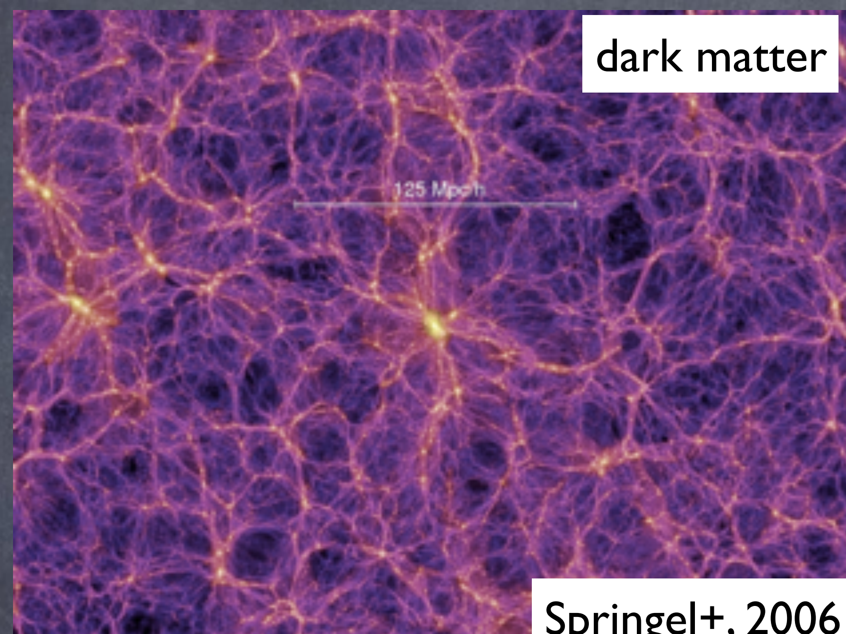
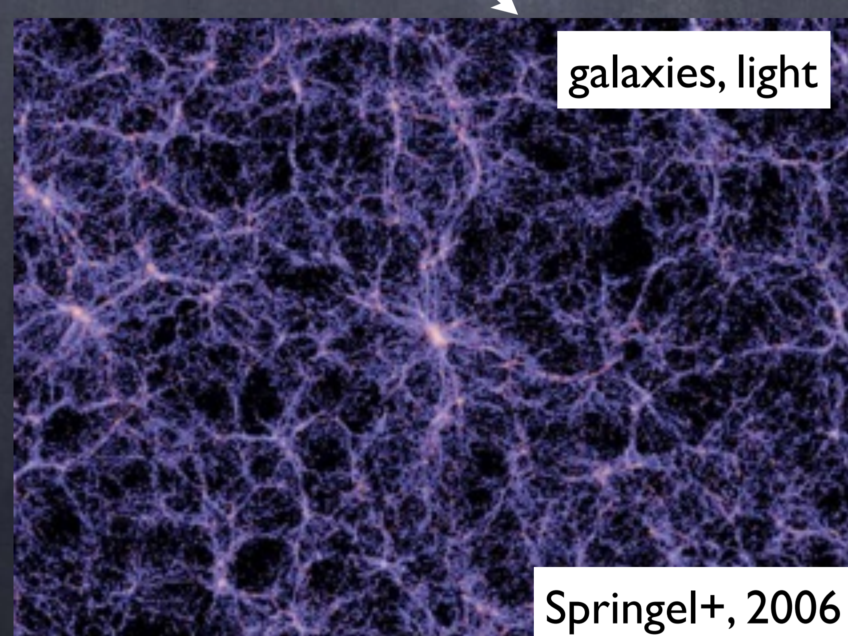
How to compare with data?

physics
+ model parameters

generate initial conditions, evolve

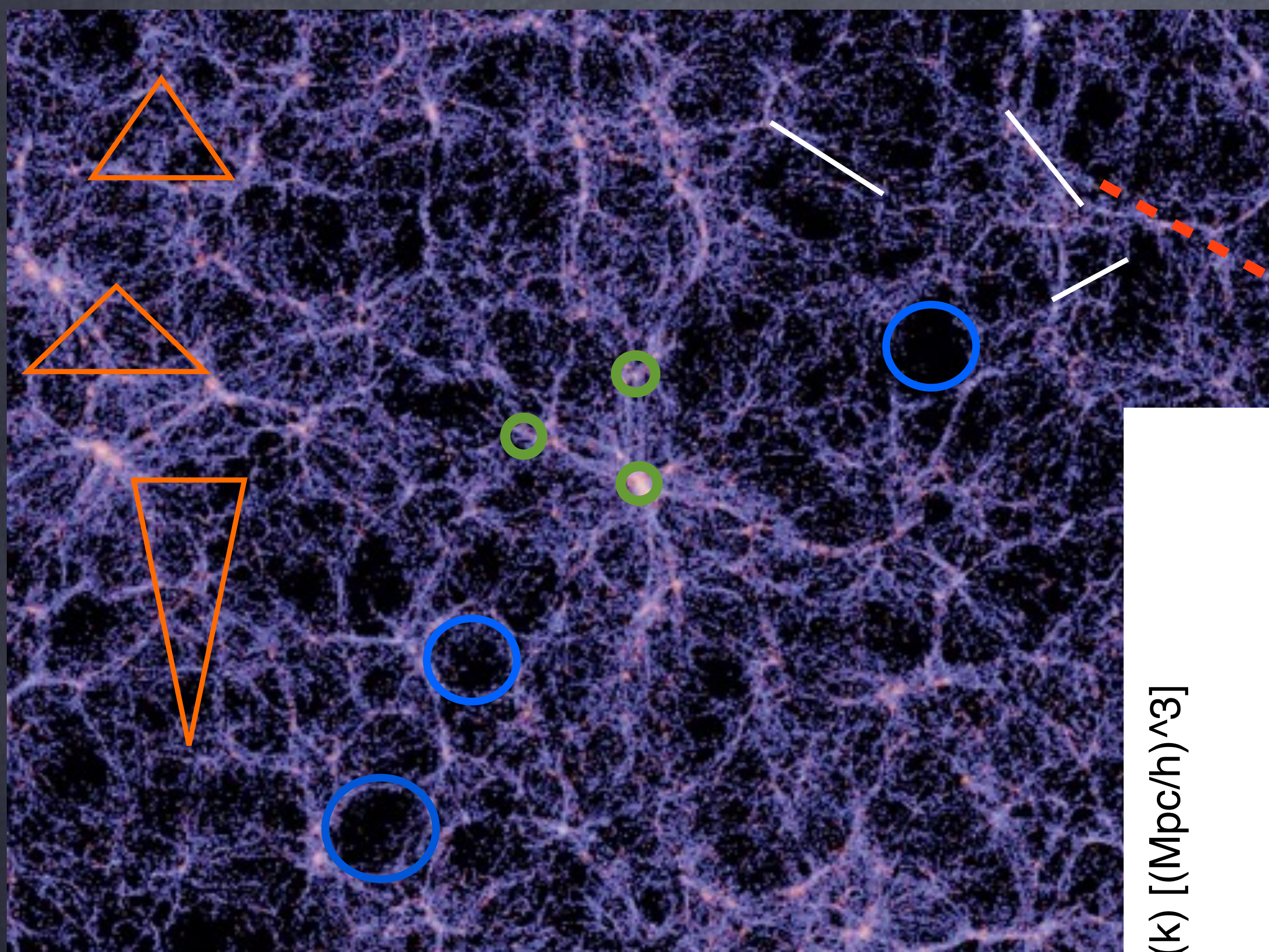


galaxy formation models ?

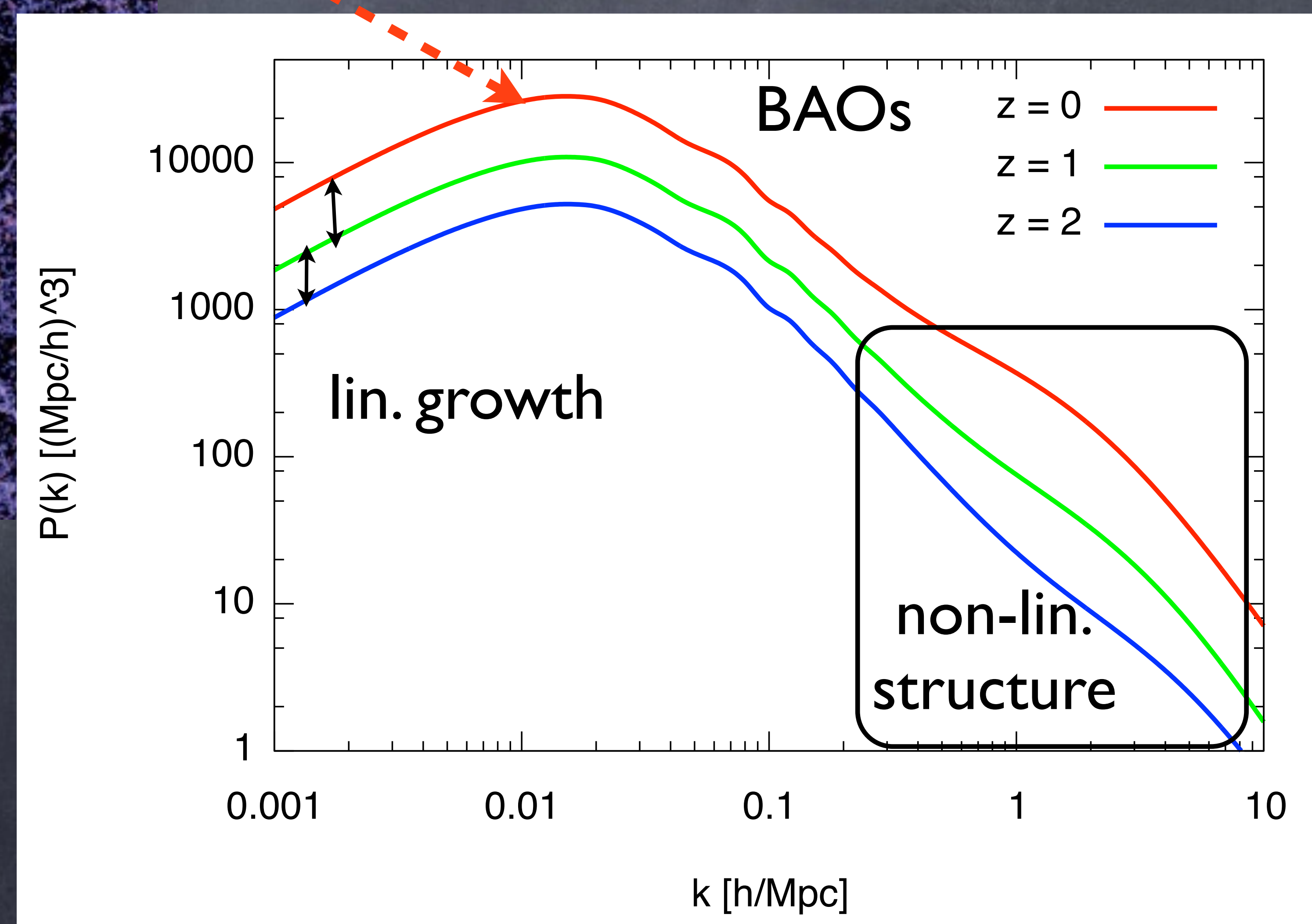


?

What to look for in the galaxy distribution?



need redshift, understand galaxy bias

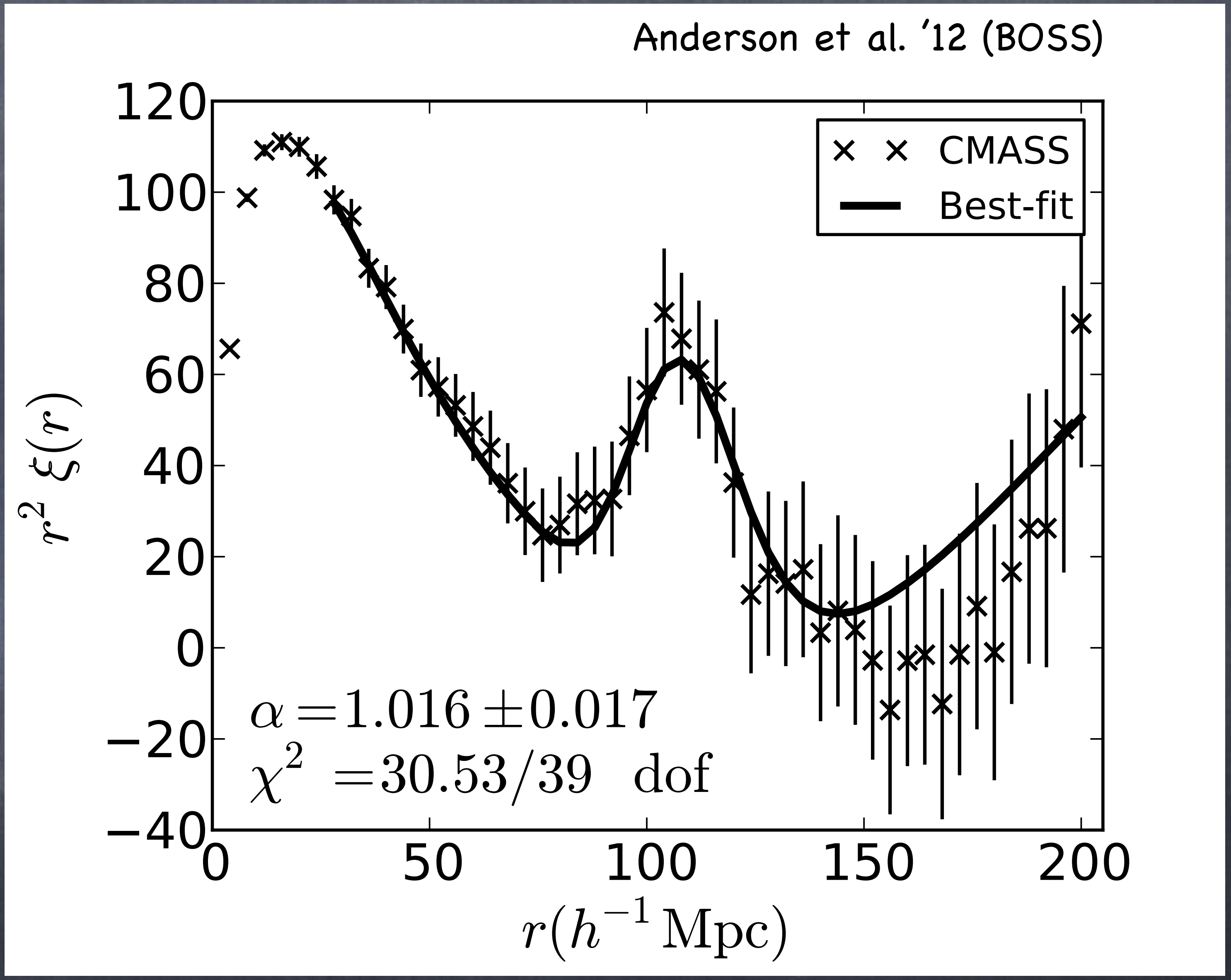


- clusters (over densities),
- voids (under densities)
- two-point correlations
- three-point correlations,...

LSS Probes of Dark Energy

Galaxy Clustering

- measure BAOs + shape of correlation function
- → growth of structure, expansion history
  - Key systematic: **galaxy bias**



LSS Probes of Dark Energy

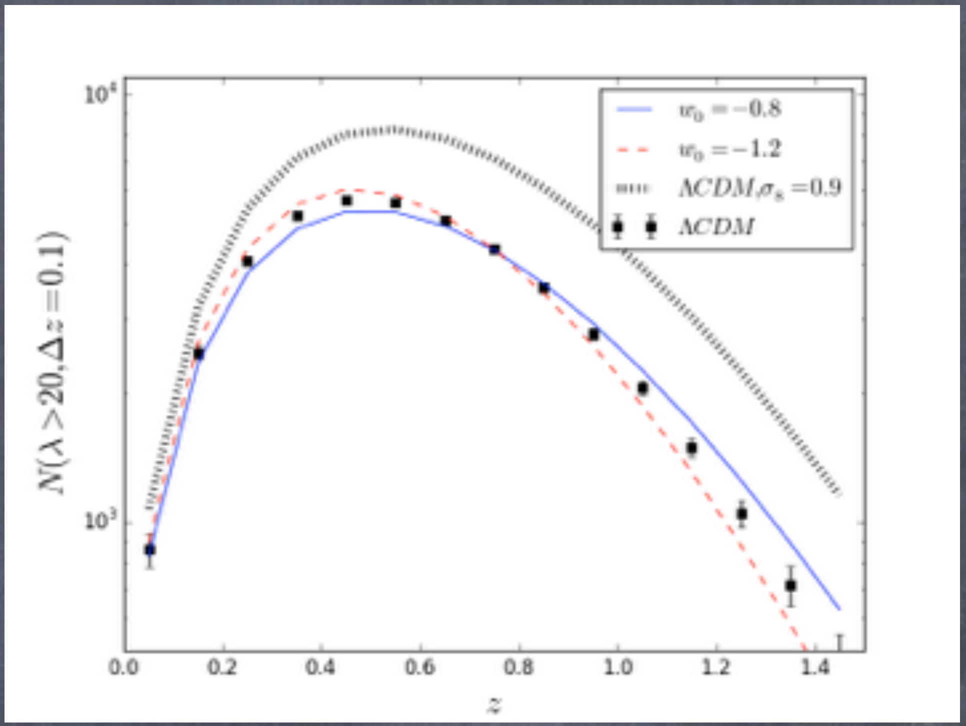
Galaxy Clusters

- measure number counts

$$N(\hat{M}, z, \Delta z) = \frac{dn}{dM dz} \Delta V(z, \Delta z)$$

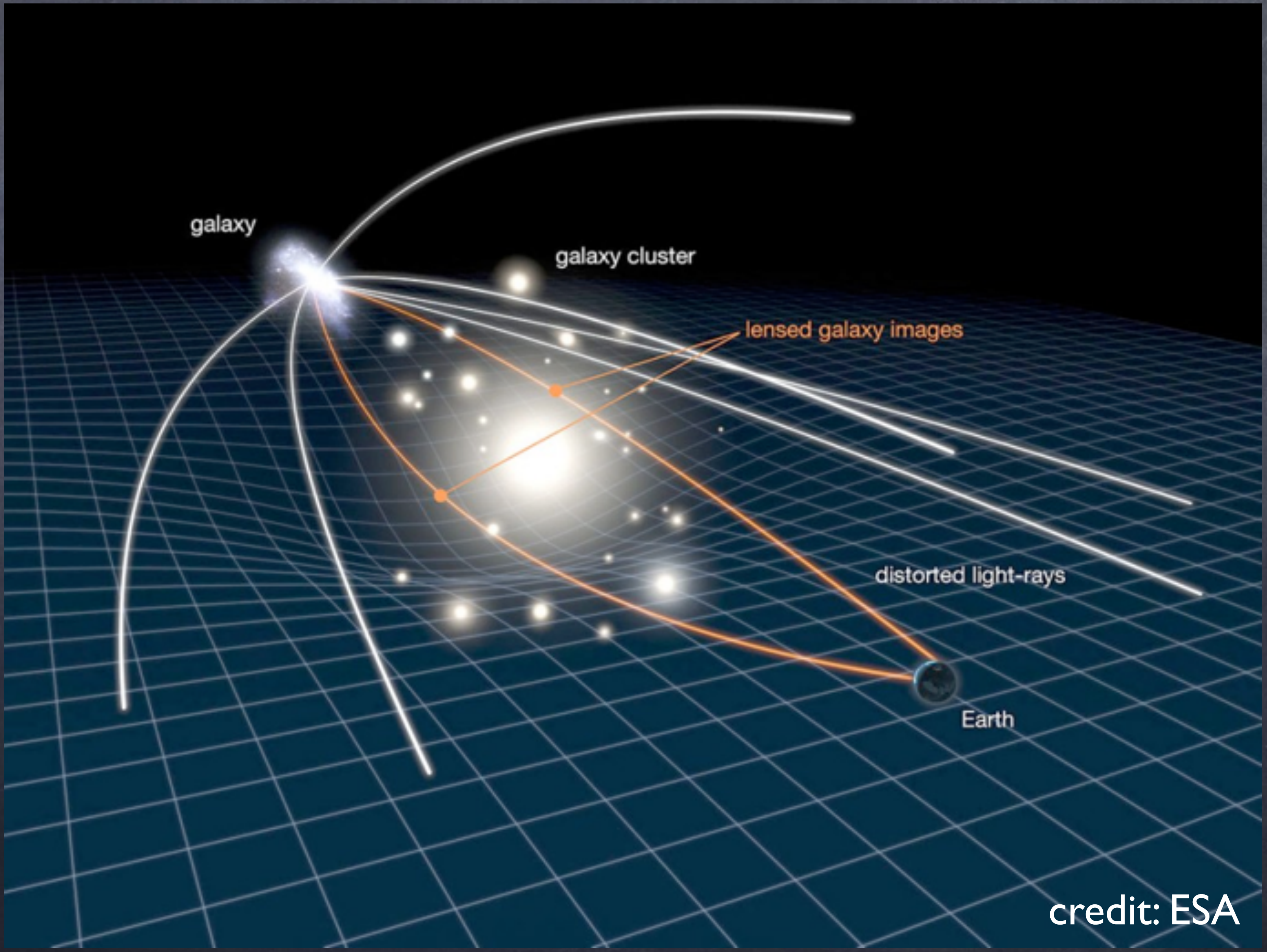
→ distribution of peaks, growth of structure, expansion history

- but need to identify clusters + member galaxies, infer masses!



LSS Probes of Dark Energy

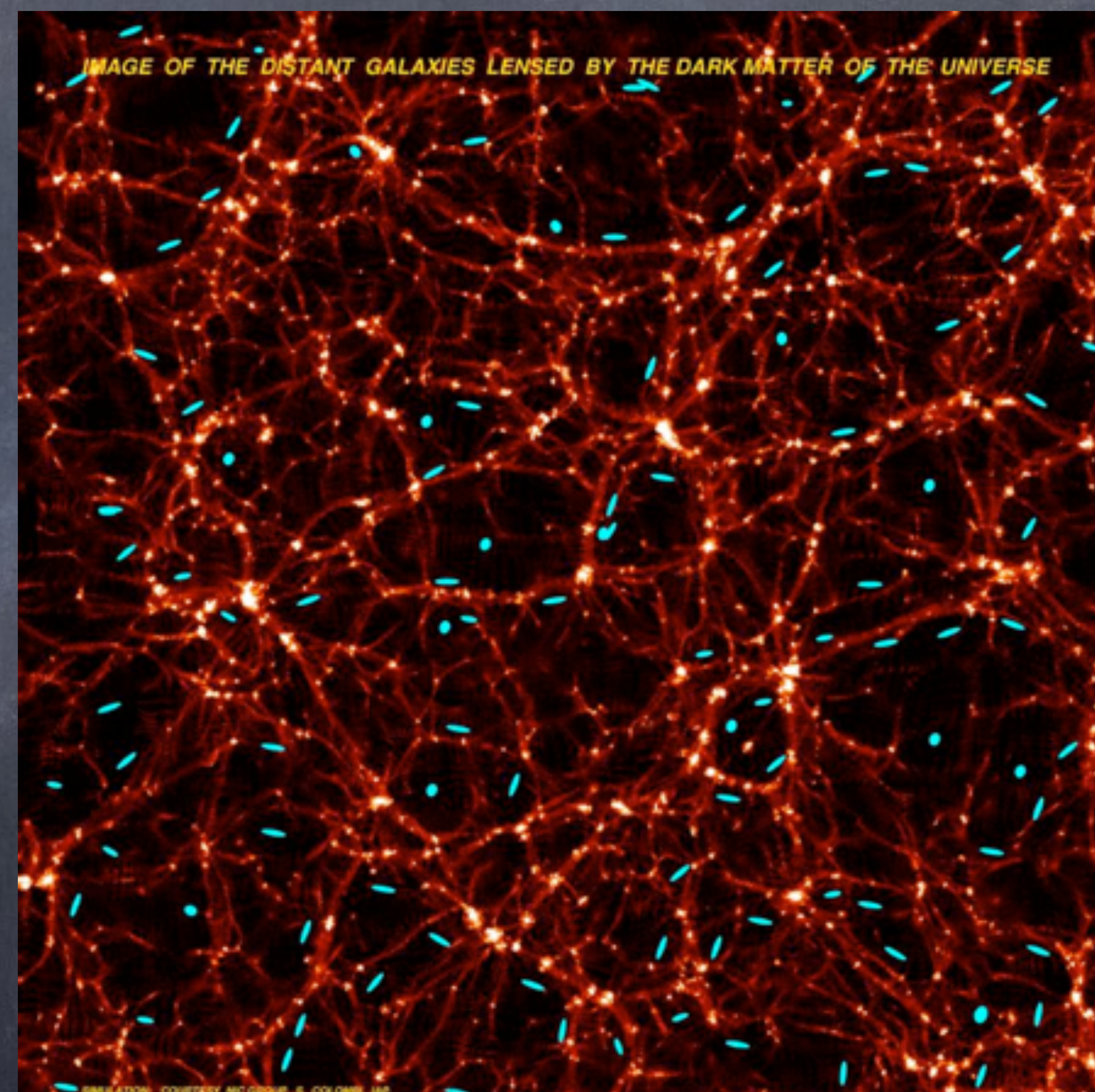
Weak Gravitational Lensing



LSS Probes of Dark Energy

Weak Gravitational Lensing I

- light deflected by tidal field of LSS
  - coherent distortion of galaxy shapes (“shear”)
- shear related to (projected) matter distribution
- key uncertainties
  - shape measurements
  - assume random intrinsic orientation, average over many galaxies

