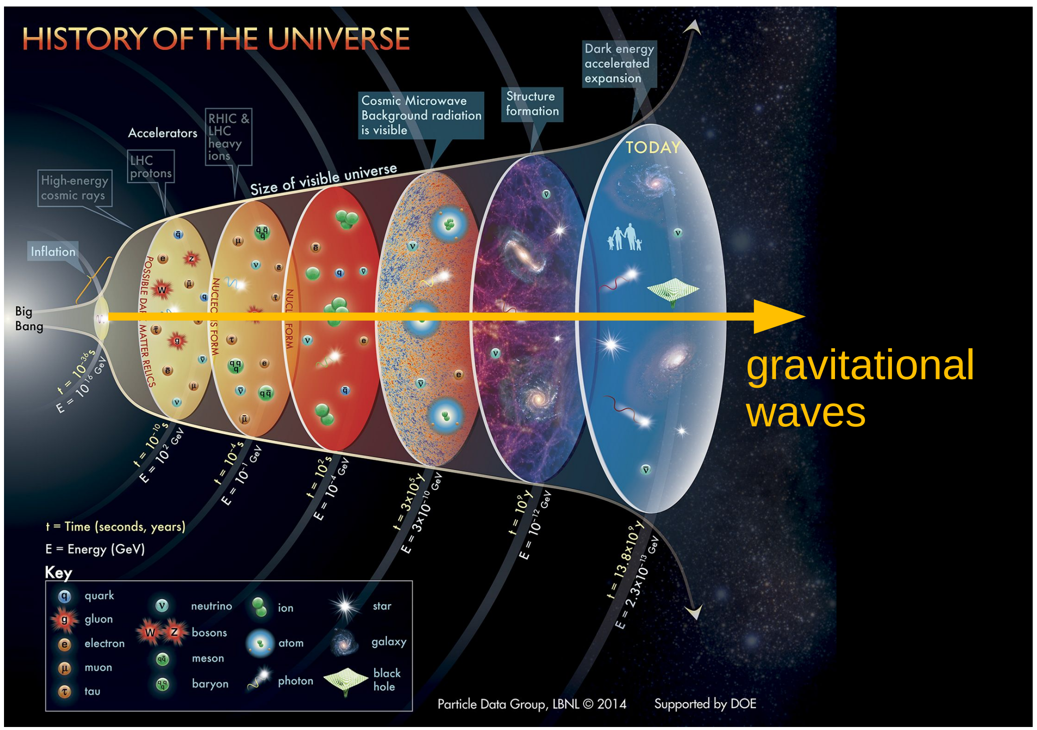
Gravitational Waves

as a probe of the early Universe

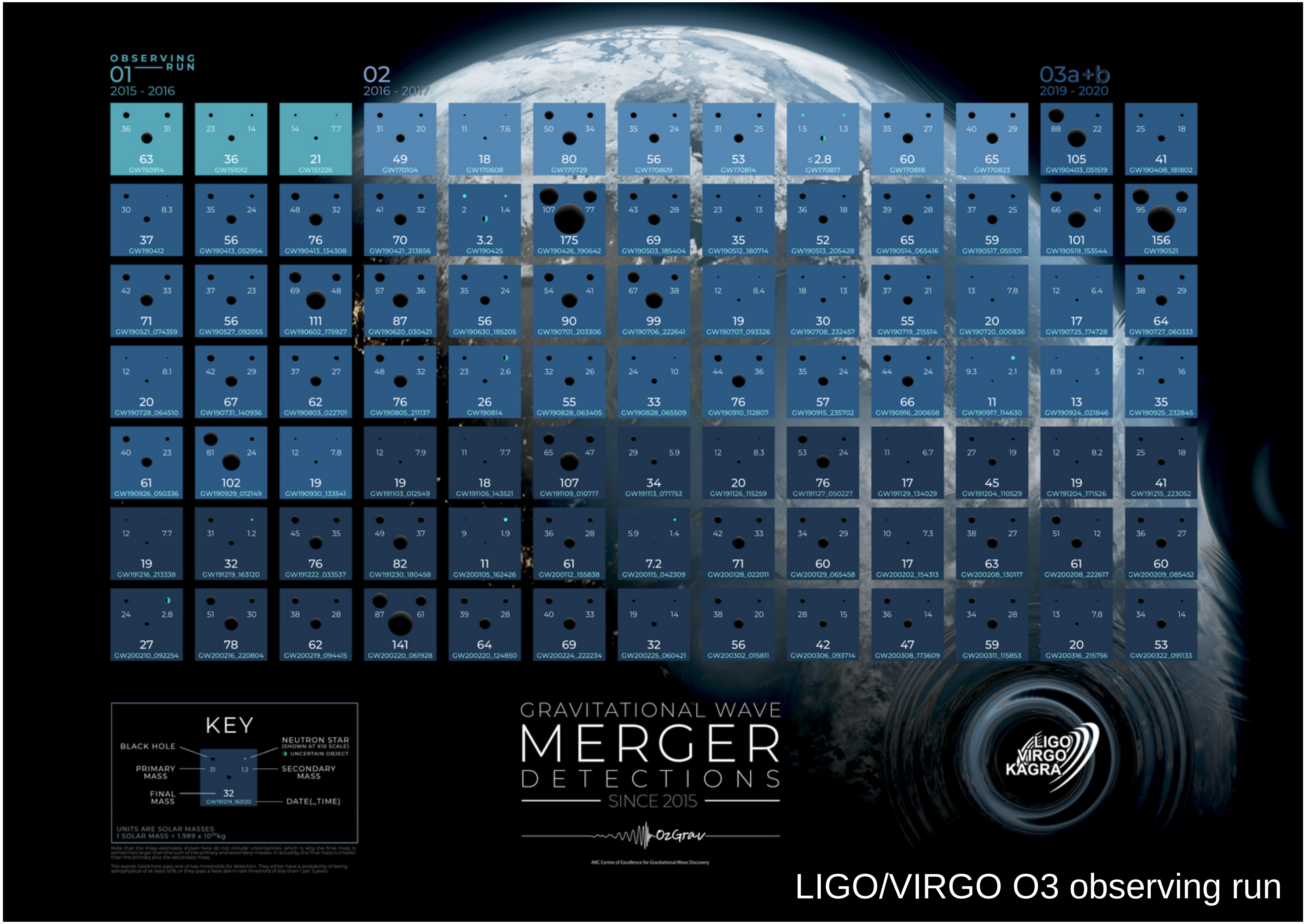


Valerie Domcke
CERN

Colloquium at DESY, Hamburg
May 16 2023

based on work with
Wilfried Buchmüller, Camilo Garcia-Cely,
Sung Mook Lee, Nick Rodd, Kai Schmitz
and members of the
LISA Cosmology Working group,
and UHF-GW initiative.

GW observations today

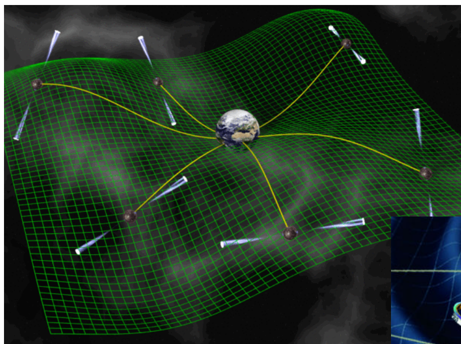


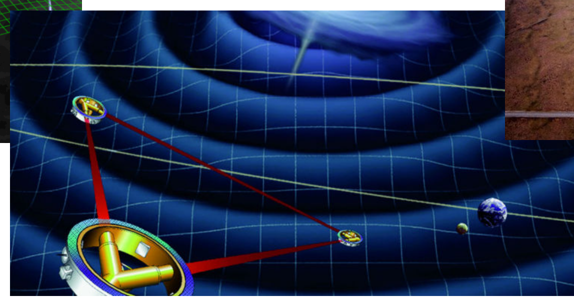
LIGO/VIRGO O3 observing run

GW observations today

pulsar timing arrays

interferometers





LISA

LIGO

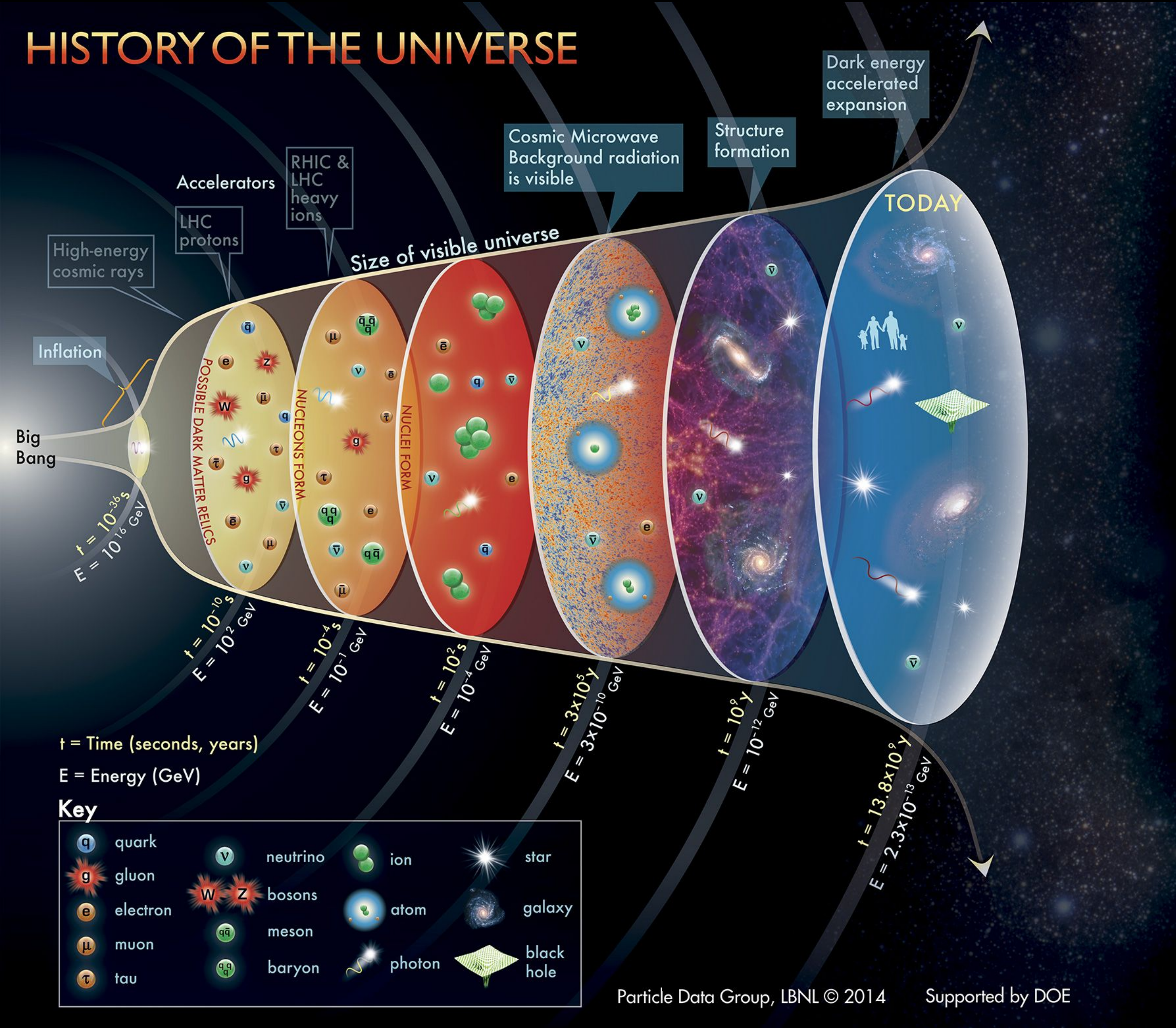
?

nHz mHz kHz

→ frequency

QCD PT EW PT GUT PT ←

mass (merging compact objects)
time (cosmological events)


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
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electron
muon
tau
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bosons
meson
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ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
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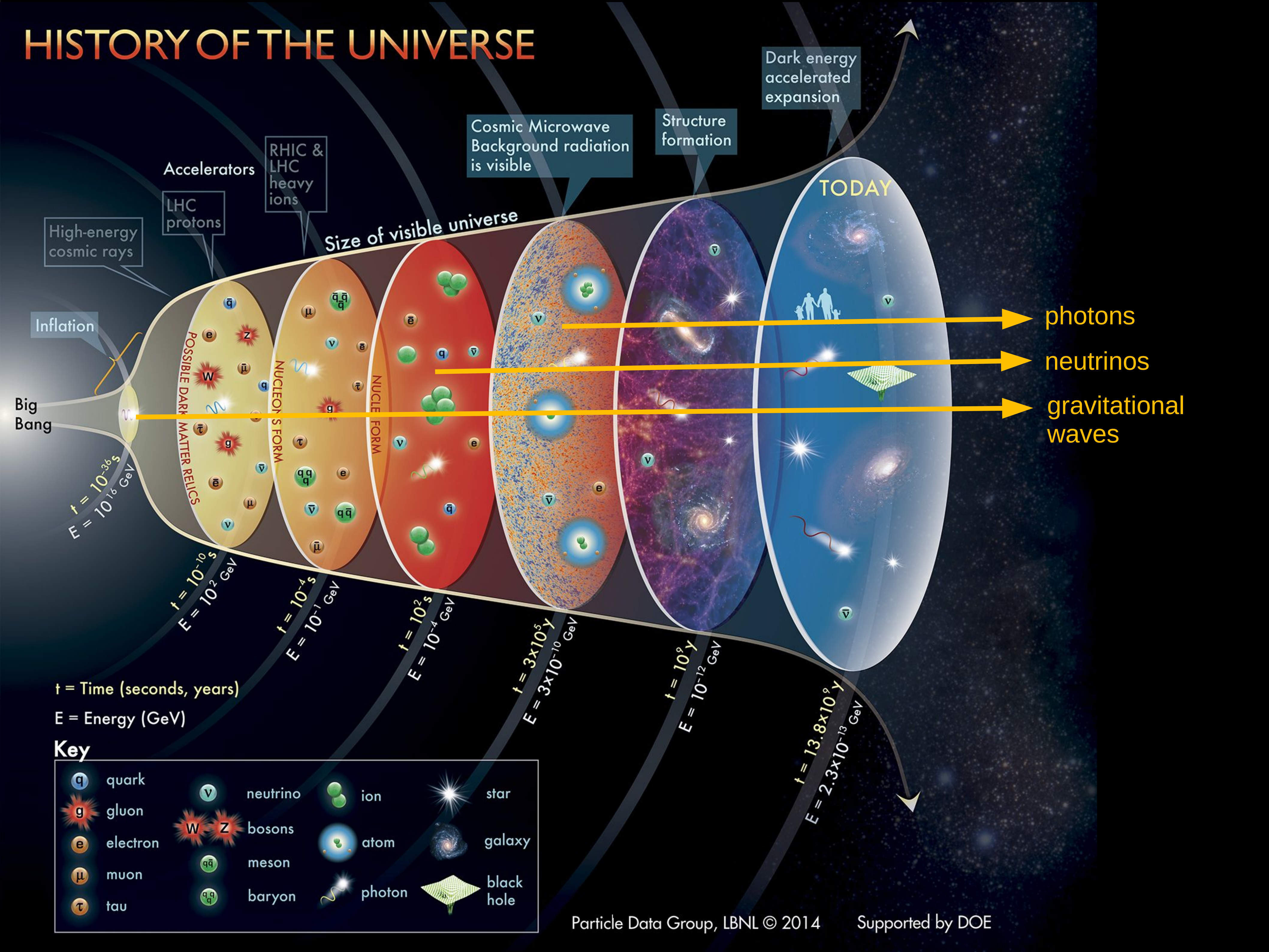

