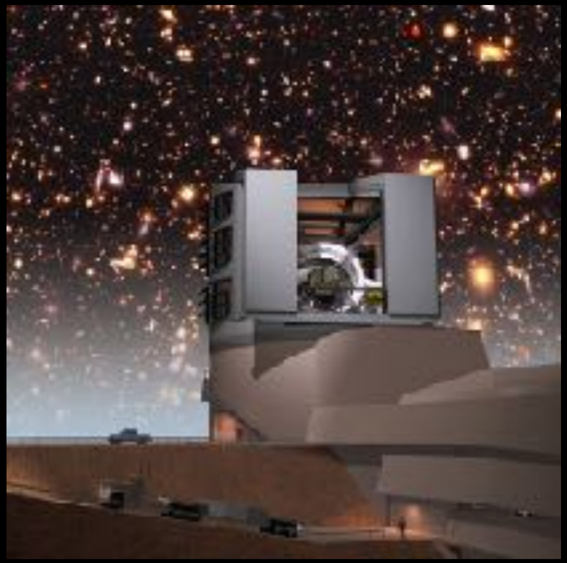
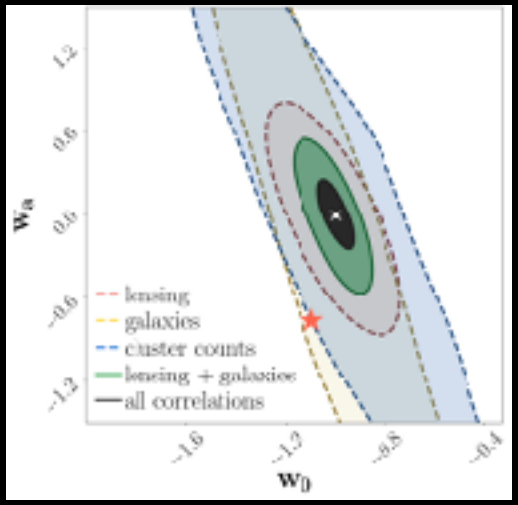




Large-Scale Structure Cosmoloy: Opportunities in the Systematics-Limited Regime

Elisabeth Krause
Steward Observatory/University of Arizona

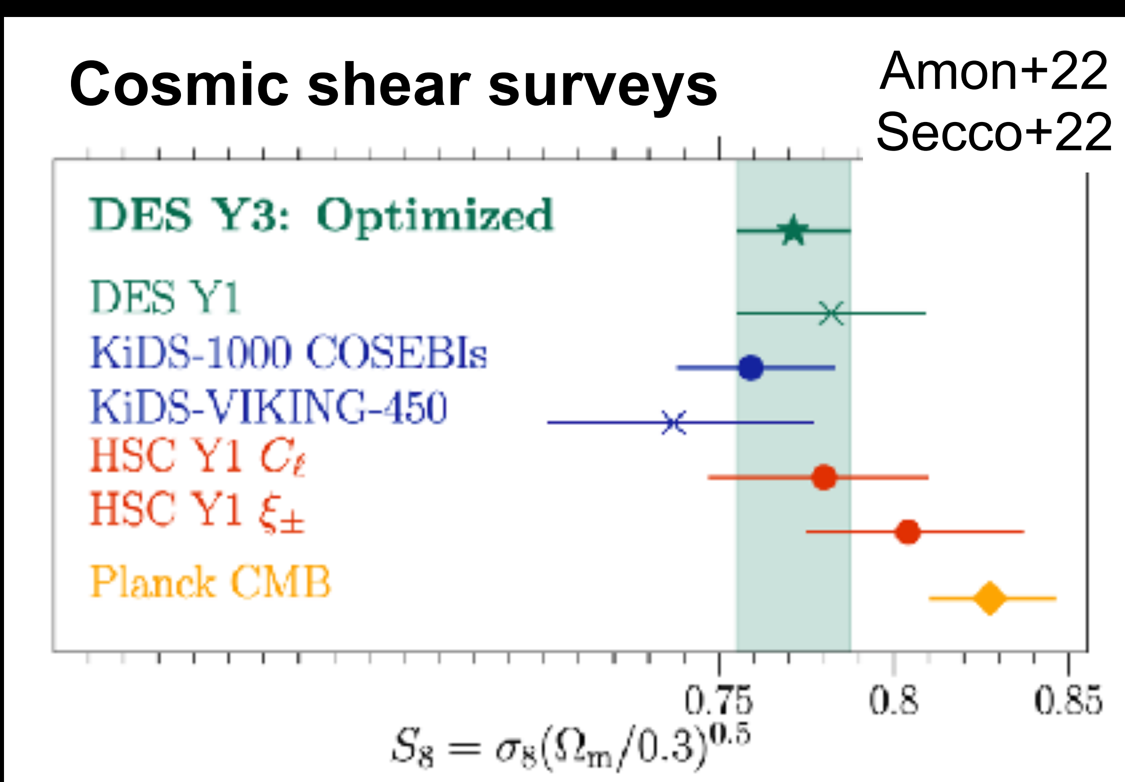
Dark Side of the Universe, Kigali - July 10, 2023

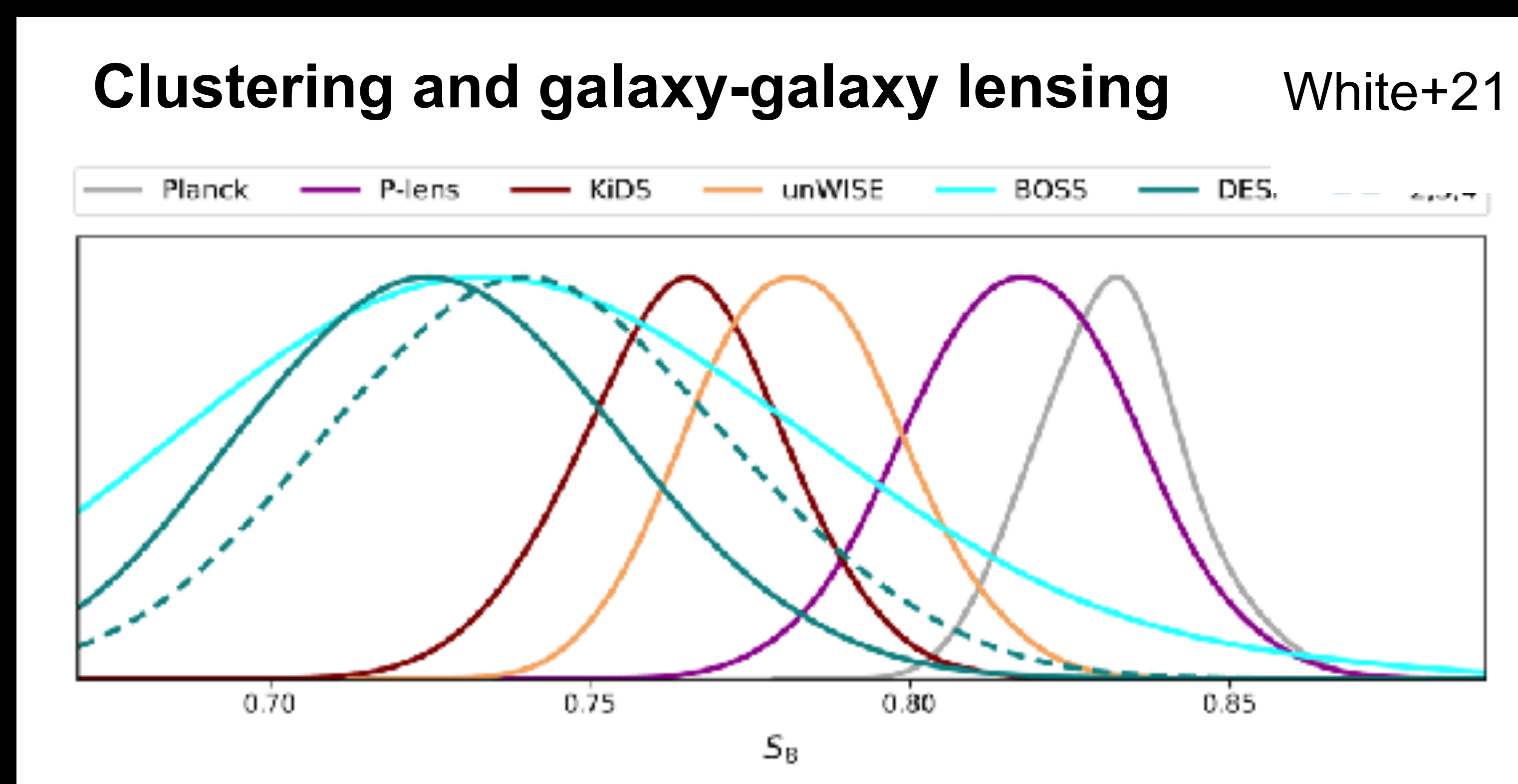
2020s: Concordance Cosmology?

Planck CMB measurements fit by νΛCDM parameterization:

$$\Omega_\mathrm{m} = 0.315 \pm 0.007\,,\ S8 = \sigma_8(\Omega_\mathrm{m}/0.3)^{0.5} = 0.832 \pm 0.012\,,\ H_0 = (67.4 \pm 0.5)\,\mathrm{km/s/Mpc}$$

- Expansion history measurements (BAO, SNe) agree to 1-2%
- Direct H_0 measurements disagree by >5σ
- Low S8 at ~1-3σ from many, but not all, structure growth probes





2020s: Concordance Cosmology?

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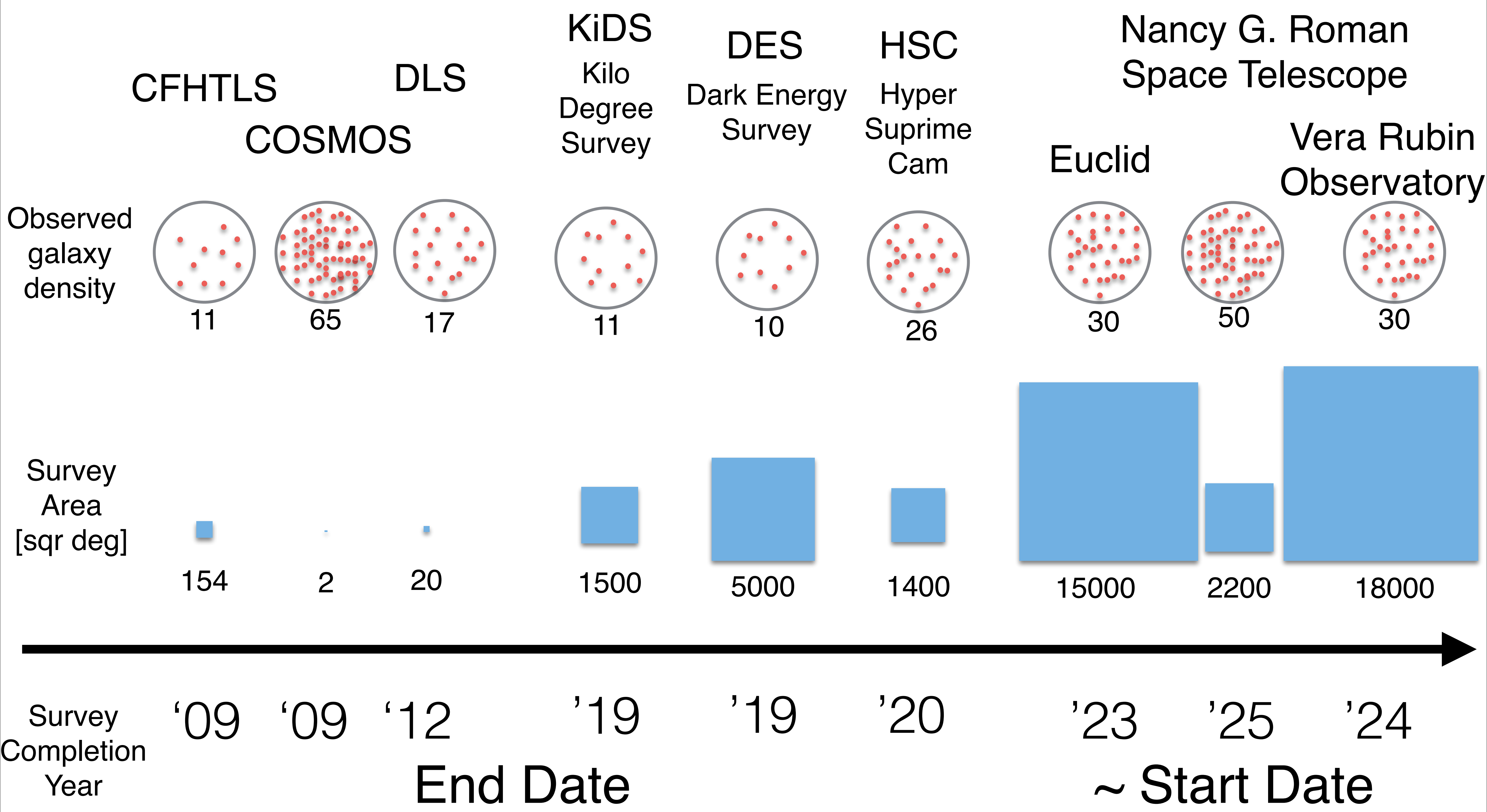
- Expansion history measurements (BAO, SNe) agree to 1-2%
- Direct H_0 measurements disagree by >5σ
- Low S8 at ~1-3σ from many, but not all, structure growth probes

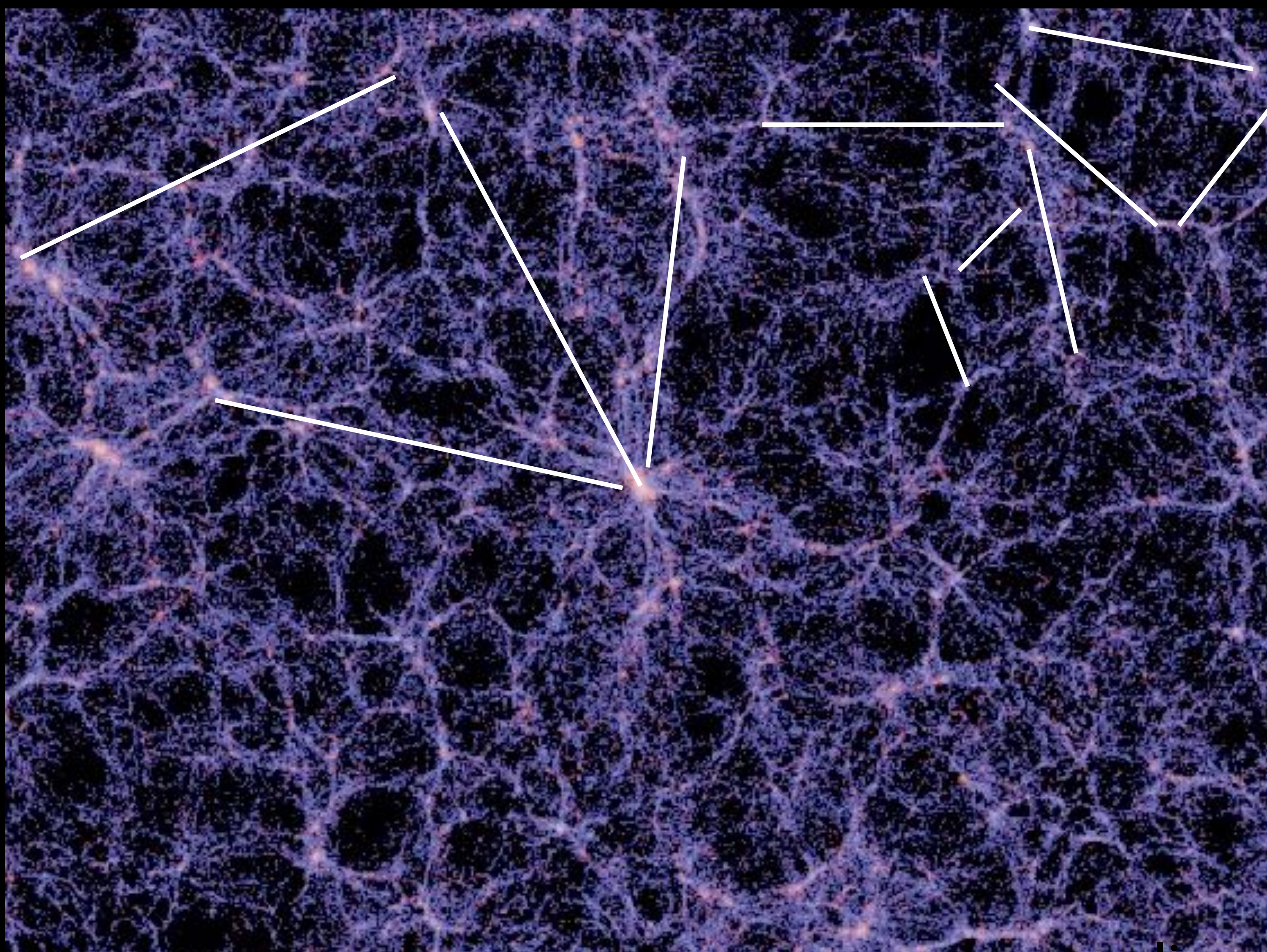
ΛCDM has described large range of observations over cosmic time, more analyses needed to tell whether late-time H0 and S8 indicate real tensions or systematics.

