Gravitational Waves from the Early Universe

Lecture 3B: Current Developments and Outlook

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Chung-Ang University, Seoul, South Korea | June 2 – 4

NANOGrav Collaboration: 2009.04496

Strong evidence for a new stochastic *common-spectrum* process at low frequencies:

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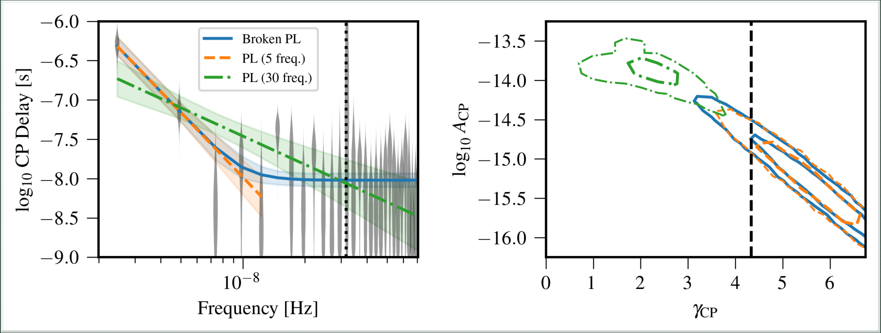

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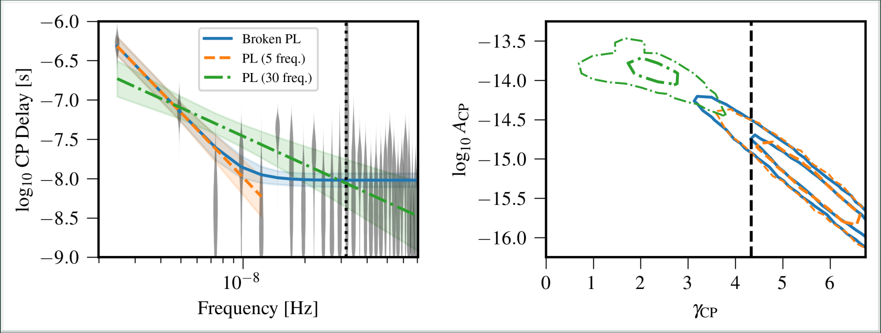

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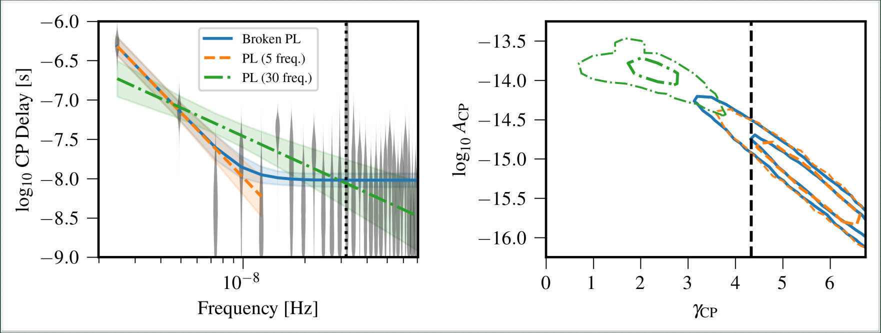

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- New signal in the timing-residual cross power spectrum; described by power-law fit:

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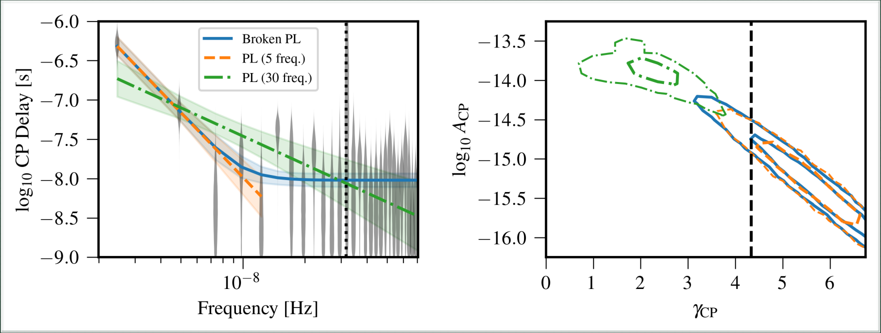

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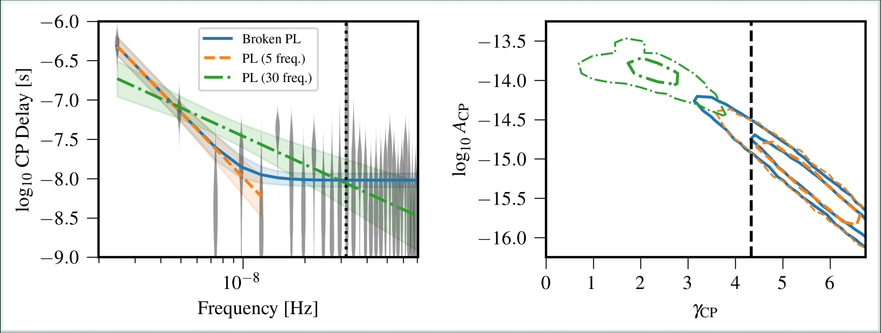

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- Consistent with the stagnation of upper bounds in recent years
- Systematics? Pulsar spin noise, solar-system effects, ... Let us assume the signal is real!

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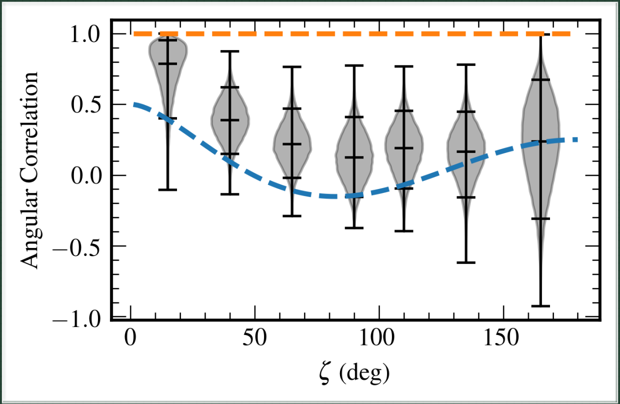

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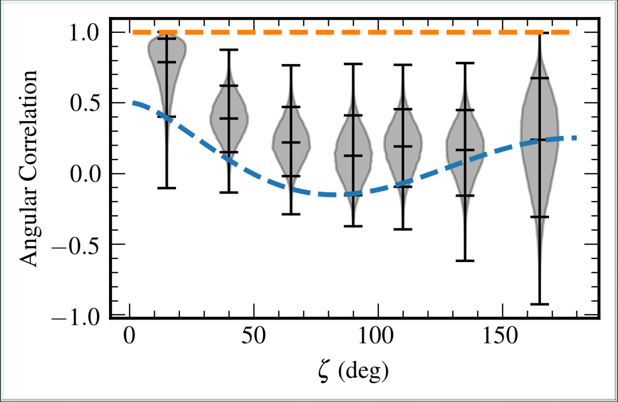

