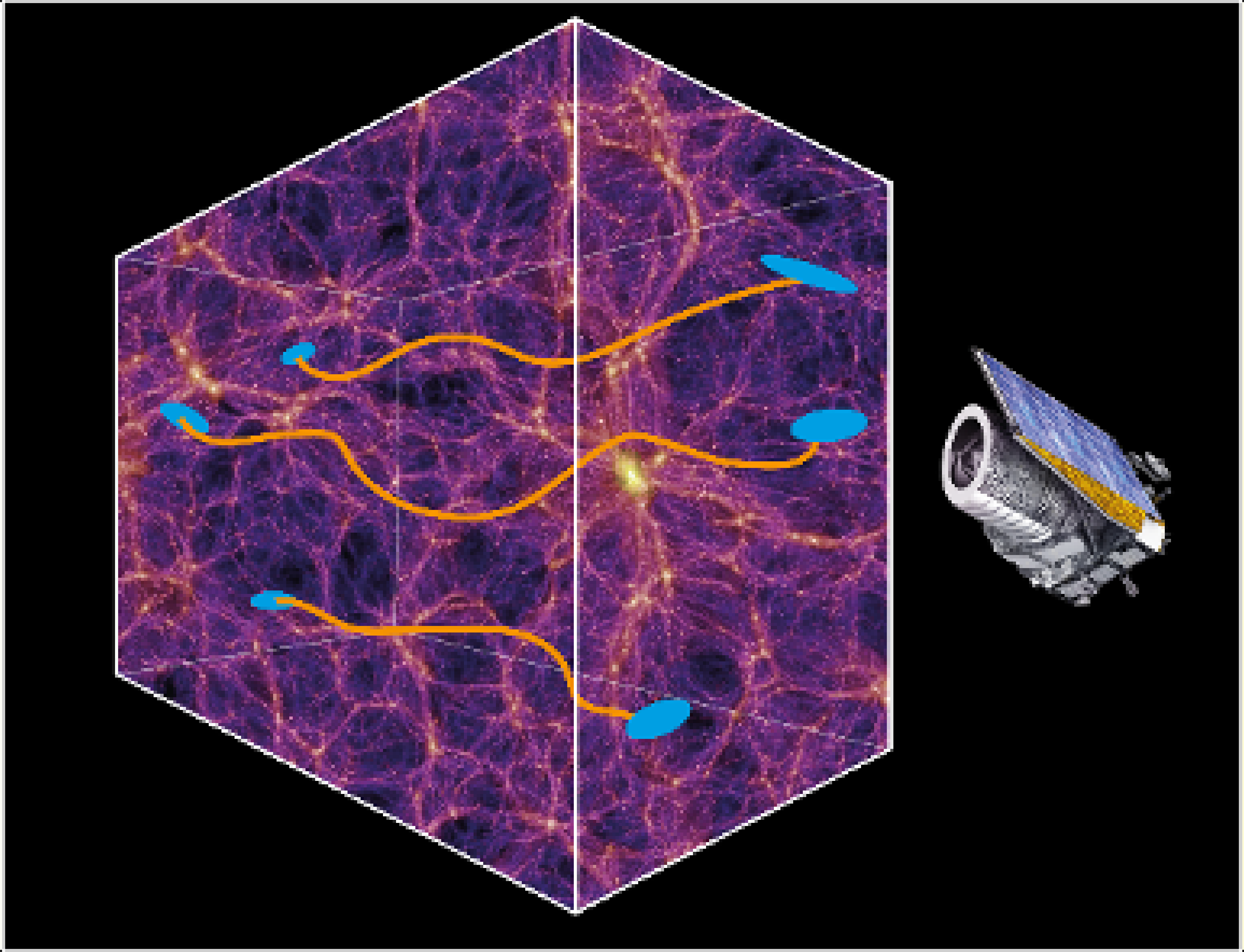
Weak Gravitational Lensing

An exciting frightening challenge



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Frascati – Sept 12th, 2023

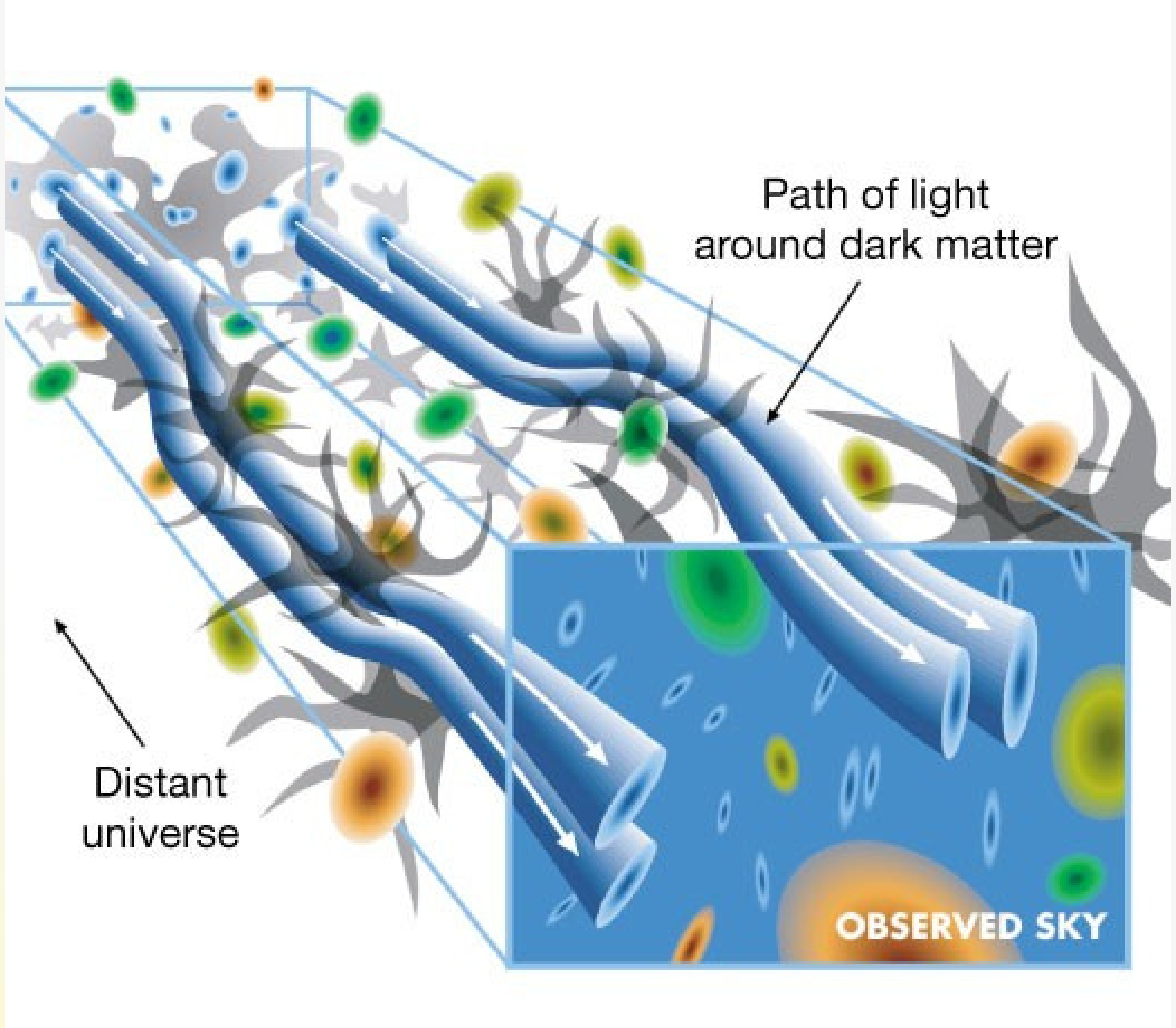
OAR
INFN ROMA Istituto Nazionale di Fisica Nucleare Sezione di Roma
ASI Agenzia Spaziale Italiana

Cosmic Shear

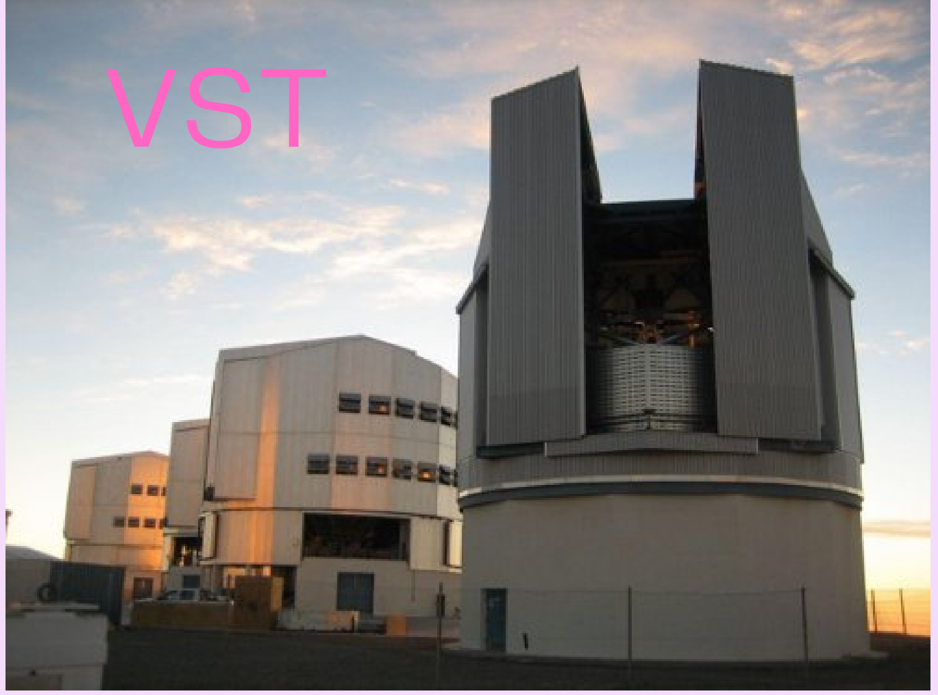
- a General Relativity effect
- light deflection due to the matter along the line of sight
- tiny modification of the shape of elliptical sources
- probe both the expansion and the growth of structures

DETF and WL Surveys

- Report of the Dark Energy Task Force (2006)
- Recommendations
  - a probe sensitive to the growth of structures
  - testing modifications of General Relativity
  - combination of techniques
  - control of systematics



THE PATH OF LIGHT FROM DISTANT SOURCES TO THE OBSERVER THROUGH THE LARGE SCALE STRUCTURE DISTRIBTUTION OF MATTER (DARK AND VISIBLE