More fundamentally, model pillars dark energy, dark matter, inflation and neutrino mass all require new physics!

Photometric LSS Surveys

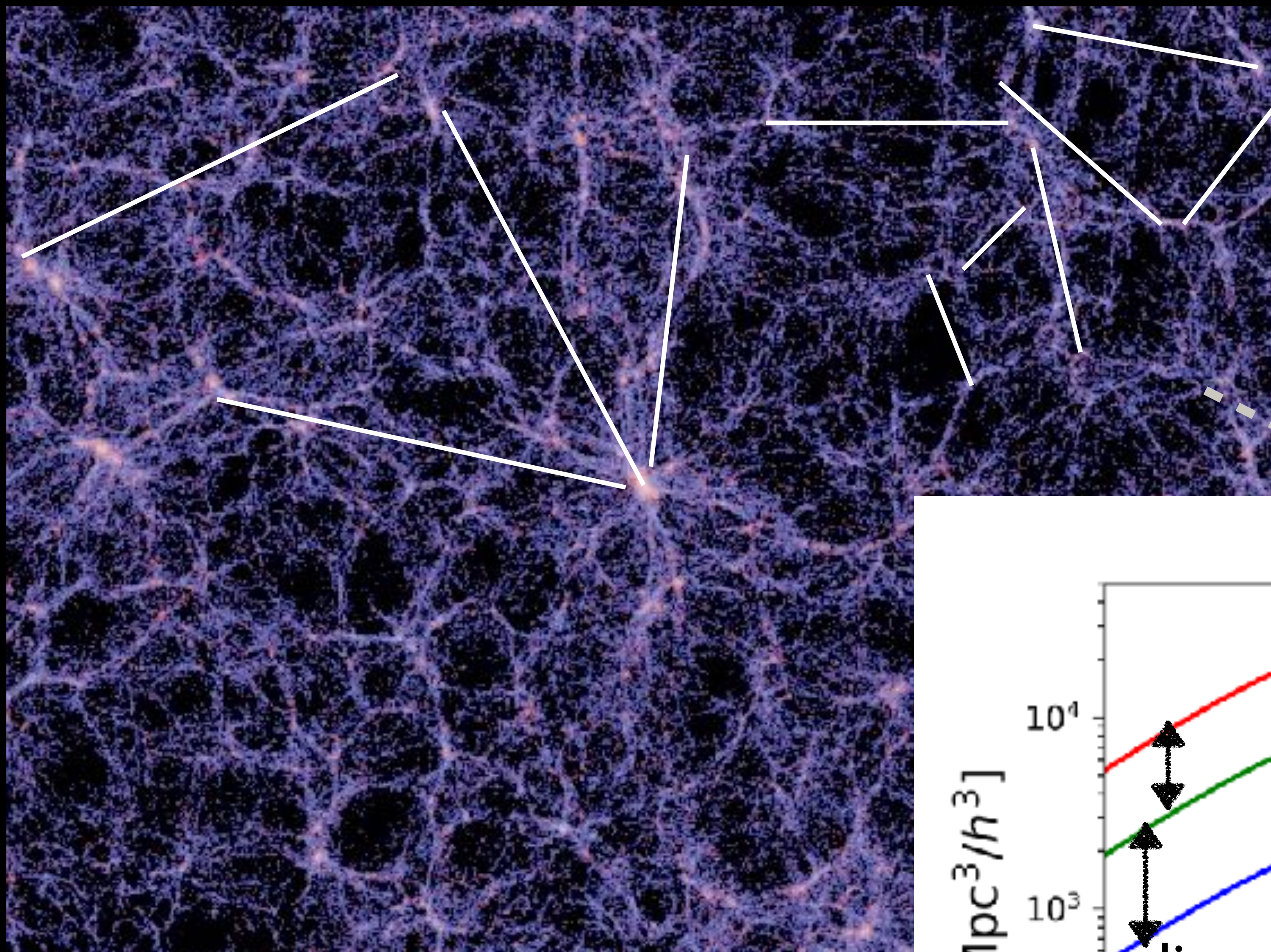


Tracer: Galaxy Clustering



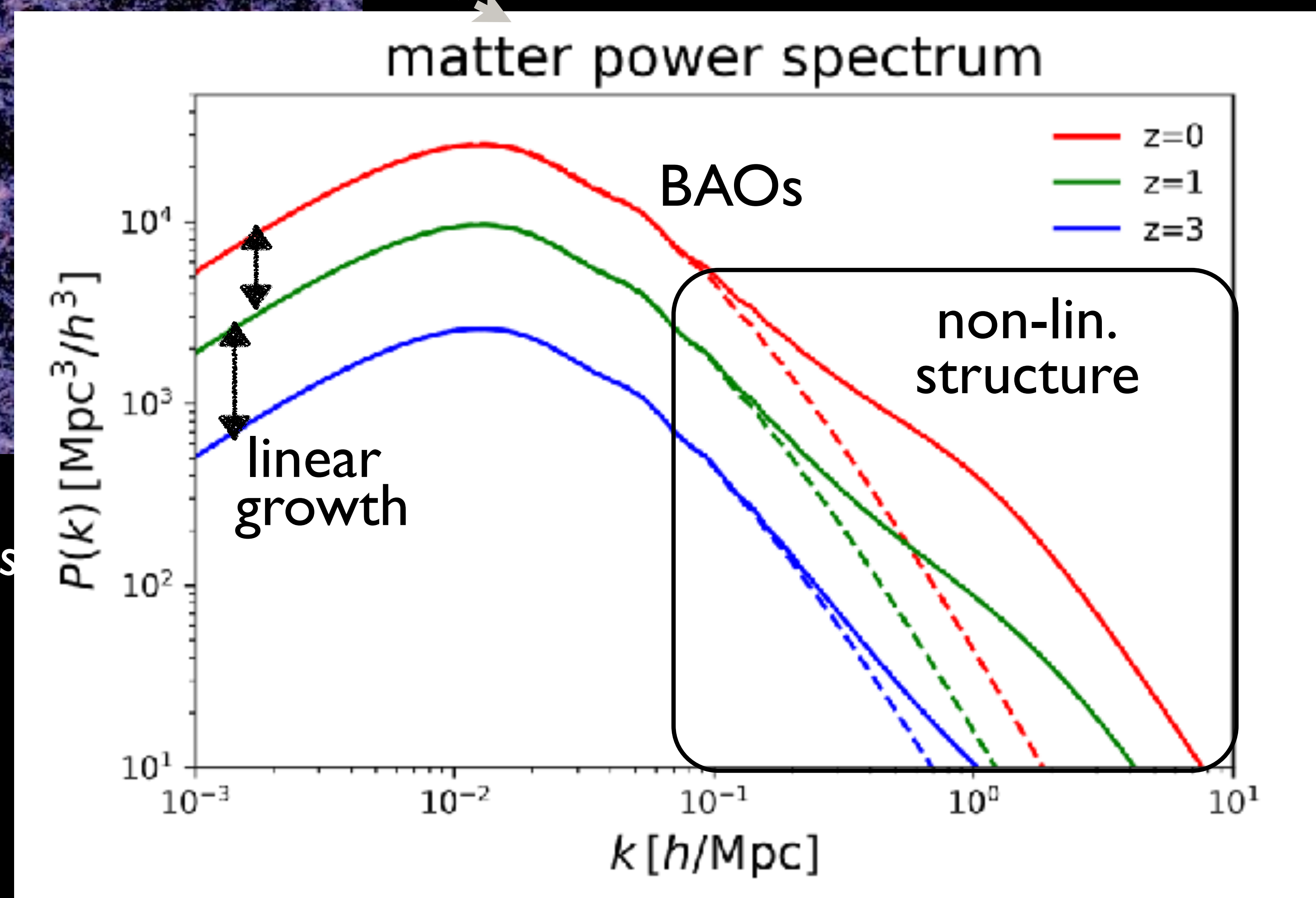
—— two-point correlations
excess probability of galaxy pairs
(over random distr.)
as function of separation

Tracer: Galaxy Clustering



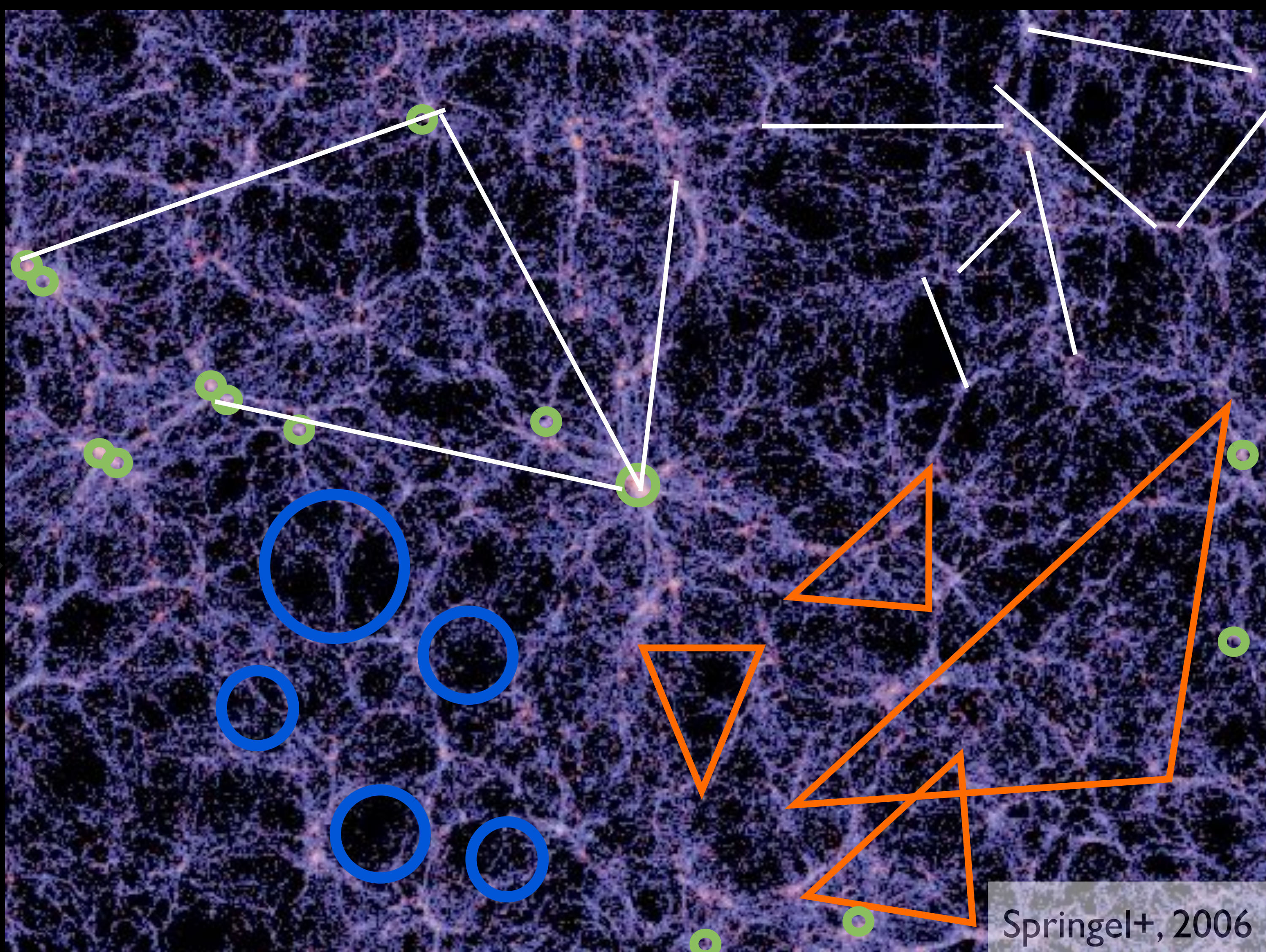
requires ~3D distances (redshift), relation between galaxy density and dark matter density (galaxy bias)

Fourier transform



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

Summary Statistics from the Galaxy Distribution



two-point correlations

clusters (over densities)

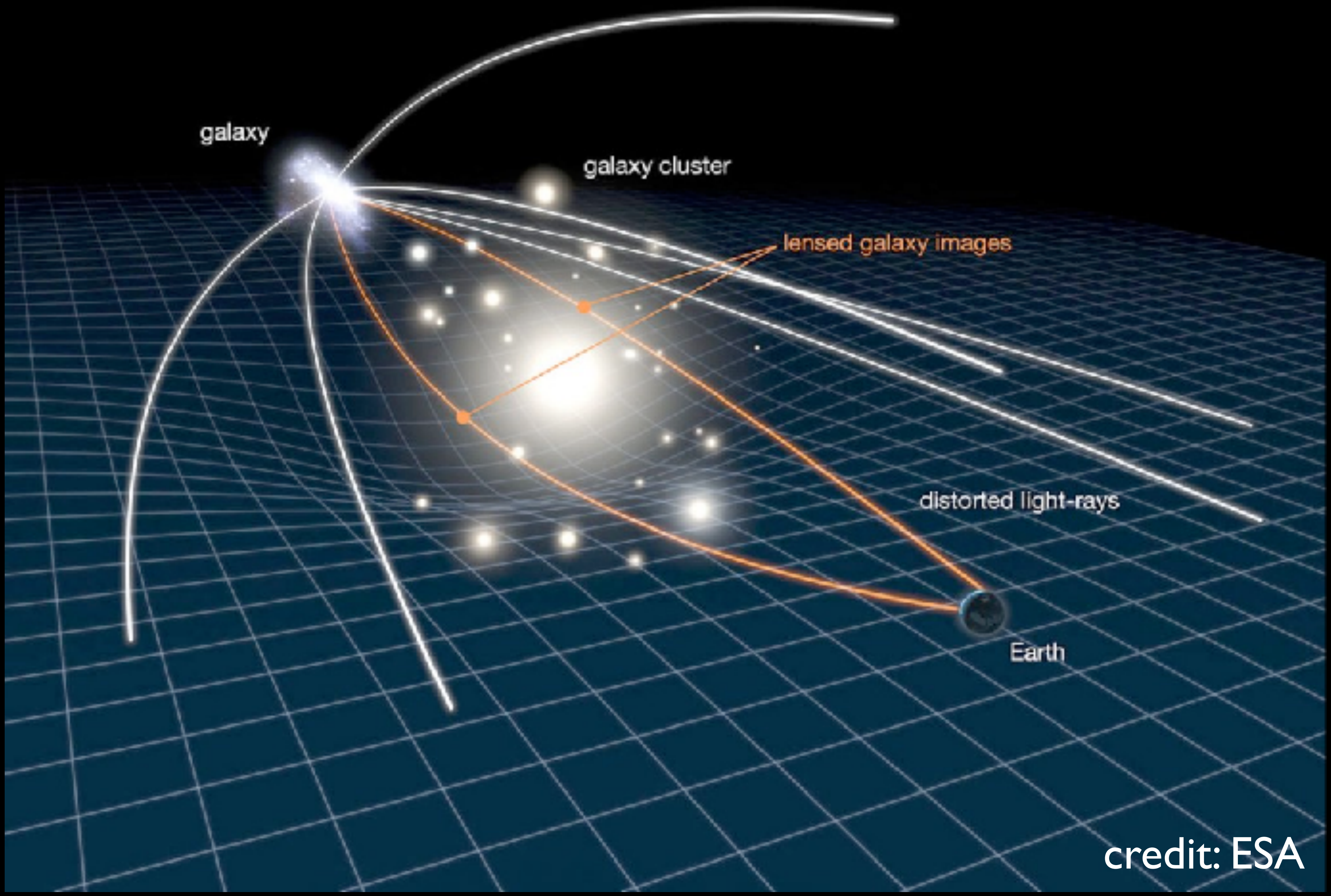
voids (under densities)

three-point correlations,...

key uncertainties

- relation between light and matter distributions: galaxy bias, cluster mass proxy
- redshift uncertainties or failures

