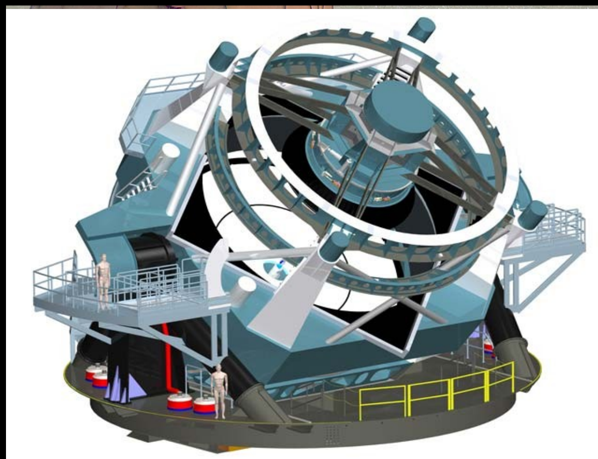
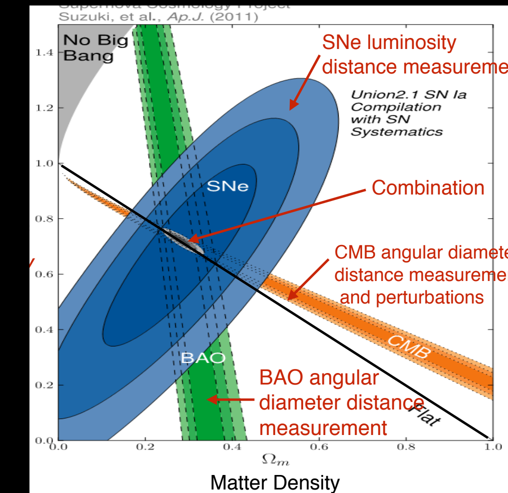




Internal and external synergies for Rubin LSST cosmology analyses

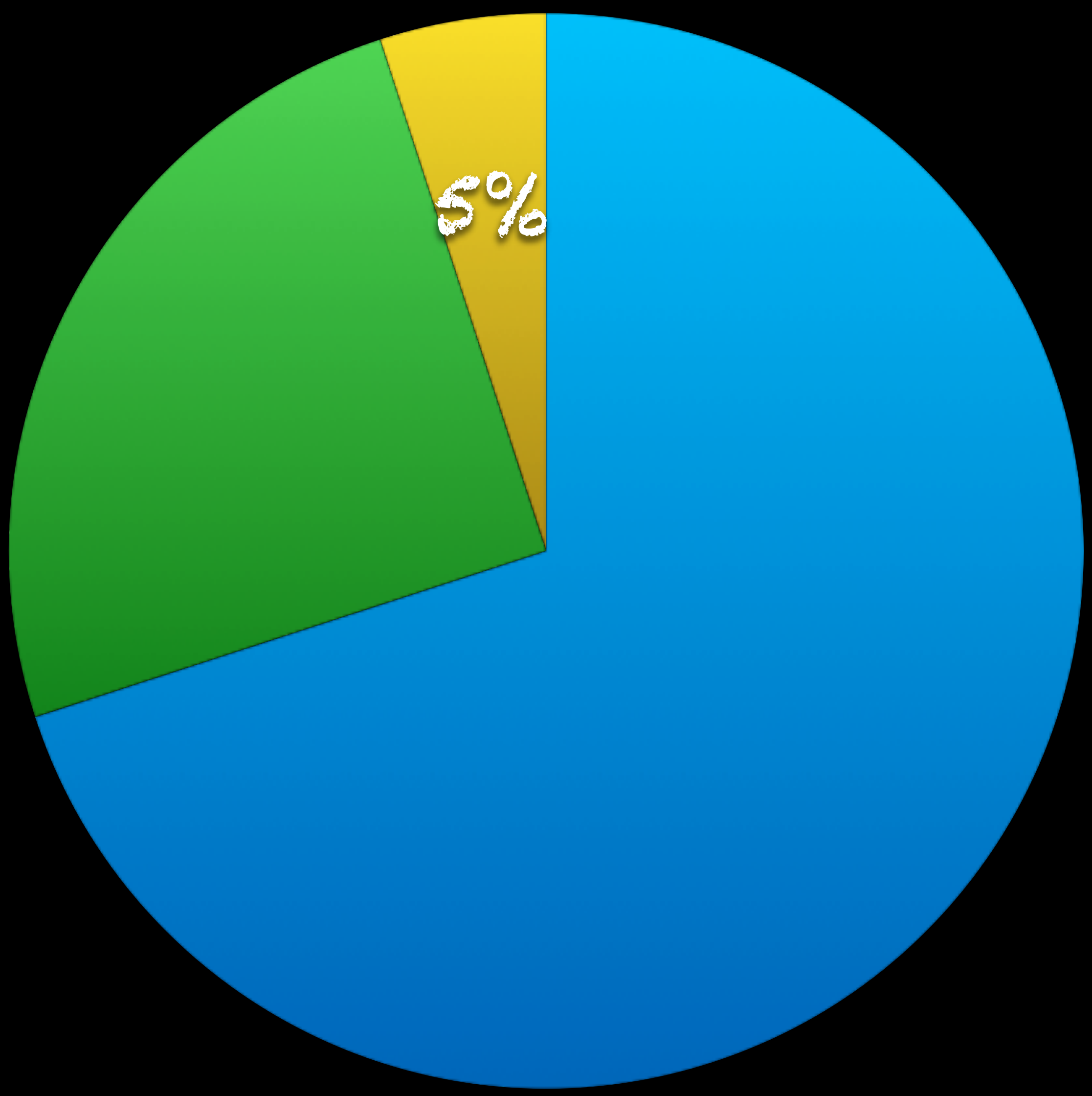
Elisabeth Krause
University of Arizona

with the DES, LSST-DESC and Roman-HLS collaborations

Synergies@Prague, 12/2021

Preview: Cosmology Analyses, ca. 2025

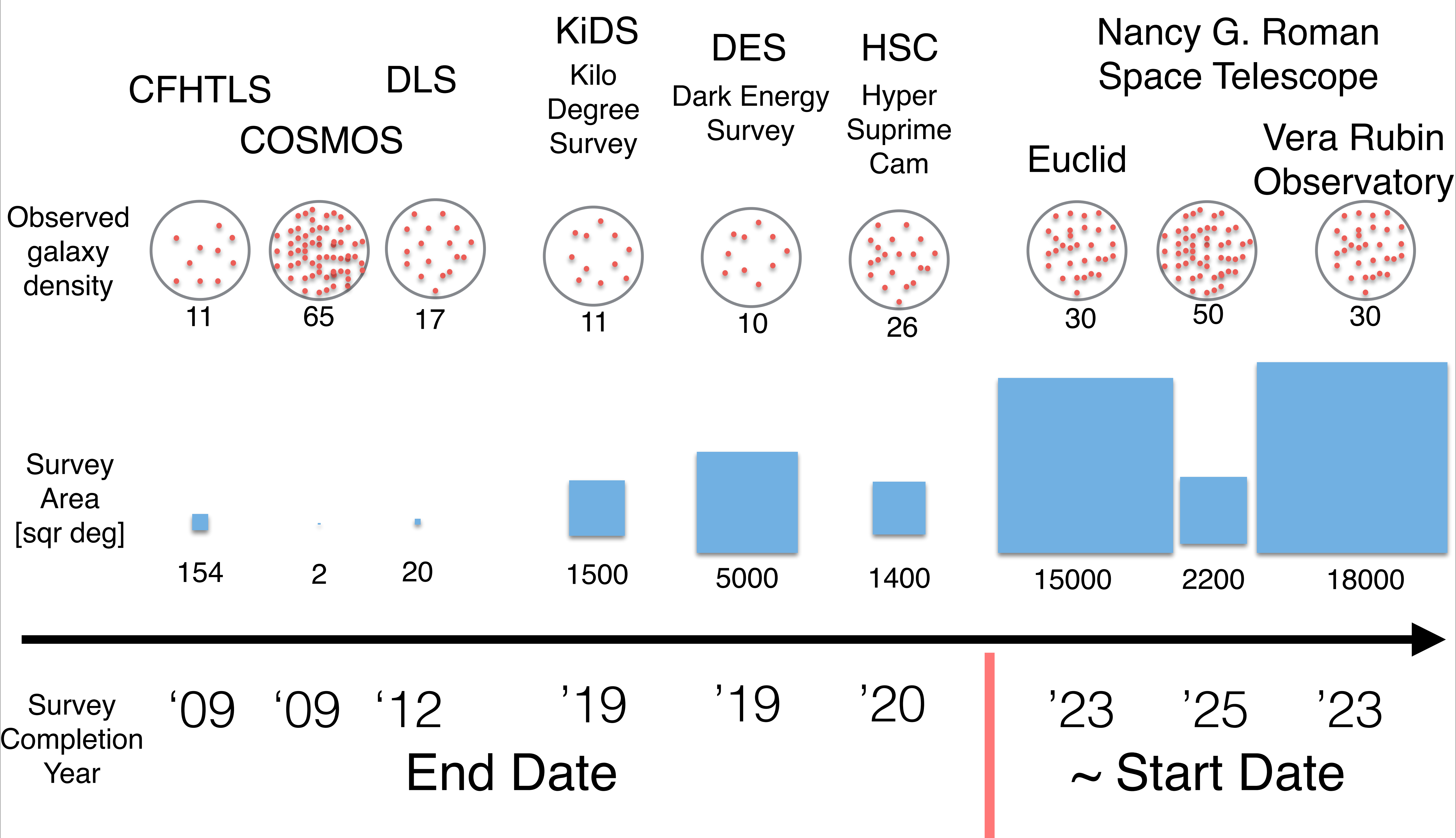
Cosmology Parameters



95% Systematics Parameters

- *known unknowns*
- *unknown unknowns*

Photometric Dark Energy Surveys



Cosmic Structure Formation

gravity drives **cosmic structure formation,** dark energy slows it down

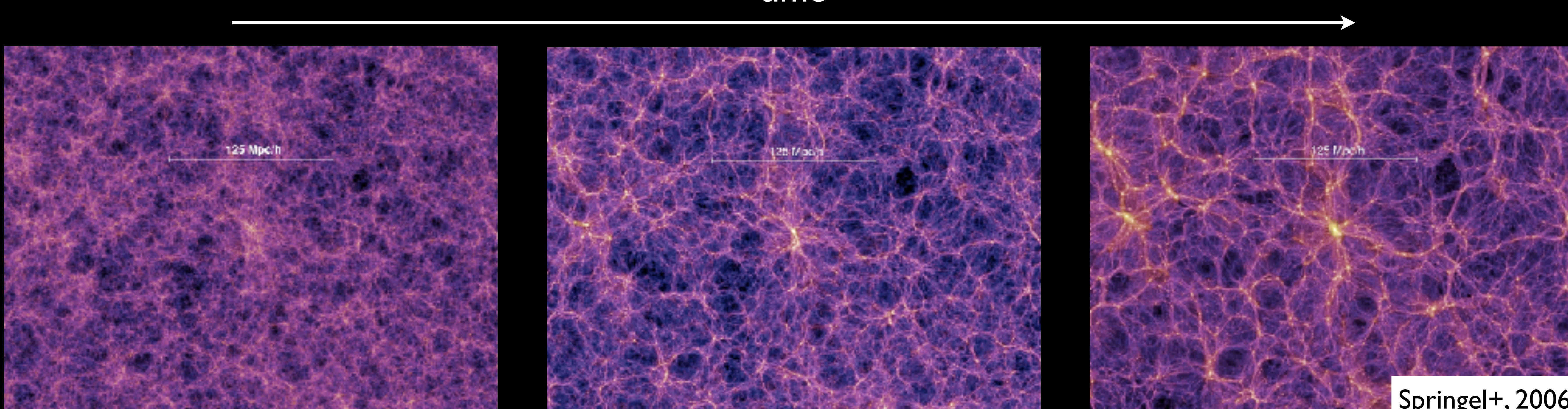
growth of structure constraints complementary to expansion rate

~linear (large) scales: perturbation theory

non-linear evolution: numerical simulations

- reliably predict *dark matter distribution, for wCDM cosmologies (+ individual MG models)*

time



Springel+, 2006

Cosmic Structure Formation

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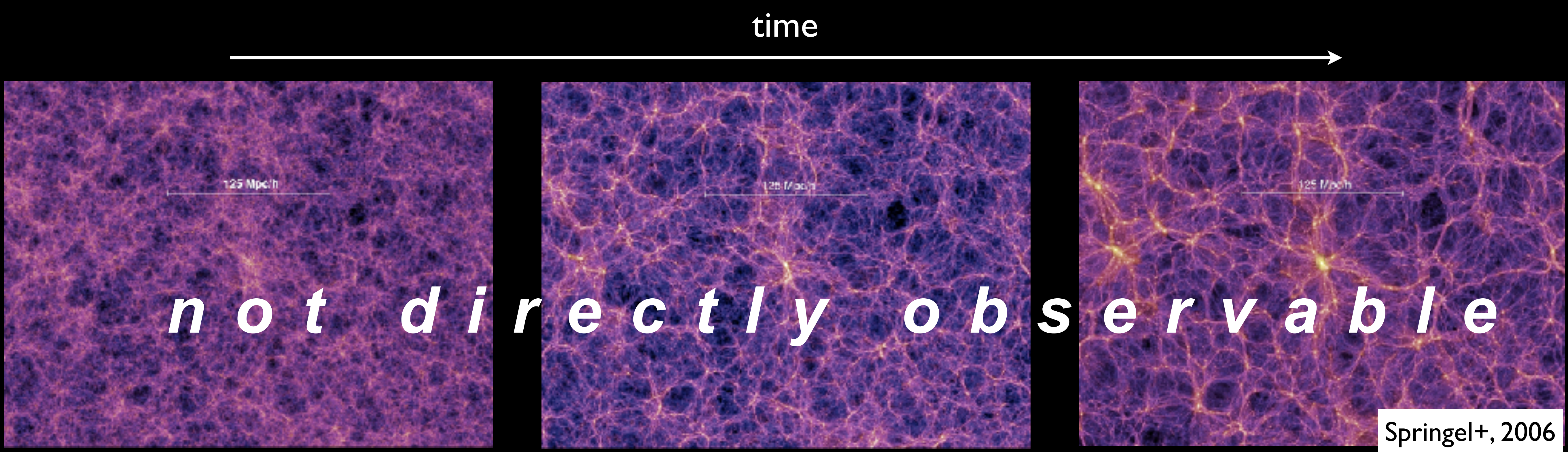
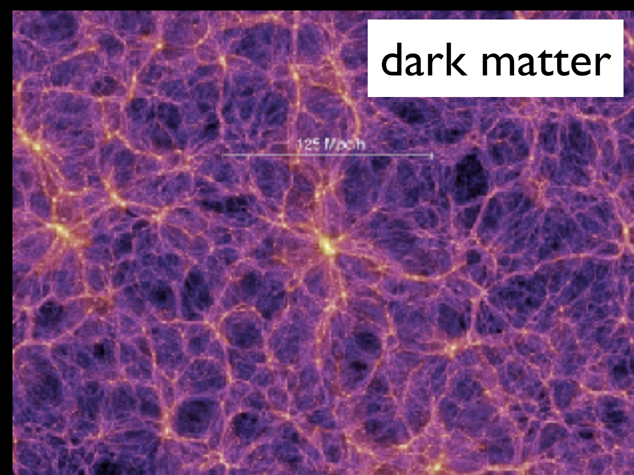


Springel+, 2006

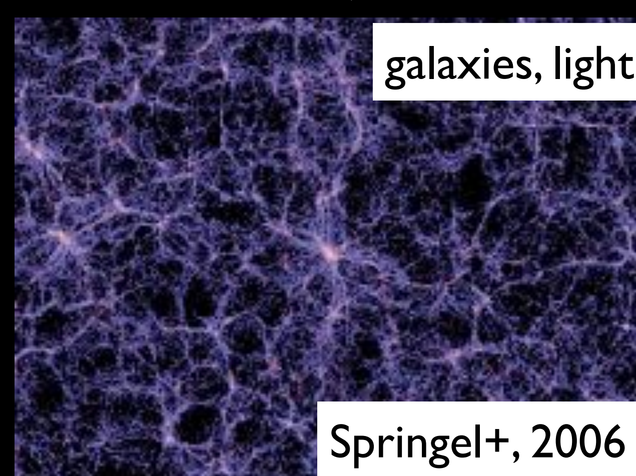
Connecting Theory and Observations

cosmological model
+ parameters

simulation/
perturbation theory

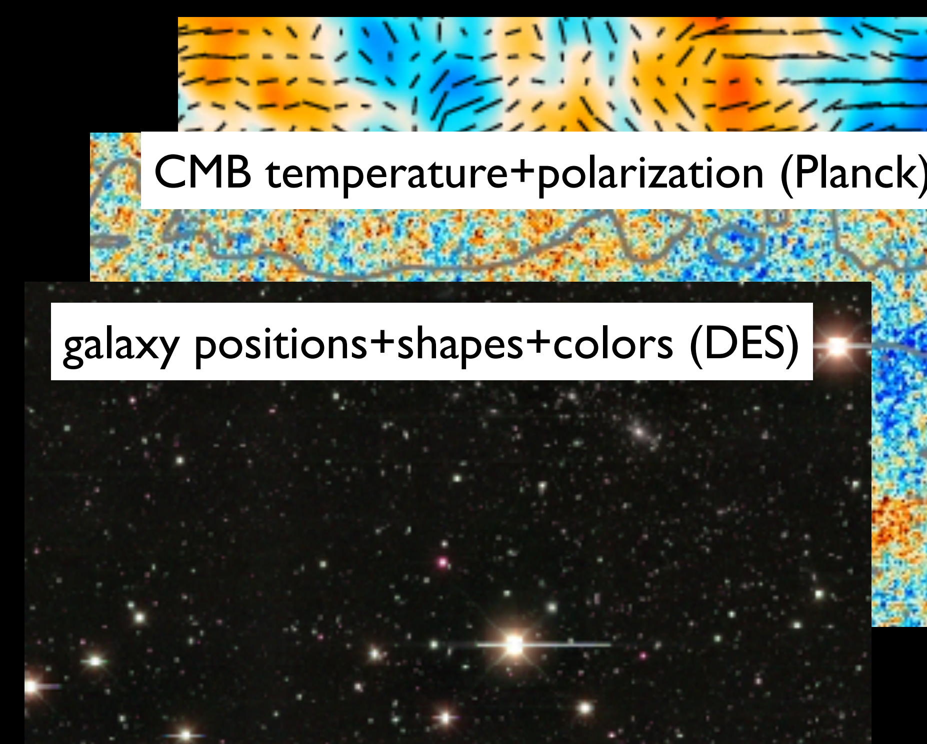


astrophysics (?)

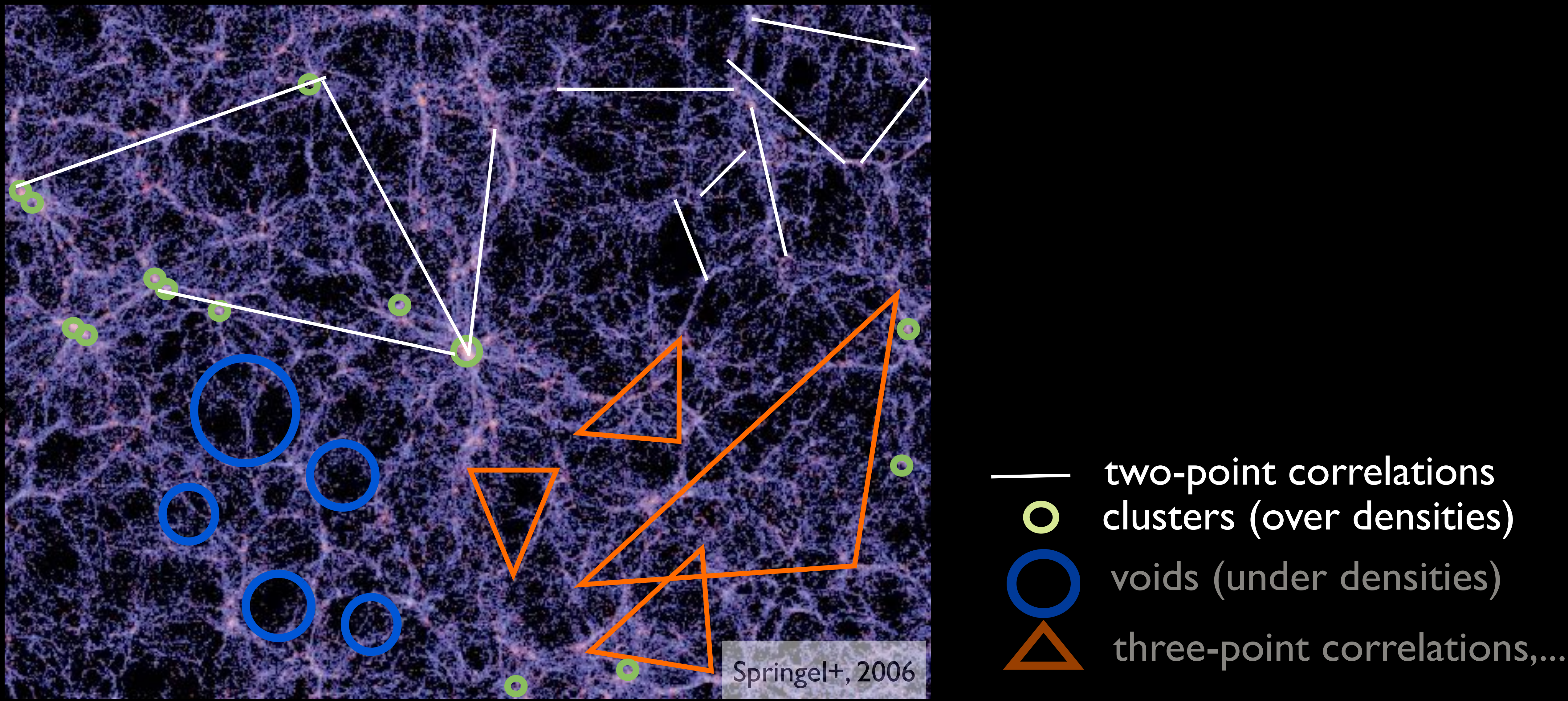


?

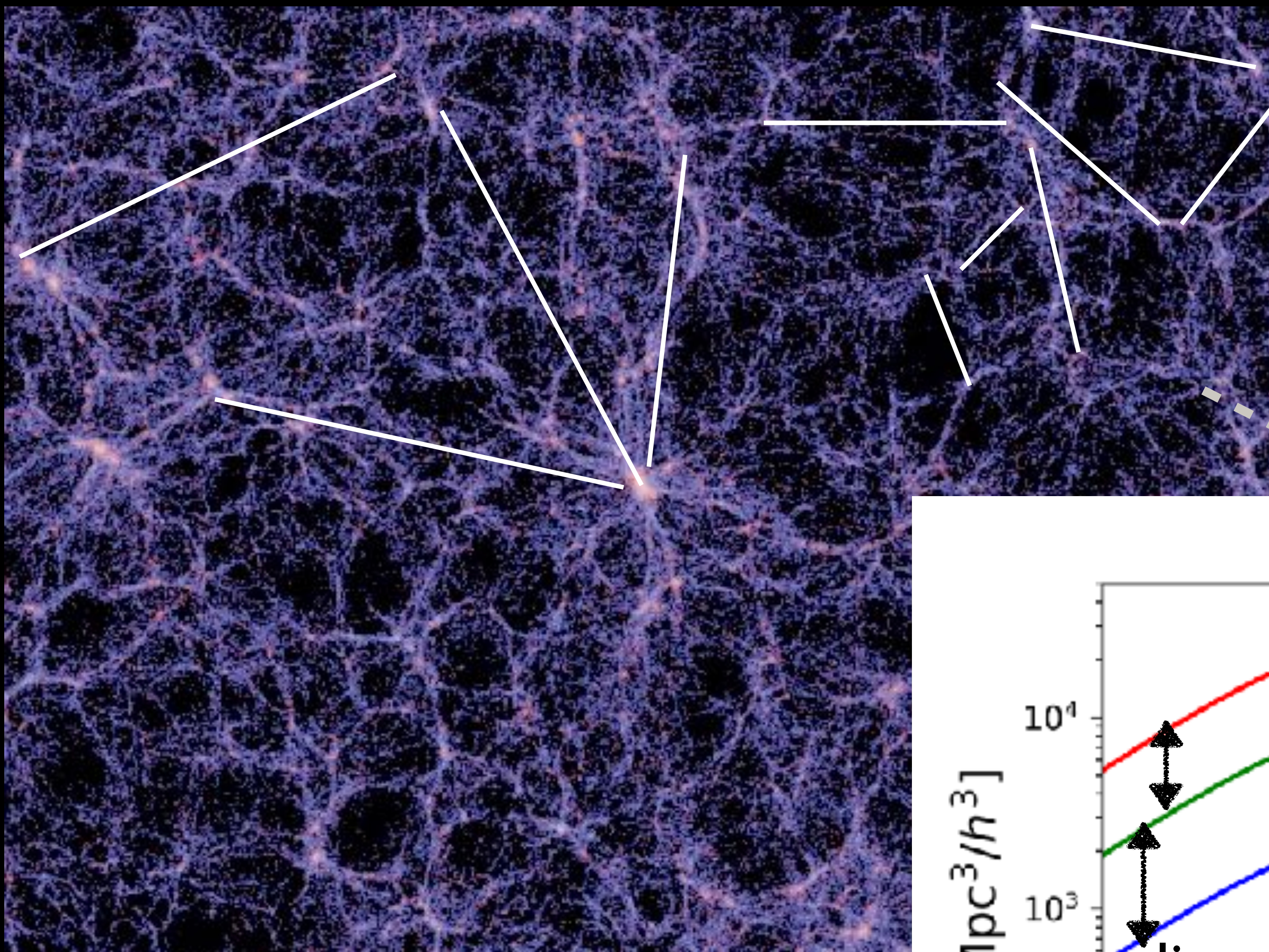
(+ other tracers of
structure formation)



