The Multi-Probe Method

DES-Y1 results on behalf of the Dark Energy Survey Collaboration

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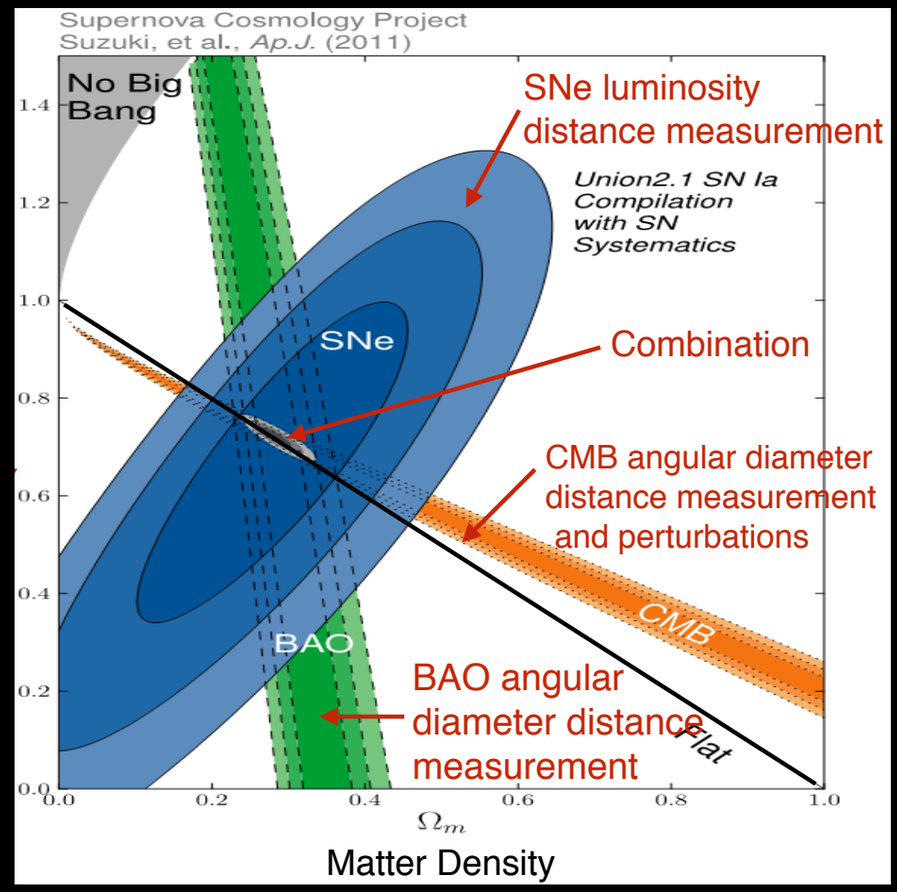
Berkeley Weak Lensing Workshop, January 2019

The Power of Combining Probes

- Best constraints obtained by combining cosmological probes
  - independent probes: multiply likelihoods

- Combining LSS probes (from same survey) requires more complicated analyses
  - 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!

