Disentangling the Stochastic Gravitational Wave Background with Deep Learning

CosmoFONDUE 2025

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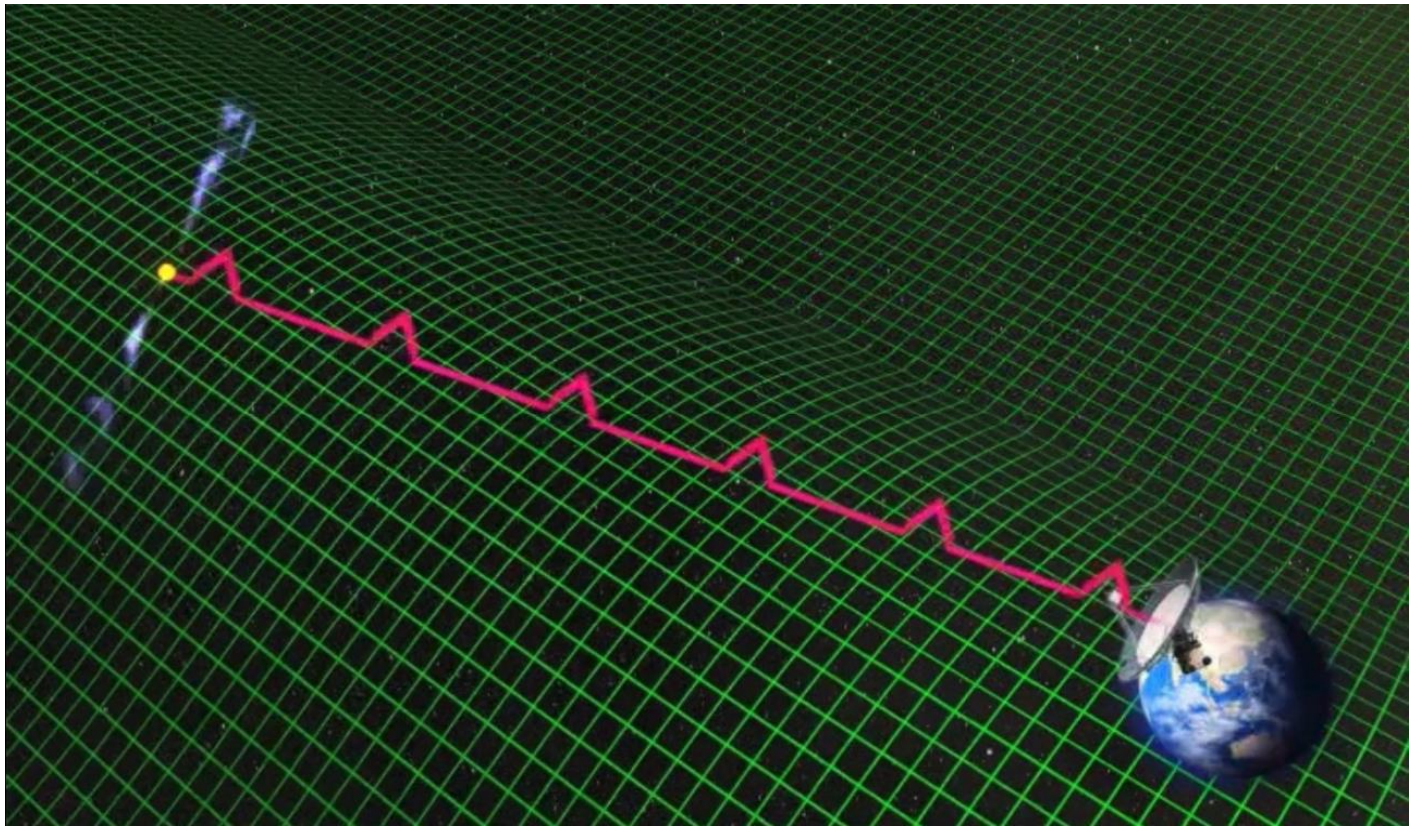
Pulsar Timing Arrays



[J. Rowe Animations]

The Astrophysical SGWB

- Total present day GW energy density distributed over redshift *[Phinney, E.S. 2001]*

$$\rho_c \, \Omega_{\rm GW}(f_d) = \int_0^\infty dz \frac{N(z)}{1+z} \left(f_s \frac{d\mathcal{E}^{(s)}_{GW}}{df_s} \right)_{f_s = (1+z) f_d}$$

- E.g. consider binaries in circular orbit:

$$f_s \frac{d\mathcal{E}_{\rm GW}}{df_s} = f_s \frac{\pi}{3 G_N} \frac{(G_N \mathcal{M})^{5/3}}{(\pi f_s)^{1/3}}$$

In reality this varies!

