Dark Energy Surveys

Elisabeth Krause, Stanford/SLAC

including preliminary results from the Dark Energy Survey collaboration

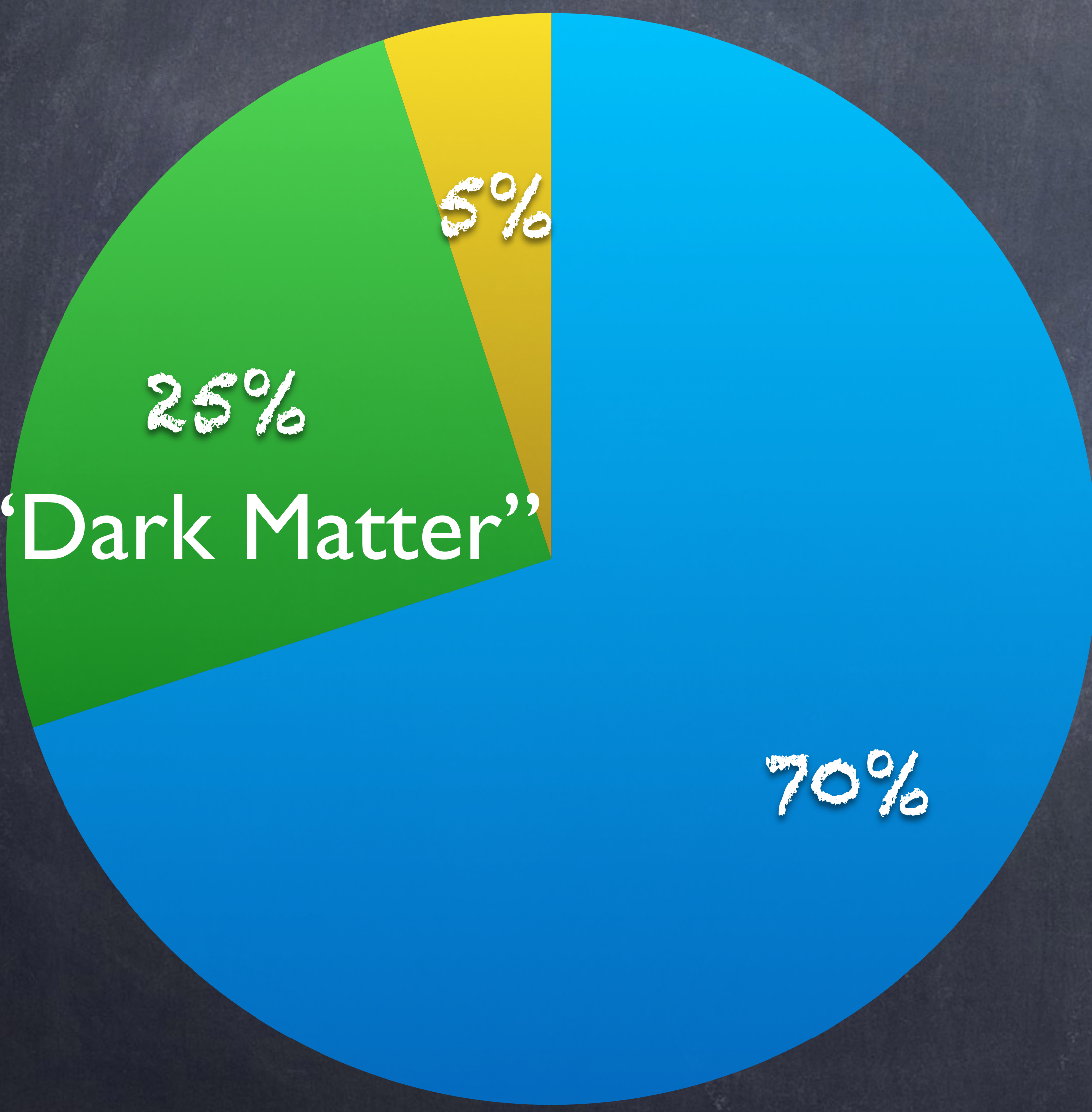
EPS-HEP 07/12/2017

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 often not quite as simple]

Our Puzzling Universe

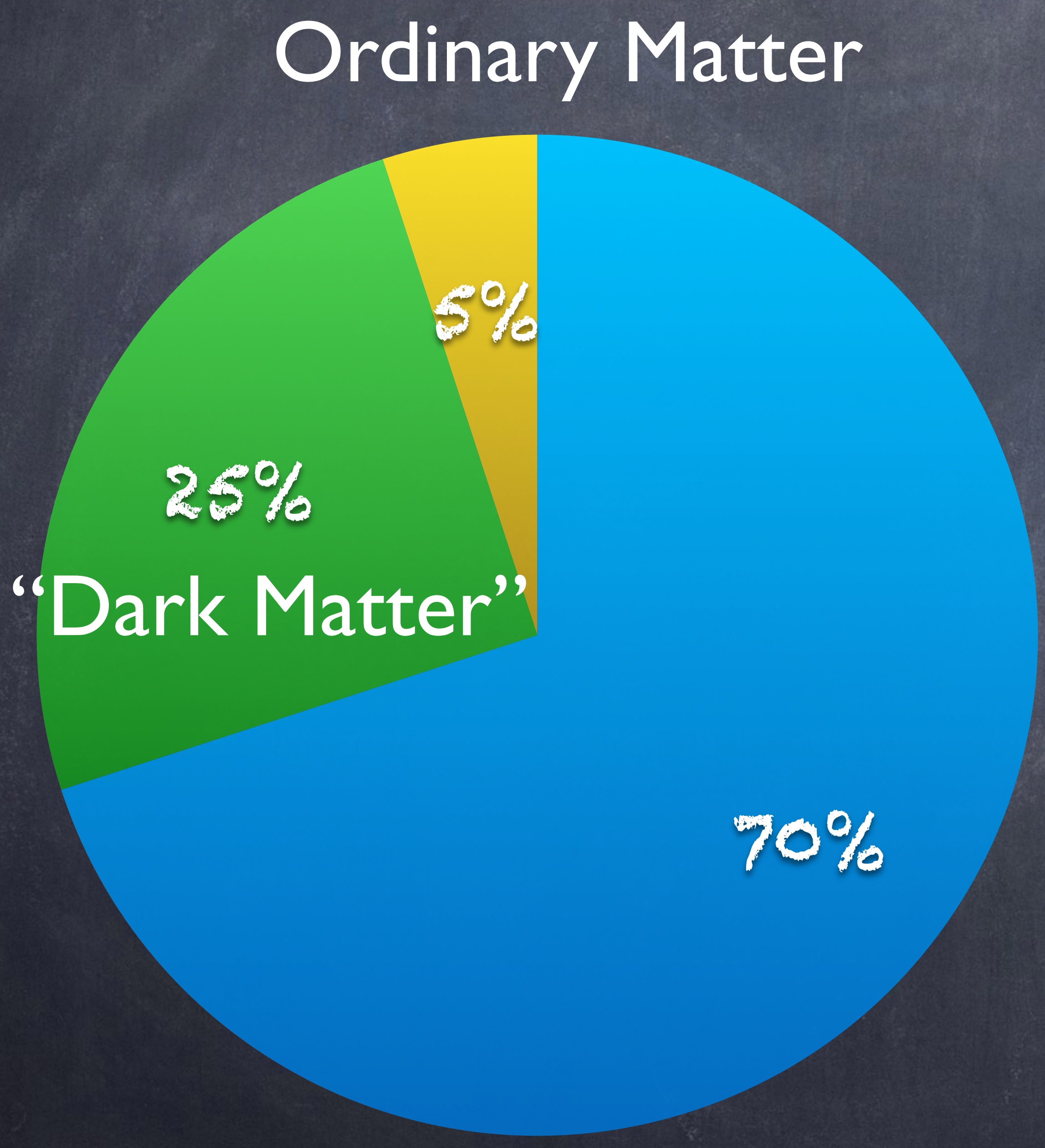


"Dark Energy"

- accelerates the expansion
- dominates the total energy density
- smoothly distributed

acceleration first measured by SN 1998

Our Puzzling Universe



“Dark Energy”

- accelerates the expansion
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acceleration first measured by SN 1998

next frontier: understand

- cosmological constant Λ: $w \equiv P/\varrho = -1$?
  - magnitude of Λ very surprising
- dynamic dark energy varying in time and space, $w(a)$?
- breakdown of GR?

Theory Space: Breaking GR

Many new DE/modified gravity theories developed over last decade

Most can be categorized based on how they **break GR**:

The only **local**, **second-order** gravitational field equations that can be derived from a **four-dimensional action** that is constructed **solely from the metric tensor**, and admitting Bianchi identities, are GR + Λ.

