NANOGrav and possible implications

Partly based on work in collaboration with Simone Blasi, Vedran Brdar, Wilfried Buchmüller, Valerie Domcke, Kohei Kamada, and Hitoshi Murayama
[1305.3392, 1912.03695, 2004.02889, 2009.06607, 2009.10649]

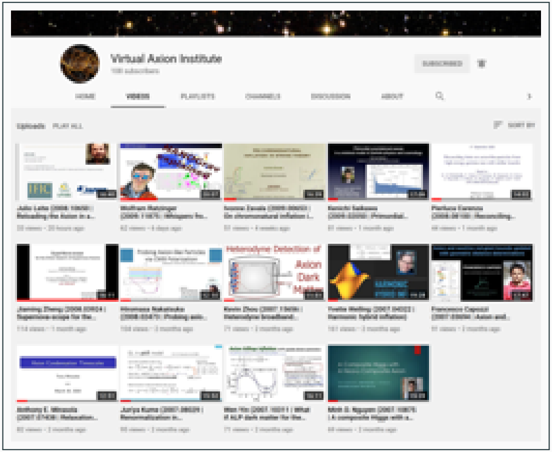
Kai Schmitz

MSCA Fellow in the CERN Theory Group

Particle and Astroparticle Theory Seminar

Max-Planck-Institut für Kernphysik | Heidelberg, Germany | 9 November 2020

YouTube series of axion talks



youtube.com/c/VirtualAxionInstitute

Milestones in recent years

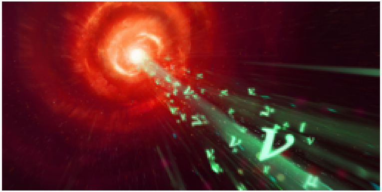
(2016) LIGO, Virgo

Gravitational waves

[Cosmos Magazine]

(2018) IceCube, Fermi-LAT

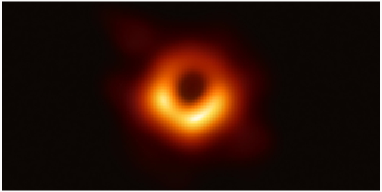
Multimessenger astronomy



[Quanta Magazine]

(2019) Event Horizon Telescope

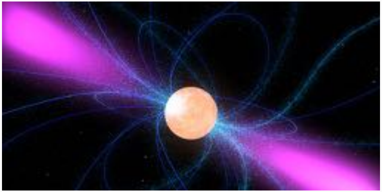
Very-long-baseline interferometry



[Event Horizon Telescope Collaboration]

(2020) NANOGrav (?)

Pulsar timing



[NASA]

Outline

Part I: NANOGrav signal

Part II: BSM interpretations

Part III: Cosmic strings

Outlook and conclusions

Part I: NANOGrav signal

NANOGrav

North American Nanohertz Observatory for Gravitational Waves

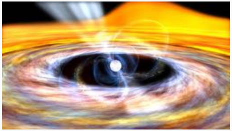
- Pulsar timing array (PTA) collaboration

  NANOGrav + PPTA + EPTA = IPTA

- Arecibo Observatory (Puerto Rico) + Green Bank Telescope (West Virginia)

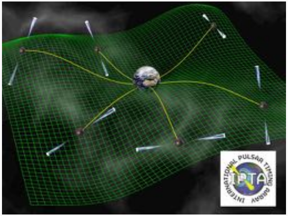
Use pulsars as ultra-precise clocks to detect nanohertz gravitational waves

- Monitor radio pulses from ms pulsars (pulsars recycled in close-binary systems)
- NANOGrav 12.5-year data set: 47 MSPs



[NASA]

Gravitational waves

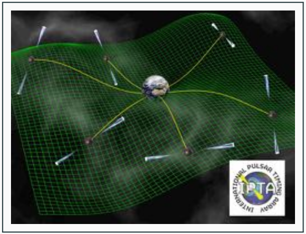


Residuals in pulse times of arrival (ToAs)

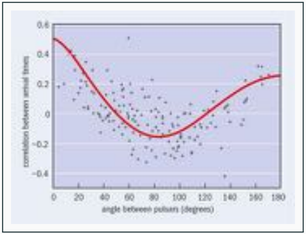
$$R^{(i)} = \mathrm{ToA}^{(i)}_{\mathrm{SSB}} - \mathrm{ToA}^{(i)}_{\mathrm{Model}}$$

- At solar-system barycenter (SSB)
  [NANOGrav Collaboration: 2001.00595]
- Model: frequency and derivatives, position, proper motion, binary dynamics, relativistic effects, ...

