Constraining Stochastic Gravitational Wave Backgrounds with Pulsar Timing Array
-
The case of phase transitions

CEA

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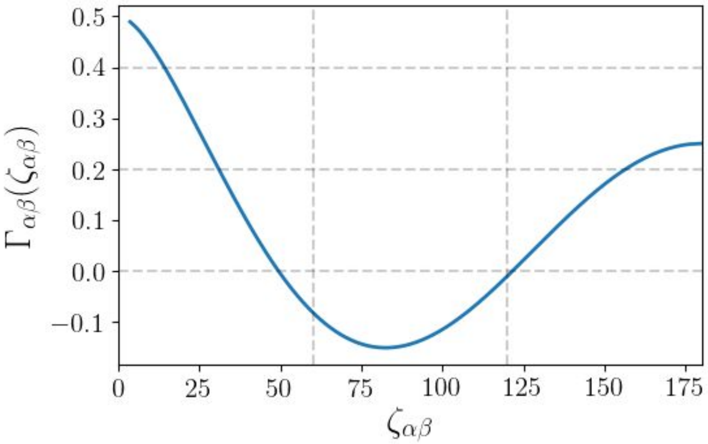
The GWB properties in PTA

- For an isotropic, unpolarized and stationary SGWB,

$$\langle \delta t_\alpha(f)^* \delta t_\beta(f') \rangle = \frac{1}{2}\Gamma_{\alpha\beta} S_r(f) \delta(f - f')$$

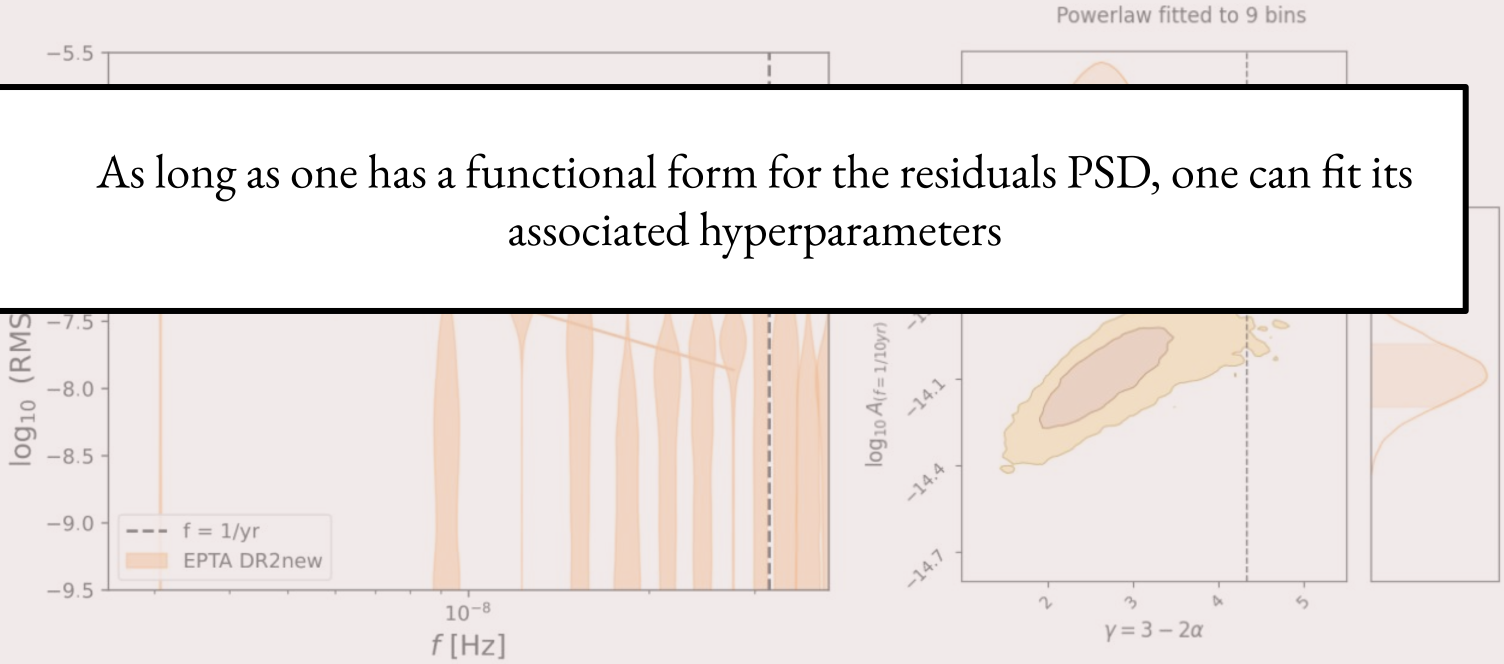
- This is characterized by both
  - Overlap reduction function $\Gamma_{\alpha\beta}$
  - Power spectral density $S_r(f)$