Summary Statistics from the Galaxy Distribution

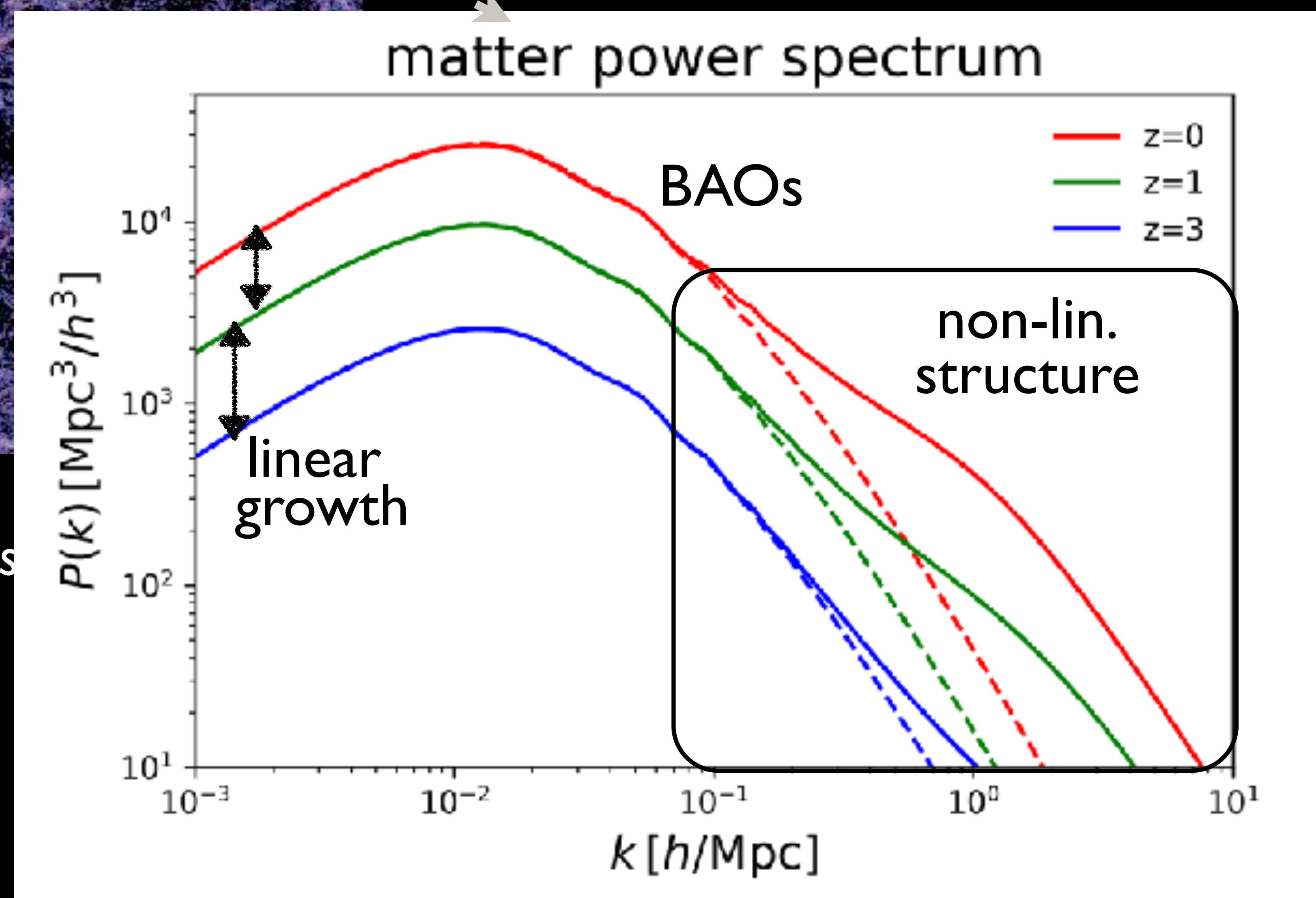


Tracer: Galaxy Clustering



requires ~3D distances (redshift), relation between galaxy density and dark matter density (galaxy bias)

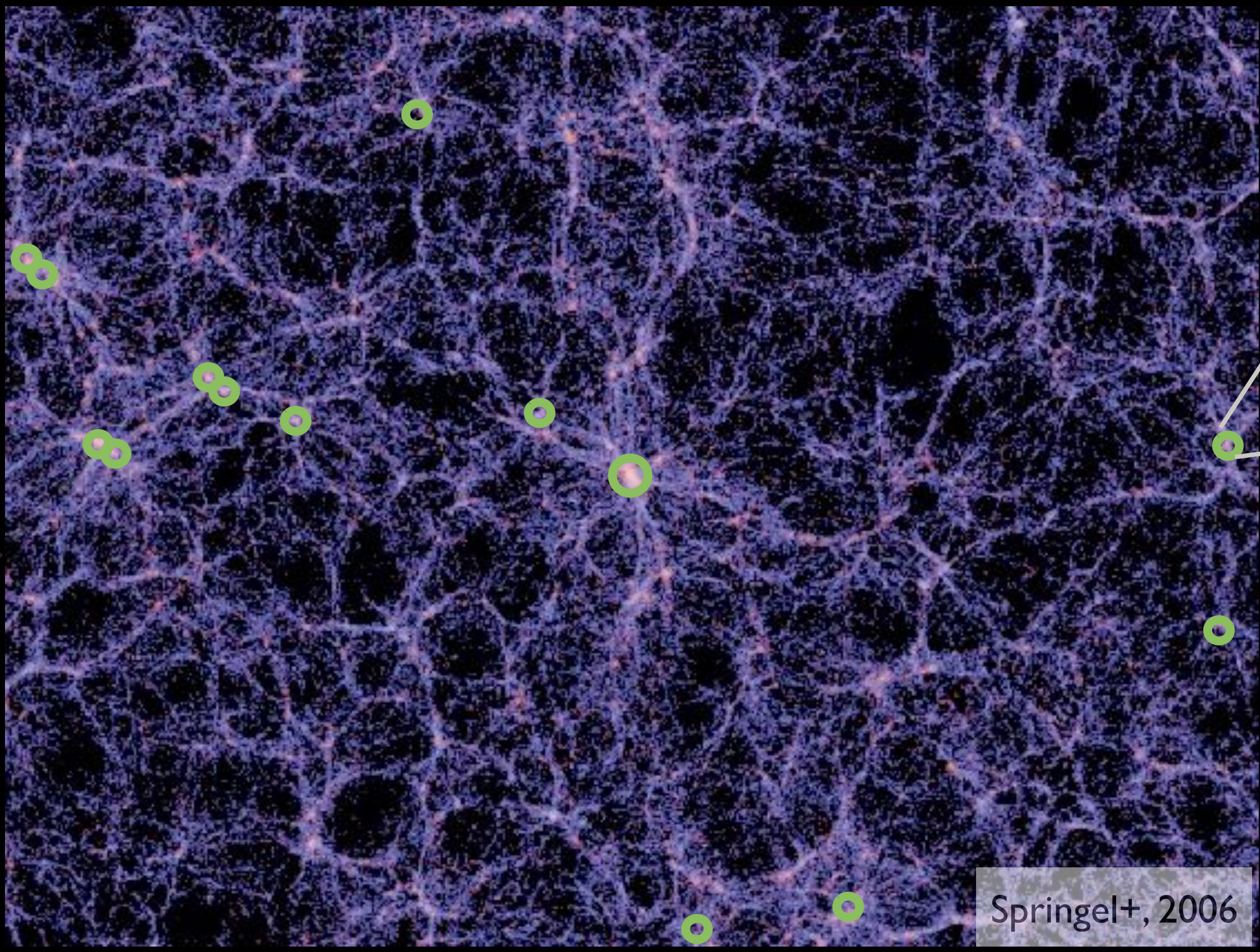
Fourier transform

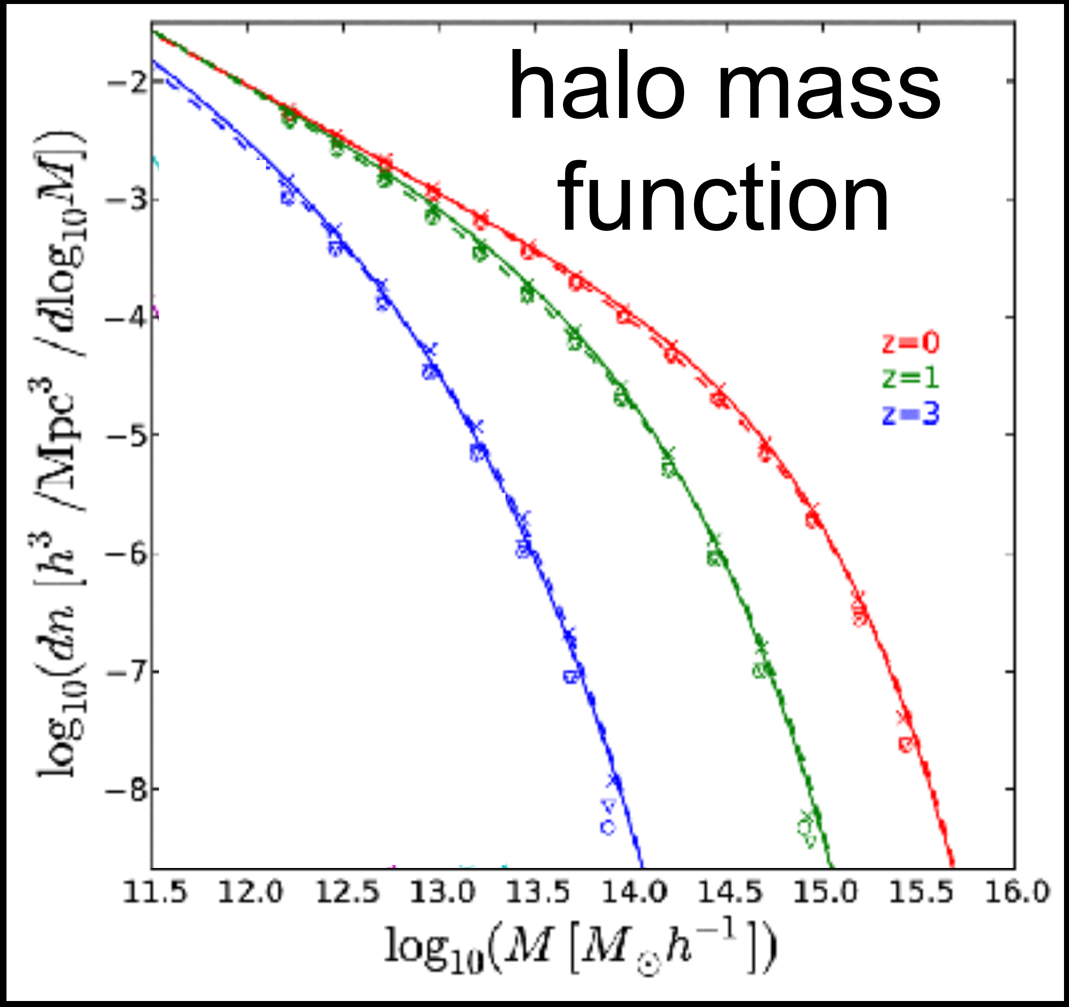


two-point correlations
excess probability of galaxy pairs
(over random distr.)
as function of separation

Tracer: Galaxy Clusters

image: DES





clusters (over densities)

requires relation between observed mass proxy (e.g. galaxy counts) and halo mass "mass-observable relation" (MOR)

Tracer: Weak Gravitational Lensing of Galaxies

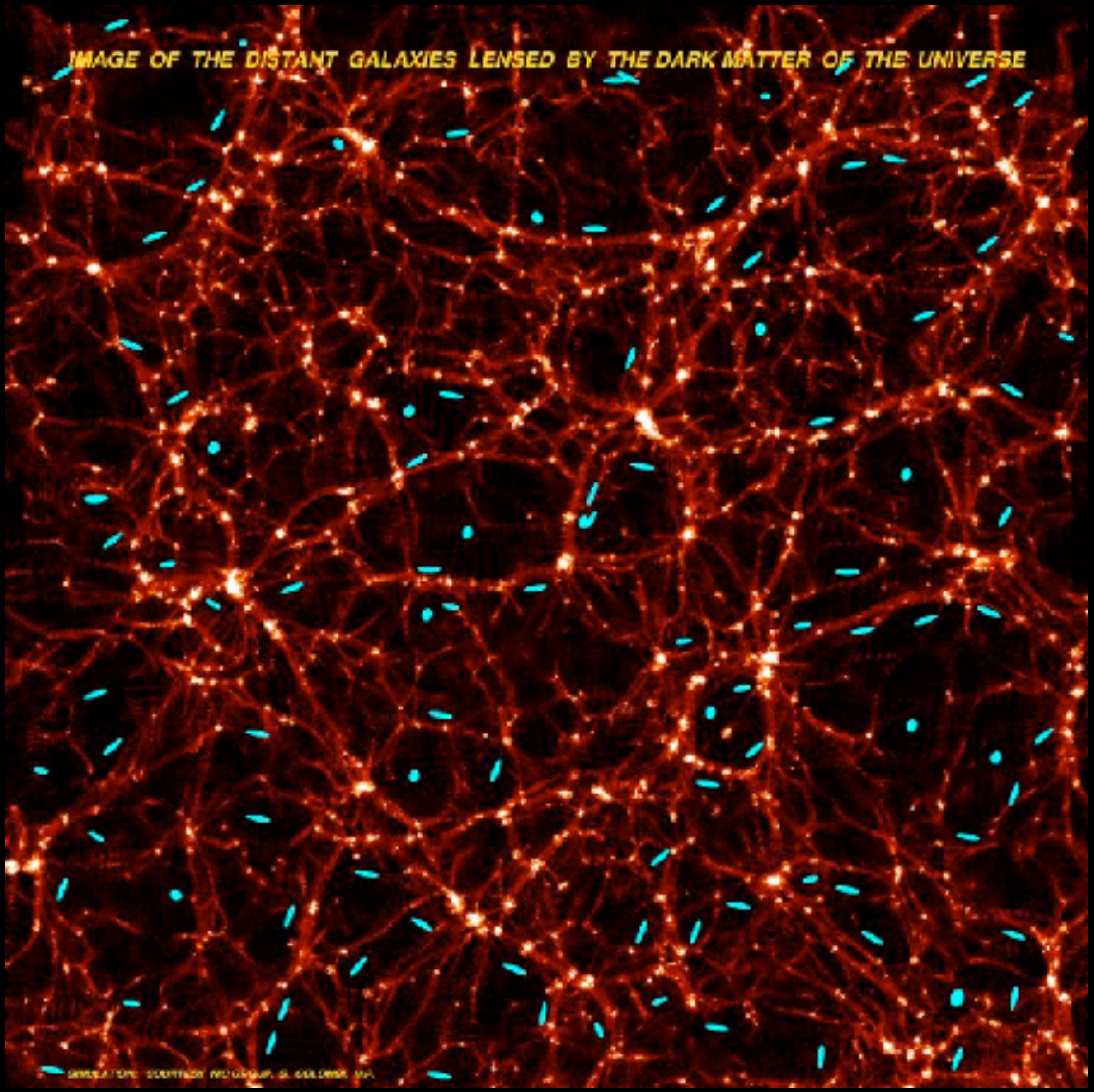
light deflected by tidal field of large-scale structure

- coherent distortion of galaxy shapes - “shear”
- shear related to (projected) matter distribution

key uncertainties

shape measurements

average over many galaxies assuming *random intrinsic orientation*



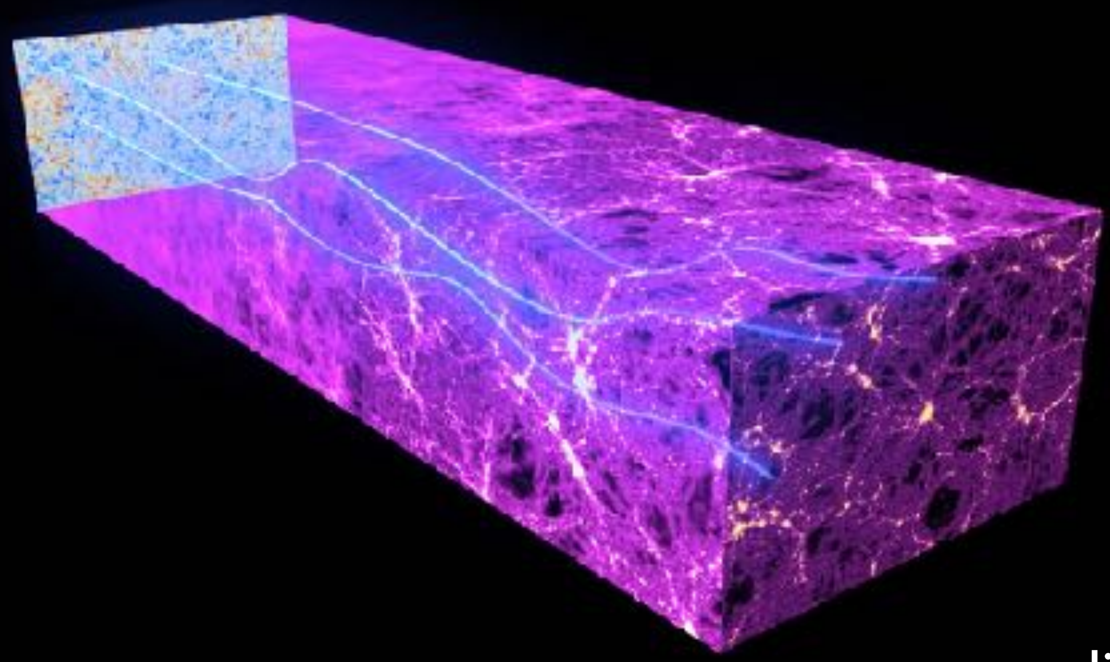
Tracer: Weak Gravitational Lensing of the CMB

light deflected by tidal field of large-scale structure

- remapping of (primary) CMB anisotropies

CMB lensing affected by different systematics than galaxy shear estimates

independent technique & consistency check

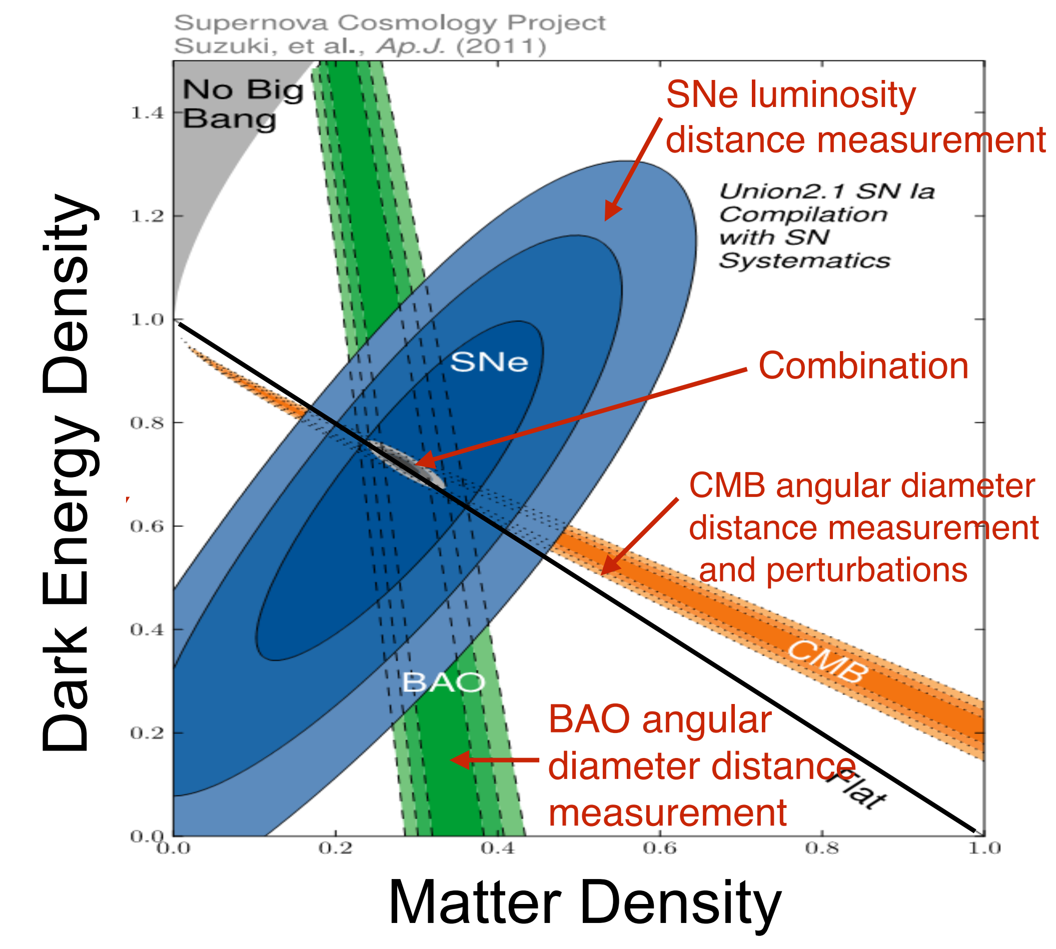


credit: ESA

The Power of Combining Probes

- best constraints obtained by combining cosmological probes
  - independent probes: multiply likelihoods
- *combining structure growth tracers* (from same survey) requires more complicated analyses
  - large-scale structure tracers probe same underlying density field, are correlated
  - correlated systematic effects

→ **requires fully-integrated joint analysis**



Joint Analysis Ingredients

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

Science Case

parameters of interest
which science?

large data vector
which probes + scales?

Joint Covariance

large and complicated, non-(block) diagonal matrix

use template + regularization

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

Cosmology Priors

Systematics Parameters

systematic effects
outnumber cosmology
parameterize + prioritize!

