Gravitational waves from metastable cosmic strings

Based on work in collaboration with W. Buchmüller, V. Domcke, and H. Murayama
[1912.03695, 2009.10649, 2107.04578]

Kai Schmitz
Junior professor at the University of Münster, Germany

Cambridge High Energy Workshop 2022, Harvard University
Phase Transitions and Topological Defects in the Early Universe
Center of Mathematical Sciences and Applications | August 3, 2022

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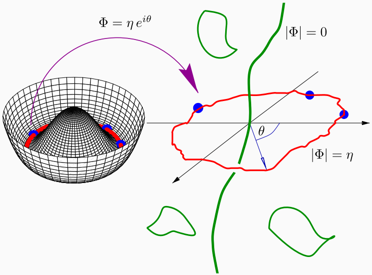

[Ringeval: 1005.4842]

Cosmic strings:

- Topological defects after $U(1)$ breaking in the early Universe

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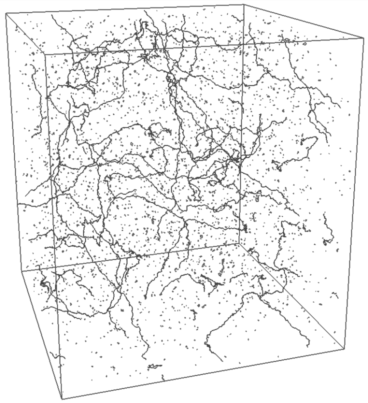

[Allen, Martins, Shellard: ctc.cam.ac.uk/outreach]

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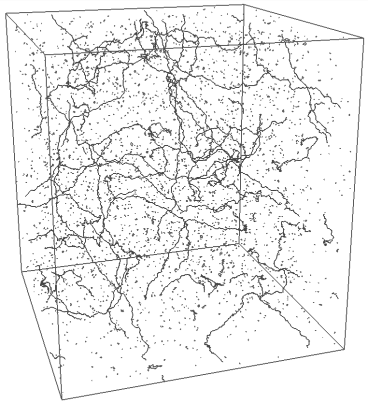

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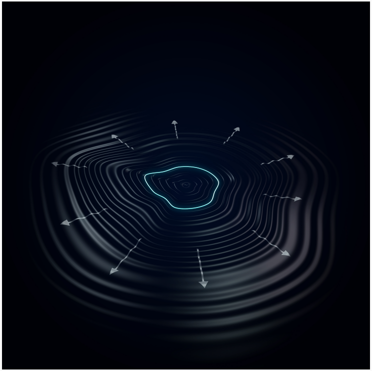

[CERN]

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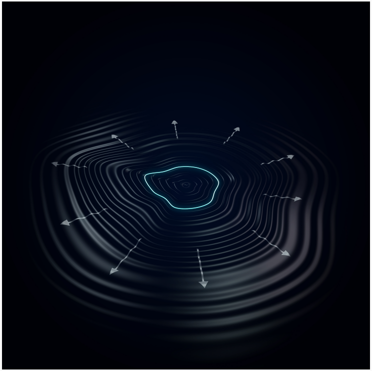

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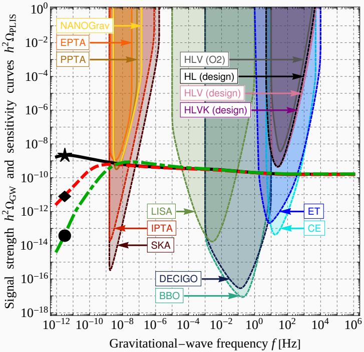
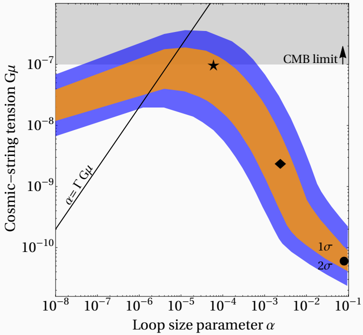
Assumption: Energy loss via particle emission off closed loops is negligible

[Matsunami, Pogosian, Saurabh, Vachaspati: 1903.05102] [Hindmarsh, Lizarraga, Urio, Urrestilla: 2103.16248]