The Hellings&Downs ORF



The GWB inference in PTA

- The PSD can be parameterised by hyper-parameters that can then be fitted to the data



As long as one has a functional form for the residuals PSD, one can fit its associated hyperparameters

The expected GWBs in the PTA band

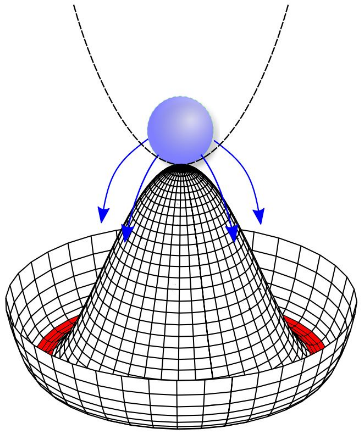
Astrophysical Sources

- GWB produced by a population of SMBHB
- Individual SMBH Binary Source
- ...

Cosmological Sources

- Phase Transitions
- Inflation
- Topological defects
- ...

Phase Transitions - The GW emission mechanisms



credits: Pierre Auclair

Direct emission

First Order Phase Transition → nucleation of true vacuum region

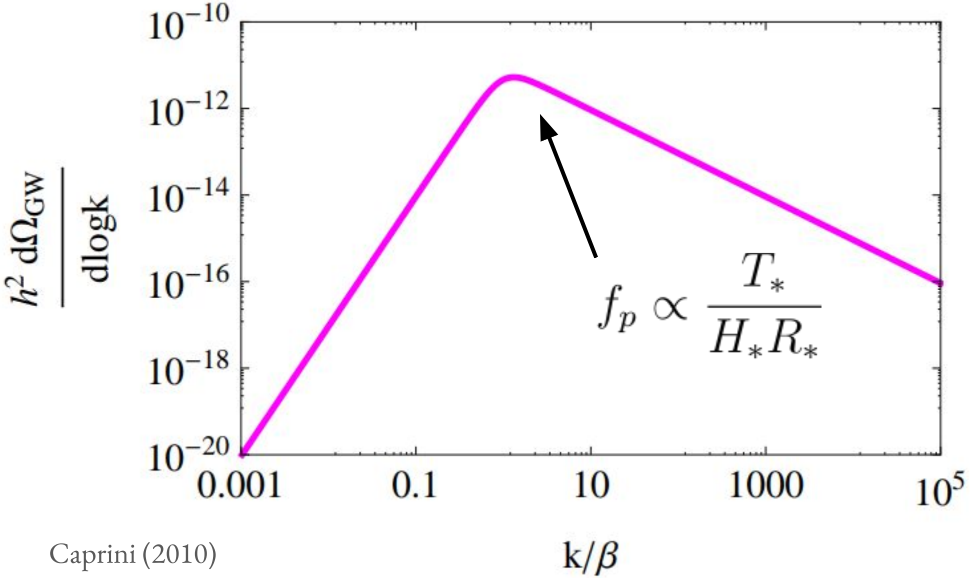
- Bubble collisions
- Sound waves
- Turbulence of the plasma

Indirect emission

Formation of a network of topological defects

- Cosmic strings
- Domain walls

The GWB from phase transitions in brief



Caprini (2010)

$$\Omega_b(f) = \mathcal{D}\,\tilde{\Omega}_b\left(\frac{\alpha_*}{1+\alpha_*}\right)^2 (H_*R_*)^2 \mathcal{S}(f/f_b)$$

$$\Omega_s(f) = \mathcal{D}\,\tilde{\Omega}_s \Upsilon(\tau_{sw})\left(\frac{\kappa_s\,\alpha_*}{1+\alpha_*}\right)^2 (H_*R_*)\mathcal{S}(f/f_s).$$

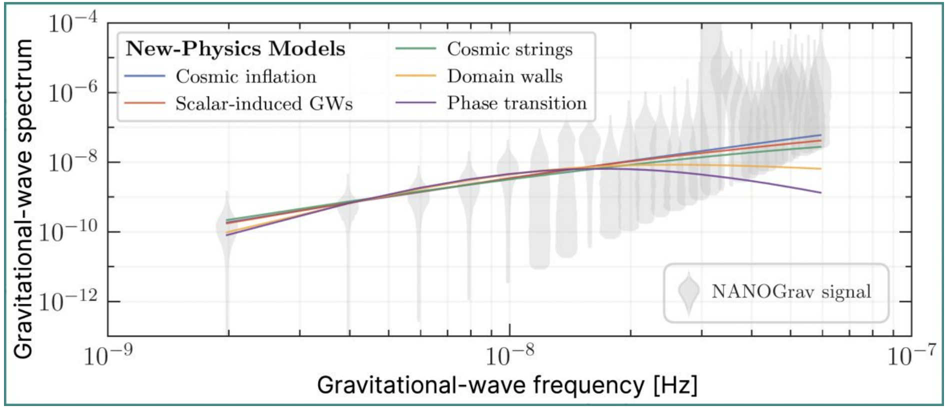
T_* Percolation temperature of the phase transition

