# Beyond the SM with Pulsar Timing

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work in collaboration with V. Brdar and K. Schmitz

Based on PRR 2 (2020) [2004.02889] & PRL 126 (2021) [2009.06607]

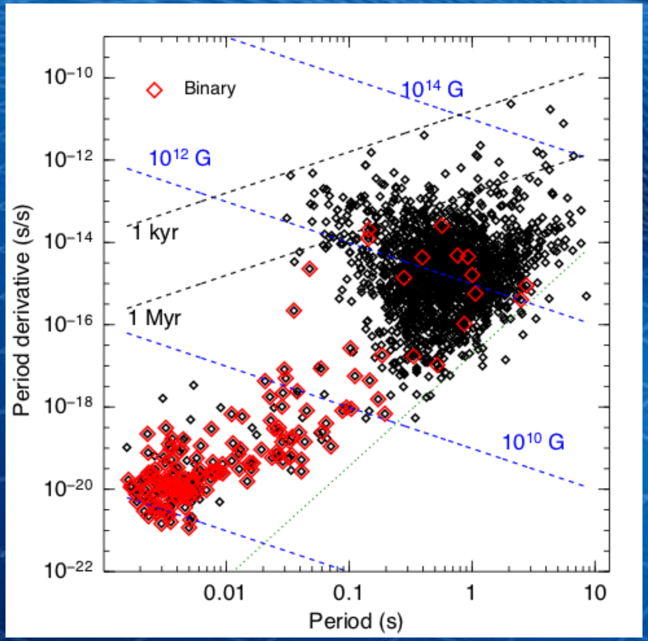
Virtual talk at HEP@VUB meeting 25/03/21

# Pulsar Timing Arrays

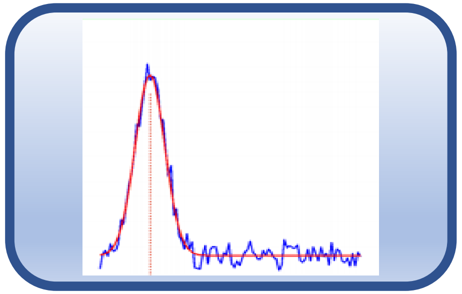
Neutron stars, $R \sim 10\ \mathrm{km},\ B \sim 10^{8} - 10^{15}\ G$

Great clocks: rapid rotation + large inertia = very stable

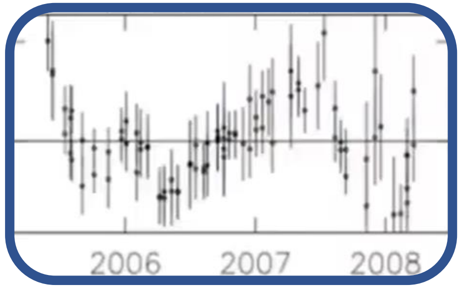
Lighthouse effect: very precise ticks when beam crosses line of sight



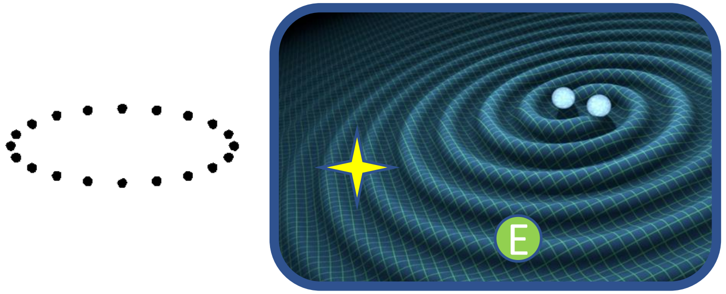
# Pulsar Timing Arrays



Observe the pulsar and measure the **Time of Arrival** (with respect to the solar system barycenter; account for propagation)




Find the **theoretical model** that fits the ToAs in terms of $\nu, \dot{\nu}$, proper motion, position, Shapiro delay,… and construct the **time residuals** $R = \mathrm{ToA_{th}} - \mathrm{ToA_m}$



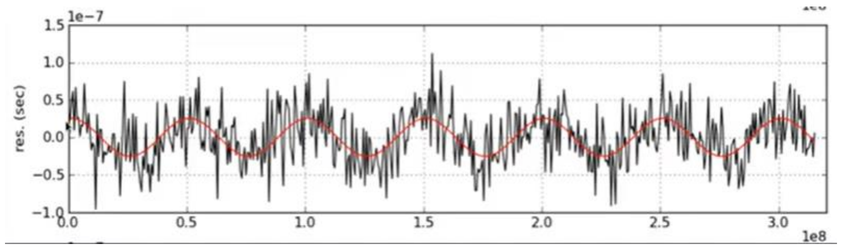

Look for **unaccounted-for physics** in the time residuals, e.g. GWs from resolved supermassive black hole binary during inspiral

$$R \sim \frac{h}{2\pi f} \sim 25.7\ \mathrm{ns} \left(\frac{\mathrm{M}}{10^9\ \mathrm{M_\odot}}\right)^{5/3} \left(\frac{D}{100\ \mathrm{Mpc}}\right)^{-1} \left(\frac{f}{50\ \mathrm{nHz}}\right)^{-1/3}$$

[Sesana et al. 0809.3412]

# Pulsar Timing Arrays

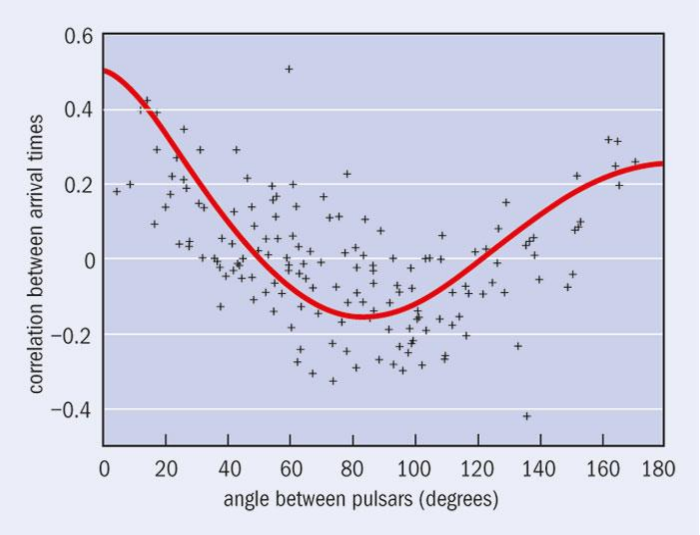
Is this is a gravitational wave?

