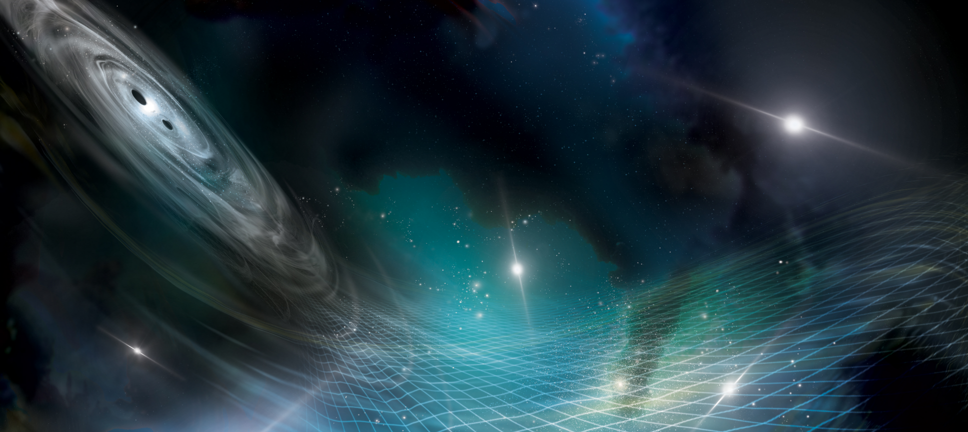


New Physics at the Pulsar Timing Array Frontier

Kai Schmitz (NANOGrav New Physics Working Group)

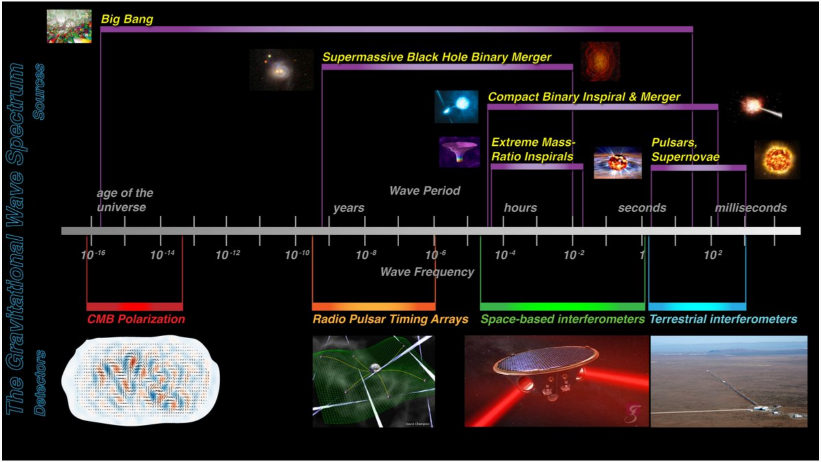
University of Münster, Institute for Theoretical Physics

Fundamental physics and GW detectors | Pollica Physics Centre | 9/9/2024

Past

GW spectrum

[NASA]

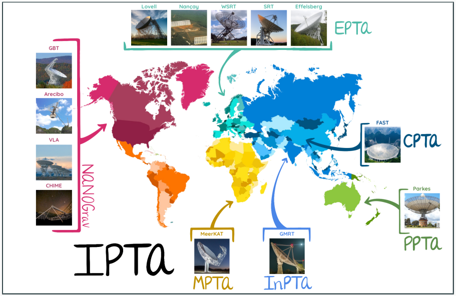


2023 Pulsar Timing Array (PTA) results: **Evidence for a GW background (GWB)**

→ Stochastic background in the nanohertz band, i.e., at frequencies $f \sim 2 \cdots 30\,\mathrm{nHz}$

→ New window onto the GW universe at frequencies 10^{10} smaller than those observed by LVK

2023 PTA results



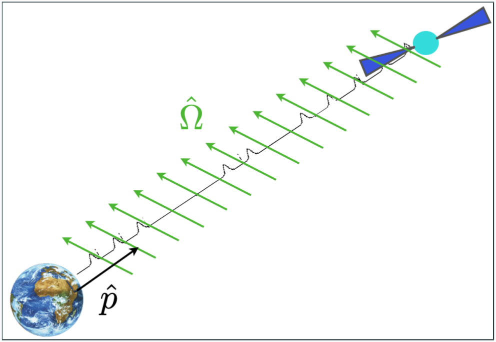
EPTA:	European PTA
CPTA:	Chinese PTA
PPTA:	Parkes PTA
InPTA:	Indian PTA
MPTA:	MeerKAT PTA

NANOGrav: North American Nanohertz Observatory for Gravitational Waves

18 papers on the arXiv on June 29, 2023

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

GW imprint in PTA data



GWs red/blue-shift the train of pulses from a pulsar

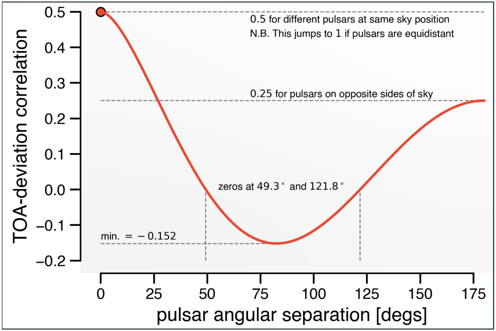
Example: Monochromatic GW moving in direction $\hat{\Omega}$

$$Z = \frac{1}{2} \frac{\hat{p}^i \hat{p}^j}{1 + \hat{\Omega} \cdot \hat{p}} \left[h_{ij} \left(t_{\rm obs}, \boldsymbol{x}_{\rm earth} \right) - h_{ij} \left(t_{\rm em}, \boldsymbol{x}_{\rm pulsar} \right) \right]$$

Main PTA observable: **Timing residual** $R_a(t) = \int_0^t dt' \, Z(t')$ for each pulsar a

Cross-correlation analysis

[Hellings, Downs: ApJ 265 (1983) L39] [2105.13270]



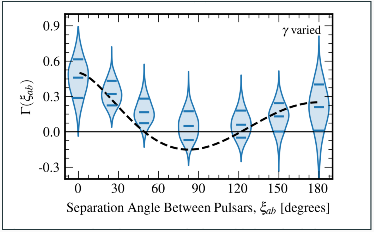
Timing-residual cross power spectrum: Correlation coefficients × power spectrum

$$\langle R_a R_b \rangle = \Gamma(\xi_{ab}) \int_0^\infty df\, P_g(f)$$

- **Hellings–Downs curve:** $\Gamma(\xi_{ab}) = \frac{3}{2} x_{ab} \ln x_{ab} - \frac{x_{ab}}{4} + \frac{1}{2}\,, \quad x_{ab} = \frac{1}{2}(1 - \cos \xi_{ab})$
- **Common power spectrum:** $P_g(f) = h_c^2/(12\pi^2 f^3) \overset{\text{ansatz}}{\rightarrow} A^2/(12\pi^2 f_{\rm yr}^3)(f/f_{\rm yr})^{-\gamma}$

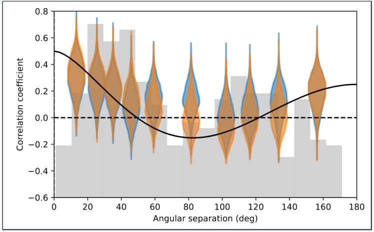
Evidence for HD correlations $\Gamma(\xi_{ab})$

2306.16213: NANOGrav



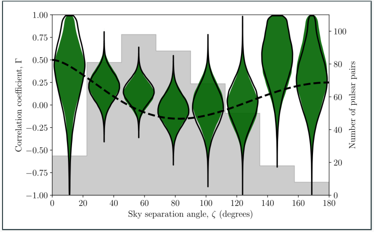
68 pulsars, 16 yr of data, HD at $\sim 3 \cdots 4\,\sigma$

2306.16214: EPTA+InPTA



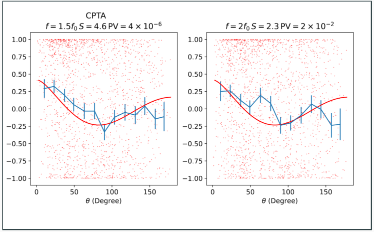
25 pulsars, 25 yr of data, HD at $\sim 3\,\sigma$

2306.16215: PPTA



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

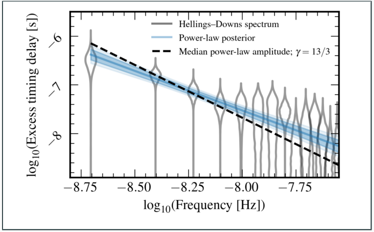
2306.16216: CPTA



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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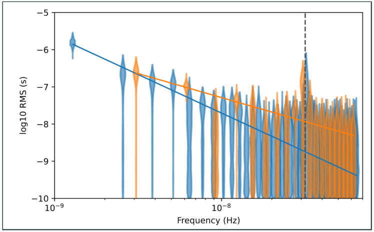

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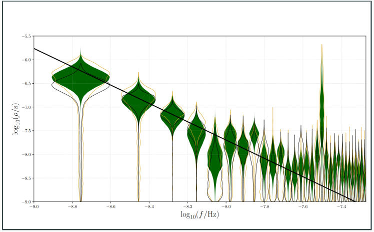

