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 (today)]

Kai Schmitz
MSCA Fellow in the CERN Theory Group

Gravitational Wave Probes of Physics Beyond Standard Model
Online workshop | Session on topological defects | 12 July 2021

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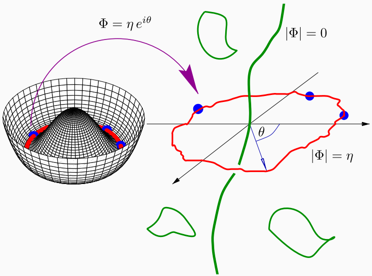
[See also talk by Hitoshi + all other talks today]



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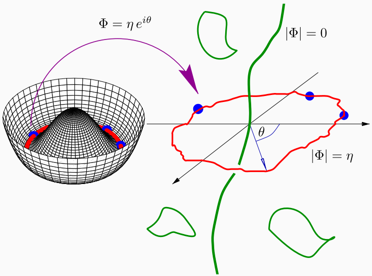

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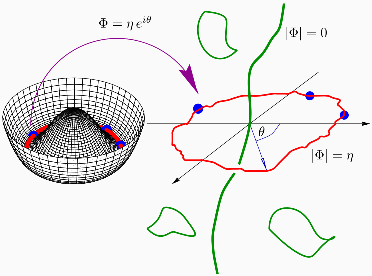

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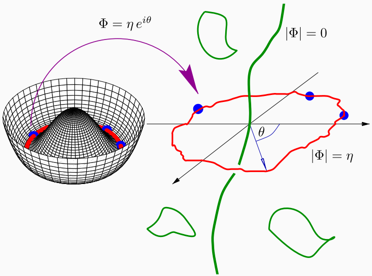

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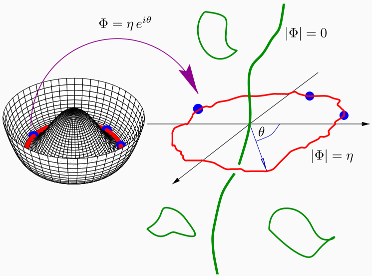

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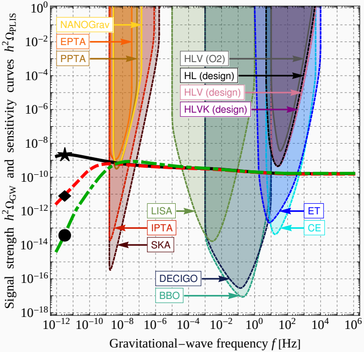
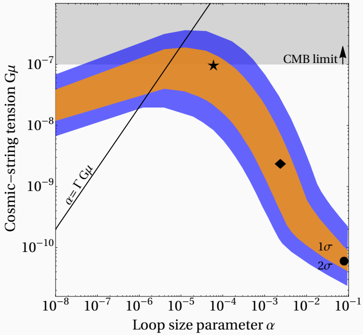
Assumption: Energy loss via particle emission off closed loops is negligible

[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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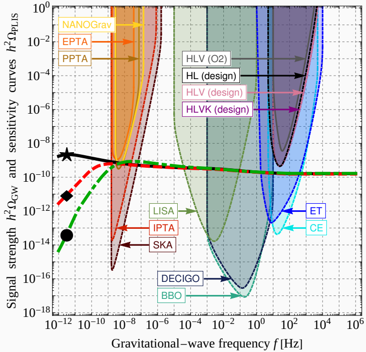

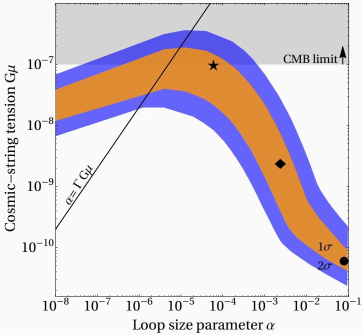

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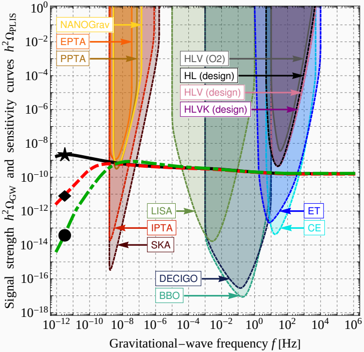

