# Galaxy Survey Cosmology Beyond Two Points

## Propagating Systematics with Simulation-Based Inference

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Science and Technology Facilities Council

Innovate UK

UK SPACE AGENCY

Institute for Computational Cosmology

Durham Centre for Extragalactic Astronomy

Durham University

KiDS Kilo-Degree Survey

Euclid consortium

**Lessons from Stage III on systematics**

**+**

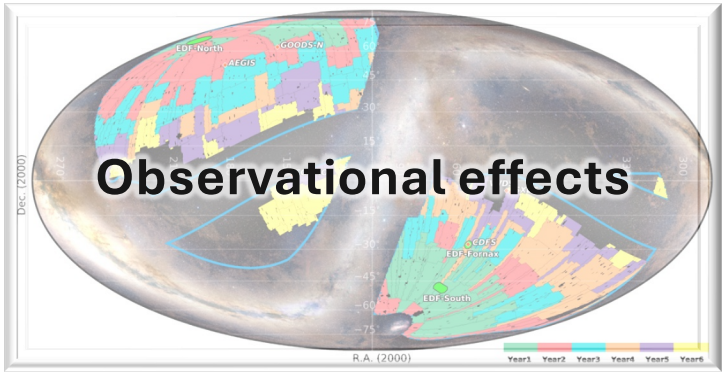
**Stage IV considerations**

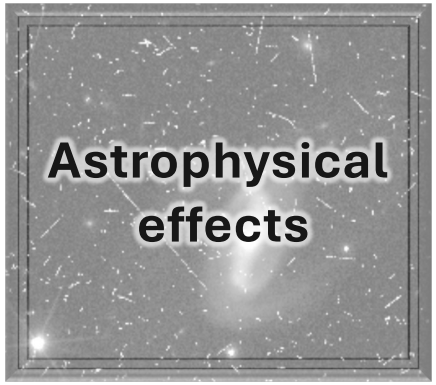
**+**

**SBI**

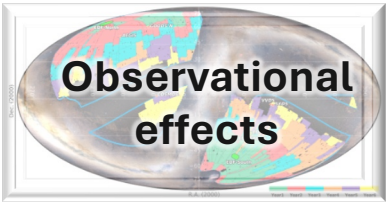
= Profit?

# Types of Systematics in Galaxy Surveys

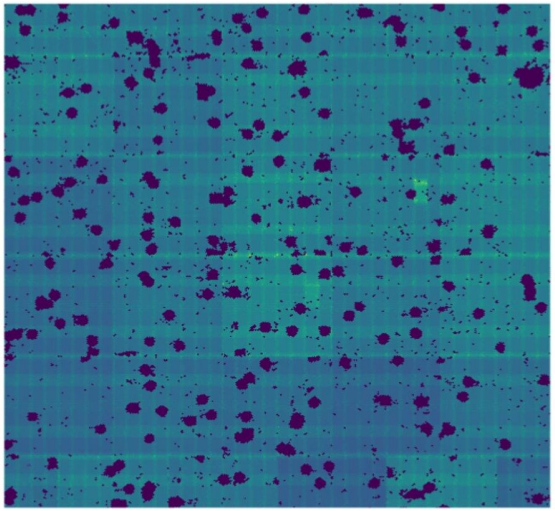




# Variable Selection in KiDS

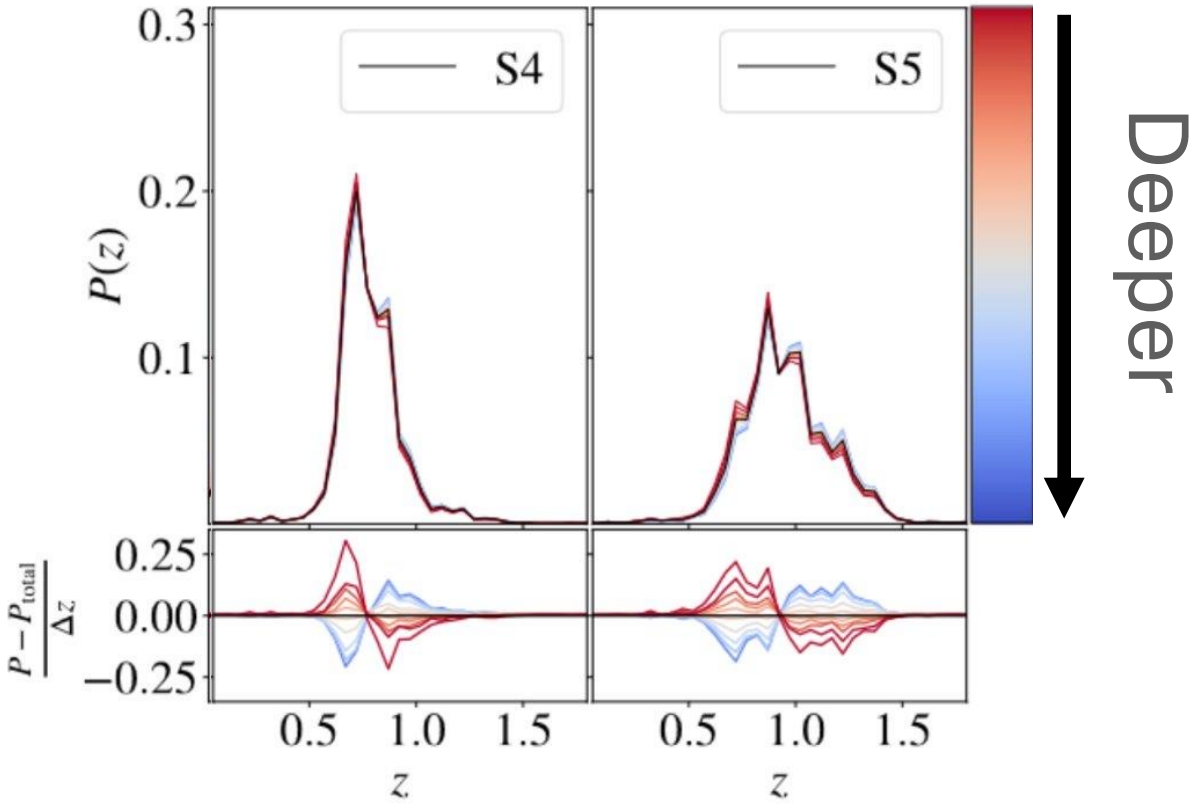



## Angular Variations

- Pointing overlap/Survey strategy
- Dithering
- Zodiacal light
- Galactic extinction
- Atmospheric extinction
- Moonlight

