Gravitational Waves from Quasi-stable Cosmic Strings and PTA Data

Rinku Maji

with George Lazarides and Qaisar Shafi

CTPU - CGA

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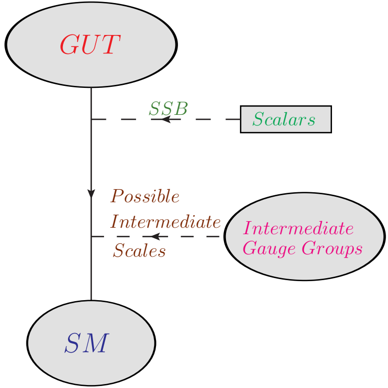
Outline

1. *Introduction*

Grand Unification Beyond the SM

- The basic idea in a Grand Unified Theory (GUT) is that the SM, $SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$, is embedded in a larger simple group, $\mathcal{G}$.

Schematic view

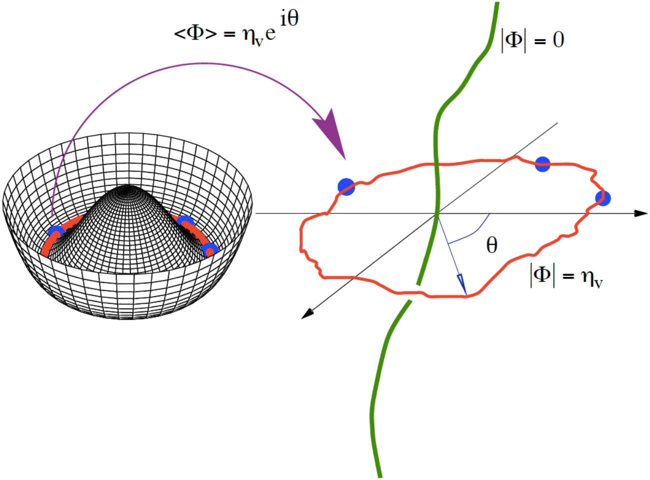


Prediction of Topological Defects

- Topological defects may appear during the SSB of a group $\mathcal{G}$ down to its subgroup $\mathcal{H}$.
- Non-trivial homotopy group $\Pi_k(\mathcal{M})$ of the vacuum manifold $(\mathcal{M} = \mathcal{G}/\mathcal{H})$ implies formation of topological defects.
- Various types of topological defects which can be formed are : domain walls (k = 0), cosmic strings (k = 1), monopoles (k = 2) etc.

2 *Cosmic Strings and Gravitational Waves*

Cosmic String



Vachaspati et. al. arXiv:1506.04039

Cosmic String Network

- String tension $\mu \simeq \pi v^2$, v is the VEV that form the string.

- Strings inter-commute, form loops, radiate GWs and the evolution of the network enters a 'scaling' regime.
- Scaling energy density $\rho_s \sim \mu/t^2$. Critical density: $\rho_c \sim 1/Gt^2$ in RD and MD.

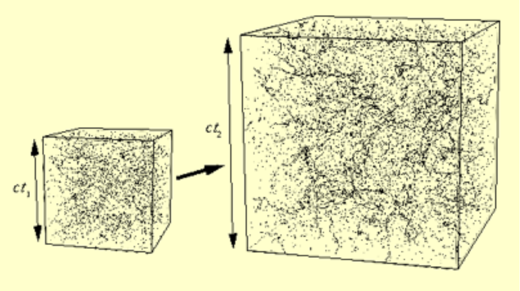
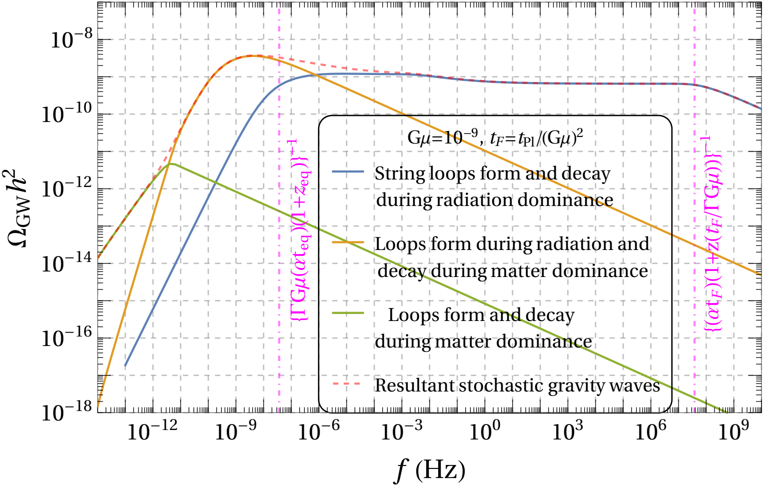


