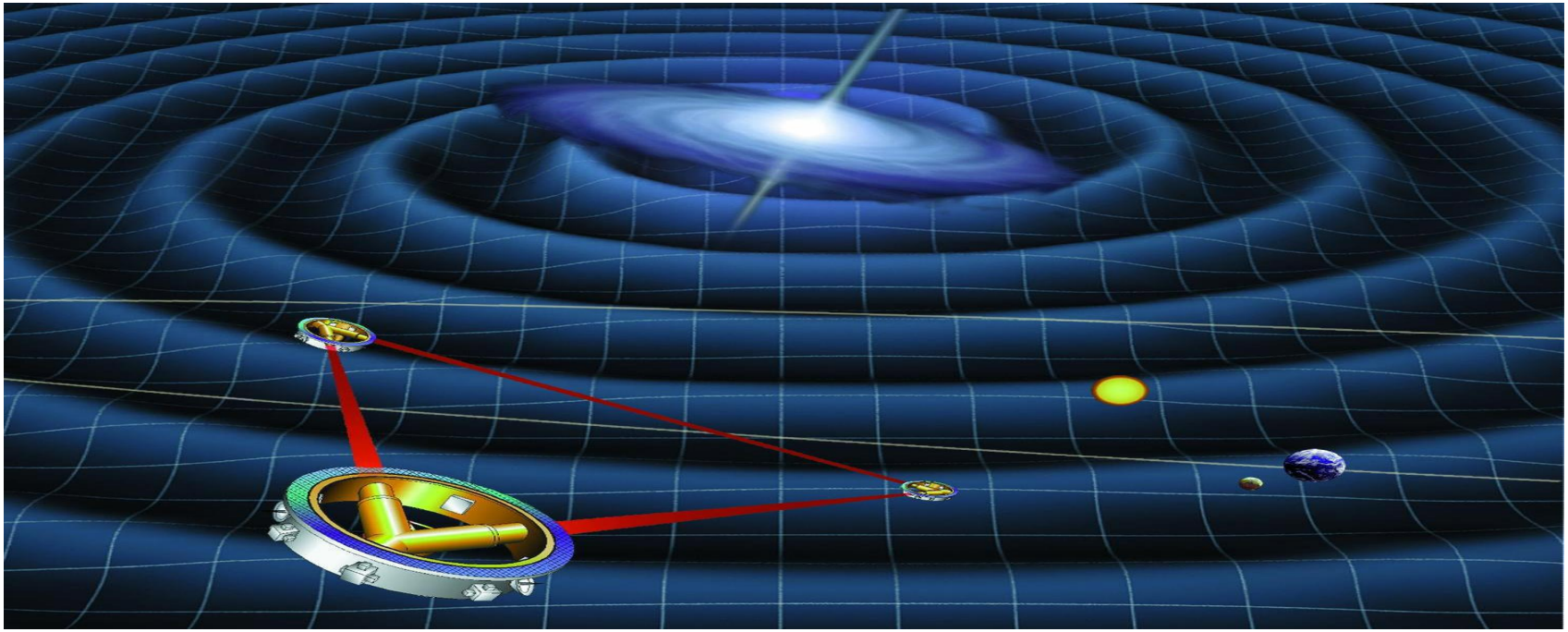
Gravitational Waves and New Physics



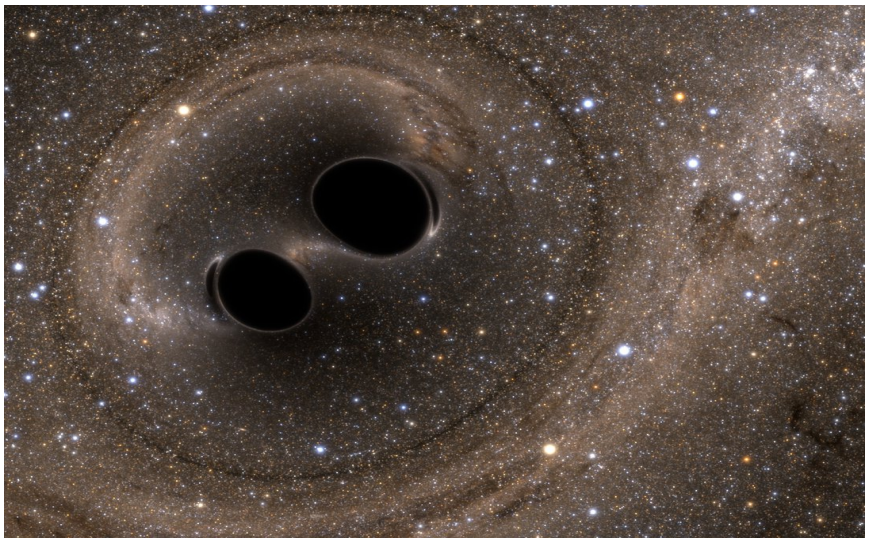
Vedran Brdar

Fermilab

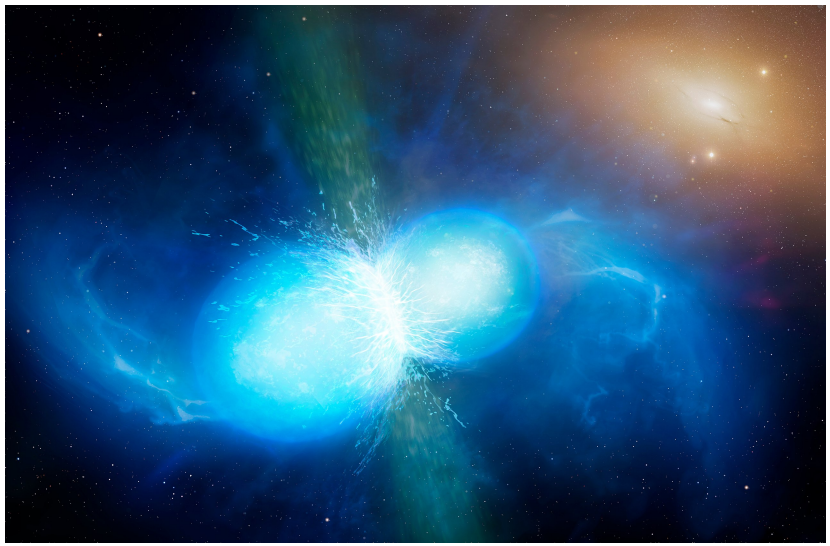
Northwestern University

Gravitational Waves from Mergers, Nobel Prize 2017

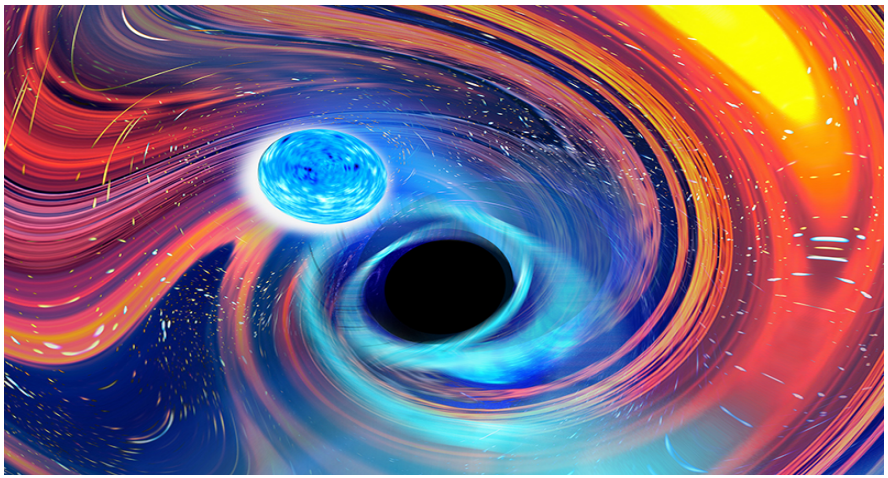
Phys. Rev. Lett. 116, 061102



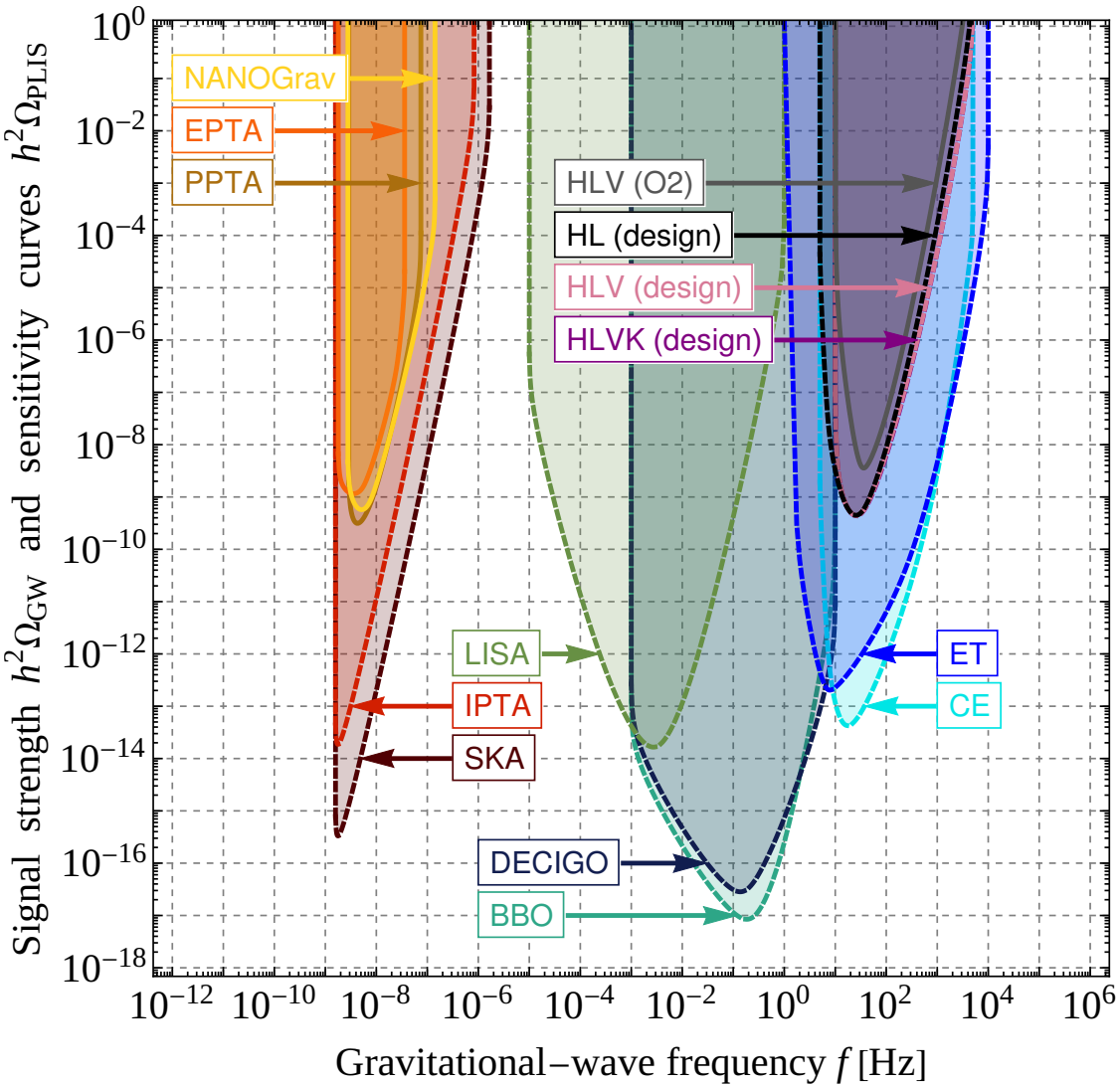
Phys. Rev. Lett. 119, 161101

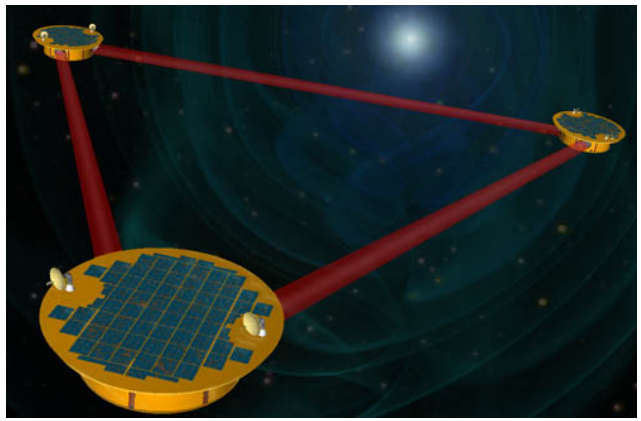


