The LSST Awakens

Multi-Probe Cosmology with LSST (and beyond)

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Collaborators: Elisabeth Krause (Stanford/SLAC), Emmanuel Schaan (Princeton), Scott Dodelson (Fermilab/UChicago)

LSST: The Experiment

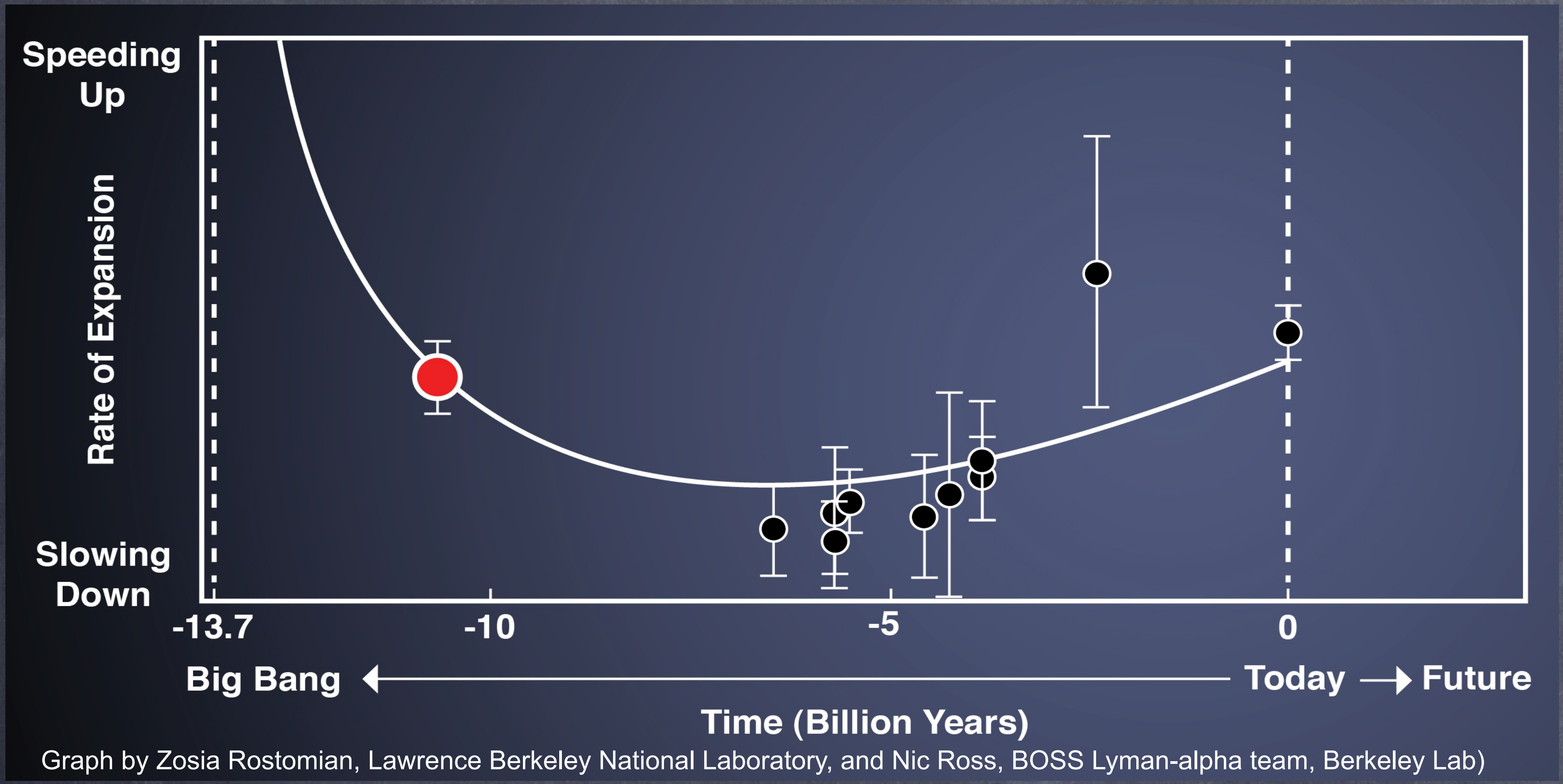
- Largest planned photometric survey
- Map visible sky every few nights (18,000 deg^2, 6 optical bands)
- Survey duration 2022-2032

LSST: Science Collaborations

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

- DESC Key Projects are detailed in the Science Roadmap (DESC-SRM)
- Multiple working groups
- This talk closely connected to work within the Theory&Joint Probes WG:
    - Understand limitations from systematics (astrophysics)
    - Advise on efficient implementation of physics modeling
    - Develop new science ideas for LSST

Dark Energy - Cosmology

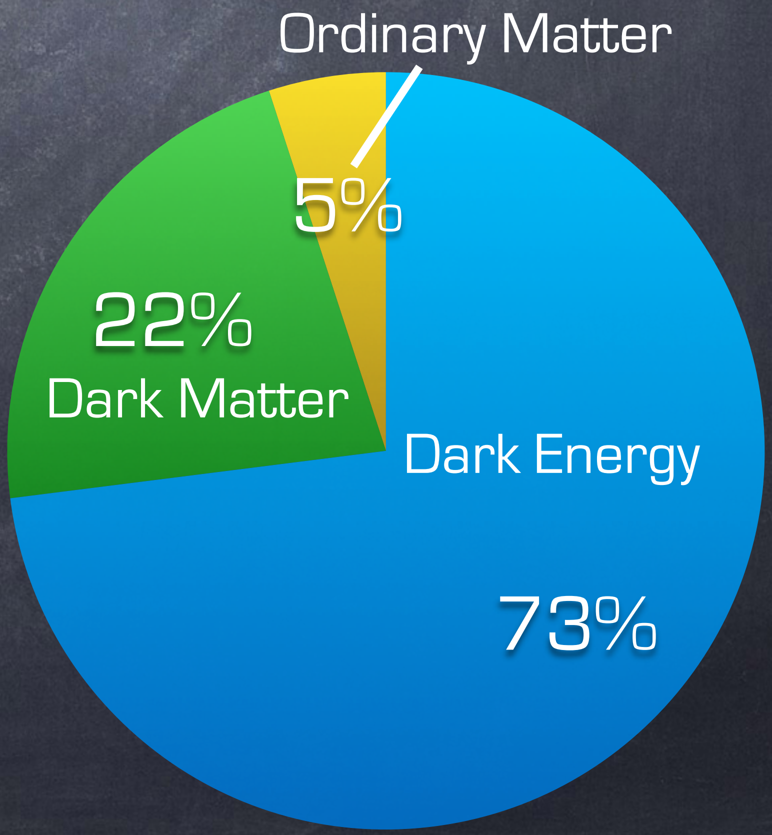


Since 1930s we know

$$\dot{a} > 0$$

SN1a (Nobel Prize 2011) and BAO have shown

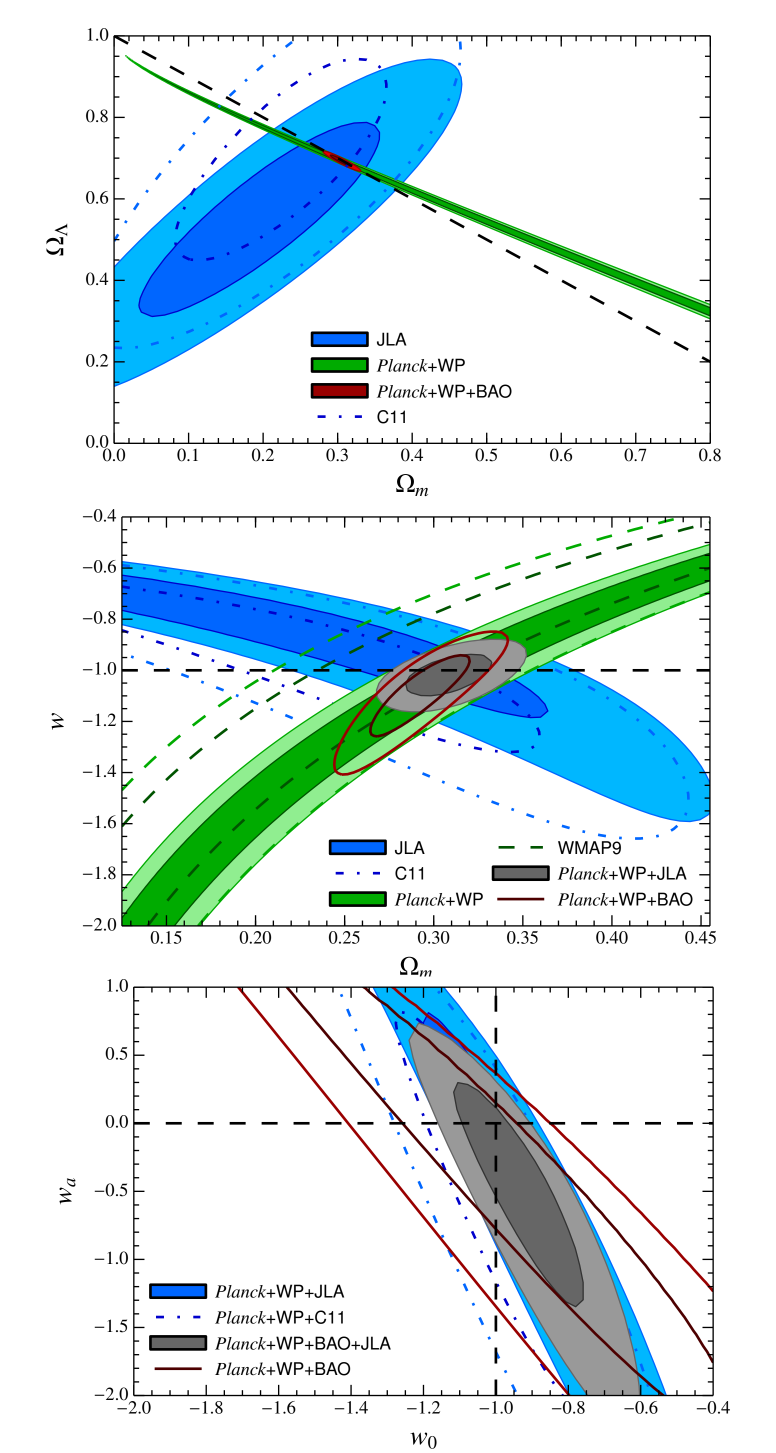
$$\ddot{a} > 0$$



- If GR is correct, and we trust the observations, the Universe is dominated by an energy density component with negative pressure
- Alternative: Modifications to GR (on large scales+late times), recover GR high-density environments via screening, use combination of lensing and dynamics to test GR

The Power of Combining Probes

- Best constraints obtained by combining cosmological probes
  - independent probes: multiply likelihoods (if individual results are consistent)
- Combining LSS probes (from same survey) requires more advanced strategies
  - clustering, clusters and WL probe same underlying density field, are correlated
  - correlated systematic effects



