Probing SUSY at Gravitational Wave Observatories

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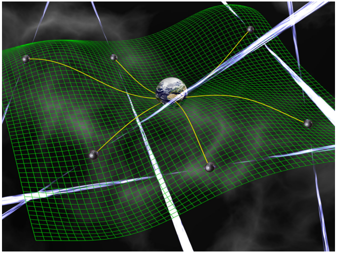
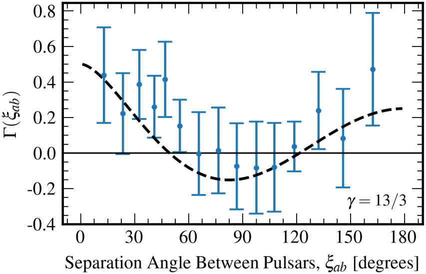
Gravitational Wave Probes of Physics Beyond Standard Model 4
June 24, 2025

Based on: - Phys.Rev.D 108 (2023) 9, 095053 (S. Antusch, KH, S. Saad, J. Steiner)
- Phys.Lett.B 856 (2024) 138924 (S. Antusch, KH, S. Saad, J. Steiner)
- JCAP 10 (2024) 007 (S. Antusch, KH, S. Saad)

Pulsar Timing Arrays: 2023

- PTA results point to a stochastic gravitational wave background (SGWB) at nHz frequencies





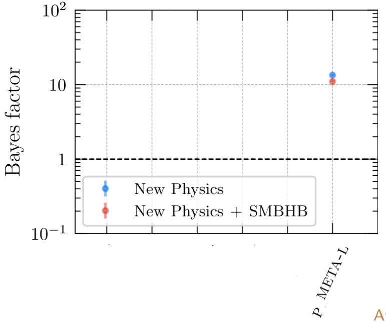
Agazie et al, ApJL 951 (2023) 1, L8

- NanoGrav, EPTA+InPTA, PPTA, CPTA

- What is the origin? Supermassive BH binaries? BSM physics?

Signals from New Physics?

- Metastable cosmic strings (MSCSs) provide a better fit than supermassive BH binaries



Afzal et al, ApJL 951 (2023) 1, L11

- MSCSs can arise in BSM scenarios with extended gauge symmetry (such as SO(10) GUTs)

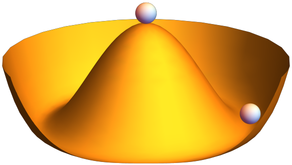
Outline

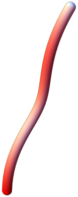
Assumption: MSCSs are the correct explanation of the PTA result

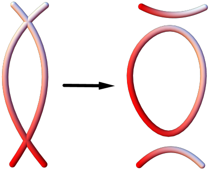
- Potential to discover signs of NP with extra DOF (such as SUSY) up to $m_{\mathrm{NP}} \sim 10^7$ GeV
- Possibility to look for non-standard cosmological effects
- Hint towards SO(10) GUTs, and help to single out SO(10) breaking chains

Cosmic Strings

- Spontaneous symmetry breaking $G \to H$ with non-trivial homotopy group $\pi_1(G/H)$, e.g. $U(1) \to 1$





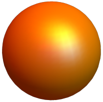


- Cosmic string tension: $\mu \sim 2\pi v_{cs}^2$

Abrikosov (1957); Nielsen, Olesen (1973); Kibble (1976)

Monopoles

- Spontaneous symmetry breaking $G \to H$ with non-trivial homotopy group $\pi_2(G/H)$, e.g. $SU(2) \to U(1)$
- Monopole mass: $m \sim \frac{4\pi v_m}{g}$

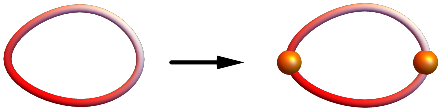


- Have to be diluted since they would overclose the universe

't Hooft (1974); Polyakov (1974); Kibble (1976); Preskill (1979)

Metastable Cosmic Strings

- Multistep spontaneous symmetry breaking, e.g.
  $SU(2) \xrightarrow[\text{production}]{\text{monopole}} U(1) \xrightarrow[\text{production}]{\text{cosmic string}} 1$

