



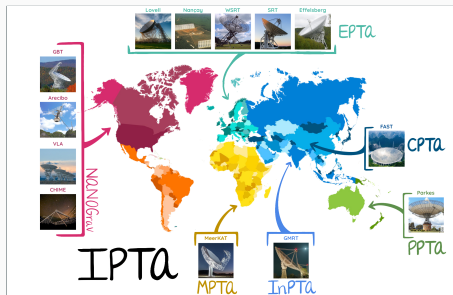
News Physics at the Pulsar Timing Array Frontier

Kai Schmitz (NANOGrav New Physics Working Group)

University of Münster, Institute for Theoretical Physics

IPTA Student Workshop | Alpine Heath, South Africa | 18th June 2026

2023 PTA results

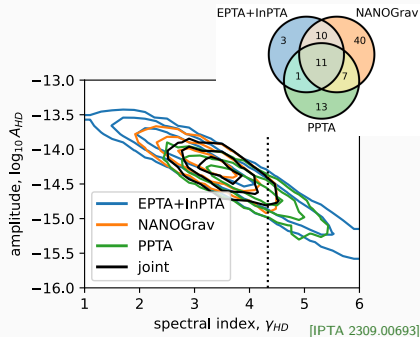
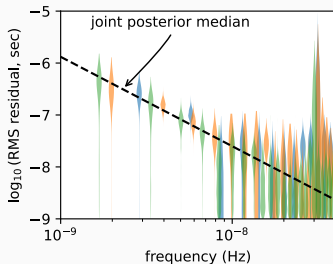


EPTA: European PTA
 CPTA: Chinese PTA
 PPTA: Parkes PTA
 InPTA: Indian PTA
 MPTA: MeerKAT PTA
 NANOGrav: North American
 Nanohertz Observatory for
 Gravitational Waves

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

Quick and rough data combination



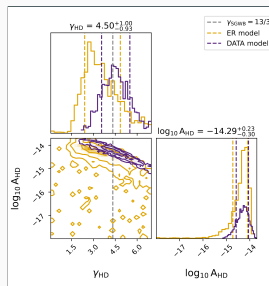
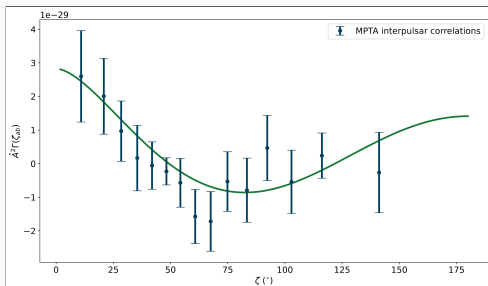
- Results from regional PTAs are consistent with each other (1σ posteriors overlap)
- Joint posterior = naive product (properly normalized) of individual posteriors
- Proper data combination and combined data analysis → [IPTA DR3](#)

[See also "Stochastic gravitational-wave background search using data from five pulsar timing arrays" by Yu, Allen (2512.08666)]

New kid on the block

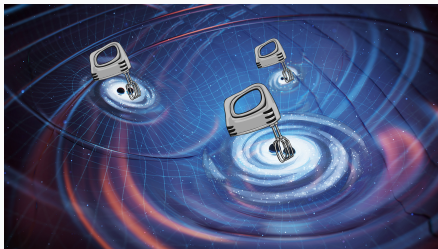
MeerKAT Pulsar Timing Array (MPTA): 83 pulsars, 4.5 yr of data

[MPTA 2412.01153]

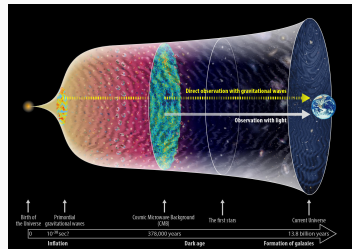


Abstract: [...] Under different assumptions about noise processes we can produce either what appear to be compelling Hellings-Downs correlations of high significance ($3\text{--}3.3\sigma$) with a spectrum close to that which is predicted, or surprisingly, under slightly different assumptions, ones that 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 [...]

① Supermassive black-hole binaries



② GWs from the Big Bang



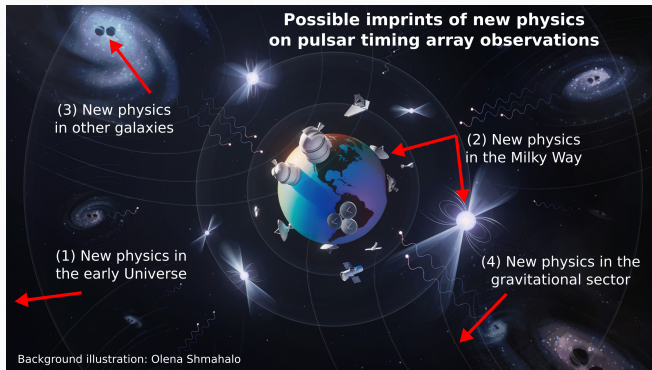
① SMBHBs (realistic)

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

② 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

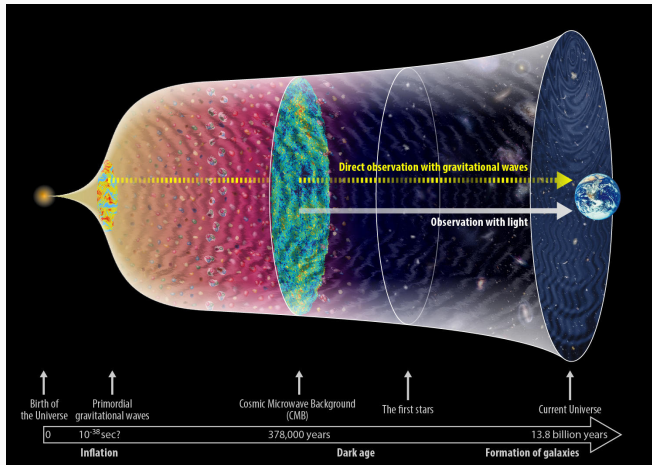
Imprints of new physics on all length scales



