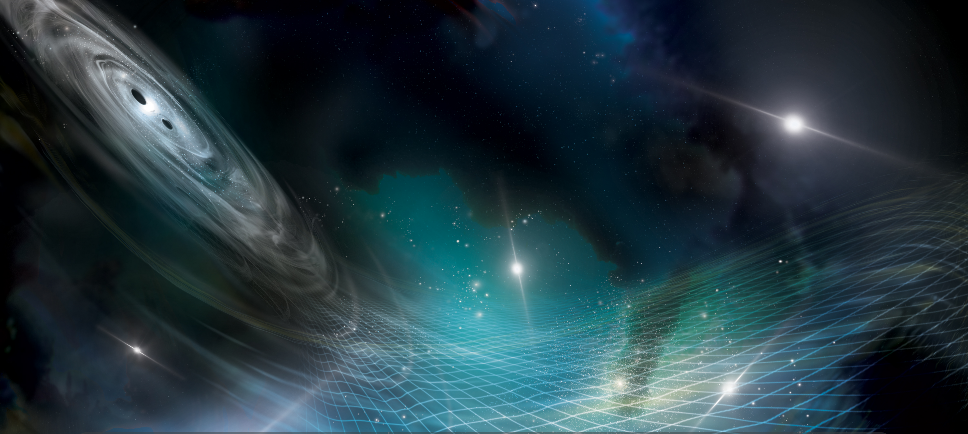
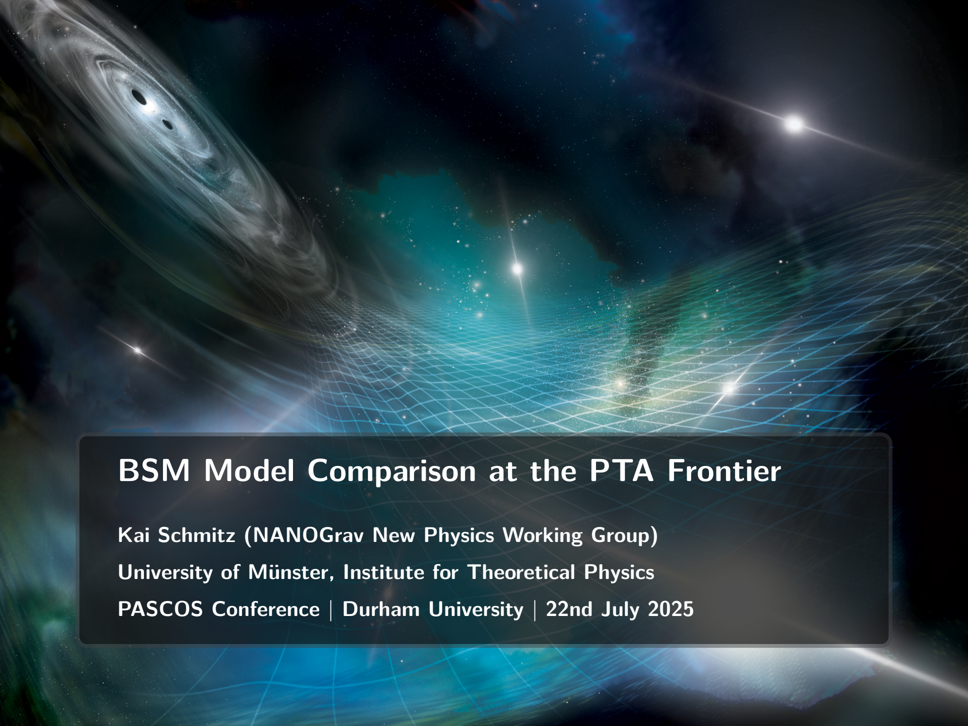


BSM Physics at the PTA Frontier

Kai Schmitz (NANOGrav New Physics Working Group)

University of Münster, Institute for Theoretical Physics

PASCOS Conference | Durham University | 22nd July 2025



BSM Model Comparison at the PTA Frontier

Kai Schmitz (NANOGrav New Physics Working Group)

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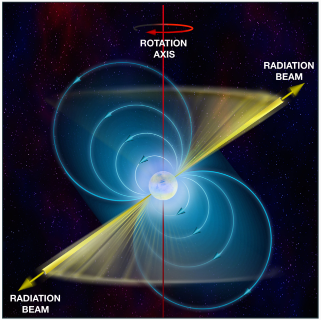
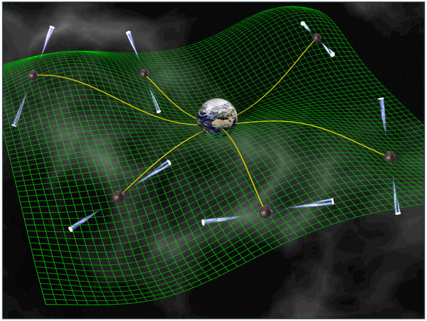
PASCOS Conference | Durham University | 22nd July 2025

Pulsar timing arrays (PTAs)

Array of pulsars across our MW spiral arm → GW detector of galactic dimensions!



[nrao.edu]



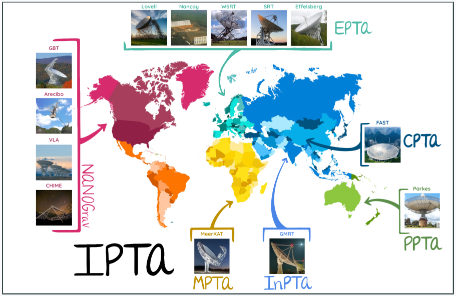
[MPIfR]

Pulsars: **Highly magnetized rotating neutron stars**

- Beamed radio pulses emitted from magnetic N and S poles → cosmic lighthouses
- Stable rotation with periods as short as a few milliseconds → celestial clocks

Look for tiny distortions in pulse times of arrival (TOAs) caused by nanohertz GWs

2023 PTA results



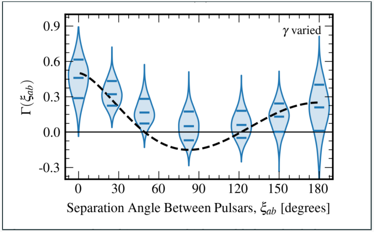
EPTA: European PTA
CPTA: Chinese PTA
PPTA: Parkes PTA
InPTA: Indian PTA
MPTA: MeerKAT PTA
NANOGrav: North American Nanohertz Observatory for Gravitational Waves

