

III Cosmological sources / Probing BSM models

Recap. • SGWB: superposition of GWs with different \vec{k} ,

astrophysical + cosmological origin

$$\bullet S_{\text{gw}} = f_{00} = \frac{1}{32\pi G} \langle h_\lambda(x, T_0) \dot{h}_\lambda(x, T_0) \rangle$$

$$= \frac{1}{32\pi^3 G} \int k^2 dk \sum_\lambda P_\lambda(k) \frac{a^2(T_*)}{a(T_0)} \quad a(T_0) = 1$$

$$\rightarrow S_{\text{gw}} = \frac{1}{S_c} \frac{\partial S_{\text{gw}}}{\partial \ln k}$$

Quiz:
/ Tr ranges of
different experiments

1) characteristic frequencies of relic GWs

redshift: $f_0 = f_* \frac{a(T_*)}{a(T_0)}$, $f_* = (\mathcal{E}_* H_*^{-1})^{-1}$

$\overset{\uparrow}{\text{observed}}$ $\overset{\uparrow}{\text{emitted}}$ $\overset{\uparrow}{\in 1}$, size of source
in units of H_*^{-1}

radiation era: $H_*^2 = \frac{\pi^2 g_* T_*^4}{90 m_p^4}$, $t \sim 1/T^2$, $g_* \sim 100$

$$\hookrightarrow f_0 \approx 10^{-8} \mathcal{E}_*^{-1} \left(\frac{T_*}{\text{GeV}} \right) \text{ Hz}$$

$$t_* \approx 10^{-22} \mathcal{E}_*^{-1} \left(\frac{1 \text{ Hz}}{f_0} \right)^2$$

e.g.	$f_0 [\text{Hz}]$	$T_* [\text{GeV}]$
$\mathcal{E}_* = 1$	10^{-8}	0.1
PTA	10^{-8}	0.1
LISA	10^{-2}	10^5
LIGO	10^2	10^9

→ in principle, access to very high energy scales!

but: $1/a^2$ suppression for high-redshift sources

note: inflation: T_* marks re-entry, not inflation scale

2) Constraints from BBN & CMB

Quiz: max fraction $\Omega_{\text{gw}} / \Omega_{\text{rad}}$ today?

"extra radiation":

after e^- decoupling: $S_{\text{rad}} = \frac{\pi^2}{30} \left(2 + \frac{7}{4} N_{\text{eff}} \left(\frac{4}{11} \right)^{4/3} \right) T^4$

SM: $N_{\text{eff}}^{\text{SM}} = 3.046$

$$\rightarrow \frac{S_{\text{gw}}(T)}{S_{\text{rad}}(T)} < \frac{S_{\text{rad}}^{\text{obs}}(T) - S_{\text{rad}}^{\text{SM}}(T)}{S_{\text{rad}}(T)} \leq \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \Delta N_{\text{eff}}$$

at BBN, CMB decoupling $\Delta N_{\text{eff}} \leq 0.2$ $\rightarrow \frac{S_{\text{gw}}}{S_{\text{rad}}} \Big|_{T < T_{\text{BBN}} / T_{\text{CMB}}} \sim 10\%$

today, $\Omega_{\text{rad}} = \frac{S_{\text{rad}}}{S_{\text{tot}}} \sim 10^{-5}$ $\Rightarrow \underline{S_{\text{gw}} \leq \Omega_{\text{rad}} \Delta N_{\text{eff}} S_{\text{tot}}}$

$\Rightarrow \underline{\Omega_{\text{gw}} \lesssim 10^{-6}}$
broad spectra

for Gws inside horizon
cut $T_{\text{BBN}} / T_{\text{CMB}}$

\rightarrow This already constrains some early Universe models.

3) Cosmological sources

Quiz: what will be the first SGWB we will see?