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t = 10⁻¹⁰ s E = 10² GeV
t = 10⁻⁴ s E = 10⁻¹ GeV
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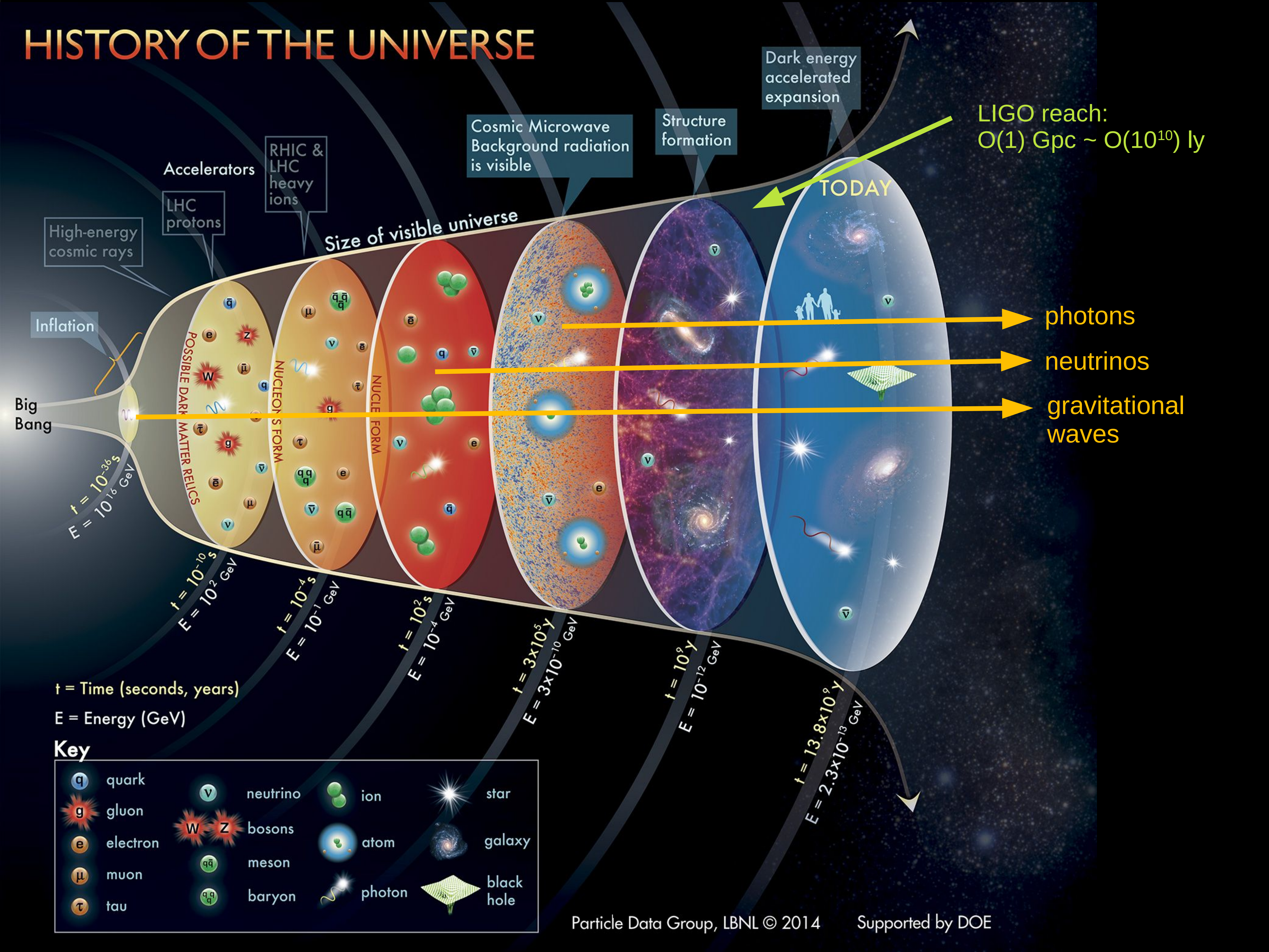
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LIGO reach:
O(1) Gpc ~ O(10^{10}) ly
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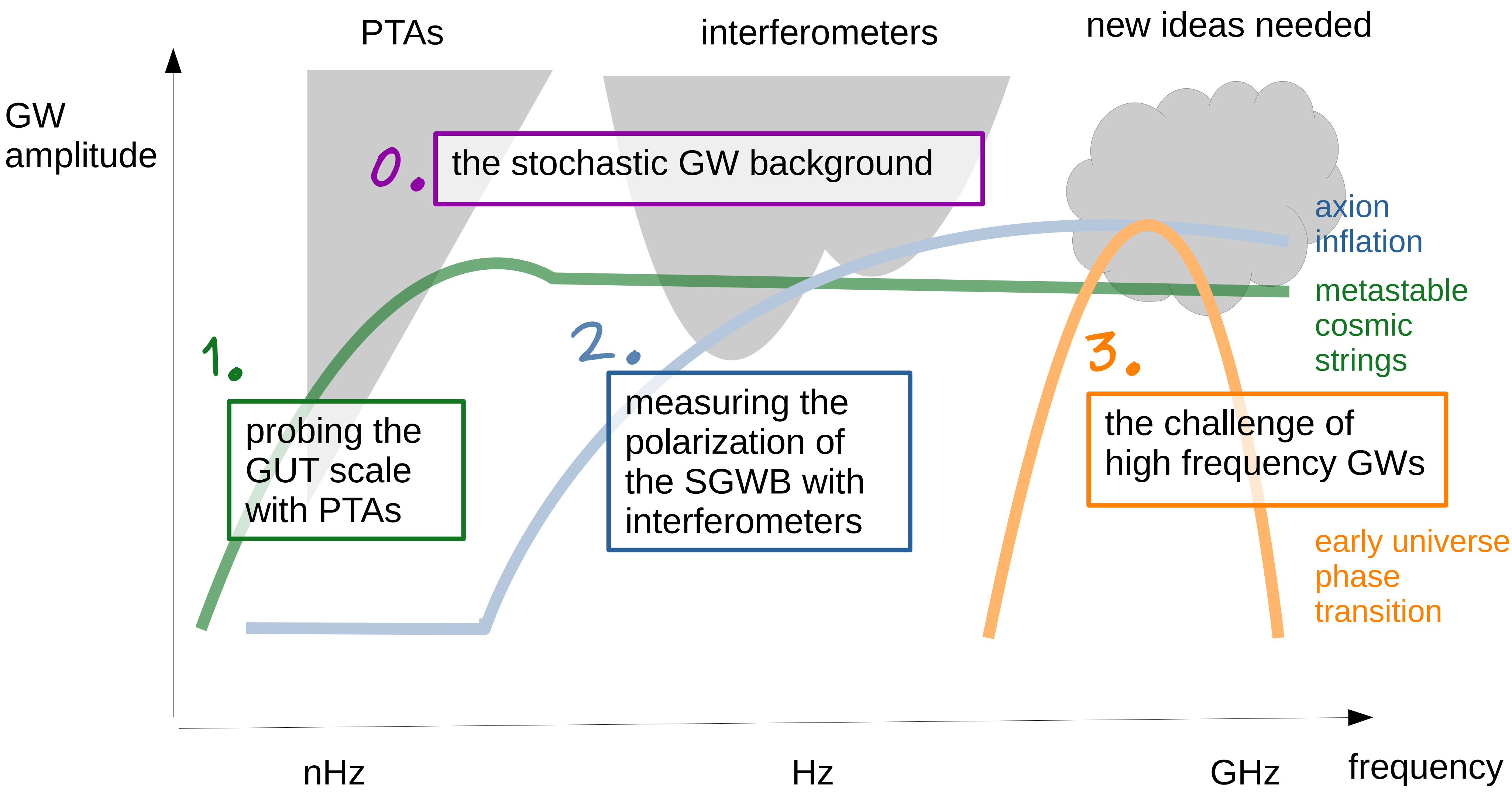
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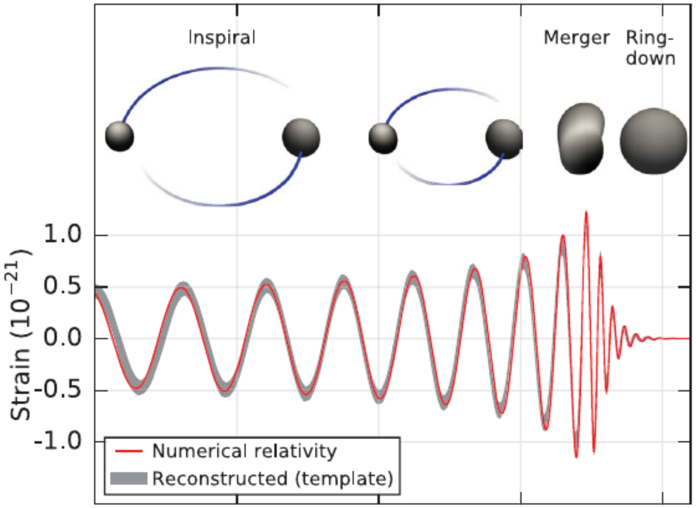
Hz
GHz
frequency

transient and stochastic signals



LIGO Livingston, USA

2015: first direct observation of GWs, collision of two black holes a billion years ago

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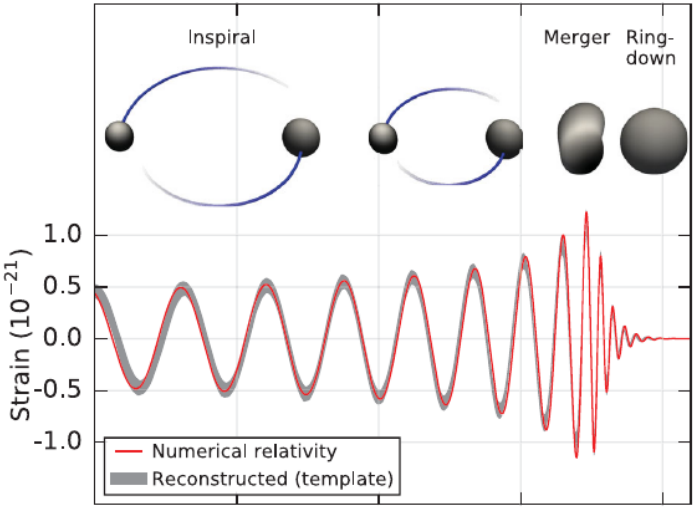

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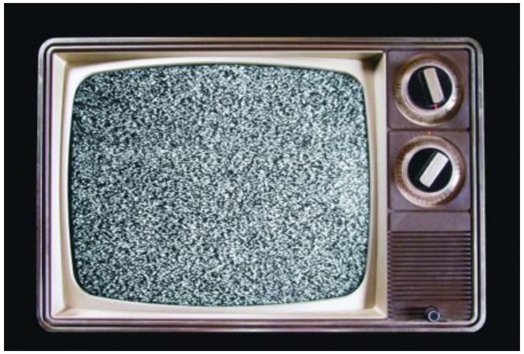
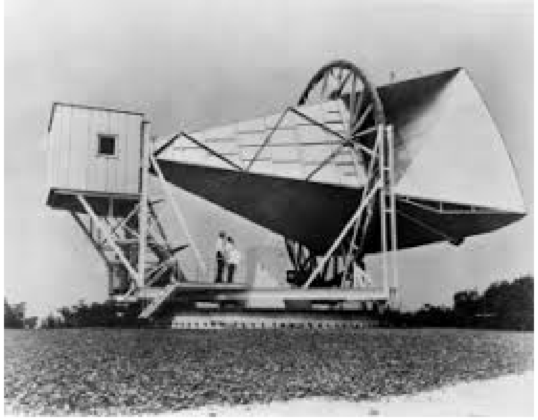


next challenge:
stochastic gravitational wave background

analagous to CMB



Penzias, Wilson `64

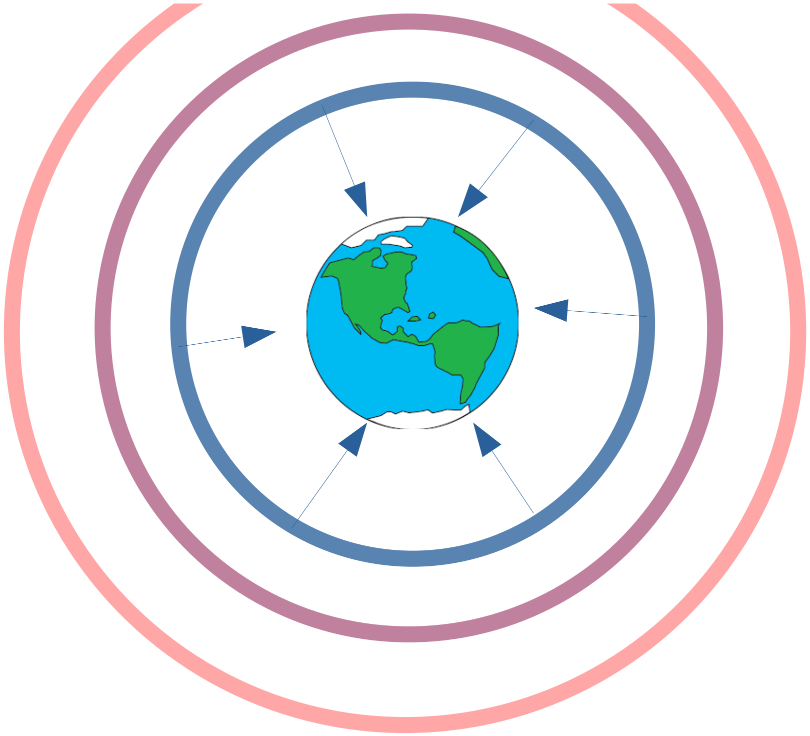
astrophyscial and cosmological contributions

possible hint by PTAs (pulsar timing arrays)

prelude: stochastic gravitational wave background

eg review by Caprini, Figueroa '18

stochastic gravitational wave background (SGWB):



astrophysical sources:

unresolved mergers
of compact objects (BH, NS, ..)

cosmological sources:

SM: inflation, thermal fluctuations
→ very small

BSM: inflation, (p)reheating,
phase transitions, ...

$$f \sim \mathrm{mHz}\ (0.01/\epsilon_*)\,(T_*/100\ \mathrm{GeV})$$

$$\epsilon_* \lesssim 1$$

primary observable:

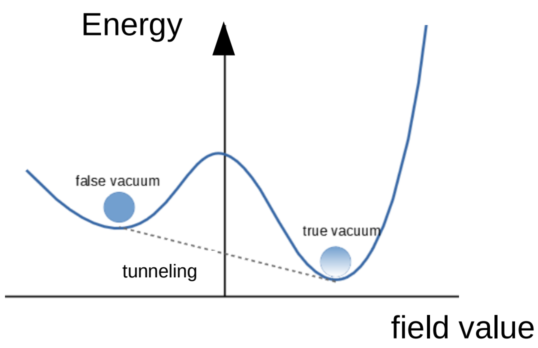
$$\Omega_{GW} = \frac{1}{\rho_c} \frac{\partial \rho_{GW}(f,\tau)}{\partial \ln f}$$

example : phase transition

Water boiling: first order phase transition

Standard Model: electroweak symmetry breaking through Higgs acquiring a vacuum expectation value

.. and beyond: extended symmetry groups (eg GUTs) spontaneously broken in cooling Universe