$$\Omega_{\rm GW}(f_d) \propto f_d^{2/3}$$

The Cosmological SGWB

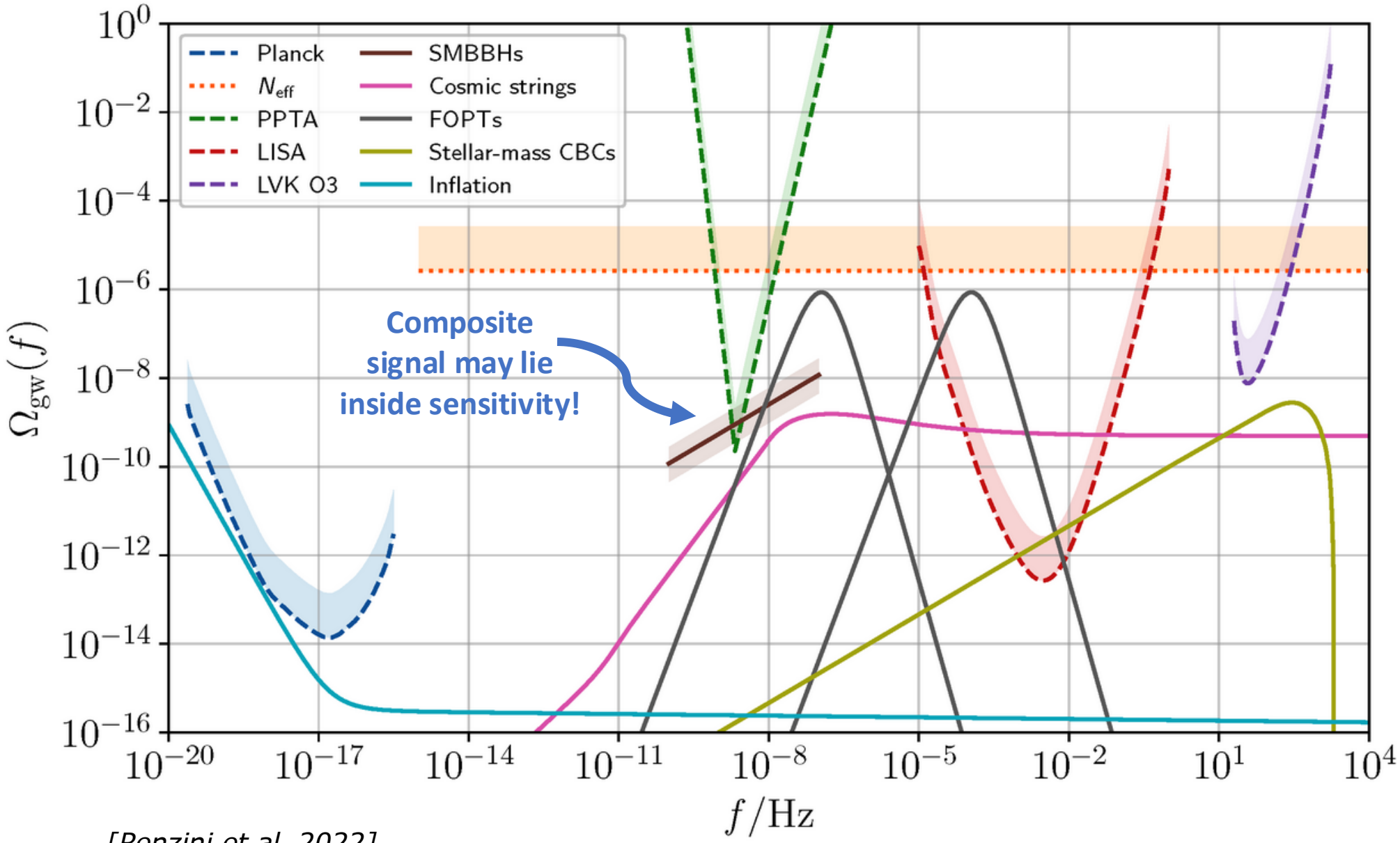
- Abundance of models

- We focus on a simple power-law profile for proof of concept

$$\Omega_{\mathrm{GW}}(f) = \mathcal{A}\left(\frac{f}{f_*}\right)^{\alpha}$$

- However our framework is readily extendible to any model

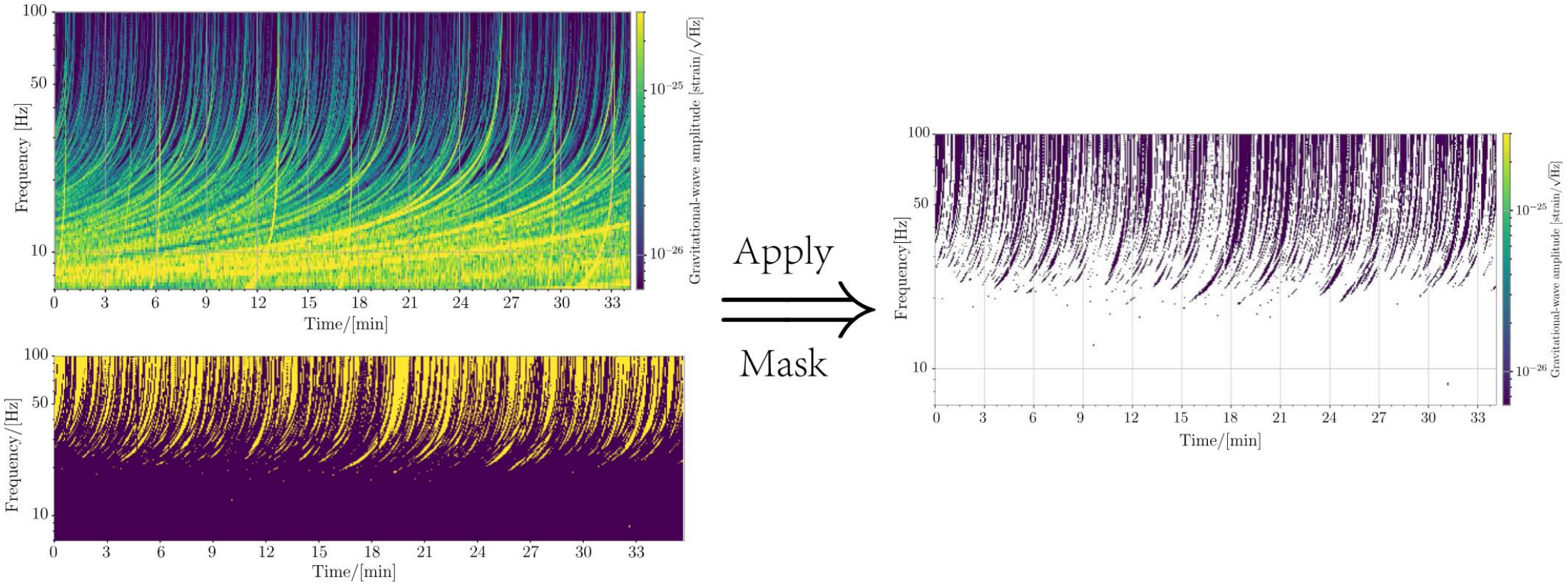
But what if there are multiple sources contributing to the SGWB?



[Renzini et al. 2022]

Current methods

- Efforts made in interferometer experiments to reduce astrophysical foreground to identify cosmological background *[Zhong et al. 2024]*