KiDS

1500 SQ DEG – (UGRIZYJHK) FILTERS – OMEGACAM – 6.22 GAL/ARCMIN2 – Z = 0.67

THE DARK ENERGY SURVEY

5000 SQ DEG – (GRIZY) FILTERS – DECAM – 5.59 GAL/ARCMIN2 – Z = 063

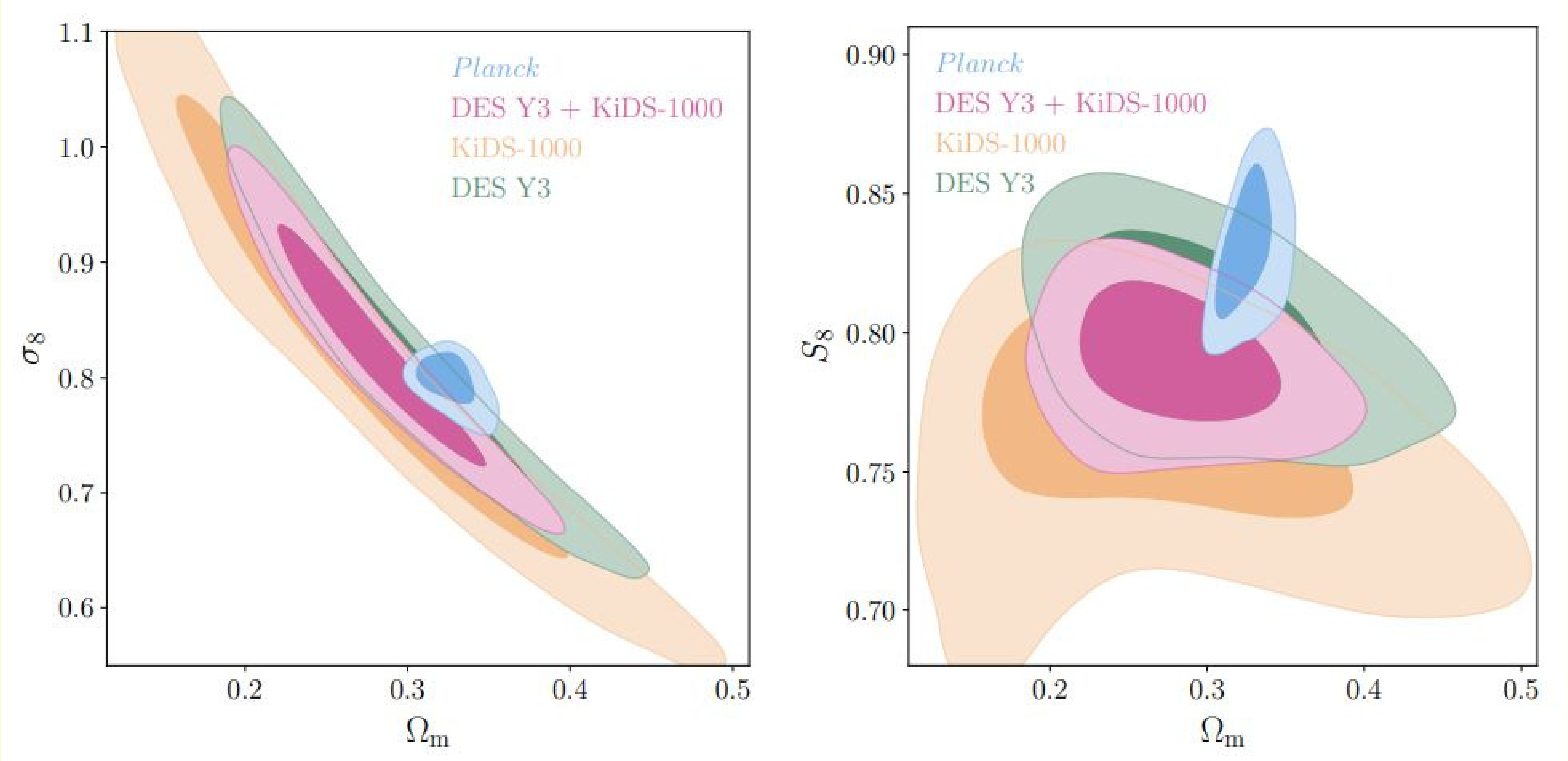
HSC

1400 SQ DEG – (GRIZY) FILTERS –
HYPER SUPRIME CAM – 14.96 GAL/ARCMIN2 – Z = 0.80

Cosmological Results from Stage III Surveys

KiDS	THE DARK ENERGY SURVEY	HSC
$S_8 = 0.763^{+0.031}_{-0.023}$	$S_8 = 0.802^{+0.023}_{-0.019}$	$\Omega_m : 0.256^{+0.056}_{-0.044}$
$\Omega_m = 0.270^{+0.056}_{-0.102}$	$\Omega_m = 0.297^{+0.040}_{-0.060}$	$\sigma_8 : 0.818^{+0.089}_{-0.091}$
$\sigma_8 = 0.833^{+0.133}_{-0.146}$	$\sigma_8 = 0.816^{+0.076}_{-0.085}$	$S_8 : 0.769^{+0.031}_{-0.034}$

WHAT ABOUT THE COMPARISON WITH PLANCK?

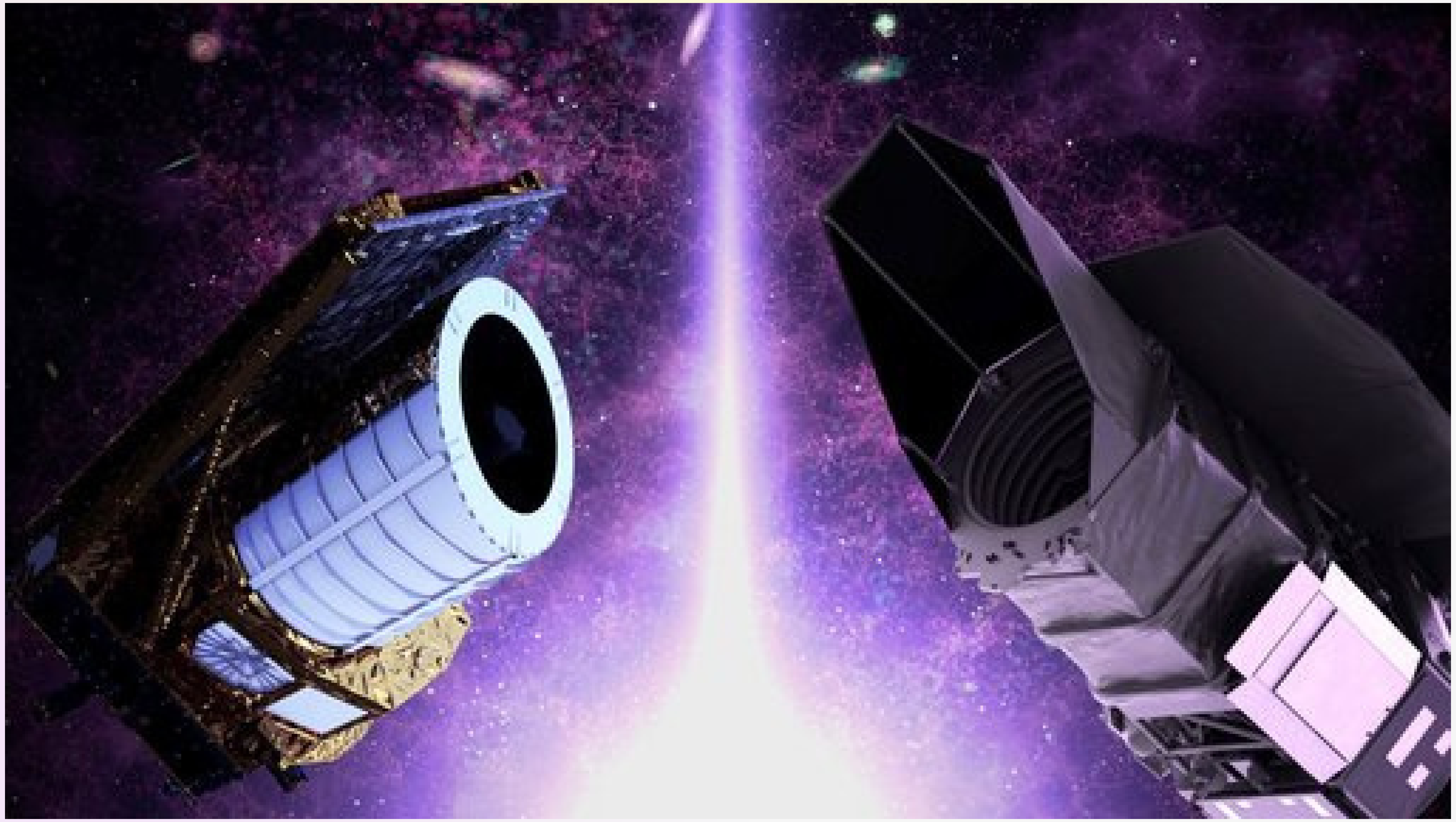


IS THERE A TENSION ON S8?

IS THERE A SINGLE ANSWER?

NEW PHYSICS OR SYSTEMATICS?

Stage IV Surveys



Ground based surveys

- Legacy Survey of Space and Time
- Vera C. Rubin Observatory

Space based surveys

- Euclid
- Nancy Grace Roman Space Telescope
- Xuntian (Chinese Survey Space Telescope)

Hiding Problems in Plain Sight

$$\mathcal{L}_{\mathcal{G}}(\mathbf{p}) = \frac{1}{(2\pi)^{d/2}|\boldsymbol{\Sigma}|^{1/2}} \exp\left[-\frac{1}{2}\left(\mathfrak{D}_{obs} - \mathfrak{D}_{th}\right)\boldsymbol{\Sigma}^{-1}\left(\mathfrak{D}_{obs} - \mathfrak{D}_{th}\right)^{T}\right]$$

$$\begin{aligned}\mathcal{L}_{\mathcal{W}}^{(k)}(\mathbf{p}) &= \left[2^{\nu d/2}|\hat{\mathbf{C}}(\ell_k)|^{\nu/2}\Gamma_d(\nu/2)\right]^{-1} \\ &\times |\hat{\mathbf{C}}(\ell_k)|^{\nu-d-1/2}\exp\left\{-\mathrm{Tr}\left[\mathbf{V}^{-1}(\ell_k)\hat{\mathbf{C}}(\ell_k)\right]/2\right\}\end{aligned}$$

Data (and systematics)

- instrumental effects
- PSF reconstruction
- shape measurement
- photo – z determination
- shear calibration

Covariance

- analytical vs numerical
- super sample covariance
- curse of dimensionality
- numerical issues
- validating solutions
- number of simulations
- shear error propagation

Theory (and systematics)

