Combining Probes of Large-Scale Structure in the Precision Cosmology Era

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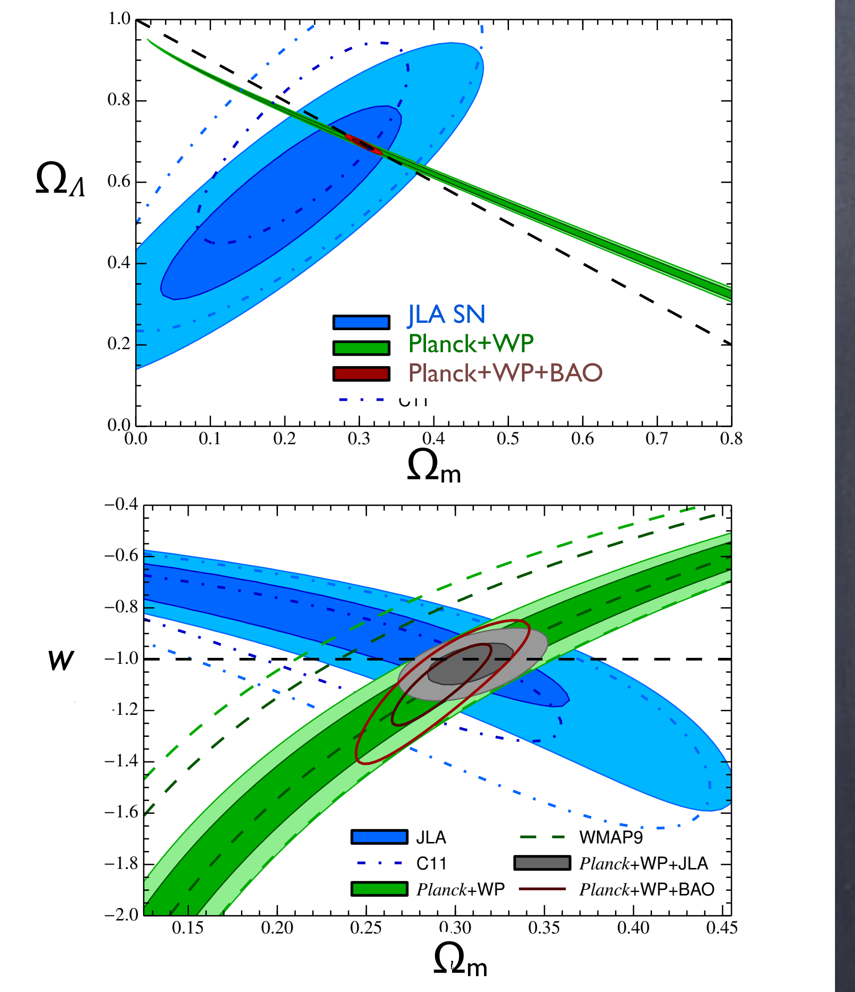
with input from the DES & LSST-DESC collaborations

Theoretical and Observational Progress on LSS, 7/20/2015

The Power of Combining Cosmological 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



Betoule et al. 2014

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

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
$\dim(\mathbf{n}) \gg \dim(\boldsymbol{\pi})$
parameterize + prioritize!