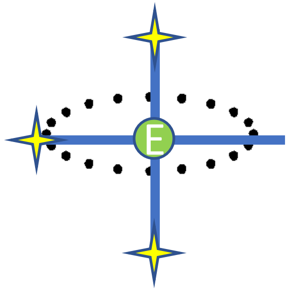



Not so fast… **red noise** can be

- offset of the clock (monopolar)
- misplaced SSB (dipolar)
- intrinsic to the source

Look at correlation of ToAs for pairs of pulsars:

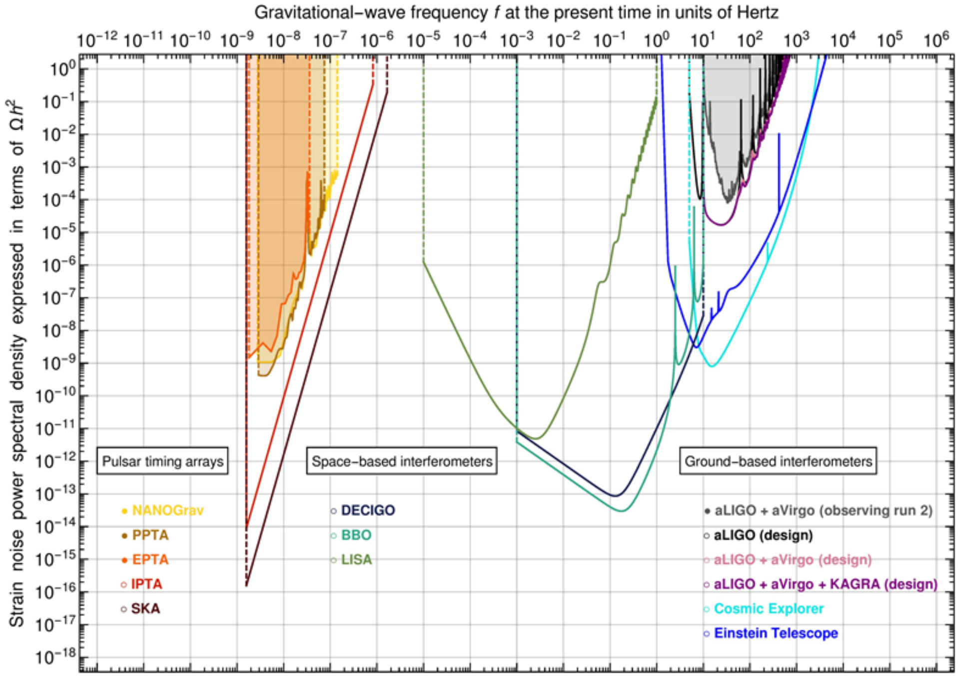



- **Hellings-Down** curve (quadrupolar), only dependence on the angle between pulsars

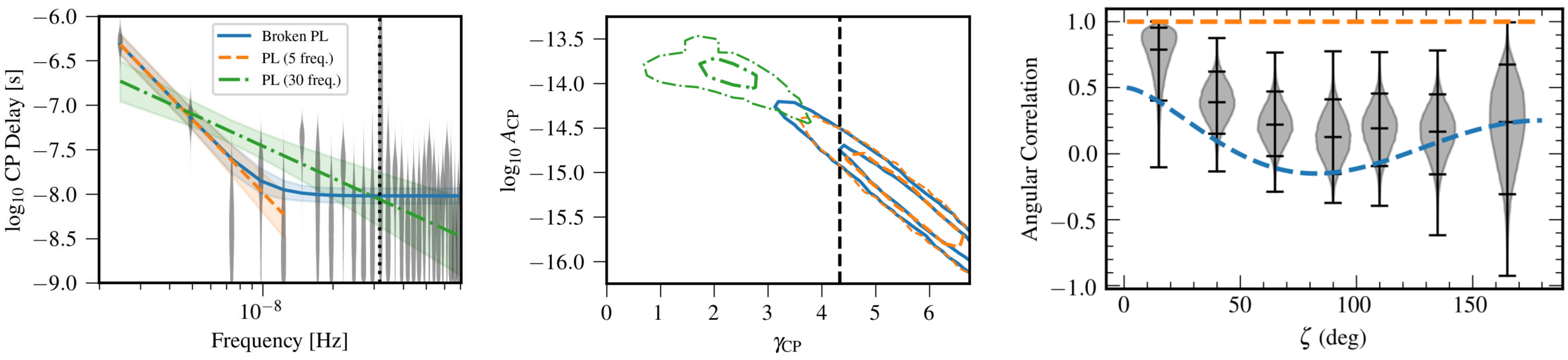
# Pulsar Timing Arrays

Pulsars are excellent probes at very low frequencies: $3\ \mathrm{nHz} \approx \frac{1}{10\ \mathrm{years}} < f < \frac{1}{1\ \mathrm{month}} \approx 400\ \mathrm{nHz}$




[Schmitz 2002.04615]

# NANOGrav 12.5-year data set [40+ ms pulsars, 2009.04496]




- Clear detection of a common red process fitted by a power law

$$S_{ab} = \Gamma_{ab}\, h_c^2(f) \left(\frac{f}{f_{\rm yr}}\right)^{-3} \qquad h_c(f) = A_{\rm GWB} \left(\frac{f}{f_{\rm yr}}\right)^{\alpha} \qquad \gamma = 3 - 2\alpha \qquad (\alpha = -2/3 \text{ for BHs})$$

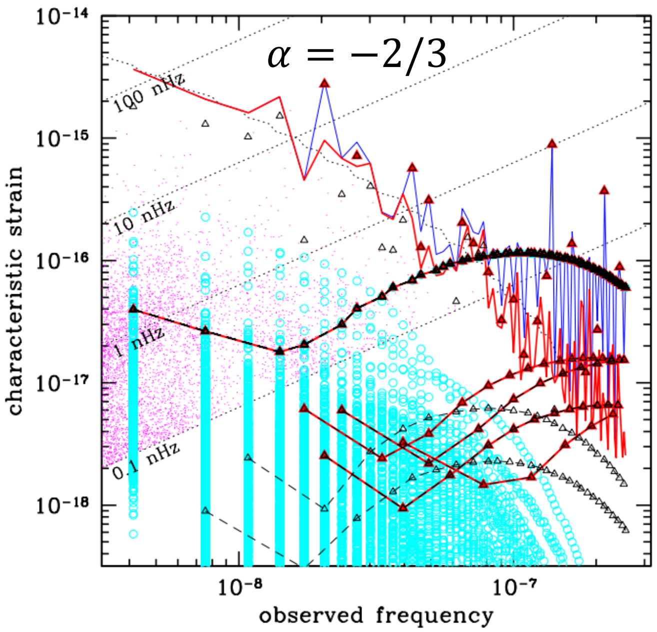
- Either monopolar or dipolar correlation is disfavored with respect to no correlation