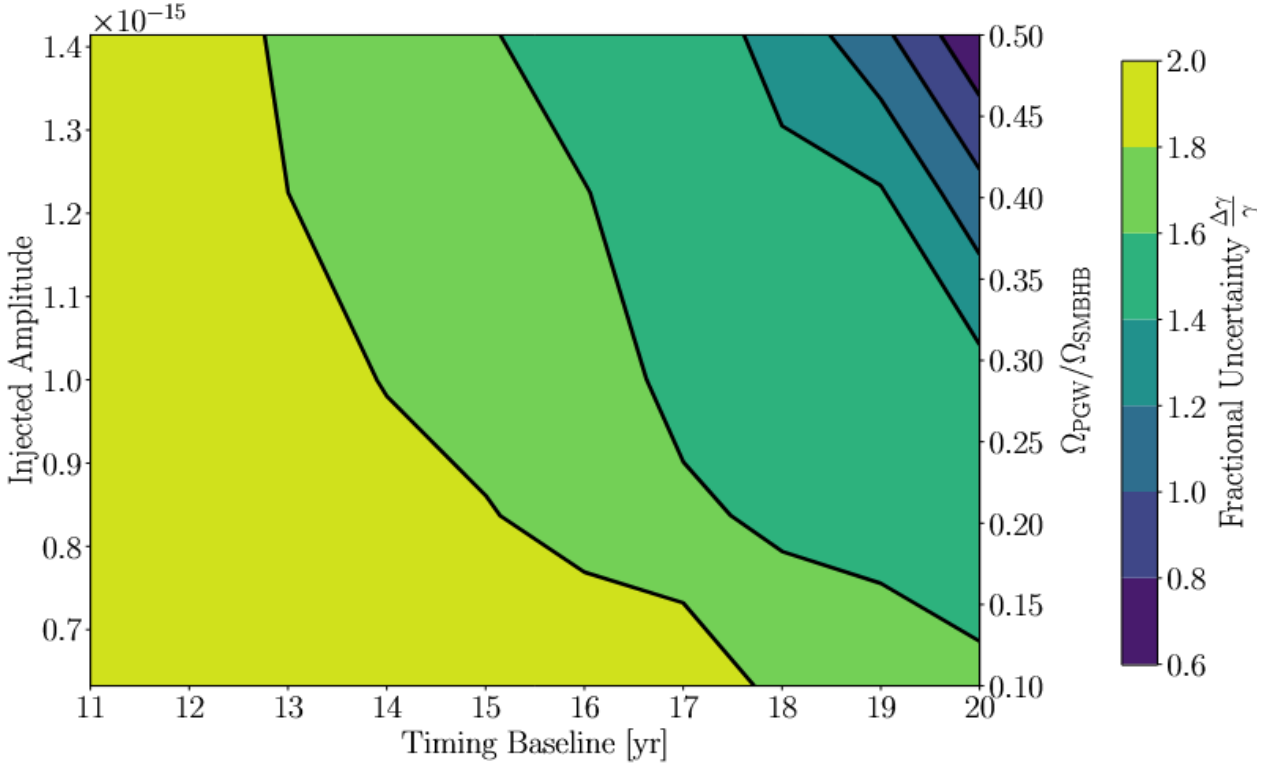


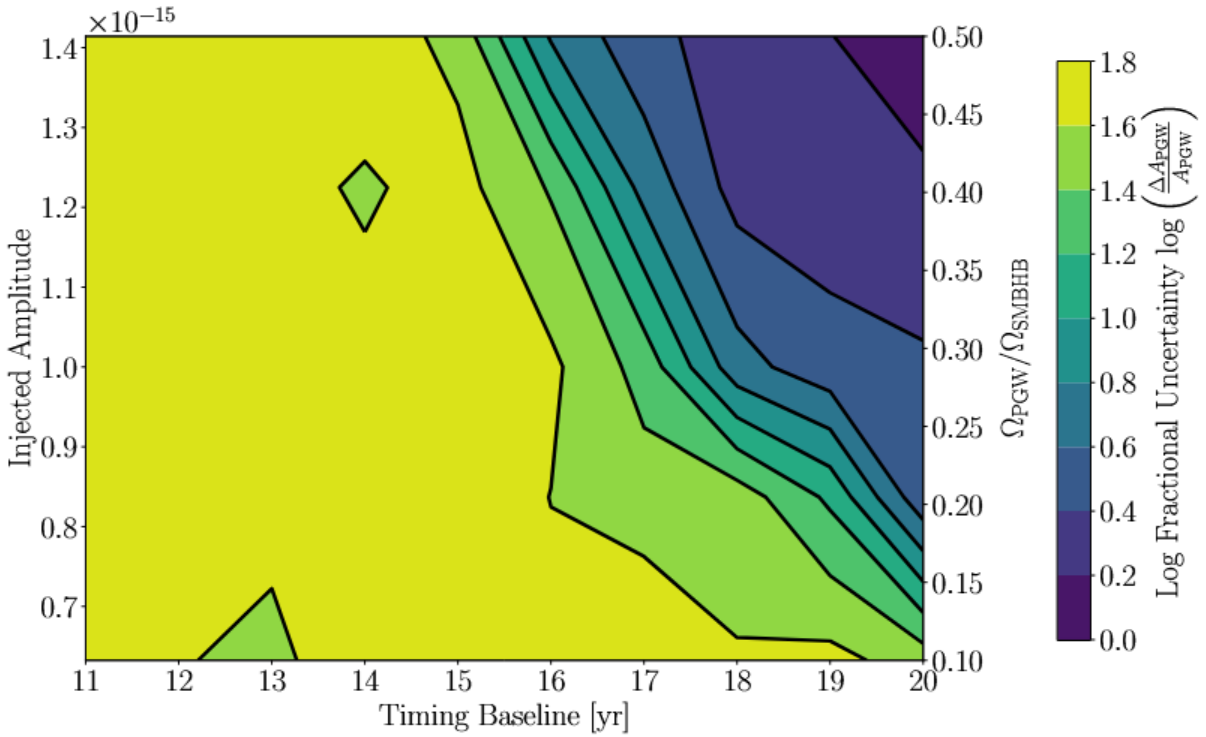
- For PTAs, usual Bayesian analysis struggles to make progress.

Current methods

Uncertainties in spectral index and amplitude of an additional primordial process on top of Astrophysical background

[Kaiser et al. 2022]





What can we learn?

- Improved cosmological and astrophysical parameter bounds
- Relatively inexpensive tests
- Holy Grail: Evidence for a cosmological source of the SGWB?

Is there a way to go beyond traditional Bayesian analysis?

Deep Learning

- Compute has become orders of magnitude cheaper/faster
- Intractable problems from 5 years ago are now cheap to solve!
- Primary goal is to bring recent advancements with structured pipelines to make the toolsets available to physicists