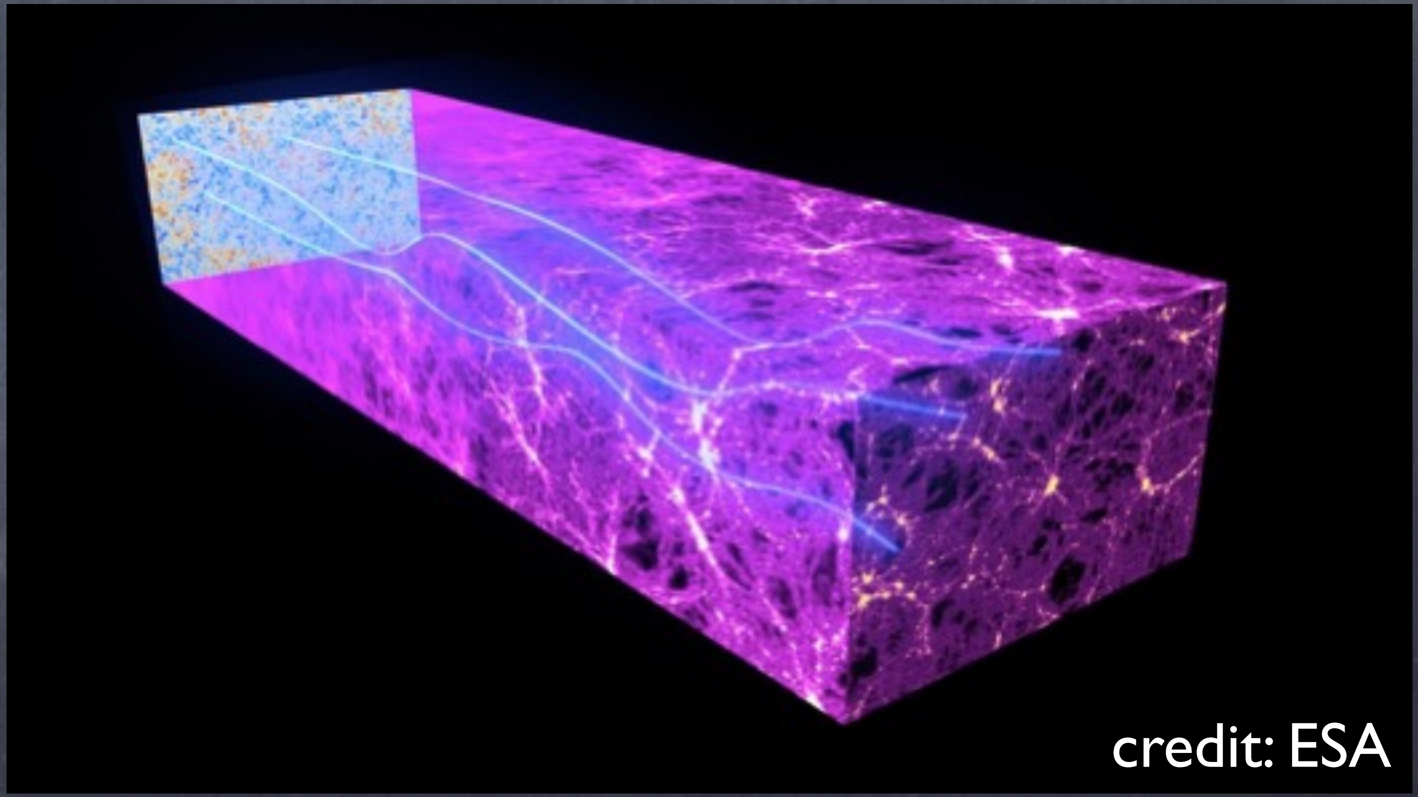


LSS Probes of Dark Energy

Weak Gravitational Lensing Ib

- light deflected by tidal field of LSS
  - coherent distortion of galaxy shapes (“shear”)
  - remapping of CMB anisotropies

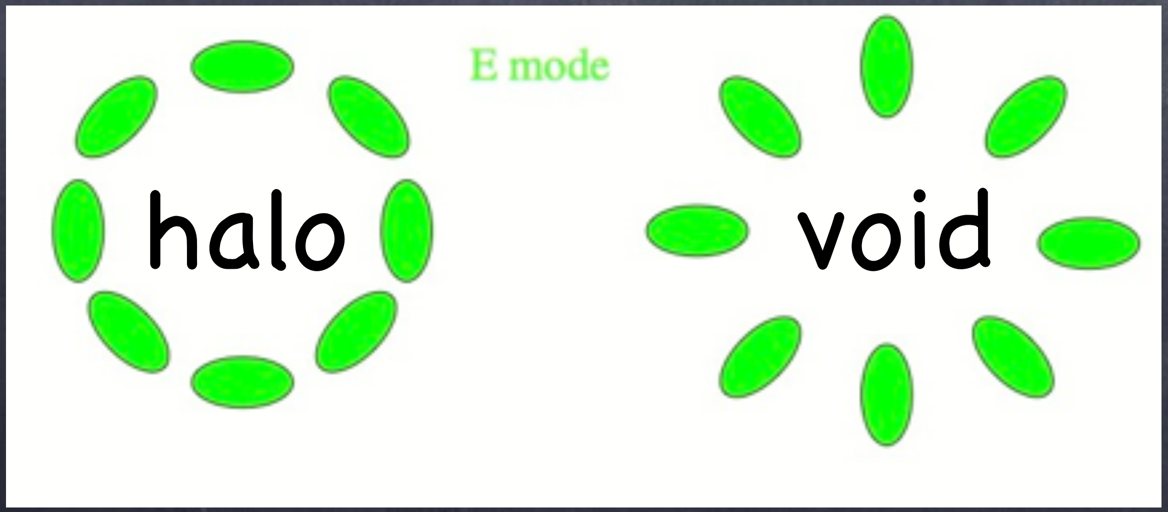
- CMB lensing affected by different systematics than shear estimates from galaxy distortions
  - consistency check


credit: ESA

LSS Probes of Dark Energy

Weak Gravitational Lensing II

- lensing produces (almost) purely E-mode type shear
  - observational B-modes >> cosmological B-modes
- measure shear correlation function/power spectrum
  - probes *total* matter power spectrum (w/ broad projection kernel)
- measure average (tangential) shear around galaxies/clusters
  - probes halo mass



~Optical Dark Energy Surveys

Spectroscopic galaxy surveys

determine redshifts of select galaxies

Galaxy Clustering

galaxy positions, types, redshifts

Supernovae

light curve, redshift

Galaxy Clusters

cluster centers, redshifts, member galaxies

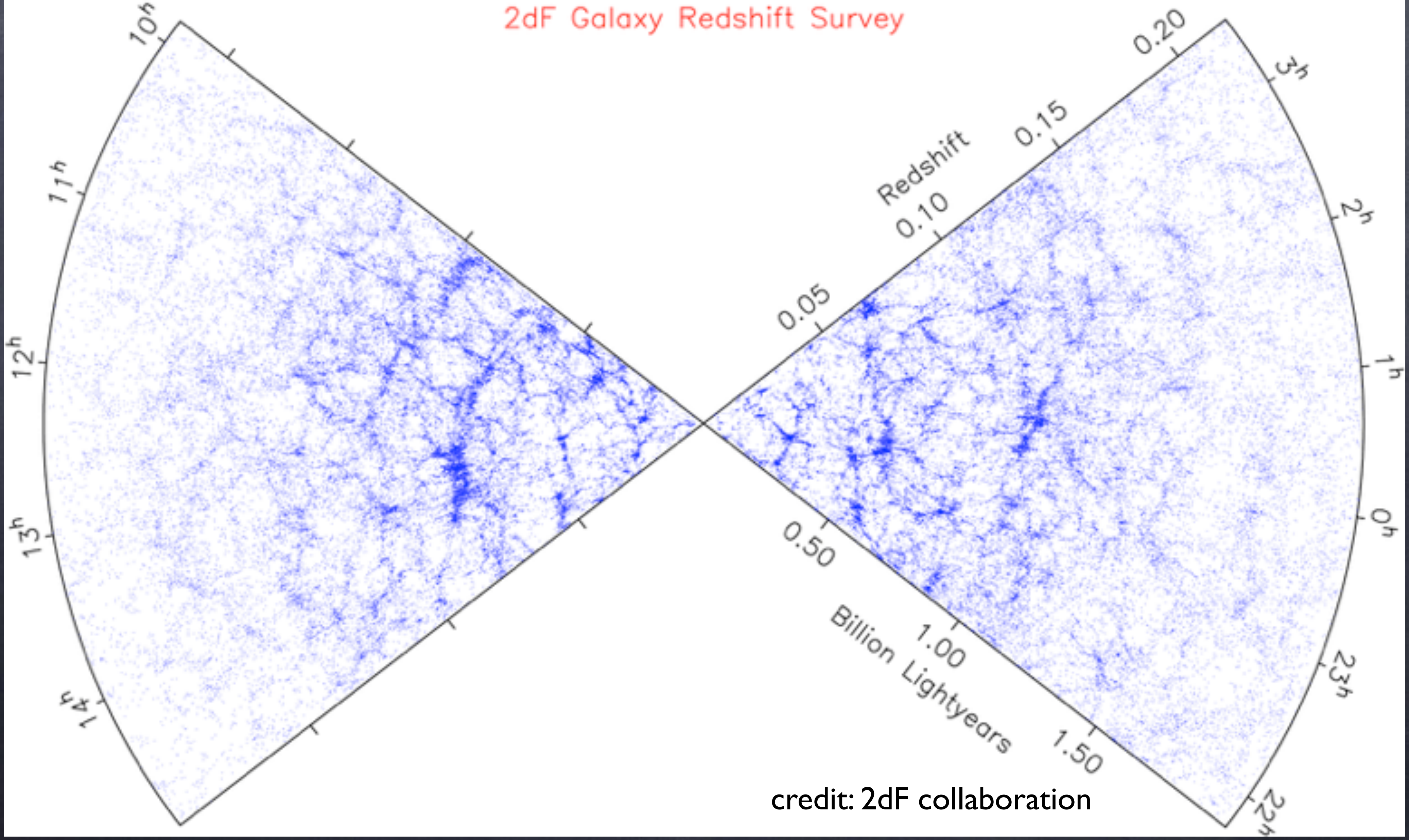
Weak Lensing

galaxy positions, shapes, types, redshifts

Spectroscopic Dark Energy Surveys

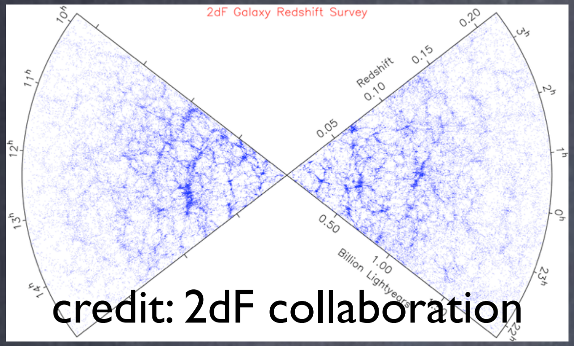
the early days: SDSS, 2-degree Field survey(2dF):

