Stop Horsing Around!

Faster GWB Spectral Characterisation for your Cosmological Convenience

William G. Lamb
Vanderbilt University, Nashville, TN, USA
Advisor: Dr. Stephen Taylor

Credit: Olena Shmahalo/NANOGrav

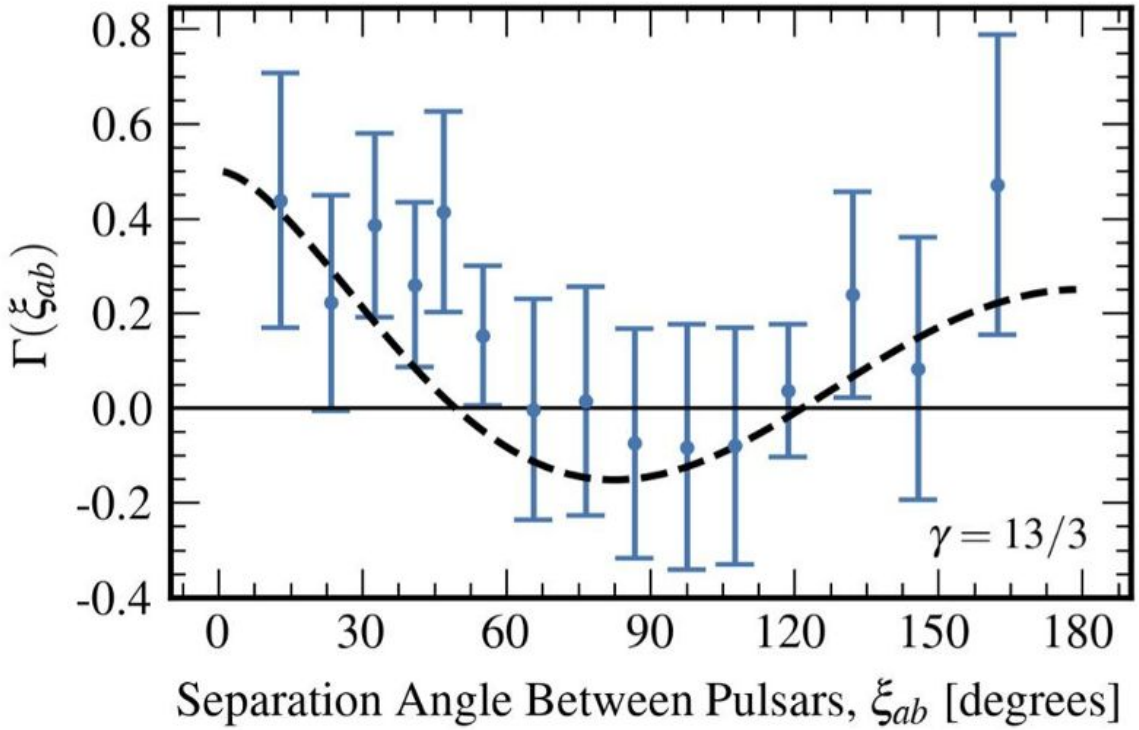
Credit: D. Weir, University of Helsinki

Overview:

- Pulsar Timing Arrays and the GWB
- Spectral Characterisation
- Free spectrum and faster refitting
- Results
- Future Prospects
- Conclusions

Evidence for the GWB

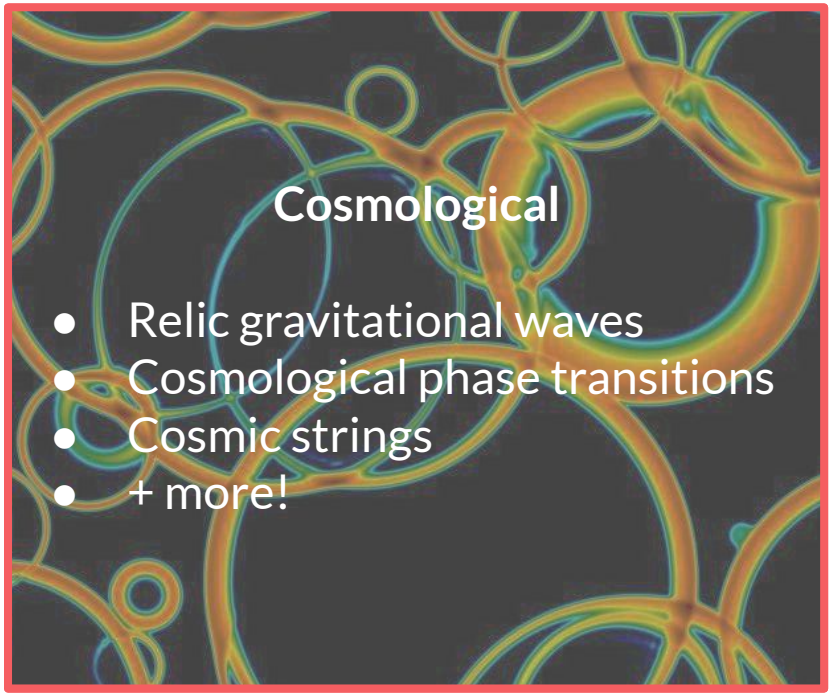
Agazie et al 2023 ApJL 951 L8



What is the source of the GWB?

Astrophysical

- **Supermassive black hole binaries (SMBHBs)**
  - Constrain astrophysical parameters
  - Measure sub-parsec interactions



Cosmological

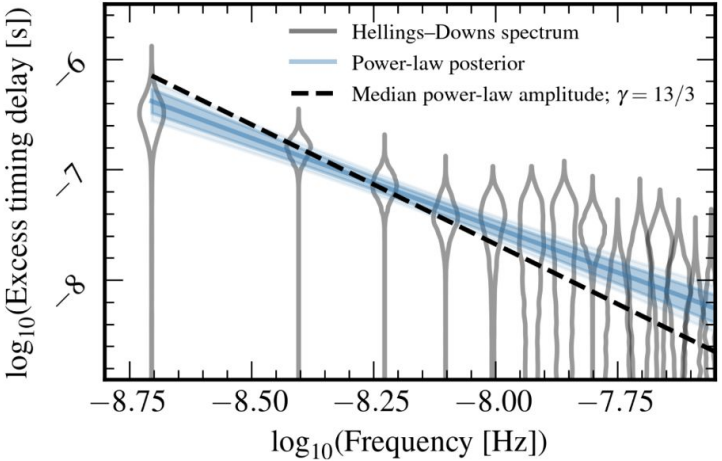
- Relic gravitational waves
- Cosmological phase transitions
- Cosmic strings
- + more!

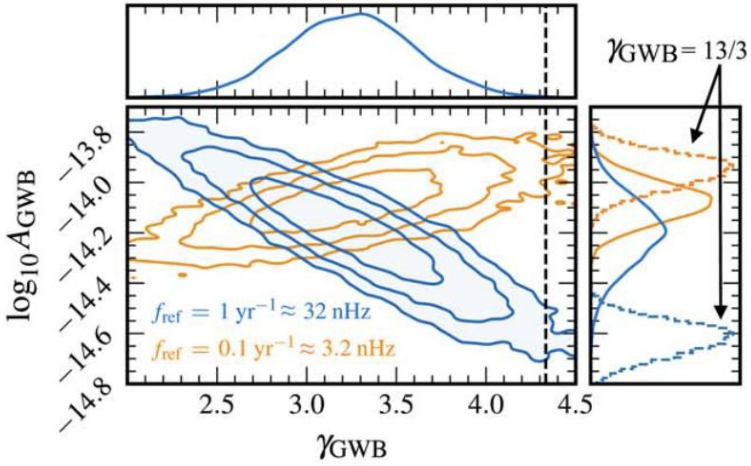
Agazie et al 2023 ApJL 951 L8

Determining the source

- Anisotropy

- Spectral Characterisation
  - Fit model spectra to data
  - Recover posterior on model parameters
  - Interpret posteriors to physical phenomena





William Glenn Lamb (william.g.lamb@vanderbilt.edu)

Spectral Characterisation so far...

