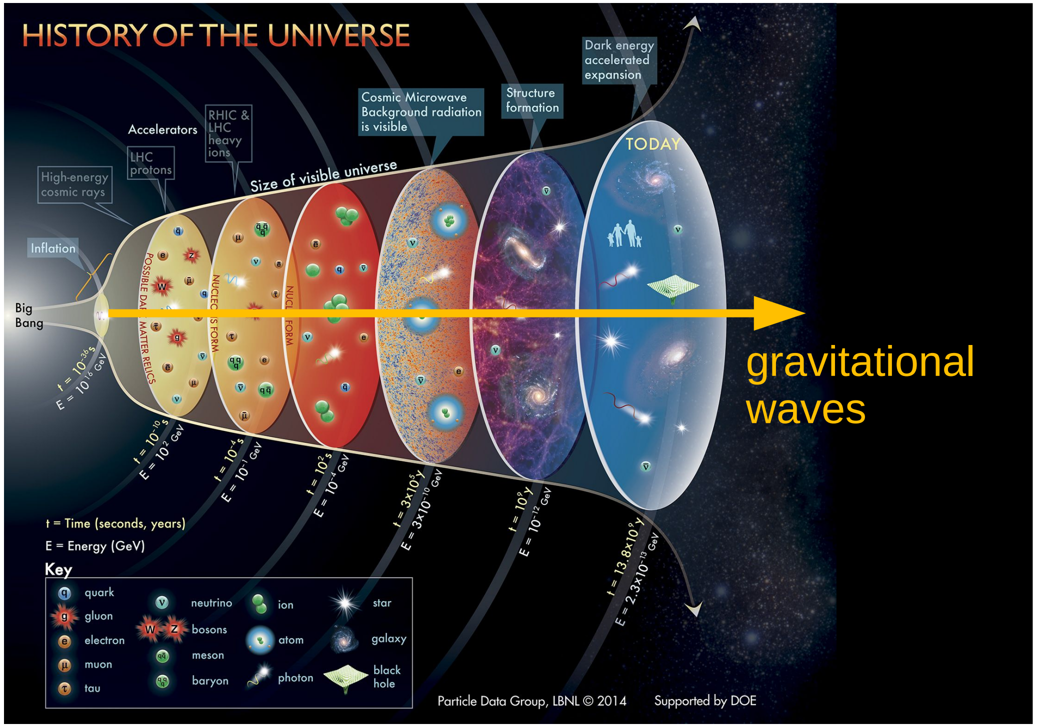
Probing the scale of grand unification

with gravitational waves



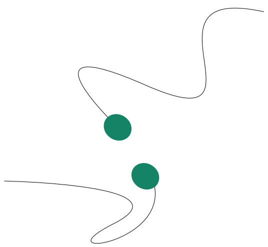
Valerie Domcke
CERN/EPFL

Online workshop
Physics of the Early Universe
June 16 2022

based on
1202.6679, 1203.0285, 1912.03695, 2009.10649, 2107.04578
w. W. Buchmüller, H. Murayama and K. Schmitz

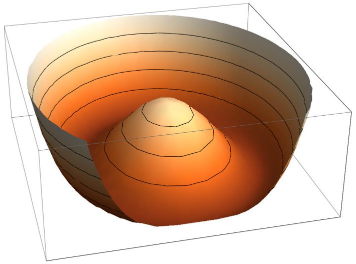
Outline

- Metastable cosmic strings



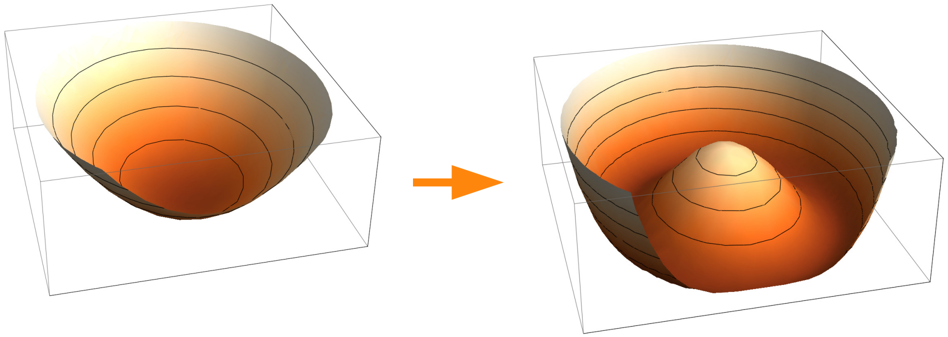
- Gravitational wave signal

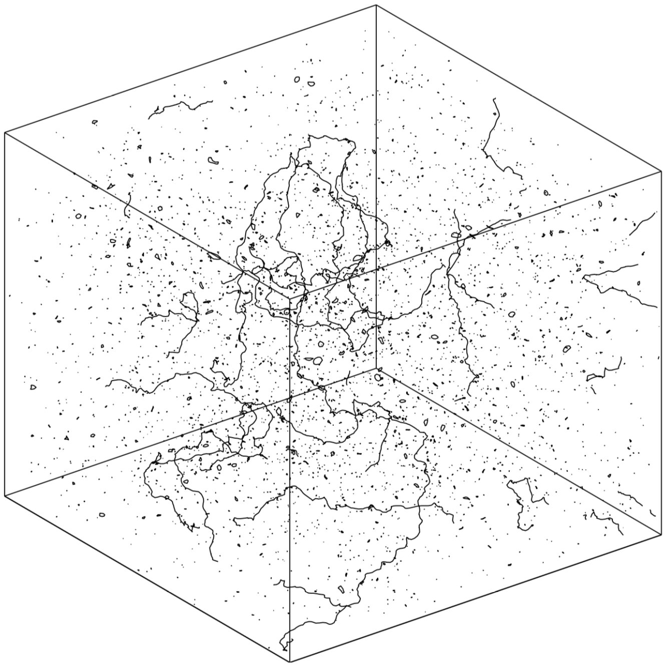
- [Spontaneous $U(1)_{B-L}$ breaking as the origin of the hot early Universe]



cosmic strings in a nutshell

- one-dimensional topological defects formed in an early Universe phase transition
- symmetry breaking pattern $G \to H$ produces cosmic strings iff $\Pi_1(G/H) \neq \mathbb{1}$





Allen & Shellard `90

- form cosmic string network, evolves through
  - string (self-)intersection & loop formation
  - emission of particles and gravitational waves

metastable cosmic strings

consider $SO(10) \to G_{SM} \times U(1)_{B-L} \to G_{SM}$

Vilenkin `82; Leblond, Shlaer, Siemens `09; Monin, Voloshin `08/09; Dror et al `19

$\Pi_1(G_{\rm SM} \times U(1)/G_{\rm SM}) = \Pi_1(U(1)) \neq \mathbb{1}$ → cosmic strings

$\Pi_1(SO(10)/G_{SM}) = \mathbb{1}$ → no cosmic strings

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resolution: no topologically stable cosmic strings

$SO(10) \to G_{SM} \times U(1)_{B-L}$ generates monopoles

$G_{SM} \times U(1)_{B-L} \to G_{SM}$ generates cosmic strings,

metastable string & monopole network

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resolution: no topologically stable cosmic strings