Gravitational Lensing



Weak Gravitational Lensing of Galaxies

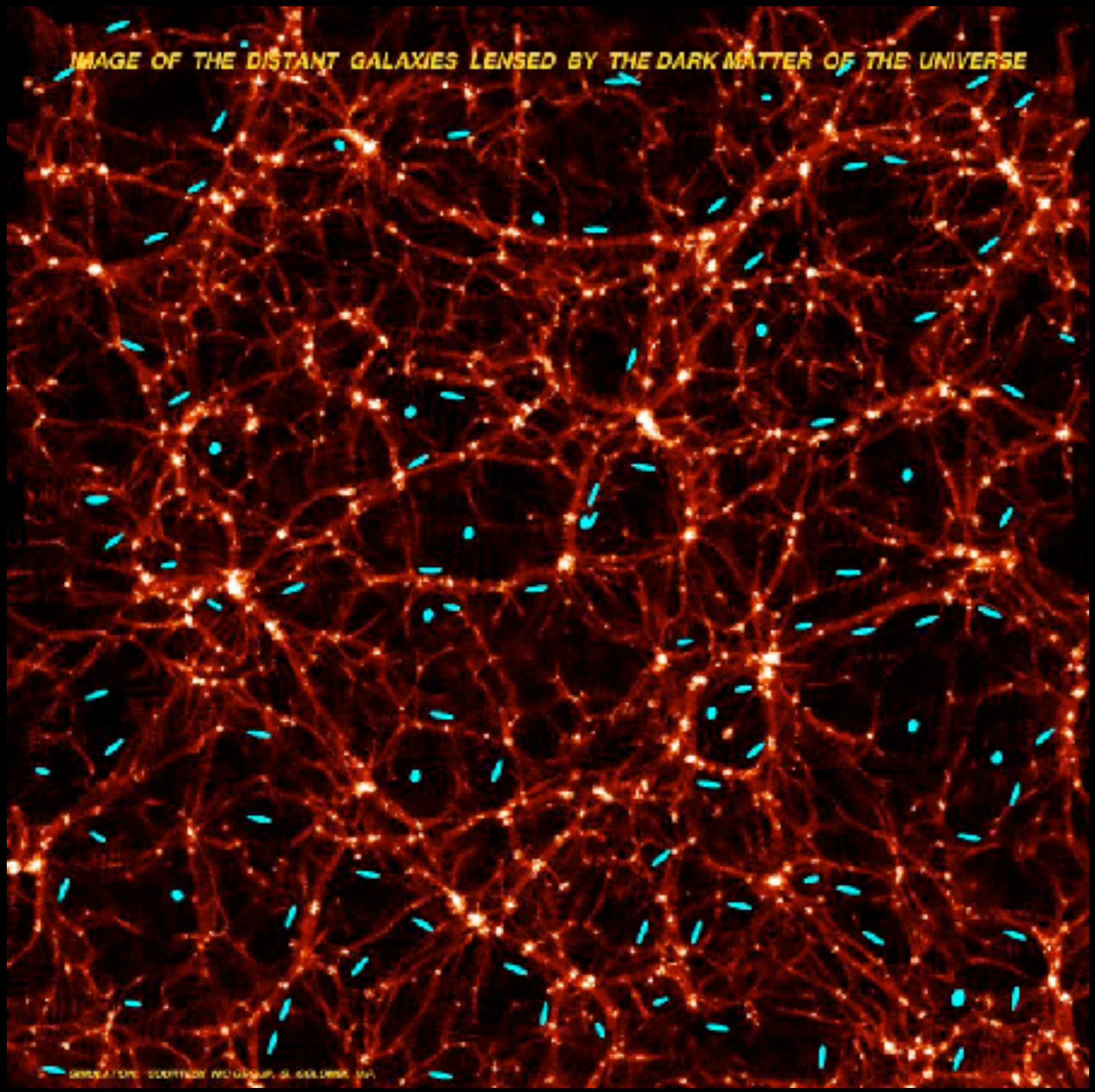
light deflected by tidal field of large-scale structure

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

key uncertainties

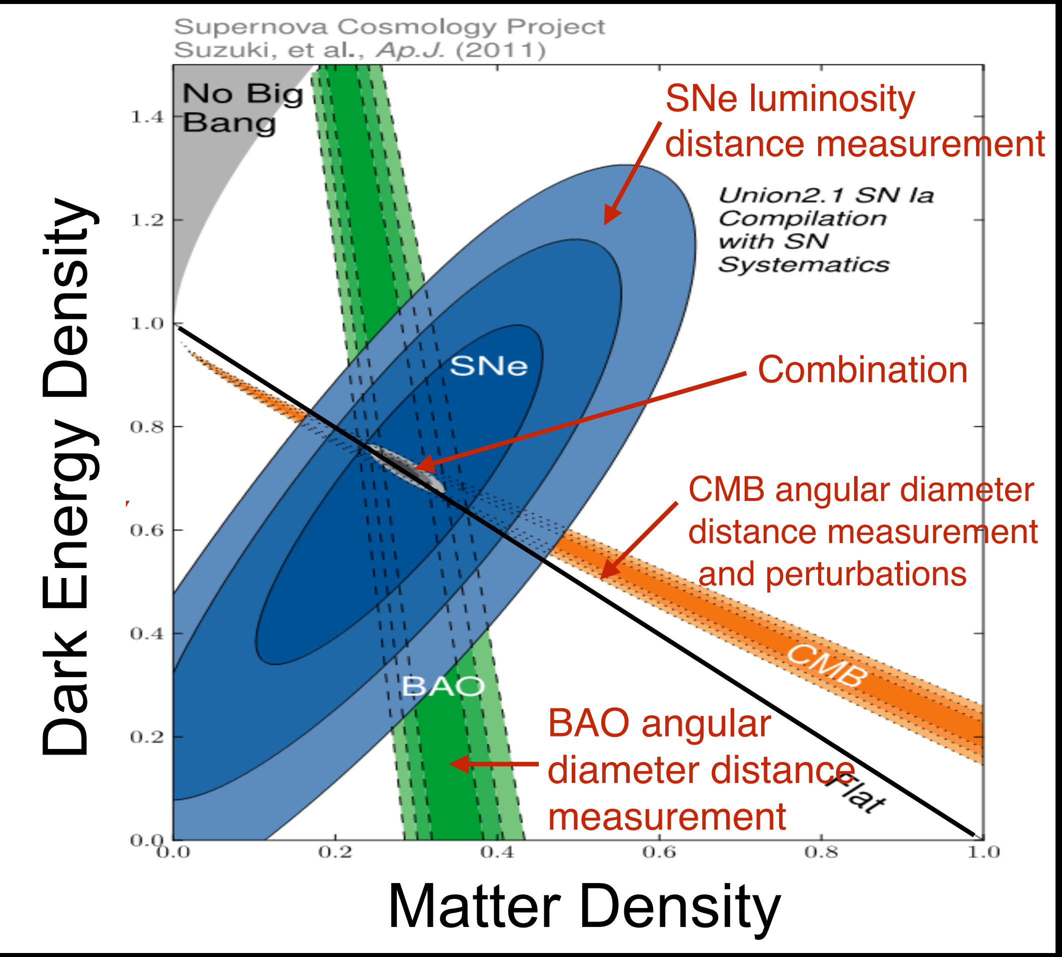
shape measurements

average over many galaxies assuming *random intrinsic orientation*



The Power of Combining Probes

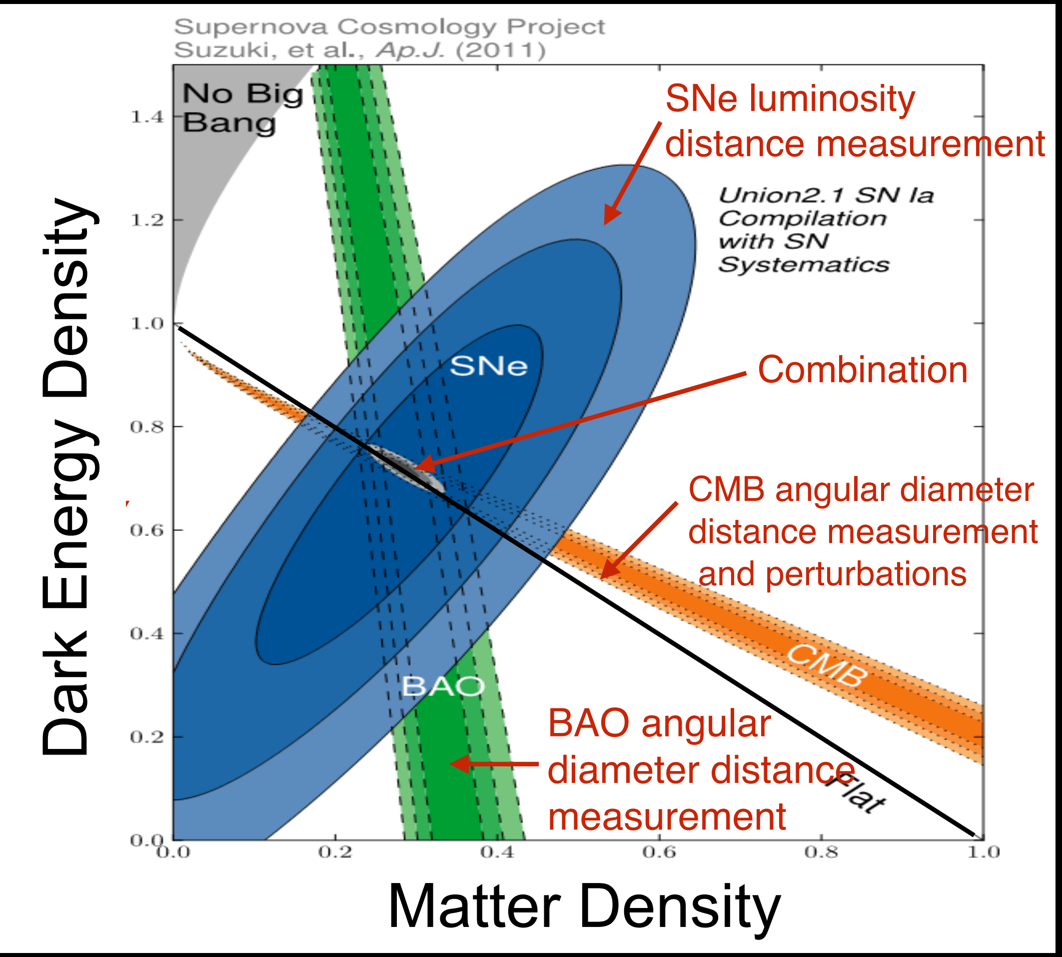
- best constraints obtained by combining cosmological probes
  - independent probes: multiply likelihoods



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 Analyses in Practice

$$\mathrm{Cov}(C(l_1),C(l_2)) = \mathrm{Cov}^{\mathrm{G}}(C(l_1),C(l_2)) + \mathrm{Cov}^{\mathrm{NG},0}(C(l_1),C(l_2)) + \mathrm{Cov}^{\mathrm{SSC}}(C(l_1),C(l_2))\,. \quad \text{(A1)}$$

The Gaussian covariance of two multi-probe power spectra is given by Hu & Jain (2004)

$$\mathrm{Cov}^{\mathrm{G}}\left(C^{ij}_{AB}(l_1),C^{kl}_{CD}(l_2)\right) = \frac{4\pi\delta_{l_1 l_2}}{\Omega_s(2l_1+1)\Delta l_1}\left[\left(C^{ik}_{AC}(l_1)+\delta_{ik}\delta_{AC}N^i_A\right)\left(C^{jl}_{BD}(l_2)+\delta_{jl}\delta_{BD}N^j_B\right)+\left(C^{il}_{AD}(l_1)+\delta_{il}\delta_{AD}N^i_A\right)\left(C^{jk}_{BC}(l_2)+\delta_{jk}\delta_{BC}N^j_B\right)\right], \quad \text{(A2)}$$

with the probe-specific noise terms N^i_A given in Table A.

The non-Gaussian covariance in the absence of survey window effects is calculated as the projected trispectrum,

$$\mathrm{Cov}^{\mathrm{NG},0}\left(C^{ij}_{AB}(l_1),C^{kl}_{CD}(l_2)\right) = \frac{1}{\Omega_s}\int_{|\mathbf{l}|\in l_1}\frac{d^2\mathbf{l}}{A(l_1)}\int_{|\mathbf{l}'|\in l_2}\frac{d^2\mathbf{l}'}{A(l_2)}\int \mathrm{d}\chi\, \frac{q^i_A(\chi)q^j_B(\chi)q^k_C(\chi)q^l_D(\chi)}{\chi^6}\; T^{ijkl}_{ABCD}(\mathbf{l}/\chi,-\mathbf{l}/\chi,\mathbf{l}'/\chi,-\mathbf{l}'/\chi;z(\chi)) \quad \text{(A3)}$$

where we approximate the $ABCD$ trispectrum as the sum of the linearly biased $(2+3+4)$-halo matter trispectrum (see e.g. Cooray & Sheth 2002; Takada & Jain 2009, for details), and a probe-specific 1-halo trispectrum:

$$T^{ijkl}_{ABCD}(\mathbf{k},-\mathbf{k},\mathbf{k}',-\mathbf{k}';z) \approx b^i_A(z)b^j_B(z)b^k_C(z)b_D(z)T_{\mathrm{m}}^{4\mathrm{h}+3\mathrm{h}+2\mathrm{h}}(\mathbf{k},-\mathbf{k},\mathbf{k}',-\mathbf{k}';z) + T^{ijkl,1\mathrm{h}}_{ABCD}(k,k,k',k';z) \quad \text{(A4)}$$

where we introduced $b_\kappa = 1$ for convenience, and the one-halo trispectrum $T^{ijkl,1\mathrm{h}}_{ABCD}$:

$$\#_{\delta_\lambda} \leqslant 1: \quad T^{ijkl,1\mathrm{h}}_{ABCD}(k,k,k',k';z) = \int dM \frac{dn}{dM}\left\langle \tilde{u}^i_A(k,M)\tilde{u}^j_B(k,M)\tilde{u}^k_C(k',M)\tilde{u}^l_D(k',M)\right\rangle \quad \text{(A5)}$$

$$\#_{\delta_\lambda} = 2: \quad T^{ijkl,1\mathrm{h}}_{\delta_{\lambda_\alpha}B\delta_{\lambda_\beta}D}(k,k,k',k';z) = \delta_{\alpha,\beta}\int dM \frac{dn}{dM}\bar{u}_{\delta_{\lambda_\alpha}}(k,M)\bar{u}^j_B(k,M)\bar{u}_{\delta_{\lambda_\beta}}(k',M)\bar{u}^l_D(k',M)\,, \quad \text{(A6)}$$

using the observable specific halo model building blocks given in Table A; $\#_{\delta_\lambda}$ is the multiplicity of the cluster density contrast in $\{ABCD\}$, and the special case in Eq. (A6) enforces the vanishing of the one-halo term between two different clusters. The ensemble average in Eq. (A5) only comes into effect on moments of the HOD, which we evaluate assuming that satellite galaxies are Poisson distributed.