Priors

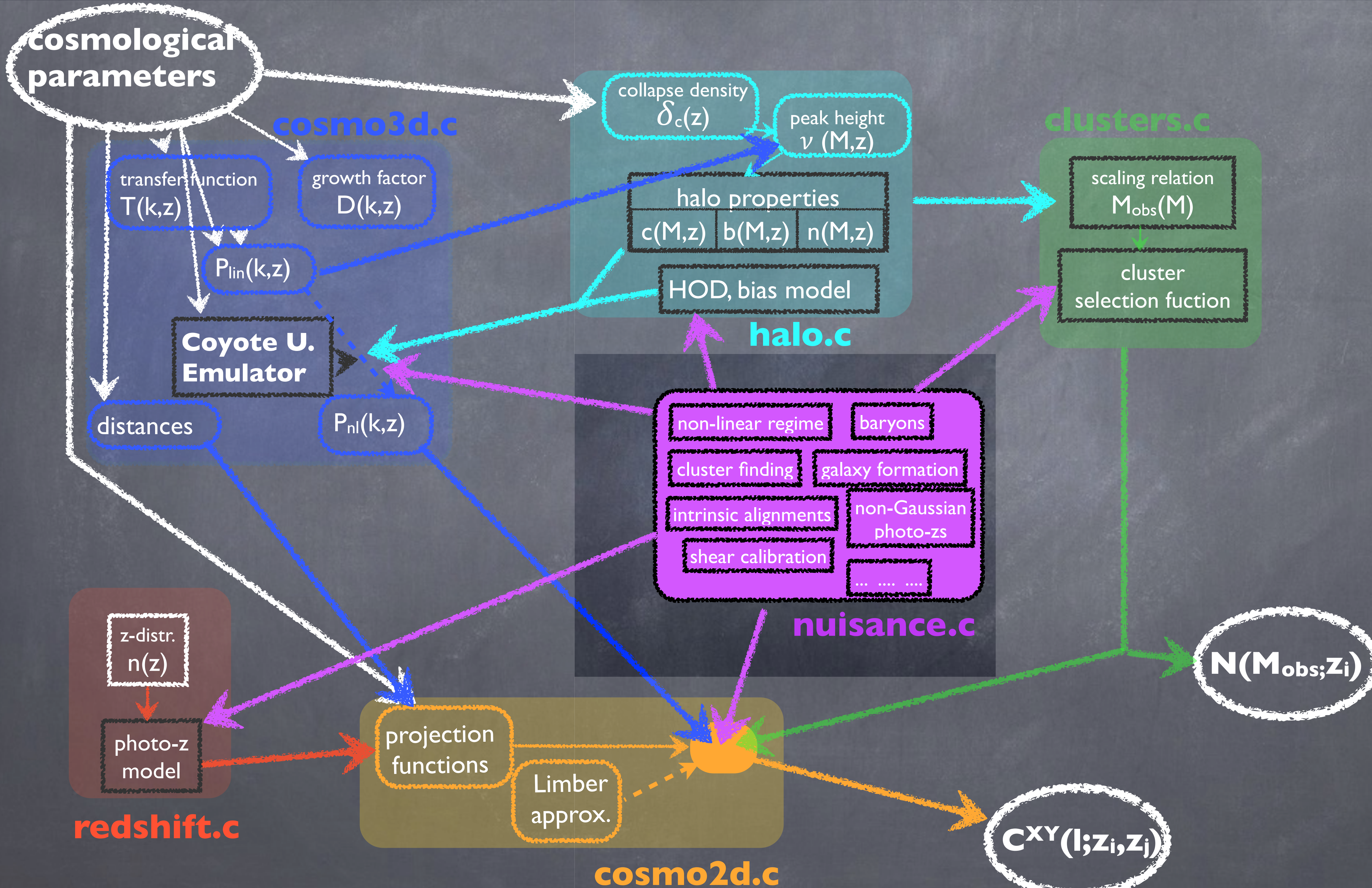
External Data
Simulations

validate

Introducing CosmoLike

- Likelihood analysis library for combined probes w_aCDM analyses
- Observables from three LSS 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 halo model (cross-)covariances
  - see Becker+15 (tomorrow) for comparison with WL mocks
- Optimized for high-dimensional likelihood analyses
- Currently limited beta release, preparing for public release

CosmoLike Data Vector



Combined Probes Systematics

- "Precision cosmology": excellent statistics - systematics dominated
- Easy to think up large list of *known* systematics + nuisance parameters
  - galaxies: LF, bias (e.g., 5 HOD parameters + b_2 per z-bin,type), photo-zs, ...
  - clusters: mass-observable relation, projection effects, off-centering, ...
  - shear: calibration, photo-zs, intrinsic alignments, shear calibration, ...
  - Σ(poll among DES working groups) ~ 500-1000 parameters
  - *does not cover previously unknown systematics*

    null test + controlling known systematics necessary preparation for identifying these
- Marginalize, self-calibrate (if model is known)
  - costly (computationally, constraining power)
  - need to prioritize