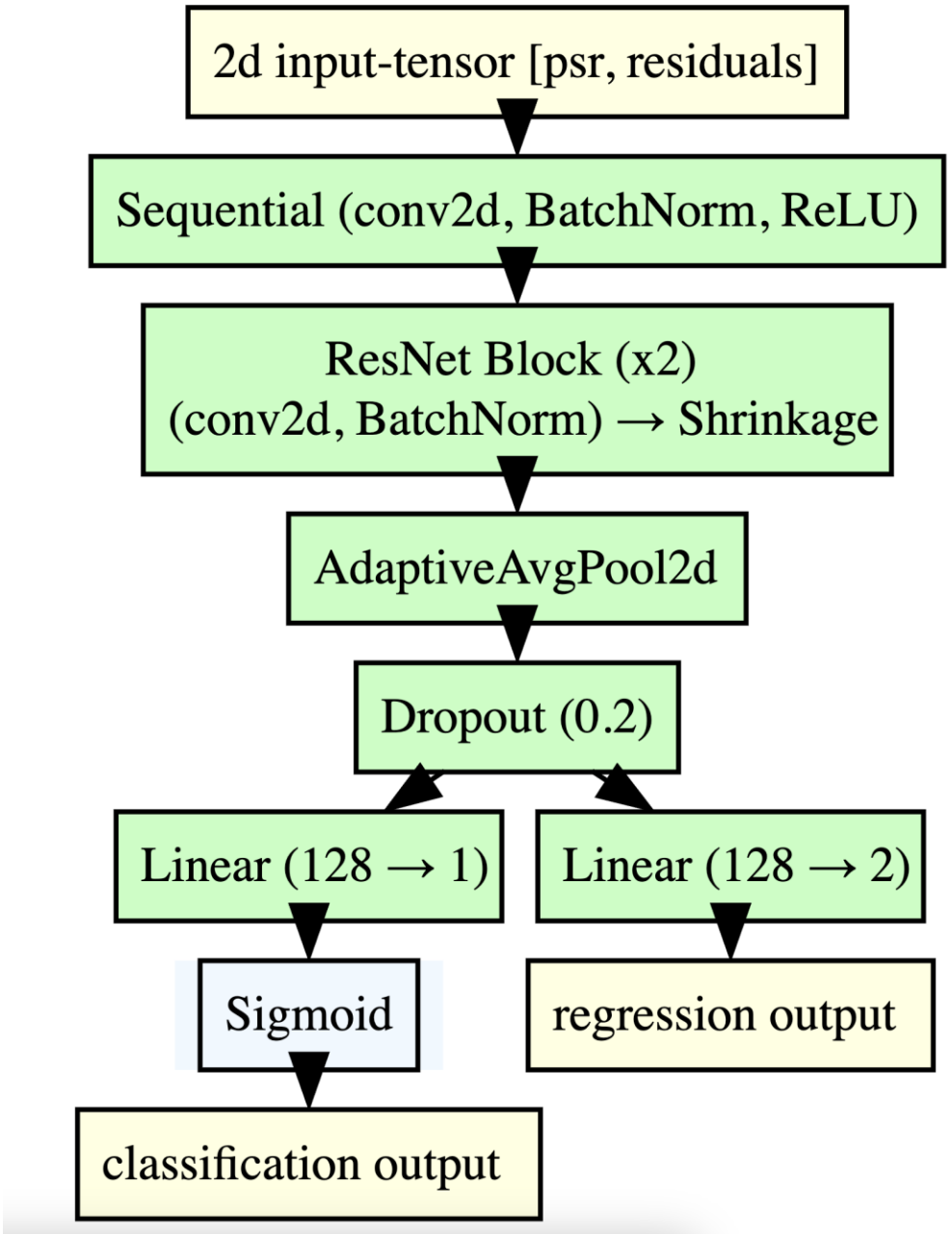
Why Deep Learning?

- Can extract patterns without needing overspecified priors

- The beauty of this methodology is that **all you need is the data!**

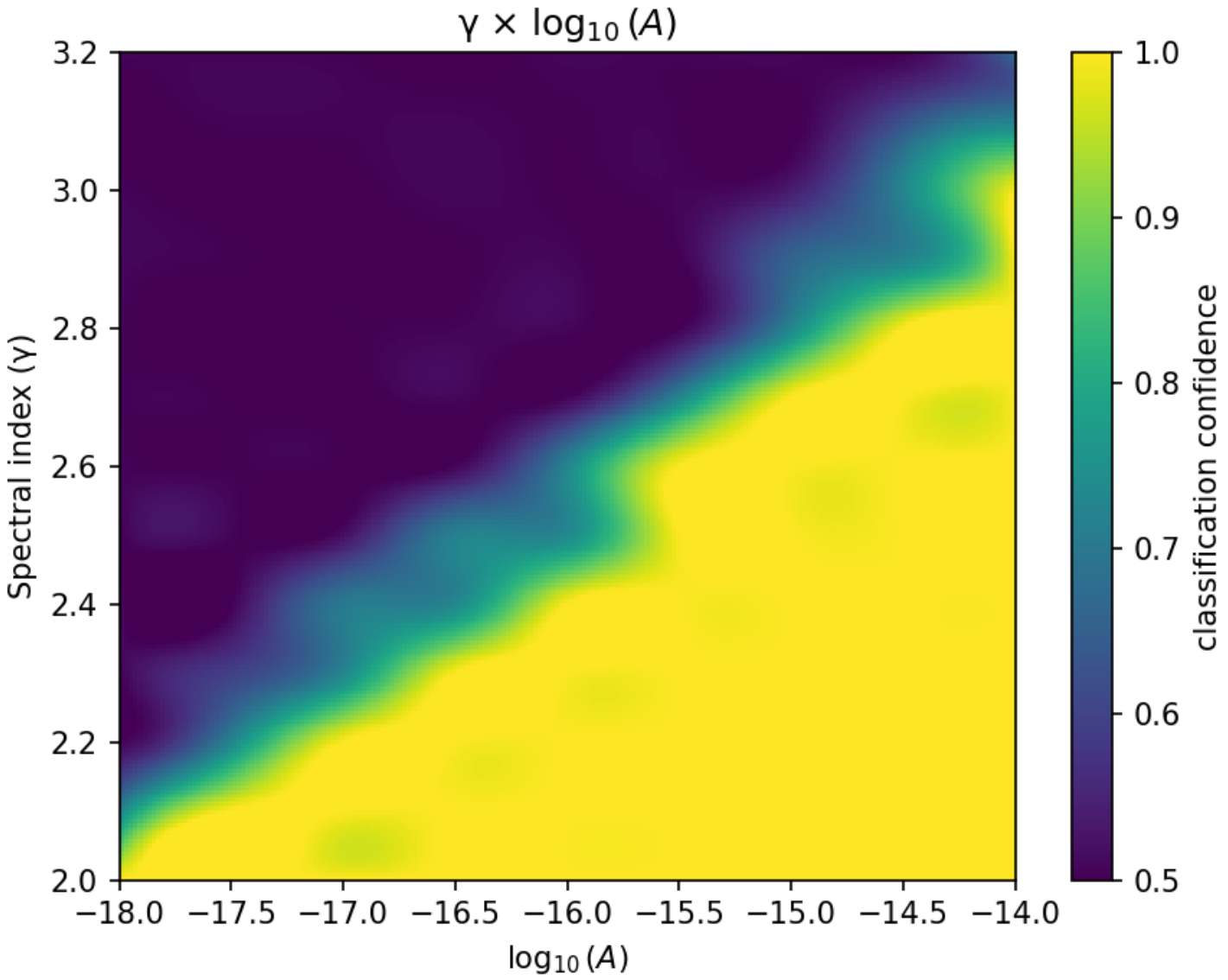
(The CNN does not need to be physics informed)

- We use a 2D Convolutional Neural Network to classify and perform parameter estimation on the matrix of timing residuals for a *synthetic dataset*



- Chosen because SGWB leaves a feint but global fingerprint across all pulsars
- Noise however is mostly local!
- Network specializes for cross-pulsar features

