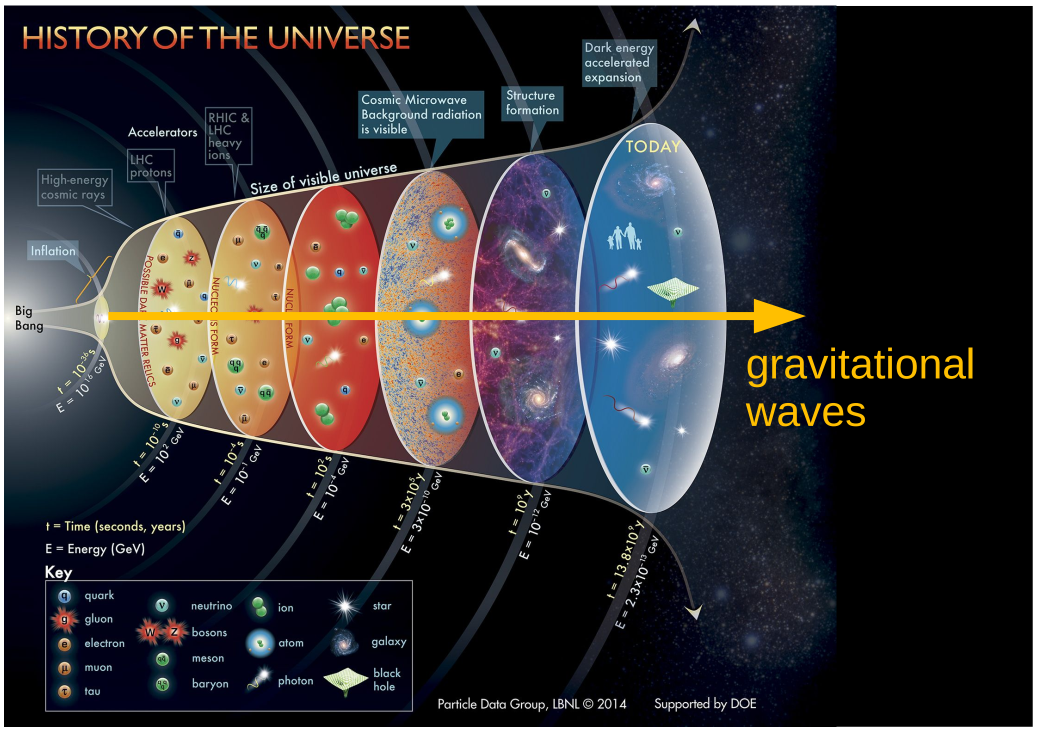
Probing the scale of grand unification with gravitational waves



Valerie Domcke
CERN/EPFL

P³ Seminar
LPTHE, Paris, 07.12.2021

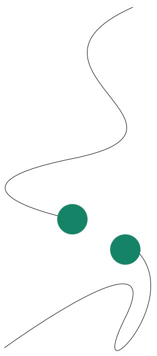
based on
1912.03695, 2009.10649, 2107.04578
w. W. Buchmüller, H. Murayama and K. Schmitz

CERN

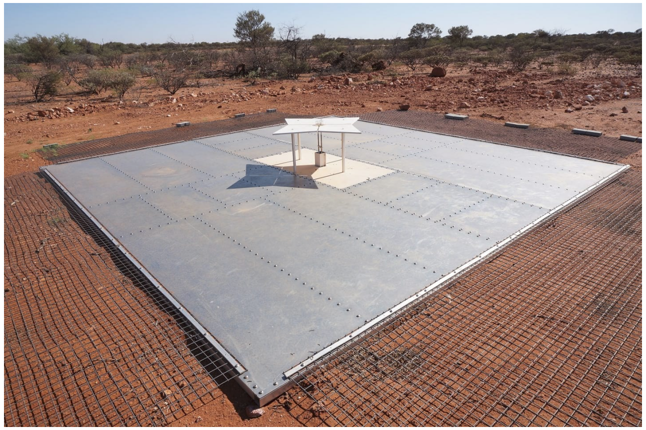
EPFL

Outline

- GWs from metastable cosmic strings



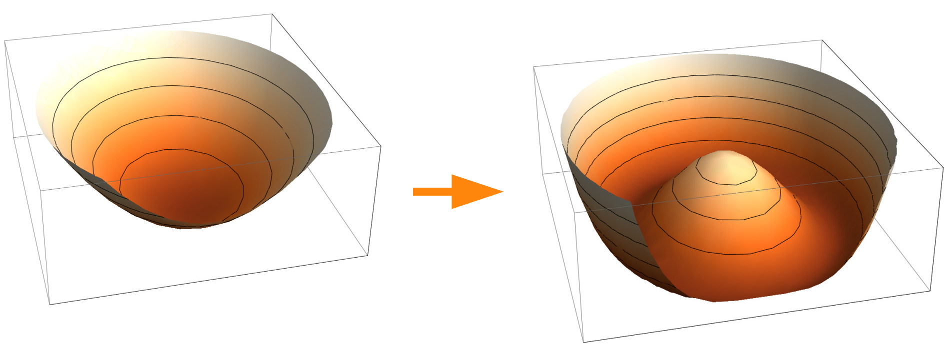
- The challenge of ultra-high frequency GWs

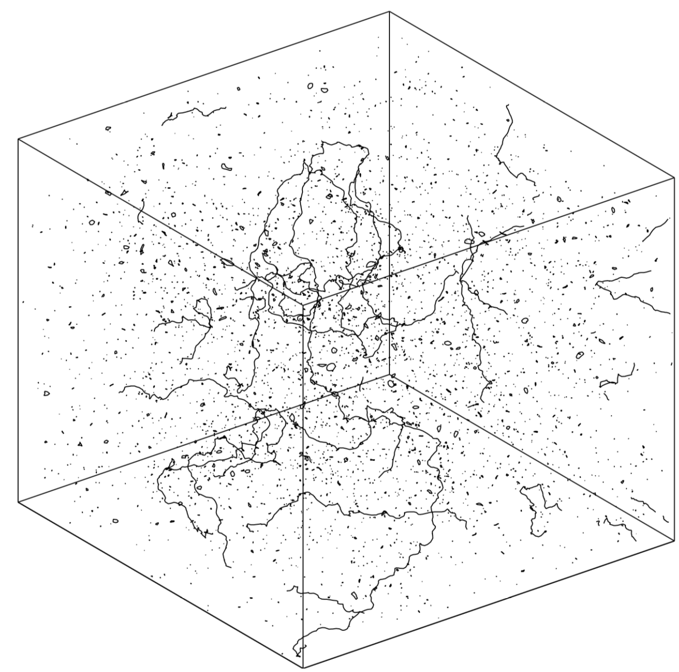


radio telescope EDGES

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

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

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

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

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

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

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

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

see also 2111.04728 'GW gastronomy'
Dunsky, Ghoshal, Murayama, Sakakihara, White

gravitational wave signal - SGWB

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

gravitational wave emission from integration over loop distribution function:

$$\Omega_{\mathrm{GW}}(f) = \frac{8\pi f (G\mu)^2}{3H_0^2} \sum_{n=1}^{\infty} C_n(f) P_n$$

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

GW power spectrum of a single loop

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

# of loops with length ℓ at time *t*

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

cosmological history

gravitational wave signal - SGWB

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

gravitational wave emission from integration over loop distribution function:

$$\Omega_{\rm GW}(f) = \frac{8\pi f (G\mu)^2}{3H_0^2} \sum_{n=1}^{\infty} C_n(f) P_n$$

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

GW power spectrum of a single loop (P_n)

\# of loops emitting GWs observed at frequency *f* today ($C_n(f)$)

