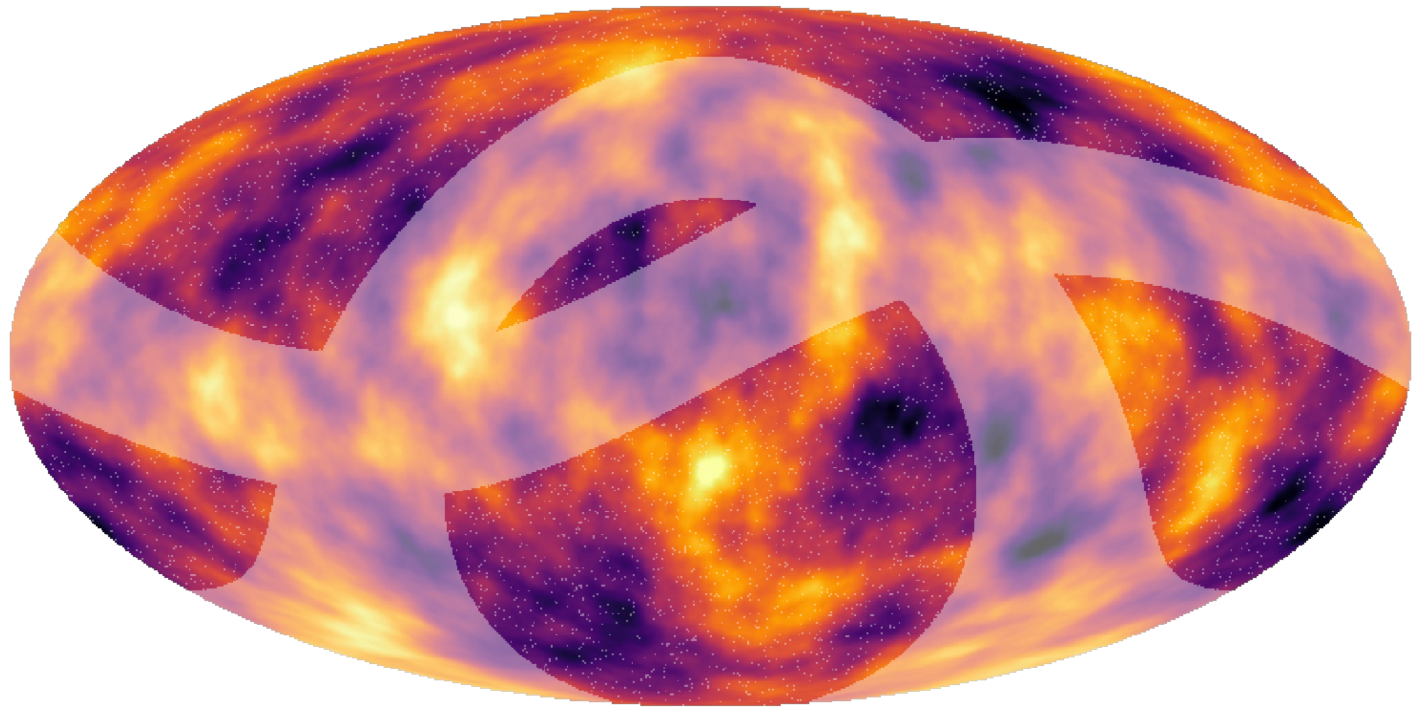
Sellentin,
Loureiro et. al, 2023

Loureiro et. al, 2023



Almanac

Field Level Inference of Full-Sky Cosmological Fields and Angular Power Spectra

Dr. Arthur Loureiro @ Statistical Challenges in 21st Century Cosmology
(Oskar Klein Centre, Stockholm University & Imperial College London)

The Almanac Team

Oskar Klein centre

ICIC Imperial Centre for Inference & Cosmology

Universiteit Leiden

UCL

Dr Arthur Loureiro
(Also visiting researcher at ICIC)

Prof. Alan Heavens

Prof. Elena Sellentin

Dr. Lorne Whiteway

Prof. Andrew Jaffe

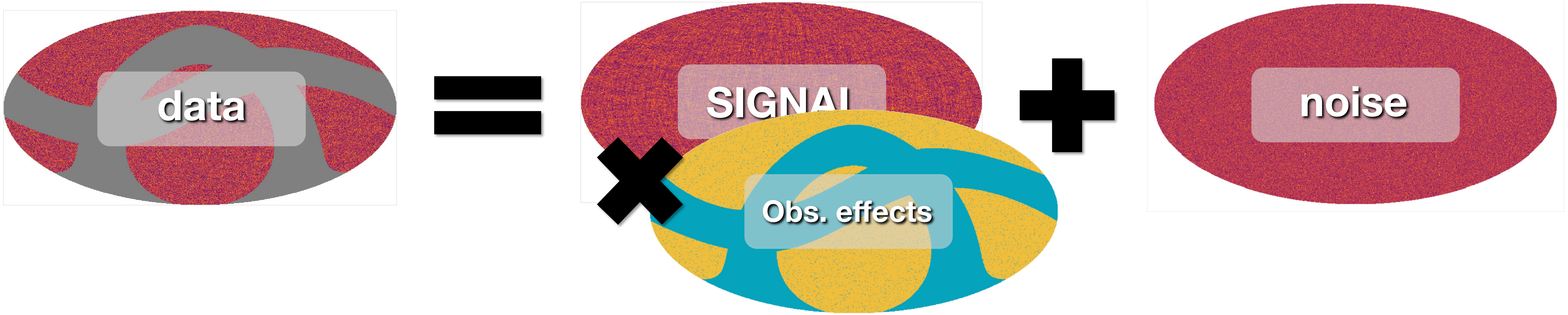
Javier S. Lafaurie

Kutay Nazli

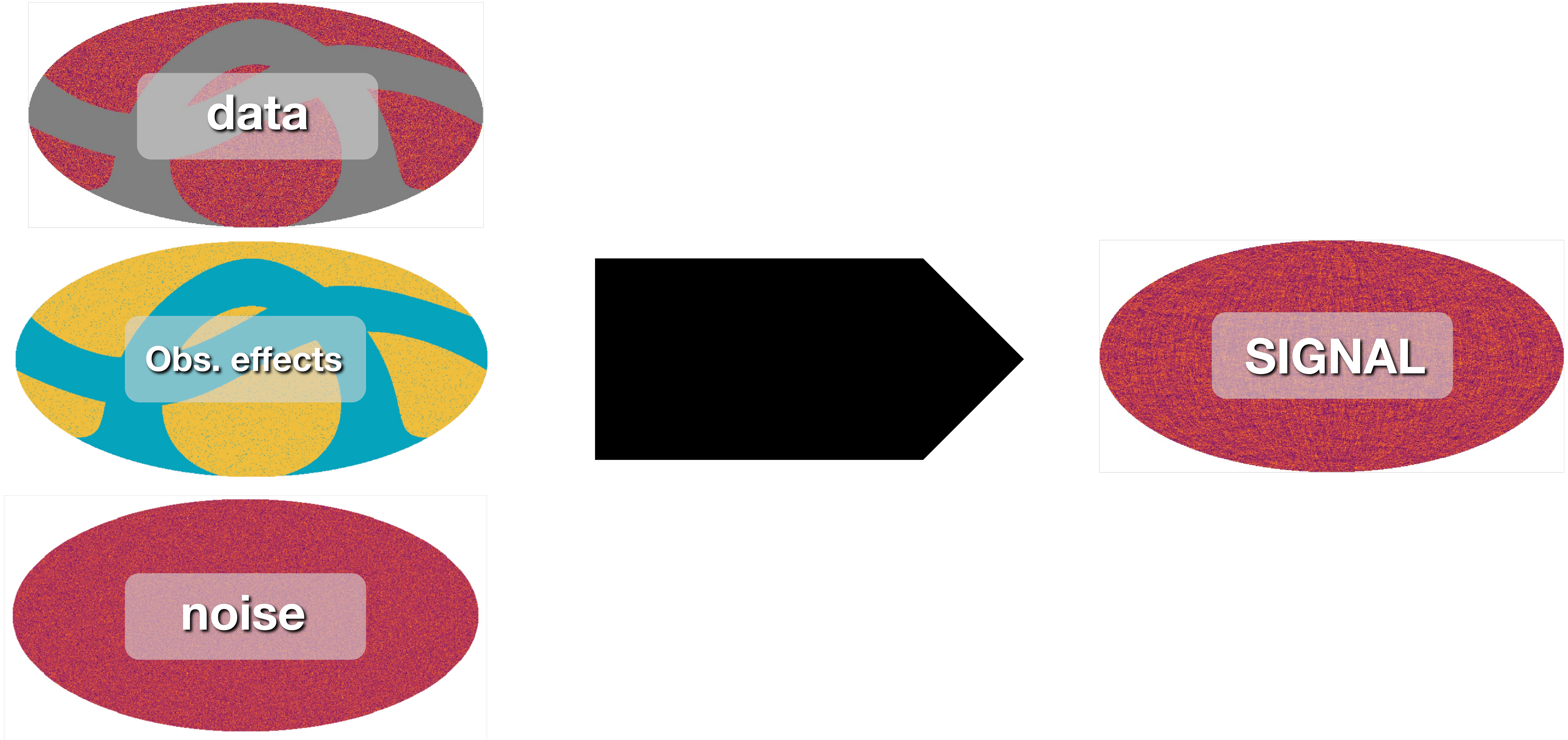
Almanac uses a highly optimised sampler to obtain full-sky, model-independent, de-noised samples for maps of cosmological fields and their angular power spectra.

Real data is incomplete and noisy

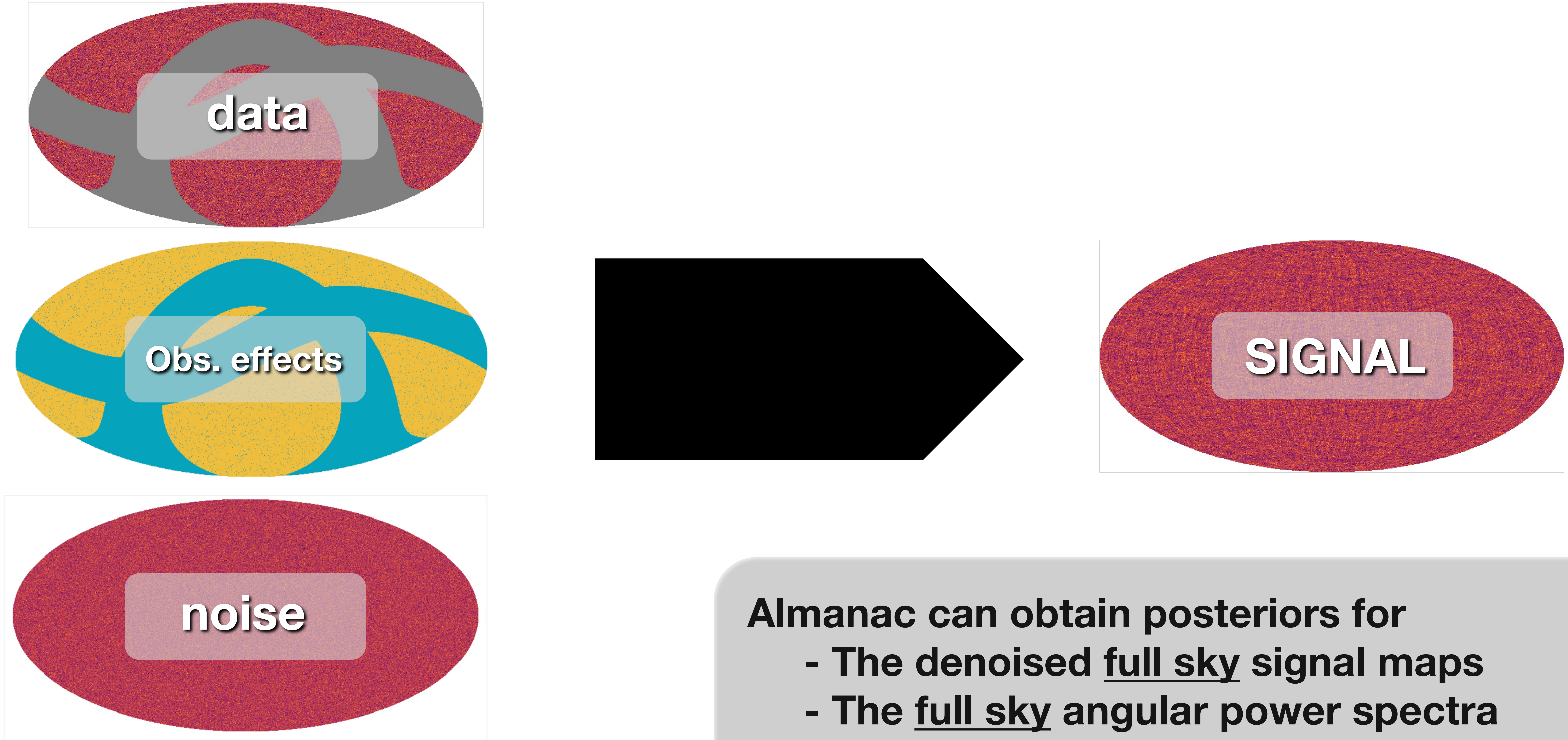
The signal we are interested is affected



Real data is incomplete and noisy



Real data is incomplete and noisy



Almanac can obtain posteriors for
- **The denoised full sky signal maps**
- **The full sky angular power spectra**

In a model-independent and unbiased way!

Almanac

Spin-0 and Spin-2 Cosmological Fields

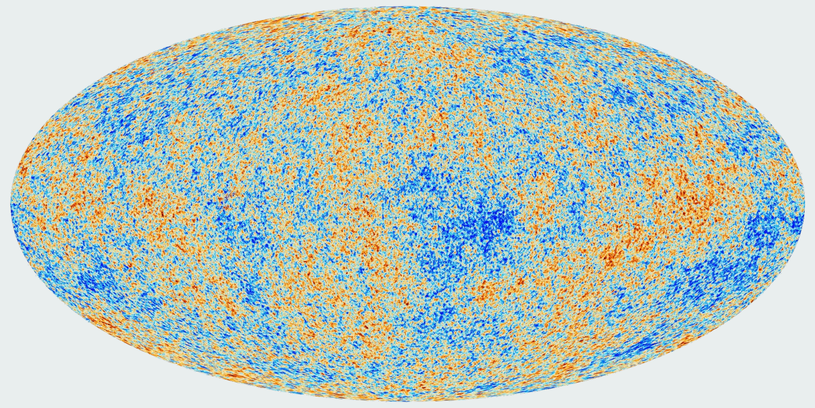
An arbitrary spin-s field can be represented in the basis of spin-s spherical harmonics

$$f(\hat{n}) = \sum_{\ell m} f_{\ell m} \; {}_sY_{\ell m}(\hat{n})$$

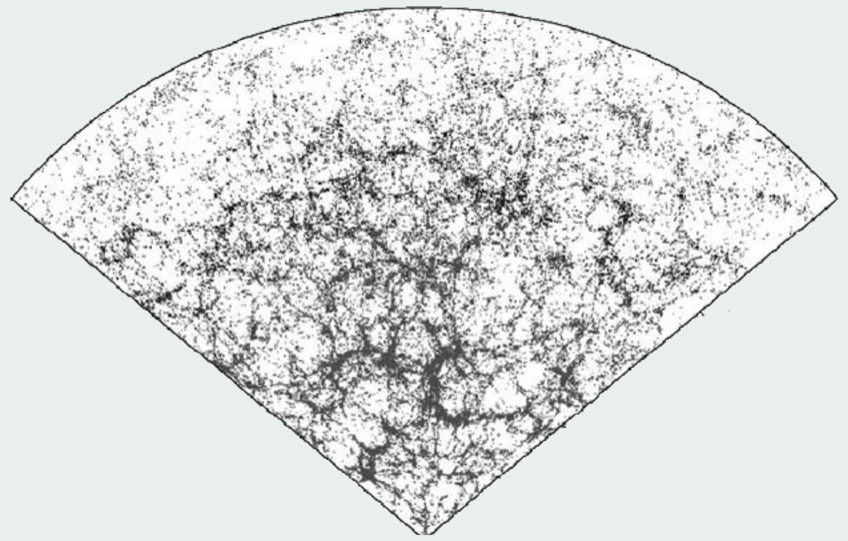
And covariance

$$\mathsf{C} \equiv \langle f_{\ell m} f^*_{\ell' m'} \rangle \delta_{\ell \ell'} \delta_{m m'}$$

