Combining Cosmological Probes in the Dark Energy Survey, and Beyond

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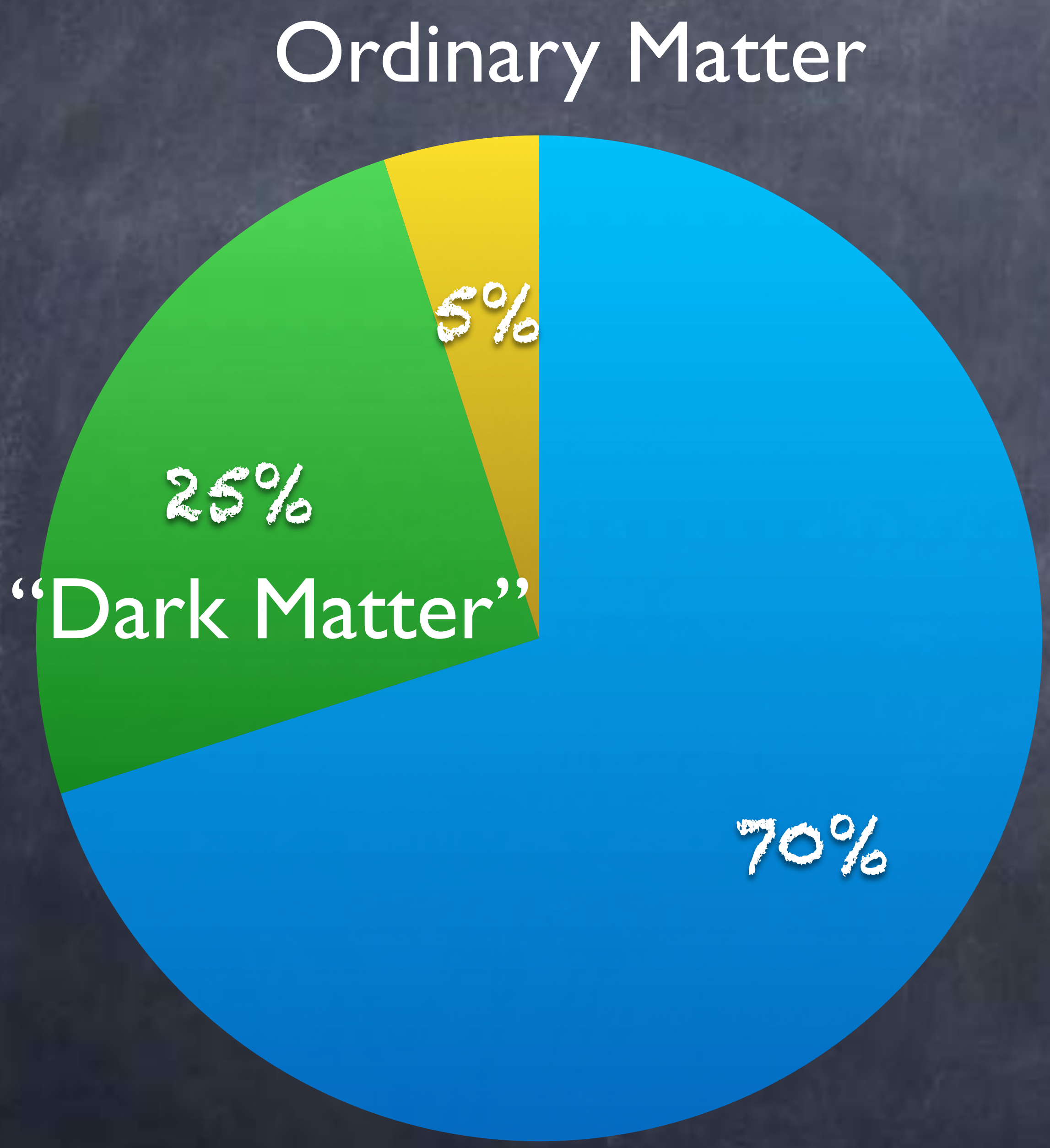
IPMU, 12/6/2016

Our Simple Universe

- On large scales, the Universe can be modeled with remarkably few parameters
  - age of the Universe
  - geometry of space
  - density of atoms
  - density of matter
  - amplitude of fluctuations
  - scale dependence of fluctuations

[of course, details often not quite as simple]

Our Puzzling Universe



"Dark Energy"

- accelerates the expansion
- dominates the total energy density
- smoothly distributed

acceleration first measured by SN 1998

next frontier: understand

Cosmic Acceleration

CMB + large-scale structure + supernovae:

homogeneity, isotropy, flatness + acceleration
impossible with GR + matter only

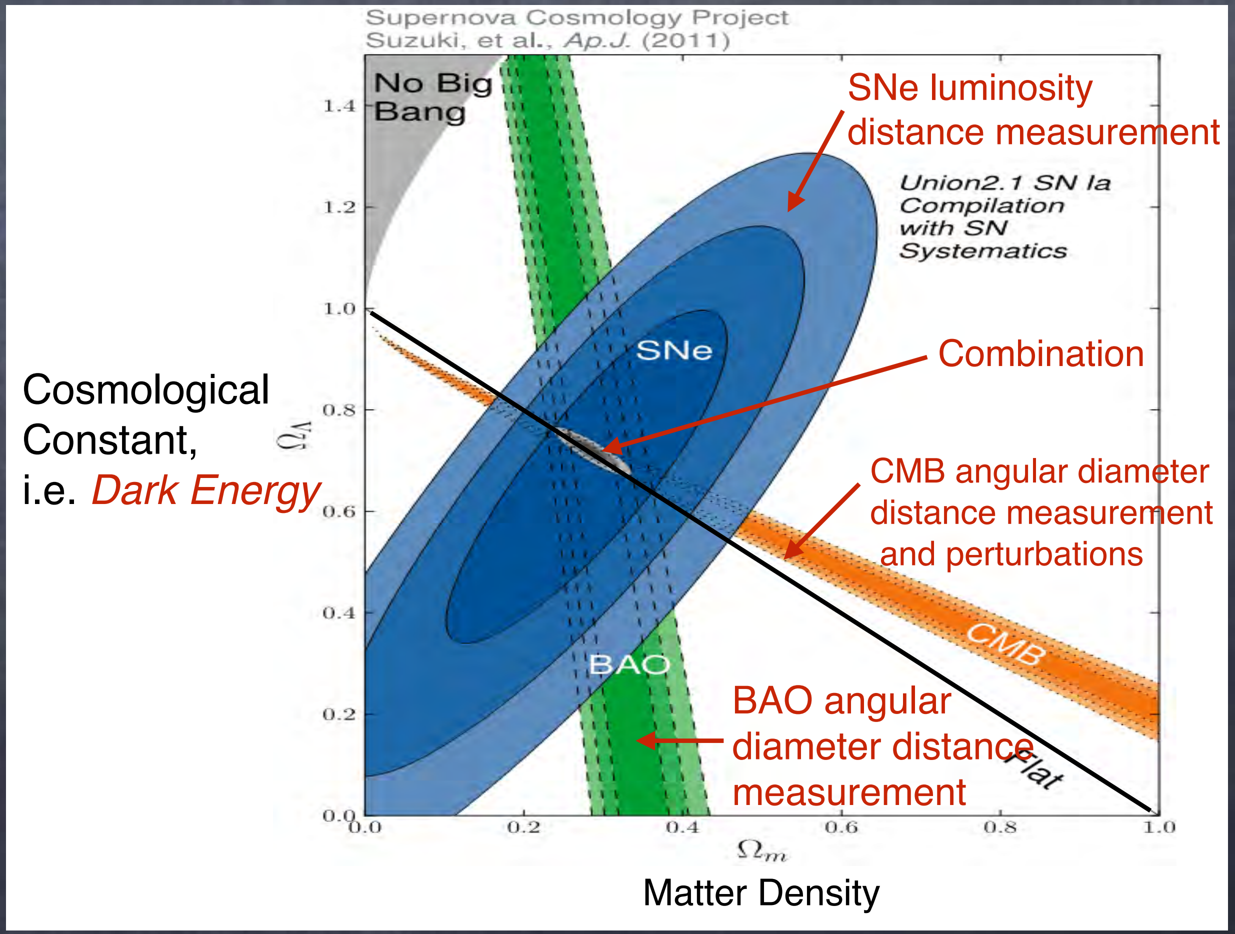
observations require a *repulsive* force

- cosmological constant Λ: w =p/ϱ=-1?
- dynamic scalar field, w(a)?

$$G_{\mu\nu} = 8\pi G\left(T_{\mu\nu} - \bar{\rho}_{\rm DE} g_{\mu\nu}\right)$$

- breakdown of GR?

dominates dynamics of late-time Universe



Testing Cosmic Acceleration

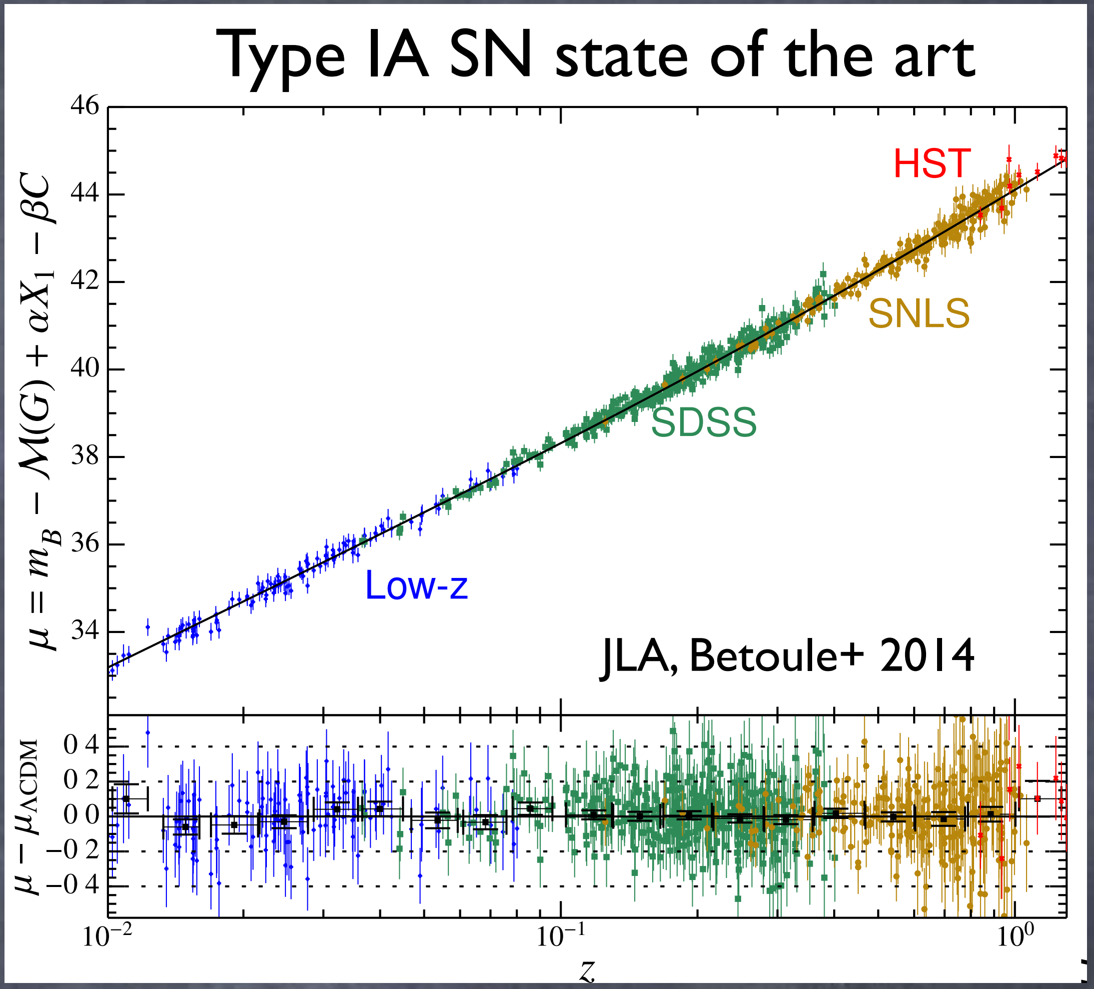
size of Λ difficult to explain

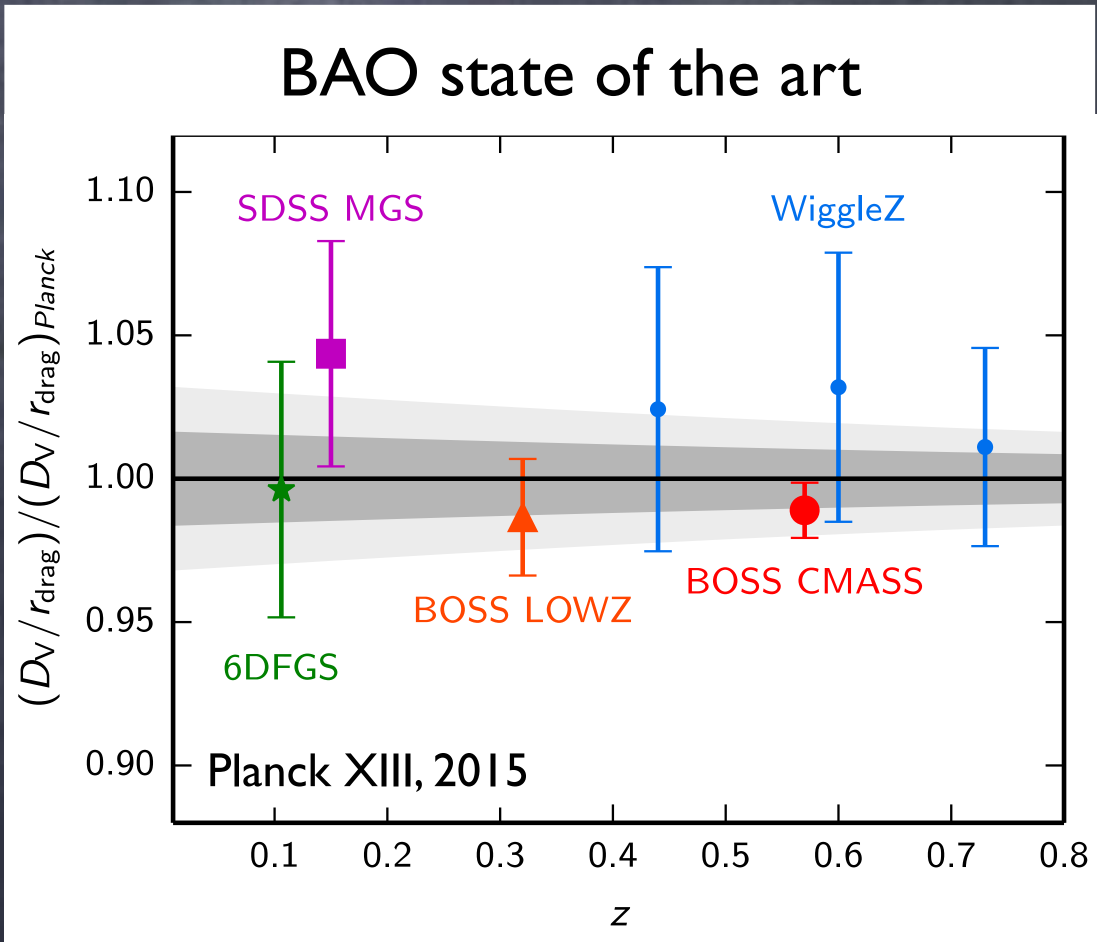
important to test GR over cosmological scales

Expansion history

$$H^2(a) = H_0^2 \left(\Omega_M a^{-3} + \Omega_{DE} a^{-3(1+w_0+w_a)} e^{-3w_a(1-a)} \right)$$

- from supernovae, CMB peaks + baryonic acoustic oscillations (BAO)
- agreement with ΛCDM
- not much information on dark energy/gravity: at most w0, wa





Cosmic Structure Formation

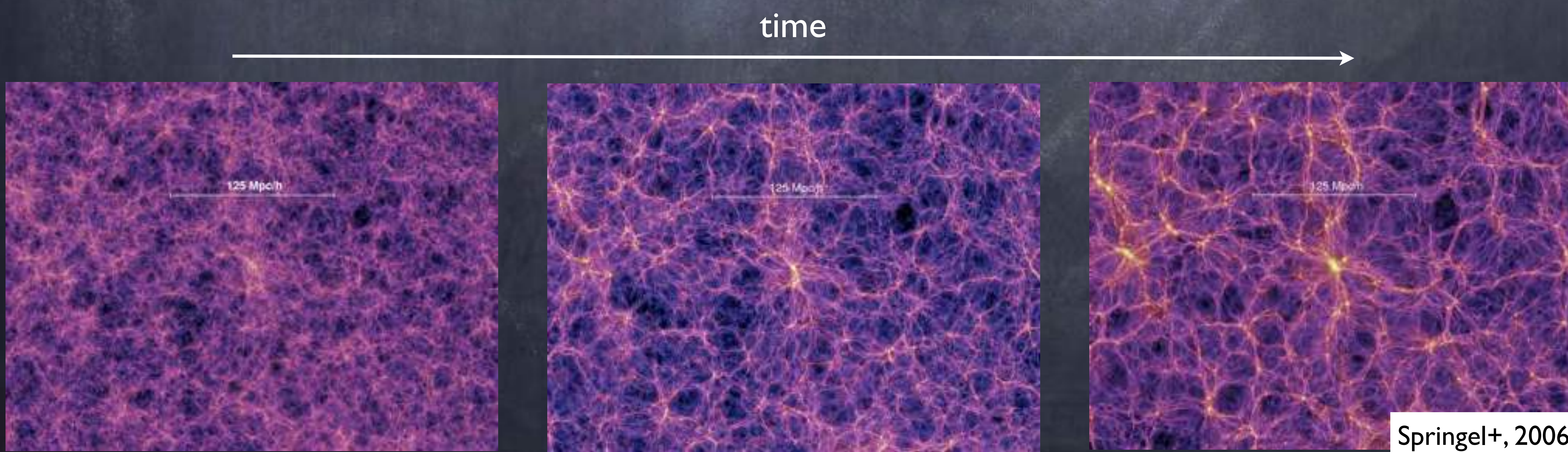
gravity drives **formation of cosmic structure,** dark energy slows it down

much more information than expansion rate

linear level: perturbed Einstein equation

non-linear evolution: numerical simulations

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

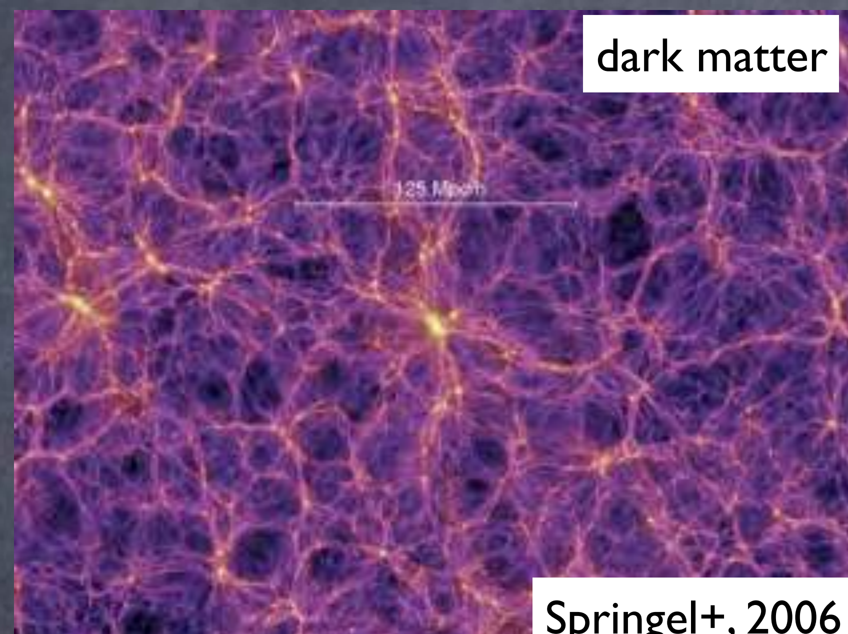


Springel+, 2006

How to connect theory to data?

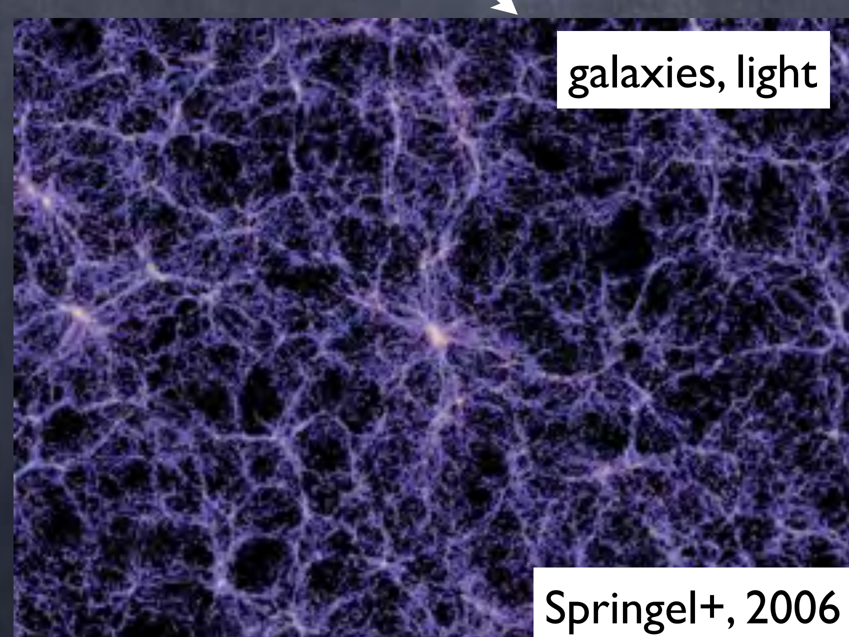
physics
+ model parameters

generate initial conditions, evolve



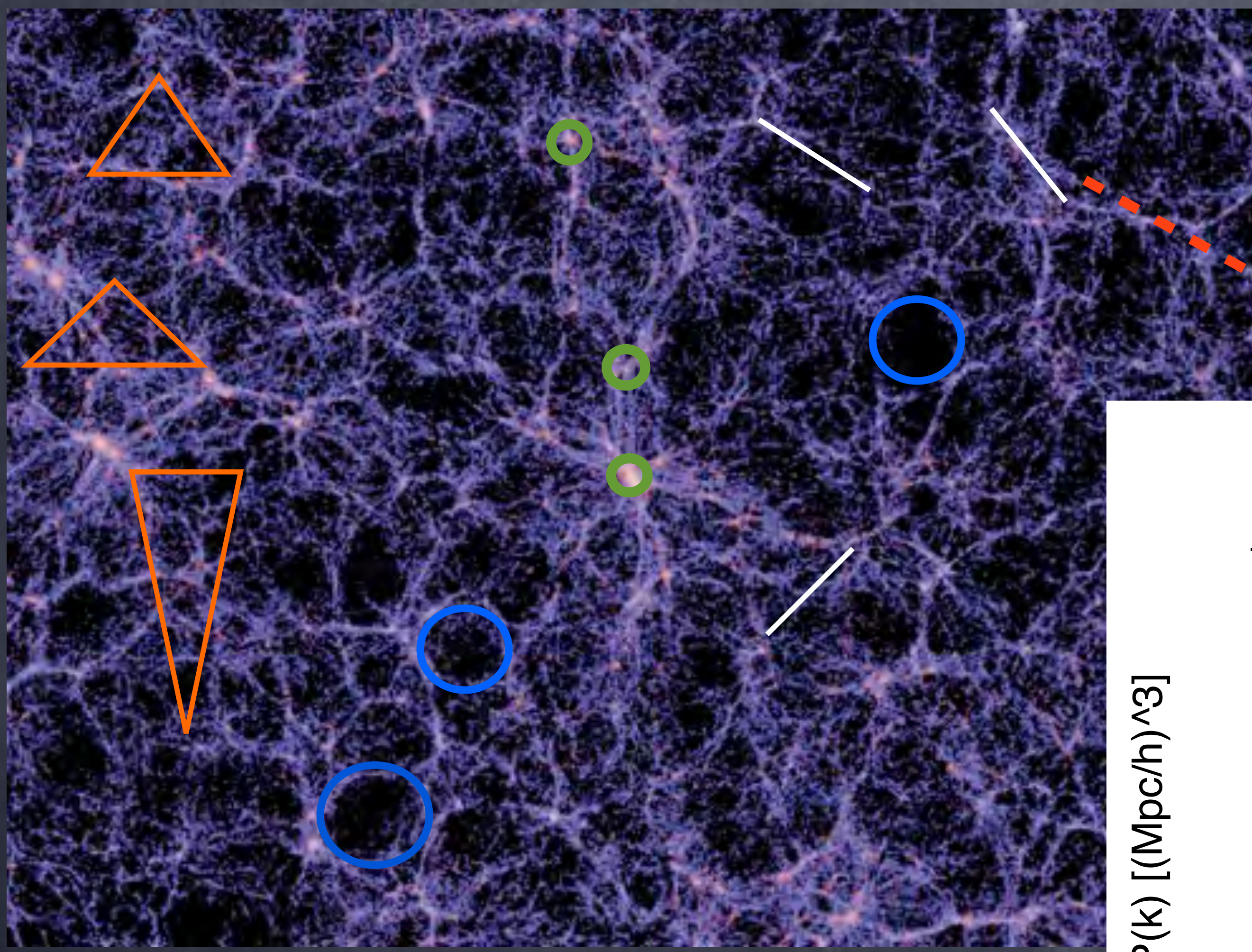
galaxy formation models

?

