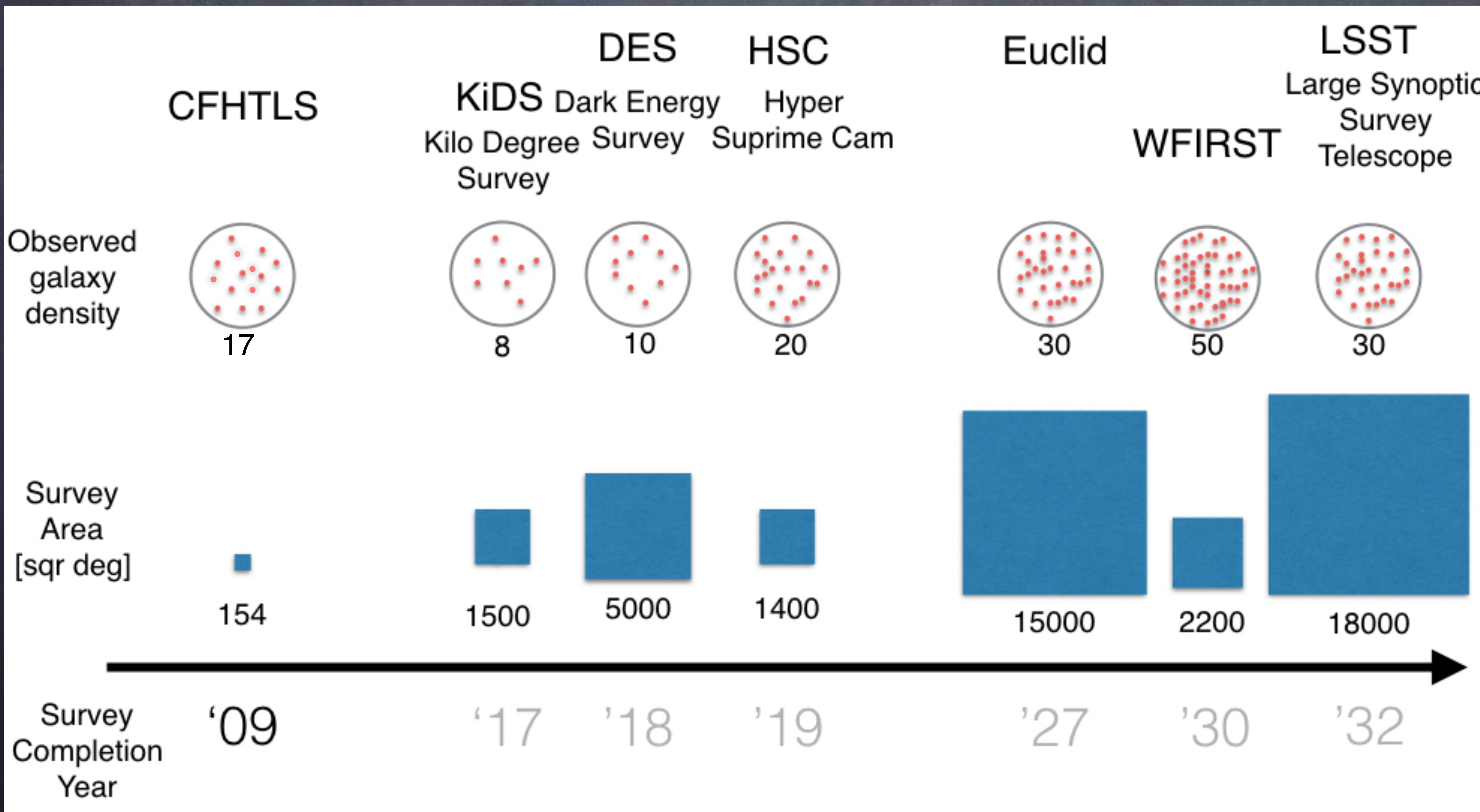
The Power of Combining Cosmological Probes

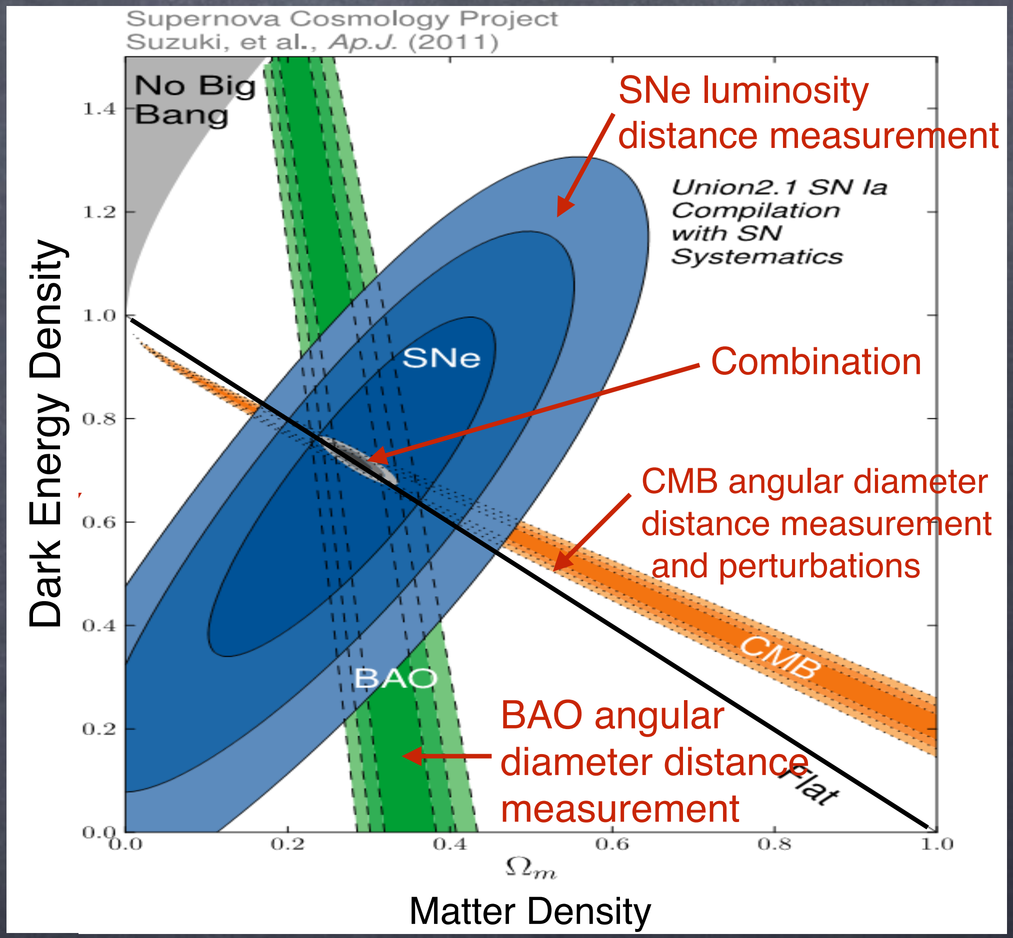
Elisabeth Krause
and the DES Theory &Combined Probes Working Group

Photometric Cosmology Surveys



The Power of Combining Probes

- Best constraints obtained by combining cosmological probes
  - independent probes: multiply likelihoods
- Combining large-scale structure probes (from same survey) requires more advanced strategies
  - clustering, clusters and WL probe same underlying density field, are correlated
  - correlated systematic effects
  - requires joint analysis



Joint Analysis Ingredients

Science Case

parameters of interest
which science?

large data vector
which probes + scales?

Likelihood Function

number counts: Poisson

2PCF: ~ Gaussian (?)

improvements needed for stage IV surveys

Model Data Vector

consistent modeling of all observables

including all cosmology + nuisance parameters

Joint Covariance

large and complicated, non-(block) diagonal matrix

use template + regularization

$$p(\boldsymbol{\pi}|\hat{\mathbf{d}}) \propto p(\boldsymbol{\pi}) \int \mathcal{L}\left(\hat{\mathbf{d}}|\mathbf{d}(\boldsymbol{\pi},\mathbf{n}),\mathcal{C}\right) p(\mathbf{n})\, \mathrm{d}^n\mathbf{n}$$

Cosmology Priors

Nuisance Parameters

systematic effects
$|\mathbf{n}| \gg |\boldsymbol{\pi}|$
parameterize + prioritize!