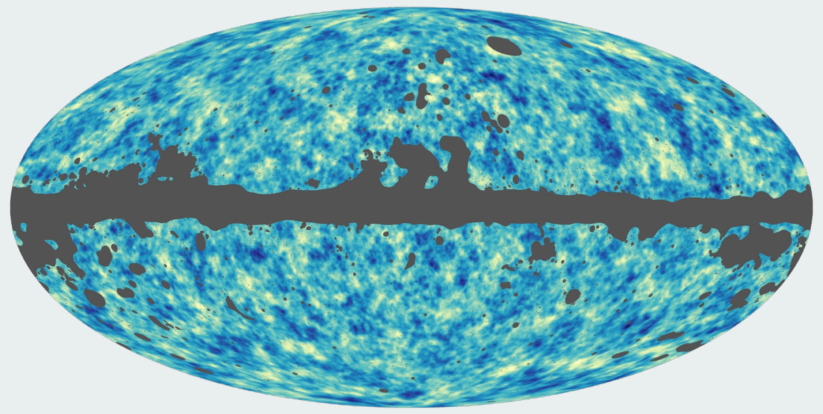
Spin-0 Fields



CMB Temperature

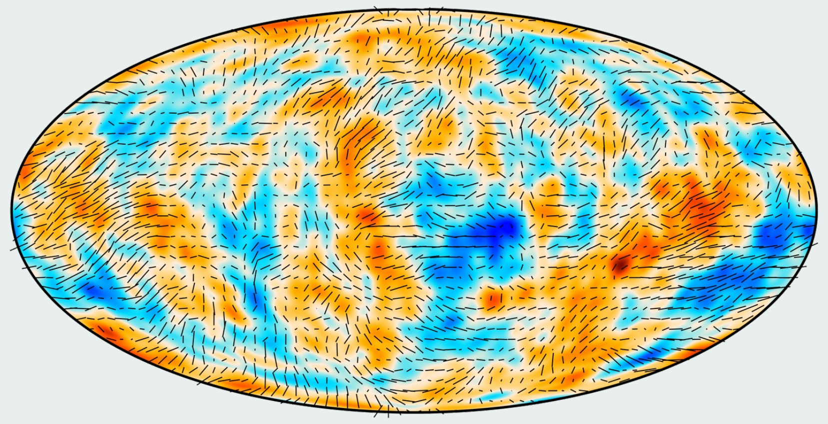


Galaxy Clustering

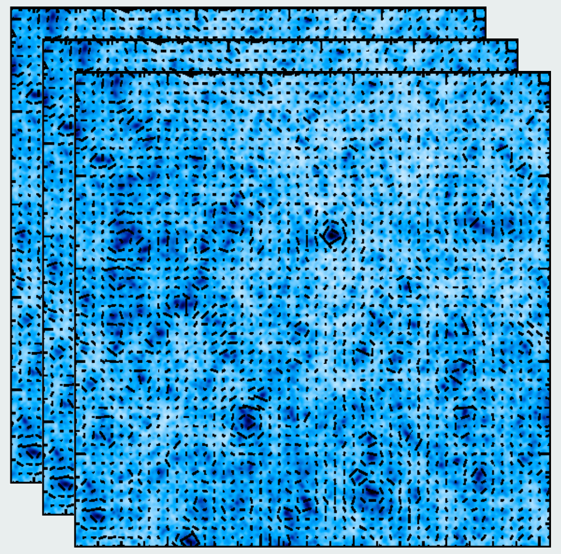


Lensing Convergence

Spin-2 Fields



CMB Polarisation

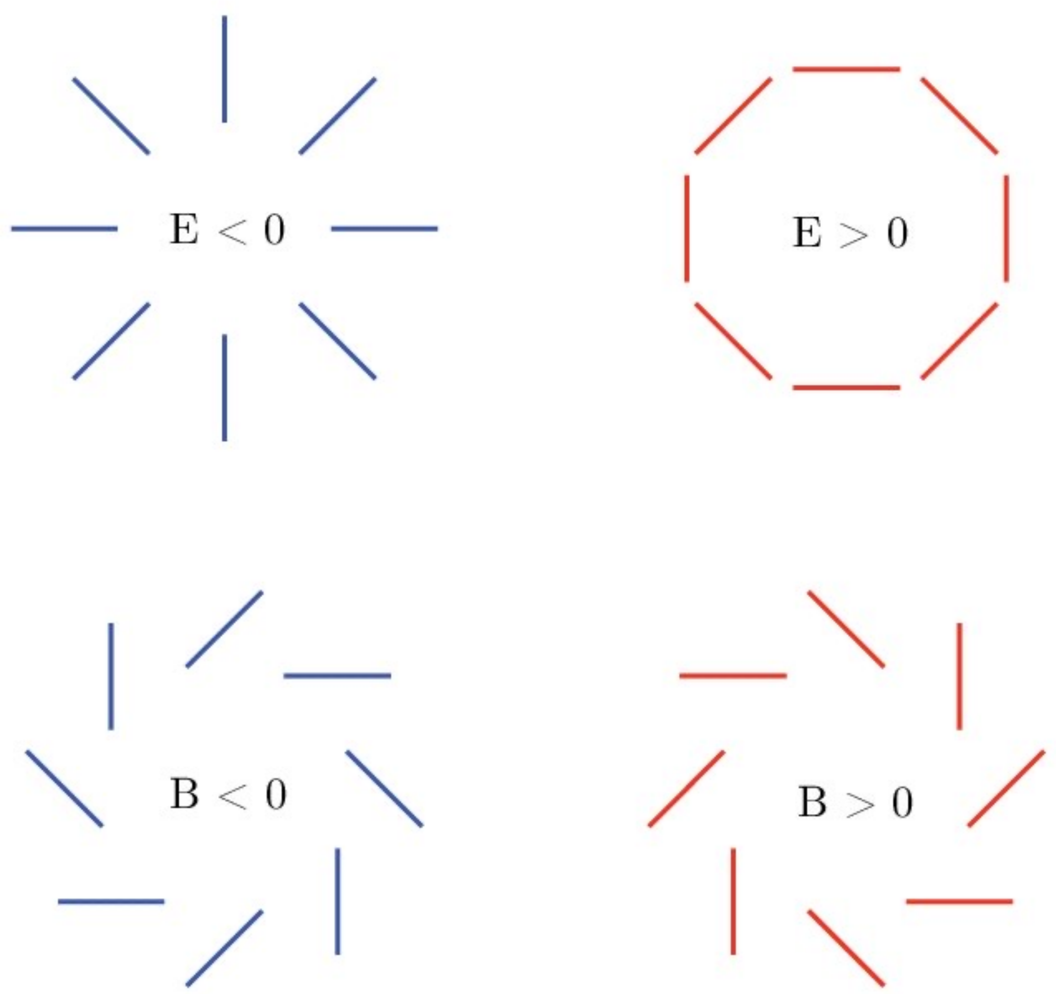


Cosmic Shear

Figures from Planck Collaboration, SDSS Collaboration & S. Pires et al. 2010

Spin-2 Data

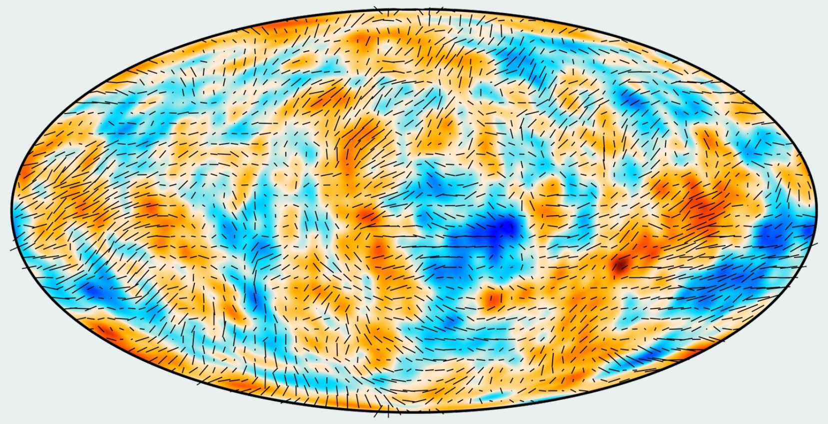
Ambiguous modes due to masking of the data



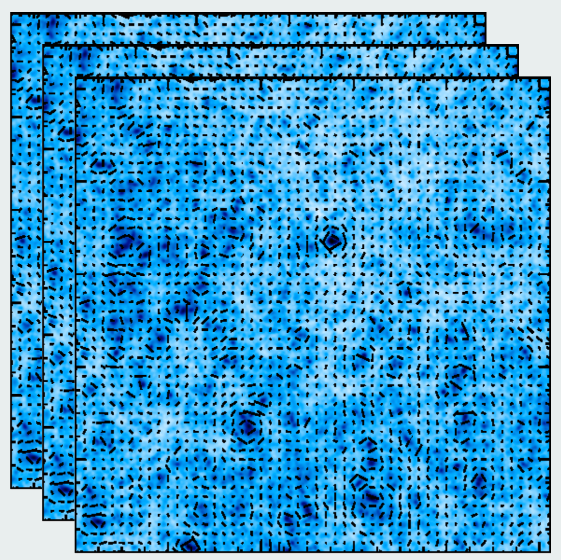
$$\tilde{E}_{\ell m} = \sum_{\ell' m'} (E_{\ell' m'} W^{+}_{\ell \ell' m m'} + B_{\ell' m'} W^{-}_{\ell \ell' m m'})$$
$$\tilde{B}_{\ell m} = \sum_{\ell' m'} (B_{\ell' m'} W^{+}_{\ell \ell' m m'} - E_{\ell' m'} W^{-}_{\ell \ell' m m'}),$$

Lewis, Challinor & Turok, 2002

Spin-2 Fields



CMB Polarisation



Cosmic Shear

+

Figures from Planck Collaboration, SDSS Collaboration & S. Pires et al. 2010

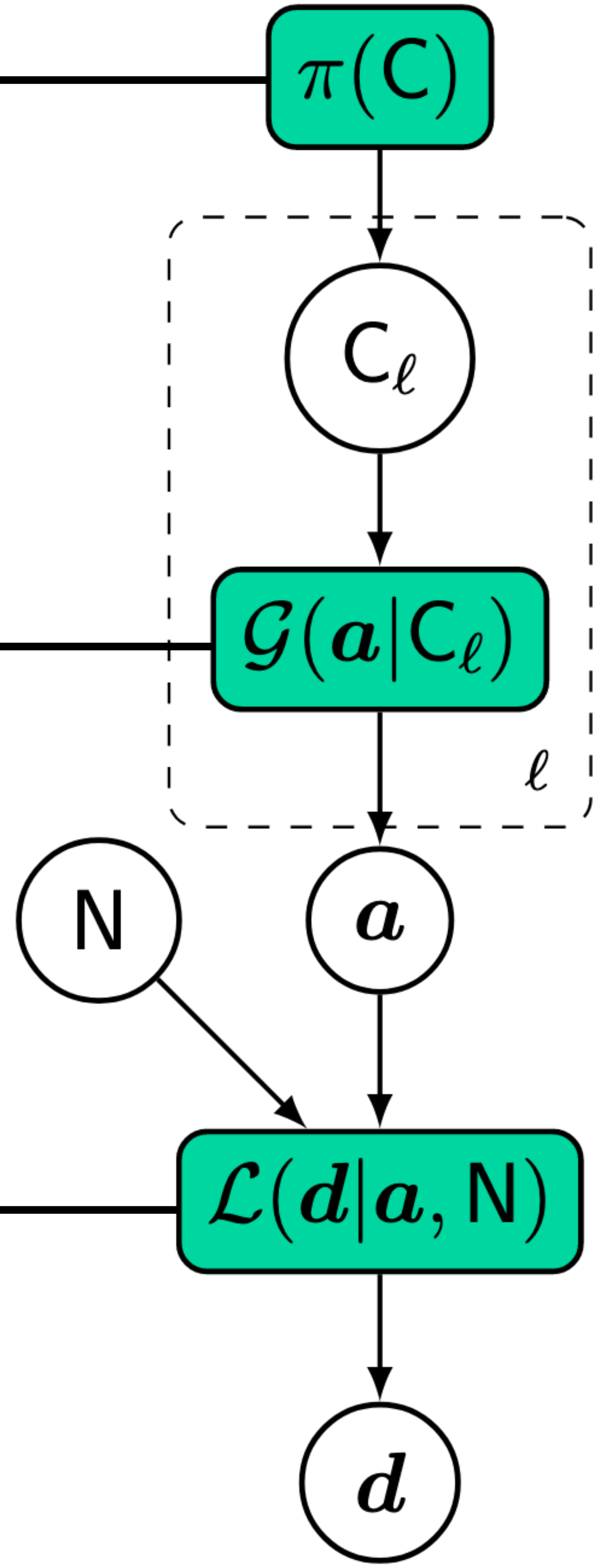
Almanac

Directed Acyclical Graph & posterior

Prior on the Angular Power Spectra

Prior on the spherical harmonic coefficients

Likelihood on the data at the field level



Loureiro et al. 2023, Sellentin, Loureiro et al, 2023

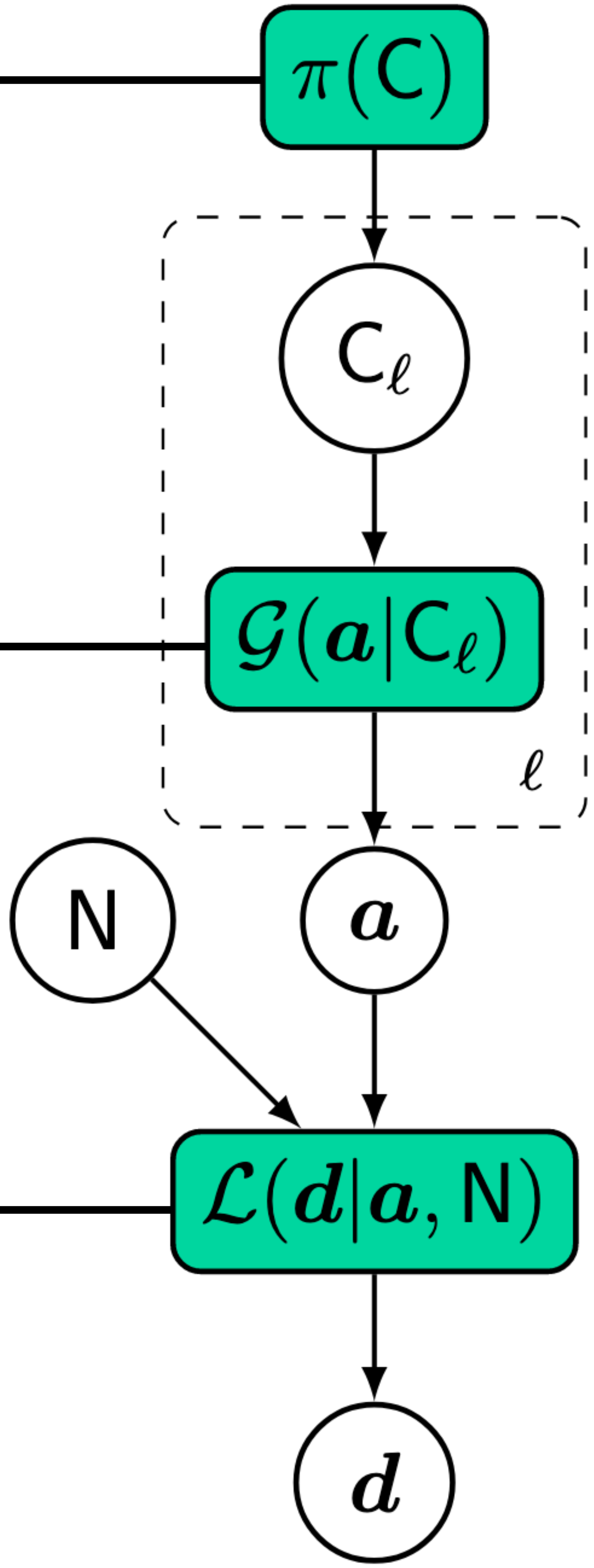
Almanac

Directed Acyclical Graph & posterior

$$\pi(\mathsf{C}) = |\mathsf{C}|^q$$

$$\mathcal{G}(\boldsymbol{a}|\mathsf{C}) = \frac{1}{\sqrt{|2\pi\mathsf{C}|}} \exp\left(-\frac{1}{2}\boldsymbol{a}^{\mathrm{T}}\mathsf{C}^{-1}\boldsymbol{a}\right)$$

$$\mathcal{L}(\boldsymbol{d}|\boldsymbol{a},\mathsf{N}) \propto \exp\left[-\frac{1}{2}(\boldsymbol{d}-\mathsf{Y}\boldsymbol{a})^{\mathrm{T}}\mathsf{N}^{-1}(\boldsymbol{d}-\mathsf{Y}\boldsymbol{a})\right]$$



Posterior: $\mathcal{P}(\mathsf{C},\boldsymbol{a}|\boldsymbol{d},\mathsf{N}) \propto \mathcal{L}(\boldsymbol{d}|\boldsymbol{a},\mathsf{N})\mathcal{G}(\boldsymbol{a}|\mathsf{C})\pi(\mathsf{C})$

Loureiro et al. 2023, Sellentin, Loureiro et al, 2023

Almanac

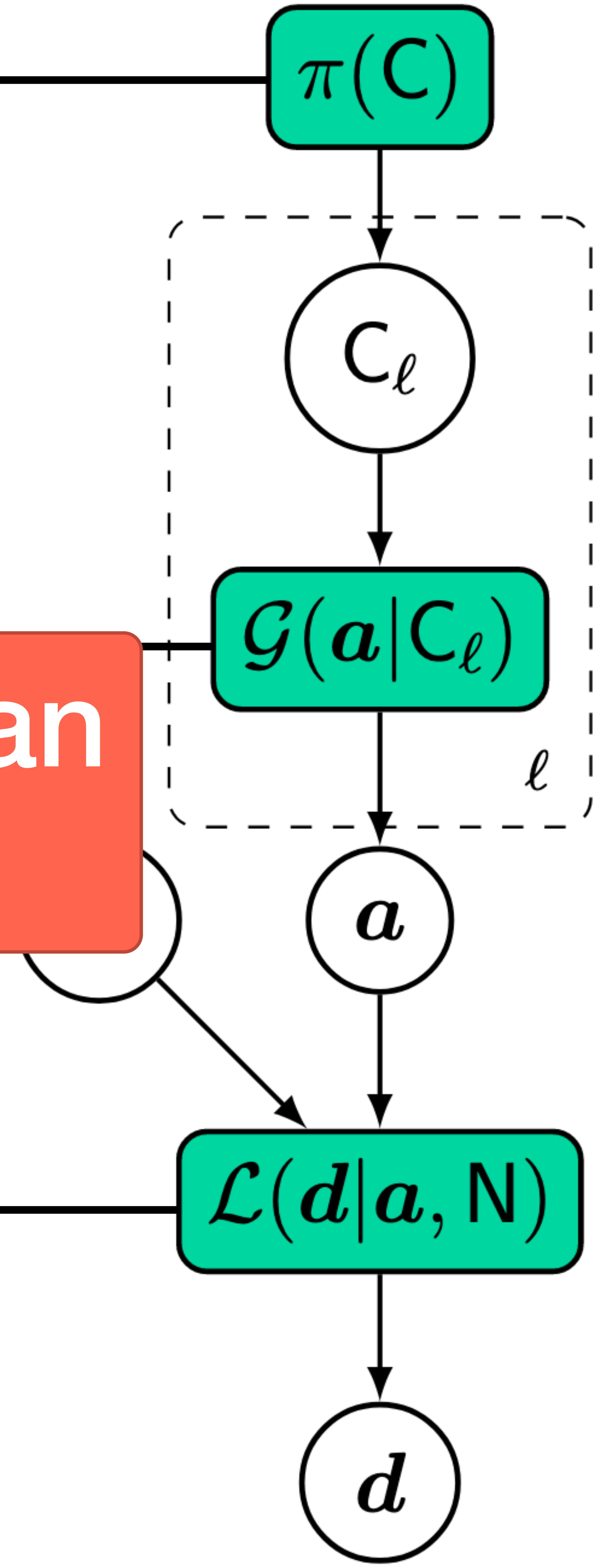
Directed Acyclical Graph & posterior

$$\pi(\mathsf{C}) = |\mathsf{C}|^q$$

$\mathcal{G}(\boldsymbol{a}|\mathsf{C})$ ...

Gaussian Prior DOES NOT mean a Gaussian posterior!!!

$$\mathcal{L}(\boldsymbol{d}|\boldsymbol{a},\mathsf{N}) \propto \exp\left[-\frac{1}{2}(\boldsymbol{d}-\mathsf{Y}\boldsymbol{a})^{\mathrm{T}}\mathsf{N}^{-1}(\boldsymbol{d}-\mathsf{Y}\boldsymbol{a})\right]$$

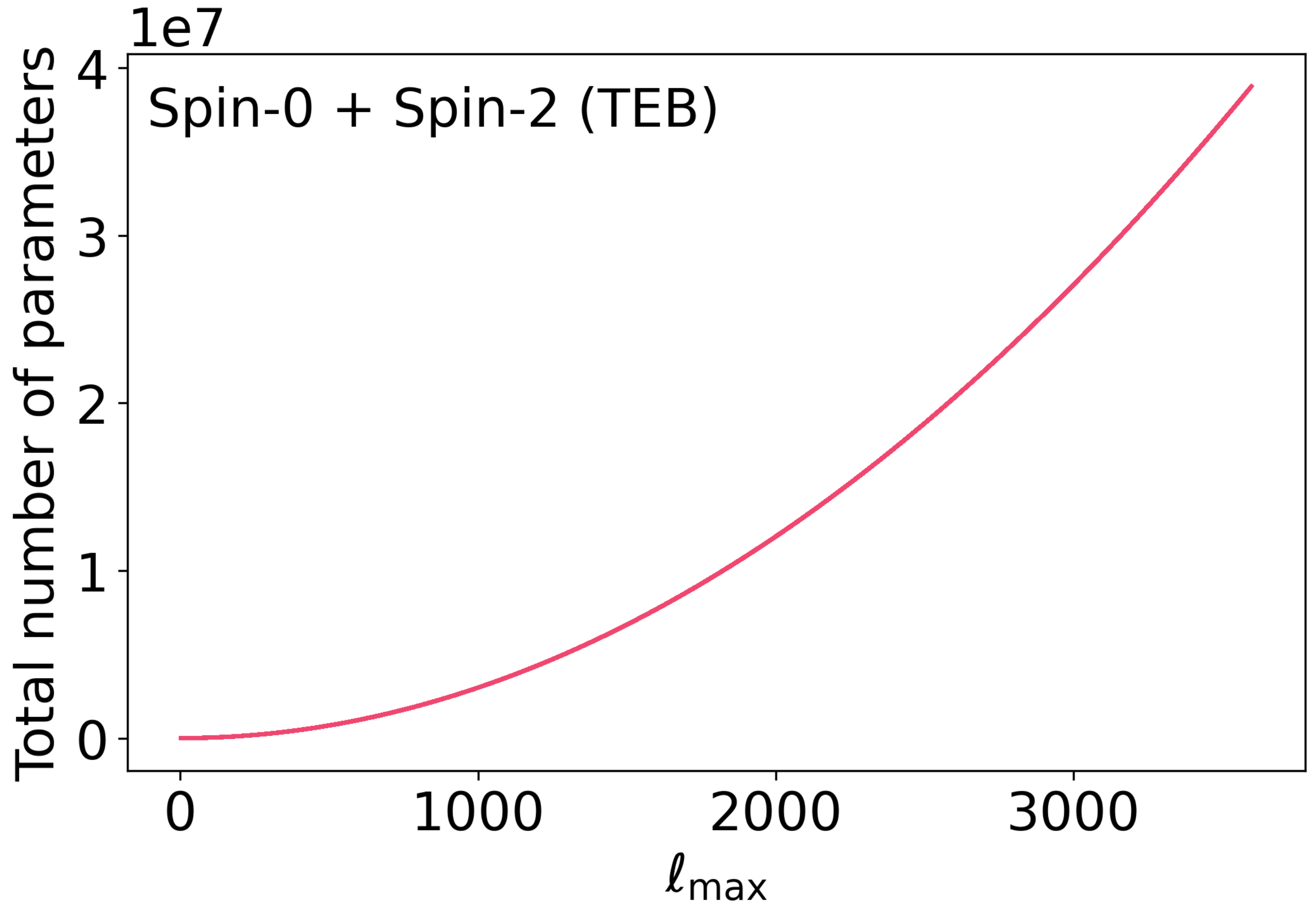


Posterior: $\mathcal{P}(\mathsf{C},\boldsymbol{a}|\boldsymbol{d},\mathsf{N}) \propto \mathcal{L}(\boldsymbol{d}|\boldsymbol{a},\mathsf{N})\mathcal{G}(\boldsymbol{a}|\mathsf{C})\pi(\mathsf{C})$