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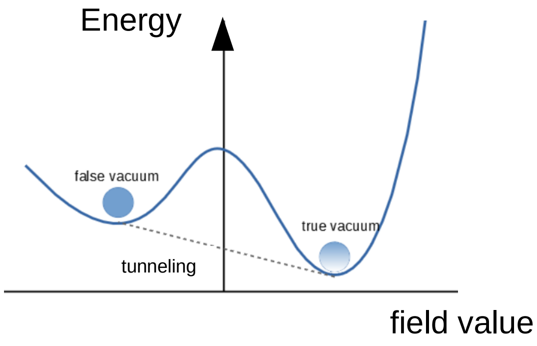
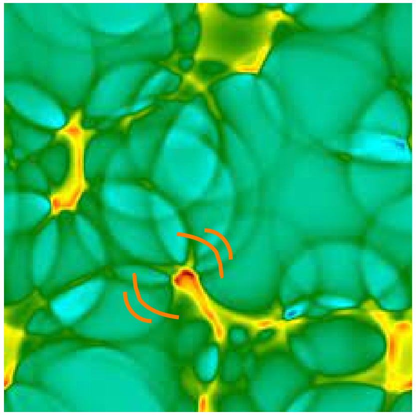
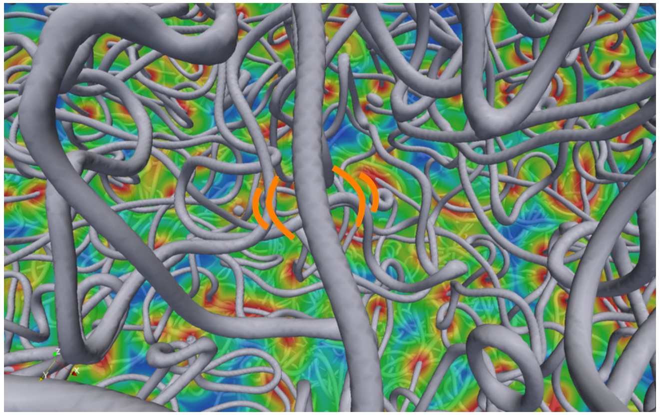
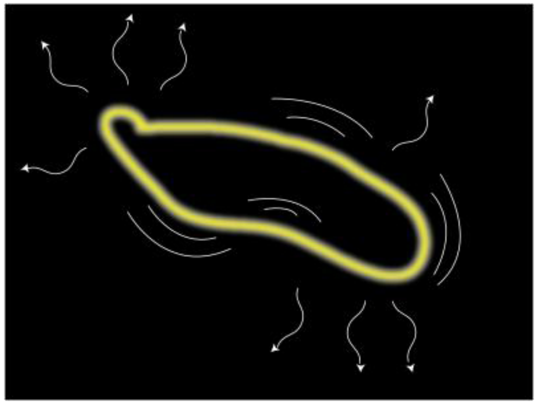




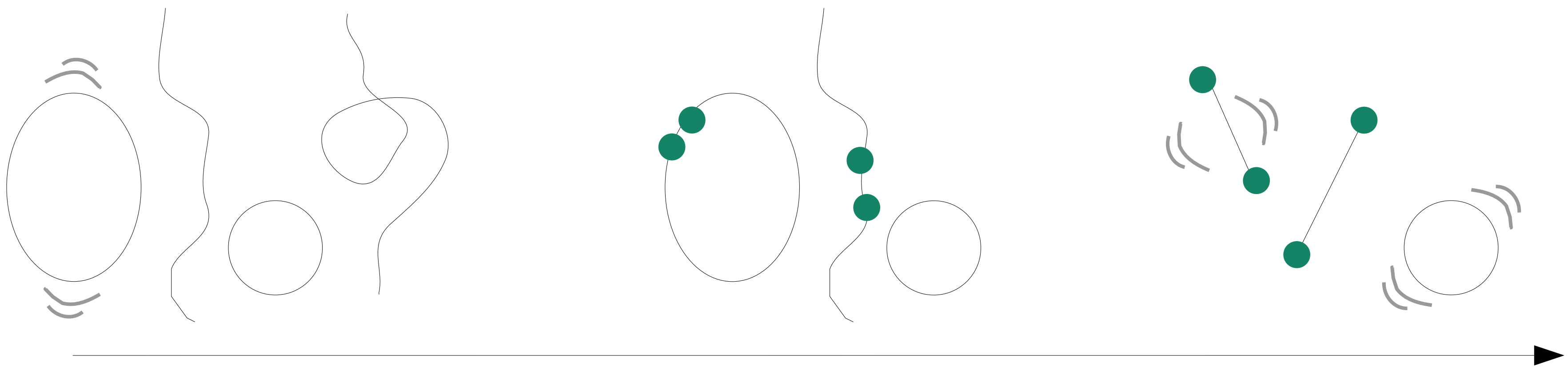




1st order PT sources GWs

topological defects formed during PT radiate GWs

example : metastable cosmic strings



scaling regime
(long strings & loops)

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

segments & loops

[see also Leblond, Shlaer, Simons `09]

cosmic strings formed
in phase transition, eg

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

spontaneous creation of monopoles
due to GUT embedding

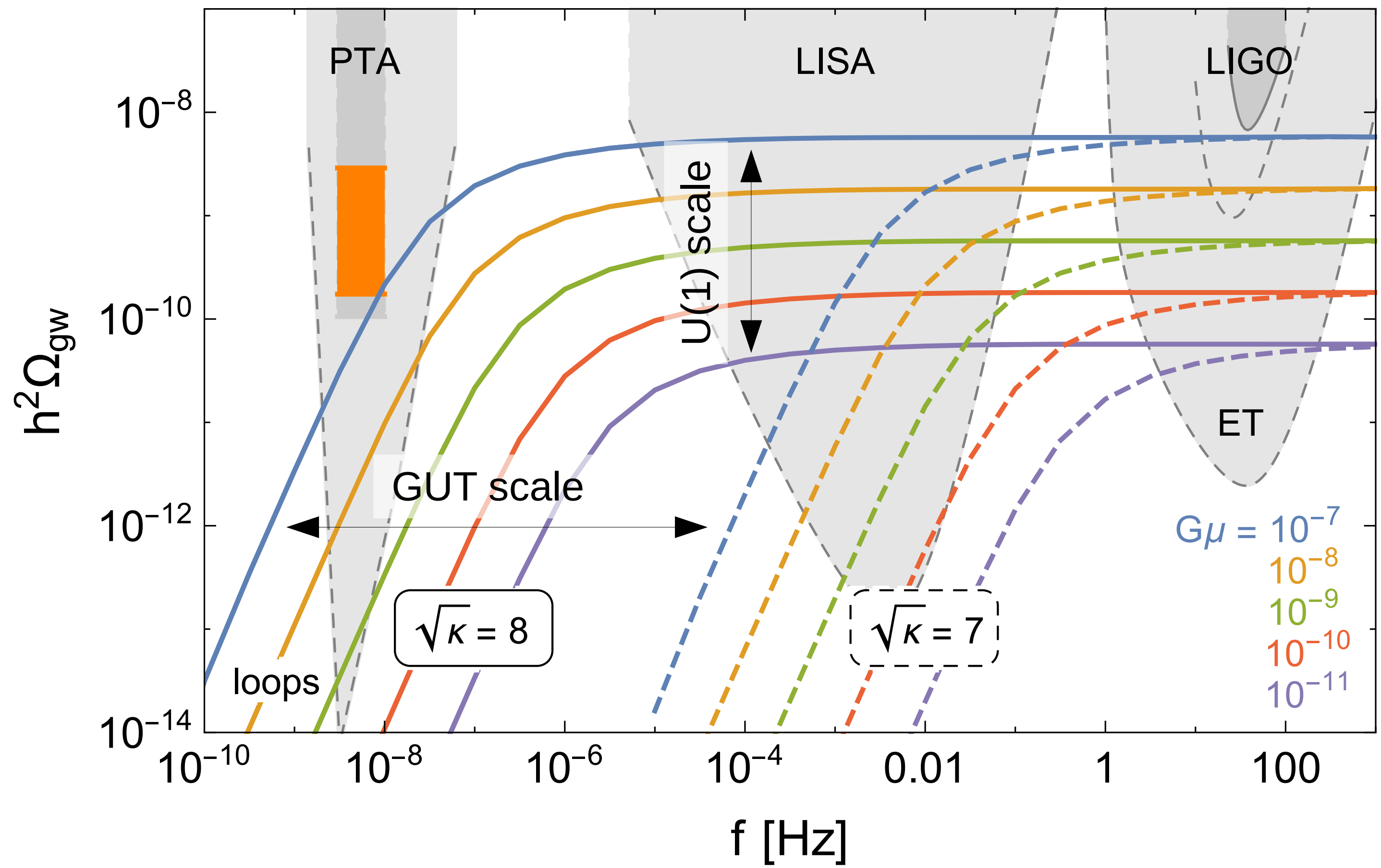
$$G_{SM} \times U(1)_{B-L} \subset SO(10)$$

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

$\mu \sim v_{B-L}^2$ string tension
$m \sim v_{GUT}$ monopole mass

example: metastable cosmic strings

Buchmüller, VD, Schmitz `21



$$SO(10)$$
$$\downarrow$$
$$G_{\mathrm{SM}} \times U(1)$$
$$\downarrow$$
$$G_{\mathrm{SM}}$$

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

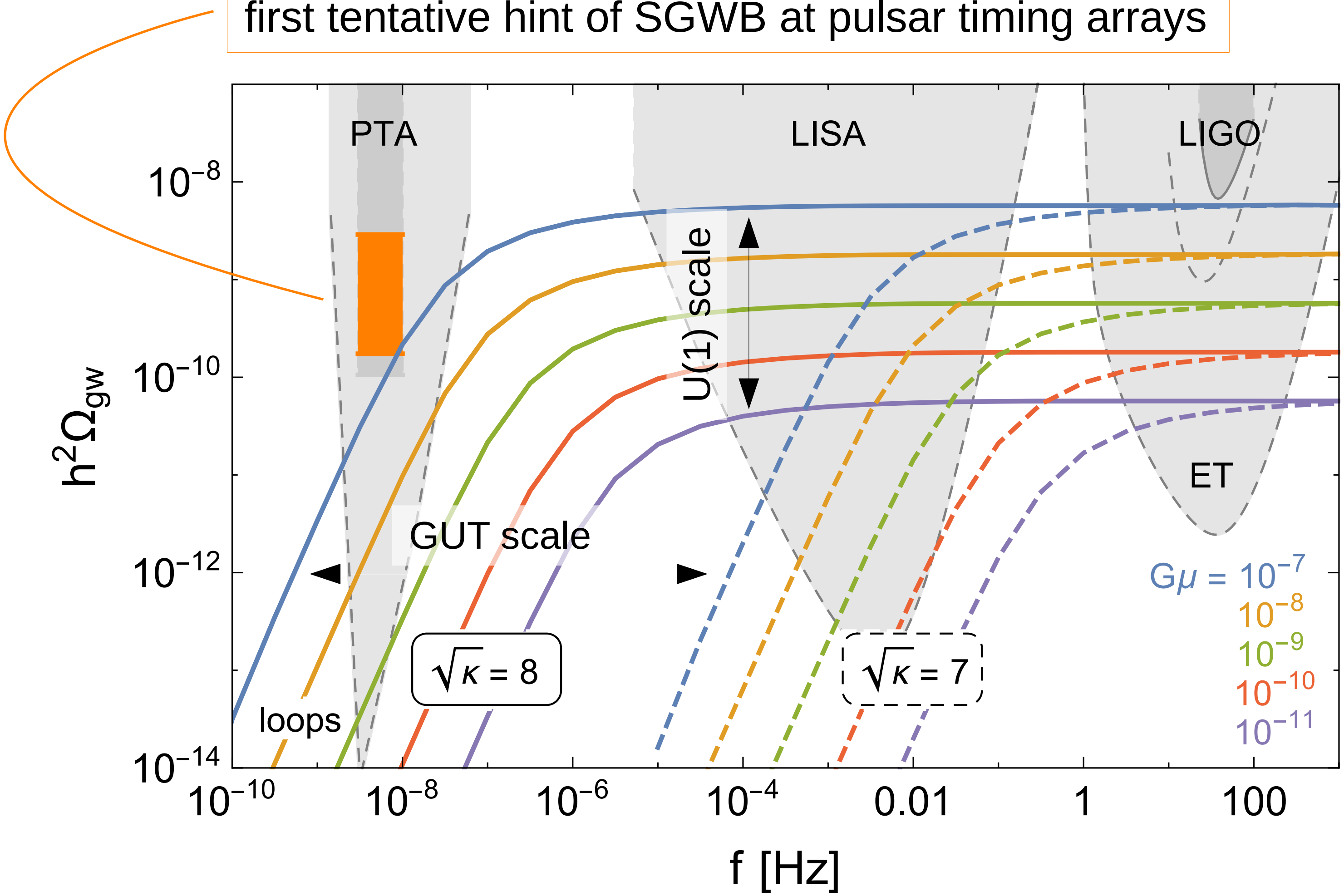
$G\mu \sim (v_{U(1)}/M_P)^2$

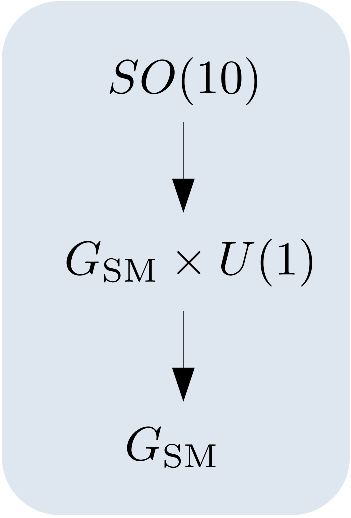
GUT-scale U(1) phase transition can be tested with GWs

example: metastable cosmic strings

Buchmüller, VD, Schmitz `21

first tentative hint of SGWB at pulsar timing arrays





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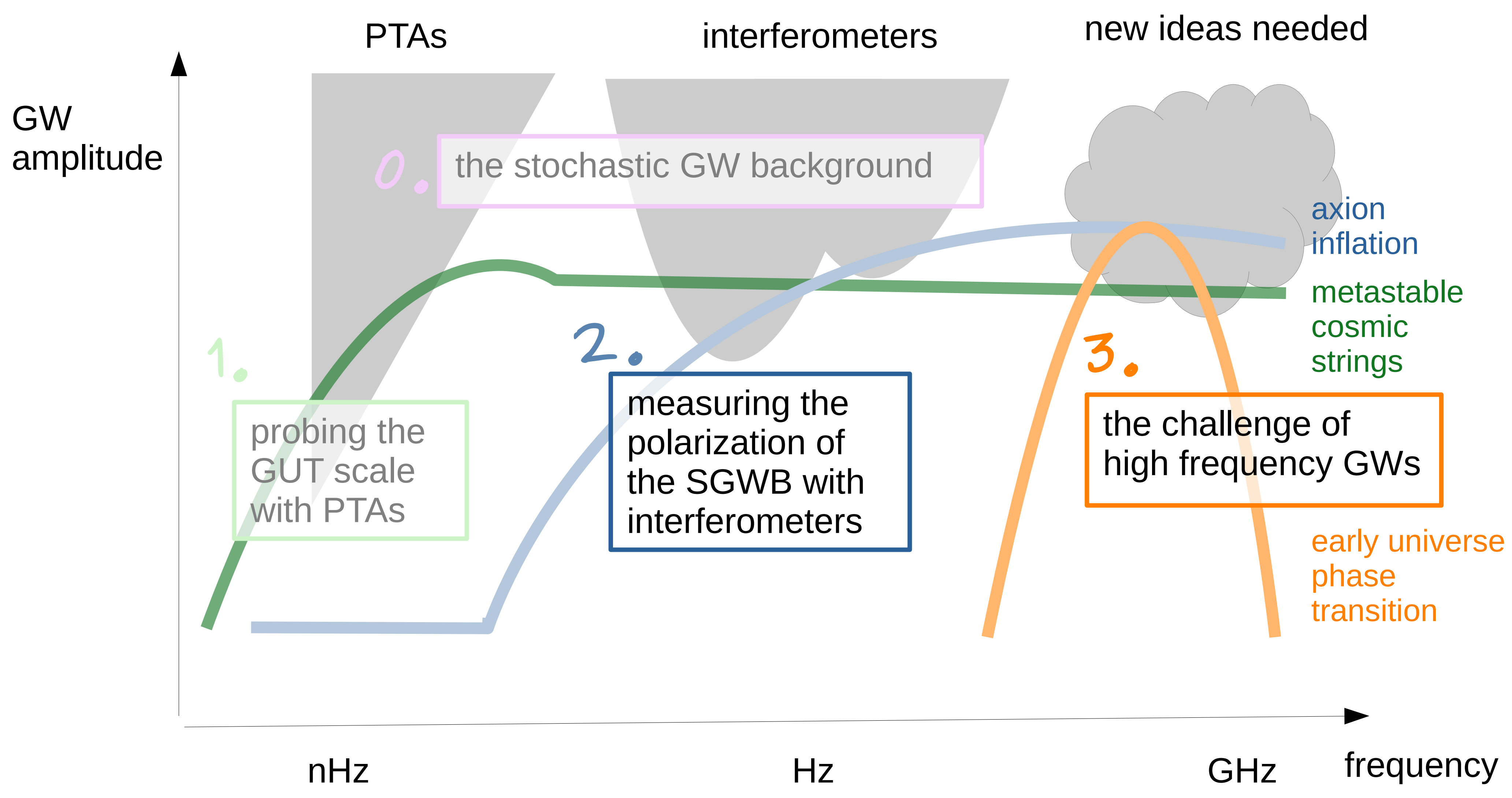
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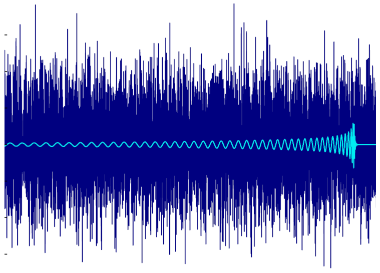
decoding the SGWB



signal vs background discrimination is very challenging!