$SO(10) \to G_{SM} \times U(1)_{B-L}$ generates monopoles

cosmic inflation dilutes monopoles

$G_{SM} \times U(1)_{B-L} \to G_{SM}$ generates cosmic strings,

decay via nucleation of monopoles

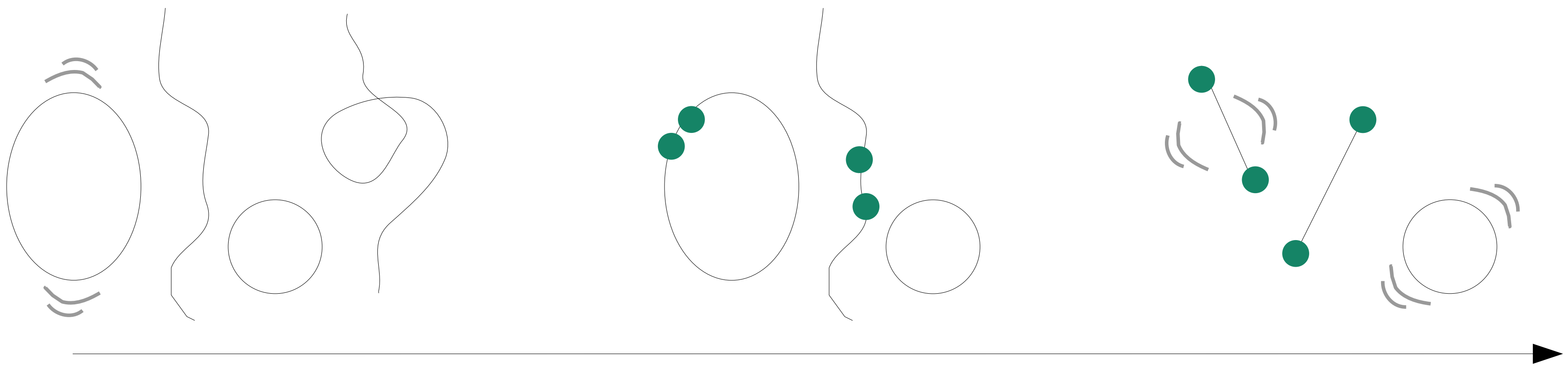
metastable string & monopole network

$$\Gamma_d \sim \mu \exp(-\pi\kappa^2)\,, \quad \kappa^2 = m^2/\mu$$

$\mu \sim v_{B-L}^2$ string tension

$m \sim v_{GUT}$ monopole mass

dynamics of metastable CS network



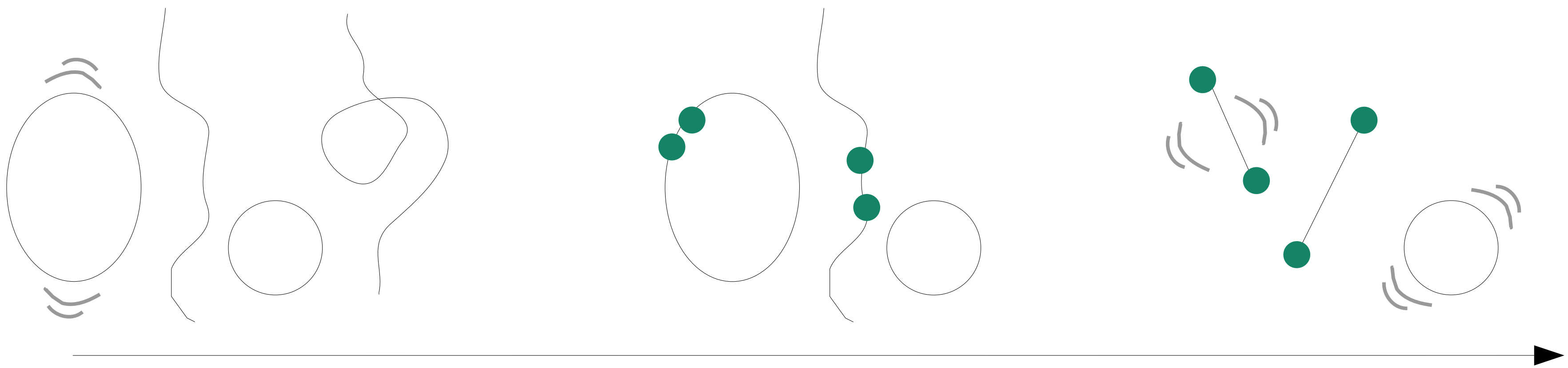
scaling regime
(long strings & loops)

$t_s = 1/\Gamma_d^{1/2}$

segments & loops

[see also Leblond, Shlaer, Simons `09]

dynamics of metastable CS network



scaling regime
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$t_s = 1/\Gamma_d^{1/2}$

segments & loops

[see also Leblond, Shlaer, Simons `09]

number densities for long strings, loops and segments from kinetic equations:

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

source term   length change per unit time

initial conditions: numerical simulations for scaling regime, matching conditions.

An example: loops

Buchmüller, VD, Schmitz `21

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

$$u\,(\ell,t) = -\Gamma G\mu \;\rightarrow\; \bar{\ell}\,(t') = \ell + \Gamma G\mu\,(t-t')$$

energy loss due to GW emission

$$S\,(\ell,t) = \frac{B}{\alpha^{3/2}\, t^4}\,\delta(\ell-\alpha t)\theta(t_s-t)$$

loop production function

Γ, B, α from numerical simulations

Blanco-Pillado, Olum, Shlaer '14

solution in radiation background:

$t < t_s$:
$$\mathring{n}\,(\ell,t) \simeq \frac{B}{t^{3/2}\,(\ell+\Gamma G\mu t)^{5/2}}\,\Theta\,(\alpha t-\ell)$$

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

Another example: segments from loops

Buchmüller, VD, Schmitz `21

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

$$u\,(\ell,t) = -\tilde{\Gamma} G\mu \;\rightarrow\; \bar{\ell}\,(t') = \ell + \tilde{\Gamma} G\mu\,(t-t')$$

energy loss due to GW emission

$$S(\ell,t) = +2\,\Gamma_d \int_\ell^\infty d\ell'\,\tilde{n}^{(l)}_{>}\,(\ell',t) + \Gamma_d\,\ell\,\mathring{n}_{>}\,(\ell,t)$$

segments from loop segments and from full loops

$\tilde{\Gamma} = \Gamma$ (simulations needed!)

solution in radiation background:

$$t < t_s : \qquad \tilde{n}^{(l)}(\ell,t) \simeq 0$$

$$t > t_s : \qquad \tilde{n}^{(l)}\,(\ell,t) \simeq \Gamma_d \left[\ell\,(t-t_s) + \frac{1}{2}\,\Gamma G\mu\,(t-t_s)^2\right] \mathring{n}\,(\ell,t)$$

(similar procedure for segments from long strings)

Outline

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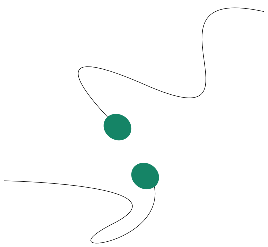

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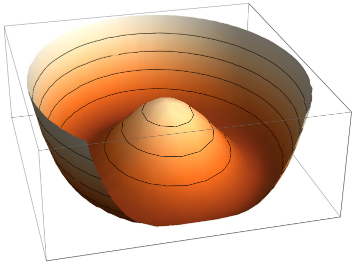

gravitational wave signal - SGWB

see eg. Auclair, Blanco-Pillado, Figueroa et al `19

gravitational wave emission from integration over loop distribution function:

$$\Omega_{\rm GW}(f) = \frac{8\pi f (G\mu)^2}{3H_0^2} \sum_{q=1}^{\infty} C_q(f) P_q$$

$$C_q(f) = \frac{2q}{f^2} \int_0^{z_{\rm max}} dz \frac{n(\ell(z), t(z))}{H(z)(1+z)^6}$$

GW power spectrum of a single loop

$P_q = \Gamma/(\zeta(4/3) q^{4/3})$

# of loops emitting GWs observed at frequency *f* today

# of loops with length ℓ at time *t*

with $\ell = 2q/((1+z)f)$

cosmological history

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$$n(\ell, z) = n(\ell, z)_{\kappa\to\infty} \times e^{-\Gamma_d[\ell(t-t_s) + 1/2\Gamma G\mu(t-t_s)^2]} \times \Theta(\alpha t_s - \ell(t_s))$$

finite CS life time

number density for stable strings

$n_r(\ell, t) = 0.18\, t^{-3/2}(\ell + 50 G\mu t)^{-5/2}$

Blanco-Pillado, Olum, Shlaer '14

decay due to monopole production and GW emission

loop production only in scaling regime

Buchmüller, VD, Schmitz `21

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with $\ell = 2q/((1+z)f)$

cosmological history

analogous for contribution from segments

$$n(\ell, z) = n(\ell, z)_{\kappa\to\infty} \times e^{-\Gamma_d[\ell(t-t_s)+1/2\Gamma G\mu(t-t_s)^2]} \times \Theta(\alpha t_s - \ell(t_s))$$

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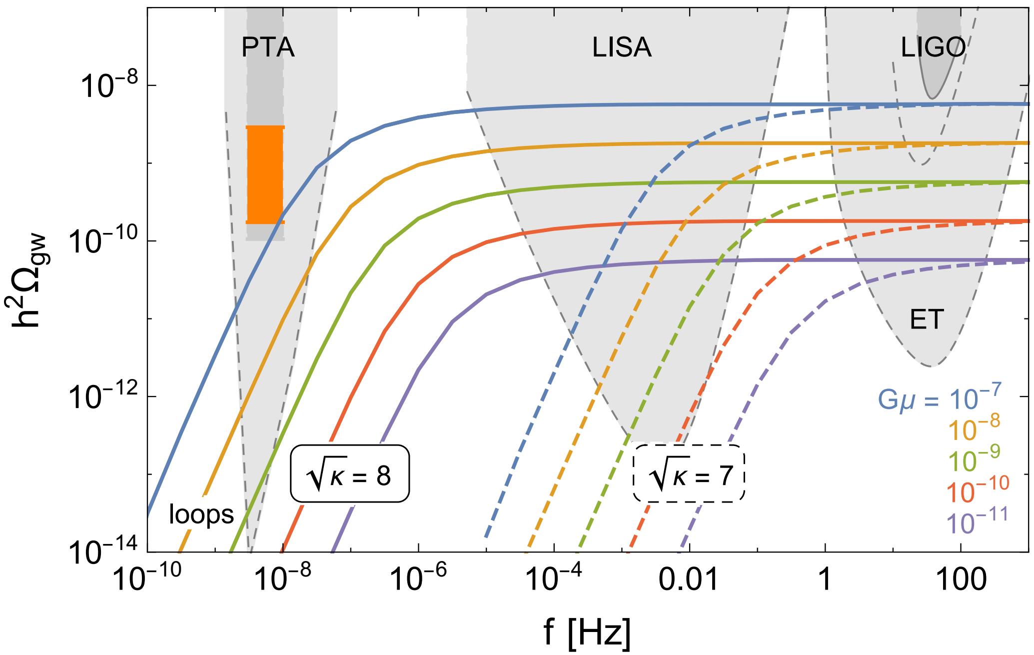
Buchmüller, VD, Schmitz `21