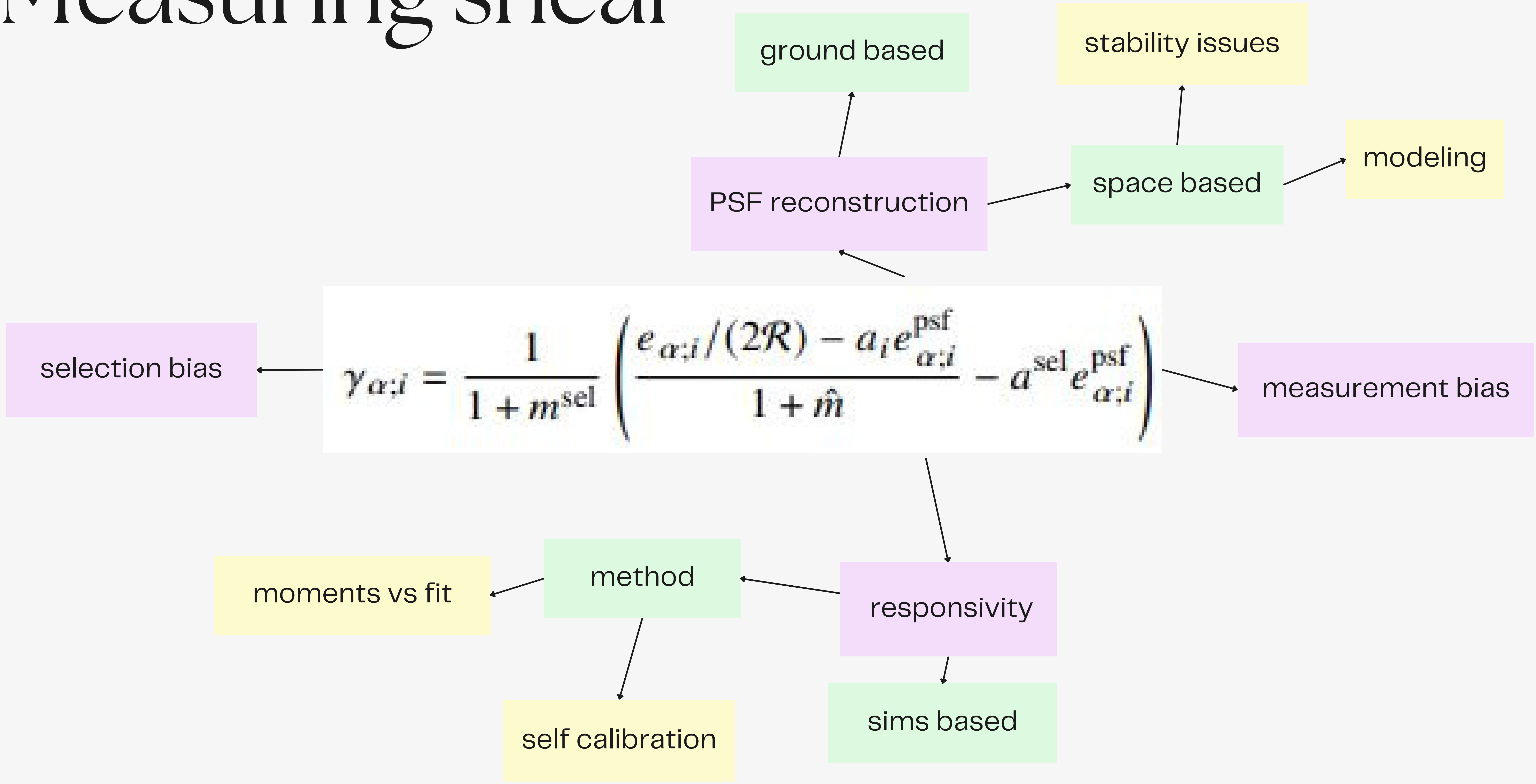
- nonlinear regime
- baryon effects
- IA modeling
- photo – z modeling
- samples choice
- nuisance parameters
  - fiducial
  - priors (if any)

NEED FOR A DEDICATED TASKFORCE - IST:LIKELIHOOD

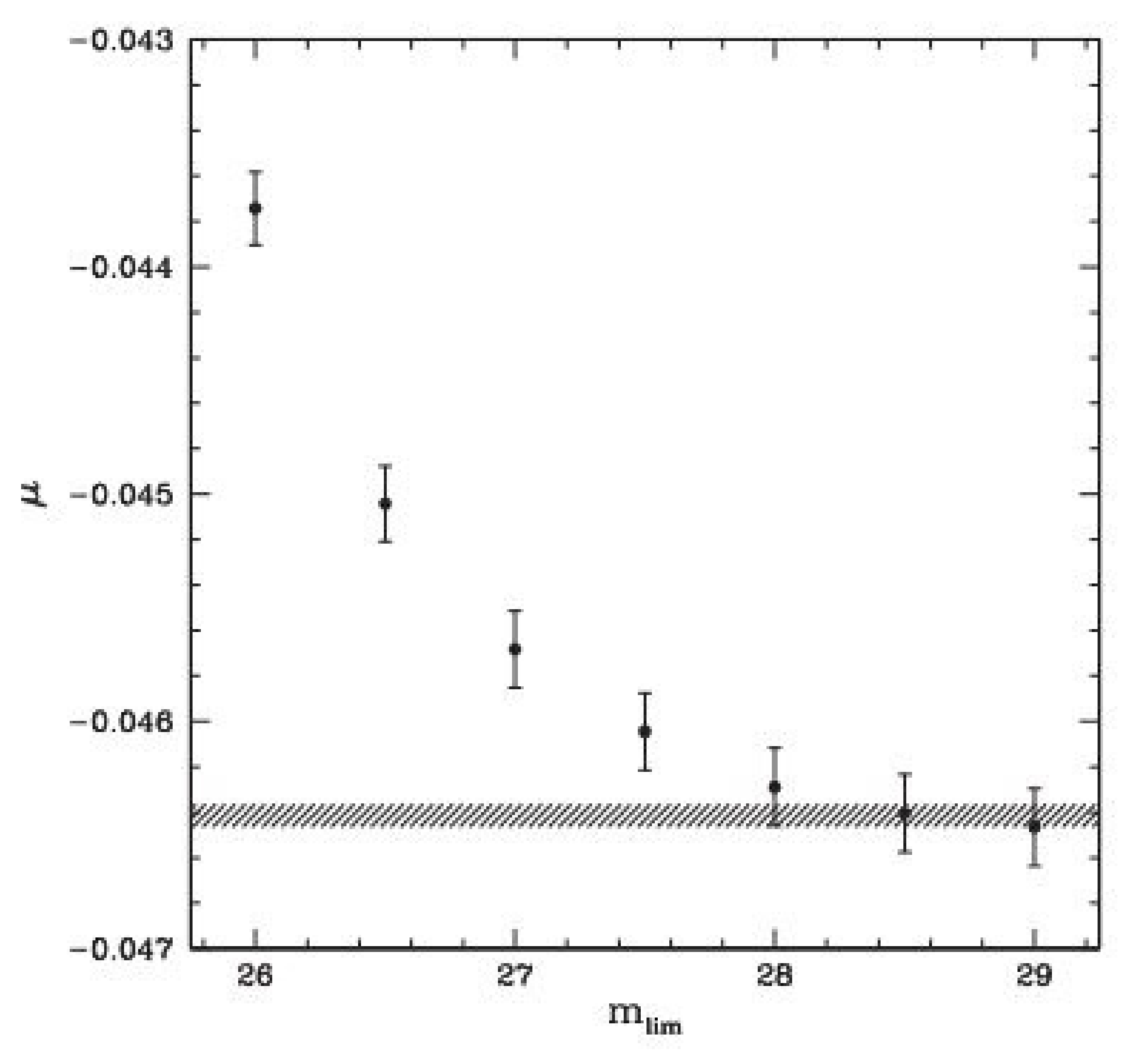
CLOE (CODE FOR LIKELIHOOD OF OBSERVABLES IN EUCLID)

Measuring shear

$$\gamma_{\alpha;i} = \frac{1}{1+m^{\mathrm{sel}}}\left(\frac{e_{\alpha;i}/(2\mathcal{R}) - a_i e^{\mathrm{psf}}_{\alpha;i}}{1+\hat{m}} - a^{\mathrm{sel}} e^{\mathrm{psf}}_{\alpha;i}\right)$$

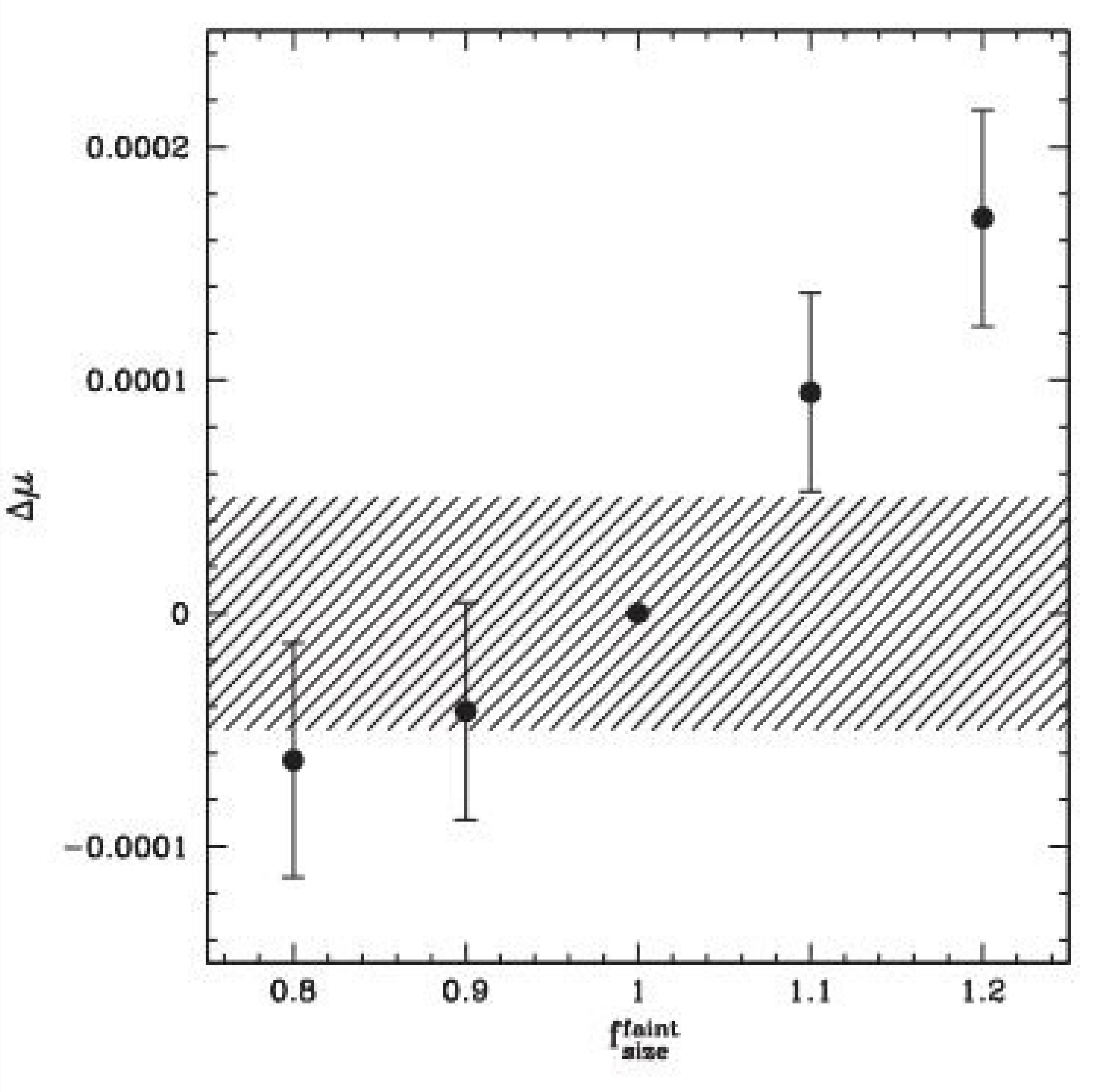


Shear Calibration against Simulations



Dependence on the limiting mag

- blending and background estimate
- need to simulate undetected galaxies too
- how to model them?
- which is their number density?
- increase in the computational time



Dependence on assumptions

- size of the galaxies
- size – luminosity relation
- scaling with redshift
- faint end slope of the LF
- details of the implementation

