

# Starlet $\ell_1$ -norm for Neutral Hydrogen Intensity Mapping

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Pauline Gorbachev

# Motivations

**Traditional 2-point statistics** (Angular power spectrum, 2-point correlation function) are **not sensitive to non-gaussian information**.

1

The **Universe** exhibit **non Gaussian features** due to non-linear growth of structures and primordial non gaussianities.

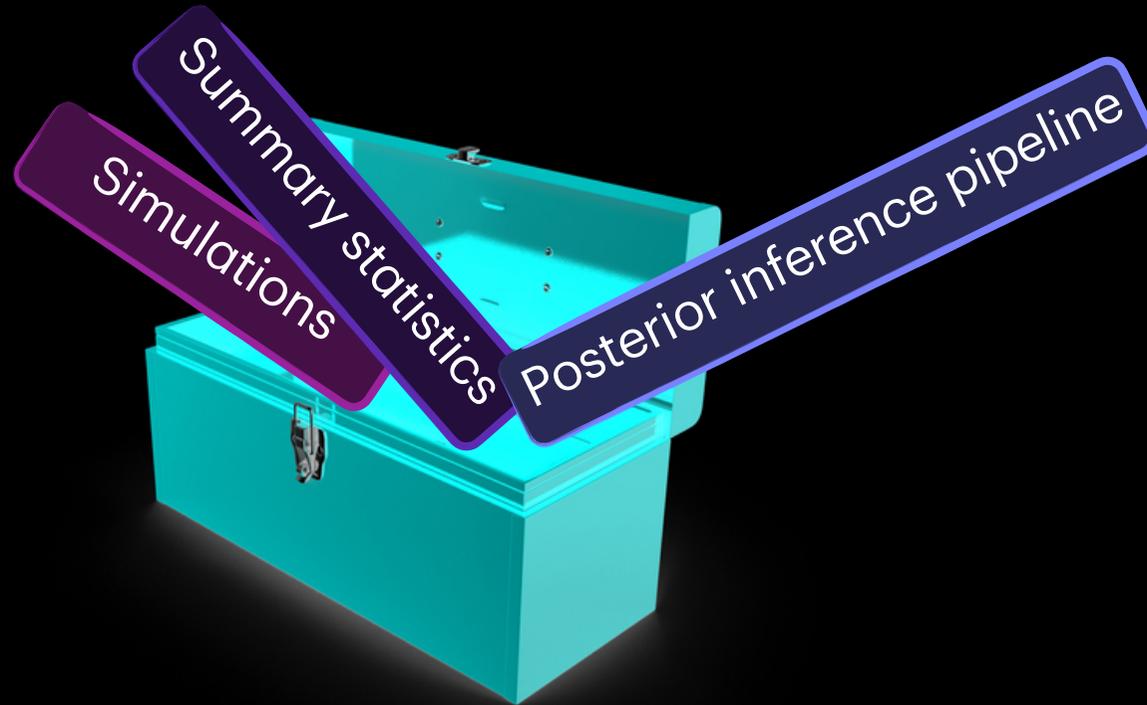
Important **information** is **lost**..

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2

Assess the **sensitivity of the Starlet l1 norm to systematics** that may affect observational data: e.g. **scanning** pattern, **residual synchrotron** contaminant after foreground removal.

# Toolbox



## Simulations

CAMB + GLASS

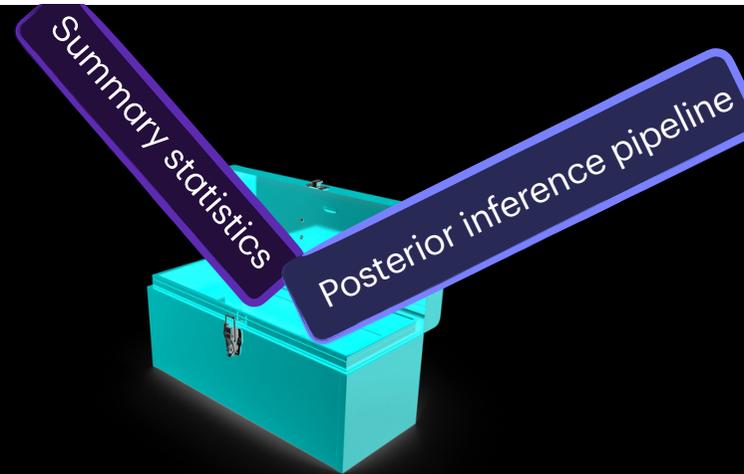
**Lognormal** simulations

**Input** parameters:  $\Omega_c$ ,  $A_s$  and  $h$

**Output:** Full sky HI brightness Temperature map of resolution 1024,  $z = 0.4-0.45$

Different realizations (seed)

Option of adding **masks**, **beam**, **noise** (MeerKLASS-like)



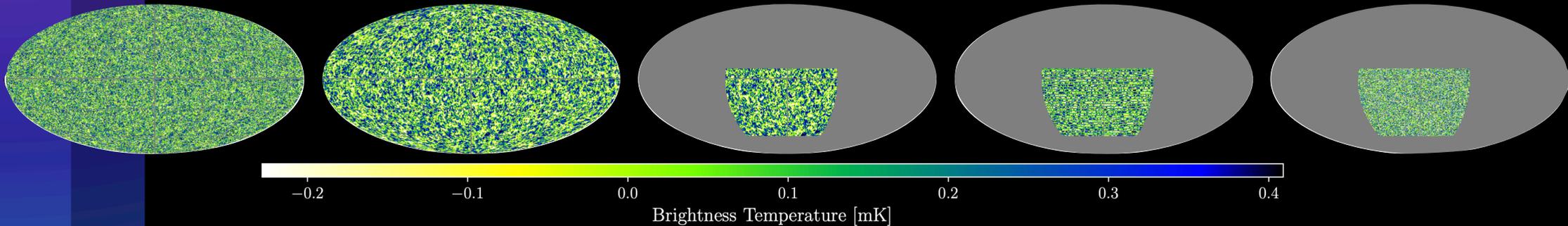
Clean

Beamed

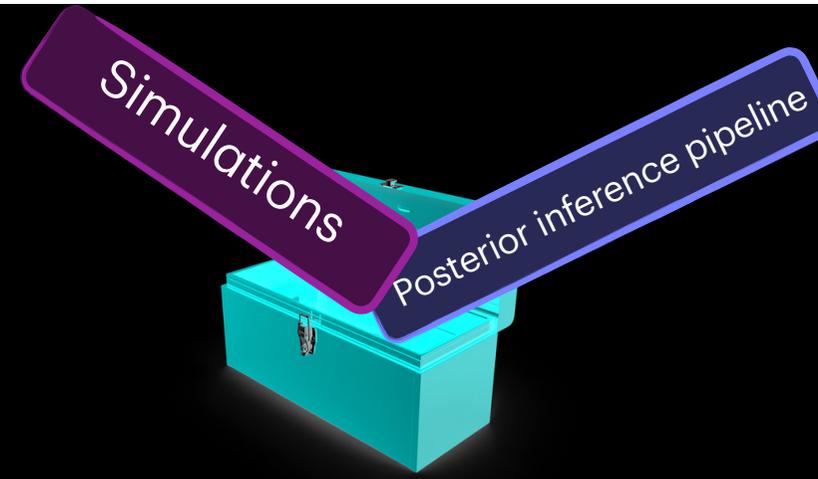
+ Masked

+ Zebras

+ Noise



Summary statistics



Starlet l1-norm

MULTI-SCALE HIGHER ORDER STATISTIC

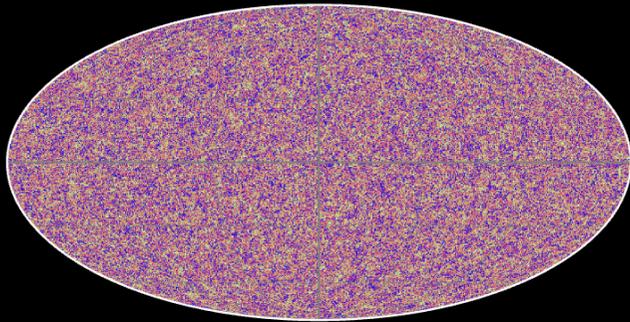
VS

Angular power spectrum

## Summary statistics

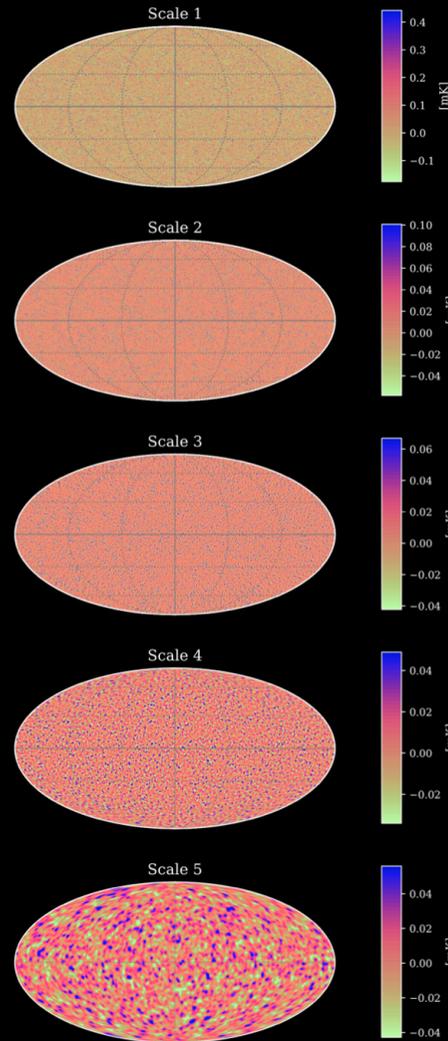
### Starlet l1-norm

$$M(\hat{n}) = \sum_{j=1}^J w_j(\hat{n}) + c_J(\hat{n}).$$



$$\ell_1^{(j,k)} = \sum_{\hat{n} \in \mathcal{B}_k} \left| \frac{w_j(\hat{n})}{\mathcal{N}_j} \right|$$