- Quadrupolar correlation vs no correlation gives inconclusive evidence

# Possible interpretations

### Astrophysical

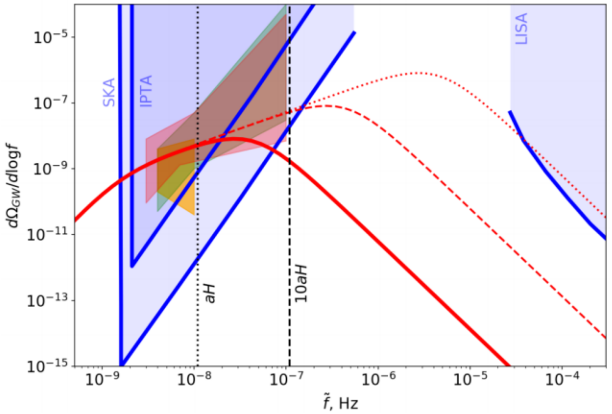
- Supermassive black hole binaries

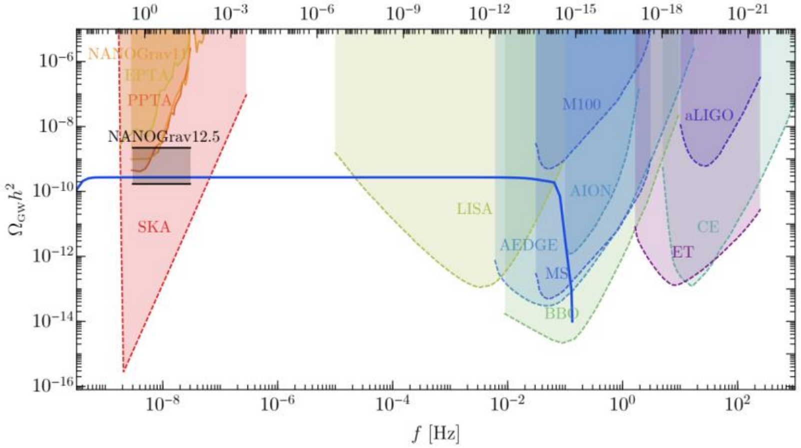



[Amaro-Seoane et al. 0910.1587]

### Cosmological + BSM

- Phase transitions [2009.09754, 2009.10327, 2009.14174, 2009.14663]
- Primordial black holes [2009.07832, 2009.08268, 2009.11853, 2010.03976]
- Audible axions [2009.11875]
- Inflation [2009.13432, 2010.05071]
- Cosmic strings [2009.06555, **2009.06607**, 2009.10649, 2009.13452]
- Domain walls [2009.13893]



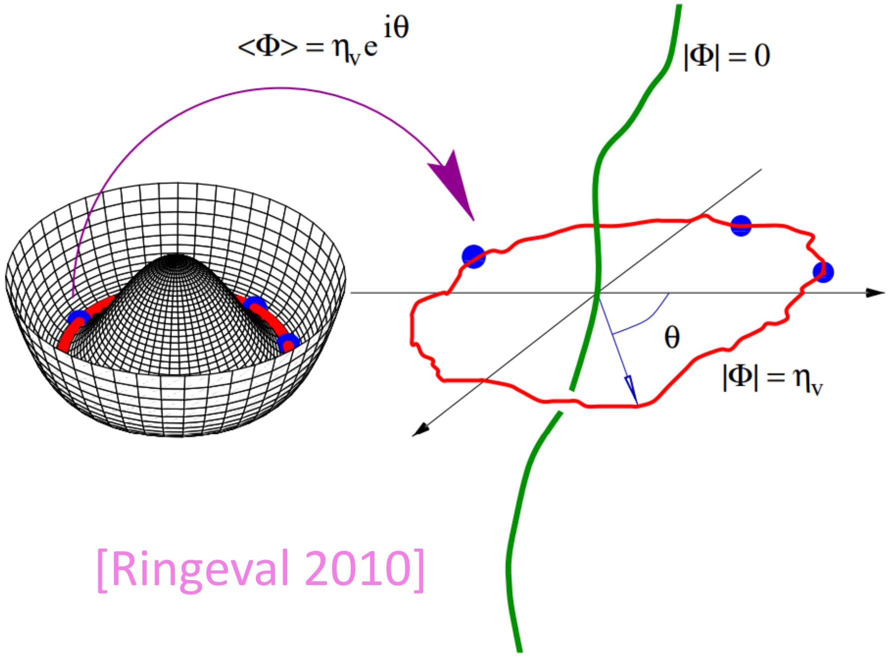



# Cosmic strings

Defects can form after a phase transition depending on topology of vacuum manifold
[Zel'dovich et al. '74, Kibble 76]

| Defect | Dimension | Homotopy group |
|---|---|---|
| Domain walls | 2 | $\pi_0(M)$ |
| Strings | 1 | $\pi_1(M)$ |
| Monopoles | Point-like | $\pi_2(M)$ |
| Textures | - | $\pi_3(M)$ |

[Vilenkin,Shellard '94]




[Ringeval 2010]

*Theorem*: $\pi_1(G/H) \cong \pi_0(H)$

GUT strings energy density $\sim 1\ M_{\oplus}/\mathrm{km}$

# Cosmic strings in field theory

They arise as non-trivial vortex solutions of classical EoM [Nielsen-Olesen 1973]

**Global U(1)**

$$\phi = \eta f(r) e^{i\theta}$$

- Energy density is log divergent

$$\mu \approx \eta^2 \log\left(\frac{m_\phi}{H}\right)$$

- Long-range interaction due to NG boson
- Massless decay mode

**Local U(1)**

$$m_\phi r \gg 1:$$

$$\phi \to \eta e^{i\theta} \quad A_\mu \to \partial_\mu \log \phi$$

- Energy density is finite ($D_\mu \phi \approx 0$)

$$\mu \approx \eta^2$$

- Only massive decay modes (besides GWs)