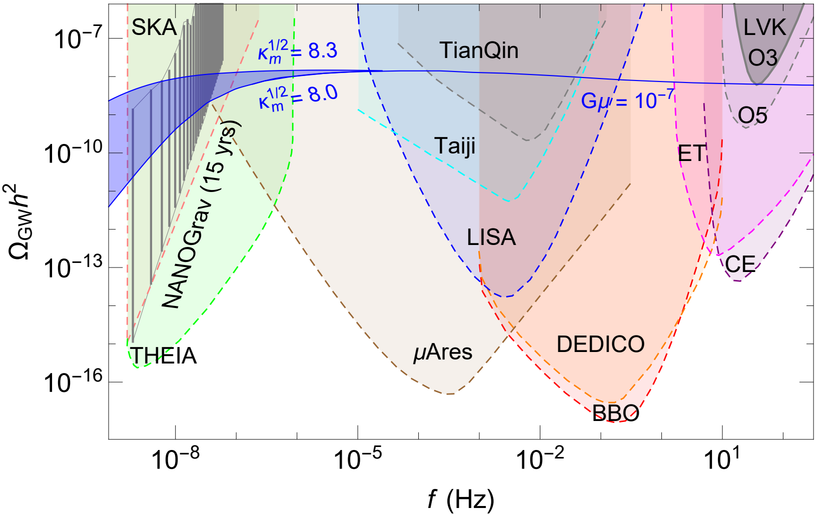


- Strings can decay by monopole-antimonopole nucleation

- Lifetime: $t_s = \sqrt{\frac{2\pi}{\mu}} e^{\pi\kappa}, \;\; \kappa = \frac{m^2}{\mu} \sim \frac{8\pi}{g^2} \frac{v_m^2}{v_{cs}^2}$

Lazarides, Shafi, Walsh (1982); Vilenkin (1982)

Gravitational Wave Spectrum



Antusch, KH, Saad, Steiner (2023)

Computation of GW Spectrum

Step 1: Determine expansion history of the universe

$$H(z) = H_0 \left(\Omega_\Lambda + (1+z)^3\Omega_{\rm mat} + (1+z)^4\mathcal{G}(z)\Omega_{\rm rad}\right)^{1/2},$$

$$\mathcal{G}(z) = \frac{g_*(z) g_{\rm S}^{4/3}(z_0)}{g_*(z_0) g_{\rm S}^{4/3}(z)}$$ degrees of freedom

Step 2: Compute cosmic string loop number density

$$\underbrace{\left[-\Gamma\, G\mu\,\partial_\ell + \partial_t\right] n(\ell,t)}_{\text{gravitational wave emission}} = \underbrace{S(\ell,t)}_{\text{loop production}} - \underbrace{3H(t)\,n(\ell,t)}_{\text{cosmic expansion}} - \underbrace{\Gamma_d \ell\, n(\ell,t)}_{\text{monopole nucleation}}$$

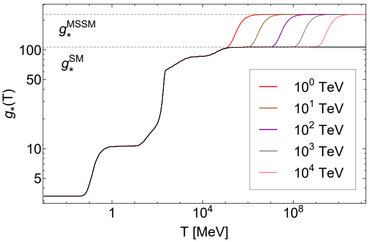
Step 3: Compute gravitational wave spectrum

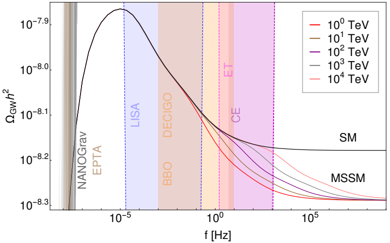
$$\Omega_{\rm GW}(f,t) = \frac{8\pi (G\mu)^2}{3H^2(t)} \sum_{k=1}^{\infty} C_k P_k\,,$$

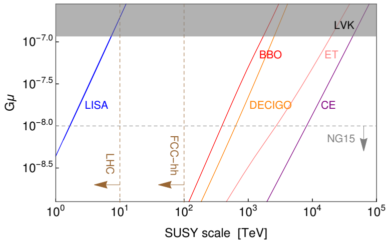
$$C_k = \frac{2k}{f^2} \int_{z(t)}^{z_c} \frac{dz}{H(z)(1+z)^6}\, n\left(\frac{2k}{f(1+z)}, t(z)\right)$$ vibration modes

Blanco-Pillado, Olum, Shlaer, (2013), (2017); Buchmüller, Domcke, Schmitz (2021)

Probing SUSY







Fisher analysis for $G\mu = 10^{-7}$

quantity	uncertainty
Δg_*	10%
m_{SUSY}	5%

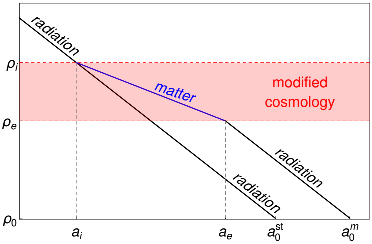
for $\begin{cases} m_{SUSY} < 2 \text{ PeV} & \text{at ET} \\ m_{SUSY} < 10 \text{ PeV} & \text{at CE} \end{cases}$

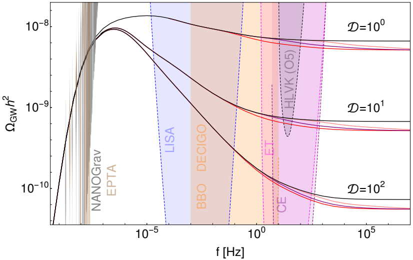
Antusch, KH, Saad, Steiner (2024)

