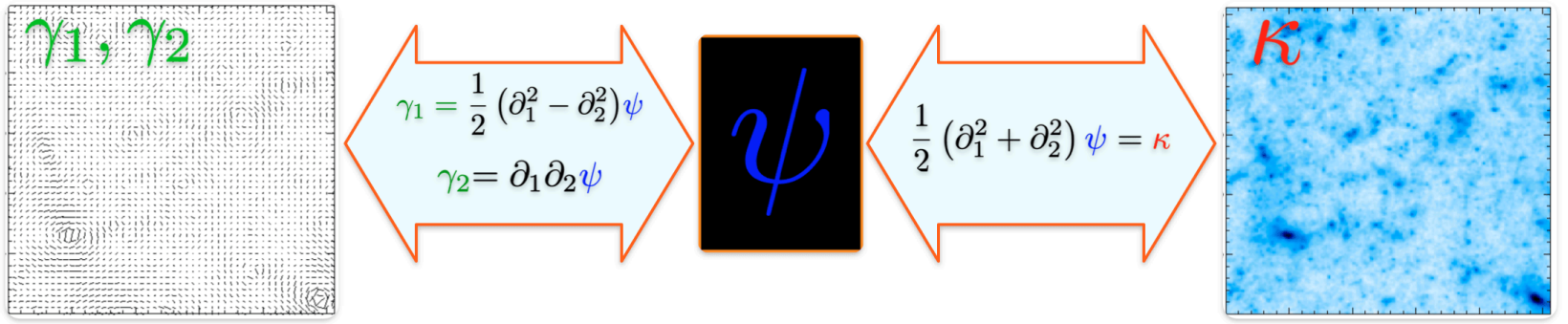
Mass mapping and cosmological inference with higher-order statistics

Andreas Tersenov

ARGOS-TITAN-TOSCA workshop, July 8, 2025

CosmoStat

Weak Lensing - Relation between κ and γ



- From **convergence** to **shear**: $\gamma_i = \hat{P}_i \kappa$
- From **shear** to **convergence**: $\kappa = \hat{P}_1 \gamma_1 + \hat{P}_2 \gamma_2$

$$\hat{P}_1(k) = \frac{k_1^2 - k_2^2}{k^2}, \quad \hat{P}_2(k) = \frac{2k_1 k_2}{k^2}$$

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- Shear measurements are discrete, **noisy**, and **irregularly sampled**
- We actually measure the **reduced shear**
- Masks and integration over a subset of $\mathbb{R}_2$ lead to border errors ⇒ **missing data problem**
- Convergence is recoverable up to a constant ⇒ **mass-sheet degeneracy problem**

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Mass mapping is an ill-posed inverse problem

Different algorithms have been introduced, with different reconstruction fidelities, in terms of RMSE

Motivating this project:

- The various algorithms have **different RMSE** performance
- In cosmology we *don't care about RMSE* of mass maps, but only about the resulting **cosmological parameters**

$\Rightarrow$ *This should be our final benchmark!*

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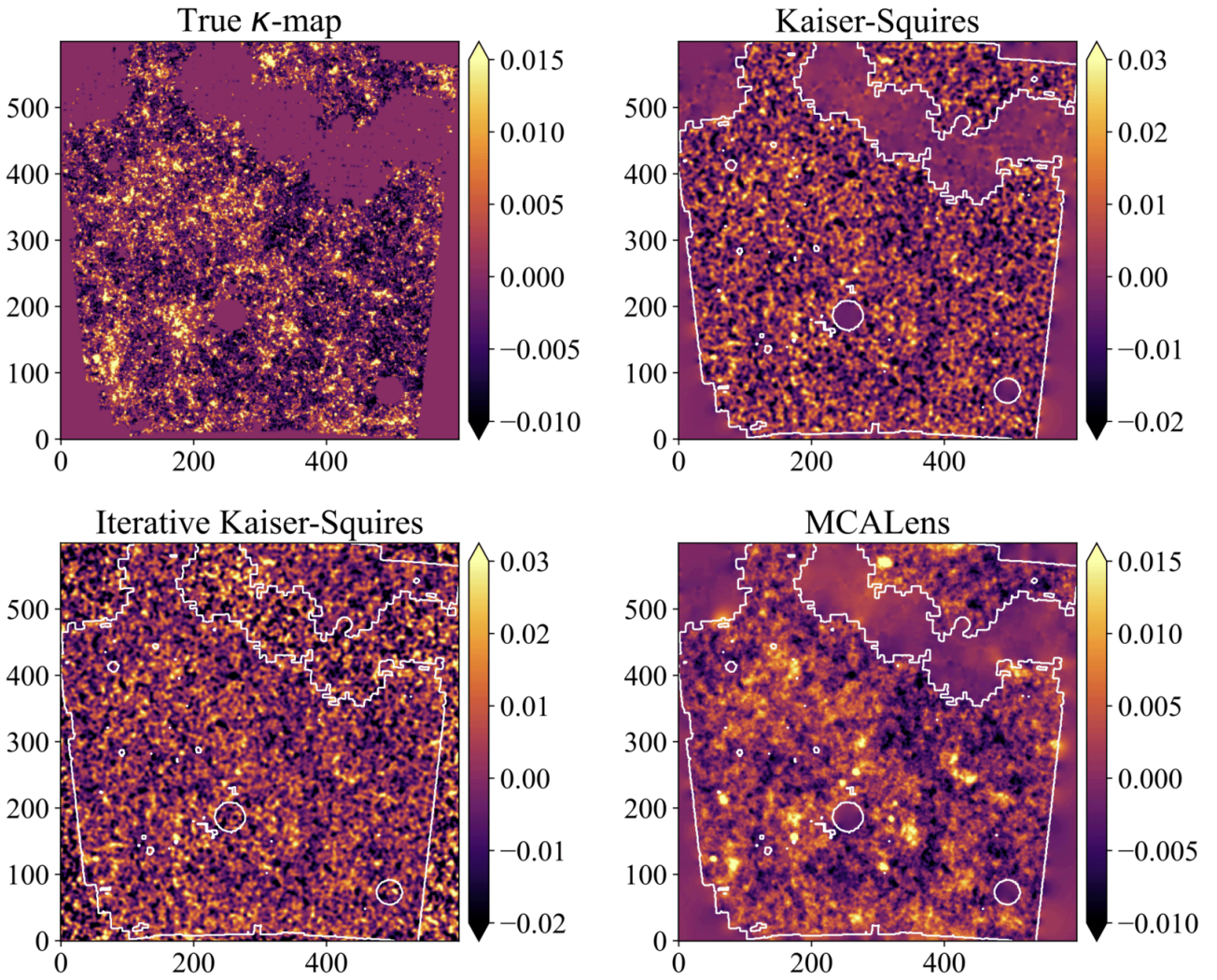
⇒ *This should be our final benchmark!*

So... does the choice of the mass-mapping algorithm have an impact on the final inferred cosmological parameters?

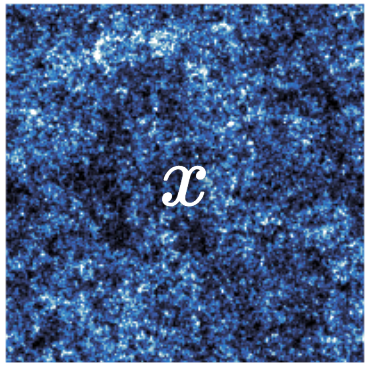
Or as long as you apply the same method to both observations and simulations it won't matter?

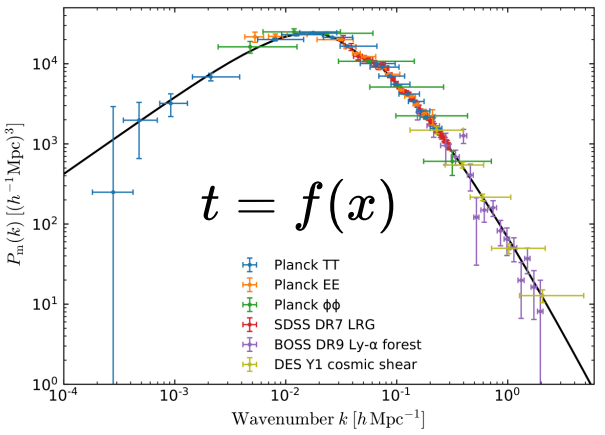
cosmoSLICS mass maps

Method	RMSE ↓
KS	1.1×10^{-2}
iKS	1.1×10^{-2}
MCALens	9.8×10^{-3}



How to constrain cosmological parameters?





For which we have/assume an analytical likelihood function

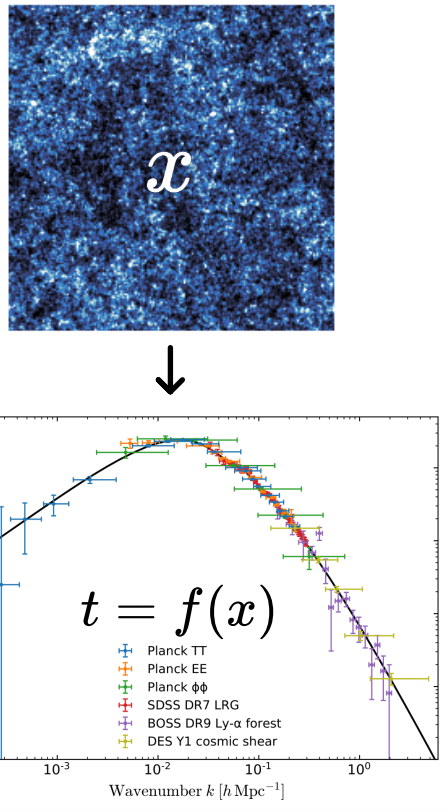
$$p\left(t = t_0 \mid \theta\right)$$

Likelihood → connects our compressed observations to the cosmological parameters

$$\underbrace{p\left(\theta \mid t = t_0\right)}_{\text{posterior}} \propto \underbrace{p\left(t = t_0 \mid \theta\right)}_{\text{likelihood}} \underbrace{p(\theta)}_{\text{prior}}$$

2pt vs higher-order statistics

The traditional way of constraining cosmological parameters misses the non-Gaussian information in the field.



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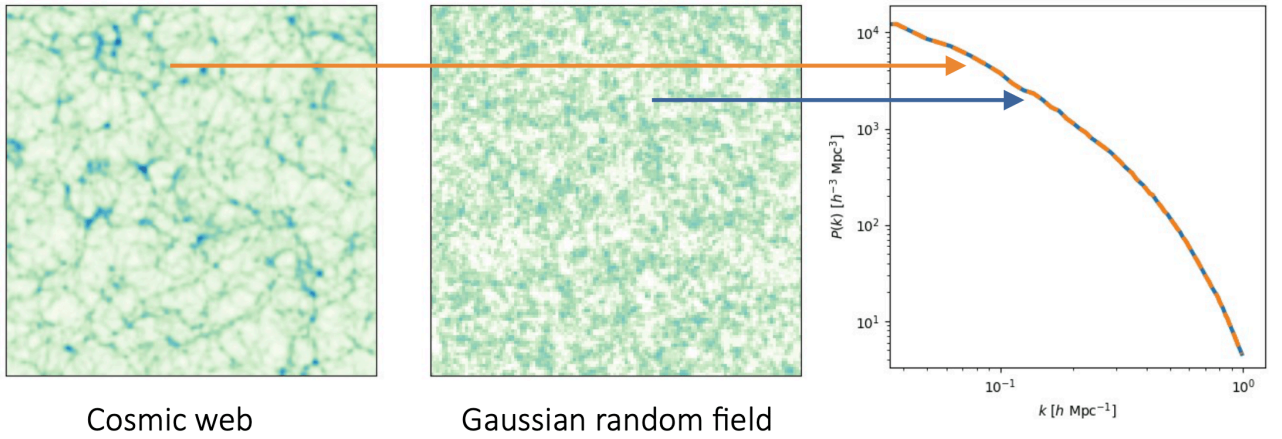
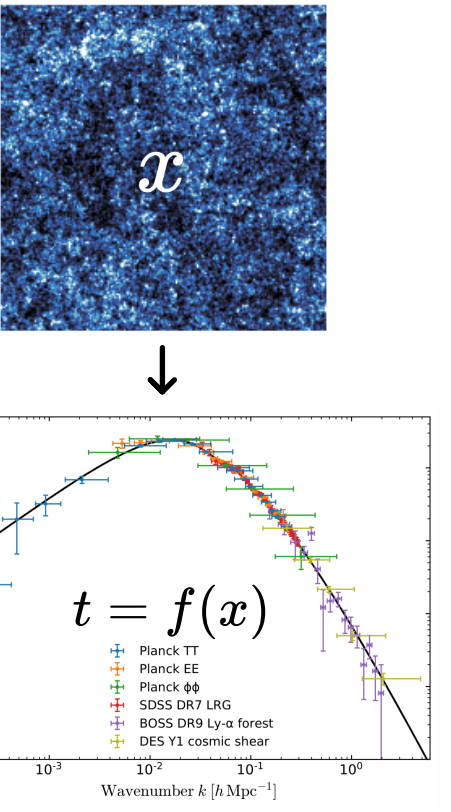


Cosmic web

Gaussian random field



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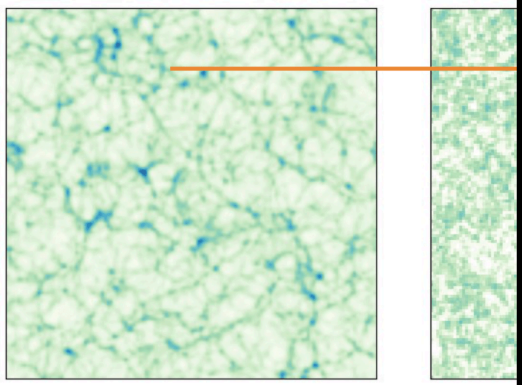

Cosmic web

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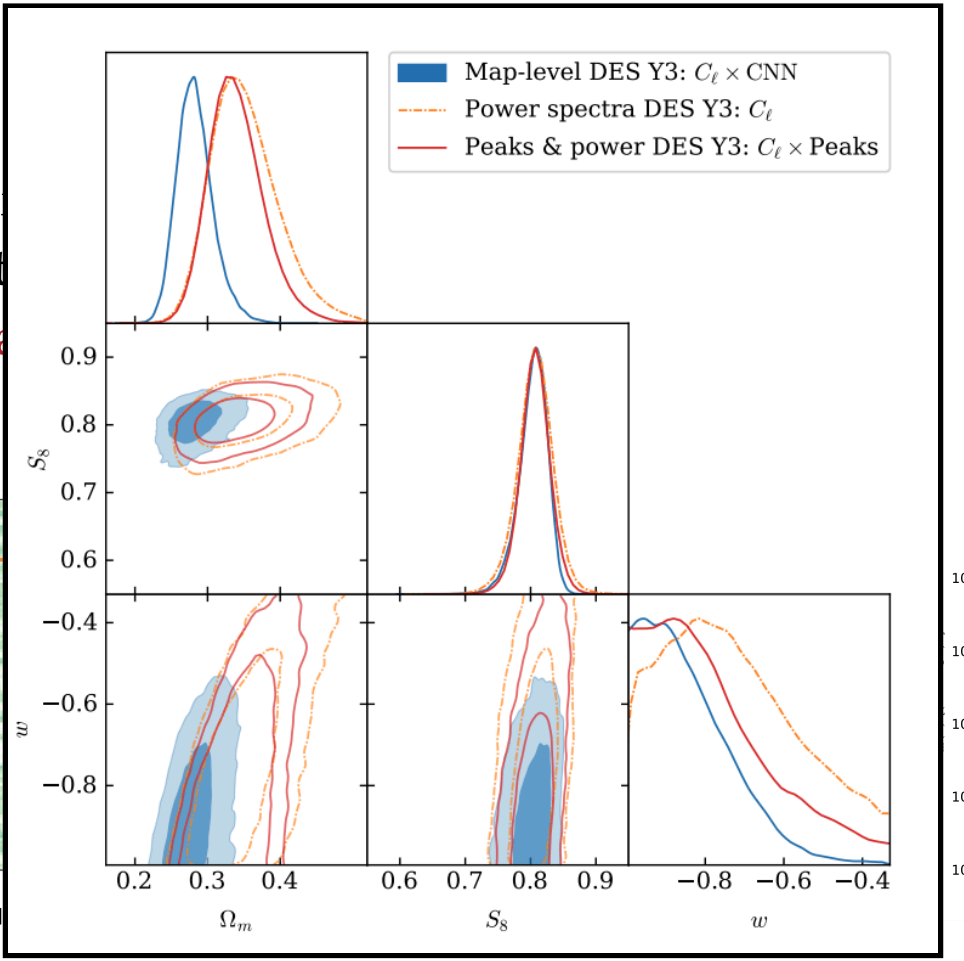
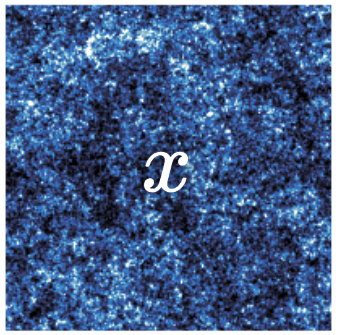
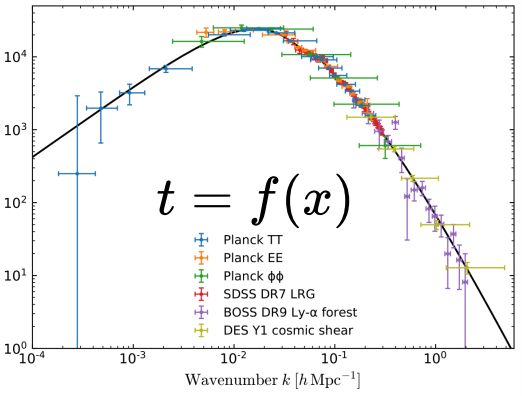