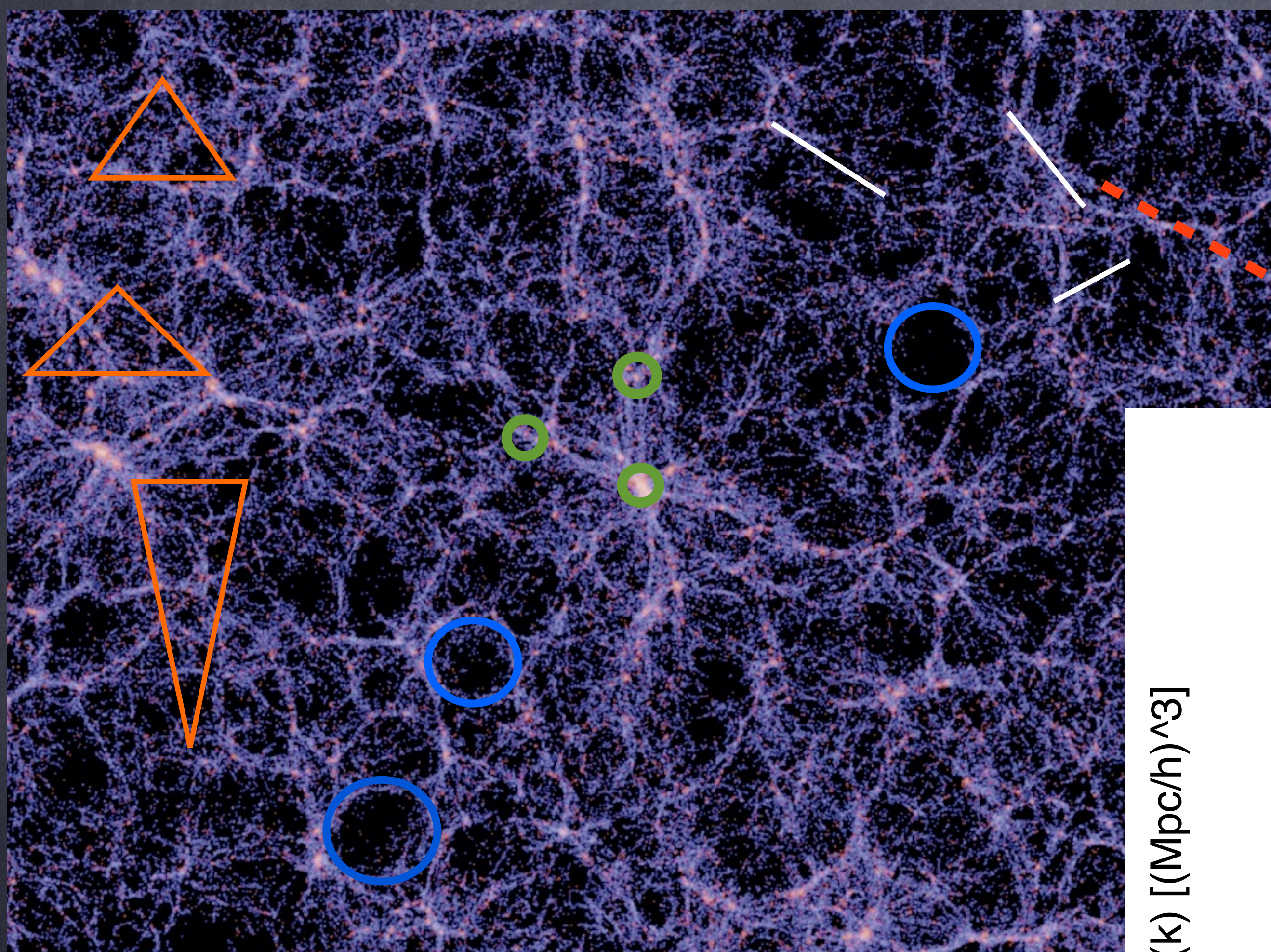
Betoule et al. 2014

Beyond Expansion History - Structure Growth based Cosmology

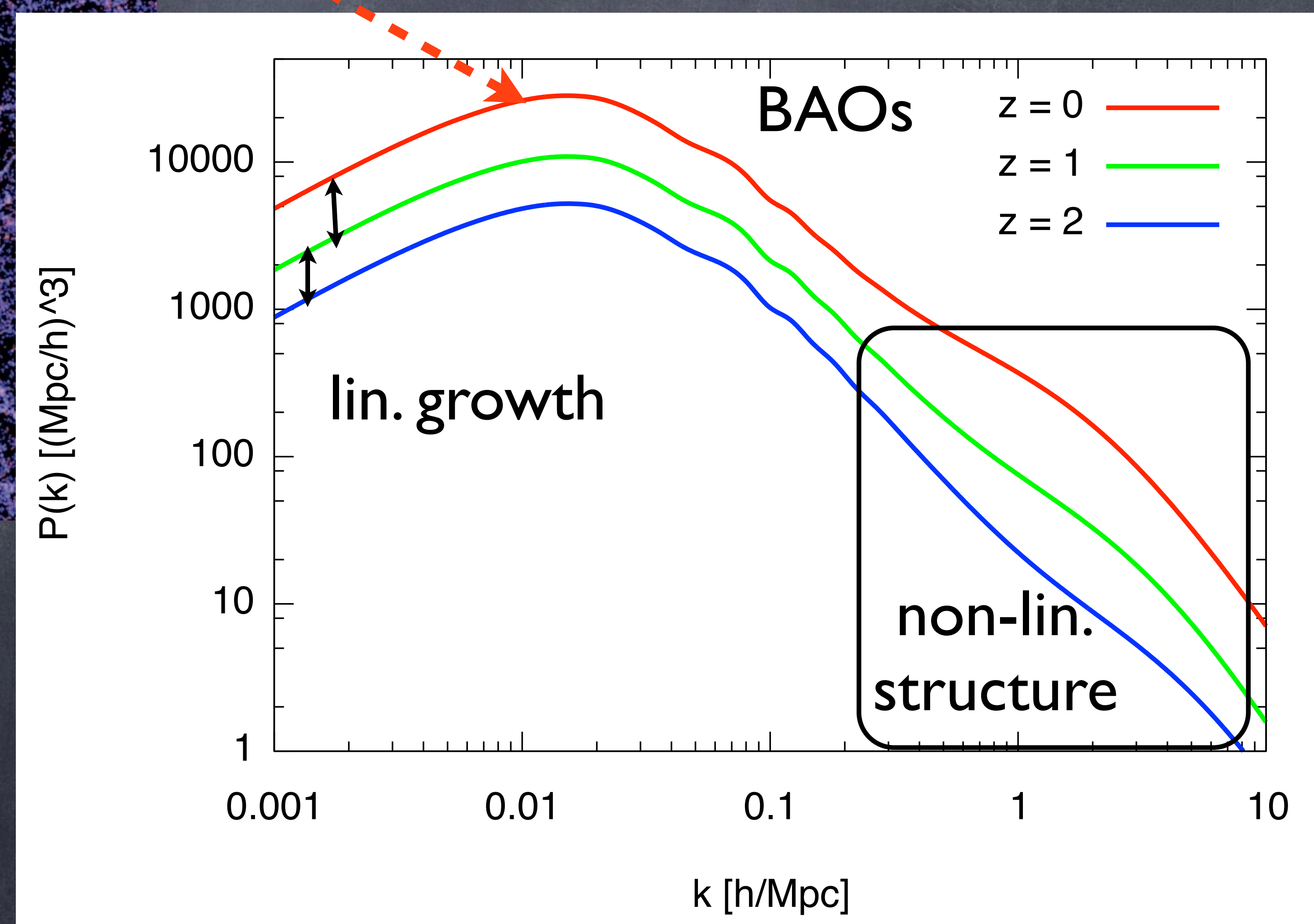
Where everything is correlated...

Cosmology through Structure Growth

More information compared to expansion history



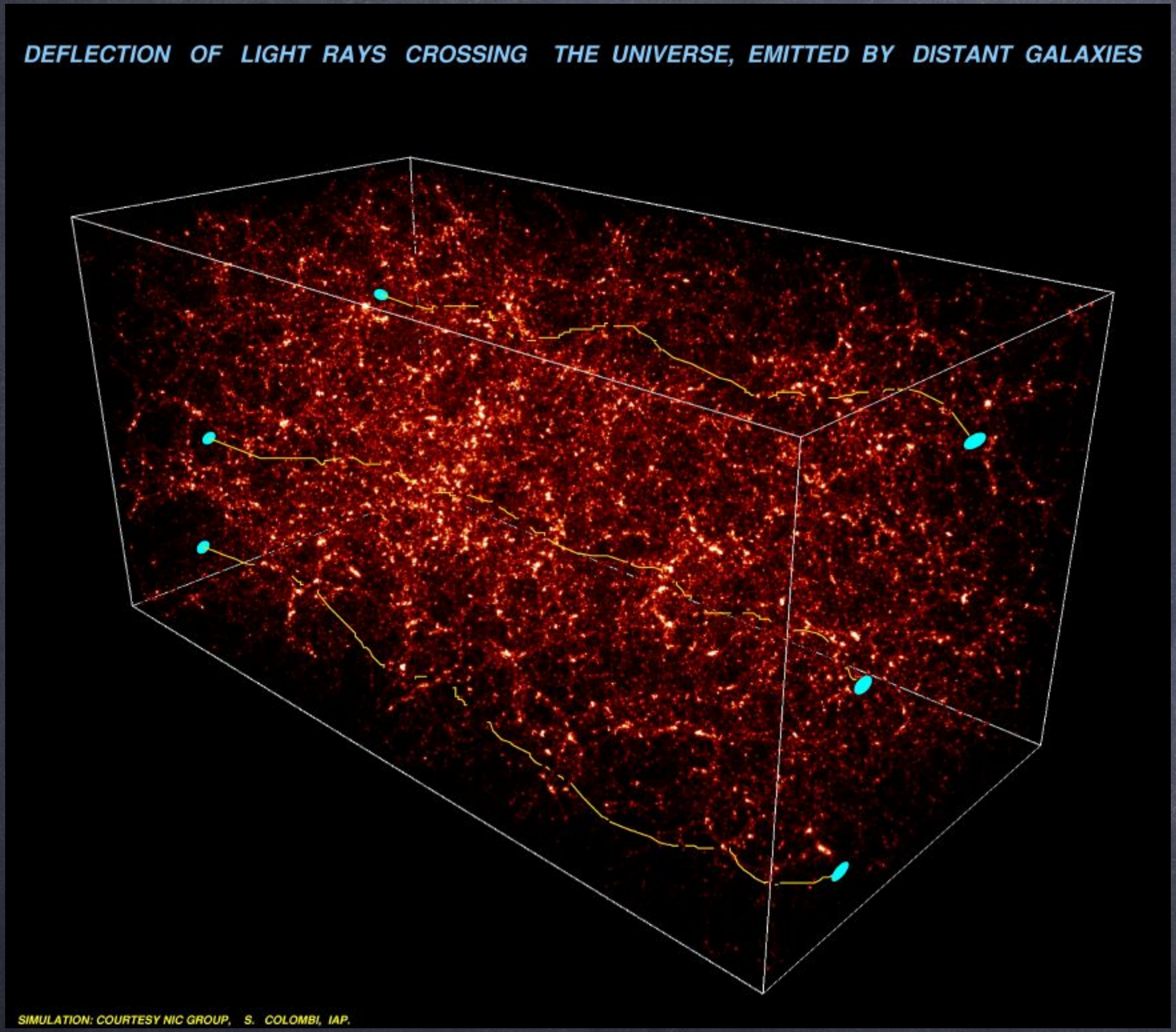
need redshift, understand galaxy bias

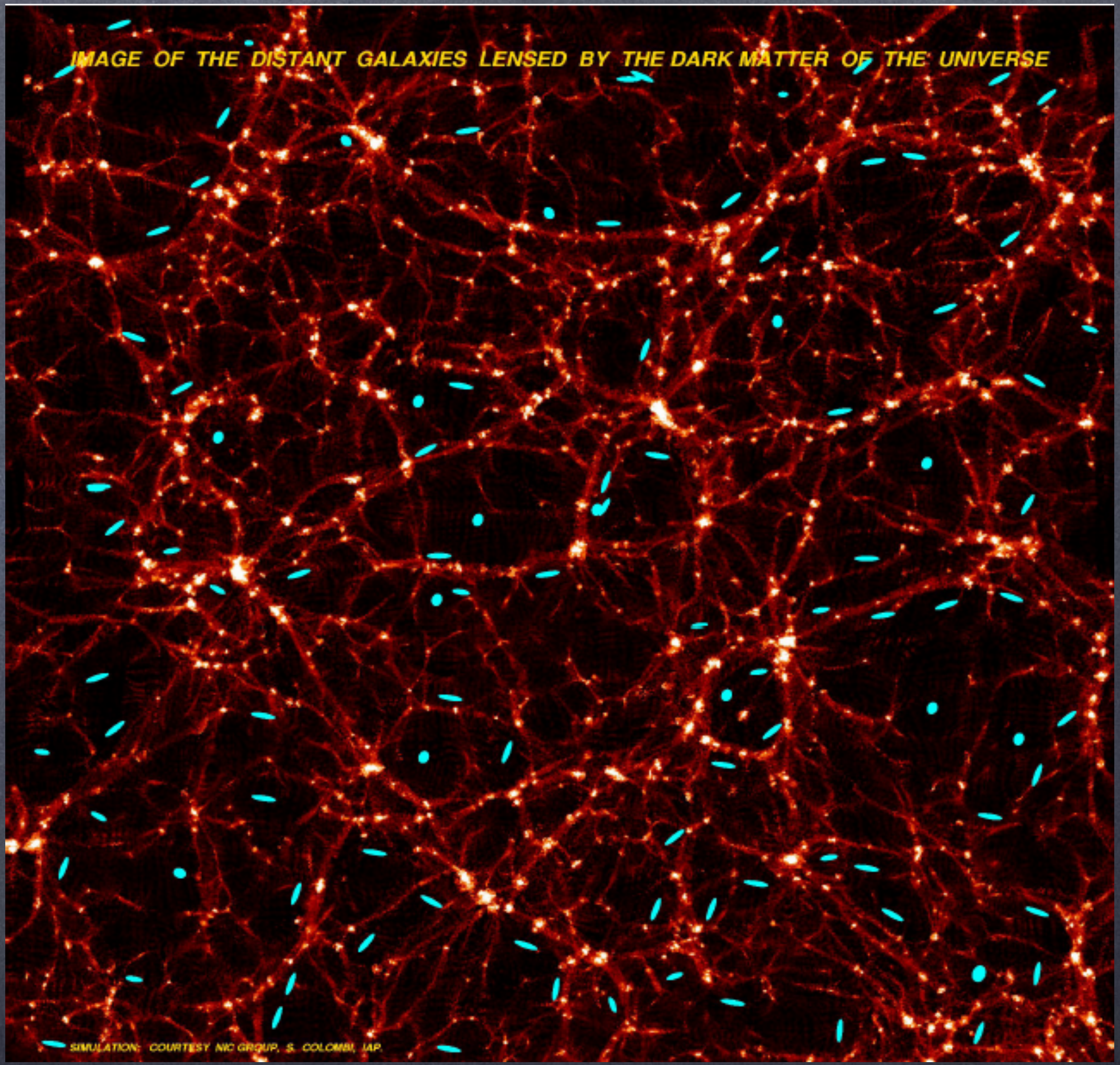


- clusters (over densities),
- voids (under densities)
- two-point correlations
- three-point correlations,...

Then there is Lensing...