- ❶ GW echo from the Big Bang
- ❷ Dark matter in the Milky Way
- ❸ SMBHBs in dense dark-matter environments
- ❹ GW propagation in modified gravity

Access to the very early Universe

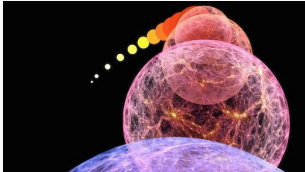
[National Astronomical Observatory of Japan, gwpo.nao.ac.jp]



- Universe becomes transparent to photons only 380,000 after the big bang
- GWs travel freely through the primordial plasma; messengers from even earlier times

① Nonmininal cosmic inflation

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

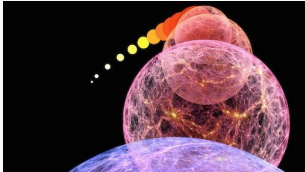


Abbreviations: CMB: cosmic microwave background; GW: gravitational wave; PBH: primordial black hole; PTA: pulsar timing array; QCD: quantum chromodynamics; QFT: quantum field theory

GW echo from the Big Bang

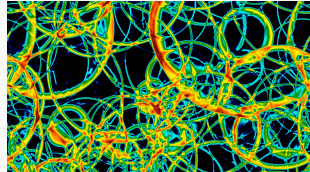
① Nonmininal cosmic inflation

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



② Cosmological phase transition

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

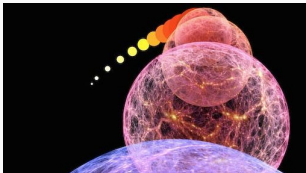


Abbreviations: CMB: cosmic microwave background; GW: gravitational wave; PBH: primordial black hole; PTA: pulsar timing array; QCD: quantum chromodynamics; QFT: quantum field theory

GW echo from the Big Bang

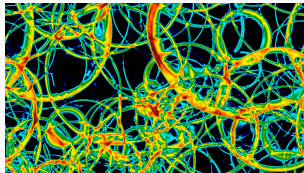
① Nonmininal cosmic inflation

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



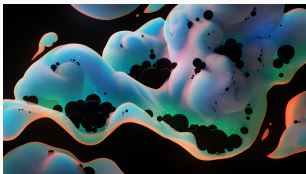
② Cosmological phase transition

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



③ Enhanced density perturbations

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

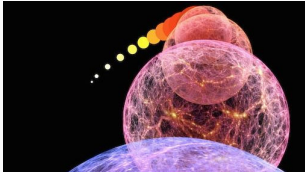


Abbreviations: CMB: cosmic microwave background; GW: gravitational wave; PBH: primordial black hole; PTA: pulsar timing array; QCD: quantum chromodynamics; QFT: quantum field theory

GW echo from the Big Bang

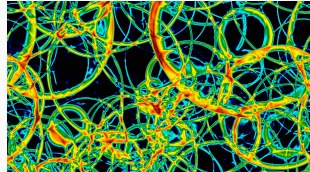
① Nonmininal cosmic inflation

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



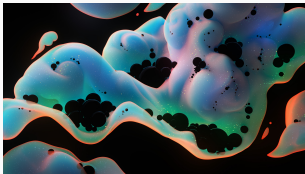
② Cosmological phase transition

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



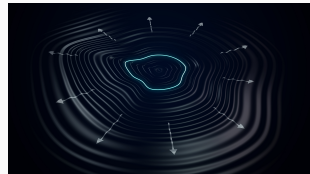
③ Enhanced density perturbations

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



④ Cosmic defects

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



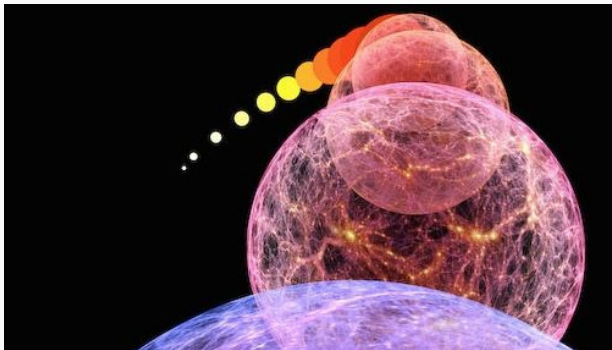
Abbreviations: CMB: cosmic microwave background; GW: gravitational wave; PBH: primordial black hole; PTA: pulsar timing array; QCD: quantum chromodynamics; QFT: quantum field theory

① BSM scenario: 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?

① BSM scenario: Cosmic inflation

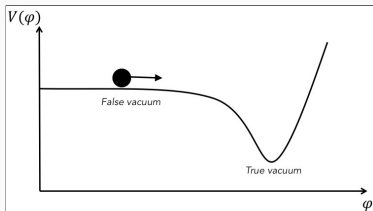
Big questions: What set the initial conditions of the Hot Big Bang: homogeneity, isotropy, spatial flatness? What seeded the temperature fluctuations in the CMB?