arXiv:2106.15163



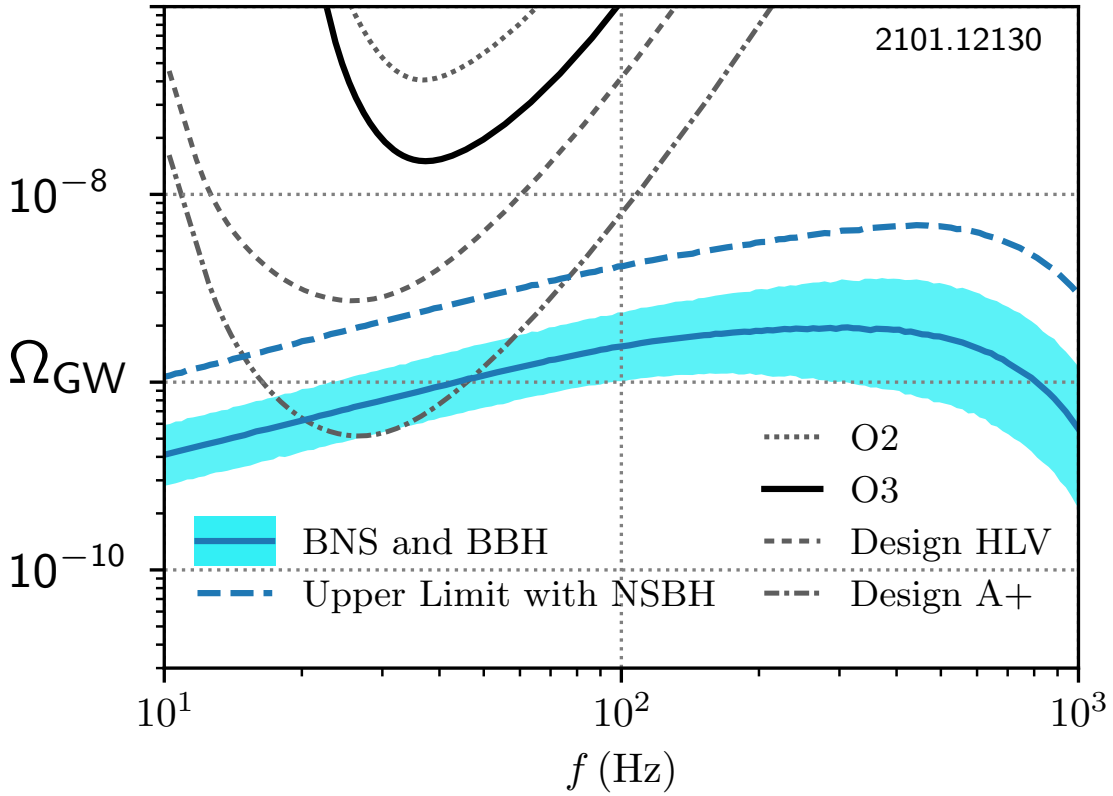
Gravitational waves – A Window to New Physics





Limits from LIGO and VIRGO

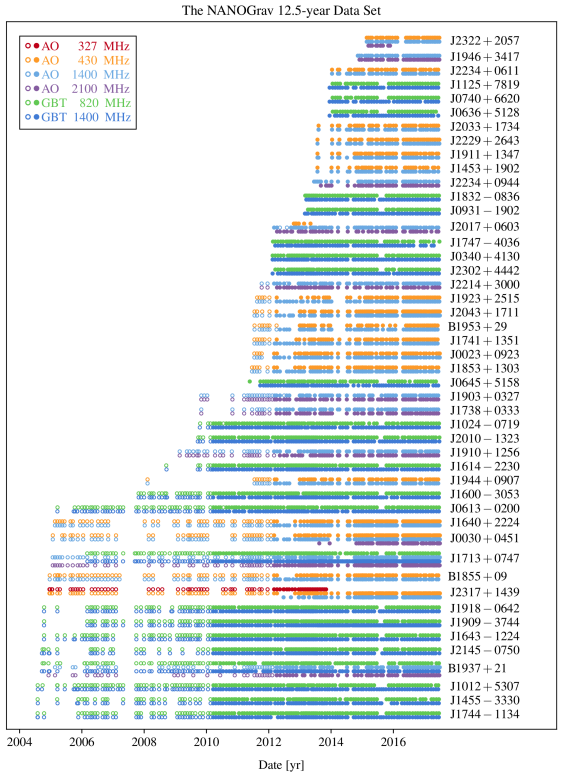
- third observing run (O3) combined with upper limits from the earlier O1 and O2 runs
- results of the search are consistent with uncorrelated noise; upper limits improve by a factor of few

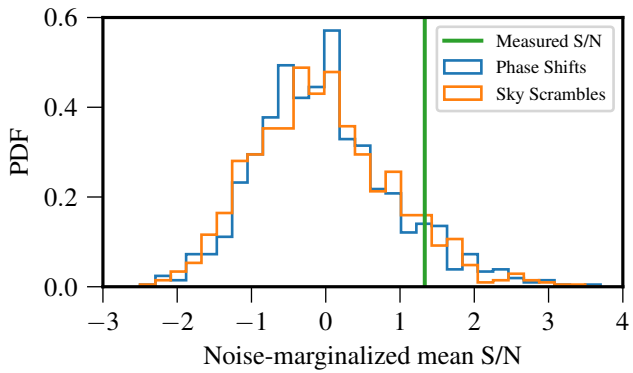


Pulsar Timing Arrays (PTA)