\# of loops with length ℓ at time *t*

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

cosmological history

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

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

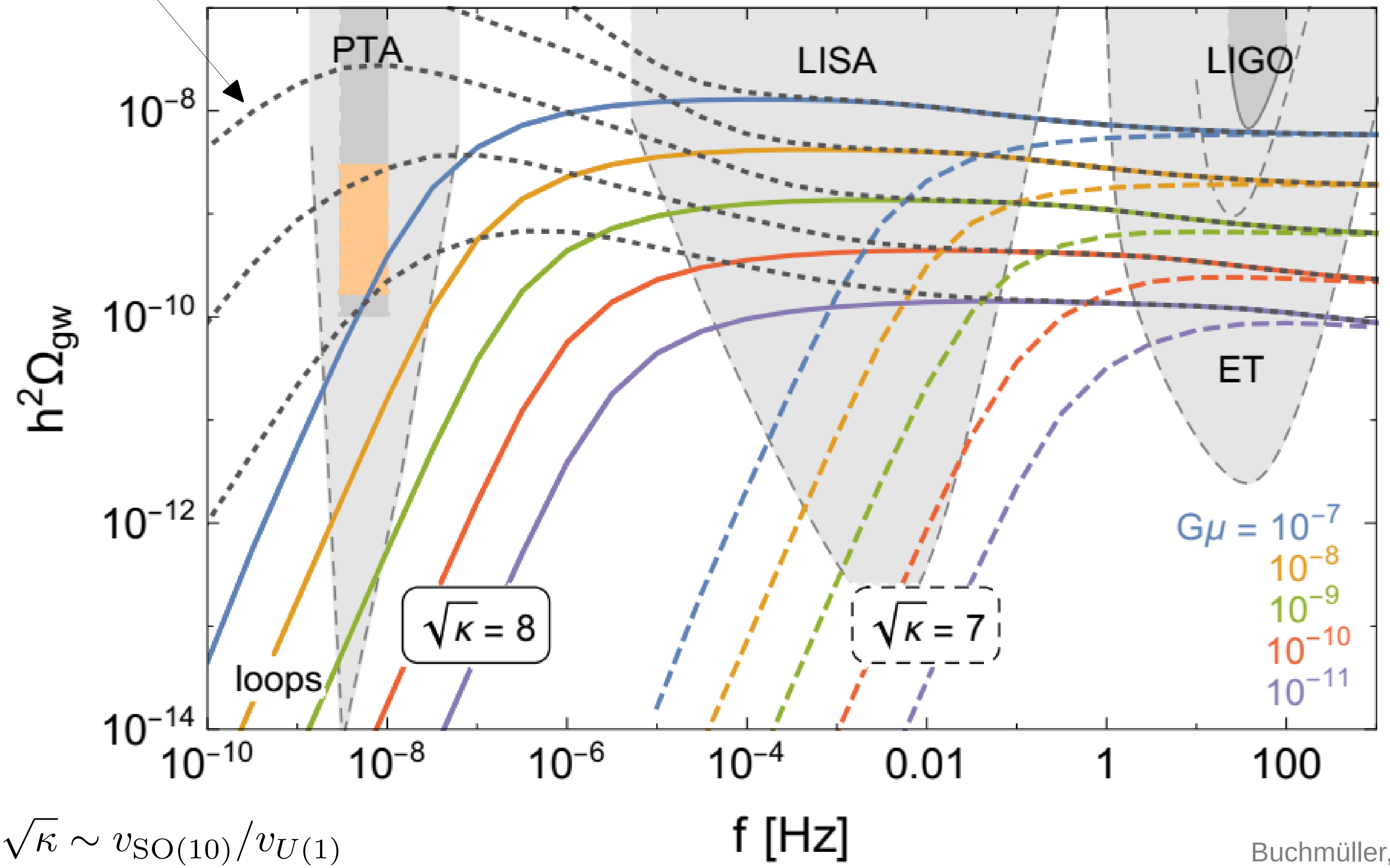
loop production only in scaling regime

Buchmüller, VD, Schmitz `21

gravitational wave spectrum

stable cosmic strings
(highly constrained by PTA)

metastable cosmic strings
discovery space for LISA, LIGO & beyond



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

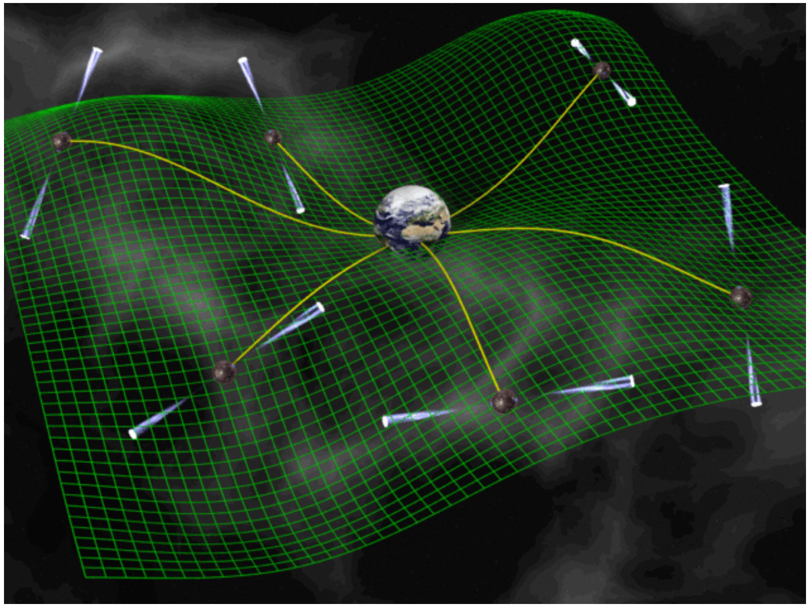
Buchmüller, VD, Schmitz `21

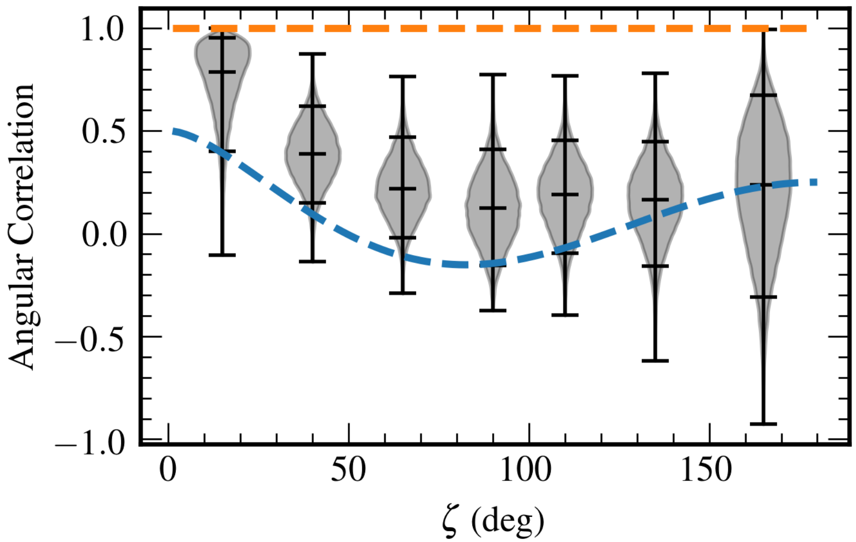
$SO(10) \to G_{\mathrm{SM}} \times U(1)_{B-L} \to G_{\mathrm{SM}}$ with $v_{B-L} \lesssim v_{GUT}$ can be tested with GWs!

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."