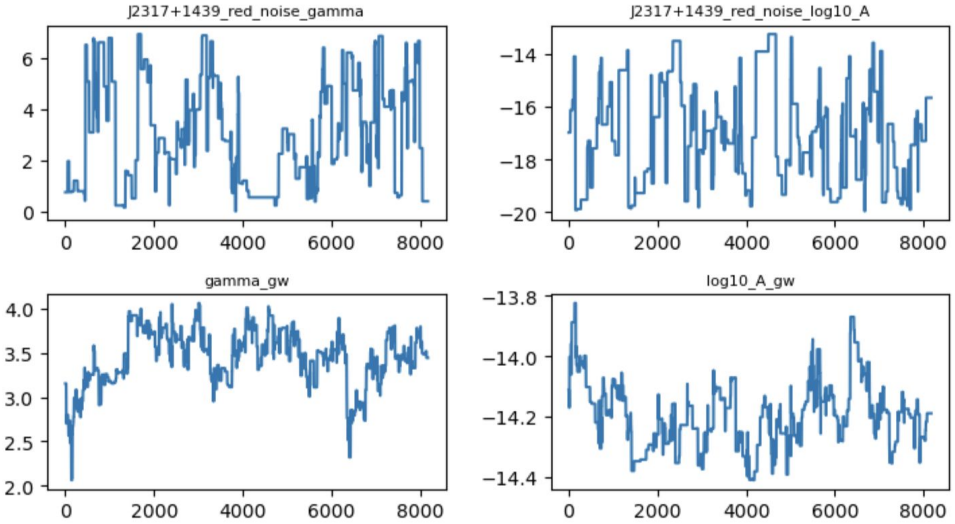
- Model:
  - Timing model (TM)
  - White noise (WN)
  - Intrinsic red noise (IRN) per pulsar
  - GWB model
  - (+ additional noise)
- Markov Chain Monte Carlo (MCMC)
- Likelihood evaluation:
  - *Uncorrelated GWB* $\propto N_p$
  - ***Correlated GWB*** $\propto N_p^2$ *(Johnson et al. 2023)*

$$S(f) \propto A^2 f^{-\gamma}$$

$$p(\vec{\delta t}|\vec{\eta}) = \frac{\exp\left(-\frac{1}{2}\vec{\delta t}^{\,\mathrm{T}}\mathbf{C}^{-1}\vec{\delta t}\right)}{\sqrt{\det\left(2\pi\mathbf{C}\right)}}$$

	PSR 1	PSR 2	PSR 3	PSR 4
PSR 1	WN + IRN + GWB	GWB	GWB	GWB
PSR 2	GWB	WN + IRN + GWB	GWB	GWB
PSR 3	GWB	GWB	WN + IRN + GWB	GWB
PSR 4	GWB	GWB	GWB	WN + IRN + GWB

MCMC Roadblocks



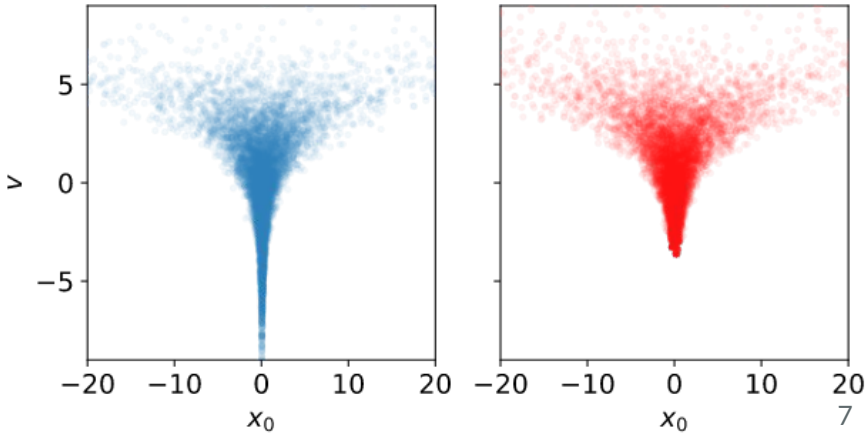
- **NANOGrav 15yr:** 67 psrs/136 params
- **IPTA DR3:** 115 psrs/232 params

- Slow MCMC
- Cannot use nested sampling

Requirements:

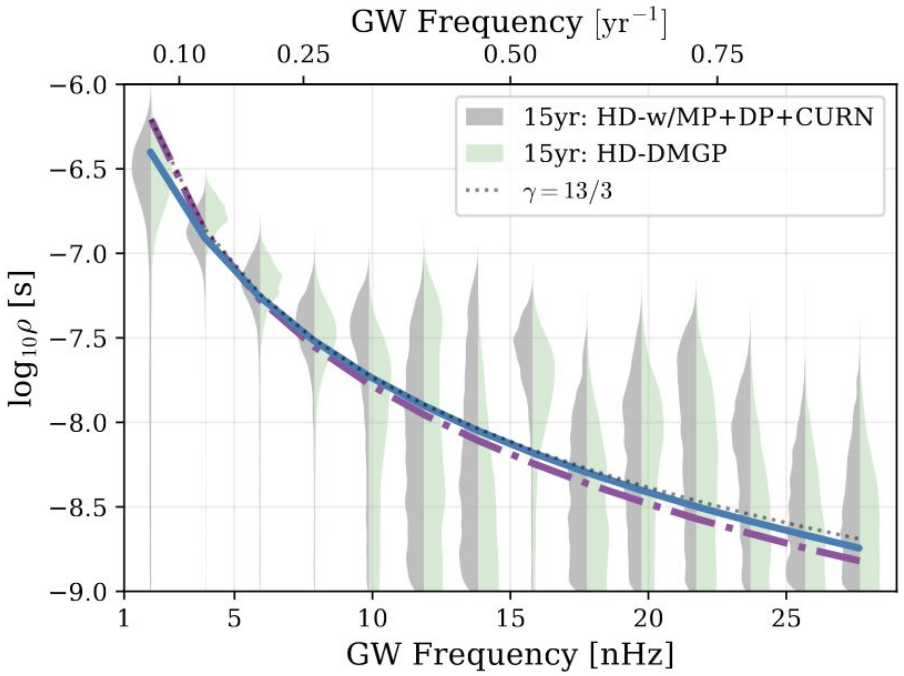
- faster, simpler analyses
- easier, more accurate noise modelling
- instant, accurate results

R. M. Neal 2003. Annals of Statistics 31 (3): 705–67



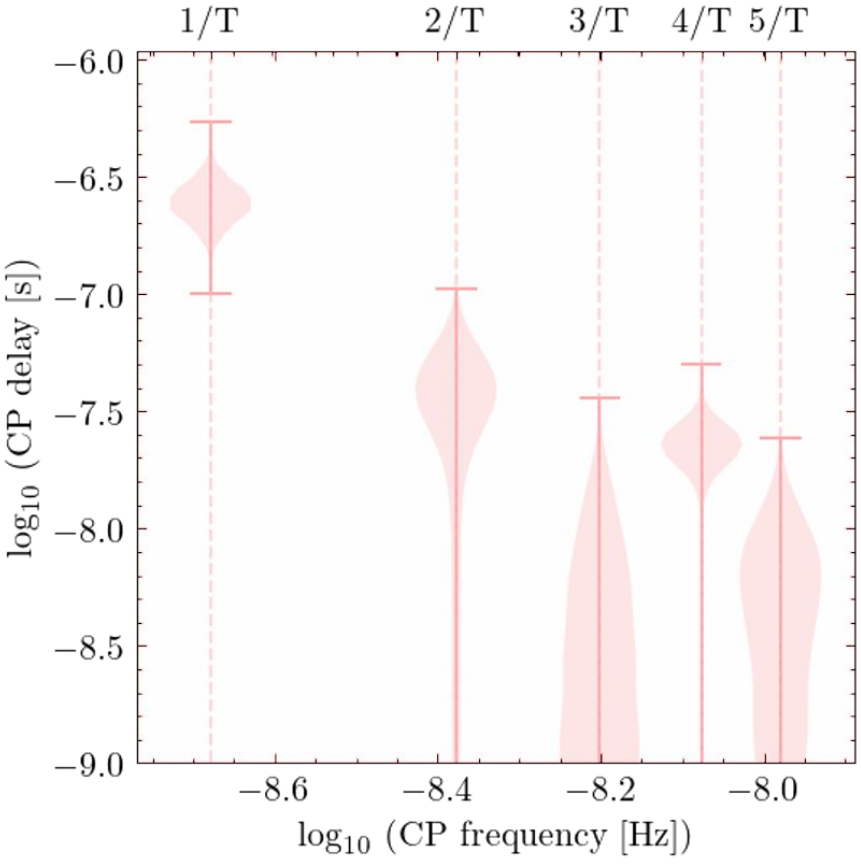
Too much noise!