$\mathcal{O}(10^5 - 10^6)$ low-z galaxies



credit: 2dF collaboration

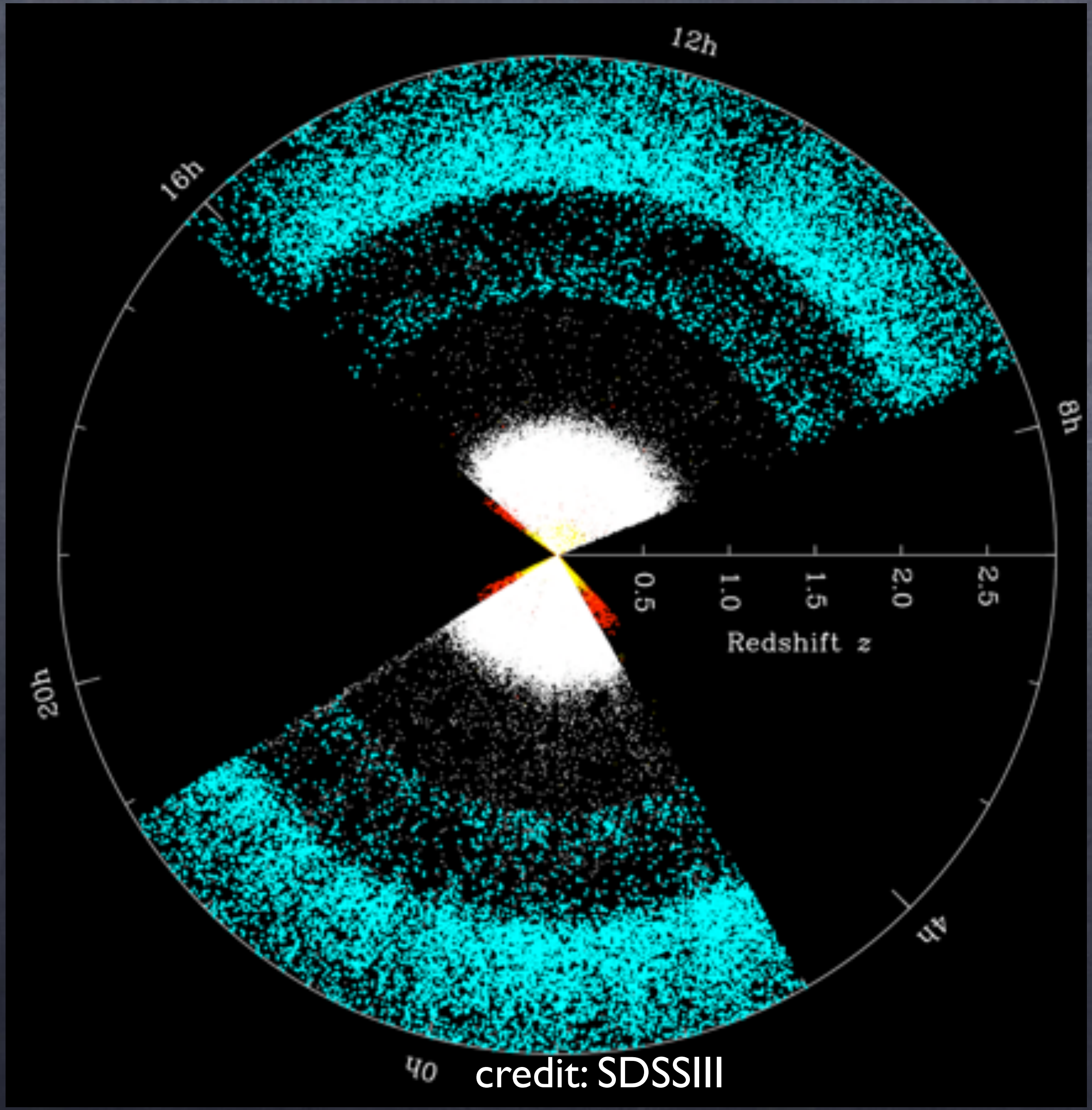
Spectroscopic Dark Energy Surveys



credit: 2dF collaboration

the present: BOSS, WiggleZ, …

$\mathcal{O}(10^6)$ intermediate-z galaxies

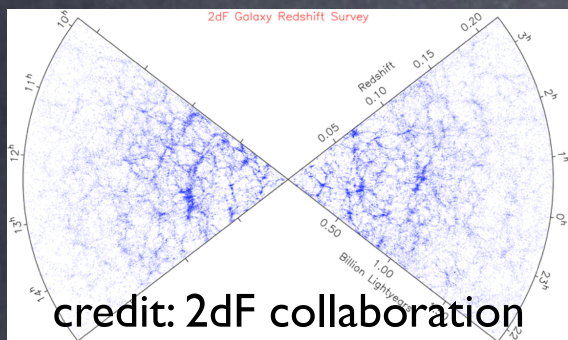


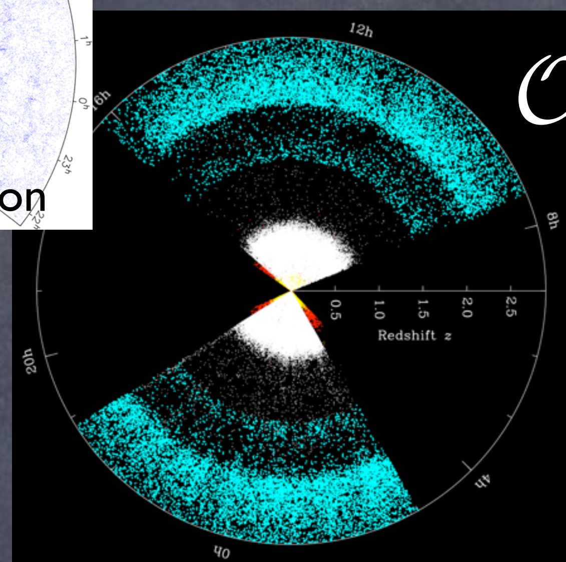
credit: SDSSIII

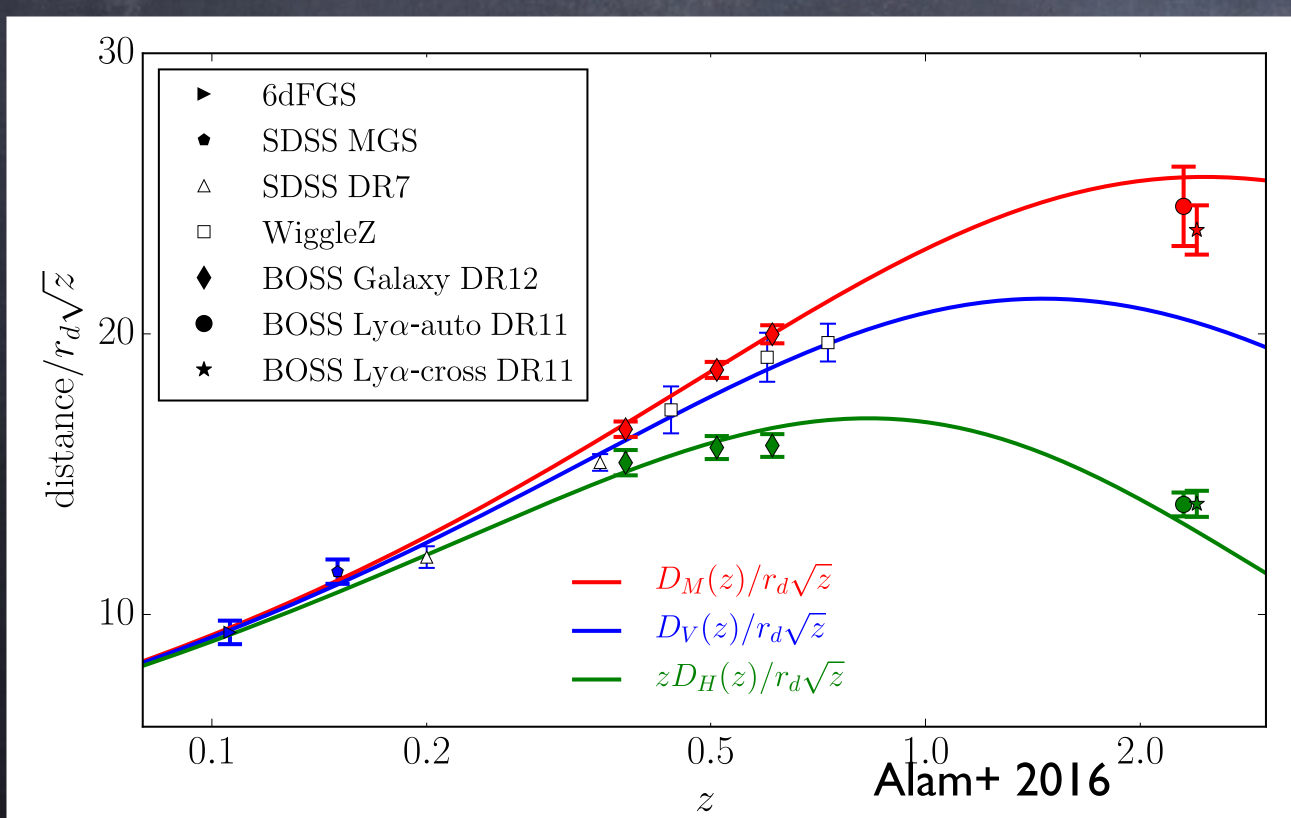
Spectroscopic Dark Energy Surveys

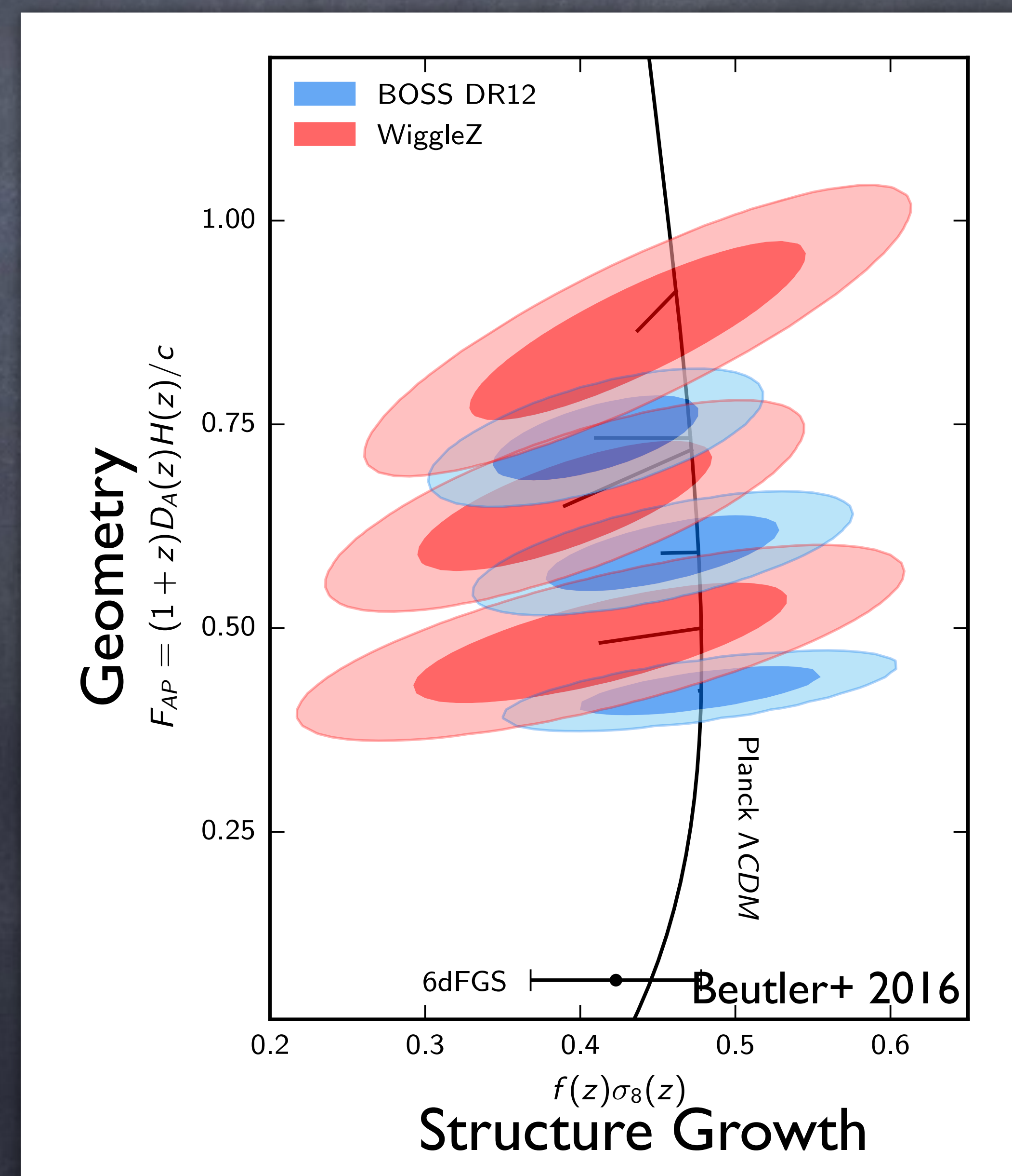
the present: BOSS, WiggleZ, …

$\mathcal{O}(10^6)$ intermediate-z galaxies





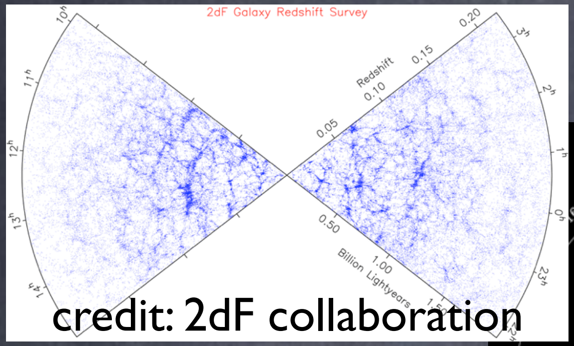


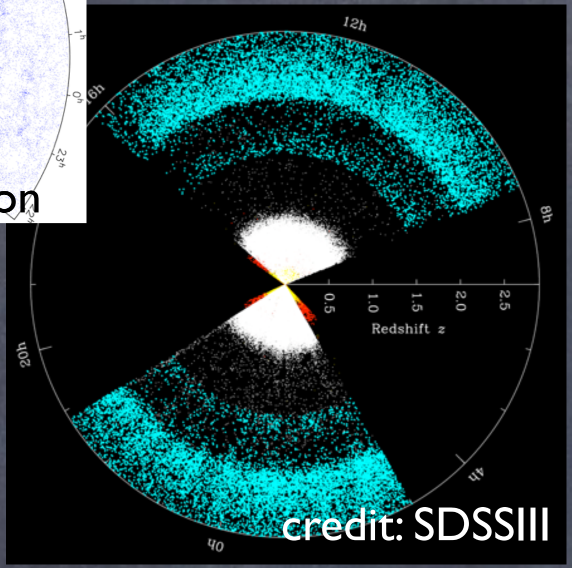


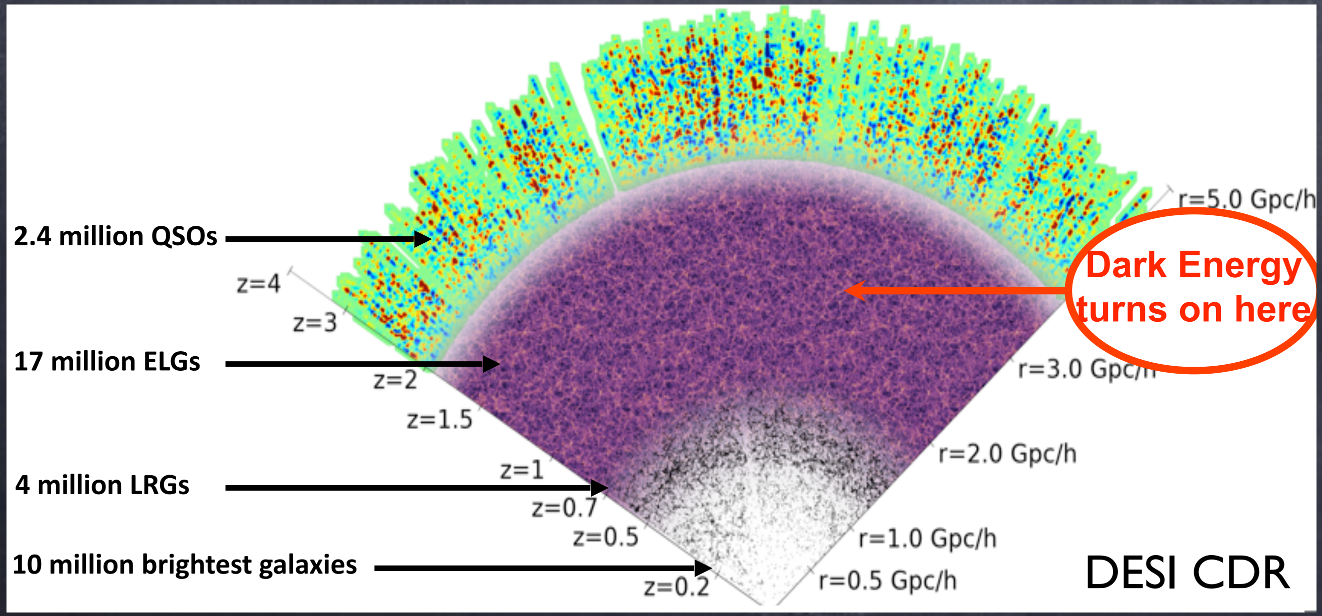
Spectroscopic Dark Energy Surveys

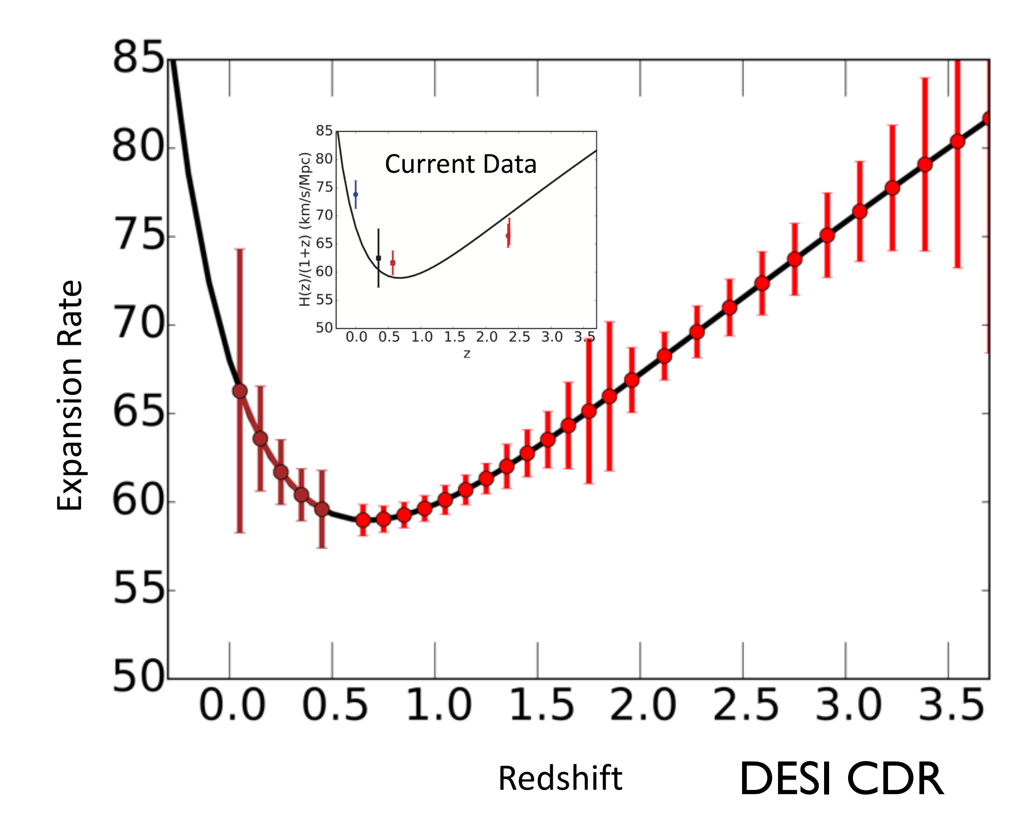
the future: Dark Energy Spectroscopic Instrument (DESI)

$\mathcal{O}(10^7)$ intermediate+high-z galaxies









~Optical Dark Energy Surveys

Spectroscopic galaxy surveys

determine redshifts of select galaxies

Photometric galaxy surveys

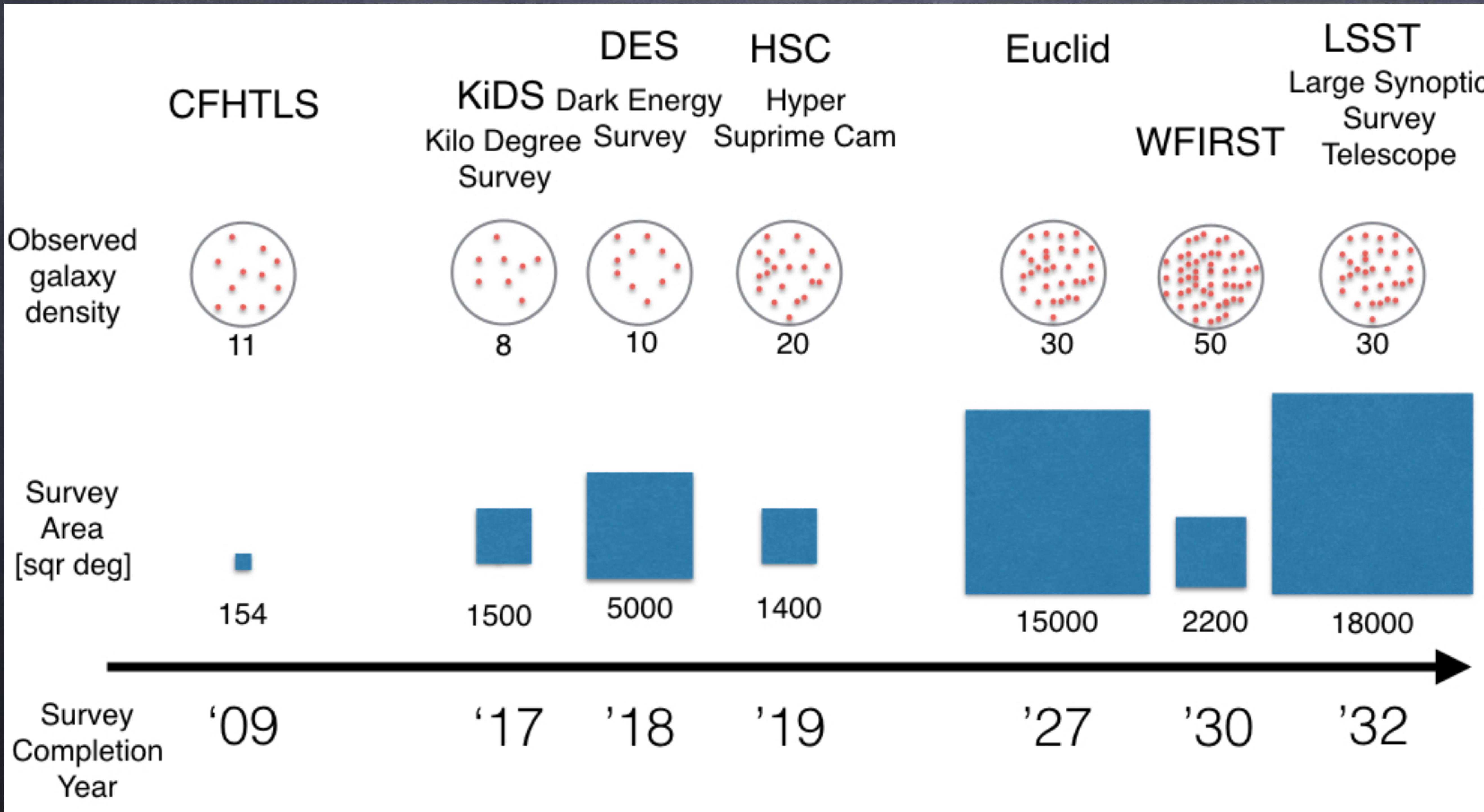
image all galaxies to lim. brightness, in multiple bands

Time domain surveys

repeated observations with suitable cadence

Galaxy Clustering galaxy positions, types, redshifts	**Supernovae** light curve, redshift
Galaxy Clusters cluster centers, redshifts, member galaxies	**Weak Lensing** galaxy positions, shapes, types, redshifts

Photometric Dark Energy Surveys



Dark Energy Survey

Two multiband imaging surveys:

- 300 million galaxies over 1/8 sky
- 4000 supernovae (time-domain)

New 570 Megapixel Dark Energy Camera on the Blanco 4-meter

- 5 bands (g,r,iz,Y), 10 tilings each

Stage III Survey using 4 complementary techniques:

I. Galaxy Clusters
II. Weak Gravitational Lensing
III. Galaxy Clustering
IV. Supernovae

DECam on the Blanco 4m at NOAO Cerro Tololo InterAmerican Observatory

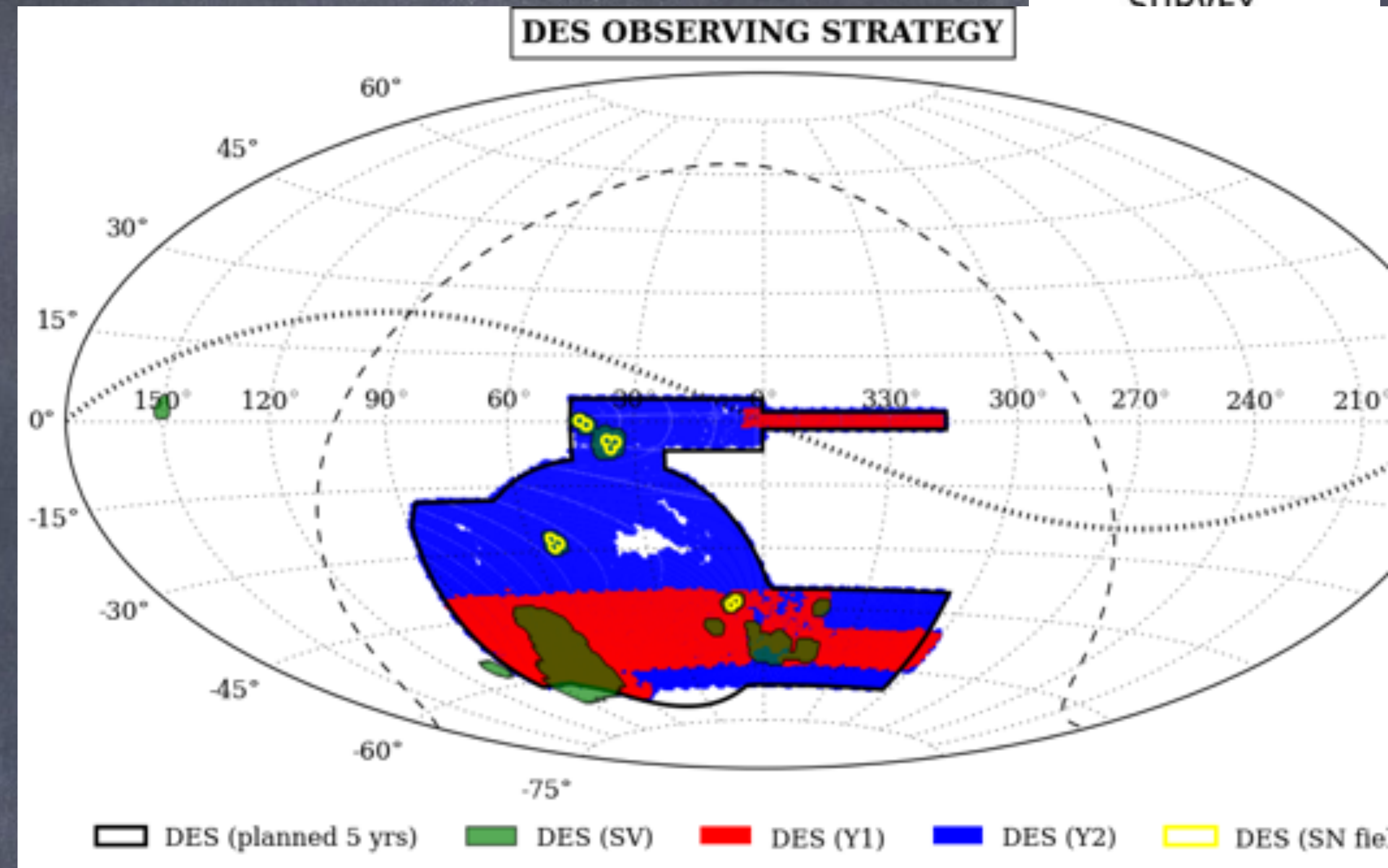
Dark Energy Survey

Survey Strategy

- first light 9/12/12
- until 9/13: Science Verification (SV)
- Survey Observations: 525 nights over 5 Sept-Feb seasons from 8/31/13
- 3 surveys: wide, SN shallow, SN deep

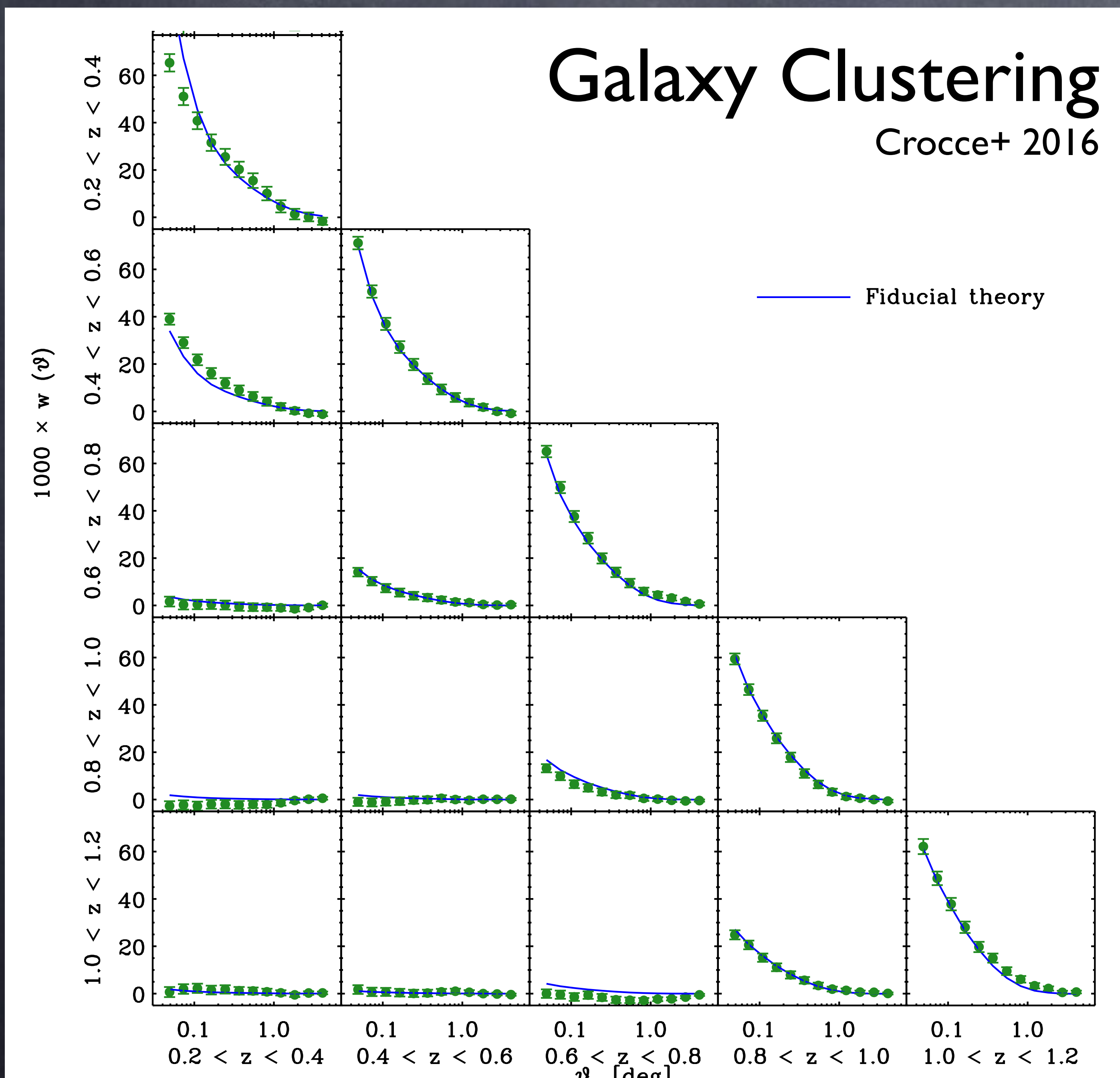
Early Science Results

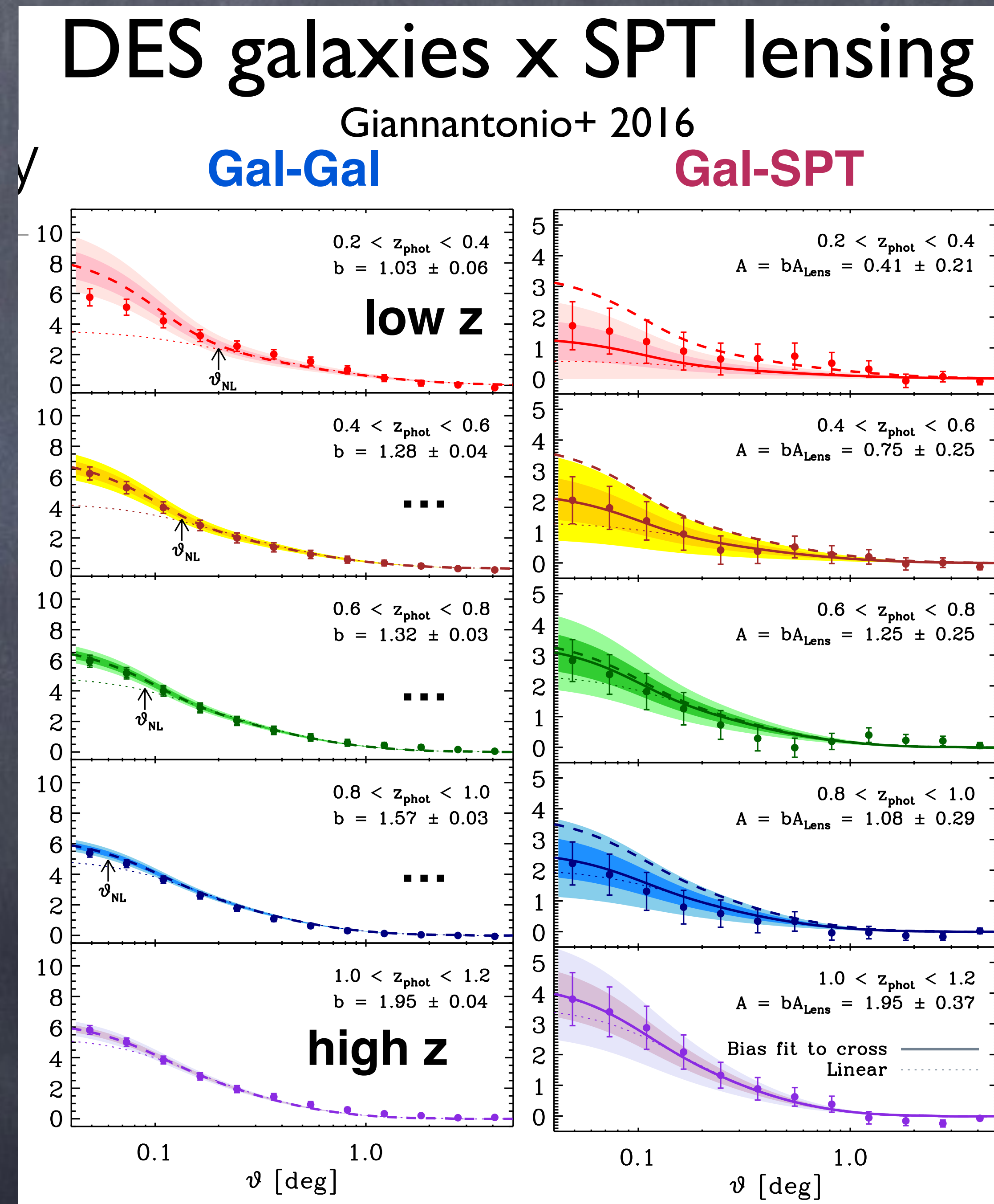
- based on 140 sd deg SV data
- 34 papers so far
  - milky way satellites, galaxy evolution, cosmology, …
  - *I will only show a few cosmology highlights*



	Area (deg²)	Exposure time (s) (per visit for SNe) Specified median PSF FWHM (arcsec) g	r	i	z	Y	Dithering	Cadence
Wide	5000	10x90 -	10x90 0.9"	10x90 0.9"	10x90 0.9"	10x45 -	10 fully interlaced tilings	10 tilings over 5 years
SN Shallow	24	1x175 -	1x150 -	1x200 -	2x200 -	-	Minimal dithers	Seeing >1.1" or 7 days since last observed
SN Deep	6	3x200 -	3x400 -	5x360 -	10x330 -			

DES: Results from Science Verification





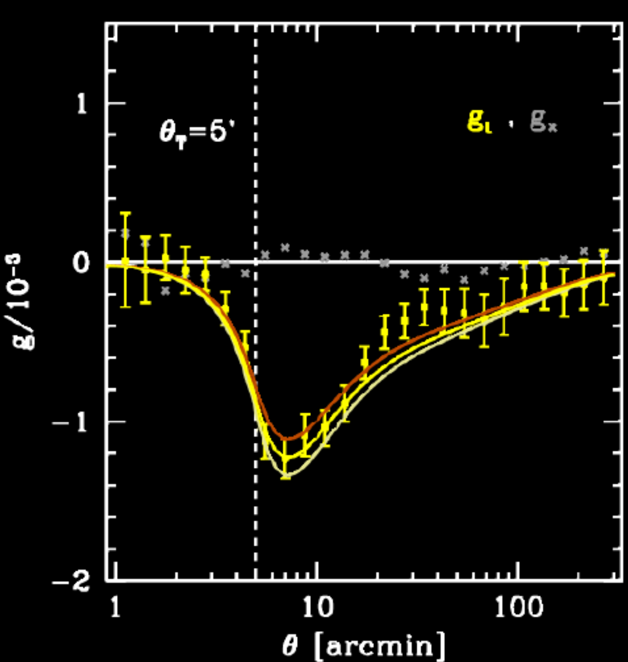
DES: Weak Lensing with Science Verification Data

Weak Lensing by Troughs (Underdense Regions)