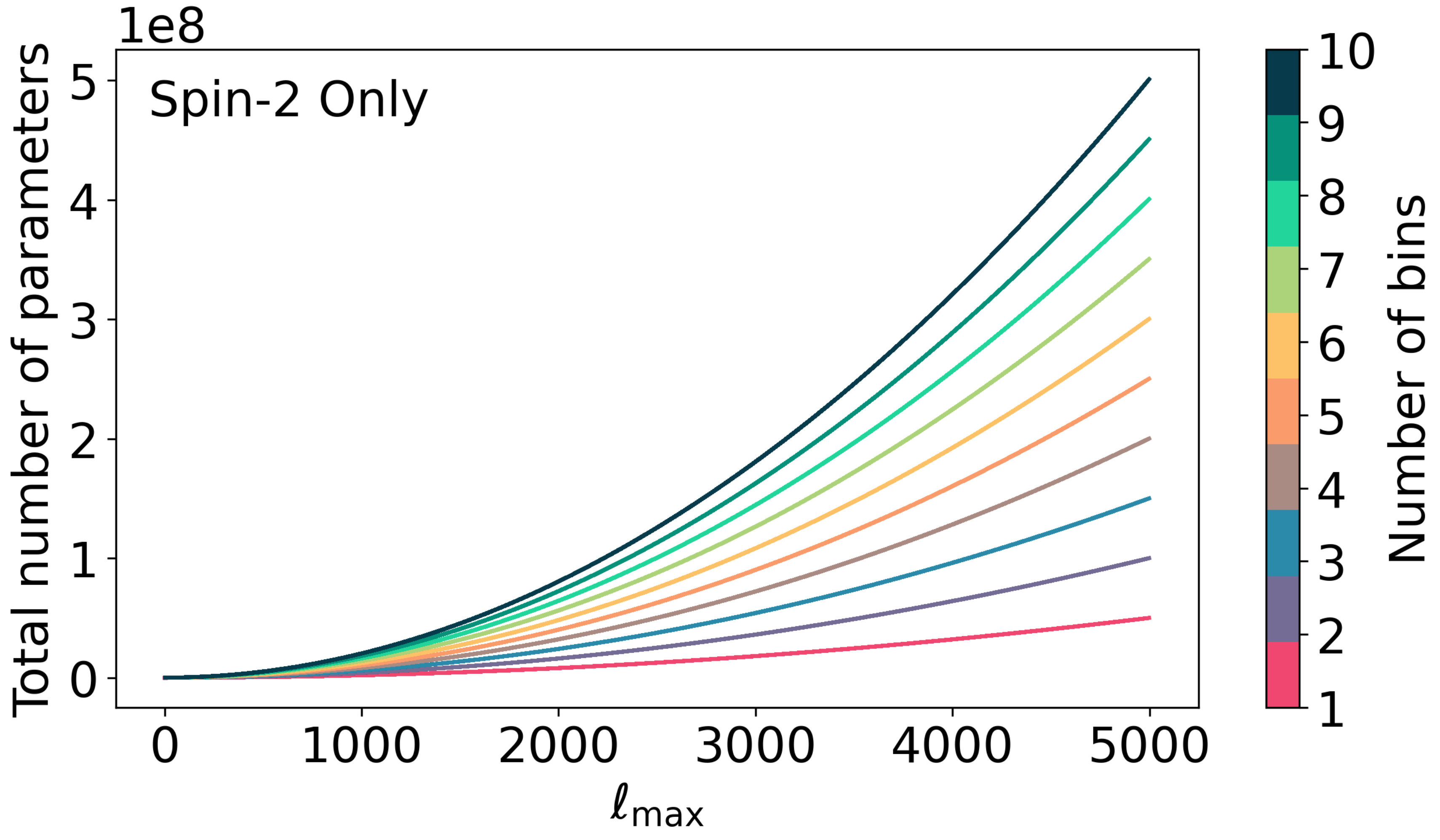
Loureiro et al. 2023, Sellentin, Loureiro et al, 2023

Almanac

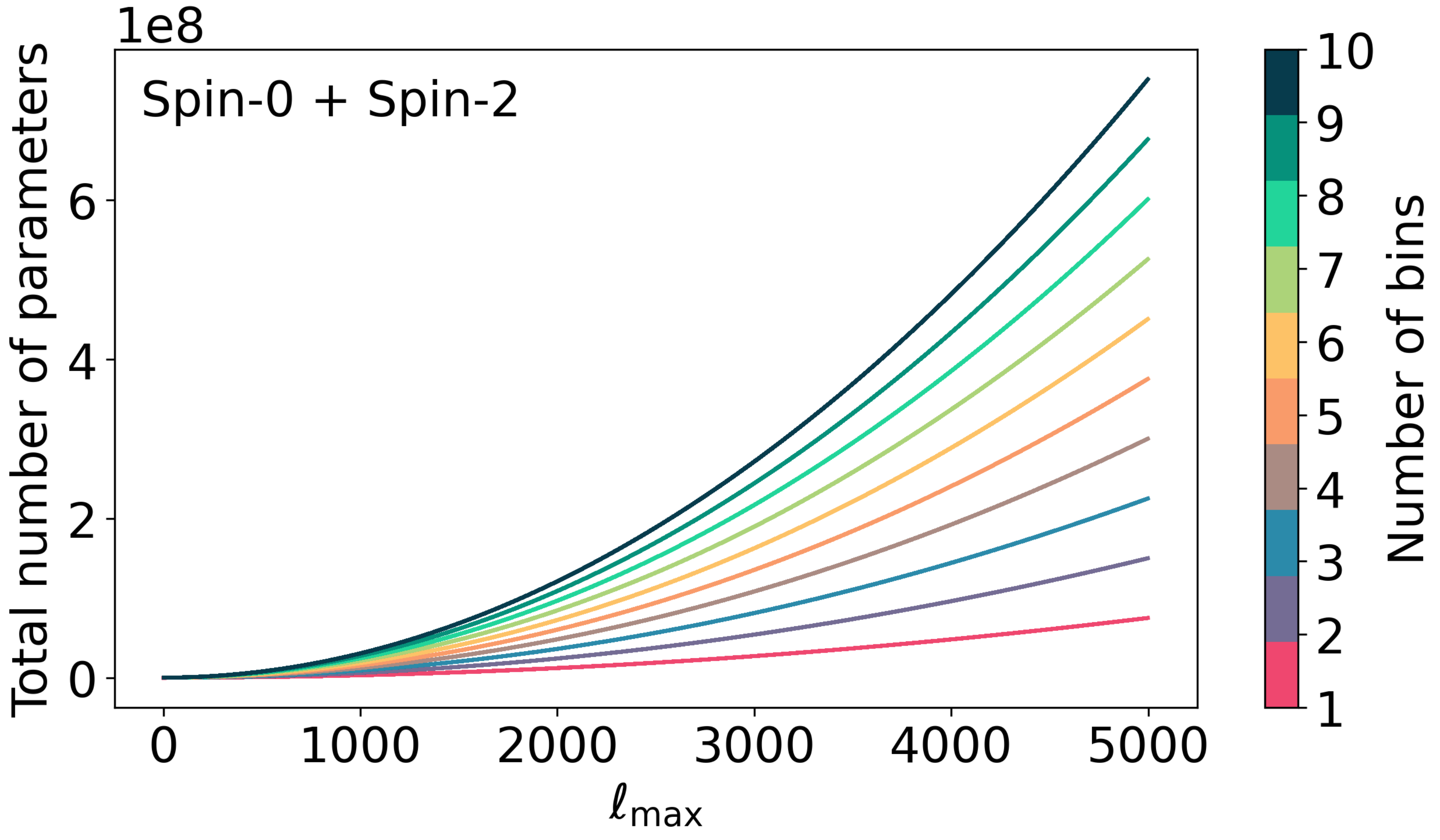
Number of free parameters



CMB Temperature + Polarisation



Stage-IV Cosmic Shear



Stage-IV 3x2pt

Our current state-of-the-art run has 16.8 Million free parameters!

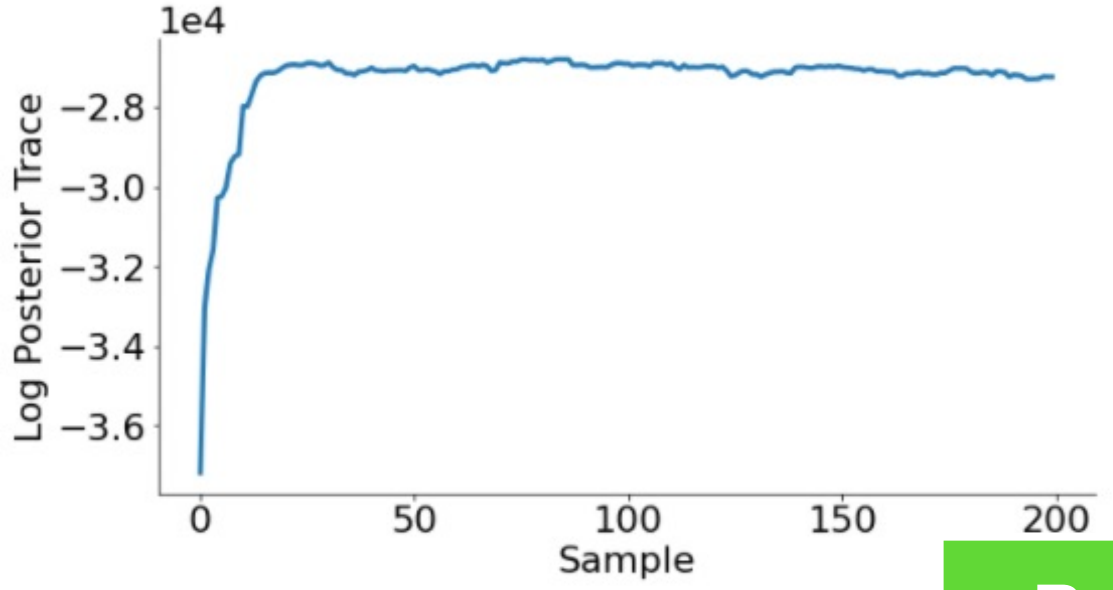
Sellentin, Loureiro et. al, 2023

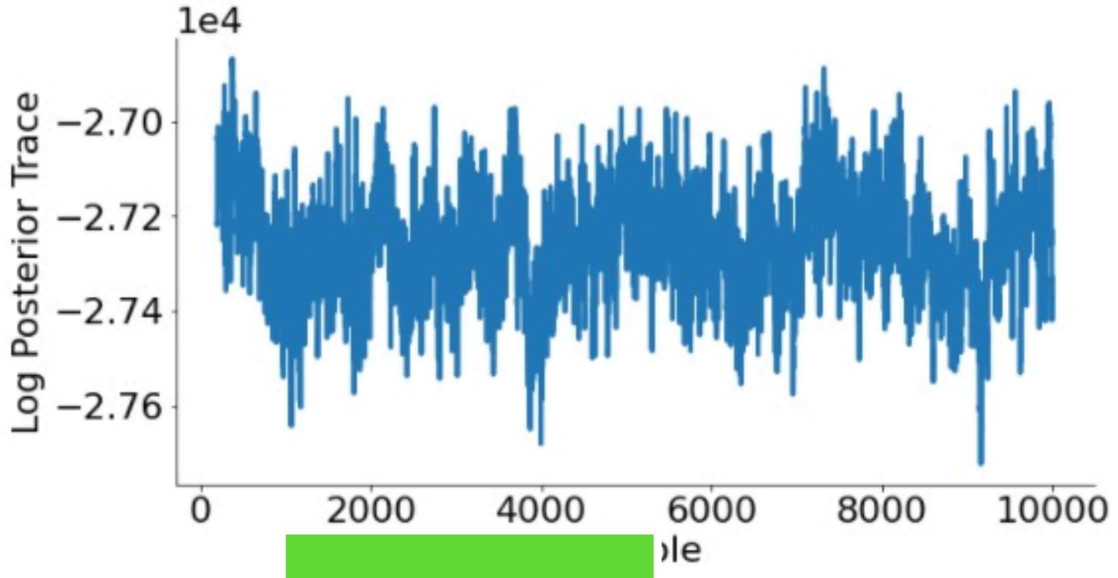
Loureiro et al. 2023, Sellentin, Loureiro et al, 2023

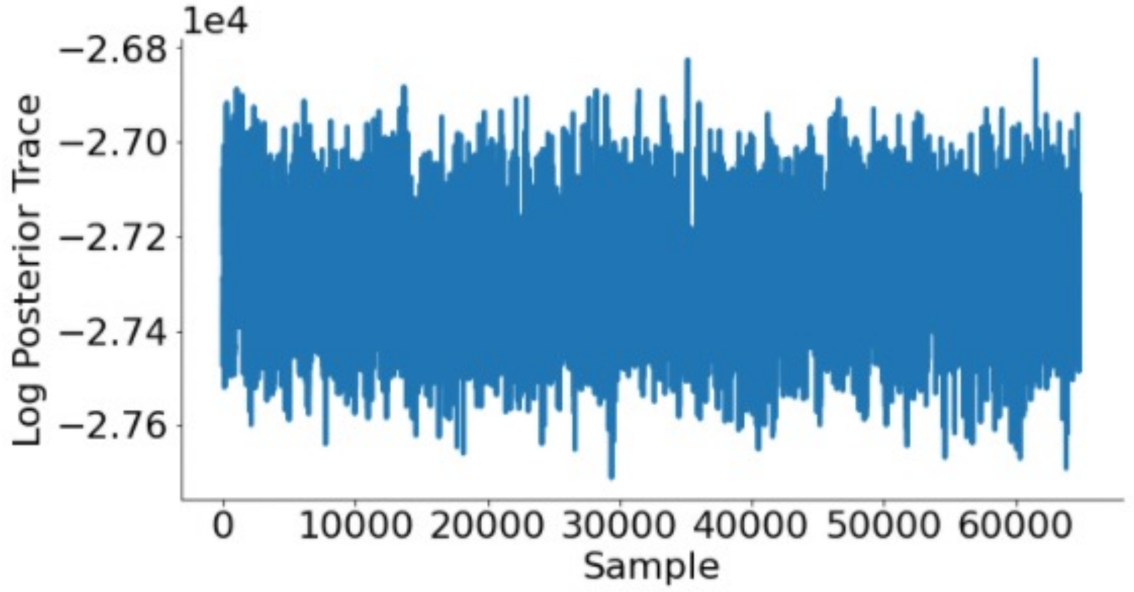
Tuned HMC

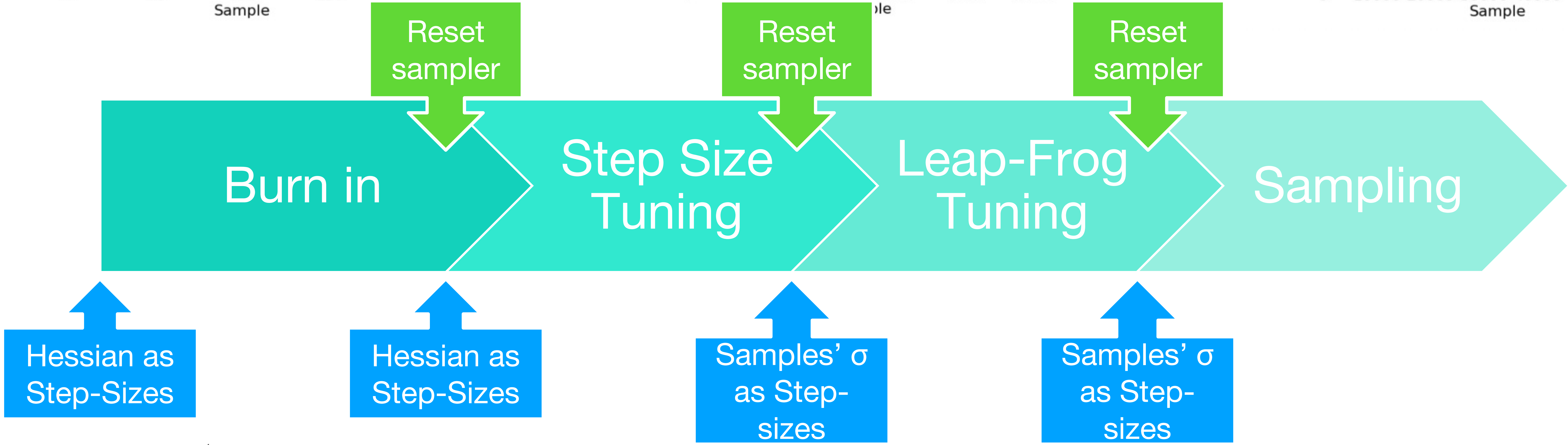
Three phase tuning

Sellentin,
Loureiro et. al, 2023







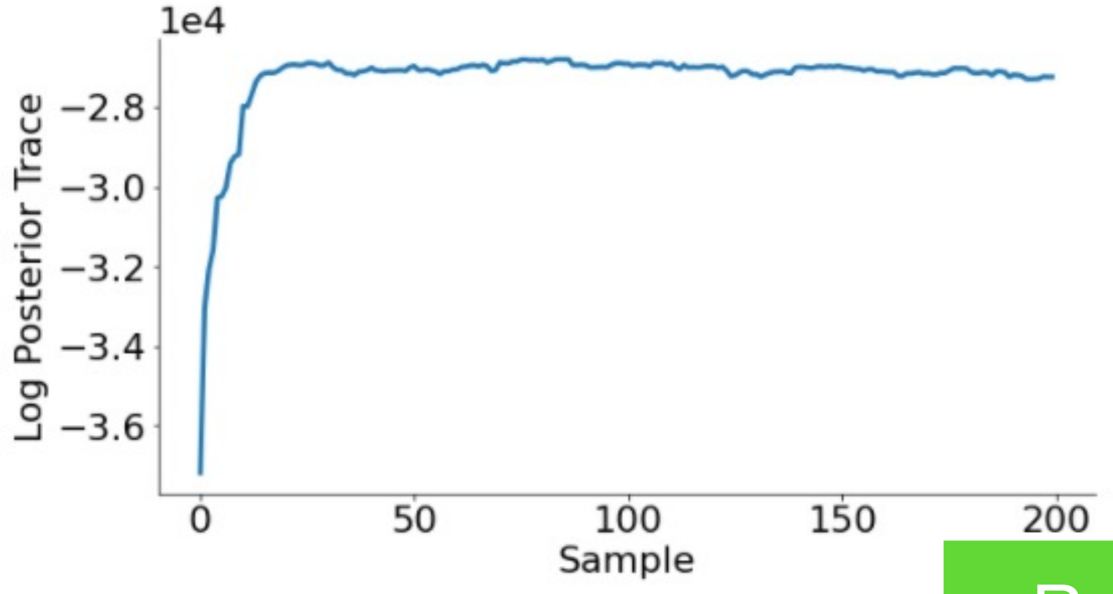


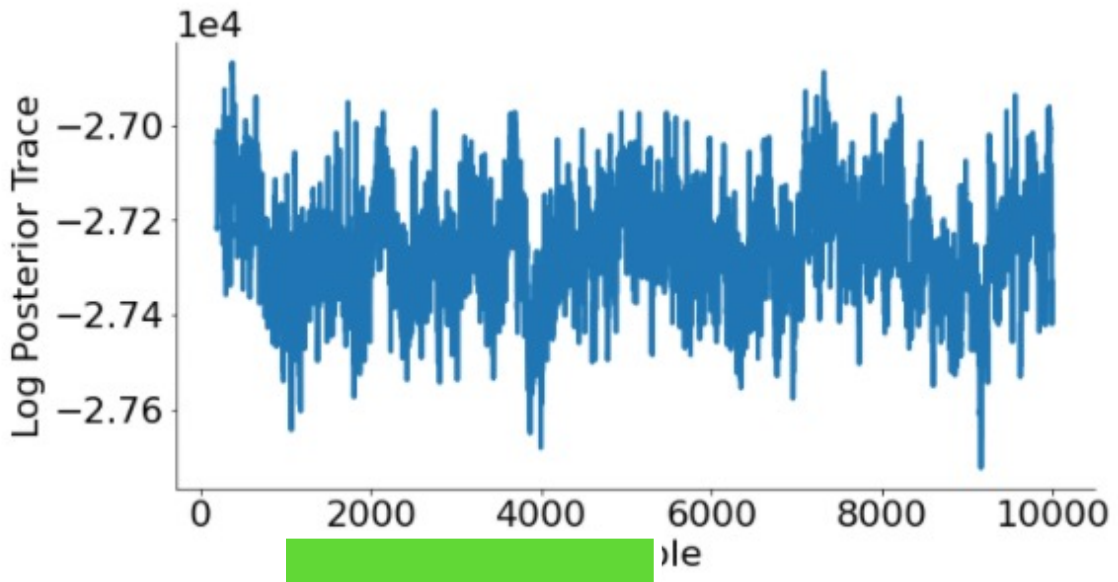
$$\mathcal{E} = \eta \left(\frac{\partial^2 \psi}{\partial \mathbf{x}^2} \right)^{-1/2}$$