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

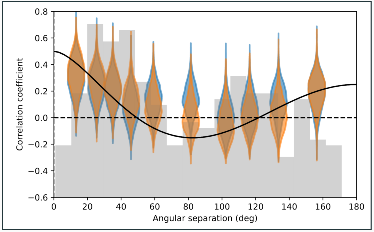
Evidence for Hellings–Downs (HD) correlations $\Gamma(\xi_{ab})$

2306.16213: NANOGrav



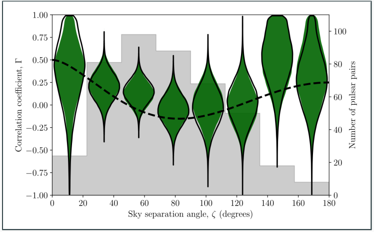
68 pulsars, 16 yr of data, HD at $\sim 3 \cdots 4\,\sigma$

2306.16214: EPTA+InPTA



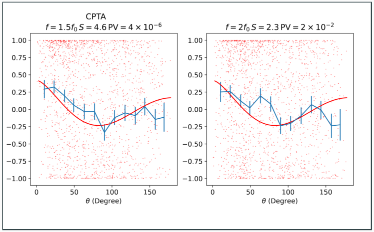
25 pulsars, 25 yr of data, HD at $\sim 3\,\sigma$

2306.16215: PPTA



32 pulsars, 18 yr of data, HD at $\sim 2\,\sigma$

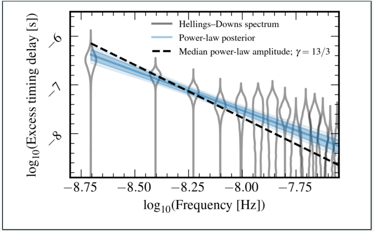
2306.16216: CPTA



57 pulsars, 3.5 yr of data, HD at $\sim 4.6\,\sigma$

Common power spectrum $\sqrt{\Delta f \, P_g\,(f)}$

2306.16213: NANOGrav



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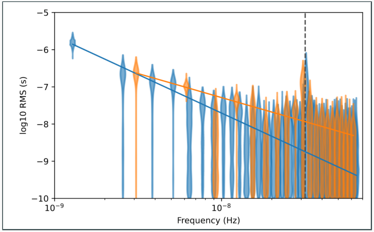

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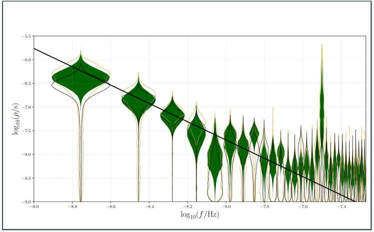


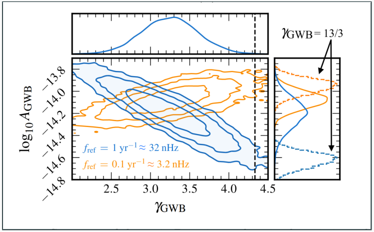
32 pulsars, 18 yr of data, HD at $\sim 2\,\sigma$

2306.16216: CPTA

57 pulsars, 3.5 yr of data, HD at $\sim 4.6\,\sigma$

Power-law parameters A and γ

2306.16213: NANOGrav



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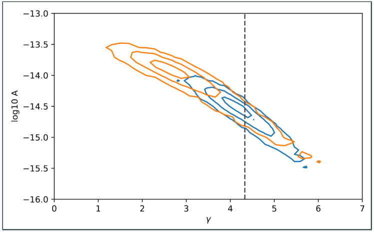

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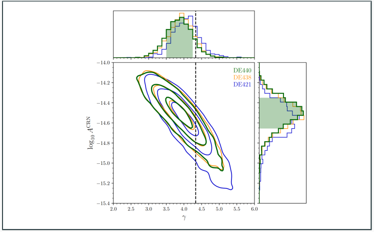

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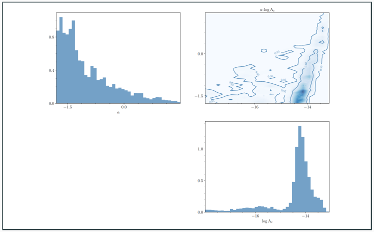
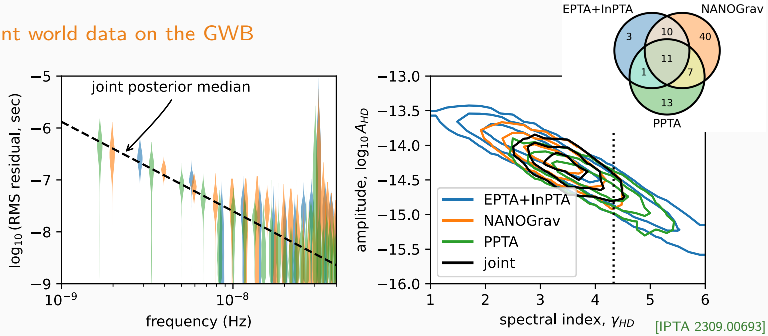


57 pulsars, 3.5 yr of data, HD at $\sim 4.6\,\sigma$

IPTA comparison

Current world data on the GWB

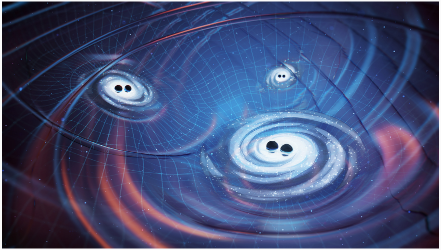


[IPTA 2309.00693]

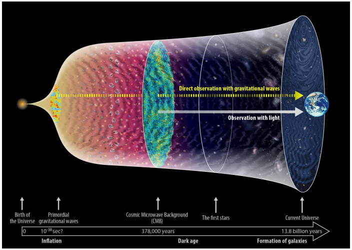
- Results from regional PTAs are consistent with each other (1σ posteriors overlap)
- Joint posterior $=$ naive product (properly normalized) of individual posteriors
- Proper data combination and combined data analysis $\rightarrow$ IPTA DR3