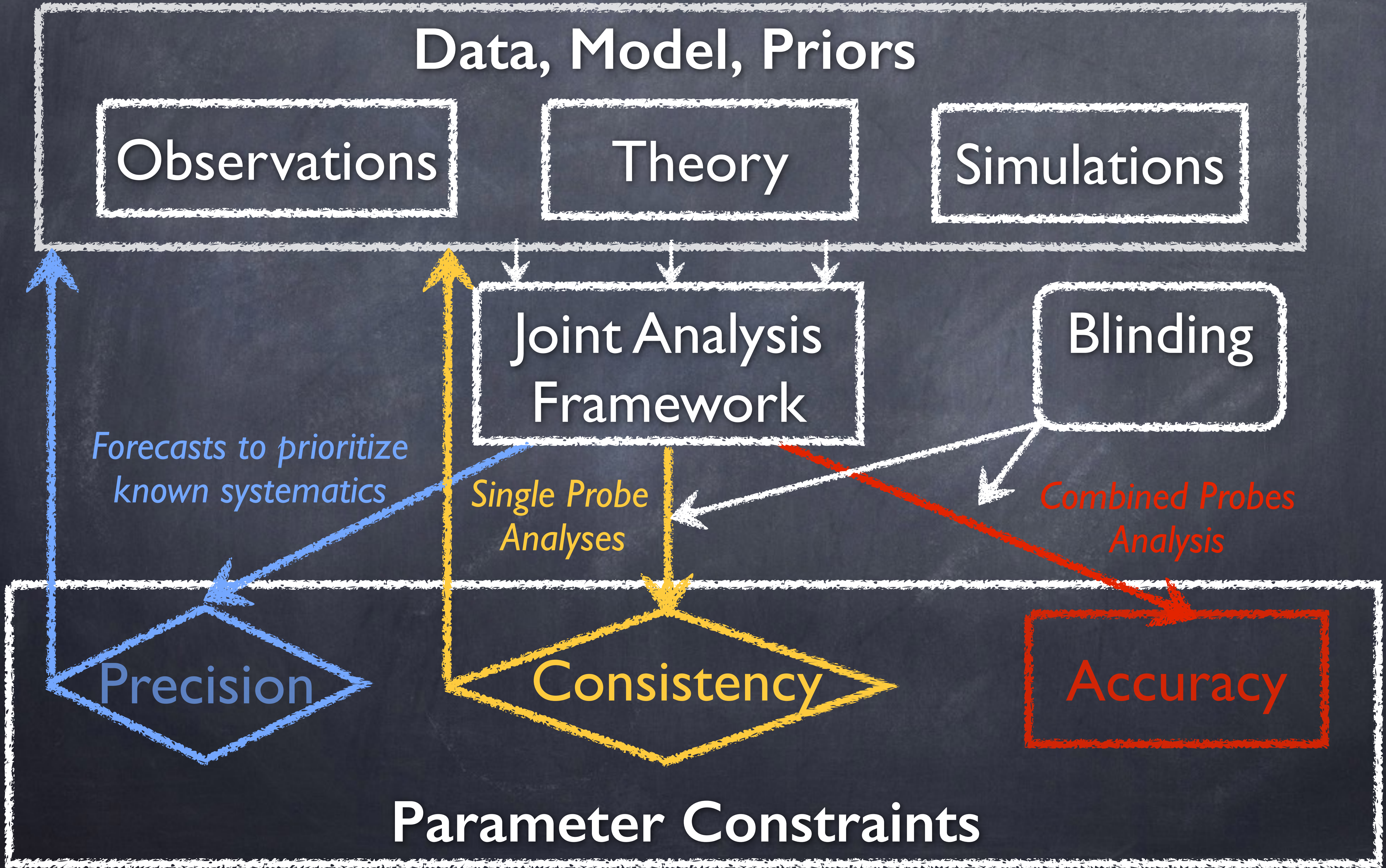
Work Plan for Known Systematics

- 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 parameterizations
  - *needs to be consistent across probes*
- Constrain systematics models, priors on nuisance parameters
  - independent observations
  - other observables from same data set
  - split data set