Priors

External Data
Simulations

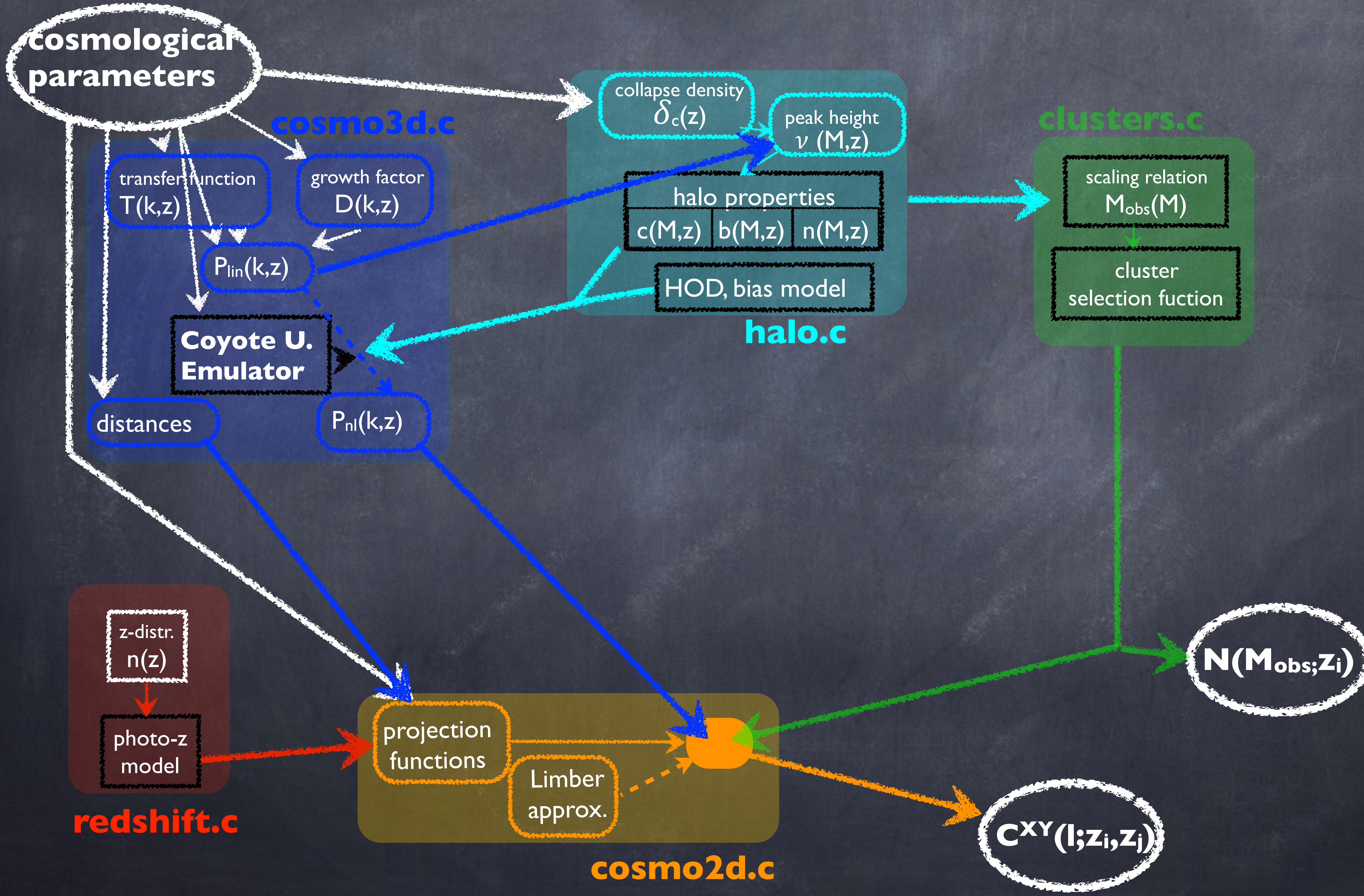
validate

Introducing CosmoLike

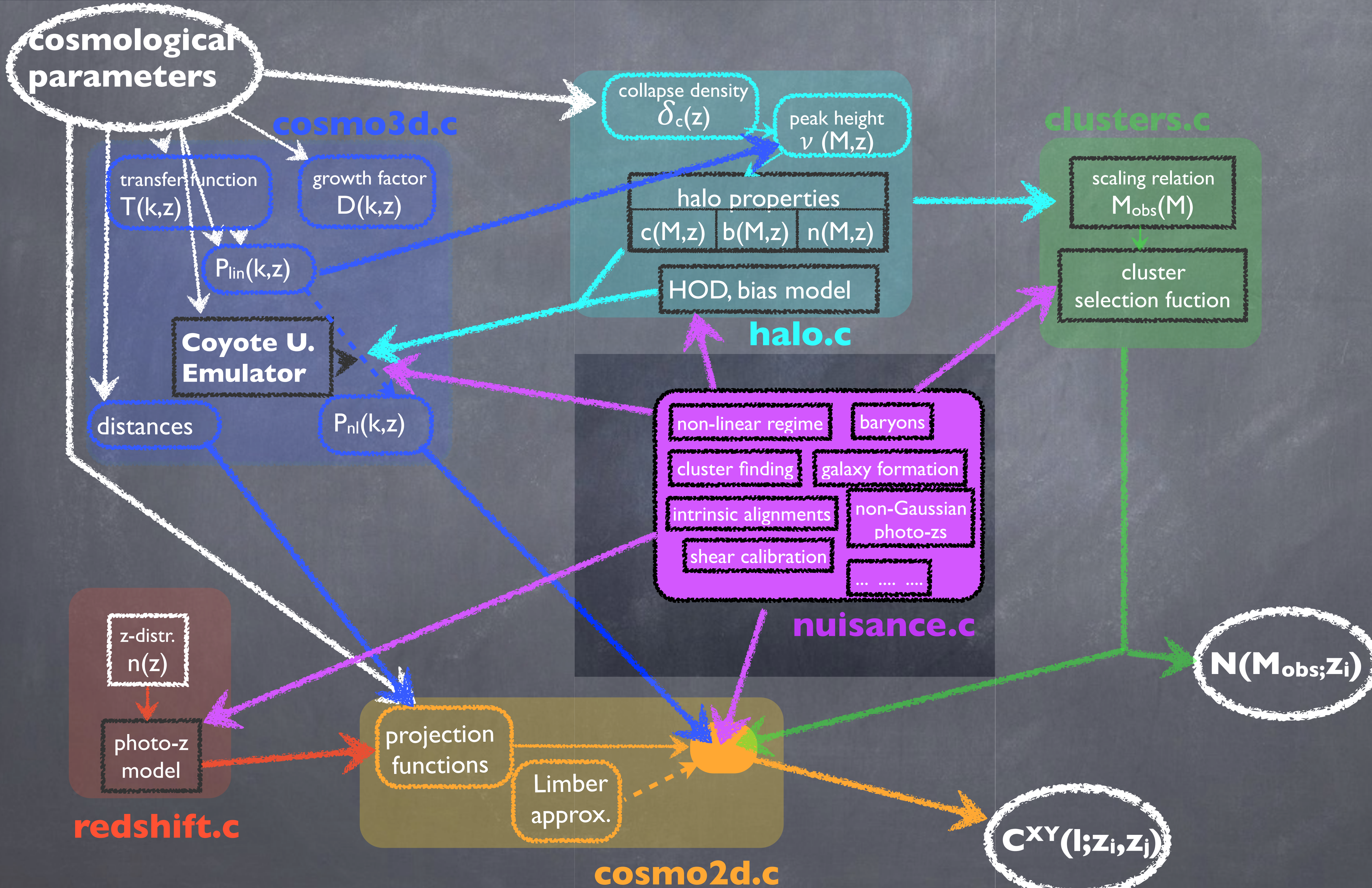
EK+Eifler 2016

- Likelihood analysis library for combined probes analyses
- Observables from three object types, and their cross-correlations
  - *galaxies* (positions), *clusters* (positions, N_{200}), *sources* (shapes, positions)
    - galaxy clustering, cluster abundance + cluster lensing (mass self-calibration), galaxy-galaxy lensing, cosmic shear, CMB cross-correlations
  - separate n(z) + specific nuisance parameters for each object type
- Consistent modeling across probes, including systematic effects
- Computes non-Gaussian (cross-)covariances
  - halo model + regularization from $\mathcal{O}(25)$ simulated realizations
- Optimized for high-dimensional likelihood analyses
- Improvements by trial and error on DES → lessons for LSST

CosmoLike Data Vector



CosmoLike Data Vector



Combined Probes Systematics

- “Precision cosmology”: excellent statistics - systematics limited
  - (and man-power limited!)
- Easy to come up with large list of systematics + nuisance parameters
  - galaxies: LF, bias (e.g., 5 HOD parameters + b_2 per z-bin,type)
  - cluster mass-observable relation: mean relation + scatter parameters
  - shear calibration, photo-z uncertainties, intrinsic alignments,...
  - Σ(poll among DES working groups) ~ 500-1000 parameters
- Self-calibration + marginalization
  - can be costly (computationally, constraining power)

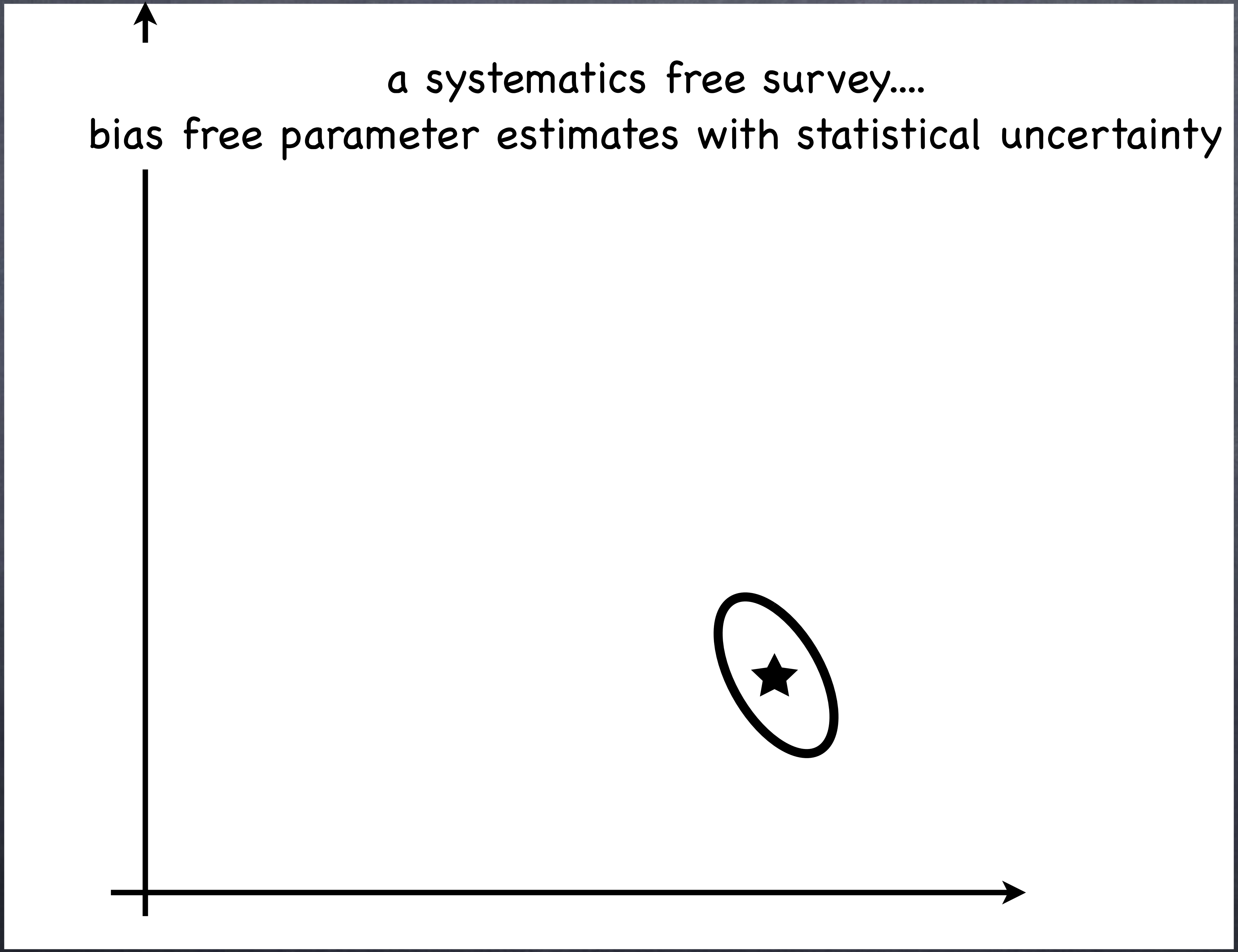
Work Plan for *Known* Systematics

- What's the dominant known systematic?

