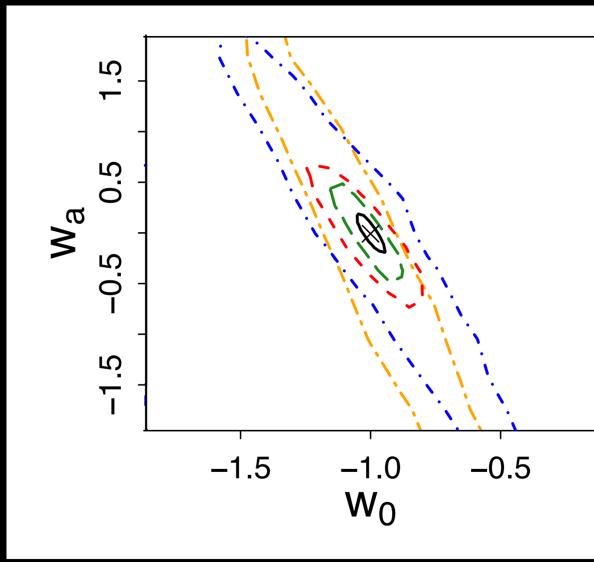
  

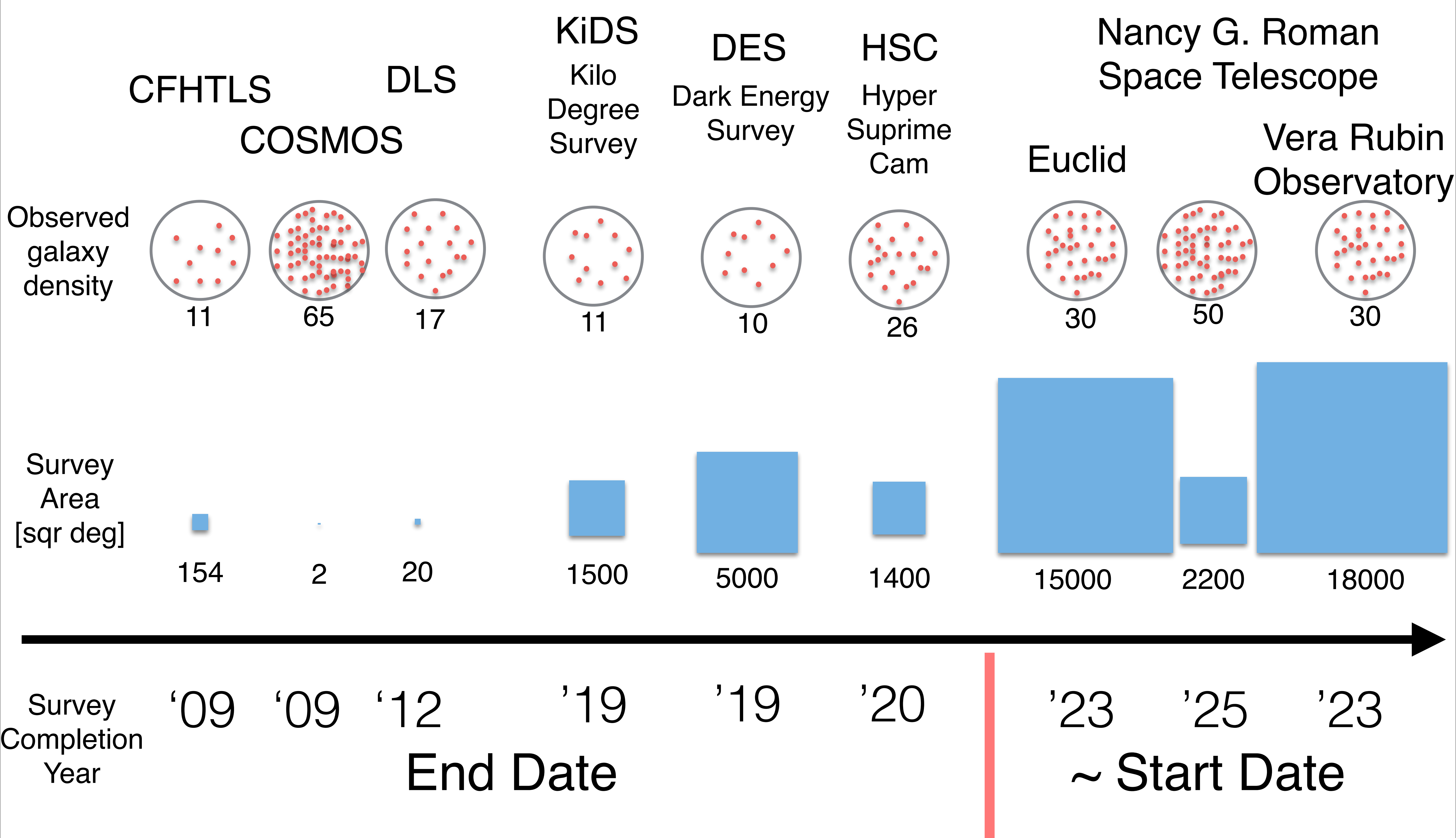
Large-Scale Structure Cosmology in the Systematics-Limited Regime

with many contributions from the Dark Energy Survey Collaboration, Vera Rubin Observatory Dark Energy Science Collaboration, and Roman Space Telescope Science Investigation Teams

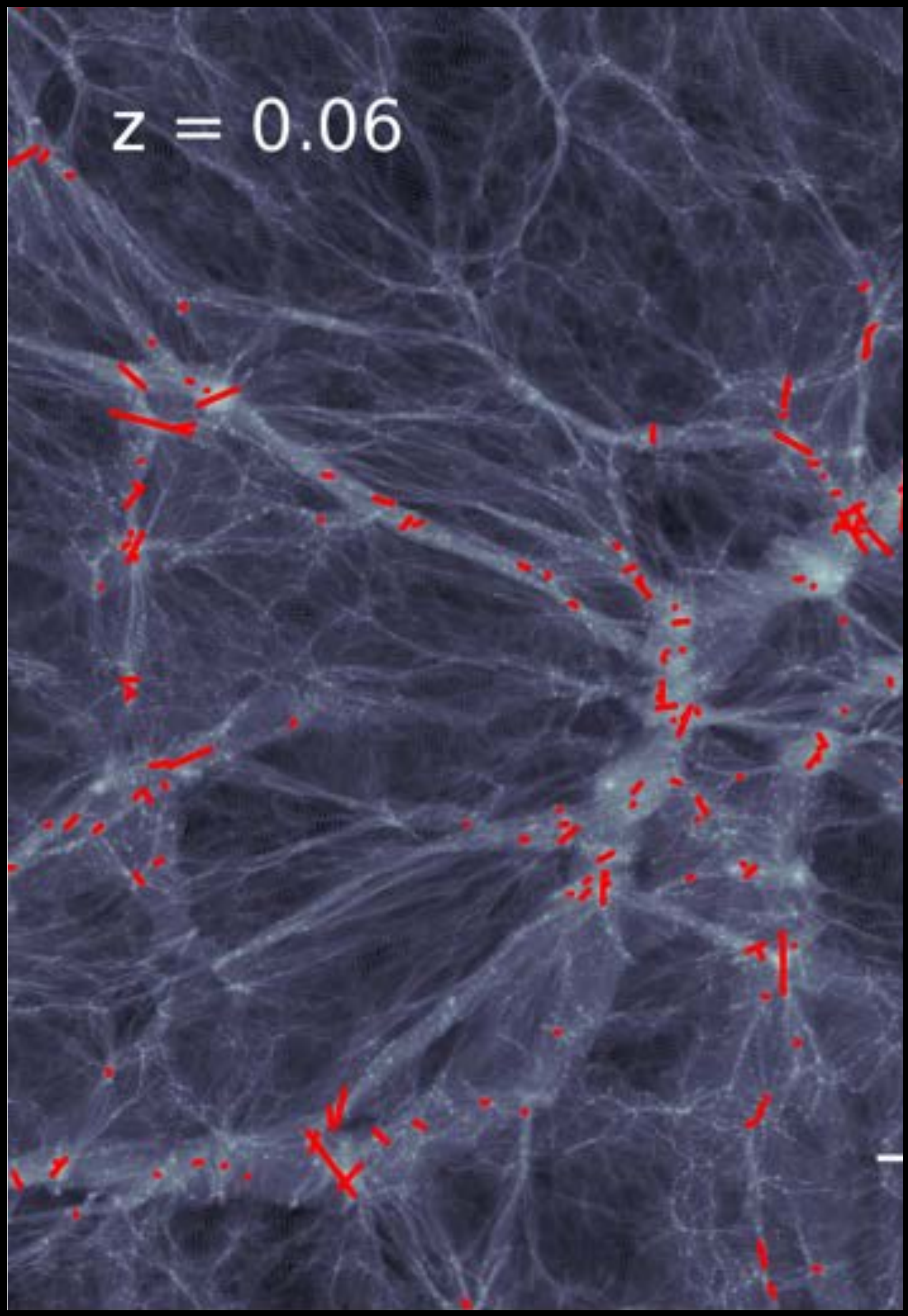
Elisabeth Krause
University of Arizona

Astroparticle Symposium, Institut Pascal, November 2022

Photometric Dark Energy Surveys



Galaxies as (Idealized) Tracers



Khandai+2014, Tenneti+2014

Observable: positions/galaxy density

$$\delta_{\rm g} = b_1\delta + b_s\delta^2 + b_s s^2 + \cdots$$

(e.g, McDonald & Roy 2009, Desjaques, Jeong & Schmidt 2018)

Observable: shapes

$$\gamma^{\rm obs} = \gamma^{\rm G} + \gamma^{\rm I}$$ (weak lensing + intrinsic shape)

intrinsic shape from collapse in tidal field

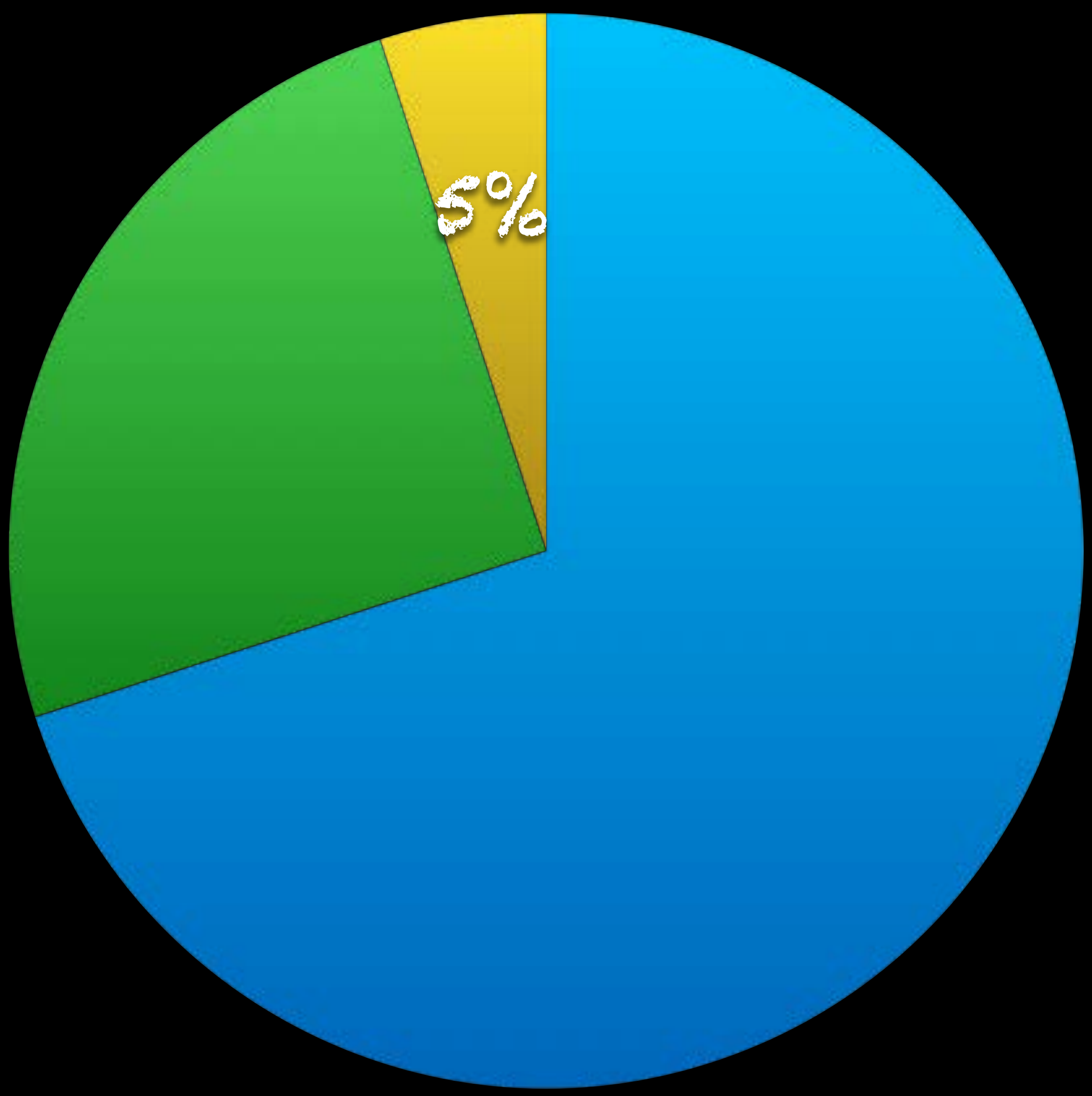
$$\gamma^{\rm I}_{ij} = C_1 s_{ij} + C_2 s_{ik}s_{kj} + C_\delta \delta s_{ij} + C_t t_{ij} + \cdots$$

(e.g, Blazek+ 2015, Schmidt+ 2015, Vlah+ 2020ab)

Predict (large-scale) scale dependence for specific galaxy type (expansion coeffs)

Need astrophysics to understand time dependence!

Preview: Cosmology Analyses, ca. 2025



Cosmology Parameters

95% Systematics Parameters
- *known unknowns*
- *unknown unknowns*

From Cosmology to Observations

Parameters	**(Unobservables)**	**Observables**	**Observations**
$\lambda_{\rm cosmo}$ $\lambda_{\rm th}$		$\lambda_{\rm astro}$	$\lambda_{\rm obs}$
initial conditions	3D matter fluctuations	(projected) tracers	maps, catalogs
energy components	matter power spectrum	tracer power spectra	tracer power spectra
background evol.	halo mass function	cluster counts	cluster counts
	…	….	….
			as measured from data

From Observations to Cosmology

$$p(\boldsymbol{\lambda}_{\rm cosmo}|\{\hat{C}(\ell),\hat{N}\}) = p(\boldsymbol{\lambda}_{\rm cosmo}) \int d\,\boldsymbol{\lambda}_{\rm th+astro+obs}\, p(\boldsymbol{\lambda}_{\rm th+astro+obs})\, p\left(P_{\rm m}, n(M)|\boldsymbol{\lambda}_{\rm cosmo+th}\right)$$
$$p(\{C(\ell),N\}|P_{\rm m}, n(M), \boldsymbol{\lambda}_{\rm astro}) p(\{\hat{C}(\ell),\hat{N}\}|\{C(\ell),N\},\boldsymbol{\lambda}_{\rm obs})$$

From Observations to Cosmology

Science Case

parameters of interest
which science?

large data vector
which probes + scales?