Lovelock's theorem (1969)

[subject to viability conditions]

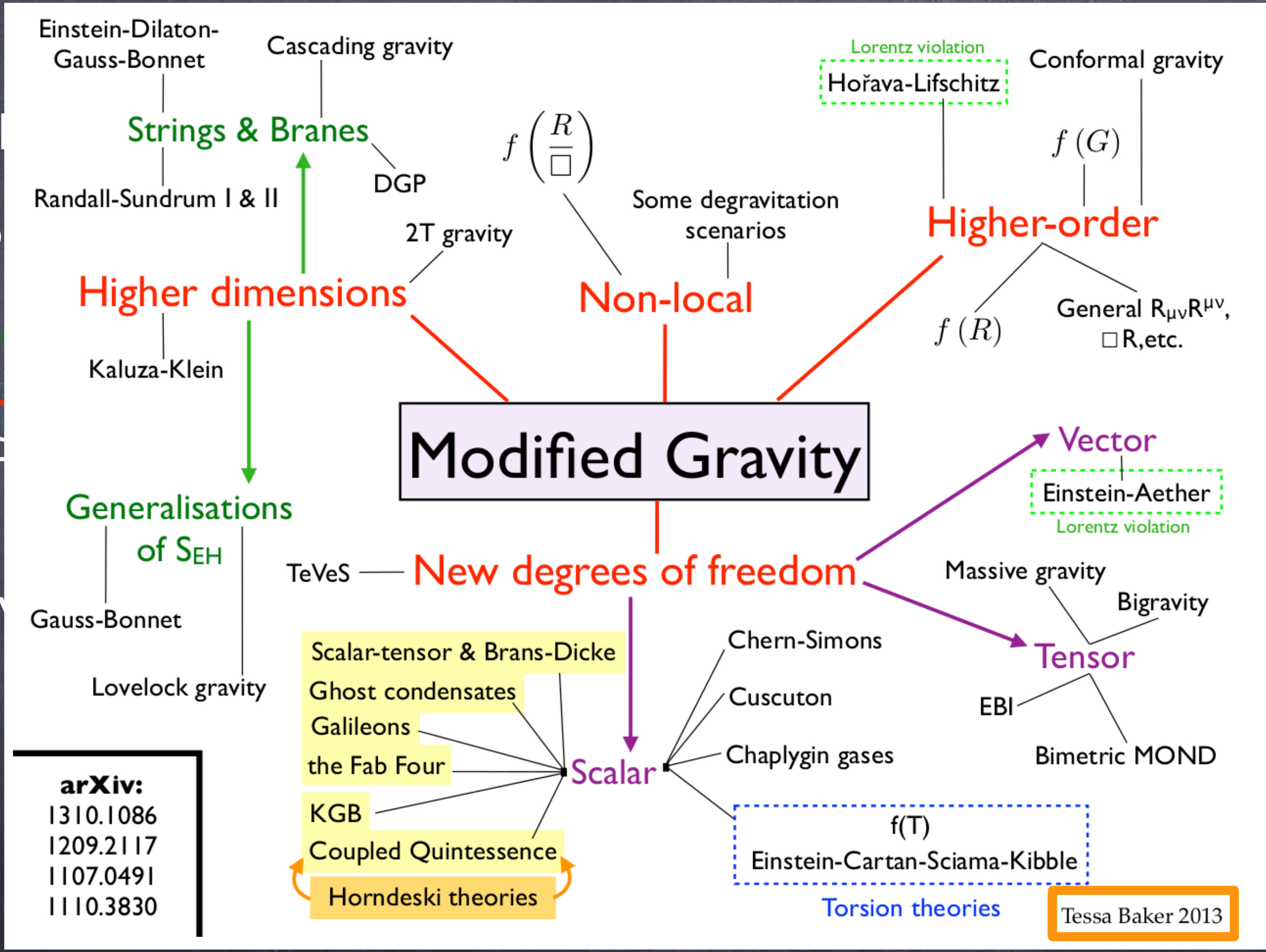
Theory Space: Breaking GR

Many new

Most can b

The only be derived from a fou the metric tensor, and theorem (1969)

Subject to



No favored alternative theory, theory space hard to summarize succinctly

Need unifying frameworks + phenomenology to compare to data

Testing Cosmic Acceleration

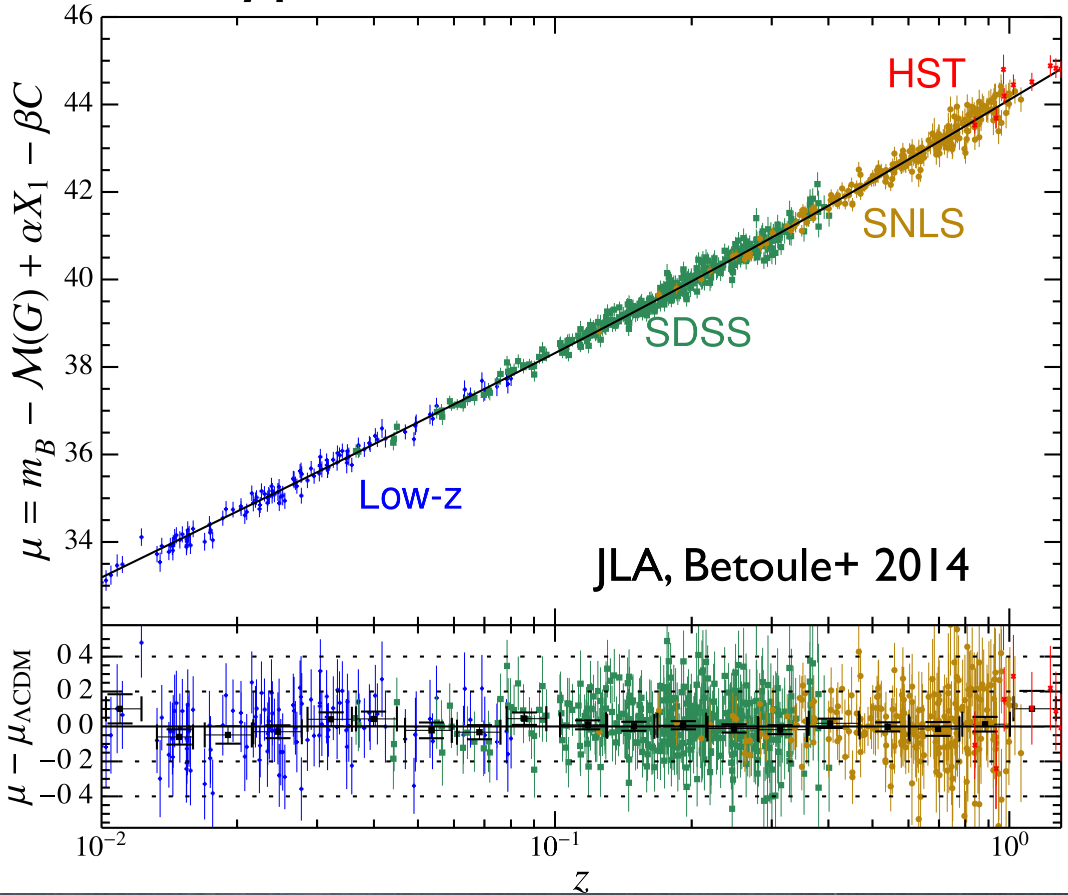
important to test GR over cosmological scales

Expansion history

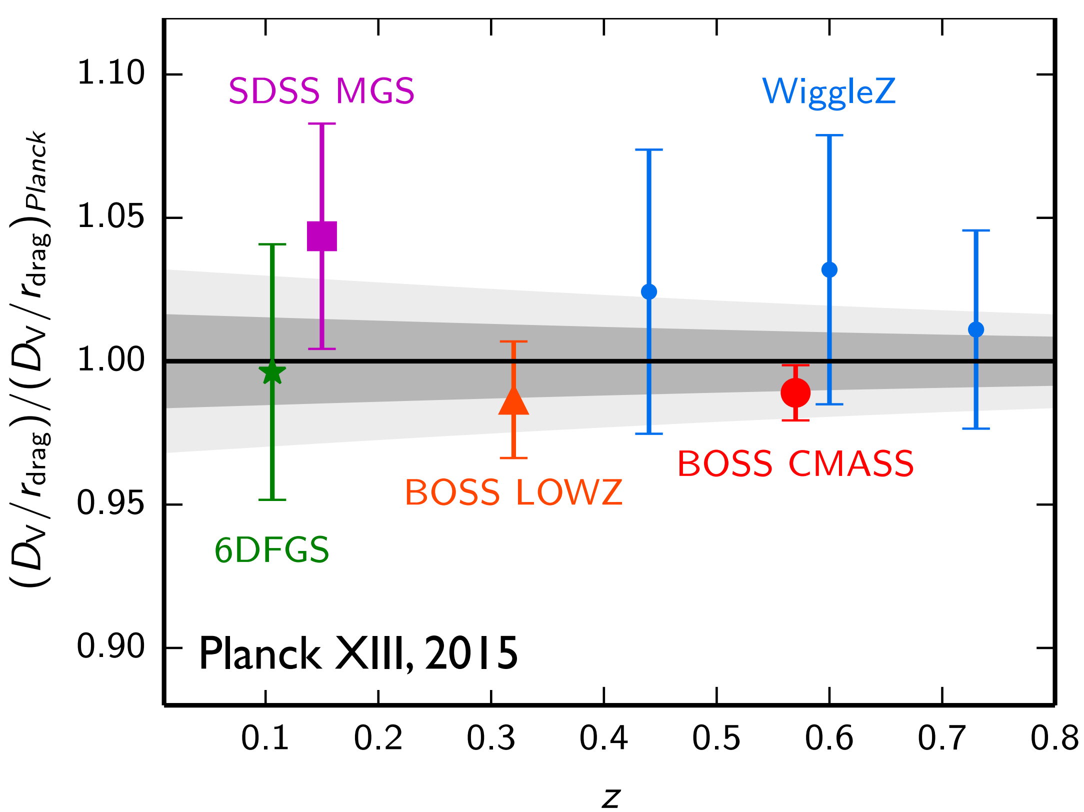
$$H^2(a) = H_0^2 \left(\Omega_M a^{-3} + \Omega_{DE} a^{-3(1+w_0+w_a)} e^{-3w_a(1-a)} \right)$$

