SIMULATION BASED INFERENCE WITH THE INTEGRATED 3-POINT CORRELATION FUNCTION

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WHAT IS SBI?

"Traditional" Bayesian Inference

- Using Bayes' Theorem:

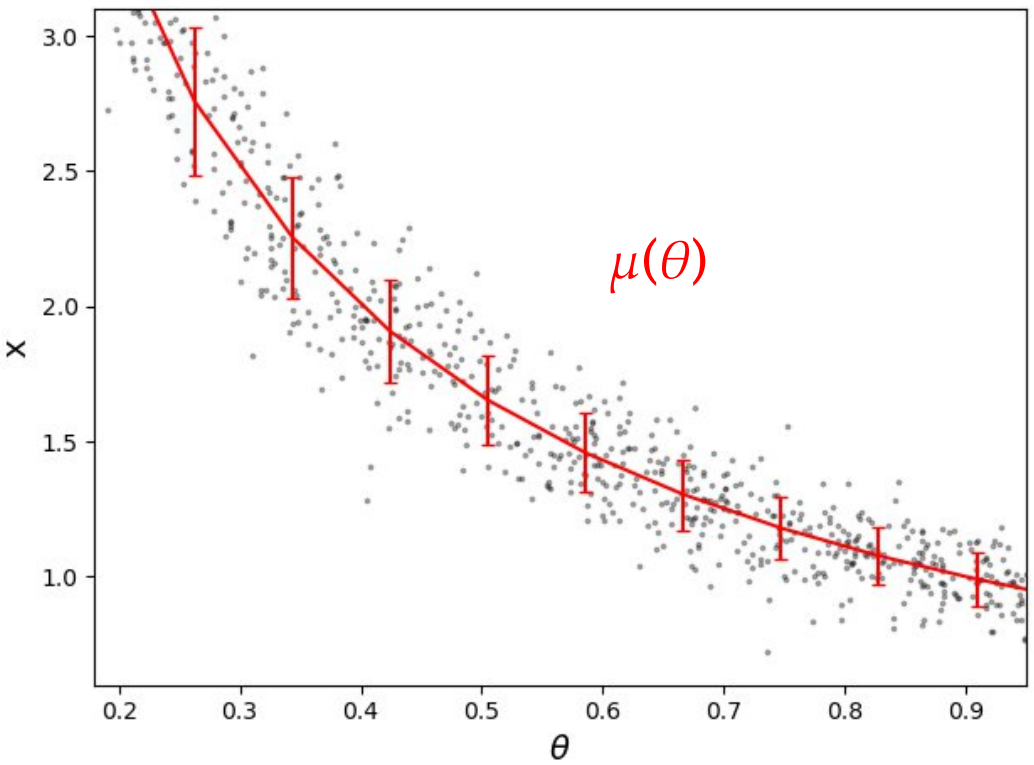
$$p(\theta|x) = \frac{p(\theta)p(x|\theta)}{p(x)} \propto p(\theta)\boxed{p(x|\theta)}$$

