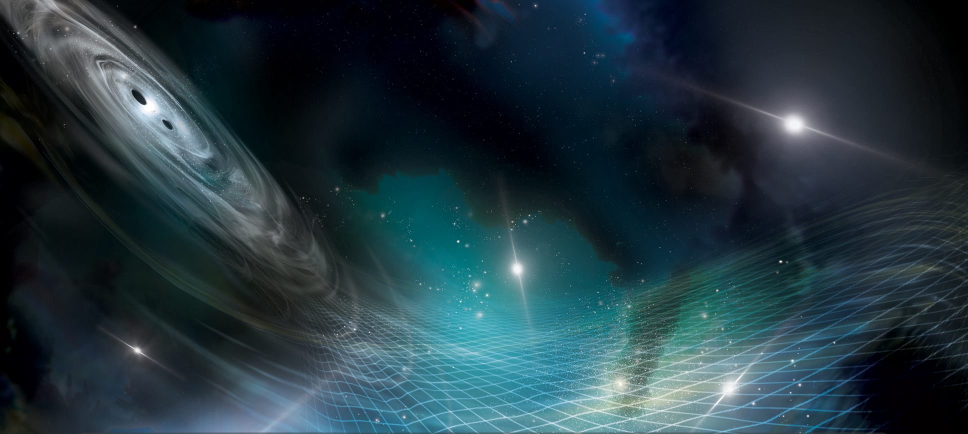


Cosmic Strings at the PTA Frontier and Beyond

Kai Schmitz (NANOGrav New Physics Working Group)

University of Münster, Institute for Theoretical Physics

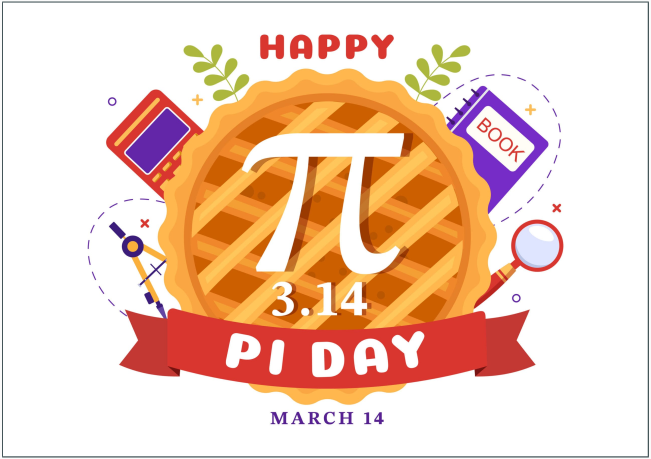
Gravitational Waves and the Early Universe | Nagoya U | 2026/03/14

What an exciting week!

I left for Japan on Tuesday, March 10th ...

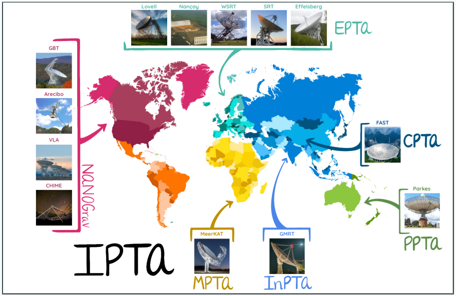
What an exciting week!

... and now I have the honor to give my presentation on π day, March 14th



The PTA Frontier

2023 PTA results



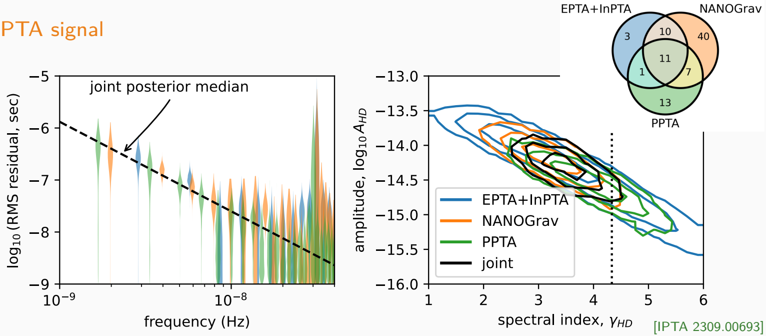
EPTA:	European PTA
CPTA:	Chinese PTA
PPTA:	Parkes PTA
InPTA:	Indian PTA
MPTA:	MeerKAT PTA
NANOGrav:	North American Nanohertz Observatory for Gravitational Waves

18 papers on the arXiv on June 29, 2023

[2306.16213]	NANOGrav	GWB
[2306.16214]	EPTA	GWB
[2306.16215]	PPTA	GWB
[2306.16216]	CPTA	GWB
[2306.16217]	NANOGrav	Data set
[2306.16218]	NANOGrav	Noise model
[2306.16219]	NANOGrav	New physics
[2306.16220]	NANOGrav	SMBHBs
[2306.16221]	NANOGrav	Anisotropies
[2306.16222]	NANOGrav	Continuous GW
[2306.16223]	NANOGrav	Analysis pipeline
[2306.16224]	EPTA	Data set
[2306.16225]	EPTA	Noise model
[2306.16226]	EPTA	Continuous GW
[2306.16227]	EPTA	Implications
[2306.16228]	EPTA	ULDM
[2306.16229]	PPTA	Noise model
[2306.16230]	PPTA	Data set

IPTA comparison

2023 PTA signal

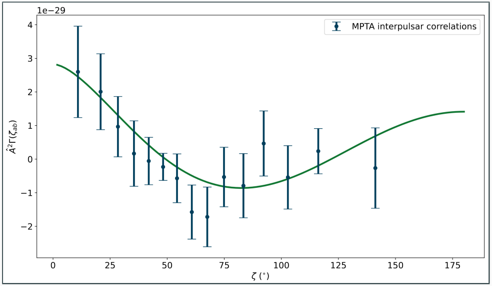


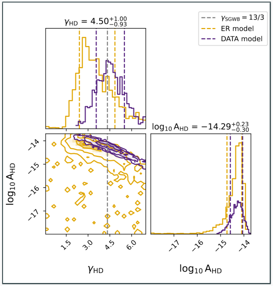
[IPTA 2309.00693]

- Results from regional PTAs are consistent with each other (1σ posteriors overlap)
- Joint posterior = naive product (properly normalized) of individual posteriors
- Proper data combination and combined data analysis → IPTA DR3

New kid on the block

MeerKAT Pulsar Timing Array (MPTA): 83 pulsars, 4.5 yr of data [MPTA 2412.01153]



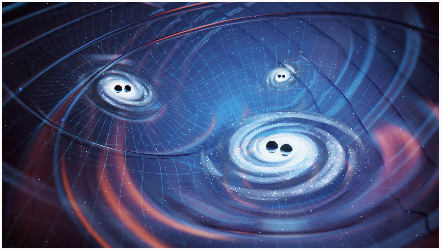


Abstract: *[...] Under different assumptions about noise processes we can produce either what appear to be compelling Hellings-Downs correlations of high significance (3–3.3 σ) with a spectrum close to that which is predicted, or surprisingly, under slightly different assumptions, ones that are insignificant. This appears to be related to the fact that many of the highest precision MeerKAT Pulsar Timing Array pulsars are in close proximity and dominate the detection statistics [...]*

Interpretations

[See talks by J. Ellis, M. Kobayashi, K. Kohri, S. Wong]

❶ Supermassive black-hole binaries



❶ SMBHBs (realistic)

- No SMBHB mergers directly observed as of yet → data-driven field thanks to PTAs
- Viable explanation, several open questions → unexpected corners of parameter space?

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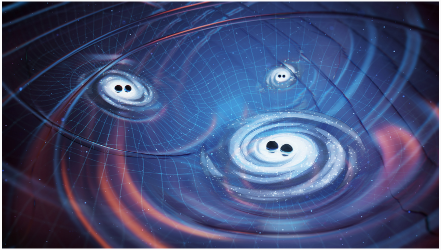
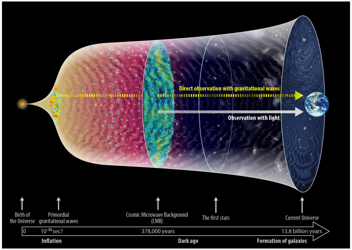


❷ GWs from the Big Bang



❶ SMBHBs (realistic)

- No SMBHB mergers directly observed as of yet → data-driven field thanks to PTAs
- Viable explanation, several open questions → unexpected corners of parameter space?