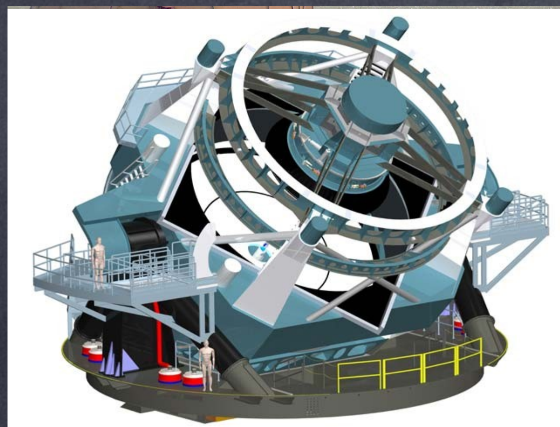
- Light rays are distorted by dark matter density fiel of the Universe
- Statistical properties of the distortion reflect statistical properties of the density field



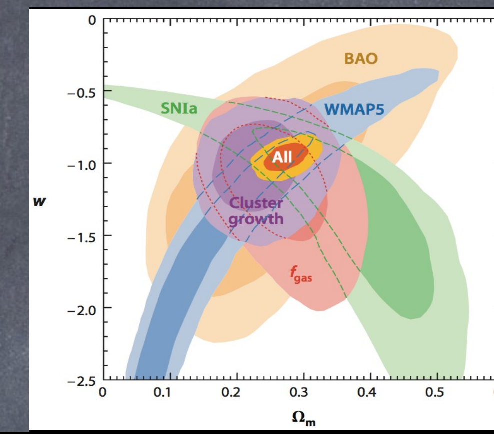


- measure shear correlation function/power spectrum
  - probes total matter power spectrum (broad projection kernel)
- measure average (tangential) shear around galaxies/clusters
  - probes halo mass

Multi-probe Analysis - Many challenges



reduced data
and catalogs



1) Independent probes
CMB, SN1a as priors

2) Large model vector
Self-consistent modeling of all observables as a function of
1) cosmological parameters (~10)
2) nuisance parameters (XXX)

large data vector

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

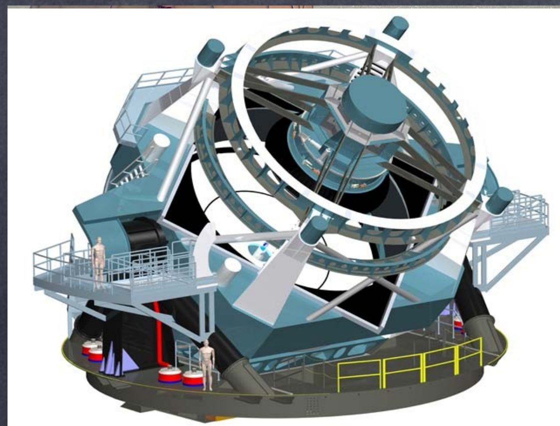
posterior probability

3) Enhanced modeling via
- Observations
- Simulations
- Theory

4) Statistics I - Likelihood function
- Multivariate Gaussian vs other parameterizations
- Non-parametric forms

4) Statistics II - Covariances
- large and complicated, non-(block) diagonal
- different methods for derivation

Multi-probe Analysis - Many challenges



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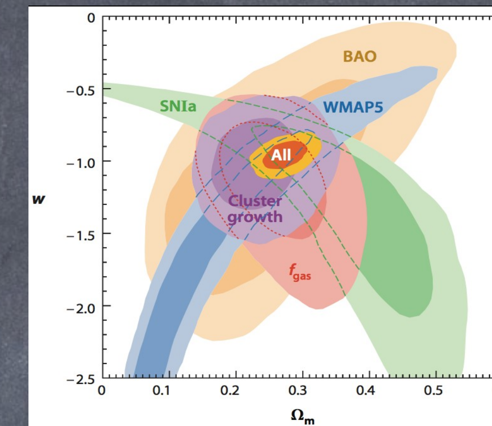

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Working Example: Simulate a Multi-Probe Likelihood Analysis for LSST

Work from Krause & TE'16

Introducing CosmoLike

Core Developers: Elisabeth Krause (Stanford/SLAC), TE

Active projects with Princeton, CMU, UManchester, Ohio State

Weak Lensing, Galaxy Clustering, Clusters, CMB-LSS correlations

Numerical Simulations

Systematics (photo-z, shape uncertainties)

Astrophysics (Intrinsic alignment, Baryons)

Explore fundamental physics (cosmic acceleration, neutrinos, tests of gravity)

Advanced statistical methods (ABC, precision matrix regularization)

Galaxy bias models (linear, HOD)

Multi-Probe Covariances

Build a consistent, multi-probe likelihood analysis framework including

- Cross-correlations of observables/systematics
- Efficient treatment of nuisance parameters

Example Data Vector and Systematics

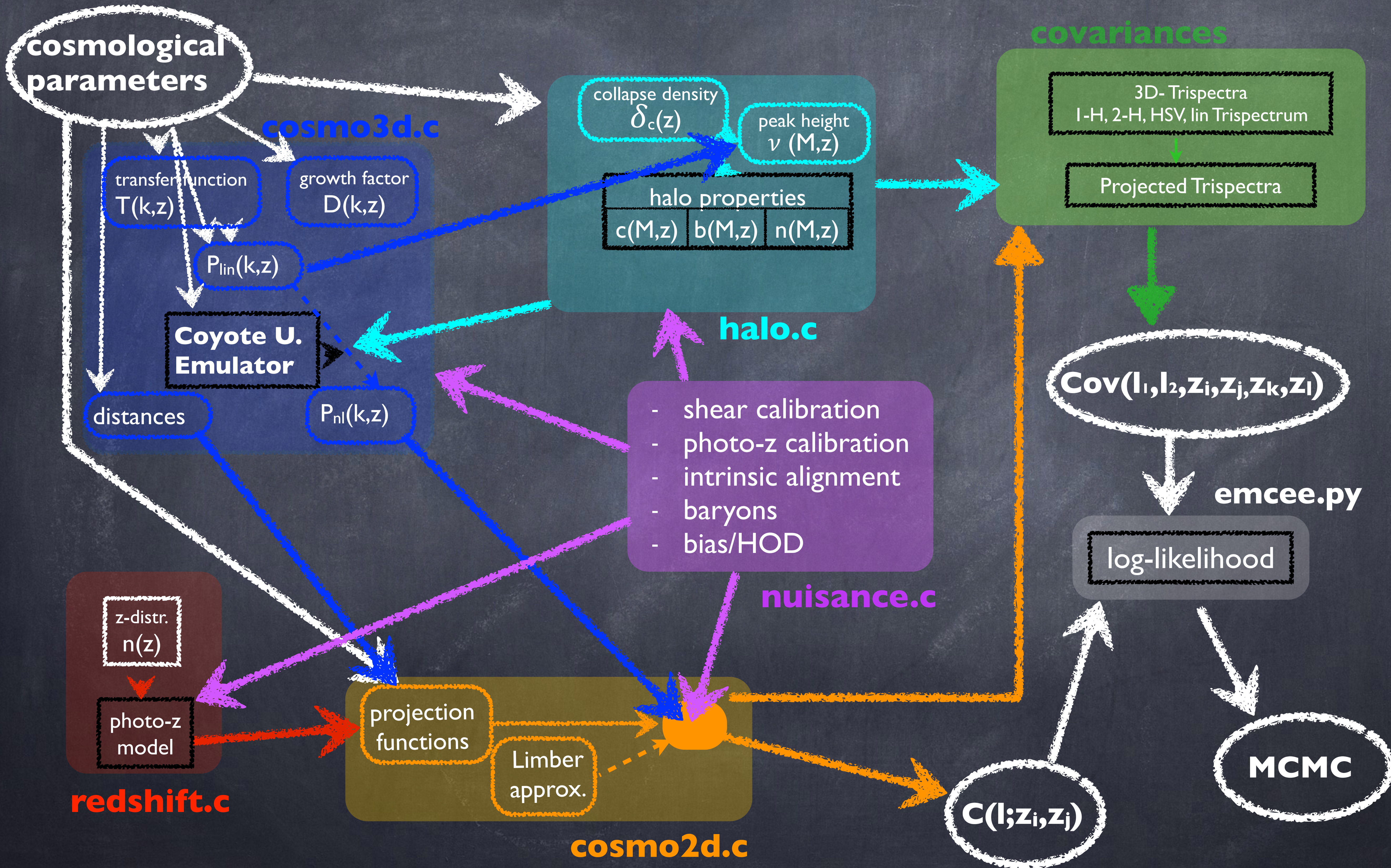
- Cosmic shear
  - 10 tomography bins
  - 25 l bins, 25 < l < 5000
- Galaxy clustering
  - 4 redshift bins (0.2-0.4,0.4-0.6,0.6-0.8,0.8-1.0)
  - compare two samples: σ_z <0.04, redMaGiC
  - linear + quadratic bias only : l bins restricted to R> 10 Mpc/h
  - HOD modeling going to R>0.1 MPC/h
- Galaxy-galaxy lensing
  - galaxies from clustering (as lenses) with shear sources
- Clusters - number counts + shear profile
  - so far, 8 richness, 4 z-bins (same as clustering)
  - tomographic cluster lensing (500 < l < 10000)

shear calibration,
photo-z (sources)
IA, baryons

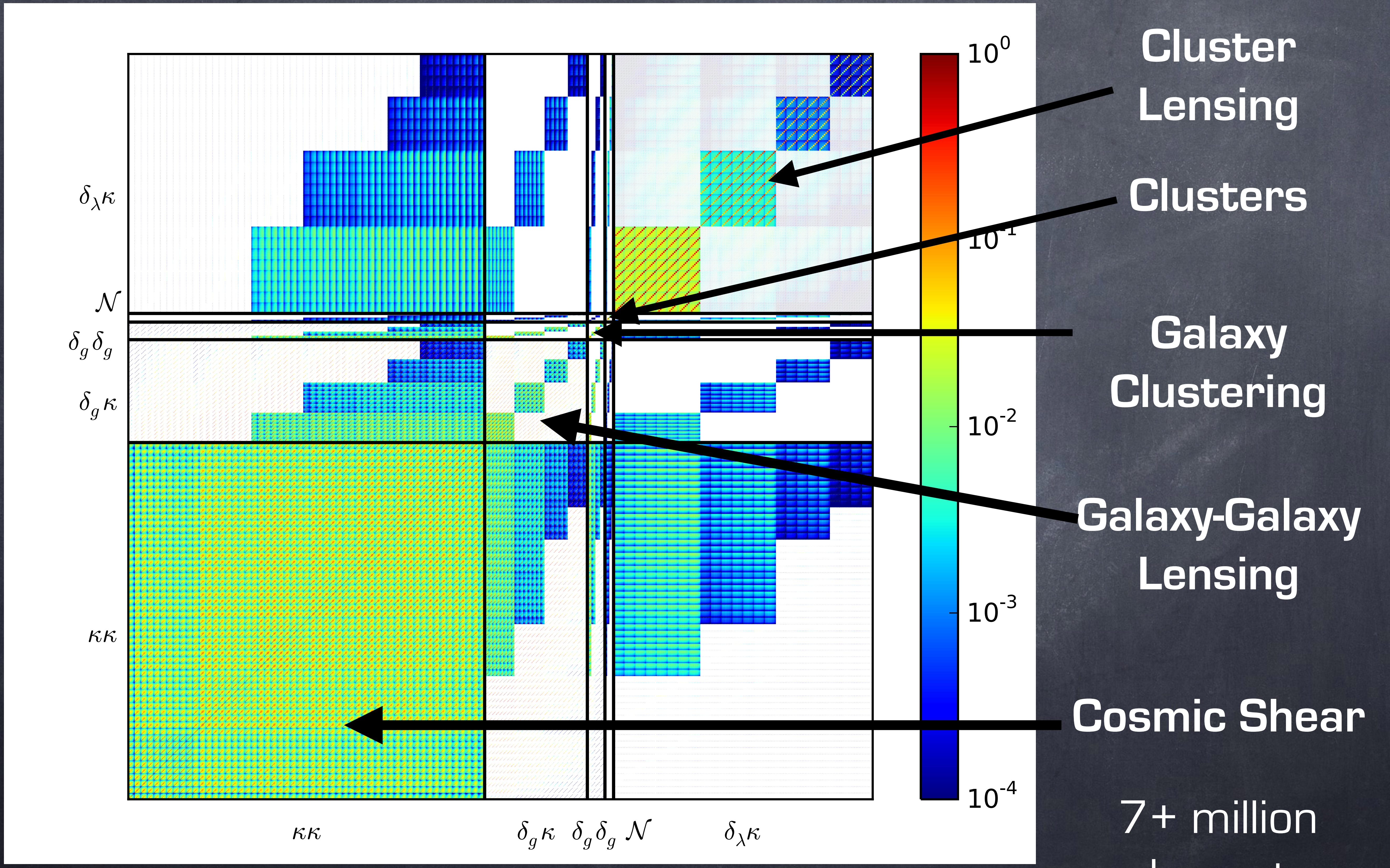
b_1, b_2,...
photo-z (lenses)