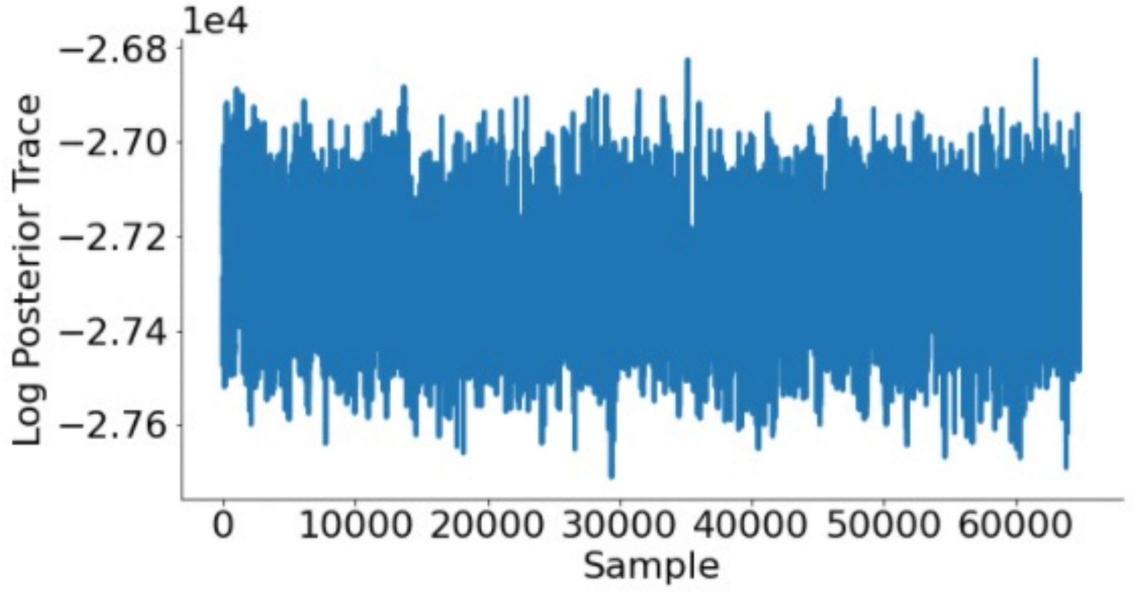
Tuned HMC

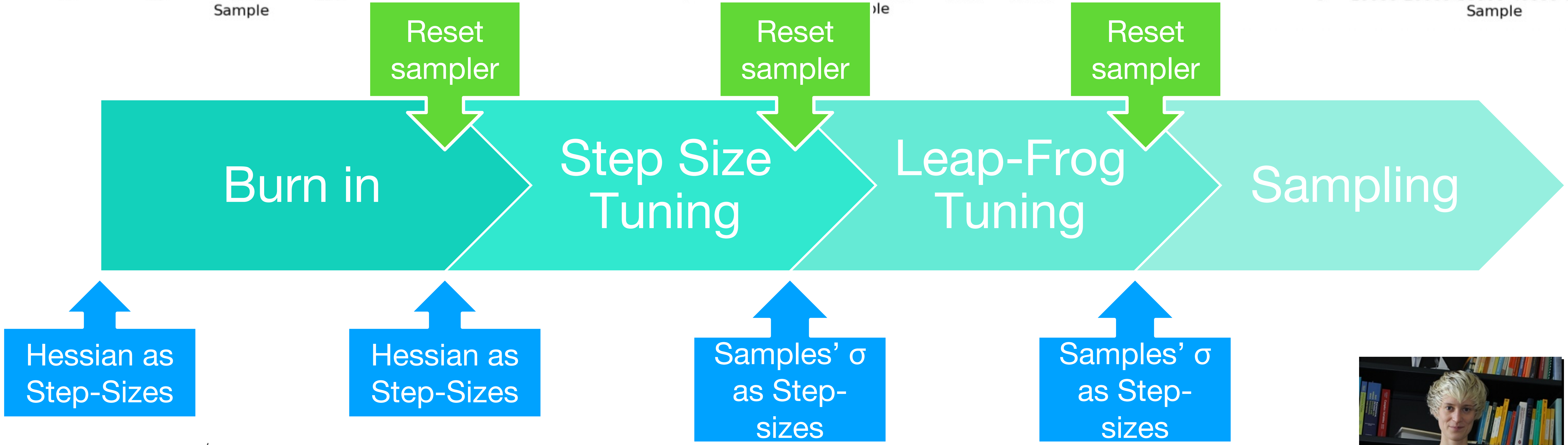
Three phase tuning

Sellentin,
Loureiro et. al, 2023









$$\mathcal{E} = \eta \left(\frac{\partial^2 \psi}{\partial \mathbf{x}^2} \right)^{-1/2}$$

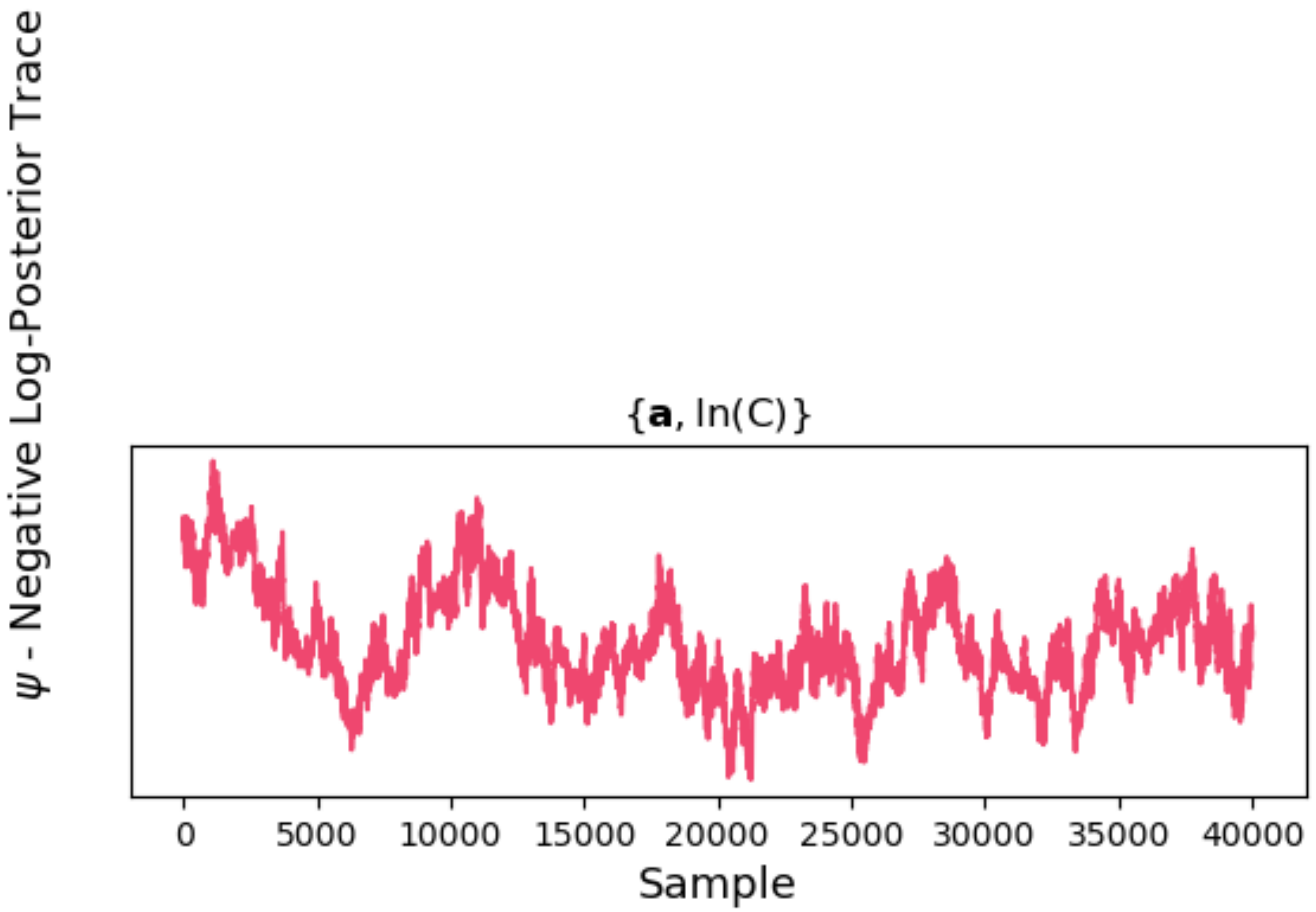
Prof. Elena Sellentin

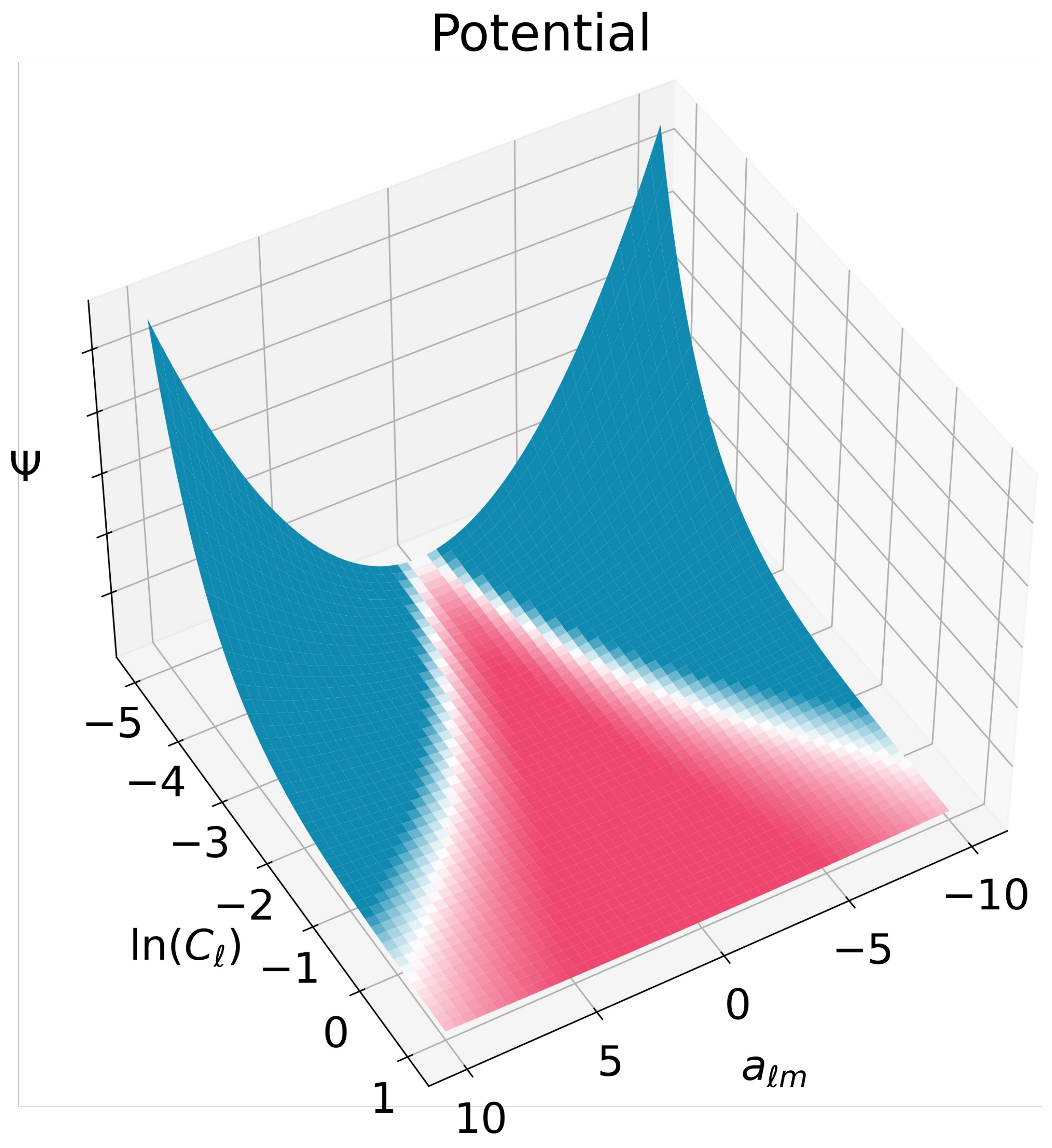
Dr. Lorne Whiteway

Coordinate System comparison

Sellentin, Loureiro et. al, 2023

Loureiro et. al, 2023

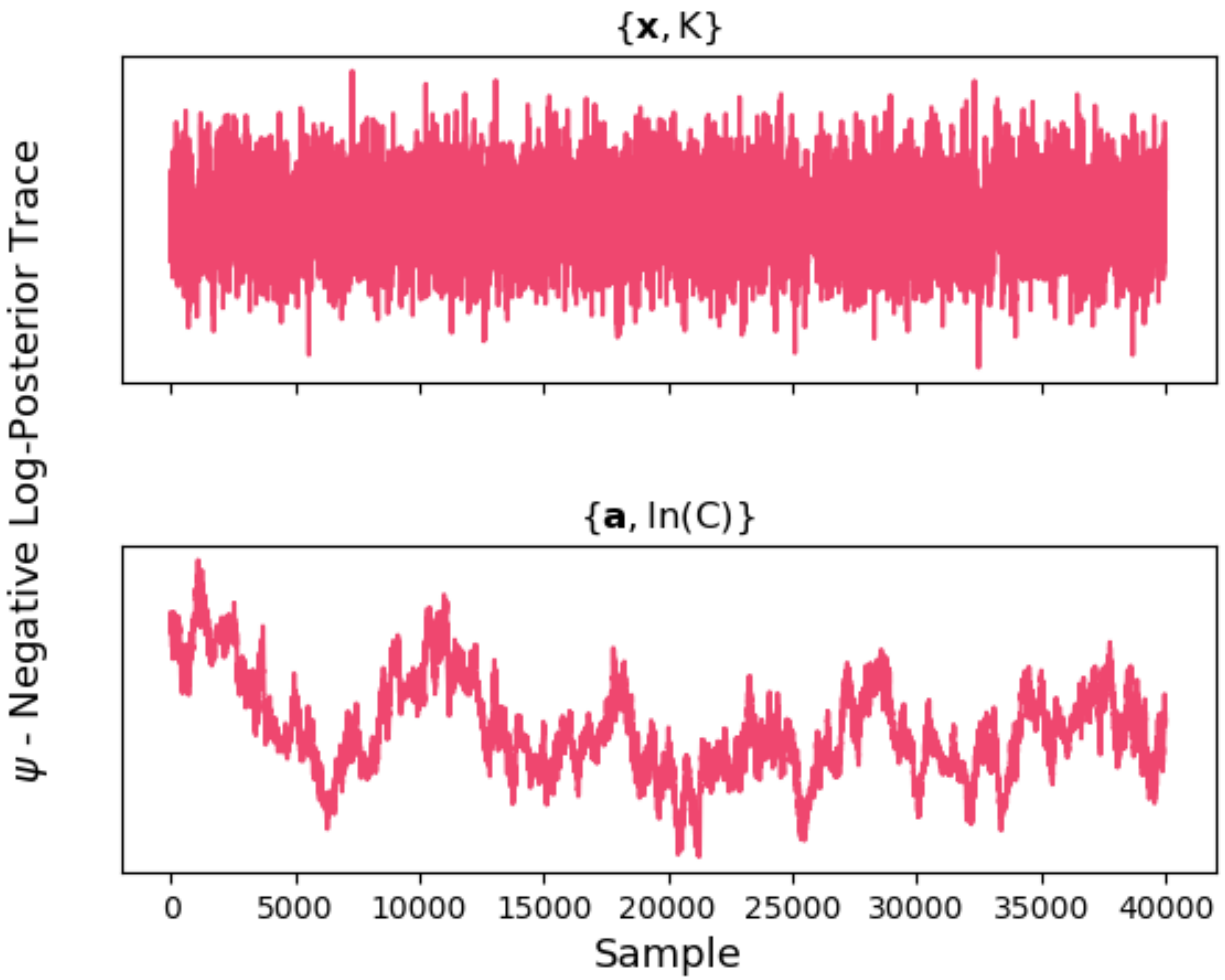


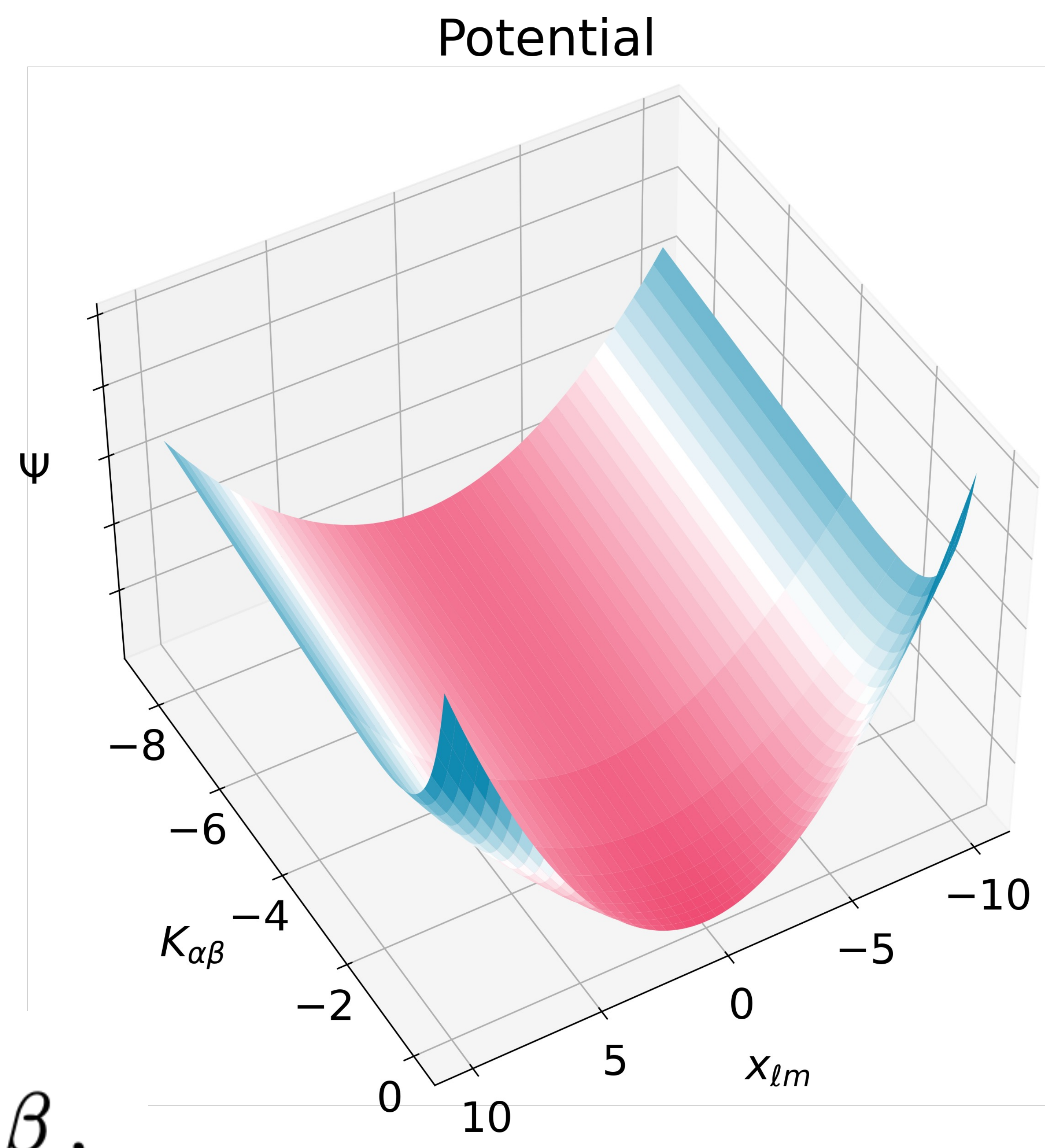


Coordinate System comparison

Sellentin, Loureiro et. al, 2023

Loureiro et. al, 2023





New Coordinate System:

$$\boldsymbol{x} = \mathsf{L}^{-1}\boldsymbol{a}$$

$$K_{\alpha\beta} = \begin{cases} \ln(L_{\alpha\beta}) & \text{if } \alpha = \beta\,, \\ L_{\alpha\beta} & \text{otherwise.} \end{cases}$$

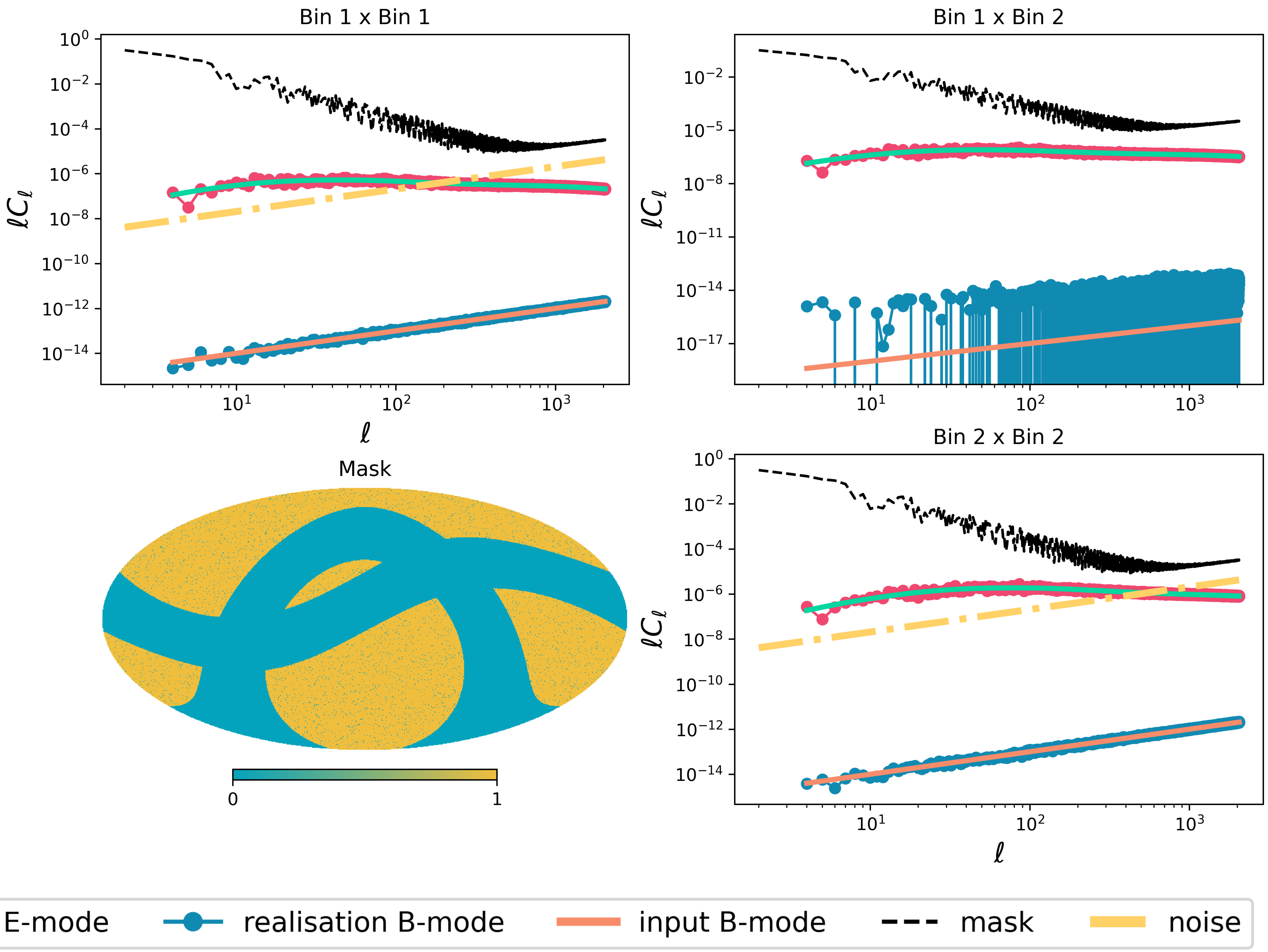
Test Cases & Results

Weak Lensing & CMB Temperature and Polarisation

Weak Lensing

Euclid-like case

- Multipoles: 4, 2048
- Nside = 1024 (12.5M pixels)
- 2 tomographic bins for a spin-2 field is 50.3M pixels!
- **16.8 Million free parameters; ~20k are C_ℓ**