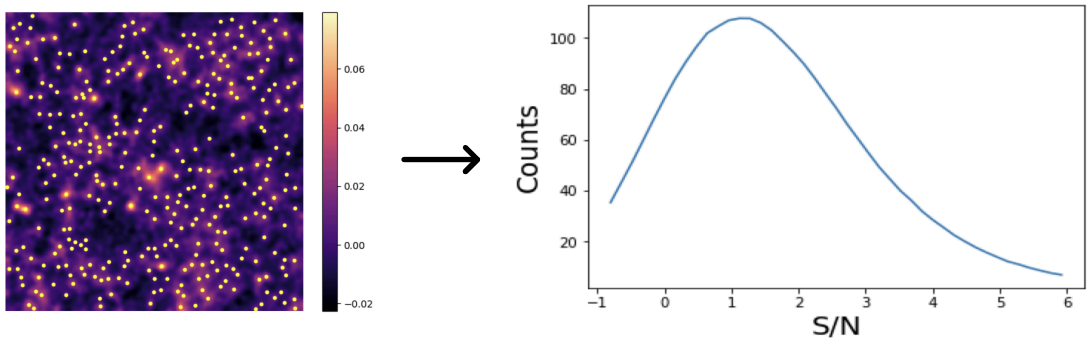
DES Y3 Results





Higher Order Statistics: **Peak Counts**

- **Peaks**: local maxima of the SNR field
- Peaks trace regions where the value of $\boldsymbol{\kappa}$ **is high** → they are associated to **massive structures**



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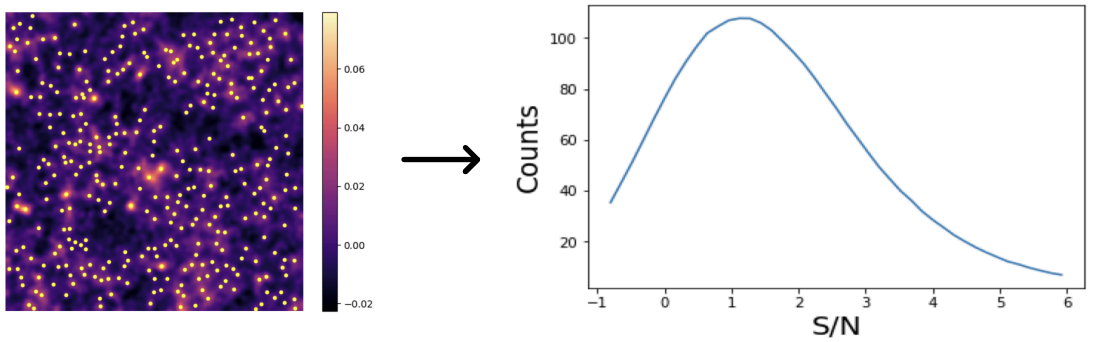
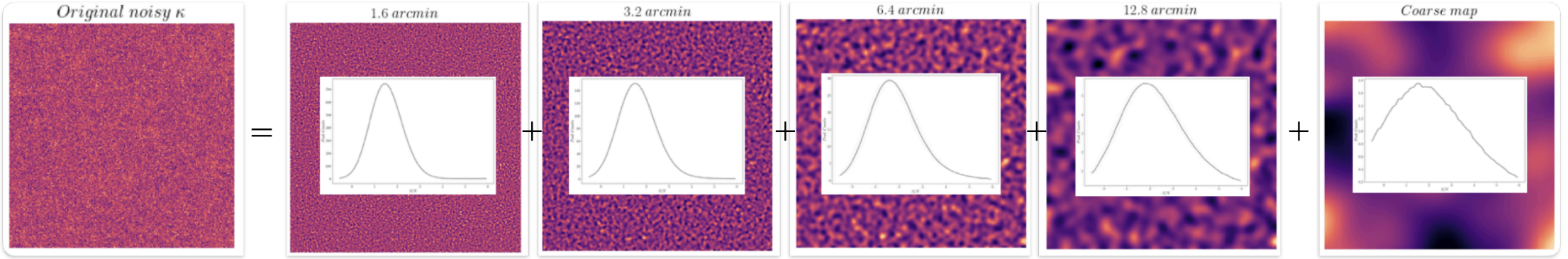


Multi-scale (wavelet) peak counts



Results

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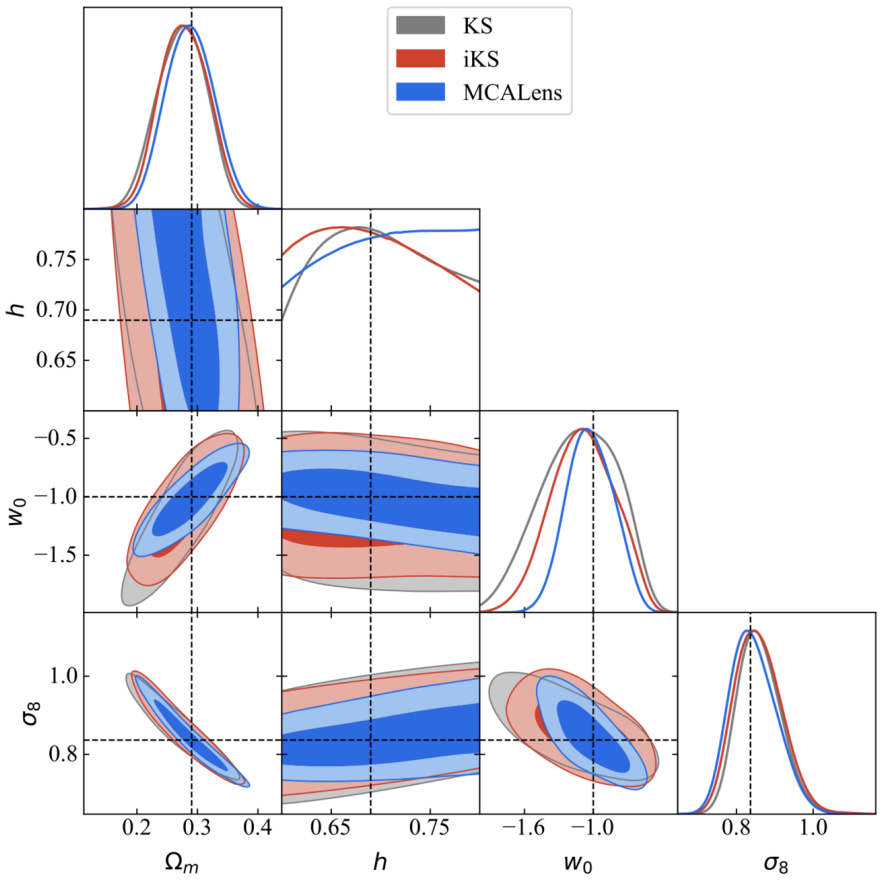
Mono-scale peaks



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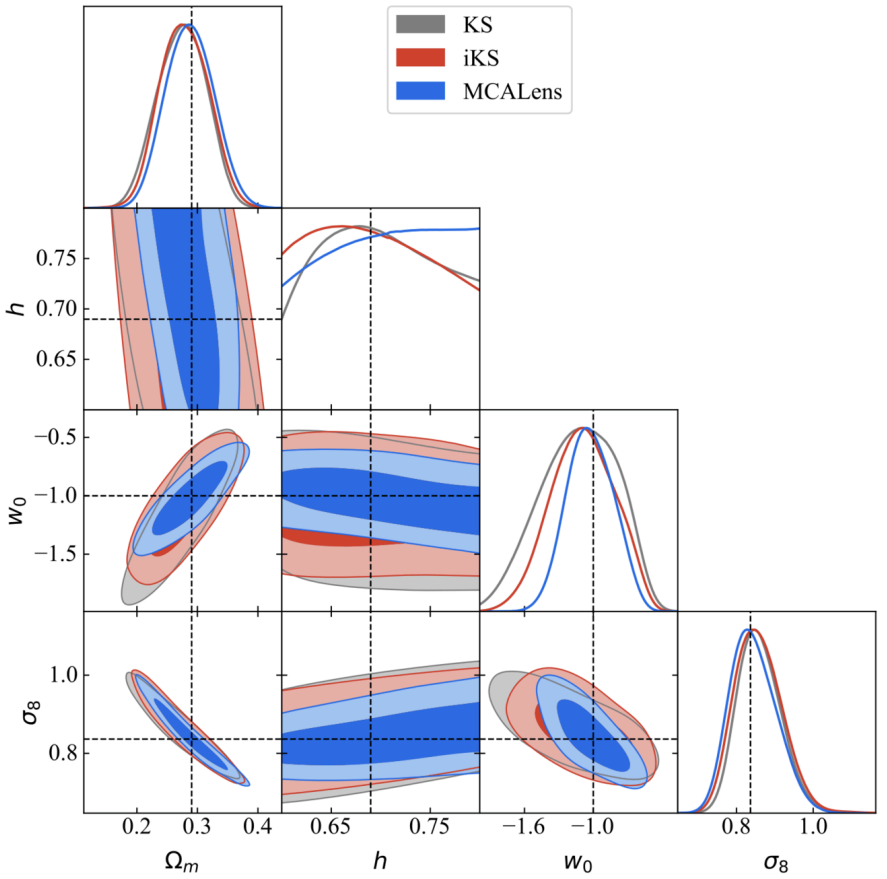

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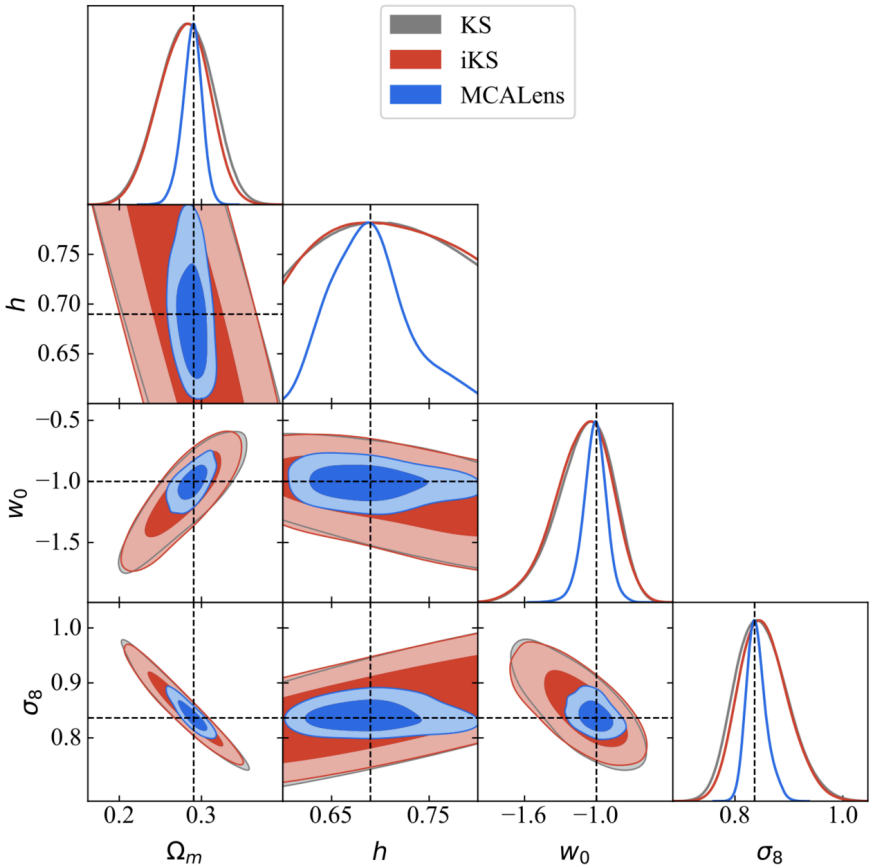

Where does this improvement come from?

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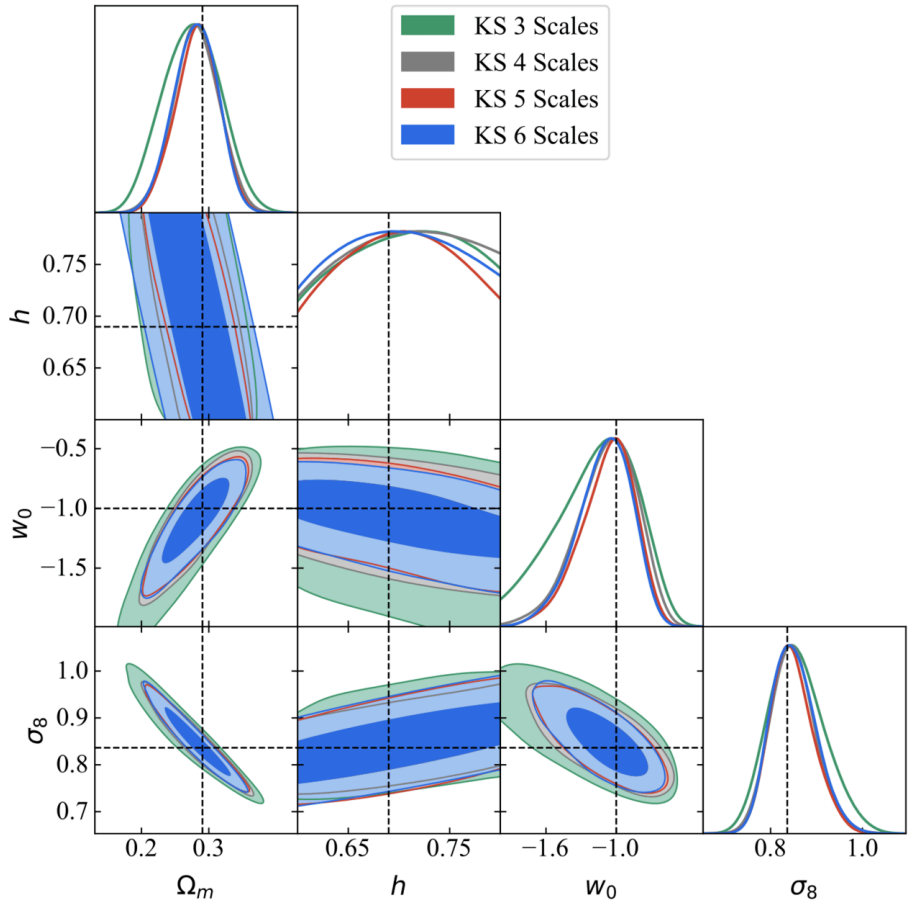
Kaiser-Squires



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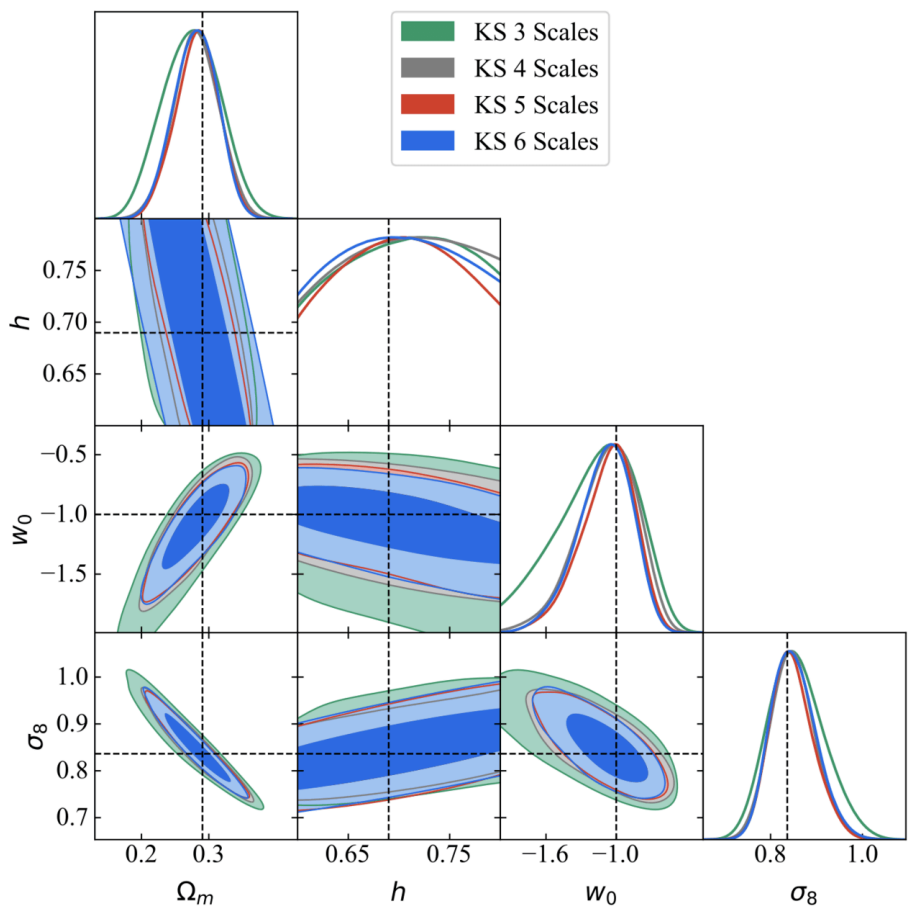
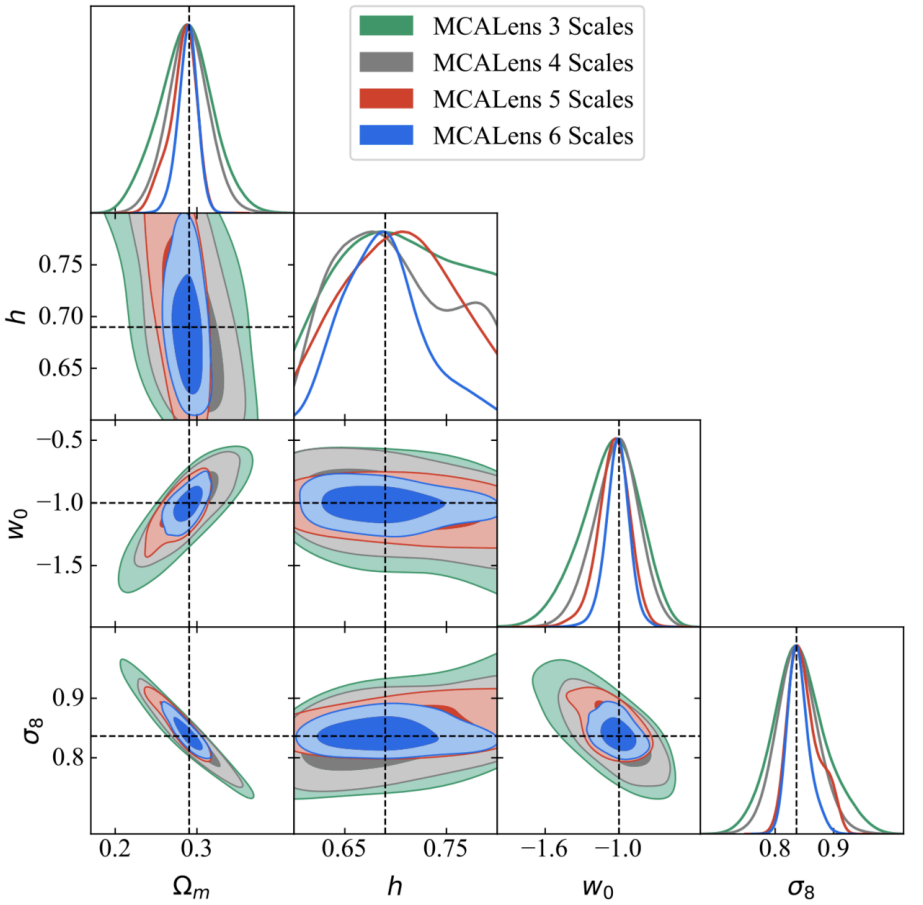