- signal cannot be shielded, noise models have uncertainties
- expected signal shape is model and parameter dependent
- cosmological and astrophysical contributions superimposed

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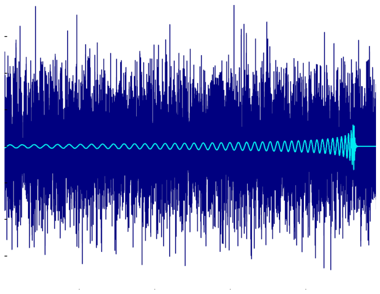

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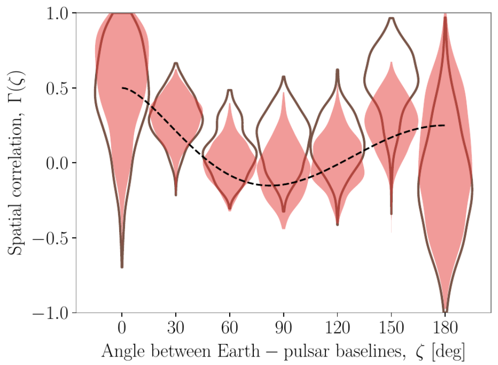
PPTA `21, 2107.12112



possible avenues

- signal vs noise channels / cross-correlation
- spectral shape
- anisotropies and polarization
- ...

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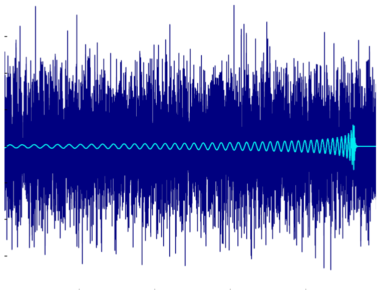

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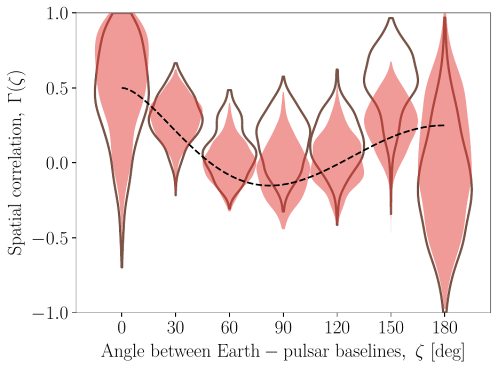
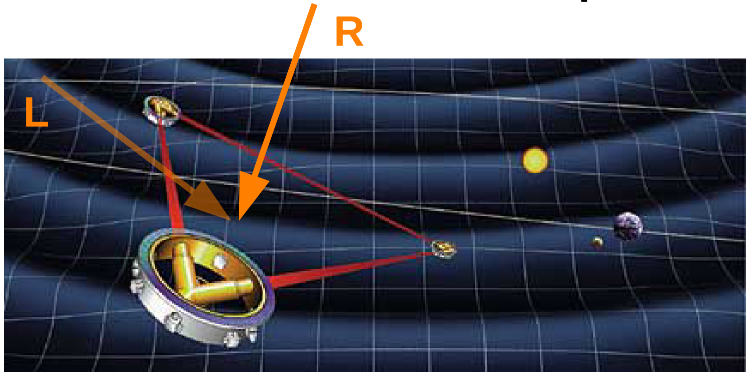


decoding the SGWB : polarization

some CP-violating models predict a **chiral** stochastic gravitational wave (GW) spectrum

a **planar** detector cannot distinguish left- and right-handed GWs from an **isotropic** source

LIGO Livingston - US



LISA (launch 2030s)

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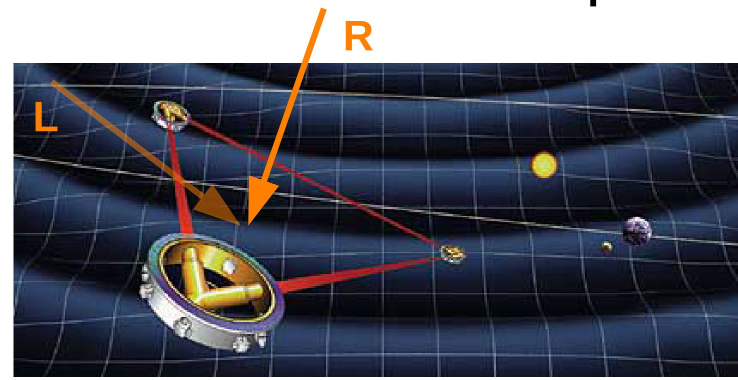

LISA (launch 2030s)

VD, Garcia-Bellido, Peloso, Pieroni, Ricciardone, Sorbo, Tasinato `20 [LISA Cosmology WG]

ground-based detectors:
network breaks

Seto, Taruya `07; Crowder et al `12

→ sensitive to maximally chiral scale-invariant spectrum if SNR > 10^3

LISA (or single ET):
kinematic cosmic dipole breaks isotropy

Seto `06

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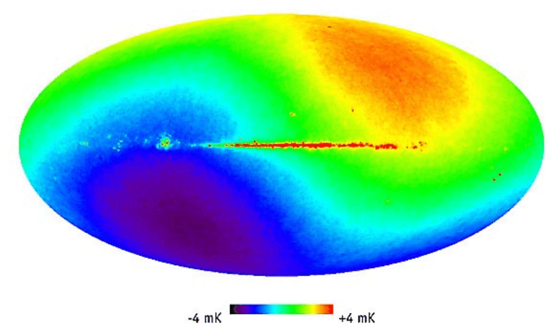

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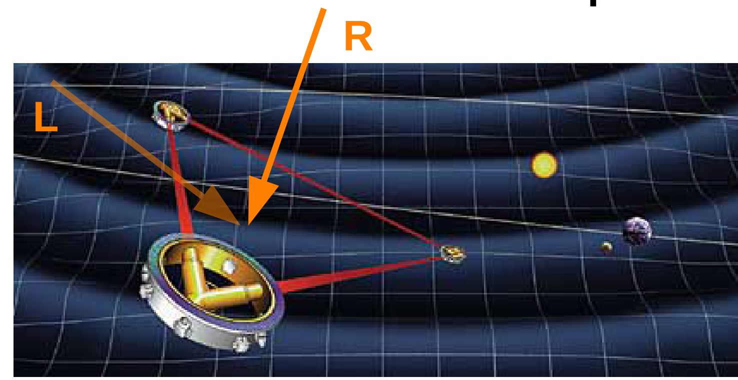

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possible for SNR > 10^3

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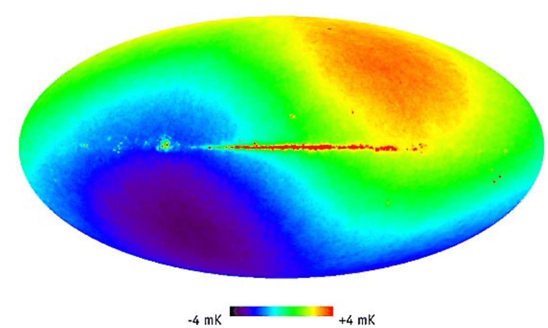

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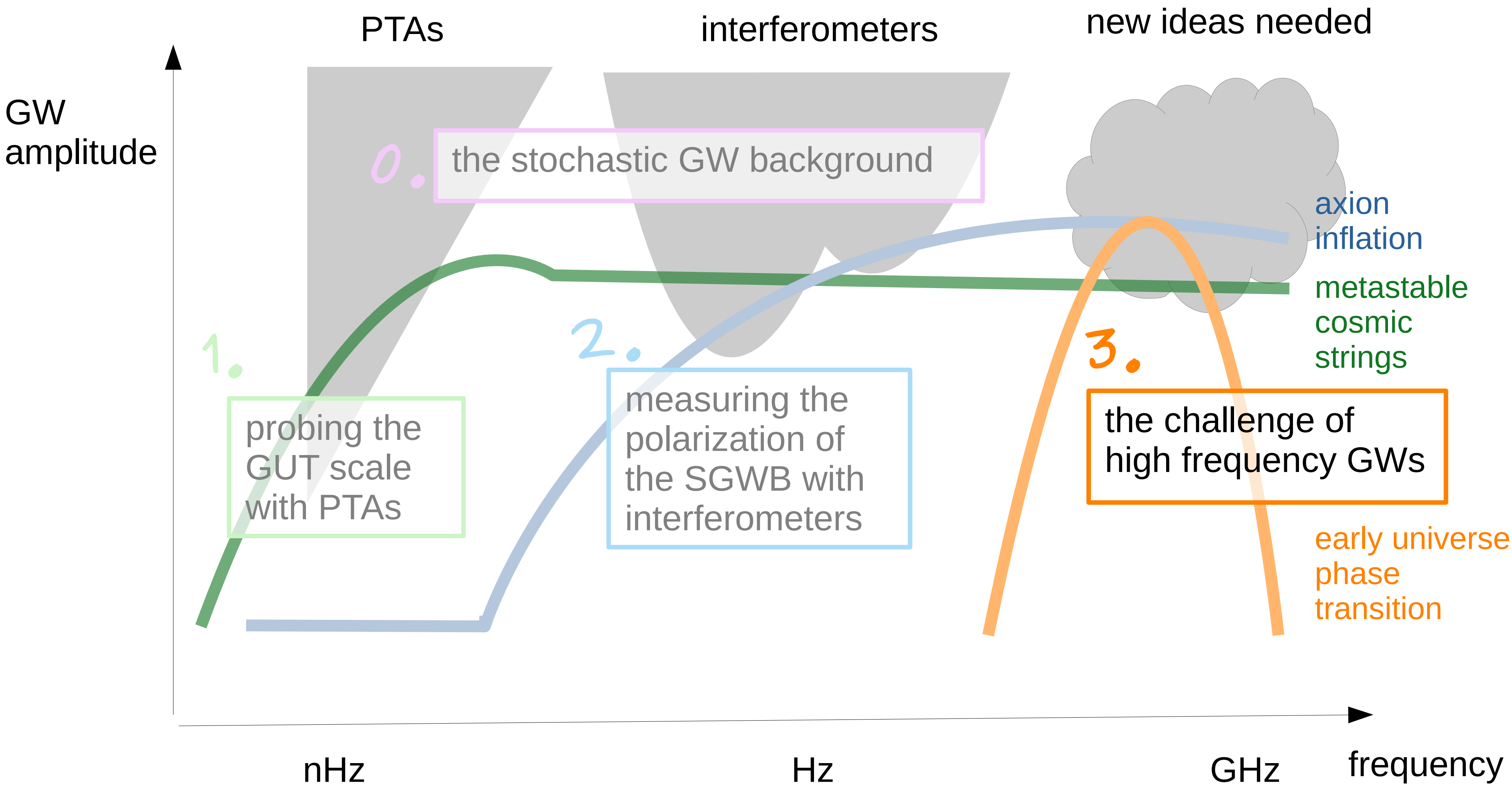
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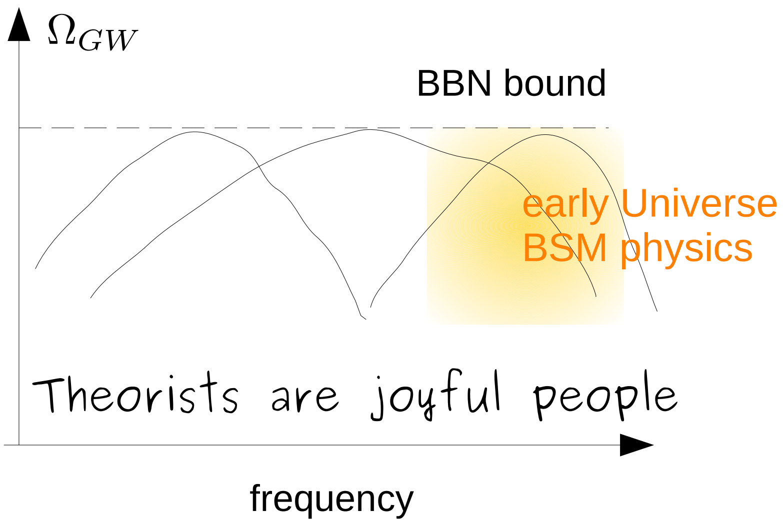
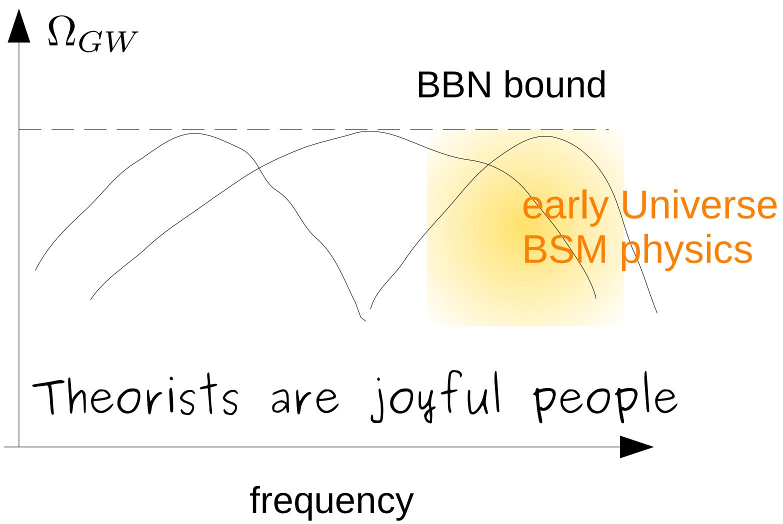
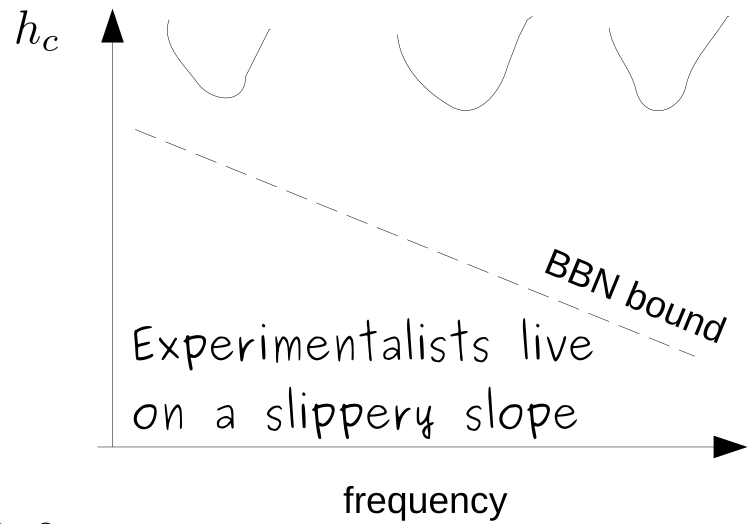
challenges in UHF GW detection