"systematic effects"
may outnumber cosmo params
parameterize + prioritize!

systematics prior
large prior volume
validate (external data, simulations)

$$p(\boldsymbol{\lambda}_{\rm cosmo}|\{\hat{C}(\ell),\hat{N}\}) = p(\boldsymbol{\lambda}_{\rm cosmo}) \int d\boldsymbol{\lambda}_{\rm th+astro+obs}\, p(\boldsymbol{\lambda}_{\rm th+astro+obs})\, p(P_{\rm m}, n(M)|\boldsymbol{\lambda}_{\rm cosmo+th})\, p(\{C(\ell),N\}|P_{\rm m}, n(M), \boldsymbol{\lambda}_{\rm astro})\, p(\{\hat{C}(\ell),\hat{N}\}|\{C(\ell),N\},\boldsymbol{\lambda}_{\rm obs})$$

Cosmology Priors

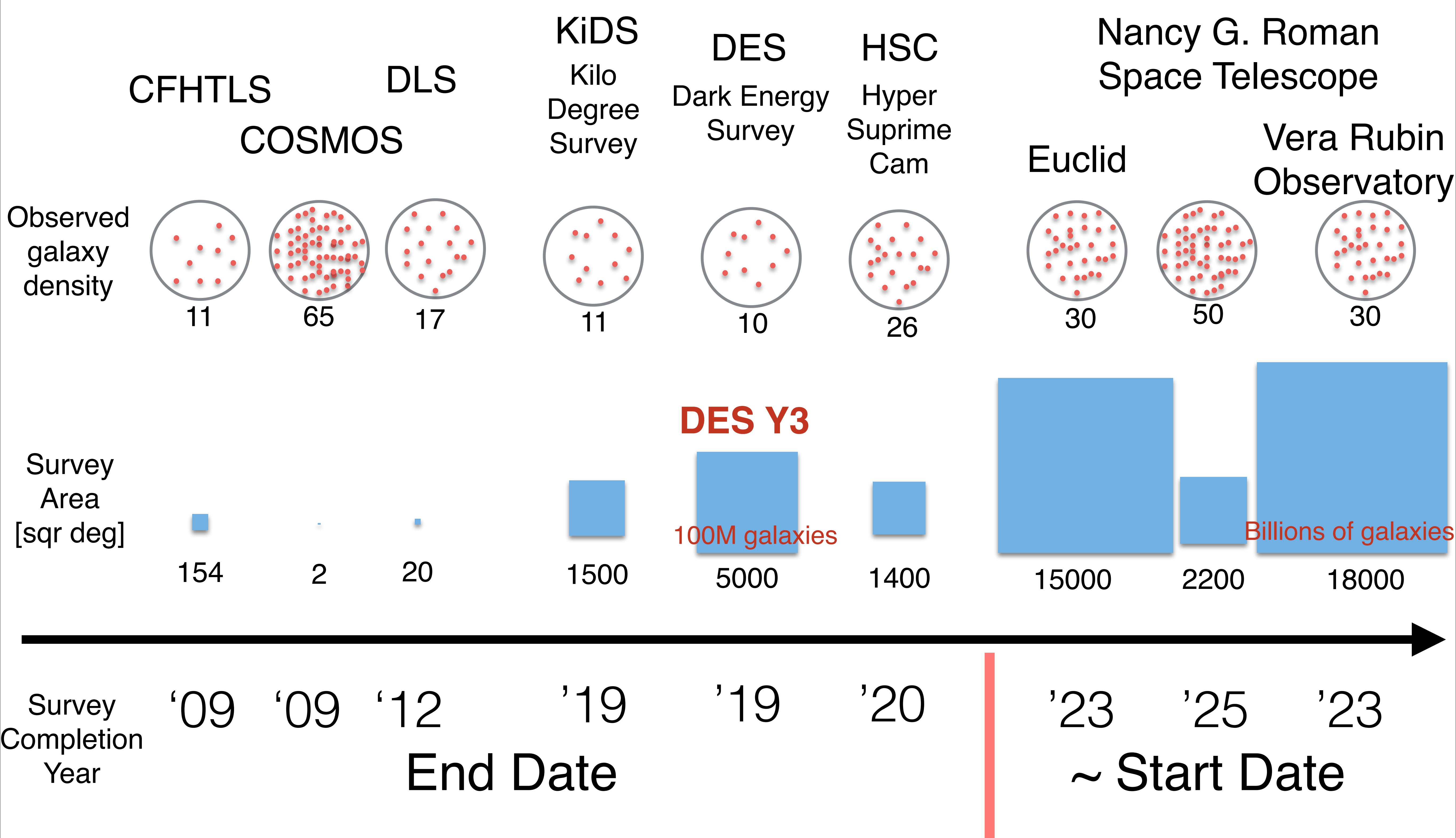
Likelihood
for observables + systematics
requires (data, sys) covariances

Model Data Vector
consistent modeling of all observables
including all (cosmo + nuisance) parameters

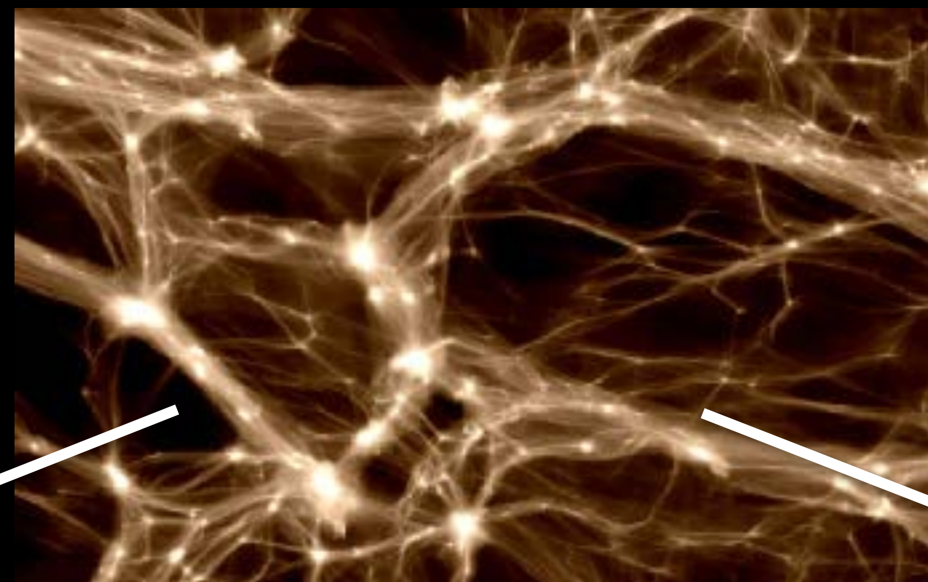
Combined Probes Systematics

- "Precision cosmology": excellent statistics - systematics limited
  - (and person-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 [2013 estimate]
- Self-calibration + marginalization?
  - costly (computationally, constraining power)

Real World Example: DES-Y3

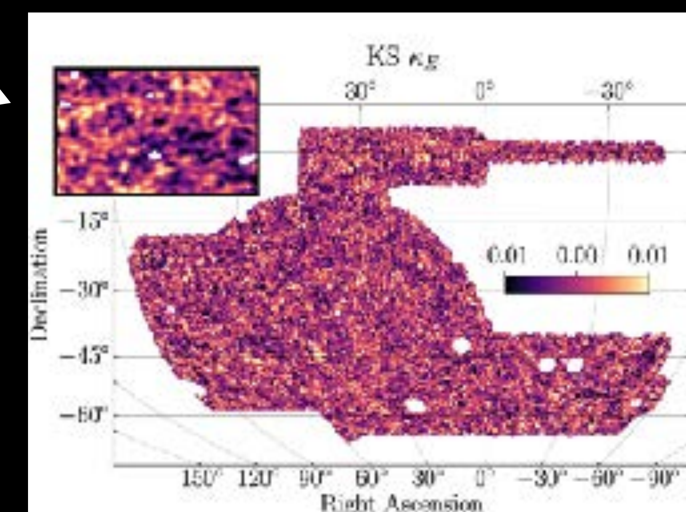


DES-Y3 WL x LSS Analysis



10M lens galaxies
split in 6 redshift bins

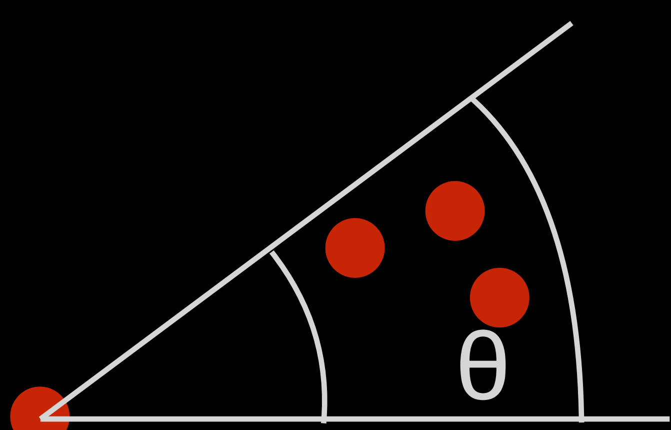
100M source galaxies
split in 4 redshift bins

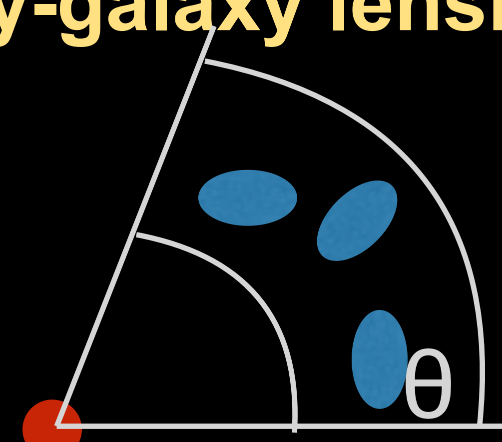


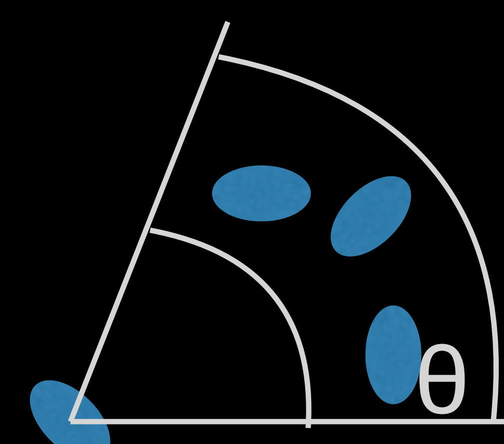
galaxies x galaxies:
angular clustering

galaxies x lensing:
galaxy-galaxy lensing

lensing x lensing:
cosmic shear



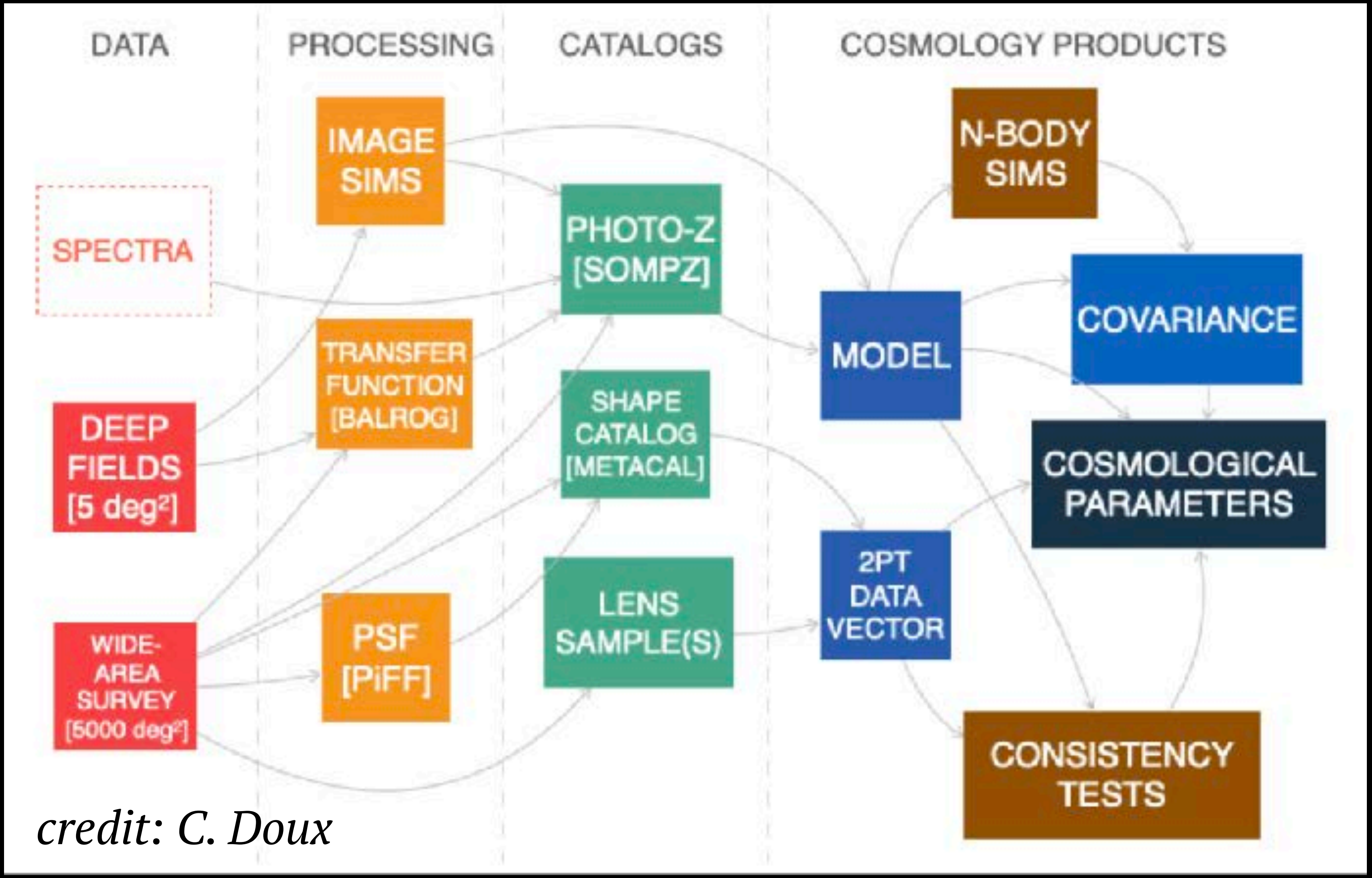




DES-Y3 Cosmology

from pixels to cosmology in 30 papers

- algorithmic + modeling improvements in all analysis stages



DES-Y3 Systematics Modeling + Mitigation

baseline systematics marginalization

- 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
- 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?

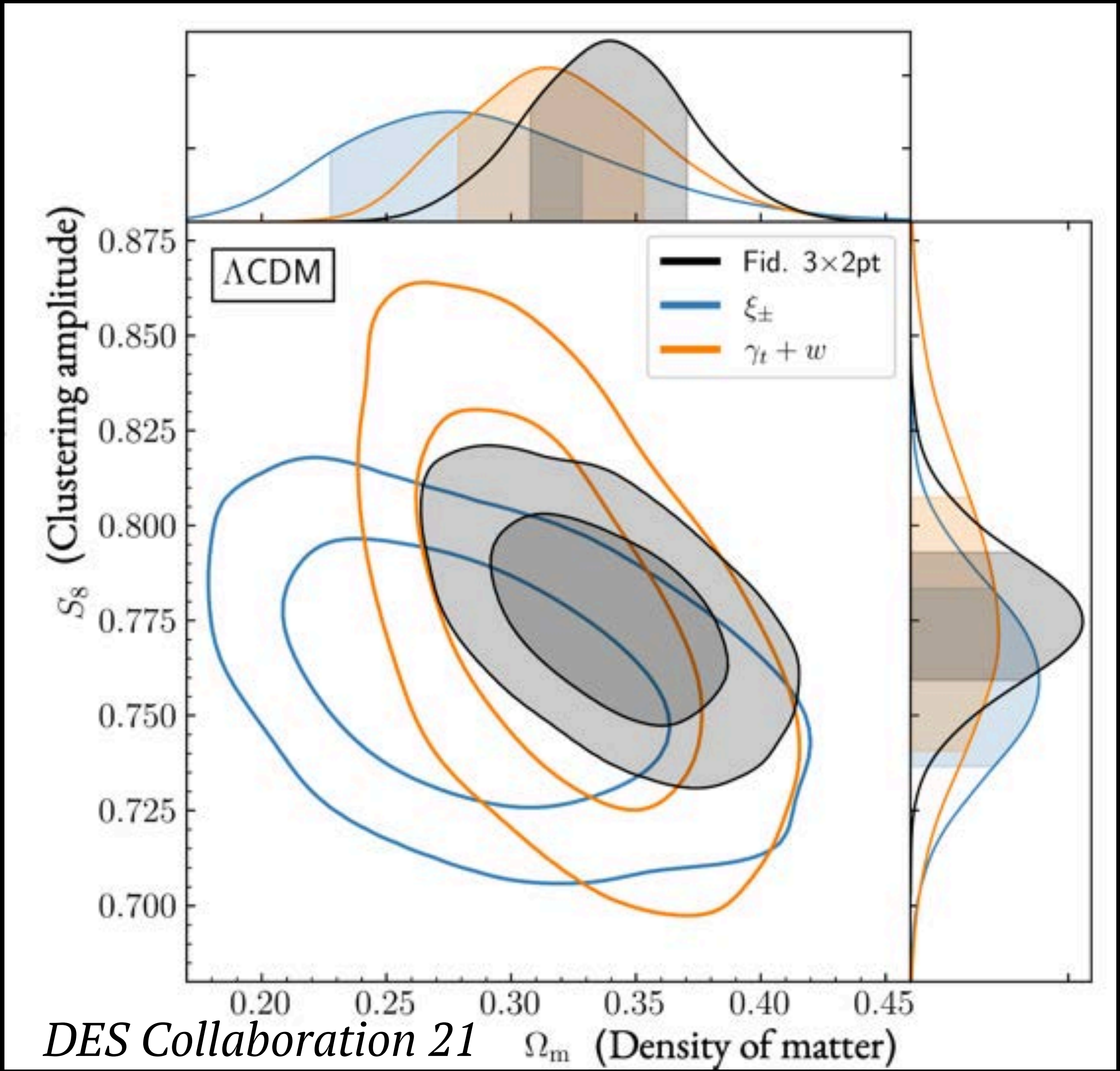
-> remove contaminated data points (*i.e., throw out large fraction of S/N*)