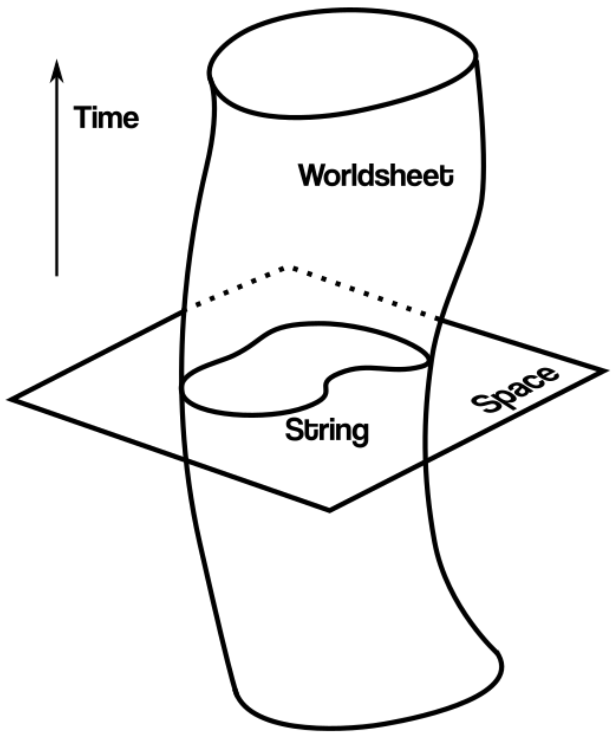
See [Gorghetto et al. 1806.04677] for Peccei-Quinn strings

# Nambu-Goto strings

Below symmetry breaking scale, **effective description** in terms of the Nambu-Goto action:

$$S = -\mu \int \sqrt{-\gamma}\, d^2\zeta + \alpha \int \kappa \sqrt{-\gamma}\, d^2\zeta + \cdots$$

Curvature may be neglected in cosmological setting: **macroscopic length** of the string (~ average curvature radius) much larger than thickness



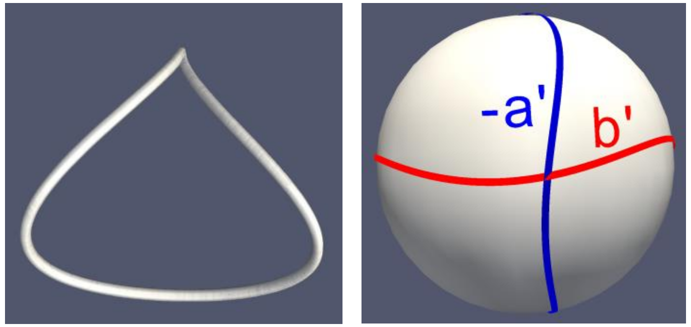

$$x^\mu = x^\mu(\zeta^a) \quad a = 0{,}1$$

**Possible exception**: points of high curvature, **cusps and kinks**. This leads to particle-production cut-off in GWs at high frequencies (above planned experiments) [Gouttenoire et al. 1912.02569]

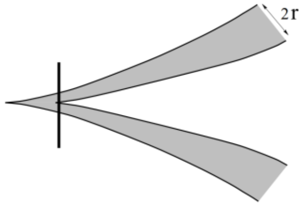
# Cosmic strings

**String dynamics**: cusp formation during loop oscillations

$$X(\sigma,\tau) = \frac{1}{2}[a(\sigma-\tau) + b(\sigma+\tau)], \quad a'^2 + b'^2 = 1$$

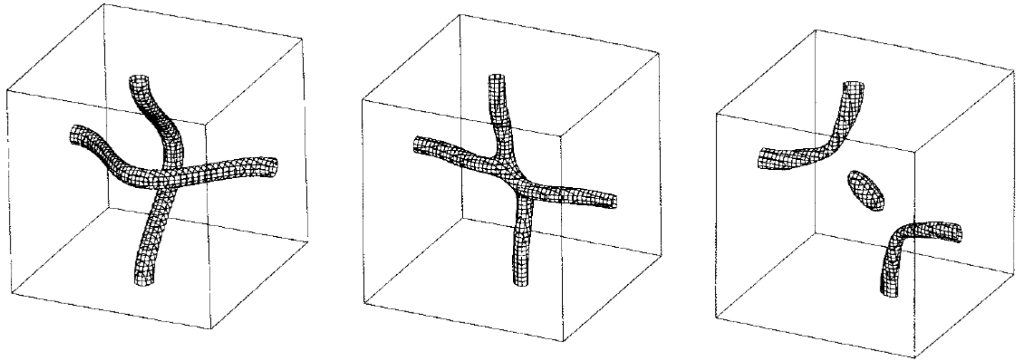


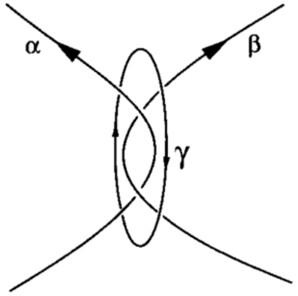

$$|\dot{X}| = \frac{1}{2}|b' - a'| = 1$$




[Olum,Blanco-Pillado gr-qc/9812040]

**String interactions**: intercommutation probability






$$\gamma = (\alpha\beta)(\beta\alpha)^{-1}$$

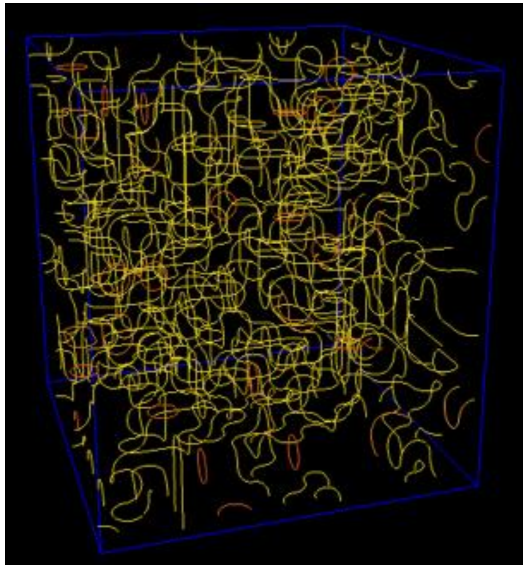
$\gamma = 1$ only for abelian strings

[Vilenkin,Shellard ’94]