α_* Strength of the transition

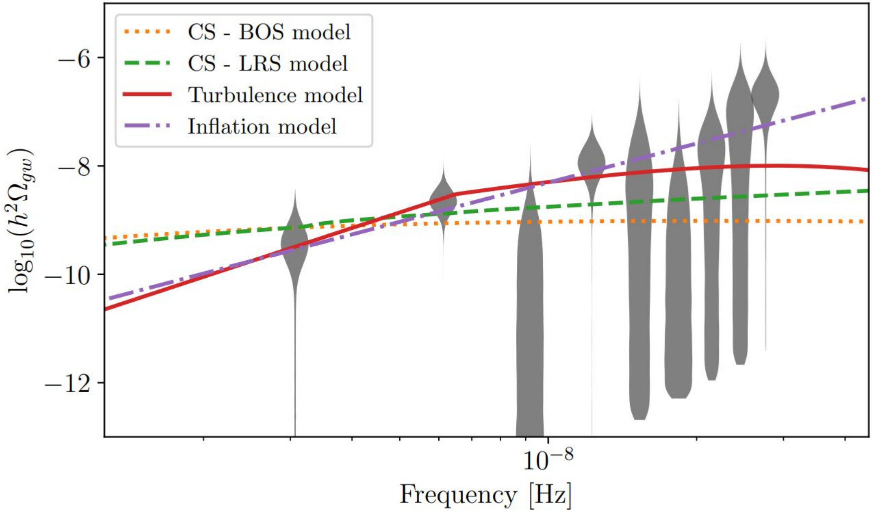
H_*R_* Average bubble separation at nucleation

→ The left and ride side slopes can either be estimated theoretically or derived using simulations

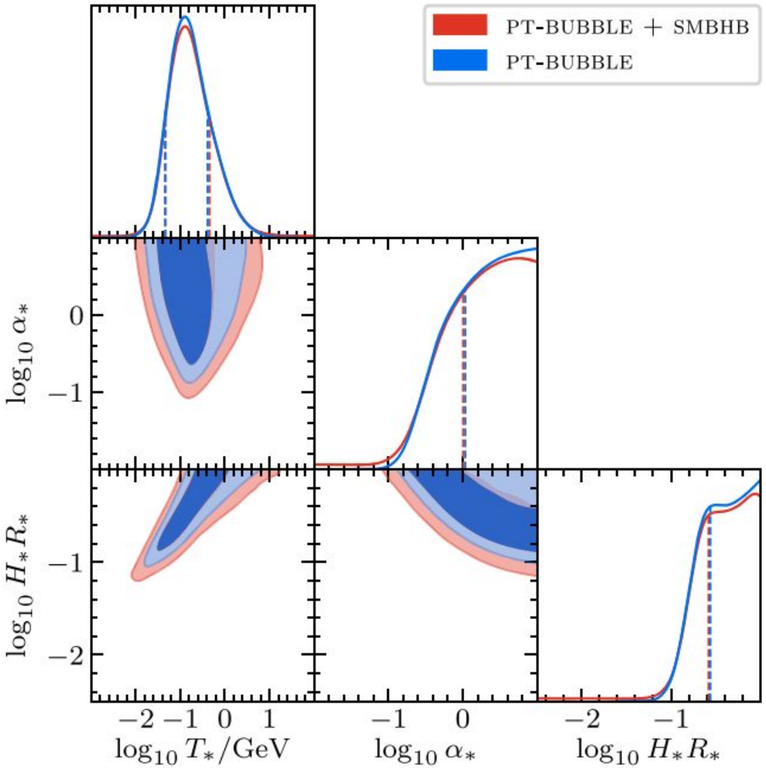
Afzal et al., 2023, The NANOGrav 15-year Data Set:
Search for Signals from New Physics.