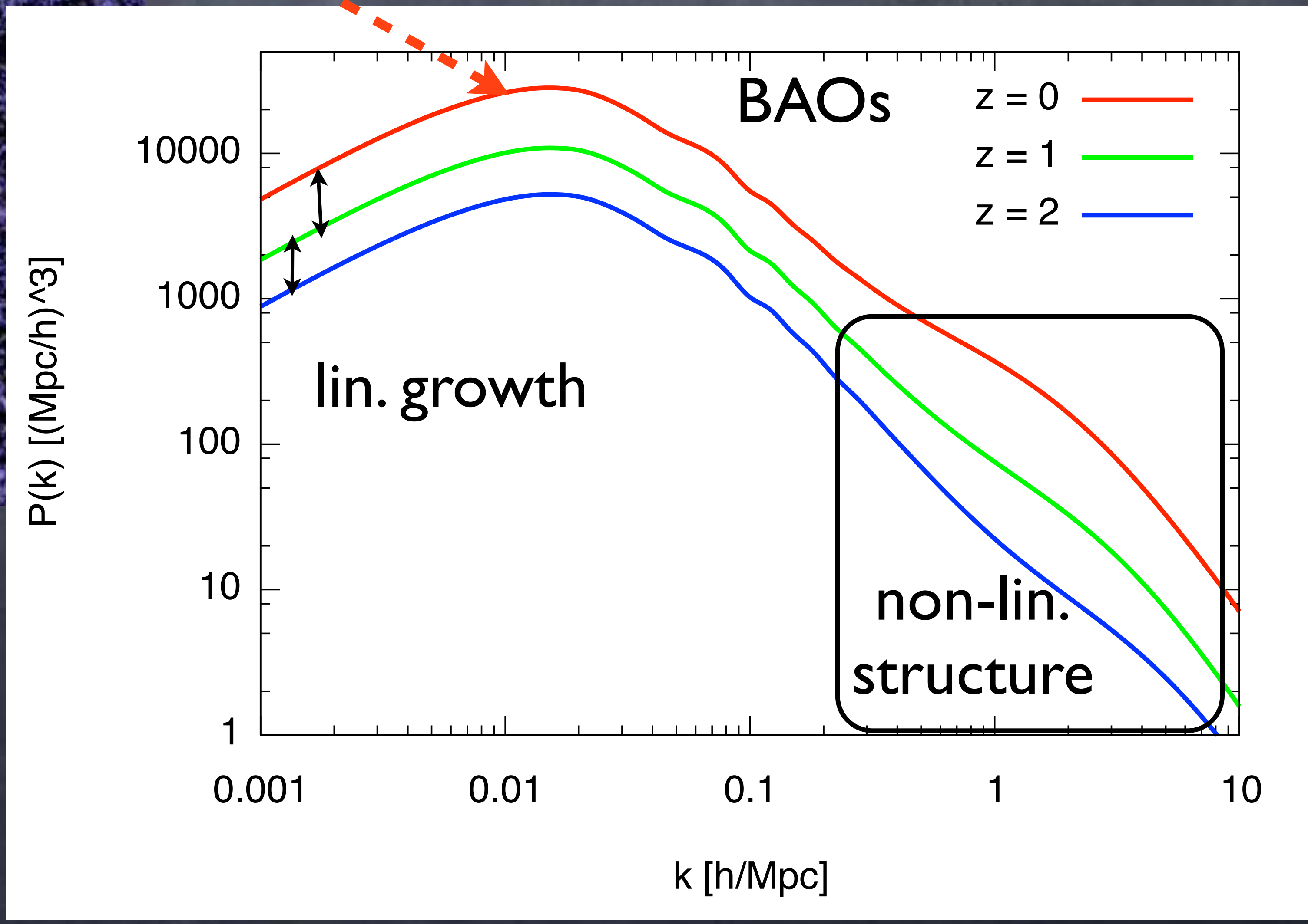


?

What to look for in the galaxy distribution?



need redshift, understand galaxy bias

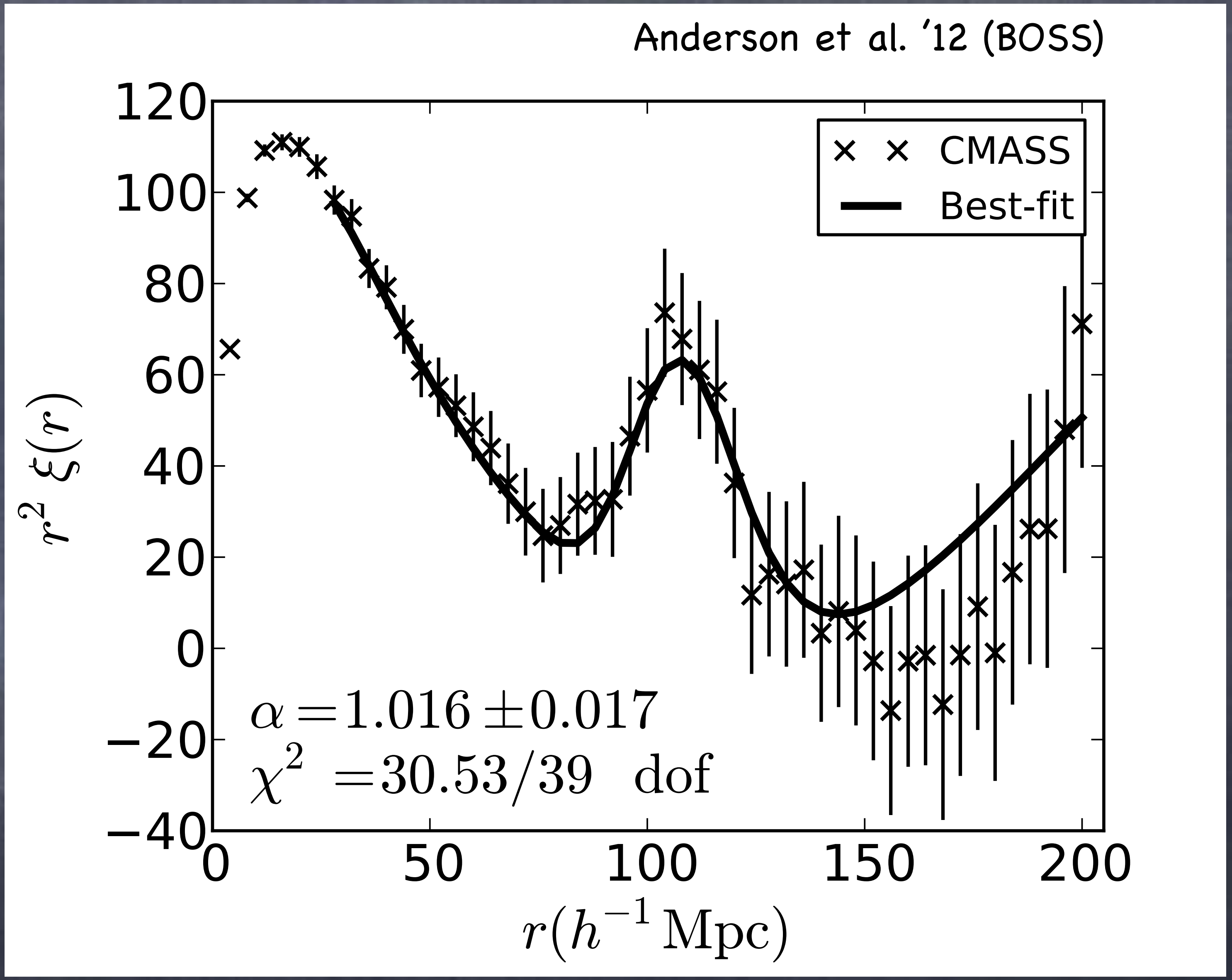


- clusters (over densities),
- voids (under densities)
- two-point correlations (galaxy positions, shapes)
- three-point correlations,...

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

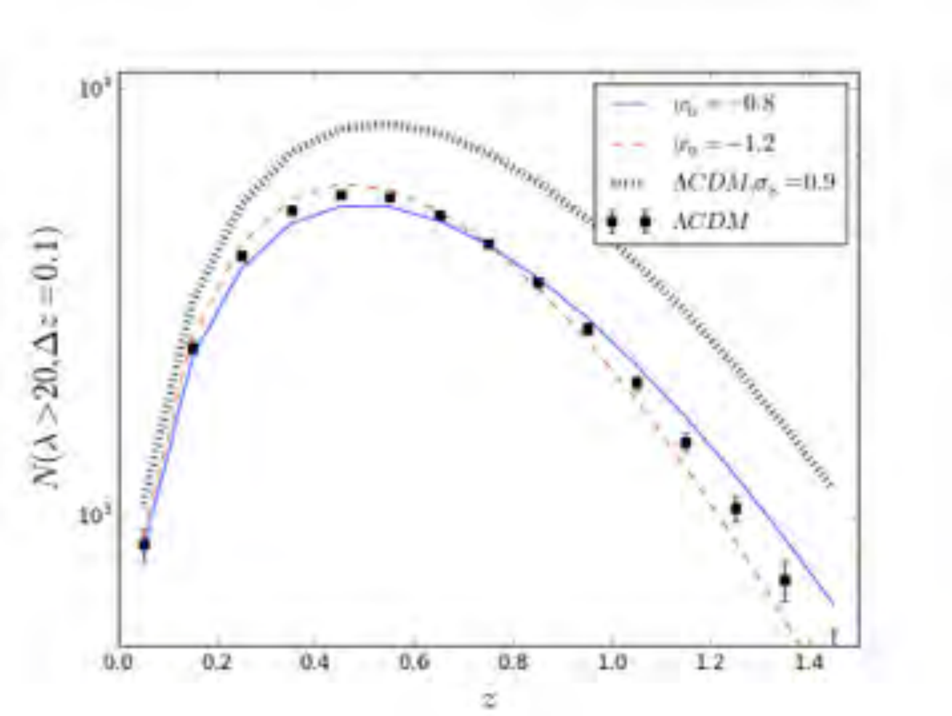
Galaxy Clusters

- 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

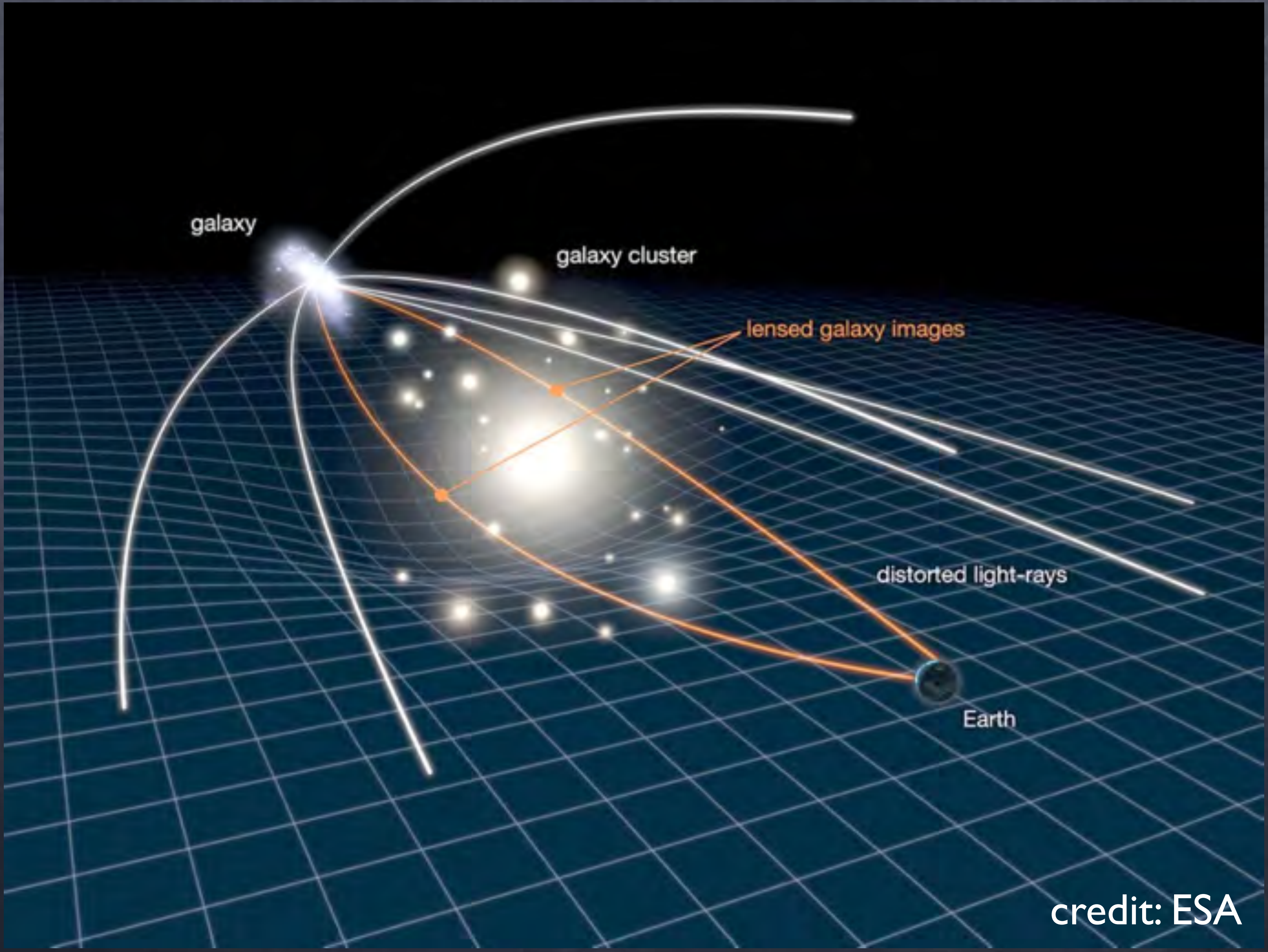
- but need to identify clusters + member galaxies, infer masses!



credit: DES

LSS Probes of Dark Energy

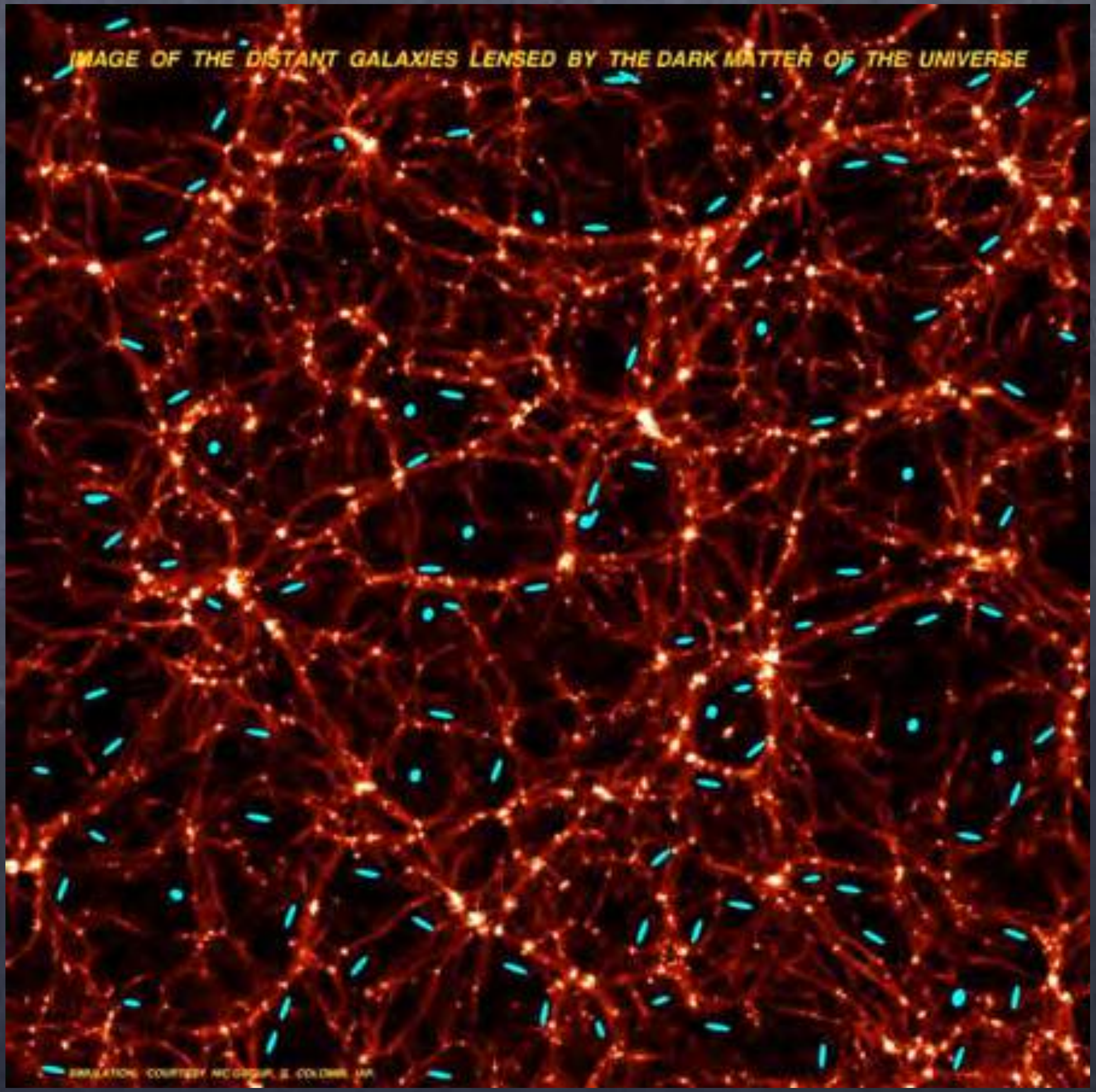
Weak Gravitational Lensing



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 I

- measure shapes of source galaxies near detection limit
  - typical S/N ~ 25
  - what could go wrong?

- parameterize mapping between true and estimated shear
  - "shear calibration" parameters, uncertainty in these parameters key systematic

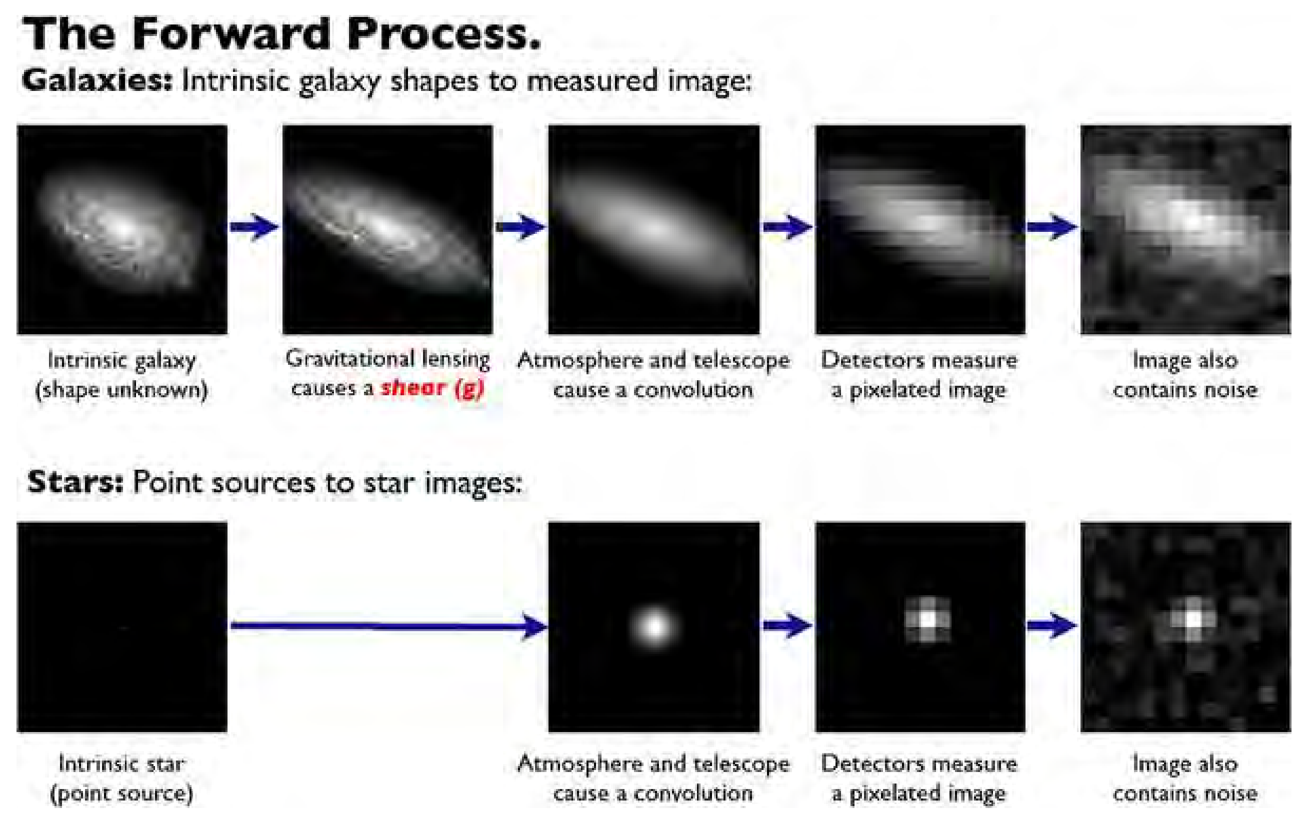
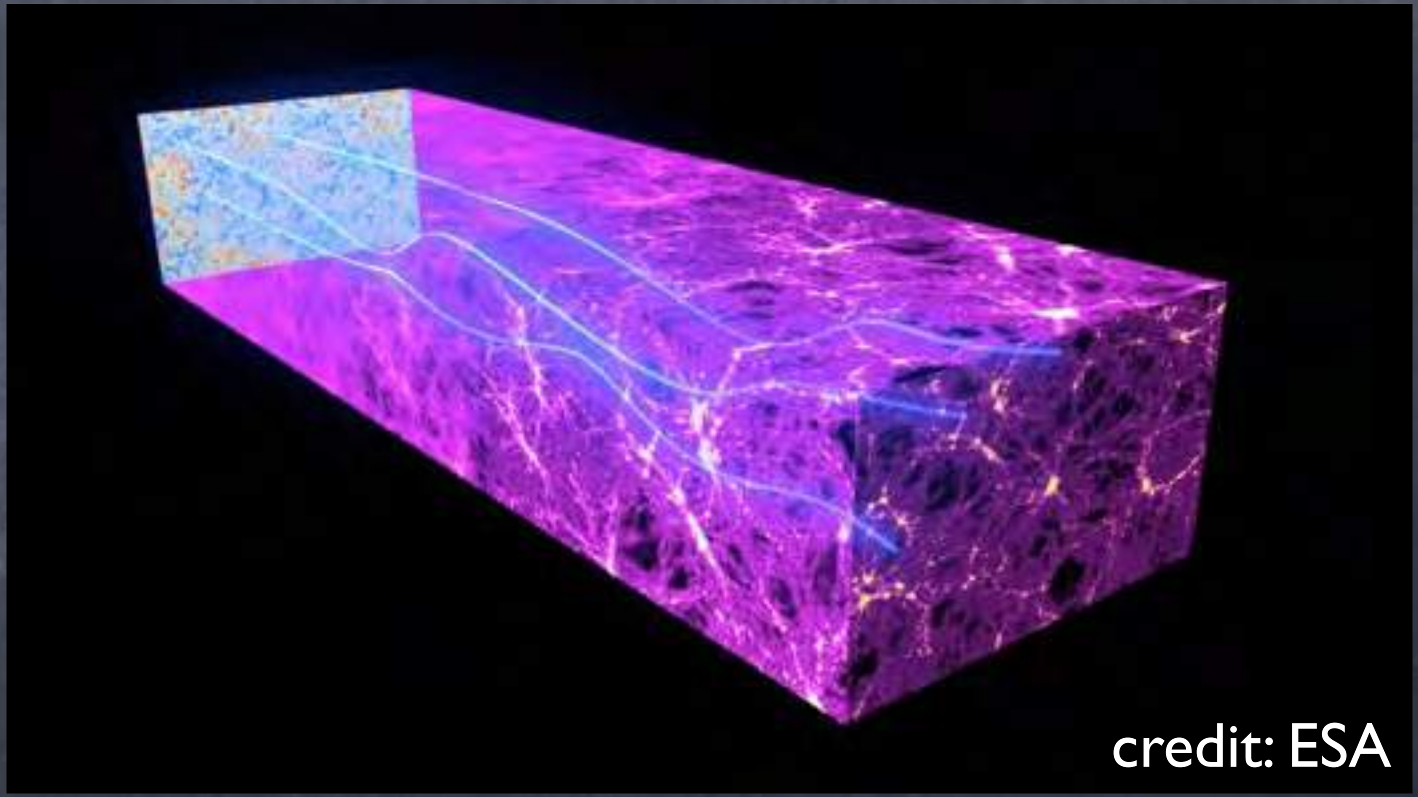


FIG. 2. *Illustration of the forward problem. The upper panels show how the original galaxy image is sheared, blurred, pixelised and made noisy. The lower panels show the equivalent process for (point-like) stars. We only have access to the right hand images.*

