Systematic error budget in Euclid galaxy clustering

Santiago Avila
on behalf of the Euclid GC systematics error budget Tiger Team

ESAC, Madrid - 23th April 2018

UNIVERSITY OF PORTSMOUTH

ICG Portsmouth

Euclid consortium

Simulations to assess and mitigate the systematic error budget of Euclid

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Group members

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Tiger team charge:

- We were asked…
  - To identify all components of the systematic error budget,
  - If possible, to estimate these factors and if not, write down a clear path to successfully estimating them.
  - To compare the expected level of syst. vs. statistical errors.
- Focused on anisotropic two-point statistics:
  - BAO-only measurements post-reconstruction (BAO).
  - Full-shape pre-reconstruction (RSD fits).

$$\theta = (\alpha_\perp, \alpha_\parallel, f\sigma_8)$$

Systematics tiger team report:

- We have produced an ongoing report
- Planned to be submitted as a review soon
- Focus on listing all components and proposing how to estimate their impact.
- Identify which Euclid group should provide a final estimate.

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Report of the Galaxy Clustering Systematic Error Budget Tiger Team

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Issue:	0
Date:	October 5, 2017
Authors:	S. Avila, C. Carbone, M. Crocce, S. de la Torre, V. Desjacques, A. Ealet, D. J. Eisenstein, G. Favole, B. Granett, J. Koda, M. Lippich, P. Monaco, A. Pezzotta, J. Pollack, A. Sánchez
Authorised by:	This document is under the custodianship of the Systematic Error Budget Tiger Team of the Euclid GC SWG.

Abstract: *This document contains a description of the systematic error budget of Euclid galaxy clustering measurements.*

Document Change History

Title: *Report of the Galaxy Clustering Systematic Error Budget Tiger Team*			
Issue	**Rev.**	**Date**	**Reason for Change**
Draft 1	1	2017-10	First complete version

Potential sources of syst errors

$$P(\theta|\mathbf{D}) = \frac{\mathcal{L}(\mathbf{D}|\theta)\ P(\theta)}{P(\mathbf{D})}$$

There are three possible sources of systematic errors:

- Data: treatment of the data to obtain galaxy clustering measurements.
- Theory: the models used to compute predictions as a function of the cosmological parameters.
- Likelihood: the assumptions made to link theory and observations.

Potential sources of syst errors

Data systematics:

- Photometric calibration
- Milky way dust
- Sky brightness
- Sample selection
- Redshift errors and confusion
- Clustering estimators

Theory systematics:

- Non-linear evolution
- Redshift-space distortions
- Galaxy bias
- Baryon-CDM / Neutrinos
- Light-cone effects
- Reconstruction

Likelihood systematics:

- Propagation of noise in C
- Biased estimates of C
- Cosmology dependence of C
- Combination of results

Classifying systematic errors

- Comparison of expected levels of syst. vs. statistical errors.
- We classify the different components according to
  - Small: $\sigma_{\mathrm{sys}}/\sigma_{\mathrm{stat}} < 0.2$
  - Medium: $0.2 < \sigma_{\mathrm{sys}}/\sigma_{\mathrm{stat}} < 0.45$
  - Large: $\sigma_{\mathrm{sys}}/\sigma_{\mathrm{stat}} > 0.45$
- Motivation: if one naively combines stat. and syst errors as

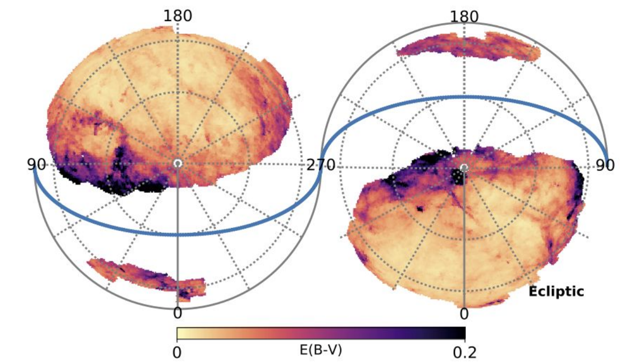
$$\sigma_{\mathrm{tot}}^2 = \sigma_{\mathrm{sys}}^2 + \sigma_{\mathrm{stat}}^2$$

these limits correspond to an increase of σ_{tot} by 2% and 10%.