Likelihood

- **Gaussian** Likelihood

$$p(x|\theta) = \mathcal{N}(\mu, C)$$

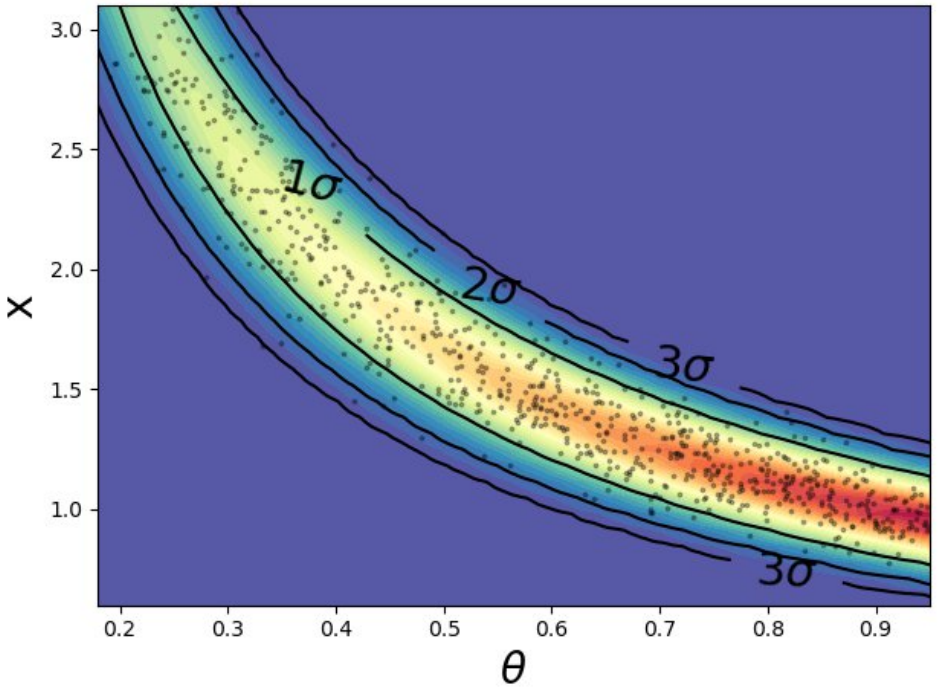
Mean (theory model)
Covariance

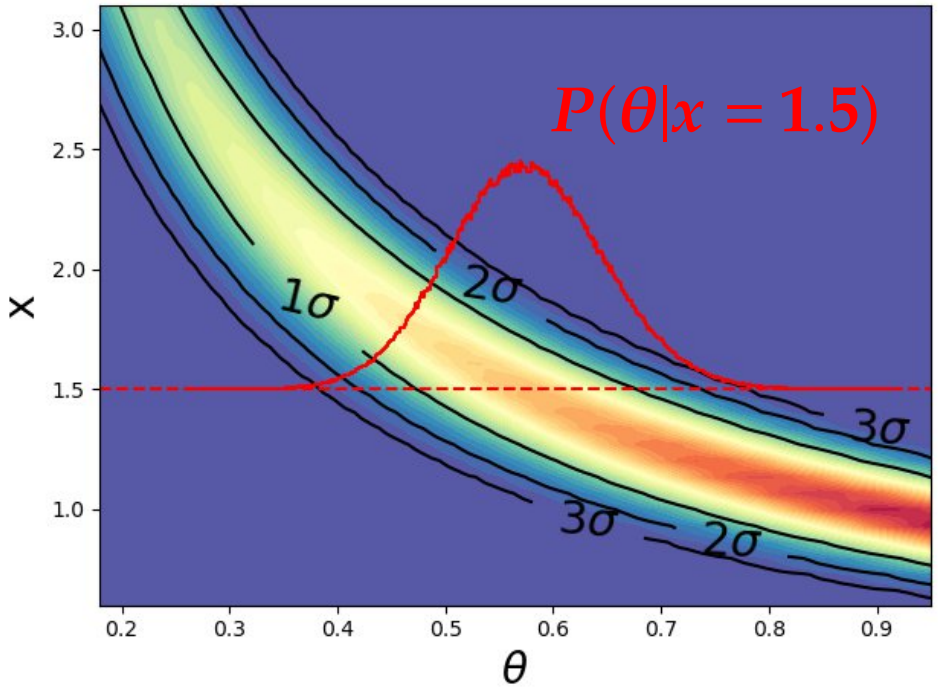


=> Estimate Covariance from simulations

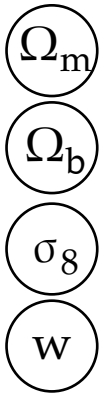
WHAT IS SBI?

Why not learn $p(\theta|x)$ directly?