CMB/BBN bound constrains energy

challenges in UHF GW detection





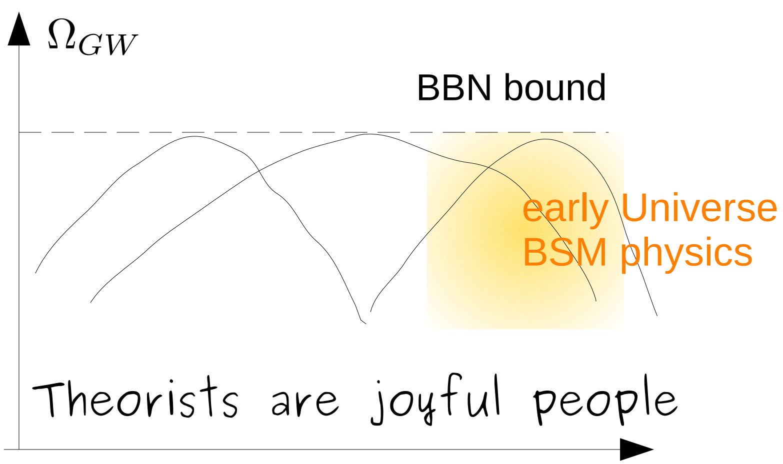
$$\Omega_{GW} \propto f^2 h_c^2$$

CMB/BBN bound constrains energy

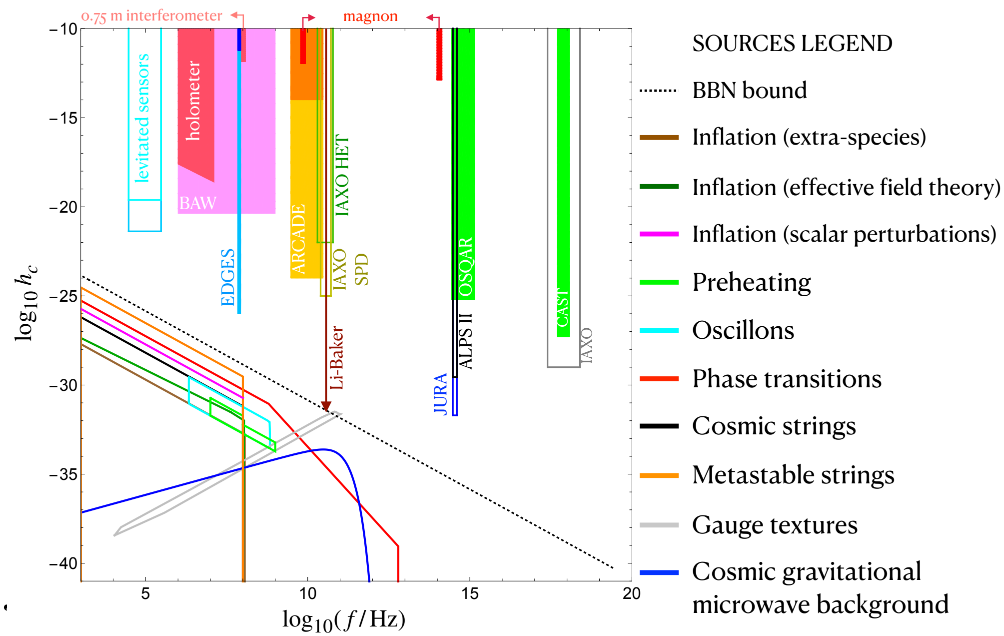
experiments measure displacement

challenges in UHF GW detection

UHG GW initiative Living Review:
https://arxiv.org/abs/2011.12414



$\Omega_{GW} \propto$



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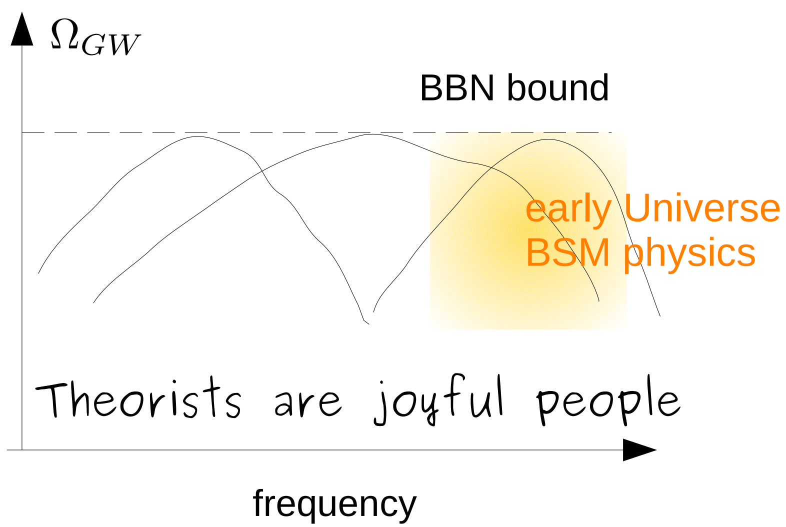

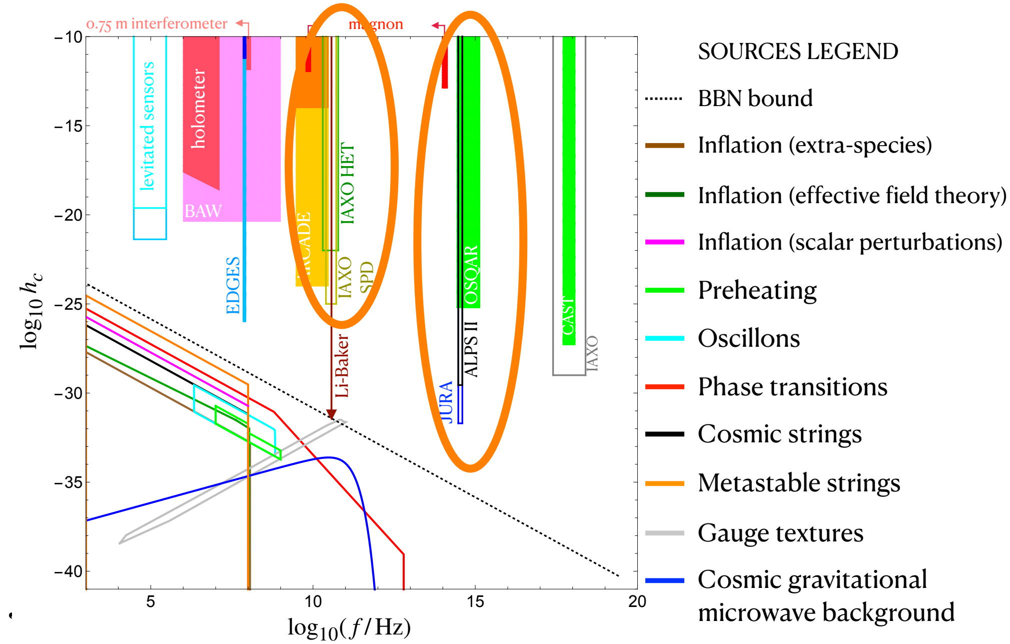

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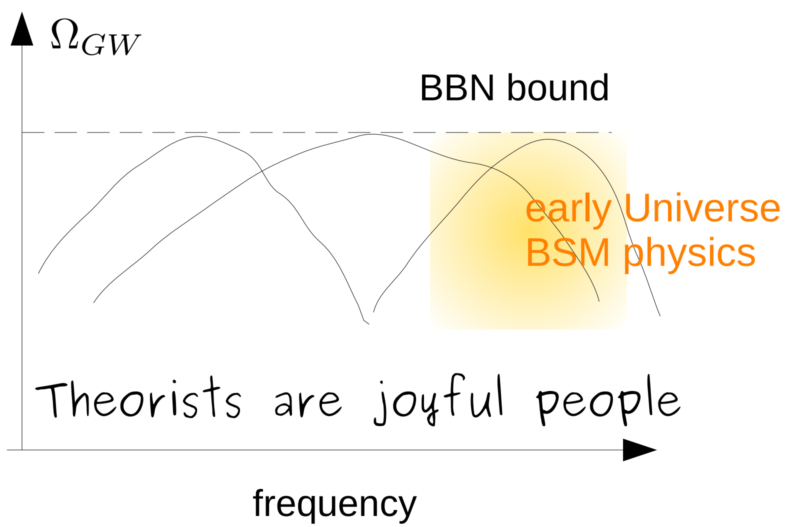
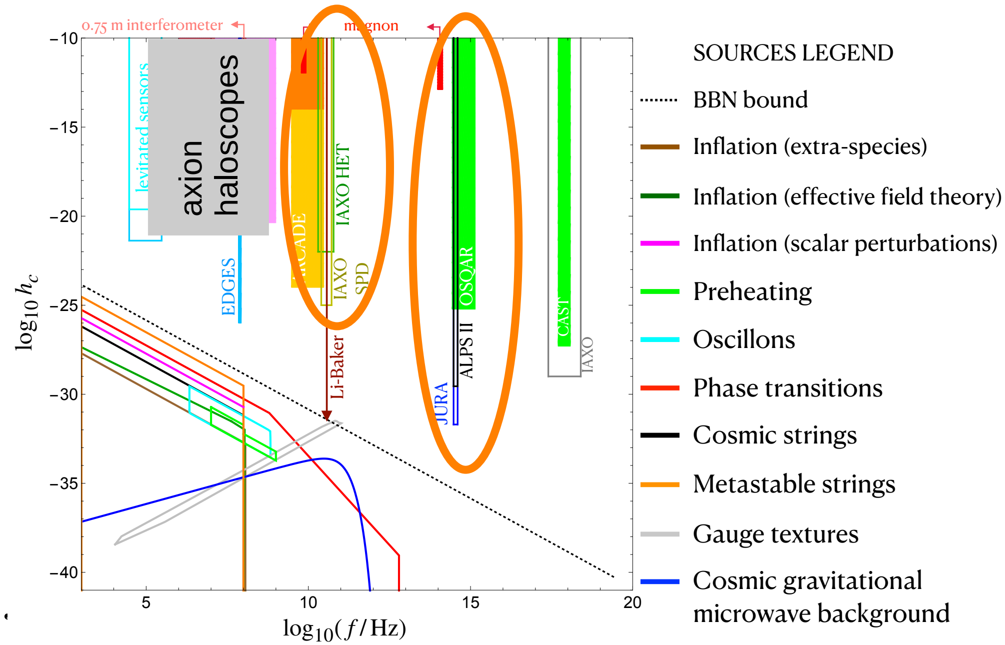




$\Omega_{GW} \propto$

CMB/BBN bound constrains energy

experiments measure displacement

GW electrodynamics

Classical electrodynamics + linearized GR, $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$:

$$\partial_\nu F^{\mu\nu} = j^\mu_{\rm eff} = (-\nabla \cdot \mathbf{P},\, \nabla \times \mathbf{M} + \partial_t \mathbf{P})$$

effective curent
effective polarization vector
effective magnetization vector

with

$$\begin{aligned} P_i &= -h_{ij} E_j + \tfrac{1}{2} h E_i + h_{00} E_i - \epsilon_{ijk} h_{0j} B_k , \\ M_i &= -h_{ij} B_j - \tfrac{1}{2} h B_i + h_{jj} B_i + \epsilon_{ijk} h_{0j} E_k , \end{aligned}$$

induced at linear order in h
in presence of external E,B field

VD, Garcia-Cely, Rodd `22

Direct analogy with axion electrodynamics

$$\mathcal{L} \supset g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B} \quad \rightarrow \quad \mathbf{P} = g_{a\gamma\gamma}\, a\, \mathbf{B}\,, \quad \mathbf{M} = g_{a\gamma\gamma}\, a\, \mathbf{E}$$

McAllister et al `18
Tobar, McAllister, Goryachev `19
Quellet, Bogorad `19

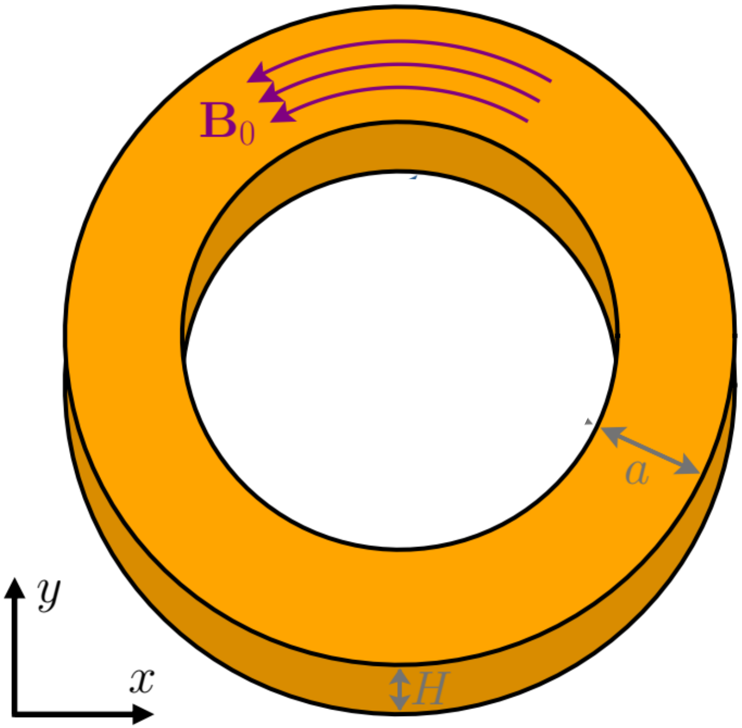
effective source terms in Maxwell‘s equation due to GW