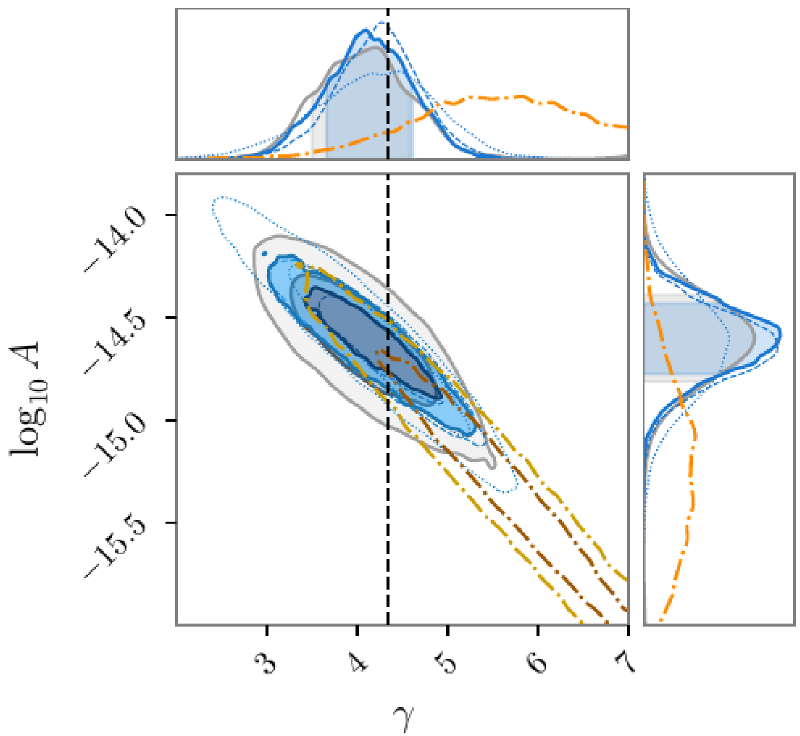


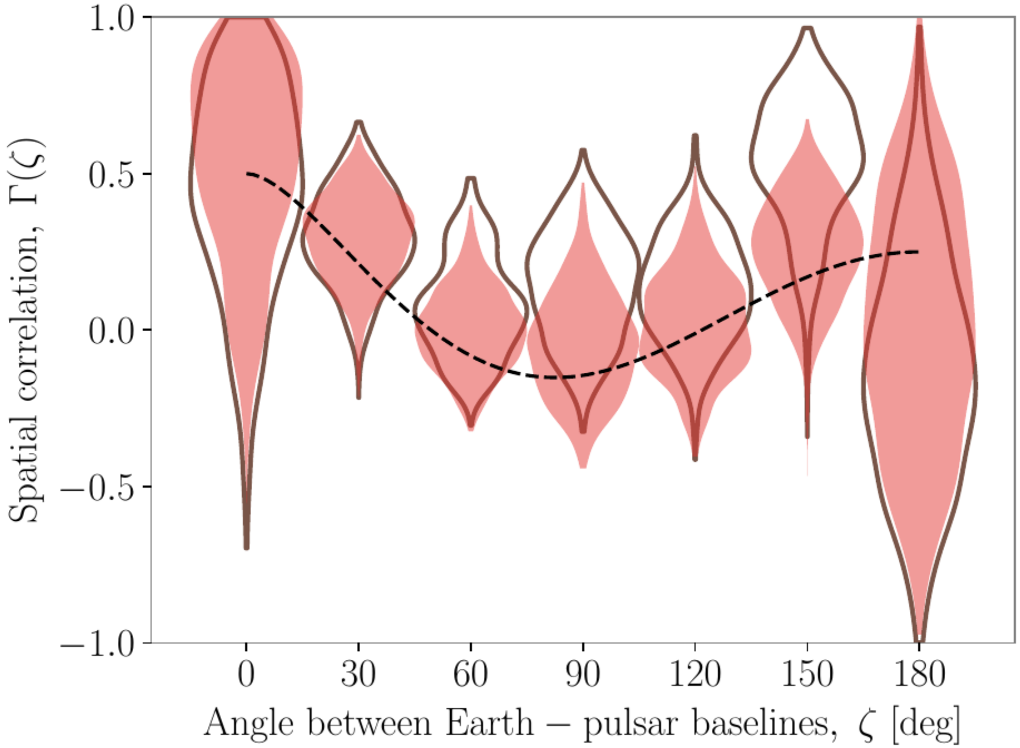
NANOGrav collaboration `20

> „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."

Parkes Pulsar timing array

PPTA `21, 2107.12112



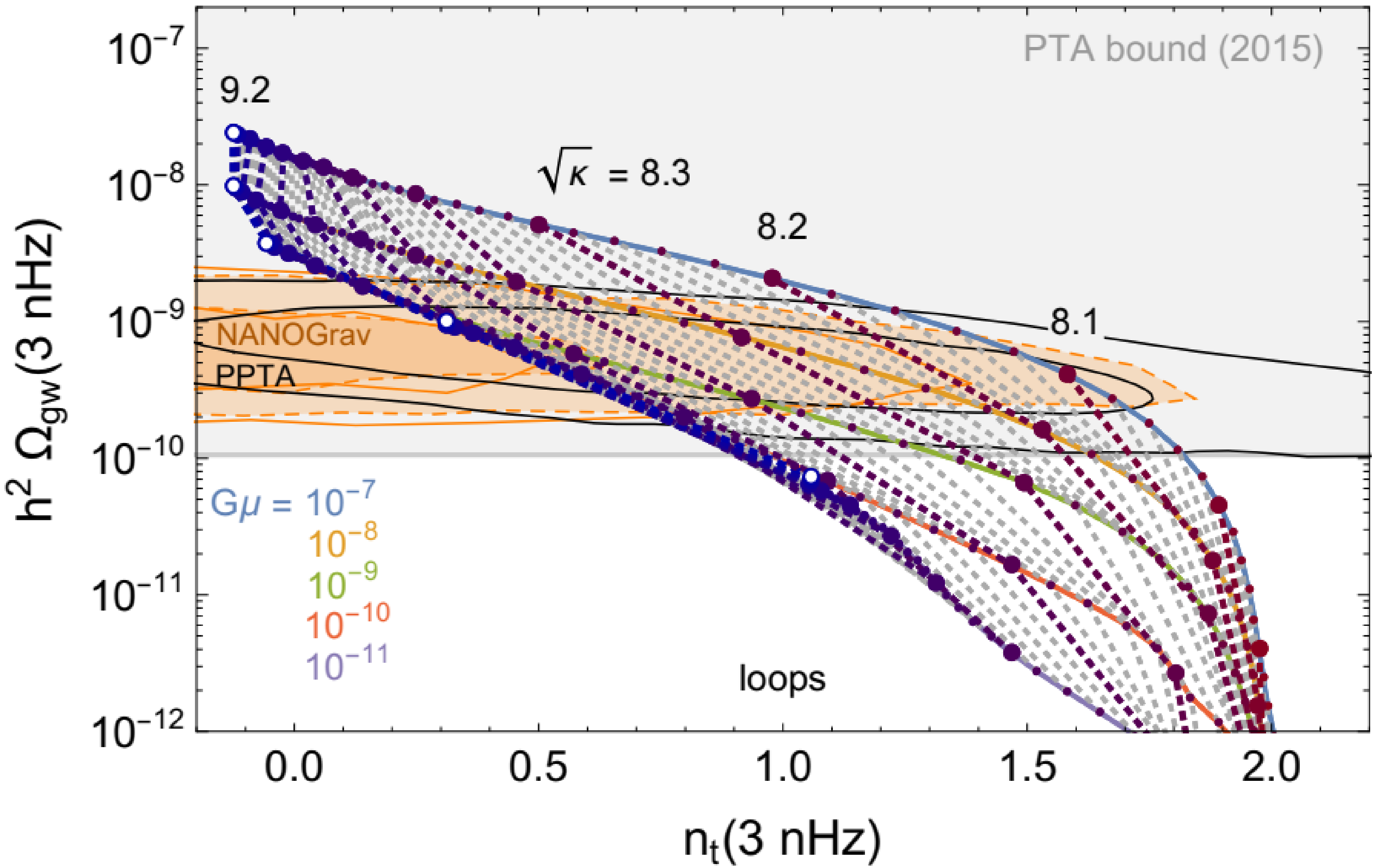


amplitude and spectral tilt compatitive with NANOGrav

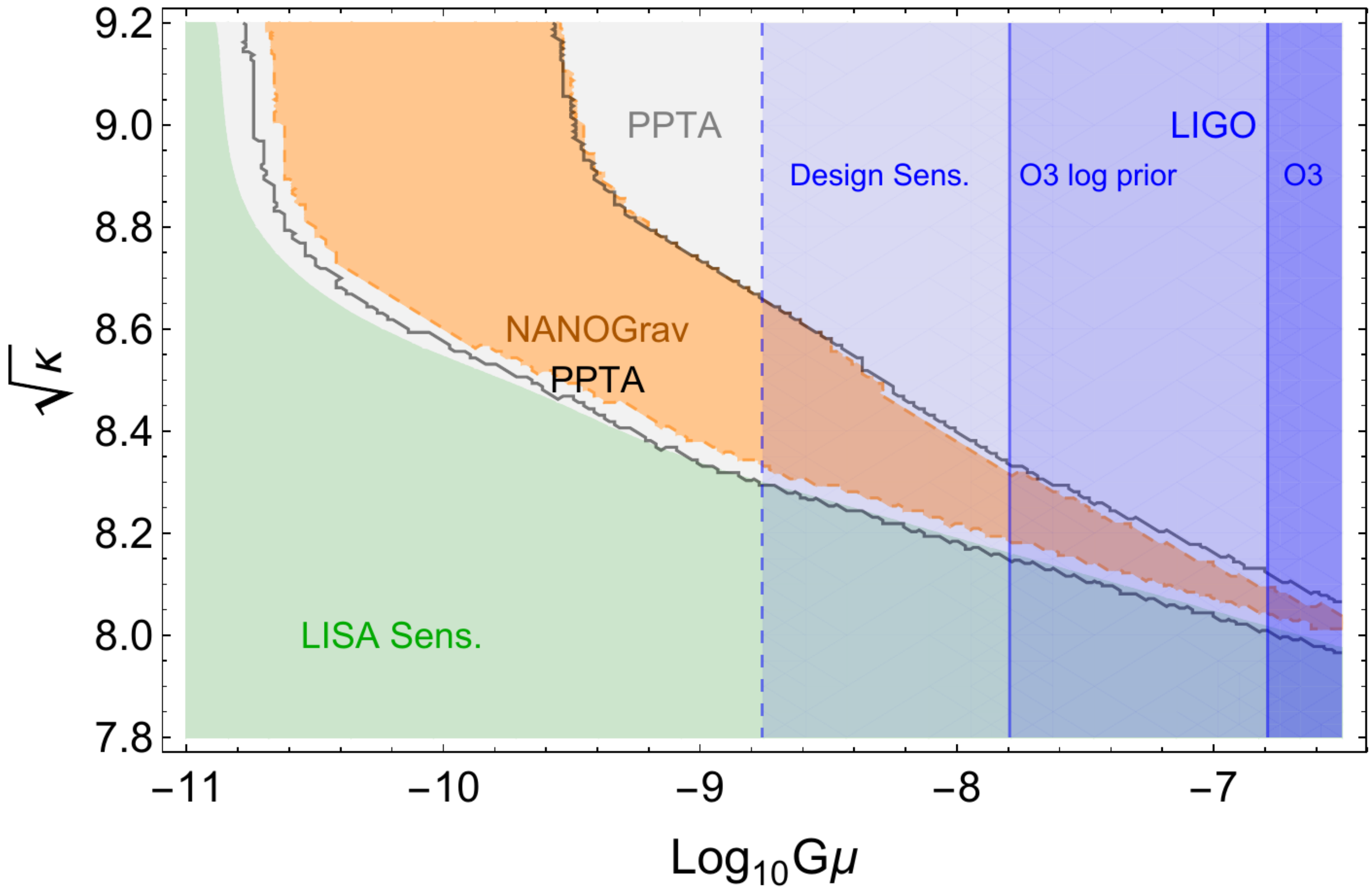
no significant detection of quandropolar spatial correlation

Maybe. Stay tuned for more data!

cosmic strings at PTAs ?



