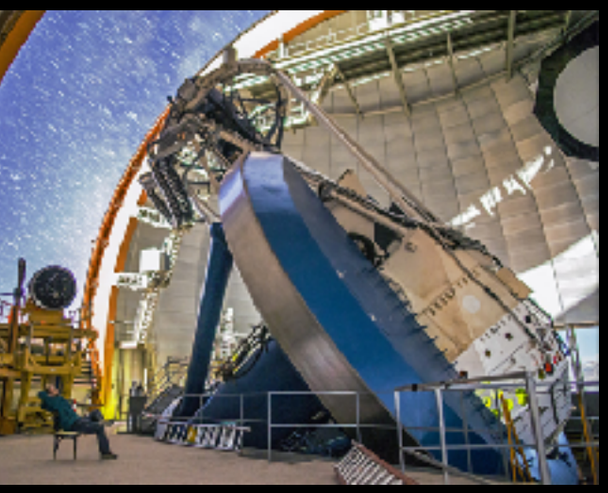
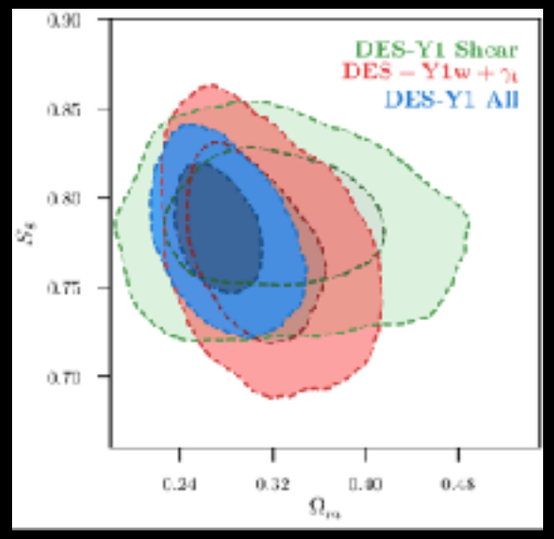




Cosmology with the Dark Energy Survey: 400+ scientists constrain fundamental physics with 100 million galaxies

with the Dark Energy Survey Collaboration

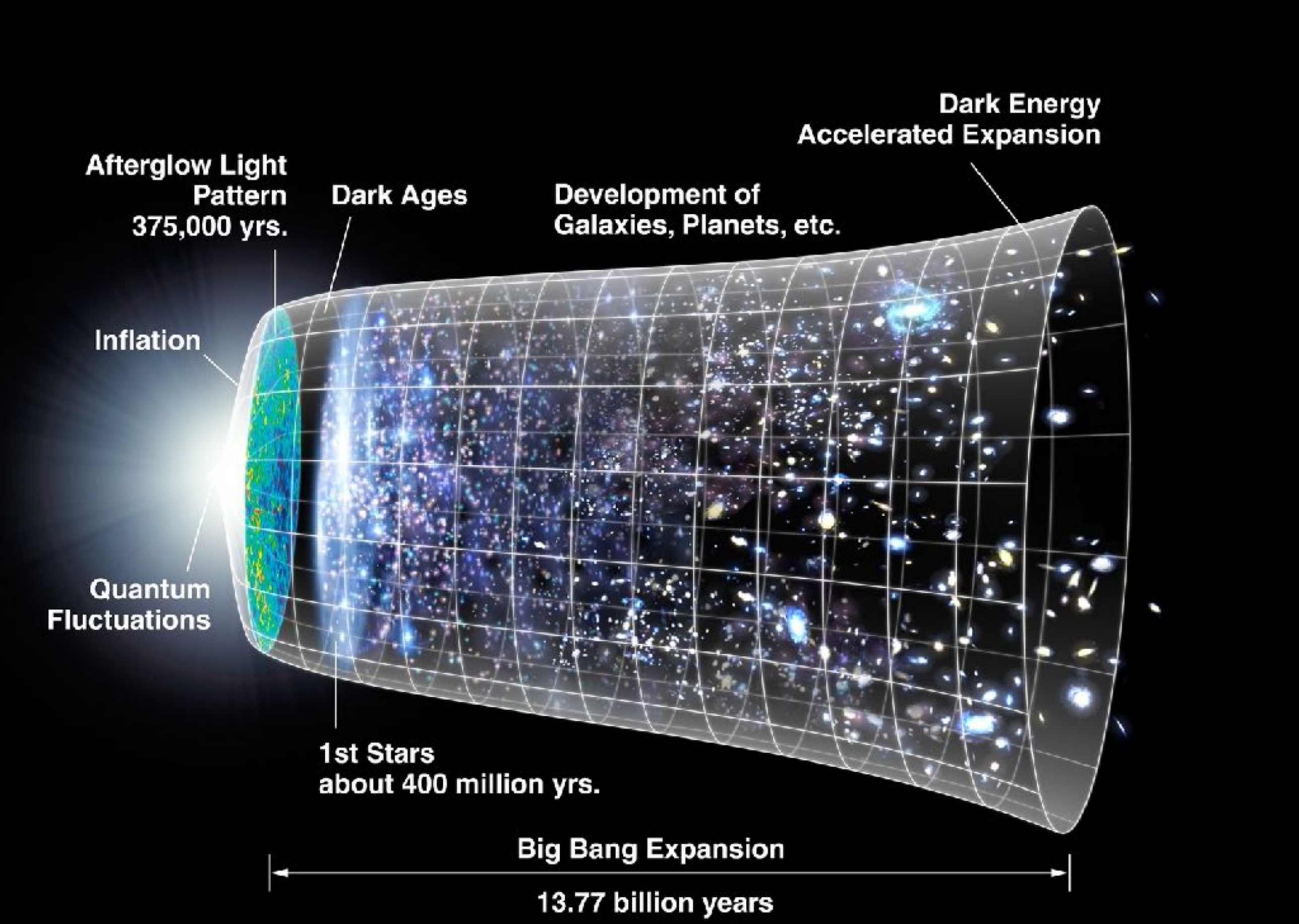
Elisabeth Krause
Steward Observatory/University of Arizona

Vanilla Cosmology

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

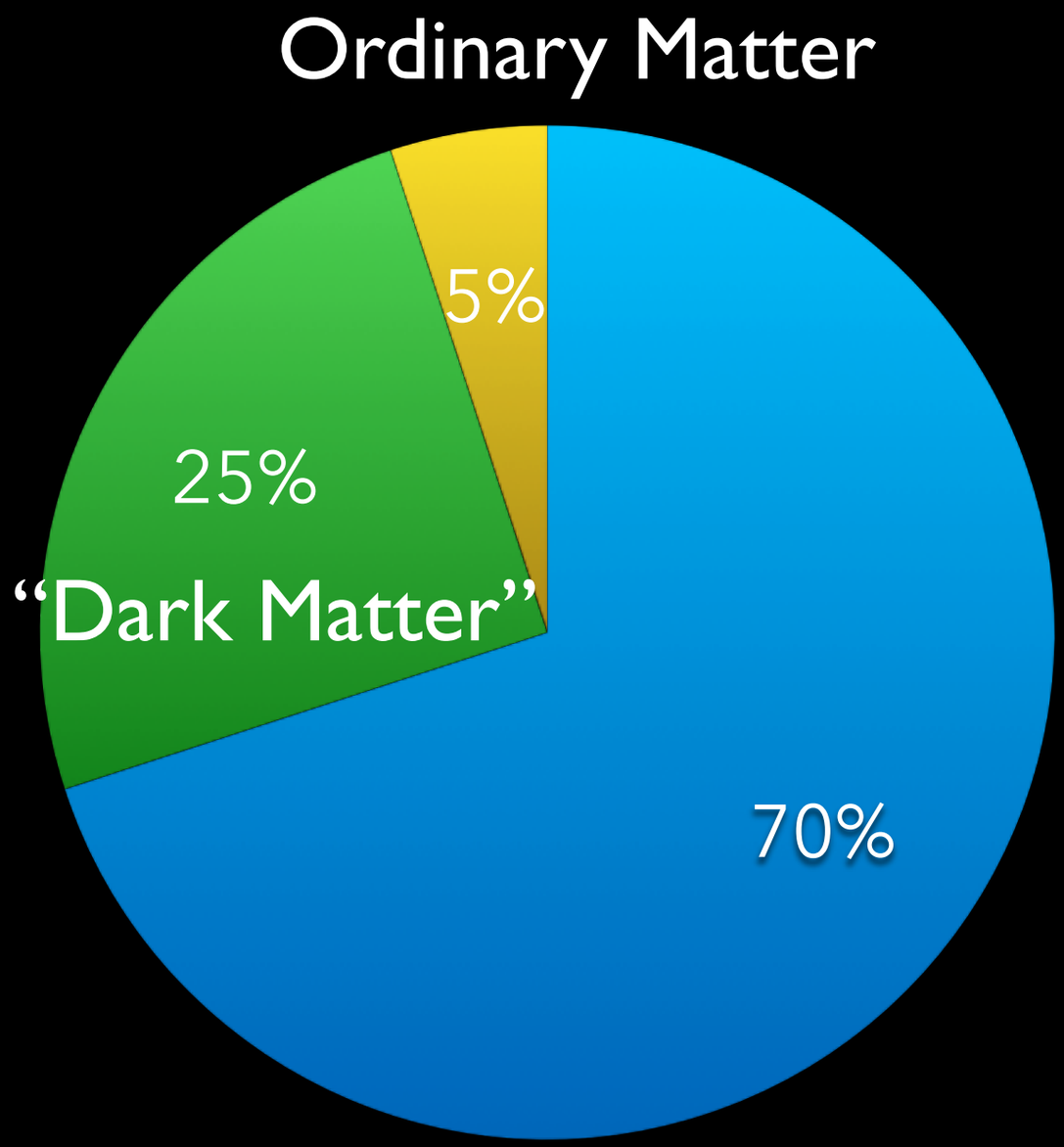
- age of the Universe
- geometry of space
- density of atoms
- density of matter
- amplitude of fluctuations
- scale dependence of fluctuations

[of course, details are not quite as simple]



credit: NASA/WMAP

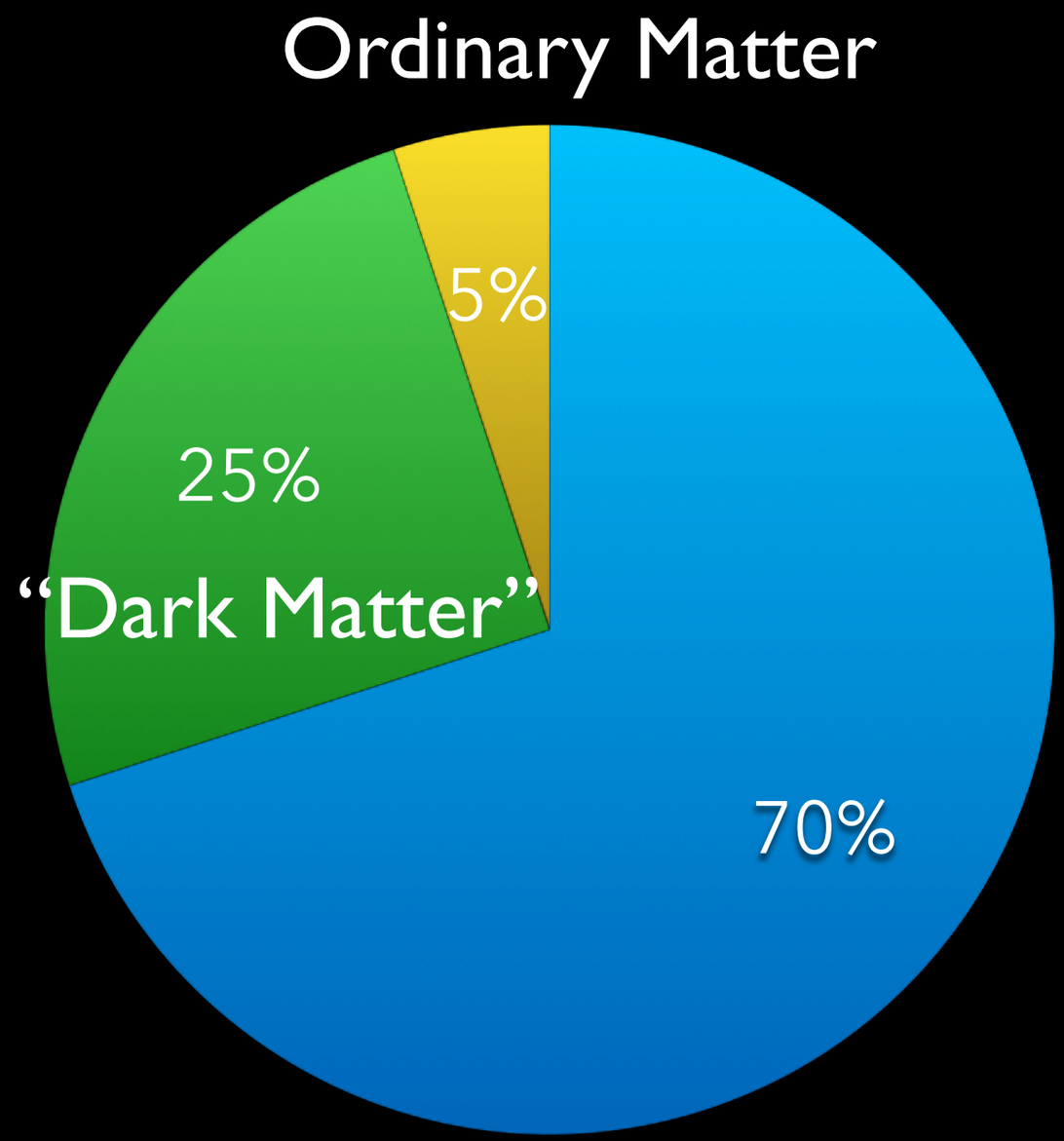
Vanilla (ΛCDM) Cosmology



"Dark Energy"

- name for accelerated expansion
- first measured by SN teams in 1998
- dominates the total energy density

