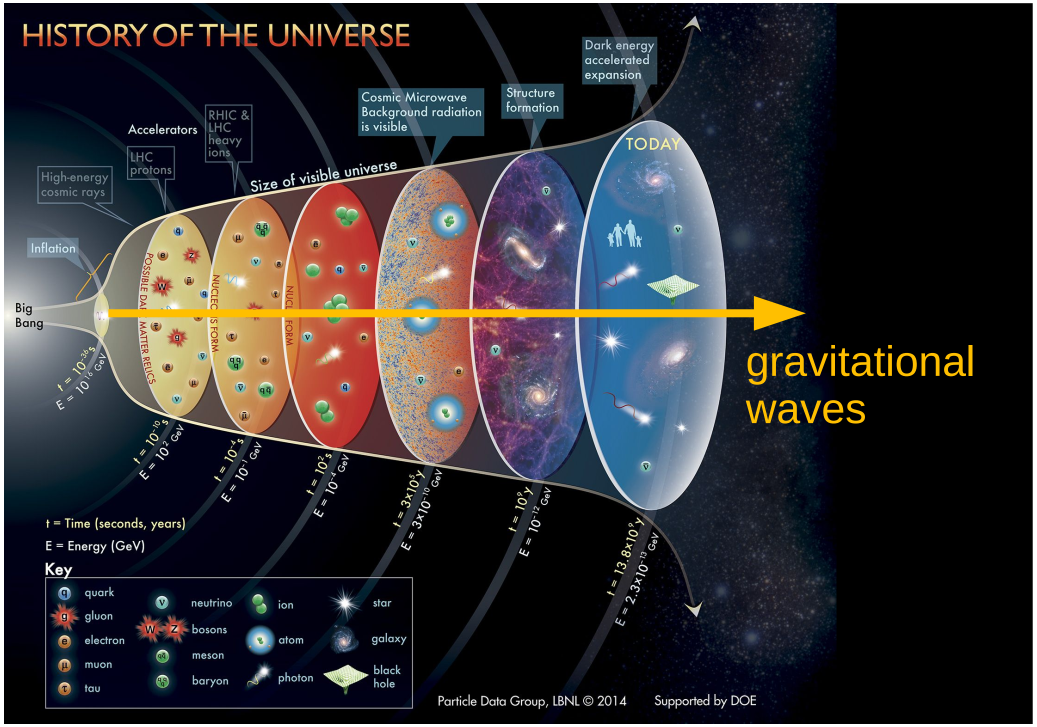
Gravitational waves

from metastable cosmic strings



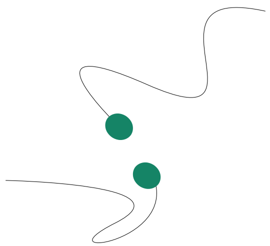
Valerie Domcke
CERN

Invisibles webinar
September 19 2023

based on
1202.6679, 1203.0285, 1912.03695, 2009.10649, 2107.04578, 2307.04691
w. W. Buchmüller, H. Murayama and K. Schmitz