N-M relation
c-M relation
off-centering

CosmoLike Internals



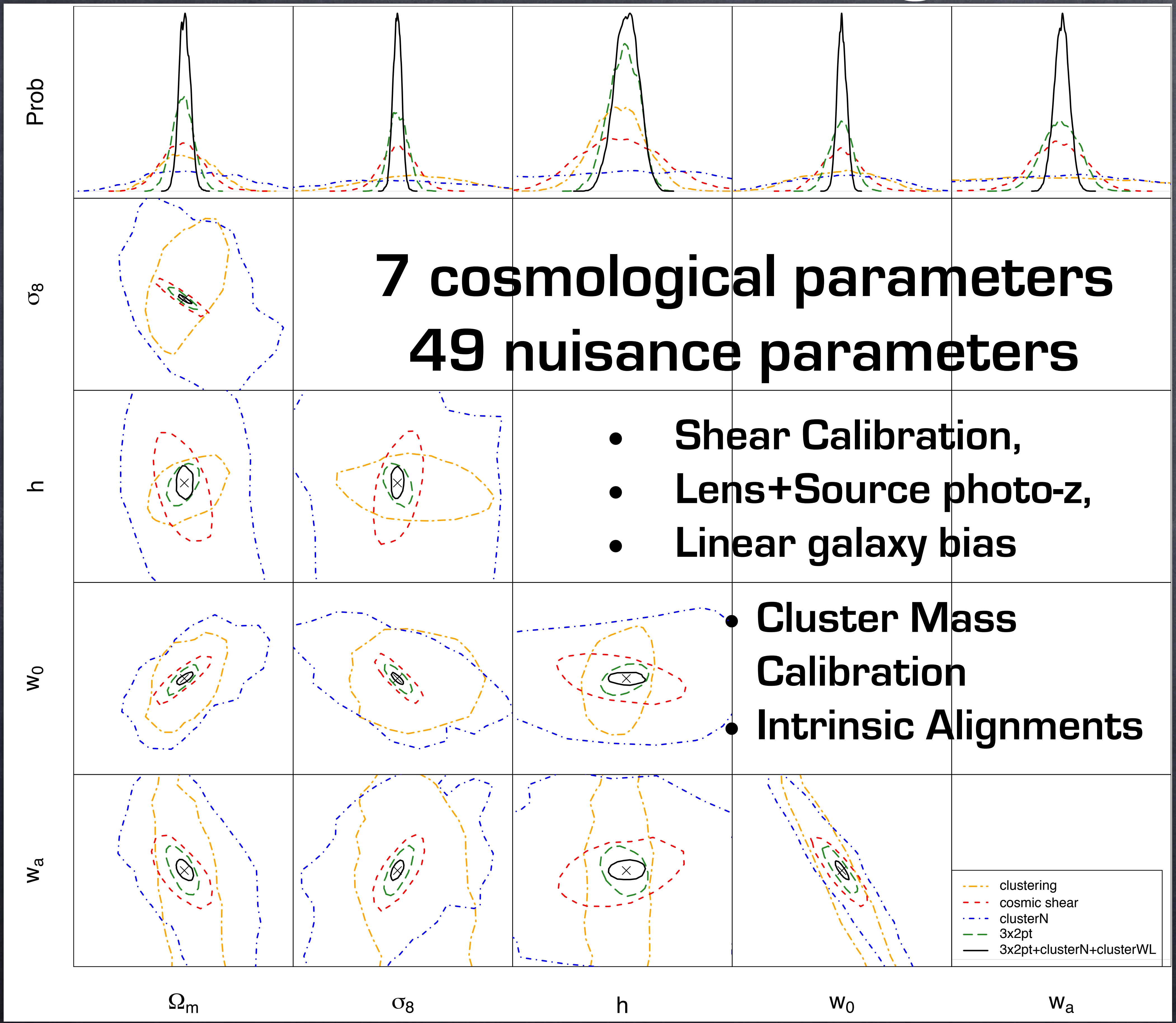
Multi-Probes Forecasts: Covariance



7+ million elements

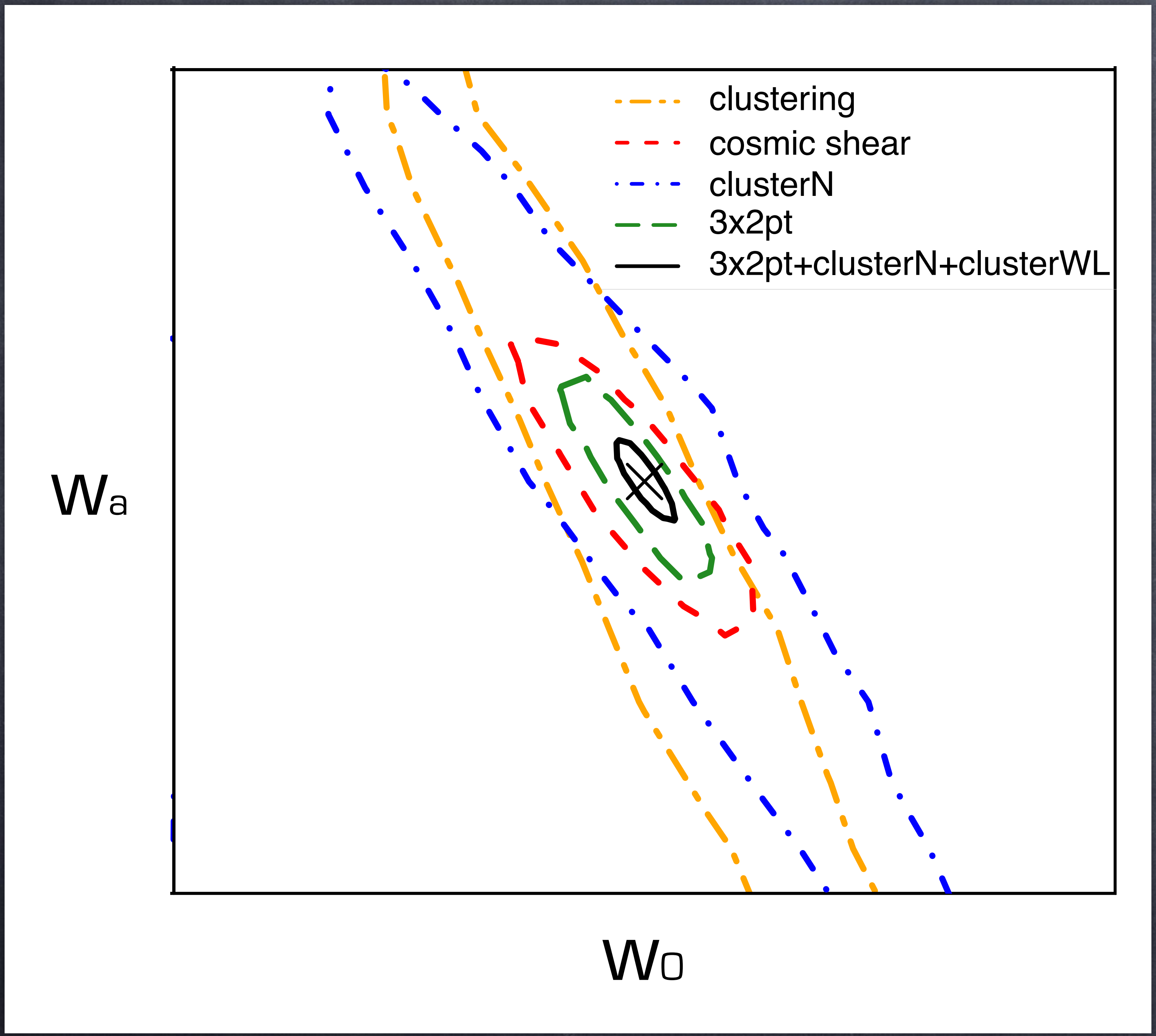
details: Krause&Eifler '16

The Power of Combining Probes



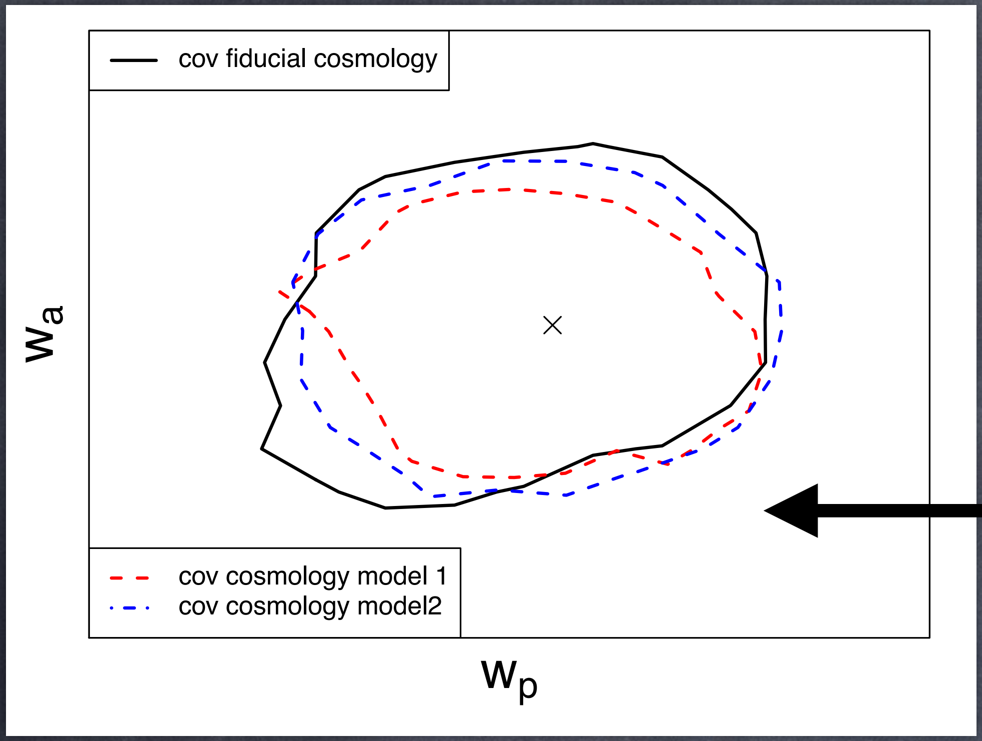
Details see
Krause & TE'16

Zoom into w_0-w_a plane

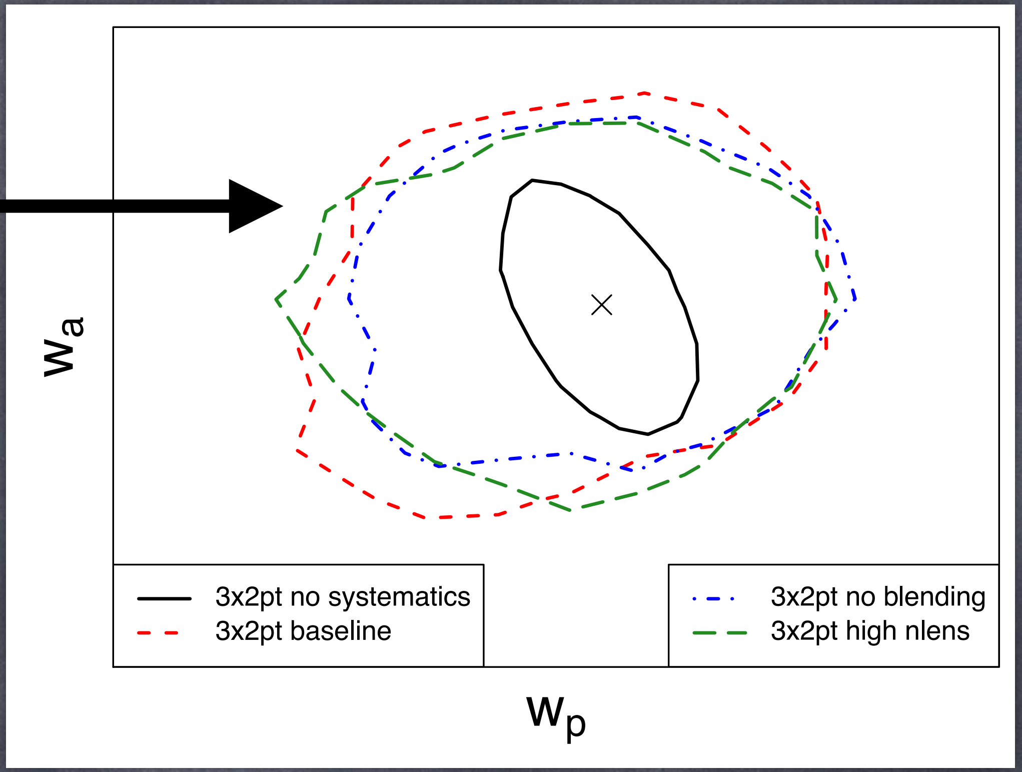


- Very non-linear gain in constraining power
- Most stringent requirements on numerical simulations, photo-z, shear calibration, etc flow from Multi-Probe Statistical Limits

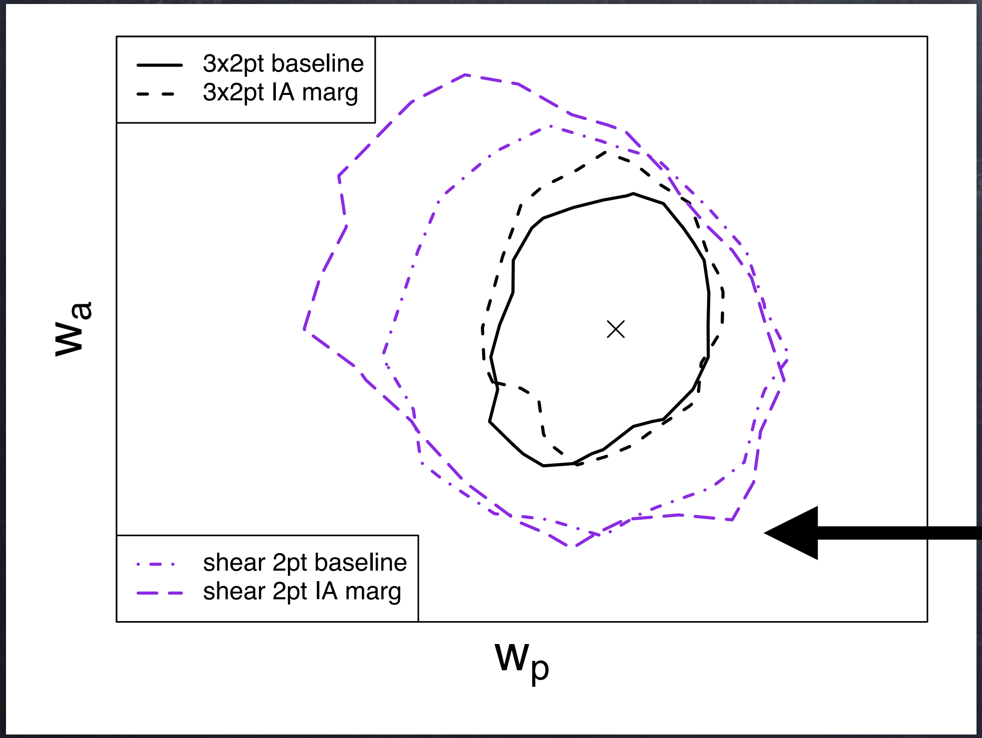
Systematics Exploration+Control



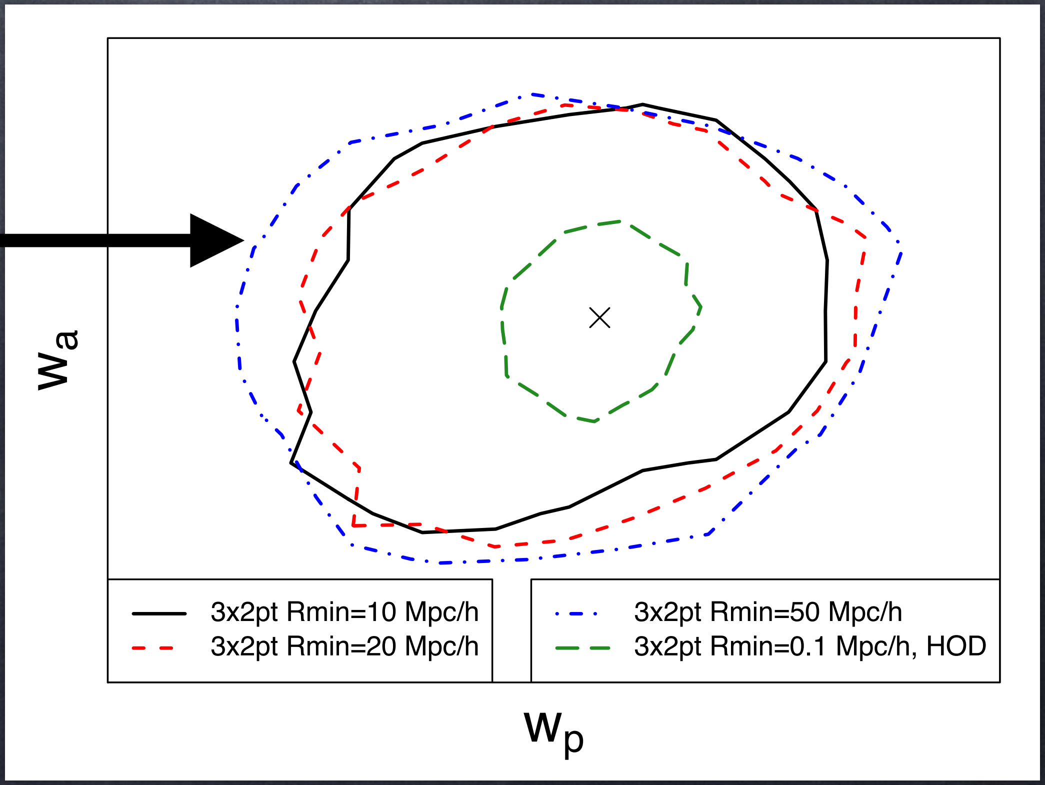
Weak Lensing
("Blending Problem")



