Fast cosmological inference with iterative emulators

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Cosmology from Home, 2022

Based on 2203.06124

In collaboration with Tim Eifler, Vivian Miranda, Sai Krishanth

THE UNIVERSITY OF ARIZONA

About me

- Current: Postdoc at University of Arizona
- Past: University of Waterloo, IIT Kanpur
- Research interest:
    - Fast inference methods using ML (This talk)
    - Bayesian field-level inference
    - Direct probes of peculiar velocity

Current and upcoming cosmological surveys

Surveys:

KIDS, HSC, eBOSS

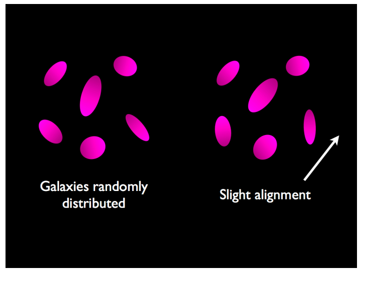
Stage-III

2020

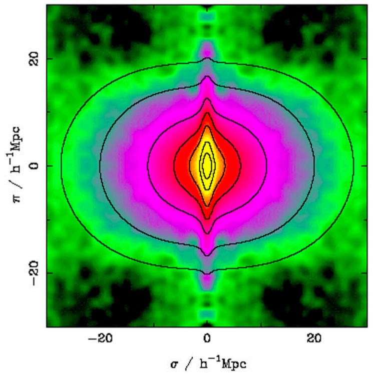
2024

2027

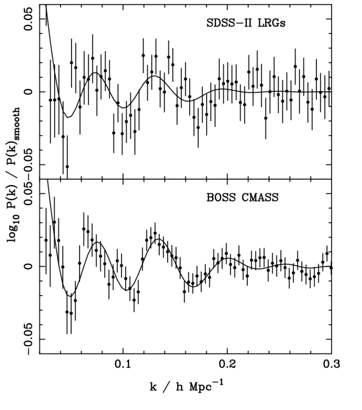
Cosmological probes:



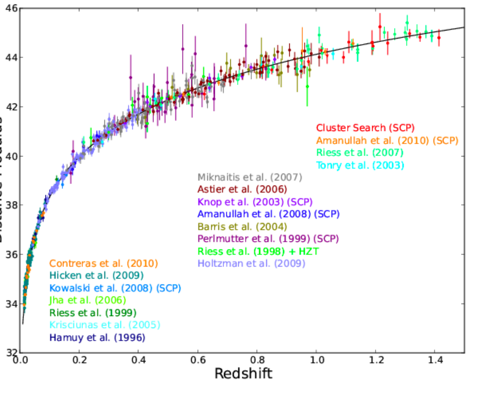
Weak Lensing



RSD



BAO



SNe

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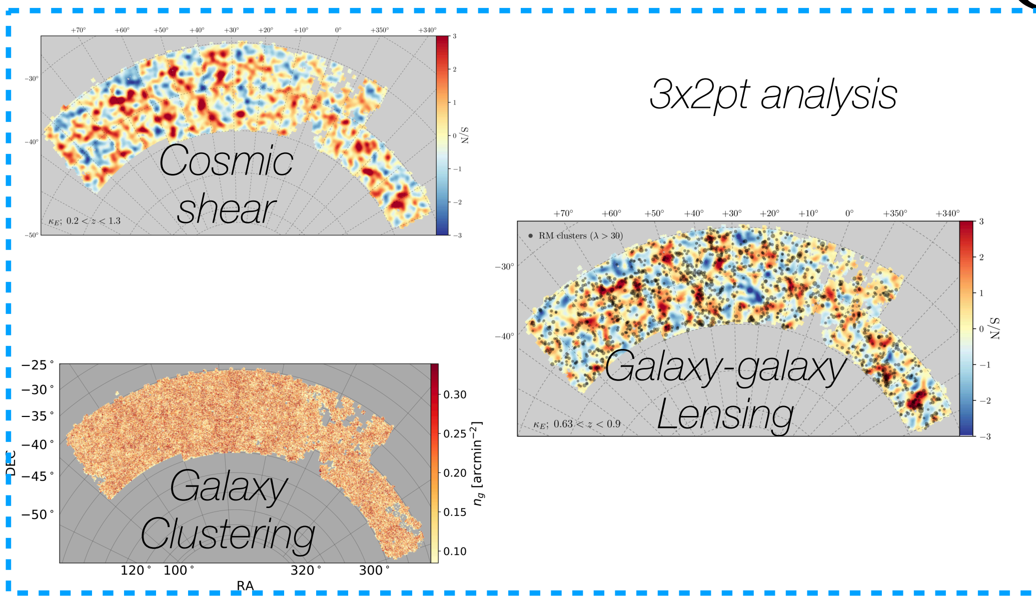
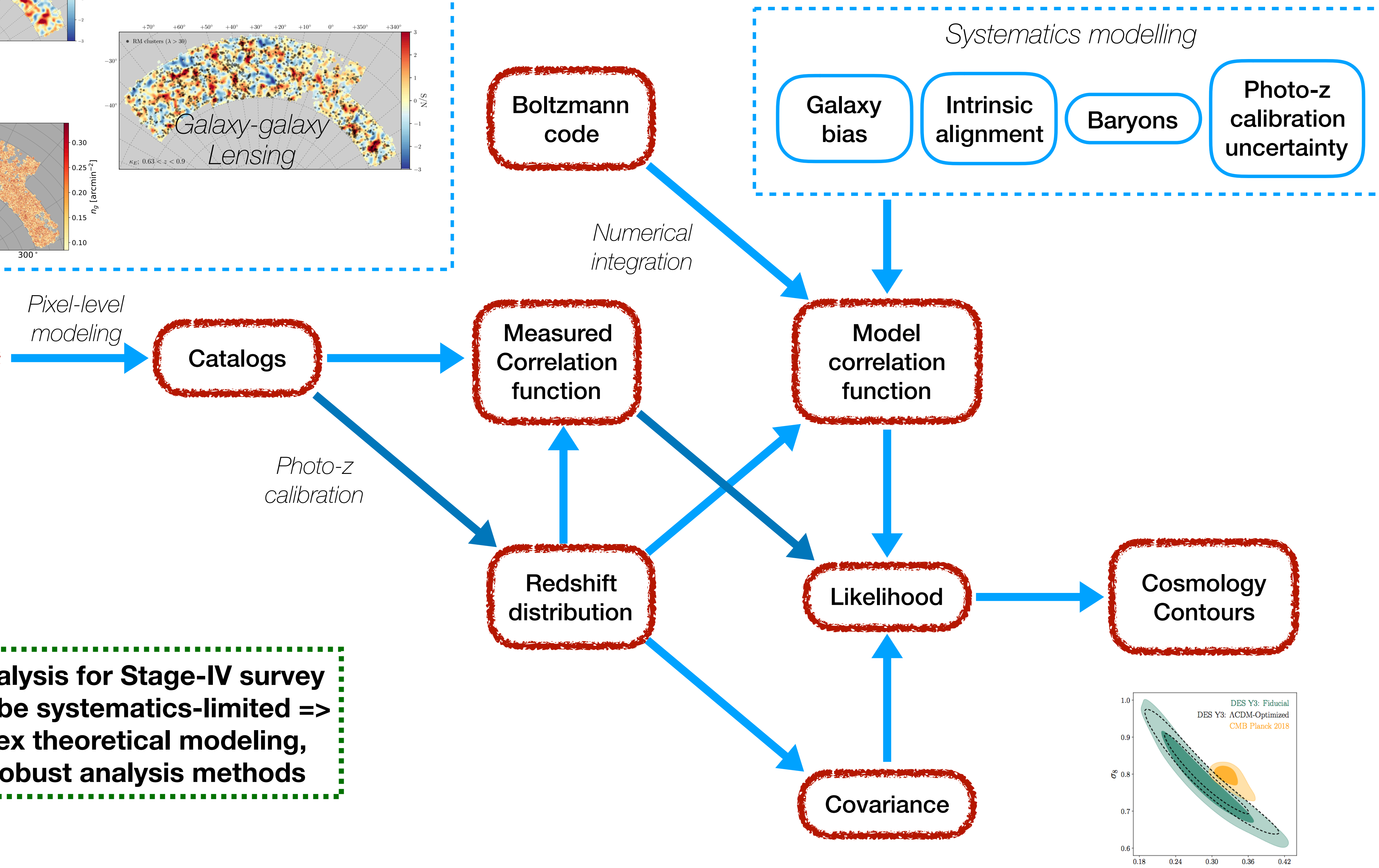
Science return:

- Nature of dark energy
- Mass of neutrino
- Primordial non-Gaussianity
- ....

Images: CFHTLens, NASA, SDSS, SCP,

Connecting theory to data



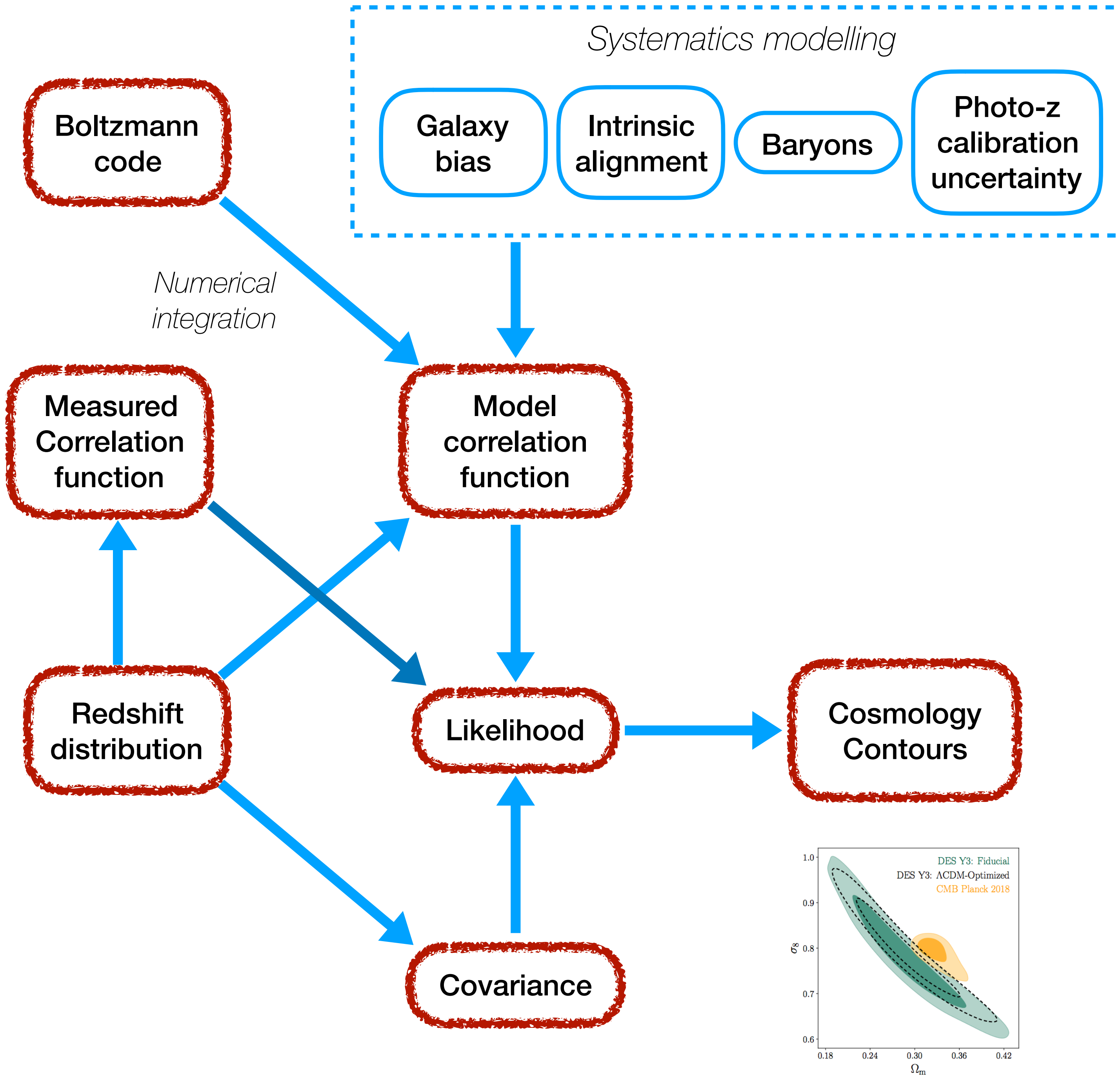


Data analysis for Stage-IV survey likely to be systematics-limited => complex theoretical modeling, Need robust analysis methods

Images: DES, NASA

Inference process

- Inference using MCMC or nested sampling algorithms
- MCMC runs are expensive, e.g, each LSST 3x2 point analysis require $\mathcal{O}$(10k CPUh)
- Robust data analysis will necessitate **thousands** of simulated MCMC runs