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

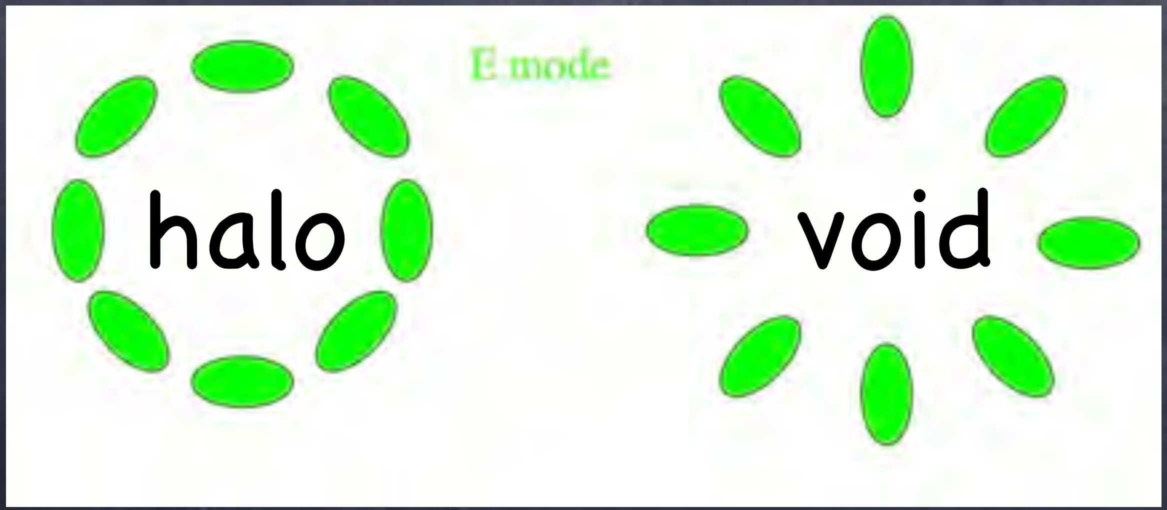


credit: ESA

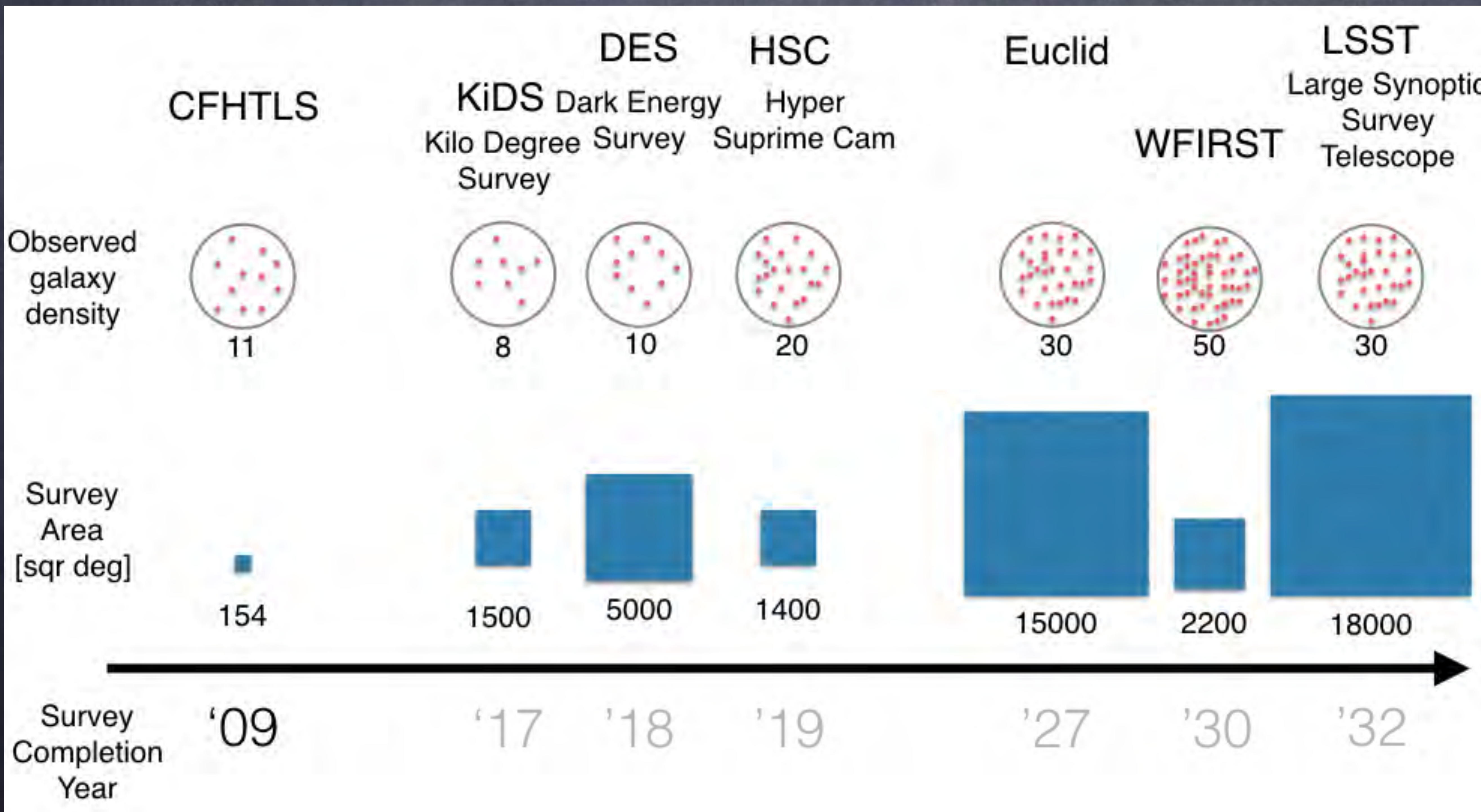
LSS Probes of Dark Energy

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



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

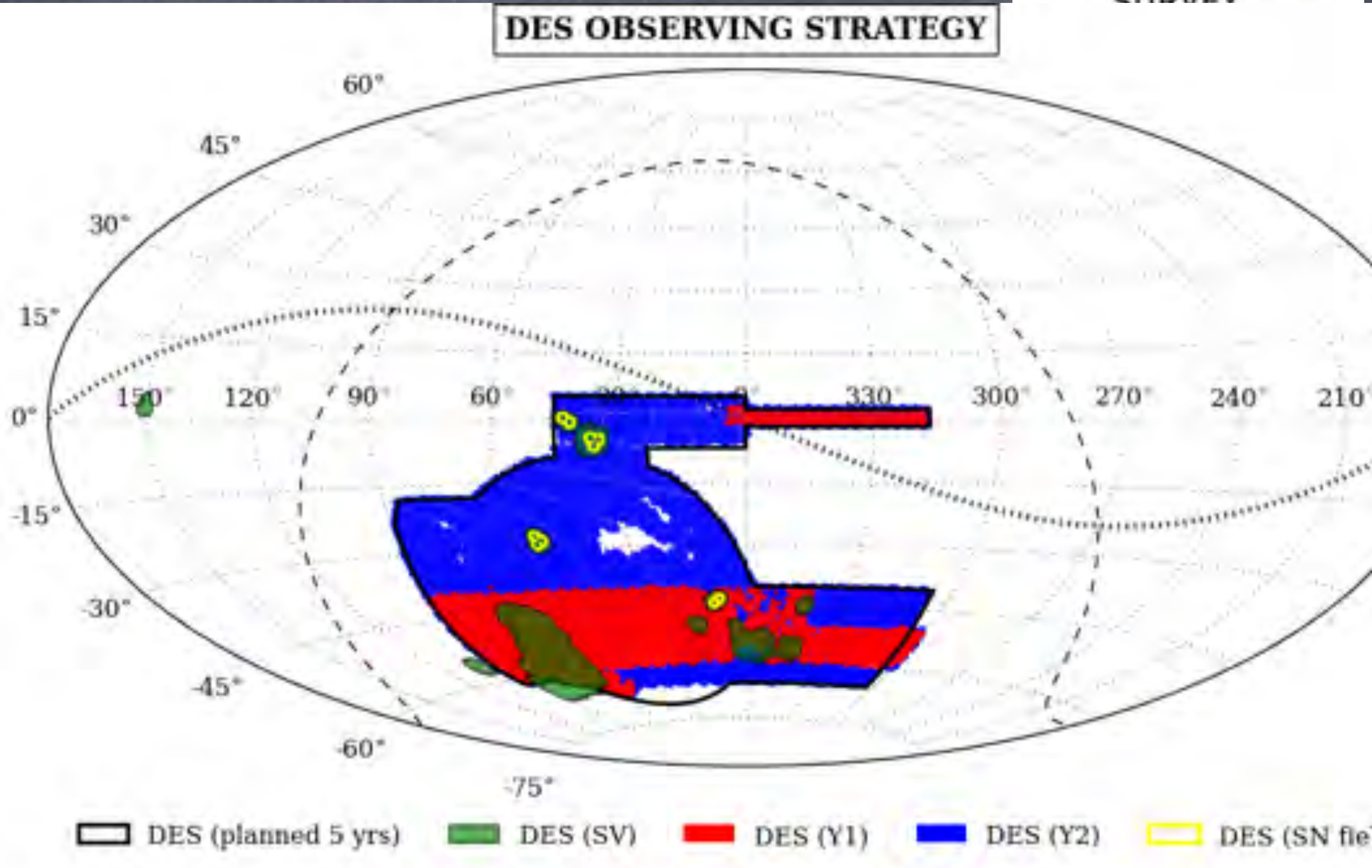
Dark Energy Survey

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

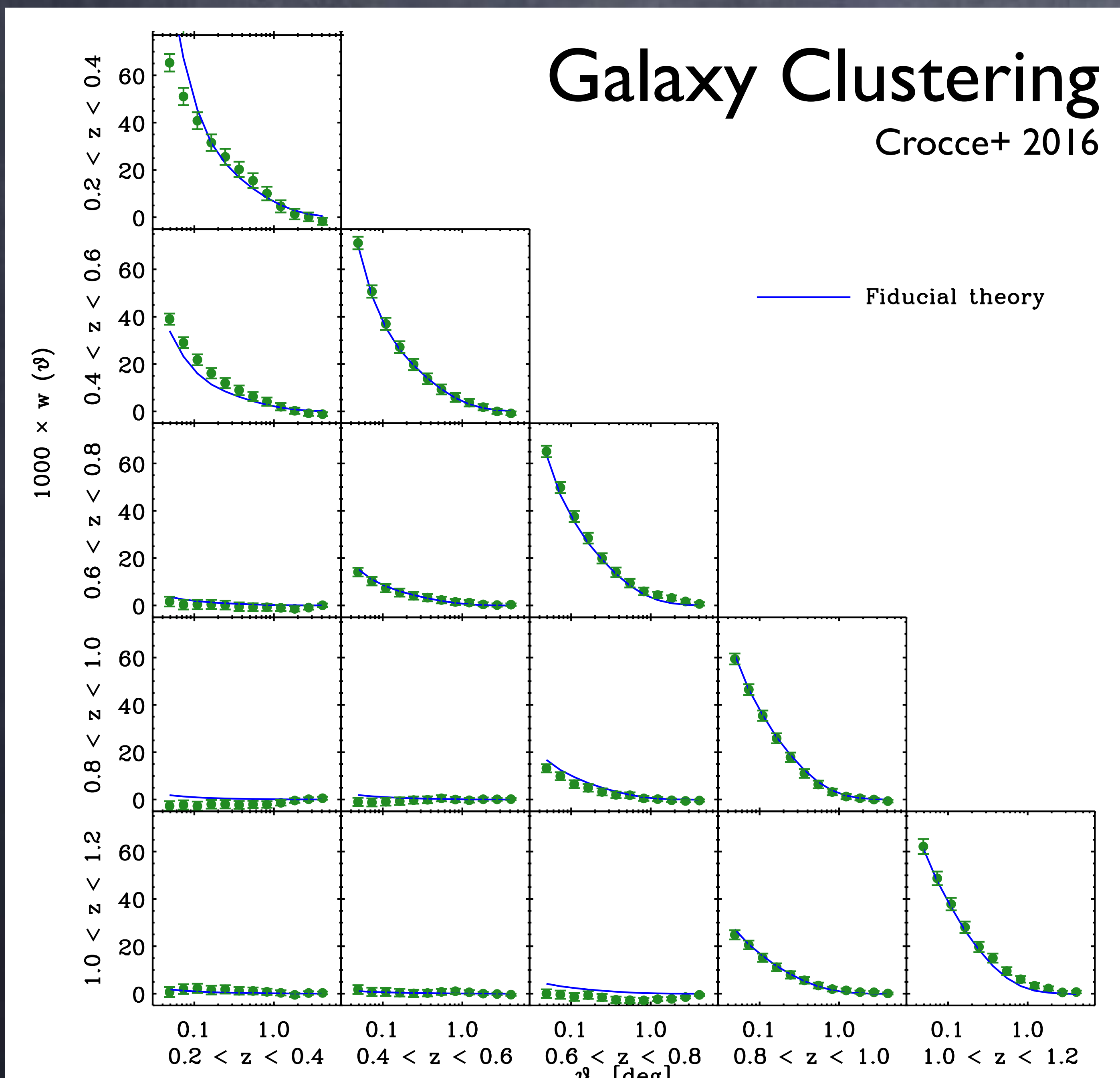
Early Science Results

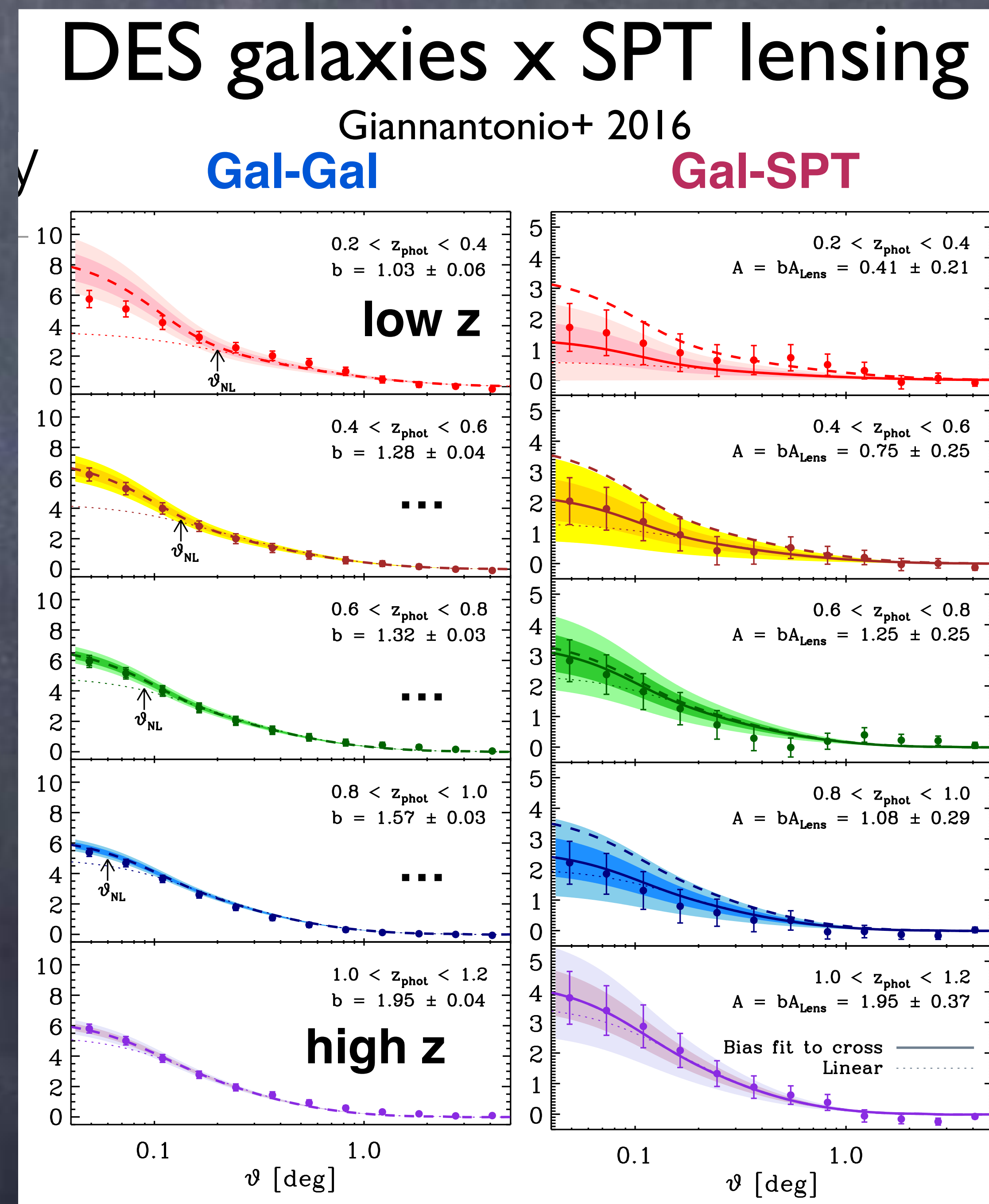
- based on 140 sd deg SV data
- 34 papers so far
  - milky way satellites, galaxy evolution, cosmology, …
  - *I will only show a few cosmology highlights*



	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





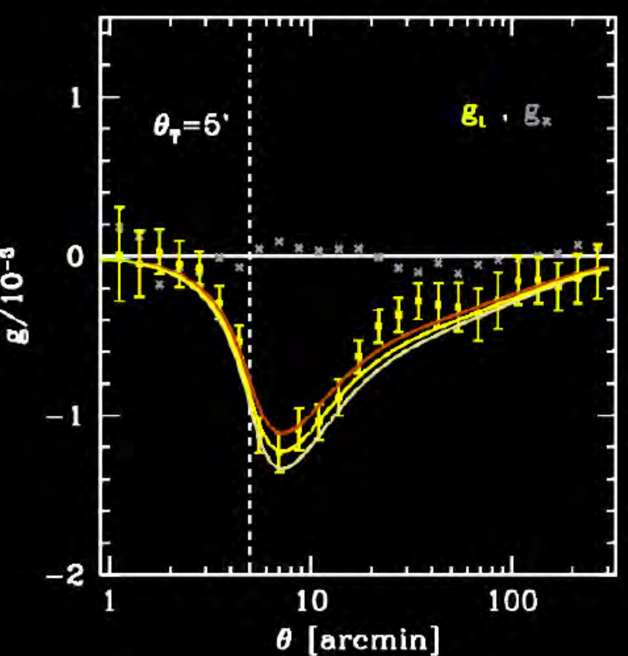
DES: Weak Lensing with Science Verification Data

Weak Lensing by Troughs (Underdense Regions)

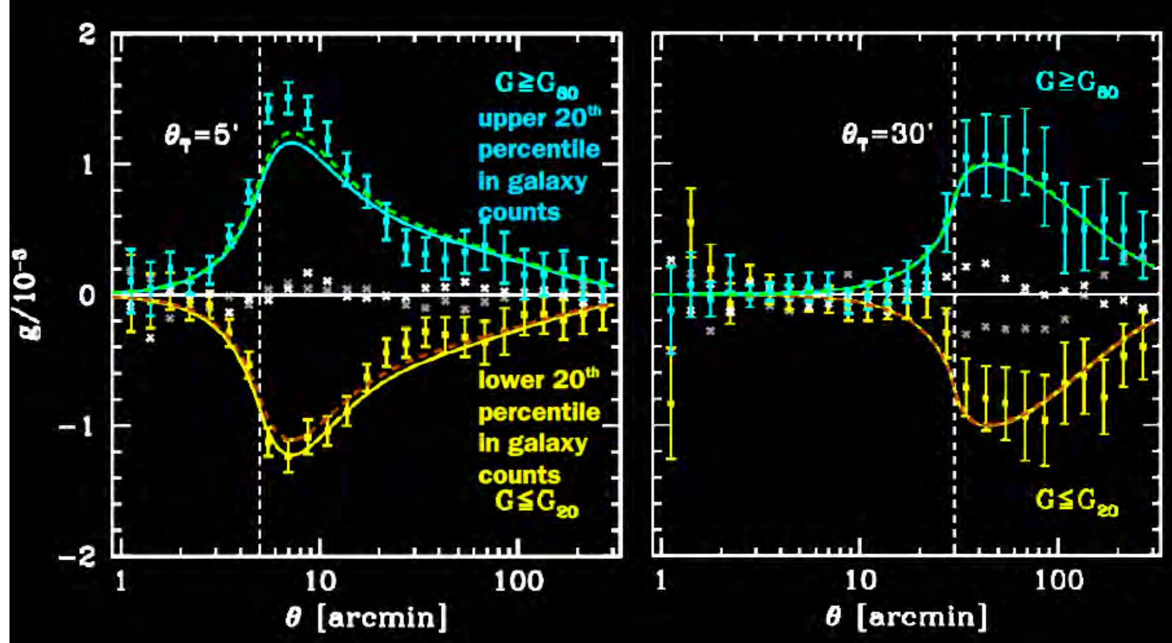
Gruen+ 2016, prediction: EK+ 2013

Measurement

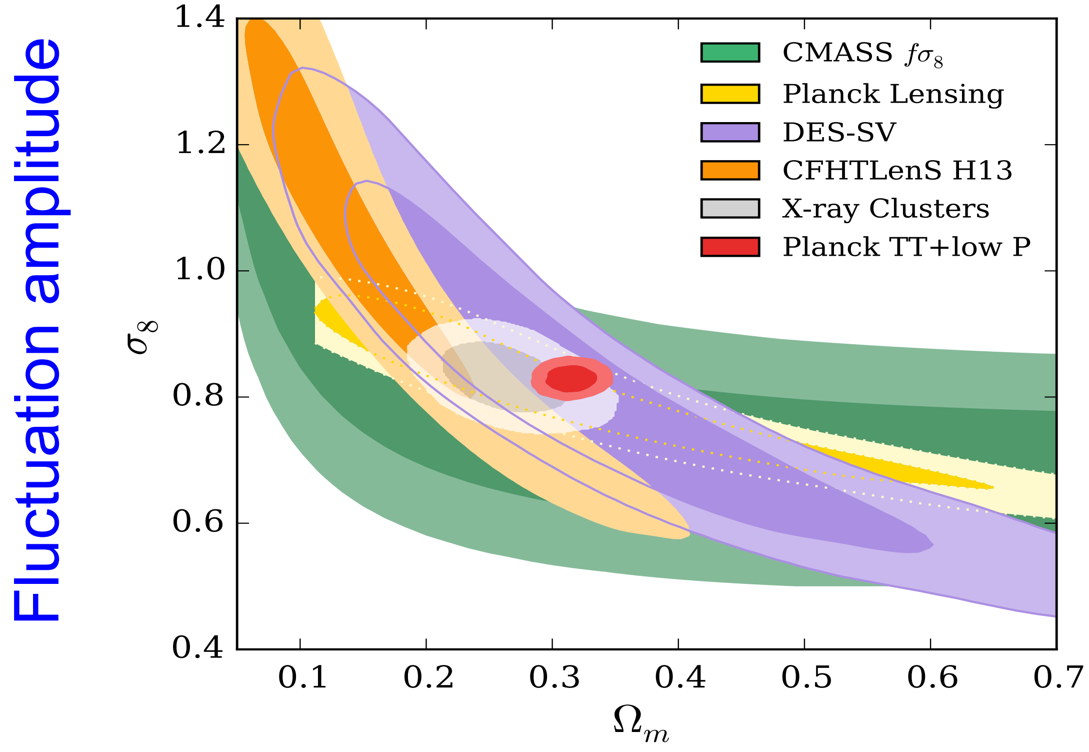
- DES SV: ~150 sq. deg, full DES depth
- tracers: Rykoff/Rozo redMaGiC galaxies, 0.2<z<0.5, L>0.5L*, 1/[1000 Mpc^3]
- troughs = lower 20th percentile
- sources: ~2x10^6 at z>0.6
- significance ~ 15σ



Measurement: under/overdensity

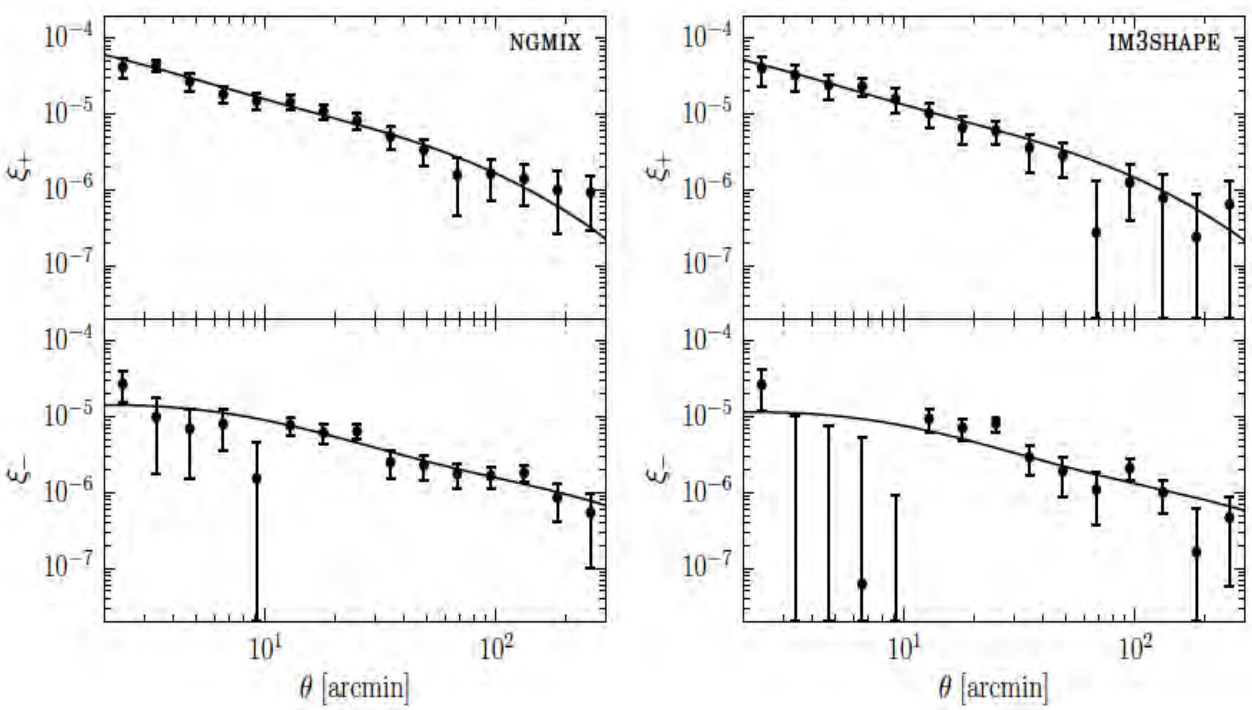


DES: Weak Lensing with Science Verification Data



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!