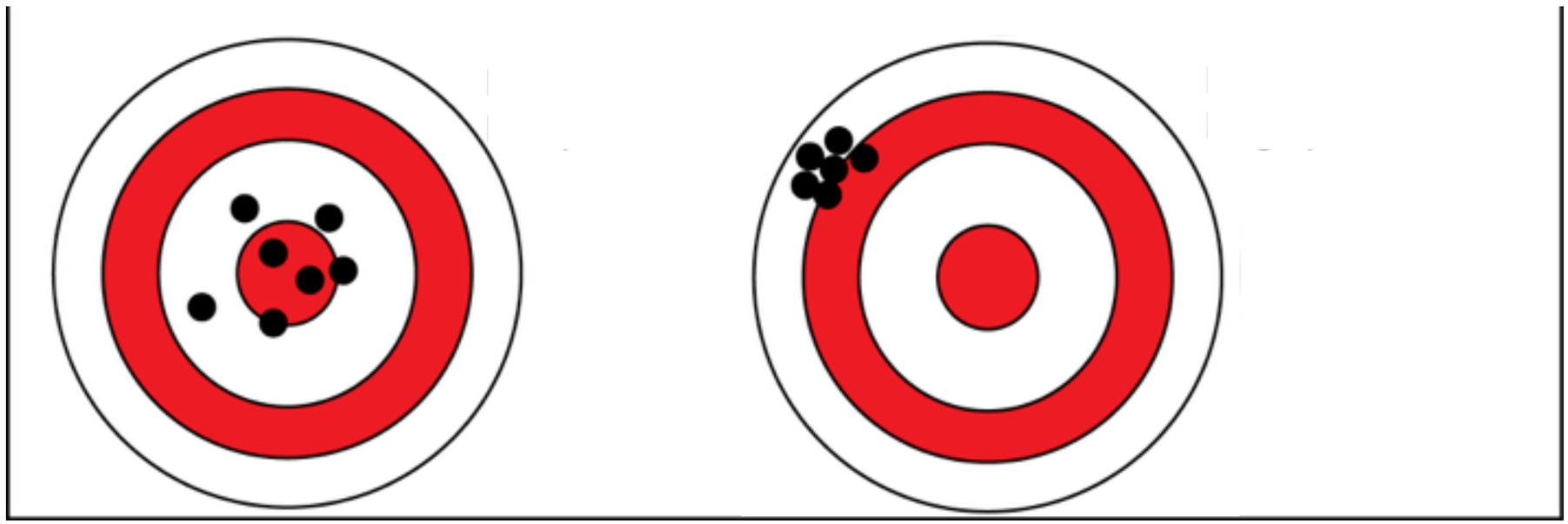
Priors

validate

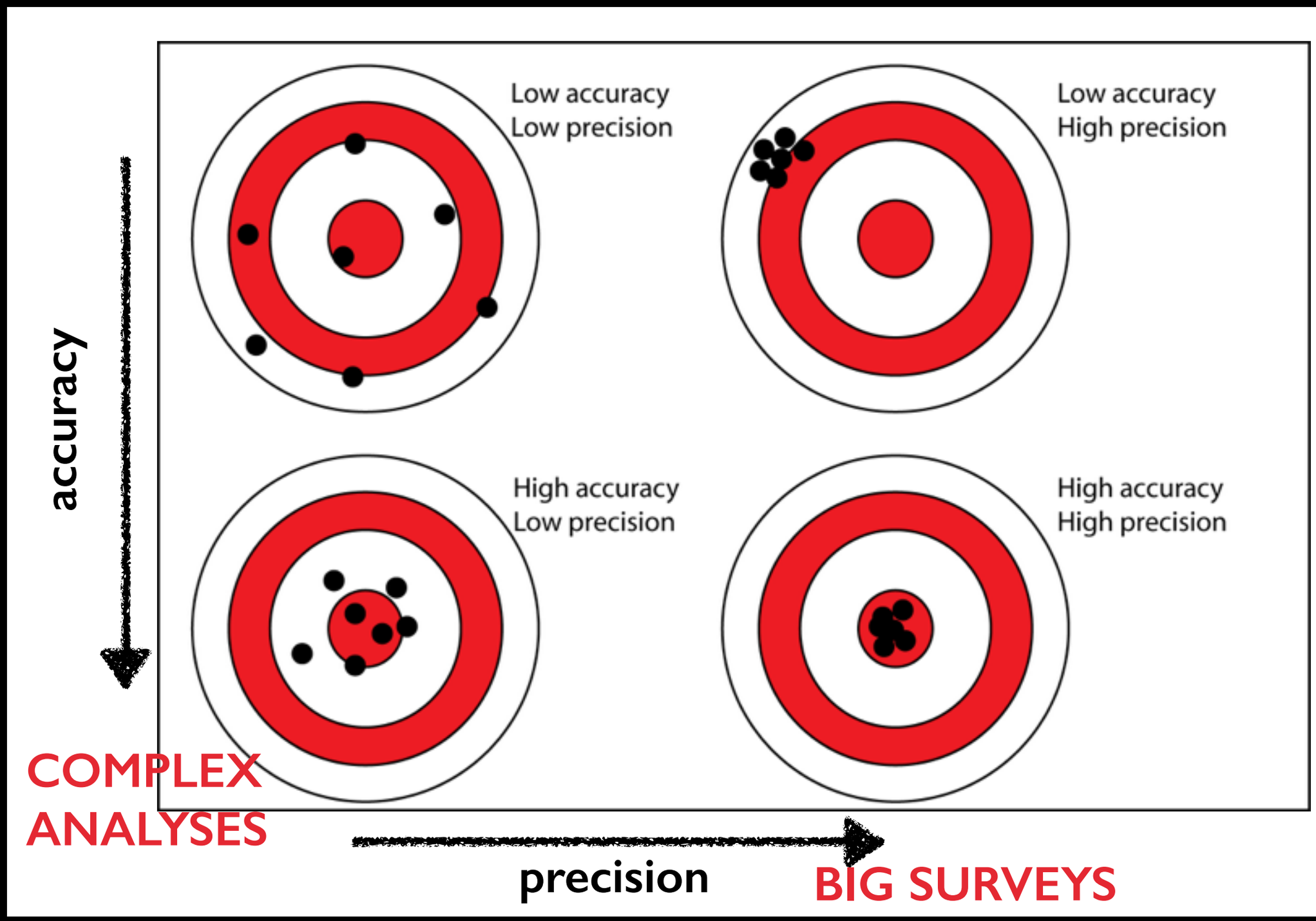
External Data
Simulations

“Precision” Cosmology

“Precision” Cosmology



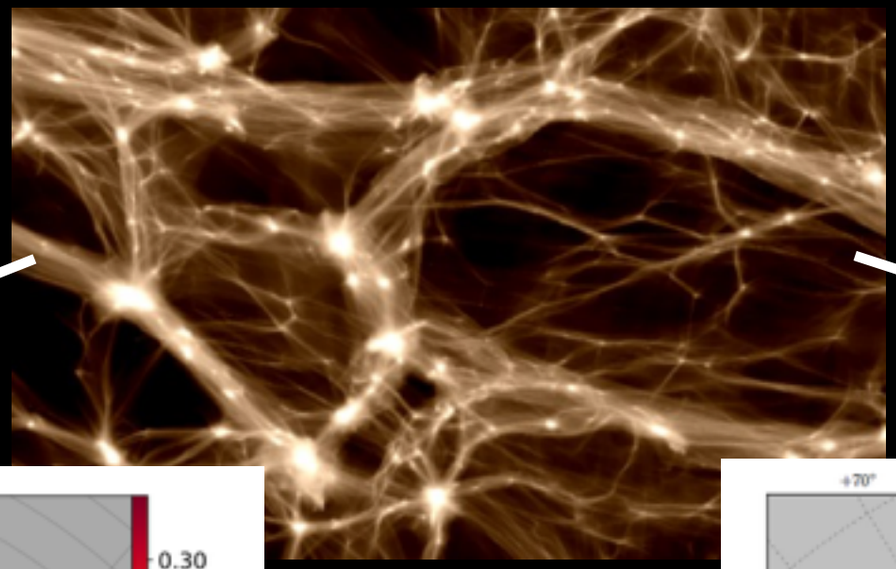
“Precision” Cosmology

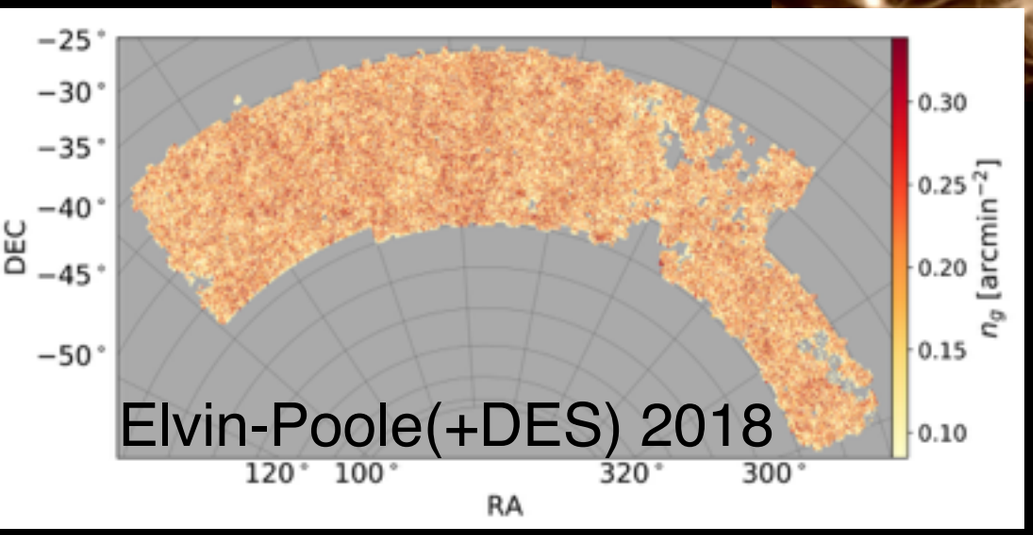


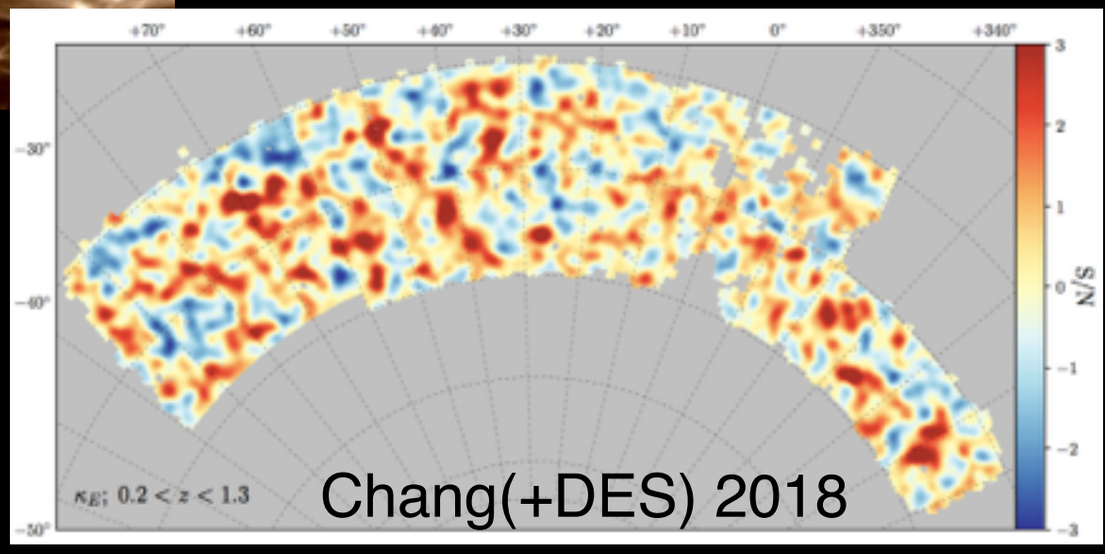
Multi-Probe Systematics
DES Aspirations

- "Precision cosmology": excellent statistics - systematics limited
  - (and person-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 [2013 estimate]
- Self-calibration + marginalization
  - can be costly (computationally, constraining power)

DES Year 1 Cosmology Analysis



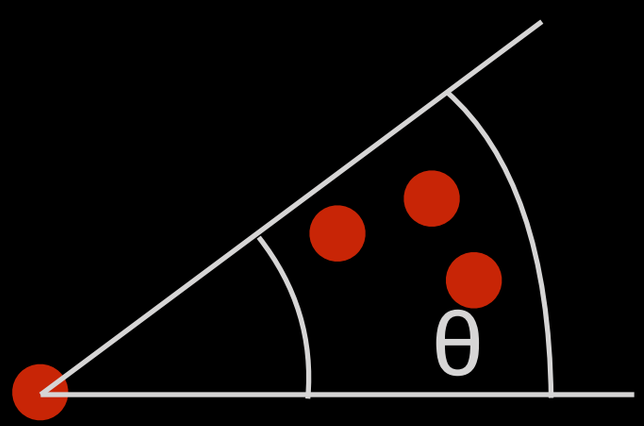


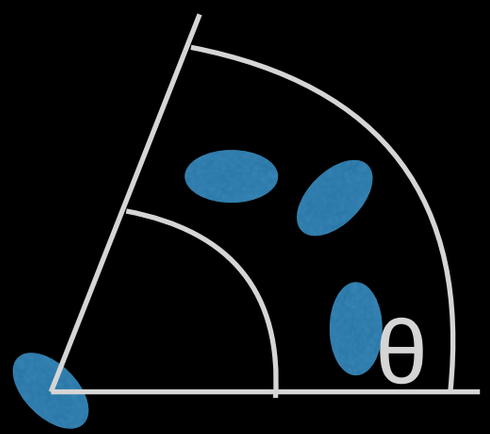


galaxies x galaxies:
angular clustering

galaxies x lensing:
galaxy-galaxy lensing

lensing x lensing:
cosmic shear





Combined Probes Systematics
DES-Y1 Reality

baseline systematics marginalization (20 parameters)

- linear bias of lens galaxies, per lens z-bin
- lens galaxy photo-zs, per lens z-bin
- source galaxy photo-zs, per source z-bin
- multiplicative shear calibration, per source z-bin
- intrinsic alignments, power-law/free amplitude per per source z-bin

-> this list is known to be incomplete

how much will **known, unaccounted-for** systematics bias Y1?

-> choice of parameterizations ≠ universal truth

are these **parameterizations sufficiently flexible** for Y1?

EK+ (DES)
1706.09359

Systematics Mitigation
incomplete model - scale cuts

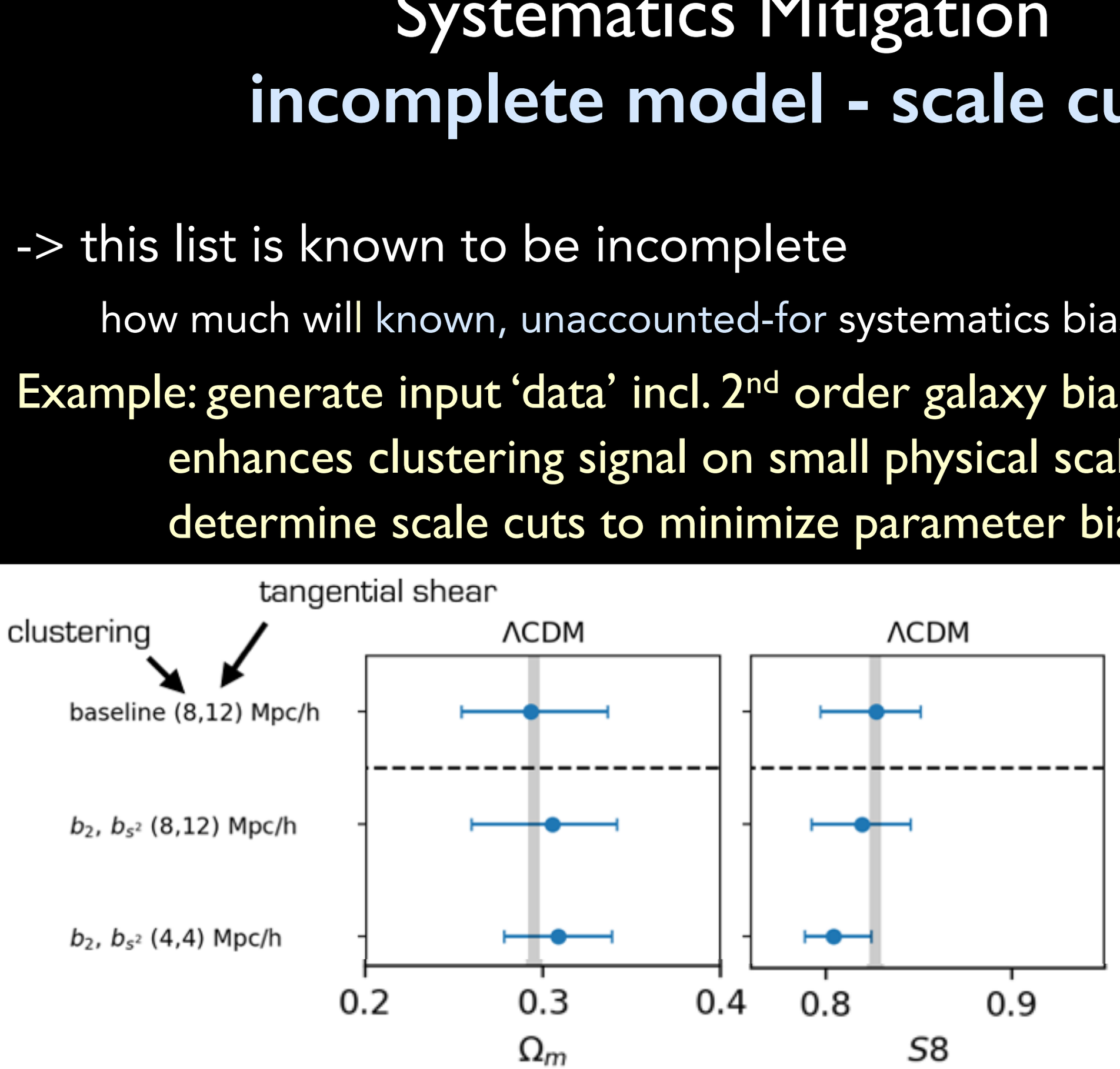
-> this list is known to be incomplete

how much will known, unaccounted-for systematics bias Y1 results?

Example: generate input 'data' incl. 2nd order galaxy bias

enhances clustering signal on small physical scales

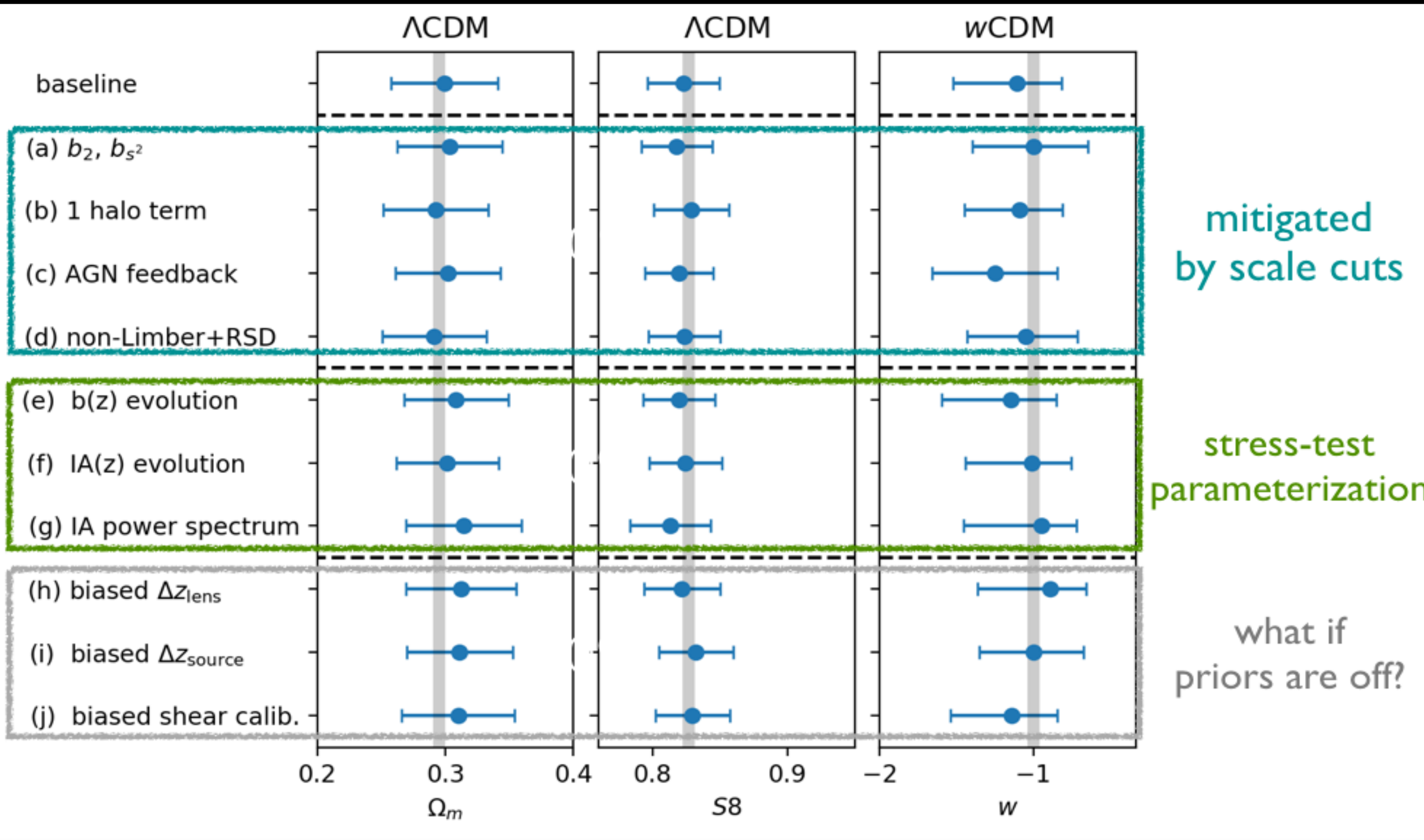
determine scale cuts to minimize parameter biases