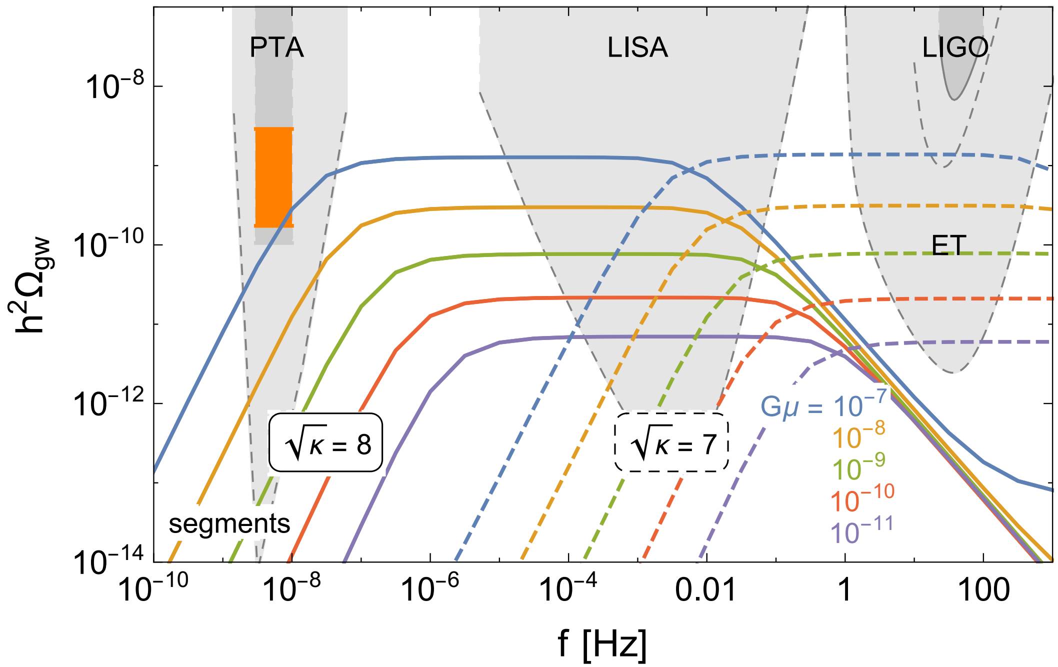
GWs from loops and segments

assuming radiation domination

Buchmüller, VD, Schmitz `21

$$\sqrt{\kappa} \sim v_{\mathrm{SO(10)}}/v_{U(1)}$$





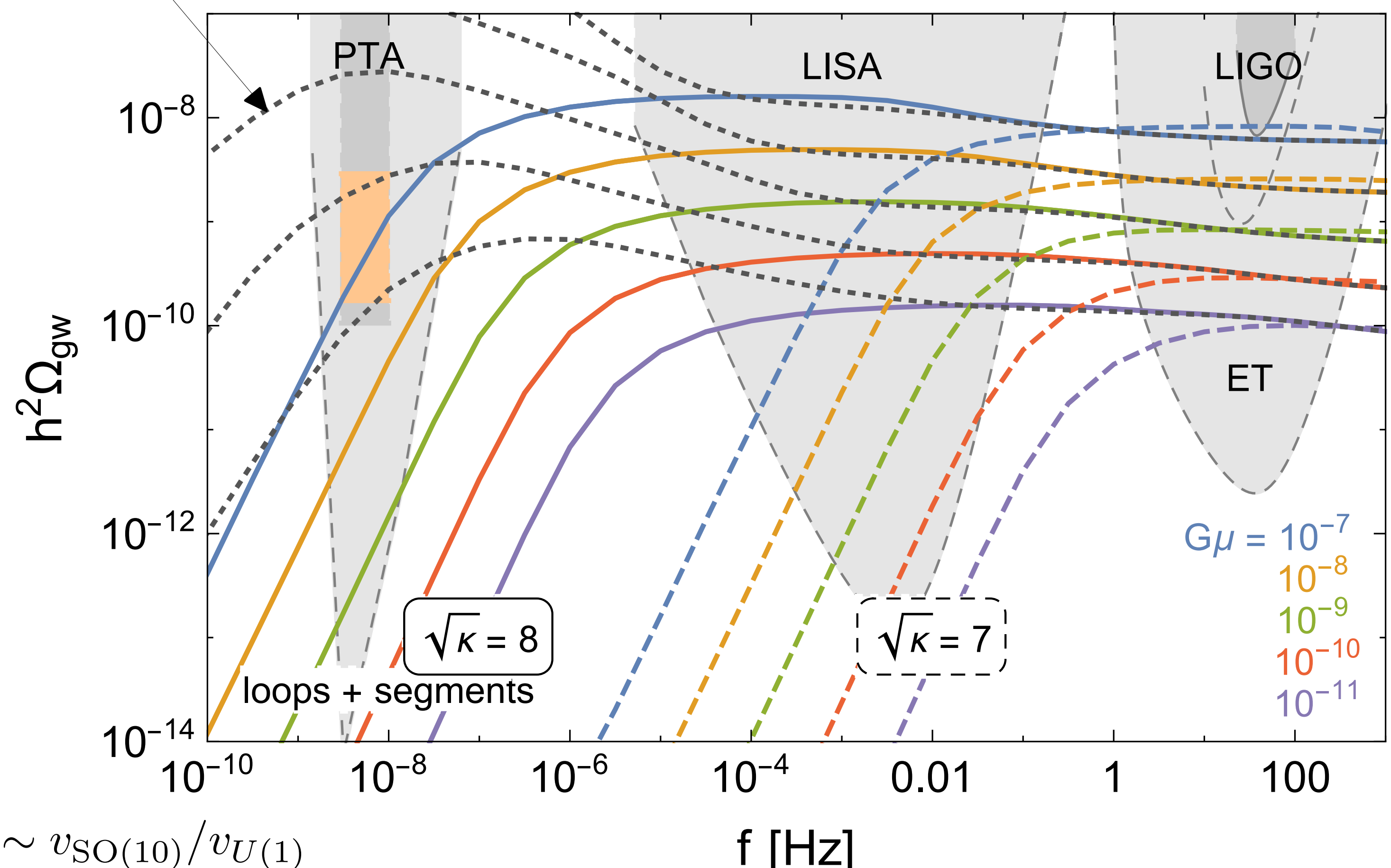
- plateau as for stable strings
- suppression at small frequencies due to finite CS life time
- dominant contribution

- only if no unconfined flux
- cut-off at high frequencies due to regularization of total emitted GW power

gravitational wave spectrum

stable cosmic strings
(highly constrained by PTA)