Incorrect PSF reconstruction

additive bias due to PSF leakage

$$g_{\rm sys} = \alpha^{(2)} e_{\rm PSF} + \beta^{(2)} \Delta e_{\rm PSF} + \alpha^{(4)} M^{(4)}_{\rm PSF} + \beta^{(4)} \Delta M^{(4)}_{\rm PSF}.$$

angular spectra

$$C_\ell \rightarrow C_\ell + \sum_{i=1}^{4} \sum_{j=1}^{4} p_i p_j C_\ell^{S_i S_j}.$$

additional terms

$$C_\ell^{\hat{g}_{\rm gal} e_{\rm PSF}} = \alpha^{(2)} C_\ell^{e_{\rm PSF} e_{\rm PSF}} + \beta^{(2)} C_\ell^{\Delta e_{\rm PSF} e_{\rm PSF}} + \alpha^{(4)} C_\ell^{M^{(4)}_{\rm PSF} e_{\rm PSF}} + \beta^{(4)} C_\ell^{\Delta M^{(4)}_{\rm PSF} e_{\rm PSF}},$$

$$C_\ell^{\hat{g}_{\rm gal} \Delta e_{\rm PSF}} = \alpha^{(2)} C_\ell^{e_{\rm PSF} \Delta e_{\rm PSF}} + \beta^{(2)} C_\ell^{\Delta e_{\rm PSF} \Delta e_{\rm PSF}} + \alpha^{(4)} C_\ell^{M^{(4)}_{\rm PSF} \Delta e_{\rm PSF}} + \beta^{(4)} C_\ell^{\Delta M^{(4)}_{\rm PSF} \Delta e_{\rm PSF}},$$

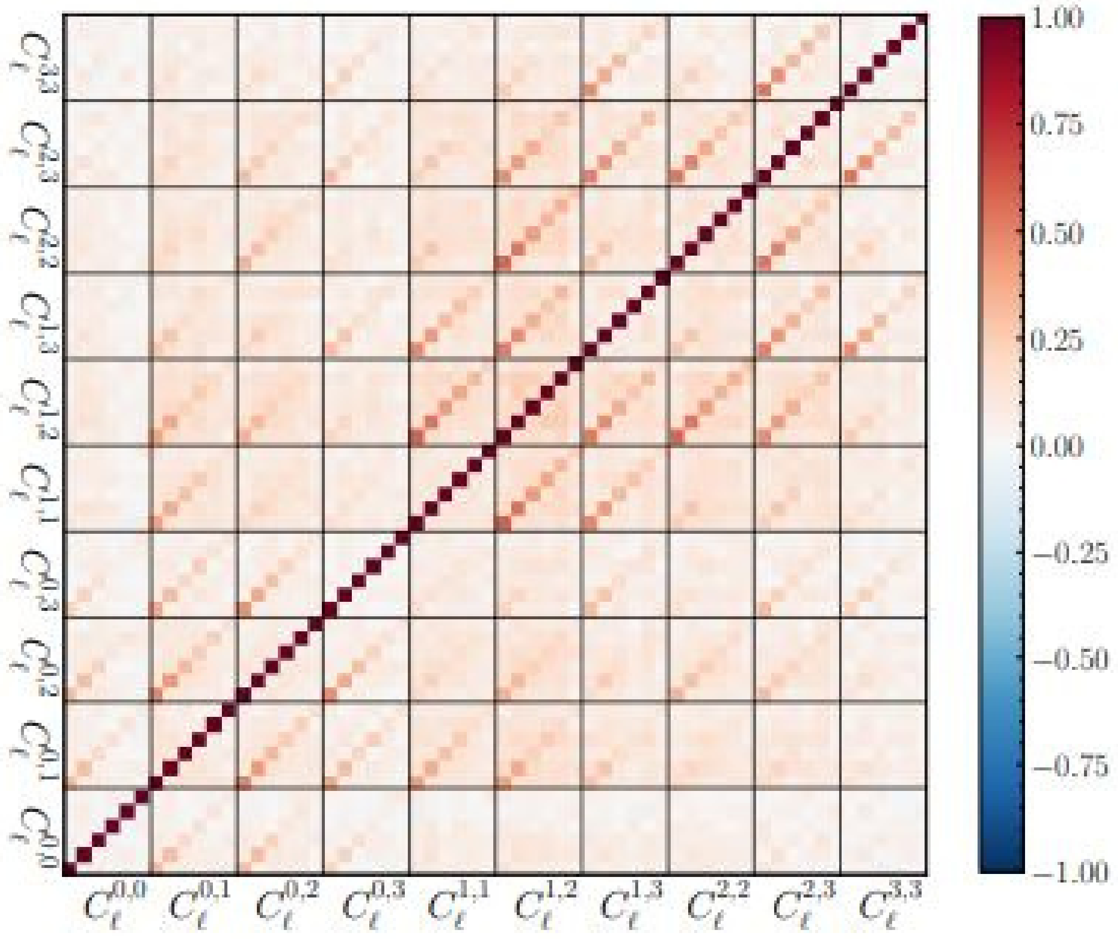
$$C_\ell^{\hat{g}_{\rm gal} M^{(4)}_{\rm PSF}} = \alpha^{(2)} C_\ell^{e_{\rm PSF} M^{(4)}_{\rm PSF}} + \beta^{(2)} C_\ell^{\Delta e_{\rm PSF} M^{(4)}_{\rm PSF}} + \alpha^{(4)} C_\ell^{M^{(4)}_{\rm PSF} M^{(4)}_{\rm PSF}} + \beta^{(4)} C_\ell^{\Delta M^{(4)}_{\rm PSF} M^{(4)}_{\rm PSF}},$$

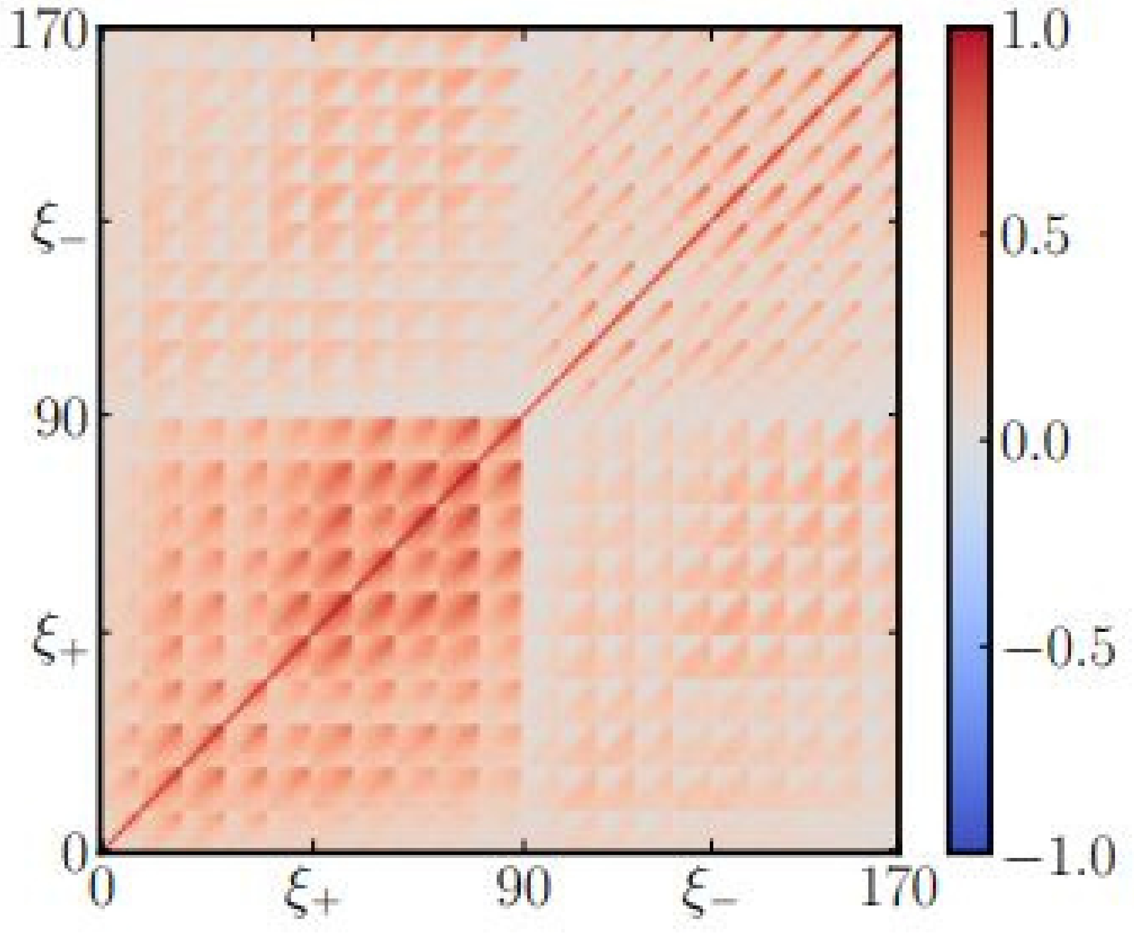
$$C_\ell^{\hat{g}_{\rm gal} \Delta M^{(4)}_{\rm PSF}} = \alpha^{(2)} C_\ell^{e_{\rm PSF} \Delta M^{(4)}_{\rm PSF}} + \beta^{(2)} C_\ell^{\Delta e_{\rm PSF} \Delta M^{(4)}_{\rm PSF}} + \alpha^{(4)} C_\ell^{M^{(4)}_{\rm PSF} \Delta M^{(4)}_{\rm PSF}} + \beta^{(4)} C_\ell^{\Delta M^{(4)}_{\rm PSF} \Delta M^{(4)}_{\rm PSF}}.$$

mitigation strategies

1. model the PSF up to the fourth order moments and remove the effect
2. check the presence of systematics looking at the star - galaxy correlation
3. get ready for including additional nuisance parameters to be marginalised over

Covariance Matrix





Analytical vs Numerical

- Why going analytical
  - need to include Super Sample Covariance
  - hard to get the necessary resolution
  - avoiding an overwhelmingly lare number of simulations
- Why going numerical
  - need to validate analytical covariance matrix
  - include (residual) instrumental systematics
  - propagate non analytical sytematics

The Curse of Dimensionality

- Three different observables
  - angular power spectra (in harmonic space, top)
  - 2 – point correlation function (in configuration space, bottom)
  - COSEBIs (separating E and B modes)
- Data vector length
  - 5 – 10 – 13 tomographic bins
  - 20 – 30 multipole bins
  - 3x2pt (shear – shear, galaxy – galaxy, shear – galaxy)

Modeling the Signal: weak lensing

shear – shear

$$C_{ij}^{\gamma\gamma}(\ell) = \int_0^{z_h} \frac{W_i^{\gamma}(\ell,z)W_j^{\gamma}(\ell,z)}{H(z)f_K^2[r(z)]} P_{mm}(k_\ell,z)dz$$

shear – IA

$$C_{ij}^{\gamma I}(\ell) = \int_0^{z_h} \frac{W_i^{\gamma}(\ell,z)W_j^{IA}(\ell,z) + W_j^{\gamma}(\ell,z)W_i^{IA}(\ell,z)}{H(z)f_K^2[r(z)]} P_{mI}(k_\ell,z)dz$$

IA – IA

$$C_{ij}^{II}(\ell) = \int_0^{z_h} \frac{W_i^{IA}(\ell,z)W_j^{IA}(\ell,z)}{H(z)f_K^2[r(z)]} P_{II}(k_\ell,z)dz$$

ingredients

- source redshift distribution (and its systematics)
- matter – matter power spectrum (in the nonlinear regime)
- matter – matter power spectrum (in the baryon dominated regime)
- IA (intrinsic alignment) modeling for the associated power spectra