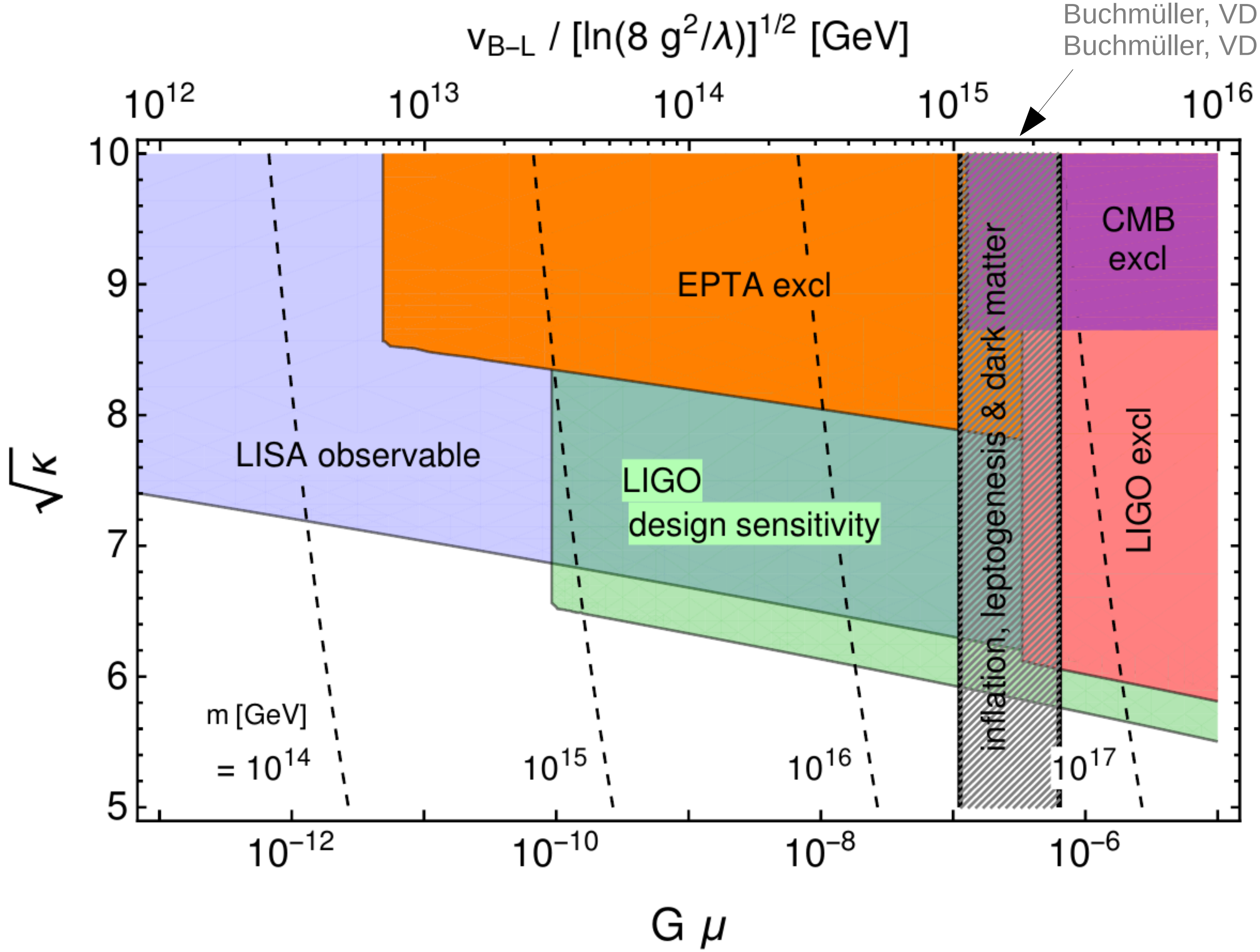
Prospects for GW searches



PTA hint will be probed with interferometers

parameter space of metastable strings

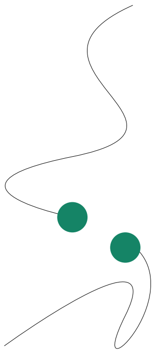
Buchmüller, VD, Schmitz `12
Buchmüller, VD, Murayama, Schmitz `20



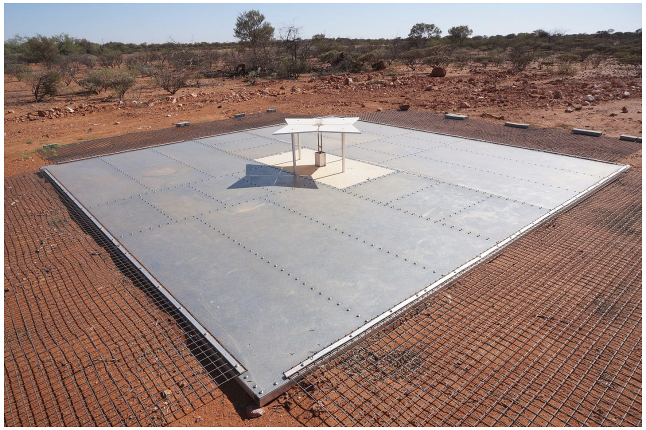
metastable GUT- scale strings are testable

