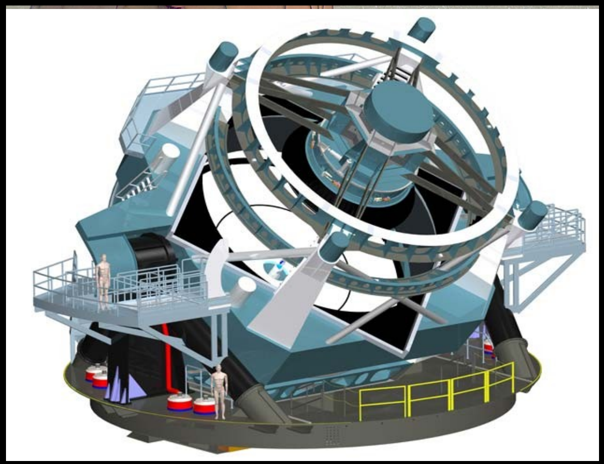
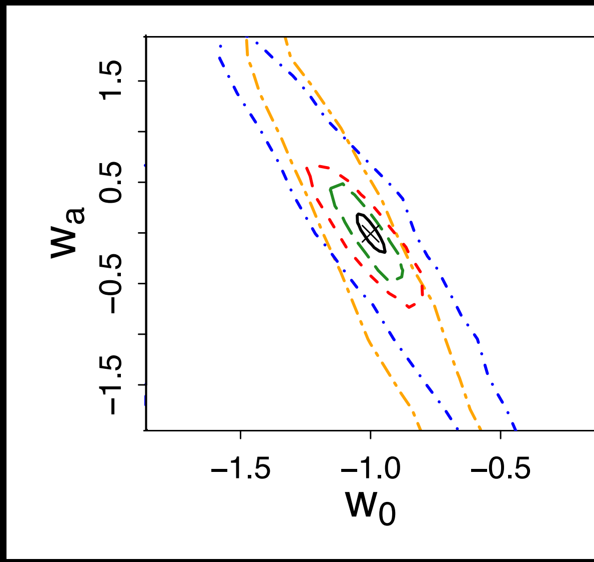




Cosmology in 2021: Concordances and Tensions

with the Dark Energy Survey Collaboration

Elisabeth Krause
Steward Observatory/University of Arizona

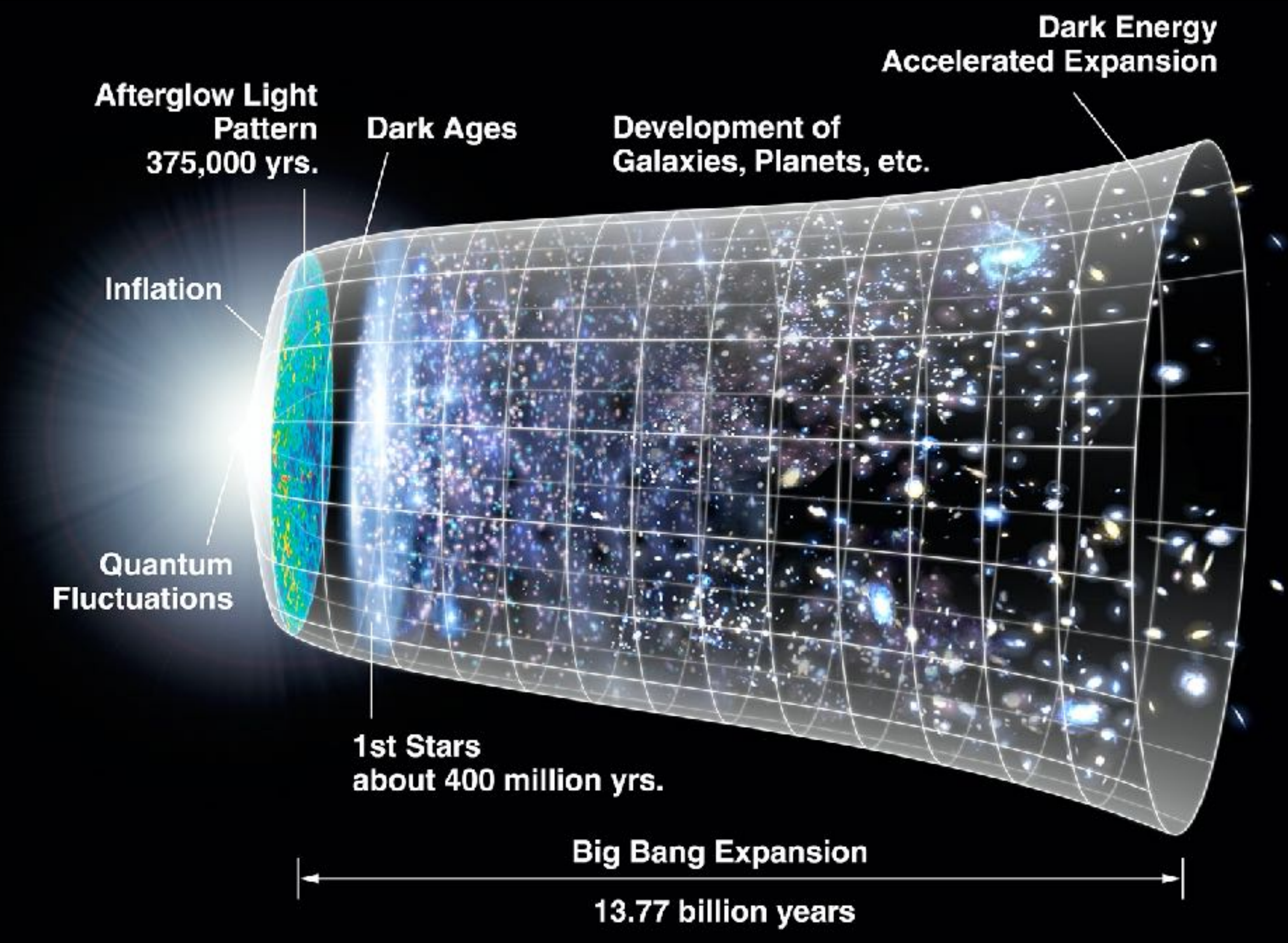
Pheno '21

Our Simple Universe

On *large scales*, the Universe can be modeled with remarkably few parameters

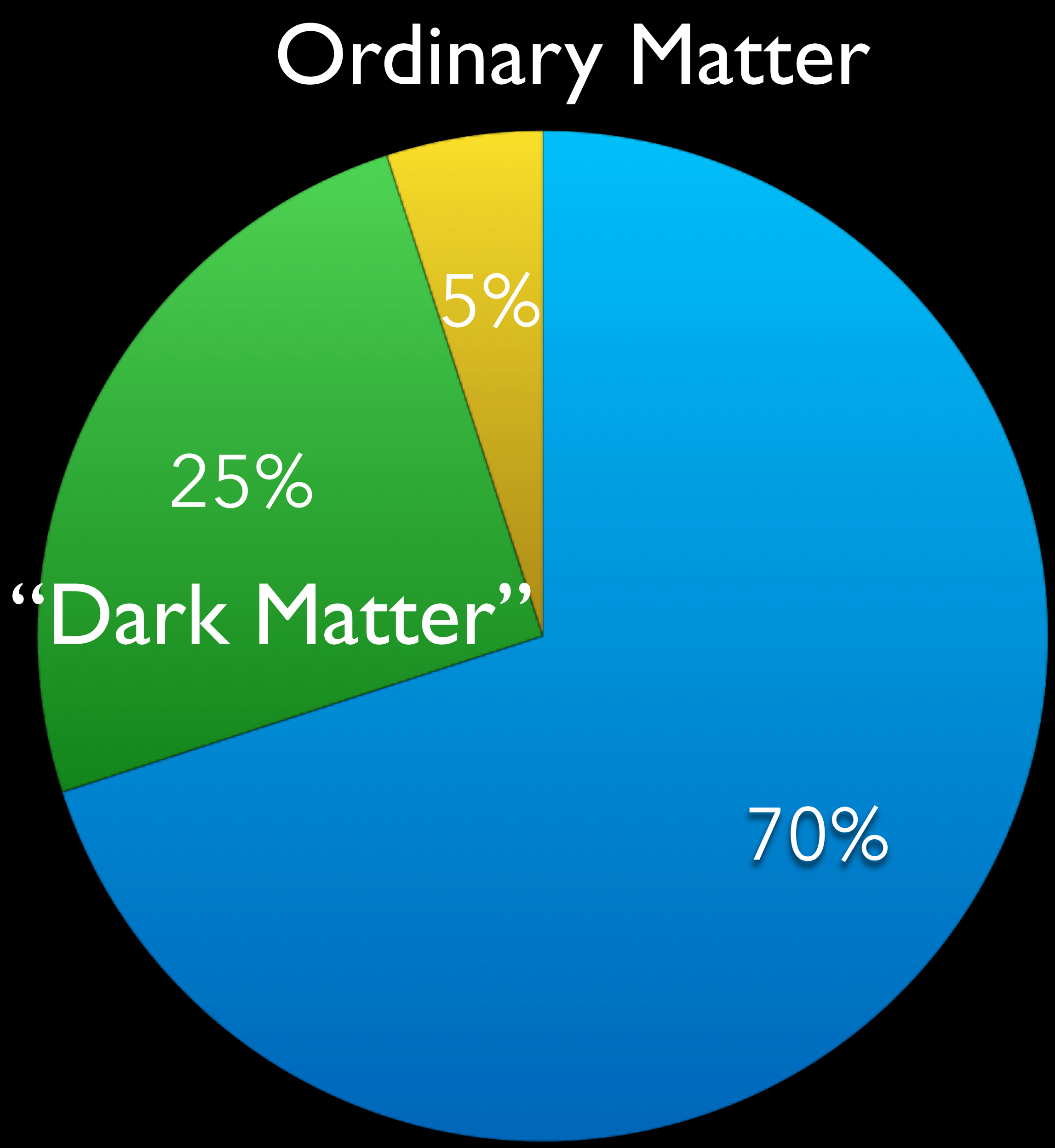
- age of the Universe
- geometry of space
- density of atoms
- density of matter
- amplitude of fluctuations
- scale dependence of fluctuations

[of course, details are not quite as simple]



credit: NASA/WMAP

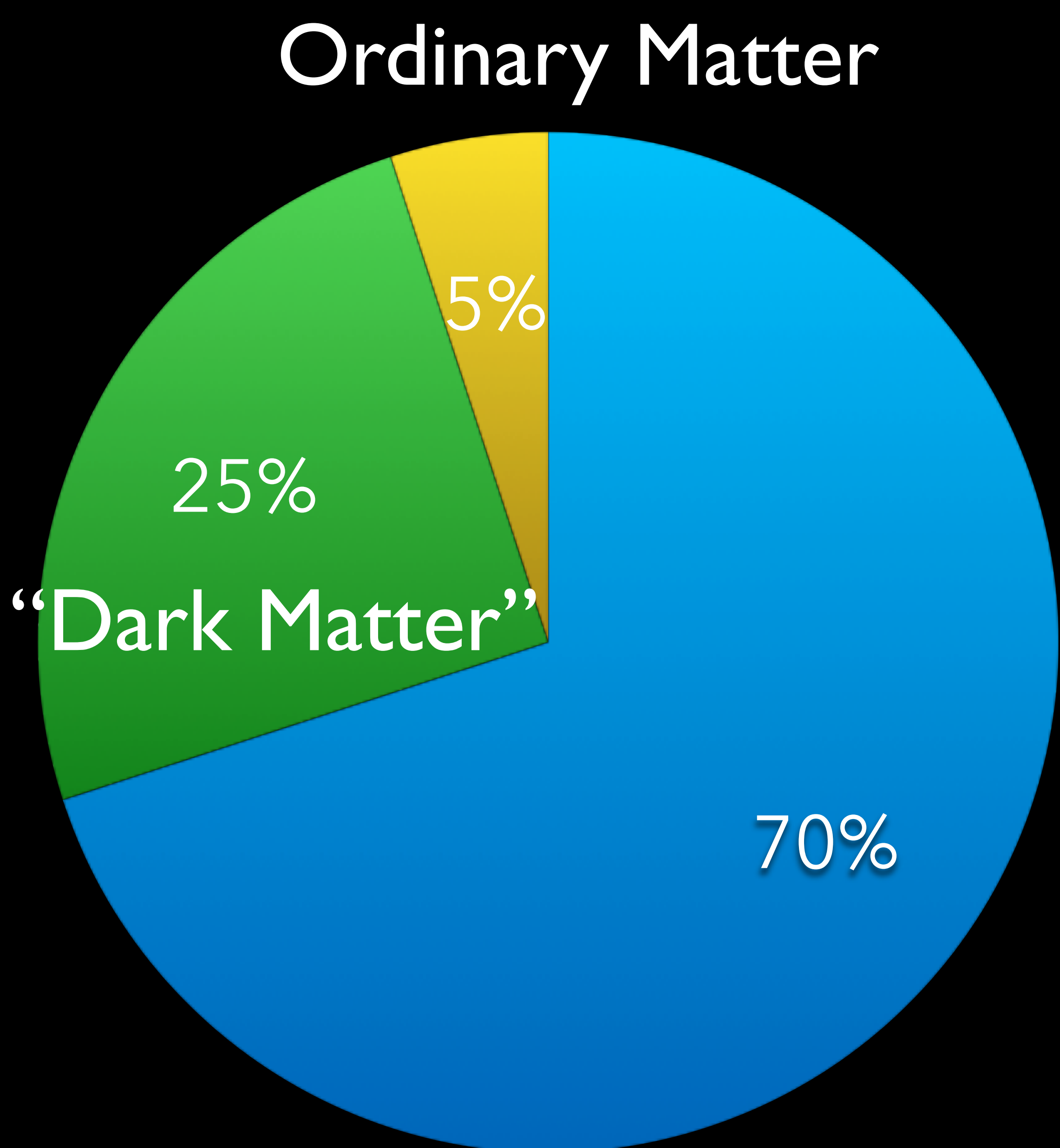
Vanilla Cosmology



"Dark Energy"

- accelerates the expansion
- dominates the total energy density
- acceleration first measured by SN 1998

Vanilla Cosmology



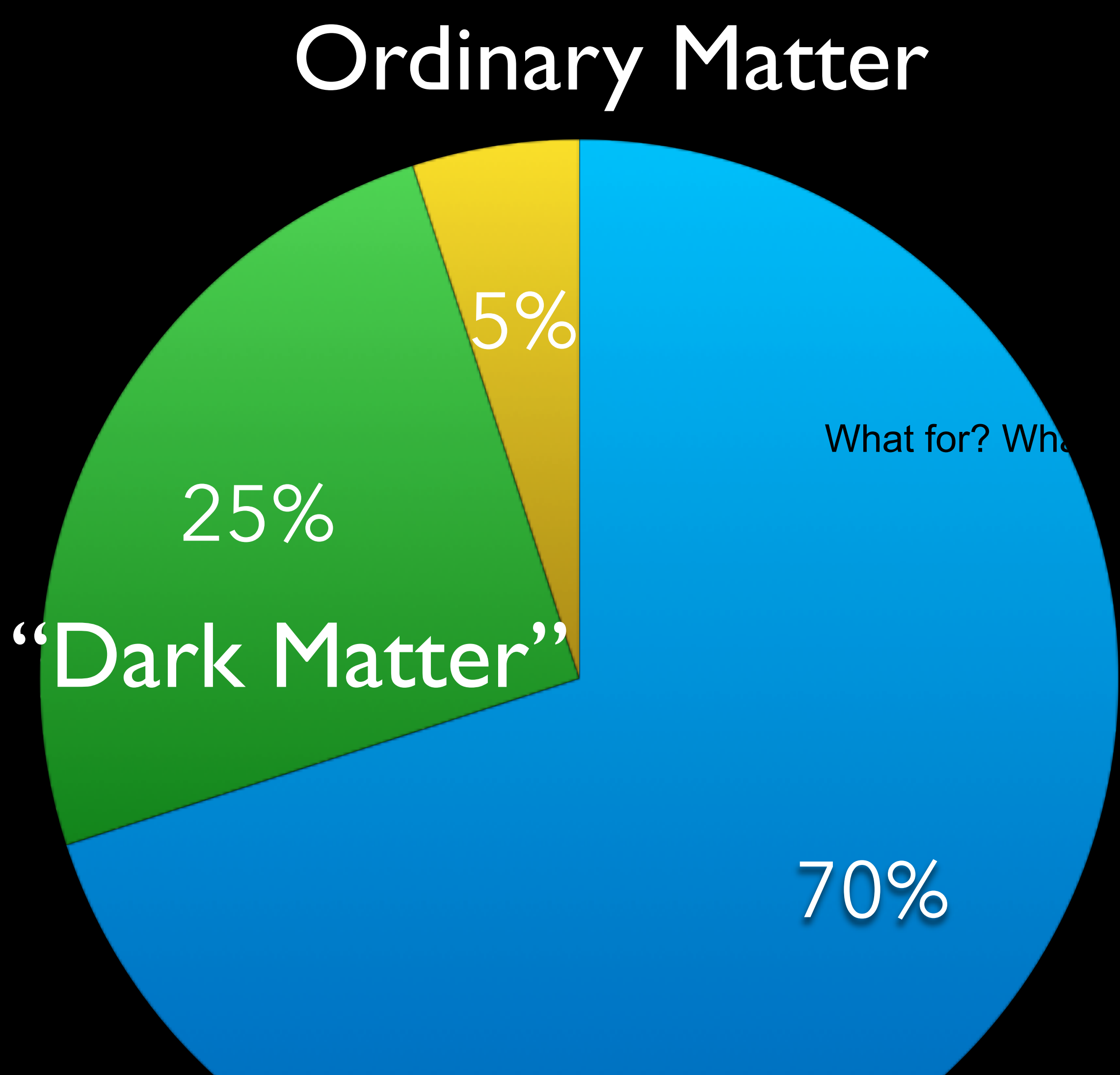
“Dark Energy”

- accelerates the expansion
- dominates the total energy density
- acceleration first measured by SN 1998

next frontier: understand

- cosmological constant Λ: $w \equiv P/\rho = -1$?
  - size of Λ difficult to explain
- dynamic scalar field, $w(a)$?
- breakdown of GR?

Vanilla Cosmology



"Dark Energy"

- accelerates the expansion
- dominates the total energy density
- acceleration first measured by SN 1998

next frontier: understand

- cosmological constant Λ: $w \equiv P/\varrho = -1$?
  - size of Λ difficult to explain
- dynamic scalar field, w(a)?
- breakdown of GR?