Interpretations

❶ Supermassive black-hole binaries



❷ GWs from the Big Bang



❶ SMBHBs (realistic)

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

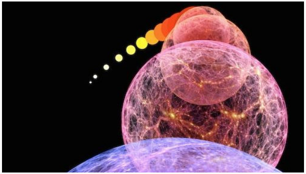
❷ New physics (speculative)

- 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

Beyond-the-Standard-Model (BSM) options

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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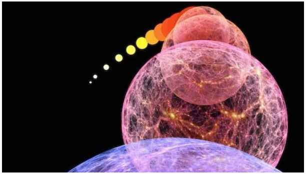
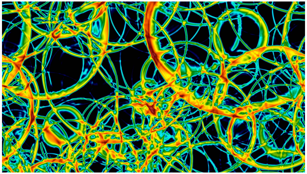


❷ Cosmological phase transition

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



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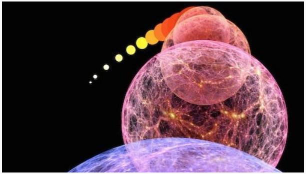

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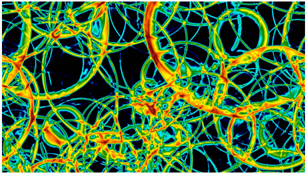
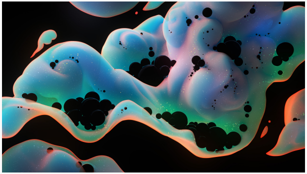


❸ Enhanced density perturbations

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



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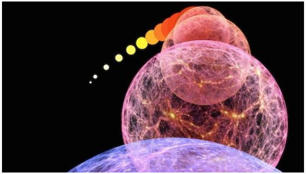

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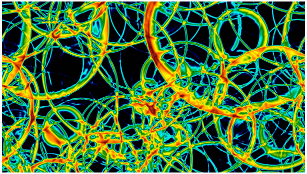

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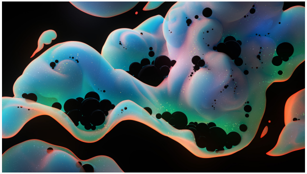
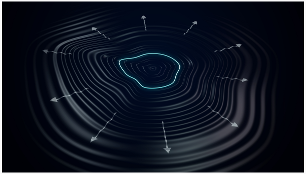


❹ Cosmic defects

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



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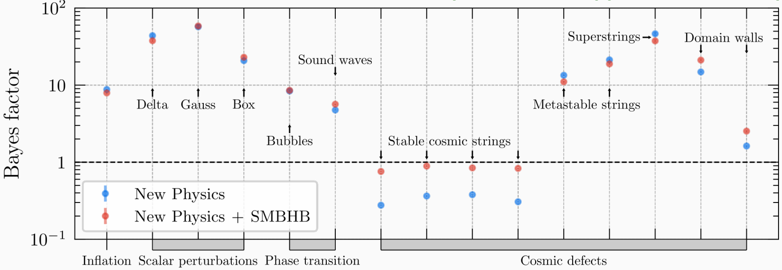
Bayesian model comparison

[NANOGrav 2306.16219] [See also: EPTA 2306.16227]

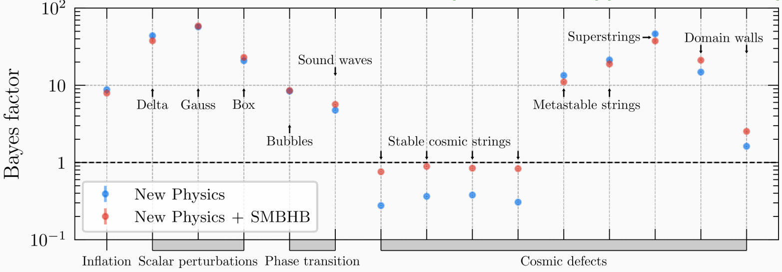


$$\text{Bayes factor } B = \frac{\text{Evidence for model } M_1,\ P\left(D|M_1\right)}{\text{Evidence for model } M_0,\ P\left(D|M_0\right)}\,, \quad M_0 = \{\text{SMBHBs only}\}$$

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

Spectral characterization of the signal

Is my BSM model capable of explaining the PTA signal?

- Bayesian fit to the data: `PTArcade`, `ceffyl`, ... (minority of all analyses)
- Compare to reference model: **constant power law** (A, γ), **free spectrum** (violins)

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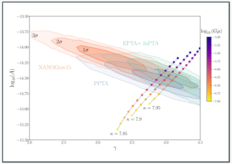
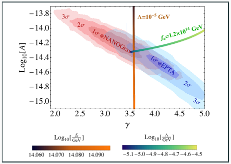
Metastable cosmic strings



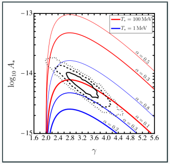
[2308.05799]

Axion domain walls



[2306.17022]

Phase transition



[2306.17205]

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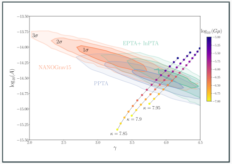

[2308.05799]

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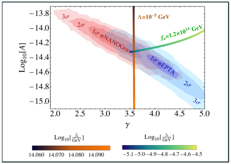

[2306.17022]

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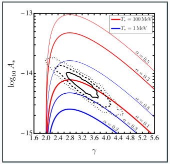


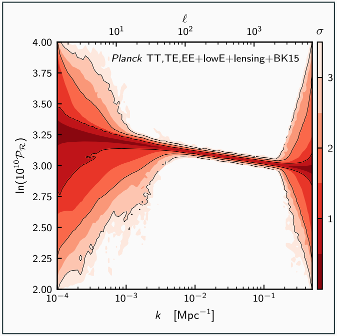
[2306.17205]