Image source: ctc.cam.ac.uk

Kibble, NPB 252 (1985) 227; Bennett, Bouchet, PRL 60 (1988) 257 ...

Stochastic Gravitational Wave Background



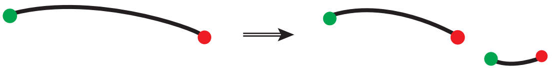
3 *Gravitational Waves from Quasi-stable Cosmic Strings*

Topologically Unstable Cosmic Strings

- Consider $G \xrightarrow{M_I} H \otimes U(1) \xrightarrow{M_{II}} H$
  with G being simply connected and $\Pi_1(G/H) \cong \Pi_0(H) = I$.

- Strings formed at M_{II} connect monopole-antimonopole $(M\bar{M})$ pairs formed at M_I.

- Strings are topologically unstable: $\Gamma_d = \frac{\mu}{2\pi} \exp\left(-\pi m_M^2/\mu\right)$ with $\mu \sim \pi M_{II}^2$ and $m_M \sim (4\pi/g) M_I$.



- However, strings are practically stable unless two breaking scales are very close ($\sqrt{\kappa} \equiv (m_M^2/\mu)^{1/2} \lesssim 9$).

Preskill, Vilenkin, Phys. Rev. D **47** (1993)

Formation of Quasi-stable Strings

- Magnetic monopoles, created prior to the cosmic strings, experience "partial" inflation.
- The lifetime of decay of the strings via quantum mechanical tunneling is larger than the age of Universe.
- The strings make random walks with step of the order of the horizon, and form a network of stable strings before the horizon reentry of the monopoles.

Lazarides, **RM**, Shafi, JCAP 08 (2022) 042

Formation of Quasi-stable Strings

- The strings inter-commute and form loops which decay into gravitational waves.
- As monopoles reenter the horizon at a cosmic time t_M, we obtain monopole-antimonopole pairs connected by string segments which also decay into gravitational waves.
- We call these quasi-stable strings as they form a stable network until the horizon reentry of monopoles.

Lazarides, **RM**, Shafi, JCAP 08 (2022) 042

Gravitational waves from Quasi-stable Strings

- The stochastic gravitational wave background receives contributions from the oscillating string loops before t_M:

$$n_r(l, t < t_M) = \frac{0.18\ \Theta(0.1t - l)}{t^{3/2}(l + \Gamma G\mu t)^{5/2}}.$$

Blanco-Pillado, Olum, Shlaer, Phys. Rev. D **89** (2014) 023512

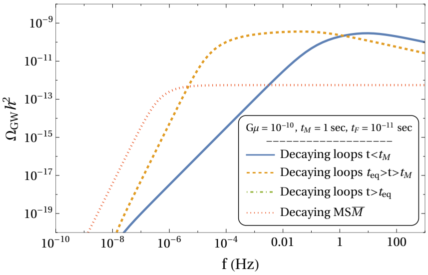
- After t_M, the contributions mainly come
  1. from the decaying string loops formed before t_M:

$$n_r(l, t > t_M) = \frac{0.18\ \Theta(0.1t_M - l - \Gamma G\mu(t - t_M))}{t^{3/2}(l + \Gamma G\mu t)^{5/2}},$$

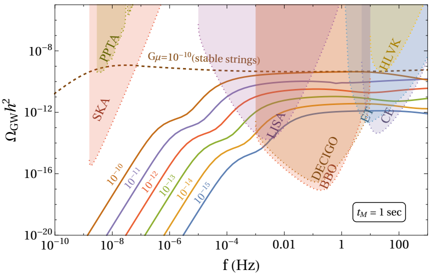
  2. from the oscillating $MS\bar{M}$ structures:

$$\tilde{n}(z) = (2t_M)^{-3}\left(\frac{1+z}{1+z_M}\right)^3.$$

- Large string loops and segments ($> 2t_M$) are absent.
- Gravitational wave spectrum in the low frequency region $f \lesssim 1/t_M(1 + z(t_M/\Gamma G\mu))$ is suppressed.