Gravitational waves



[physicsworld.com]



Residuals in pulse times of arrival (ToAs)

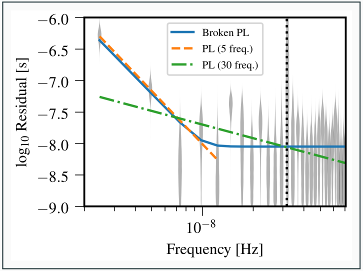
$$R^{(i)} = \mathrm{ToA}^{(i)}_{\mathrm{SSB}} - \mathrm{ToA}^{(i)}_{\mathrm{Model}}$$

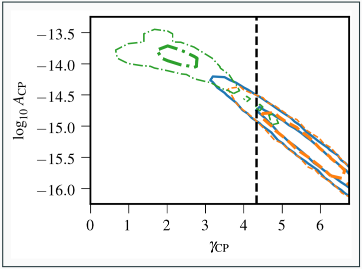
- At solar-system barycenter (SSB)
  [NANOGrav Collaboration: 2001.00595]
- Model: frequency and derivatives, position, proper motion, binary dynamics, relativistic effects, ...

Inter-pulsar angular correlations

- GWs $\rightarrow$ quadrupolar correlations
- Hellings–Downs (HD) curve $\Gamma_{ij}\left(\psi\right)$
  [Hellings, Downs: Astrophys. J. 265 (1983) L39]

Strong evidence for a new stochastic common-spectrum process at low f





- Timing-residual power spectrum

$$S_{ij}(f) \propto \Gamma_{ij}\, A_{\rm CP}{}^2\, (f/f_{\rm yr})^{-\gamma_{\rm CP}}$$

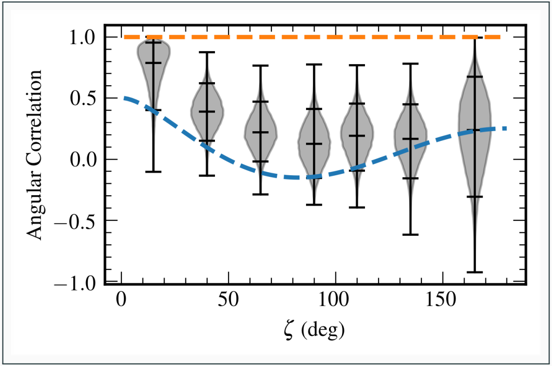
- Consistent with the stagnation of upper bounds in recent years

- Flat Bayesian prior on intrinsic red noise in previous studies: signal power → noise power?
[Hazboun, Simon, Siemens, Romano: 2009.05143]

- Systematics? Pulsar spin noise, solar-system effects, ...

Angular correlations

[NANOGrav Collaboration: 2009.04496]



- No monopole (clock error) or dipole (SSB error) correlations
- Evidence for quadrupolar HD correlations not yet conclusive
- No-correlations hypothesis mildly rejected at $p \sim 0.05$

Supermassive black-hole binaries

Astrophysical interpretation:
Supermassive black-hole binaries

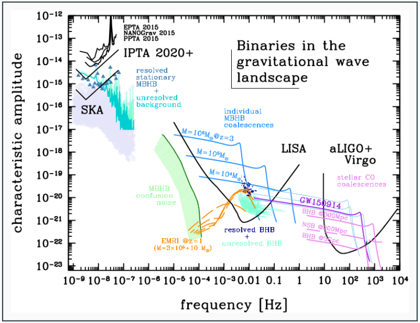
- Characteristic GW strain h_c

$$S(f) \propto h_c^2(f)/f^3$$

$$h_c(f) = A(f/f_{\mathrm{yr}})^{-2/3}$$

- Expectation: stochastic background + popcorn noise from resolved binaries

[De Rosa et al.: 2001.06293]



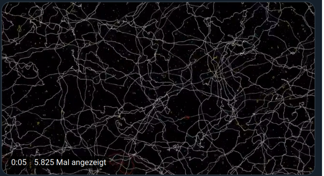
Unknowns: Origin of seeds? Growth history? Binary formation? Merger rate? Final-parsec problem? Lots of ideas, but only more data will tell.