Classification confidence

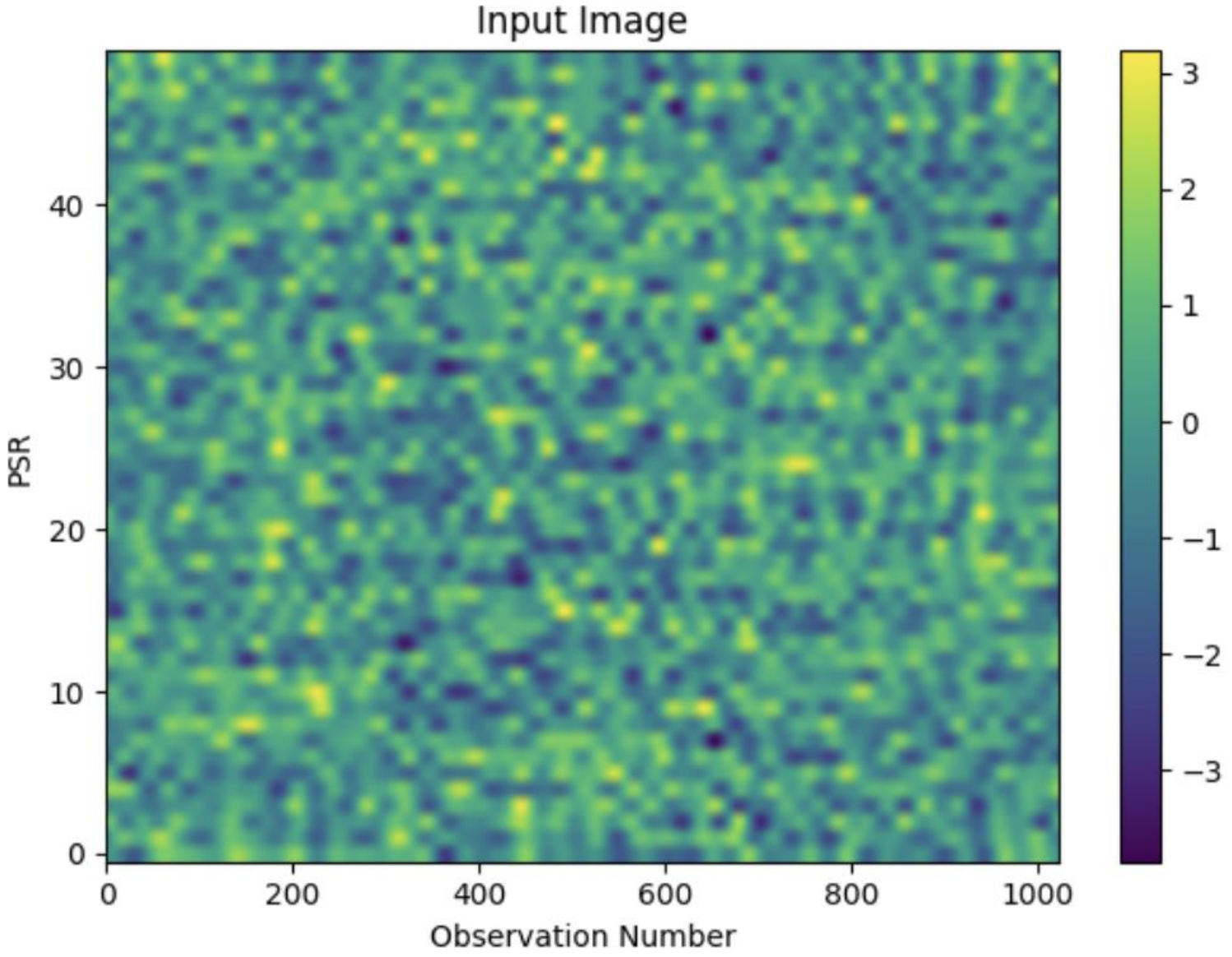


Interpretability

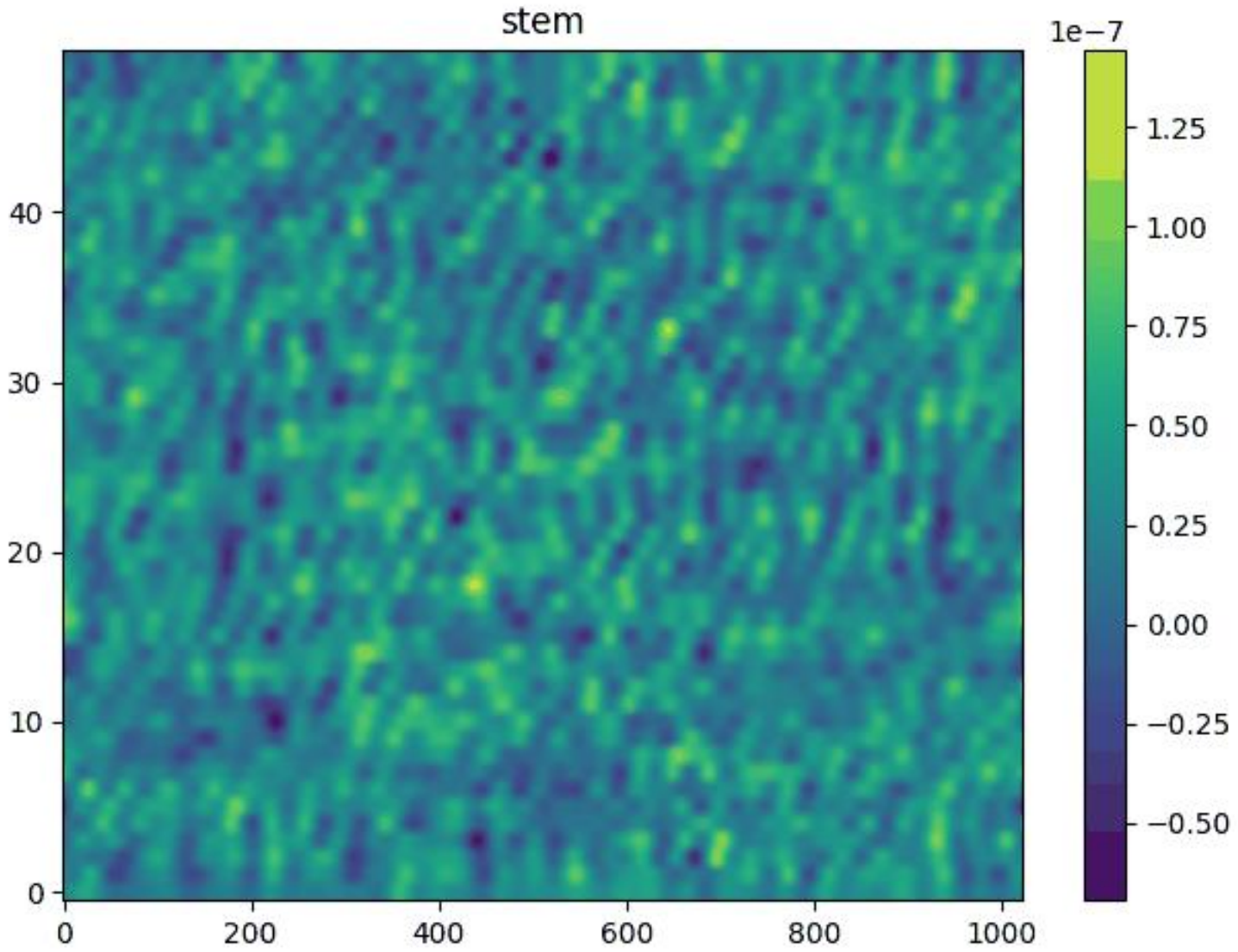
The myth that neural networks are black boxes is no longer true!

