Title: Probing the scale of grand unification with gravitational waves

Speakers: Valerie Domcke

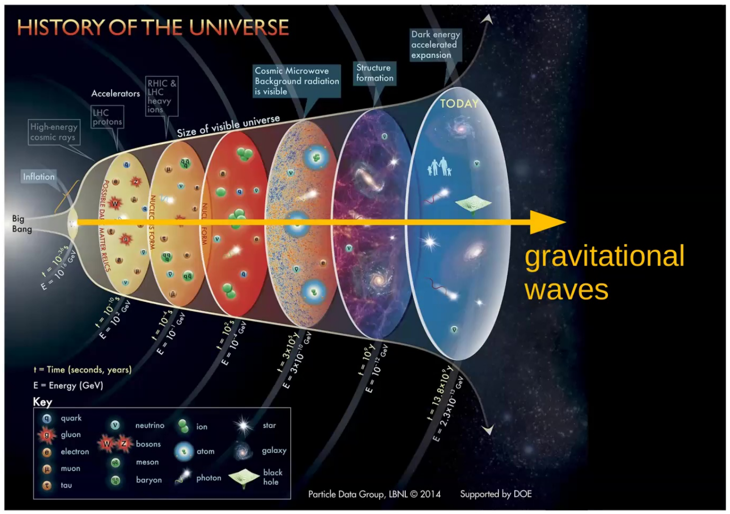
Series: Particle Physics

Date: June 22, 2021 - 1:00 PM

URL: http://pirsa.org/21060001

Abstract: Cosmic strings arise as remnants of phase transitions in the early Universe, often related to theories of grand unification (GUTs). If such a phase transitions occurs at high energies, the resulting cosmic string network generates a sizable amount of gravitational waves. Most work so far has focused on the gravitational wave signal from topologically stable cosmic strings. In this talk I will introduce metastable cosmic strings, which are a generic consequence of many GUTs. I will discuss how this idea can be probed in various ongoing and upcoming gravitational wave experiments, from pulsar timing arrays to space- and ground-based interferometers. In the final part of my talk I will discuss a recent proposal on using the radio telescopes to probe this and other sources of ultra high frequency gravitational waves.