Krause, Eifler+ 1706.09359

non-linear galaxy bias

Systematics Mitigation
imperfect parameterizations



Multi-Probe Blinding

Goal: minimize experimenters' bias

Blind only to cosmology parameter values

- systematic effects are convoluted with signal, need to blindly test various systematics parameterizations
- null-tests are essential, blinding scheme has to allow these
- blinding scheme has to allow looking at measurements

Implementation: two-staged blinding process

- shear catalogs scaled by unknown factor, until catalogs fixed
- cosmo params shifted by unknown vector, until full analysis fixed
- (do not overplot measurement + theory)
- (clearly state any post-unblinding changes in paper)

DES Collaboration 2018
1708.01530

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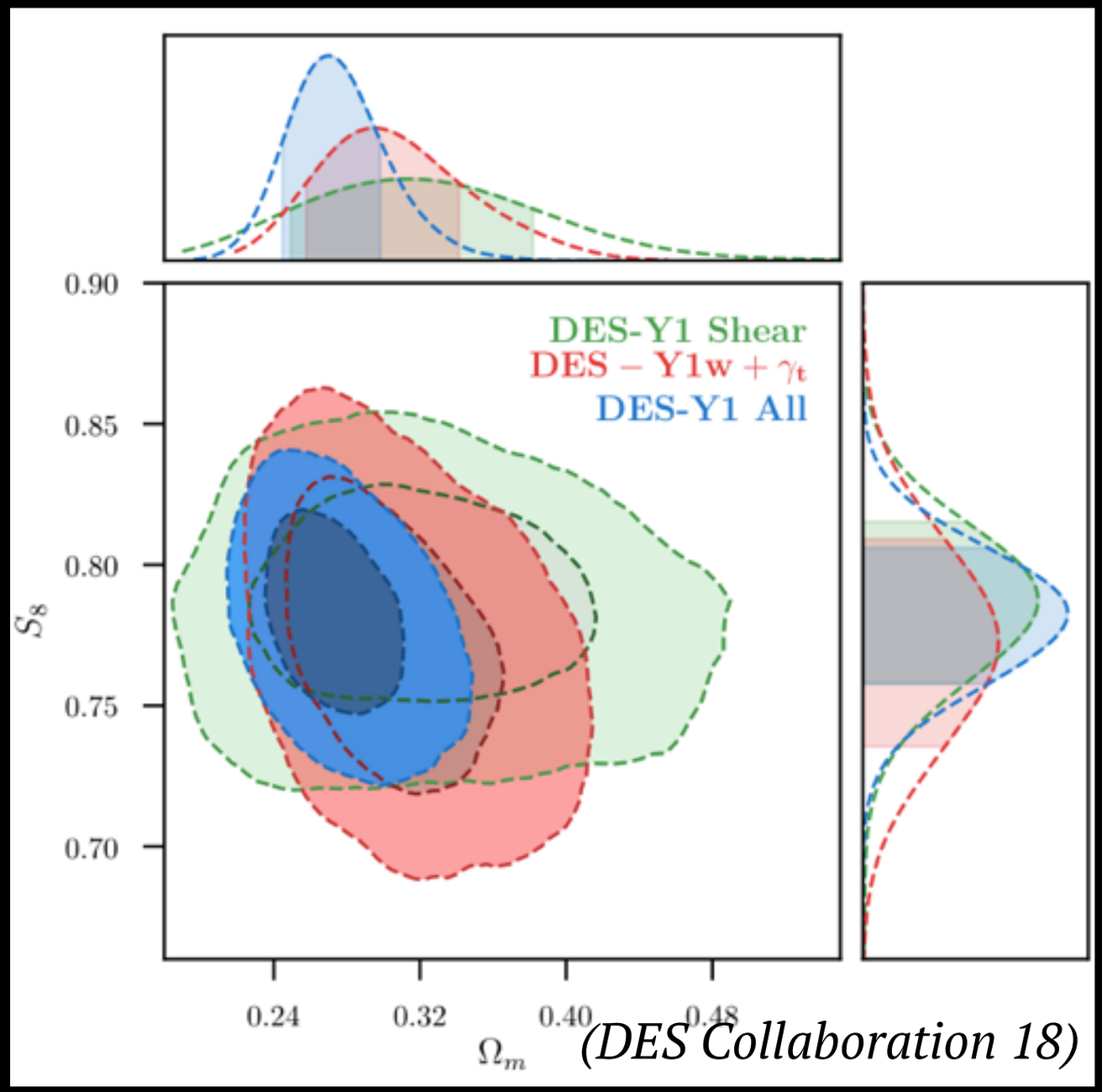
Q: Consider consistency across probes null-test, or result?

DES Y1 Results: LCDM Multi-Probe Constraints



(DES Collaboration 18)

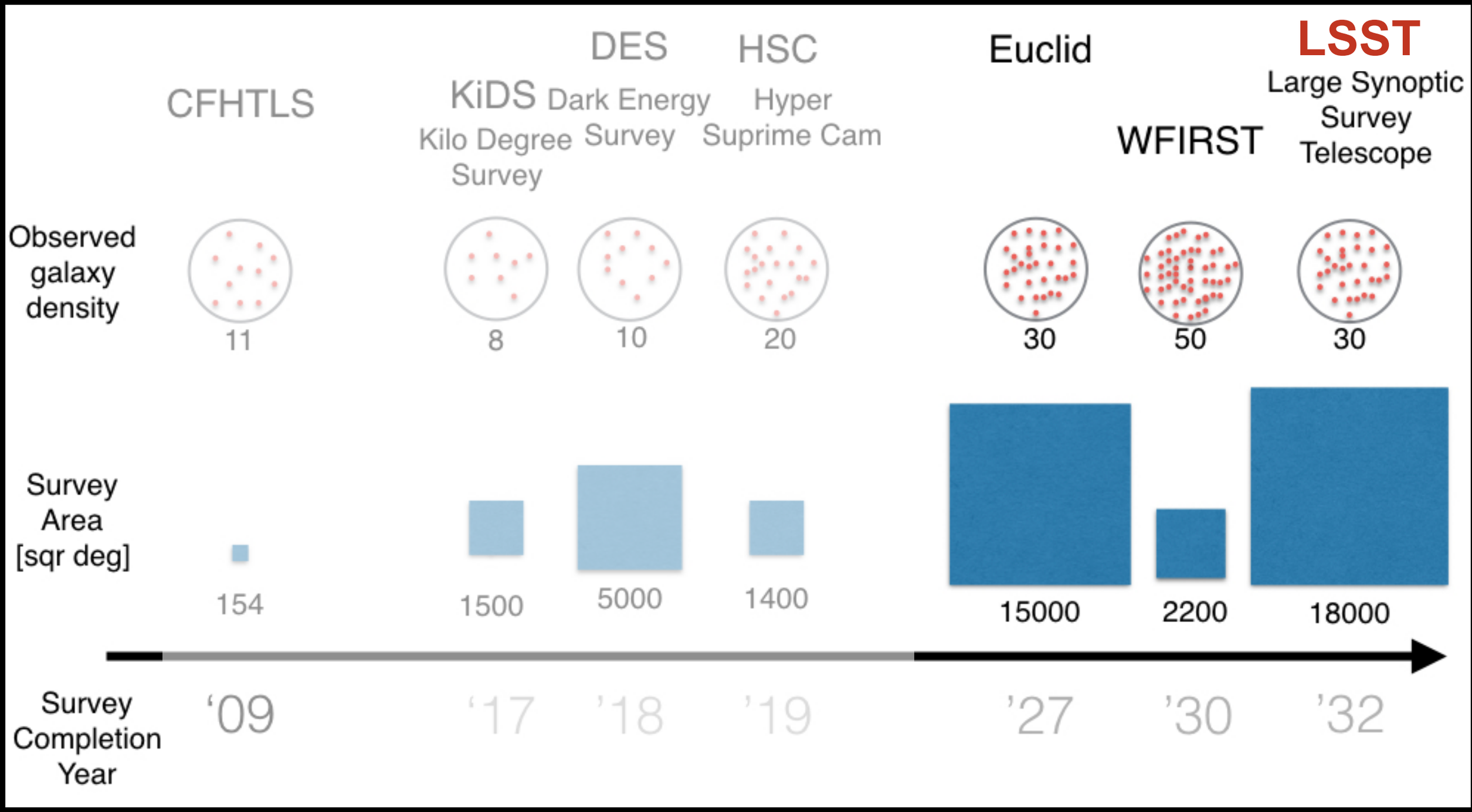
Amplitude of Structure Growth

Matter Density

- DES-Y1 most stringent constraints from weak lensing to date
- marginalized 4 cosmology parameters, 10 clustering nuisance parameters, and 10 lensing nuisance parameters
- consistent (Bayes Factor R = 583) cosmology constraints from weak lensing and clustering in configuration space

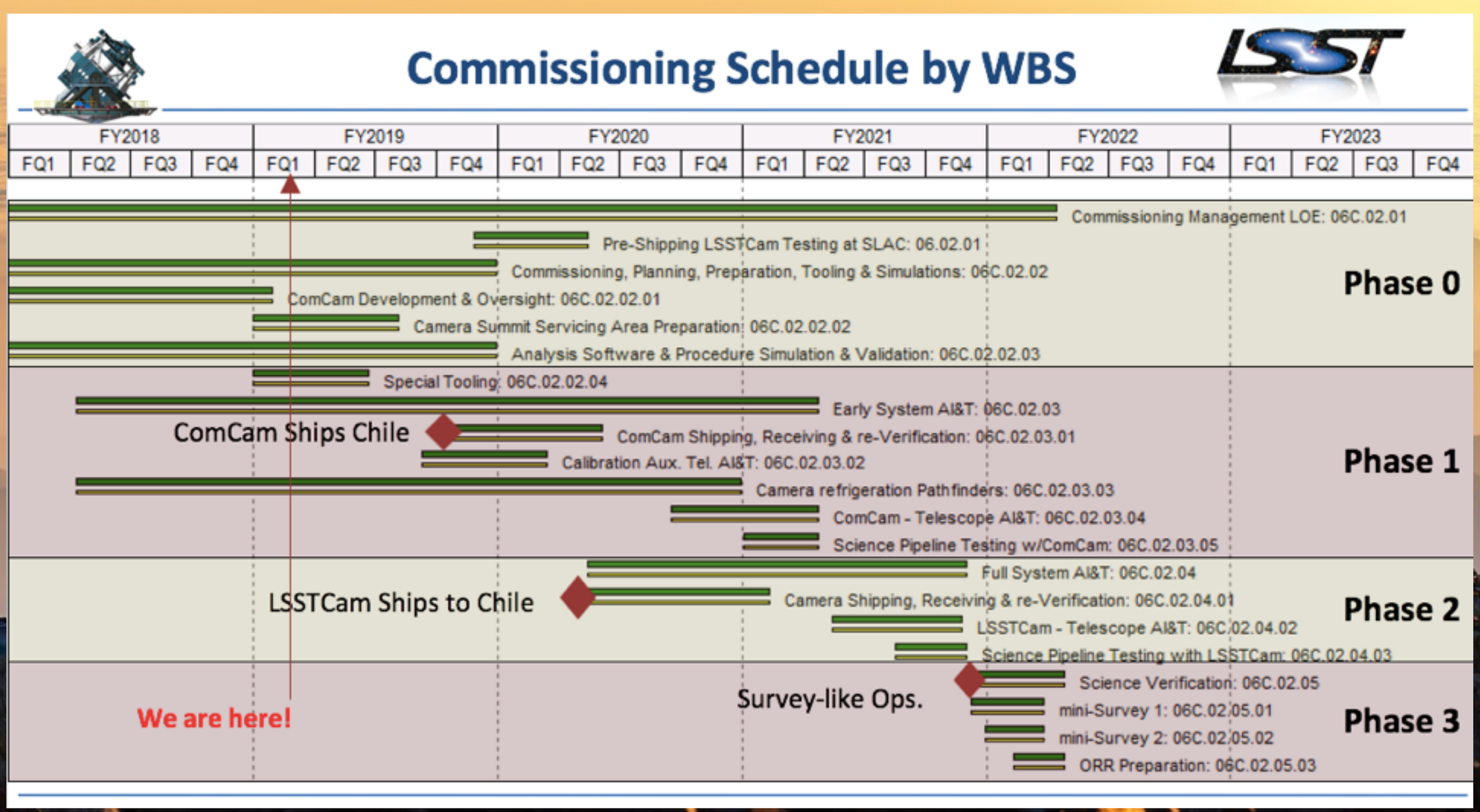
-> Troxel's talk for detailed results

Photometric Cosmology Surveys



LSST!