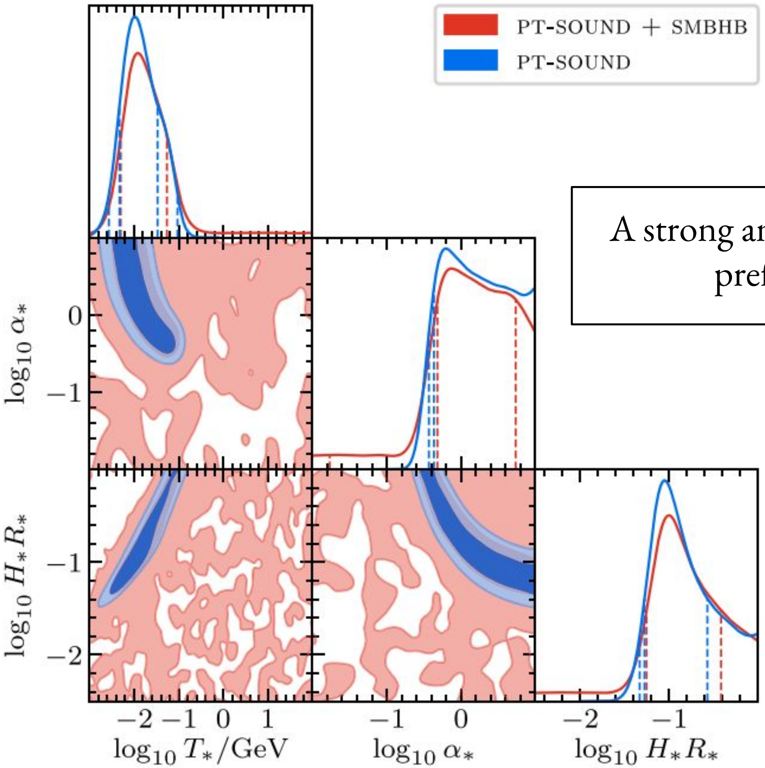


Antoniadis et al., 2023, The second data release from the EPTA
IV. Implications for massive black holes, dark matter, and the early Universe



Results from NANOGrav 15yr dataset



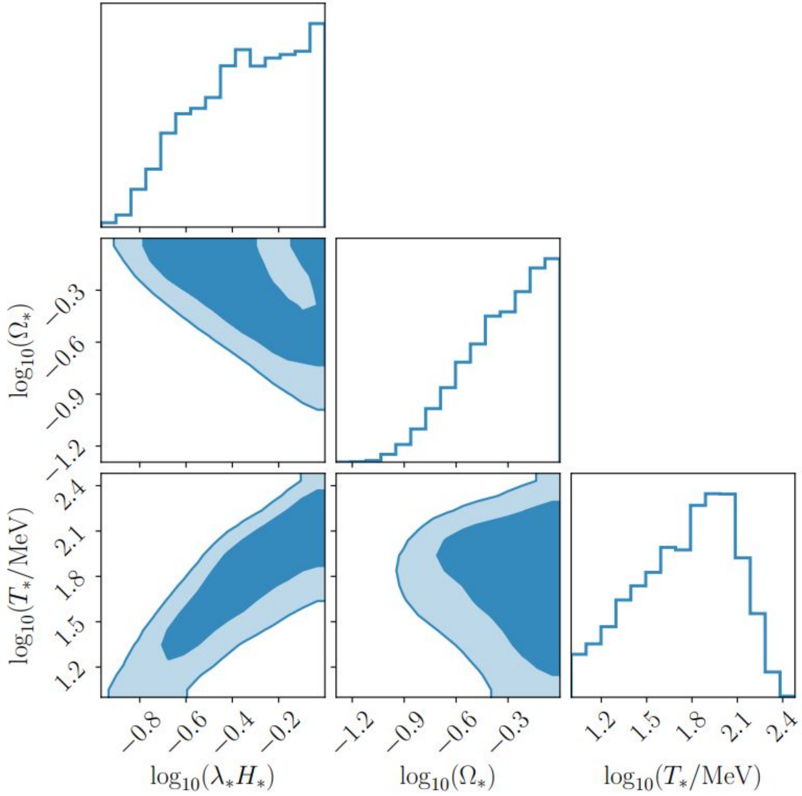


A strong and slow PT is preferred

→ Compatible with BSM models in which the chiral-symmetry-breaking phase transition in quantum chromodynamics (QCD) is a strong first-order phase transition [Li et al. 2021; Neronov et al. 2021]

$$\Omega_{\rm GW}(f) = 3\,\mathcal{A}\,\Omega_*^2\,(\lambda_*\mathcal{H}_*)^2 F_{\rm GW,0}\,S_{\rm turb}(\lambda_* f)$$

Turbulence after QCD phase transition



[EPTA, IV, 2023]

λ_* Characteristic scale of the turbulence

Ω_* Ratio of the turbulent energy density to the radiation one

T_* Temperature scale of the phase transition

→ The preferred set of parameters require a lot of turbulent energy density but can fit also fit the data with smaller values of Ω_*

See Roper Pol et al [2201.05630] for model description

Beyond the spectral inference

- The consistency with the spectral properties of the observed signal is not our only way to infer the origin of the GW signal