Gravitational waves as a probe of the very early universe



Valerie Domcke
CERN/EPFL

@ Perimeter Institute
22.06.2021

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*

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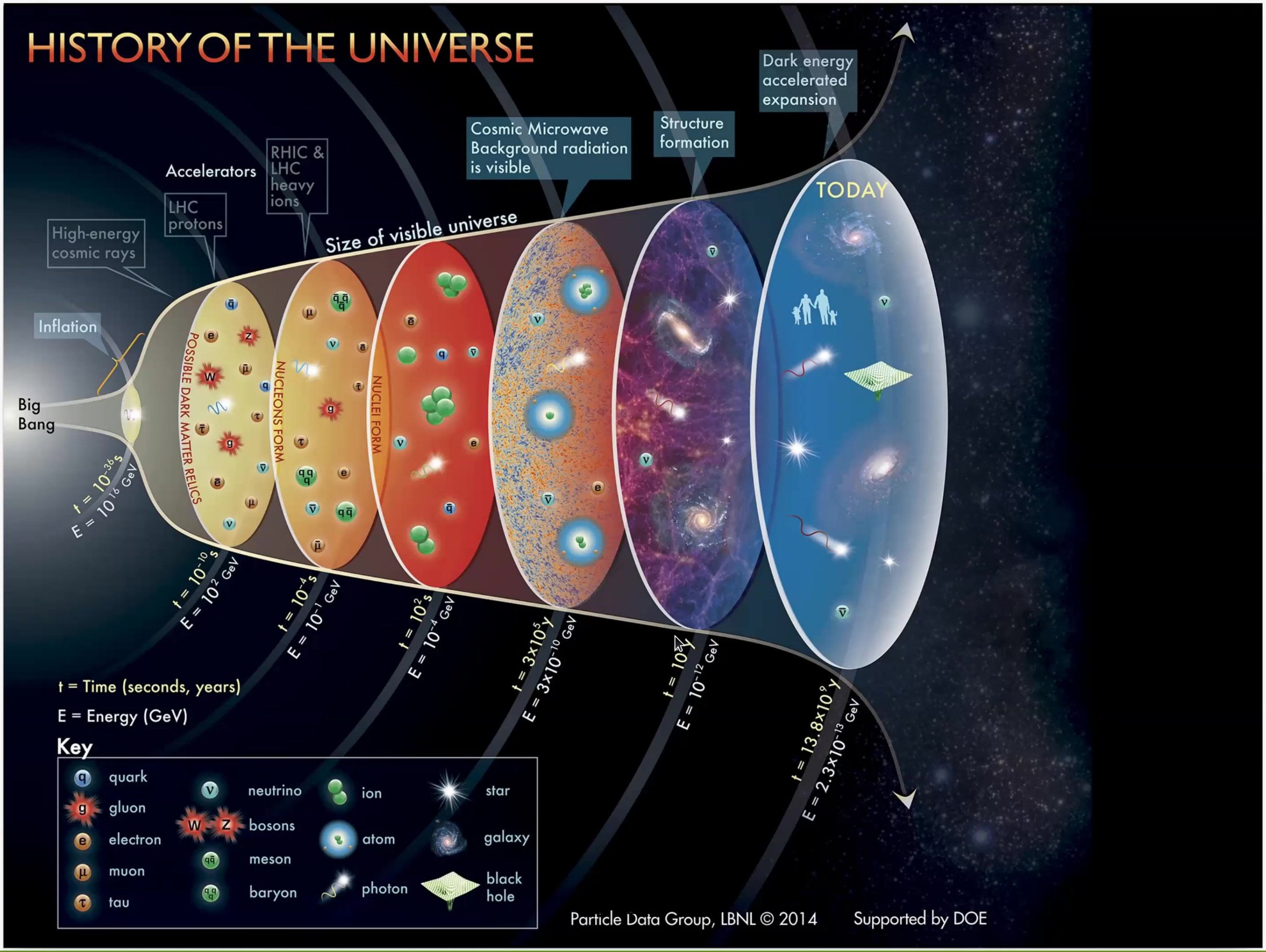
HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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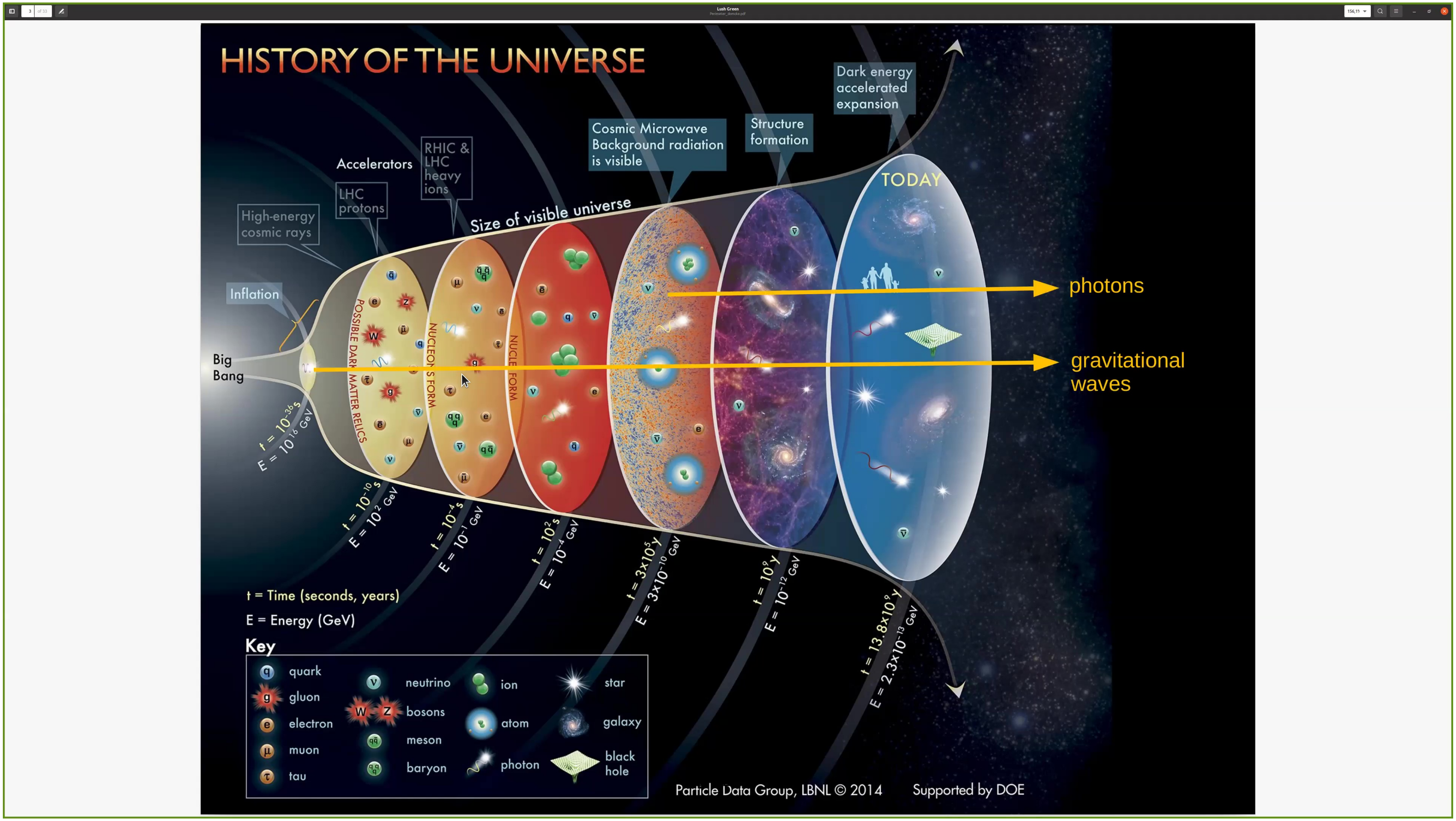
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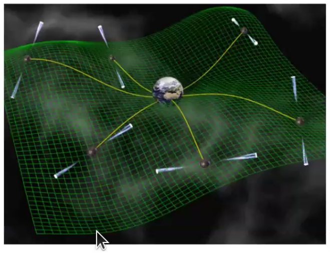
Hunting for gravitational waves