- DMX vs DM GP
- Spurious noise processes
- Intrinsic red noise models
- Data combination/timing is an art



Free Spectrum (*Lentati et al. 2013*)

- Minimally-modelled spectral characterisation of GWB
  - Posterior of power spectrum at each Fourier frequency
- Kernel density estimators (KDEs)
  - Represent red noise with probability distributions per frequency
- Slow analysis…
  - One time only!
  - Effectively *marginalises* other noise processes!



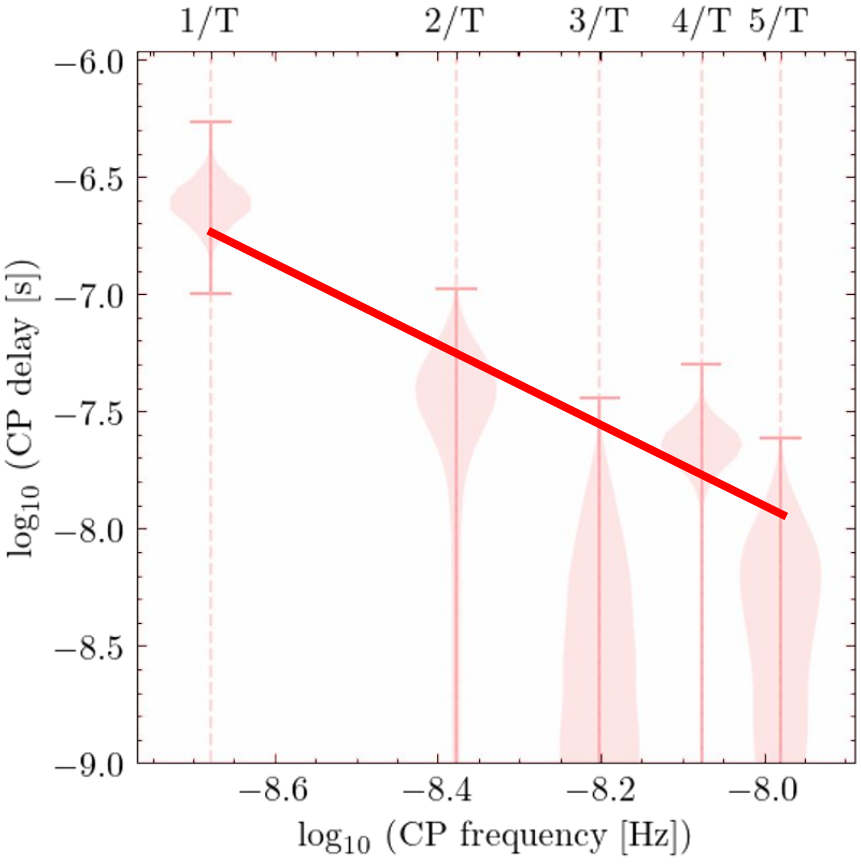
PTA Free Spectrum Refit

Likelihood factorised over frequencies

$$p(\vec{\delta t}) \sim \prod_{k=1}^{N_f} p_k(\rho_k|\vec{\delta t})$$

MCMC:

1. Compute spectrum
2. Calculate probability per frequency
3. Take product
4. ***Results in minutes with ceffyl!***



Generalised Factorised Likelihoods (GFL)

(Romano+ 2021, Taylor+ 2022, Lamb+ 2023)

Likelihood factorised over frequencies and pulsars

$$p(\vec{\delta t}) \sim \prod_{p=1}^{N_p} \prod_{k=1}^{N_f} p_k(\rho_k | \vec{\delta t_p})$$

GFL Lite: Fit GWB only

GFL: Fit intrinsic red noise per pul… *…n dev)*

MCMC:

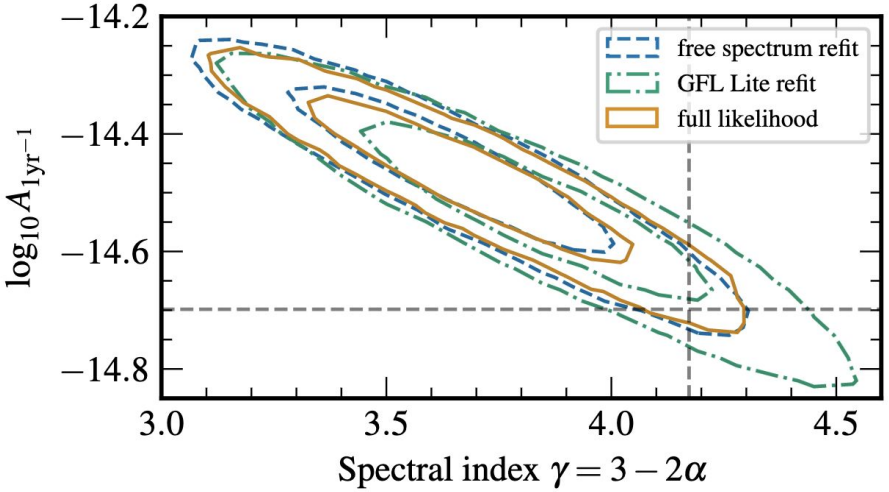
1. Compute spectrum
2. Calculate probability per frequency and pulsar
3. Take product
4. ***Results in minutes with ceffyl!***

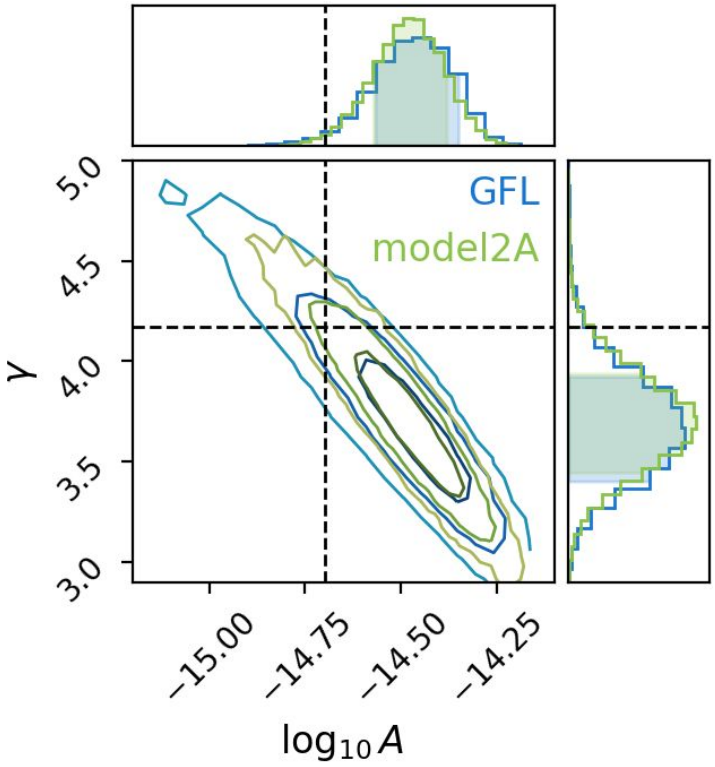
IN DEVELOPMENT

	PSR 1	PSR 2	PSR 3	PSR 4
PSR 1	WN + IRN + GWB	GWB	GWB	GWB
PSR 2	GWB	WN + IRN + GWB	GWB	GWB
PSR 3	GWB	GWB	WN + IRN + GWB	GWB
PSR 4	GWB	GWB	GWB	WN + IRN + GWB