Outline

- GWs from metastable cosmic strings

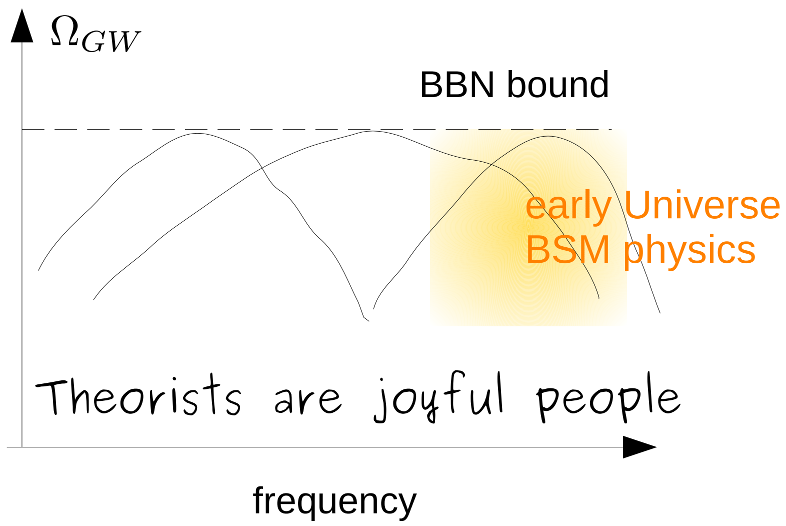


- The challenge of ultra-high frequency GWs



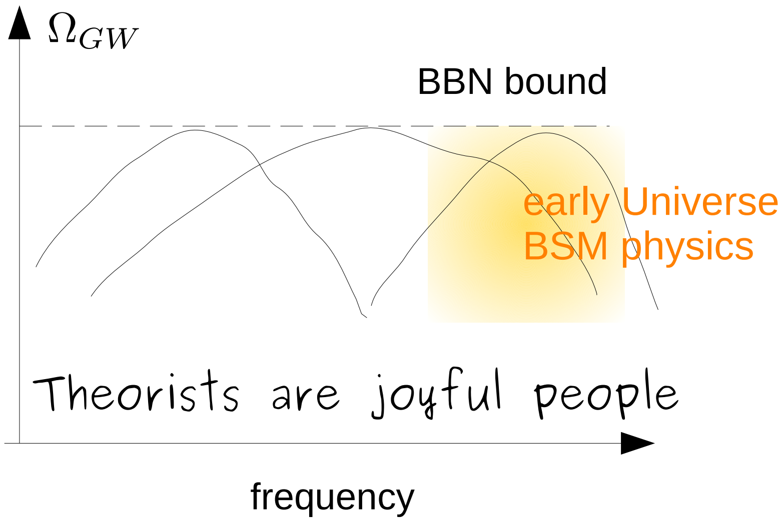
radio telescope EDGES

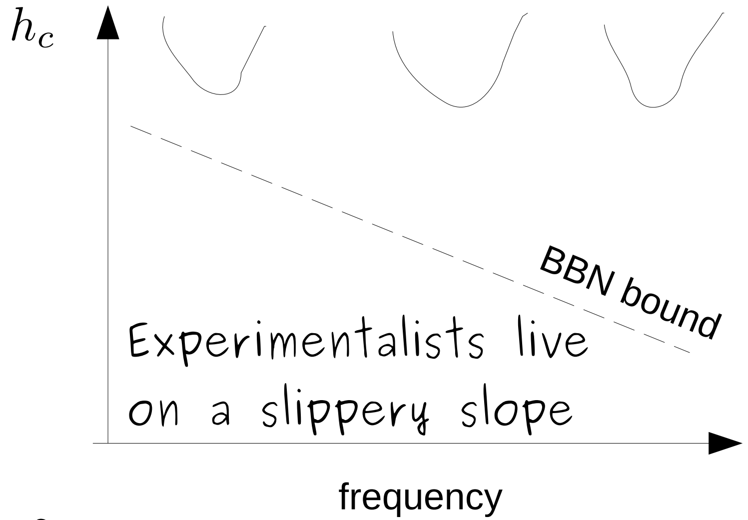
challenges in UHF GW detection



CMB/BBN bound constrains energy

challenges in UHF GW detection



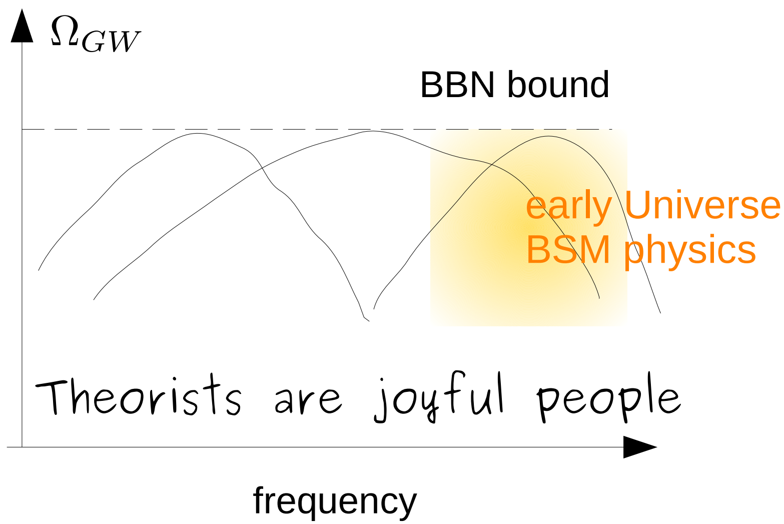


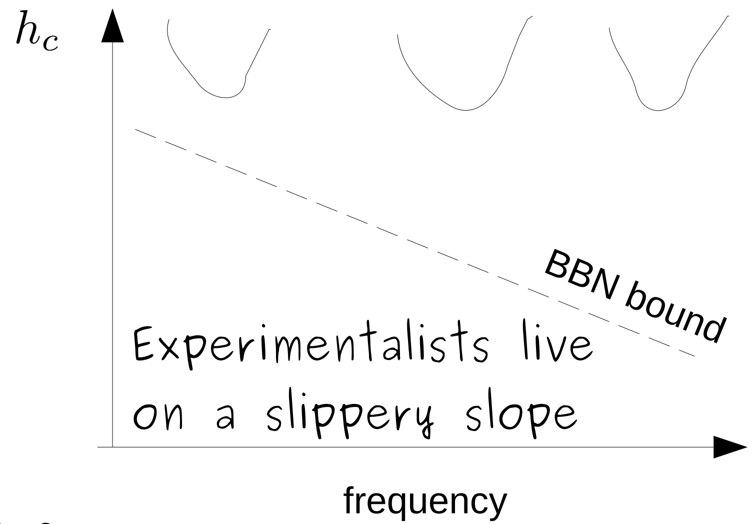
$$\Omega_{GW} \propto f^2 h_c^2$$

CMB/BBN bound constrains energy

experiments measure displacement

challenges in UHF GW detection

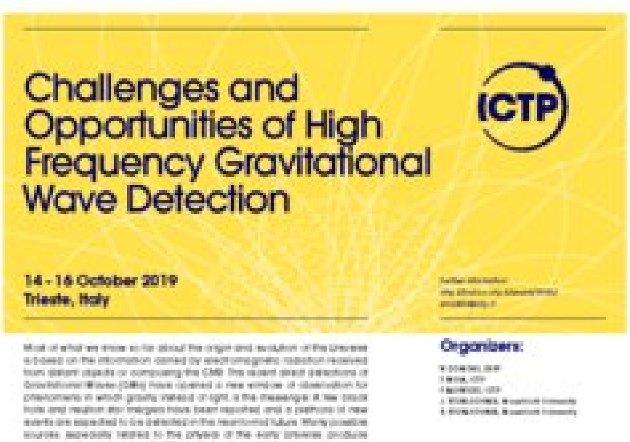


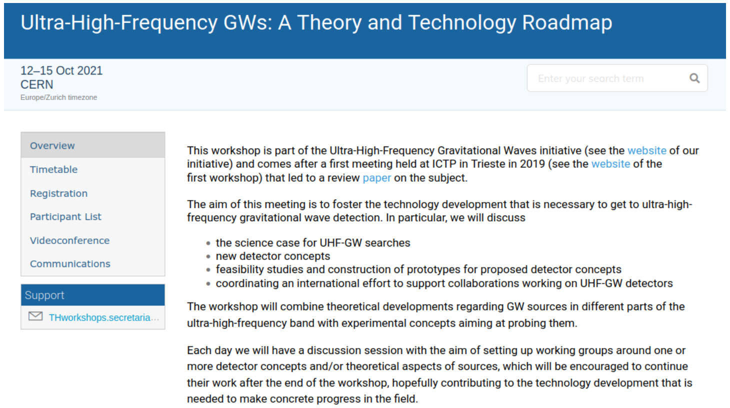


$$\Omega_{GW} \propto f^2 h_c^2$$

CMB/BBN bound constrains energy

experiments measure displacement





Ultra-High-Frequency GWs: A Theory and Technology Roadmap

12–15 Oct 2021
CERN
Europe/Zurich timezone

Overview
Timetable
Registration
Participant List
Videoconference
Communications
Support
THworkshops.secretaria...

This workshop is part of the Ultra-High-Frequency Gravitational Waves initiative (see the website of our initiative) and comes after a first meeting held at ICTP in Trieste in 2019 (see the website of the first workshop) that led to a review paper on the subject.

The aim of this meeting is to foster the technology development that is necessary to get to ultra-high-frequency gravitational wave detection. In particular, we will discuss

- the science case for UHF-GW searches
- new detector concepts
- feasibility studies and construction of prototypes for proposed detector concepts
- coordinating an international effort to support collaborations working on UHF-GW detectors

The workshop will combine theoretical developments regarding GW sources in different parts of the ultra-high-frequency band with experimental concepts aiming at probing them.

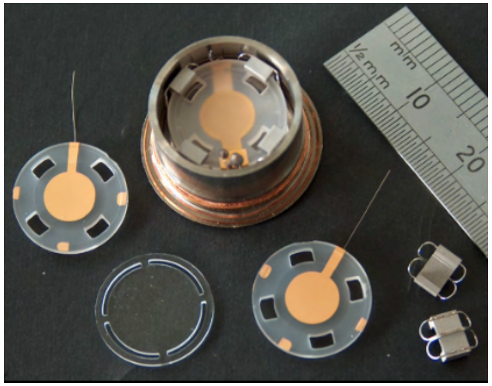
Each day we will have a discussion session with the aim of setting up working groups around one or more detector concepts and/or theoretical aspects of sources, which will be encouraged to continue their work after the end of the workshop, hopefully contributing to the technology development that is needed to make concrete progress in the field.

all talks available online:

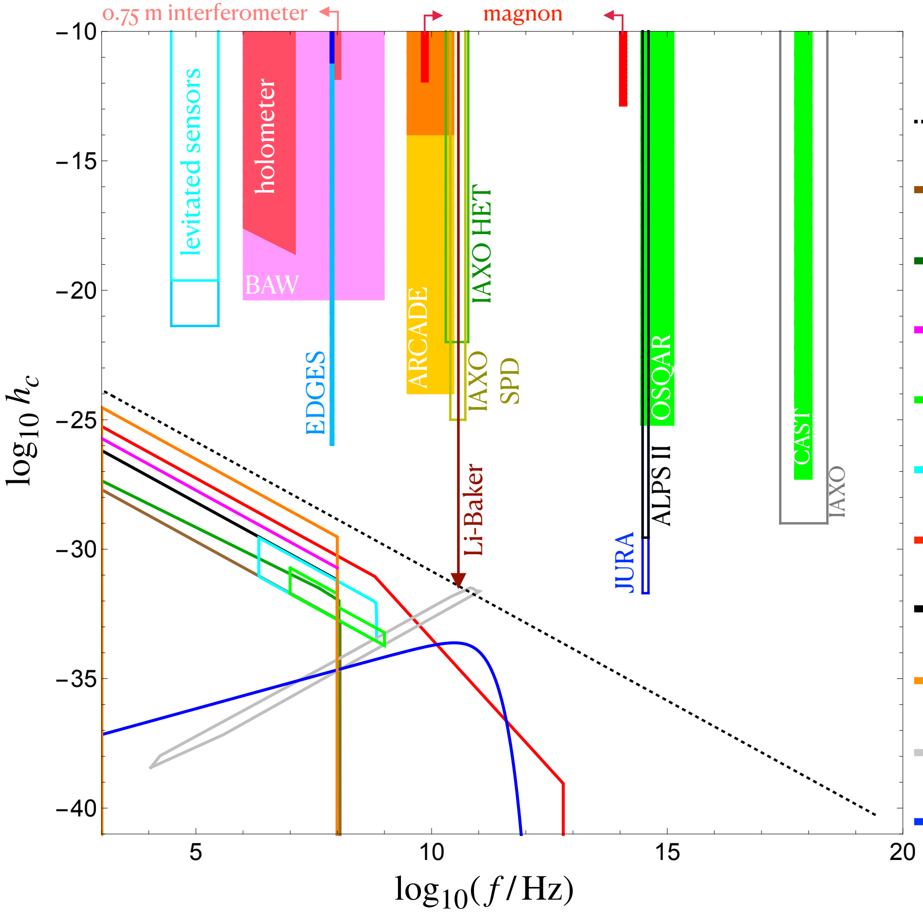
1st workshop
http://indico.ictp.it/event/9006/

2nd workshop:
https://indico.cern.ch/event/1074510/

ALPS II



Bulk accoustic wave devices at UWA



SOURCES LEGEND
- BBN bound
- Inflation (extra-species)
- Inflation (effective field theory)
- Inflation (scalar perturbations)
- Preheating
- Oscillons
- Phase transitions
- Cosmic strings
- Metastable strings
- Gauge textures
- Cosmic gravitational microwave background

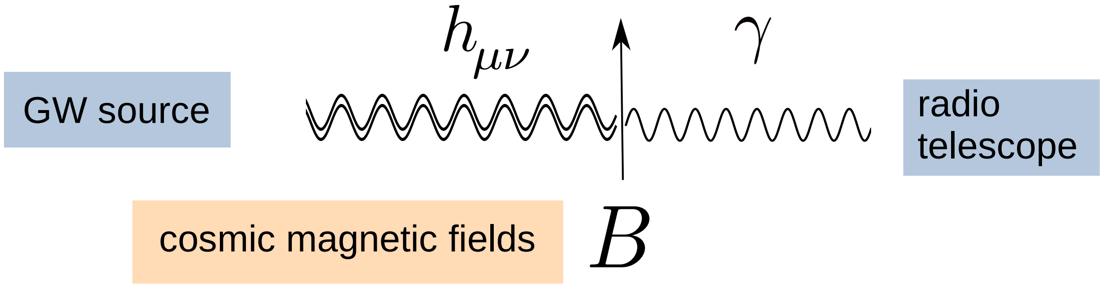
Living Review on sources & detectors: https://arxiv.org/abs/2011.12414

radio telescopes as UHF GW detectors?

Detection of cosmological sources at high frequencies (MHz – GHz) is challenging.

→ compensate small coupling with cosmologically big detector:

VD, Garcia-Cely
PRL 126 (2021) 2, 021104

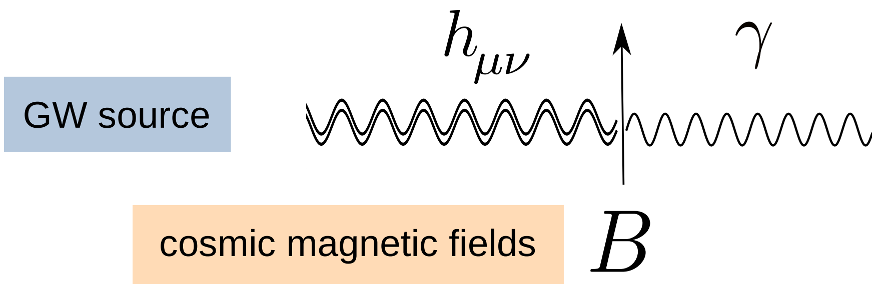


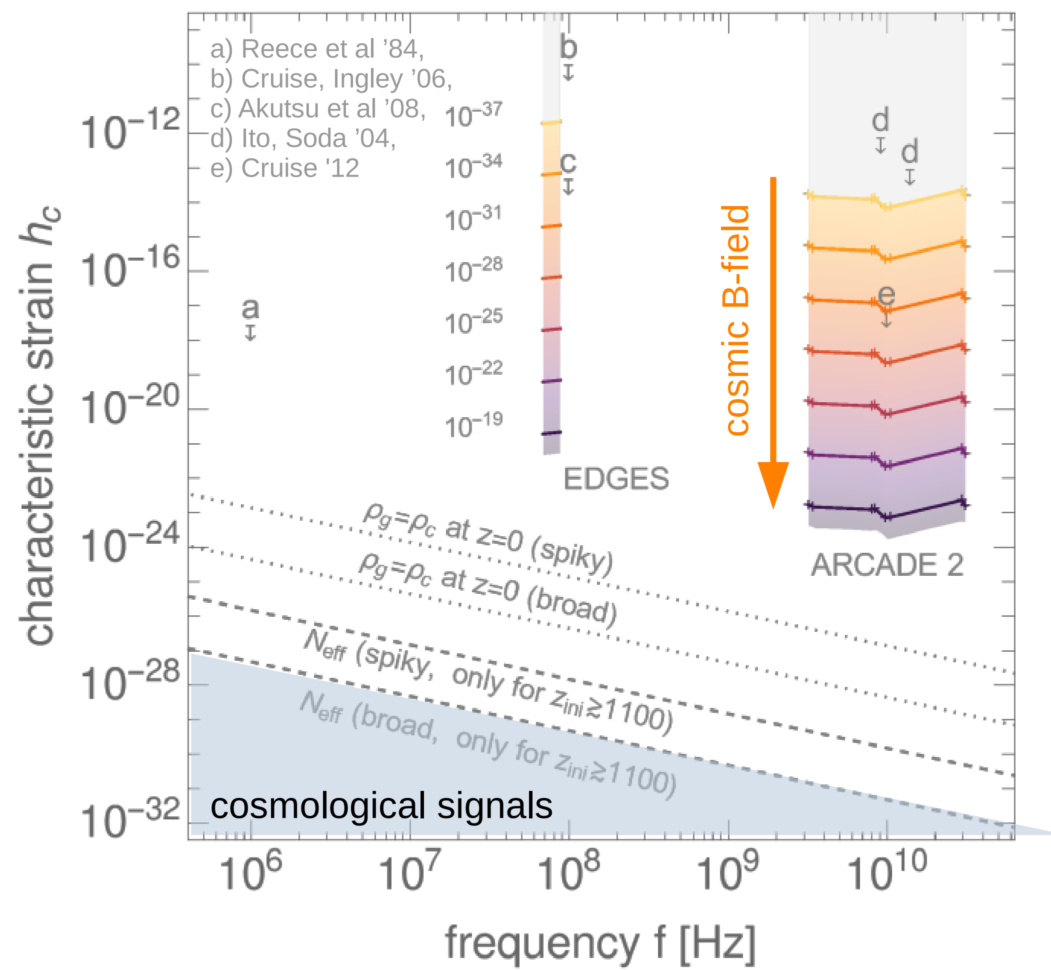
radio telescopes as UHF GW detectors?

Detection of cosmological sources at high frequencies (MHz – GHz) is challenging.

→ compensate small coupling with cosmologically big detector:

VD, Garcia-Cely
PRL 126 (2021) 2, 021104



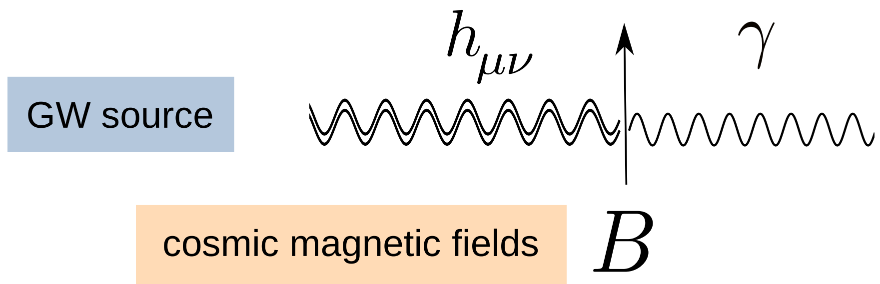


radio telescopes as UHF GW detectors?