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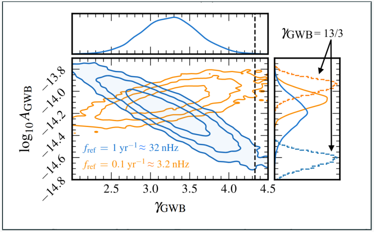
Power-law parameters A and γ

2306.16213: NANOGrav



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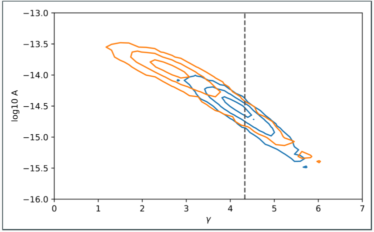

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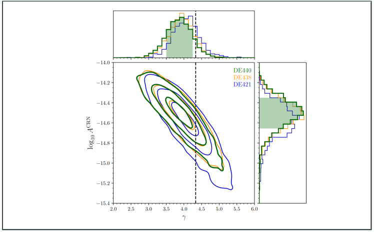

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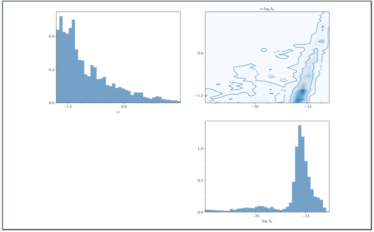

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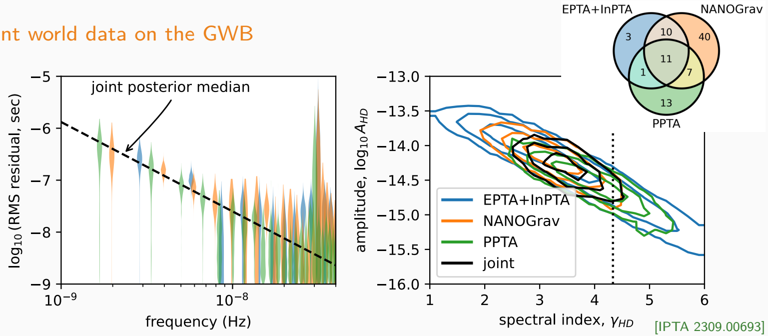
IPTA comparison

Current world data on the GWB

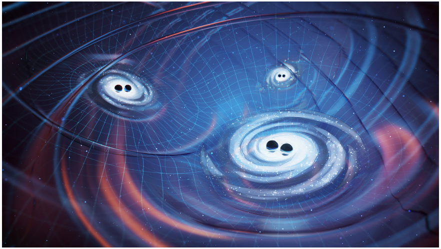


[IPTA 2309.00693]

- 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



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?

→ Matias's talk on Tuesday

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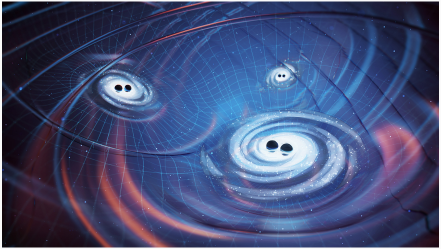
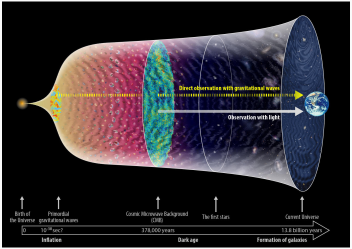


❷ GWs from the Big Bang



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?

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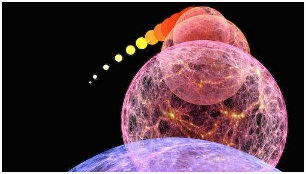
❷ New physics (speculative)

- 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



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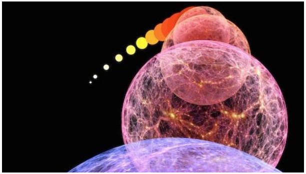
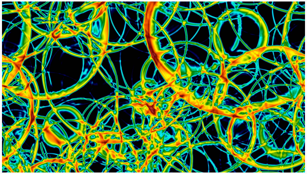


❷ Cosmological phase transition

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



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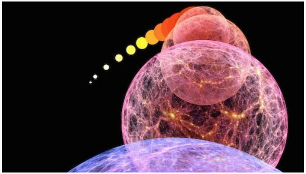

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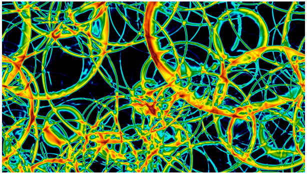
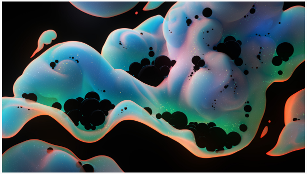


❸ Enhanced density perturbations

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



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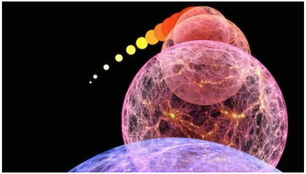

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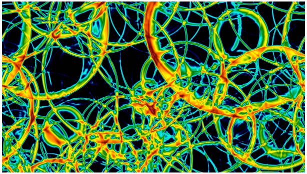

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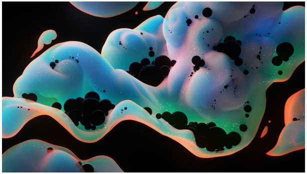
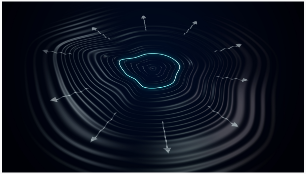


❹ Cosmic defects

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



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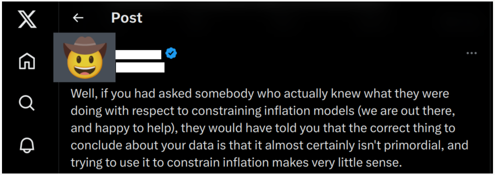
Why care about exotic sources?

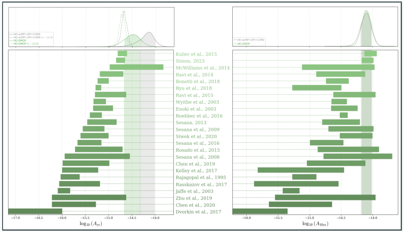


Do we *really* believe that PTAs could be seeing a GW echo from the Big Bang?

- **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

Three reasons to care about exotic sources

[NANOGrav 2306.16220]



❶ Surprisingly loud signal

- Need to go to unexpected corners of parameter space
- E.g., higher local binary density, shorter delay times, etc.
- Is the data trying to tell us something? Probably not, but …

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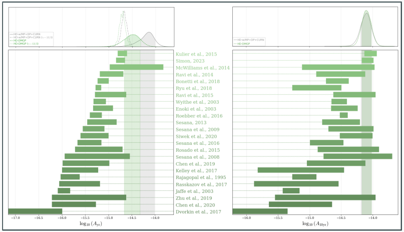

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❷ Maximize our confidence in the SMBHB interpretation

- Tension may go away with better noise modelling, more data, etc.
- But still, better be able to rule out GWs from the Big Bang (as far as possible).

Three reasons to care about exotic sources

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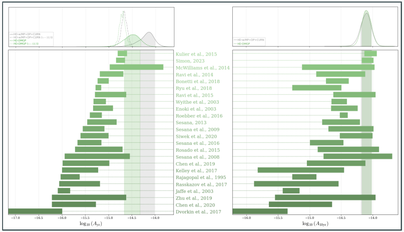

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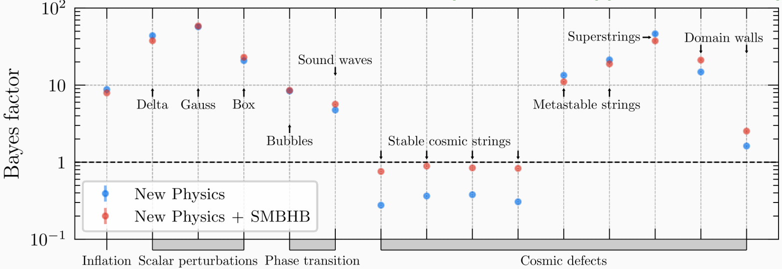
❸ Access and constrain new regions of parameter space

- PTA frontier → new bounds, complementary to energy and intensity frontiers
- Identify benchmark scenarios relevant for LISA, DECIGO, CE, ET, etc.

→ Angelo's talk on Wednesday; Antoine's talk next week

Bayesian model comparison

[NANOGrav 2306.16219] [See also: EPTA 2306.16227]

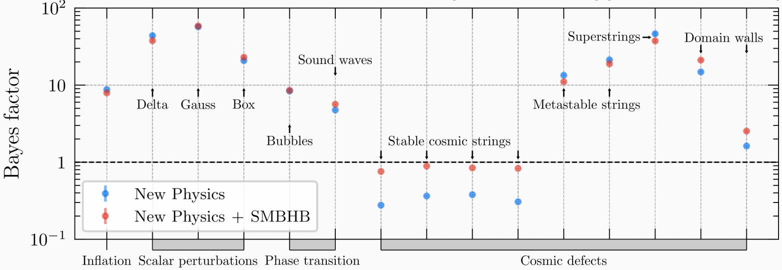


$$\text{Bayes factor } B = \frac{\text{Evidence for model } M_1,\ P\left(D|M_1\right)}{\text{Evidence for model } M_0,\ P\left(D|M_0\right)}\,, \quad M_0 = \{\text{SMBHBs only}\}$$

- 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!