-> choice of parameterizations ≠ universal truth

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

EK+2021

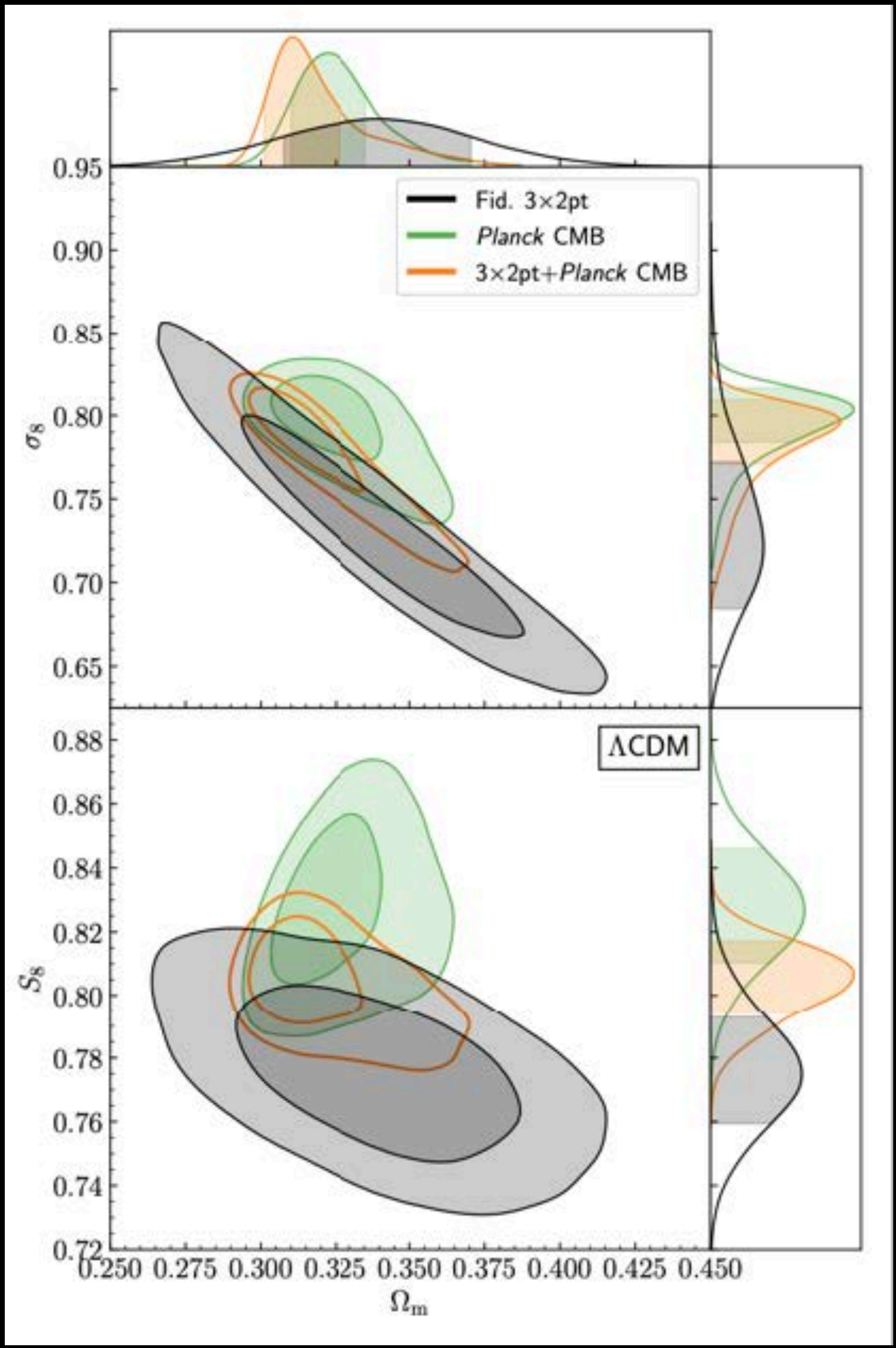
DES Y3 Results: LCDM Multi-Probe Constraints



DES Collaboration 21

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

DES Y3 ↔ Planck



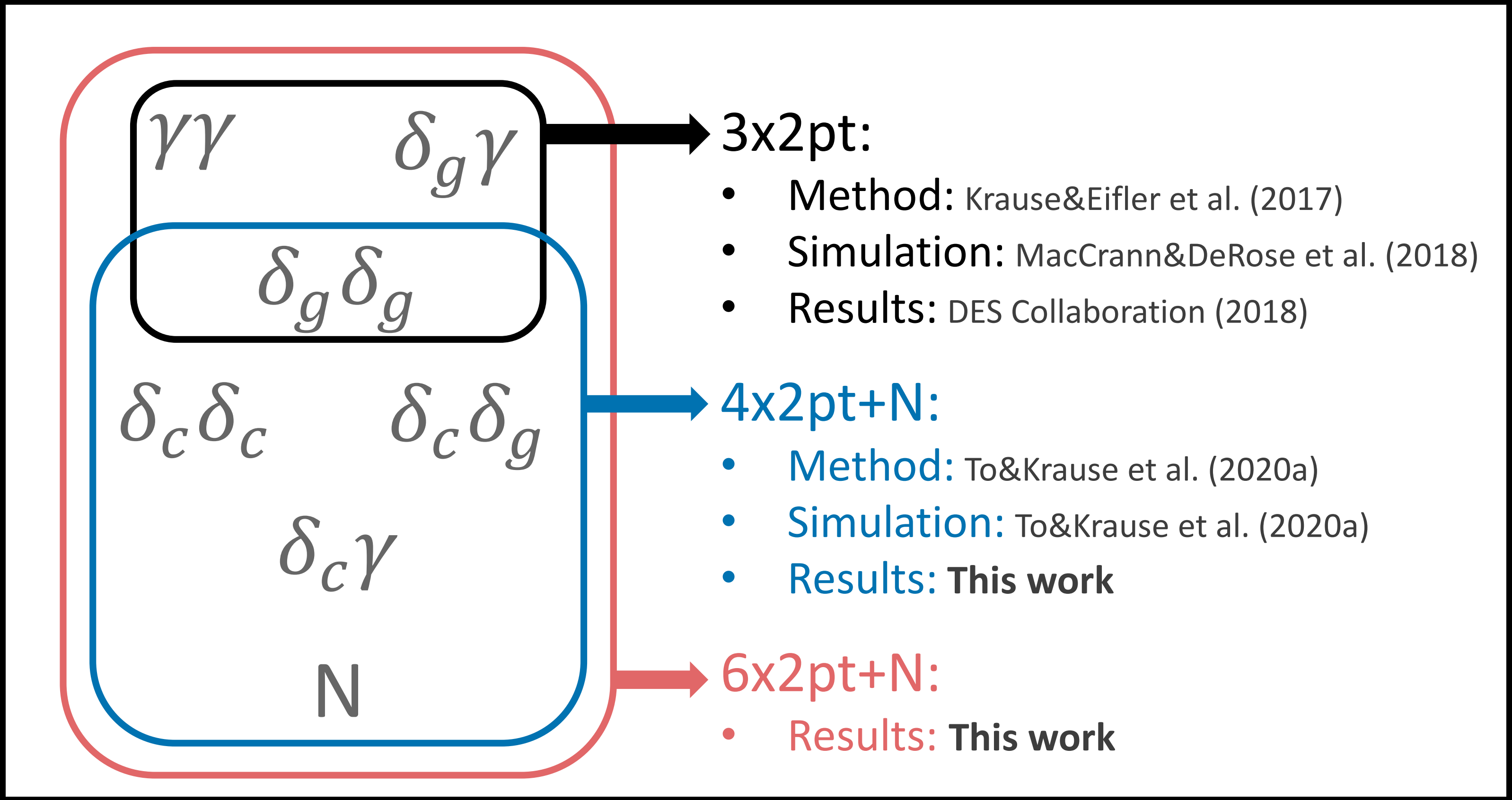
Compatibility with Planck is measured over the full LCDM parameter space -> 6 parameters (Lemos, Raveri + 20)

S8 and Ω_m drive the result to 1.5σ or p=0.13 when considering parameter differences optimal metrics (Raveri & Hu 18)

- **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



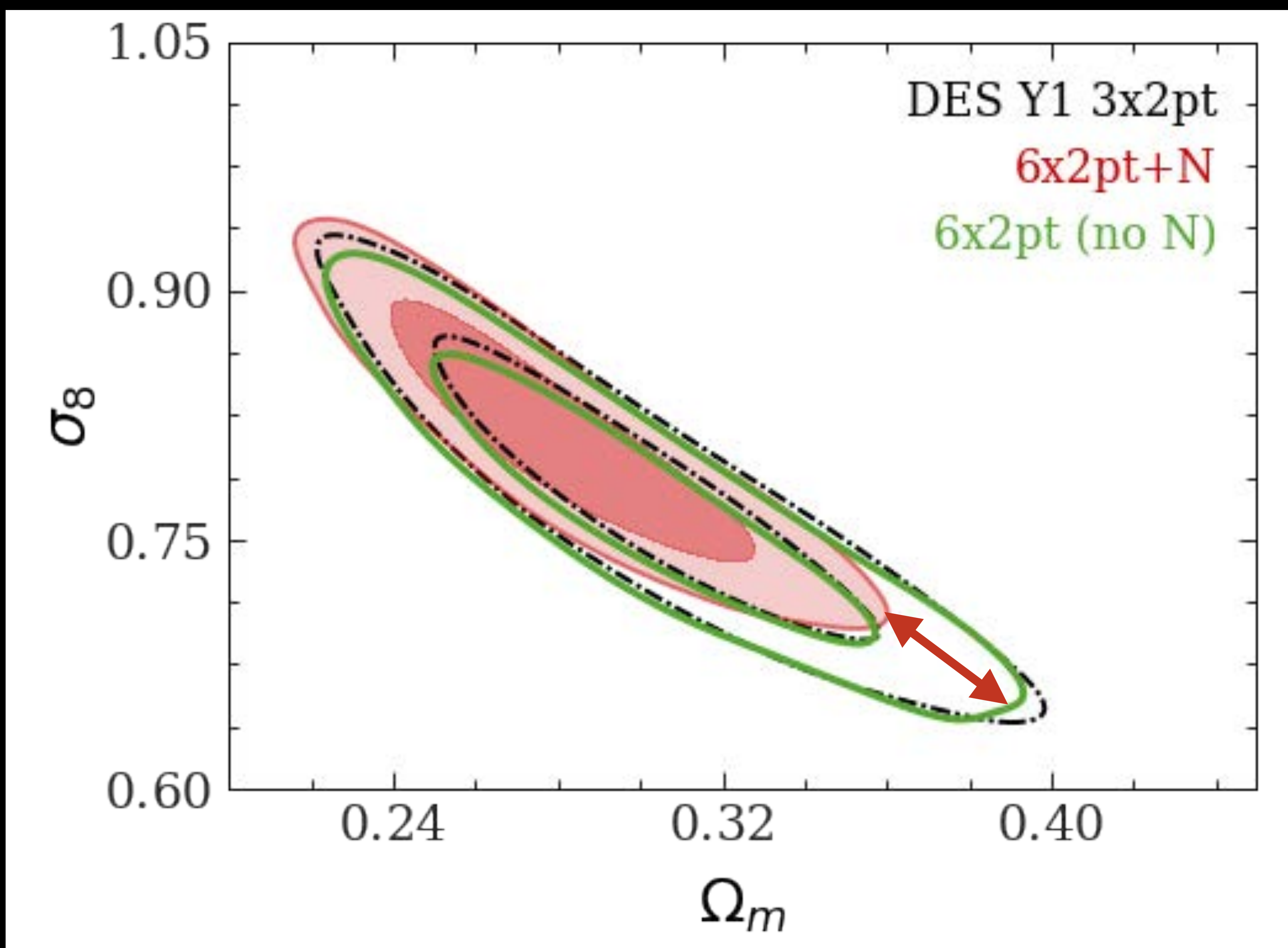
- joint likelihood analysis validated on DES-like mock catalogs (Buzzard, DeRose+2020)
- MOR calibrated from large-scale clustering, account for selection bias

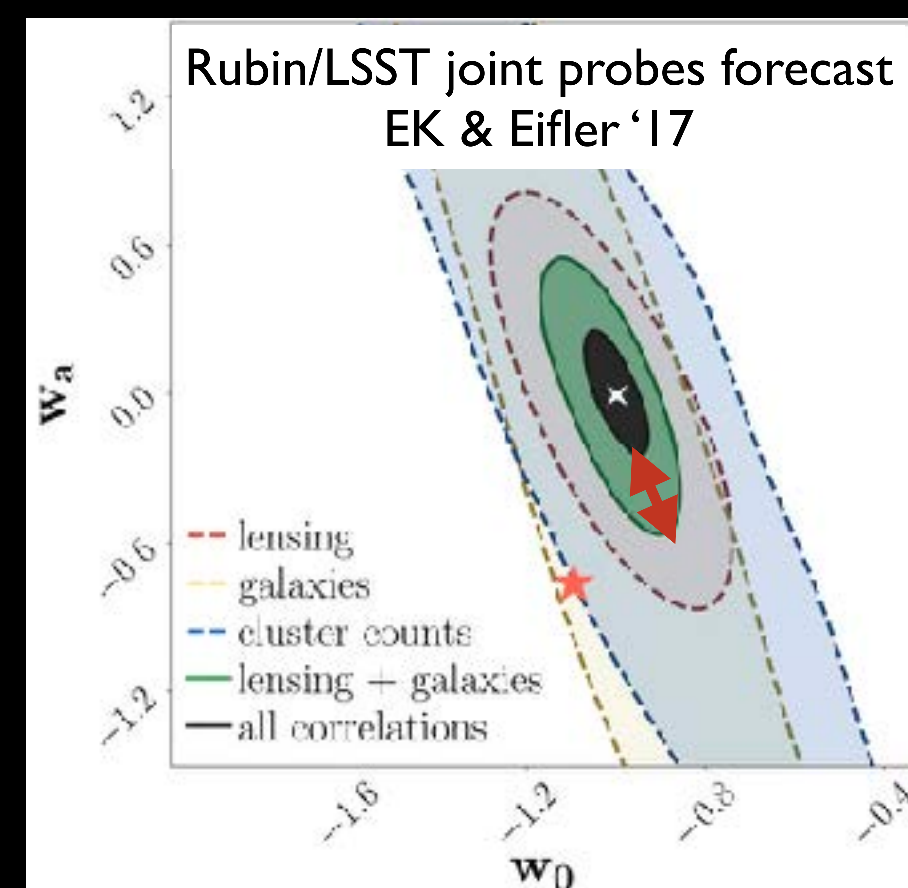
✓ cosmology constraints consistent with other DES probes