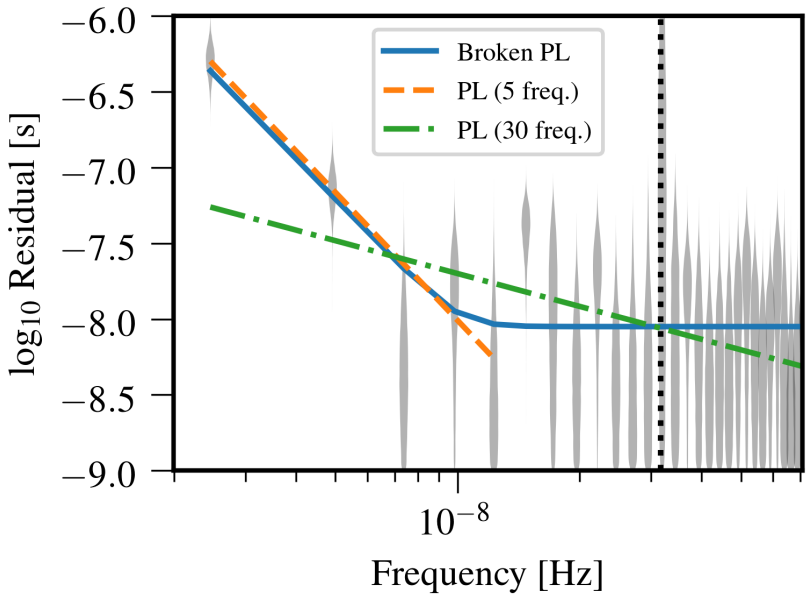
- PPTA (25)
- EPTA (42)
- NANOGrav (47)

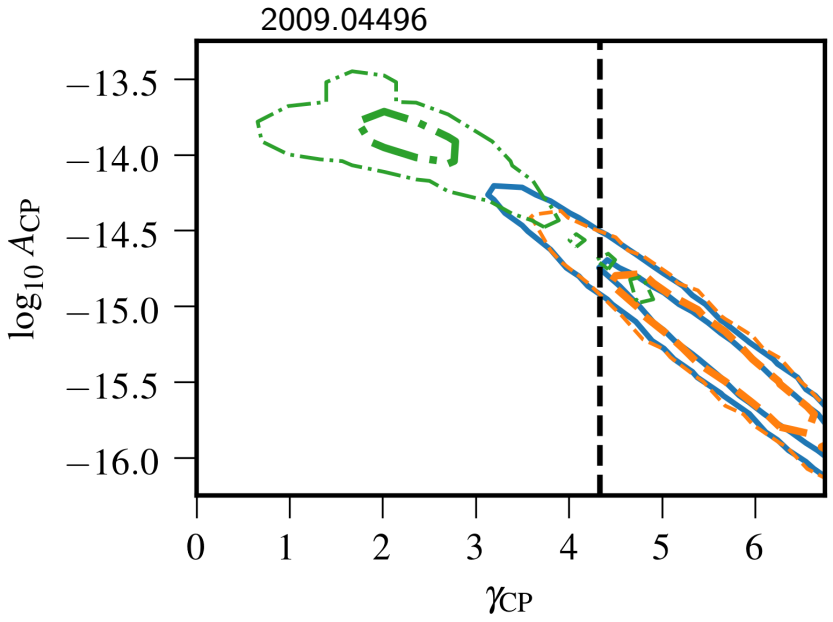
- NANOGrav reported a strong preference for a stochastic common spectrum process in 12.5-year data set analysis (2009.04496)
- this claim "survived" the 2nd data release of PPTA (2107.12112)
- despite the hint, results are still inconclusive with respect to GW discovery
- missing piece: quadrupolar spatial correlation (Hellings & Downs, 1983)



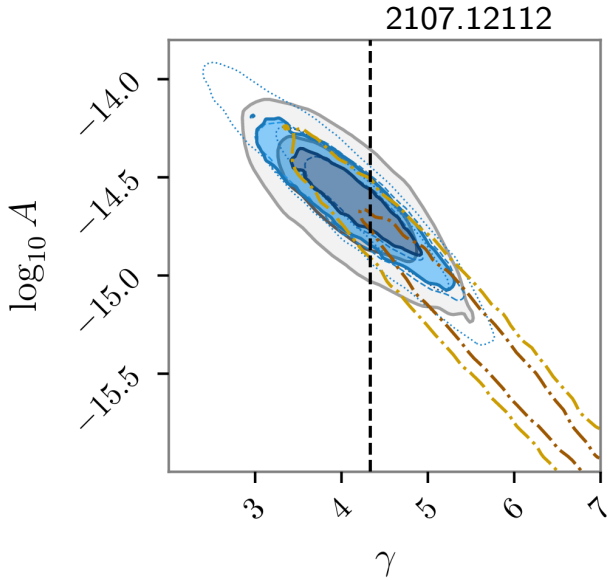


Pulsar Timing Arrays (PTA)



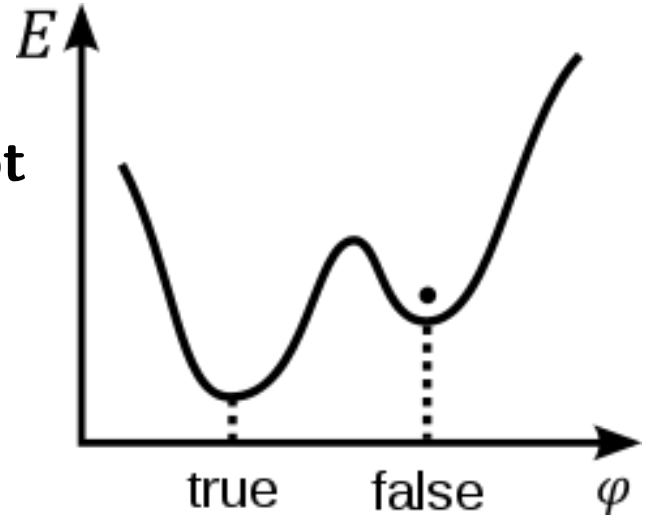


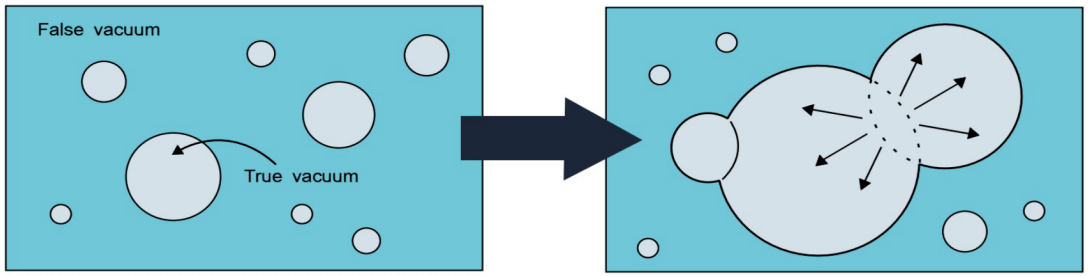
- median value of A_{CP} higher than the 95% CL upper limit from 11 year data set
- change in the analysis strategy lead to the increase in sensitivity at low frequencies
- supermassive black hole binaries?



First-Order Phase Transitions

- First-order phase transitions proceed via nucleation of bubbles of the new phase
- Electroweak and QCD phase transition are **not** of first-order in the Standard Model
- New physics!



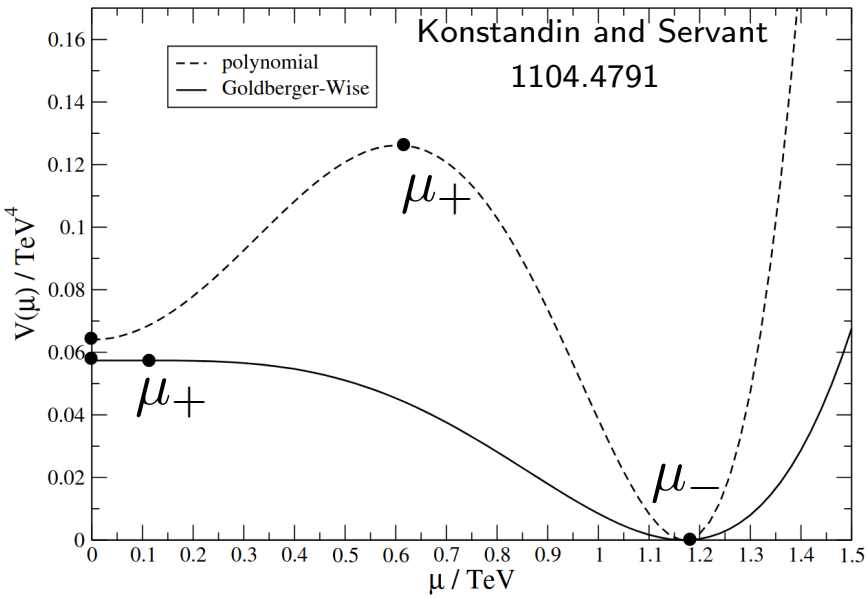


- inverse duration of the phase transition
$$\beta = H(T_n)\,T_n \cdot \frac{\mathrm{d}}{\mathrm{d}T}\left(S_3/T\right)_{T=T_n}$$
- normalized energy from the transition
$$\alpha \simeq \Delta V/\rho_{\mathrm{rad}}(T_n)$$