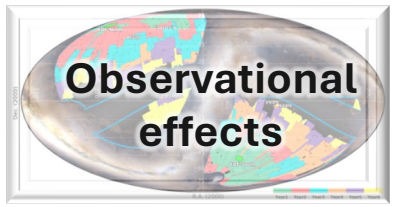


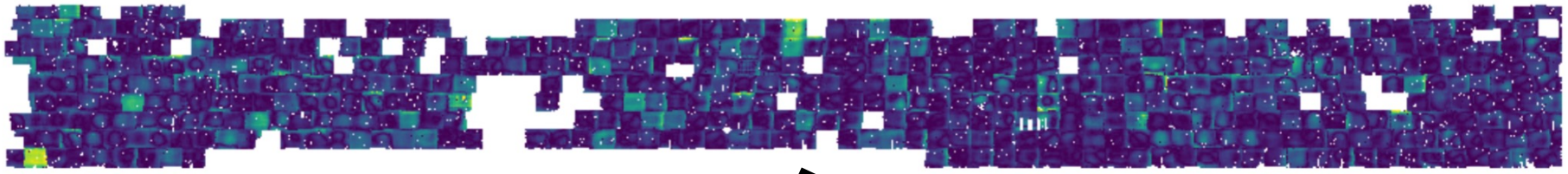
## Line-of-Sight Variations




von Wietersheim-Kramsta, Lin et al. (2024); arxiv:2404.15402

# PSF Variations in KiDS

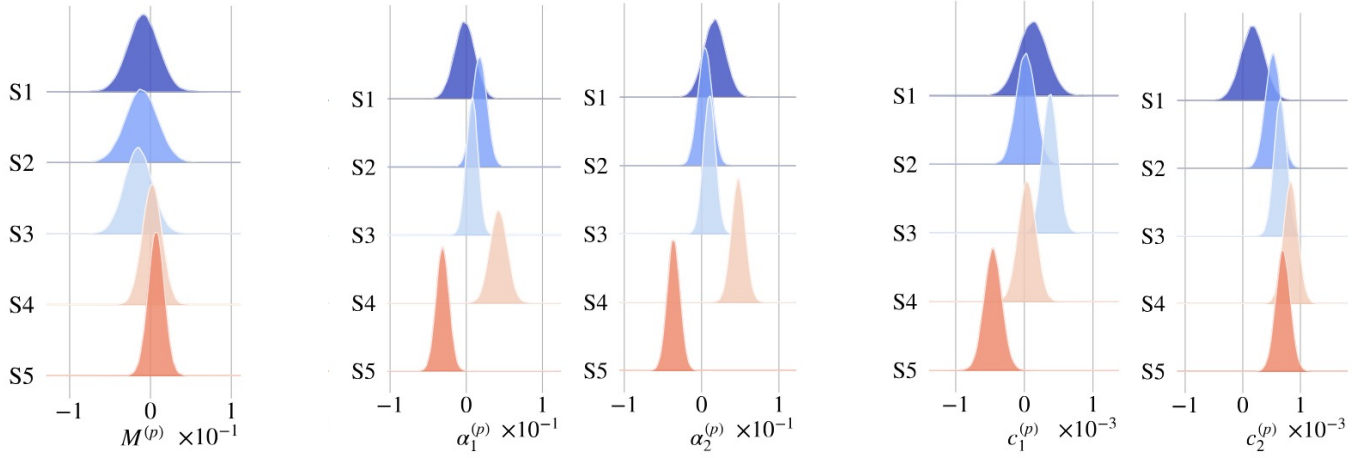



$$\epsilon_{\rm obs}(p, m; \Theta) = \left(1 + M^{(p)}\right)\epsilon_{\rm lensed}(\Theta) + \alpha^{(p)}\epsilon_{\rm PSF}(m) + \beta^{(p)}\delta\epsilon_{\rm PSF} + c^{(p)}$$

Pixel — Tomographic bin — Multiplicative shear bias — PSF shear bias — Additive shear bias

$\delta\epsilon_{\rm PSF} \to 0$

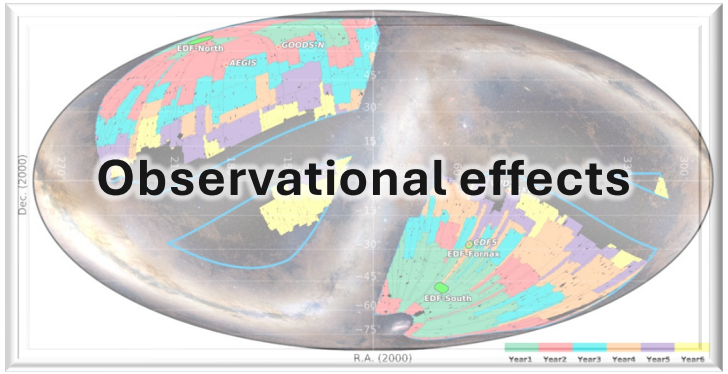
**Pre-marginalization of 25 parameters from shear calibration**

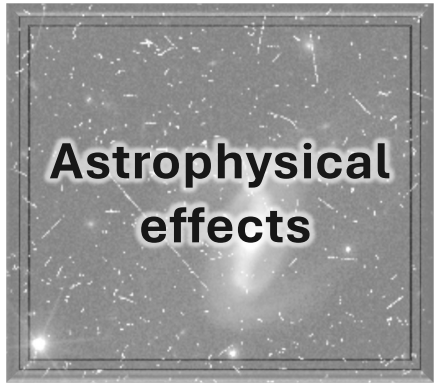



von Wietersheim-Kramsta, Lin et al. (2024)