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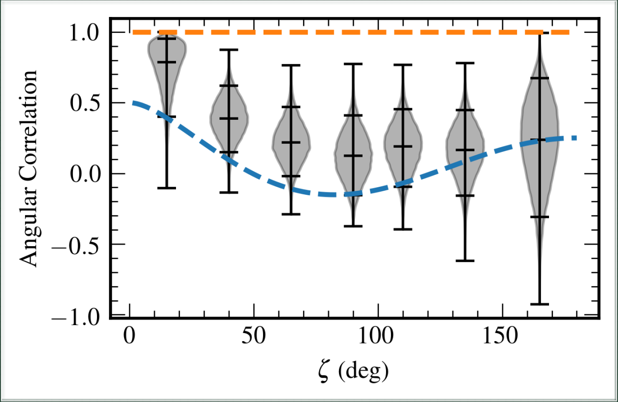

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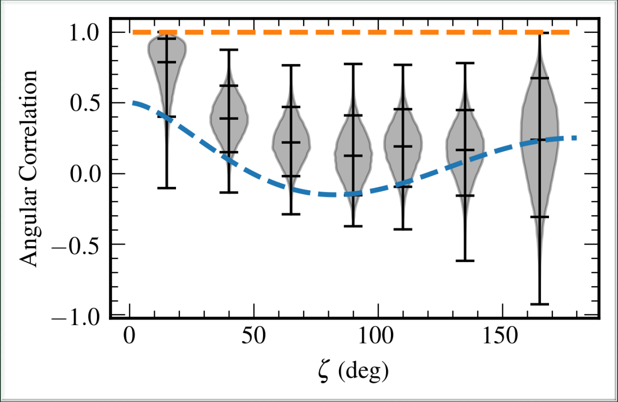

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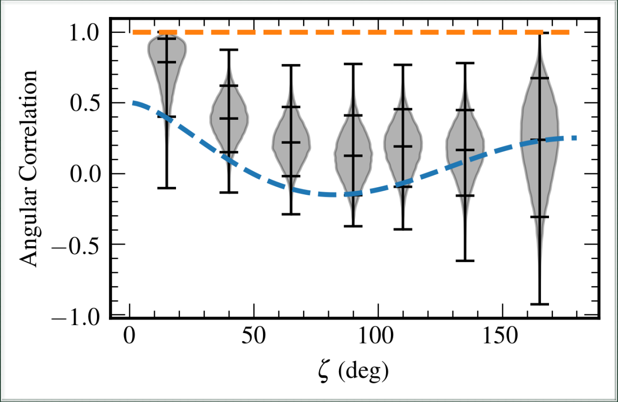

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- No-correlations hypothesis mildly rejected at p value of around $p \sim 0.05$, that is, $2\,\sigma$

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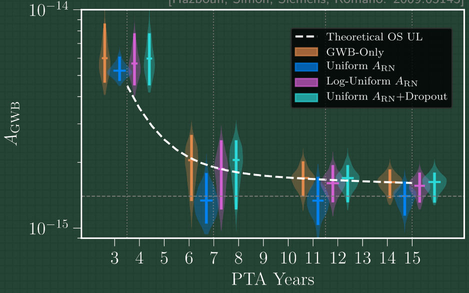
[Hazboun, Simon, Siemens, Romano: 2009.05143]



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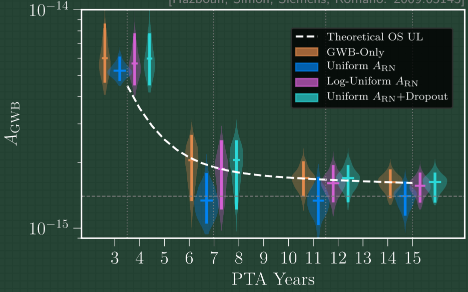

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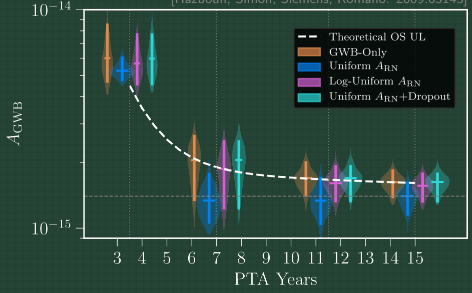

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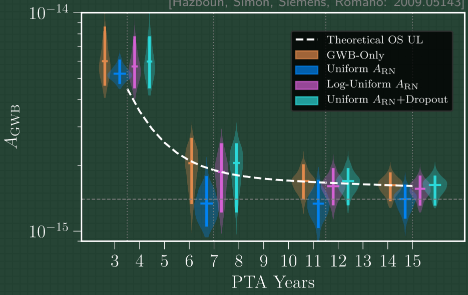

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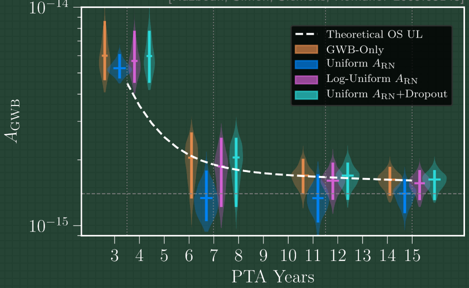

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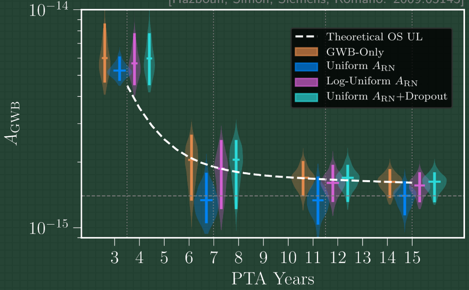

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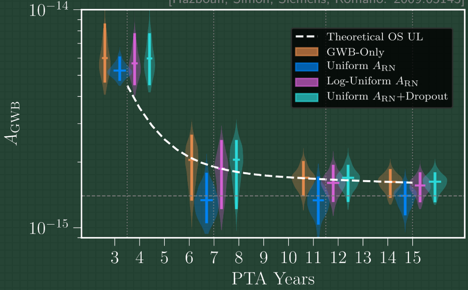

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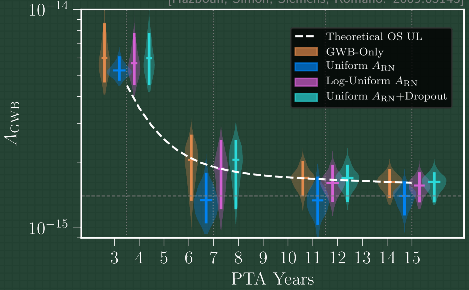

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Solution: More data, larger signal-to-noise ratio! Again, let us assume the signal is real.