DES: Multi-Probe Analysis with Science Verification Data

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

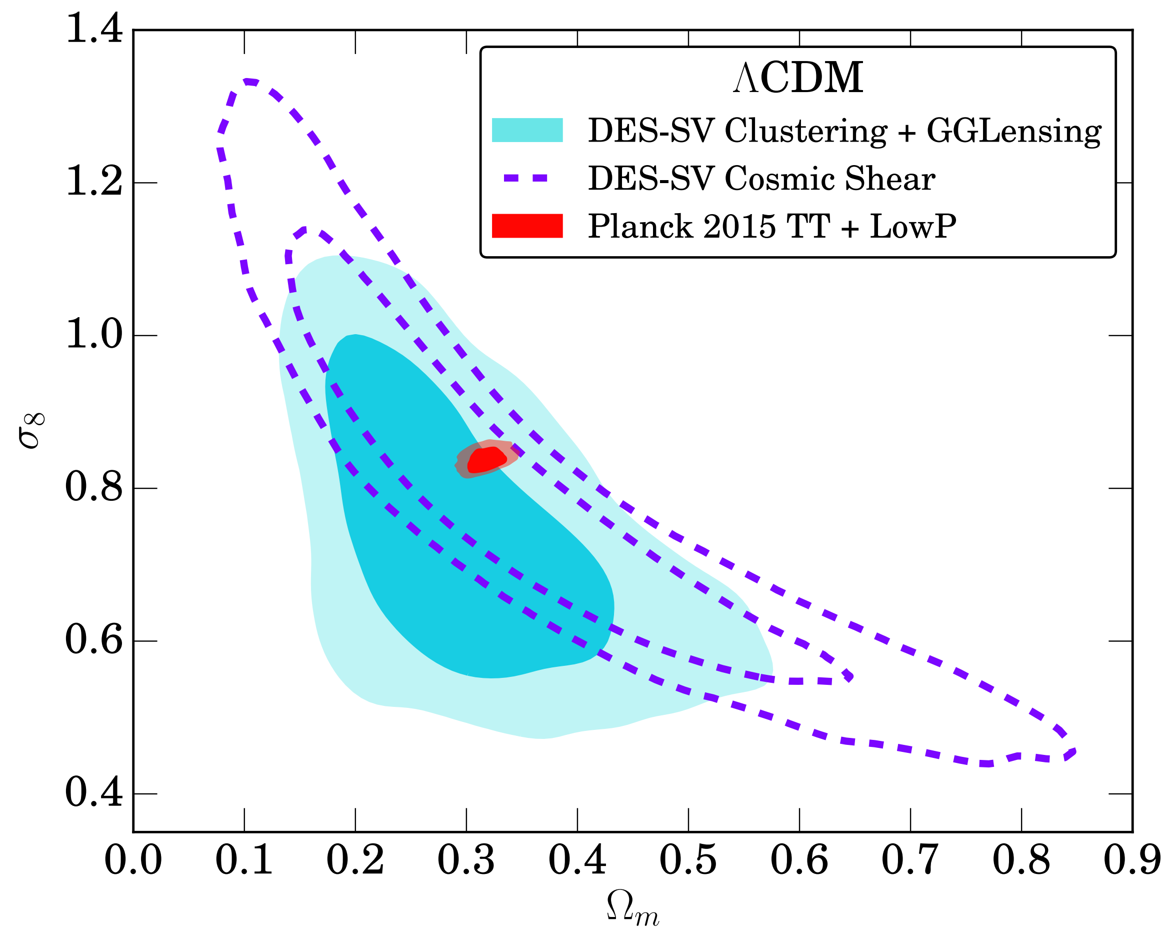


Figure 4. Constraints on Ω_m and σ_8 using DES-SV Cosmic Shear (dashed purple), DES-SV $w(\theta) \times \gamma_t(\theta)$ (this work, filled blue) and Planck 2015 using a combination of temperature and polarization data (TT+lowP, filled red). In each case, a flat ΛCDM model is used.

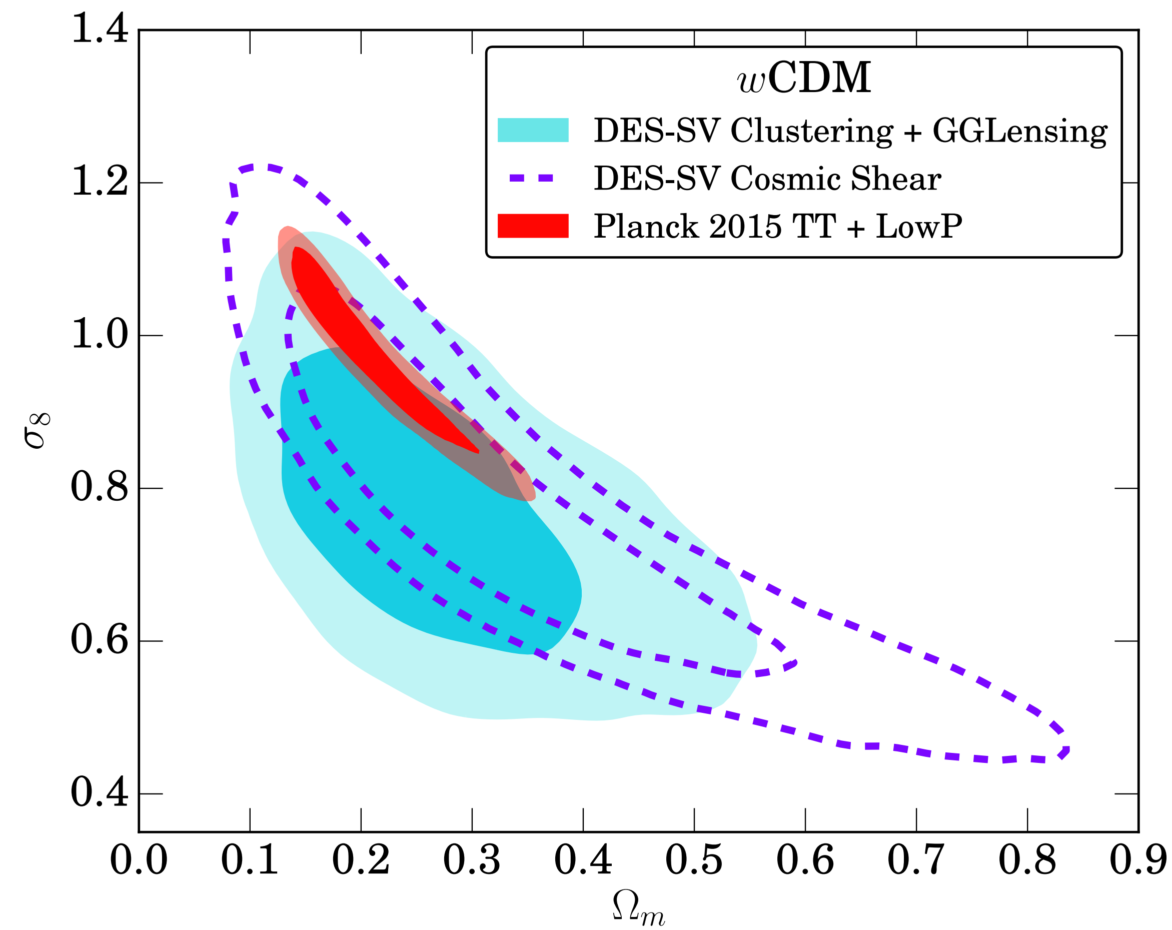


Figure 5. Constraints on Ω_m and σ_8 assuming a wCDM model using DES-SV Cosmic Shear (dashed purple), DES-SV $w(\theta) \times \gamma_t(\theta)$ (this work, blue) and Planck 2015 using temperature and polarization data (TT+lowP, red).

LSST: The Experiment

- largest planned LSS survey
- map visible sky every 3 nights
- high priority in P5, decadal survey
- construction started 2015
- commissioning first light 2019
- survey duration 2022-2032

LSST: Science Collaborations

- Solar System
- Stars, Milky Way, Local Volume
- Transients
- Galaxies
- Active Galactic Nuclei
- Informatics and Statistics
- Dark Energy

The LSST Dark Energy Science Collaboration

Prepare for and carry out cosmology analyses with the LSST survey

- five key cosmology probes, organized in Working Groups (WG)
  - Galaxy Clustering, Galaxy Clusters, Strong Lensing, Supernovae, Weak Lensing; Theory & Joint Probes
- "Enabeling Analyses" WGs: understand LSST system + systematics

lots of work until 2019, lots to learn from ongoing surveys!

The LSST Dark Energy Science Collaboration

DESC cosmology likelihood - late 2015
to be implemented within Science WGs

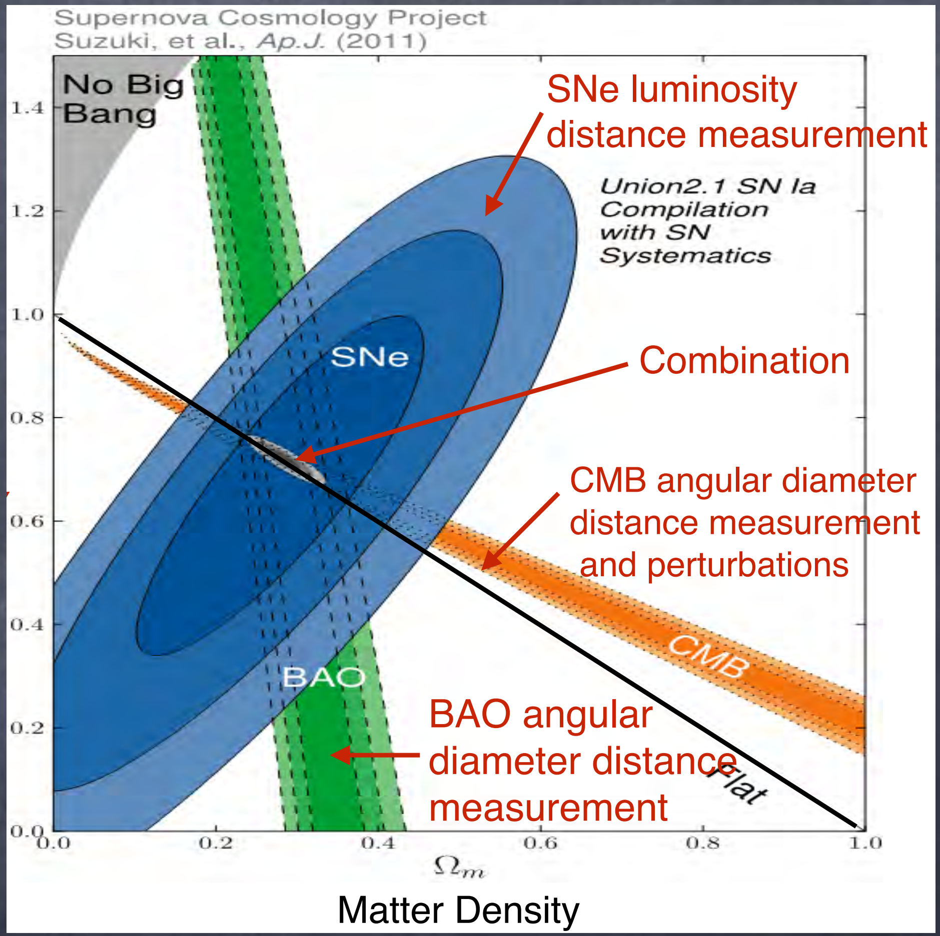
Prepare for and carry out cosmology

- five key cosmology probes, organiz
  - Galaxy Clustering, Galaxy Clusters, Str
    Theory & Joint Probes
- “Enabeling Analyses” WGs: underst

lots of work until 2019, now is a good time for new ideas!

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

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

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

Cosmology Priors

Nuisance Parameters

systematic effects

$|\mathbf{n}| \gg |\boldsymbol{\pi}|$

parameterize + prioritize!

Priors

External Data

Simulations

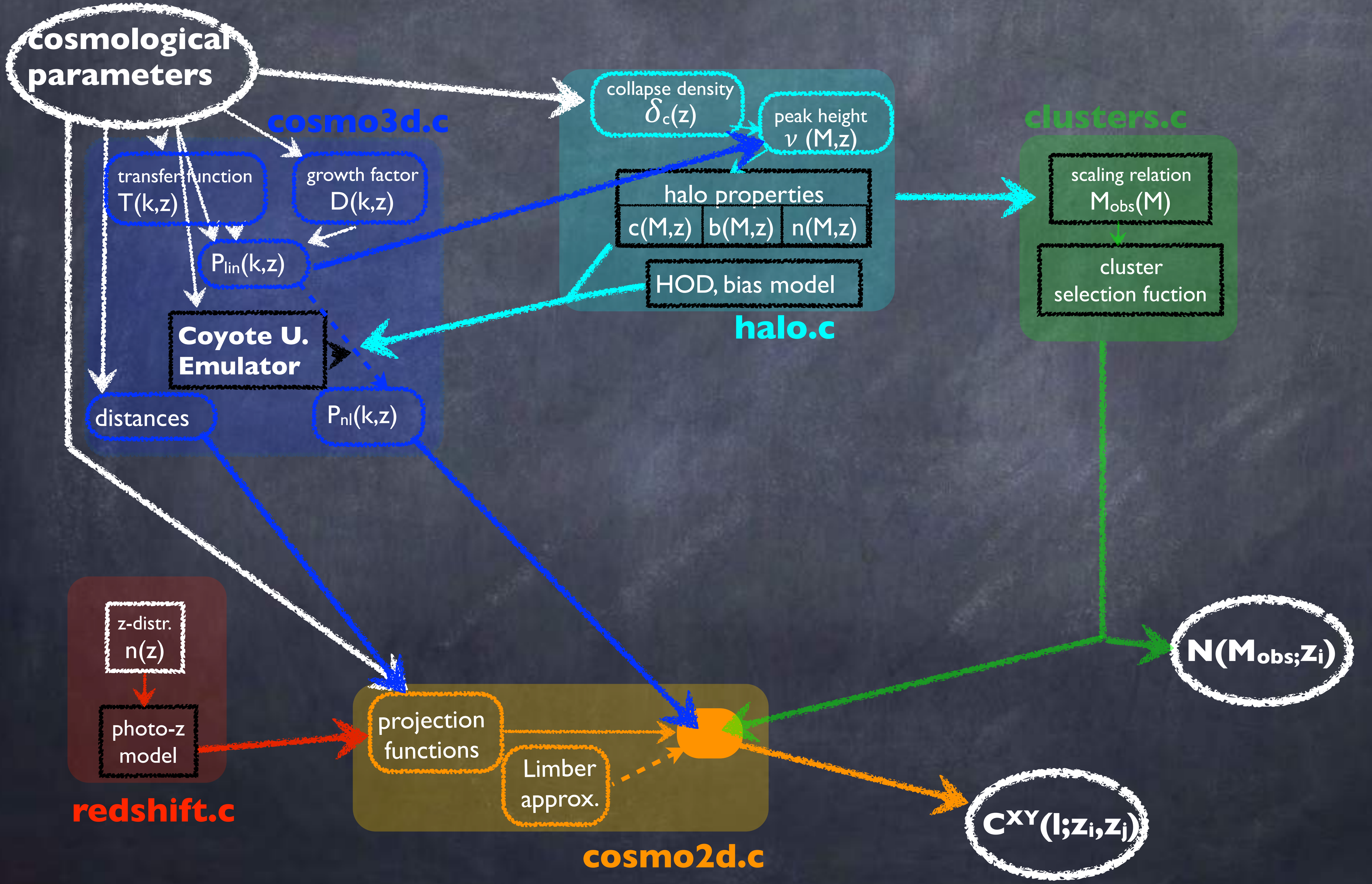
validate

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



Combined Probes Forecasts: Covariance

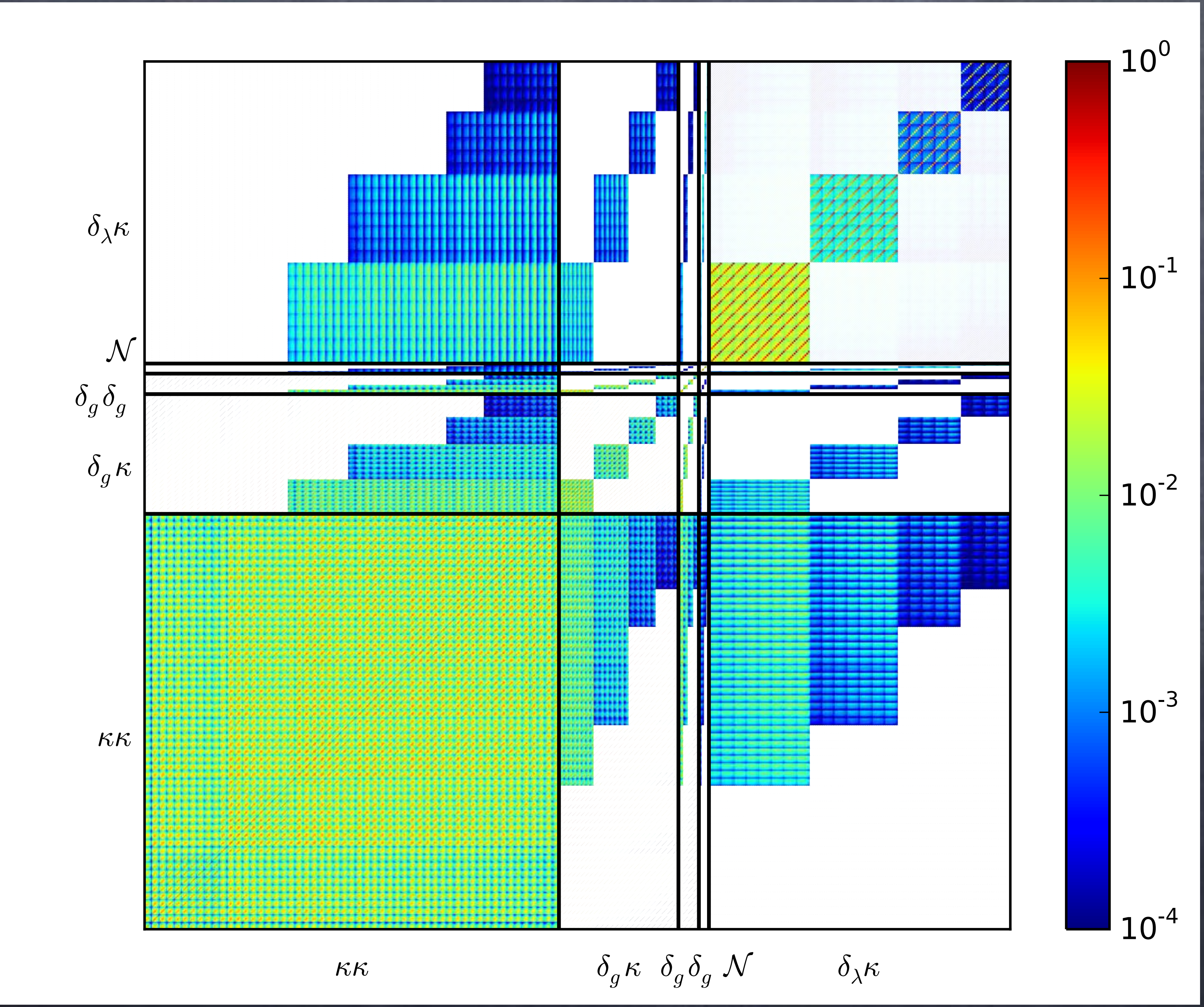
- SN uncorrelated, hooray [for now].
- Analytic covariance for everything else:
  - halo model bispectrum + trispectrum, sample variance
    - Cov (N,N): Poisson + power spectrum
    - Cov (<δδ>, N): bispectrum, power spectrum
    - Cov (<δδ>, <δδ>), etc.: Covariance of 2pt statistics of (projected)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

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

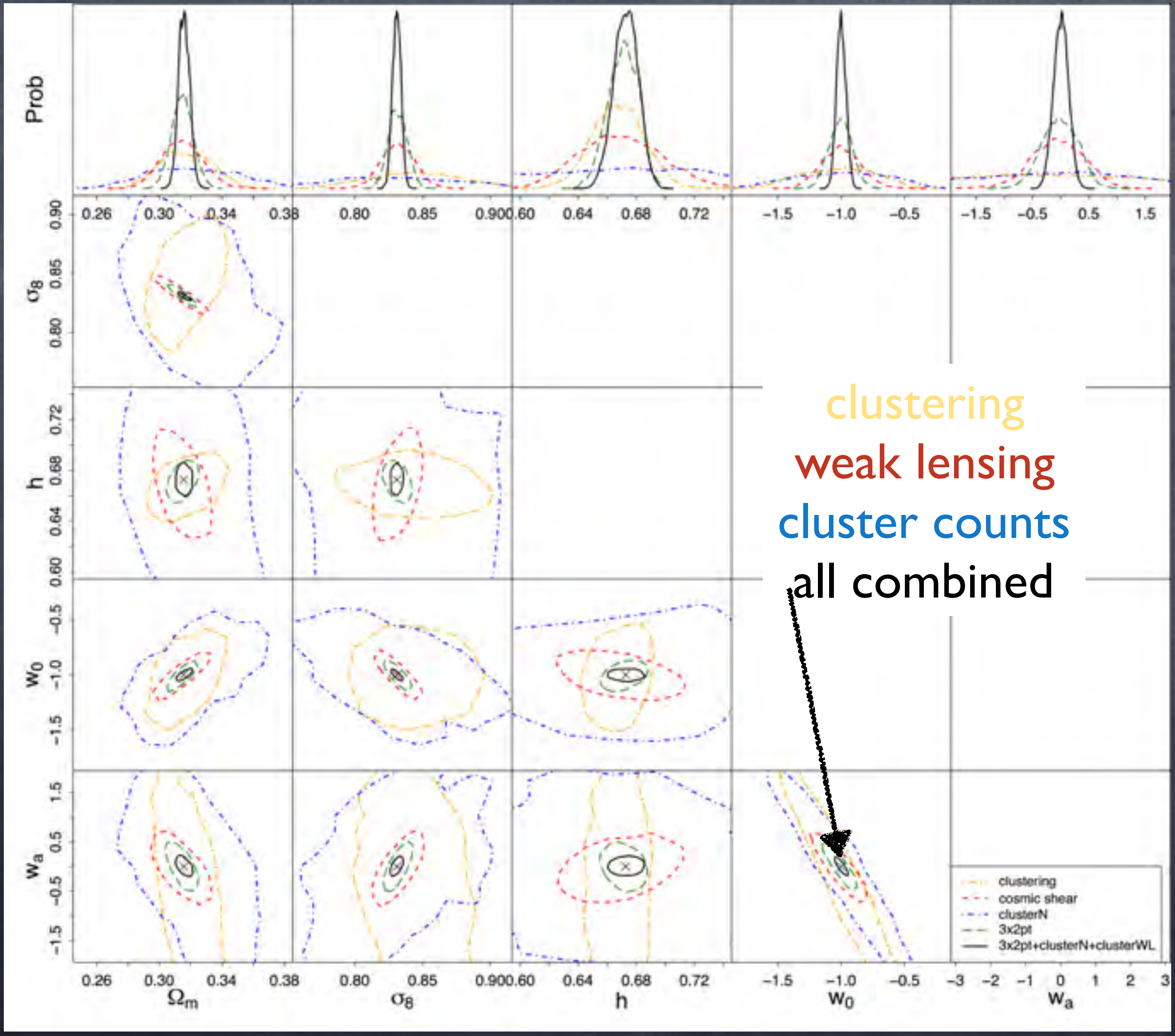
- LSST forecasts: > 7 million elements...