Vanilla (ΛCDM) Cosmology



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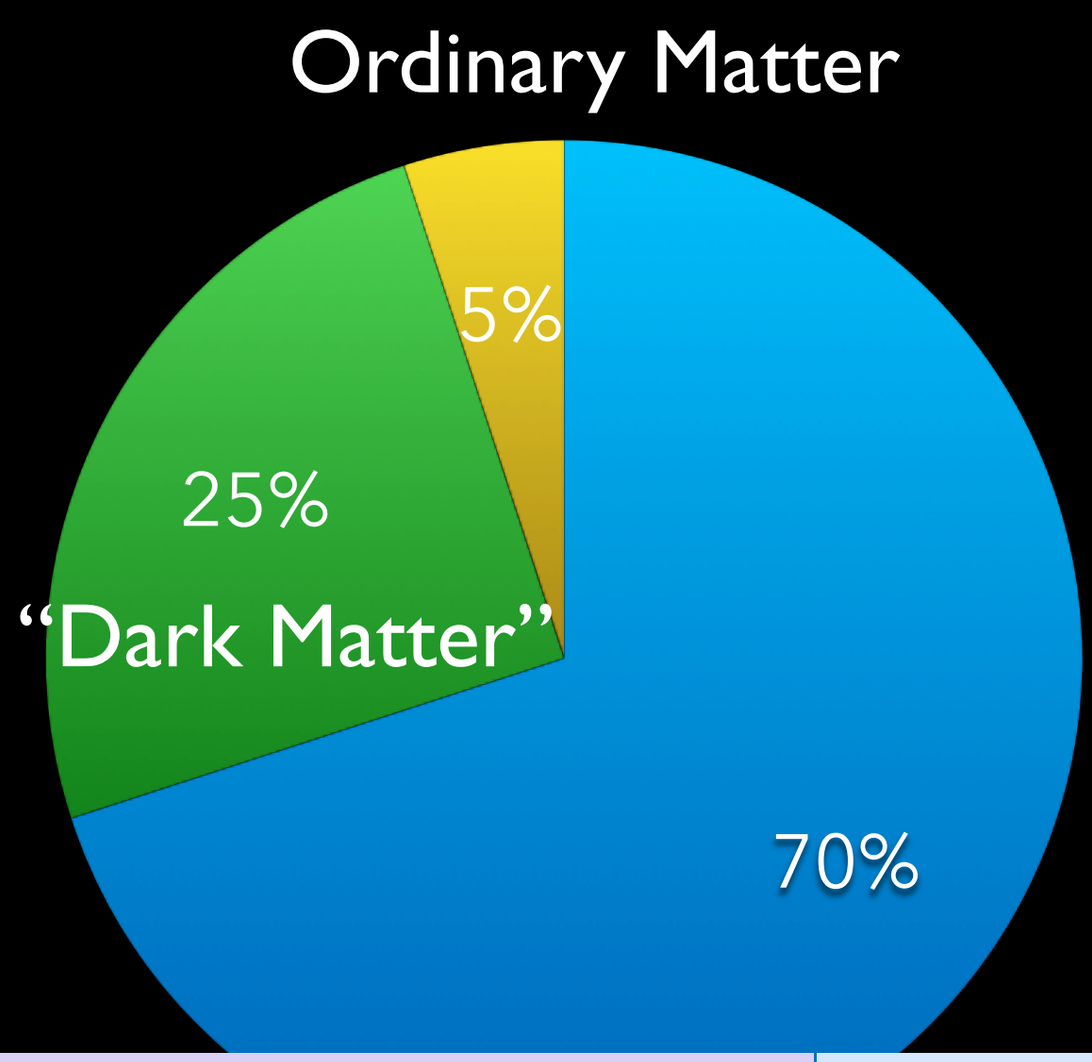
next frontier: understand

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

Vanilla (ΛCDM) Cosmology



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- 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

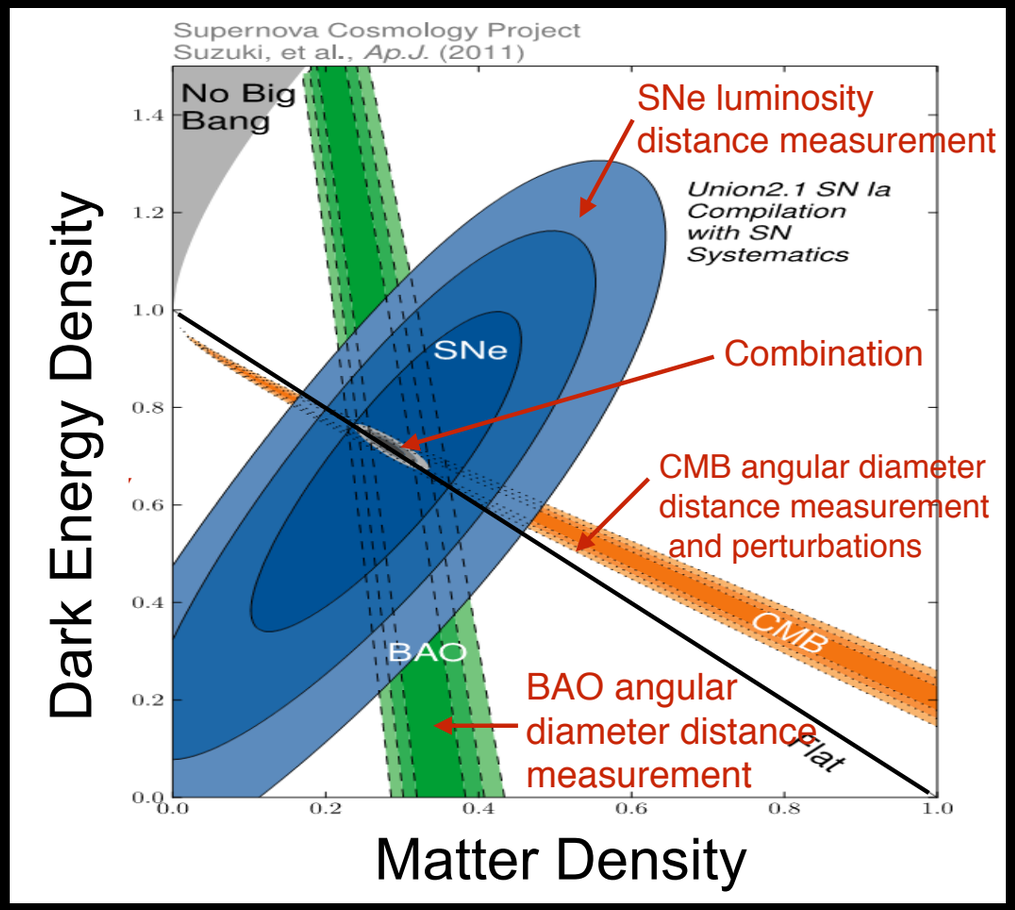
Standard candle: brightness of source with know luminosity

Standard ruler: angle subtended by known scale

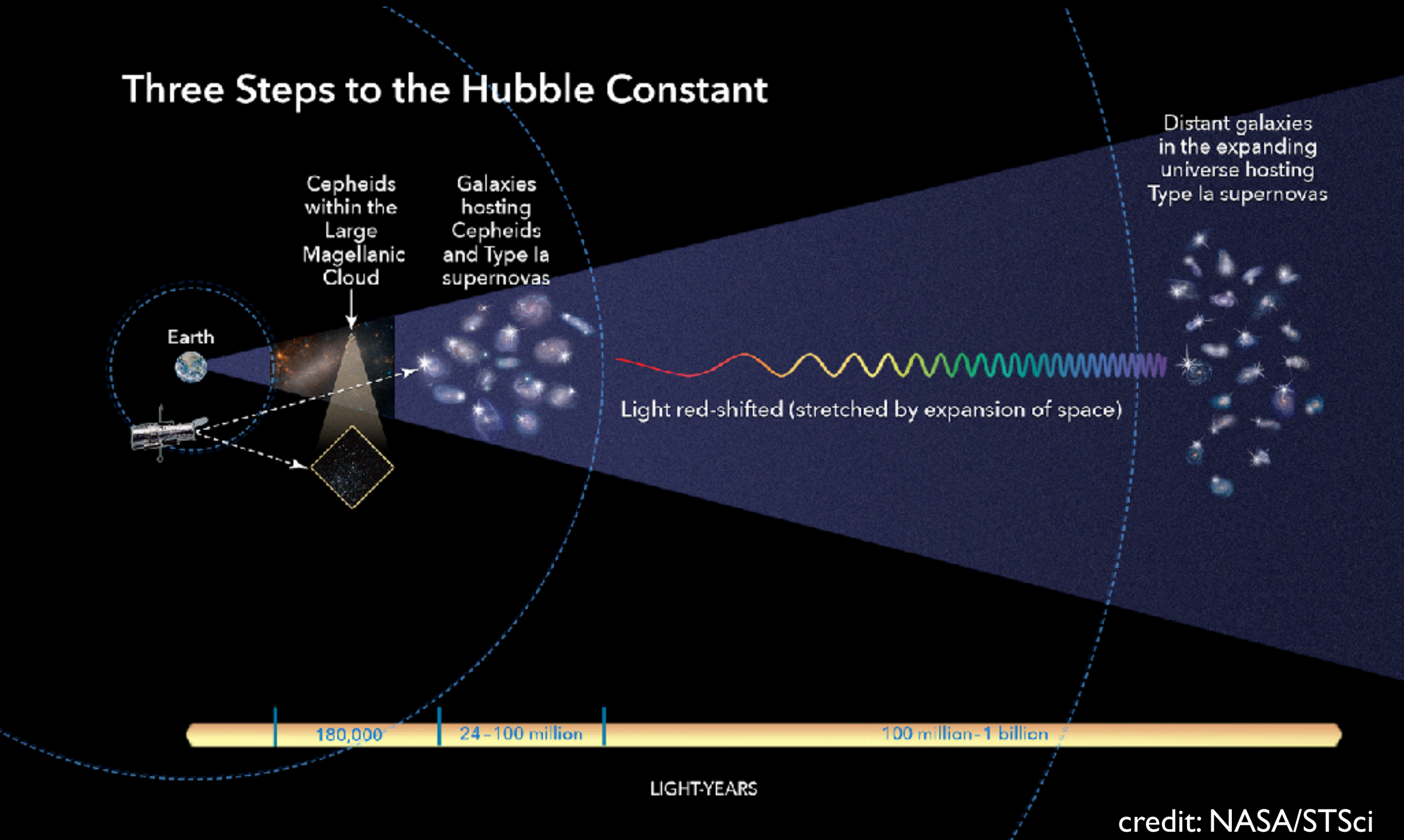
Early 2000s: Concordance Cosmology

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



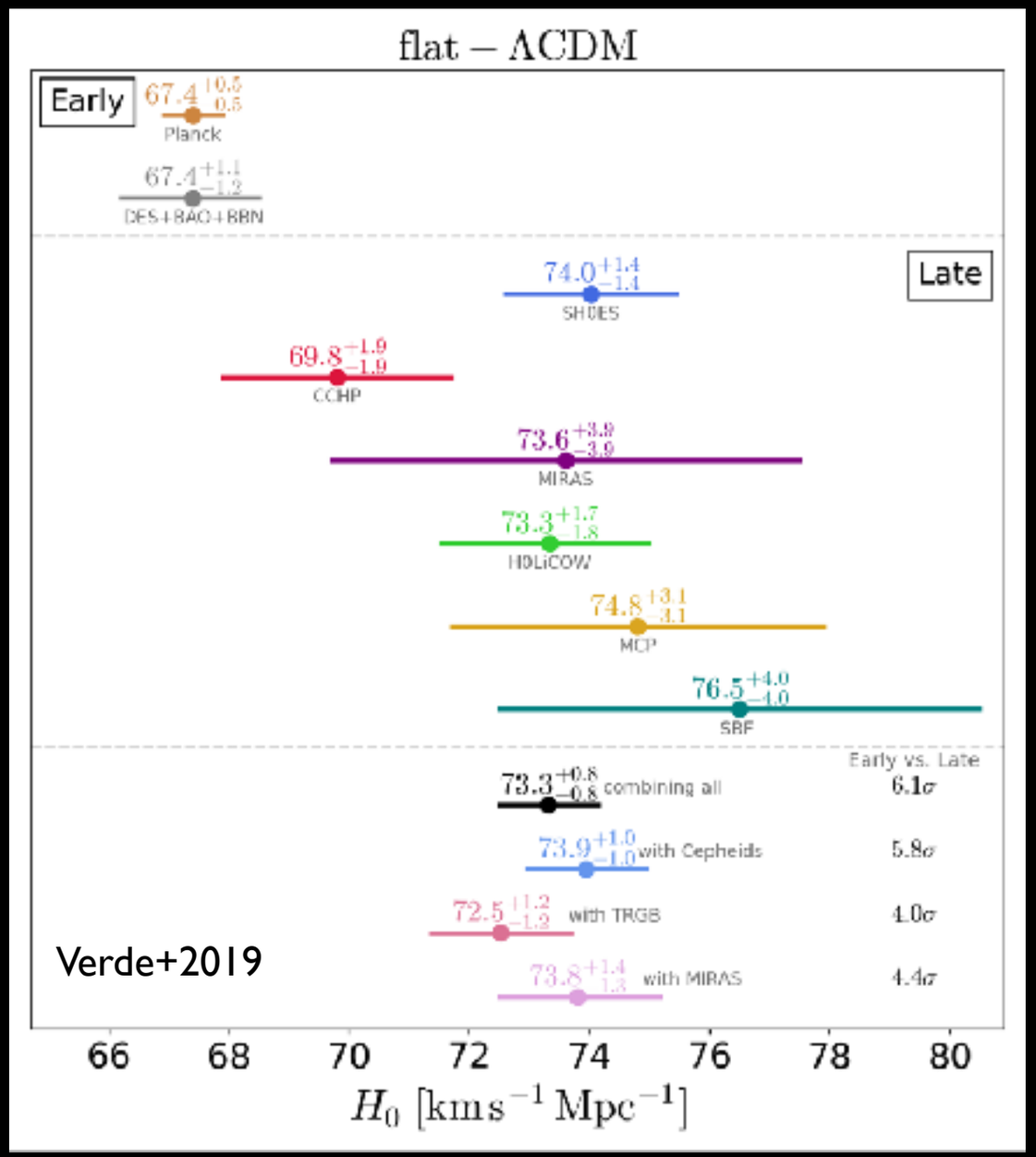
The Distance Ladder



credit: NASA/STSci

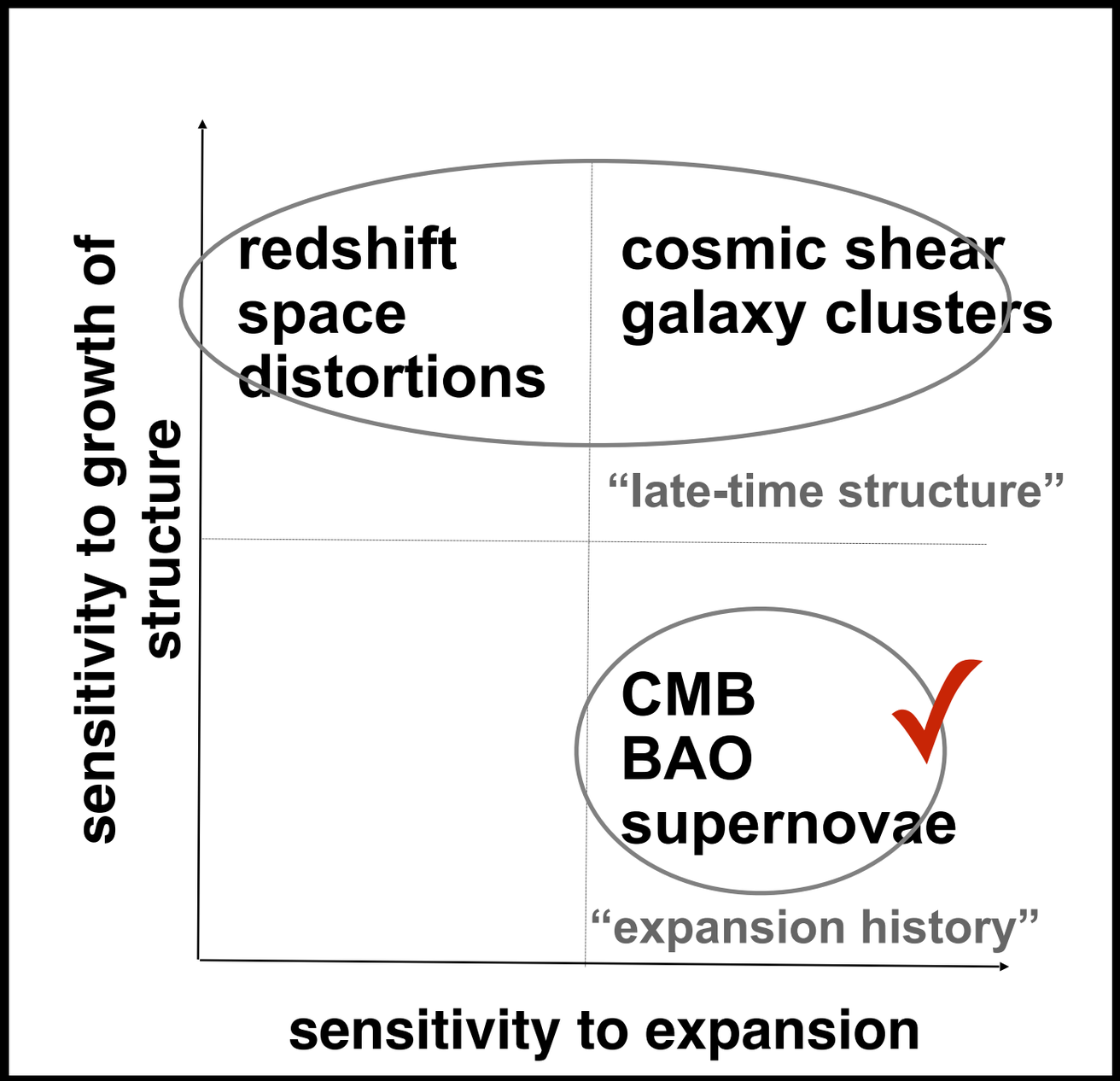
2020s: Concordance Cosmology?