Outline

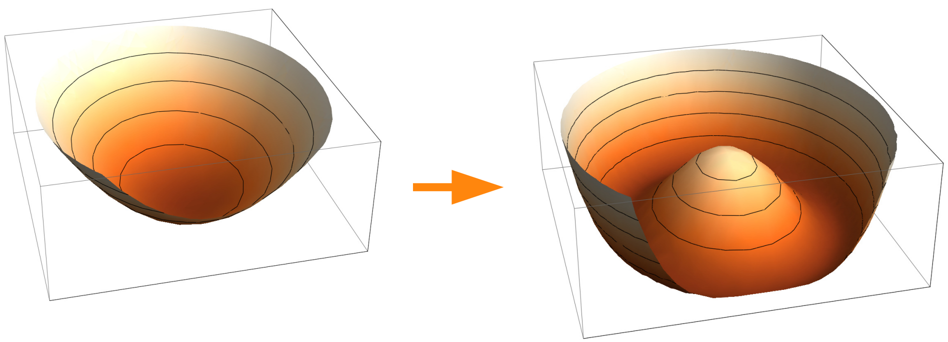
- Metastable cosmic strings

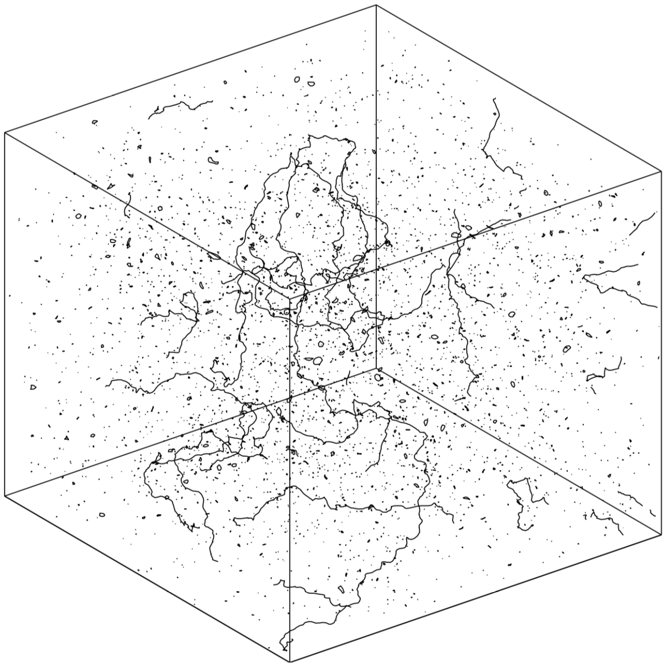


- Gravitational wave signal

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

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

cosmic inflation dilutes monopoles

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

decay via nucleation of monopoles

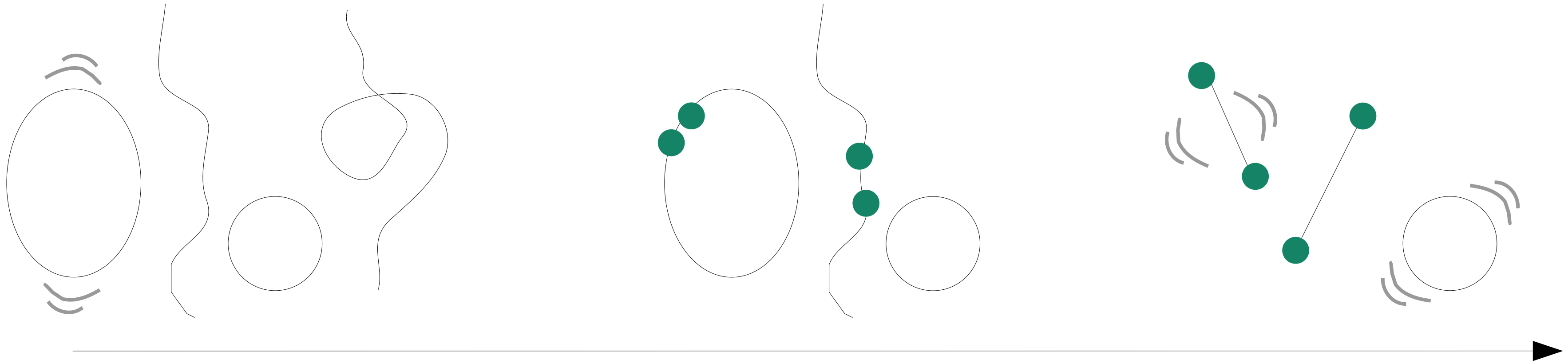
metastable string & monopole network

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

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

$m \sim v_{GUT}$ monopole mass

dynamics of metastable CS network



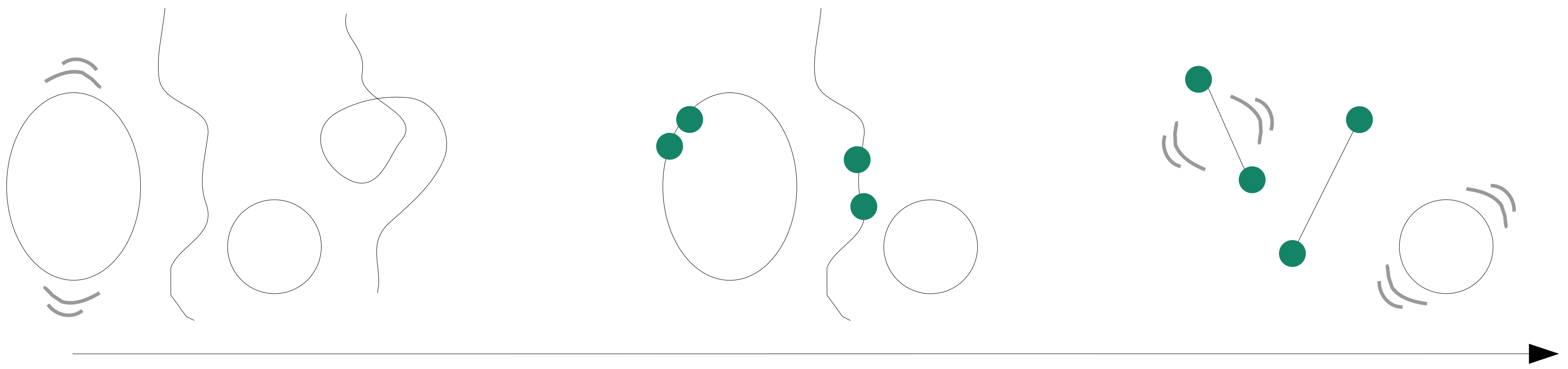
scaling regime
(long strings & loops)

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

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:

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

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

Another example: segments from loops

Buchmüller, VD, Schmitz `21

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

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

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:

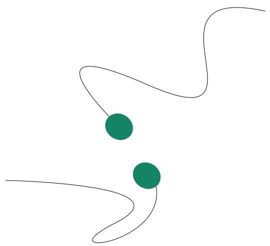
$$t < t_s\, : \qquad \tilde{n}^{(l)}(\ell, t) \simeq 0$$

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

(similar procedure for segments from long strings)

Outline

- Metastable cosmic strings



- Gravitational wave signal

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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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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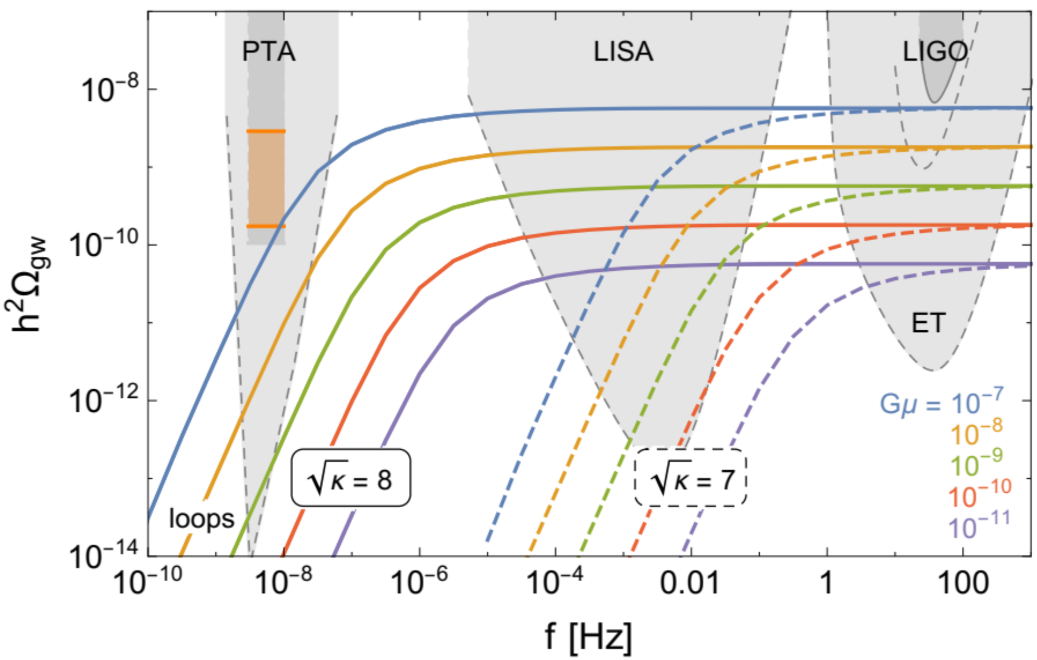
Buchmüller, VD, Schmitz `21