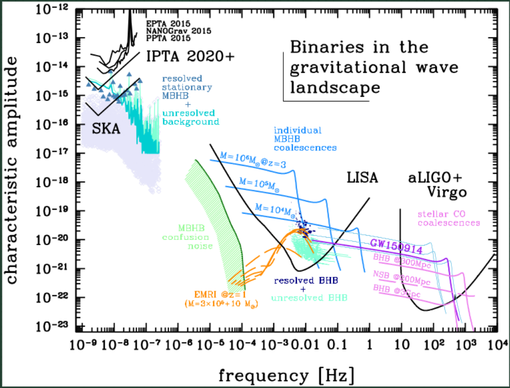
Outline Lecture 3B

1. NANOGrav signal
2. Possible interpretations
3. Cosmic strings
4. Outlook
5. Summary

Supermassive black-hole binaries

- Binaries of supermassive black holes believed to form during galaxy mergers

[De Rosa et al.: 2001.06293]



Astrophysical interpretation

Supermassive black-hole binaries

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- Characteristic GW strain h_c

$$S(f) \propto \frac{h_c^2(f)}{f^3} \qquad (2)$$

$$h_c(f) = A\left(\frac{f}{f_{\rm yr}}\right)^{-2/3} \qquad (3)$$

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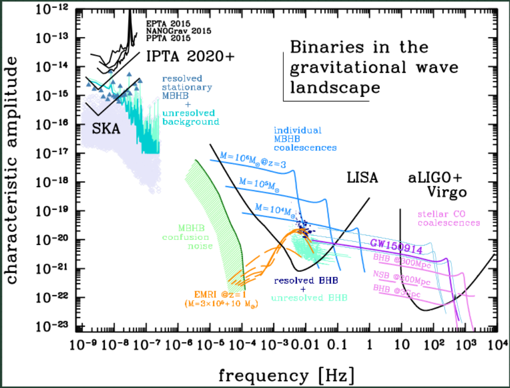

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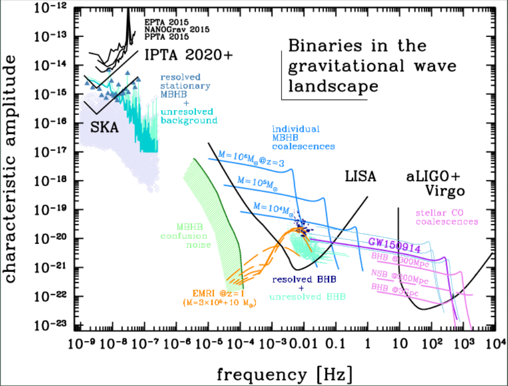

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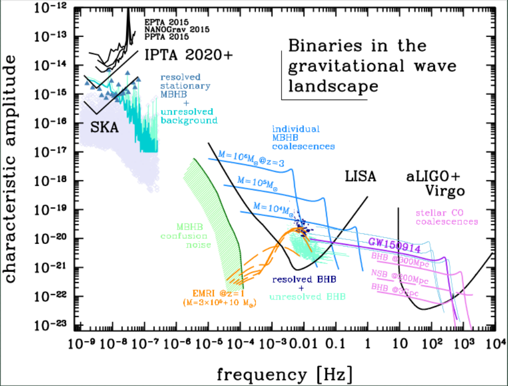

Unknowns: Origin of seeds? Growth history? Binary formation? Merger rate? Final-parsec problem: How to achieve enough dynamical friction such that close binary forms within the age of the Universe? Lots of ideas in the literature, but in the end we need more data.

GW signal from supermassive black-hole binaries

A practical theorem on SGWBs: [Phinney: astro-ph/0108028]

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Total GW energy emitted by a population of mergers across cosmic history:

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Circular binary with component masses M_1 and M_2 in the Newtonian limit:

$$\frac{dE_{\rm GW}}{d\,(\ln f_r)} = \frac{1}{3G}\,(\pi f_r)^{2/3}\left(G\mathcal{M}_{\rm chirp}\right)^{5/3}\,, \qquad \mathcal{M}_{\rm chirp} = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}} \tag{5}$$

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$$\frac{dE_{\rm GW}}{d\left(\ln f_r\right)} = \frac{1}{3G}\left(\pi f_r\right)^{2/3}\left(G\mathcal{M}_{\rm chirp}\right)^{5/3}, \qquad \mathcal{M}_{\rm chirp} = \frac{\left(M_1 M_2\right)^{3/5}}{\left(M_1+M_2\right)^{1/5}} \tag{5}$$

Frequency dependence of the stochastic background from supermassive black-hole binaries:

$$\boxed{\Omega_{\rm GW}\left(f\right) = \frac{2\pi^2}{3\,H_0^2}\, f^2 h_c^2(f) \propto f^{2/3}\,, \qquad h_c\left(f\right) \propto f^{-2/3}} \tag{6}$$

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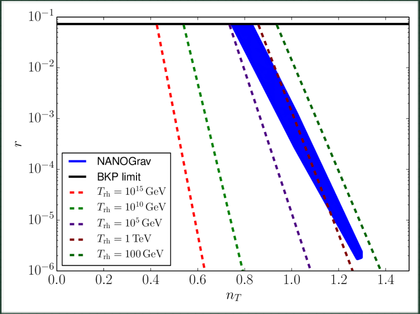

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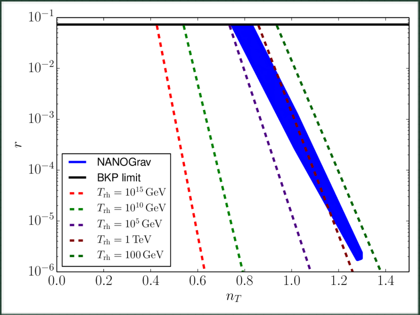

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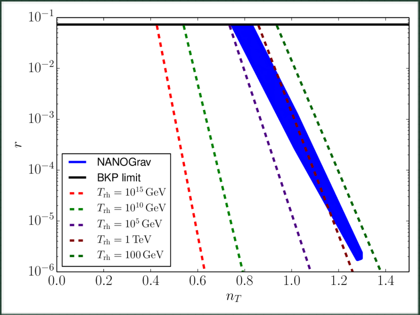

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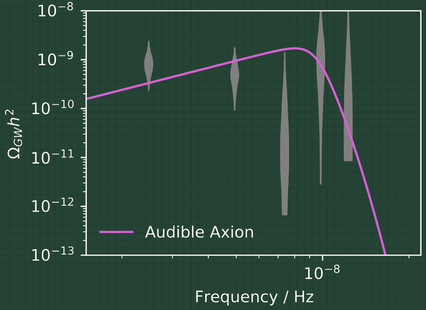

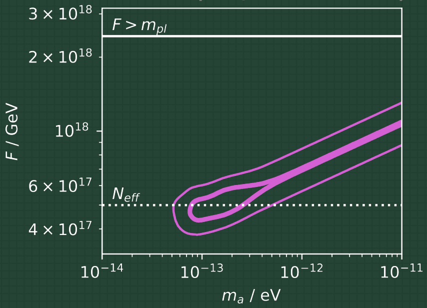

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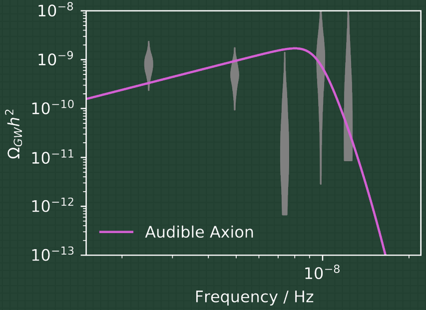

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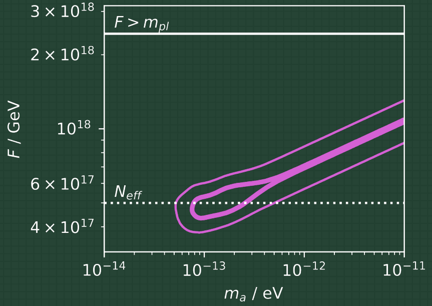

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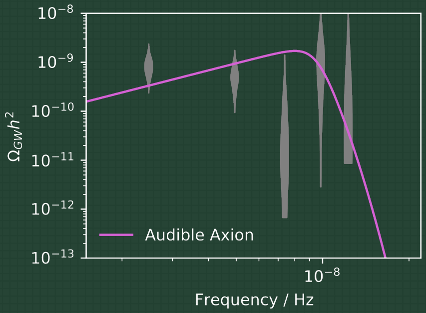