Are data from **early Universe** and **late Universe** fit by the same parameters?	Do measurements of **expansion history** and **growth of structure** agree?	**Does the dark energy equation of state change as space expands?**

Measurements of Expansion History

comparison of distance and redshift

Standard candle: brightness of source with know luminosity

Standard ruler: angle subtended by known scale

Measurements of Expansion History

comparison of distance and redshift

Standard candle: brightness of source with know luminosity

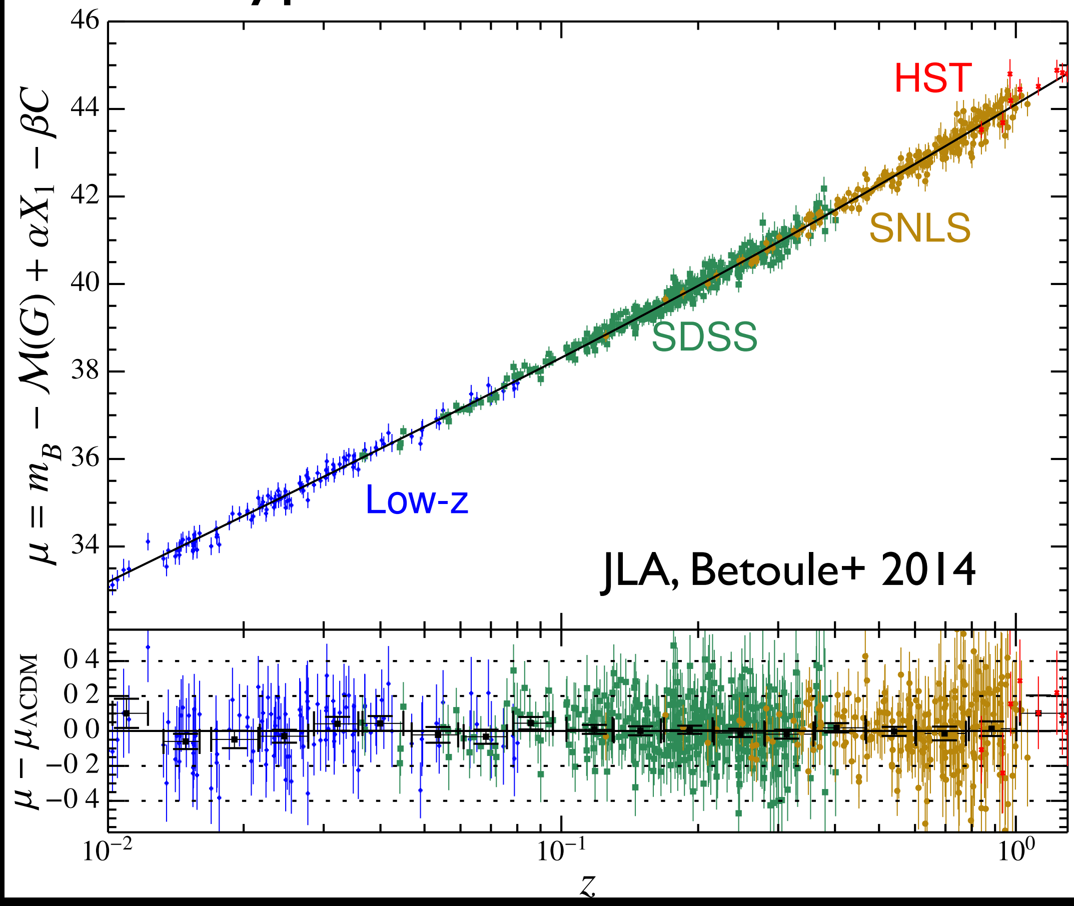
- SNe: luminosity can be determined from duration/color

Standard ruler: angle subtended by known scale

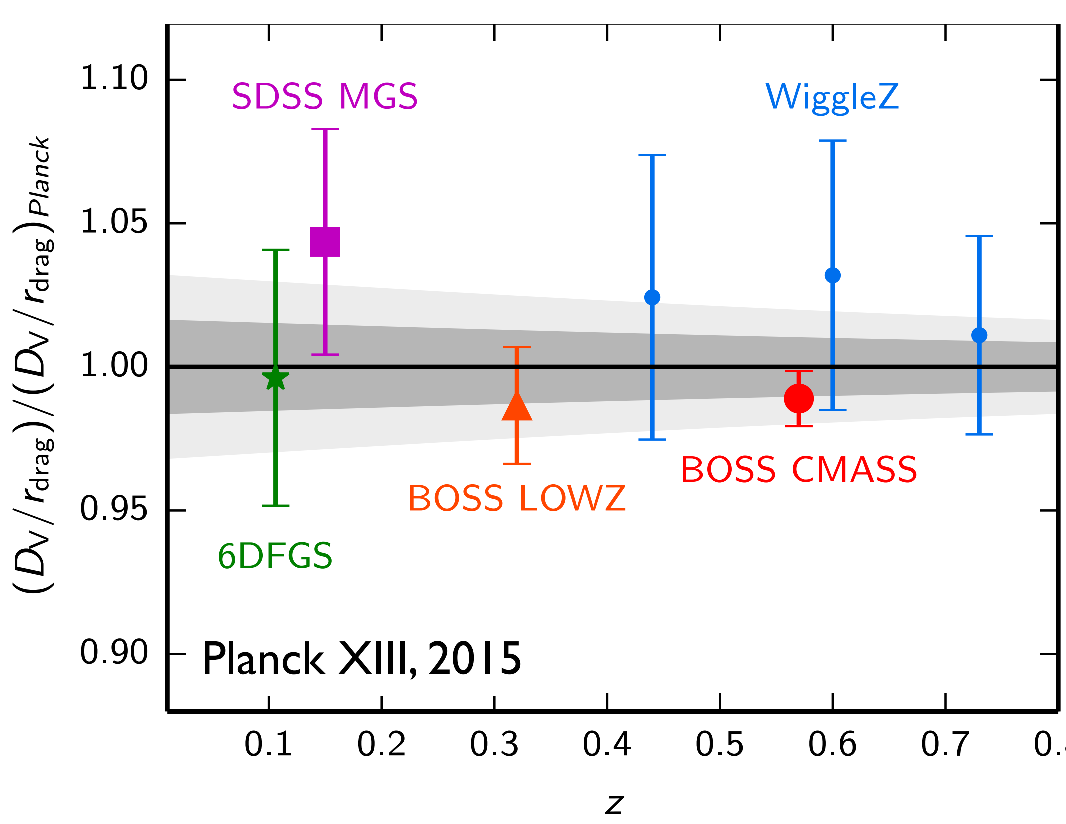
- CMB: sound horizon in early Universe (380,000 years)
- BAO: same scale, but evolved for billions of years

These measurements are consistent with the CMB in LCDM, tightly constrain flatness, matter density

Type IA SN state of the art



BAO state of the art



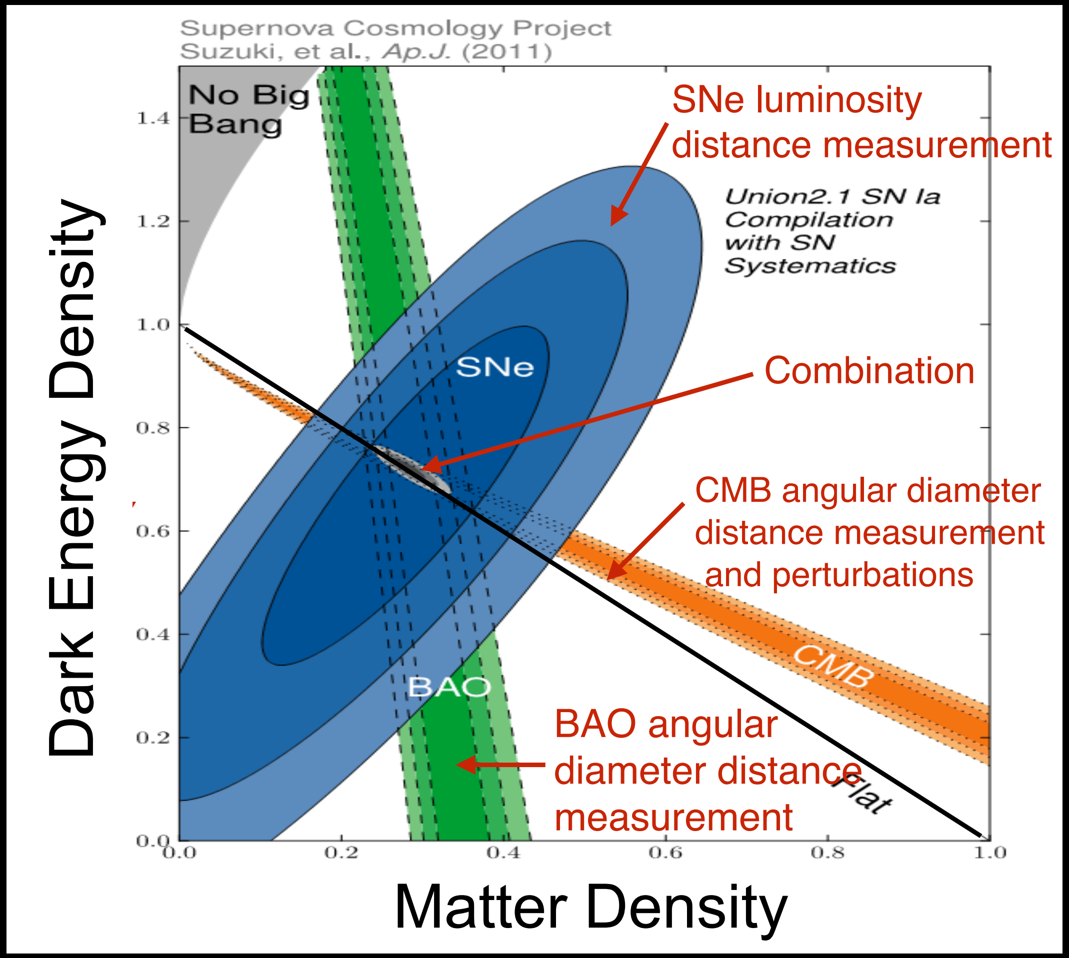
Early 2000s: Concordance Cosmology

Expansion History Measurements:

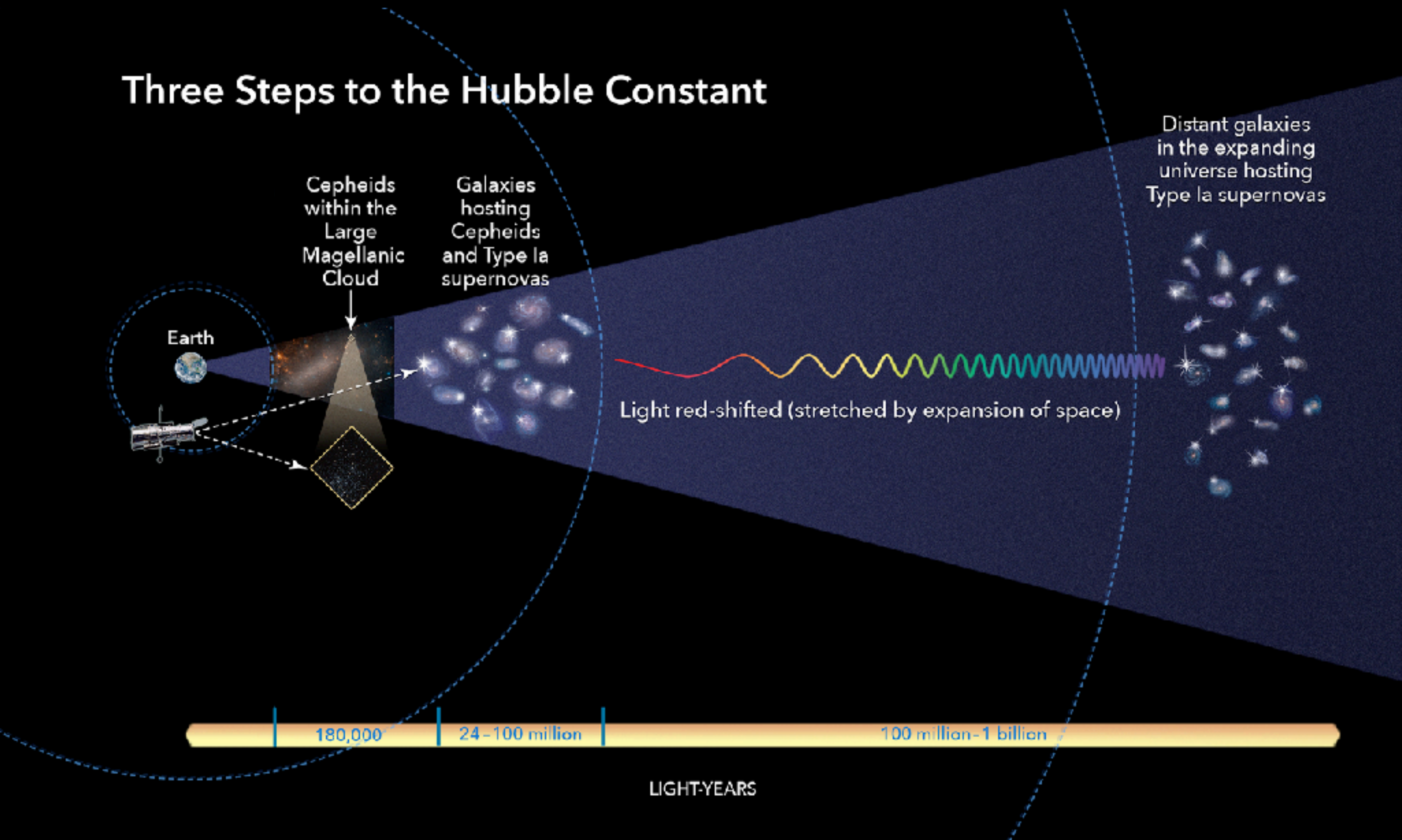
- Cosmic Microwave Background (CMB) angular scale of sound horizon in the early Universe

- Baryonic Acoustic Oscillations (BAO) angular scale of sound horizon imprinted in late-time galaxy distribution

- Supernovae (SNe) apparent brightness of exploding white dwarfs with ~known intrinsic luminosity