pulsar timing arrays

interferometers



LIGO

nHz mHz kHz

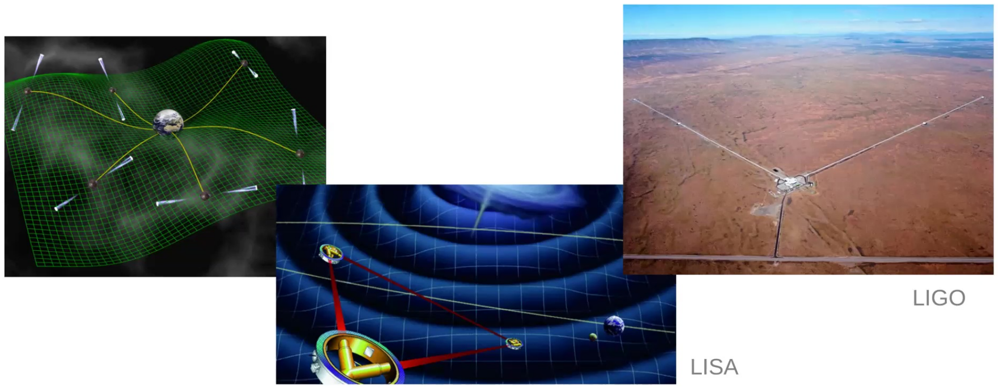
frequency

mass (merging compact objects)
time (cosmological events)

Hunting for gravitational waves

pulsar timing arrays

interferometers



LISA

LIGO

?

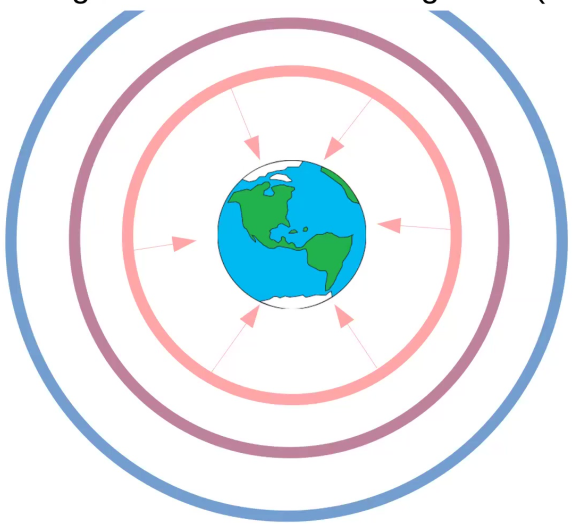
nHz mHz kHz

frequency

mass (merging compact objects)
time (cosmological events)

prelude: stochastic gravitational wave background

stochastic gravitational wave background (SGWB):



analogous to:

CMB: Penzias, Wilson `64

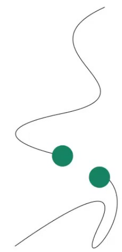
observable quantity in direct detection:

probed by two-point (cross-) correlation of detector time stream

$$\Omega_{GW} = \frac{1}{\rho_c} \frac{\partial \rho_{GW}(k,\tau)}{\partial \ln k}\,, \quad \rho_{GW} = \frac{1}{32\pi G} \langle \dot{h}_{ij}(\vec{x},\tau)\dot{h}^{ij}(\vec{x},\tau)\rangle$$

Outline

- GWs from metastable cosmic strings



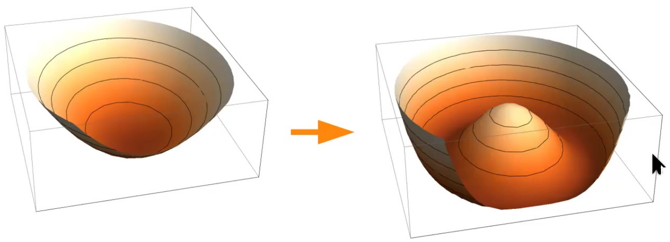
- Hunting for ultra high frequency GWs

radio telescope EDGES

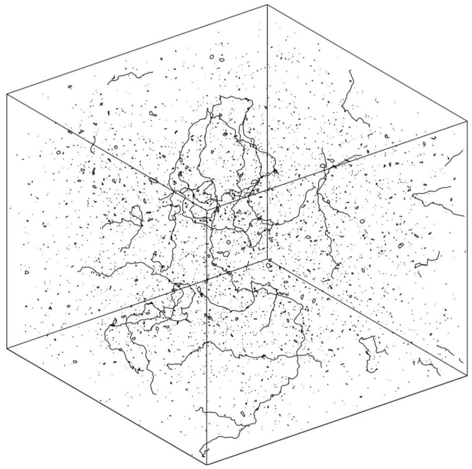
metastable cosmic strings

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

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 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:

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

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

GW power spectrum of a single loop

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

# of loops with length ℓ at time t

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

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

Blanco-Pillado, Olum, Shlaer '14

cosmological history

decay of cosmic string network at

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

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

Buchmüller, VD, Murayama, Schmitz `19

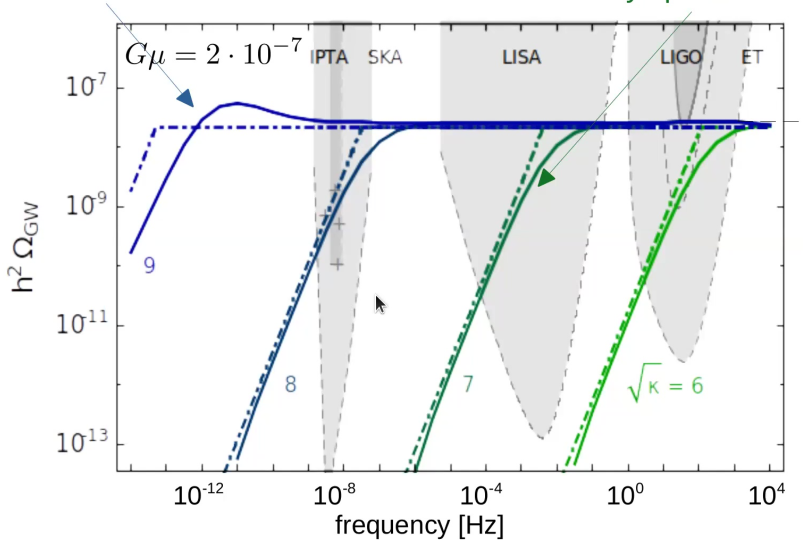
$$\Omega_{\rm GW}(f) = 3.3 \cdot 10^{-8} \left(\frac{G\mu}{10^{-7}}\right)^{1/2} \min[(f/f_*)^{3/2}, 1]\,, \quad f_* = 3.0 \cdot 10^{14}\ {\rm Hz}\ e^{-\pi\kappa/4} \left(\frac{10^{-7}}{G\mu}\right)^{1/2}$$

metastable cosmic strings

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

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

disclaimer: only GWs from loops considered, for segments see Leblond, Shlaer, Siemens `09

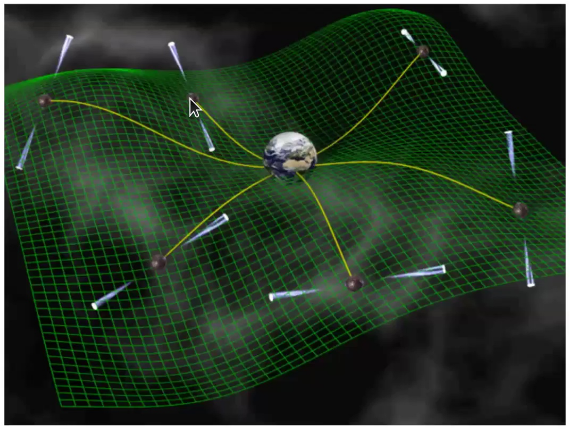
Buchmüller, **VD**, Murayama, Schmitz `19

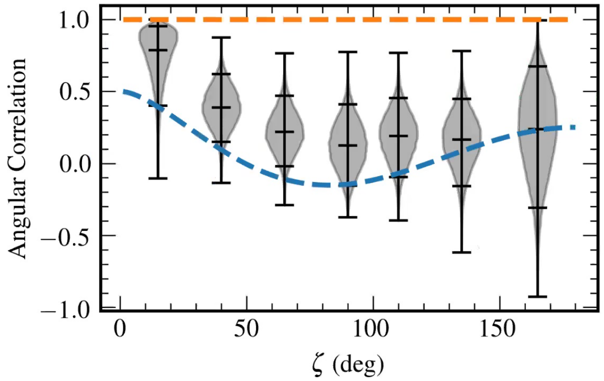
$SO(10) \to G_{\mathrm{SM}} \times U(1)_{B-L} \to G_{\mathrm{SM}}$ with $v_{B-L} \lesssim v_{GUT}$ can be tested with GWs!

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."

metastable cosmic strings

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

stable cosmic strings
(highly constrained by PTA)

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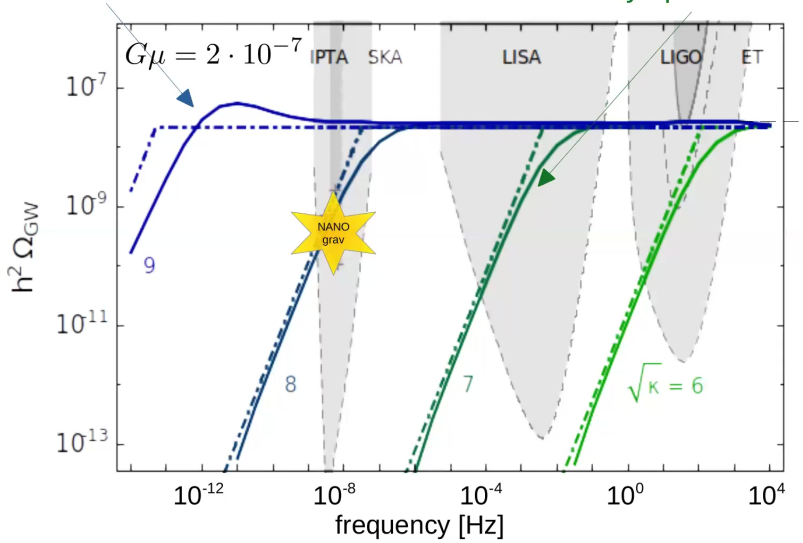