MCALens



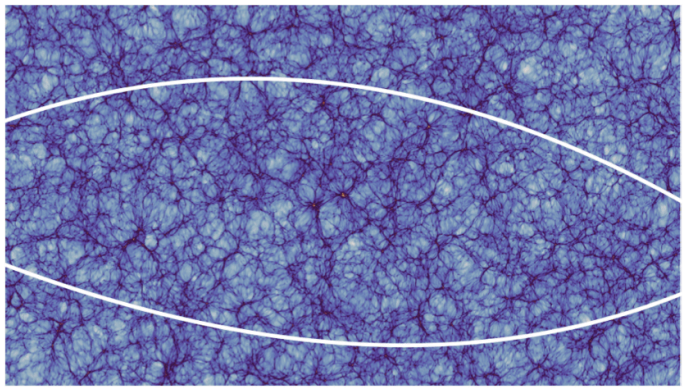
Baryonic effects

- Effects that stem from astrophysical processes involving **ordinary matter** (gas cooling, star formation, AGN feedback)
- They modify the matter distribution by redistributing gas and stars within halos.
- Suppress matter clustering on small scales
- Depend on the cosmic baryon fraction and cosmological parameters.
- Must be modeled/marginalized over to avoid biases in cosmological inferences from WL.

0:00

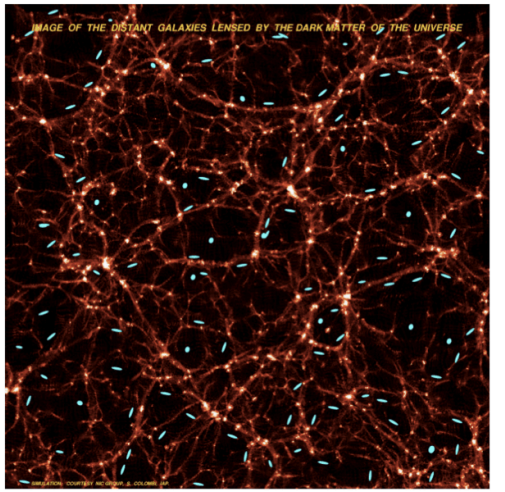
Baryonic impact on LSS statistics

Far galaxies



Large Scale Structure: DM + baryons

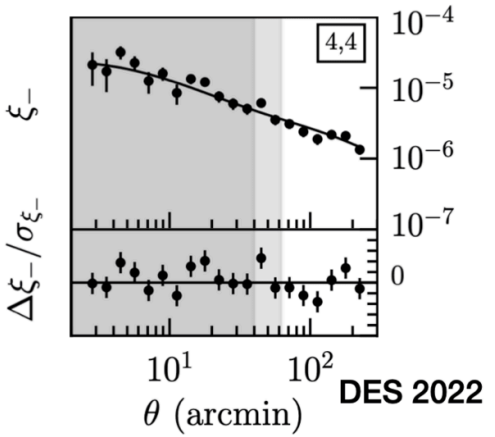
Observer



Courtesy of NYC group, S.Colombi

Correlation of galaxy shapes due to LSS gravity

$$C_{\gamma_i\gamma_j}(\ell) = \int_0^{\chi_H} \frac{g_i(\chi) g_j(\chi)}{\chi^2} P\left(\frac{\ell}{\chi}, z(\chi)\right) d\chi$$



Credit: Giovanni Aricò

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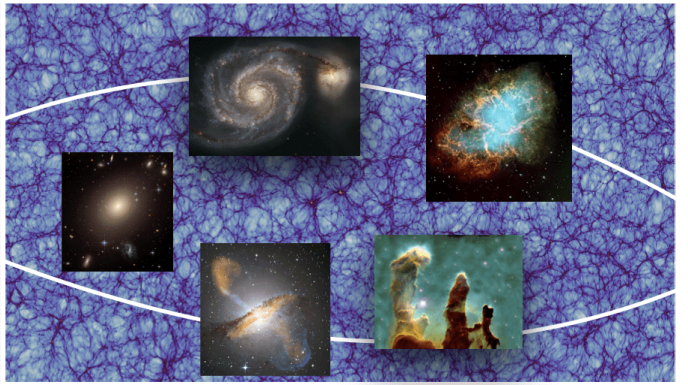

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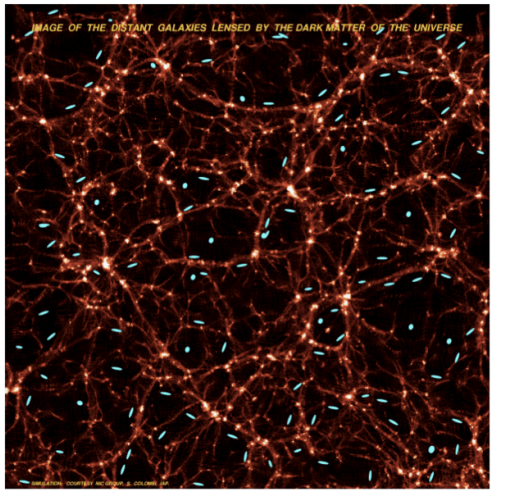

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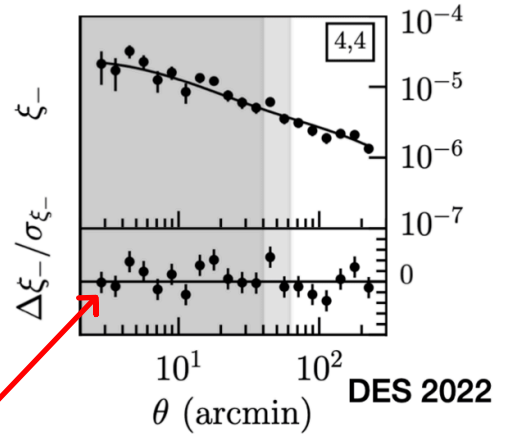

baryonic effects in *P(k)*

Credit: Giovanni Aricò

Project: Testing impact baryonic effects on WL HOS

Idea - Explore two things:

- Information content of summary statistics as a function of scale cuts
- Testing the impact of baryonic effects on posterior contours

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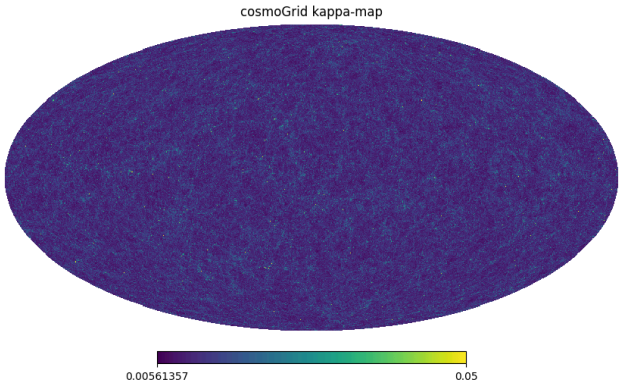
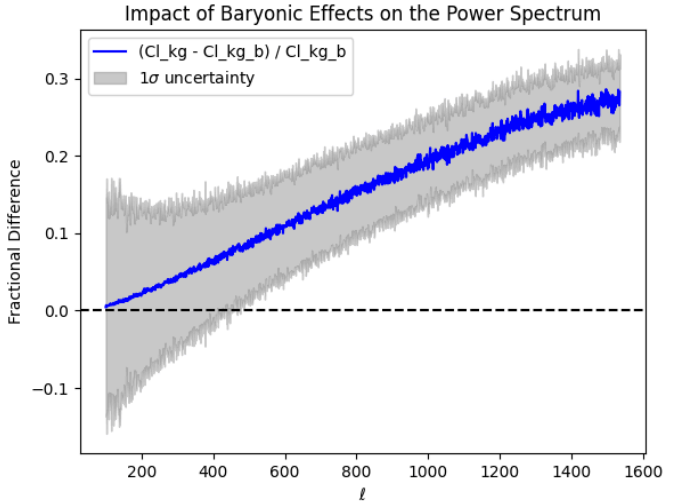
This will show:

1. On what range of scales can the different statistics be used without explicit model for baryons
2. Answer the question: **how much extra information beyond the PS** these statistics can access in practice