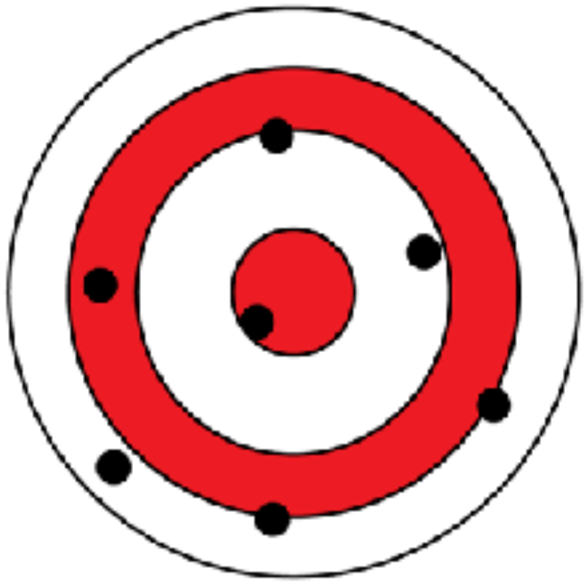
Priors

validate

External Data

Simulations

"Precision" Cosmology

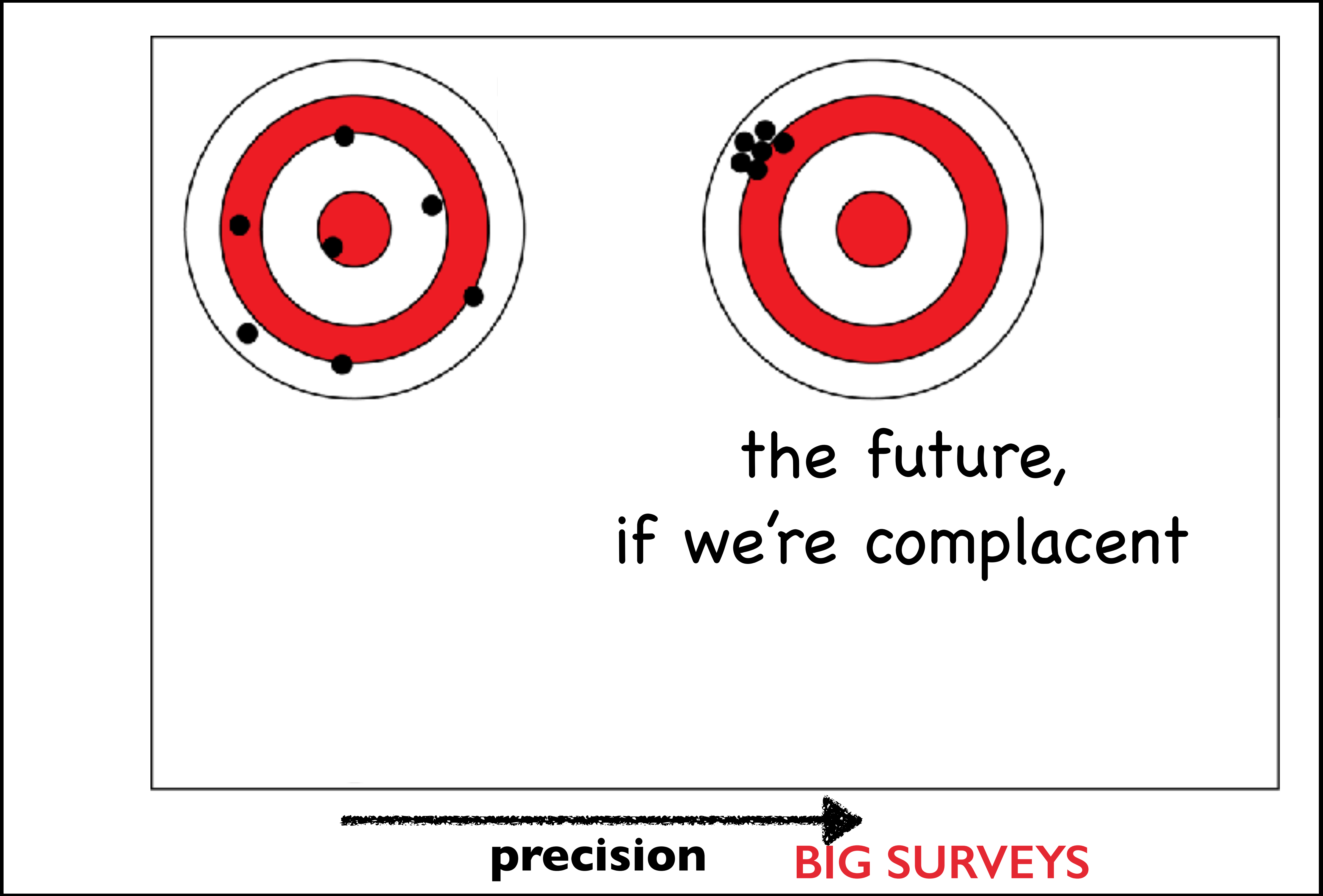


our situation today

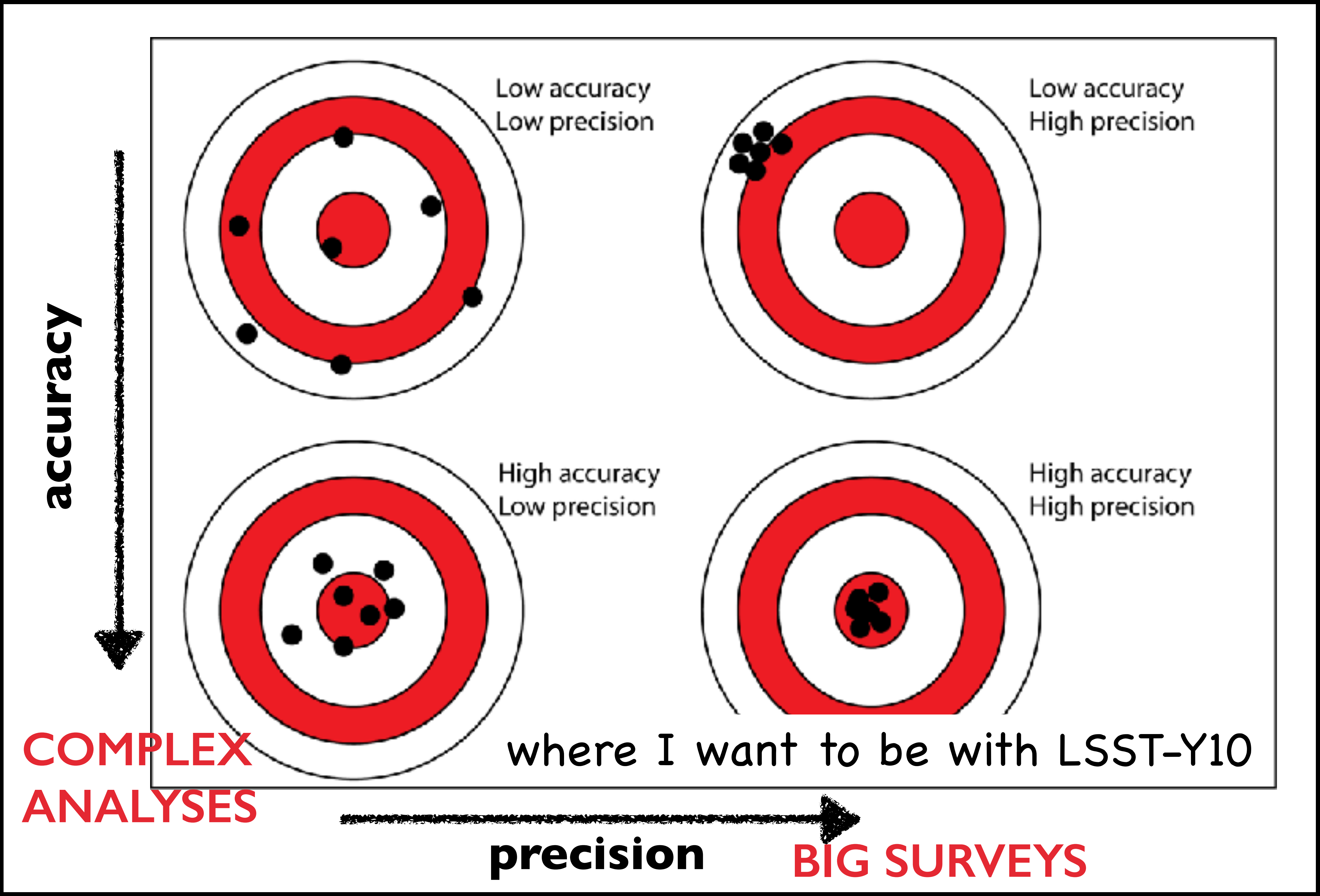
precision

BIG SURVEYS

"Precision" Cosmology



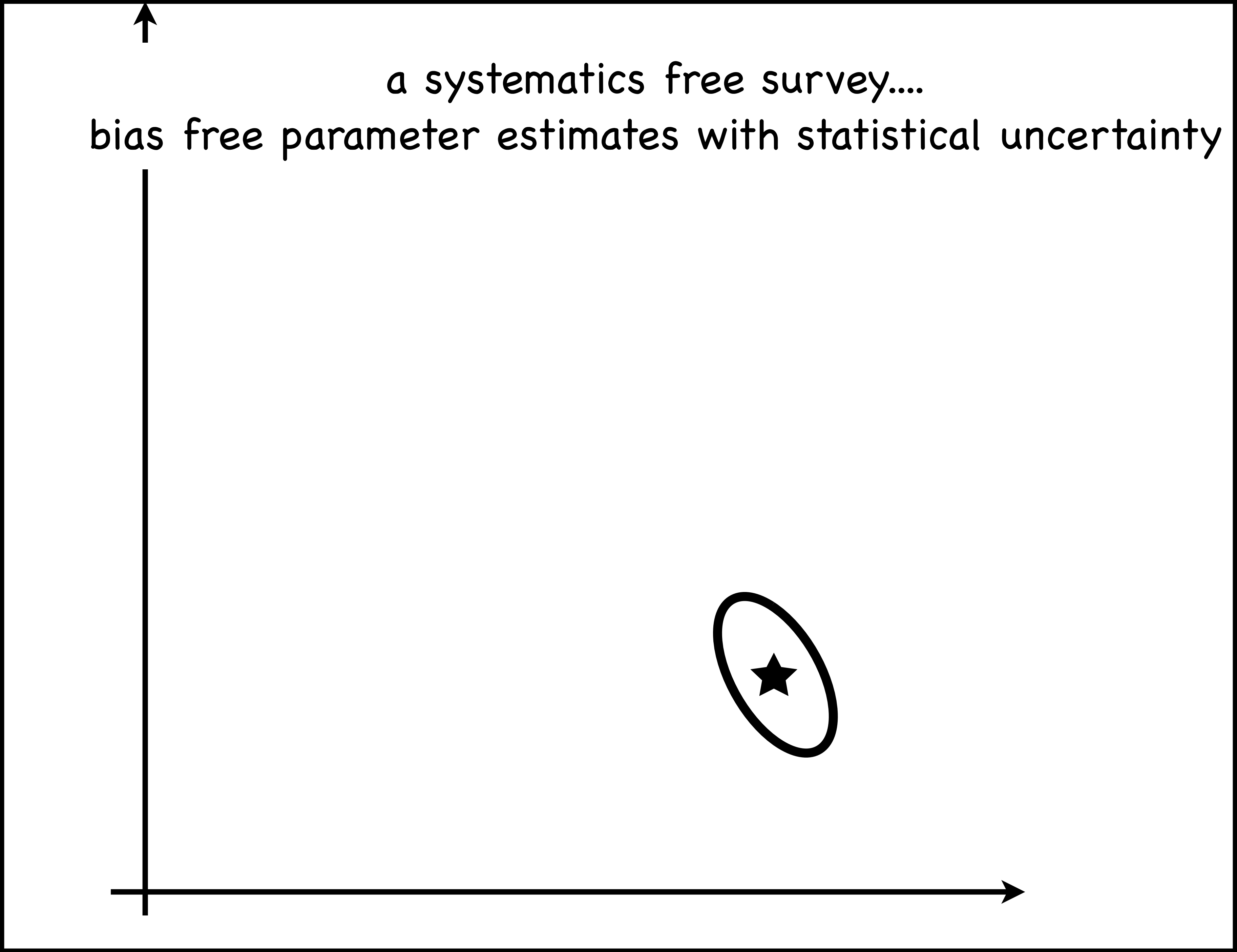
"Precision" Cosmology



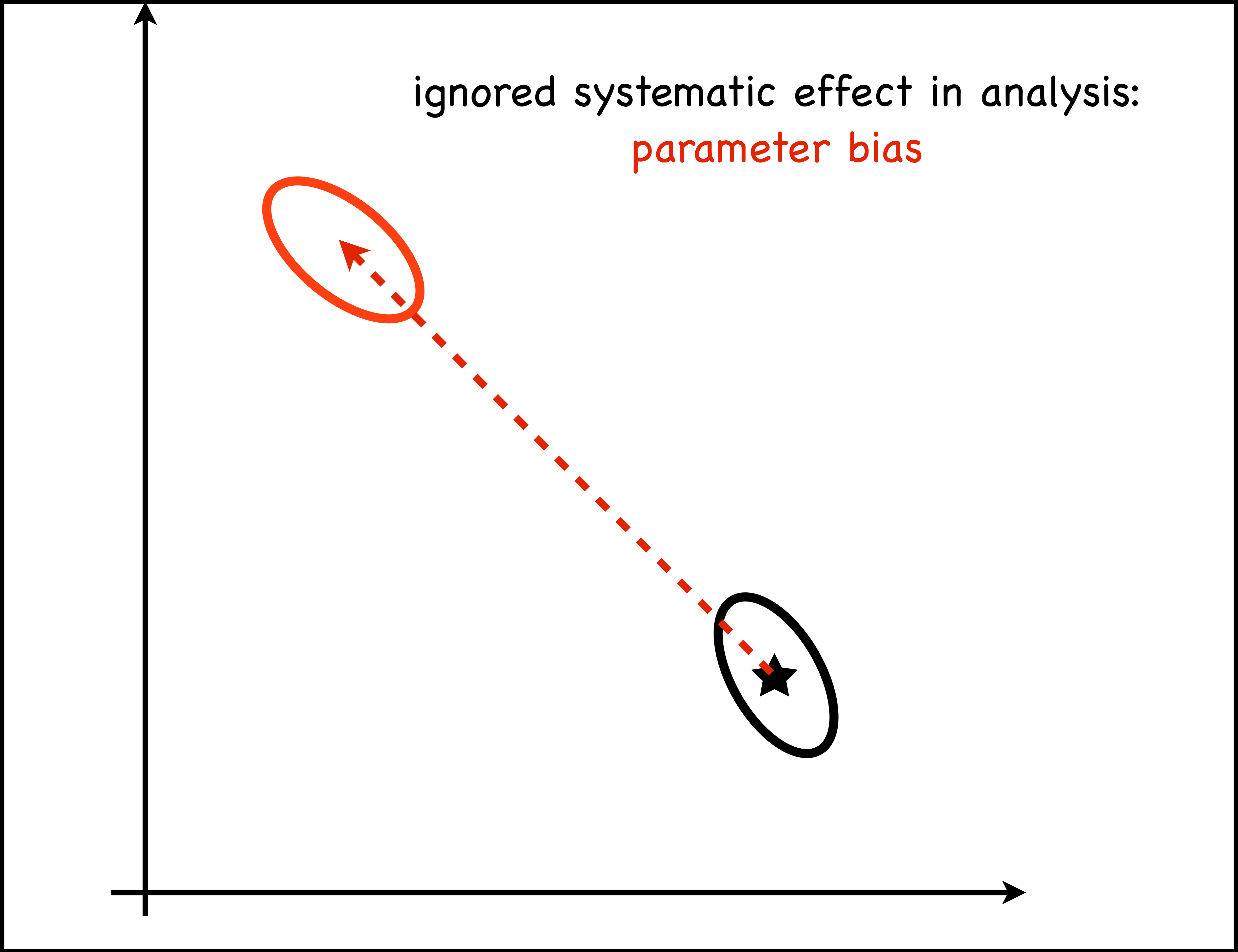
Combined Probes Systematics

- “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?
  - costly (computationally, constraining power)

