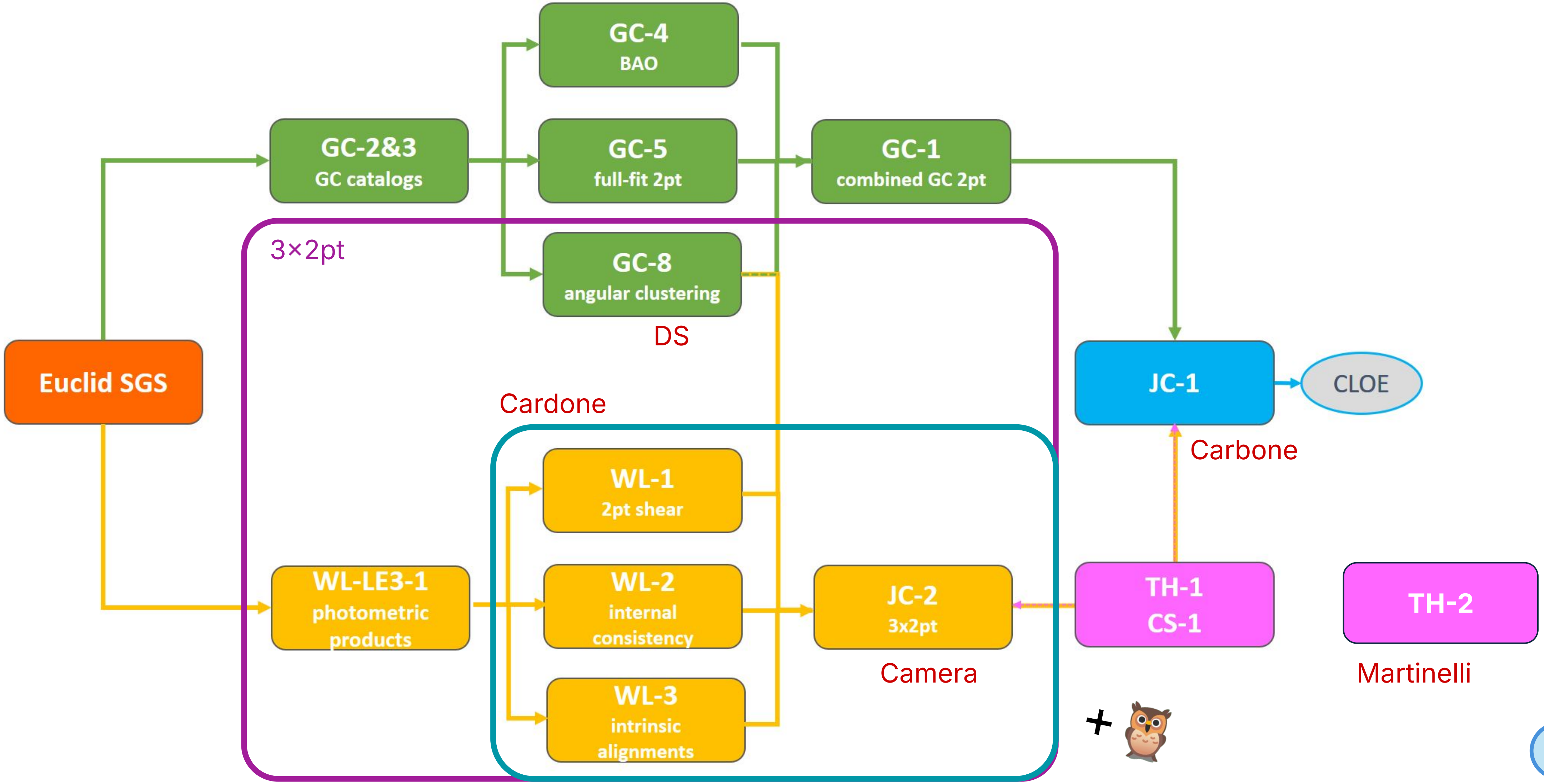
3x2pt (+HOWLS) science

Davide Sciotti (+ many others!)

Euclid Italia 2025

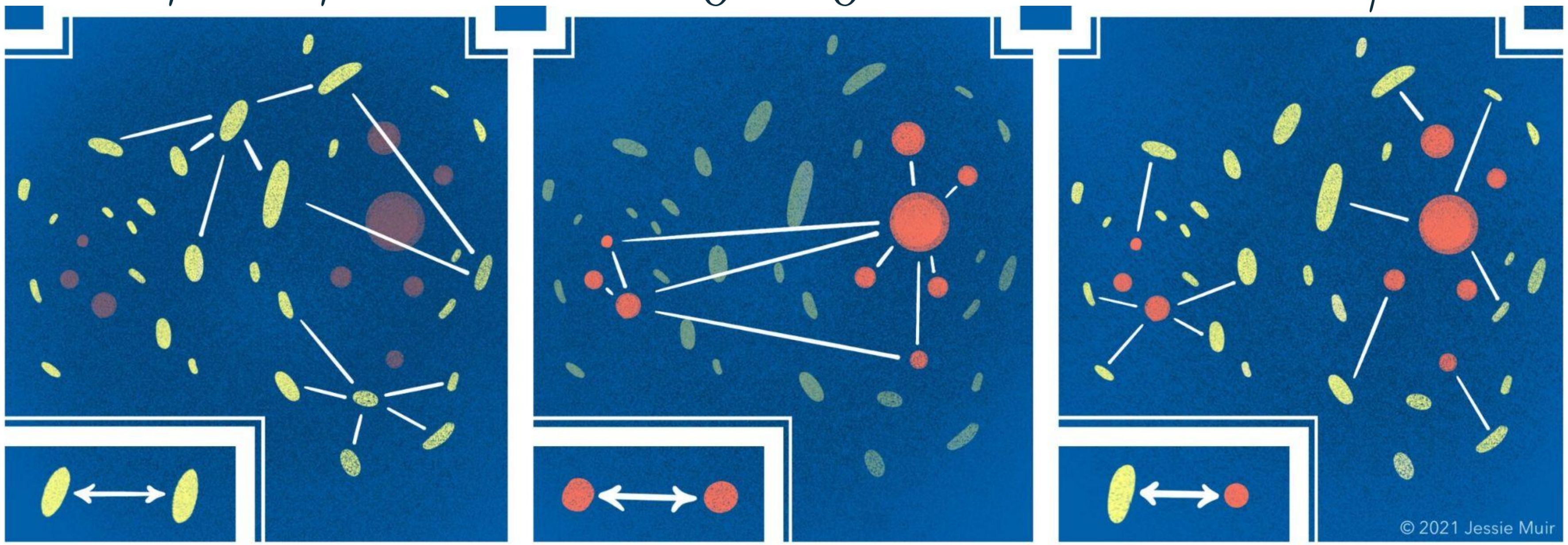
KP structure and interactions



3x2pt photometric observables

- **3x** (WL, GCph, GGL) **2pt** *angular* CF/PS
- Fundamental quantities: **positions** (ra, dec, z) and **shapes** (e_1, e_2)

$\gamma - \gamma$ $\delta - \delta$ $\delta - \gamma$



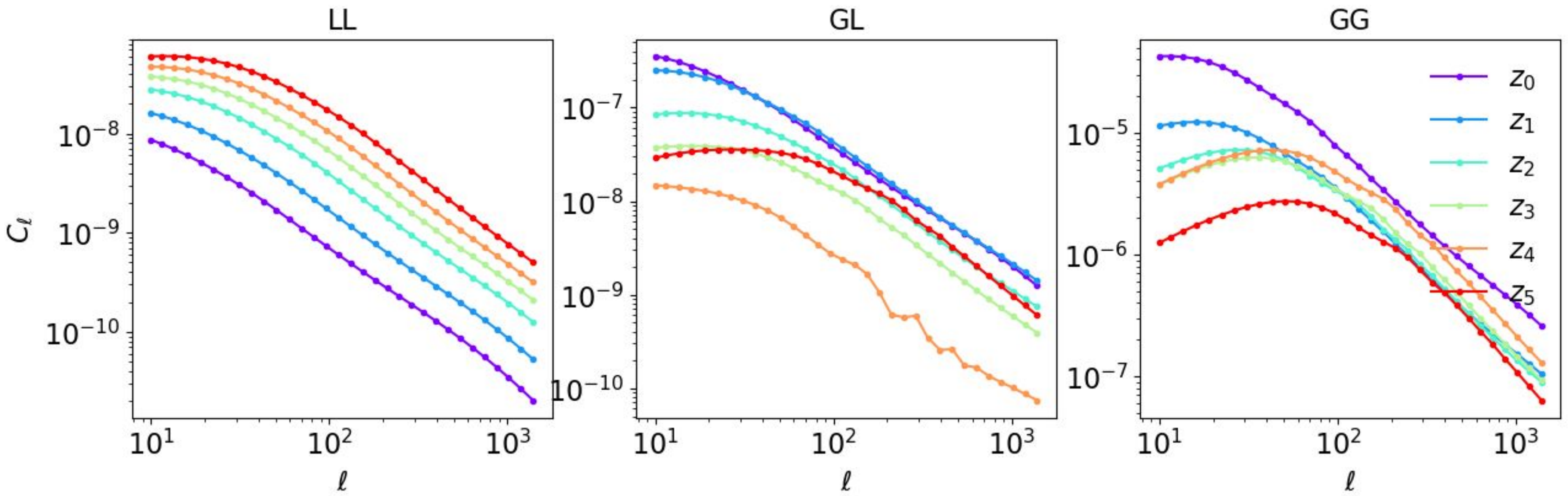
Theoretical modelling: HS

- Tracers of (density, shear) field → SHT → $a_{\ell m}$ → C_ℓ
- Complete summary if fields are Gaussian (they are not!)

$$C_{ij}^{AB}(\ell) = \int \mathrm{d}z \, \frac{c W_i^A(z) \, W_j^B(z)}{H(z) \, f_K^2[r(z)]} \, P_{AB}\left[\frac{\ell + 1/2}{f_K[r(z)]}, z\right]$$

- Radial projection of the matter PS, weighted by probe-specific radial kernels
- Depend on geometry, expansion history, initial conditions...