Present

Spectral characterization of the signal

Is my BSM model capable of explaining the PTA signal?

- Bayesian fit to the data: `PTArcade`, `ceffyl`, ... ($< 10\,\%$ of all analyses)
- Compare to reference model: power law (A, γ), free spectrum (violins)

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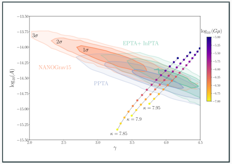
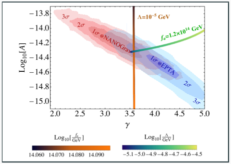
Metastable cosmic strings



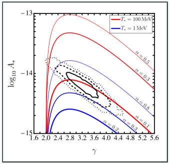
[2308.05799]

Axion domain walls



[2306.17022]

Phase transition



[2306.17205]

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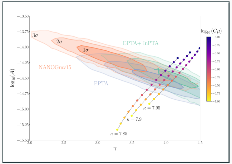

[2308.05799]

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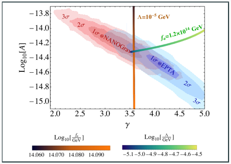

[2306.17022]

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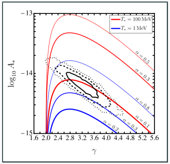


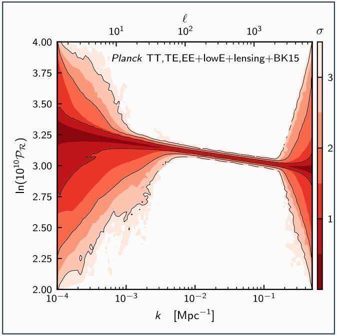
[2306.17205]

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)

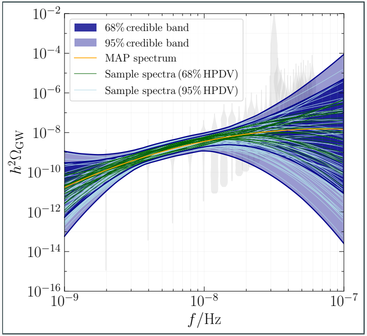
Running power law

Primordial scalar power spectrum



[PLANCK 1807.06211]

GW power spectrum in the PTA band

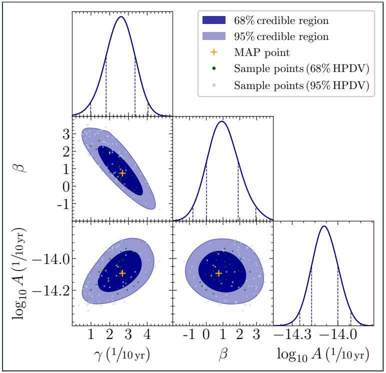


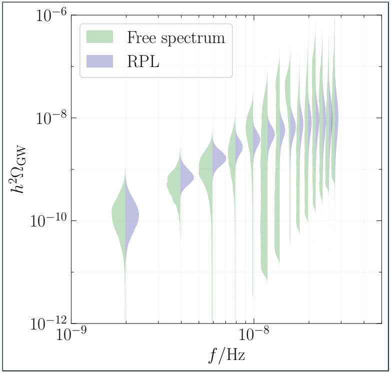
[NANOGrav 2408.10166]

- **CMB:** Running of n_s tightly constrained, $\alpha_s = dn_s/d\ln k = -0.0045 \pm 0.0067$
  $\rightarrow$ OK to compare your favorite inflation model to power-law template (A_s, n_s)
- **PTA:** Running of γ only loosely constrained, $\beta = d\gamma/d\ln k = 0.92^{+0.98}_{-0.91}$
  $\rightarrow$ Better compare your favorite GWB model to running-power-law (RPL) template (A, γ, β)

RPL posteriors

[NANOGrav 2408.10166]

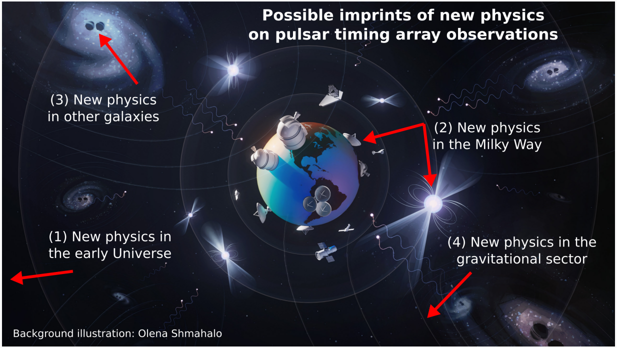




Point and interval estimates based on the 1D marginalized posteriors

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	$[-0.80, 2.96]$

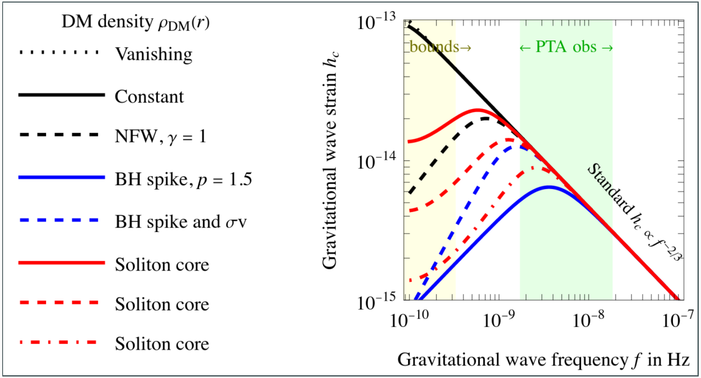
Imprints of new physics on all length scales



1. Stochastic **GWs from the Big Bang** as the source of the 2023 PTA signal
2. Deterministic contributions to timing residuals from **dark matter in the Milky Way**
3. Effect of **dense dark-matter environments** on the GWB signal from SMBHBs
4. Nonstandard propagation of GWs in scenarios of **modified gravity**

SMBHBs in dense dark-matter halos

[Goshal, Strumia: 2306.17158]



Additional energy loss because of dynamical friction in a dense DM environment

- Suppression of GWB signal from SMBHBs at low frequencies → spectral turnover
- Probe density profile of dark matter in the direct vicinity of SMBHBs

Dark matter in the Milky Way

Additional **non-GWB** signal in PTA data on top of the stochastic GWB

Search for ultralight dark matter (UDM) and dark-matter substructures

- Metric perturbations, Doppler $U(1)$ forces, pulsar spin fluctuations, clock shifts
- Doppler and Shapiro signals because of passing primordial black holes

→ Nataliya's, William's talks next week

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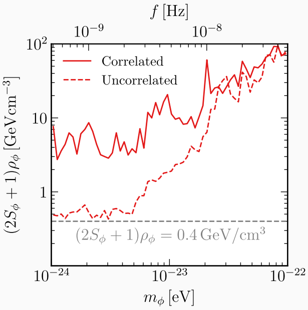
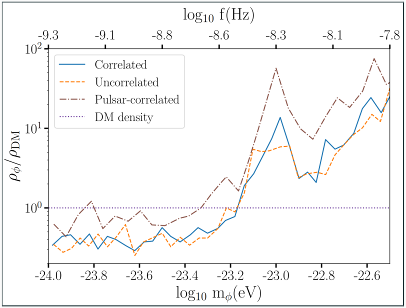
Example: Metric perturbations from an oscillating ULDM field



[NANOGrav 2306.16219]



[EPTA 2306.16228]

Modified gravity

New physics in the gravitational sector:

Graviton mass, subluminal propagation speed, modified dispersion relations, etc.

→ Maxence's, Llibert's talks next week

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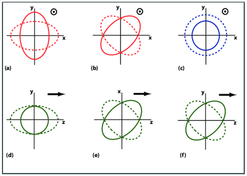
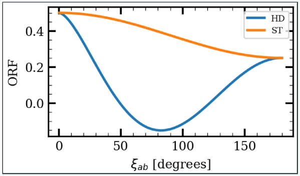
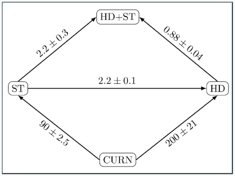
[NANOGrav 2310.12138]



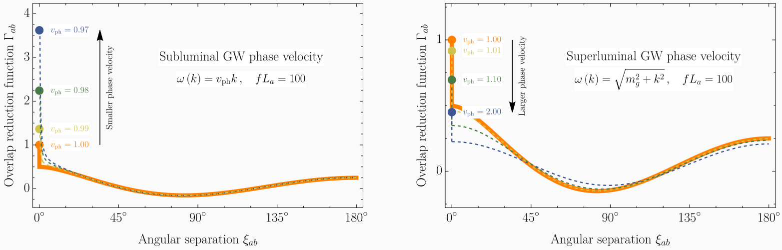




❶ **Scalar and vector polarization states on top of usual tensor polarization states**

- Exotic polarization states → nonstandard overlap reduction functions $\Gamma\left(\xi_{ab}\right)$
- NANOGrav 2310.12138: Search for scalar transverse (ST) mode; no evidence
- Better agreement between Bayesian and frequentist analyses for HD correlations

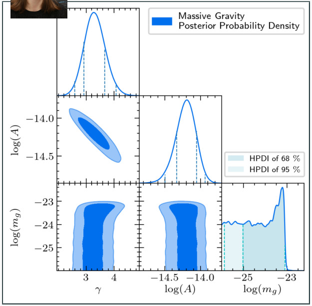
[2407.04464]