Images: DES, NASA

Simulated likelihood analyses

Quantifying the impact of different systematic effects

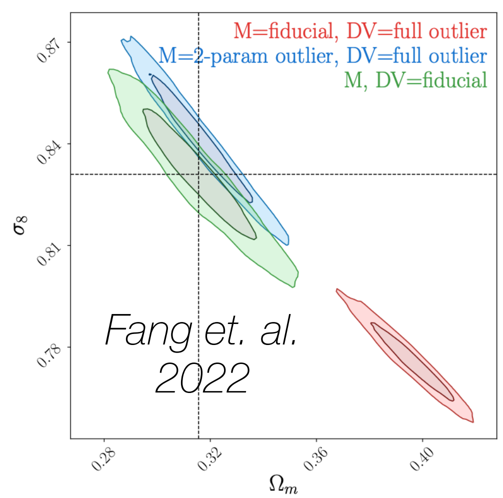
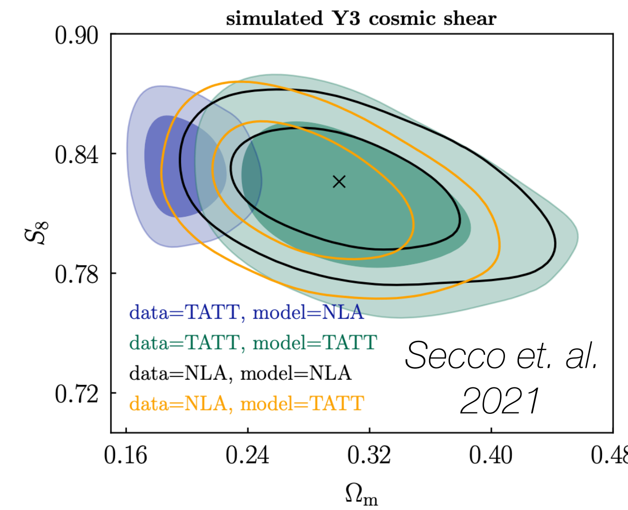
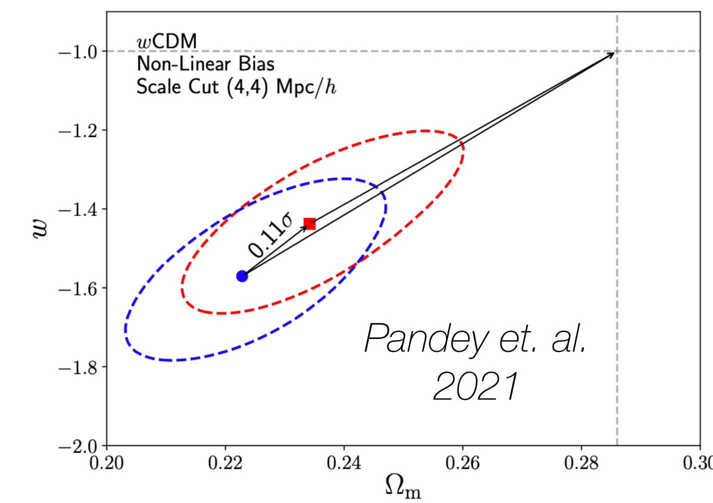


Photo-z bias/outliers

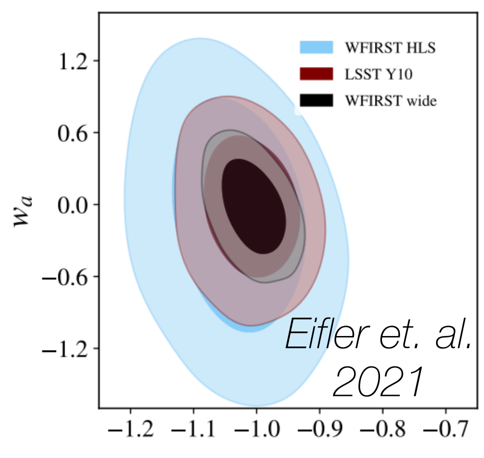


Intrinsic alignment



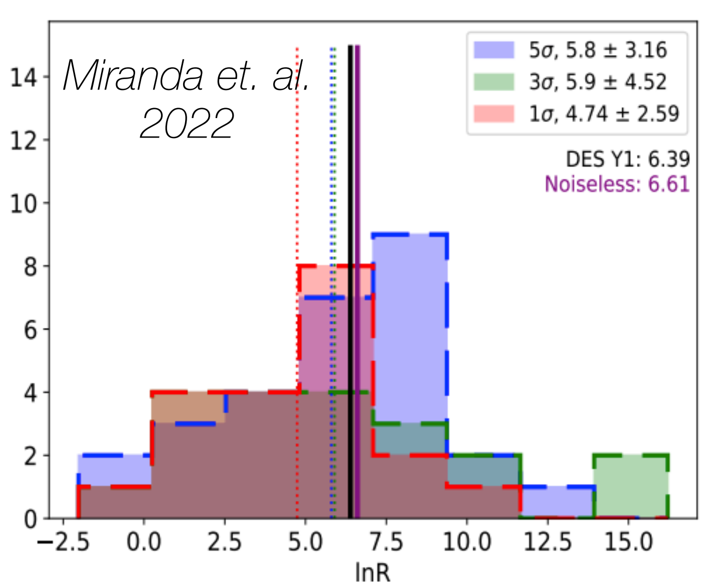
Galaxy bias

Optimizing survey strategy



Different survey strategy (e.g, deep / wide) impacts the science return.