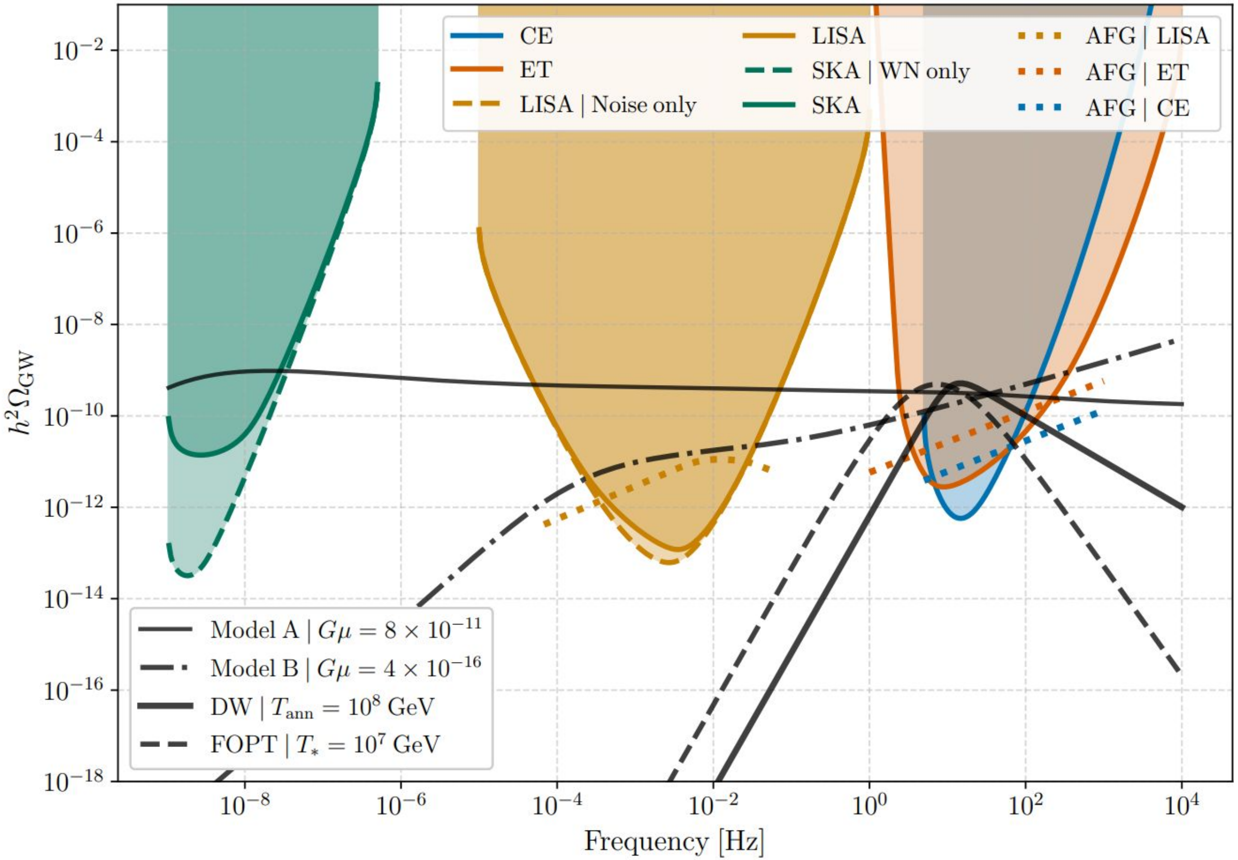
- Indeed, astrophysical and cosmological signals are expected to have different properties

  1. Anisotropy

  2. Non-stationarity

- Those properties are under current investigations by the different PTAs

The synergy of GW detectors



Summary

- The common correlated red noise seen by the PTA collaborations open a new window on the early Universe via GW observation

- The spectral properties of the common signal can be compared to theoretical expectations to constrain their parameters

- Cosmological phase transitions are a possible source of GWB in the PTA band

- The data are consistent with a strong and slow first order PT happening around 10 to 100 MeV

- Further data but also study beyond the spectral properties are needed to identify the origin of this signal

Backup slides

Primordial GWs | SGWB from inflation

→ very simple modelisation : **power law** to link the large CMB scales to small PTA scales

Tensor to scalar ratio

Tensor spectral index

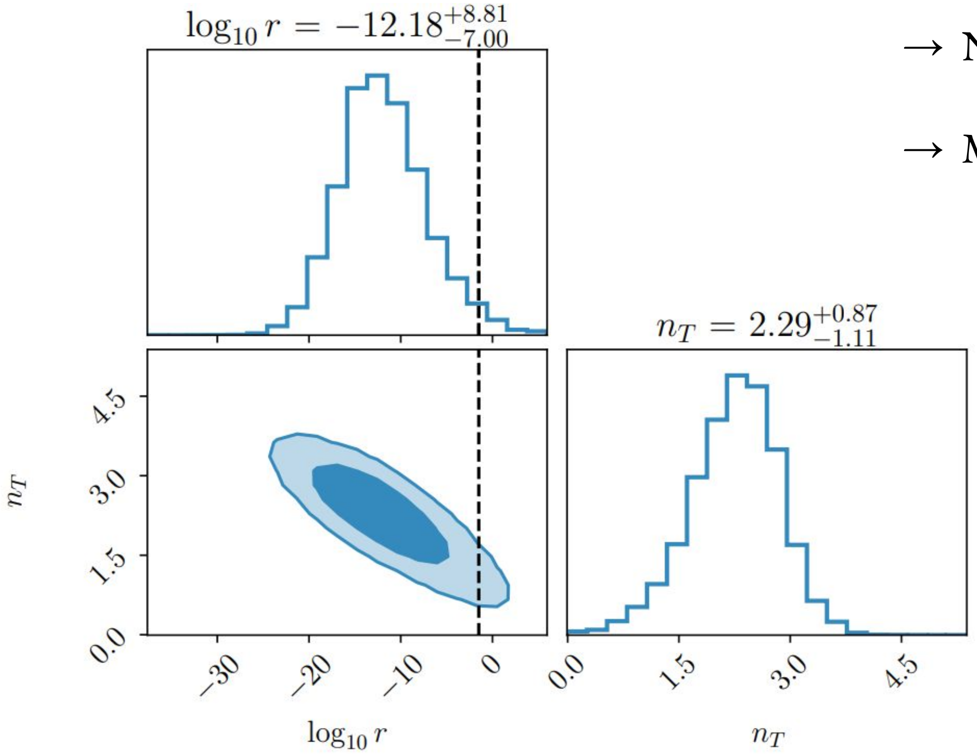
$$\Omega_{\rm GW}(f) \approx 1.5 \times 10^{-16} \left(\frac{r}{0.032}\right)\left(\frac{f}{f_*}\right)^{n_T}$$