Simple toy models of modified gravity with a nonstandard dispersion relation

- Subluminal GW phase velocity: $\omega = v_{\rm ph}\, k$
- Superluminal GW phase velocity (massive gravity): $\omega = \sqrt{k^2 + m_g^2}$

$$v_{\rm ph} = \frac{\omega}{k}\,, \qquad v_{\rm gr} = \frac{\partial \omega}{\partial k}$$



[Kim Wassner, BSc thesis, U Münster, unpublished]

❷ Massive gravity

- GW dispersion relation $\omega = \sqrt{k^2 + m_g^2}$, focus on tensor polarization states
- ORF depends on group velocity, $v_{\rm gr} < c$, and hence **implicitly** on GW frequency
- Upper limit of the 95 % credible interval:

$$m_g < 8 \times 10^{-24}\,\mathrm{eV}$$

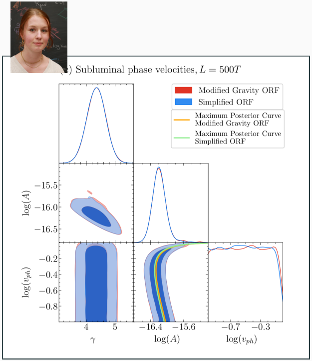
$$\Gamma_{\rm ab} = \frac{1+\delta_{ab}}{16\,{v_{\rm gr}}^5}\left[2v_{\rm gr}\left(3+\left(6-5{v_{\rm gr}}^2\right)\delta\right) - 6\left[1+\delta+{v_{\rm gr}}^2(1-3\delta)\right]\ln\left(\frac{1+v_{\rm gr}}{1-v_{\rm gr}}\right) - \frac{3A}{B}\ln C\right]$$

$$A = 1 + 2{v_{\rm gr}}^2(1-2\delta) - {v_{\rm gr}}^4\left(1-2\delta^2\right)\,, \qquad B = \sqrt{(1-\delta)\left(2-{v_{\rm gr}}^2(1+\delta)\right)}$$

$$C = \frac{A - 2v_{\rm gr}\left(1-{v_{\rm gr}}^2\delta\right)B}{\left({v_{\rm gr}}^2-1\right)^2}\,, \qquad \delta = \cos\xi_{ab}\,, \qquad v_{\rm gr} = \frac{\partial\omega}{\partial k} = \sqrt{1-\left(\frac{f_g}{f}\right)^2}$$

Subluminal GW phase velocity

[Work in progress]



[Nina Cordes, BSc thesis, U Münster, unpublished]

❸ Subluminal GW phase velocity

- GW dispersion relation $\omega = v_{\rm ph} k$
- ORF depends on phase velocity $v_{\rm ph} < c$ and **explictly** on GW frequency f
- If $v_{\rm ph}$ small enough, ORF dominated by auto correlation coefficients $\Gamma_{aa} \gg \Gamma_{ab}$
- Flat direction in parameter space in terms of A, $v_{\rm ph}$, and pulsar distance L_a:

$$f_1 L_a\, v_{\rm ph} \left({v_{\rm ph}}^2 - 1\right)^2 A^2 \sim 4 \times 10^{-31}$$

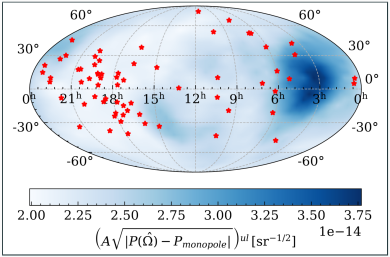
$$\Gamma_{ab}(f) = \sum_{\ell=2}^{\infty} a_\ell(f)\, P_\ell(\cos\xi_{ab}) \,, \qquad c_\ell(f) = \int_{-1}^{+1} dx \left[1 - e^{-i\,2\pi f L\left(1+x/v_{\rm ph}\right)}\right] \frac{\left(1-x^2\right)^2}{1+x/v_{\rm ph}} \frac{d^2}{dx^2} P_\ell(x)$$

$$a_\ell(f) = \frac{3}{2}(2\ell+1)\, \frac{(\ell-2)!}{(\ell+2)!} \frac{|c_\ell(f)|^2}{16} \,, \qquad \Gamma_{aa}^{\rm LO}(f) = \Theta\left(1 - v_{\rm ph}\right) \frac{3}{4}\pi^2 f\, L_a\, v_{\rm ph} \left(v_{\rm ph}^2 - 1\right)^2$$

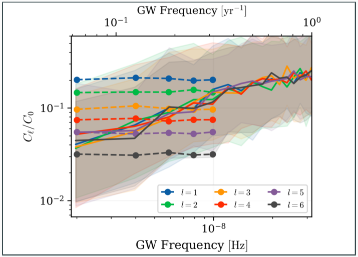
[2407.04464]

Future

Complementary observables: Anisotropies



[NANOGrav 2306.16221]



Search for anisotropies in the GWB signal in the sky

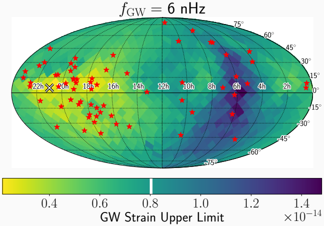
- Current sensitivity already at the level of expected anisotropies from SMBHBs
- No signal detected → sky-dependent upper limits on deviation from monopole

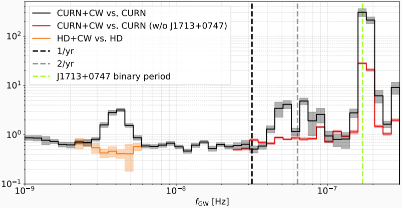
No detection of anisotropies with future data sets → hint of primordial origin!?

→ Andrea's talk next week

Complementary observables: Continuous waves

[NANOGrav 2306.16222]





Search for continuous-wave signals from individual nearby SMBHB systems

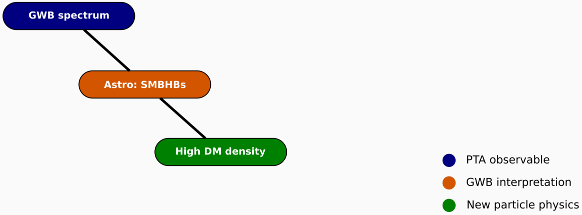
- Interesting hints in the data, which, however, do not withstand further scrutiny
- Overall, no signal detected → sky-dependent upper limits on GW amplitude

Summary

Summary


GWB spectrum
Astro: SMBHBs
PTA observable
GWB interpretation

Summary


GWB spectrum
Astro: SMBHBs
High DM density
PTA observable
GWB interpretation
New particle physics