Starlet Decomposition of HI IM Simulated Map

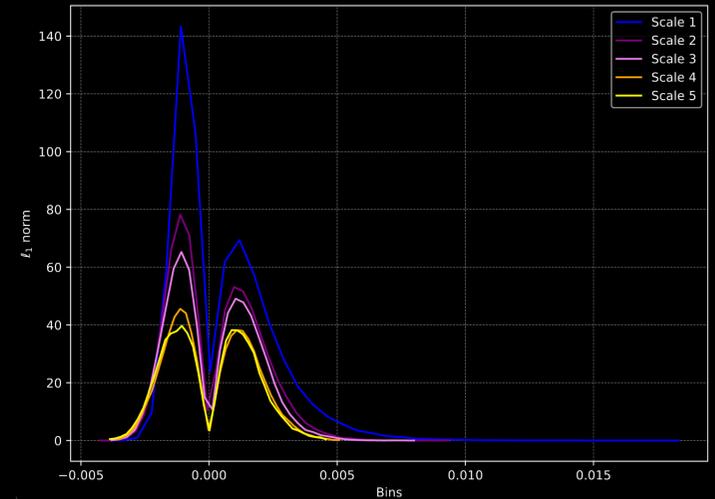


Simulations

Posterior inference pipeline



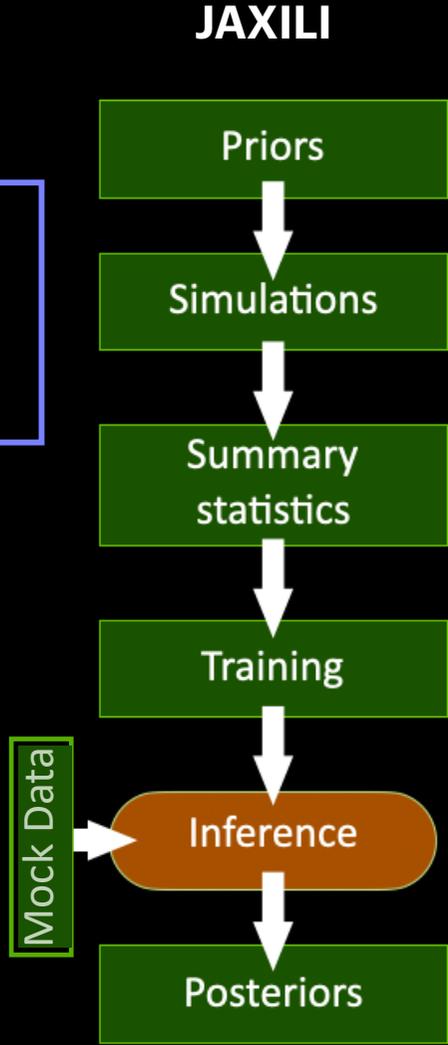
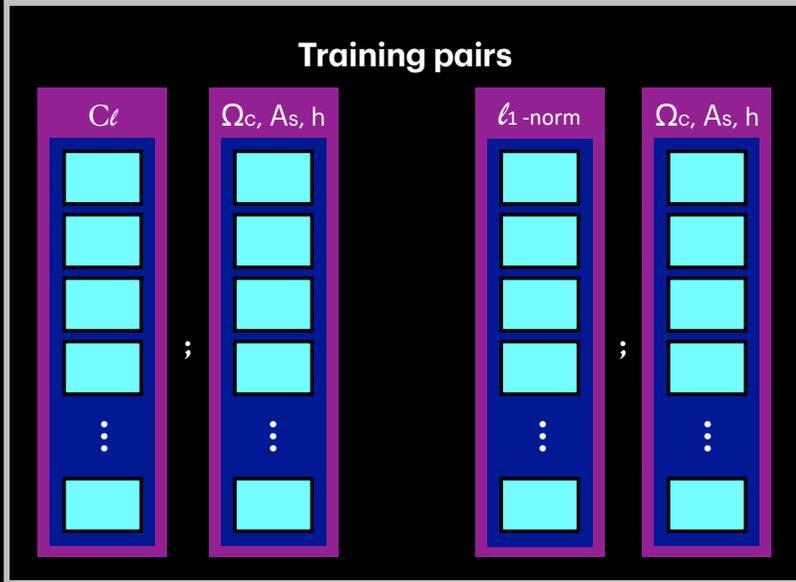
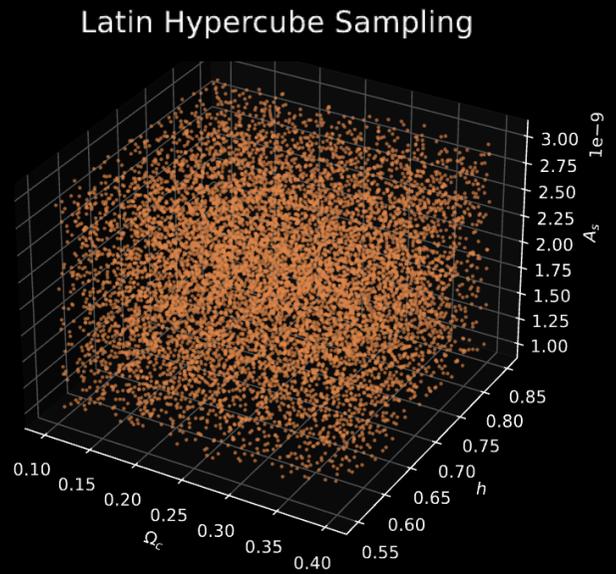
$\ell_1$  norm vs Bins



# Simulation Based Inference (SBI)

**No** Need for an explicit likelihood  
Training set computed **once**  
Training time - few minutes (with JAXILI)  
<https://github.com/sachager/jaxili>

**Splitting of data set 10 000**  
Training set: 7 000  
Validation set: 2 000  
Test set: 1 000

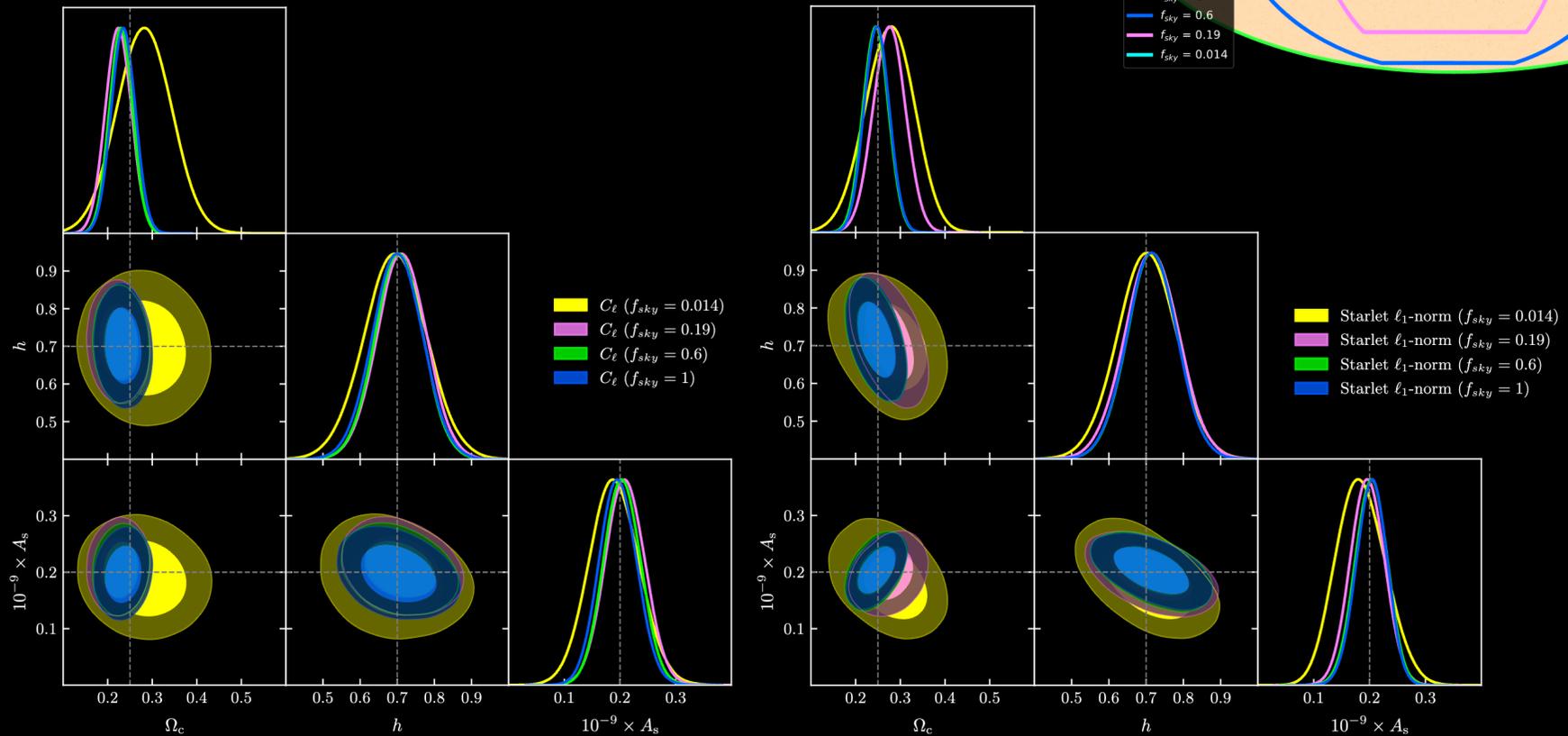


# Results

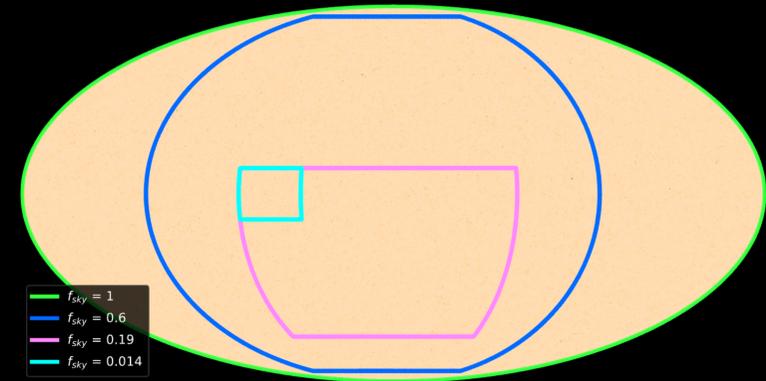
# Sky fraction

- Constraining power decreases with sky-fraction
- Non-linear decrease ← mask induced mode coupling