- Several interpretability methodology can now be leveraged e.g.
- Integrated gradients, Layer Grad CAM, UMAP, Autoencoders etc.

Interpretability



Interpretability



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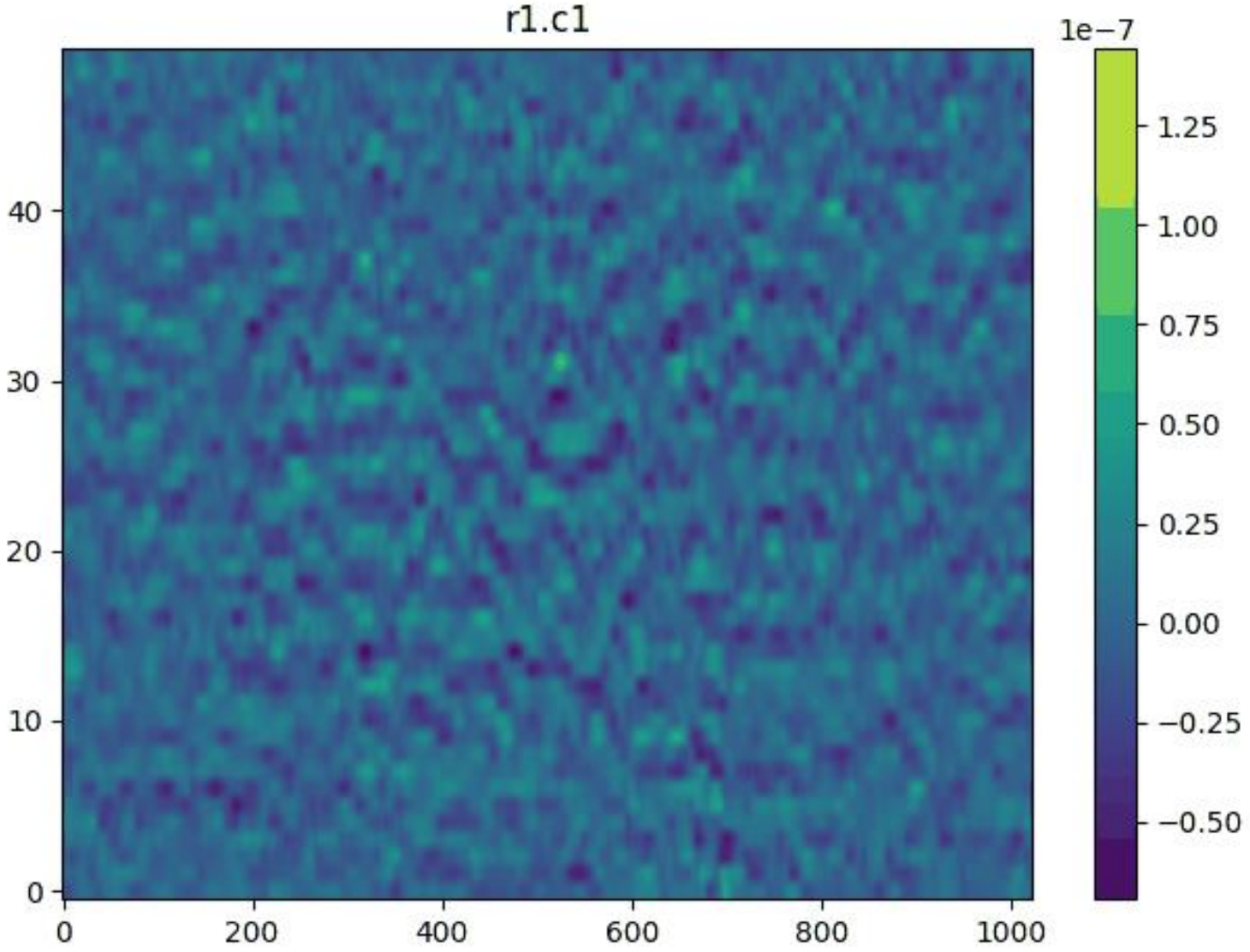

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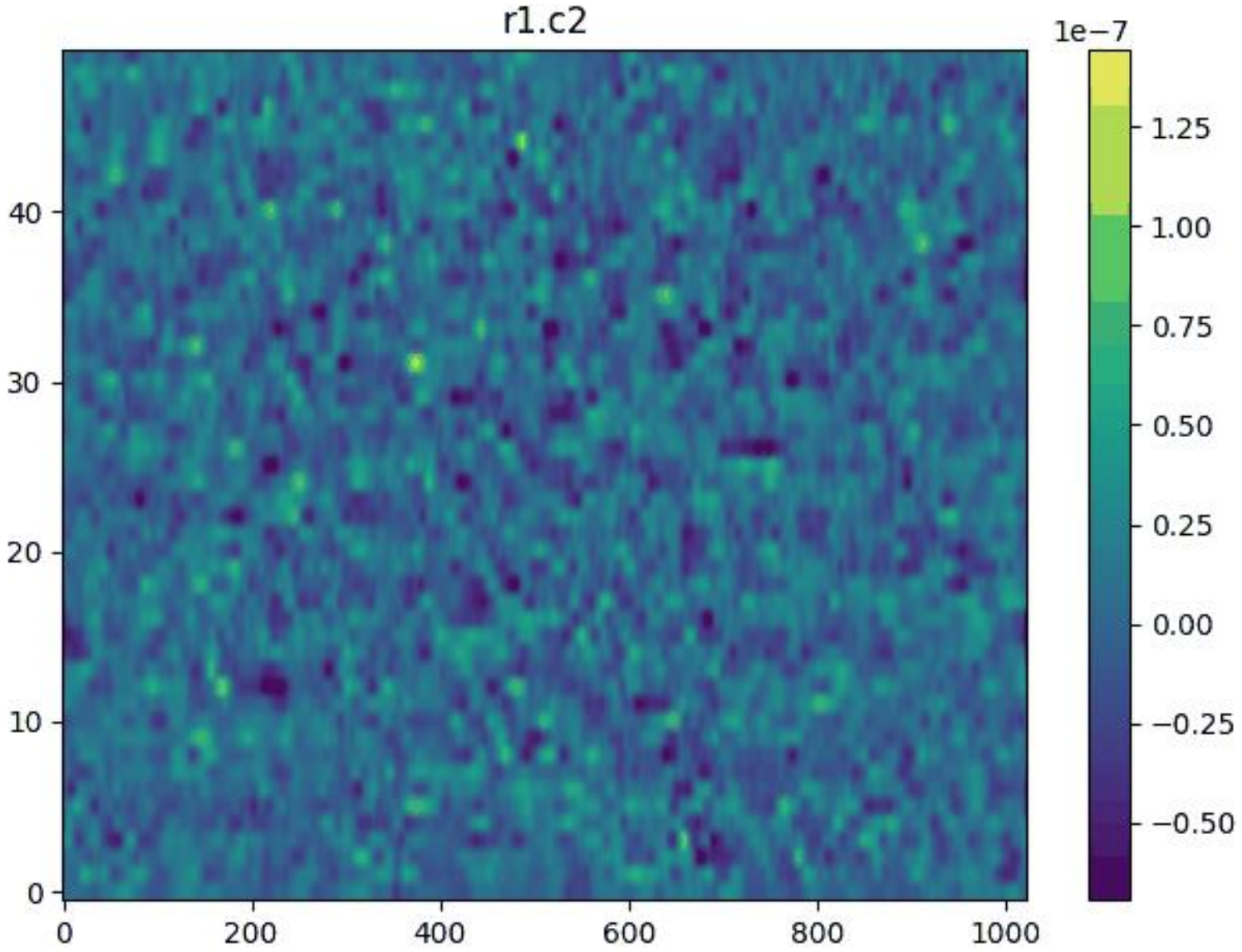