Loureiro et al. 2023 (ArXiv:2210.13260)

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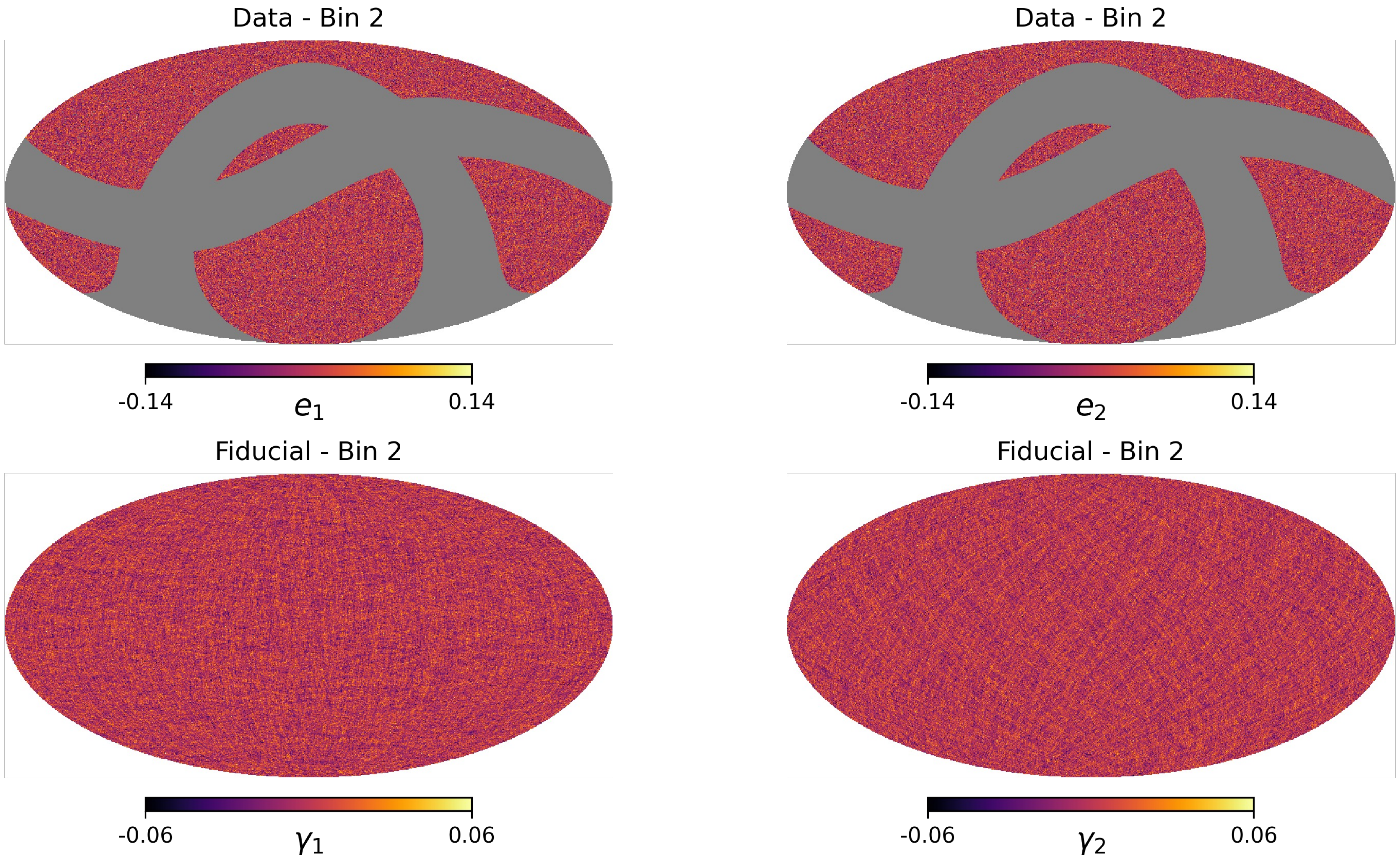


Loureiro et al. 2023 (ArXiv:2210.13260)

Weak Lensing

Loureiro et. al, 2023

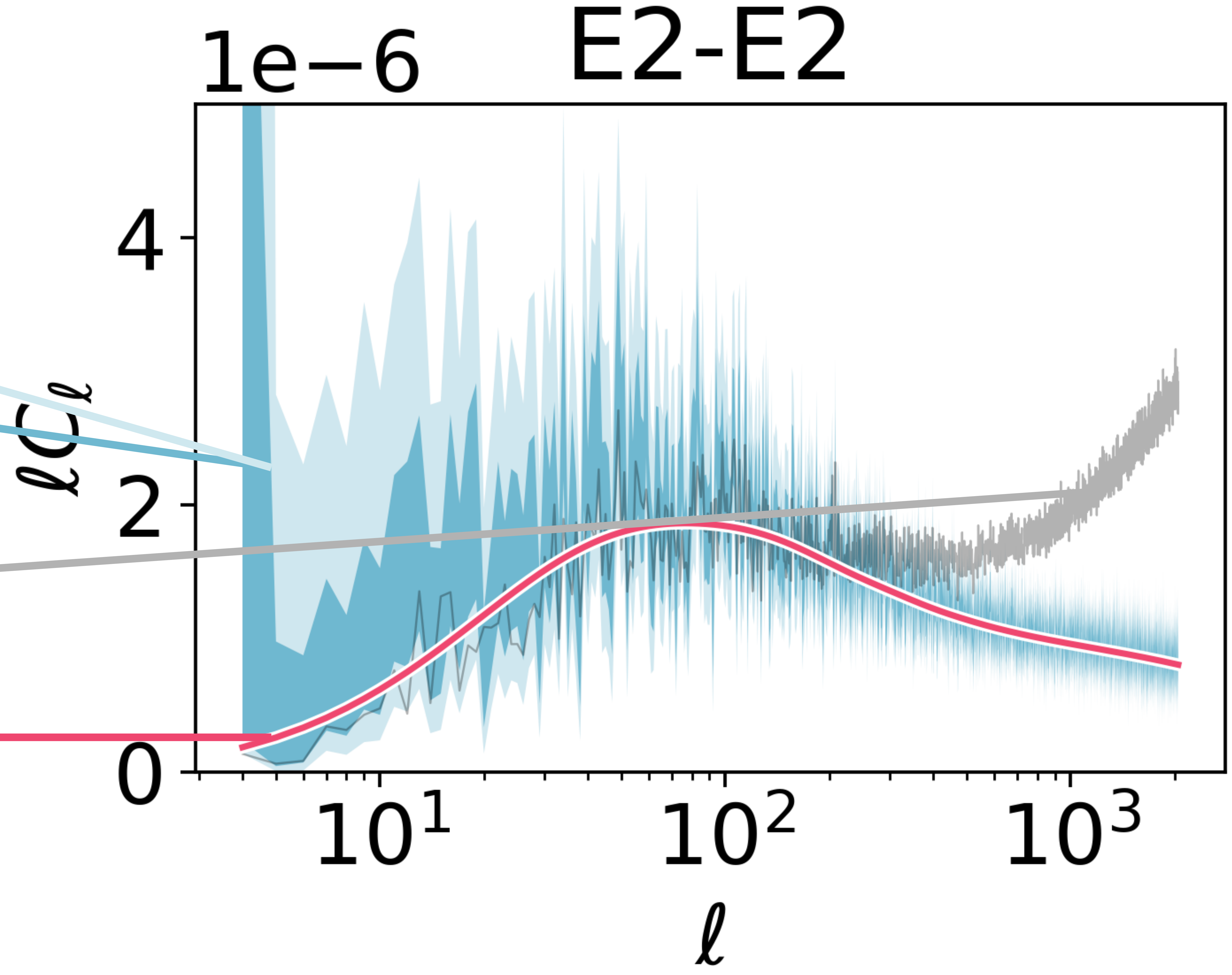
Angular Power Spectra

Posterior PDF

- Almanac 95% C.I.
- Almanac 68.3% C.I.