# Cosmic strings

**Formation**:

- $\rho_\infty \sim$ 80% in long strings
- $\rho_L \sim$ 20% small loops



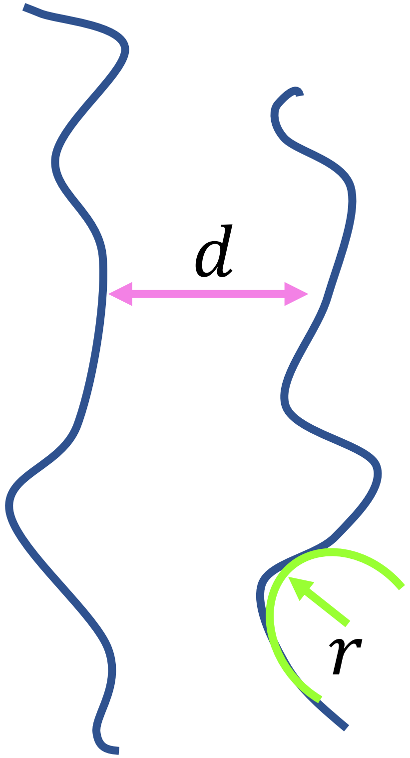
**Evolution**:

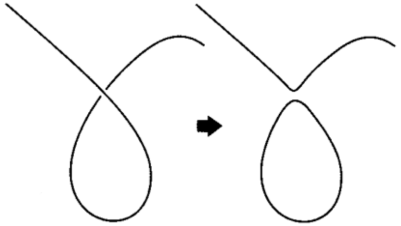
- Naive $\rho_\infty \sim \mu\, a/a^3$, leads to string domination
- Expansion of the Universe + large intercommutation lead to scaling

$$\rho_\infty \sim \mu/t^2$$

- Small loops need to be produced at large rate to maintain scaling,

$$\rho_L/\rho_\infty \to 100$$

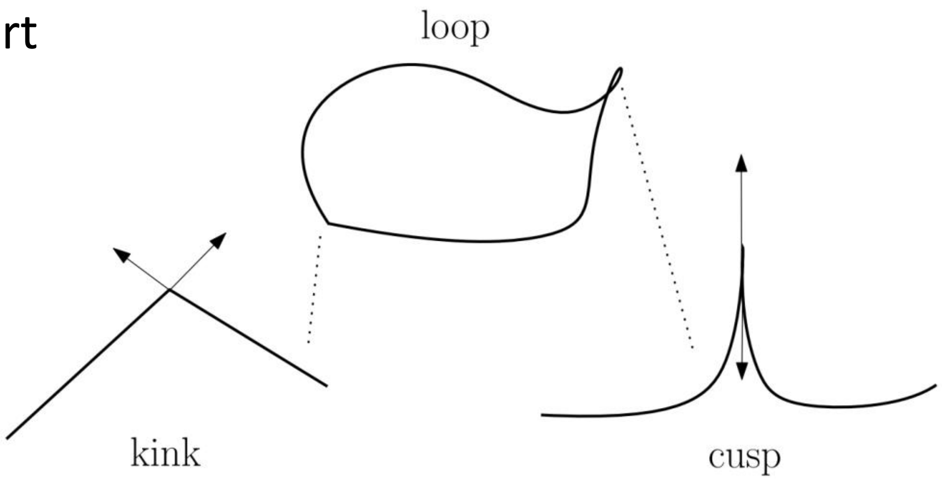


# Cosmic strings

[Gouttenoire et al. 1912.02569]

Small loops do not feel the expansion of the Universe and start oscillating: **long-lasting source of GWs**




**Emission power** $\mathrm{P} = \Gamma G\mu^2$, loops shrink with time:

VOS: $l(t) = l(t_i) - \Gamma\, G\, \mu\, (t - t_i),\ \ l(t_i) = \boldsymbol{\alpha}\, t_i$

Presence of small-scale structure populates **higher harmonics** on top of fundamental mode

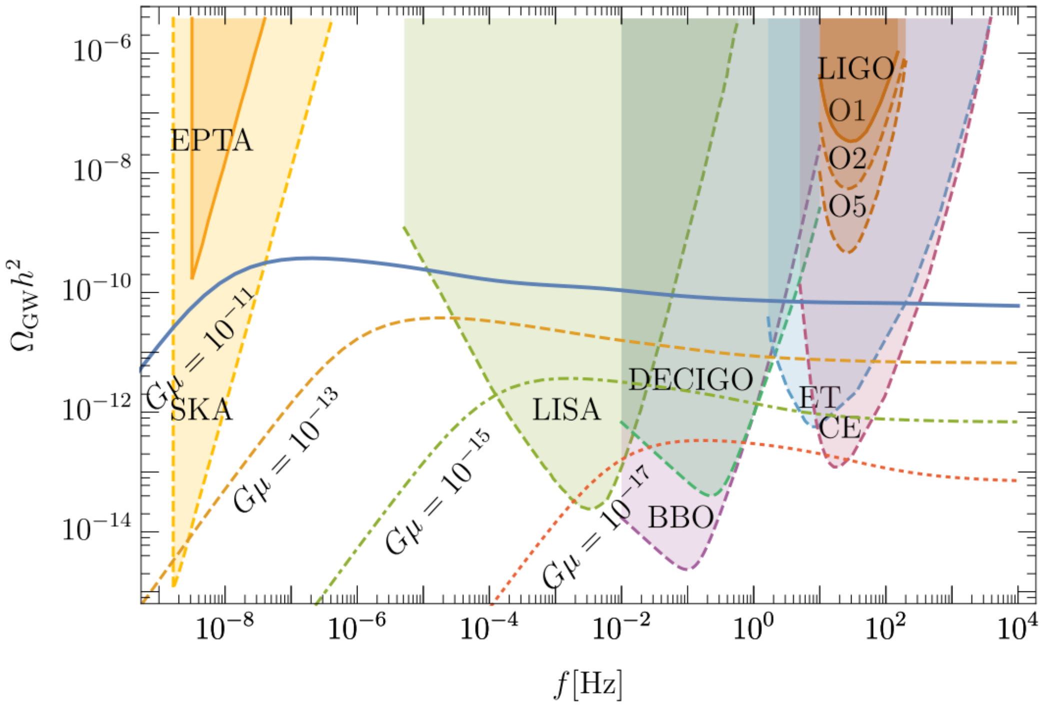
$$f_k = \frac{2k}{l(t)}, \qquad P_k = \Gamma\, G\mu^2 \frac{k^{-n}}{\sum_{p=1}^{\infty} p^{-n}}$$

| Kink | Cusp | Kink collision |
|---|---|---|
| $n = 5/3$ | $n = 4/3$ | $n = 2$ |

# Cosmic strings

Dilution, redshift, loop production rate

$$\Omega_{GW}(f) = \frac{1}{\rho_c}\left(\frac{d\,\rho_{GW}}{d\log f}\right) = \frac{f}{\rho_c}\sum_k \frac{P_k}{\alpha+\Gamma G\mu}\int_{t_F}^{t_0}\left(\frac{a(\tilde{t})}{a(t_0)}\right)^3\cdot\left(\frac{a(\tilde{t})}{a(t_0)}\right)^2\frac{2k}{f^2}\cdot\left(\frac{a(t_i)}{a(\tilde{t})}\right)^3\frac{F_\alpha\, C_{\text{eff}}(t_i)}{\alpha\, t_i^4}\,\mathrm{d}\tilde{t}$$




