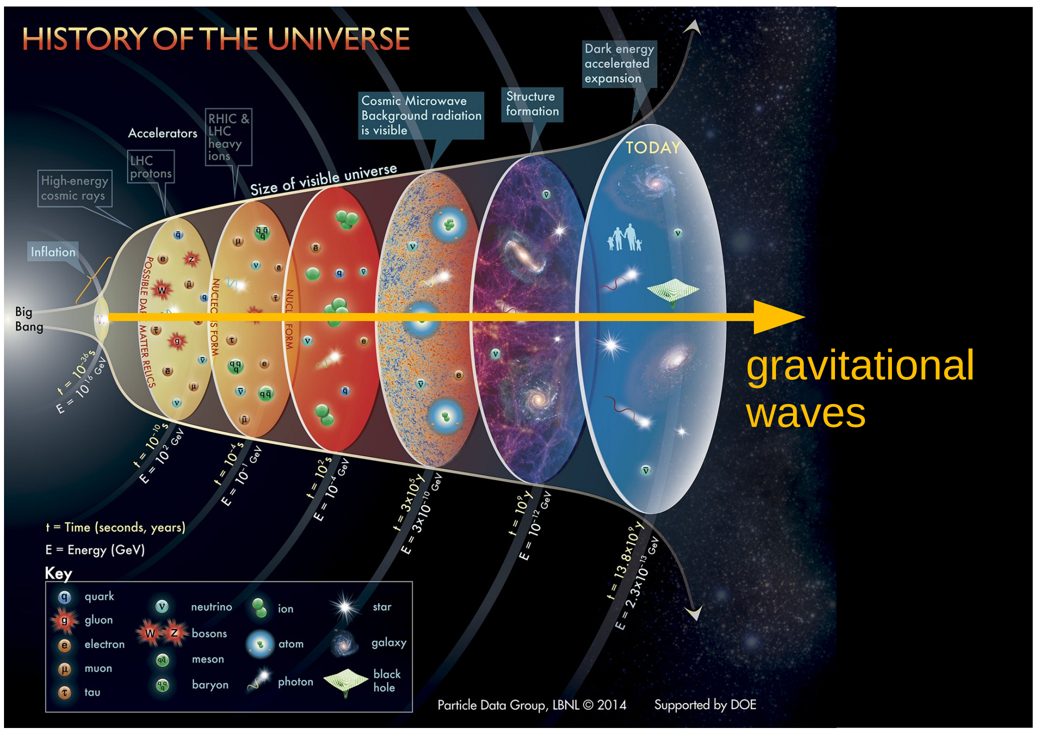
Gravitational waves as a probe of the very early universe



Valerie Domcke
CERN/EPFL

@ GWMess2021
31.03.2021

based mainly on
1912.03695 & 2009.10649,
w. W. Buchmüller, H. Murayama and K. Schmitz
2006.01161
w. C. Garcia-Cely
2011.12414
w. N. Aggarwal, F. Muia, F. Quevedo, J. & S. Steinlechner *et al*

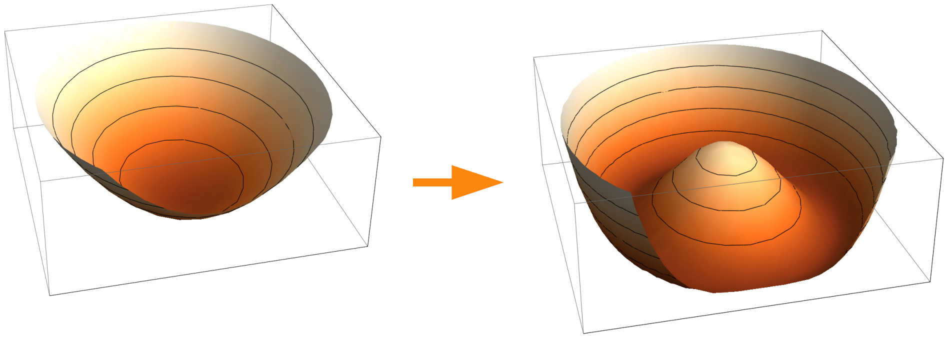
Outline

- GWs from metastable cosmic strings
- Hunting for ultra high frequency GWs

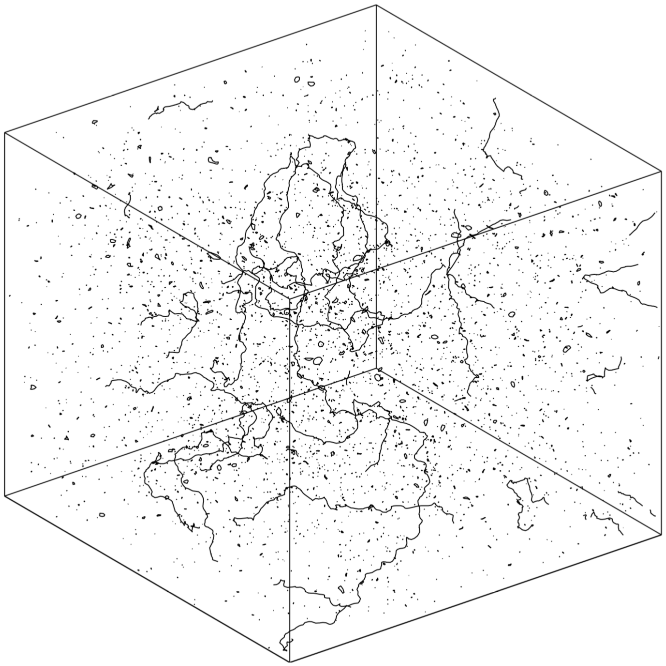
metastable cosmic strings

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 $\Pi_1(G/H) \neq \mathbb{1}$



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



Allen & Shellard `90

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

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metastable string & monopole network

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cosmic inflation dilutes monopoles

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

decay via Schwinger production 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

gravitational wave signal - SGWB

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

gravitational wave emission from integration over loop distribution function:

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

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

GW power spectrum of a single loop

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

# of loops with length ℓ at time *t*

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

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

cosmological history

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decay of cosmic string network at

$\bar{\ell}\, \Gamma_d = H$

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GW power spectrum of a single loop (P_n)

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# of loops with length ℓ at time *t* ($\mathcal{N}(\ell(z), t(z))$)

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

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

cosmological history ($H(z)(1+z)^6$)

evaluated analytically for $\ell \ll 50\, G\mu t$ and $\ell \gg 50\, G\mu t$:

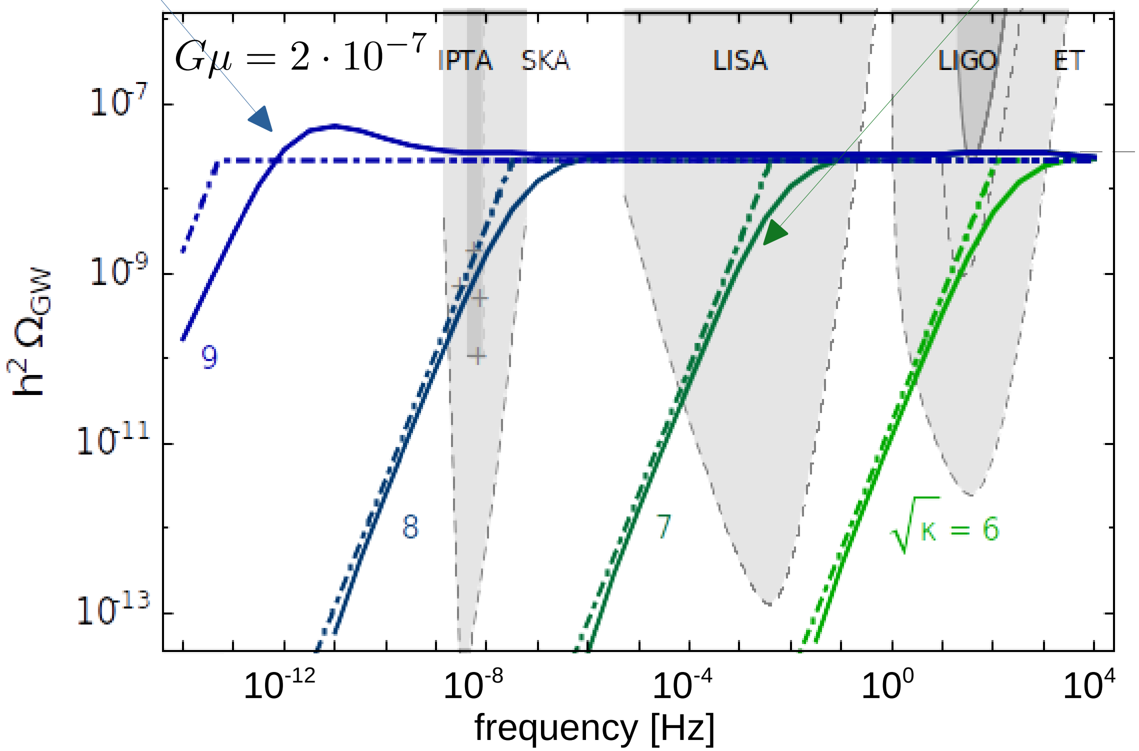
Buchmüller, VD, Murayama, Schmitz `19

$$\Omega_{\rm GW}(f) = 3.3 \cdot 10^{-8} \left(\frac{G\mu}{10^{-7}}\right)^{1/2} \min[(f/f_*)^{3/2}, 1]\,, \quad f_* = 3.0 \cdot 10^{14}\ {\rm Hz}\ e^{-\pi\kappa/4} \left(\frac{10^{-7}}{G\mu}\right)^{1/2}$$

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

stable cosmic strings
(highly constrained by PTA)

metastable cosmic strings
discovery space for LISA, LIGO & beyond



extends to GHz, depending on SSB scale and reheating model

solid: numericial
dashed: analytical

Buchmüller, **VD**, Murayama, Schmitz `19

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

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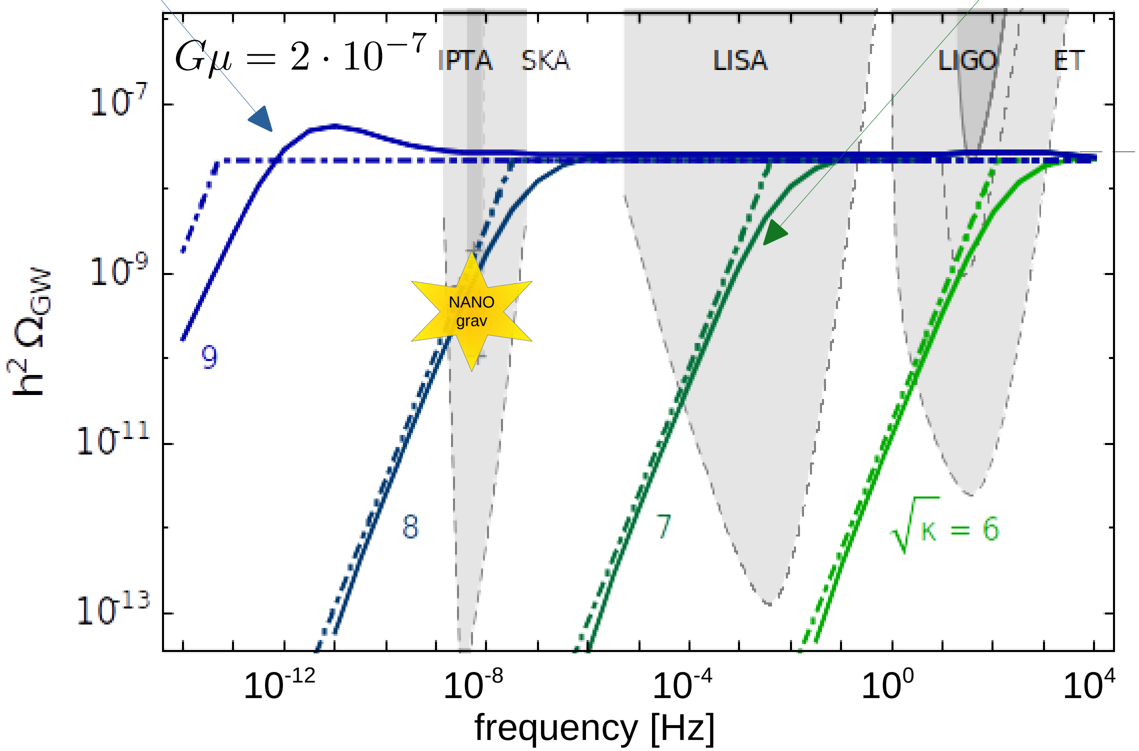

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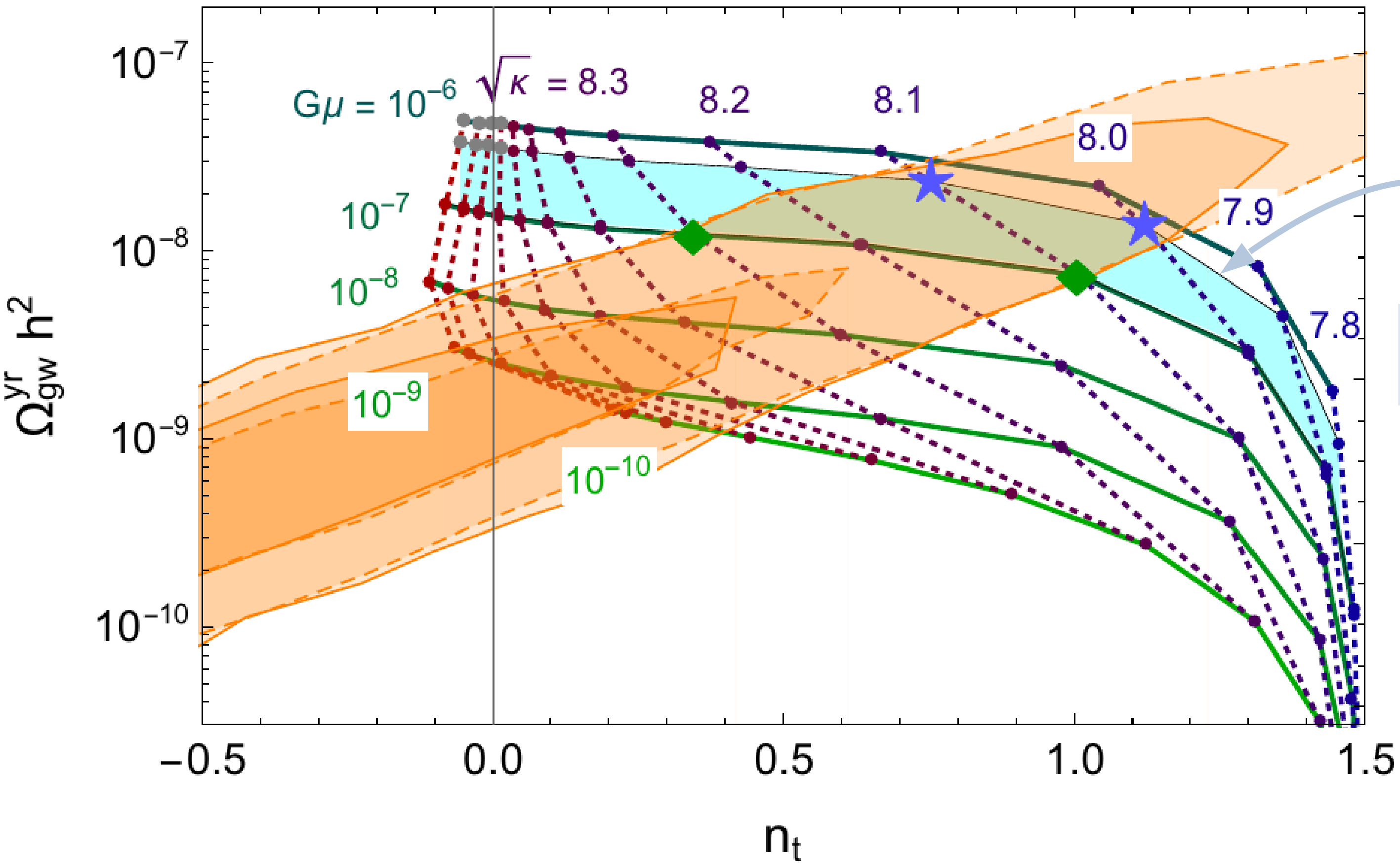
Has NANOGrav seen metastable strings?