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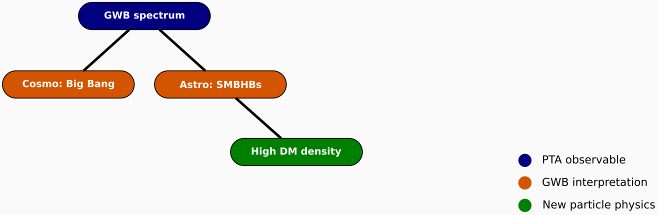
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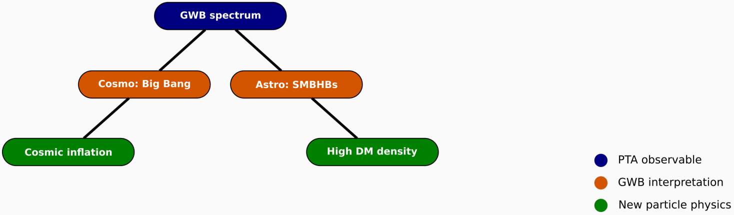
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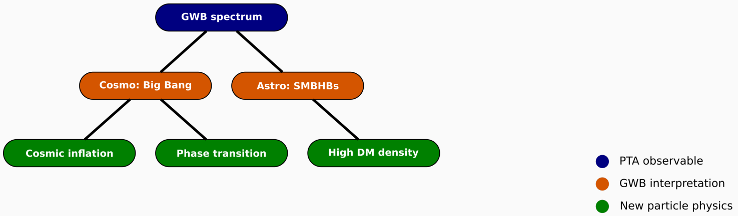
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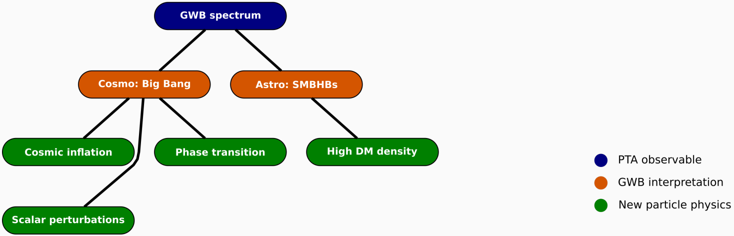
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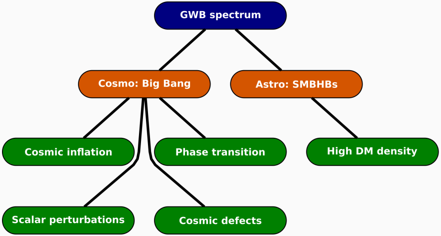
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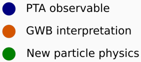
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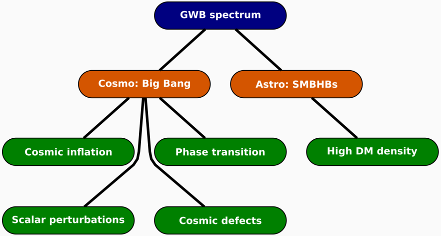
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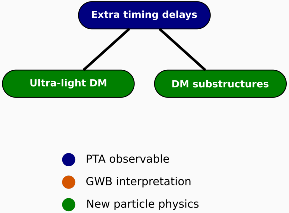
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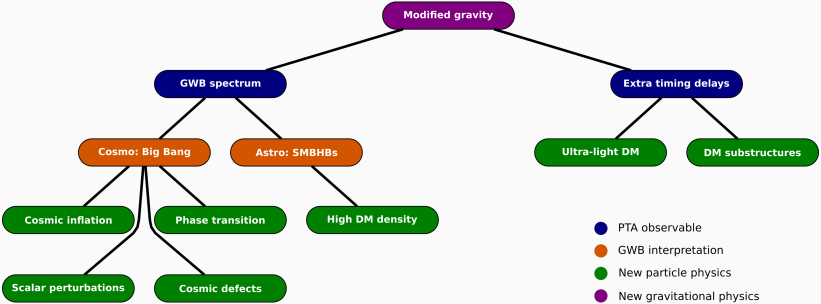
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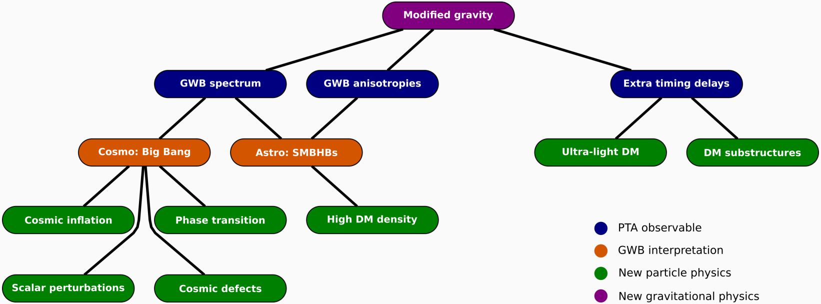
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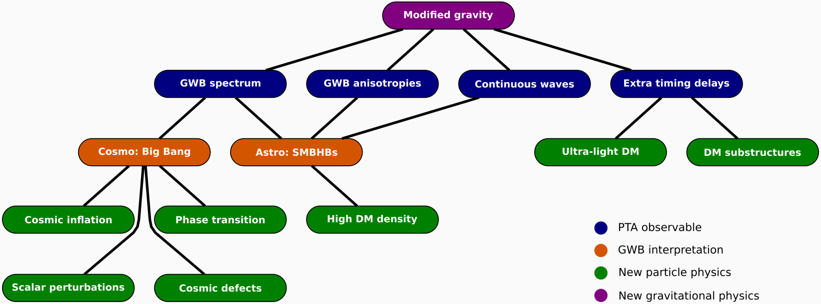
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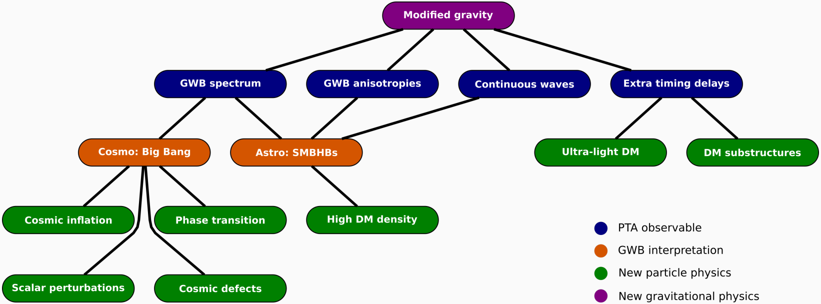
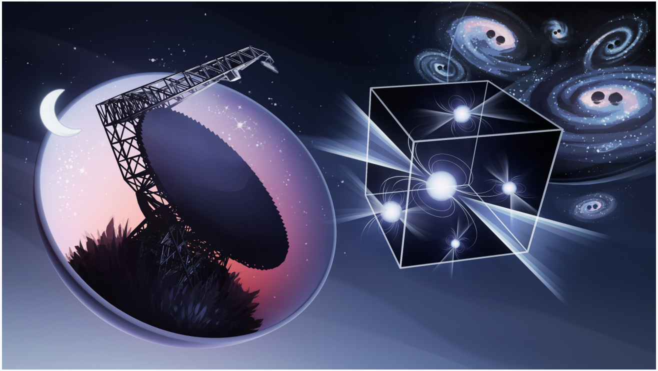


Prospect: Combined information on GWB spectrum, anisotropies, continuous-wave signals (plus other GW searches, CMB observations, etc.) → origin of the PTA signal

This is only the beginning!



A bright future for GW science with PTAs

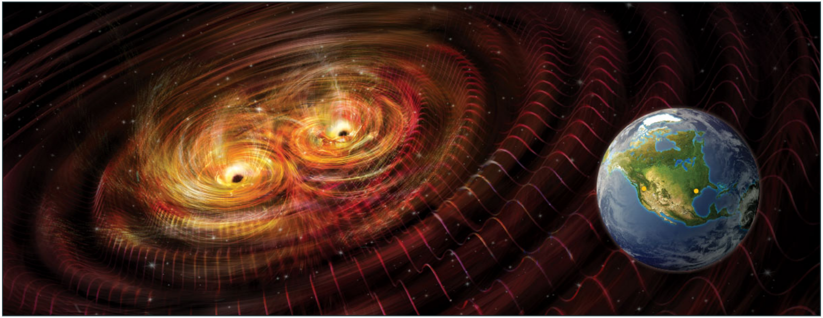
- Status: Common-spectrum process; $3 \cdots 4\,\sigma$ evidence for HD correlations
- Next: HD correlations at $5\,\sigma$, spectral shape, anisotropies across the sky, ...
- Promise: Deep insights into galaxy and BH evolution and/or new physics

Stay tuned!

And thanks a lot for your attention

Supplementary material

Gravitational waves



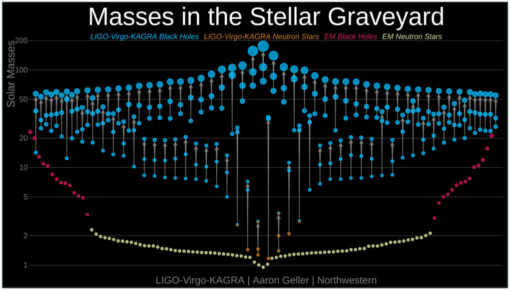
[sciencenews.org]

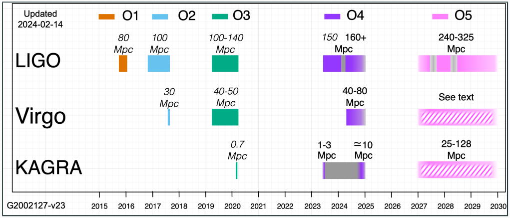
Gravitational waves (GWs): **Ripples in spacetime propagating at the speed of light**

- 1916: Predicted by Albert Einstein based on his general theory of relativity
- 2016: LIGO/Virgo Collaboration announces the detection of *GW150914*
- 2017: Rainer Weiss, Barry Barish, and Kip Thorne receive Nobel Prize in Physics

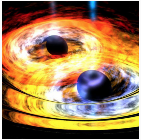
Ground-based GW laser interferometers now routinely observe GW events

$\rightarrow$ Transients of astrophysical origin in the "audio band", i.e., at frequencies $f \sim 10 \cdots 1000\,\mathrm{Hz}$

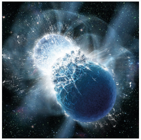




BH–BH mergers



NS–NS mergers

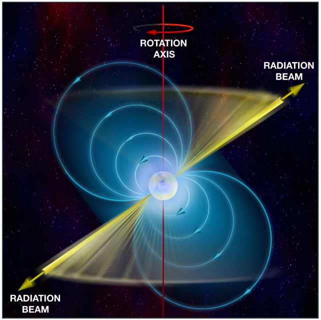


BH–NS mergers

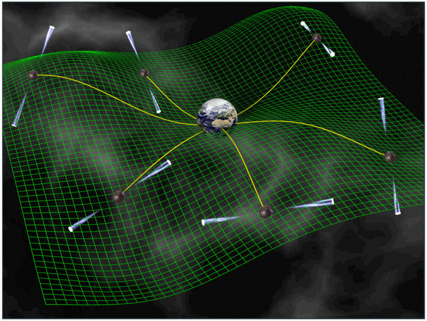
Images: [LIGO–Virgo–KAGRA] [NASA] [Skyworks Digital Inc., The Kavli Foundation] [OzGrav, ARC Centre of Excellence]

Pulsar timing arrays (PTAs)

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



[nrao.edu]



[MPIfR]

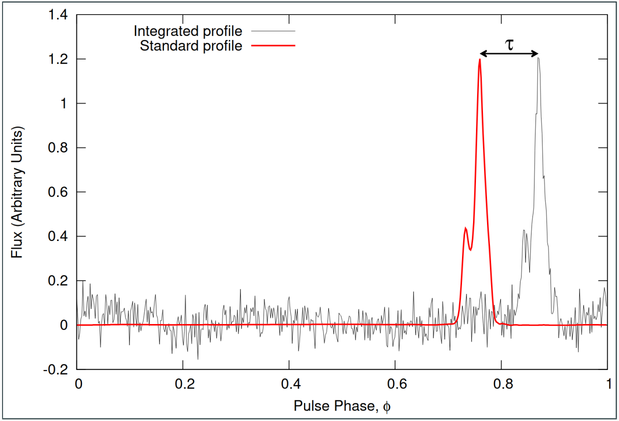
Pulsars: **Highly magnetized rotating neutron stars**