## Posterior Comparison: Starlet $\ell_1$ -norm vs $C_\ell$



# Sky fraction



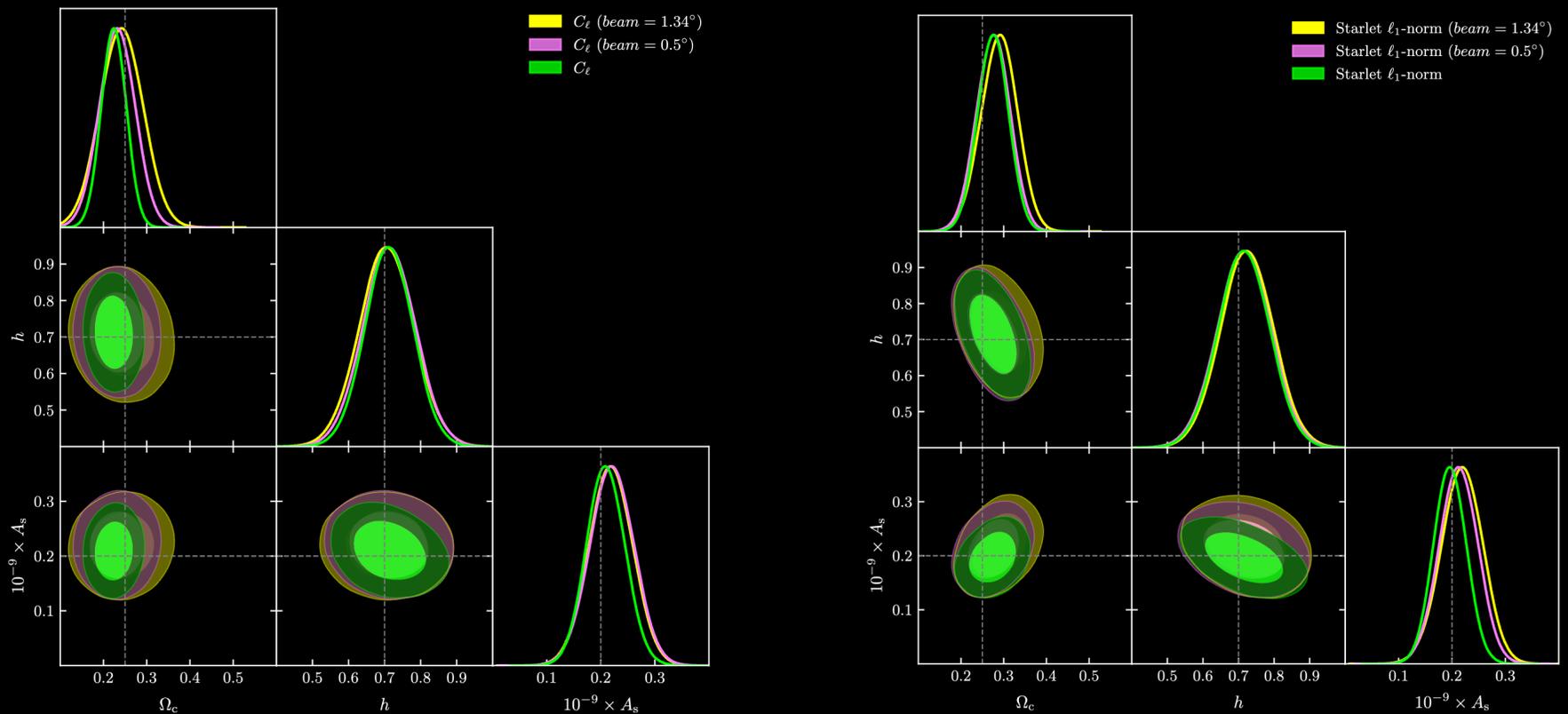
Posterior Comparison: Starlet  $\ell_1$ -norm vs  $C_\ell$

Statistic	$f_{\text{sky}}$	Normalized FoM	Improvement vs $C_\ell$
$C_\ell$	1.0	1.00	—
$S\ell_1$	1.0	1.59	1.59×
$C_\ell$	0.6	1.00	—
$S\ell_1$	0.6	1.32	1.32×
$C_\ell$	0.19	1.00	—
$S\ell_1$	0.19	1.07	1.07×
$C_\ell$	0.014	1.00	—
$S\ell_1$	0.014	1.82	1.82×

# Gaussian Beam

- Stronger contour degradation for CI
- SI1 more robust to beam smoothing ← sensitive to structures

Posterior Comparison: Starlet  $\ell_1$ -norm vs  $C_\ell$   $f_{sky} = 0.19$



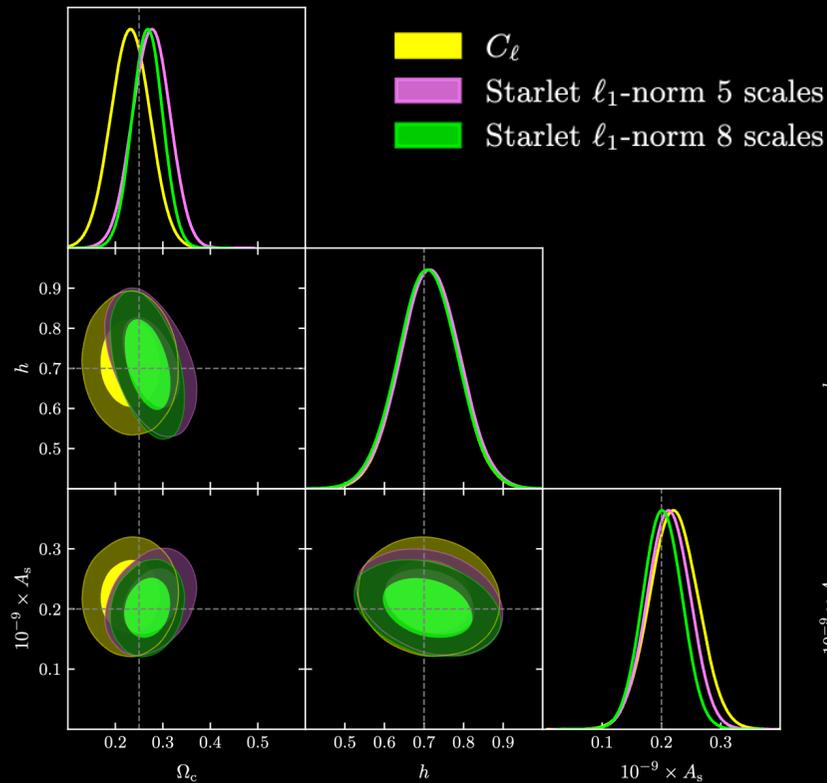
# Gaussian Beam

Posterior Comparison: Starlet  $\ell_1$ -norm vs  $C_\ell$   $f_{sky} = 0.19$

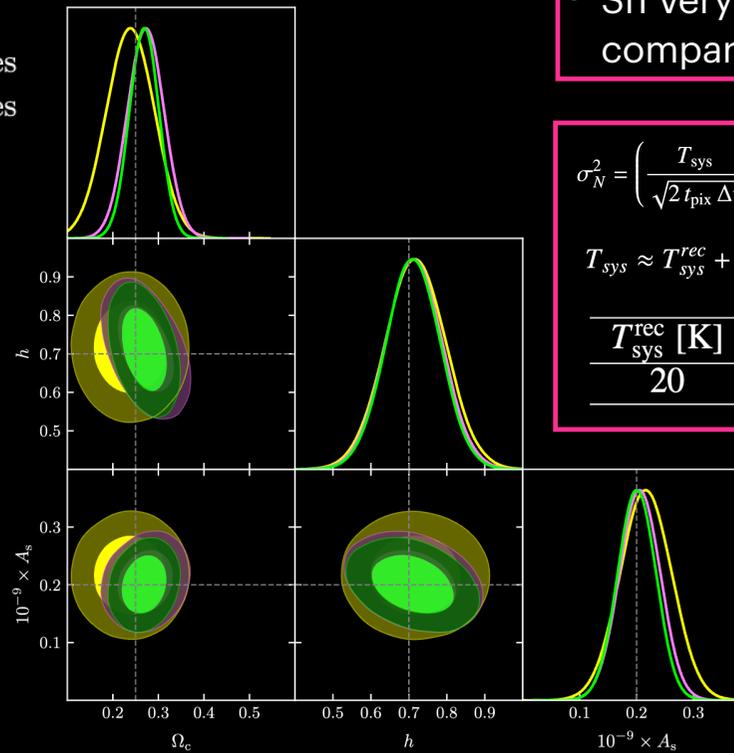
Statistic	beam	Normalized FoM	Improvement vs $C_\ell$
$C_\ell$	no	1.00	—
$S\ell_1$	no	1.07	1.07×
$C_\ell$	0.5 deg	1.00	—
$S\ell_1$	0.5 deg	1.34	1.34×
$C_\ell$	1.34 deg	1.00	—
$S\ell_1$	1.34 deg	1.40	1.40×