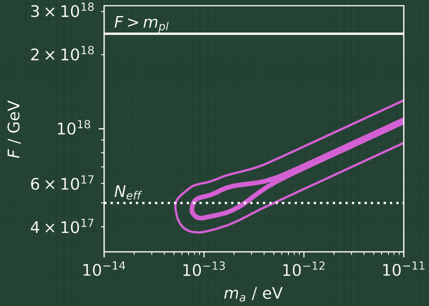

- NANOGrav constraint on parameter space competitive with $N_{\rm eff}$
- Future probes: Axion experiments (CASPEr), black-hole superradiance

Global axion strings

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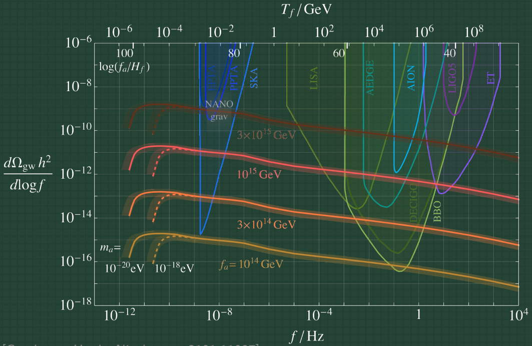

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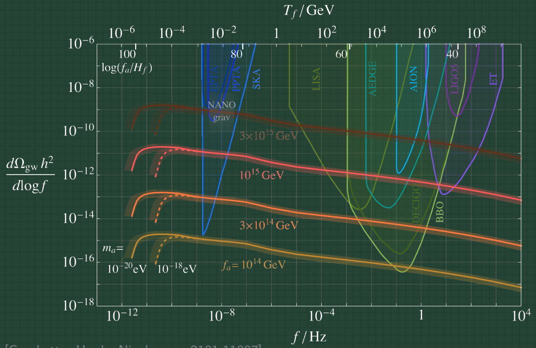

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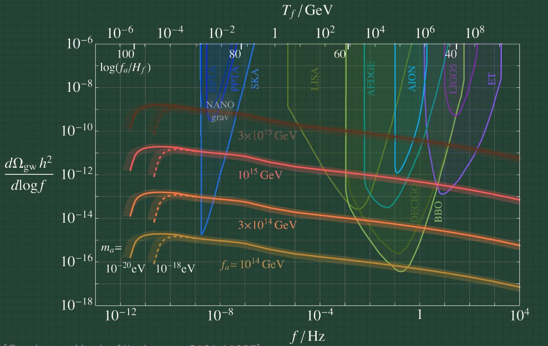

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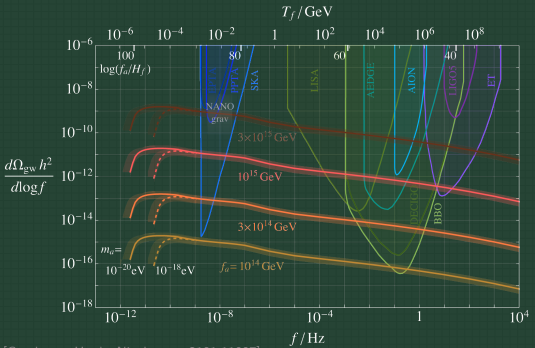

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Local strings more attractive explanation of the signal!?

Primordial black holes

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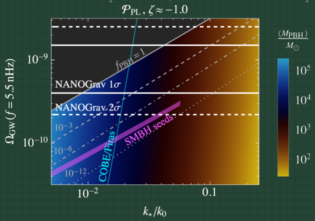

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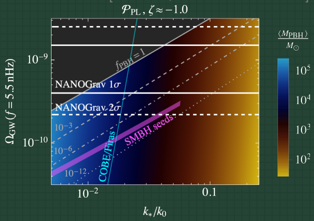

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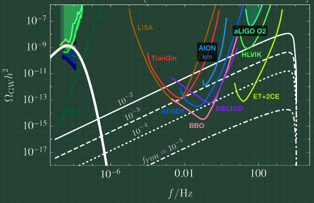

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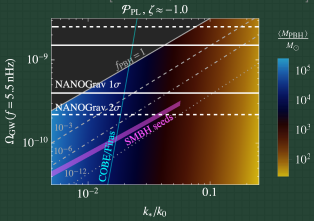

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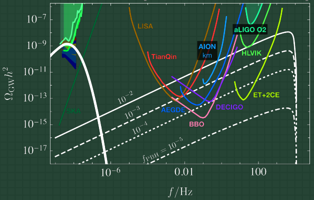

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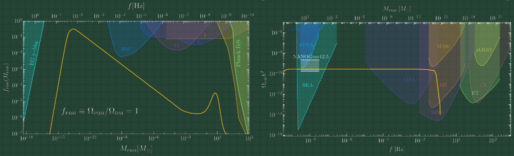

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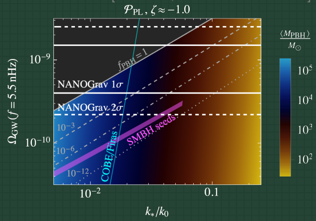

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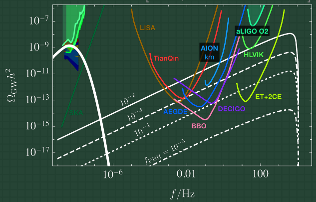

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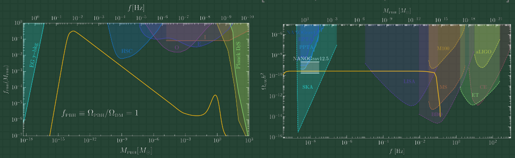

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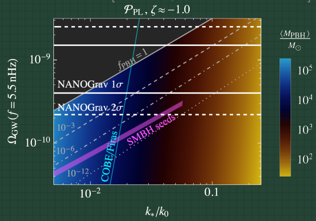

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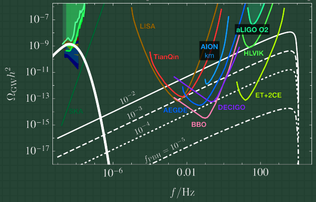

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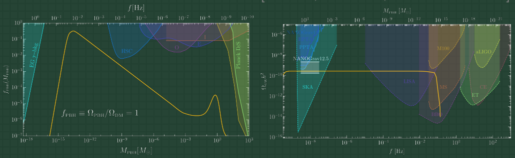

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Range of predictions reflects uncertainties and opportunities of this mechanism. Open questions:

- Input scalar power spectrum
- Press–Schechter formalism versus peak theory
- Window function to smooth density perturbations
- Threshold for PBH formation, critical collapse

Phase transitions

Mechanism: Strong first-order cosmological phase transition → GWs from:

- Collisions of vacuum bubbles (strongly supercooled phase transitions)
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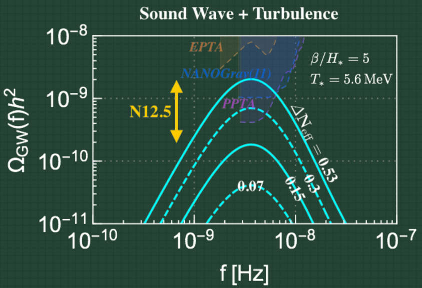