# KiDS-SBI: Cosmic Shear Systematics

**Modelled at field level:**


PSF Variations

Shear Measurement Bias

**All correlated across 5 tomographic bins!**

Spatial variability in selection

Redshift uncertainty + variations

Survey mask

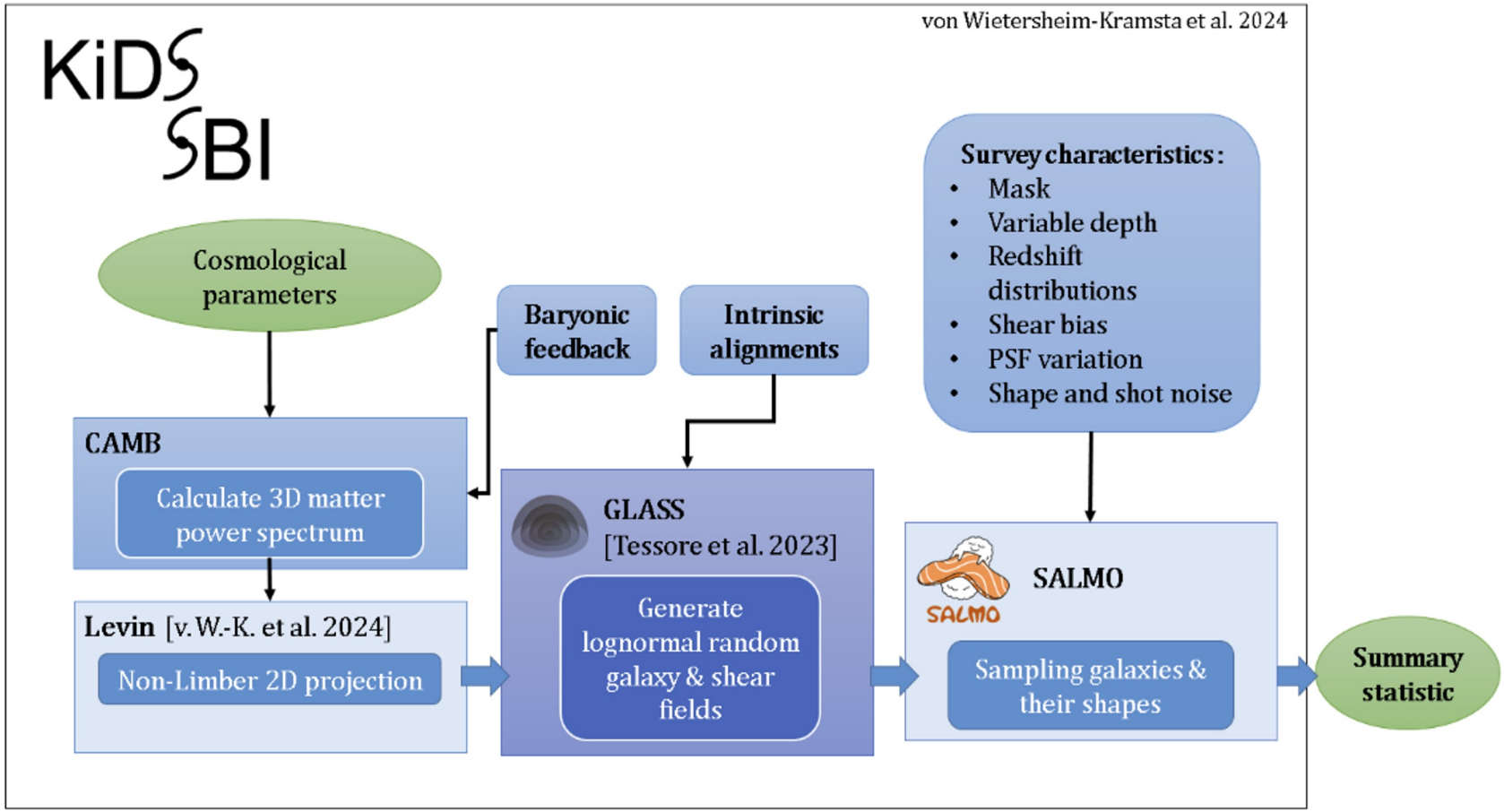
Shape & shot noise

Source clustering

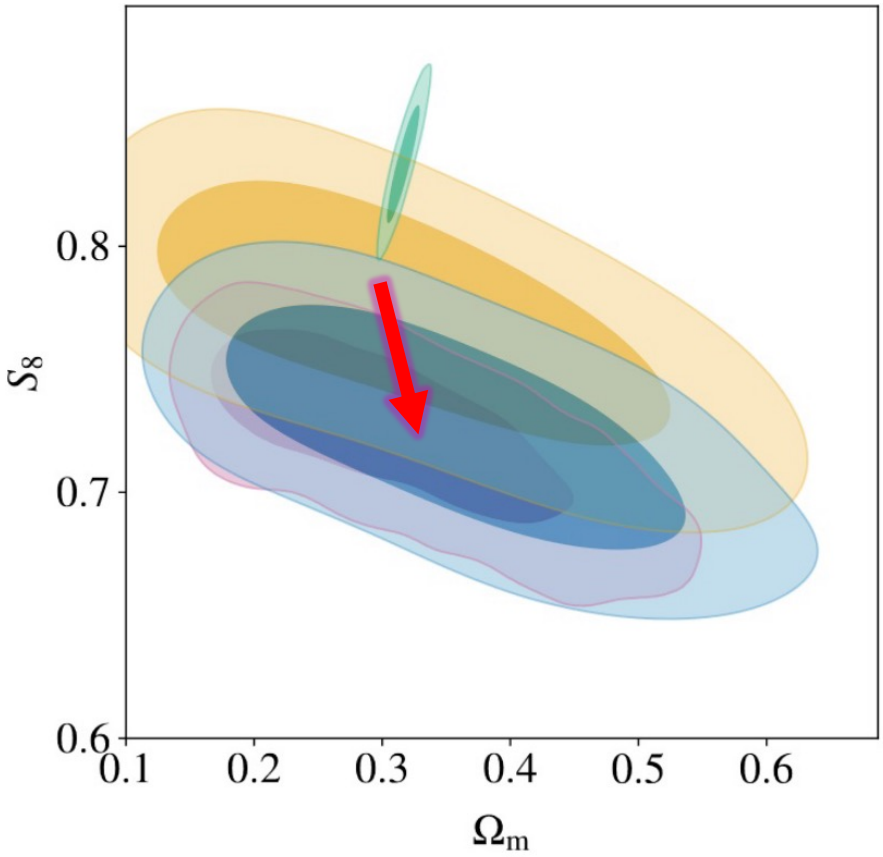
NLA intrinsic alignments

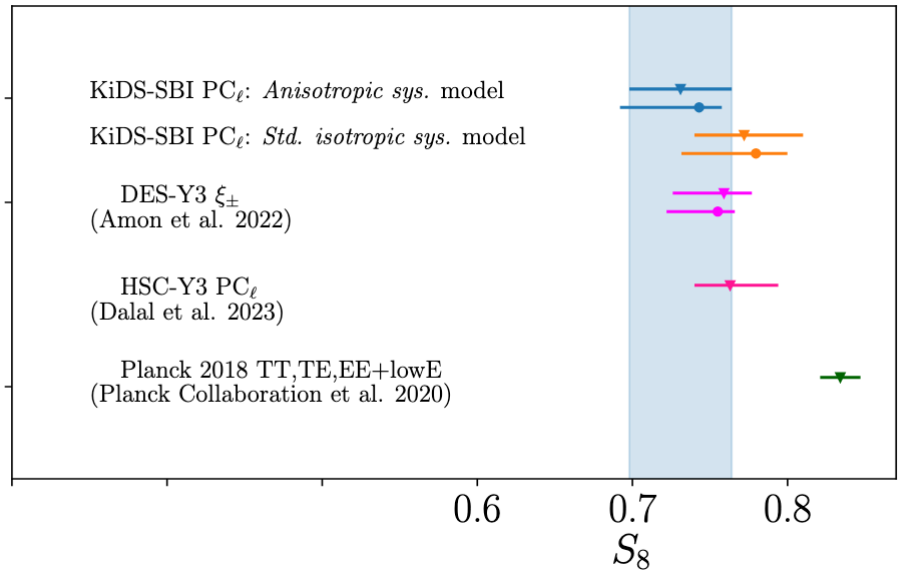
Baryon feedback (*2-point level*)