# Improving S11 with additional scales

Posterior Comparison: Starlet  $\ell_1$ -norm vs  $C_\ell$   $f_{sky} = 0.19$ ,  $beam = 0.5^\circ$



+ noise



- Additional scales capture a wider range of structural info
- S11 very robust to noise compared to  $C_\ell$

$$\sigma_N^2 = \left( \frac{T_{\text{sys}}}{\sqrt{2} t_{\text{pix}} \Delta\nu} \right)^2$$

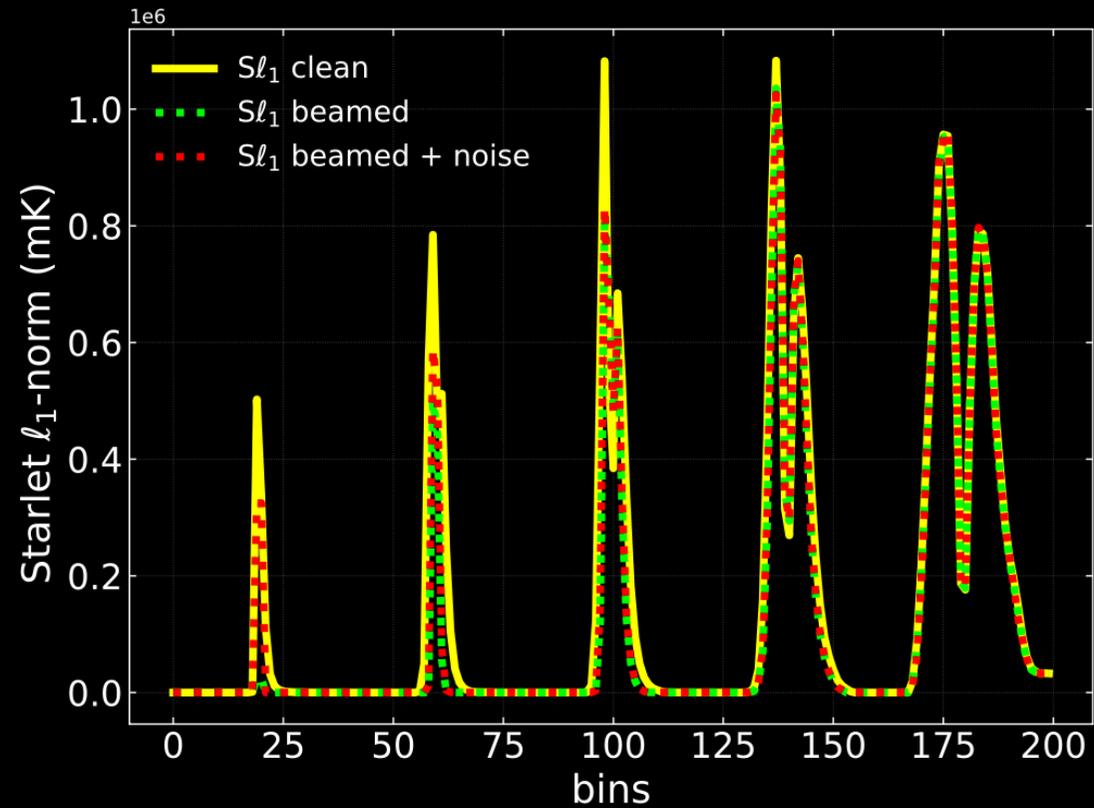
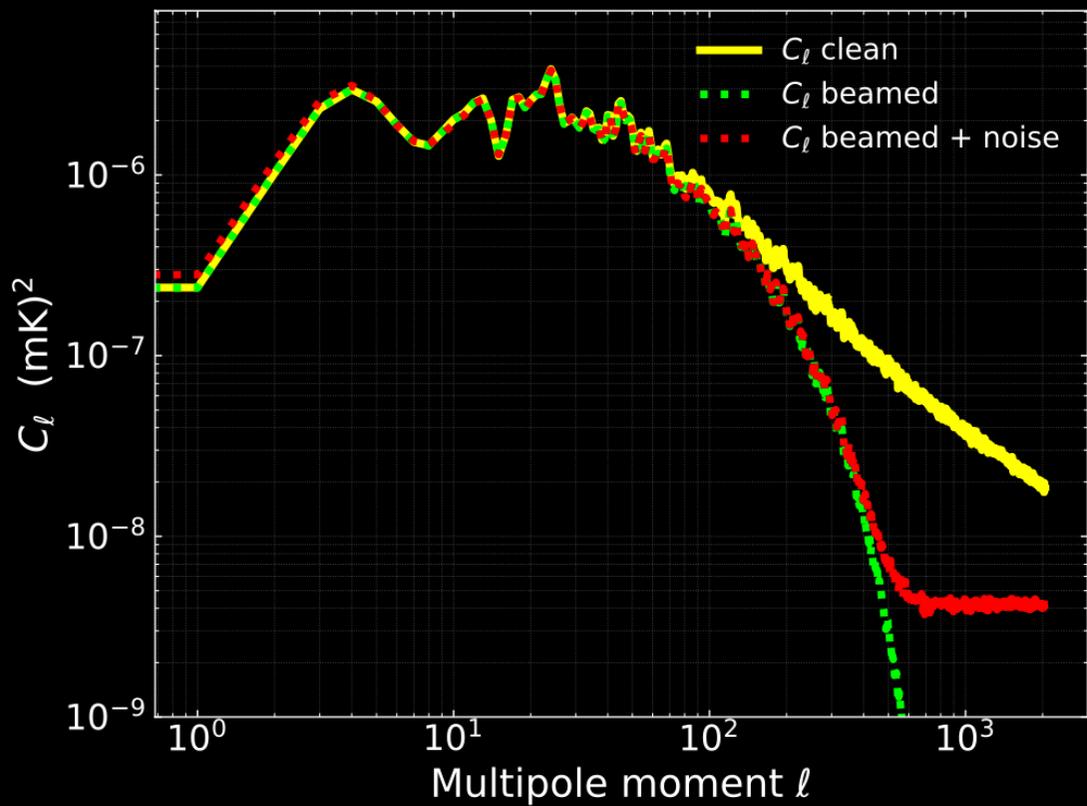
$$T_{\text{sys}} \approx T_{\text{sys}}^{\text{rec}} + T_{\text{CMB}} + 10\text{K} \left( \frac{1420[\text{MHz}]}{400[\text{MHz}](1+z)} \right)^{-2.75}$$

$T_{\text{sys}}^{\text{rec}}$ [K]	$f$	$t_{\text{obs}}$ [s]	$N_{\text{dish}}$
20	1	7,200,000	64

# Improving $Sl_1$ with additional scales

Noiseless case		
Statistic	Normalized FoM	Improvement vs $C_\ell$
$C_\ell$	1.00	—
$Sl_1$ (5 scales)	1.34	1.34×
$Sl_1$ (8 scales)	1.79	1.79×
Noisy case		
Statistic	Normalized FoM	Improvement vs $C_\ell$
$C_\ell$	1.00	—
$Sl_1$ (5 scales)	2.09	2.09×
$Sl_1$ (8 scales)	2.81	2.81×

# Robustness to beam and noise



# 'Zebras' patterns

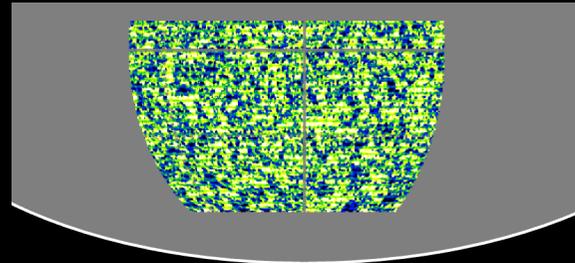
Multiplicative

$$T_{\text{sys}}(\hat{\mathbf{n}}) = T_{\text{HI}}(\hat{\mathbf{n}}) [1 + A \sin(\omega \theta)]$$

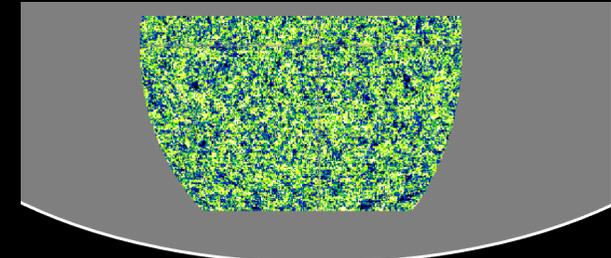
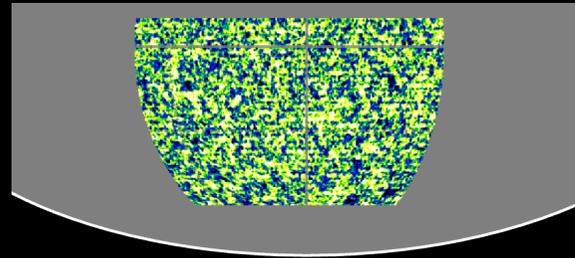
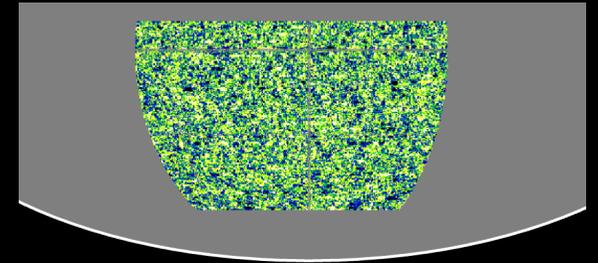
Additive