Different components.



GWs spectra.

Lazarides, **RM**, Shafi, JCAP 08 (2022) 042

4 *Observational Prospects and PTA*

Observational Constraints from Defects

- Stable domain walls contradict standard cosmology.

  Zeldovich, Kobzarev, Okun, Zh. Eksp. Teor. Fiz. **67**, 3-11 (1974)

- Upper bound on comoving monopole number density: $Y_M = n_M/s \gtrsim 10^{-27}$. MACRO: EPJC 25 511, IceCube: PRL 128 (2022) 051101, ANTARES: JHEAp 34 (2022) 1, ...

- CMB constraint on stable strings: $G\mu \lesssim 10^{-7}$.

  PhysRevD.93.123503, ...

- LIGO-VIRGO O3 data constraint on "undiluted" strings: $G\mu \lesssim 10^{-7}$ around decaHz frequencies.

  PhysRevLett.126.241102

- PTA experiments put a constraint on stable cosmic strings : $G\mu \lesssim 10^{-10}$ around the nanoHertz frequencies.

  arXiv:2306.16219,...

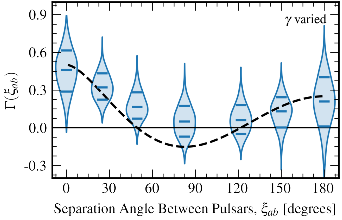
Evidence of GWB in PTA

EPTA

NANOGrav

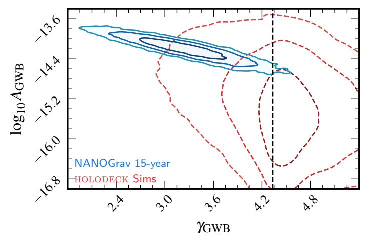
PPTA

InPTA Indian Pulsar Timing Array

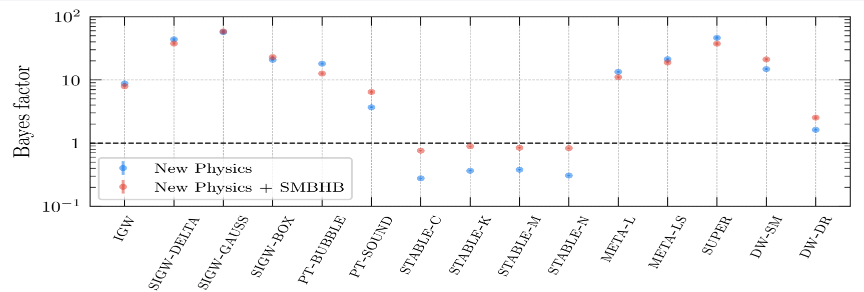


NG15:2306.16219,...

Mergers of SMBHBs?

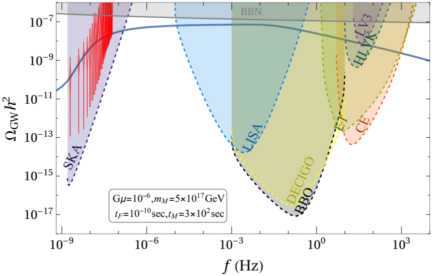


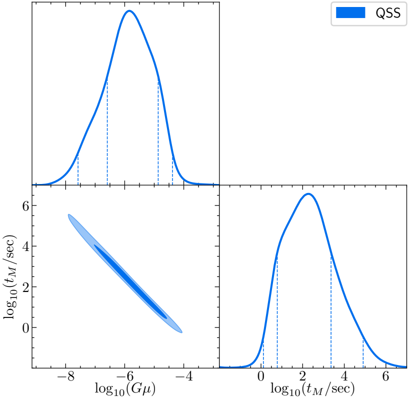
Cosmological Origin? New Physics?