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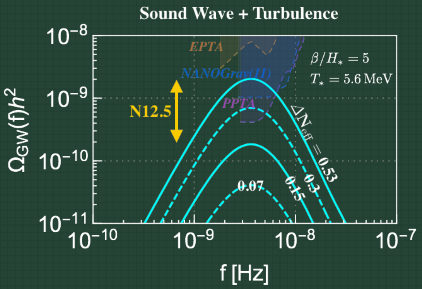

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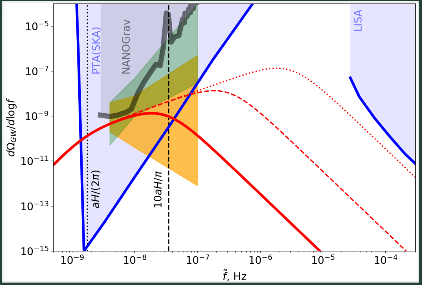
[Neronov, Pol, Caprini, Semikoz: 2009.14174]



- Magnetohydrodynamic turbulence during first-order QCD phase transition (nonstandard lepton asymmetry)
- Magnetic field relaxes H_0 tension

Nambu–Goto strings

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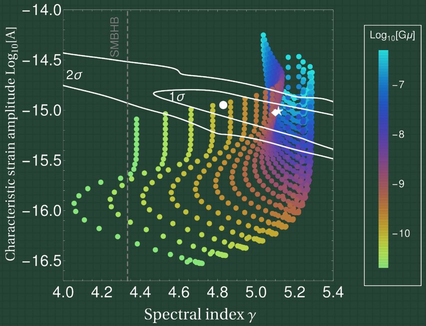

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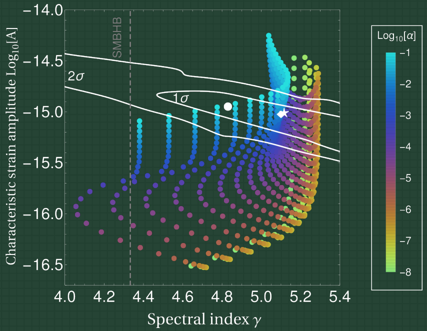

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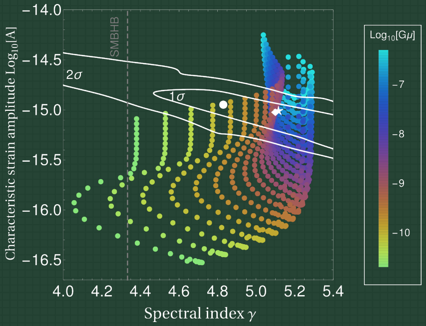

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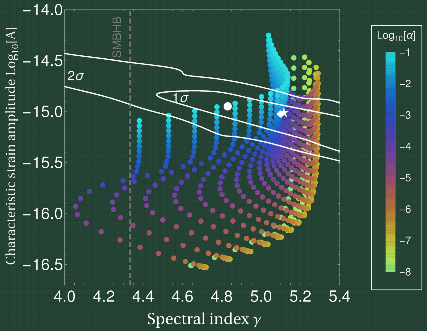

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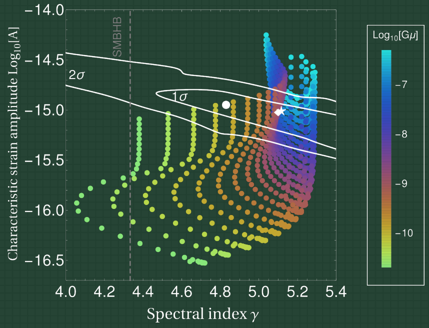
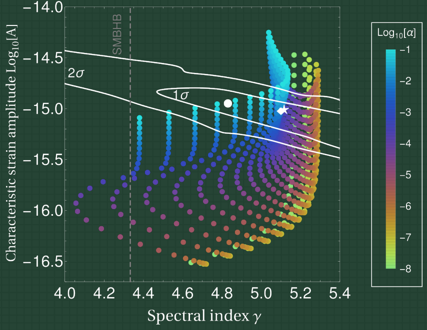
- Fit GW spectrum in the NANOGrav frequency range by a power law, convert to γ and A

Nambu–Goto strings

Mechanism: Spontaneous breaking of a local $U(1)$ symmetry $\to$ scaling network of local cosmic strings $\to$ GW emission by cosmic-string loops in the Nambu–Goto approximation

[Blasi, Brdar, **KS**: 2009.06607]
[See also Ellis, Lewicki: 2009.06555]





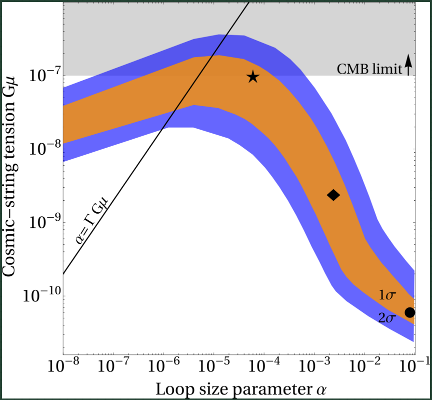
Color code: String tension $G\mu$

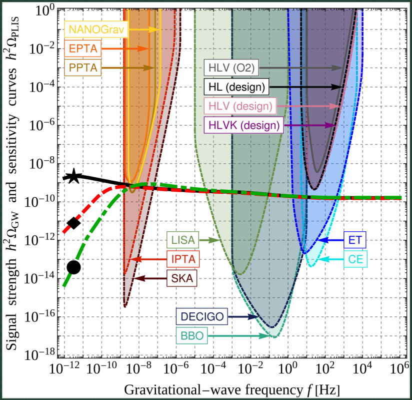
Color code: Loop size α

- Fit GW spectrum in the NANOGrav frequency range by a power law, convert to γ and A
- Straightforward to populate the NANOGrav $1\,\sigma$ and $2\,\sigma$ regions, compare to SMBHs

Observational prospects

[Blasi, Brdar, **KS**: 2009.06607]





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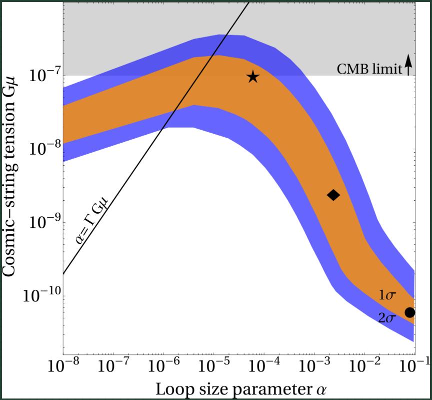

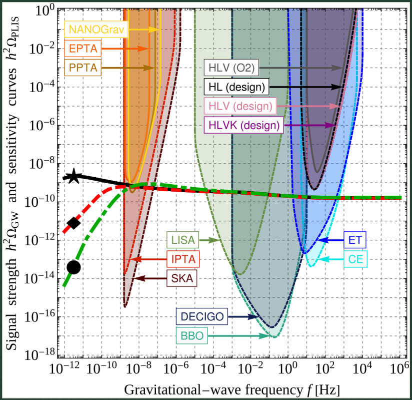

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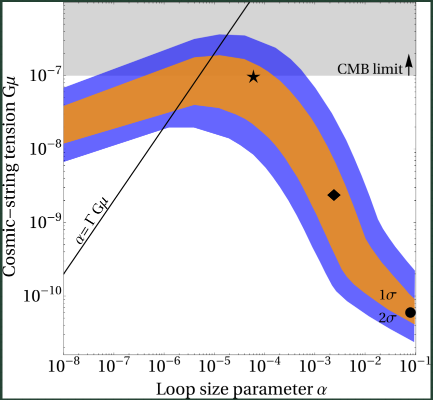