LSST!


Commissioning Schedule by WBS
FY2018
FY2019
FY2020
FY2021
FY2022
FY2023
FQ1 FQ2 FQ3 FQ4 FQ1 FQ2 FQ3 FQ4 FQ1 FQ2 FQ3 FQ4 FQ1 FQ2 FQ3 FQ4 FQ1 FQ2 FQ3 FQ4 FQ1 FQ2 FQ3 FQ4
Commissioning Management LOE: 06C.02.01
Pre-Shipping LSSTCam Testing at SLAC: 06.02.01
Commissioning, Planning, Preparation, Tooling & Simulations: 06C.02.02
ComCam Development & Oversight: 06C.02.02.01
Camera Summit Servicing Area Preparation: 06C.02.02.02
Analysis Software & Procedure Simulation & Validation: 06C.02.02.03
Phase 0
Special Tooling: 06C.02.02.04
Early System AI&T: 06C.02.03
ComCam Ships Chile
ComCam Shipping, Receiving & re-Verification: 06C.02.03.01
Calibration Aux. Tel. AI&T: 06C.02.03.02
Camera refrigeration Pathfinders: 06C.02.03.03
ComCam - Telescope AI&T: 06C.02.03.04
Science Pipeline Testing w/ComCam: 06C.02.03.05
Phase 1
Full System AI&T: 06C.02.04
LSSTCam Ships to Chile
Camera Shipping, Receiving & re-Verification: 06C.02.04.01
LSSTCam - Telescope AI&T: 06C.02.04.02
Science Pipeline Testing with LSSTCam: 06C.02.04.03
Phase 2
Science Verification: 06C.02.05
Survey-like Ops.
mini-Survey 1: 06C.02.05.01
mini-Survey 2: 06C.02.05.02
ORR Preparation: 06C.02.05.03
Phase 3
We are here!

The LSST Dark Energy Science Collaboration

Prepare for and carry out cosmology analyses with the LSST survey

- 6 cosmology Science Working Groups (SWG)

  Galaxy Clustering, Galaxy Clusters, Strong Lensing, Supernovae, Weak Lensing; Theory & Joint Probes

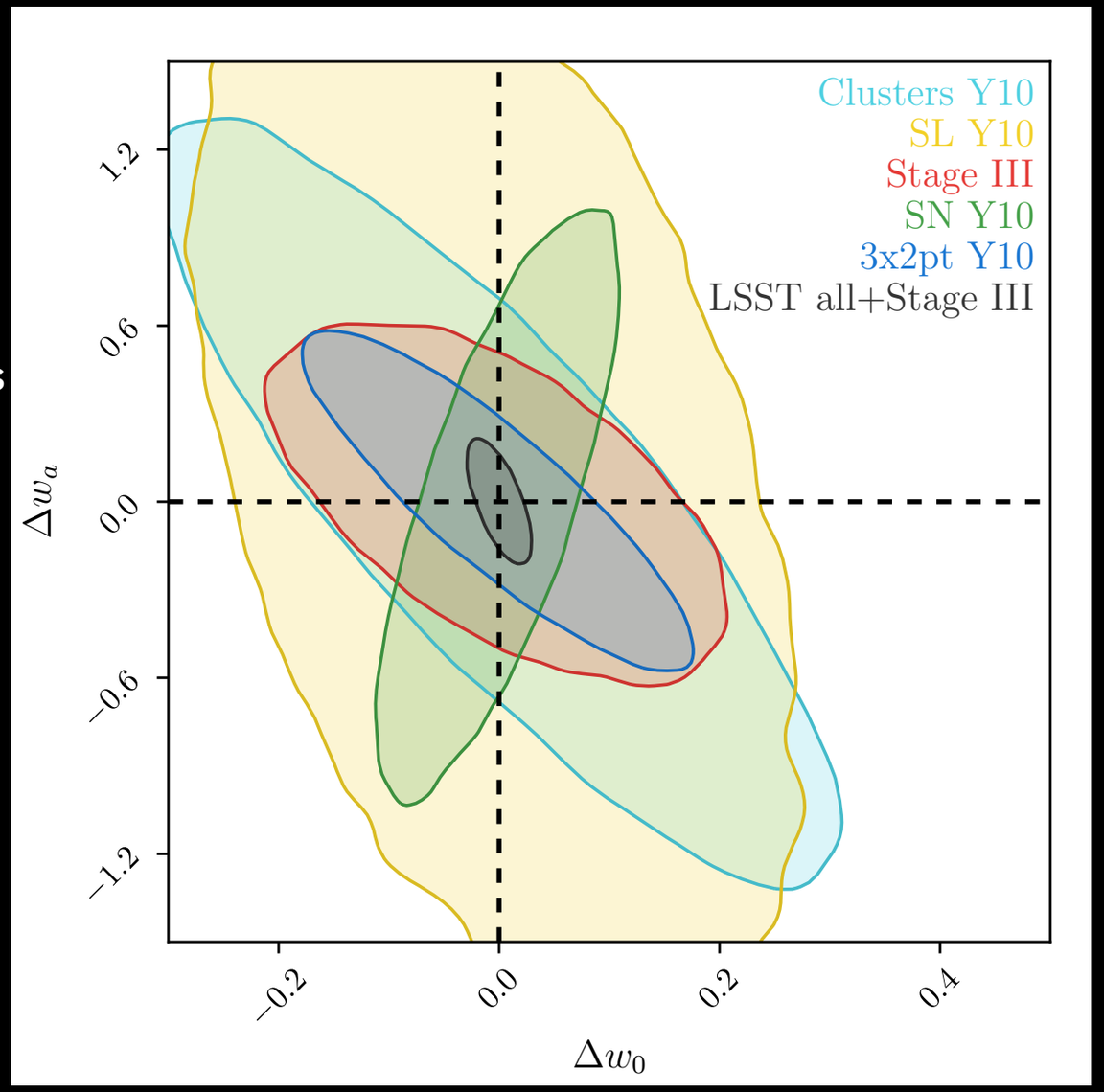
- "Enabeling Analyses" WGs: understand LSST system + systematics

lots of work until first data, lots to learn from ongoing surveys!

The Power of Multi-Probe Analyses with LSST

1809.01669, incl. links to data products & Fisher Matrices

- first joint forecast by science collaboration since LSST Science Book (2009)
    - based on much more mature survey & analysis assumptions, understanding of systematics
- joint forecasts including cross-correlations (statistical & systematical)
- consider two classes of systematics
    - *self-calibrated*, e.g. galaxy bias, intrinsic alignments, cluster mass-observable relation
    - *externally calibrated*, e.g. photo-zs, shear calibration, photometric calibration



Preparing for *Known* Systematics

What's the dominant known systematic for LSST cosmology?

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

[answer will likely involve galaxy evolution]

- Specify data vector (probes + scales)
- Identify + model systematic effects
  - find consistent parameterization for all probes
- Constrain parameterization + priors on nuisance parameters
  - independent observations
  - other observables from same data set/ split data set