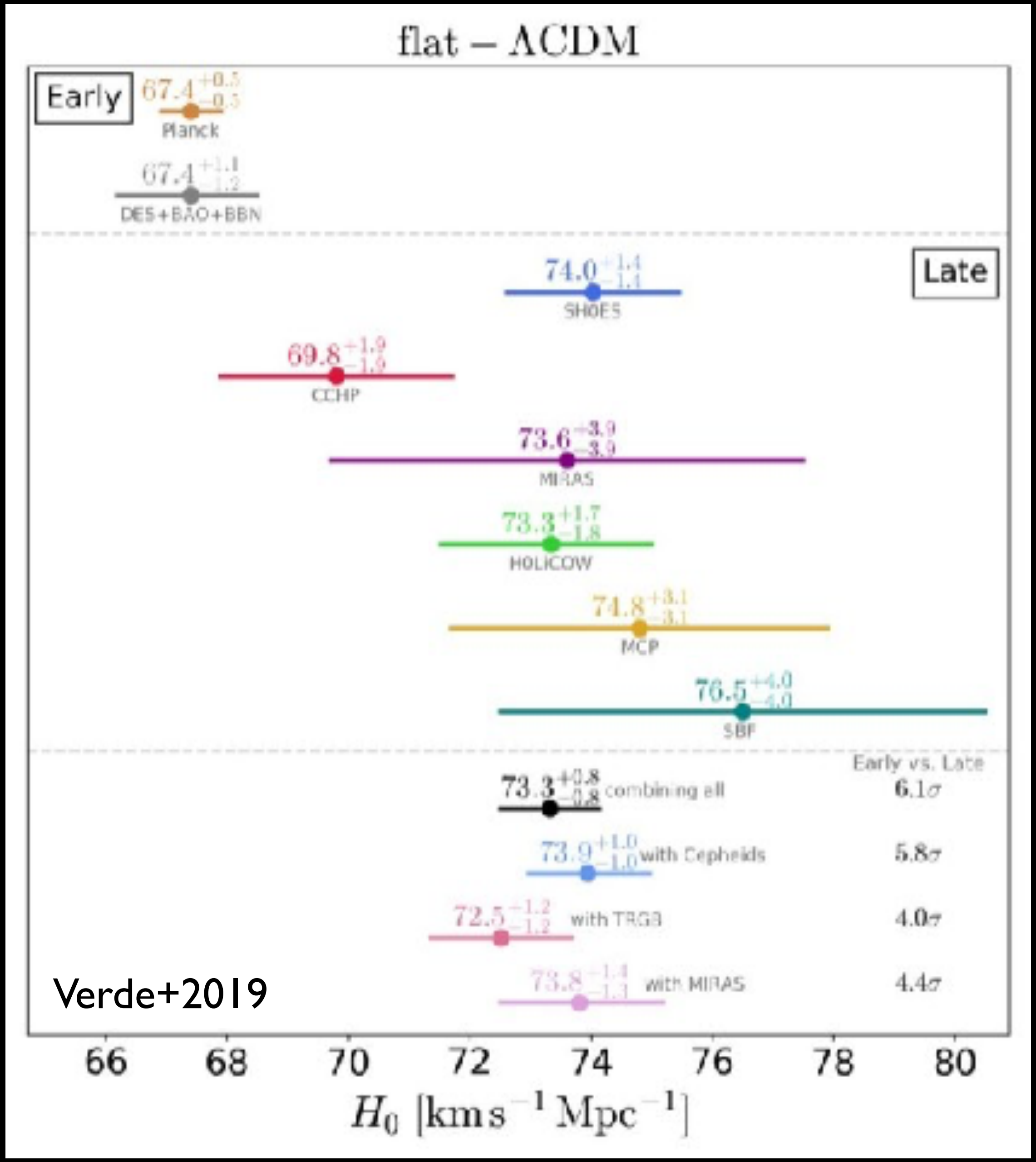


The Distance Ladder



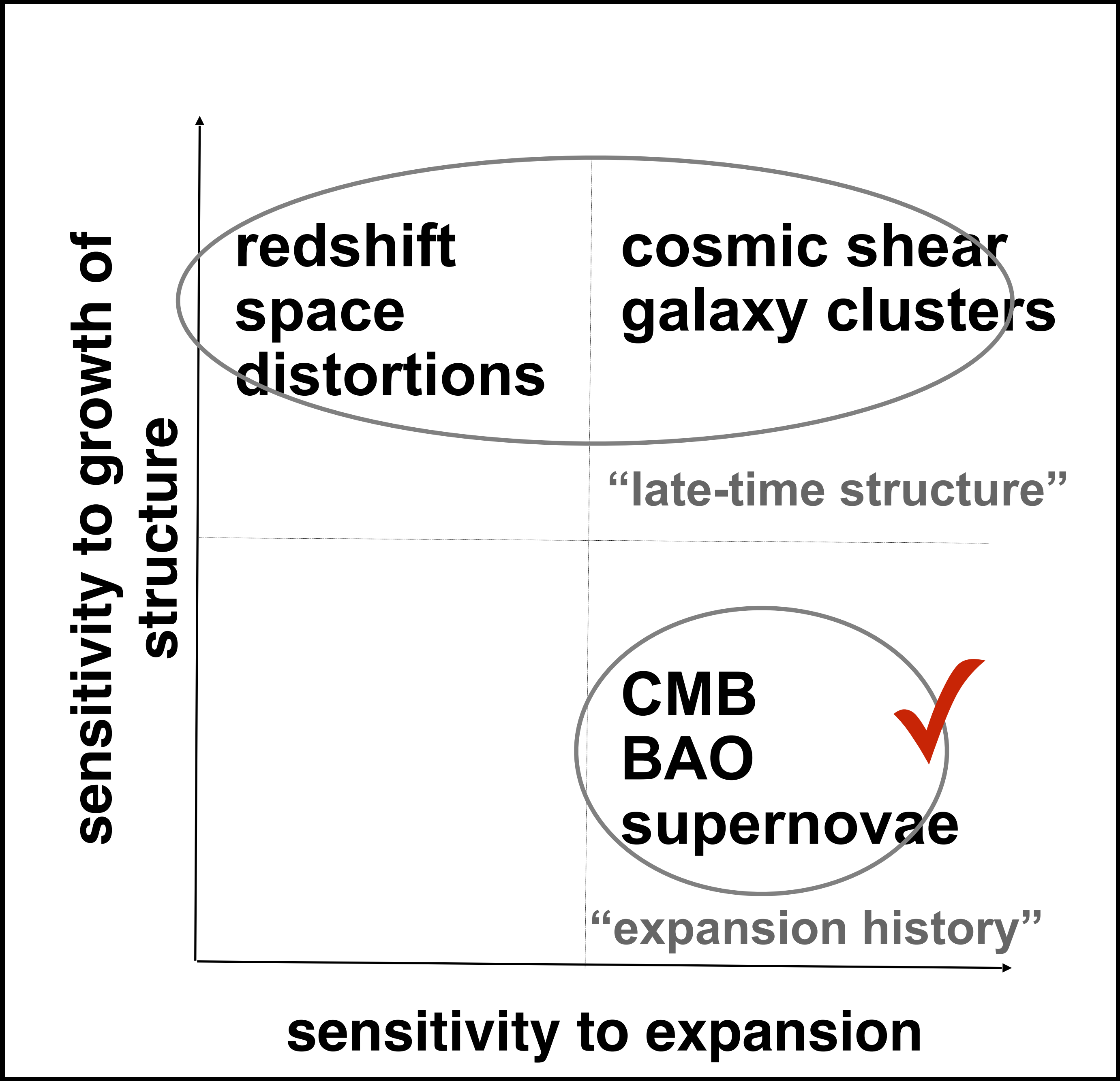
2020s: Concordance Cosmology?

Hubble Parameter - expansion rate



significant tension between early and late Universe physics!

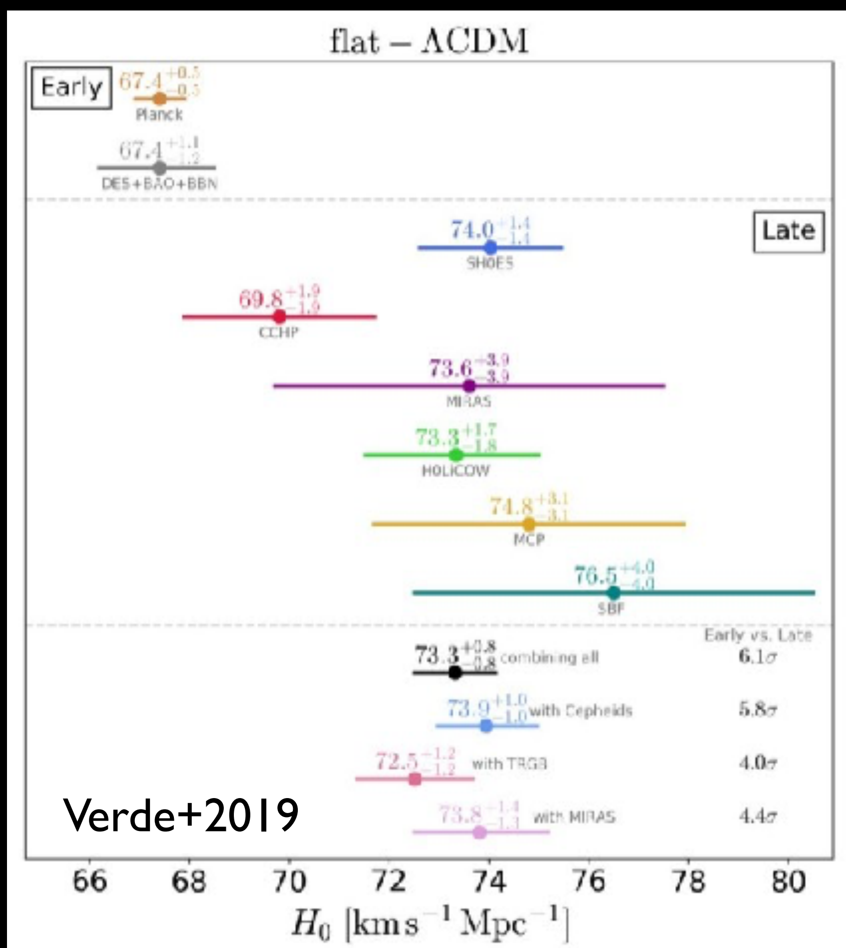
2020s: Concordance Cosmology?



Q: Do all these measurements agree with predictions in the same, fiducial ΛCDM model?

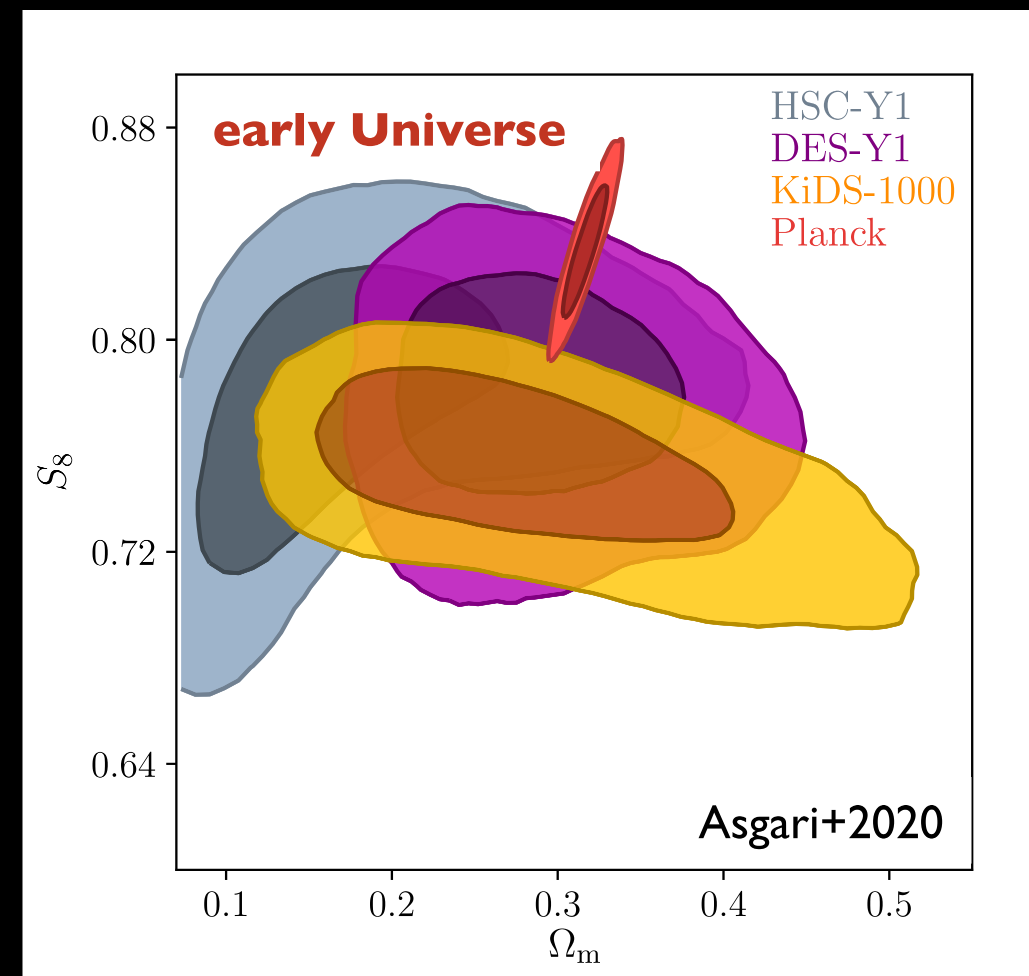
2020s: Concordance Cosmology?

Hubble Parameter - expansion rate



significant tension between
early and late Universe physics!

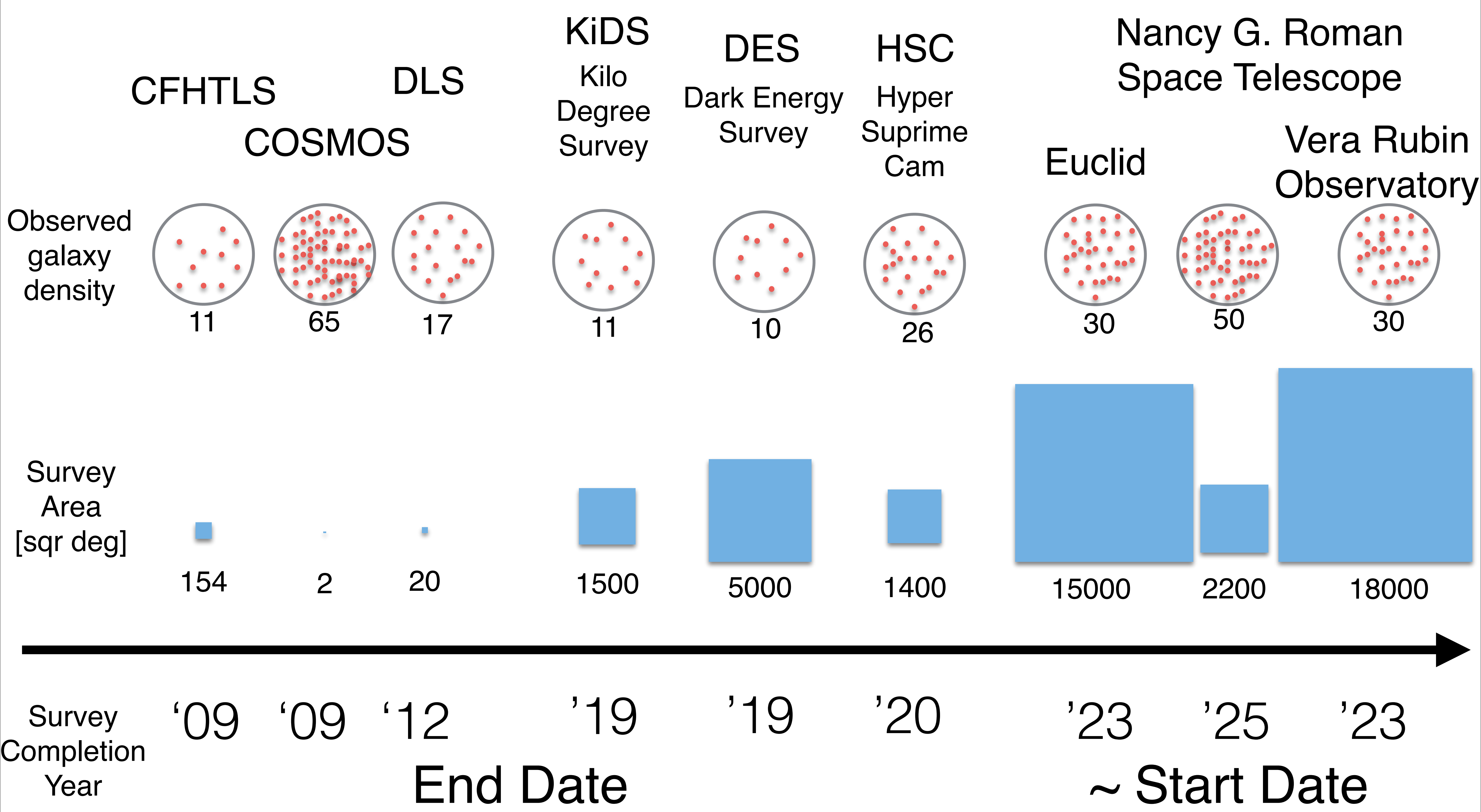
S8 - amplitude of structure growth



hints at possible tension between
early and late Universe physics?

→ **let's shrink these error bars**

Photometric LSS Surveys



Cosmic Structure Formation

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

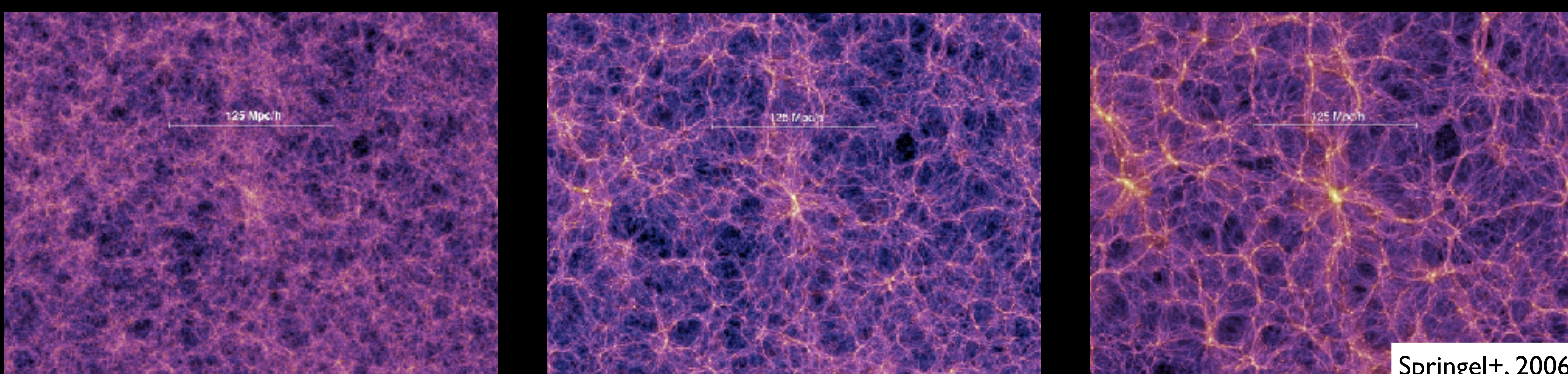
growth of structure constraints complementary to expansion rate

~linear (large) scales: perturbation theory

non-linear evolution: numerical simulations

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

time →



Springel+, 2006

Cosmic Structure Formation

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

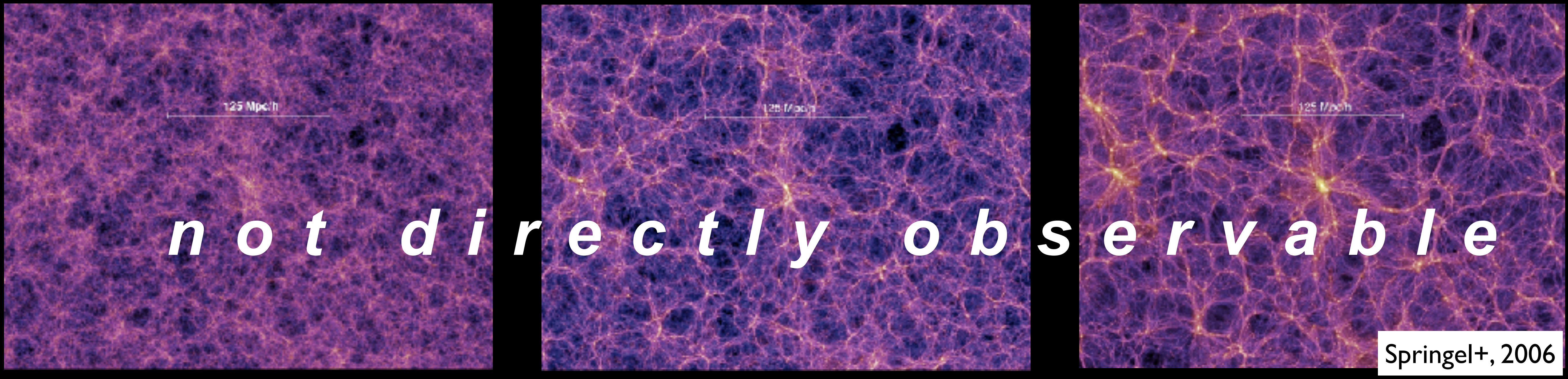
growth of structure constraints complementary to expansion rate

~linear (large) scales: perturbation theory

non-linear evolution: numerical simulations

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

time



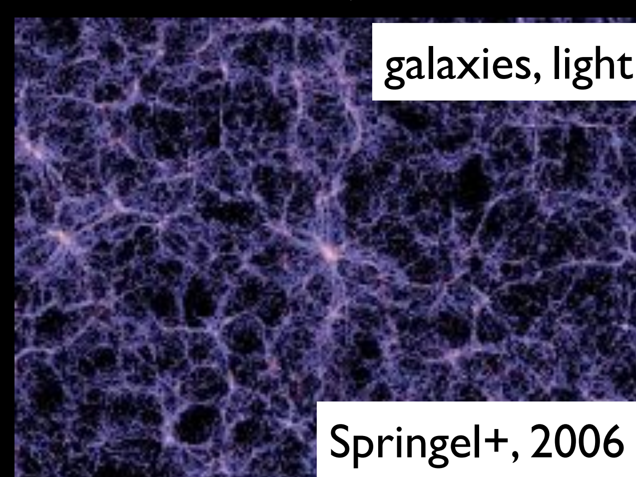
Springel+, 2006

Connecting Theory and Observations

cosmological model
+ parameters

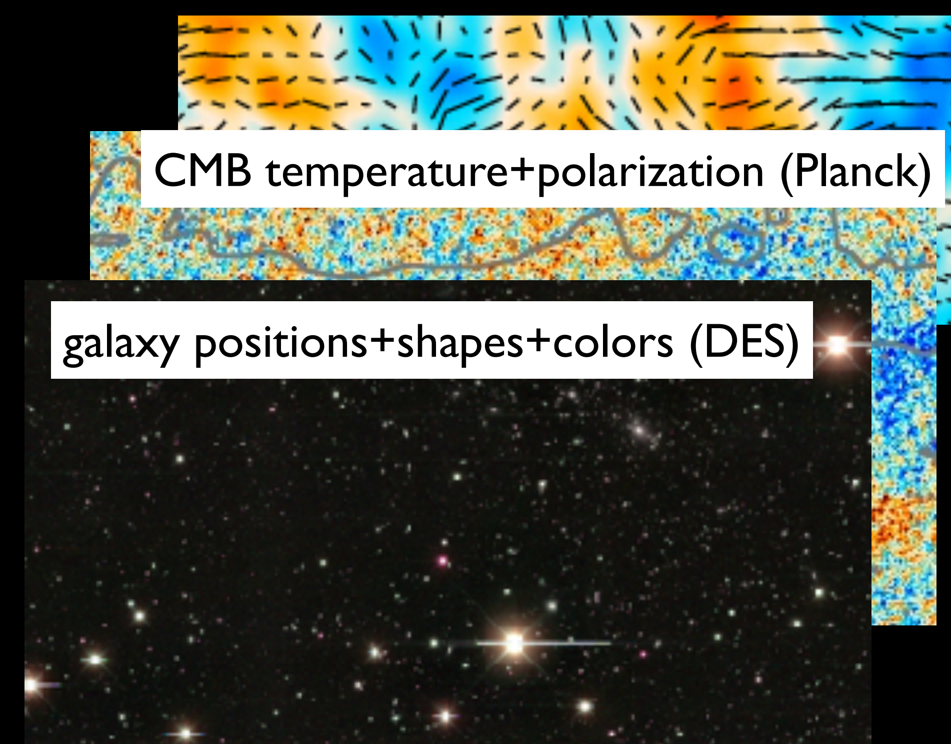
simulation/
perturbation theory

astrophysics (?)