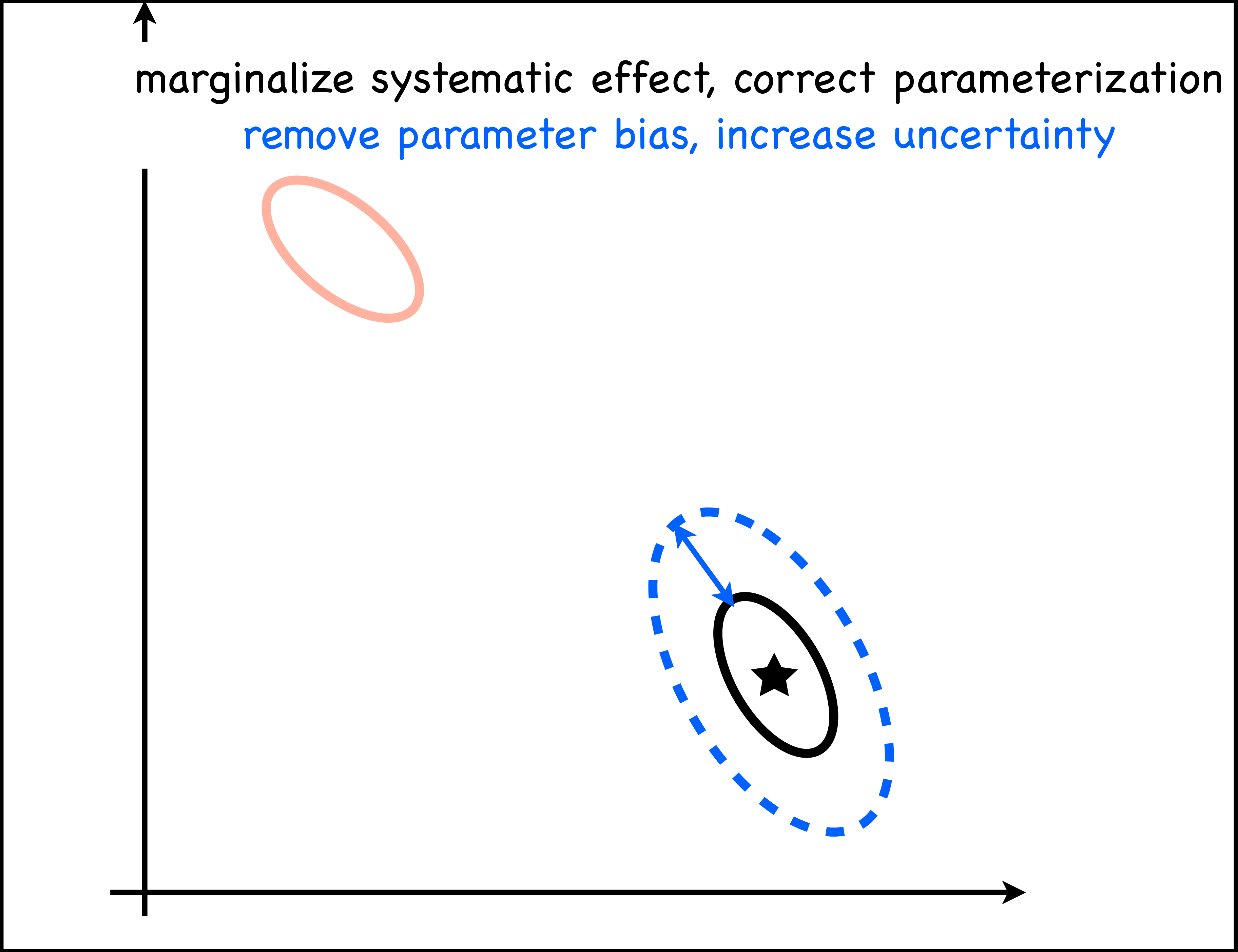
The Trouble with Systematics



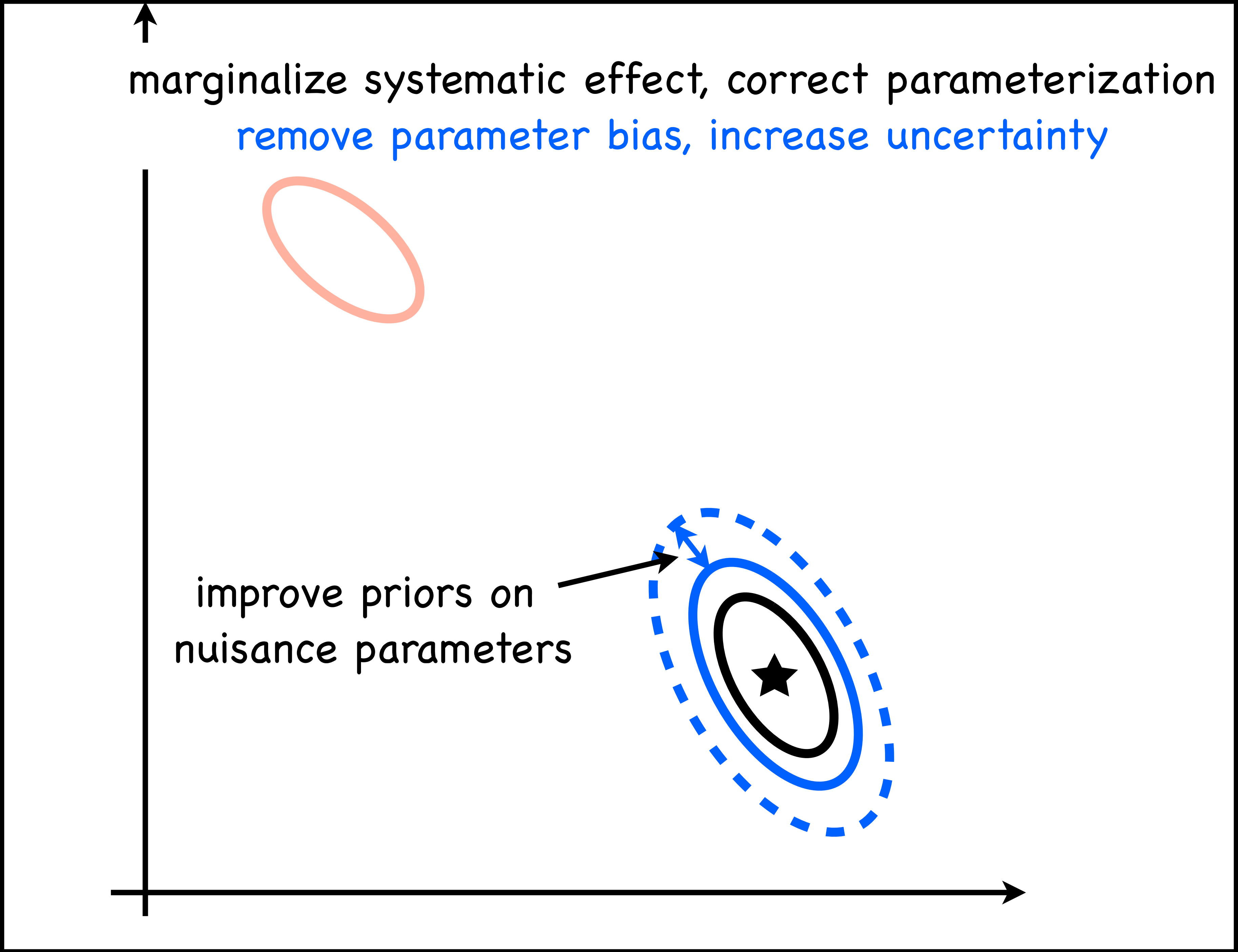
The Trouble with Systematics



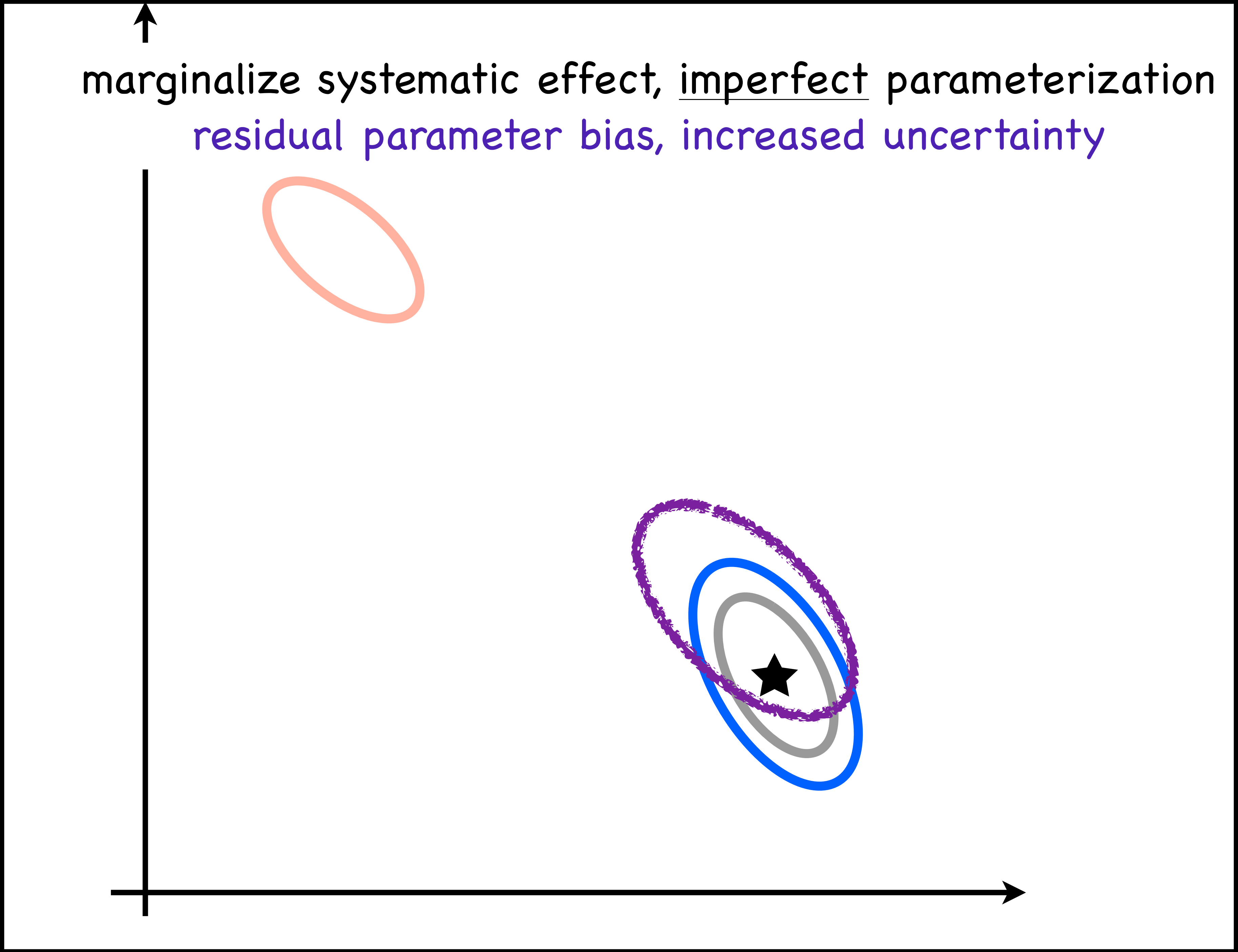
The Trouble with Systematics



The Trouble with Systematics

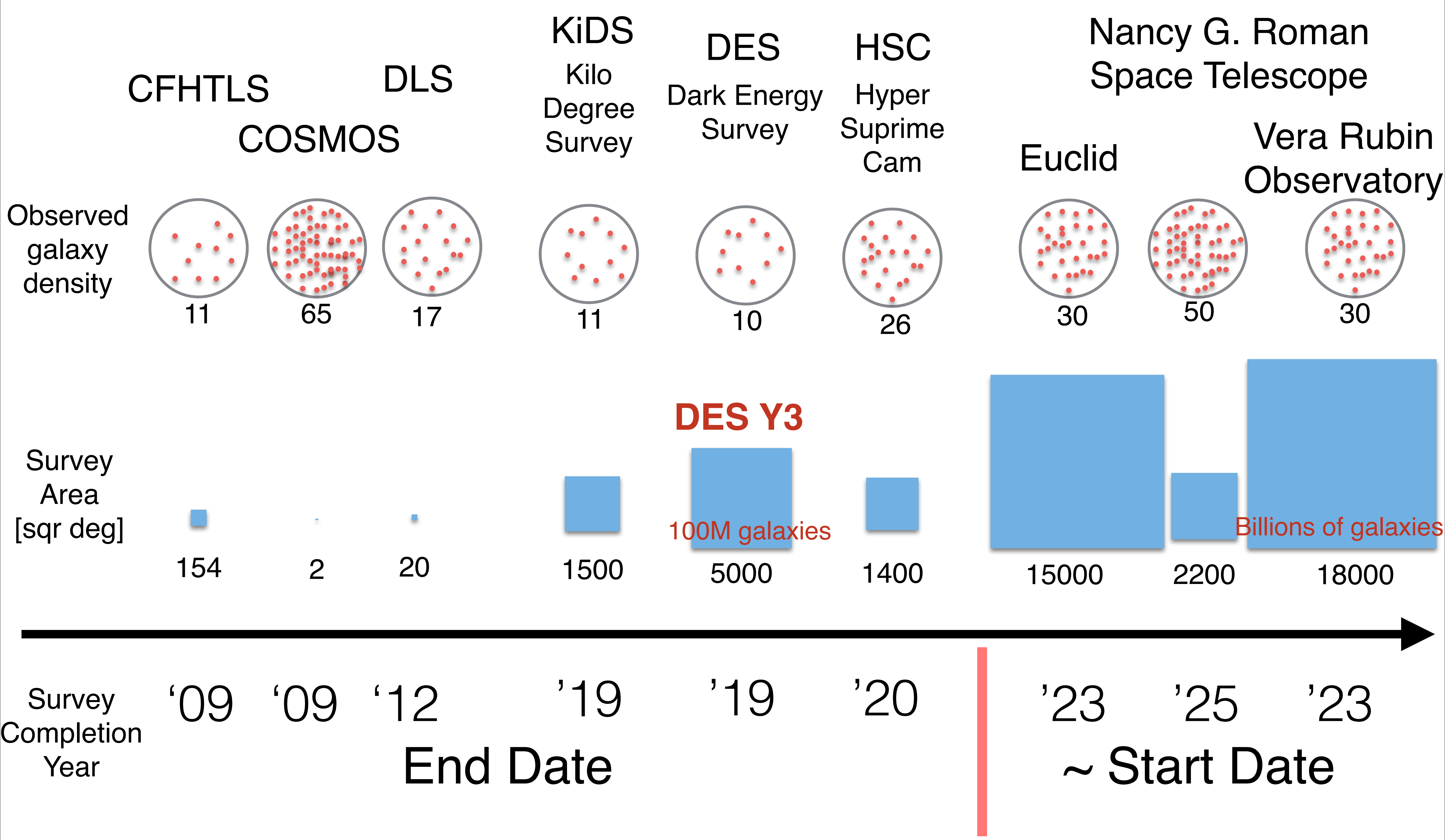


The World is not Perfect

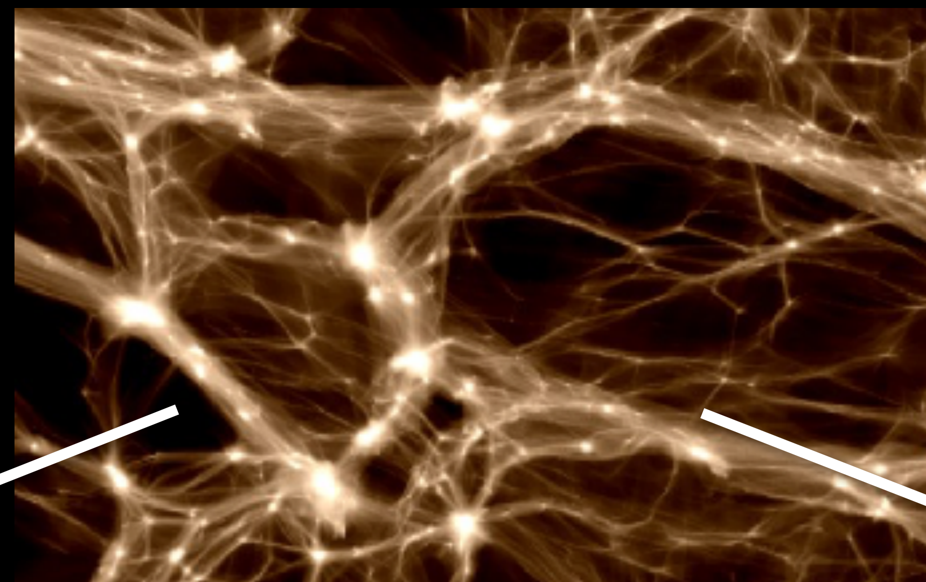


imperfect IA mitigation examples for Rubin: EK, Eifler & Blazek '16

Real World Example: DES-Y3

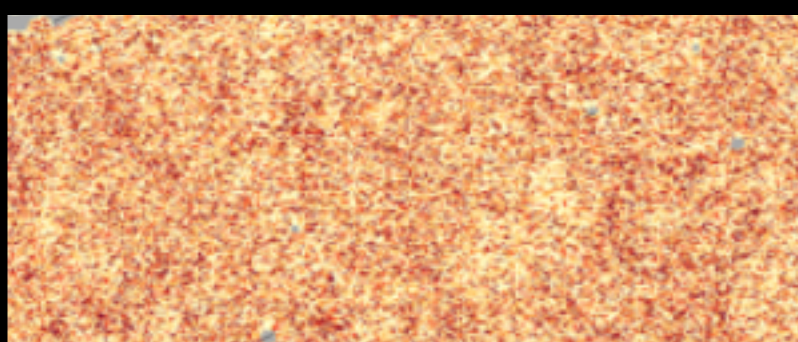


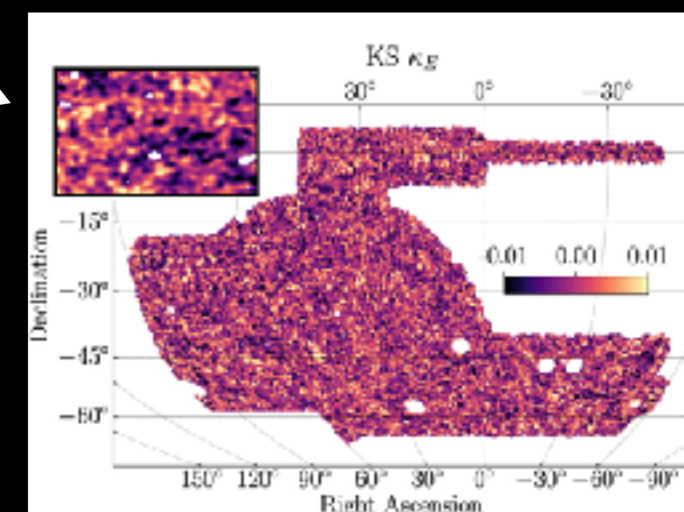
DES-Y3 WL x LSS Analysis



10M lens galaxies
split in 6 redshift bins

100M source galaxies
split in 4 redshift bins

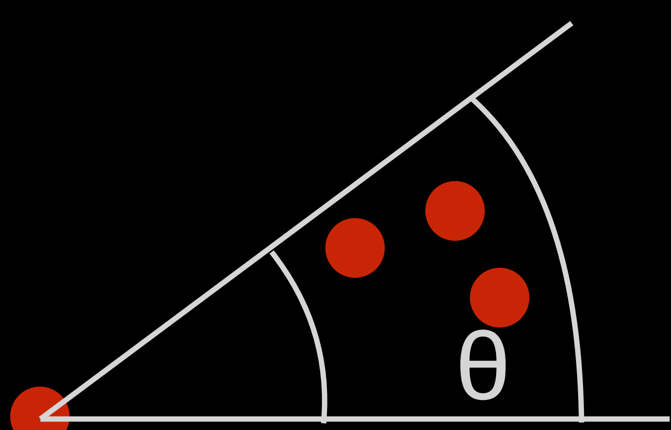


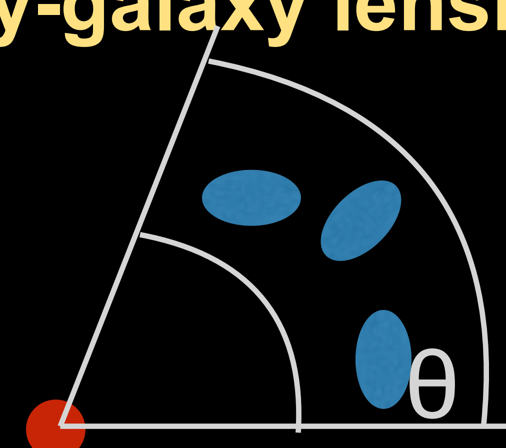


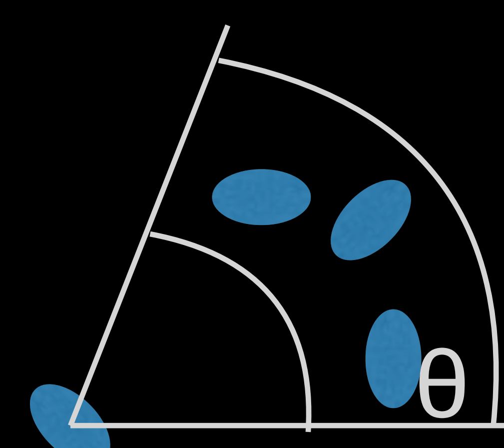
galaxies x galaxies:
angular clustering

galaxies x lensing:
galaxy-galaxy lensing

lensing x lensing:
cosmic shear



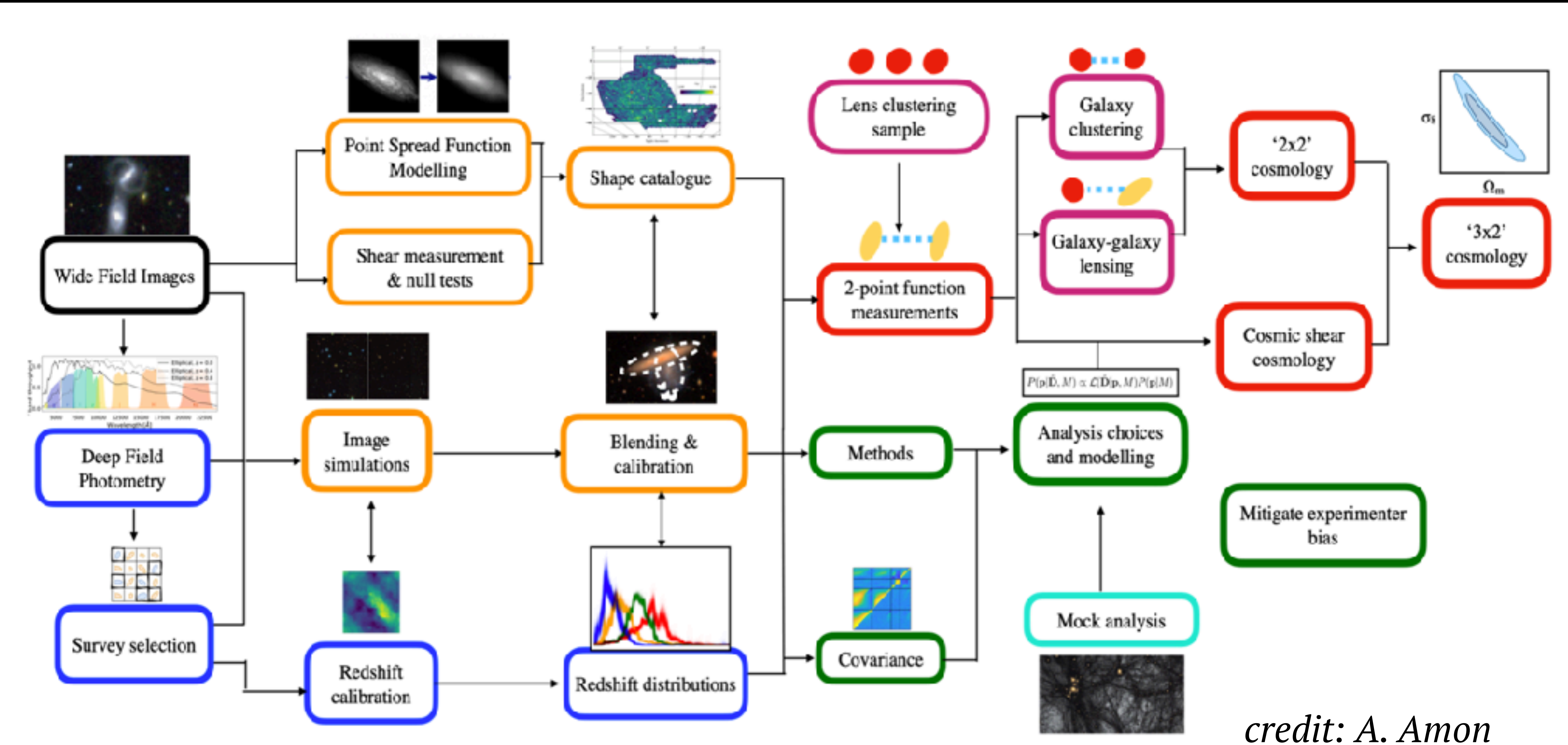




DES-Y3 Cosmology

from pixels to cosmology in 30 papers

- algorithmic + modeling improvements in all analysis stages



credit: A. Amon

DES-Y3 Systematics Modeling + Mitigation

baseline systematics marginalization

- linear bias of lens galaxies, per lens z-bin
- magnification bias of lens galaxies, per lens z-bin
- intrinsic alignments, tidal alignment + tidal torquing, power-law z-evolution
- lens galaxy photo-zs, per lens z-bin
- source galaxy photo-zs, per source z-bin
- multiplicative shear calibration, per source z-bin

-> this list is known to be incomplete

how much will **known, unaccounted-for** systematics bias Y3?

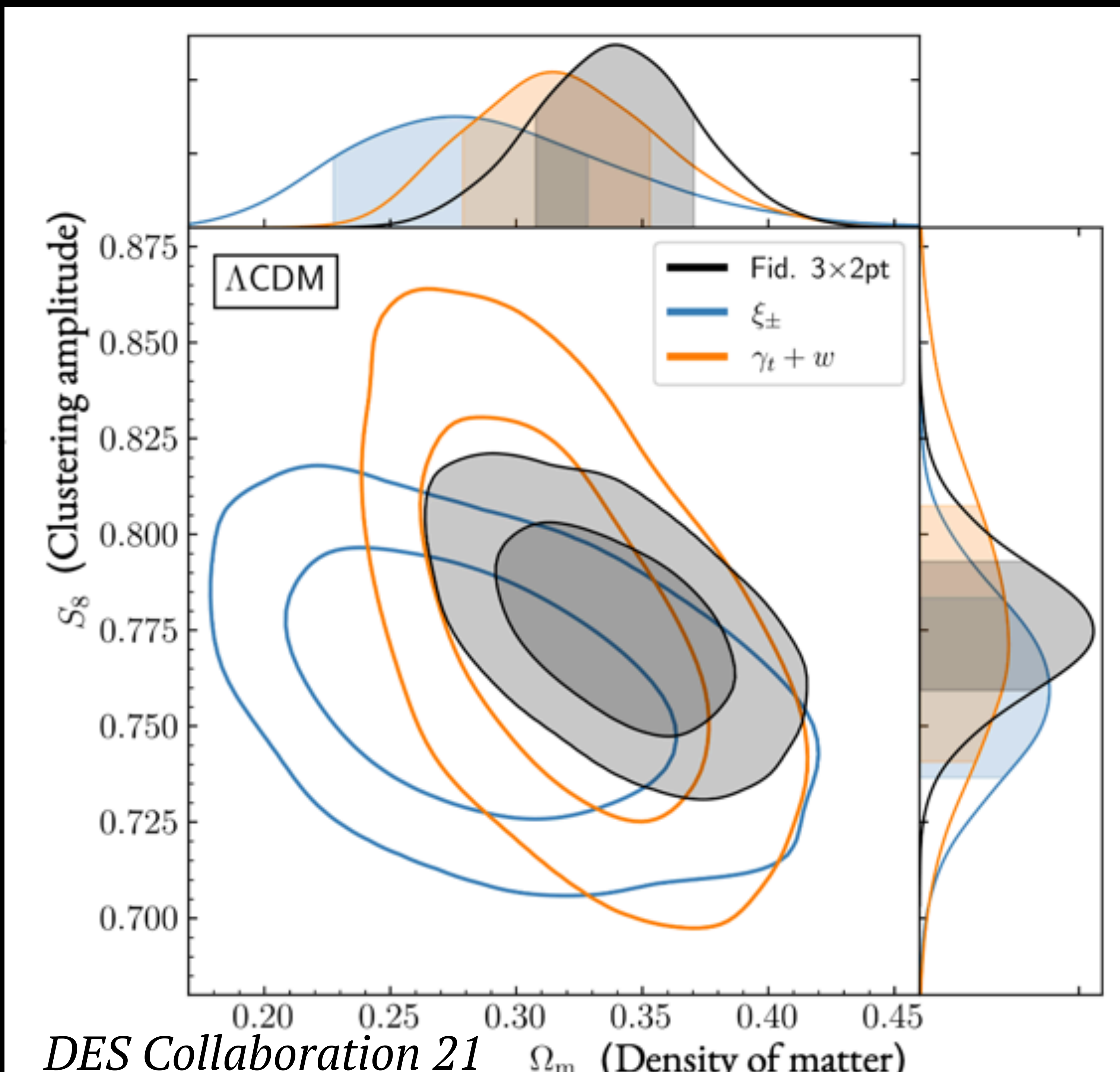
-> remove contaminated data points (*i.e.*, *throw out large fraction of S/N*)

-> choice of parameterizations ≠ universal truth

are these **parameterizations sufficiently flexible** for Y3?

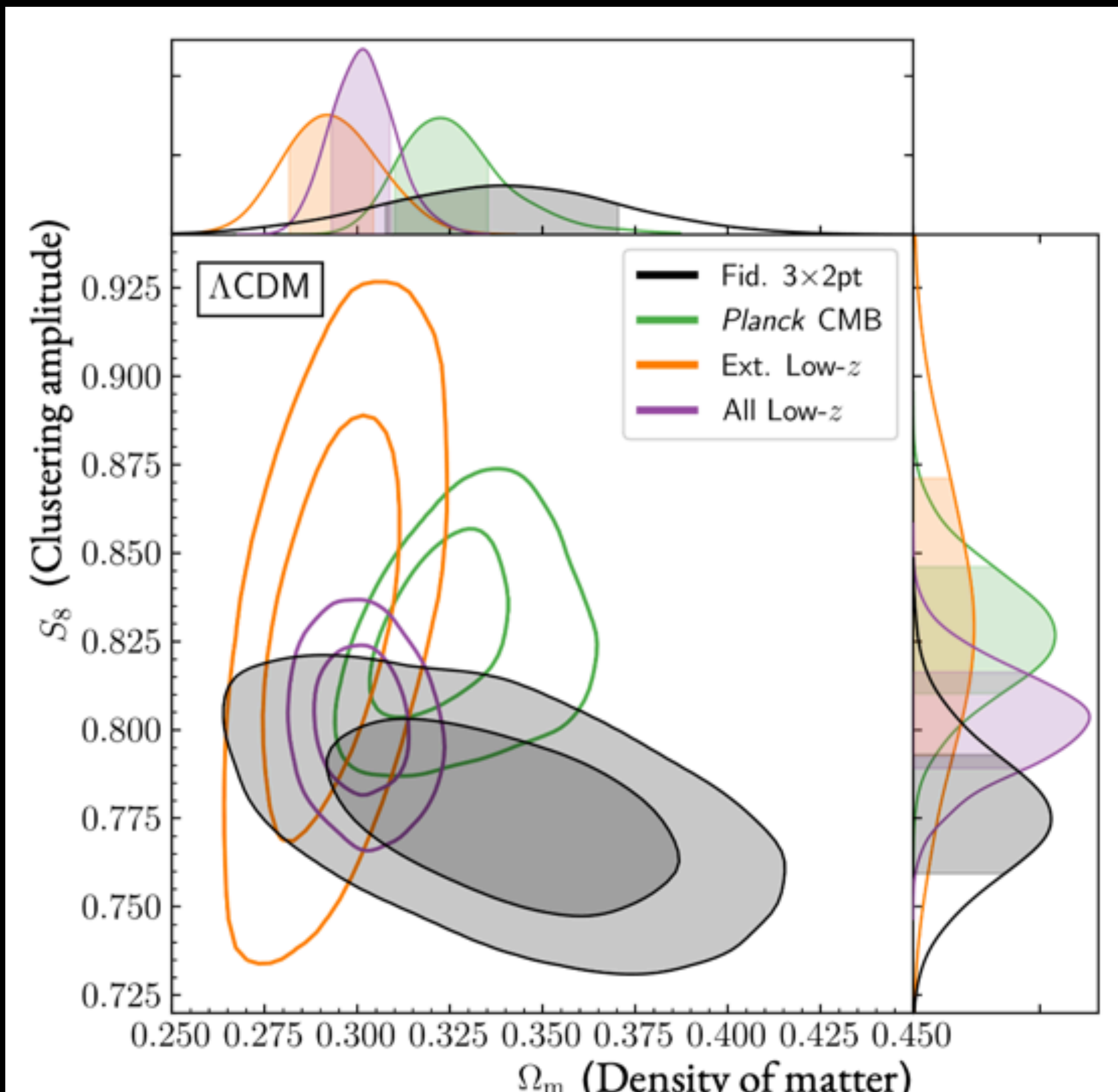
EK+2021

DES Y3 Results:
LCDM Multi-Probe Constraints



- marginalized 4 cosmology parameters, lens and source sample clustering nuisance parameters
- consistent cosmology constraints from weak lensing and clustering in configuration space

DES Y3 ↔ External Data



Each of these data sets is consistent with the other two.

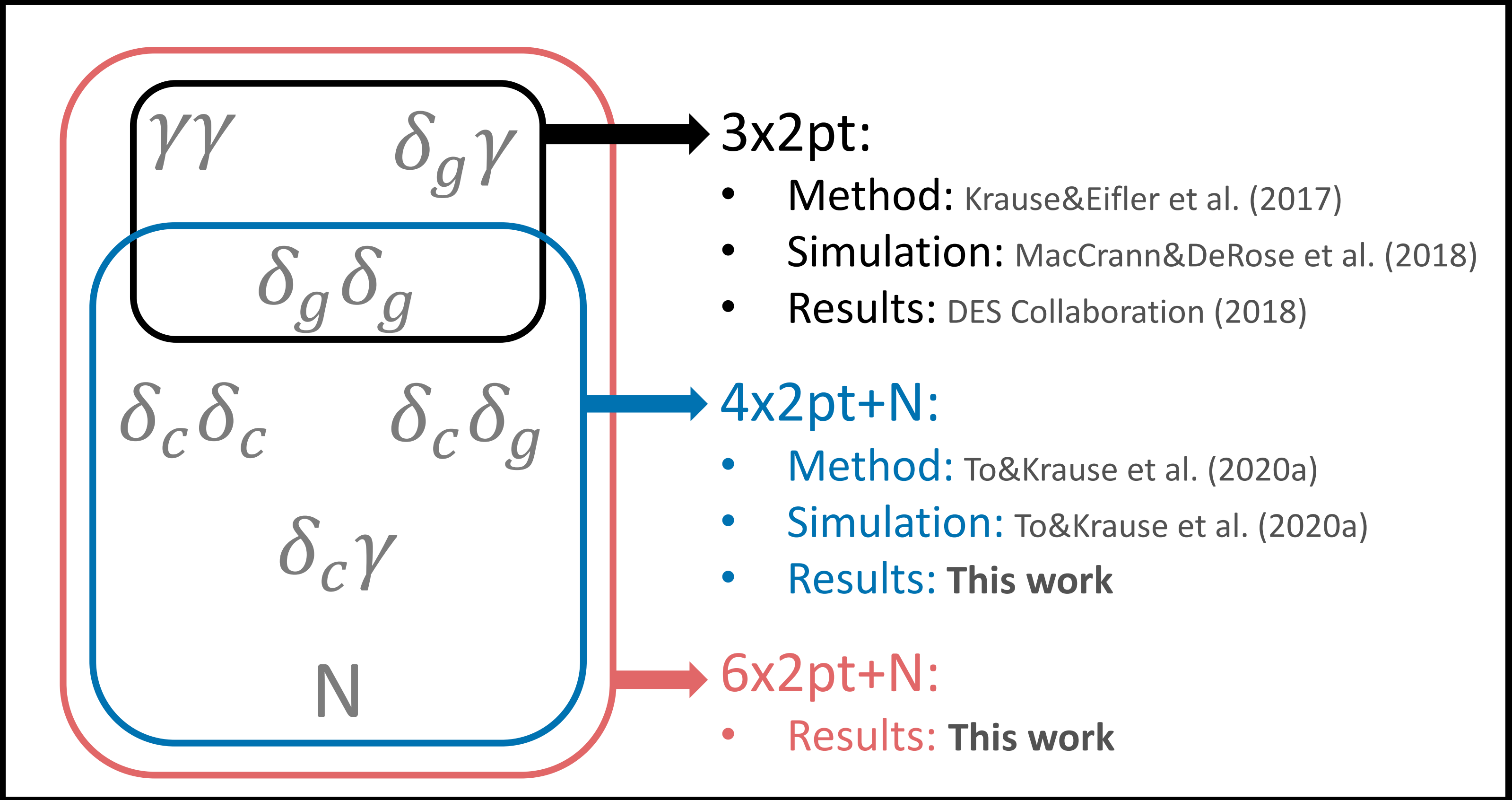
We can combine DES and the other complementary low-redshift probes and test consistency with Planck CMB.

We find consistent results at 0.9σ or p=0.34.

- **Future: observe more galaxies, combine more probes, and achieve better systematics control!**

Beyond 3x2pt: DES-Y1 Cluster Counts x 2PCFs

To, EK+ 2021a,b: cluster cosmology constraints from abundances and large-scale two-point statistics

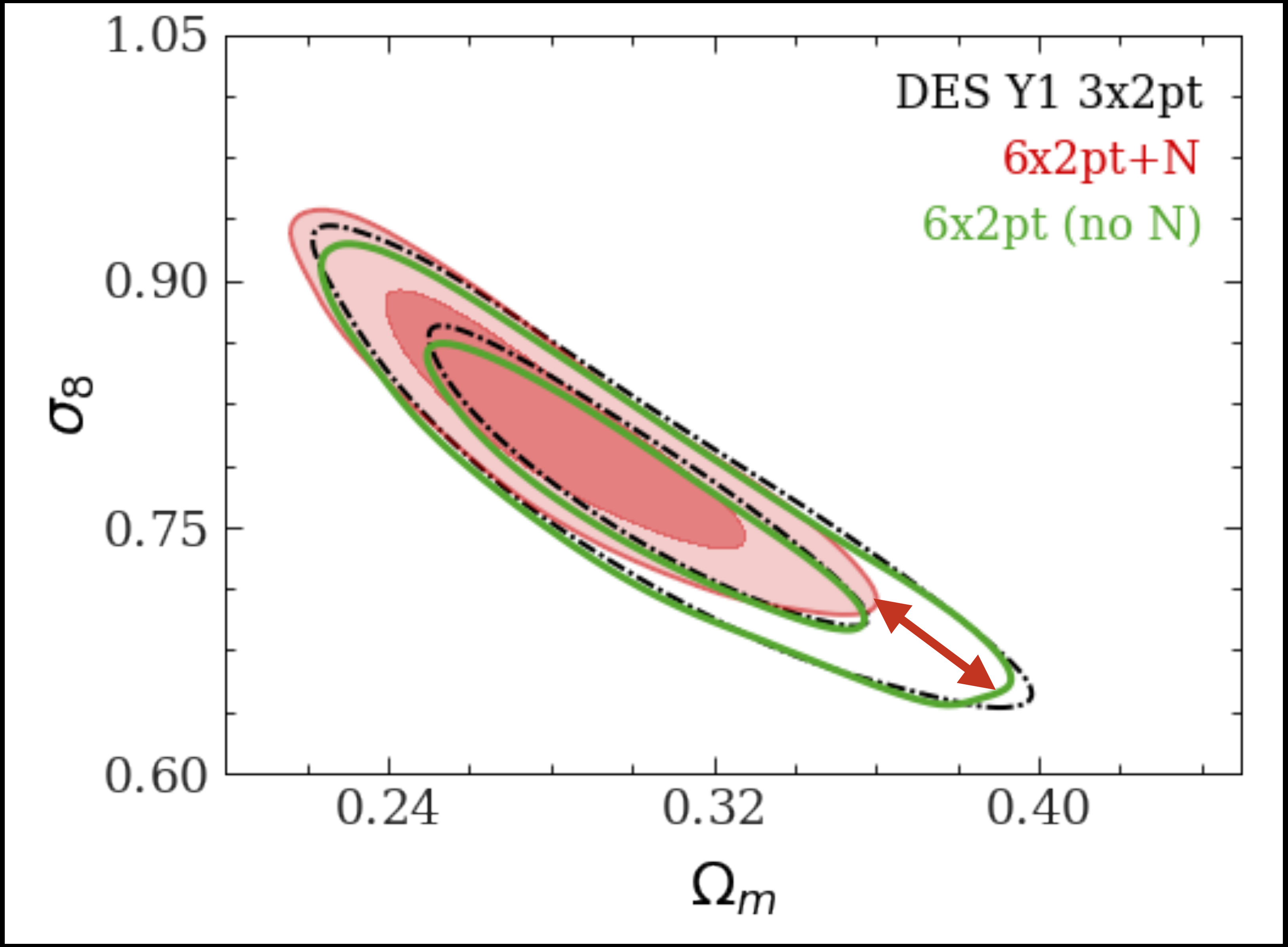


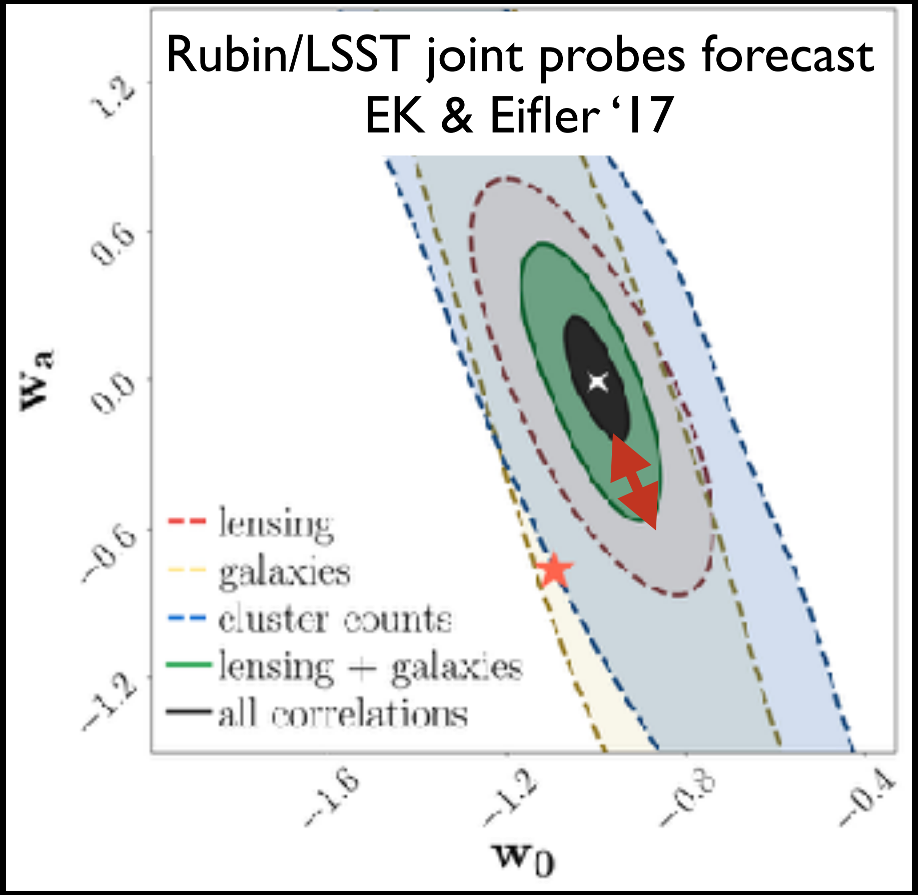
- joint likelihood analysis validated on DES-like mock catalogs (Buzzard, DeRose+2020)
- MOR calibrated from large-scale clustering, account for selection bias
- ✓ cosmology constraints consistent with other DES probes