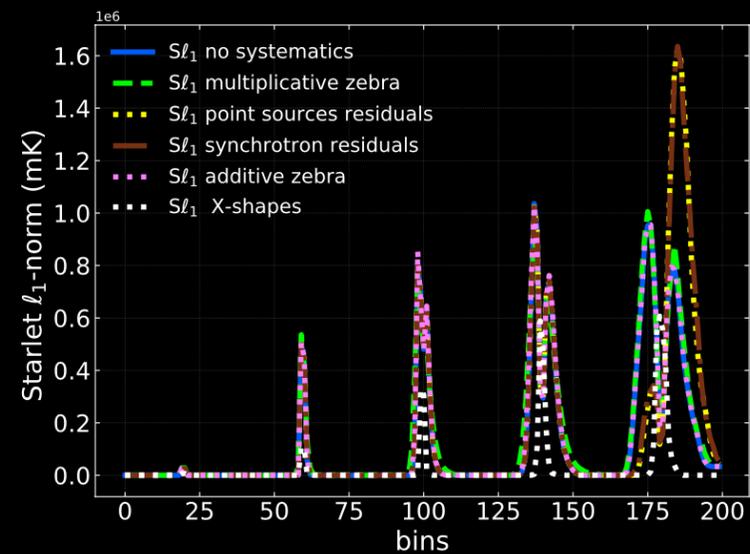
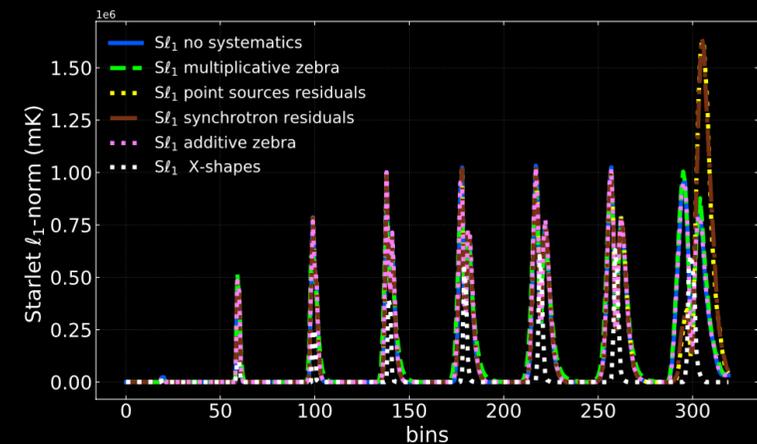
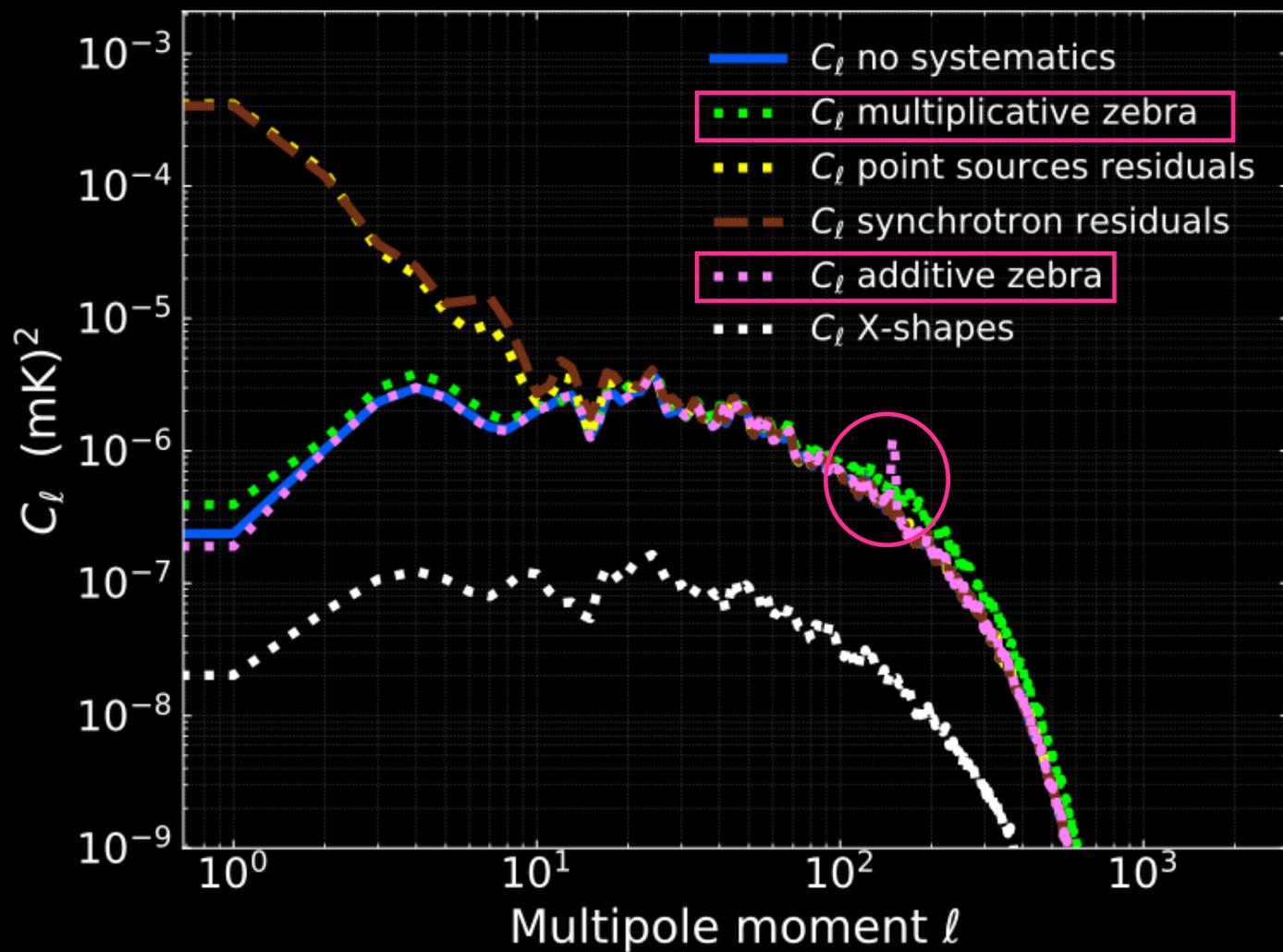
$$T_{\text{sys}}(\hat{\mathbf{n}}) = T_{\text{HI}}(\hat{\mathbf{n}}) + A \sin(\omega \theta)$$

$f_{\text{sky}} = 0.19$ ,  $\text{beam} = 0.5^\circ$ , zebras



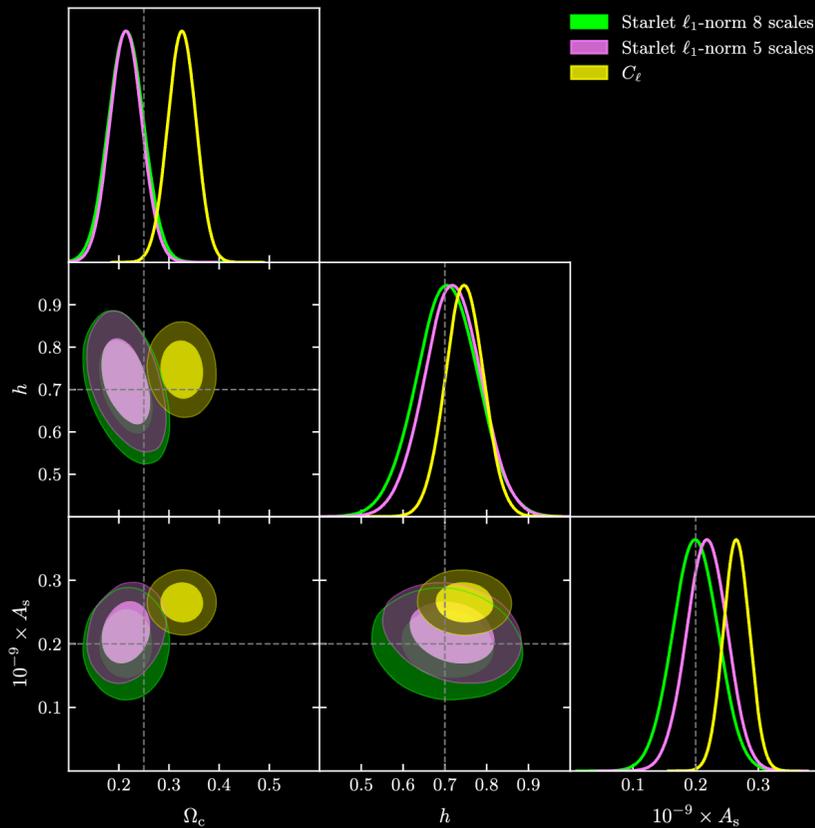
$f_{\text{sky}} = 0.19$ ,  $\text{beam} = 0.5^\circ$ , zebras + noise