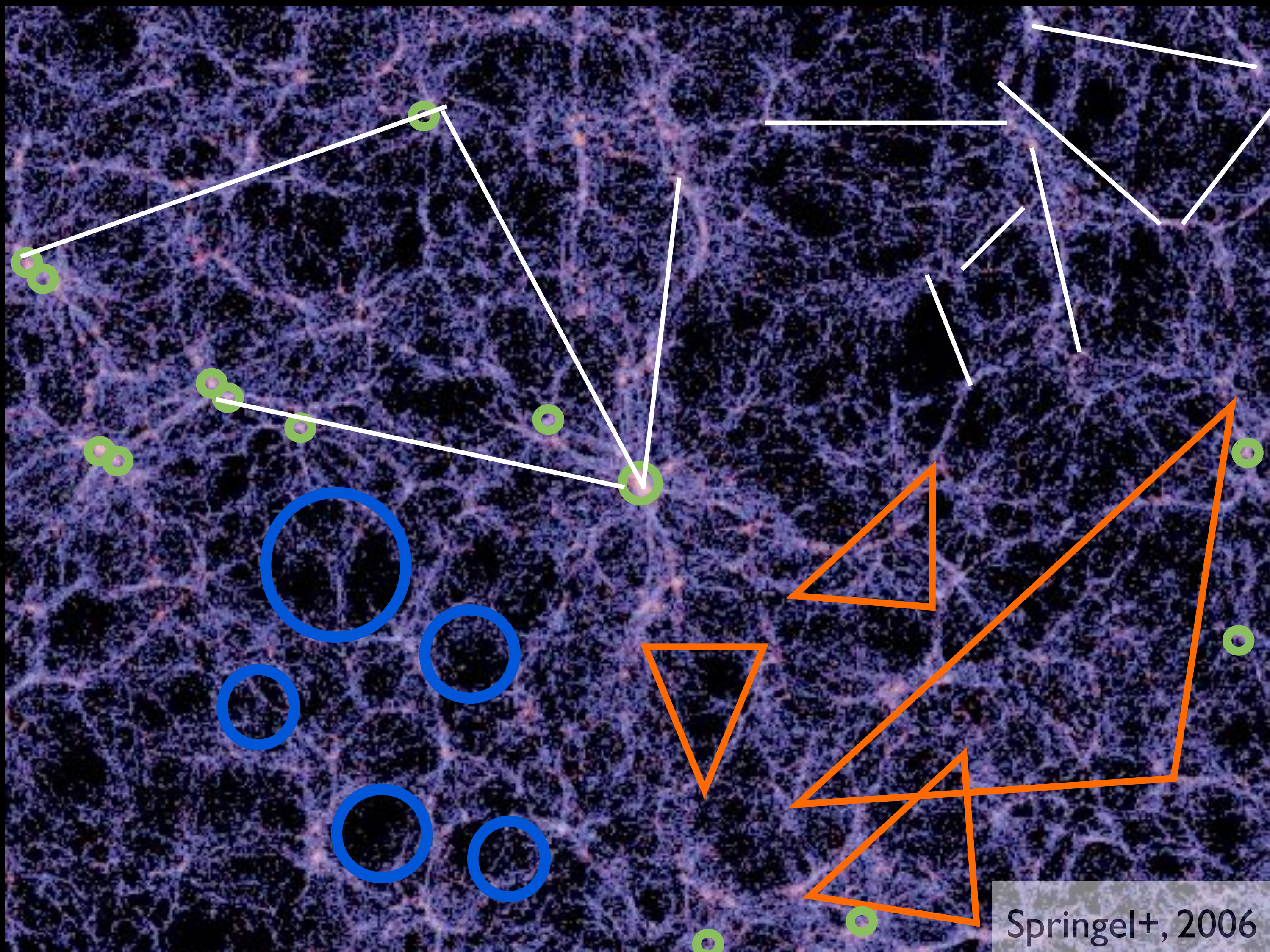


?

(+ other tracers of
structure formation)

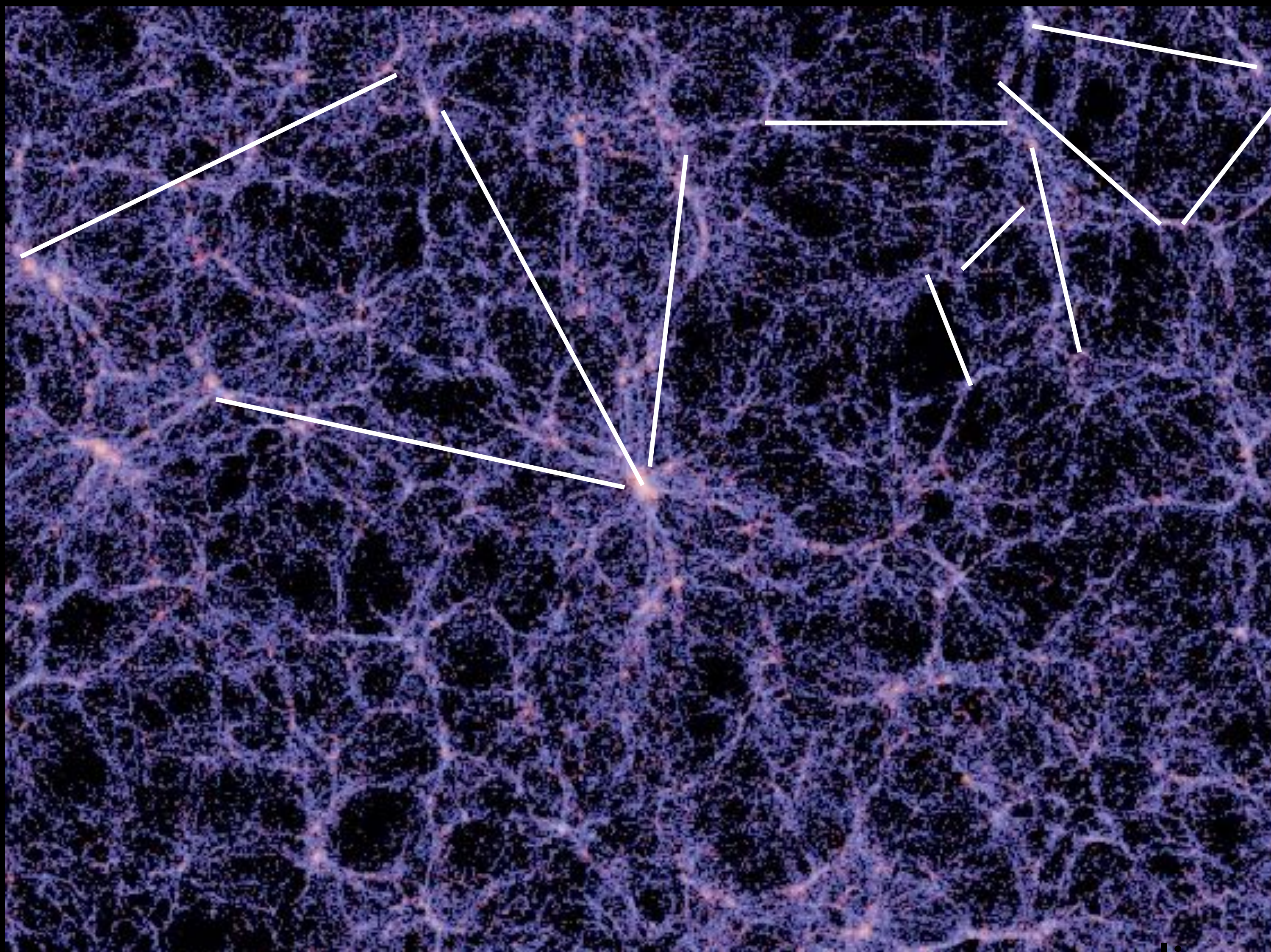


Summary Statistics from the Galaxy Distribution



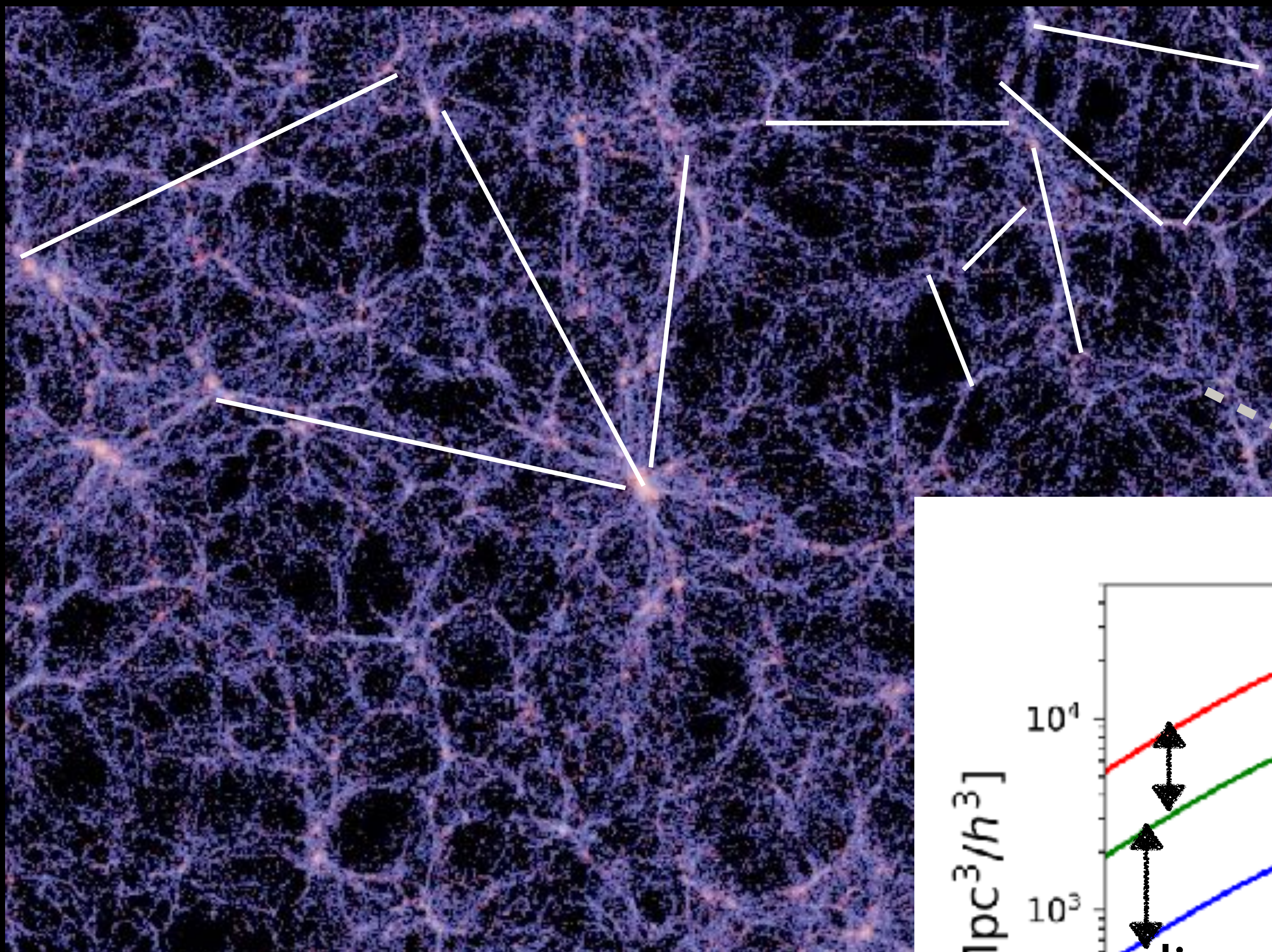
two-point correlations
clusters (over densities)
voids (under densities)
three-point correlations,...

Tracer: Galaxy Clustering



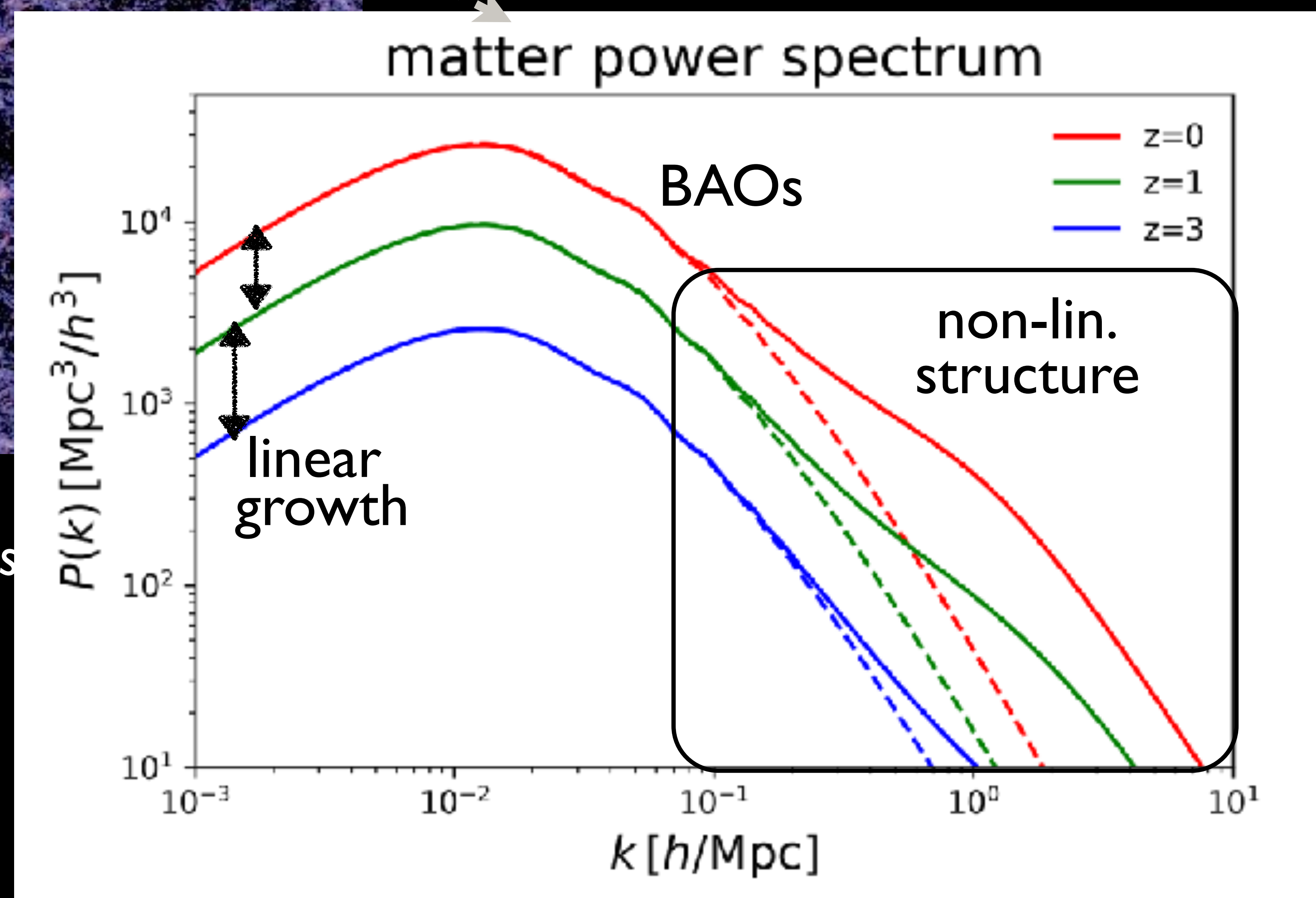
two-point correlations
excess probability of galaxy pairs
(over random distr.)
as function of separation