- 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

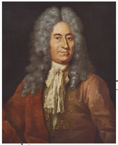
Times of arrival

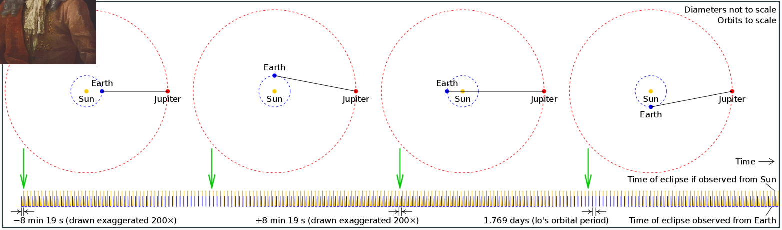
[Alessandro Ridolfi, PhD thesis (2017)]



- Measure **times of arrival** and compare to predictions from a **timing model**
- **Timing residuals** for each individual pulsar → GW signature in cross-correlations

First measurement of the speed of light by Ole Rømer in 1676





[Wikimedia]

	Ole Rømer	Pulsar timing arrays
Clock ticks:	Eclipses of Jupiter's moon Io	Pulses from galactic pulsars
Time delay:	Earth's motion around the sun	GWs stretching and squeezing
Effect:	$\pm 8\,\mathrm{min}\ 9\,\mathrm{s}$ over a year	$\pm\mathcal{O}(100)\,\mathrm{ns}$ over ten years

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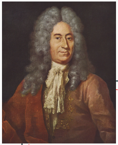

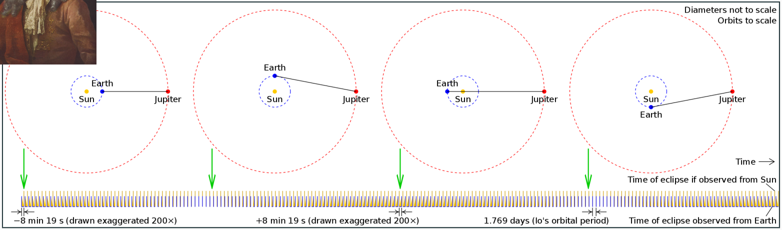

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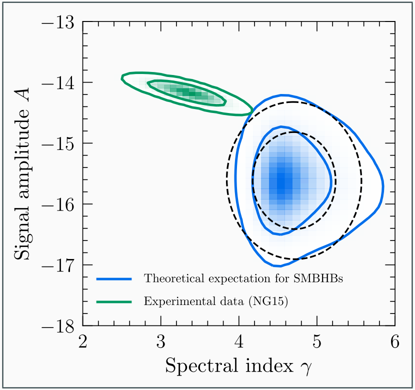
Effect:	$\pm 8\,\mathrm{min}\ 9\,\mathrm{s}$ over a year	$\pm\mathcal{O}(100)\ \mathrm{ns}$ over ten years

Main idea: GWs cause an excess time delay in the pulse times of arrival (TOAs)

Confirm GW origin of the signal by cross-correlating the timing residuals of pulsar pairs

Simple evolution model

[NANOGrav 2306.16219]

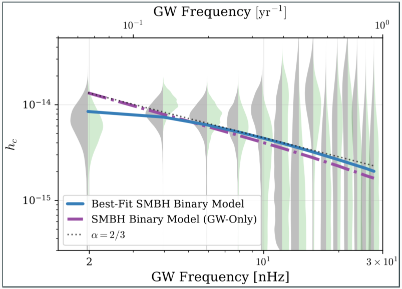


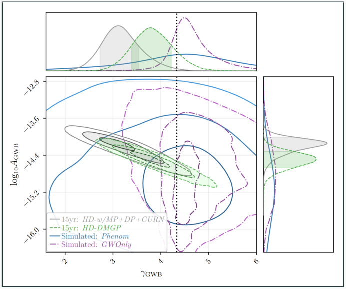
- Assume SMBHBs on circular orbits and purely GW-driven orbital evolution
- 95 % regions barely touch → 2σ tension between observations and theory
- GW-only evolution unable to bring binaries to the PTA band within a Hubble time

State of the art prior to 2023 PTA results → SMBHB reference model in 2306.16219

Phenomenological models

Self-consistent phenomenological models accounting for environmental interactions





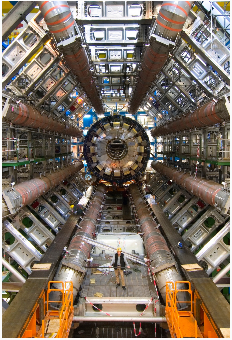
SMBHB interpretation: **Need to go to unexpected corners of parameter space**

- Parameter shifts towards larger GWB amplitudes than previously expected
- Generally higher binary masses or densities, or highly efficient binary mergers

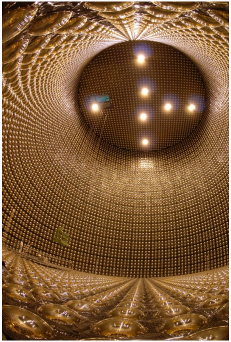
Work in progress → Use phenomenological models in future model comparisons

PTA frontier of particle physics

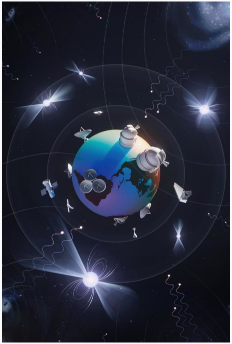
Energy frontier



Intensity frontier



PTA frontier
F

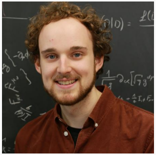


New physics at the PTA frontier

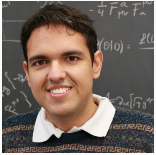
- Probe BSM models in regions of parameter space inaccessible by other methods
- Derive new constraints, irrespective of the origin of the PTA signal
- Complementary to laboratory searches at the energy and intensity frontiers

Our team

R. v. Eckardstein*



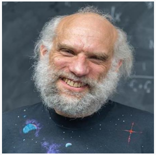
R. Lino d. Santos*



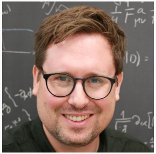
Andrea Mitridate

Jonathan Nay

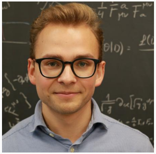
Ken Olum



Kai Schmitz*



Tobias Schröder*



Tanner Trickle

David Wright

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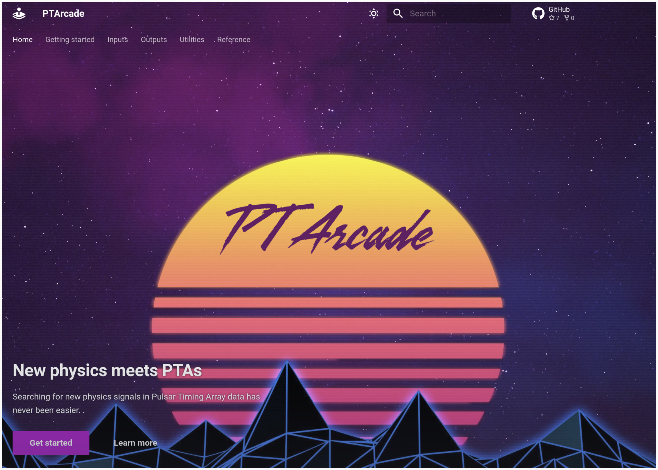
1. Searches for signals from new physics in NANOGrav data → 2306.16219
2. New software tools for fitting BSM models to PTA data → `PTArcade`

* Current or former members of my research group, *Particle Cosmology Münster*

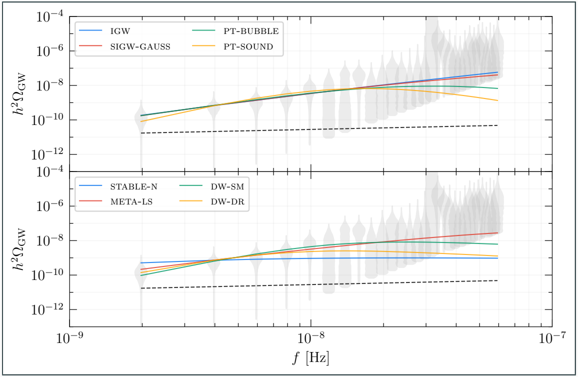
PTArcade



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

Median GW spectra



Solid lines: Median GW spectra for BSM models based on parameter posteriors
Dashed line: SMBHB prediction based on central values of our 2D parameter prior

---

No surprise, GW spectra resulting in a good fit all look similar *by construction*
Focus on parameter inference. Need complementary observables to identify origin.

❶ Cosmic inflation

Big questions: What set the initial conditions of the Hot Big Bang: homogeneity, isotropy, spatial flatness? What seeded the temperature fluctuations in the CMB?