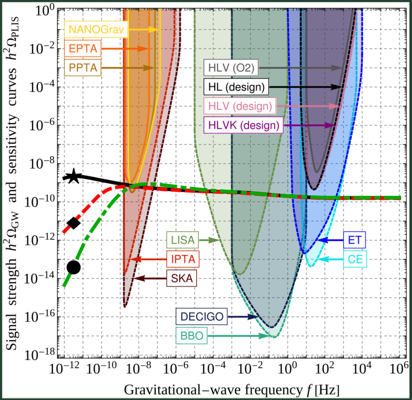

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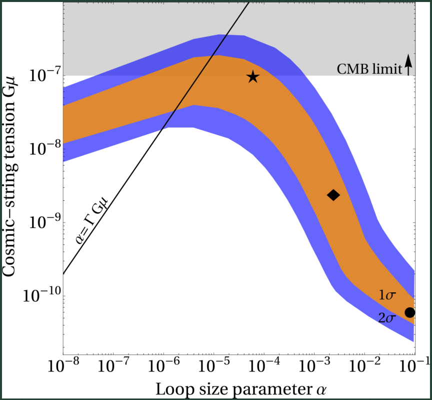

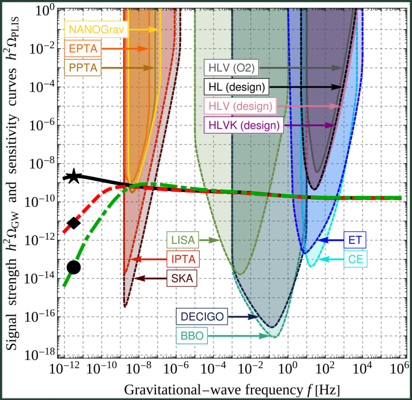

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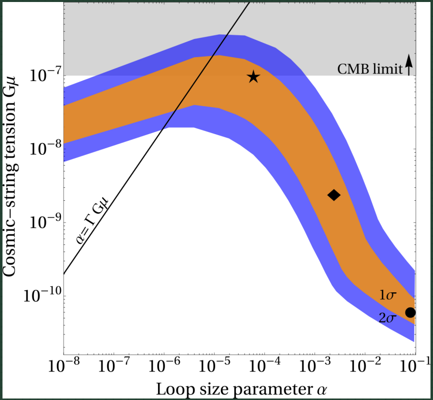

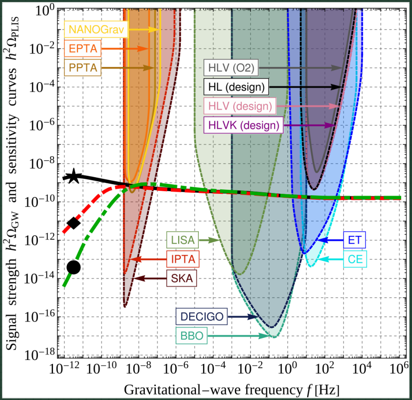

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- Consistent with the idea of $U(1)$ symmetry breaking in the context of grand unification

Right-handed neutrinos

Possible origin of cosmic strings in particle physics: Seesaw extension of the Standard Model

Right-handed neutrinos

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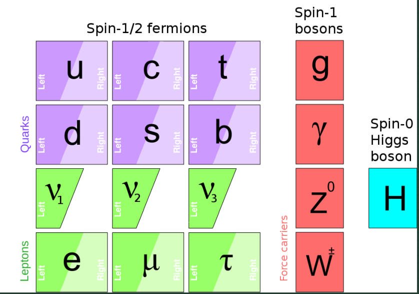

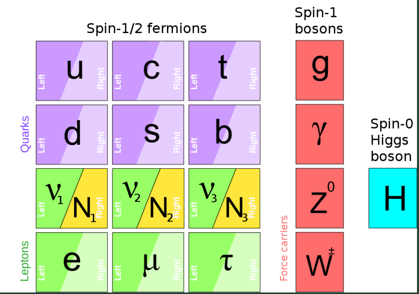

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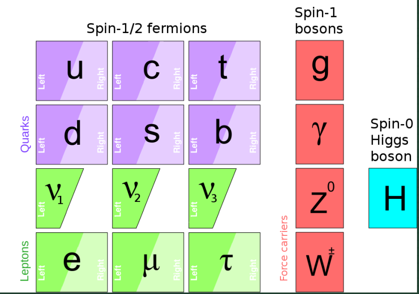

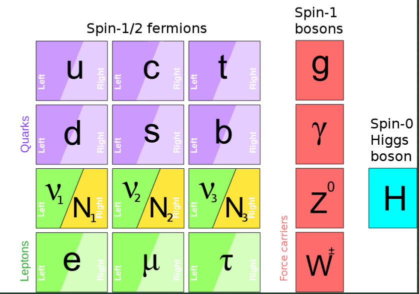

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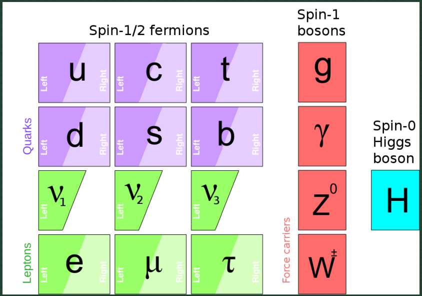

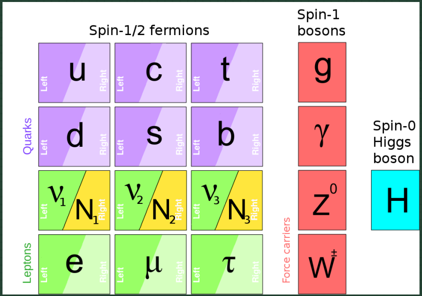

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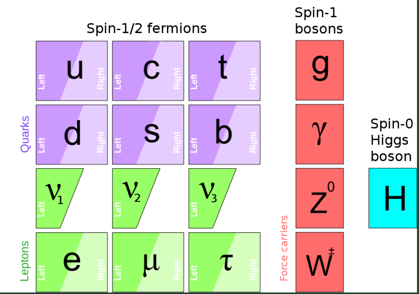

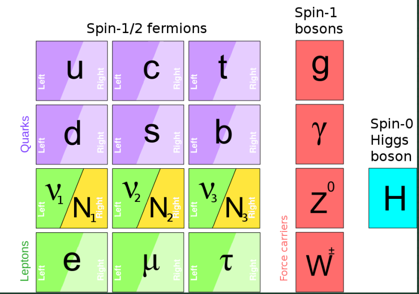

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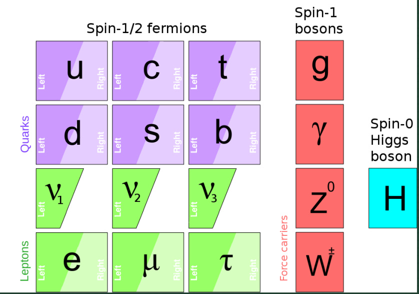