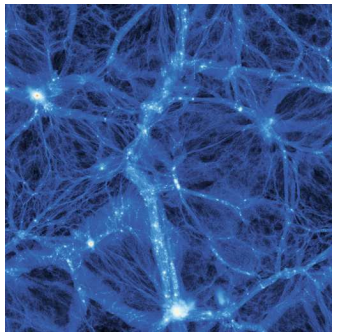




THE SBI PIPELINE

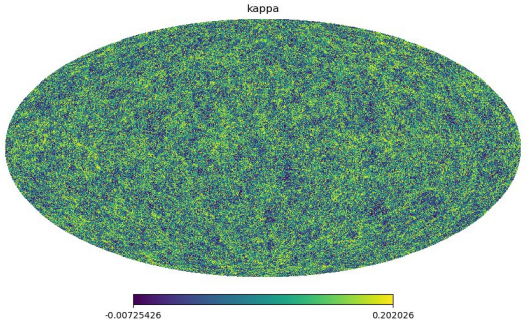


Cosmological Parameters θ



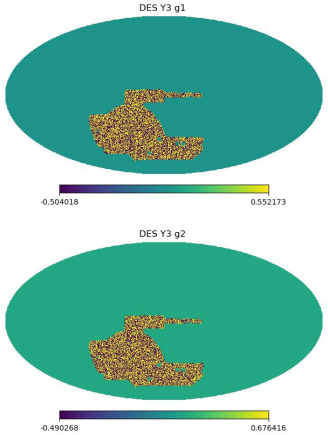
N–Body Simulations

LOS Projection



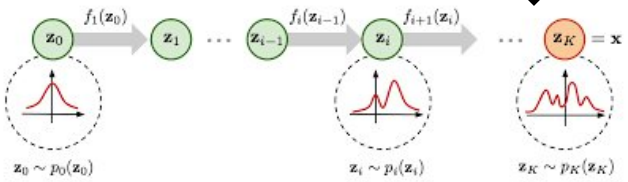
Weak Lensing Maps

Measure x



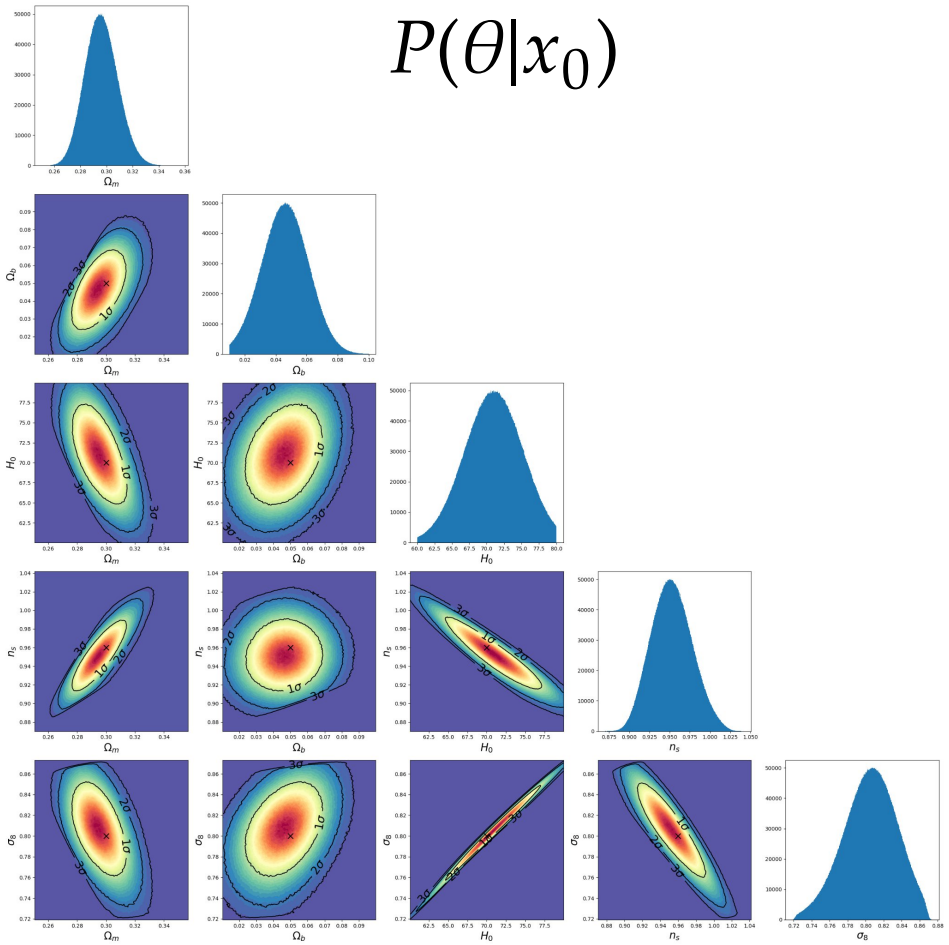
(mock) DES Data

Measure x_0



Normalizing Flow

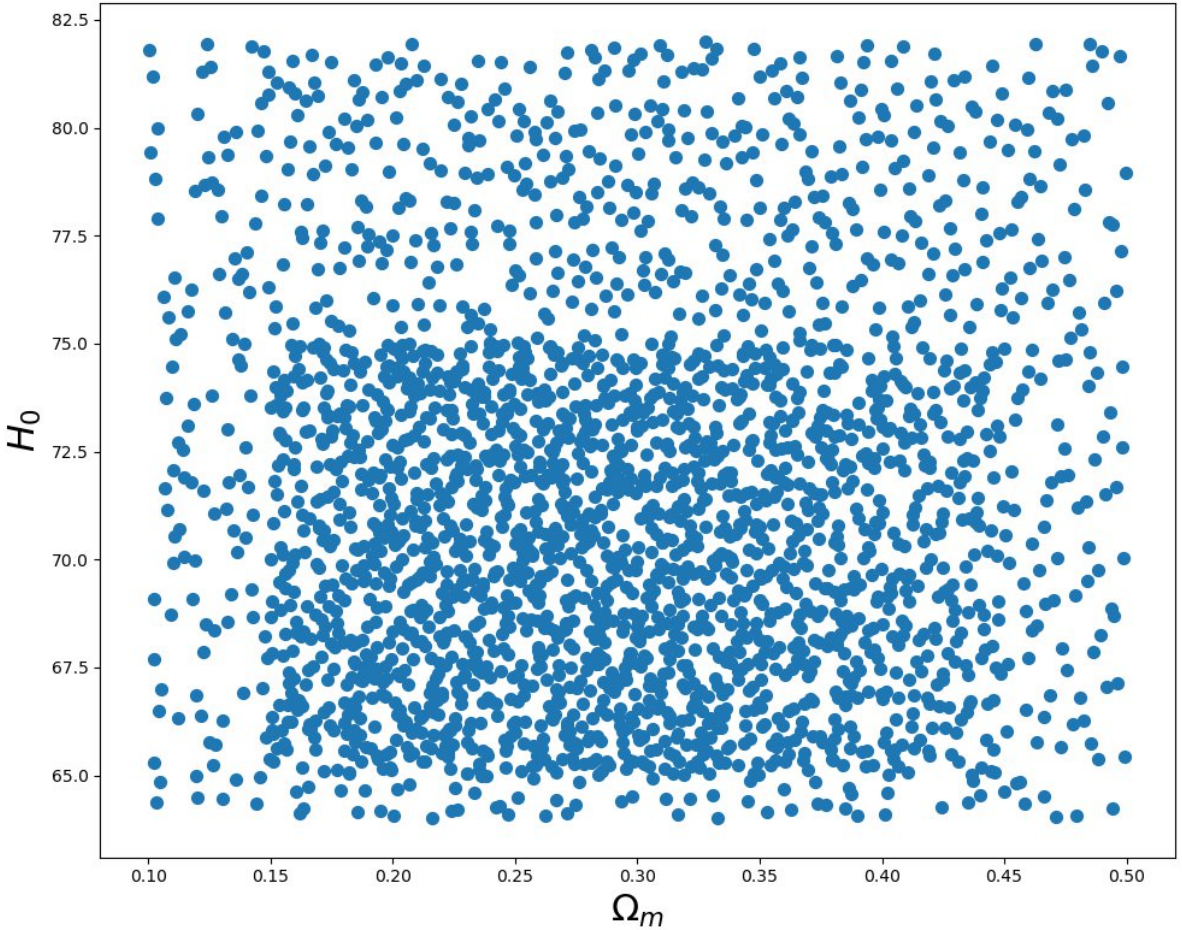
Evaluate



$P(\theta|x_0)$

THE COSMOGRID V1 SIMULATIONS

- 2500 flat wCDM Cosmologies with 7 realizations at different initial conditions each.
  - Varying $\mathrm{H}_0, \sigma_8, \Omega_\mathrm{m}, \Omega_\mathrm{b}, \mathrm{n}_\mathrm{s}, w$