❷ New physics (speculative)

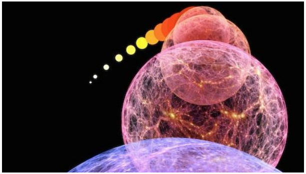
- Logical possibility: PTA signal is not of SMBHB origin or receives several contributions
- **Probe** and **constrain** cosmology at early times as well as particle physics at high energies

BSM options

[See talks by D. Artigas, L. Gil, T. Hiramatsu, J. Lee, J.-P. Li, P. Schicho, V. Q. Tran, A. Vikman]

❶ Nonmininal cosmic inflation

- Accelerated expansion before the Hot Big Bang
- **Complementarity:** PTAs + CMB observations



Abbrevations: CMB: cosmic microwave background; GW: gravitational wave; PBH: primordial black hole; PTA: pulsar timing array; QCD: quantum chromodynamics; QFT: quantum field theory

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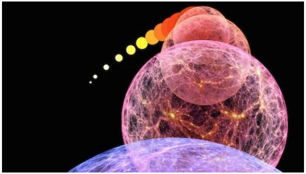
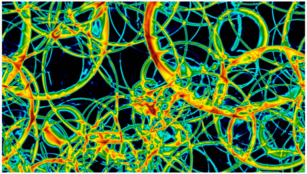


❷ Cosmological phase transition

- First-order transition in the QFT vacuum structure
- **Complementarity:** PTAs + QCD / dark-sector physics



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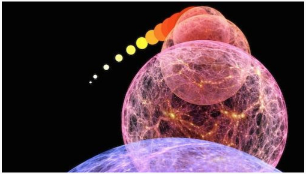

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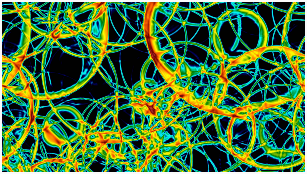
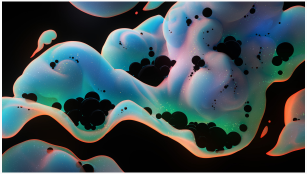


❸ Enhanced density perturbations

- Overdensities that emit GWs and collapse to PBHs
- **Complementarity:** PTAs + primordial black holes



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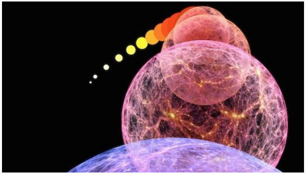

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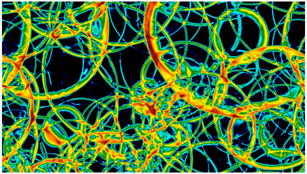

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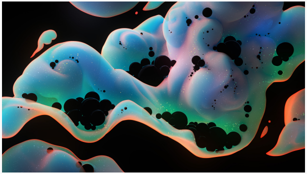
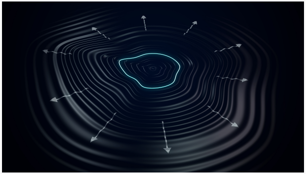


❹ Cosmic defects

- Phase transition remnants preserving the old vacuum
- **Complementarity:** PTAs + grand unified theories



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Why care about exotic sources?

Do we *really* believe that PTAs could be seeing a GW echo from the Big Bang?

- **Inflation:** Vacuum tensor perturbations from single-field slow-roll inflation not enough
- **Phase transition:** Standard Model predicts QCD crossover; issues with dark radiation
- **Scalar-induced GWs:** Ultra-slow roll is signal engineering; PBH overproduction?
- **Defects:** Spectrum from stable strings too flat; metastable strings must decay at right time

No consensus in the SMBHB community

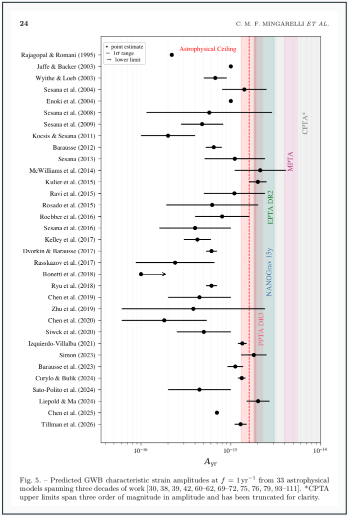
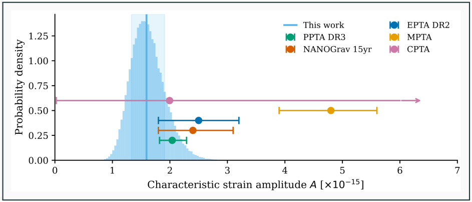


Fig. 5. – Predicted GWB characteristic strain amplitudes at $f = 1\,{\rm yr}^{-1}$ from 33 astrophysical models spanning three decades of work [30, 38, 39, 42, 60–62, 69–72, 75, 76, 79, 93–111]. *CPTA upper limits span three order of magnitude in amplitude and has been truncated for clarity.

[Mingarelli: 2601.18859]

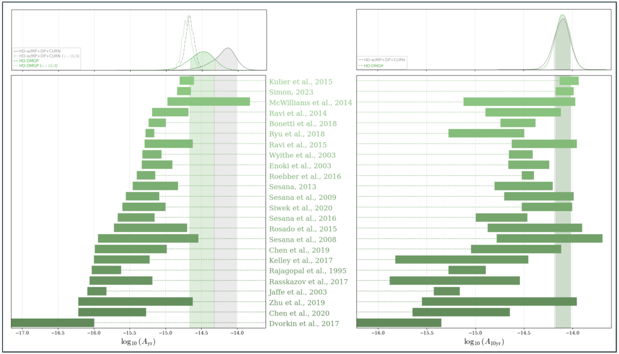


Ceiling amplitude

- Based on Liepold and Ma (2024)
- Local SMBH mass density derived from galaxy stellar mass function, calibrated at high masses using the volume-limited MASSIVE survey (all early-type galaxies with $M_* \gtrsim 10^{11.5} M_\odot$ within 108 Mpc)

Three reasons to care about exotic sources

[NANOGrav 2306.16220]



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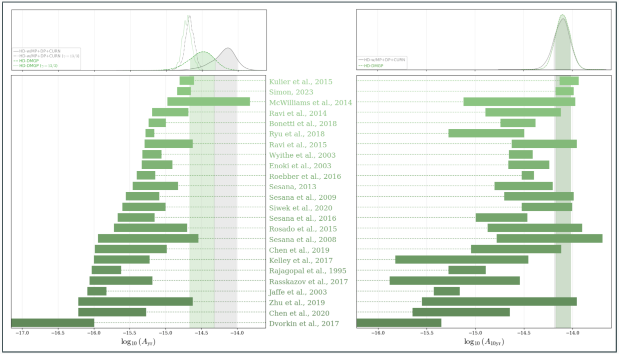

❶ Surprisingly loud signal

Unexpected corners of SMBHB parameter space, e.g., higher binary density, shorter delay times

Three reasons to care about exotic sources

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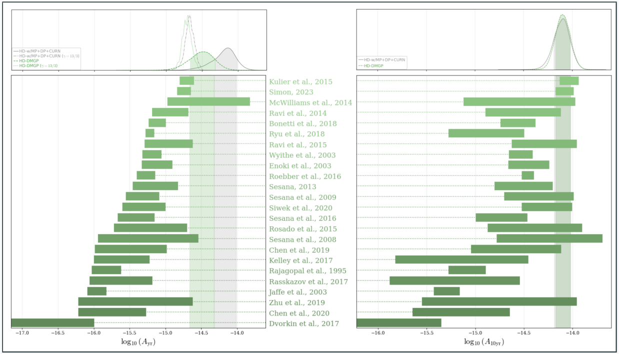

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❷ Maximize our confidence in the SMBHB interpretation

Tension may go away with better noise modelling, more data, etc. On top, rule out alternatives!

Three reasons to care about exotic sources

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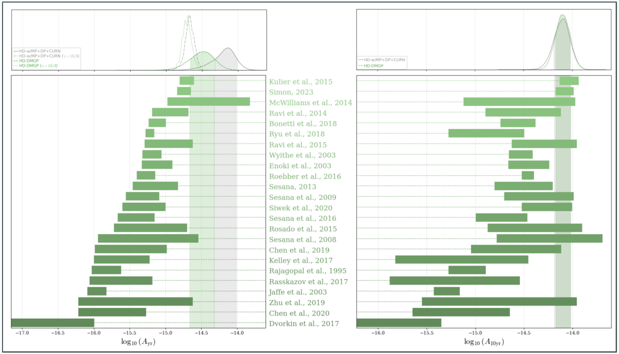

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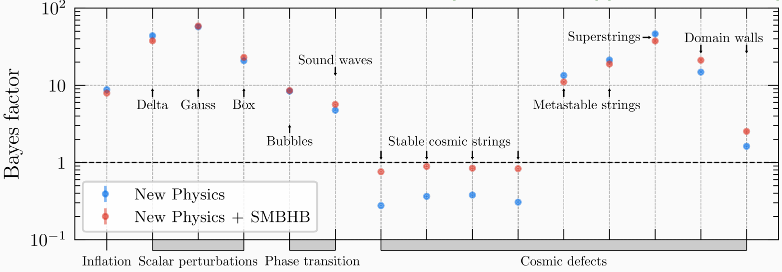
Unexpected corners of SMBHB parameter space, e.g., higher binary density, shorter delay times

❷ Maximize our confidence in the SMBHB interpretation
Tension may go away with better noise modelling, more data, etc. On top, rule out alternatives!

❸ New physics at the PTA frontier: Access and constrain new regions of parameter space
New bounds, complementary to energy and intensity frontiers. Benchmarks for LISA, etc.!