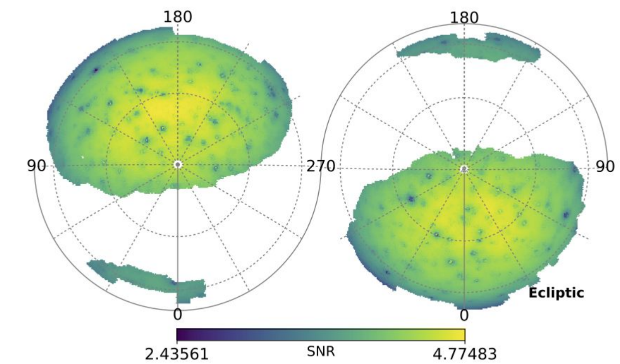
Data systematics

- Flux limit
  - NIR YJH photometric detection limit
  - Spectrophotometric calibration error
  - Foreground extinction
  - Luminosity-dependent bias couples flux limit with clustering signal

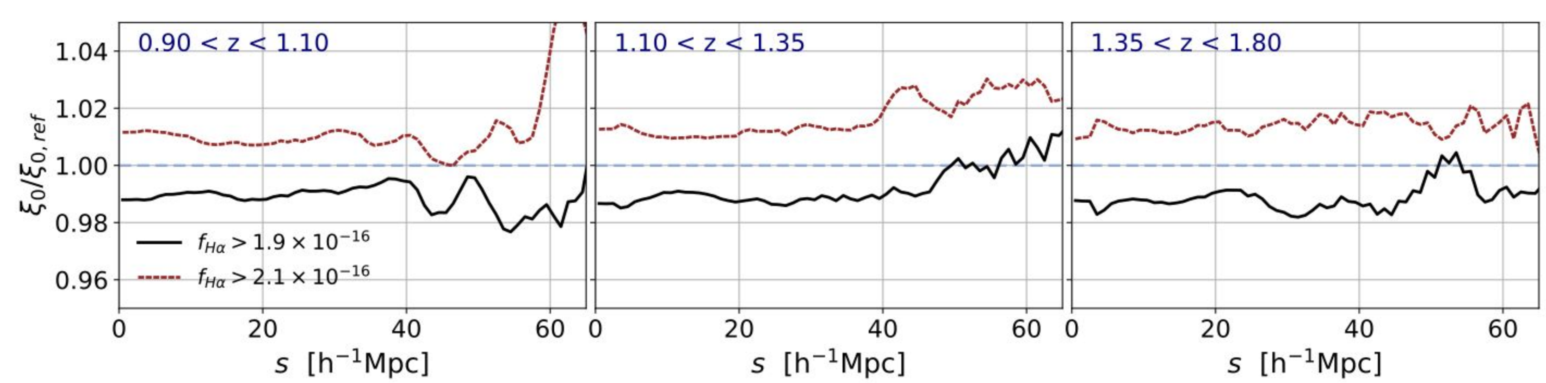
E(B-V) map



Halpha line SNR map (stray light and zodi)



Flagship v1.3.2: Monopole correlation function with varying Halpha flux limit (+- 5%)



BAO: small
RSD: small

Data systematics

- Obscuration
  - Uncorrelated with LSS:
    - Foreground stars, galaxies
    - Zeroth-order images
    - Persistent images
  - Correlated with LSS
    - Galaxies in target redshift range, zeroth-order images, persistence

🟢 **BAO: small**
🟢 **RSD: small**

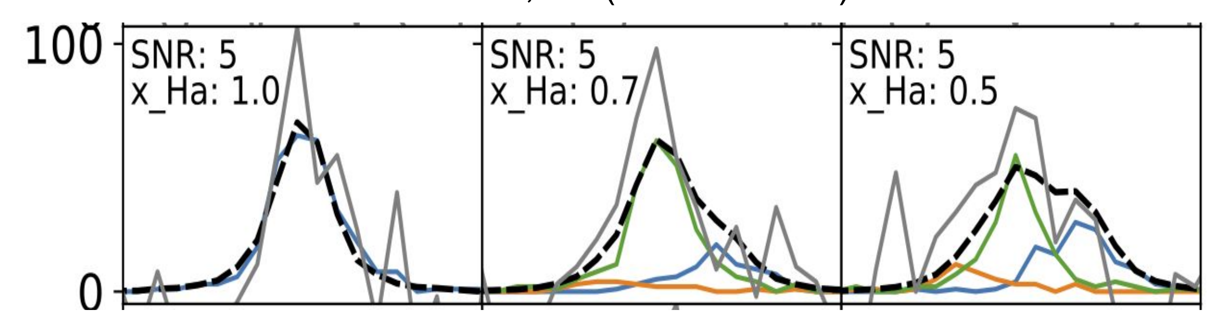
Data systematics

- Redshift error
  - Measurement error potentially correlated with density field
  - Non-Gaussian PDF
  - Wavelength calibration