- bubble nucleation rate
$$\Gamma(T) \simeq T^4 \left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} \exp^{-S_3/T}$$
- nucleation temperature
$$\int_{T_n}^{T_c} \frac{\mathrm{d}T}{T} \frac{\Gamma(T)}{H(T)^4} \sim 1$$

Gravitational Waves From Bubble Collisions

- bubble collisions used to be considered as the main contribution of GWs in first-order phase transition $\Longrightarrow$ "runaway" scenario with bubble walls moving at ultrarelativistic speeds ($\gamma \gg \sqrt{1 - v_w^2}$) Bodeker, Moore, 0903.4099 Caprini et al., 1512.06239
- calculation of a friction on a bubble including higher order effects (primarily transition radiation) changes the picture $\Longrightarrow$ most of the energy does not convert to the energy of the Higgs field Bodeker, Moore, 1703.08215 Caprini et al., 1910.13125



- exception: extremely supercooled phase transitions
- achievable in scale-invariant models (in contrast to polynomial potentials)
- $T_n \simeq \sqrt{\mu_- \mu_+} \ll \mu_-$ in scale-invariant realizations
- plasma friction expected to play a negligible role

The Neutrino Option

Brivio and Trott, 1703.10924,1809.03450

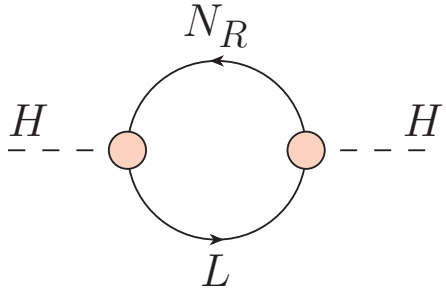
- Why the Higgs is so light? Why neutrinos are so light?
- connection?

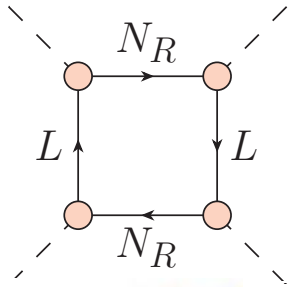
$$-\mathcal{L} = \frac{1}{2} M \bar{N}_R N_R^c + y_\nu \bar{L} \tilde{H} N_R + h.c.$$

1) Assumptions: Majorana **scale** M; Higgs potential **vanishes** at M

2) Integrate out N_R

3) RG evolution





SM Higgs potential reproduced at EW scale for $M \simeq 10^7 ... 10^8$ GeV and $y_\nu \lesssim 10^{-4}$

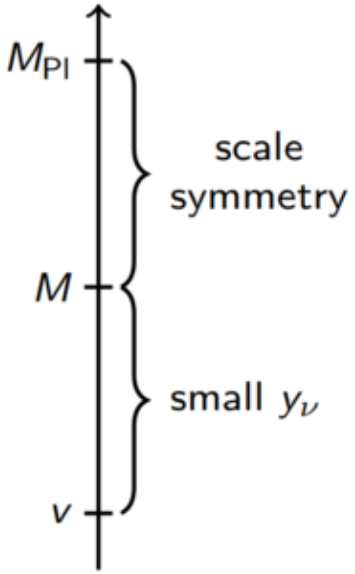
A Realization Based on Symmetry?

VB, Emonds, Helmboldt, Lindner arXiv:1807.11490

Understanding neutrino option at a more fundamental level?

$\Longrightarrow$ Classical scale invariance

$$-\mathcal{L} \supseteq \frac{1}{2} y_M S \bar{N}_R N_R^c + y_\nu \bar{L} \tilde{H} N_R + \text{h.c.} + \lambda (H^\dagger H)^2 + \lambda_S S^4$$
$$+ \lambda_R R^4 + \lambda_{HS} S^2 (H^\dagger H) + \lambda_{HR} R^2 (H^\dagger H) + \lambda_{SR} S^2 R^2$$



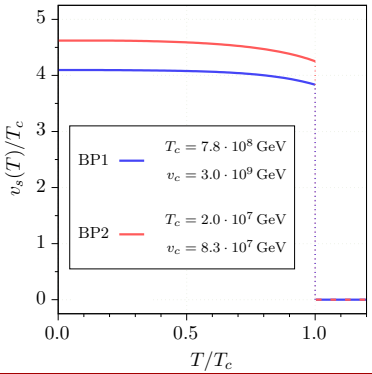
Gildener, Weinberg Phys.Rev. (1976)

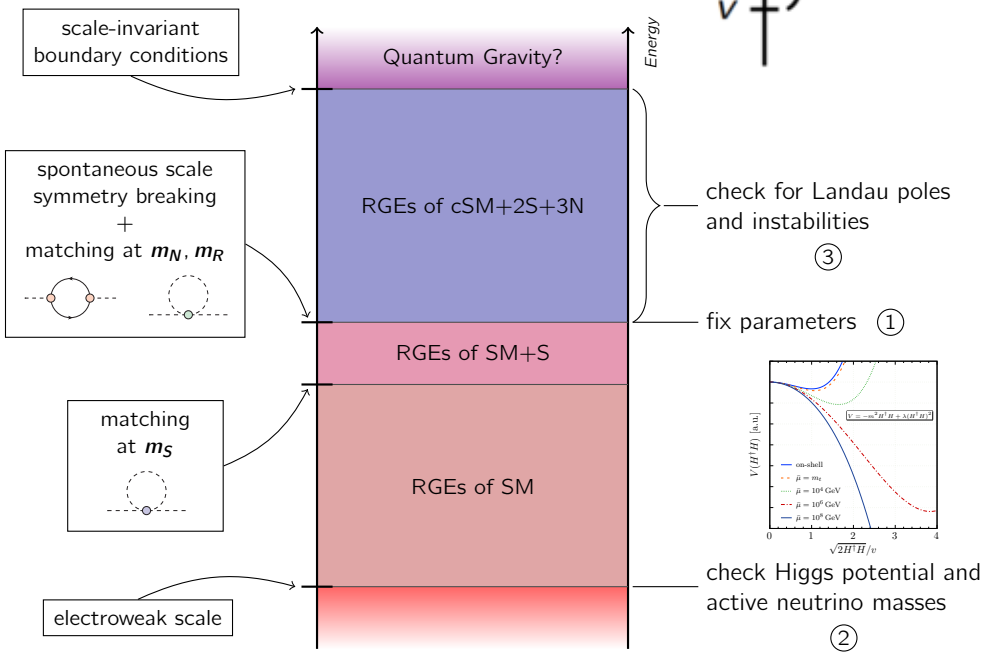
SSB pattern: $\langle H \rangle = \langle R \rangle = 0$

$\langle S \rangle \equiv v_s \gtrsim 10^7$ GeV

1-loop finite T effective potential

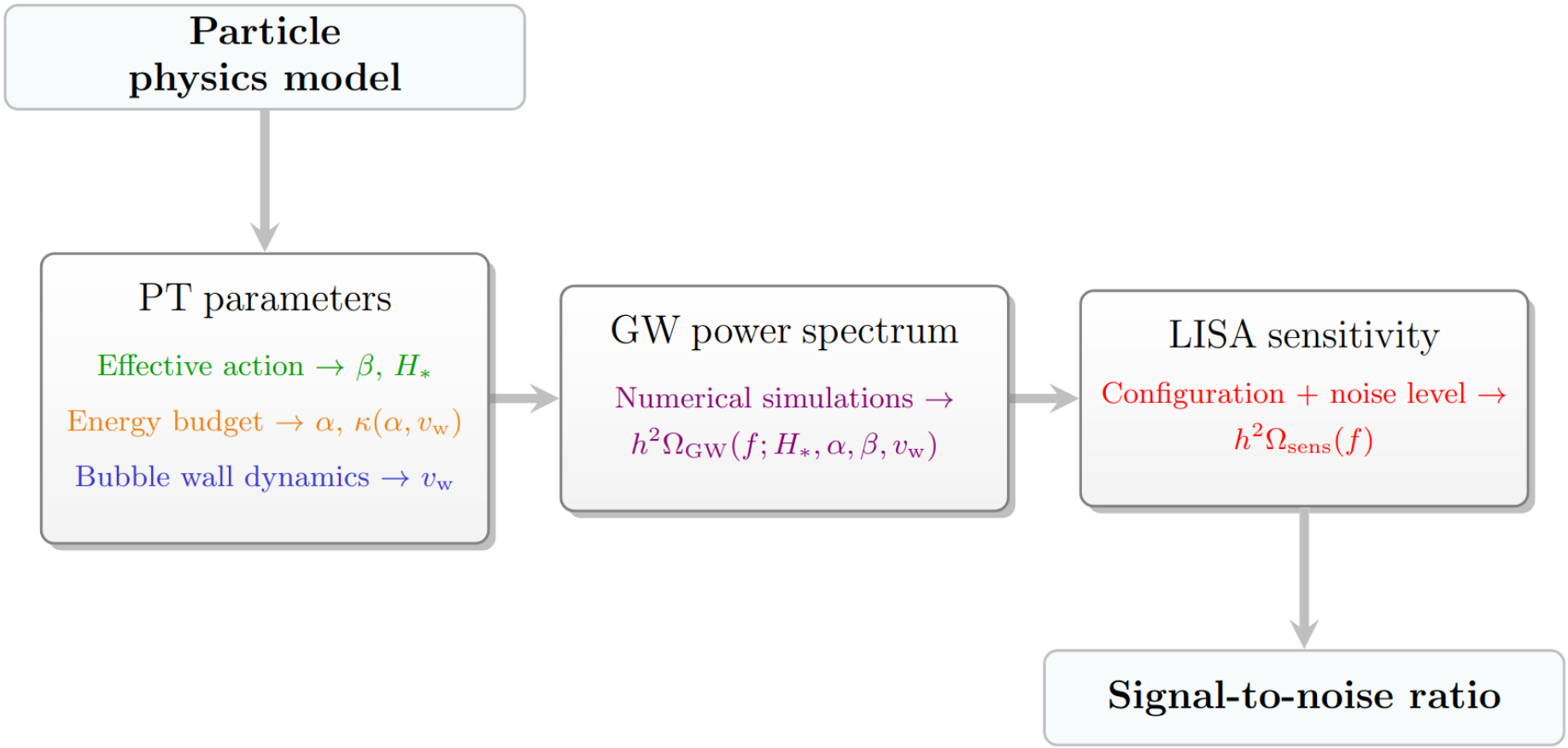
$V_{\rm CW}(S) + V_{\rm FT}(S,T) + V_{\rm daisy}(S,T)$