See also: Battye, Caldwell, Shellard (1997); Cui, Lewicki, Morrissey, Wells (2018); Auclair et al. (2019)

Probing Intermediate Matter Era

- Additional dilution of earlier produced gravitational waves approximately by factor $\mathcal{D} = \frac{a_e}{a_i}$





Antusch, KH, Saad, Steiner (2024)

See also: Cui, Lewicki, Morrissey, Wells (2017, 2018); Auclair et al. (2019); Gouttenoire, Servant, Simakachorn (2019a, 2019b); Blasi, Brdar, Schmitz (2020); Ghoshal, Gouttenoire, Heurtier, Simakachorn (2023)

MSCSs from SO(10) GUTs

- Criteria
  - Gauge coupling unification
  - Proton decay bounds
  - Fermion masses
  - Hierarchy problem
  - Doublet-triplet splitting
  - Cosmic inflation
  - Lower-dimensional representations

- $W = W_{\text{GUT}-\text{breaking}} + \underbrace{W_{\text{inflation}} + W_{\text{mixed}}}_{W_{\text{intermediate-breaking}}} + W_{\text{DTS}} + W_{\text{Yukawa}}$

Antusch, KH, Saad, Steiner (2023); Antusch, KH, Saad (2024)

SO(10) Breaking

- $\mathbf{45_H} + \mathbf{45'_H} + \mathbf{16_H} + \overline{\mathbf{16}}_\mathbf{H}$
  - $B-L$ direction $\mathbf{45_H} \sim \langle a, a, a, 0, 0\rangle$
  - I_{3R} direction $\mathbf{45'_H} \sim \langle 0, 0, 0, b, b\rangle$

- Breaking chains

$$(a)\quad \underbrace{SO(10) \xrightarrow[M_{\rm GUT}]{45_H} 3221 \xrightarrow[M_I]{45'_H} \overbrace{3211}^{\text{}}}_{\text{monopoles}} \xrightarrow[M_{II}]{16_H+\overline{16}_H} 321$$

cosmic strings: $3211 \xrightarrow[M_{II}]{16_H+\overline{16}_H} 321$

$$(b)\quad \underbrace{SO(10) \xrightarrow[M_{\rm GUT}]{45'_H} 421 \xrightarrow[M_I]{45_H} 3211}_{\text{monopoles}} \xrightarrow[M_{II}]{16_H+\overline{16}_H} 321$$

cosmic strings: $3211 \xrightarrow[M_{II}]{16_H+\overline{16}_H} 321$

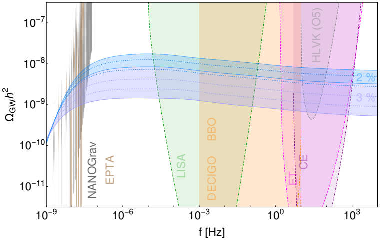
$$(c)\quad \underbrace{SO(10) \xrightarrow[M_{\rm GUT}]{45_H+45'_H} 3211}_{\text{monopoles}} \xrightarrow[M_I]{16_H+\overline{16}_H} 321$$

cosmic strings: $3211 \xrightarrow[M_I]{16_H+\overline{16}_H} 321$

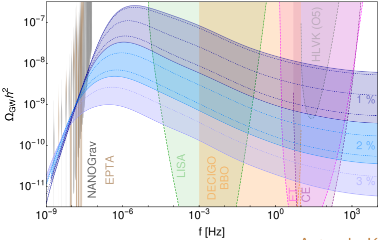
Antusch, KH, Saad, Steiner (2023); Antusch, KH, Saad (2024)

Gravitational Wave Spectrum

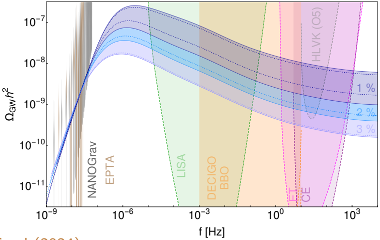
GW spectrum with standard cosmology, case (a)



GW spectrum with an intermediate matter era, case (a)



GW spectrum with an intermediate matter era, case (b)



Antusch, KH, Saad (2024)

Summary

Assumption: MSCSs are the correct explanation of the PTA result

- Fantastic reach for NP with extra DOF (such as SUSY)
  - ET and CE can look for NP scales as high as 10^7 GeV with measurement uncertainty of 5% for the NP scale and 10% for the number of DOF
- Probe for non-standard cosmological effects (such as an intermediate phase of MD)
  - Would delay discovery at LVK, but signs of extra particle DOF from NP could nevertheless be observed
- MSCSs could originate from the symmetry breaking of an SO(10) GUT