Joint Analysis Plan

Model, Priors

Theory

Simulations

Refine Systematics Model

Analysis Code

Forecasts Impact

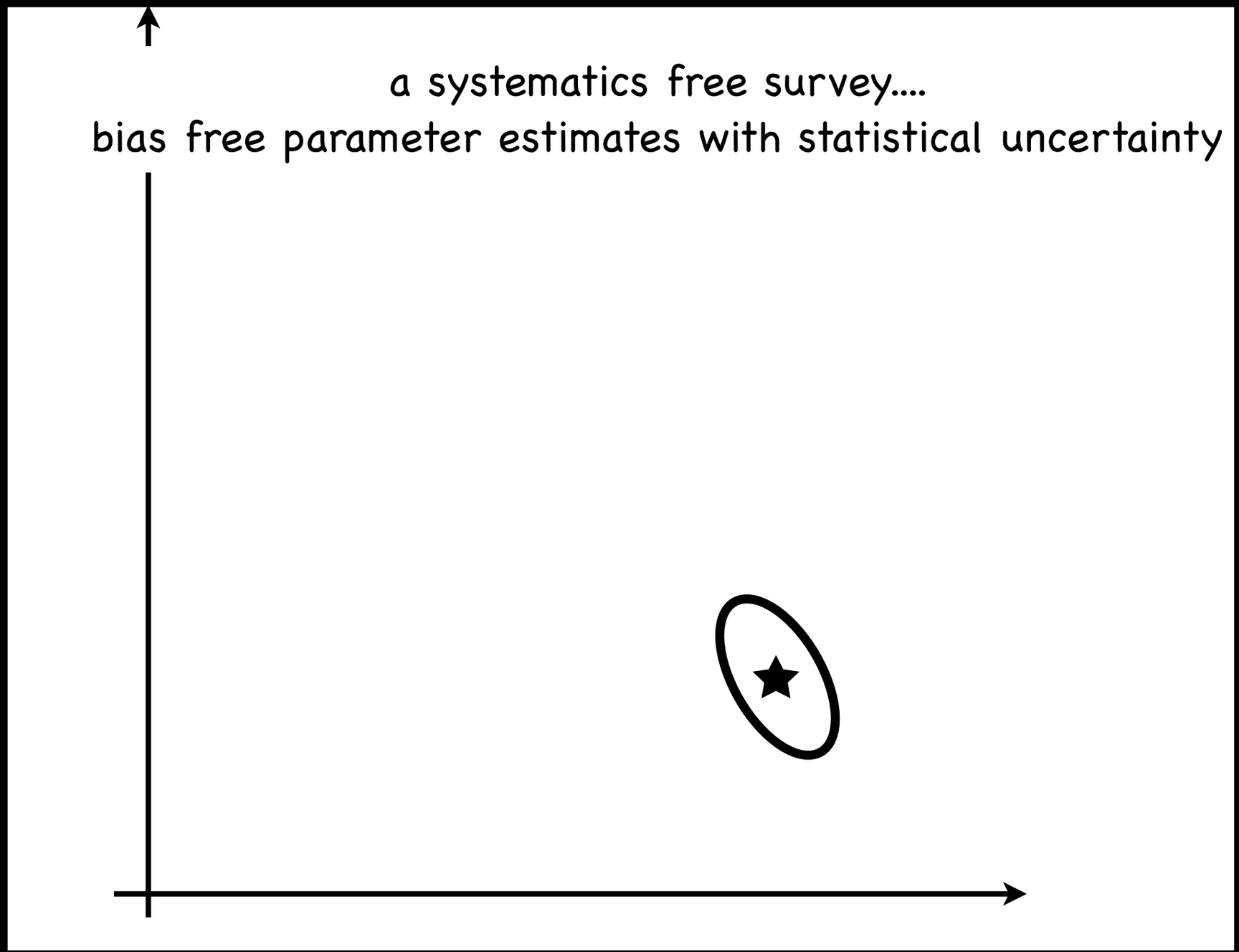
Precision

Consistency

Accuracy

Parameter Constraints

The Trouble with Systematics



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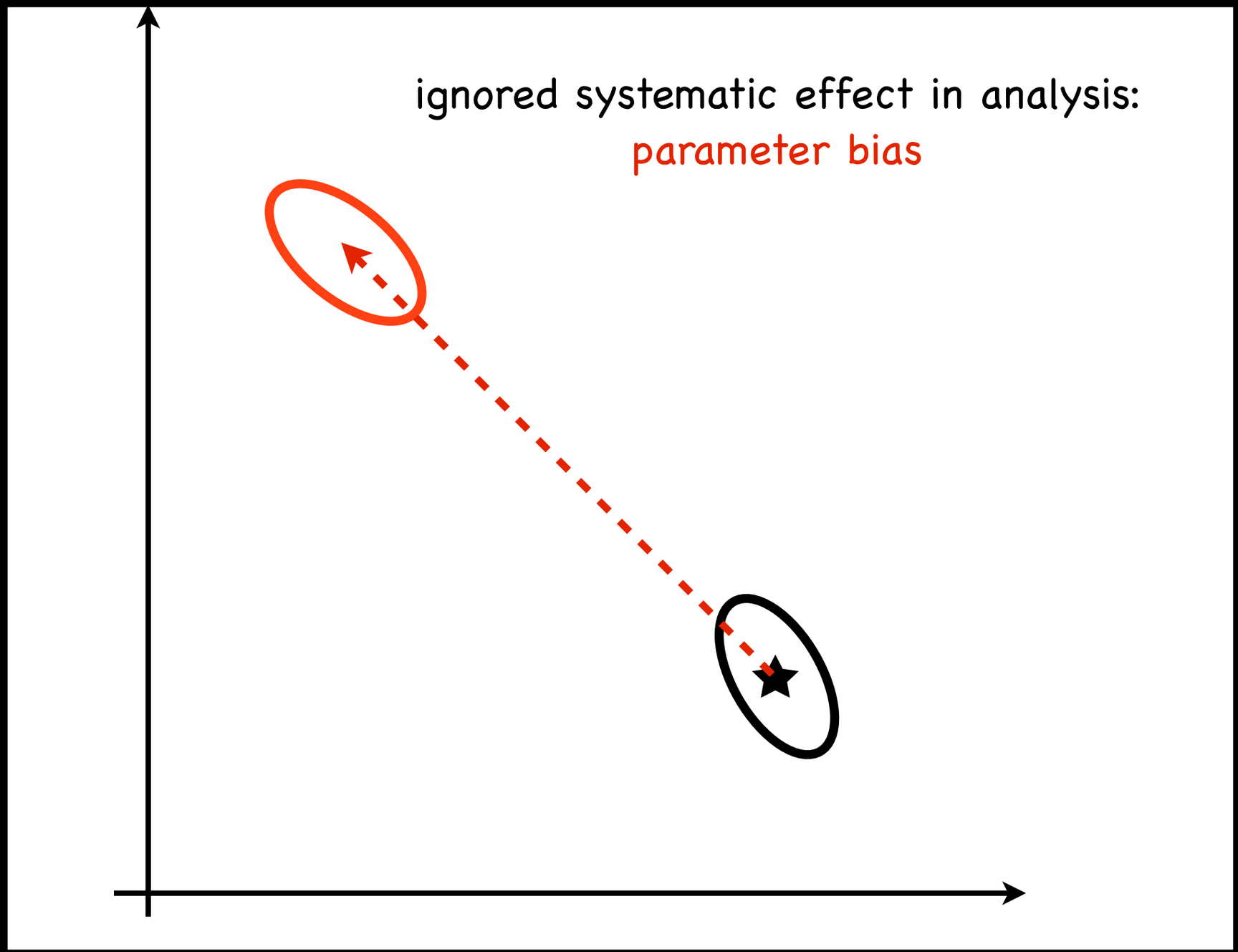

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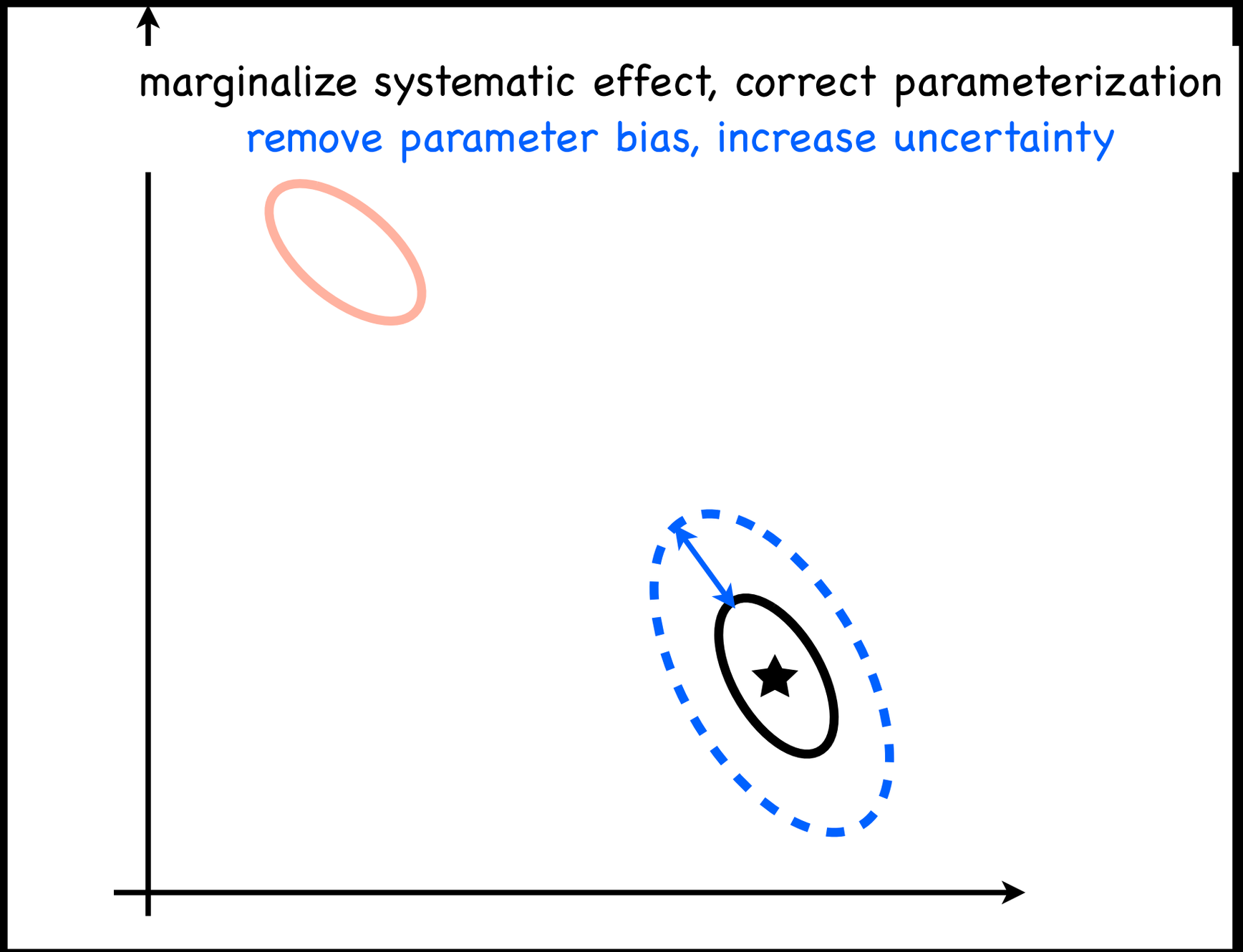

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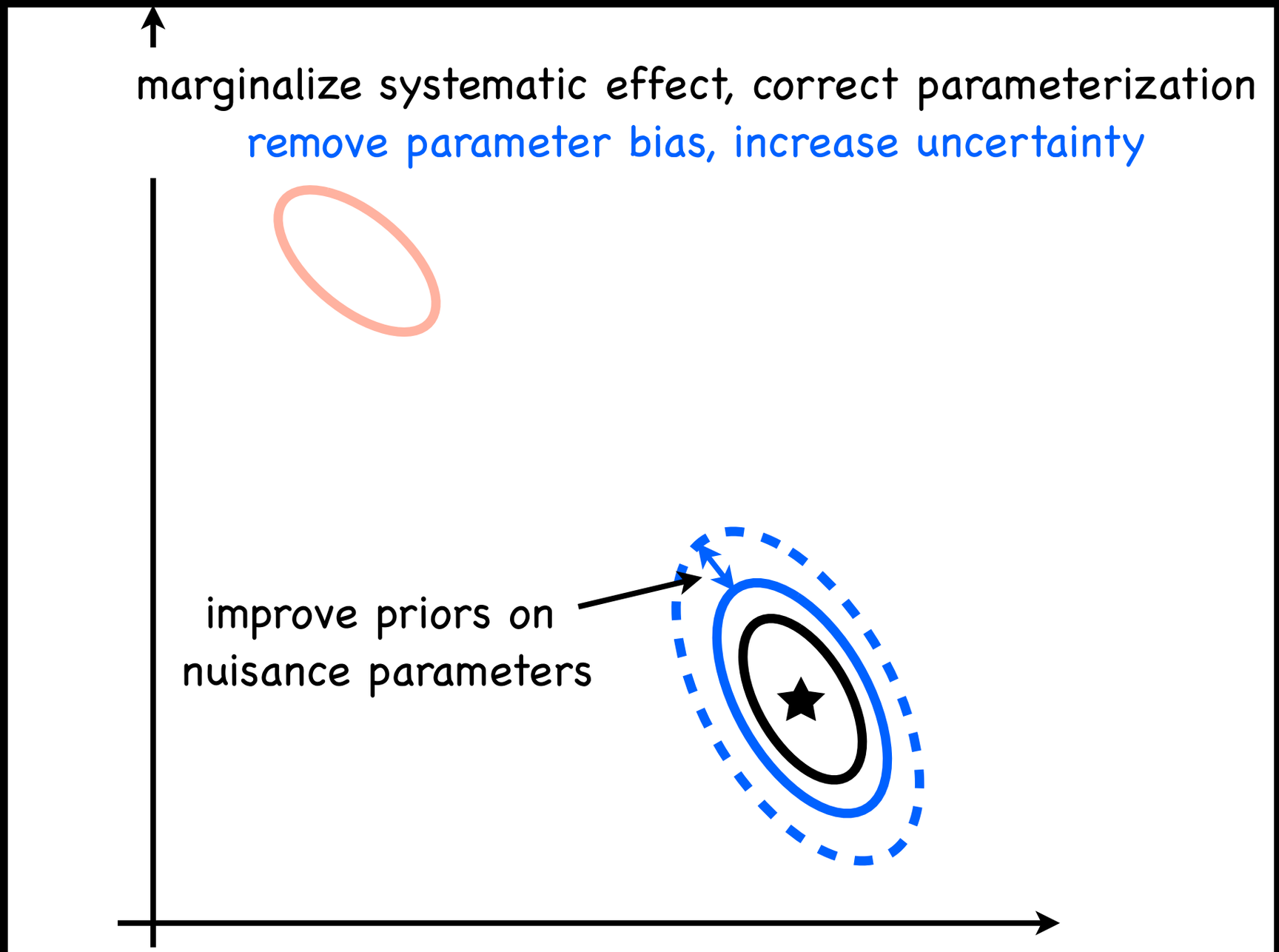
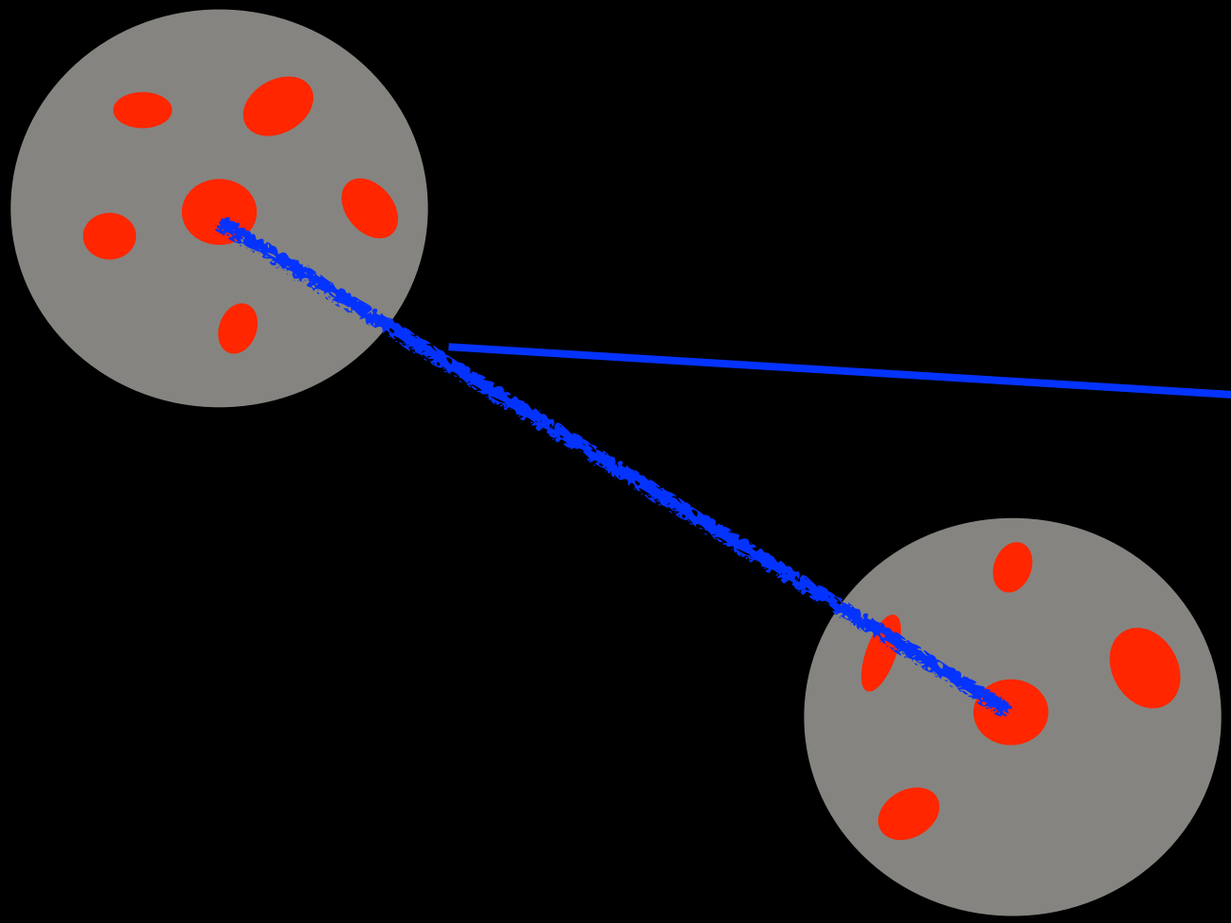