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

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

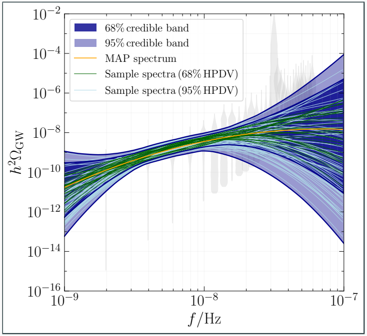
Running power law (RPL)

Primordial scalar power spectrum



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

GW power spectrum in the PTA band

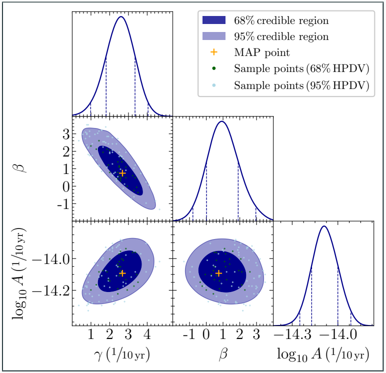


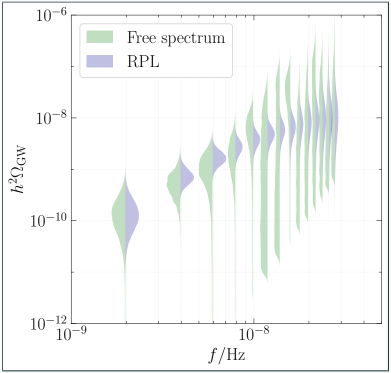
[NANOGrav: 2408.10166]

- **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)

RPL posteriors

[NANOGrav: 2408.10166]



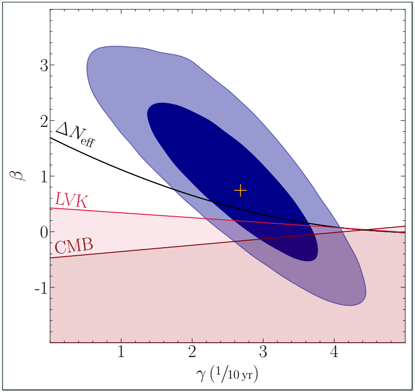


Point and interval estimates based on the 1D marginalized posteriors

Parameter	1D MAP value	95 % HPDI credible interval
Amplitude $\log_{10} A(1/10\,\mathrm{yr})$	-14.09	$[-14.25, -13.91]$
Spectral index $\gamma(1/10\,\mathrm{yr})$	2.60	$[0.98, 4.05]$
Running of the spectral index β	0.92	$[-0.80, 2.96]$

GWs from inflation

[NANOGrav: 2408.10166]

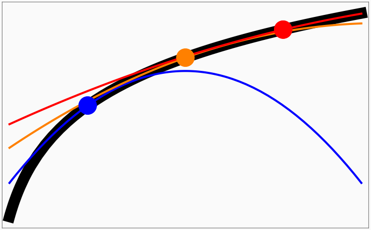


Extrapolate RPL spectrum all the way from CMB to LVK frequencies

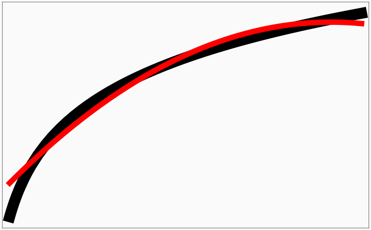
- Toy model of GWs from inflation; not realistic, but interesting benchmark
- Large viable parameter space consistent with $\Delta N_{\rm eff}$, CMB, LVK — unlike CPL

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)

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

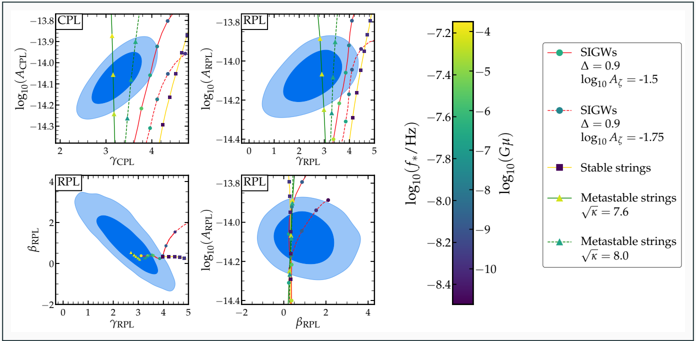
❷ Match BSM and RPL spectra **globally** by minimizing the "SNR of their difference"

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

[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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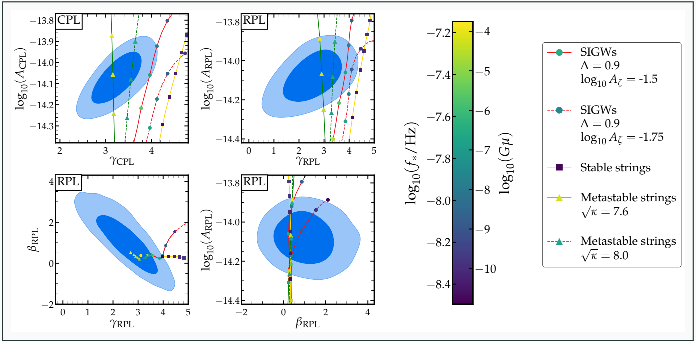


Next step: Pullback of the RPL posterior density onto the BSM parameter space

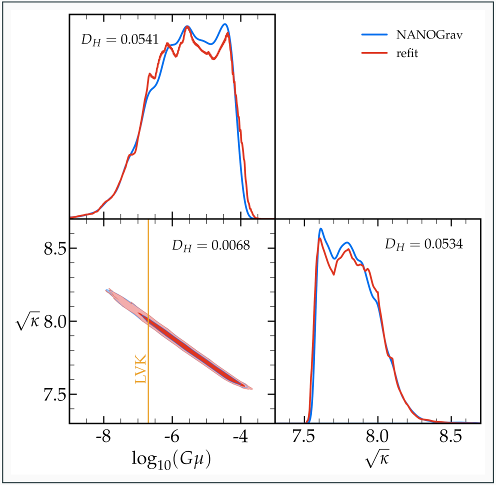
$$\mathcal{L}\left(D|\boldsymbol{\theta}_{\rm BSM}\right) \propto \left(P_{\rm RPL} \circ \Phi\right)\left(\boldsymbol{\theta}_{\rm BSM}\right) \tag{3}$$