The super-sample covariance describes the response of the summary statistics to a large scale background density mode; adapting the notation of Takada & Hu (2013); Schaan et al. (2014) to the multi-probe power spectrum case, it is given by

$$\mathrm{Cov}^{\mathrm{SSC}}\left(C^{ij}_{AB}(l_1),C^{kl}_{CD}(l_2)\right) = \int \mathrm{d}\chi\, \frac{q^i_A(\chi)q^j_B(\chi)q^k_C(\chi)q^l_D(\chi)}{\chi^4}\,\frac{\partial P_{AB}(l_1/\chi,z(\chi))}{\partial\delta_b}\frac{\partial P_{CD}(l_2/\chi,z(\chi))}{\partial\delta_b}\sigma_b(\Omega_s;z(\chi))\,, \quad \text{(A7)}$$

with $\sigma_b(\Omega_s,z(\chi))$ the variance of the background mode over the survey window,

$$\sigma_b(\Omega_s;z) = \int\frac{d^2k_\perp}{(2\pi)^2}P_{\mathrm{lin}}(k_\perp,z)|\tilde{W}_s(k_\perp,z)|^2 \approx \int\frac{d^2k_\perp}{(2\pi)^2}P_{\mathrm{lin}}(k_\perp,z)\left[\frac{2J_1(k_\perp\chi(z)\theta_s)}{k_\perp\chi(z)\theta_s}\right]^2, \quad \text{(A8)}$$

EK & Eifler '17 (1601.05779)

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

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

Cosmology Priors

Systematics Parameters

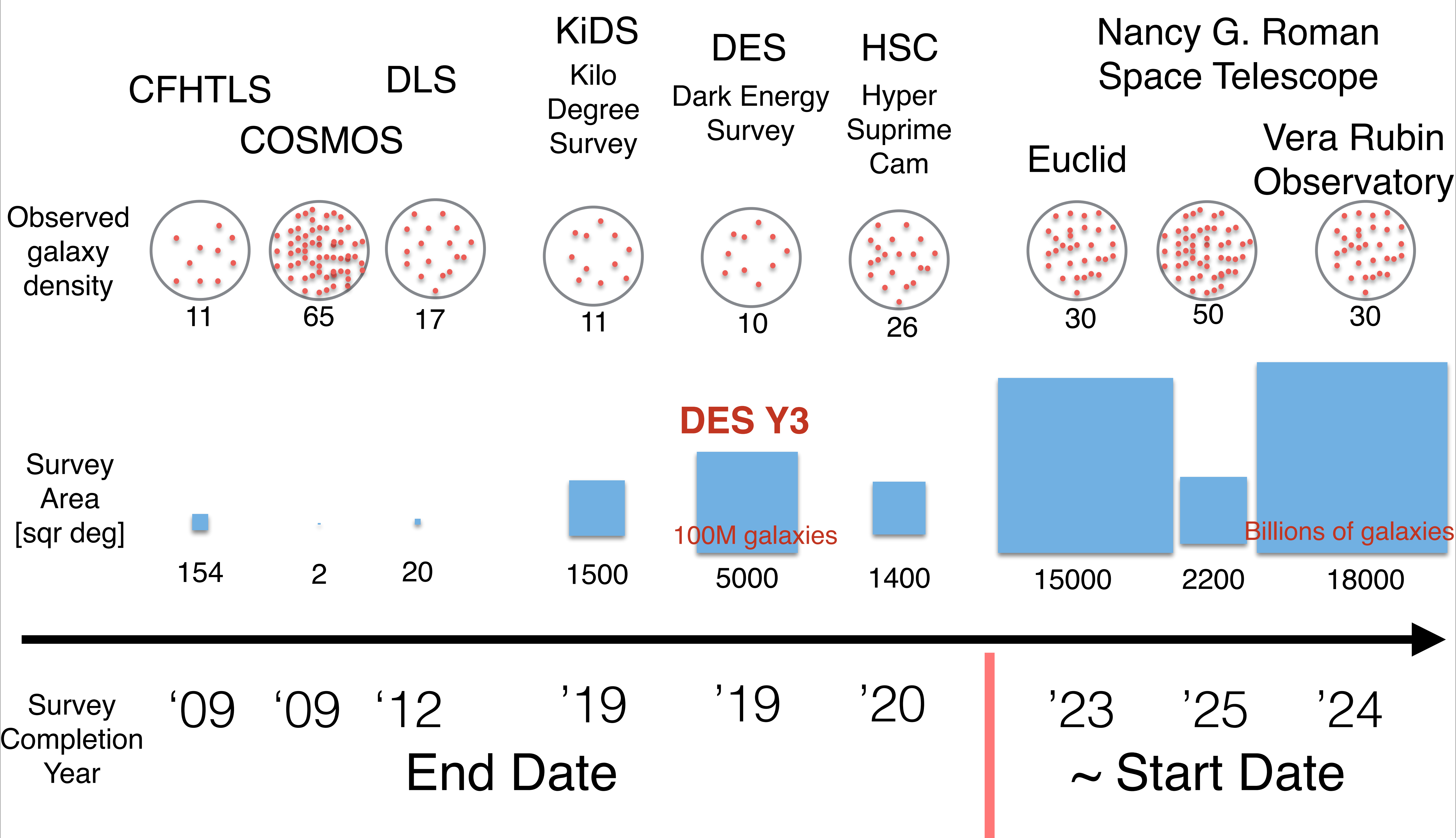
systematic effects
outnumber cosmology
parameterize + prioritize!

Priors

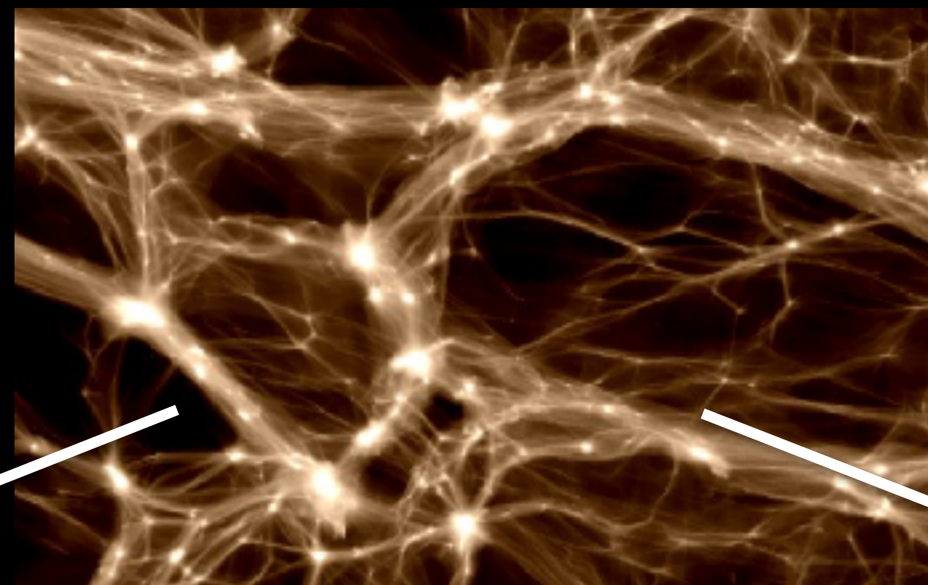
External Data
Simulations

validate

Real World Example: DES-Y3

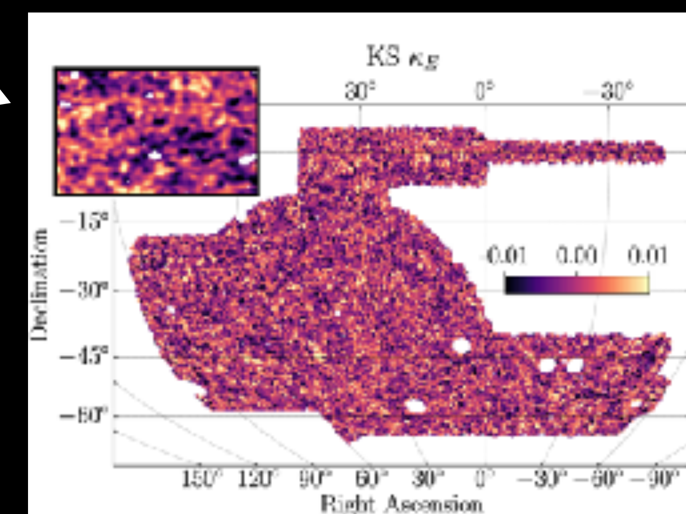


DES-Y3 WL x LSS Analysis



10M lens galaxies
split in 6 redshift bins

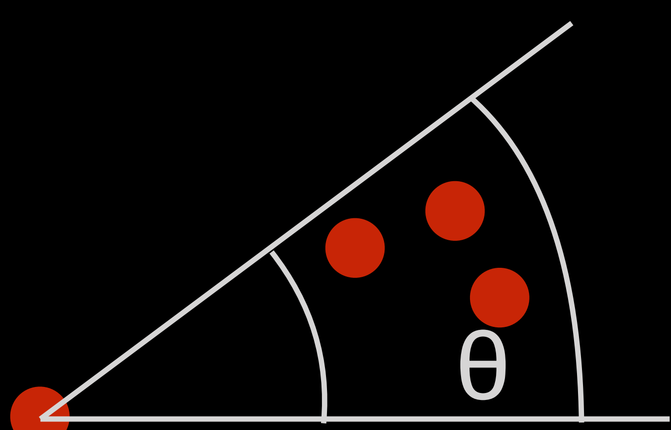
100M source galaxies
split in 4 redshift bins

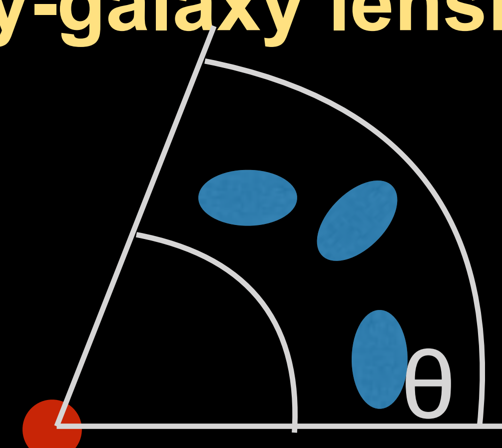


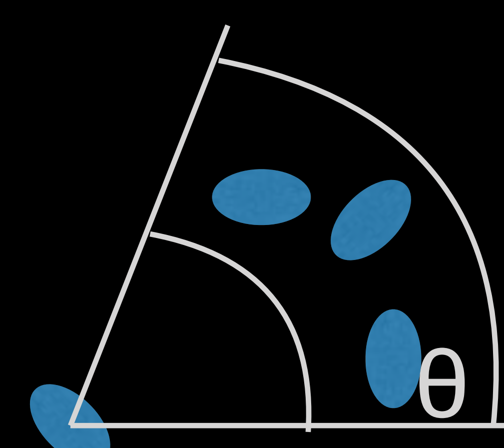
galaxies x galaxies:
angular clustering

galaxies x lensing:
galaxy-galaxy lensing

lensing x lensing:
cosmic shear



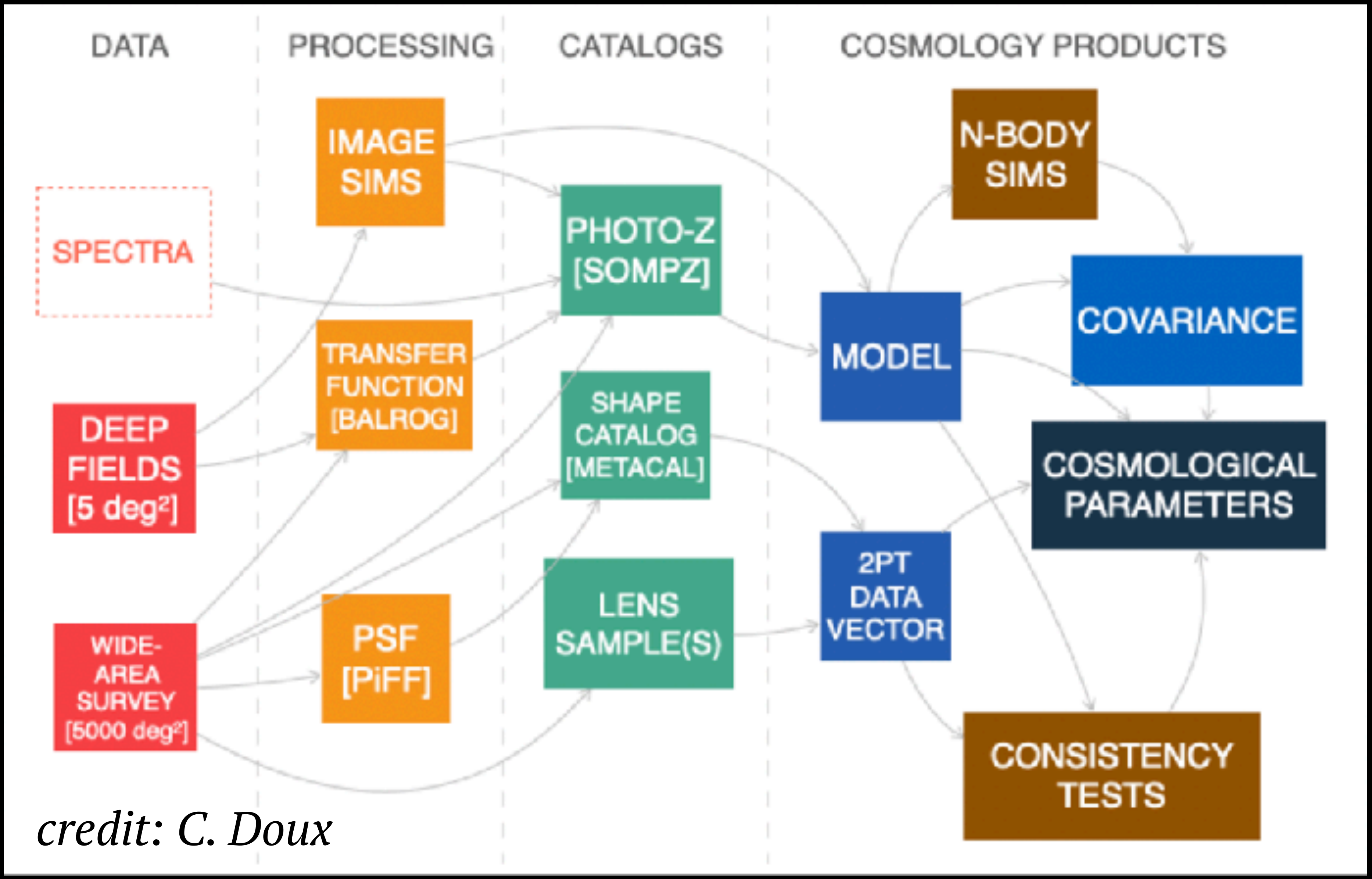




DES-Y3 Cosmology

from pixels to cosmology in 30 papers:

- algorithmic + modeling improvements in all analysis stages



DES-Y3 Results
Systematics Modeling + Mitigation

3x2pt measurements modeled by cosmology and *simple* systematics parameterization

astrophysics (15 parameters): relate galaxy density + shapes to matter distribution

- 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

observational uncertainties (13 parameters)

- lens galaxy photo-zs, per lens z-bin
- source galaxy photo-zs, per source z-bin
- multiplicative shear calibration, per source z-bin

EK+2021

DES-Y3 Results
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observational uncertainties (13 parameters)

- 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?

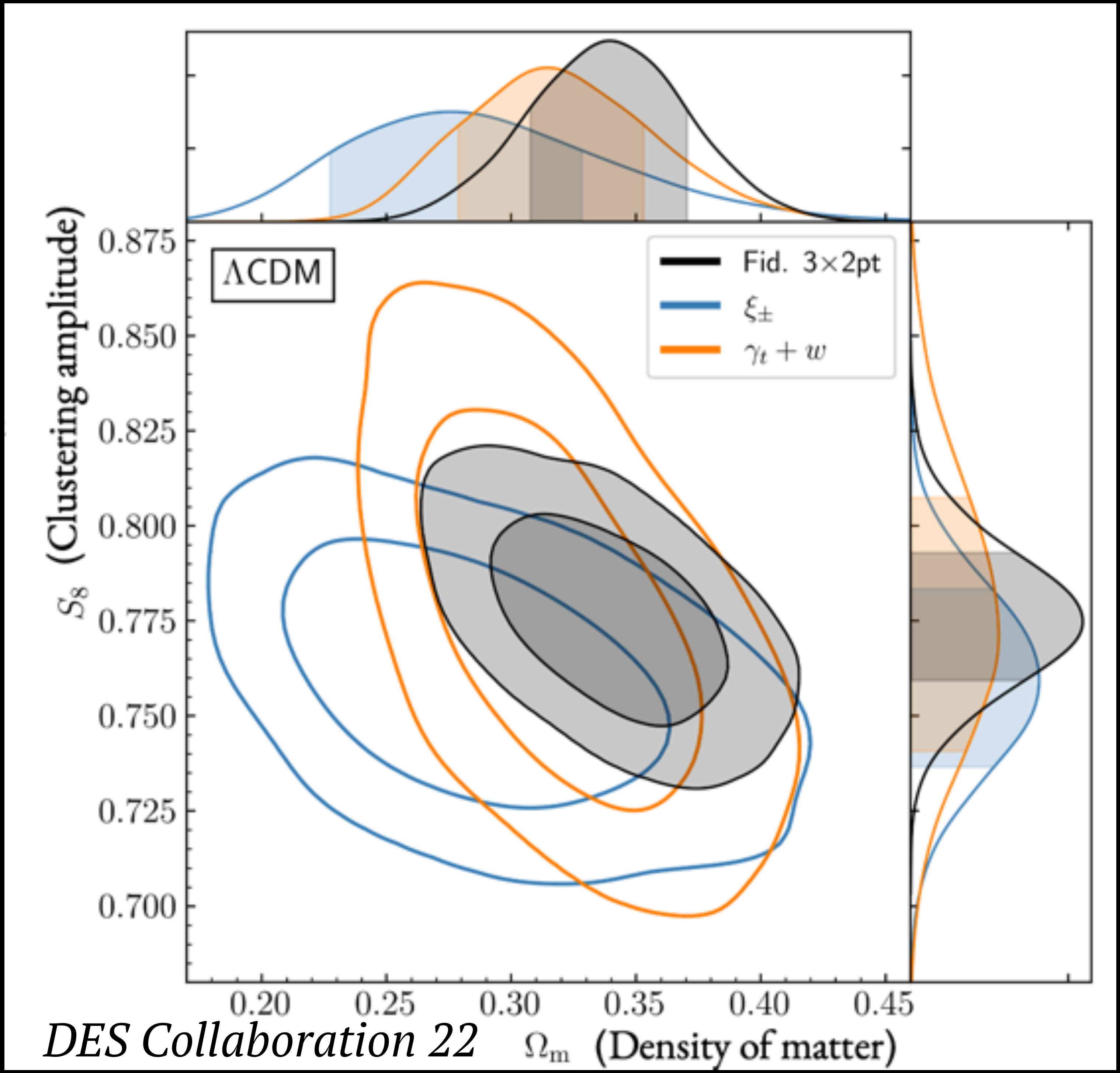
-> remove contaminated data points (*i.e., throw out large fraction of S/N*)