Hubble Parameter - expansion rate



significant tension between early and late Universe physics!

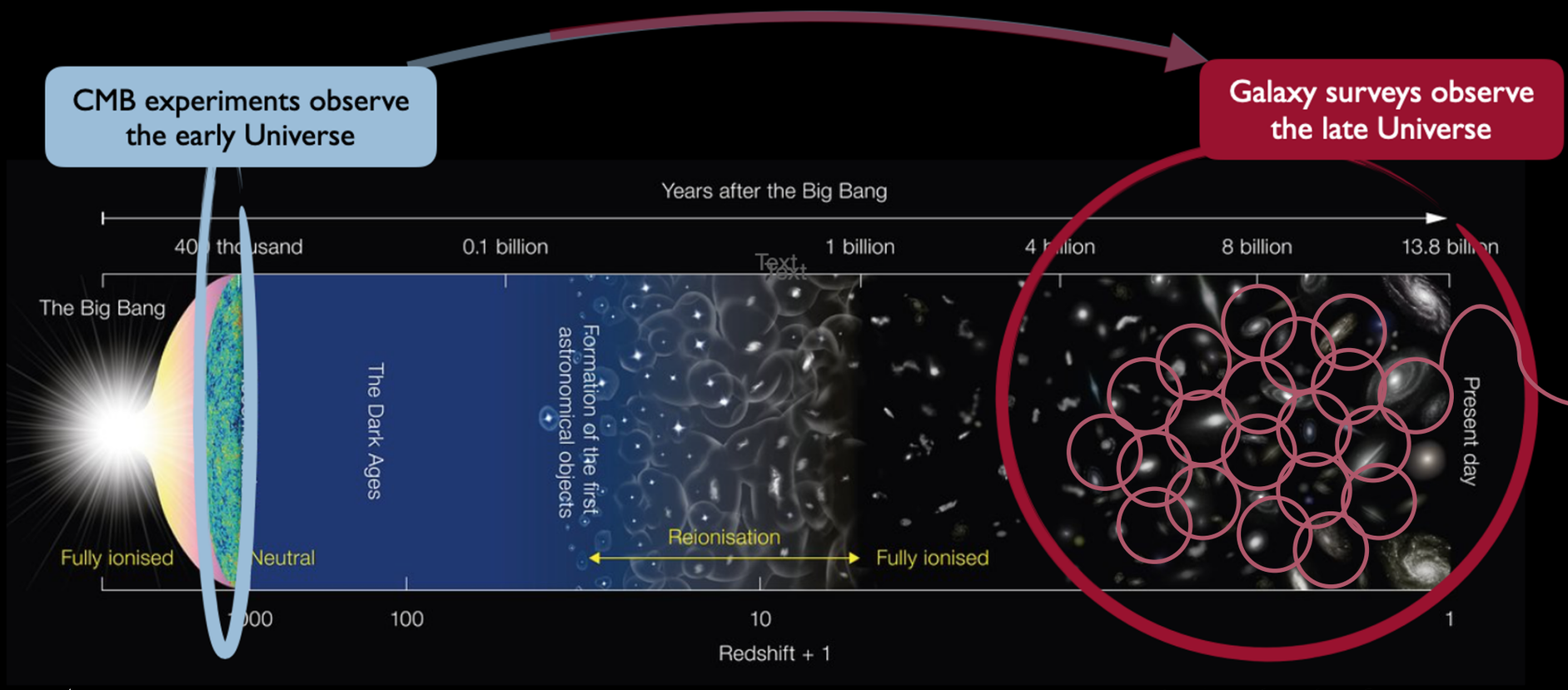
2020s: Concordance Cosmology?



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

Comparing Cosmic Structure Growth Over 13.4 Billion Years

Testing ΛCDM: Is the late time clustering compatible with the ΛCDM prediction assuming initial conditions from the CMB?



Spheres with radius 8 Mpc/h

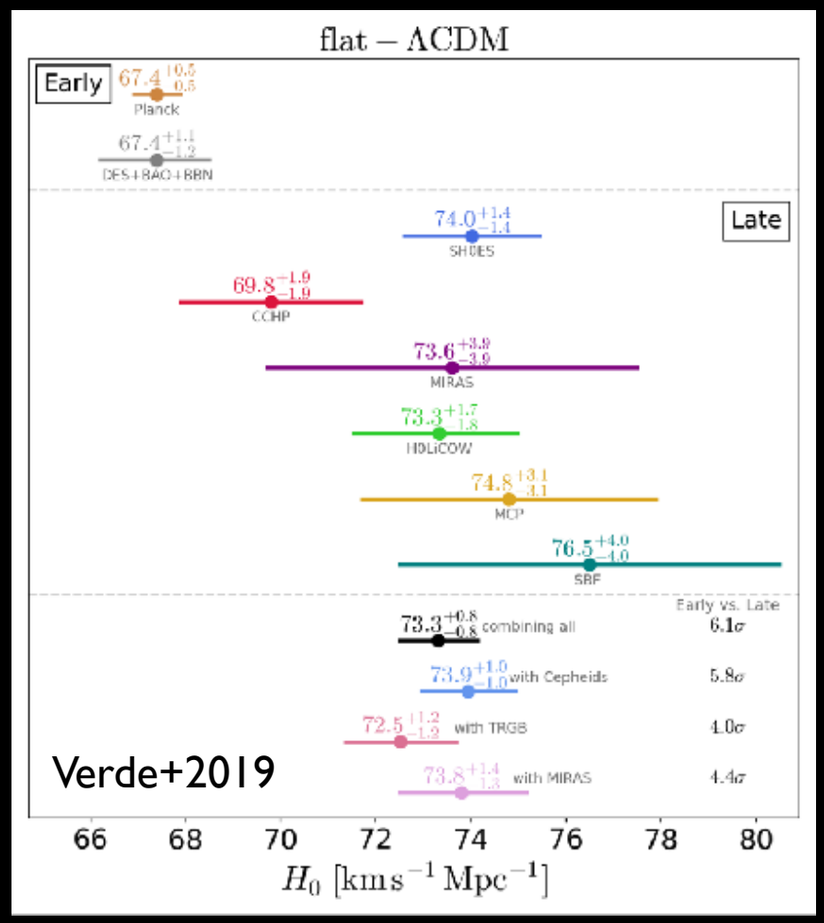
A_s: Amplitude of primordial scalar density fluctuations.

Image credit: NAOJ

σ_8: Amplitude of mass fluctuations today.

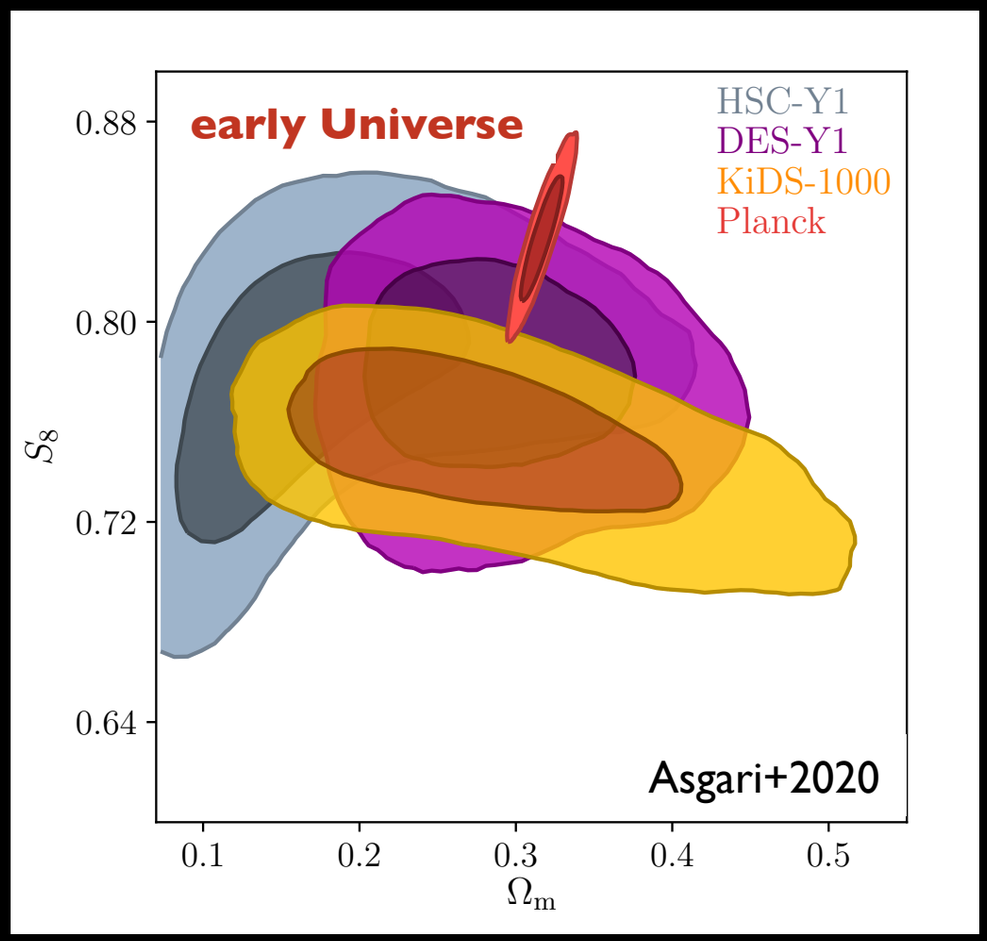
2020s: Concordance Cosmology?

Hubble Parameter - expansion rate



significant tension between early and late Universe physics!

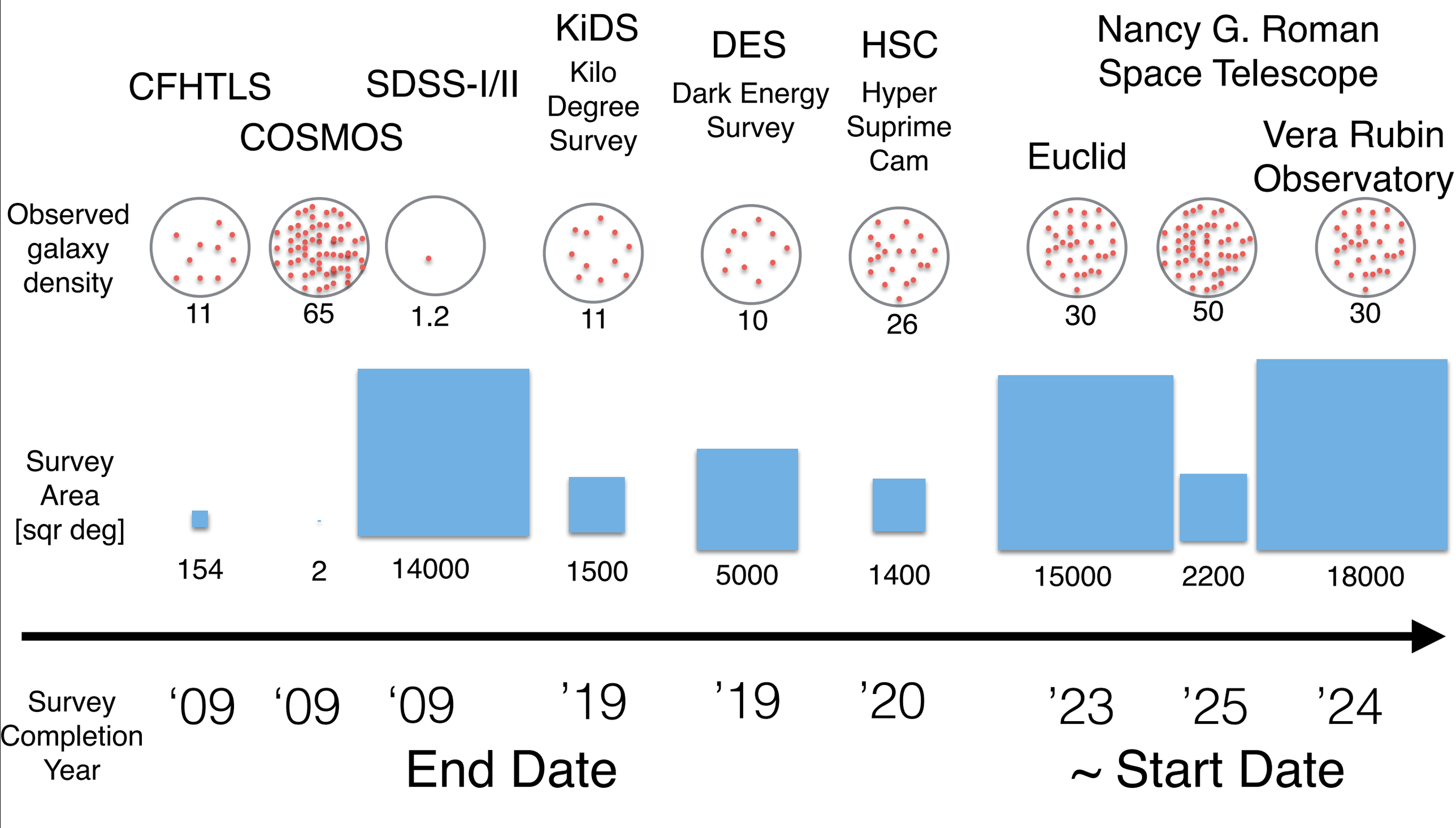
S8 - amplitude of structure growth



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

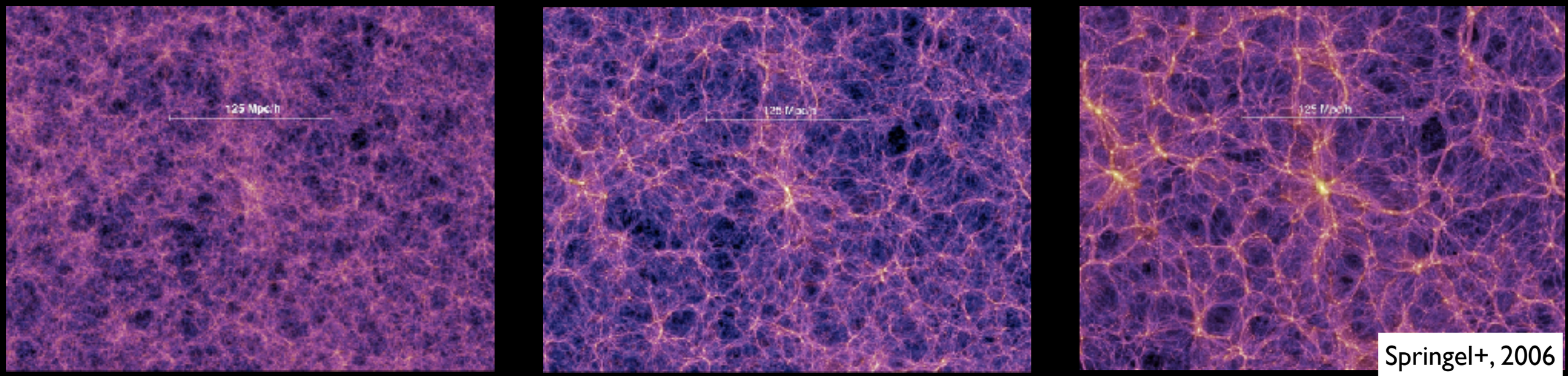
growth of structure constraints complementary to expansion rate