Buchmüller, **VD**, Schmitz `20



Spontaneous B-L breaking linking inflation, baryogenesis & dark matter

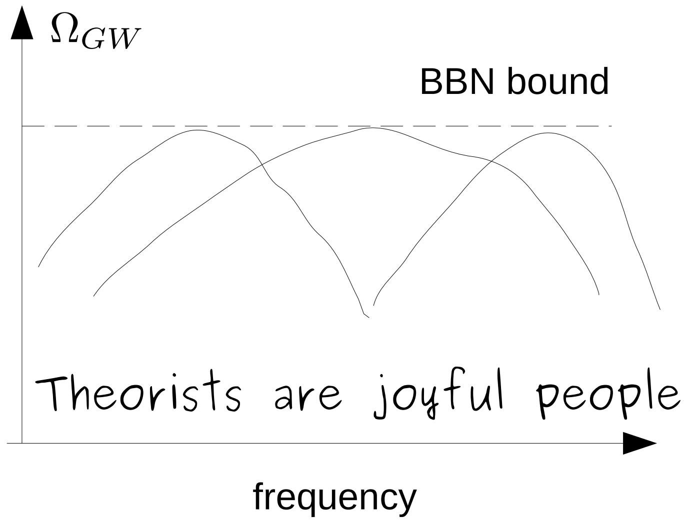
Buchmüller, VD, Schmitz `12,
Buchmüller, VD, Kamada, Schmitz `13+`14
Buchmüller, VD, Murayama, Schmitz `19

Maybe. Stay tuned for more data!

Outline

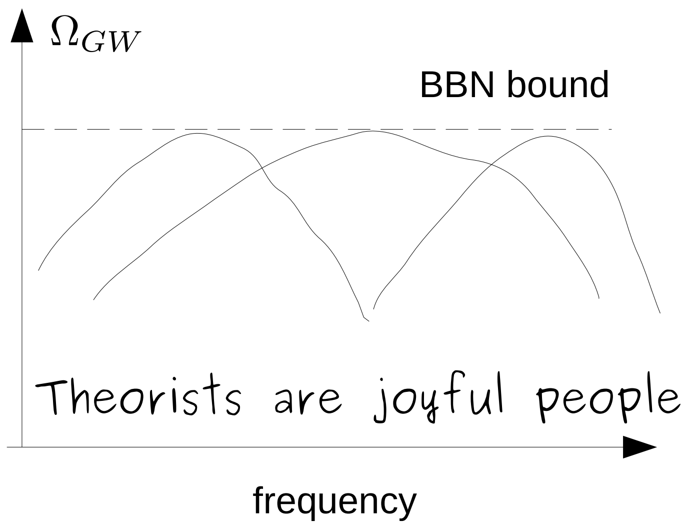
- GWs from metastable cosmic strings
- Hunting for ultra high frequency GWs

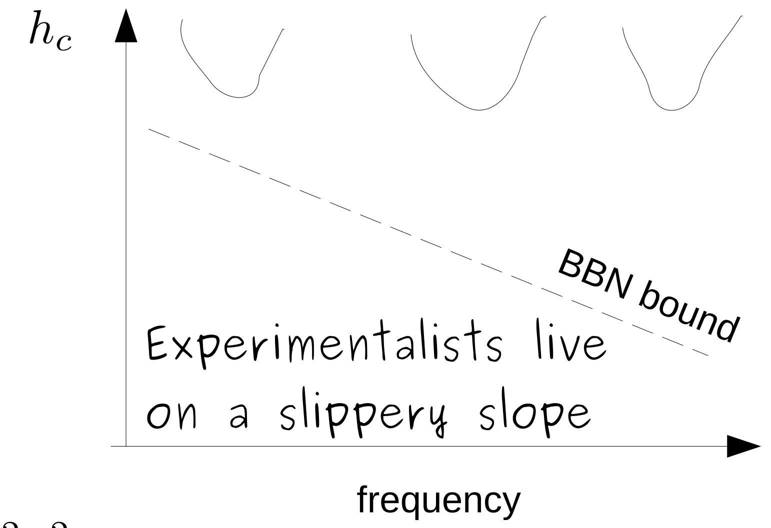
challenges in HFGW detection



CMB/BBN bound constrains energy

challenges in HFGW detection





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

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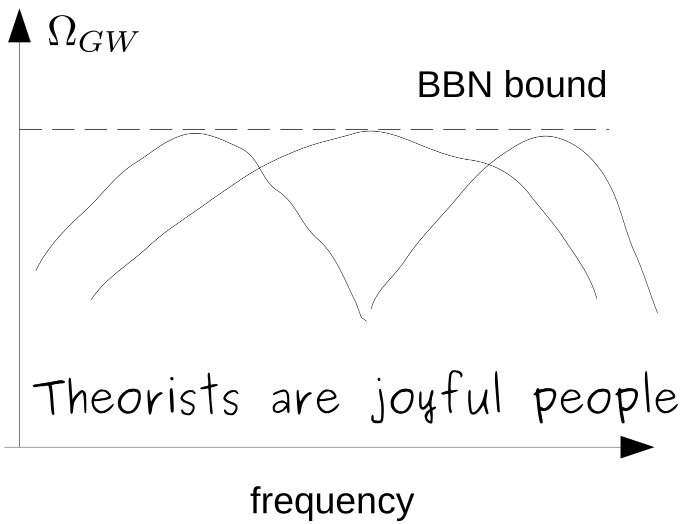
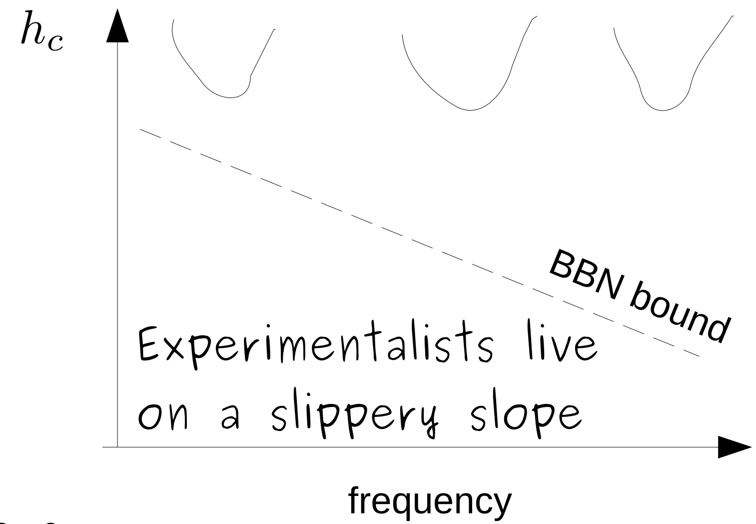
experiments measure displacement

challenges in HFGW detection





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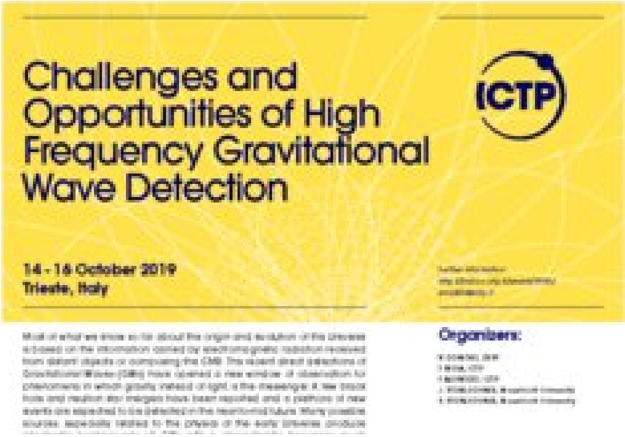
experiments measure displacement