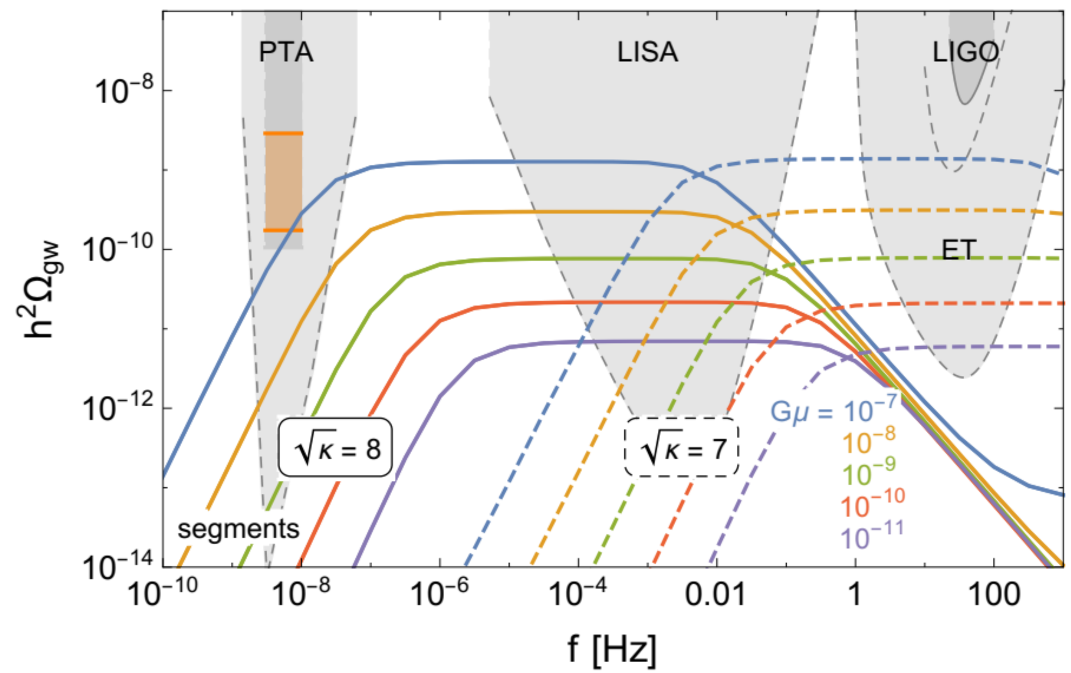
GWs from loops and segments

assuming radiation domination

Buchmüller, VD, Schmitz `21

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





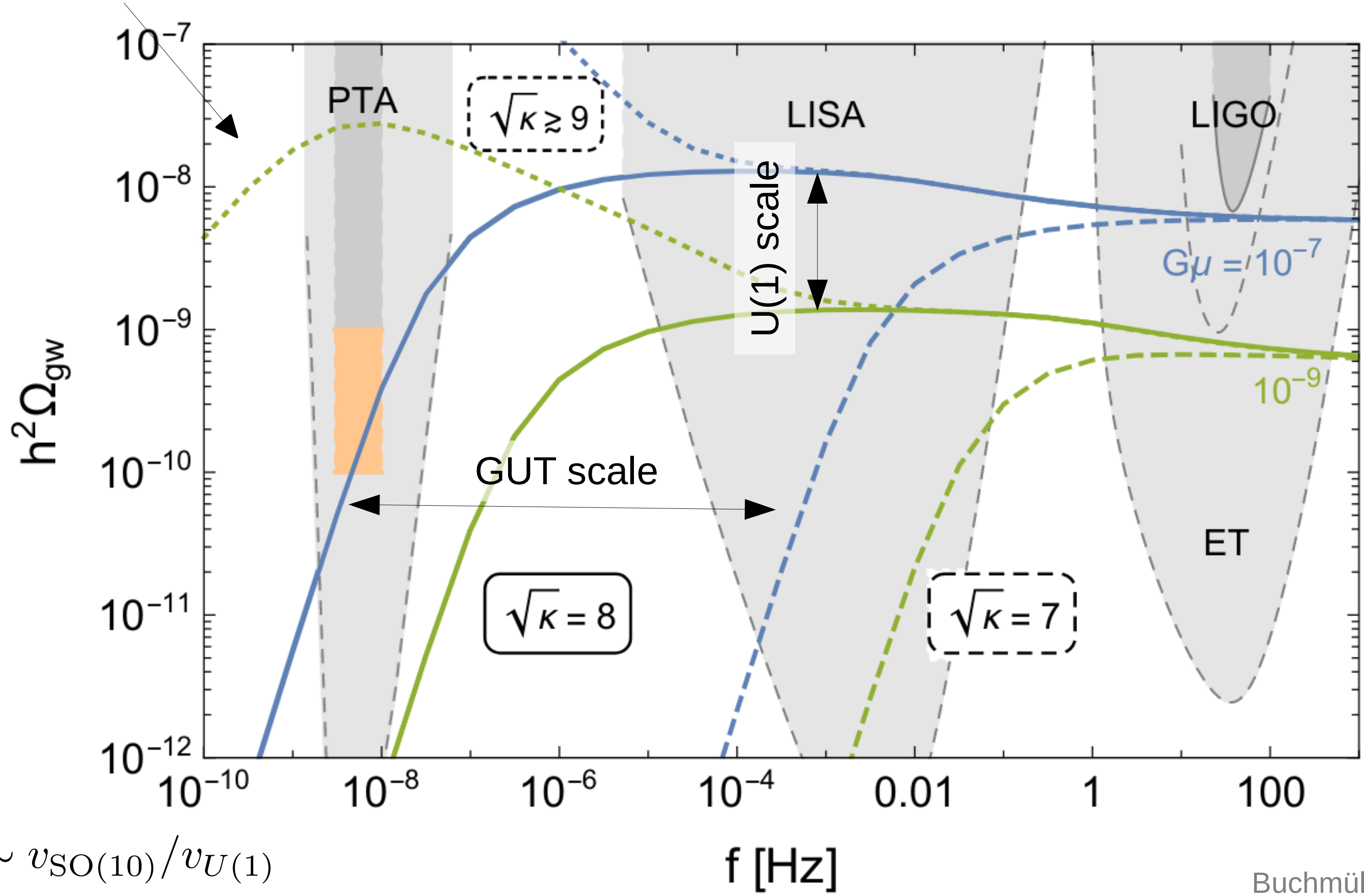
- plateau as for stable strings
- suppression at small frequencies due to finite CS life time
- dominant contribution