Combined Probes Forecasts: Covariance



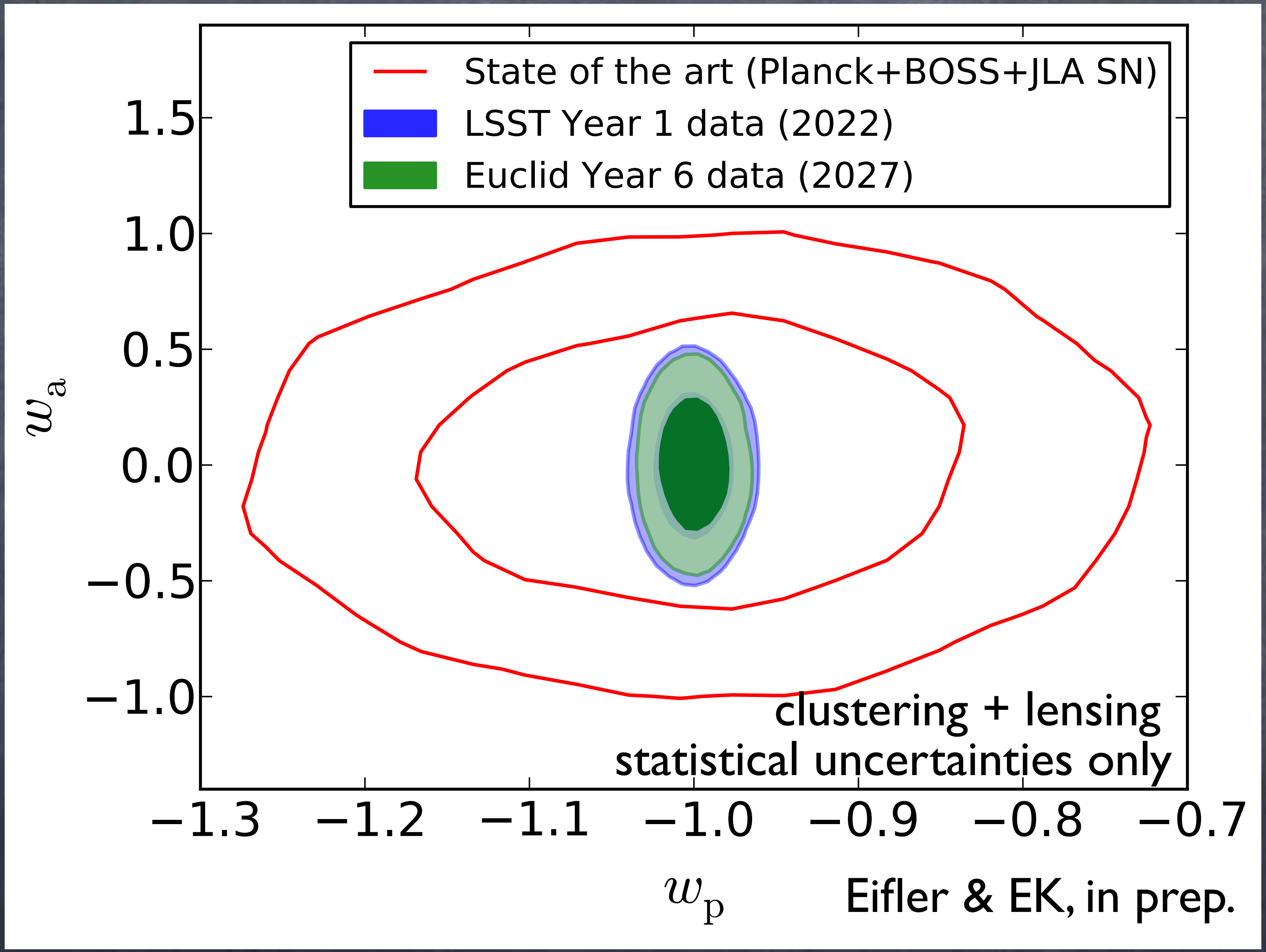
details: EK & Eifler'16

The Power of Combining Probes



EK & Eifler'16

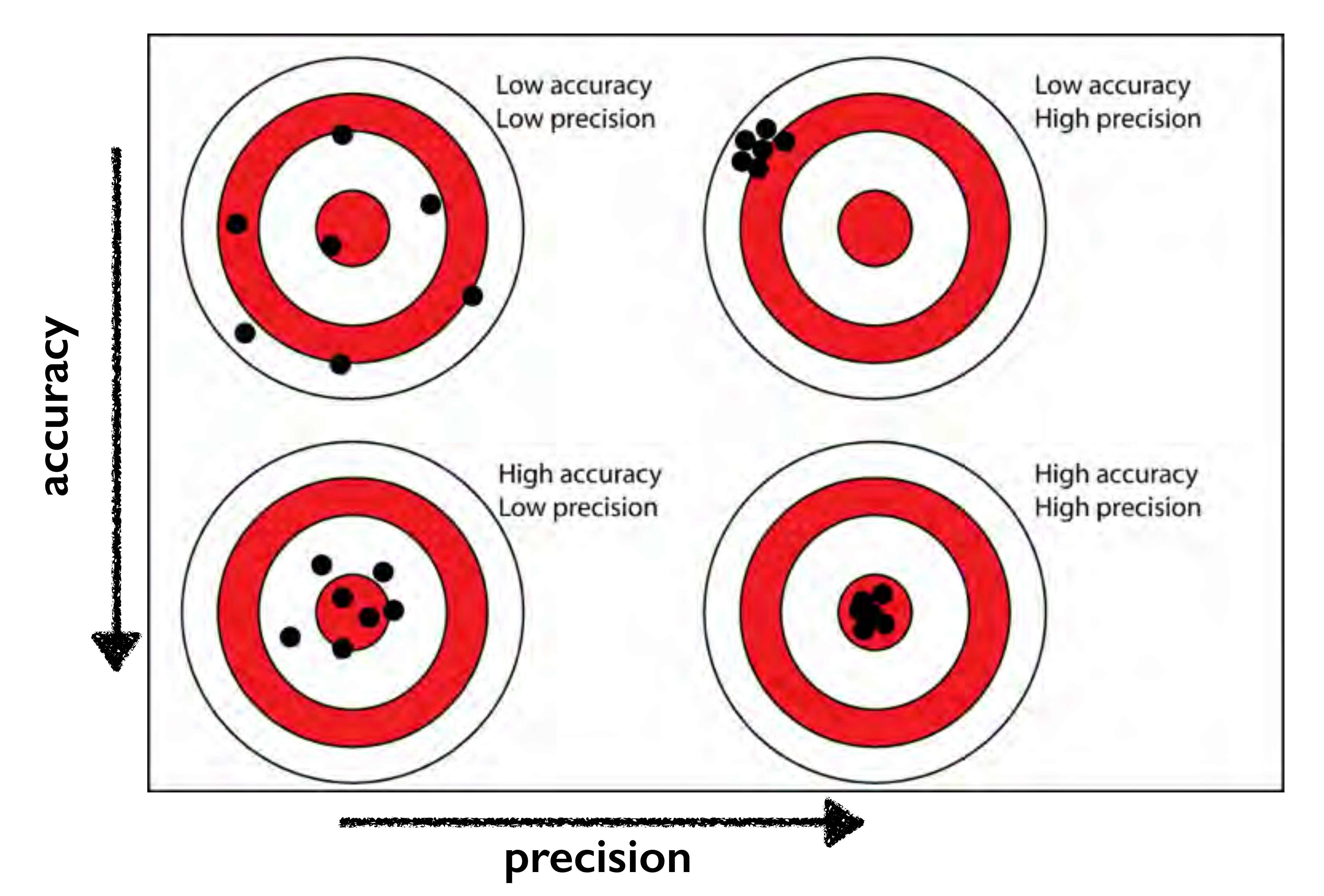
The LSST Awakens



LSST Year 1 data will be deeper and wider than complete Euclid survey

cosmology analyses will be exciting from the start!

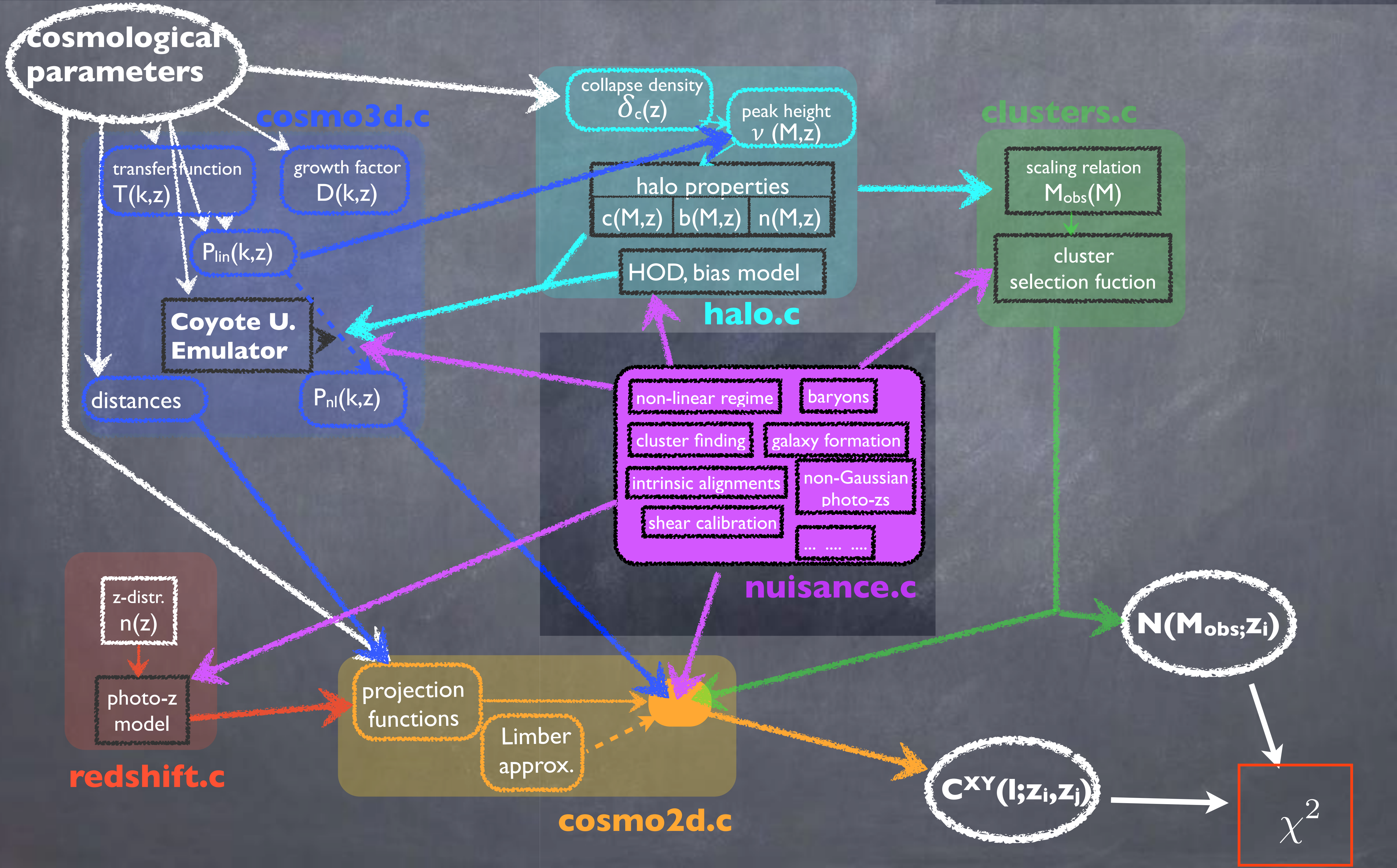
‘Precision’ Cosmology



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



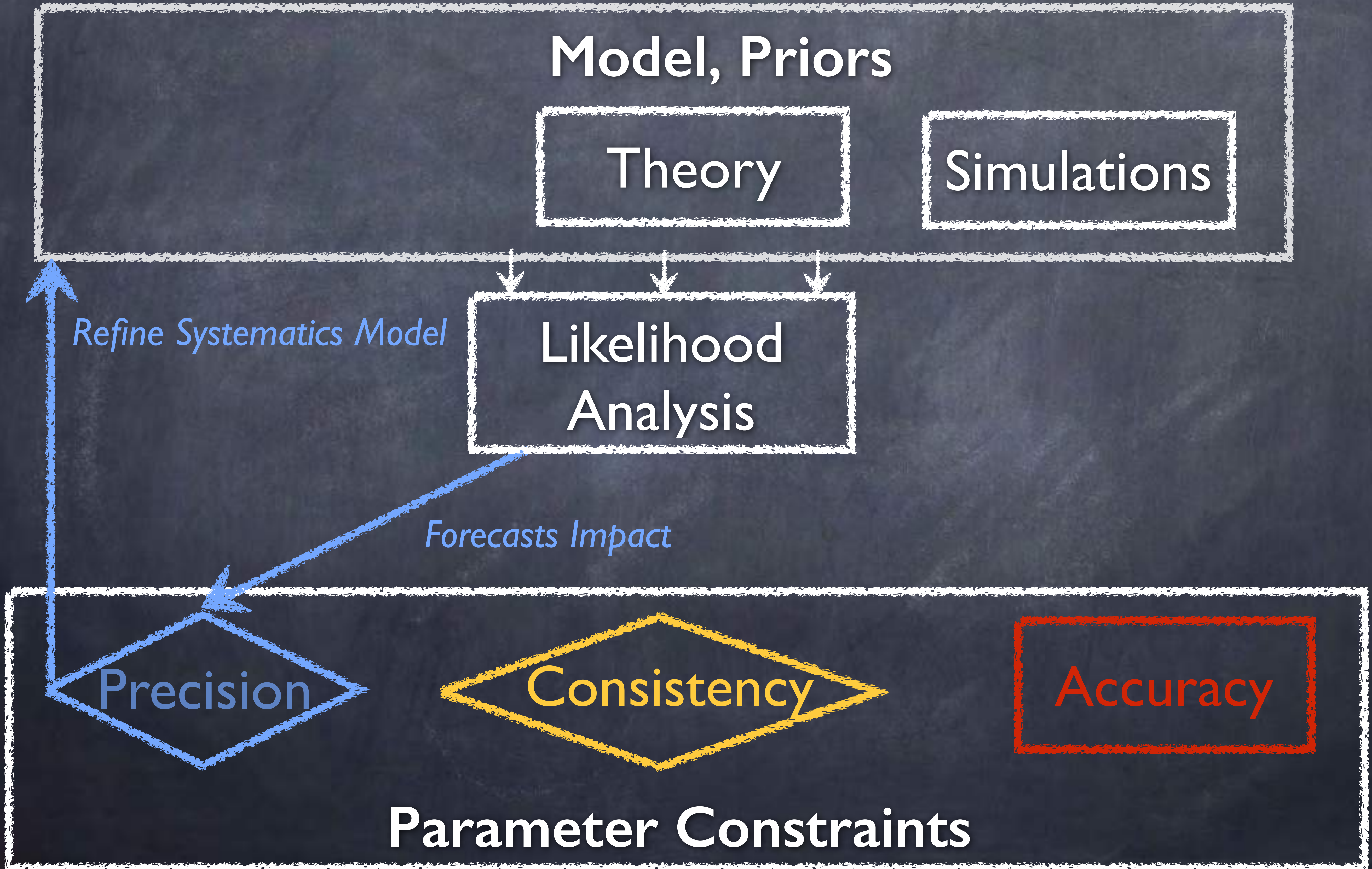
Work Plan for *Known* Systematics

- What's the dominant known systematic?

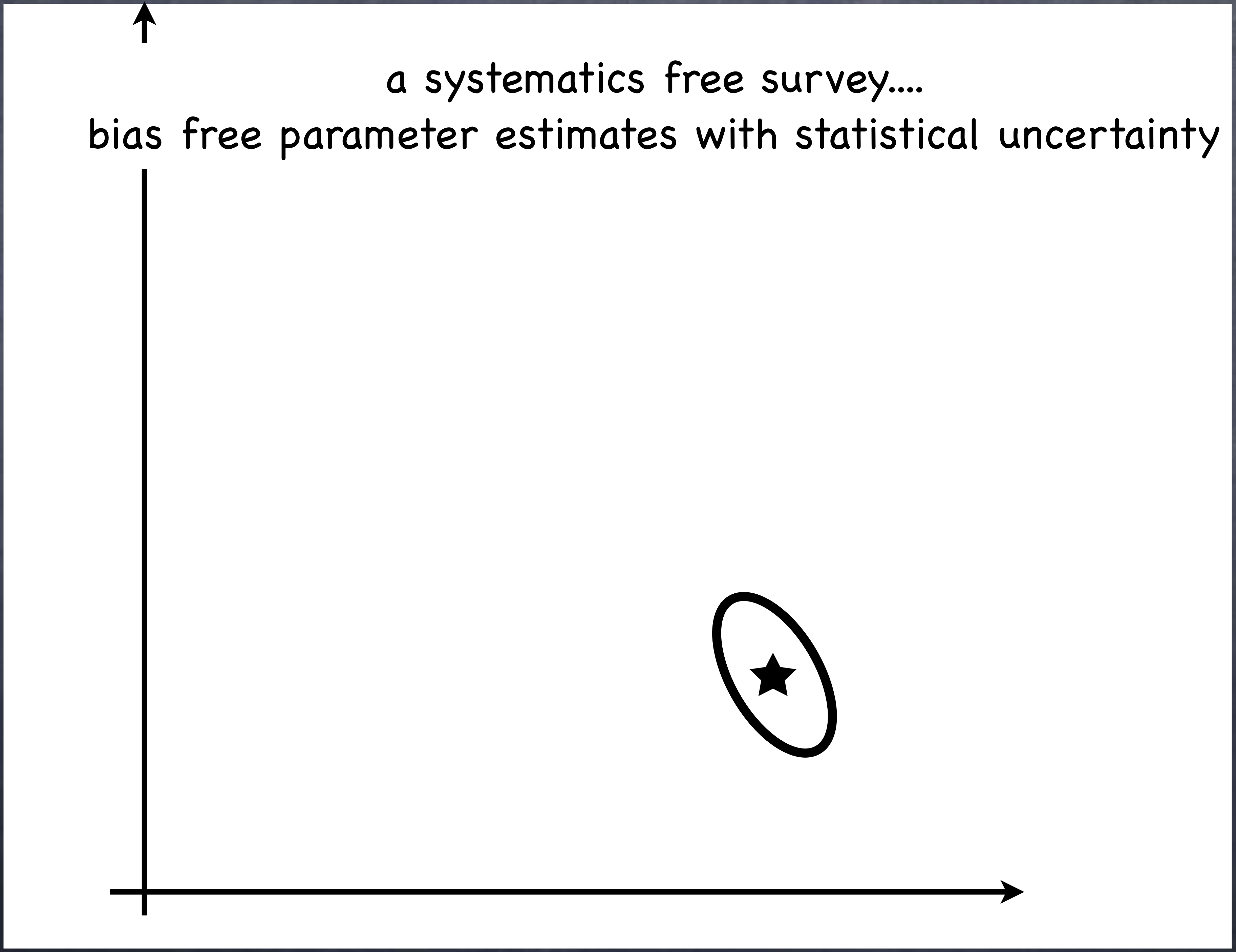
  No one-fits-all answer, need to be more specific!

- 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 I



The Trouble with Systematics



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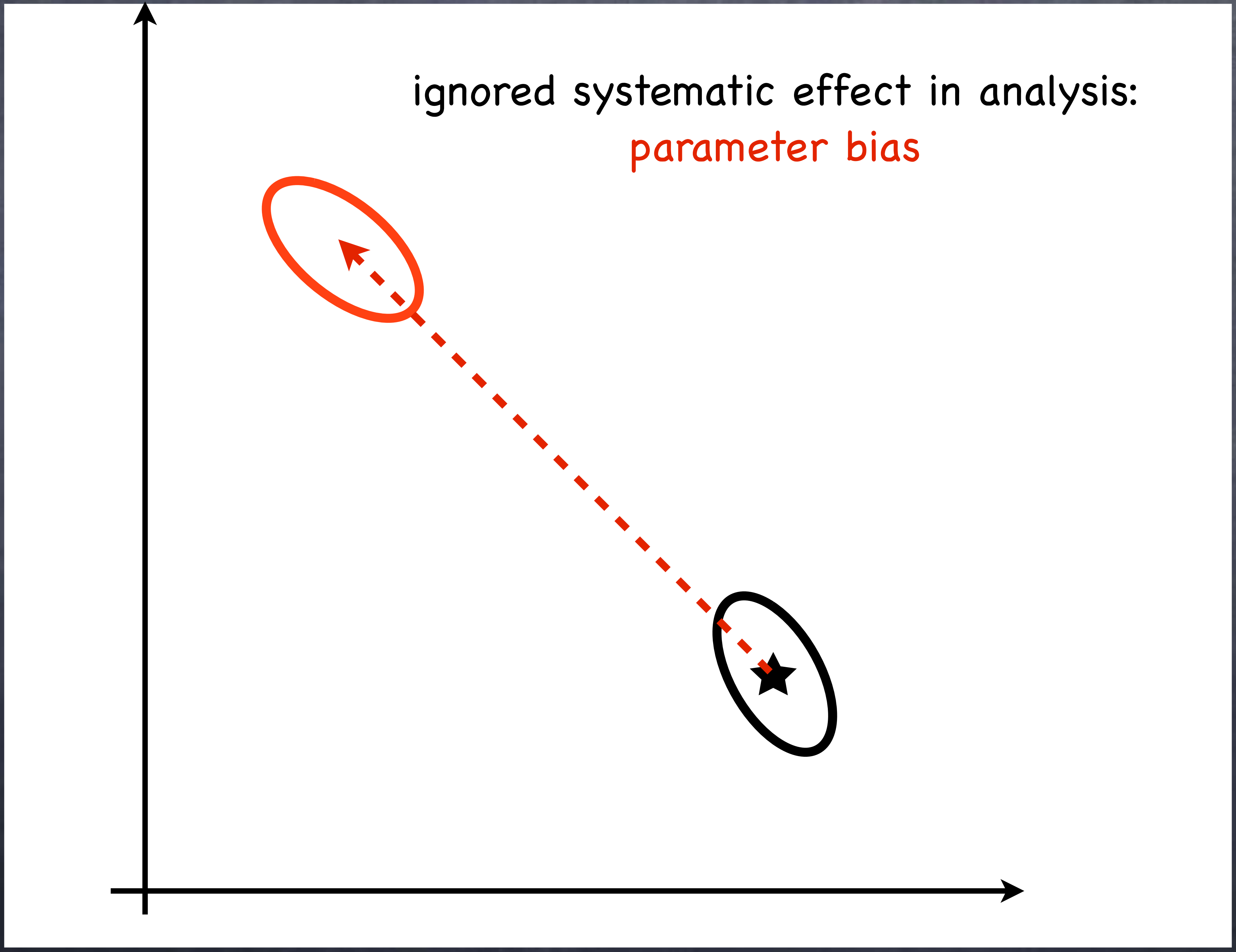

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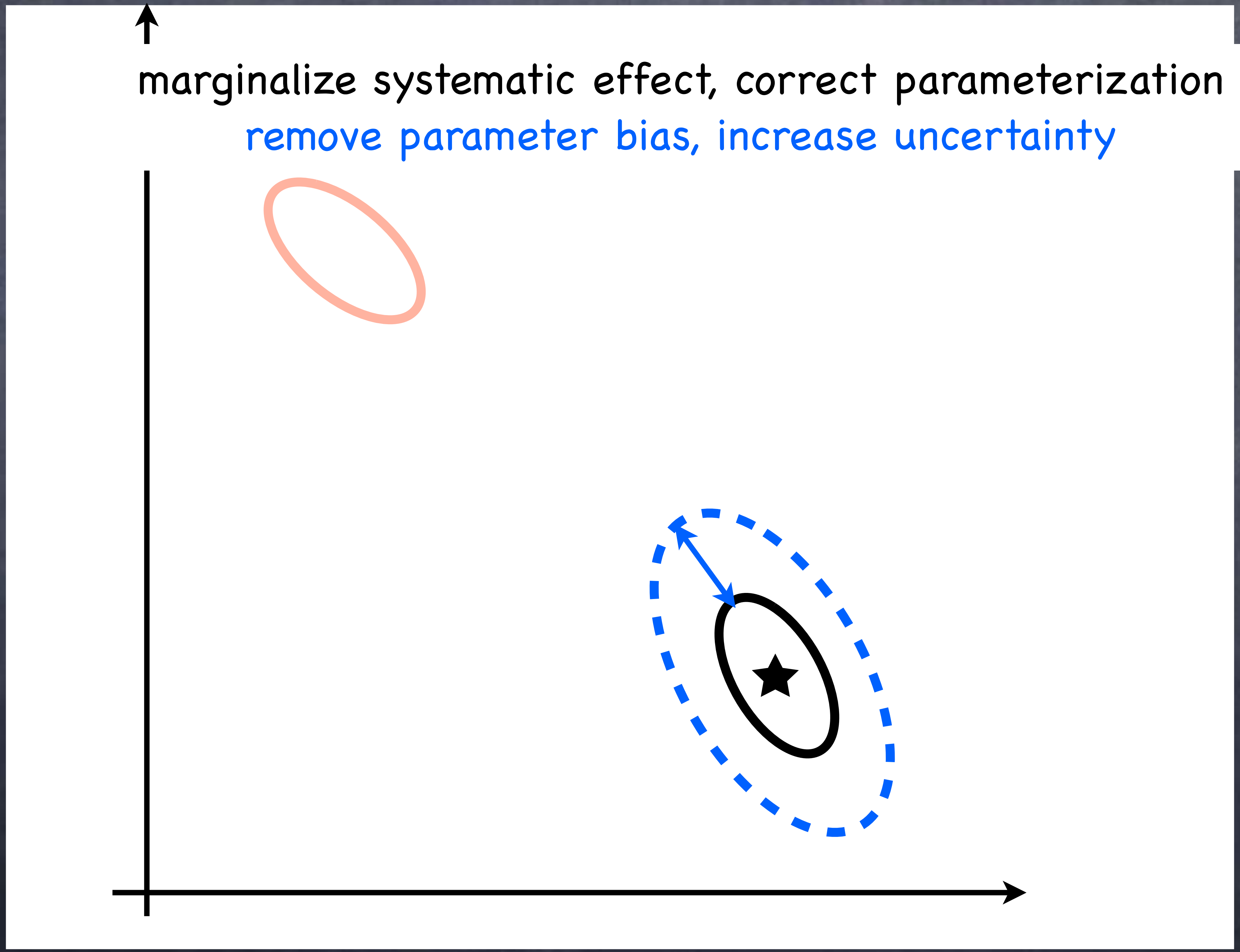