Part II: BSM interpretations

Reaction in the community and media

[quantamagazine.org]

Quanta Magazine @QuantaMagazine · 29. Sep.
Cosmic strings, if they exist, are giant one-dimensional tubes of pure energy that stretch across the observable universe. Some physicists think a new data analysis could be the first evidence of these cracks in space-time.
quantamagazine.org/pulsar-data-ma…



11 88 244

ABSTRACTIONS BLOG

Some Physicists See Signs of Cosmic Strings From the Big Bang

Subtle aberrations in the clockwork blinking of stars could become "the result of the century." That's if the distortions are produced by a network of giant filaments left over from the birth of the universe.

› Read article — By THOMAS LEWTON

Interpretations put forward so far

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

Primordial black holes

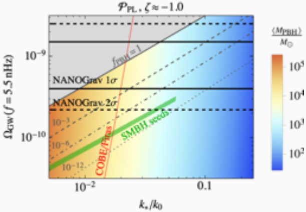
Inflation $\rightarrow$ comoving curvature / density perturbations $\rightarrow$ primordial black holes + scalar-induced GWs at second order in perturbation theory

---

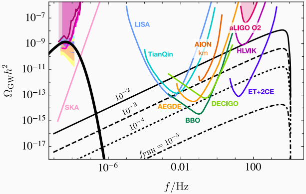
Primordial black holes

Inflation → comoving curvature / density perturbations → primordial black holes + scalar-induced GWs at second order in perturbation theory

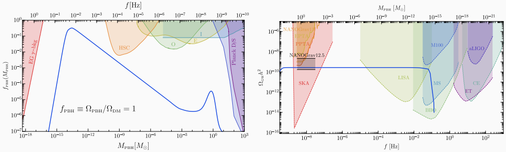
❶ [Vaskonen, Veermäe: 2009.07832]



❷ [Kohri, Terada: 2009.11853]



❸ [De Luca, Franciolini, Riotto: 2009.08268]



1. $10^3\, M_\odot$ PBHs + SMBH seeds
2. $10^0\, M_\odot$ PBHs + SGWB from mergers
3. $10^{-12}\, M_\odot$ PBHs + PBH dark matter

Unknowns: Input scalar power spectrum? Window function? Critical collapse? …

[See also Domènech, Pi: 2010.03976]

Phase transitions

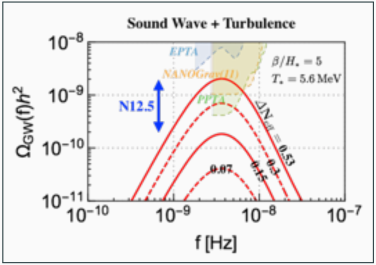
Strong first-order phase transition $\rightarrow$ gravitational waves from collisions of vacuum bubbles and / or sound waves and turbulence in the plasma

---

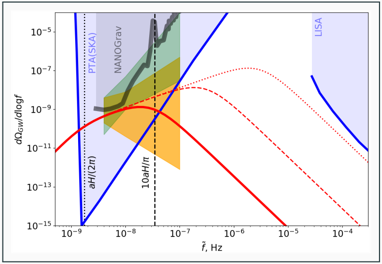
Phase transitions

Strong first-order phase transition → gravitational waves from collisions of vacuum bubbles and / or sound waves and turbulence in the plasma

[Nakai, Suzuki, Takahashi, Yamada: 2009.09754]



[Neronov, Pol, Caprini, Semikoz: 2009.14174]



- PT in a decoupled dark sector
- $\Delta N_{\text{eff}} \sim 0.4$ relaxes H_0 tension

- Turbulence from QCD PT
- B field relaxes H_0 tension

[See also Addazi, Cai, Gan, Marciano, Zeng: 2009.10327; Li, Ye, Piao: 2009.14663]