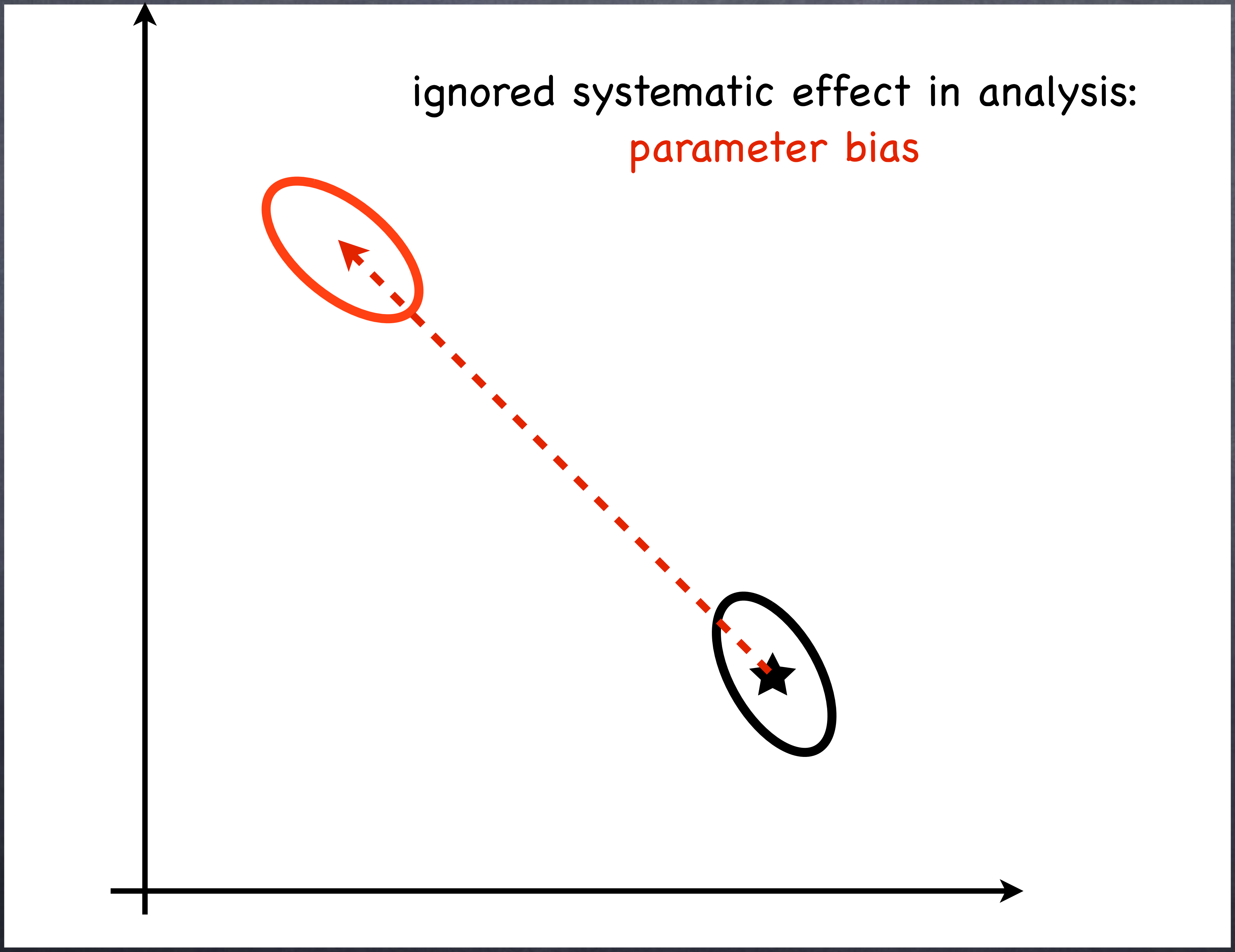
  No one-fits-all answer, need to be more specific!

- Specify data vector (probes + scales)
- Identify + model systematic effects
  - find suitable parameterization(s)
  - *need to be consistent across probes*
- Constrain parameterization + priors on nuisance parameters
  - independent observations
  - other observables from same data set
  - split data set