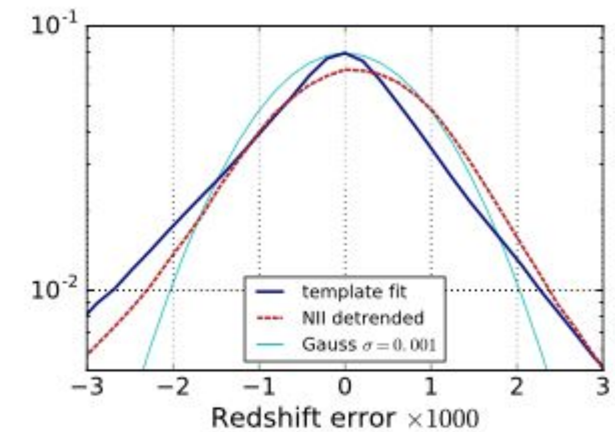
  - Preliminary study on parameter constraints started

BAO: small
RSD: medium

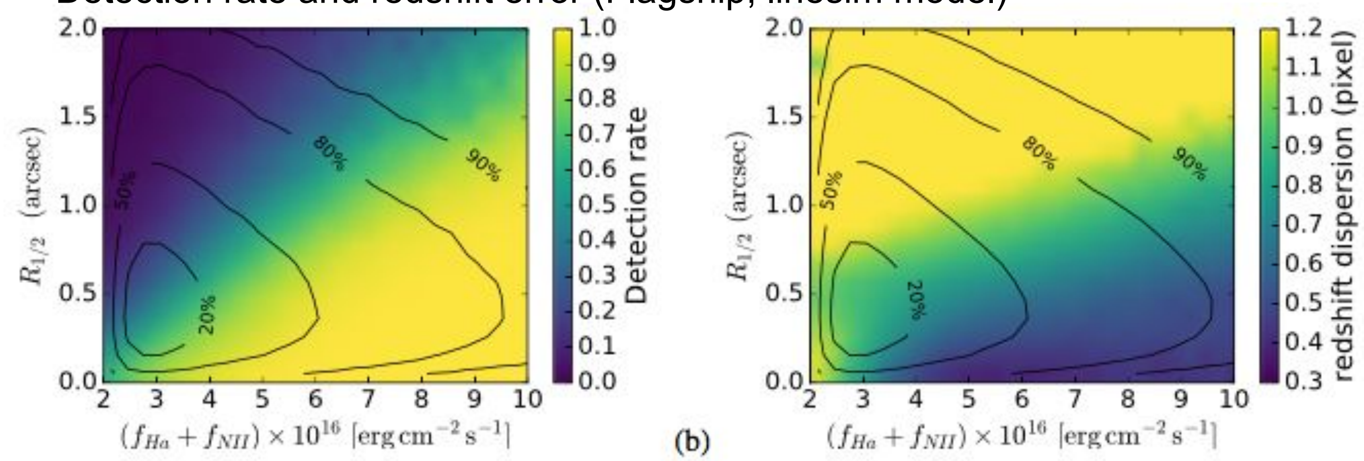
Linesim model blend: Ha, NII (medium SNR)



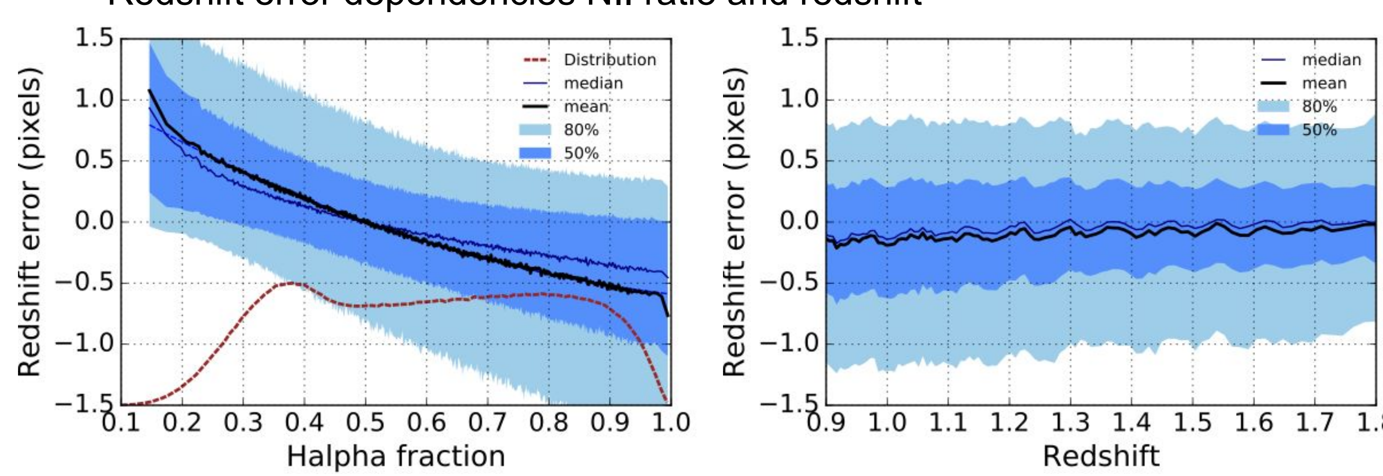
Redshift error PDF
(Flagship, linesim model)