Modeling the Signal: clustering

galaxy – galaxy

$$C_{ij}^{gg}(\ell) = \int_0^{z_h} \frac{\mathcal{W}_i^g(z)\mathcal{W}_j^g(z)}{f_K^2[r(z)]H(z)} P_{gg}(k_\ell, z) dz$$

galaxy – mag

$$C_{ij}^{g\mu}(\ell) = \int_0^{z_h} \frac{\mathcal{W}_i^g(z)\mathcal{W}_j^\mu(\ell, z) + \mathcal{W}_i^\mu(\ell, z)\mathcal{W}_j^g(z)}{f_K^2[r(z)]H(z)} P_{mg}(k_\ell, z) dz$$

mag – mag

$$C_{ij}^{\mu\mu}(\ell) = \int_0^{z_h} \frac{\mathcal{W}_i^\mu(\ell, z)\mathcal{W}_j^\mu(\ell, z)}{f_K^2[r(z)]H(z)} P_{mm}(k_\ell, z) dz$$

ingredients

- lens redshift distribution (and its systematics)
- galaxy – galaxy power spectrum i.e. the galaxy bias in the nonlinear regime
- magnification bias modelling (luminosity only or size magnification too?)
- slope of the lens luminosity function and its dependence on redshift

Modeling the Signal: gal - gal lensing

gal – shear

$$C_{ij}^{\gamma g}(\ell) = \int_0^{z_h} \frac{\mathcal{W}_i^{\gamma}(\ell, z)\mathcal{W}_j^{g}(\ell, z)}{f_K^2[r(z)]H(z)} P_{mg}(k_\ell, z)dz$$

gal – IA

$$C_{ij}^{Ig}(\ell) = \int_0^{z_h} \frac{\mathcal{W}_i^{IA}(\ell, z)\mathcal{W}_j^{g}(\ell, z)}{f_K^2[r(z)]H(z)} P_{Ig}(k_\ell, z)dz$$

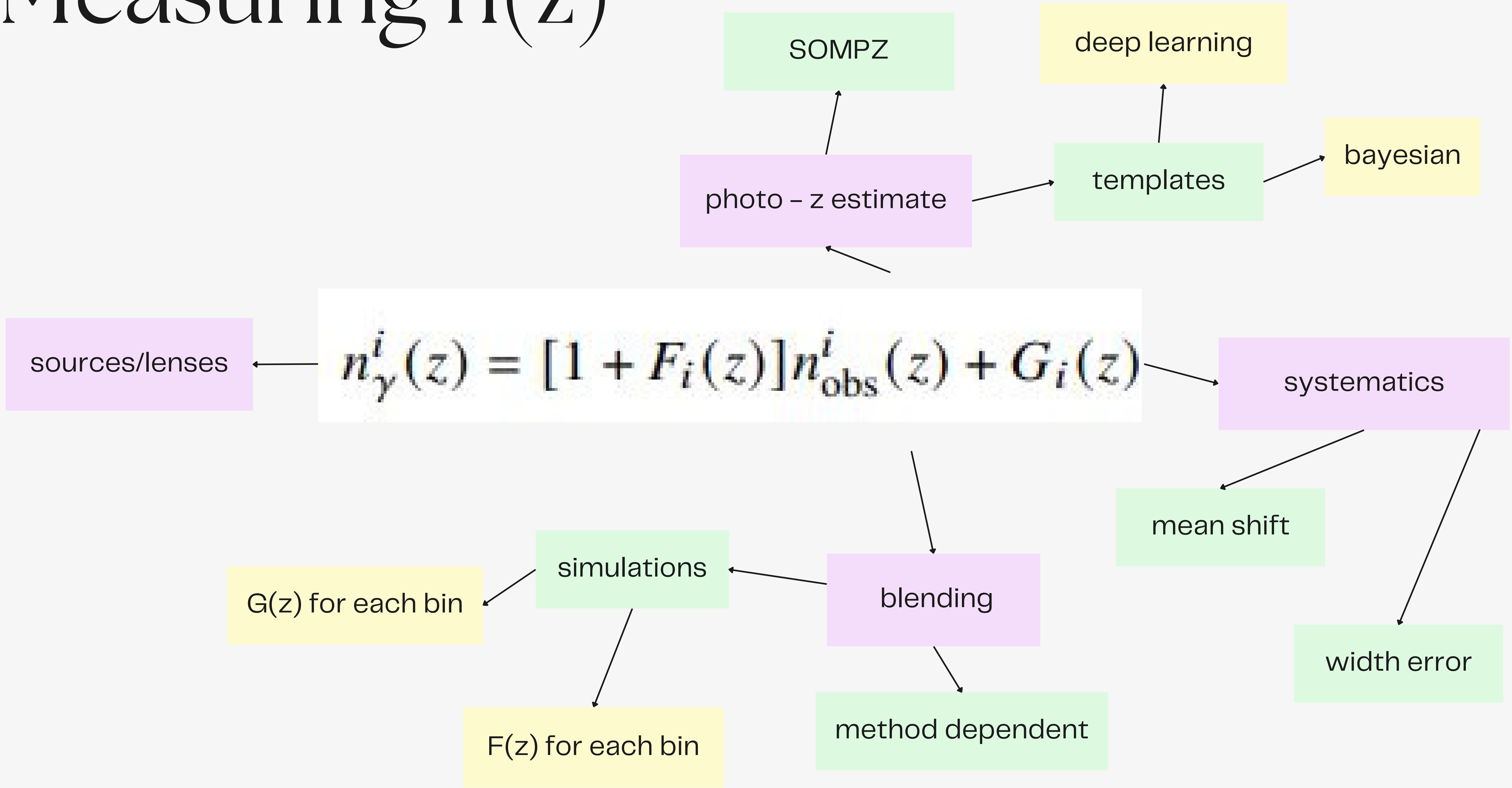
mag – shear

$$C_{ij}^{\gamma\mu}(\ell) = \int_0^{z_h} \frac{\mathcal{W}_i^{\gamma}(\ell, z)\mathcal{W}_j^{\mu}(\ell, z)}{f_K^2[r(z)]H(z)} P_{mm}(k_\ell, z)dz$$

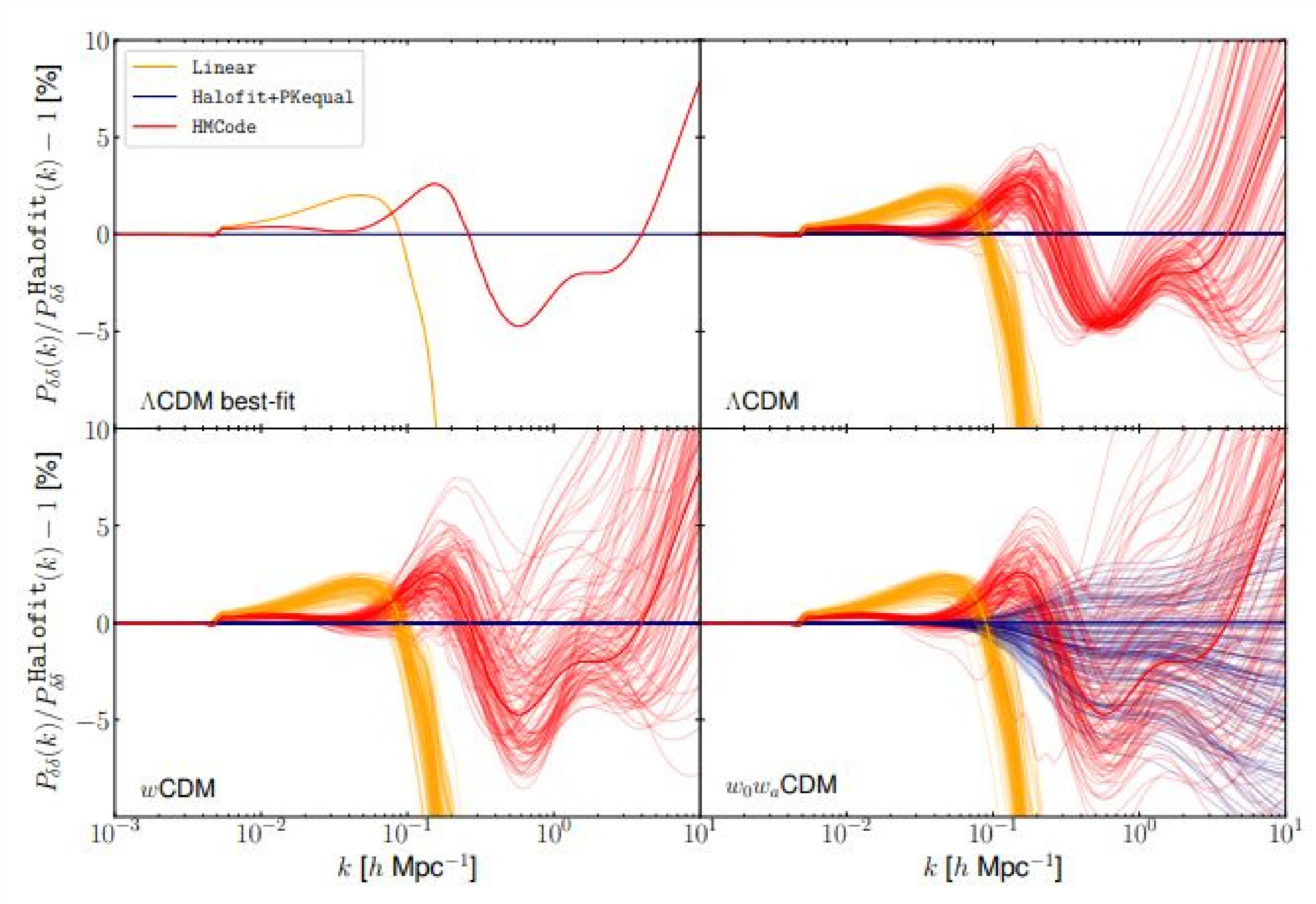
mag – IA

$$C_{ij}^{I\mu}(\ell) = \int_0^{z_h} \frac{\mathcal{W}_i^{IA}(\ell, z)\mathcal{W}_j^{\mu}(\ell, z)}{f_K^2[r(z)]H(z)} P_{mI}(k_\ell, z)dz$$

Measuring n(z)