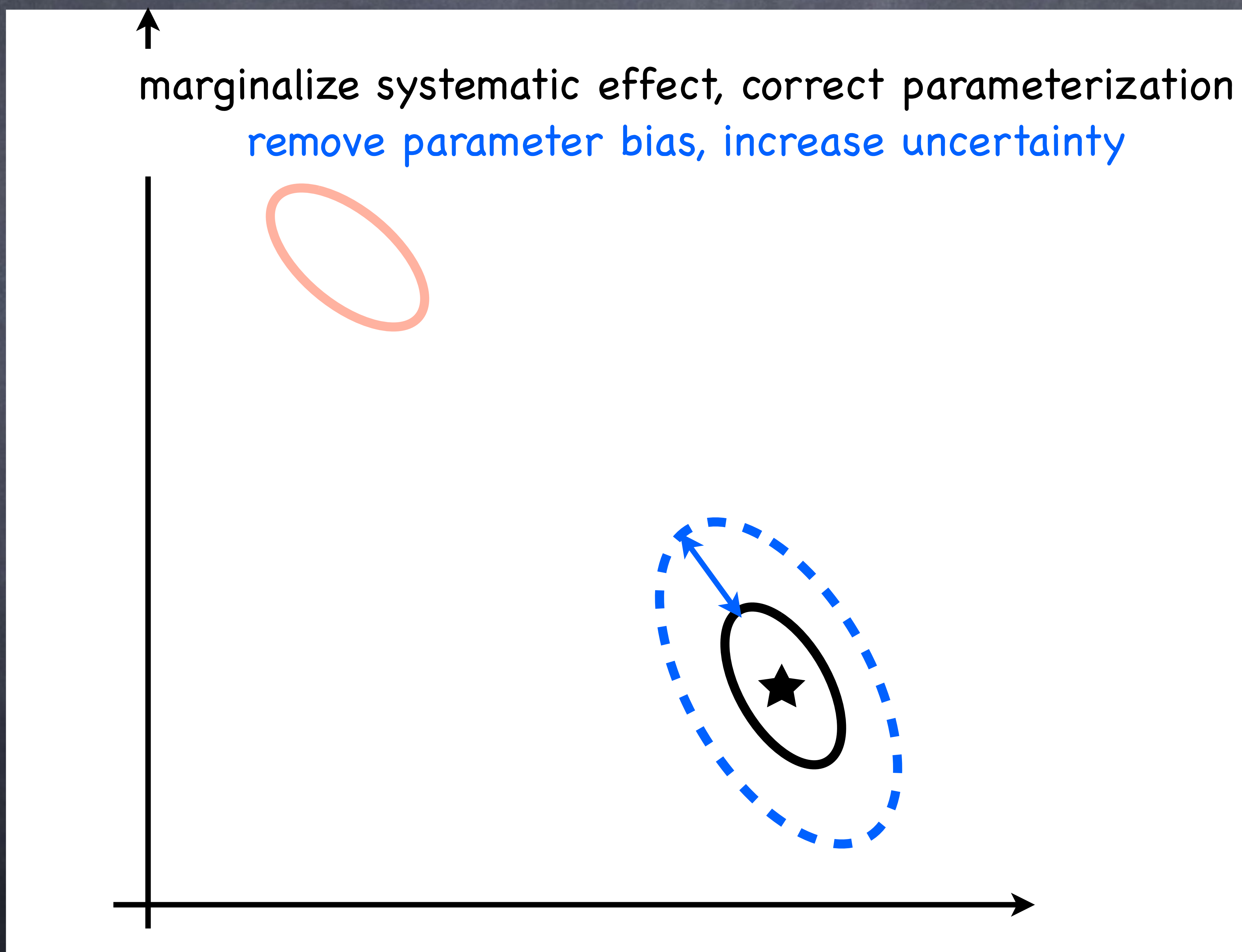
The Trouble with Systematics



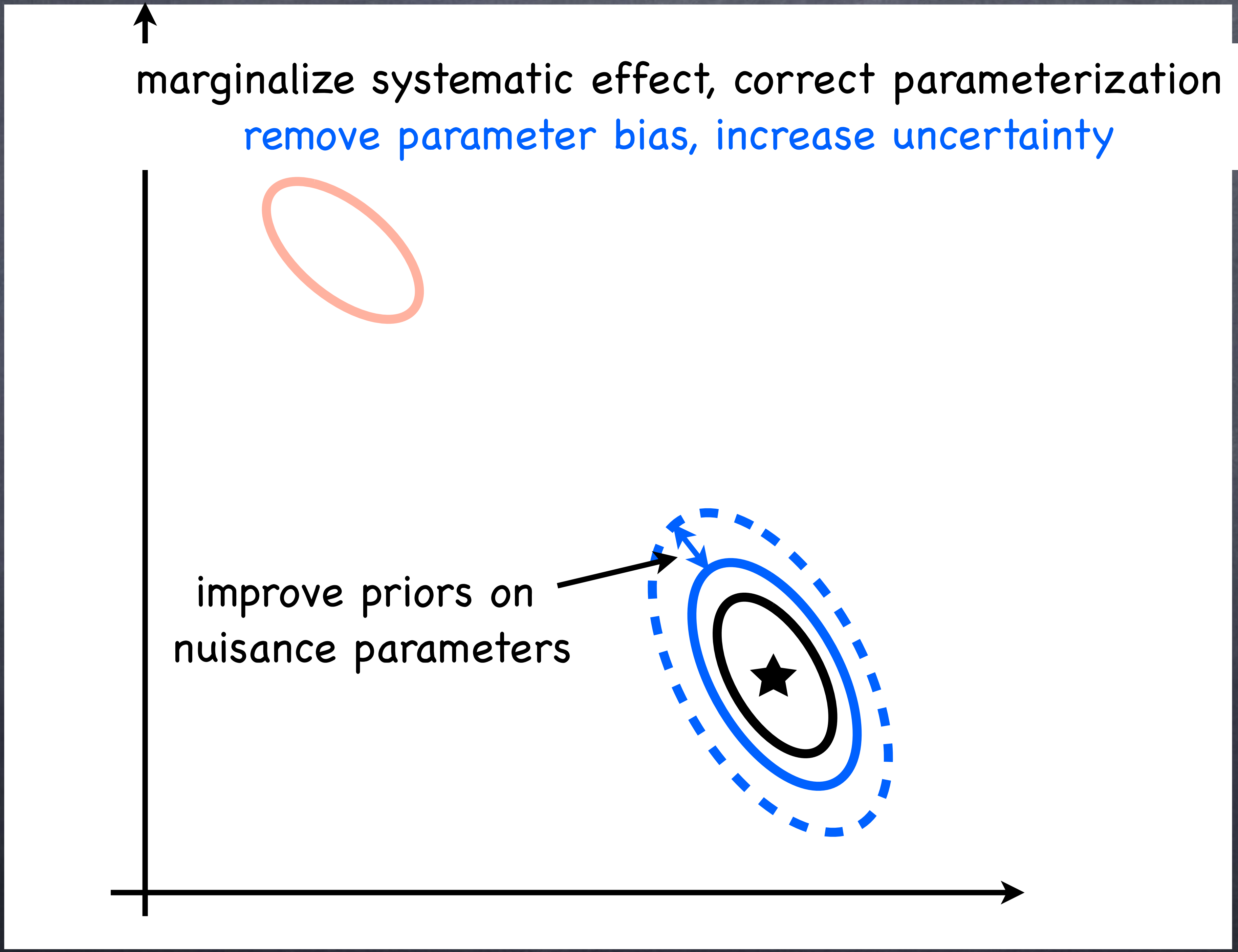
The Trouble with Systematics



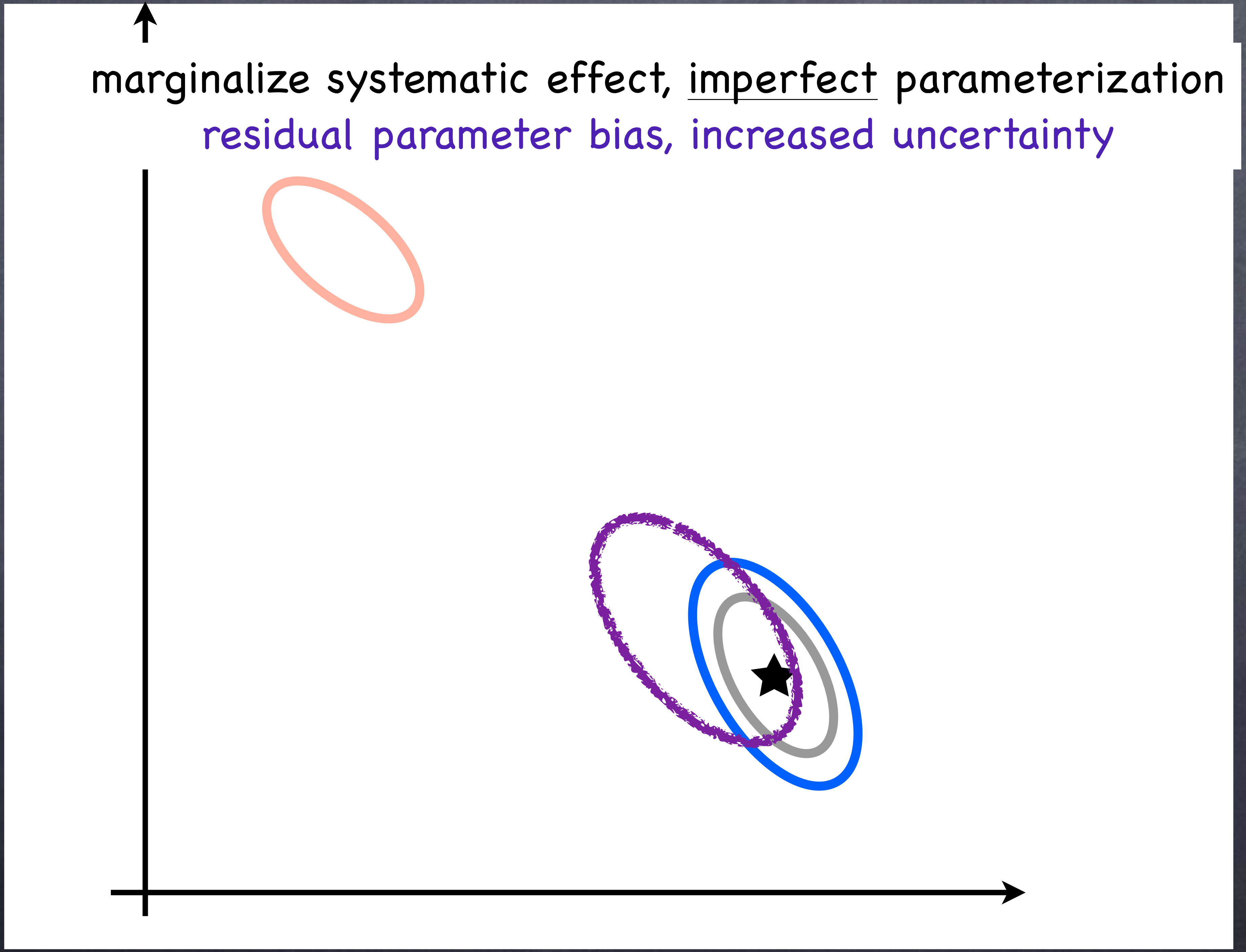
The Trouble with Systematics



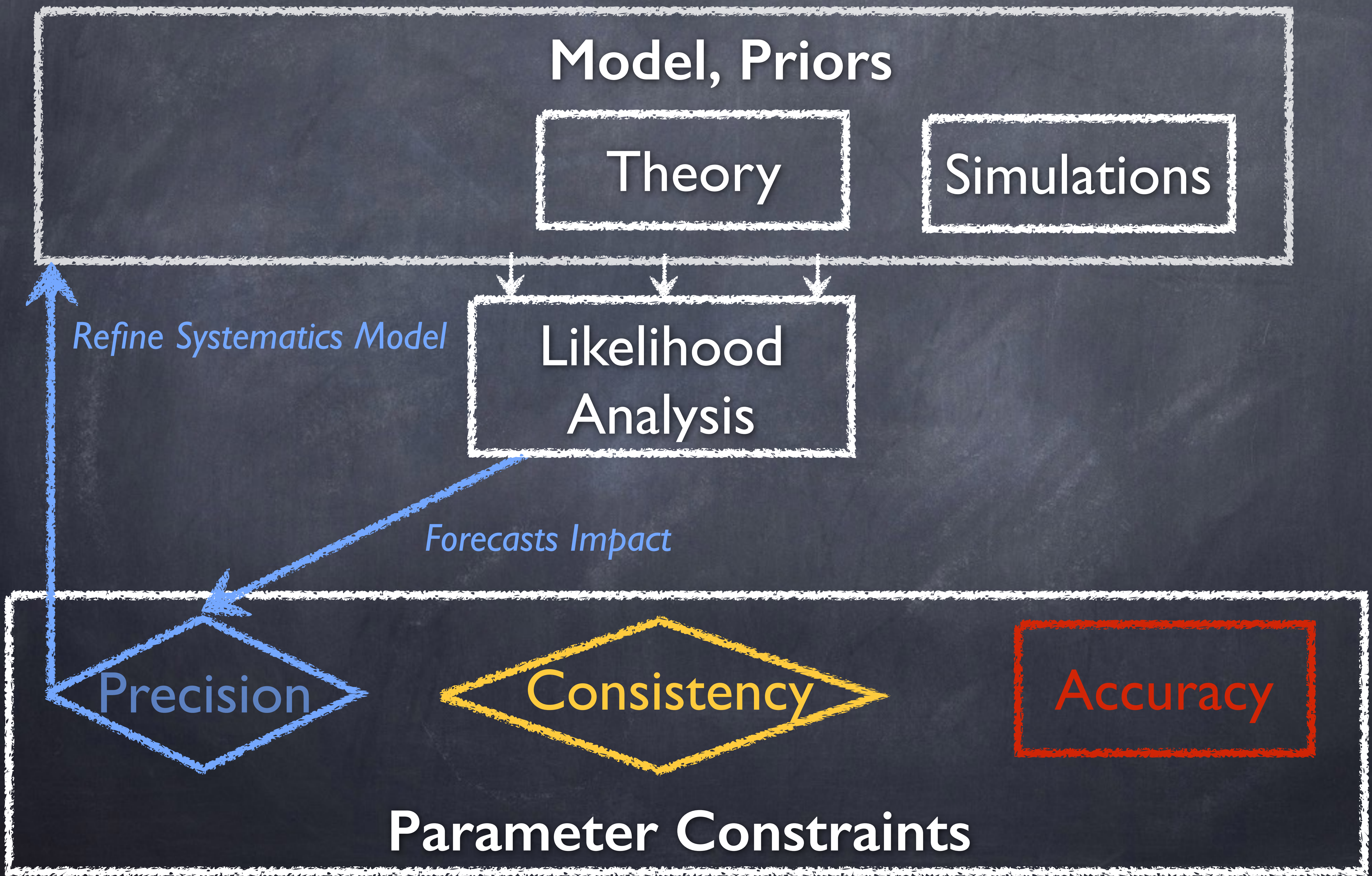
The Trouble with Systematics



The Trouble with Systematics



Joint Analysis Work Plan: Step I



Fundamental Physics from Galaxy Surveys

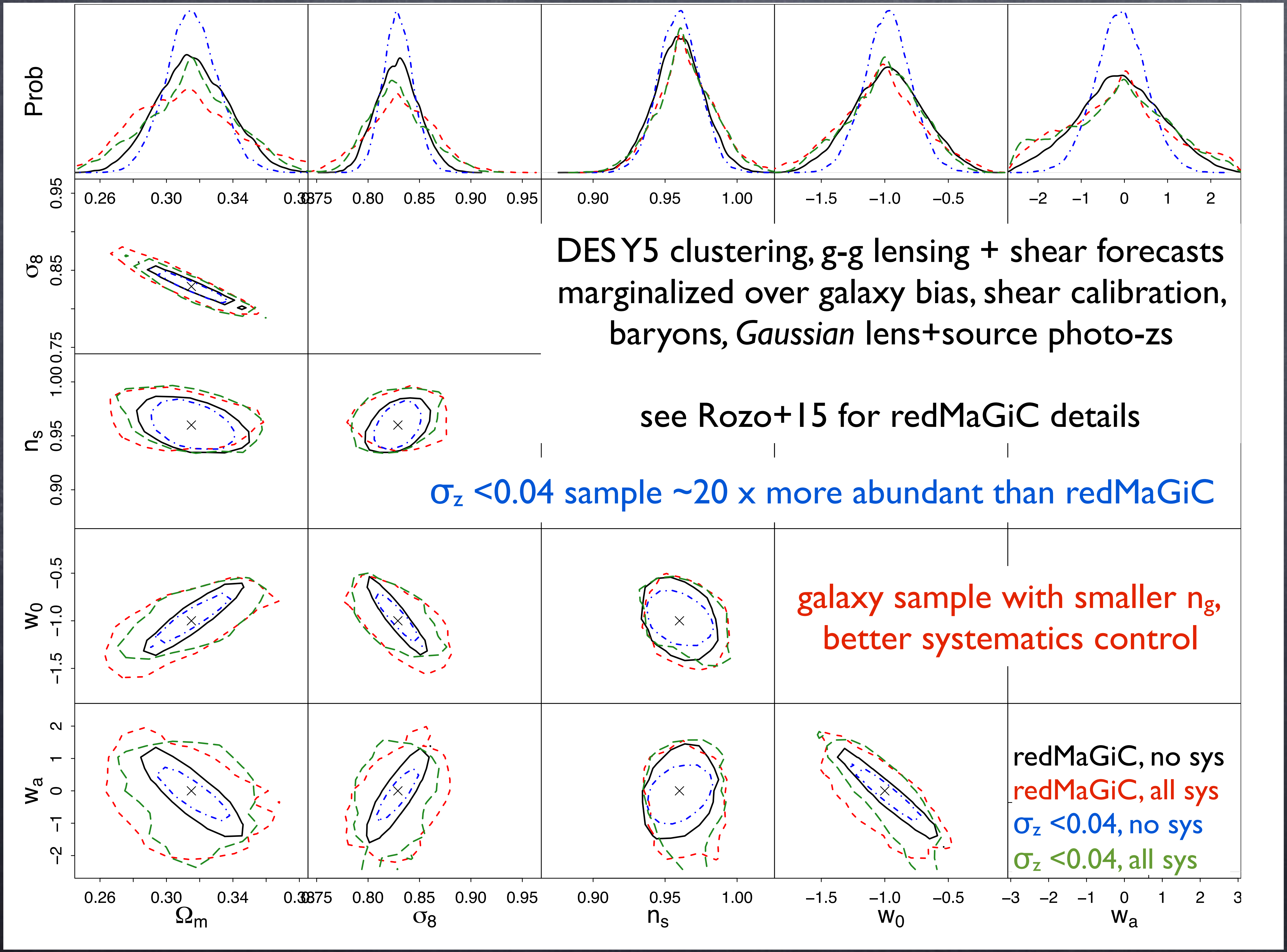
Galaxies are not simple point-like tracer particles

- how much do we need to understand for accurate cosmology?

