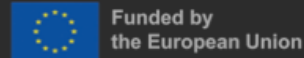


# Starlet $l_1$ -norm for HI intensity mapping

Supervisors : Jean-Luc Starck, Stefano Camera

Collaborator : Marta Spinelli

2026 Non Gaussian Universe

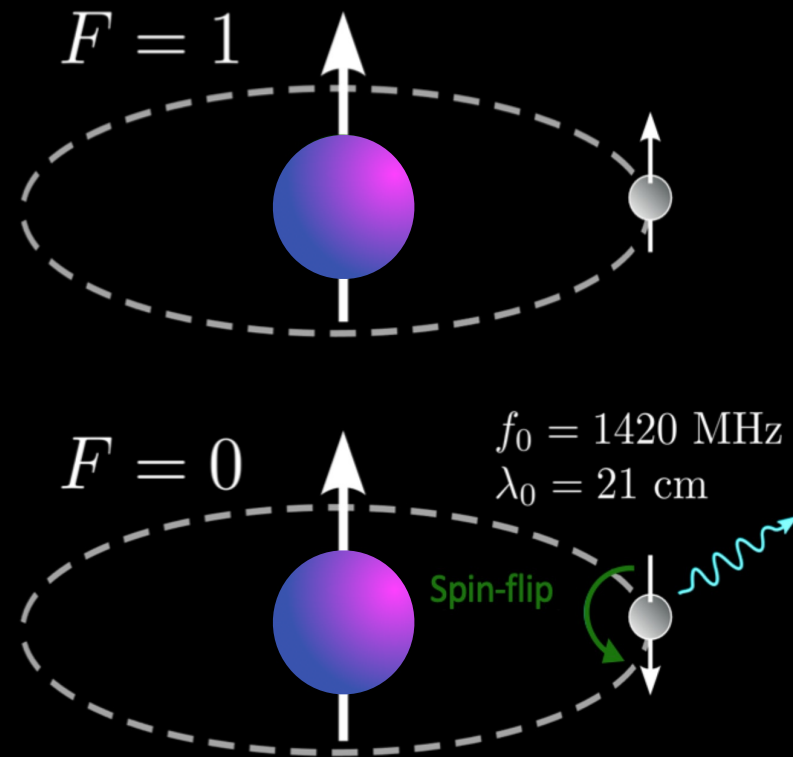


Pauline Gorbachev

# Physical background

- Hydrogen: most abundant element in the Universe.
- After reionization, HI is located inside galaxies.

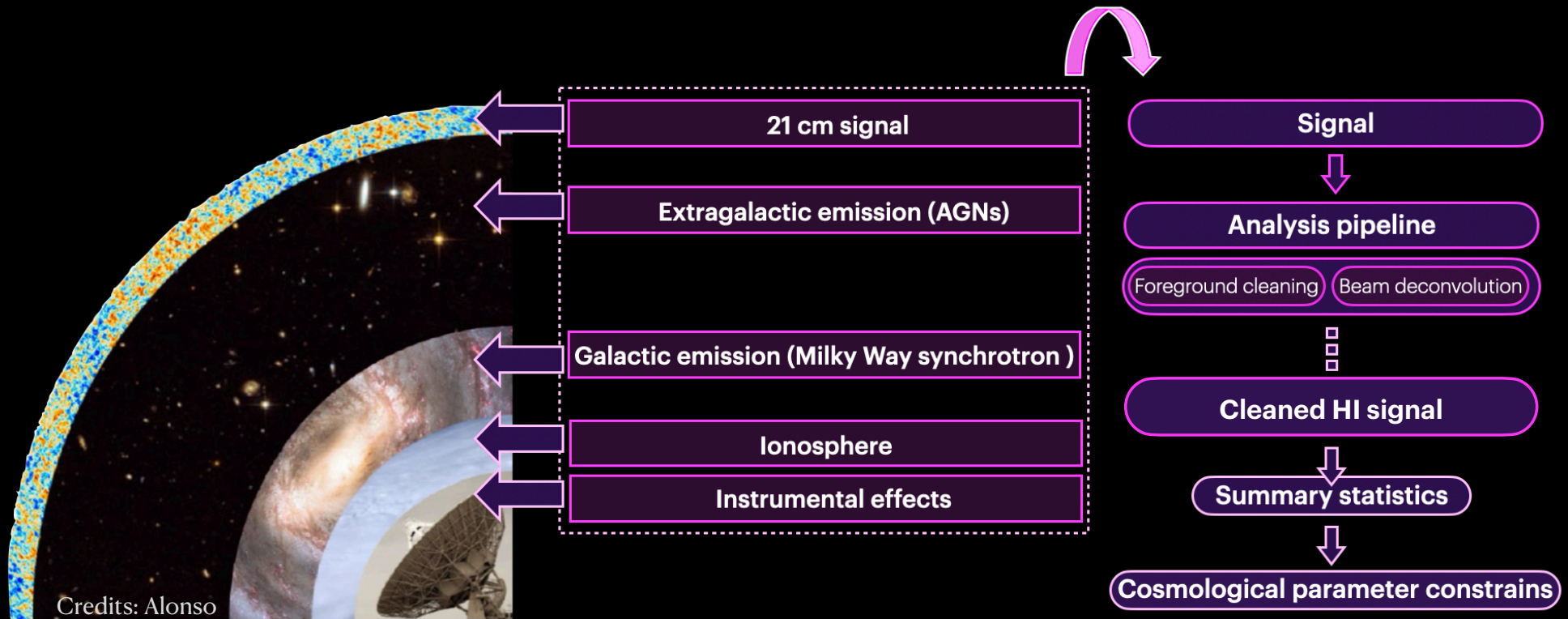
⇒ **biased tracer** of the underlying **matter distribution** of the Universe.



HI hyperfine transition

# End-to-end measurements

Credits: :Marta Spinelli



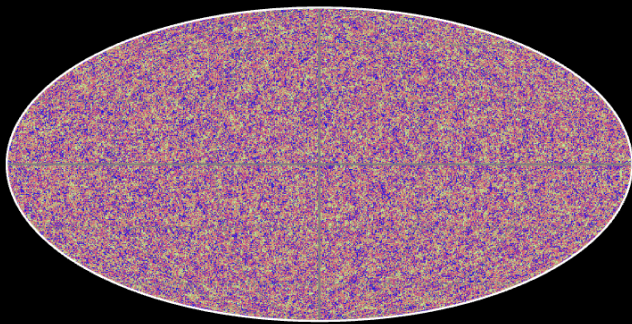
# Motivations for Higher order Statistics

- At late times the **HI signal** becomes highly **non Gaussian**.
- Traditional **2-pt statistics miss** important **information**.  
→ **Higher order statistic** are needed.
- The **starlet l1 norm** is especially **effective** as it **is sensitive to morphological structures across multiple spatial scales**, making it a powerful probe of non-gaussian features.