metastable cosmic strings:
discovery space for LISA, LIGO & beyond

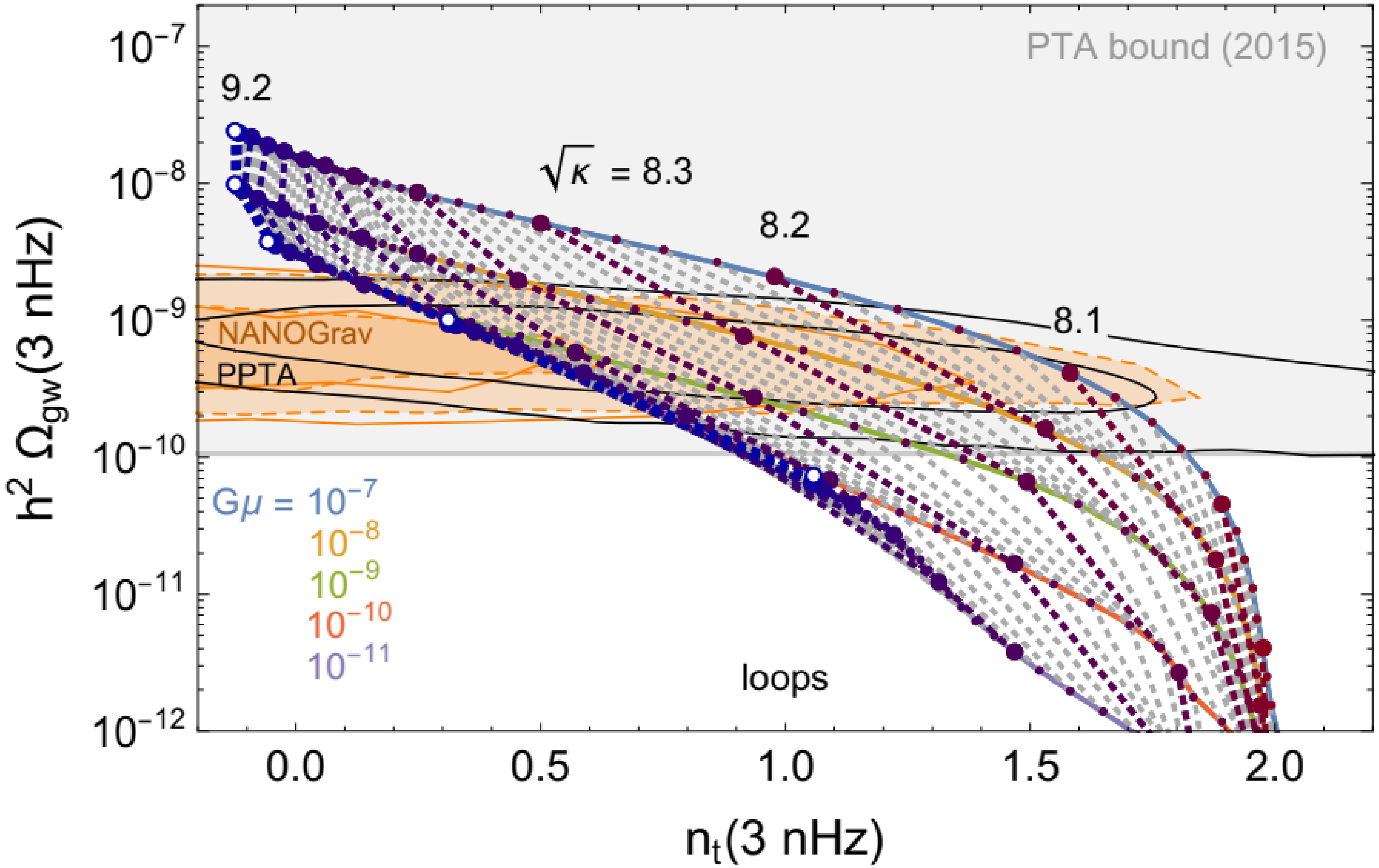


$\sqrt{\kappa} \sim v_{\mathrm{SO}(10)}/v_{U(1)}$

Buchmüller, VD, Schmitz `21

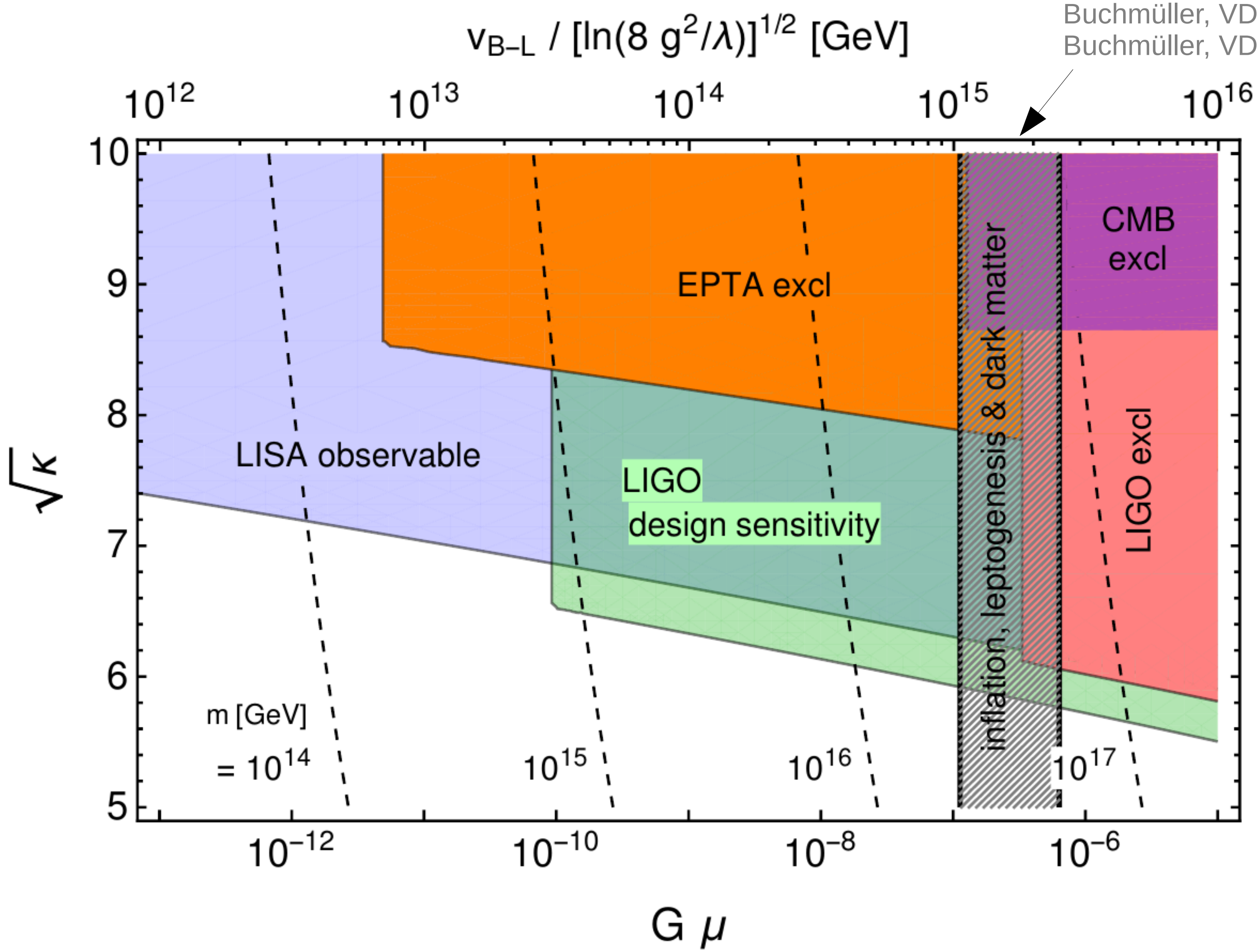
$SO(10) \to G_{\mathrm{SM}} \times U(1)_{B-L} \to G_{\mathrm{SM}}$ with $v_{B-L} \lesssim v_{GUT}$ can be tested with GWs!

metastable cosmic strings at PTAs ?



parameter space of metastable strings

Buchmüller, VD, Schmitz `12
Buchmüller, VD, Murayama, Schmitz `20



metastable GUT- scale strings are testable

parameter space of metastable strings

Buchmüller, VD, Schmitz `12
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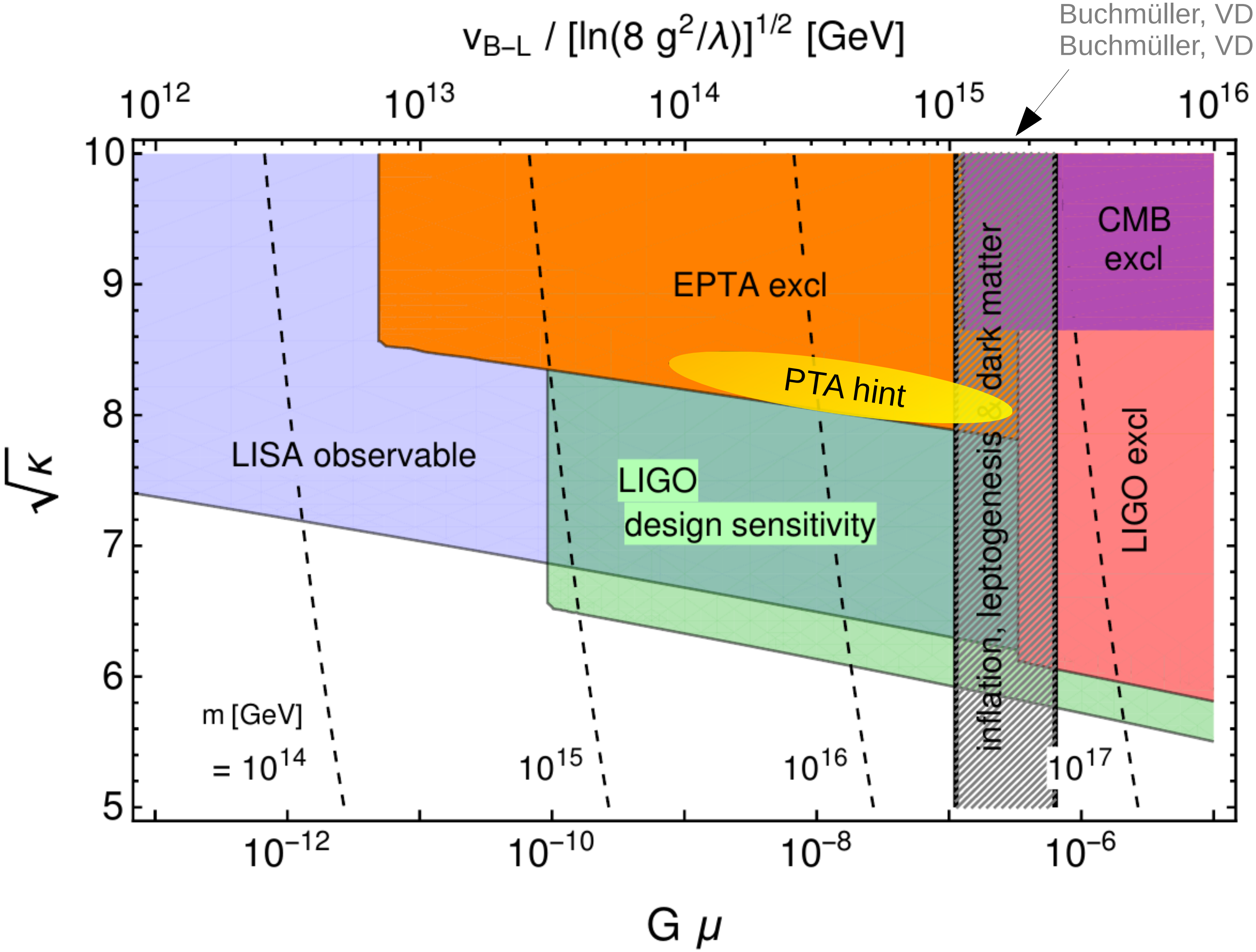

metastable GUT- scale strings are testable

conclusions & outlook

- Metastable cosmic strings are a fairly generic byproduct of GUTs with large stochastic GW signals possible at PTAs, LIGO or LISA

  ⟶ testable with upcoming GW detectors

- Excess noise observed in NANOGrav and PPTA data may be the first glimpse at a SGWB ?