Assessing tensions

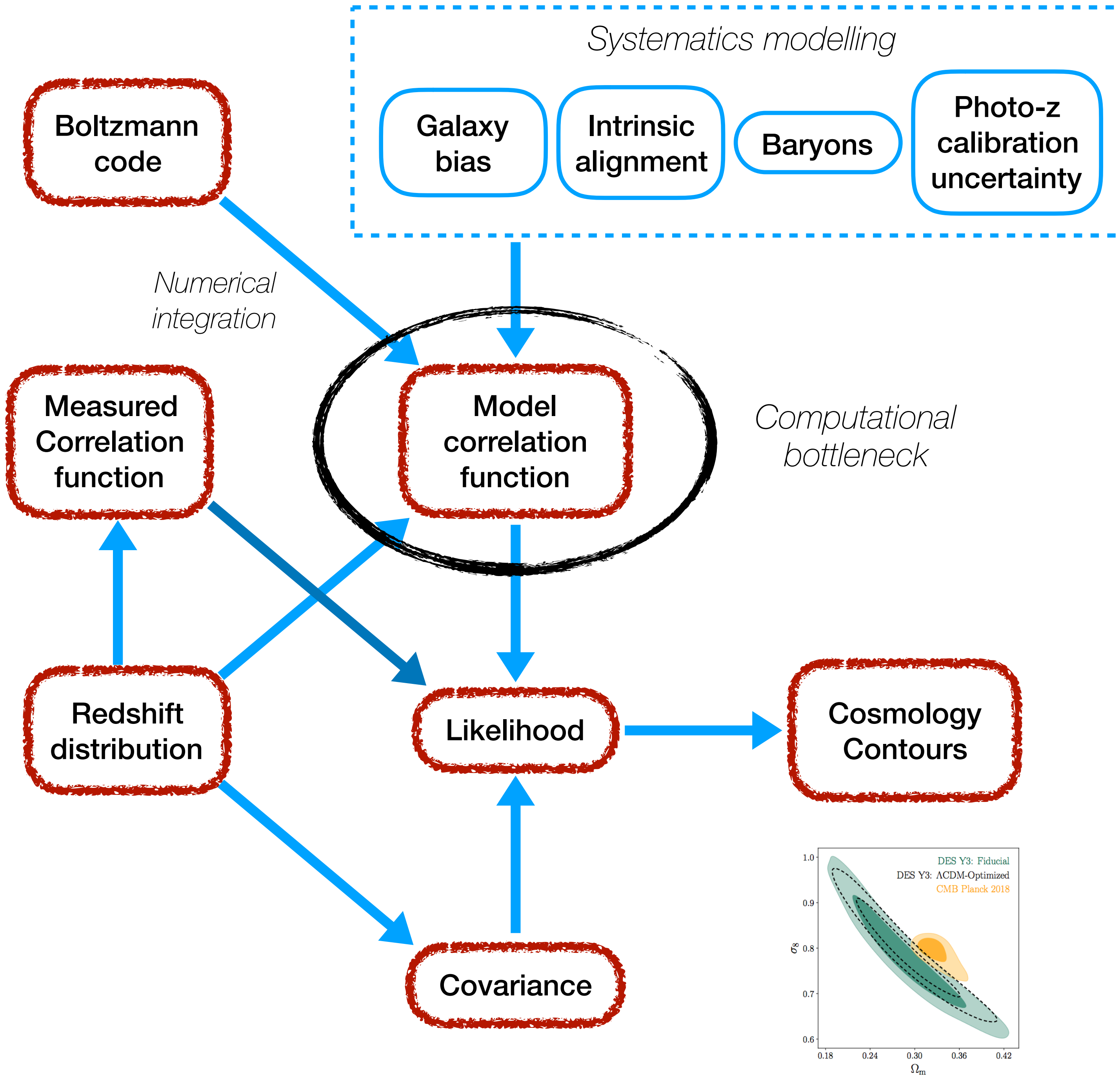


Each of these require hundreds/thousands of MCMC runs.

Computational cost prohibitive.

Challenge I: slow evaluation of model data vector

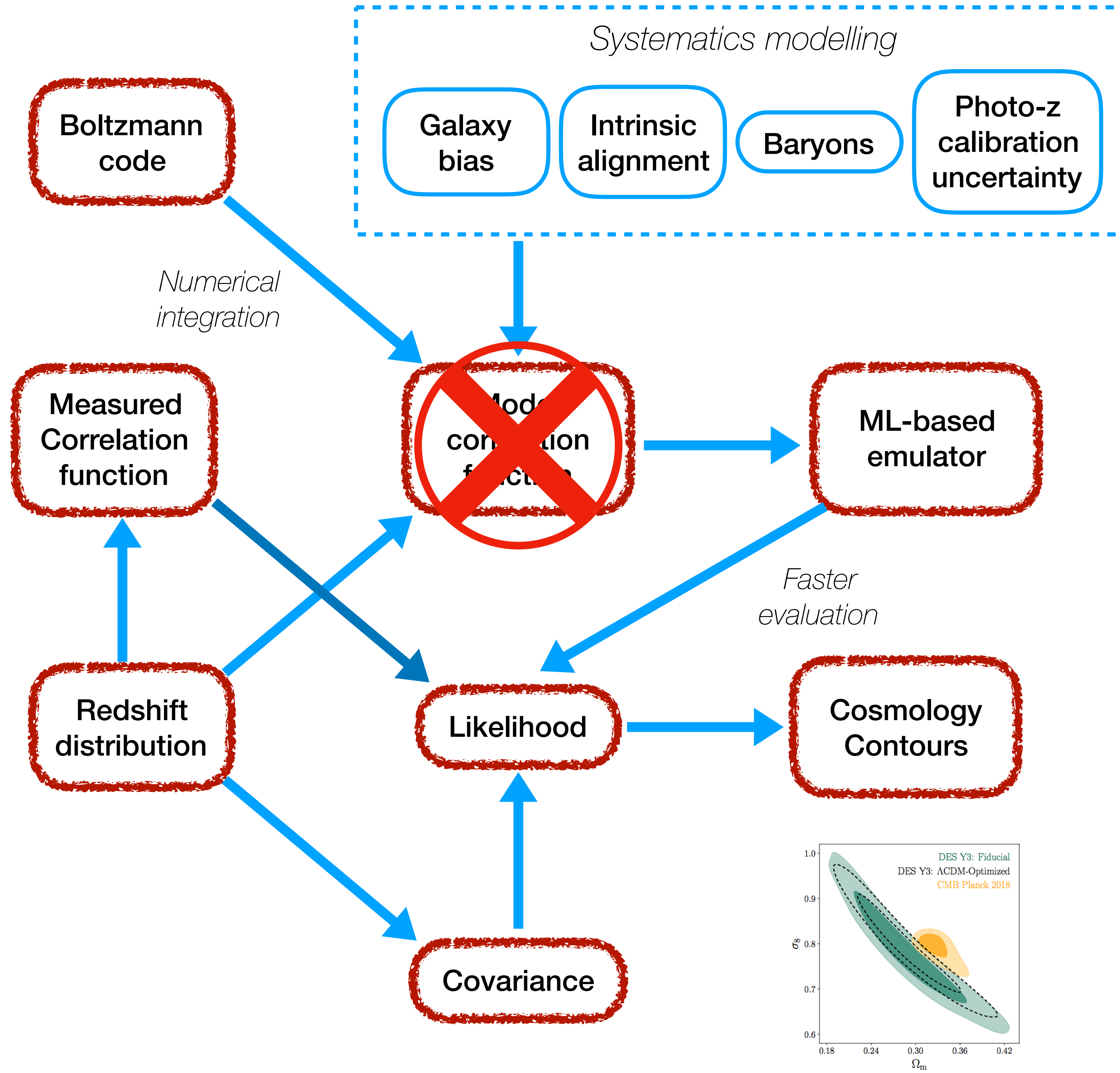
- Boltzmann codes / numerical integration are expensive.
- $\mathcal{O}(10^5 - 10^6)$ evaluations required in each MCMC analysis.



Images: DES, NASA

Challenge I: slow evaluation of model data vector

- Boltzmann codes / numerical integration are expensive.
- $\mathcal{O}(10^5 - 10^6)$ evaluations required in each MCMC analysis.
- _Alternative_: Use an emulator to speed-up data vector evaluation.
- After the initial computation of the data vectors, each call in MCMC very fast