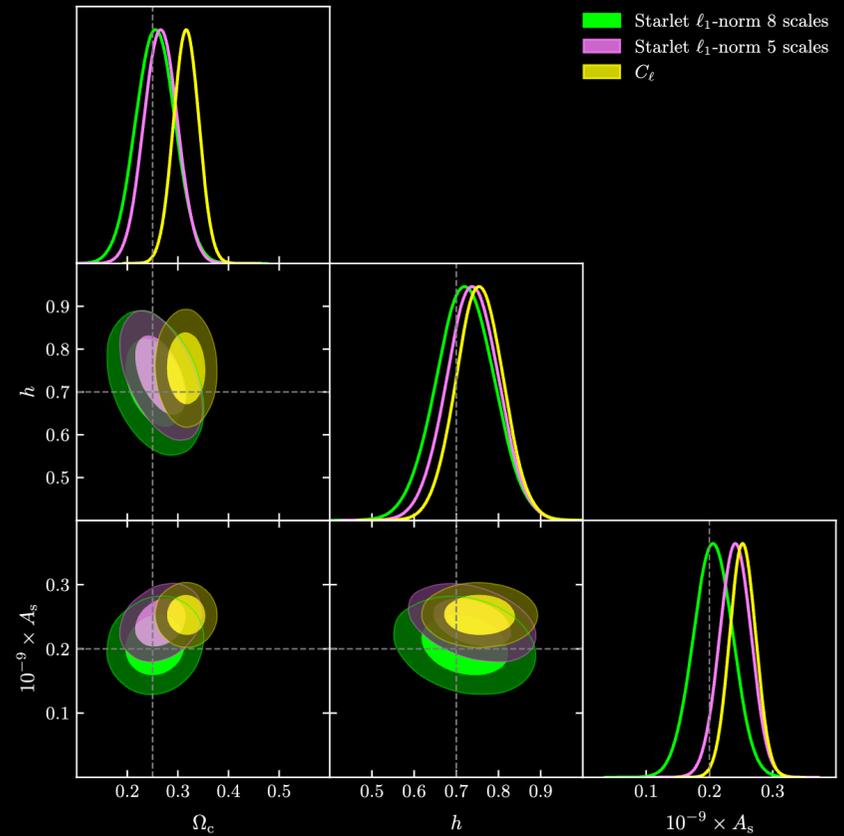


# Multiplicative 'Zebras'-stripe patterns

Posterior Comparison: Starlet  $\ell_1$ -norm vs  $C_\ell f_{sky} = 0.19$ ,  $beam = 0.5^\circ$ , zebras

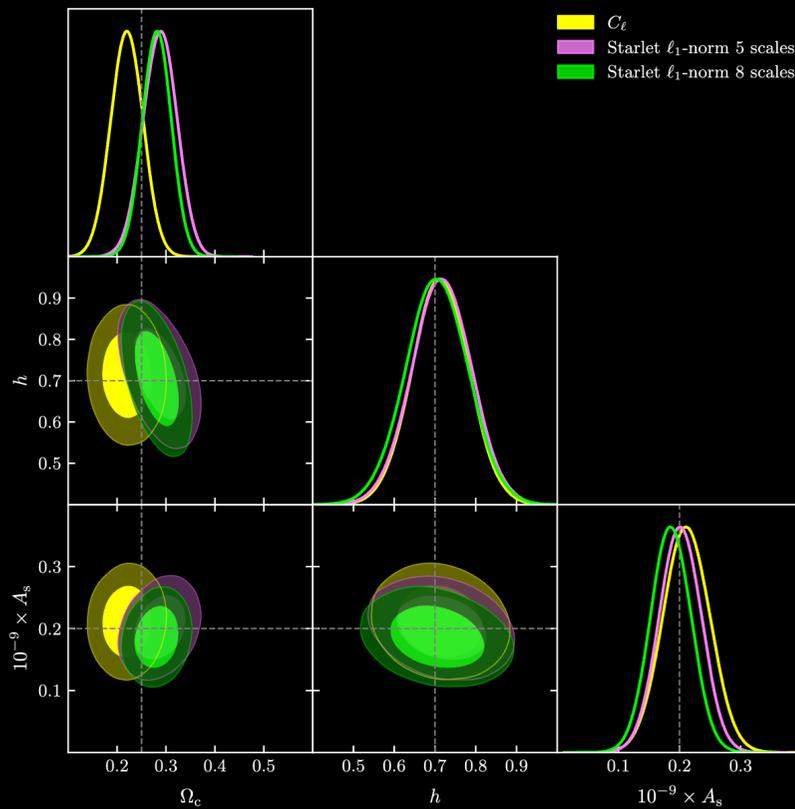


Starlet  $\ell_1$ -norm vs  $C_\ell f_{sky} = 0.19$ ,  $beam = 0.5^\circ$ , zebras + noise

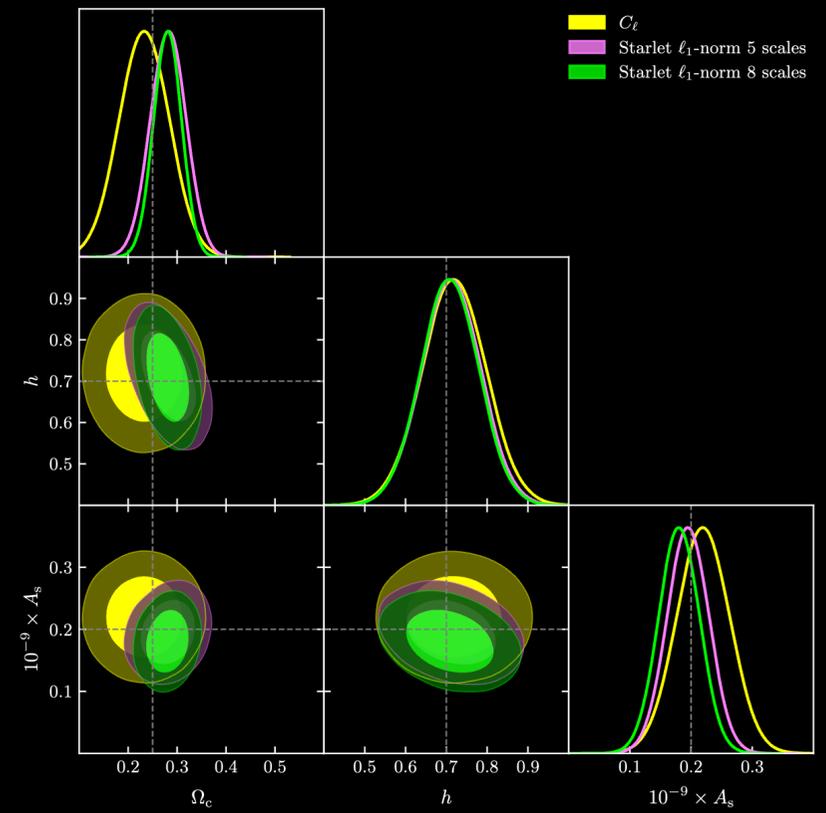


# Additive 'Zebras'-stripe patterns

Posterior Comparison: Starlet  $\ell_1$ -norm vs  $C_\ell$   $f_{sky} = 0.19$ ,  $beam = 0.5^\circ$ , zebras

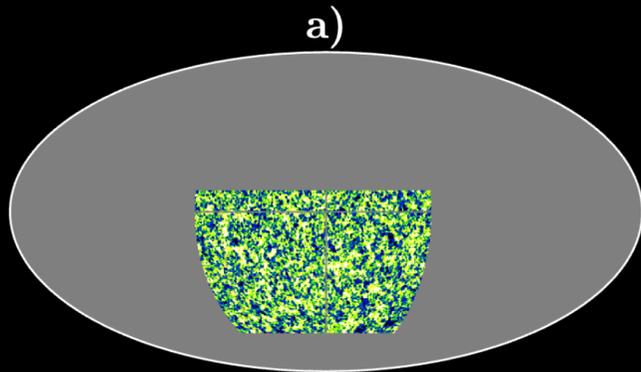


Starlet  $\ell_1$ -norm vs  $C_\ell$   $f_{sky} = 0.19$ ,  $beam = 0.5^\circ$ , zebras + noise

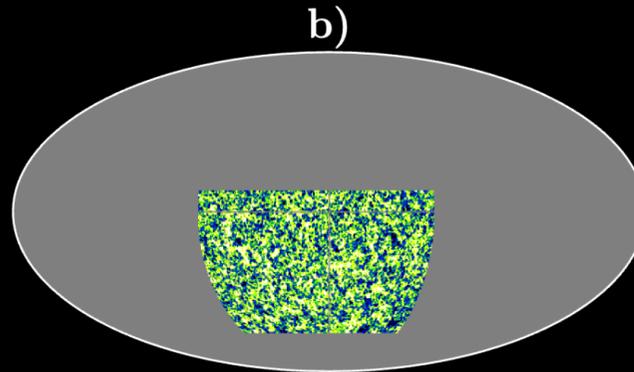


# Residual synchrotron contamination

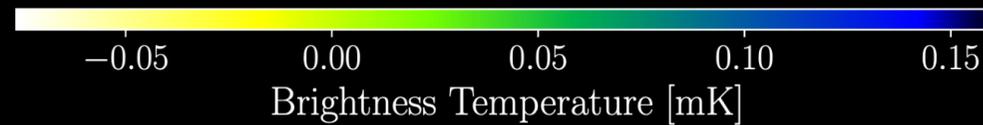
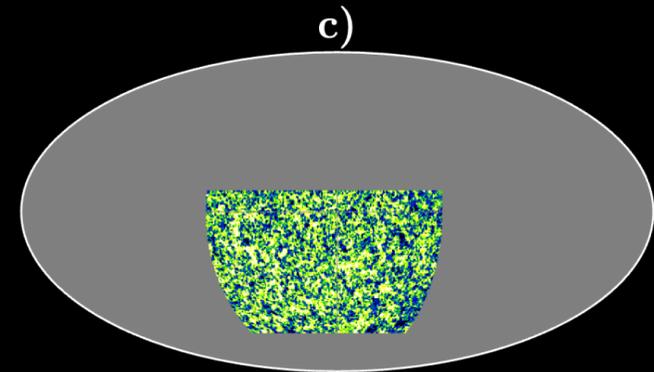
0.0005% synchrotron