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

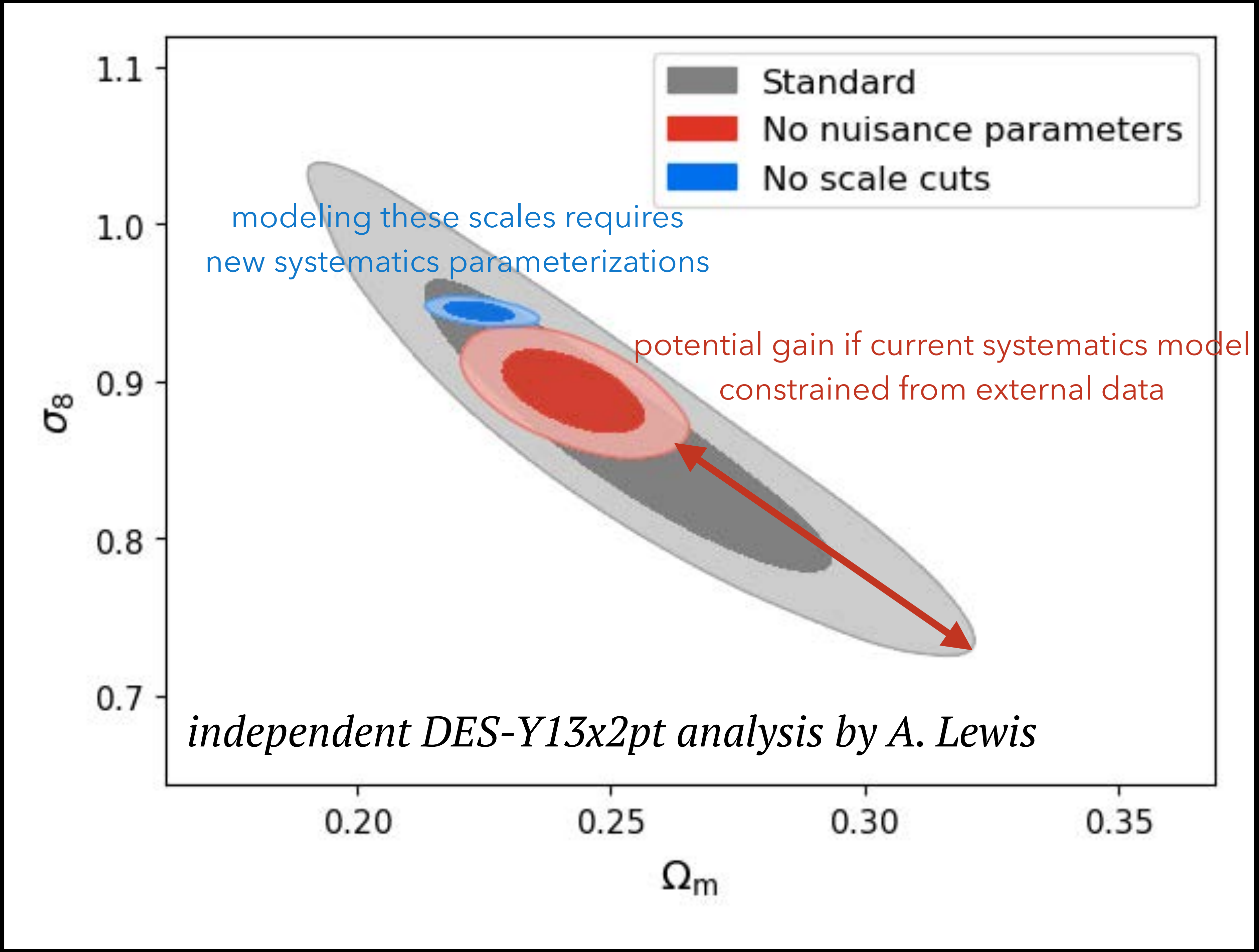
this analysis unlocks constraining power from number counts

substantial gain, *iff accurate MOR calibration*



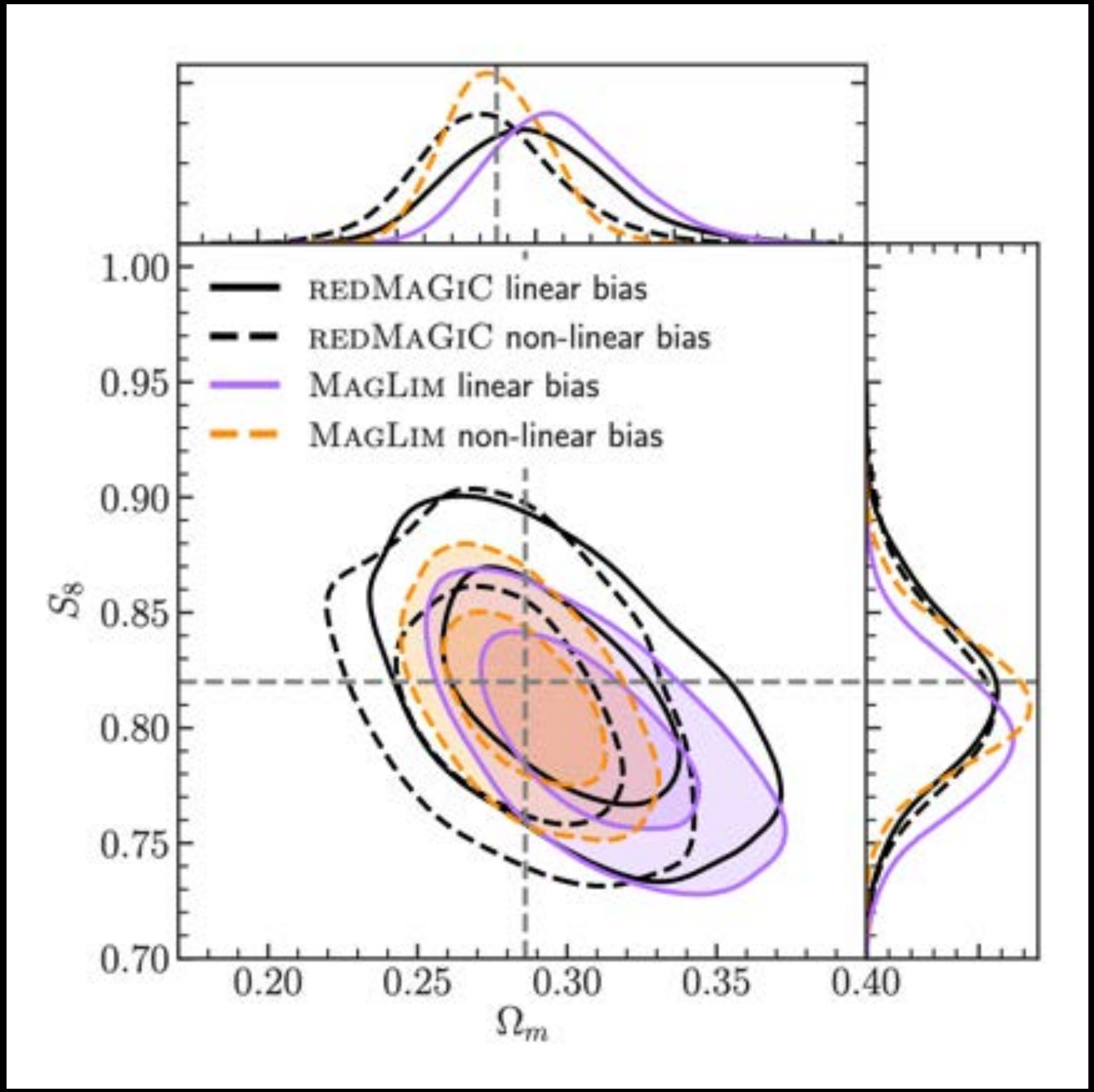


3x2pt Systematics Mitigation
Opportunity Space...



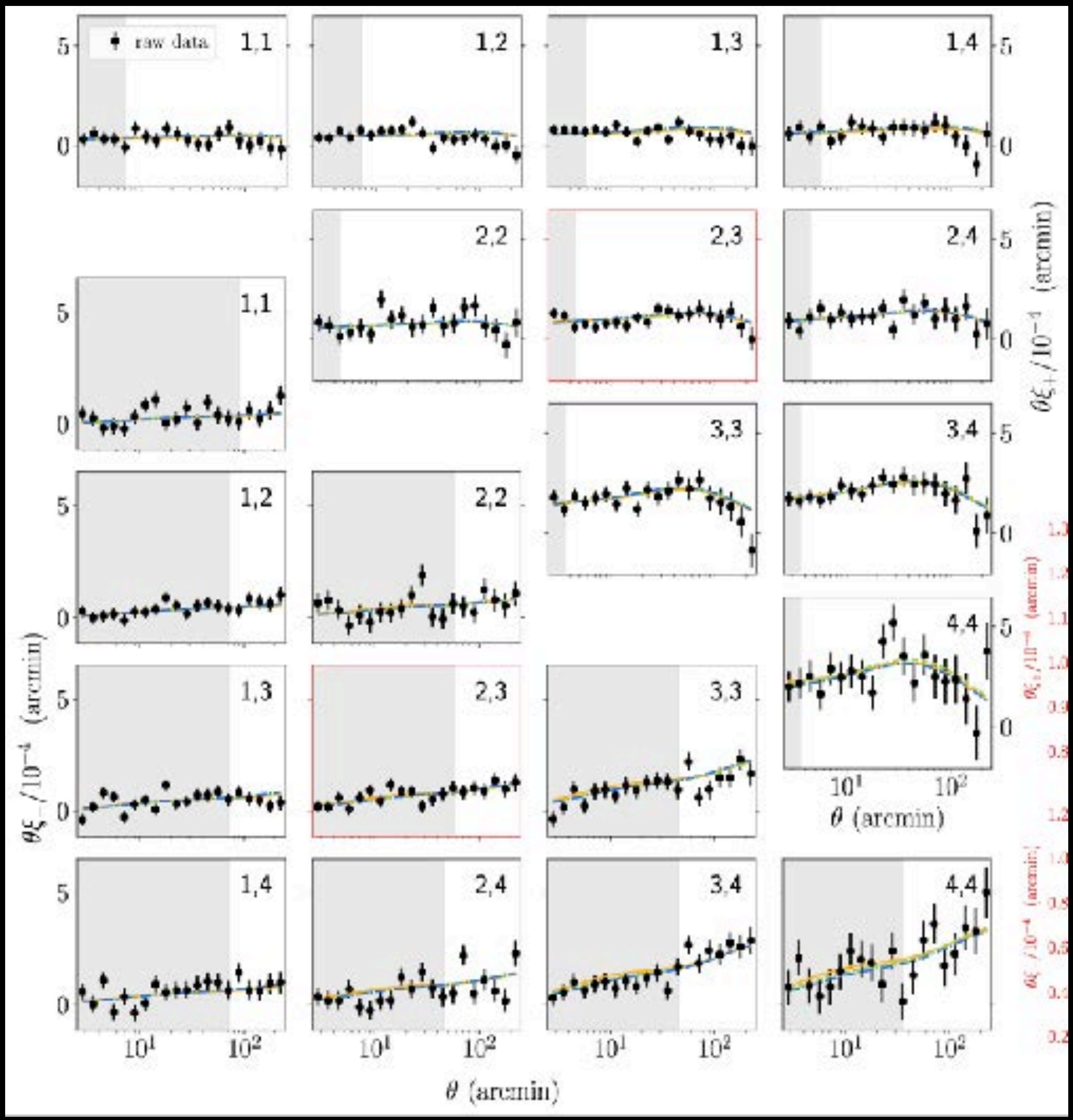
Systematics Opportunities and Challenges: Non-Linear Bias Modeling

Pandey, EK+2022, Porredon, Crocce+2022:
DES-Y3 clustering + g-g lensing analyses



- Pandey, EK+ 2020: minimal 1-loop bias model for DES-Y3 analyses
- increased statistical power and reduced model complexity enable analysis with non-linear bias modeling
- linear bias x non-linear matter power spectrum sufficient for > 8 Mpc/h
- limited increase in constraining power when including smaller scales + non-linear bias model

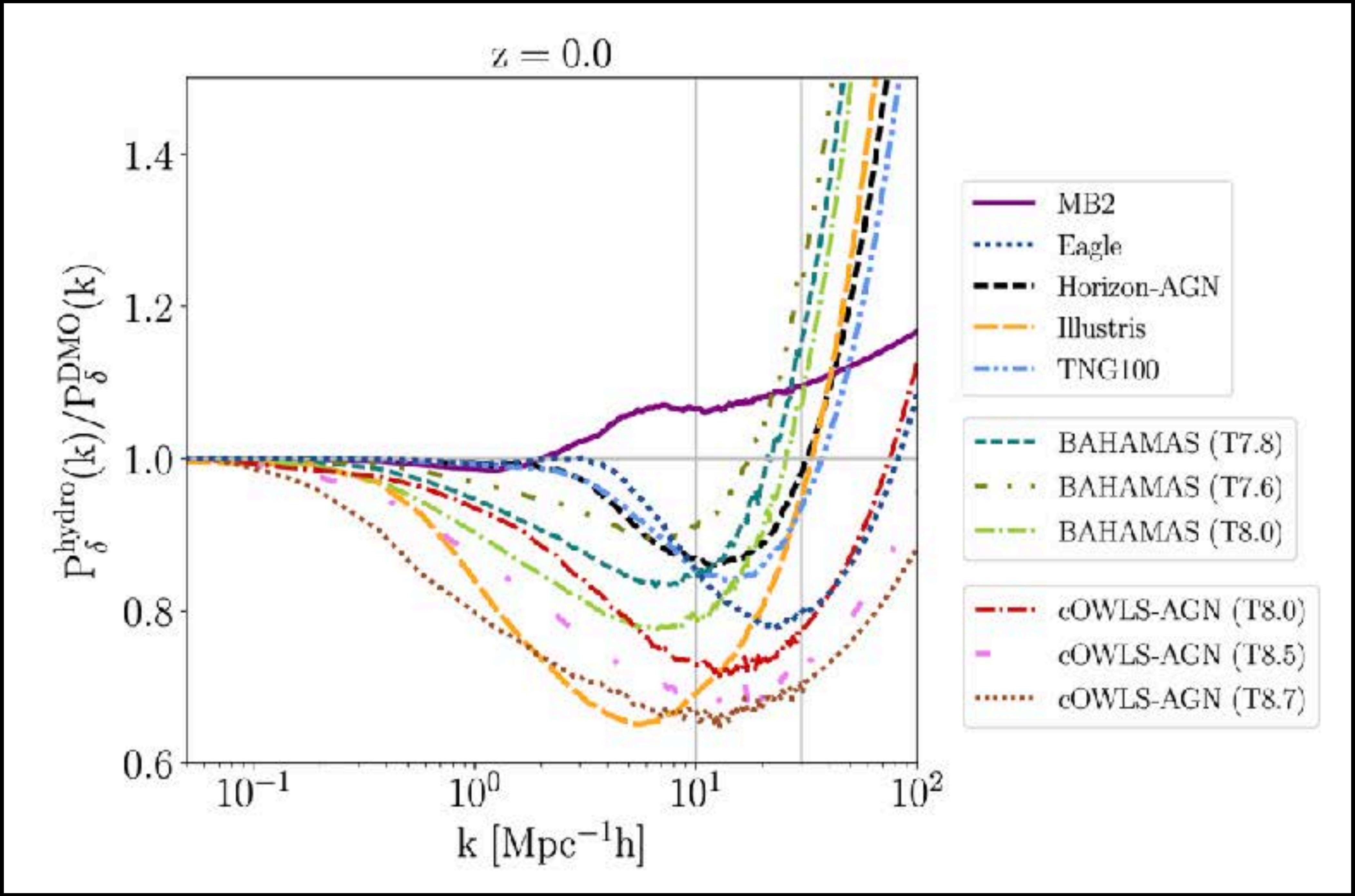
Systematics Opportunities and Challenges: Baryonic Effects in WL Analyses