- Cosmological B-L breaking can link hybrid inflation, reheating, leptogenesis and dark matter production at GUT scale – *testable* !

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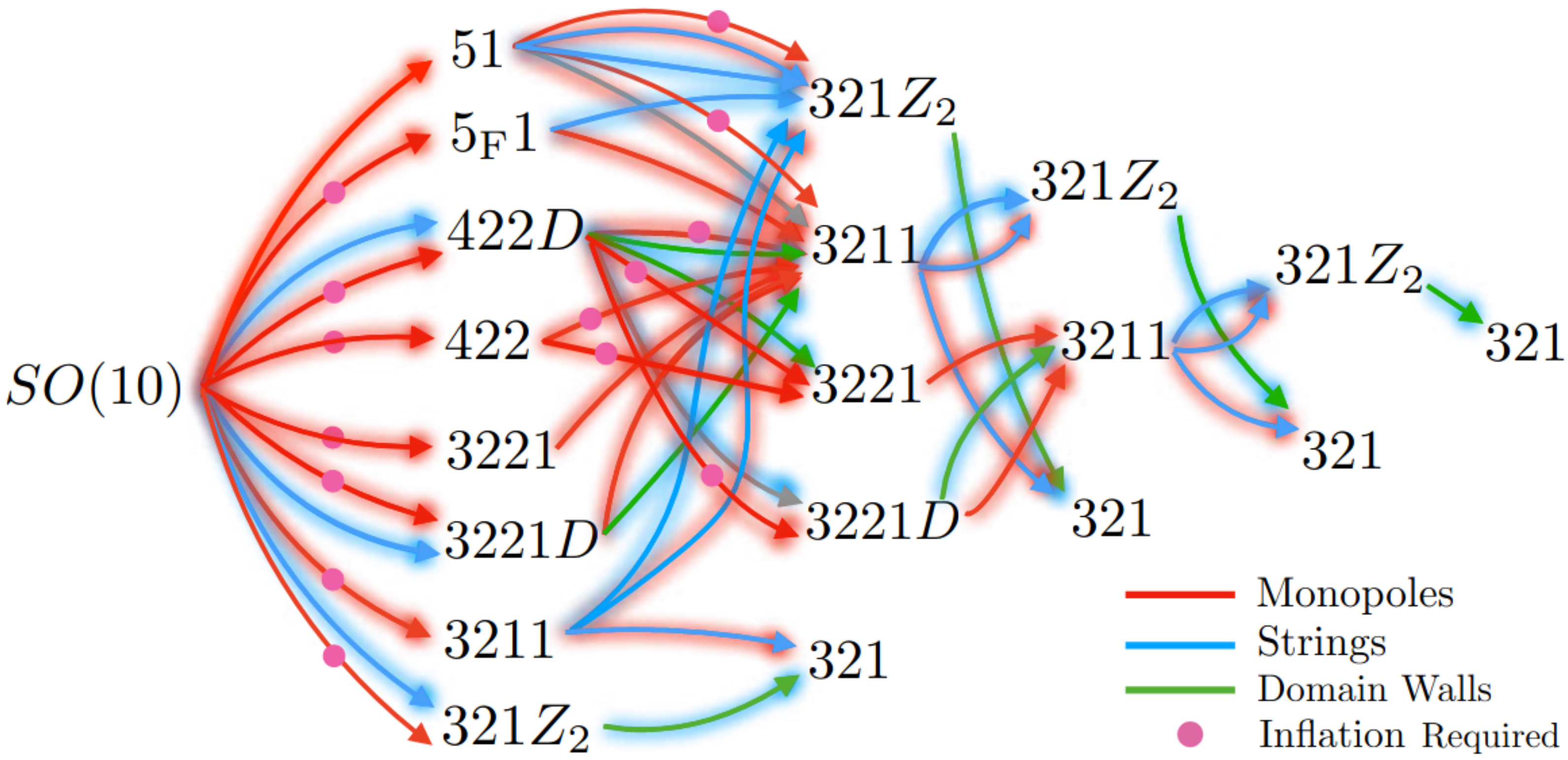
Questions ?

backup slides

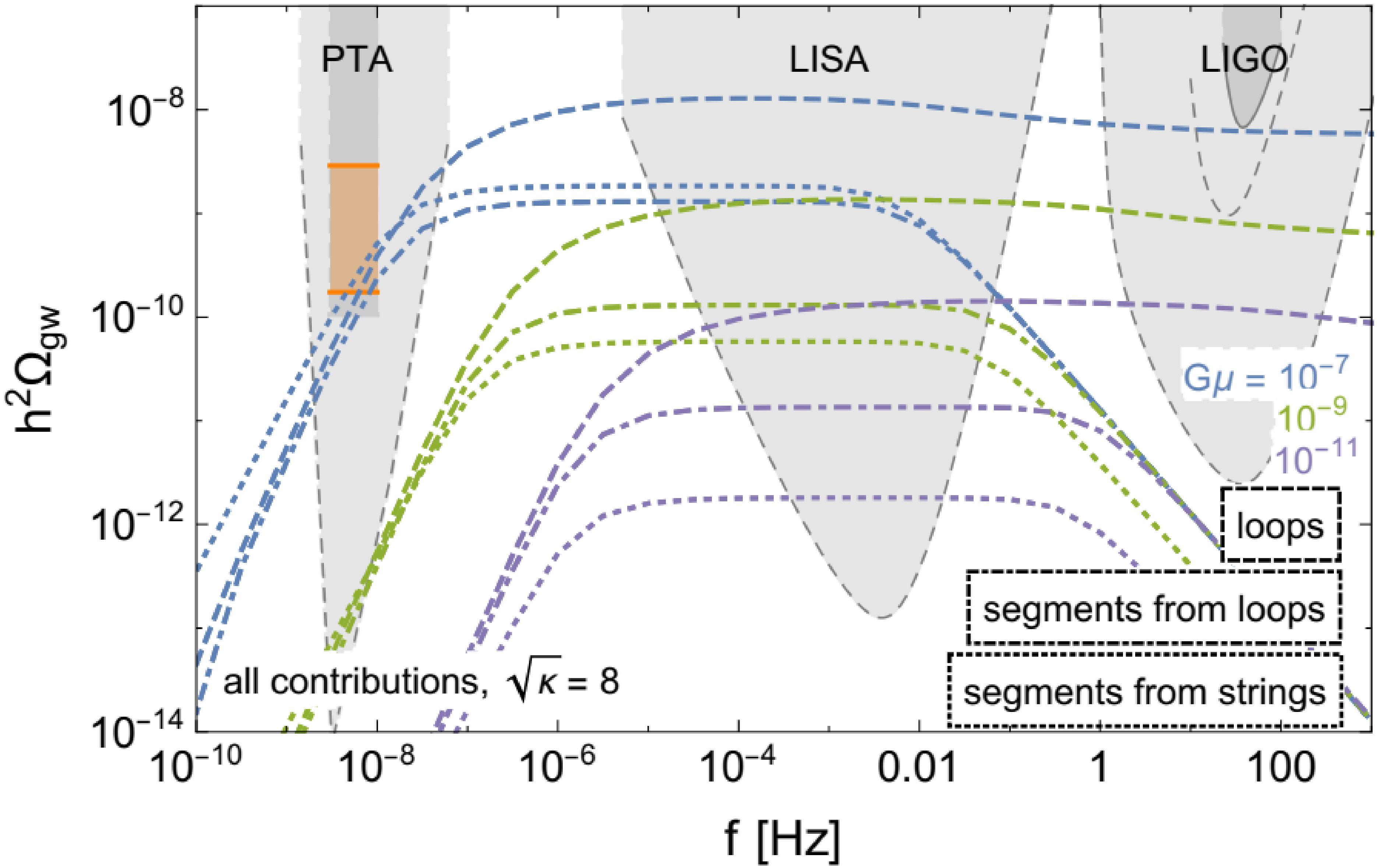
examples of symmetry breaking patterns

from Dunsky, Ghoshal, Murayama, Sakakihara, White `21

$$\begin{aligned} 51 &= SU(5)\times U(1)_X/\mathbb{Z}_5\ ,\\ 5_{\rm F}1 &= SU(5)_{\rm flipped}\times U(1)_{\rm flipped}/\mathbb{Z}_5\ ,\\ 422 &= SU(4)_c\times SU(2)_L\times SU(2)_R/\mathbb{Z}_2\ ,\\ 3221 &= SU(3)_c\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}/\mathbb{Z}_6\ ,\\ 3211 &= SU(3)_c\times SU(2)_L\times U(1)_Y\times U(1)_X/\mathbb{Z}_6\ ,\\ 321 &= SU(3)_c\times SU(2)_L\times U(1)_Y/\mathbb{Z}_6. \end{aligned} \qquad (20)$$