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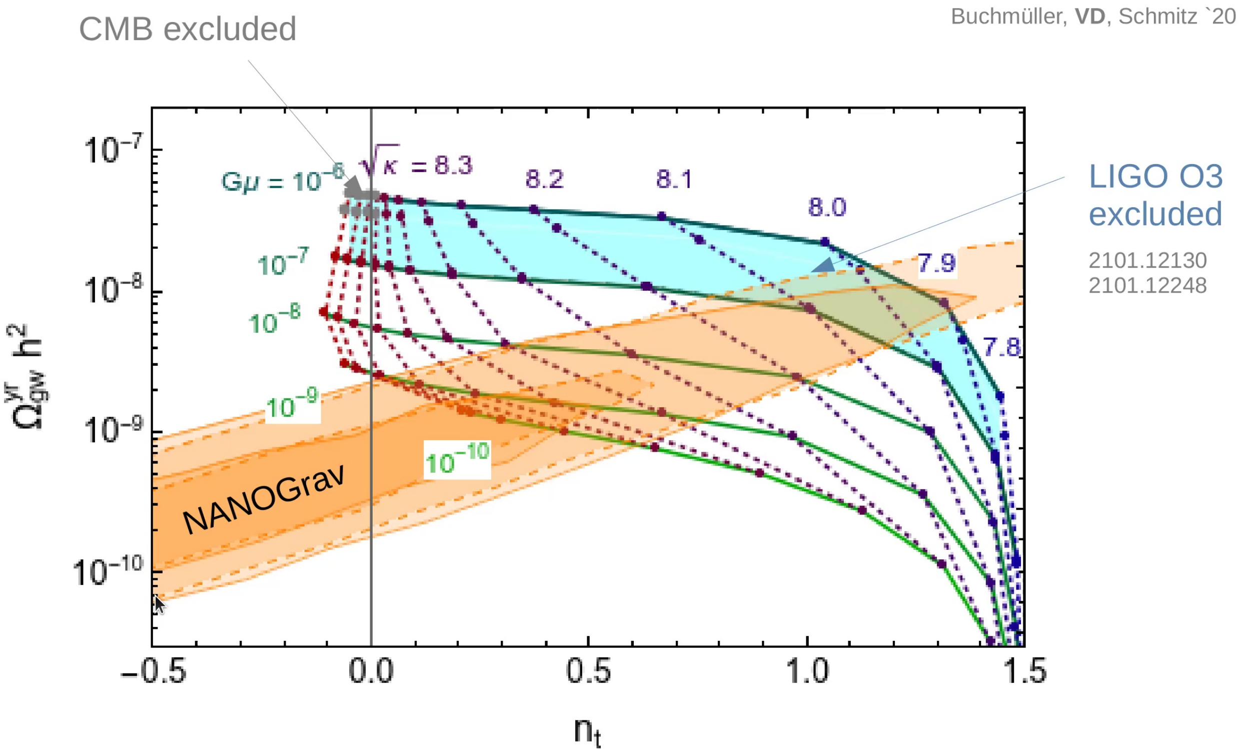
Has NANOGrav seen metastable strings?

Buchmüller, **VD**, Schmitz `20



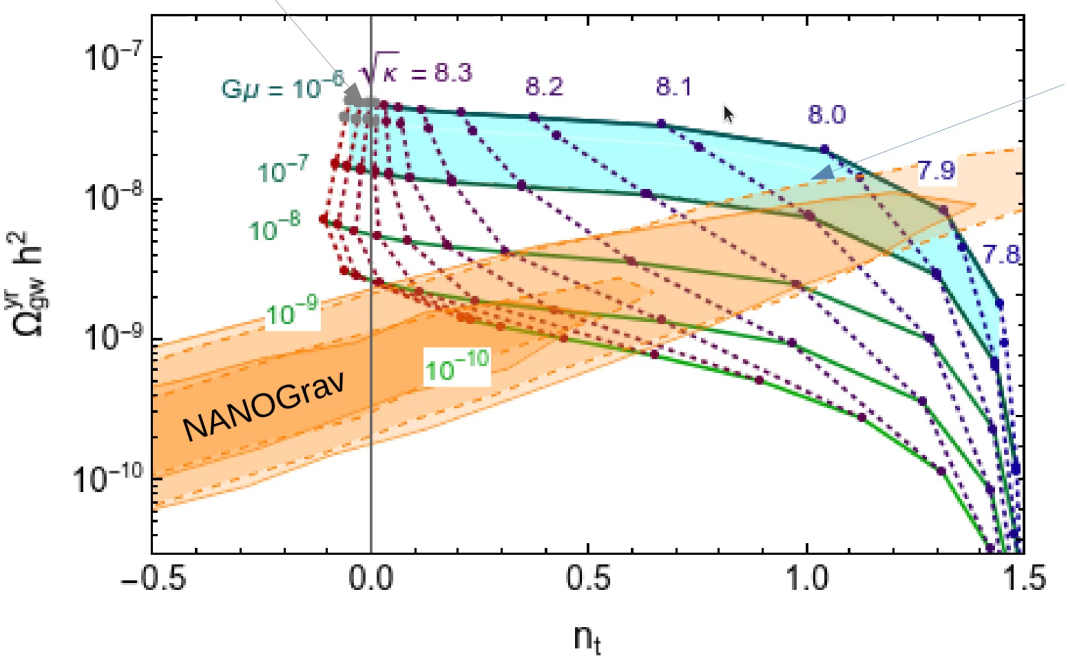
2101.12130
2101.12248

Maybe. Stay tuned for more data!