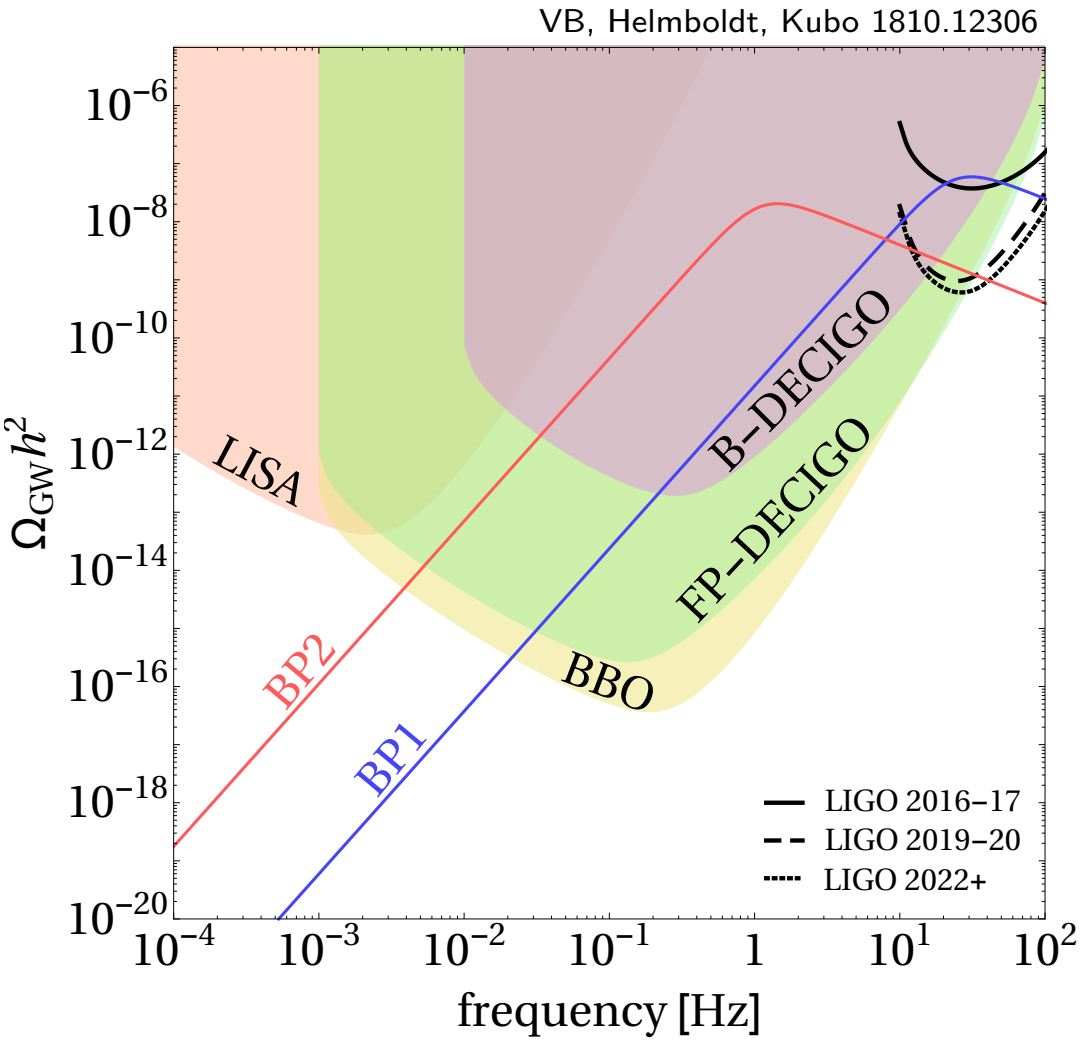


Cookbook

Caprini et al., 1910.13125



Gravitational Wave Spectrum



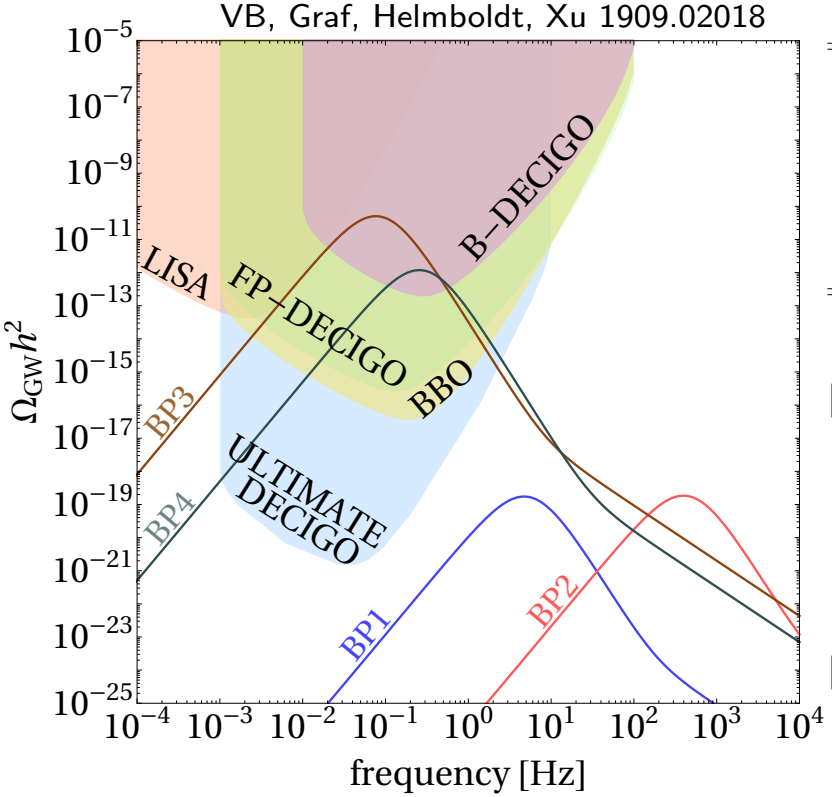
- viable parameter points can have $f_{\rm peak}$ at frequencies where LIGO is most sensitive $\Longrightarrow$ seesaw scales inaccessible in laboratory are tested

Left-Right Symmetric Model

1) $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ 2) $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

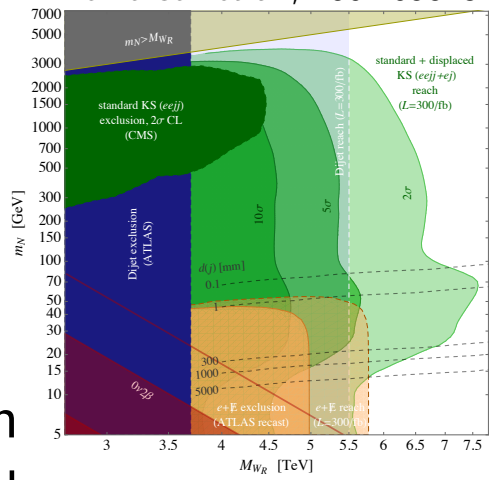
$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_2 \end{pmatrix} \qquad \langle \Delta_L \rangle = v_L \qquad \langle \Delta_R \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

VB, Graf, Helmboldt, Xu 1909.02018



	α	β/H	T_n [GeV]	T_c [GeV]
BP1	0.0035	4007	5896	6216
BP2	0.0034	3458	5.754×10^5	6.063×10^5
BP3	0.46	626.2	608.3	9451
BP4	0.17	1433	897.3	1468

