the form:

$$\Psi_{N_i,\Delta_R}(x,y) = \psi_{N_i,\Delta_R}(x) f_{i,\Delta_R}(y), \quad \text{with} \quad f_{i,\Delta_R}(y) \simeq \sqrt{\frac{2M_{i,\Delta_R}}{m_{5D}}}\, e^{-M_{i,\Delta_R}|y-L|}.$$

where $M_{i,\Delta_R} > 0$ is the bulk mass that localizes $f_{i,\Delta_R}(y)$ away from $y = 0$. This generates the effective 4D couplings:

$$\lambda_\alpha^{\text{eff}} \propto \lambda_\alpha^{(5D)} \cdot e^{-M_\alpha L}$$

where $\alpha = \{\text{RHN}, \Delta_R\}$.

Extra dimensions explain small couplings geometrically!

Cosmic Strings (CSs)

$$\beta \equiv \frac{m^2_{\Delta_R}}{m^2_{W_R}} = \frac{\lambda}{2g^2} \qquad \begin{cases} \beta < 1: & \text{Type-I (Attractive)} \\ \beta > 1: & \text{Type-II (Repulsive)} \end{cases}$$

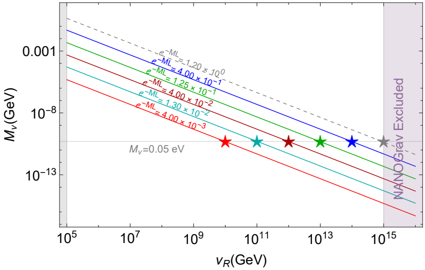
Parameter: $G\mu_{\rm cs}$

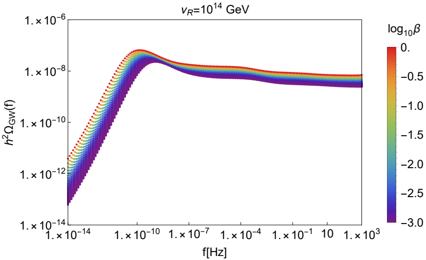
$$\mu_{cs} \simeq 2\pi B(\beta) v_R^2$$

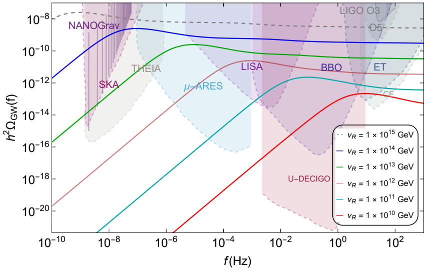
Here v_R is the VEV of the scalar field Δ_R. The function $B(\beta)$ encodes the dependence on the scalar-to-gauge mass ratio. We adopt a phenomenological interpolation formula that approximates numerical solutions across $\beta \leq 1$:

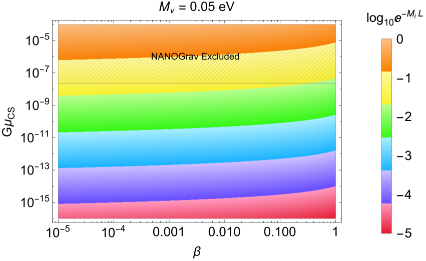
$$B(\beta) \simeq (1 + |Log\,(\beta)\,|)^{-1}.$$

Results


0.001
10^{-8}
10^{-13}
M_ν(GeV)
10^5
10^7
10^9
10^{11}
10^{13}
10^{15}
v_R(GeV)
e^{-ML} = 1.20 × 10^0
e^{-ML} = 4.00 × 10^{-1}
e^{-ML} = 1.25 × 10^{-1}
e^{-ML} = 4.00 × 10^{-2}
e^{-ML} = 1.30 × 10^{-2}
e^{-ML} = 4.00 × 10^{-3}
M_ν=0.05 eV
NANOGrav Excluded


v_R=10^{14} GeV
$h^2\Omega_{GW}(f)$
f[Hz]
$\log_{10}\beta$


$h^2\Omega_{GW}(f)$
f(Hz)
NANOGrav
SKA
THEIA
μ-ARES
LISA
BBO
ET
CE
LIGO O3
O5
U-DECIGO
v_R = 1 × 10^{15} GeV
v_R = 1 × 10^{14} GeV
v_R = 1 × 10^{13} GeV
v_R = 1 × 10^{12} GeV
v_R = 1 × 10^{11} GeV
v_R = 1 × 10^{10} GeV


M_ν = 0.05 eV
$G\mu_{CS}$
β
NANOGrav Excluded
$\log_{10} e^{-M_i L}$

Conclusion

- Possible sources of NANOGrav 15-year dataset
- Super Heavy Metastable Current-carrying CSs are still consistent with LIGO O3 and PTAs
- The geometric explanation for tiny neutrino masses in extra dimensions and the production of observable cosmic strings provides a rare testable bridge between neutrino physics and the early universe.