Bayesian model comparison

[NANOGrav 2306.16219] [See also: EPTA 2306.16227]

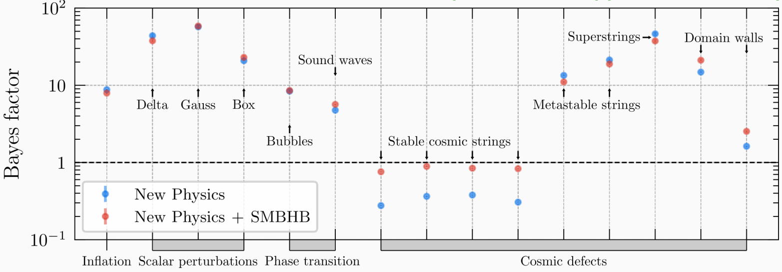


$$\text{Bayes factor } B = \frac{\text{Evidence for model } M_1,\ P(D|M_1)}{\text{Evidence for model } M_0,\ P(D|M_0)}, \quad M_0 = \{\text{SMBHBs only}\}$$

- Many BSM models reach Bayes factors of the order of $10 \cdots 100$
- Interesting but not conclusive; lots of uncertainties in SMBHB and BSM models

Bayesian model comparison

[NANOGrav 2306.16219] [See also: EPTA 2306.16227]



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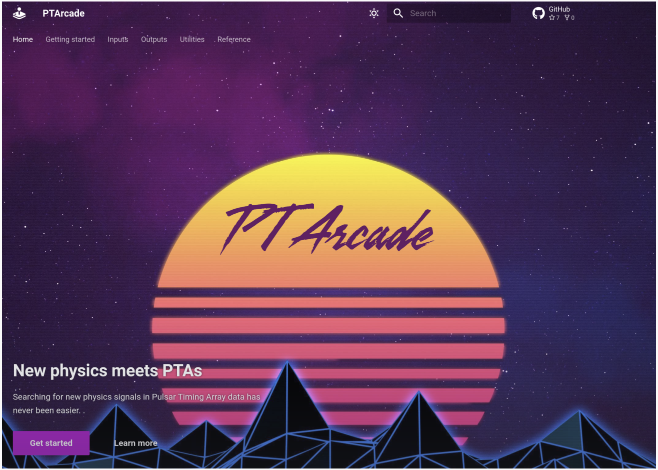
- Interesting but not conclusive; lots of uncertainties in SMBHB and BSM models

Call to action: Improve modelling on both the astro and the cosmo side!

PTArcade



Our code developed for 2306.16219: Fit your favorite BSM model to the NG15 data!

New functionalities, new models, and new data (when available) added on a steady basis

Cosmic Strings

Cosmic strings

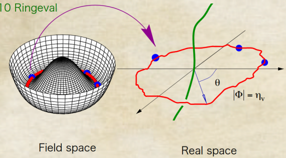
[See talk by K. Kamada]

Cosmic string: '76 Kibble

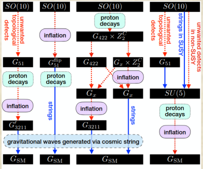
2-dimensional topological defect associated with U(1) symmetry breaking

Generated in the early Universe through phase transition, such as GUT breaking, to form a network of infinite string and loops.

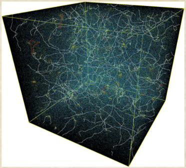
'10 Ringeval



'21 King+



'22 da Cunha+



Network enters the "scaling regime" '85 Kibble, '89 Albrecht&Turok

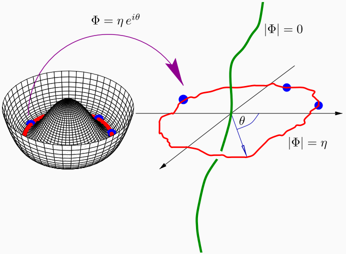
The physical model parameter is only string tension, $\mu \sim 2\pi\eta_v^2$

Slide Background Courtesy: H. Oide

Cosmic strings

[See talk by K. Kamada]

[Ringeval: 1005.4842]



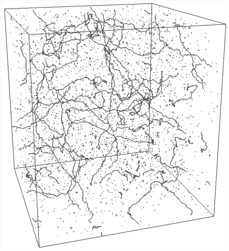
- **Topological defects** after spontaneous symmetry breaking, s.t. $\pi_1(\mathcal{M})$ nontrivial
- For instance, breaking of global / local $U(1)$; symmetry restored at string cores
- Condensed matter: Magnetic field vortices (quantum vortices) in a superconductor

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 time of formation, in units of the horizon $d_h \sim t \sim H^{-1}$

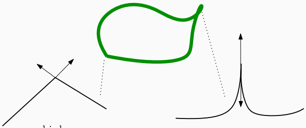
Gravitational waves from cosmic strings

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



Infinitely long 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

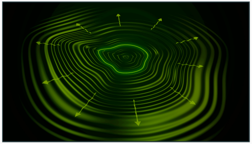
- Nambu–Goto strings: Infinitely thin, particle emission irrelevant at late times
- Abelian-Higgs strings: Short-lived loops, decay into massive particles

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

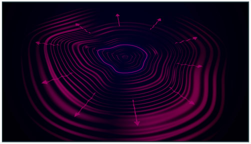
Models

[See talks by A. Chitose, K. Kamada, R. Maji, I. Rybak]

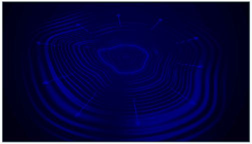
Abelian-Higgs strings



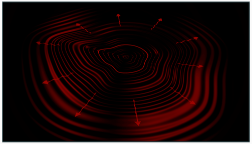
Cosmic superstrings



Global strings

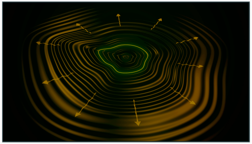


Current-carrying strings



Quasi-stable strings

Metastable strings



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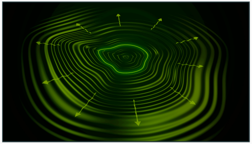

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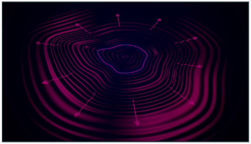

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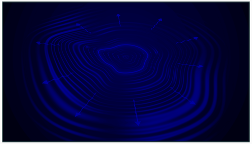

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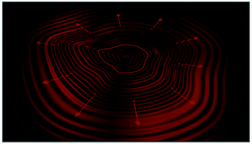

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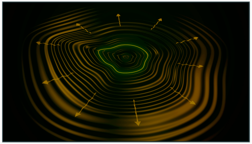


Plan

❶ Review metastable strings

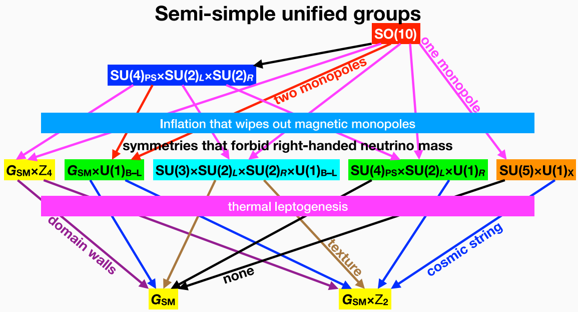
❷ Discuss fit to NG15 data

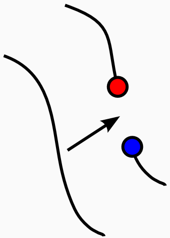
❷ *Use as an example to make a few remarks about BSM fits to PTA data in general*

Cosmic defects from $SO(10)$ symmetry breaking

[See talk by K. Kamada]

[Dror, Hiramatsu, Kohri, Murayama, White: 1908.03227]
[See also King, Pascoli, Turner, Zhou: 2005.13549, 2106.15634]





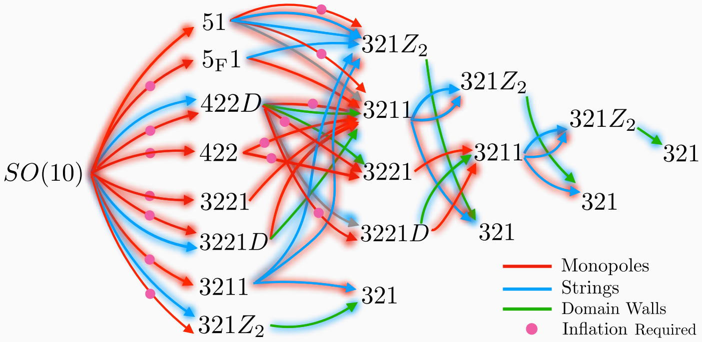
Defects are either topologically stable or … not

Example: Metastable cosmic strings from spontaneous symmetry breaking of the form

$$G \to H \to K\,, \qquad \pi_1\,(H/K) \ncong \{\mathbb{1}\} \quad \text{but} \quad \pi_1\,(G/K) \cong \{\mathbb{1}\}$$

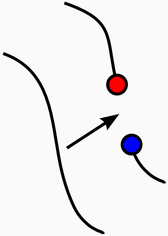
Metastable-string models

[Dunsky, Ghoshal, Murayama, Sakakihara, White: 2111.08750]



Minimal toy models

1. $SU(2)_A \quad \to \quad \text{Inflation} \quad \to \quad U(1)_A \quad \to \quad \text{nothing}$
2. $SU(2)_A \times U(1)_B \quad \to \quad \text{Inflation} \quad \to \quad U(1)_A \times U(1)_B \quad \to \quad U(1)_C$