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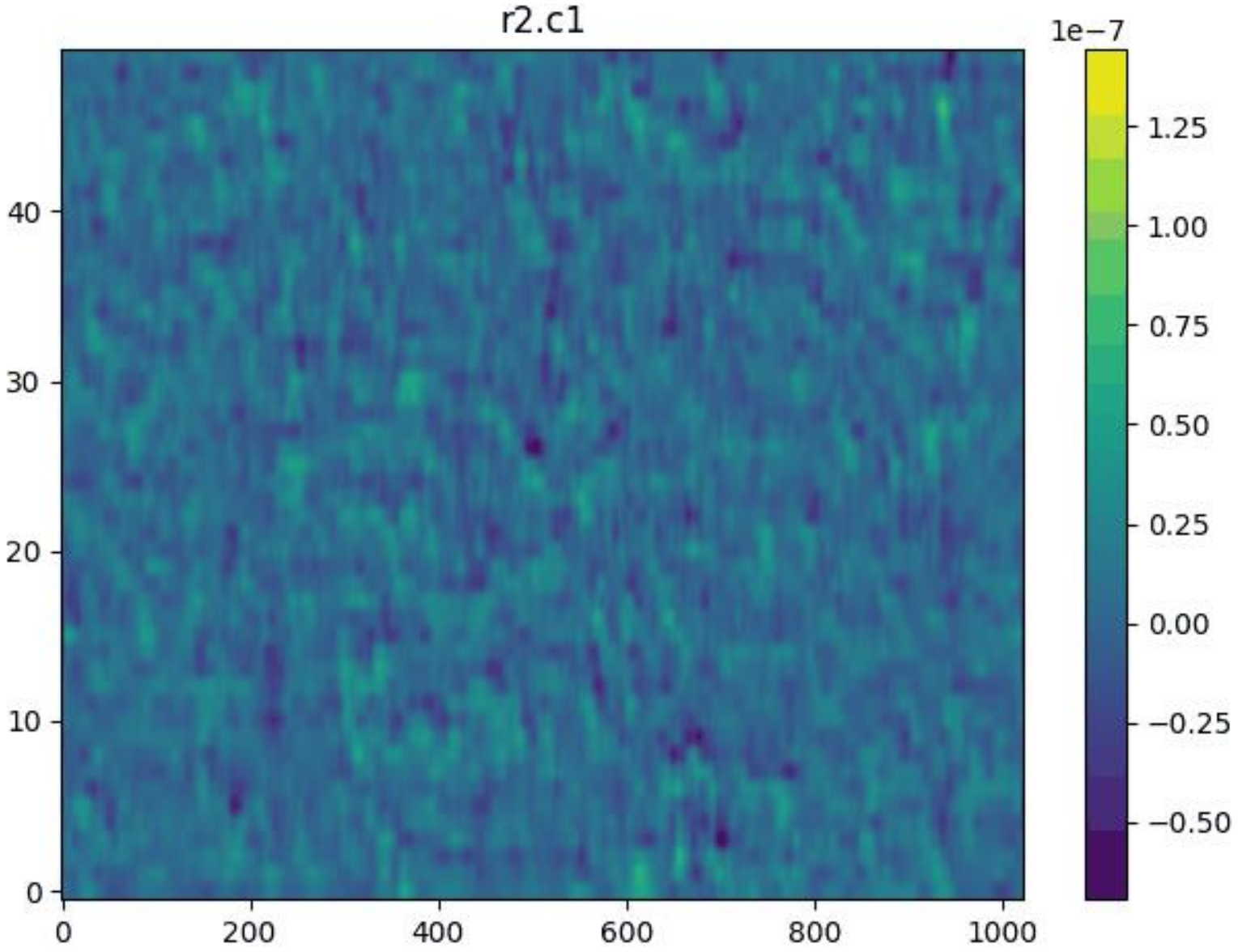