- from supernovae, CMB peaks + baryonic acoustic oscillations (BAO)
- agreement with ΛCDM
- limited information on dark energy/ modified gravity: at most w0, wa

Type IA SN state of the art



BAO state of the art



Cosmic Structure Formation

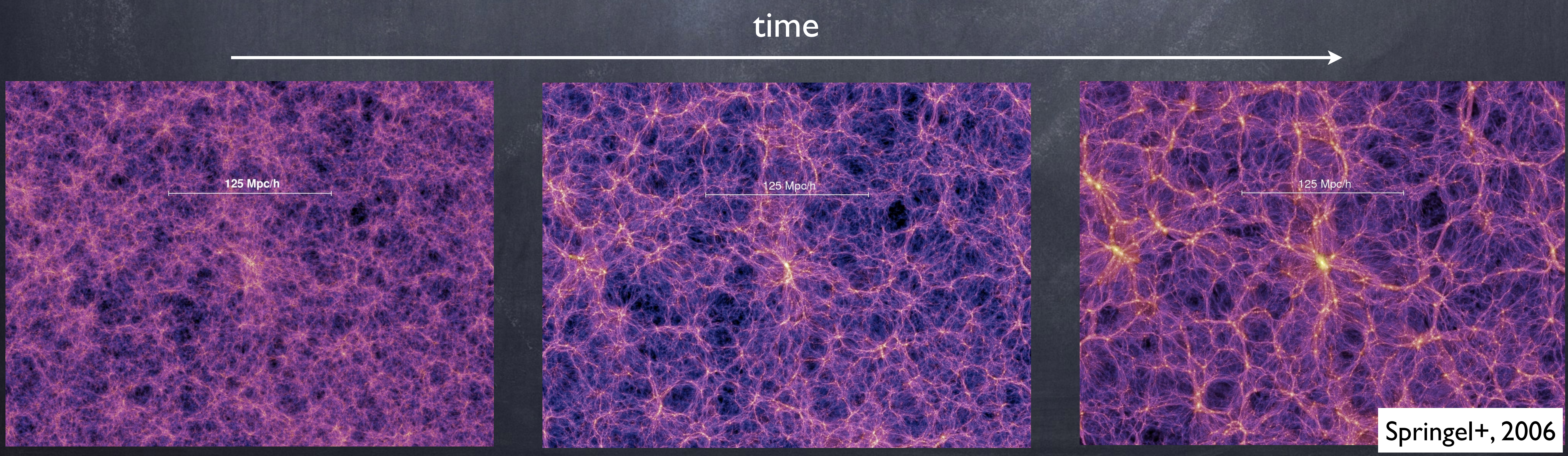
gravity drives **formation of cosmic structure,** dark energy slows it down

growth of structure contains much more information than expansion rate

linear level: perturbation theory

non-linear evolution: numerical simulations

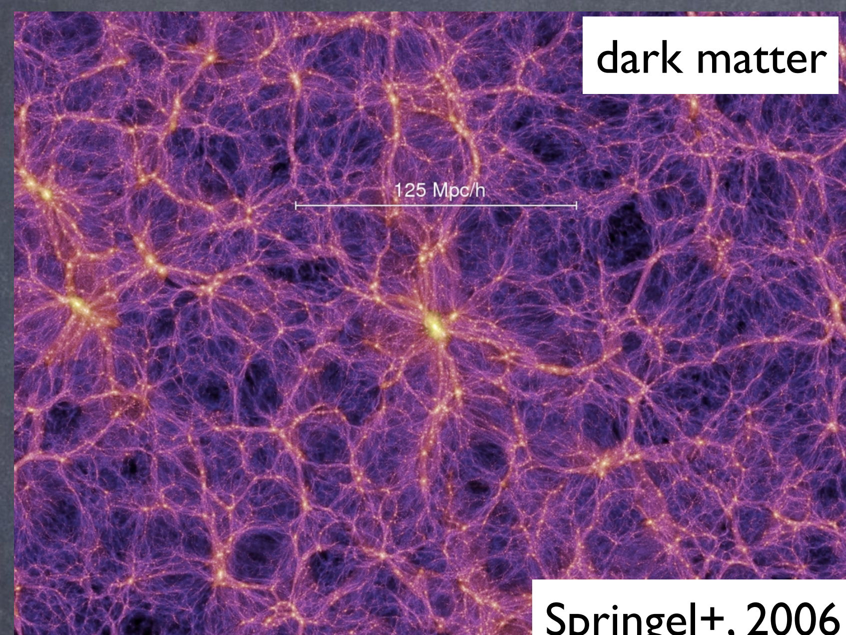
- reliably predict *dark matter distribution, for wCDM cosmologies* + *individual MG models*



Connect theory to data

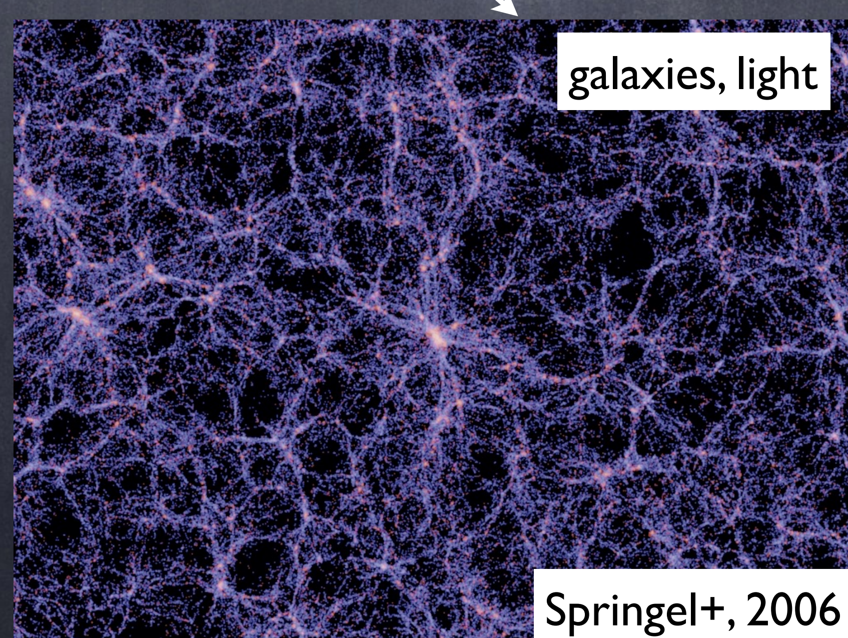
fundamental physics
+ model parameters

generate initial conditions, evolve



galaxy formation models

?