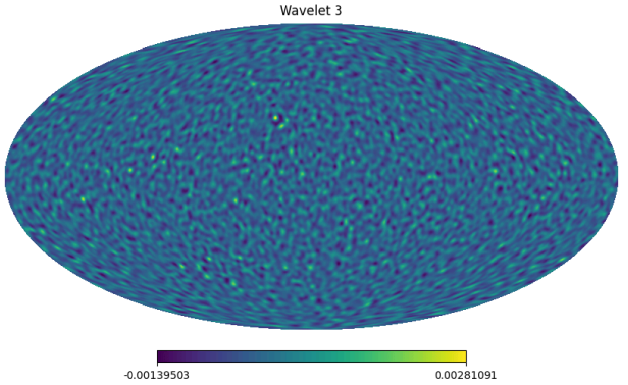
cosmoGRID simulations

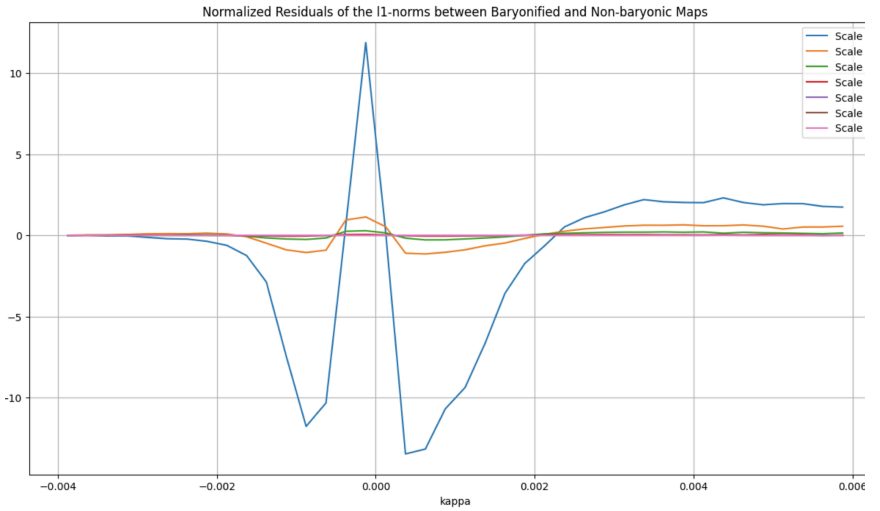
Power Spectrum



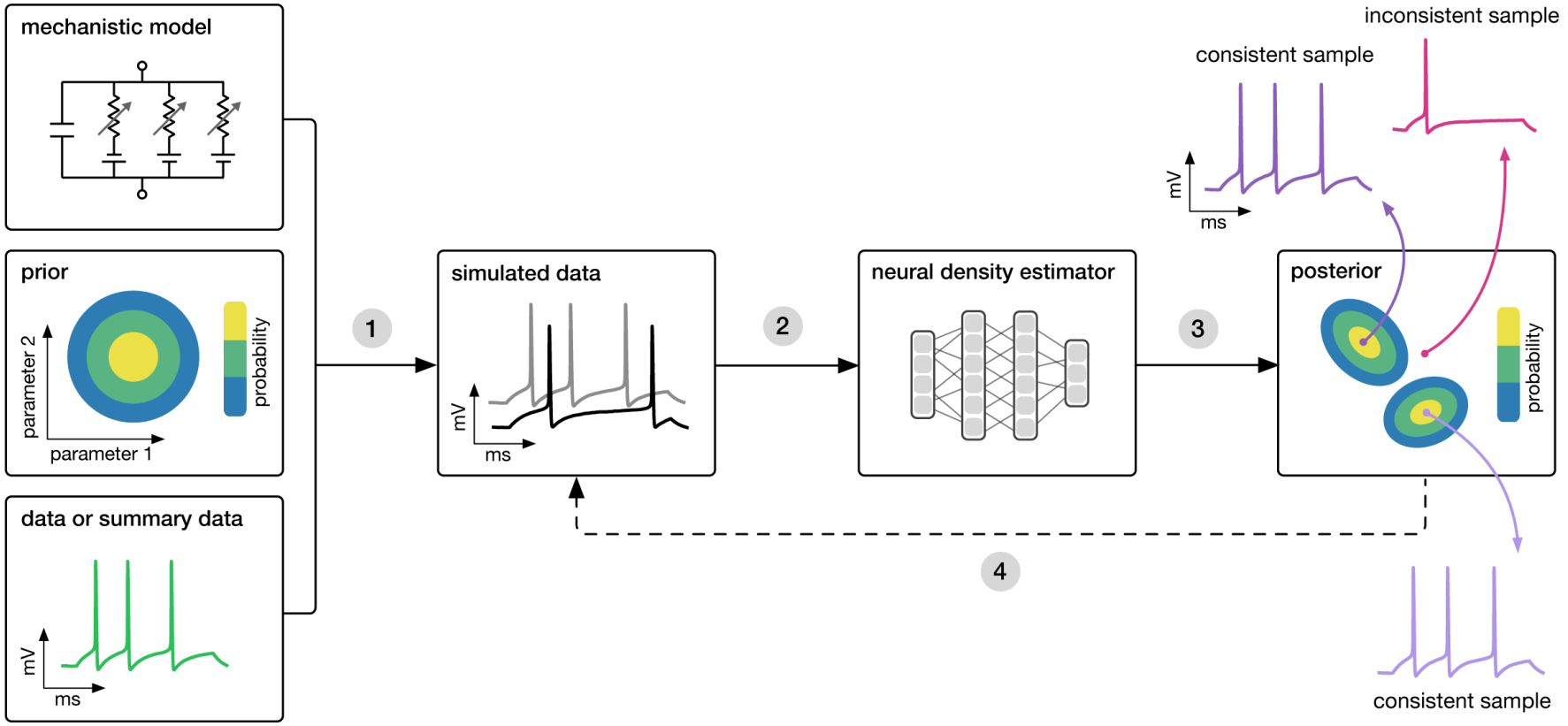


Wavelet l1-norm

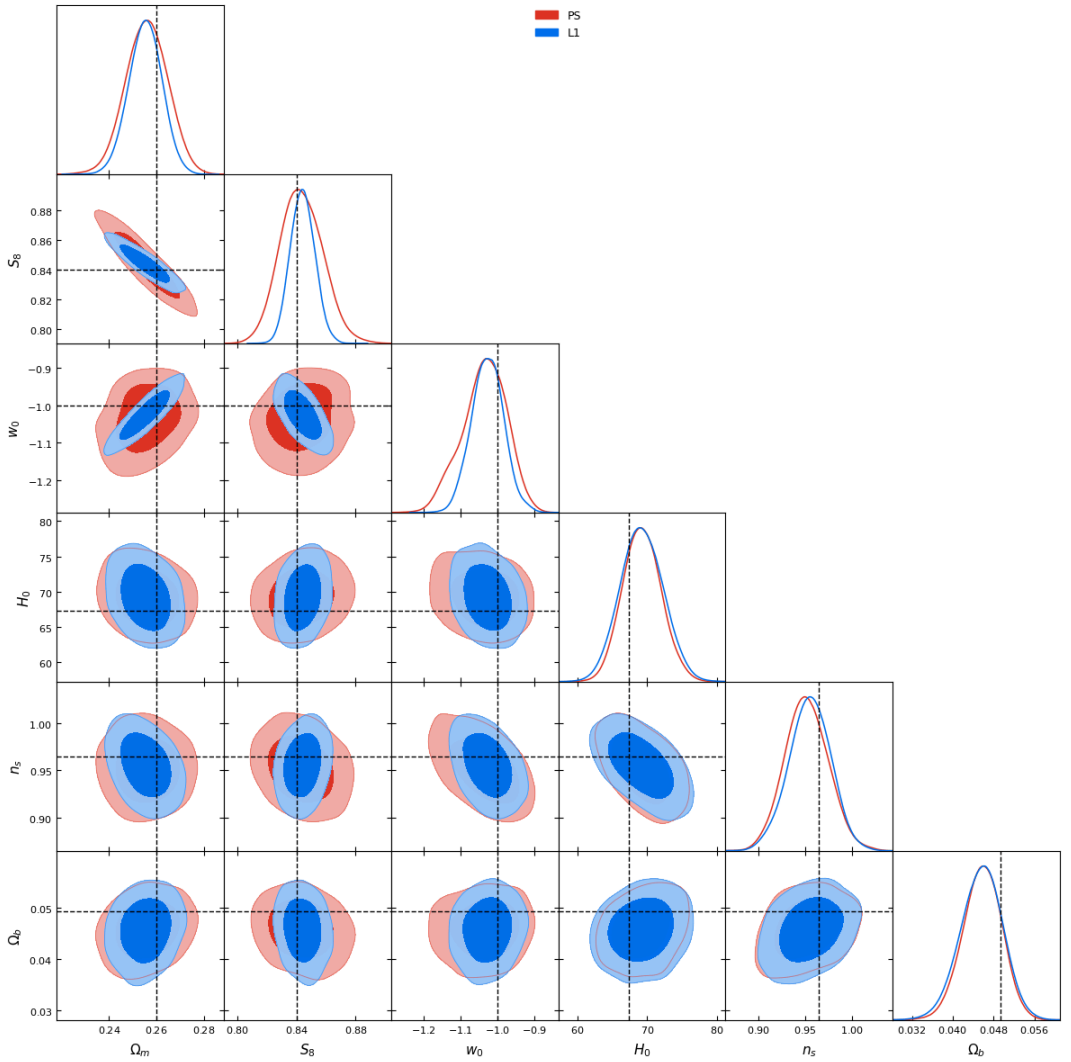




Inference method: SBI

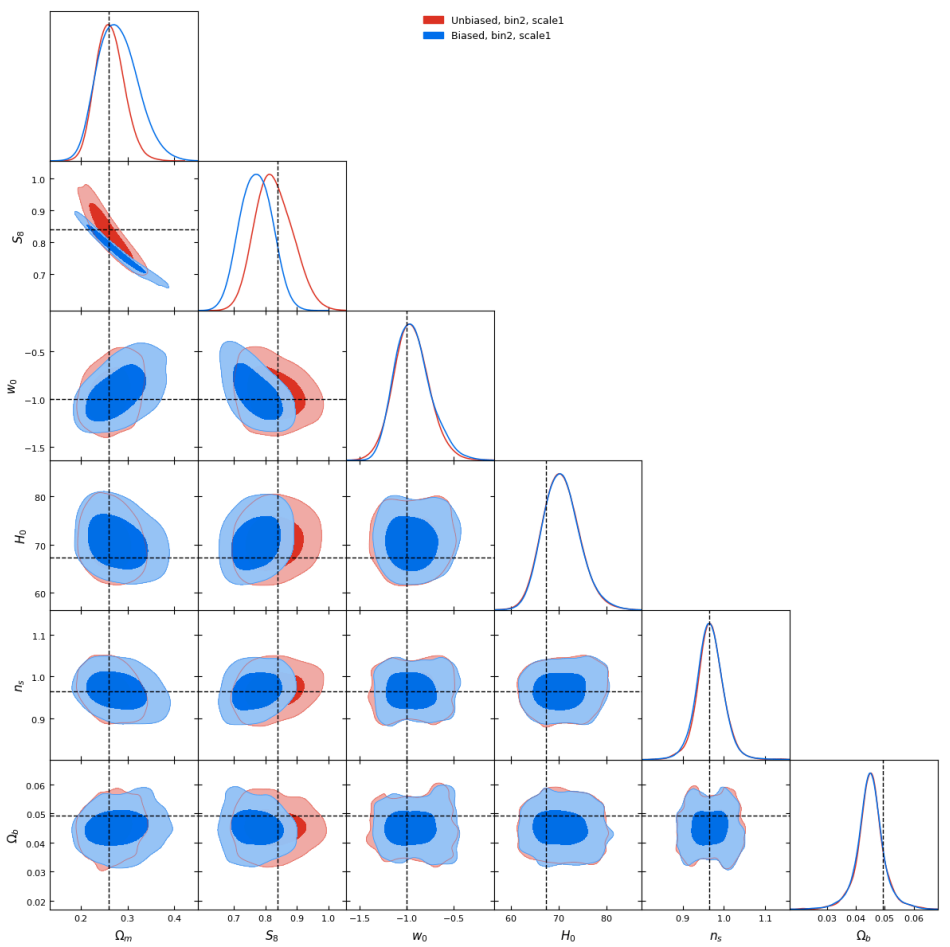


Power spectrum vs l1-norm (scale: ~10arcmin)

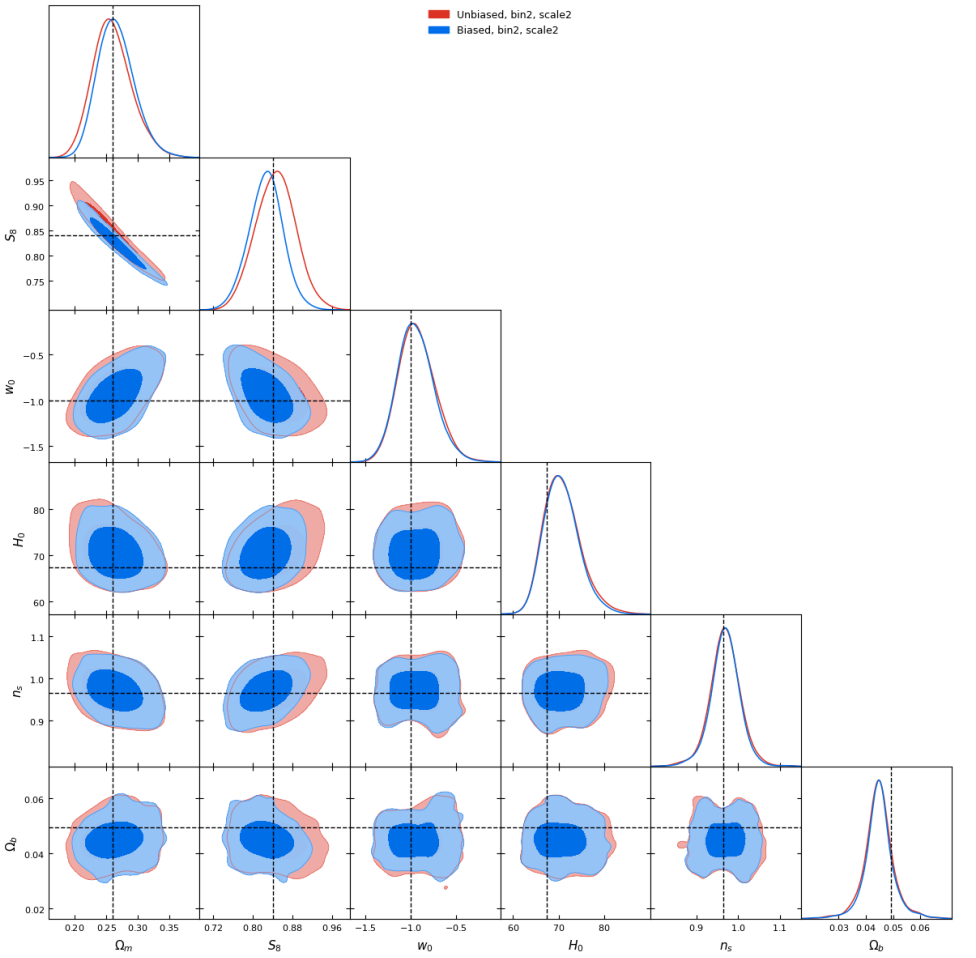


What about the baryonic effects? Do we have any bias?

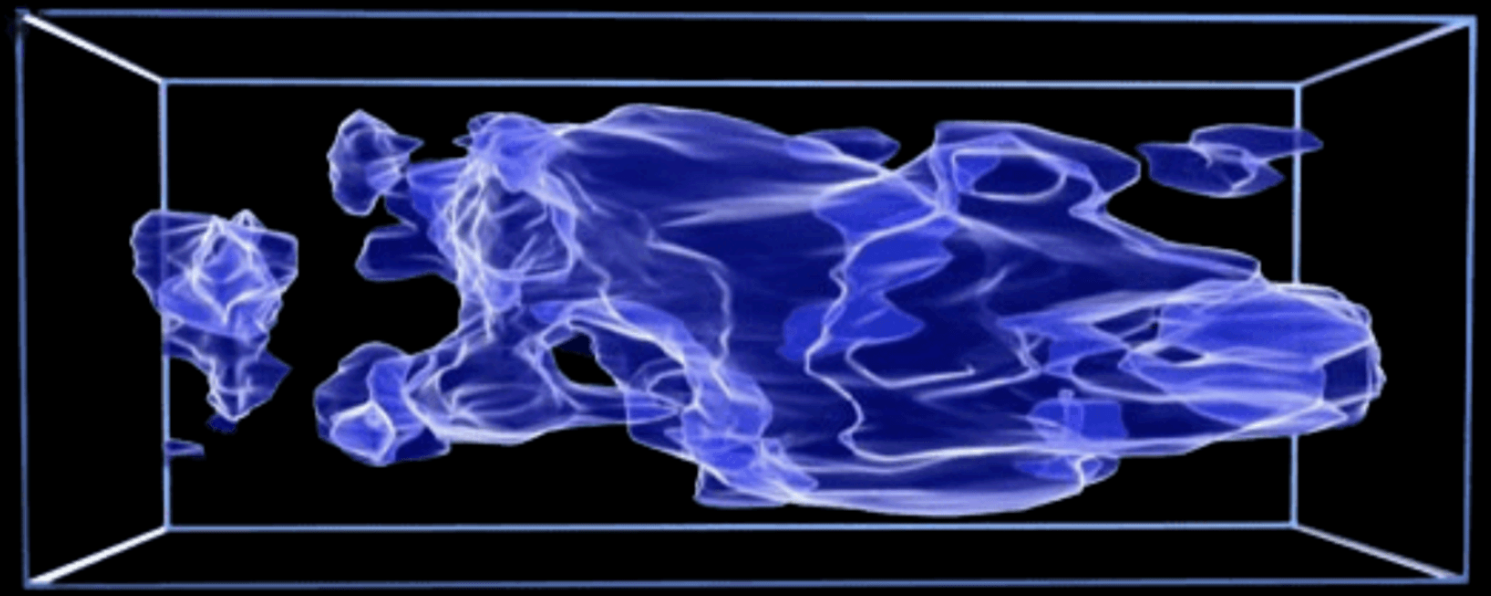
l1-norm, scale 1 (~10arcmin)



l1-norm, scale 2 (~20arcmin)



Weak lensing tomography



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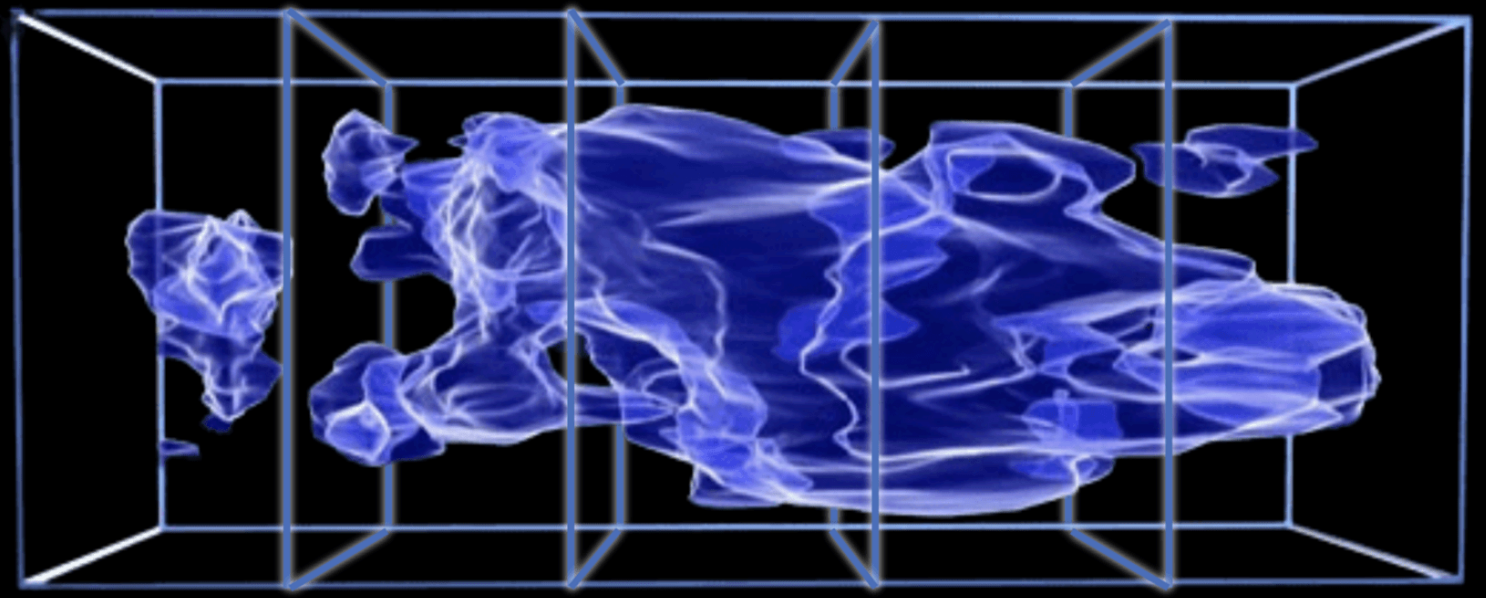

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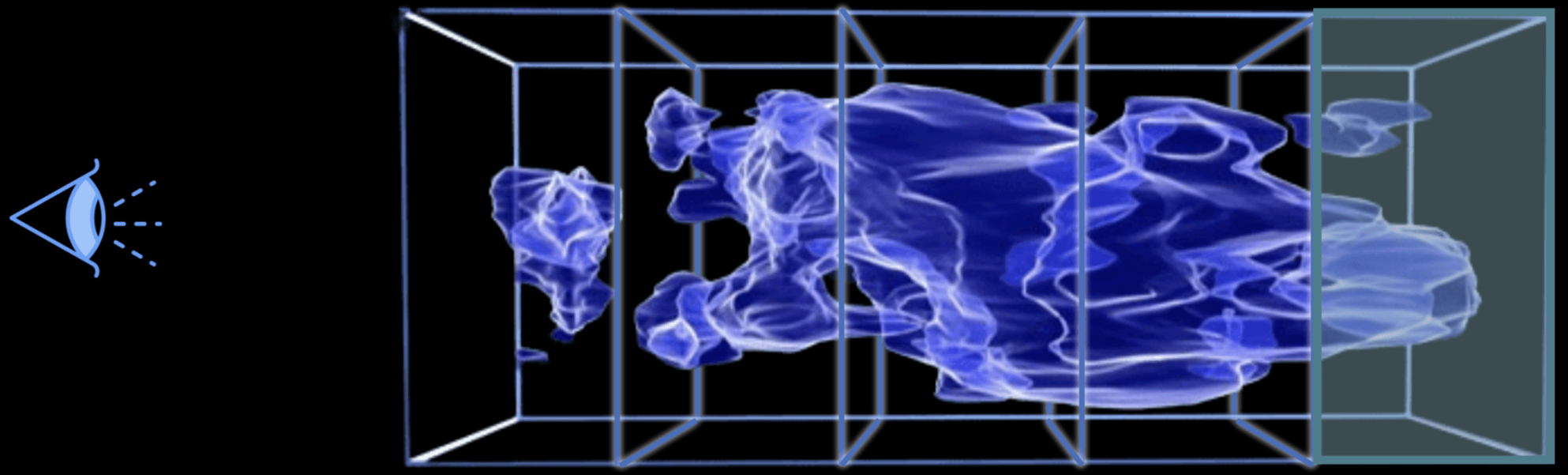

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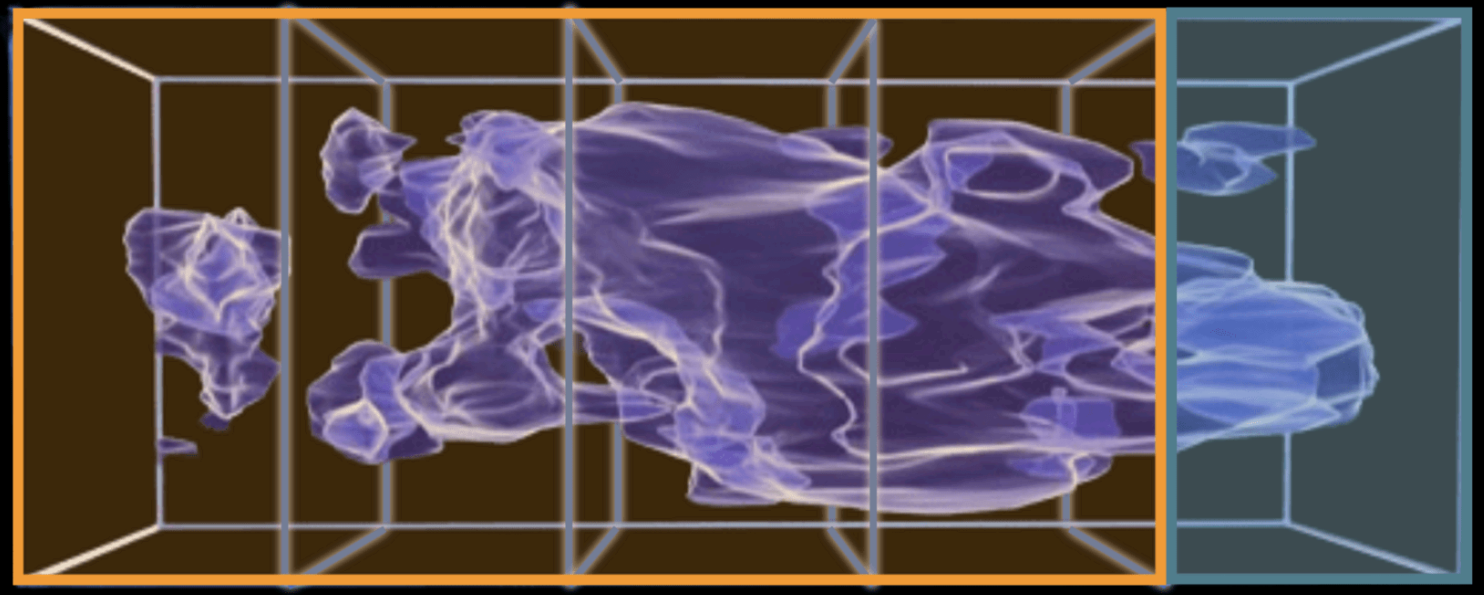