Cls


LL
GL
GG
C_ℓ
10^{-8}
10^{-9}
10^{-10}
10^{-7}
10^{-5}
10^{-6}
10^{1}
10^{2}
10^{3}
ℓ
z_0
z_1
z_2
z_3
z_4
z_5

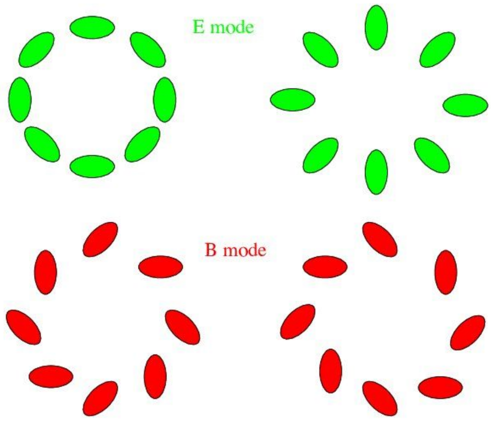
Theoretical modelling: CS

- HS: modelling
  - multipoles are uncorrelated
- CS: data
  - Mask effects (bright stars, PSF residuals, angular systematics) are local
  - We directly measure angles and physical separations
- Can map one into the other with a (numerically challenging) Hankel transform
- Additional 2pt statistics: COSEBIs, bandpowers, ...

$$\xi^{\pm}_{ij}(\theta) \simeq \frac{1}{2\pi}\int_{\ell_{\rm low}}^{\ell_{\rm top}} \ell\, J_{2\mp2}(\ell\theta)\, C^{\rm LL}_{ij}(\ell)\, {\rm d}\ell$$

$$\xi^{\rm GG}_{ij}(\theta) \simeq \frac{1}{2\pi}\int_{\ell_{\rm low}}^{\ell_{\rm top}} \ell\, C^{\rm GG}_{ij}(\ell)\, J_0(\ell\theta)\,,$$

$$\xi^{\rm GL}_{ij}(\theta) \simeq \frac{1}{2\pi}\int_{\ell_{\rm low}}^{\ell_{\rm top}} \ell\, C^{\rm GL}_{ij}(\ell)\, J_2(\ell\theta)\,,$$



Systematics: WL

- **IA**
  - input: IA model, associated params

$$e_{\rm obs} = e_{\rm int} + \gamma + e_{\rm IA}$$

- **Multiplicative shear bias** (residual):
  - input: m-bias values

$$\hat{\boldsymbol{\gamma}} = (1+m)\,\boldsymbol{\gamma}$$

$$\begin{cases} C_{ij}^{\rm LL}(\ell) \rightarrow (1+m_i)\,(1+m_j)\,C_{ij}^{\rm LL}(\ell)\,, \\ C_{ij}^{\rm GL}(\ell) \rightarrow (1+m_j)\,C_{ij}^{\rm GL}(\ell)\,, \\ C_{ij}^{\rm GG}(\ell) \rightarrow C_{ij}^{\rm GG}(\ell)\,, \end{cases}$$

- **dz**$_i$: redshift distribution shifts
  - input: dz (WL) values

$$n^i(z) = n^i_{pz}(z - \Delta z^i)$$

Systematics: GCph

- **Galaxy bias (linear and nonlinear)!**
  - input: $b_i^{\rm photo}(z)$
- **RSD**
  - input: growth rate, galaxy bias
- **Magnification bias**
  - input: luminosity function (log) slope (for a flux-limited sample)
- $\boldsymbol{dz_i}$: redshift distribution shifts
  - input: dz (GCph) values
- $\boldsymbol{\sigma z_i}$ redshift distribution stretch
  - input: σz (GCph) values

$$P_{\rm gg}^{\rm photo}(k,z) = [b^{\rm photo}(z)]^2 P_{\rm m}(k,z)$$

$$W_i^{\rm RSD}(\ell,z) = \sum_{m=-1}^{+1} \frac{L_m(\ell)\, H[z_m(\ell,z)]\, f_{\rm g}[z_m(\ell,z)]\, n_i^{\rm L}[z_m(\ell,z)]}{c\, b_{\rm g}^{\rm photo}[z_m(\ell,z)]}$$

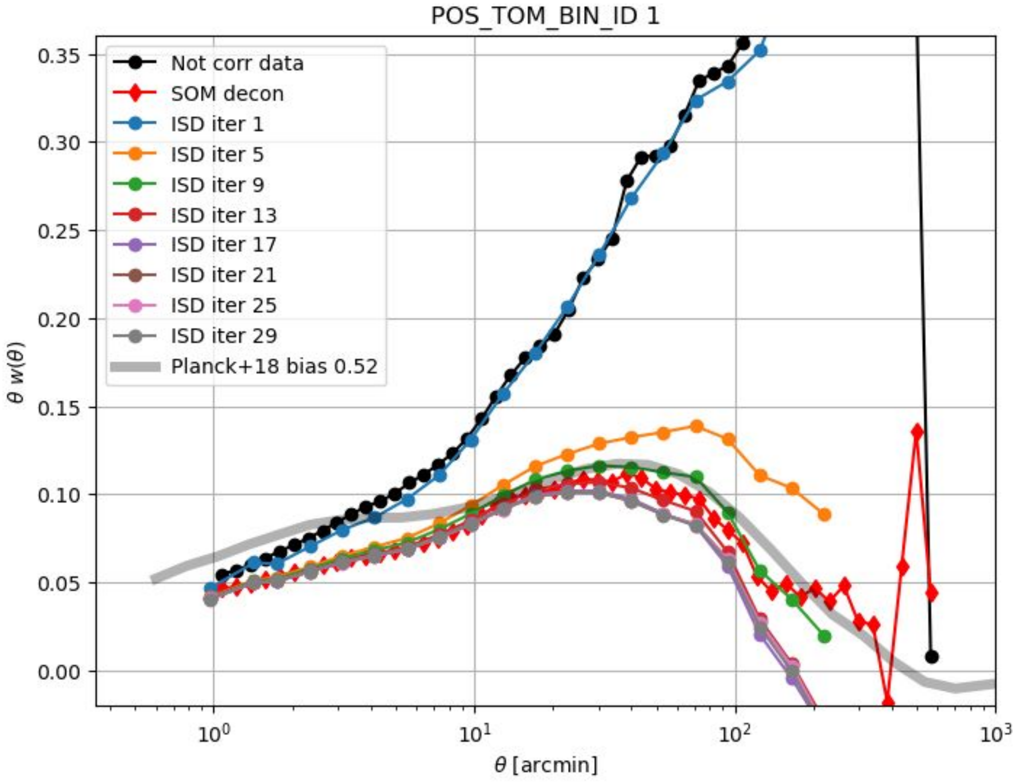
$$b_{\rm mag}(z) = 5\, s(z) - 2$$

$$n^i(z) = n^i_{pz}(z - \Delta z^i)$$

$$n^i(z) = \frac{1}{\sigma z^i} n^i_{pz} \left(\frac{z - \langle z \rangle}{\sigma z^i} + \langle z \rangle \right)$$

Other systematics

- **Spatially varying survey properties**
  - Non-uniform depth, reddening, extinction, stellar contamination...
  - Accounted for in the visibility map (e.g. ISD)
- **PSF**
  - Additive bias (*c*): leakage of PSF anisotropy → spurious B-modes
  - Multiplicative bias (*m*): misestimation of PSF size → biased shear amplitude



Credit: J. M. Perez, VMPZ-ID

Other systematics

- **Shot noise**
  - Due to discrete sampling of matter field
  - Accounted for in the analytical covariance
- **Shape noise**
  - Due to intrinsic ellipticity dispersion
  - Accounted for in the analytical covariance
- **Nonlinear clustering**
  - Marginalised over/mitigated with scale cuts
- **Baryonic effects**
  - Marginalised over/mitigated with scale cuts