Rate of monopole nucleation events per string length

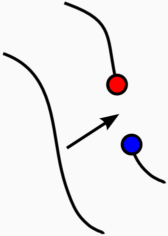
[Vilenkin: Nucl. Phys. B 196 (1982) 240]
[Preskill, Vilenkin: hep-ph/9209210]
[Monin, Voloshin: 0808.1693]

$$\Gamma_d = \frac{d\#}{dt d\ell} = \frac{\mu}{2\pi} e^{-\pi\kappa}, \qquad \kappa = \frac{m^2}{\mu} \tag{1}$$

- String tension μ, monopole mass m
- Strings are not topologically stable, decay on cosmological times scales

Decay rate of metastable strings

[See talk by A. Chitose]



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Monopoles with and without unconfined magnetic flux

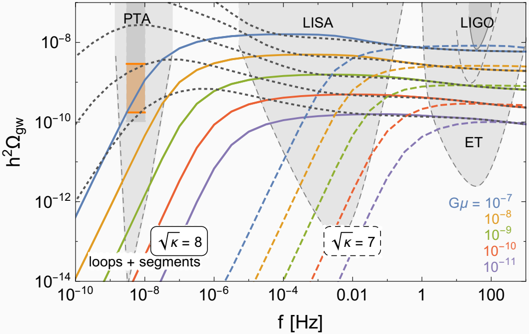
Model ❶ No unconfined flux: energy loss only via emission of GWs

Model ❷ Unconfined flux: $M\bar{M}$ annihilation, emission of massless gauge bosons

[But see also Chitose, Ibe, Neda, Shirai: 2507.12386 (*Do Cosmic String Segments Emit Gravitational Waves?*)]

GW spectrum

[Buchmüller, Domcke, KS: 1912.03695, 2009.10649, 2107.04578, 2307.04691]

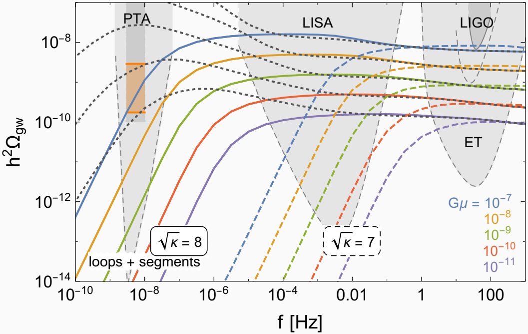


Model ❶ No unconfined flux: GWs from loops and segments → META-LS (!?)

Model ❷ Unconfined flux: GWs from loops → META-L

GW spectrum

[Buchmüller, Domcke, KS: 1912.03695, 2009.10649, 2107.04578, 2307.04691]



Model ❶ No unconfined flux: GWs from loops and segments → META-LS (!?)

Model ❷ Unconfined flux: GWs from loops → META-L

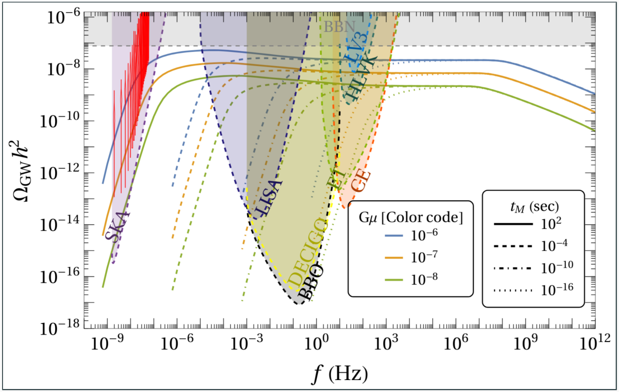
Number density of metastable loops

$$n_{\text{loops}}^{\text{meta}}(\ell, t) = n_{\text{loops}}^{\text{stable}}(\ell, t)\ e^{-\Gamma_d\left[\ell(t-t_*)+1/2\,\Gamma G\mu(t-t_*)^2\right]}\,\theta(t_s - t_*)\,, \qquad \Gamma_d t_s^2 \sim 1$$

From metastable to quasi-stable strings

[See talk by R. Maji]

[Maji, Shafi: 2603.02996]



Number density of quasi-stable loops $(t_M \equiv t_s)$

$$n_{\rm loops}^{\rm quasi}(\ell, t) = \lim_{\Gamma_d \to 0} n_{\rm loops}^{\rm meta}(\ell, t) = n_{\rm loops}^{\rm stable}(\ell, t) \times 1 \times \theta\left(t_s - t_*\right), \qquad \Gamma_d t_s^2 \lll 1$$

Take-home messages

1. Check the stability of the defects in your GUT model
  - Meta-/quasi-stable strings rather than stable strings in many cases

Cosmic Strings at the PTA Frontier

Metastable strings: Fit to the NG15 data

Decay rate per length

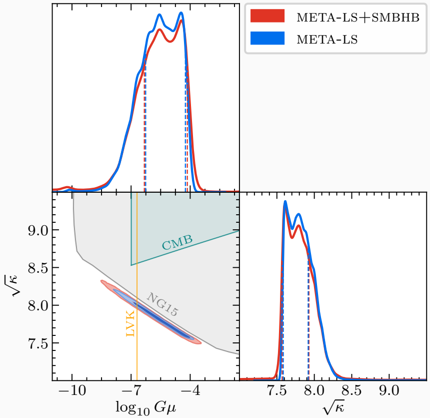
$$\Gamma_d = \frac{\mu}{2\pi}\, e^{-\pi\kappa}$$

Parameters

μ Tension (energy per length)

κ Decay parameter

[NANOGrav 2306.16219]



Lessons

- Prefered parameter values → input for **GUT model building** at $E \lesssim 10^{16}\,\mathrm{GeV}$
- Metastable strings yield a good fit; can be probed / excluded by **LVK observations**
- PTA bounds outperform **CMB bounds**, *irrespective of the origin of the signal (!)*

Three tiers of BSM model fits to PTA data

How about other scenarios? Is *my BSM model* capable of explaining the PTA signal?

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Three tiers of BSM model fits to PTA data

How about other scenarios? Is *my BSM model* capable of explaining the PTA signal?

A: Bayesian fit to the actual data, i.e., the NG15 timing residuals

B: Bayesian fit to a condensed, downstream data product, e.g., NG15 violins

Three tiers of BSM model fits to PTA data

How about other scenarios? Is *my BSM model* capable of explaining the PTA signal?

A: Bayesian fit to the actual data, i.e., the NG15 timing residuals

B: Bayesian fit to a condensed, downstream data product, e.g., NG15 violins

C: Comparison to a simple reference model, e.g., **constant power law** (A, γ)

Three tiers of BSM model fits to PTA data

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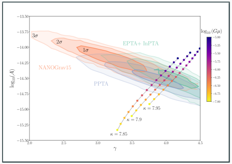
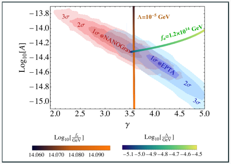
Metastable cosmic strings



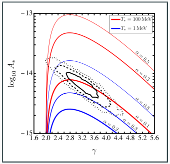
[2308.05799]

Axion domain walls



[2306.17022]

Phase transition



[2306.17205]

Three tiers of BSM model fits to PTA data

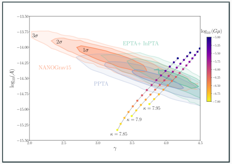
How about other scenarios? Is *my BSM model* capable of explaining the PTA signal?

A: Bayesian fit to the actual data, i.e., the NG15 timing residuals

B: Bayesian fit to a condensed, downstream data product, e.g., NG15 violins

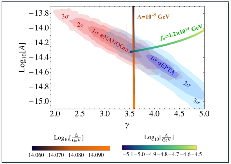
C: Comparison to a simple reference model, e.g., **constant power law** (A, γ)

Metastable cosmic strings



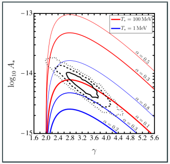
[2308.05799]

Axion domain walls



[2306.17022]

Phase transition



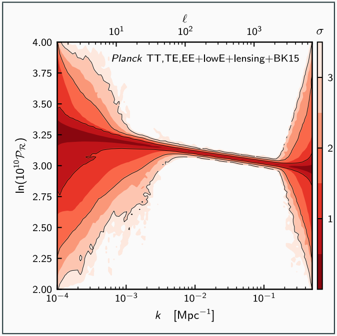
[2306.17205]

However, power-law spectrum just a rough approximation in many models

- Perform Bayesian fit to timing data (or least violins) after all: `PTArcade`, `ceffyl`
- Compare to more flexible reference model: **running power law** (A, γ, β)

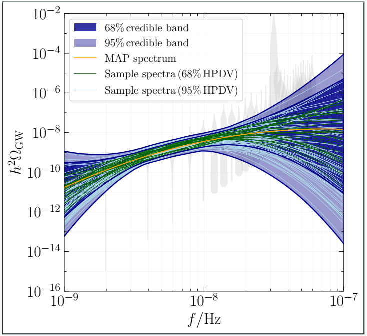
Running power law (RPL)

Primordial scalar power spectrum



[PLANCK: 1807.06211] [See also ACT: 2503.14454]