Refit methods

arXiv:2303.15442v2

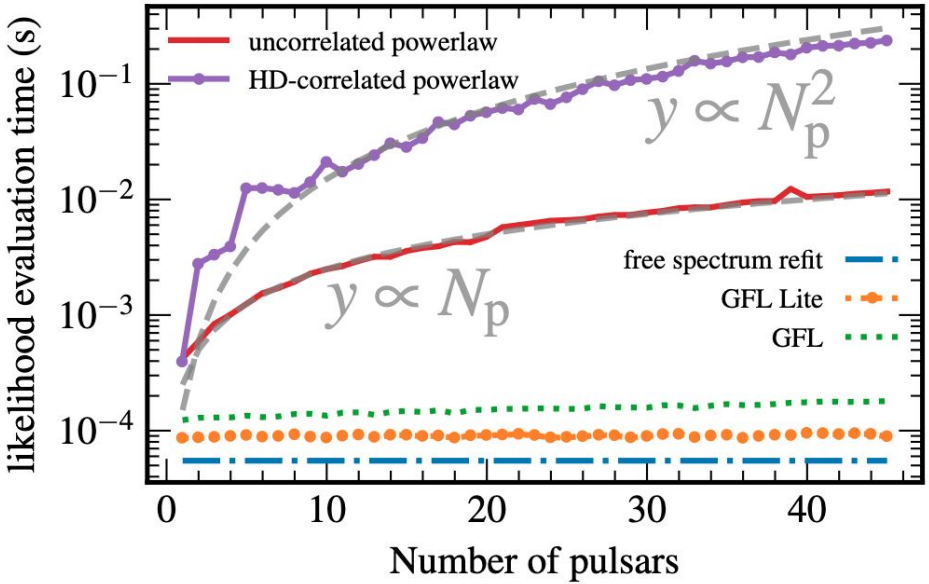




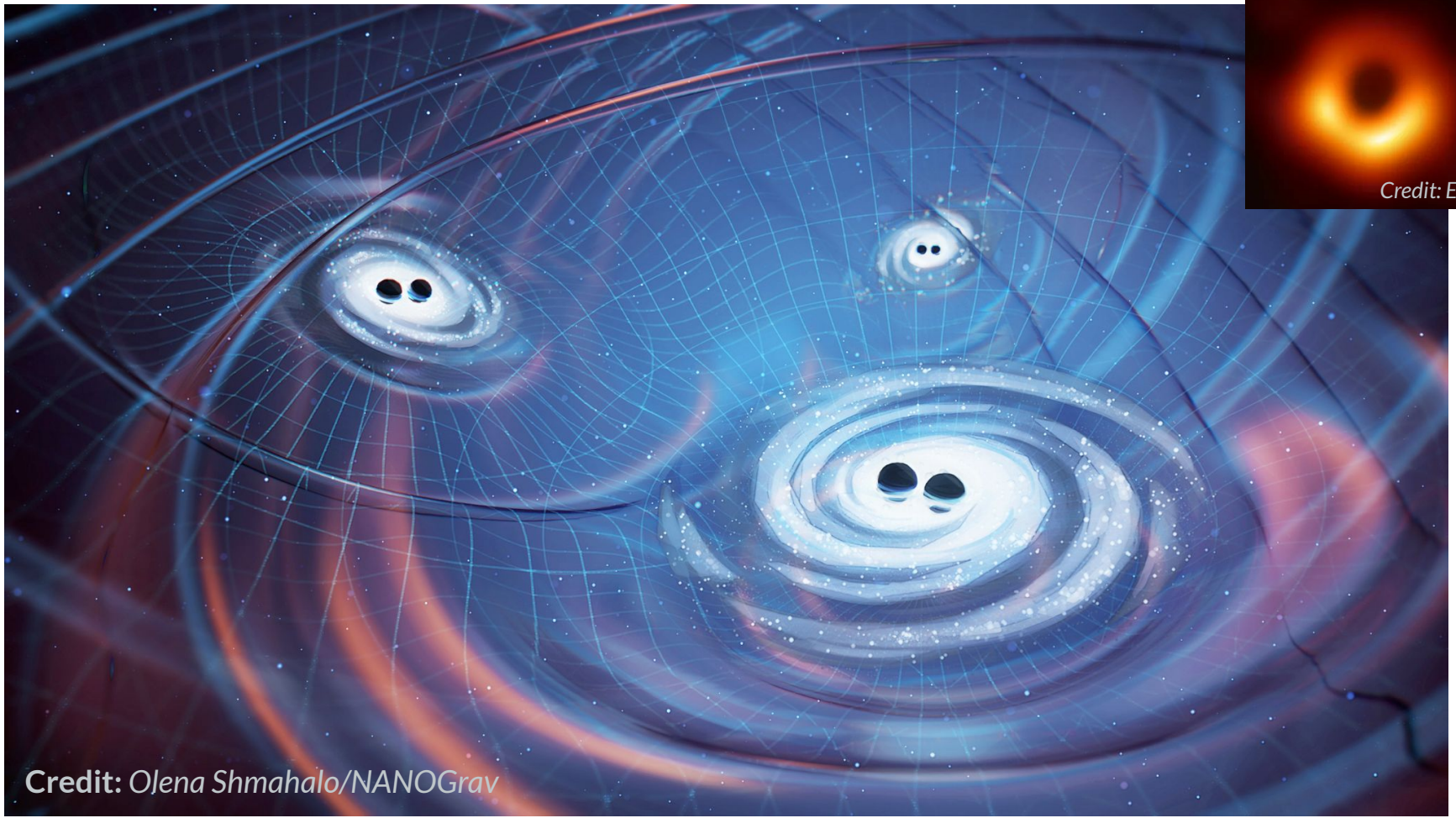
ceffyl

- 2-4 orders of magnitude faster than enterprise!
  - On 45 simulated pulsars
- Easy to use!
- Less parameters, better sampling
- ***github.com/astrolamb/ceffyl***

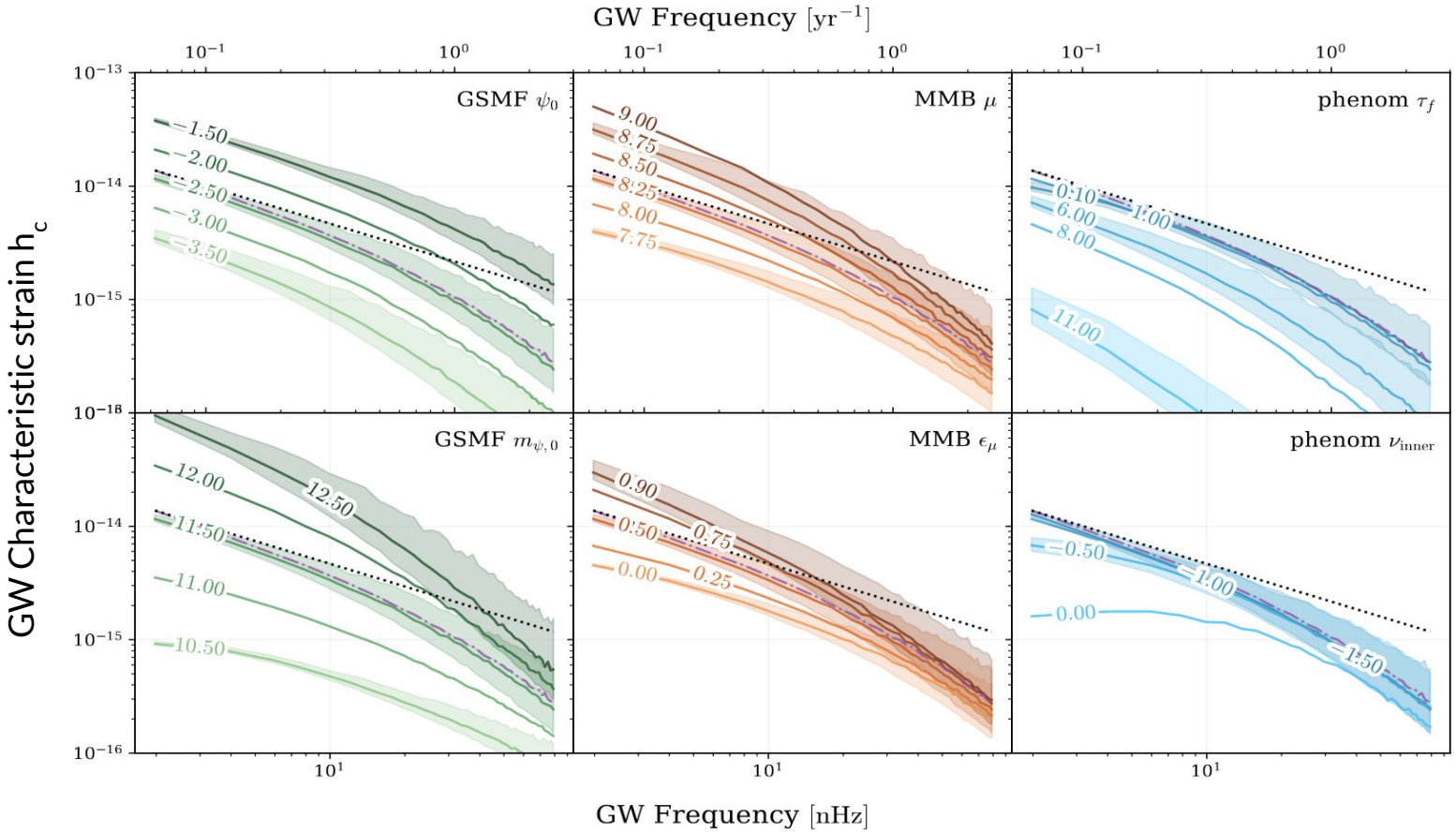
- Wrapper code: ***PTArcade***
  - Specifically designed for the new physics community
  - PTA free spectrum refit
  - **andrea-mitridate.github.io/PTArcade/**