- frequencies >> 100 Hz are very challenging
- laser interferometers seem impossible



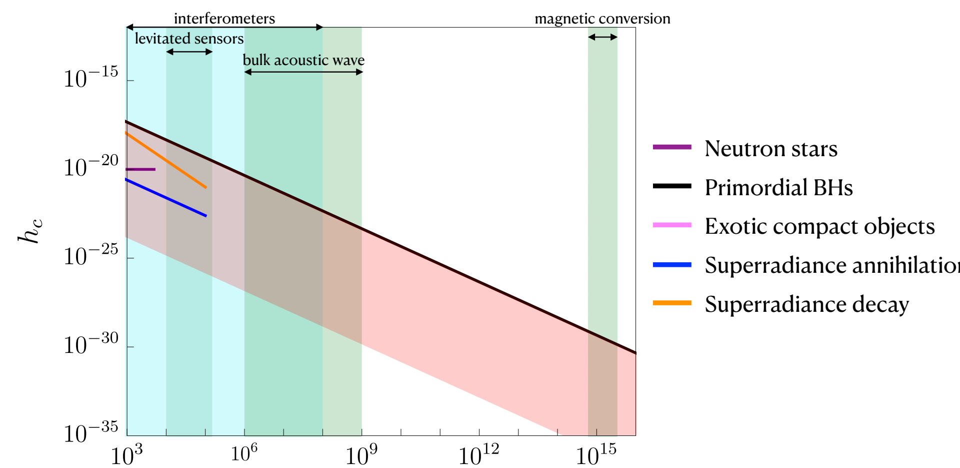
UHF Gws – sources & detector concepts

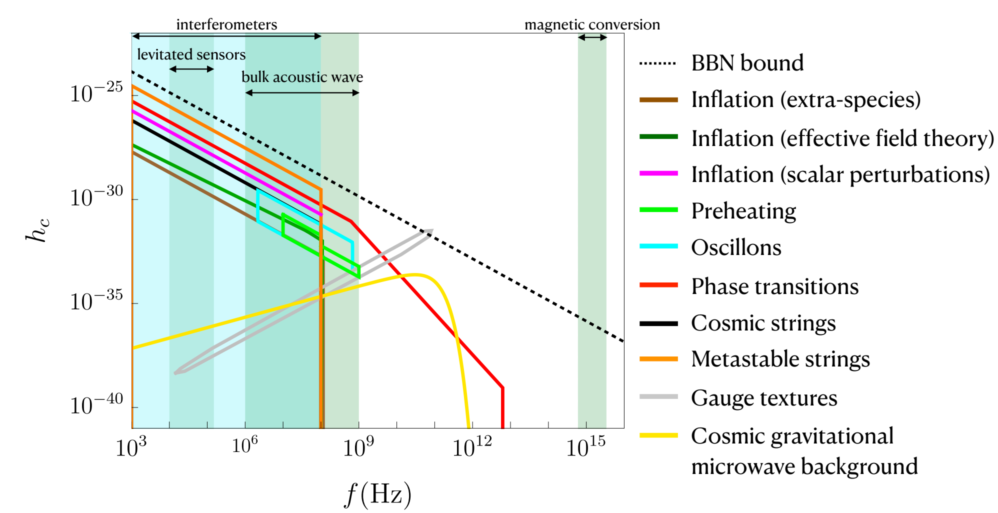
Technical concept	Frequency	Proposed sensitivity (dimensionless)	Proposed sensitivity $\sqrt{S_n(f)}$
Spherical resonant mass, Sec. 4.1.3 [286]			
Mini-GRAIL (built) [293]	2942.9 Hz	10^{-20} $2.3 \cdot 10^{-23}\,(*)$	$5 \cdot 10^{-20}\,\text{Hz}^{-\frac{1}{2}}$ $10^{-22}\,\text{Hz}^{-\frac{1}{2}}\,(*)$
Schenberg antenna (built) [290]	3.2 kHz	$2.6 \cdot 10^{-20}$ $2.4 \cdot 10^{-23}\,(*)$	$1.1 \cdot 10^{-19}\,\text{Hz}^{-\frac{1}{2}}$ $10^{-22}\,\text{Hz}^{-\frac{1}{2}}\,(*)$
Laser interferometers			
NEMO (devised), Sec. 4.1.1 [25, 276]	$[1 - 2.5]$ kHz	$9.4 \cdot 10^{-26}$	$10^{-24}\,\text{Hz}^{-\frac{1}{2}}$
Akutsu's proposal (built), Sec. 4.1.2 [281, 332]	100 MHz	$7 \cdot 10^{-14}$ $2 \cdot 10^{-19}\,(*)$	$10^{-16}\,\text{Hz}^{-\frac{1}{2}}$ $10^{-20}\,\text{Hz}^{-\frac{1}{2}}\,(*)$
Holometer (built), Sec. 4.1.2 [283]	$[1 - 13]$ MHz	$8 \cdot 10^{-22}$	$10^{-21}\,\text{Hz}^{-\frac{1}{2}}$
Optically levitated sensors, Sec. 4.2.1 [59]			
1-meter prototype (under construction)	$(10 - 100)$ kHz	$2.4 \cdot 10^{-20} - 4.2 \cdot 10^{-22}$	$(10^{-19} - 10^{-21})\,\text{Hz}^{-\frac{1}{2}}$
100-meter instrument (devised)	$(10 - 100)$ kHz	$2.4 \cdot 10^{-22} - 4.2 \cdot 10^{-24}$	$(10^{-21} - 10^{-23})\,\text{Hz}^{-\frac{1}{2}}$
Inverse Gertsenshtein effect, Sec. 4.2.2			
GW-OSQAR II (built) [301]	$[200 - 800]$ THz	$h_{c,n} \simeq 8 \cdot 10^{-26}$	×
GW-CAST (built) [301]	$[0.5 - 1.5]\,10^6$ THz	$h_{c,n} \simeq 7 \cdot 10^{-28}$	×
GW-ALPs II (devised) [301]	$[200 - 800]$ THz	$h_{c,n} \simeq 2.8 \cdot 10^{-30}$	×
Resonant polarization rotation, Sec. 4.2.4 [311]			
Cruise's detector (devised) [312]	$(0.1 - 10^5)$ GHz	$h \simeq 10^{-17}$	×
Cruise & Ingley's detector (prototype) [313, 314]	100 MHz	$8.9 \cdot 10^{-14}$	$10^{-14}\,\text{Hz}^{-\frac{1}{2}}$
Enhanced magnetic conversion (theory), Sec. 4.2.5 [315]	5 GHz	$h \simeq 10^{-30} - 10^{-26}$	×
Bulk acoustic wave resonators (built), Sec. 4.2.6 [320, 321]	(MHz – GHz)	$4.2 \cdot 10^{-21} - 2.4 \cdot 10^{-20}$	$10^{-22}\,\text{Hz}^{-\frac{1}{2}}$
Superconducting rings, (theory), Sec. 4.2.7 [322]	10 GHz	$h_{0,n,\text{mono}} \simeq 10^{-31}$	×
Microwave cavities, Sec. 4.2.8			
Caves' detector (devised) [324]	500 Hz	$h \simeq 2 \cdot 10^{-21}$	×
Reece's 1st detector (built) [325]	1 MHz	$h \simeq 4 \cdot 10^{-17}$	×
Reece's 2nd detector (built) [326]	10 GHz	$h \simeq 6 \cdot 10^{-14}$	×
Pegoraro's detector (devised) [327]	$(1 - 10)$ GHz	$h \simeq 10^{-25}$	×
Graviton-magnon resonance (theory), Sec. 4.2.9 [328]	$(8 - 14)$ GHz	$9.1 \cdot 10^{-17} - 1.1 \cdot 10^{-15}$	$(10^{-22} - 10^{-20})\,\text{Hz}^{-\frac{1}{2}}$

Table 1: Summary of existing and proposed detectors with their respective sensitivities. See Sec. 4.3 for details.