Images: DES, NASA

Challenge II: Emulation in high dimensions

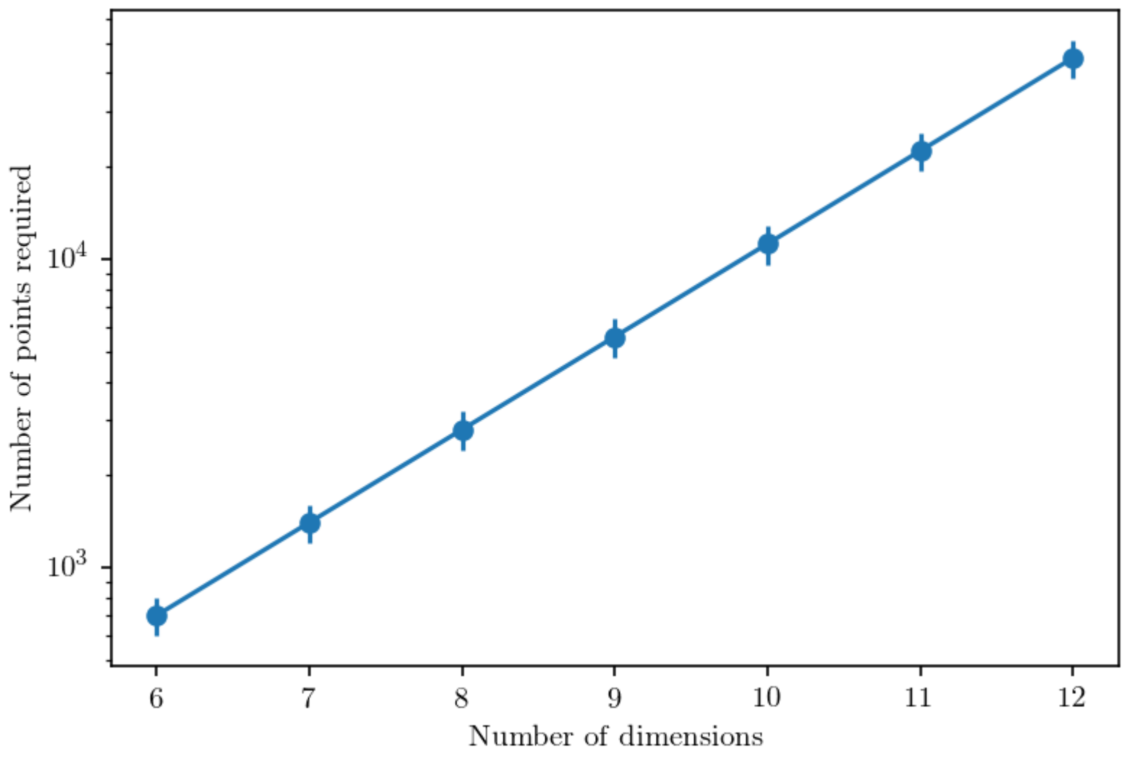
- Stage-IV analyses systematics-limited => more complex systematics modeling

- $\sim \mathcal{O}(\gtrsim 50)$ dimensional inference

- High dimensional emulation is hard (Curse of dimensionality)

- Numerical experiment:
  - Create LH sample within $[-4\sigma, 4\sigma]$ of a D-dim Gaussian
  - Determine # of points required to sample to get 50 points within 3σ ball

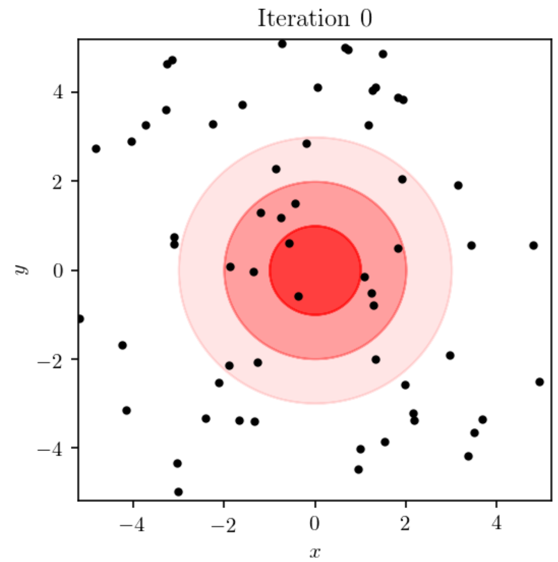
Emulation in high dimension is non-trivial!

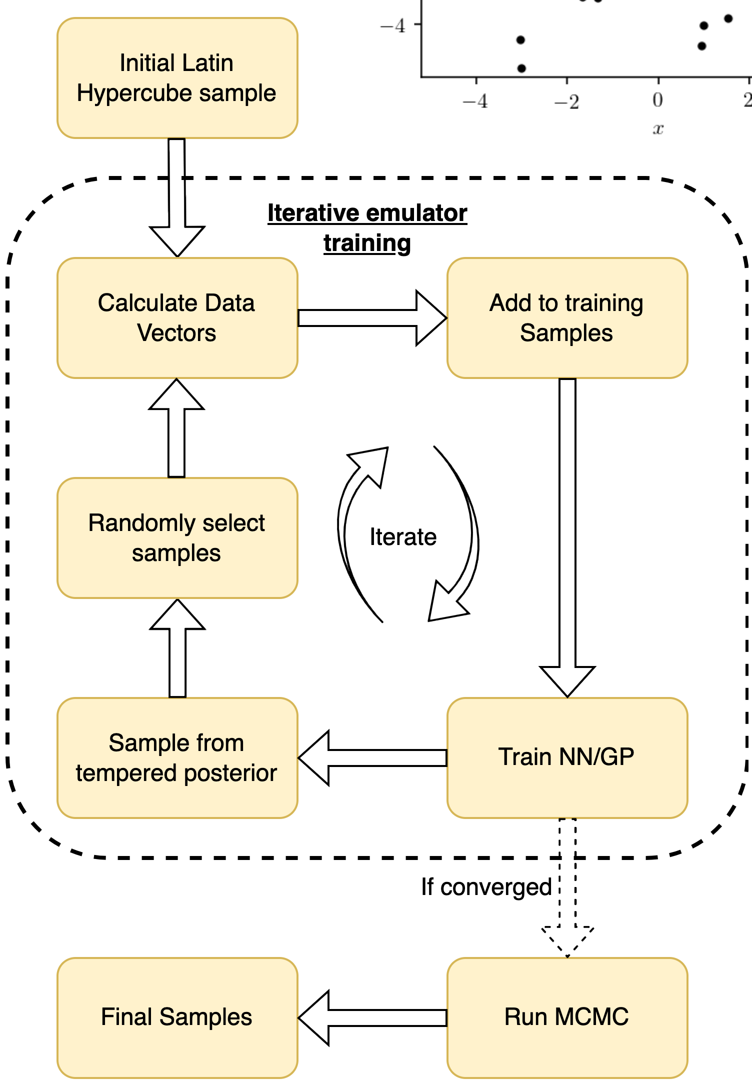


Need:

- $\mathcal{O}(10^5)$ *points for 12 dimensions*
- $\mathcal{O}(10^7)$ *points for 20 dimensions*