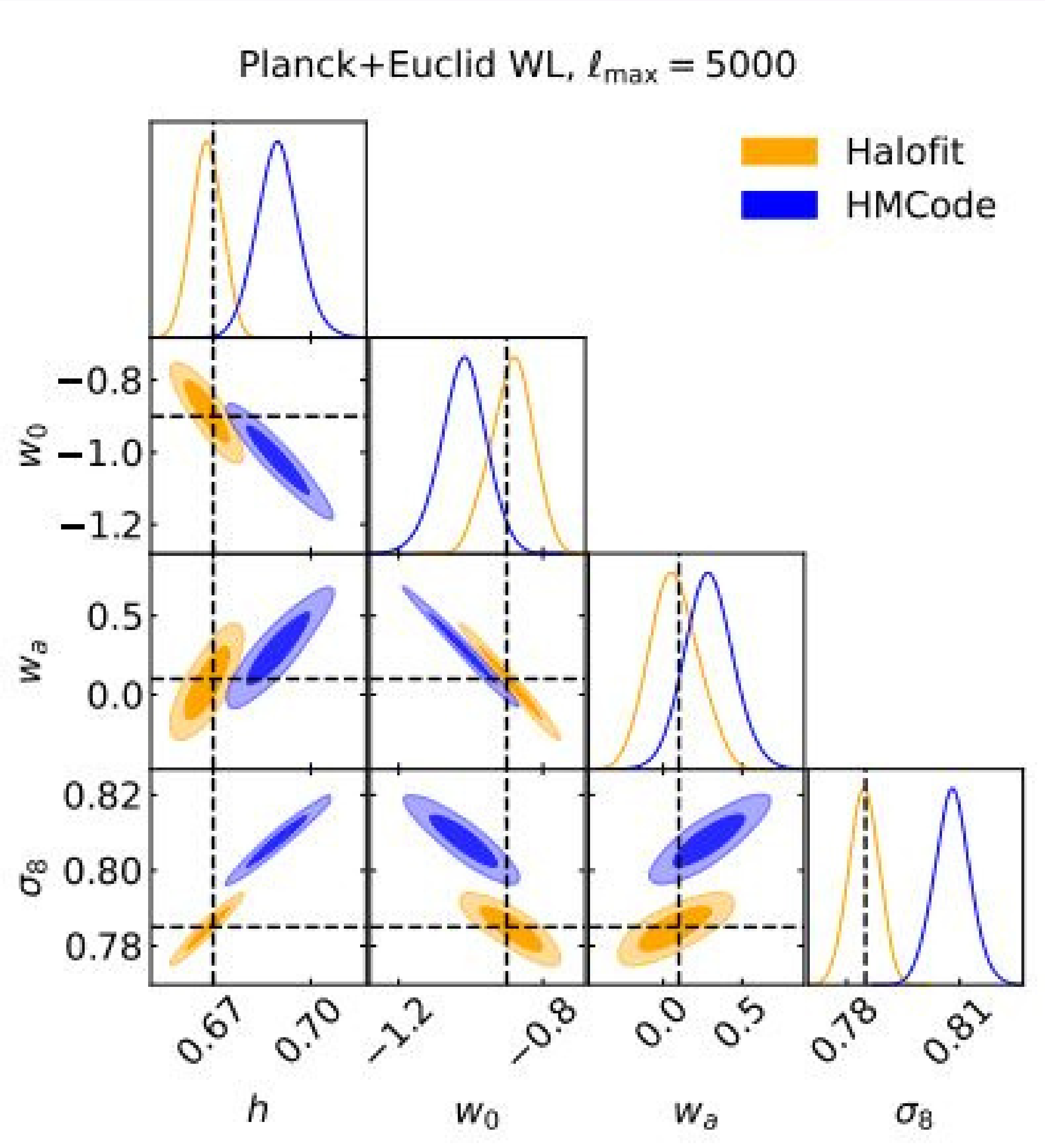


Matter power spectrum in the nonlinear regime



Need to model P(k,z) at large k

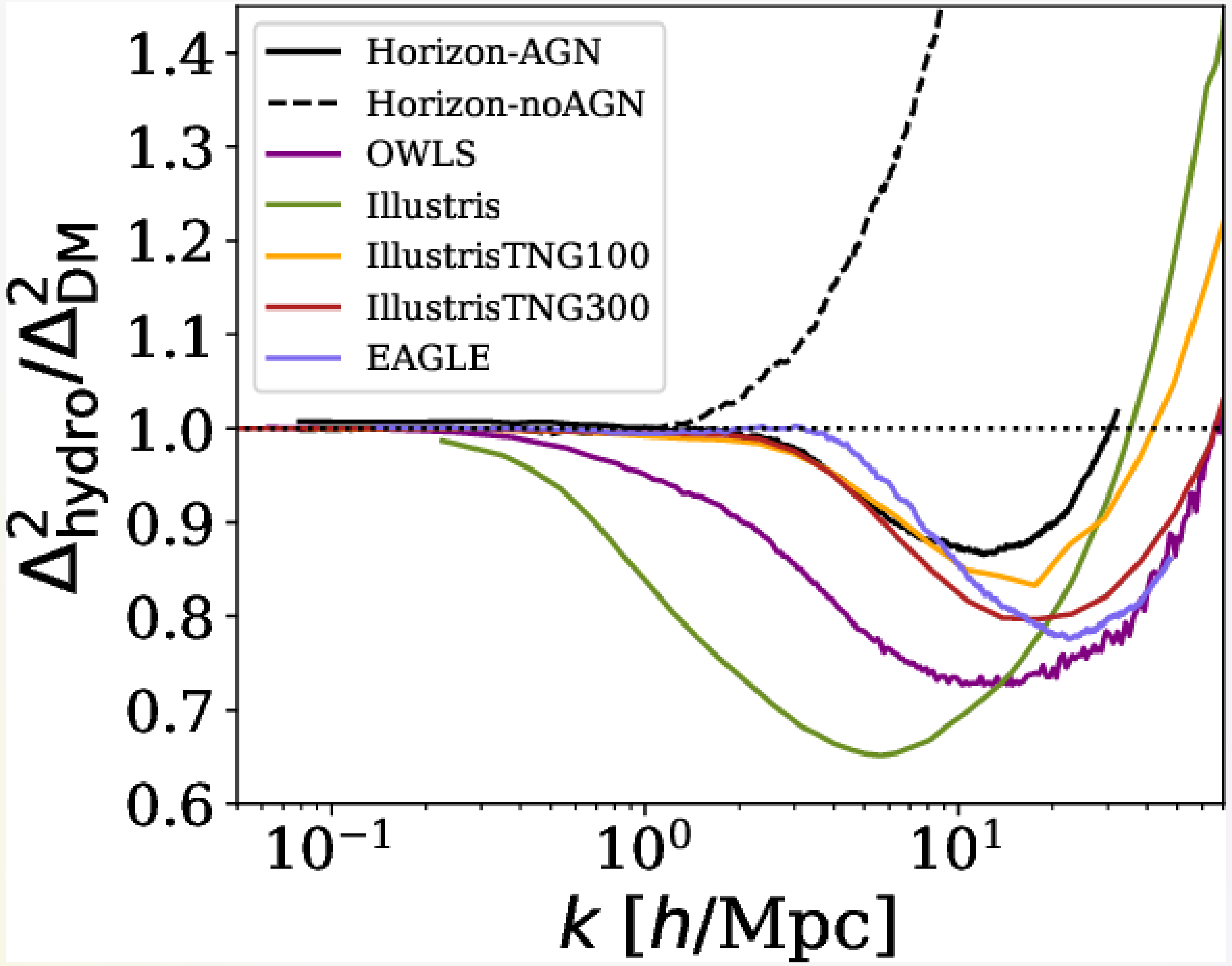
- different recipes available
  - TakaBird (Takahashi + Bird)
  - HMCode (2016 and 2020)
  - PkEqual
  - emulators (BACCO, EE2)
- disagreement among rival models
- need for high resolution simulations
- what about modified gravity?
  - few cases available (e.g., f(R) and JBD)
  - response based methods (e.g., ReACT)



Bias from incorrect modeling

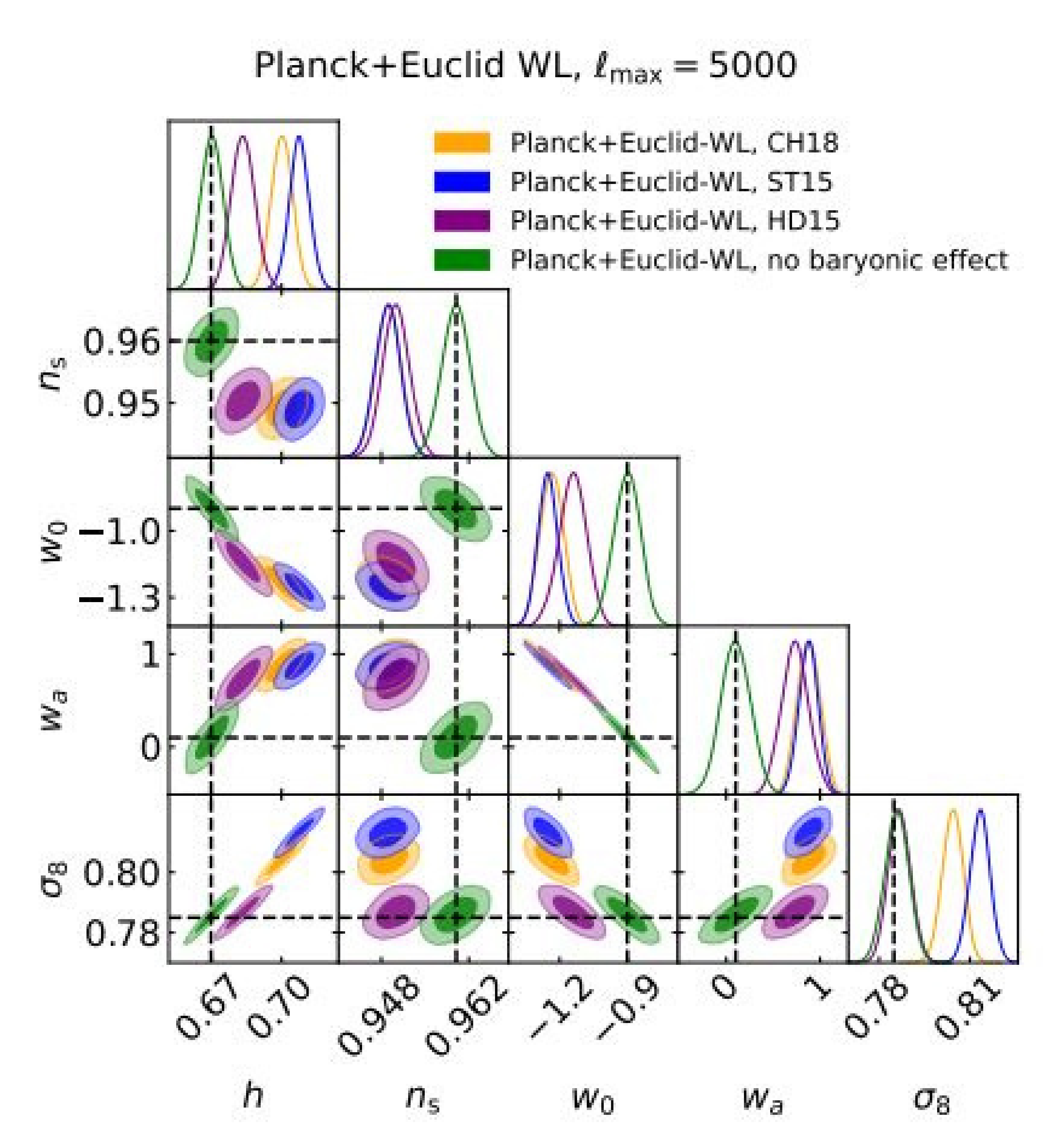
- Planck + Euclid
- mock with one model, fit with another
- strong bias on cosmological parameters
- larger for larger multipoles
- larger for larger constraining power