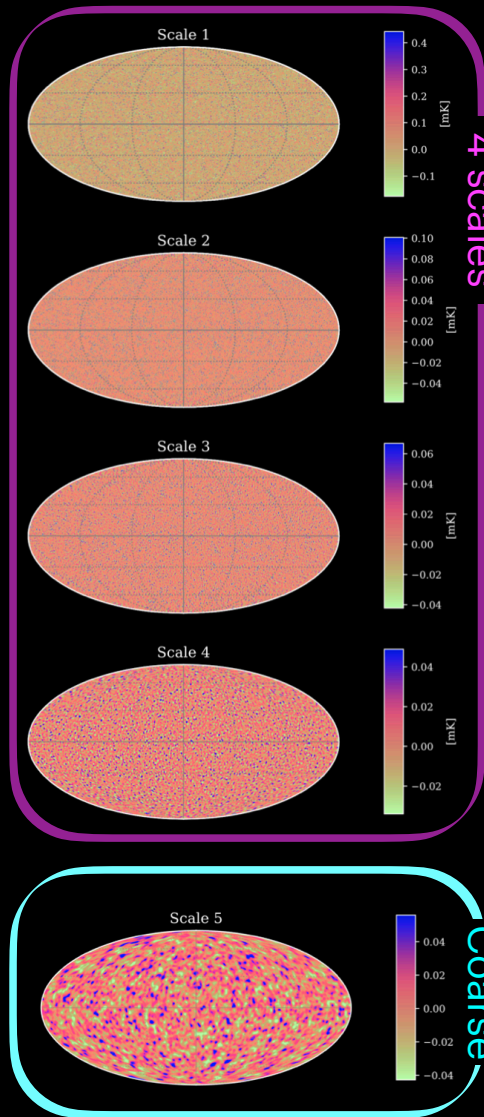
# Starlet l1-norm

Multi-scale higher order statistics

HI map  $M(\hat{n})$

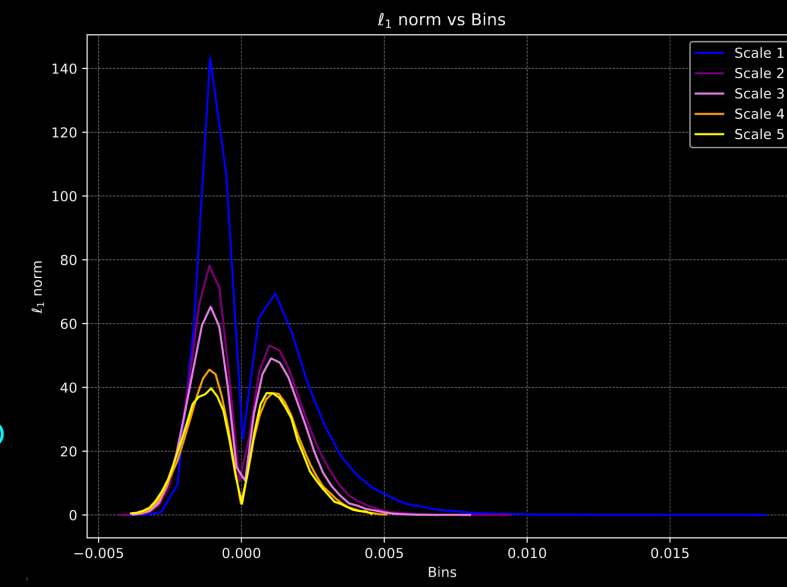


$$M(\hat{n}) = \sum_{j=1}^J w_j(\hat{n}) + c_J(\hat{n}).$$



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

$$\mathcal{B}_k = \left\{ \hat{n} \mid T_k \leq \frac{w_j(\hat{n})}{\mathcal{N}_j} < T_{k+1} \right\}$$



Can the *starlet*  $\ell_1$ -norm yield **tighter** constraints than  $C_\ell$ ?

# Posterior Inference pipeline

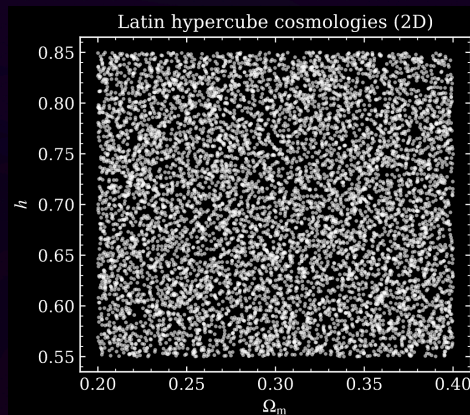
## SIMULATION-BASED INFERENCE · SBI

### WHY SBI

- No explicit likelihood required
  - Training set computed once
  - Training time: a few minutes
- [github.com/sachaguer/jaxili](https://github.com/sachaguer/jaxili)

### PRIOR SAMPLING

8 000 cosmologies drawn on a 2D Latin hypercube



### PARAMETERS

$\Omega_m \in [0.20, 0.40]$   
 $h \in [0.55, 0.87]$

### Training pairs

$\xi_1$ -norm ·  $\Omega_m, h$



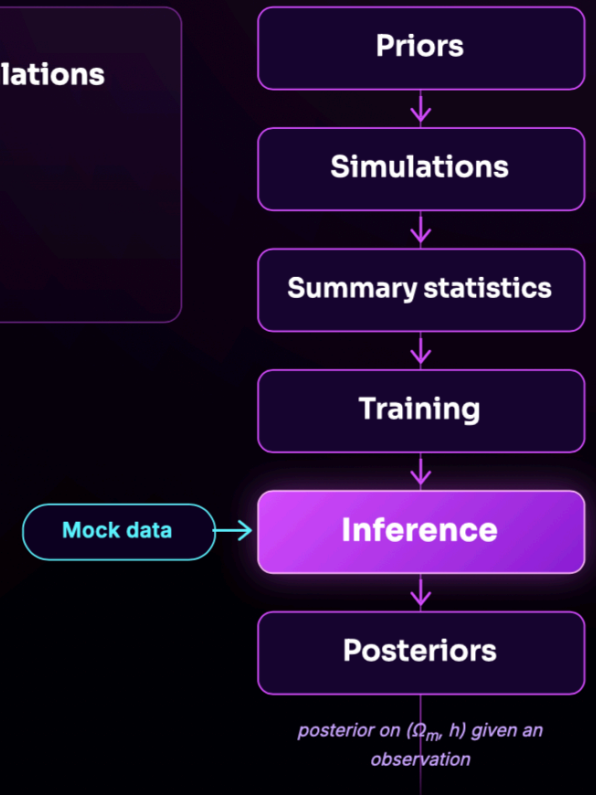
summary statistic  $\leftrightarrow$  parameters

### DATASET SPLIT

8 000 simulations

TRAIN  
5 600 (70%)  
VALIDATION  
1 600 (20%)  
TEST  
800 (10%)