- 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

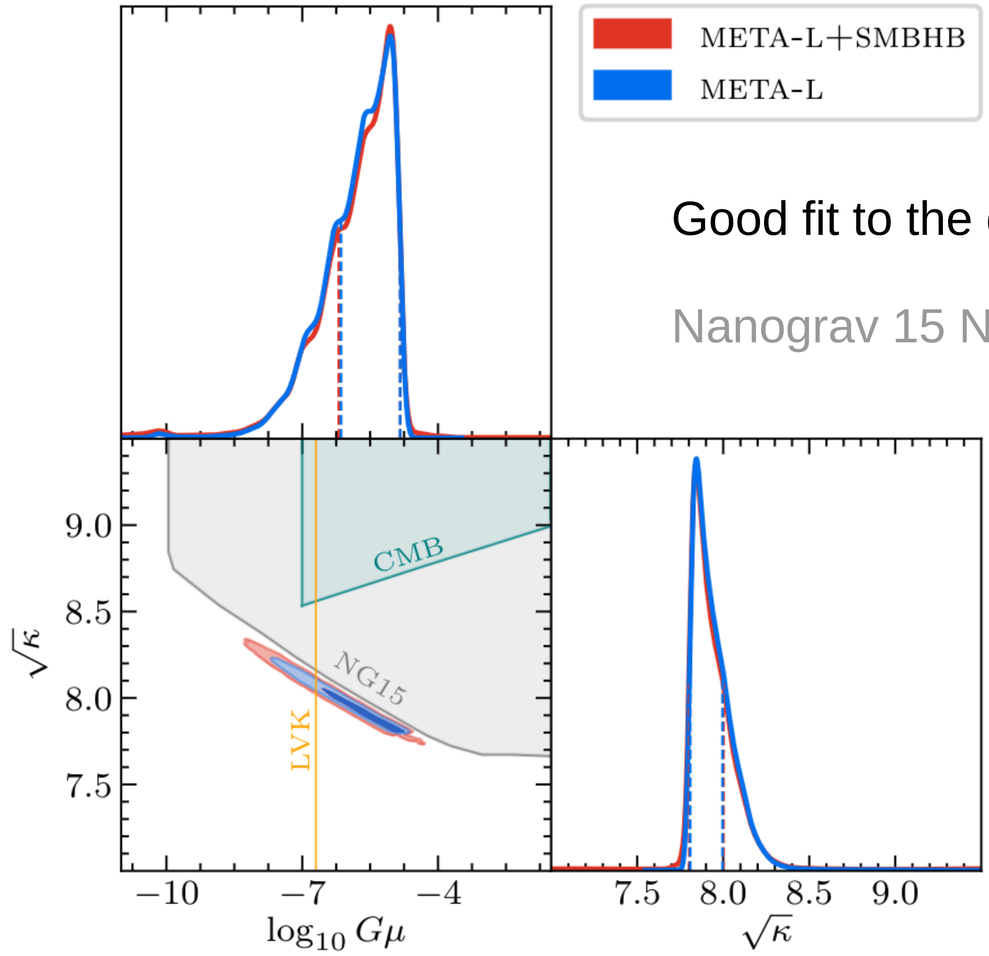


$\sqrt{\kappa} \sim v_{\mathrm{SO}(10)}/v_{U(1)}$

Buchmüller, VD, Schmitz `21

GUT-scale U(1) phase transition can be tested with GWs

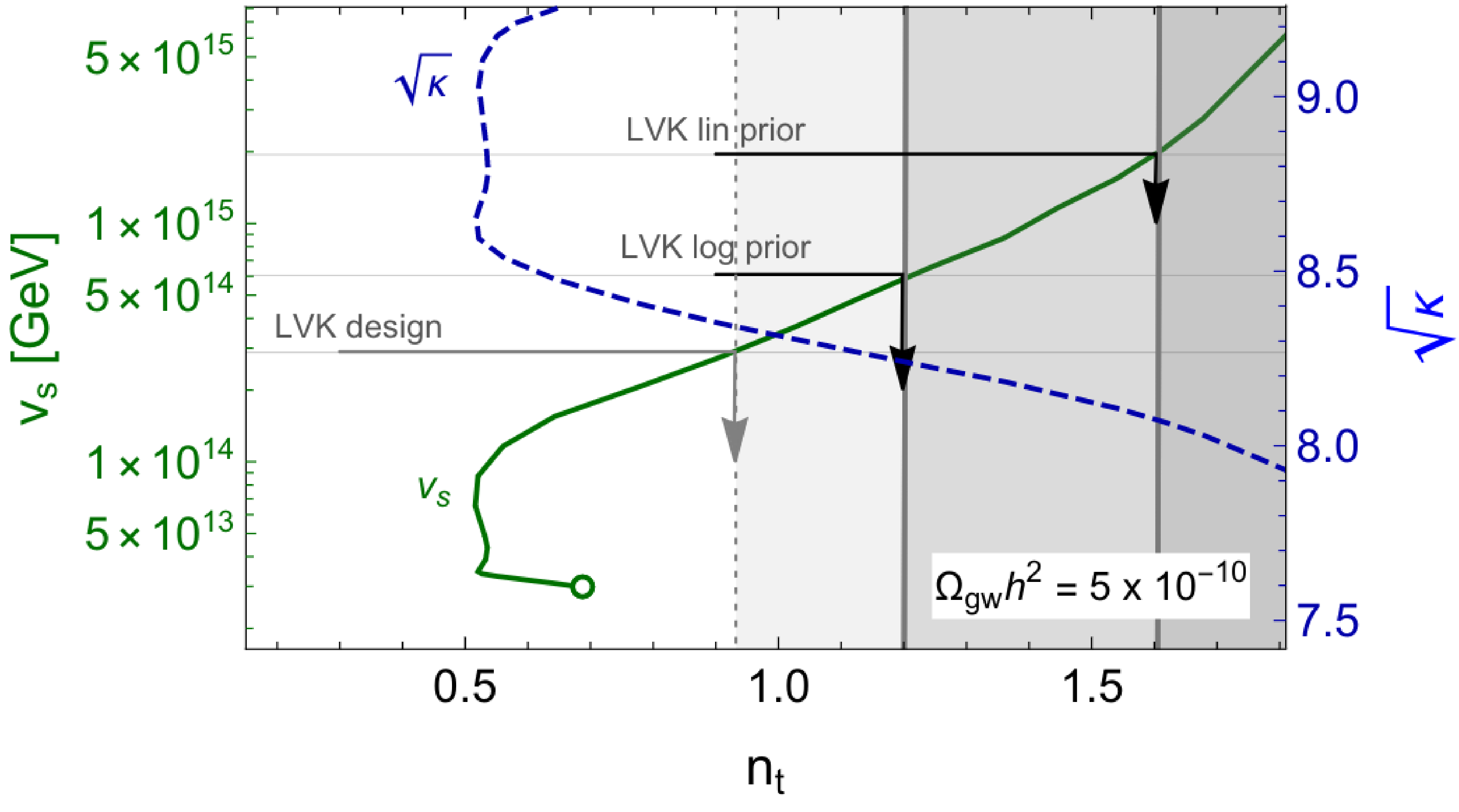
metastable cosmic strings at PTAs ?