GW power spectrum in the PTA band

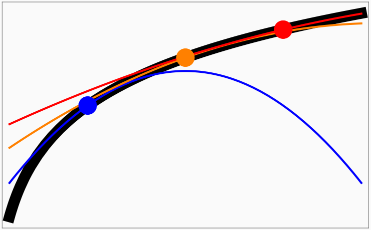


[NANOGrav: 2408.10166]

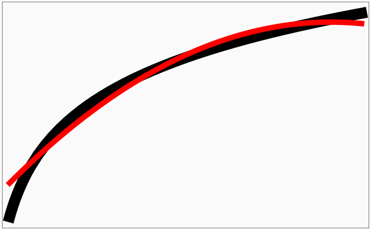
- **CMB:** Running of n_s tightly constrained, $\alpha_s = {}^{dn_s}/_{d\ln k} = 0.0060^{+0.0055}_{-0.0055}$ [P-ACT]
  OK to compare your favorite inflation model to constant-power-law (CPL) template (A_s, n_s)
- **PTA:** Running of γ only loosely constrained, $\beta = {}^{d\gamma}/_{d\ln k} = 0.92^{+0.98}_{-0.91}$
  Better compare your favorite GWB model to running-power-law (RPL) template (A, γ, β)

From new physics to a running power law

❶ BSM–RPL map: **Local matching**



❷ BSM–RPL map: **Global matching**



❶ Match BSM and RPL spectra **locally** at fixed pivot frequency (CMB-like approach)

$$\left.\frac{d^n \ln \Omega_{\mathrm{BSM}}}{d\,(\ln f)^n}\right|_{f_{\mathrm{pivot}}} = \left.\frac{d^n \ln \Omega_{\mathrm{RPL}}}{d\,(\ln f)^n}\right|_{f_{\mathrm{pivot}}} \,, \quad n = 0, 1, 2 \tag{2}$$

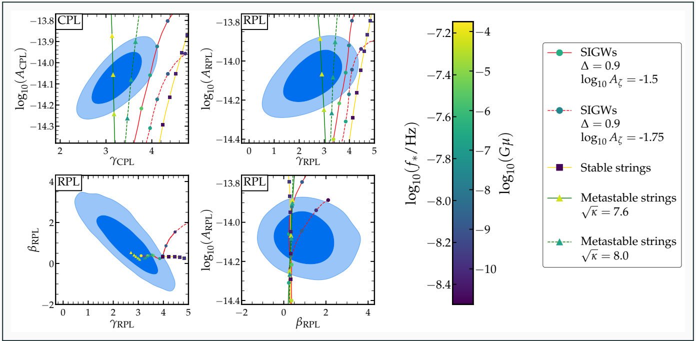
❷ Match BSM and RPL spectra **globally** by minimizing the "SNR of their difference"

$$\Delta\chi^2 = 2T \int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} \left(\frac{\Omega_{\mathrm{BSM}}\,(f;\boldsymbol{\theta}_{\mathrm{BSM}}) - \Omega_{\mathrm{RPL}}\,(f;\boldsymbol{\theta}_{\mathrm{RPL}})}{\Omega_{\mathrm{sens}}\,(f)}\right)^2 \mathrm{d}f \tag{3}$$

[Kuroyanagi, Chiba, Takahashi: 1807.00786] [Caldwell, Smith, Walker: 1812.07577] [D'Eramo, **KS**: 1904.07870]

Map onto the RPL parameter space

[Esmyol, Iovino, **KS**: 2506.23574]



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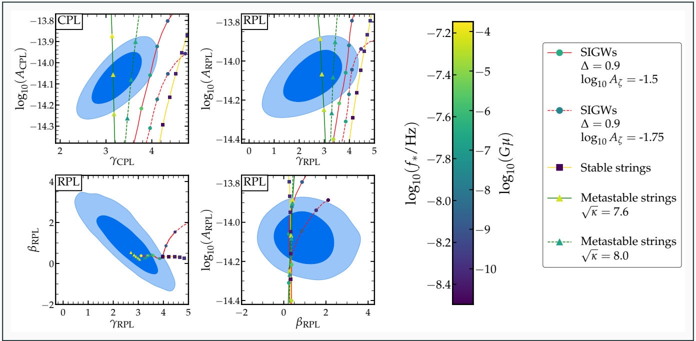
[Esmyol, Iovino, **KS**: 2506.23574]



Next step: Pullback of the RPL posterior density onto the BSM parameter space

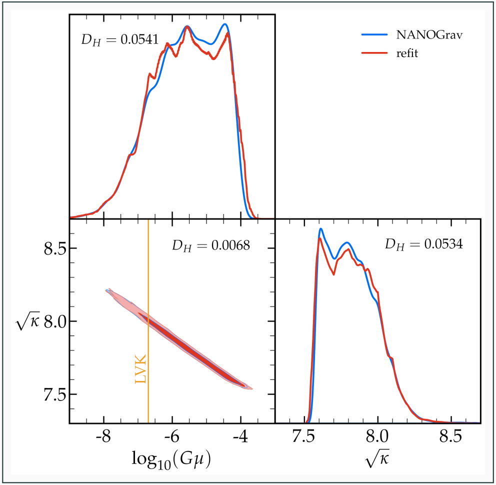
$$\mathcal{L}\left(D|\boldsymbol{\theta}_{\rm BSM}\right) \propto \left(P_{\rm RPL} \circ \Phi\right)\left(\boldsymbol{\theta}_{\rm BSM}\right) \tag{4}$$

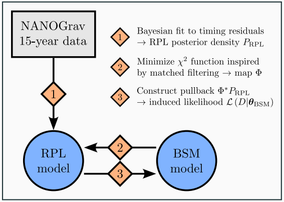
Bayes' theorem: Combine induced likelihood with priors for BSM model parameters

$$P\left(\boldsymbol{\theta}_{\rm BSM}|D\right) = \frac{\left[\left(P_{\rm RPL} \circ \Phi\right)\left(\boldsymbol{\theta}_{\rm BSM}\right)\right] \pi\left(\boldsymbol{\theta}_{\rm BSM}\right)}{\int \left[\left(P_{\rm RPL} \circ \Phi\right)\left(\boldsymbol{\theta}_{\rm BSM}\right)\right] \pi\left(\boldsymbol{\theta}_{\rm BSM}\right)\, {\rm d}\boldsymbol{\theta}_{\rm BSM}} \tag{5}$$

RPL refits: Metastable cosmic strings

Reference model: **RPL** | BSM–RPL map: **Global matching** [MSc thesis of David Esmyol]

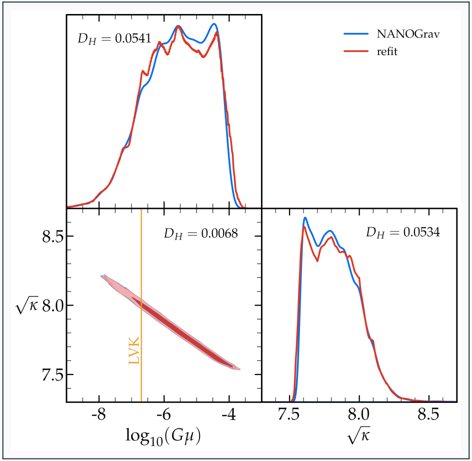




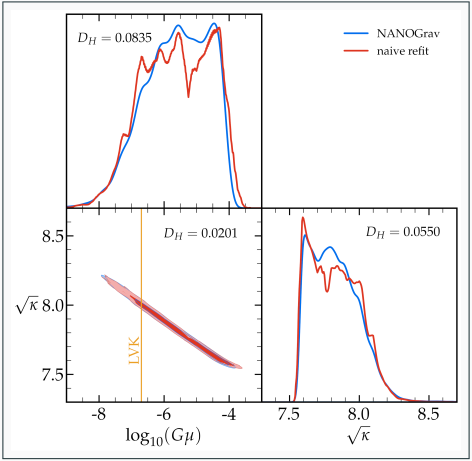
- Small Hellinger D_H → **Excellent agreement**
- Coarse resolution of parameter grid → **Nontrivial posteriors**
- Feature, not a bug → **Nontrivial cross-check**

Comparison to simpler refitting techniques

Reference model: **RPL** | BSM–RPL map: **Global matching**

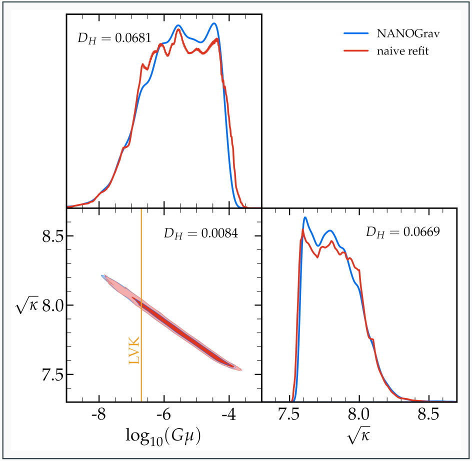


Reference model: **RPL** | BSM–RPL map: **Local matching** ($f_{\mathrm{pivot}} = 0.1\,\mathrm{yr}^{-1}$)