Joint Analysis Flow Chart



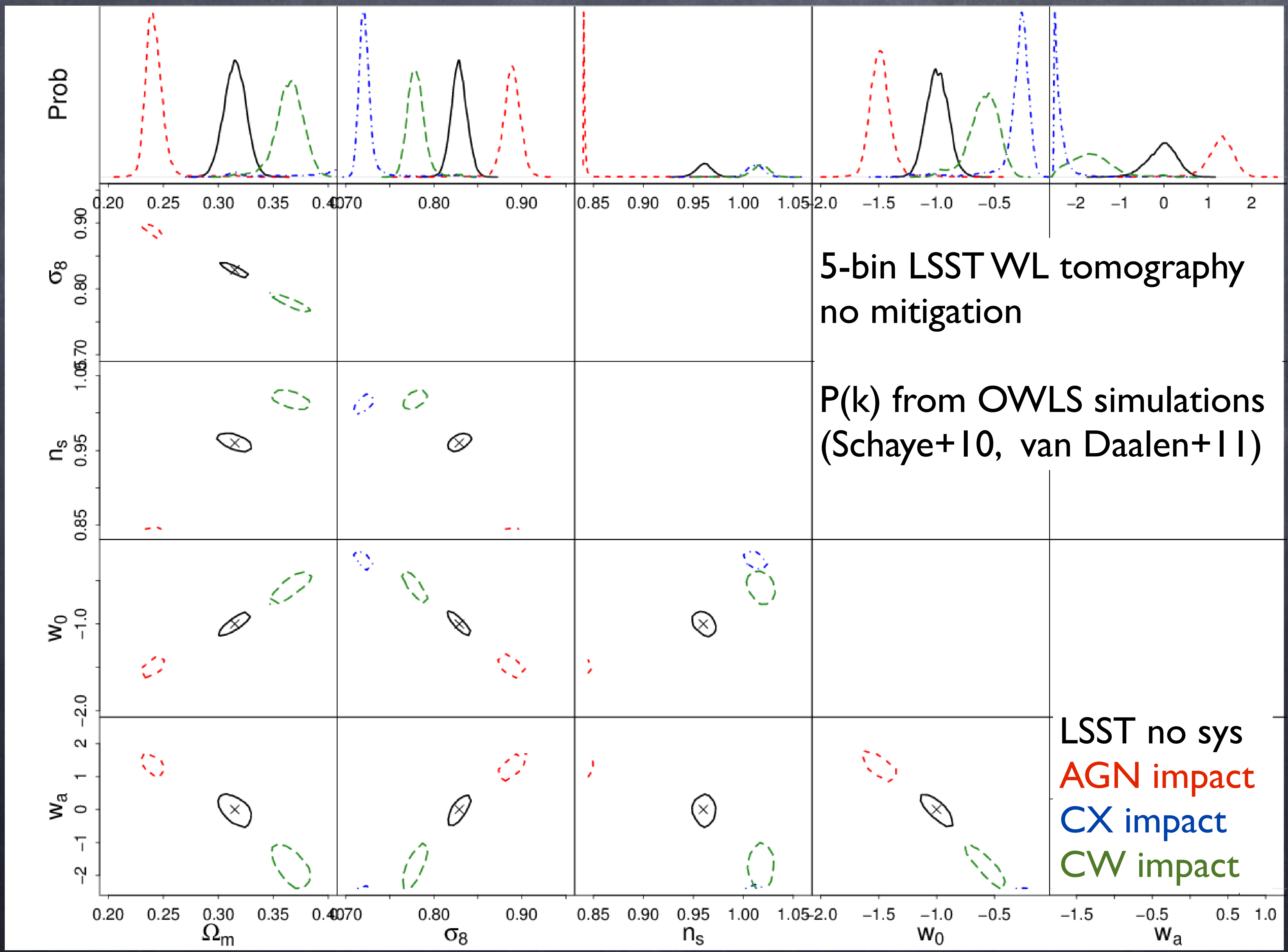
Work Plan for Known Systematics

- Specify data vector
- Identify + model systematic effects
- Combine theory, simulation + data to improve models + priors

Worked example: LSST WL tomography: 5 z-bins, 20 < l < 5000

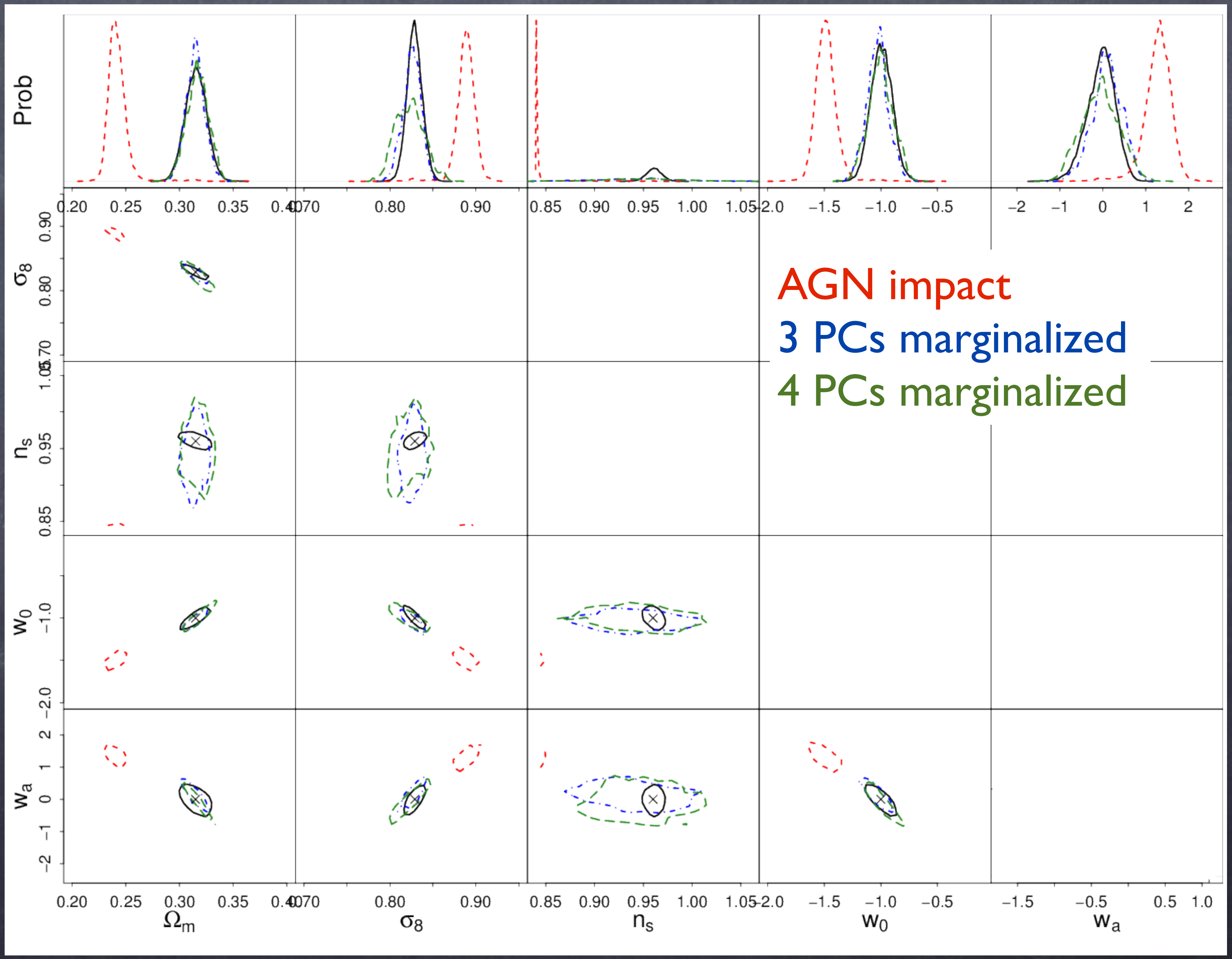
impact + mitigation of baryons, intrinsic alignments