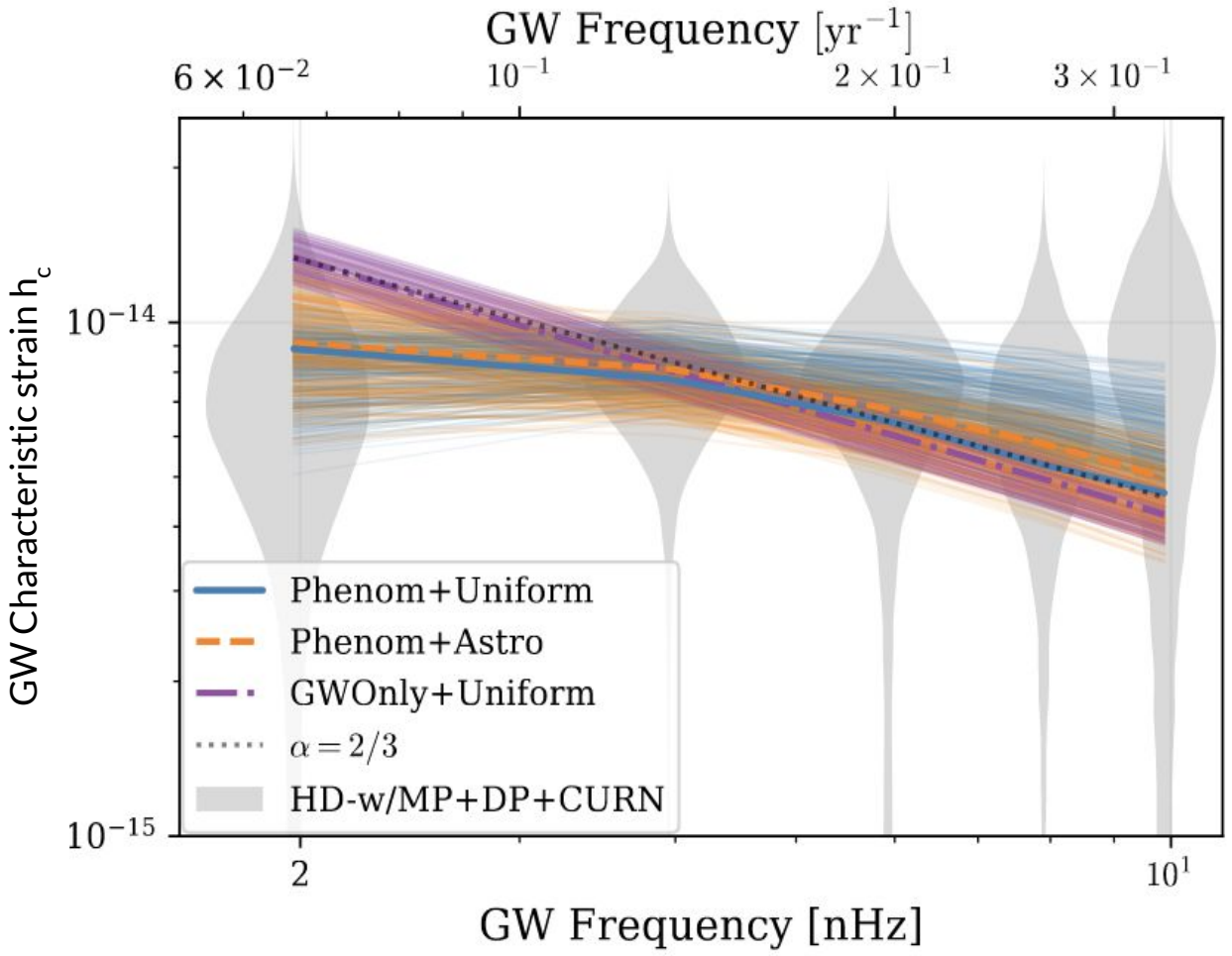
Some astrophysics...


Credit: Olena Shmahalo/NANOGrav

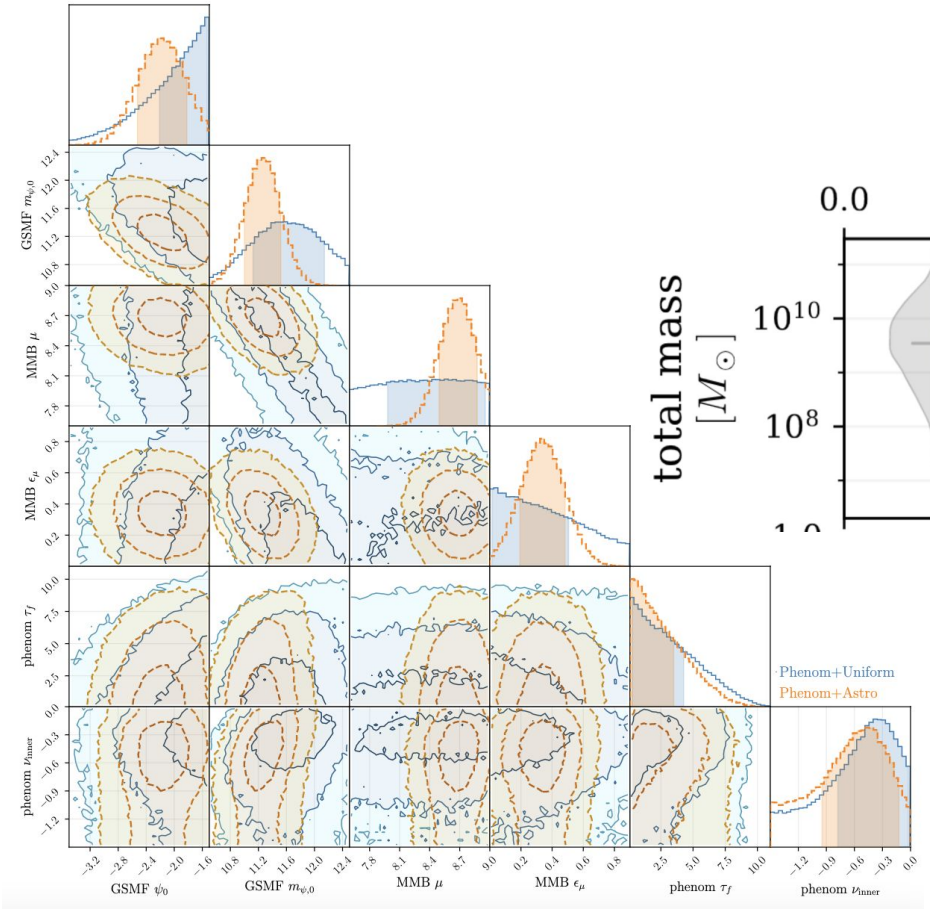
Credit: EHT

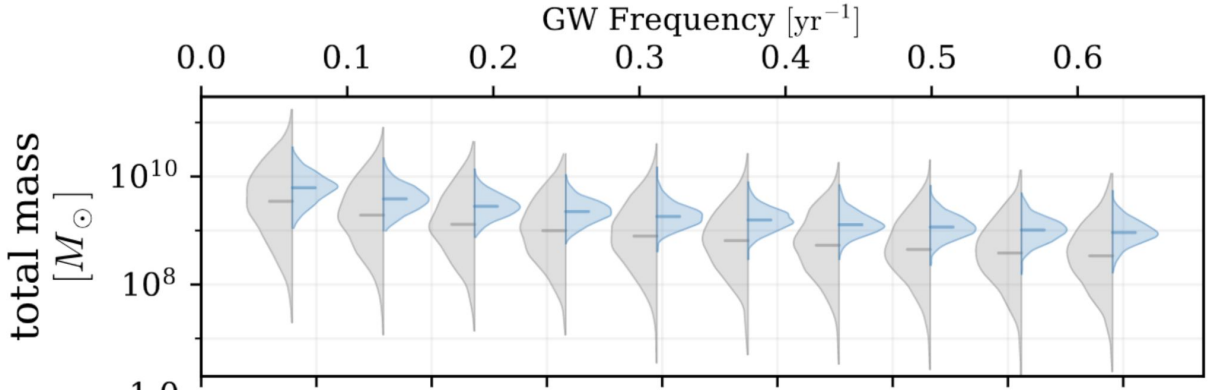


arXiv:2306.16220v1



arXiv:2306.16220v1





Conclusions:

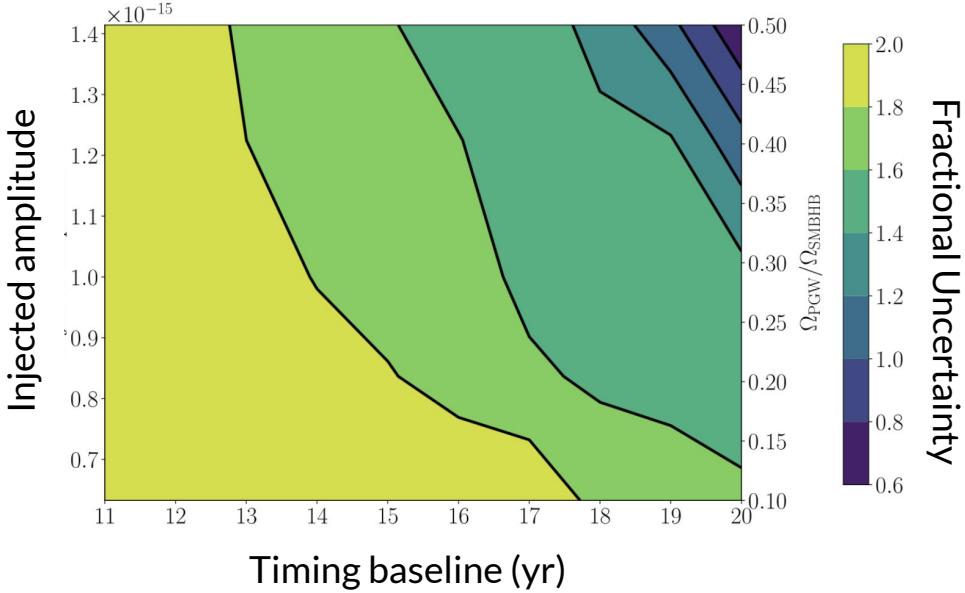
- High-mass SMBHBs
- 0.01-0.1 pc separations

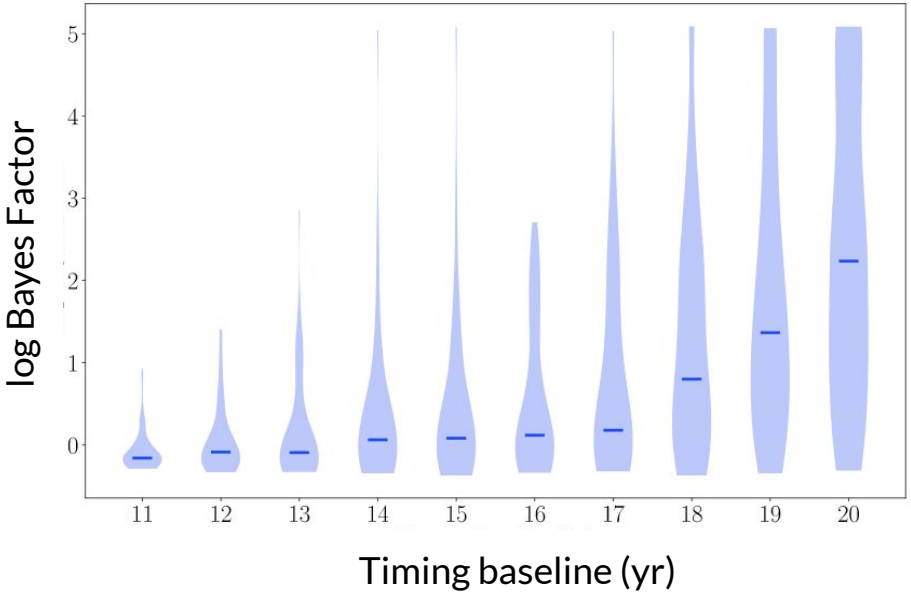
arXiv:2306.16220v1

William Glenn Lamb (william.g.lamb@vanderbilt.edu)

Some cosmology...