~linear (large) scales: perturbation theory

non-linear evolution: numerical simulations

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

time



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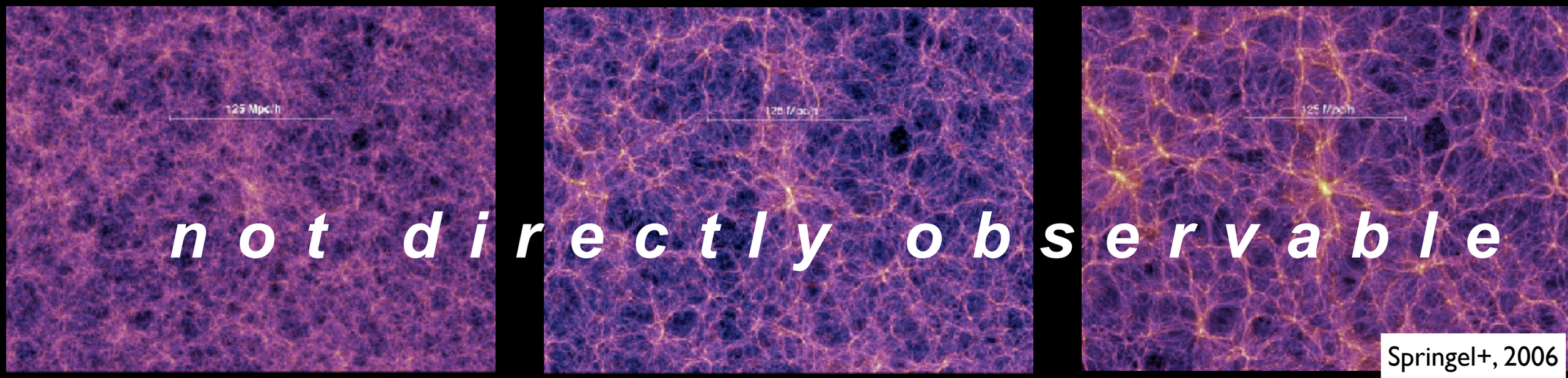
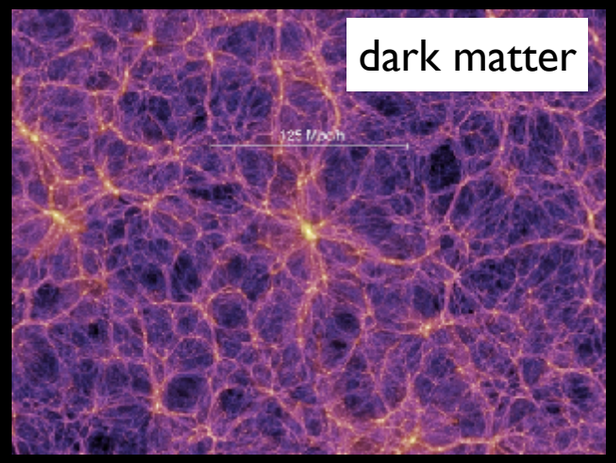


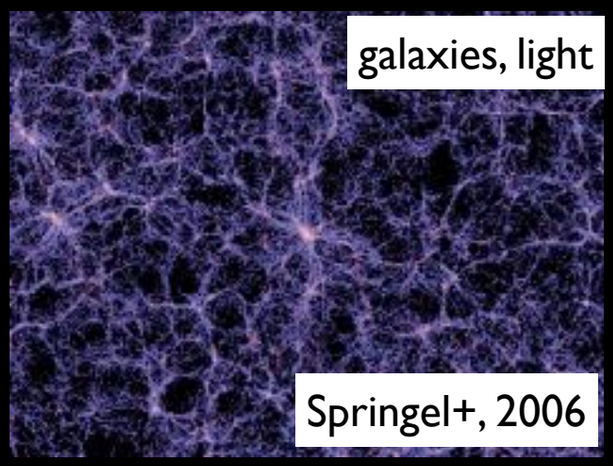
Connecting Theory and Observations

cosmological model
+ parameters

simulation/
perturbation theory

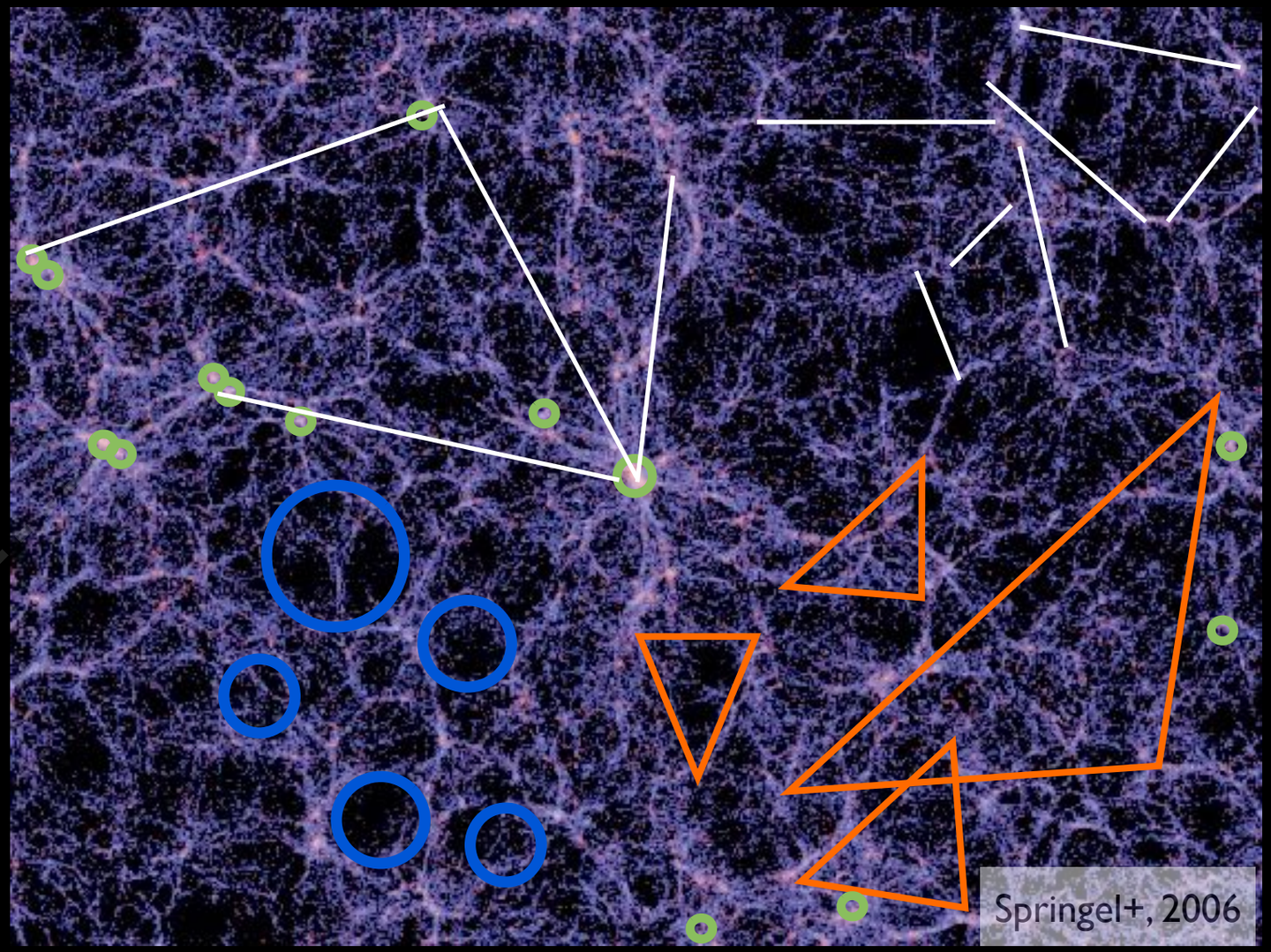


astrophysics (?)



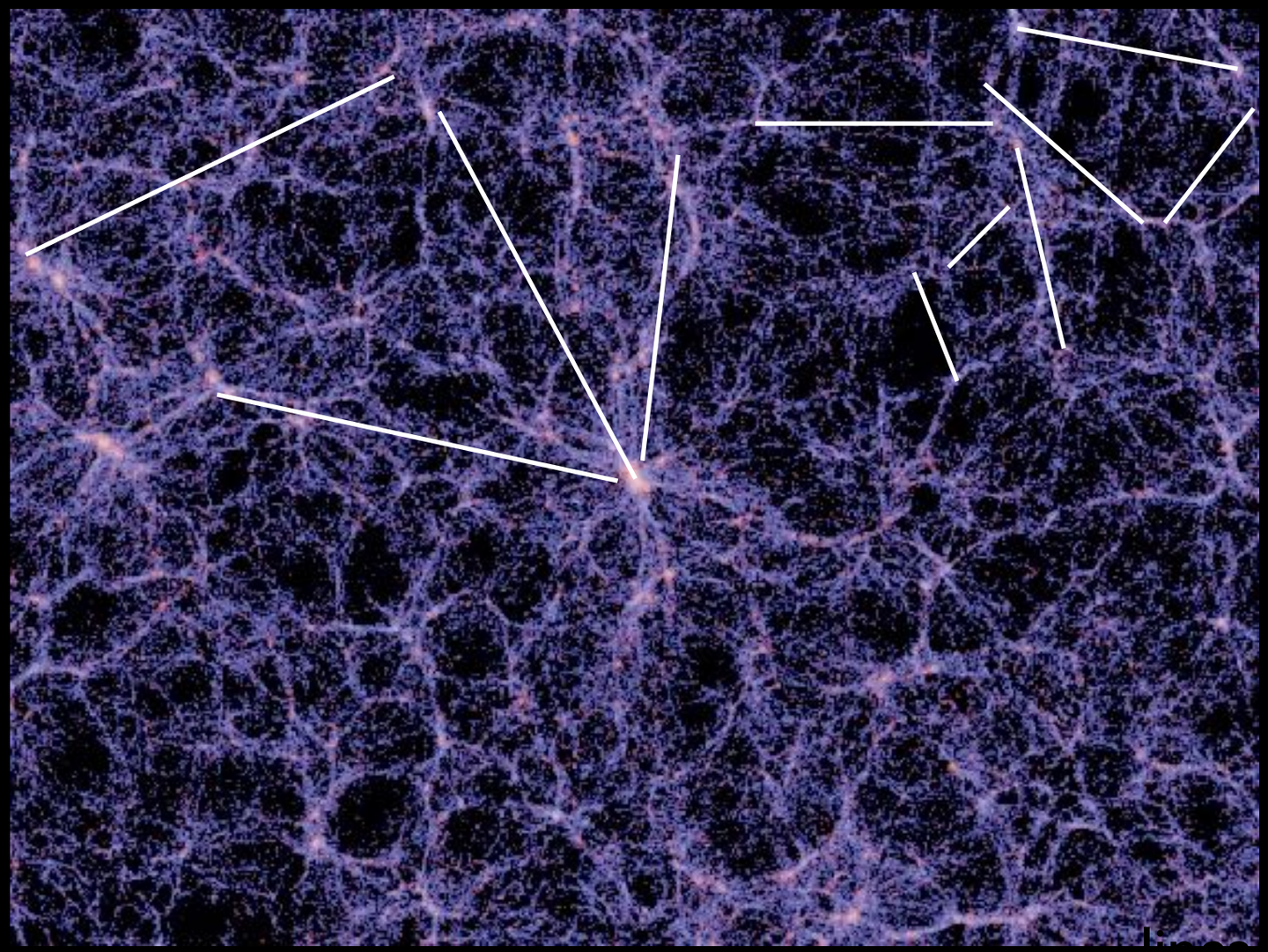
?

Summary Statistics from the Galaxy Distribution



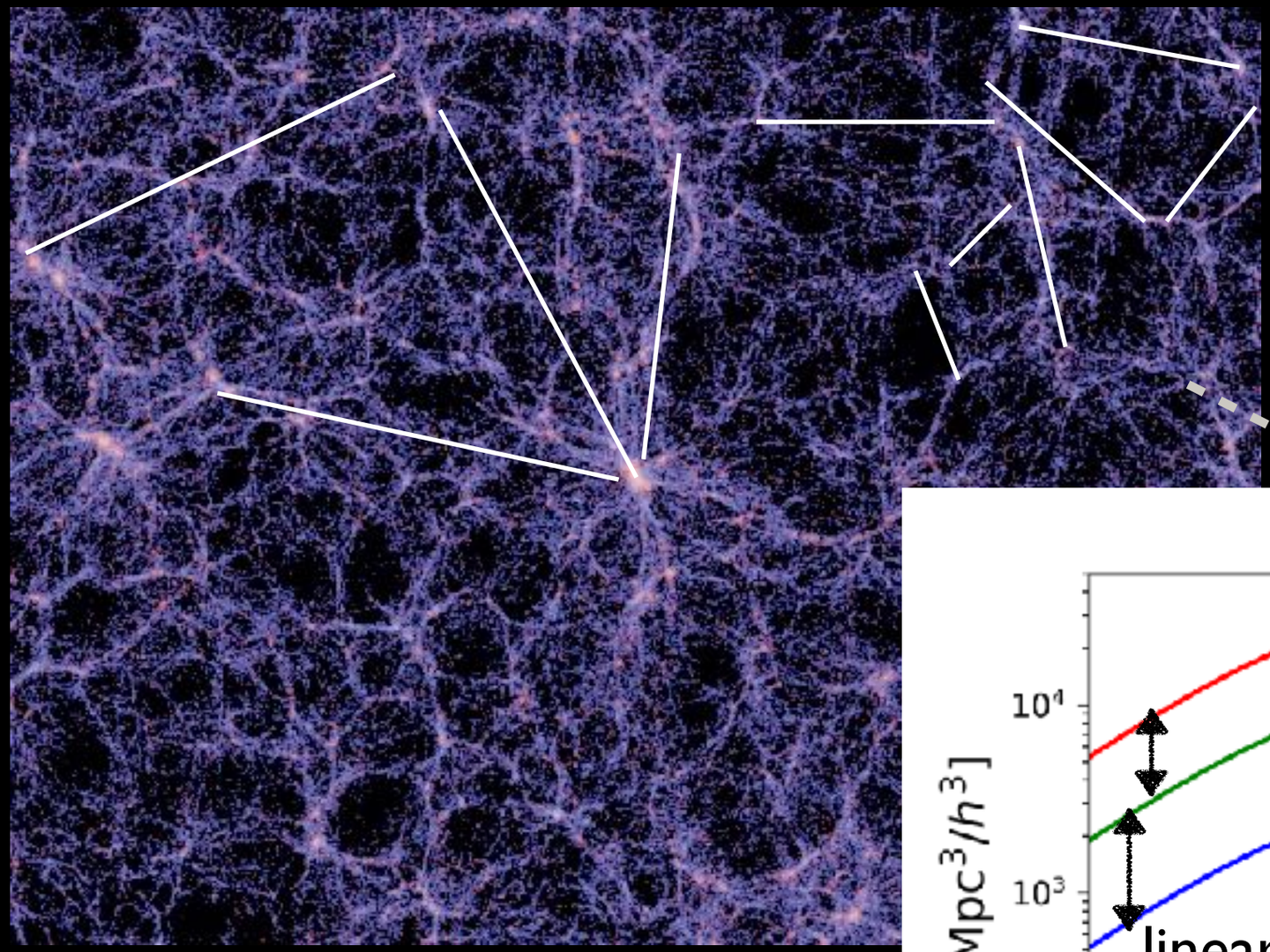
two-point correlations
clusters (over densities)
voids (under densities)
three-point correlations,...