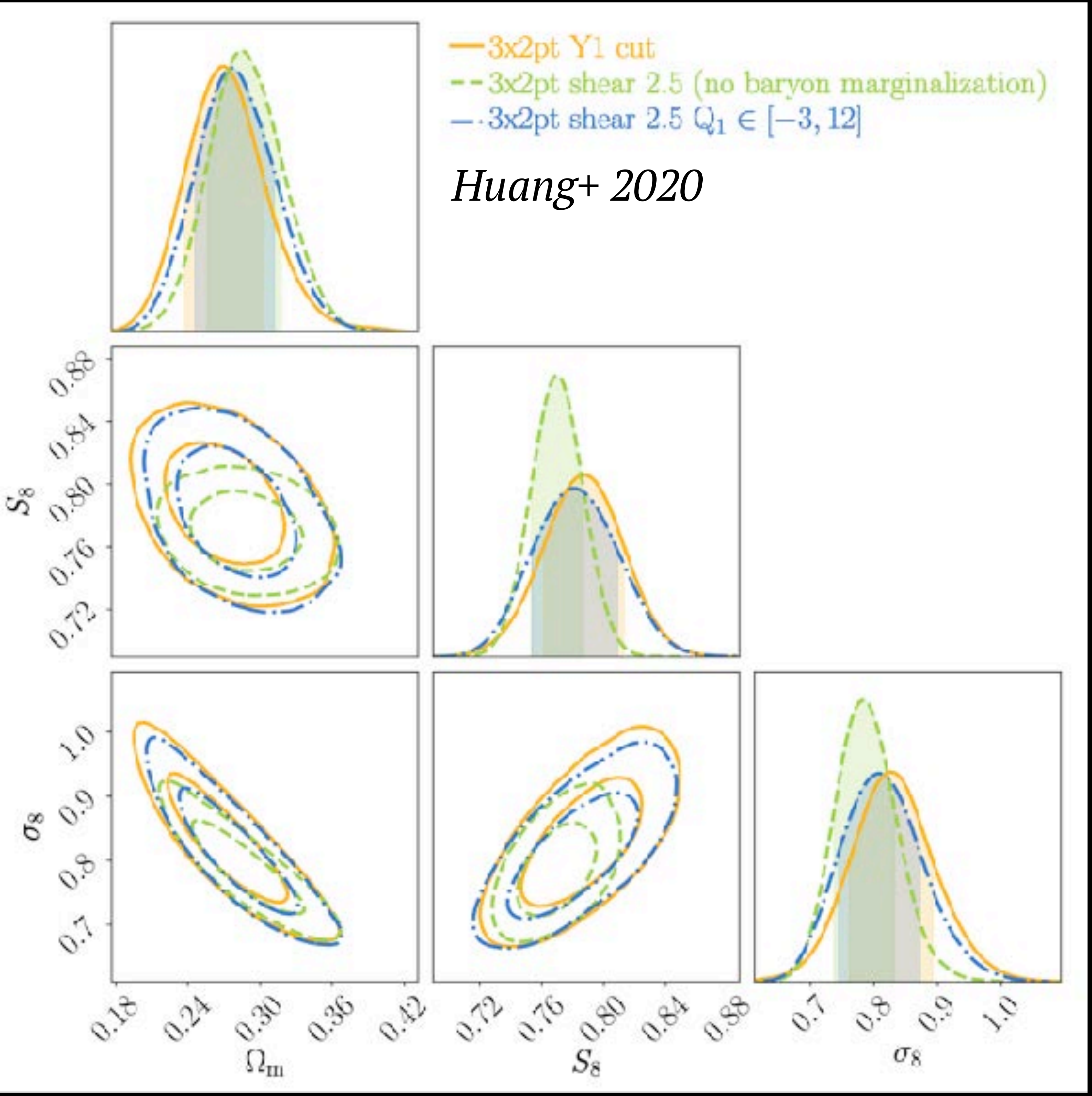
DES-Y1 baseline: small scale correlation function measurements **excluded because of baryonic effects**

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

Baryonic Effects in WL Analyses

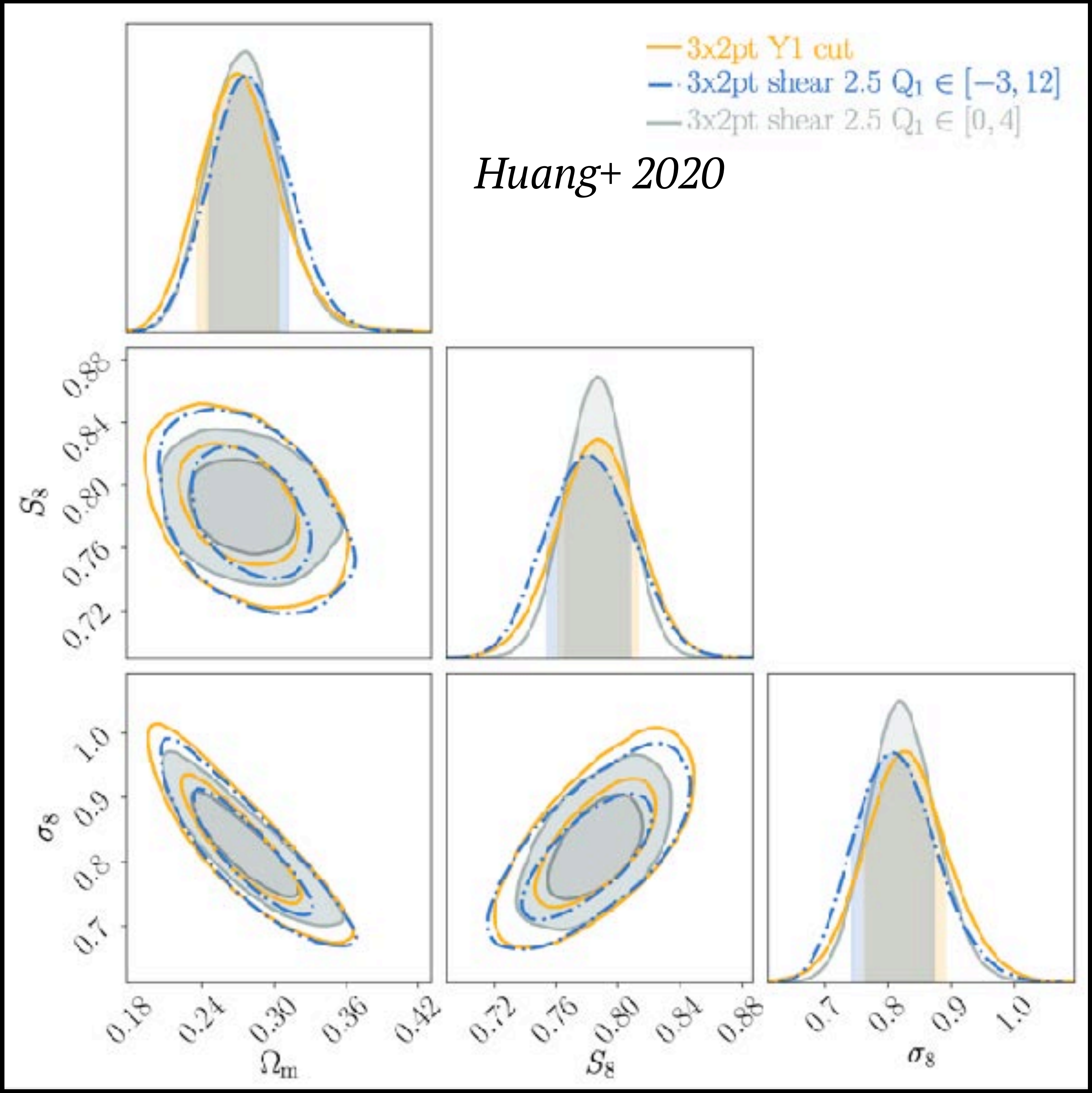


Baryonic Effects in WL Analyses Cosmology Constraints



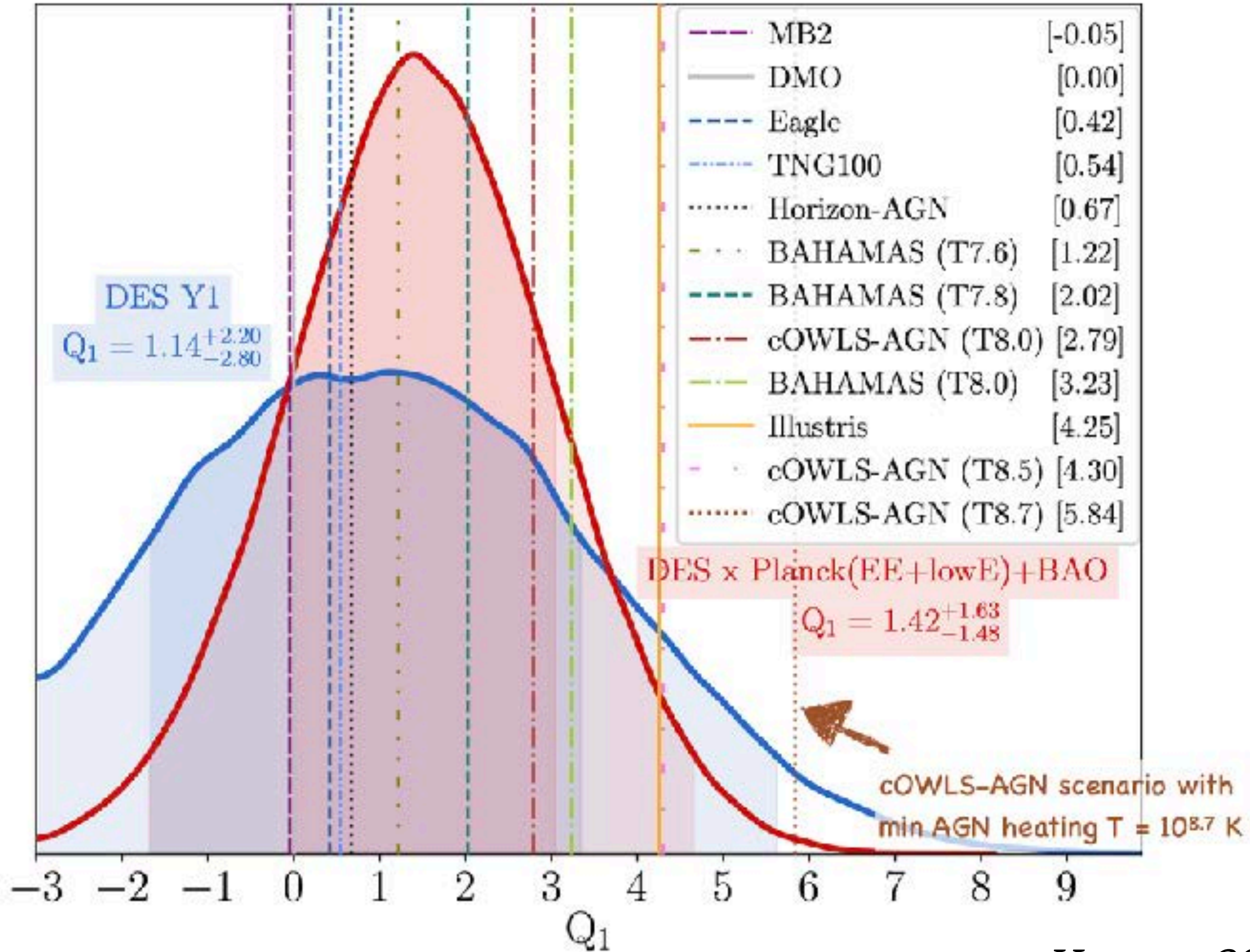
- DES-Y1 including all scales, baryons not included in the modeling (don't do that!)
- DES-Y1 baseline (conservative scale cuts)
- DES-Y1 including all scales, baryonic effects modeled using **PCA with non-informative prior**

Baryonic Effects in WL Analyses Cosmology Constraints



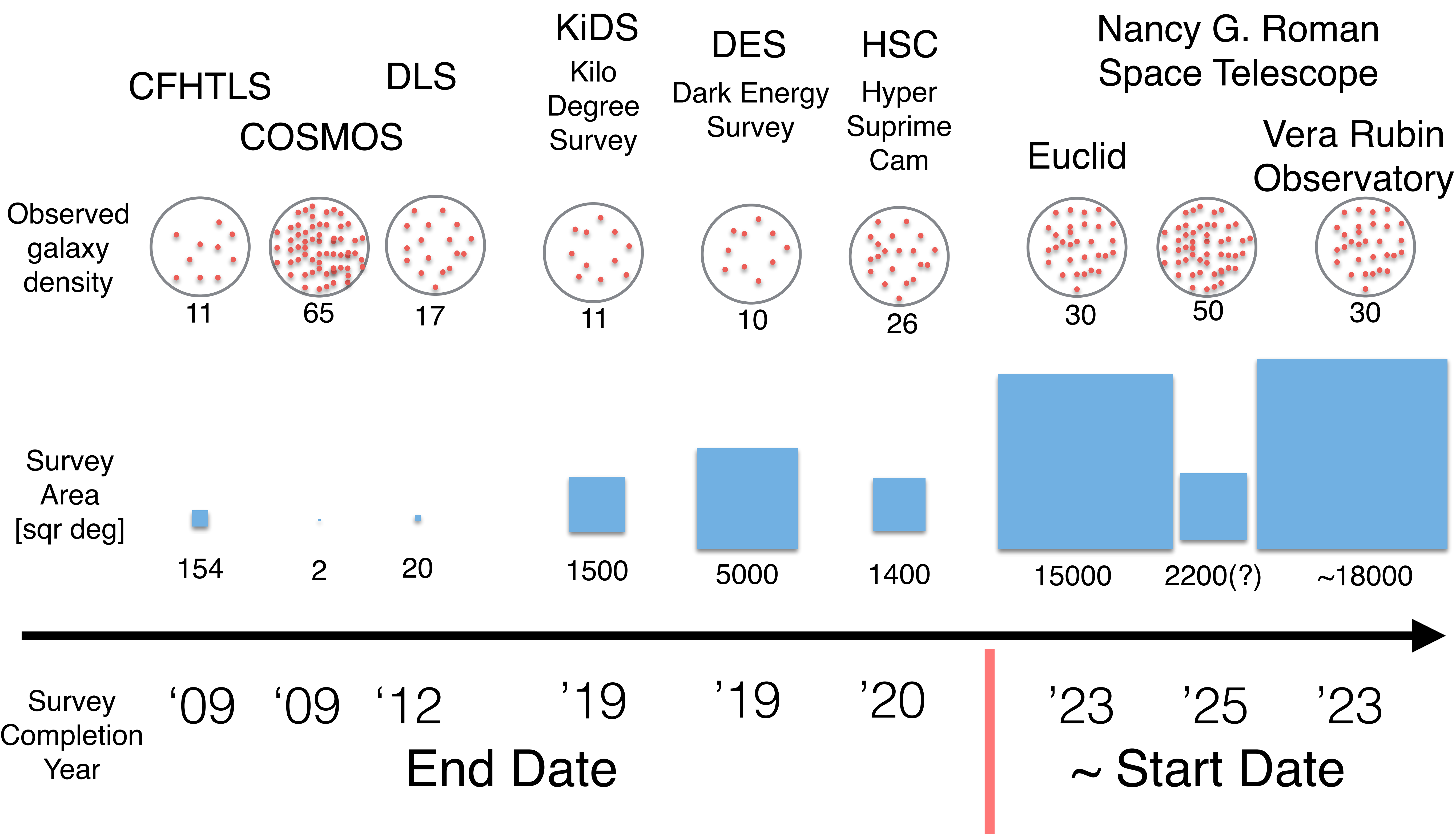
- DES-Y1 baseline (conservative scale cuts)
- DES-Y1 including all scales, baryonic effects modeled using **PCA with non-informative prior**
- DES-Y1 including all scales, baryonic effects modeled using **PCA with informative prior**