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 → primordial scalar and tensor perturbations

Background dynamics



Klein–Gordon equation

$$\ddot{\phi}(t) + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

Friedmann equation

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 \approx \frac{V}{3M_{\text{Pl}}^2}$$

Slow-roll inflation

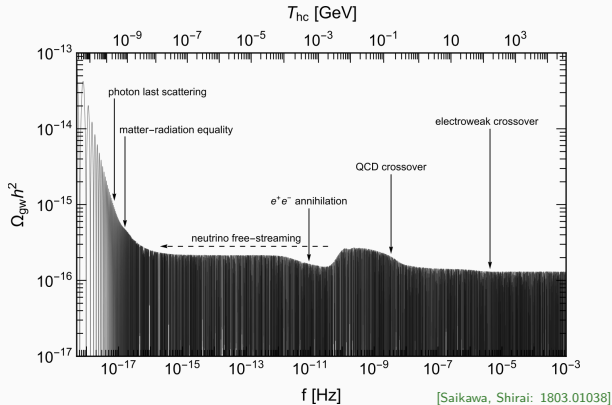
- Scalar inflaton field ϕ slowly rolls down scalar potential, $\ddot{\phi} \ll 3H\dot{\phi}$, $dV/d\phi$
- $V(\phi) \approx \text{const} \approx$ slowly decaying cosmological constant $\rightarrow$ exponential expansion

Perturbation theory

Vacuum continuously sources perturbations in the inflaton field and in the metric

[Guth 1981] [Linde 1982] [Albrecht & Steinhardt 1982]

Logbook of the expansion history



Scale-invariant GW spectrum from inflation, redshifted to the present epoch

- Cosmic logbook encoding the entire expansion history of the early Universe
- Major events in the early Universe leave their imprint in the SGWB signal
- Approximately flat plateau at $\Omega_{\text{gw}} \sim \Omega_{\text{r}}/24 rA_s \sim 2 \times 10^{-16} (r/0.044)$

Primordial tensor spectrum

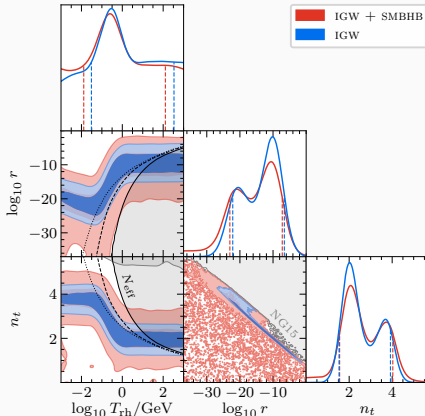
$$\mathcal{P}_h = r A_s \left(\frac{f}{f_{\text{cmb}}} \right)^{n_t}$$

Parameters

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

Lessons

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

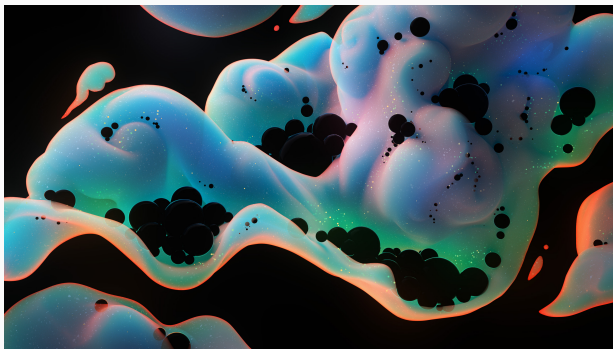


② BSM scenario: Primordial black holes

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?

② BSM scenario: 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?

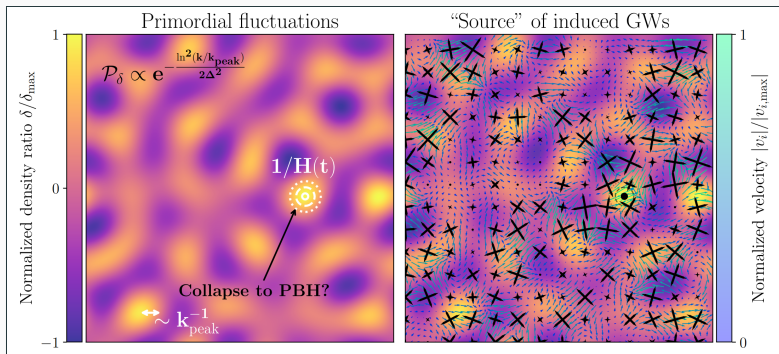


PBHs: Form in the gravitational collapse of large overdensities in the early Universe

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

Scalar-induced GWs (SIGWs) at second order in perturbation theory

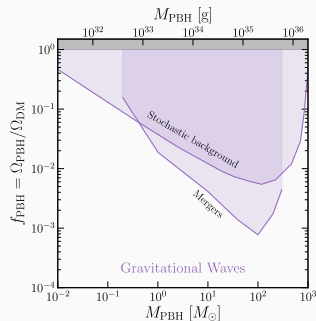
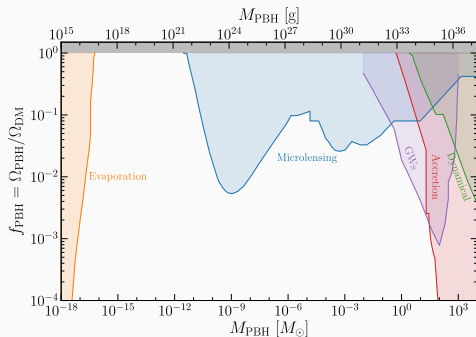
[2402.17388]



Cosmological perturbation theory

- Scalar and tensor modes couple to each other at second order, $h_{ij} \leftrightarrow \partial_i \Phi \partial_j \Phi$
- Enhanced density modes leave (re-enter) Hubble horizon during (after) inflation
- Collapse into PBHs and source SIGWs upon horizon re-entry during radiation era

Associated PBH formation



[Green, Kavanagh: 2007.10722]

Collapse of horizon mass when overdense regions re-enter the causal horizon

- Statistics of primordial density perturbations translate into PBH mass fraction
- Part of dark-matter (DM) relic density; up to 100 % for asteroid-scale masses
- DM mass fraction $f_{\text{PBH}} \sim 10^{-3}$ and masses of $\mathcal{O}(10) M_{\odot} \rightarrow$ LIGO / Virgo!?