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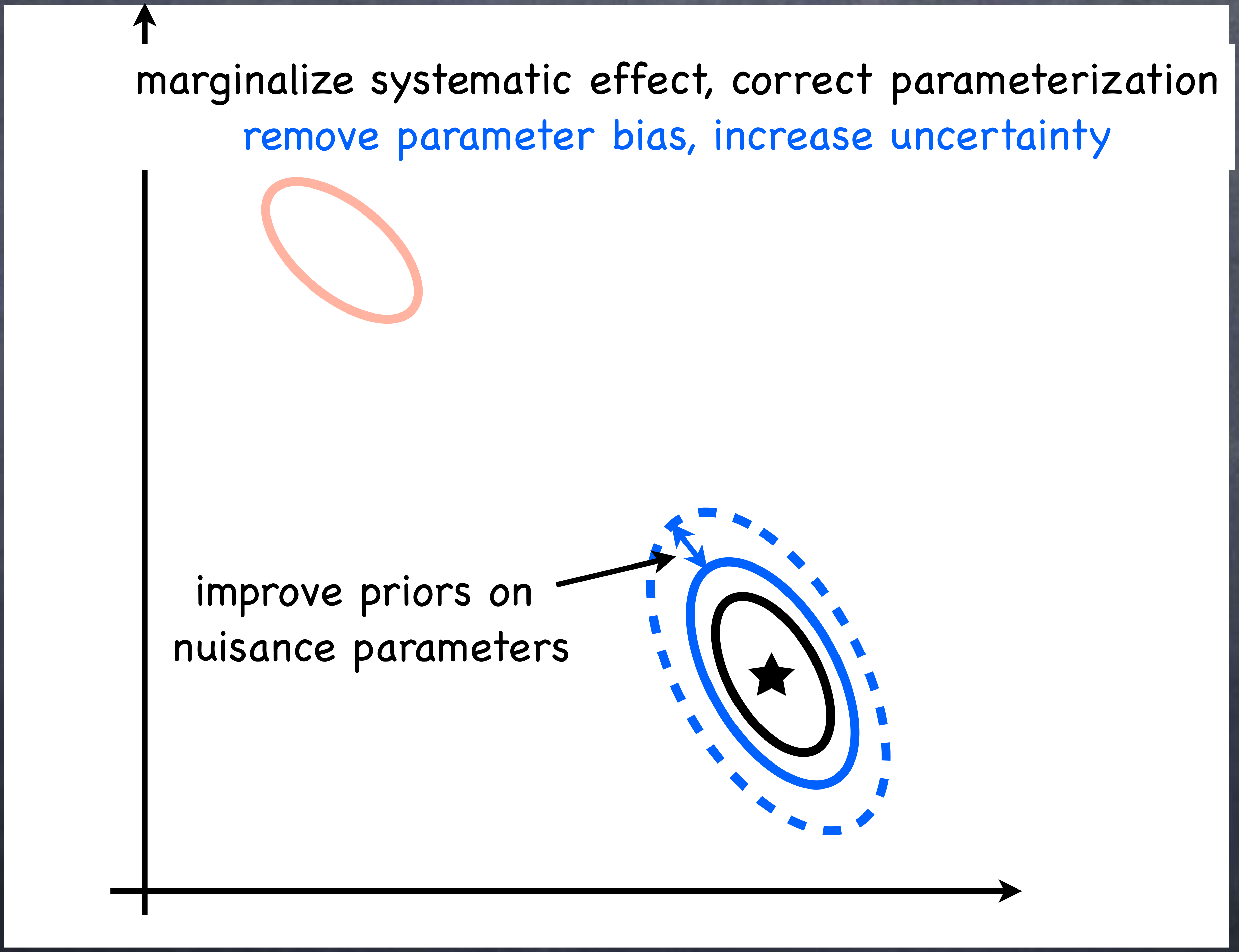

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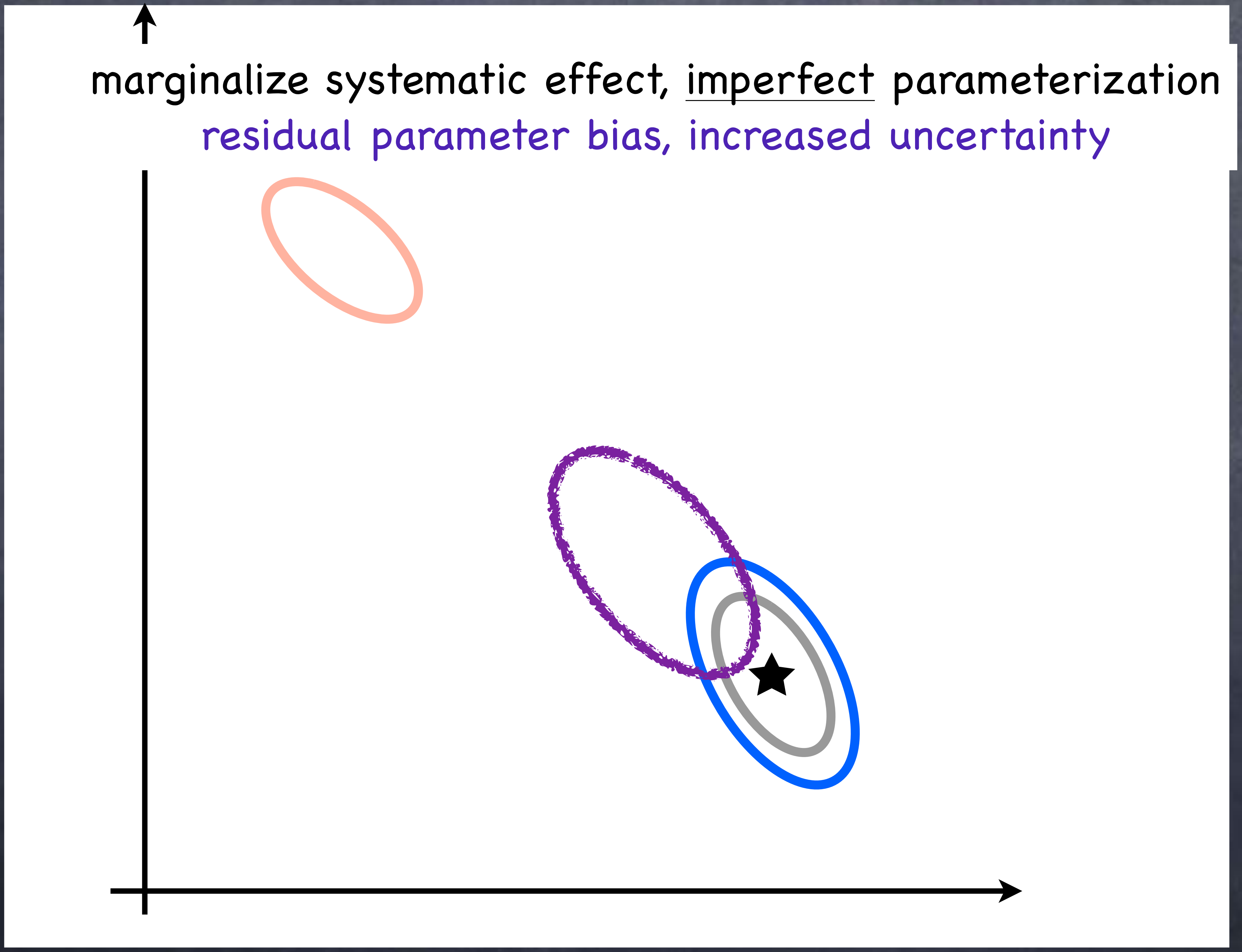
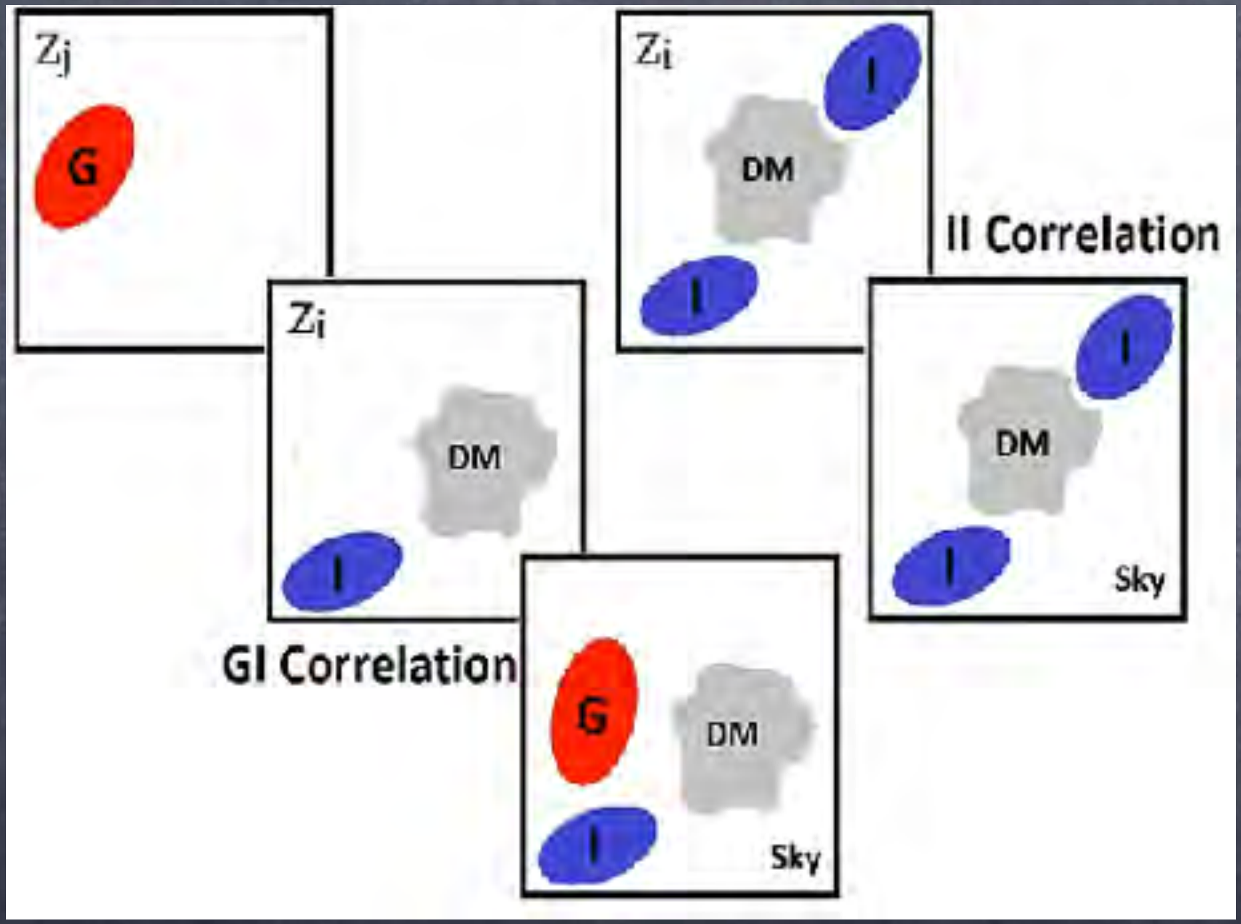


Intrinsic Alignments

- 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

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

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

Linear IA Models

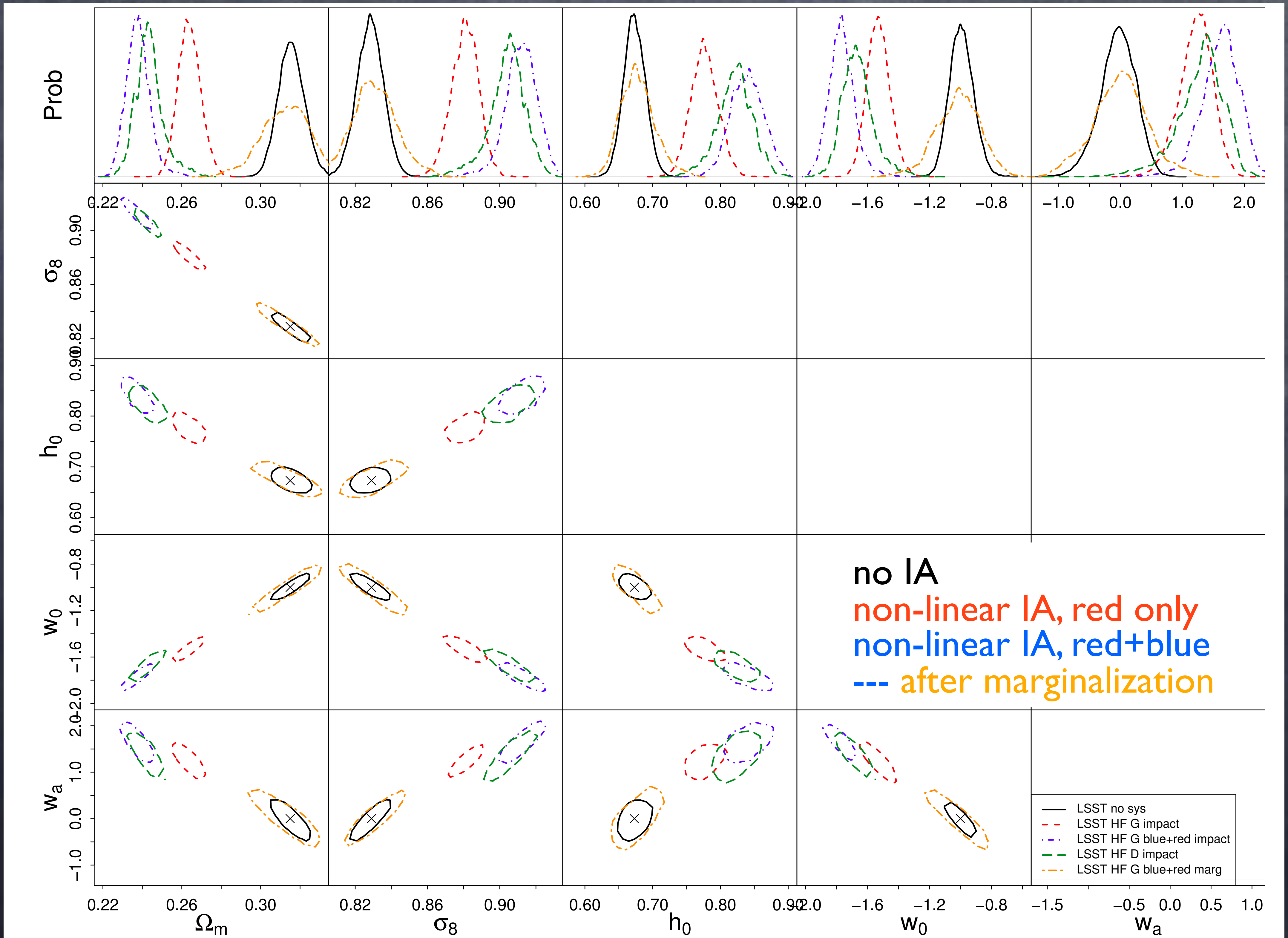
$$P_{\rm GI}(k,a) = A(L,a,\Omega_{\rm M},?) f_{\rm GI}\left(P_\delta(k,a), P_{\rm lin}(k,a), ?\right)$$

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

- 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)

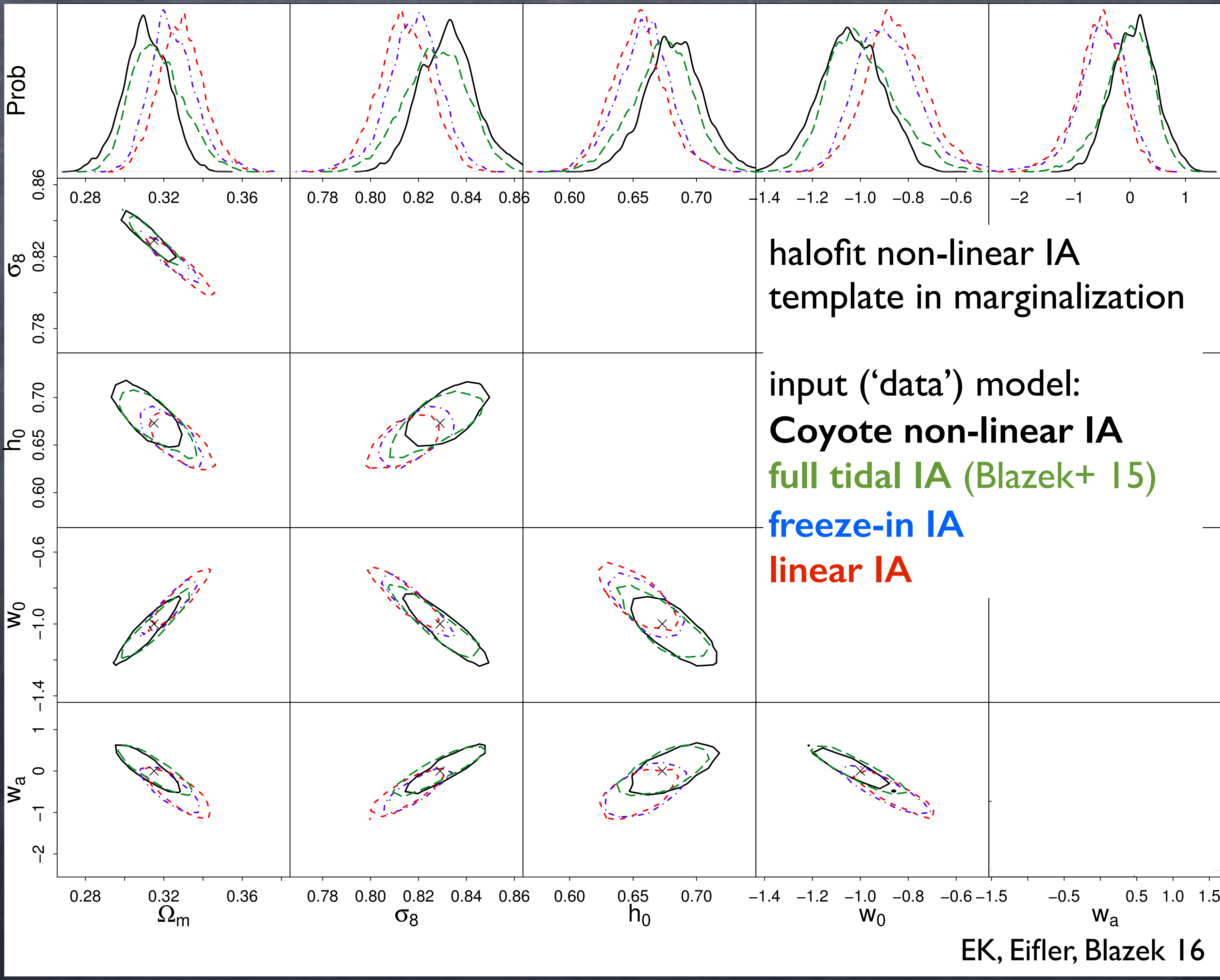
    $$A = A_0 \left(\frac{L}{L_0}\right)^\beta \left(\frac{1+z}{1+z_0}\right)^\eta$$
  - if only red galaxies aligned $A \to A \times f_{\rm red}$
  - what's $\langle A \rangle_L$, f_{red} for deep surveys like LSST/WFIRST?
    - so far, extrapolate LF from shallower surveys (GAMA, DEEP2)

Impact of Linear Alignments LSST WL



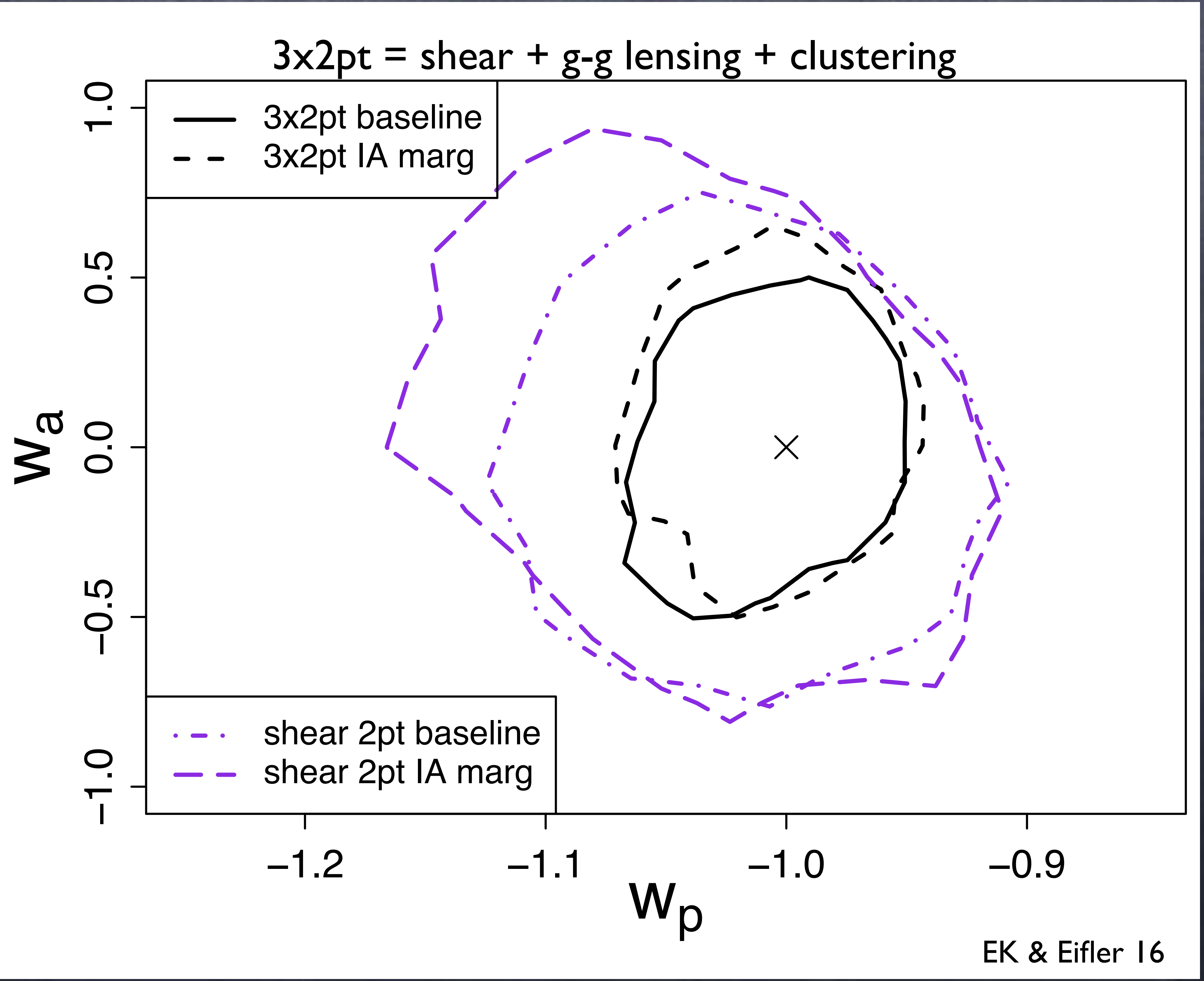
IA Mitigation: Amplitude marginalization, power spectrum shape uncertainties

- 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



IA Mitigation: multi-probe to the rescue

- Marginalized over IA amplitude normalization + redshift scaling (A_0, β, η, η_{high-z}), 6 LF parameters
- also include shear calibration, photo-z, galaxy bias uncertainties
- joint analysis with g-g lensing + clustering reduces (relative) degradation from IA marginalization