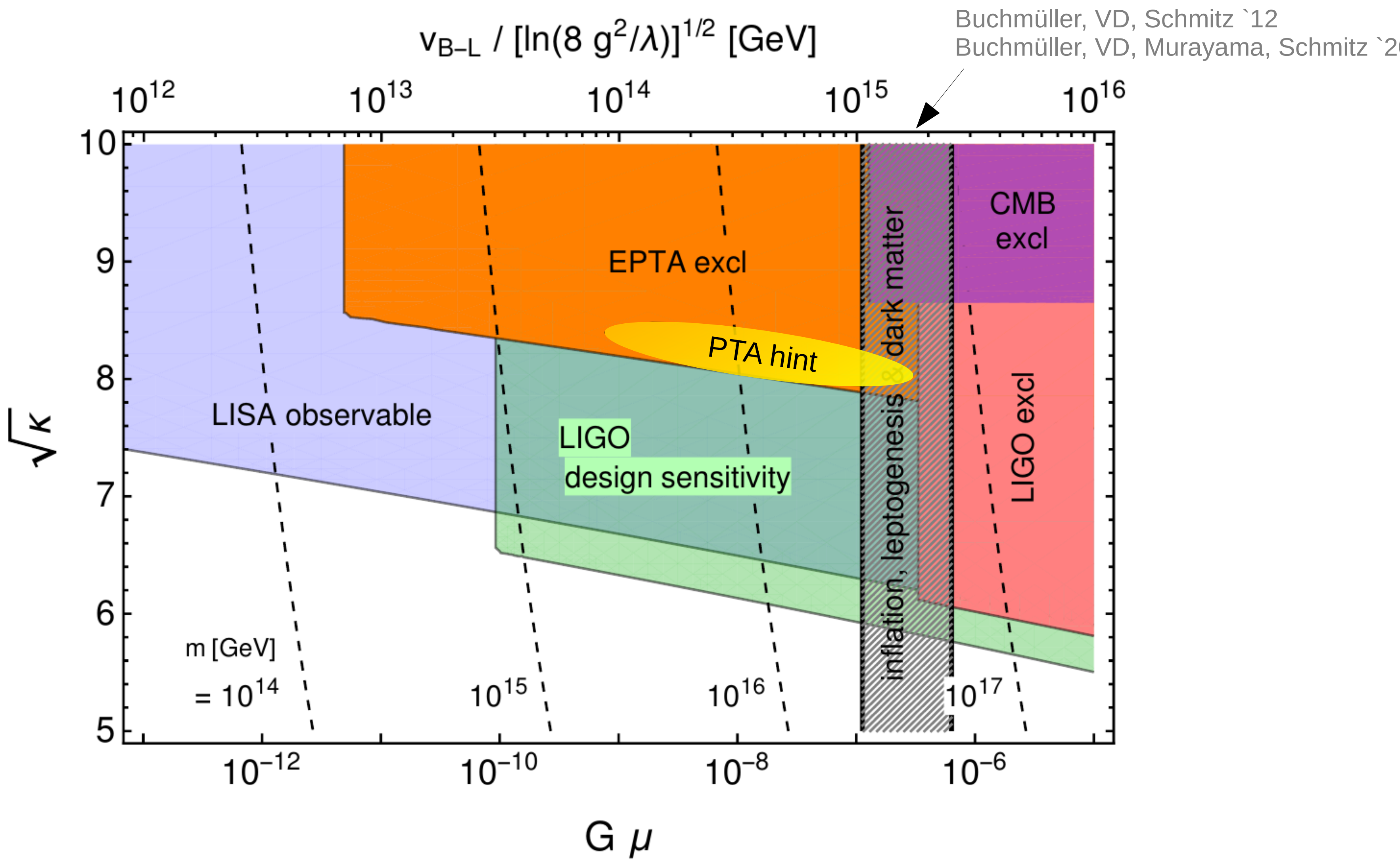
Good fit to the data

Nanograv 15 NP paper

PTAs – what next?