[Cui et al. 1808.08968]

| Production $t_i$ | Emission $\tilde{t}$ | $\Omega_{GW}$ (k=1) |
|---|---|---|
| Radiation | Radiation | $\sim f^0$ |
| Radiation | Matter | $\sim f^{-1/2}$ |
| Matter | Radiation | $\sim f^{-1}$ |

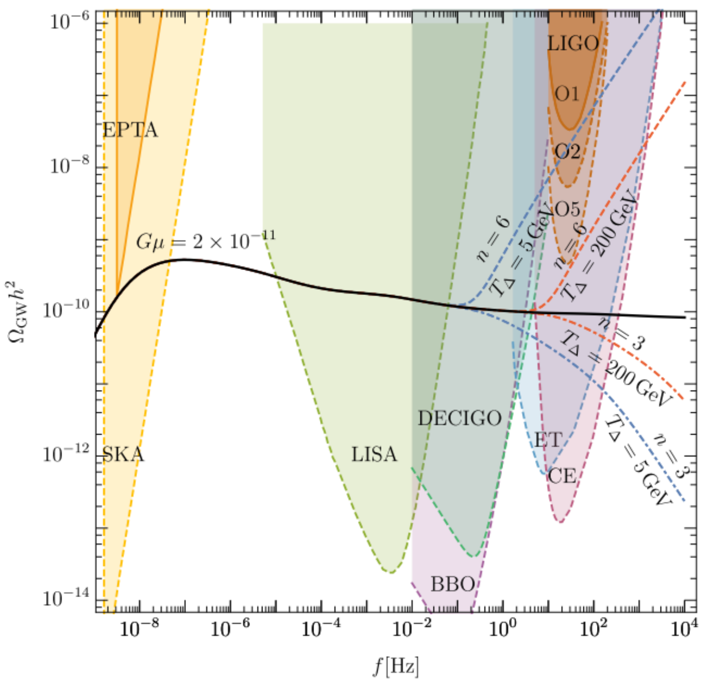
Biggest contribution at $\sim 1/2$ of loop lifetime:

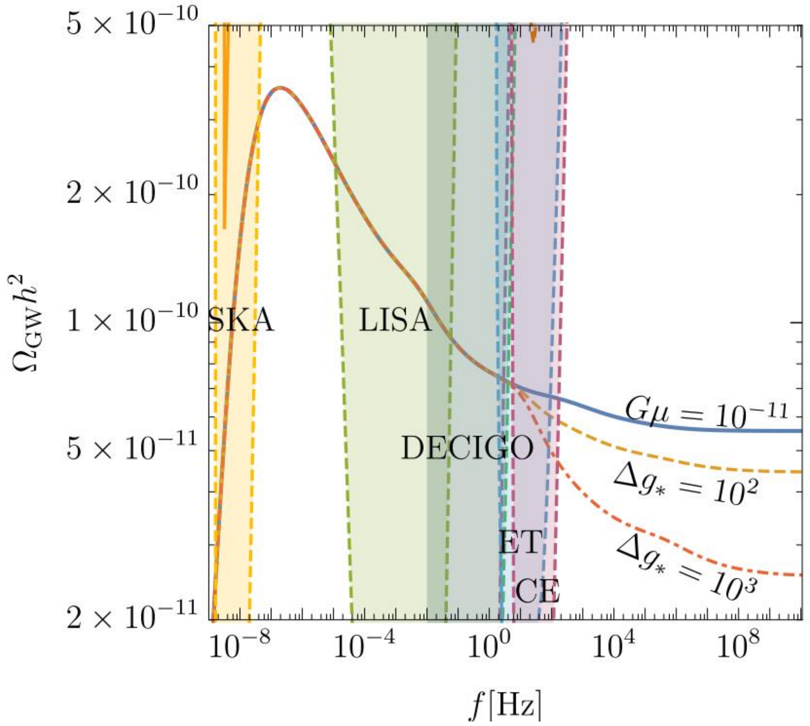
$$\tilde{t} = t_M \simeq \frac{\alpha t_i}{2\Gamma G\mu} \simeq \frac{a(t_M)}{f\ \Gamma G\mu\ a_0}$$

# Cosmic strings

… probe cosmology prior to BBN

$$f_\Delta = \left(\frac{8}{z_{eq}\alpha\Gamma G\mu}\right)^{\frac{1}{2}} \left(\frac{g_*(T_\Delta)}{g_*(T_0)}\right)^{\frac{1}{4}} \left(\frac{T_\Delta}{T_0}\right) t_0^{-1}$$