Has NANOGrav seen metastable strings?

CMB excluded

Buchmüller, **VD**, Schmitz `20



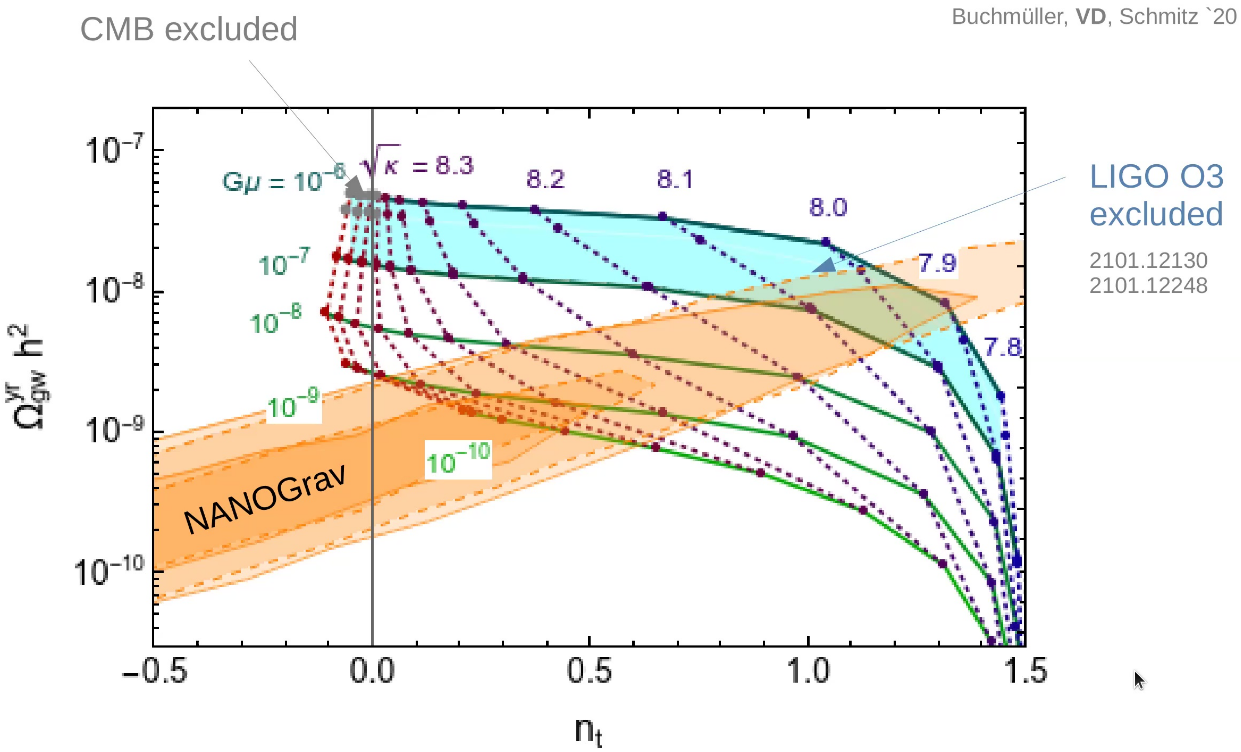
LIGO O3 excluded

2101.12130
2101.12248

Maybe. Stay tuned for more data!

Has NANOGrav seen metastable strings?

Buchmüller, **VD**, Schmitz `20



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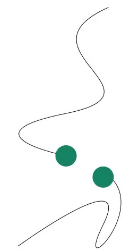
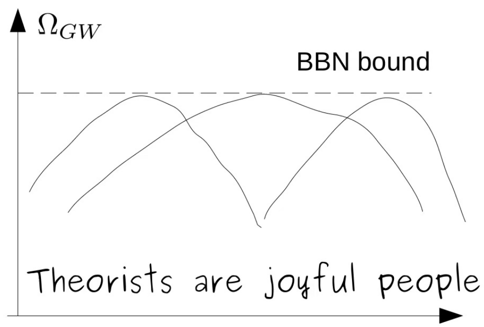
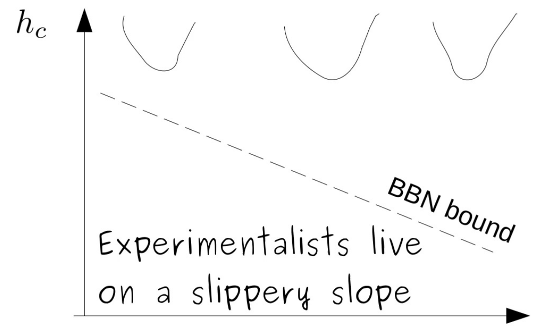