### THE PIPELINE

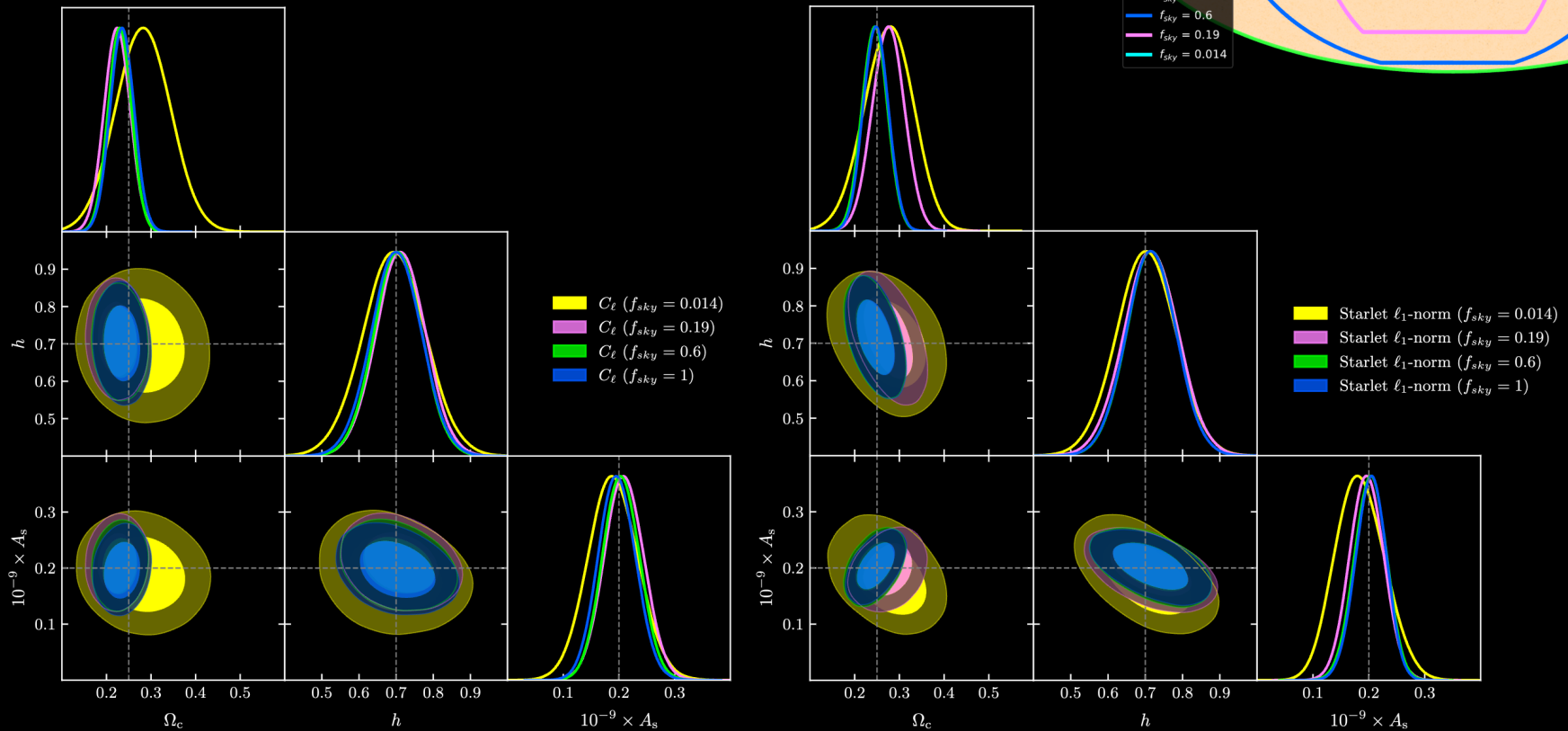


# Results

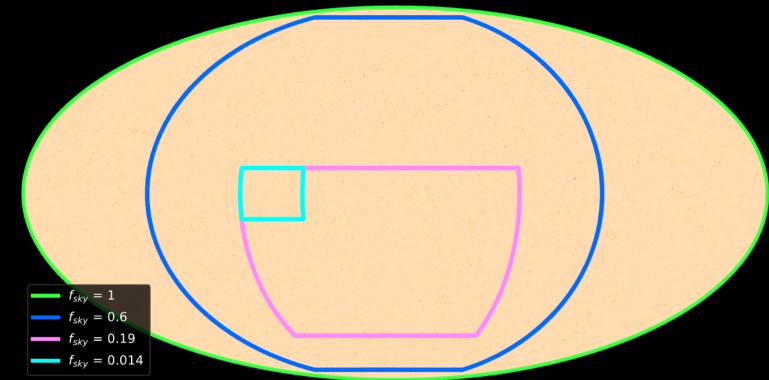
# Sky fraction

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

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



# Sky fraction



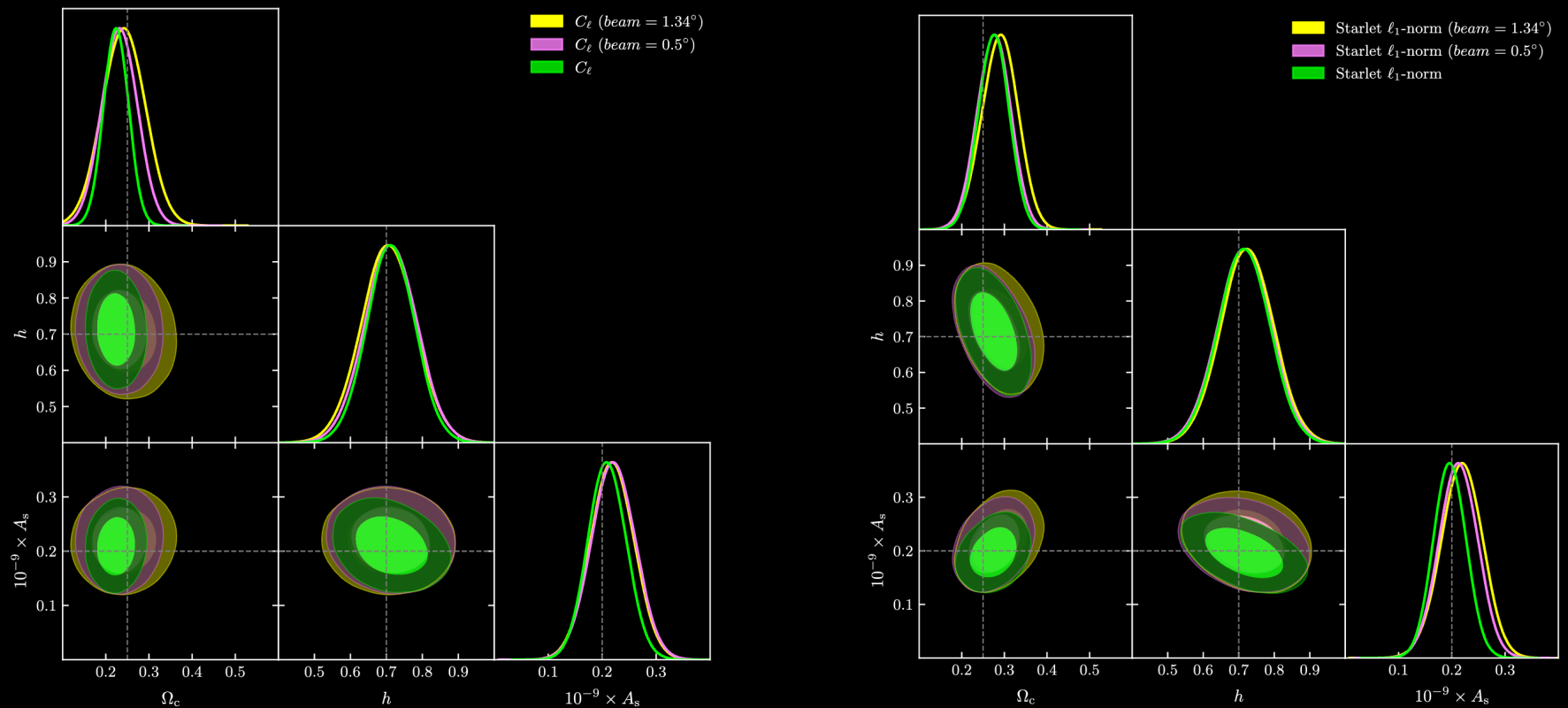
Posterior Comparison: Starlet  $\ell_1$ -norm vs  $C_\ell$

| 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  $C_\ell$   $f_{sky} = 0.19$



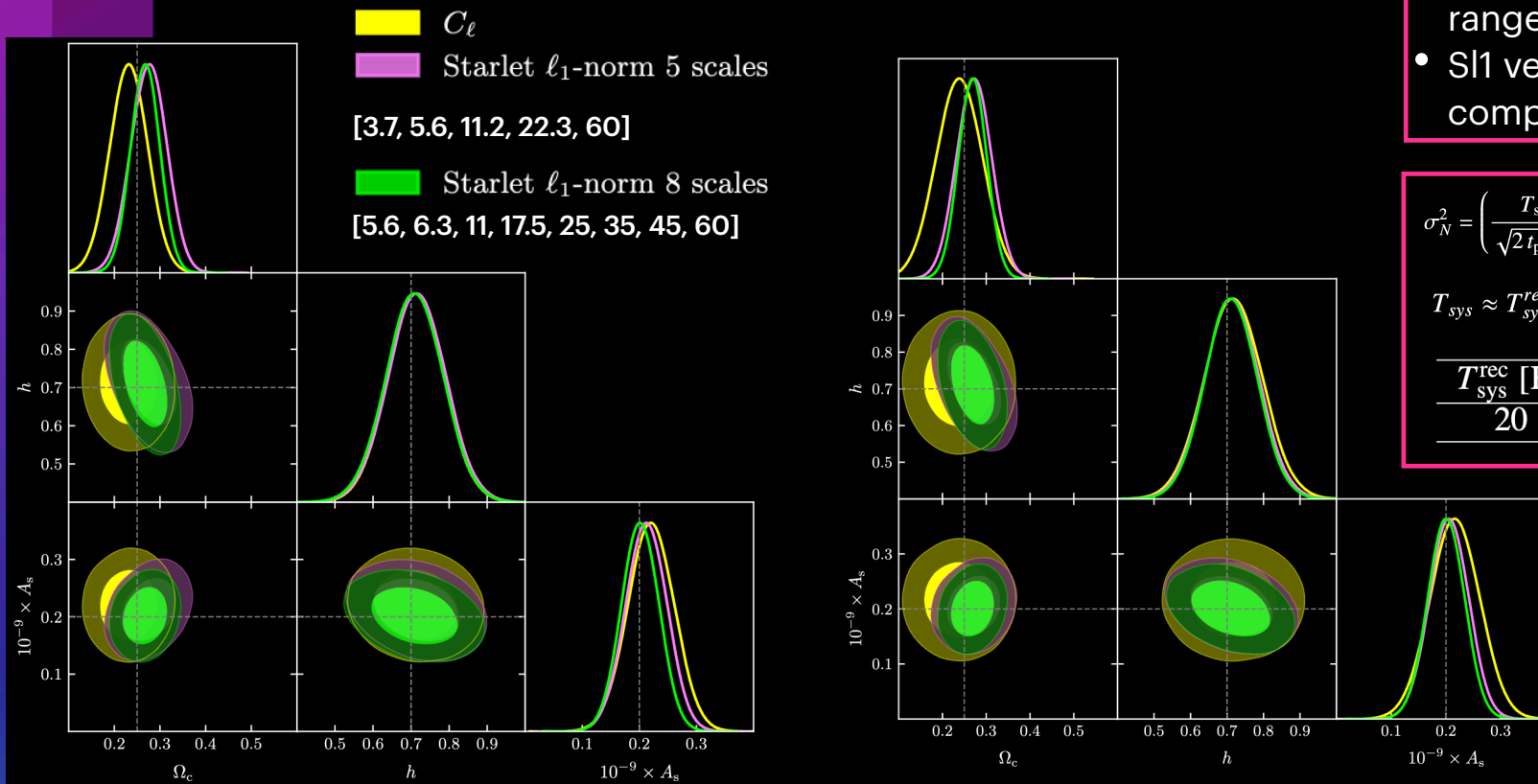
# Gaussian Beam

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 intermediate 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 C1