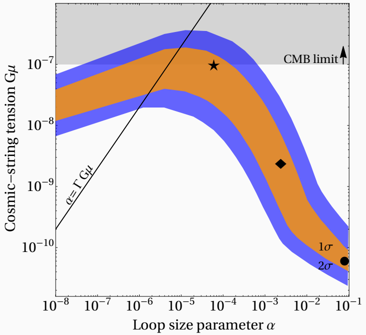

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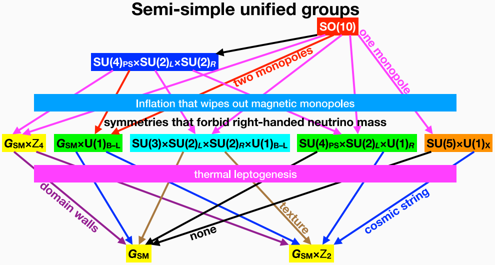
- ☹ Signal at higher frequencies too small for LIGO, Virgo, KAGRA

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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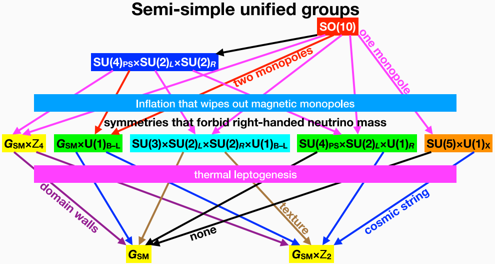

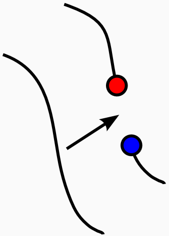

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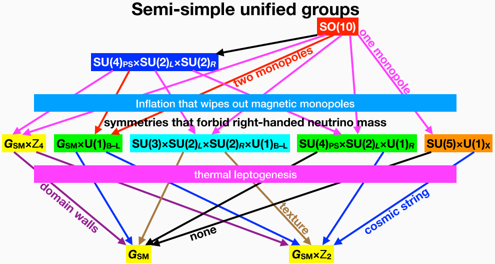

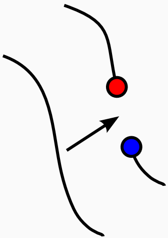

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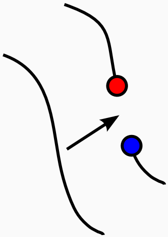
Assumption: Inflation dilutes monopoles; otherwise string–monopole gas

Monopole pair production



Decay rate per string length:

[Vilenkin: Nucl. Phys. B 196 (1982) 240]
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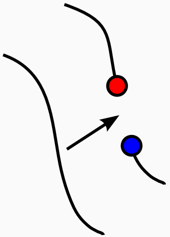

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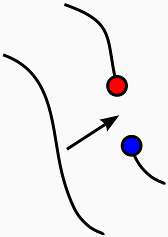

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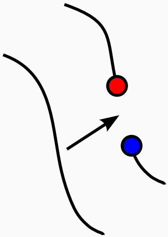

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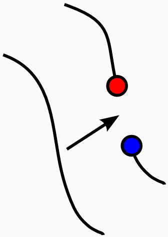

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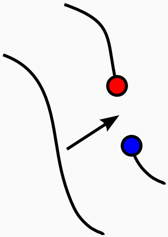

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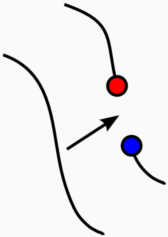

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Monopoles with and without unconfined magnetic flux:

- 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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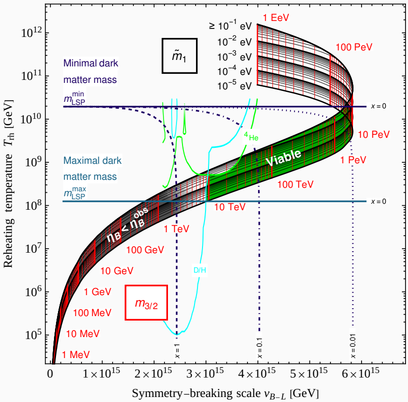

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$v_{B-L} \sim (3 \cdots 6) \times 10^{15}\,\mathrm{GeV}$

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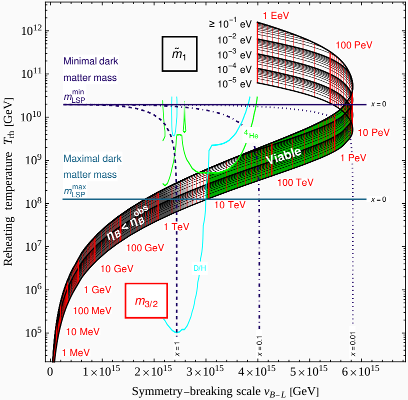

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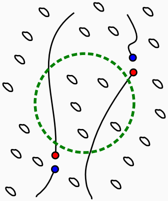
Minimal alternative: $SU(2) \times U(1) \xrightarrow{\text{triplet}} U(1) \times U(1) \xrightarrow{\text{doublets}} U(1)$

[Buchmüller: 2102.08923]

Strategy

End of scaling when long string segments begin to enter the horizon:
[Leblond, Shlaer, Siemens: 0903.4686]

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



Scaling regime, $t < t_s$

- Loops: emit GWs, decay into segments negligible
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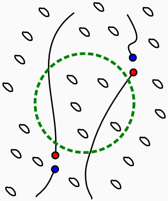

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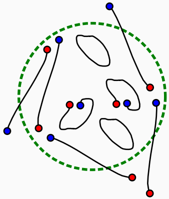

Decay regime, $t > t_s$

- 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, $\overset{\circ}{n}$ 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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- Segments from segments: $S = 2 \, \Gamma_d \int_\ell^\infty d\ell' \, \tilde{n}(\ell', t)$

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

- 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 $\tilde{n}$:

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

Source term S:

- Loops from long strings (loop production function): $S \propto t^{-4}\,\delta\,(\ell - \alpha t)$
- Loops during the decay regime: $S = 0$
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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] [See also talk by Jose Juan today]

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

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because of new exponential suppression factor:

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Similar results for $\overset{\circ}{n}{}_{<}^{\mathrm{rr}}$, $\overset{\circ}{n}{}_{<}^{\mathrm{rm}}$, $\overset{\circ}{n}{}_{<}^{\mathrm{mm}}$, $\overset{\circ}{n}{}_{>}^{\mathrm{rm}}$, $\overset{\circ}{n}{}_{>}^{\mathrm{mm}}$, $\tilde{n}_{<}^{(s)\,\mathrm{rr}}$, $\tilde{n}_{<}^{(s)\,\mathrm{mm}}$, $\tilde{n}_{>}^{(s)\,\mathrm{rr}}$, $\tilde{n}_{>}^{(s)\,\mathrm{rm}}$, $\tilde{n}_{>}^{(s)\,\mathrm{mm}}$, $\tilde{n}_{>}^{(l)\,\mathrm{rr}}$, $\tilde{n}_{>}^{(l)\,\mathrm{rm}}$, $\tilde{n}_{>}^{(l)\,\mathrm{mm}}$. 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:

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

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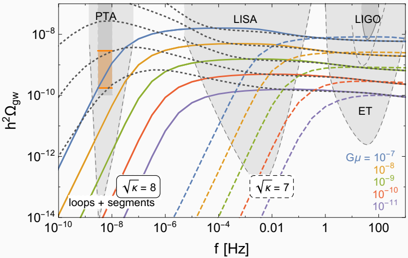