-> choice of parameterizations ≠ universal truth

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

EK+2021

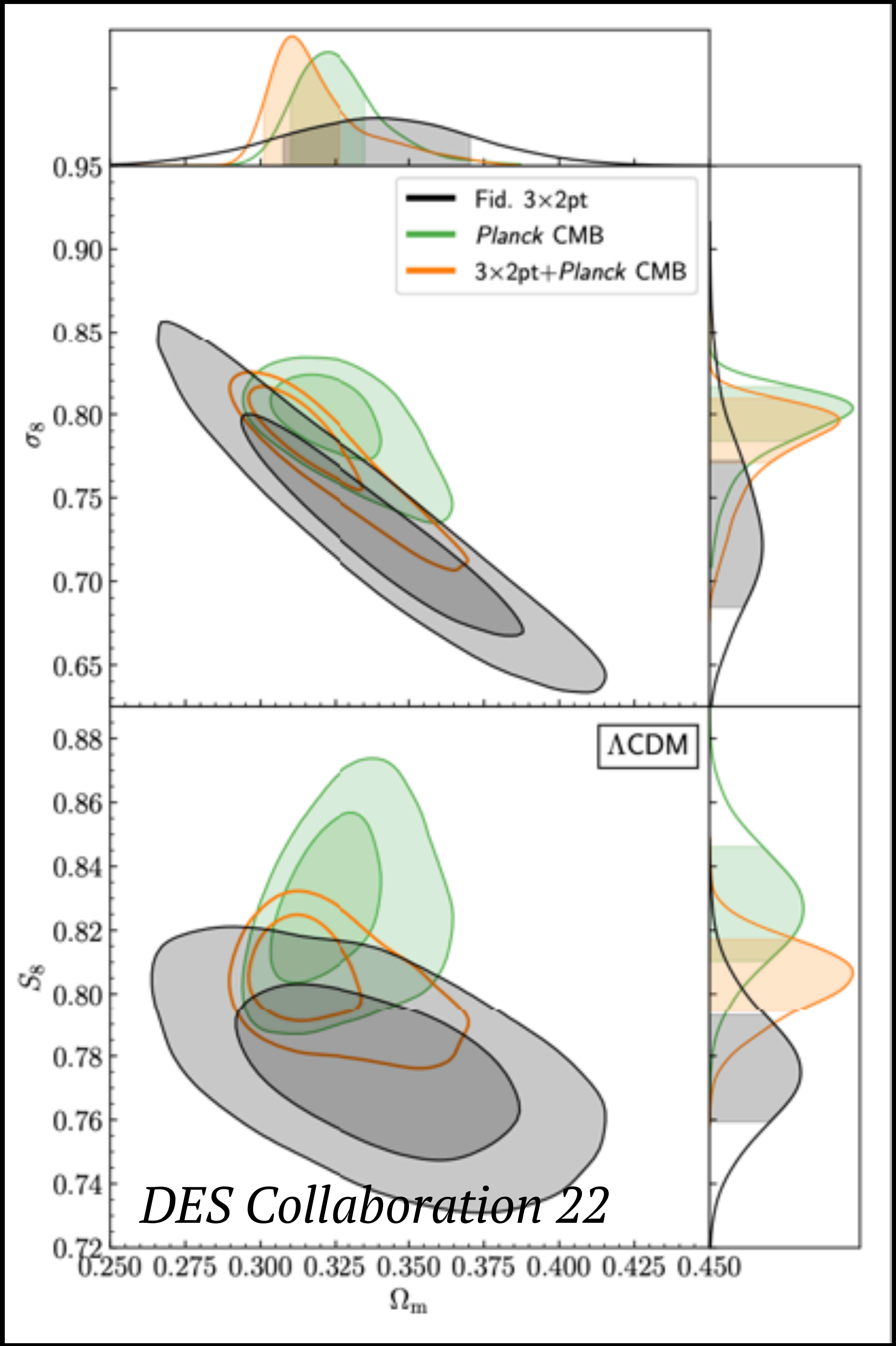
DES Y3 Results: LCDM Multi-Probe Constraints



DES Collaboration 22

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

DES Y3 ↔ Planck



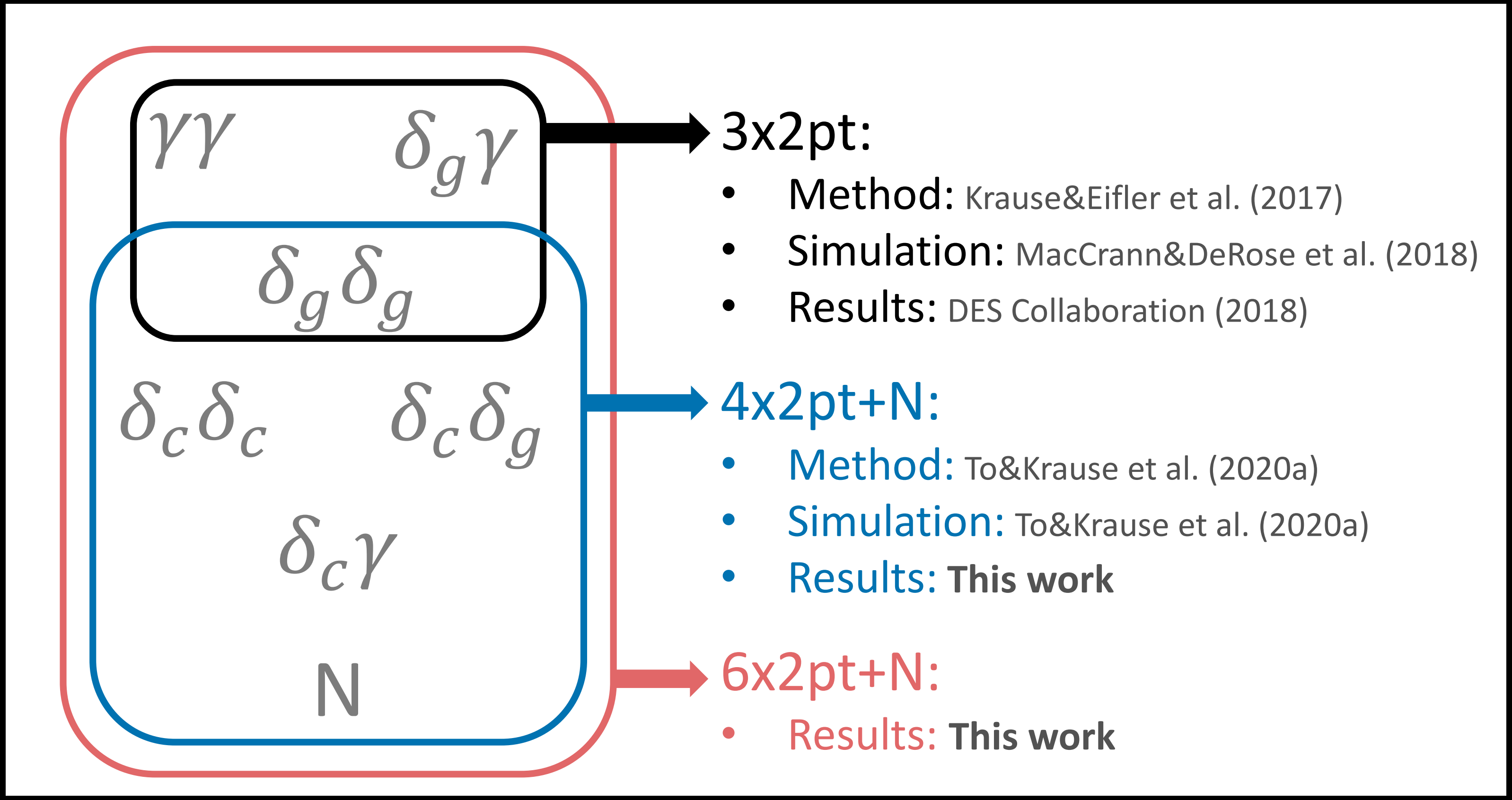
Compatibility with Planck is measured over the full 6-parameter LCDM space (Lemos, Raveri + 20)

S8 and Ω_m drive the result to 1.5σ or p=0.13

- **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



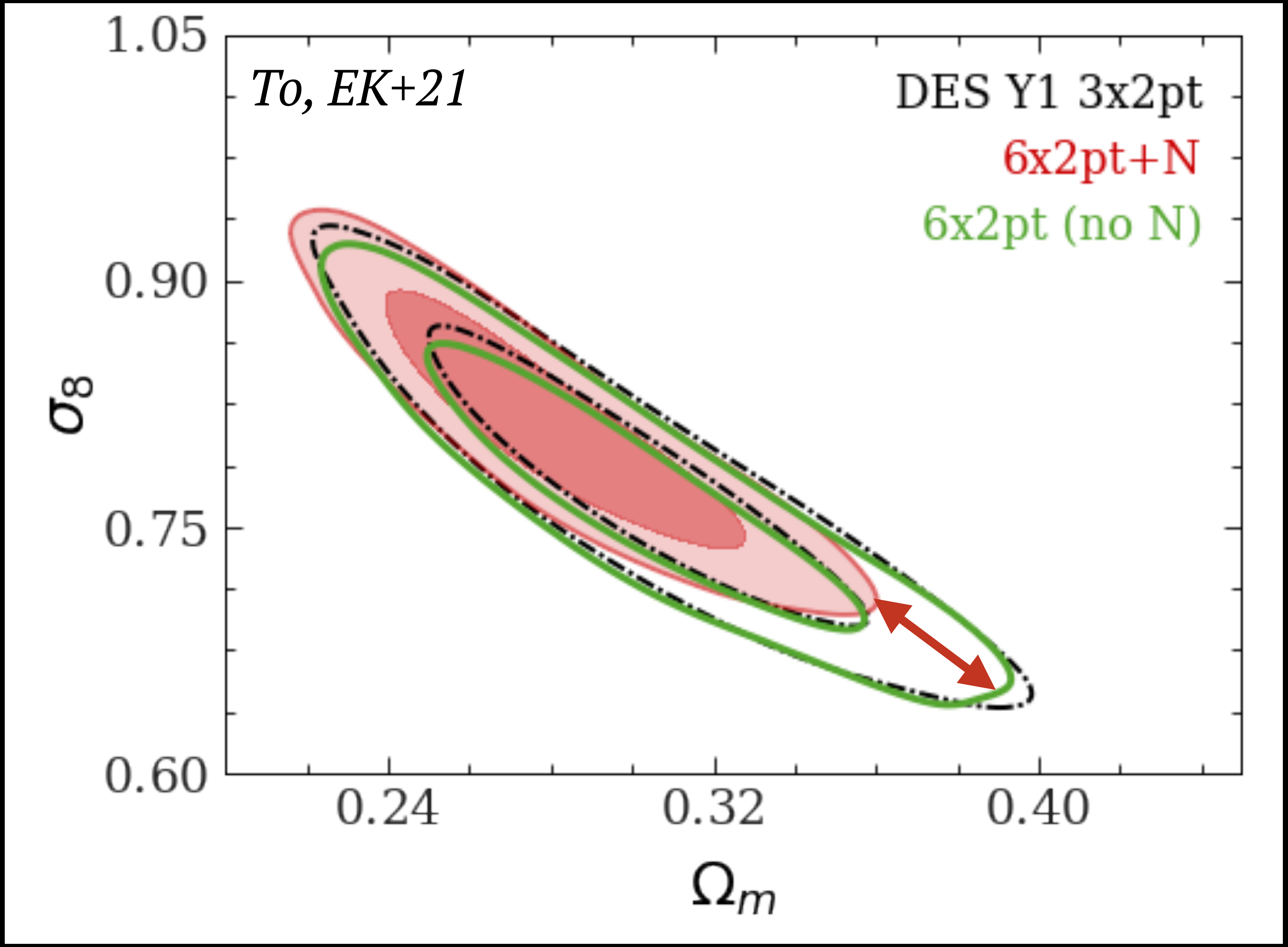
- joint likelihood analysis validated on DES-like mock catalogs (Buzzard, DeRose+2020)
- MOR calibrated from large-scale clustering, account for selection bias

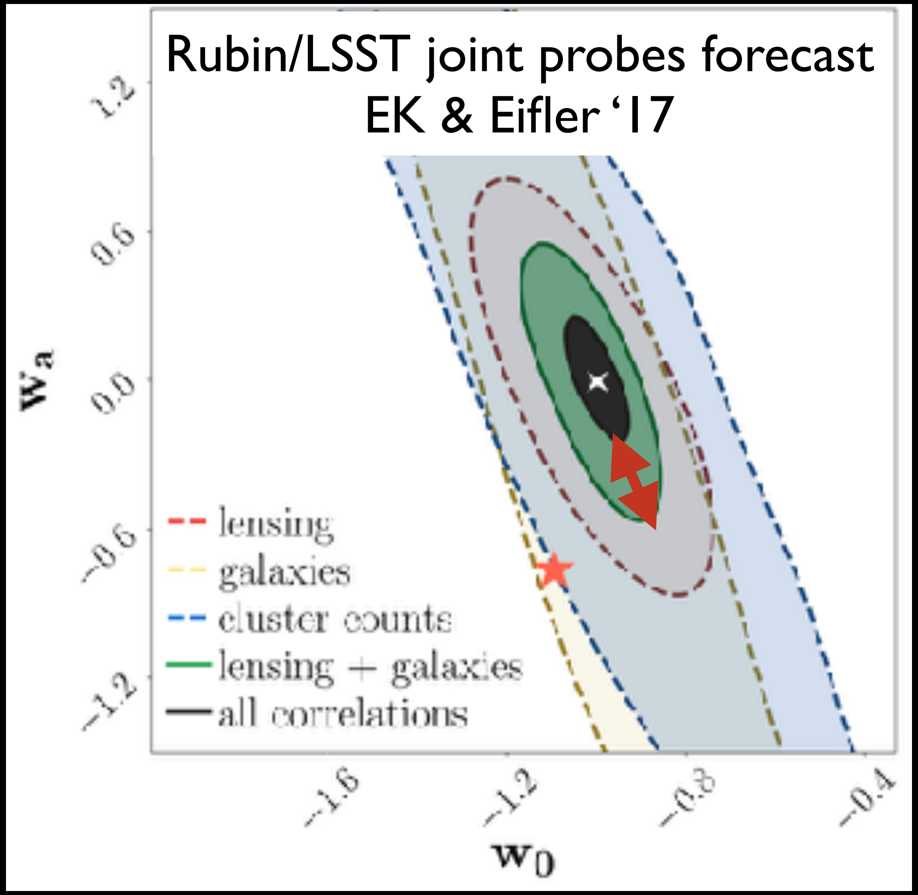
✓ cosmology constraints consistent with other DES probes