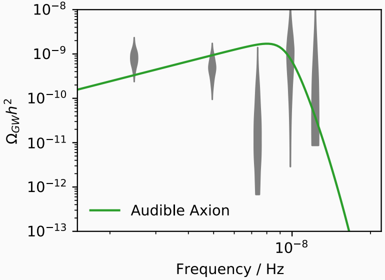
Audible axions

Axion–vector coupling $\mathcal{L} \supset -q/4\, a/F\, X_{\mu\nu}\tilde{X}^{\mu\nu}$ $\rightarrow$ exponential particle production when $H \sim m_a$ $\rightarrow$ gravitational waves sourced by dark photon

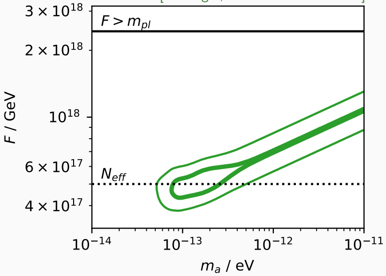
---

Audible axions

Axion–vector coupling $\mathcal{L} \supset -q/4\, a/F\, X_{\mu\nu}\tilde{X}^{\mu\nu}$ → exponential particle production when $H \sim m_a$ → gravitational waves sourced by dark photon



[Ratzinger, Schwaller: 2009.11875]



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

Inflation

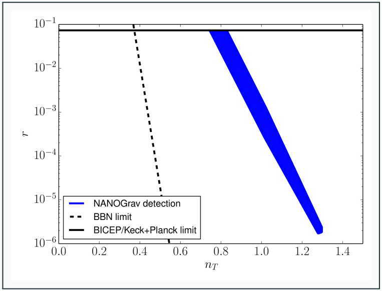
Inflation $\rightarrow$ vacuum fluctuations of the metric stretched to super-horizon size $\rightarrow$ classical gravitational waves re-entering the horizon after inflation

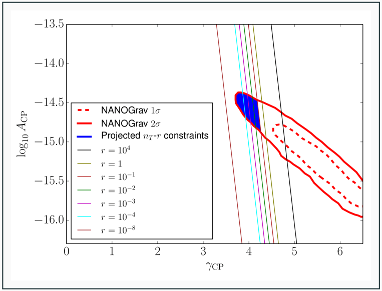
---

Inflation $\rightarrow$ vacuum fluctuations of the metric stretched to super-horizon size $\rightarrow$ classical gravitational waves re-entering the horizon after inflation

---

[Vagnozzi: 2009.13432]



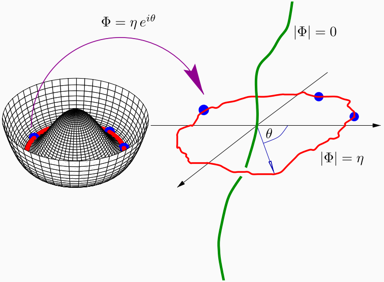


- NANOGrav requires extremely blue tensor tilt, $P_t = r\, A_s\, (k/k_*)^{n_t}$
- Extrapolation to large scales clashes with $N_{\rm eff}$ and LIGO / Virgo

Part III: Cosmic strings

Cosmic strings

[Ringeval: 1005.4842]



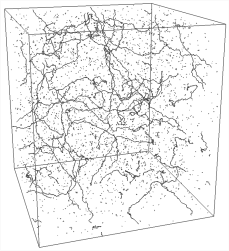
- Topological defects after spontaneous $U(1)$ breaking
- Global / local $U(1)$ symmetry restored at the core of strings
- Condensed matter: magnetic field vortices in a superconductor

Relevant parameters

- $G\mu$: String tension = energy per unit length, in units of $G = 1/M_{\mathrm{P}}^2$
- α: Size of string loops at the time of formation, in units of H^{-1}

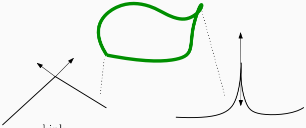
Gravitational waves from cosmic strings

[Allen, Martins, Shellard: ctc.cam.ac.uk/outreach]



Infinite strings and string loops;
scaling regime: $\rho_{\rm cs} \propto \rho_{\rm crit} \propto H^2$

[Gouttenoire, Servant, Simakachorn: 1912.02569]