IA Summary

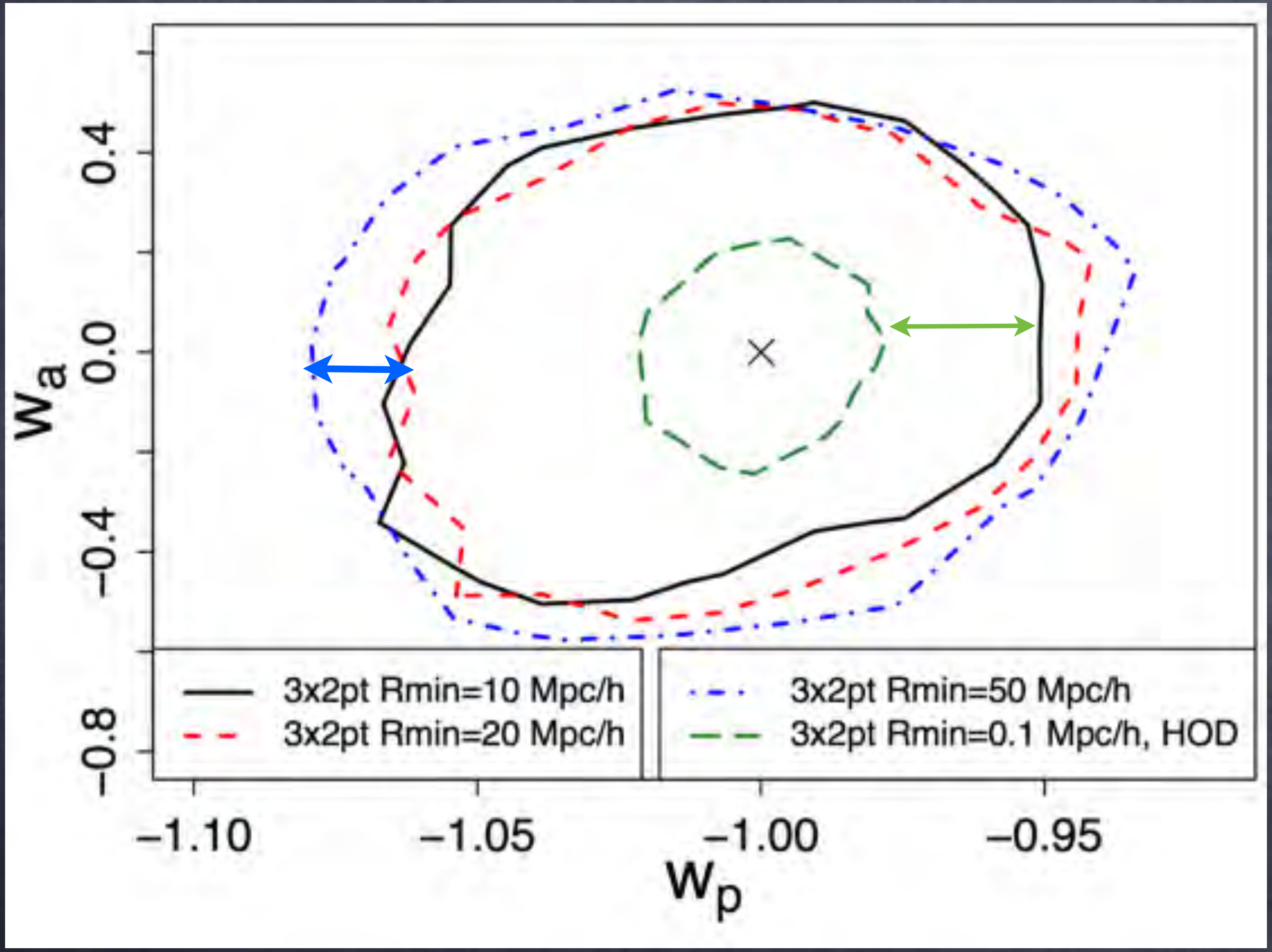
forecasts for tidal alignment contamination of LSST WL

- 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*

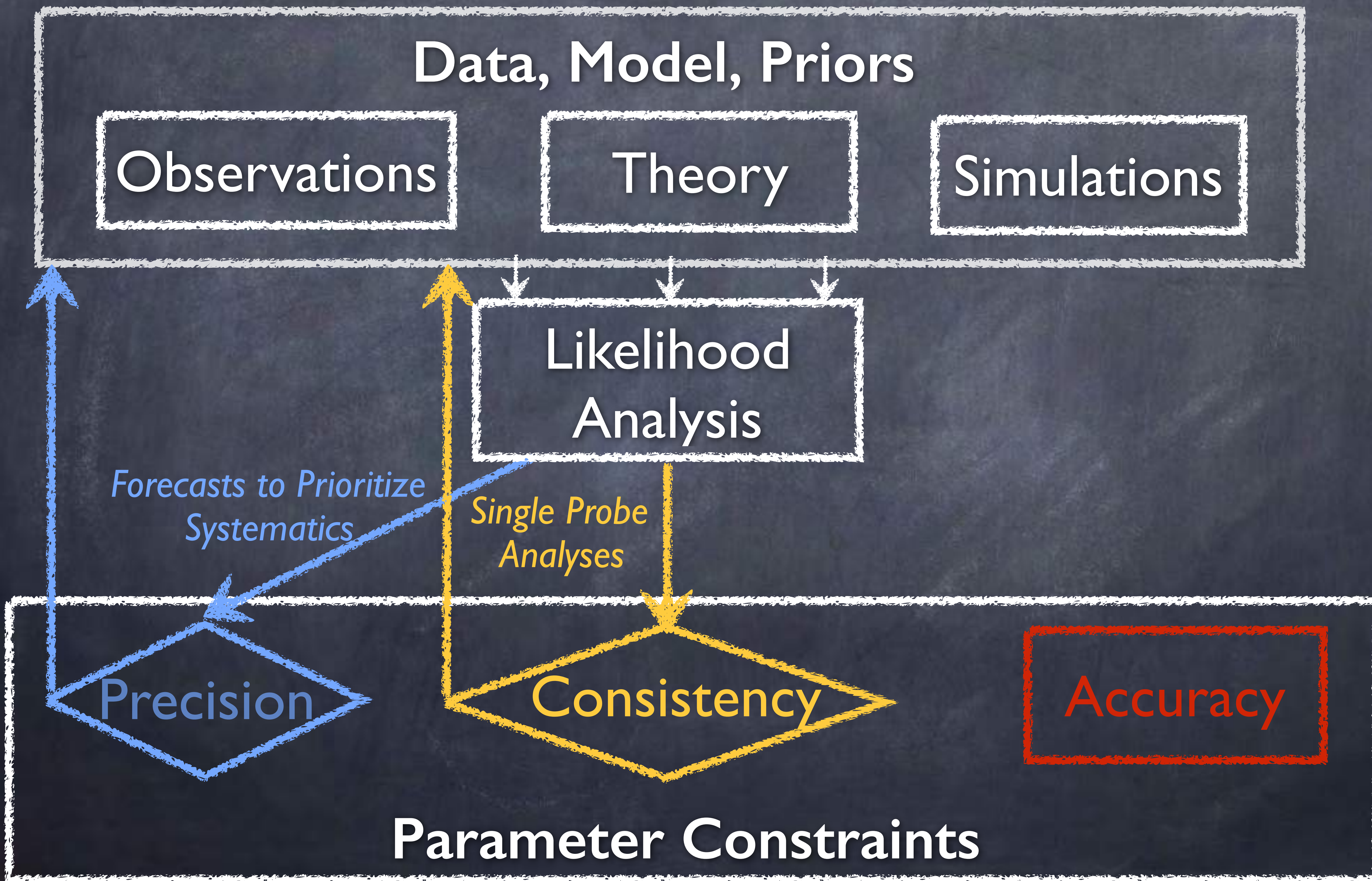
Cosmology Gains from Modeling Galaxy Bias



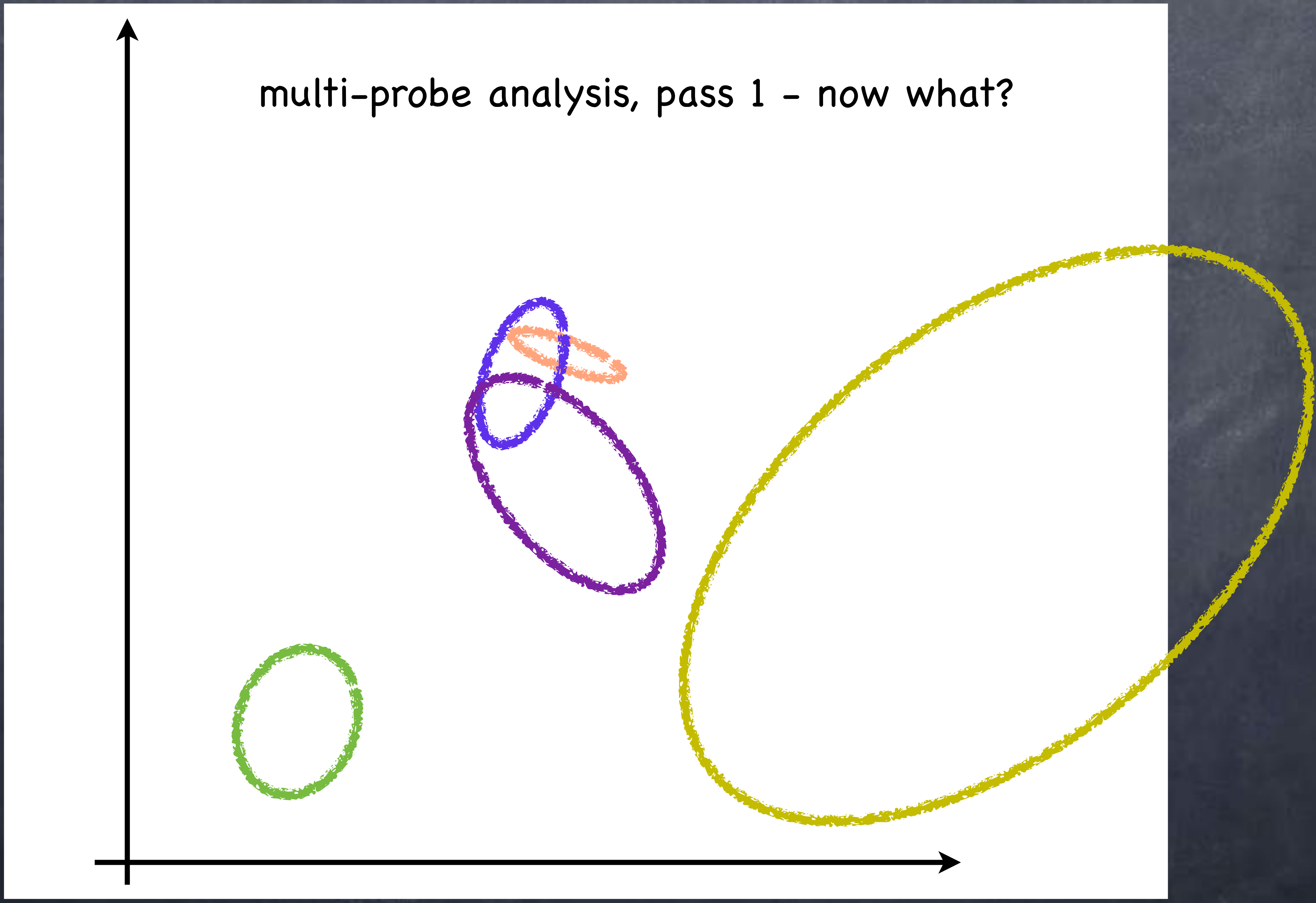
LSST, WL + clustering
WL to l < 5000
clustering: vary cut-off scales
develop perturbative biasing up to k ~ 0.6 h/Mpc - with well-constrained new parameters
understand non-linear regime

details: EK & Eifler 16

Joint Analysis Work Plan

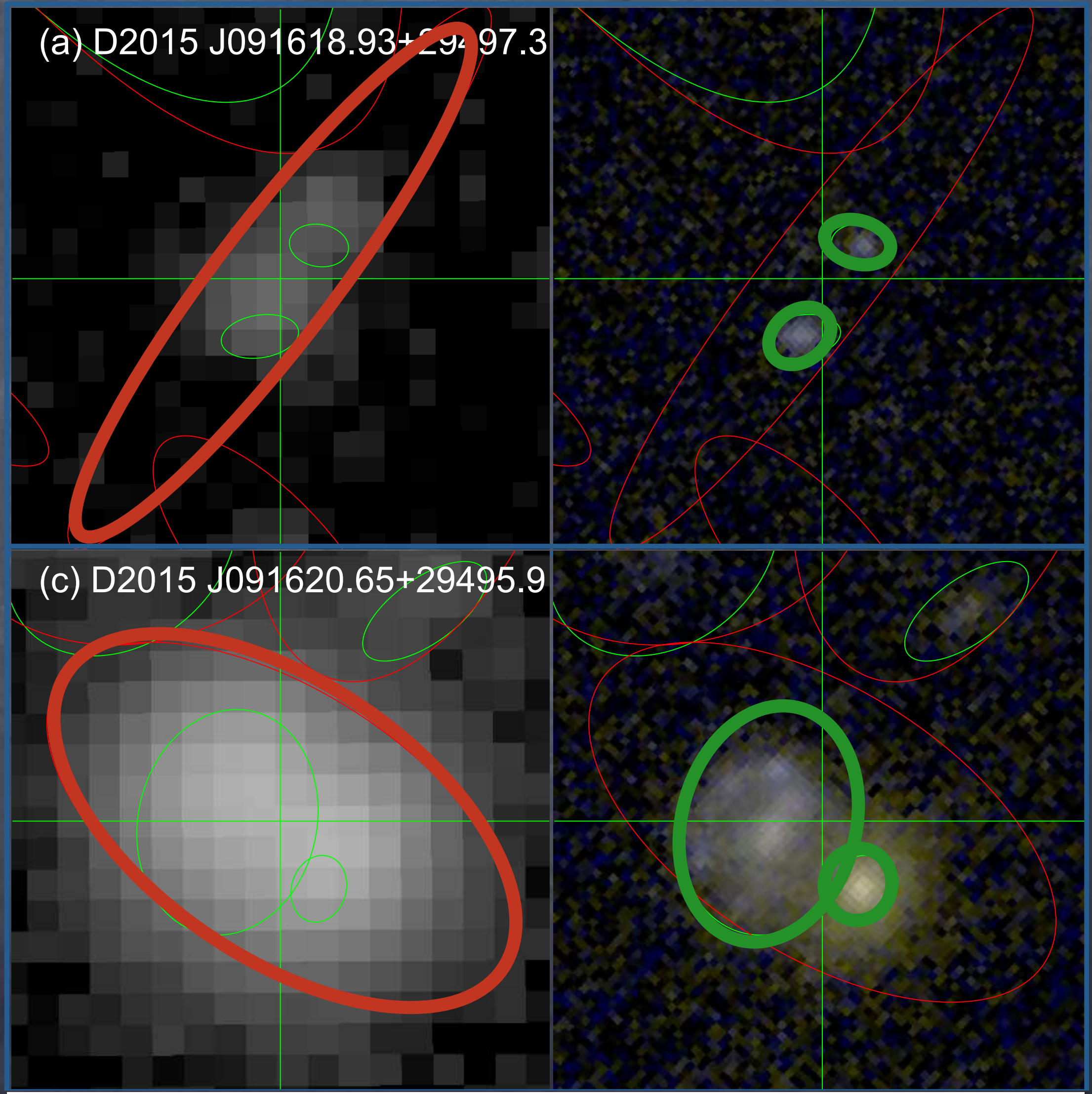


Unknown Systematics? vs. New Physics?



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]



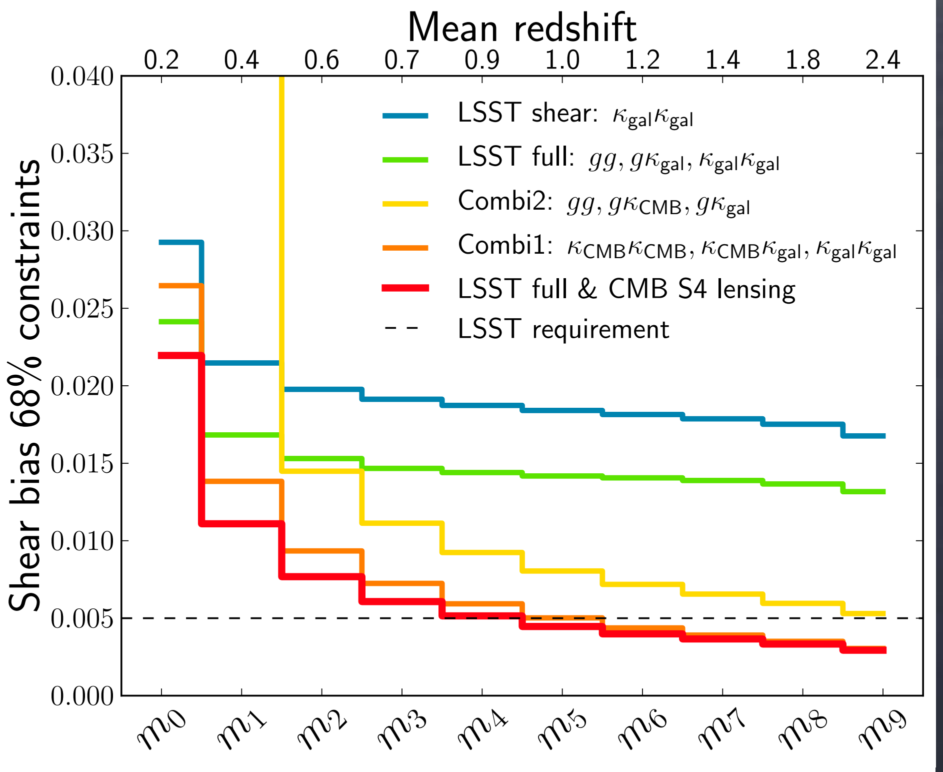
Subaru HST-ACS
ground vs. space-based shape measurements
Dawson+ 2016

Unknown Systematics? vs. New Physics?

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

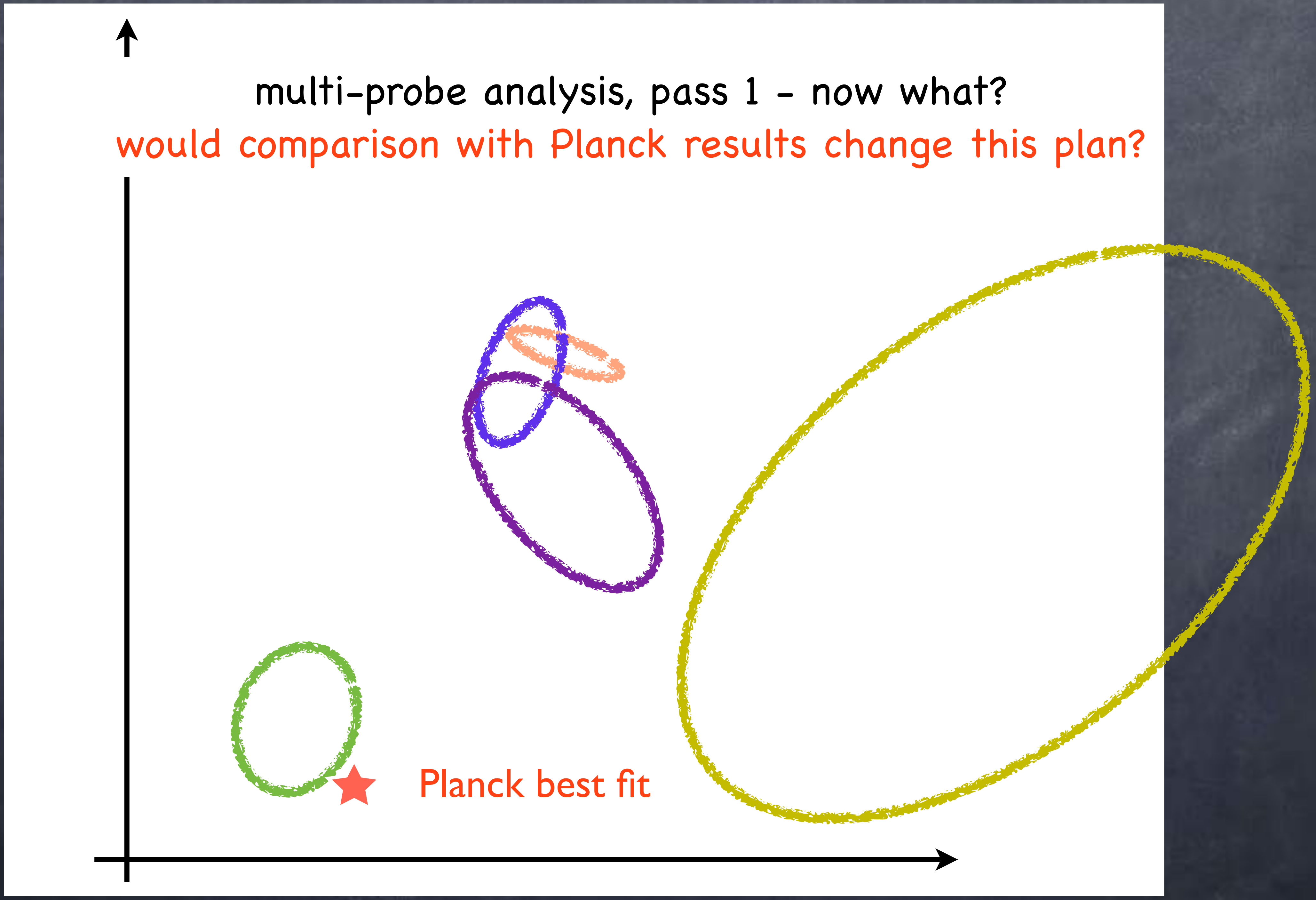
    [potentially expensive]
- correlate with different surveys
  - predict cross-correlations based on LSST analysis
  - constrain uncorrelated systematics
  - e.g., cross-correlation with CMB-S4 lensing
- invent optimized estimators

  [fun, but not a general solution]



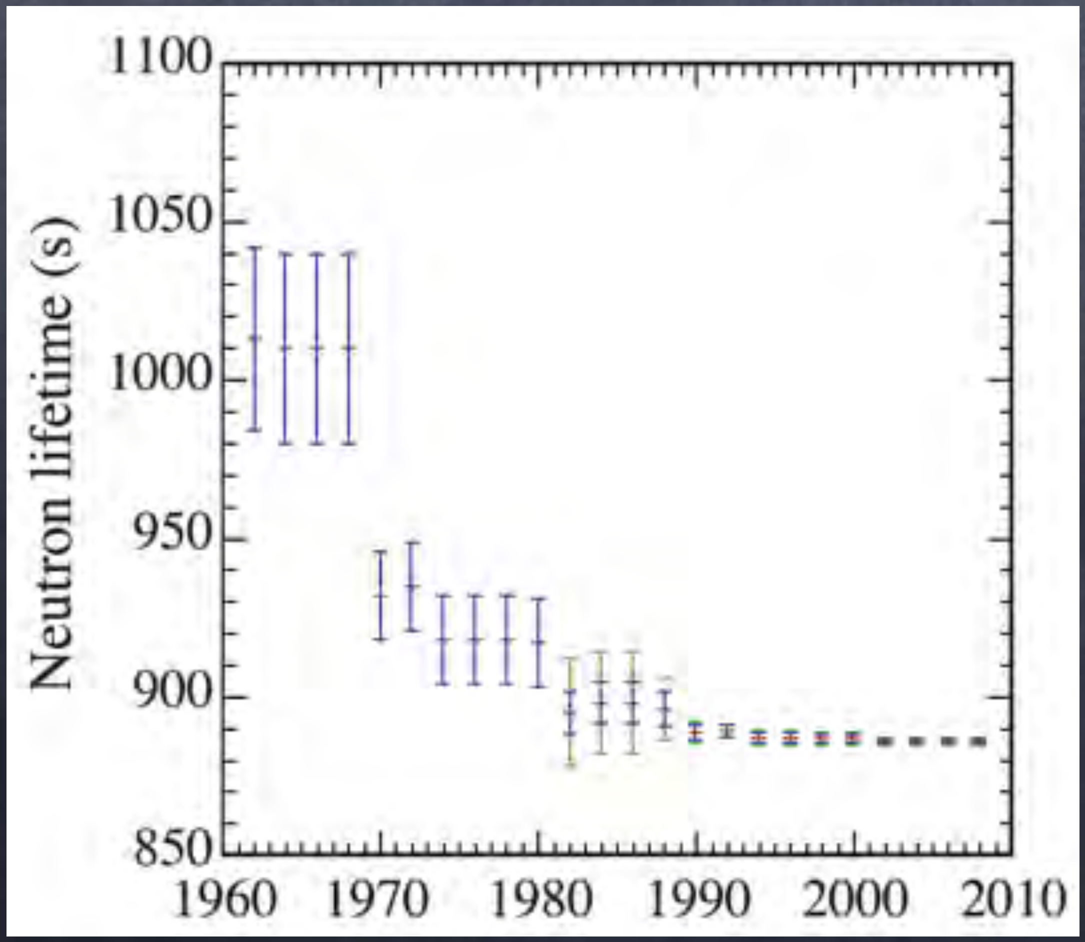
LSST WL x CMB-S4 lensing
calibrate shear calibration bias
Schaan, EK,+ 2016