Baryonic Effects in WL Analyses
Feedback Constraints



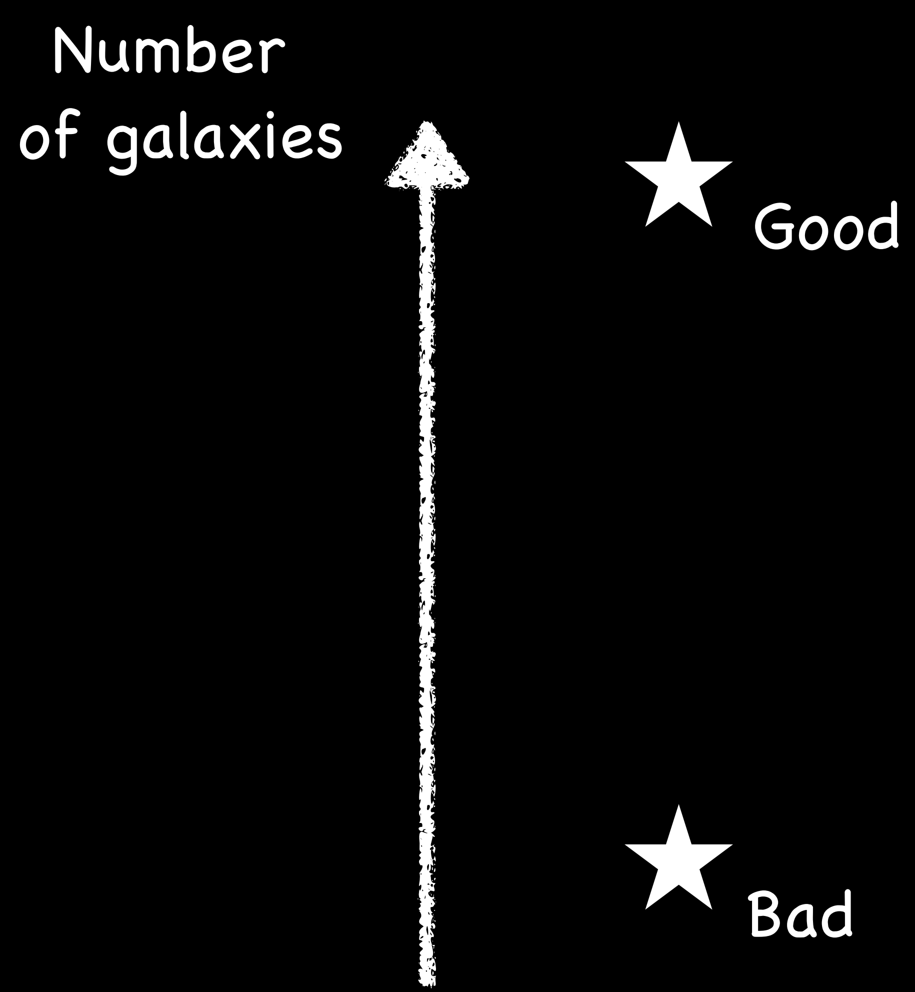
Huang+ 2020

The Future

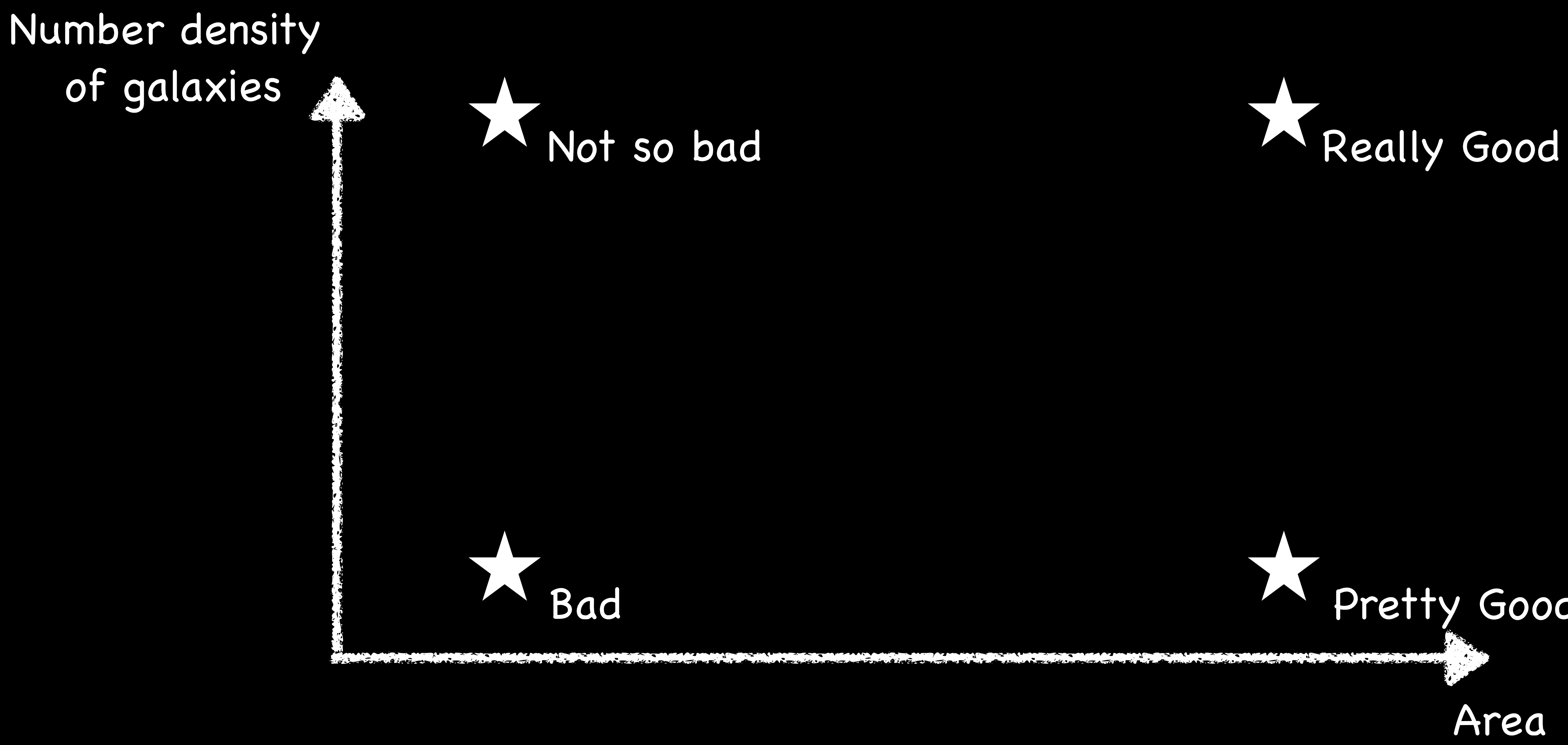


CFHTLS
COSMOS
DLS
KiDS
Kilo Degree Survey
DES
Dark Energy Survey
HSC
Hyper Suprime Cam
Euclid
Nancy G. Roman Space Telescope
Vera Rubin Observatory
Observed galaxy density
11
65
17
11
10
26
30
50
30
Survey Area [sqr deg]
154
2
20
1500
5000
1400
15000
2200(?)
~18000
Survey Completion Year
'09
'09
'12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

Survey Optimization I



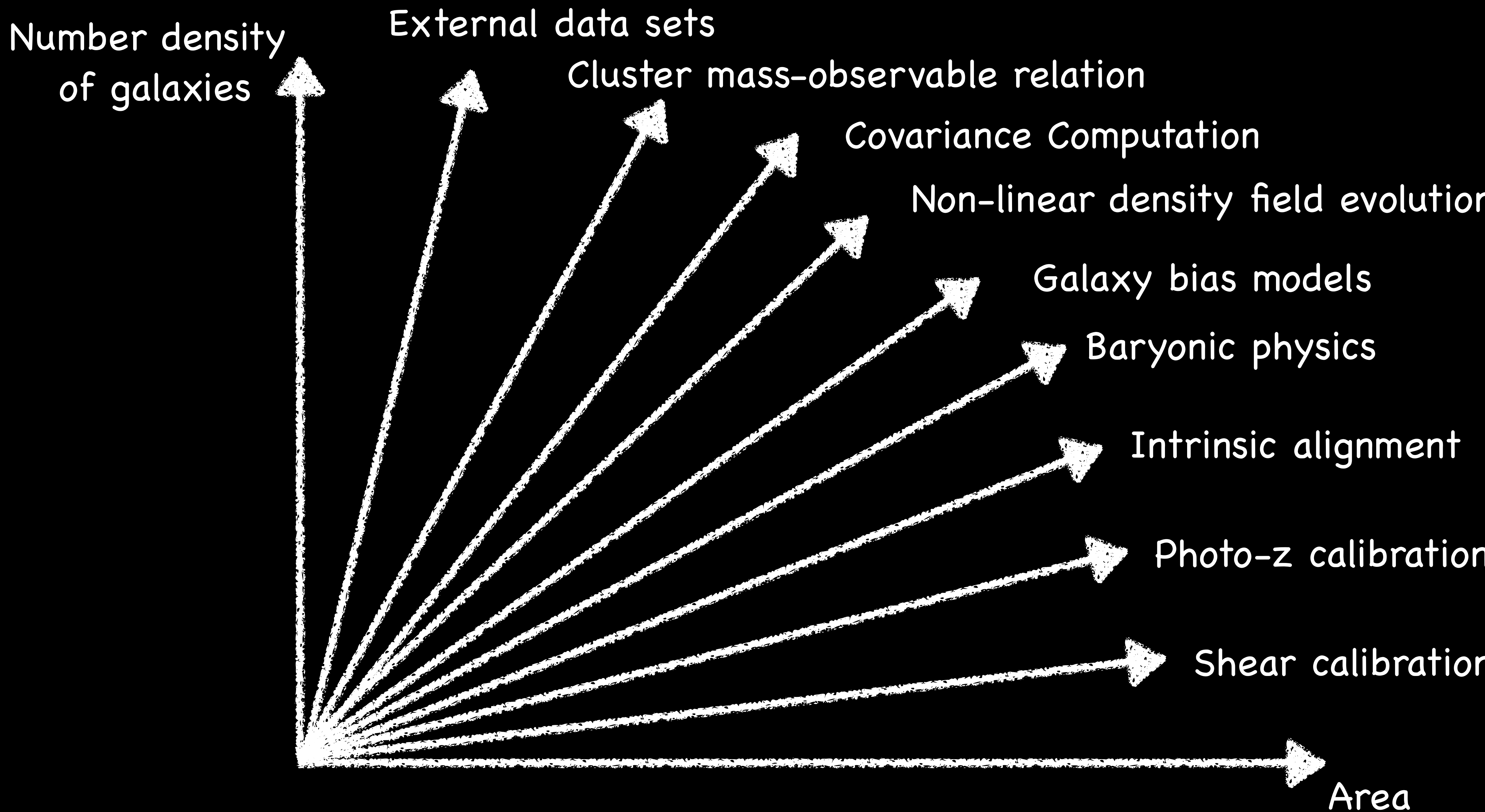
Survey Optimization II



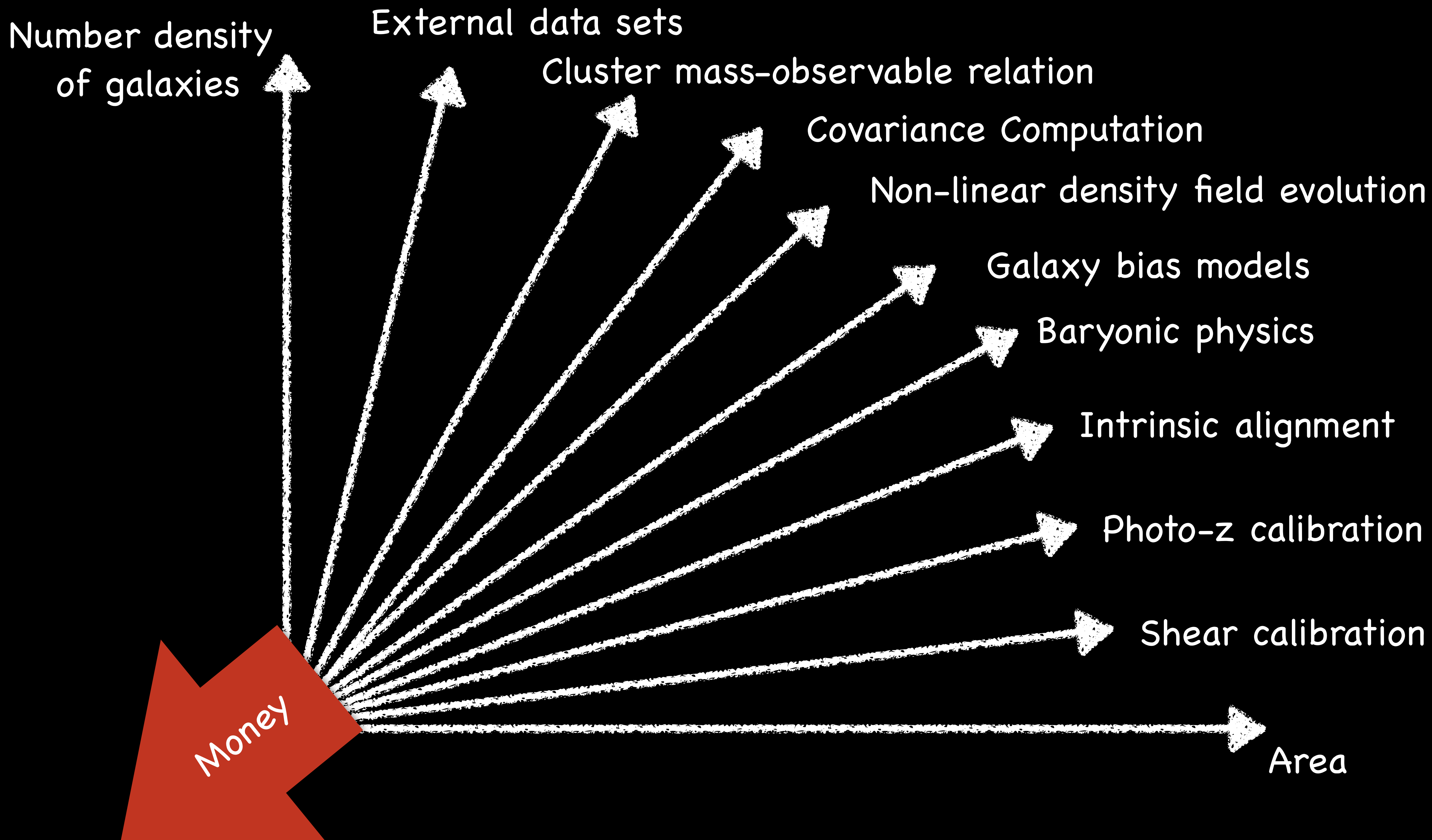
Statistical error bars only (simplified):

- Area is more important than depth
- Even more true since non-gaussian Covariances became fashionable