Gravitational waves from

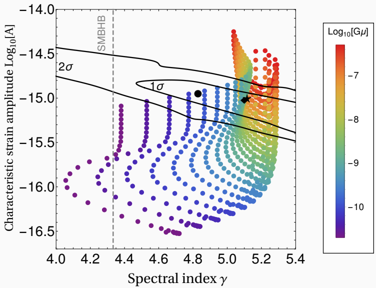
- Cusps
- Kinks
- Kink–kink collisions

- Nambu–Goto action: infinitely thin strings, no particle emission
- Abelian-Higgs model: short-lived loops, decay into massive particles

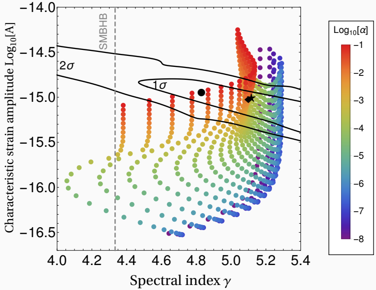
[Vachaspati, Vilenkin: PRD 31 (1985) 3052] [LISA Cosmology Working Group, Auclair et al.: 1909.00819]

Stable local Nambu–Goto strings

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



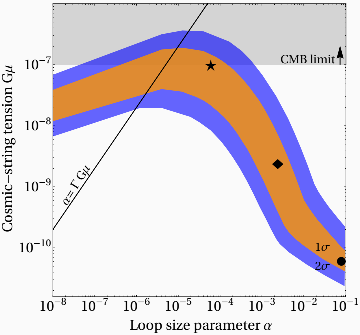
Color code: String tension



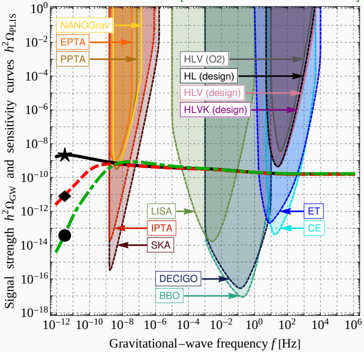
Color code: Loop size

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

Observational prospects



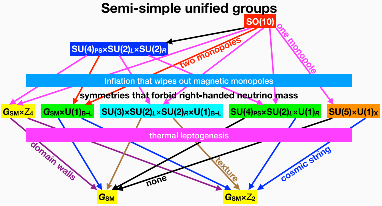
[Blasi, Brdar, **KS**: 2009.06607]



- Entire viable parameter space will be probed in future experiments
- $G\mu \sim 10^{-(10\cdots 7)}$ points to $U(1)$ breaking scale $v \sim 10^{14\cdots 16}\,\mathrm{GeV}$

Cosmic strings and leptogenesis

[Dror, Hiramatsu, Kohri, Murayama, White: 1908.03227]
[See also King, Pascoli, Turner, Zhou: 2005.13549]



GW signature of leptogenesis

- Protect right-handed-neutrino masses by local GUT symmetry
- Break symmetry in cosmological phase transition → strings, GWs

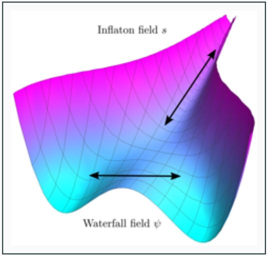
---

Minimal scenario:

$B-L$ phase transition after hybrid inflation

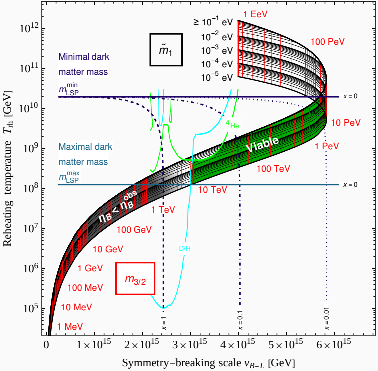
$$W_{B-L} = \kappa T\left(S\bar{S} - 1/2\, v_{B-L}^2\right) + 1/2\, h_i\, S N_i N_i$$

T: Inflaton. S, $\bar{S}$: symmetry-breaking waterfall fields. N_i: right-handed neutrinos