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

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

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

# Improving $Sl_1$ with additional scales

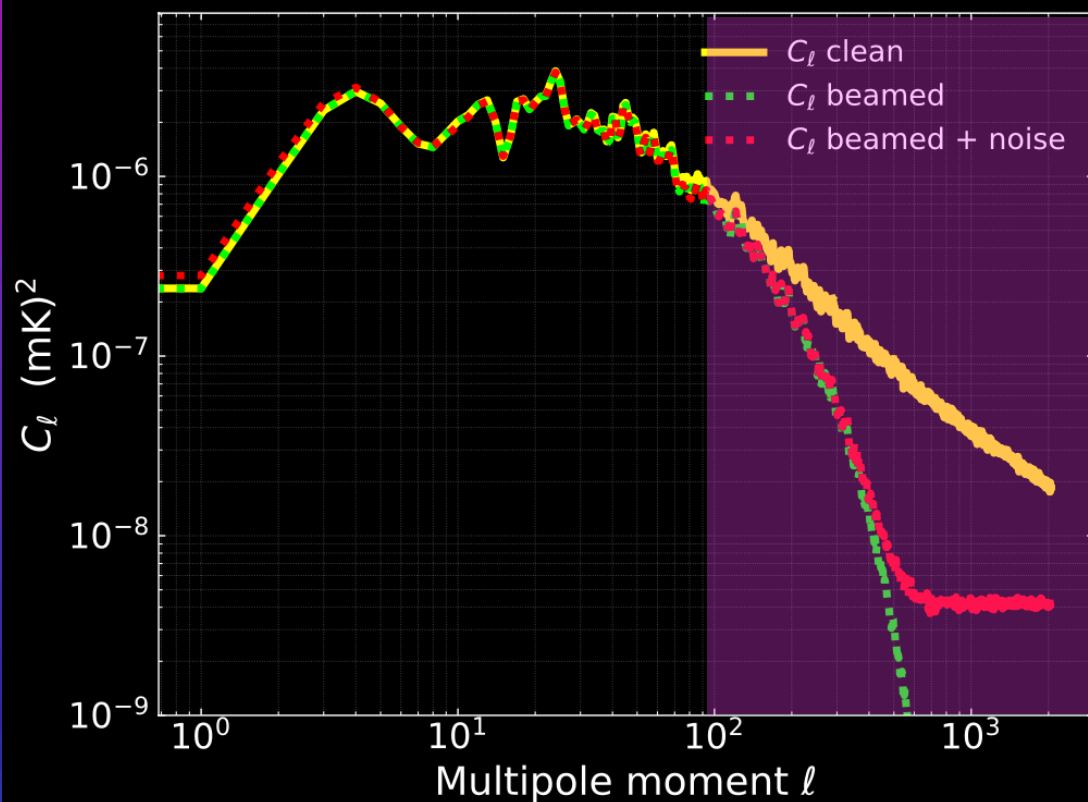
| Noiseless case    |                |                         |
|-------------------|----------------|-------------------------|
| Statistic         | Normalized FoM | Improvement vs $C_\ell$ |
| $C_\ell$          | 1.00           | —                       |
| $Sl_1$ (5 scales) | 1.34           | 1.34×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

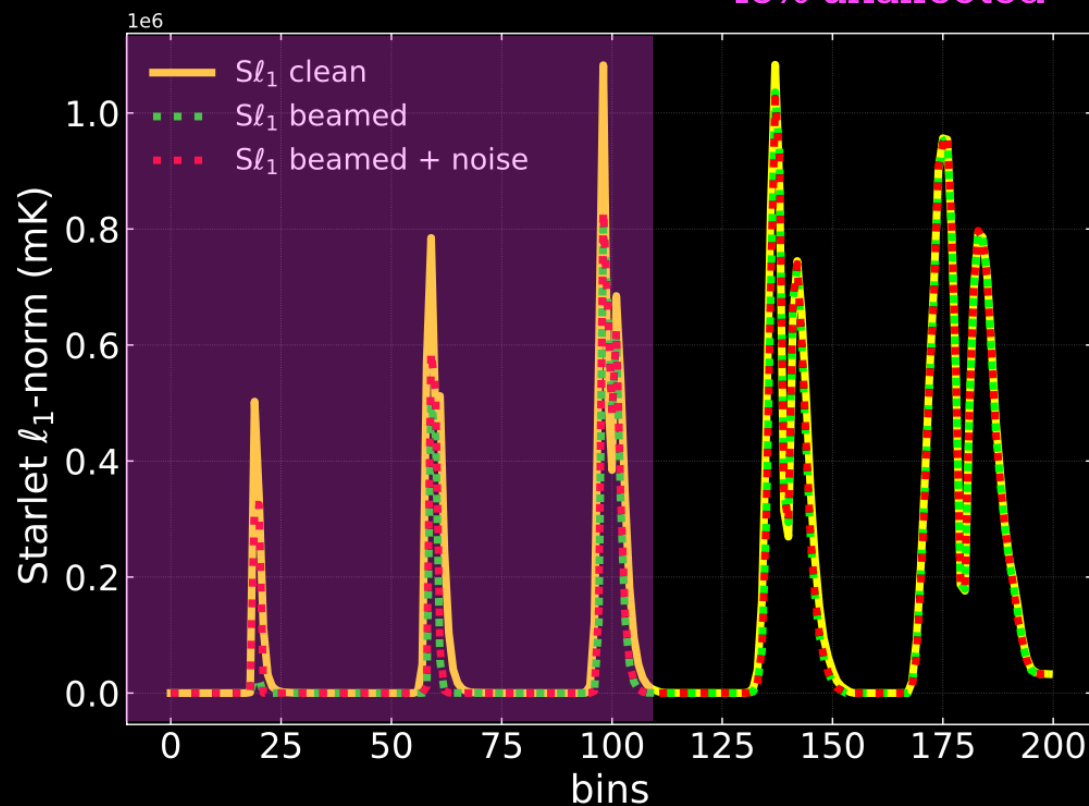
| Noisy case        |                |                         |
|-------------------|----------------|-------------------------|
| Statistic         | Normalized FoM | Improvement vs $C_\ell$ |
| $C_\ell$          | 1.00           | —                       |
| $Sl_1$ (5 scales) | 2.09           | 2.09×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

# Robustness to beam and noise

~10% unaffected



~45% unaffected



# 'Zebras' patterns

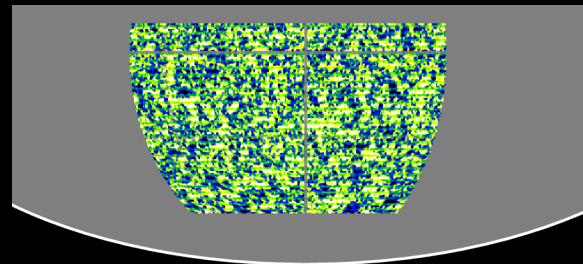
Multiplicative

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

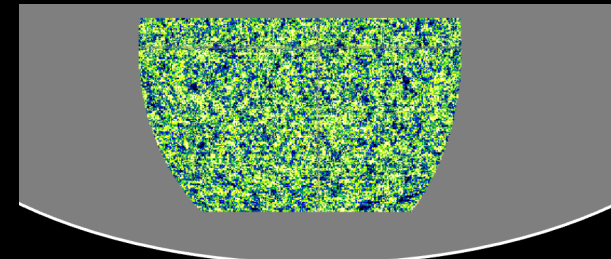
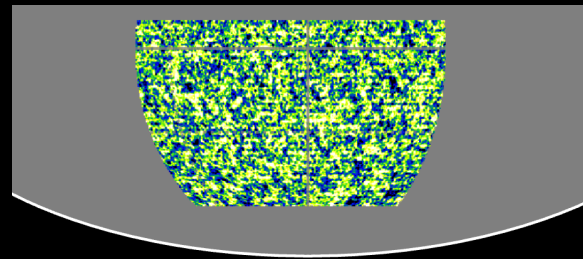
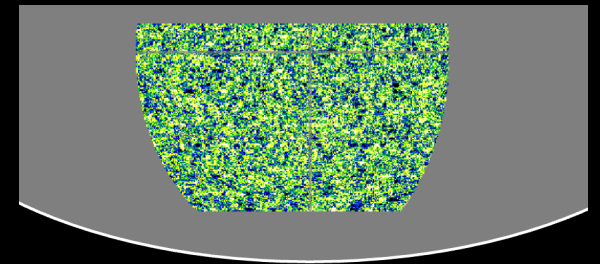
Additive