Matter power spectrum in the baryons regime



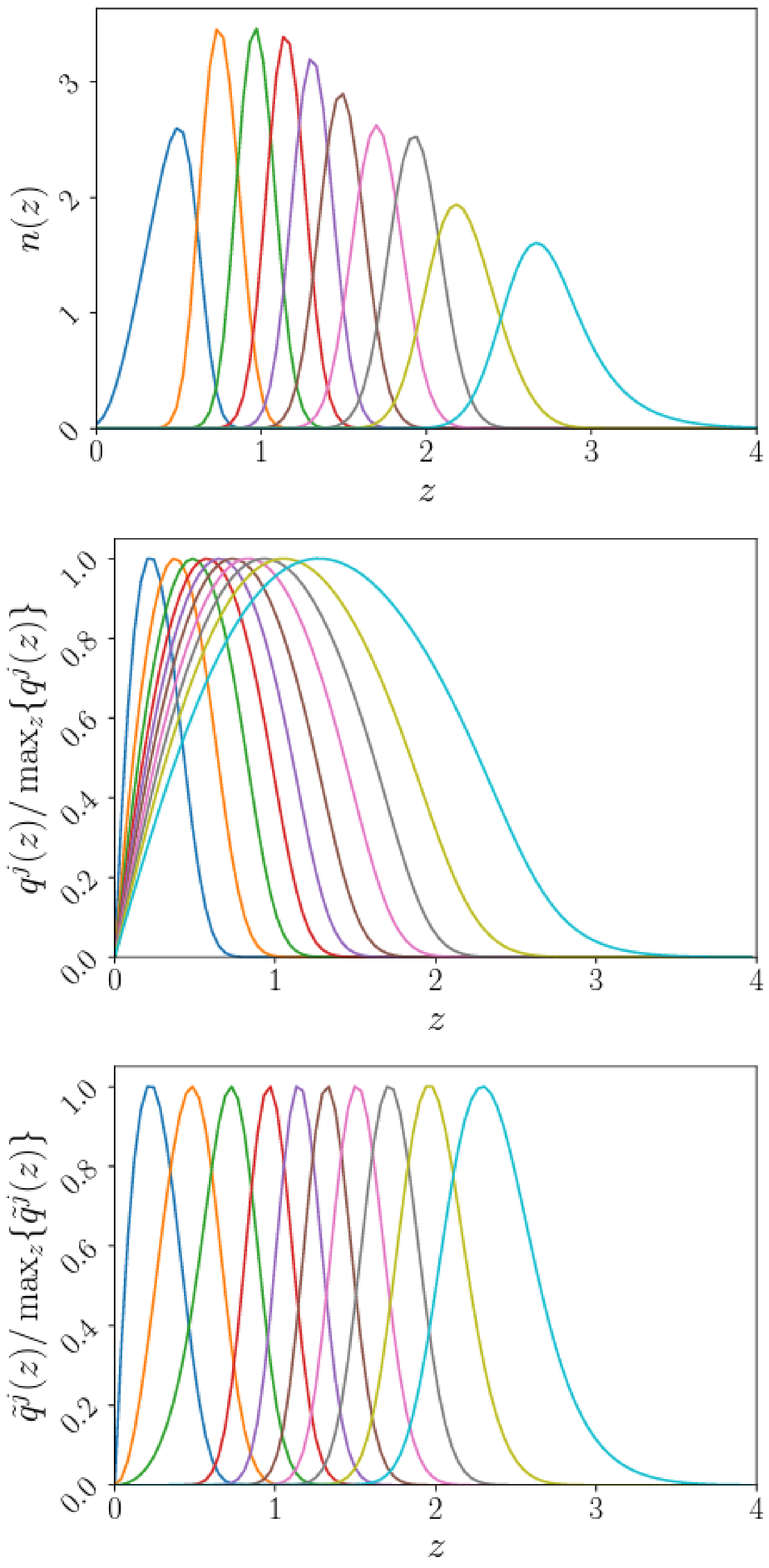
Need to model P(k,z) at galaxy scale

- different simulations available
- disagreement among simulations
- different recipes available
    - approximate correction formulae
    - emulators based approaches
    - baryon correction recipes
    - baryonification methods



Bias from incorrect modeling

- Planck + Euclid
- mock with one model, fit with another
- strong bias on cosmological parameters
- larger for larger multipoles
- larger for larger constraining power



Mitigating Nonlinear and Baryons Effects

Scale cuts

- Remove scales strongly affected by nonlinearities and baryons
- In practice: only fit data up to lmax(i, j) = kmax r(z, i, j)
- Bias under control but:
  - loss of constraining power
  - maximum k to be chosen in a model dependent way
  - still including contribution from k > kmax because of lensing kernel

BNTtransform

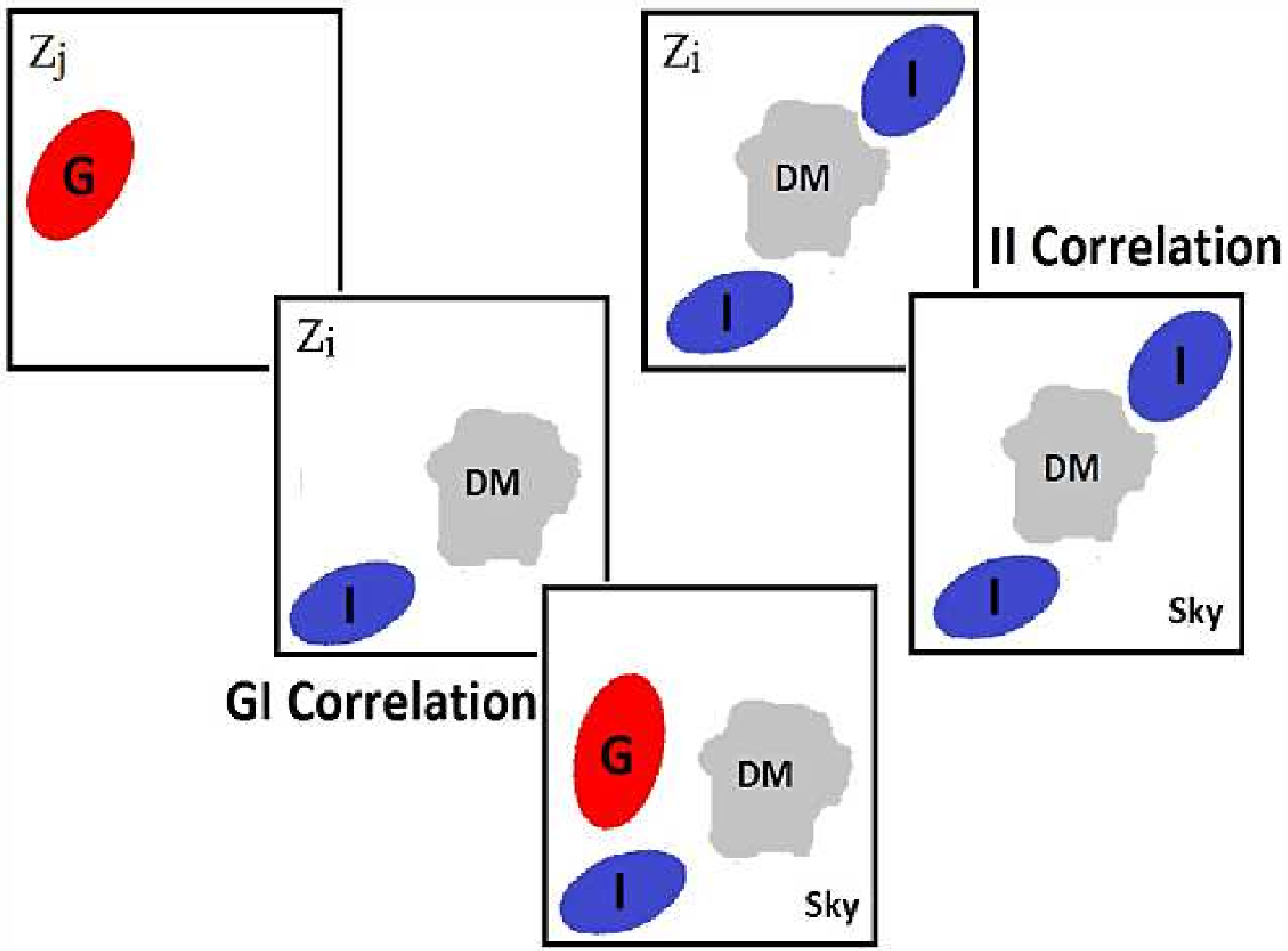
- Perform a linear transformation of the source n(z)
  - lensing efficiency kernels less superimposed
  - cleaner removal of nonlinear scales when doing scale cuts
  - to be applied on both data vector, covariance, and theory
- improving scale cuts
  - redefine the way scale cuts are estimated hence allowing for larger kmax
  - recovering some of the signal hence lower loss of constraining power

Intrinsic Alignment

- galaxies are not randomly oriented
- correlation between galaxy ellipticities
- correlation with shear

IA Modeling

- eNLA: extendend nonlinear linear alignment
  - proportional to matter power spectrum
  - redshift and lum dependent amplitude
  - same for all galaxies
- TATT: tidal alignment and tidal torquing
  - tidal alignment for elliptical galaxies
  - tidal torquing for spiral galaxies
  - sums of three different terms
  - redshift dependent amplitudes



$$A_1(z) = -a_1 \bar{C}_1 \frac{\rho_{\rm crit}\Omega_{\rm m}}{D(z)} \left(\frac{1+z}{1+z_0}\right)^{\eta_1}$$

$$A_2(z) = 5 a_2 \bar{C}_1 \frac{\rho_{\rm crit}\Omega_{\rm m}}{D(z)^2} \left(\frac{1+z}{1+z_0}\right)^{\eta_2}$$

$$A_{1\delta}(z) = b_{\rm ta} A_1(z)\,,$$

You can hit me all day long, but I'm never giving up on my dream

Monkey D. Luffy

Never giving up on WL dream

Challenge	Solution
• **Data** ◦ PSF reconstruction ◦ shape measurement ◦ shear calibration ◦ photo – z determination • **Covariance** ◦ super sample covariance for 3x2pt ◦ curse of dimensionality • **Theory** ◦ nonlinear modeling at large k ◦ bias from incorrect recipe ◦ IA modeling	• **Data** ◦ accurate modeling and stable PSF ◦ LensMC, MetaCalibration, ReGauss ◦ fast and realistic image simulations ◦ SOMPZ and other methods • **Covariance** ◦ better understanding of approximations ◦ speeding up numerical codes • **Theory** ◦ fast and accurate emulators ◦ BNT for clean scale cuts ◦ priors from simulations and observations