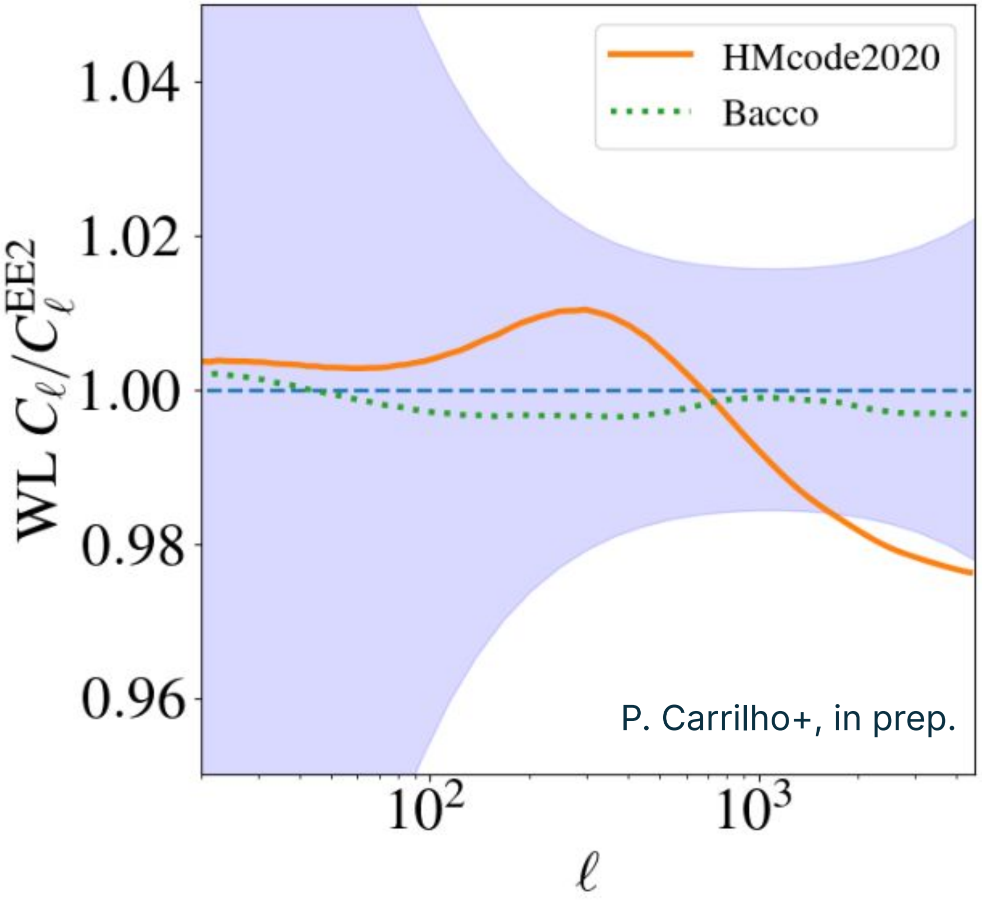
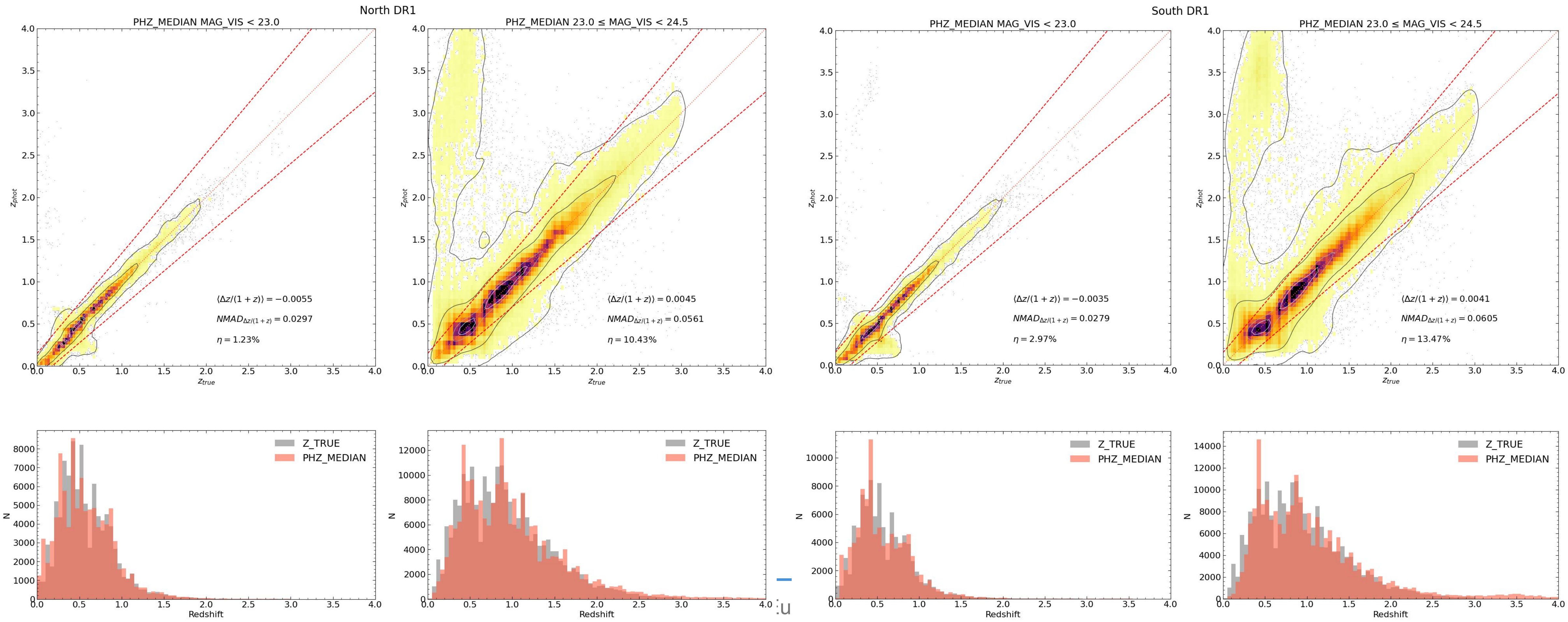


Photo-z

Template-fitting with Phosphoros

Credits:
M. Bolzonella,
C. Carbone



Towards DR1 analysis: tasks

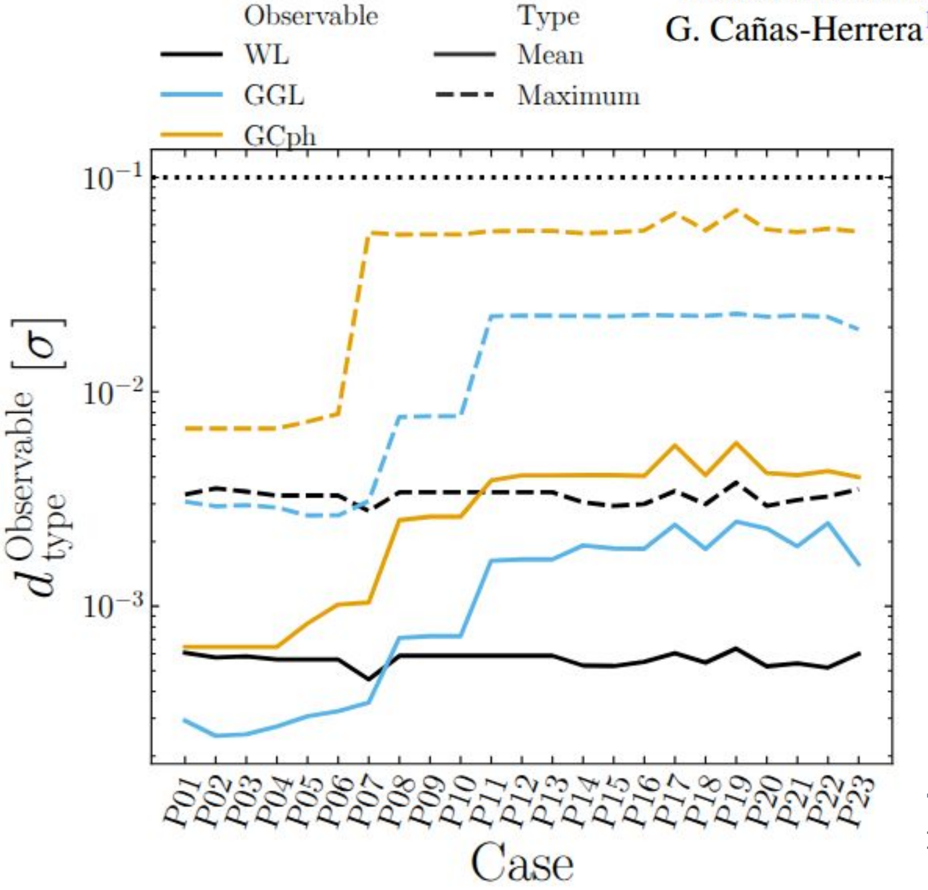
- Pipeline development
  - Observables & likelihood: `cloelib` + `cloelike` ✅/🚧
  - Covariance: `Spaceborne` ✅
  - Data IO: `euclidlib` ✅
- Pipeline validation:
  - Against independent codes ✅
  - Using simulations (FS2) ✅/🚧
  - Using (real!) data 🚧
- Analysis choices 🚧
  - Sample selection, nonlinear modelling, systematics, scale cuts, priors...
  - Optimize in terms of **bias** and **constraining** power (FoB and FoM)
- Data exploration (RR2) 🚧
  - Sources of spurious correlation
  - Star-galaxy separation
  - Impact of catalogue selection (depth, phz quality...)
  - Internal consistency (splits, N/S...)
  - ...