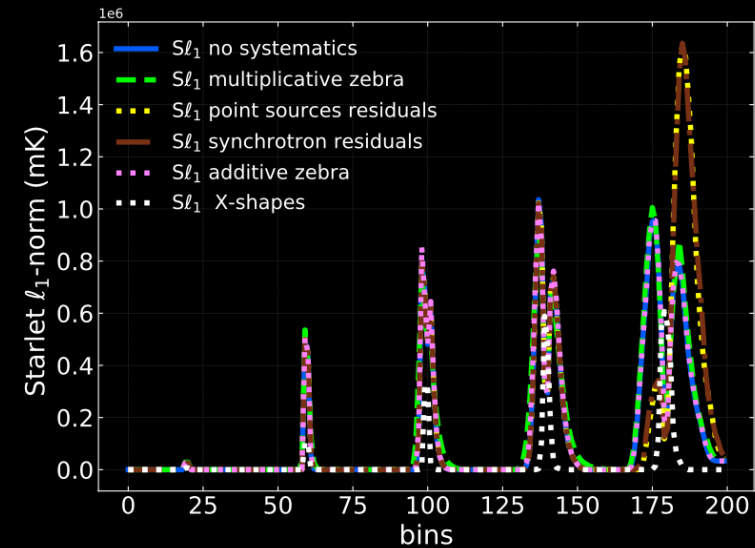
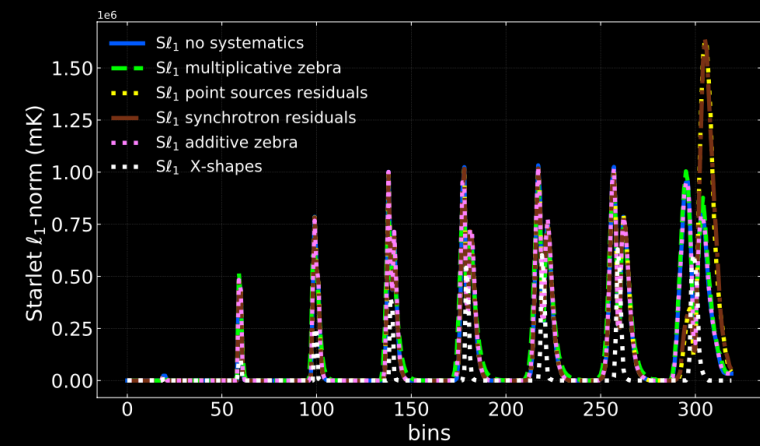
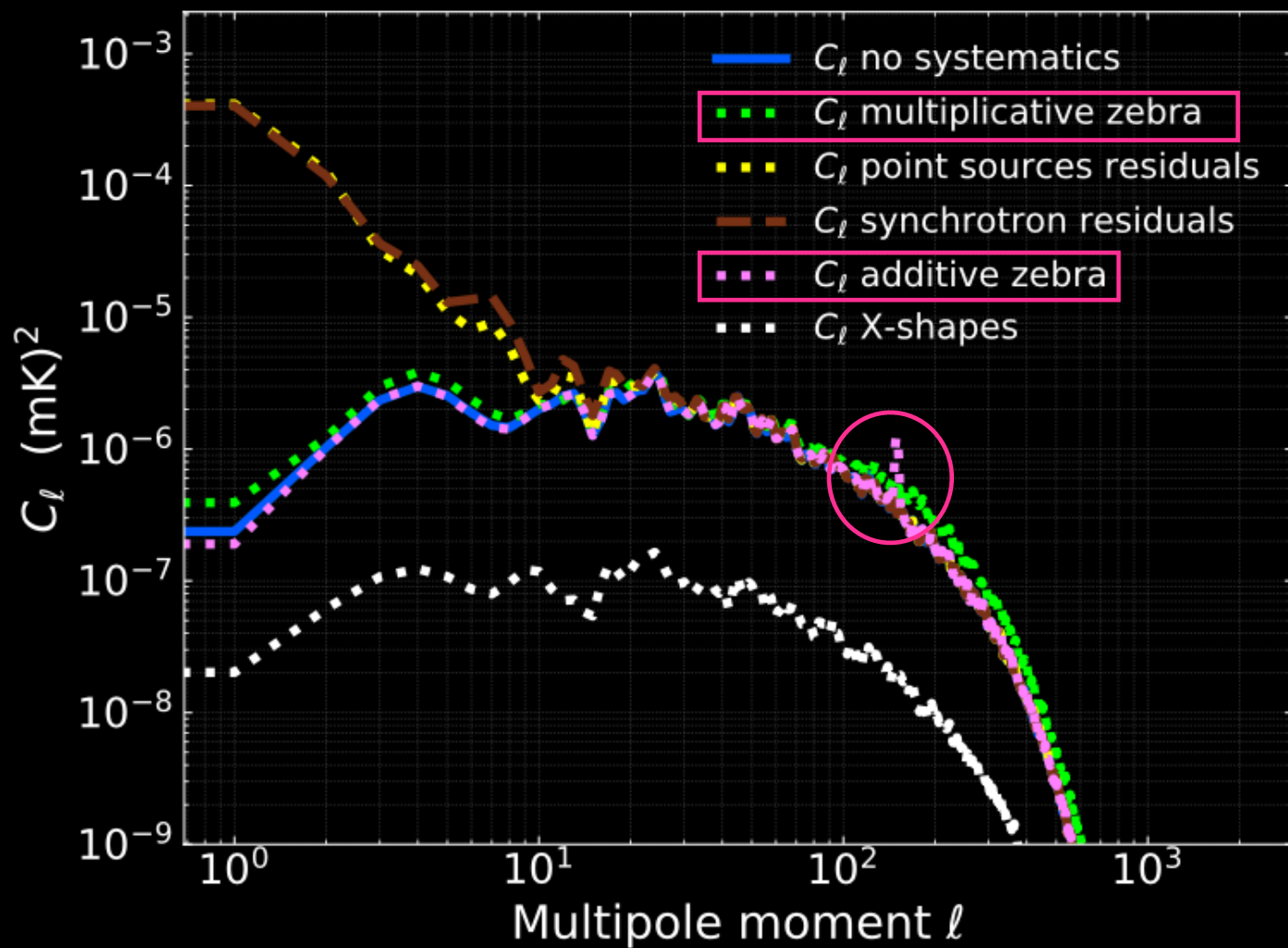
$$T_{\text{sys}}(\hat{\mathbf{n}}) = T_{\text{HI}}(\hat{\mathbf{n}}) + A \sin(\omega \theta)$$

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



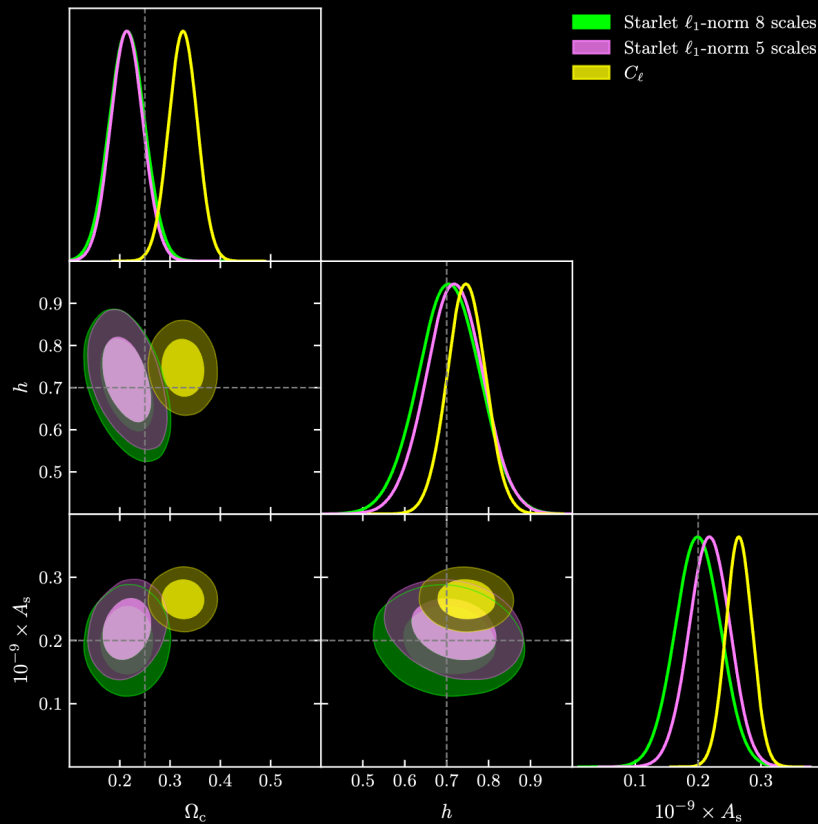
$f_{\text{sky}} = 0.19, \text{beam} = 0.5^\circ, \text{zebras} + \text{noise}$