Detection rate and redshift error (Flagship, linesim model)



Redshift error dependencies NII ratio and redshift



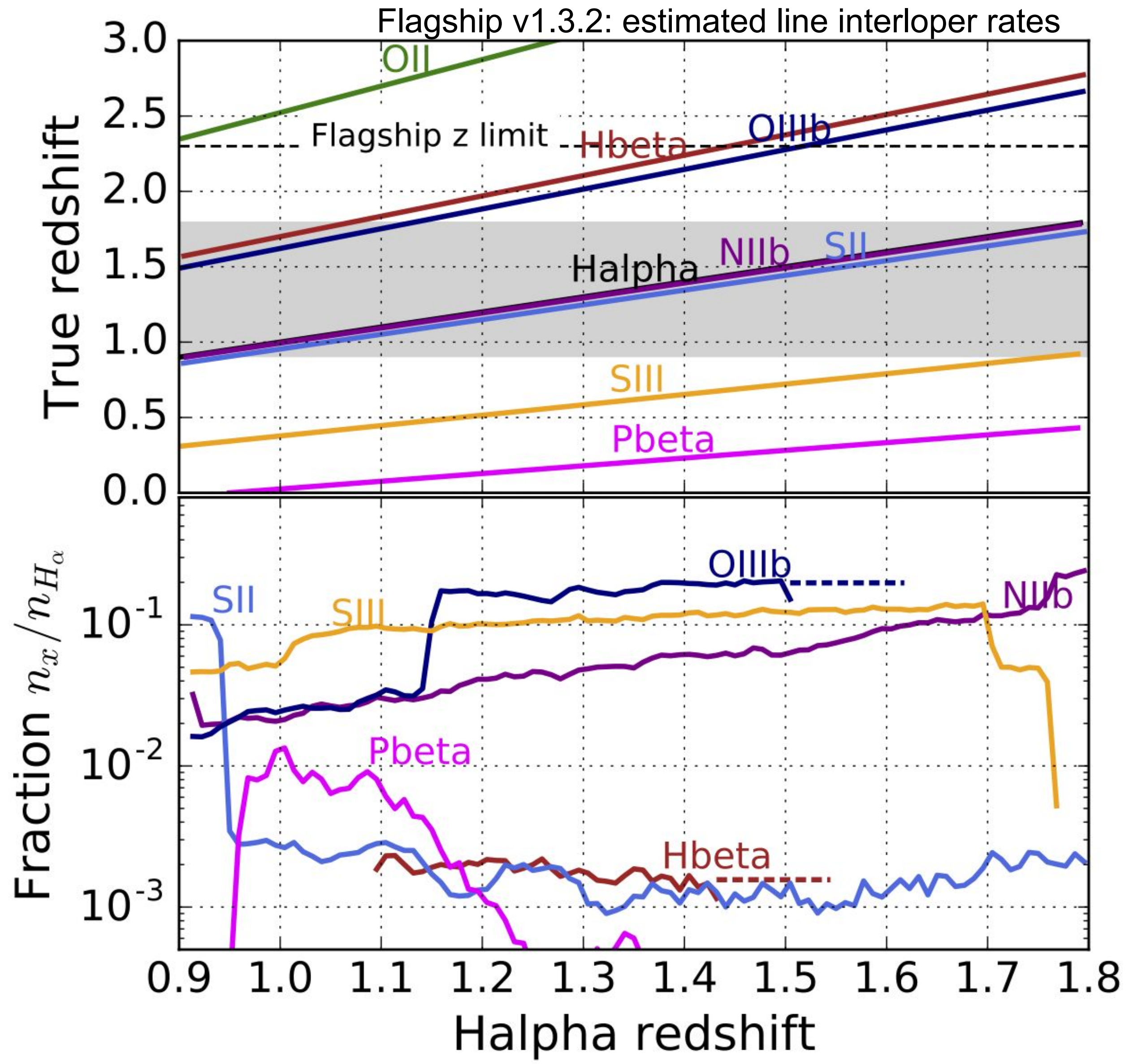
Data systematics

- Line misidentification (Redshift error)
  - Modify the signal:

$$P_{\rm obs}(k,\mu,z_{H\alpha}) = (1-\Sigma_i f_i)^2 P_{H\alpha}(k,\mu,z_{H\alpha}) + \sum_i f_i^2 \gamma_{\perp,i}^2 \gamma_{\parallel,i} P_{\rm cont}(q(k,\mu),\mu_q(\mu),z_{{\rm cont},i})$$

  - Can be corrected for if we now the fraction of interlopers and their bias.
  - But any uncertainty in those, will propagate to an uncertainty in P(k)
  - Photo-z prior crucial.