Tracer: Galaxy Clustering



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

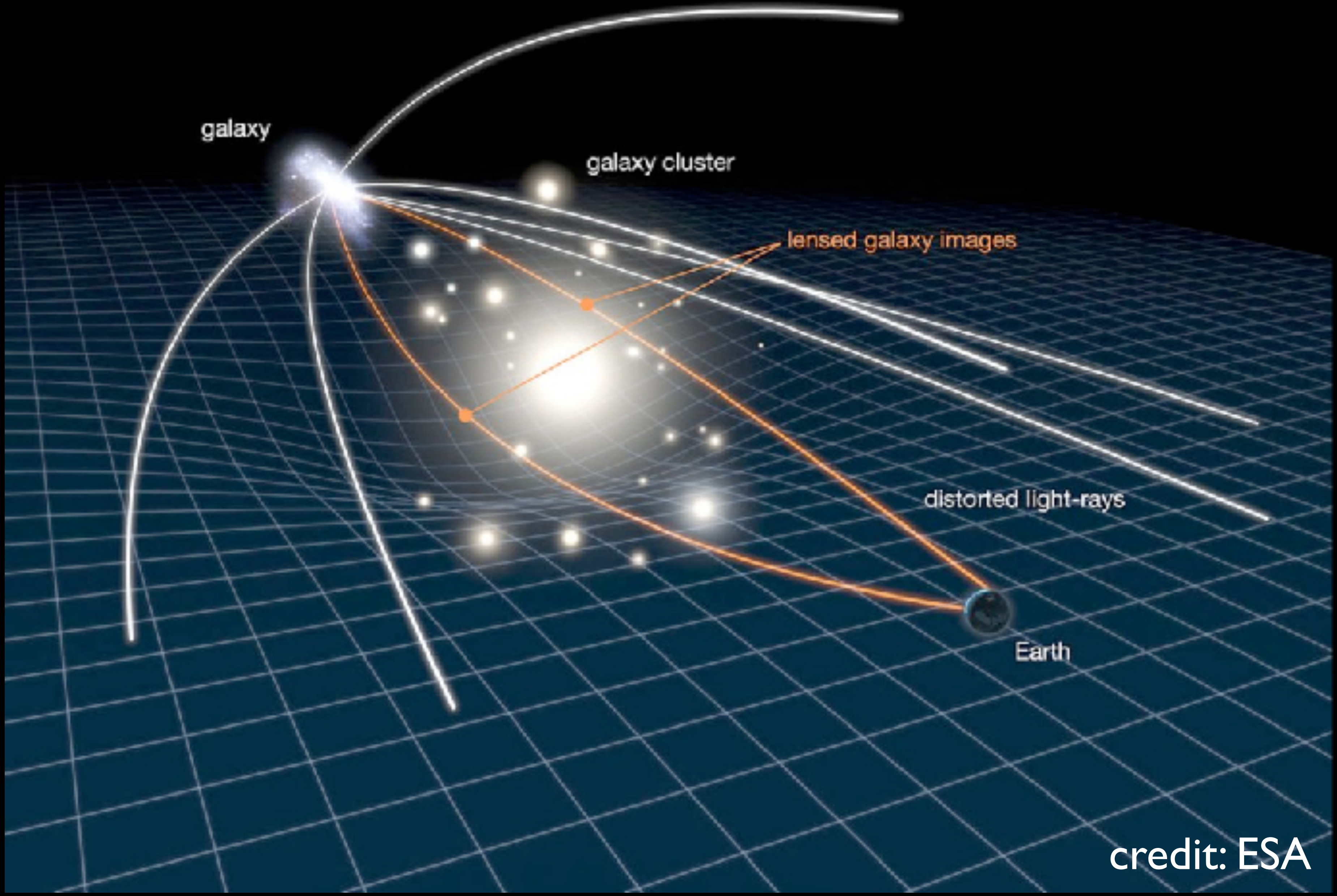
Fourier transform



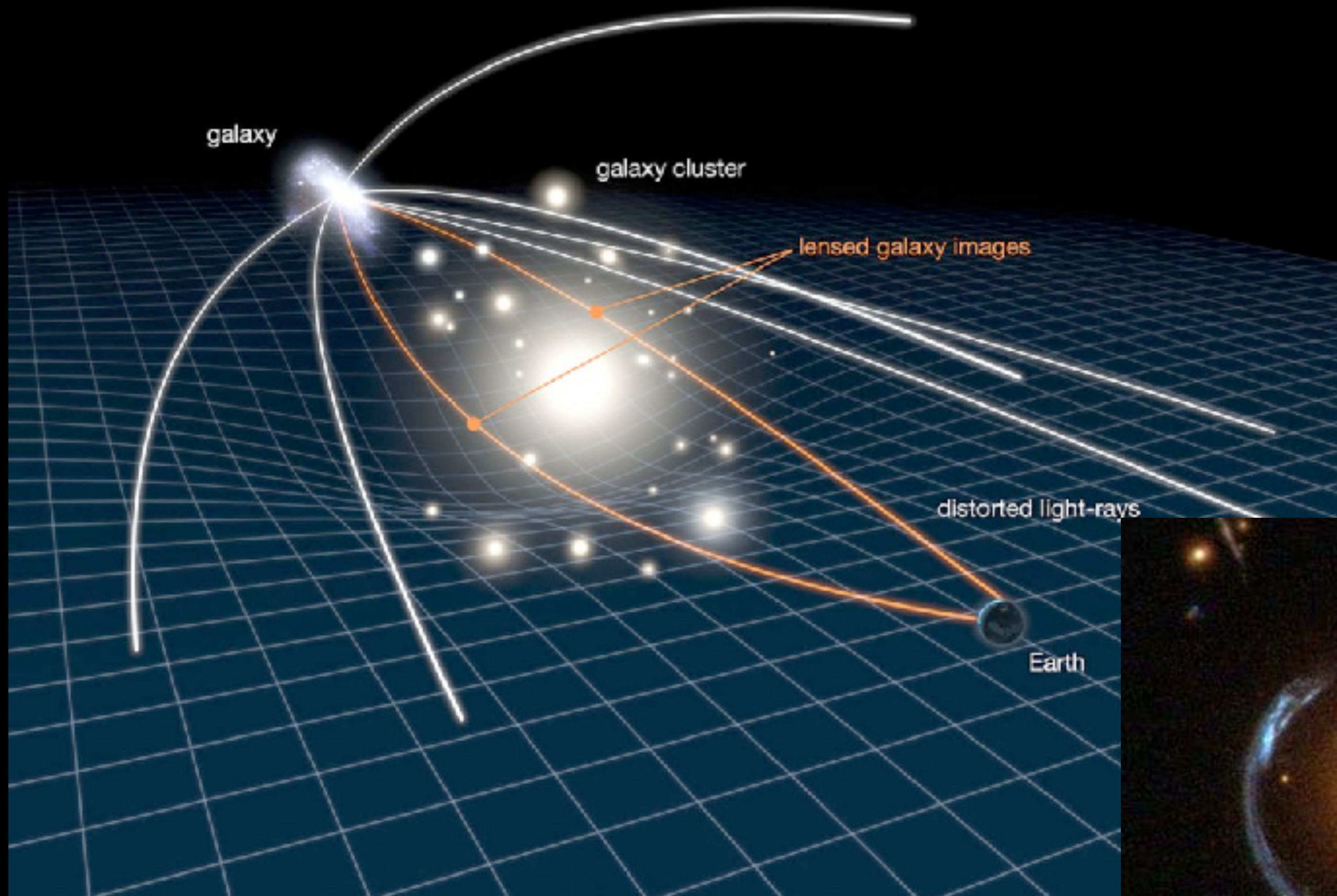
— two-point correlations

excess probability of galaxy pairs
(over random distr.)
as function of separation

Tracer: Gravitational Lensing



Tracer: Gravitational Lensing



credit: ESA/Hubble & NASA

Tracer: Weak Gravitational Lensing of Galaxies

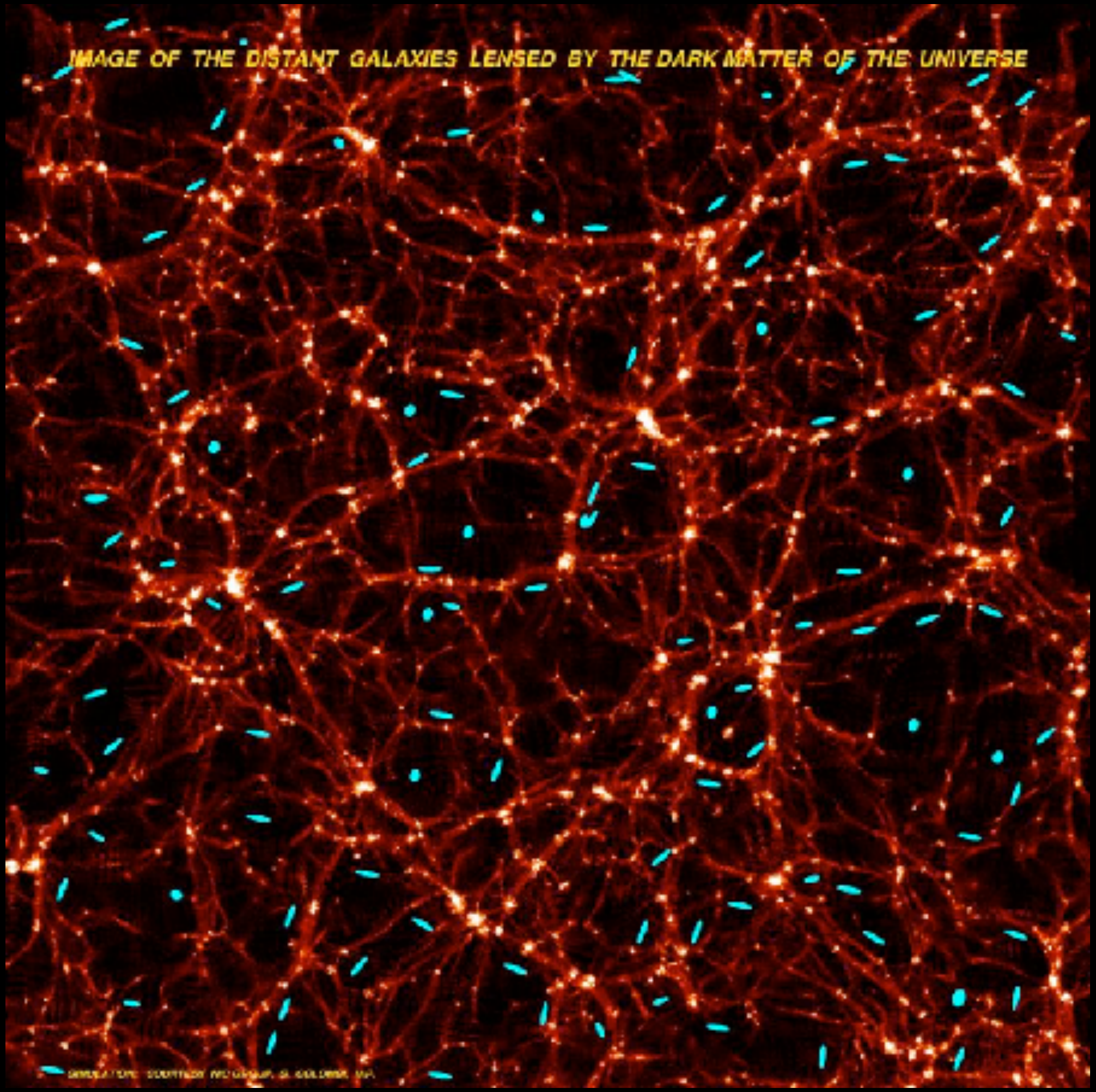
light deflected by tidal field of large-scale structure

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

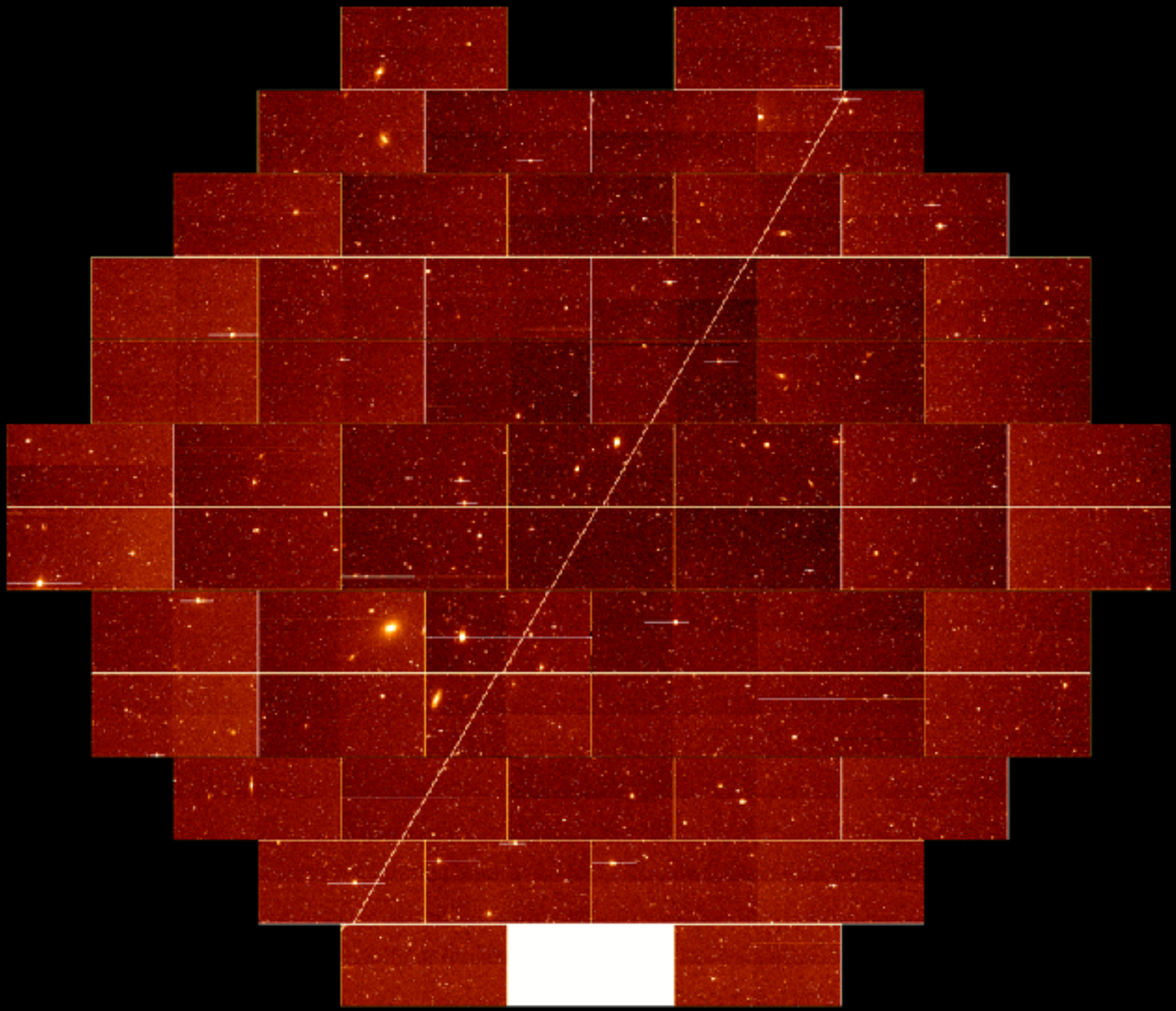
key uncertainties

shape measurements

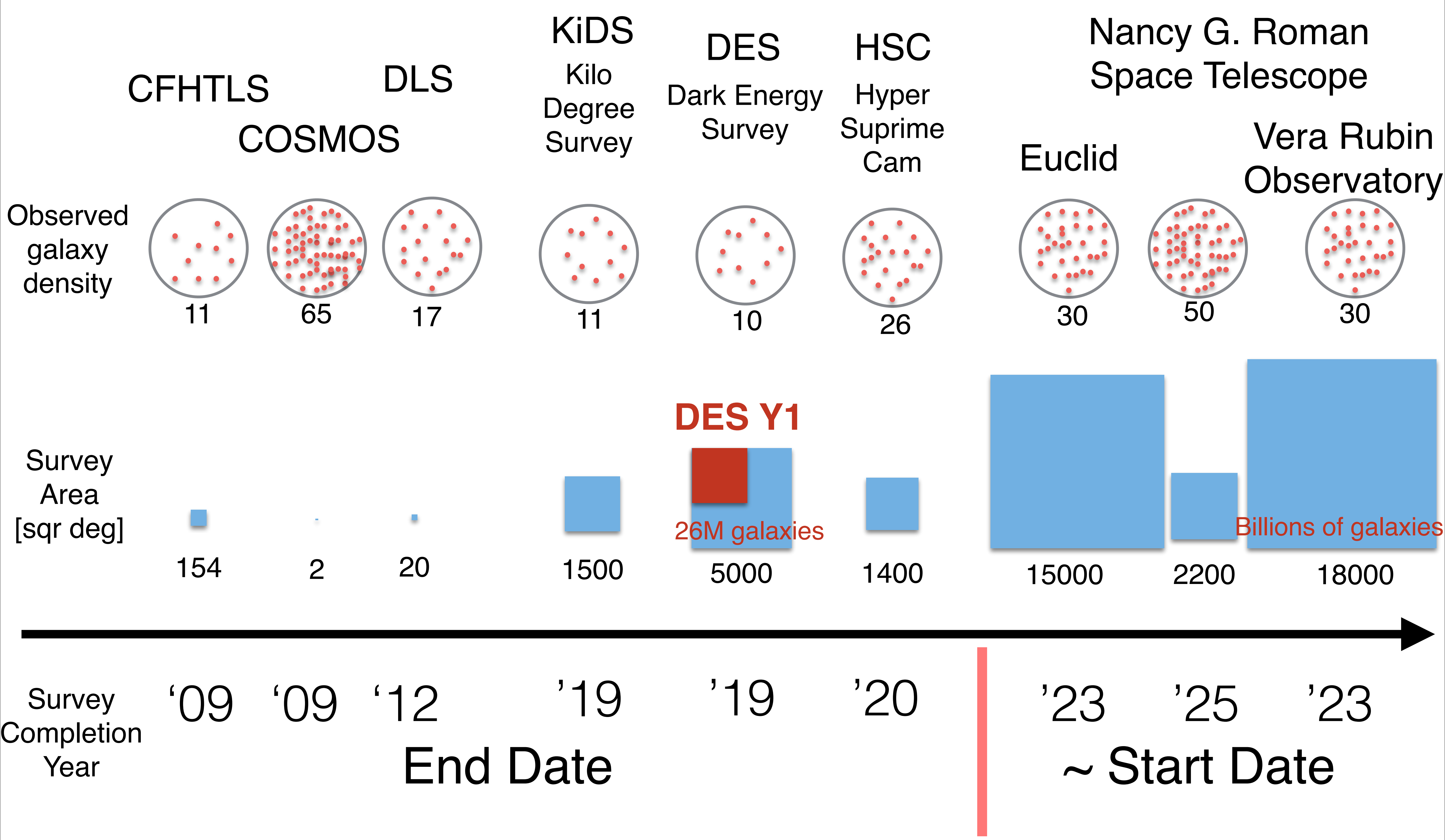
average over many galaxies assuming *random intrinsic orientation*