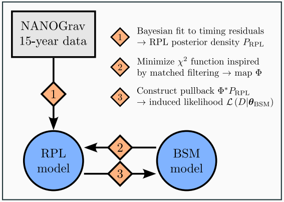
Bayes' theorem: Combine induced likelihood with priors for BSM model parameters

$$P\left(\boldsymbol{\theta}_{\rm BSM}|D\right) = \frac{\left[\left(P_{\rm RPL} \circ \Phi\right)\left(\boldsymbol{\theta}_{\rm BSM}\right)\right]\pi\left(\boldsymbol{\theta}_{\rm BSM}\right)}{\int \left[\left(P_{\rm RPL} \circ \Phi\right)\left(\boldsymbol{\theta}_{\rm BSM}\right)\right]\pi\left(\boldsymbol{\theta}_{\rm BSM}\right)\, \mathrm{d}\boldsymbol{\theta}_{\rm BSM}} \tag{4}$$

RPL refits: Metastable cosmic strings

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

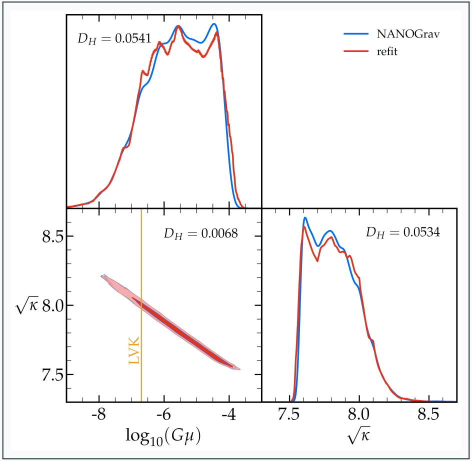




- Small Hellinger D_H → **Excellent agreement**
- Coarse resolution of parameter grid → **Nontrivial posteriors**
- Feature, not a bug → **Nontrivial cross-check**

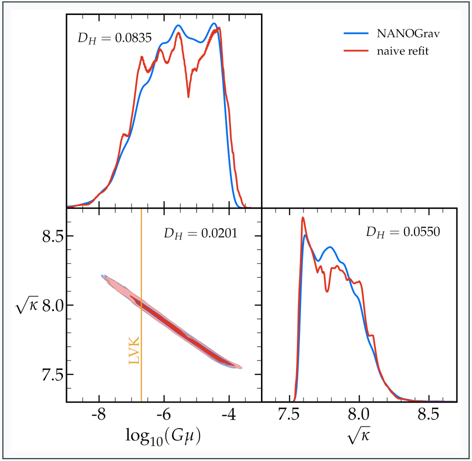
Comparison to simpler refitting techniques

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



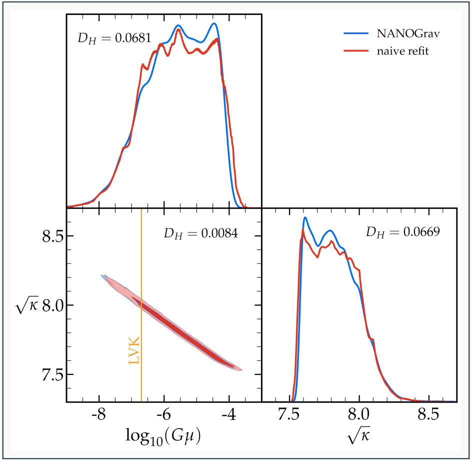
Comparison to simpler refitting techniques

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



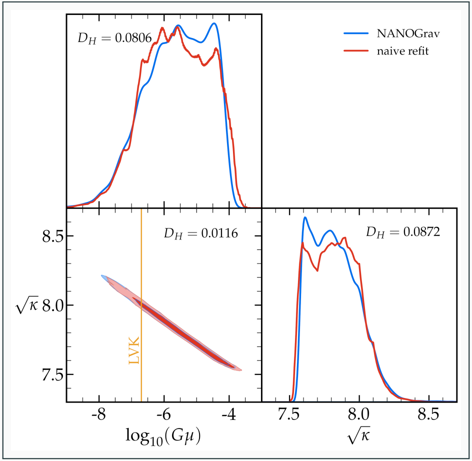
Comparison to simpler refitting techniques

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



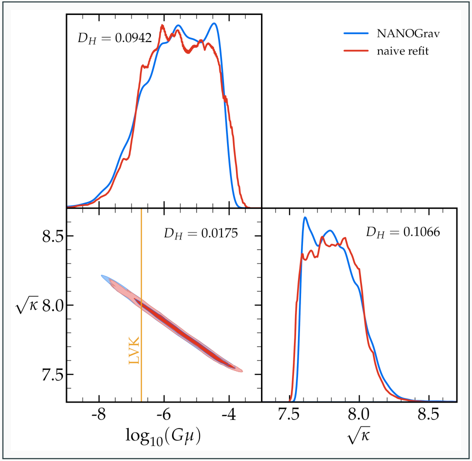
Comparison to simpler refitting techniques

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



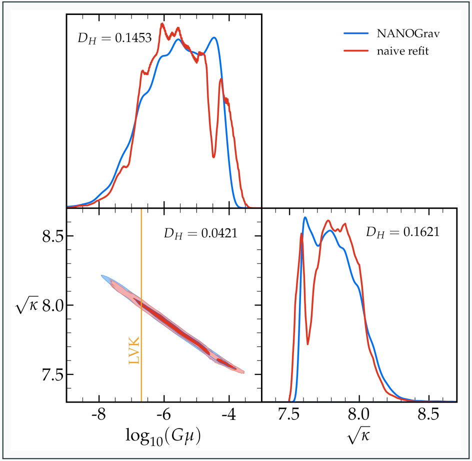
Comparison to simpler refitting techniques