CLOE(lib) validation

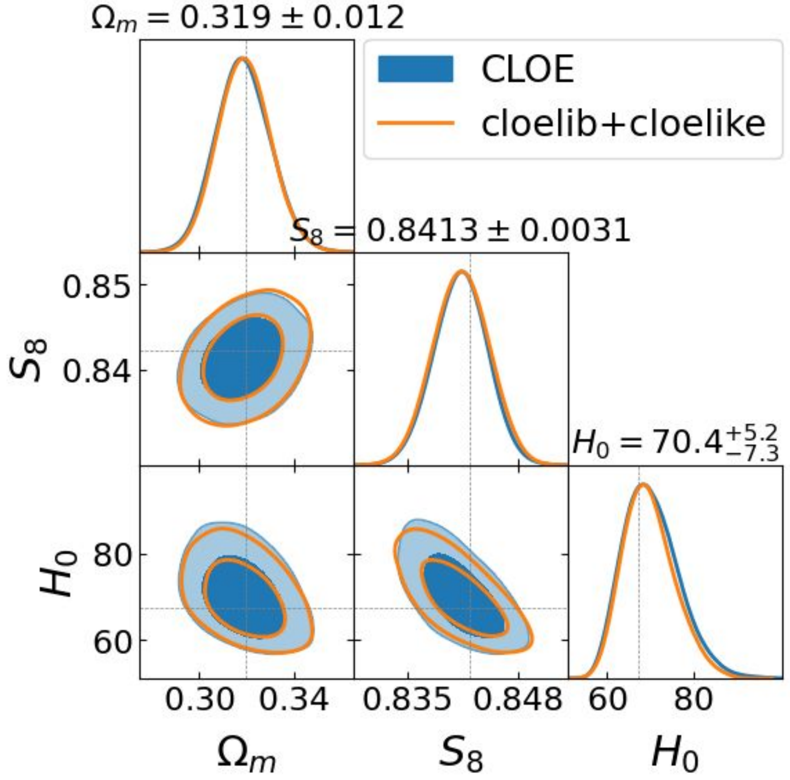
Euclid preparation

TBD. Cosmology Likelihood for Observables in Euclid (CLOE). 4: Validation and Performance

Euclid Collaboration: M. Martinelli*[1,2], A. Pezzotta[3,4], D. Sciotti[1,2], L. Blot[5,6], M. Bonici[7,8], S. Camera[9,10,11], G. Cañas-Herrera[12,13,14], V. F. Cardone[1,2], P. Carrilho[15], S. Casas[16], S. Davini[17], S. Di Domizio[18,17], S. Farrens[19],