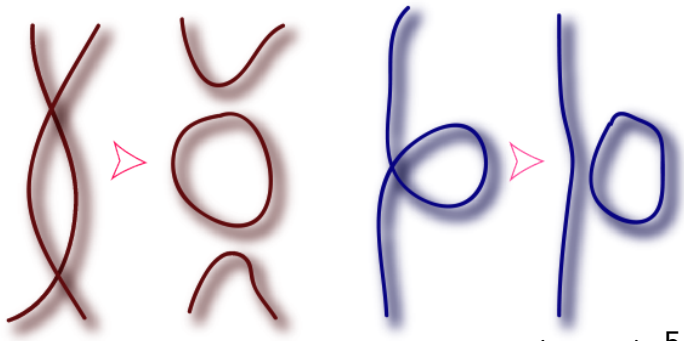
Nemevsek et al., 1801.05813



- dominant contribution from sound waves and magnetohydrodynamic turbulence
- gravitational waves as a complementary probe to collider tests

Gravitational Waves from Cosmic Strings

- long strings intersect and form loops which oscillate and emit energy in the form of GWs



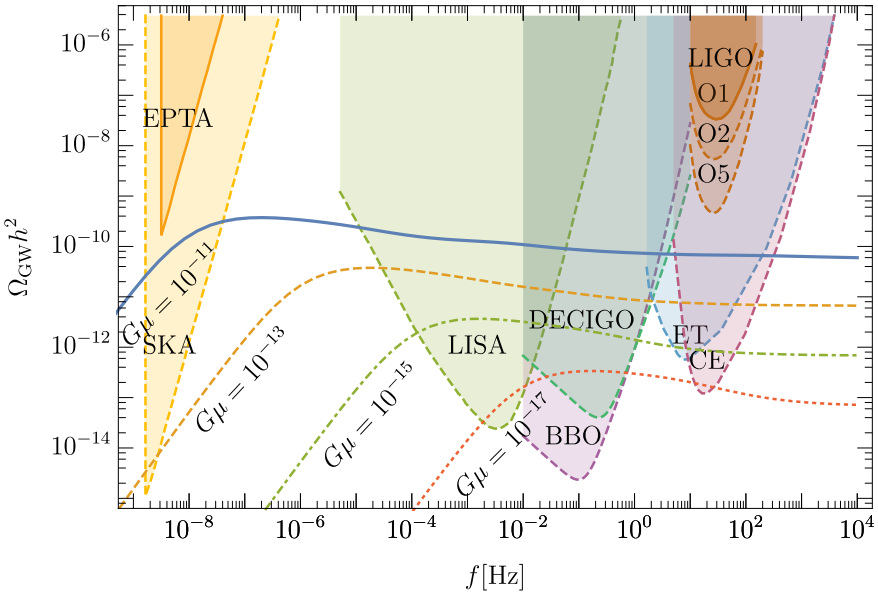
1711.03104, 1808.08968, 1909.00819

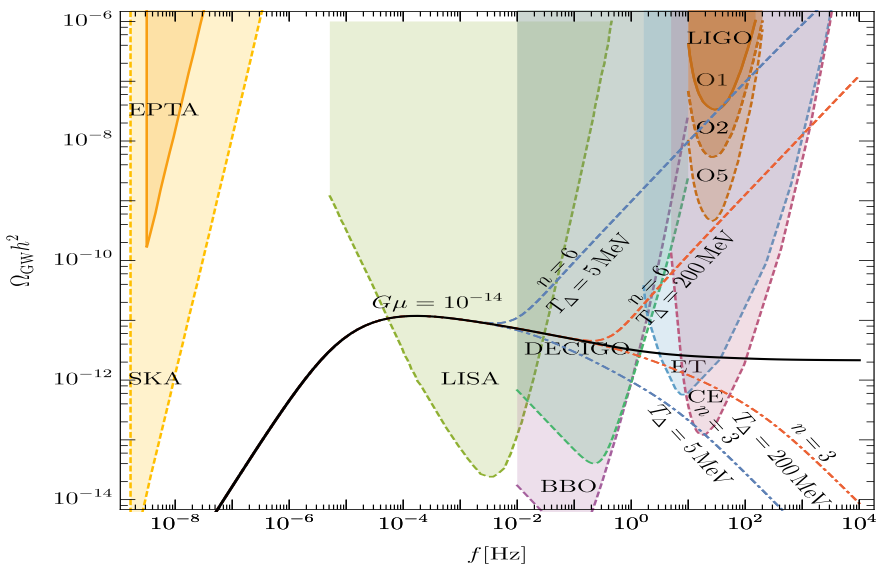
$$C_k(f) = \frac{2k}{f^2}\int_{t_{\rm scl}}^{t_0} dt \left(\frac{a(t)}{a(t_0)}\right)^5 n(\ell_k, t)$$

$$P_k = \frac{\Gamma}{k^q\,\zeta(q)};\ q = 4/3$$

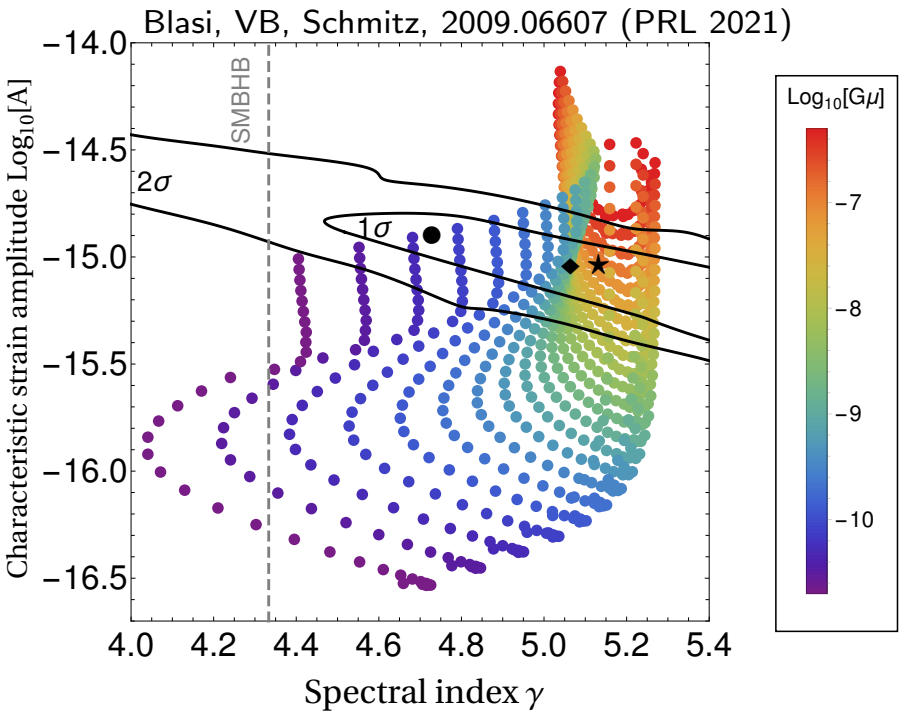
$$\Omega_{\rm gw}(f) = \sum_{k=1}^{\infty}\Omega_{\rm gw}^{(k)}(f) = \frac{8\pi}{3H_0^2}(G\mu)^2 f \sum_{k=1}^{\infty} C_k P_k$$