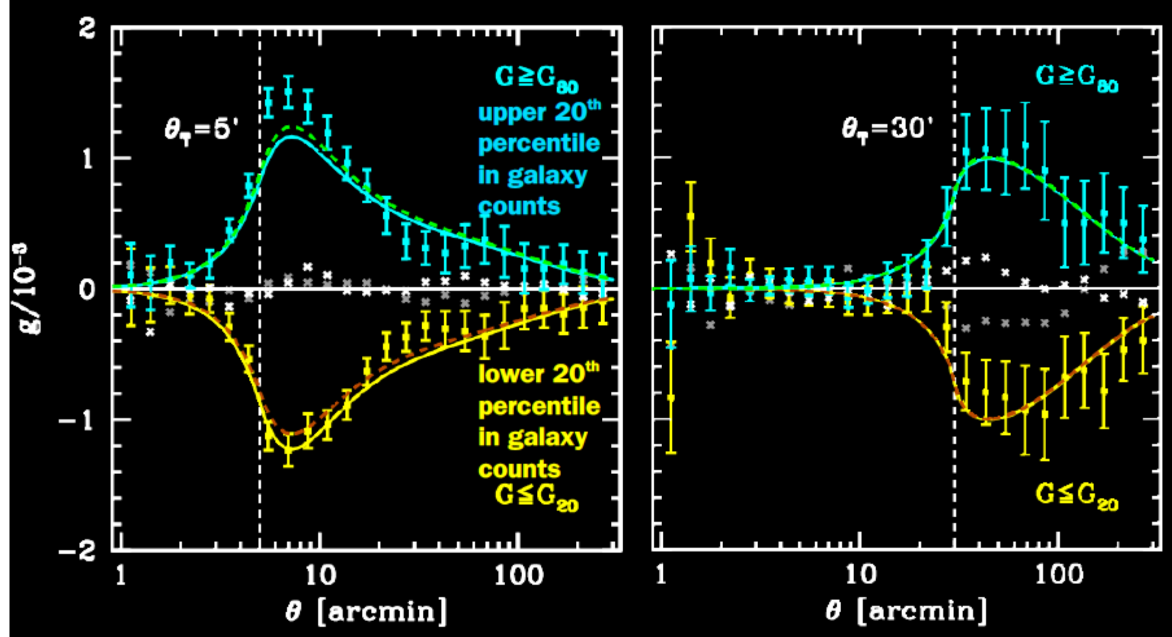
Gruen+ 2016

Measurement

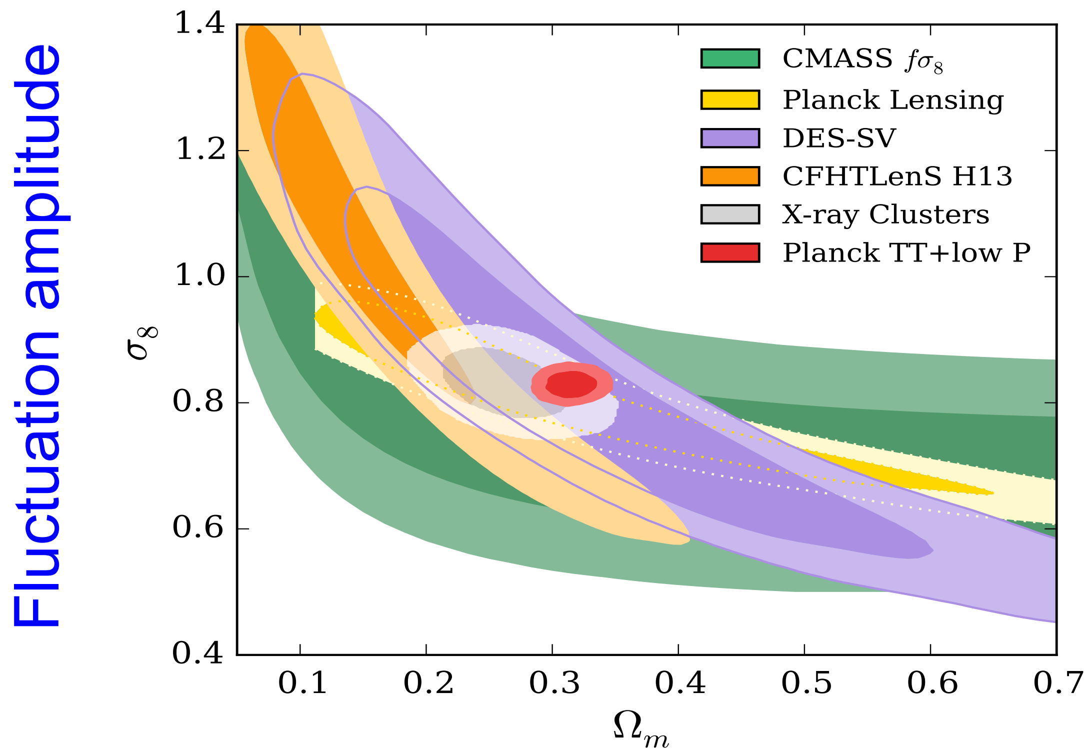
- DES SV: ~150 sq. deg, full DES depth
- tracers: Rykoff/Rozo redMaGiC galaxies, 0.2<z<0.5, L>0.5L*, 1/[1000 Mpc^3]
- troughs = lower 20th percentile
- sources: ~2x10^6 at z>0.6
- significance ~ 15σ



Measurement: under/overdensity

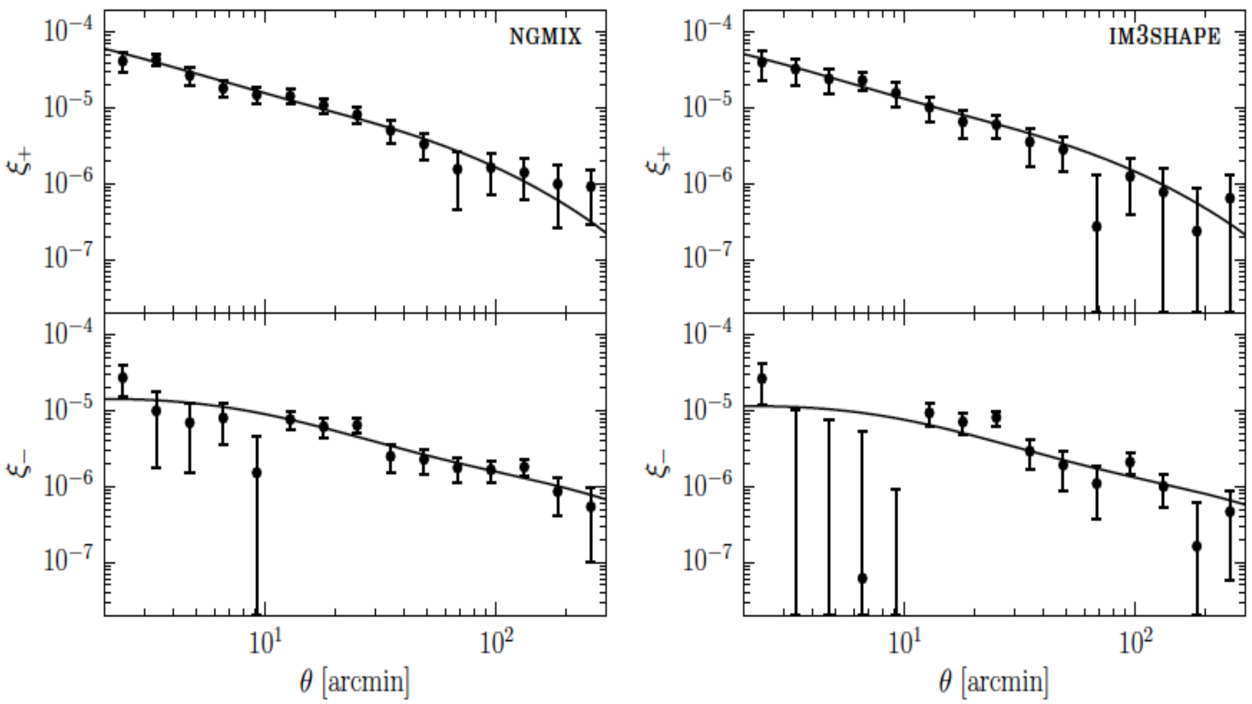


DES: Weak Lensing with Science Verification Data



Cosmological parameters

DES Collaboration+ 2016



2pt xi (+-) from two shear pipelines

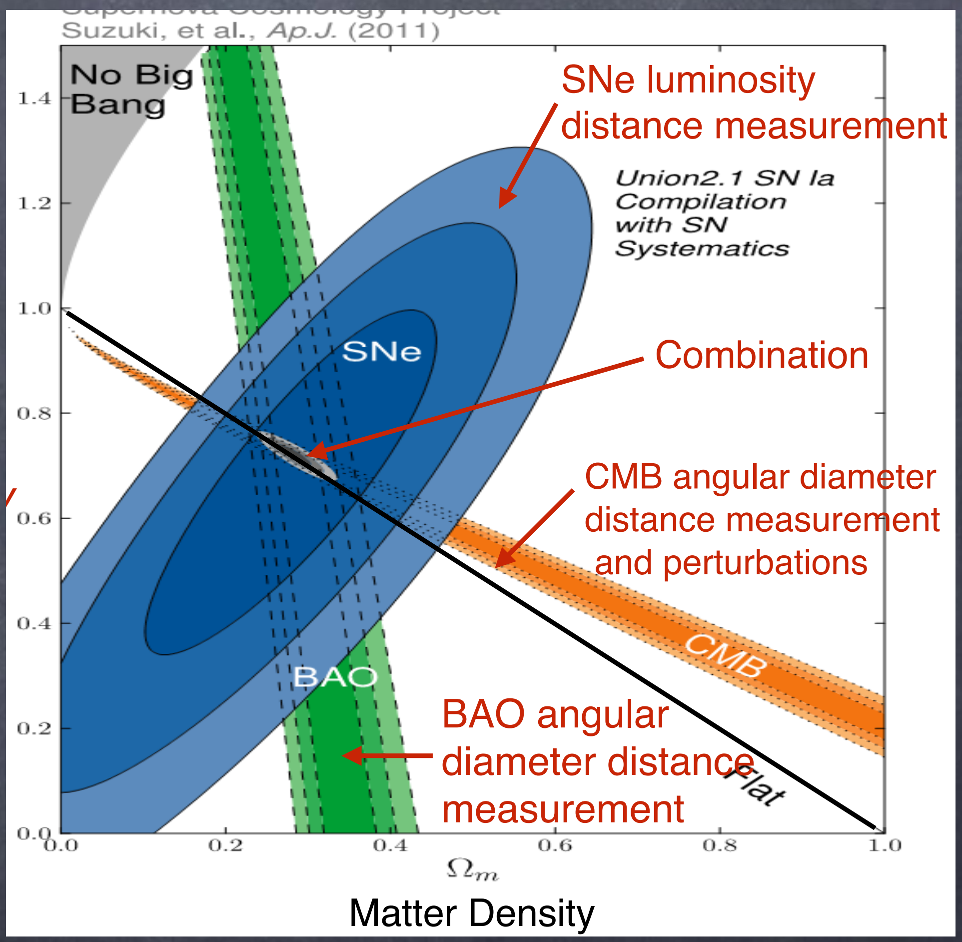
Becker+ 2016

A first step, 5 years of data to come

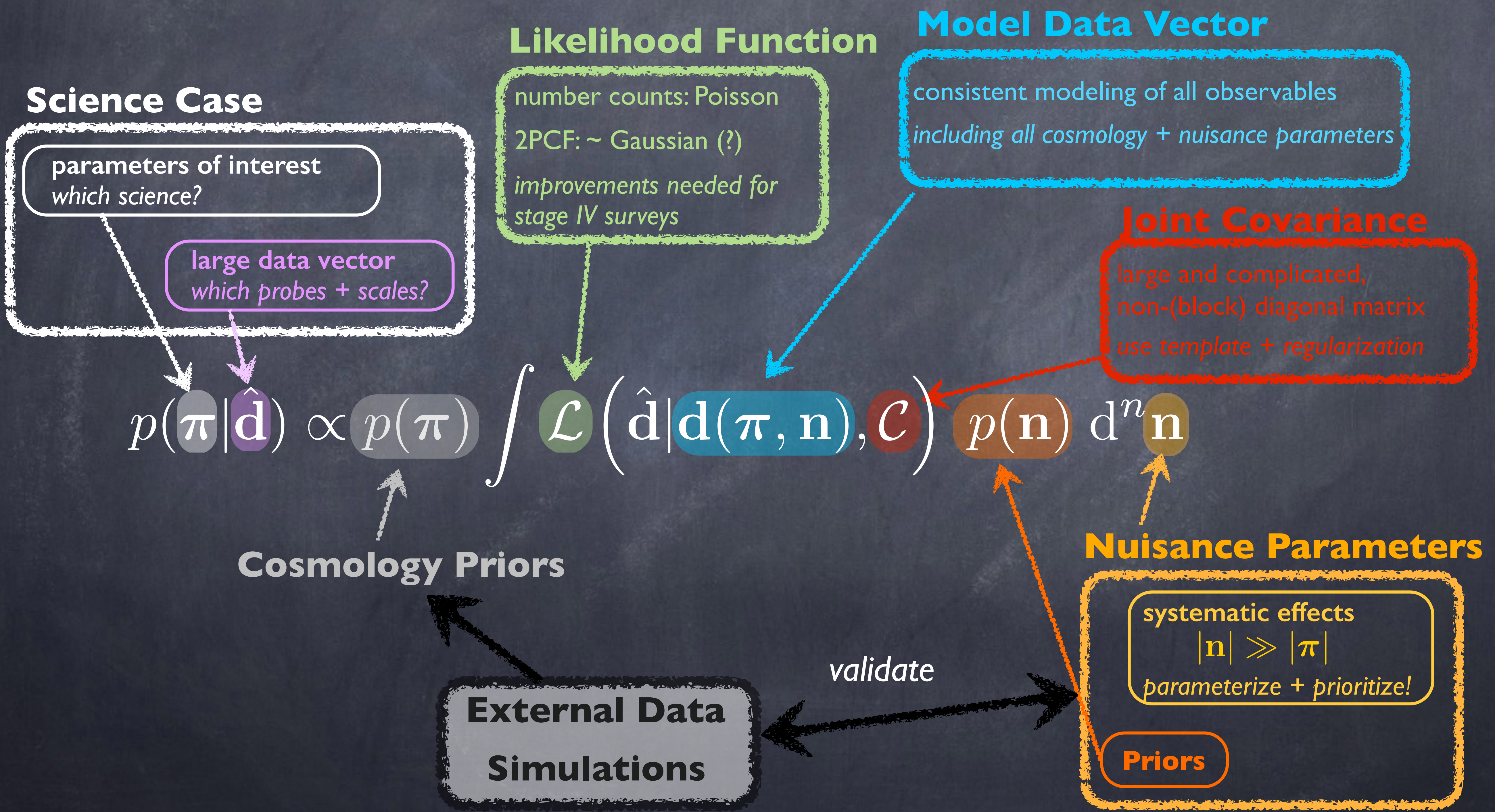
Y1 analyses coming to arXiv soon!

The Power of Combining Probes

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



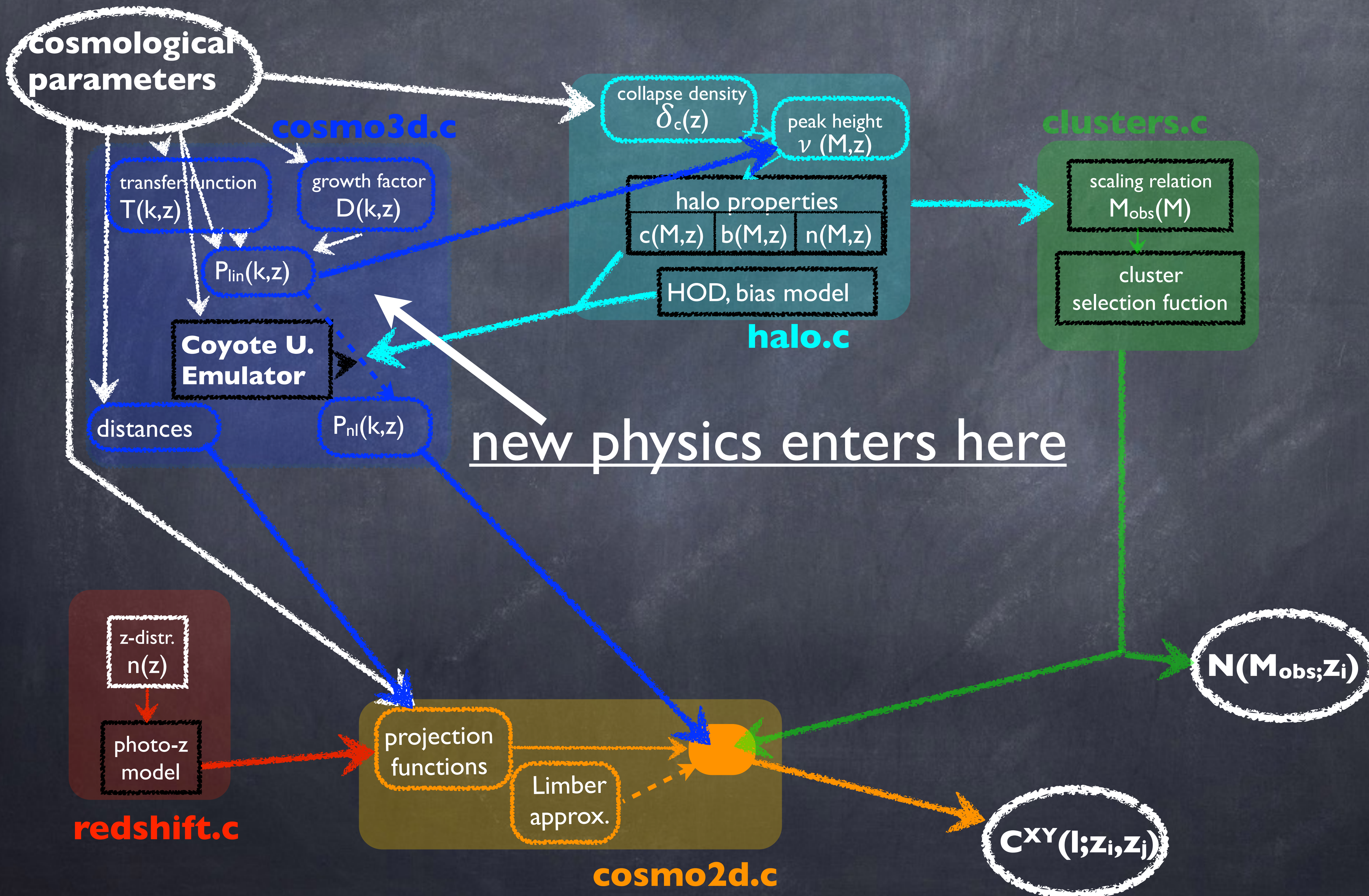
Joint Analysis Ingredients



Introducing CosmoLike

- 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
- Independent from CosmoSIS (Zuntz+15) framework halo model
  - DES multi-probe analyses validated with two independent pipelines
- Improvements by trial and error on DES → lessons for LSST

CosmoLike Data Vector



Combined Probes Forecasts: Covariance

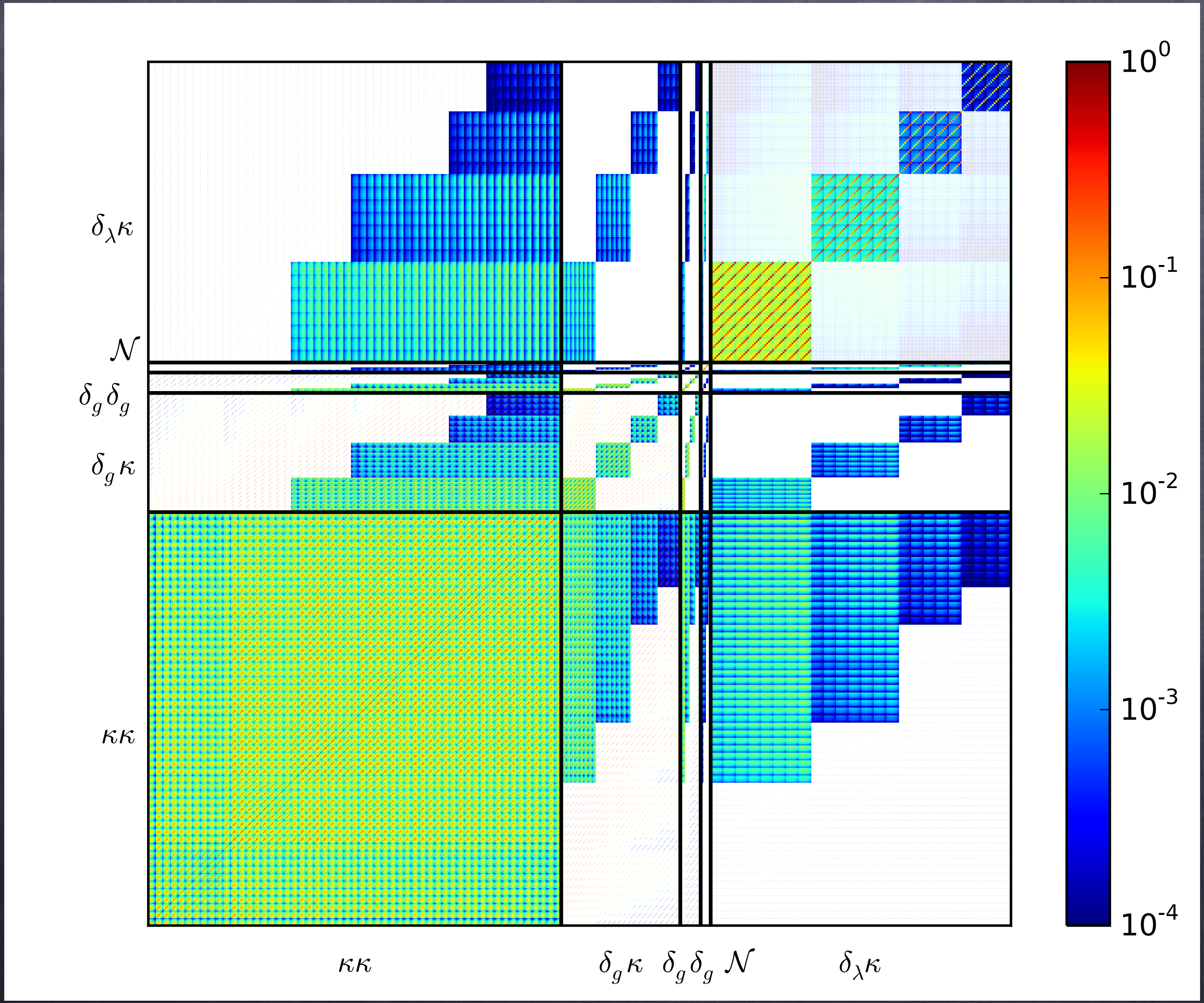
- SN uncorrelated, hooray.
- Analytic covariance for everything else:
  - halo model bispectrum + trispectrum, sample variance
    - Cov (N,N): Poisson + power spectrum
    - Cov (<δδ>, N): bispectrum, power spectrum
    - Cov (<δδ>, <δδ>), etc.: Covariance of 2pt statistics of (projected) density field

	N	<δδ>	<δκ>	<κκ>
N	Cov (N, N)	Cov (<δδ>, N)	Cov (<δκ>, N)	Cov (<κκ>, N)
<δδ>	Cov (<δδ>, N)	Cov (<δδ>, <δδ>)	Cov (<δδ>, <δκ>)	Cov (<δδ>, <κκ>)
<δκ>	Cov (<δκ>, N)	Cov (<δκ>, <δδ>)	Cov (<δκ>, <δκ>)	Cov (<δκ>, <κκ>)
<κκ>	Cov (<κκ>, N)	Cov (<κκ>, <δδ>)	Cov (<κκ>, <δκ>)	Cov (<κκ>, <κκ>)

$$\mathrm{Cov}(P(\mathbf{k}_1), P(\mathbf{k}_2)) \approx \underbrace{\frac{2\delta_D(\mathbf{k}_1+\mathbf{k}_2)}{N_{k_1}} P^2(k_1)}_{\text{Gaussian cosmic variance}} + \underbrace{\frac{\bar{T}(k_1,k_2)}{V_s}}_{\text{non}-\text{Gaussian c.v.}} + \underbrace{\frac{\partial P(k_1)}{\partial \rho_L}\frac{\partial P(k_2)}{\partial \rho_L}\sigma^2(\rho_L)}_{\text{sample variance}}$$

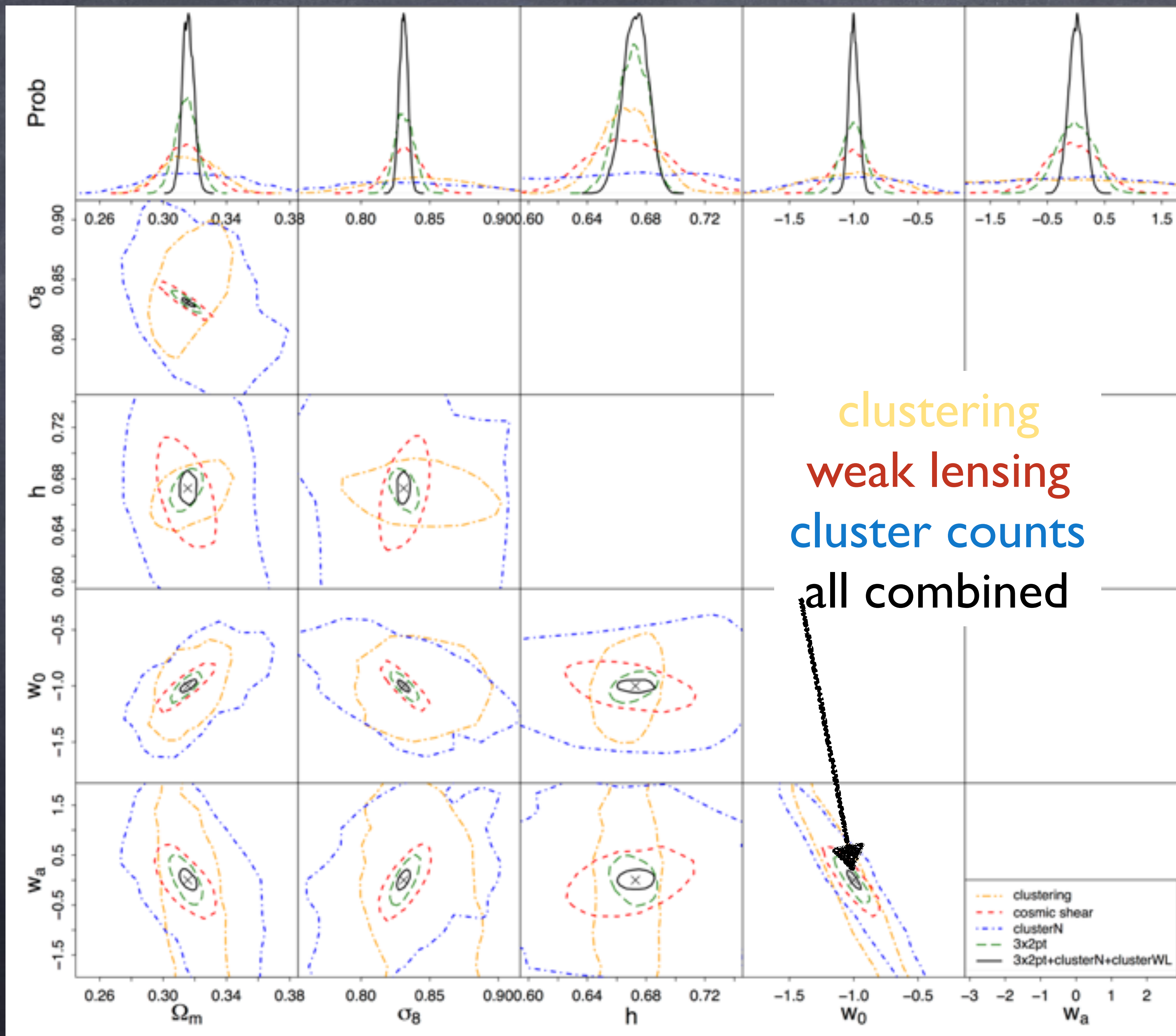
- LSST forecasts: > 7 million elements...