Beyond 3x2pt:
DES-Y1 Cluster Counts x 2PCFs

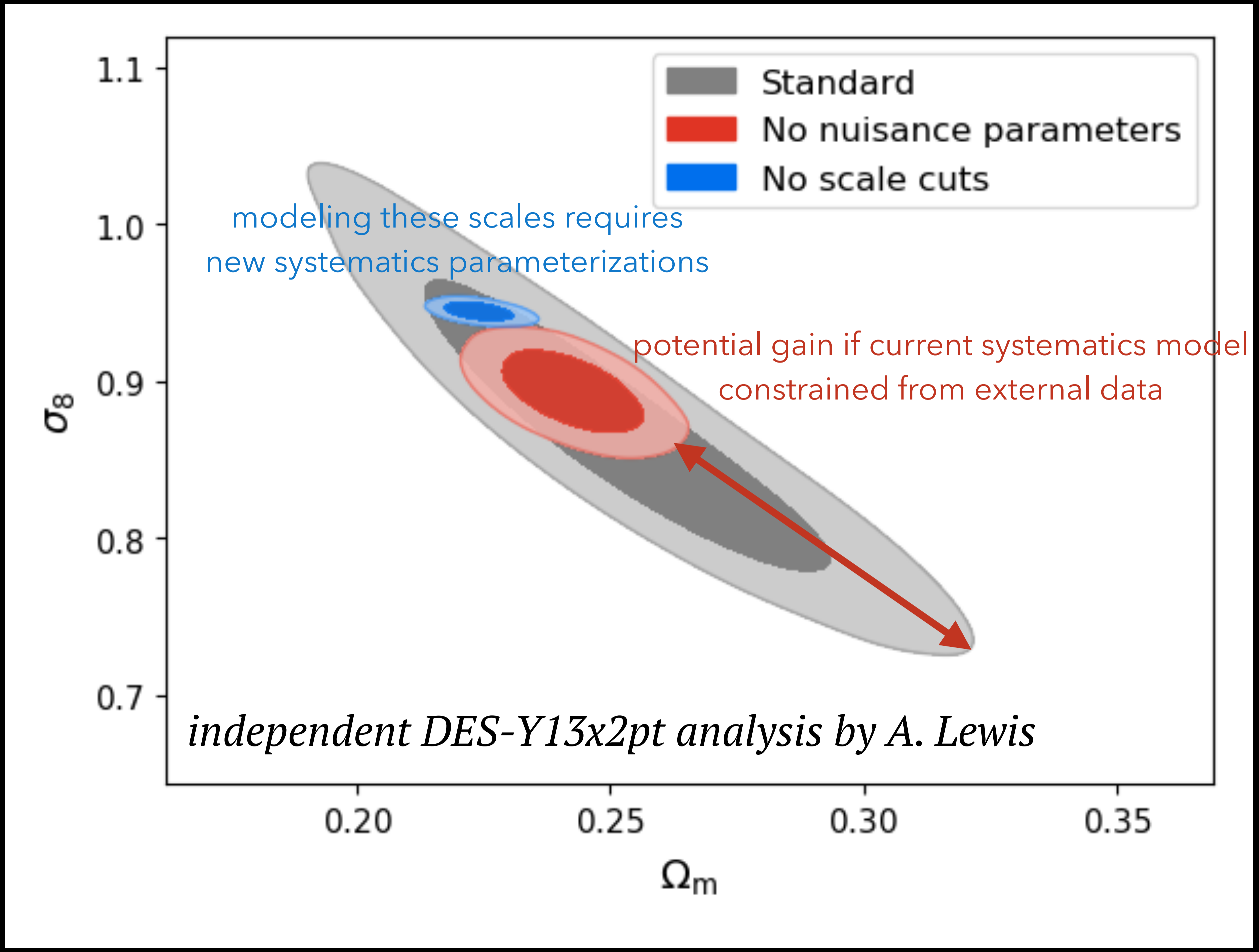
this analysis unlocks constraining power from number counts

substantial gain, *iff accurate MOR calibration*

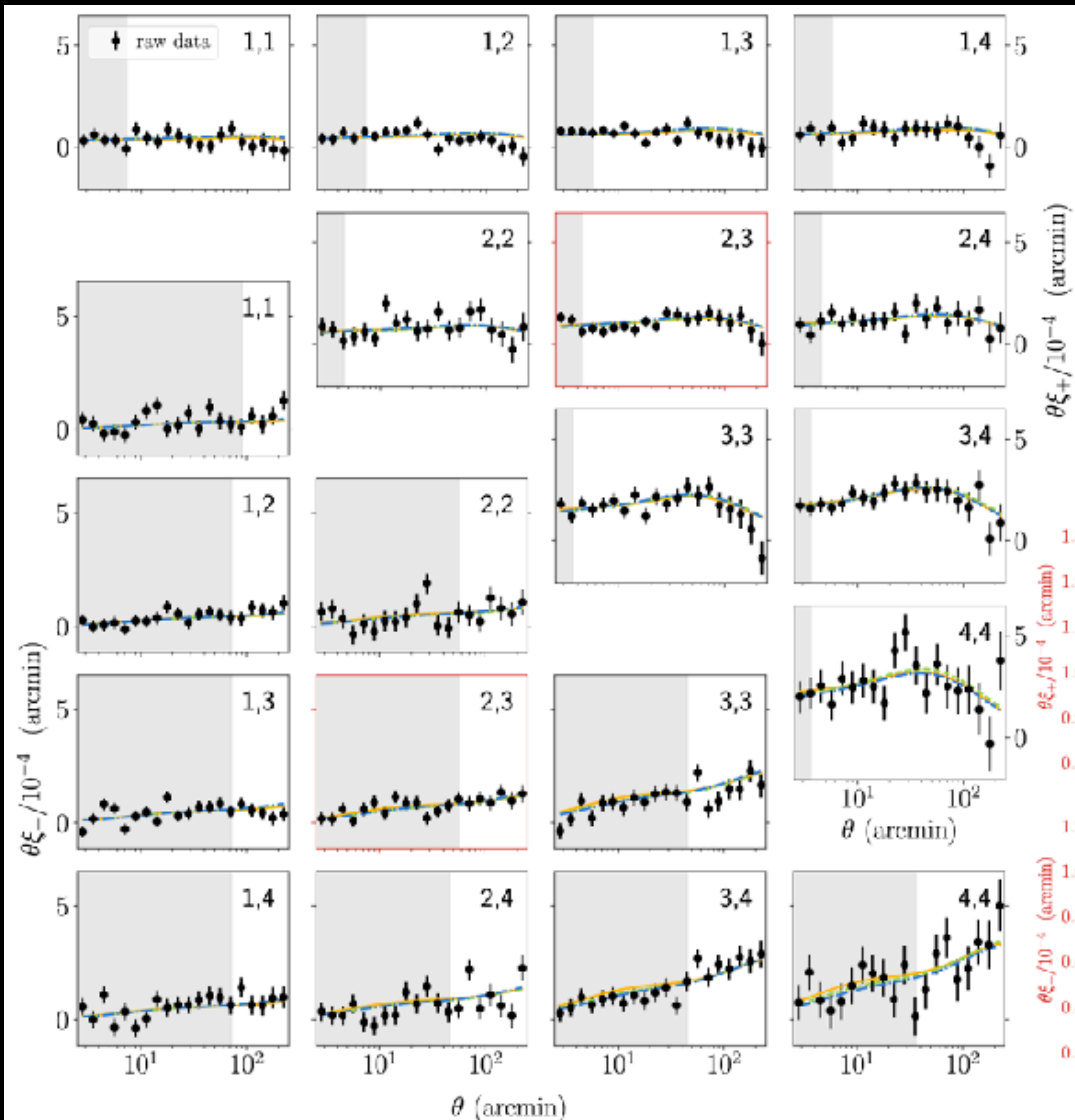




3x2pt Systematics Mitigation
Opportunity Space...



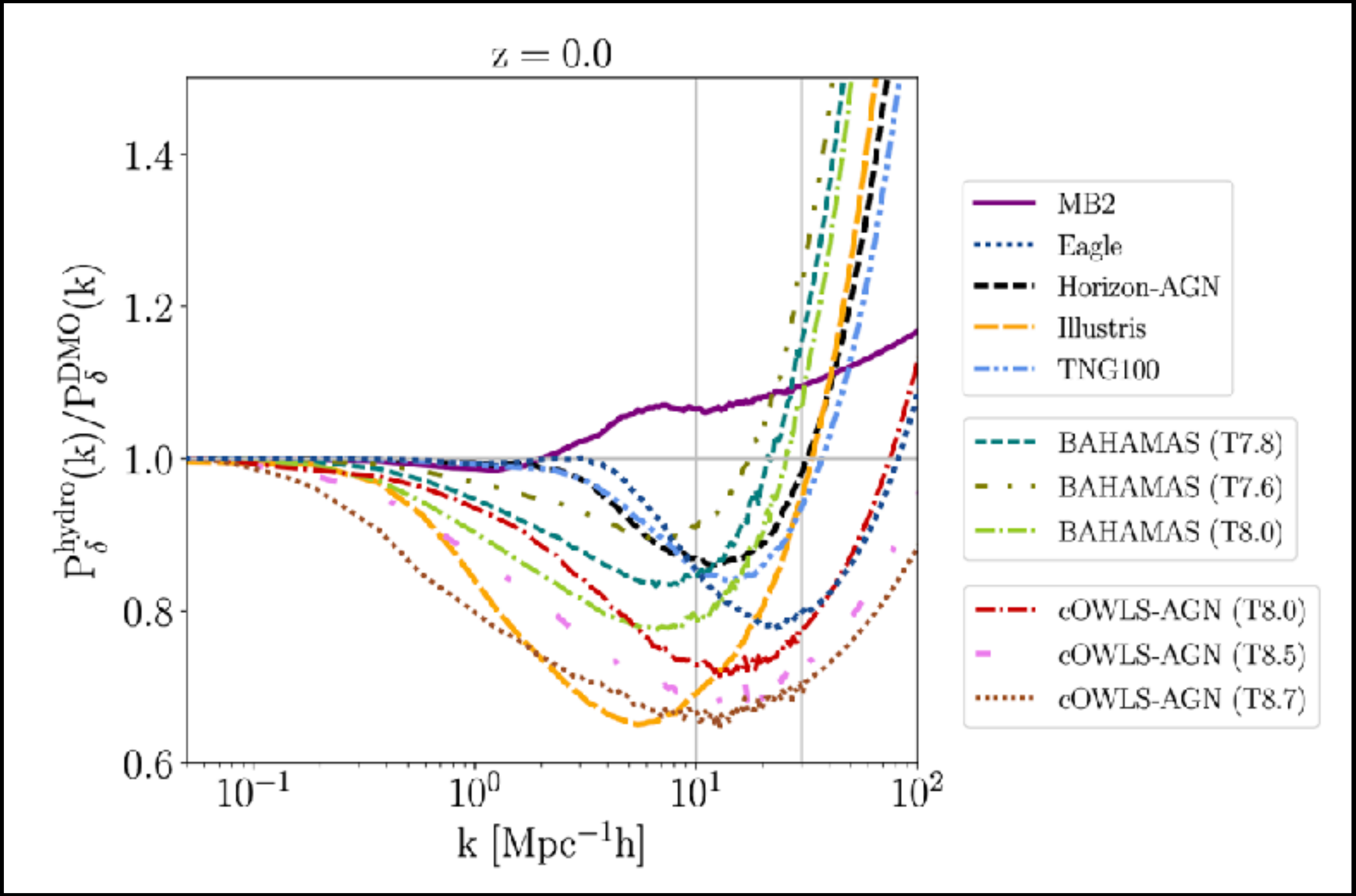
DESY1 WL Correlation functions



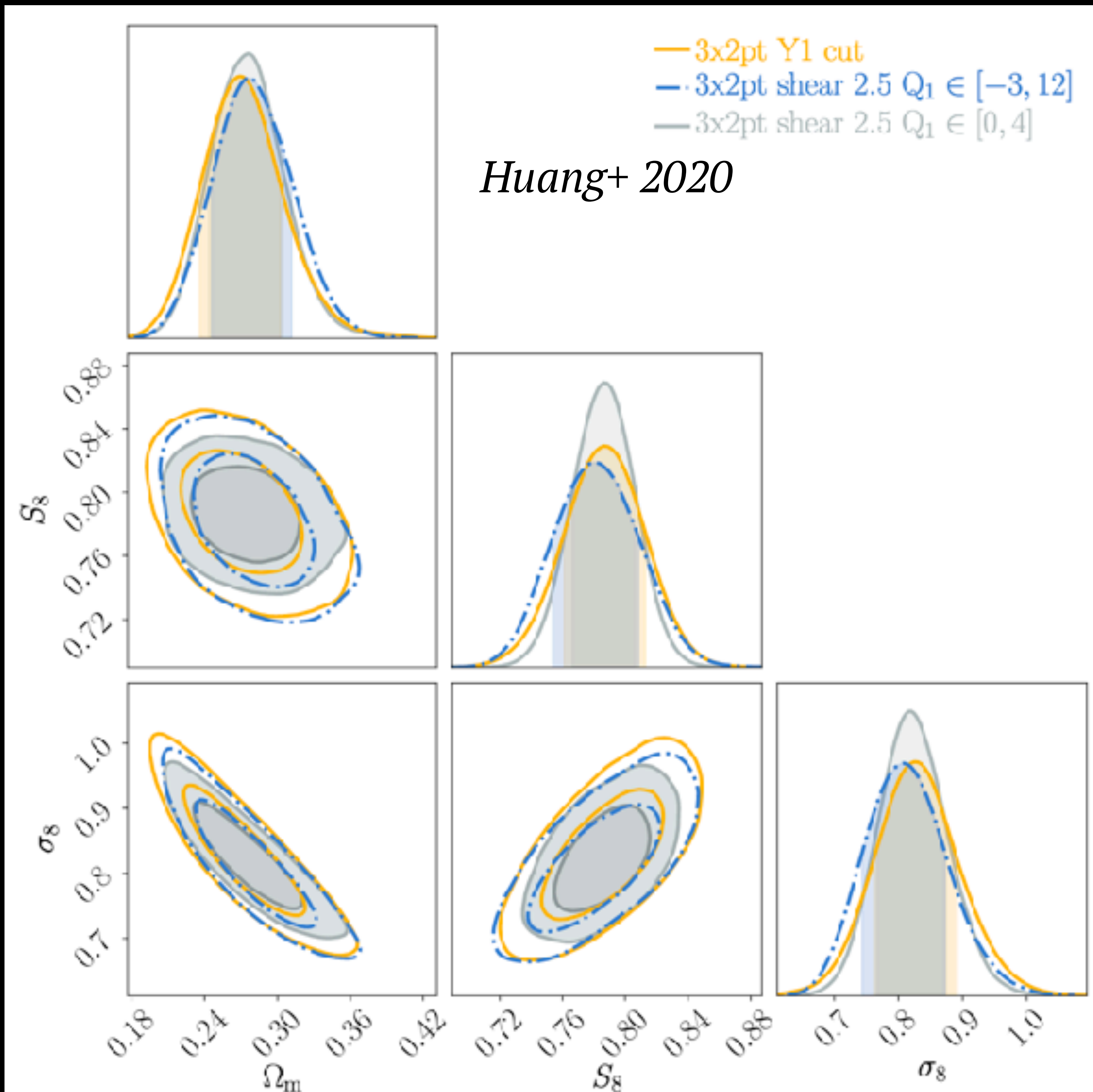
DES-Y1 baseline: small scale correlation function measurements **excluded because of baryonic effects**

Huang+2020: reanalyze DESY1 **including all WL measurements down to 2.5′**

Baryonic Effects in WL Analyses

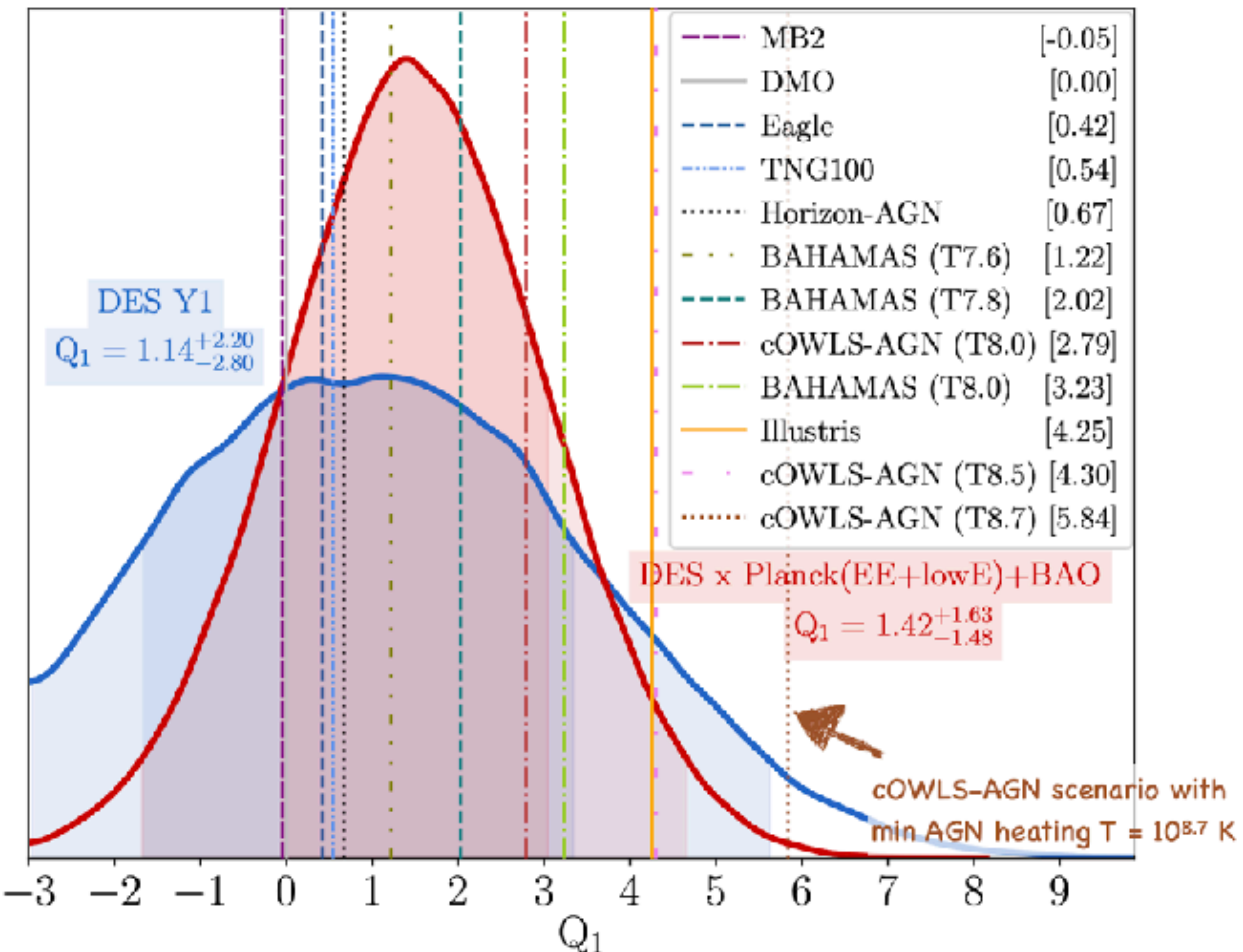


Baryonic Effects in WL Analyses Cosmology Constraints



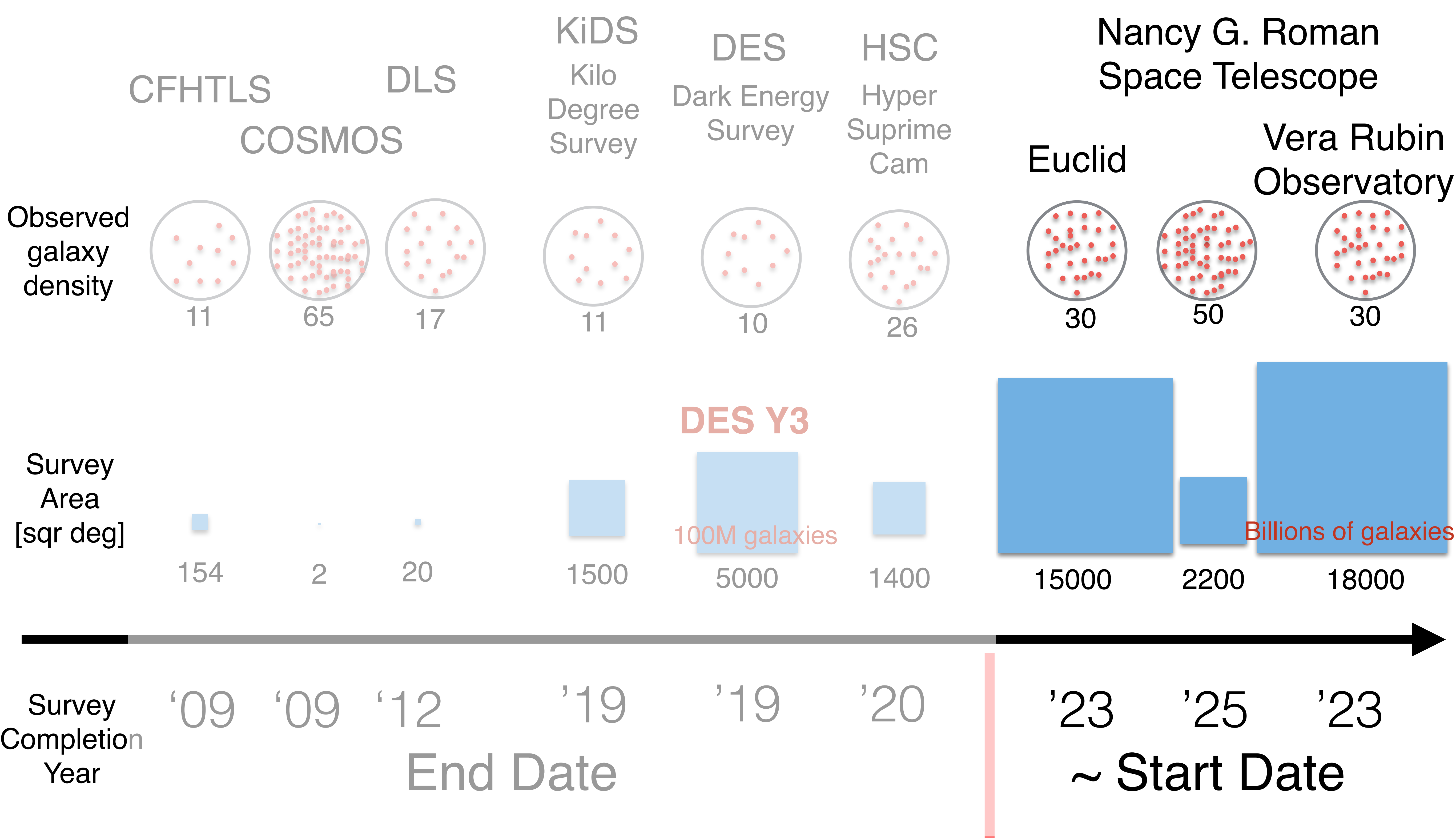
- DES-Y1 baseline (conservative scale cuts)
- DES-Y1 including all scales, baryonic effects modeled using **PCA with non-informative prior**
- DES-Y1 including all scales, baryonic effects modeled using **PCA with informative prior**

Baryonic Effects in WL Analyses
Feedback Constraints



Huang+ 2020

The Future (is starting soon)

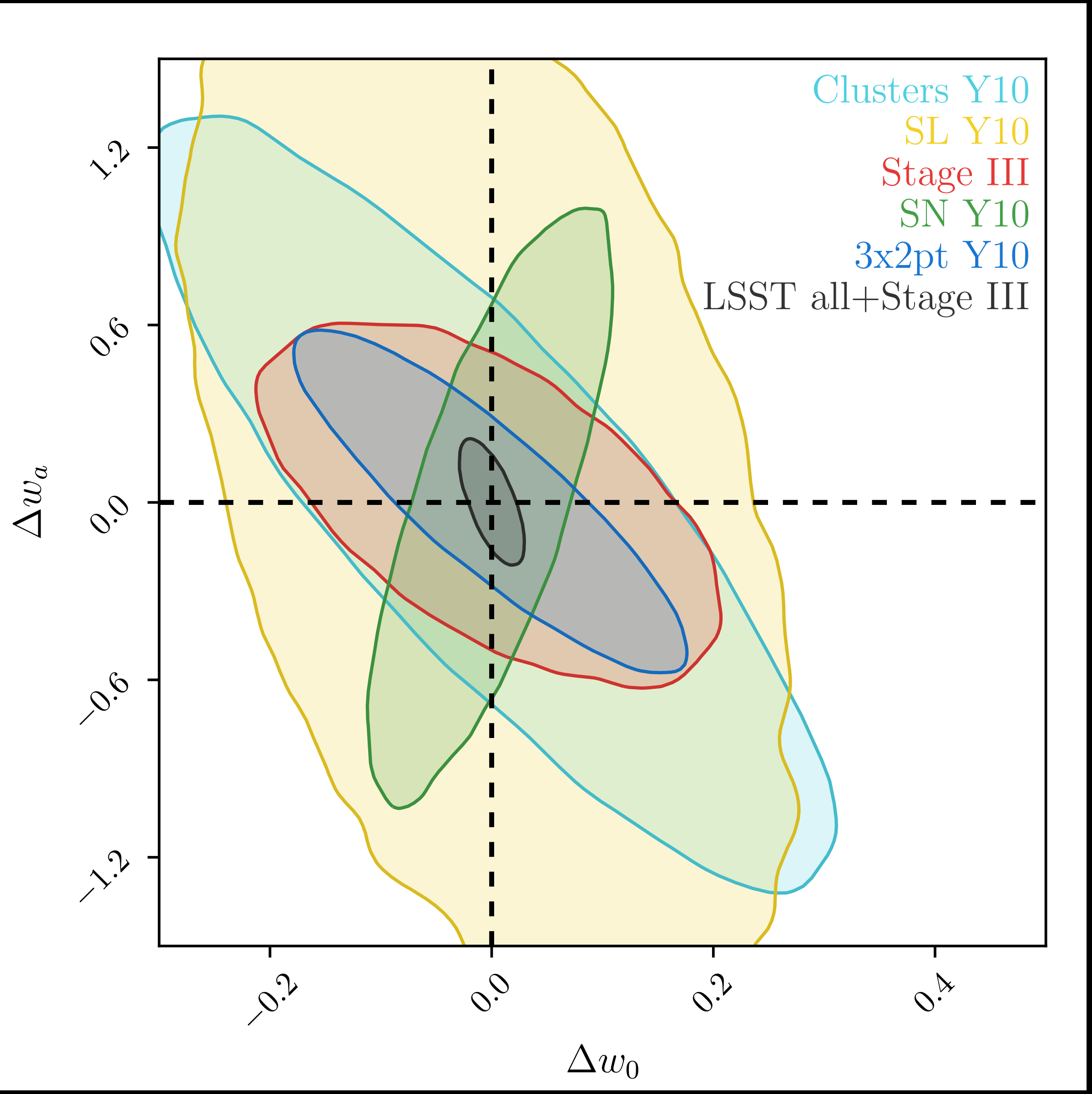


Rubin Observatory!