Stable cosmic strings and NANOGrav

[Blasi, Brdar, **KS**: 2009.06607]
[See also Ellis, Lewicki: 2009.06555]





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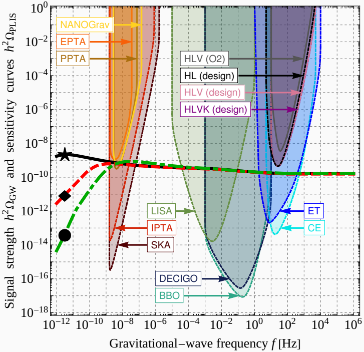

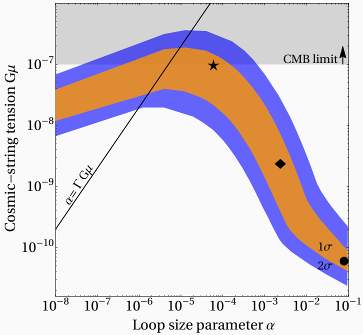

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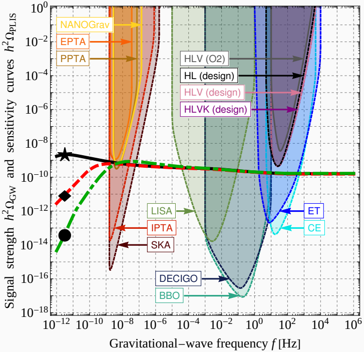

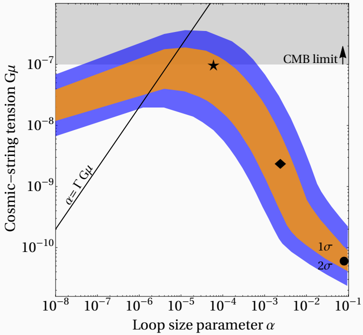

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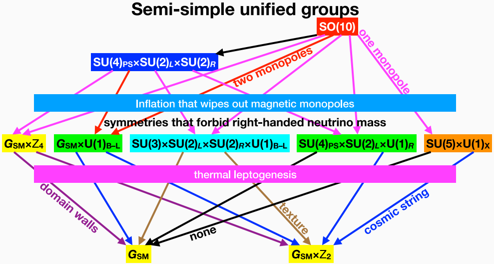
- ☹ Signal at higher frequencies too small for LIGO, Virgo, KAGRA

Cosmic strings and grand unification

[Dror, Hiramatsu, Kohri, Murayama, White: 1908.03227]
[See also King, Pascoli, Turner, Zhou: 2005.13549, 2106.15634]



UV embedding of the seesaw mechanism in GUT models:

Neutrino mass, leptogenesis, cosmic strings, GWs, proton decay

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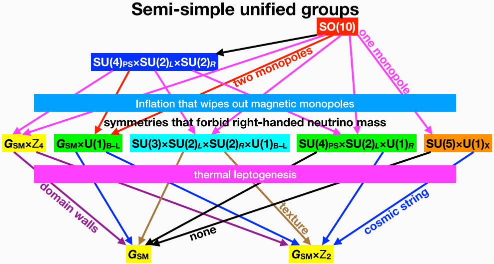

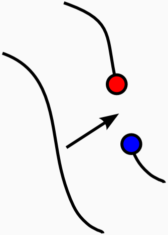

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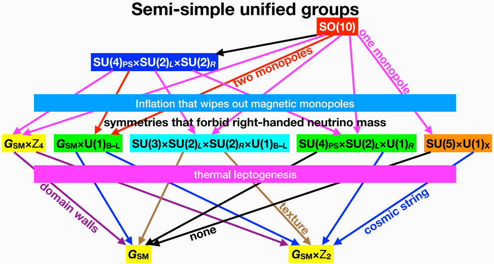

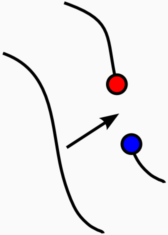

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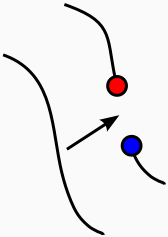
Assumption: Inflation dilutes monopoles; otherwise string–monopole gas