Combined Probes Forecasts: Covariance



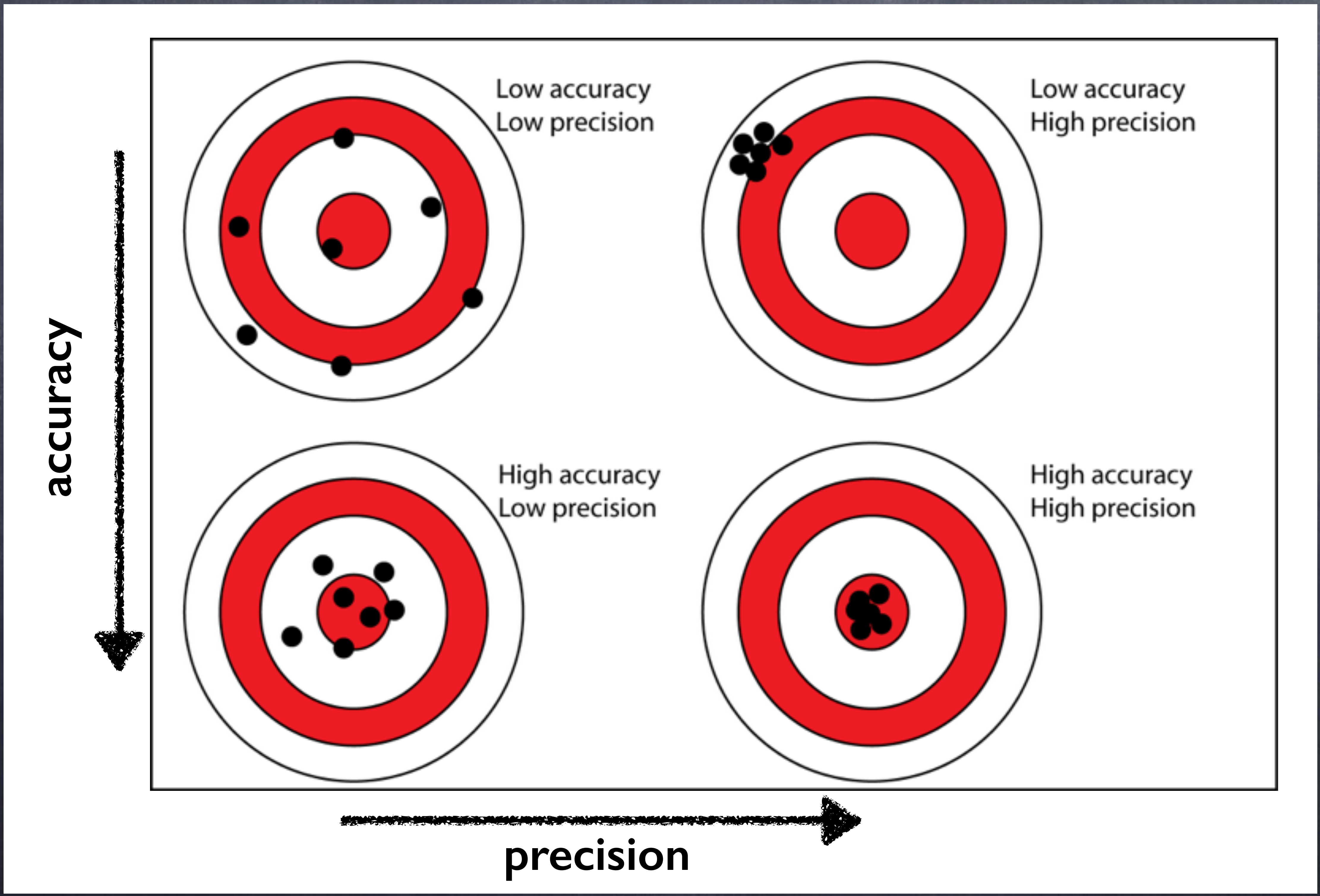
details: EK16b

The Power of Combining Probes



EK & Eifler'16

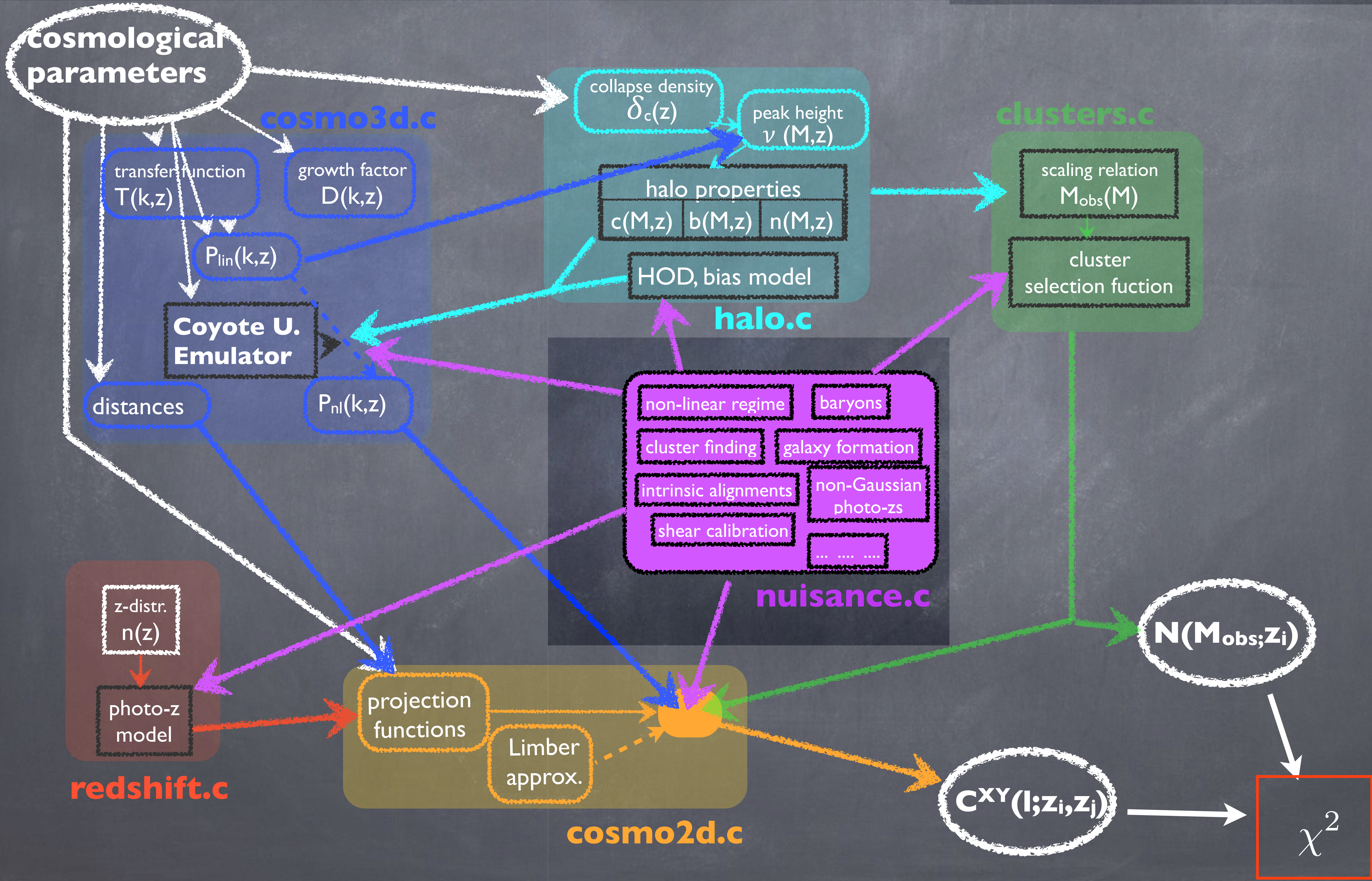
'Precision' Cosmology



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)

CosmoLike Data Vector



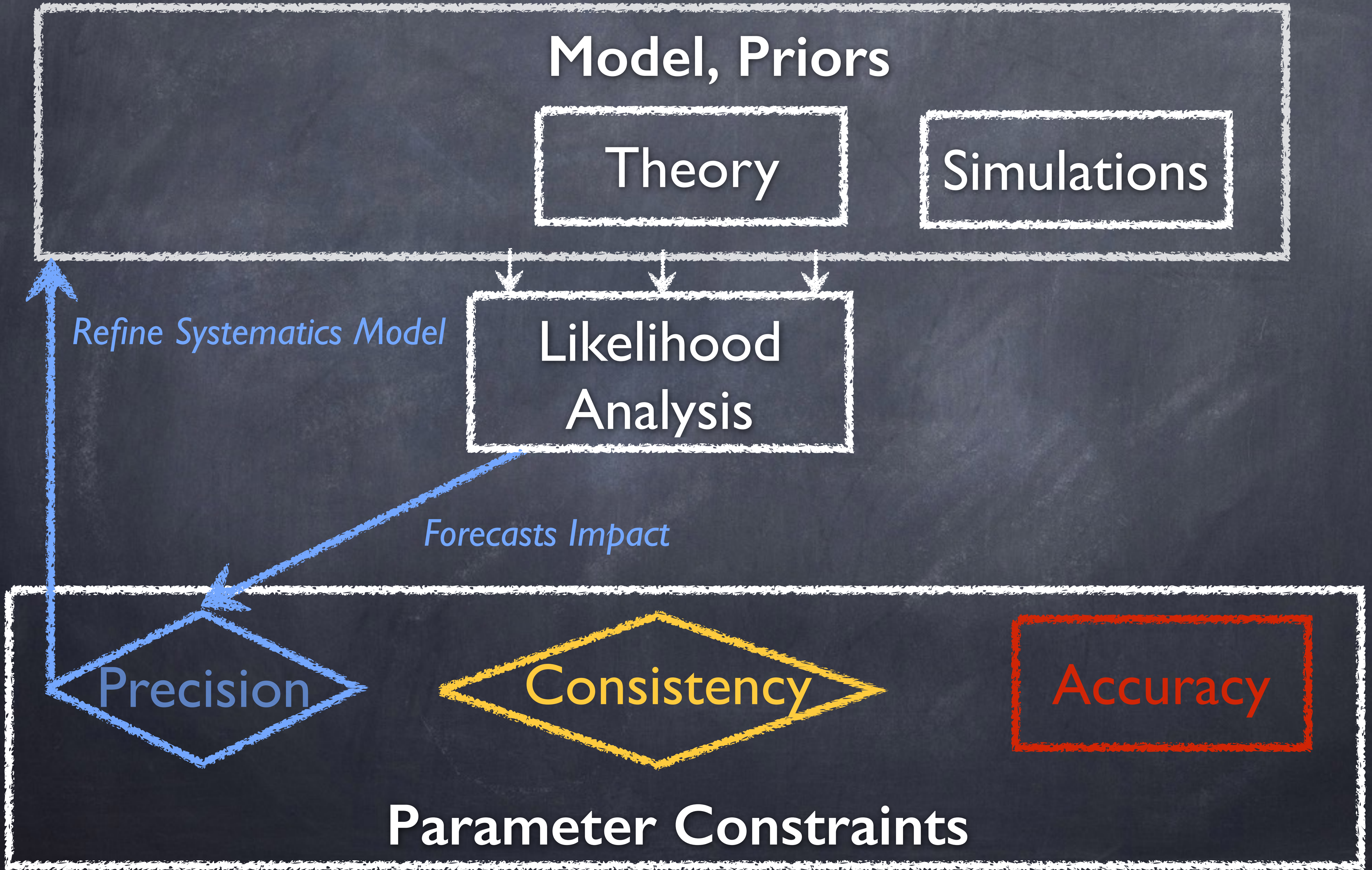
Work Plan for *Known* Systematics

- What's the dominant known systematic?

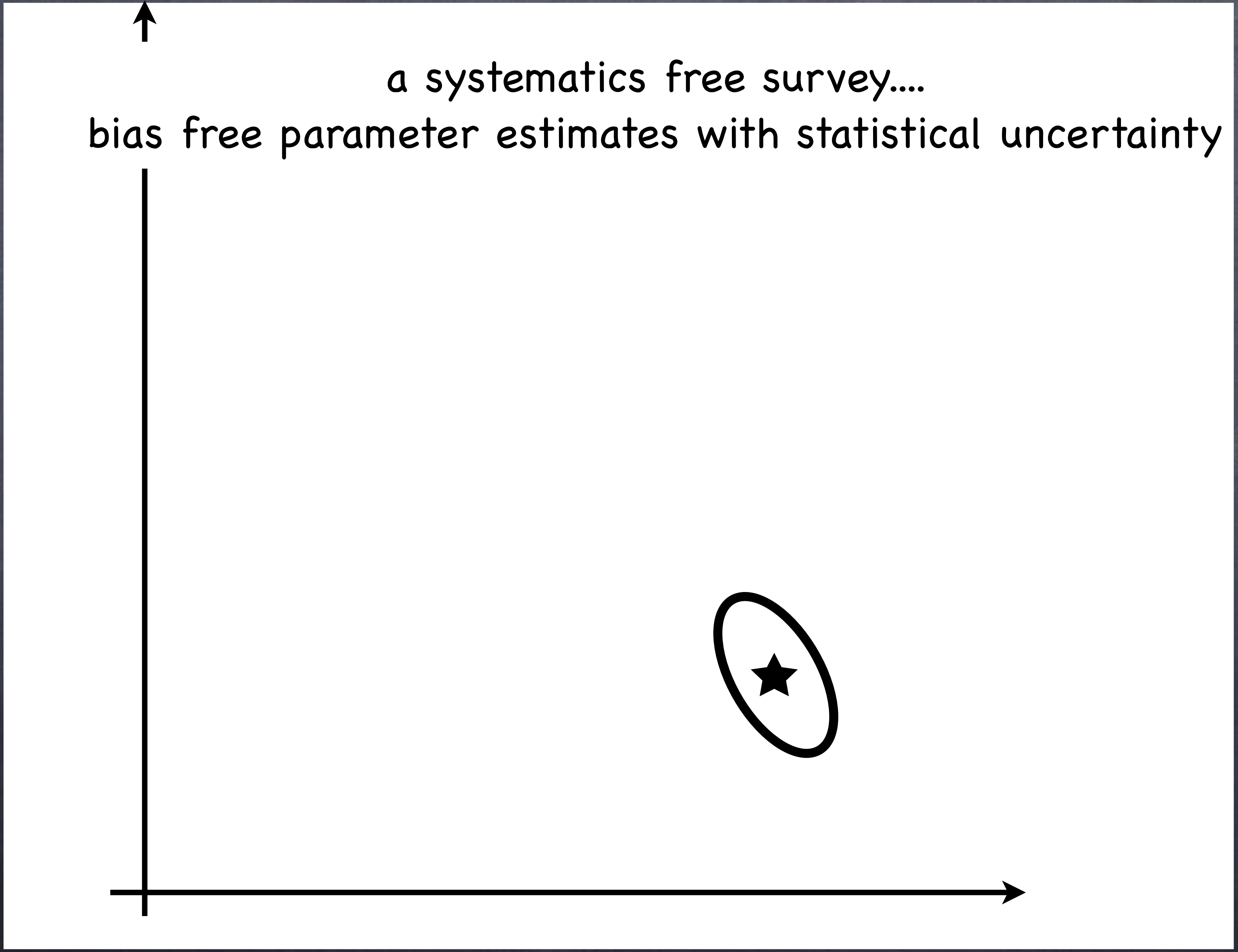
  No one-fits-all answer, need to be more specific!

- 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

Joint Analysis Work Plan: Step 1



The Trouble with Systematics



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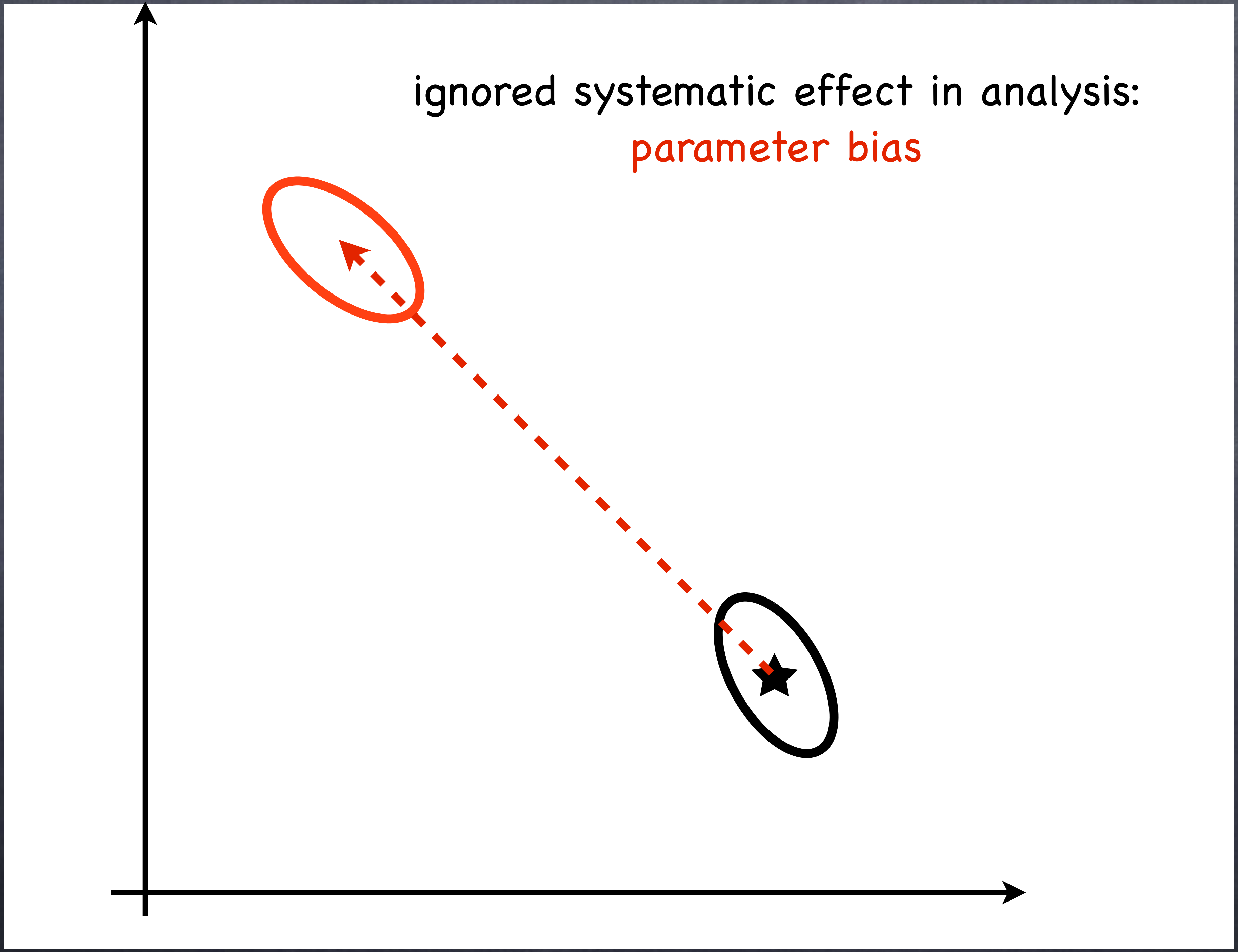
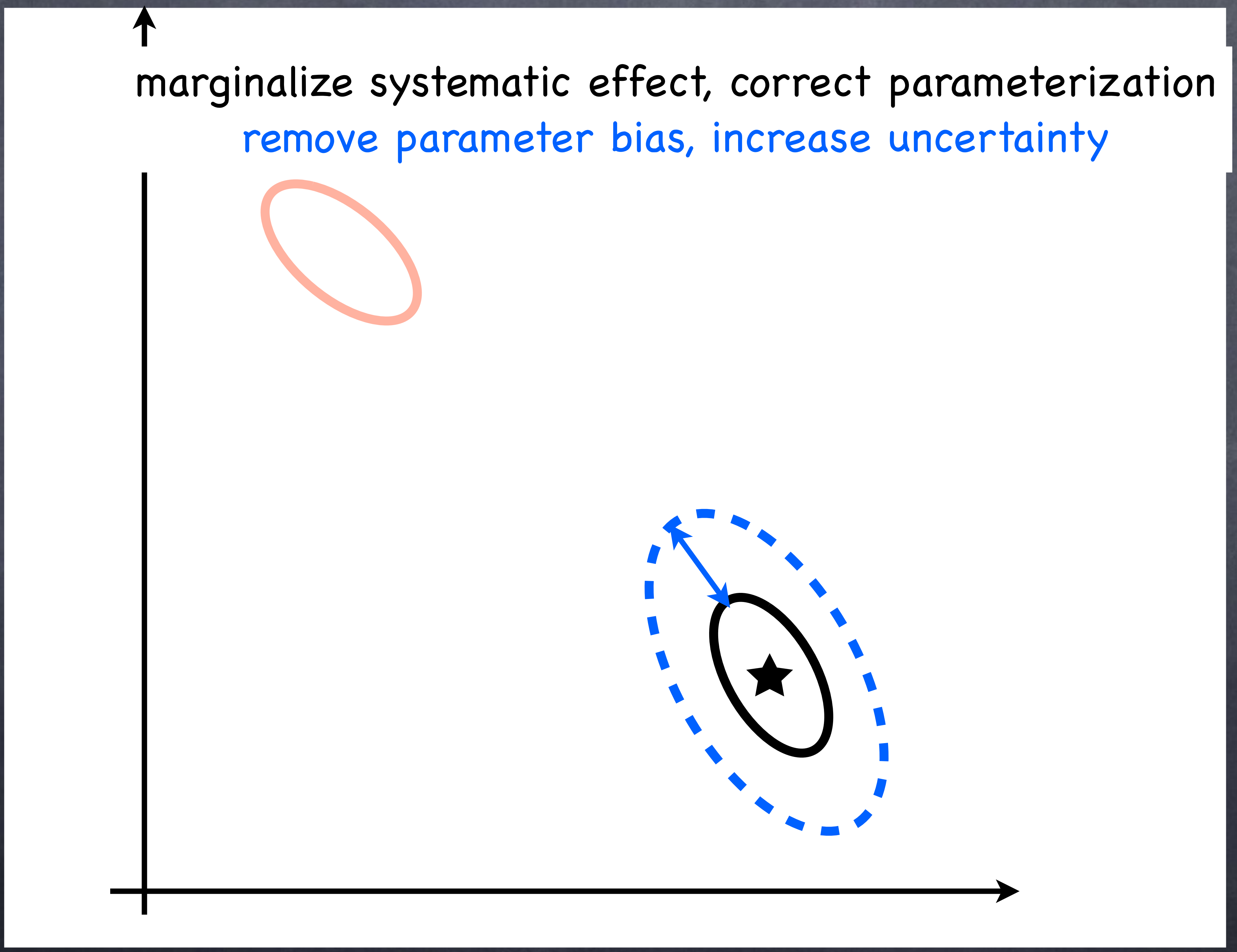
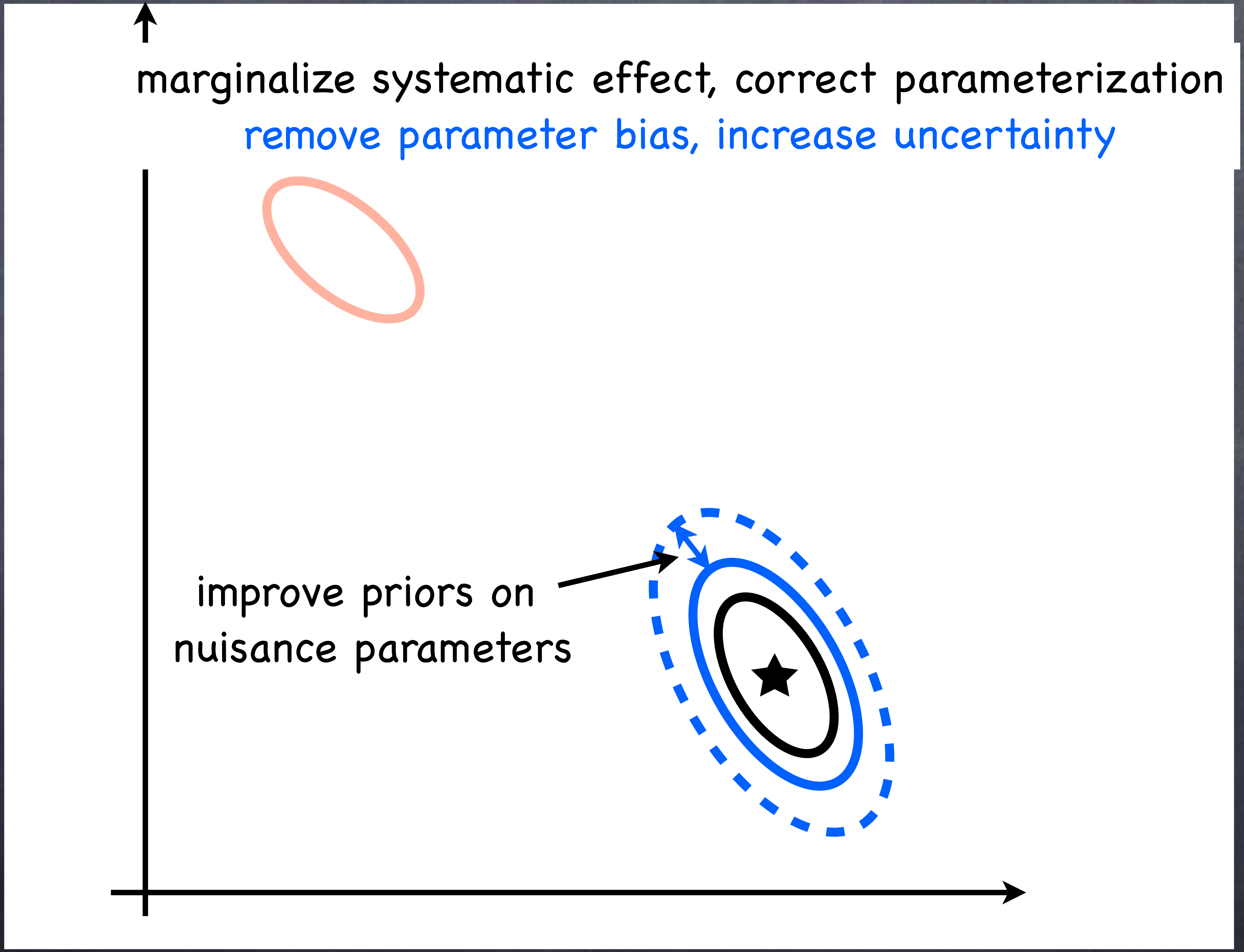