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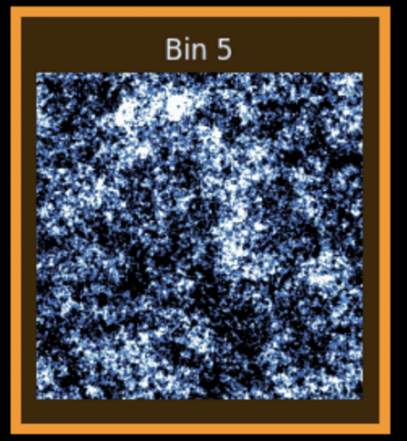

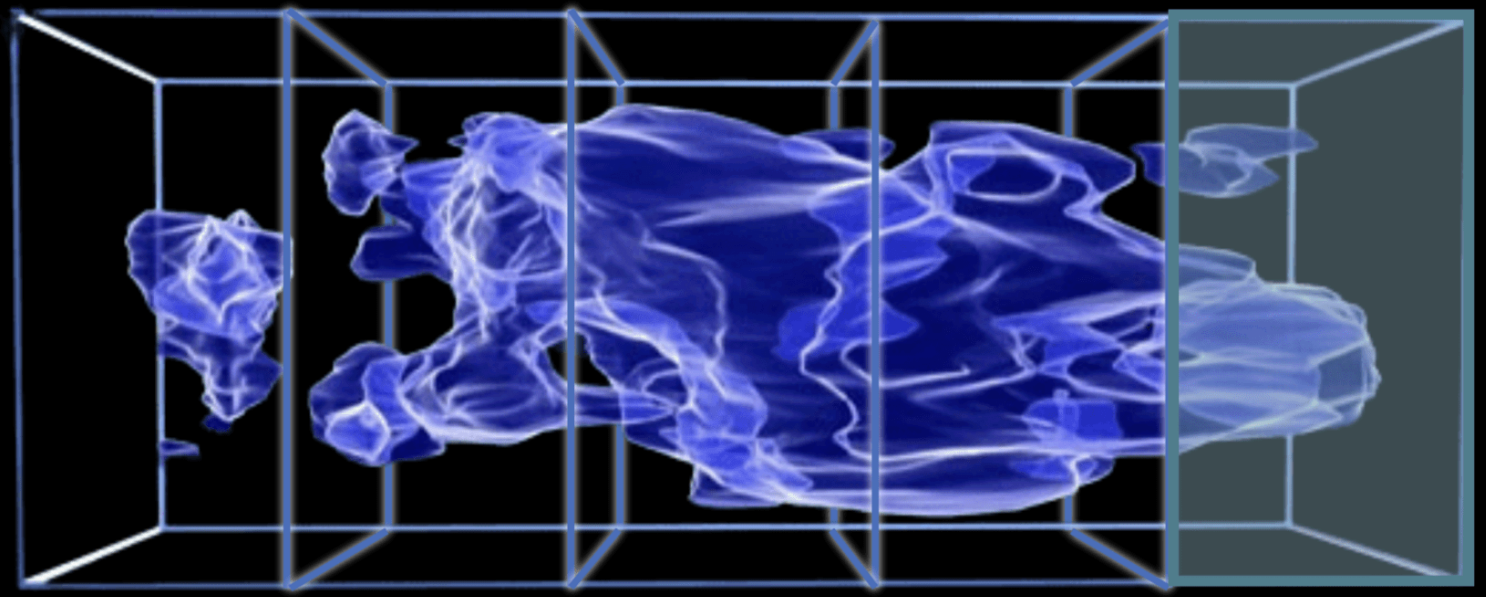

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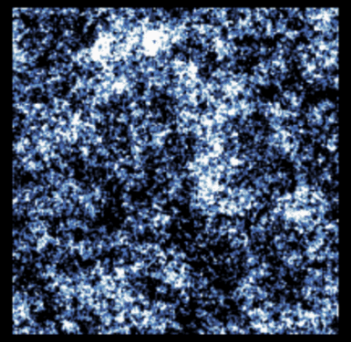

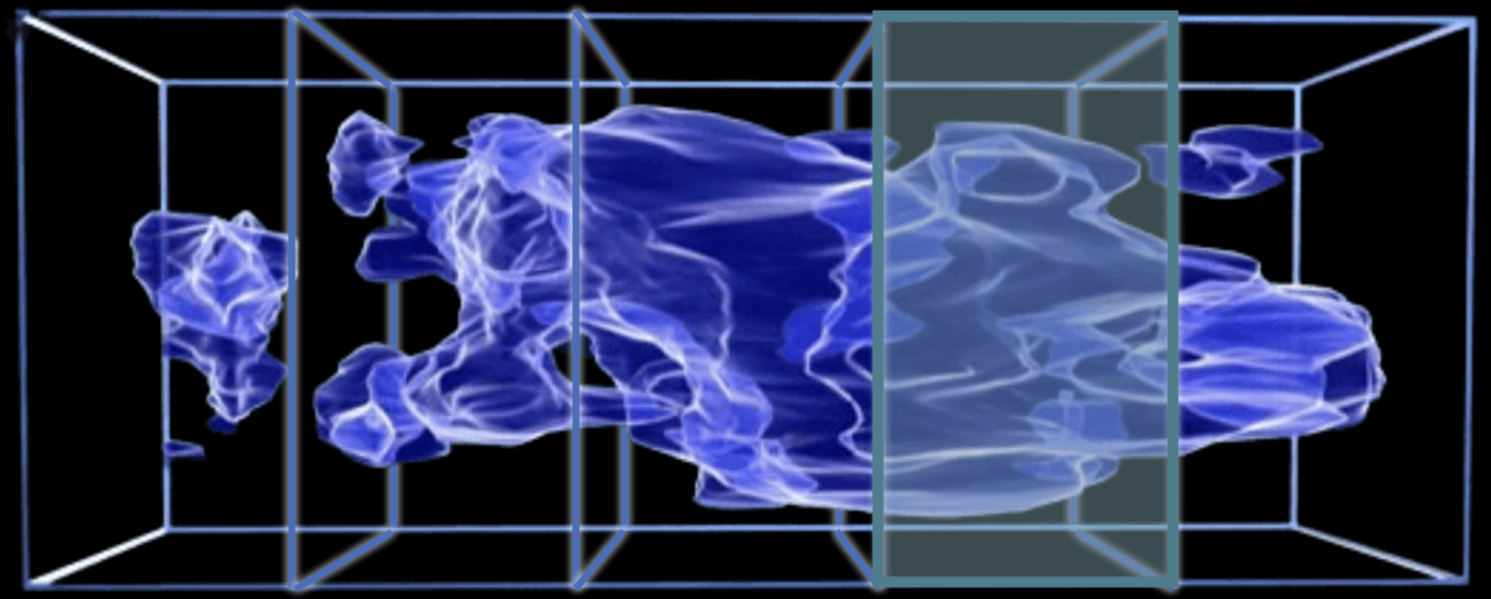

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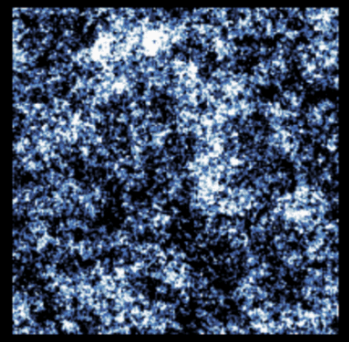

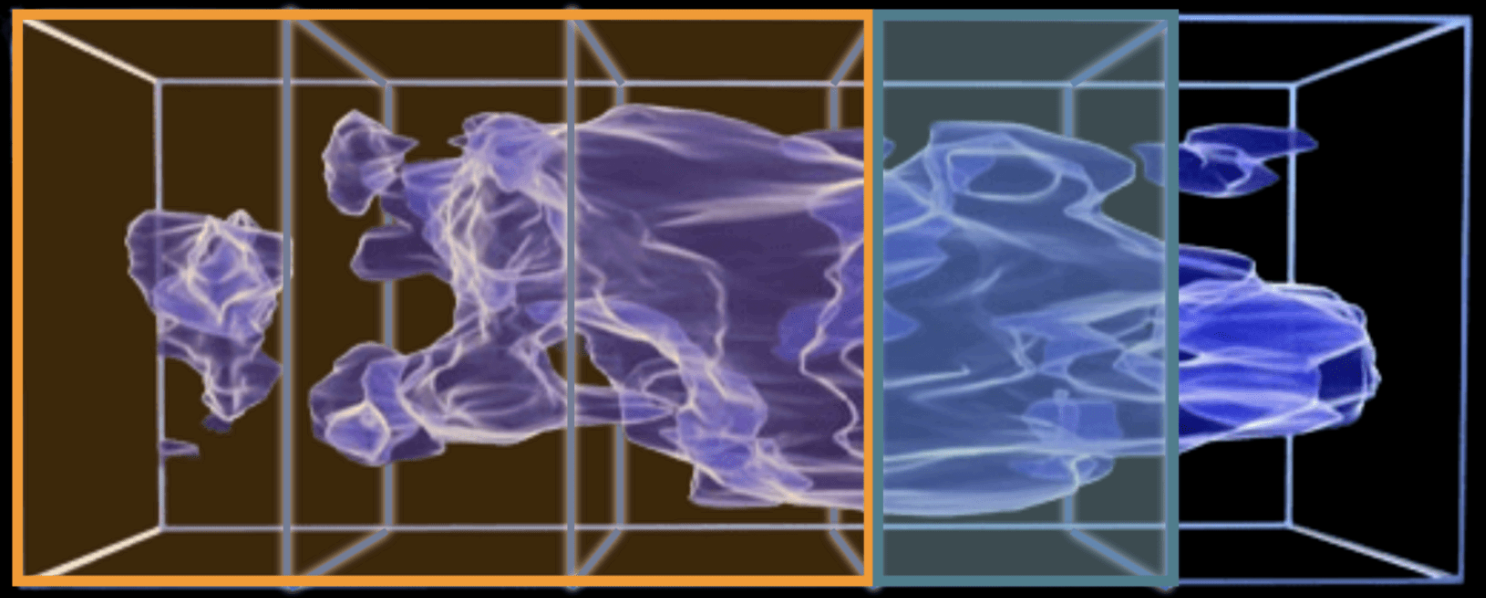

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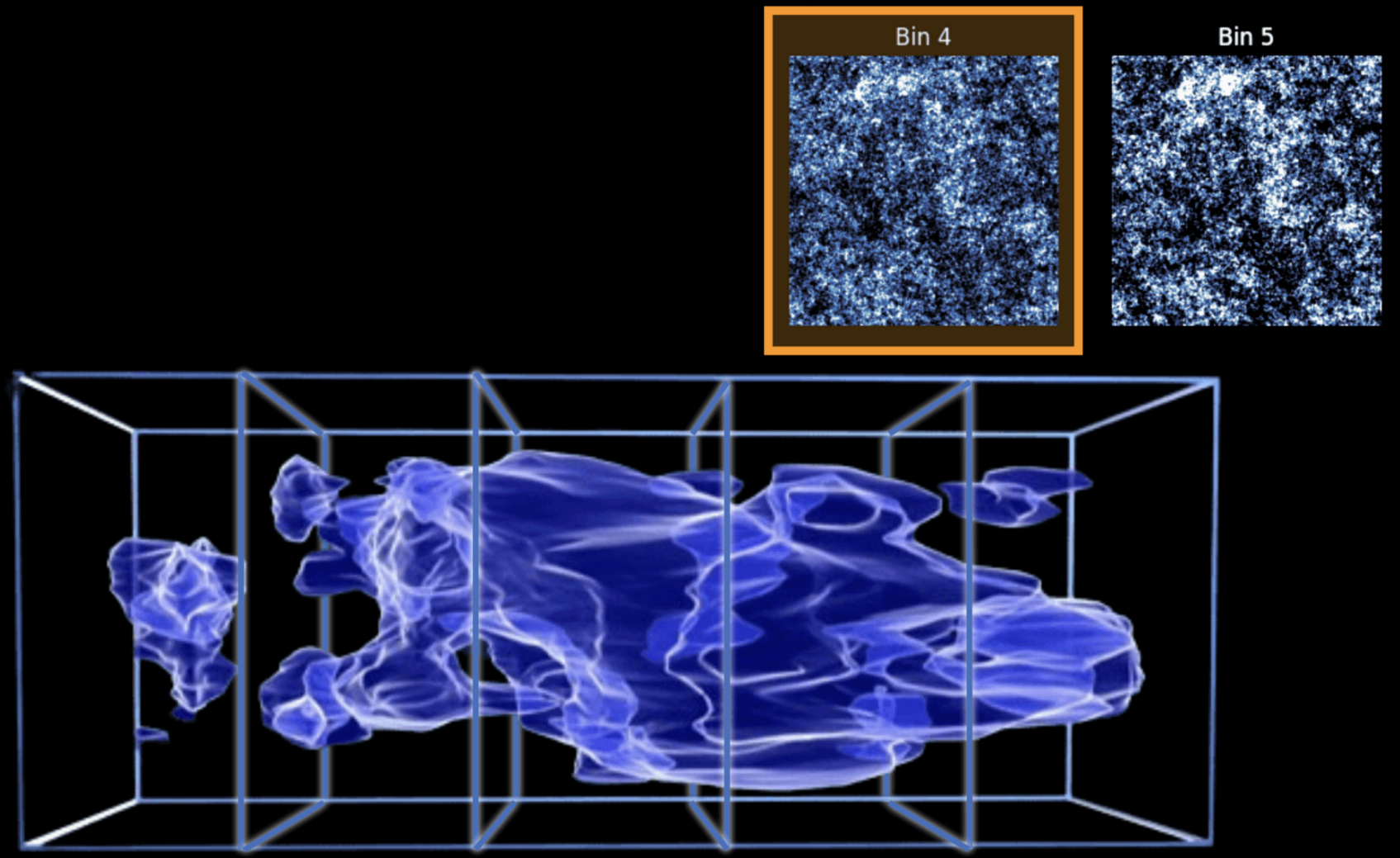

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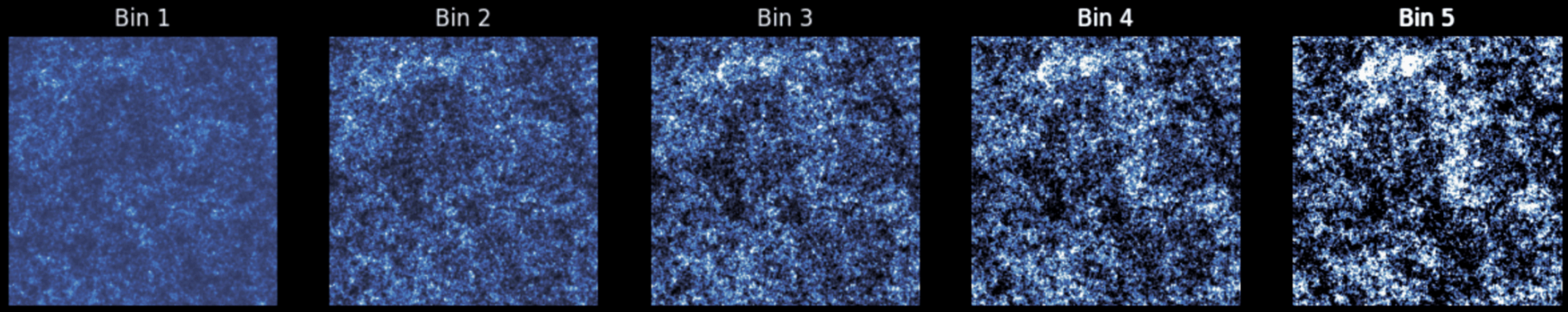
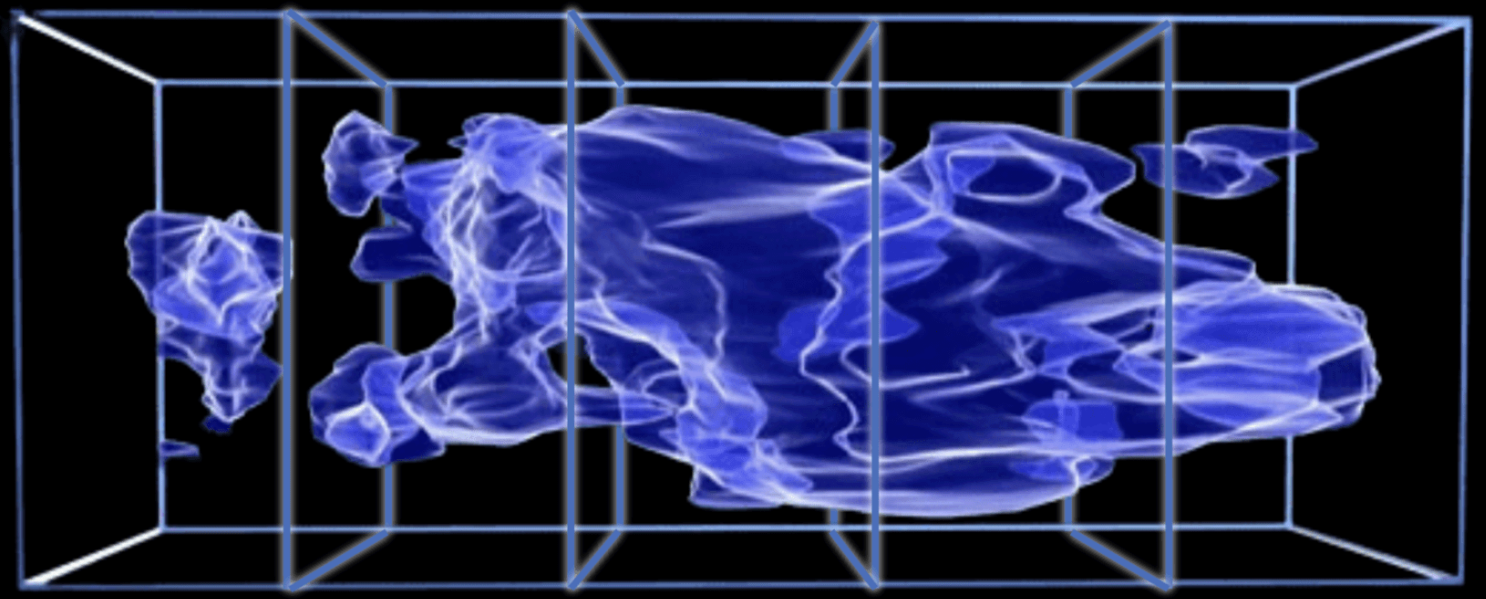
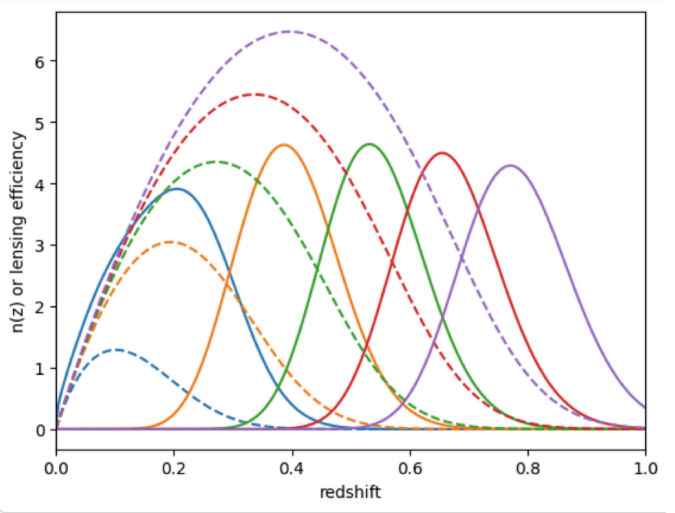