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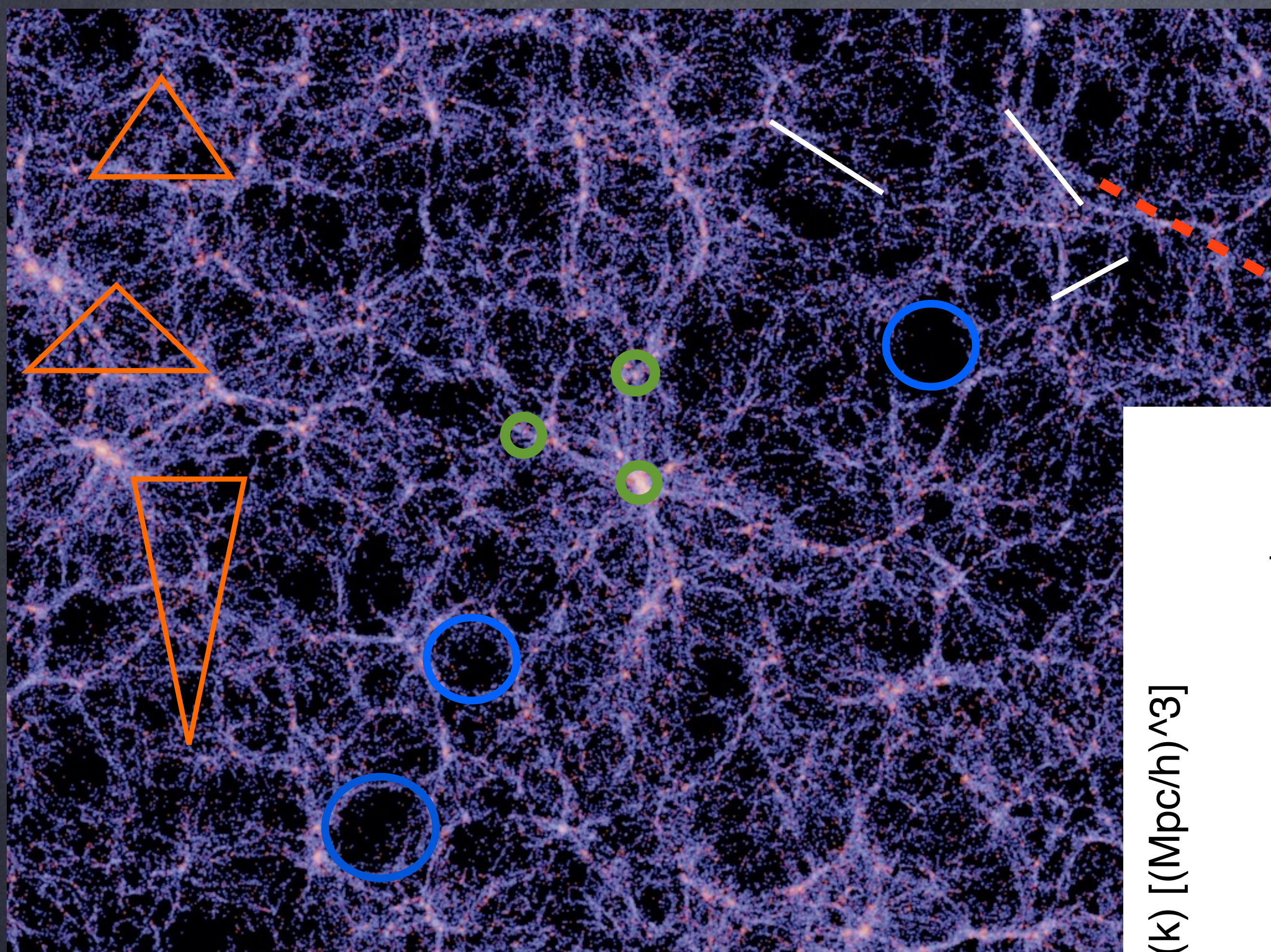
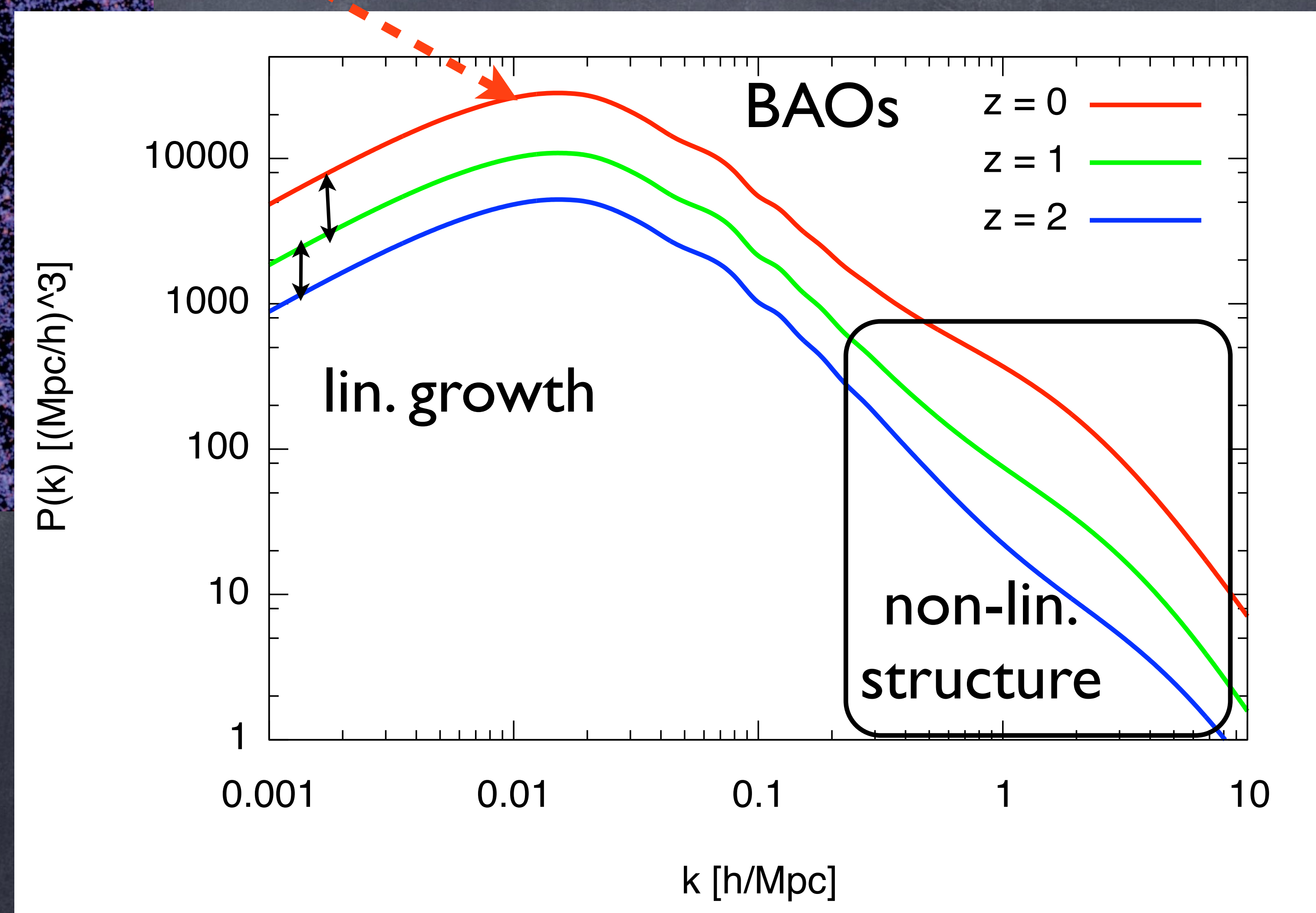
What to look for in the galaxy distribution?



need redshift, understand galaxy bias

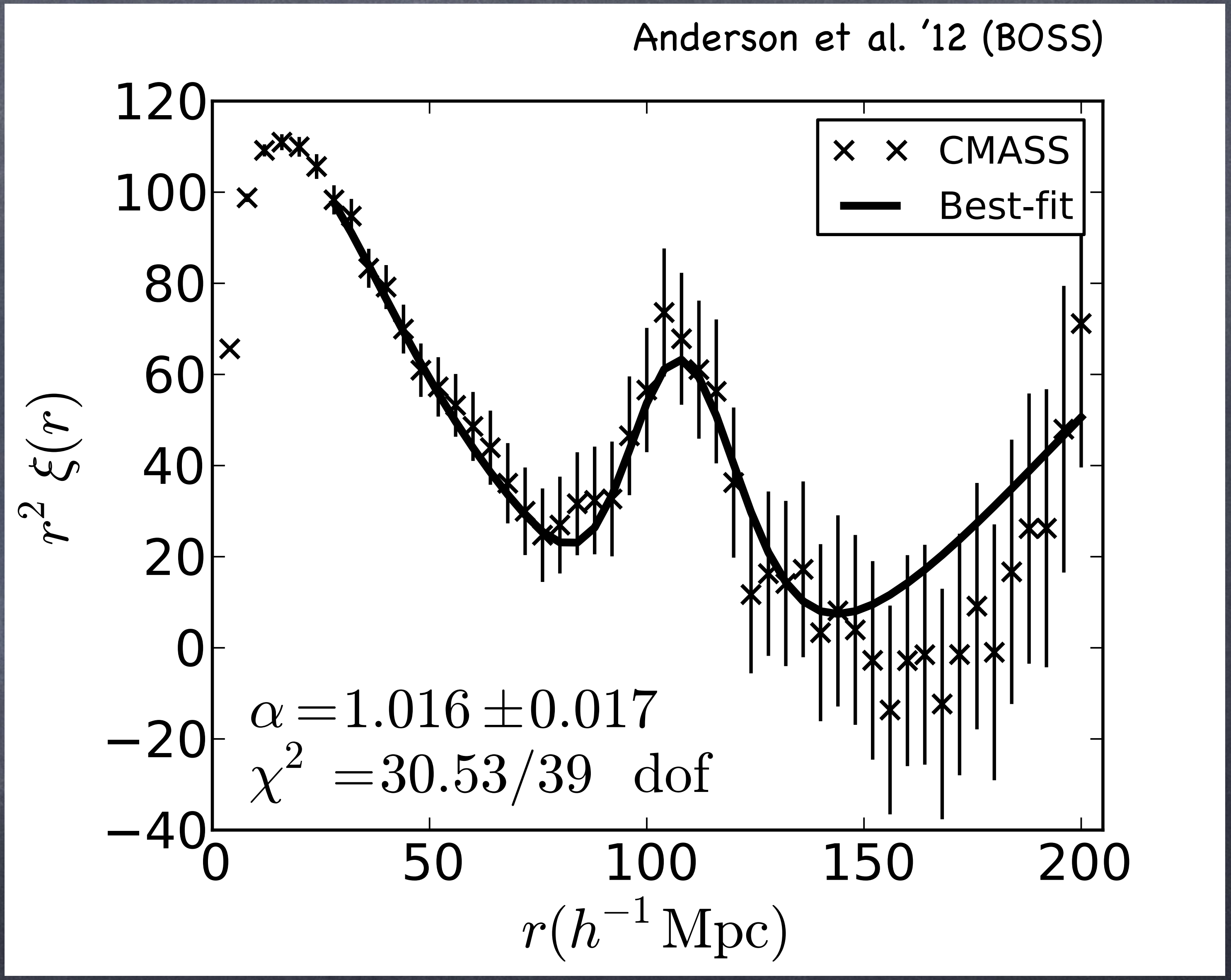


- clusters (over densities),
- voids (under densities)
- two-point correlations
- three-point correlations,...