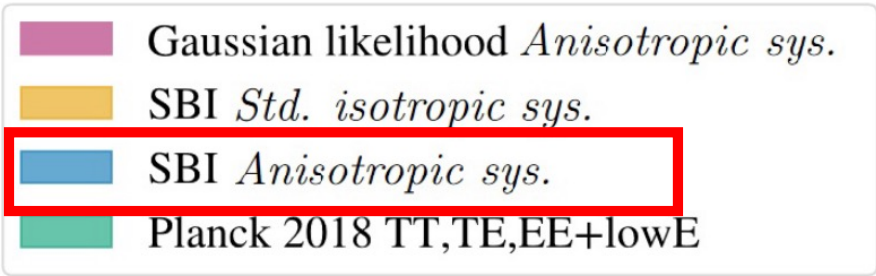
# Simulation-Based Inference w/ KiDS



# KiDS-SBI: KiDS-1000 1x2pt

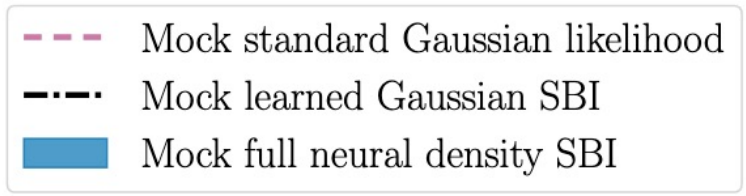


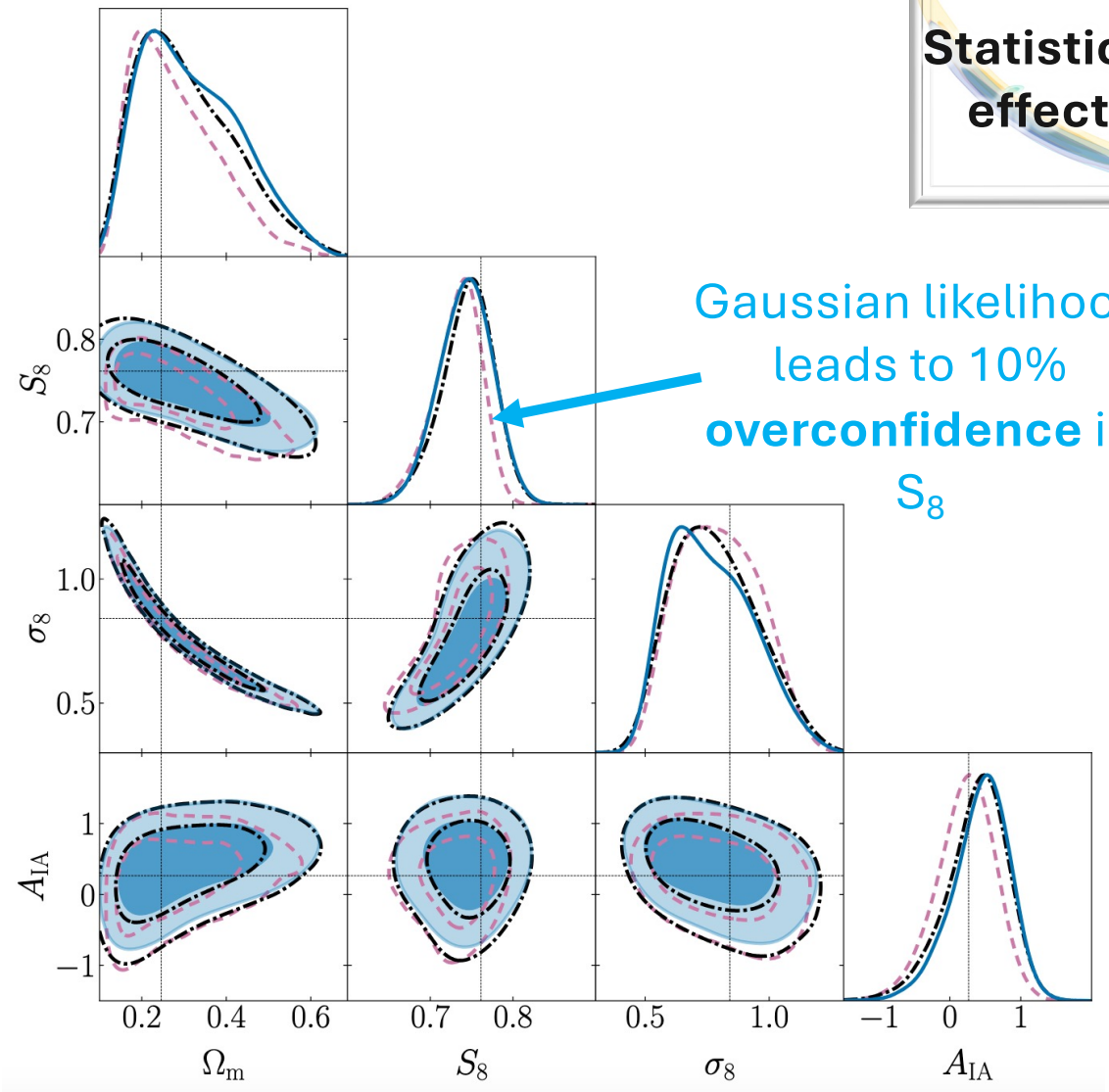




von Wietersheim-Kramsta, Lin et al. (2024)

# KiDS-SBI:
## Parameter-Dependent Likelihood



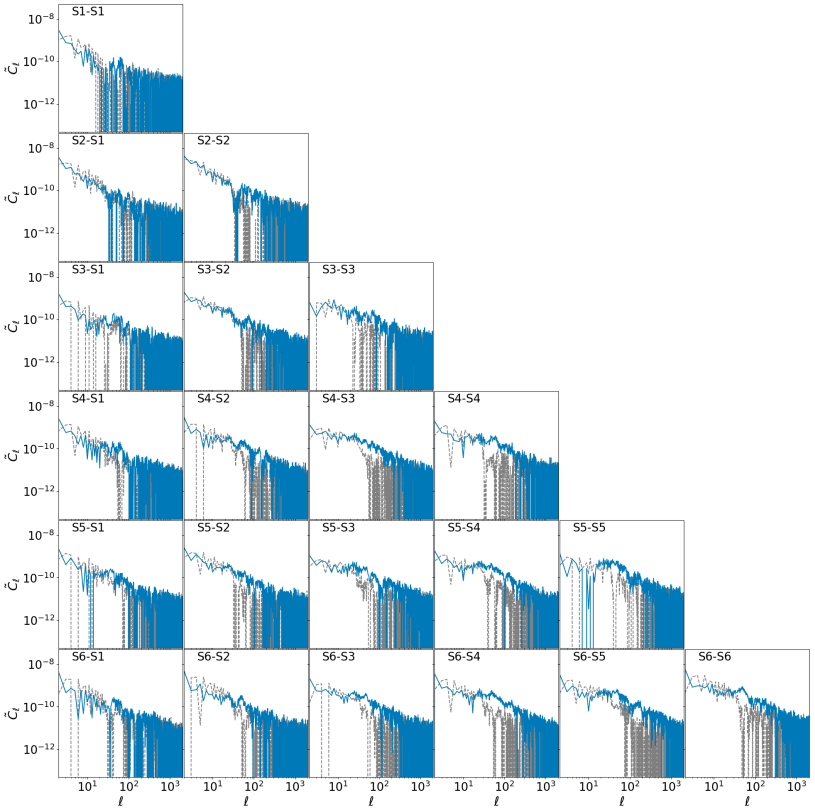





Gaussian likelihood leads to 10% **overconfidence** in $S_8$

von Wietersheim-Kramsta, Lin et al. (2024)
Lin, von Wietersheim-Kramsta et al. (2022)