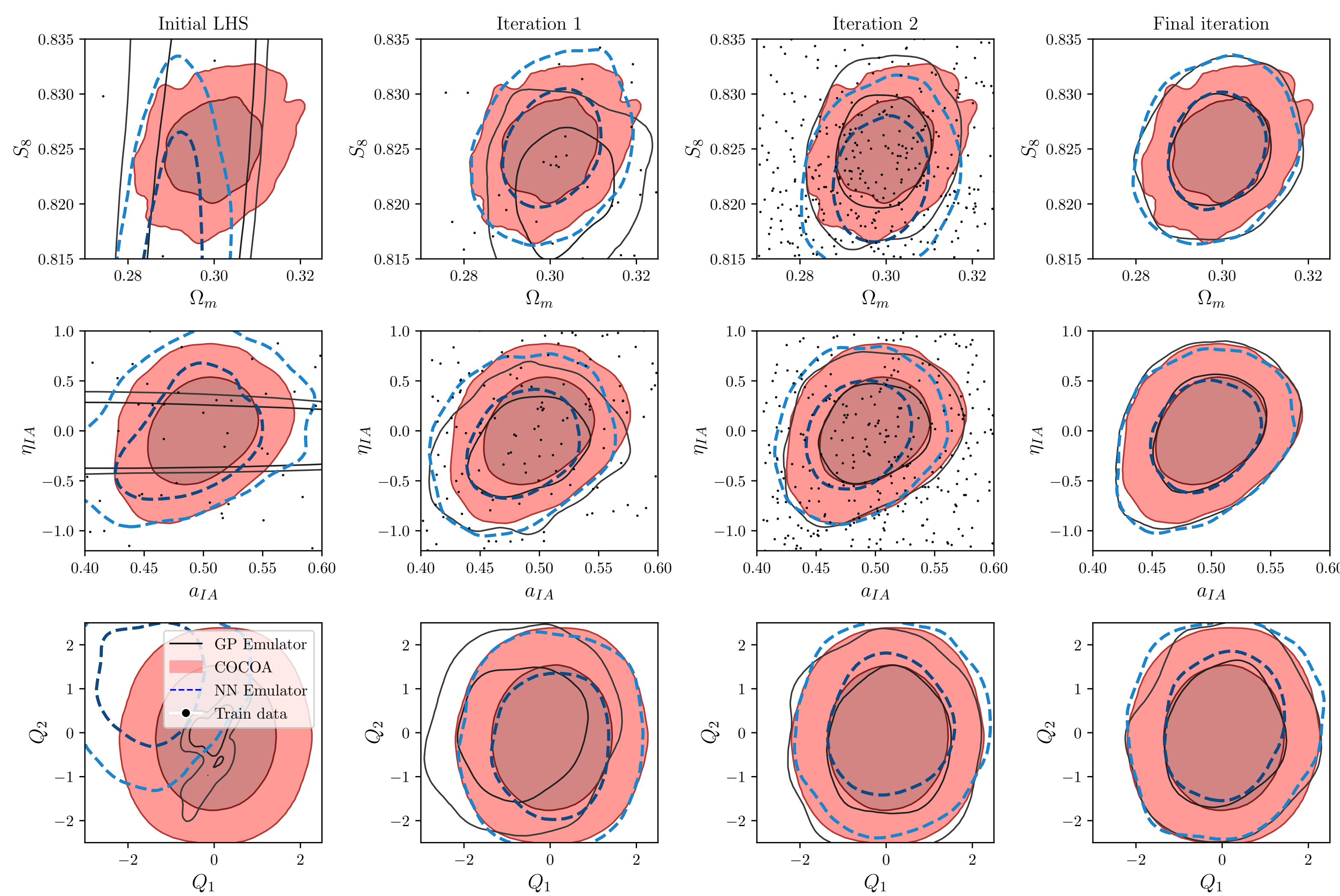
Iterative Emulator to the rescue



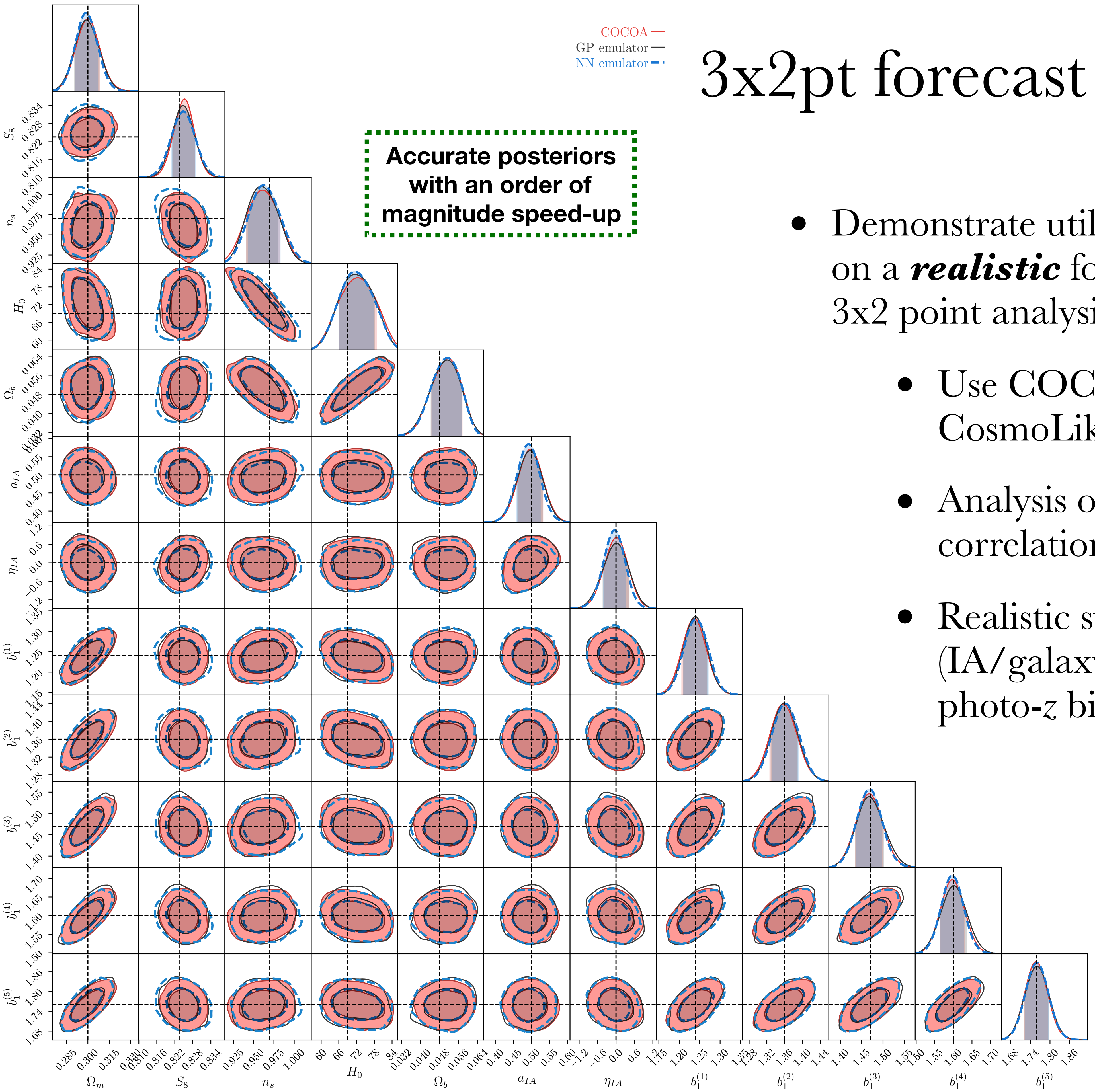


Motivation: **For inference, we only need high-fidelity emulation in the high posterior region**