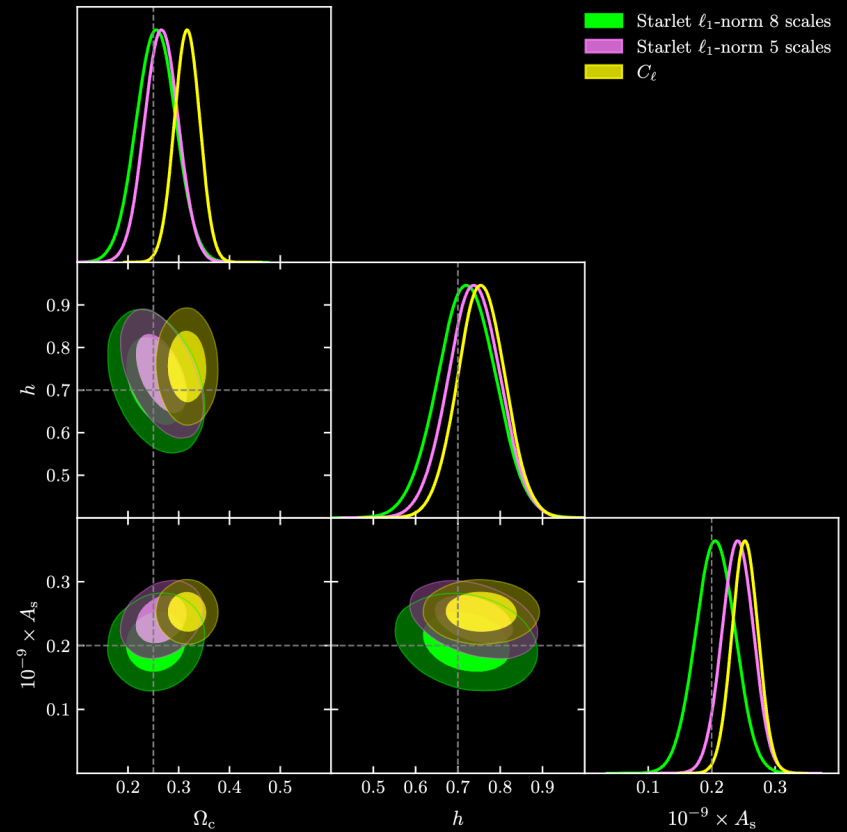


# Multiplicative 'Zebras'-stripe patterns

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

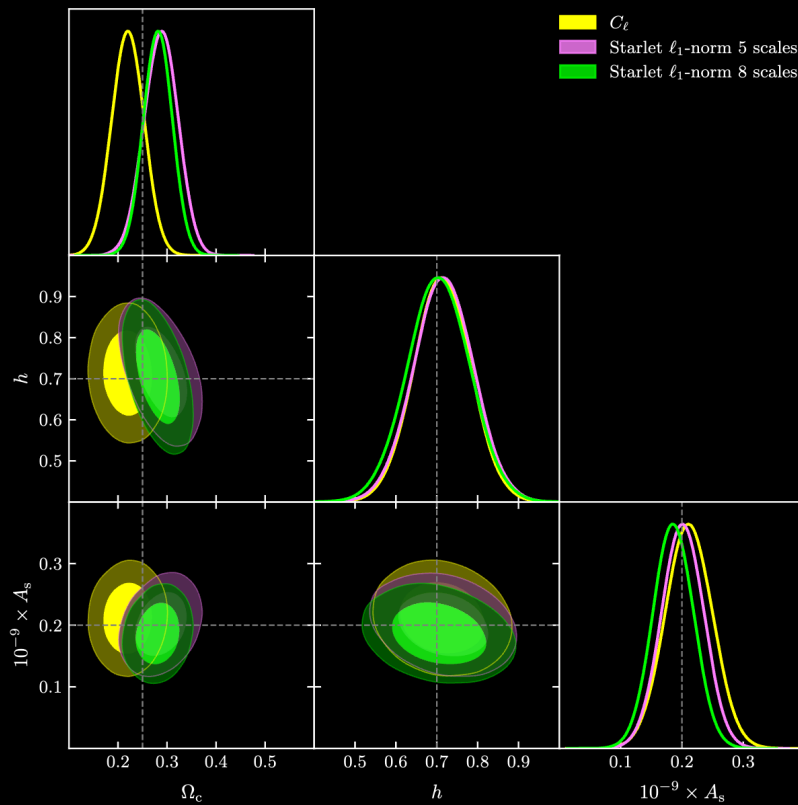


Starlet  $\ell_1$ -norm vs  $C_\ell f_{sky} = 0.19$ ,  $beam = 0.5^\circ$ , zebras + noise