    (Wong et al 2016, Pullet et al 2016)



BAO: small
RSD: small

Data systematics

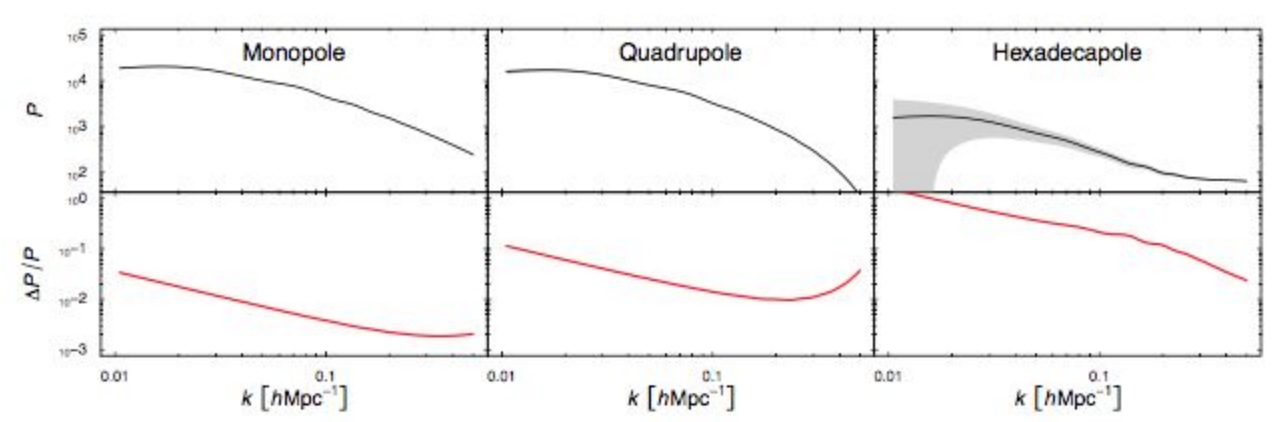
- Confusion
  - Reduced detection efficiency in crowded fields
  - Undersampled density peaks reduce clustering amplitude on large scales
  - Loss of pairs on small scales
  - Affects angular modes, leaks into LOS

BAO: unknown
RSD: unknown

Data systematics

- Estimators
  - 2pt correlation function multipoles
  - Power spectrum multipoles
  - Wide-angle effects

Flagship v1.3.2: Estimator error budget for power spectrum multipoles



BAO: small
RSD: small

Data systematics

- Quantities to measure from Deep and Wide to control systematics
  - Halpha luminosity function (redshift, density dependence)
  - Number density of interloper populations (OIII, Hbeta, OII, SIII)
  - Linear bias of samples (Halpha, OIII, Hbeta)
  - Confusion / slitless effects

Theory systematics

- Dark matter nonlinear evolution
- Redshift space distortions
- Galaxy density / velocity / assembly bias
- Relative Baryon-CDM fluctuations
- Massive neutrinos
- Light-cone & projection effects
- Reconstruction

Theory systematics

- BAO: medium
- RSD: large

- Dark matter nonlinear evolution

  - Much work over past years (probably the best understood)
  - Different publicly available codes, we might want a uniform validation of all of them
  - Additional calibration against N-body simulations may be necessary to achieve required accuracy

Theory systematics

BAO: small
RSD: large

- Redshift space distortions
- Galaxy density / velocity / assembly bias

- Minimal bias+RSD model includes 7 [z-dependent] parameters.
- Essential to test its validity & explore its extensions
- Perform blind tests of various bias+RSD models using mocks in periodic boxes [beware of degeneracies]

- Define how mocks trace assembly / velocity bias
- These may require further exploration with hydro simulations

Theory systematics

- Relative baryon-CDM fluctuations

BAO: small ?
RSD: small ?

  - Magnitude of these effects is uncertain.
  - Assess whether we can mitigate them using PS alone / PS+bispec / etc. / measurements
  - Further tests with hydrodynamical simulations ?
  - Open problem in the literature

Theory systematics

BAO: small
RSD: large

- Massive neutrinos
  - Well understood, but most numerical / analytical implementations make approximations
  - Perform blind tests of various bias+RSD implementations of massive neutrinos using "periodic mocks"
  - Ultimate test (neutrino sims with galaxies from SAM or HOD etc) still needed

Theory systematics

- BAO: small ?
- RSD: small ?