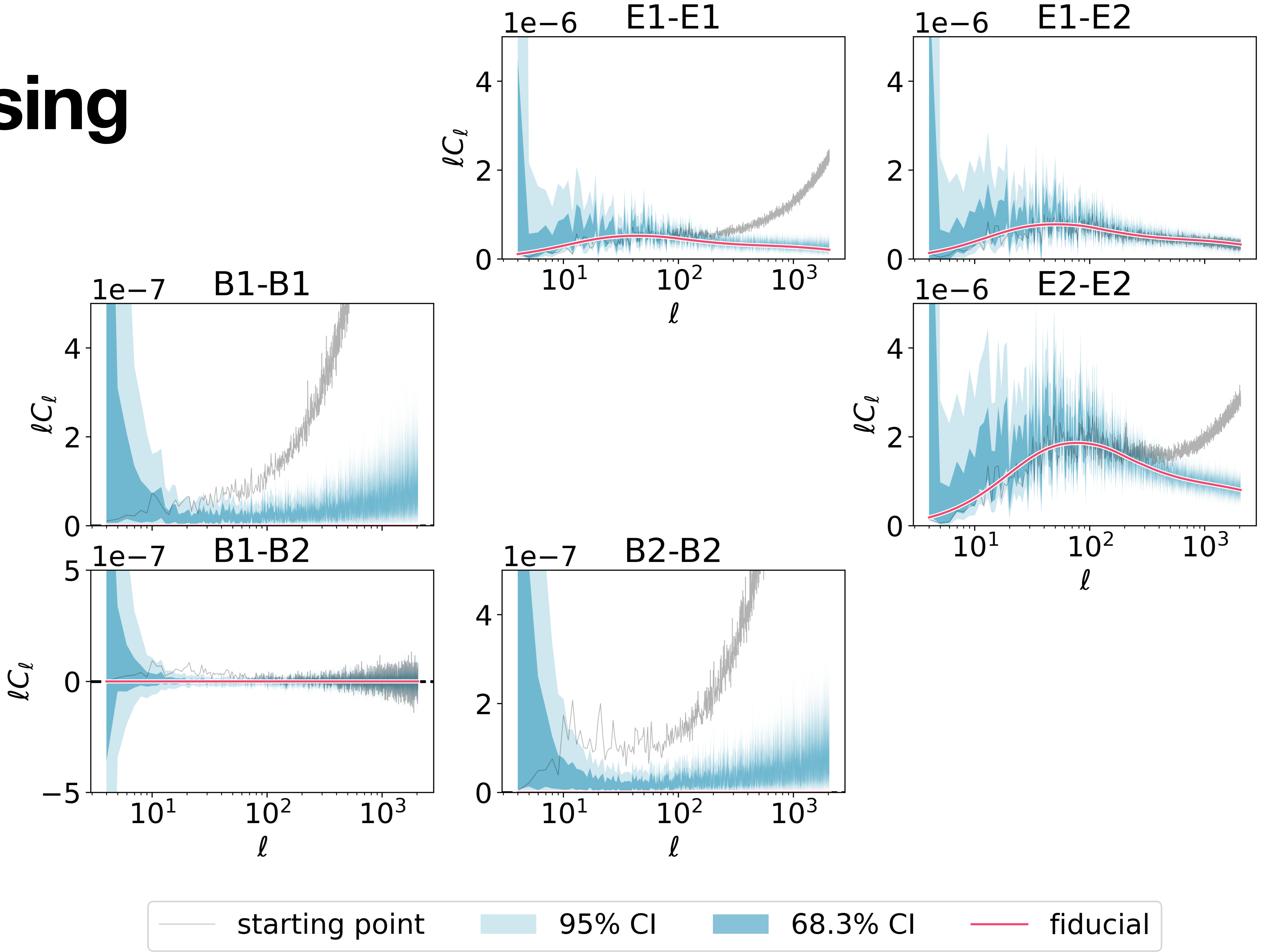
Starting Point: Pseudo-C_ℓ

True Cosmology



Weak Lensing

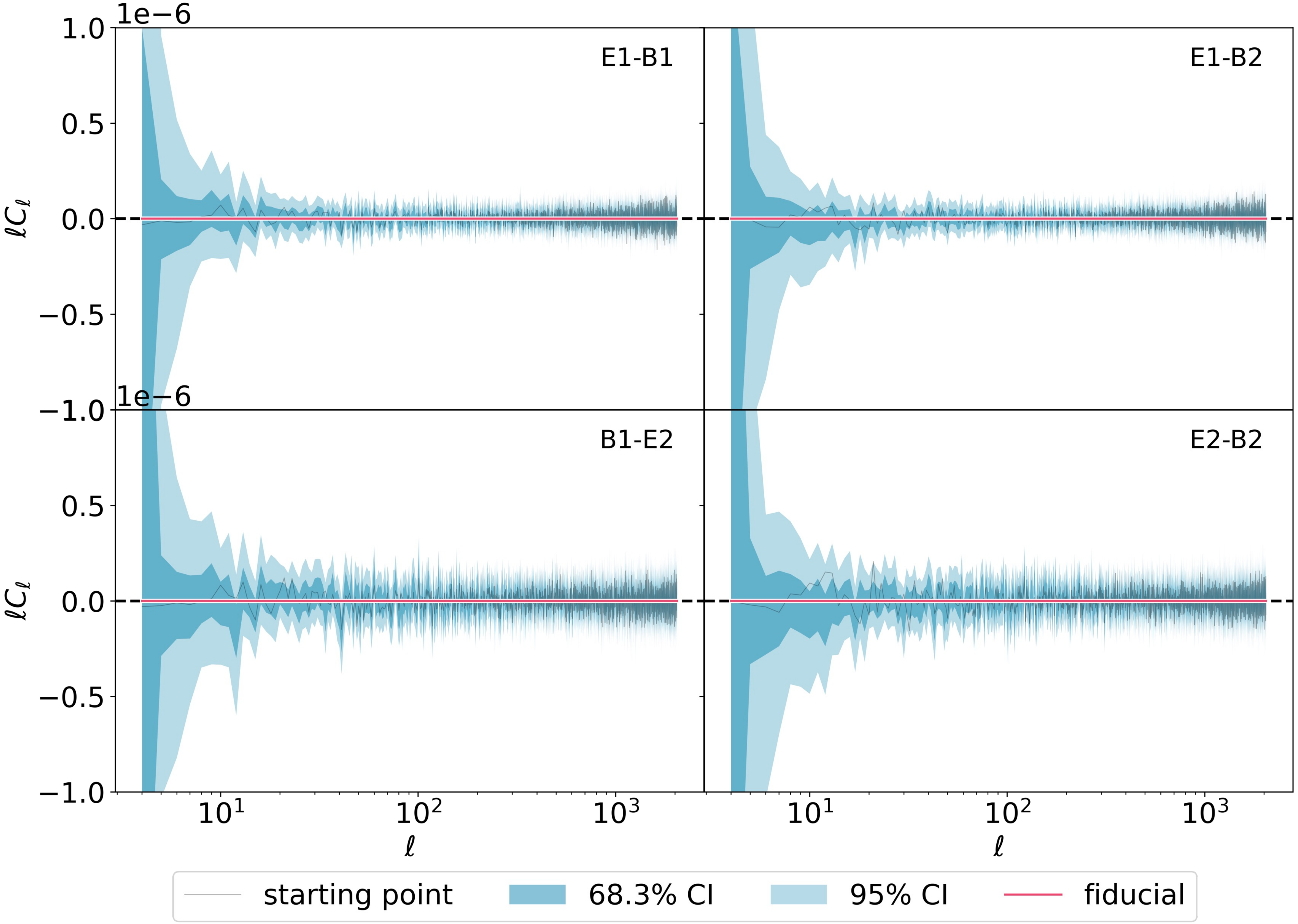
Angular Power Spectra



Loureiro et. al, 2023

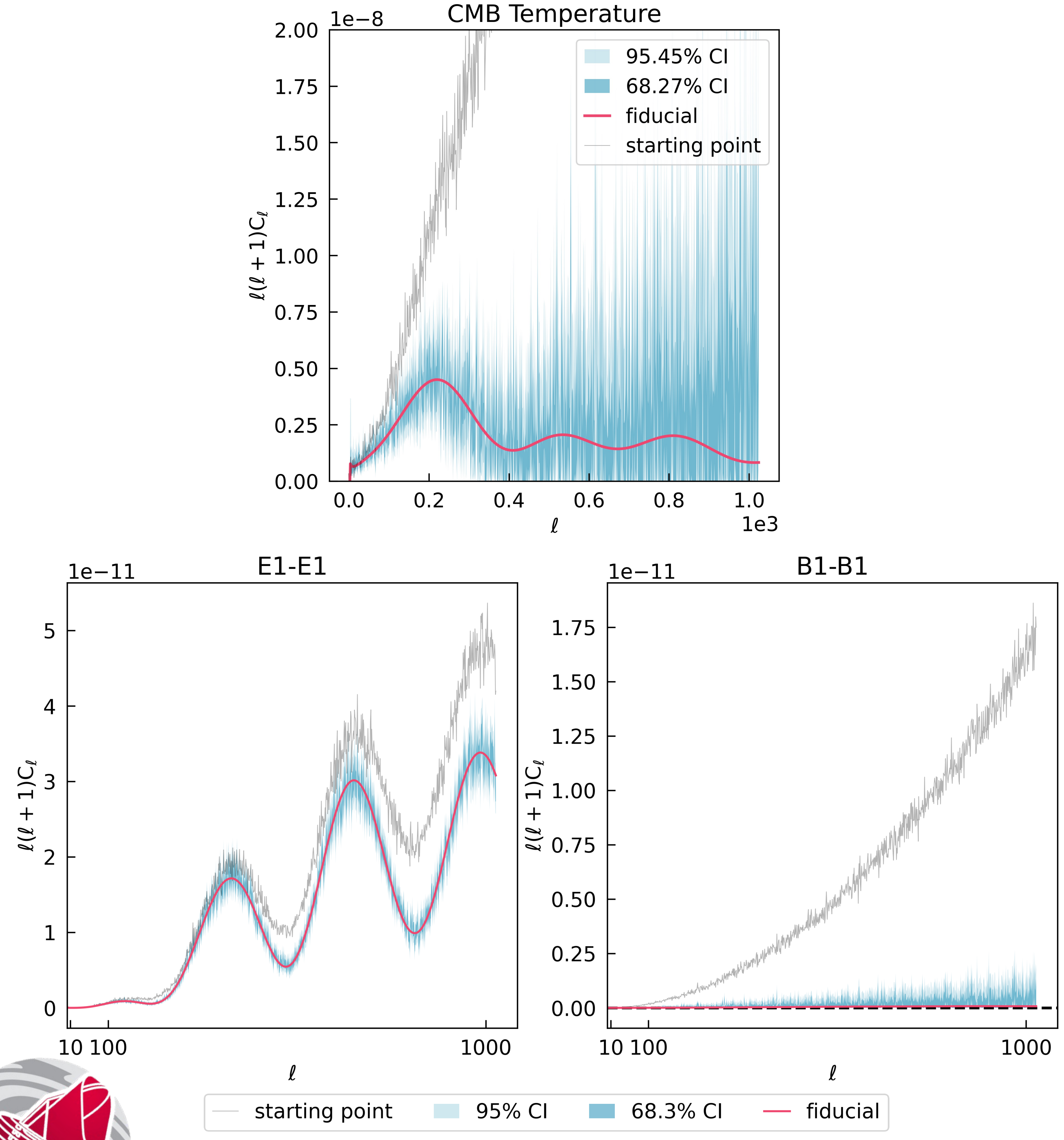
Weak Lensing

Angular Power Spectra



CMB Angular Power Spectra

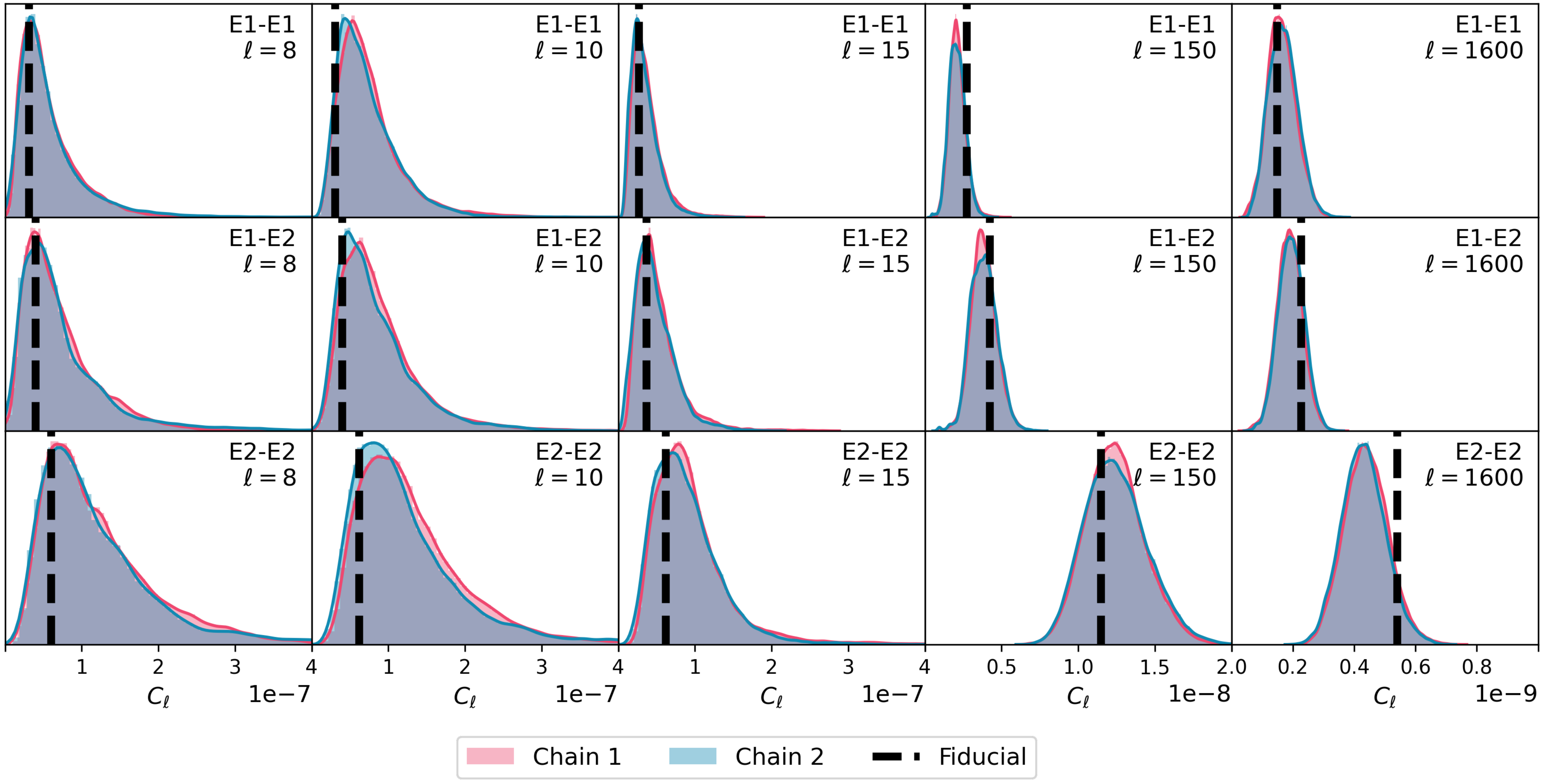
Sellentin,
Loureiro et. al, 2023



CMB Temperature & Polarisation

Weak Lensing

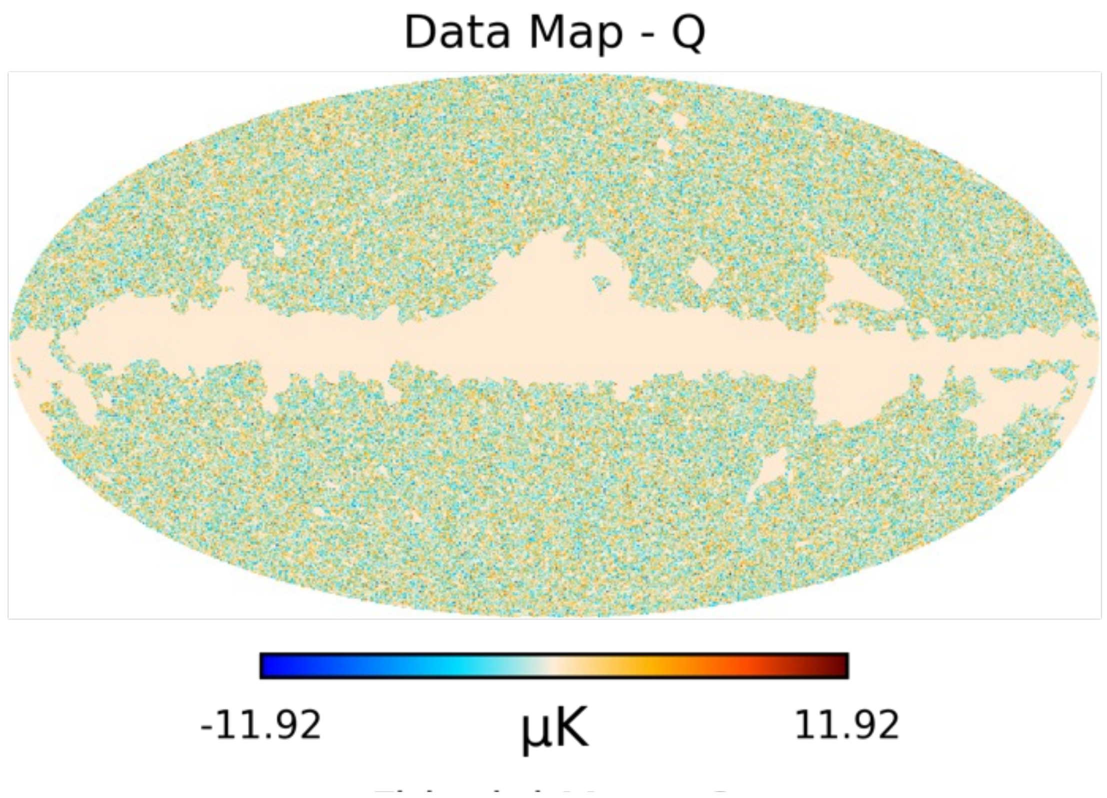
Angular Power Spectra

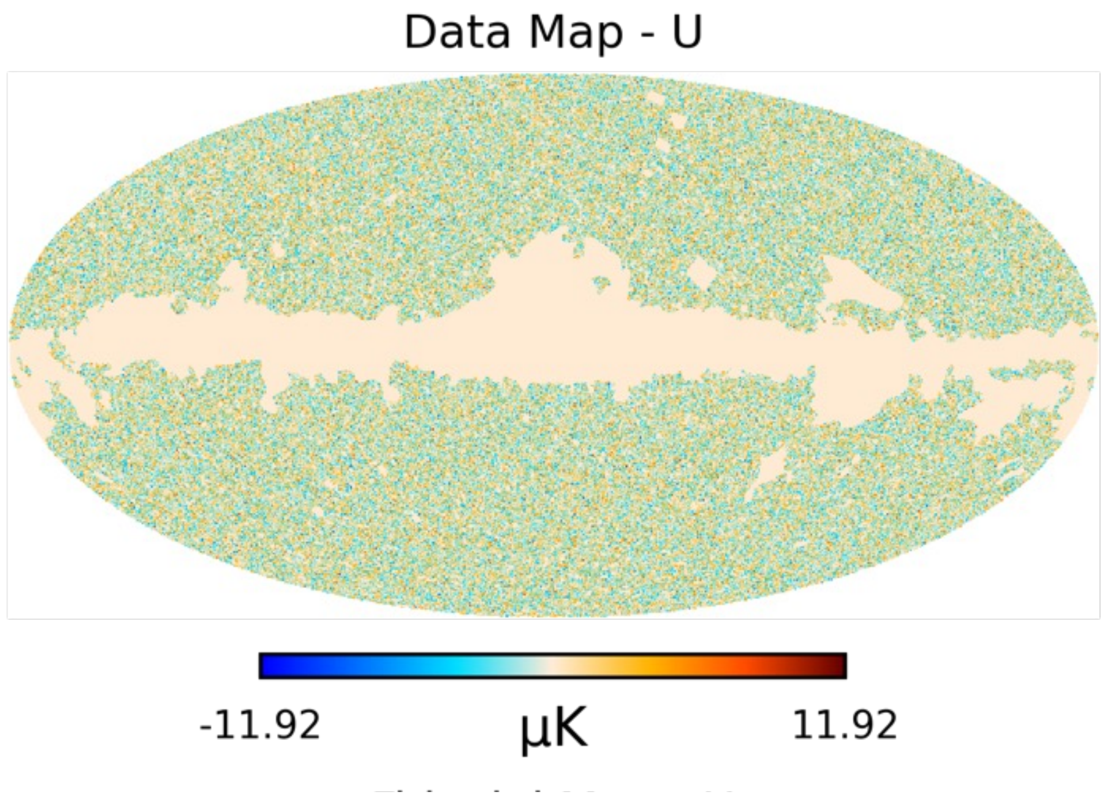


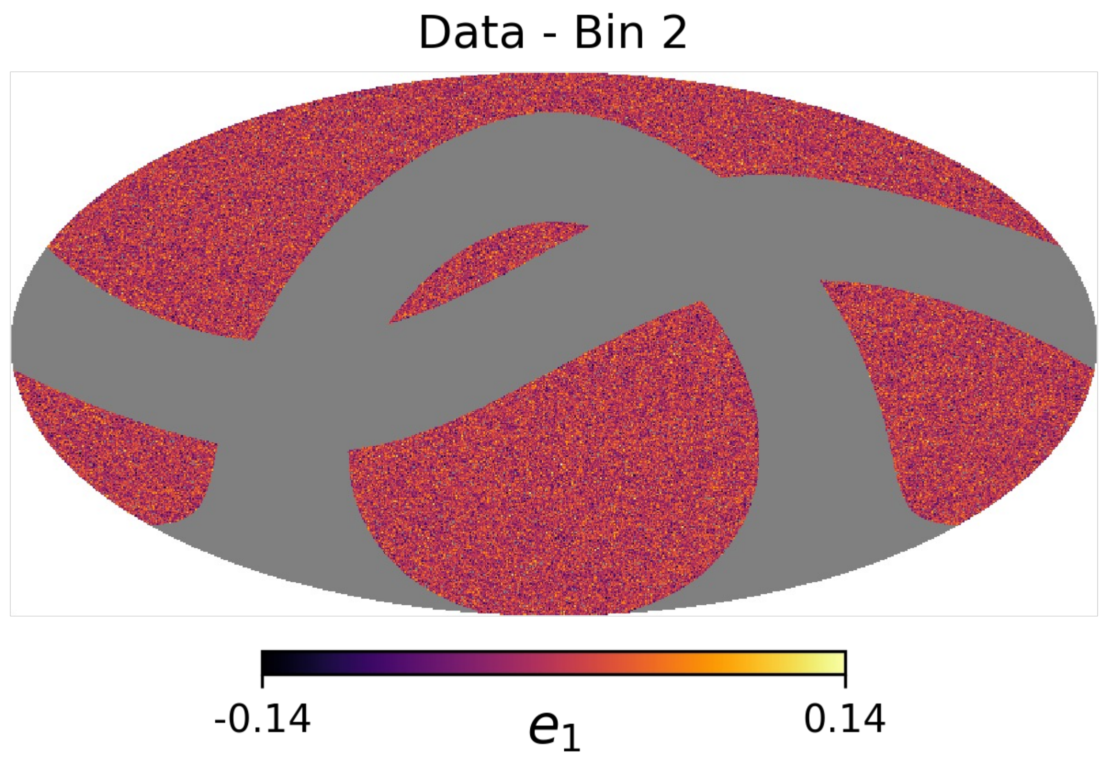
Loureiro et. al, 2023

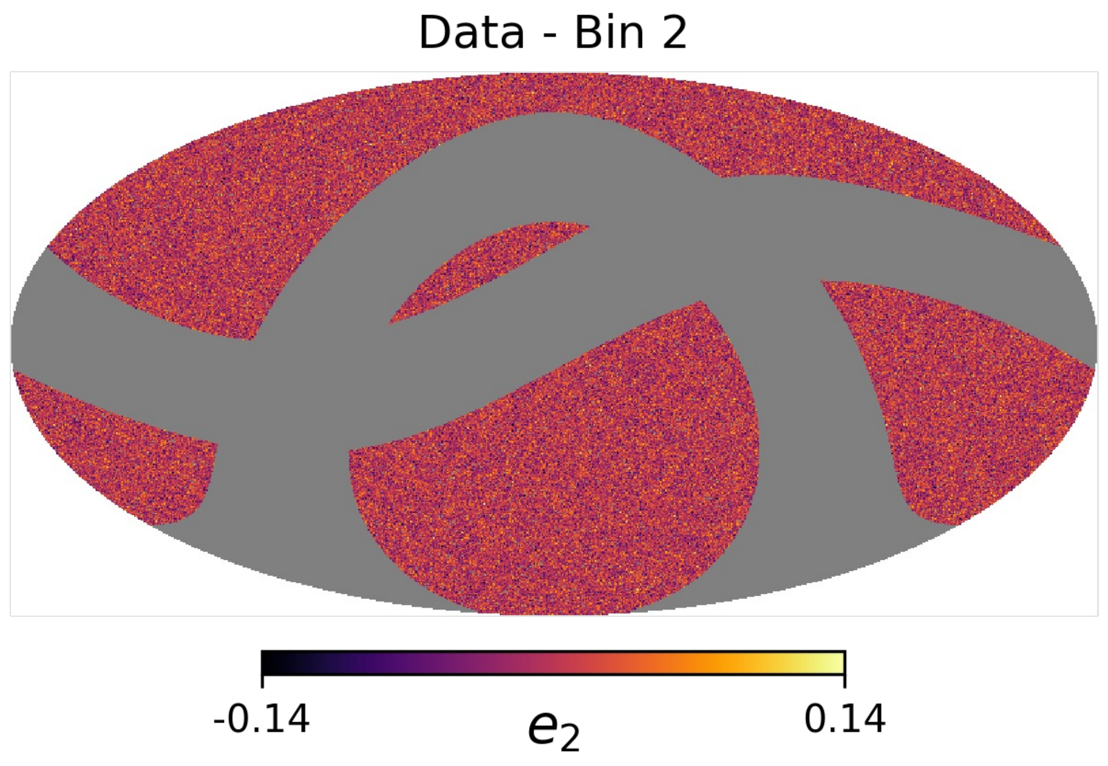
Partial Sky E/B-Leakage

A Spin-2 problem for CMB Polarisation and Weak Lensing









$$\begin{aligned}\widetilde{E}_{\ell m} &= \sum_{\ell' m'} (E_{\ell' m'} W^{+}_{\ell\ell' mm'} + B_{\ell' m'} W^{-}_{\ell\ell' mm'}) \\ \widetilde{B}_{\ell m} &= \sum_{\ell' m'} (B_{\ell' m'} W^{+}_{\ell\ell' mm'} - E_{\ell' m'} W^{-}_{\ell\ell' mm'}),\end{aligned}$$