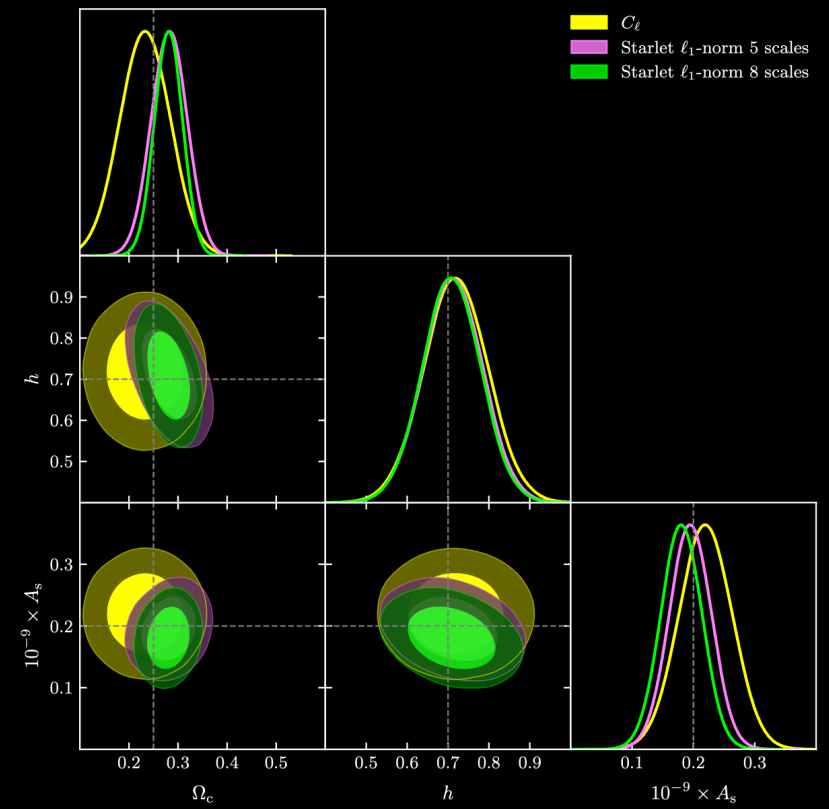


# Additive 'Zebras'-stripe patterns

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



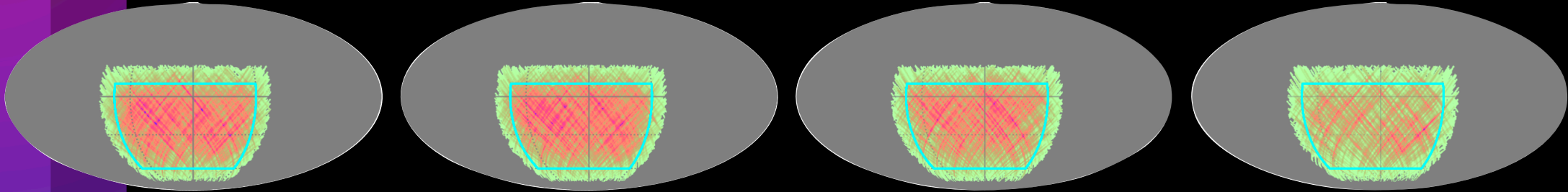
# X-shape mask

Weight : 10X

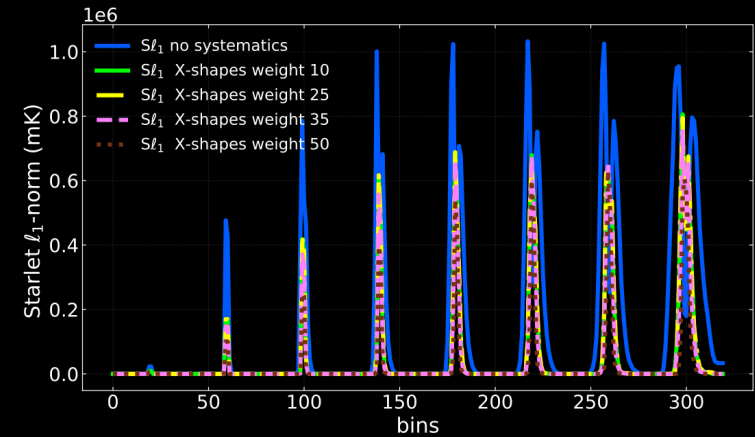
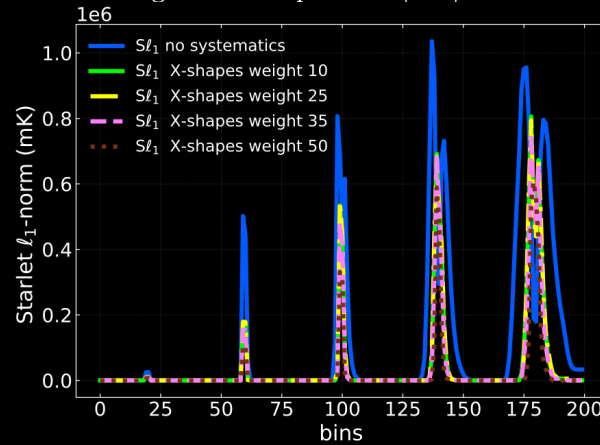
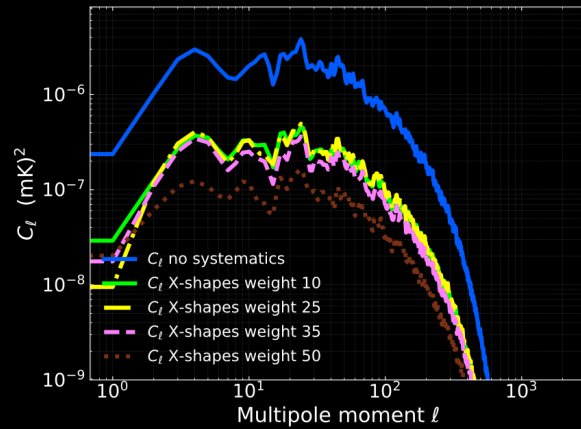
Weight : 25X

Weight : 35X

Weight : 50X



Brightness Temperature [mK]



# X-shape multiplicative

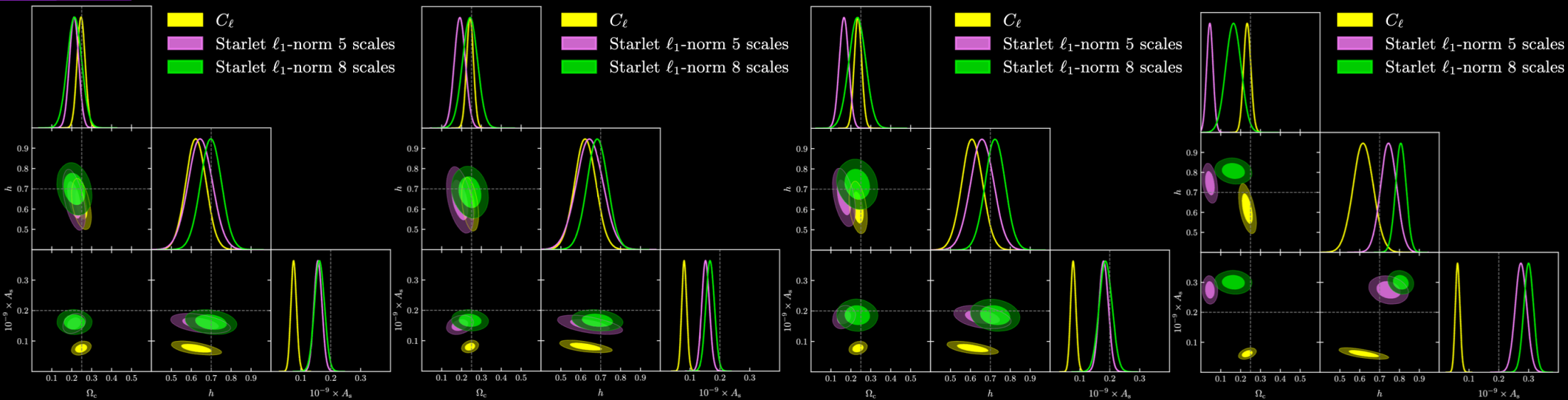
Posterior Comparison: Starlet  $\ell_1$ -norm vs  $C_\ell$   $f_{sky} = 0.19$ ,  $beam = 0.5^\circ$ .