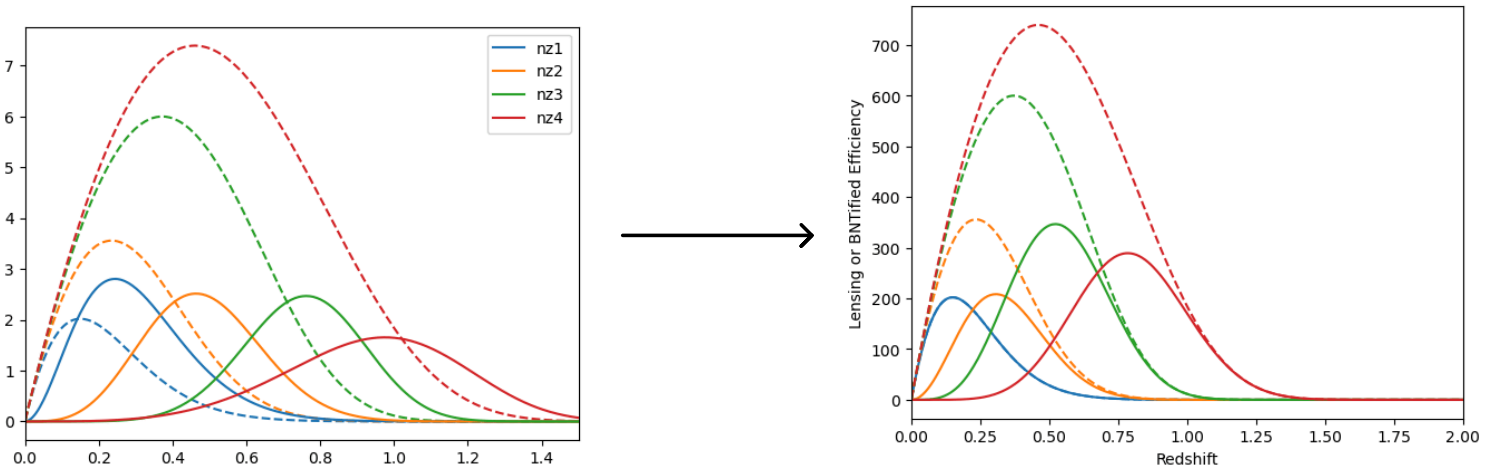
BNT transform

- When we observe cosmic shear, contributions come from mass at different redshifts.
- This creates projection effects: large and small-scale structures get mixed up.
- These effects make it harder to accurately analyze data and extract information



BNT transform

- **BNT Transform**: A method to "null" or remove contributions from unwanted redshift ranges.
- It reorganizes the weak-lensing data so that only specific redshift ranges contribute to the signal, making it easier to analyze.
- It focuses on isolating lensing contributions by sorting out overlapping signals.



How are statistics impacted?

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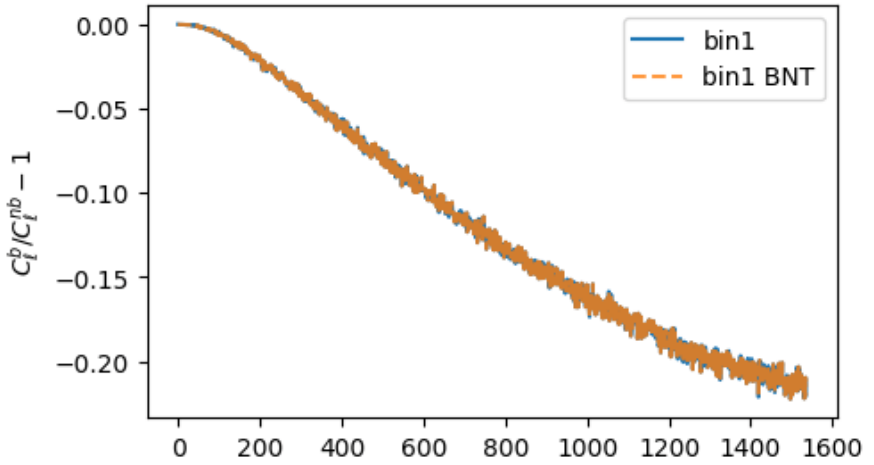

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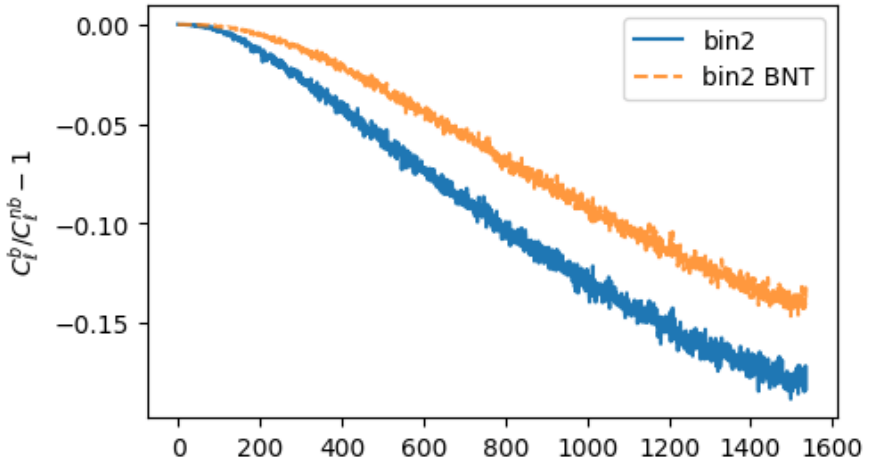

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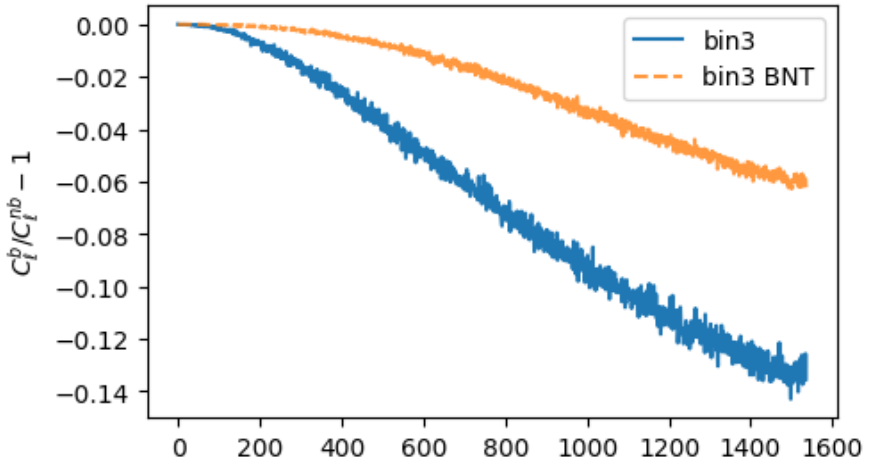

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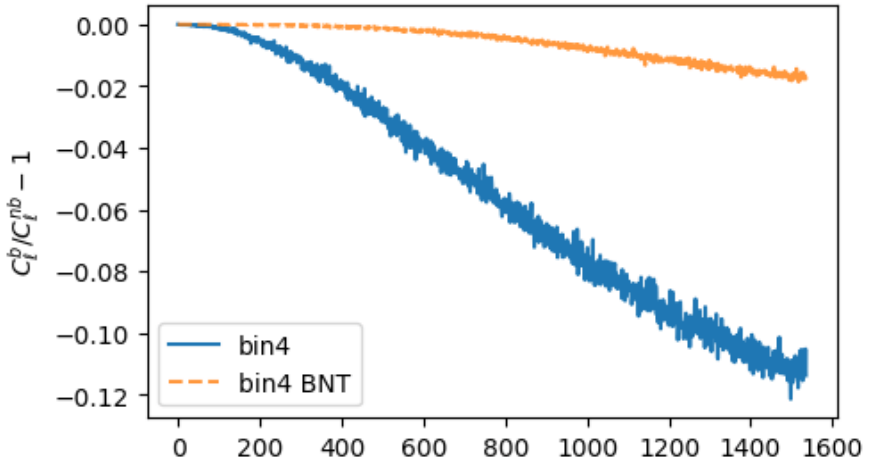

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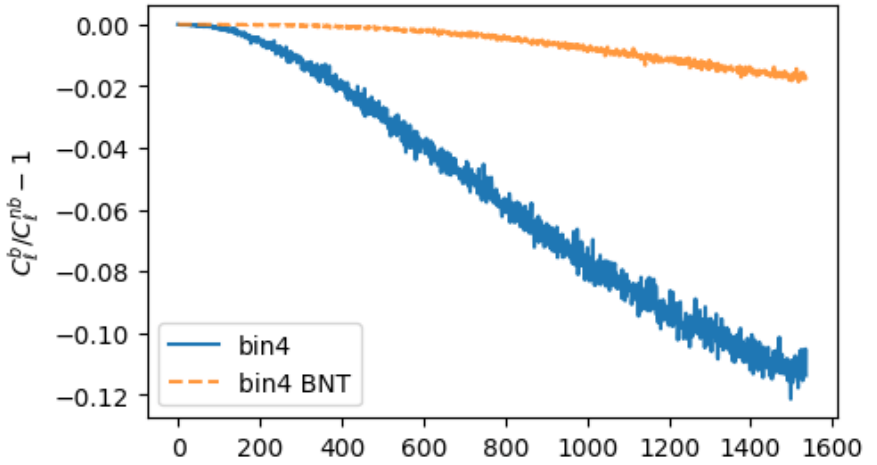
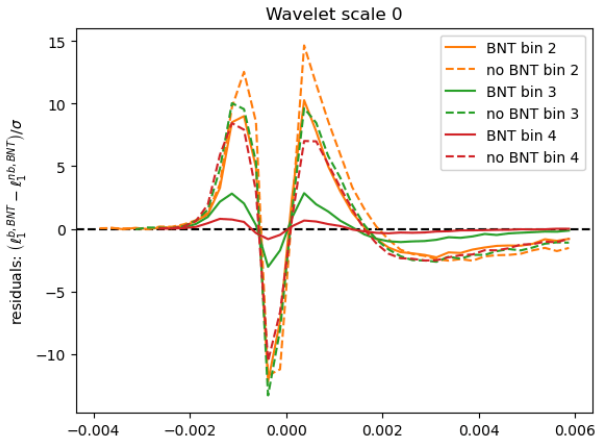
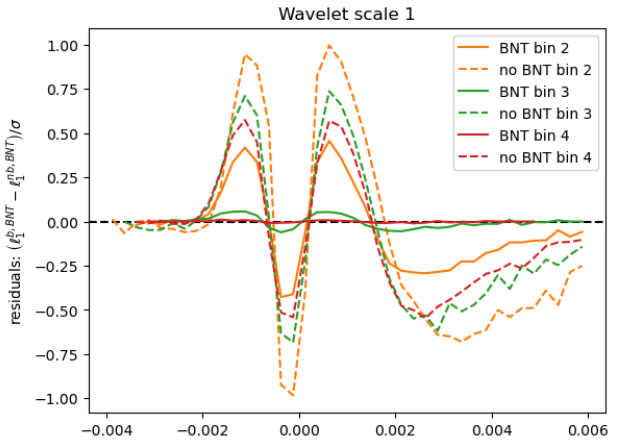
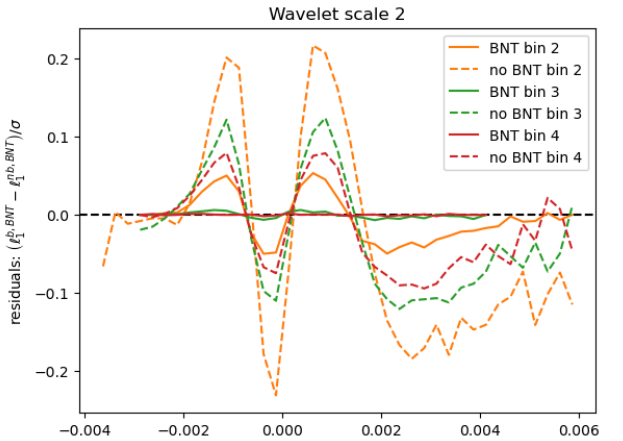




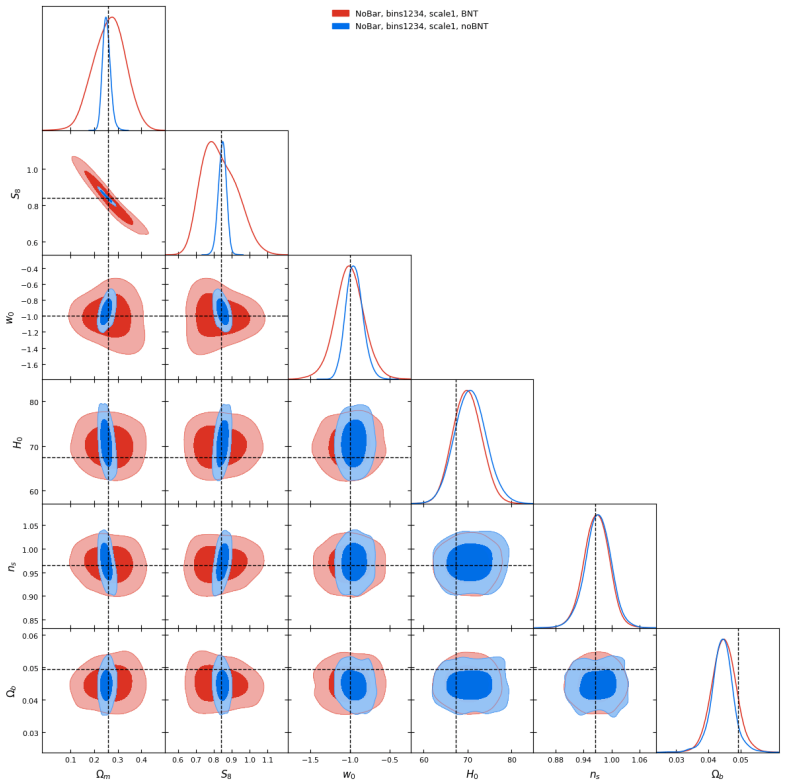




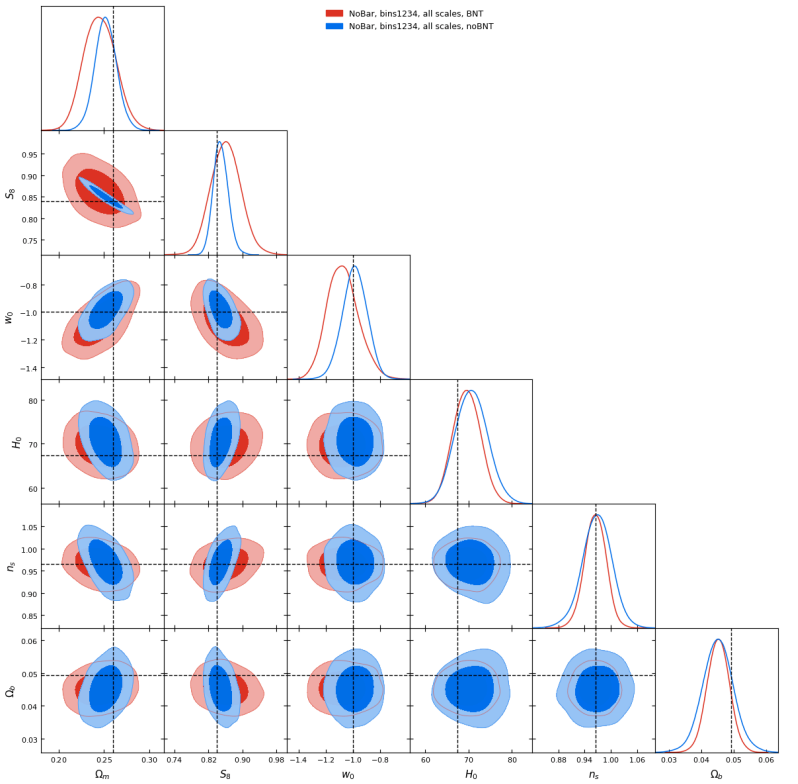
What about contours?