GW signal in axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

VD, Garcia-Cely, Rodd `22
VD, Garcia-Cely, Lee, Rodd (in progress)

static magnetic field



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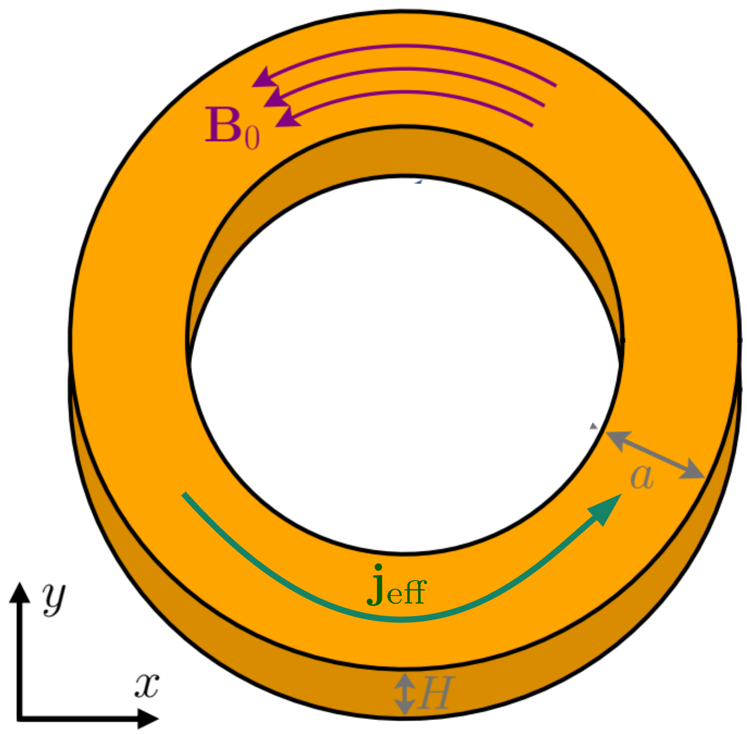

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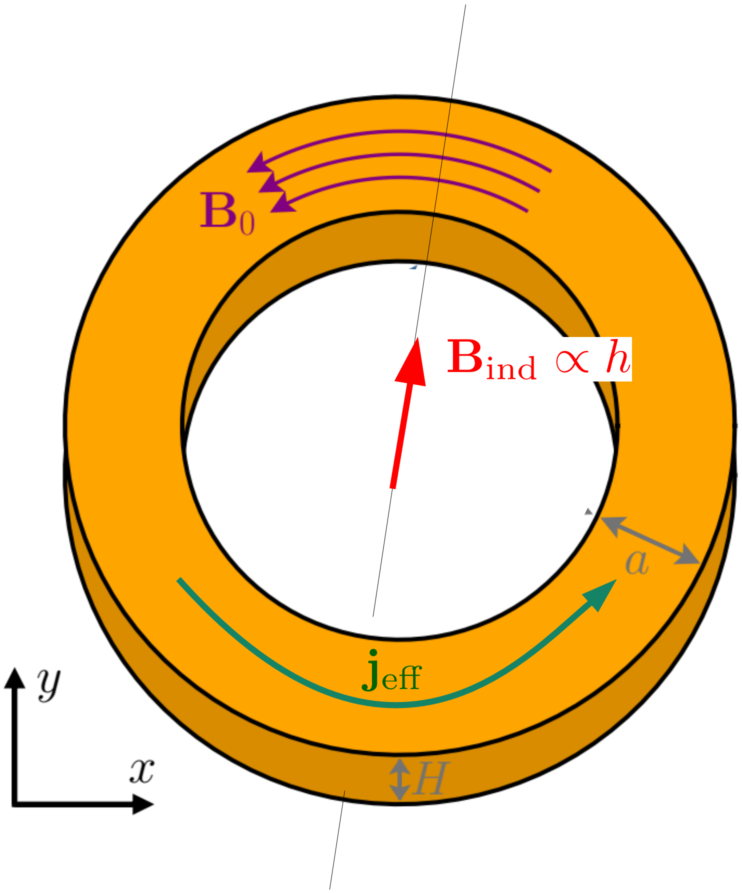

static magnetic field

effective current

induced oscillating magnetic field

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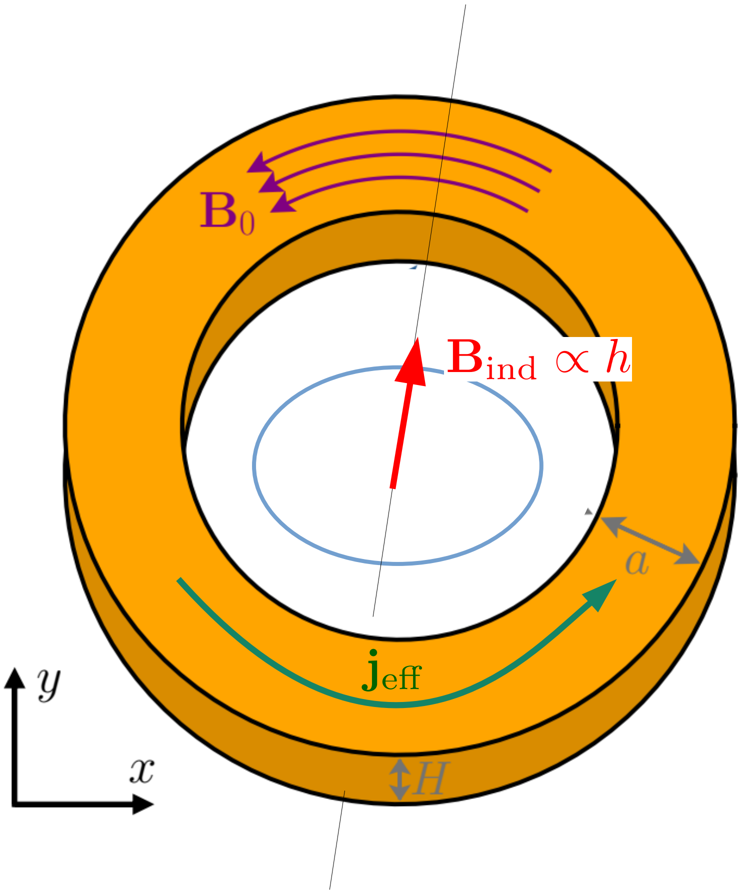

static magnetic field

effective current

induced oscillating magnetic field

measure magnetic flux (~ h)
through pickup loop

at leading order in (ωR) :

$$\Phi_{\text{gw}} = \frac{i\, e^{-i\omega t}}{16\sqrt{2}}\, h^\times \omega^3 B_0 \pi r^2 R a(a+2R) s^2_{\theta_h}$$

GW signal in axion haloscopes

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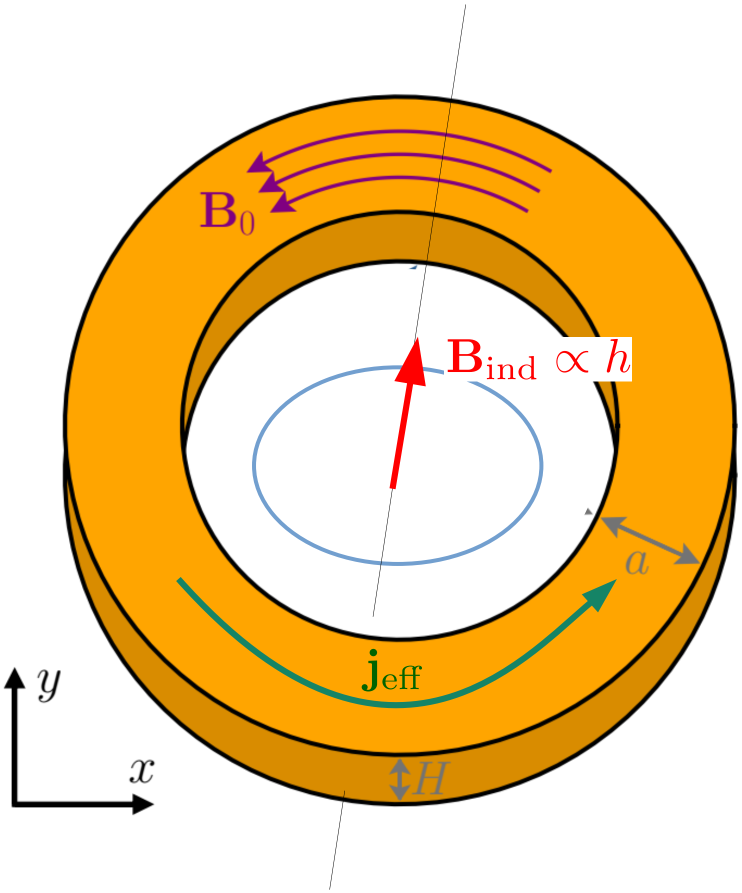

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match to axion induced flux to recast axion-photon coupling bounds as GW bounds

$$\Phi_a = e^{-i\omega t}\, g_{a\gamma\gamma} \sqrt{2} B_0 \pi r^2 R \ln(1 + a/R)$$

- set bounds recasting existing axion searches
- parametric improvement w modified pick-up loop

axion haloscopes: bounds and prospects

VD, Garcia-Cely, Rodd `22

circular pickup loop

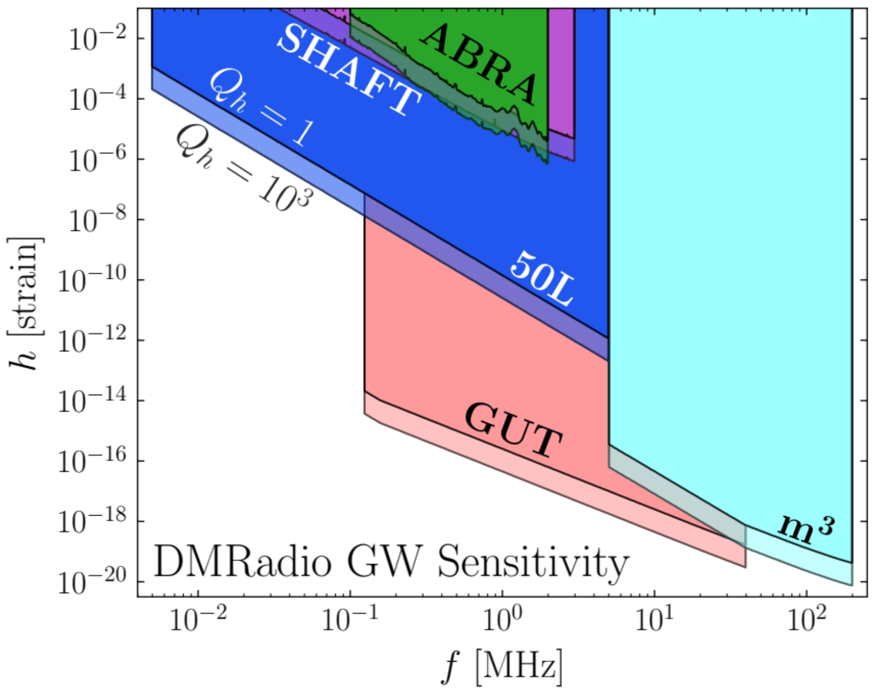
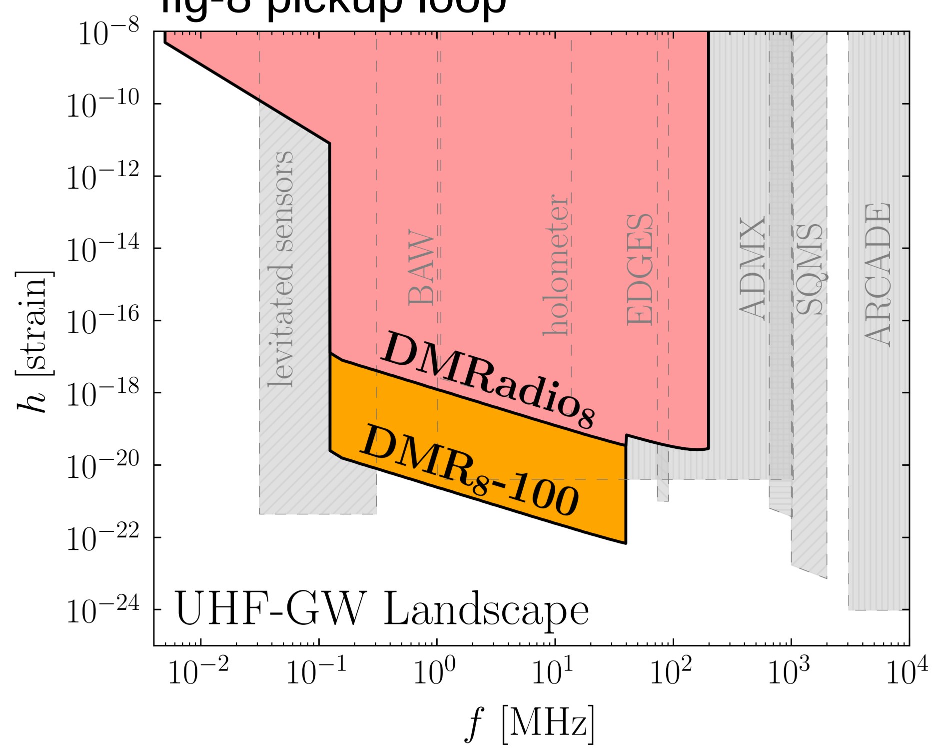


fig-8 pickup loop



bounds from recasting ABRA [2102.06722] and SHAFT limits [2003.03348]

prospects for DM Radio proposals [Snowmass Letters of Interest CF2]

still far away from BBN bound, but clear synergies with axion searches

see also Ejilli et al `19, Berlin et al `21,`23

Conclusions and Outlook

The stochastic gravitational wave background

- astrophysical and cosmological contributions expected
- possibly first hint at pulsar timing arrays – stay tuned!
- further characterization (spectrum, anisotropies, polarization..) will be crucial for BSM interpretations

The search for high-frequency gravitational waves

- GW signals >> kHz would be a smoking gun of BSM physics
- GW electrodynamics has clear similarities with axion electrodynamics: Important synergies between axion searches and UHF GW searches
- New bounds and prospects for low-mass axion haloscopes as GW detectors

Thank you!

backup slides

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)

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

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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# of loops with length ℓ at time *t*

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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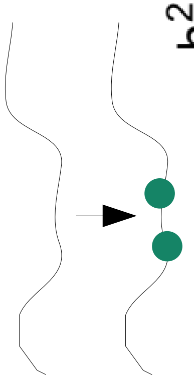
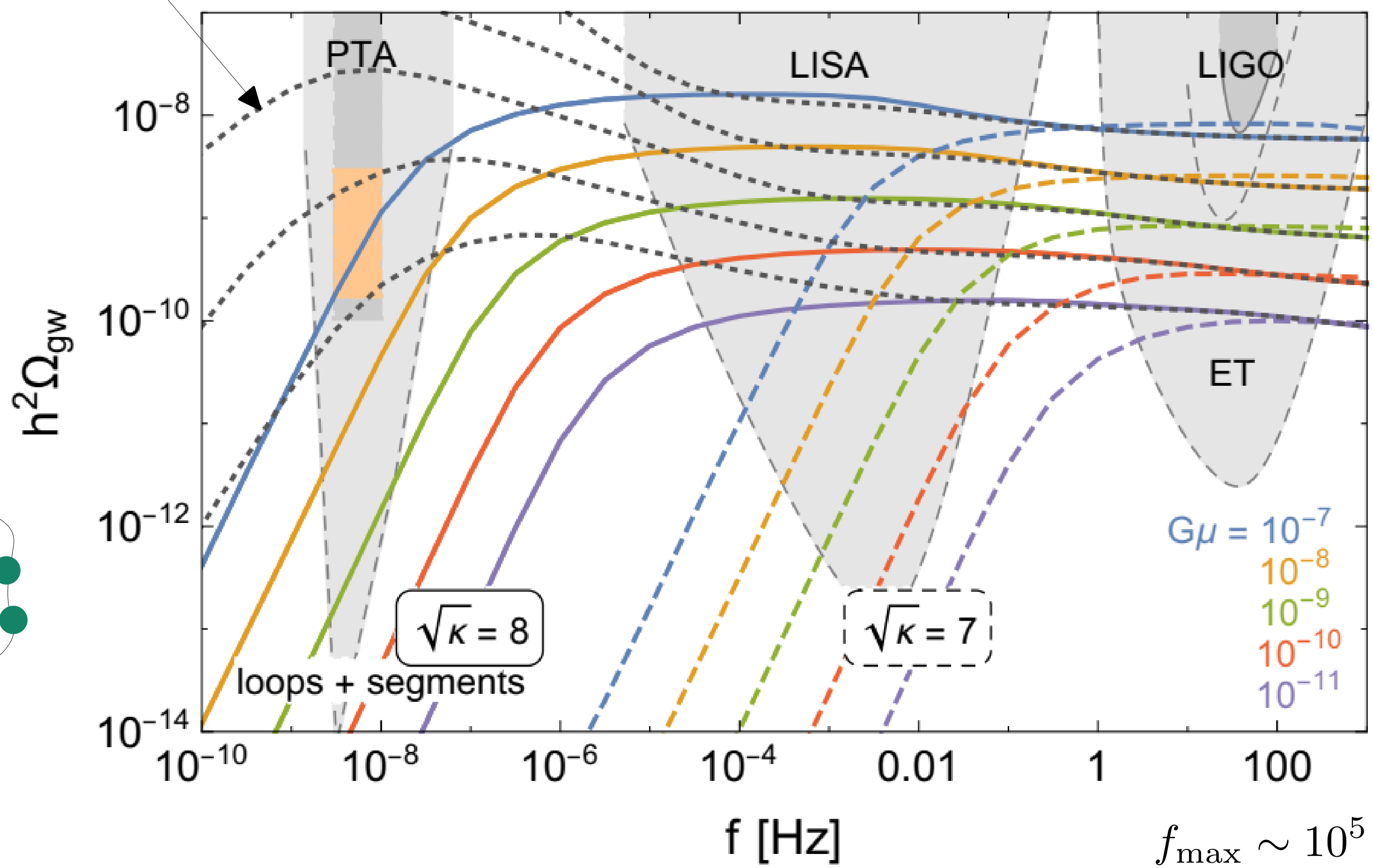
example: metastable cosmic strings

topologically stable cosmic strings
(highly constrained by PTA)