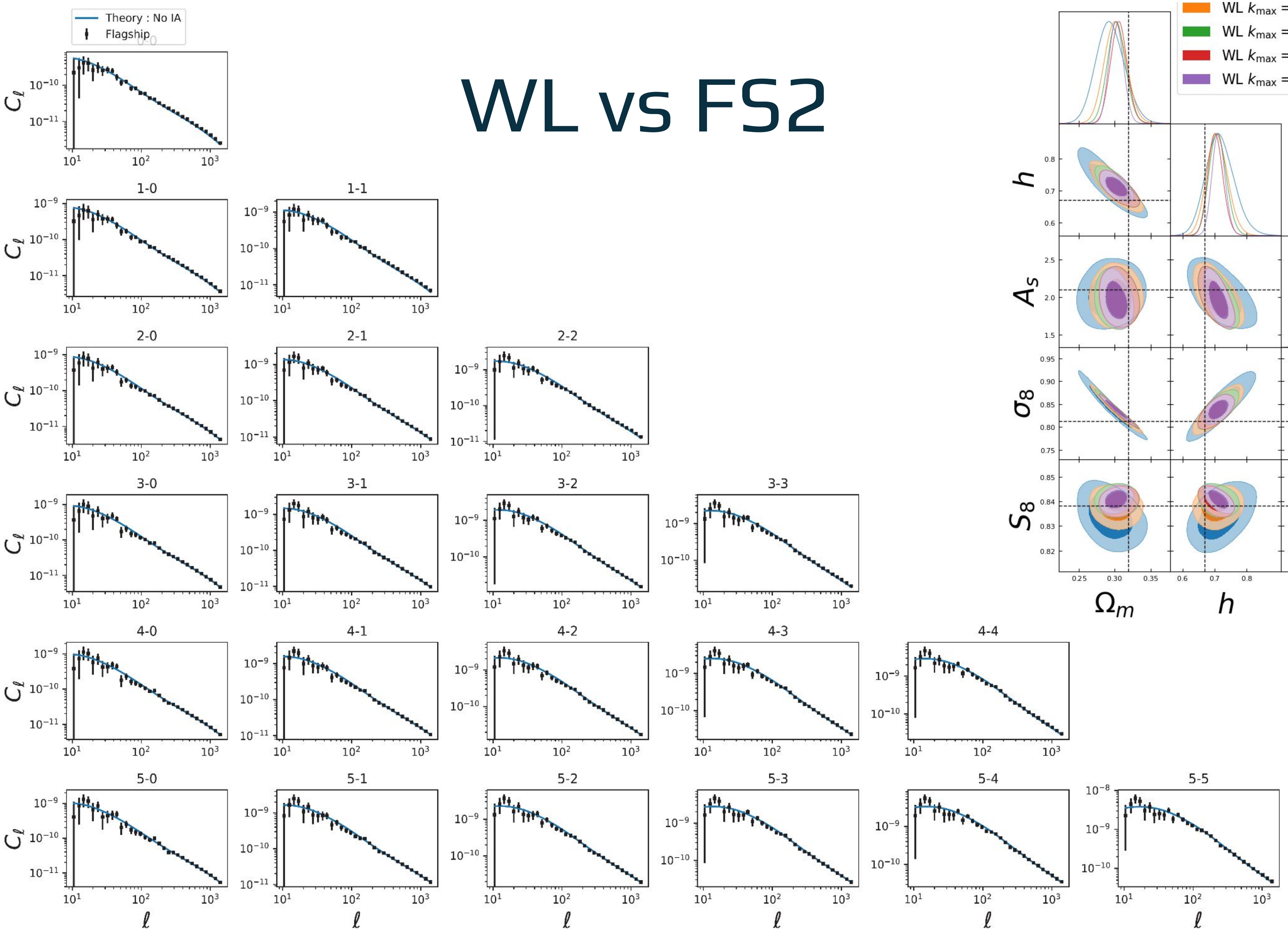


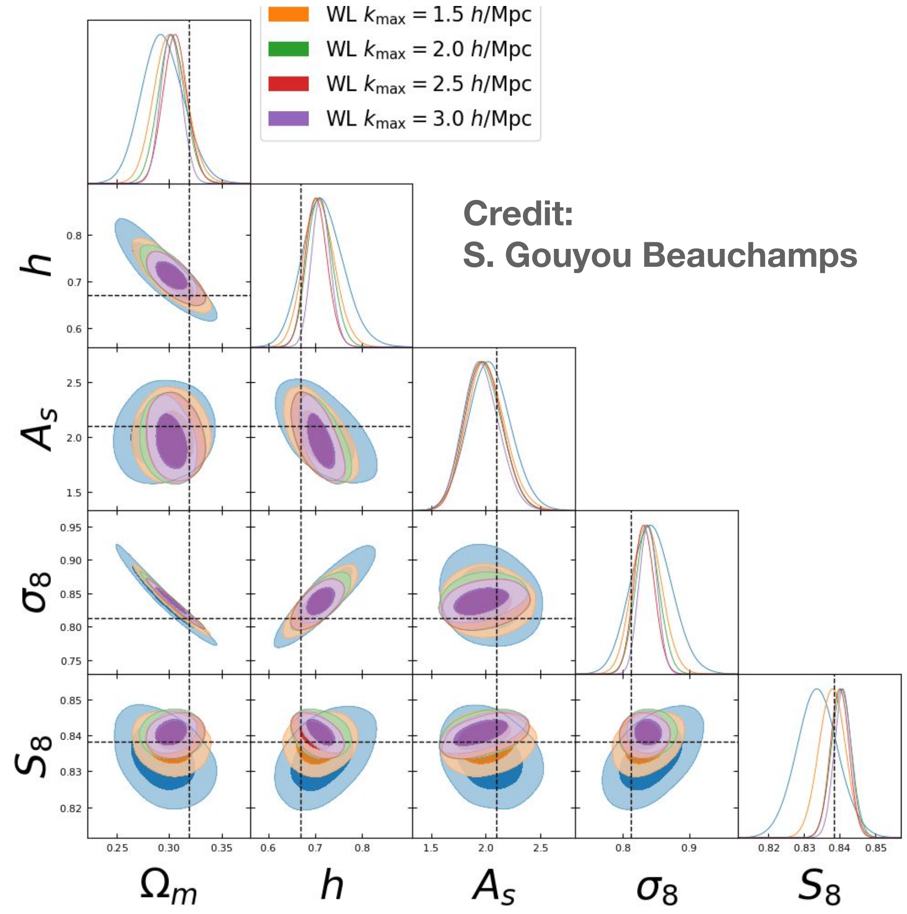
Credit:
M. Martinelli



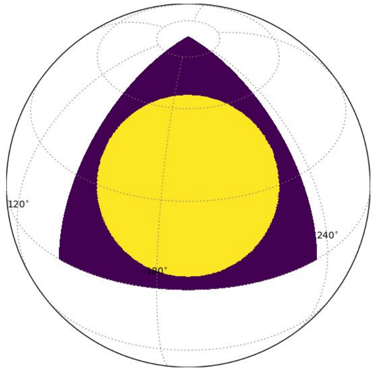
Credit:
J. Coloma

WL vs FS2





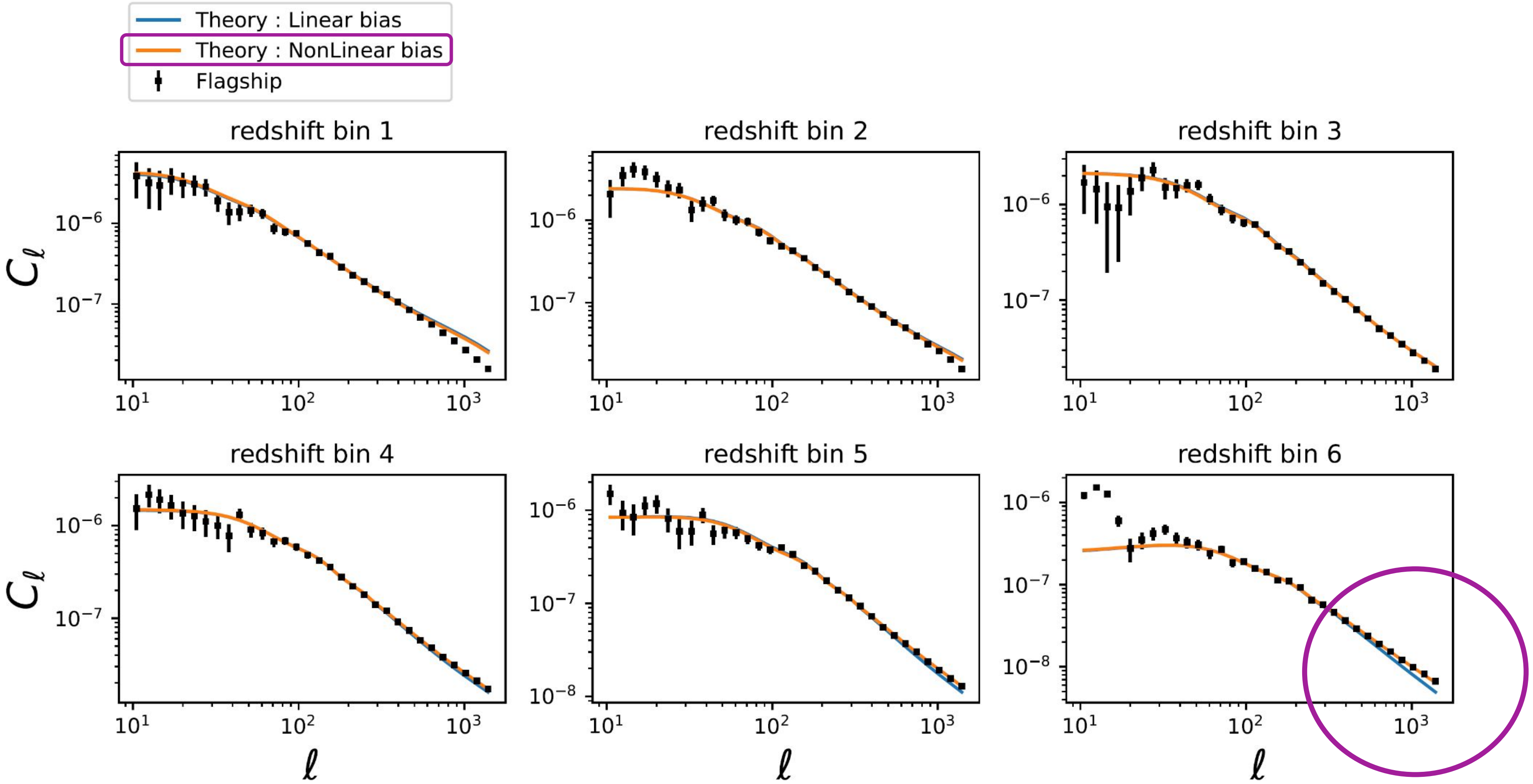
Credit:
S. Gouyou Beauchamps



30deg-cone on FS2

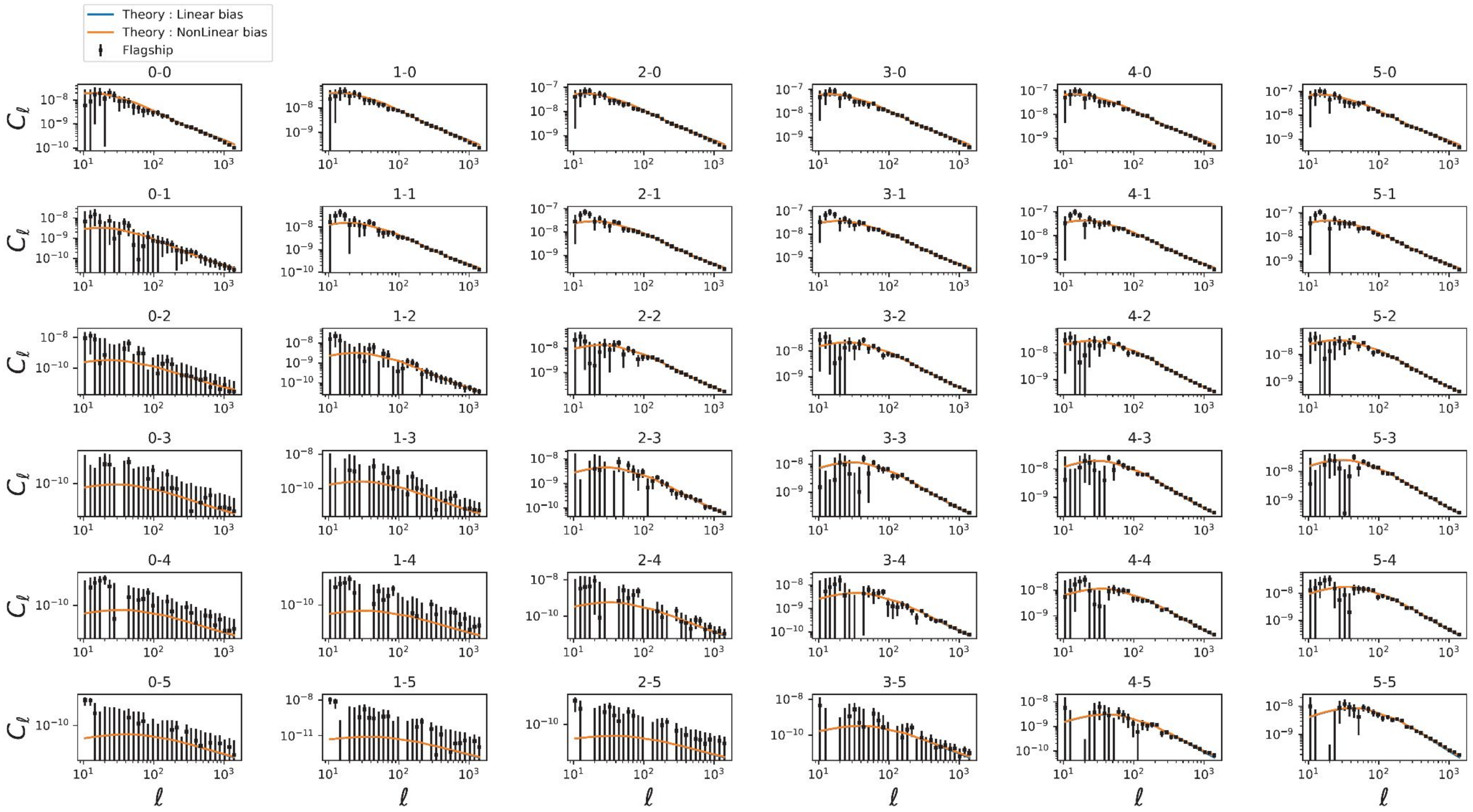
Credit: S. Gouyou Beauchamps, C. Carbone

GCph vs FS2



GGL vs FS2

Credit: S. Gouyou Beauchamps, C. Carbone



Covariance: Spaceborne

👥 Main contributors

- **D. Sciotti**: main developer and maintainer
- **S. G. Beauchamps**: SSC validation, partial-sky implementation
- **M. Bonici**: general structure, PyCCL interface, code optimization
- **R. Reischke**: NG cov, real-space validation
- **C. Garcia-Garcia**: partial-sky validation
- **J. R. Zapatero**: validation against jackknife

🌍 Coordinates (open repository)