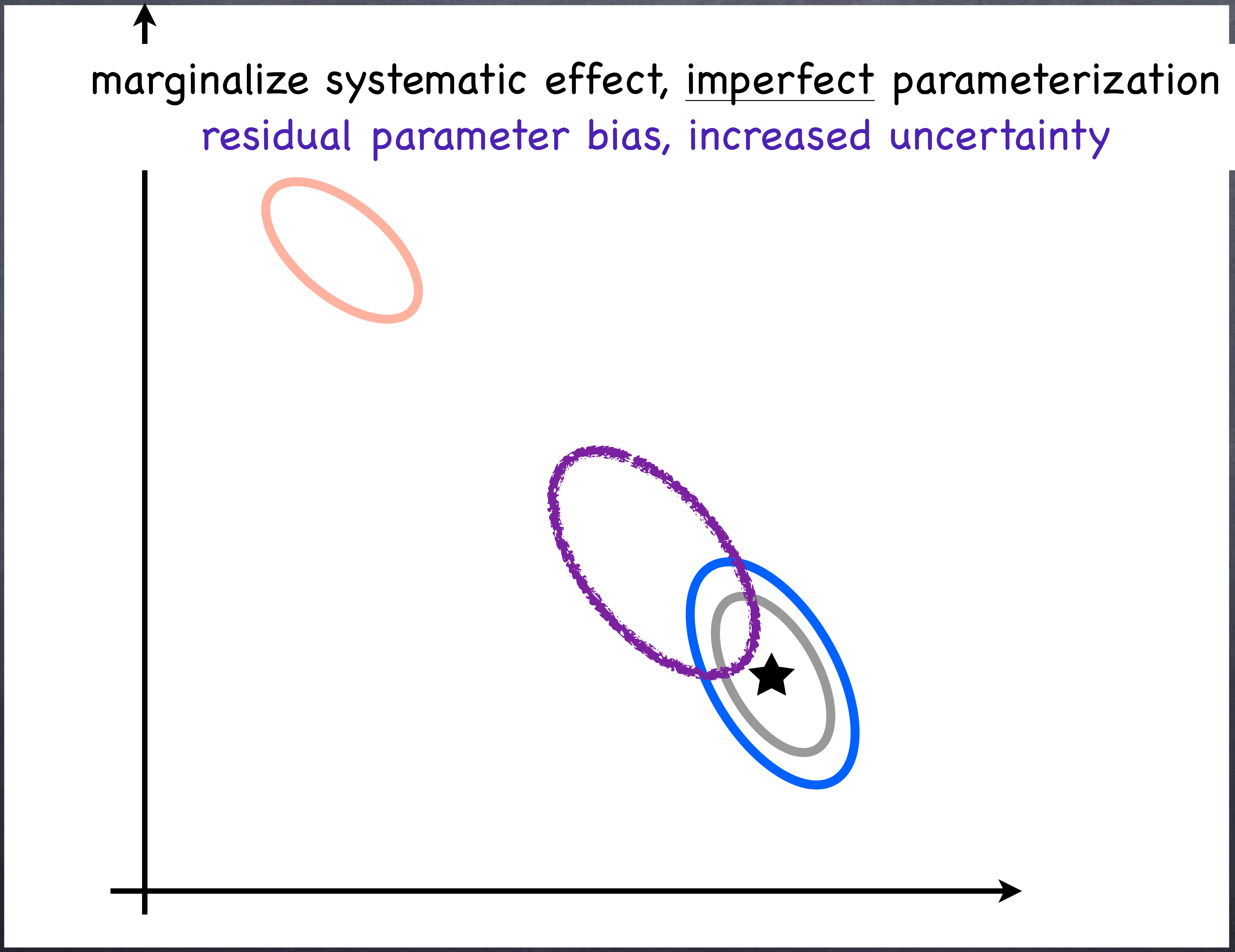
The Trouble with Systematics



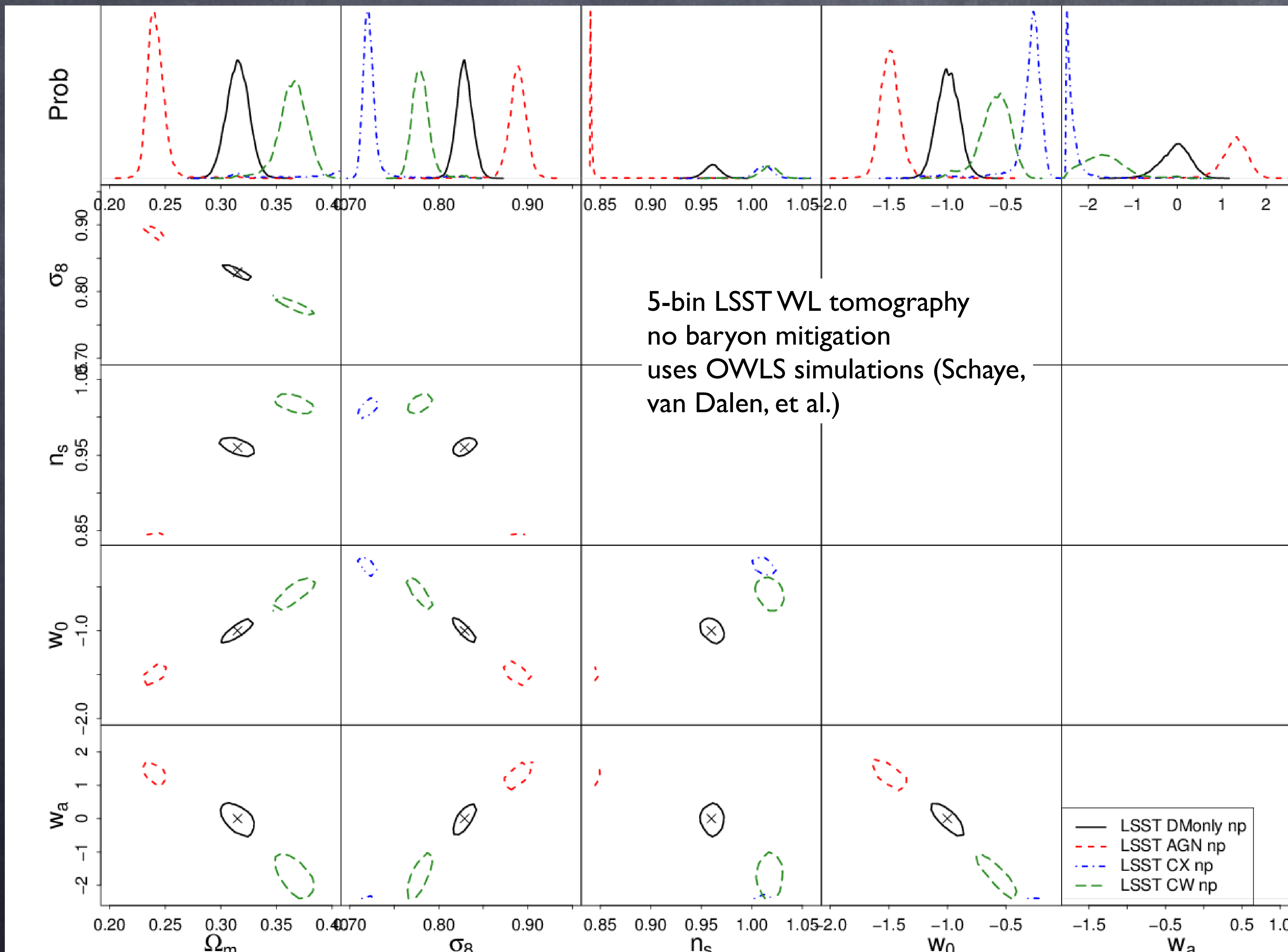
The Trouble with Systematics



The Trouble with Systematics

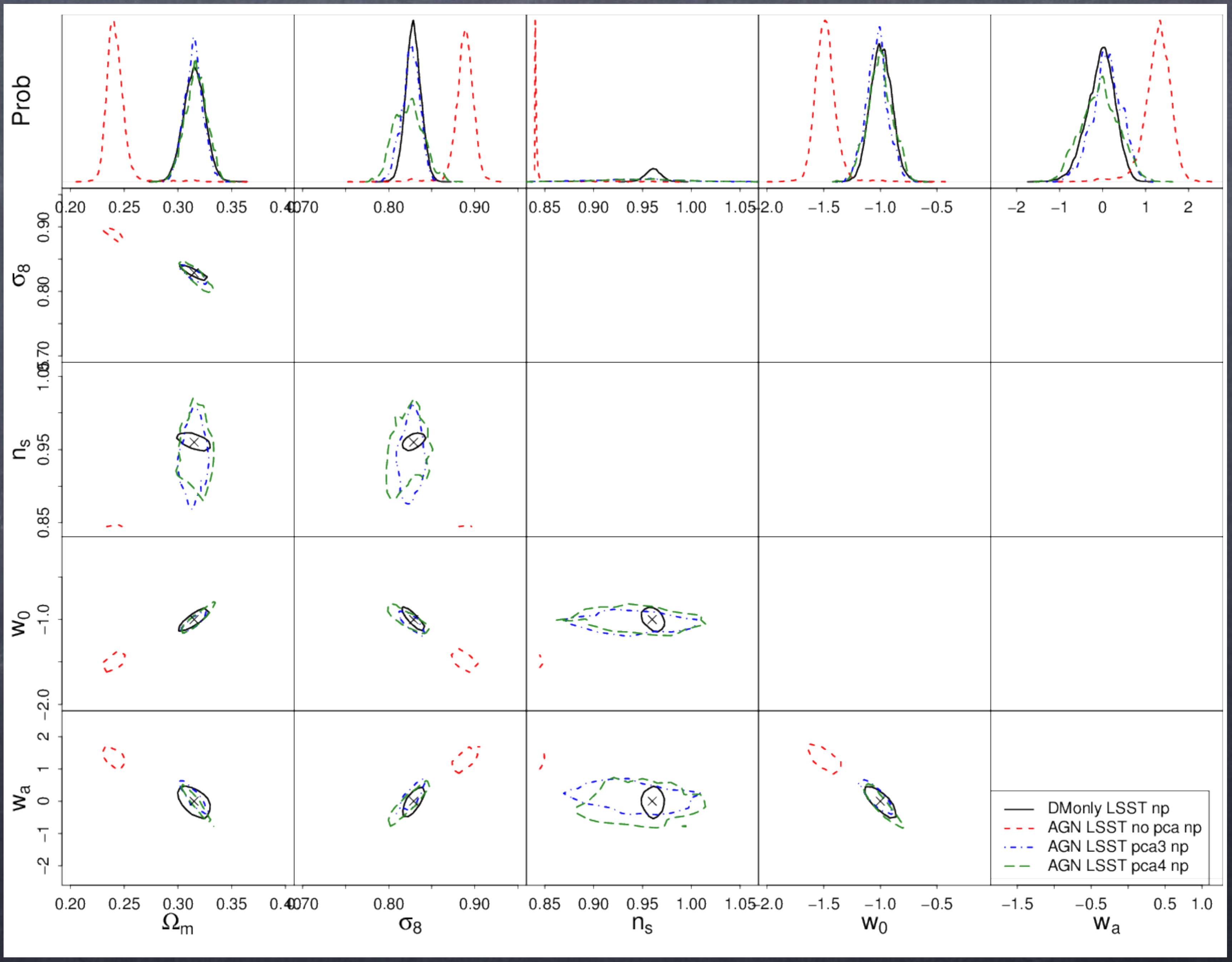


Impact of Baryons on LSST WL



Mitigation of Baryons in WL

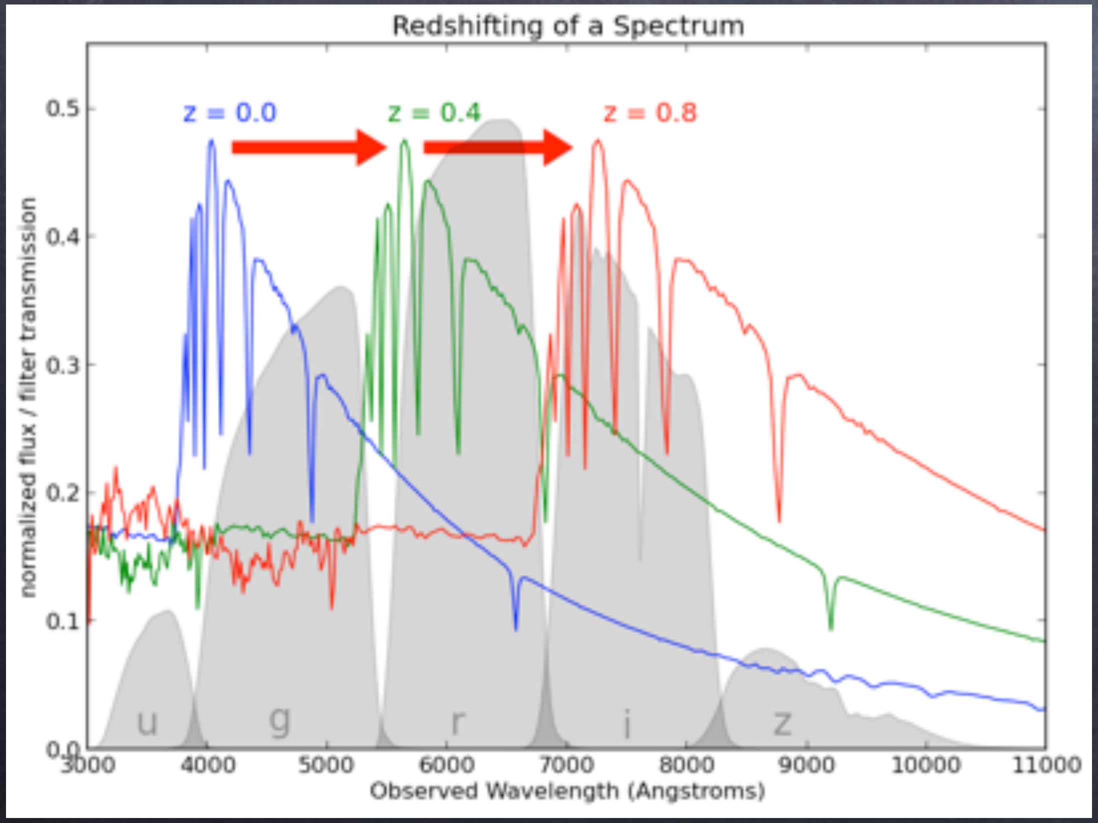
- PCA based mitigation strategy (Eifler, EK, et al. 15)
- Reduce FoM degradation by improving priors on range of baryonic scenarios
  - measure stacked halo profiles (e.g. SZ, X-ray)
  - update parameter range for hydro sims
  - feed these into updated marginalization scheme

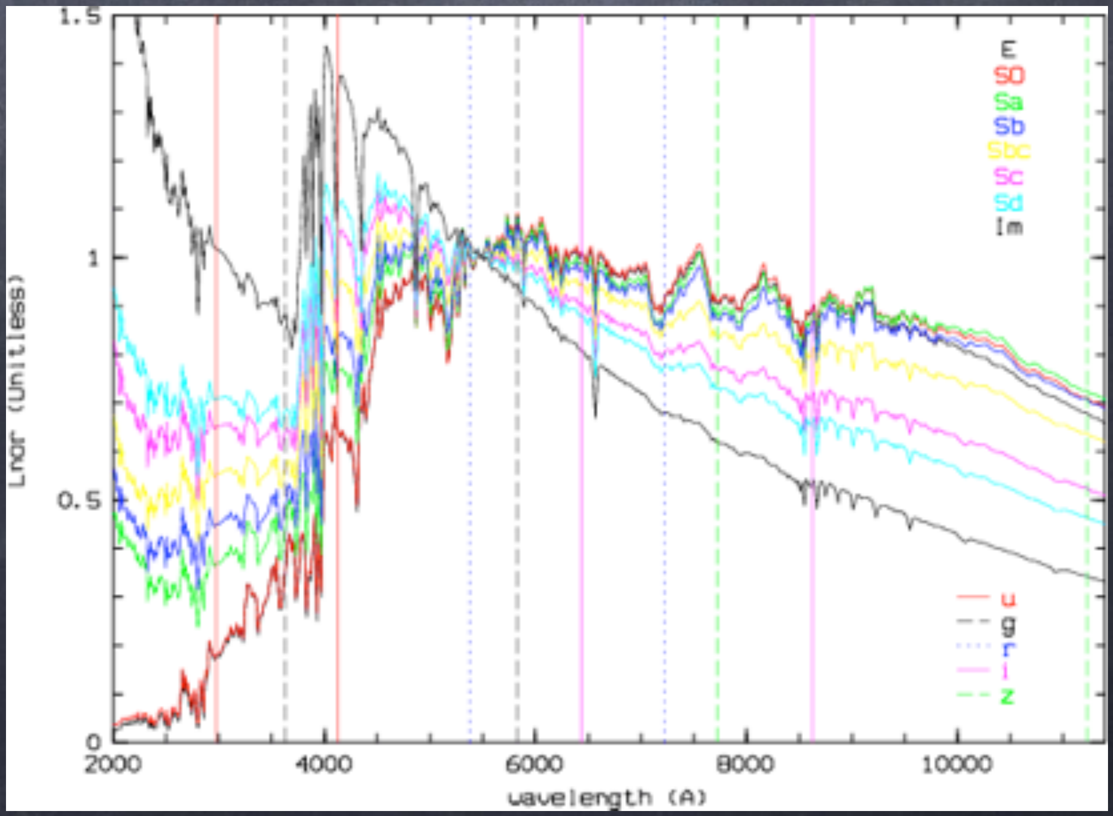


Physics from Galaxies

- galaxy evolution: not as clean as the CMB
  - galaxies come in all shape, sizes, colors
  - what do we need to understand for cosmology?
- estimate redshift/distance: measure galaxy colors (flux in different filters)

  ambiguous for some galaxy types + imperfect photometry





Physics from Galaxies

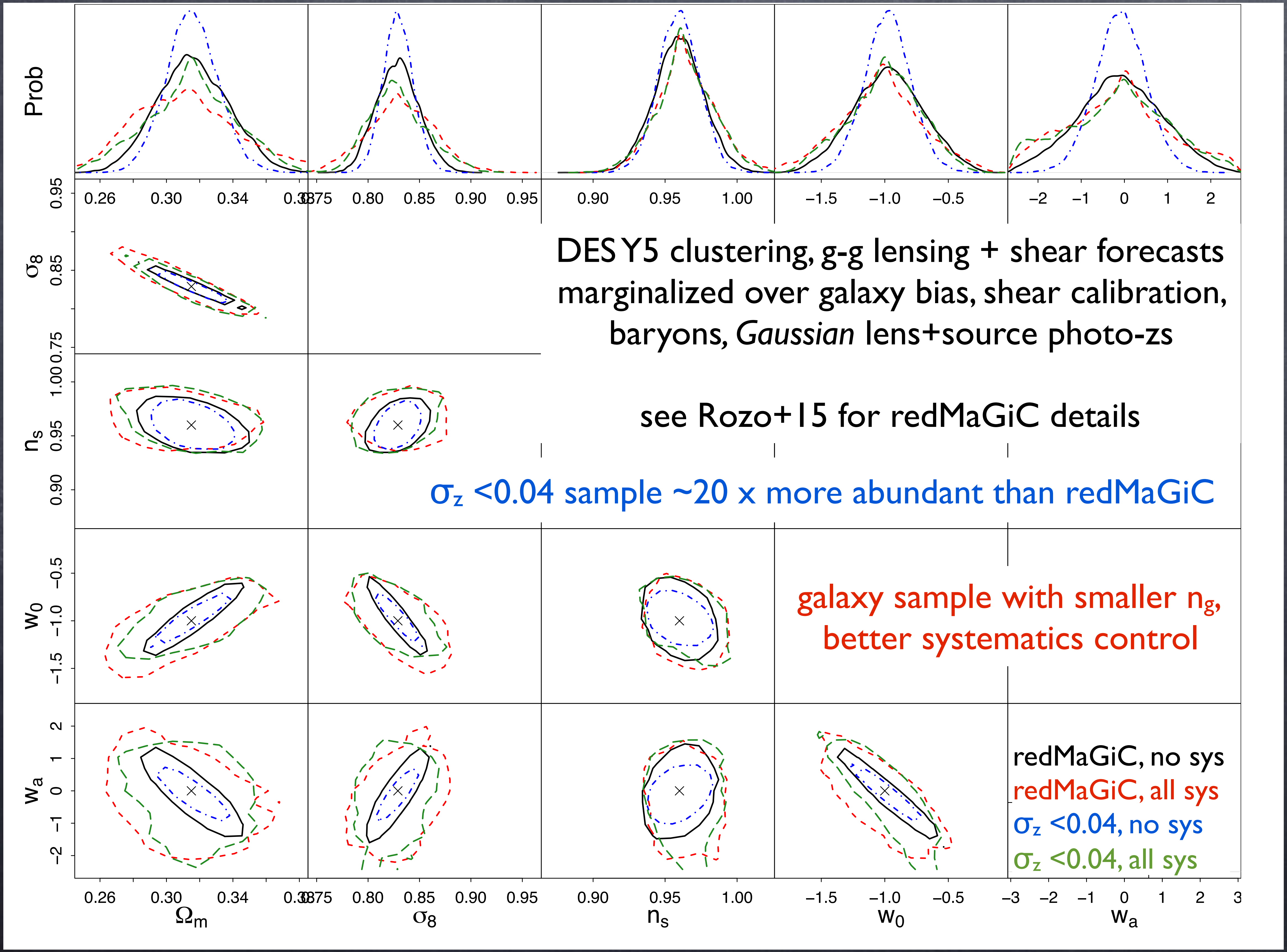
- galaxy evolution: not as clean as the CMB
  - what do we need to understand for cosmology?
- estimate redshift/distance: measure galaxy colors (flux in different filters)
- relation between a galaxy population and matter field, galaxy bias
  - on large scales, linear relation between galaxies and matter density
  - perturbative methods in quasi-linear regime large, active area of research
    - comes at the cost of extra parameters
  - on small scales, several galaxies within massive halos
  - all of these models function of redshift + galaxy type

Physics from Galaxies

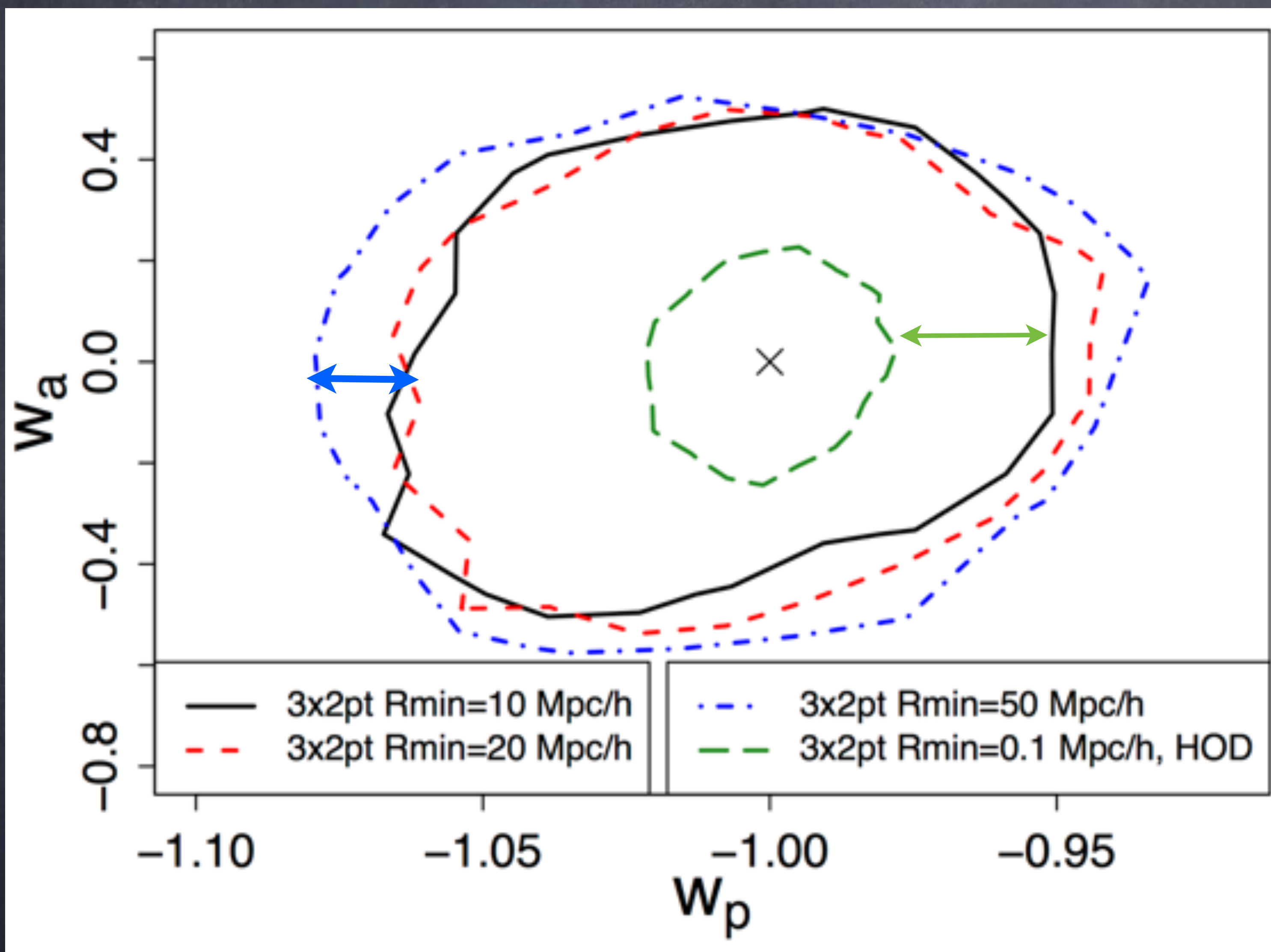
- galaxy evolution: not as clean as the CMB
  - what do we need to understand for cosmology?
- estimate redshift/distance: measure galaxy colors (flux in different filters)
- relation between a galaxy population and matter field, galaxy bias
  - on large scales, linear relation between galaxies and matter density
  - perturbative methods in quasi-linear regime active area of research (e.g.,
    - comes at the cost of extra parameters
  - on small scales, several galaxies within massive halos

- <u>accuracy better for some types of galaxies than for others</u>
  - 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?