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

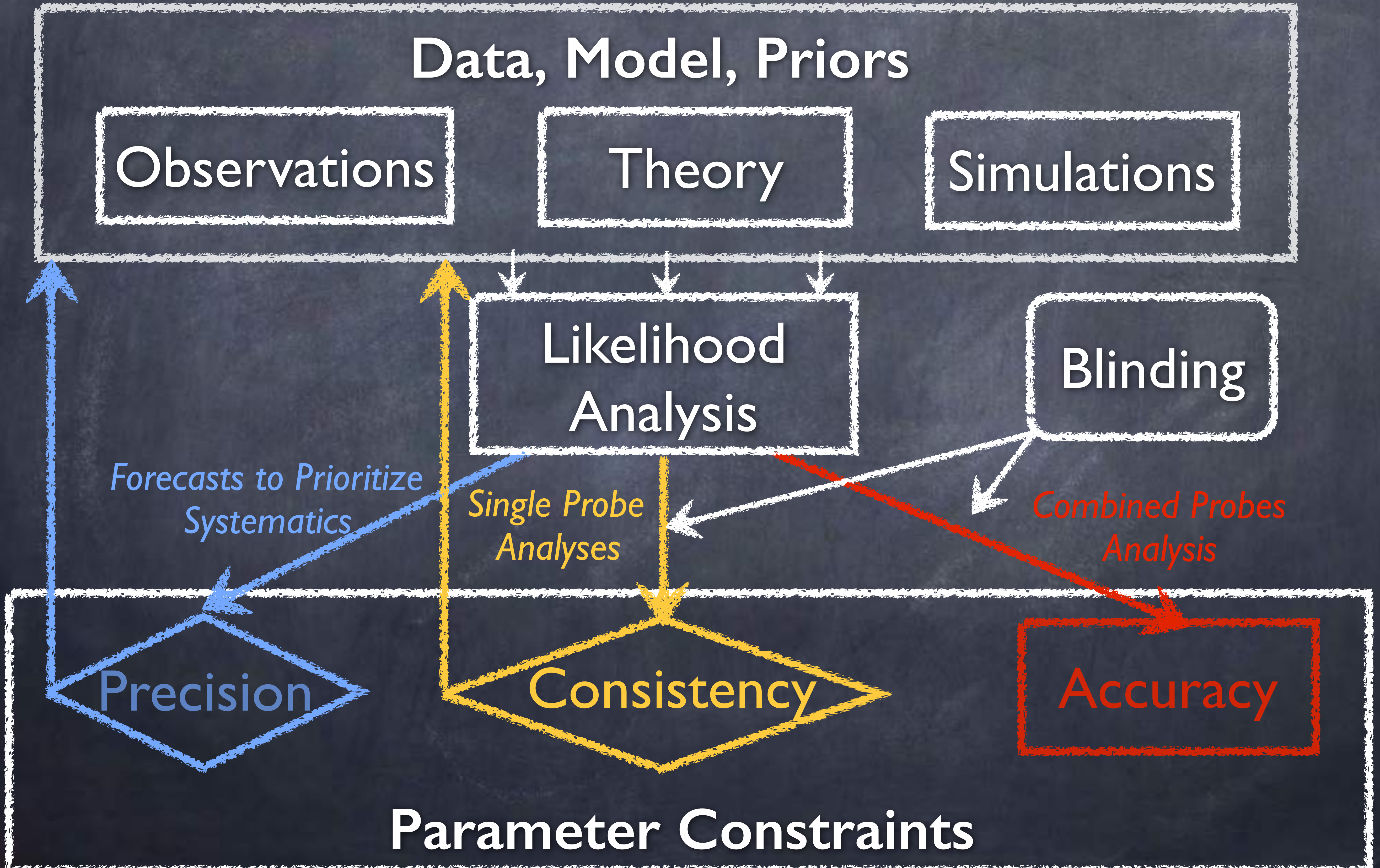
Blind Analysis Strategies for DES-Y3

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

$$\hat{w}(\theta) \to \hat{w}(\theta) + \frac{\partial w}{\partial \Omega_\mathrm{m}} \Delta\Omega_\mathrm{m}$$

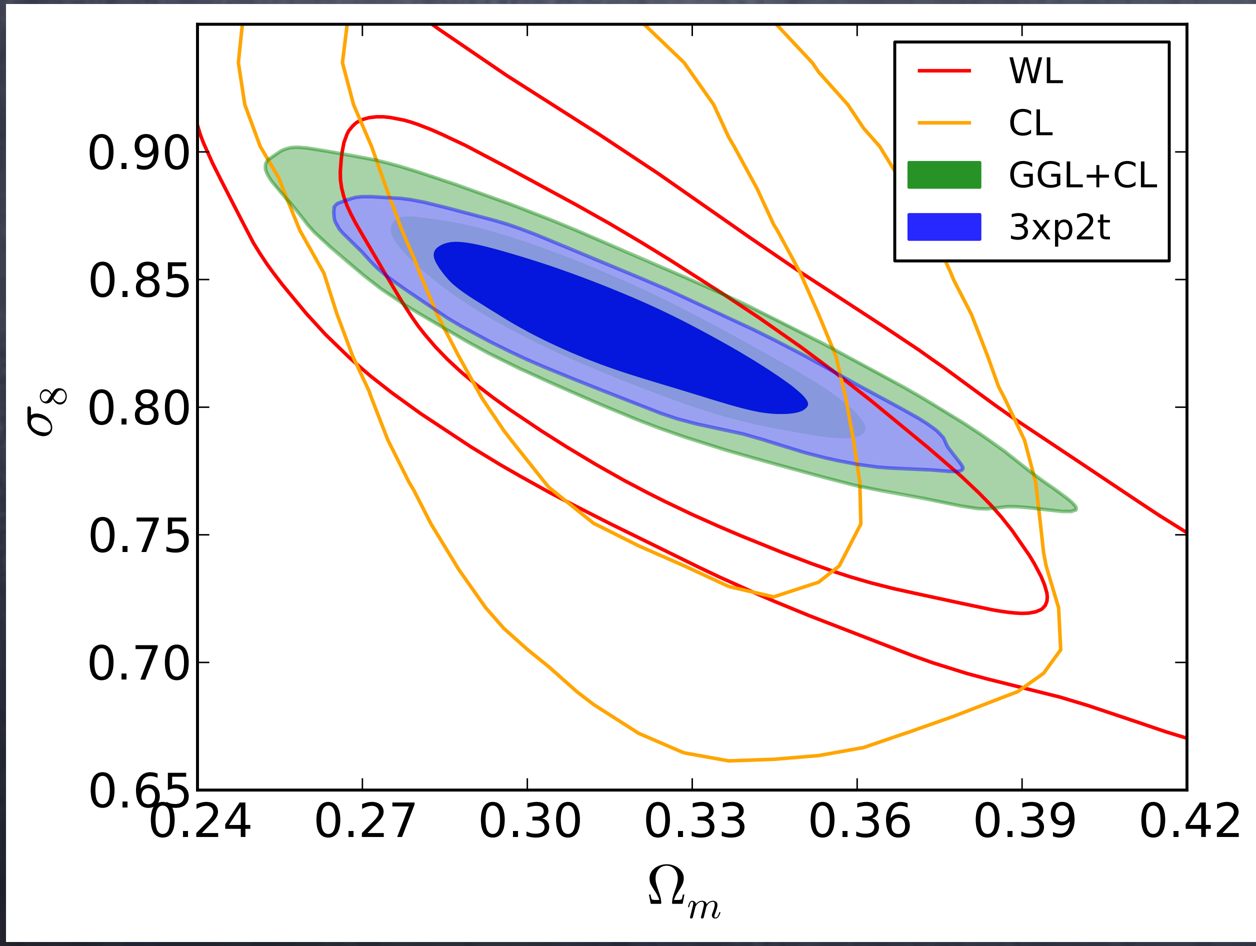
    - still defining null-test, 'allowed' plots for sample selection
  - parameter estimation
    - off-set all parameter results by (constant) random numbers
    - needed: decisions on models to run, model selection criteria

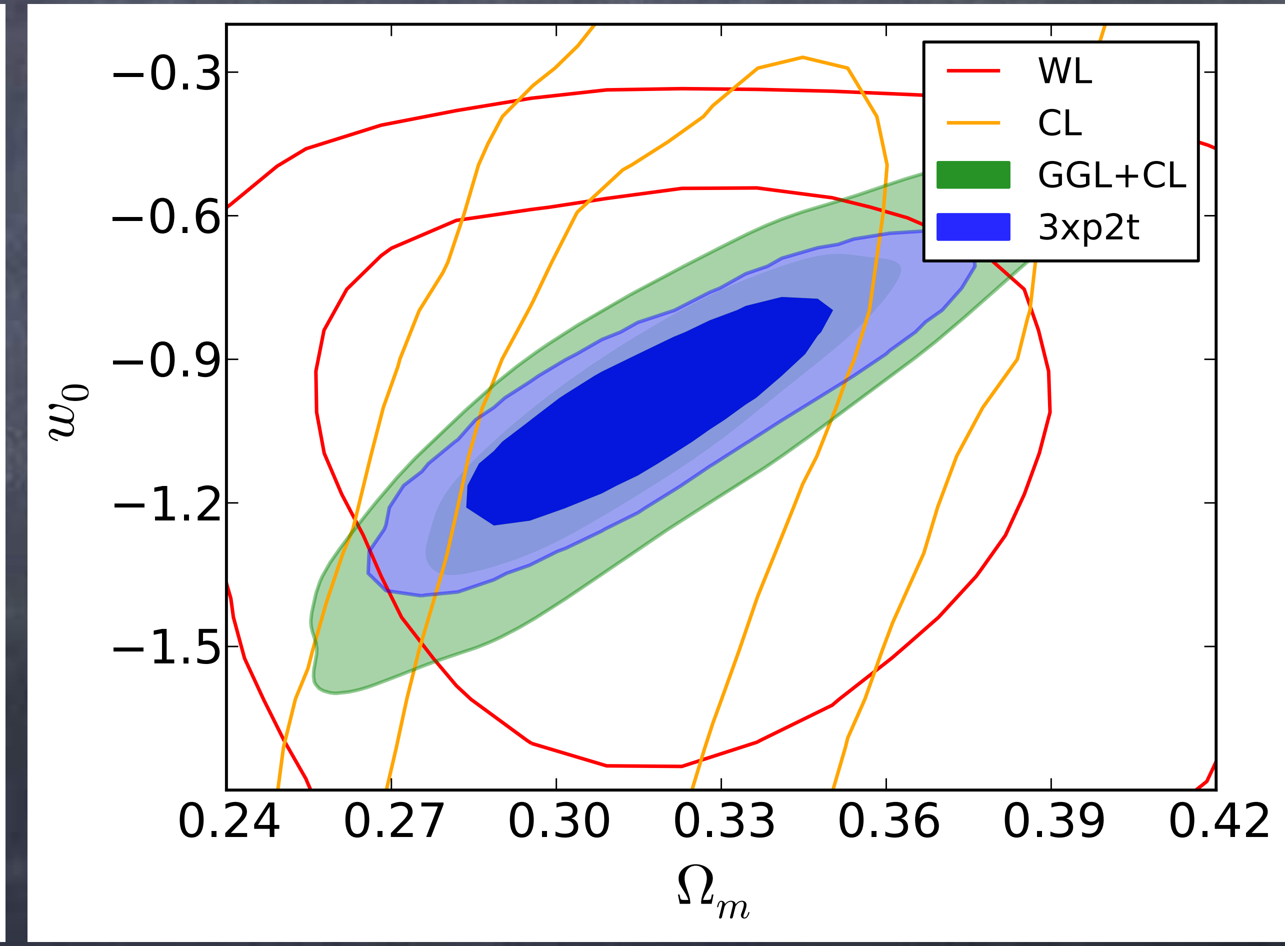
Joint Analysis Work Plan



DES Multi-Probe Analyses

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

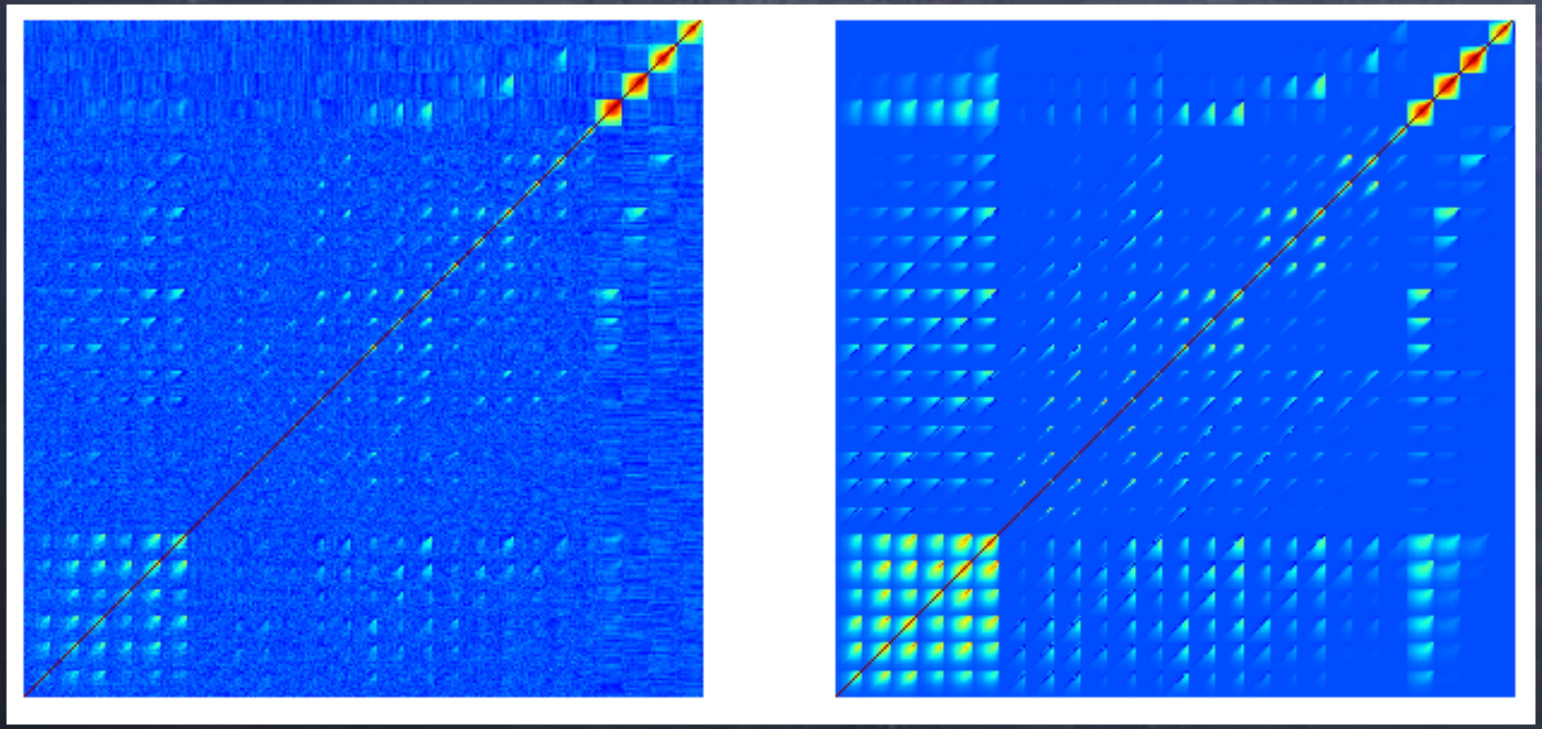




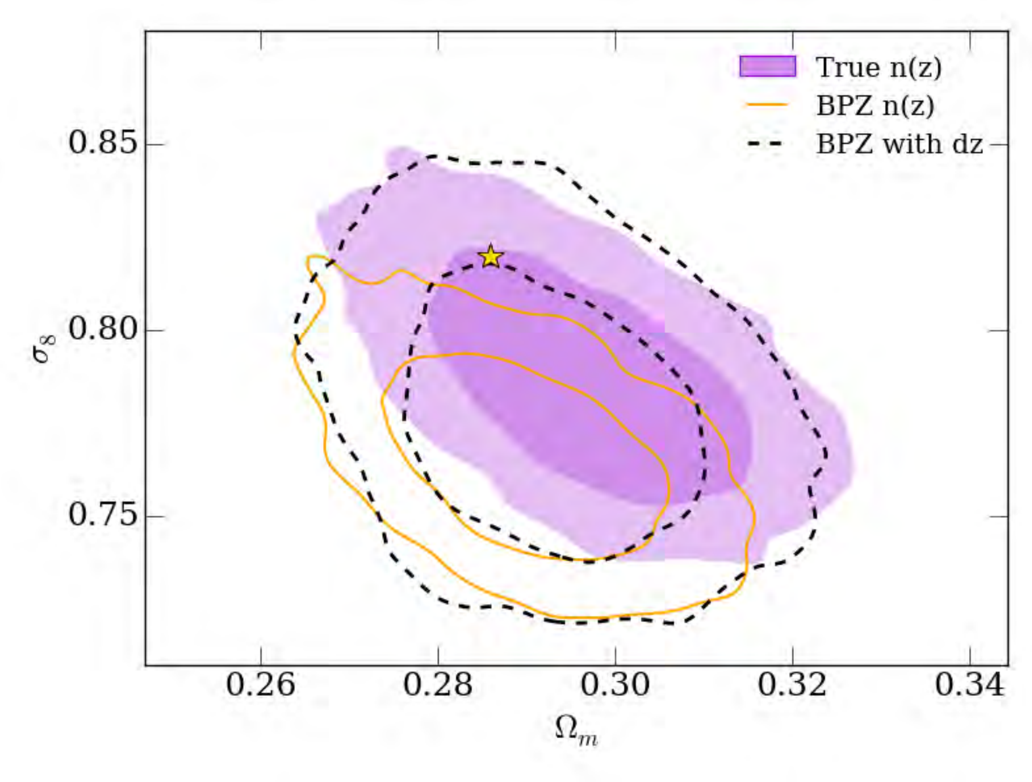
Forecasts based on Y1 n(z), marginalizing over ~60 systematics parameters

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



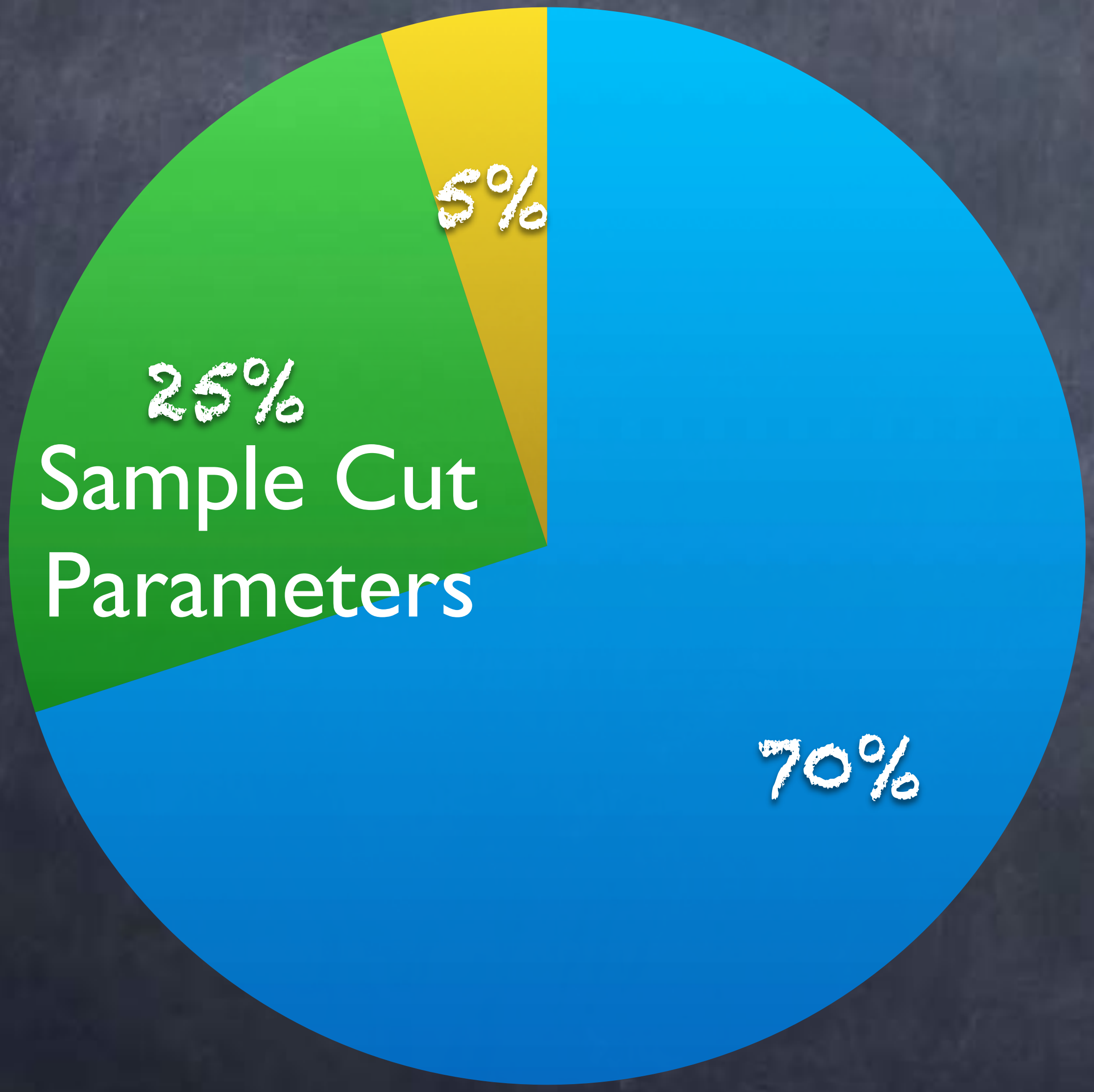
simulated + analytic covariance



analysis of mock data (N. MacCrann)

A Second Cosmology Pie Chart

Cosmology Parameters

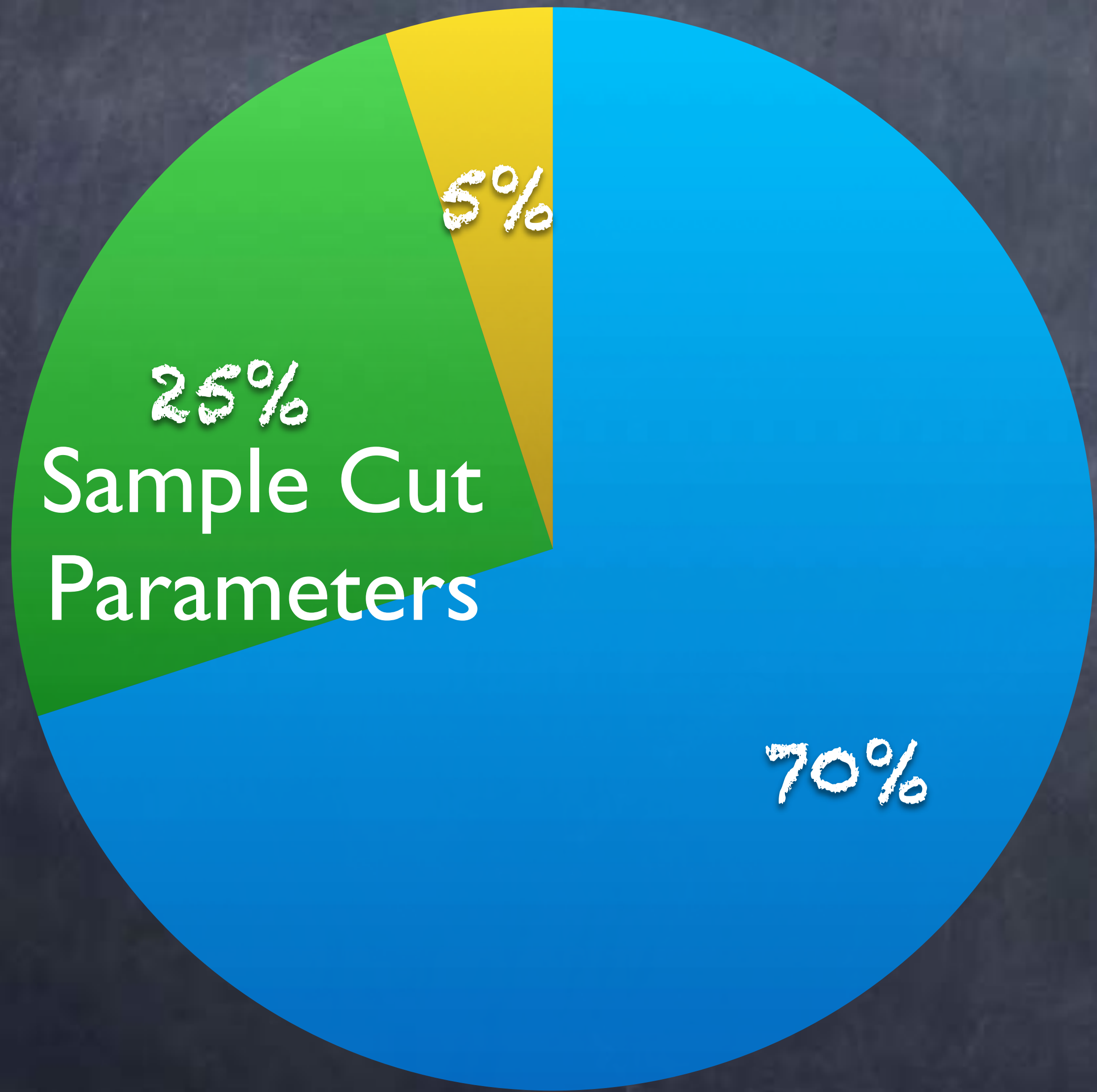


"Systematics Parameters"

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

A Second Cosmology Pie Chart

Cosmology Parameters



"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
- 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!