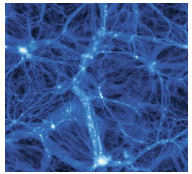
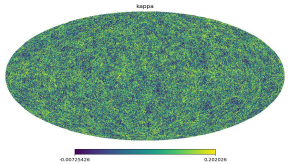
Simulation Based Inference with the Integrated 3-Point Correlation Function of Cosmic Shear

David Gebauer
with Stella Seitz & Anik Halder

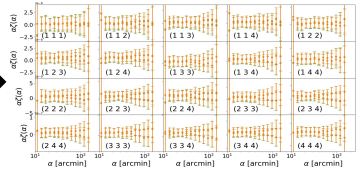
The SBI Pipeline



N-Body Simulations

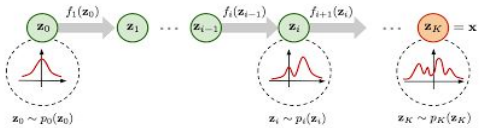


Weak Lensing Maps



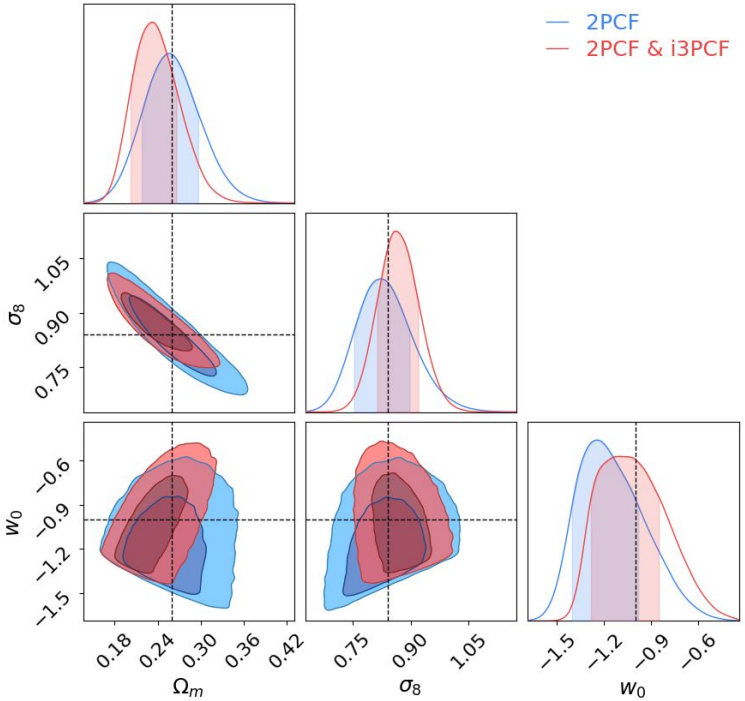
Summary Statistics

Forward Model



Normalizing Flow (Generative Model)