A) Inflation

vacuum fluctuations of single-field slow-roll inflation:

$$r < 0.1 \rightarrow \Omega_{\text{gw}}(t) \sim \text{const}, < 10^{-15} \rightarrow \text{too small}$$

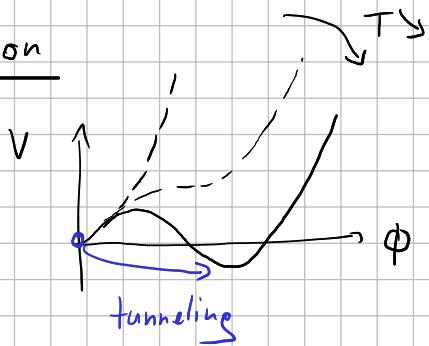
but: blue-tilted spectrum
can obey CMB bound while
giving large signals at fLISA, fLIGO

[LISA: $\sim 10^{-13}$]
[LIGO: $\sim 10^{-8}$]

e.g. axion inflation

B) 1st order phase transition

- bubble collisions
- MHD turbulence
- sound waves



$$f_{\text{peak}} \sim 10^{-3} \text{ Hz} \quad \frac{T}{100 \text{ GeV}}$$

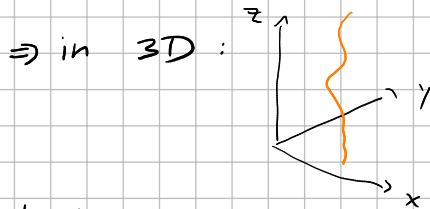
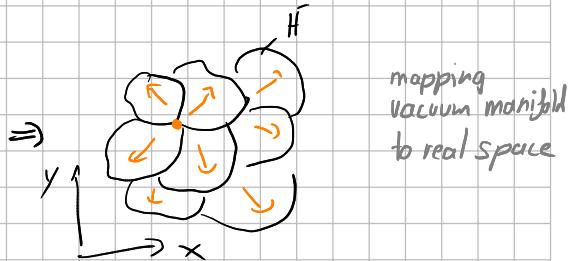
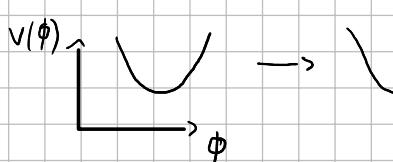
→ LISA will probe EW PT

$$\mathcal{R}_{\text{GW}} \approx 10^{-6} \quad \text{depending on strength of PT}$$

// Break

C) Cosmic strings

consider $U(1)$ phase transition



- one-dimensional topological defect

• energy $\mu \sim v^2$ per unit length

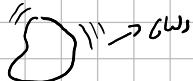
- more generally, arise iff $G \rightarrow H$ with $T_h(G/H) \neq 1$

evolution of CS network

- (self-) intersection generates loops:



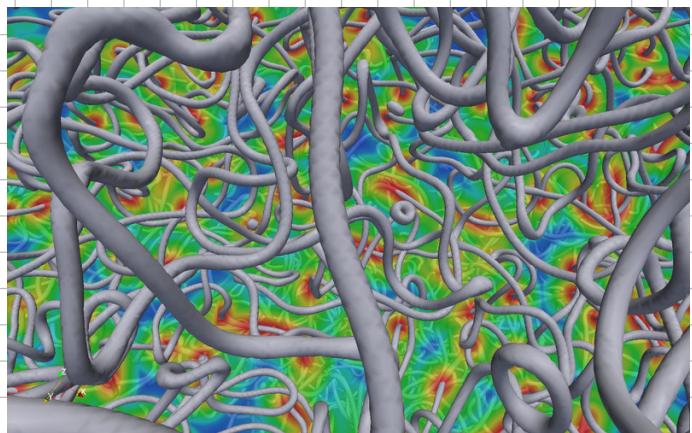
- emission of particles & gravitation waves



→ scaling regime:
(fix point of this evolution)