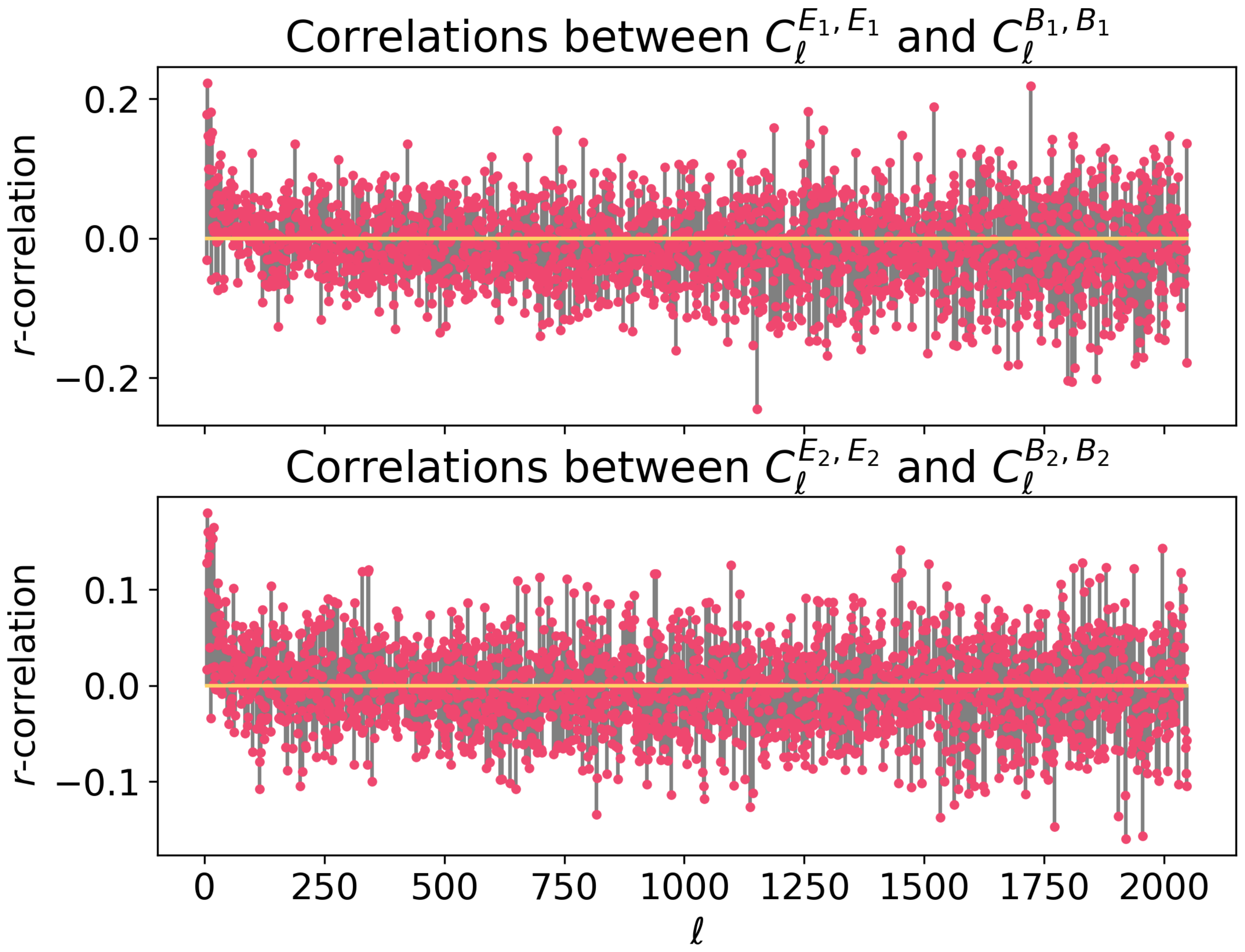
Lewis, Challinor & Turok, 2002

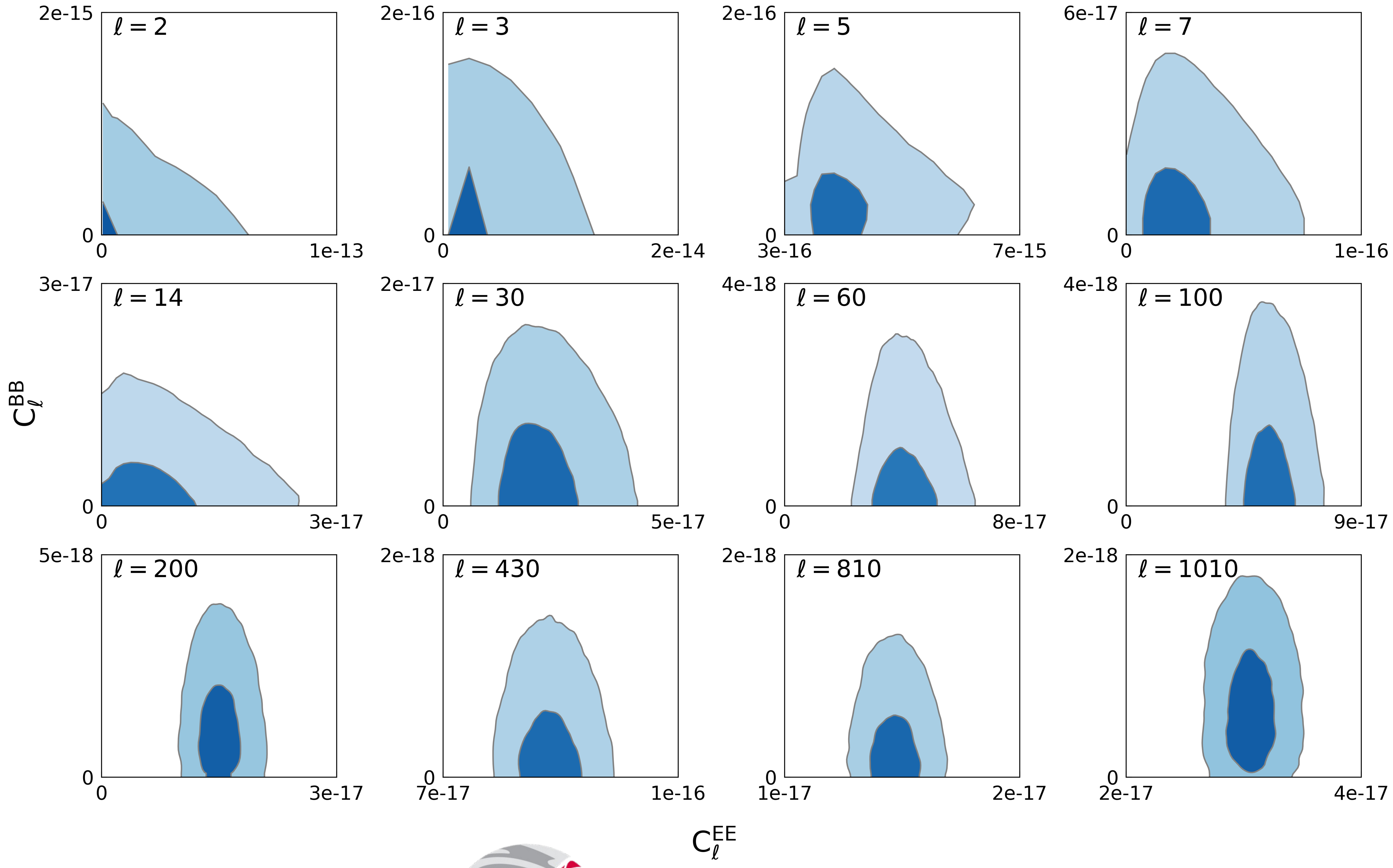
Partial Sky E/B-Leakage

No longer an issue with Almanac

Sellentin, Loureiro et. al, 2023

Loureiro et. al, 2023





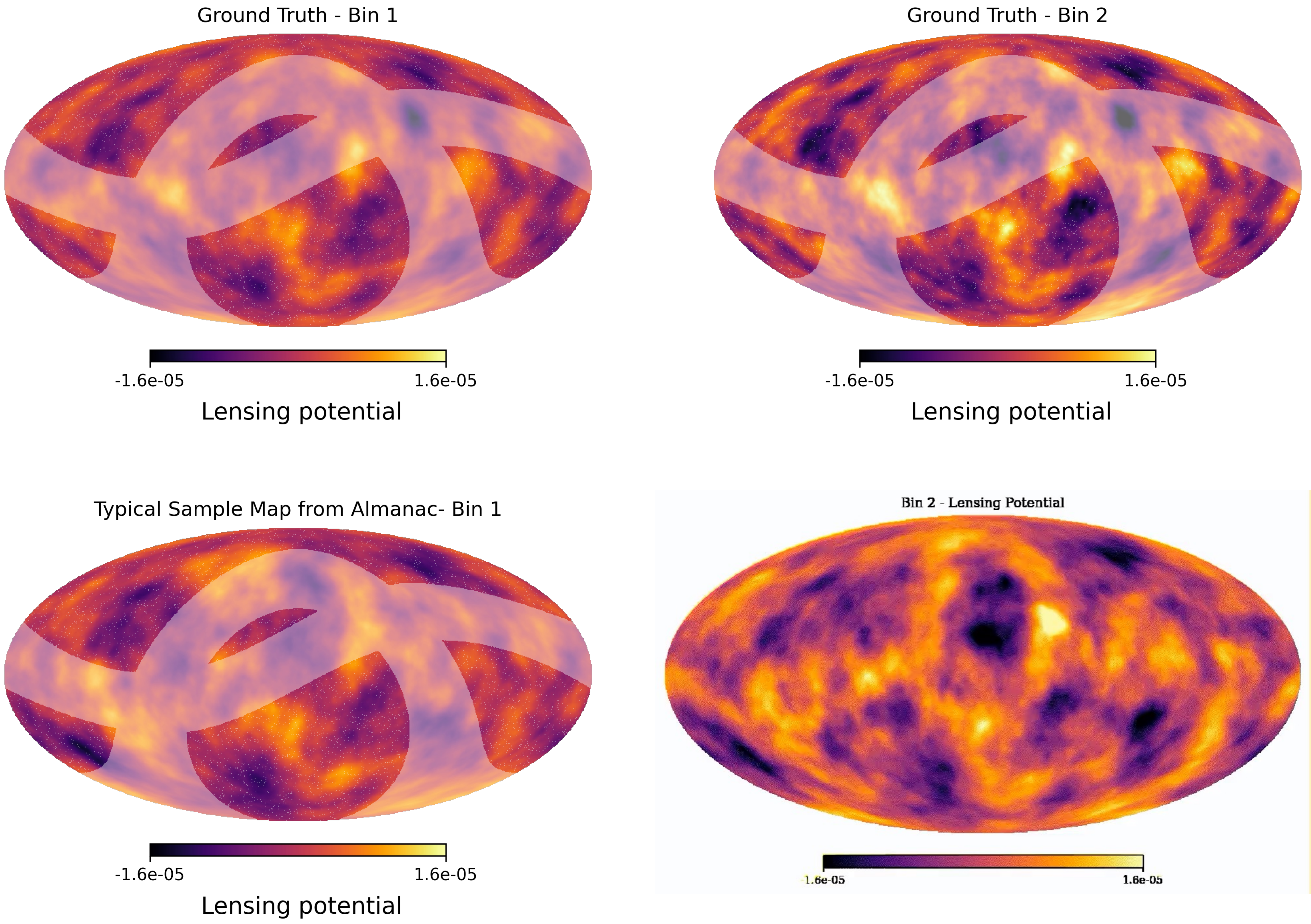
Euclid-like tomographic Weak Lensing

CMB Polarisation

Weak Lensing

Reconstructed Lensing Potential

$$\tilde{\Psi}_{\ell m} = -\frac{2}{\ell(\ell+1)}\kappa_{\ell m}$$

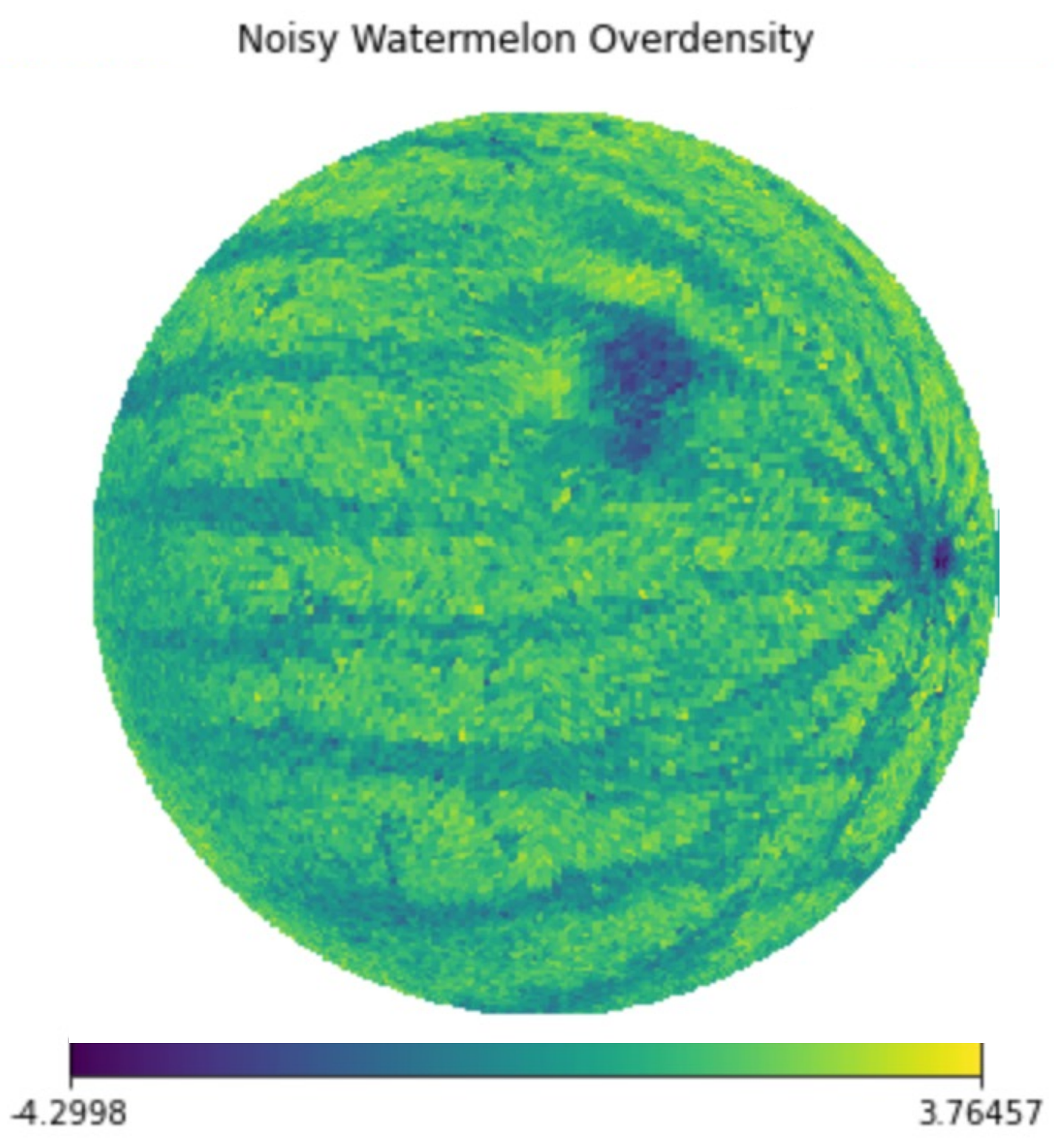


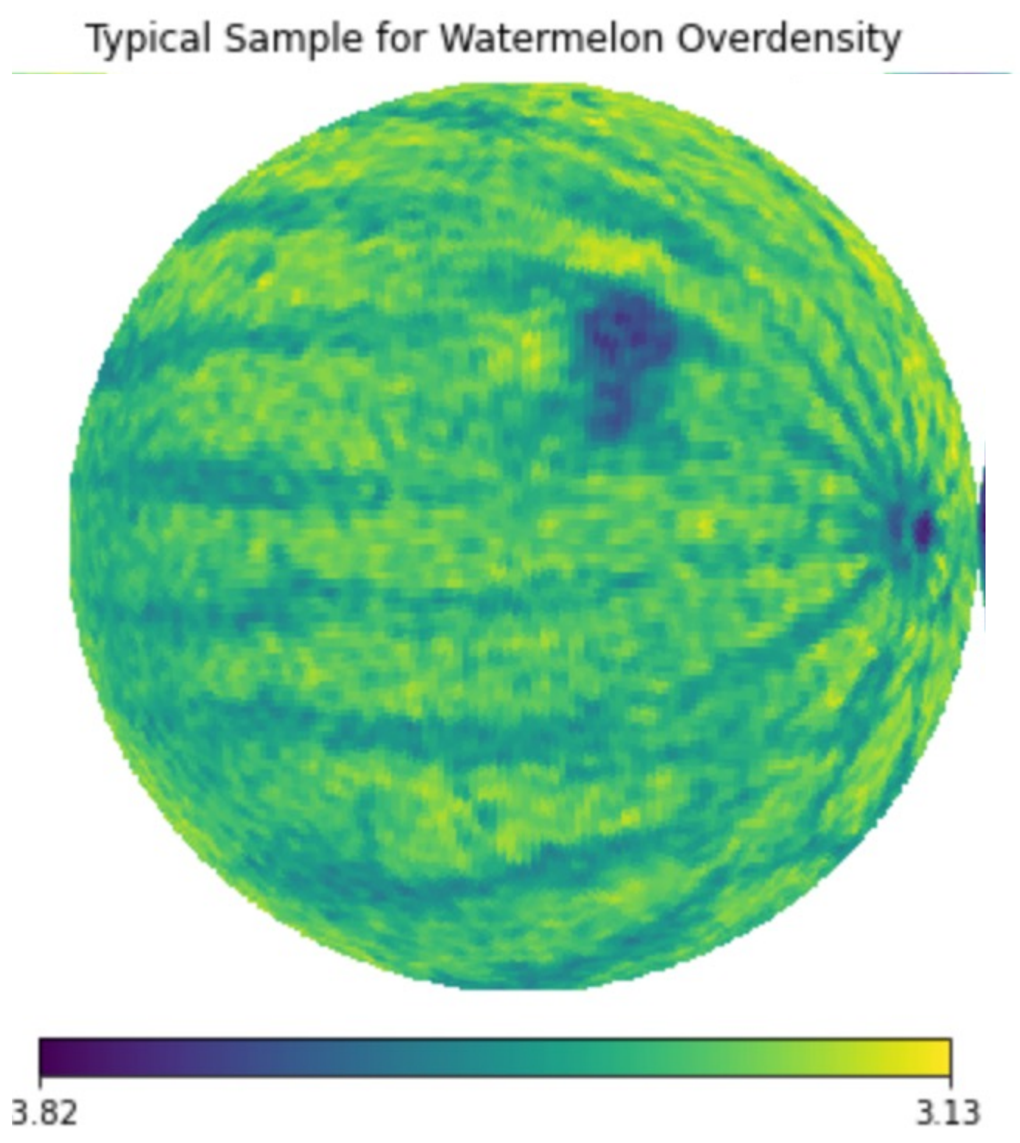
Loureiro et. al, 2023

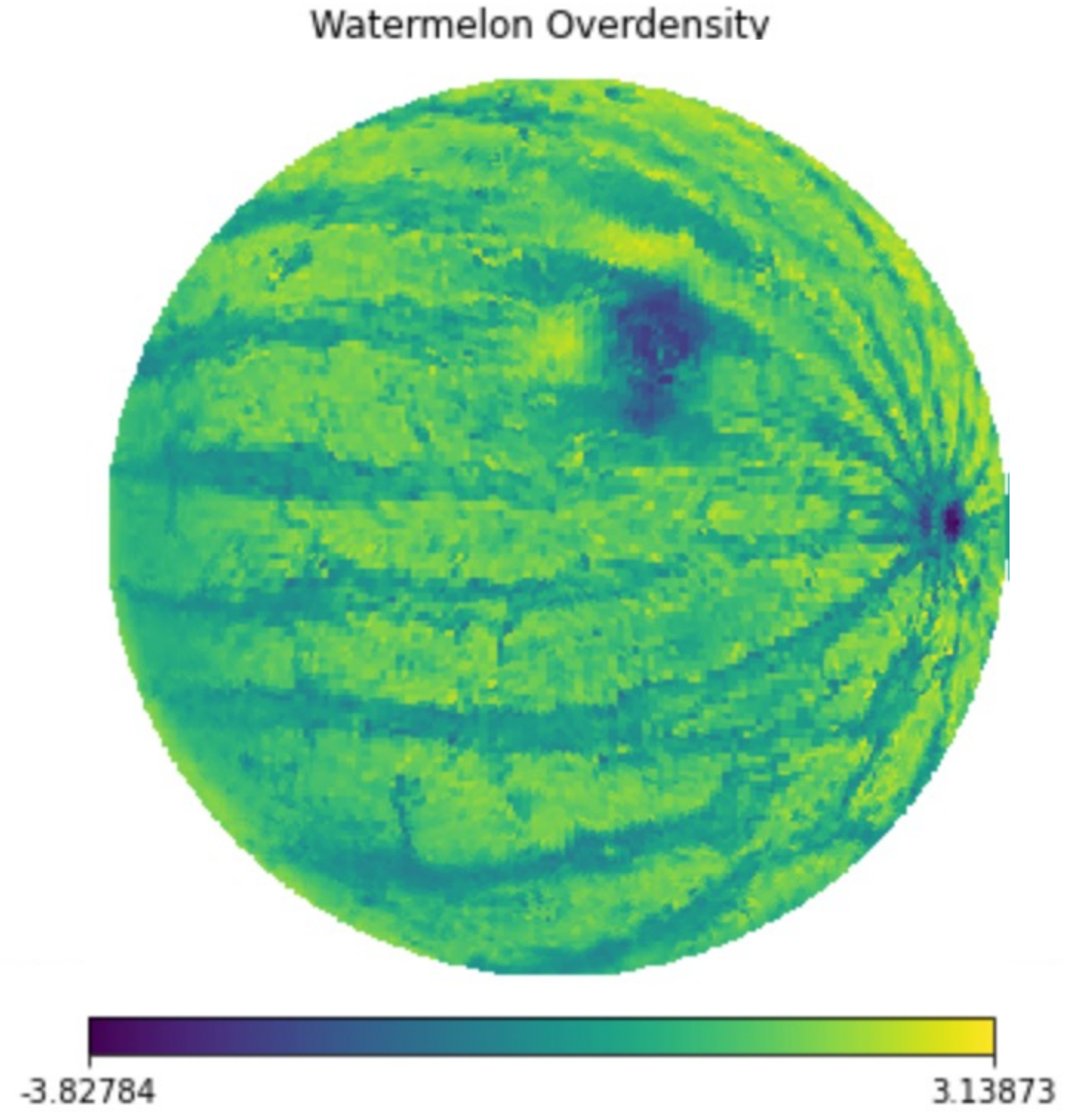
The maps are not necessarily gaussian!

Gaussian prior ≠ Gaussian Posterior

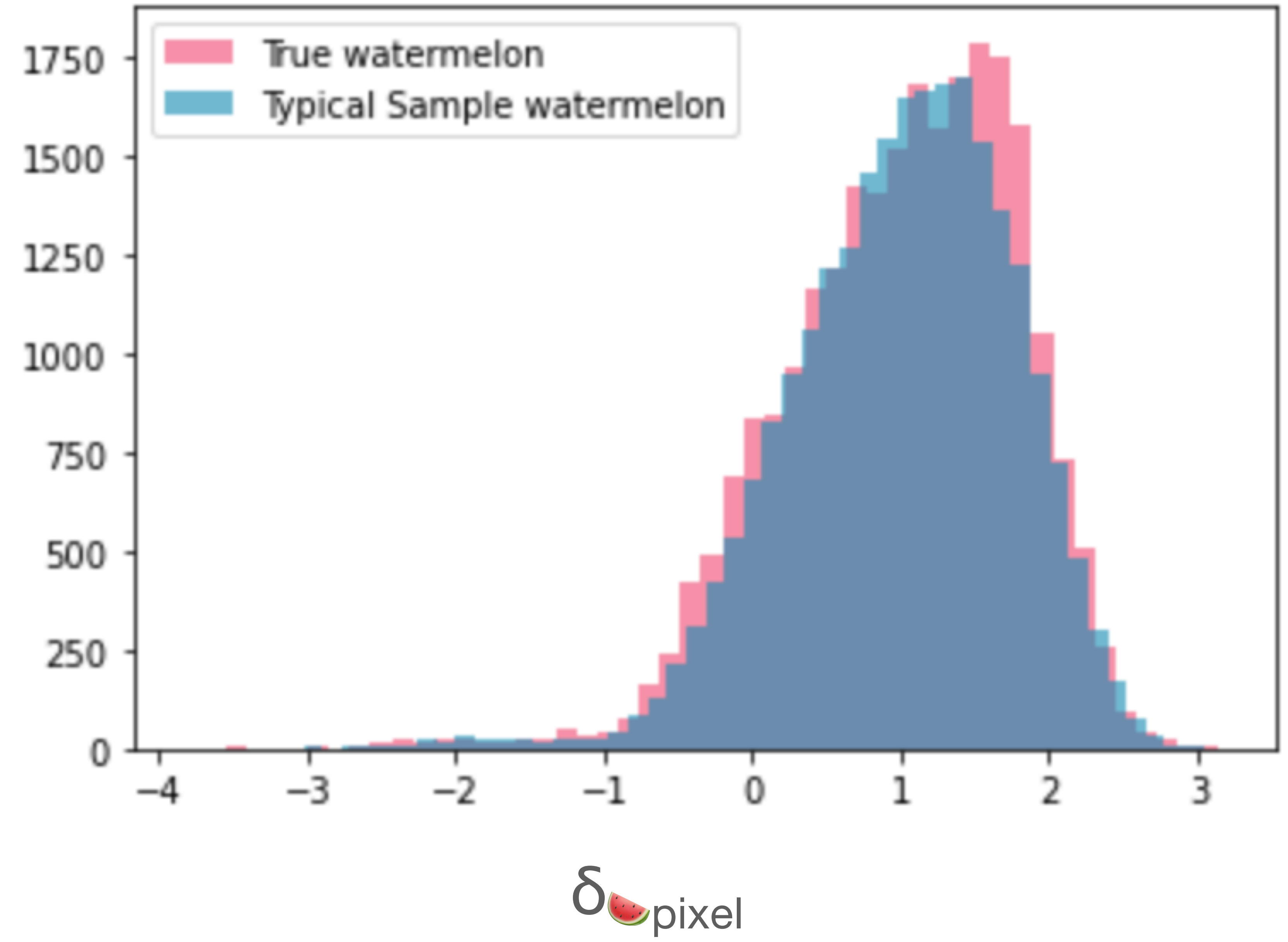
Half a watermellon is “famously non-gaussian”*