Idea: **Use an iterative emulator to focus into the high posterior region, adding samples from the high posterior region**



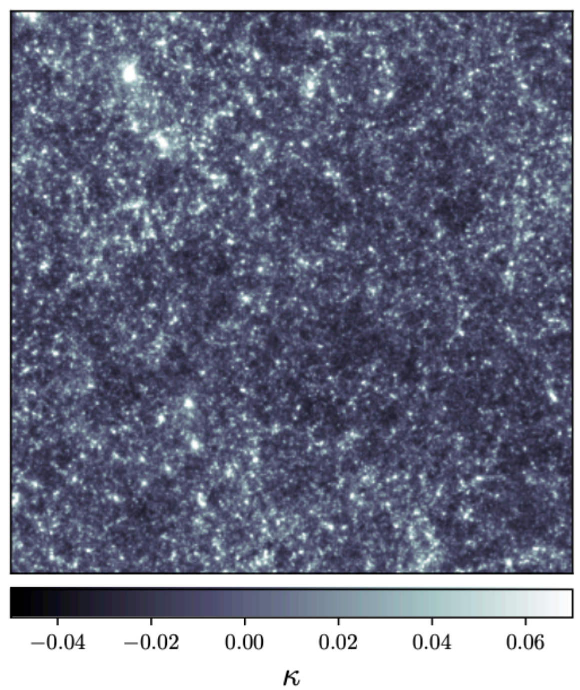
3x2pt forecast for LSST-Y1



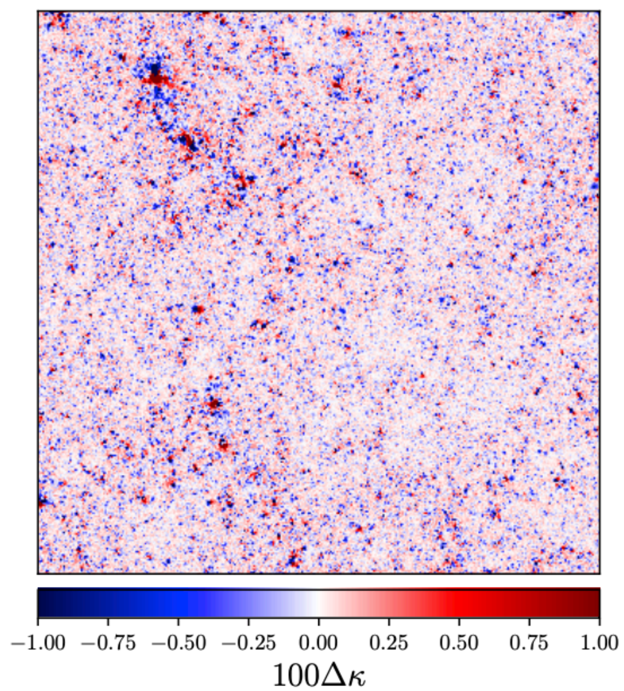
- Demonstrate utility of the emulator on a ***realistic*** forecast of LSST-Y1 3x2 point analysis:
    - Use COCOA (COBAYA/ CosmoLike joint architecture)
    - Analysis of real space correlation functions
    - Realistic systematics modeling (IA/galaxy bias/baryons/ photo-*z* bias)

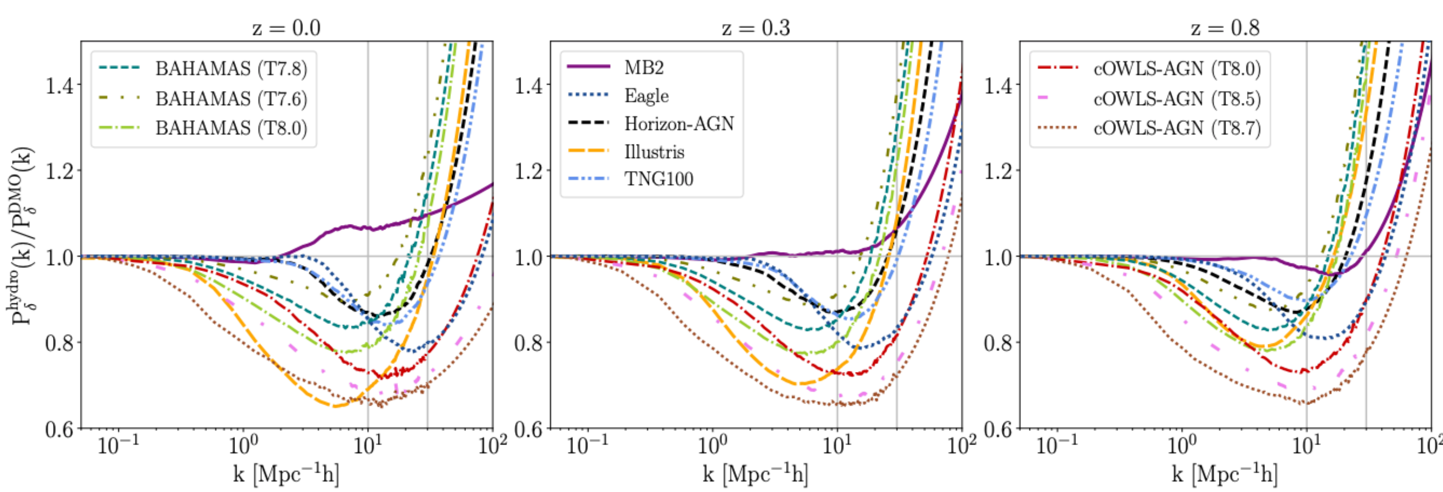
Case study: Impact of baryons on 3x2pt analysis