Primordial scalar spectrum

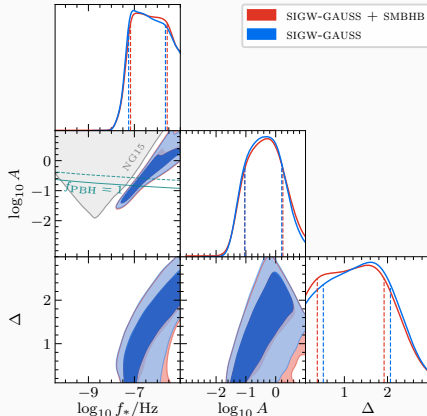
$$\mathcal{P}_s = \frac{A}{\sqrt{2\pi} \Delta} \exp \left[-\frac{(\ln(f/f_*))^2}{2 \Delta^2} \right]$$

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

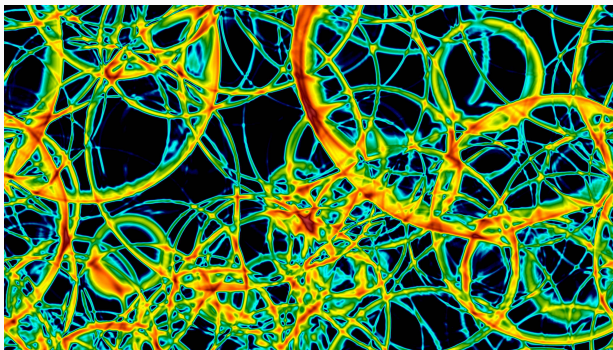


③ BSM scenario: Phase transition

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?

③ BSM scenario: 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?

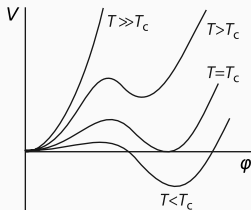


Cosmological phase transitions: Changes in the quantum field theory vacuum structure

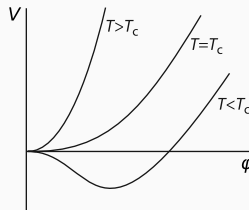
- SM predicts smooth crossovers; strong first-order phase transitions require BSM
- GWs from bubble collisions, sound waves, and magnetohydrodynamic turbulence

First-order phase transitions

First-order phase transition



Second-order phase transition



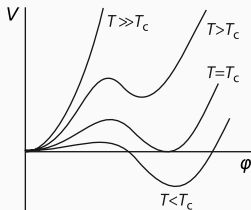
[Kinnunen, Baarsma, Martikainen, Törmä: 1706.07076]

GWs from strong first-order phase transitions (SFOTs)

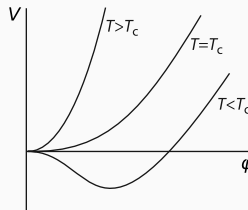
- Barrier in the effective potential of the order parameter (scalar field)
- Thermal jump or quantum tunneling $\rightarrow$ bubble nucleation in position space
- Bubbles expand, accelerate, transfer energy to the surrounding plasma, and collide

First-order phase transitions

First-order phase transition



Second-order phase transition



[Kinnunen, Baarsma, Martikainen, Törmä: 1706.07076]

GWs from strong first-order phase transitions (SFOPTs)

- Barrier in the effective potential of the order parameter (scalar field)
- Thermal jump or quantum tunneling $\rightarrow$ bubble nucleation in position space
- Bubbles expand, accelerate, transfer energy to the surrounding plasma, and collide

Three sources of GWs

- Ω_b : Bubble collisions, gradient energy in the scalar field
- Ω_s : Sound waves, compression and rarefaction waves in the bulk plasma
- Ω_t : Magnetohydrodynamic turbulence, vortical motion in the bulk plasma

Peak amplitude and frequency

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

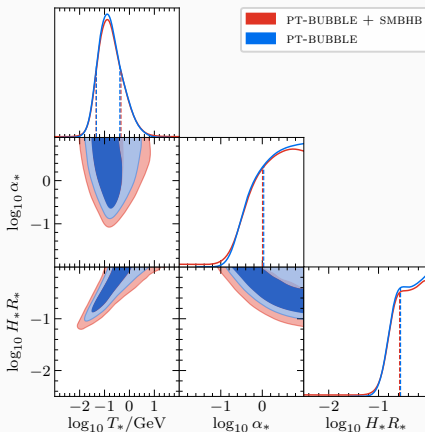
$$f_{\text{peak}} \propto \frac{T_*}{H_* R_*}$$

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 $T_* \sim 100$ MeV
- Just the right ballpark for BSM modifications of the **QCD phase transition**
- Alternatively, phase transition in a **dark sector** → complementary to lab searches

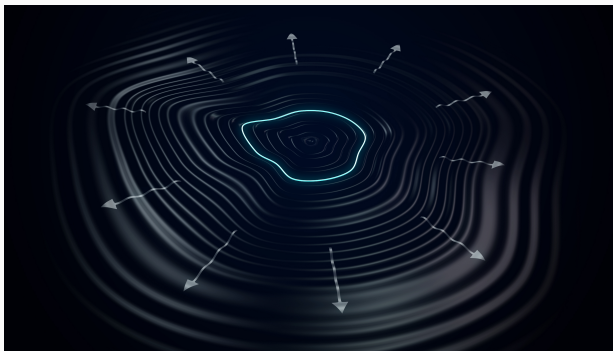


④ BSM scenario: Cosmic defects

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?