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

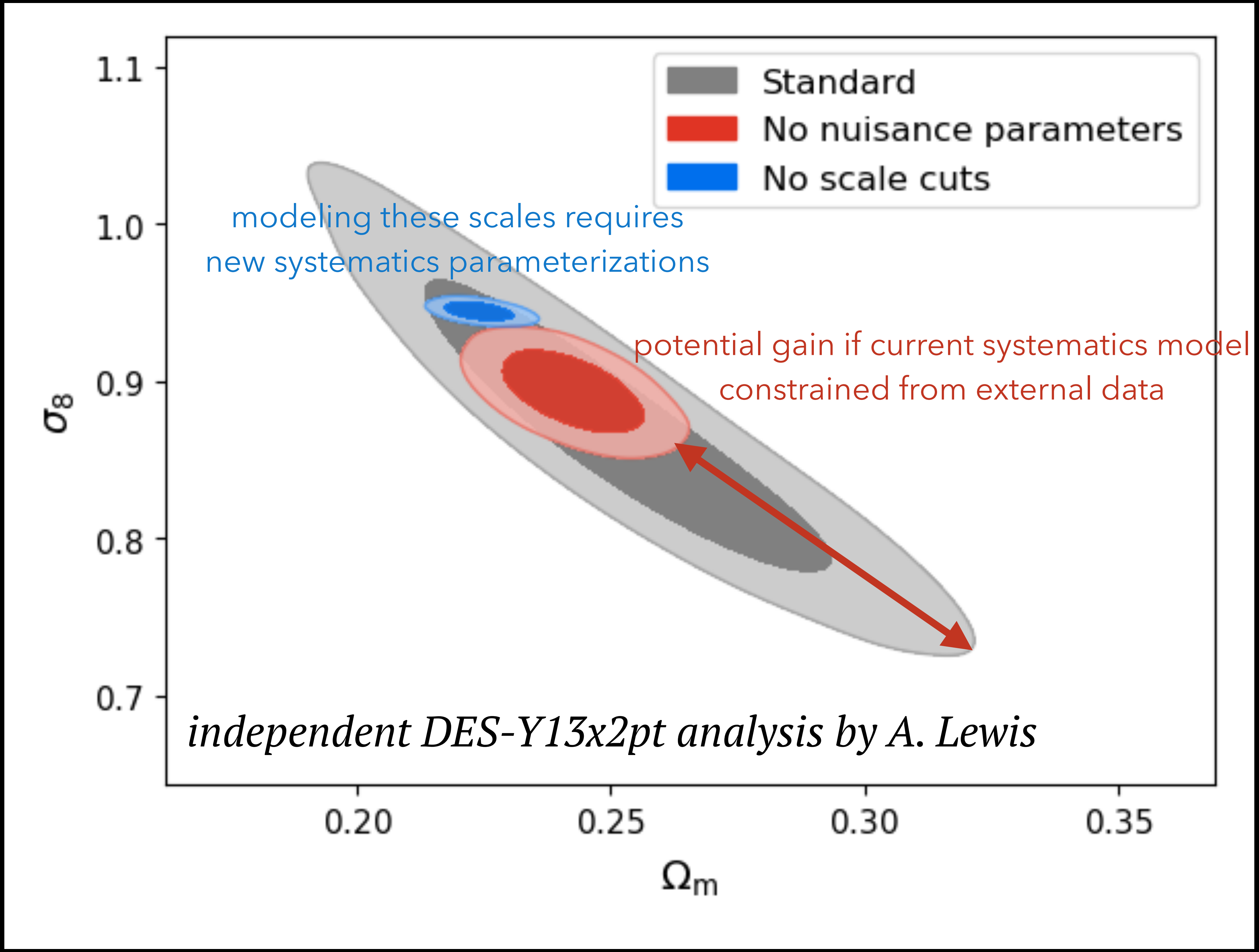
this analysis unlocks constraining power from number counts

substantial gain, *iff accurate MOR calibration*

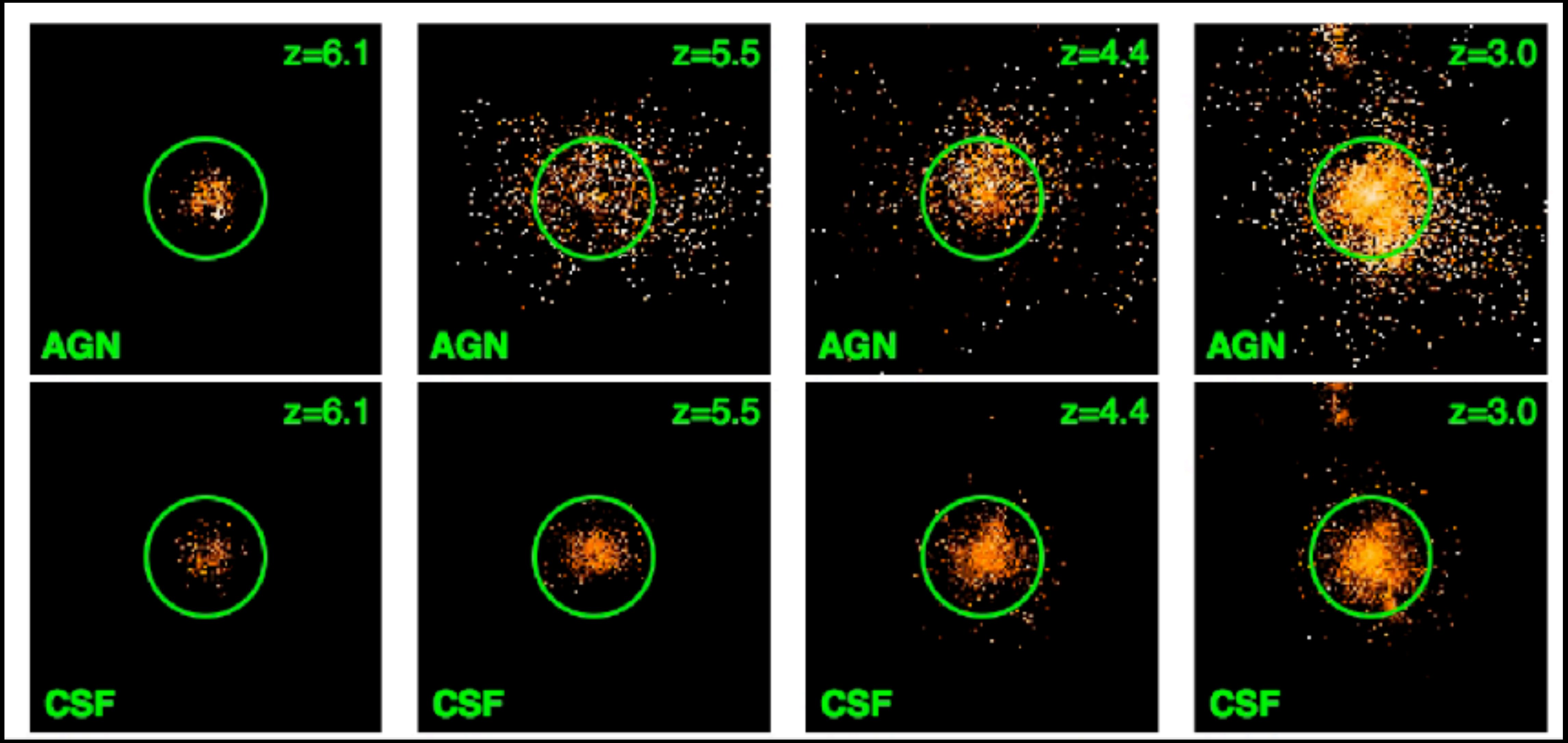




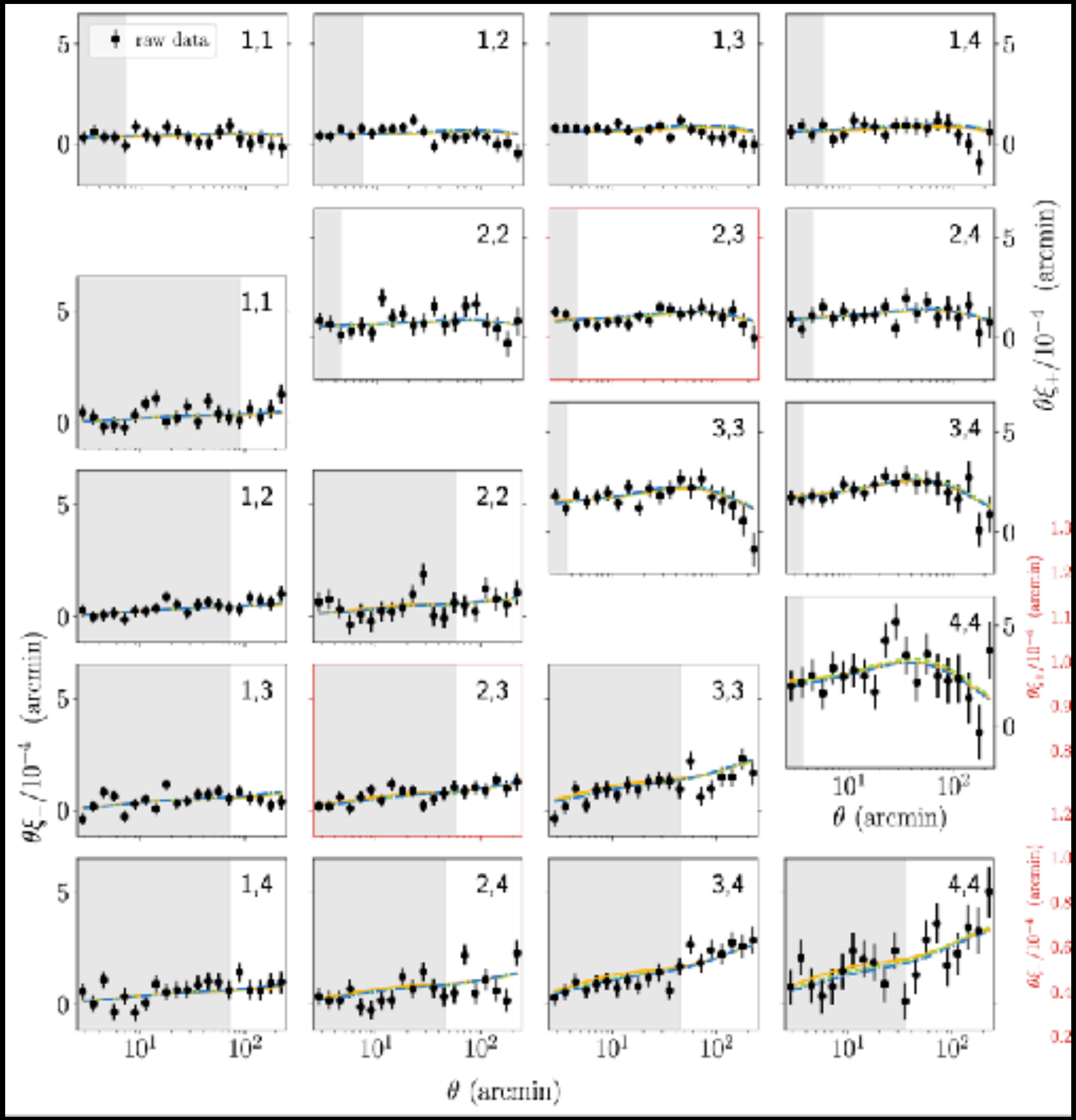
3x2pt Systematics Mitigation
Opportunity Space...



Systematics Opportunities and Challenges: Baryonic Effects in WL Analyses



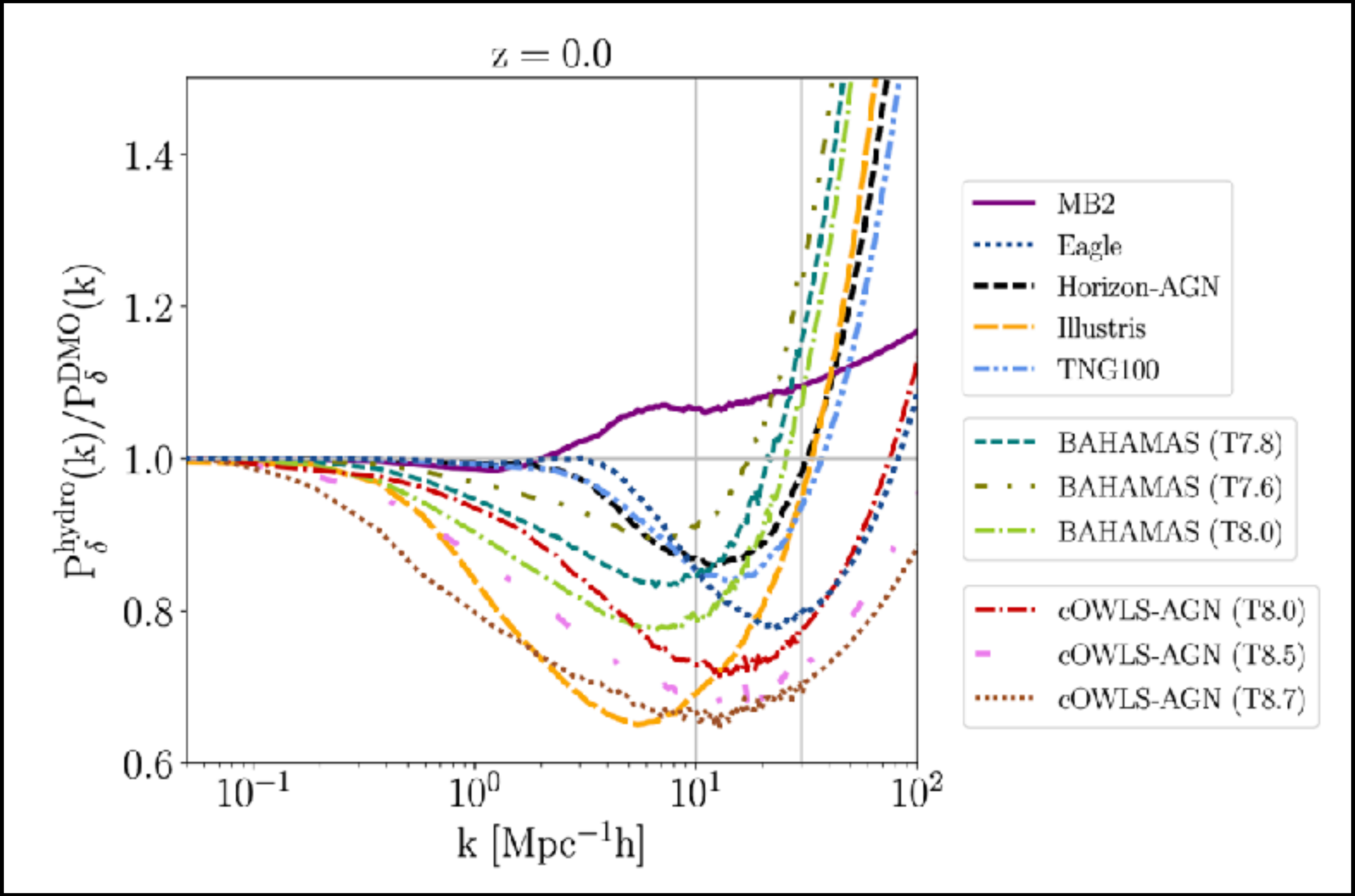
Systematics Opportunities and Challenges: Baryonic Effects in WL Analyses



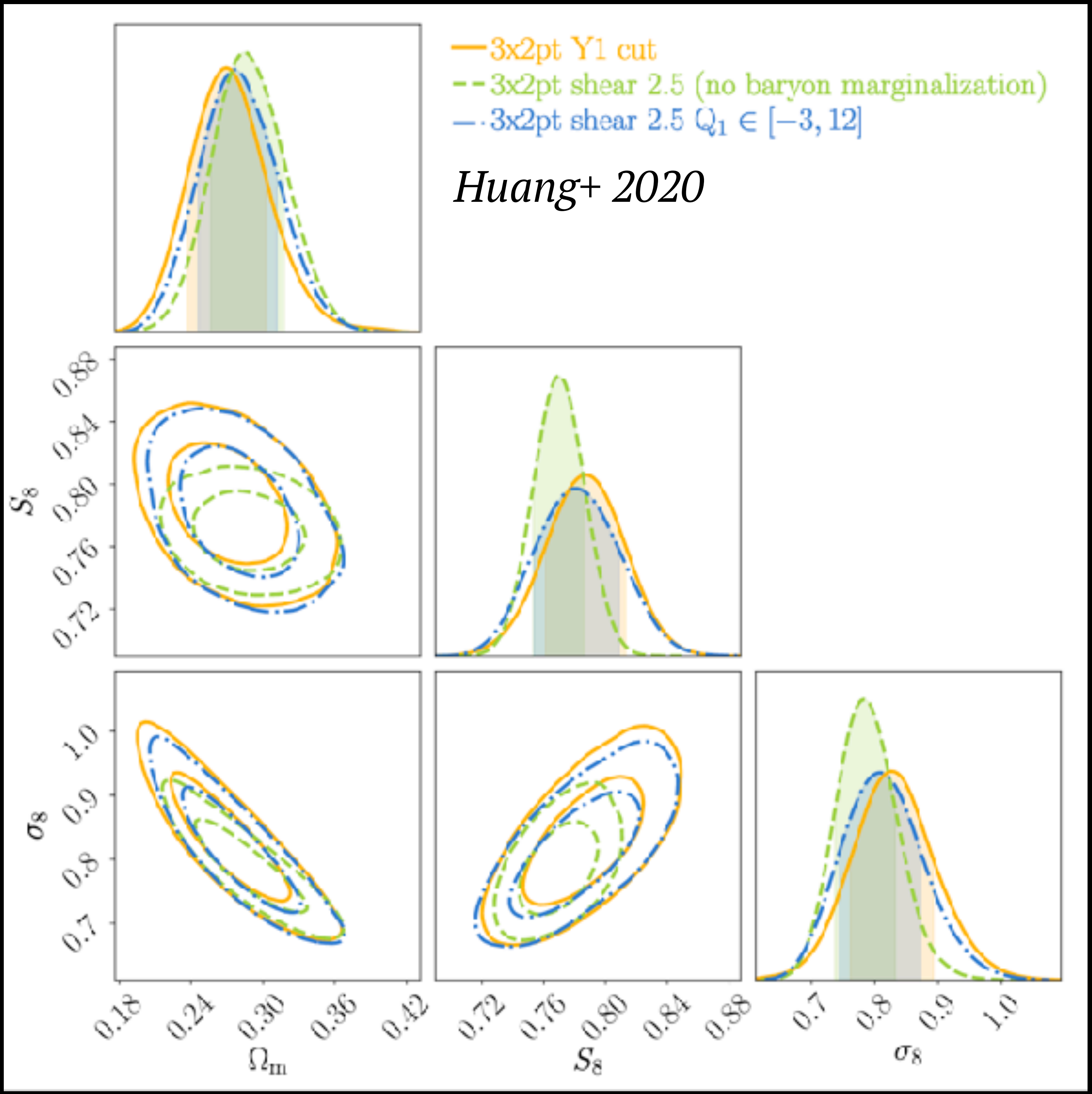
DES-Y1 baseline: small scale correlation function measurements **excluded because of baryonic effects**