35

White Paper:
Aggarwal, VD, Muia, J. Steinlechner, S. Steinlechner, Quevedos et al `20





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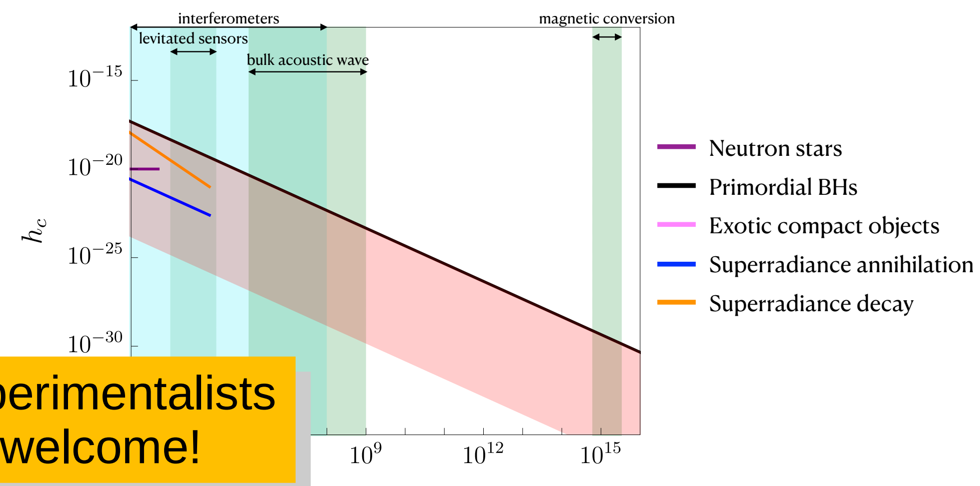
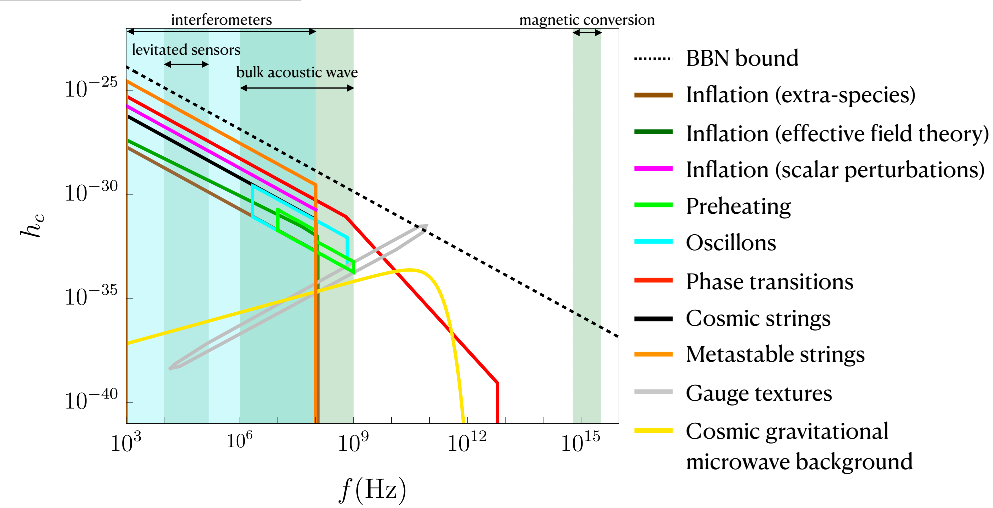


New members (experimentalists and theorists) very welcome!

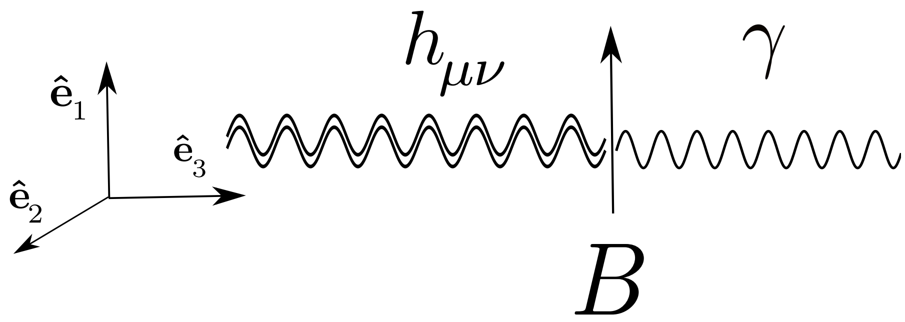


a cosmological high frequency GW detector

(inverse) Gertsenshtein effect

Gertsenshtein `62; Boccaletti et al `70

GW source



radio telescopes ARCADE 2 and EDGES, Rayleigh-Jeans tail of CMB spectrum

VD, Garcia-Cely `20

cosmic magnetic fields

inhomogeneities in B and n_e set coherence length of oscillation

probability of conversion:

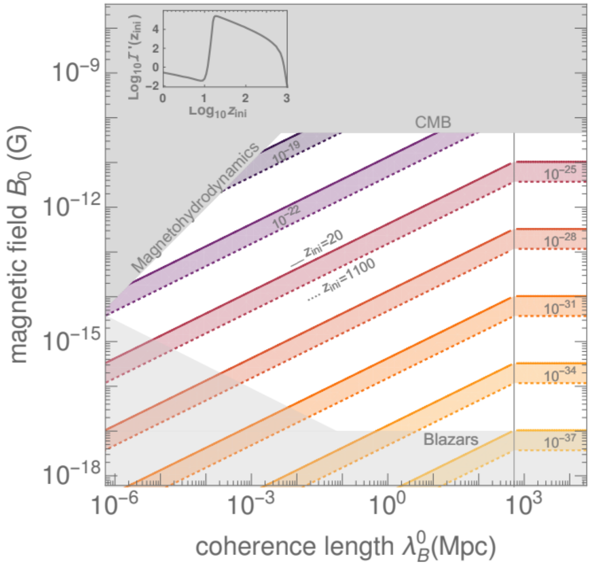
$$\mathcal{P} \equiv \int_{l.o.s.} \langle \Gamma_{h \leftrightarrow \gamma} \rangle dt = \int_0^{z_{\rm ini}} \frac{\langle \Gamma_{h \leftrightarrow \gamma} \rangle}{(1+z)\, H} dz$$