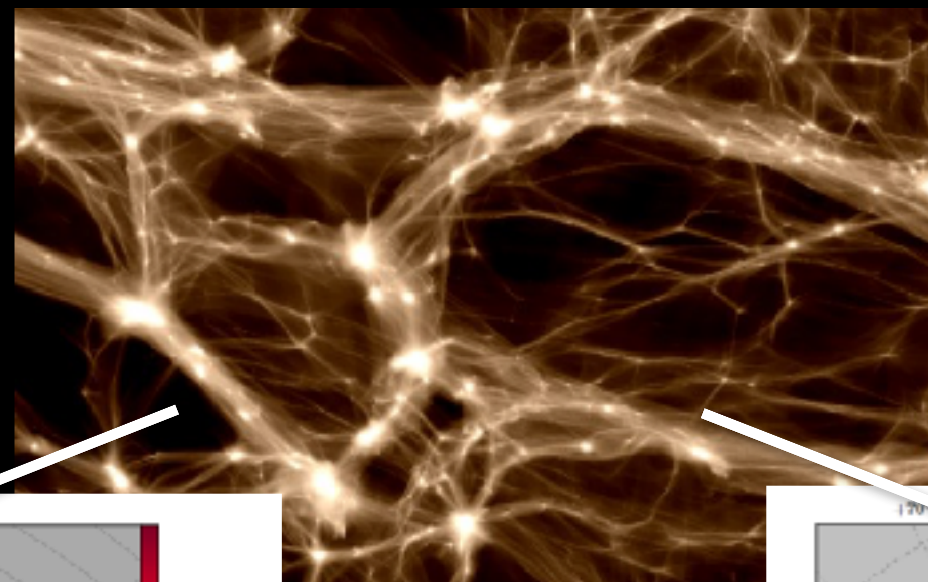
Weak Gravitational Lensing: typical DES galaxies



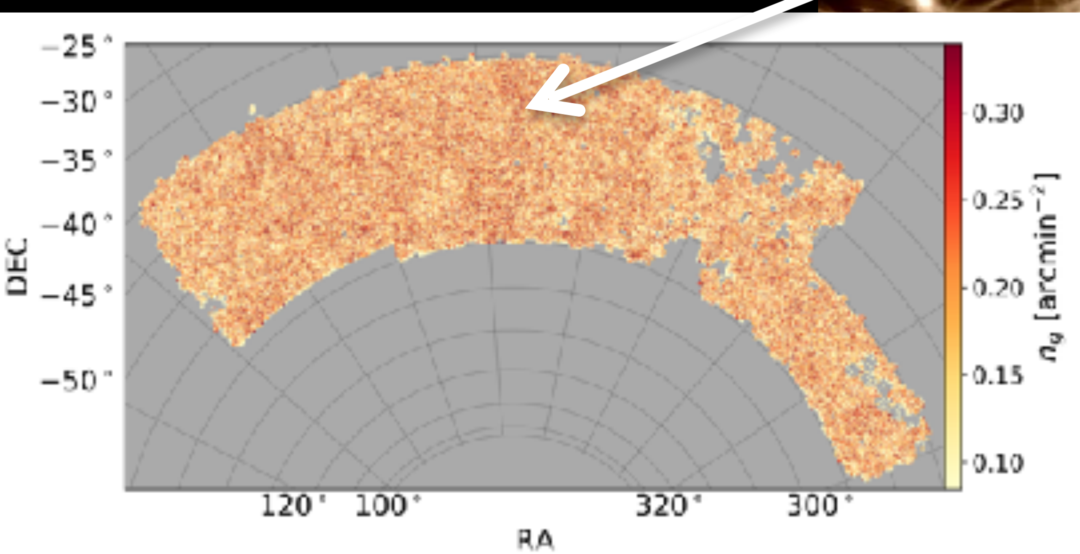
Real World Example: DES-Y1



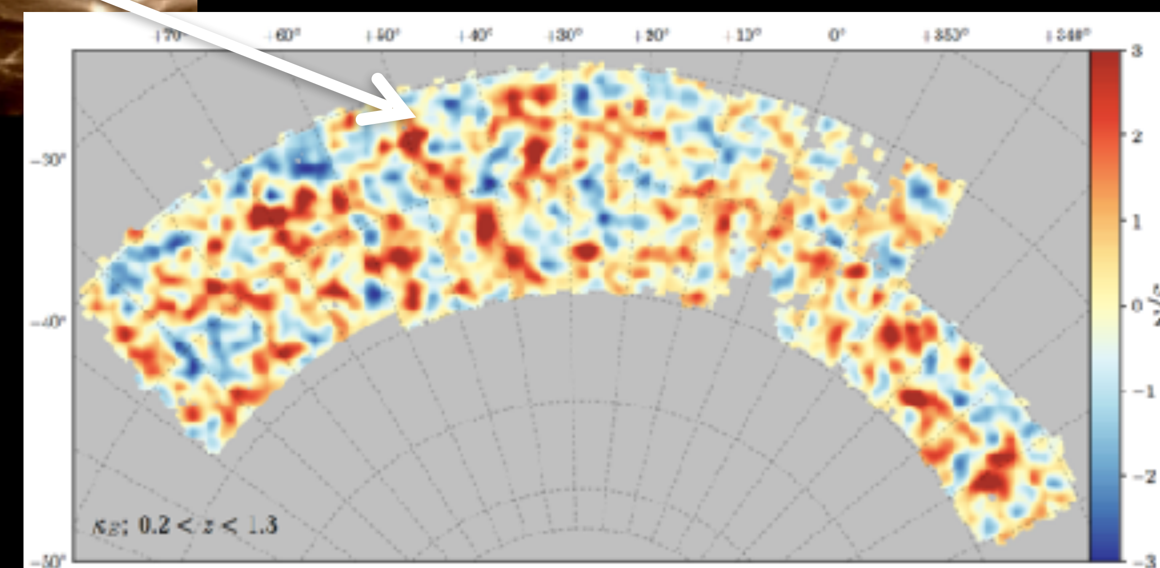
DES-Y1 WL x LSS Analysis



660K redMaGiC galaxies split in 5 redshift bins



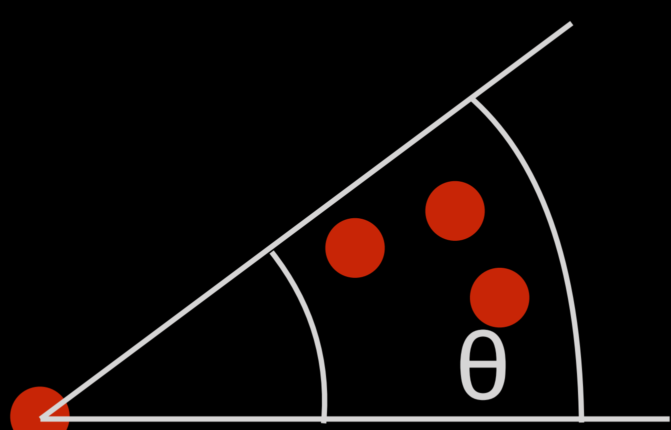
26M source galaxies split in 4 redshift bins

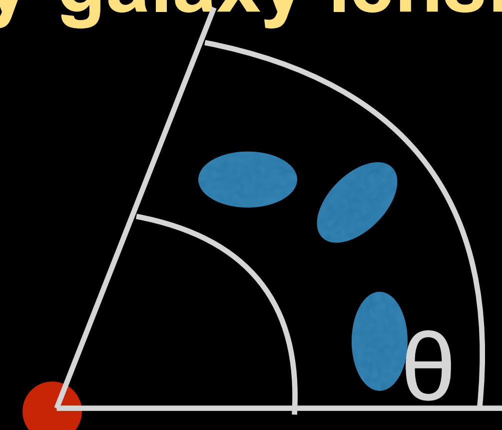


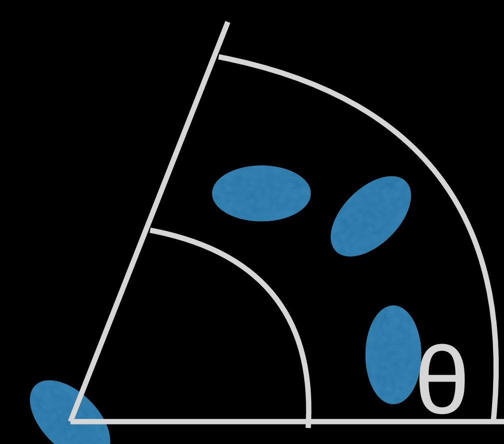
galaxies x galaxies:
angular clustering

galaxies x lensing:
galaxy-galaxy lensing

lensing x lensing:
cosmic shear







DES-Y1 Systematics Modeling + Mitigation

baseline systematics marginalization (20 parameters)

- linear bias of lens galaxies, per lens z-bin
- lens galaxy photo-zs, per lens z-bin
- source galaxy photo-zs, per source z-bin
- multiplicative shear calibration, per source z-bin
- intrinsic alignments, power-law/free amplitude per per source z-bin

-> this list is known to be incomplete

how much will **known, unaccounted-for** systematics bias Y1?

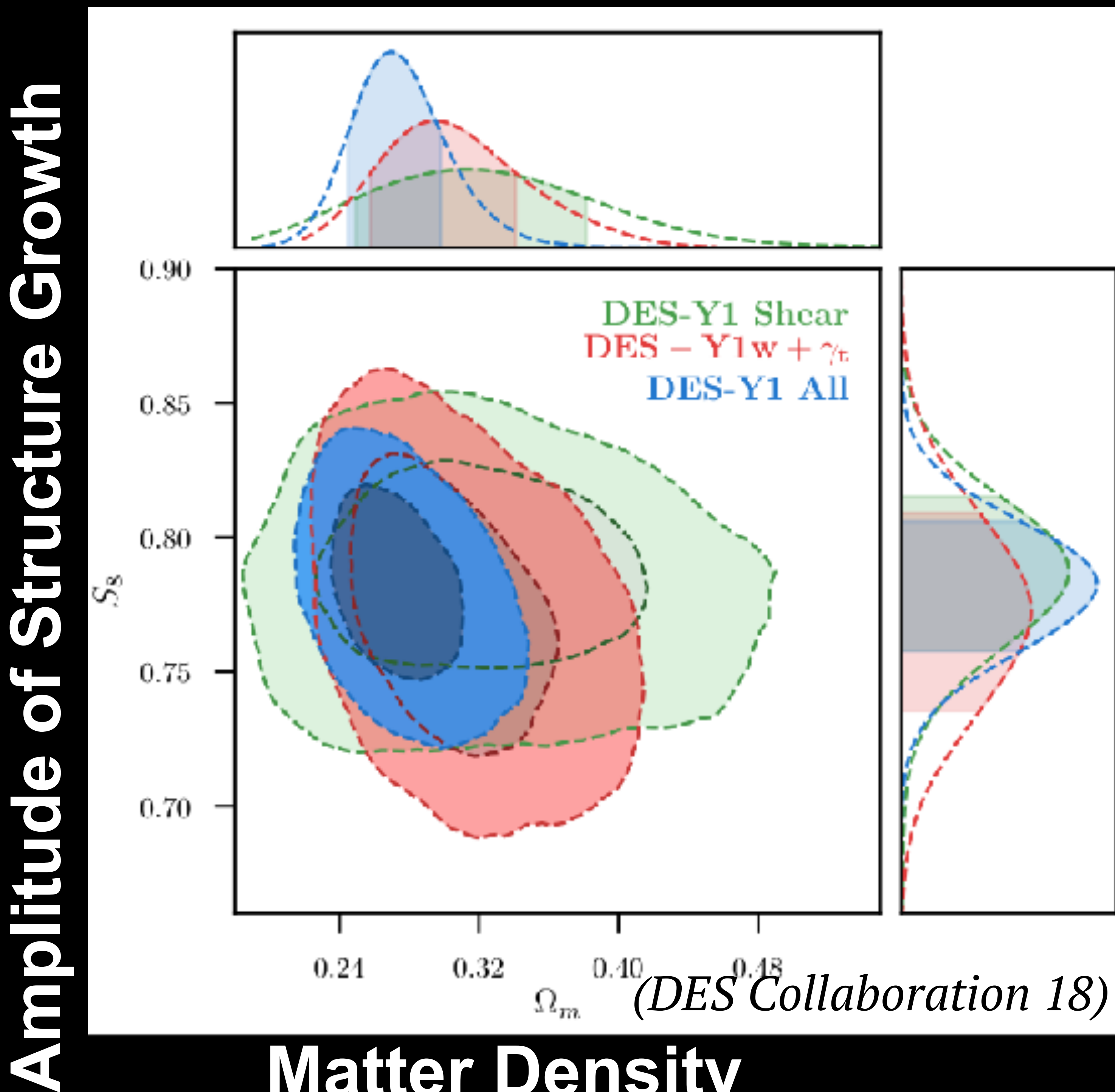
-> remove contaminated data points (*i.e., throw out large fraction of S/N*)

-> choice of parameterizations ≠ universal truth

are these **parameterizations sufficiently flexible** for Y1?

EK+(DES)1706.09359

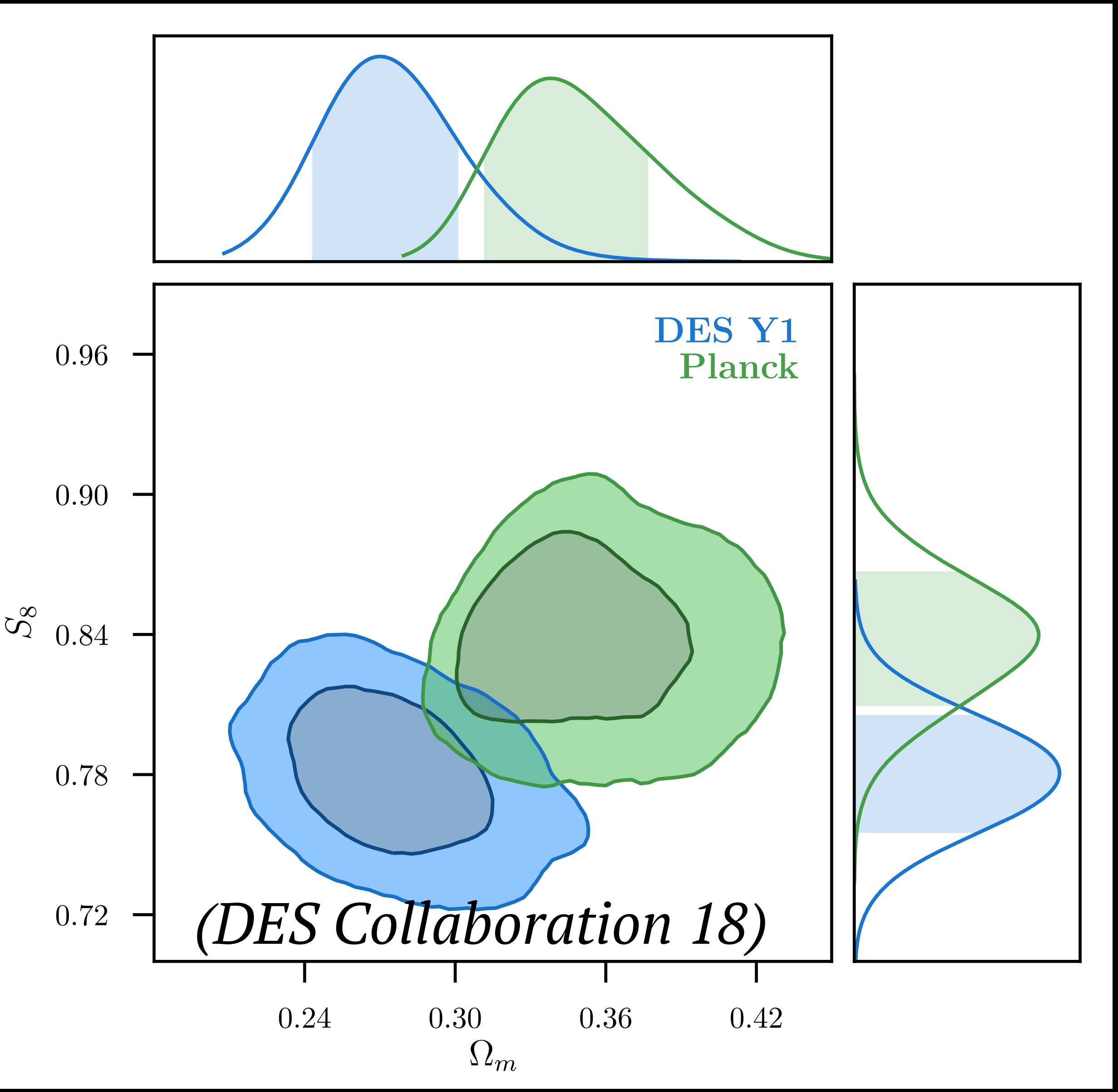
DES Y1 Results:
LCDM Multi-Probe Constraints



- marginalized 4 cosmology parameters, 10 clustering nuisance parameters, and 10 lensing nuisance parameters
- consistent cosmology constraints from weak lensing and clustering in configuration space

DES Y1 ↔ Early Universe (Planck)