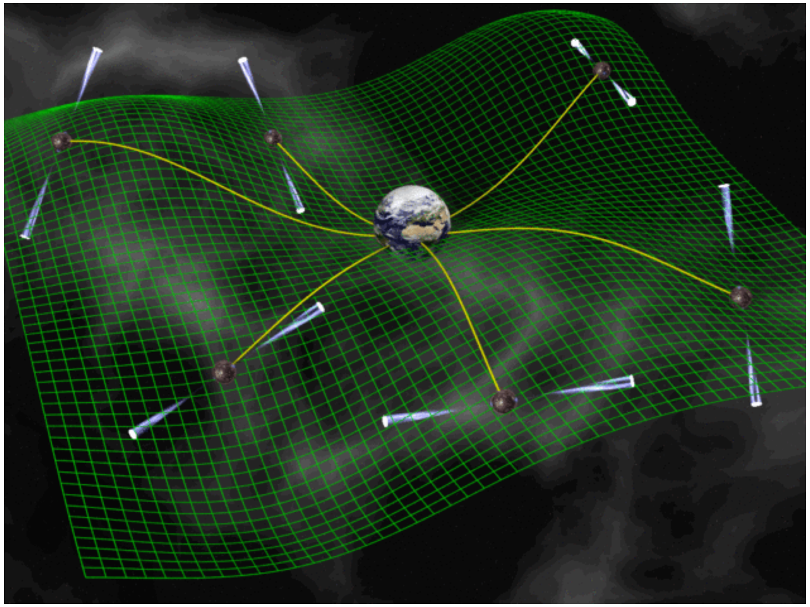
GWs from segments

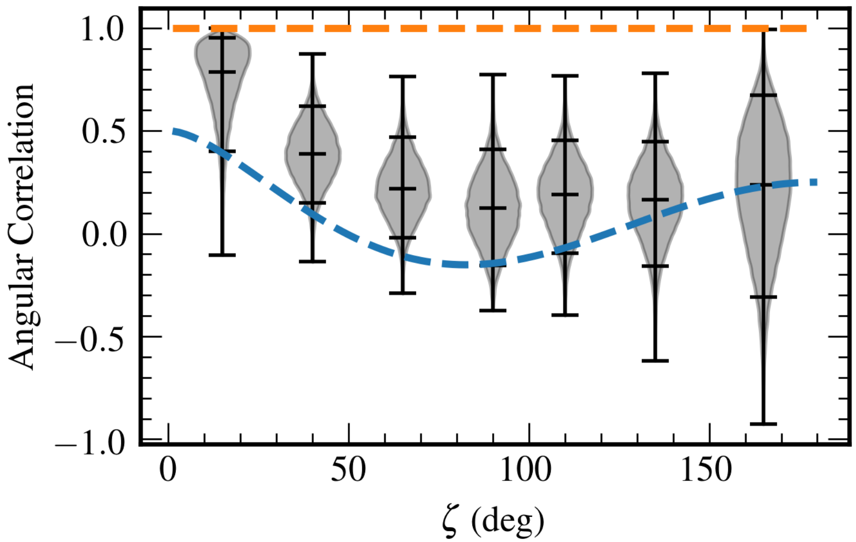


NANOGrav: A first glimpse of the SGWB?

Pulsar timing array NANOGrav, Sept 2020:

> “Our analysis finds strong evidence of a stochastic process, modeled as a power-law, with common amplitude and spectral slope across pulsars.“



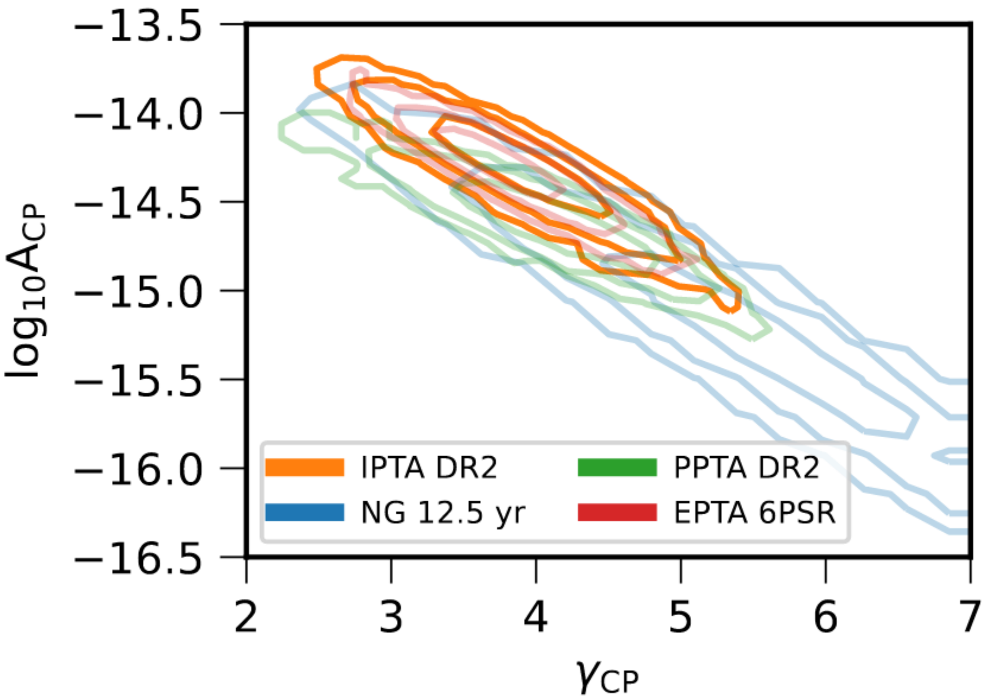


NANOGrav collaboration `20

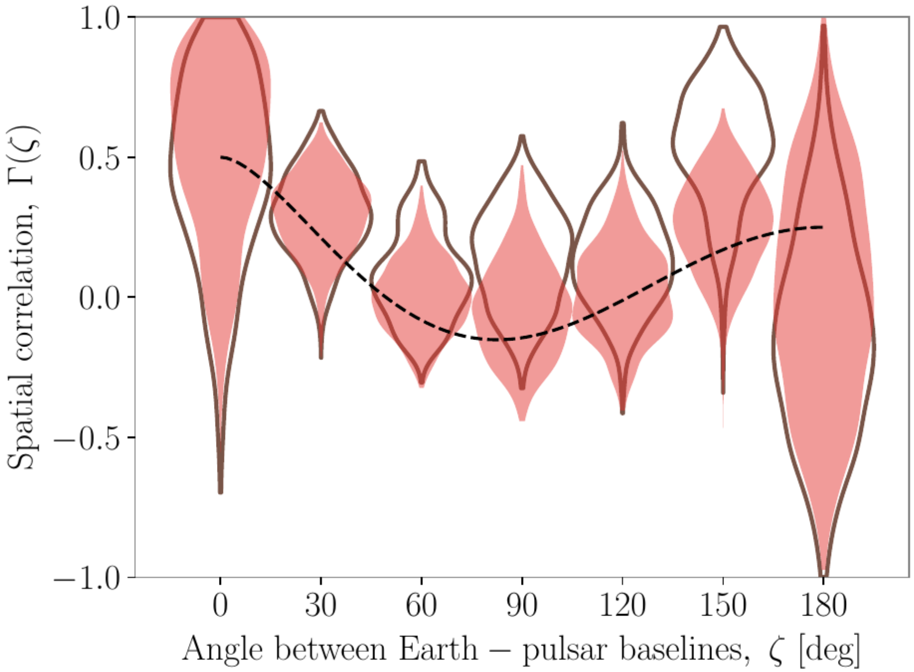
„However, we find no statistically significant evidence that this process has quadrupolar spatial correlations, which we would consider necessary to claim a GWB detection consistent with General Relativity.“

PPTA, EPTA and IPTA results

IPTA `22, 2201.03980



PPTA `21, 2107.12112



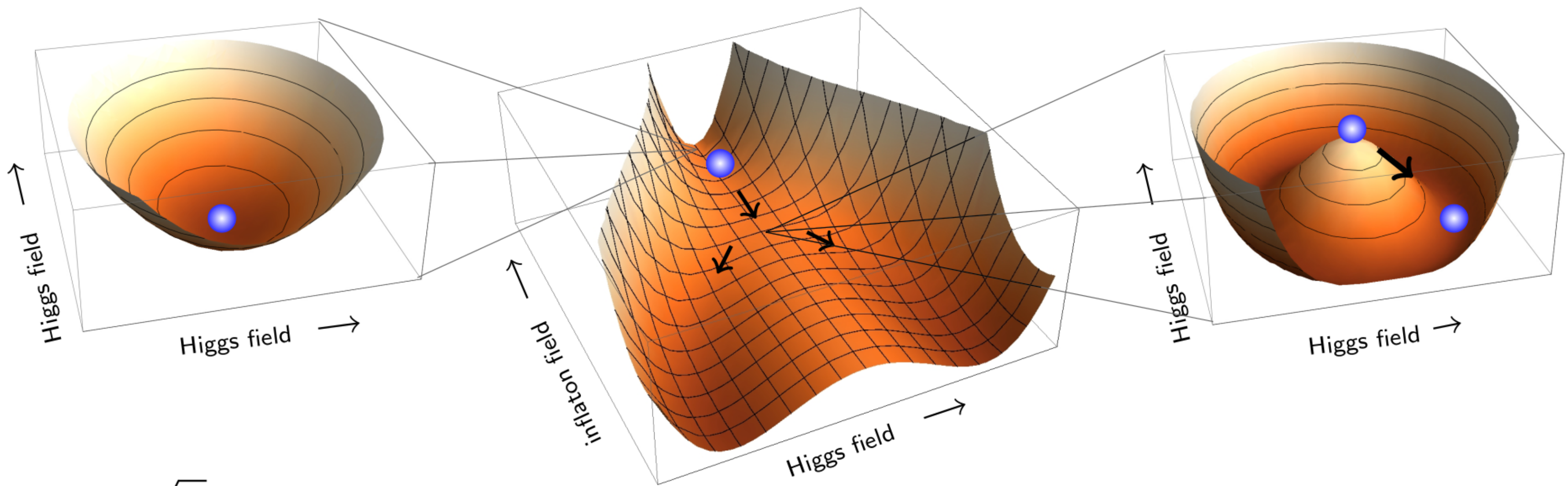
amplitude and spectral tilt compatitive with NANOGrav

no significant detection of quandropolar spatial correlation

Maybe. Stay tuned for more data!