Tracer: Galaxy Clustering



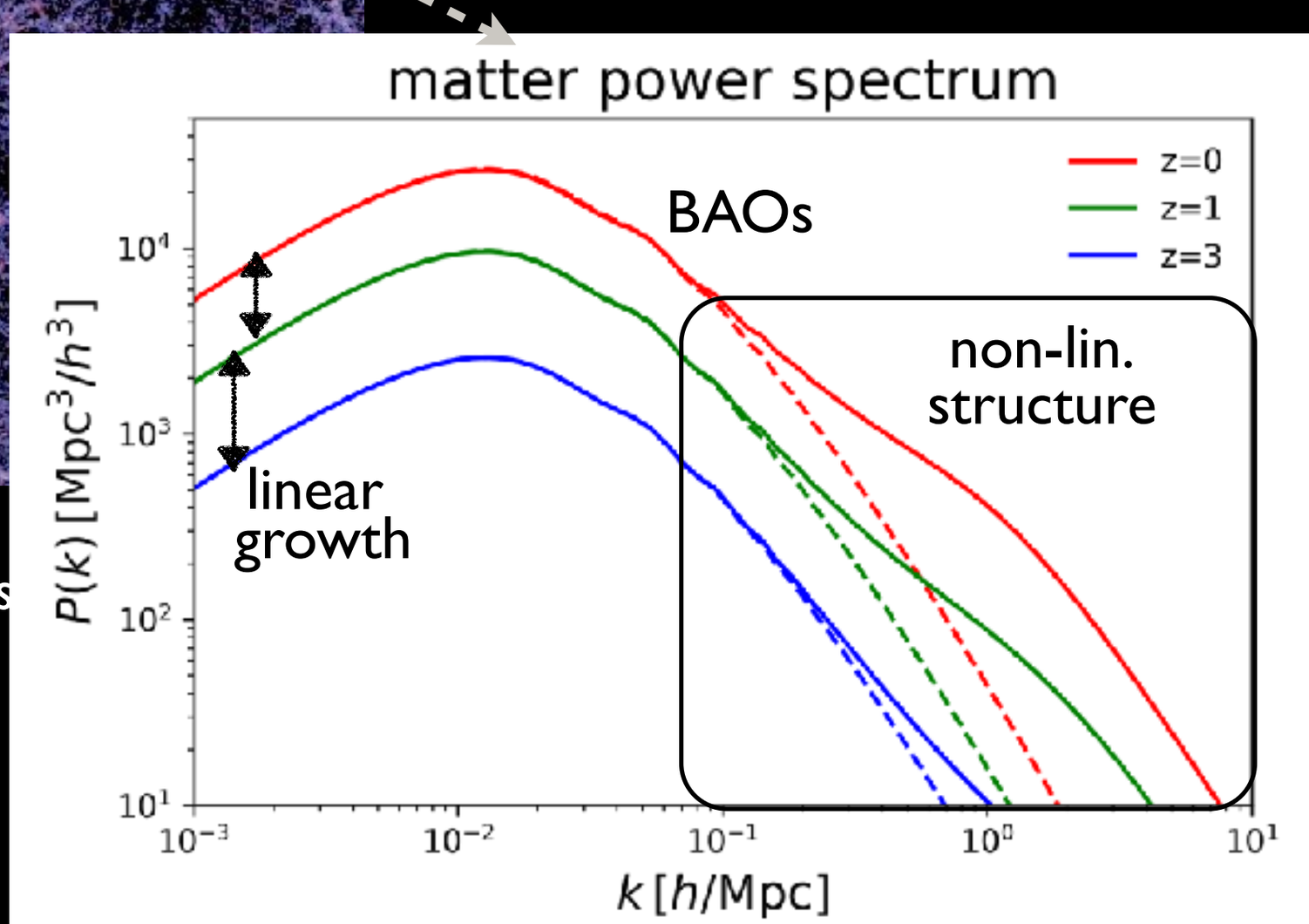
two-point correlations
excess probability of galaxy pairs
(over random distr.)
as function of separation

Tracer: Galaxy Clustering



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

Fourier transform



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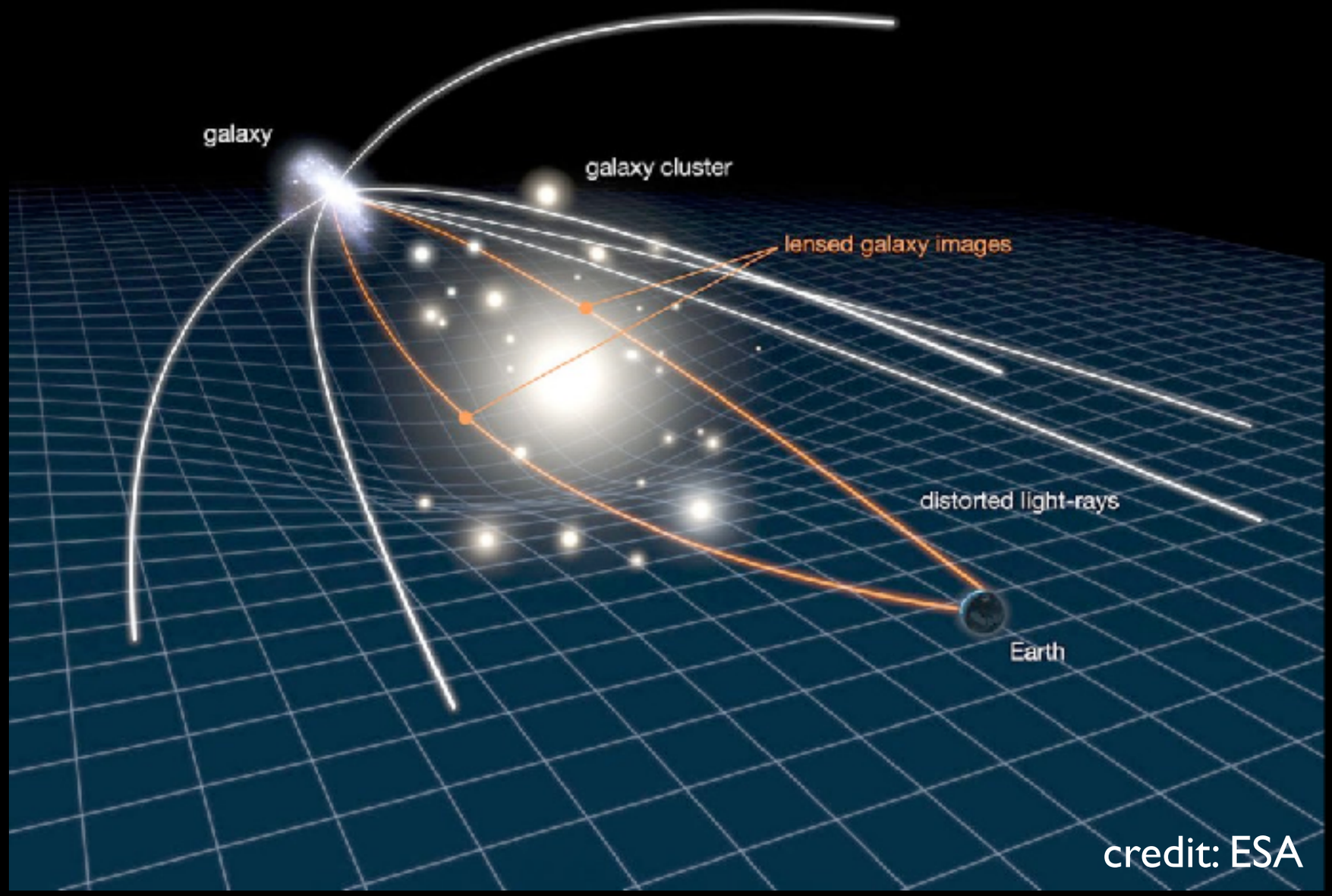
Tracer: Gravitational Lensing



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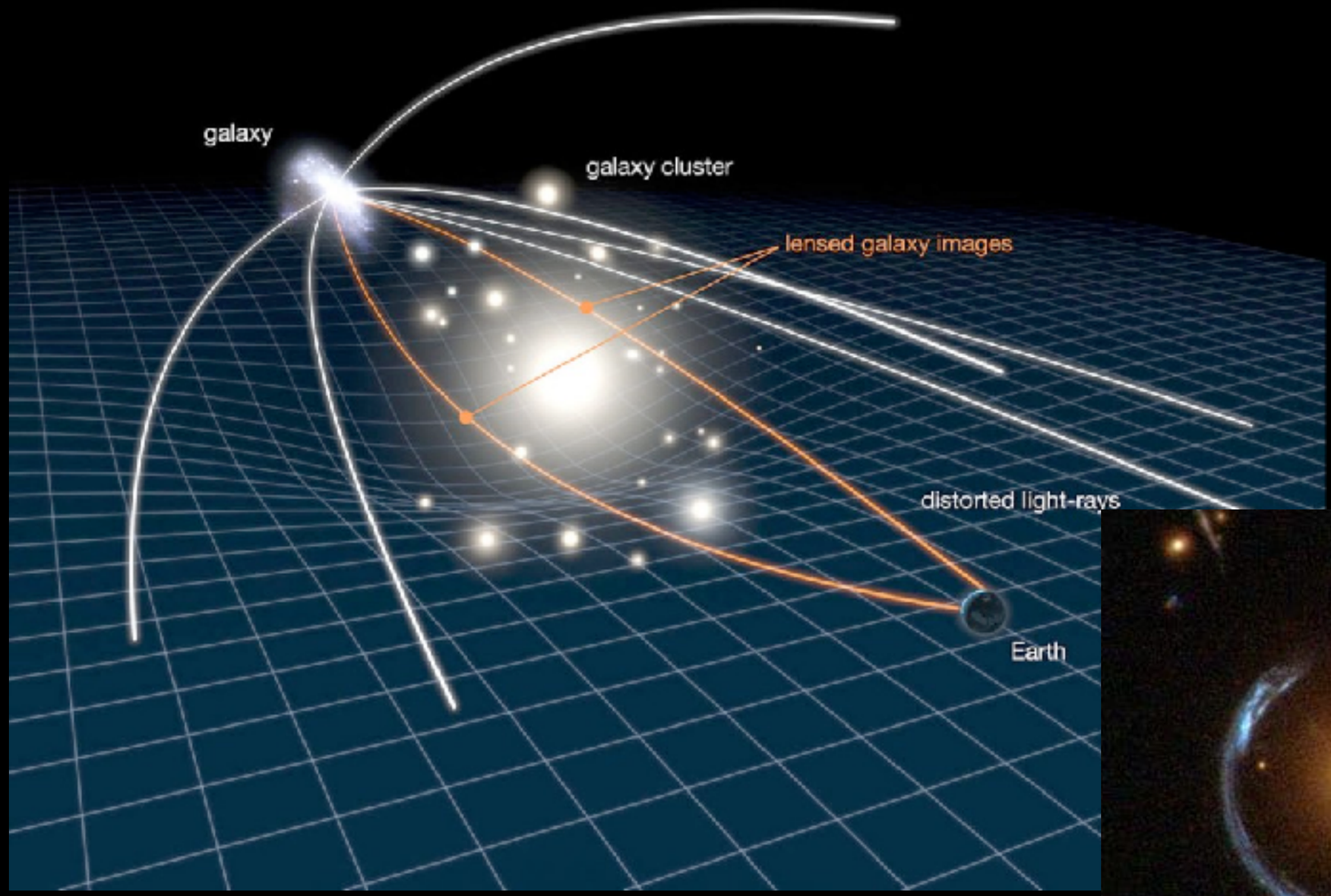


credit: ESA/Hubble & NASA

Tracer: Weak Gravitational Lensing of Galaxies

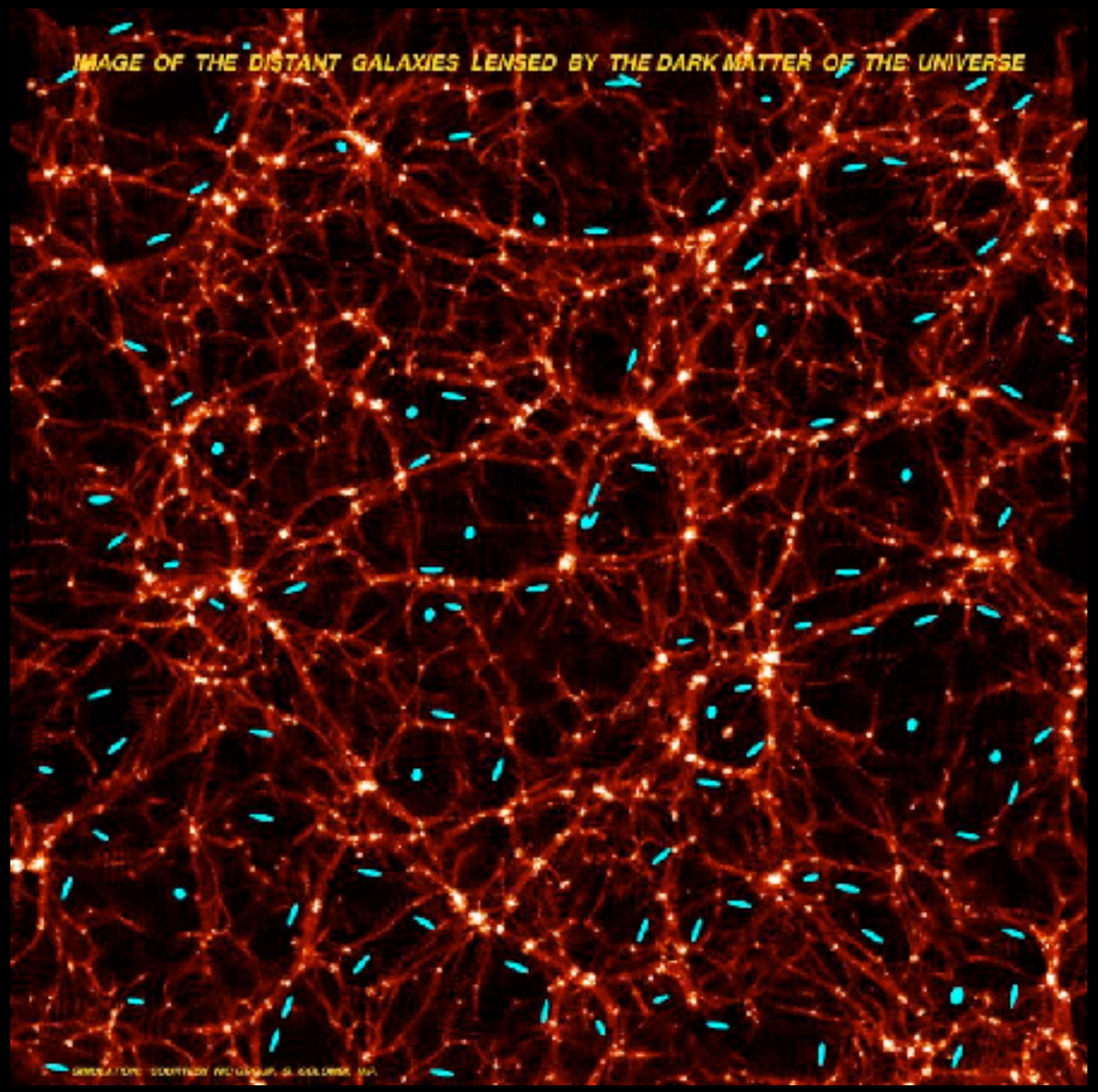
light deflected by tidal field of large-scale structure