④ BSM scenario: 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?

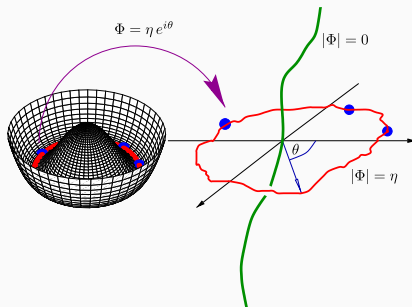


Cosmic strings / domain walls: Defects after spontaneous breaking of GUT symmetries

- 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

Cosmic strings

[Ringeval: 1005.4842]



Properties

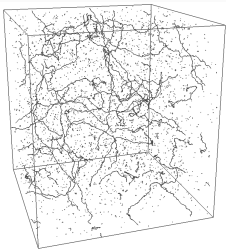
- Topological defects after spontaneous $U(1)$ breaking in the early Universe
- Global / local $U(1)$ symmetry restored (never broken) at the core of strings
- Condensed matter analog: magnetic field vortices in a superconductor

Relevant parameters

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

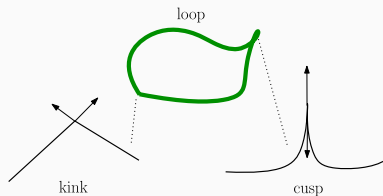
Gravitational waves from cosmic strings

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



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

[Gouttenoire, Servant, Simakachorn: 1912.02569]

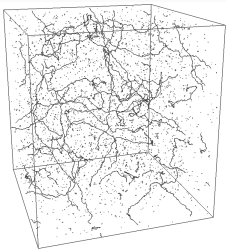


Gravitational waves from

- Cusps
- Kinks
- Kink–kink collisions

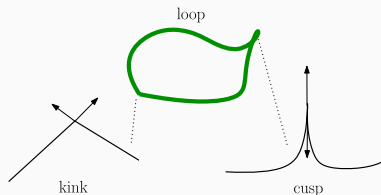
Gravitational waves from cosmic strings

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



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

[Gouttenoire, Servant, Simakachorn: 1912.02569]



Gravitational waves from

- Cusps
- Kinks
- Kink–kink collisions

-
- **Nambu–Goto action:** infinitely thin strings, no particle emission
 - **Abelian-Higgs model:** short-lived loops, decay into massive particles
 - **Nonminimal models:** Metastable strings, current-carrying cosmic strings, ...

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

Decay rate per length

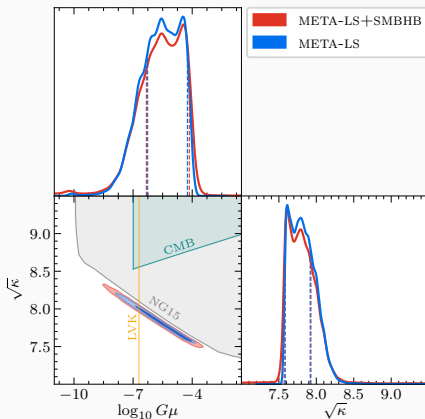
$$\Gamma_d = \frac{\mu}{2\pi} e^{-\pi\kappa}$$

Parameters

- μ Tension (energy per length)
- κ Decay parameter

Lessons

- Preferred parameter values $\rightarrow$ input for **GUT model building** at $E \lesssim 10^{16}$ 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 (!)*



Why care about exotic sources?

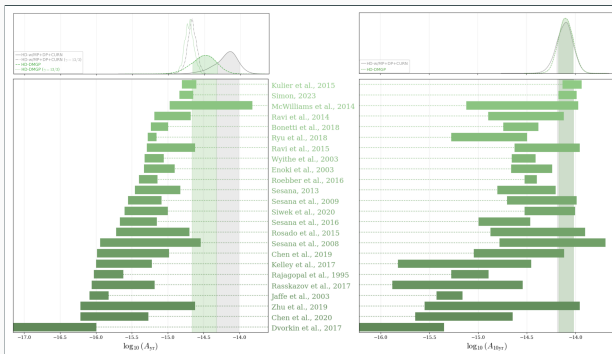


Do we *really* believe that PTAs could be seeing a GW echo from the Big Bang?

- **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

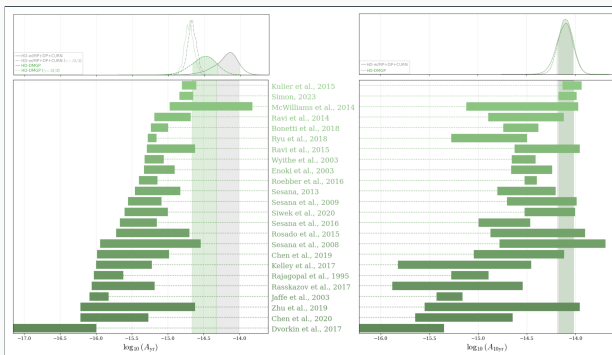
Three reasons to care about exotic sources

[NANOGrav 2306.16220]



Three reasons to care about exotic sources

[NANOGrav 2306.16220]