# KiDS-SBI: KiDS-Legacy

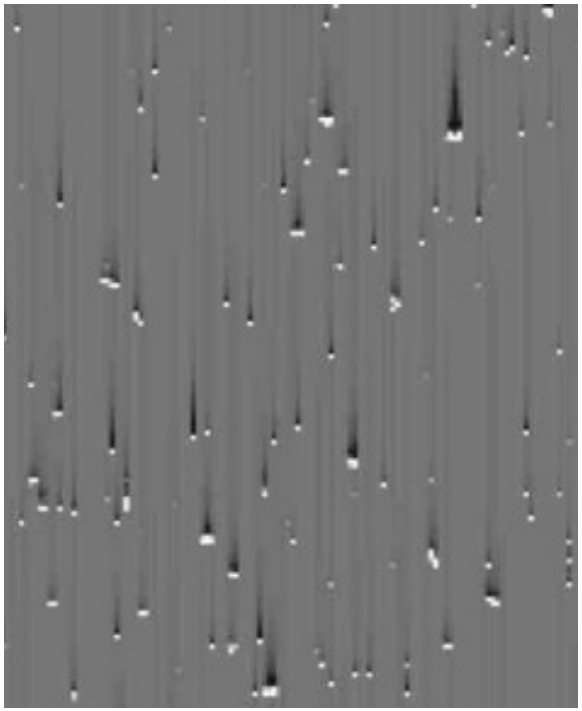



Lin, von Wietersheim-Kramsta et al. (in prep.)

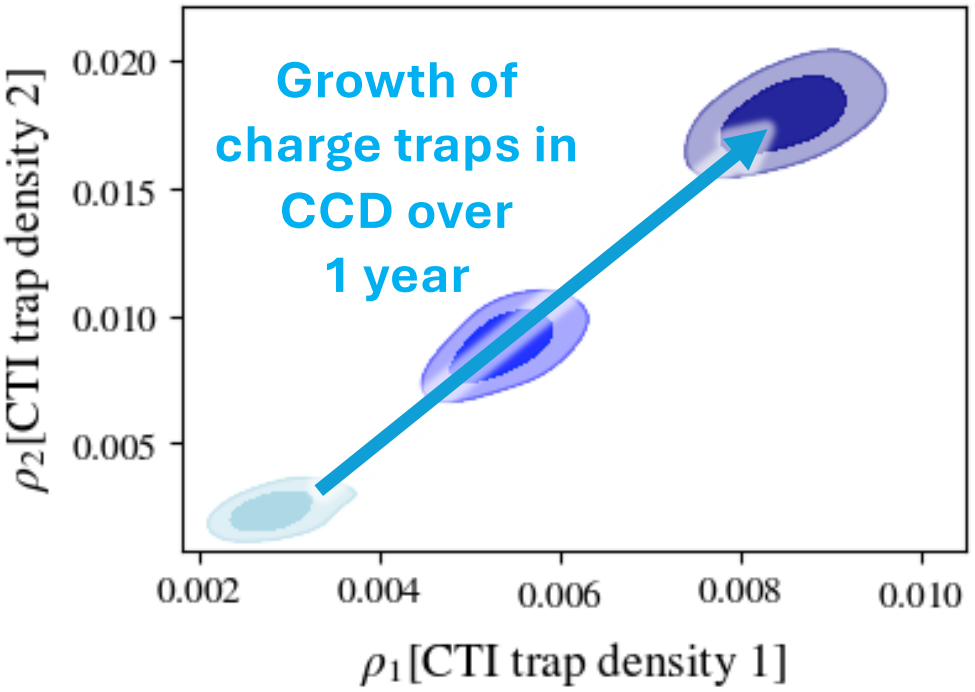
+ extra 350 deg$^2$
+ 1 extra i-band pass
+ 1 tomographic bin
+ new images sims for calib.
+ new redshift calibration
+ new baryon feedback model
+ new mass-dependent IAs model

+ new var. depth tracer & models
+ new compression

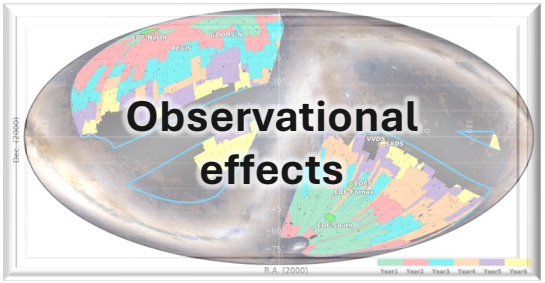
# *Euclid*: Unique Challenges
## e.g. Radiation Damage

Massey et al. (2025)
McCracken et al. (2025)