LSS Probes of Dark Energy

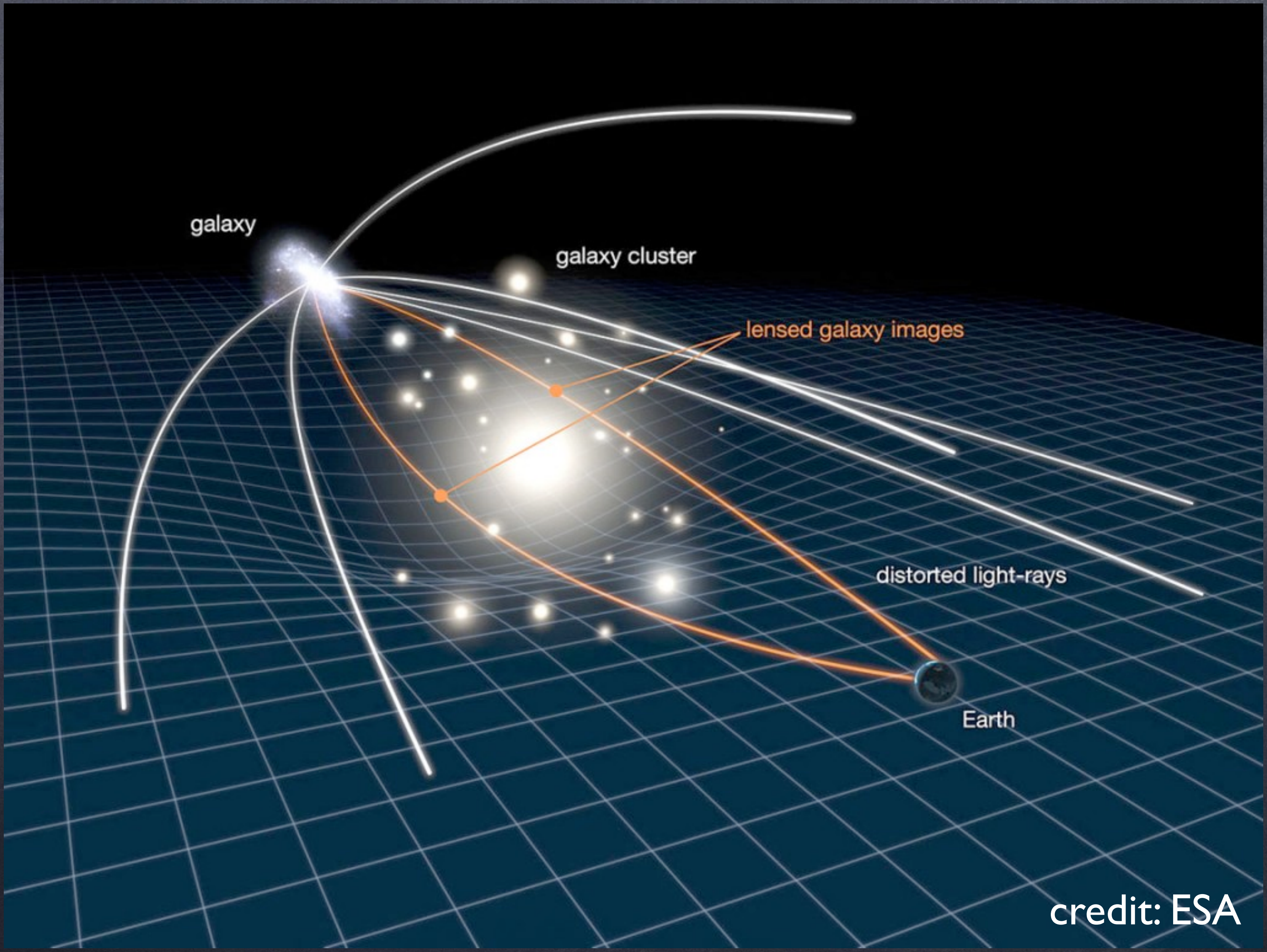
Galaxy Clustering

- measure BAOs + shape of correlation function
- $\rightarrow$ growth of structure, expansion history
  - Key systematic: **galaxy bias**



LSS Probes of Dark Energy

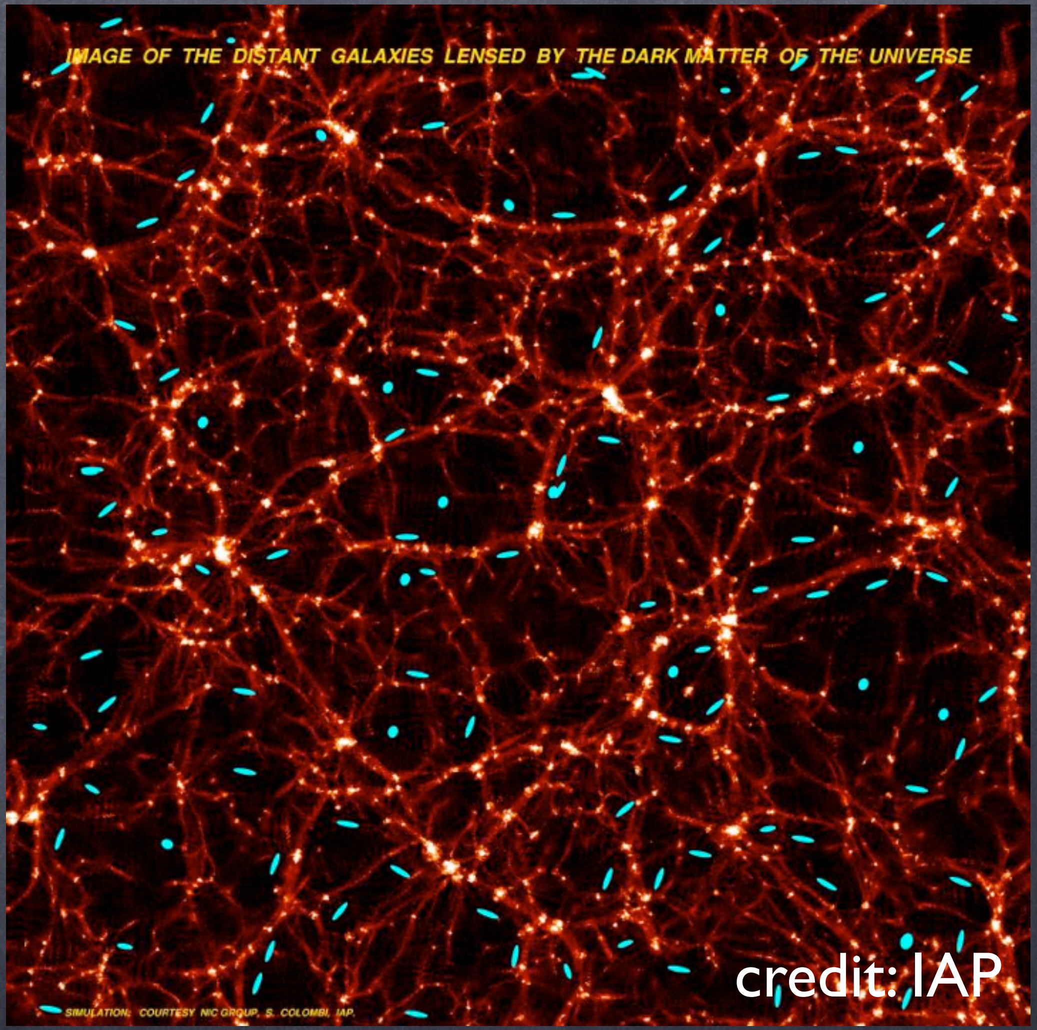
Weak Gravitational Lensing



LSS Probes of Dark Energy

Weak Gravitational Lensing

- light deflected by tidal field of LSS
  - coherent distortion of galaxy shapes "shear"
- shear related to projected matter distribution
- key systematics
  - shape measurements
  - assume random intrinsic orientation, average over many galaxies



- measure **shear correlation function/power spectrum**
  - probes *total* matter power spectrum (w/ broad projection kernel)
- measure average (tangential) **shear around galaxies/clusters**
  - probes halo mass