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

Baryonic Effects in WL Analyses

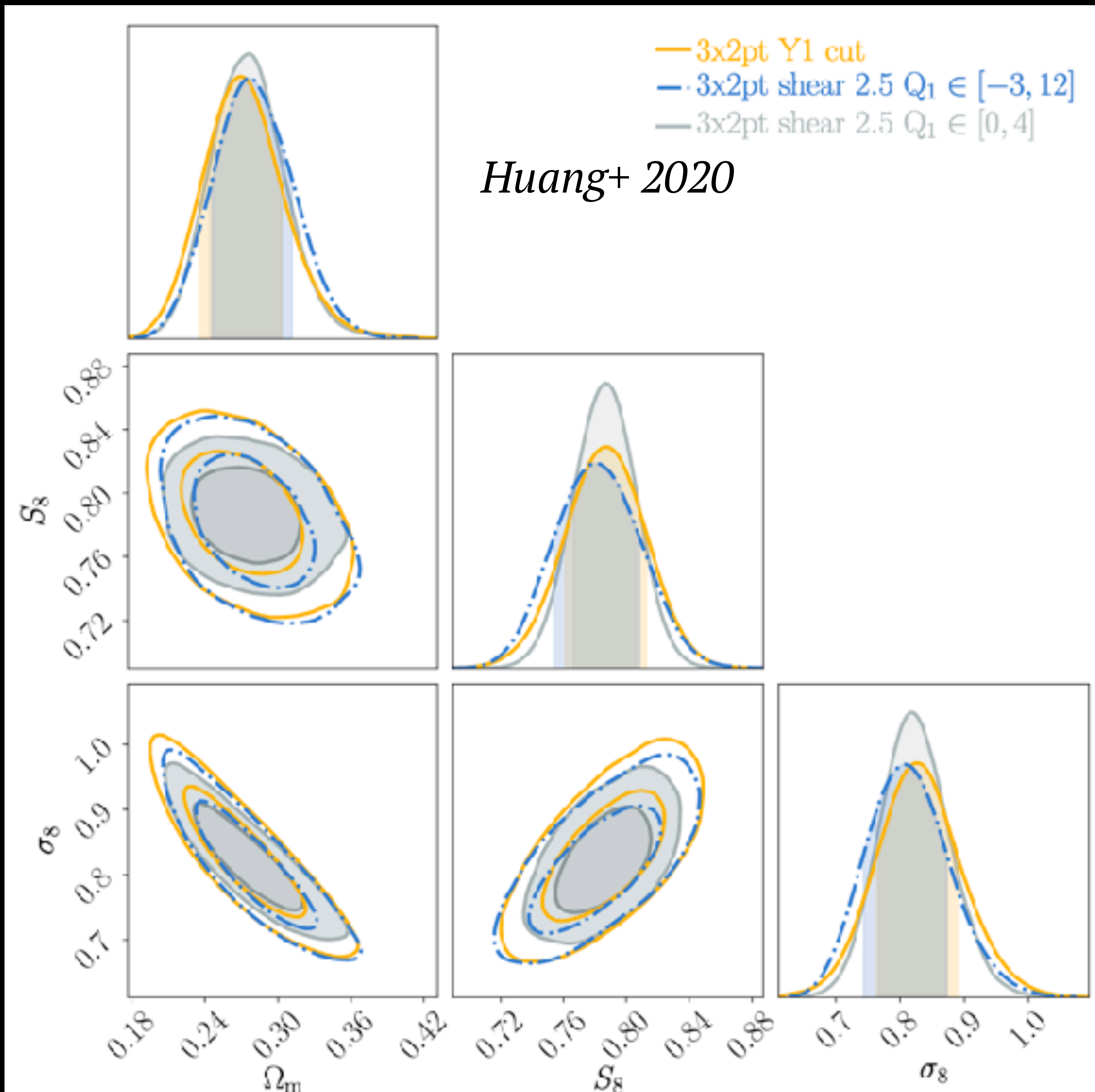


Baryonic Effects in WL Analyses Cosmology Constraints



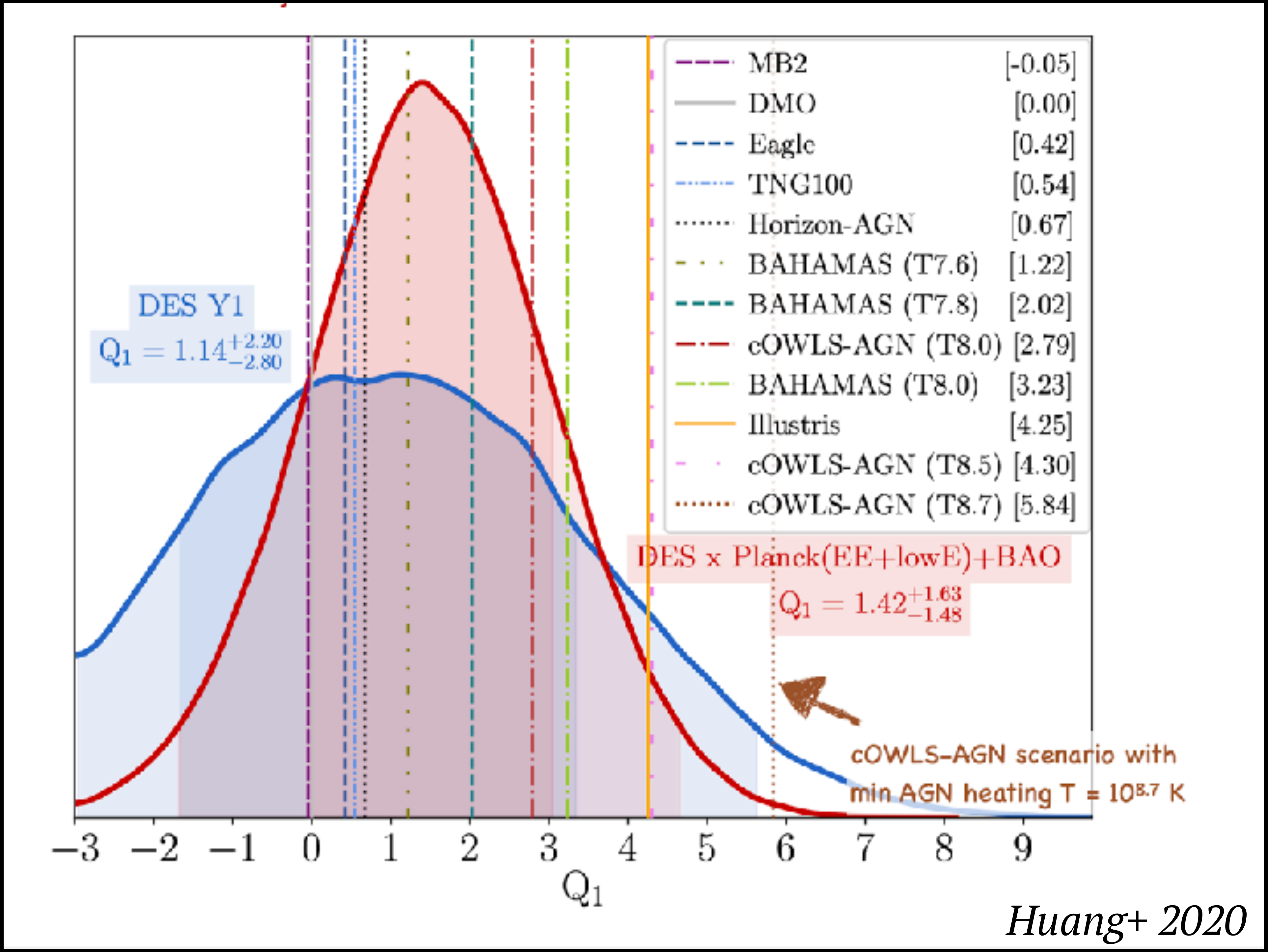
- DES-Y1 including all scales, baryons not included in the modeling (don't do that!)
- DES-Y1 baseline (conservative scale cuts)
- DES-Y1 including all scales, baryonic effects modeled using **PCA with non-informative prior**

Baryonic Effects in WL Analyses Cosmology Constraints

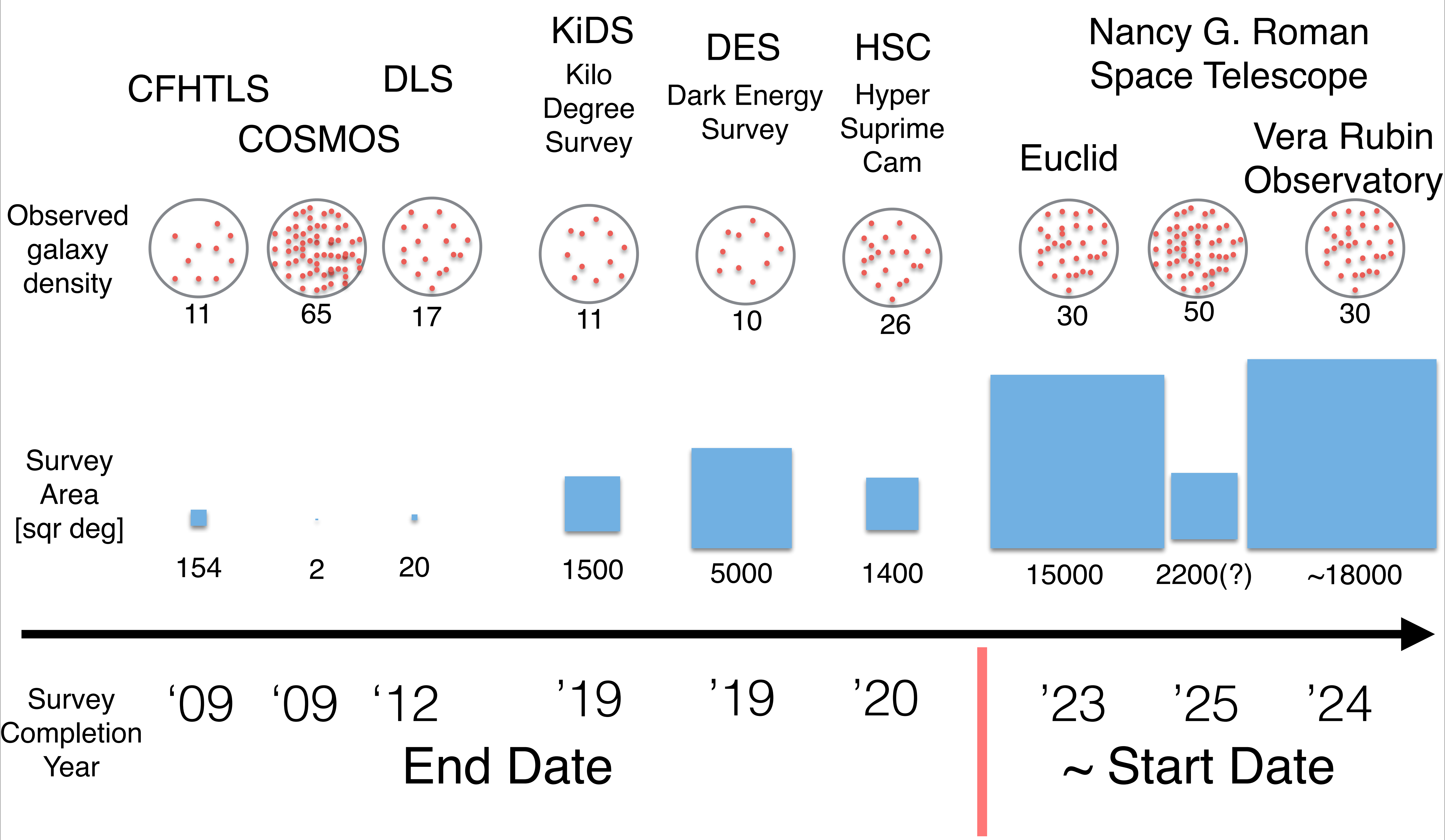


- DES-Y1 baseline (conservative scale cuts)
- DES-Y1 including all scales, baryonic effects modeled using **PCA with non-informative prior**
- DES-Y1 including all scales, baryonic effects modeled using **PCA with informative prior**

Baryonic Effects in WL Analyses
Feedback Constraints

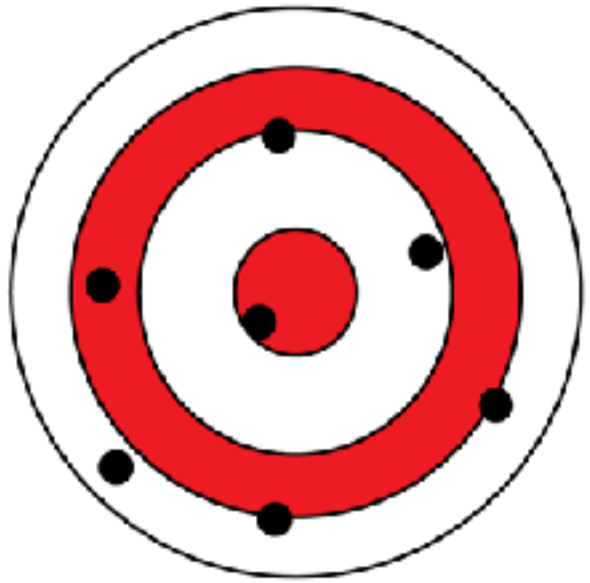


The Future



CFHTLS
COSMOS
DLS
KiDS
Kilo Degree Survey
DES
Dark Energy Survey
HSC
Hyper Suprime Cam
Nancy G. Roman Space Telescope
Euclid
Vera Rubin Observatory
Observed galaxy density
11
65
17
11
10
26
30
50
30
Survey Area [sqr deg]
154
2
20
1500
5000
1400
15000
2200(?)
~18000
Survey Completion Year
'09
'09
'12
'19
'19
'20
'23
'25
'24
End Date
~ Start Date