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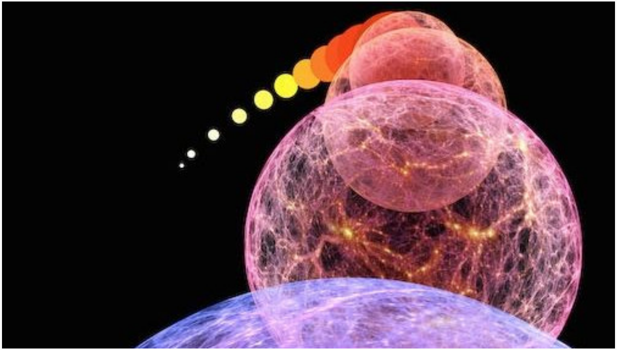


Cosmic inflation: Stage of exponentially fast expansion before the Hot Big Bang

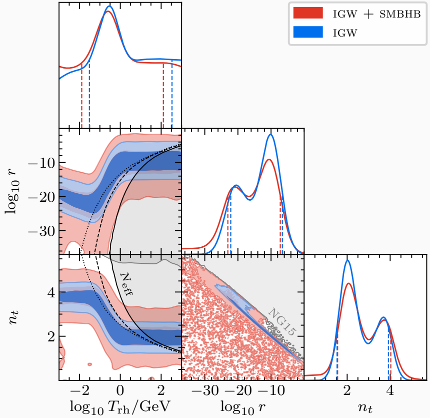
- Requires form of dark energy, e.g., potential energy of a scalar “inflaton” field
- Inflaton and metric fluctuations $\rightarrow$ primordial scalar and tensor perturbations

Primordial tensor spectrum

$$\mathcal{P}_t = r\,A_s \left(\frac{f}{f_{\rm cmb}}\right)^{n_t}$$

Parameters

$T_{\rm rh}$	Reheating temperature
r	Tensor-to-scalar ratio
n_t	Tensor spectral index



Lessons

- Strongly blue-tilted spectrum, $n_t \sim 2 \cdots 4 \to$ probe **nonminimal inflation models**
- Transition from **reheating** to the Hot Big Bang in the PTA band for $T_{\rm rh} \sim 1\,{\rm GeV}$
- If GWB extrapolated to higher frequencies $\to$ large contribution to **dark radiation**

❷ Phase transition

Big questions: How are the Higgs mechanism and the quark–hadron transition realized in the early Universe? Are there other fundamental forces beyond the Standard Model?

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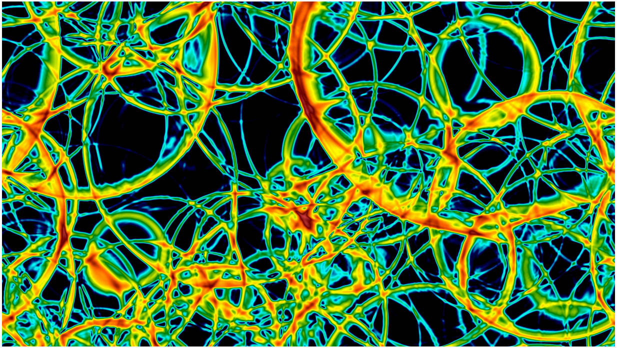


Cosmological phase transitions: Changes in the quantum field theory vacuum structure

- SM predicts smooth crossovers; strong first-order phase transitions require BSM
- GWs from bubble collisions, sound waves, and magnetohydrodynamic turbulence

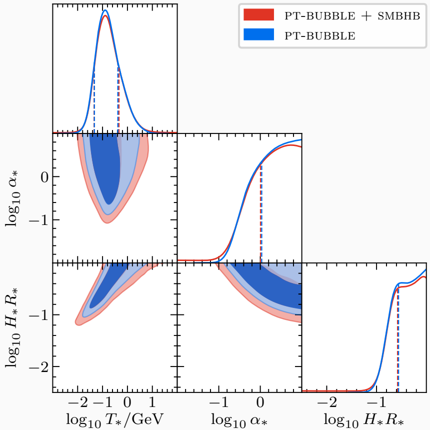
Peak amplitude and frequency

$$\Omega_{\rm GW}^{\rm peak} \propto (H_* R_*)^2 \left(\frac{\alpha_*}{1+\alpha_*}\right)^2$$

$$f_{\rm peak} \propto \frac{T_*}{H_* R_*}$$

Parameters

T_*	Percolation temperature
α_*	Transition strength
$H_* R_*$	Bubble separation



Lessons

- Strong ($\alpha_* \sim 1$) and slow ($H_* R_* \sim 1$) transition at a temperature $T_* \sim 100\,{\rm MeV}$
- Just the right ballpark for BSM modifications of the **QCD phase transition**
- Alternatively, phase transition in a **dark sector** $\rightarrow$ complementary to lab searches

❸ Primordial black holes

Big questions: Are some of the black holes seen by LVK of primordial origin? To what extent do PBHs contribute to dark matter? How do galactic SMBHs form?

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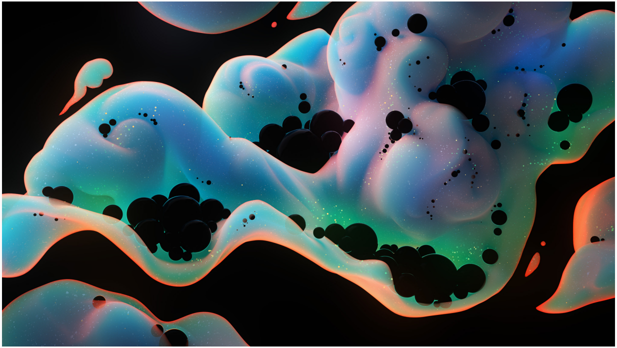
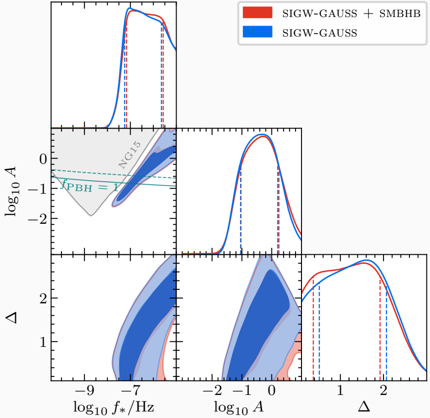


PBHs: Form in the gravitational collapse of large overdensities in the early Universe

- Typical scenario: Scalar perturbations enhanced during ultra-slow-roll inflation
- Enhanced scalar perturbations → GWs at second order in perturbation theory

Primordial scalar spectrum

$$\mathcal{P}_s = \frac{A}{\sqrt{2\pi}\,\Delta}\,\exp\left[-\frac{\left(\ln\left(f/f_*\right)\right)^2}{2\,\Delta^2}\right]$$



Parameters

f_*	Peak frequency
A	Peak amplitude
Δ	Width

Lessons

- Require large-amplitude peak in $\mathcal{P}_s$ $\rightarrow$ input for building models of **inflation**
- **PBH dark matter** might be possible; but some tension with PBH overproduction
- On-going debate on impact of **non-Gaussianities** on efficiency of PBH production

❹ Cosmic defects

Big questions: How are the tiny SM neutrino masses generated? What is the origin of the matter–antimatter asymmetry? Is the SM embedded in a grand unified theory?

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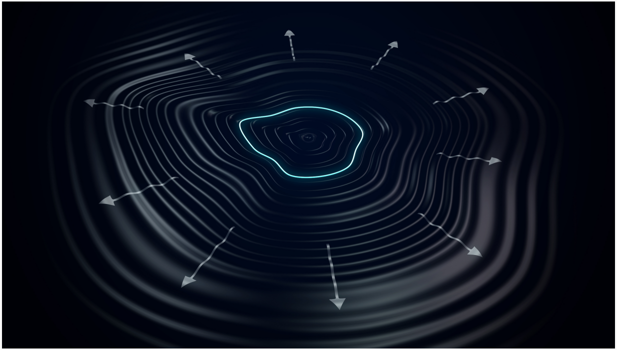
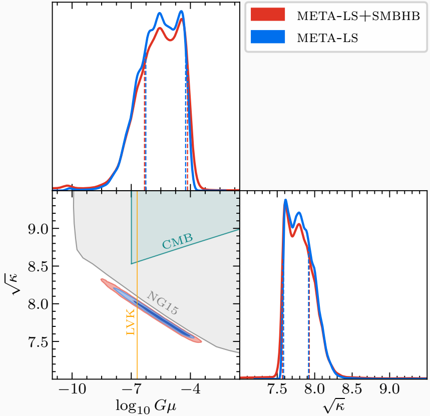


Cosmic strings / domain walls: Defects after spontaneous breaking of GUT symmetries

- Typical scenario: $U(1)_{B-L}$ breaking $\rightarrow$ neutrino masses, leptogenesis, and strings
- Dynamics and decay of defect networks yield anisotropic stress and hence GWs



Decay rate per length

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

Parameters

μ Tension (energy per length)

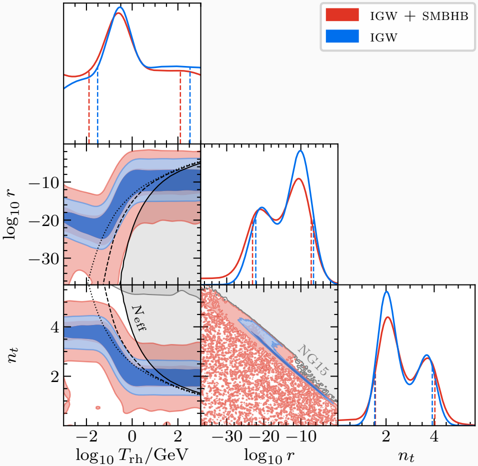
κ Decay parameter

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 (!)*

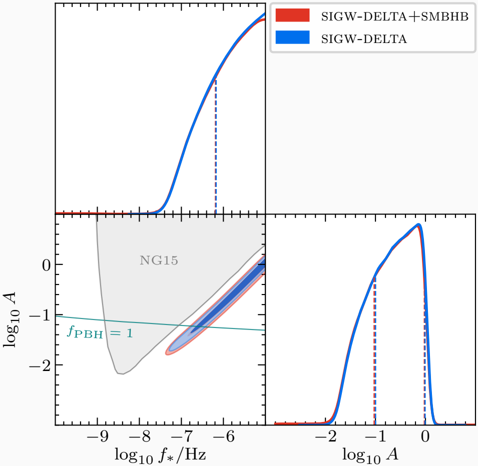
Bayesian inference: posteriors, point values, credible intervals, etc.