Thanks for your attention!

Backup Slides

Δ_R Lagrangian and Potential

The relevant kinetic and potential terms for Δ_R are given by:

$$\mathcal{L} \supset \mathrm{Tr}[(D_A\Delta_R)^\dagger(D^A\Delta_R)] - V(\Delta_R),$$

with the covariant derivative defined as:

$$D_A\Delta_R = \partial_A\Delta_R - ig\,[W_{RA}, \Delta_R] - i2g_{B-L}B_A\Delta_R,$$

where ∂_A is the ordinary derivative, g, W_{RA} is the associated gauge coupling and bosons with $SU(2)_R$ respectively, g_{B-L}, B_A is the associated gauge coupling and bosons of $U(1)_{B-L}$. The scalar potential for Δ_R is,

$$V(\Delta_R) = -\mu^2\,\mathrm{Tr}[\Delta_R^\dagger\Delta_R] + \lambda\left(\mathrm{Tr}[\Delta_R^\dagger\Delta_R]\right)^2.$$

Vacuum Stability:

$$\langle\Phi\rangle = \begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_2 \end{pmatrix}, \quad \langle\Delta_L\rangle = 0, \quad \langle\Delta_R\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix},$$

with $v_R \gg \kappa_1$, $\kappa_2 \sim v_{\text{EW}}$. This structure arises in the type-I seesaw limit of the LRSM, where the cross-couplings between Φ, Δ_L and Δ_R in the full scalar potential can be chosen small enough that the global minimum satisfies $\langle\Delta_L\rangle \approx 0$, $\langle\Phi\rangle \simeq v_{\text{EW}} \ll \langle\Delta_R\rangle \simeq v_R$ while maintaining vacuum stability (Mohapatra:1979ia).

$$v_L \simeq \gamma v_{\text{EW}}^2 / v_R$$

Validity of the 4D effective field theory (EFT):

To ensure the validity of the 4D effective field theory (EFT) at the temperature of the $SU(2)_R \times U(1)_{B-L}$ phase transition ($T \sim v_R$), we must impose that the compactification scale, $M_c \sim 1/L$ is significantly higher than v_R. This avoids Kaluza-Klein mode excitation and higher-dimensional operators disrupting the dynamics of CS formation. Consequently, we require

$$v_R \ll M_c < M_i. \tag{1}$$

This hierarchy ensures that the 4D description of the phase transition and the resulting topological defects remains robust.

Mass Generation via Seesaw Mechanism

The relevant Yukawa Lagrangian terms are:

$$\mathcal{L}_Y \supset -Y_\ell \overline{L}_L \Phi L_R - Y_D \overline{L}_L \tilde{\Phi} L_R - \frac{1}{2} Y_R \overline{L^c_R} \Delta_R L_R + \text{h.c.}$$

After symmetry breaking the 6×6 neutrino mass matrix in the basis (ν_L, ν_R) can be written as

$$M_\nu = \begin{pmatrix} m_L & m_D \\ m_D^T & M_R \end{pmatrix},$$

with $m_L = Y_L v_L, m_D = Y_D v_{\text{EW}}$ and $M_R = Y_R v_R$. After diagonalizing

$$M_\nu = m_L - m_D\, M_R^{-1}\, m_D^T \xrightarrow{m_L \to 0} -m_D\, M_R^{-1}\, m_D^T$$ Type-I seesaw!

For our parameter space $v_L \ll v_R$ holds!

GW Emission

The total GW density at the present frequency f is,

$$\Omega_{\rm GW}(f) \simeq \frac{2\,\Gamma\, G\mu_{cs}^2}{\rho_c\, f}\,\frac{\zeta}{\alpha\,(\alpha+\Gamma\, G\mu_{cs})} \times \int_{t_f}^{t_0} d\tilde{t}\left(\frac{a(\tilde{t})}{a(t_0)}\right)^5 \left(\frac{a(t_i)}{a(\tilde{t})}\right)^3 t_i^{-4}.$$

Here $\Gamma \simeq 50$ quantifies the efficiency of GW emission, $G\mu_{cs}$ is the dimensionless string tension, $\rho_c = 3H_0^2/(8\pi G)$ is the critical density (H_0 is the Hubble parameter today and G is Newton's constant). We considered the largest width of the loop parameterized by $\alpha = 0.1$ and $\zeta = 10$, which quantifies the net energy flux associated with the loops. The upper limit on the integration is up to the present time t_0, the lower limit t_f is the time when the CSs enter the scaling regime, $a(t)$ being the scale factor and t_i is the loop formation time given as,

$$t_i = \frac{\tilde{l} + \Gamma\, G\mu_{cs}\,\tilde{t}}{\alpha + \Gamma\, G\mu_{cs}}.$$

Here $\tilde{l} = 2a(\tilde{t})/(fa(t_0))$ is the size of the loop.