Evaluate for Observation

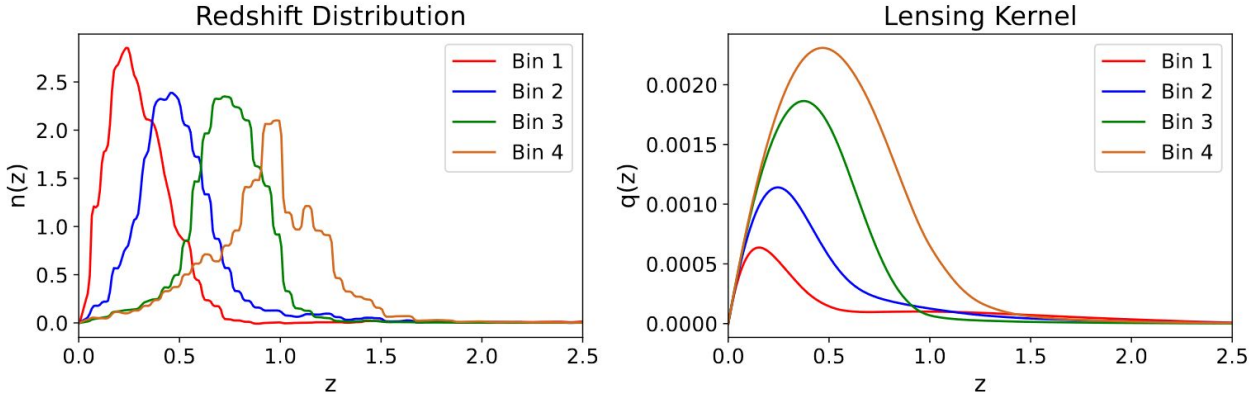


Weak Lensing Cosmology

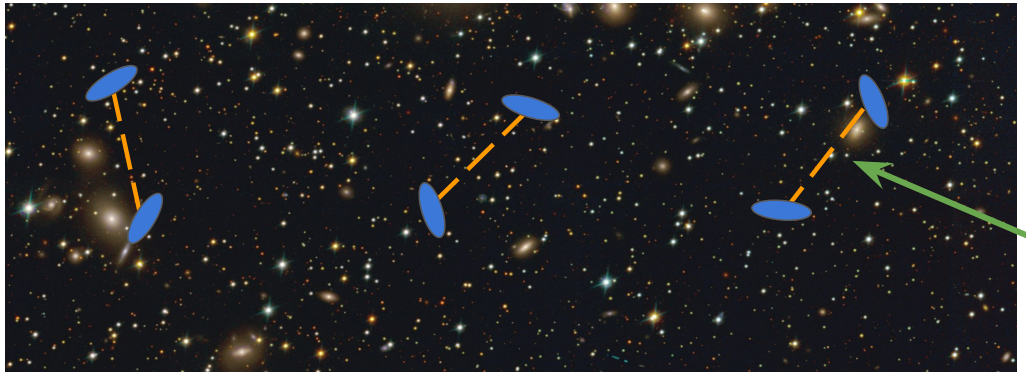
Cosmic shear probes LOS projection of the matter density field

$$(\gamma_1, \gamma_2) = \partial^{-2} \int_0^\infty d\chi \, W(\chi, \chi_i) (\partial_x^2 - \partial_y^2, 2\partial_x \partial_y) \delta(\chi \hat{\mathbf{n}}_i)$$

Weight W depends on redshift of source galaxies:



Weak Lensing Cosmology



Background source galaxy shape WITH lensing

$\hat{\xi}_{\pm}(\theta)$

Shear 2-point correlation functions

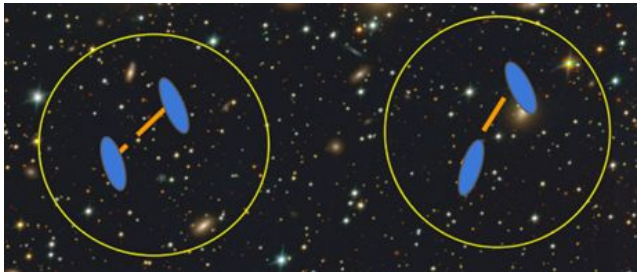
$$\xi_{\pm}(\theta) = \int \frac{\mathrm{d}\ell\ \ell}{2\pi} J_{0/4}(\ell\theta) \int \mathrm{d}\chi \frac{q_\kappa^2(\chi)}{\chi^2} P_m^{\mathrm{3D}}(\ell/\chi, \chi)$$

Fourier transform of the line-of-sight projection of the **3D matter power spectrum**

Integrated 3-Point Correlation Function

i3PCF correlates local 2PCF with shear aperture mass

Probes the line-of-sight projection of the integrated 3D matter bispectrum



Halder et al. 23

$$\zeta_\pm(\theta) = \left\langle M_{\rm ap}(\boldsymbol{\theta}_C)\ \hat{\xi}_\pm(\theta;\boldsymbol{\theta}_C)\right\rangle = \frac{1}{A(\theta)}\int \frac{\mathrm{d}\ell\ \ell}{2\pi}\mathcal{B}_\pm(\ell) J_{0/4}(\ell\theta)$$

Integrated bispectrum:

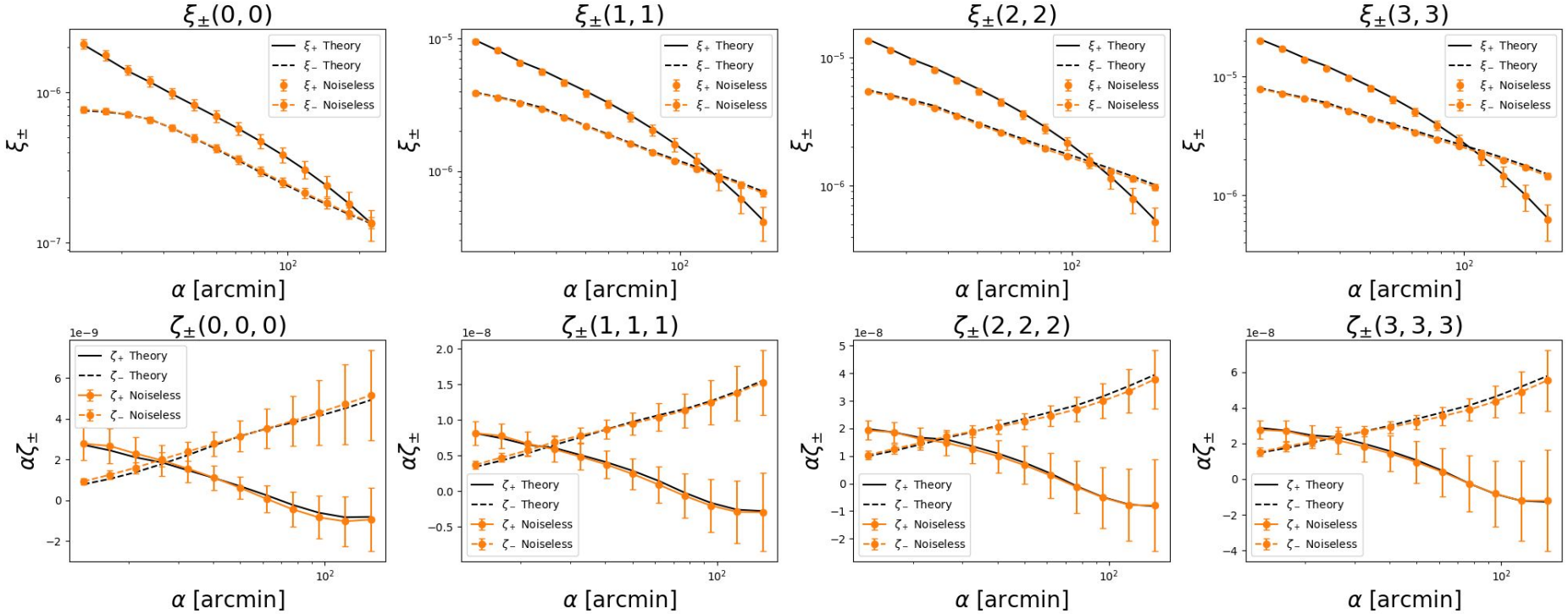
$$\mathcal{B}_\pm(\ell) = \int \mathrm{d}\chi\ \frac{q_\kappa^3(\chi)}{\chi^4}\int_{\boldsymbol{\ell}_1}\int_{\boldsymbol{\ell}_2} B_\delta^{\rm 3D}\left(\frac{\boldsymbol{\ell}_1}{\chi},\frac{\boldsymbol{\ell}_2}{\chi},\frac{-\boldsymbol{\ell}_{12}}{\chi};\chi\right) e^{2i\left(\phi_{\boldsymbol{\ell}_2}\mp\phi_{-\boldsymbol{\ell}_{12}}\right)} U(\boldsymbol{\ell}_1)W(\boldsymbol{\ell}_2+\boldsymbol{\ell})W(-\boldsymbol{\ell}_{12}-\boldsymbol{\ell})$$

Line-of-sight projection

3D matter bispectrum

Window functions

Validation with Theory



Systematic Effects

- **Photometric redshift uncertainty**

$$n^i(z) \to n^i(z - \Delta_z^i)$$

- **Shear calibration** (bias from shear measurement pipeline)

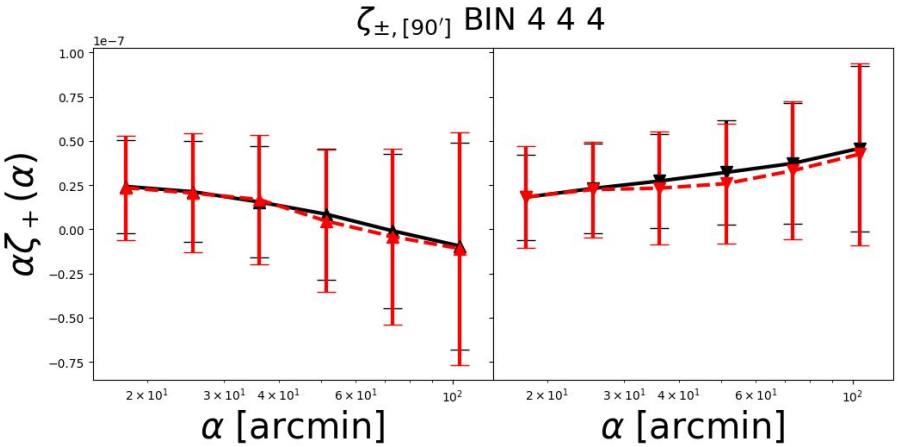
$$\zeta^{ijk}_{\pm,\mathrm{obs}}(\alpha) = (1+m_i)(1+m_j)(1+m_k)\zeta^{ijk}_{\pm,\mathrm{true}}(\alpha)$$