Amplitude of Structure Growth

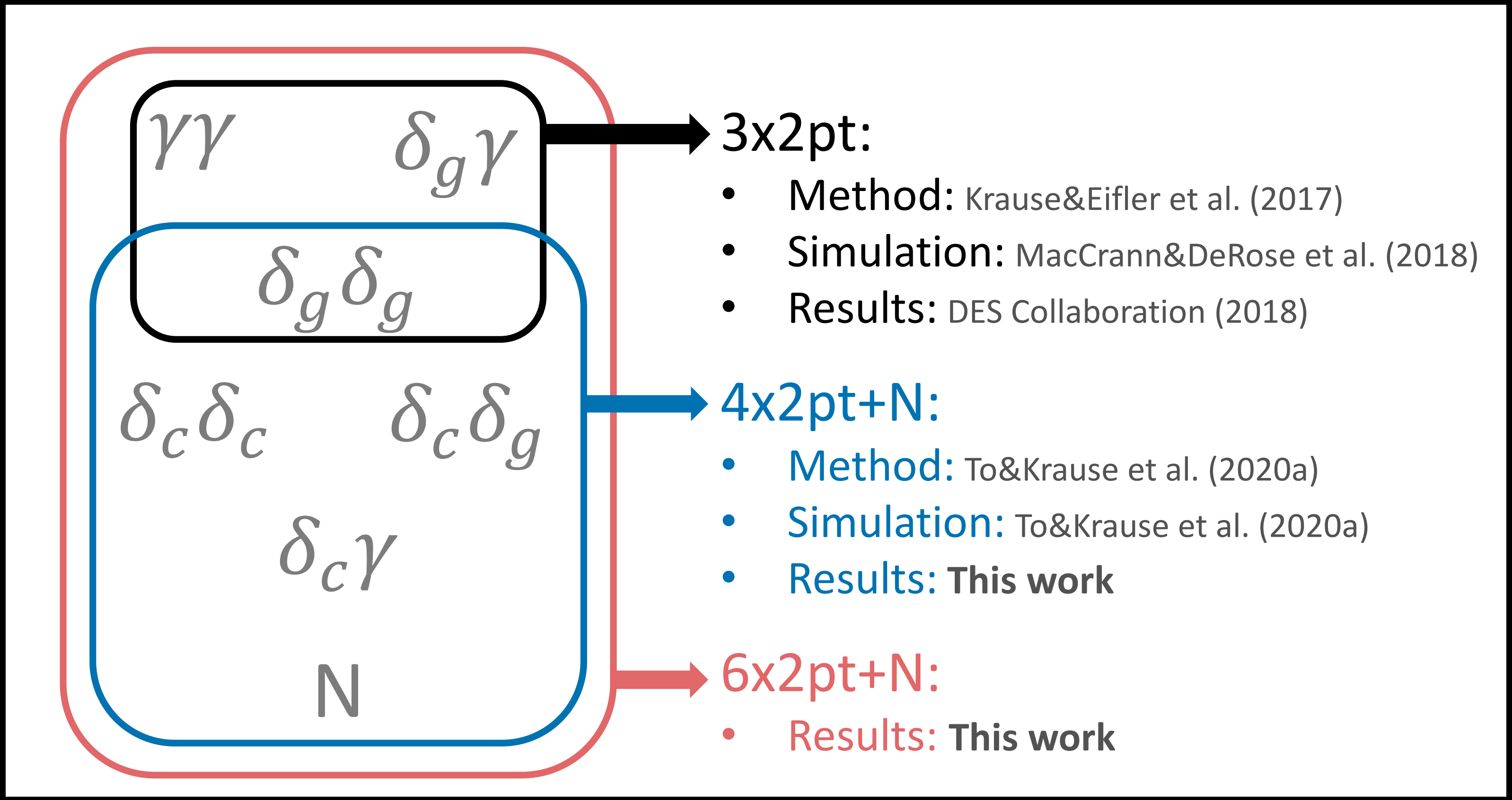


Matter Density

- DES-Y1 and Planck (TT+lowP, without CMB lensing) constrain S_8 and Ω_m with comparable strength
- central values differ by $>1\sigma$, in the same direction as other lensing analyses (CFHTLS, KiDS, HSC)
- **Future: observe more galaxies, combine more probes, and achieve better systematics control!**

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

To, EK+ 2021a,b: cluster cosmology constraints from abundances and large-scale two-point statistics



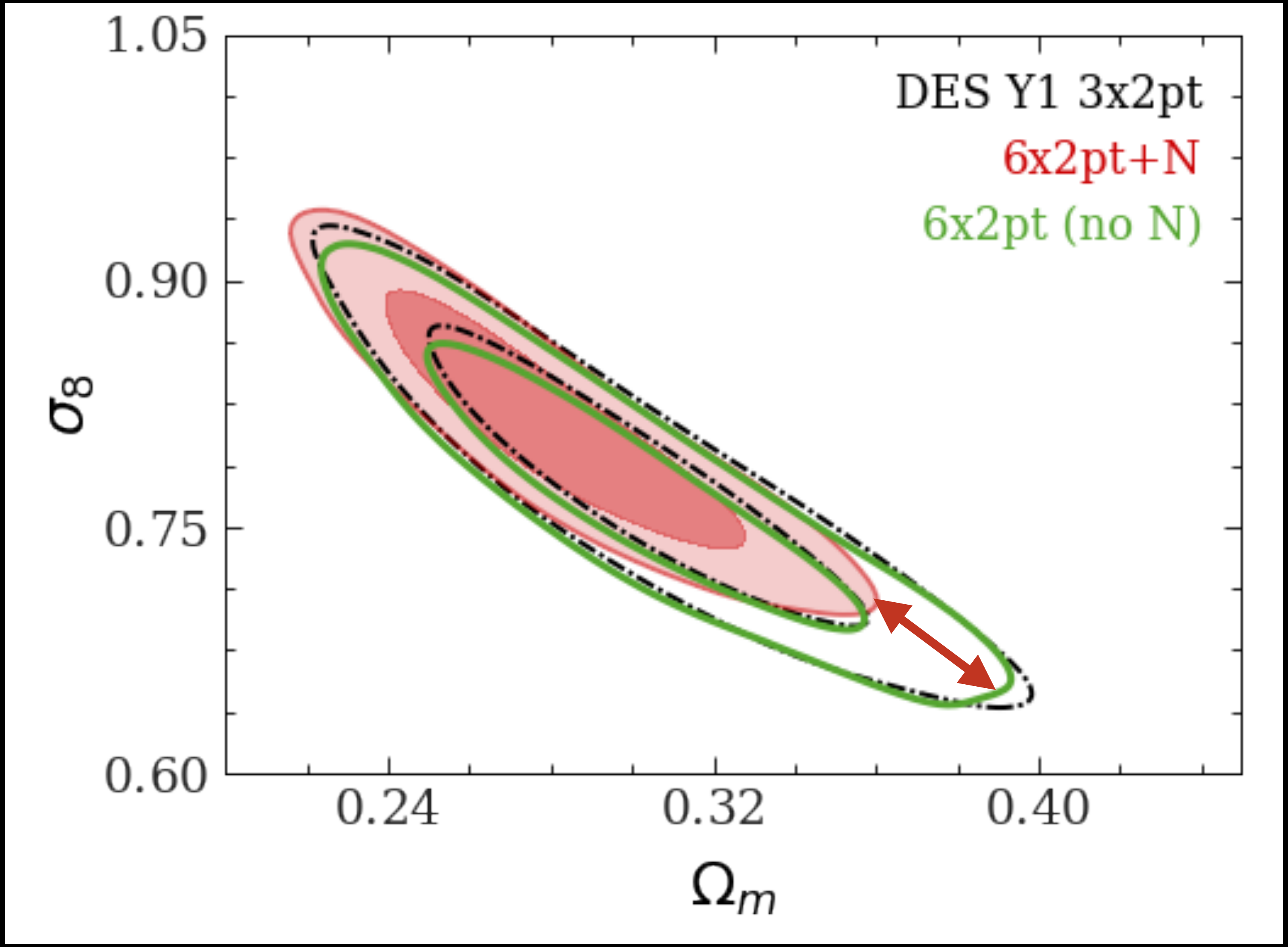
- joint likelihood analysis validated on DES-like mock catalogs (Buzzard, DeRose+2020)
- MOR calibrated from large-scale clustering, account for selection bias

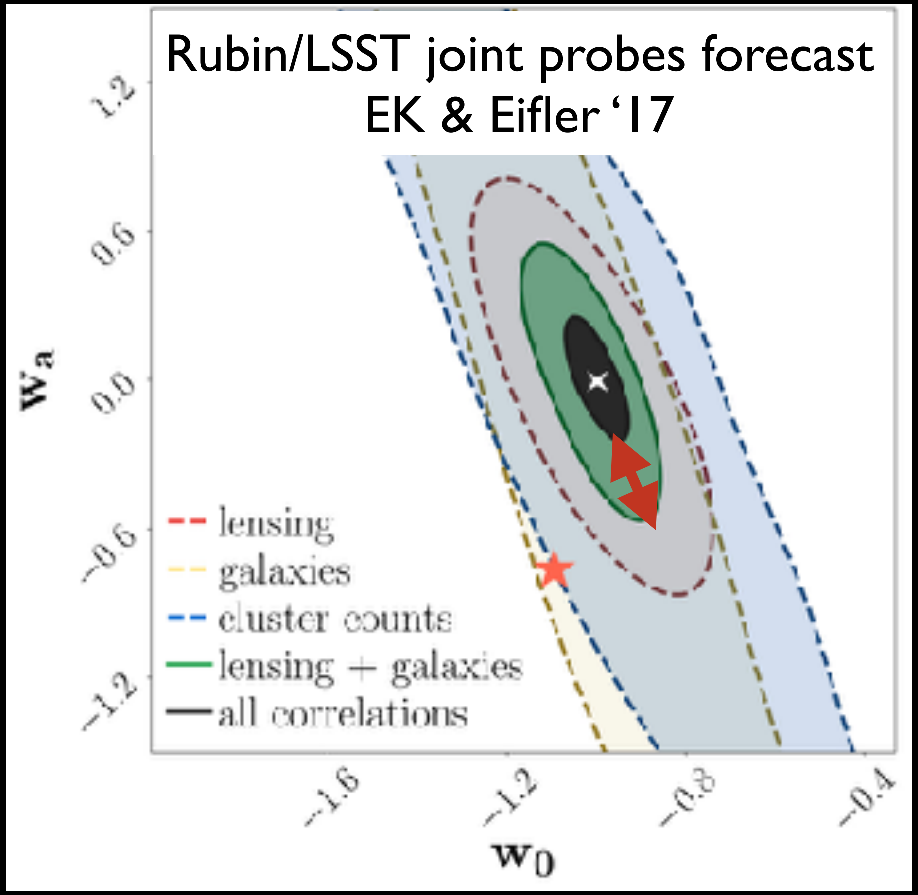
✓ cosmology constraints consistent with other DES probes

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

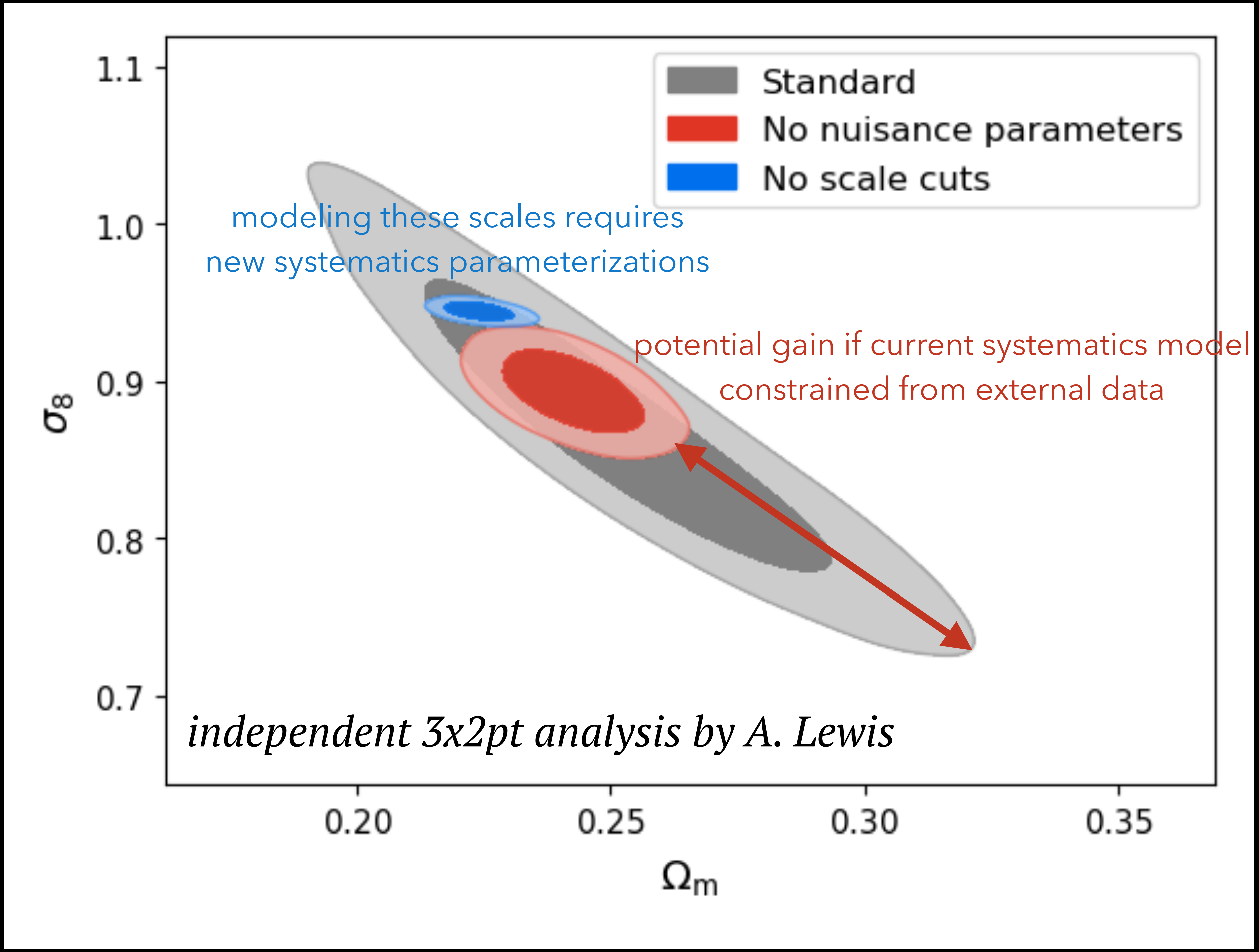
this analysis unlocks constraining power from number counts

substantial gain, *iff accurate MOR calibration*





DES-Y1 Systematics Mitigation
Opportunity Space...



Systematics Opportunities and Challenges: Baryonic Effects in WL Analyses

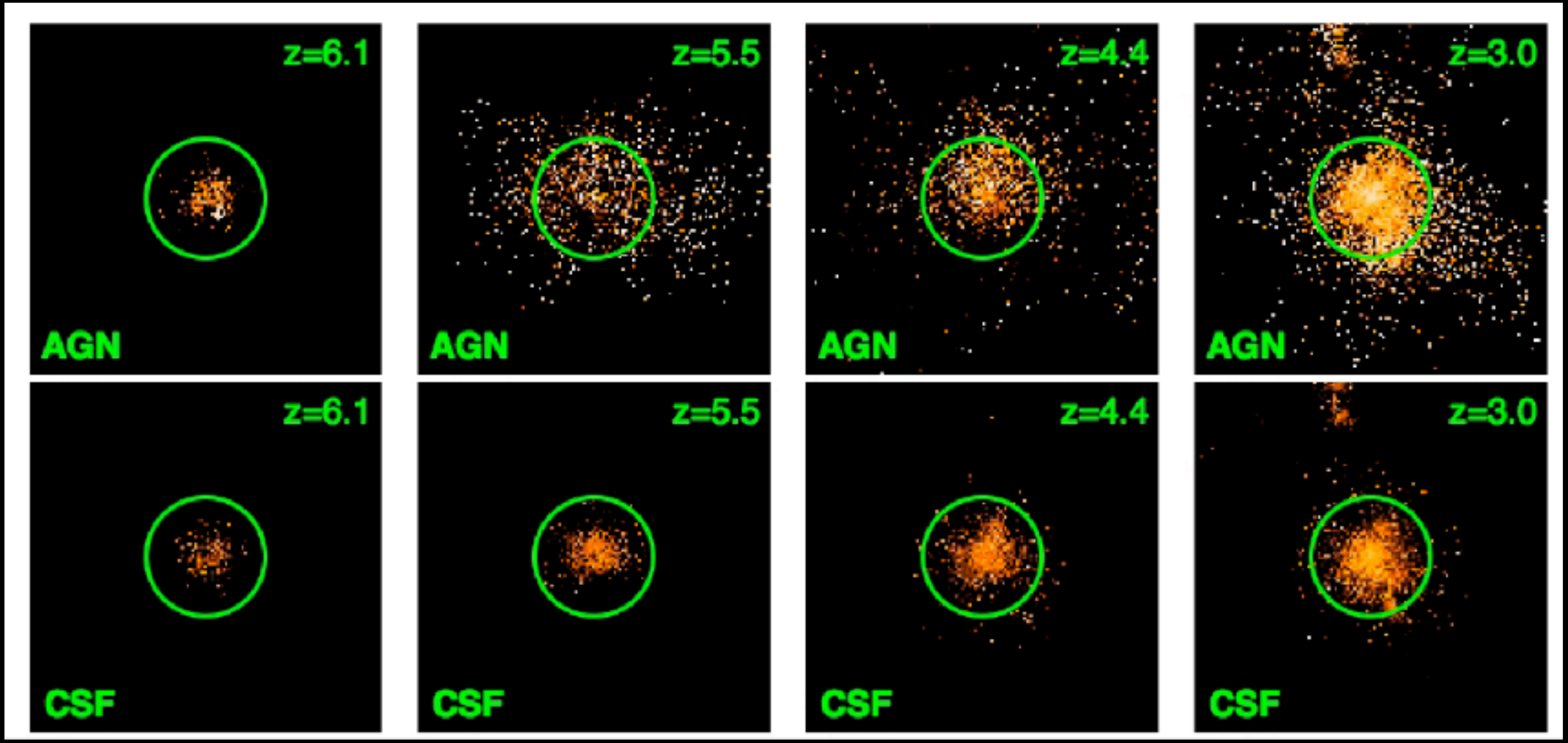
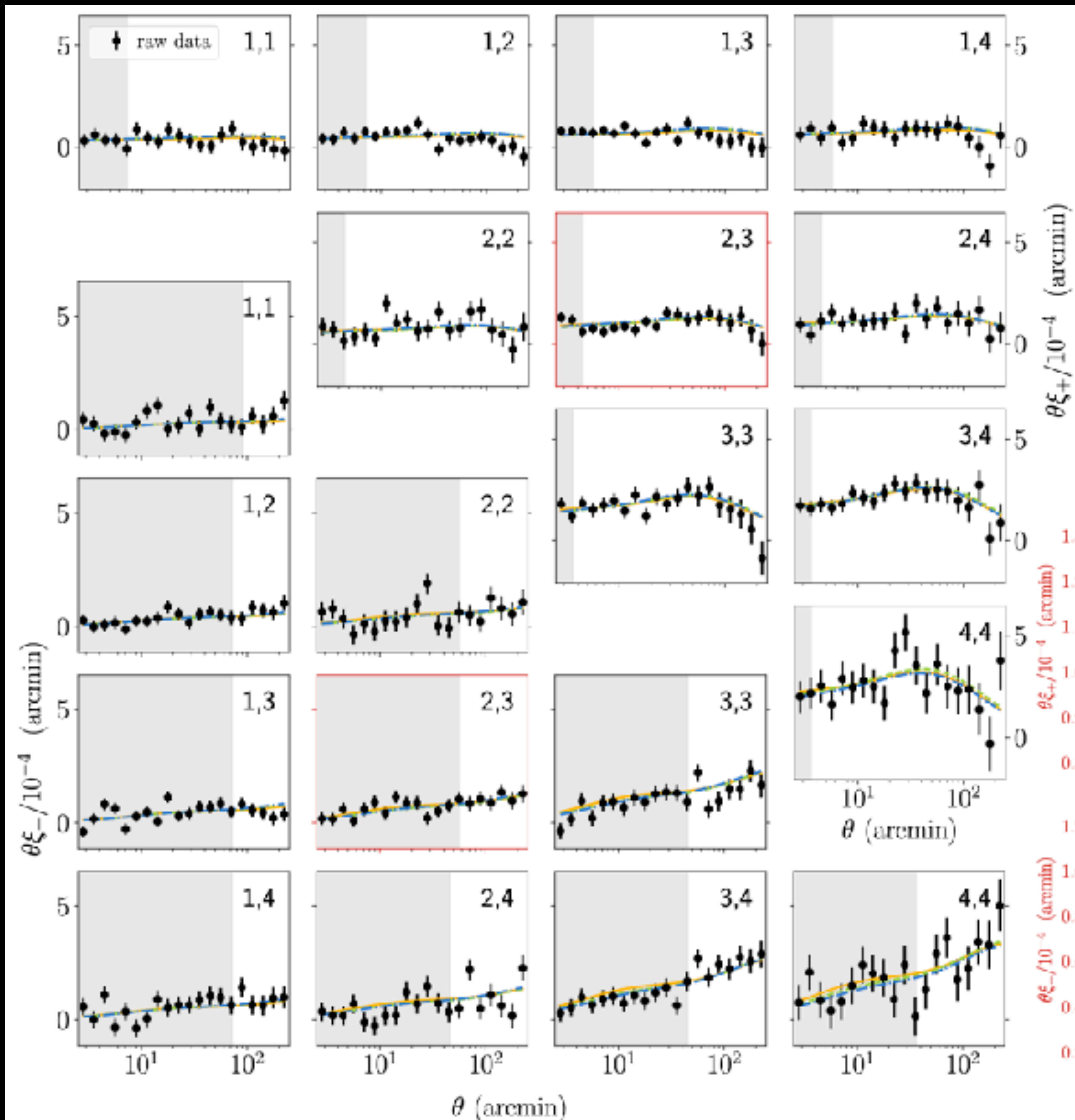