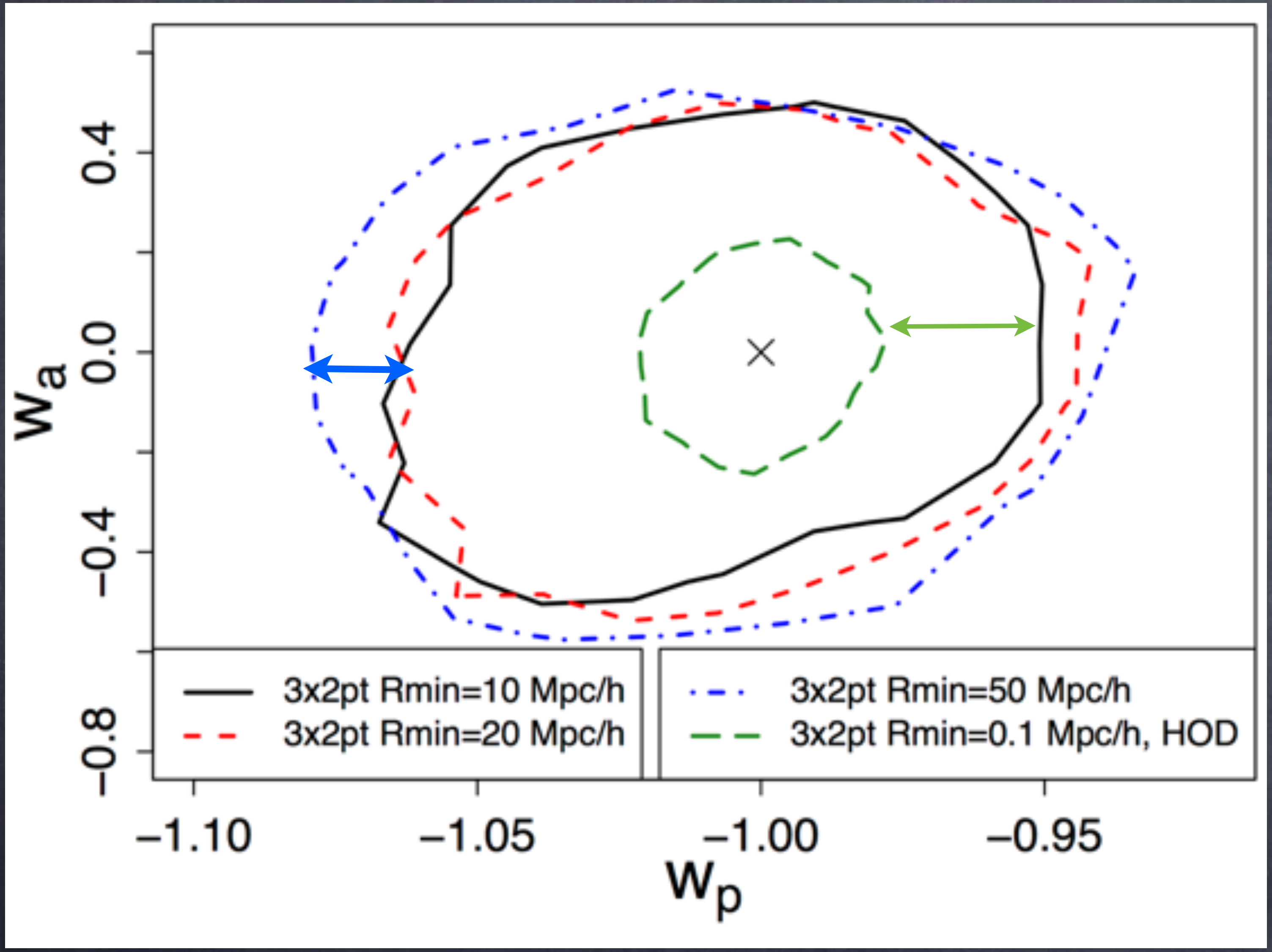
- photometric redshifts
- galaxy bias
- tidal fields -> galaxy orientations
- …

- accuracy better for some types of galaxies than for others
  - how many galaxies do we need (to understand) for cosmology?
  - worked examples on next slides

DES Forecasts: Photo-zs vs. Shot Noise



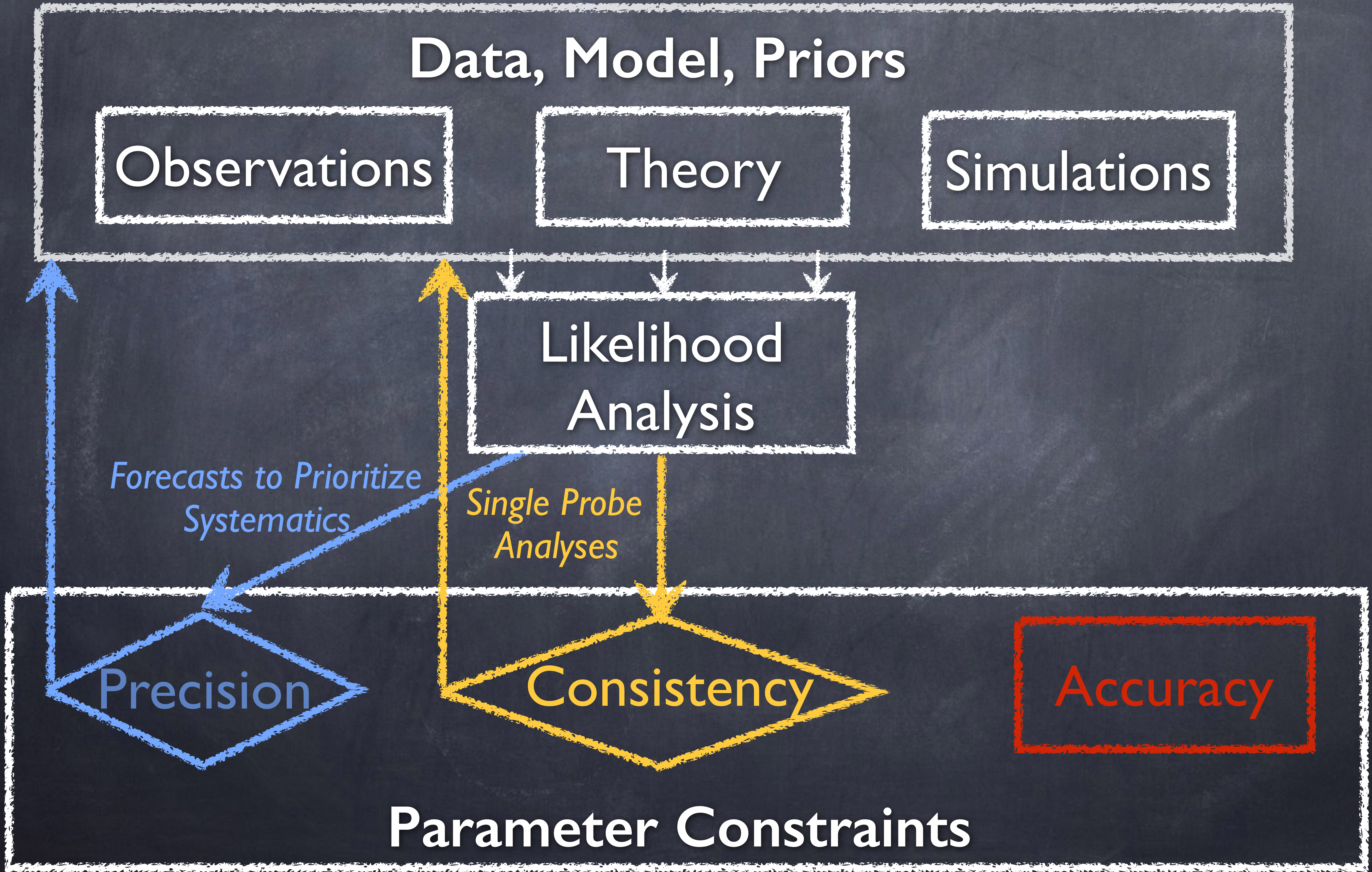
Cut-off for Galaxy Bias Models?



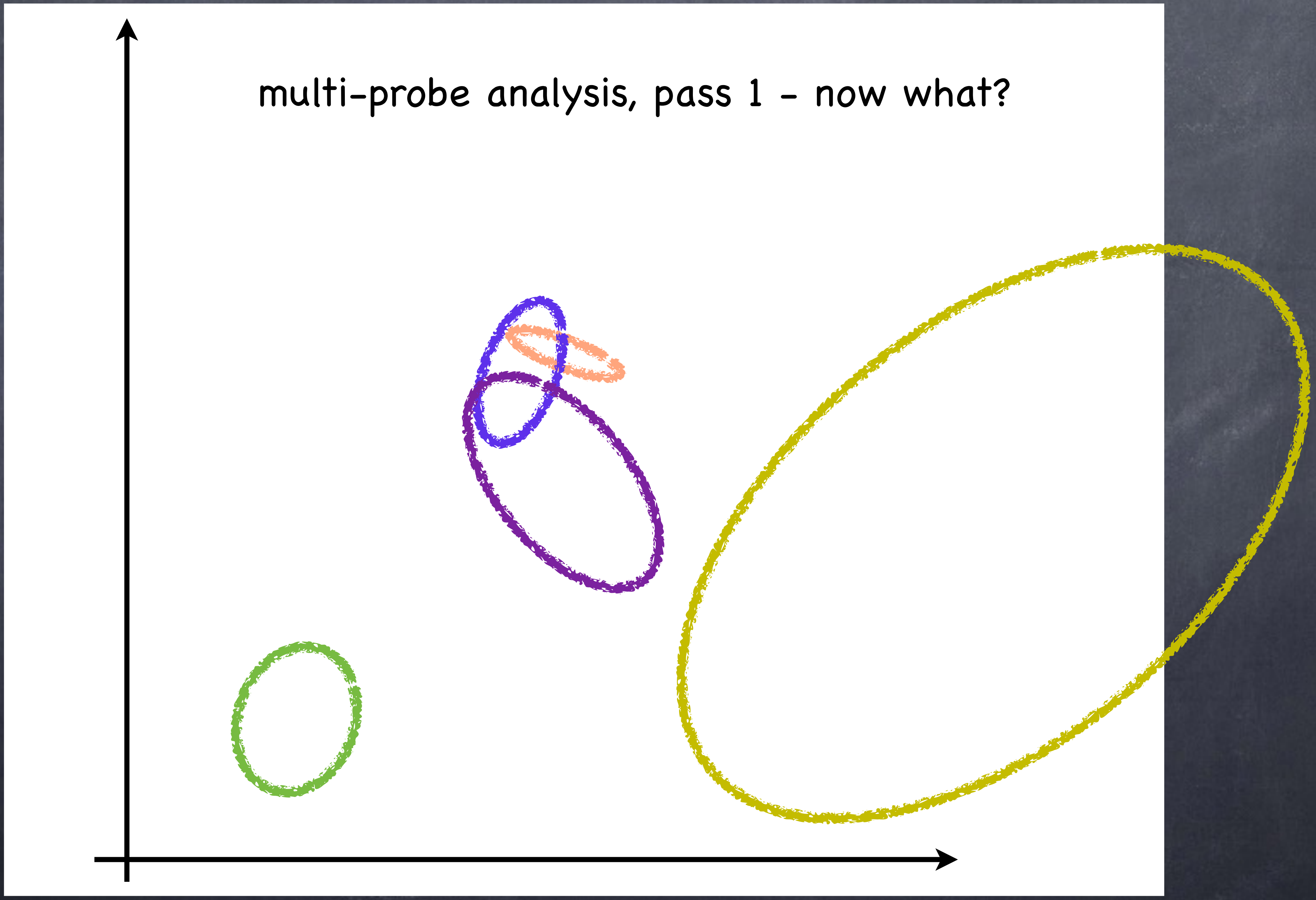
LSST, WL + clustering
WL to l < 5000
clustering: vary cut-off scales
develop perturbative biasing up to k ~ 0.6 h/Mpc - with well-constrained new parameters
understand non-linear regime

details: EK & Eifler '16

Joint Analysis Work Plan



Unknown Systematics? vs. New Physics?