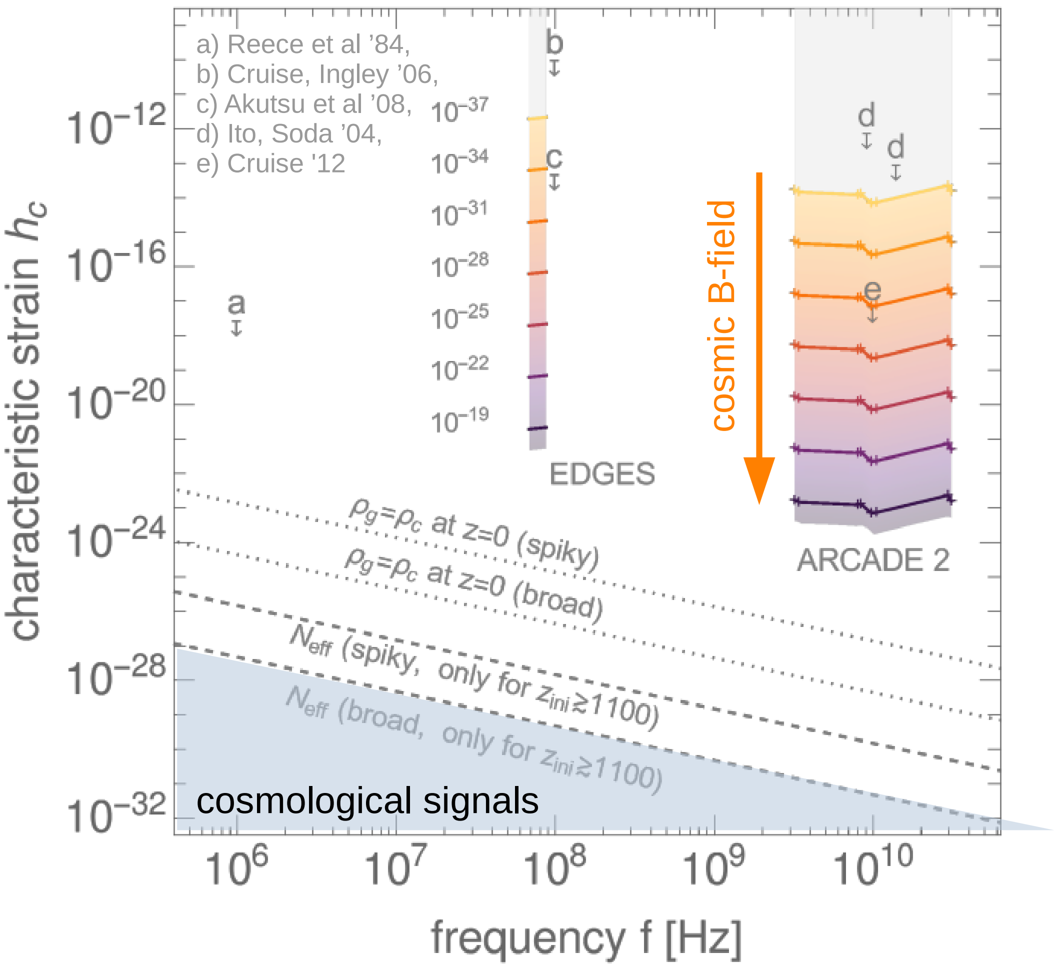
Detection of cosmological sources at high frequencies (MHz – GHz) is challenging.

→ compensate small coupling with cosmologically big detector:

VD, Garcia-Cely
PRL 126 (2021) 2, 021104



- promising, but significant improvements needed

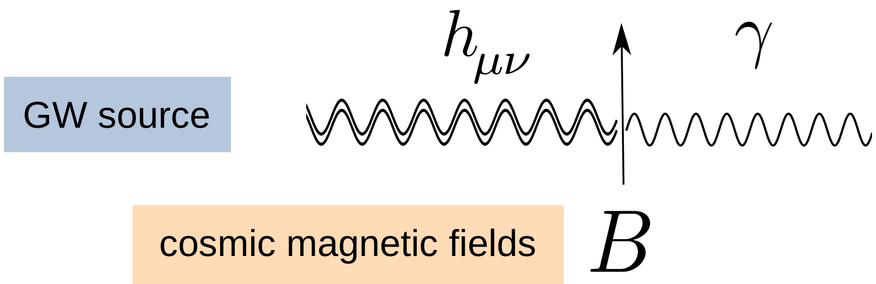


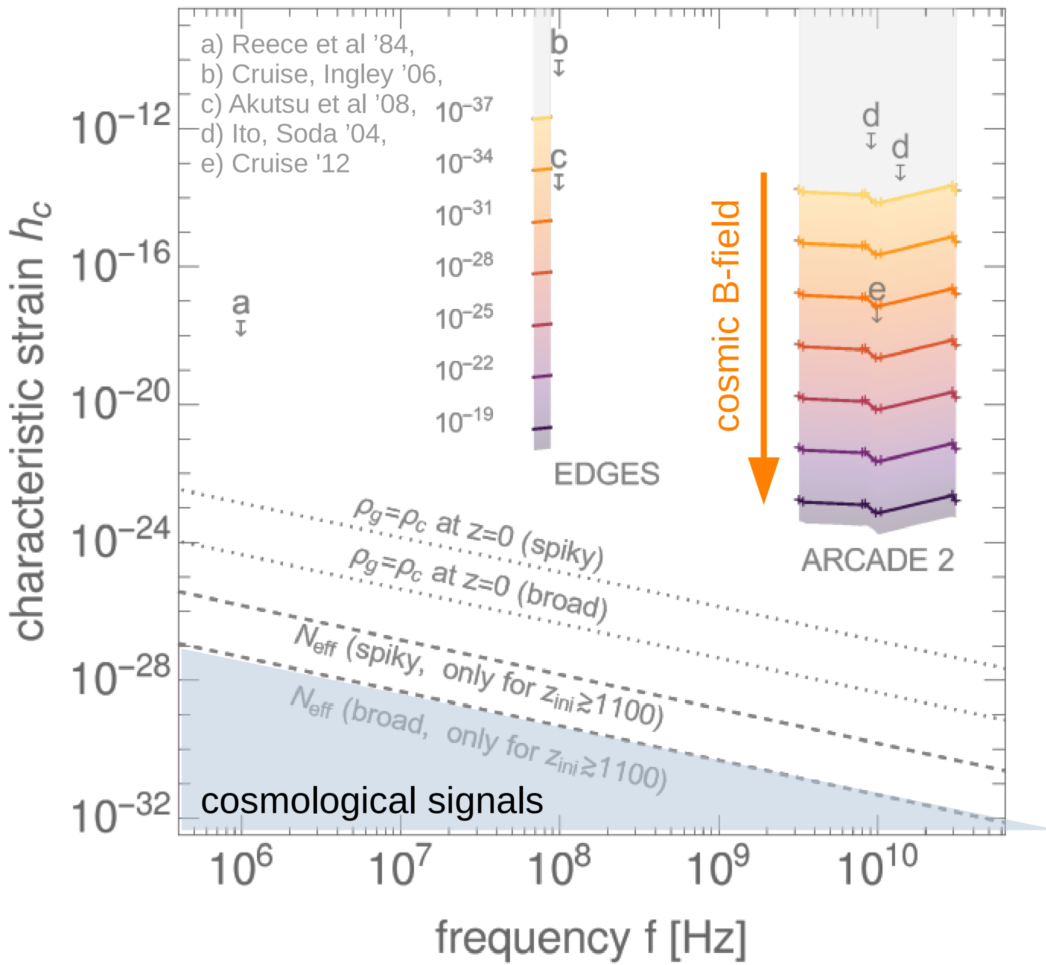
radio telescopes as UHF GW detectors?

Detection of cosmological sources at high frequencies (MHz – GHz) is challenging.

→ compensate small coupling with cosmologically big detector:

VD, Garcia-Cely
PRL 126 (2021) 2, 021104





- promising, but significant improvements needed
- a lot of room for new ideas (laboratory & cosmo)

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 ?

- UHF GW frontier: challenging, plenty of room for new ideas

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 ?

- UHF GW frontier: challenging, plenty of room for new ideas

„such detectors [laser interferometers] have so low sensitivity that they are of little experimental interest" [Misner, Thorne, Wheeler 1974]

← nobel prize 2016 for detection of GWs with LIGO

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 ?