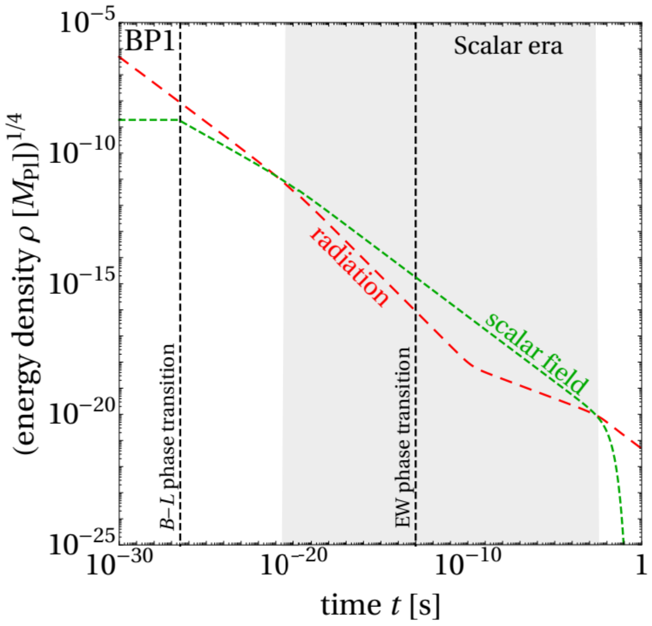



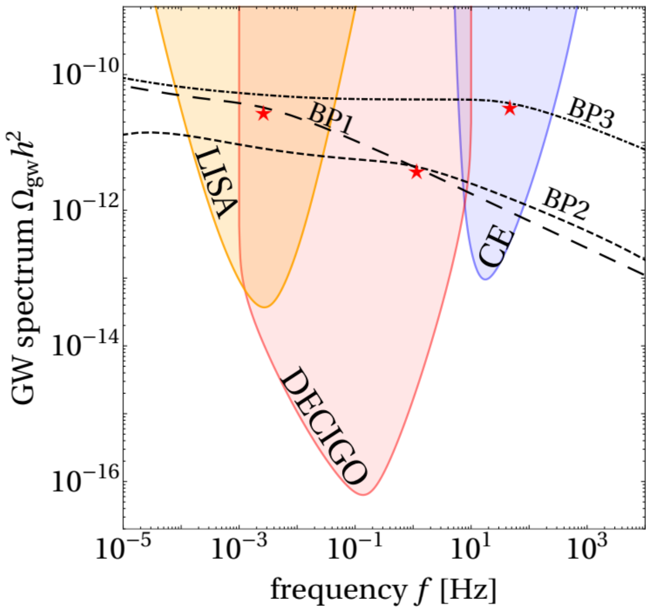

[Cui et al. 1808.08968]

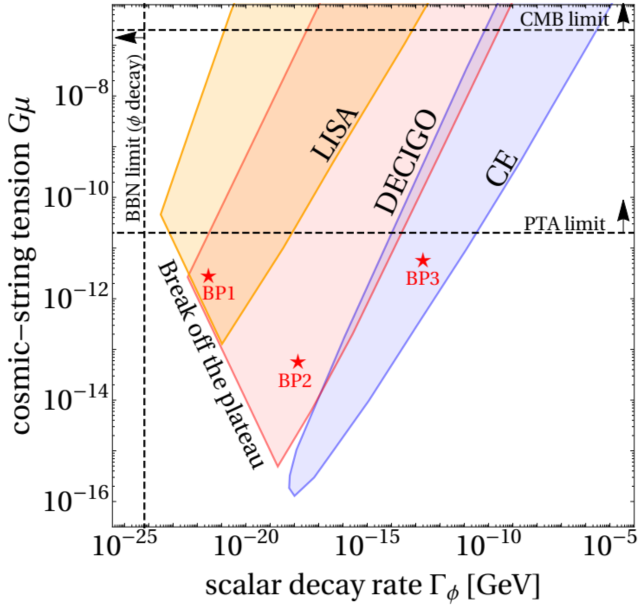
# Cosmic strings

[SB,Brdar,Schmitz 2004.02889]

Early matter domination in a gauged B-L model,  off-shell decays $\phi \rightarrow NN$, Z'Z'… sets life-time



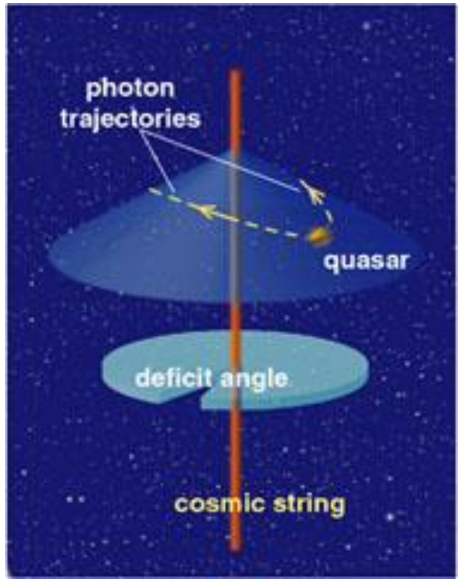

i) Height of GW plateau: $G\mu$ ii) Broken power law $f^0 \rightarrow f^{-1/3}$ from higher modes iii) Break location: width $\Gamma_\phi$

# Some bounds on cosmic strings

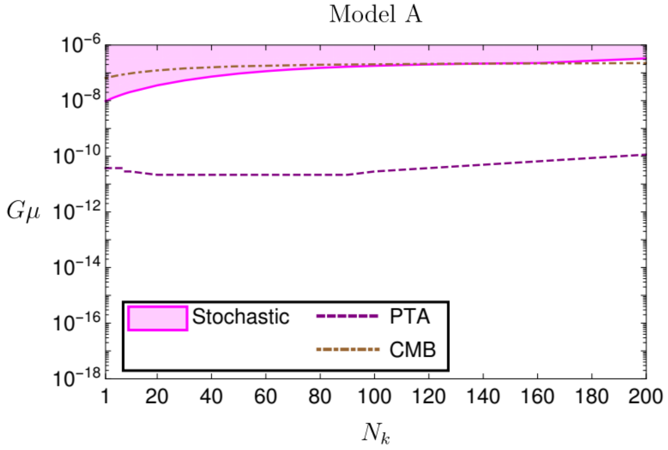
- $\Delta N_{\rm eff}$ from BBN and CMB + isocurvature perturbations: $G\mu \lesssim 10^{-7}$ (no structure formation)
- Pulsar timing: $G\mu < 10^{-10}$ $(\alpha = 0.1)$ [NANOGrav 11-year ApJ, 859]
- Conical metric with deficit angle

$$\Delta = 8\pi G\mu,$$

$G\mu < 10^{-7}$ from double images




- LIGO-Virgo: $G\mu < 10^{-8}$ (Model A)

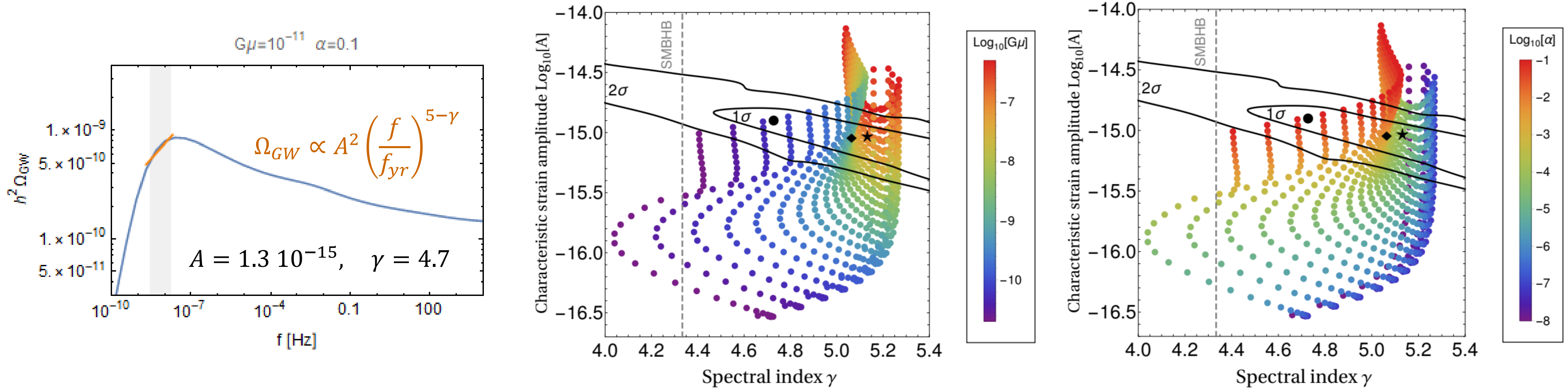



[LVK coll. 2101.12248]