Impact of Baryons on LSST WL



Mitigation of Baryons in WL

- PCA based mitigation strategy (Eifler, EK, et al. 14)
- 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



Intrinsic Alignments

- Not all weak lensing source galaxies randomly oriented
- 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

Linear IA Models

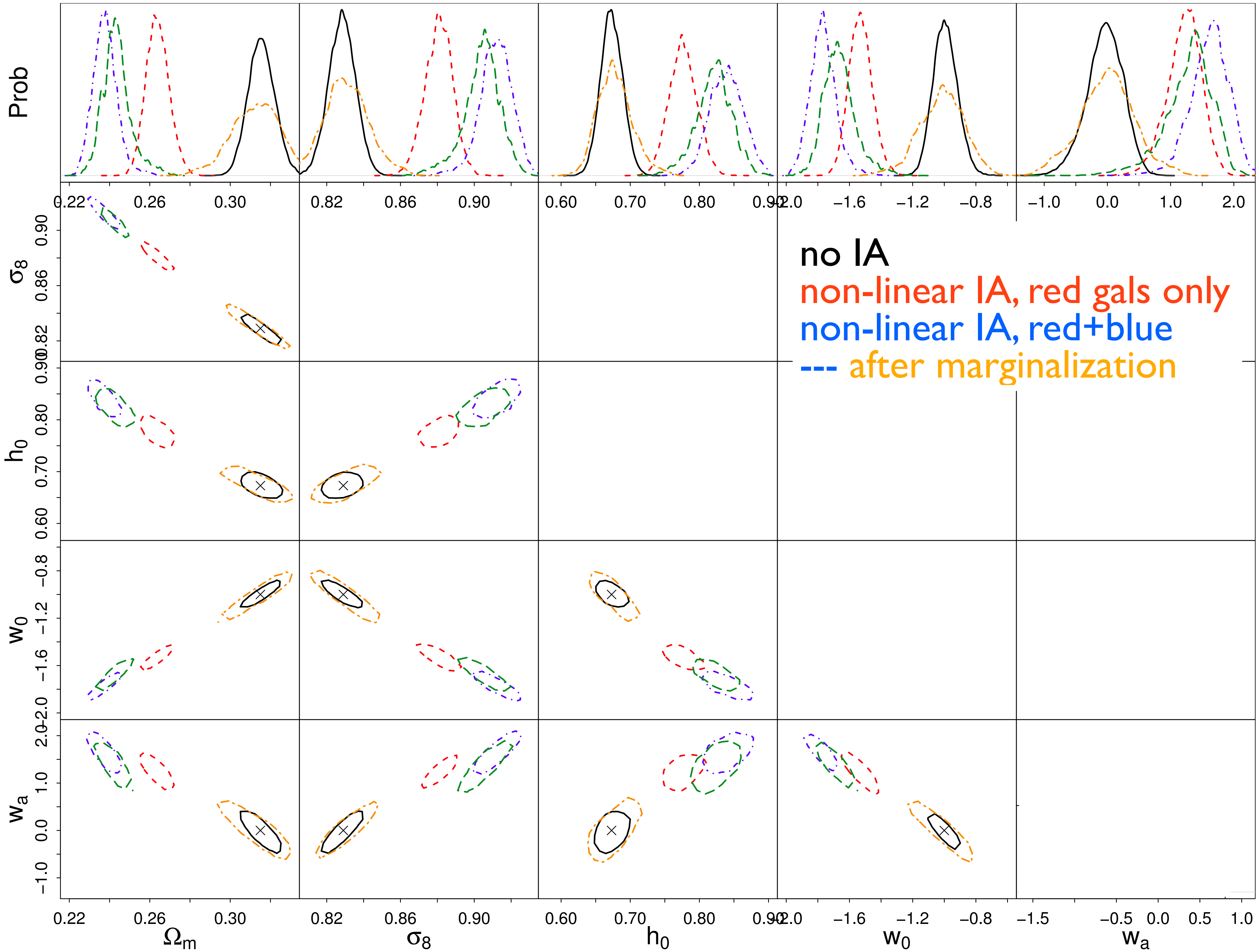
$$P_{\mathrm{GI}}(k,a) = A(L,a,\Omega_{\mathrm{M}},?)f_{\mathrm{GI}}\left(P_\delta(k,a),P_{\mathrm{lin}}(k,a),?\right)$$
$$P_{\mathrm{II}}(k,a) = A^2(L,a,\Omega_{\mathrm{M}},?)f_{\mathrm{II}}\left(P_\delta(k,a),P_{\mathrm{lin}}(k,a),?\right)$$