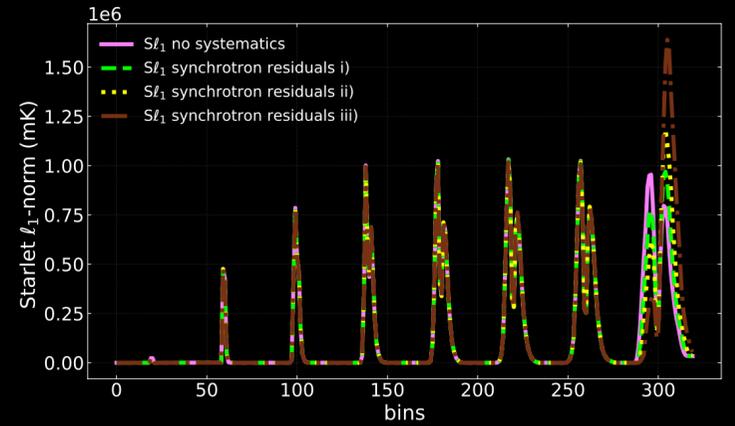
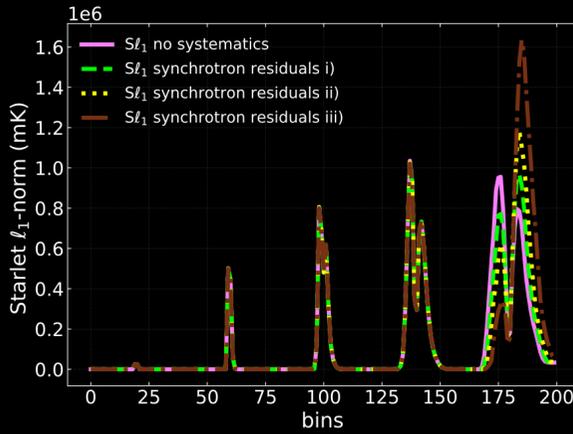
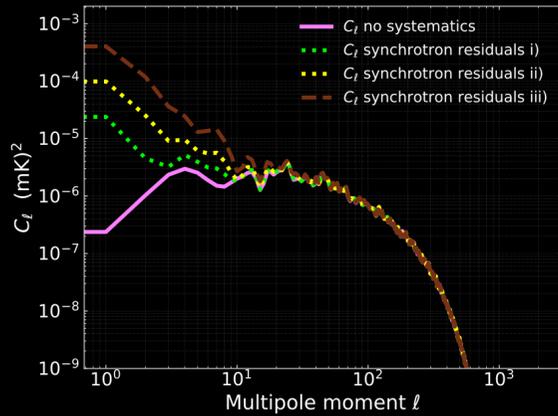
0.001% synchrotron



0.002% synchrotron



# Synchrotron



i) 0.0005% ii) 0.001% iii) 0.002%

Large scale effects

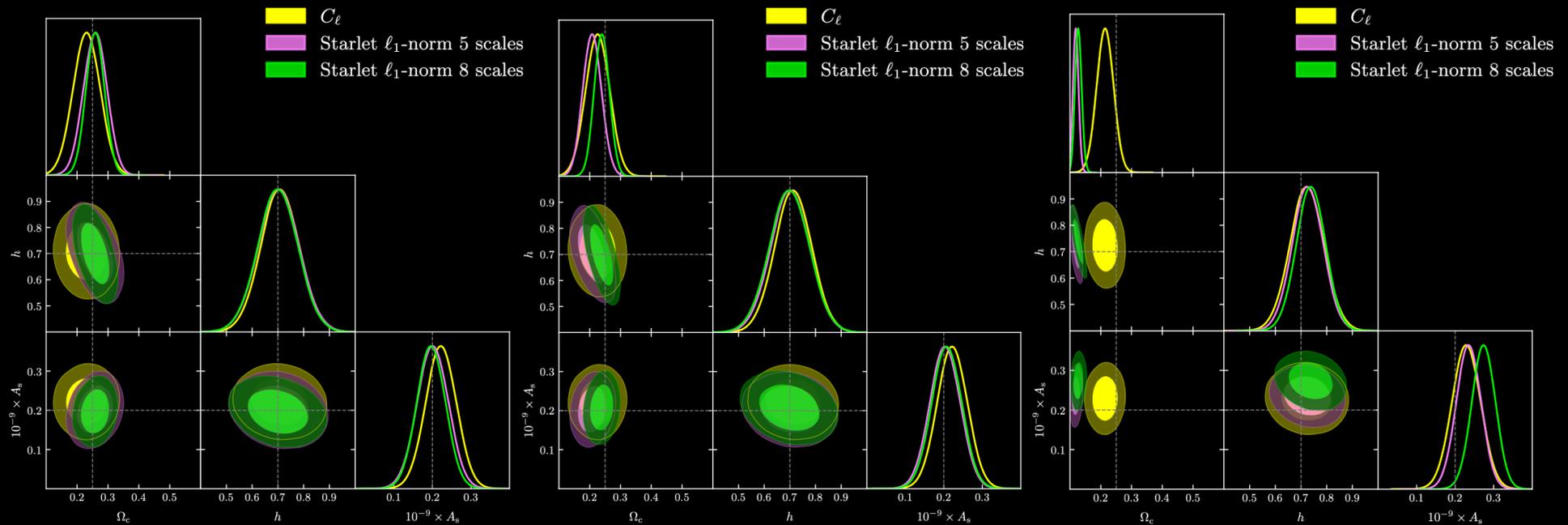
# Residual synchrotron contamination

Posterior Comparison: Starlet  $\ell_1$ -norm vs  $C_\ell$   $f_{sky} = 0.19$ ,  $beam = 0.5^\circ$

0.0005% synchrotron

0.001% synchrotron

0.002% synchrotron

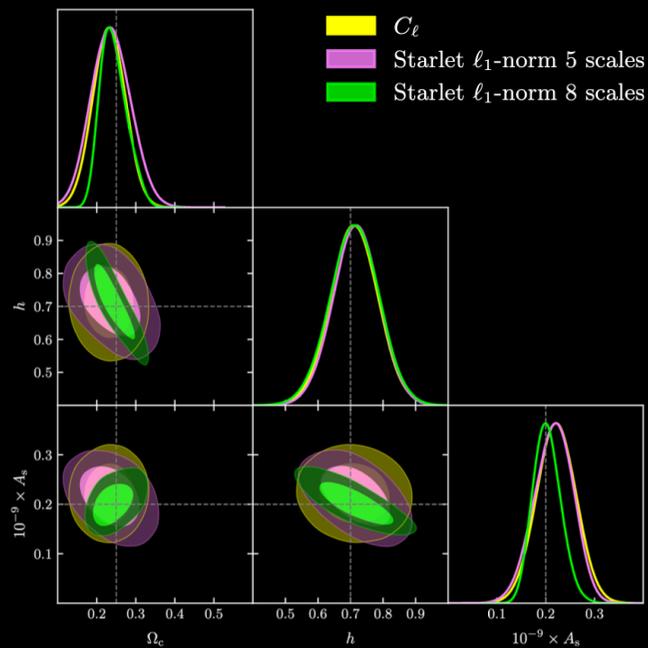


# Residual synchrotron contamination

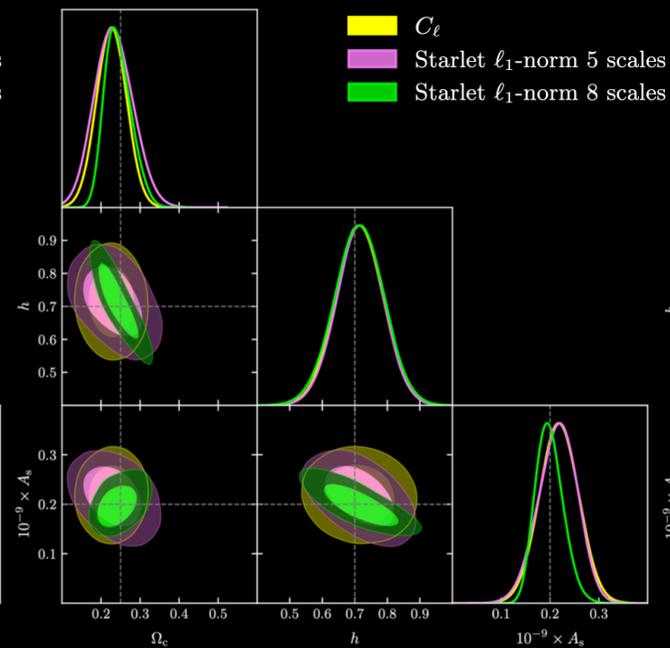
## Without coarse scale

Posterior Comparison: Starlet  $\ell_1$ -norm vs  $C_\ell$   $f_{sky} = 0.19$ ,  $beam = 0.5^\circ$