~Optical Dark Energy Surveys

Spectroscopic galaxy surveys

determine redshifts of select galaxies

Galaxy Clustering

galaxy positions, types, redshifts

Supernovae

light curve, redshift

Galaxy Clusters

cluster centers, redshifts, member galaxies

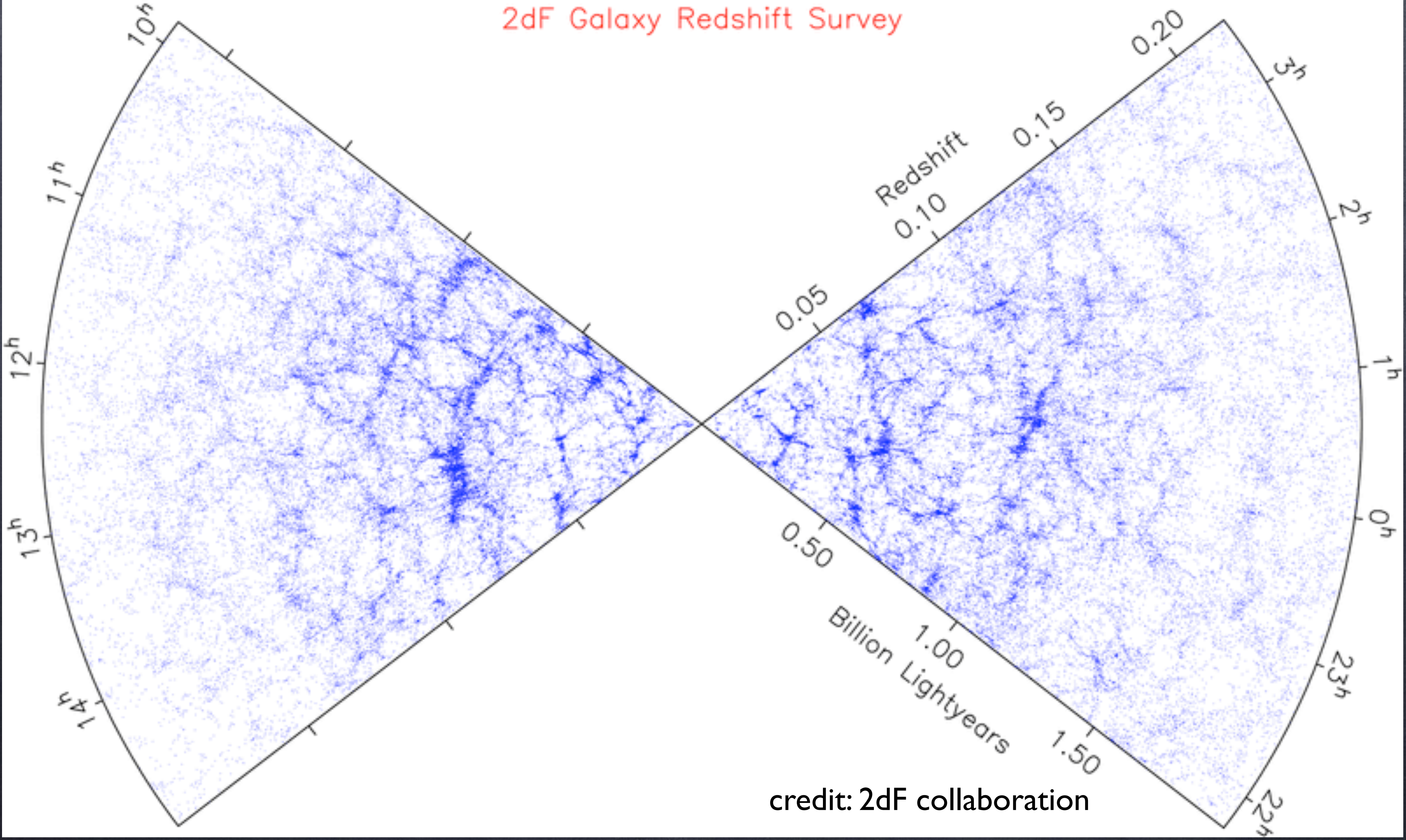
Weak Lensing

galaxy positions, shapes, types, redshifts

Spectroscopic Dark Energy Surveys

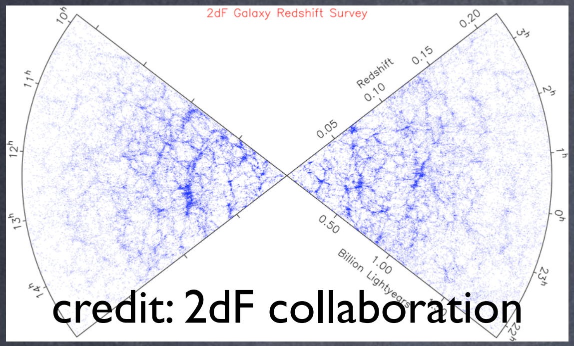
the early days: SDSS, 2-degree Field survey(2dF):