Distinguishing two powerlaws *(Kaiser et al. 2021)*

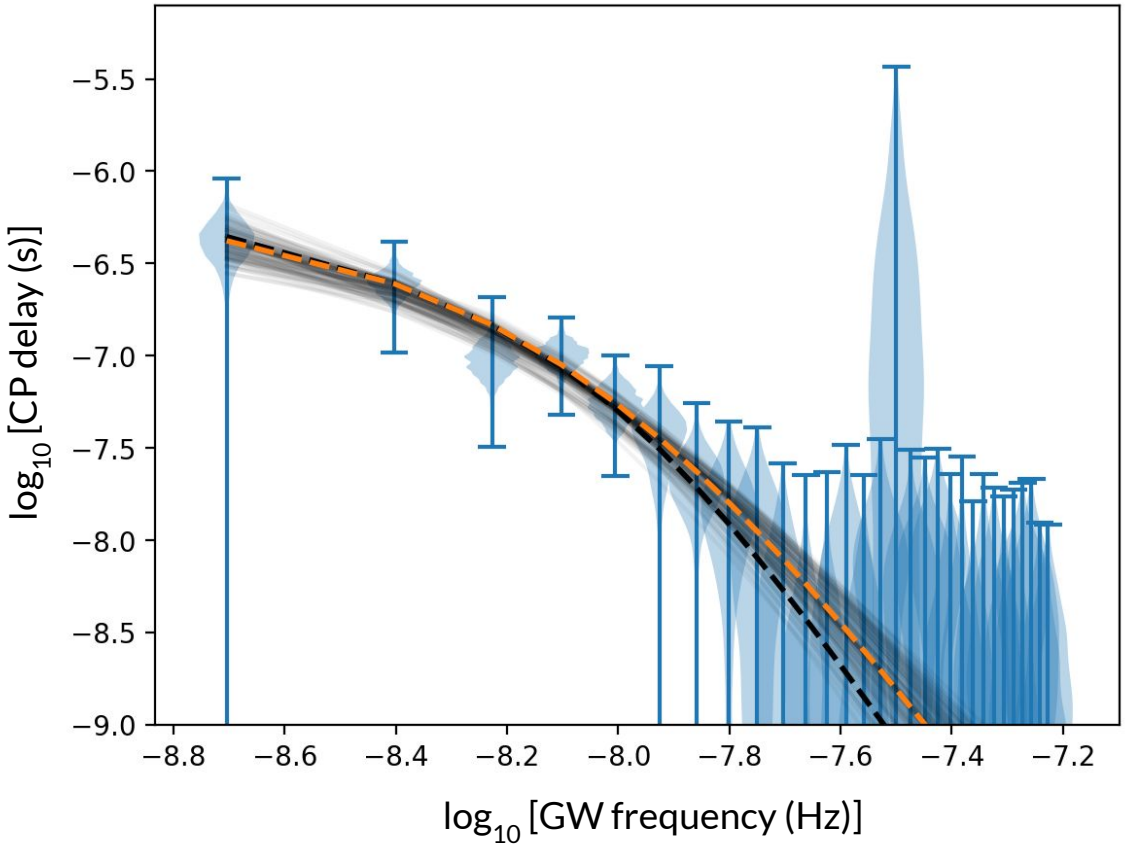




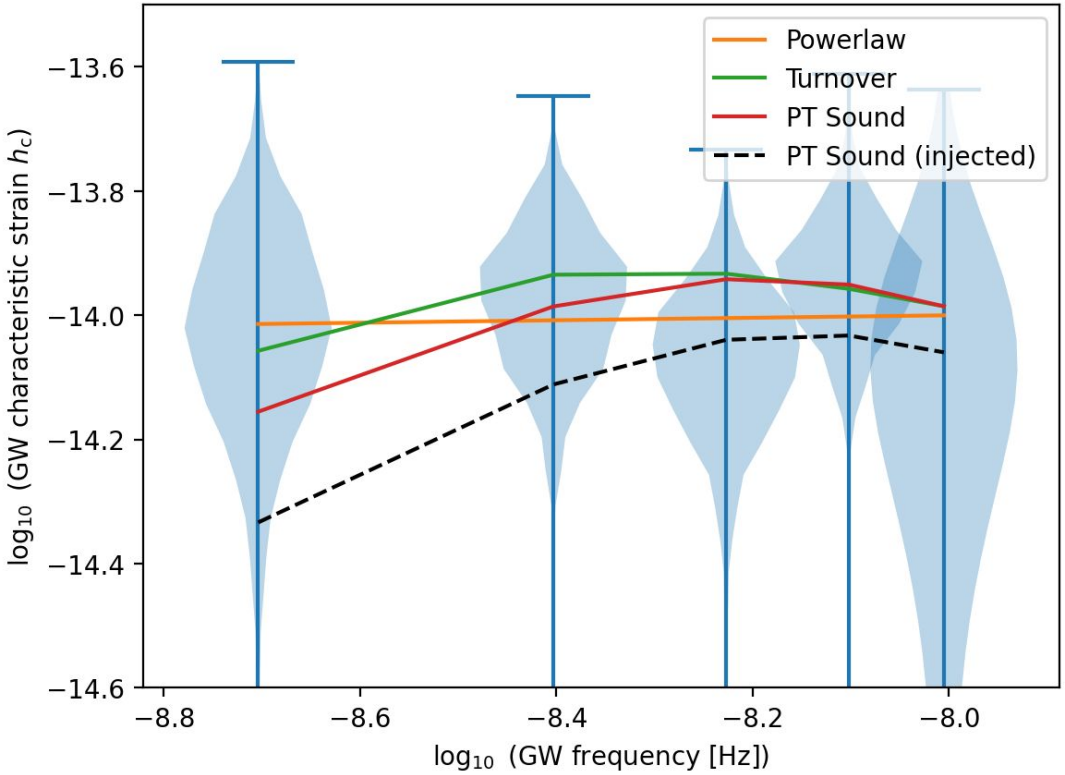
‘cosmo4cast’

Forecasting time to distinguishing between astrophysical and cosmological sources

- NG15-based simulations
- Use refit methods to forecast as function of:
  - number of pulsars
  - number of frequencies
  - timing baseline
  - noise characteristics
- Compute:
  - Bayes factors
  - null hypotheses
  - posterior uncertainties



‘cosmo4cast’



NG15-based simulation
with a GWB from sound waves
from a phase transition (PT Sound)

Bayes factors:

PT-sound vs powerlaw = 2.33

PT-sound vs turnover = 3.08

ceffyl refit: arXiv:2303.15442
PTArcade: arXiv: 2306.16377
Ultranest: arXiv:2101.09604

‘cosmo4cast’

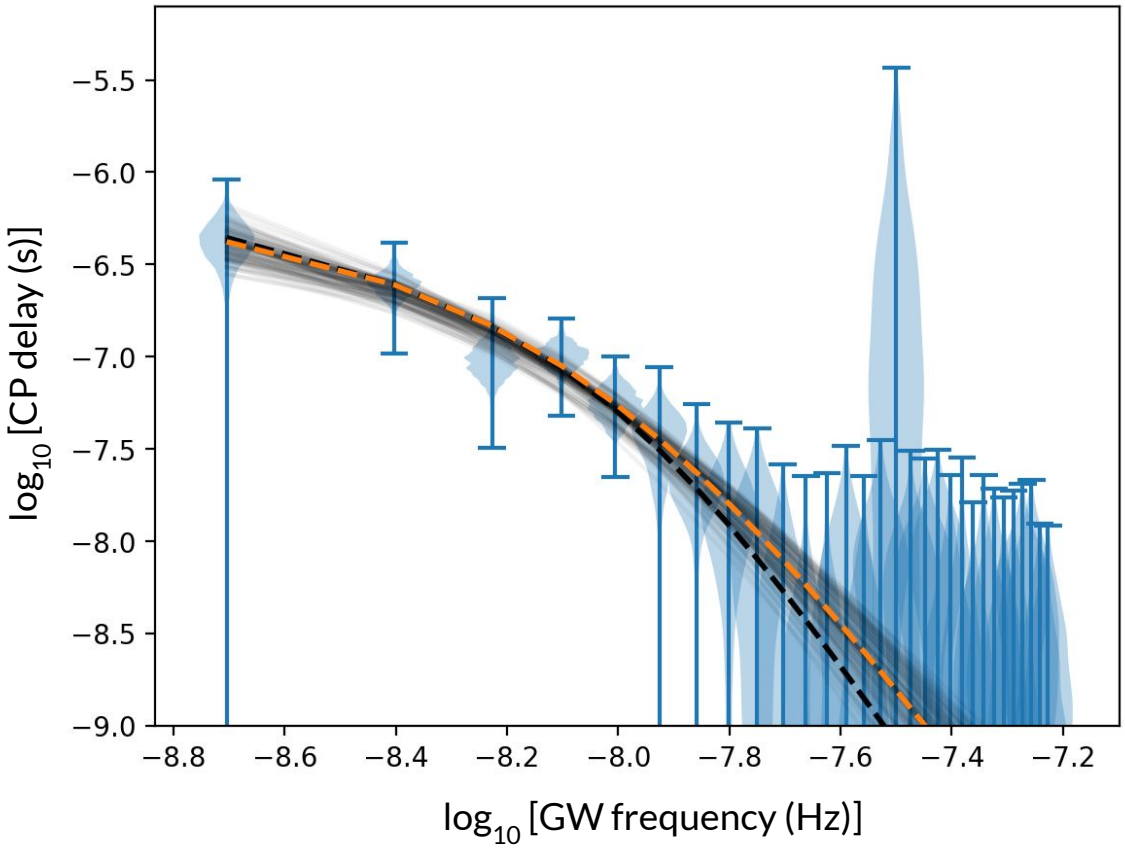
- Injected ‘strong’ broken powerlaw GWB
- 15, 20, 25 yr simulation

Bayes factors - BPL vs PL:

15yr ~ 120

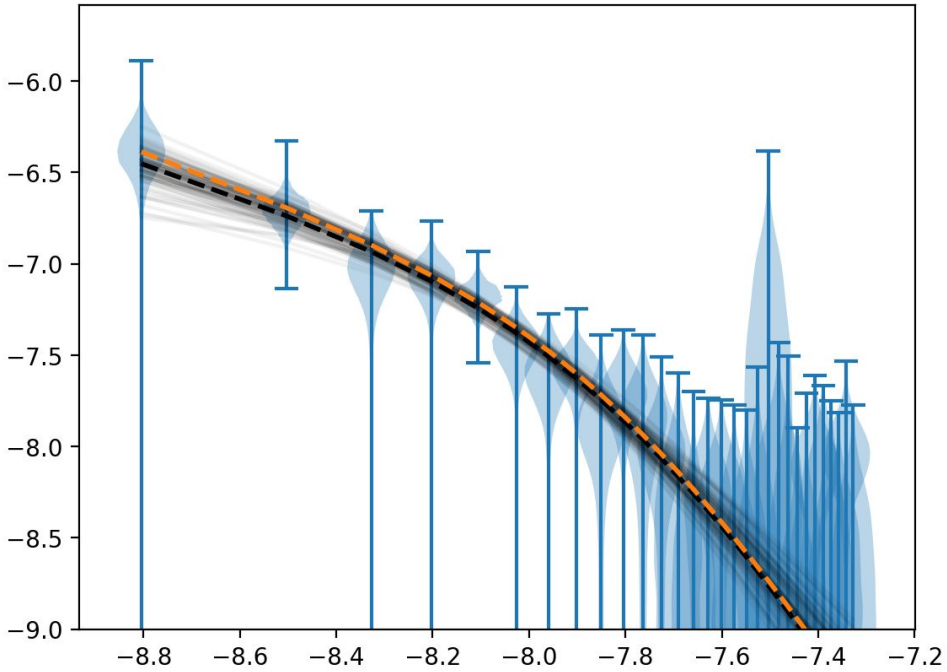
20yr ~ 4

25yr ~ 10^6

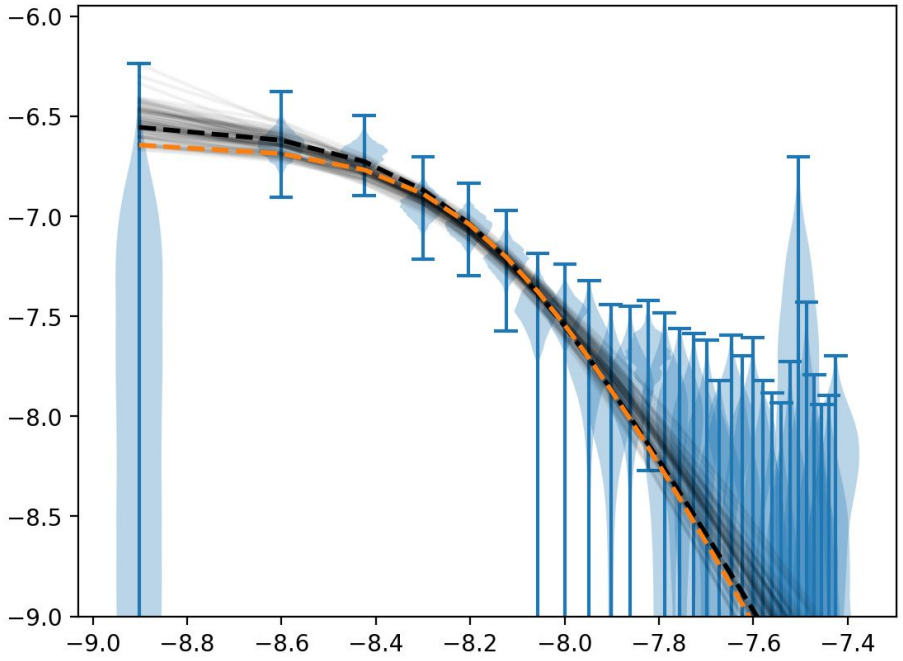


‘cosmo4cast’