Rubin Observatory LSST-Dark Energy Science Requirements Document

1809.01669, incl. links to data products & Fisher Matrices

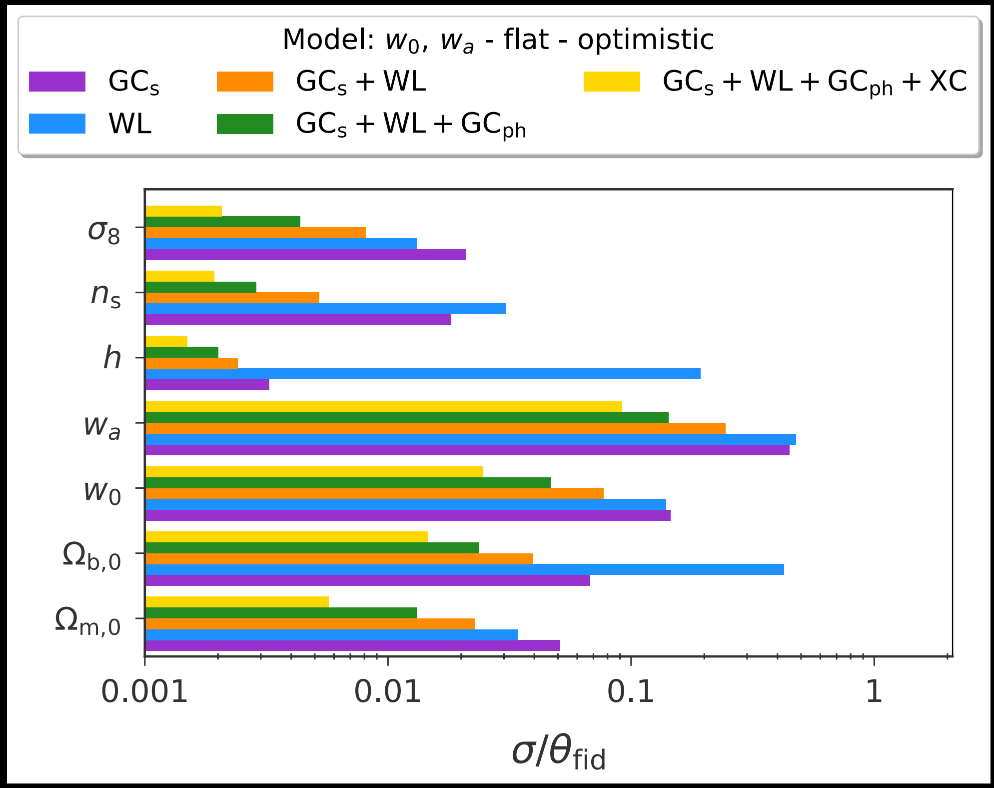
- first joint forecast by science collaboration since LSST Science Book (2009)
    - based on much more mature survey & analysis assumptions, understanding of systematics
- joint forecasts including cross-correlations (statistical & systematical)
- consider two classes of systematics
    - *self-calibrated*,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

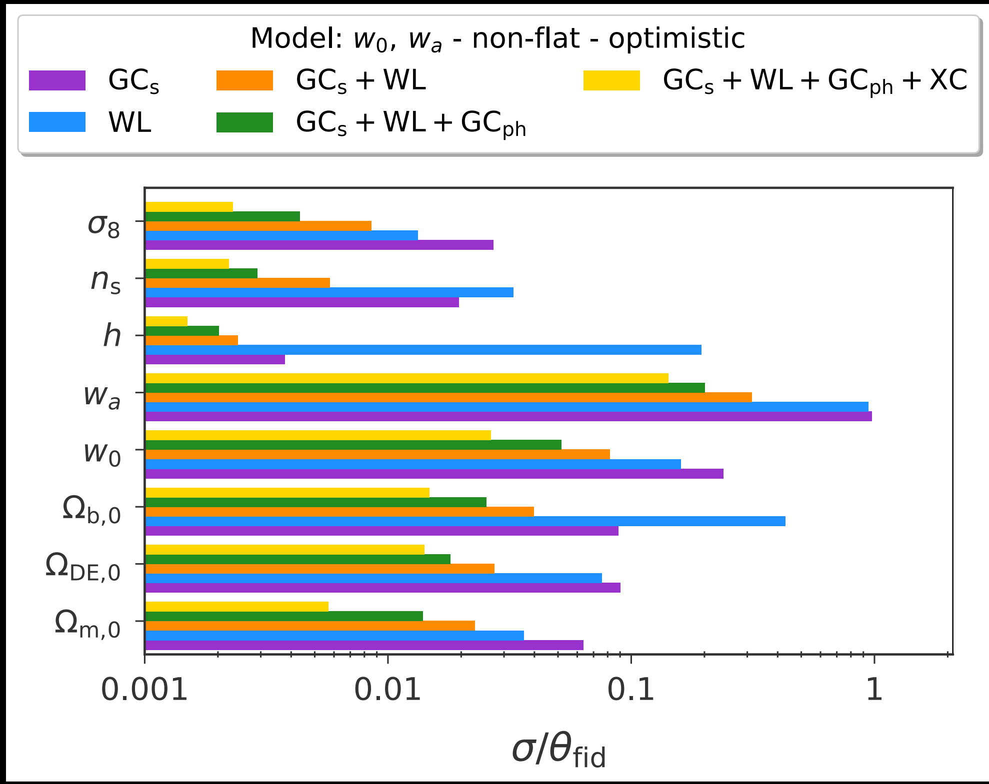


Euclid Cosmological Probes Forecasts

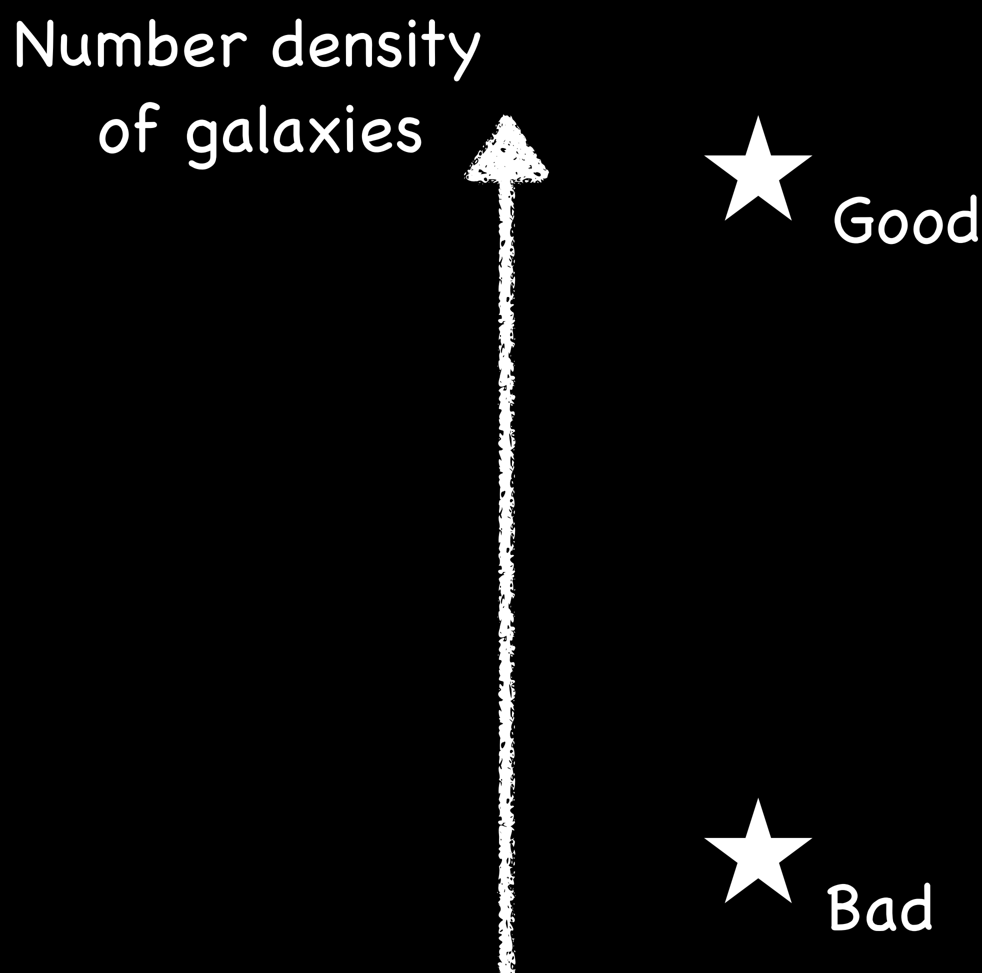
1910.09273

- joint Fisher forecasts from spectroscopic clustering, photometric clustering, weak lensing (+cross correlations)
- extensive validation of forecasting codes
- detailed assumptions about astrophysical and observational systematics
- forecasts for several extended cosmological models

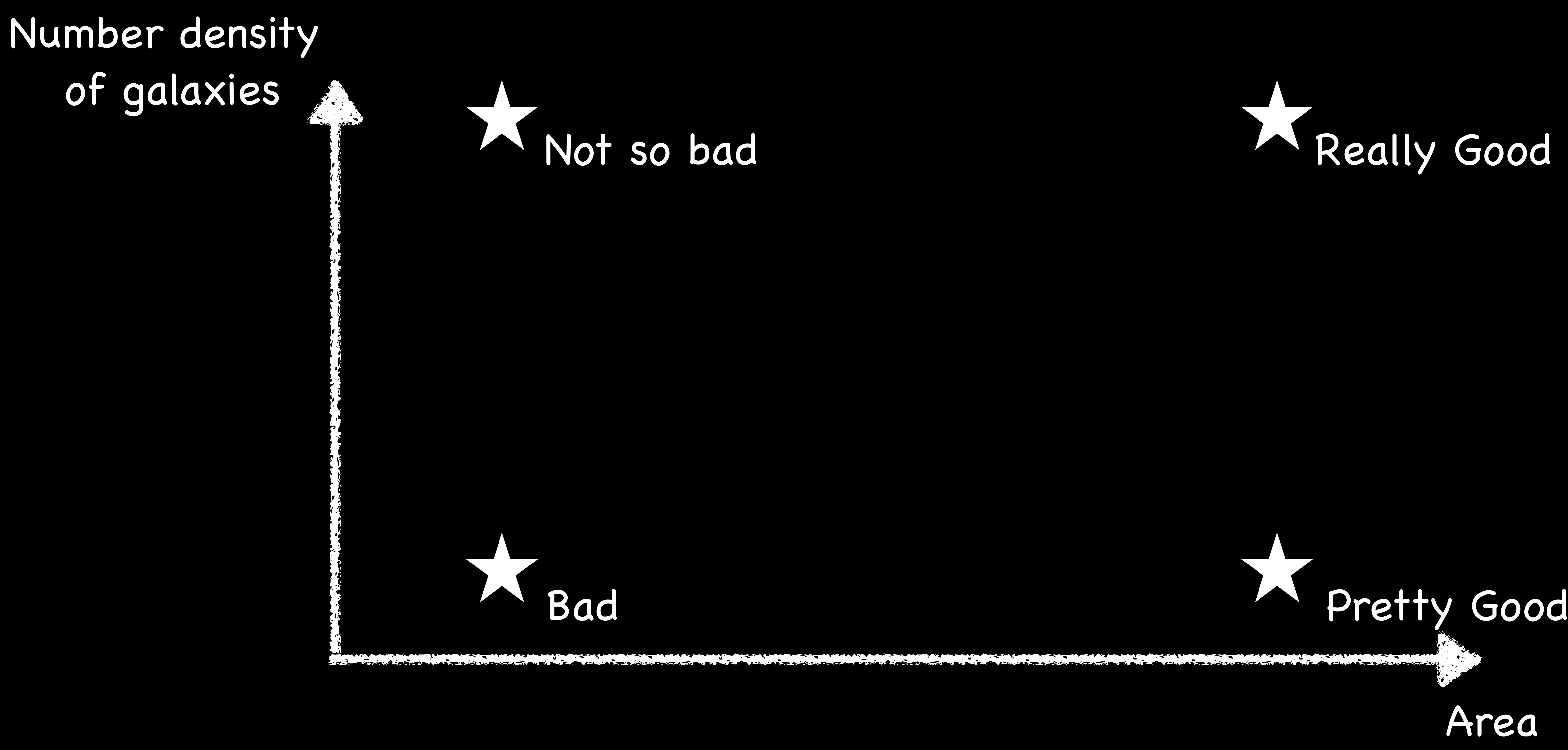




Survey Optimization I



Survey Optimization II



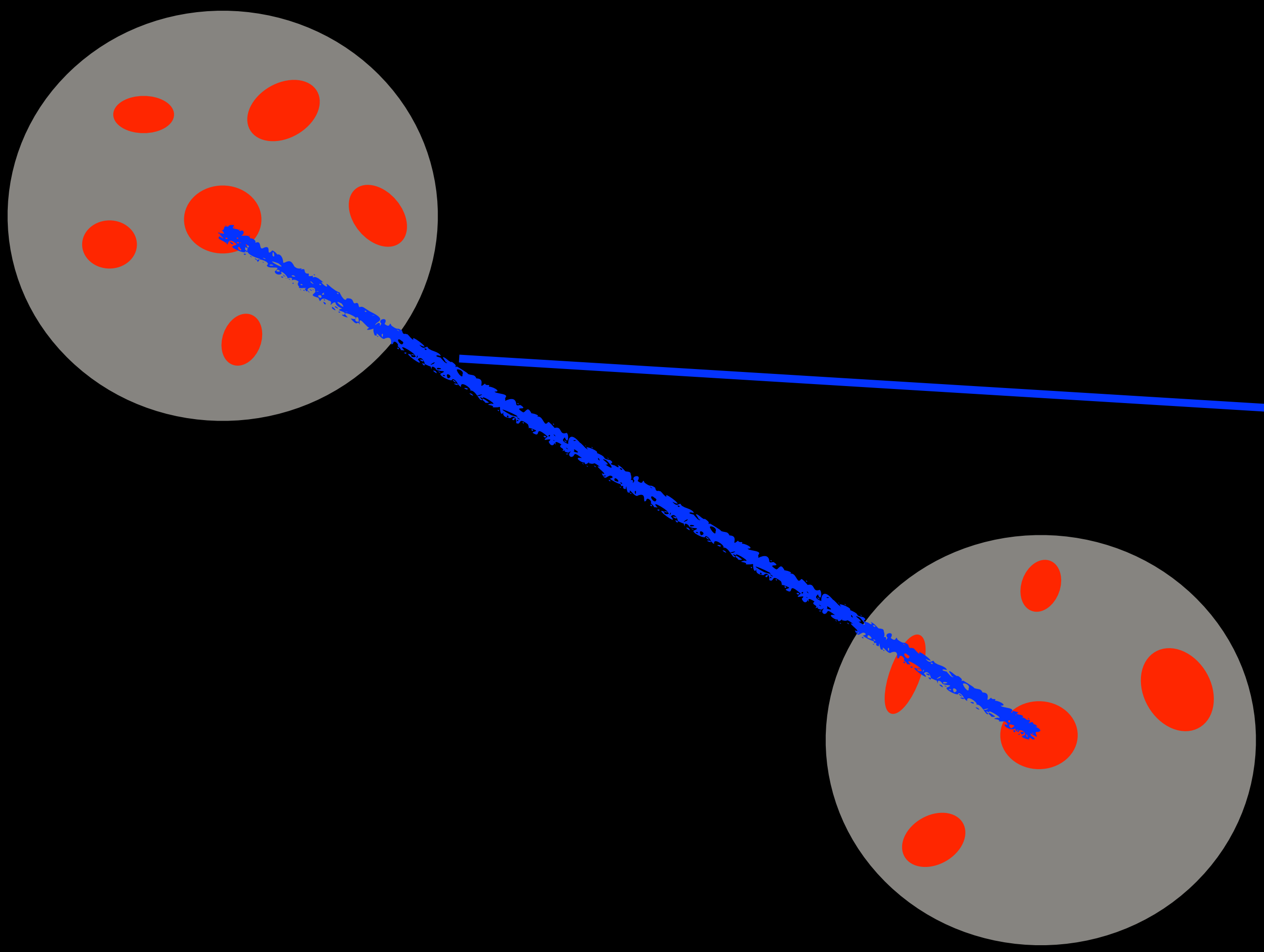
Statistical error bars only (simplified):

- Area is more important than depth
- Even more true since non-gaussian Covariances became fashionable

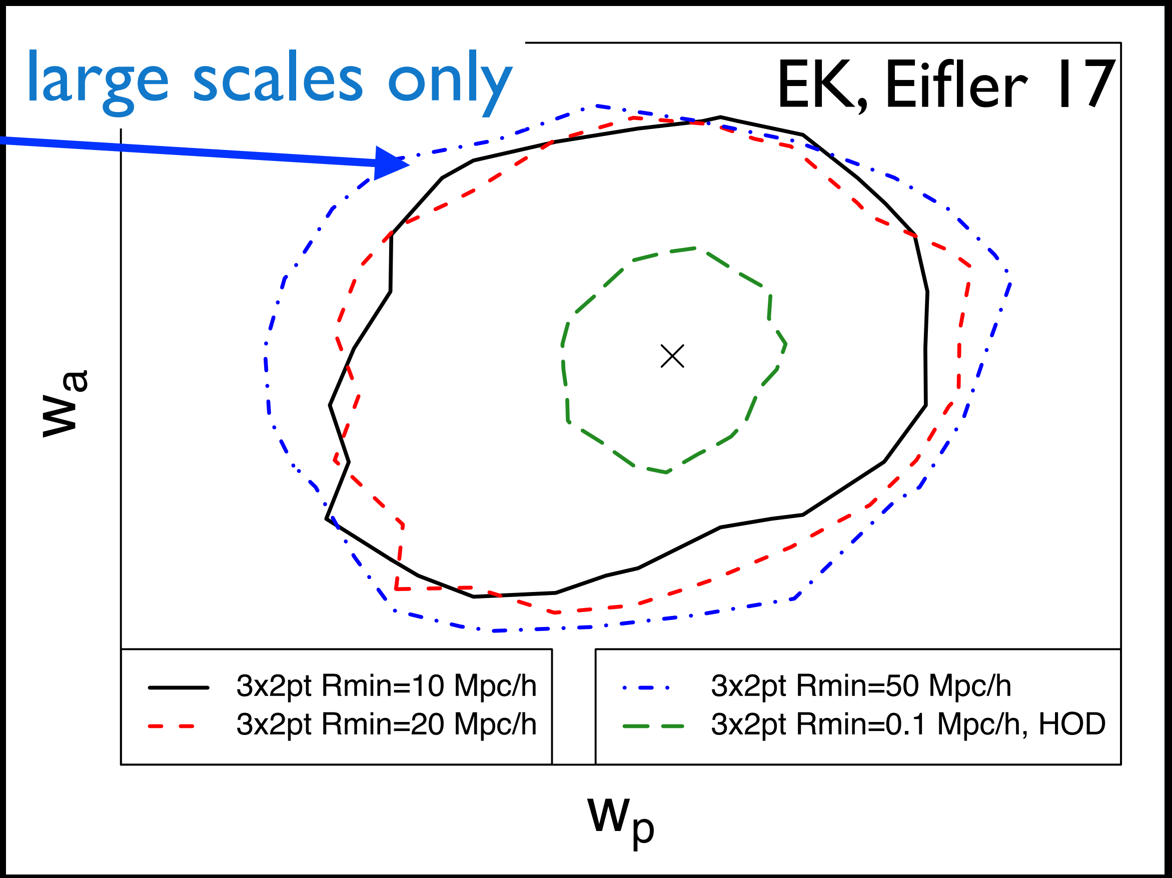
Systematics Example: Galaxy Bias

galaxy evolution: very rich physics compared to primary CMB

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



LSST's constraining power combining WL, and galaxies using



Systematics Example: Galaxy Bias

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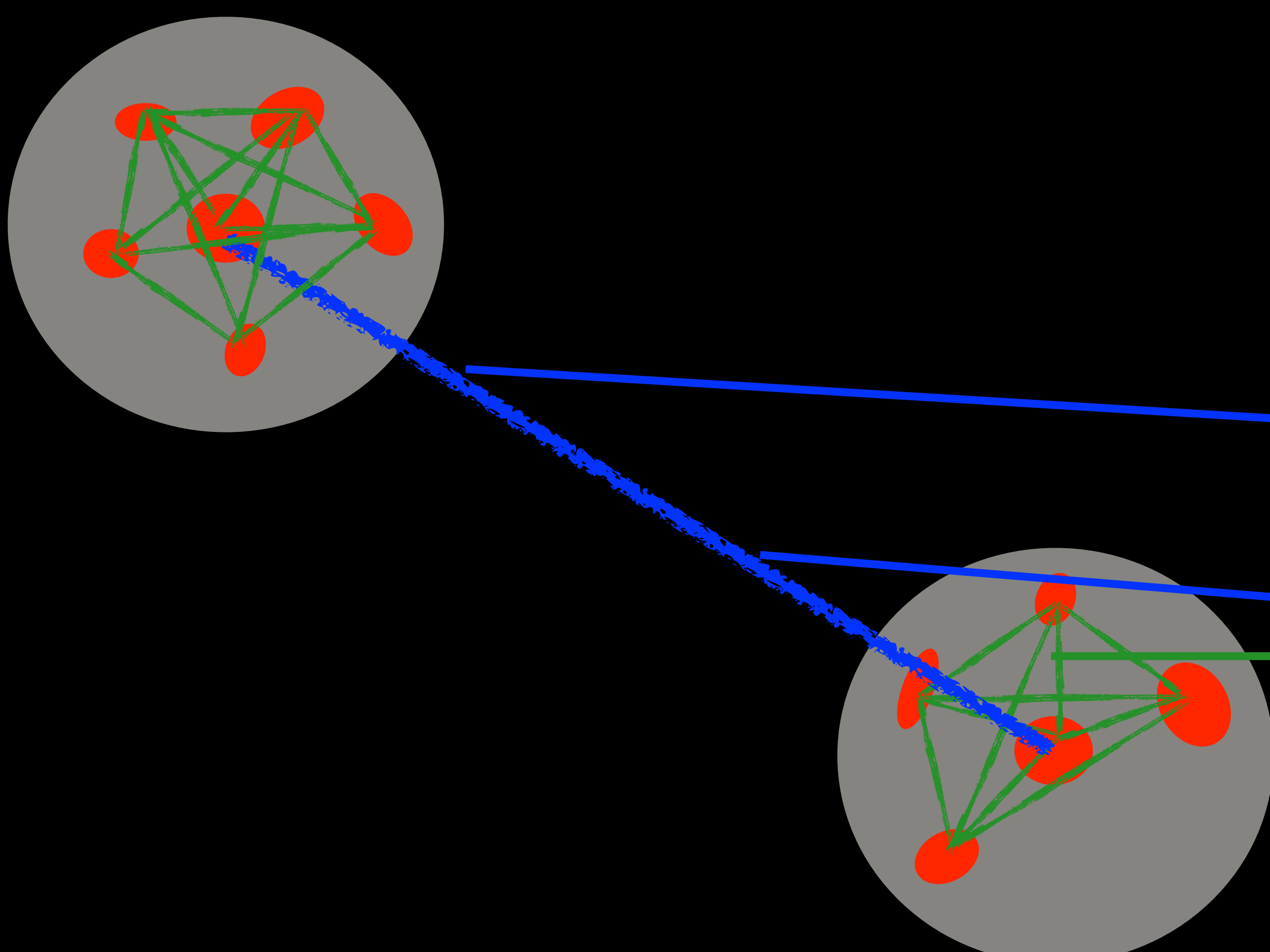
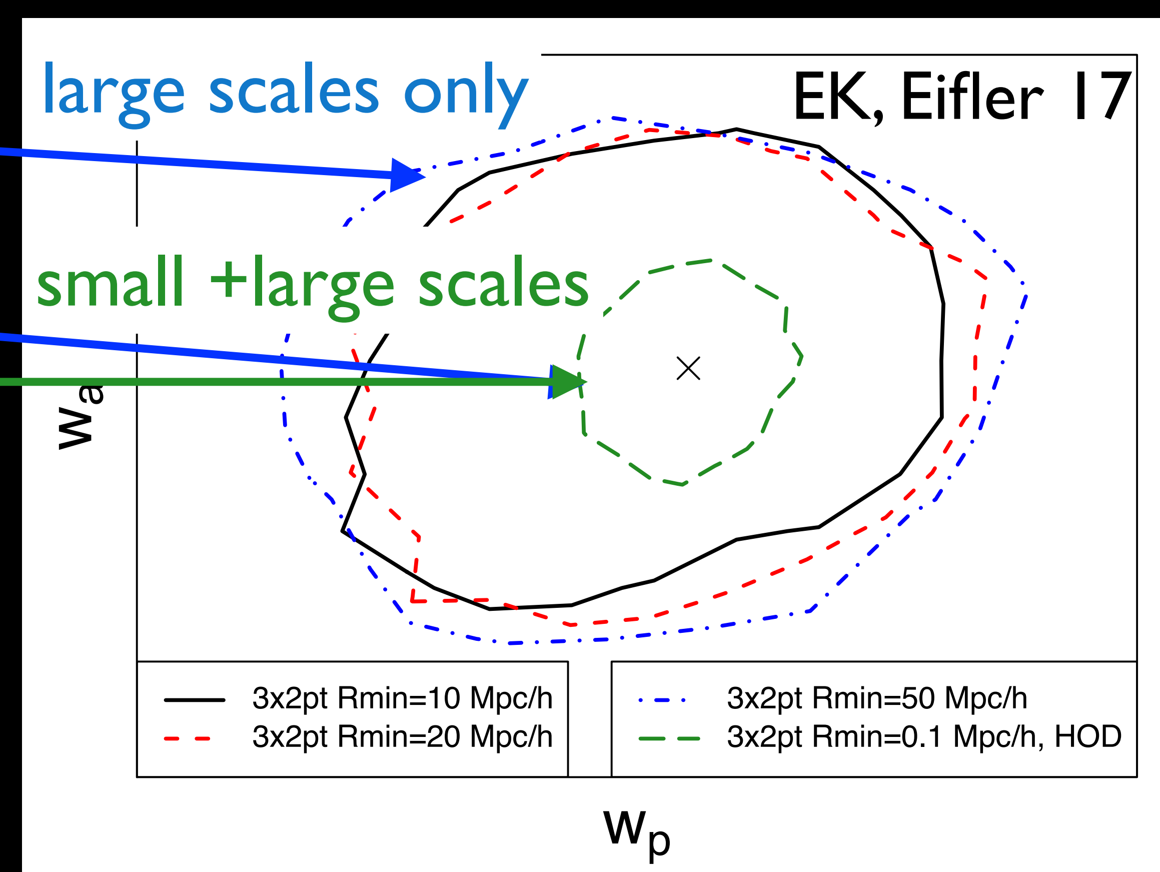
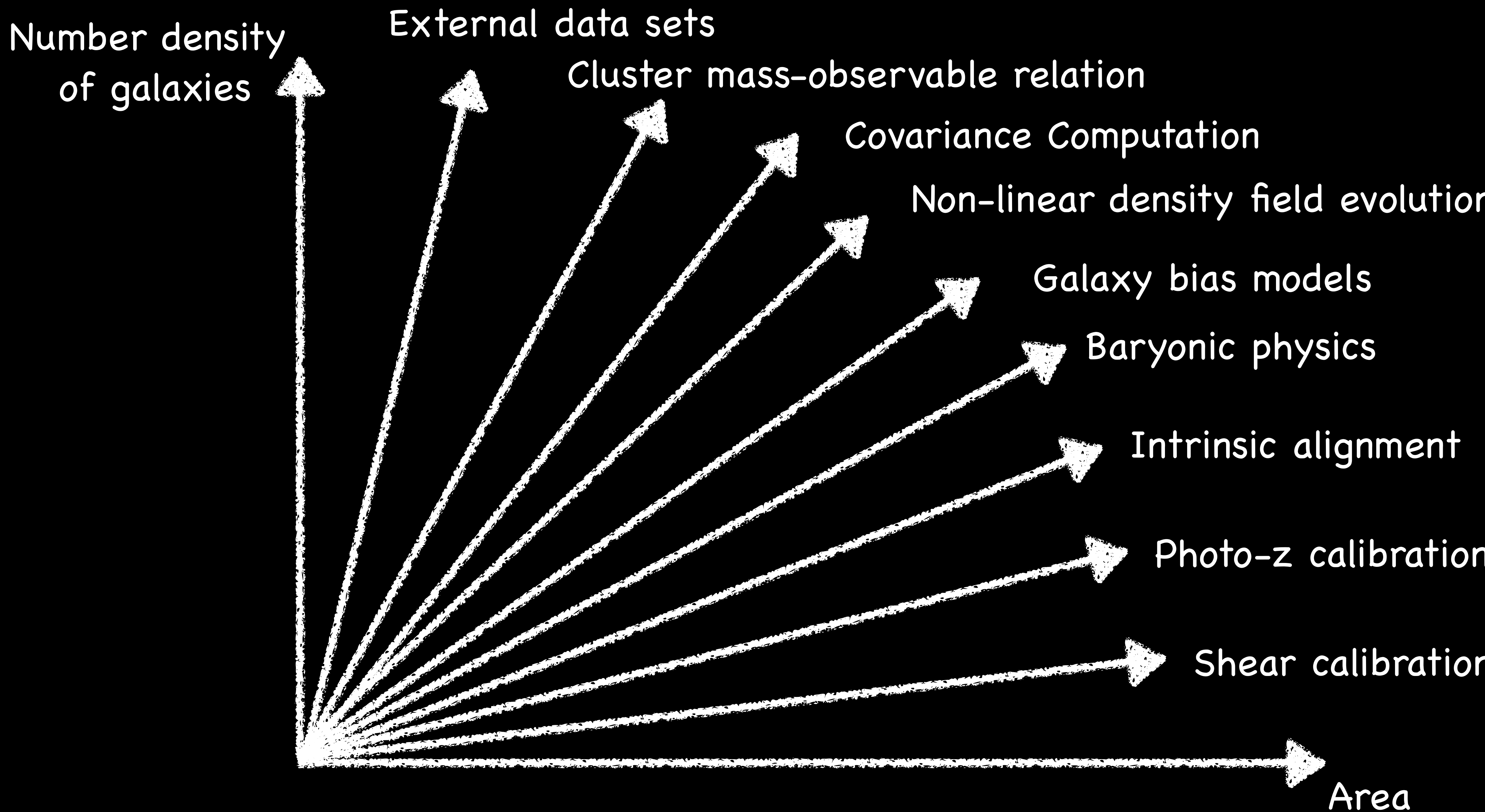