Original Watermelon Healpix Map



***Based on Nicolas Tessore’s AstroJoke on twitter about measuring a cantaloupe’s PCL**

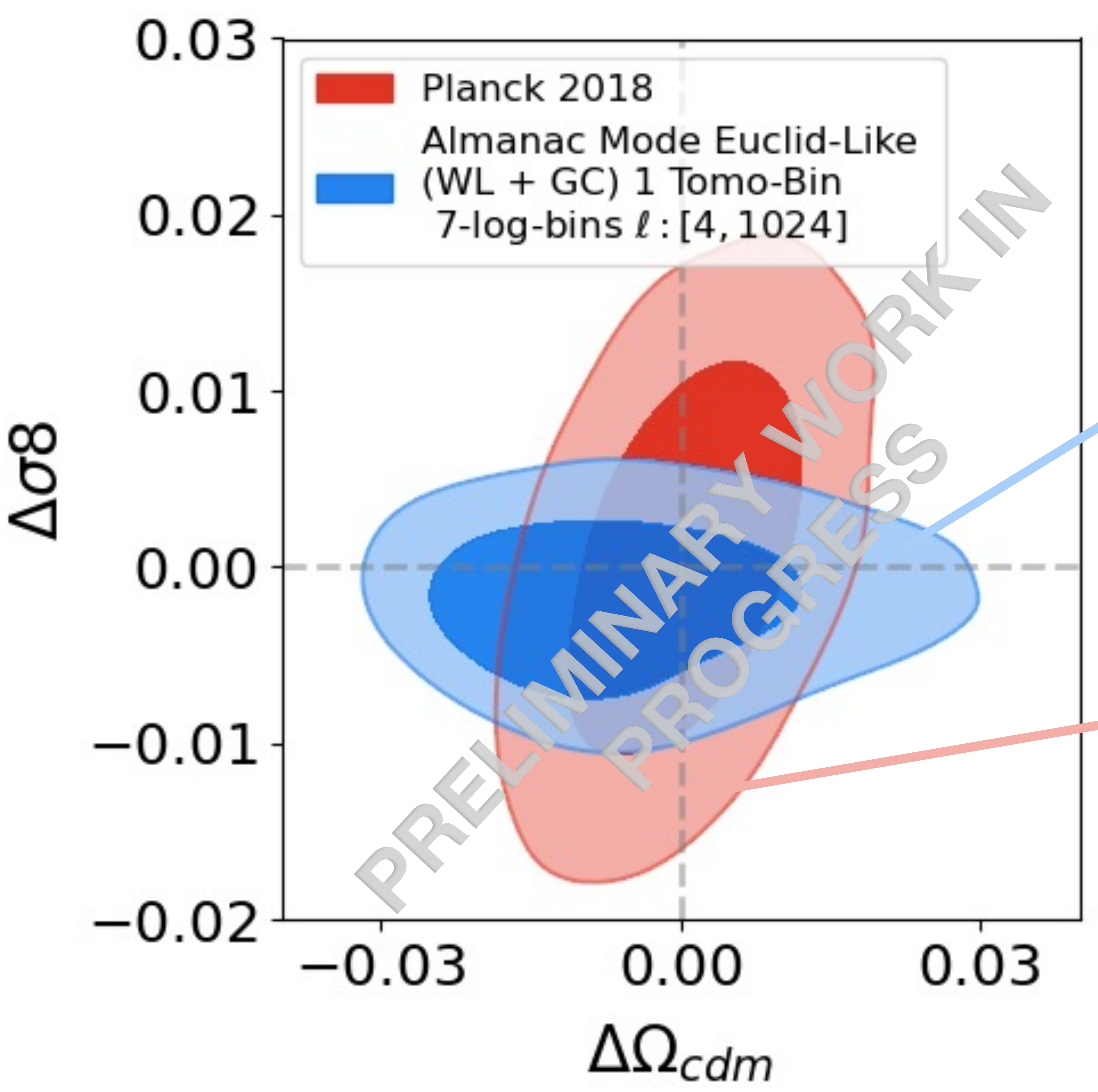
Extracting Cosmology

Using point estimates and normalizing flows

Cosmology with point estimates

Work lead by PhD Candidate Javier Lafaurie

Universiteit Leiden



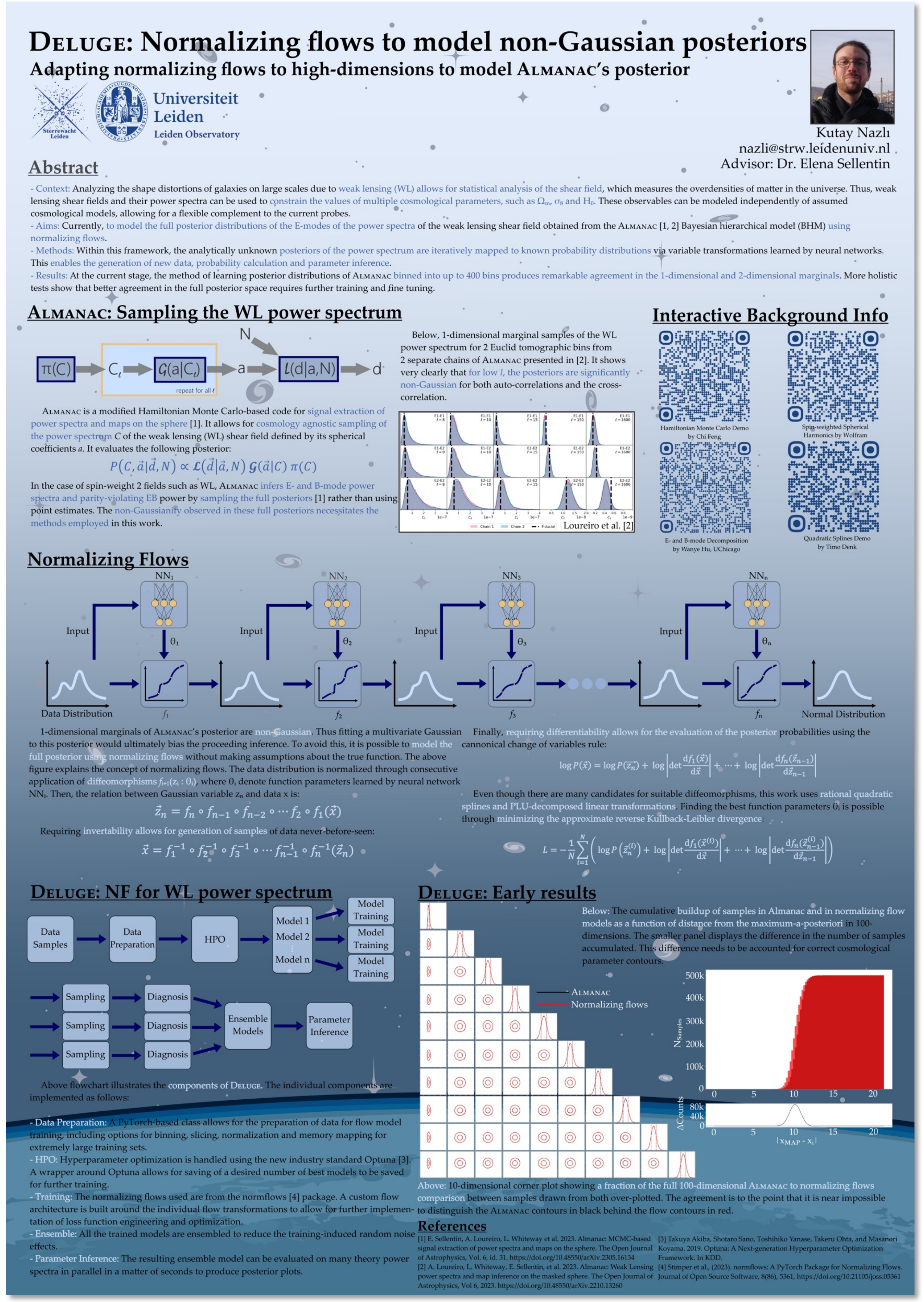
Using Almanac Post. Mode and Covariance:
- Sampling σ_8, Ω_{cdm}, Ω_b, h, n_s
- Other parameters fixed
- Single redshift bin, 1 out of 10 (more coming!)
- Weak Lensing + Galaxy Clustering
- Gaussian covariance: $\mathcal{P}(\theta|d) \propto \mathcal{L}(d|\theta)\pi(\theta)$

Full Planck 2018

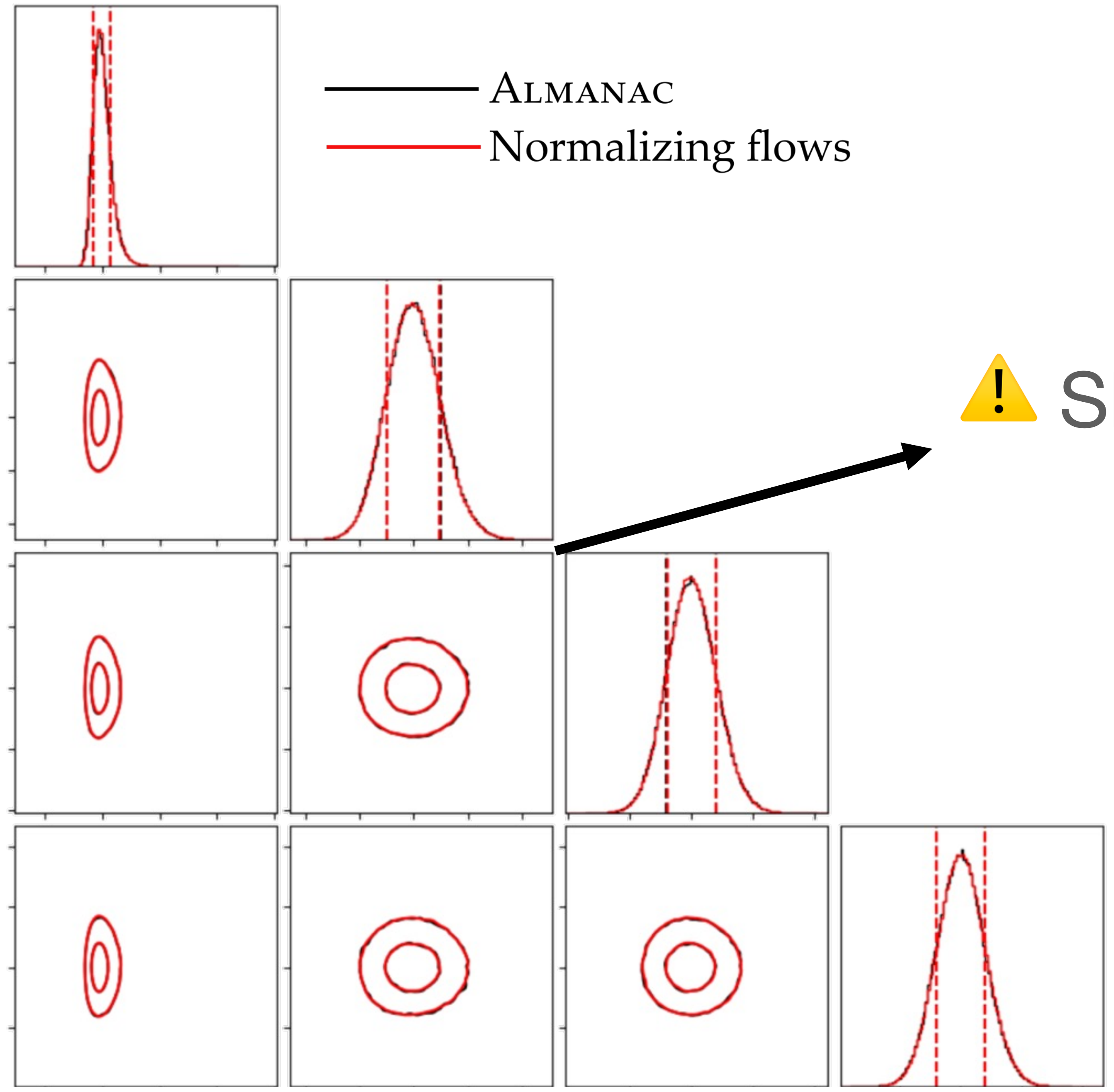
⚠️ *This is an illustrative comparison ; parameter spaces are different (for now)!* ⚠️

Cosmology with Normalising Flows

Work lead by PhD Candidate Kutay Nazli

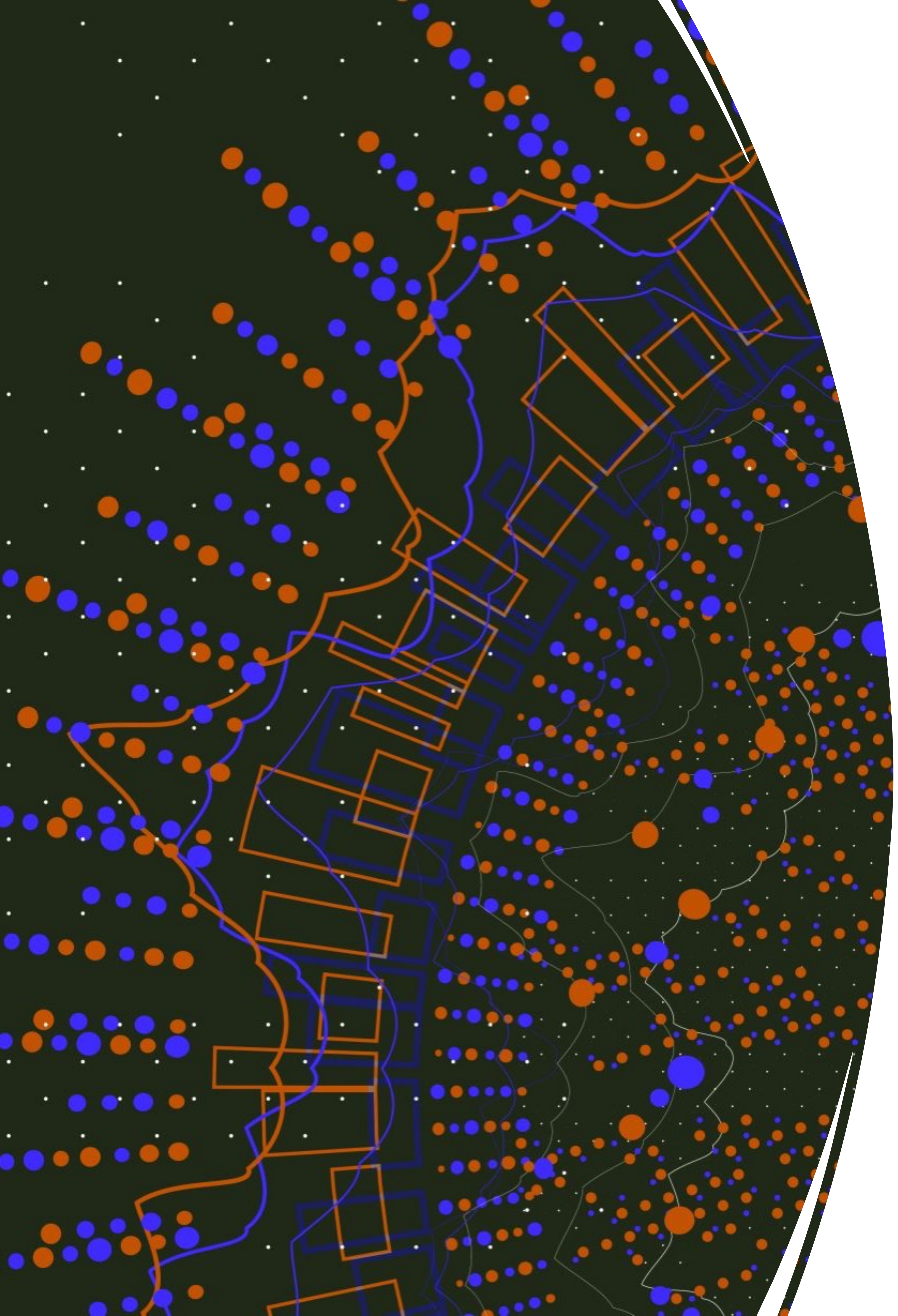


Goal: to obtain a normalising flow representing the full non-gaussian posterior of Almanac angular power spectra



⚠️ Showing her just a small subsection ⚠️
of the 20k dimensional space!

Check out Kutay's poster and chat with him for more!



Summary

- **Almanac uses one of the most optimized samplers to simultaneously sample full-sky cosmological signal fields and their angular power spectra!**
- **Almanac produces data products that are model-independent: we can use them to test ΛCDM, wCDM, w_0w_aCDM, that weird cosmological model from Penrose… anything!**
- **We can already achieve the expected scales for Stage-IV Weak Lensing surveys with accuracy and precision!**

Next:

- Applications to Stage III Survey Data
- **Cosmological analysis from point estimates (Javier Lafaurie)**
- **Cosmological analysis using normalising flows (Kutay Nazli)**
- Primordial non-gaussianities with Weak Lensing Fields

Interested?

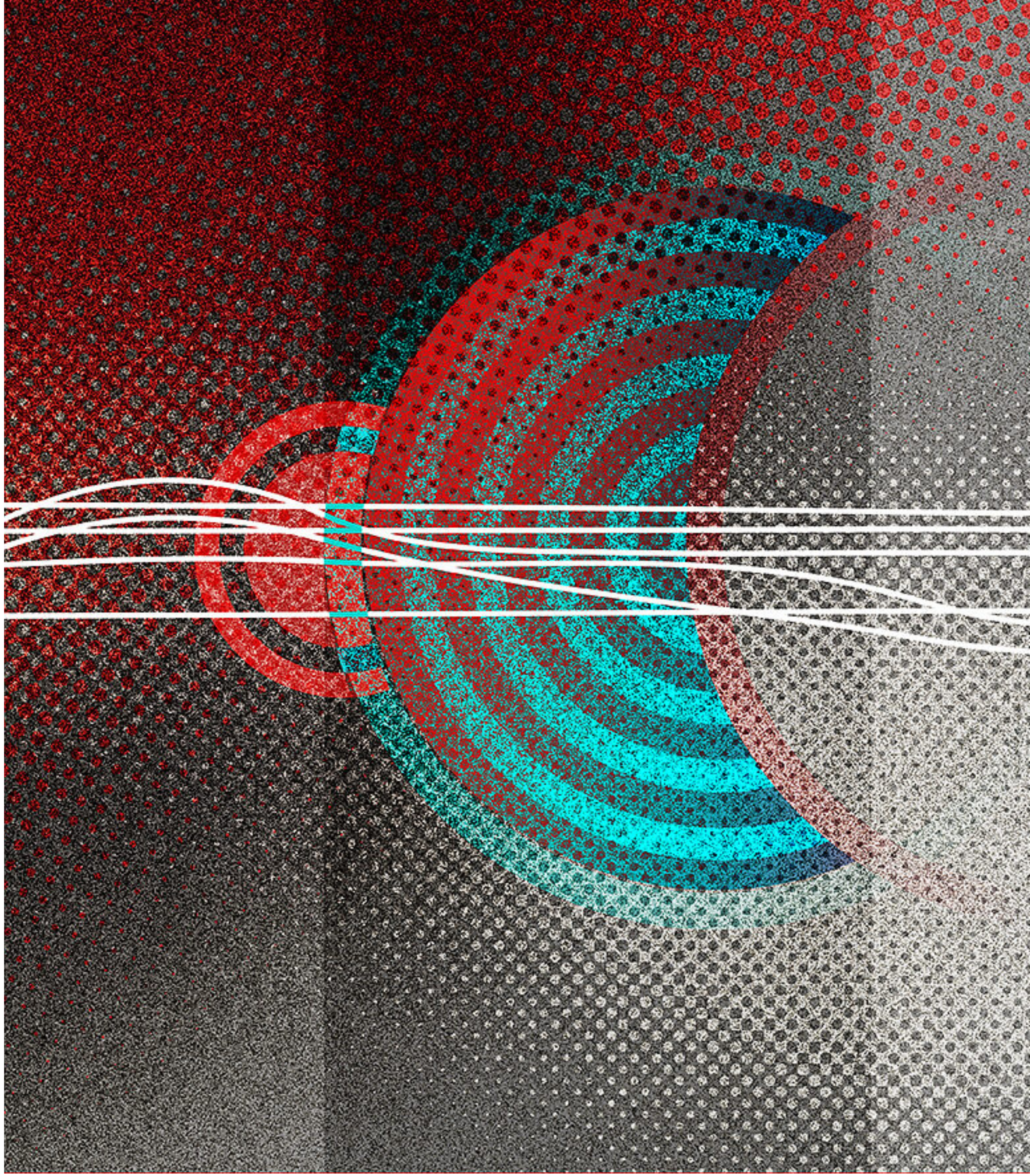
Come talk to us here!

That's me, (obviously…)

Prof. Elena Sellentin

Kutay Nazli

Prof. Alan Heavens



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