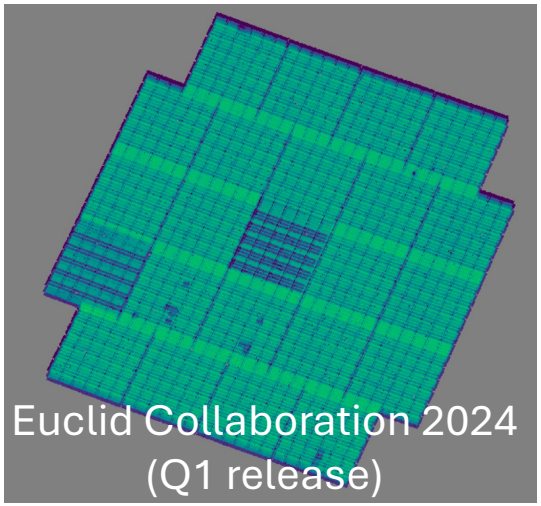


# *Euclid*: Unique Challenges
## e.g. Variable Depth



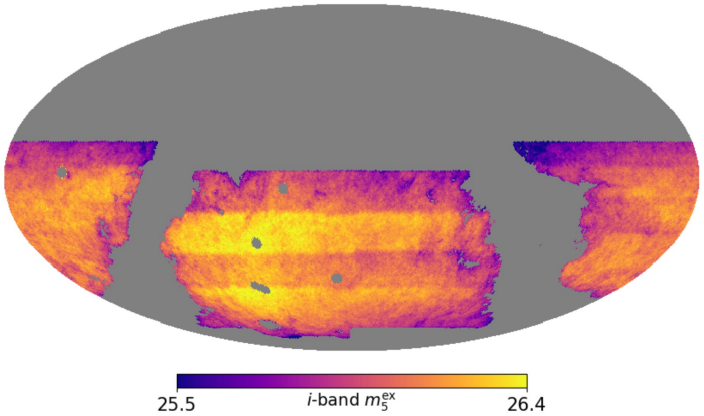

**Angular Variation** **vs.** **Line-of-Sight Variation**

- Shapes measured by VIS
- Single-visit survey
- Space-based



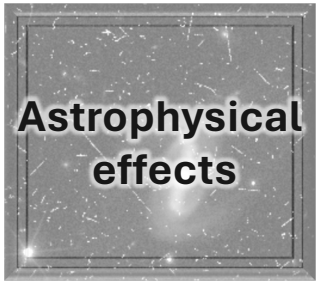

- Photometry by partner surveys
- (Some) multi-epoch surveys
- (Some) ground-based

e.g. depth variation in Rubin LSST




Hang et al. 2024

# Towards 3x2pt SBI: Galaxy Bias Forward Model



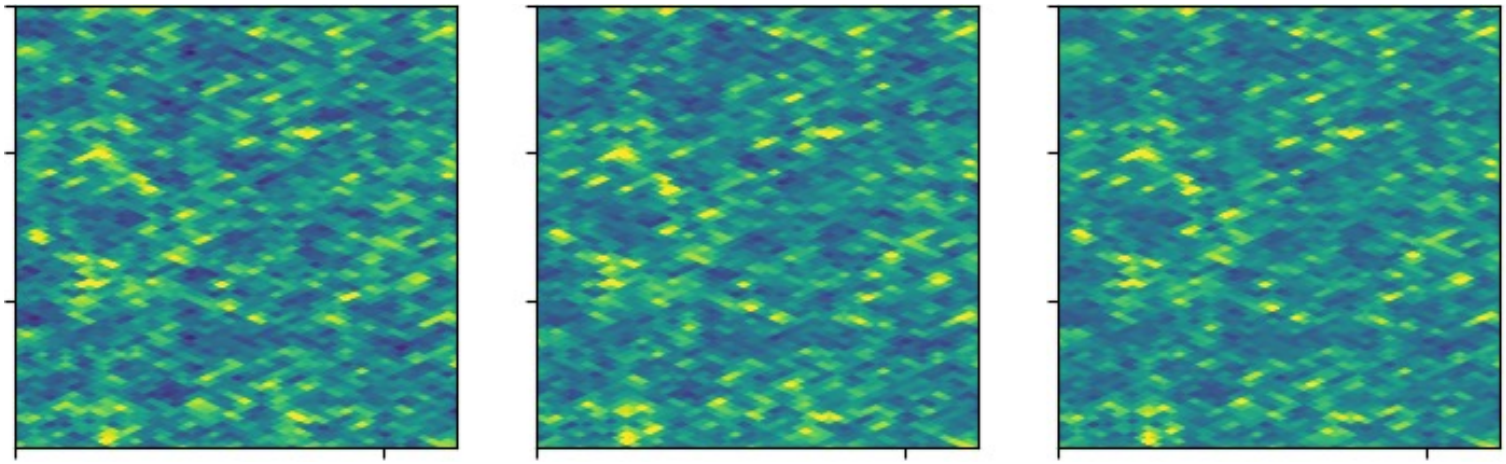

Novel fully analytic model tested with FLAMINGO

**Galaxy density from hydro sims**

**From this work**

**Standard linear galaxy bias model**

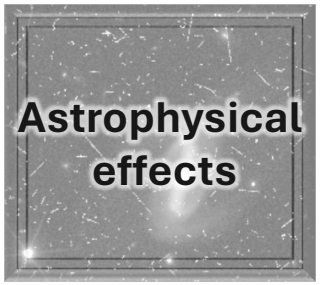
$\delta^{\mathrm{g}}$



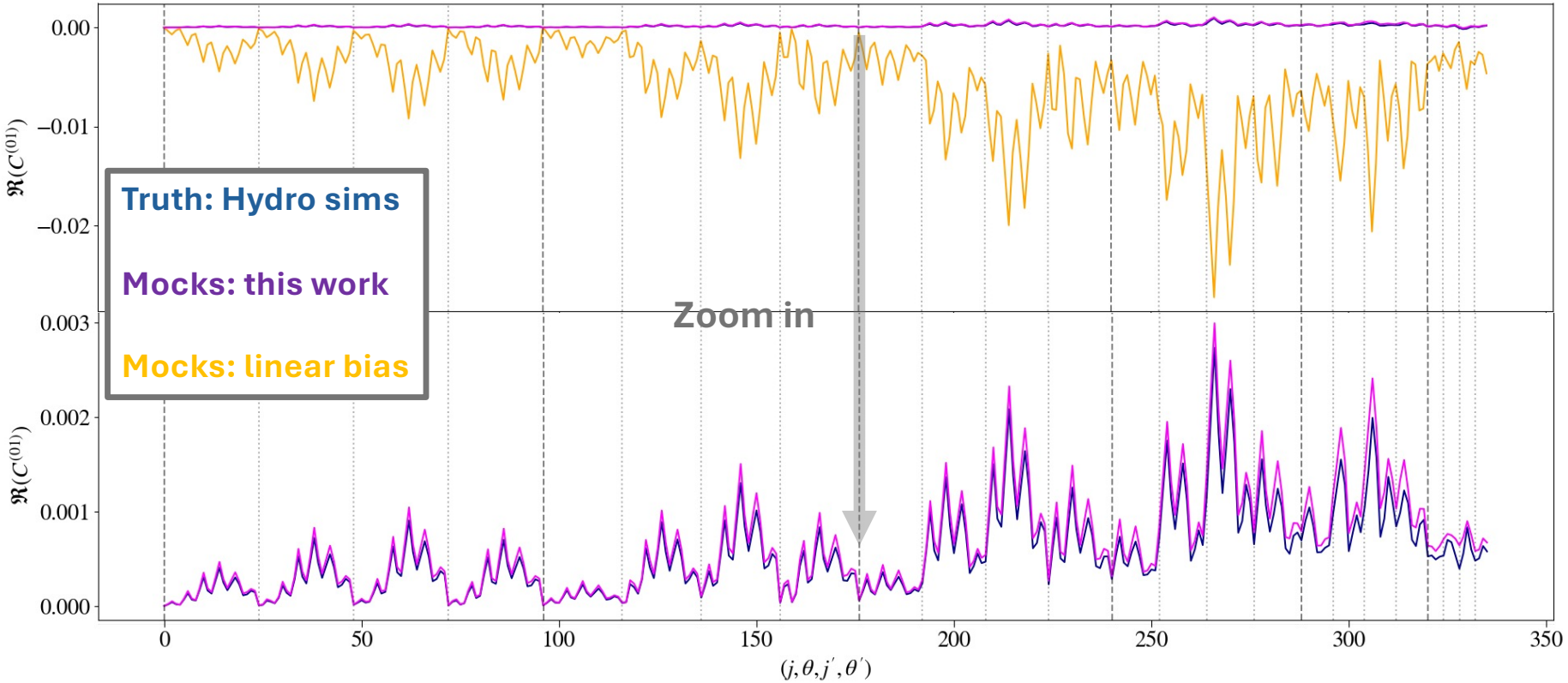
10 deg x 10 deg Cartesian projection

von Wietersheim-Kramsta et al. (in prep.)