CMB scale (~ 0.05 Mpc^{-1})

→ 2 model parameters, for **slow roll** inflation: $n_T \simeq 0$

→ Constraints from CMB (Planck collaboration) : $r < 0.076$ and $-0.55 < n_T < 2.54$ at 95%

Explaining all the PTA CRN with inflation ?



→ Not compatible with classic slow roll inflation

→ Must be a blue tilted spectrum

Obtaining upper limit including simple circular SMBHB background

$$n_T = a \log_{10}\left(\frac{r}{0.032}\right) + b$$

$$a = -0.16, b = 0.70$$

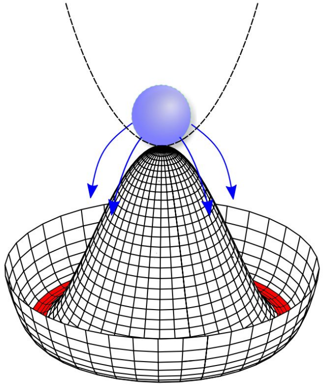
How cosmic strings produce GWs ?

Some **assumptions** used

→ stable cosmic strings associated to a local symmetry

→ intercommutation probability of 1

→ GW emission is dominant (Nambu-Goto strings)

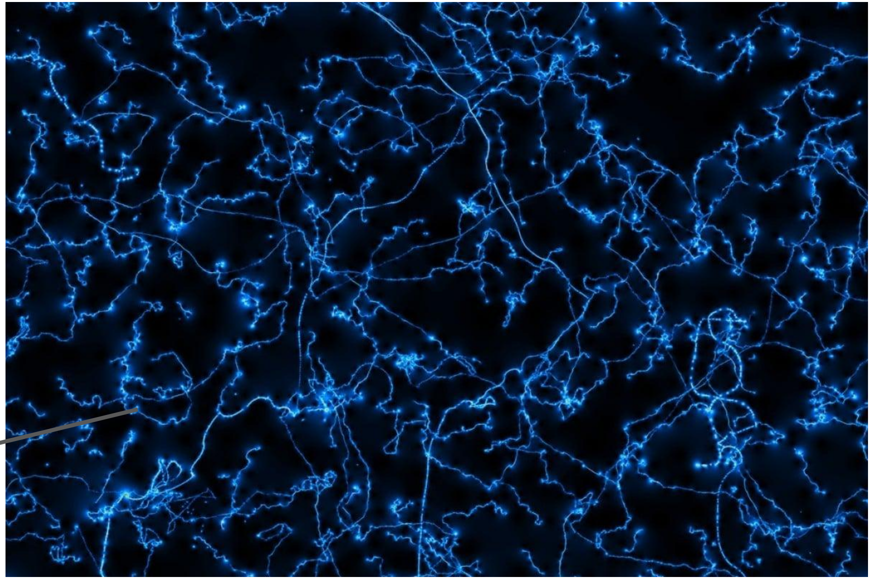


credits: Pierre Auclair

spontaneous symmetry breaking

→

at $\eta \propto \sqrt{G\mu}$



credits: freeastroscience

→ Loops are produced and emit GWs via oscillation and burst emission (cusp, kink, kink-kink collision)