Monopole pair production



Decay rate per string length:

[Vilenkin: Nucl. Phys. B 196 (1982) 240]
[Preskill, Vilenkin: hep-ph/9209210]
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$$\Gamma_d = \frac{d\#}{dt d\ell} = \frac{\mu}{2\pi}\, e^{-\pi\,\kappa}\,, \qquad \kappa = \frac{m^2}{\mu} \tag{1}$$

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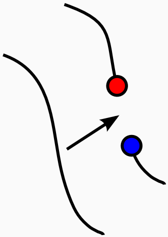

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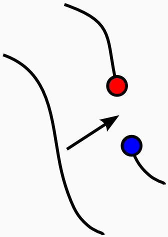

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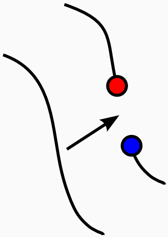

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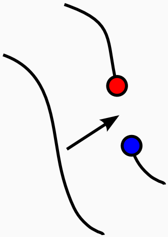

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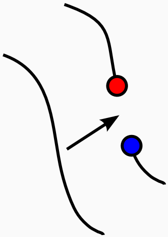

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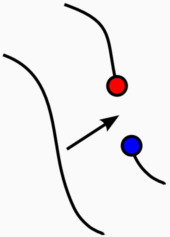

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Monopoles with and without unconfined magnetic flux:

- Unconfined flux: $M\bar{M}$ annihilation, emission of massless gauge bosons
- No unconfined flux: energy loss only via emission of gravitational waves

Possible scenarios

$$W_{B-L} = \lambda T \left(S\bar{S} - \frac{1}{2}\, v_{B-L}^2 \right) + \frac{h_i}{M_*} S^2 N_i^2 \tag{2}$$

$B-L$ phase transition after supersymmetric hybrid inflation:

- T: inflaton, S, $\bar{S}$: Higgs / waterfall fields, N_i: right-handed neutrinos

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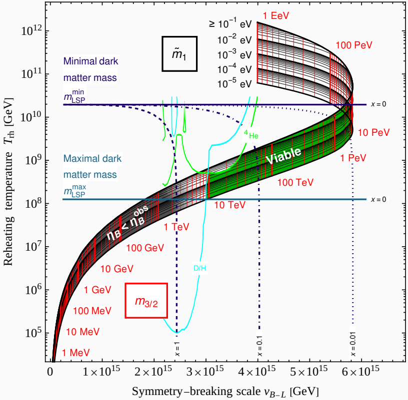

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$v_{B-L} \sim (3 \cdots 6) \times 10^{15}\,\mathrm{GeV}$

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[Buchmüller, Domcke, **KS**: 1111.3872, 1202.6679, 1203.0285]
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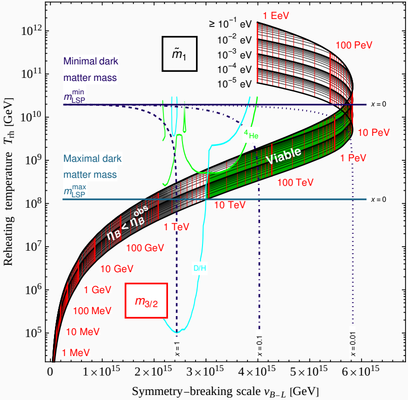

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Minimal alternative: $SU(2) \times U(1) \xrightarrow{\text{triplet}} U(1) \times U(1) \xrightarrow{\text{doublets}} U(1)$

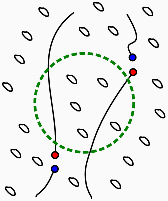
[Buchmüller: 2102.08923]

Strategy

End of scaling when long string segments begin to enter the horizon:

[Leblond, Shlaer, Siemens: 0903.4686]

$$\Gamma_d \, \ell \, t_s \sim \Gamma_d H^{-1} \, t_s \sim \Gamma_d t_s^2 \sim 1 \quad \Rightarrow \quad t_s \sim \frac{1}{\sqrt{\Gamma_d}} \tag{3}$$