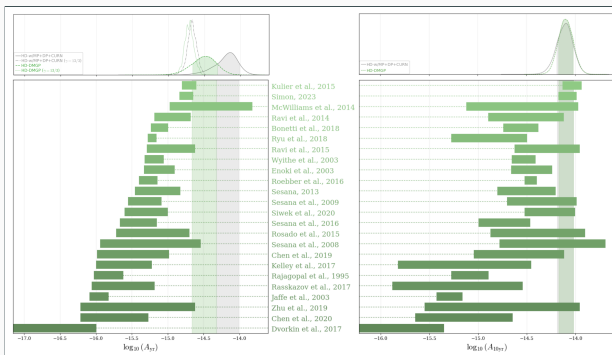


❶ Surprisingly loud signal

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

Three reasons to care about exotic sources

[NANOGrav 2306.16220]



❶ Surprisingly loud signal

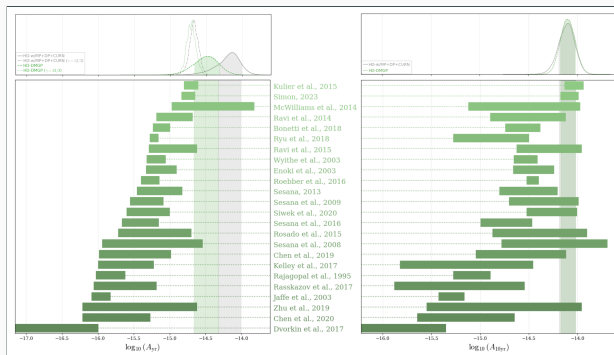
Unexpected corners of SMBHB parameter space, e.g., higher binary density, shorter delay times

❷ Maximize our confidence in the SMBHB interpretation

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

Three reasons to care about exotic sources

[NANOGrav 2306.16220]



❶ Surprisingly loud signal

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

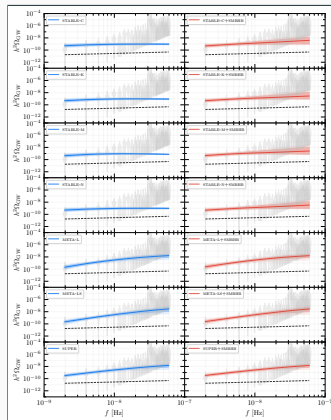
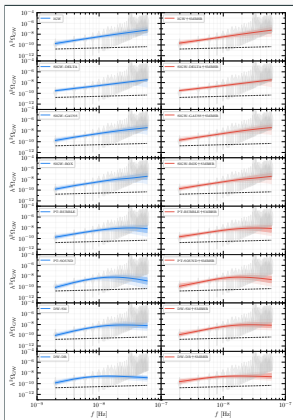
❷ Maximize our confidence in the SMBHB interpretation

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

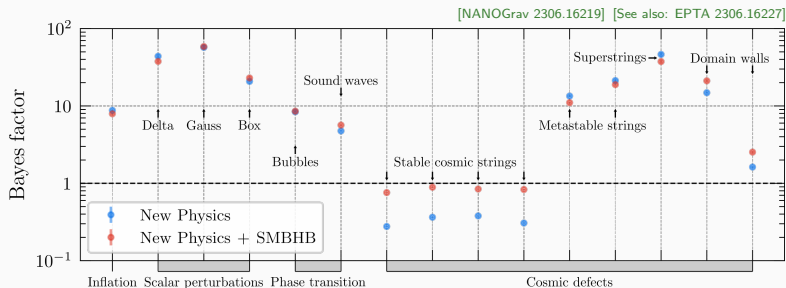
New bounds, complementary to energy and intensity frontiers. Benchmarks for LISA, etc.!

[NANOGrav 2306.16219]



- Blue: BSM spectrum | Red: BSM spectrum + SMBHB spectrum
- GW spectra resulting in a good fit of the data look similar by construction
- Most cosmological signals well approximated by a running power law (parabola)

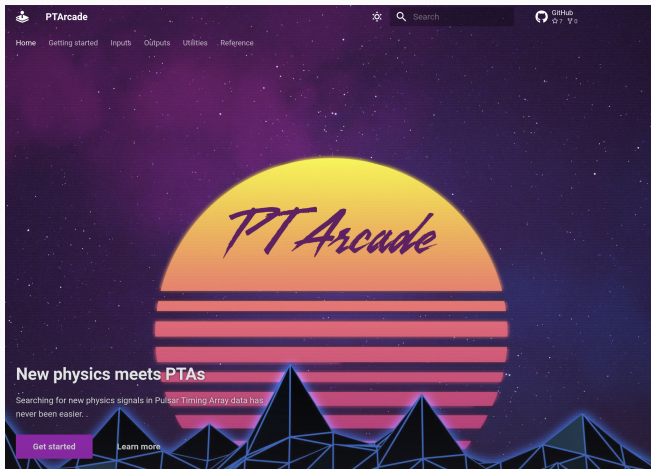
Bayesian model comparison



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

- 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

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

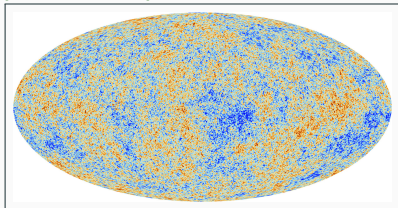


Our code developed for 2306.16219: Fit your favorite BSM model to the NG15 data!
New functionalities, new models, and new data (when available) added on a steady basis

GWB = CMB of the 21st century?