parameter space of metastable strings



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

- Signal 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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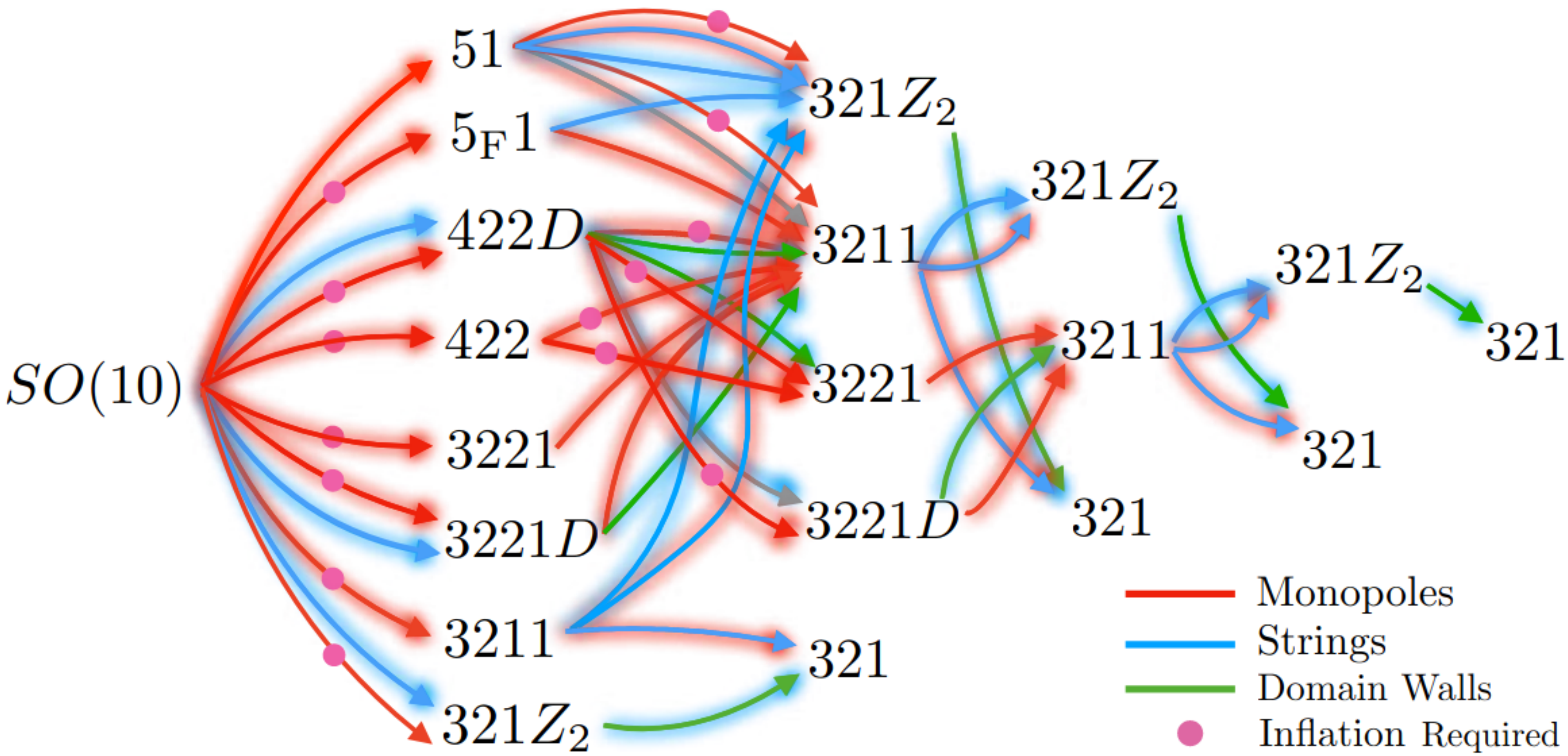
Questions ?