- **Intrinsic alignment** (non-linear linear alignment (NLA) model)

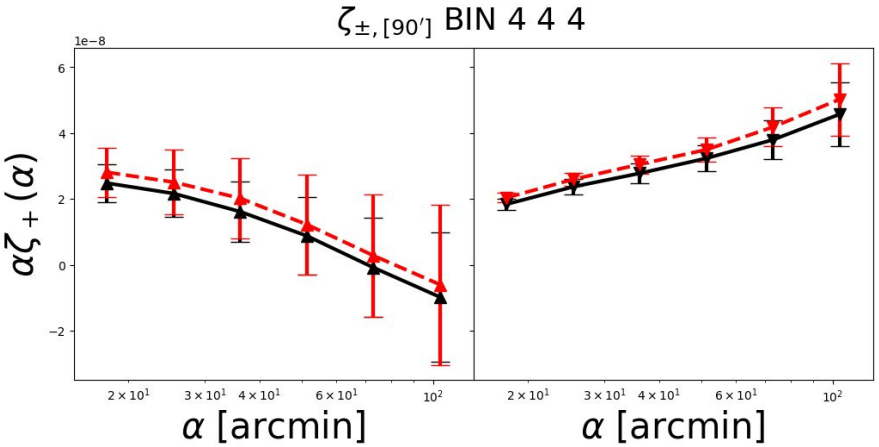
$$q^i_\kappa(\chi) \longrightarrow q^i_\kappa(\chi) - A\left(z\left(\chi\right)\right)\frac{n^i_\kappa(z(\chi))}{\bar{n}^i_\kappa}\frac{dz}{d\chi} \qquad A(z) = A_{\mathrm{IA},0}\left(\frac{1+z}{1+z_0}\right)^{\alpha_{\mathrm{IA}}}\frac{C_1\rho_{\mathrm{m},0}}{D(z)}$$

Testing Additional Systematics

Source Galaxy Clustering
(including shape noise)



Reduced Shear
(without shape noise)

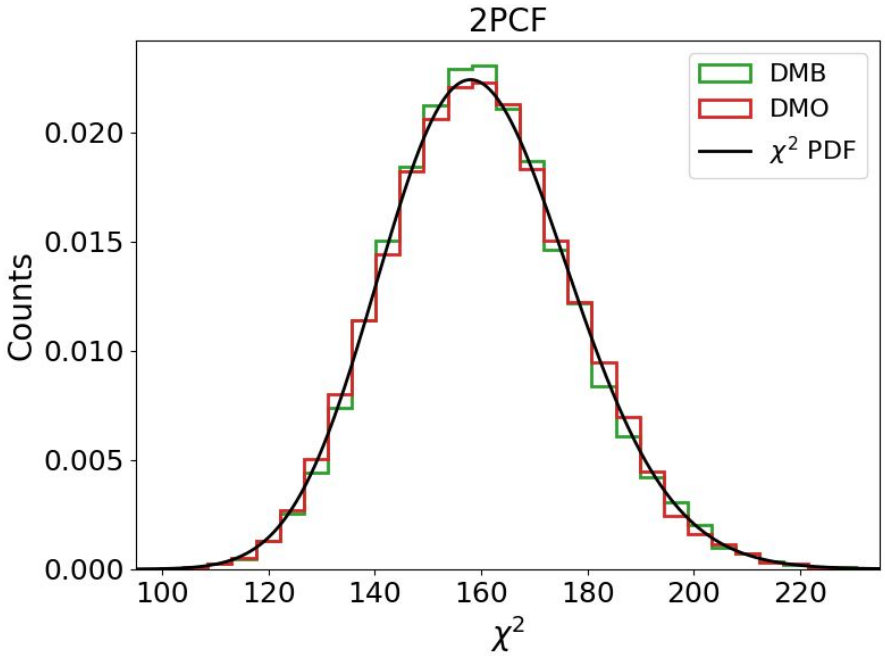


Gaussianity of the Likelihood

We calculate χ^2 for 16000 fiducial sims with respect to mean:

$$\chi^2 = (d_i - \hat{d})^T C^{-1} (d_i - \hat{d})$$

- 2PCF is fitted well by χ^2 distribution



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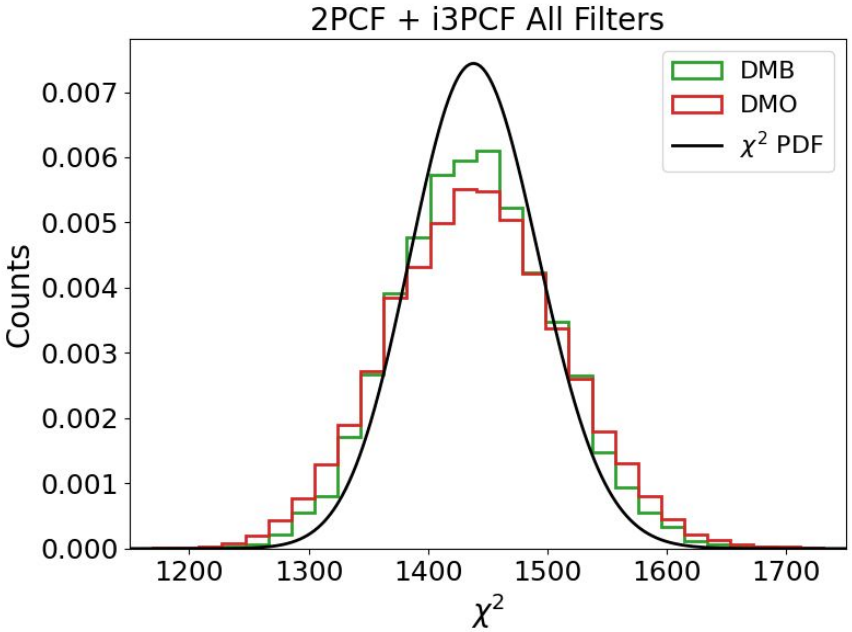

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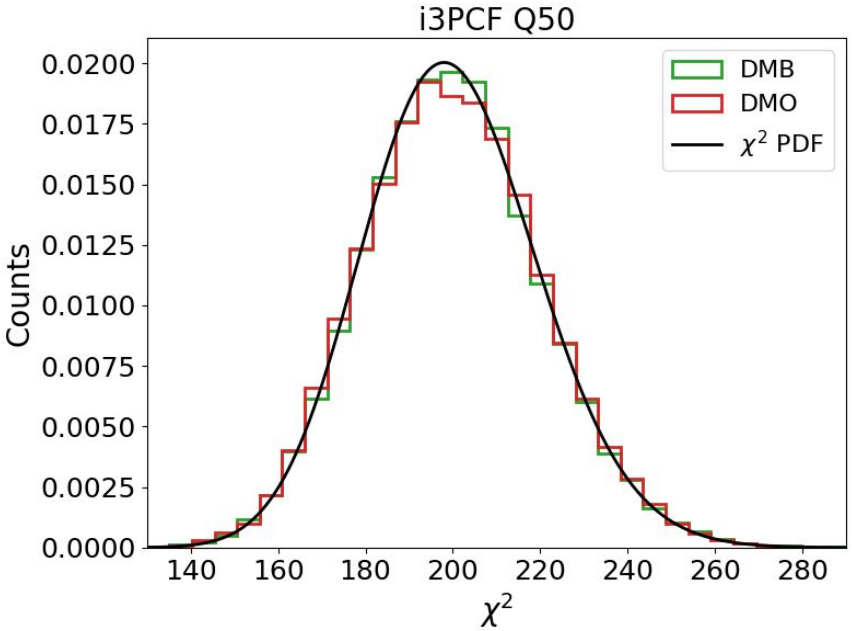
- Only slight deviation for 50’ filter