X-shape weight: 10X

25X

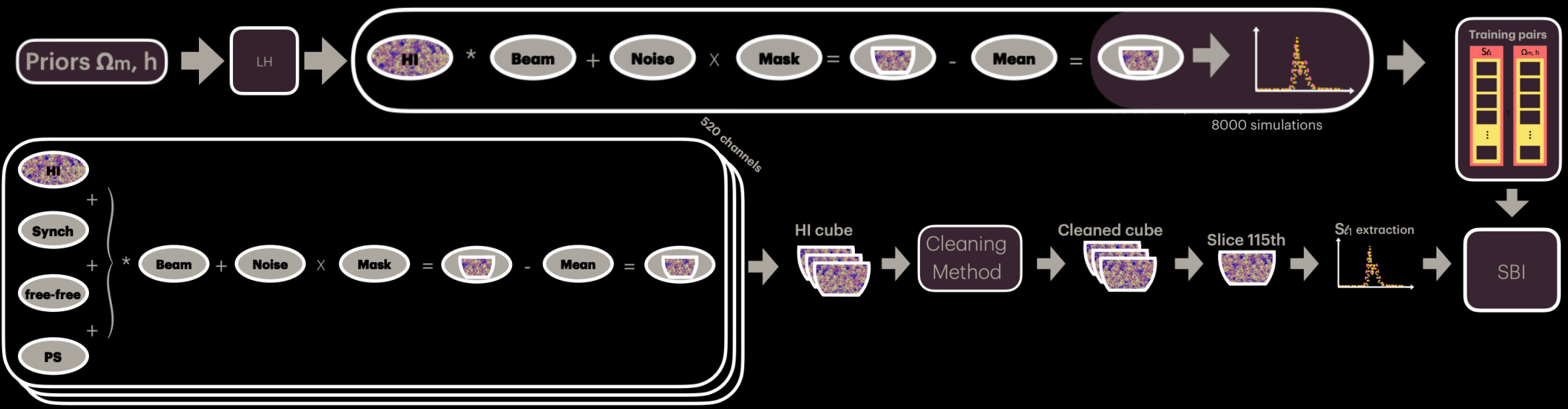
35X

50X

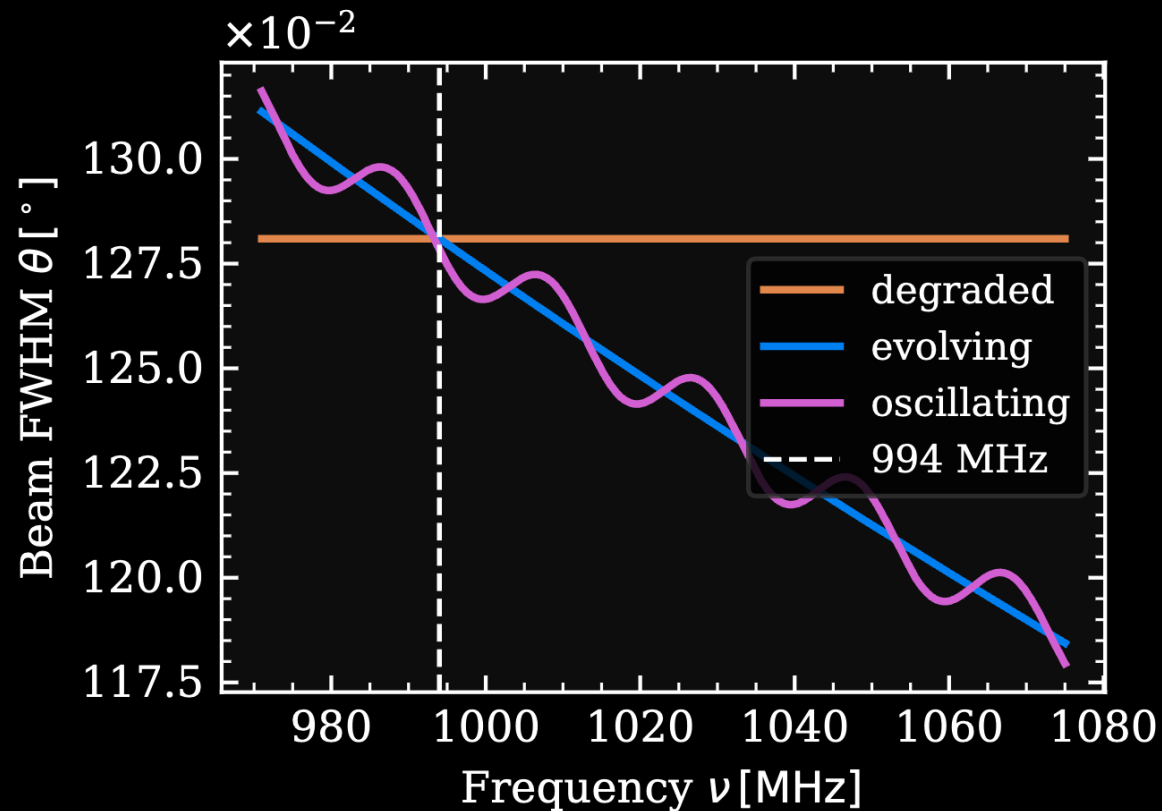


# **Impact** of foreground cleaning methods on *cosmological parameter recovery*

Athanasia Gkogkou, Victor Bonjean, Jean Luc Starck, Stefano Camera, Marta Spinelli



# Beam scenarios



- SKY FRACTION

$$f_{\text{sky}} = 0.19$$

- BEAM & NOISE

**MeerKLASS-like**

- DATA CUBE

**520 slices**, 971–1075 MHz

$$\Delta\nu = 0.2 \text{ MHz}$$

Inference: slice 115 @ 994 MHz

$$n_{\text{side}} = 512$$

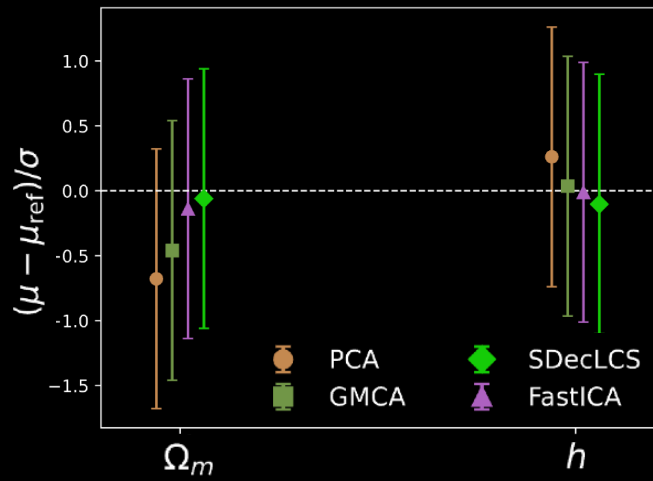
# Foreground cleaning methods

State of the art cleaning methods

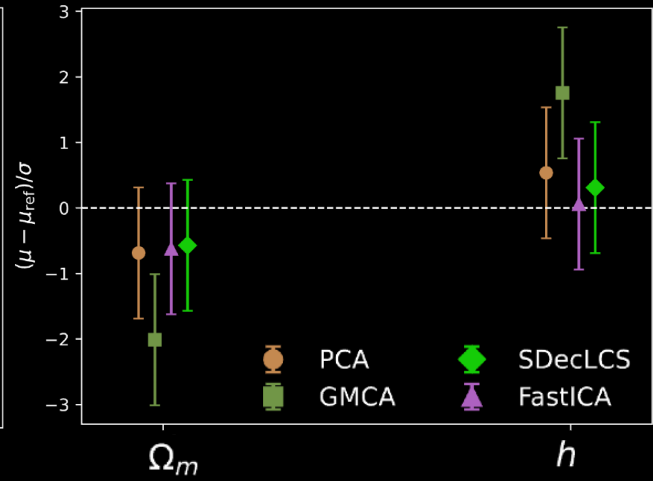
- **PCA** (Principal Component Analysis)
  - **FastICA** (Independent Component Analysis)
  - **GMCA** (Generalized Morphological Component Analysis)
- 
- **SDecLCS** (SDecGMCA learnlet joint component separation and deconvolution on the sphere in the learnlet domain, beam-aware)

Gkogkou + 2026, Bonjean + 2026

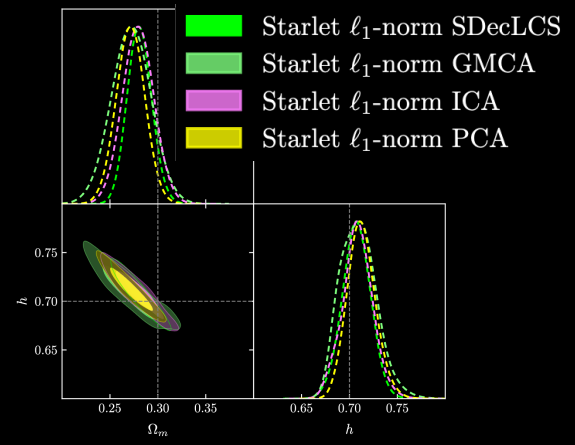
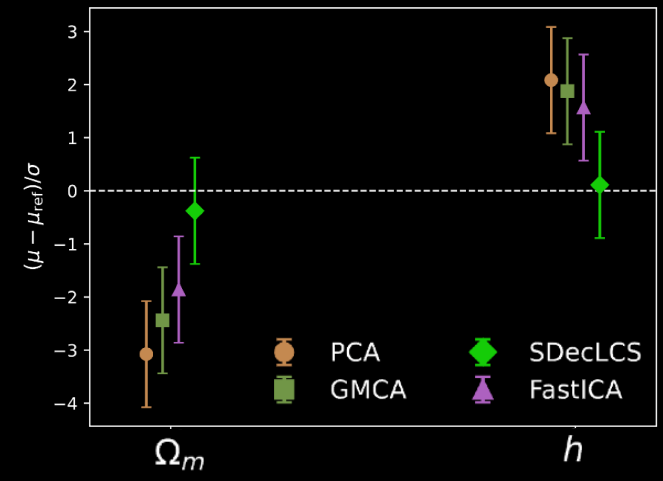
# Degraded beam



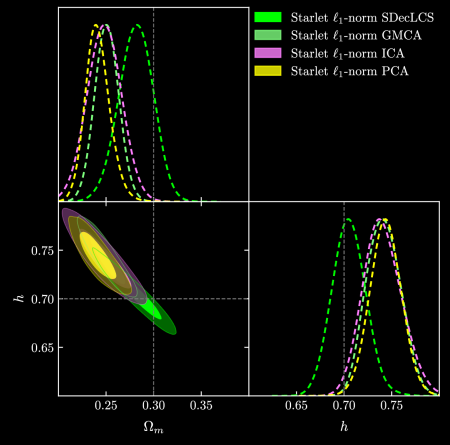
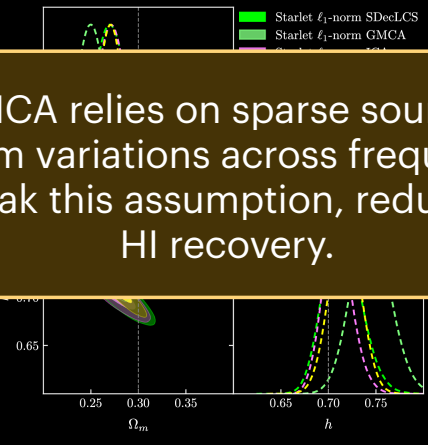
# Evolving beam



# Oscillating beam



GMCA relies on sparse sources, beam variations across frequency break this assumption, reducing HI recovery.



# Conclusions

- **Starlet l1 norm yield tighter constrains than C1 in all study cases.**
- Starlet l1 norm is robust to noise and systematics.

- 
- **First end to end pipeline linking HI IM simulation, foreground cleaning methods and cosmological parameter inference.**
  - SDecLCS is the only method working in oscillating beam scenario.

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## Next Steps

- **Apply this pipeline on MeerKLASS Lband21 data**

# Thank you