illustration from OWLS collaboration

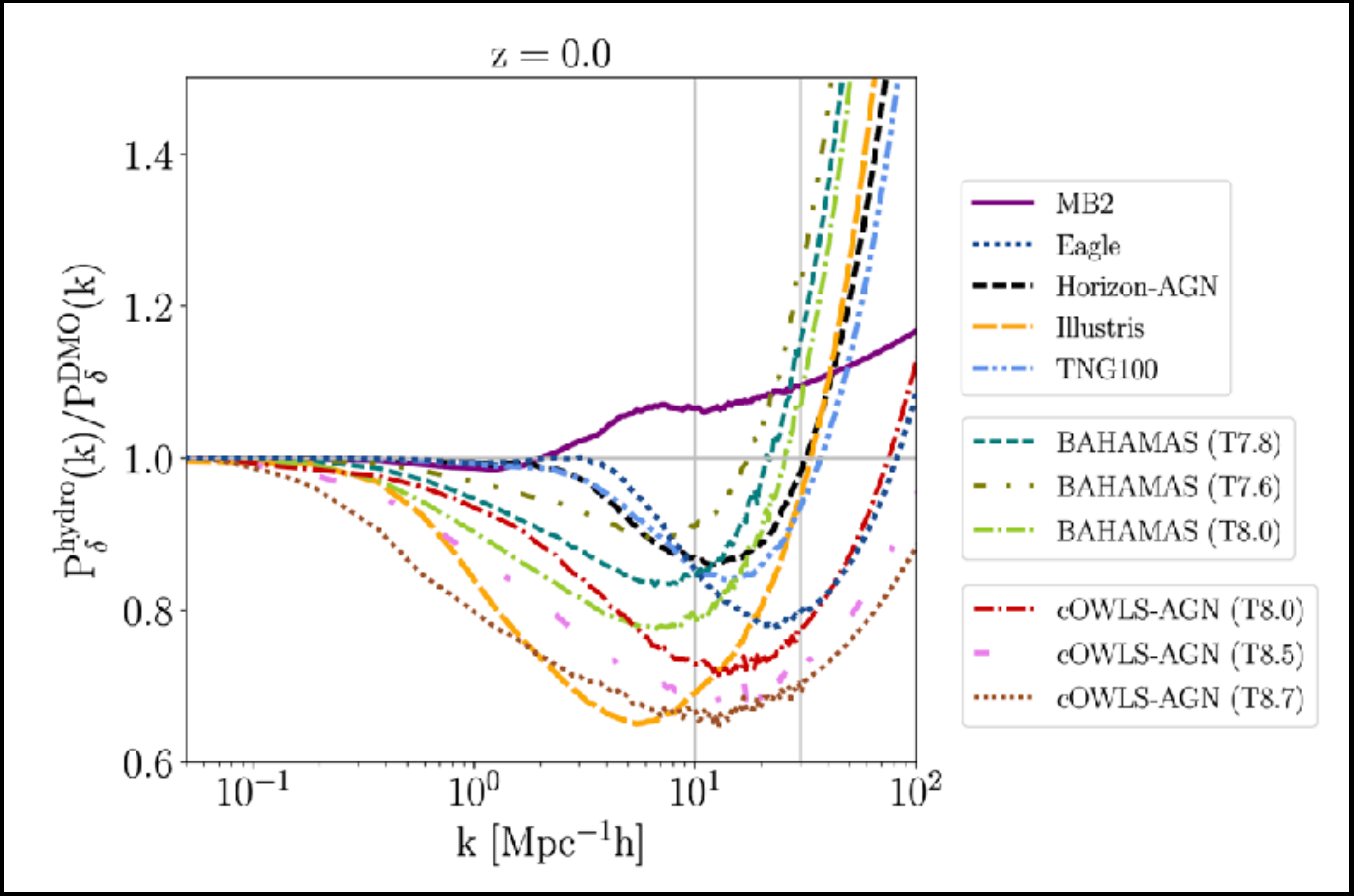
DESY1 WL Correlation functions



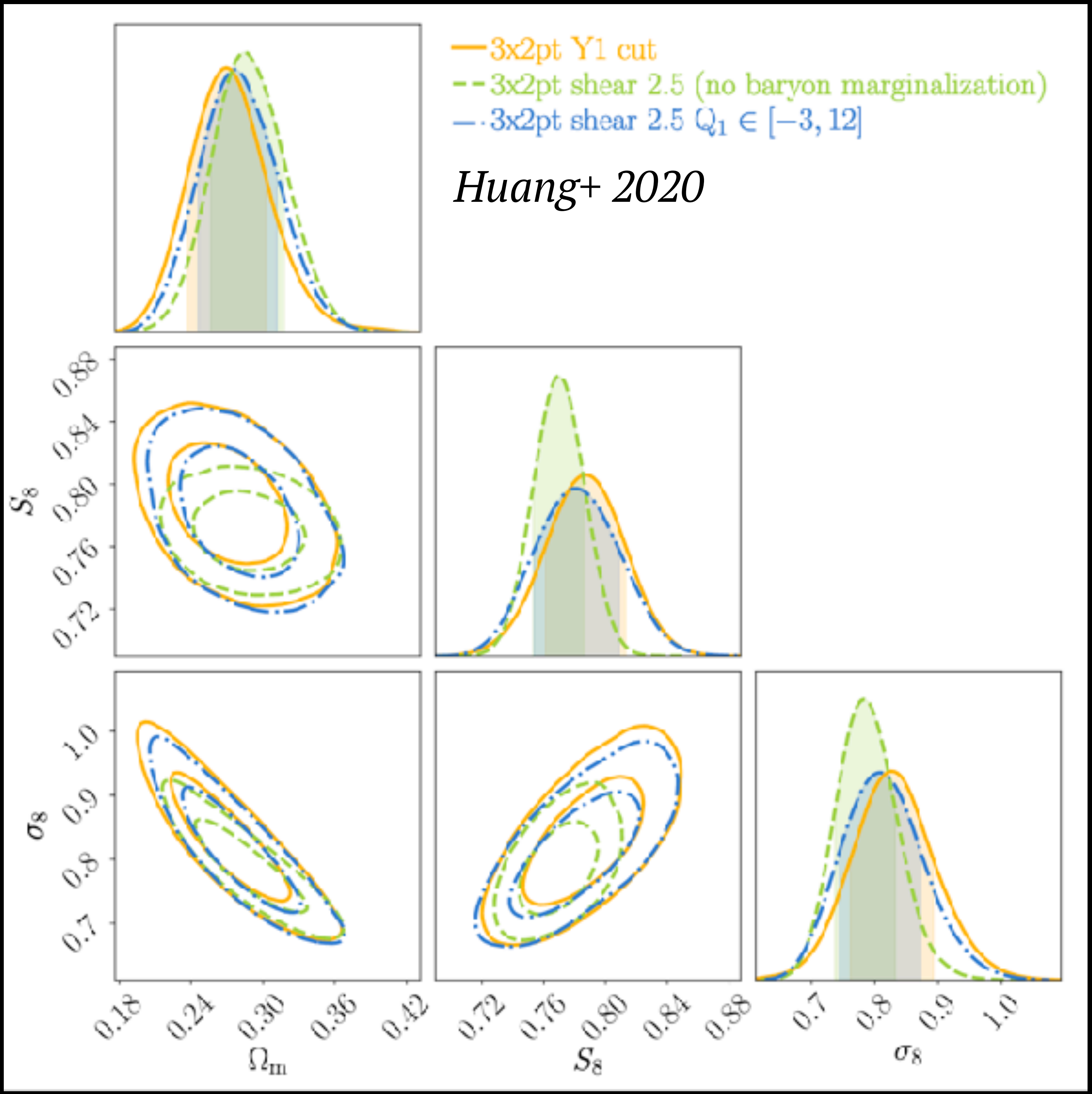
DES-Y1 baseline: small scale correlation function measurements **excluded because of baryonic effects**

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

Baryonic Effects in WL Analyses

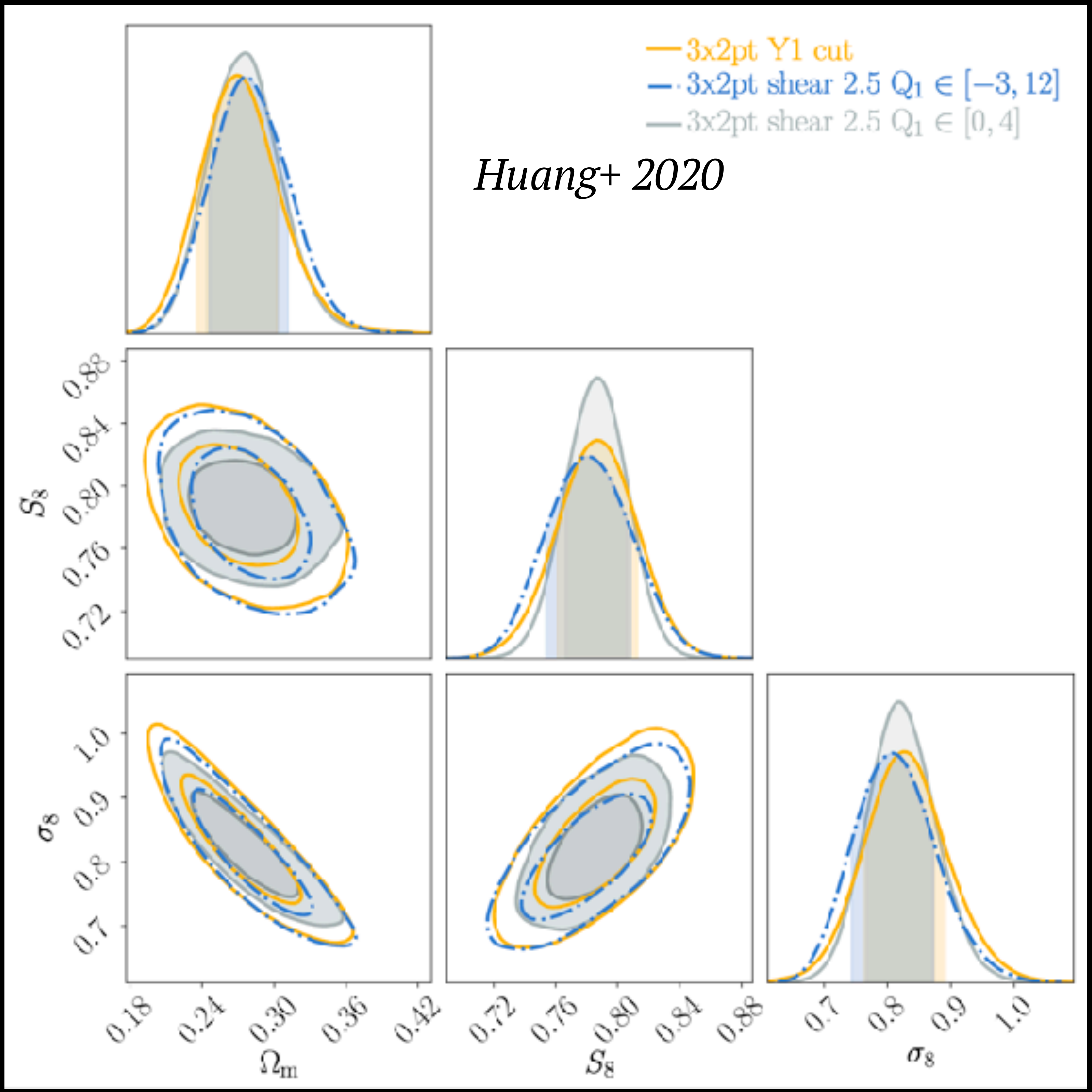


Baryonic Effects in WL Analyses Cosmology Constraints



- 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

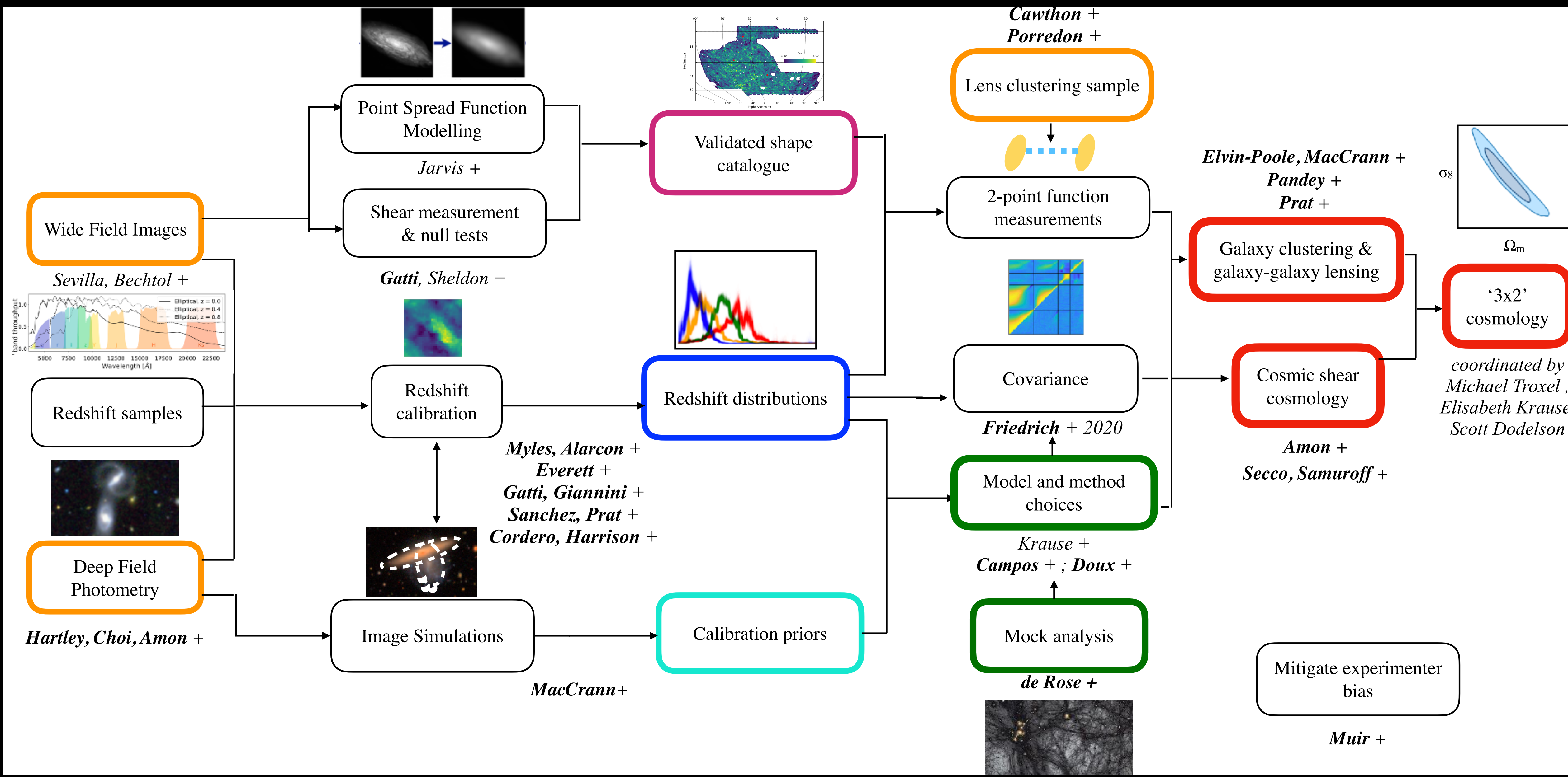


- DES-Y1 baseline (conservative scale cuts)
- DES-Y1 including all scales, baryonic effects modeled using **PCA with non-informative prior**
- DES-Y1 including all scales, baryonic effects modeled using **PCA with informative prior**

This Thursday: DES-Y3 Cosmology

Analysis of DES Year-3 3x2pt: webinar on 5/27, 11:30 am Eastern

- full area (~5000 sqdeg) + increased depth
- algorithmic + modeling improvements in all analysis stages



Conclusions

The simple, 6-parameter LCDM model has been remarkably successful

- describes wide range of cosmological epochs and observables
- intriguing tension (H0) and fluctuation (S8) are emerging

- (most) cosmological constraints will be systematics limited
  - require astrophysics, accurate systematics parameterizations+priors
- DES-Y3 results coming this week: webinar 5/27, 11:30 am Eastern
  - https://fnal.zoom.us/j/94822142182?pwd=UnlPSzg0NXdNdlFzK3R2VWV6aEk1dz09
- Precision cosmology requires collaboration across surveys + wavelengths, planning for analysis frameworks to combine data from all surveys!