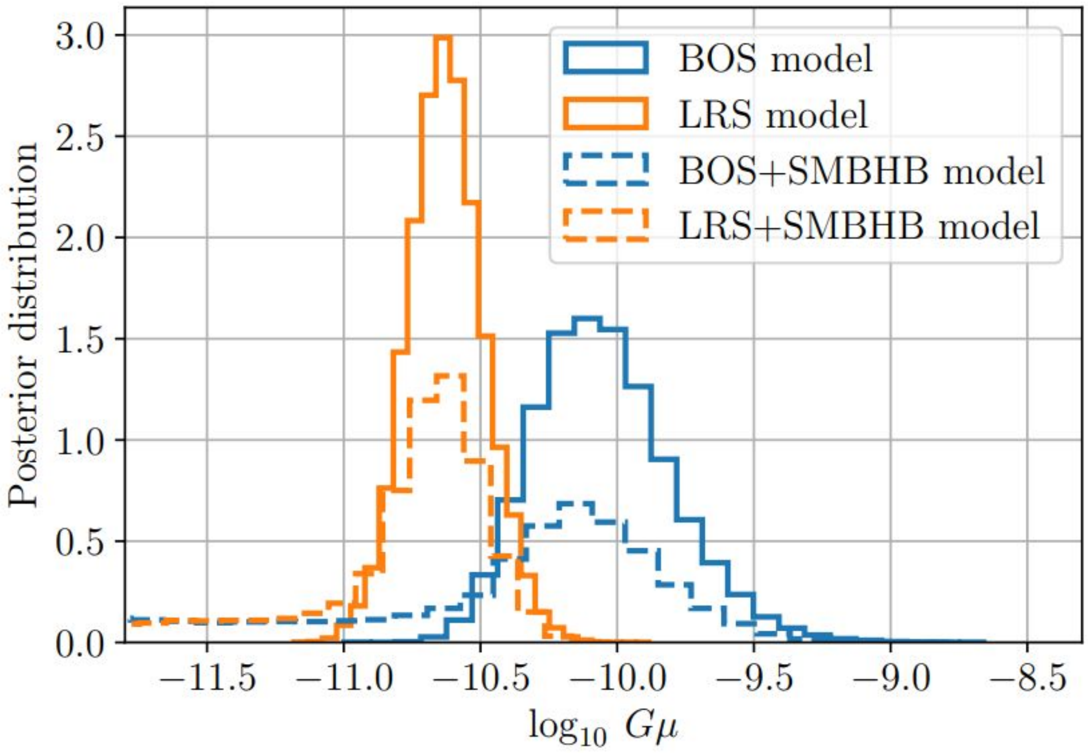
$$f_n = \frac{2n}{\ell}$$

Constraints for smooth loops network

$$\frac{\mathrm{d}\rho_{gw}}{\mathrm{d}f} = \frac{2G\mu^2}{f}\sum_b \frac{N_b\Gamma^{(b)}}{\zeta(q_b)} \times \sum_{n=1}^{+\infty}\int \frac{n^{1-q_b}\,\mathrm{d}z}{(1+z)^5 H(z)}\mathbf{n}\left[\frac{2n}{(1+z)f}, t(z)\right]$$

summing over cosmic time

Loop number density
(two models used: BOS, LRS)



→ 90% symmetric credible intervals

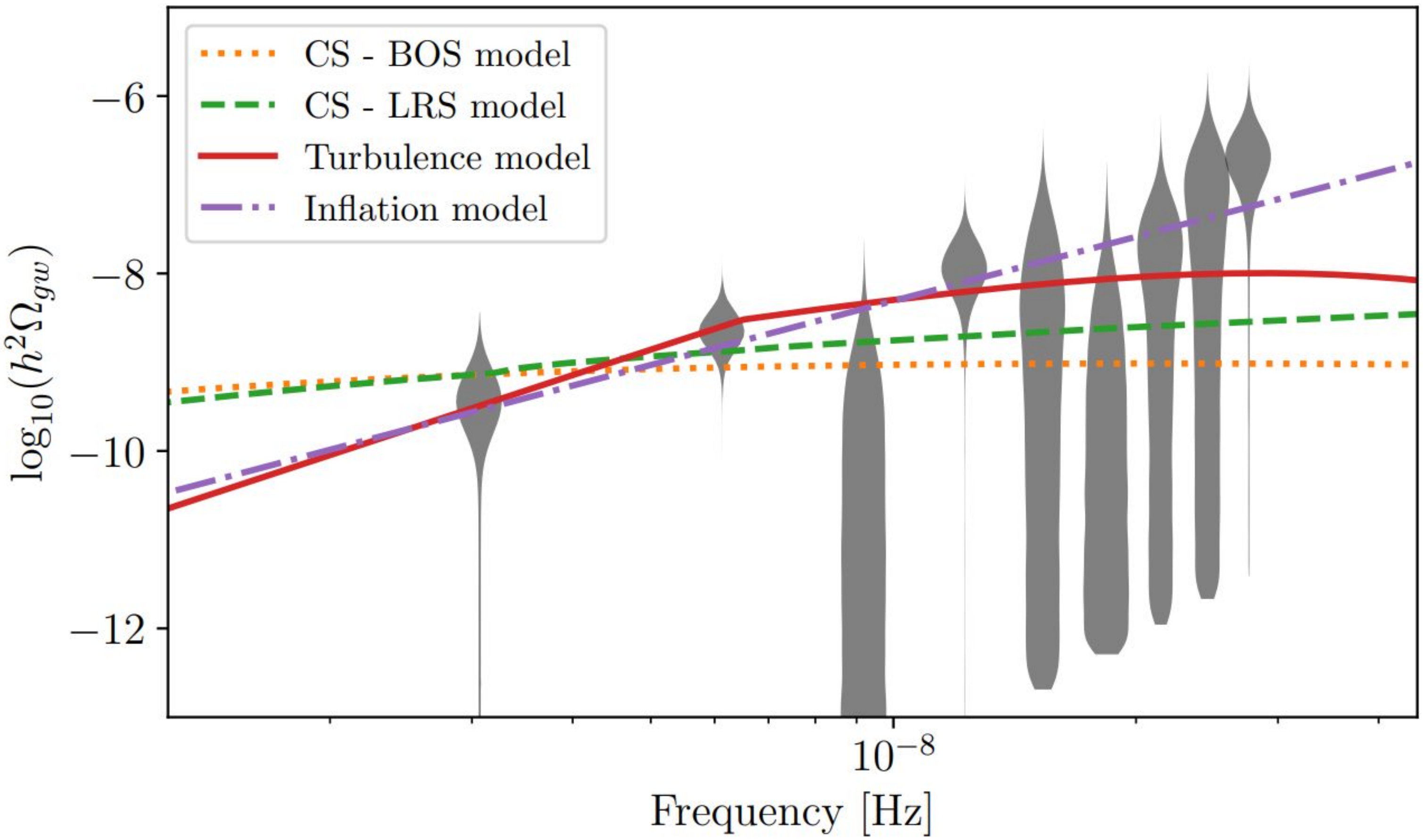
BOS model $\log_{10} G\mu = -10.06^{+0.48}_{-0.36}$