# Towards 3x2pt SBI: Galaxy Bias Forward Model




e.g. $C^{(0,1)}$ term in the wavelet phase harmonic expansion




von Wietersheim-Kramsta et al. (in prep.)

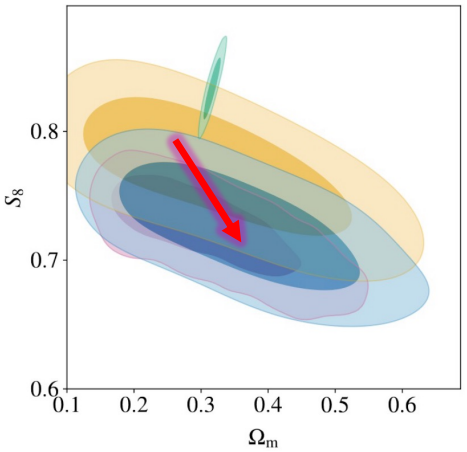
# Conclusions

- Lesson from Kilo-Degree Survey:
  - **Complex correlated systematics** matter
  - **Field-level forward modelling + SBI** incorporates them

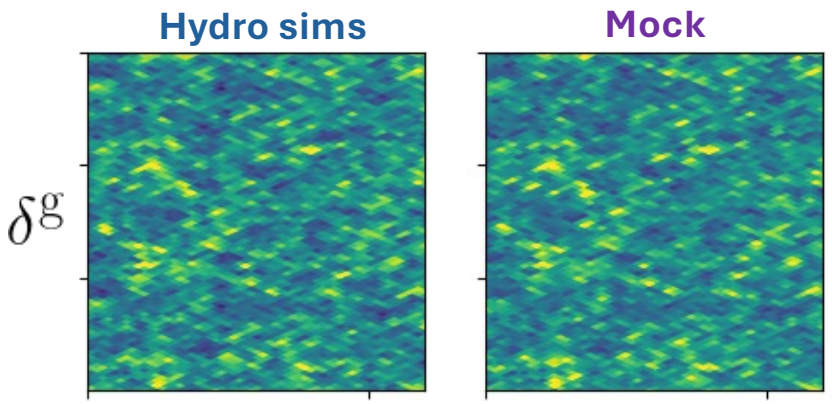
- Consideration from Stage IV (*Euclid*):
  - **Increased sensitivity** to increasingly complex systematics

- Systematics from source clustering & 3x2pt SBI:
  - **Improved galaxy bias models**

**= Profit …?**




von Wietersheim-Kramsta, Lin et al. (2024)