- Light-cone & other projection effects (RSD excluded)

  - Most projection effects (lensing etc.) can be predicted within linear perturbation theory
  - Can be corrected for if the survey window function / galaxy luminosity function are well understood.
  - Perform tests using realistic "light-cone mocks" generated with Fast Dynamical Approximations

Theory systematics

BAO: large
RSD: none

- Reconstruction
  - Test the sensitivity of BAO reconstruction to the choice of "internal" parameters (smoothing, displacement etc.), the survey window function etc.
  - Perform blind reconstruction tests using "periodic mocks" (explore sensitivity to bias) and "light-cone mocks" (explore sensitivity to survey mask etc.)

Likelihood systematics

- Incorrect propagation of the noise in the covariance matrix
- Biased estimates of the covariance matrix
- Cosmology dependence of the covariance matrix
- Incorrect shape of the likelihood function
- Combination of results from multiple statistics

Likelihood systematics

- Incorrect propagation of the noise in the covariance matrix
  - Covariance matrices usually estimated from N_s mocks
  - The noise in C increases the final uncertainties

$$\frac{\sigma_{\rm extra}}{\sigma_{\rm ideal}} \simeq \frac{(N_{\rm b} - N_{\rm p})}{2\,(N_{\rm s} - N_{\rm b})} < 0.1$$

  - For standard BAO & RSD analyses: $N_b = 84$, 10 z-shells

$$\sigma_{\rm extra} < 0.1\sigma_{\rm ideal} \rightarrow N_{\rm s} \approx 450$$
$$\sigma_{\rm extra} < 0.02\sigma_{\rm ideal} \rightarrow N_{\rm s} \approx 1900$$

  - Joint fit of all z-shells would require $N_s = 4\,000$ (20 000).