A consistent cosmology

[Buchmüller, Domcke, Murayama, **KS**: 1912.03695]



SUSY model based on $U(1)_{B-L}$ breaking at the end of inflation:

- ✓ Inflation and reheating
- ✓ Leptogenesis
- ✓ WIMP (LSP) dark matter
- ✓ Big-bang nucleosynthesis
- ✓ Froggatt–Nielsen flavor model
- ✓ Neutrino phenomenology

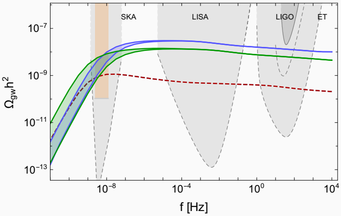
[Buchmüller, **KS**, Vertongen: 1008.2355, 1104.2750]
[Buchmüller, Domcke, **KS**: 1111.3872, 1202.6679, 1203.0285]
[Buchmüller, Domcke, Kamada, **KS**: 1305.3392, 1309.7788]

$v_{B-L} \sim (3 \cdots 6) \times 10^{15}\,\mathrm{GeV}$: Consistent with NANOGrav if strings are

- Stable and form small loops, $\alpha \sim 10^{-4}$ [Blasi, Brdar, **KS**: 2009.06607]
- Metastable and form large loops, $\alpha \sim 10^{-1}$ [Buchmüller, Domcke, **KS**: 2009.10649]

Metastable strings

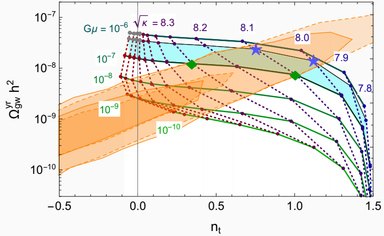
[Buchmüller, Domcke, **KS**: 2009.10649]



GWs from a collapsing string network

- $SO(10)$ embedding w/o $\mathbb{Z}_2$ parity at low energies: $W \supset \frac{1}{M_*} S\, S\, N_i N_i$
- Monopole–antimonopole pairs via Schwinger effect: $\Gamma_{\rm cs} \sim \frac{\mu}{2\pi} e^{-\pi\kappa}$

- Mass of $SO(10)$ monopoles: $m = \sqrt{\kappa\mu} \sim 3 \cdots 8 \times 10^{16}\,\mathrm{GeV}$
- Within reach of LIGO, Virgo, KAGRA at design sensitivity!



Outlook and conclusions

Outlook

[Goncharov et al.: 2010.06109]

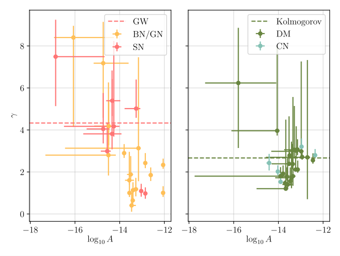


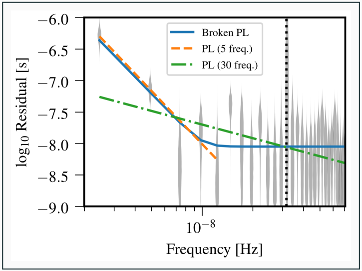
Figure 1. Strength and spectral index for red noise processes for the PPTA-DR2 pulsars. Left panel: spin noise (SN), band noise (BN) and system noise (GN). Right panel: DM noise and chromatic noise (CN) with strength referenced to $K = 1400$ MHz. The main feature of the left panel is the clustering of 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.

More pulsar timing data

- NANOGrav 2009.04496: *“The analysis of this joint [IPTA] data set is ongoing, and early results are again consistent with those discussed here.”*
- 2010.06109: Individual noise models for the 26 PPTA pulsars
- NANOGrav 15-year data set: 2.5 more years, 20+ new pulsars
- More data, new radio telescopes: MeerKAT, FAST, SKA

Stay tuned!

Conclusions



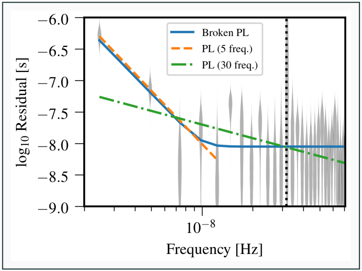
[NANOGrav Collaboration: 2009.04496]

Take-home messages:

- NANOGrav might have caught a first glimpse of a stochastic GW background.
- To claim a detection, HD correlations will need to be confirmed in the future.