20th century

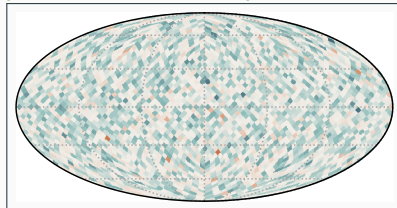
[PLANCK Collaboration]



CMB: Cosmic microwave background

21th century

[Sato-Polito, Kamionkowski: 2305.05690]

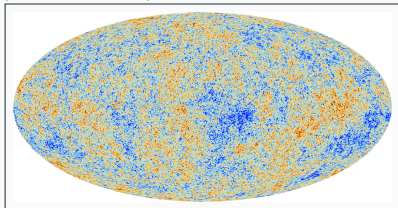


GWB: Gravitational-wave background

GWB = CMB of the 21st century?

20th century

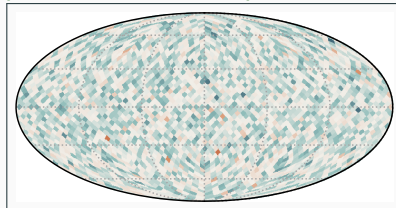
[PLANCK Collaboration]



CMB: Cosmic microwave background

21th century

[Sato-Polito, Kamionkowski: 2305.05690]



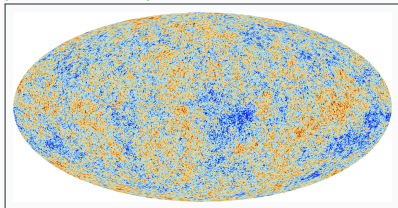
GWB: Gravitational-wave background

GWB property	<i>Astro interpretation</i>	<i>Cosmo interpretation</i>
Stochastic?	Yes + "continuous waves" (CWs)	Yes

GWB = CMB of the 21st century?

20th century

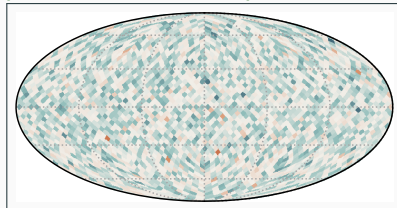
[PLANCK Collaboration]



CMB: Cosmic microwave background

21th century

[Sato-Polito, Kamionkowski: 2305.05690]



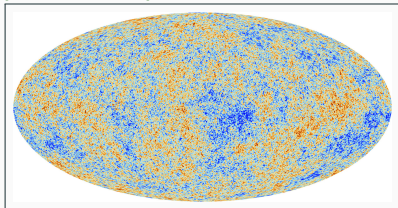
GWB: Gravitational-wave background

GWB property	Astro interpretation	Cosmo interpretation
Stochastic?	Yes + "continuous waves" (CWs)	Yes
Stationary?	Likely yes for $T_{\text{obs}} \sim 10 \cdots 100 \text{ yr}$	Yes

GWB = CMB of the 21st century?

20th century

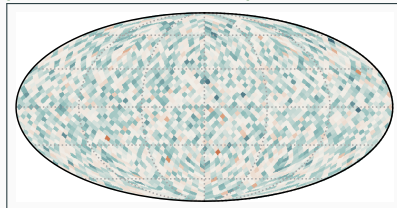
[PLANCK Collaboration]



CMB: Cosmic microwave background

21th century

[Sato-Polito, Kamionkowski: 2305.05690]



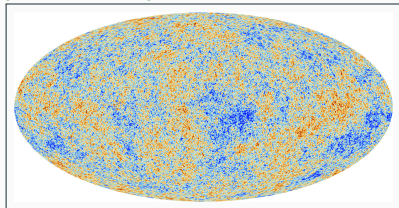
GWB: Gravitational-wave background

GWB property	Astro interpretation	Cosmo interpretation
Stochastic?	Yes + "continuous waves" (CWs)	Yes
Stationary?	Likely yes for $T_{\text{obs}} \sim 10 \cdots 100 \text{ yr}$	Yes
Isotropic?	Large intrinsic anisotropies	Small intrinsic + kinematic anisotropies

GWB = CMB of the 21st century?

20th century

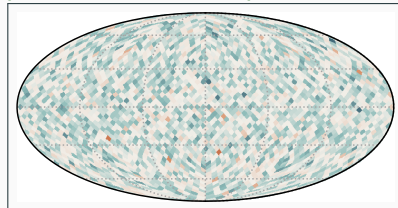
[PLANCK Collaboration]



CMB: Cosmic microwave background

21th century

[Sato-Polito, Kamionkowski: 2305.05690]



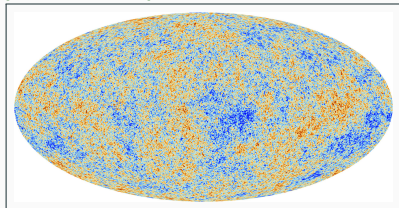
GWB: Gravitational-wave background

GWB property	Astro interpretation	Cosmo interpretation
Stochastic?	Yes + “continuous waves” (CWs)	Yes
Stationary?	Likely yes for $T_{\text{obs}} \sim 10 \cdots 100 \text{ yr}$	Yes
Isotropic?	Large intrinsic anisotropies	Small intrinsic + kinematic anisotropies
Unpolarized?	Polarization from shot noise	Usually yes, but model-dependent

GWB = CMB of the 21st century?