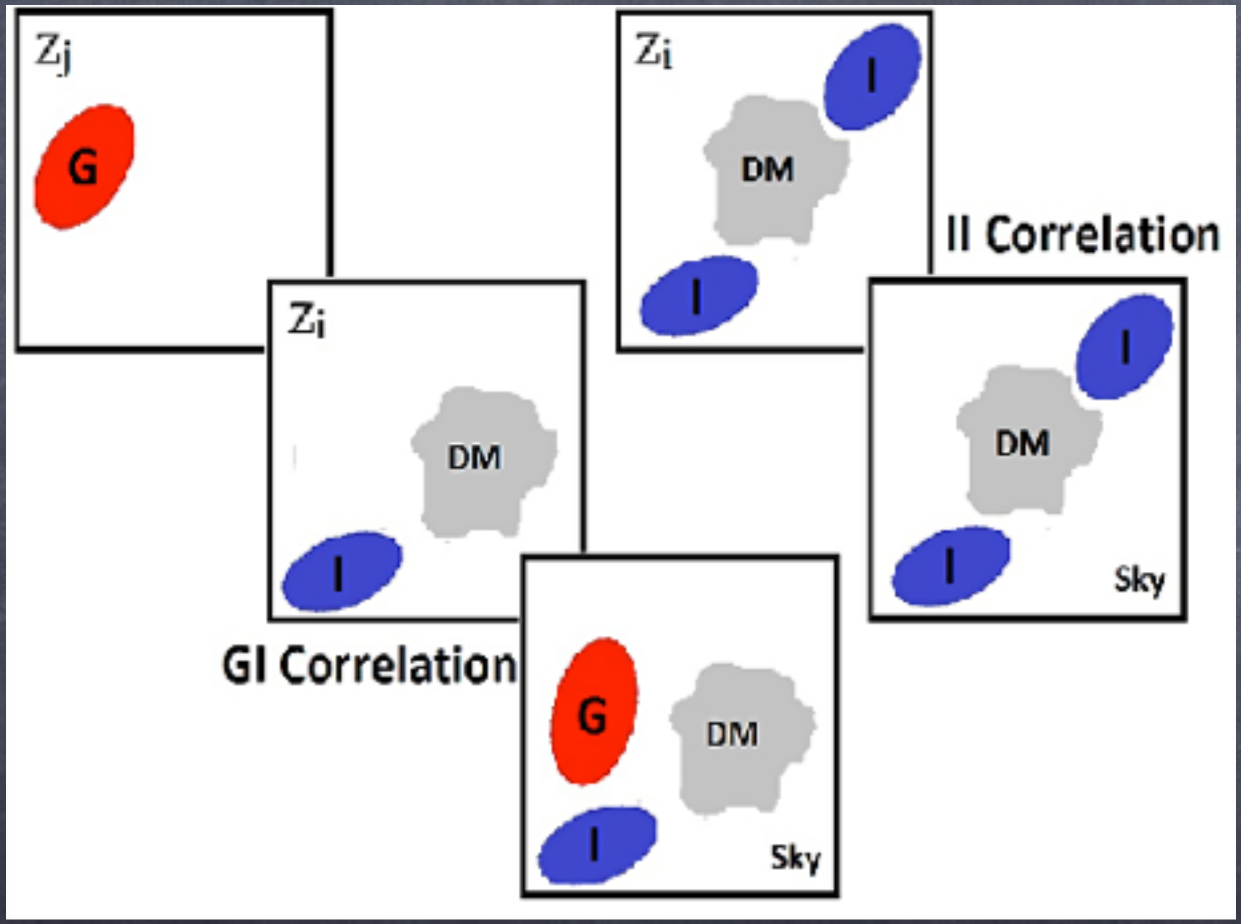


LSST, WL + clustering
WL to l < 5000
clustering: vary cut-off scales
solve perturbative bias to k ~ 0.6 h/Mpc - with well-constrained parameters
understand non-linear regime

details EK16b

Intrinsic Alignments

- not all (source) galaxies randomly oriented - e.g. tidal alignments



- potentially scary systematic

Intrinsic Alignments Models

- Alignment mechanisms: halo shape vs. angular momentum
  - collapse in tidal field causes halo shape alignments - *linear IA*
    - leading description for (large-scale) alignment of early type galaxies
    - well-detected, e.g. Mandelbaum+06, Hirata+07, Joachimi+11, Singh+14
  - tidal torquing may cause halo spin-up, angular momentum correlations - *quadratic IA*
    - may cause shape alignments of late type galaxies,
    - no clear detection so far
- This analysis: linear IA only (follow-up on quadratic IA in progress)
- Many different flavors/variation for linear IA models

$$P_{\mathrm{GI}}(k,a) = A(L,a,\Omega_{\mathrm{M}},?)f_{\mathrm{GI}}\left(P_\delta(k,a),P_{\mathrm{lin}}(k,a),?\right)$$

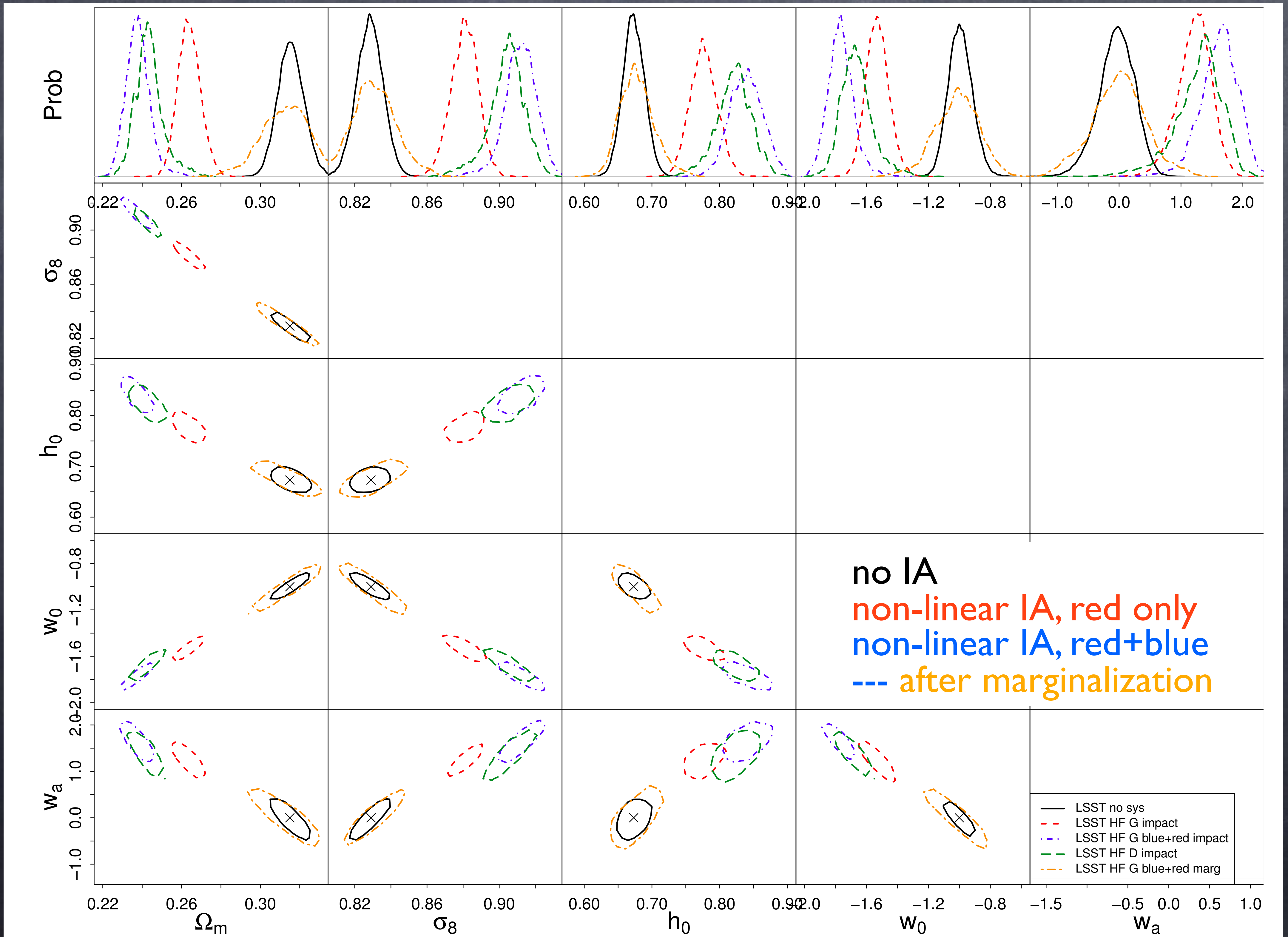
$$P_{\mathrm{II}}(k,a) = A^2(L,a,\Omega_{\mathrm{M}},?)f_{\mathrm{II}}\left(P_\delta(k,a),P_{\mathrm{lin}}(k,a),?\right)$$

Linear IA Models

$$P_{\rm GI}(k,a) = A(L,a,\Omega_{\rm M},?) f_{\rm GI}\left(P_\delta(k,a), P_{\rm lin}(k,a),?\right)$$
$$P_{\rm II}(k,a) = A^2(L,a,\Omega_{\rm M},?) f_{\rm II}\left(P_\delta(k,a), P_{\rm lin}(k,a),?\right)$$

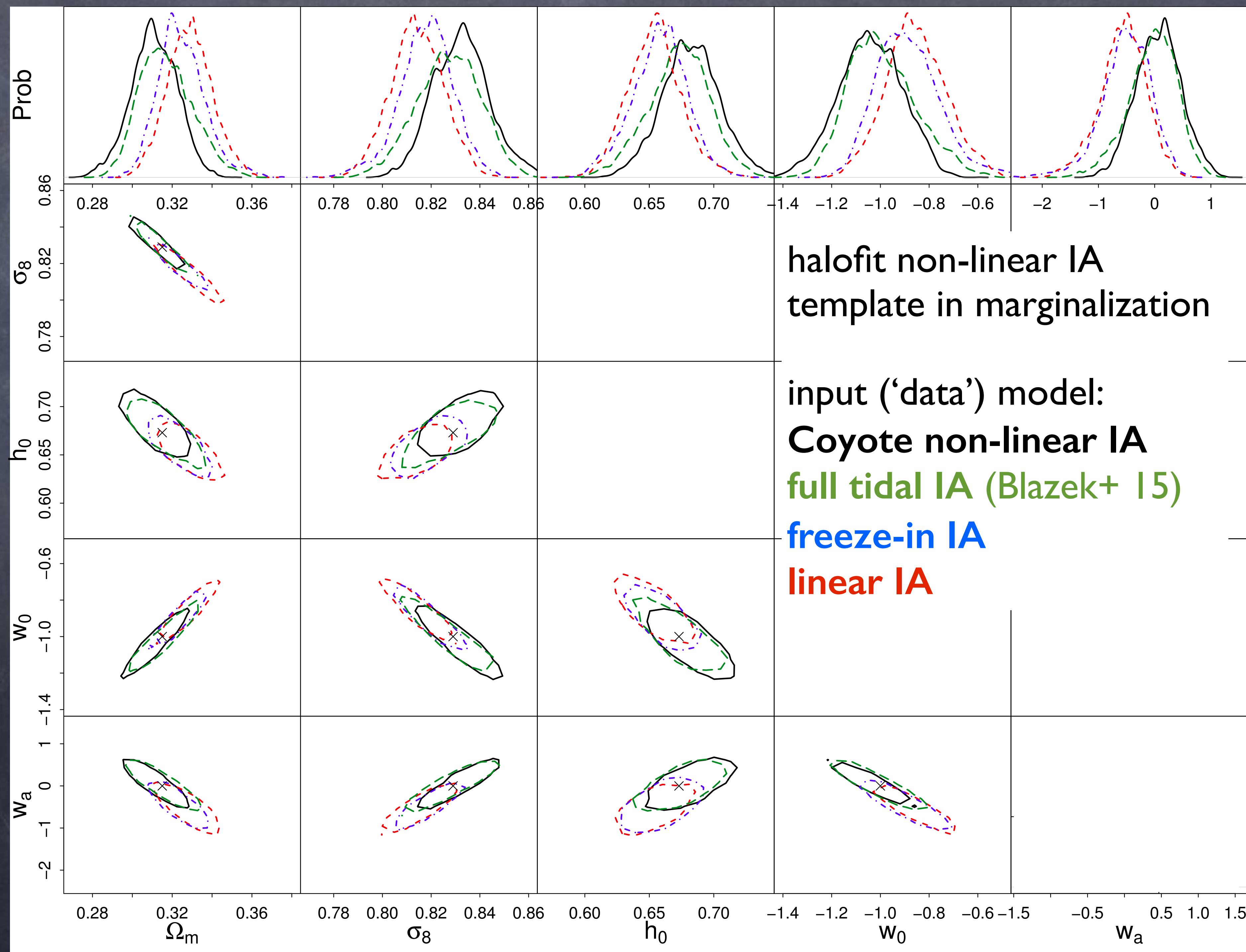
- model shapes (f_{GI}, f_{II}) - an incomplete list
  - linear (Catelan+01, Hirata+04): $f = P_{lin}$
  - freeze-in (Kirk+12): $f_{II} = P_{lin}(k,z_f)$, f_{GI}= sqrt($P_{lin}(k,z_f)$ P_δ (k,z))
  - effective field theory of LSS (Blazek+15)
  - non-linear (Bridle&King 07): $f = P_\delta$
- what's A?
  - old forecasts (e.g. Kirk+12): constant - based on SDSS L4 (Hirata+07)
  - Joachimi et al. 11 fit dependence on <L>, z (see also Singh+14)
    $$A = A_0 \left(\frac{L}{L_0}\right)^\beta \left(\frac{1+z}{1+z_0}\right)^\eta$$
  - if only red galaxies aligned $A \rightarrow A \times f_{\rm red}$
  - what's $\langle A \rangle_L$, f_{red} for deep surveys like LSST/WFIRST?
    - so far, extrapolate LF from shallower surveys (GAMA, DEEP2)

Impact of Linear Alignments LSST WL



IA Mitigation: Amplitude marginalization, power spectrum shape uncertainties

- Marginalized over amplitude normalization + redshift scaling (A_0, β, η, $\eta_{high\text{-}z}$), 6 LF parameters
- Biases from uncertainties in IA template
- Next steps: reduce FoM degradation by including priors on range of parameters + allowed templates
  - joint analysis with g-g lensing + clustering



EK, Eifler, Blazek 16a

IA Summary

forecasts for tidal alignment contamination of LSST WL

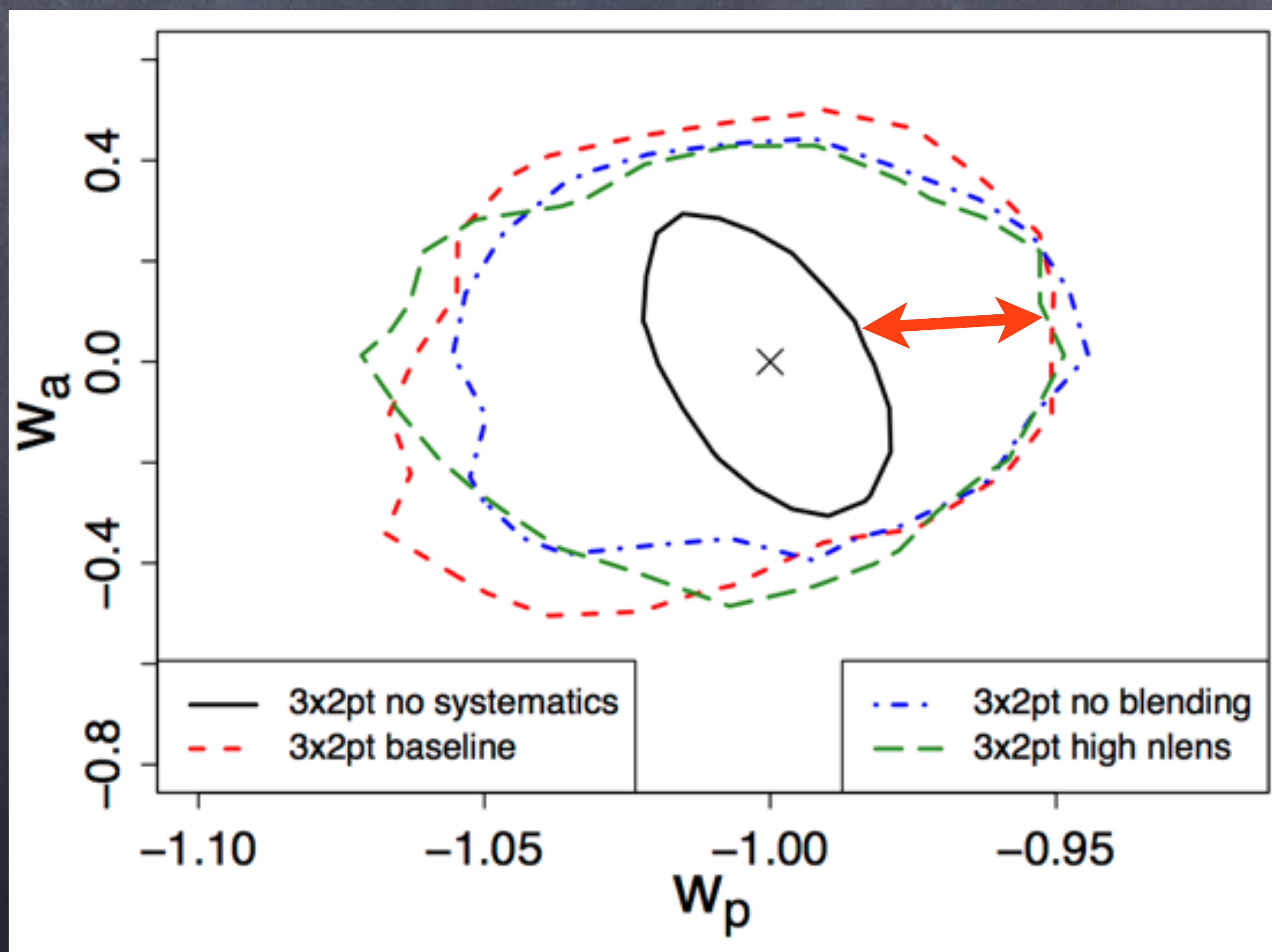
- without mitigation, significant (~ 2σ) bias - less severe than earlier forecasts
  - lower impact due to non-Gaussian covariance, luminosity weighted amplitude
- basic mitigation successfully reduces bias
  - <1σ for worst-case scenario (linear vs non-linear)
- 10-parameter marginalization causes some loss in precision
  - can be improved by joint probes analysis (self-calibration with g-g lensing, clustering), or improved priors from external observation
- so far, removal of red galaxies best mitigation strategy...

key uncertainties

- luminosity function for LSST galaxies (all, red)
- extrapolation of IA scaling to low-L, high-z
- *quadratic alignments*