Cosmological B-L breaking

extend SM by gauging $U(1)_{B-L}$ & adding 3 RH neutrinos:



$$W = \frac{\sqrt{\lambda}}{2}\,\Phi\,(v_{B-L}^2 - 2\,S_1 S_2) + \frac{1}{\sqrt{2}} h_i^n n_i^c n_i^c S_1 + h_{ij}^\nu n_i^c \mathbf{5}_j^* H_u + W_{MSSM}$$

Before

- hybrid inflation

[Dvali *et al.* '94]

Phase transition

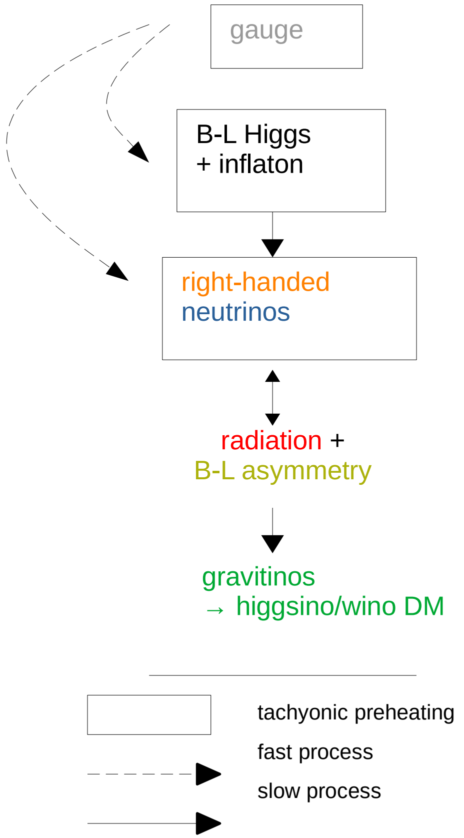
- tachyonic preheating
- cosmic strings

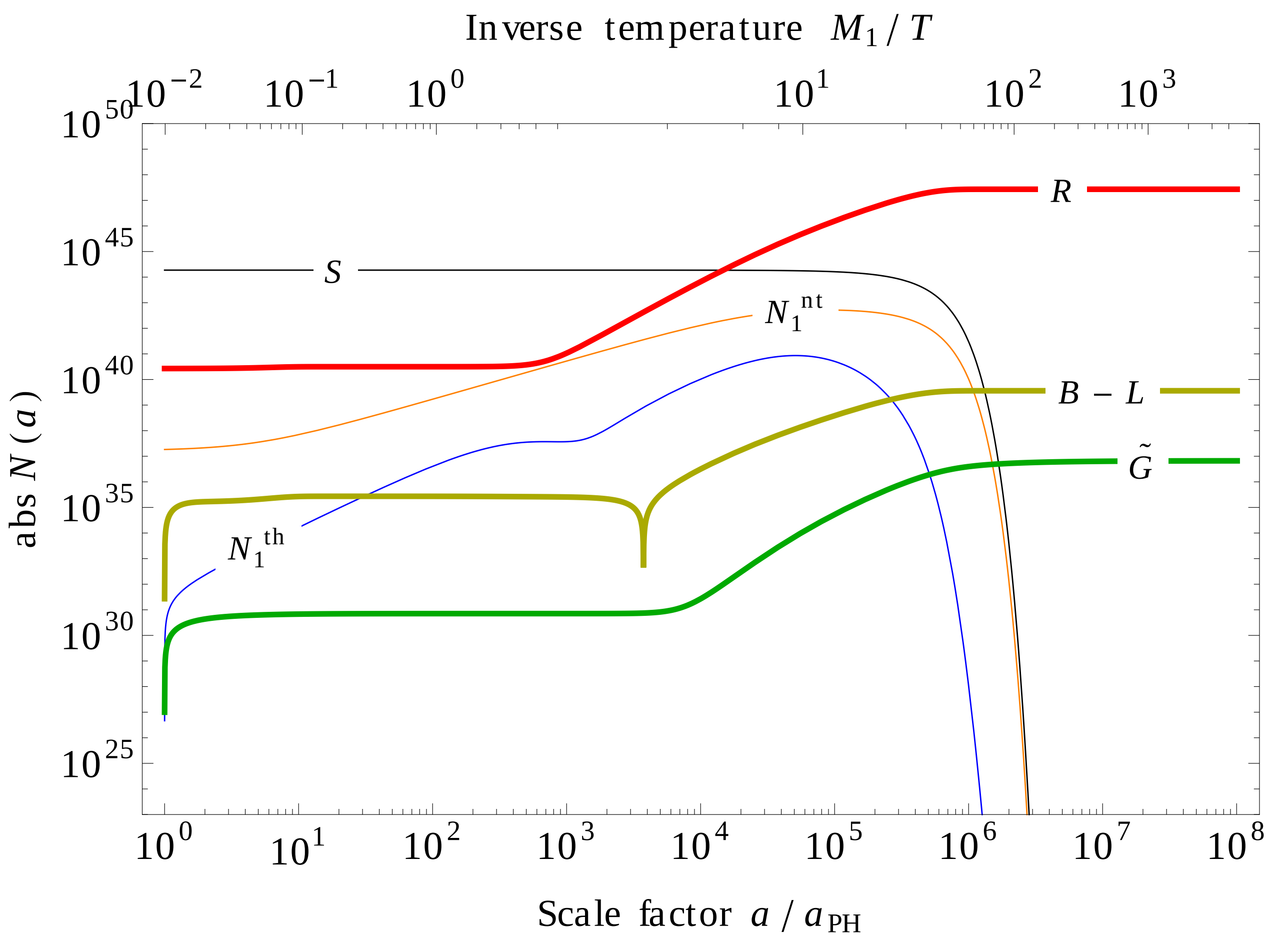
After

- reheating
- leptogenesis
- dark matter

cosmological B-L breaking

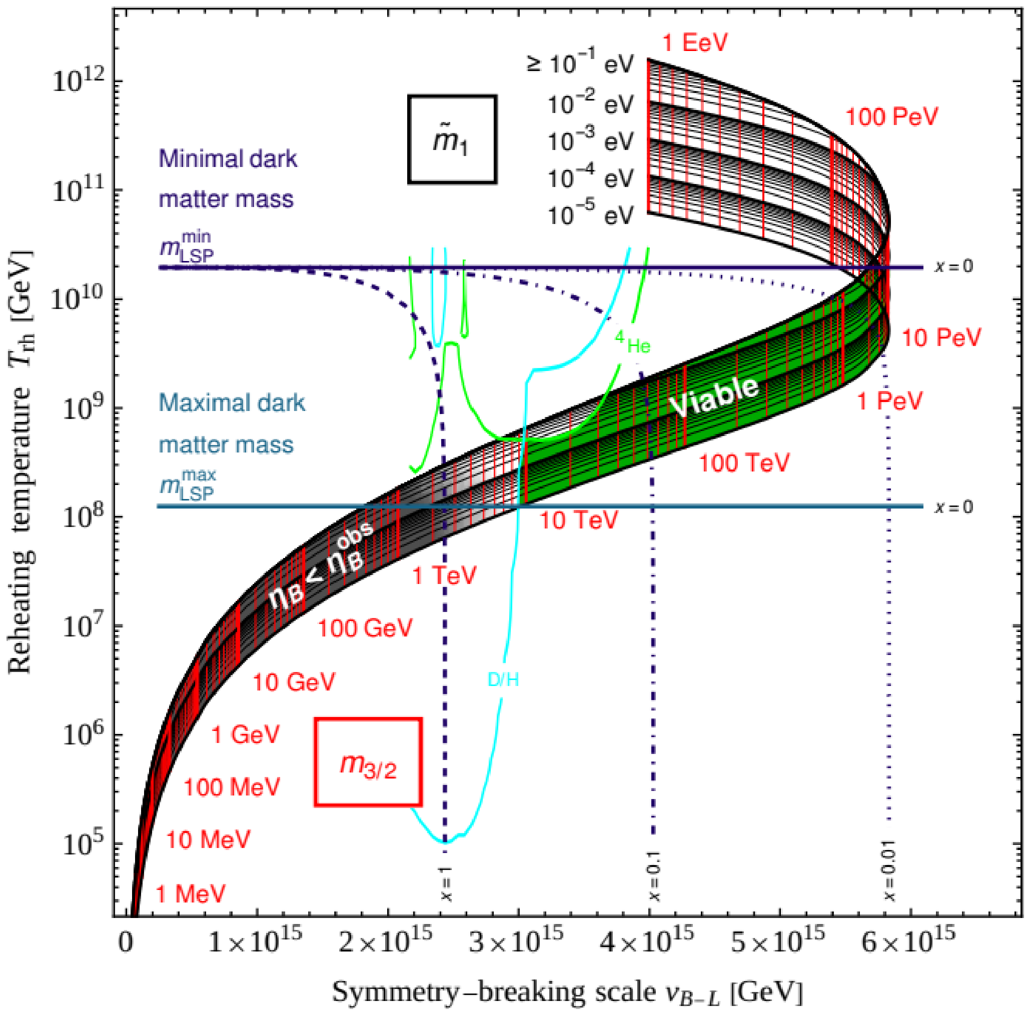
Buchmüller, VD, Schmitz `12,
Buchmüller, VD, Kamada, Schmitz `13+`14





parameter space

Buchmüller, VD, Schmitz `12,
Buchmüller, VD, Kamada, Schmitz `13+`14
Buchmüller, VD, Murayama, Schmitz `19