Fundamental Physics from Galaxies

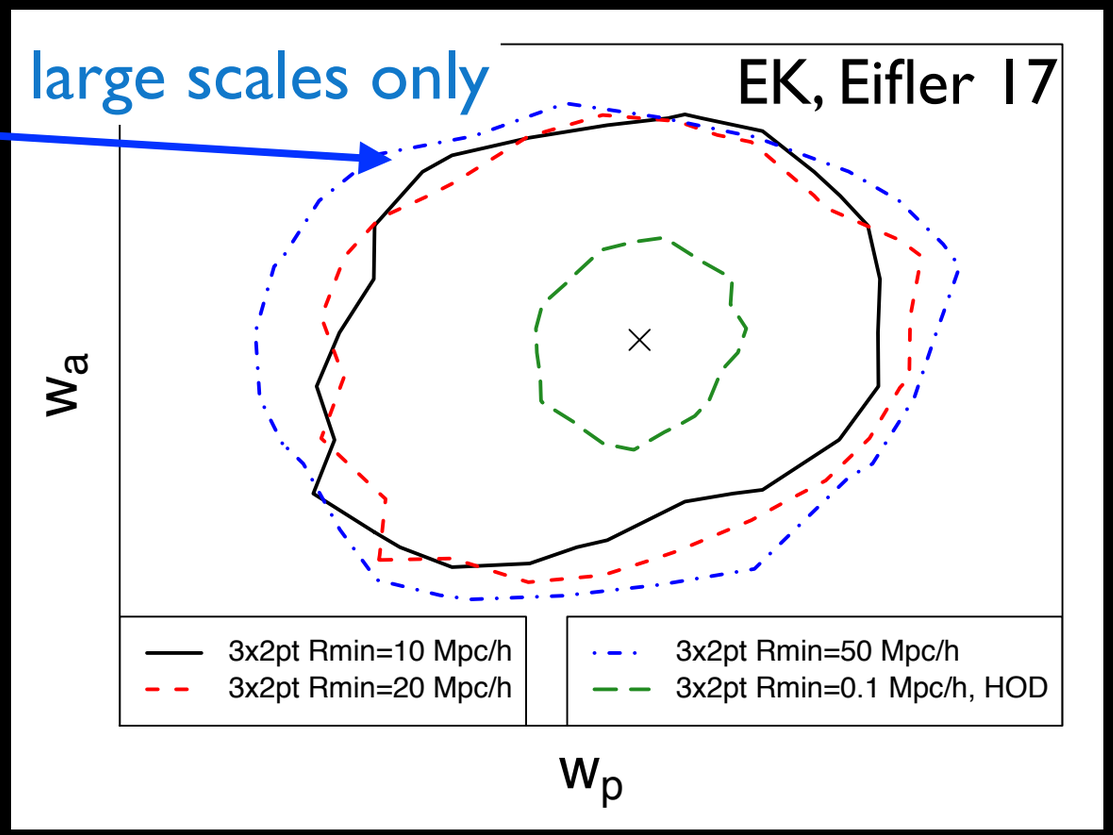
galaxy evolution: very rich physics compared to primary CMB

what do cosmologists need to know?

- galaxy bias: relation between a galaxy population and matter distribution



LSST's constraining power combining WL, and galaxies using



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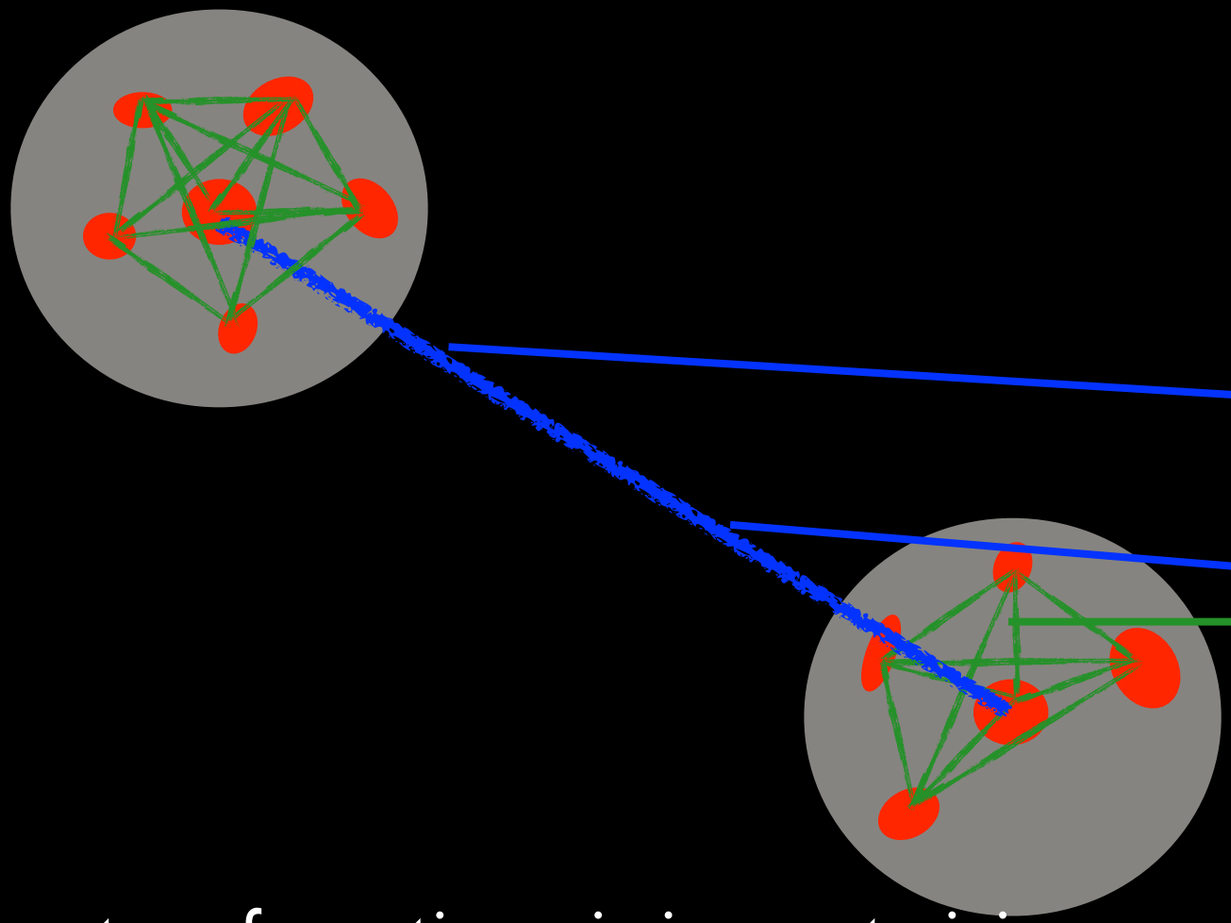
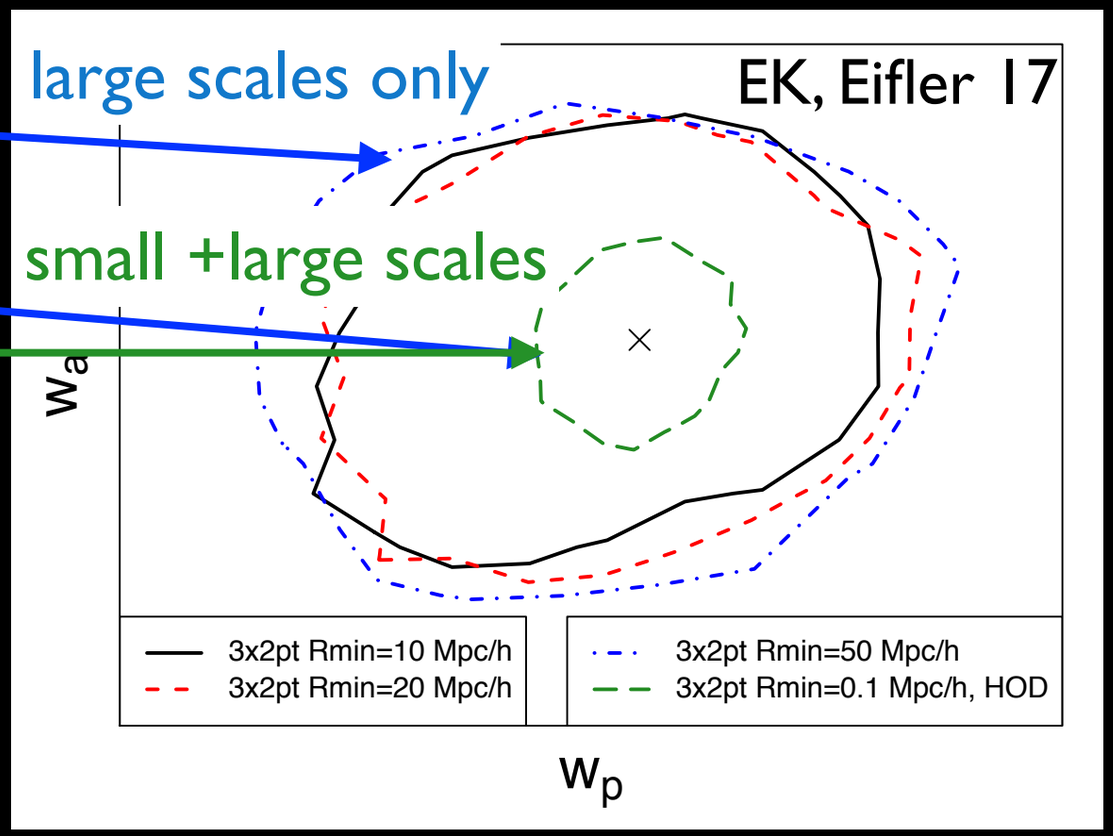
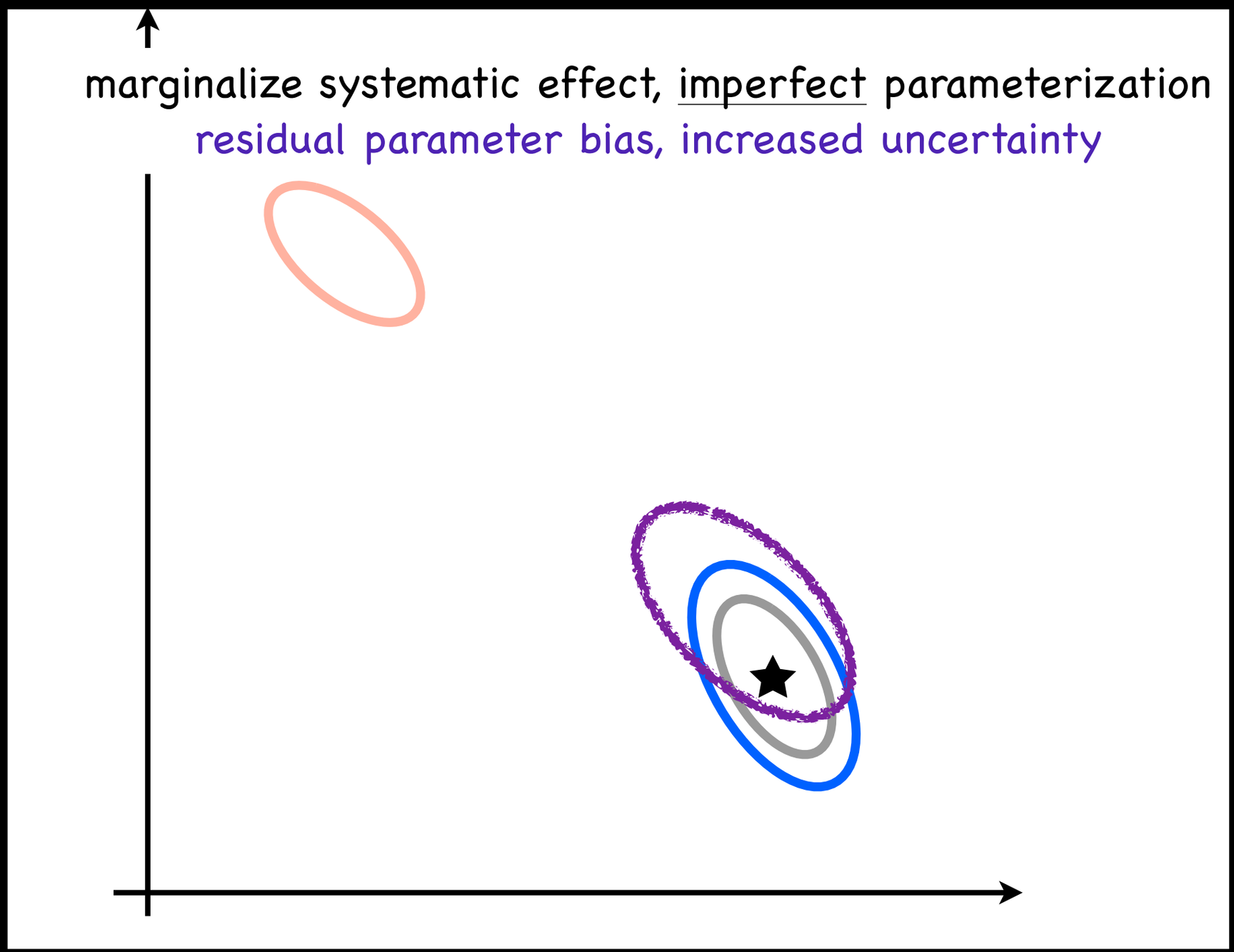


transformative gain in constraining power
(comparable to $f_{sky}>1$ for large scales only)
iff small scales modeled accurately