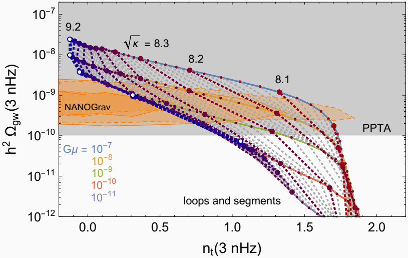

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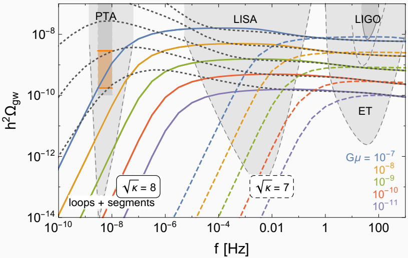

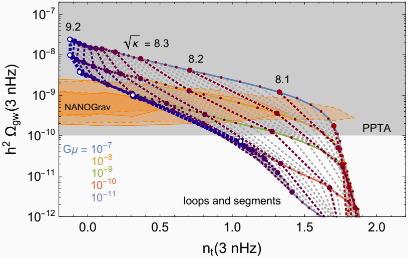

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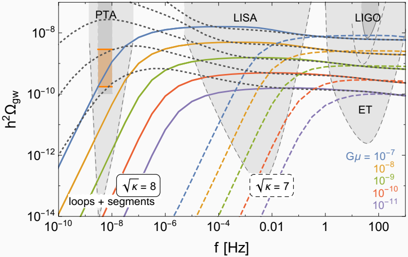

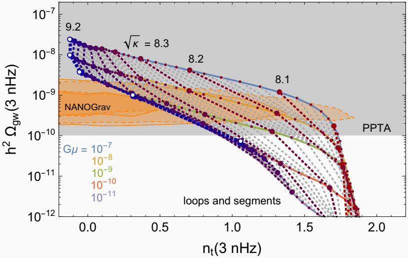

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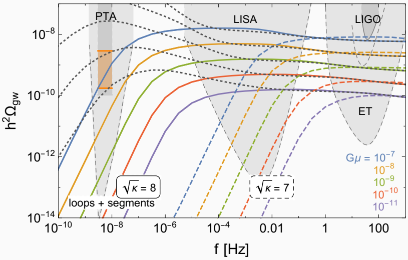

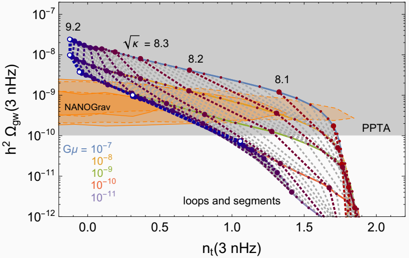

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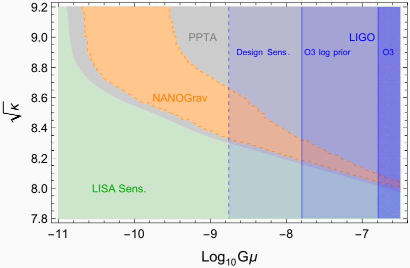
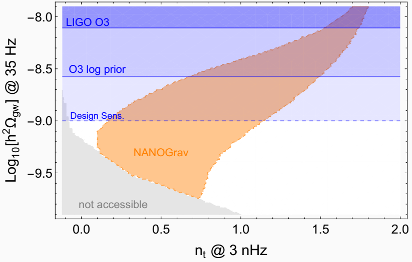
- Suppress spectrum in nHz range, explain NANOGrav for larger $G\mu$

Observational prospects

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





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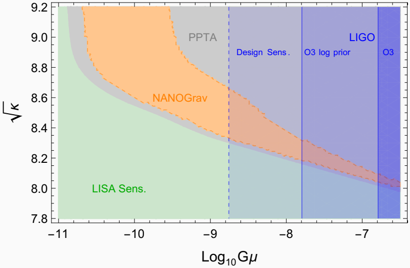