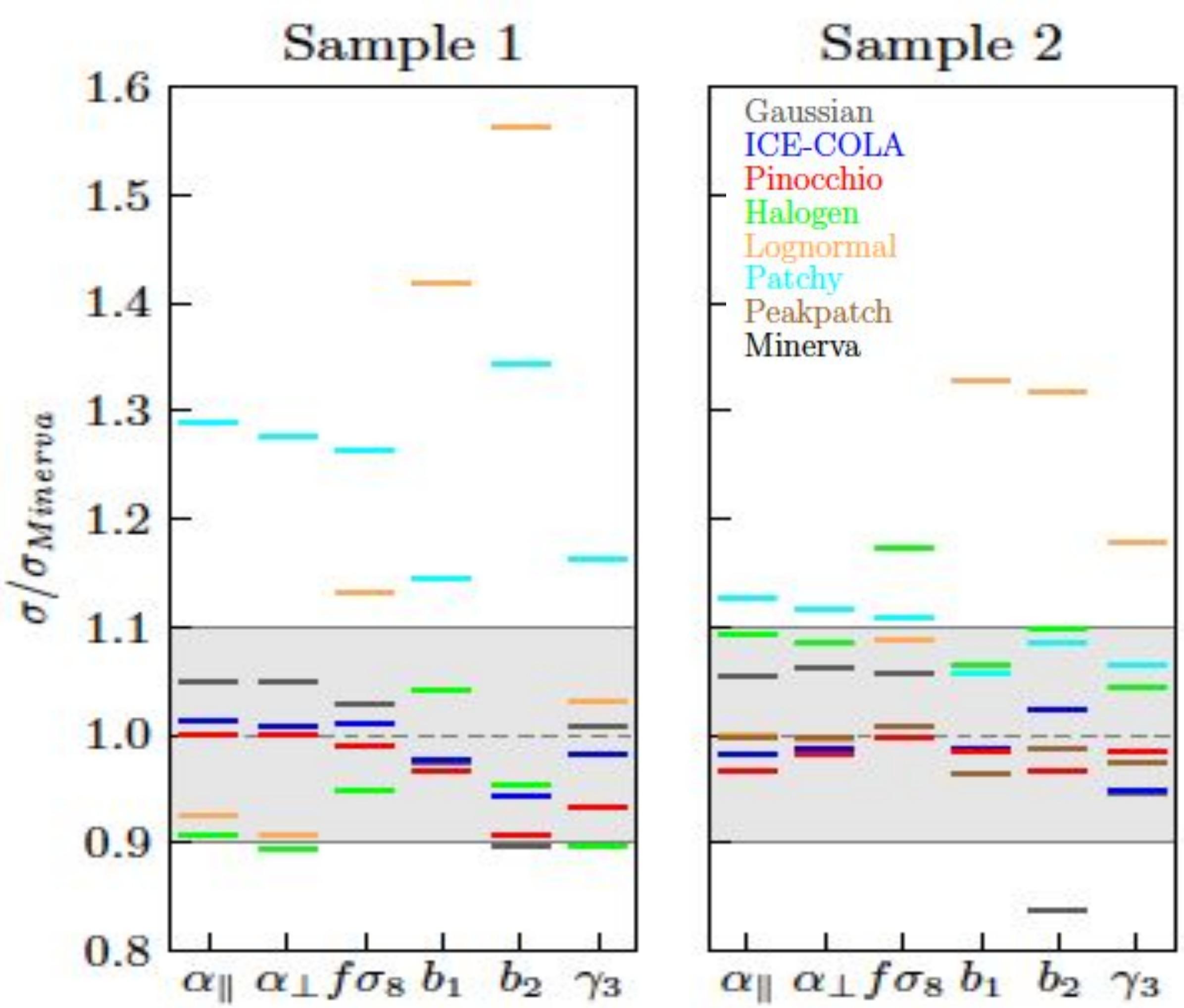
Likelihood systematics

- Incorrect propagation of the noise in the covariance matrix
  - **Action:** Need to review these estimates based on Sellentin & Heavens (2017).
  - **Mitigation strategies:** multiple methods can minimize the impact of the noise in **C**, reducing the required N_s
  - The noise in **C** is likely to be a sub-dominant part of the total systematic error budget.

BAO: small
RSD: small

Likelihood systematics

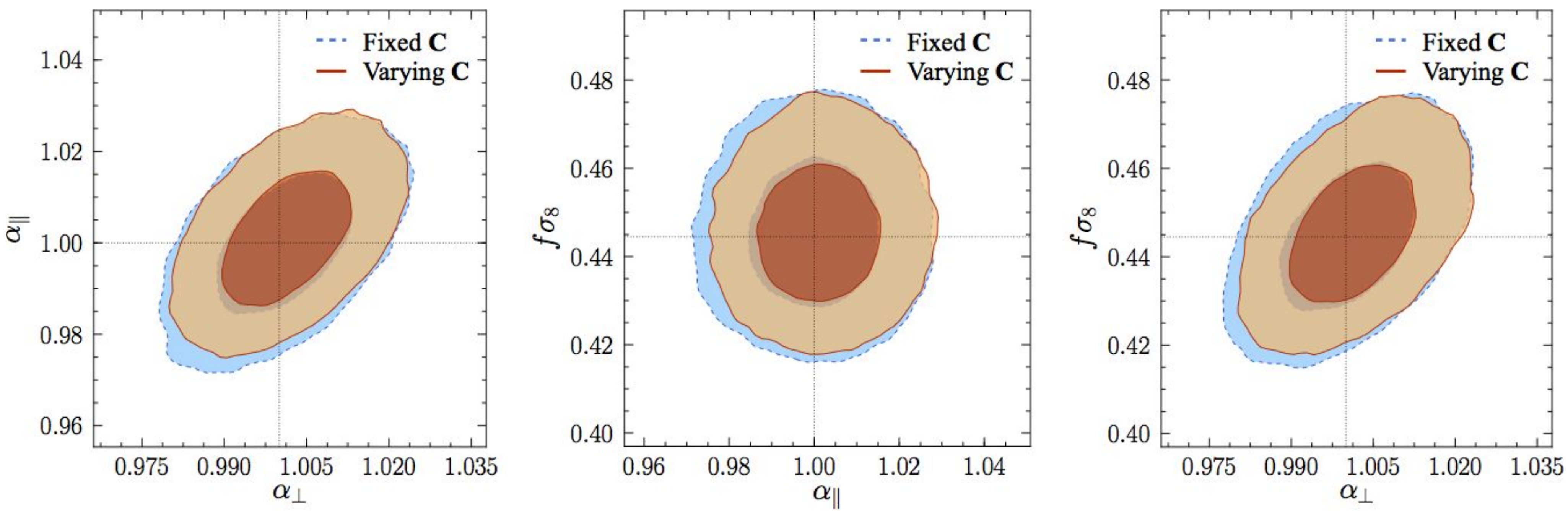
- Biased estimates of **C**
  - Covariance estimates will likely rely on approximate N-body methods.
  - Need to test the accuracy or these estimates.
  - On-going comparison of N-body and approximate methods



BAO: small-med?
RSD: small-med

Likelihood systematics

- Cosmology dependence of **C**
  - The covariance matrix is commonly kept fixed.
  - Impact of varying **C**(**θ**) can be tested using synthetic data.



  - In this case, the 68% CL on $\alpha_{per,par}$ are 5% smaller when C is varied, for $f\sigma_8$ the difference is 10%.

Likelihood systematics

- Cosmology dependence of **C**
  - The cosmology dep. of C has an impact on the constraints.
  - Challenging to estimate **C**(θ) using only mock catalogues.
  - Highlights the importance of developing accurate, fast to evaluate, models of **C**.
  - Alternative: modify *L* so that it can be computed using a fixed **C** (e.g. Hamimeche & Lewis 2008, Kalus et al. 2016).