LSST's constraining power
combining WL, and galaxies using



The Trouble with Systematics



imperfect IA mitigation examples: EK+16b

Joint Analysis Plan

Data, Model, Priors

Observations

Theory

Simulations

Analysis Code

Forecasts to Prioritize Systematics

Single Probe Analyses

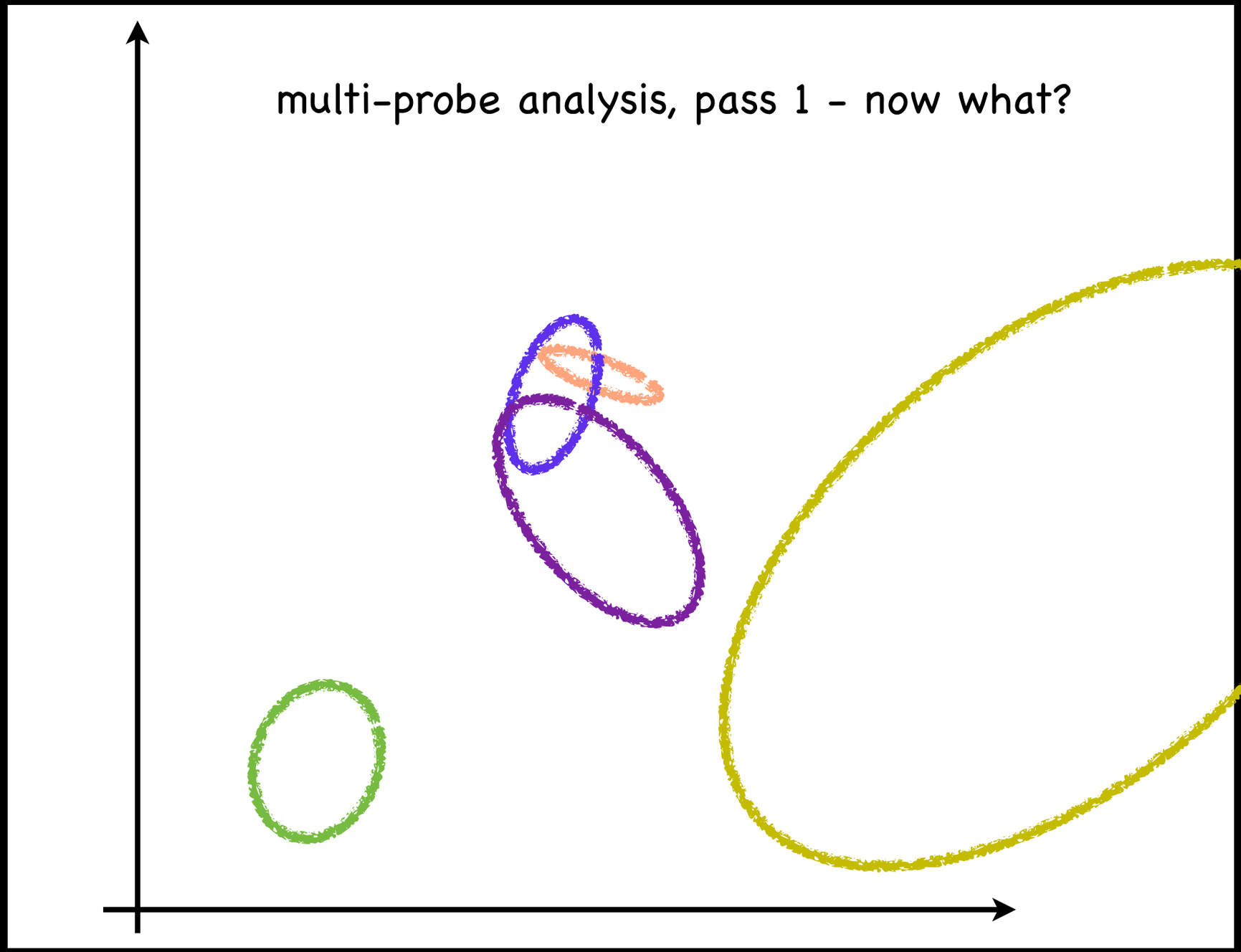
Precision

Consistency

Accuracy

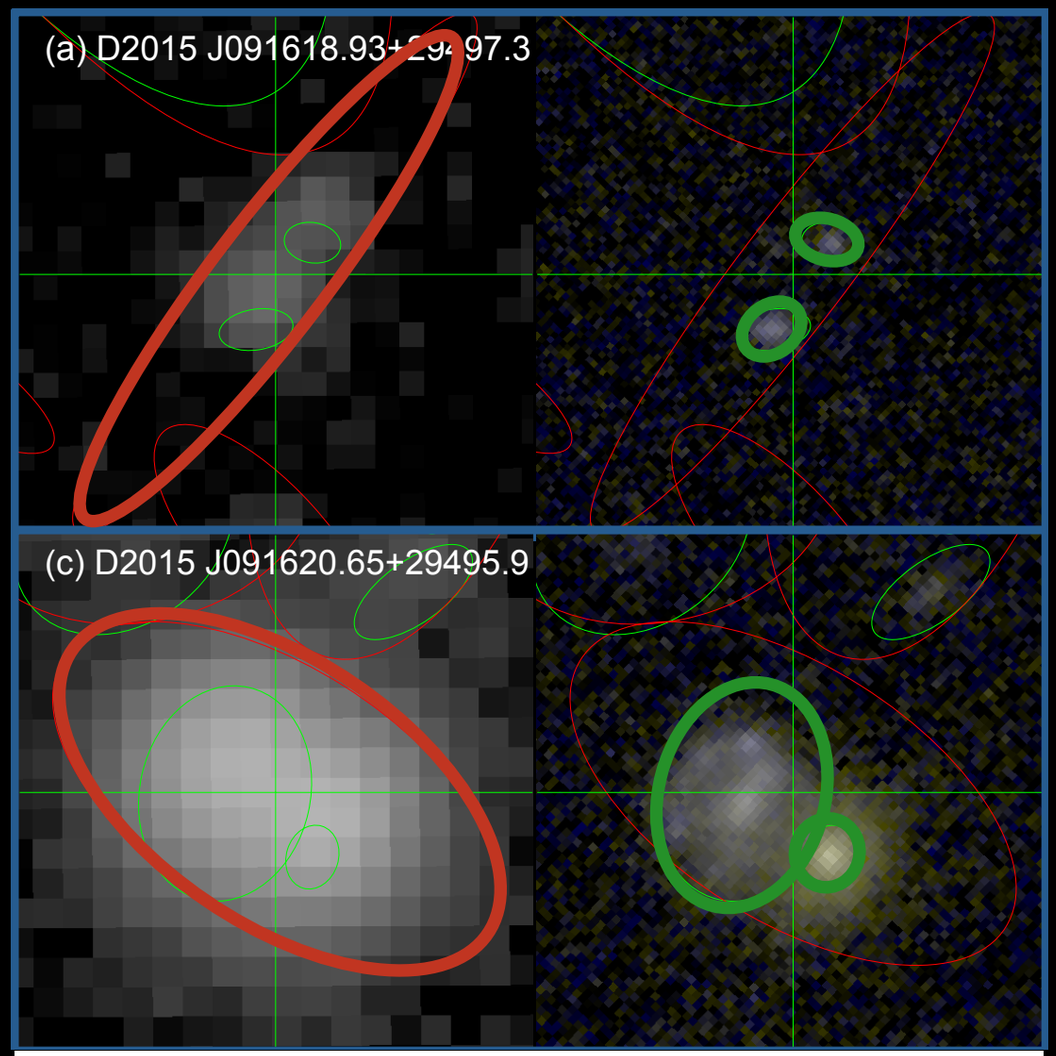
Parameter Constraints

Unknown Systematics? vs. New Physics?



Unknown Systematics? vs. New Physics?

- scale dependence?
- dependence on galaxy/cluster selection?
- calibrate with more accurate measurements
  - spectroscopic redshifts
  - low-scatter cluster mass proxies
  - galaxy shapes from space-based imaging
  - [potentially expensive]