- 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))
  - full tidal model: EFT + density weighting (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 $A \rightarrow A \times f_{\mathrm{red}}$
  - what's $\langle A\rangle_L$, f_{red} for deep surveys like LSST/WFIRST?
    - so far, extrapolate LF from shallower surveys (GAMA, DEEP2)

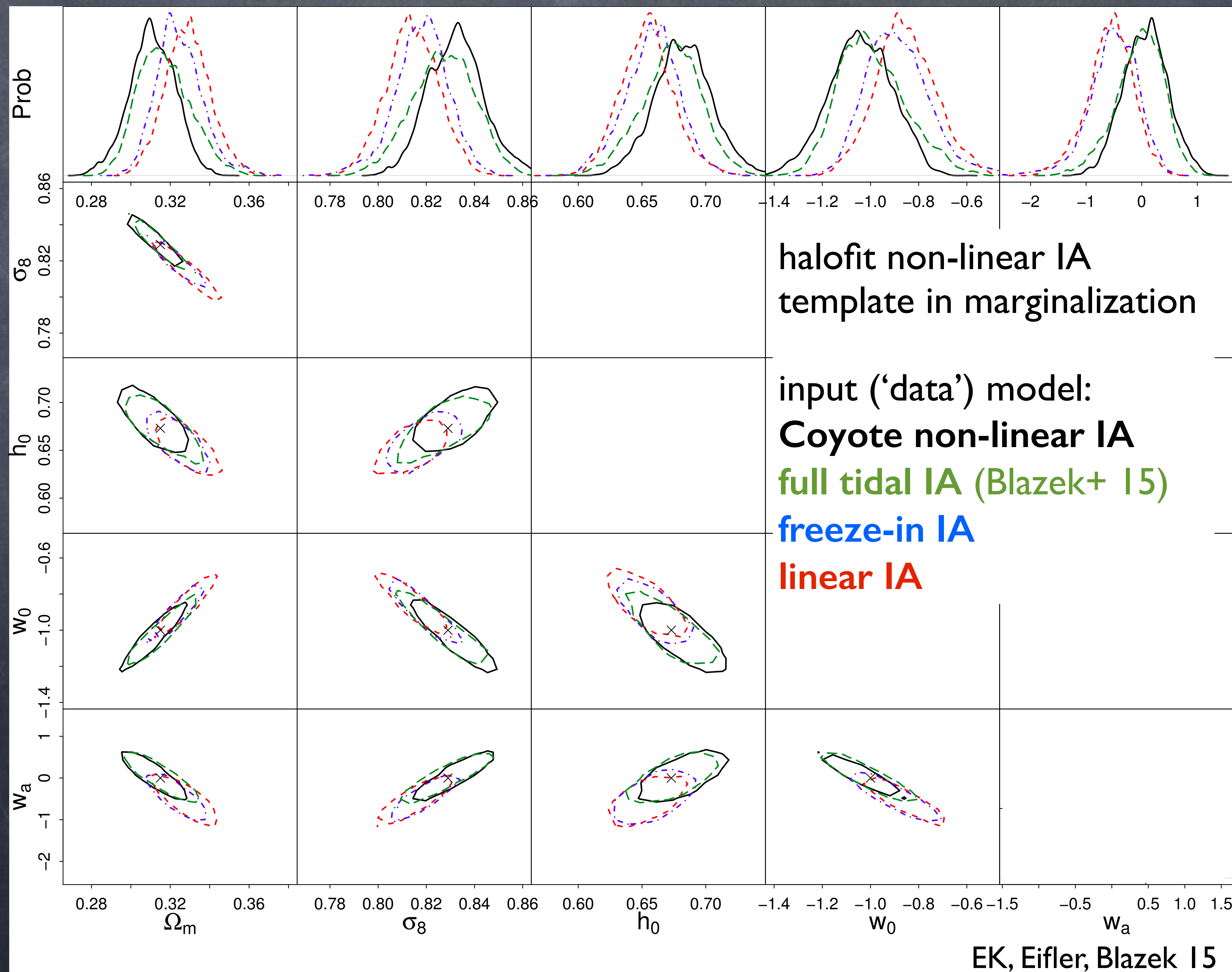
Impact of Linear Alignments on LSST WL



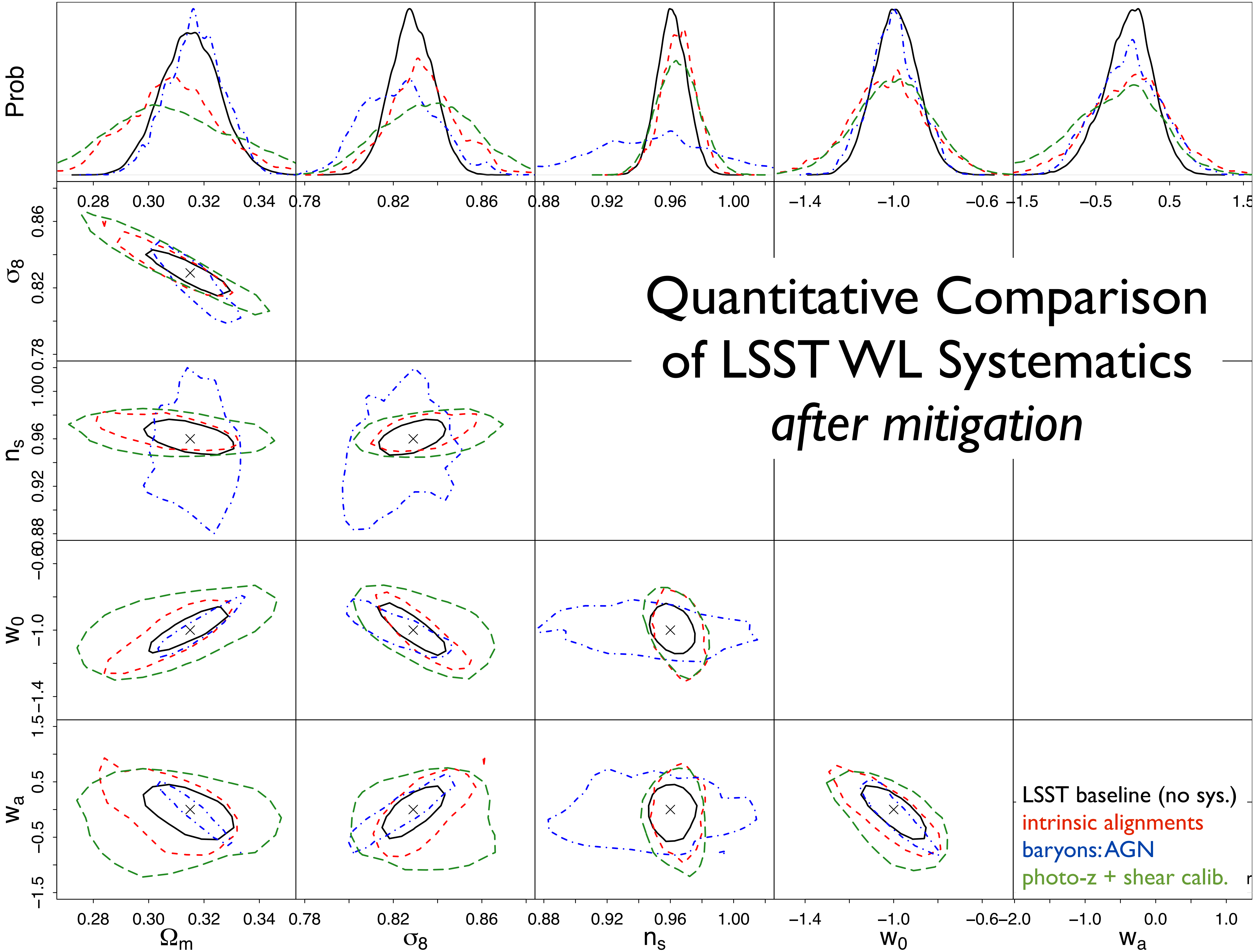
EK, Eifler, Blazek 15

IA Mitigation: Amplitude marginalization, power spectrum shape uncertainties

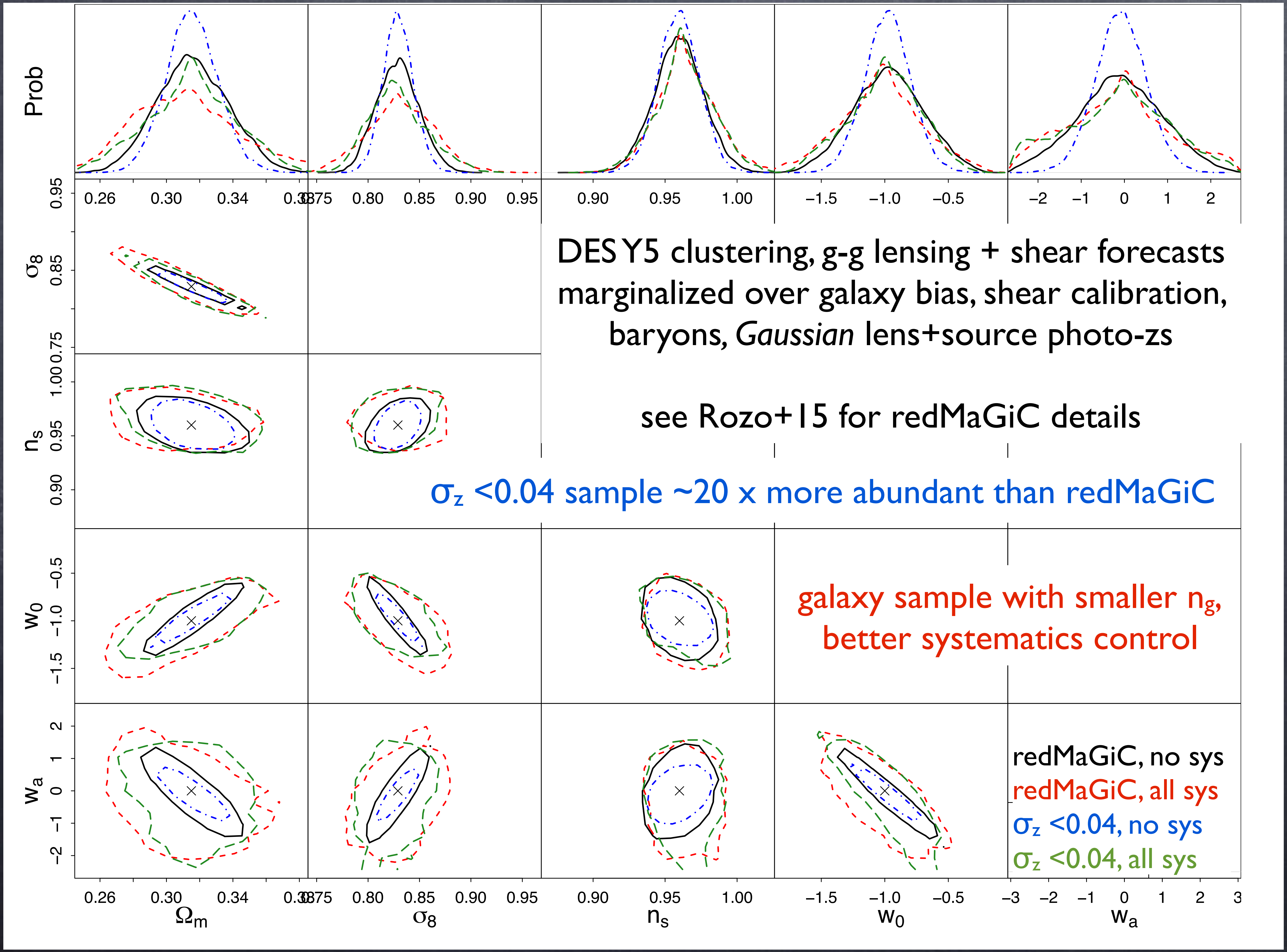
- Marginalized over amplitude normalization + redshift scaling (A_0, β, η, $\eta_{\text{high-z}}$), 6 LF parameters
- Biases from uncertainties in IA template
- Next steps: reduce FoM degradation by including priors on range of parameters + allowed templates
  - joint analysis with g-g lensing + clustering



Quantitative Comparison of LSST WL Systematics *after mitigation*



DES Forecasts: Photo-zs vs. Shot Noise