BAO: small?
RSD: small-med

Likelihood systematics

- Incorrect shape of the likelihood function
  - The likelihood function is assumed to be Gaussian

$$-2\ln \mathcal{L}(\boldsymbol{D}|\boldsymbol{\theta}) = \left(\boldsymbol{D} - \boldsymbol{T}(\boldsymbol{\theta})\right)^{t} \boldsymbol{\Psi} \left(\boldsymbol{D} - \boldsymbol{T}(\boldsymbol{\theta})\right),$$

  - The propagation of the noise in **C**, or the use of a fixed **C** might require to use non-Gaussian *L*.
  - These recipes assume that the underlying *L* is Gaussian.
  - **Action:** study the posterior dist. inferred from sets of N-body simulations and mock catalogues (ongoing).
  - Impact: currently unknown

BAO: unknown
RSD: unknown

Likelihood systematics

- Combination of results from multiple statistics
  - BAO & RSD constraints often described in terms of

$$D_{\mathrm{M}}(z)/r_{\mathrm{d}},\ H(z)r_{\mathrm{d}},\ f\sigma_8$$

  - Several results can be combined into a set of *consensus constraints* (e.g. Sánchez et al. 2017).
  - The choice of the parameter basis might be sub-optimal.
  - The combination assumes that the posteriors of the different methods are Gaussian.
  - **Action**: evaluate the need of a more general basis.
  - **Action**: generalize the method to allow for non- Gaussian distributions.

BAO: small?
RSD: small?

Simulation requirements: Overview

- Challenge: control the systematics at a level far below the Euclid statistical uncertainty.
- Rule out brute-force investigations
- Tractable approach:
  - Perform differential analyses (e.g. sims based on the same white noise, turn on and off a given systematic effect, etc.)
  - Use fast, approximate methods along with N-body
  - Use comoving outputs of Flagship (or other high-res sims.)
  - Implement blind tests

Simulation requirements: Overview

- Euclid analyses will combine various types of simulations:
  - Idealized sims of analytically known clustering.
  - Fast mocks in periodic volumes.
  - N-body simulations in periodic volumes.
  - Fast mocks at fixed time with survey geometry.
  - Light-cones based on fast methods with full geometry
  - Light-cones based on N-body sims with full geometry.
  - Detailed pixel level simulations

Simulation requirements

- Large number of galaxy mocks obtained with fast dynamical methods:

  - Light-cone effects / Bias+RSD / Reconstruction
  - Spec-phot calibration, Milky Way extinction
  - Redshift error
  - Slitless confusion
  - Covariance matrix estimates.
  - Cosmology dependence of **C**
  - Non-Gaussian likelihood function.

Simulation requirements

- Galaxy mocks painted on N-body simulations:

- Bias+RSD / Reconstruction / Massive Neutrinos
- Redshift error
- Slitless confusion
- Non-Gaussian likelihood function.

Simulation requirements

- Detailed pixel-level simulations

  - Simulate a small area and reduce with full OU pipeline.
  - Effects to model: exposure footprint, backgrounds (zodi, in-field and out-field stray light, cosmic rays), instrumental transmission, PSF, SNR of dispersed images, obscuration, detector persistence, redshift measurement
  - Use bypass algorithms to imprint specific effects on full-sky galaxy mocks

See next talk by Dida Markovic

Simulation requirements

- Further tests with hydrodynamical simulations ?

- Galaxy velocity & assembly bias / Baryon-CDM

Simulation requirements

- Most demanding requirements in terms of number of mocks come from the estimation of **C** ($N \sim 2000$).
- Several methods can help to reduce this number.
- Mock catalogues are used for multiple tests (e.g. to test for the significance of potential oddities in the data).
- It would be advisable to plan for the construction of these mocks even if the final requirements for **C** are small.

Conclusions

- Summary of systematic errors:

Systematic effect	impact on BAO	impact on RSD	Maturity of mitigation
Photometric calibration	small	small	high
Milky Way extinction	small	small	high
Redshift measurement error	small	medium?	high
Confusion from overlapping spectra	unknown	unknown	low
Deep field	small?	small?	low
Clustering estimators: power spectrum	small	small	high
Clustering estimators: two-point correlation function	small	small	high
Clustering estimators: wide-angle effects	small	small	high
Reconstruction	large	none	medium
Nonlinear evolution of dark-matter	medium	large	medium
Redshift-space distortions	low	large	low
Galaxy density bias	low	large	low
Massive neutrinos	low	large	medium
Galaxy velocity bias	low	large	low
Variations of model template with cosmology	low	unknown	low
Lightcone & projection effects	low?	low?	low
Relative velocity and density perturbations between baryons and dark matter	small?	small?	small?
Noise in the covariance matrix	small	small	high
Biased estimates of the covariance matrix	small-med?	small-med	high
Cosmology dependence of the covariance matrix	small?	small	low
Incorrect shape of the likelihood function	unknown	unknown	low
Combination of results from multiple statistics	small	small	high