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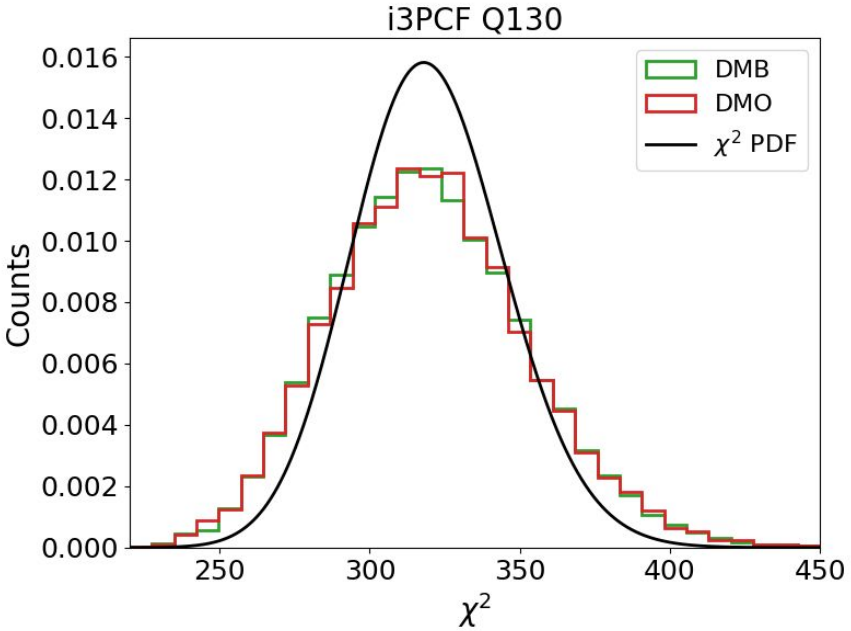
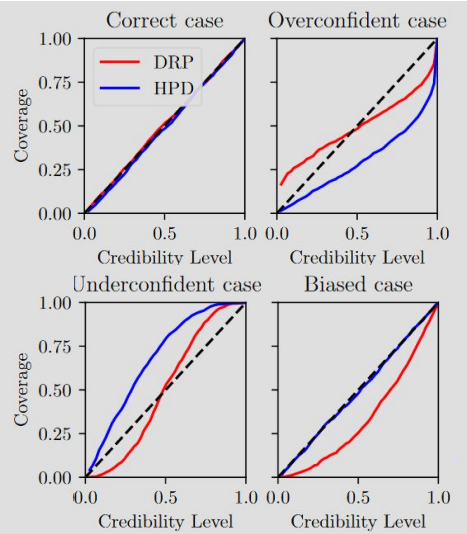


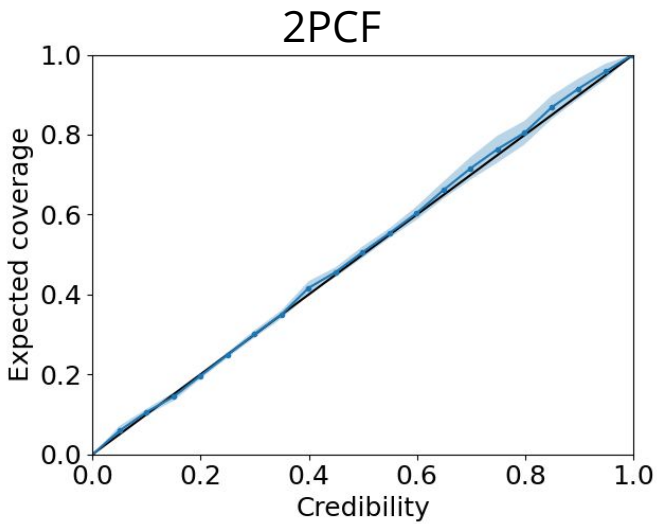
⇒ Likelihood increasingly non-Gaussian when approaching squeezed limit

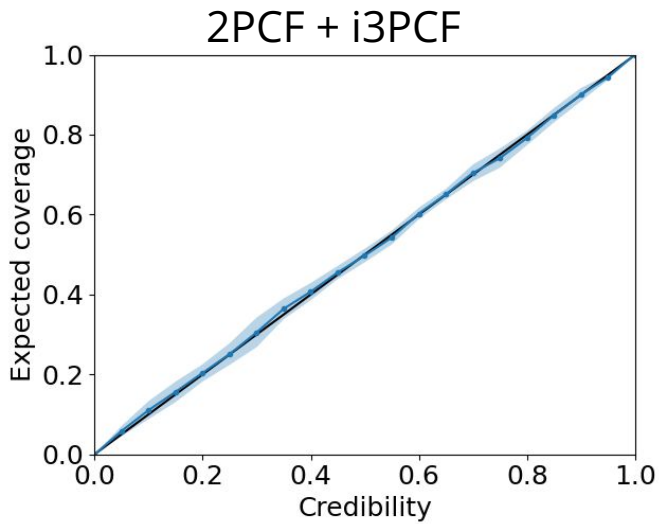
Validating SBI

Coverage Test:

- Are the resulting posteriors accurate?
- “Tests of Accuracy with Random Points” (TARP) ⇒ Lemos et al. 2023

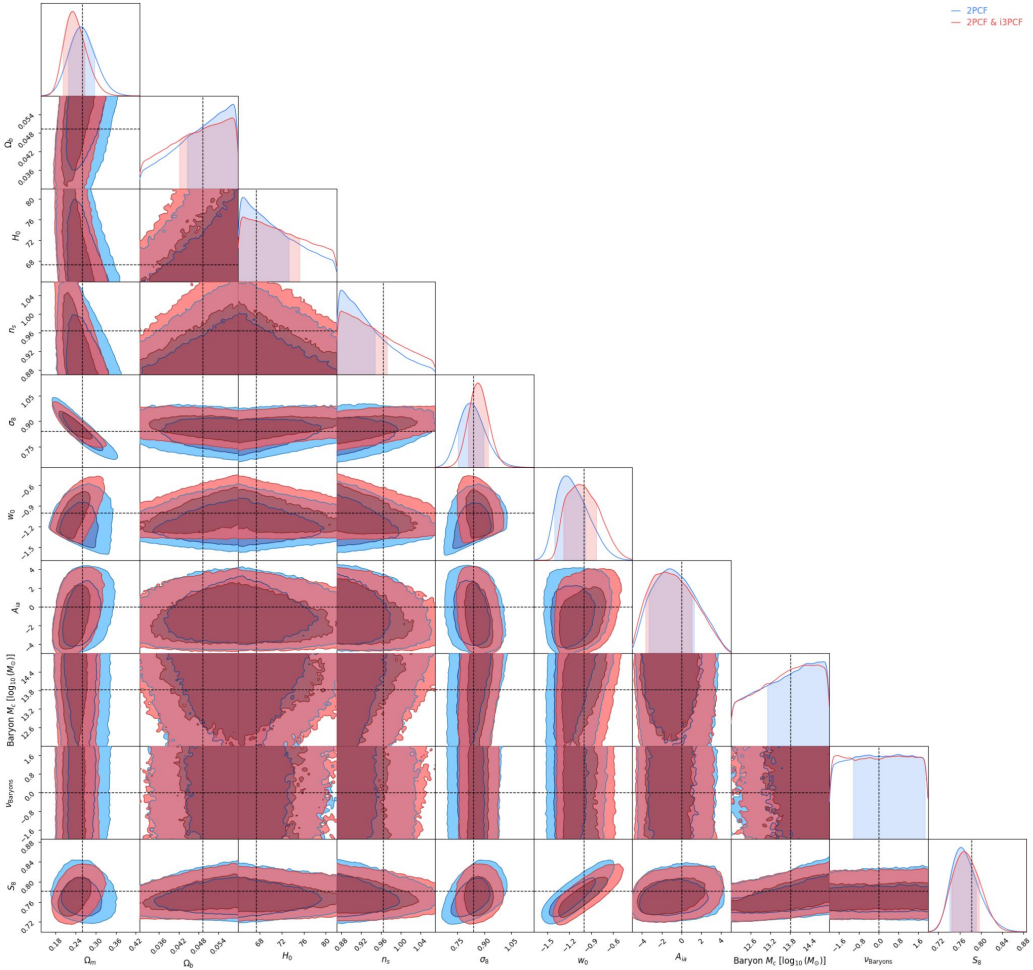






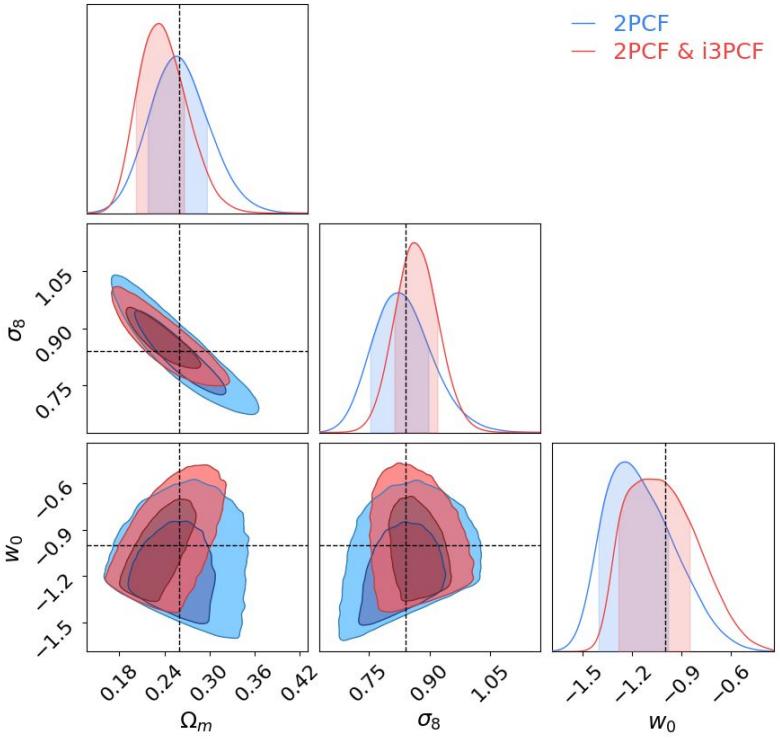
Fiducial Results

- We can constrain Ω_m, σ_8 and w_0
- Other parameters unconstrained



Fiducial Results

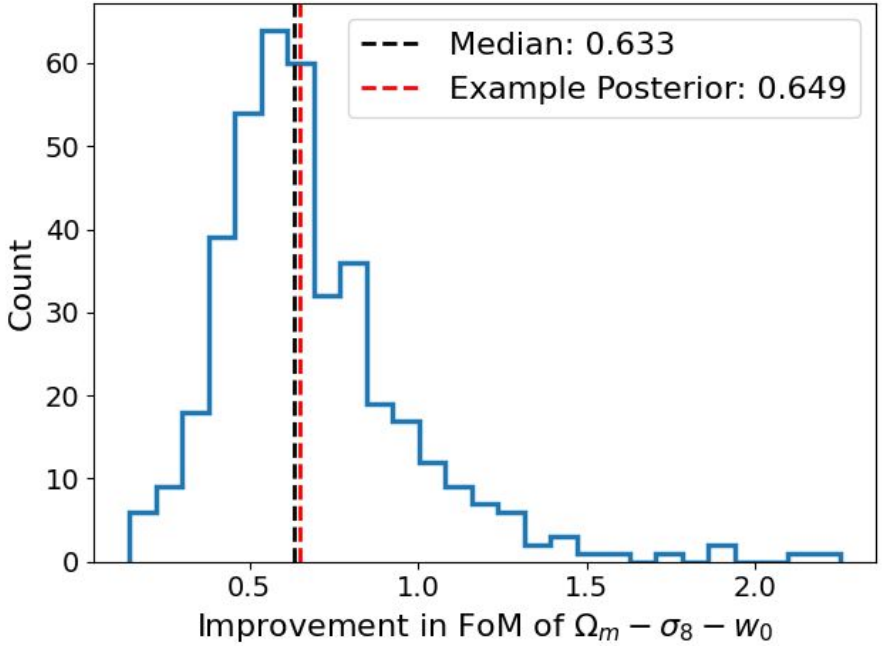
- We can constrain Ω_m, σ_8 and w_0
- Other parameters unconstrained
- Focus on constrained parameters:
  - Recover true parameters
  - w_0 not improved?
  - 65% improvement in FoM



Improvements

- Compare 2PCF constraints with and without i3PCF for 400 sims
- Median improvement of 63%
- Large scatter depending on realisation
- Improvement driven by Ω_m & σ_8
- w_0 Improvements small

⇒ Projection effects due to prior



Summary & Outlook

- We have developed a pipeline which can:
  - Create realistic mock weak lensing observables
  - Evaluate correlation functions efficiently
  - Test the effect of systematics
  - Obtain posteriors from Observations
- I'm now working on:
  - Further validate application to data
- Future directions:
  - Add (photometric) galaxy clustering
  - Add more summary statistics (e.g. 1-pt PDF)
  - Apply to Stage IV surveys