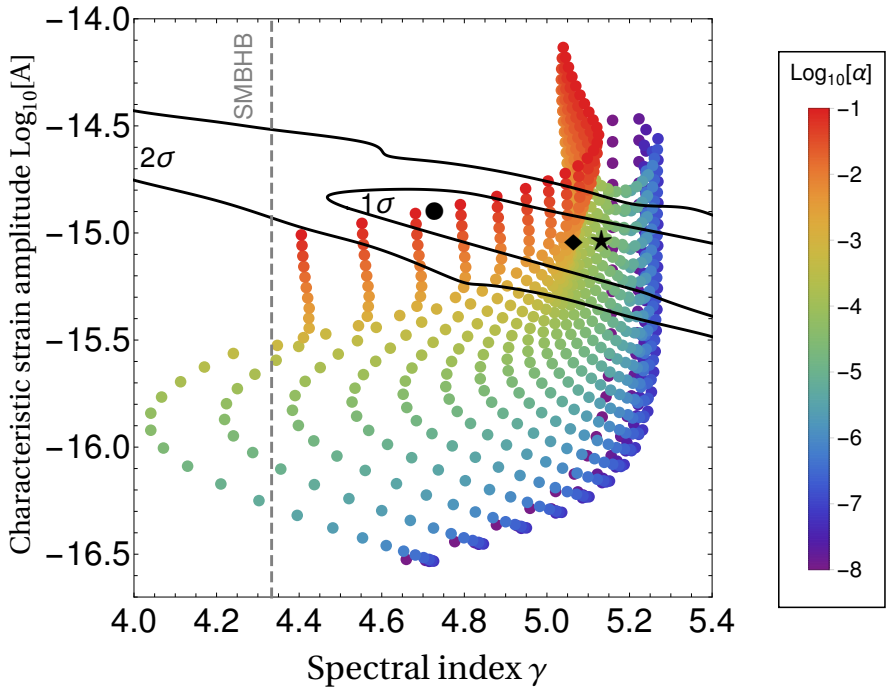
1808.08968





Cosmic String Explanation of NANOGrav Result

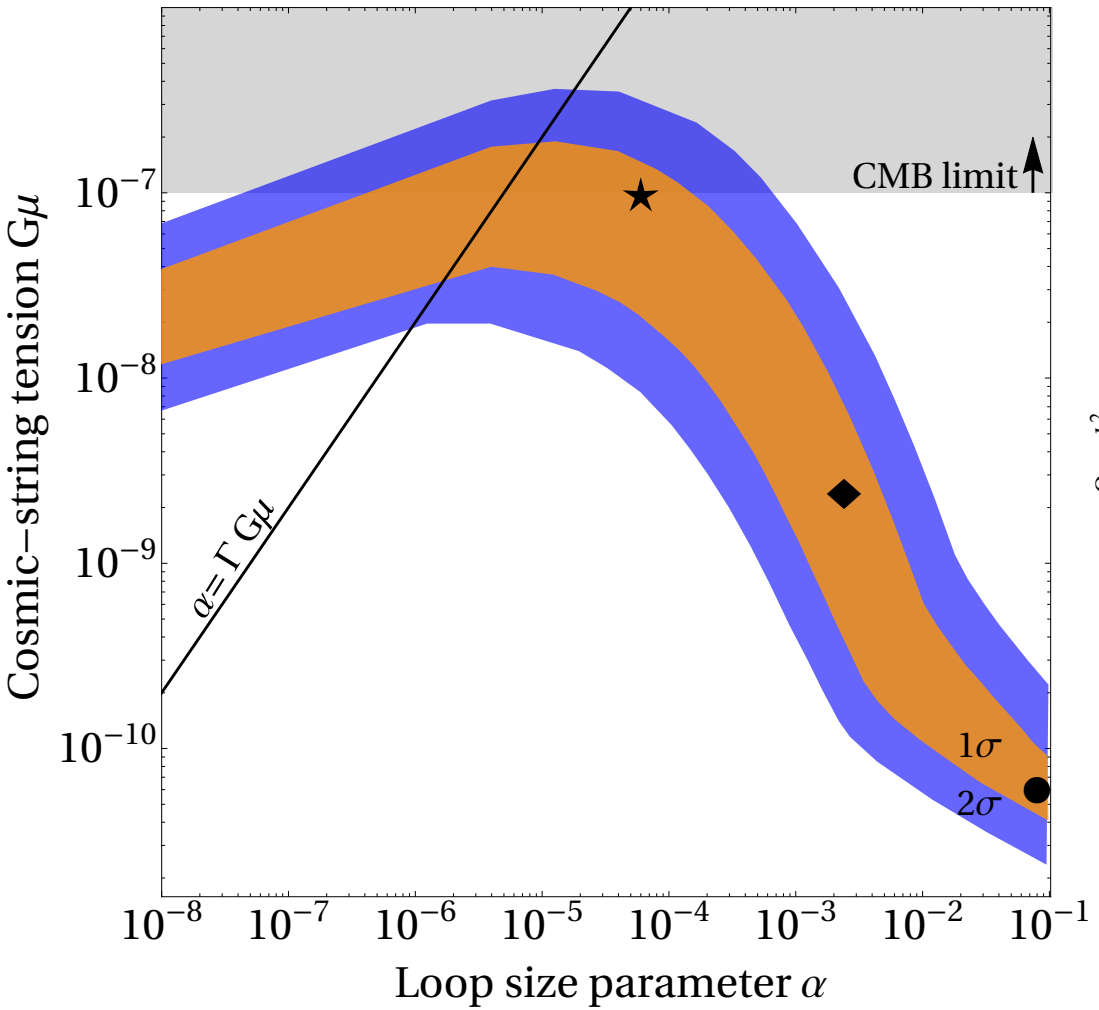


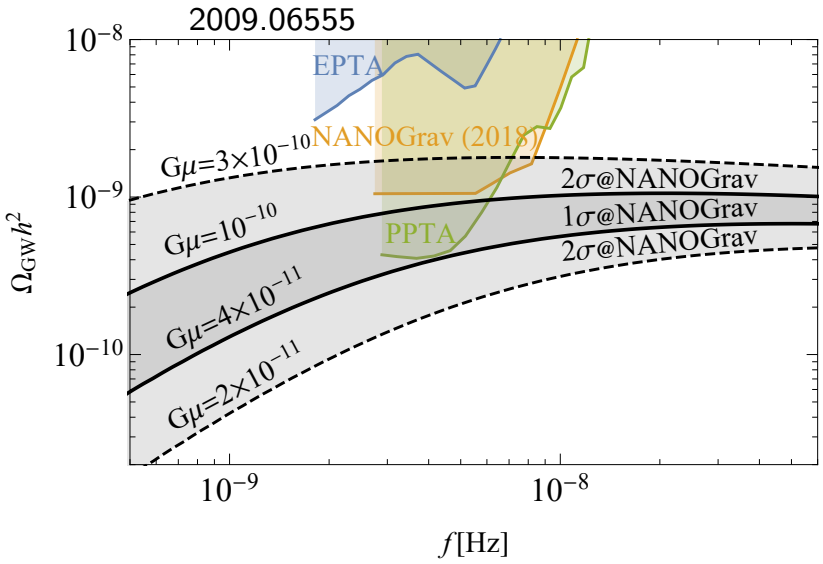


- cosmic-string-induced GW spectrum reproduces NANOGrav signal across large ranges of $G\mu$ and α

	α	$G\mu$	γ	A
★	6.0×10^{-5}	1.0×10^{-7}	5.13	9.25×10^{-16}
◆	2.4×10^{-3}	2.4×10^{-9}	5.06	9.20×10^{-16}
●	1.0×10^{-1}	6.0×10^{-11}	4.73	1.28×10^{-15}

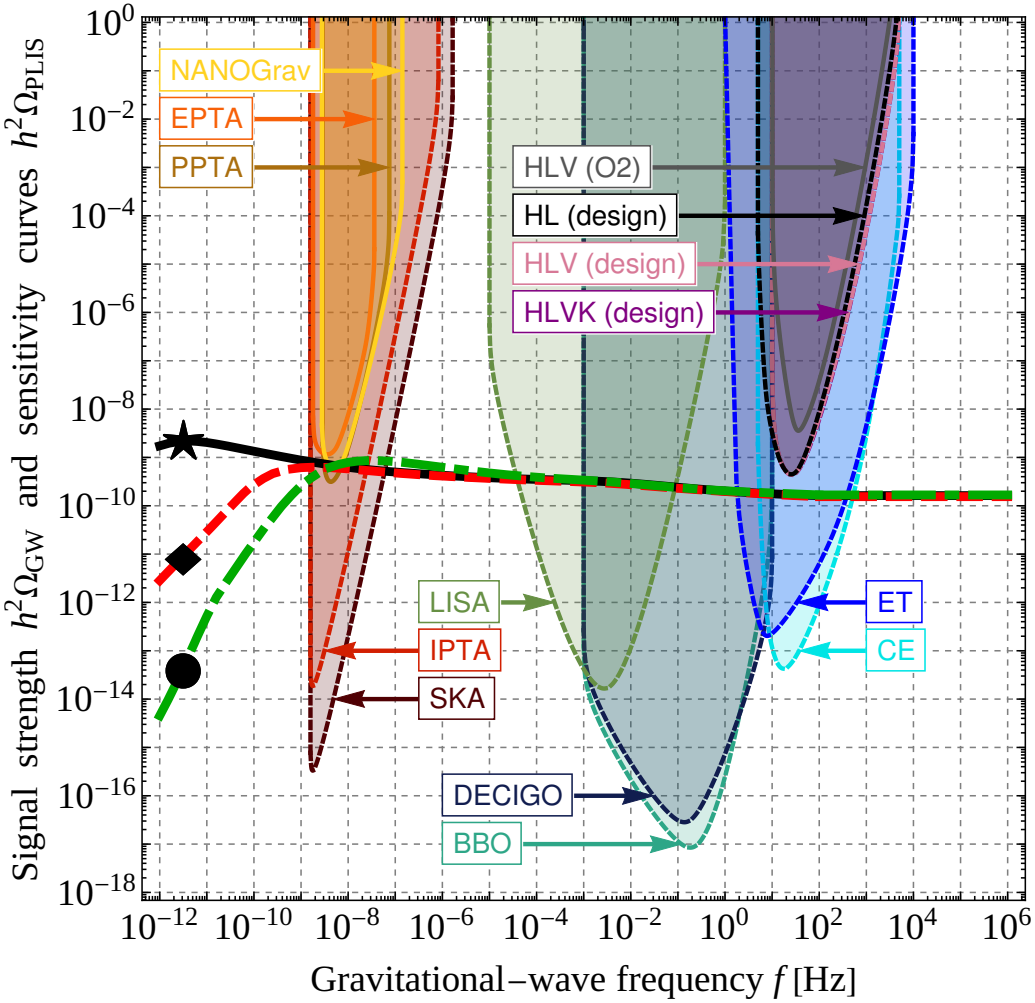
Cosmic String Explanation of NANOGrav Result