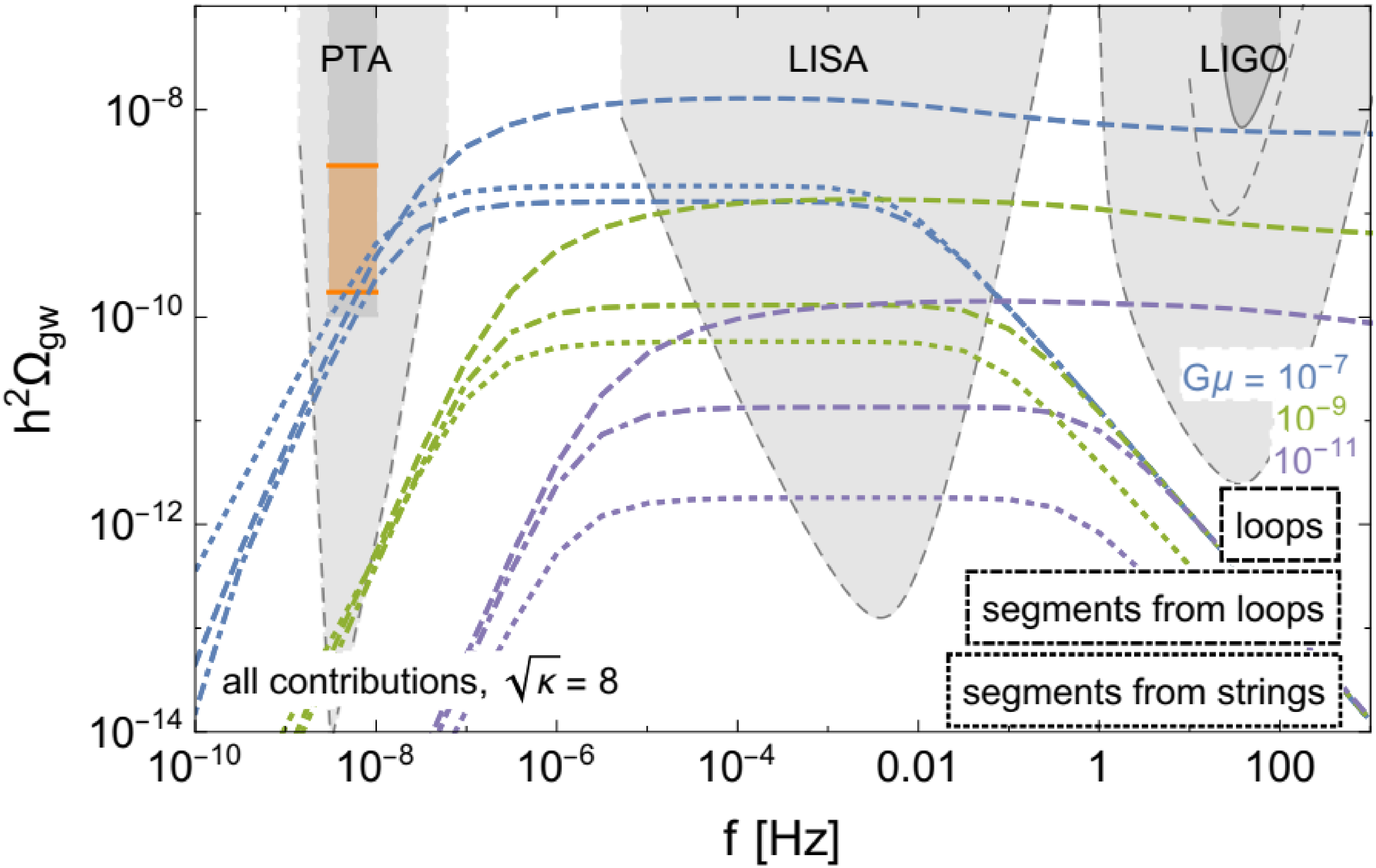
- UHF GW frontier: challenging, plenty of room for new ideas

Questions ?

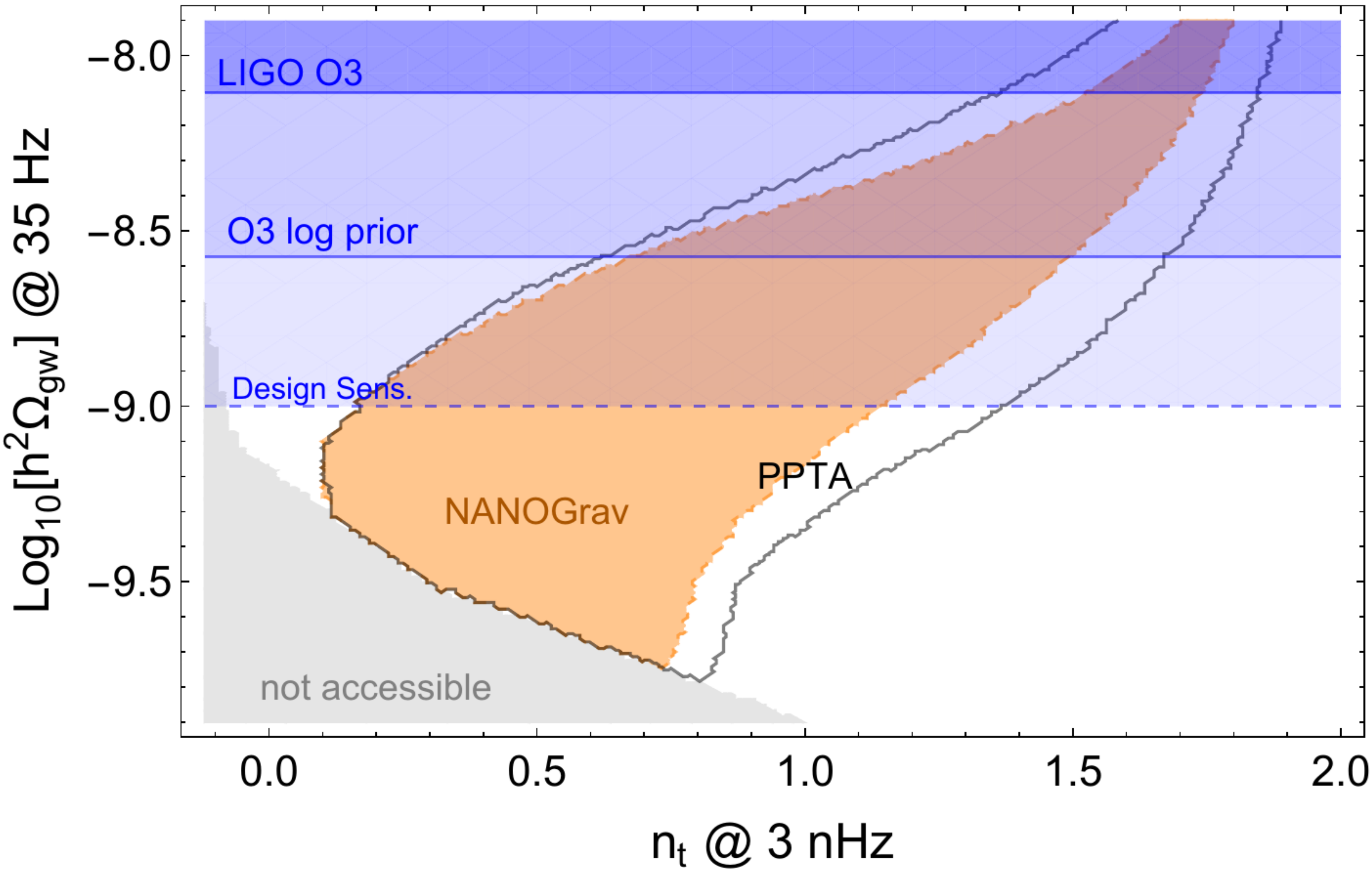
„such detectors [laser interferometers] have so low sensitivity that they are of little experimental interest" [Misner, Thorne, Wheeler 1974]

← nobel prize 2016 for detection of GWs with LIGO backup slides

GWs from segments



Prospects



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

BBN bound

radiation energy after electron decoupling:

photons — neutrinos — BSM

$$\rho_{rad} = \frac{\pi^2}{30}\left(2 + \frac{7}{4}\left(\frac{4}{11}\right)^{4/3}(3.046 + \Delta N_{eff})\right) T^4$$

at BBN or CMB decoupling:

$$\rho_{GW}(T) < \Delta\rho_{rad}(T) \quad \Rightarrow \quad \left(\frac{\rho_{GW}}{\rho_\gamma}\right)_{T_{BBN,CMB}} \leq \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\Delta N_{eff} \simeq 0.05$$

→ at BBN, CMB decoupling ~ 5 % GW energy density allowed

today:

$$\frac{\rho^0_{GW}}{\rho^0_c} = \Omega^0_\gamma \left(\frac{g^0_s}{g_s(T)}\right)^{4/3} \frac{\rho_{GW}(T)}{\rho_\gamma(T)} \leq 10^{-5}\Delta N_{eff} \simeq 10^{-6}$$

note: constraint on *total* GW energy

→ today, energy fraction < 10^{-6} (for GWs present at BBN / CMB decoupling)