- GitHub
- Readthedocs

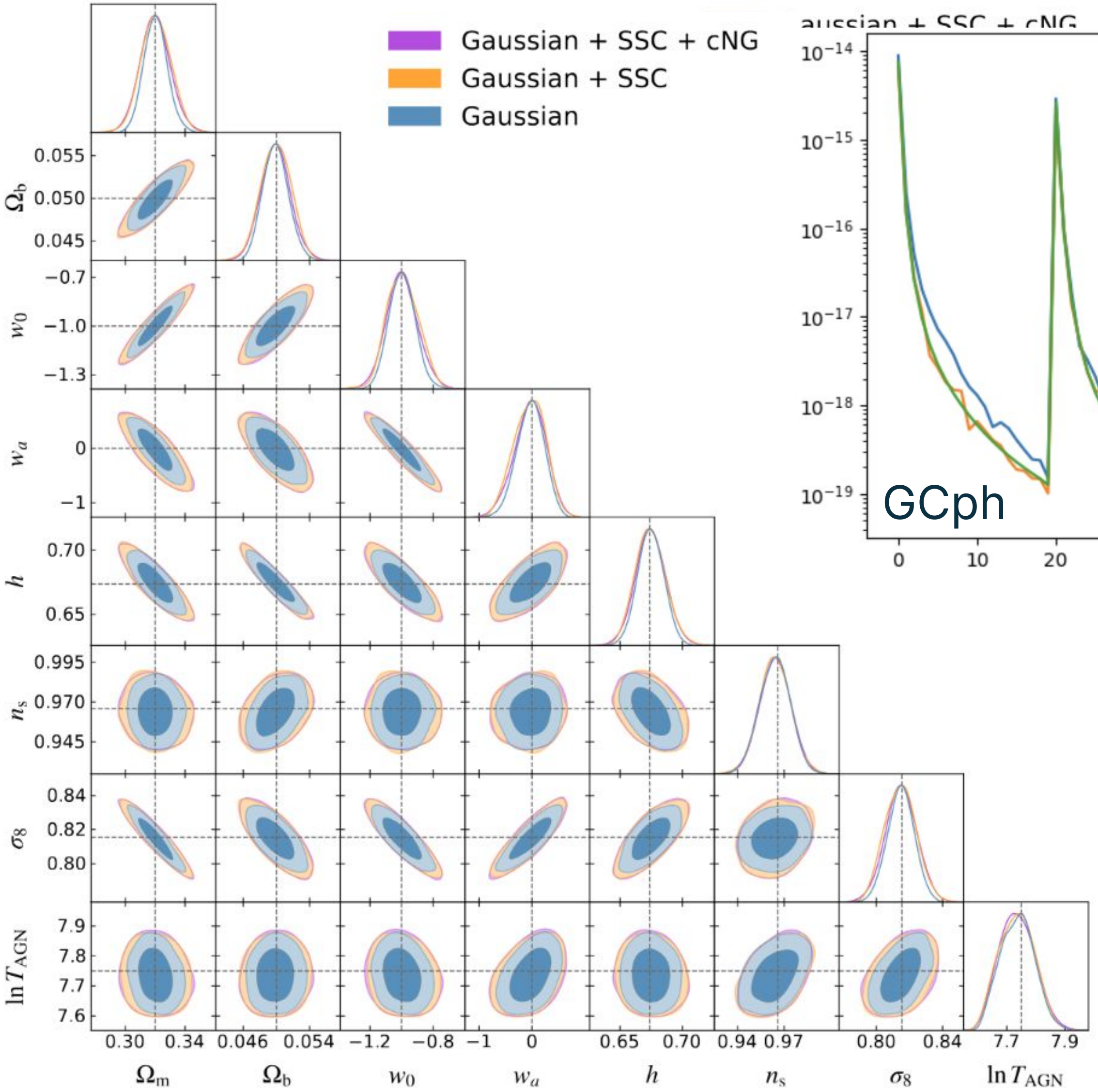
⚡ Key features

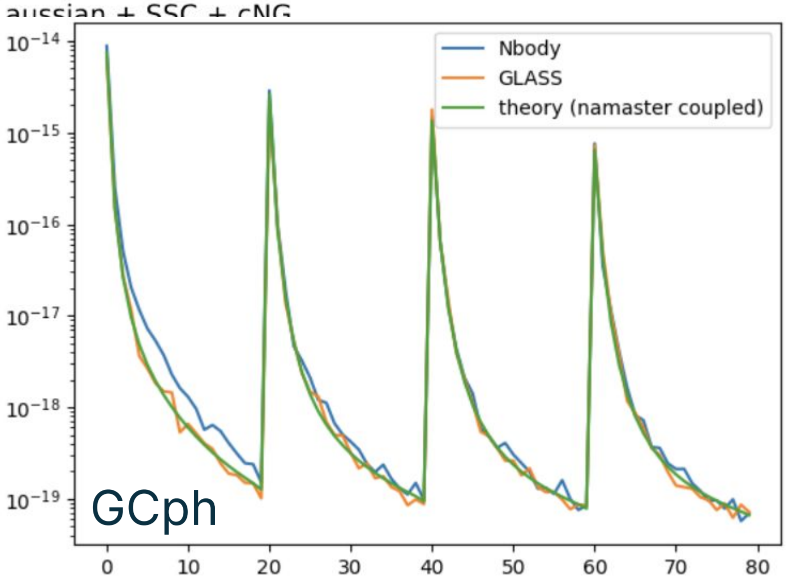
- Fast & parallel
- Interface with CCL (/cloelib)
- G, SSC, cNG
- Harmonic and real space
- Coupled/decoupled cov (int. with Namaster)
- and more!

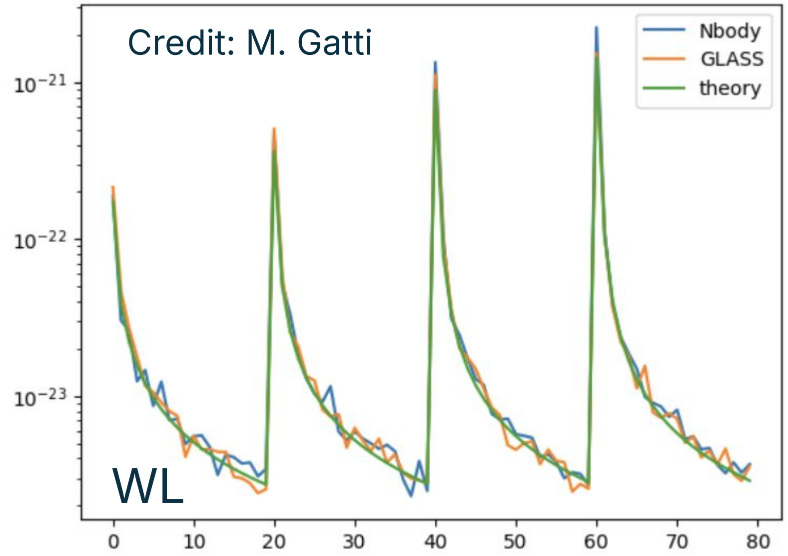
Validation

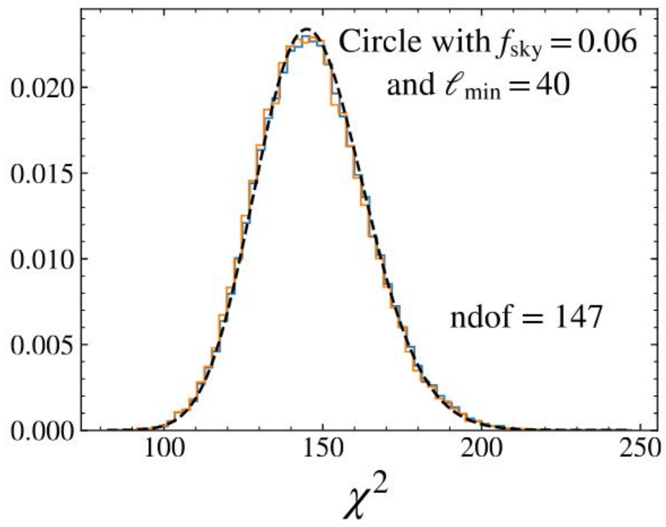
Euclid preparation. TBD. Theoretical modelling and numerical implementation of the harmonic-space 3×2pt covariance

Euclid Collaboration: D. Sciotti, M. Bonici, S. G. Beauchamps, G. Cañas-Herrera, R. Reischke, J. Coloma, M. Crocce, C. Giocoli, A. Pourtsidou, N. Tessore, M. Tsedrik, , et al.