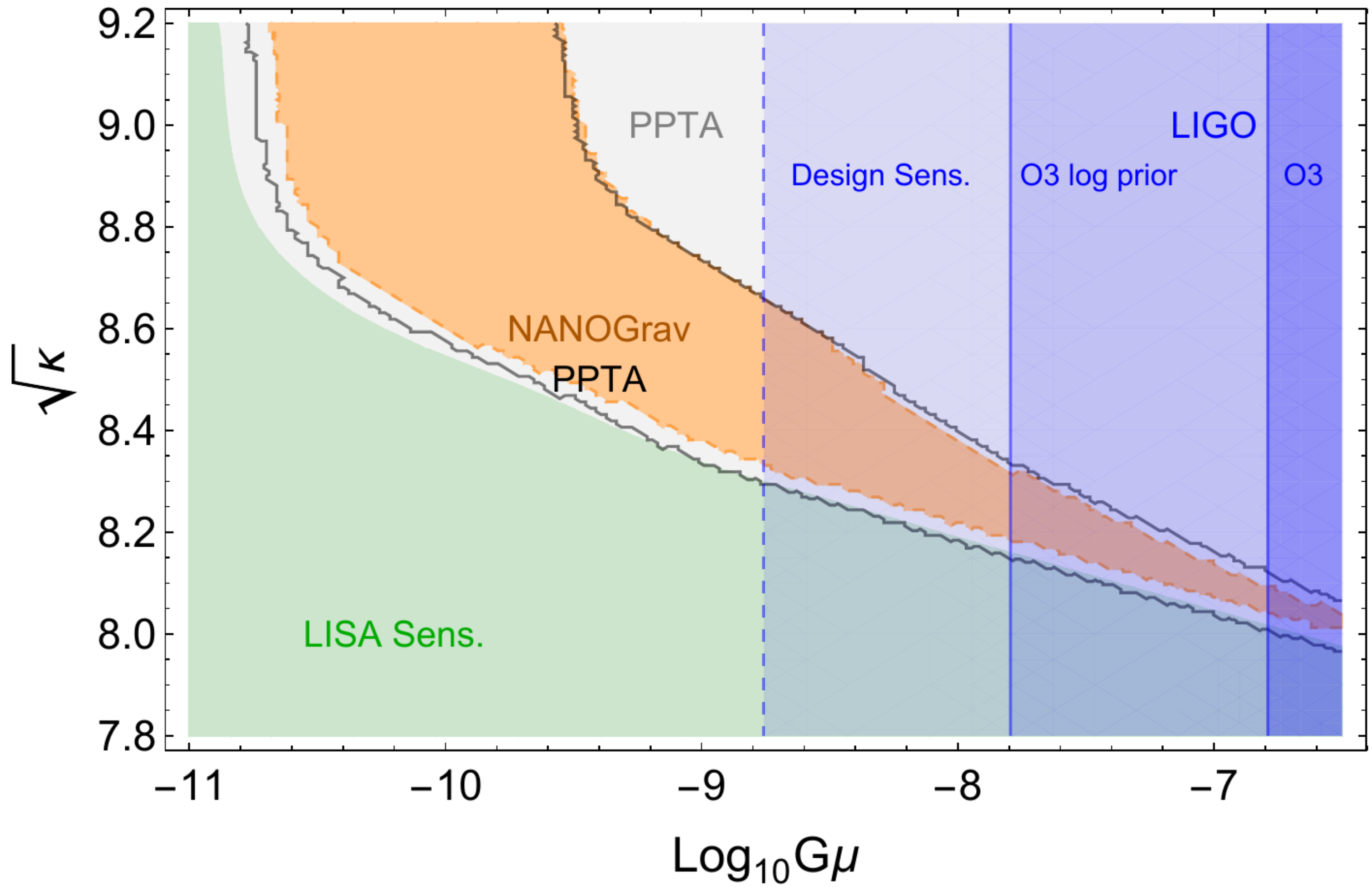
parameters:
$v_{B-L}, T_{rh}, \widetilde{m}_1, m_{3/2}, m_{LSP}$

observables:
$A_s, n_s, \Omega_{DM}, \eta_B$

viable parameter space well constrained, in particular
B-L breaking scale ~ O(1) x 10^{15} GeV

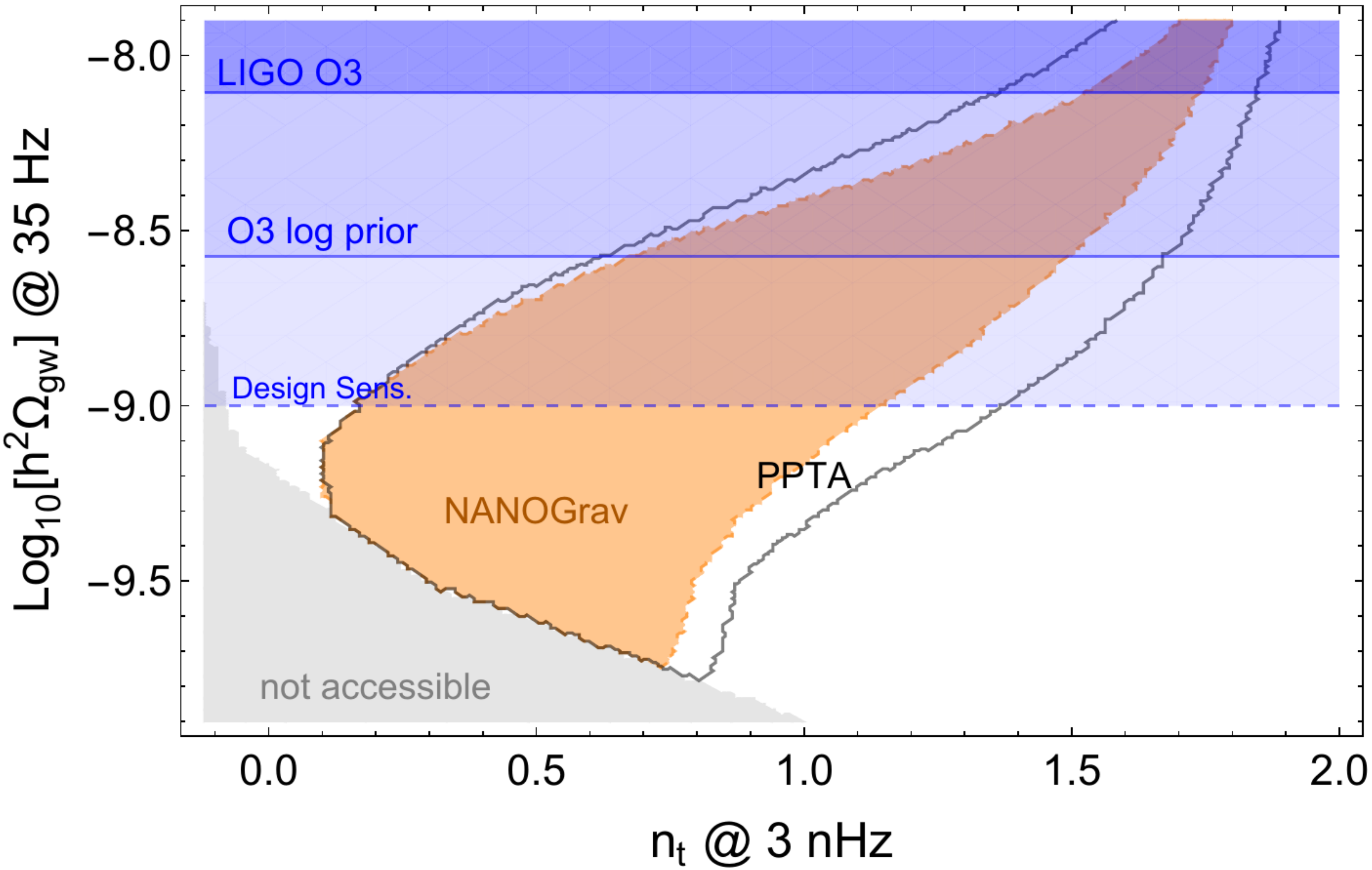
→ metastable cosmic strings

prospects for GW searches



PTA hint will be probed with interferometers

Prospects



LIGO O3
O3 log prior
Design Sens.
PPTA
NANOGrav
not accessible
−8.0
−8.5
−9.0
−9.5
0.0
0.5
1.0
1.5
2.0
$\mathrm{Log}_{10}[h^2\Omega_{gw}]$ @ 35 Hz
n_t @ 3 nHz