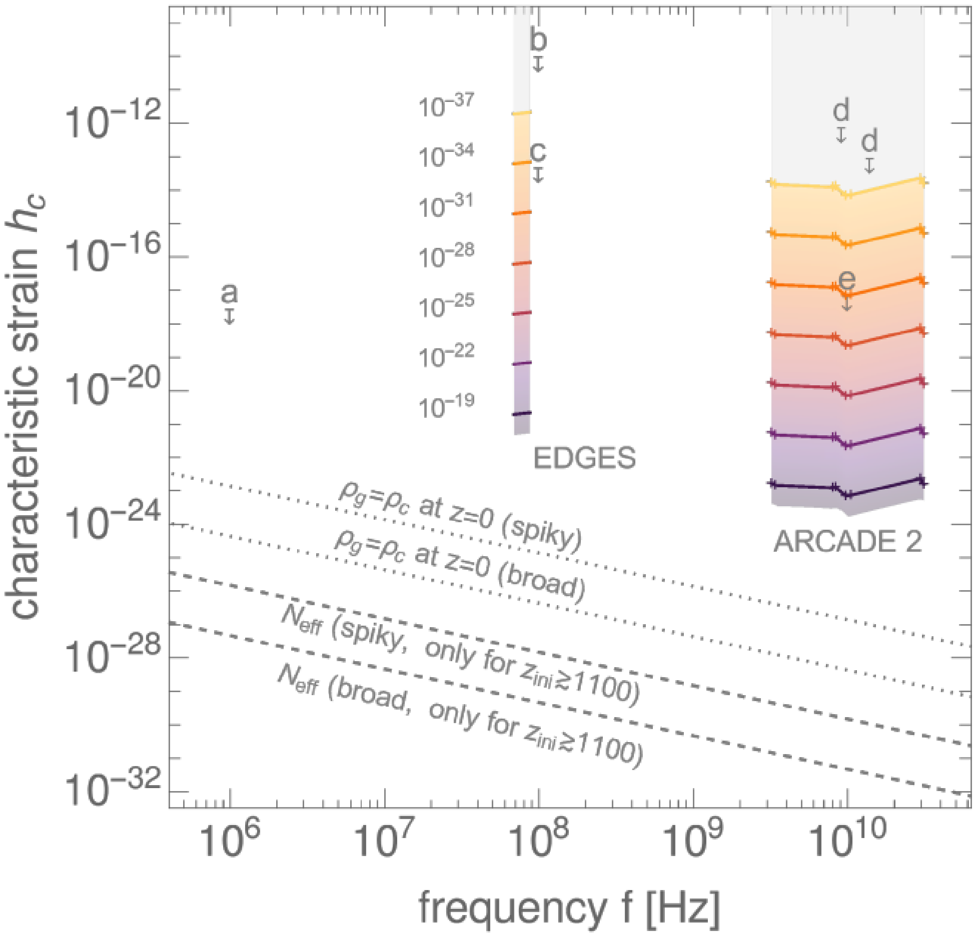
similar to neutrino oscillations, or axion-photon oscillations

the potential of radio telescopes

$$\delta f_\gamma(\omega/T, T_0) = \mathcal{P} \cdot f_{gw}(\omega/T, T_{ini})$$

VD, Garcia-Cely `20





a) Reece et al '84, b) Cruise, Ingley '06,
c) Akutsu et al '08, d) Ito, Soda '04, e) Cruise'12

21cm astronomy has promising opportunities for GW searches

Conclusions & Outlook

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

- UHF GWs are an exciting but challenging window to the Early Universe

  - UHF GW initiative taking shape

  - radio telescopes can probe UHF GWs

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nobel prize 2016 for detection of GWs with LIGO

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Questions ?

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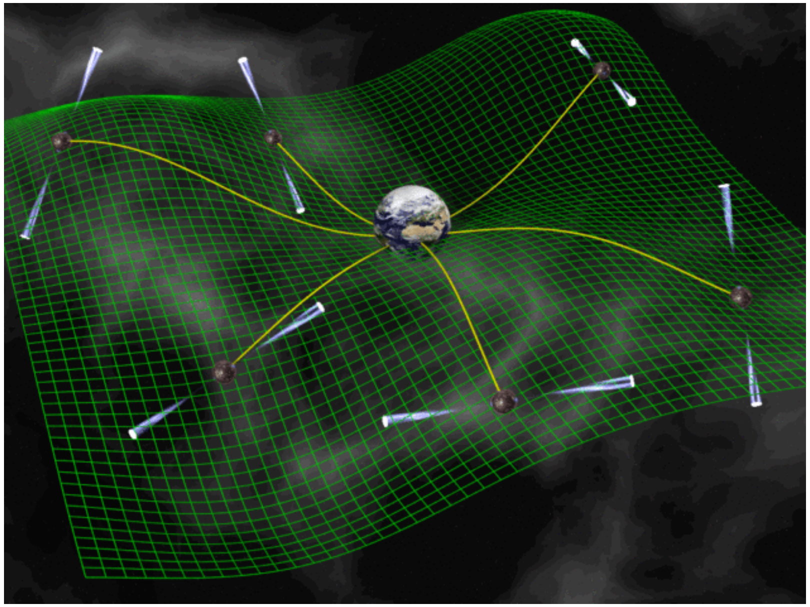
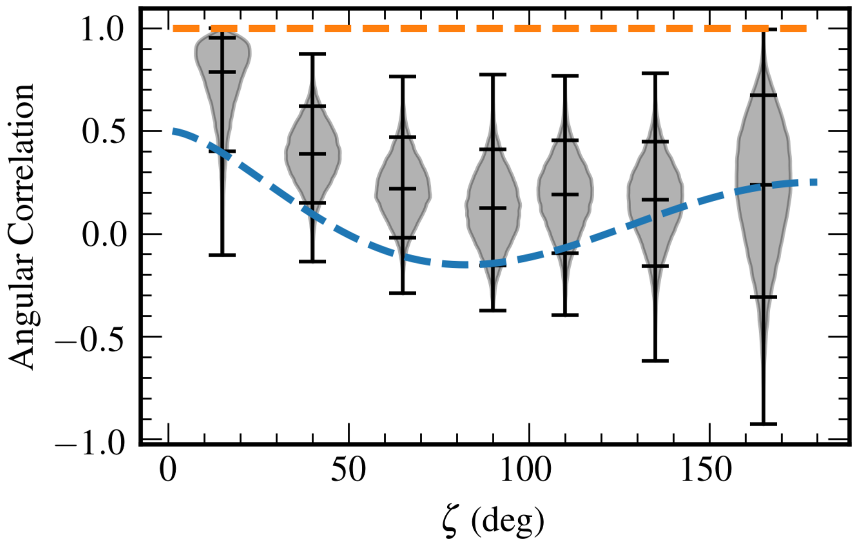
nobel prize 2016 for detection of GWs with LIGO backup

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."