- Hunting for ultra high frequency GWs

radio telescope EDGES

challenges in HFGW detection



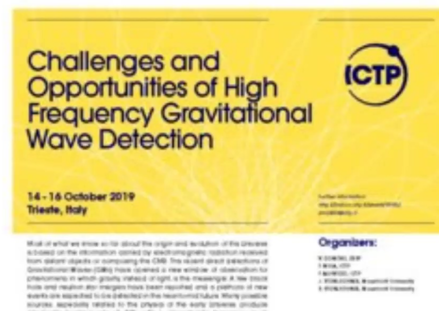


$$\Omega_{GW} \propto f^2 h_c^2$$

CMB/BBN bound constrains energy

experiments measure displacement

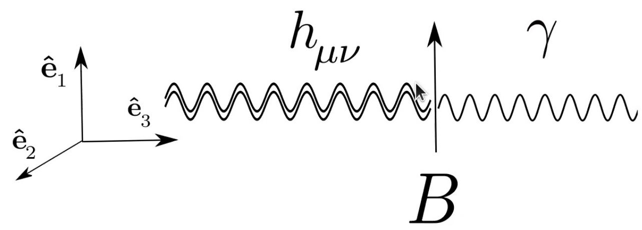
- frequencies >> 100 Hz are very challenging
- laser interferometers seem impossible



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

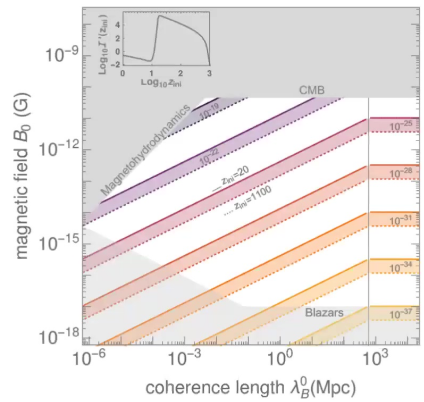
probability of conversion: $$\mathcal{P} \equiv \int_{l.o.s.} \langle \Gamma_{h\leftrightarrow\gamma} \rangle dt = \int_0^{z_{\rm ini}} \frac{\langle \Gamma_{h\leftrightarrow\gamma} \rangle}{(1+z)\,H} dz$$