“Precision” Cosmology

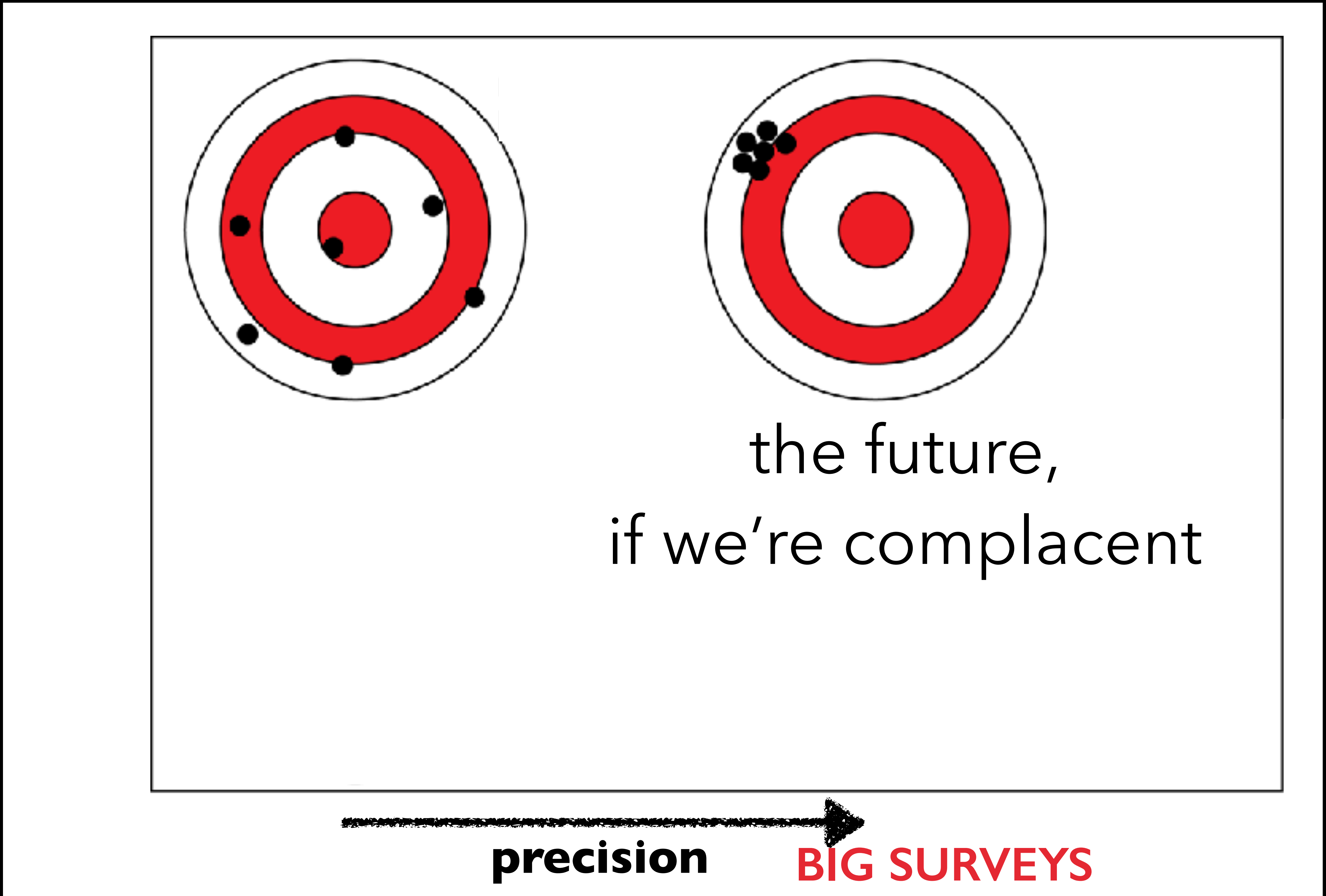


our situation today

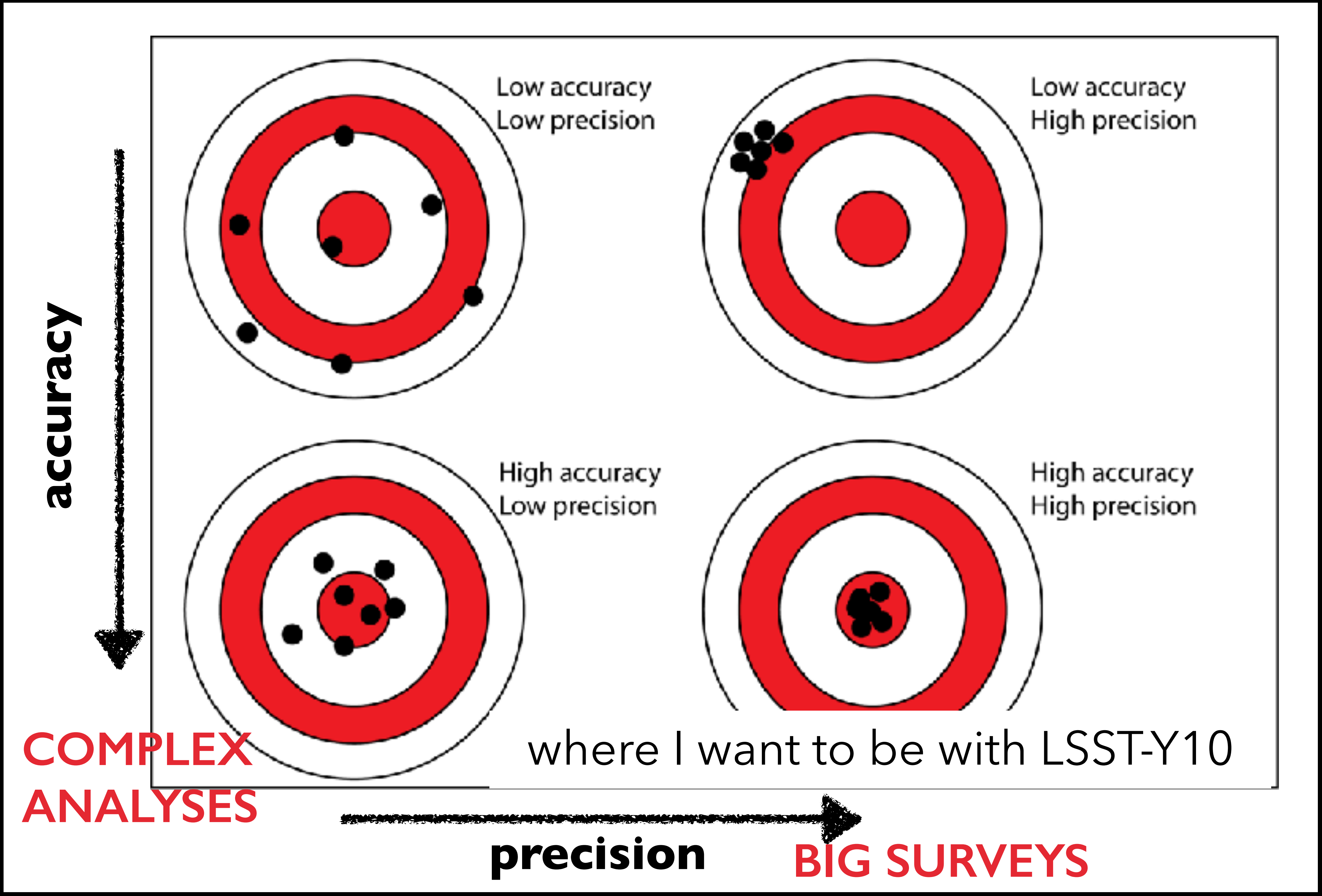
precision

BIG SURVEYS

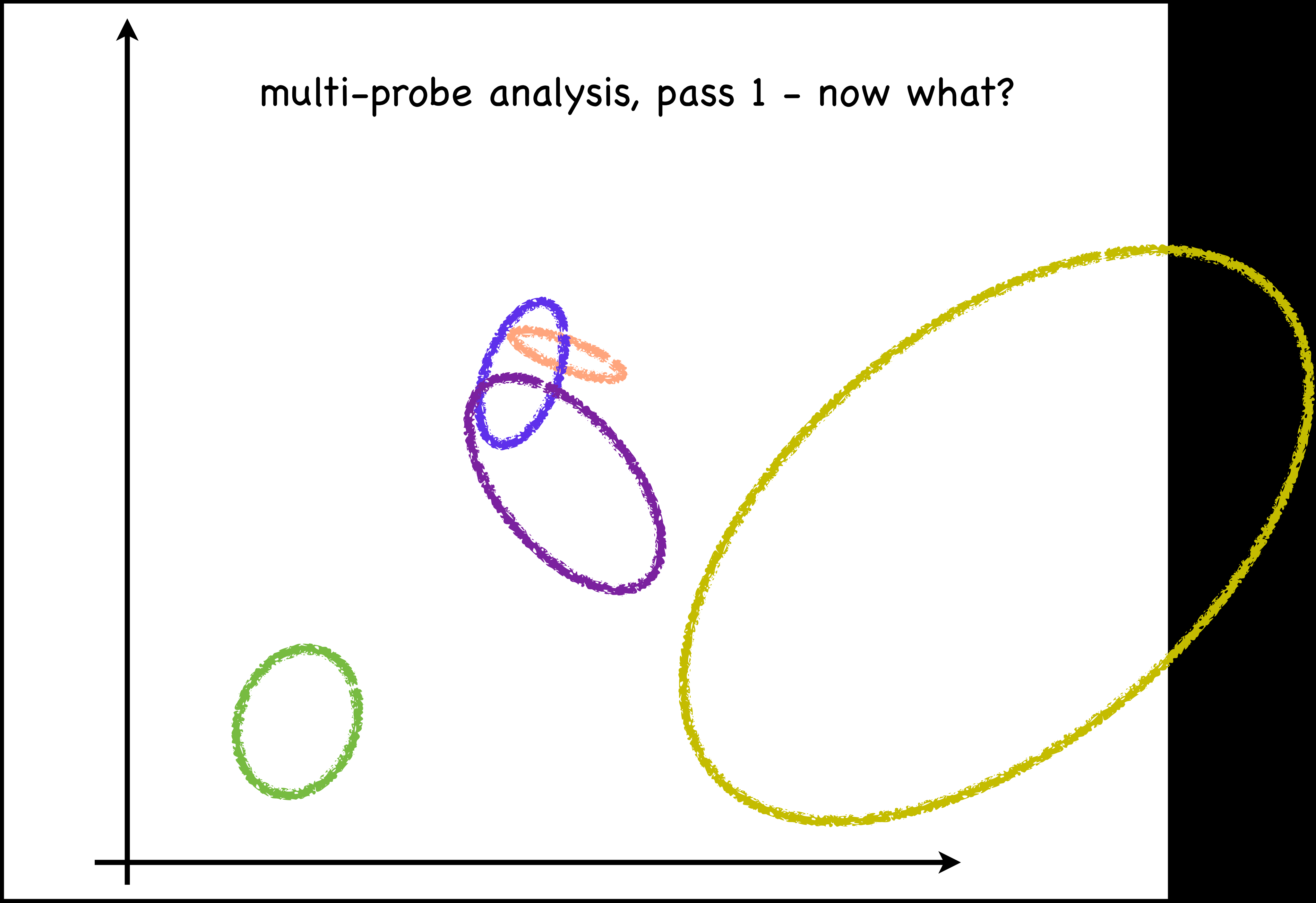
“Precision” Cosmology



“Precision” Cosmology

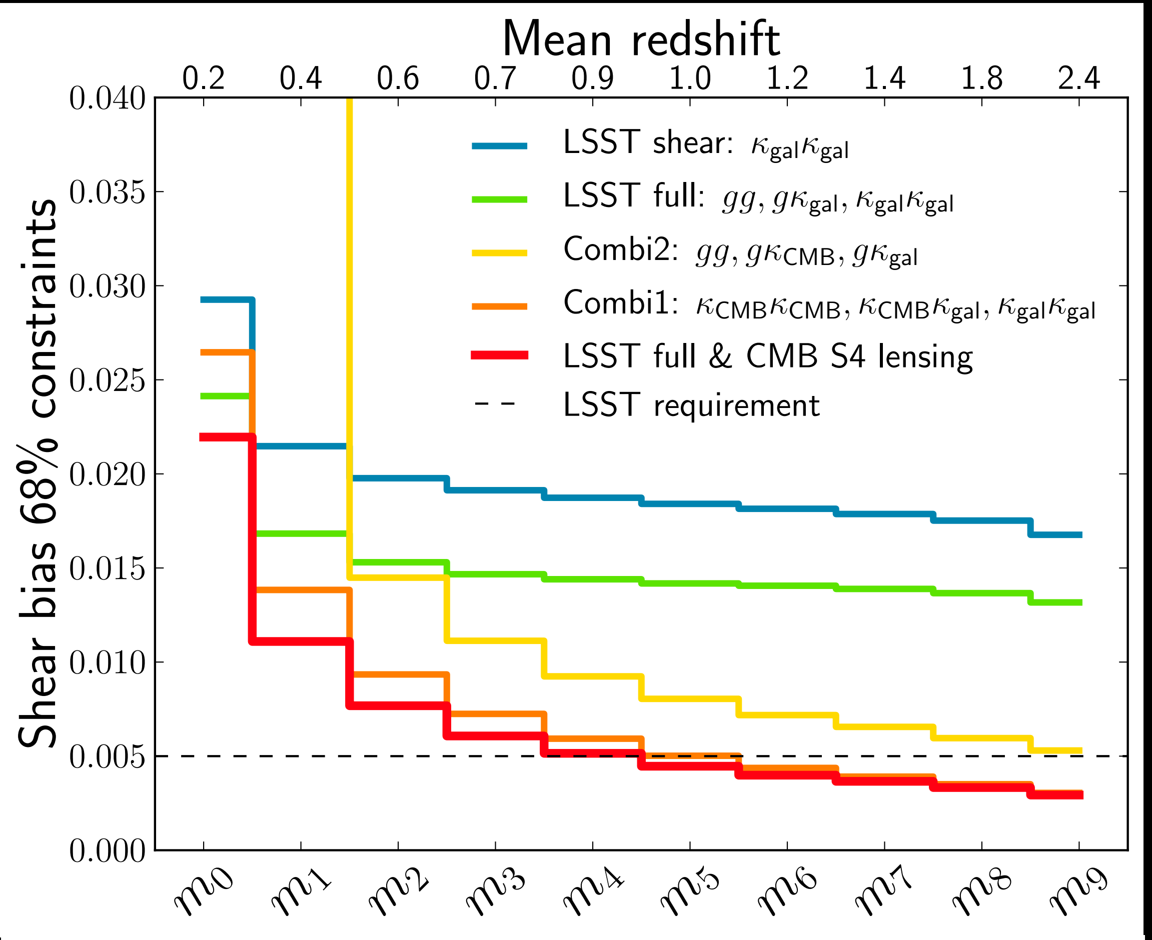


Unknown Systematics? vs. New Physics?



Unknown Systematics? vs. New Physics?

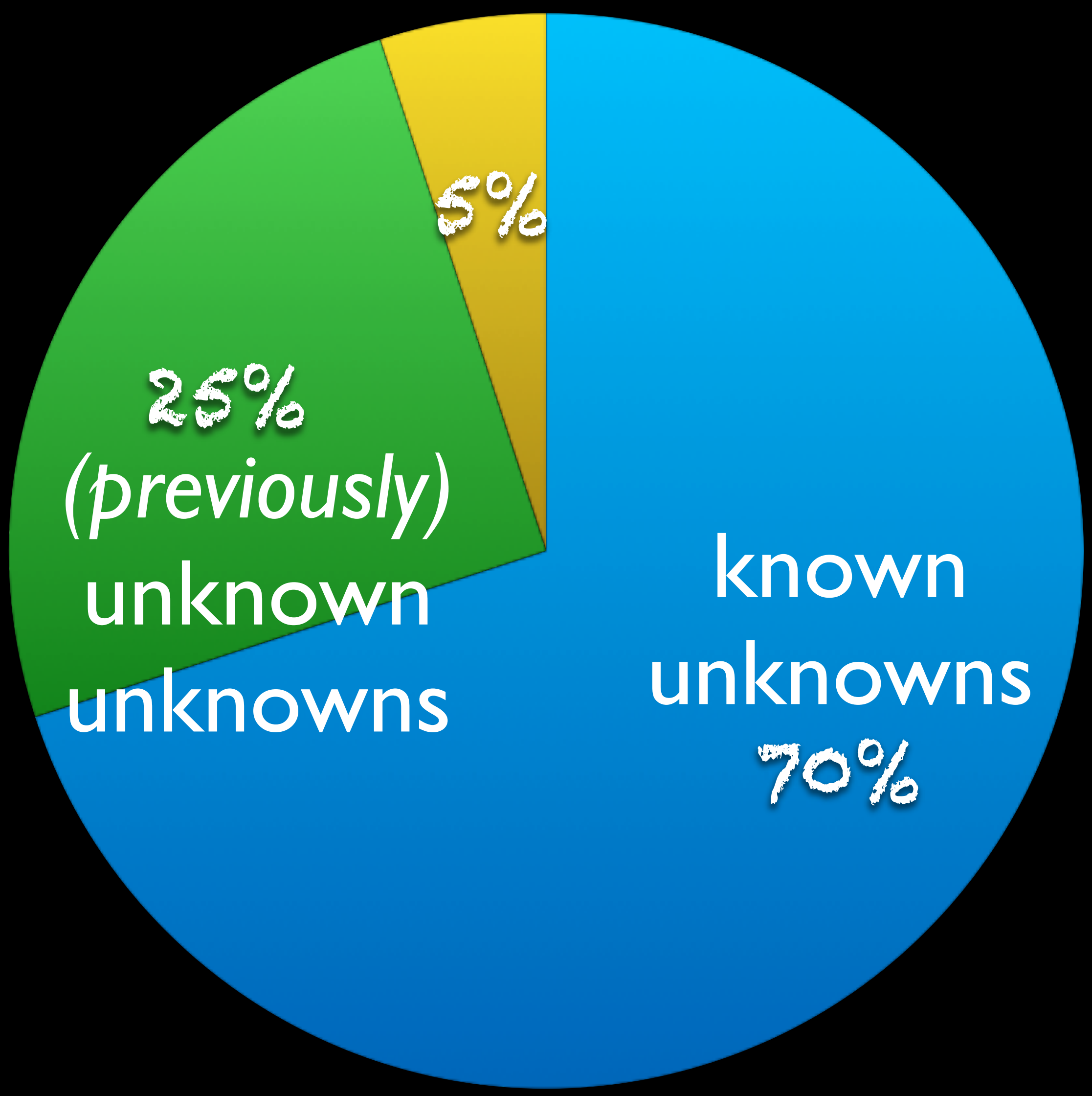
- scale dependence?
- dependence on galaxy/cluster selection?
- calibrate with more accurate measurements
  - spectroscopic redshifts
  - low-scatter cluster mass proxies
  - galaxy shapes from space-based imaging
  - [potentially expensive]
- correlate with other surveys
  - compare to predicted cross-correlations
  - constrain uncorrelated systematics



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

Cosmology Analysis Parameters

Cosmology Parameters



Systematics Parameters

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

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!