QSS and NANOGrav 15 year data

Parameters	Bayesian Credible Intervals	
	68%	95%
$\log_{10}(G\mu)$	$[-6.59, -4.87]$	$[-7.58, -4.38]$
$\log_{10}(t_M/\text{sec})$	$[0.78, 3.36]$	$[0.12, 4.91]$





Lazarides, **RM**, Shafi, Phys. Rev. D **108** (2023) 095041

5 *Summary*

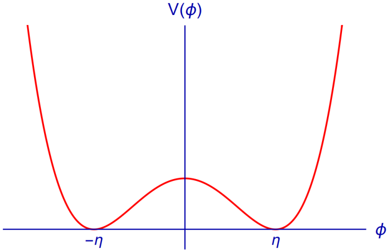
Summary

- The QSS can be formed for $\sqrt{\kappa} \gtrsim 9$, where the scales for monopoles and strings could be well-separated.
- Gravitational wave spectrum generated by QSS will be accessible in the foreseeable future at a number of proposed experiments.
- The GWs from superheavy QSS with $G\mu \sim 10^{-6}$ (GUT scale!) can explain the evidence of GWs in recent PTA data with $t_M \sim 10^2$ sec.
- A partial inflation or an early matter domination helps to alleviate the LIGO-VIRGO O3 bound.

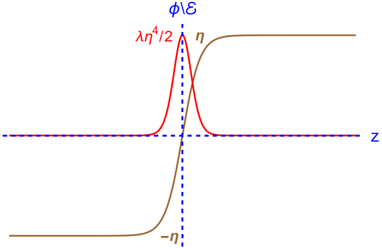
Thank You

Back up slides

Example : Domain wall

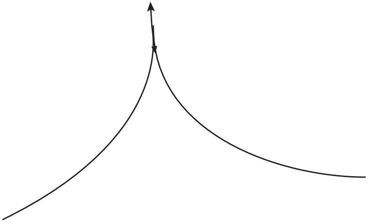


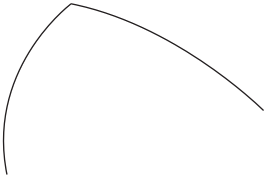
- $\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{\lambda}{4}(\phi^2 - \eta^2)^2$
- Vacuum manifold consists of two disconnected elements : $\langle\phi\rangle = \pm\eta$: $\Pi_0(\mathcal{M}) = \mathbb{Z}_2$.
- Boundary conditions : $\phi \to \pm\eta$ as $z \to \pm\infty$.



- Stationary solution : $\phi(z) = \eta \tanh\left(\sqrt{\frac{\lambda}{2}}\eta z\right)$.
- Energy density : $\mathcal{E} = \frac{\lambda\eta^4}{2}\text{sech}^4\left(\sqrt{\frac{\lambda}{2}}\eta z\right)$.
- Energy per unit area : $\frac{2\sqrt{2}}{3}\sqrt{\lambda}\eta^3$ on xy plane $\Rightarrow$ *Domain Wall*

Cusp and Kink





Strings and Gravitational Waves

- Loops of initial length $\boxed{l_i = \alpha t_i}$ $(\alpha \simeq 0.1)$ decay via emission of gravity waves. Blanco-Pillado, Olum, Shlaer, Phys. Rev. D **89** (2014) 023512

$$\frac{dE_{\rm GW}^{(k)}}{dt} = \Gamma_k G\mu^2; \quad \Gamma_k \propto k^{-n} \quad \text{with } n = \begin{cases} 4/3 & \text{cusps} \\ 5/3 & \text{kinks} \\ 2 & \text{kink-kink collisions.} \end{cases}$$

- The redshifted frequency of a normal mode k, emitted at time $\tilde{t}$, as observed today, is given by Vilenkin, Shellard, 1994, CUP

$$f = \frac{a(\tilde{t})}{a(t_0)} \frac{2k}{\alpha t_i - \Gamma G\mu(\tilde{t} - t_i)}, \quad \text{with} \quad \Gamma = \sum \Gamma_k \sim 50$$