- Output: 69 particle shells up to z=3.5
- Additional effects included in post-processing:
  - Baryonification
  - Photo-z bias
  - Multiplicative bias
  - Intrinsic Alignment (NLA)

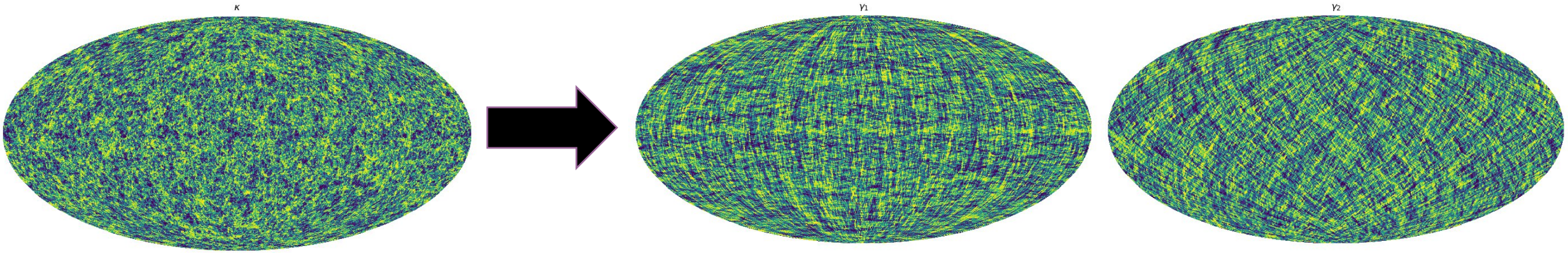


CREATING WEAK LENSING MAPS

- Convergence are projected overdensities

$$\kappa(\theta_{\mathrm{pix}}) \approx \frac{3}{2}\Omega_m \sum_b W_b \frac{H_0}{c}\left[\frac{N_{\mathrm{pix}}}{4\pi}\frac{V_{\mathrm{sim}}}{N_{\mathrm{part}}^{\mathrm{sim}}}\left(\frac{H_0}{c}\right)^2 \frac{n_p(\theta_{\mathrm{pix}}, \Delta\chi_b)}{\mathcal{D}^2(z_b)} - \left(\frac{c}{H_0}\Delta\mathcal{D}_b\right)\right]$$