similar to neutrino oscillations, or axion-photon oscillations

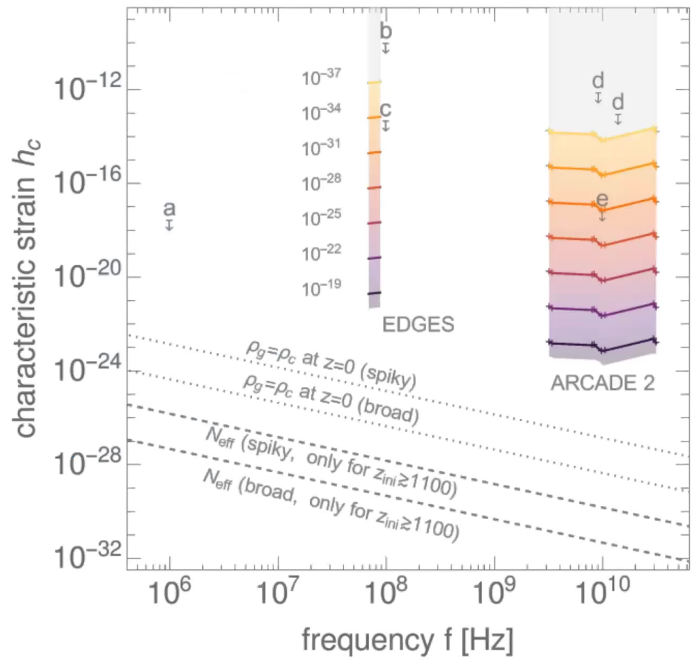
the potential of radio telescopes

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

VD, Garcia-Cely `20



cosmic magnetic fields:
Durrer, Neronov '13



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

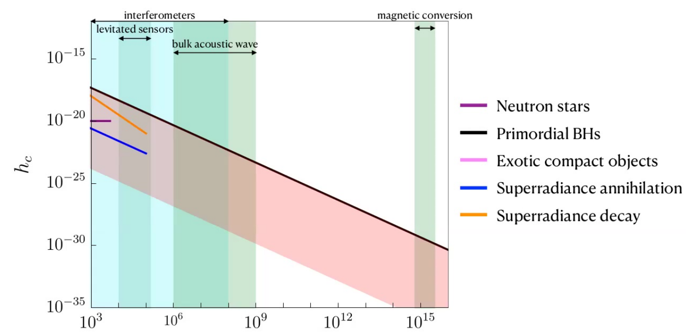
UHF Gws – sources & detector concepts

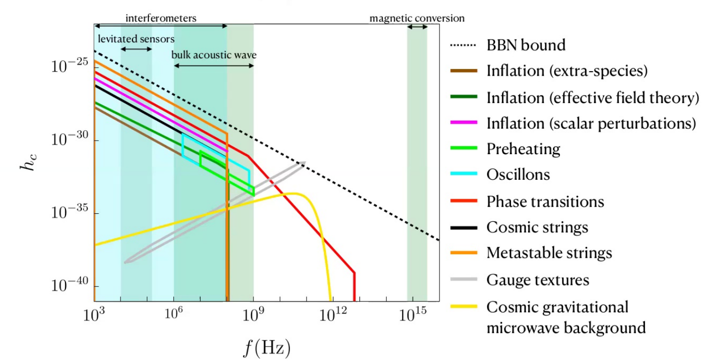
Technical concept	Frequency	Proposed sensitivity (dimensionless)	Proposed sensitivity $\sqrt{S_n(f)}$
Spherical resonant mass, Sec. 4.1.3 [286]			
Mini-GRAIL (built) [293]	2942.9 Hz	10^{-20} $2.3 \cdot 10^{-23}$ (*)	$5 \cdot 10^{-20}\,\mathrm{Hz}^{-\frac{1}{2}}$ $10^{-22}\,\mathrm{Hz}^{-\frac{1}{2}}$ (*)
Schenberg antenna (built) [290]	3.2 kHz	$2.6 \cdot 10^{-20}$ $2.4 \cdot 10^{-23}$ (*)	$1.1 \cdot 10^{-19}\,\mathrm{Hz}^{-\frac{1}{2}}$ $10^{-22}\,\mathrm{Hz}^{-\frac{1}{2}}$ (*)
Laser interferometers			
NEMO (devised), Sec. 4.1.1 [25, 276]	[1 – 2.5] kHz	$9.4 \cdot 10^{-26}$	$10^{-24}\,\mathrm{Hz}^{-\frac{1}{2}}$
Akutsu's proposal (built), Sec. 4.1.2 [281, 332]	100 MHz	$7 \cdot 10^{-14}$ $2 \cdot 10^{-19}$ (*)	$10^{-16}\,\mathrm{Hz}^{-\frac{1}{2}}$ $10^{-20}\,\mathrm{Hz}^{-\frac{1}{2}}$ (*)
Holometer (built), Sec. 4.1.2 [283]	[1 – 13] MHz	$8 \cdot 10^{-22}$	$10^{-21}\,\mathrm{Hz}^{-\frac{1}{2}}$
Optically levitated sensors, Sec. 4.2.1 [59]			
1-meter prototype (under construction)	(10 – 100) kHz	$2.4 \cdot 10^{-20} - 4.2 \cdot 10^{-22}$	$(10^{-19} - 10^{-21})\,\mathrm{Hz}^{-\frac{1}{2}}$
100-meter instrument (devised)	(10 – 100) kHz	$2.4 \cdot 10^{-22} - 4.2 \cdot 10^{-24}$	$(10^{-21} - 10^{-23})\,\mathrm{Hz}^{-\frac{1}{2}}$
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	$8.9 \cdot 10^{-14}$	$10^{-14}\,\mathrm{Hz}^{-\frac{1}{2}}$
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)	$4.2 \cdot 10^{-21} - 2.4 \cdot 10^{-20}$	$10^{-22}\,\mathrm{Hz}^{-\frac{1}{2}}$
Superconducting rings, (theory), Sec. 4.2.7 [322]	10 GHz	$h_{0,n,\mathrm{mono}} \simeq 10^{-31}$	×
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	$9.1 \cdot 10^{-17} - 1.1 \cdot 10^{-15}$	$(10^{-22} - 10^{-20})\,\mathrm{Hz}^{-\frac{1}{2}}$

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





Valerie Domcke - CERN/EPFL

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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„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

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Questions ?

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Sustainable HEP

28-30 June 2021
CERN
Europe/Zurich timezone

Search...

- Overview
- Registration
- Participant List
- Videoconference Rooms

This virtual Zoom workshop aims at discussing the transition to a sustainable future in the field of high-energy physics (HEP), in particular, changes in our travel culture, based on some of the crucial lessons we learned during 2020: Online formats can be a viable alternative to traditional in-person meetings and enable broader participation and inclusion of previously underrepresented groups of researchers. At the same time, efficient communication and networking can be challenging in online formats. The workshop will therefore bring together various perspectives to develop a balanced and deliberate approach to our post-pandemic travel culture and its connection to the questions of climate action, sustainability, and social justice. The workshop will take place from 3 to 7 pm CEST on Monday through Wednesday. The program will consist of impulse talks, panel discussions, a best-practice examples session, and asynchronous flash talks accompanied by a discussion forum on Mattermost: mattermost.web.cern.ch/sustainable-hep (not open yet). All talks will be recorded and made available to the participants for the duration of the workshop, so as to allow for participation from all time zones.

Impulse talk: Monday, June 28th
Kenneth Hiltner (English and Environmental Studies, University of California, Santa Barbara)

Panel 1: Monday, June 28th
The Challenge for Institutions

- Susann Görlinger (ETH Zurich)
- Jan Louis (DESY, University of Hamburg)
- Rob Myers (Perimeter Institute)
- ...

Panel 2: Tuesday, June 29th
Social-Justice Dimension of Online Formats

- Clifford Johnson (University of Southern California)
- Prince Osei (African Institute for Mathematical Sciences, Quantum Leap Africa)
- Fernando Quevedos (University of Cambridge)
- Sumati Surya (Raman Research Institute)

Best-Practice Examples:

- Rachel Grange (ETH Zurich)
- Shaun Hotchkiss (University of Auckland)
- Rogerio Rosenfeld (ICTP São Paulo)
- Michael Spannowsky (University of Durham)
- ...

registration open @
https://indico.cern.ch/event/1004432/

Organizers:
Niklas Beisert (ETH Zurich)
Valerie Domcke (CERN/EPFL)
Astrid Eichhorn (CP3 Origins)
Kai Schmitz (CERN)

20 / 20

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