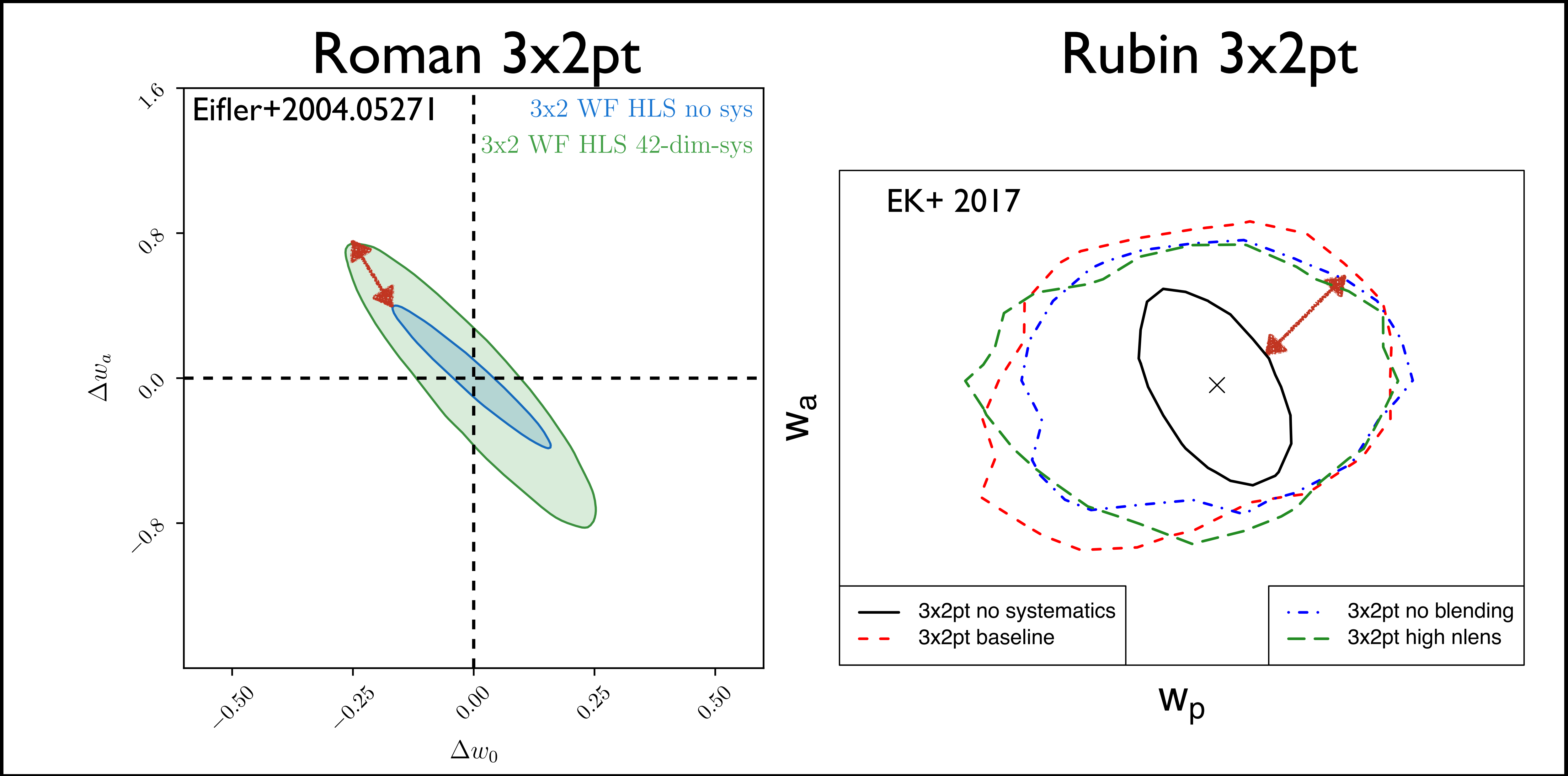
Survey Optimization III



Survey Optimization III



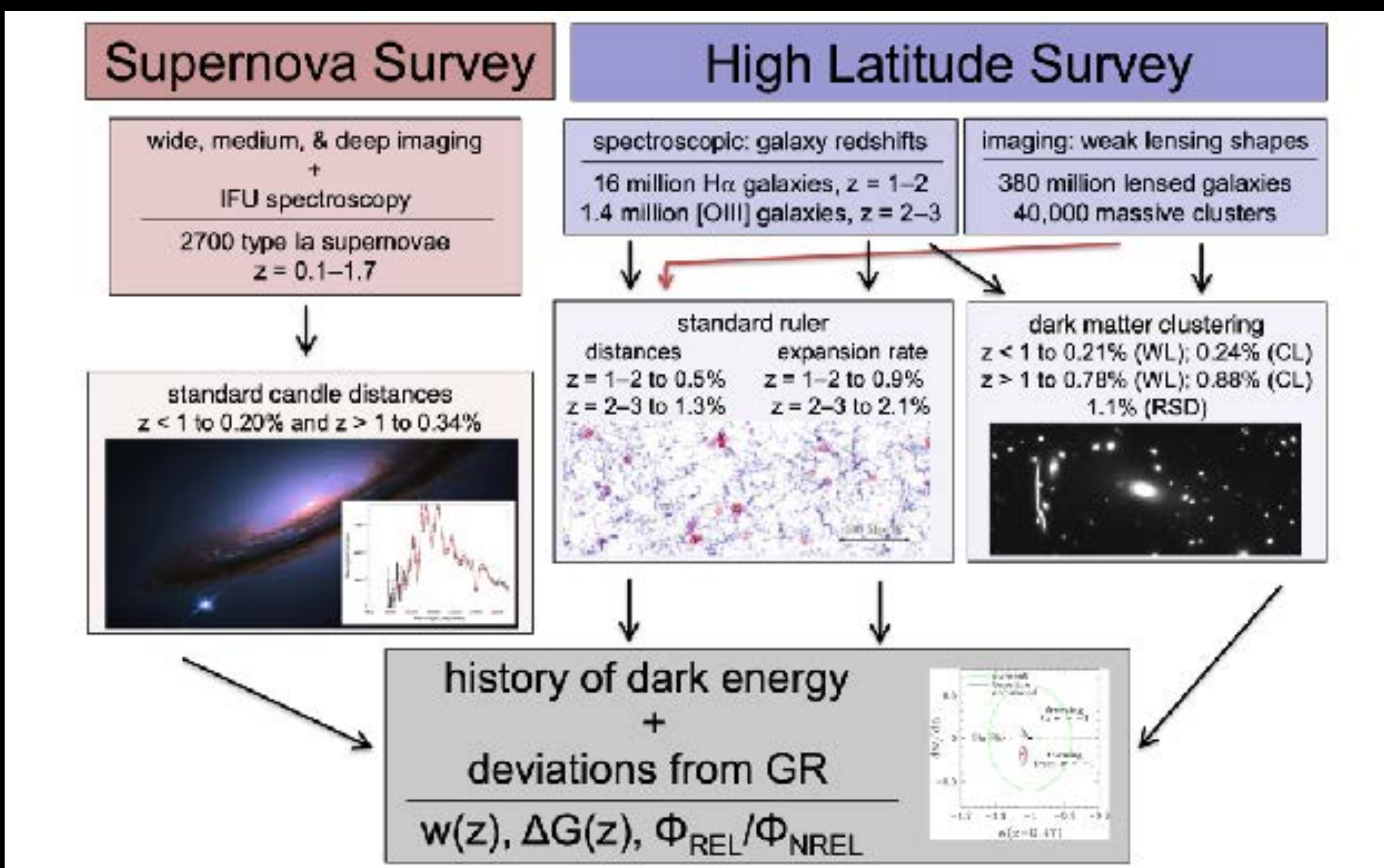
Stage-IV 3x2pt forecasts
(*details matter*)

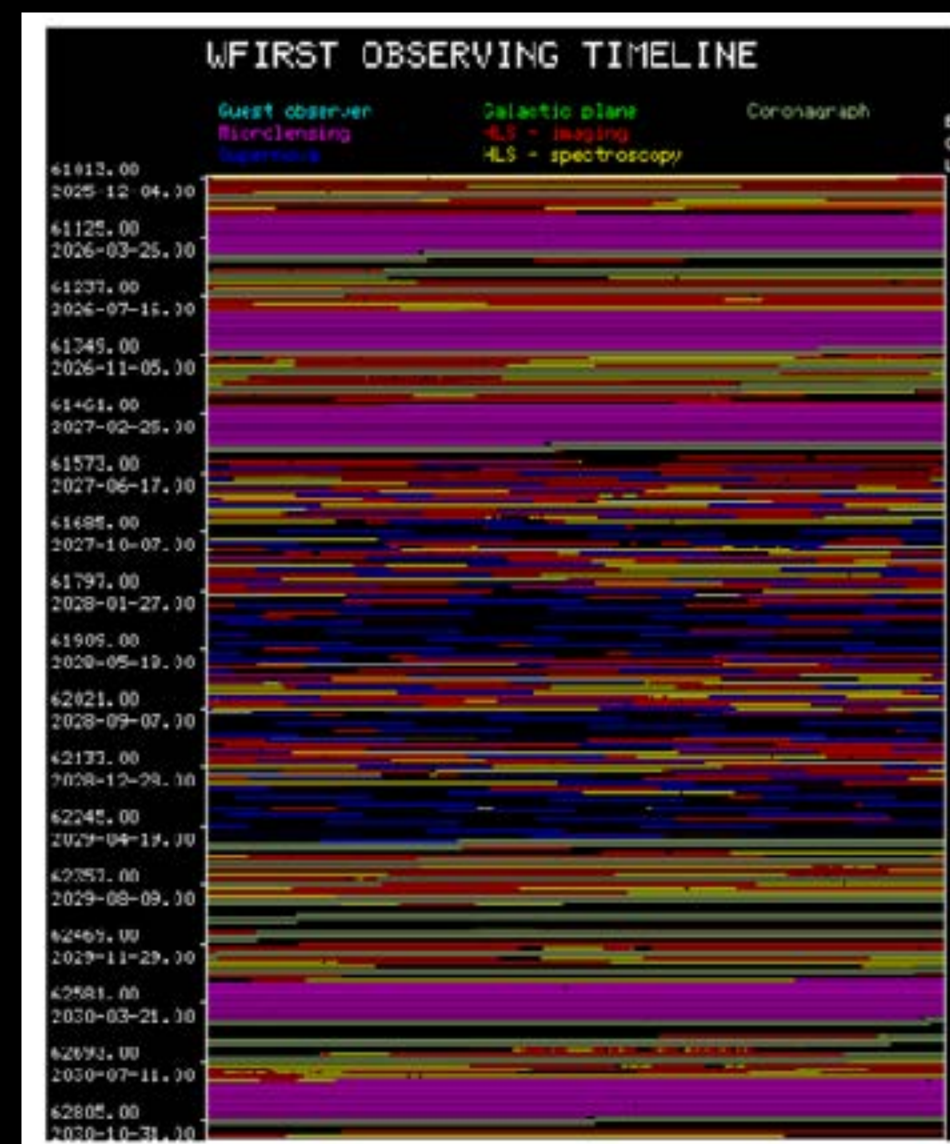


marginalized over {linear galaxy bias, lens photo-z, source photo-z} per tomography bin

Roman Space Telescope Forecasting

- Observing Strategy is not yet defined. Community input is important to define a mission that benefits all science
- No expendables that limit the survey strategy or the survey duration to 5-years (propellant for at least 10 years of observations, no active cryogens)

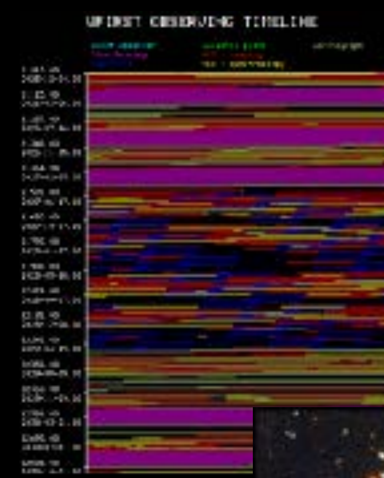


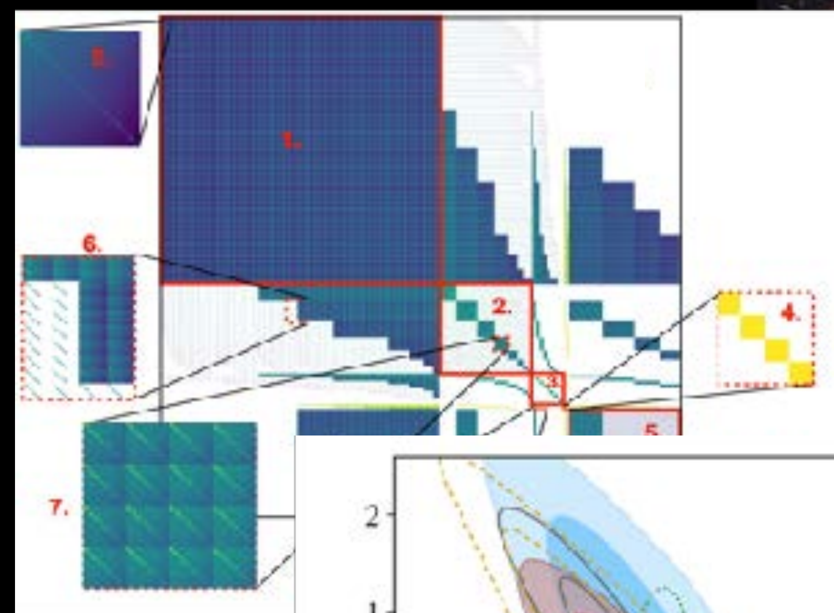


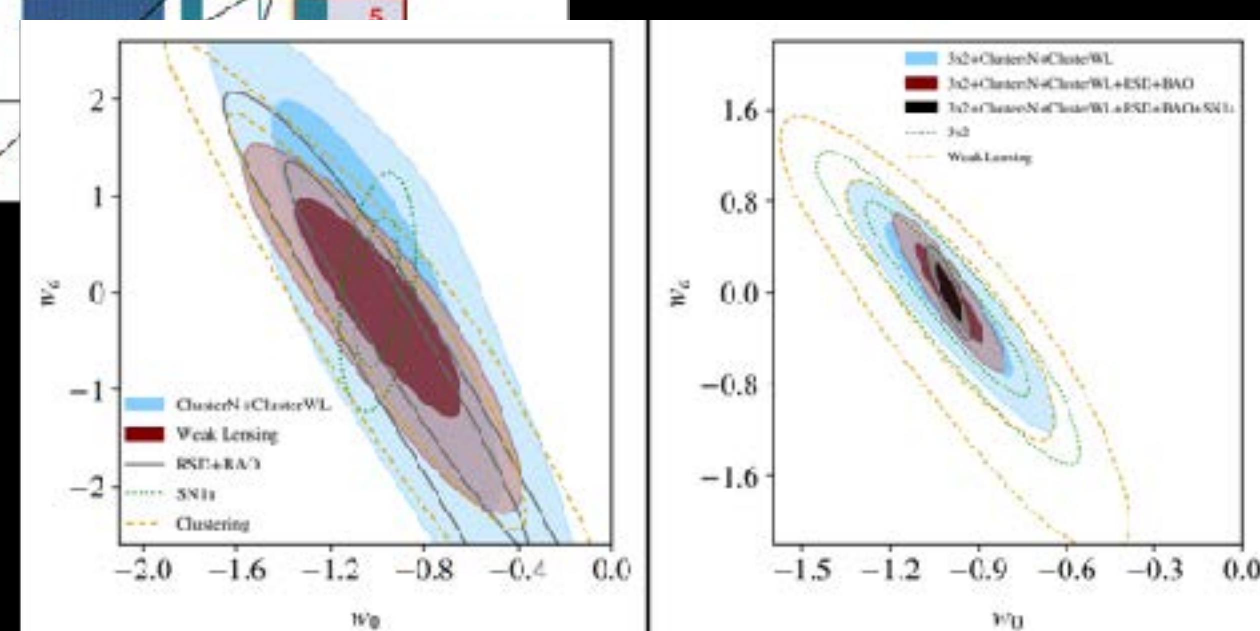
Roman Space Telescope Forecasting

Forecast Machinery (Eifler+2004.05271)

- WFIRST Exposure Time Calculator (Hirata+12): realistic survey area + depth
- CANDELS WFIRST catalog (Hemmati+18): redshift distribution for lensing and clustering sample, galaxy clusters
- Combine
    - Cosmic shear
    - Galaxy-Galaxy Lensing
    - Galaxy Clustering (photo)
    - Cluster Number Counts
    - Cluster Weak Lensing
    - Galaxy Clustering (Spectro)
    - SN1a (Hounsell+2018)
- Non-Gaussian Multi-Probe Covariance
- 80+ systematic parameters
- full simulated likelihood analyses

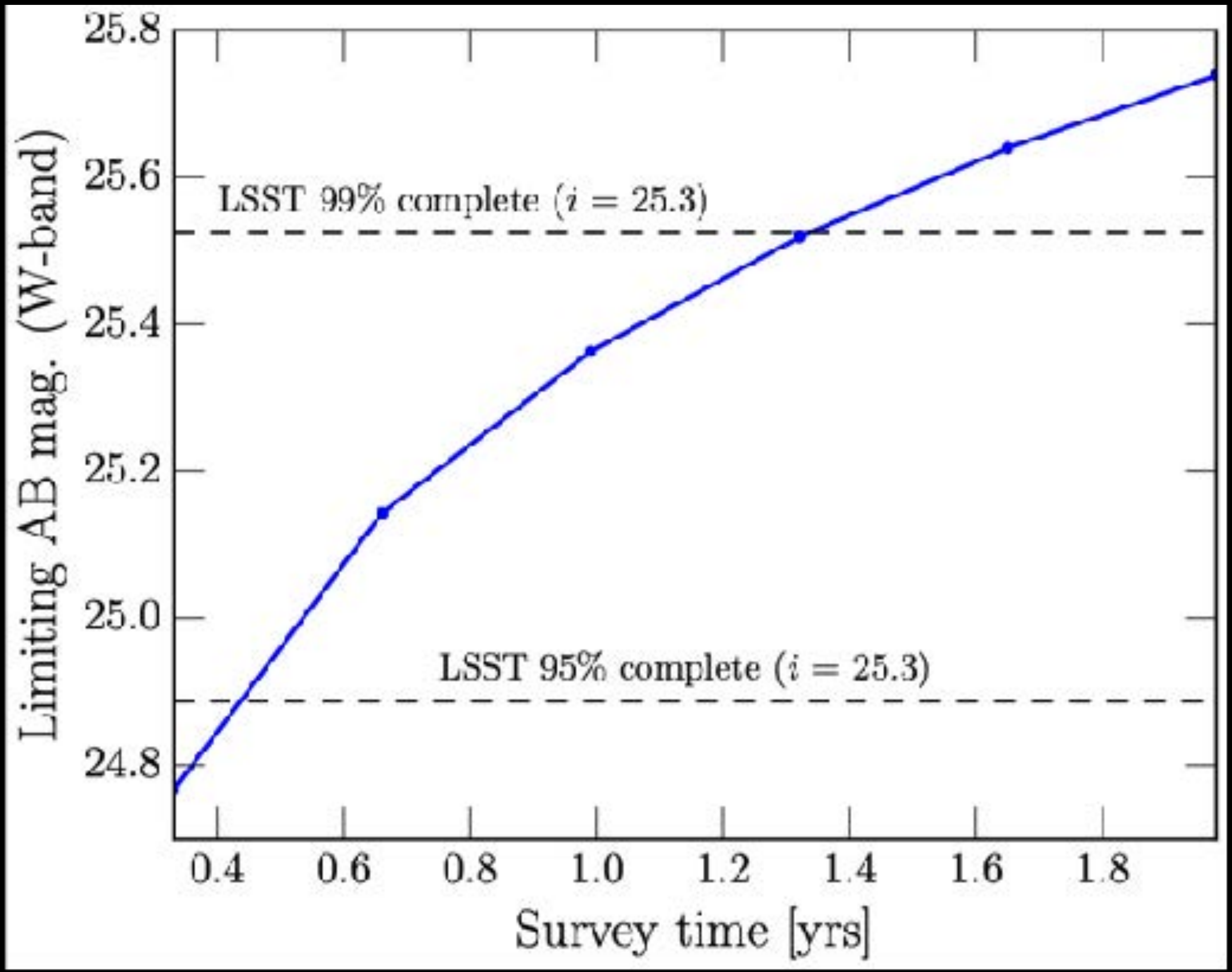






(Hypothetical) Roman Wide Survey: W-band, 18000 deg^2

2004.04702, based on exposure time calculator, Hirata+ 2012



5 months Roman-wide: **obtain space quality shape measurements for 95% of the LSST Y10 gold sample**