$$\frac{\sigma_{\text{CS}}}{S_{\text{tot}}} \approx \text{const}$$

with $O(1)$ CS
per Hubble volume



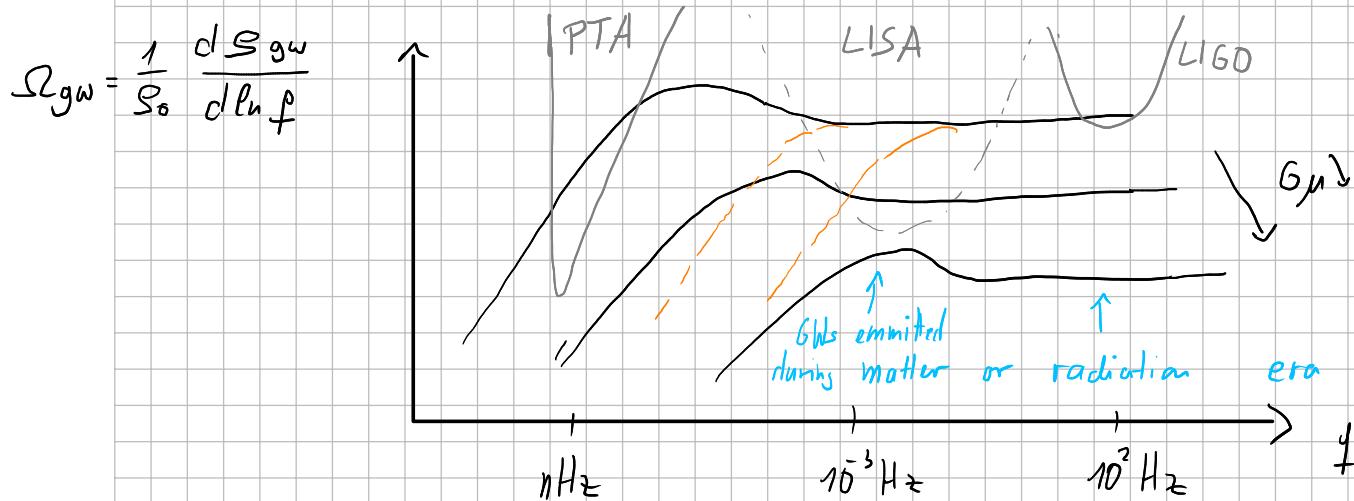
Simulation, University of Geneva

GW signal:

$$S_{gw}(t, f) = \sum_{n=1}^{\infty} C_n(t) P_{gw,n}$$

harmonic \rightarrow # of loops emitting GWs observed at frequency f at time t \downarrow $\ell = 2n/(f(1+z))$
 power spectrum of single loop \leftarrow # of loops of length ℓ at time t
 $C_n = \frac{2n}{\ell^2} \int dz \frac{N(\ell(z), t(z))}{H(z)(1+z)^6}$ \leftarrow cosmological history

$N(\ell(z), t(z))$:- analytically, assuming loops sourced with $\ell H = \alpha = \text{const.}$
 - numerically, e.g., Blanco-Pillado, Olum, Shlaer



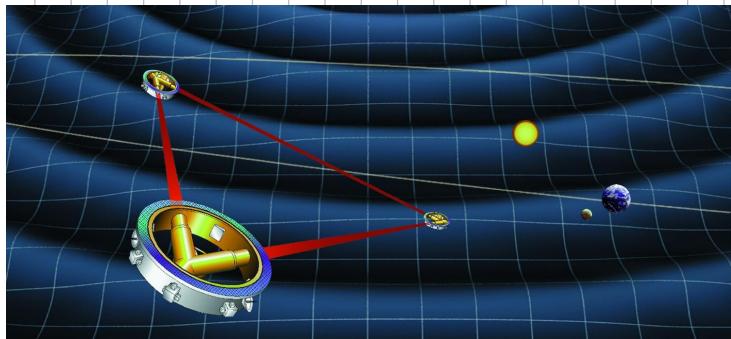
\Rightarrow Large symmetry breaking scales have been excluded

$$[\text{PTA: } G_\mu \lesssim 10^{-10} \quad \sim v \lesssim 10^{14} \text{ GeV}]$$

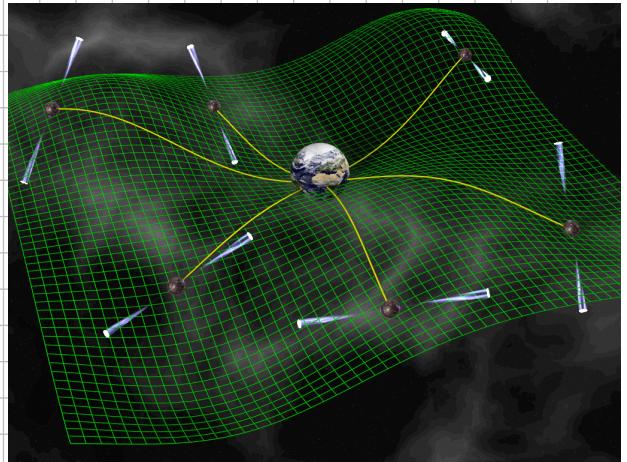
\Rightarrow complementary to collider searches,
 probe of GUT physics.

\Rightarrow recent work: in some GUT models, strings can decay via monopole pair production
 \rightarrow suppression of Ω_{gw} at low f

GW probes



LISA



PTA



LIGO