LSST's constraining power combining WL, and galaxies using

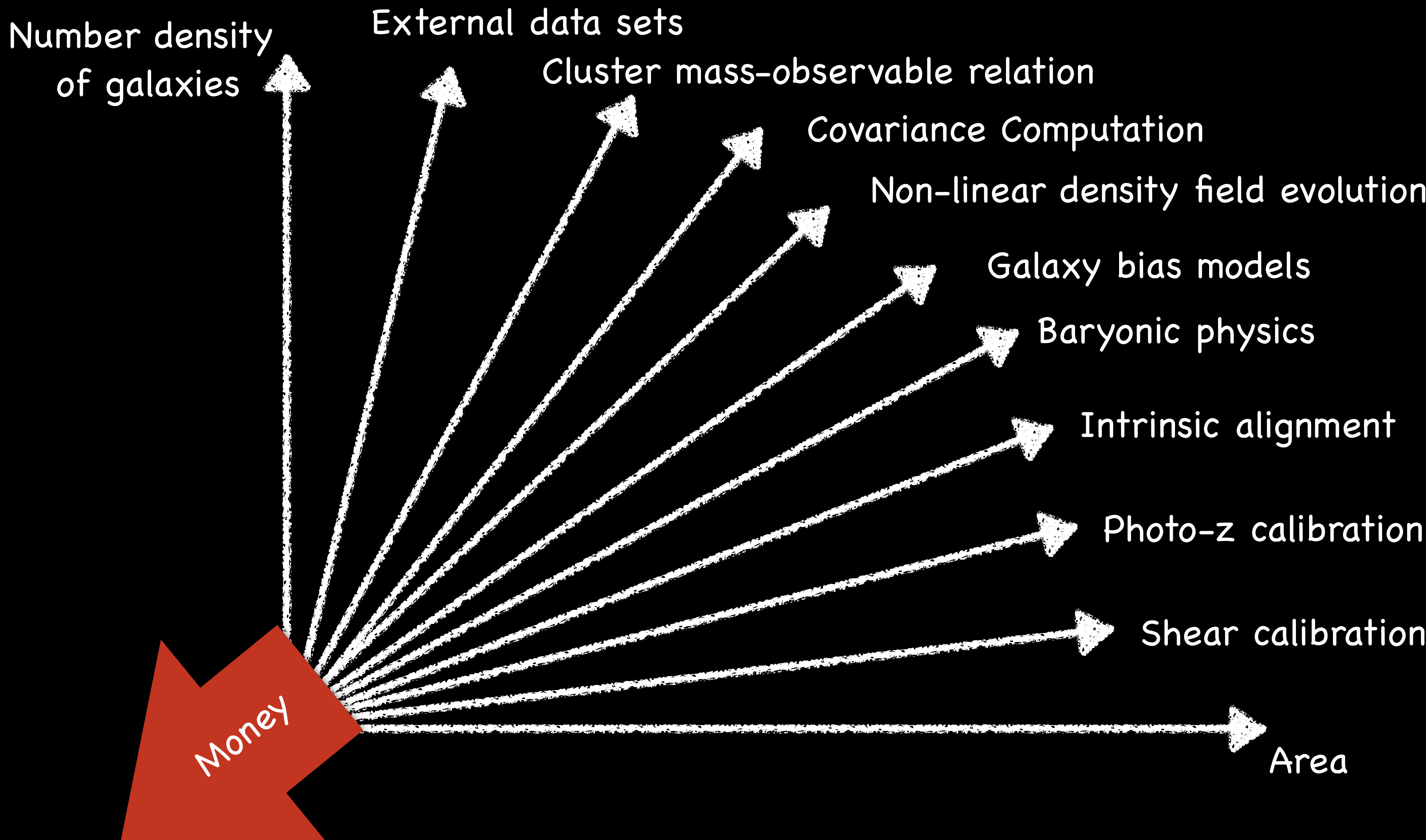


transformative gain in constraining power (comparable to $f_{sky}>1$ for large scales only) *iff small scales modeled accurately*

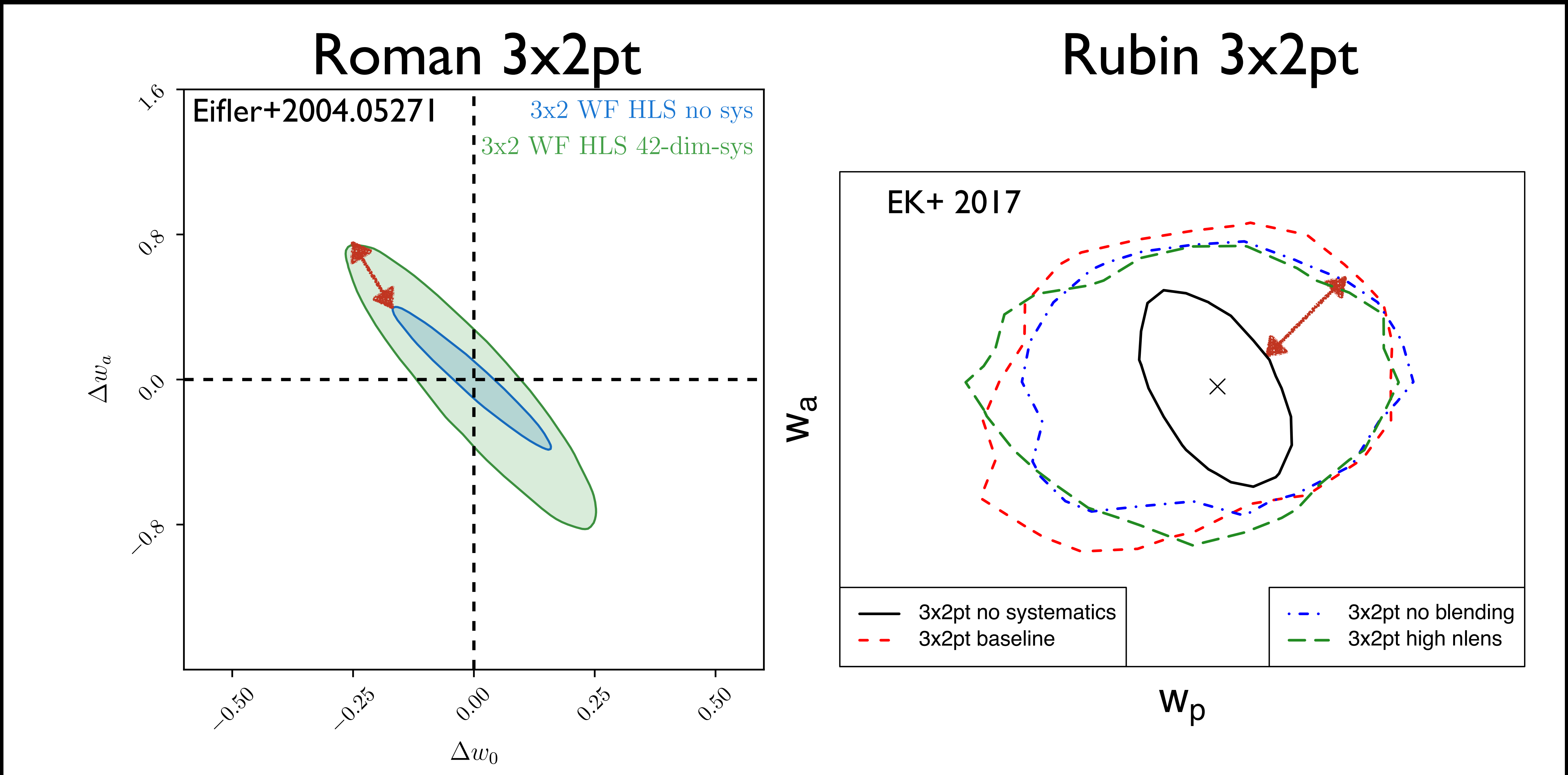
Survey Optimization III



Survey Optimization III



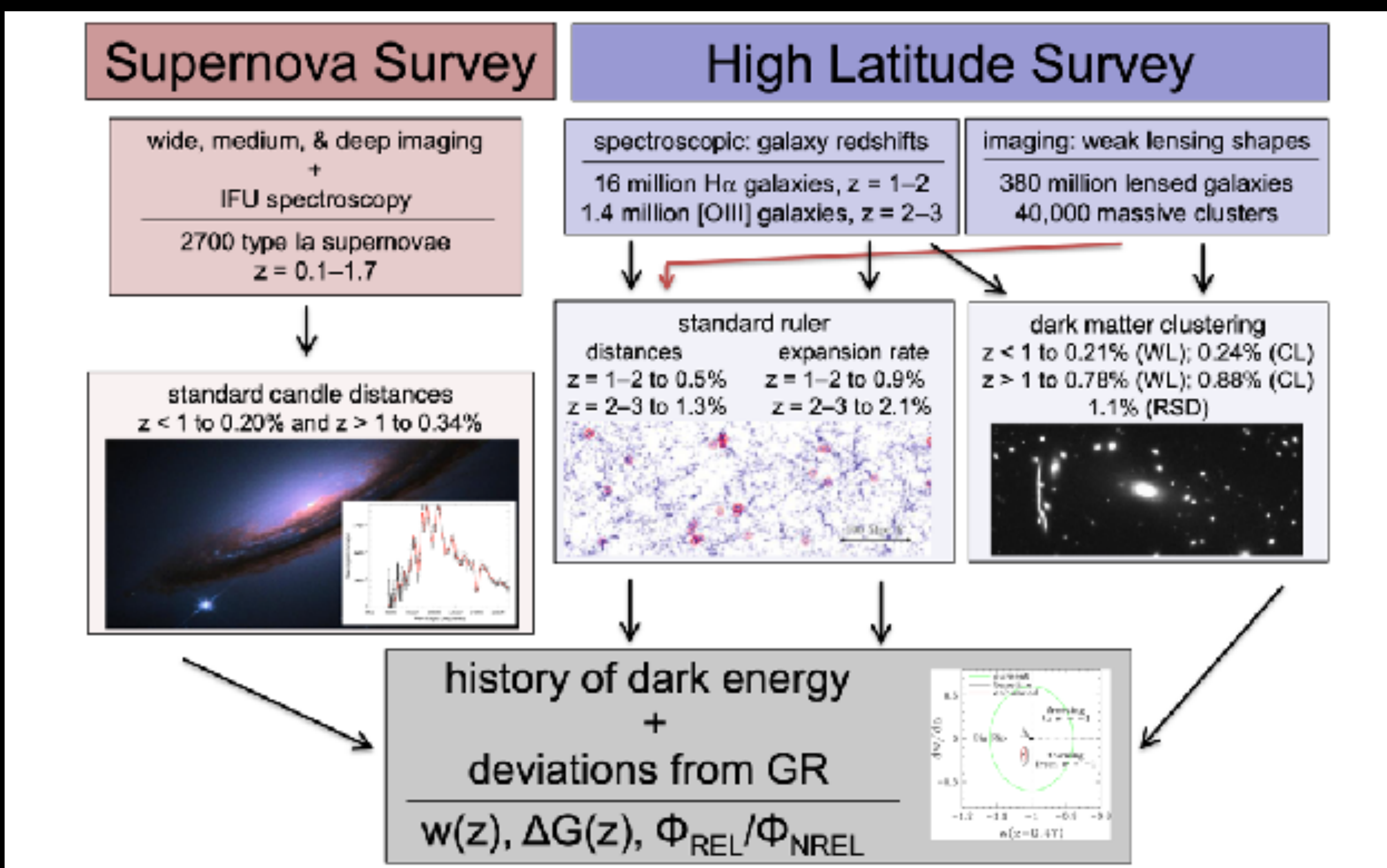
Stage-IV 3x2pt forecasts
(*details matter*)

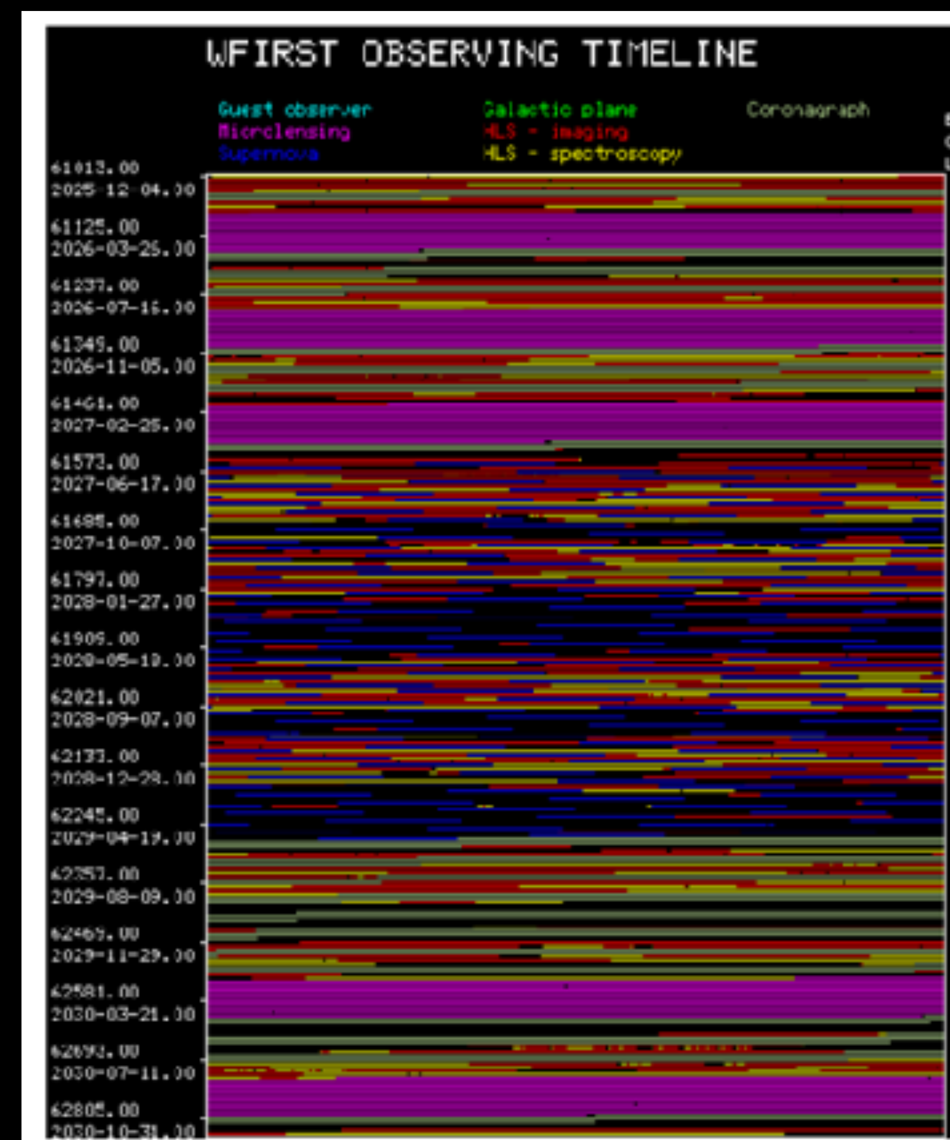


marginalized over {linear galaxy bias, lens photo-z, source photo-z} per tomography bin

Roman Space Telescope Forecasting

- Observing Strategy is not yet defined. Community input is important to define a mission that benefits all science
- No expendables that limit the survey strategy or the survey duration to 5-years (propellant for at least 10 years of observations, no active cryogens)

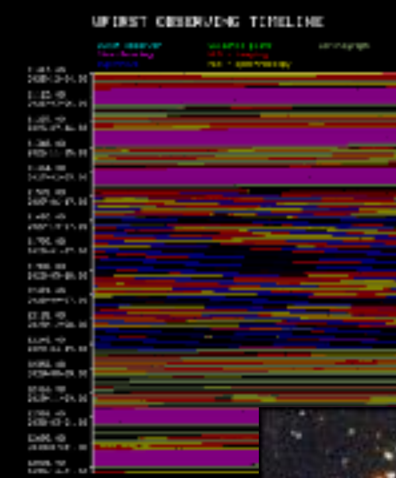


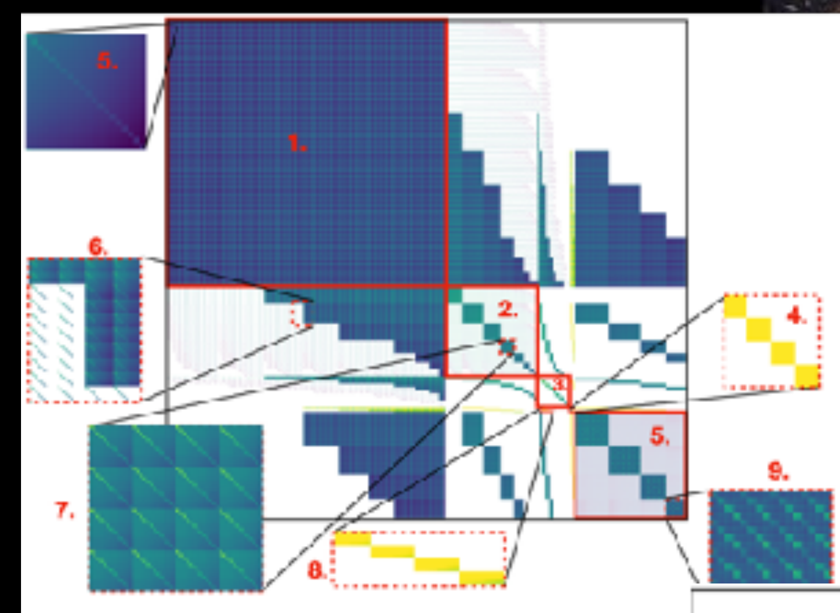


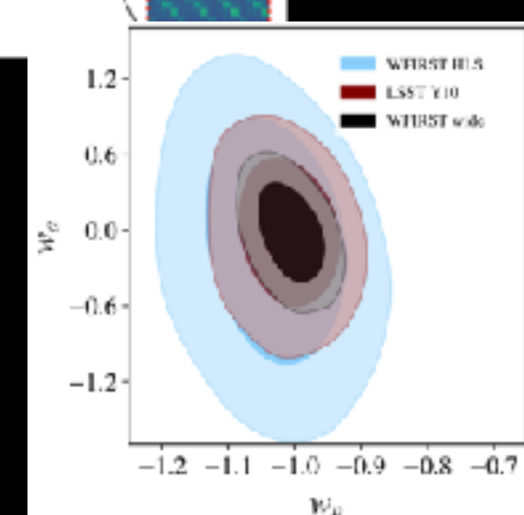
Roman Space Telescope Forecasting

Forecast Machinery (Eifler+2004.05271)

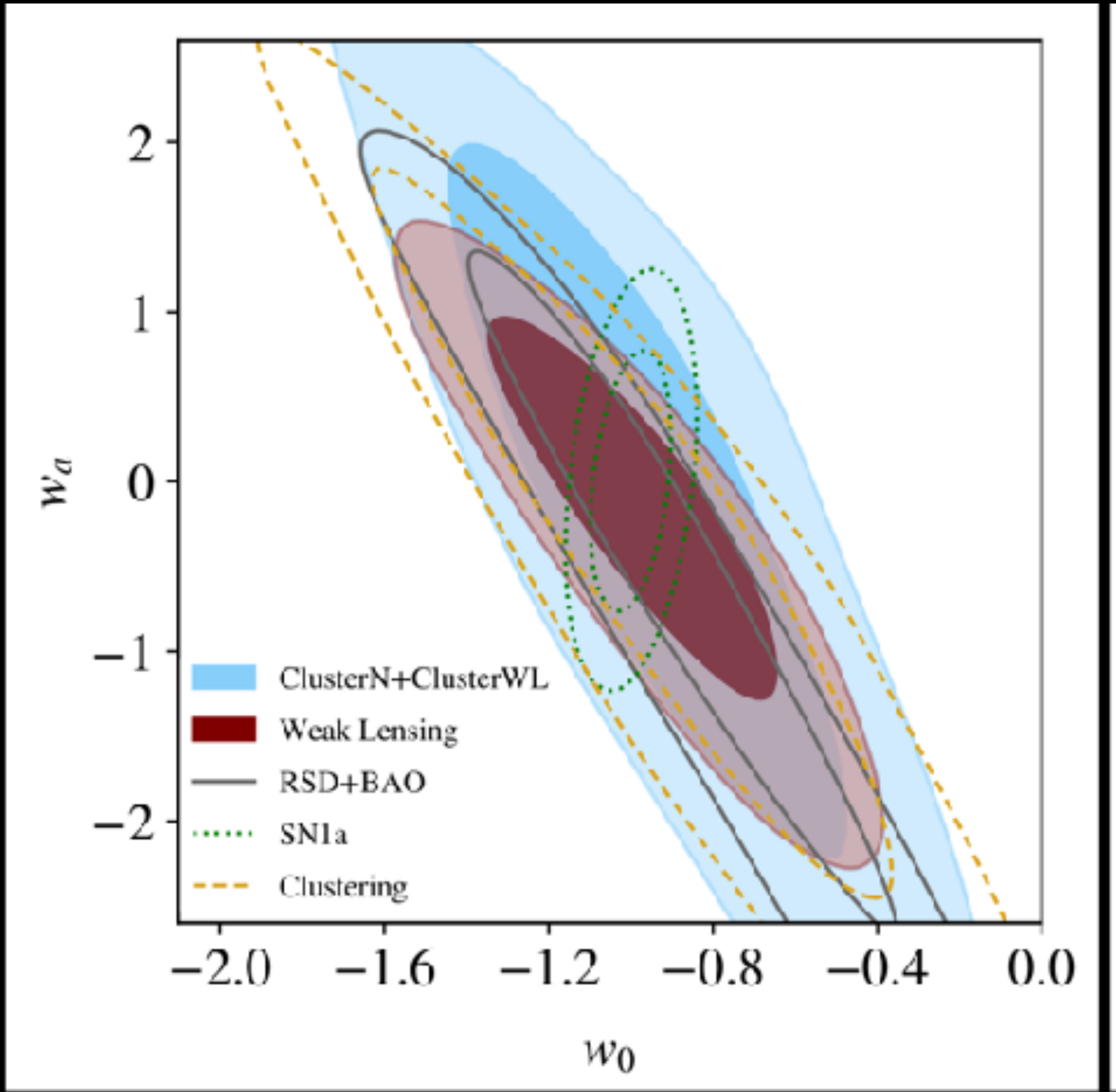
- WFIRST Exposure Time Calculator (Hirata+12): realistic survey area + depth
- CANDELS WFIRST catalog (Hemmati+18): redshift distribution for lensing and clustering sample, galaxy clusters
- Combine
  - Cosmic shear
  - Galaxy-Galaxy Lensing
  - Galaxy Clustering (photo)
  - Cluster Number Counts
  - Cluster Weak Lensing
  - Galaxy Clustering (Spectro)
  - SN1a (Hounsell+2018)
- Non-Gaussian Multi-Probe Covariance
- 80+ systematic parameters
- full simulated likelihood analyses



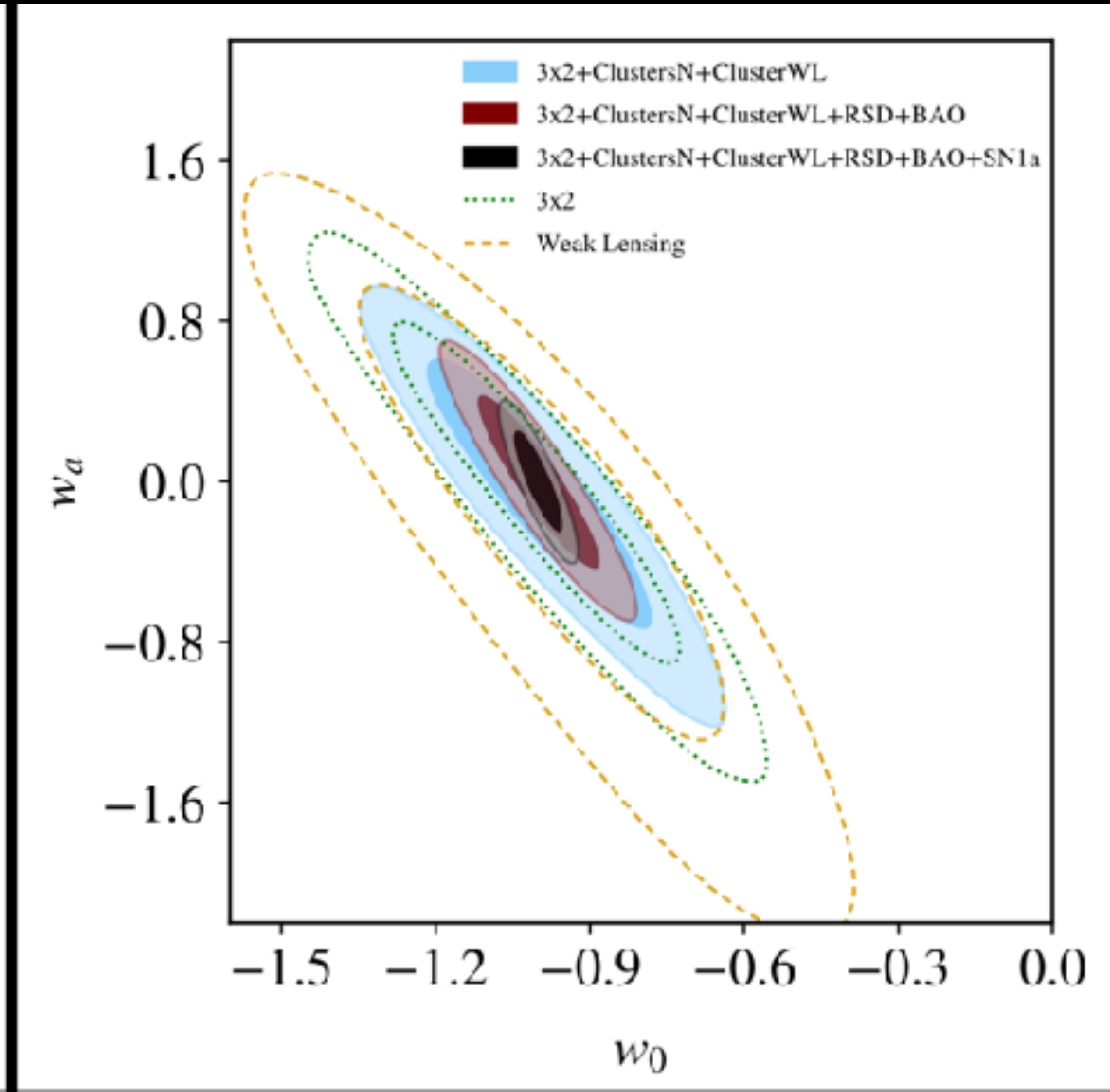




Roman Forecasts: Reference Survey



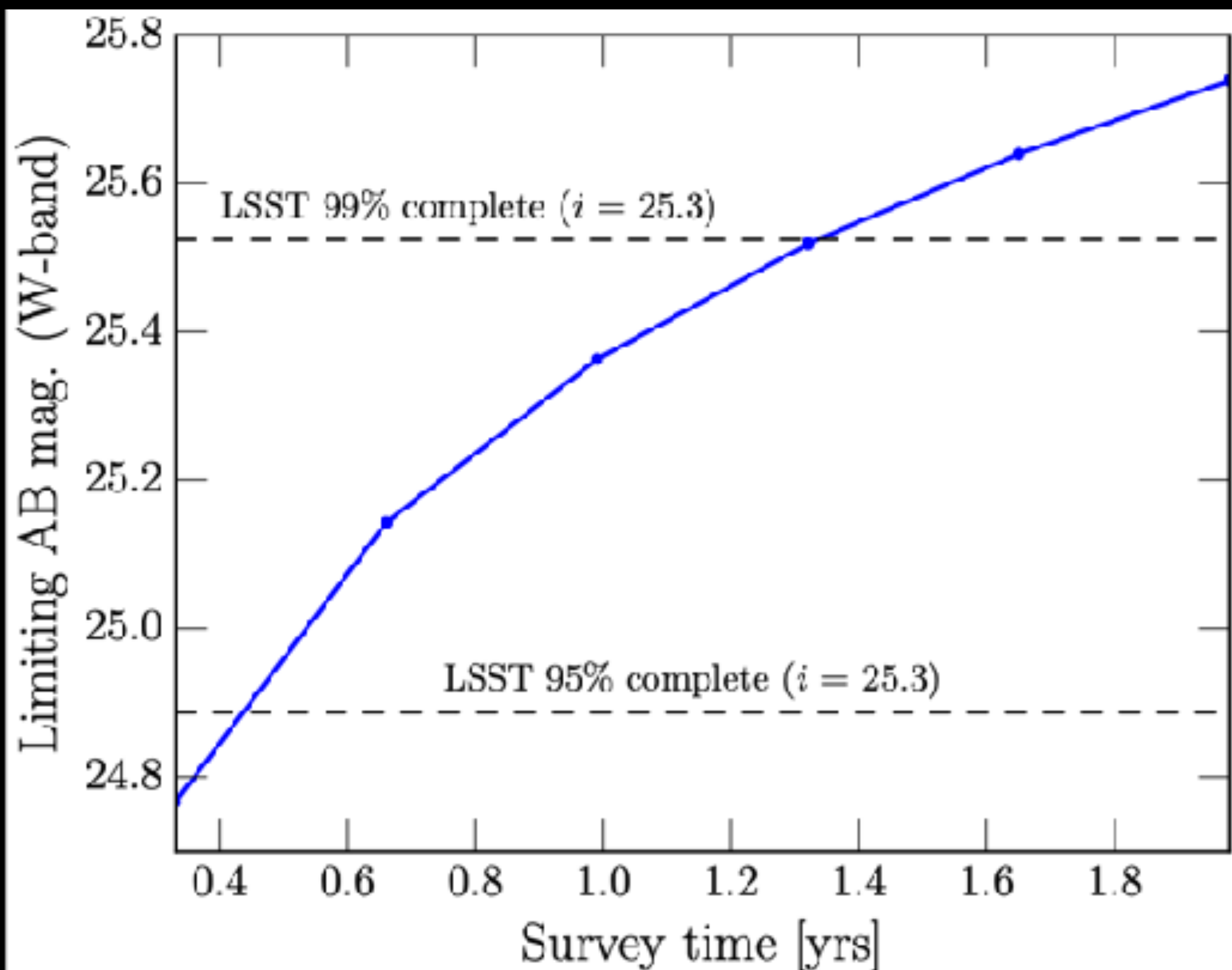
individual probes



combined probes

(Hypothetical) Roman Wide Survey: W-band, 18000 deg^2

2004.04702, based on exposure time calculator, Hirata+ 2012



5 months: Roman can cover all of LSST's area and obtain space quality shape measurements for 95% of the LSST Y10 gold sample