Cosmological B-L breaking

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

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

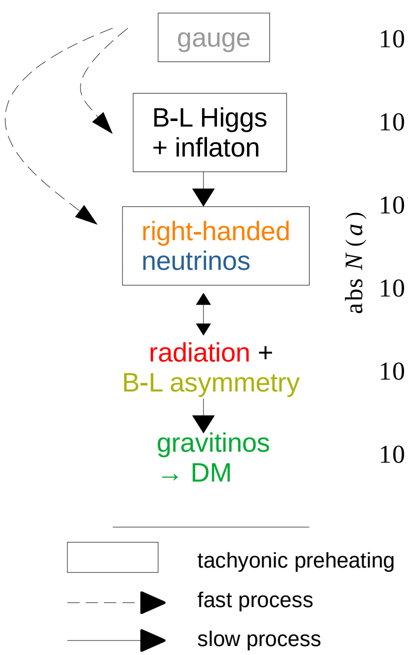
$U(1)_{B-L}$ unbroken: hybrid inflation

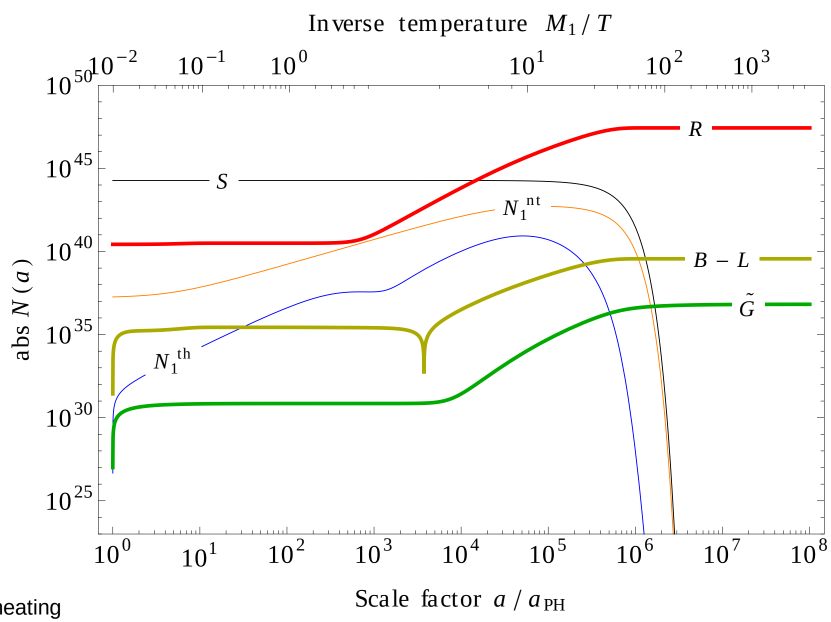
$U(1)_{B-L}$ breaking: cosmic strings, tachyonic preheating

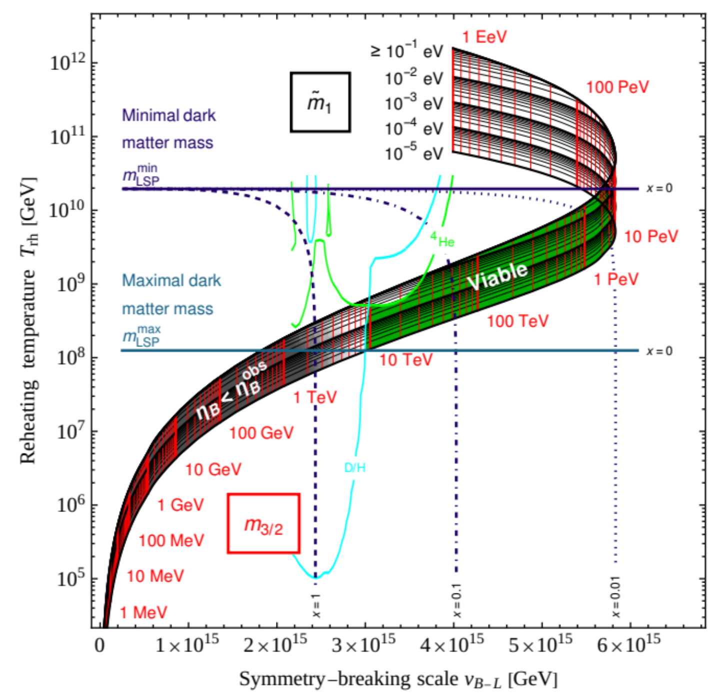
$U(1)_{B-L}$ broken: reheating, leptogenesis, DM

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

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



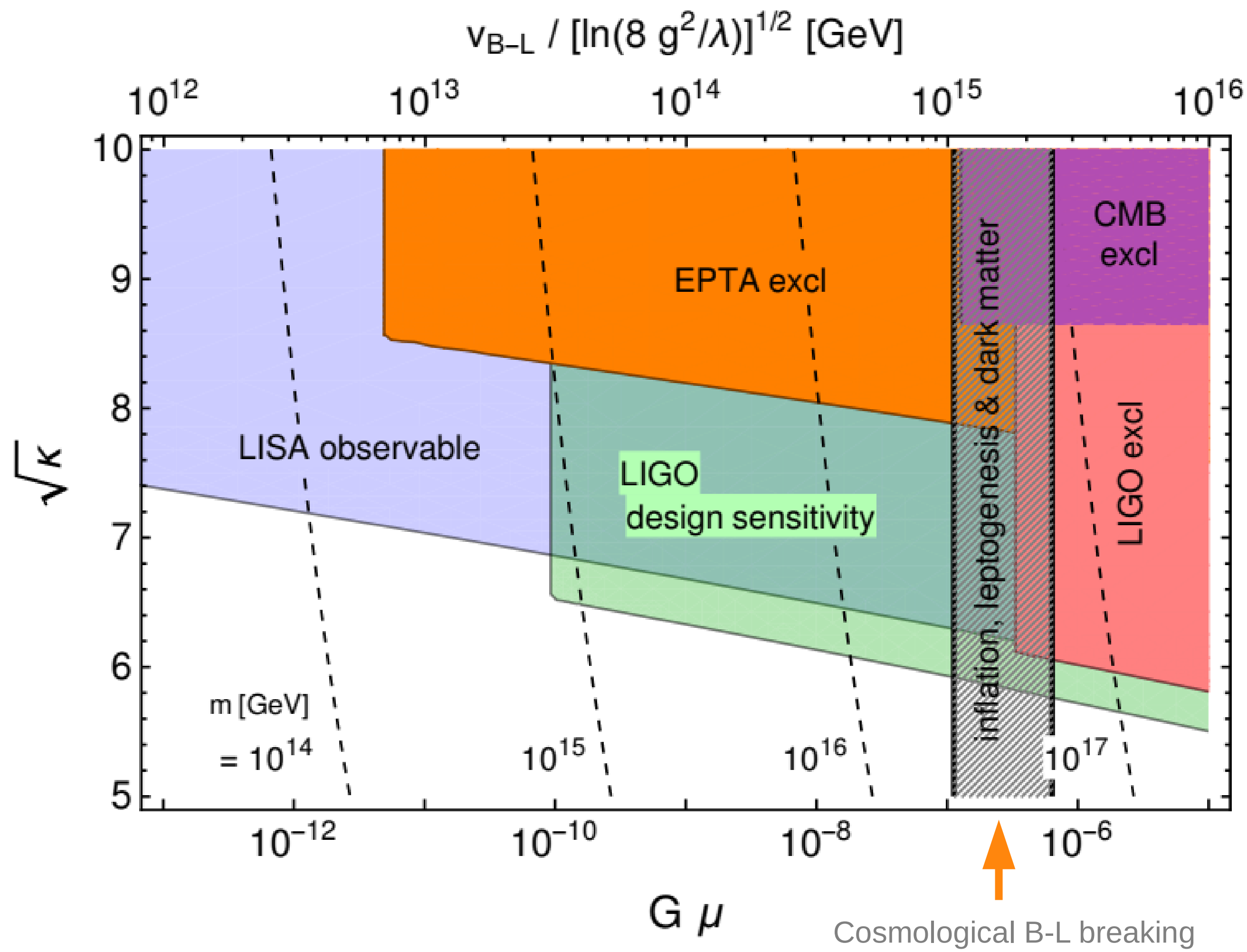




Cosmological B-L breaking

SO(10) embedding:

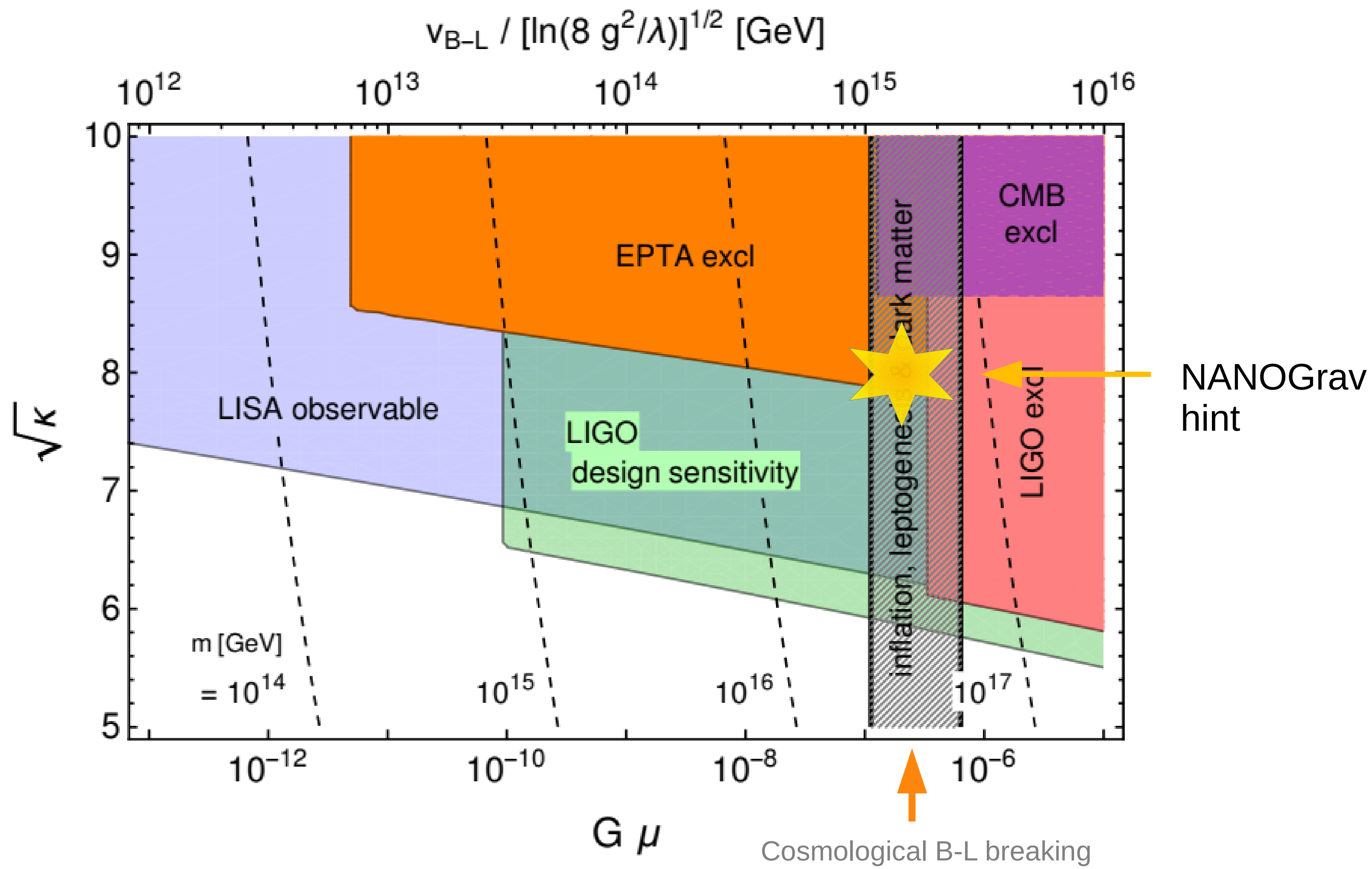
Buchmüller, **VD**, Murayama, Schmitz `19



Testable with LIGO + PTA !

SO(10) embedding:

Buchmüller, **VD**, Murayama, Schmitz `19



Testable with LIGO + PTA !

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:

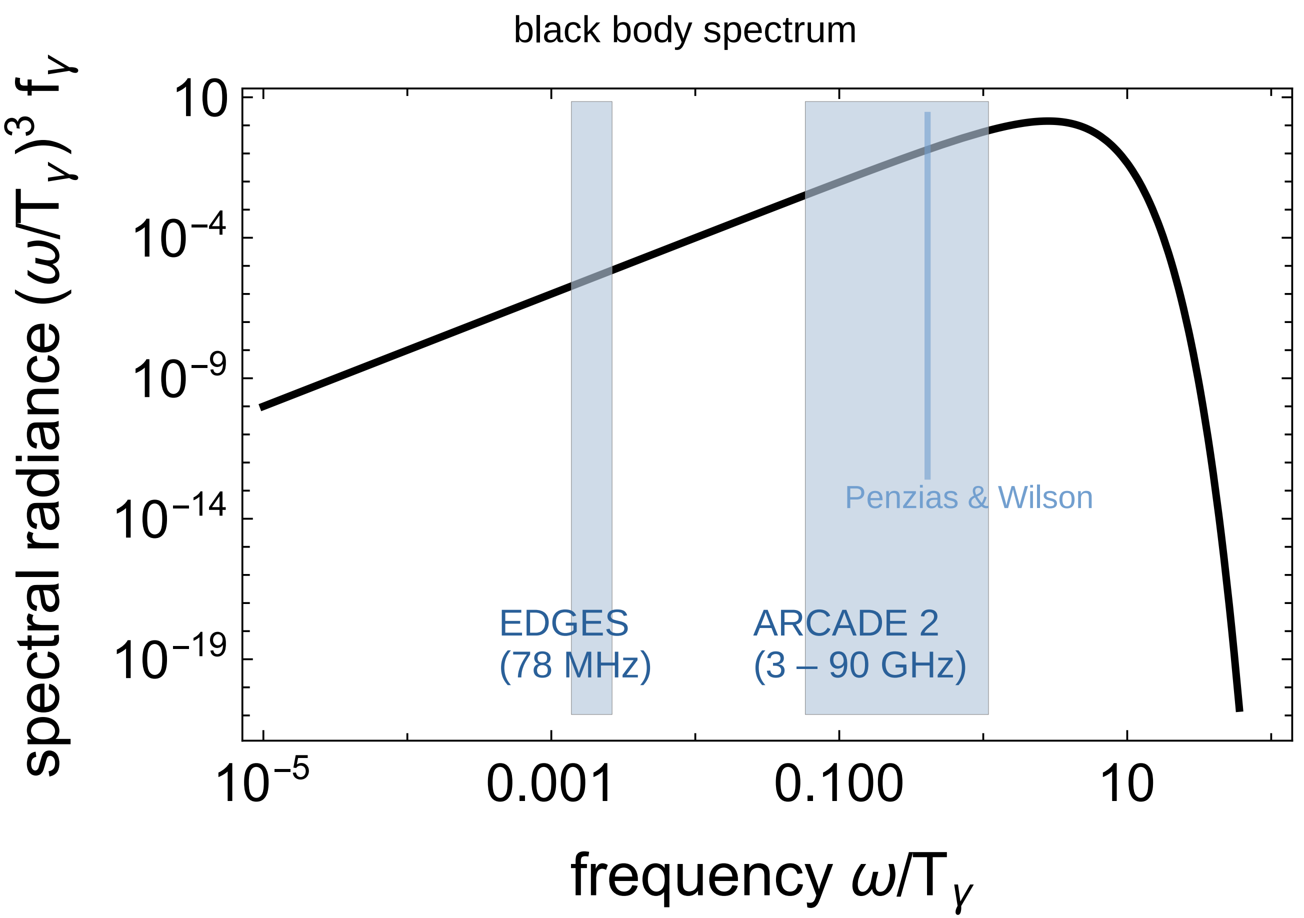
$$\frac{\rho^0_{GW}}{\rho^0_c} = \Omega^0_\gamma\left(\frac{g^0_s}{g_s(T)}\right)^{4/3}\frac{\rho_{GW}(T)}{\rho_\gamma(T)} \leq 10^{-5}\Delta N_{eff} \simeq 10^{-6}$$

note: constraint on *total* GW energy

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

CMB Rayleigh Jeans tail

VD, Garcia-Cely `20



Rayleigh Jeans tail: sizable contribution possible without violating BBN/CMB bound