20th century

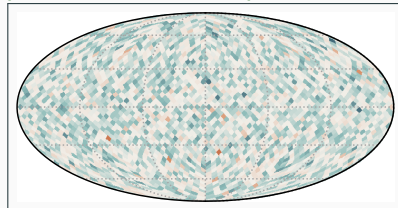
[PLANCK Collaboration]



CMB: Cosmic microwave background

21th century

[Sato-Polito, Kamionkowski: 2305.05690]



GWB: Gravitational-wave background

GWB property	Astro interpretation	Cosmo interpretation
Stochastic?	Yes + "continuous waves" (CWs)	Yes
Stationary?	Likely yes for $T_{\text{obs}} \sim 10 \cdots 100 \text{ yr}$	Yes
Isotropic?	Large intrinsic anisotropies	Small intrinsic + kinematic anisotropies
Unpolarized?	Polarization from shot noise	Usually yes, but model-dependent
Gaussian?	Non-Gaussianities from loud sources	Usually yes, but model-dependent

Dark matter in the Milky Way

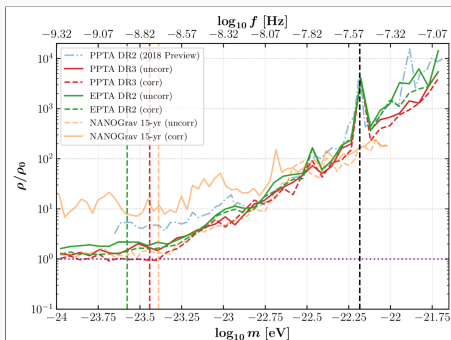
Additional **non-GWB** signal in PTA data on top of the stochastic GWB

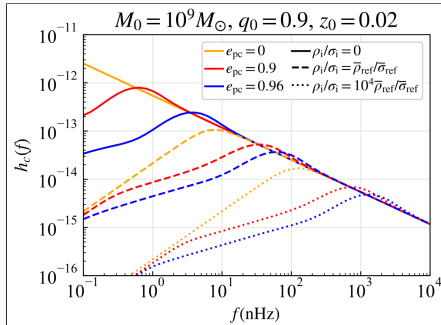
Search for **ultralight dark matter** (ULDM) and **dark-matter substructures**

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

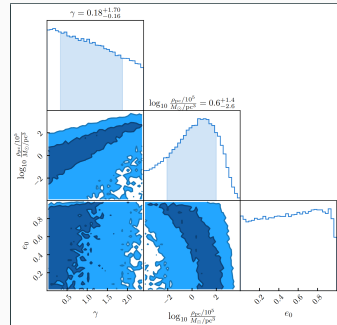
Example: Metric perturbations from an oscillating ULDM field

[Hu et al. 2605.02172]





[NANOGrav 2411.05906]

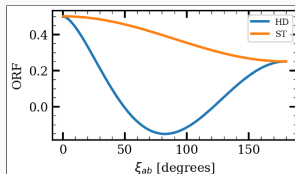
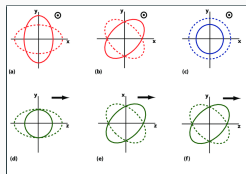


Additional energy loss because of dynamical friction and three-body interactions

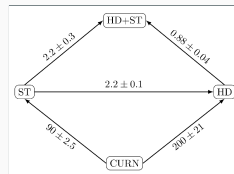
- Suppression of GWB signal from SMBHBs at low frequencies → spectral turnover
- Probe density profile of baryonic + dark matter in the direct vicinity of SMBHBs

New physics in the gravitational sector

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

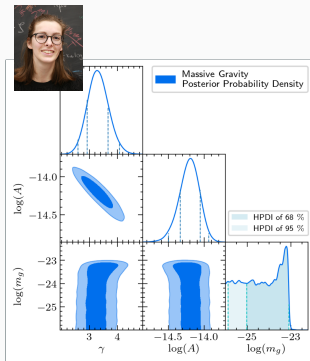


[NANOGrav 2310.12138]



1 Scalar and vector polarization states on top of usual tensor polarization states

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



[Kim Wassner, BSc thesis, U Münster]

2 Massive gravity

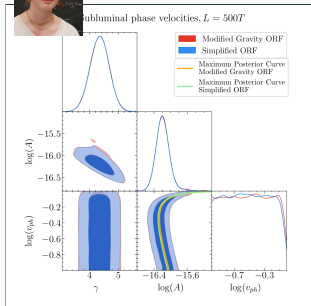
- GW dispersion relation $\omega = \sqrt{k^2 + m_g^2}$, focus on tensor polarization states
- ORF depends on group velocity, $v_{gr} < c$, and hence **implicitly** on GW frequency
- Upper limit of the 95 % credible interval:

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

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

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

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



[Nina Cordes, BSc thesis, U Münster]

3 Subluminal GW phase velocity

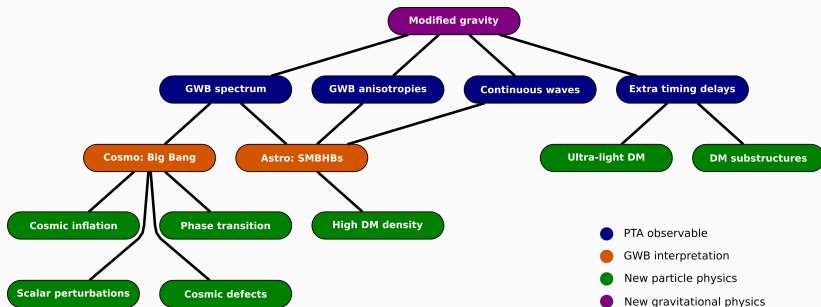
- GW dispersion relation $\omega = v_{\text{ph}} k$
- ORF depends on phase velocity $v_{\text{ph}} < c$ and **explicitly** on GW frequency f
- If v_{ph} small enough, ORF dominated by auto correlation coefficients $\Gamma_{aa} \gg \Gamma_{ab}$
- Flat direction in parameter space in terms of A , v_{ph}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

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

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

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

Summary



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



Stay tuned!

And thanks a lot for your attention