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

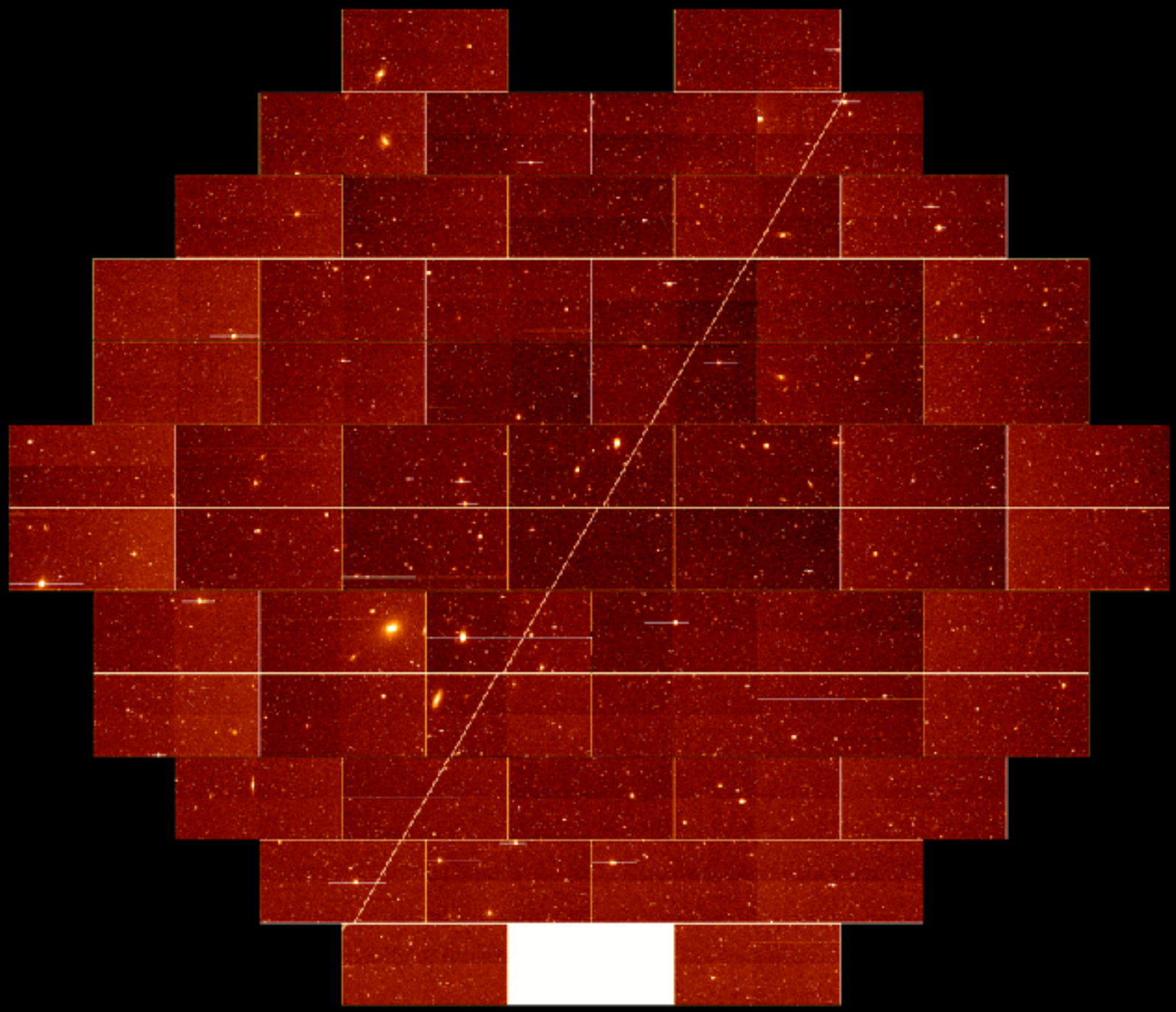
key uncertainties

shape measurements

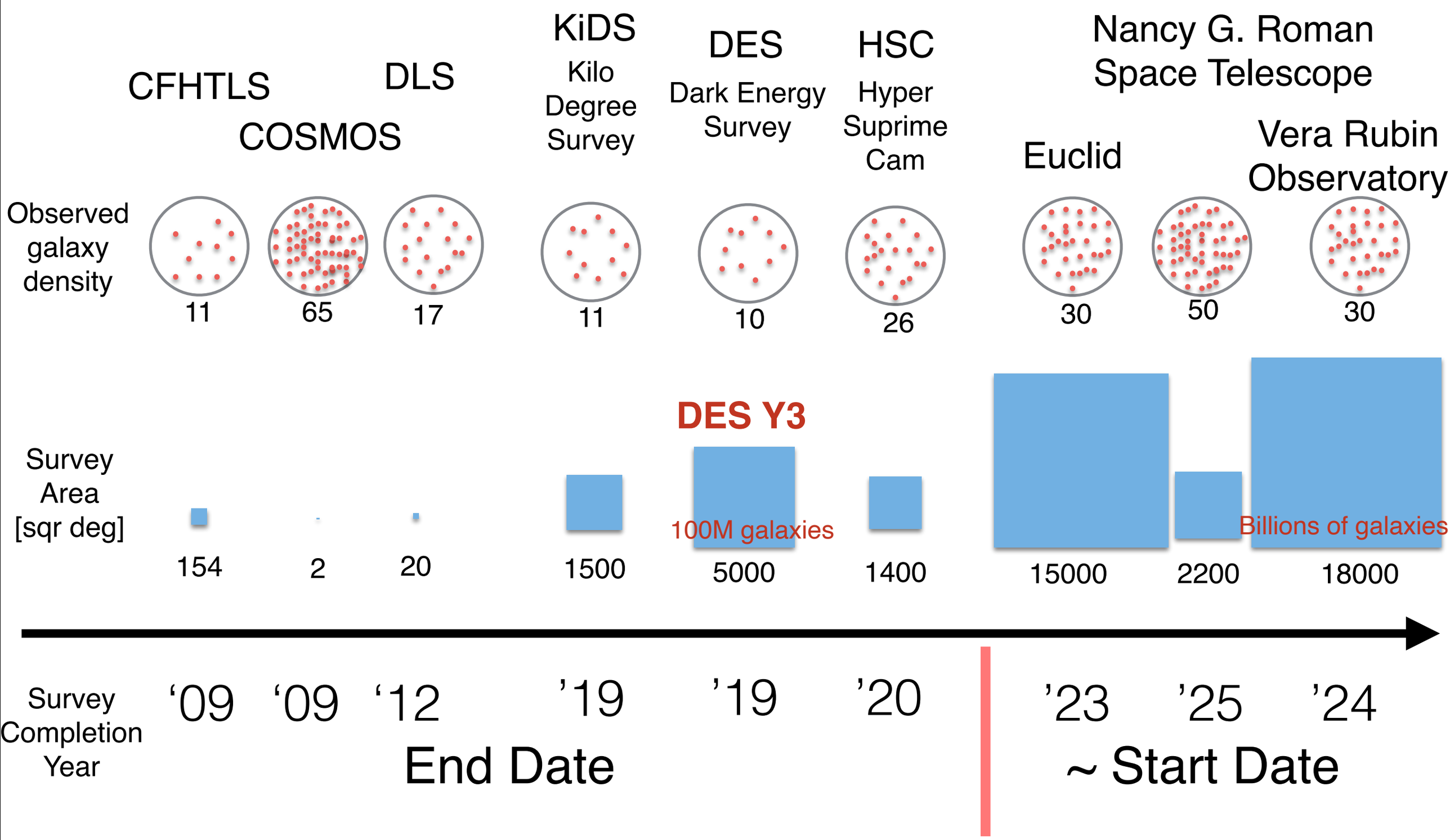
average over many galaxies assuming *random intrinsic orientation*



Weak Gravitational Lensing: typical DES galaxies



Real World Example: DES-Y3



The Dark Energy Survey

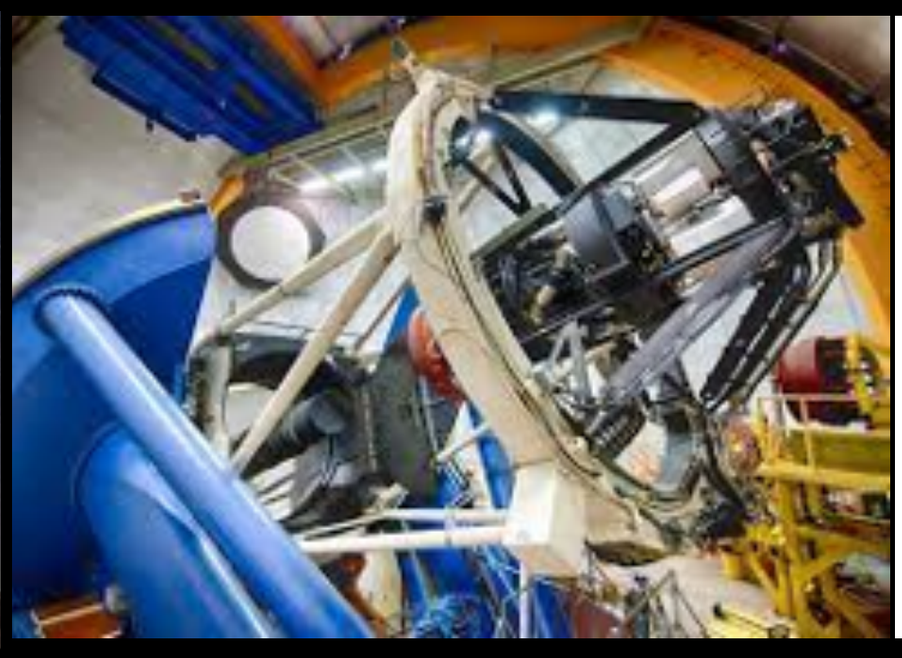
Imaging survey on Blanco 4-m telescope at CTIO in Chile

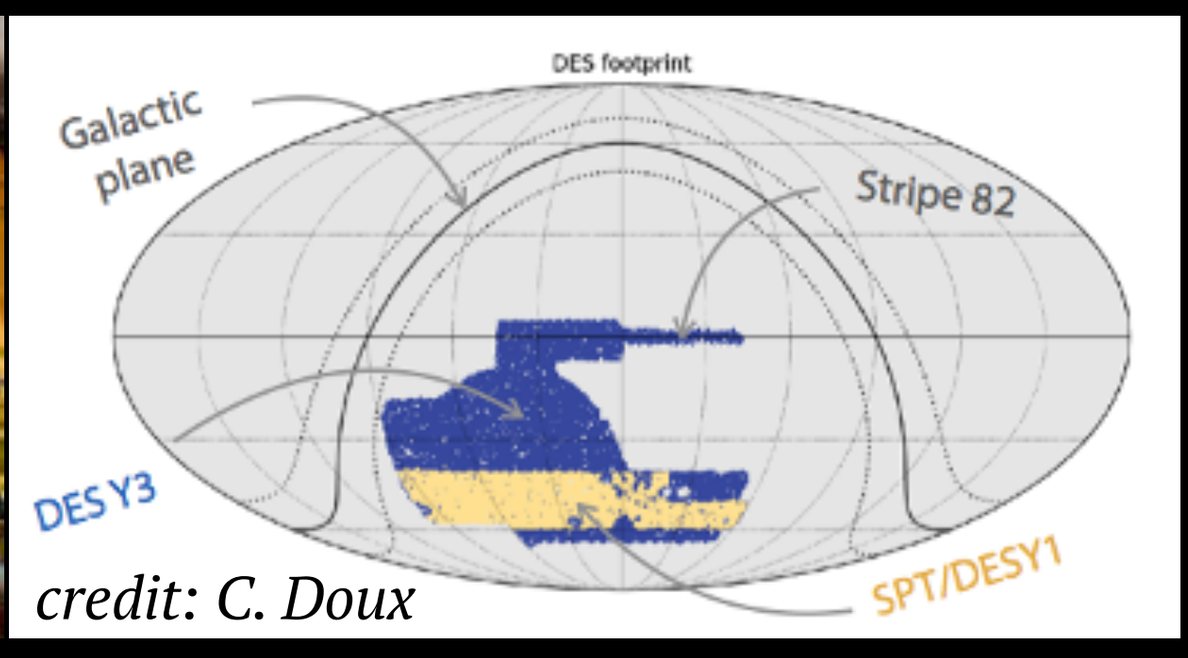
DECam: 3.0 sq. deg. field-of-view, 570 Mpixels, grizY filters

5000 sq. deg. footprint, observed 2013-2019, wide field + supernova fields

DR2 (6 years) of 543M galaxies + 145M stars to r~23.5

Data released to the public: https://des.ncsa.illinois.edu/home





credit: C. Doux

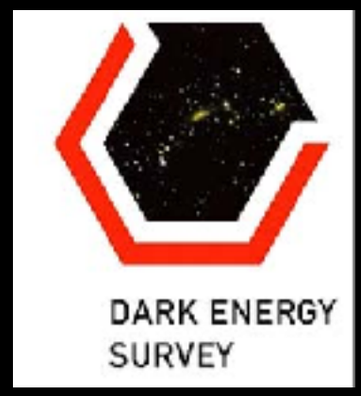
Dark Energy Survey Collaboration

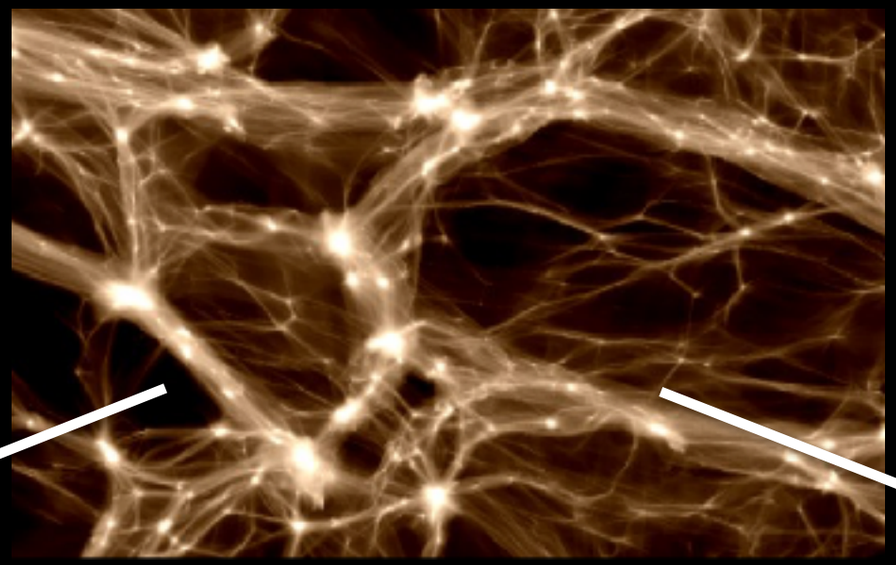
~400 scientists from 25 institutions in 7 countries