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



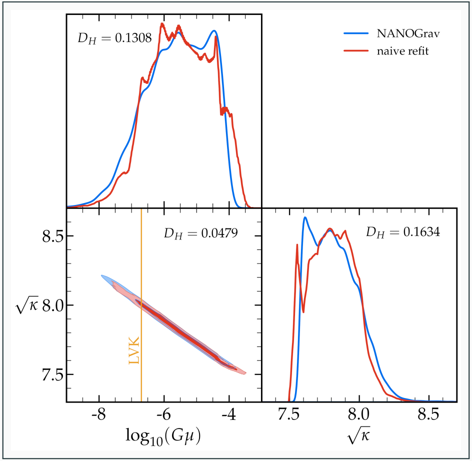
Comparison to simpler refitting techniques

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



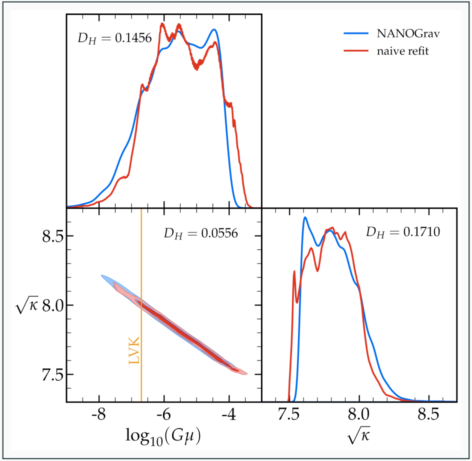
Comparison to simpler refitting techniques

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



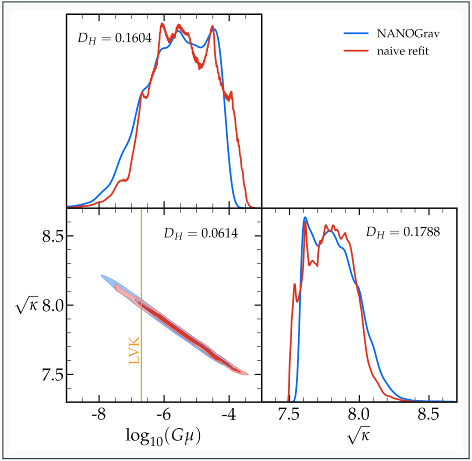
Comparison to simpler refitting techniques

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



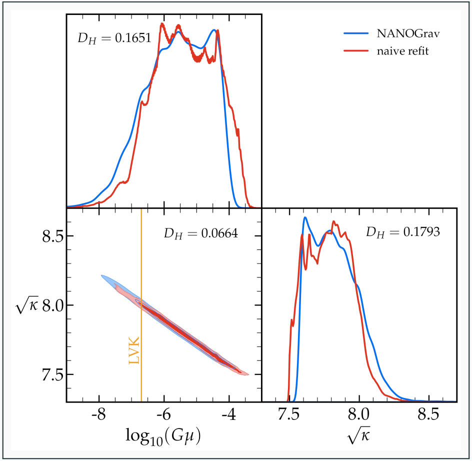
Comparison to simpler refitting techniques

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

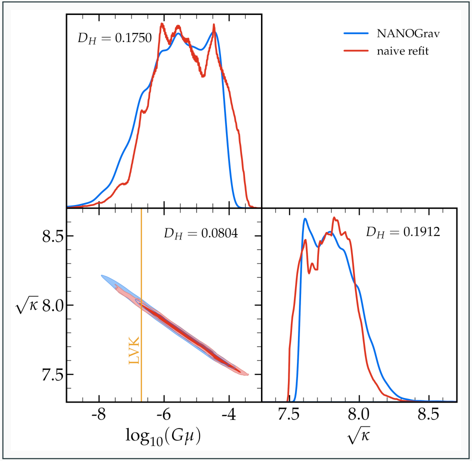


Comparison to simpler refitting techniques

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

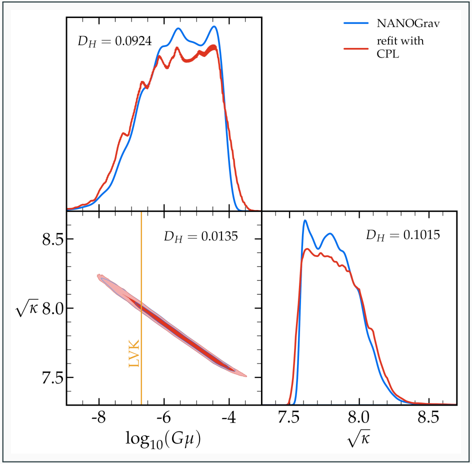


Reference model: **RPL** | BSM–RPL map: **Local matching** ($f_{\mathrm{pivot}} = 1.0\,\mathrm{yr}^{-1}$)



Naive refits are sensitive to choice of f_{pivot}

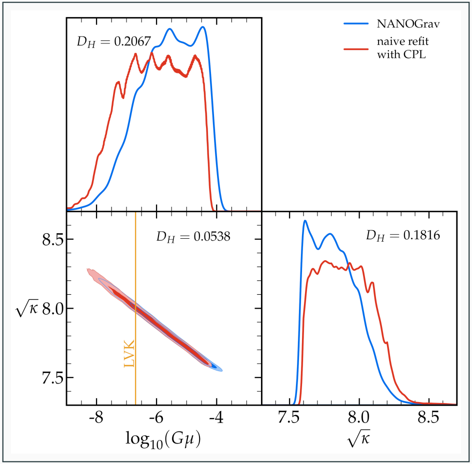
Reference model: **CPL** | BSM–CPL map: **Global matching**



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

Comparison to simpler refitting techniques

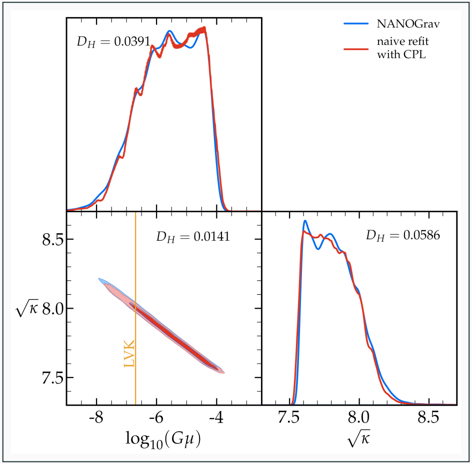
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.1\,{\rm yr}^{-1}$)