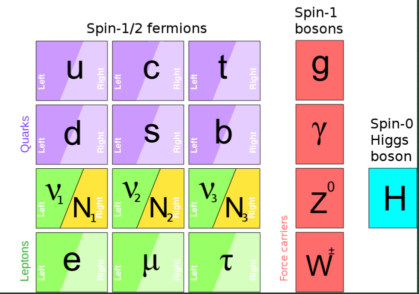

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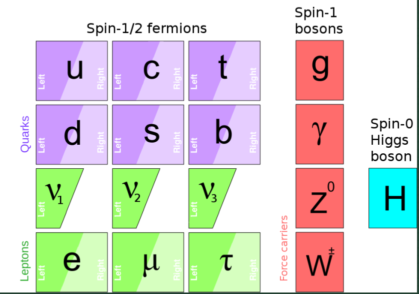

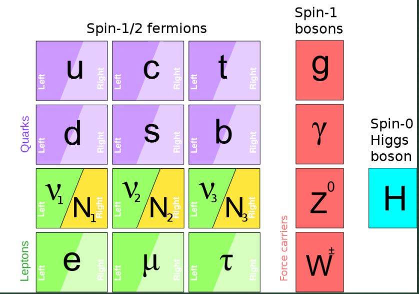

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Breaking of $U(1)_{B-L}$ in the early Universe generates large right-handed-neutrino masses.

Cosmic strings and leptogenesis

Cosmic $B - L$ strings $\rightarrow$ ideal candidates for cosmic strings created in the early Universe!

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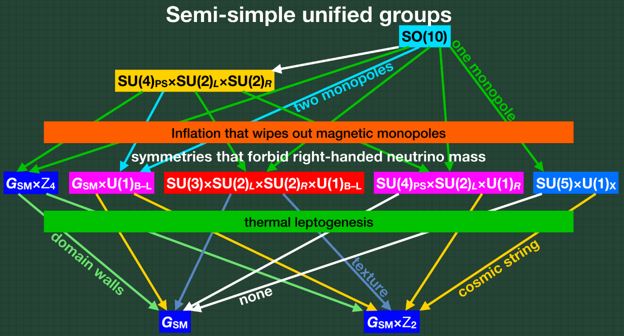

[Dror, Hiramatsu, Kohri, Murayama, White: 1908.03227]

General picture:

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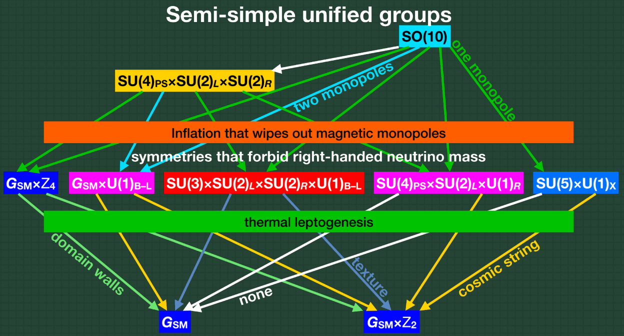

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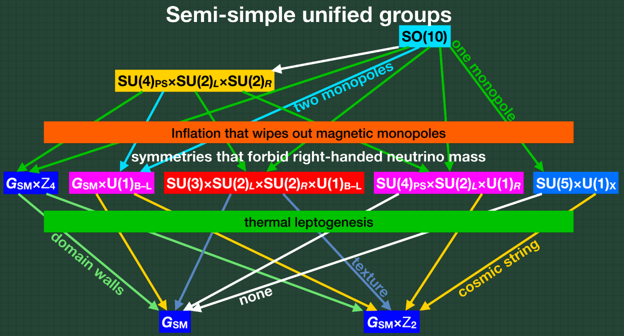

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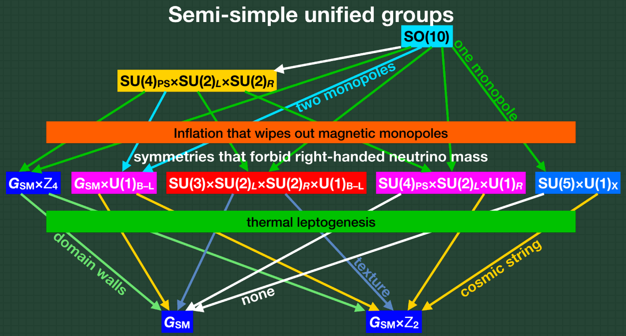

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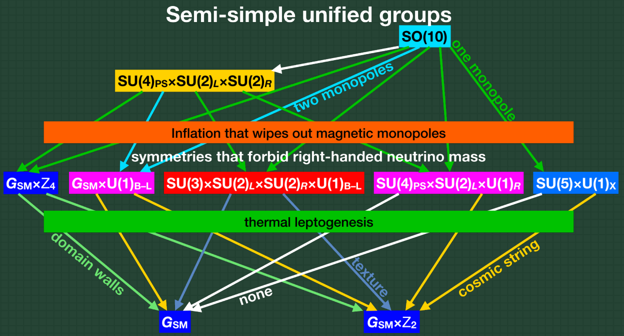

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General picture:

- Seesaw extension of the SM embedded in a grand unified theory
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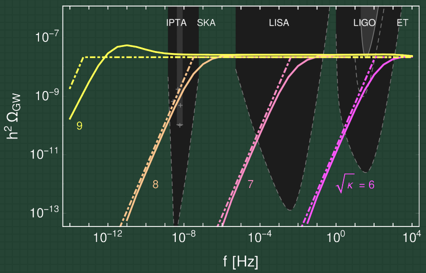
- Massive right-handed neutrinos explain neutrino oscillations and baryon asymmetry
- Spontaneous symmetry breaking also results in cosmic strings and hence GWs

On-going research

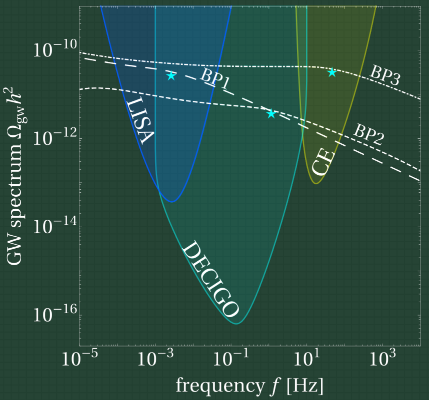
[Buchmuller, Domcke, Murayama, Schmitz: 1912.03695]



Metastable strings:

- Embed $U(1)$ in larger gauge group whose breaking does not lead to cosmic strings, e.g., $SO(10)$
- Cosmic strings unstable against Schwinger pair production of $SO(10)$ monopole–antimonopole pairs
- Strings decay in the early Universe; characteristic drop in the GW spectrum at higher frequencies than usual

[Blasi, Brdar, Schmitz: 2004.02889]

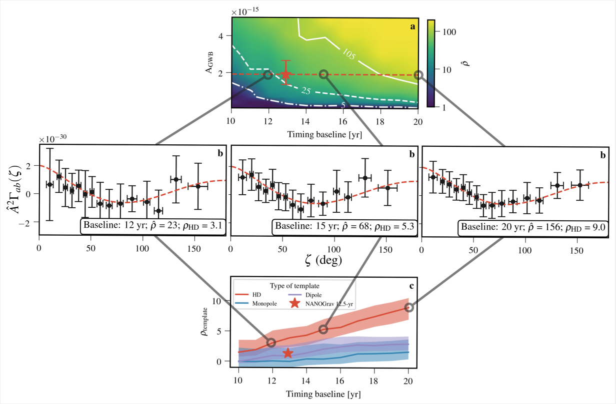


Scalar era after $U(1)$ breaking:

- Assume second-order phase transition and long-lived $U(1)$-breaking field
- Matter domination, effect on transfer function, break in the GW spectrum

Projection based on emulated data

[NANOGrav Collaboration: 2010.11950]



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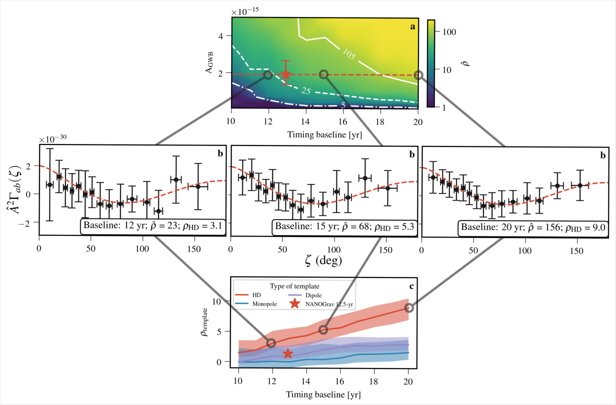

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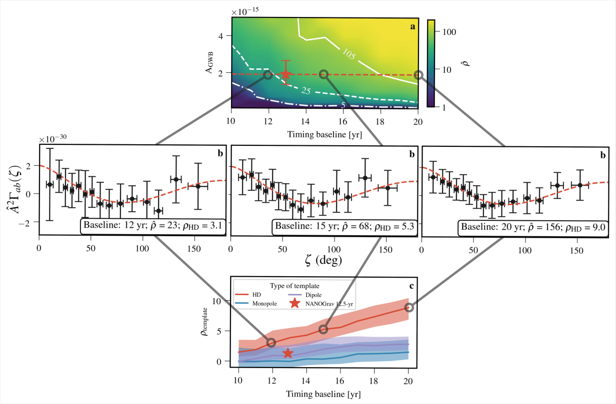

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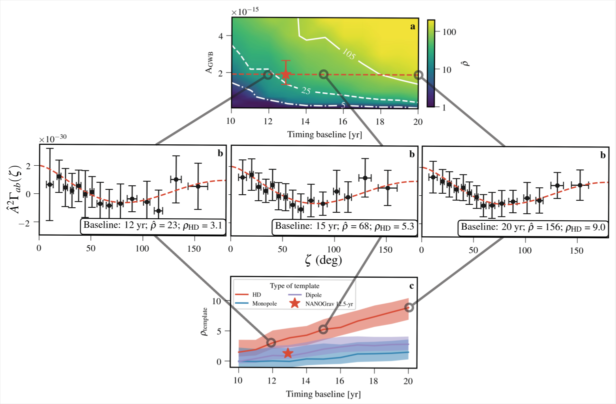

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- However, much *faster* progress for combined data sets and more pulsars

More data and analyses

NANOGrav + other data sets:

2010.06109: *"The second IPTA data release includes the 9-year NANOGrav data set alongside EPTA and PPTA timing observations. The analysis of this joint data set is ongoing, and early results are again consistent with those discussed here."*

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NANOGrav 15-year data set on the horizon: 2.5 more years of data, $20+$ new pulsars

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[Goncharov et al.: 2010.06109]

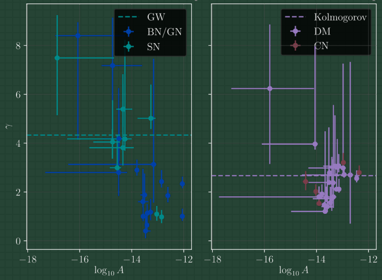

Figure 1. Strength and spectral index for red noise processes for the PPTA-DR2 pulsars. Left panel: spin noise (SN), band noise (BN) and system noise (GN). Right panel: DM noise and chromatic noise (CN) with strength referenced to $K = 1400$ MHz. The main feature of the left panel is the clustering of red noise parameters around two areas of the parameter space: where γ is between 3 and 10 (mostly spin noise), and where γ is between 0 and 3 (mostly band noise and system noise). For some pulsars, we found only marginal preference to choose between competing noise models with band and system noise, see Section 4.1 for more details. The green dashed line in the right panel highlights $\gamma = 8/3$, predicted for the standard model of DM variations from Kolmogorov turbulence. The red dashed line (GW) highlights the spectral index $\gamma = 13/3$, predicted for a red noise process induced by the stochastic gravitational-wave background. The three pulsars with spin-noise power-law index closest to 13/3 correspond to the top strongest contributors to the common red noise in Arzoumanian et al. (2020), which are visible from Parkes.

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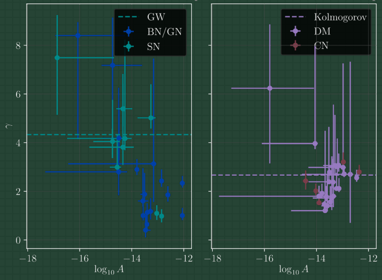

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More data, new radio telescopes:

[xinhuanet.com] [phys.org]

Summary Lecture 3B

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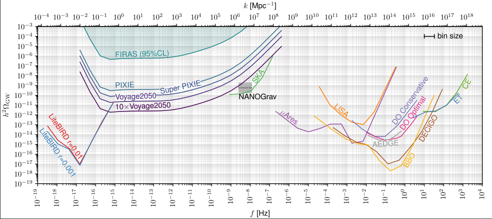
- Next few years will be decisive in the search for (and detection of) a SGWB signal!

End of Lecture 3B ... but there is one more slide!

Bright future for GW astronomy and cosmology

[sciencephoto.com]



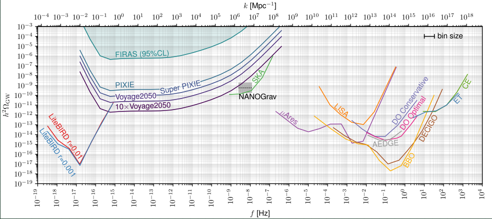
[Kite, Ravenni, Patil, Chluba: 2010.00040]

An invitation:

The invention of the telescope in the early 1600s revolutionized astronomy and our view of the cosmos. Now, with the advent of sensitive GW detectors, another window onto the Universe opens up that will again revolutionize our understanding of the world around us. We have now set sail and *just* left the port, to venture into an endless ocean of opportunities, discoveries, and surprises. Our SGWB treasure map is still blank, except for a very first data point maybe; and no one knows where the journey will lead us — but it will surely be exciting. I invite you to come on board and be part of this adventure that will shape the course of physics in the 21st century.

Bright future for GW astronomy and cosmology

[sciencephoto.com]



[Kite, Ravenni, Patil, Chluba: 2010.00040]

An invitation:

The invention of the telescope in the early 1600s revolutionized astronomy and our view of the cosmos. Now, with the advent of sensitive GW detectors, another window onto the Universe opens up that will again revolutionize our understanding of the world around us. We have now set sail and *just* left the port, to venture into an endless ocean of opportunities, discoveries, and surprises. Our SGWB treasure map is still blank, except for a very first data point maybe; and no one knows where the journey will lead us — but it will surely be exciting. I invite you to come on board and be part of this adventure that will shape the course of physics in the 21st century.

Thanks a lot for your attention!