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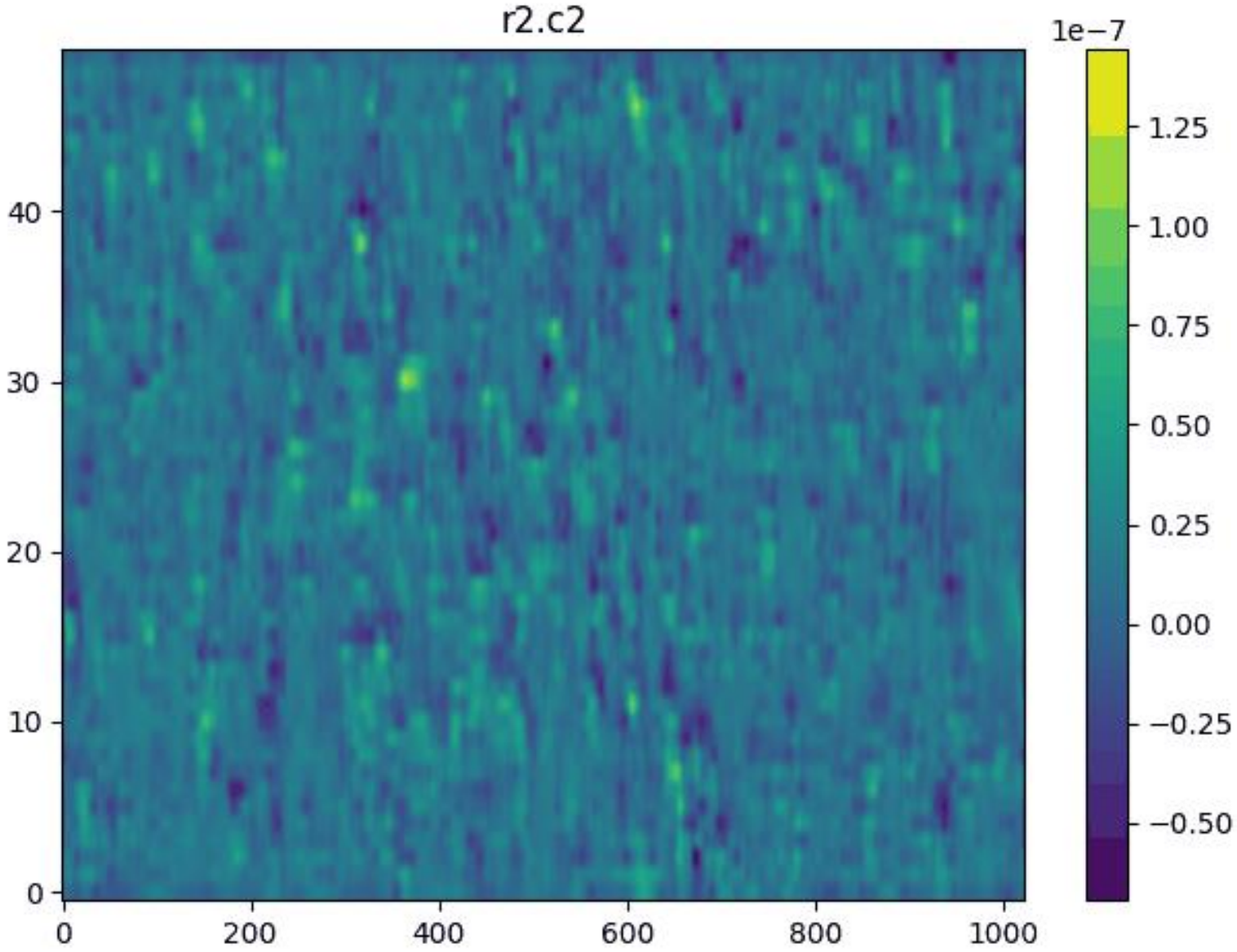

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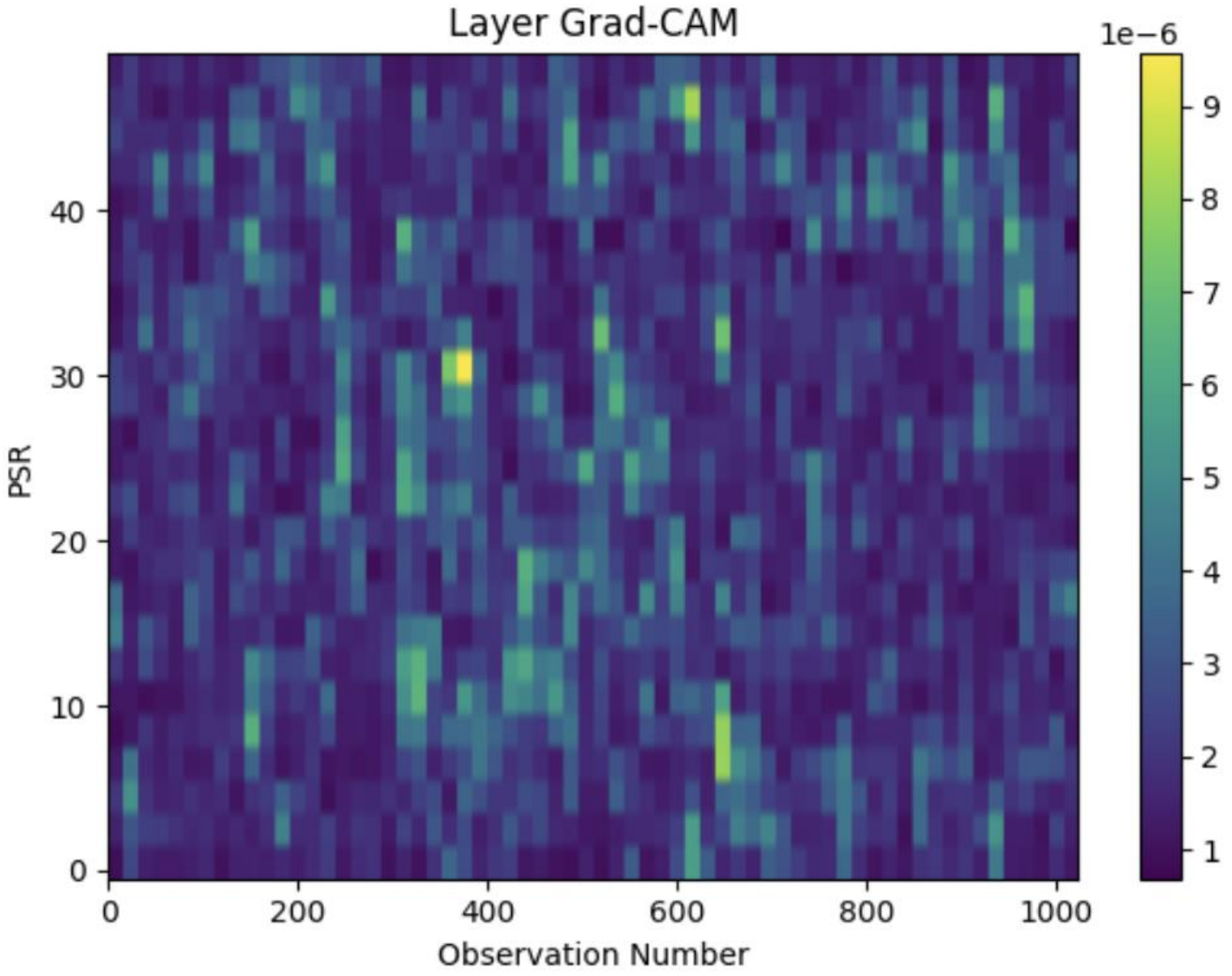

Coming Soon...

- The paper!
- Improvements on current synthetic data generation models in PTAs
- An open-source ML pipeline for Cosmological model classification and parameter estimation in PTAs

Thank you for listening!