Buchmüller, VD, Schmitz `21

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





$SO(10)$
↓
$G_{\rm SM} \times U(1)$
↓
$G_{\rm SM}$

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

$G\mu \sim (v_{U(1)}/M_P)^2$

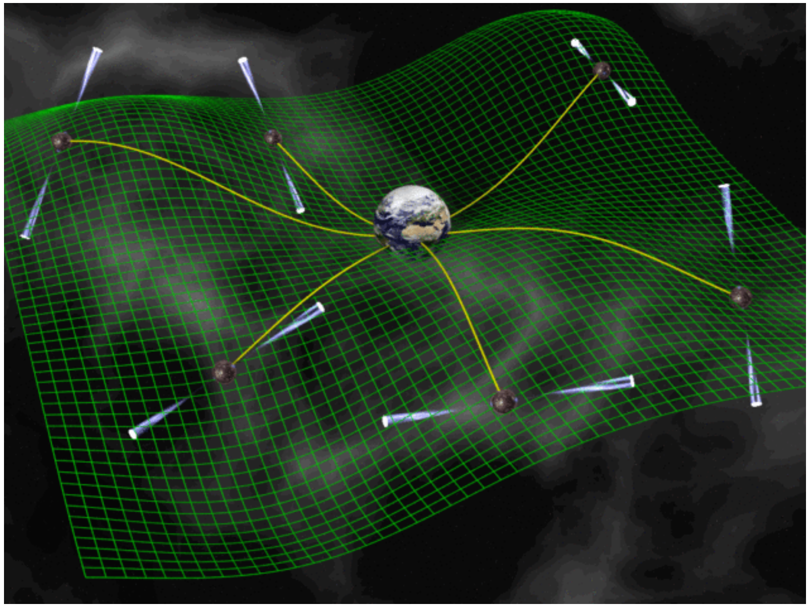
$f_{\rm max} \sim 10^5 \text{ MHz} \, (T_*/10^{12} \text{ GeV})$

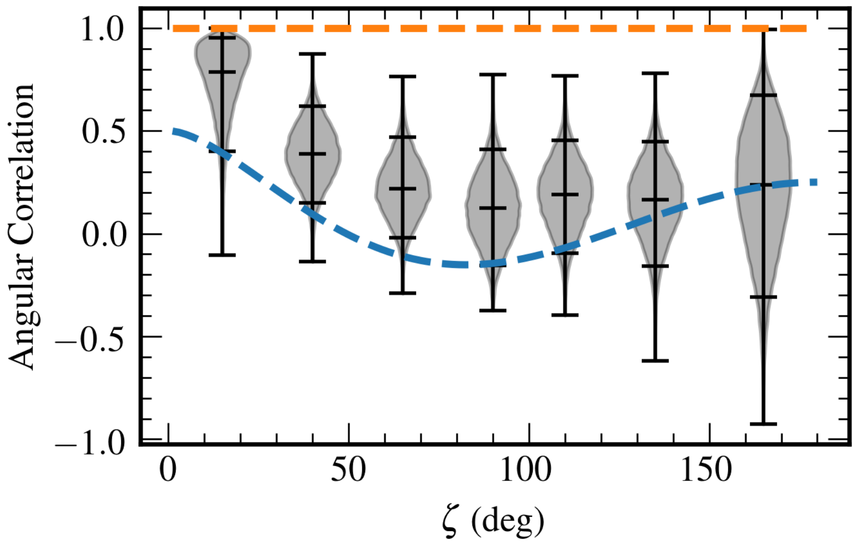
GUT-scale U(1) phase transition can be tested with GWs

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."



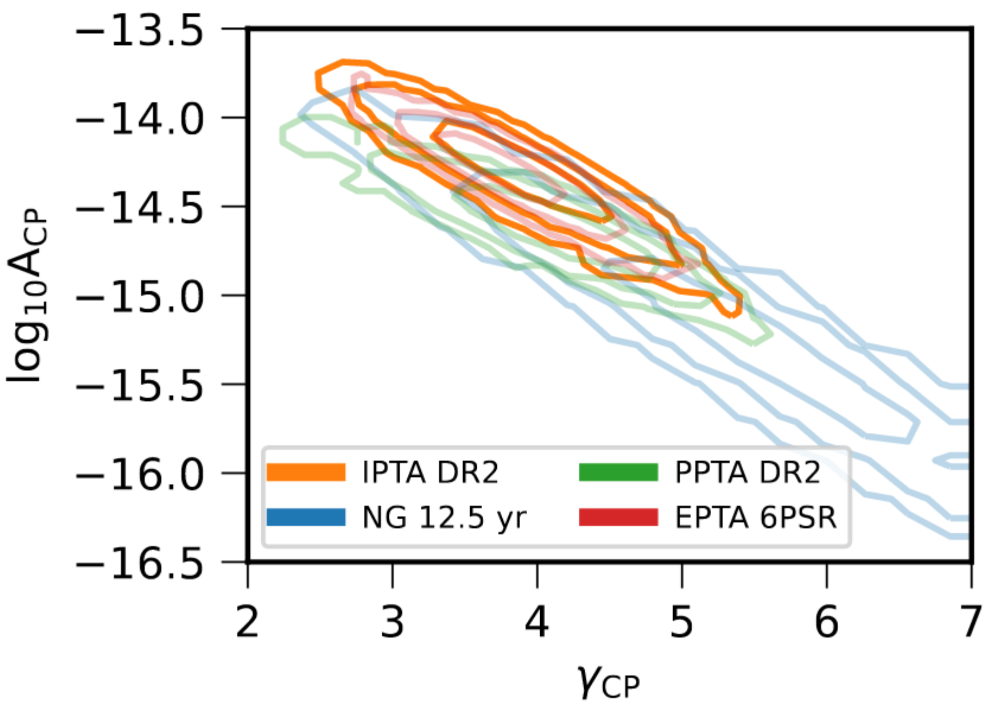


NANOGrav collaboration `20

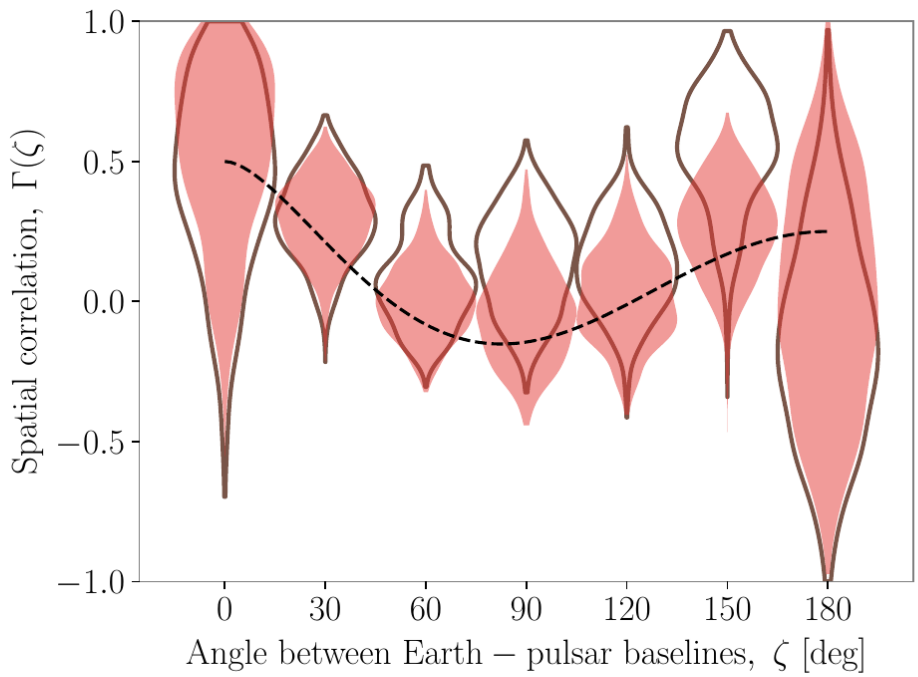
„However, we find no statistically significant evidence that this process has quadrupolar spatial correlations, which we would consider necessary to claim a GWB detection consistent with General Relativity."

PPTA, EPTA and IPTA results

IPTA `22, 2201.03980



PPTA `21, 2107.12112

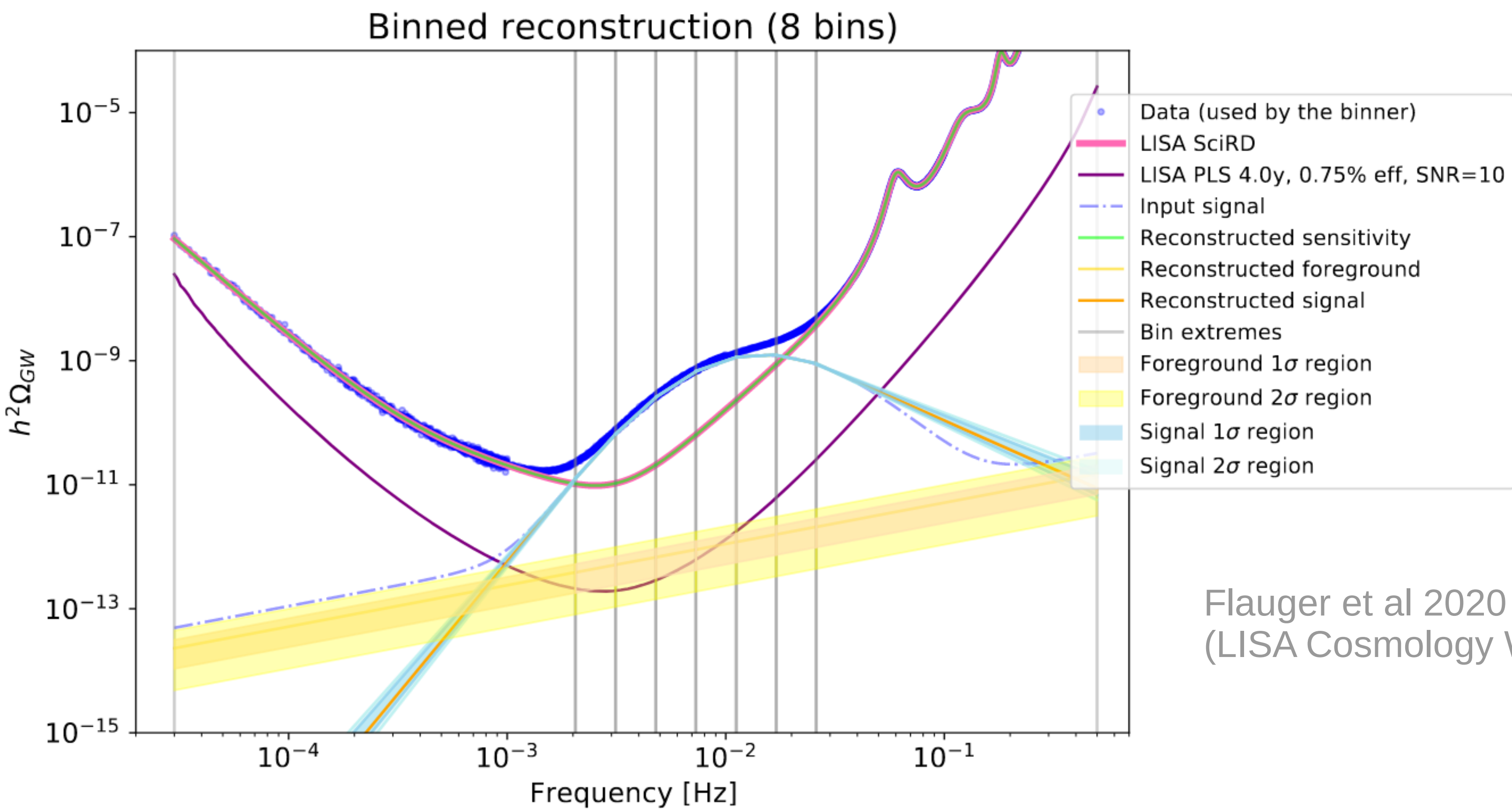


amplitude and spectral tilt
compatitive with NANOGrav

no significant detection of
quandropolar spatial correlation

Maybe. Stay tuned for more data!