KappaTNG mass maps



Osato, Liu, '21



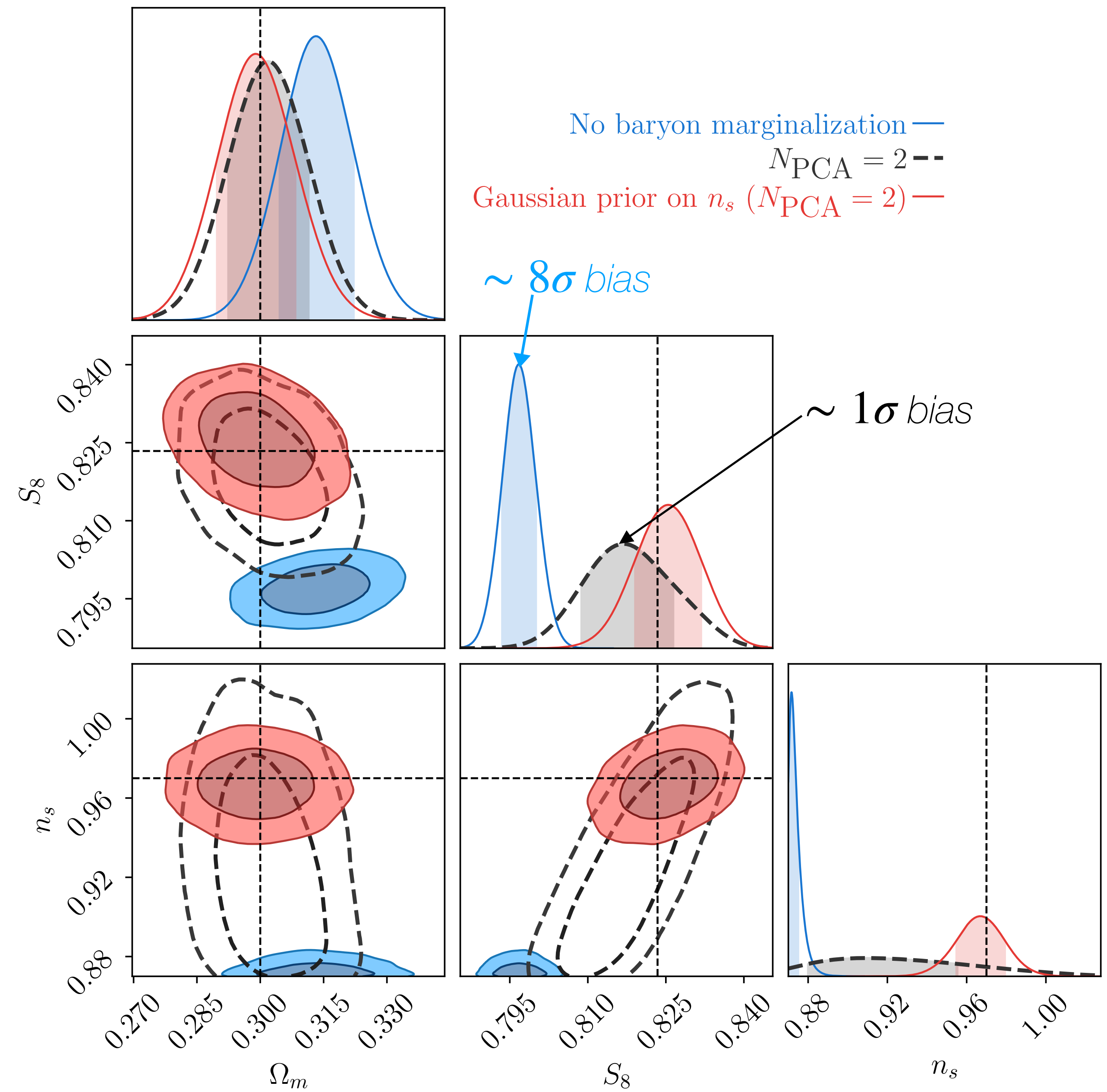


Huang+, 21

- Baryons impact the distribution of matter on small scales
- Usually mitigated by cutting small scales in the analysis
- Need simulated analyses to determine scale cuts/ analysis choice to mitigate baryonic effects

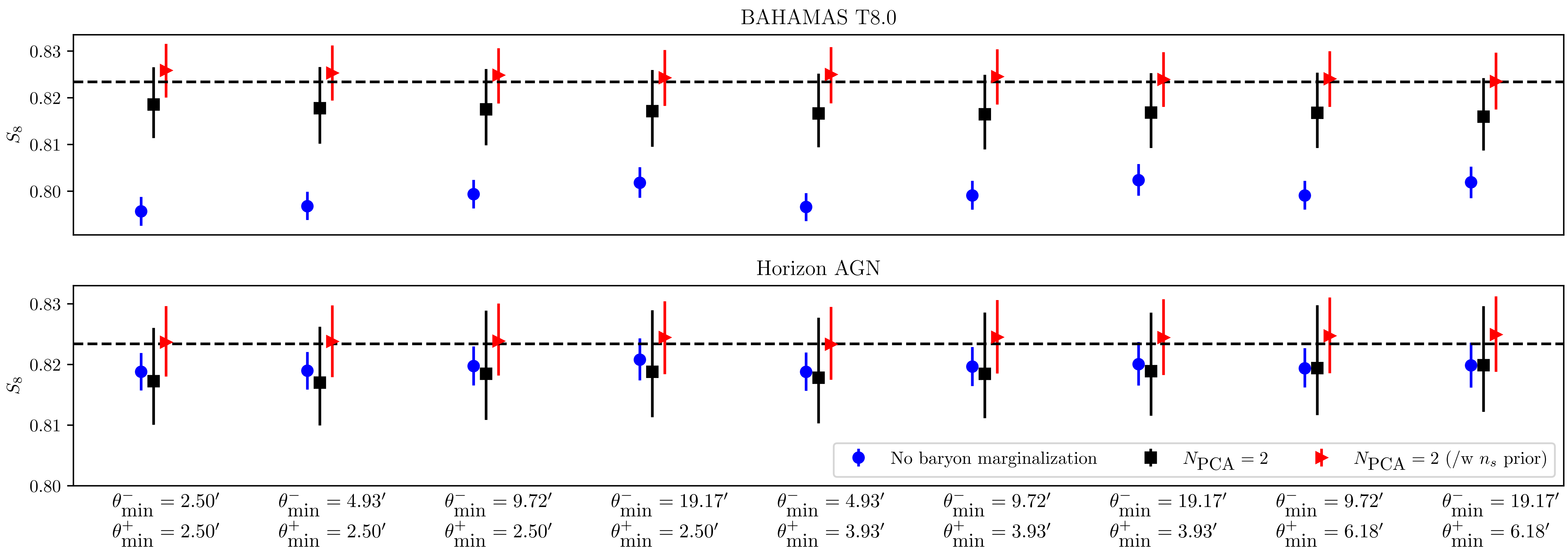
Case study: Impact of baryons on 3x2pt analysis

- Study different scale-cuts by reusing trained emulator
- Use scales up to 2.5 arcmin
- Highly biased for BAHAMAS (T8.0) w/o any mitigation scheme
- Mitigated using a PCA marginalization approach
- Impose prior on n_s to eliminate residual biases



Baryon marginalization assuming BAHAMAS (T8.0) contaminated data vector

(Extremely) Fast scale-cut analyses



- 5 minutes wall-time per analysis. $\mathcal{O}(1000)$ speed-up!
- Need one trained emulator for: *i)* Different scale cuts, *ii)* Different priors, *iii)* Different observed data vector, *iv)* Sub-space of parameter space.

Summary

- Challenges for data analysis of upcoming surveys:
  - ✴ Computation cost for inference is prohibitive
  - ✴ Emulation in high-dimensions is non-trivial
- We designed an iterative scheme that leads to fast and accurate inference. Demonstrated on LSST-Y1 3x2 point forecast.
- Ideal for:
  - ✴ Quantifying impact of different systematics
  - ✴ Optimizing survey strategy
  - ✴ Assessing tensions