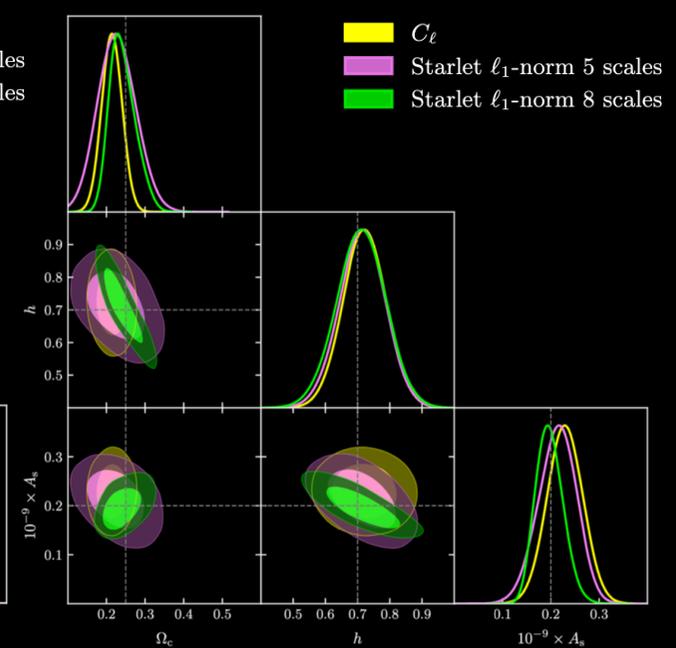
0.0005% synchrotron



0.001% synchrotron

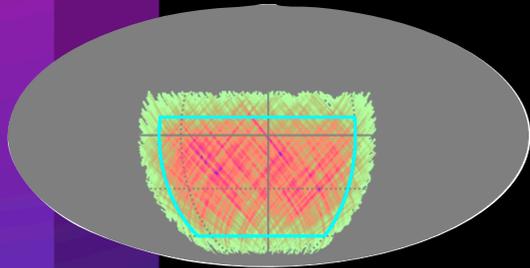


0.002% synchrotron

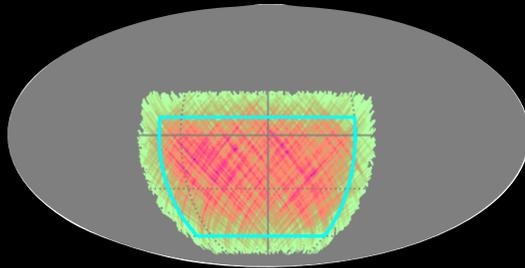


# X-shape mask

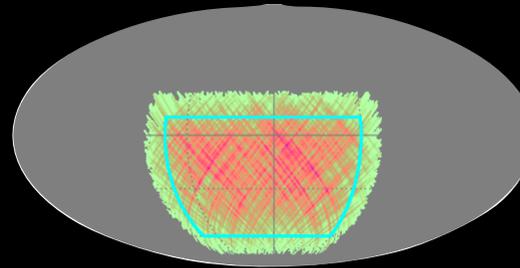
Weight : 10X



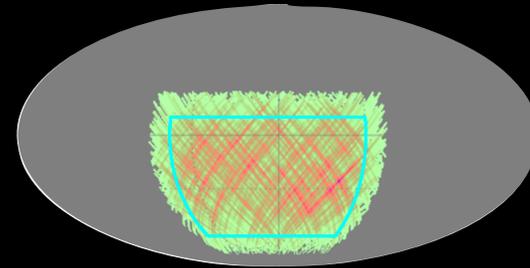
Weight : 25X



Weight : 35X

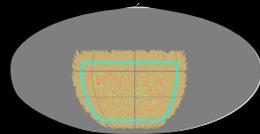


Weight : 50X

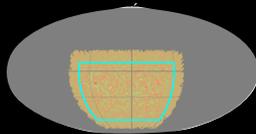


## Multiplicative

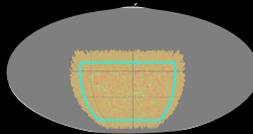
10X



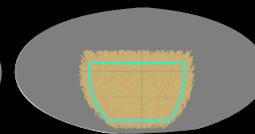
25X



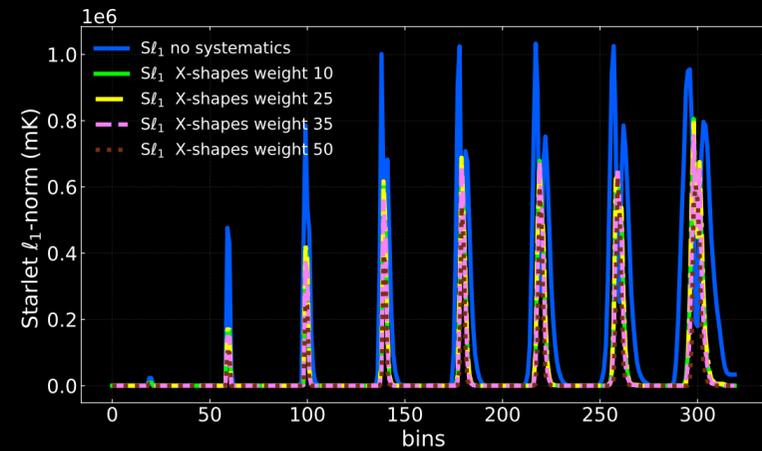
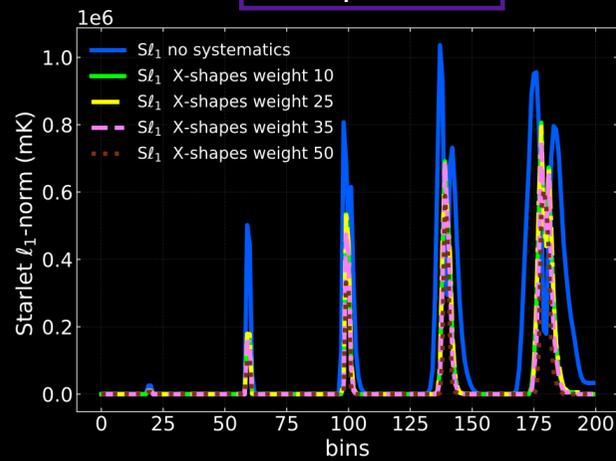
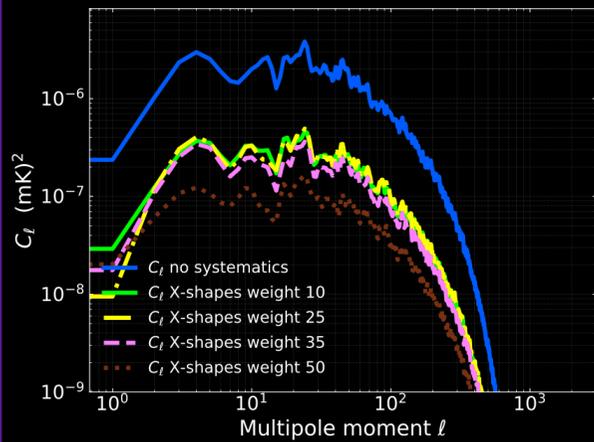
35X



50X



## Multiplicative



# X-shape multiplicative

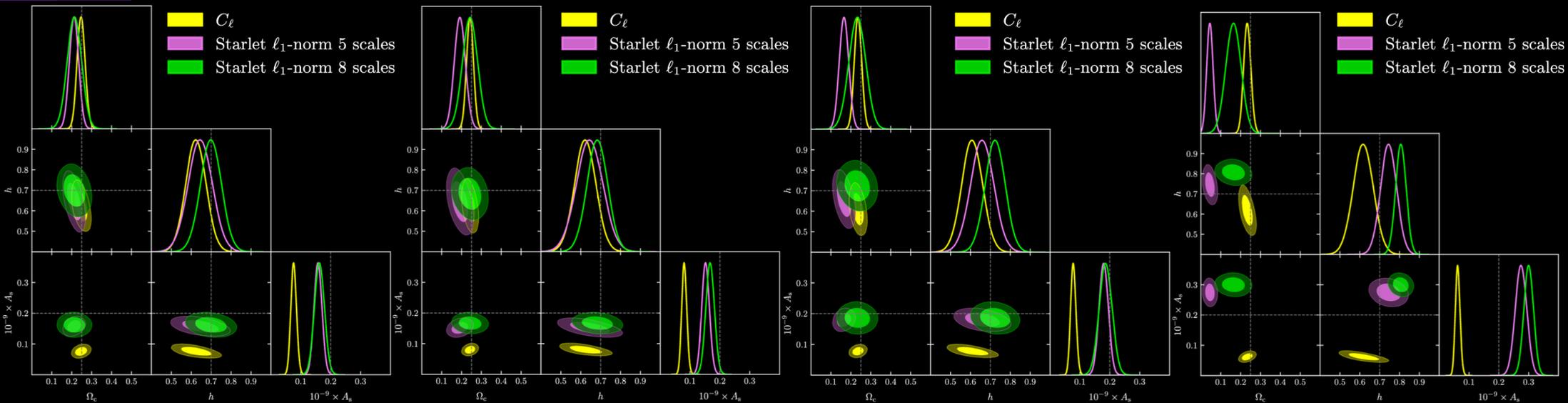
Posterior Comparison: Starlet  $\ell_1$ -norm vs  $C_\ell$   $f_{sky} = 0.19$ ,  $beam = 0.5^\circ$ .

X-shape weight: 10X

25X

35X

50X



# Conclusions

Starlet l1 norm :

- Consistently outperforms the CI in all scenarios.
- with 8 scales outperforms the CI by 2.81x in beamed noisy case.
- is robust to noise.
- the coarse scale is sensitive foreground residuals.
- more stable against scanning patterns (with 8 scales).

# Next Step

Impact of the foreground cleaning method on the cosmological parameter recovery

# Thank you