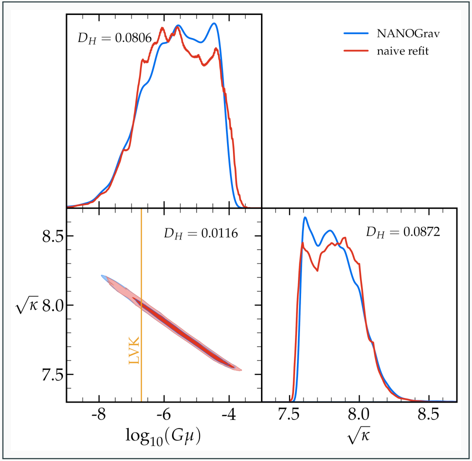
Comparison to simpler refitting techniques

Reference model: **RPL** | BSM–RPL map: **Local matching** ($f_{\rm pivot} = 0.2\,{\rm yr}^{-1}$)



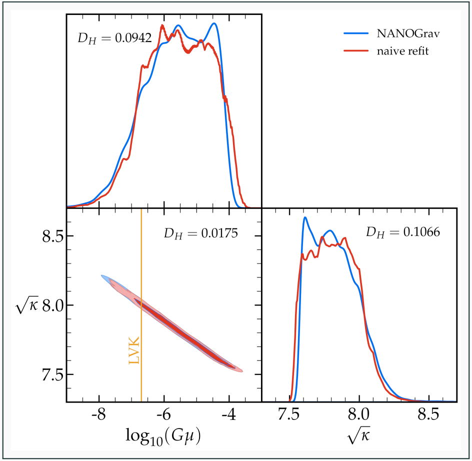
Comparison to simpler refitting techniques

Reference model: **RPL** | BSM–RPL map: **Local matching** ($f_{\text{pivot}} = 0.3\,\text{yr}^{-1}$)



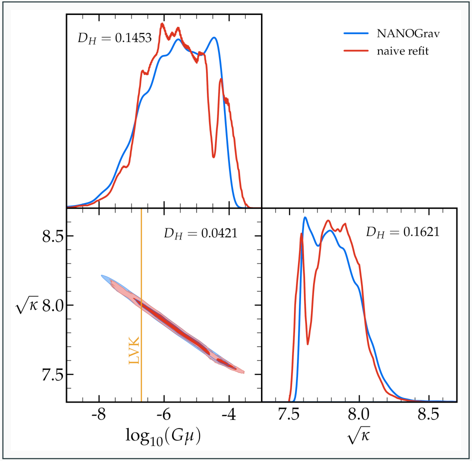
Comparison to simpler refitting techniques

Reference model: **RPL** | BSM–RPL map: **Local matching** ($f_{\rm pivot} = 0.4\,{\rm yr}^{-1}$)



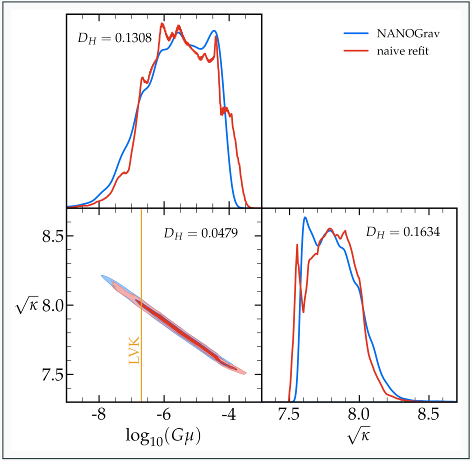
Comparison to simpler refitting techniques

Reference model: **RPL** | BSM–RPL map: **Local matching** ($f_{\rm pivot} = 0.5\,{\rm yr}^{-1}$)



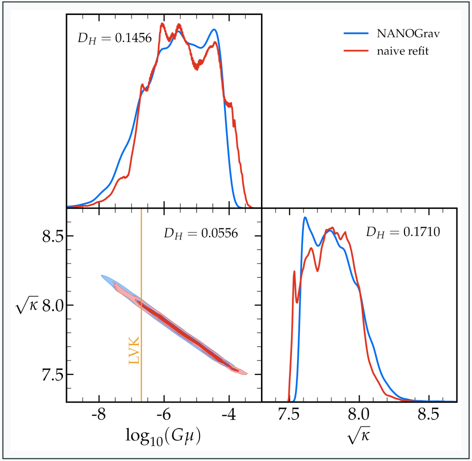
Comparison to simpler refitting techniques

Reference model: **RPL** | BSM–RPL map: **Local matching** ($f_{\rm pivot} = 0.6\,{\rm yr}^{-1}$)



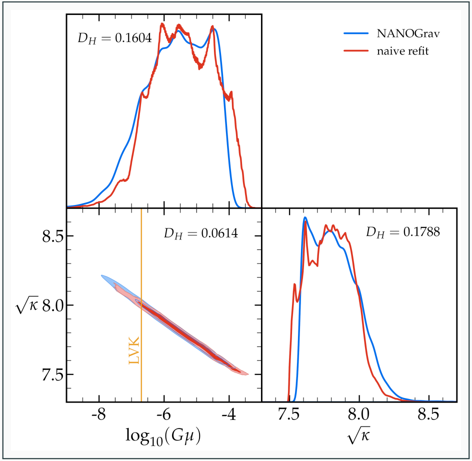
Comparison to simpler refitting techniques

Reference model: **RPL** | BSM–RPL map: **Local matching** ($f_{\rm pivot} = 0.7\,{\rm yr}^{-1}$)

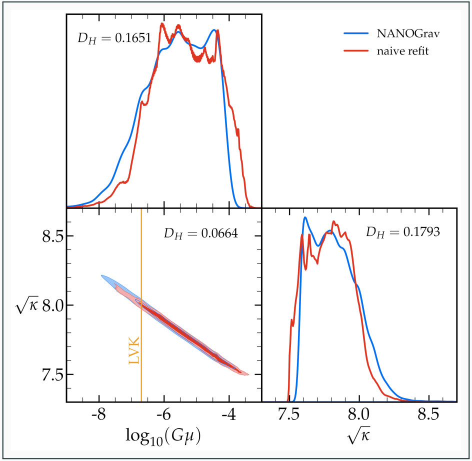


Comparison to simpler refitting techniques

Reference model: **RPL** | BSM–RPL map: **Local matching** ($f_{\text{pivot}} = 0.8\,\text{yr}^{-1}$)

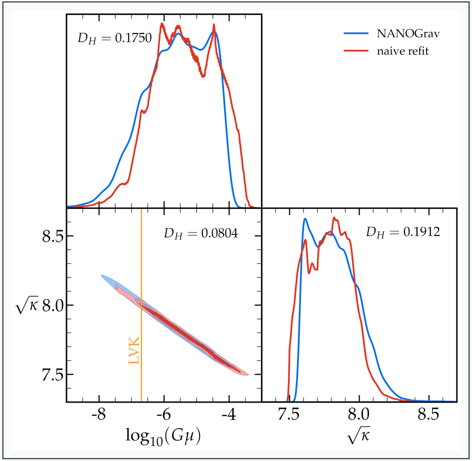


Reference model: **RPL** | BSM–RPL map: **Local matching** ($f_{\rm pivot} = 0.9\,{\rm yr}^{-1}$)



Comparison to simpler refitting techniques

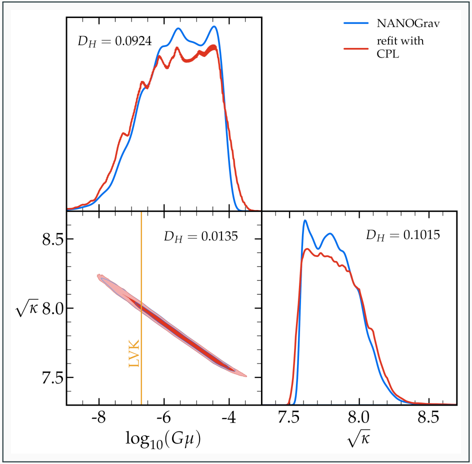
Reference model: **RPL** | BSM–RPL map: **Local matching** ($f_{\rm pivot} = 1.0\,{\rm yr}^{-1}$)



Naive refits are sensitive to choice of $f_{\rm pivot}$

Comparison to simpler refitting techniques

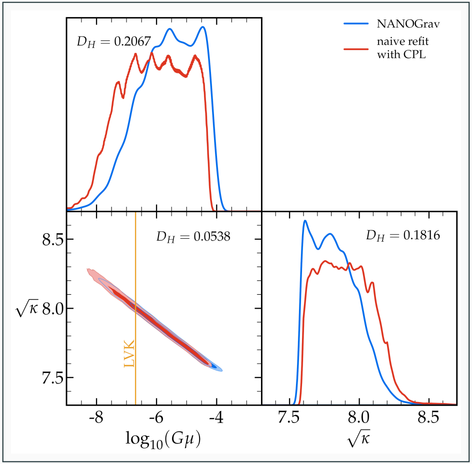
Reference model: **CPL** | BSM–CPL map: **Global matching**



Naive refits are sensitive to choice of f_{pivot}; RPL refits more accurate than CPL refits