- Can be converted to shear using Kaiser–Squires method

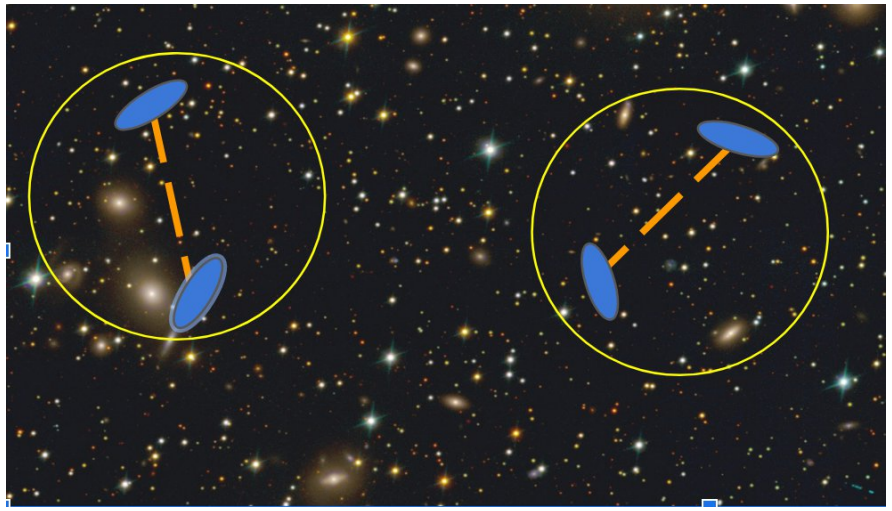


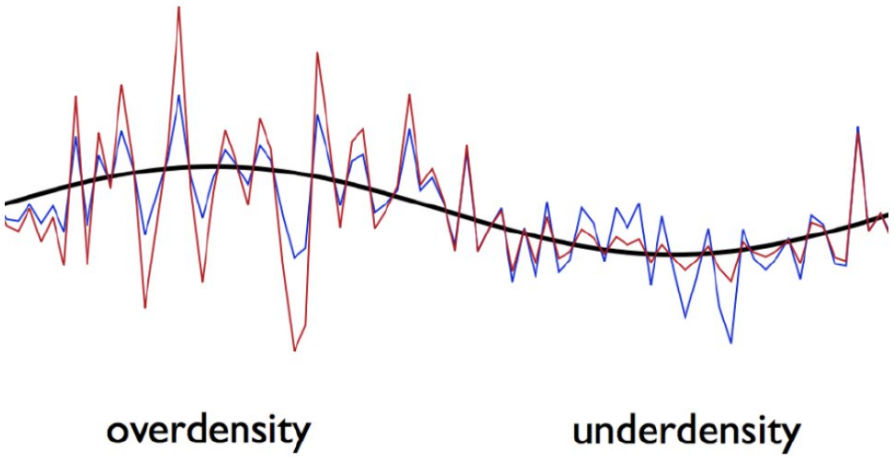
Convergence

Shear – γ_1

Shear – γ_2

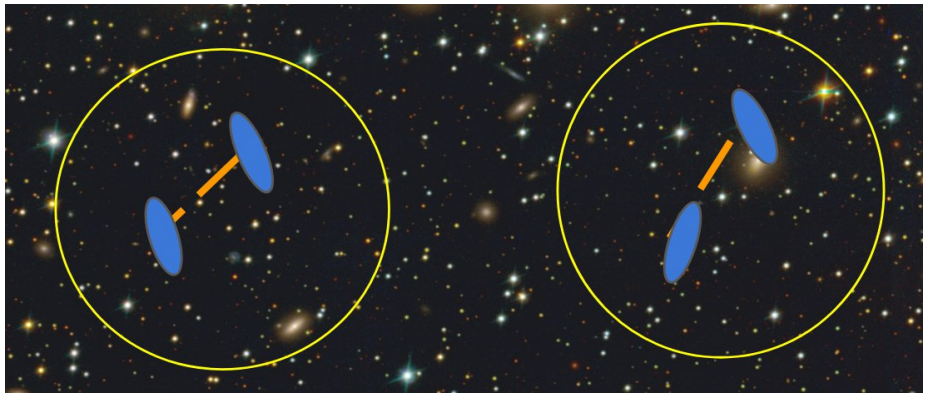
MEASURING CORRELATION FUNCTIONS





MEASURING CORRELATION FUNCTIONS

$$\zeta_\pm(\alpha) = \left\langle \hat{M}_{\rm ap}(\boldsymbol{\theta}_C)\, \hat{\xi}_\pm(\alpha; \boldsymbol{\theta}_C) \right\rangle$$



Halder+23

- Correlate local 2PCF with shear aperture mass
- $\mathrm{M_{ap}}$ measures shear relative to patch centre

  ⇒ Can be calculated in O(n)

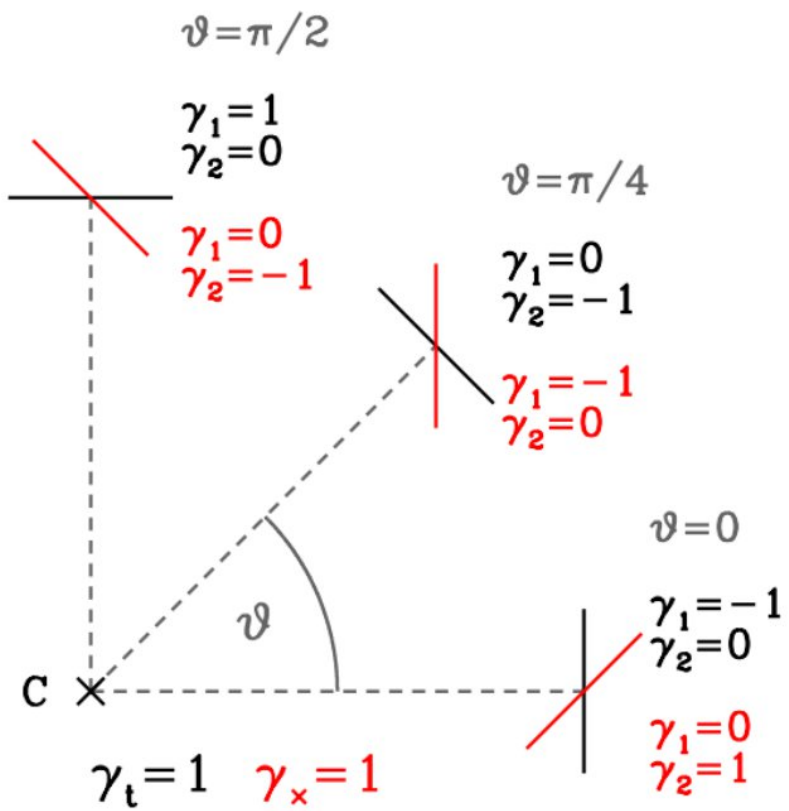
MEASURING CORRELATION FUNCTIONS

Shear 2PCF:

- Compares shear values at pairs within some angular distance

  - $\gamma_t^i = -\gamma_1^i \cos\left(2\vartheta^i\right) - \gamma_2^i \sin\left(2\vartheta^i\right)$
  - $\gamma_x^i = -\gamma_1^i \cos\left(2\vartheta^i\right) + \gamma_2^i \sin\left(2\vartheta^i\right)$

- Sum over pairs:
- $\xi_\pm(\theta) = \frac{\sum_{i,j} w_i w_j (\gamma_t^i \gamma_t^j \pm \gamma_\times^i \gamma_\times^j)}{\sum_{i,j} w_i w_j}$



Grün (2015)

COSMOFUSE

Problem:

- Measuring 2PCF scales as $O(n^2)$
- Tree algorithms are not efficient on many small patches

⇒ Would take **O(years)** to measure on all simulations

Solution:

- Same mask is used on all maps

⇒ Same pairs & rotation angles

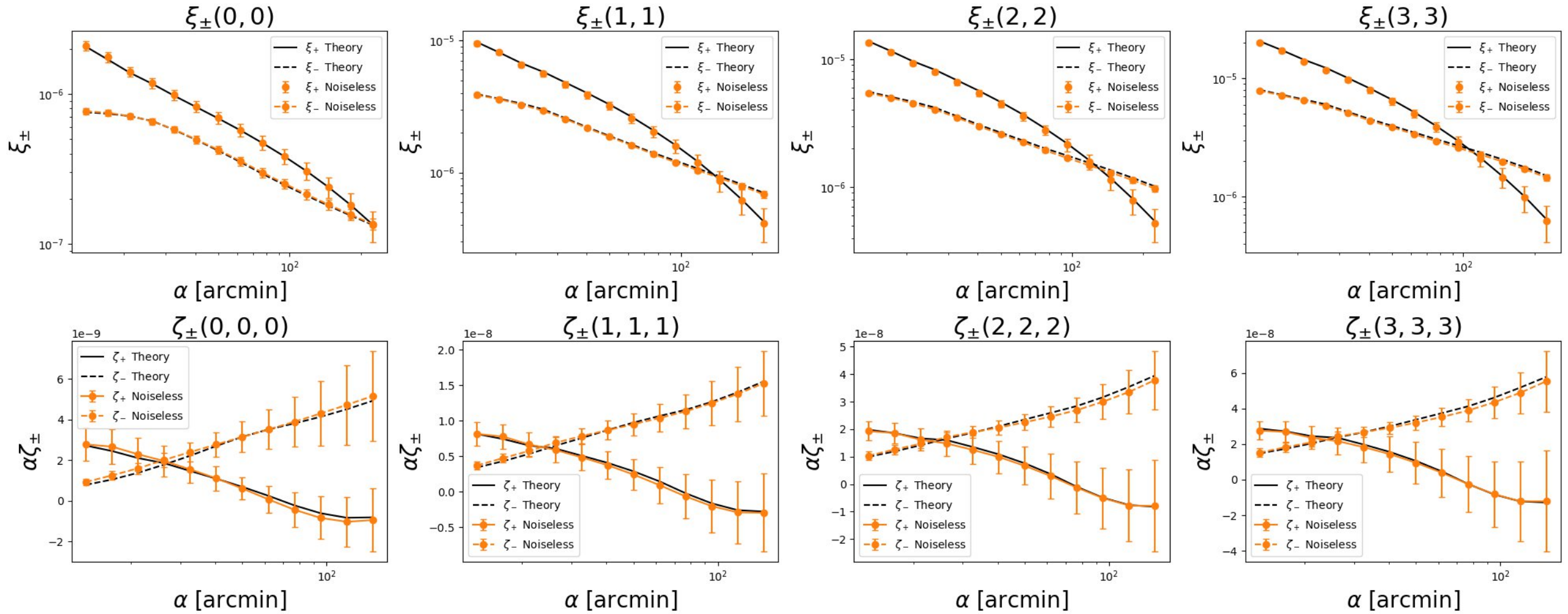
- <u>Find pairs once, then reuse</u>

300x speed up using GPUs!

github.com/D–Gebauer/CosmoFuse

install with: “pip install git+https://github.com/D–Gebauer/CosmoFuse/tree/main”

VALIDATION WITH THEORY



NORMALIZING FLOWS

- We start with a well-known distribution (Gaussian)
- Perform bijective transformations
- Every layer represents one such transformation
- Base distribution is transformed to target distribution

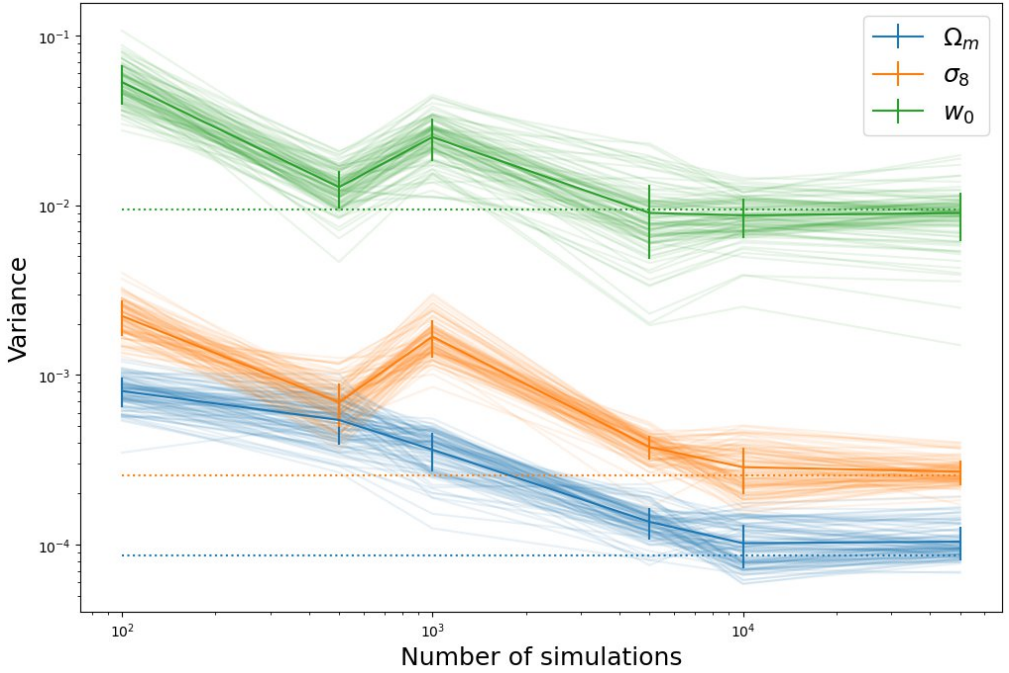
Inverse describes Probability at that point
=> Remapping onto Gaussian