$\mathcal{O}(10^5 - 10^6)$ low-redshift galaxies



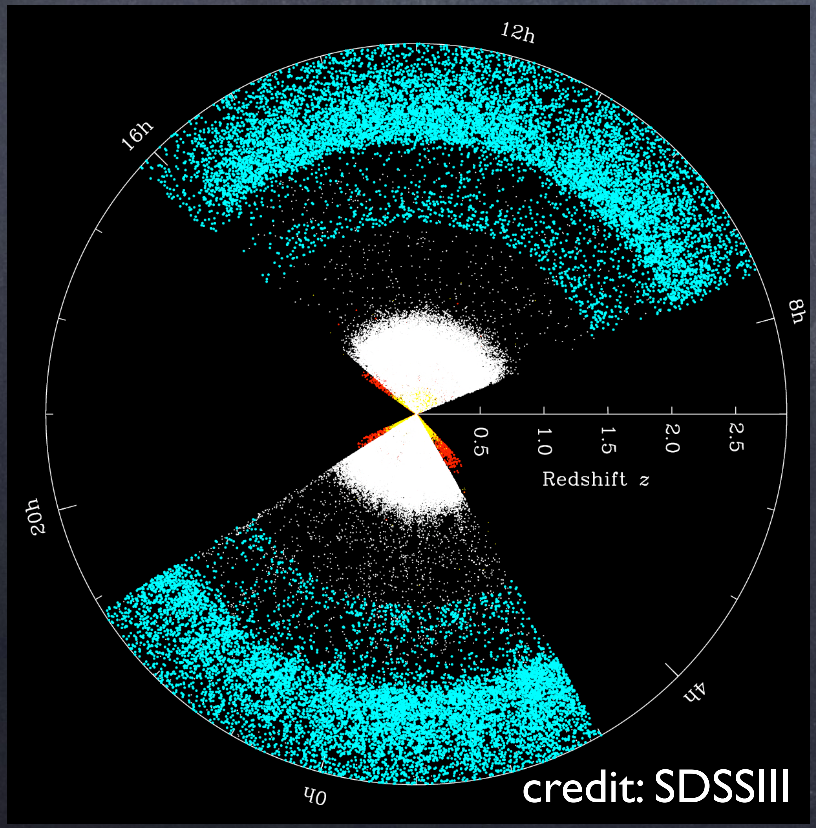
credit: 2dF collaboration

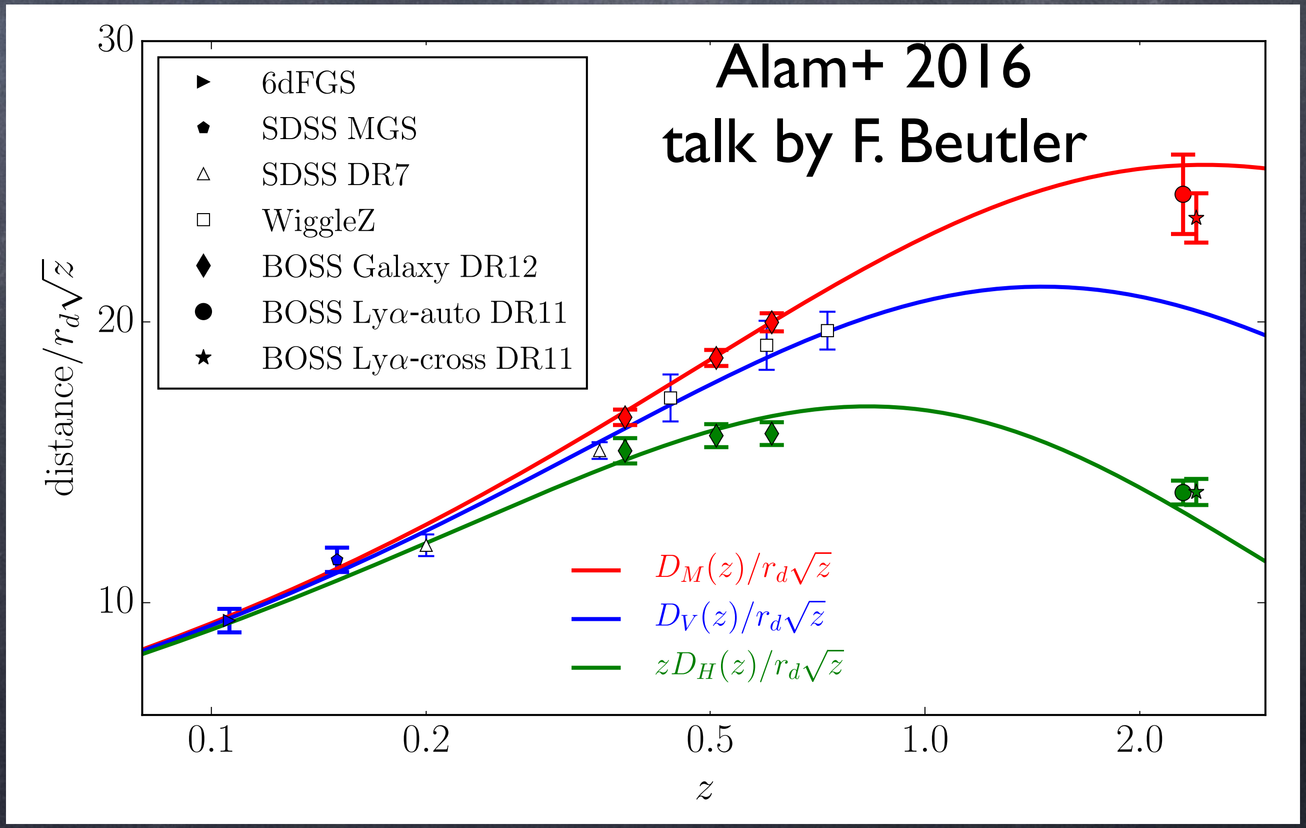
Spectroscopic Dark Energy Surveys



the present: BOSS, WiggleZ, …

$\mathcal{O}(10^6)$ intermediate-redshift galaxies

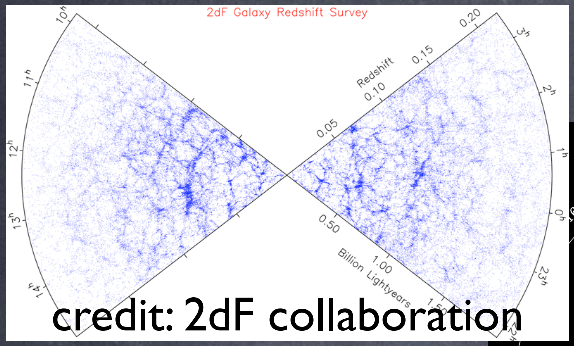




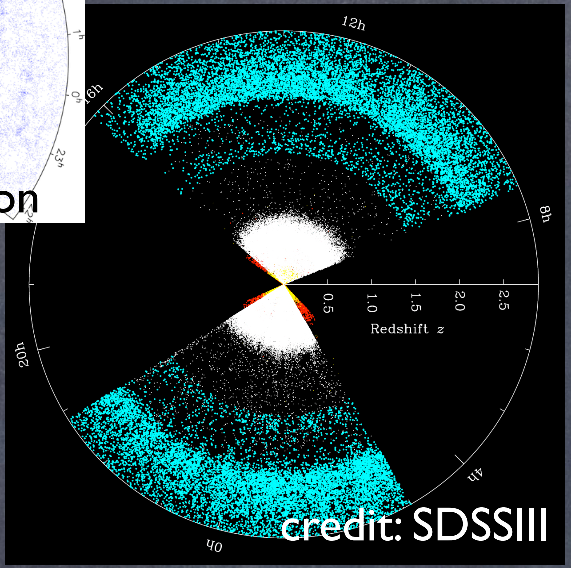
Spectroscopic Dark Energy Surveys

the future: Dark Energy Spectroscopic Instrument (DESI)

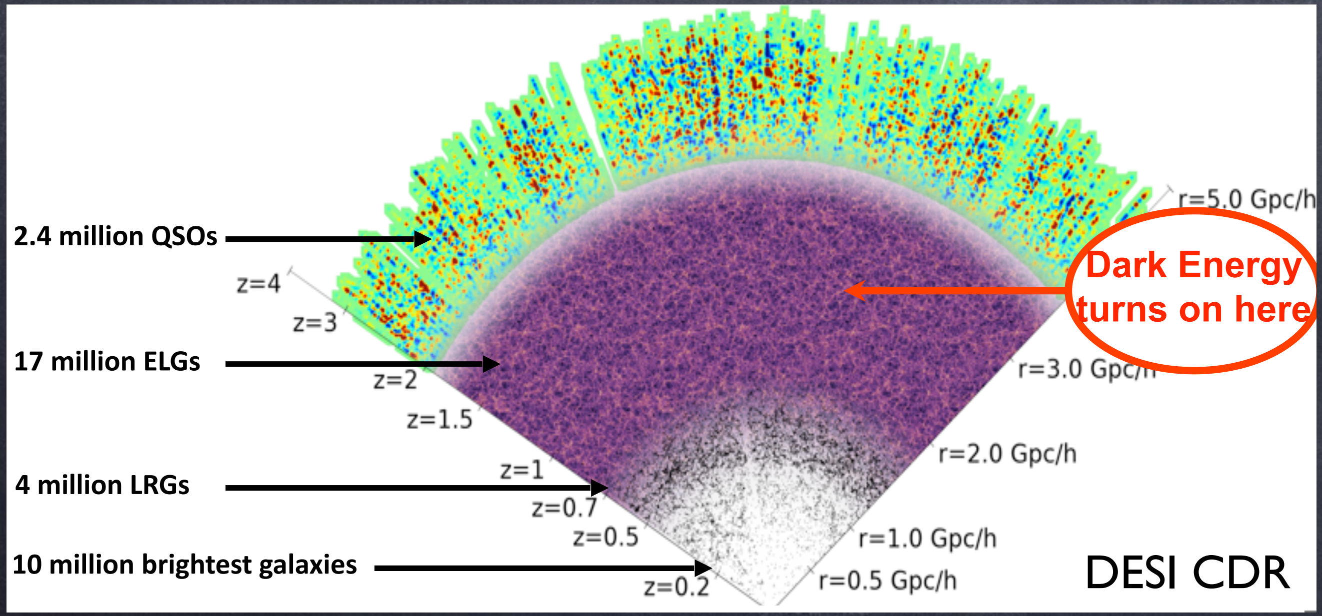
$\mathcal{O}(10^7)$ intermediate+high-z galaxies