Much of the analysis leadership by Early Career Scientists

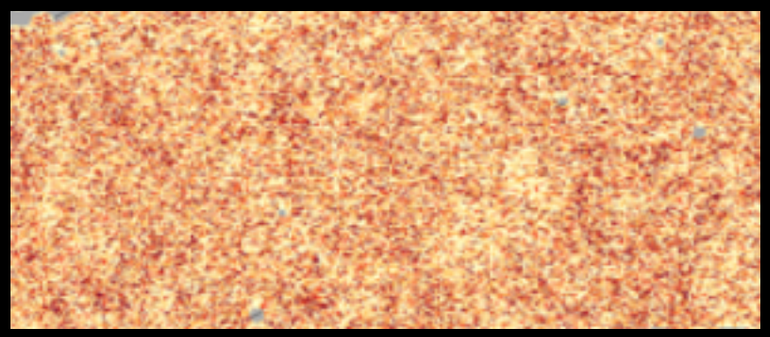
Learn more about DES: Scientists of the Week, Darchive, #ThisIsDES, #Darkbite

DES-Y3 WL x LSS Analysis

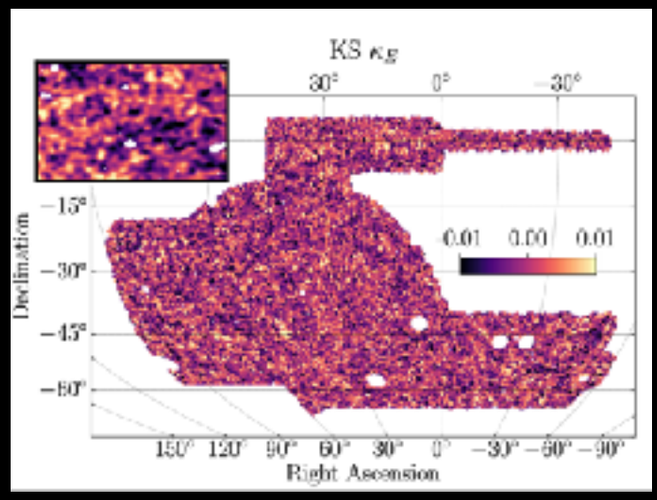




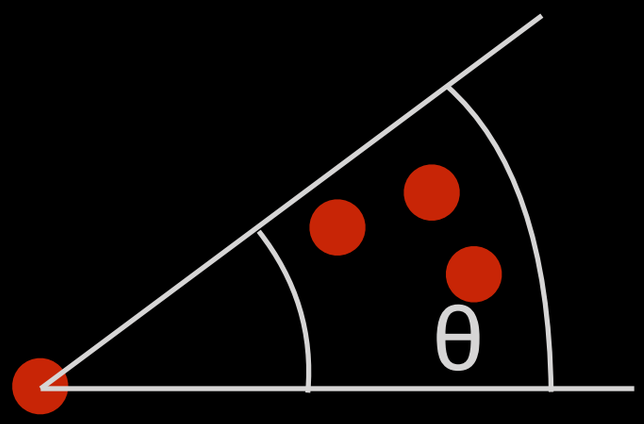
10M lens galaxies
split in 6 redshift bins



100M source galaxies
split in 4 redshift bins

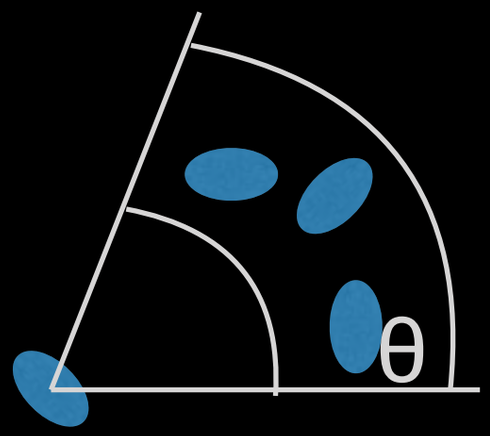


galaxies x galaxies:
angular clustering



galaxies x lensing:
galaxy-galaxy lensing

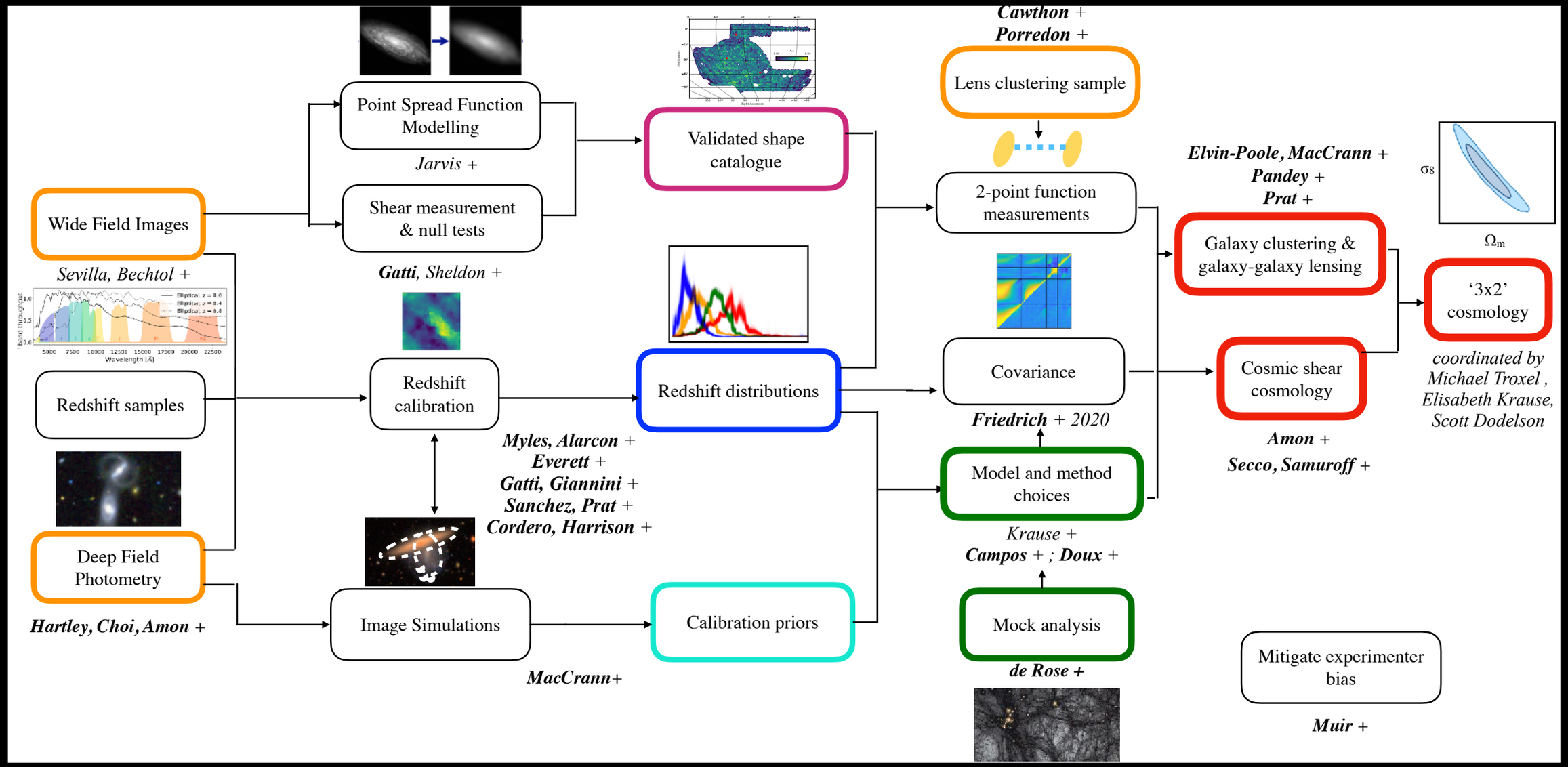
lensing x lensing:
cosmic shear



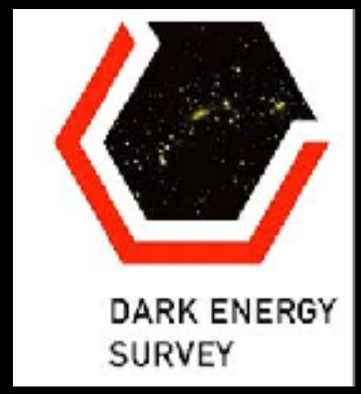
DES-Y3 Cosmology

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

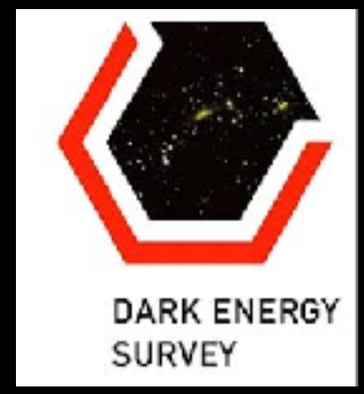
- linear bias of lens galaxies, per lens z-bin
- magnification bias of lens galaxies, per lens z-bin
- intrinsic alignments, tidal alignment + tidal torquing, power-law z-evolution

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
Systematics Modeling + Mitigation



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observational uncertainties (13 parameters)

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

-> this list is known to be incomplete

how much will **known, unaccounted-for** systematics bias Y3?

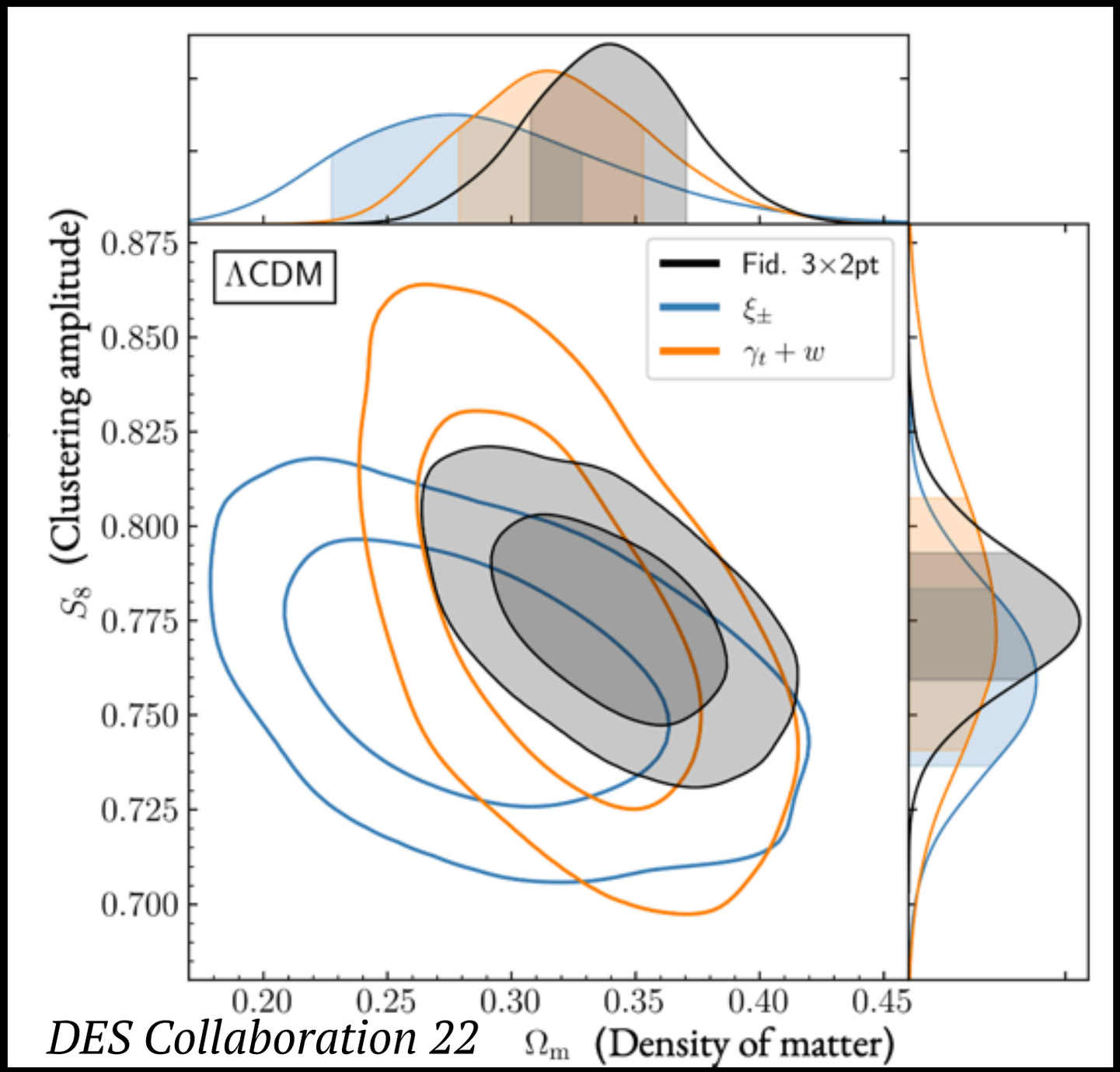
-> remove contaminated data points (*i.e., throw out large fraction of S/N*)

-> choice of parameterizations ≠ universal truth

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

EK+2021

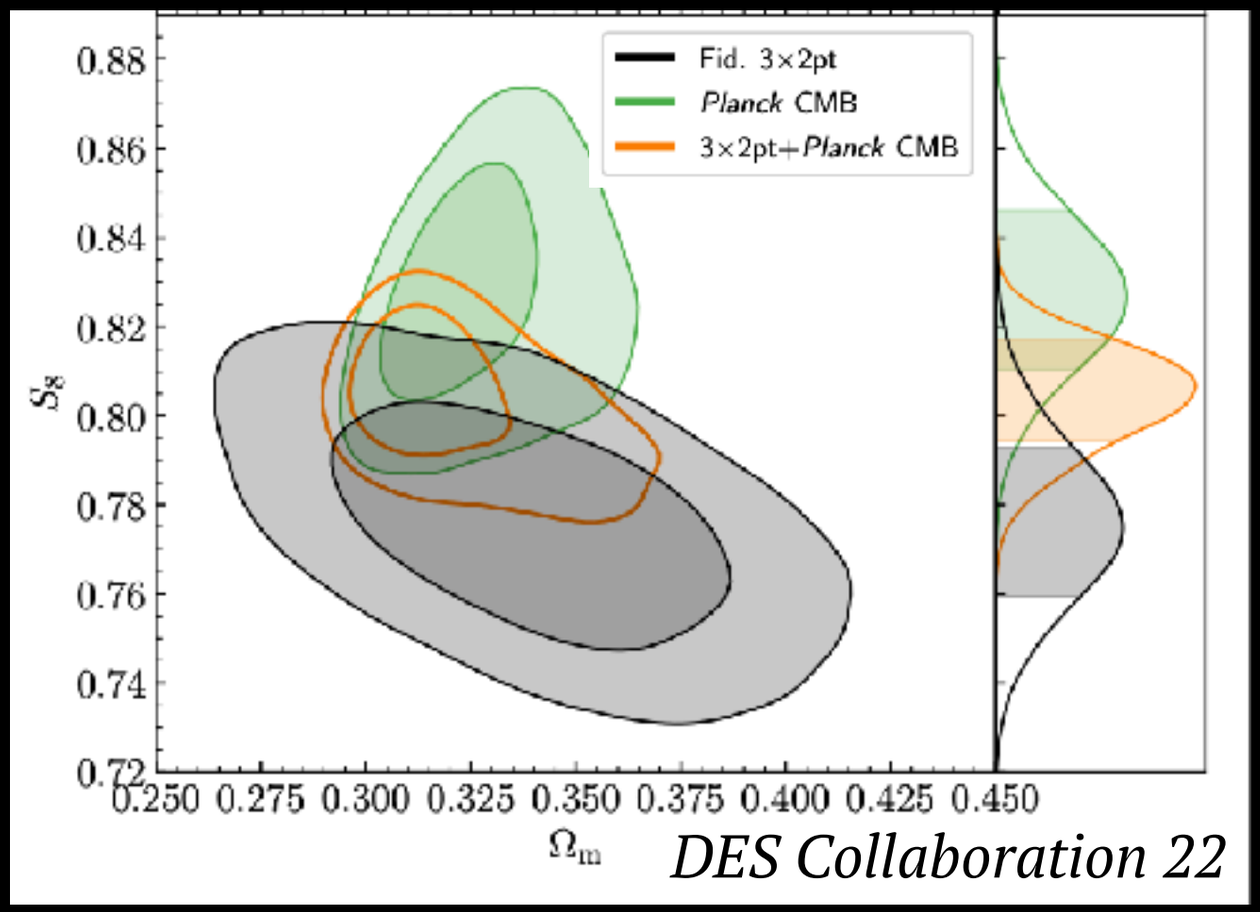
DES Y3 Results: LCDM Multi-Probe Constraints