Advanced Statistical Methods
("Covariance Methods")



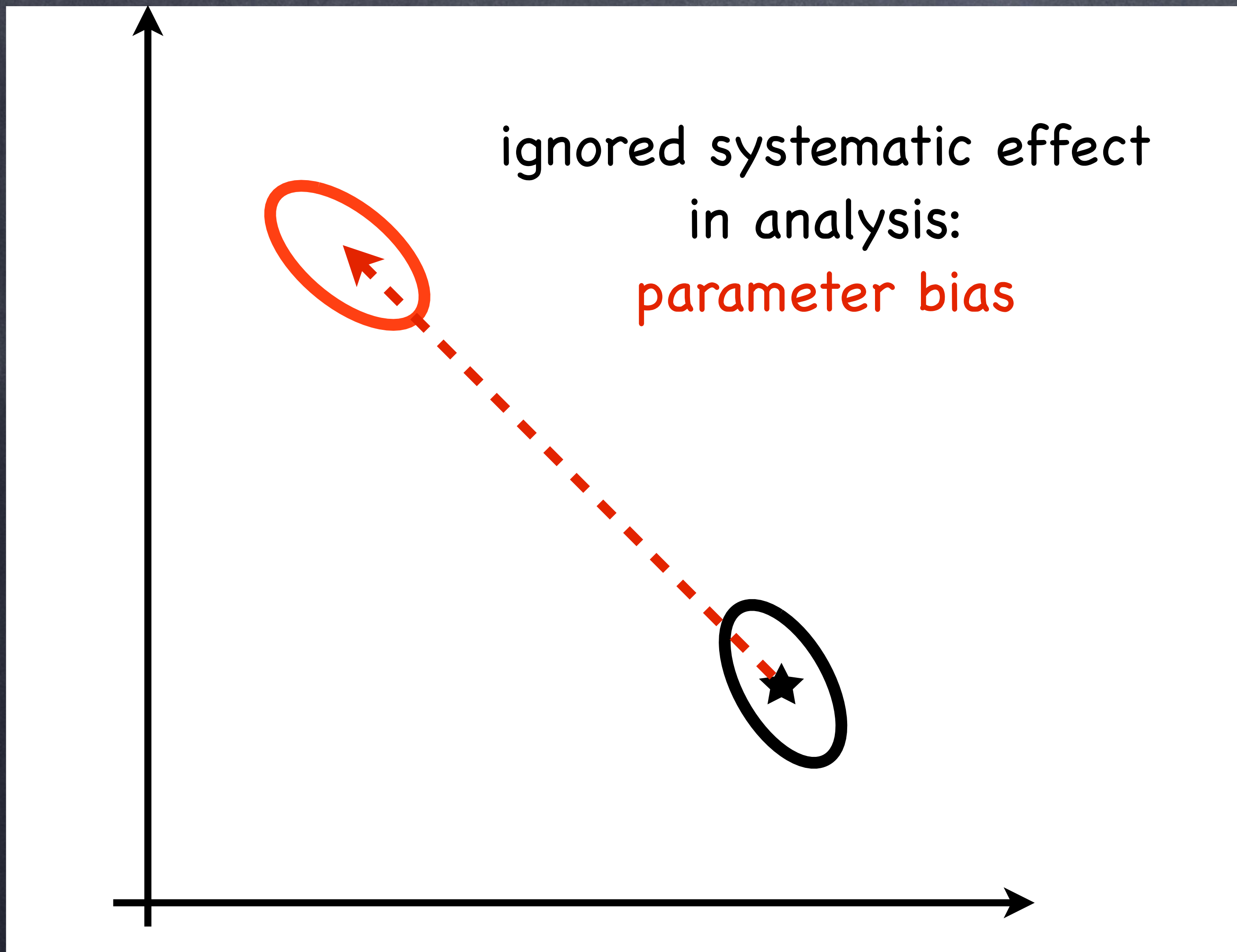
Simulating Galaxies
("HOD vs lin galaxy bias")

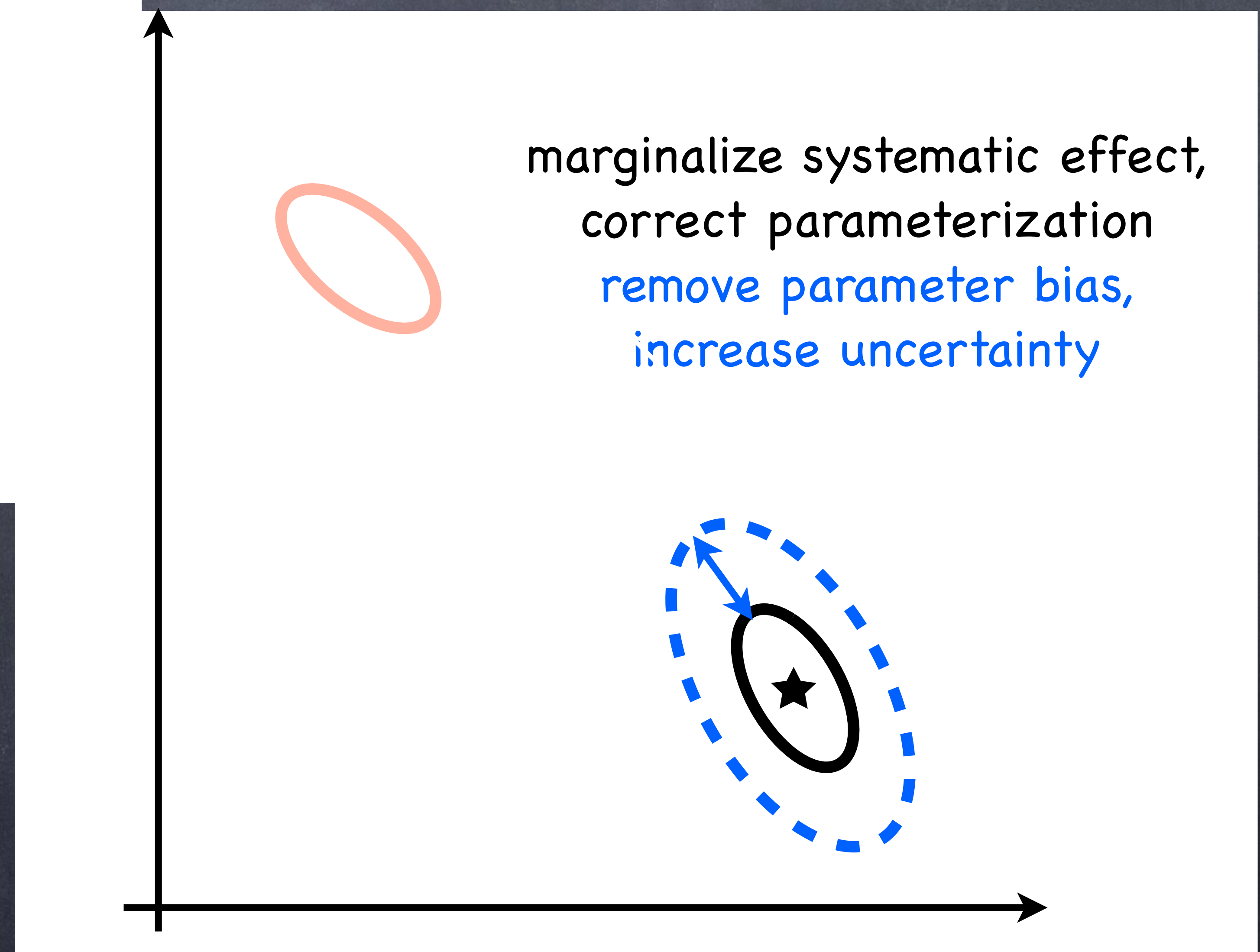


Intrinsic Alignment
("IA mitigation")