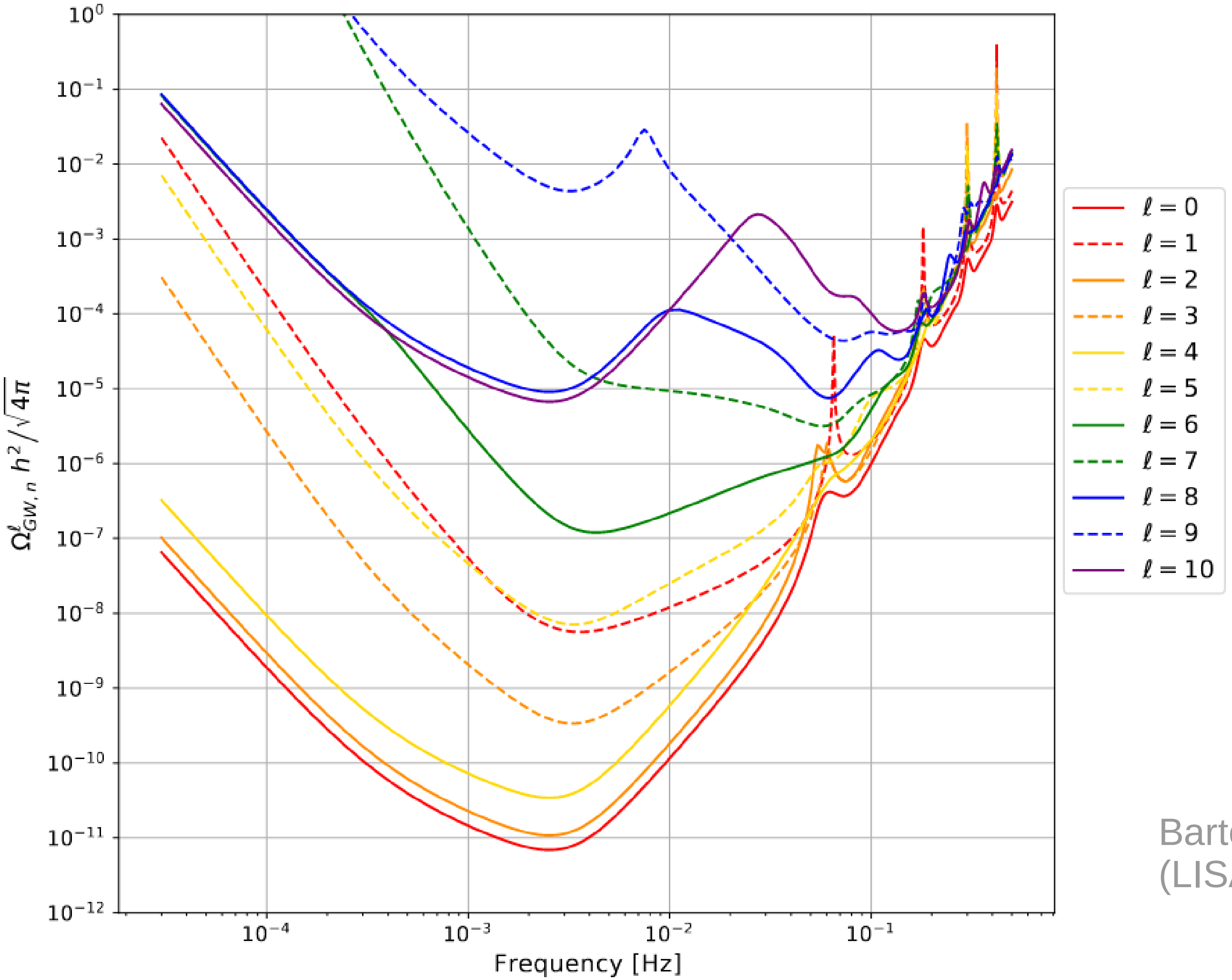
decoding the SGWB: spectrum



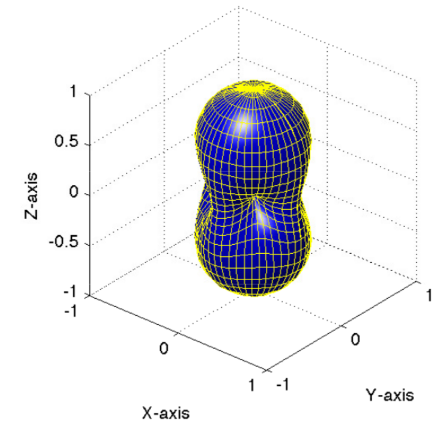
Flauger et al 2020
(LISA Cosmology WG)

Challenge: simultaneous reconstruction of noise, 'foreground' and 'signal'

decoding the SGWB : anisotropies



LISA sensitivity to different multipoles

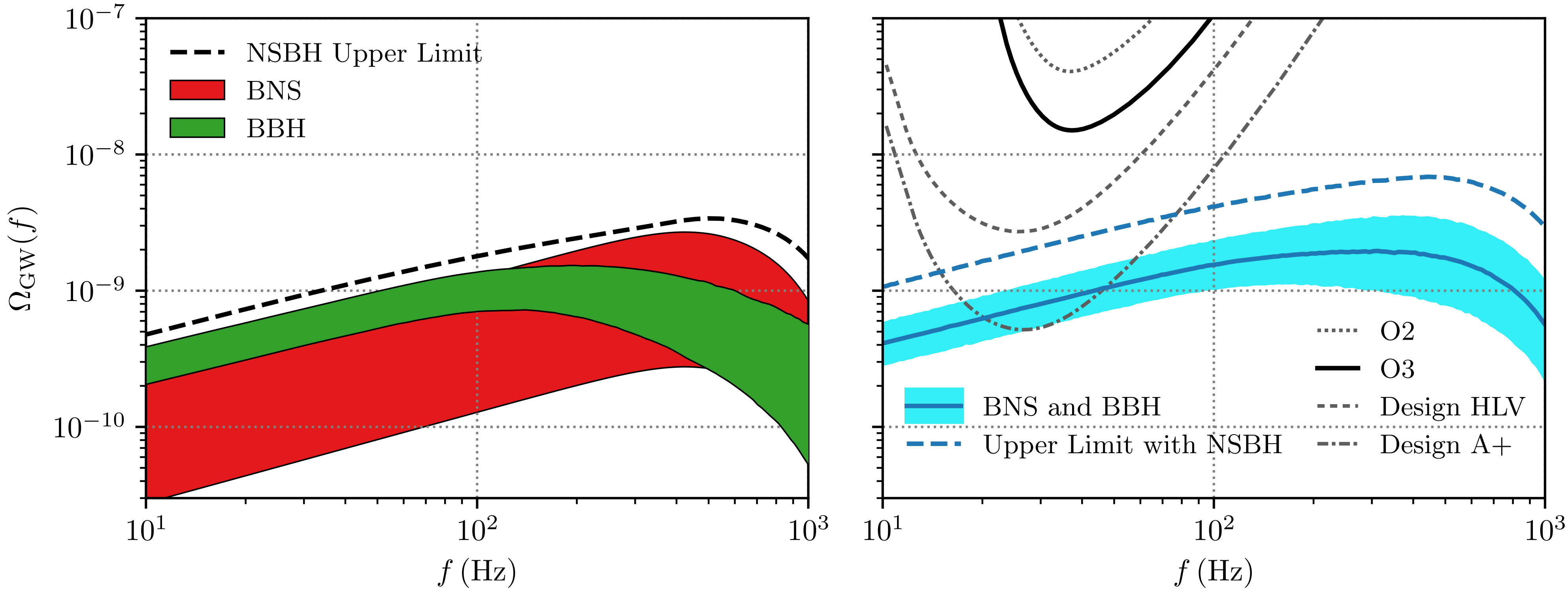


limited angular resolution due to broad antenna pattern of GW interferometers

Bartolo et al 2022
(LISA Cosmology WG)

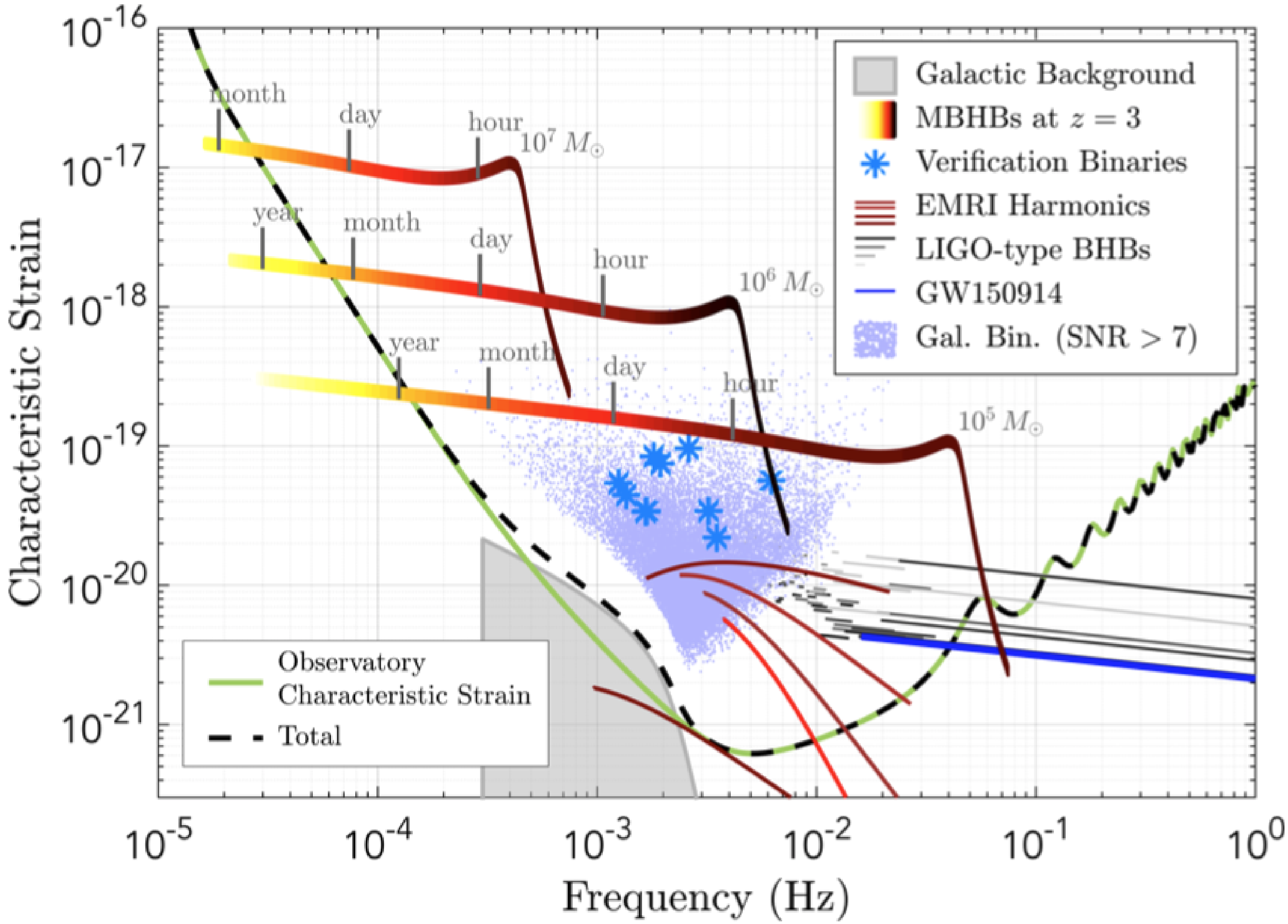
LIGO stochastic backgrounds

LIGO VIRGO O3 run, 2021



- possibly within reach of advanced LIGO / VIRGO / KAGRA
- not an intrinsically stochastic background: ET / Cosmic Explorer can resolve all BBHs in the Universe

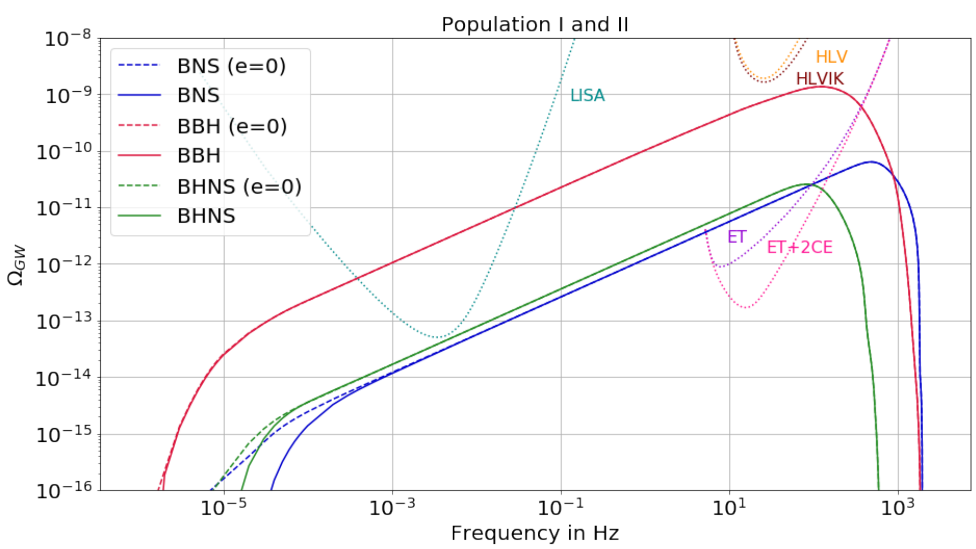
LISA and backgrounds

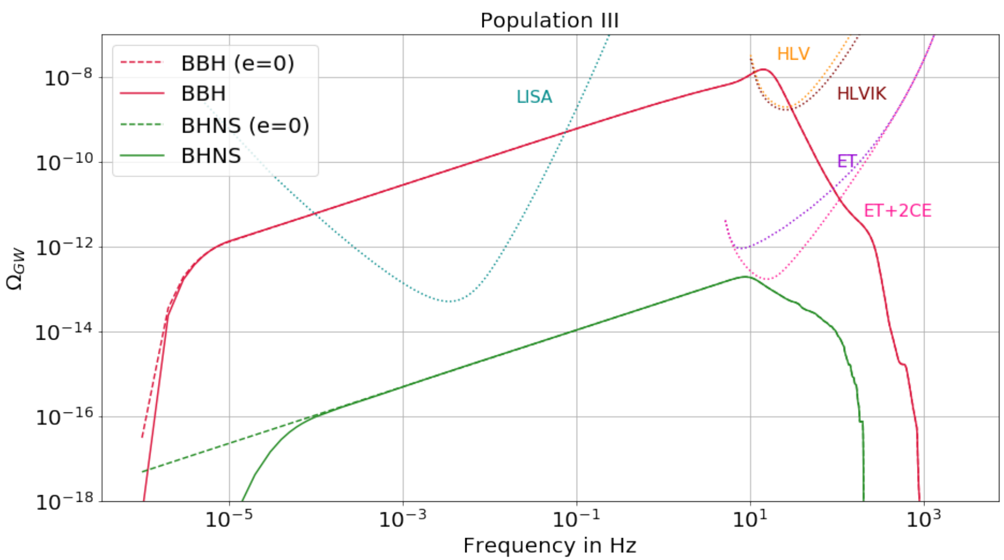


LISA mission proposal `17

LISA stochastic backgrounds

Périgois, Belczynski, Bulik, Regimbeau `21





- merger rate will be well measured by LIGO/VIRGO/KAGRA
- thousands of resolved BHBs, millions of unresolved BHBs [Sesana `16]
- overlapping signals → confusion noise. Isotropic? Gaussian? ...

[a note on frames]

GR is invariant under coordinate transformations, but linearized GR is not

Transverse traceless (TT) gauge

$$h_{ij}^{TT} = (h^+ e_{ij}^+(\phi_h, \theta_h) + h^\times e_{ij}^\times(\phi_h, \theta_h))e^{i(\mathbf{k}\cdot\mathbf{r} - \omega \mathbf{t})}$$

- coordinates fixed by freely falling test masses
- GW takes very simple form $h_{0\mu} = 0, h_i^i = 0, \partial_j h^{ij} = 0$
- rigid body seems to 'oscillate' in presence of GW

Proper detector frame

- coordinates fixed by laboratory frame
- GW takes a more involved form
- description of experimental setup and observables is straightforward

$$h_{00} = \omega^2 F(\mathbf{k}\cdot\mathbf{r})\,\mathbf{b}\cdot\mathbf{r}, \qquad b_j \equiv r_i h_{ij}^{\mathrm{TT}}\big|_{\mathbf{r}=0},$$
$$h_{0i} = \frac{1}{2}\omega^2\left[F(\mathbf{k}\cdot\mathbf{r}) - iF'(\mathbf{k}\cdot\mathbf{r})\right]\left(\hat{\mathbf{k}}\cdot\mathbf{r}\; b_i - \mathbf{b}\cdot\mathbf{r}\;\hat{k}_i\right),$$
$$h_{ij} = -i\omega^2 F'(\mathbf{k}\cdot\mathbf{r})\left(|\mathbf{r}|^2\, h_{ij}^{\mathrm{TT}}\big|_{\mathbf{r}=0} + \mathbf{b}\cdot\mathbf{r}\,\delta_{ij} - b_i r_j - b_j r_i\right),$$

VD, Garcia-Cely, Rodd `22
s.a. Berlin et al `21

we will consider a plane wave plane wave in the proper detector frame