- Astrophysical interpretation: supermassive black-hole binaries
- BSM interpretations: PBHs, phase transitions, ..., cosmic strings!
- Cosmic $B-L$ strings possibly related to leptogenesis, inflation, ...

Conclusions



[NANOGrav Collaboration: 2009.04496]

Take-home messages:

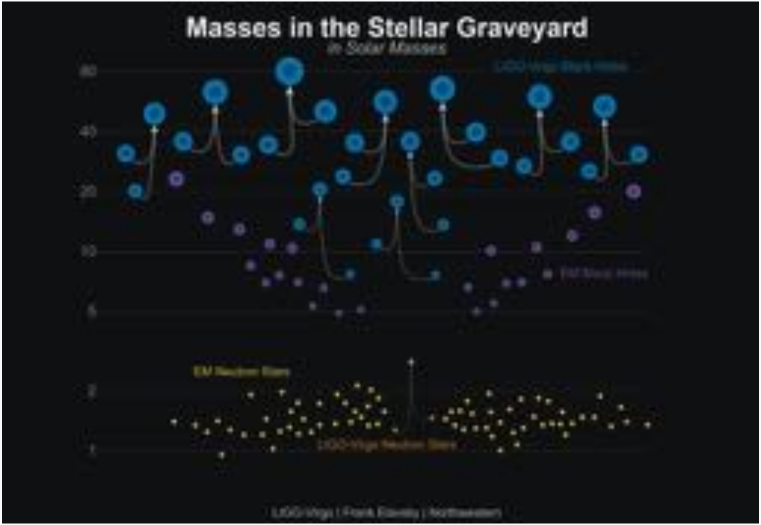
- NANOGrav might have caught a first glimpse of a stochastic GW background.
- To claim a detection, HD correlations will need to be confirmed in the future.

- Astrophysical interpretation: supermassive black-hole binaries
- BSM interpretations: PBHs, phase transitions, ..., cosmic strings!
- Cosmic $B-L$ strings possibly related to leptogenesis, inflation, ...

Thanks a lot for your attention!

Supplementary Material

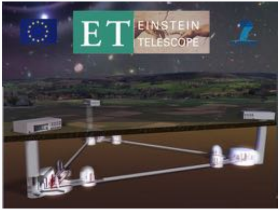
GW events during LIGO / Virgo Observing Runs 1 and 2



[LIGO / Virgo, *Gravitational-Wave Transient Catalog (GWTC) 1*, 1811.12907]

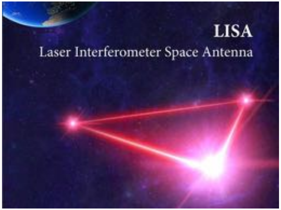
Multifrequency gravitational-wave astronomy