1year: Same as above for all sky

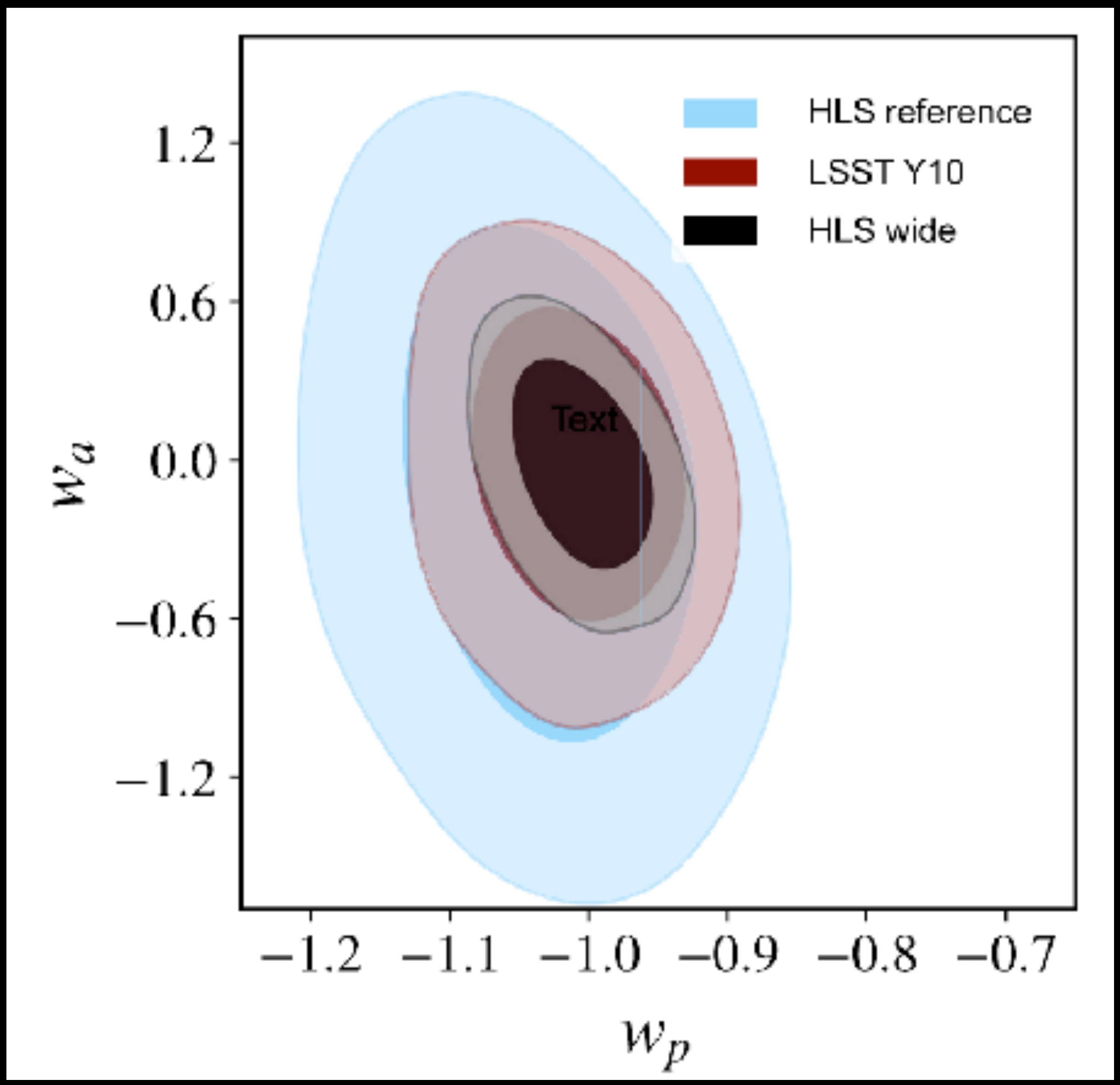
Interesting for many science cases beyond DE

Disclaimer: W-band only survey is more easily affected by systematics

Idea: Combine W-band survey with Roman multi-band photometry as in the reference survey

(Hypothetical) Roman Wide Survey: 3x2pt Roman x Rubin Forecasts

2004.04702, based on exposure time calculator, Hirata+ 2012



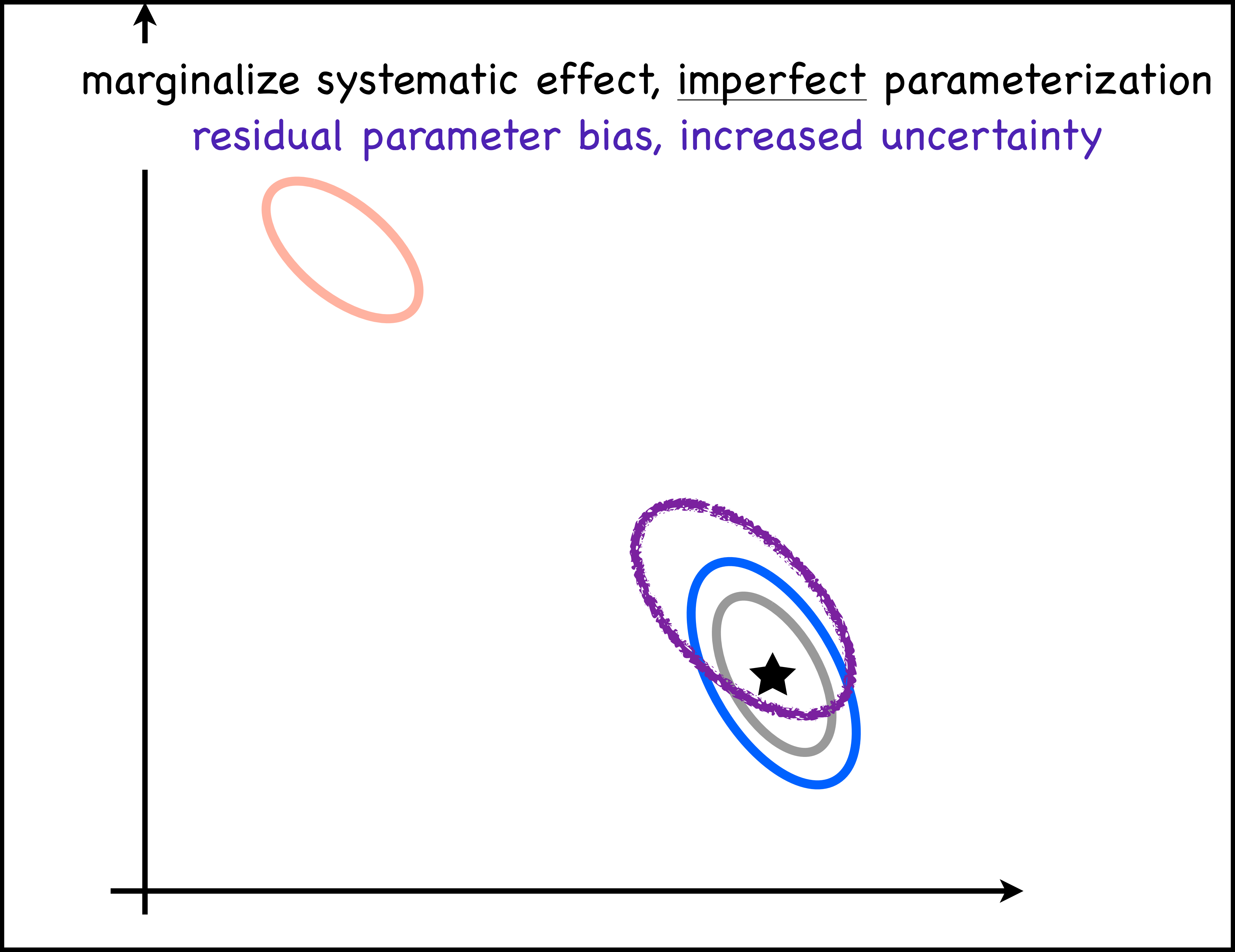
Weak lensing and Galaxy Clustering (photo-z) only, no clusters, spec-z, SN, CMB

Includes 56 dims of systematics modeling:
Shear calibration, galaxy bias, photo-z, IA, baryons

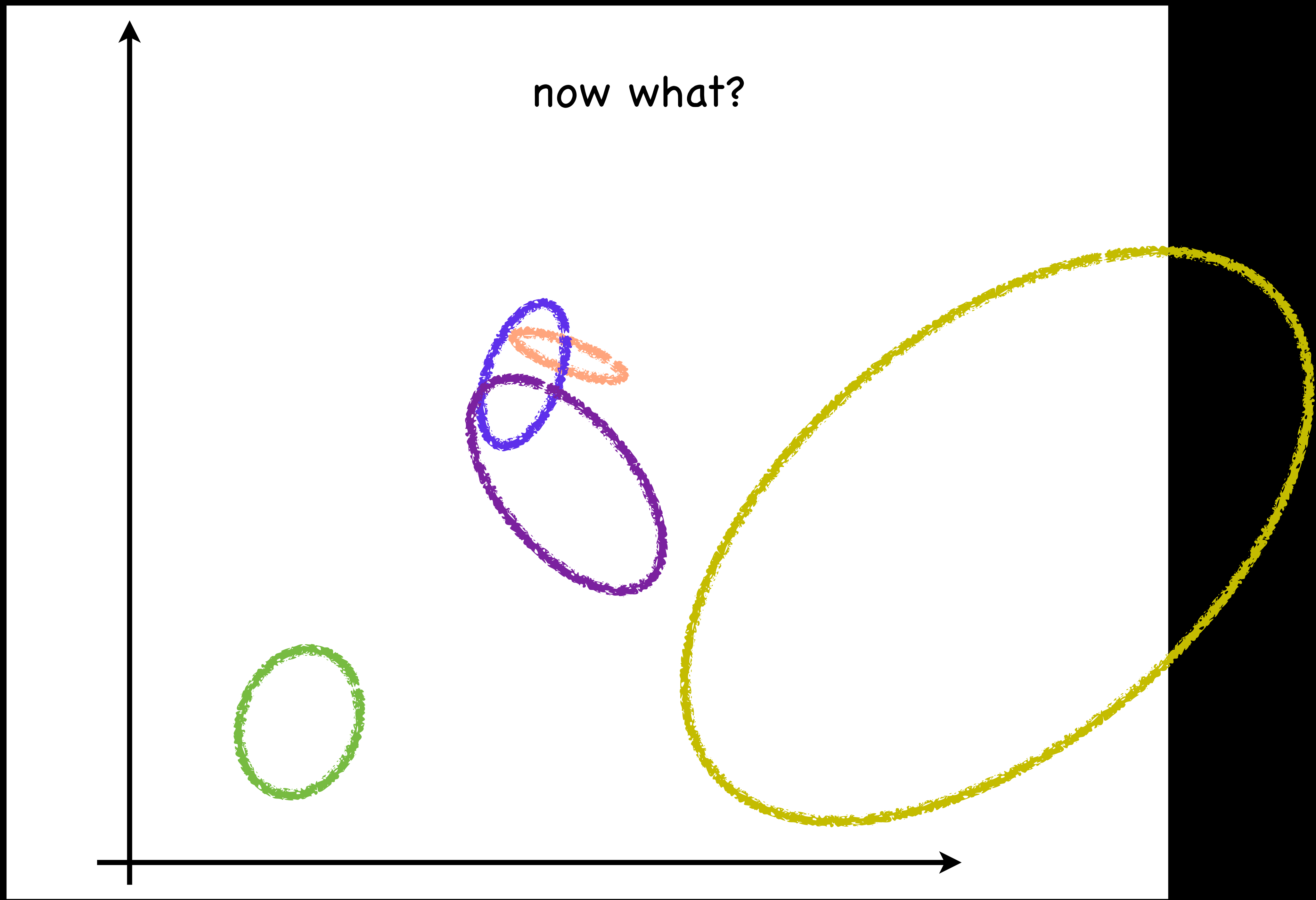
FoM (Roman wide + Rubin)=
2.4 x FoM (Rubin only)
FoM (Roman wide + Rubin) =
5.5 x FoM (Roman Reference survey)

Disclaimer: The usual caveats to the FoM metric apply

Reality is different



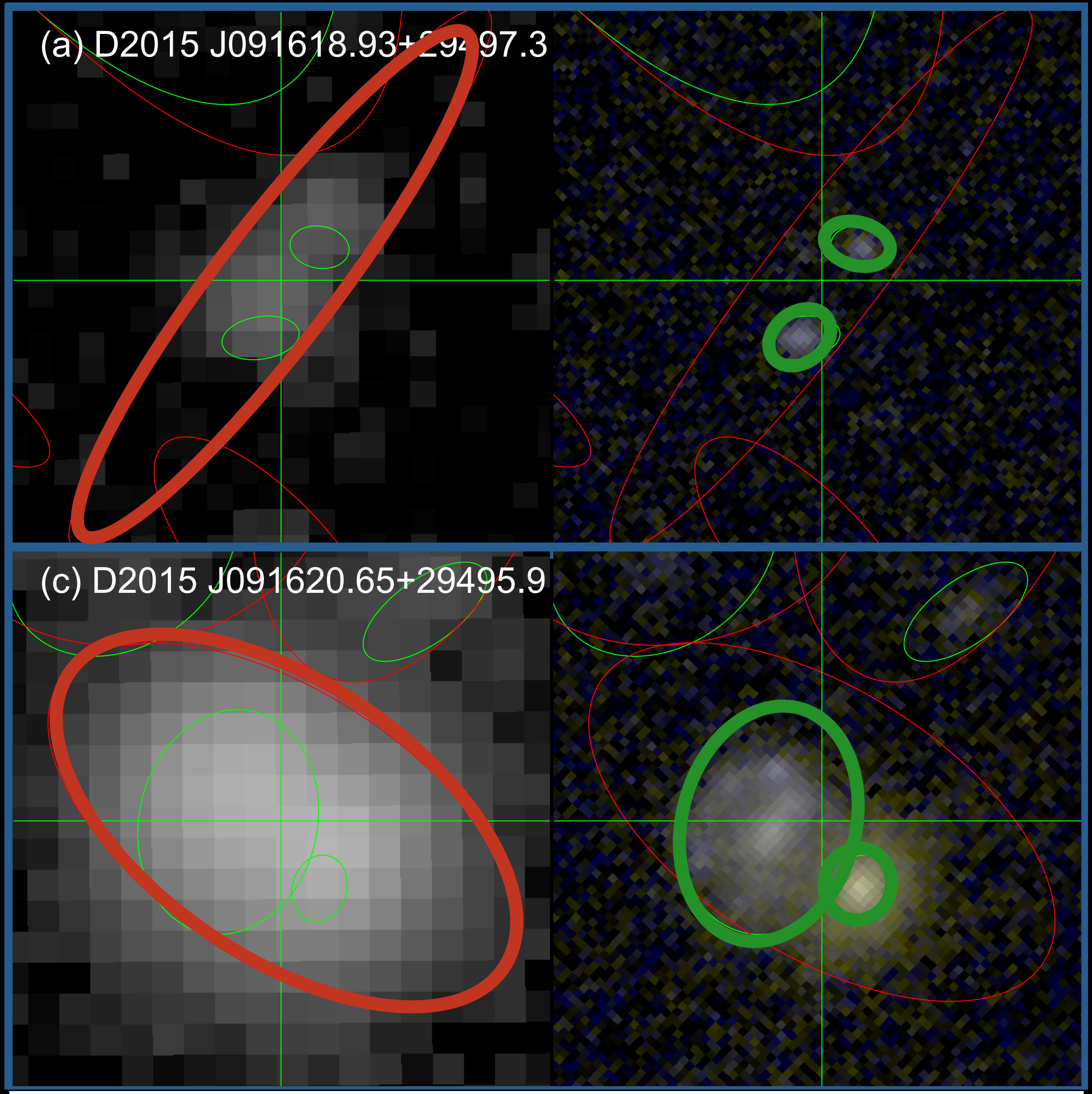
Single Probe Analysis, Pass 1



Unknown Systematics? vs. New Physics?

Unknown Systematics? vs. New Physics?

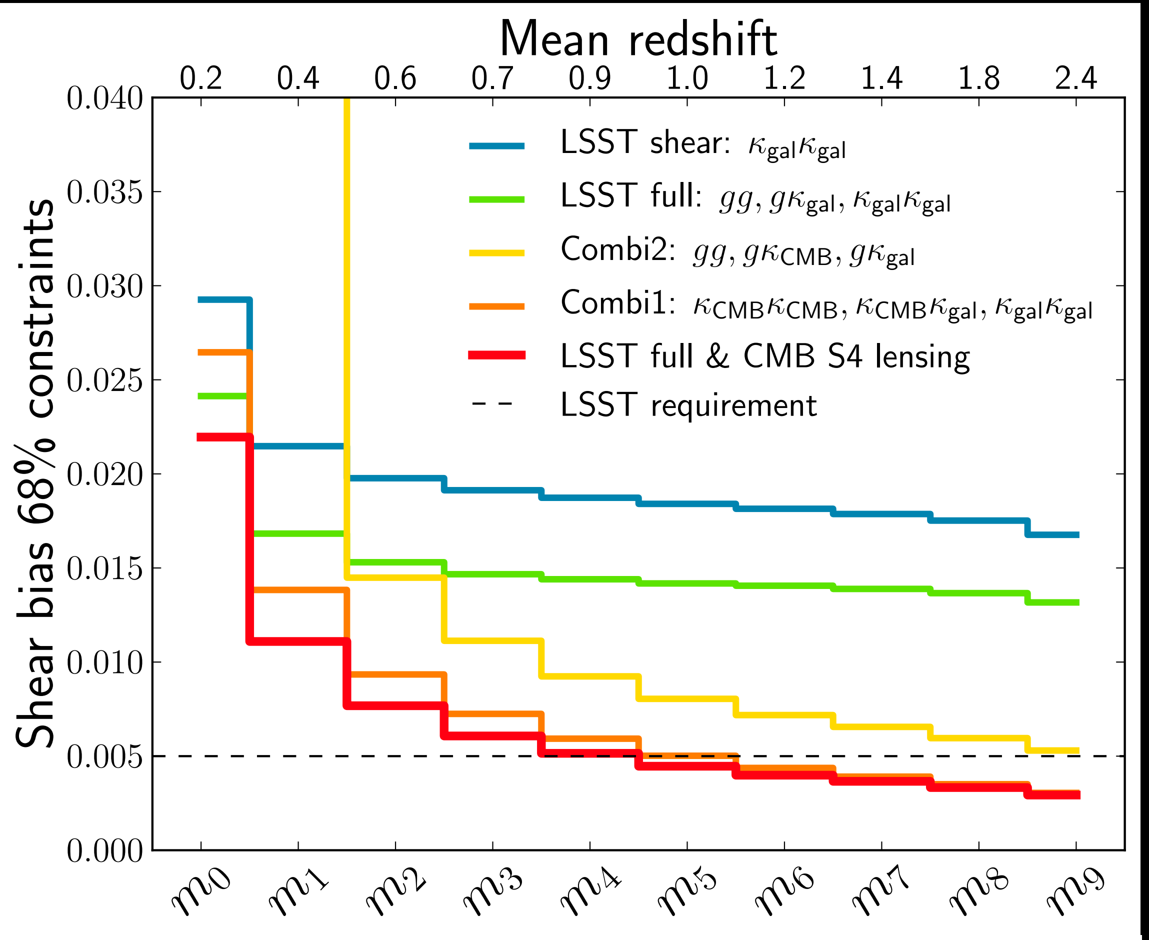
- scale dependence?
- dependence on galaxy/cluster selection?
- calibrate with more accurate measurements
  - spectroscopic redshifts
  - low-scatter cluster mass proxies
  - galaxy shapes from space-based imaging
  - [potentially expensive]



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

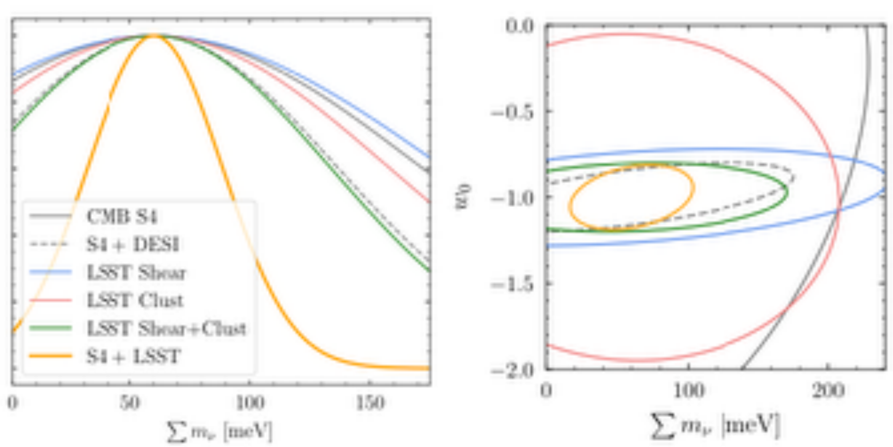


LSST WL x CMB-S4 lensing
calibrate shear calibration bias
Schaan, EK,+17

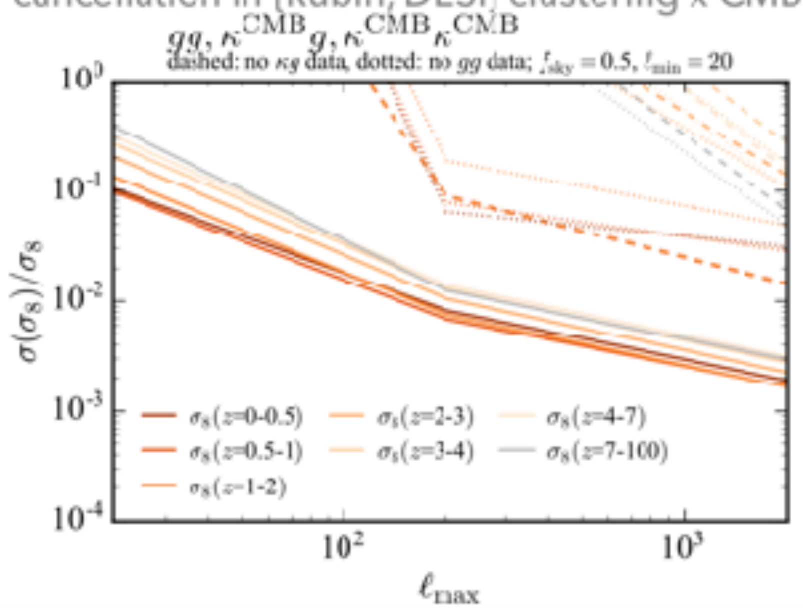
Unknown Systematics? vs. New Physics? CMB synergies

Mishra-Sharma, Dunkley & Alonso 2018: constraints on DE and neutrino mass in w_aCDM cosmologies

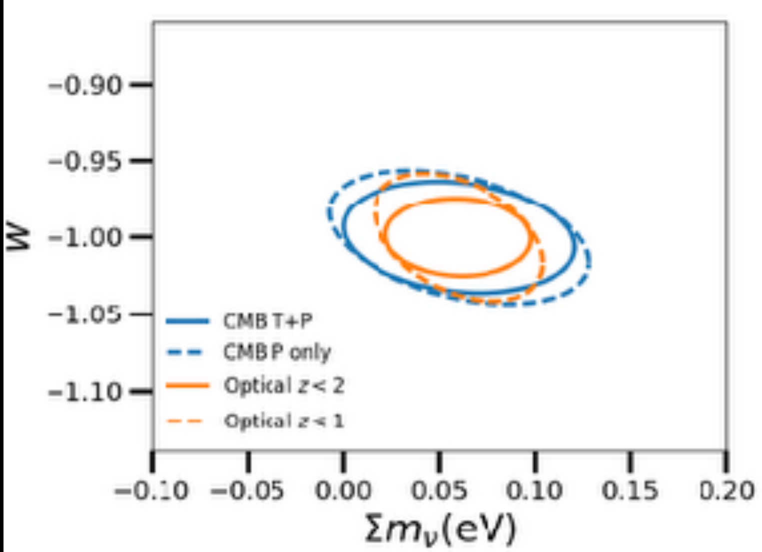
$\boxed{\boxed{gg}, \kappa^{\rm LSST} g, \boxed{\kappa^{\rm LSST}\kappa^{\rm LSST}}}, \kappa^{\rm CMB} g, \kappa^{\rm CMB}\kappa^{\rm LSST}, \boxed{\kappa^{\rm CMB}\kappa^{\rm CMB}}$



Schmittfull & Seljak 2018: cosmic variance cancellation in {Rubin, DESI} clustering x CMB-S4

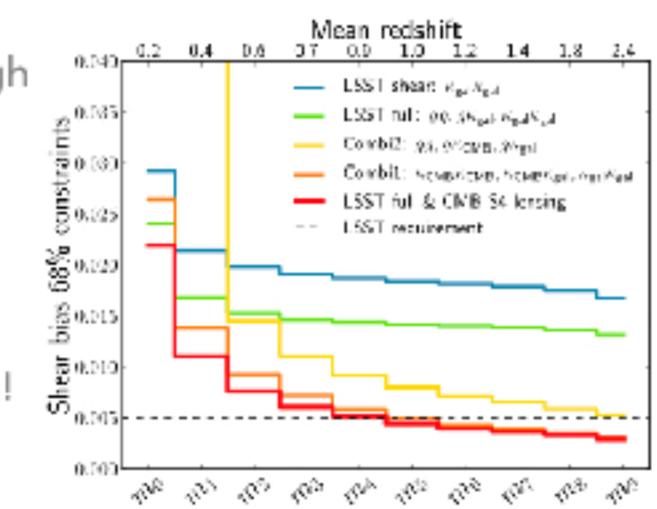


Madhavacheril, Battaglia & Miyatake 2017: improved self-calibration of cluster mass-observable relations of tSZ selected clusters with CMB-S4 and Rubin Obs.



Valinotto 2012, Das et al. 2013: Calibrate shape measurement uncertainties (shear calibration) through cross-correlation of CMB lensing and galaxy lensing

- Baxter et al. 2016: demonstration on DES-SV x SPT data
- results from DES-Y1 x SPT forthcoming!
- Schaan et al. 2017: LSST x CMB-S4 reaches LSST calibration requirement for high-z galaxies
- alternatively, calibrate A_L



LSST WL x CMB-S4 lensing calibrate shear calibration bias Schaan et al17

Conclusions

We're entering the decade of very large galaxy surveys

- BOSS, KiDS,DES, HSC, PFS -> DESI, Rubin, Euclid, Roman,…
- + radio surveys: impressive forecasts, complementary systematics

- (most) cosmological constraints will be systematics limited
  - require accurate systematics parameterizations+priors
- different probes and analysis methods enable accurate cosmology
  - identify and understand systematics effects
  - maximize constraining power
- Precision cosmology requires collaboration across surveys + wavelengths, planning for analysis frameworks to combine data from all surveys!