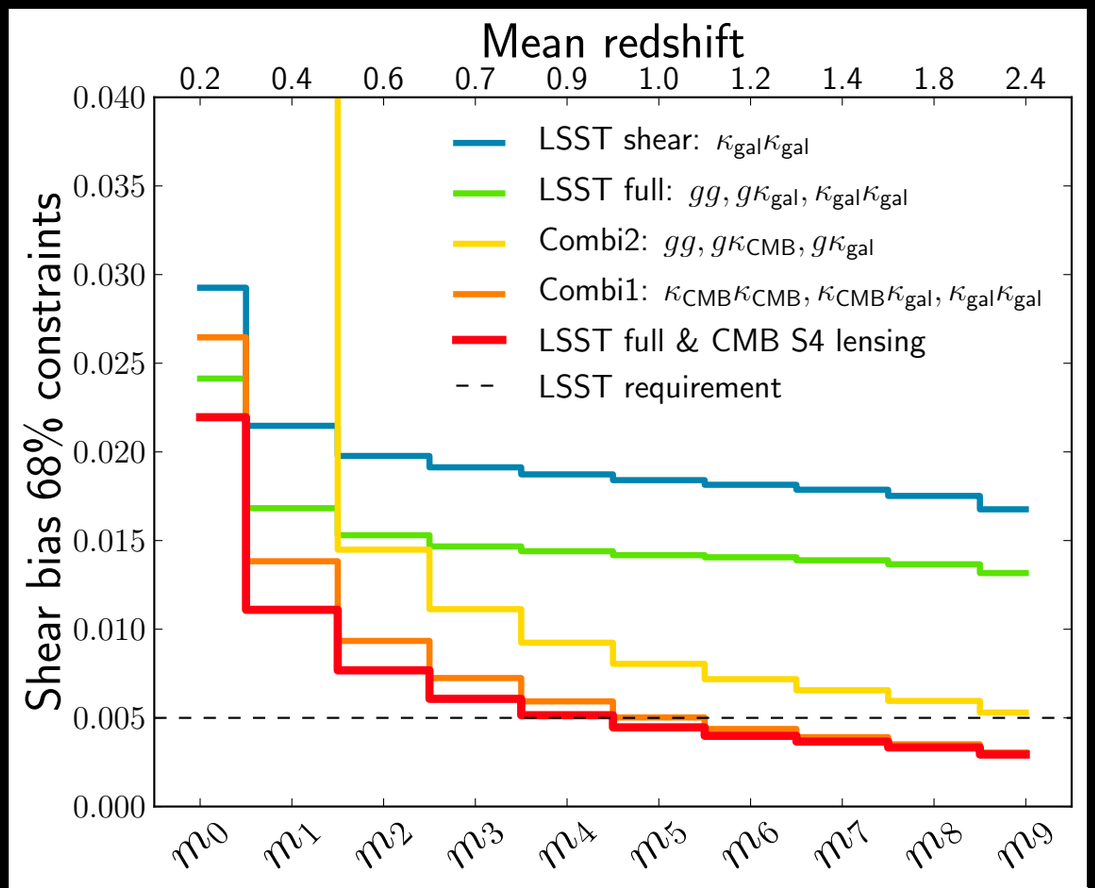


Subaru HST-ACS

ground vs. space-based shape measurements
Dawson+ 2016

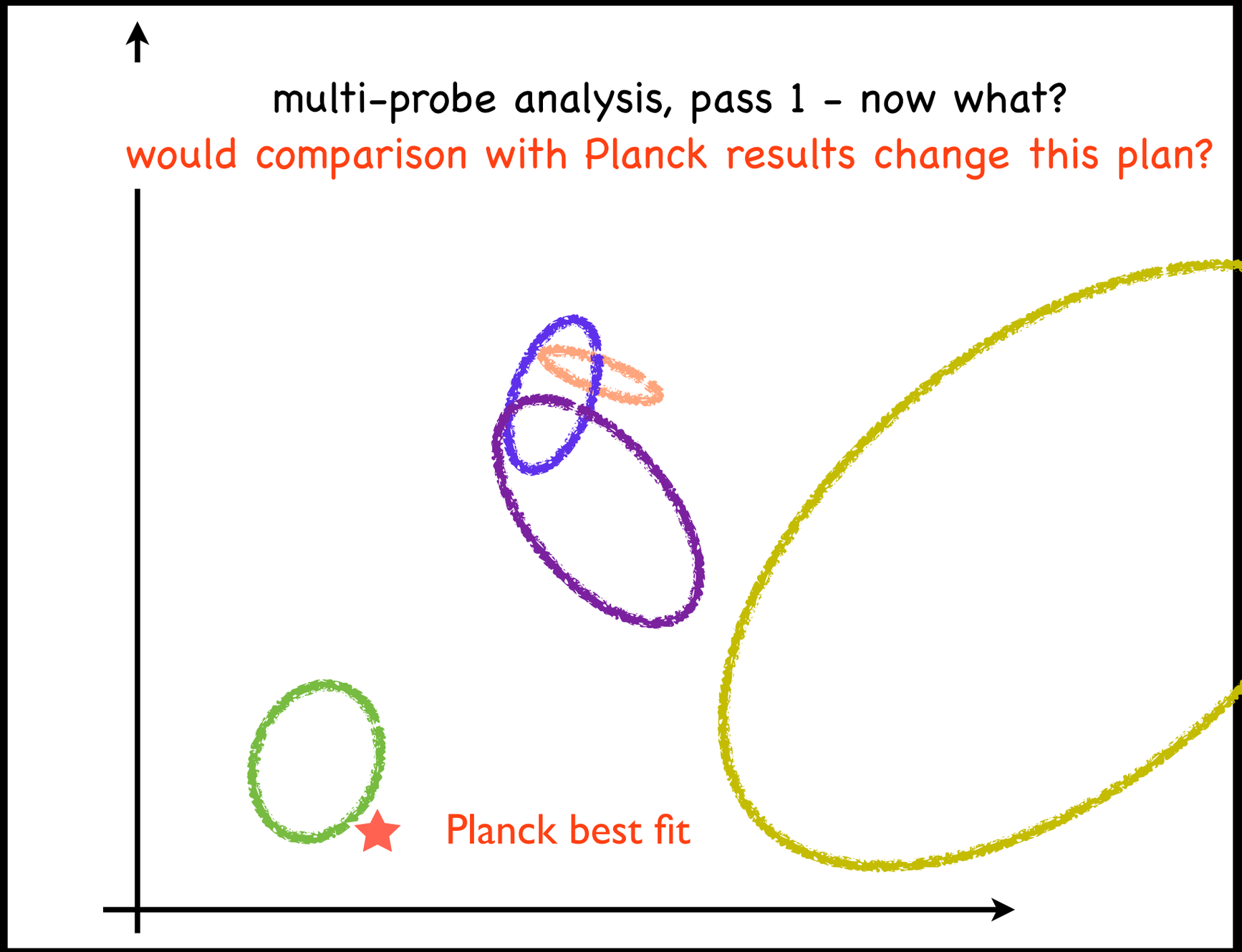
Unknown Systematics? vs. New Physics?

- scale dependence?
- dependence on galaxy/cluster selection?
- calibrate with more accurate measurements
  - spectroscopic redshifts
  - low-scatter cluster mass proxies
  - galaxy shapes from space-based imaging
  - [potentially expensive]
- correlate with other surveys
  - compare to predicted cross-correlations
  - constrain uncorrelated systematics



LSST WL x CMB-S4 lensing
calibrate shear calibration bias
Schaan, EK,+17

Unknown Systematics? vs. New Physics?



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Blinding

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Single Probe Analyses

Combined Probes Analysis

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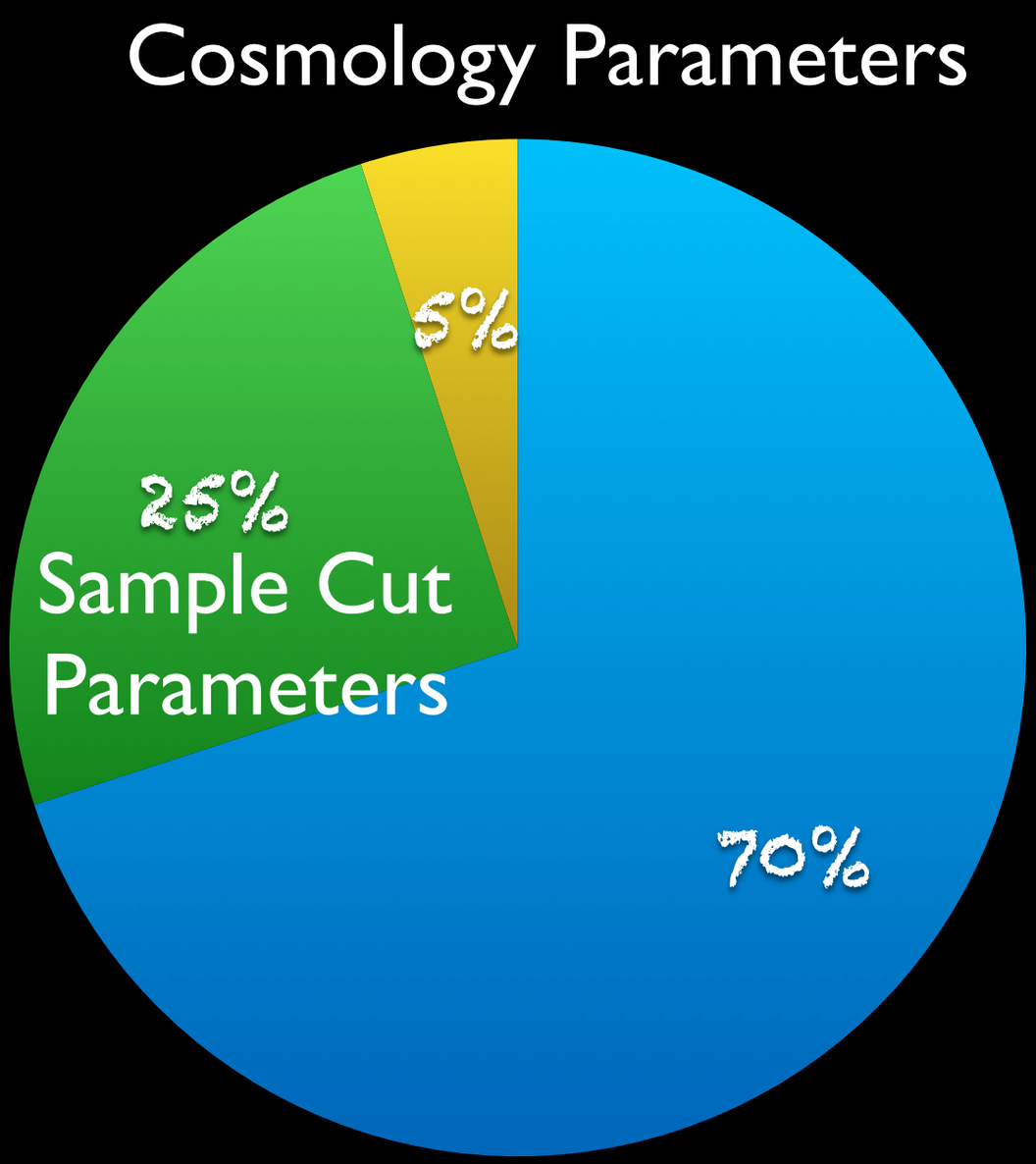
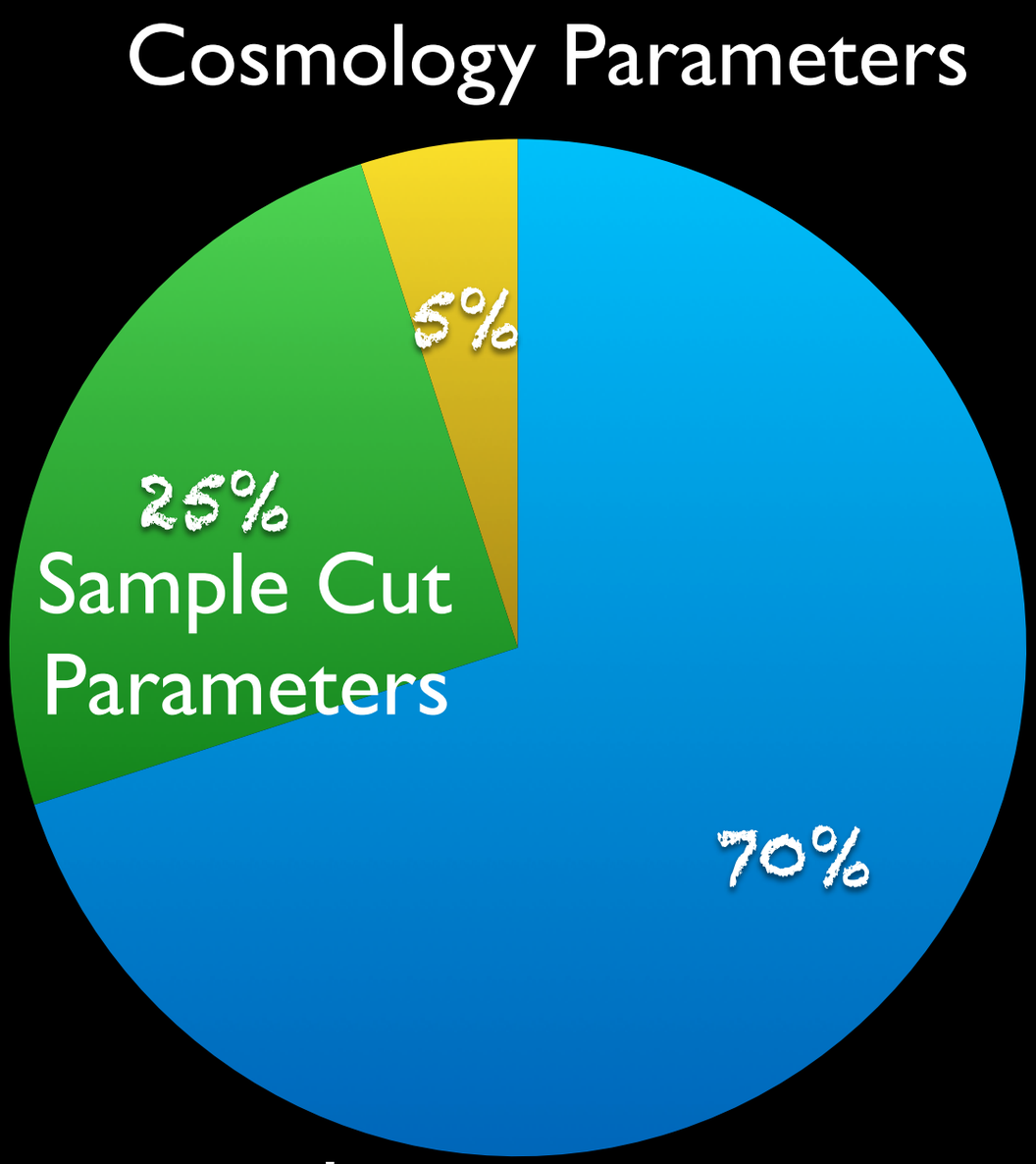
Cosmology Analysis Parameters



“Systematics Parameters”

- observational systematics
  - survey specific
- astrophysical systematics
  - probe + survey specific

Cosmology Analysis Parameters



"Systematics Parameters"

- observational systematics
  - survey specific
- astrophysical systematics
  - probe + survey specific

sample cuts + systematics highly interconnected

→ 95% systematics…

Conclusions

- We're entering the decade of very large galaxy surveys
    - KiDS,DES, HSC, PFS -> DESI, LSST, Euclid, WFIRST,…
- Cosmological constraints soon to be systematics limited
- Combined Probes analyses enable accurate cosmology constraints
    - identify and understand systematics effects
    - maximize constraining power
- Need collaboration across surveys + wavelengths, plan for analysis frameworks to combine data from all surveys
- Let's get to work!
    - http://www.lsst-desc.org/