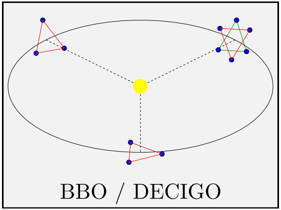
Ground



$f \sim 10 \cdots 1000\,\mathrm{Hz}$

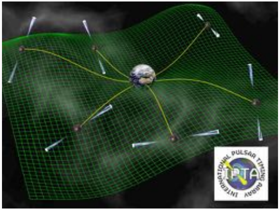
Space





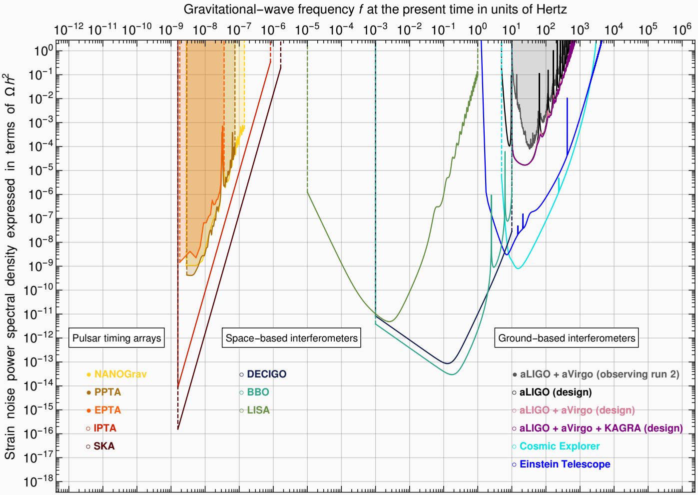
$f \sim 1 \cdots 1000\,\mathrm{mHz}$

Sky



$f \sim 1 \cdots 10\,\mathrm{nHz}$

Strain noise power spectral densities



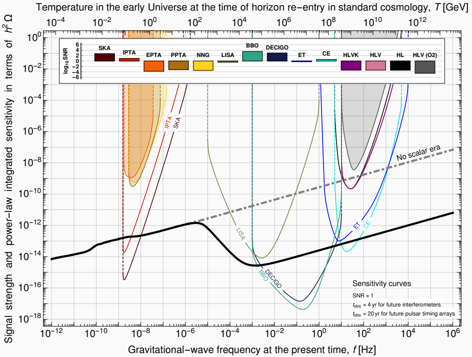
[**KS**, *New sensitivity curves for gravitational-wave experiments*, 2002.04615]

Gravitational-wave fingerprint of a scalar era

Probe the expansion history of the early Universe, assuming:

- A blue-tilted background of primordial GWs from (axion) inflation.
- A "scalar era" dominated by coherent scalar-field oscillations.

[D'Eramo, **KS**, *Imprint of a scalar era on the primordial spectrum of gravitational waves*, Phys. Rev. Research. 1, 013010 (2019)]



Example:

Baryogenesis from flavon decays

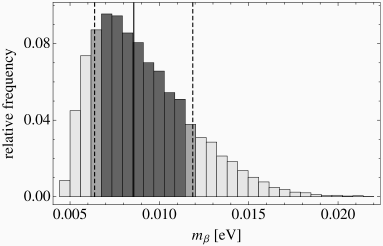
[Chen, Ipek, Ratz, 1903.06211]

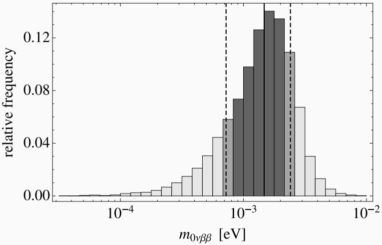
$$m_\phi = 3\,\mathrm{TeV}$$

$$\Gamma_\phi = 10^{-13}\,\mathrm{GeV}$$

$$\phi_{\rm ini} = 10^{16}\,\mathrm{GeV}$$

Froggatt–Nielsen flavor model

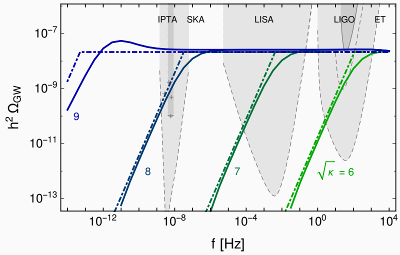


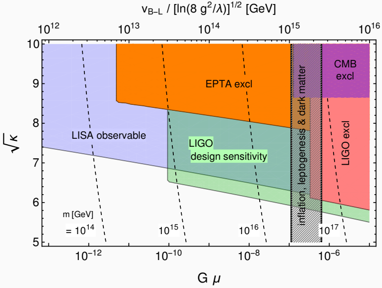


[Buchmüller, Domcke, **KS**, *Predicting θ_{13} and the Neutrino Mass Scale from Quark Lepton Mass Hierarchies*, 1111.3872]

Metastable cosmic strings

[Buchmüller, Domcke, Murayama, **KS**, 1912.03695]





$SO(10)$ embedding w/o $\mathbb{Z}_2$ parity at low energies: $W \supset \frac{1}{M_*} S\, S\, N_i N_i$

Cosmic strings decay into monopole–antimonopole pairs: $\Gamma_{\rm cs} \sim \frac{\mu}{2\pi} e^{-\pi\kappa}$

Smoking gun signature: $f^{3/2}$ at low frequencies, f^0 at high frequencies