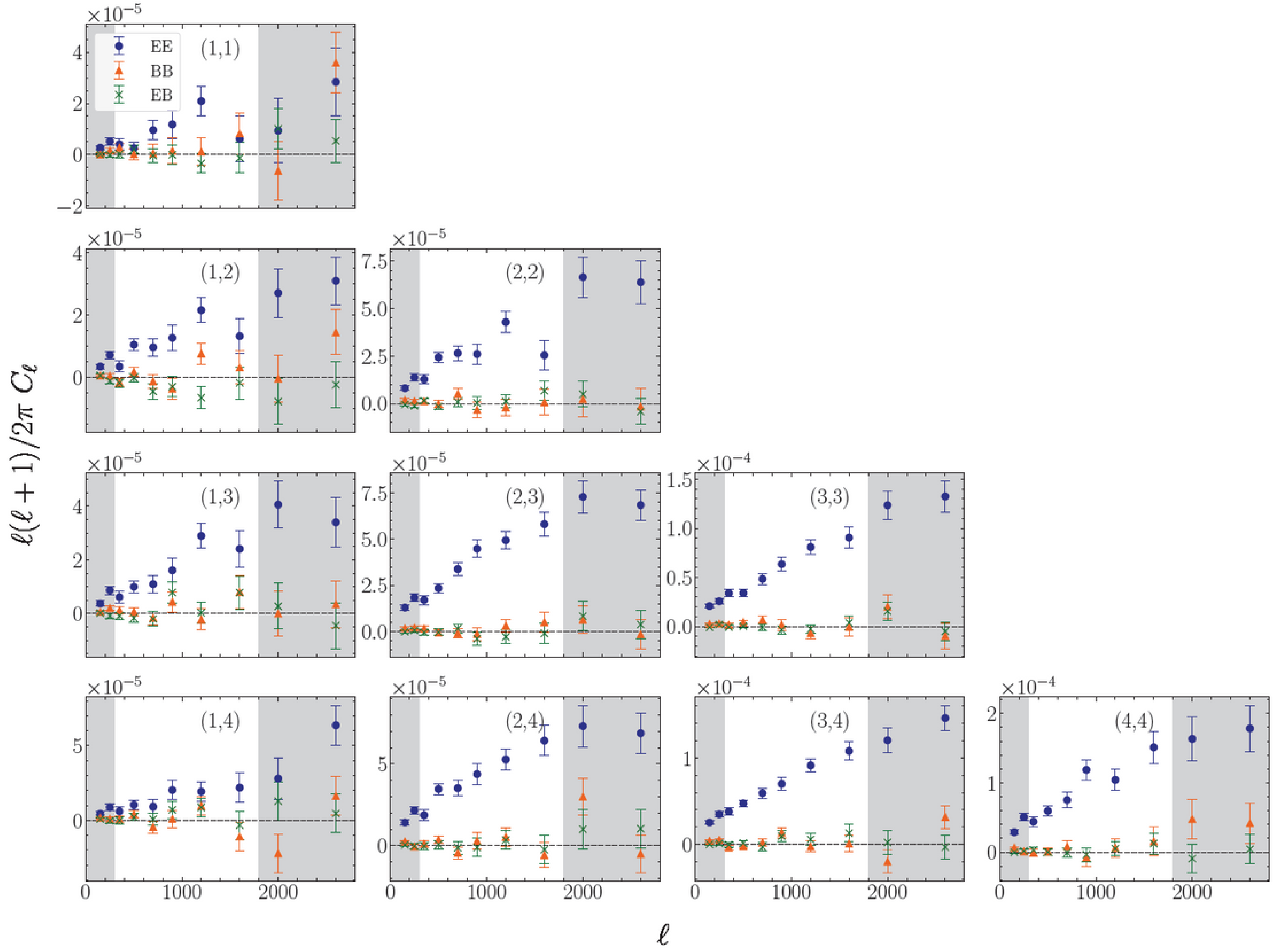
Parameters

Minimalist model (for Euclid like dataset)

- cosmoloy: 7
- galaxy bias: 4 – 13
- magnification: 4 – 13
- IA modelling: 2 – 5
- photo – z mean shift: 13 (+ 13?)
- shear multiplicative bias. 13
- baryon correction: 1 – 6

Total Number of Parameters: 31 – 70

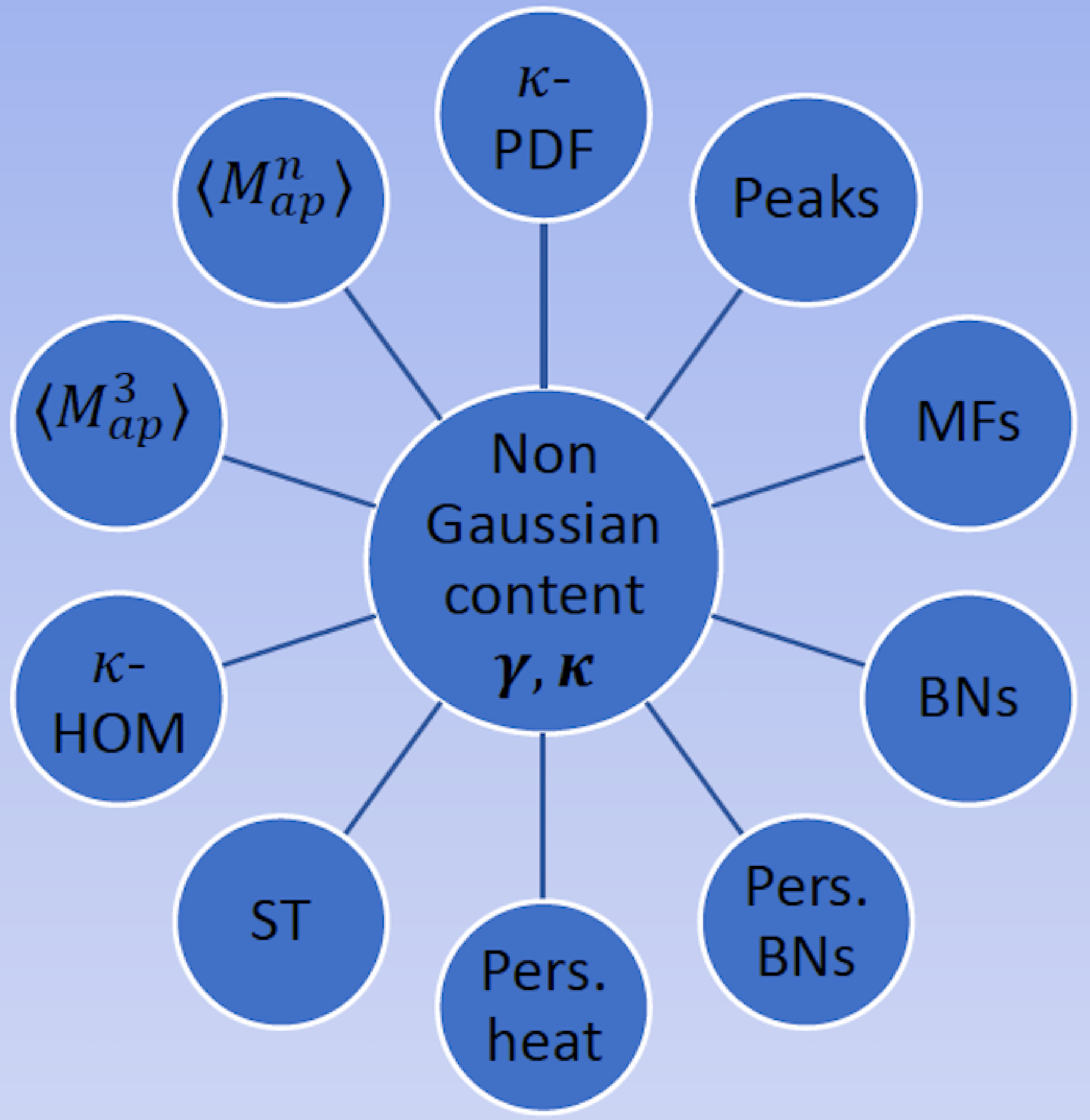
- dominated by nuisance parameters
  - slow convergence of MCMC
  - fiducial values from simulations
  - priors to reduce degeneracy
  - loss of constraining power



Tomography Angular Power Spectra as measured from HSC data in four redshift bins

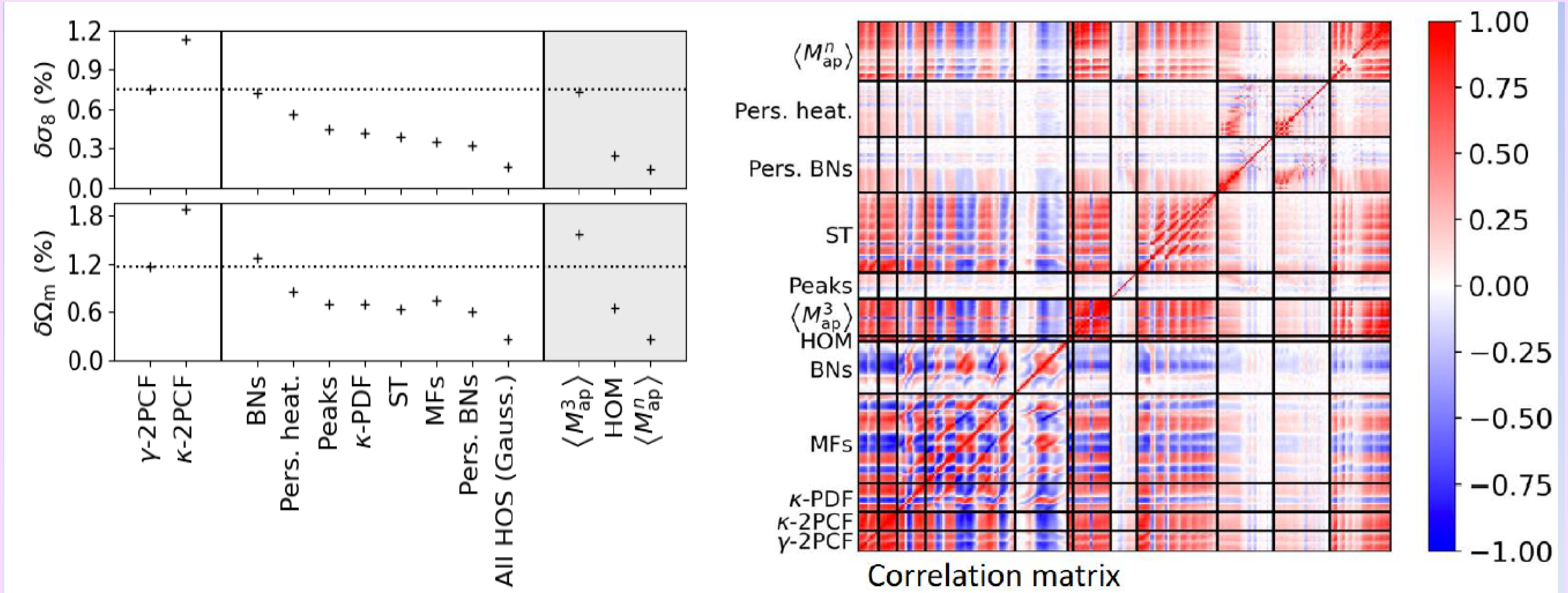
Additional WL Power - High Order Statistics

- **HOWLS** → **Euclid key project** → designed **to extract non-gaussian cosmological information** of the future Euclid lensing data → currently counting 10 different HOS



Shear two-point correla-tion functions (**γ-2PCF**)	Convergence two-point correlation function (**κ-2PCF**)	Convergence one-point probability dis-tribution (**κ-PDF**)
Convergence Minkowski functionals (**MFs**)	Convergence Betti numbers (**BNs**)	Aperture mass peak counts (**peaks**)
Higher-order convergence moments (**HOM**)	Third order aperture mass moments ($\langle \boldsymbol{M_{ap}^3} \rangle$)	n-th order aperture mass moments ($\langle \boldsymbol{M_{ap}^n} \rangle$)
Aperture mass persistent homology Betti numbers (**pers. BNs**)	Aperture mass persistent homology heatmap (**pers. heat.**)	Convergence scattering transform coefficients (**ST**)

Additional WL Power - High Order Statistics



Get Ready for Making Dreams Come True