What about contours?

Scale 1 (~7arcmin)



Multiscale



Why this reduction in constraining power?

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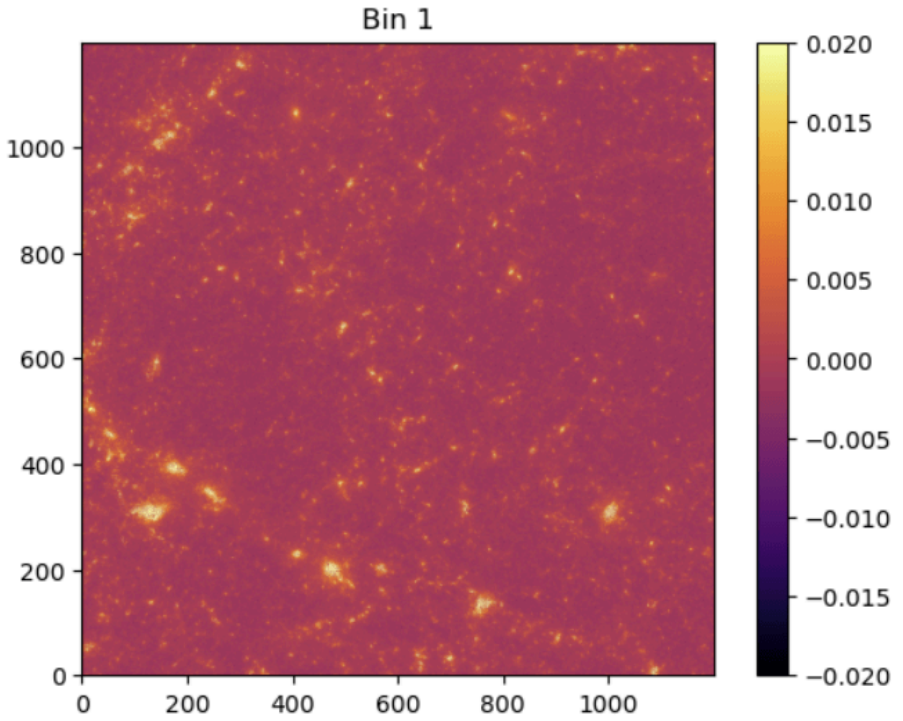
no BNT



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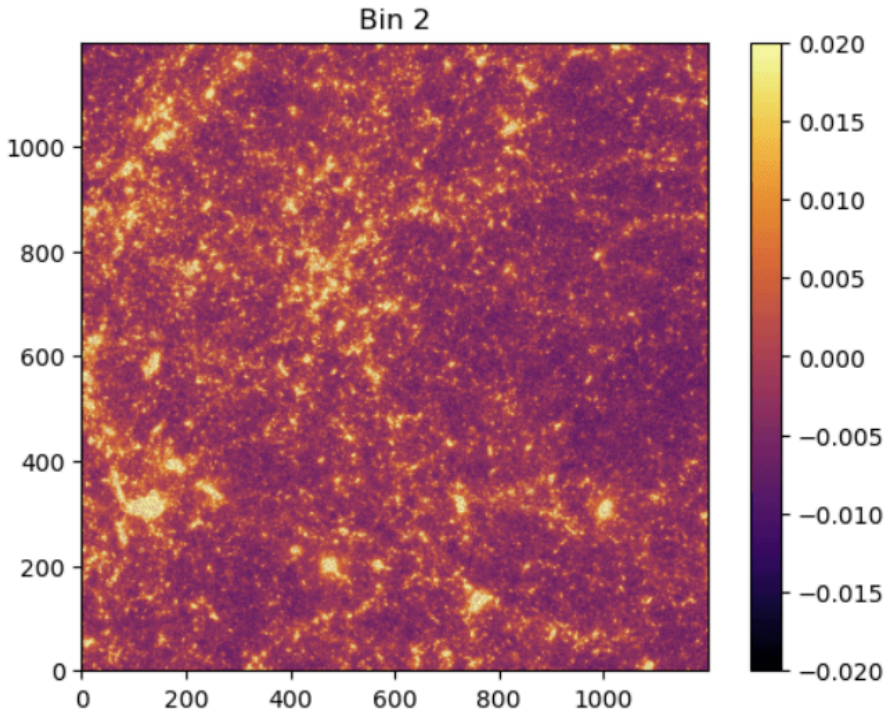

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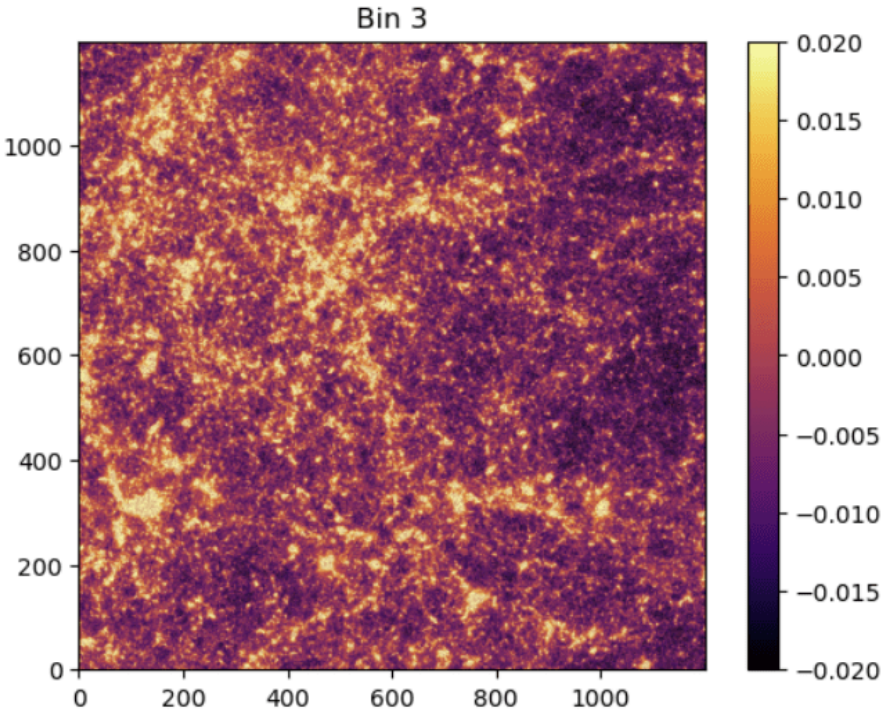

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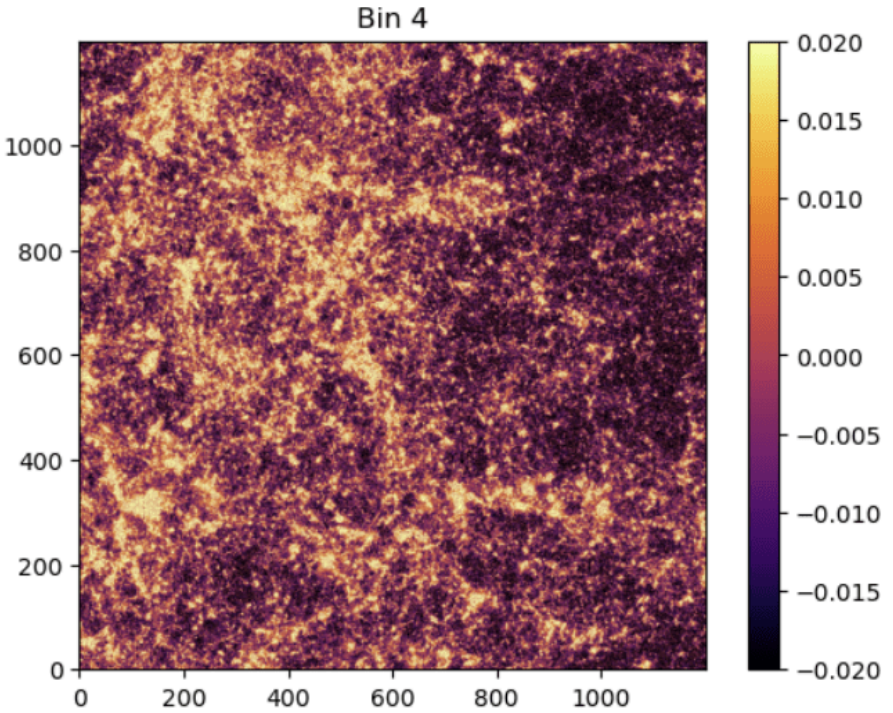

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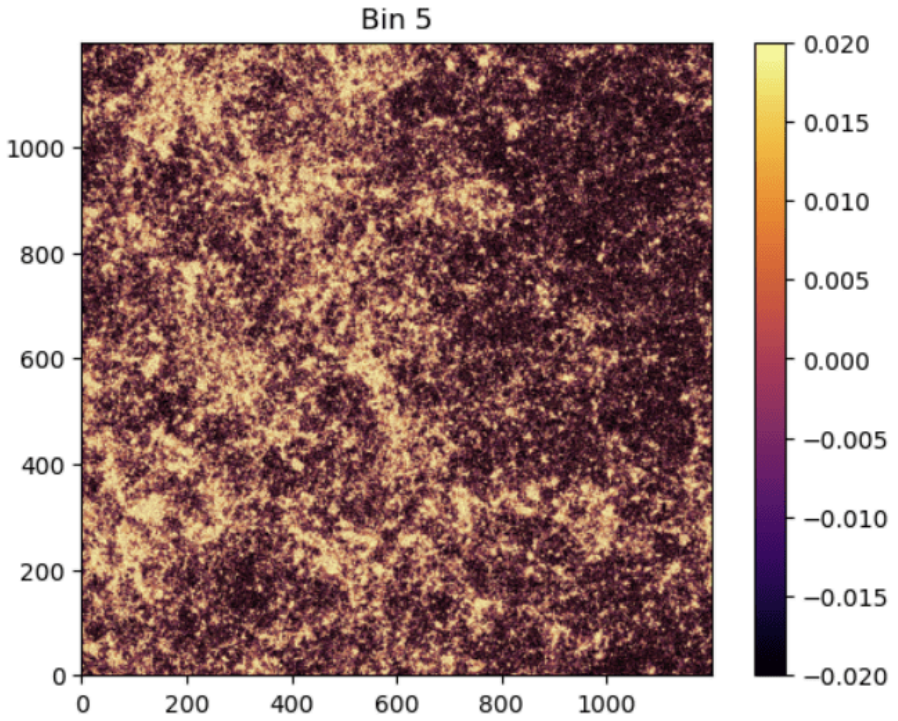

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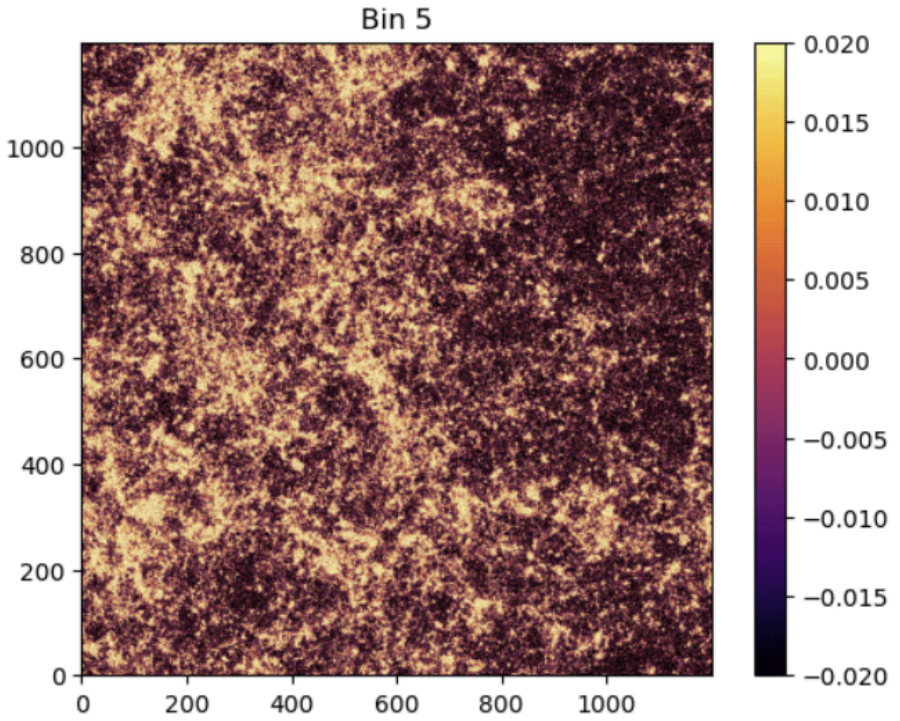
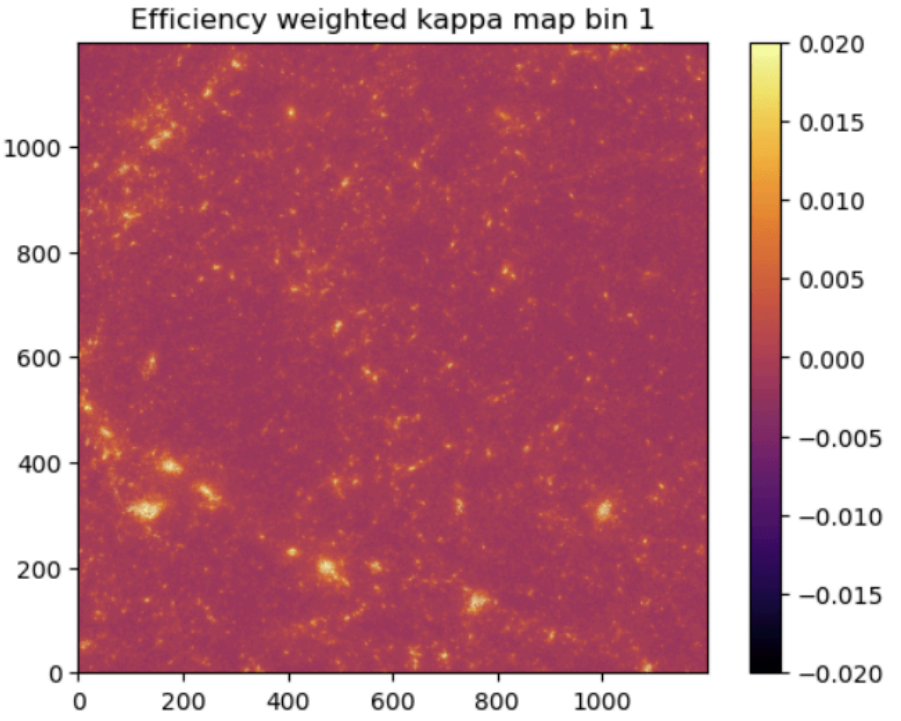


BNT



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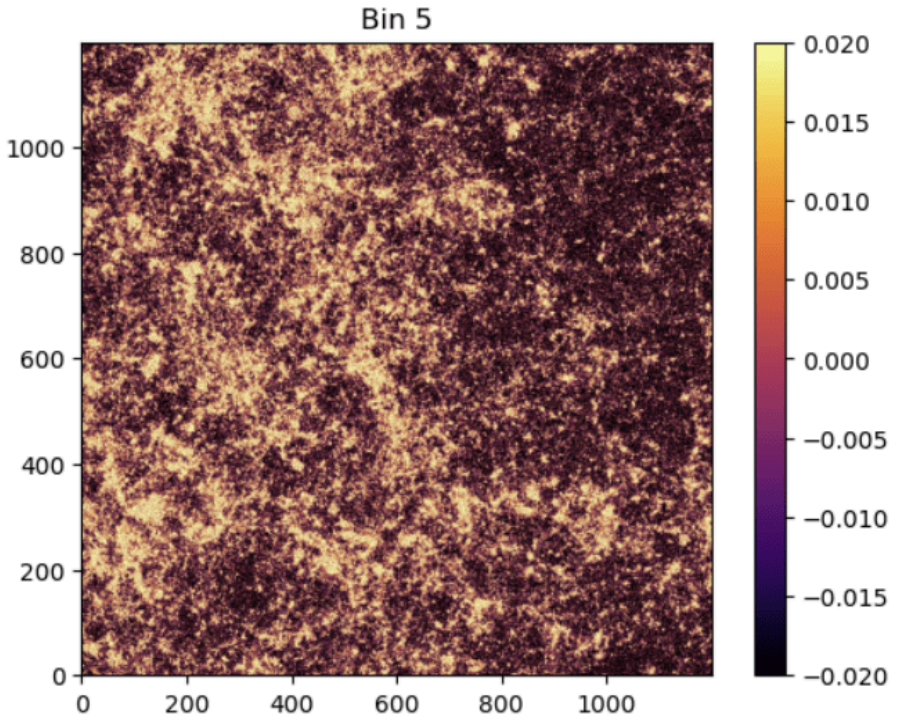