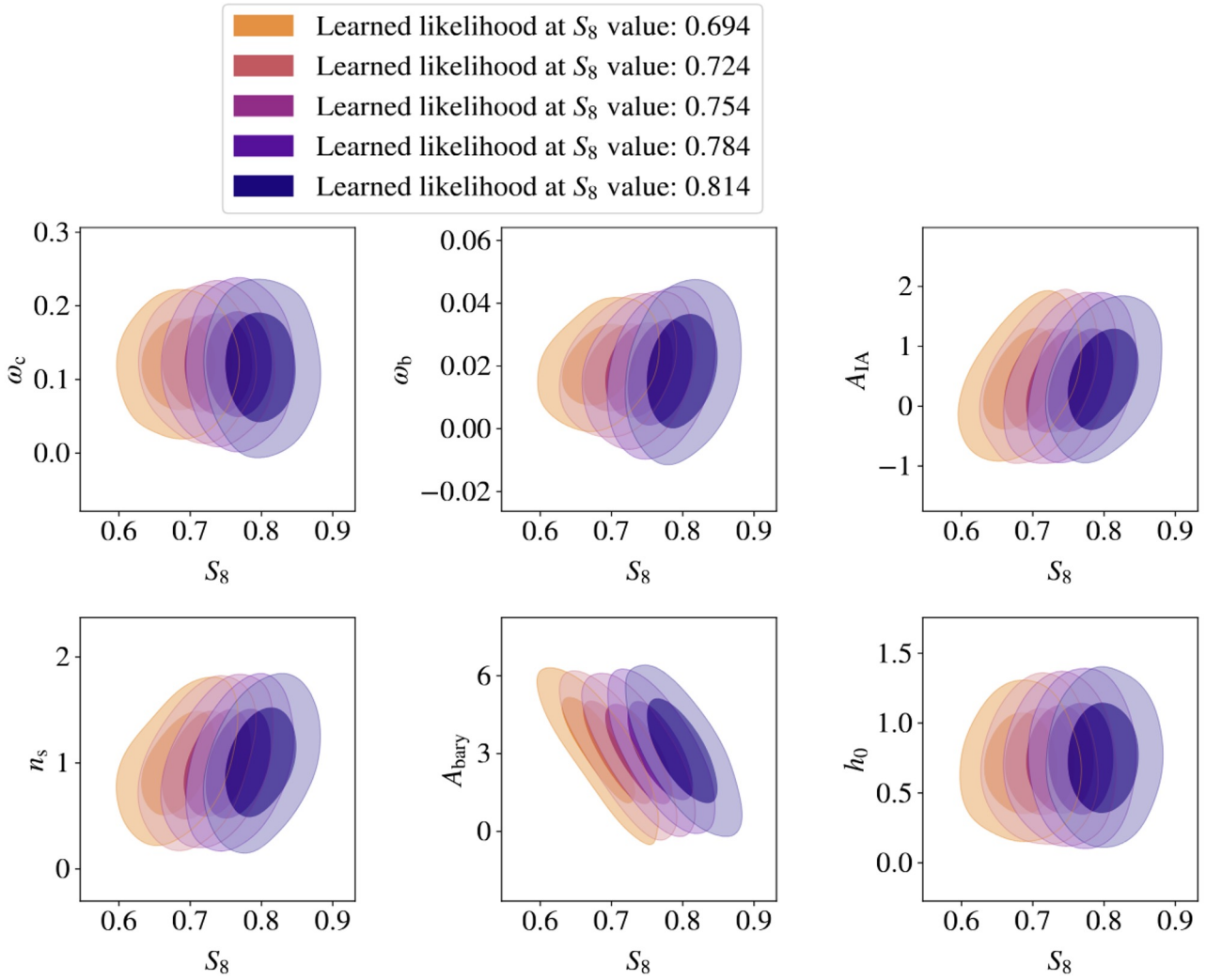


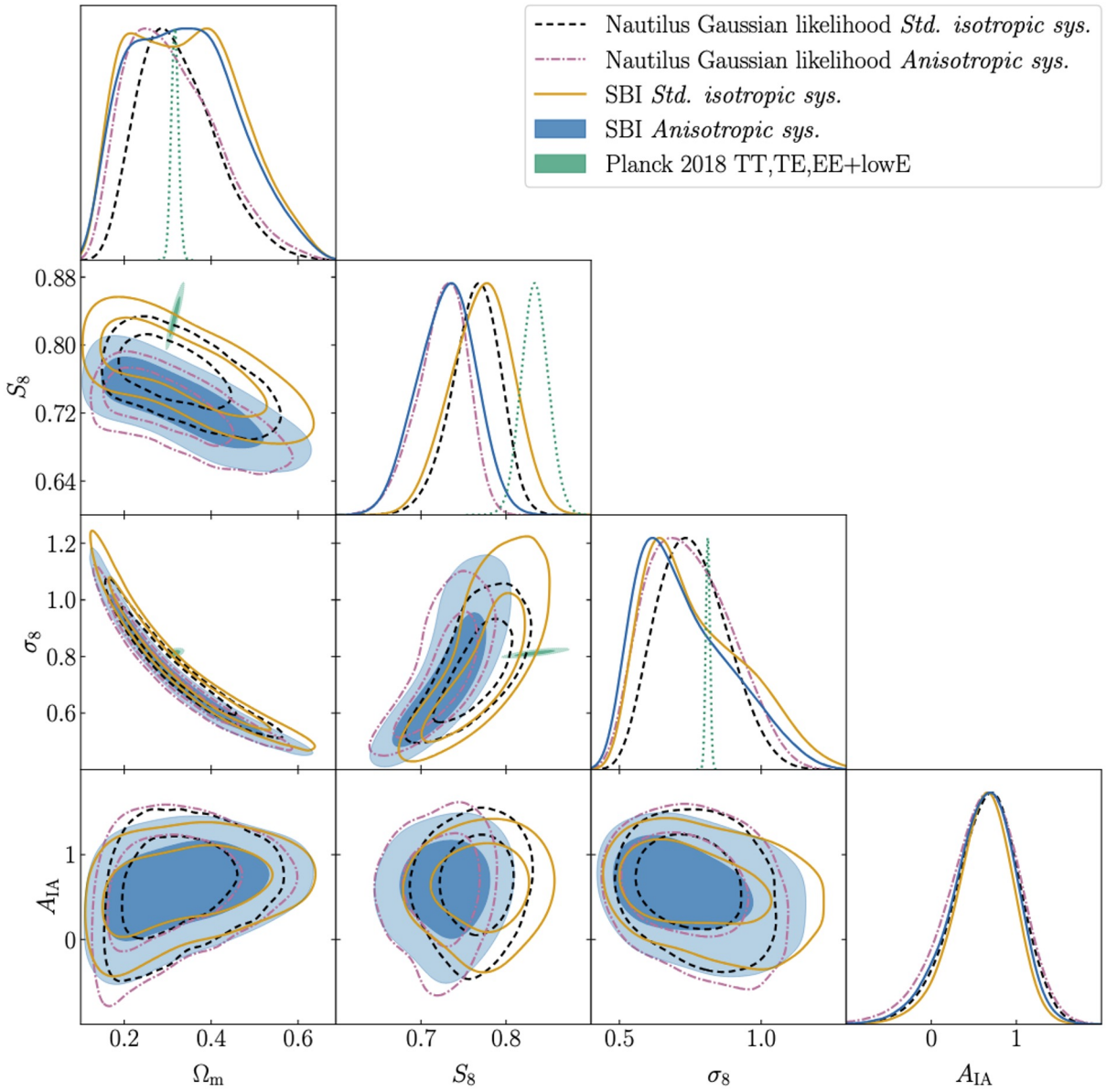

von Wietersheim-Kramsta et al. (in prep.)

# Extra

5 cosmological + 7 nuisance + 25 pre-marginalised parameters

| Parameter | Symbol | Prior type | Prior range | Fiducial |
|---|---|---|---|---|
| Density fluctuation amp. | $S_8$ | Flat | [0.1, 1.3] | 0.76 |
| Hubble constant | $h_0$ | Flat | [0.64, 0.82] | 0.767 |
| Cold dark matter density | $\omega_c$ | Flat | [0.051, 0.255] | 0.118 |
| Baryonic matter density | $\omega_b$ | Flat | [0.019, 0.026] | 0.026 |
| Scalar spectral index | $n_s$ | Flat | [0.84, 1.1] | 0.901 |
| Intrinsic alignment amp. | $A_{IA}$ | Flat | [-6, 6] | 0.264 |
| Baryon feedback amp. | $A_{bary}$ | Flat | [2, 3.13] | 3.1 |
| Redshift displacement | $\boldsymbol{\delta}_z$ | Gaussian | $\mathcal{N}(\mathbf{0}, \boldsymbol{C}_z)$ | $\mathbf{0}$ |
| Multiplicative shear bias | $M^{(p)}$ | Gaussian | $\mathcal{N}(\overline{M}^{(p)}, \sigma_M^{(p)})$ | $\overline{M}^{(p)}$ |
| Additive shear bias | $c_{1,2}^{(p)}$ | Gaussian | $\mathcal{N}(\overline{c}_{1,2}^{(p)}, \sigma_{c_{1,2}}^{(p)})$ | $\overline{c}_{1,2}^{(p)}$ |
| PSF variation shear bias | $\alpha_{1,2}^{(p)}$ | Gaussian | $\mathcal{N}(\overline{\alpha}_{1,2}^{(p)}, \sigma_{\alpha_{1,2}}^{(p)})$ | $\overline{\alpha}_{1,2}^{(p)}$ |


Learned likelihood at $S_8$ value: 0.694
Learned likelihood at $S_8$ value: 0.724
Learned likelihood at $S_8$ value: 0.754
Learned likelihood at $S_8$ value: 0.784
Learned likelihood at $S_8$ value: 0.814
$\omega_c$
$\omega_b$
$A_{IA}$
$n_s$
$A_{bary}$
$h_0$
$S_8$


Nautilus Gaussian likelihood *Std. isotropic sys.*
Nautilus Gaussian likelihood *Anisotropic sys.*
SBI *Std. isotropic sys.*
SBI *Anisotropic sys.*
Planck 2018 TT,TE,EE+lowE
$S_8$
$\sigma_8$
$A_{\rm IA}$
$\Omega_{\rm m}$
0.88
0.80
0.72
0.64
1.2
1.0
0.8
0.6
1
0
0.2
0.4
0.6
0.7
0.8
0.5
1.0
0
1