Systematics exploration and control is key to LSST success

Systematics Trouble





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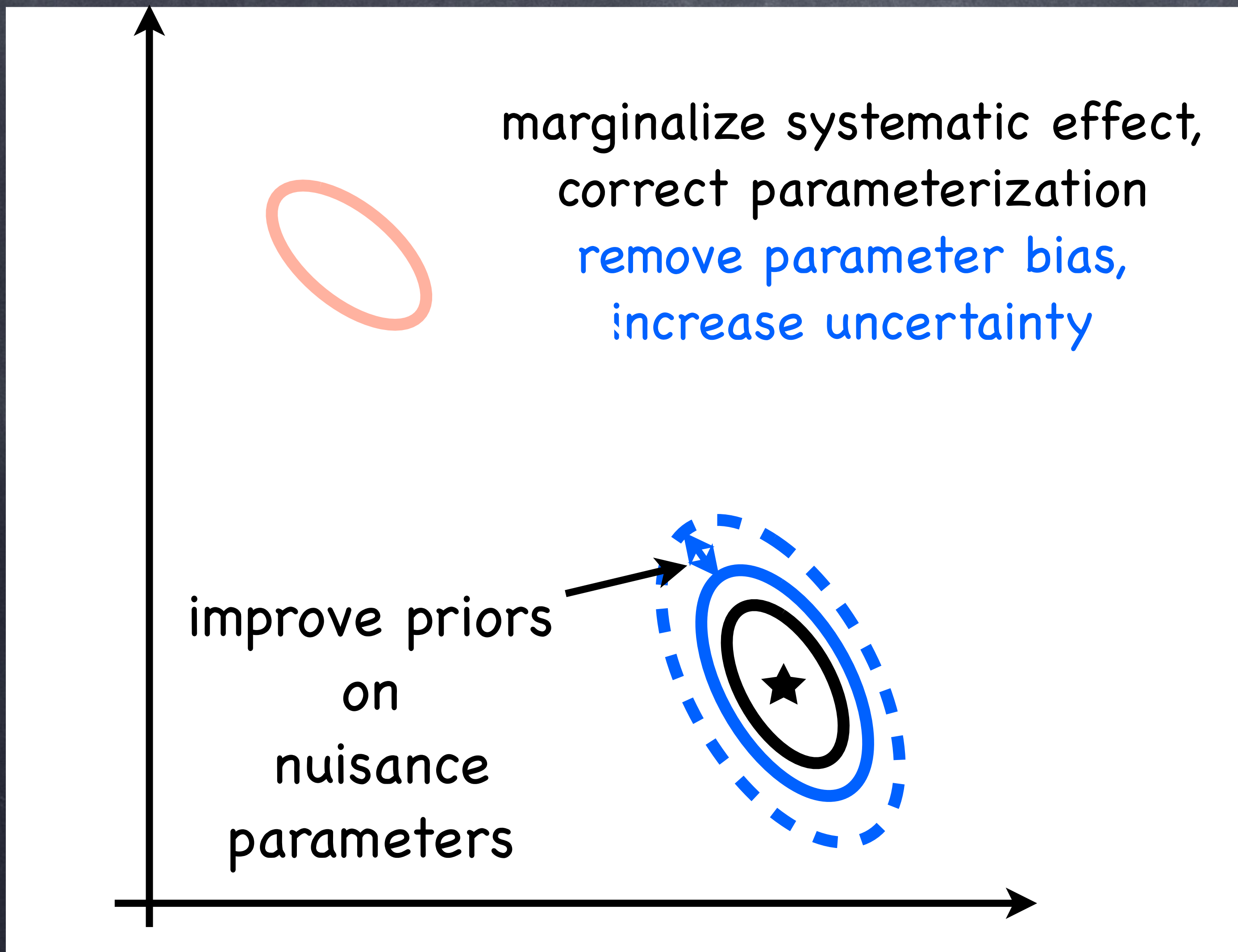
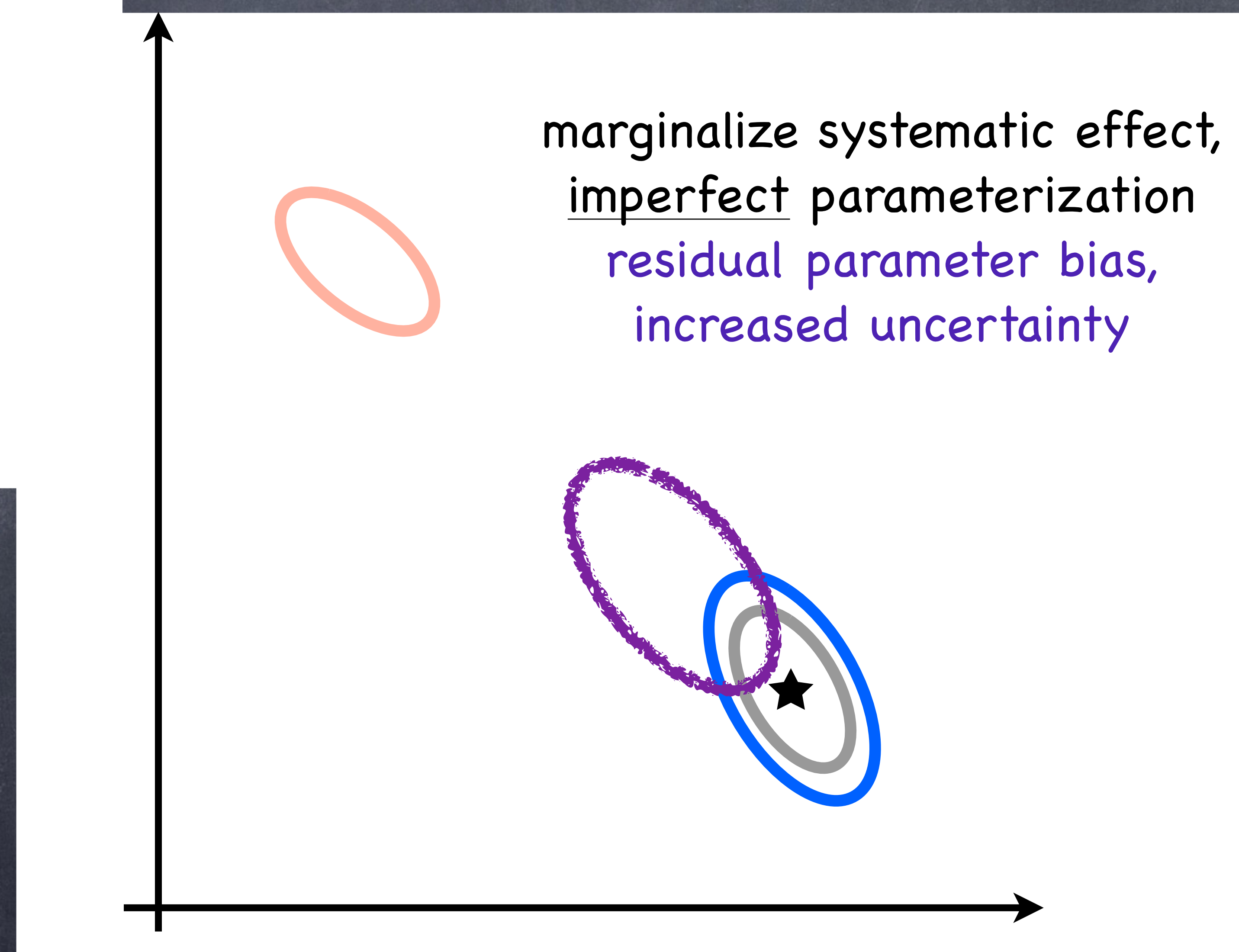
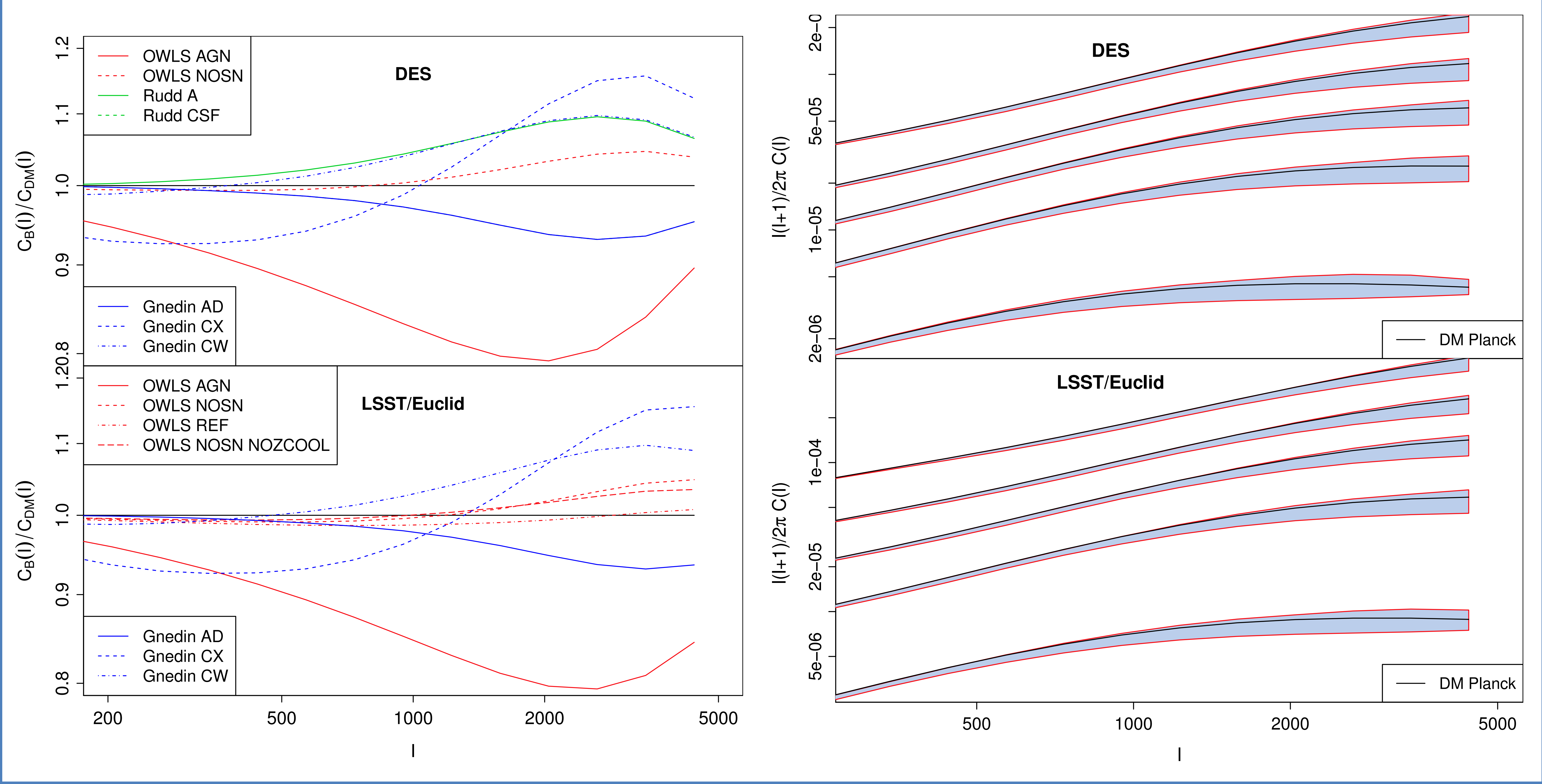


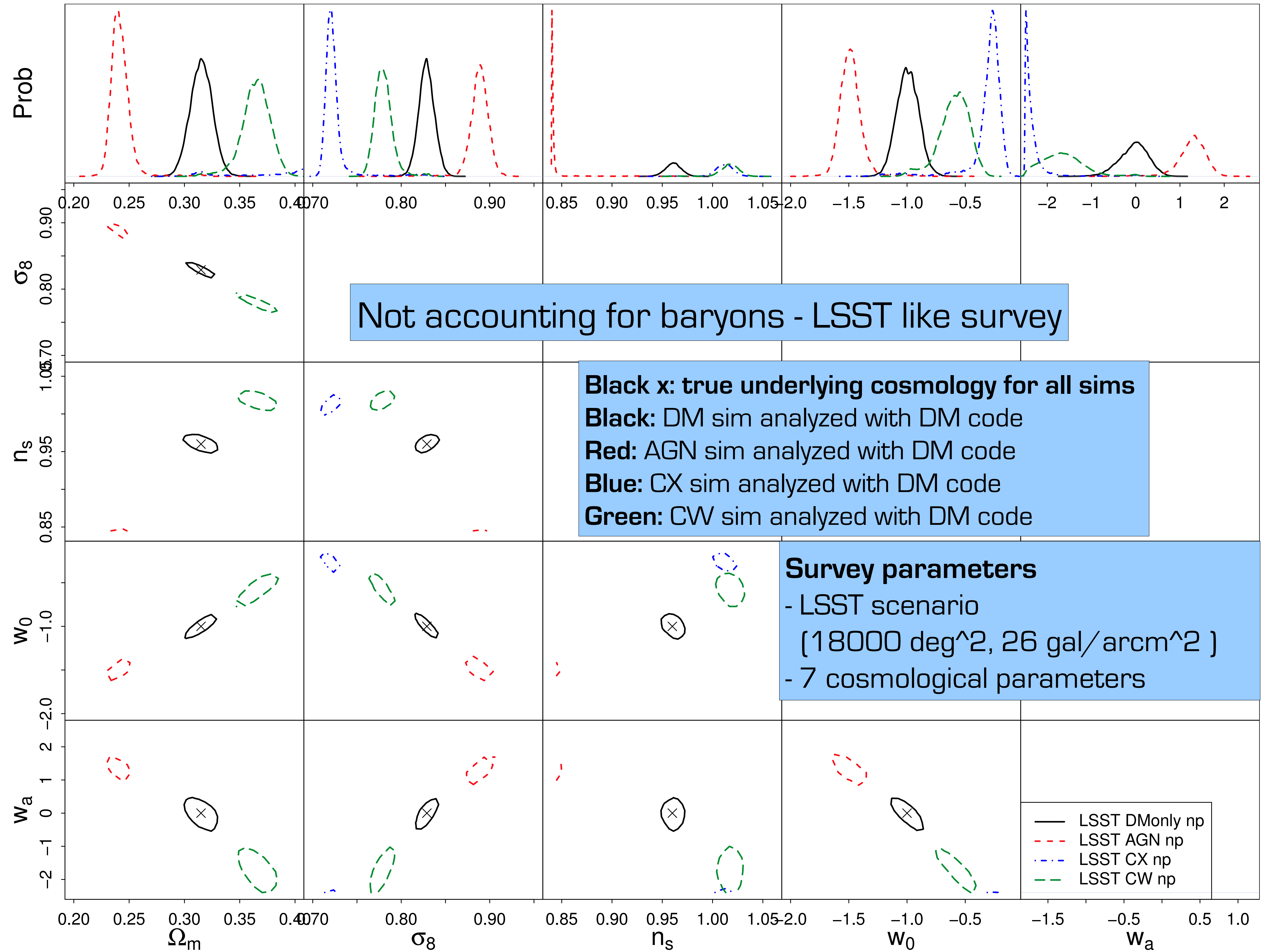


Example: Baryonic Uncertainties in LSST WL

Work from TE, Krause, Dodelson et al '15

1) Compute shear tomography power spectra from 14 numerical simulations with different baryonic physics





Not accounting for baryons - LSST like survey
Black x: true underlying cosmology for all sims
Black: DM sim analyzed with DM code
Red: AGN sim analyzed with DM code
Blue: CX sim analyzed with DM code
Green: CW sim analyzed with DM code
Survey parameters
- LSST scenario
(18000 deg^2, 26 gal/arcm^2)
- 7 cosmological parameters
LSST DMonly np
LSST AGN np
LSST CX np
LSST CW np
Prob
Ω_m
σ_8
n_s
w_0
w_a

PCA-marginalization/Mode removal

1) At each point in cosmology define set

$$\mathbf{M}_j(\mathbf{p}_{\mathrm{nu}}) \in \left\{\mathbf{M}(\mathbf{p}_{\mathrm{nu}}|\mathbf{p}_{\mathrm{co}})\right\}$$

2) Calculate differences to DM → create matrix

$$\Delta_{ij} = M_{ij} - M_i^{\mathrm{DM}}$$

3) SVD on difference matrix → cols of U contain PCs

$$\boldsymbol{\Delta} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^t$$

4) Perform likelihood calculation in PC space

$$\chi^2(\mathbf{p}_{\mathrm{co}}, \mathbf{p}_{\mathrm{nu}}) = (\mathbf{D}-\mathbf{M})^t\mathbf{U}\mathbf{U}^t\mathbf{C}^{-1}\mathbf{U}\mathbf{U}^t(\mathbf{D}-\mathbf{M})$$