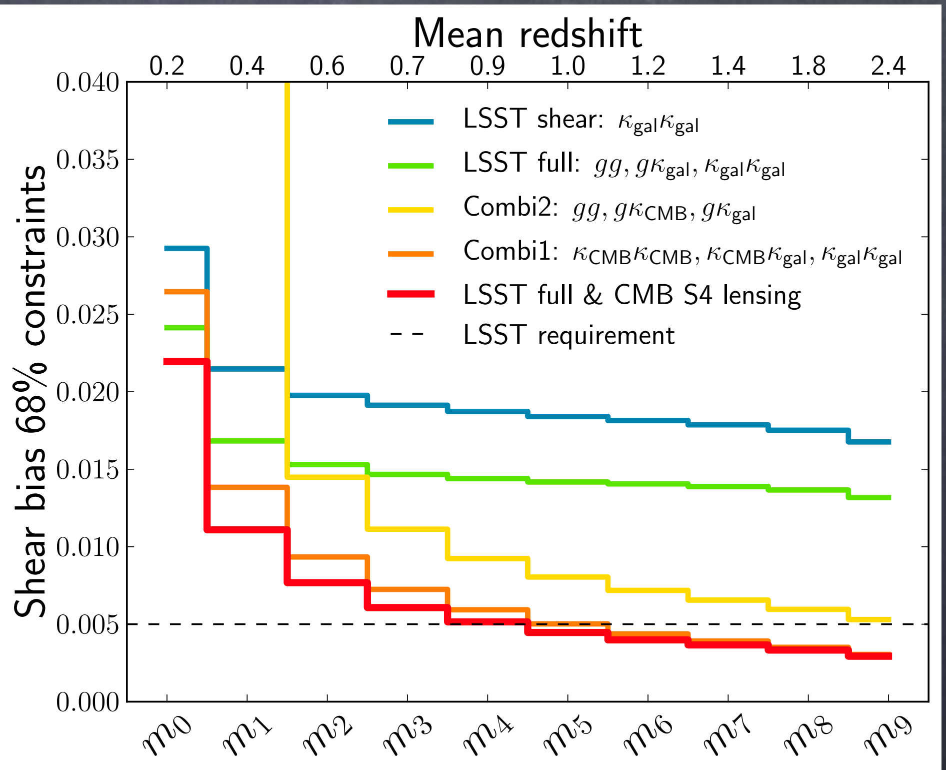
Unknown Systematics? vs. New Physics?

- scale dependence?
- dependence on galaxy selection?
- calibrate with more accurate measurements
  - spectroscopic redshifts
  - galaxy shapes from space-based imaging
    [potentially expensive]

Unknown Systematics? vs. New Physics?

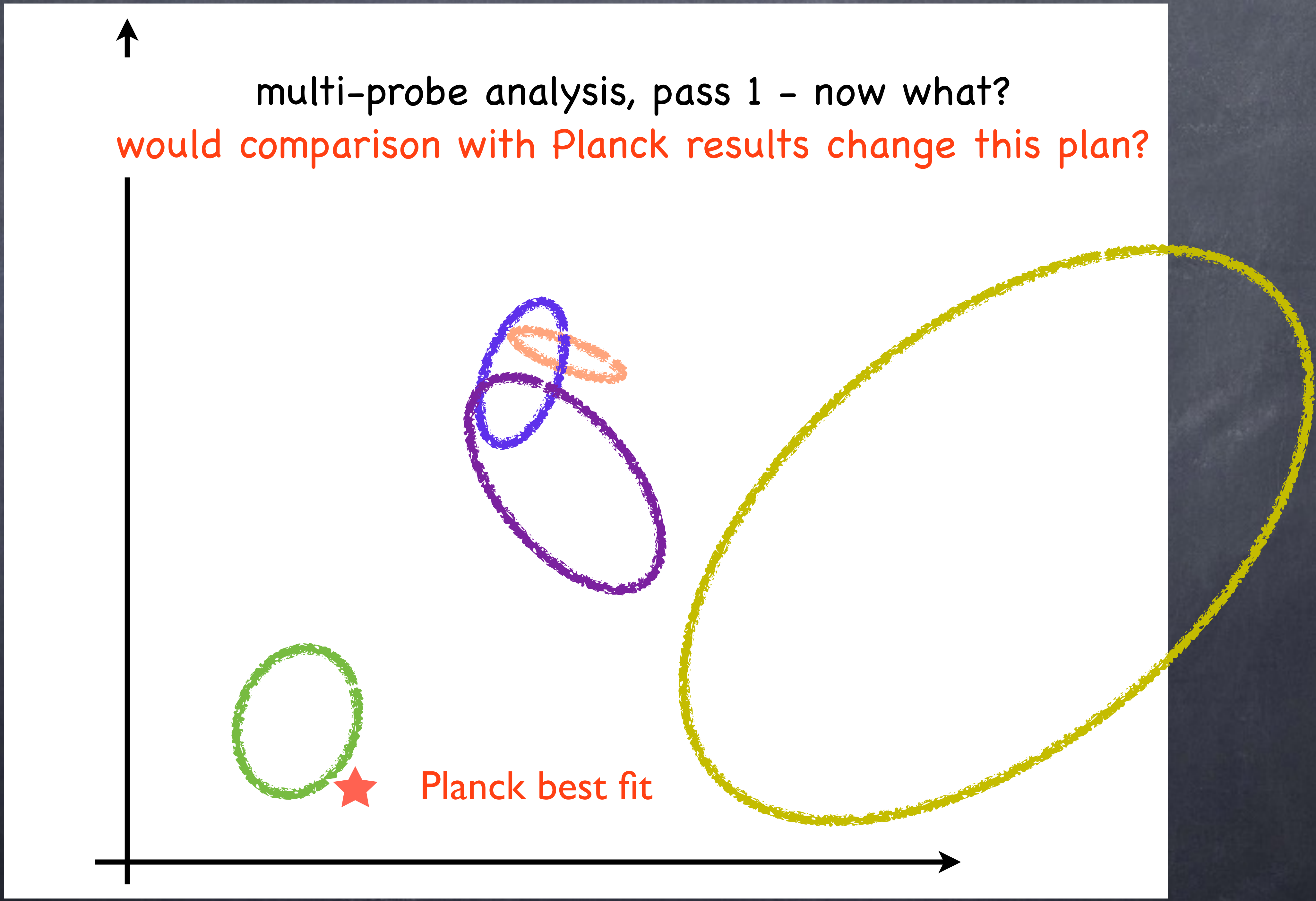
- scale dependence?
- dependence on galaxy selection?
- calibrate with more accurate measurements
  - spectroscopic redshifts
  - galaxy shapes from space-based imaging [potentially expensive]
- correlate with different surveys
  - predict cross-correlations based on LSST analysis
  - constrain uncorrelated systematics
  - e.g., cross-correlation with CMB-S4 lensing
- invent optimized estimators

  [fun, but not a general solution]



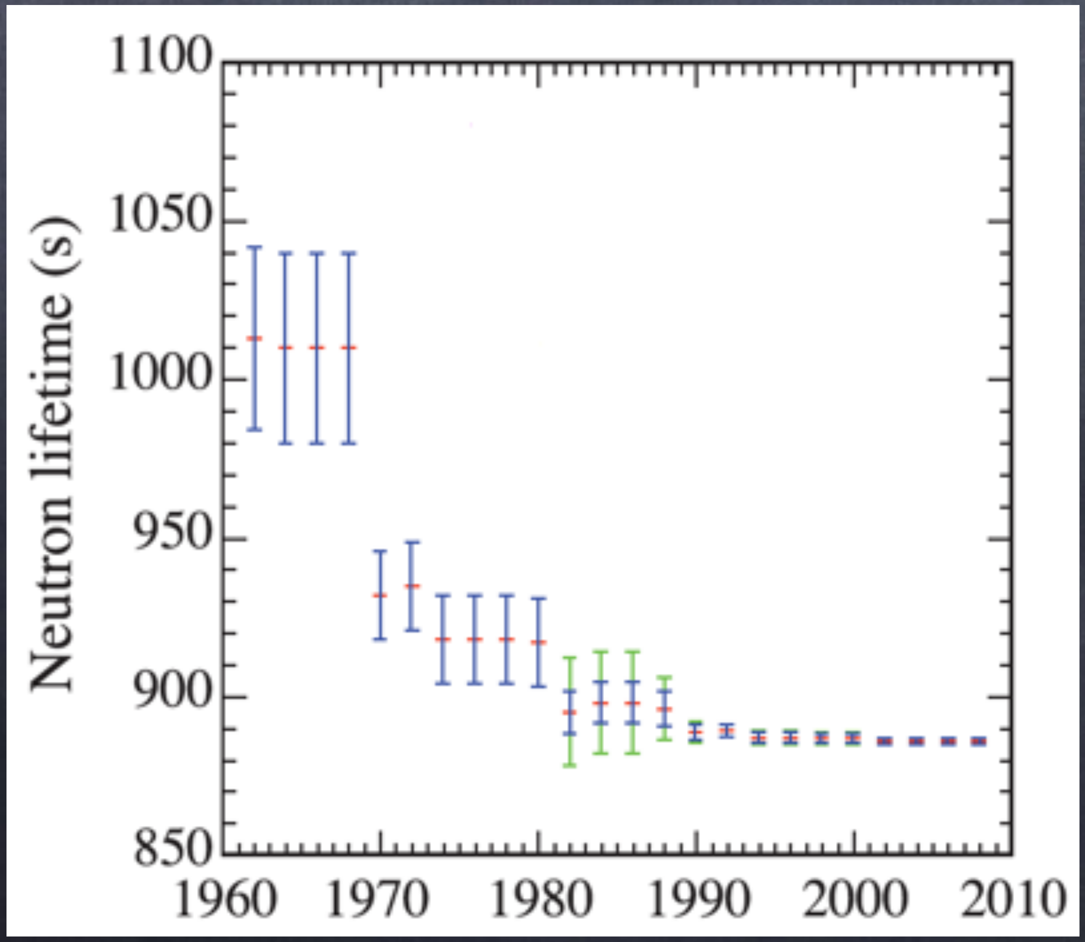
LSST WL x CMB-S4 lensing
calibrate shear calibration bias
Schaan, EK,+ 2016

Unknown Systematics? vs. New Physics?



Experimenter Bias?