Comparison to simpler refitting techniques

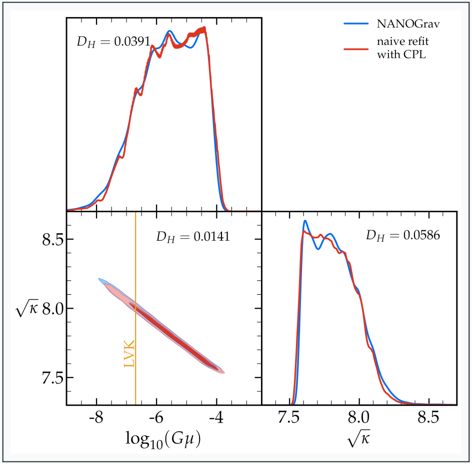
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.1\,{\rm yr}^{-1}$)



Naive refits are sensitive to choice of $f_{\rm pivot}$; RPL refits more accurate than CPL refits

Comparison to simpler refitting techniques

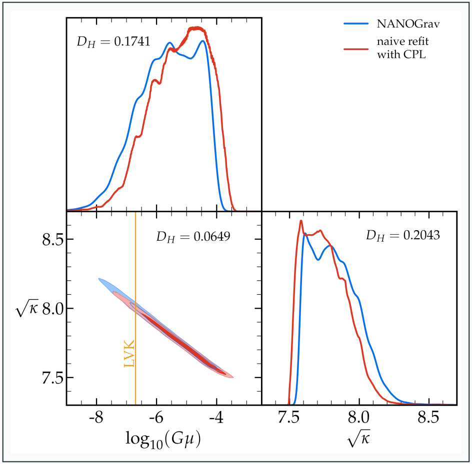
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.2\,{\rm yr}^{-1}$)



Naive refits are sensitive to choice of $f_{\rm pivot}$; RPL refits more accurate than CPL refits

Comparison to simpler refitting techniques

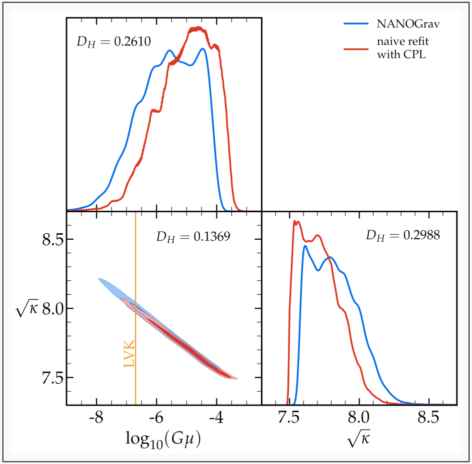
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.3\,{\rm yr}^{-1}$)



Naive refits are sensitive to choice of $f_{\rm pivot}$; RPL refits more accurate than CPL refits

Comparison to simpler refitting techniques

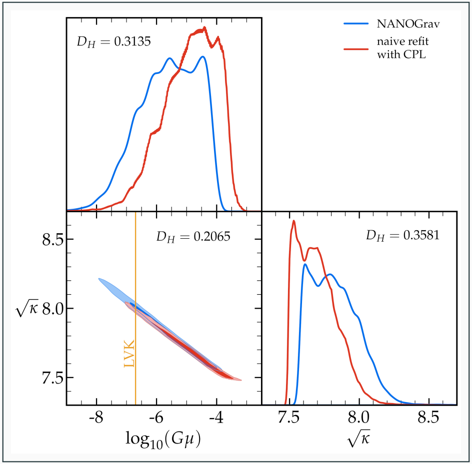
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.4\,{\rm yr}^{-1}$)



Naive refits are sensitive to choice of $f_{\rm pivot}$; RPL refits more accurate than CPL refits

Comparison to simpler refitting techniques

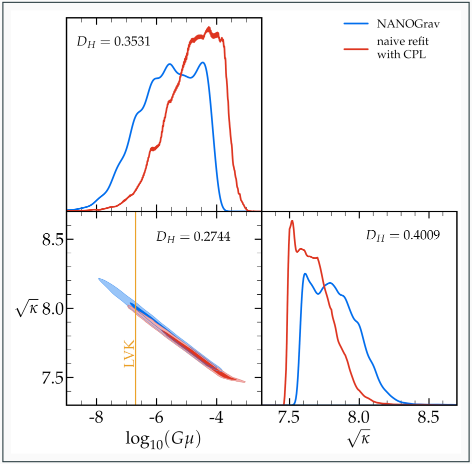
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.5\,{\rm yr}^{-1}$)



Naive refits are sensitive to choice of $f_{\rm pivot}$; RPL refits more accurate than CPL refits

Comparison to simpler refitting techniques

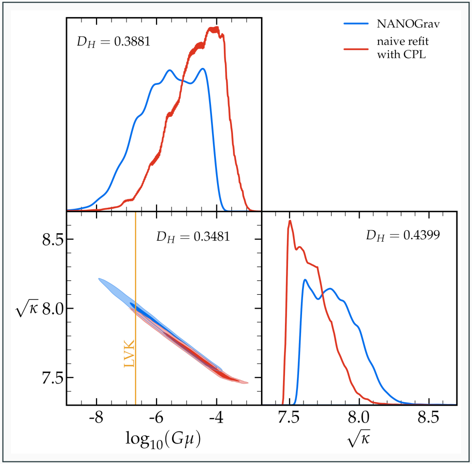
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.6\,{\rm yr}^{-1}$)



Naive refits are sensitive to choice of $f_{\rm pivot}$; RPL refits more accurate than CPL refits

Comparison to simpler refitting techniques

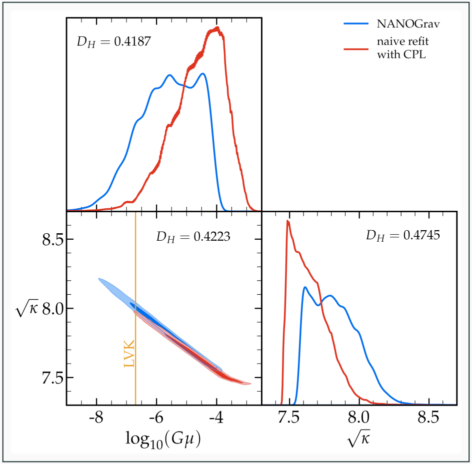
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.7\,{\rm yr}^{-1}$)



Naive refits are sensitive to choice of $f_{\rm pivot}$; RPL refits more accurate than CPL refits

Comparison to simpler refitting techniques

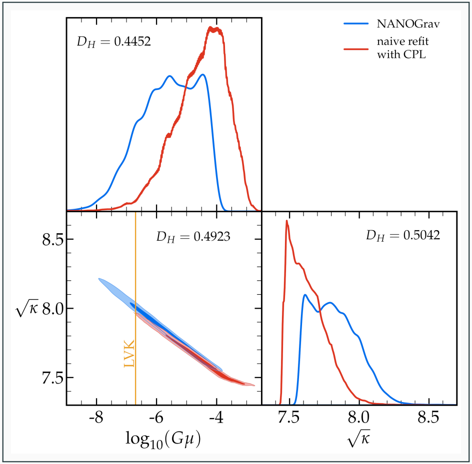
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.8\,{\rm yr}^{-1}$)



Naive refits are sensitive to choice of $f_{\rm pivot}$; RPL refits more accurate than CPL refits

Comparison to simpler refitting techniques

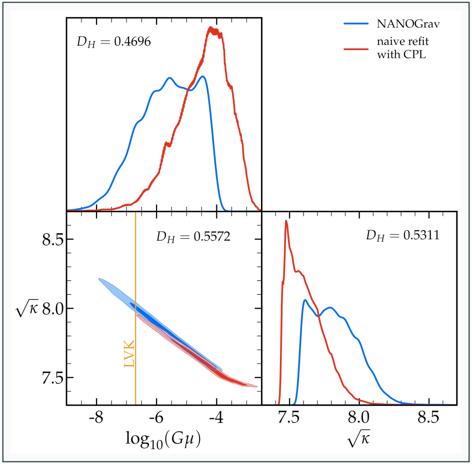
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.9\,{\rm yr}^{-1}$)



Naive refits are sensitive to choice of $f_{\rm pivot}$; RPL refits more accurate than CPL refits

Comparison to simpler refitting techniques

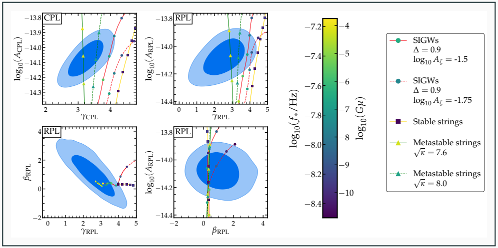
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 1.0\,{\rm yr}^{-1}$)

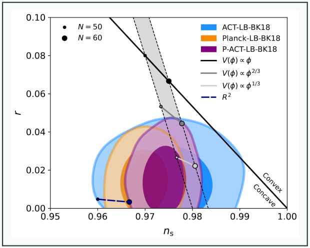


Naive refits are sensitive to choice of $f_{\rm pivot}$; RPL refits more accurate than CPL refits

Summary: CPL / RPL refits

[Esmyol, Iovino, **KS**: 2506.23574] [ACT: 2503.14454]