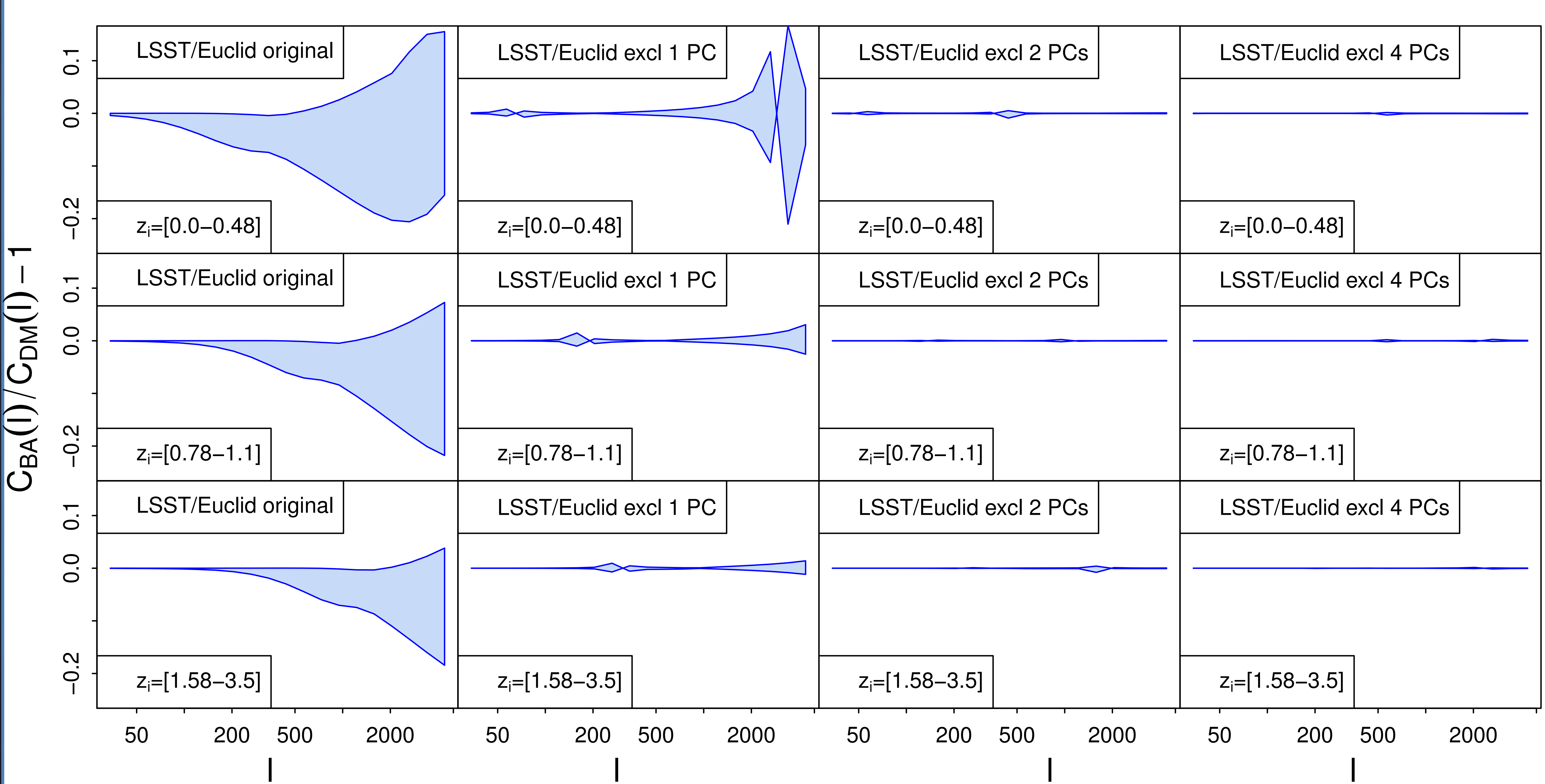
$$\mathbb{1} = \mathbf{U}\mathbf{U}^t$$

5) Project out the baryon sensitive PCs

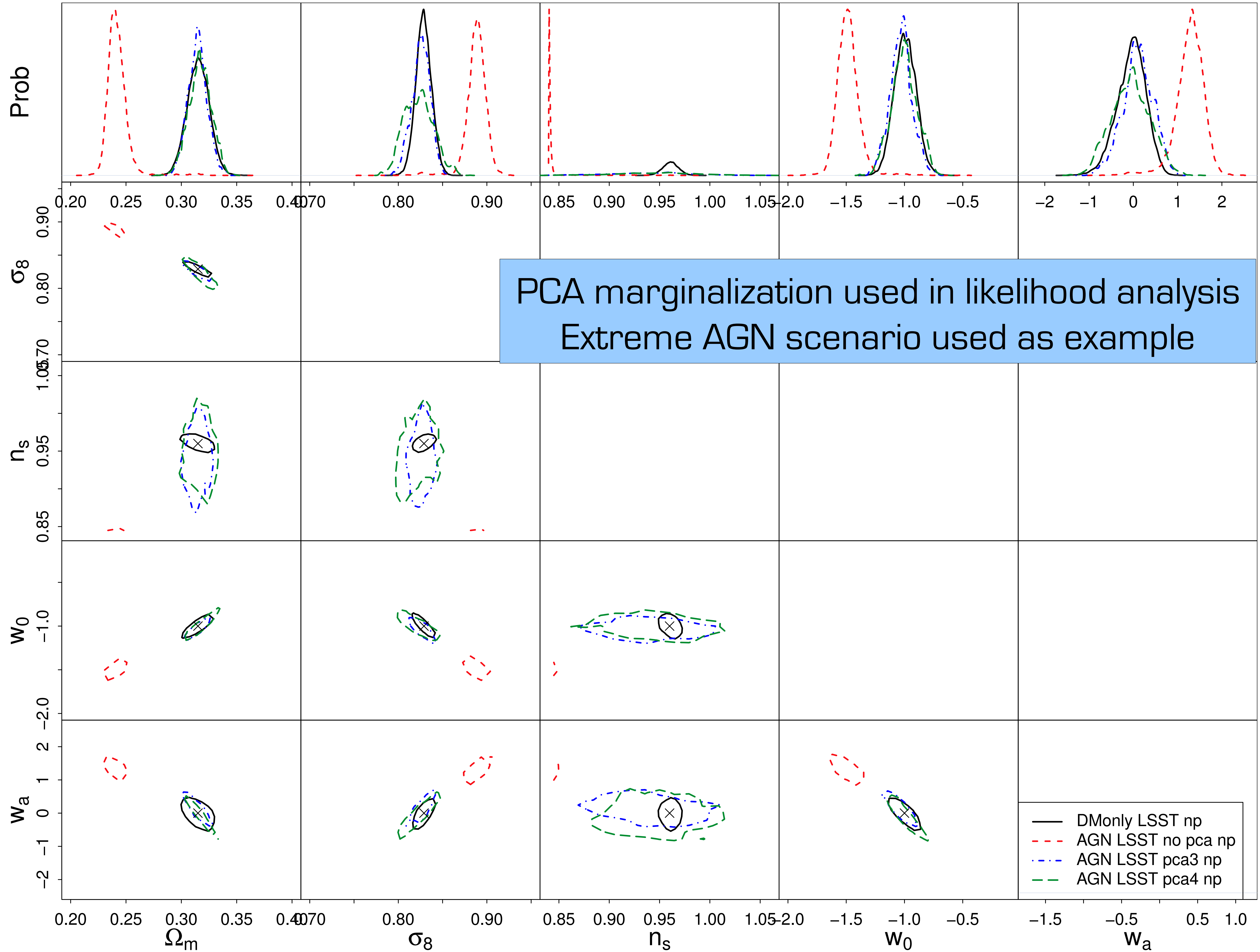
$$\chi^2(\mathbf{p}_{\mathrm{co}}, \mathbf{p}_{\mathrm{nu}}) = (\mathbf{P}\mathbf{U}^t\mathbf{D} - \mathbf{P}\mathbf{U}^t\mathbf{M})^t(\mathbf{P}\mathbf{U}^t\mathbf{C}\mathbf{U}\mathbf{P})^{-1}(\mathbf{P}\mathbf{U}^t\mathbf{D} - \mathbf{P}\mathbf{U}^t\mathbf{M})$$

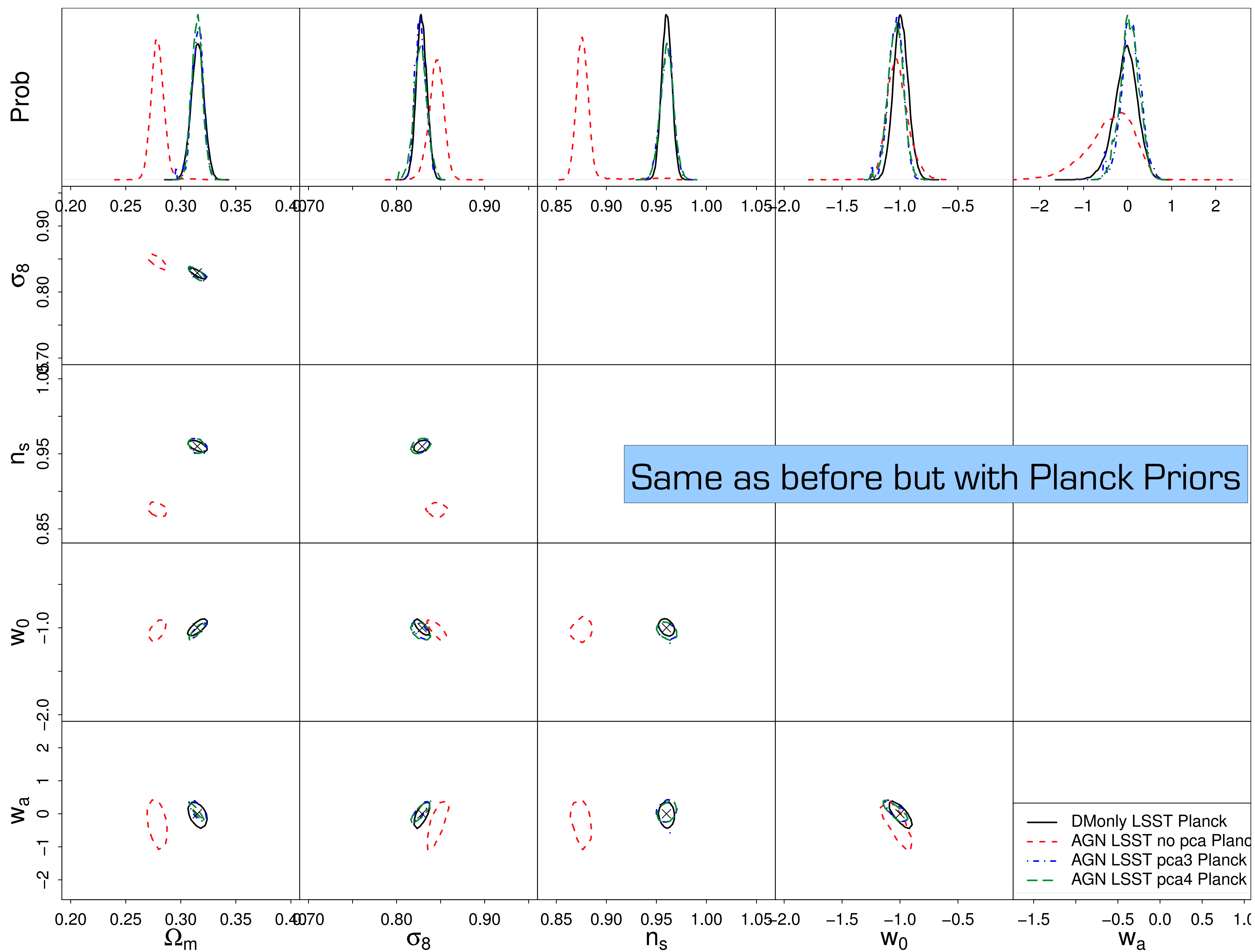
PCA-marginalization/Mode removal

2) Transform C(l) to PC space -> remove contaminated modes -> transform back to C(l)



PCA marginalization used in likelihood analysis
Extreme AGN scenario used as example



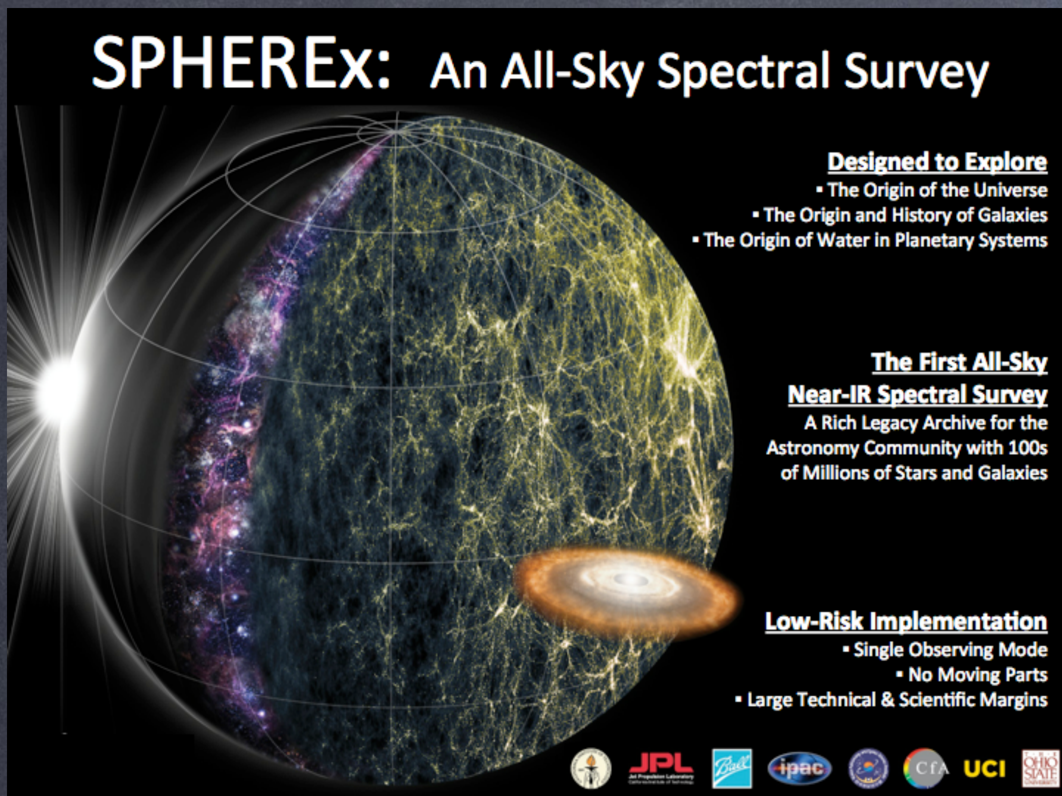


Same as before but with Planck Priors
Prob
σ_8
n_s
w_0
w_a
Ω_m
DMonly LSST Planck
AGN LSST no pca Planc
AGN LSST pca3 Planck
AGN LSST pca4 Planck