DES Collaboration 22

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

DES Y3 Results: Late vs. Early Universe

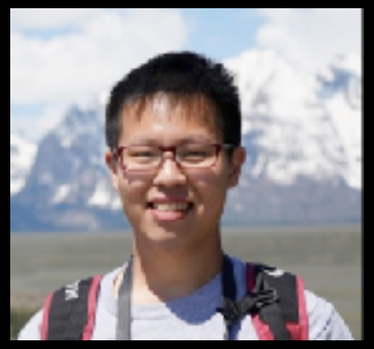


DES Collaboration 22

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)

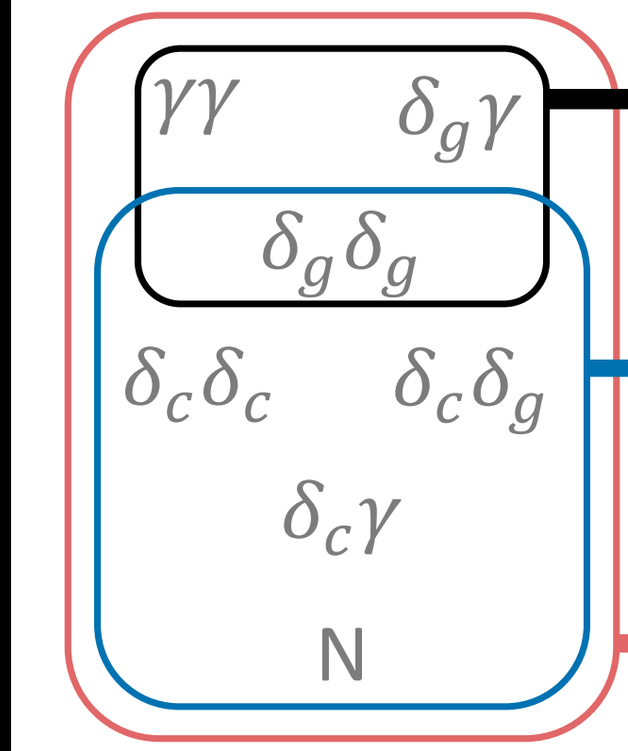
- **Future: observe more galaxies, combine more probes, and achieve better systematics control!**



Beyond 3x2pt: Cluster Counts x 2PCFs

DARK ENERGY SURVEY

To, EK+(DES) 2021a,b: DES-Y1 cluster cosmology constraints from abundances and large-scale two-point statistics



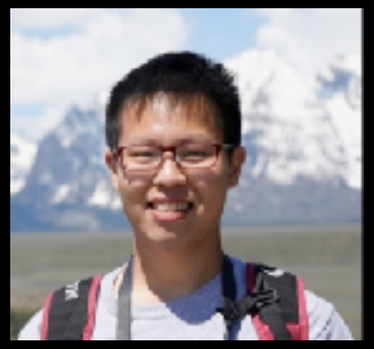
3x2pt:
- Method: Krause&Eifler et al. (2017)
- Simulation: MacCrann&DeRose et al. (2018)
- Results: DES Collaboration (2018)

4x2pt+N:
- Method: To&Krause et al. (2020a)
- Simulation: To&Krause et al. (2020a)
- Results: **This work**

6x2pt+N:
- Results: **This work**

- 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

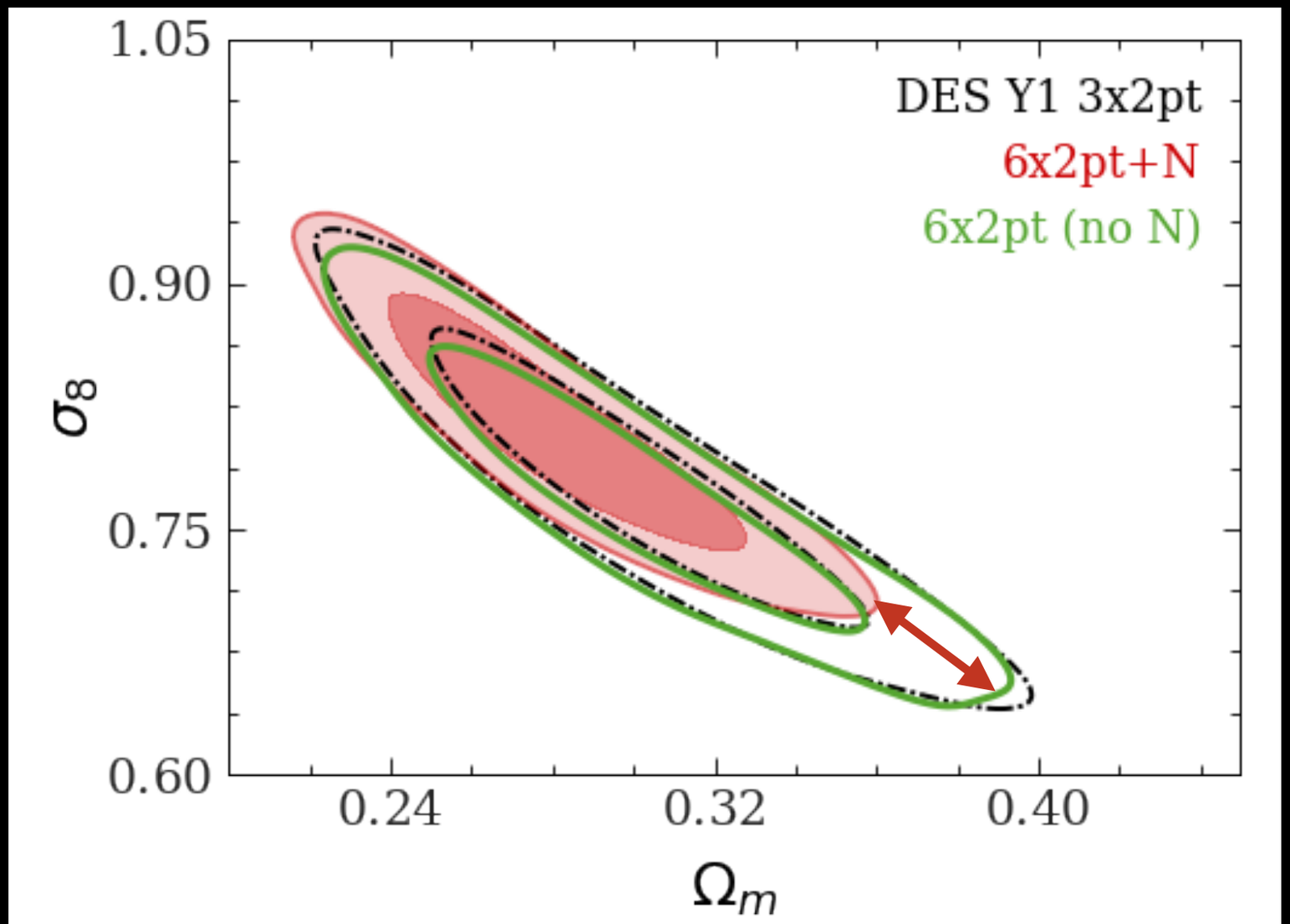


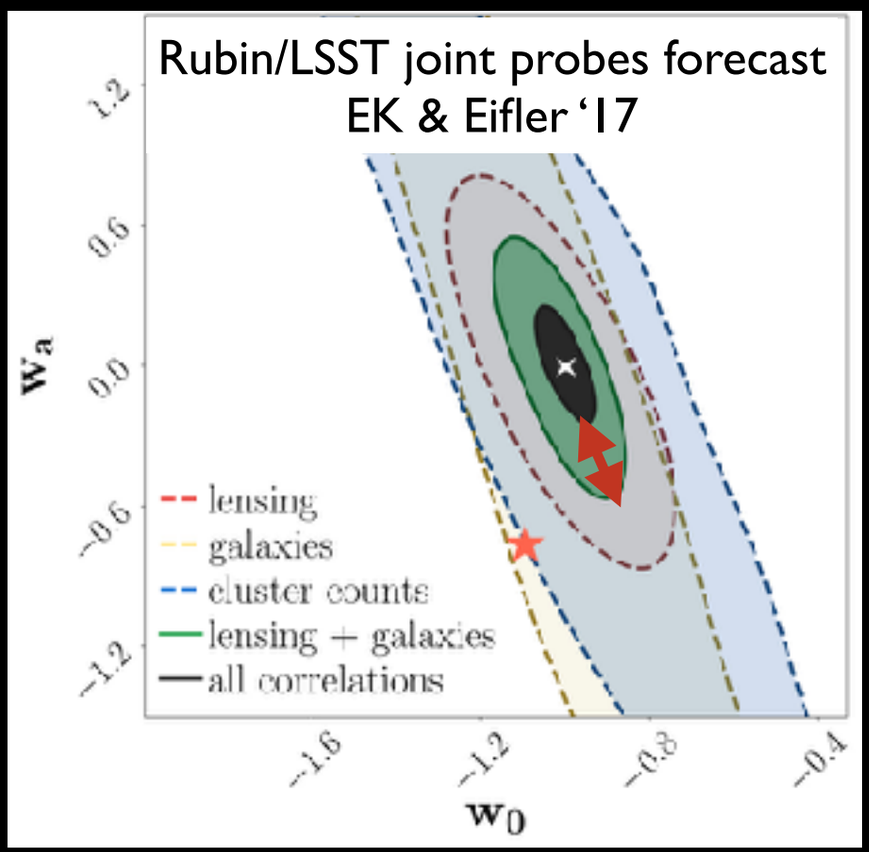
Beyond 3x2pt: Cluster Counts x 2PCFs

DARK ENERGY SURVEY

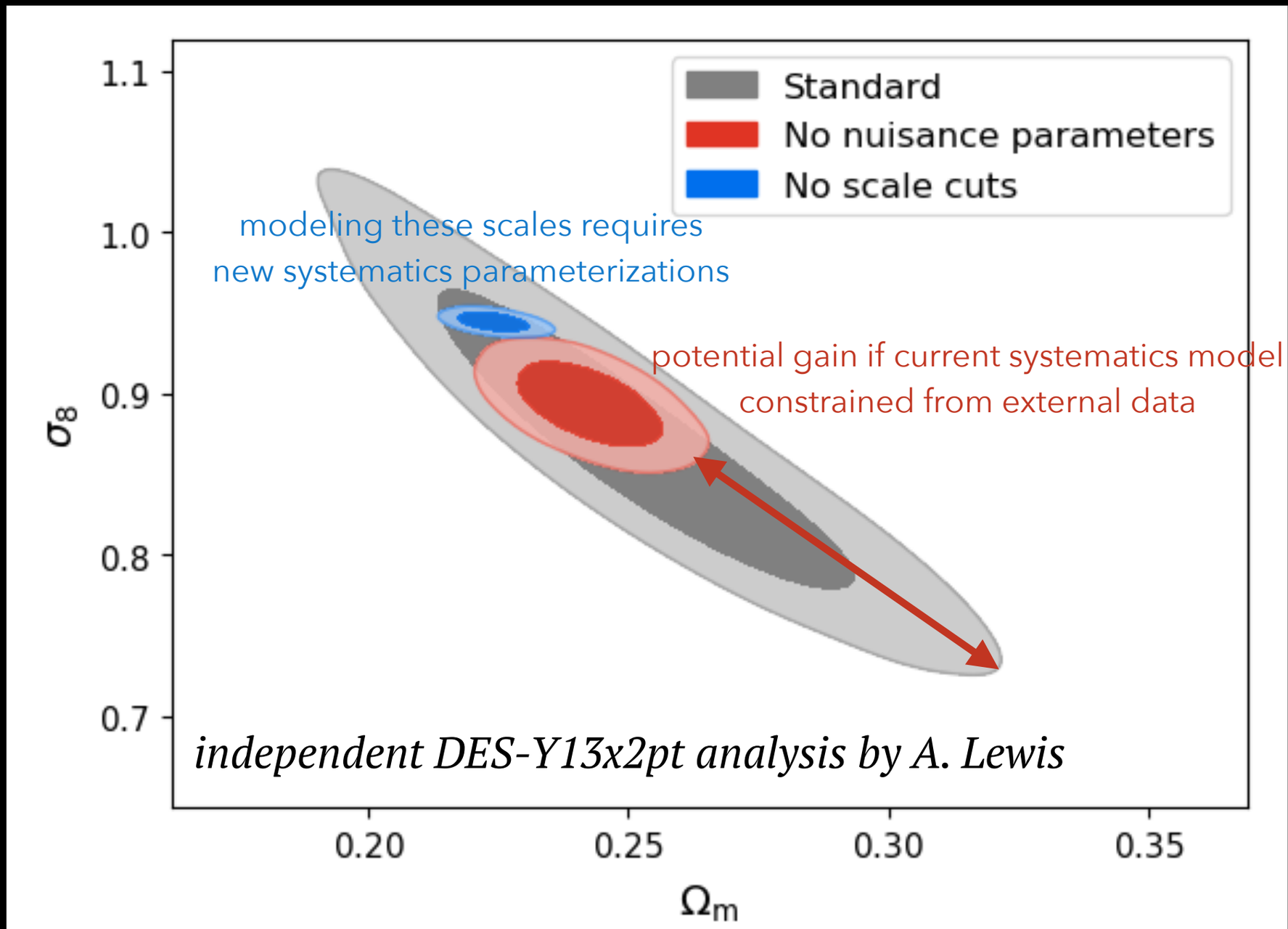
this analysis unlocks constraining power from number counts

substantial gain, *iff accurate MOR calibration*





3x2pt Systematics Mitigation
Opportunity Space...



Conclusions

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

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

- DES-Y3 and other weak lensing results hint at low amplitude w.r.t. CMB
- (most) cosmological constraints will be systematics limited
    - require astrophysics, accurate systematics parameterizations+priors

- Precision cosmology requires collaboration across surveys + wavelengths, planning for analysis frameworks to combine data from all surveys!

Thank you!

DES is producing exciting multi-probe cosmology constraints

These analyses require expertise from pixels to galaxies to theory

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