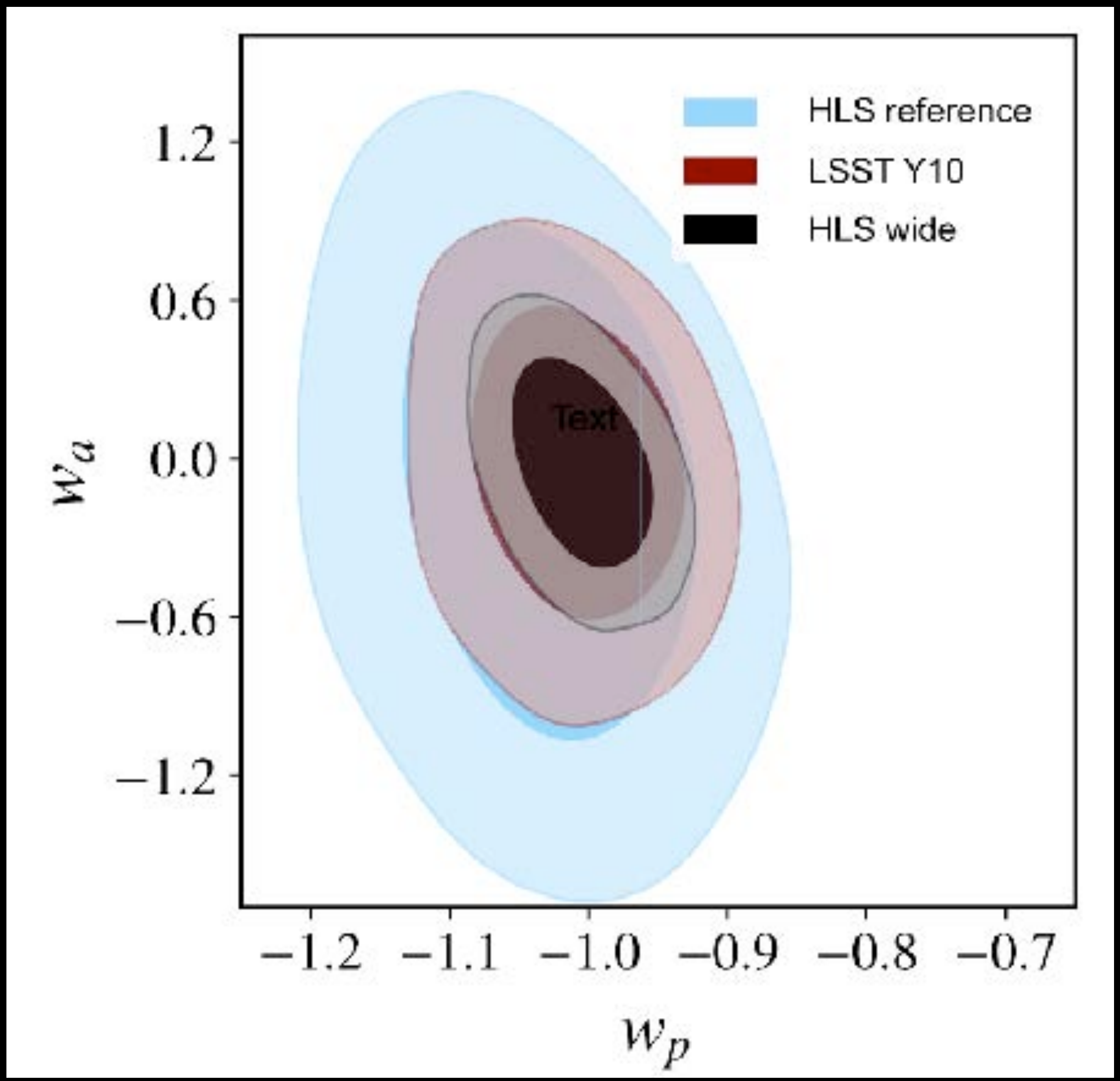
1year: same for all sky

Disclaimer: W-band only survey is more easily affected by systematics

Combine W-band survey with Rubin multi-band photometry

(Hypothetical) Roman Wide Survey: 3x2pt Roman x Rubin Forecasts

2004.04702, based on exposure time calculator, Hirata+ 2012

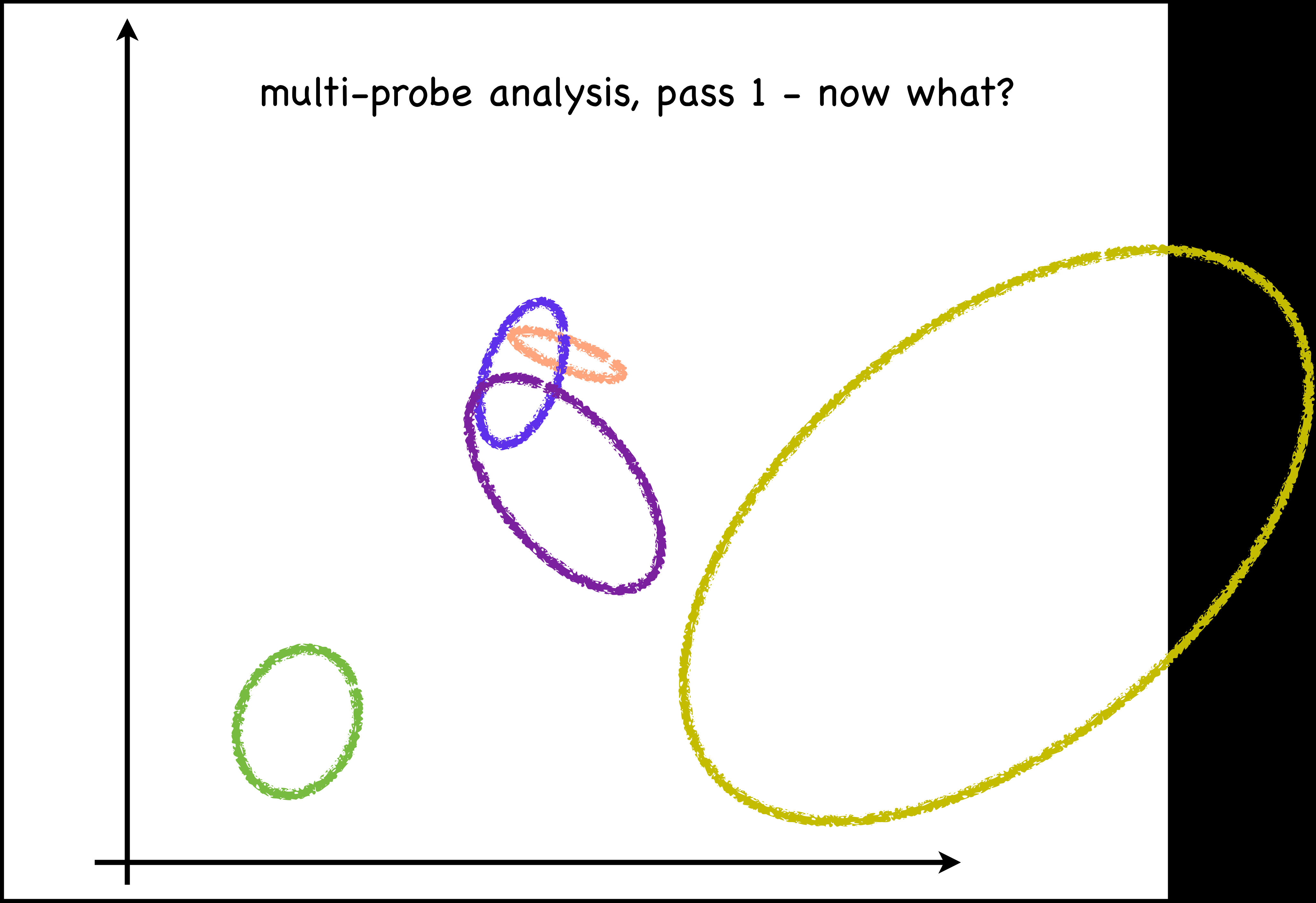


3x2pt forecast

Includes 56 dims of systematics modeling: Shear calibration, galaxy bias, photo-z, IA, baryons

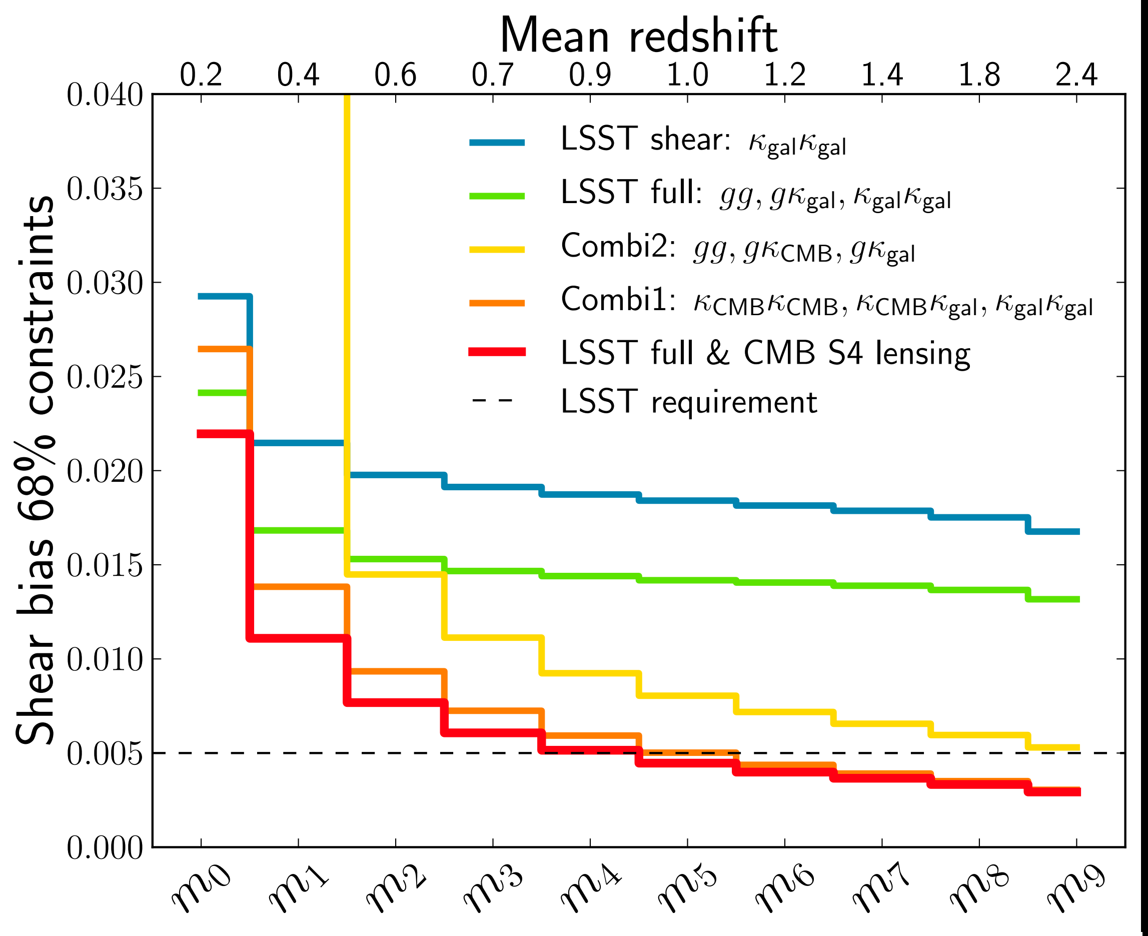
FoM (Roman wide + Rubin)=
2.4 x FoM (Rubin only)
FoM (Roman wide + Rubin) =
5.5 x FoM (Roman Reference survey)

Unknown Systematics? vs. New Physics?



Unknown Systematics? vs. New Physics?

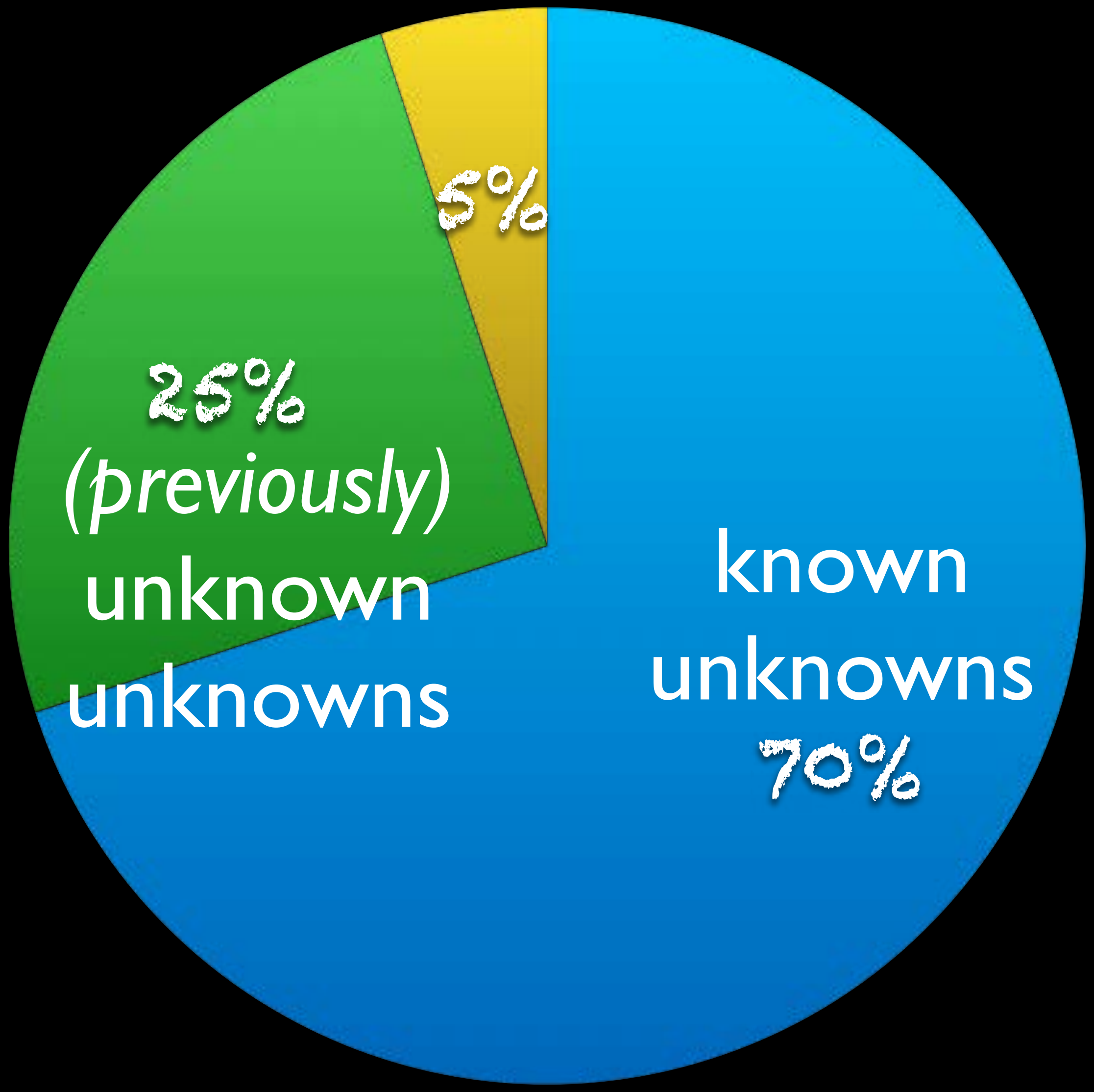
- scale dependence?
- dependence on galaxy/cluster selection?
- calibrate with more accurate measurements
  - spectroscopic redshifts
  - low-scatter cluster mass proxies
  - galaxy shapes from space-based imaging
  - [potentially expensive]
- correlate with other surveys
  - compare to predicted cross-correlations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