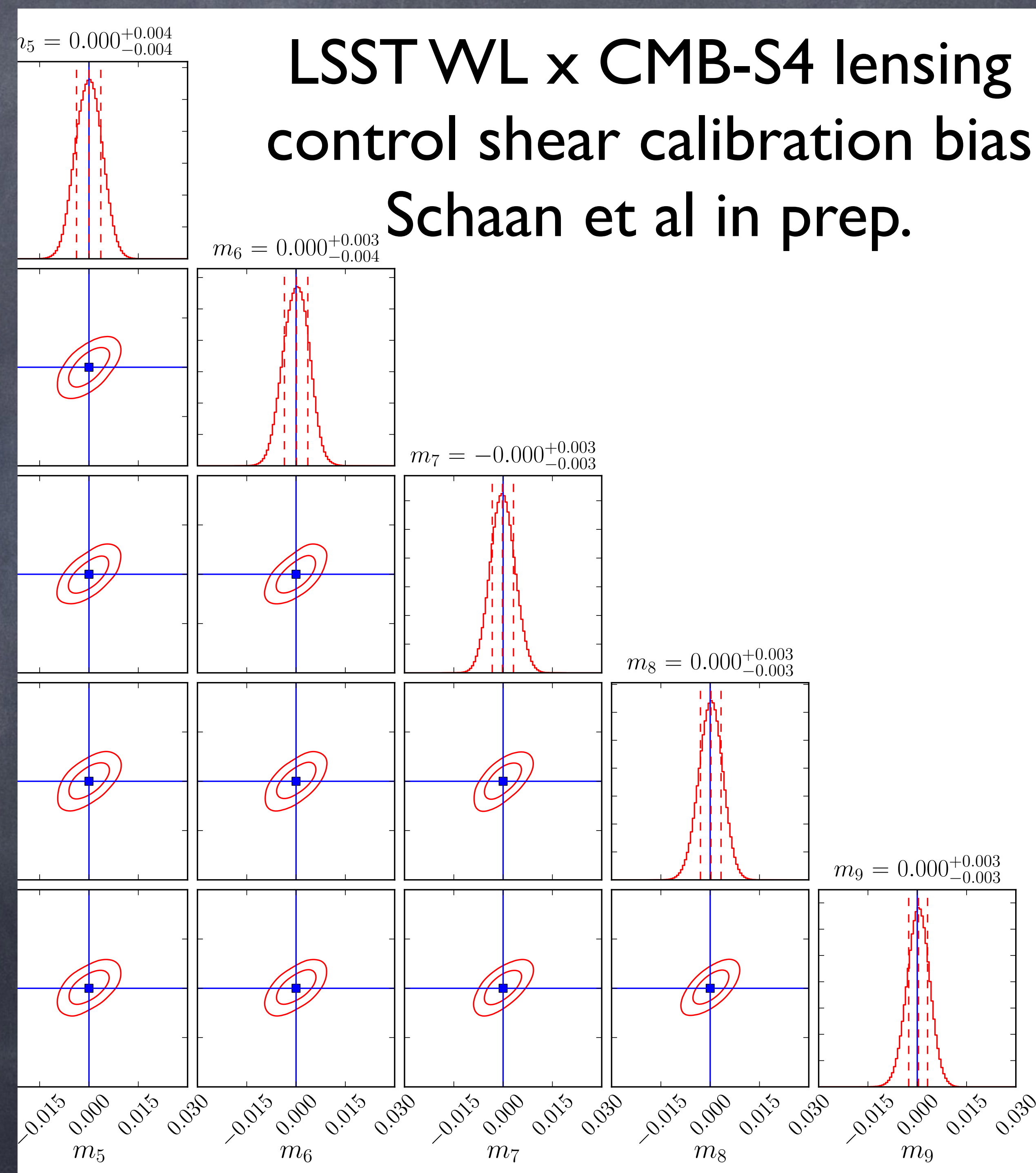
Similar Study on Galaxy Intrinsic Alignment contaminating LSST WL can be found in Krause, TE, Blazek '16

Moving on to Synergies with External Data Sets

Systematics control: External data sets



- Within the Dark Energy Survey, dust is one of the main concerns for high-precision photometry
- Use SPHEREx to solve LSST dust problems
- Many other SPHEREx-LSST synergies (LSST Y1)



Systematics control: External data sets

- LSST- DESI overlap is highly desirable
- Difficult since Airmass "prohibits" U-band (324- 395nm) observations in the north

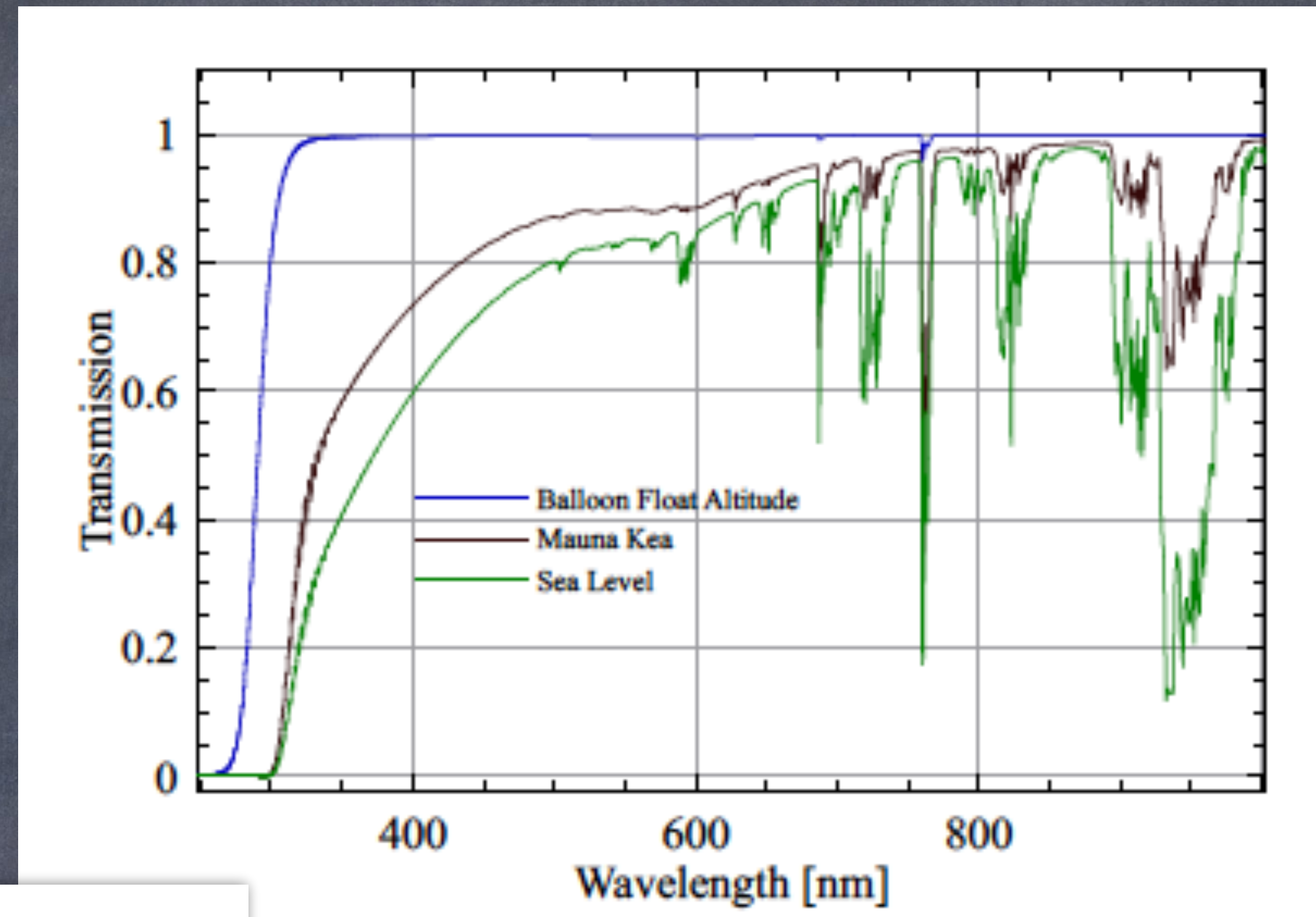
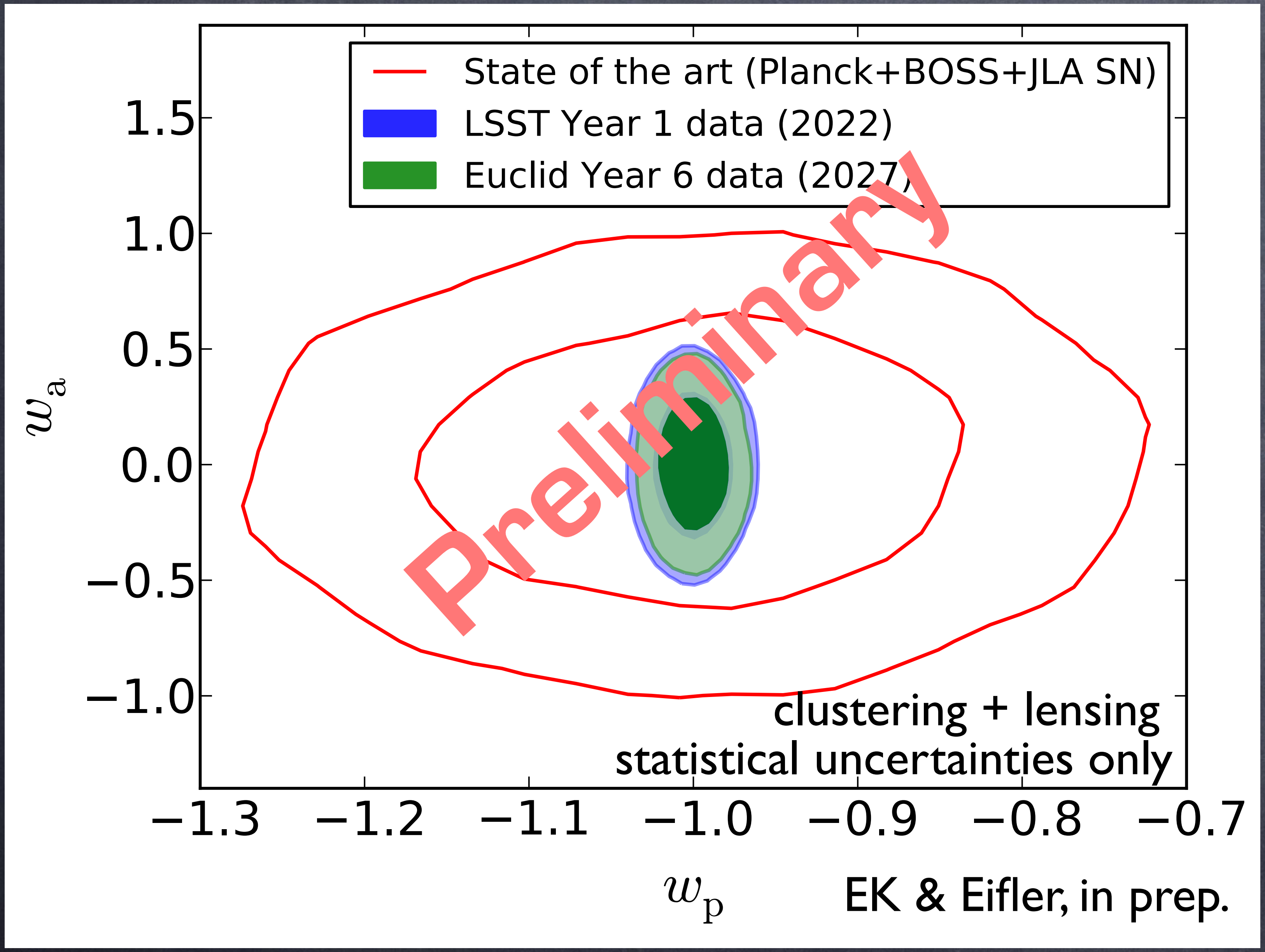


Table 1. Assumed mission parameters for a Small, Medium, Large ULDB. The last row contains the computed survey area at Euclid depth.

	Euclid	Small	Medium	Large
Dark time per day (h)	24	12	12	12
Mission duration (d)	2195	100	100	100
Camera FoV (deg^2)	0.57	1	1.5	2
Primary Mirror (m^2)	1.13	1.13	2.55	4.52
Survey Strategy	0.6	1	1	1
A_{survey} (deg^2, Euclid depth)	15,000	1,000	3,382	7,993

- **Idea:** Use NASA's newly developed Ultra-Long Duration Balloon Capability to get U-band coverage
- Test Mission (SuperBIT) launches Spring '17 or '18

The LSST Awakens (soon)

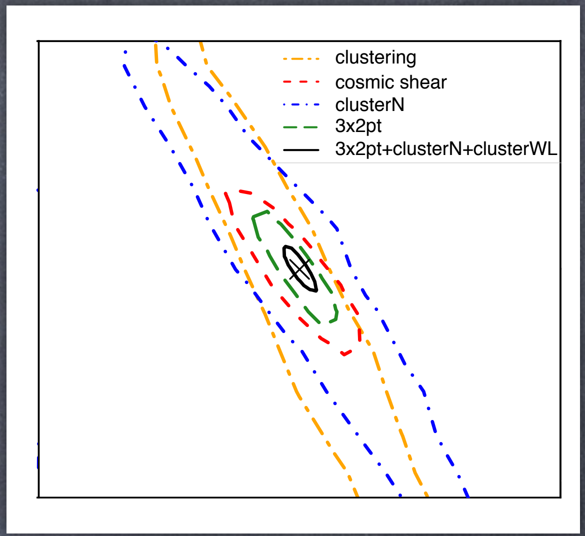


- **LSST Y1** will cover 18,000 deg2 to r-mag ~ 25.5 AB
- Realistic Cosmology Forecasts (Non-Gaussian covs) show that area is much more important than number density of galaxies (Cosmic Variance is more important than Noise terms)
- LSST Dark Energy Prime Time will come early (2023)

Why am I excited about LSST ?

Multi-Probe with LSST and Multi-Survey around LSST Cosmology

1. LSST Y1 data → Check single Probes for Consistency →



2. LSST Y1 data + SPHEREx + Planck
3. LSST Y10 data + WFIRST + CMB-S4

Until then...

- Learn about systematics (Simulated analyses, DES, HSC)
- Think about Ultra-Long Duration Balloon Synergies