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

Comparison to simpler refitting techniques

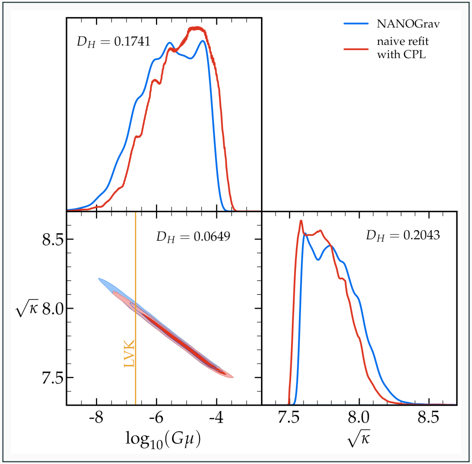
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\mathrm{pivot}} = 0.2\,\mathrm{yr}^{-1}$)



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

Comparison to simpler refitting techniques

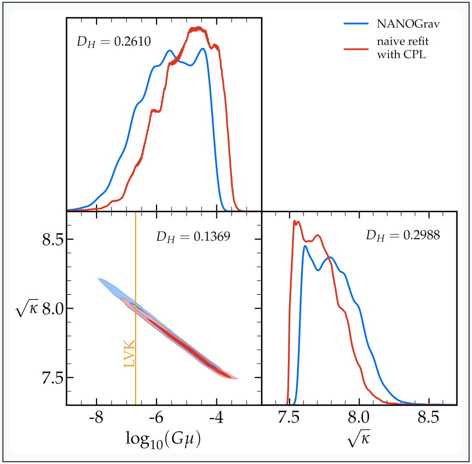
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.3\,{\rm yr}^{-1}$)



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

Comparison to simpler refitting techniques

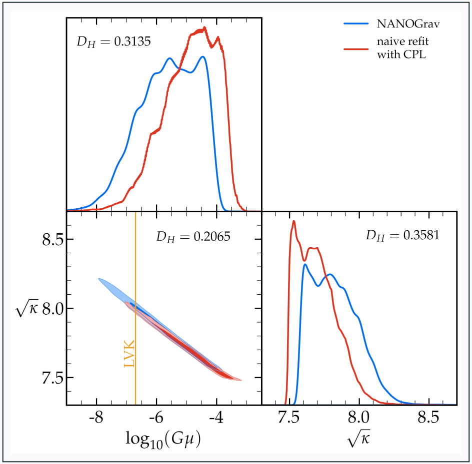
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\mathrm{pivot}} = 0.4\,\mathrm{yr}^{-1}$)



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

Comparison to simpler refitting techniques

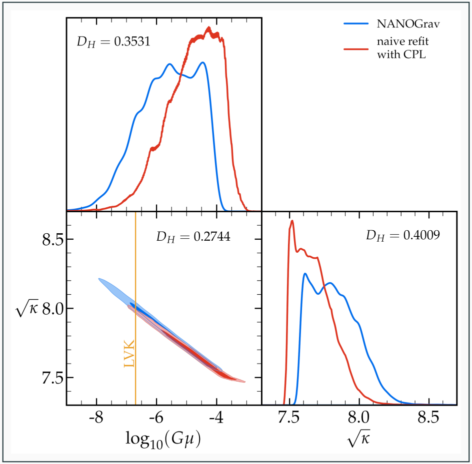
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\mathrm{pivot}} = 0.5\,\mathrm{yr}^{-1}$)



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

Comparison to simpler refitting techniques

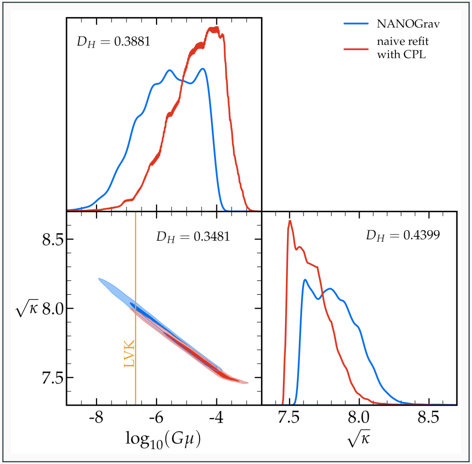
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\text{pivot}} = 0.6\,\text{yr}^{-1}$)



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

Comparison to simpler refitting techniques

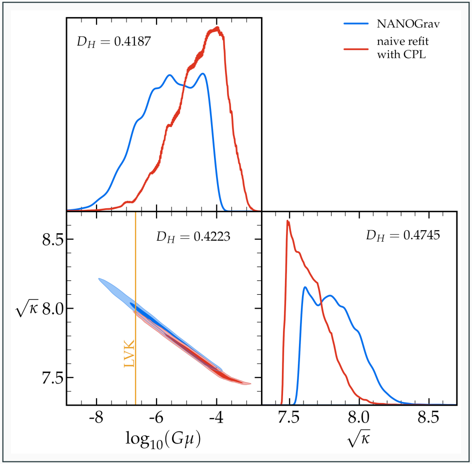
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\rm pivot} = 0.7\,{\rm yr}^{-1}$)



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

Comparison to simpler refitting techniques

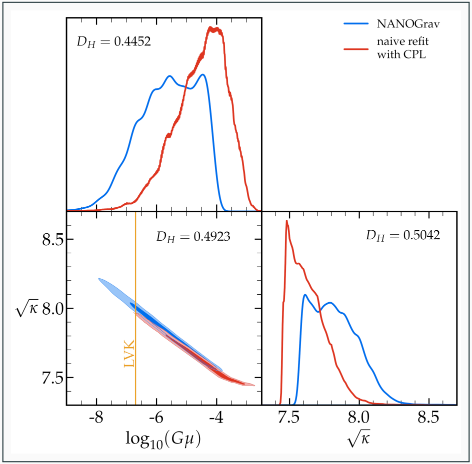
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\mathrm{pivot}} = 0.8\,\mathrm{yr}^{-1}$)