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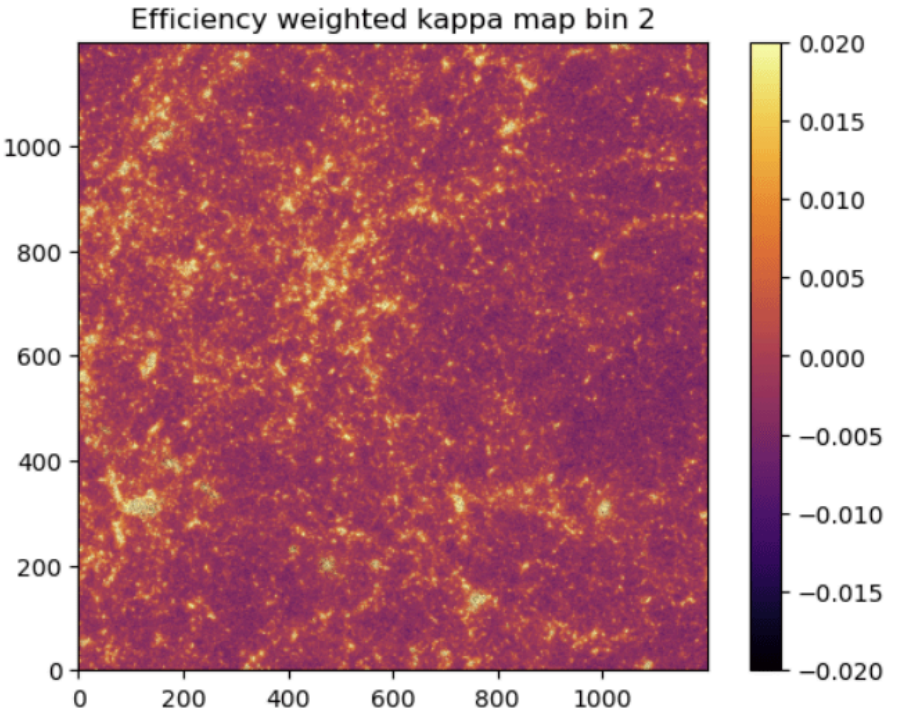

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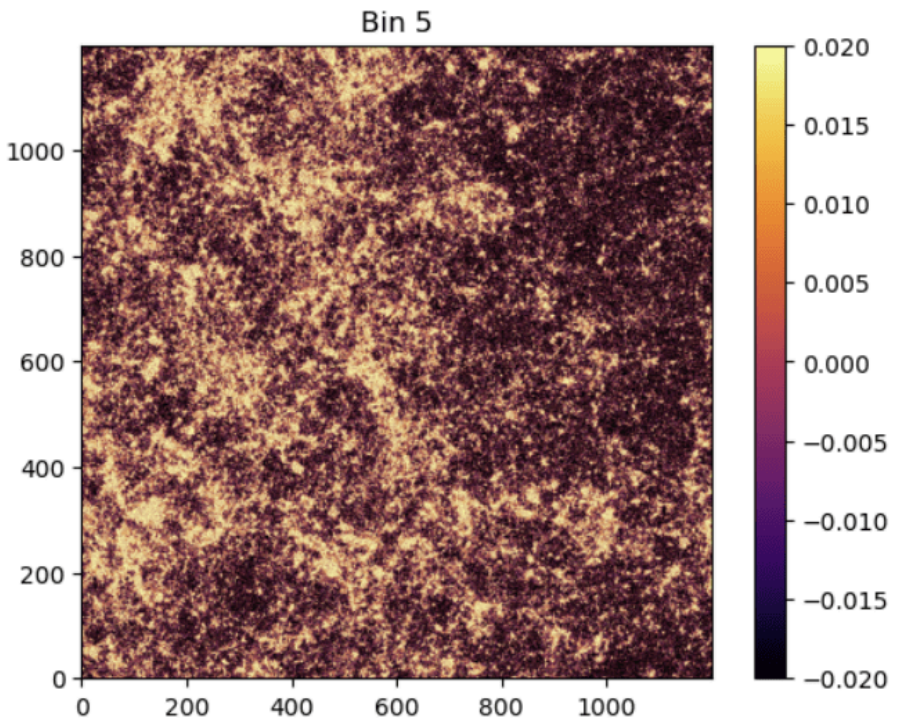

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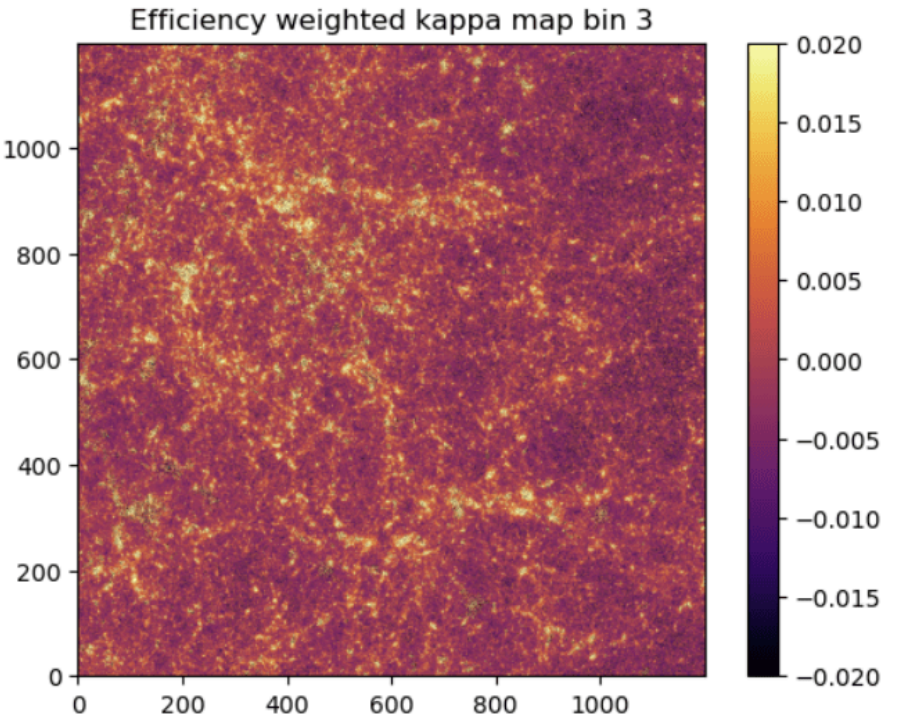

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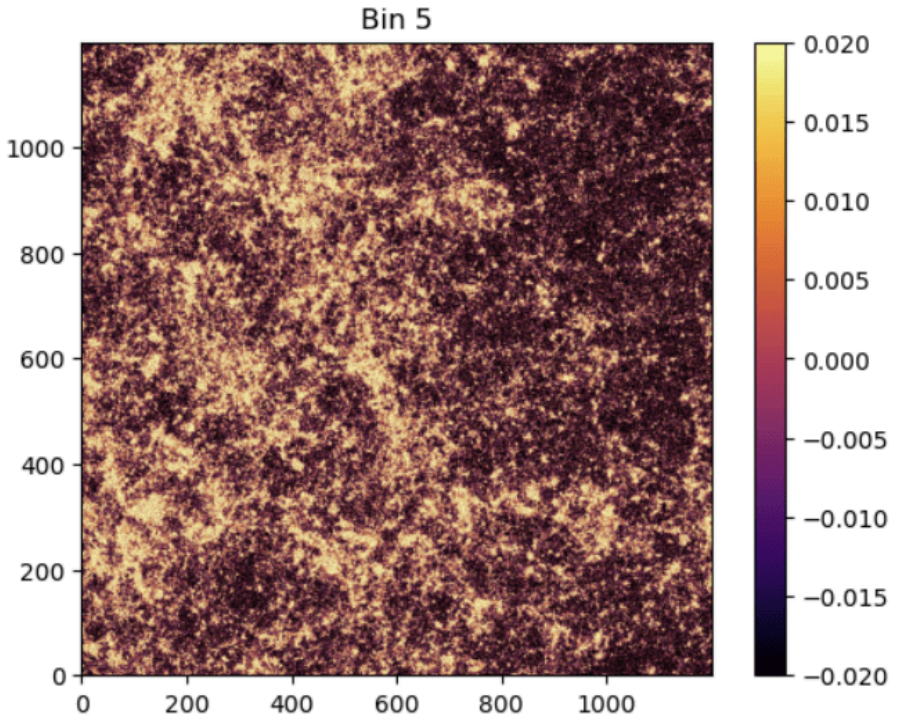

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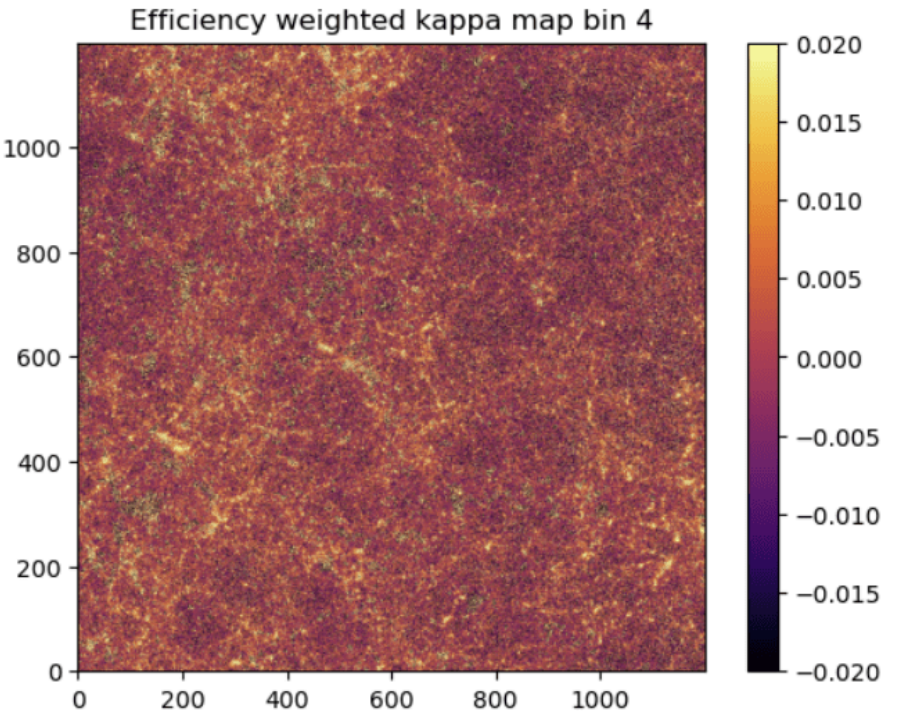

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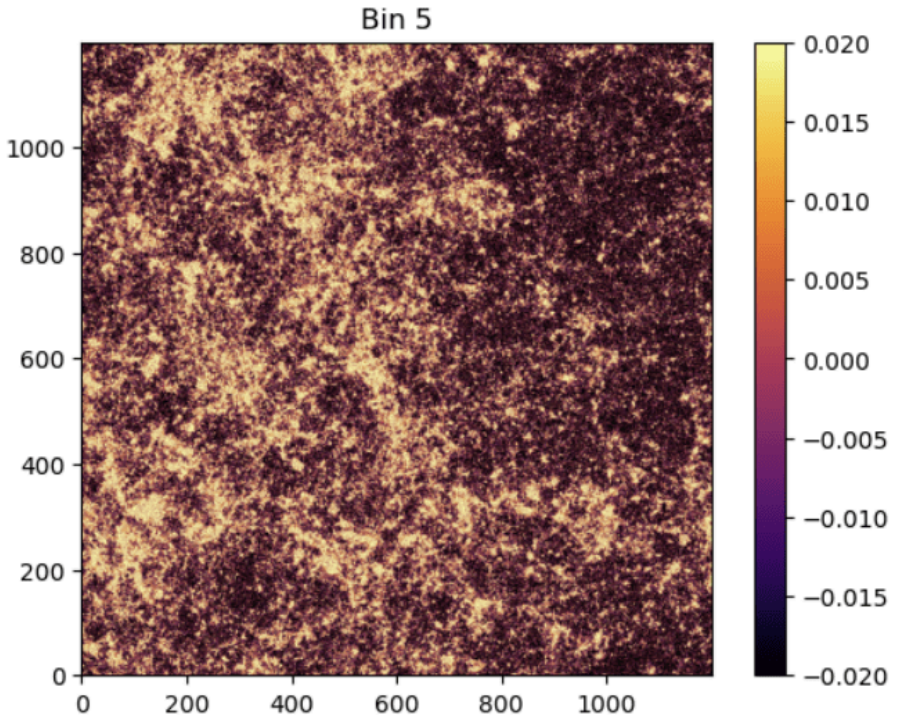

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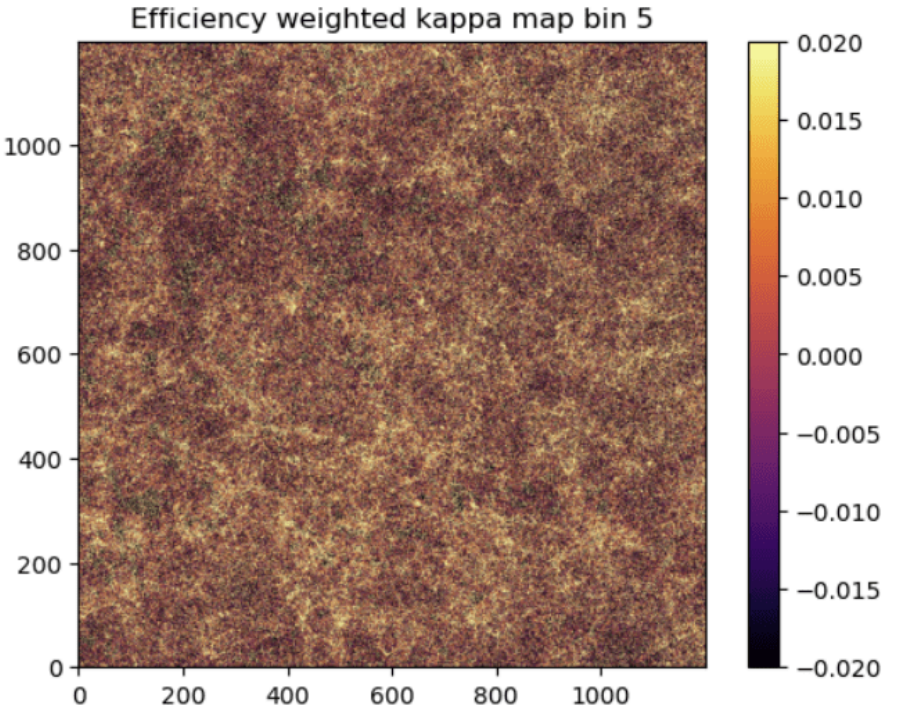
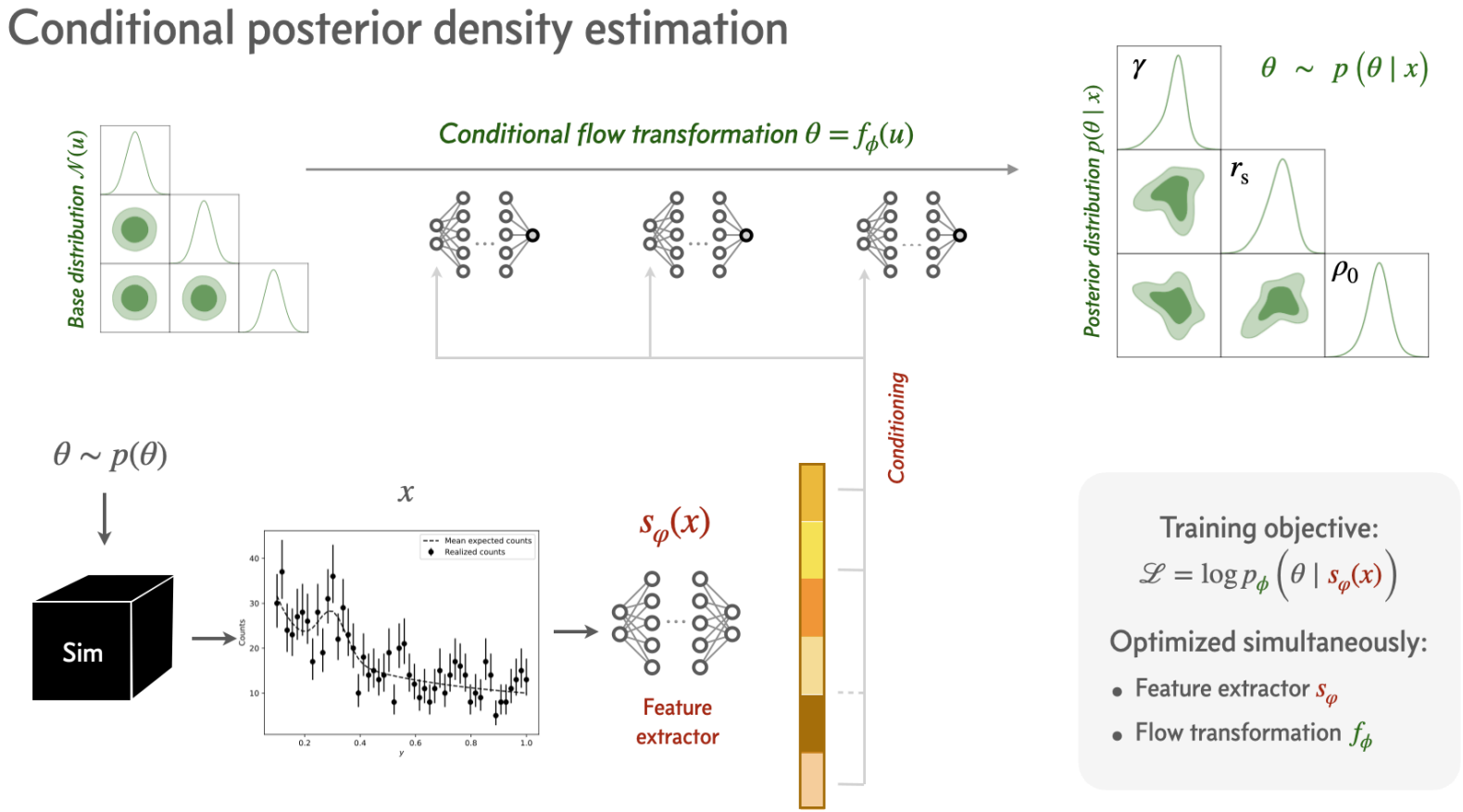


Hope: Neural Summaries (VMIM)



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