# Cosmic strings & NANOGrav

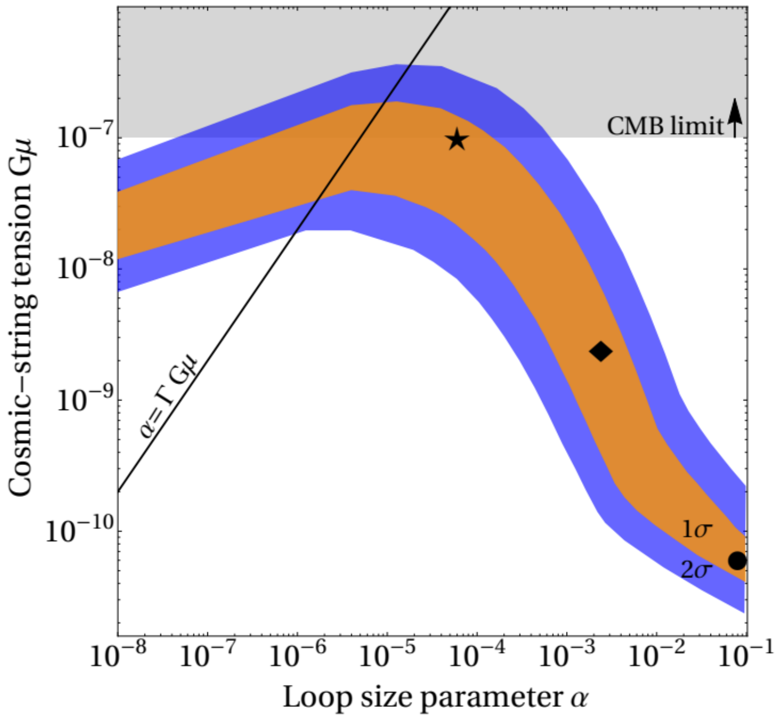
Power-law fit of the GW signal (cusps) between $2\ 10^{-9} \rightarrow 2\ 10^{-8}$ Hz

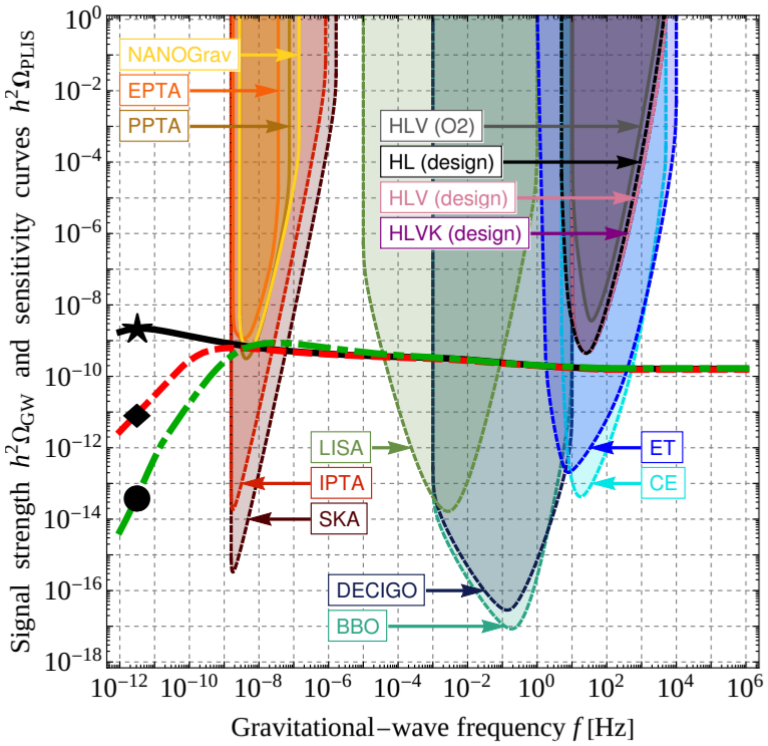
[SB,Brdar,Schmitz 2009.06607]




See also [Ellis,Lewicki 2009.06555] and [Blanco-Pillado et al. 2102.08194]

# Cosmic strings & NANOGrav



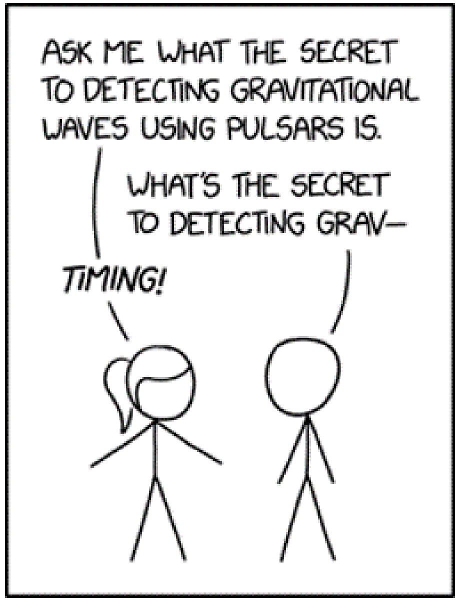




- Detection prospects of the plateau at future experiments
- Symmetry breaking scale can hint to BSM scenarios

$$h^2\Omega_{\rm GW}^{\rm flat} = 2\;10^{-4}\left(\frac{\alpha}{0.1}\right)\left(\frac{G\mu}{\Gamma}\right)^{1/2}$$

$$\text{SSB} = 10^{16}\;\text{GeV}\left(\frac{G\mu}{10^{-7}}\right)^{1/2}$$

# Conclusion




- Strong evidence for a stochastic red process in NANOGrav 12.5-year data set with 40+ pulsar timing array
- Quadrupolar correlation still inconclusive
- Joint analysis within IPTA collaboration ongoing
- Astrophysical and Cosmological (BSM) interpretations of signal have been proposed in terms of GWs

- Cosmic strings (topological defects) are interesting: formation independent of the strength of the phase transition, large signal in GWs, connection to fundamental physics
- NANOGrav may have just provided the first observation :)