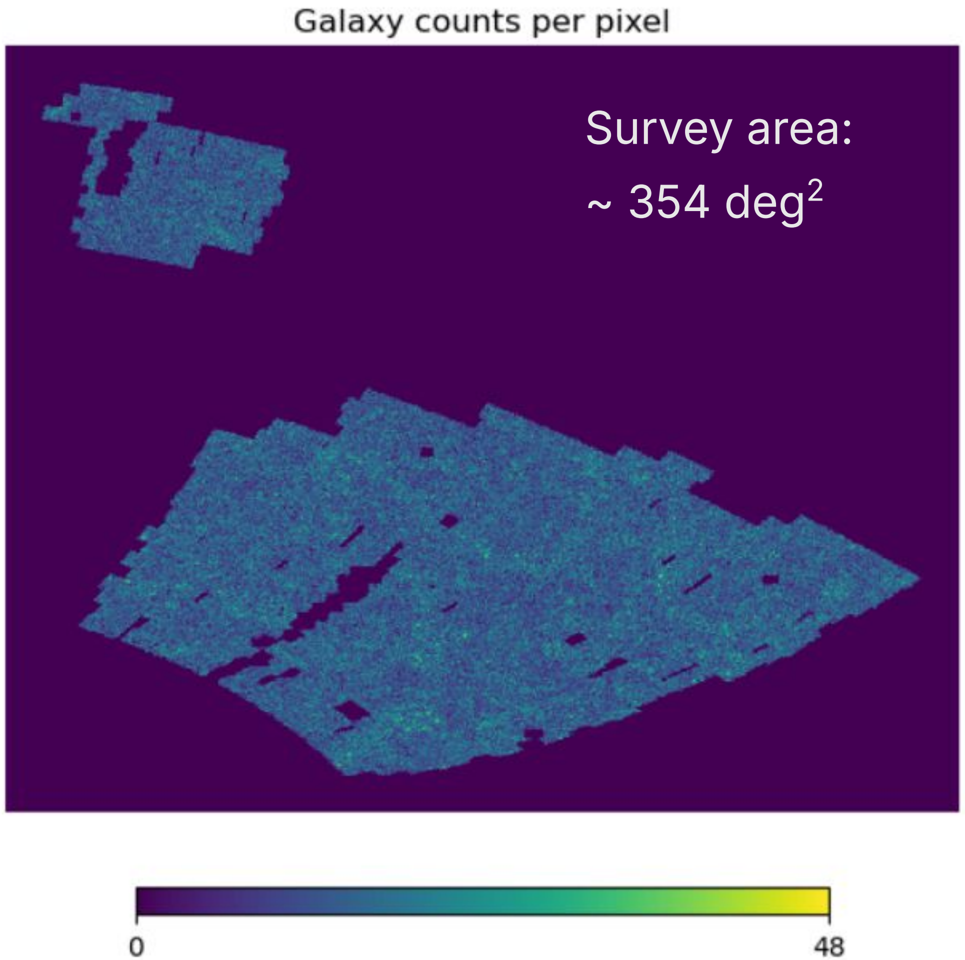






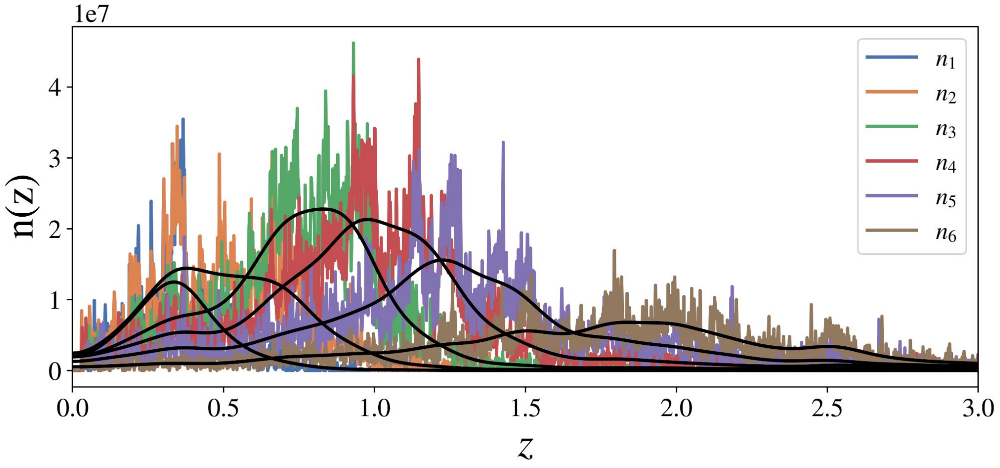


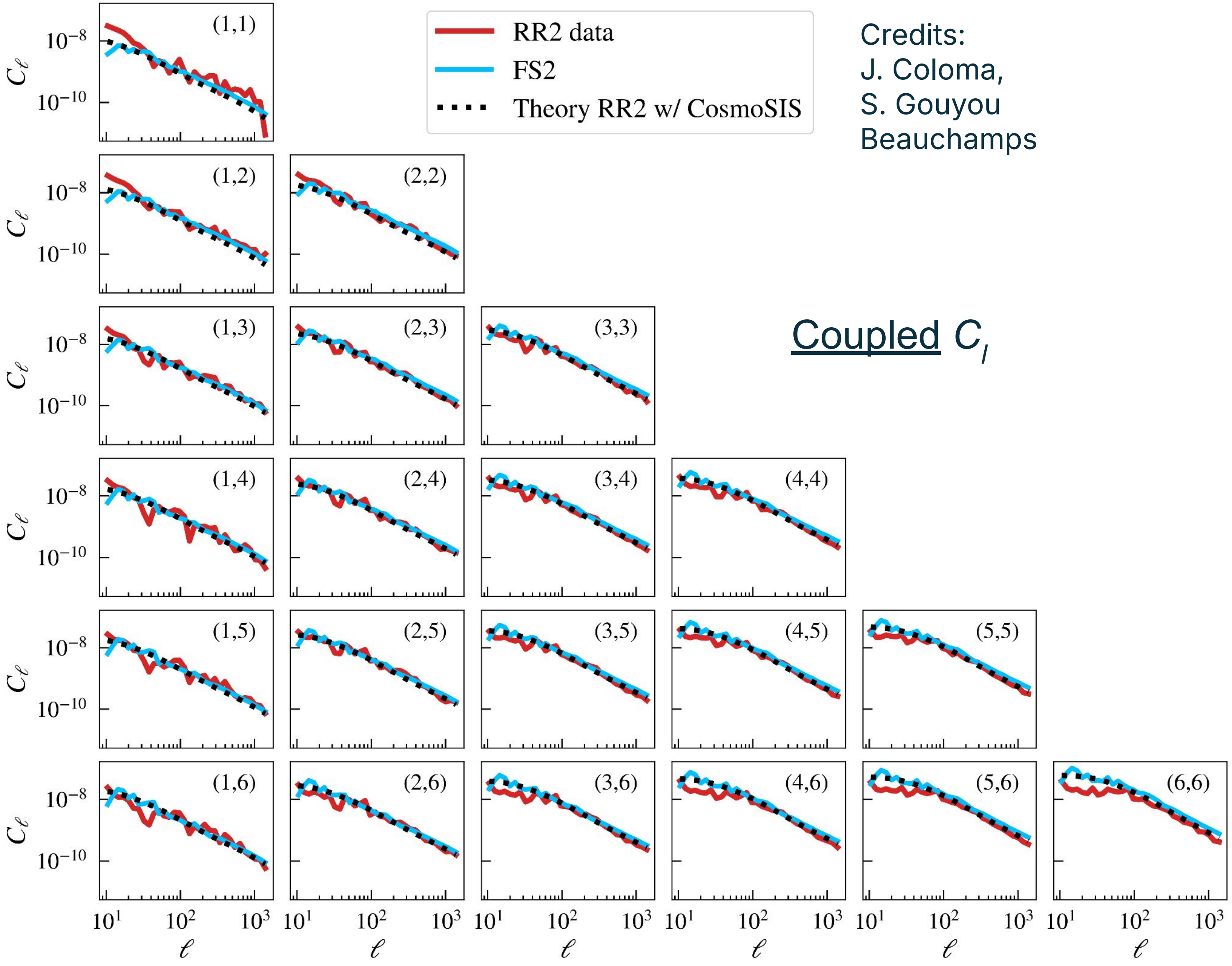
RR2 visibility mask & galaxy counts



First RR2 spectra

- **Data:**
  - Catalogue v1_1, w/o “bad tiles”
  - Unit weights, LensMC
  - Binary mask
- **Sim:**
  - FS2 30deg cone
  - Both sim and data rescaled to full-sky
- **Theory:**
  - CosmoSIS pcl library
  - RR2 smoothed n(z)’s
  - FS2 cosmology (no baryons/IA/mag.



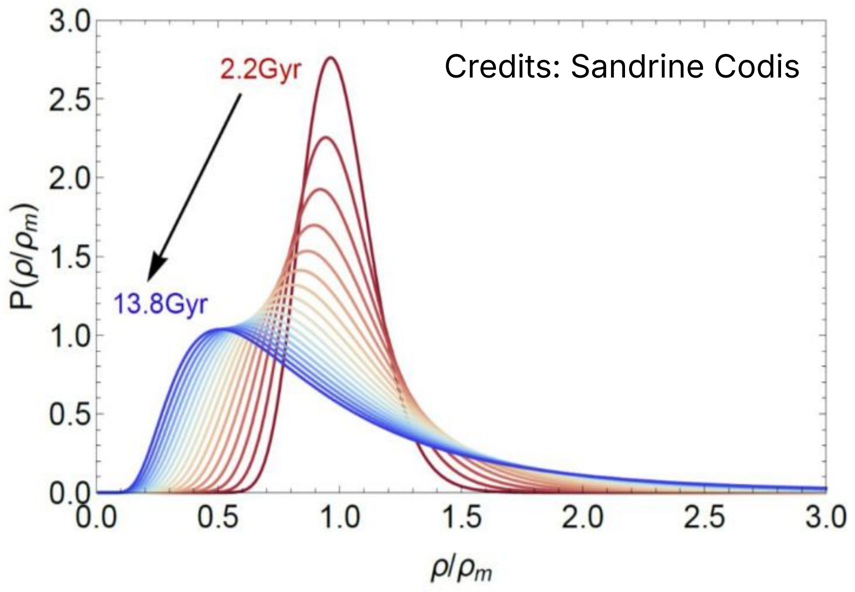


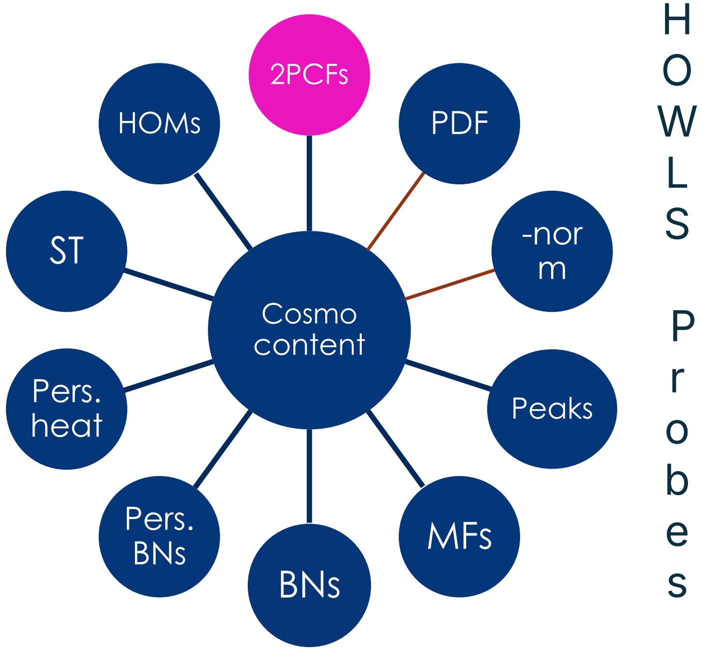
Credits:
J. Coloma,
S. Gouyou Beauchamps

Coupled C_l

Higher-order statistics

Simulated Density Matter distribution





Slide by Simone Vinciguerra

2-pt statistics (γ-2PCFs, κ-2PCF):

✔ Supported by solid theoretical models

× Only sensitive to the Gaussian information

Higher Order Statistics (HOSs):

✔ Capture Gaussian & non-Gaussian content

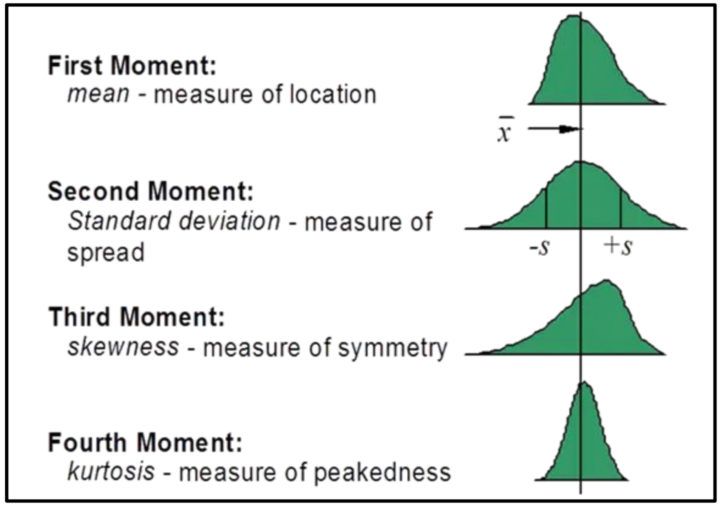
× Mostly lacking of theoretical models

Slide by Simone Vinciguerra

Higher-order statistics

1-point statistics Moments, PDF, ...