backup slides

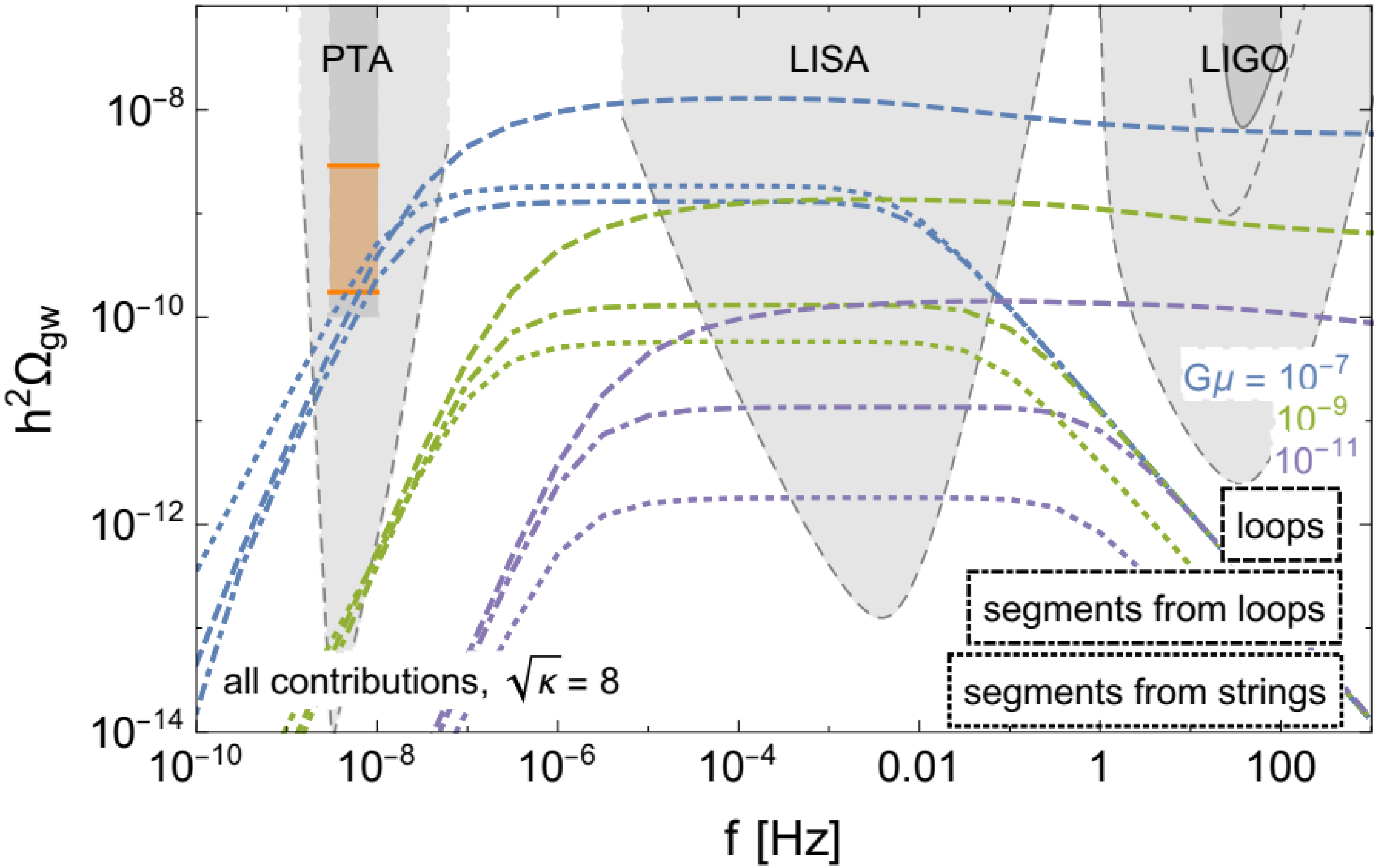
examples of symmetry breaking patterns

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

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

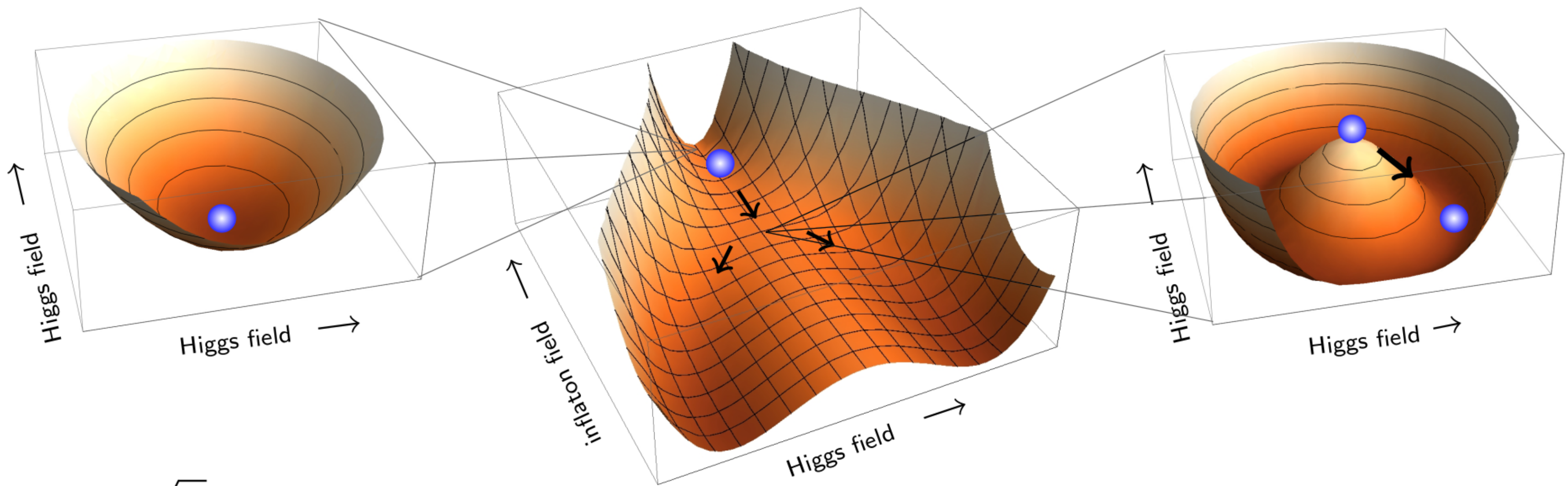


GWs from segments



Cosmological B-L breaking

extend SM by gauging $U(1)_{B\text{-}L}$ & 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