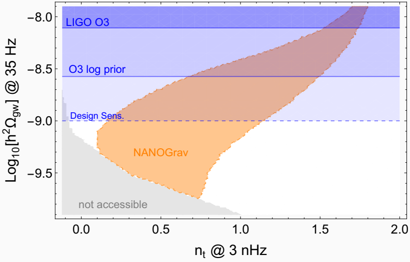

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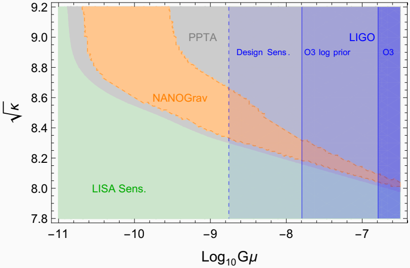

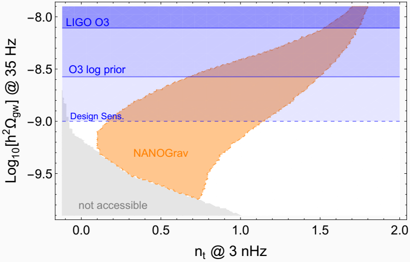

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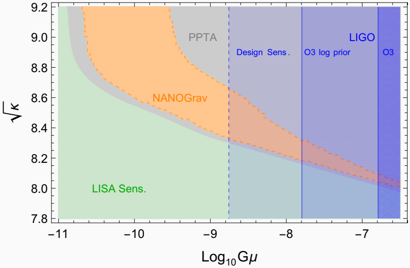

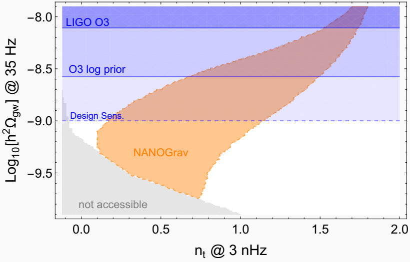

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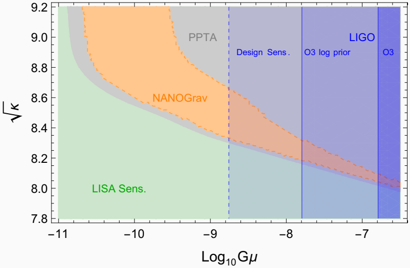

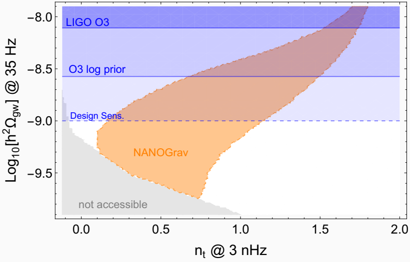

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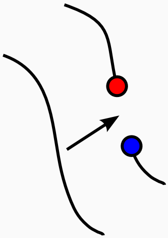
- LISA will probe the entire parameter space consistent with NANOGrav

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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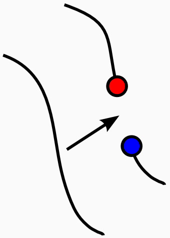

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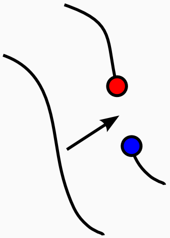

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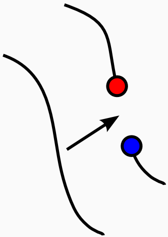

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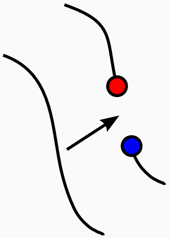

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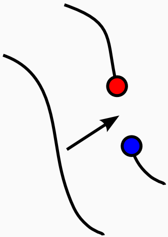

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Thank you very much for your attention!