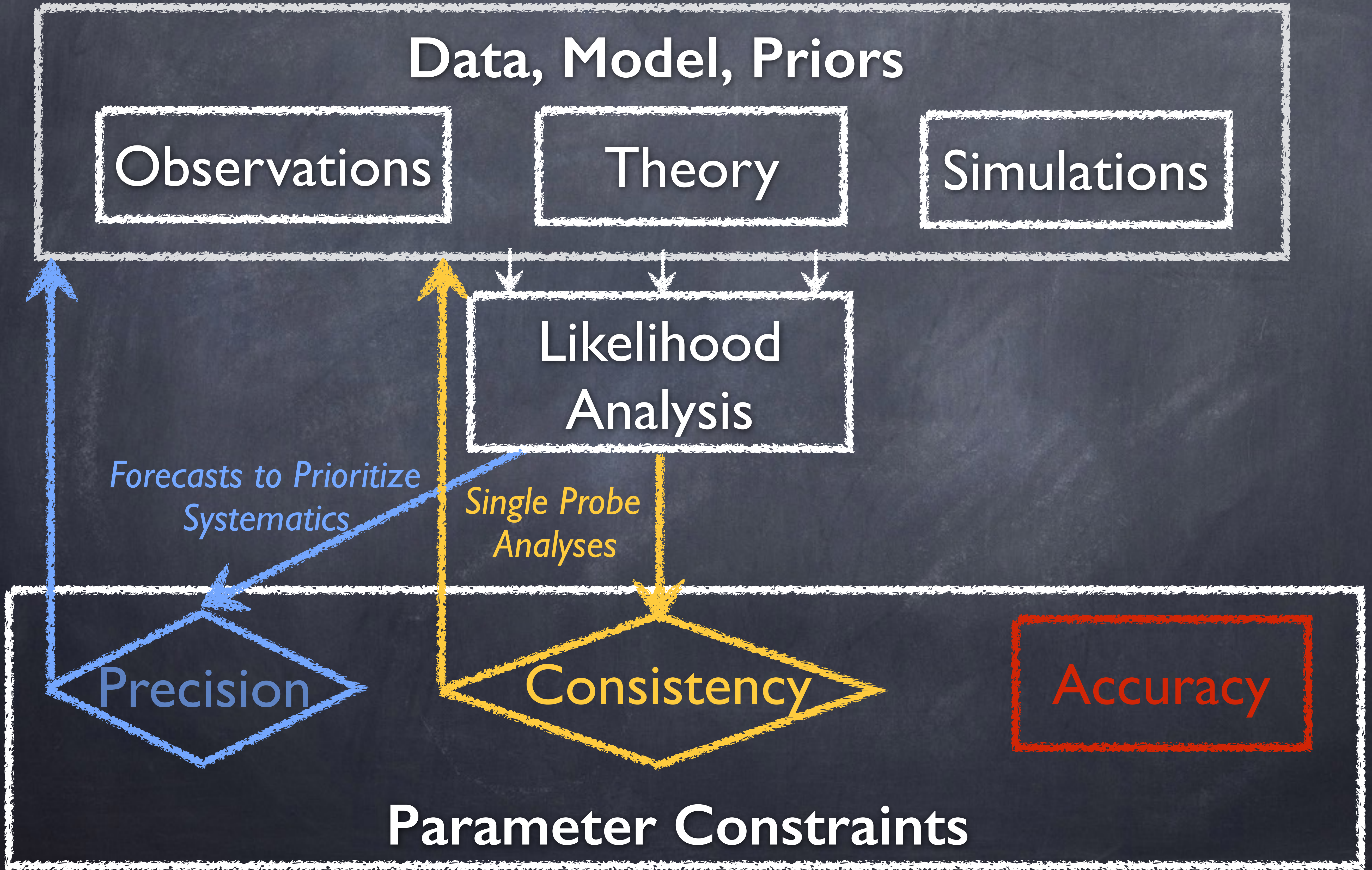
Combined Probes Systematics

- “Precision cosmology”: excellent statistics - systematics limited

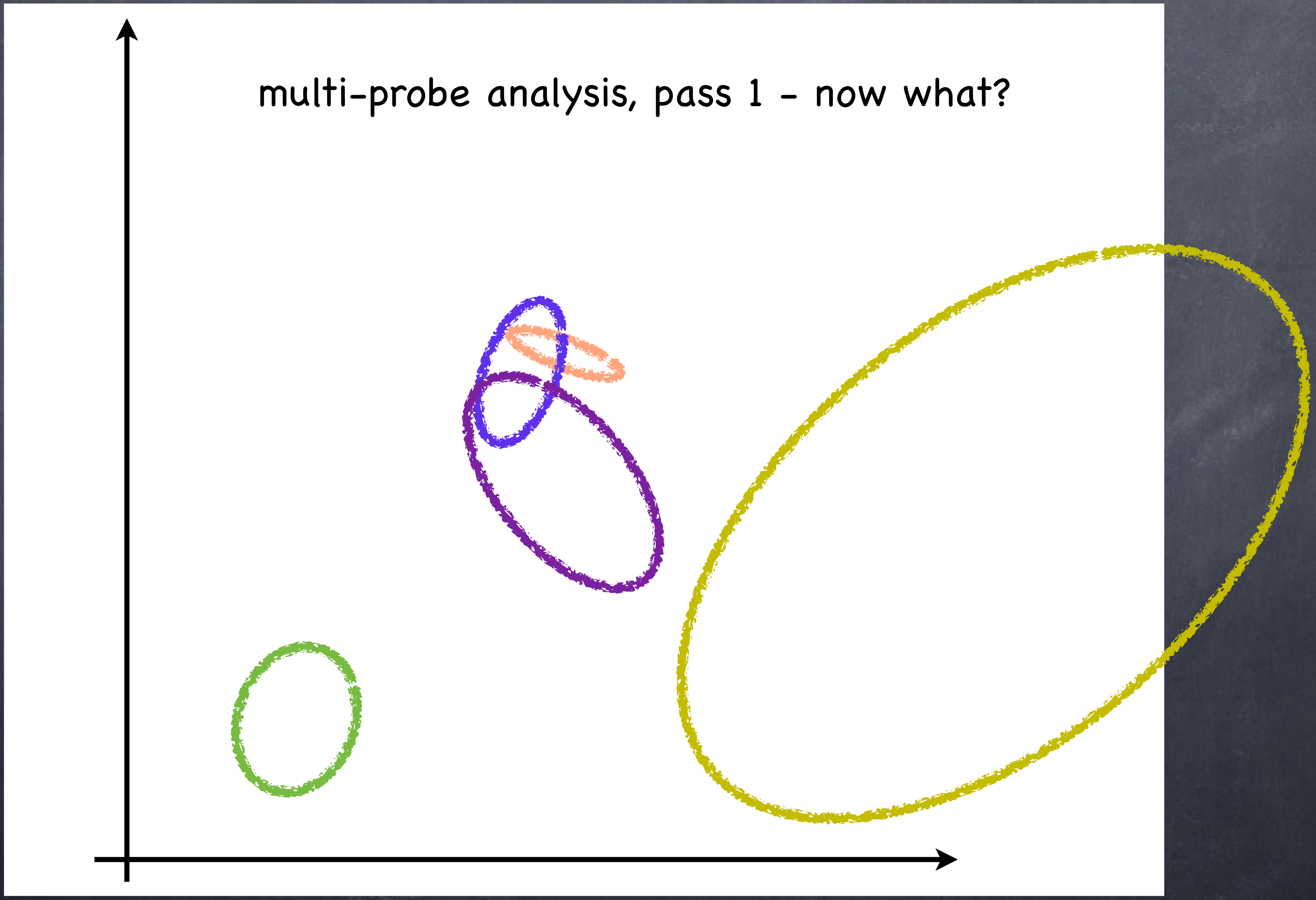


EK & Eifler’16

Joint Analysis Work Plan

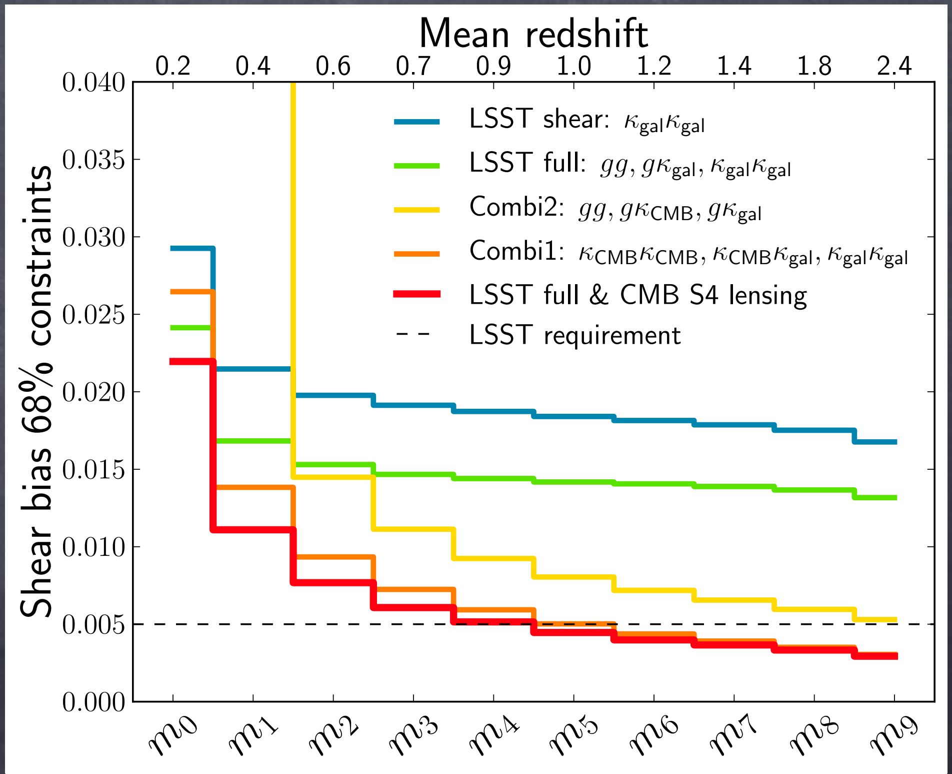


Unknown Systematics? vs. New Physics?



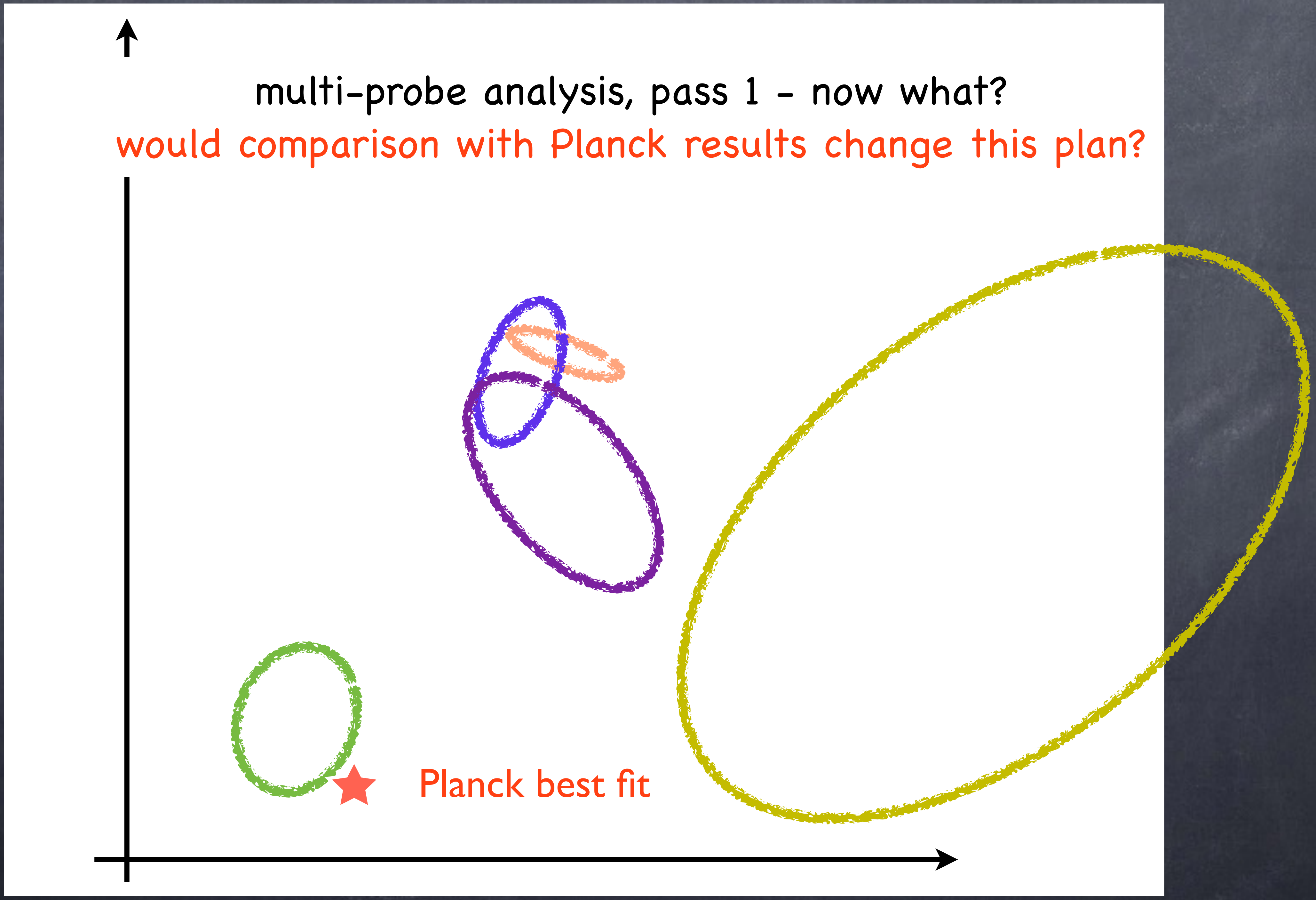
Unknown Systematics? vs. New Physics?

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



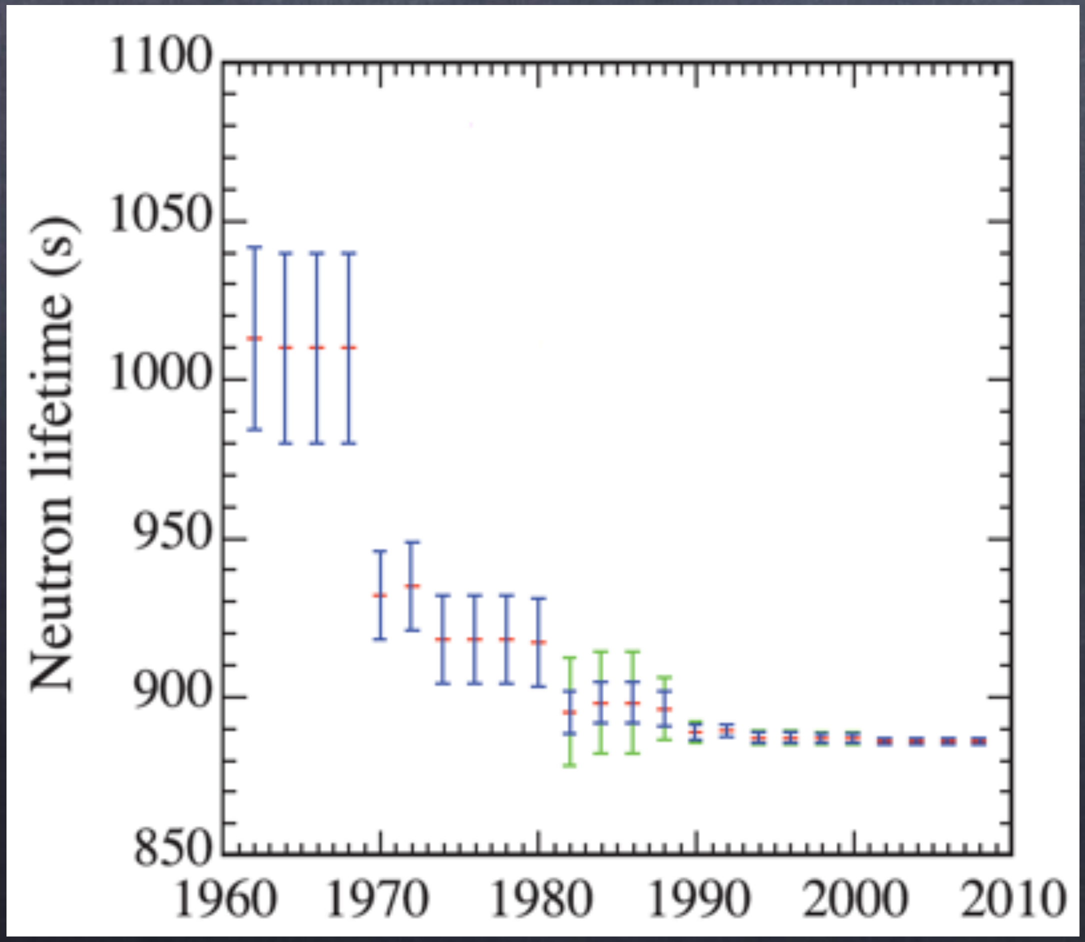
LSST WL x CMB-S4 lensing
calibrate shear calibration bias
Schaan, EK,+ 2016

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

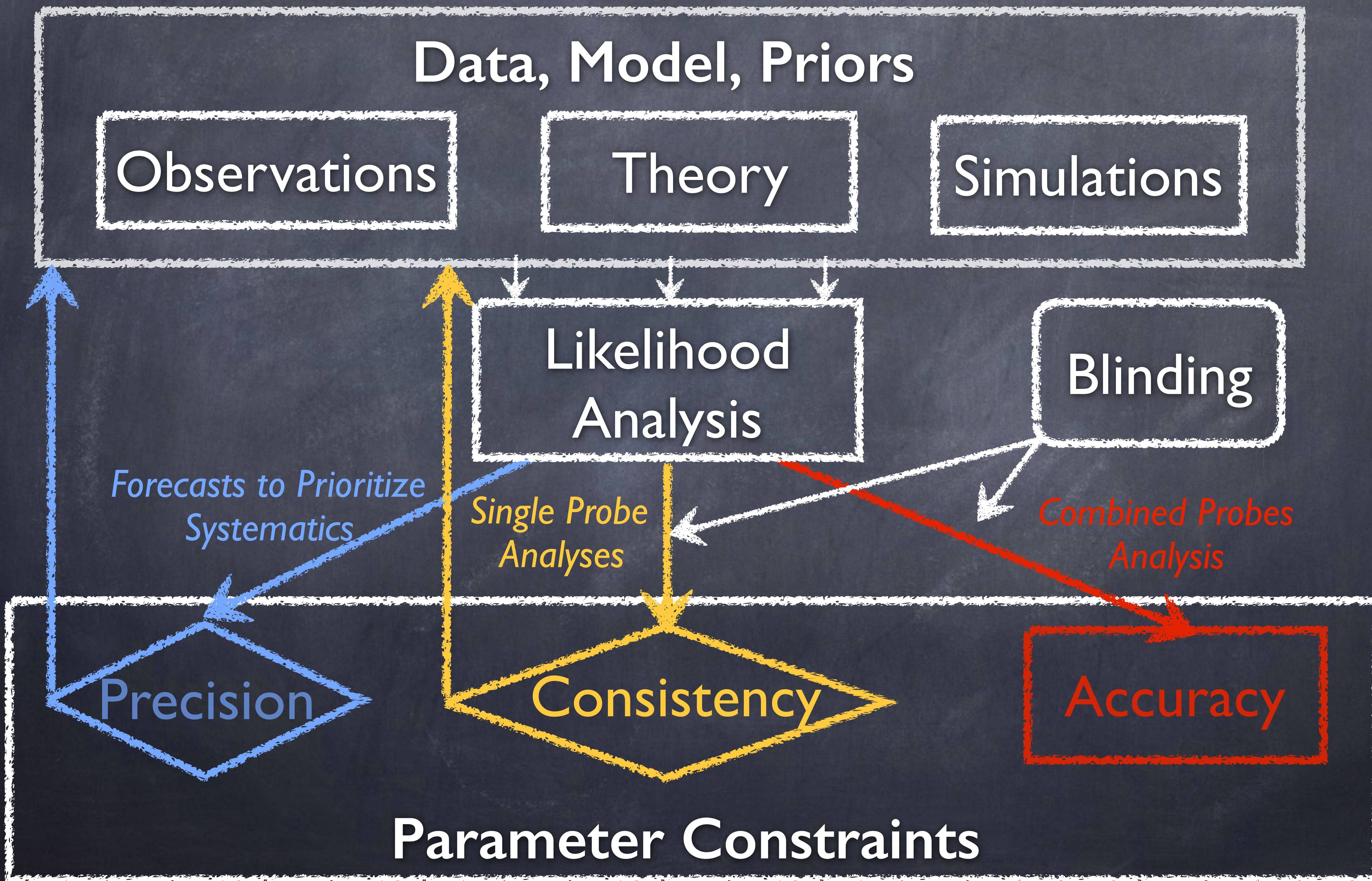
Blind Analysis Strategies for DES-Y3

- Two-stage process
  - measurement (correlation & mass functions)
    - shear catalog blinded, cluster calibration under debate
    - transform correlation functions (Muir, Elsner + in prep.)

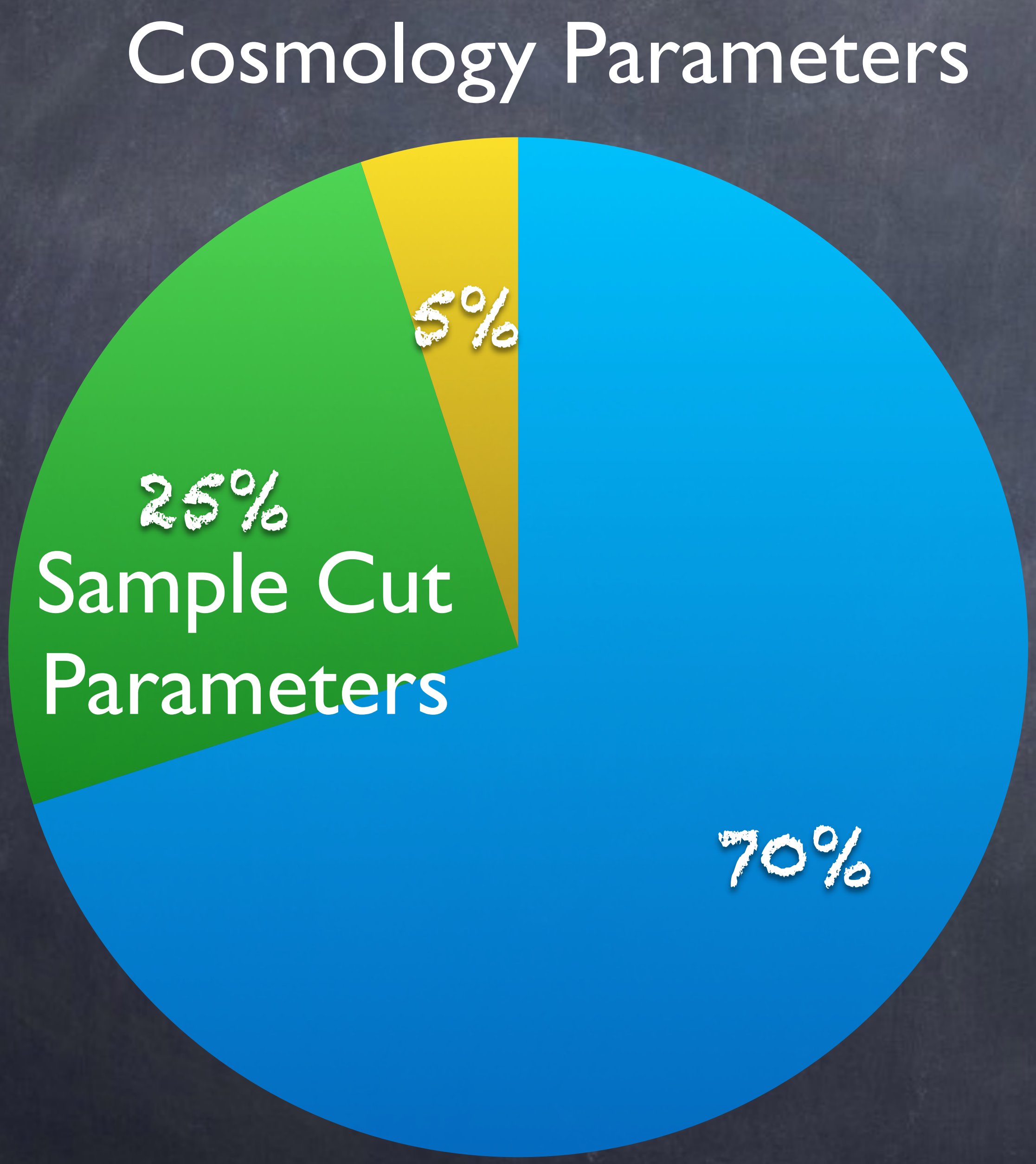
$$\hat{w}(\theta) \rightarrow \hat{w}(\theta) + \frac{\partial w}{\partial \Omega_{\rm m}} \Delta\Omega_{\rm m}$$

    - 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



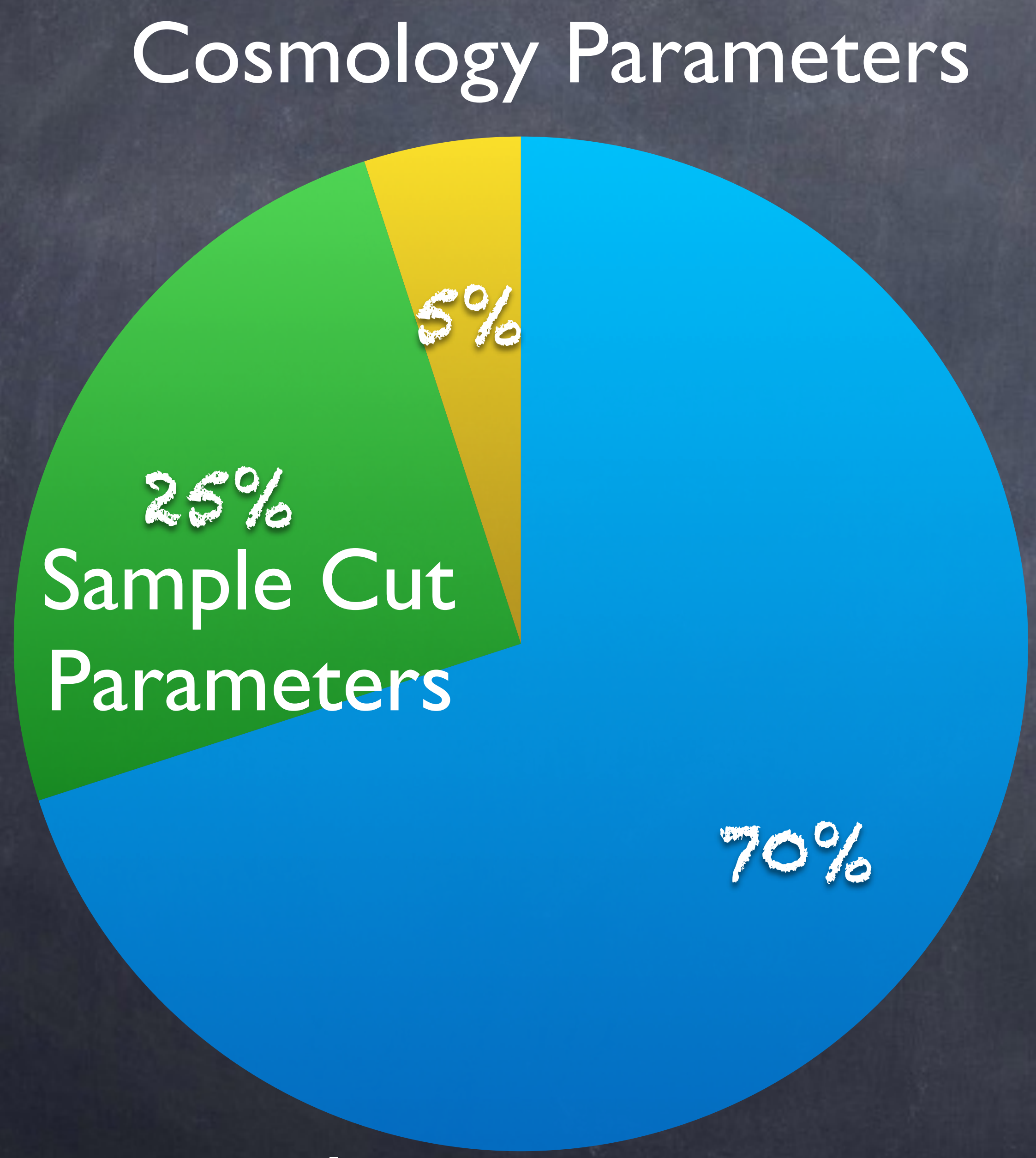
A Second Cosmology Pie Chart



"Systematics Parameters"

- observational systematics
  - survey specific
- astrophysical systematics
  - observable + survey specific

A Second Cosmology Pie Chart



"Systematics Parameters"

- observational systematics
  - survey specific
- astrophysical systematics
  - observable + survey specific

sample cuts + systematics highly interconnected

→ 95% systematics…

Conclusions

- Existence of cosmic acceleration requires new fundamental physics
- 2020s decade of cosmological surveys: CMB-S4, DESI, LSST, WFIRST,…
- Cosmological constraints soon to be systematics limited
    - understand astrophysics
    - understand systematics
    - understand observables (voids, clusters, galaxies, etc…)
- Combine observables + surveys to understand/calibrate systematics
- Combine different surveys to robustly confirm/rule out ΛCDM
- Need collaboration across surveys, plan for analysis frameworks to combine observables from all surveys