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- Loops: emit GWs, decay into segments negligible
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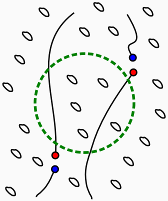

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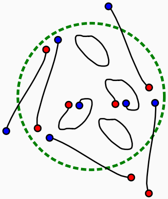

Decay regime, $t > t_s$

- Loops: emit GWs and decay into segments
- Segments from loops and long strings: emit GWs and decay into segments; no production of new loops

Formal description

Kinetic equation for the number densities of loops and segments, $\mathring{n}$ and $\tilde{n}$:

$$\partial_t \, n(\ell, t) = S(\ell, t) - \partial_\ell \left[u(\ell, t) \, n(\ell, t) \right] - \left[3H(t) + \Gamma_d \, \ell \right] n(\ell, t) \tag{4}$$

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Time derivative of the string length $u = \dot{\ell}$:

- Long strings during scaling: $u = 3H\,(t)\, \ell - 2\ell / t$

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- Long strings during scaling: $u = 3H\,(t)\,\ell - 2\ell/t$
- Loops and segments when radiating off GWs: $u = -\Gamma G\mu$, $-\tilde{\Gamma} G\mu$

Formal description

Kinetic equation for the number densities of loops and segments, $\mathring{n}$ and $\tilde{n}$:

$$\partial_t\, n(\ell, t) = S(\ell, t) - \partial_\ell \left[u(\ell, t)\, n(\ell, t)\right] - \left[3H(t) + \Gamma_d\, \ell\right] n(\ell, t) \quad (4)$$

Source term S:

- Loops from long strings (loop production function): $S \propto t^{-4}\, \delta(\ell - \alpha t)$
- Loops during the decay regime: $S = 0$
- Segments from loops: $S = \Gamma_d\, \ell\, \mathring{n}(\ell, t)$
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Challenge: Solve set of partial integro-differential equations in both the scaling and decay regimes, match solutions at $t = t_s$. (Plus, RD / MD.)

Number densities

Loop number density during the decay regime in the radiation era:

[Cf. Blanco-Pillado, Olum, Shlaer: 1309.6637] [Cf. Blanco-Pillado, Olum: 1709.02693]

$$\mathring{n}^{\rm rr}_{>}(\ell, t) = \frac{B\, e^{-\Gamma_d\left[\ell(t-t_s)+1/2\,\Gamma G\mu(t-t_s)^2\right]}}{t^{3/2}\left(\ell + \Gamma G\mu t\right)^{5/2}}\,\Theta\left(\alpha t_s - \bar{\ell}(t_s)\right)\,\Theta\left(t_{\rm eq} - t\right) \quad (5)$$

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because of new exponential suppression factor:

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Similar results for $\mathring{n}_{<}^{\mathrm{rr}}$, $\mathring{n}_{<}^{\mathrm{rm}}$, $\mathring{n}_{<}^{\mathrm{mm}}$, $\mathring{n}_{>}^{\mathrm{rm}}$, $\mathring{n}_{>}^{\mathrm{mm}}$, $\tilde{n}_{<}^{(s)\,\mathrm{rr}}$, $\tilde{n}_{<}^{(s)\,\mathrm{mm}}$, $\tilde{n}_{>}^{(s)\,\mathrm{rr}}$, $\tilde{n}_{>}^{(s)\,\mathrm{rm}}$, $\tilde{n}_{>}^{(s)\,\mathrm{mm}}$, $\tilde{n}_{>}^{(l)\,\mathrm{rr}}$, $\tilde{n}_{>}^{(l)\,\mathrm{rm}}$, $\tilde{n}_{>}^{(l)\,\mathrm{mm}}$. The integro-differential equation for $\tilde{n}_{>}^{(l)}$ is solved by an infinite series that needs be evaluated order by order.