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

Comparison to simpler refitting techniques

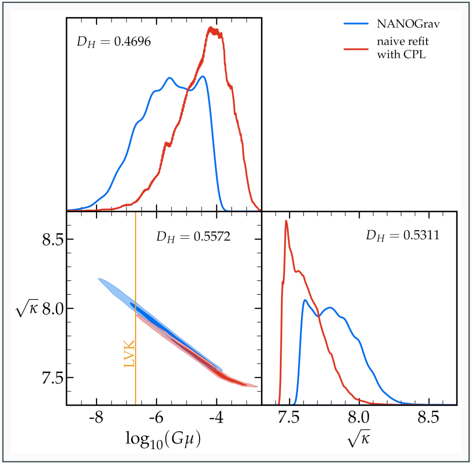
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\mathrm{pivot}} = 0.9\,\mathrm{yr}^{-1}$)



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

Comparison to simpler refitting techniques

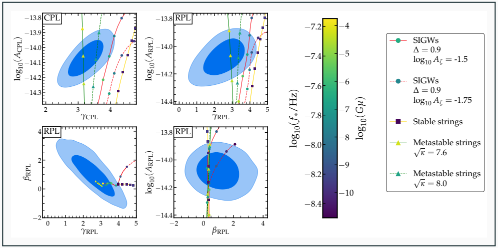
Reference model: **CPL** | BSM–CPL map: **Local matching** ($f_{\text{pivot}} = 1.0\,\text{yr}^{-1}$)



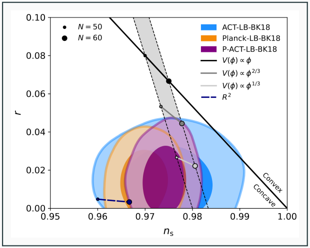
Naive refits are sensitive to choice of f_{pivot}; RPL refits more accurate than CPL refits

Summary: CPL / RPL refits

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



[ACT: 2503.14454]



PTA

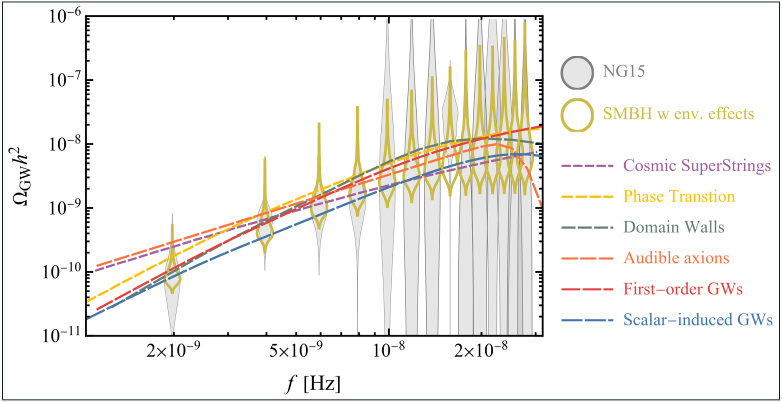
- Reference models: **CPL** (A, γ), **RPL** (A, γ, β)
- Better match GW spectra **globally** across full frequency band, e.g., via χ^2 minimization

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

[NANOGrav: 2408.10166]

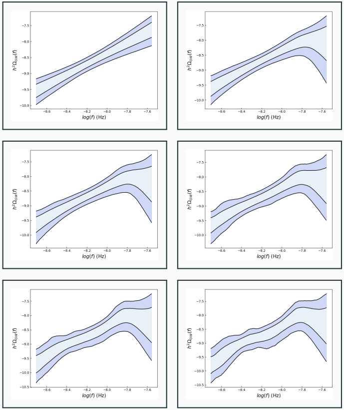


Another common approach: Refit to **free spectral model**, i.e., the $h^2\Omega_{\rm GW}$ "violins"

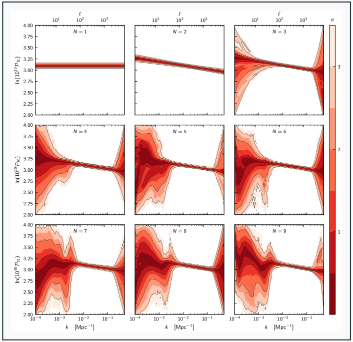
- More information than in the CPL / RPL model, less than in the full TOA data
- But physically unrealistic; rather expect a smooth spectrum $\to$ Compromise?

Piecewise power-law reconstruction of the GWB signal

[NANOGrav: to appear soon]

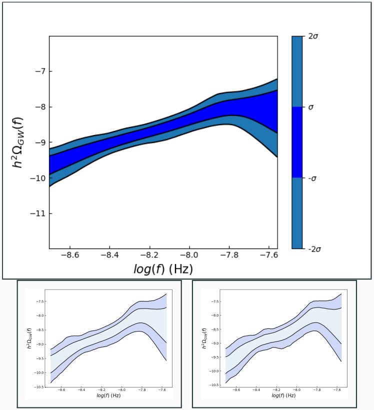


[PLANCK: 1807.06211]

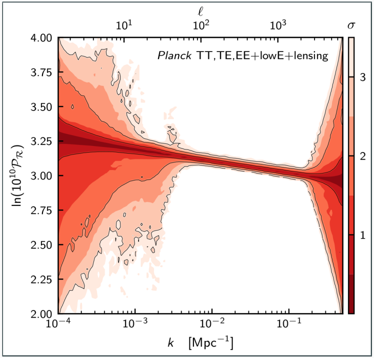


Piecewise power-law reconstruction of the GWB signal

[NANOGrav: to appear soon]



[PLANCK: 1807.06211]



Bayesian model average (BMA)

- Marginalize over # of power-law segments; weight models by relative evidence
- Refit BSM models to Bayesian periodogramm (“violins”) of the BMA spectrum

Conclusions

Take-home messages

1. Lots of exciting BSM models that can be probed at the PTA frontier
2. Parameter inference at three different levels
   - Bayesian MCMC fit to the PTA timing residuals → `PTArcade`
   - Refit to the "violins" of the free spectral model → `ceffyl`
   - Refit to the posterior of the running-power-law (RPL) model → [2408.10166, 2506.23574]
3. Better match BSM and RPL spectra globally ("no slow-roll approximation")
4. Use CMB literature as an inspiration for PTA science, and vice versa

Stay tuned!

And thanks a lot for your attention