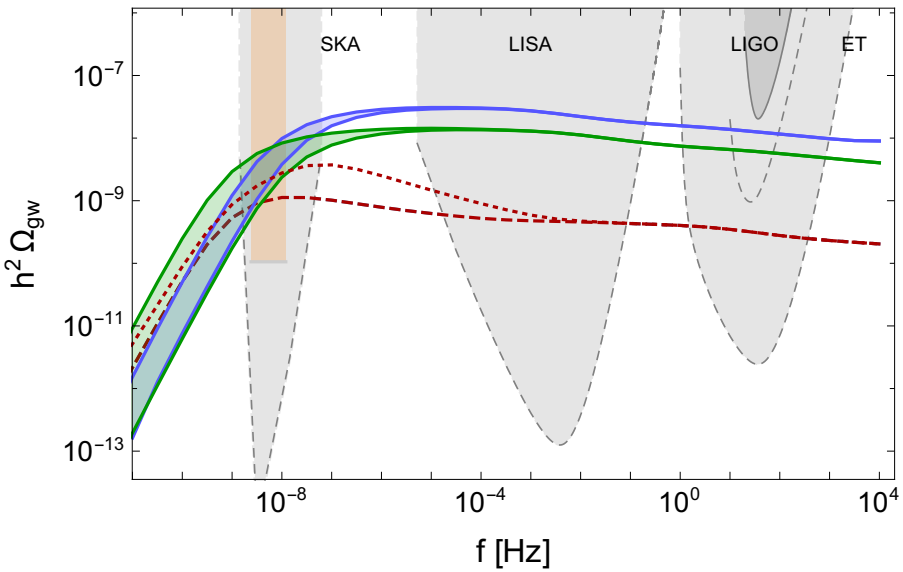
- solutions in the range $10^{-11} \lesssim G\mu \lesssim 10^{-6}$

Cosmic String Explanation of NANOGrav Result

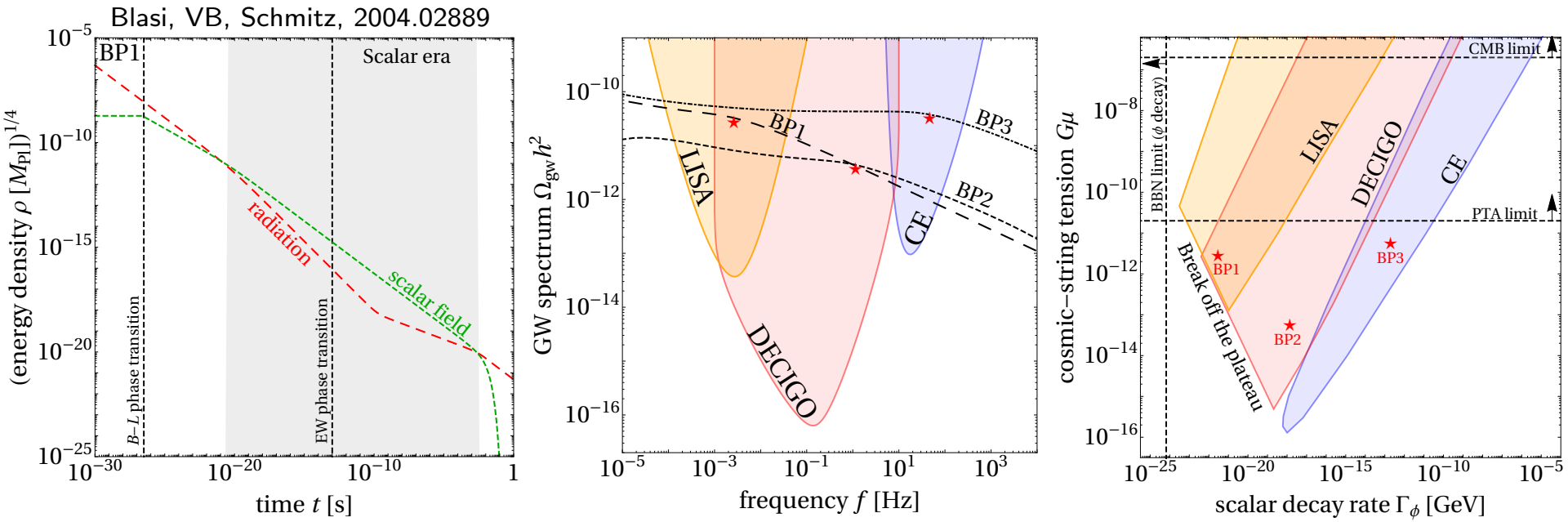


- the expected spectrum is within the sensitivity reach of LISA, DECIGO, BBO, the *Einstein Telescope*, and *Cosmic Explorer*
- LIGO+Virgo+KAGRA will not be able to detect the signal at a sufficient signal-to-noise ratio but...

Metastable cosmic strings, 2009.10649



Fingerprint of Low-Scale Leptogenesis



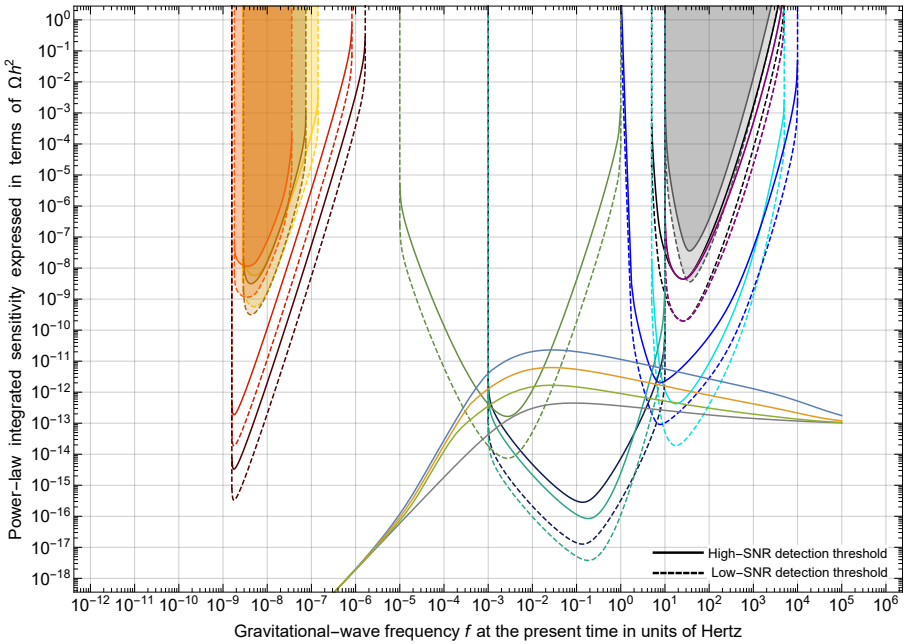
- detecting a characteristically shaped break in the GW spectrum would represent a smoking gun for a scalar era after the phase transition
- realization in a minimal gauged $B - L$ model
- weakly coupled scalar $\rightarrow$ separation of scales:

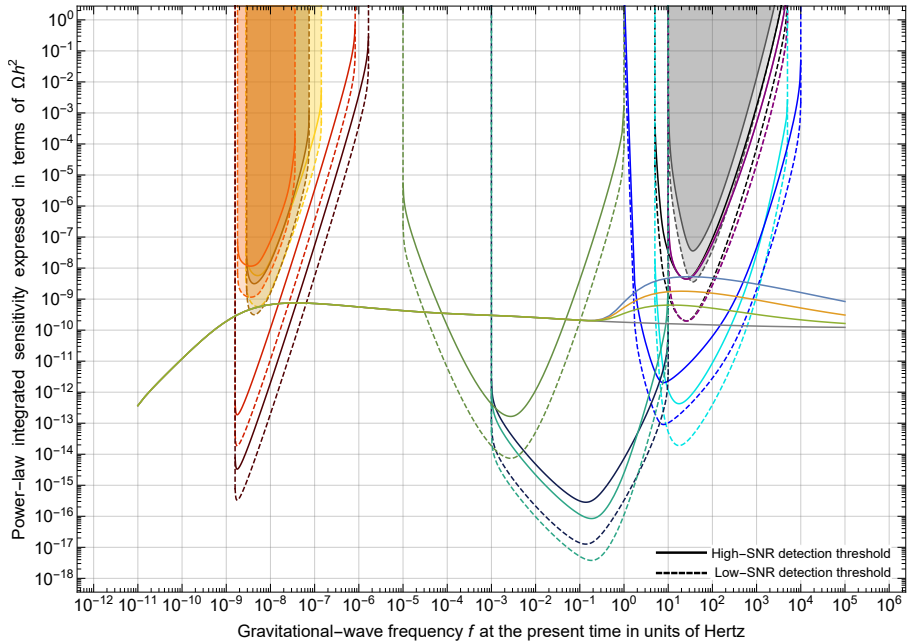
scalar mass scale (unification)

RHN mass scale (low-scale leptogenesis motivated by naturalness)

Beyond Vanilla Cosmic Strings

Auclair, Blasi, VB, Schmitz, 21xx.xxxxx





- current-carrying strings can induce an enhancement in the spectrum

Summary

- Exciting prospects regarding the testability of stochastic gravitational wave background

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- New physics effects through first-order phase transitions, cosmic strings...
- Powerful probe of new physics across the scales
- Synergy with other phenomena in high-energy physics (generation of neutrino masses, leptogenesis...)