- nuisance parameters will outnumber cosmological parameters by far
  - what models + priors to adapt? when is the analysis done?
  - *don't use (implicit) w = -1 prior to constrain galaxy properties*



a warning from particle physics
Credit: A. Roodman, R. Kessler, Particle Data Group

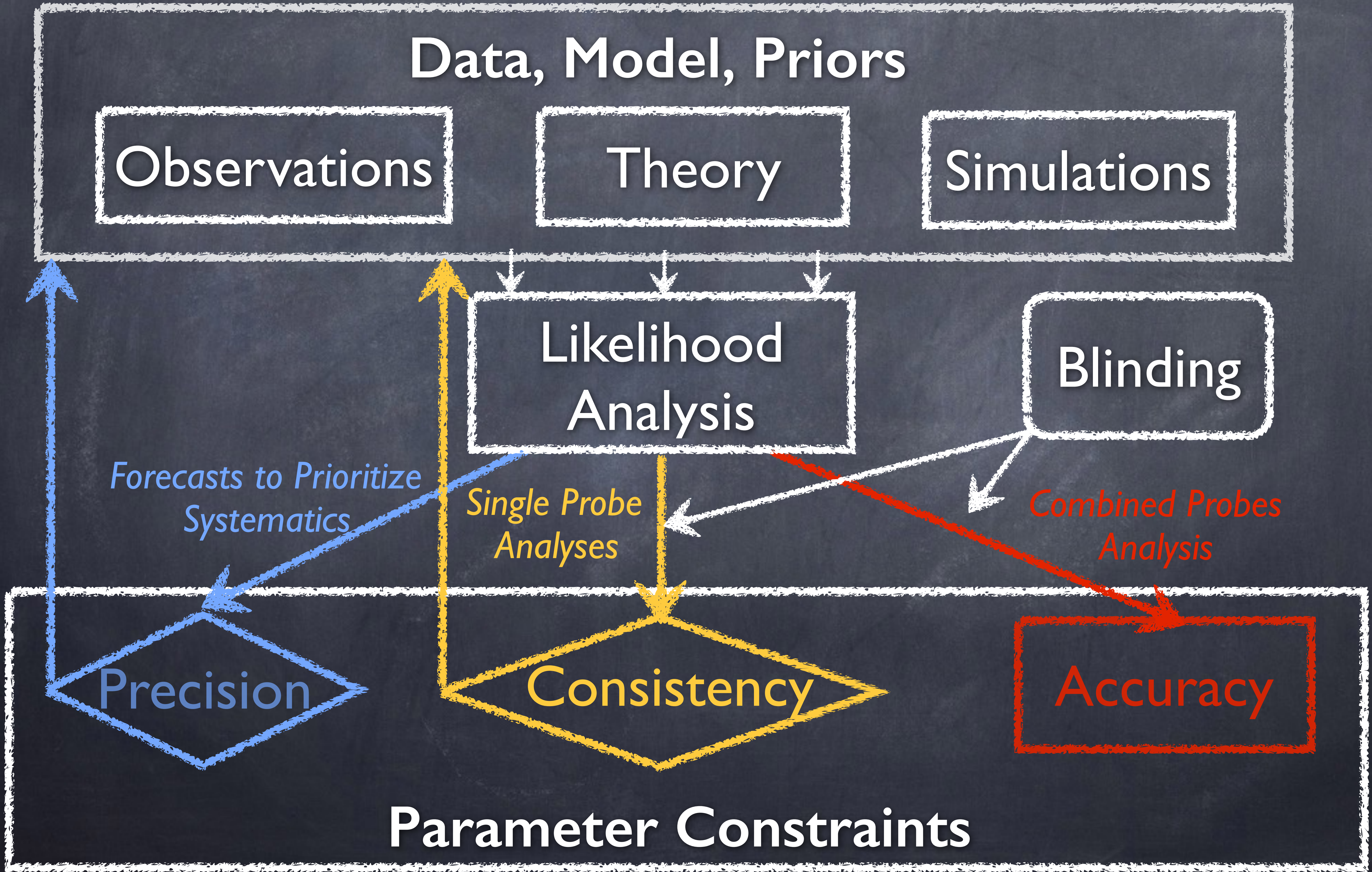
Why Blind Analyses?

- Experimenter's bias
    - choice of data samples + selections
    - choice of priors + evaluation of systematics
    - decision to stop work + publish
- Blind Analysis: Method to prevent experimenter's bias
    - hide the answer
    - must be customize for measurement

Blind Analysis Strategy for DES-Y3

- Two-stage process
  - measurement (correlation & mass functions)
    - shear catalog blinded, cluster calibration under debate
    - transform correlation functions (Muir, Elsner + in prep.)
      $$\hat{w}(\theta) \to \hat{w}(\theta) + \frac{\partial w}{\partial \Omega_{\rm m}} \Delta\Omega_{\rm m}$$
    - still defining null-test, 'allowed' plots for sample selection
  - parameter estimation
    - off-set all parameter results by (constant) random numbers
    - needed: decisions on models to run, model selection criteria

Joint Analysis Work Plan



DES Multi-Probe Analyses

- Kwan+16: Clustering + Galaxy-Galaxy Lensing (DES-SV, 140 sqdeg)

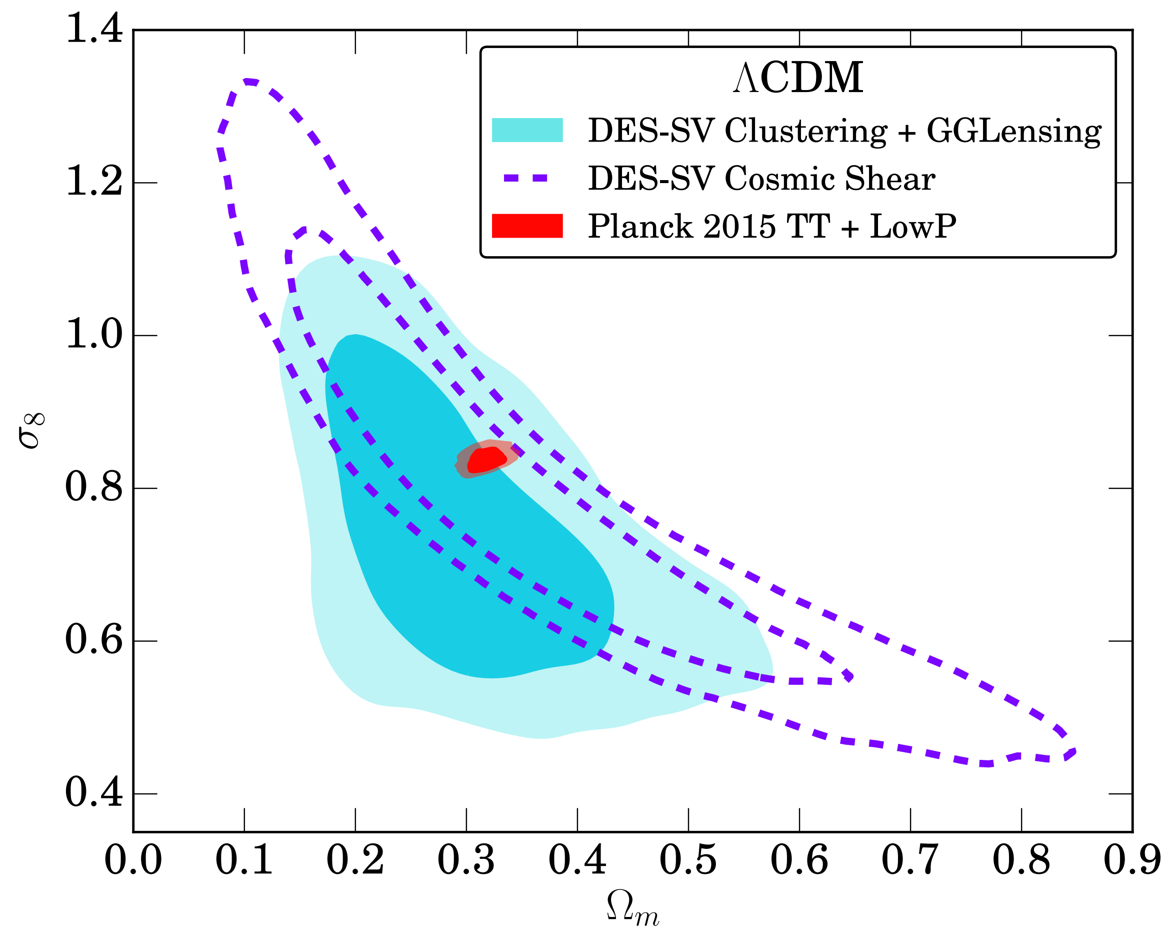


Figure 4. Constraints on Ω_m and σ_8 using DES-SV Cosmic Shear (dashed purple), DES-SV $w(\theta) \times \gamma_t(\theta)$ (this work, filled blue) and Planck 2015 using a combination of temperature and polarization data (TT+lowP, filled red). In each case, a flat ΛCDM model is used.