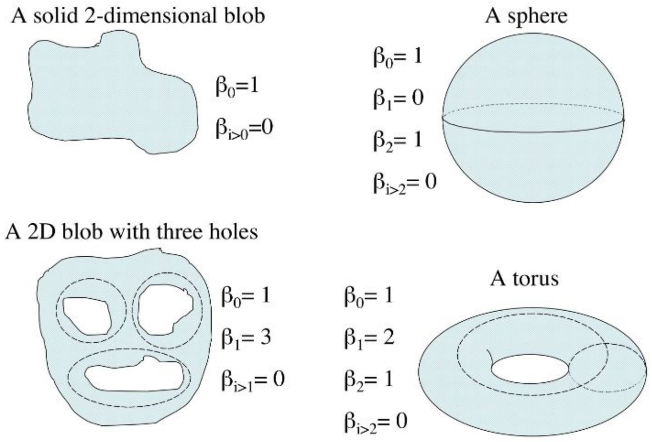
- Probing the higher order cumulants of the field.



Fiveable. "3.5 Higher-order moments – Theoretical Statistics." Edited by Becky Bahr, Fiveable, 2024

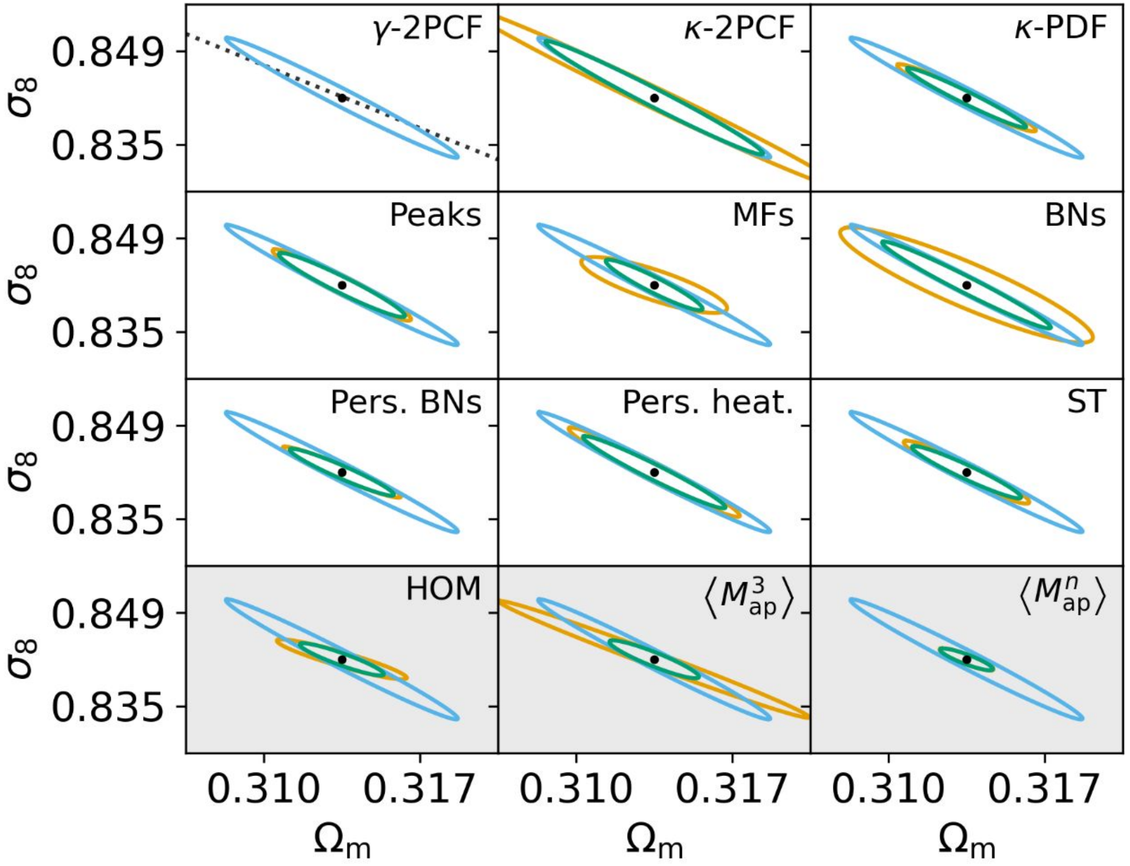
Topological statistics Peaks, MFs, BNs, ...

- Probing the distribution of maxima, minima, saddles and their connectivity.



B. Walker (2008)

Euclid Preparation. XXVIII. Ajani, HOWLS+



- 7/10 HOSs compared against 2PCF (γ, κ)
- Non-tomographic precision-forecasts on (Ω_m, σ_8)
- Individual constraining power improved up to a factor 2

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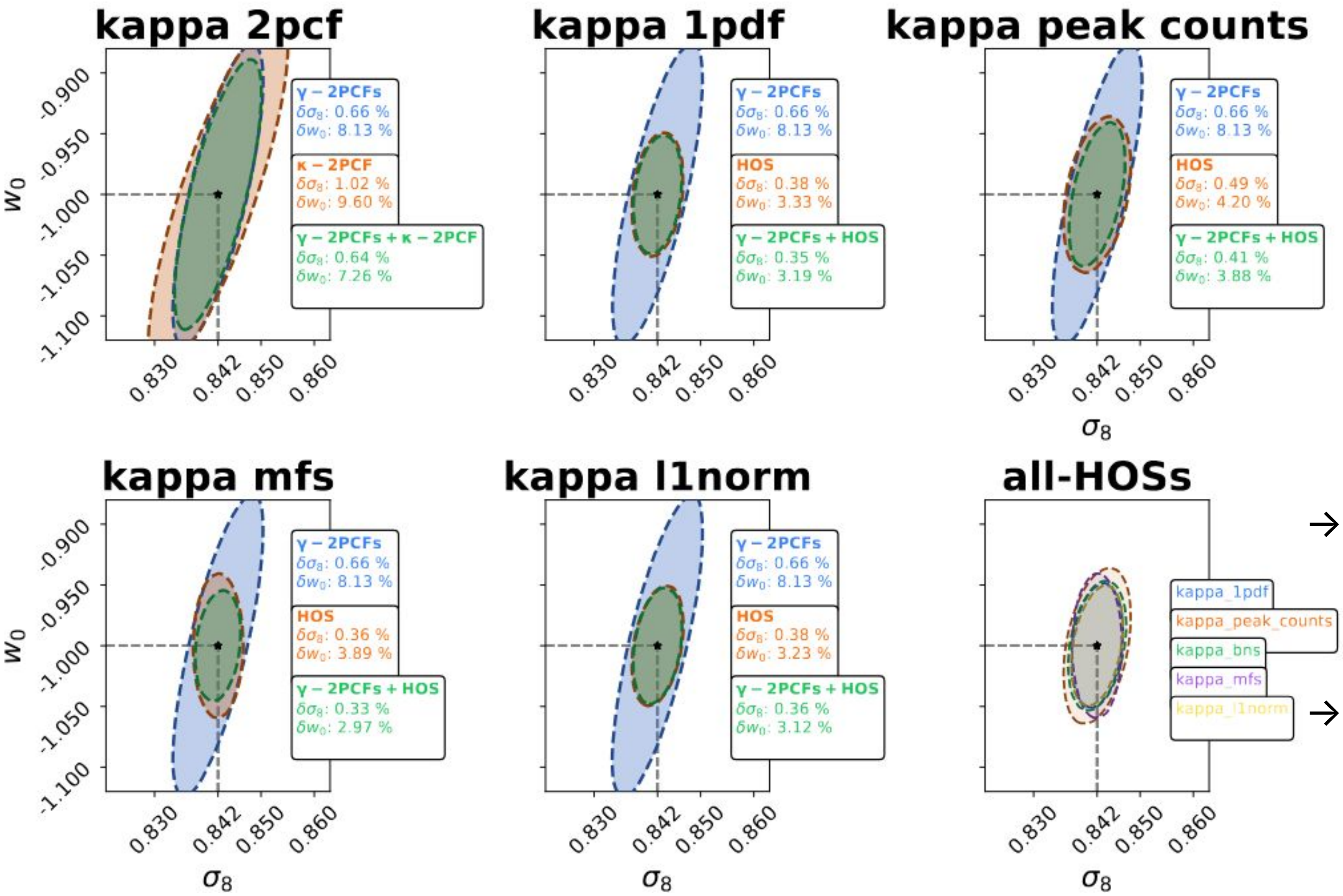
HOSs comparison: Vinciguerra+, in prep



→ 2pt information already captured by HOSs

→ Factor 2 gain over 2pt

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Conclusions

- 3×2pt is a machine with **lots** of moving parts
- Analysis tools are being finalised and validated, with promising results (e.g., by recovering unbiased FS2 cosmology using different summary statistics)
- First application on RR2 data seems very good!
- The parameter space of analysis choice has many dimensions and is difficult to explore:
    - Sample selection (mostly dictated by **data quality**: photo-z and shape measurement quality, sample size, contamination, ability to run pipelines)
    - Scale cuts (mostly dictated by **modelling uncertainties**: NL bias, NL clustering, baryonic feedback…)
- HOS show the potential to boost constraining power without adding external information
- Timeline is extremely tight, but…


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