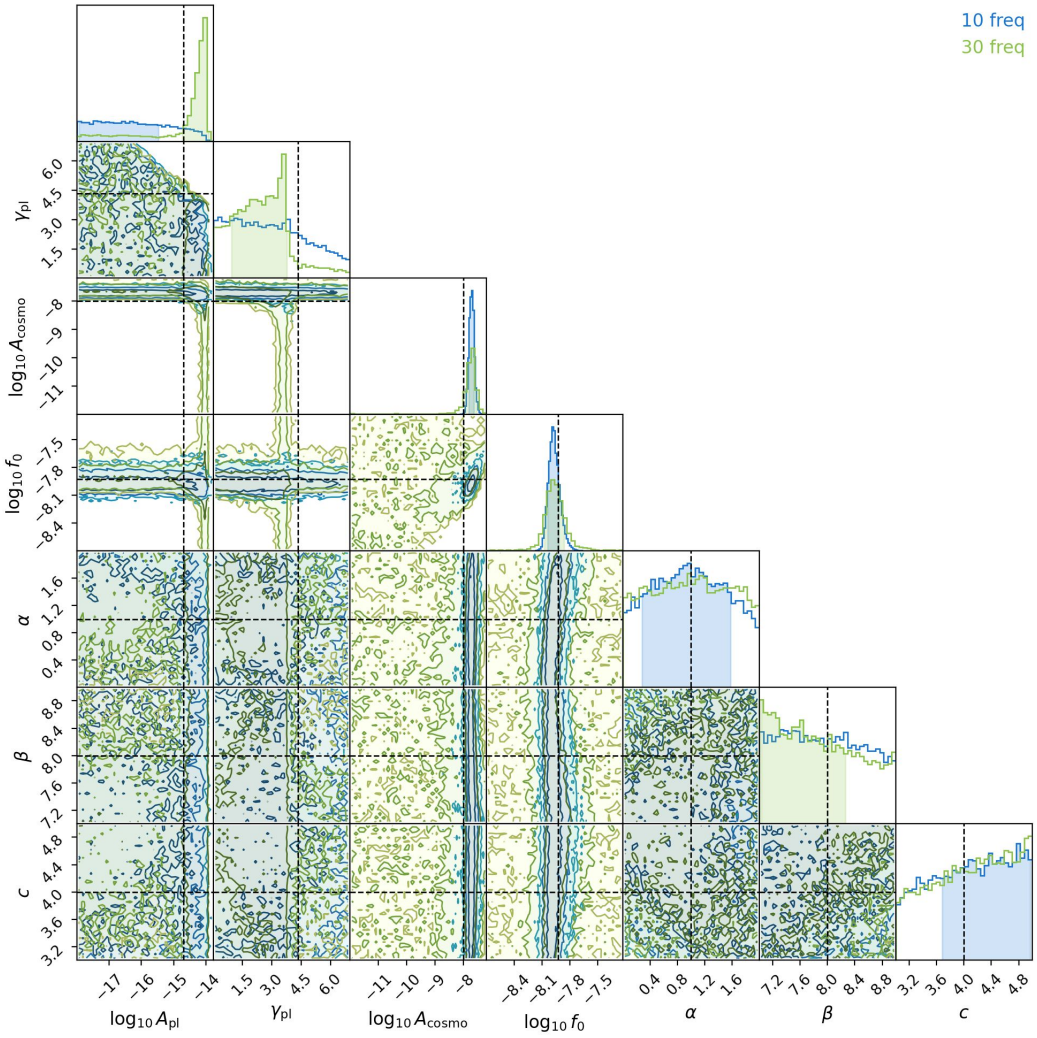
20 yr | BF ~ 4



25 yr | BF ~ 10^6



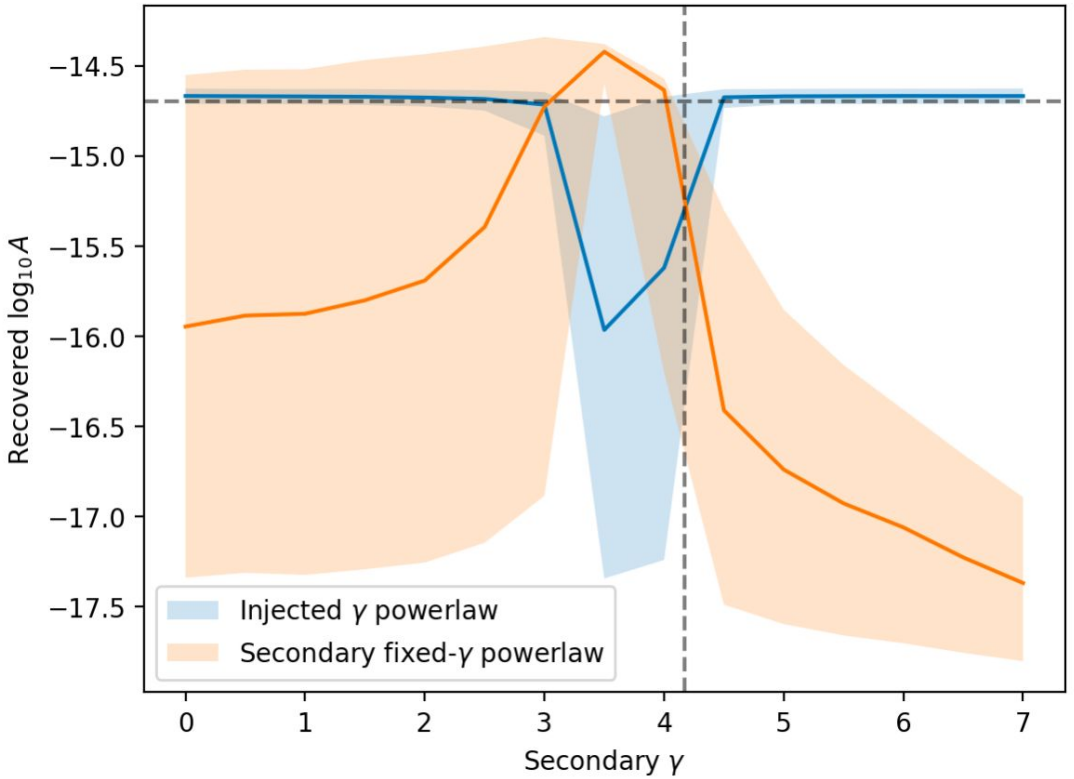
Recovering multiple backgrounds



William Glenn Lamb (william.g.lamb@vanderbilt.edu)

Can we distinguish between multiple backgrounds?

- Simulated data set with 10 frequency GWB, (gamma=4.17, log10A=-14.7)
- Fit 10 frequency powerlaw with fixed gamma=4.17
- Fit 10 frequency powerlaw with fixed gamma between [0, 7]
- Recover amplitude from both



ceffyl refit: arXiv:2303.15442
A. Kaiser et al 2022 ApJ 938 115
G. Boileau et al 2021 PRD 103, 103529

Summary

- Faster GWB spectral characterisation with ***ceffyl***
- Will help determine source of the GWB
- Investigating PTA requirements to distinguish between signals

Next steps

- Develop GFL *(promising results!)*
- Improve PTA noise models
- ***DETERMINE GWB SOURCE***

Thank you!

Refit methods paper

Use ceffyl yourself!

github.com/astrolamb/ceffyl

github.com/andrea-mitridate/PTArcade

Acknowledgements:

- Royal Astronomical Society Travel Award
- Russell G. Hamilton Graduate Leadership Institute Development Award
- NANOGrav Physics Frontier Center, #2020265