Conclusions

- Combining correlated observables requires joint models + analyses
- For systematics limited analyses:
  - find suitable parameterizations for systematic effects
    - must be consistent across probes
    - simulations, specific observables (internal/external data)
  - constrain nuisance parameters
    - self-calibration, external data sets
  - observations often not shot noise limited, smaller sample with better systematics control may give better constraints
- Use forecasts to prioritize preparatory systematics research + requirements
  - photo-zs key area for improvements

DES Forecasts: Data Vector

- focus on Y5 performance, n(z)+systematics informed by SV data
- cosmic shear
  - 5 tomography bins
  - 25 l bins, 25 < l < 5000
- galaxy clustering
  - 3 redshift bins (0.2-0.4,0.4-0.6,0.6-0.8)
  - compare two samples: σ_z <0.04; redMaGiC (n ~ $10^{-3}(h/\mathrm{Mpc})^3$, Rozo+2015)
  - linear + quadratic bias only : l bins restricted such to k < 0.5 *h*/Mpc
- galaxy-galaxy lensing
  - galaxies from clustering (as lenses) with shear sources
- clusters - number counts + shear profile
  - so far, 8 richness, 3 z-bins (same as clustering)
  - tomographic cluster lensing (500 < l < 10000)
- SN forecasts to be provided by Dan Scolnic

Backup Slides

DES Forecasts: Covariance

- SN ~uncorrelated, hooray.
- Analytic non-Gaussian 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>)

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

- 1600x1600 tomographic combined probes covariance, and it's positive definite!

DES Forecasts: Nuisance Parameters?

- cosmic shear
  - 5 tomography bins
  - 25 l bins, 25 < l < 5000
- galaxy clustering
  - 3 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 k < 0.5 *h*/Mpc
- 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)
- SN forecasts to be provided by Dan Scolnic

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

b_1, b_2
photo-z (lenses)

N-M relation
c-M relation
off-centering
completeness

work in progress