Redshift

$\frac{dl}{dt} = -\Gamma G\mu \Rightarrow$ Loop size at time $\tilde{t}$

SO(10) symmetry breaking and monopoles

$$\begin{aligned} SO(10) &\xrightarrow{M_{\rm GUT}} SU(4)_c \times SU(2)_L \times SU(2)_R \\ &\xrightarrow{M_I} SU(3)_c \times U(1)_{B-L} \times SU(2)_L \times U(1)_R \\ &\xrightarrow{M_{II}} SU(3)_c \times SU(2)_L \times U(1)_Y . \end{aligned}$$

- Symmetry breaking $SU(4)_C \to SU(3)_C \times U(1)_{B-L}$ produces 'Red' monopoles with magnetic fluxes

$$X \equiv B - L + 2T_c^8/3 = diag(1, 1, -1, -1).$$

- $SU(2)_R \to U(1)_R$ generates 'Blue' monopoles with fluxes

$$T_R^3 = diag(1, -1).$$

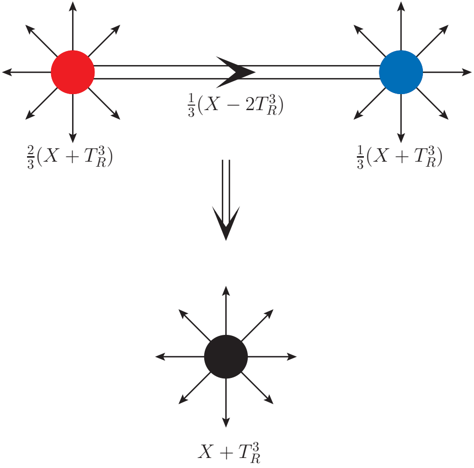
Lazarides, Shafi, JHEP 10 (2019) 193

Strings connecting monopoles

- $U(1)_R \times U(1)_{B-L} \to U(1)_Y$ generates topologically unstable strings.

- These strings connects
  1. a blue monopole to a red monopole: $\mathbf{M_R S M_B}$,
  2. a monopole to its anti-monopole.

- Red and blue monopoles combined to form stable Schwinger monopoles.



Lazarides, Shafi, JHEP 10 (2019) 193

Lazarides, **RM**, Shafi, JCAP 05 (2024)

Pulsar Timing Arrays

- Pulsars are rapidly spinning neutron stars with a strong magnetic field $\Rightarrow$ Radiate beam of radio waves.
- Repeating pulses are observed as the radio beam intersects the observers periodically.
- Millisecond pulsar (MSP) produces exceedingly stable and regular pulse profile $\Rightarrow$ "Perfect Clock".

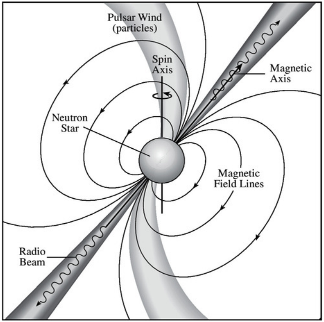
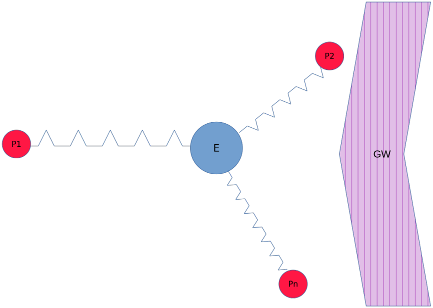


Image source: K.R. Lang, NASA's Cosmos

Pulsar Timing Arrays



- Measurement of the time of arrival (ToA) of pulses can reveal tiny distortion of spacetime fabric due to gravity waves (GWs) $\Rightarrow$ Pulsar timing!

Image source: Wikipedia

- Difference between observed ToA and the expected ToA from timing model gives time residual.
- Time residual contains information about other signals like GWs.