PTA

- Reference models: **CPL** (A, γ), **RPL** (A, γ, β)
- Better match GW spectra **globally** across full frequency band, e.g., via χ^2 minimization

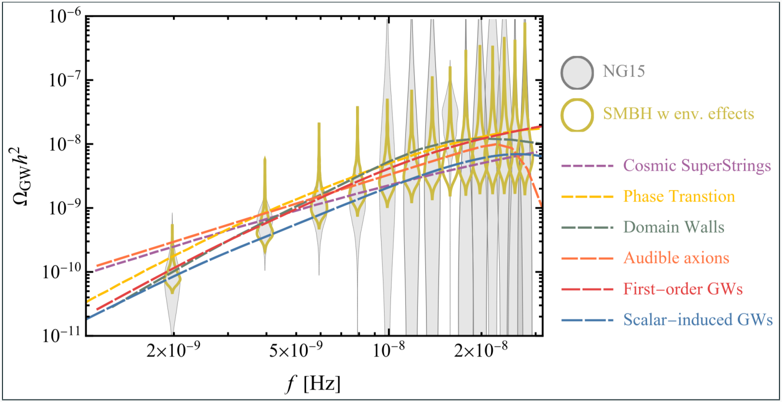
CMB

- Reference models: **CPL** (A_s, n_s), **RPL** (A_s, n_s, α_s)
- Match primordial power spectra **locally** at fixed pivot scale, e.g., $k_{\rm pivot} = 0.05\,{\rm Mpc}^{-1}$
- OK thanks to slow-roll approximation, but dependence on N_e illustrates deviation from CPL

Best option: Fit BSM models directly to raw PTA / CMB data without CPL or RPL detour

Free-spec refits

[Ellis, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Raidal, Urrutia, Vaskonen, Veermäe: 2308.08546]



Another common approach: Refit to **free spectral model**, i.e., the $h^2\Omega_{\mathrm{GW}}$ violins

- More information than in the CPL / RPL model, less than in the full TOA data
- Factorized $\mathcal{L}(D|\vec{\rho}) = \prod_i \mathcal{L}(D|\rho_i)$; no interpulsar / no interfrequency correlations

Take-home messages

❶ Check the stability of the defects in your GUT model
- Meta-/quasi-stable strings rather than stable strings in many cases

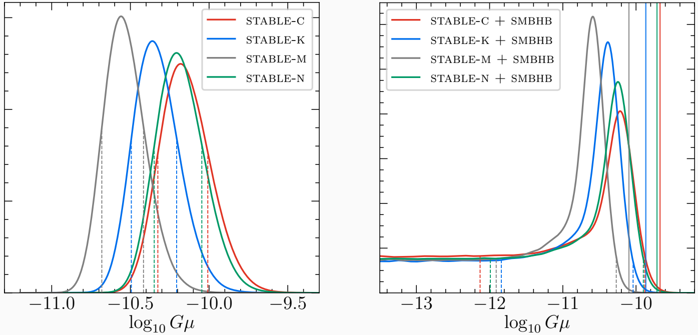
❷ Decide which level of rigor you want to apply in fits to PTA data
- Simplified approaches (e.g., CPL refits) can lead to rather inaccurate results

… and beyond

 [NANOGrav: 2306.16219]

Different models for topologically stable Nambu–Goto strings

- GW emission dominated by cusps (c), kinks (k), fundamental mode (m); numerical result (n)
- GWs from cosmic strings only or in combination with GWs from supermassive BH binaries



Bayesian fit to NG15 timing residuals

[NANOGrav: 2306.16219]

Different models for topologically stable Nambu–Goto strings

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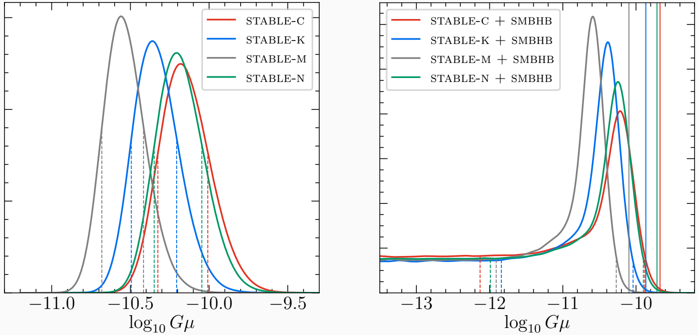
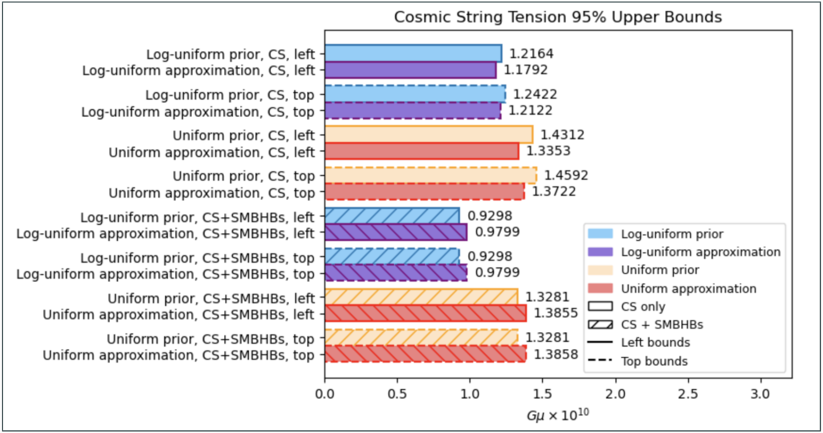


Most rigorous approach to data analysis, but still lots of uncertainties

- **Model uncertainties:** Most ingredients on the theory side come with big uncertainties
- **Statistical uncertainties:** Bayesian vs. frequentist statistics, prior dependence, etc.

Details of the statistical analysis

[Oliva Bitcon (Fulbright student) 2025]

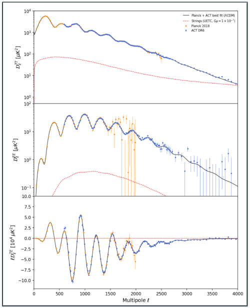


Same NANOGrav and MCMC data, but different choices in the statistical analysis

Variation in the upper limit by a factor of ~ 1.5

Updated CMB limits

Upper limits on string tension for cosmic strings and superstrings



Model Type	Parametrization	Priors on $\alpha, \tilde{c}$	Planck	Planck + ACT
Cosmic Strings	$G\mu$	Flat	1.17×10^{-7}	1.16×10^{-7}
		Gaussian	6.85×10^{-8}	6.26×10^{-8}
	$\log_{10} G\mu$	Flat	3.53×10^{-8}	3.53×10^{-8}
		Gaussian	3.96×10^{-8}	3.66×10^{-8}
Cosmic Superstrings	$G\mu_F$	Flat	5.34×10^{-8}	6.55×10^{-8}
		Gaussian	3.28×10^{-8}	2.63×10^{-8}
	$\log_{10} G\mu_F$	Flat	1.54×10^{-8}	1.52×10^{-8}
		Gaussian	1.71×10^{-8}	1.38×10^{-8}

TABLE I: 95% C.L. upper limits on the cosmic string tension $G\mu$ and $G\mu_F$. The "Planck" column uses the CamSpec PR4 likelihood, while the "Planck + ACT" column uses the ACT DR6 likelihood combined with a cut version of the *Planck* 2018 PR3 likelihood. Results are shown across different models, parametrizations, and prior assumptions.

[Raidal, Avgoustidis, Copeland, Moss: 2602.18272]

- **Cosmic strings:** Variation in the upper limit by a factor of ~ 3.3
- **Cosmic superstrings:** Variation in the upper limit by a factor of ~ 4.7

Take-home messages

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- Meta-/quasi-stable strings rather than stable strings in many cases

❷ Decide which level of rigor you want to apply in fits to PTA data

- Simplified approaches (e.g., CPL refits) can lead to rather inaccurate results

❸ Be explicit about the assumptions and details of your statistical analysis

- Different prior choices etc. lead to different outcomes for the same data

Take-home messages

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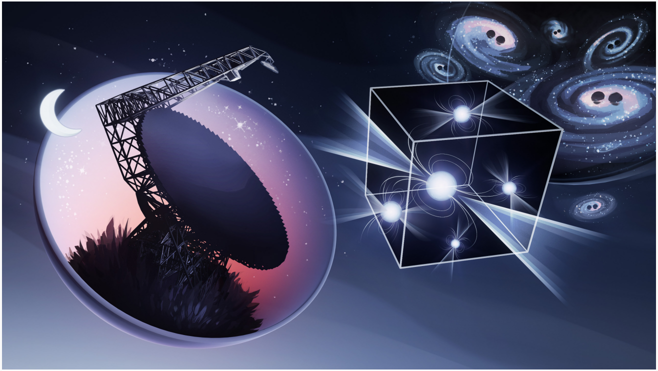
This is only the beginning!



A bright future for GW science with PTAs

- Status: Common-spectrum process; $3 \cdots 4\,\sigma$ evidence for HD correlations
- Next: HD correlations at $5\,\sigma$, spectral shape, anisotropies across the sky, ...
- Promise: Deep insights into galaxy and BH evolution and/or new physics

Stay tuned!

And thanks a lot for your attention