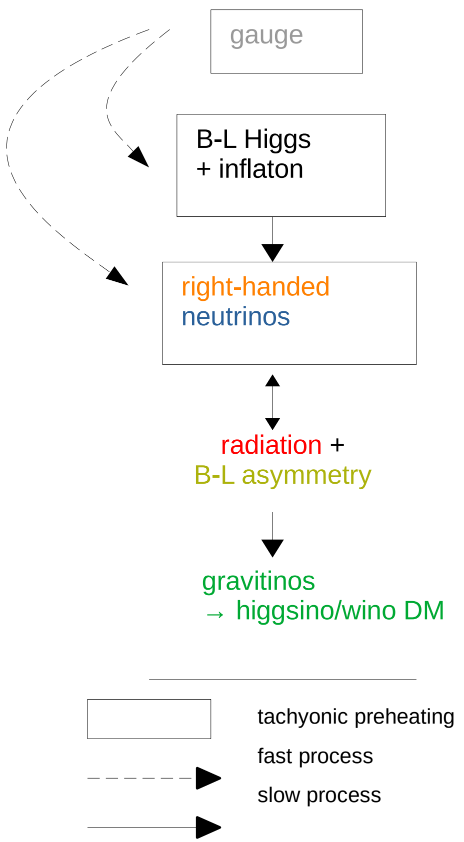
- tachyonic preheating
- cosmic strings

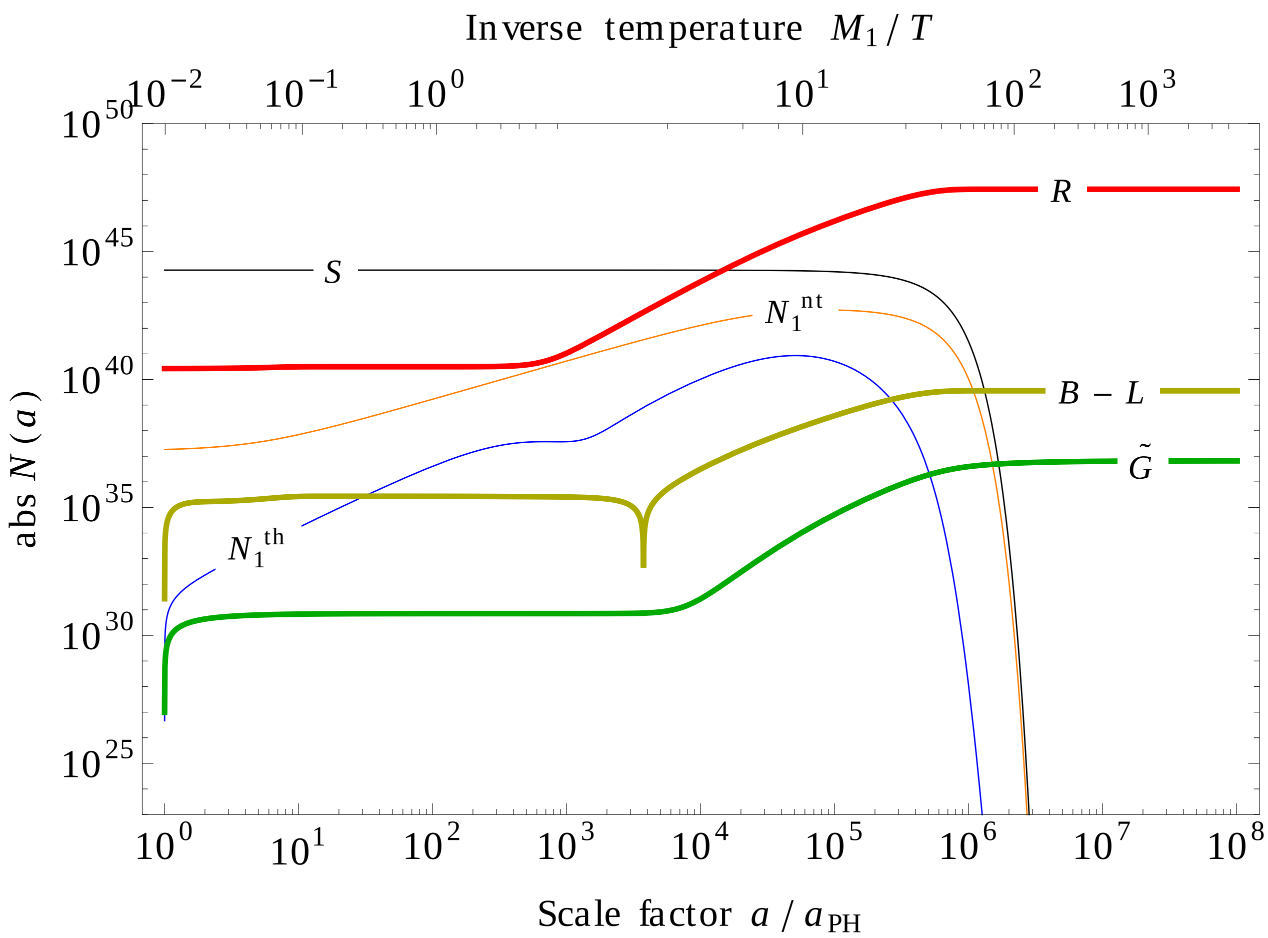
After

- reheating
- leptogenesis
- dark matter

cosmological B-L breaking

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





Buchmüller, VD, Schmitz `12,
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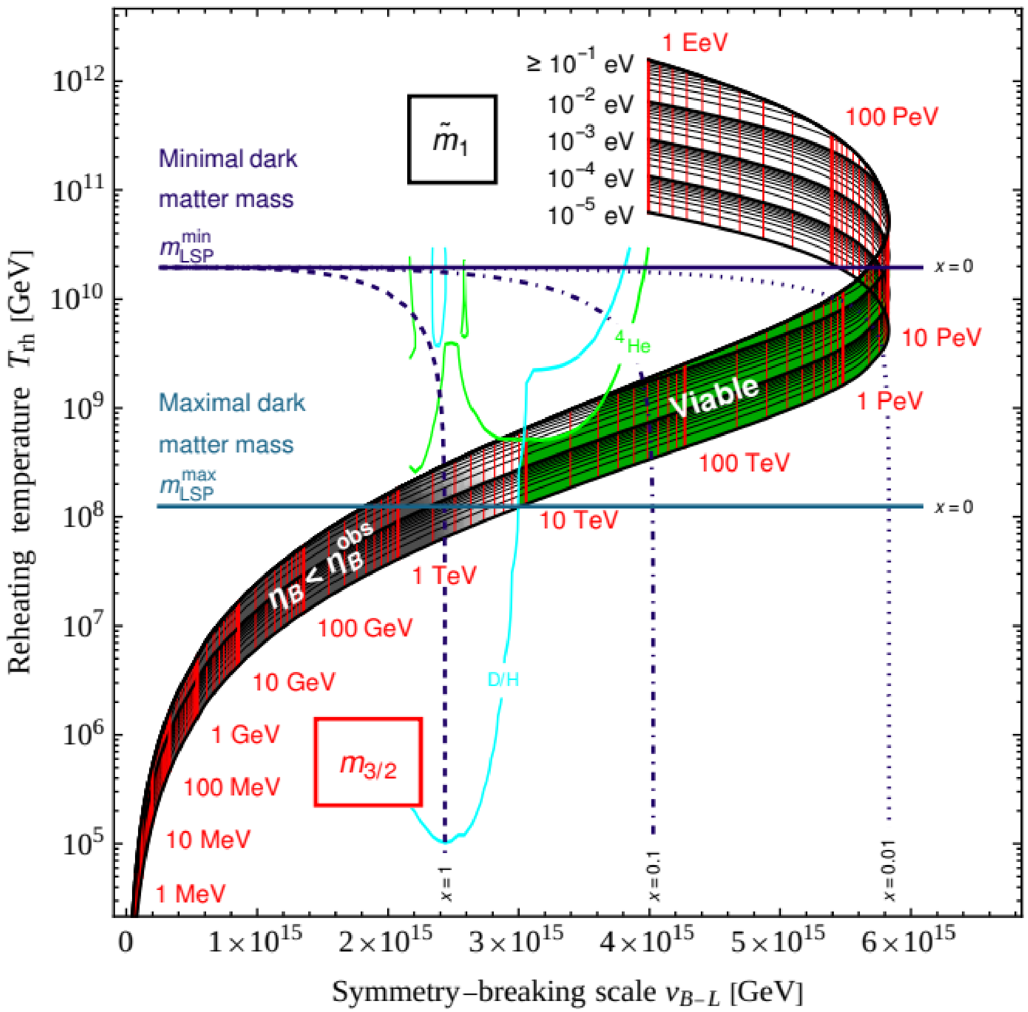
Buchmüller, VD, Murayama, Schmitz `19



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