Spectrum

Compute GW spectrum following the standard procedure:

$$\Omega_{\mathrm{gw}}(f) = \frac{G\mu^2}{\rho_{\mathrm{crit}}} \sum_k P_k \frac{2k}{f} \int_{t_{\mathrm{ini}}}^{t_0} dt \left[\frac{a(t)}{a(t_0)}\right]^5 n\left(\frac{a(t)}{a(t_0)} \frac{2k}{f}, t\right) \tag{7}$$

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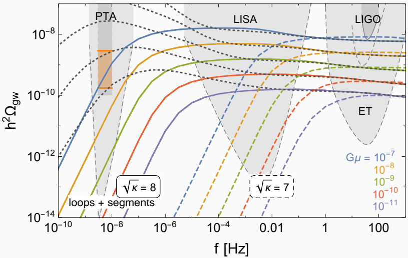

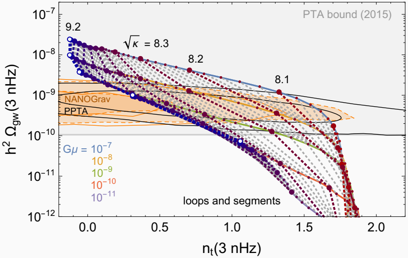

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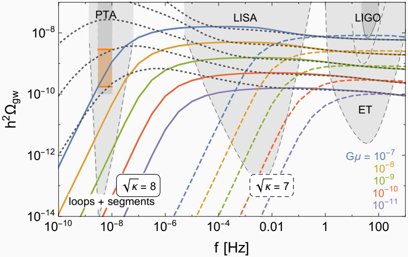

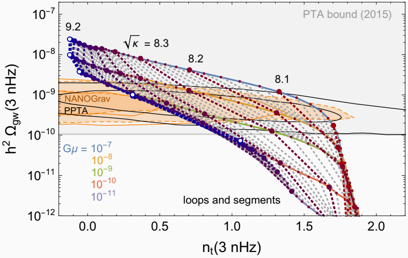

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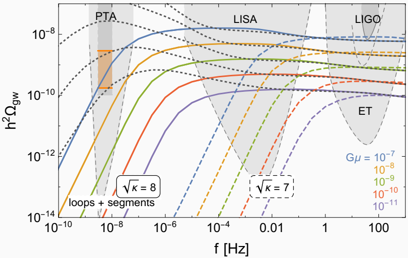

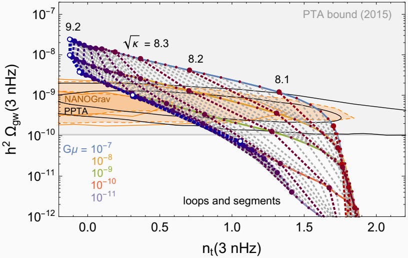

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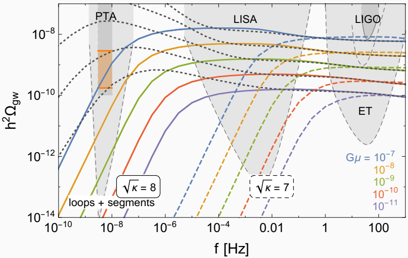

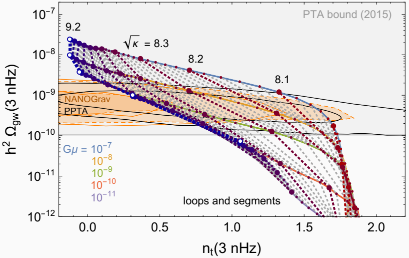

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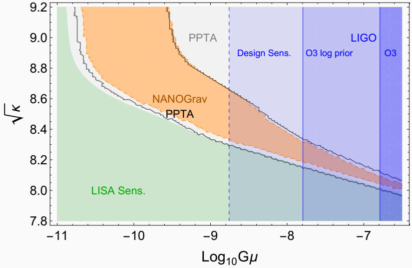
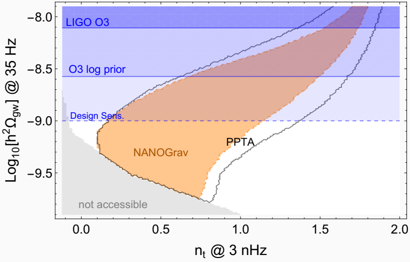
Observational prospects

Extrapolate spectrum to large f and compare with LIGO, Virgo, KAGRA:





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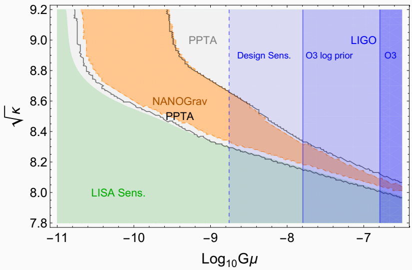

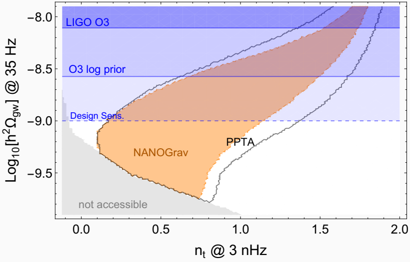

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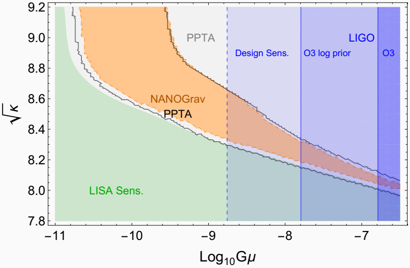

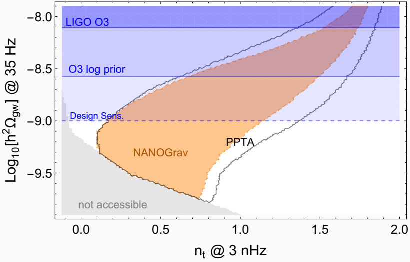

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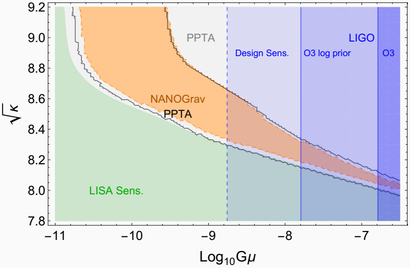

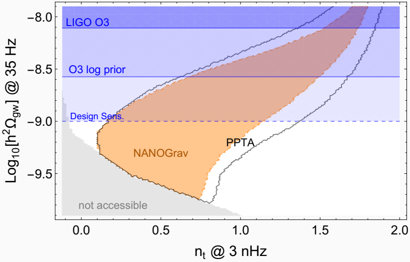

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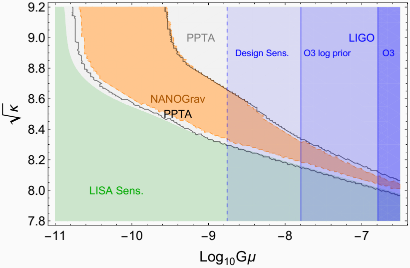

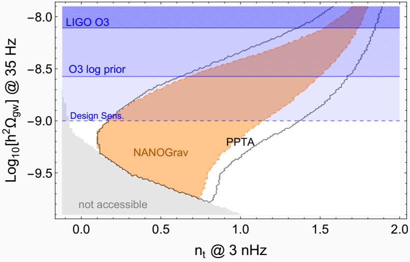

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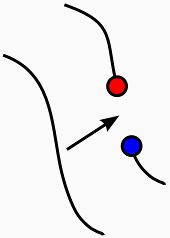
- LISA will probe the entire parameter space consistent with NANOGrav

Conclusions and outlook



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- Prediction in many GUT models when combined with inflation to solve the monopole problem

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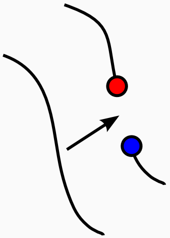

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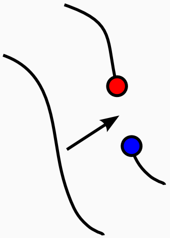

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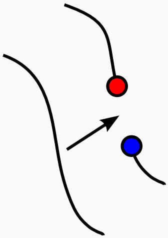

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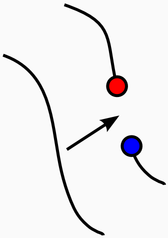

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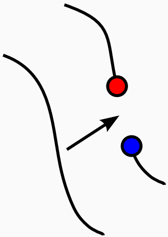

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Thank you very much for your attention!