Pulsar Timing Arrays

- Impossible to distinguish between GWs signal and other source of signal in the timing residual of a single pulsar.
- Need correlations between the timing residuals of different pulsars $\Rightarrow$ Pulsar Timing Array (PTA).
- Gravity waves generate unique quadrupolar correlations between timing residuals of pulsar pairs.
- Correlations depend on the angular separations between the pulsar pairs and follow the Hellings and Downs correlation curve. **APJ. 265, L39 (1983)**

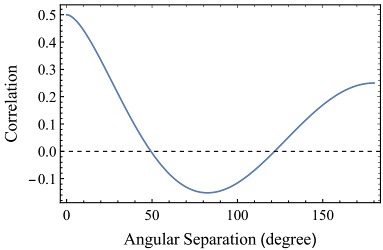
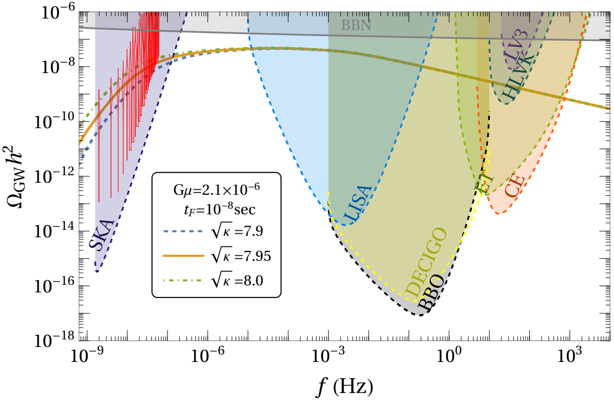


Figure: Hellings and Downs curve.

Metastable Strings: PTA and LIGO-VIRGO



- The GWs from MSS explain PTA data at nanoHertz frequency, but violate the bound from LIGO-VIRGO third observing run!
- An early matter domination or partial inflation can reduce the spectra at high f.

Lazarides, **RM**, Moursy, Shafi, JCAP 03 (2024) 006
RM, Park, JCAP 01 (2024) 015

Formation of Metastable Strings (MSS)

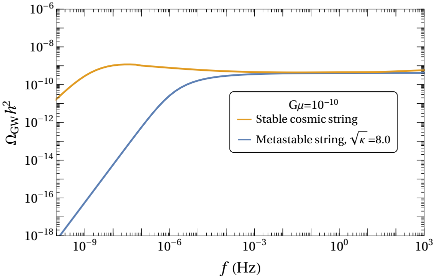
- Magnetic monopoles, created prior to the cosmic strings, experience inflation.
- The lifetime of decay of the strings via quantum mechanical tunneling is much smaller than the age of Universe.
- The strings form a network of stable strings before the time $t_s = 1/\sqrt{\Gamma_d}$.
- The strings network disappear at a time $t_e \sim 1/\sqrt{\Gamma_d \Gamma G\mu}$.

Leblond, Shlaer, Siemens, PRD **79** (2009) 123519

Buchmuller, Domcke, Schmitz, JCAP **12** (2021) 006

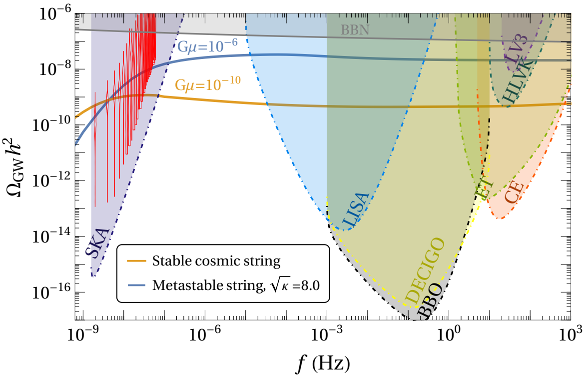
Metastable Strings and GWs

- The strings inter-commute and form loops which decay into gravitational waves.
- String loops larger than αt_s are absent.



- Gravitational wave spectrum in the low frequency region, $f \lesssim 1/\Gamma G\mu t_e(1+z_e)$, becomes suppressed.

PTA and Observational Prospects of Strings



- Pulsar Timing Arrays (PTAs)
  1. found evidence of a stochastic background which can be explained by superheavy "metastable" strings $G\mu \sim 10^{-6} - 10^{-5}$.
  2. put a contraint "undiluted stable" cosmic strings : $G\mu \lesssim 10^{-10}$.

in the nanoHertz frequencies. arXiv:2306.16219,...