VALIDATING SBI

Two Types: Coverage & Convergence Tests:

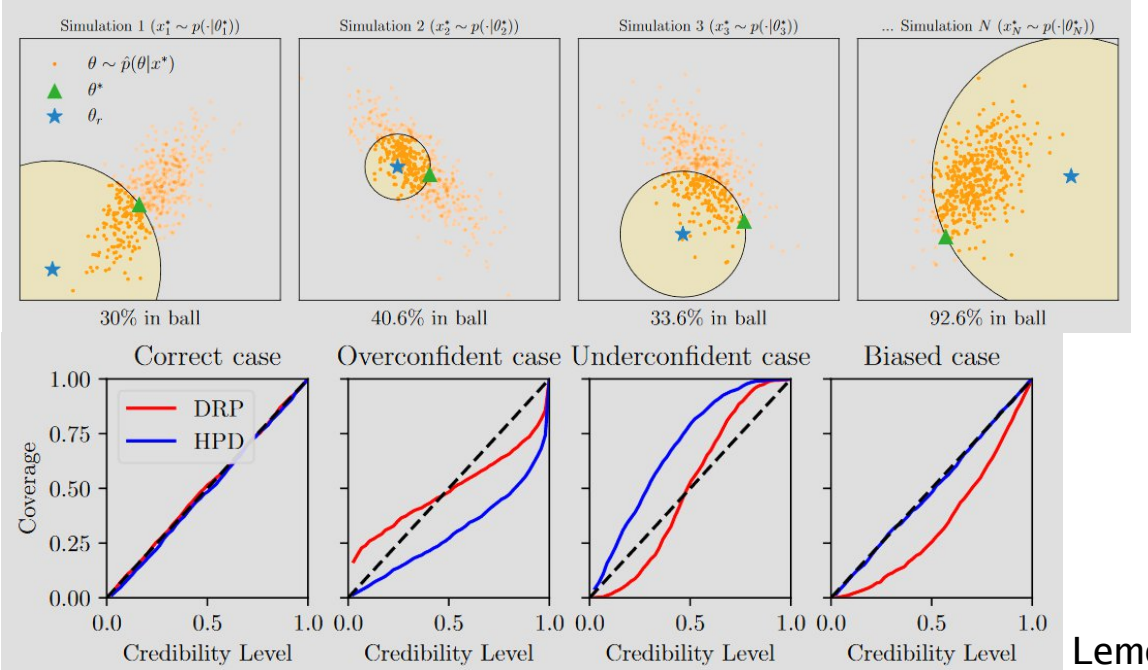
Convergence:

- Are enough simulations used for training?
- Train only on subset, estimate performance



Coverage:

- Are the resulting posteriors accurate
- "Tests of Accuracy with Random Points" (TARP)



Lemos+23

SUMMARY & OUTLOOK

- We have developed a pipeline which can:
  - Simulate mock DES observations including realistic noise & systematics
  - rapidly compute i3PCFs
  - WIP: perform SBI analysis

⇒ **This will allow comparison with traditional likelihood based higher order statistics analyses**

- In the future:
  - Add further probes (Galaxy Clustering, CMB lensing etc.)
  - Add further statistics (e.g. $\langle M_{\rm ap}^3 \rangle$)
  - Apply to new surveys (like EUCLID)

⇒ **Easy to extend/adapt**

github.com/D-Gebauer/CosmoFuse

WEAK LENSING SYSTEMATICS

- Baryonification on map level
  - from Schneider+19
  - Calculate displacement of particles relative to hydro simulations
  - 2 additional parameters describing mass of gas in halos as $M_c(z) = M_c^0(1+z)^\nu$
- Photometric redshift uncertainty

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

- Shear calibration (bias from shear measurement pipeline)

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

- Intrinsic Alignment (NLA model)

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