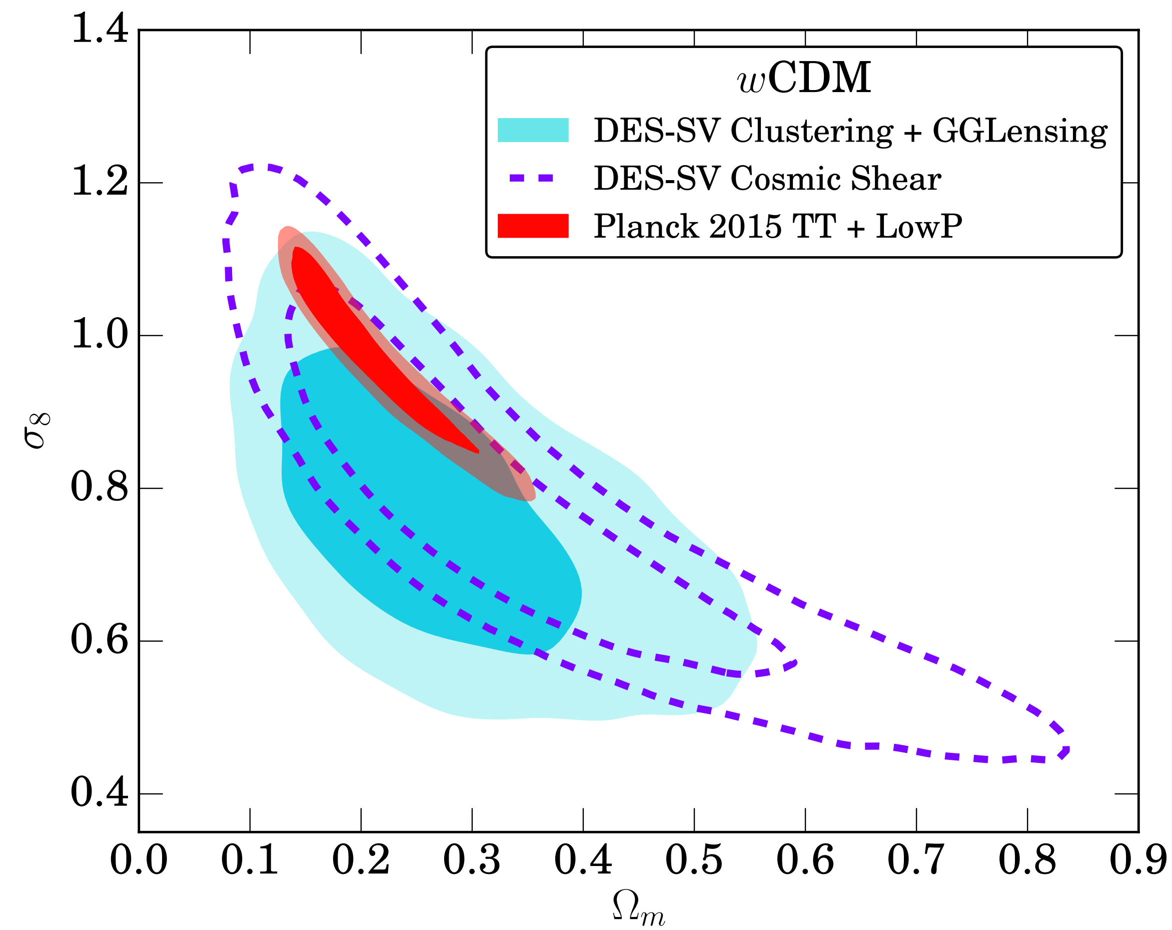
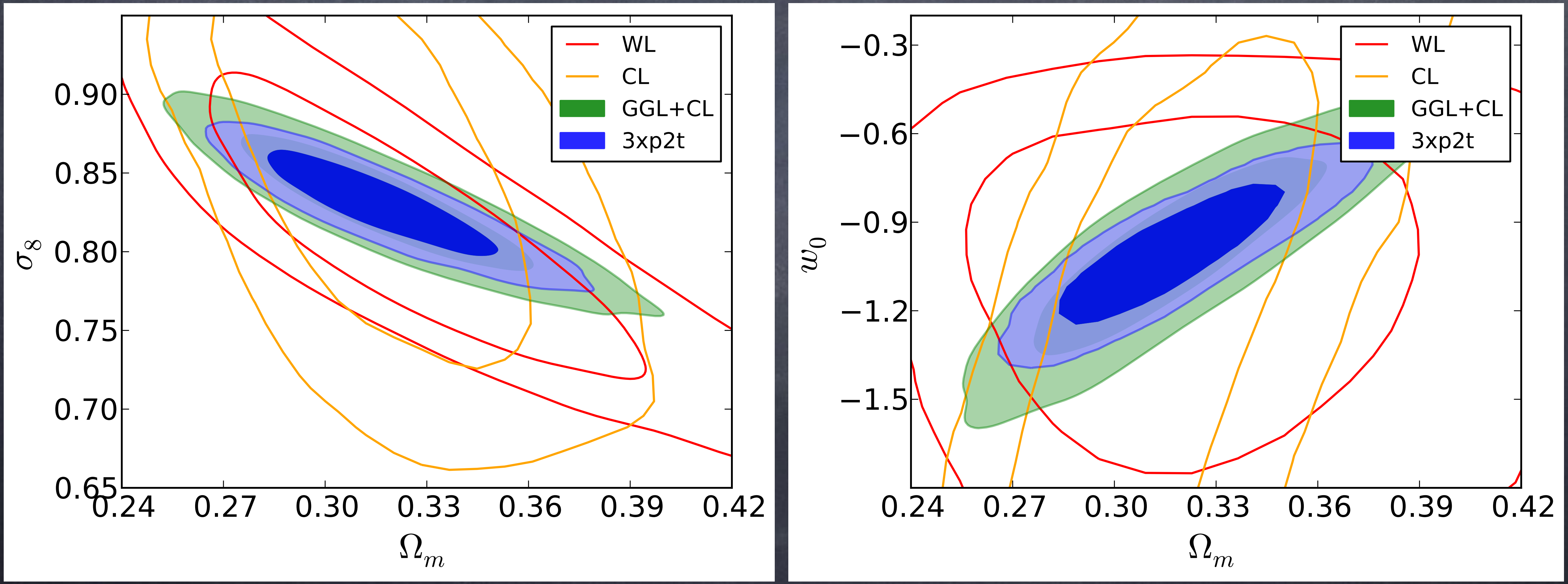


Figure 5. Constraints on Ω_m and σ_8 assuming a wCDM model using DES-SV Cosmic Shear (dashed purple), DES-SV $w(\theta) \times \gamma_t(\theta)$ (this work, blue) and Planck 2015 using temperature and polarization data (TT+lowP, red).

DES Multi-Probe Analyses

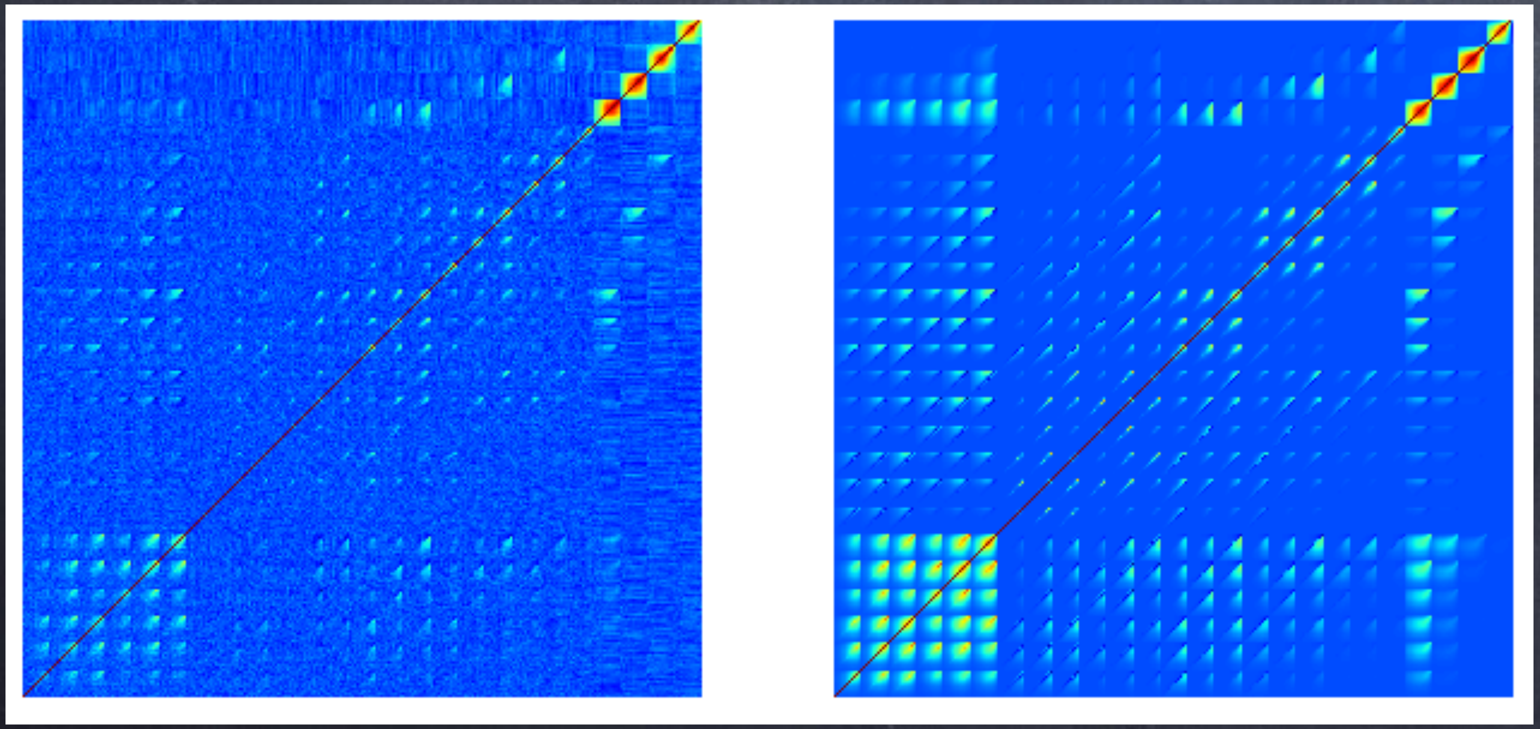
- Kwan+16: Clustering + Galaxy-Galaxy Lensing (DES-SV, 140 sqdeg)
- Analysis of Y1 data (1000 sqdeg) ongoing



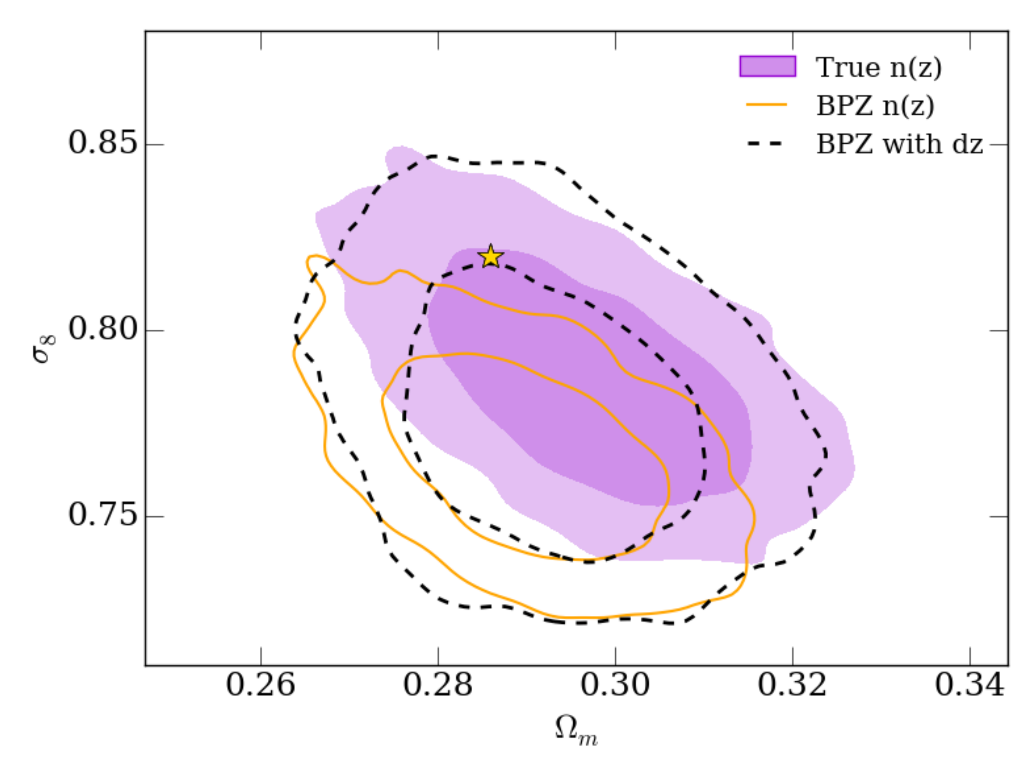
Forecasts based on Y1 n(z), marginalizing over ~60 systematics parameters

DES Multi-Probe Analyses

- Kwan+16: Clustering + Galaxy-Galaxy Lensing (DES-SV, 140 sqdeg)
- Analysis of Y1 data (1000 sqdeg) ongoing
  - two independent cosmology pipelines (CosmoLike, CosmoSIS)
  - validation on DES mock catalogs



simulated + analytic covariance



analysis of mock data (N. MacCrann)

Conclusions

- Existence of cosmic acceleration requires new fundamental physics
- We’re entering the ~decade of galaxy survey cosmology
  - KiDS,DES, HSC, PFS -> DESI, LSST, Euclid, WFIRST,…
- Cosmological constraints soon to be systematics limited
  - understand astrophysics
  - understand systematics
- Combine observables + surveys to understand/calibrate systematics
- Combine different surveys to robustly confirm/rule out ΛCDM

DES-Y1 results coming to arXiv this winter!