Inflationary gravitational waves (IGW)



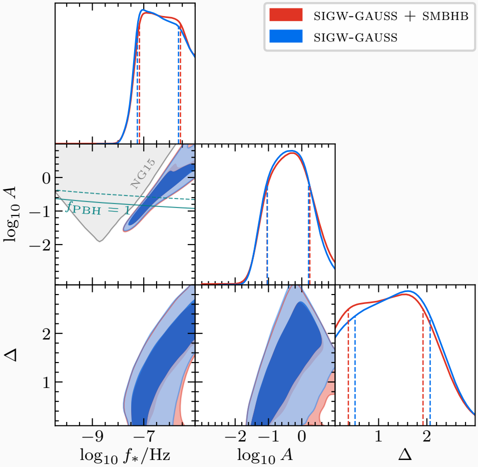
Bayesian inference: posteriors, point values, credible intervals, etc.

Scalar-induced gravitational waves, δ-function-shaped $\mathcal{P}_{\mathcal{R}}$ (SIGW-DELTA)



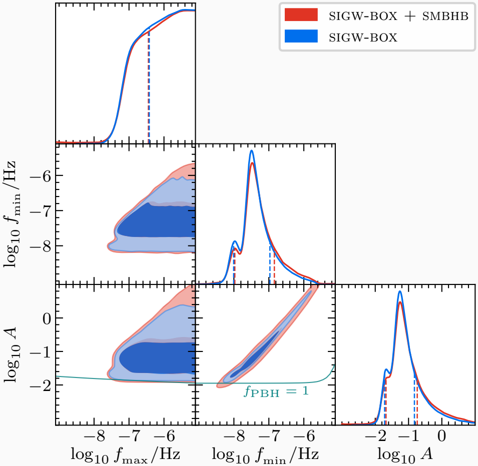
Bayesian inference: posteriors, point values, credible intervals, etc.

Scalar-induced gravitational waves, bell-curve-shaped $\mathcal{P}_{\mathcal{R}}$ (SIGW-GAUSS)



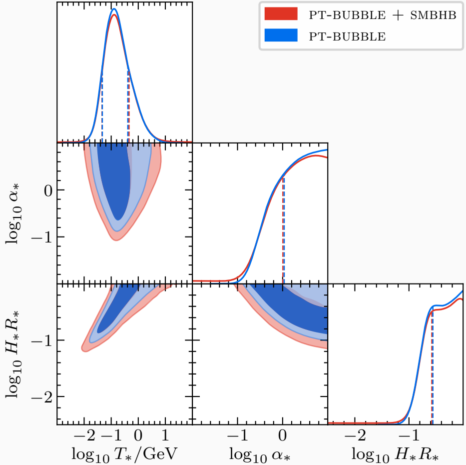
Bayesian inference: posteriors, point values, credible intervals, etc.

Scalar-induced gravitational waves, box-shaped $\mathcal{P}_{\mathcal{R}}$ (SIGW-BOX)



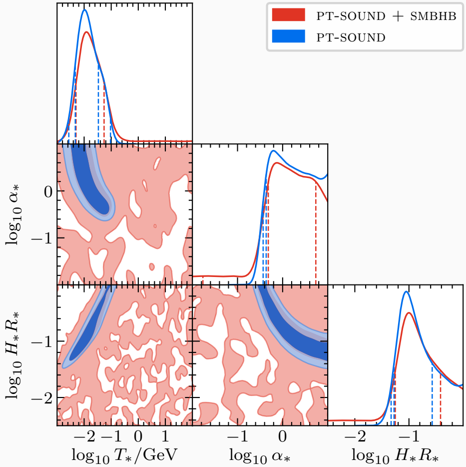
Bayesian inference: posteriors, point values, credible intervals, etc.

Phase transition, bubble collisions (PT-BUBBLE)

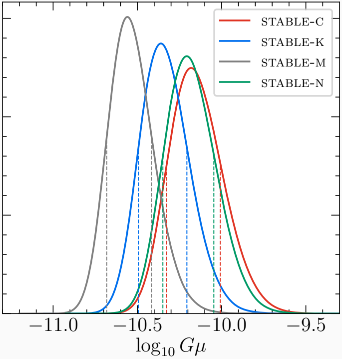


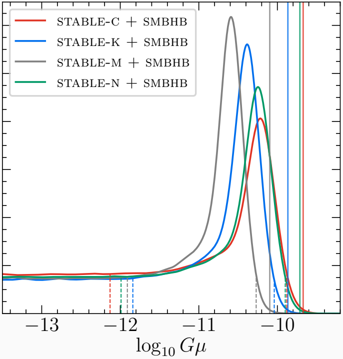
Bayesian inference: posteriors, point values, credible intervals, etc.

Phase transition, sound waves (PT-SOUND)



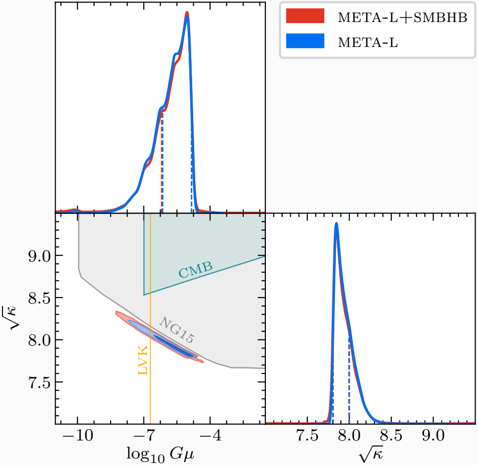
Stable cosmic strings (STABLE)





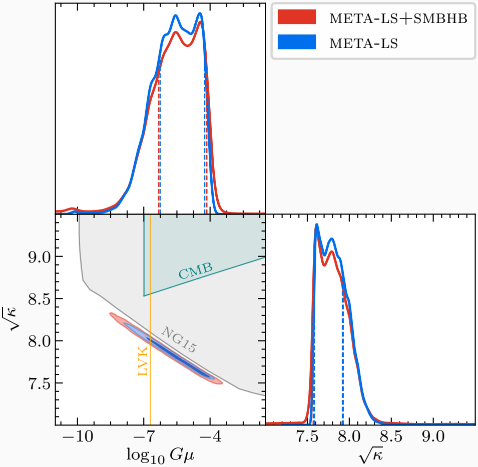
Bayesian inference: posteriors, point values, credible intervals, etc.

Metastable cosmic strings, loops (META-L)



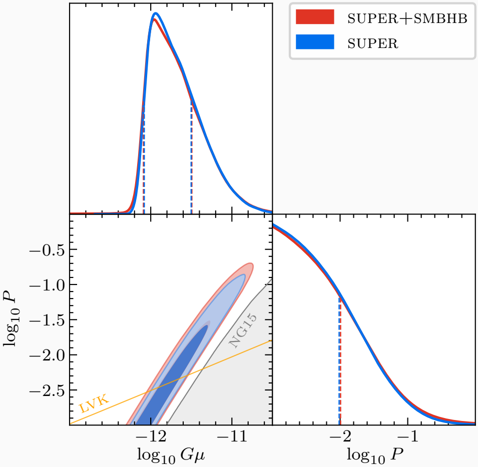
Bayesian inference: posteriors, point values, credible intervals, etc.

Metastable cosmic strings, loops and segments (META-LS)



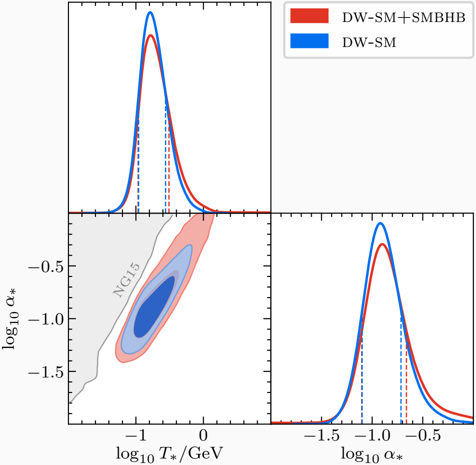
Bayesian inference: posteriors, point values, credible intervals, etc.

Cosmic superstrings (SUPER)



Bayesian inference: posteriors, point values, credible intervals, etc.

Domain walls, decay into Standard Model particles (DW-SM)



Bayesian inference: posteriors, point values, credible intervals, etc.

Domain walls, decay into dark radiation (DW-DR)