LRS model $\log_{10} G\mu = -10.63^{+0.24}_{-0.22}$

→ 95% confidence upper limit extracted from a **two component SGWB** analysis

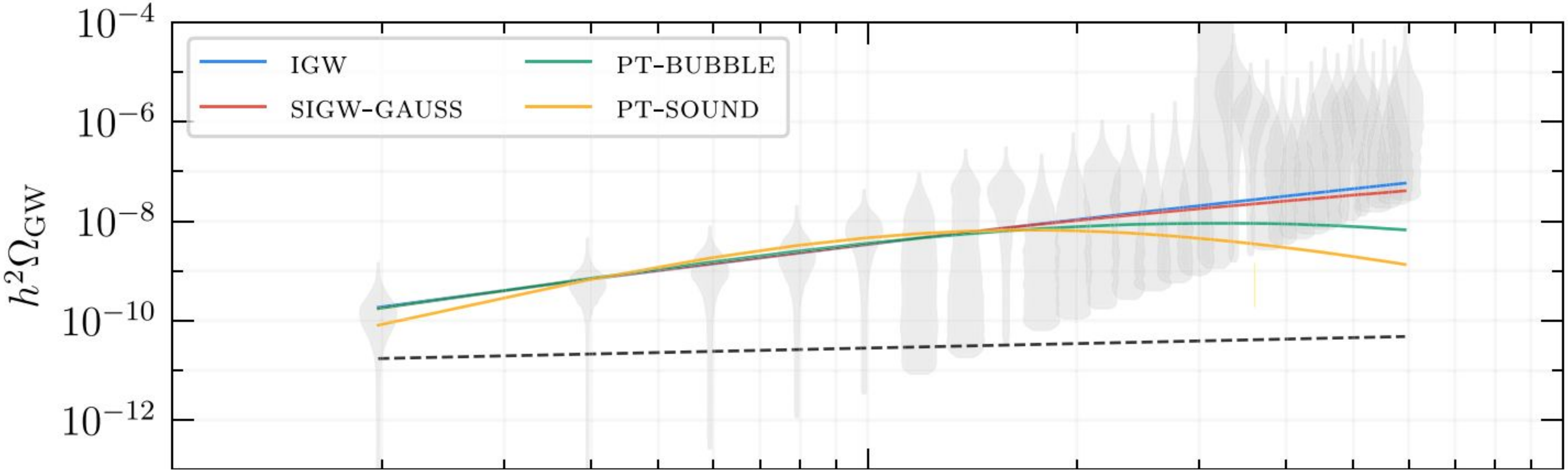
BOS+SMBHB model $\log_{10} G\mu < -9.75$

LRS+SMBHB model $\log_{10} G\mu < -10.44$



CS - BOS model
CS - LRS model
Turbulence model
Inflation model
-6
-8
-10
-12
$\log_{10}(h^2\Omega_{gw})$
10^{-8}
Frequency [Hz]

Afzal et al., 2023, The NANOGrav 15-year Data Set:
Search for Signals from New Physics.



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