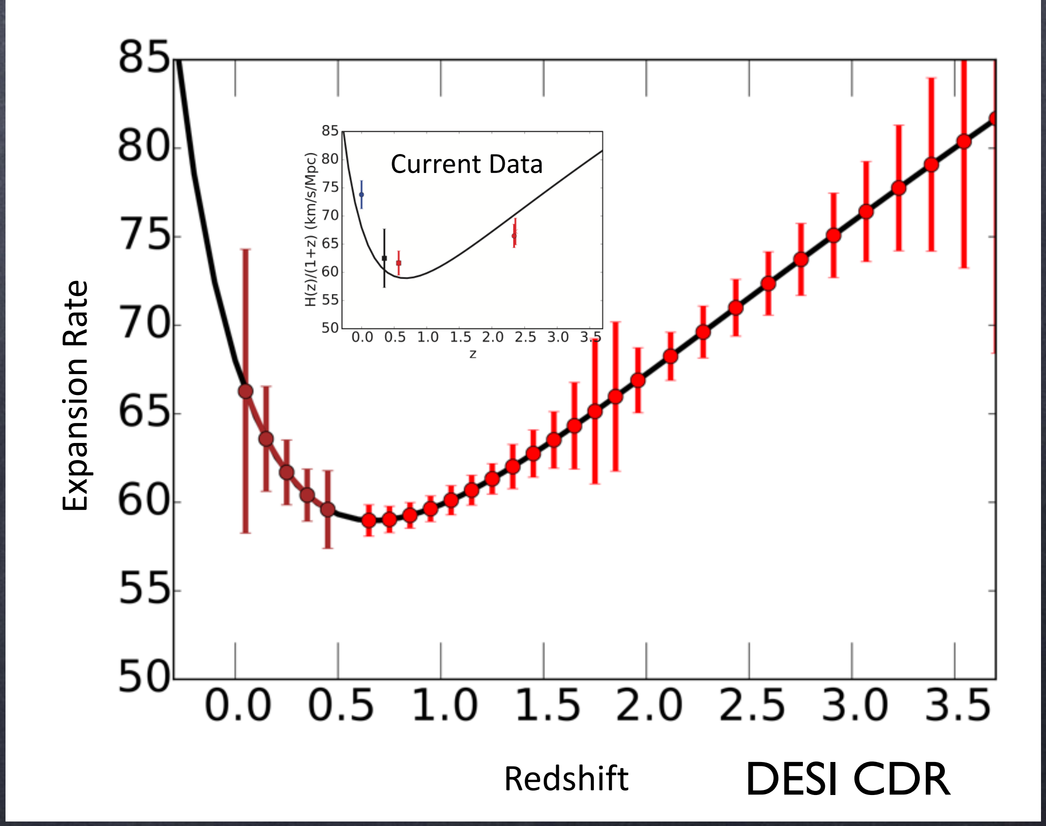
credit: 2dF collaboration



credit: SDSSIII



DESI CDR



DESI CDR

~Optical Dark Energy Surveys

Spectroscopic galaxy surveys

determine redshifts of select galaxies

Photometric galaxy surveys

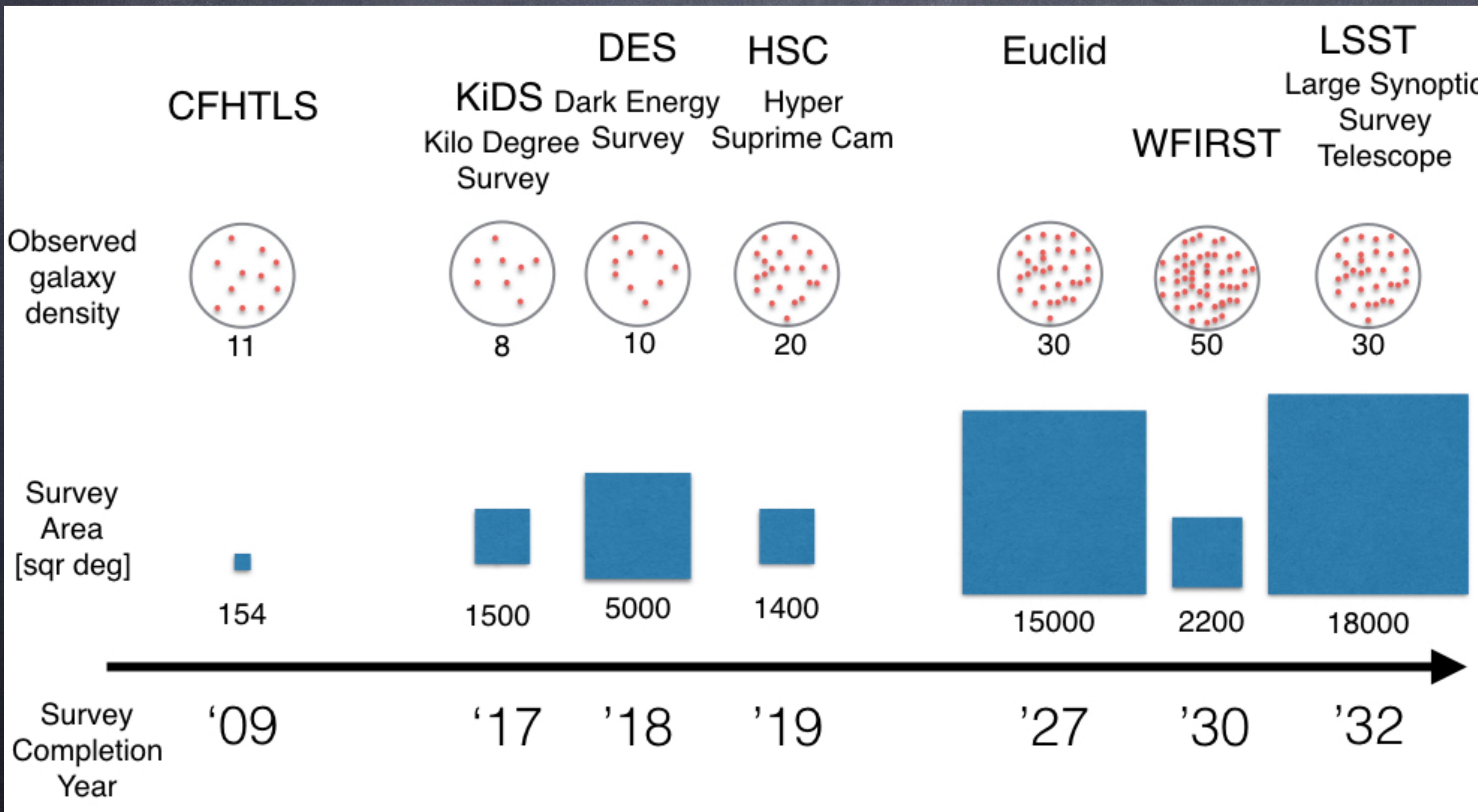
image all galaxies to lim. brightness, in multiple bands

Time domain surveys

repeated observations with suitable cadence

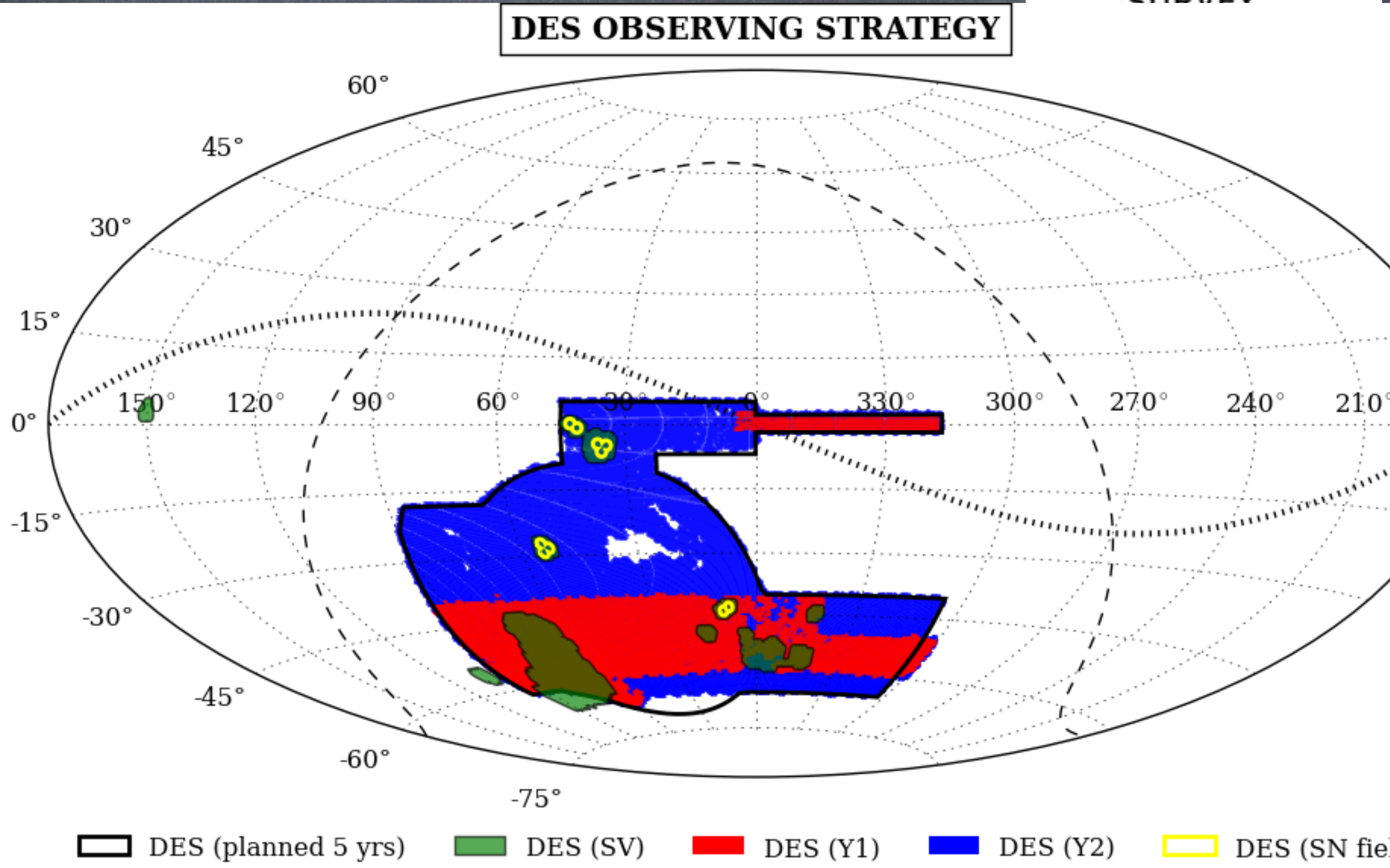
Galaxy Clustering galaxy positions, types, redshifts	**Supernovae** light curve, redshift
Galaxy Clusters cluster centers, redshifts, member galaxies	**Weak Lensing** galaxy positions, shapes, types, redshifts

Photometric Dark Energy Surveys



Dark Energy Survey

- two multi band imaging surveys
  - 300M galaxies over 1/8 sky
  - 4000 supernovae
- Stage III survey using four complementary techniques
  - galaxy clustering, weak lensing, galaxy clusters, supernovae
- 9/12-9/13: Science Verification (SV)
- currently finalizing DES-Y1 analysis



	Area (deg²)	Exposure time (s) (per visit for SNe) Specified median PSF FWHM (arcsec) g	r	i	z	Y	Dithering	Cadence
Wide	5000	10x90 -	10x90 0.9"	10x90 0.9"	10x90 0.9"	10x45 -	10 fully interlaced tilings	10 tilings over 5 years
SN Shallow	24	1x175 -	1x150 -	1x200 -	2x200 -	-	Minimal dithers	Seeing >1.1" or 7 days since last observed
SN Deep	6	3x200 -	3x400 -	5x360 -	10x330 -			

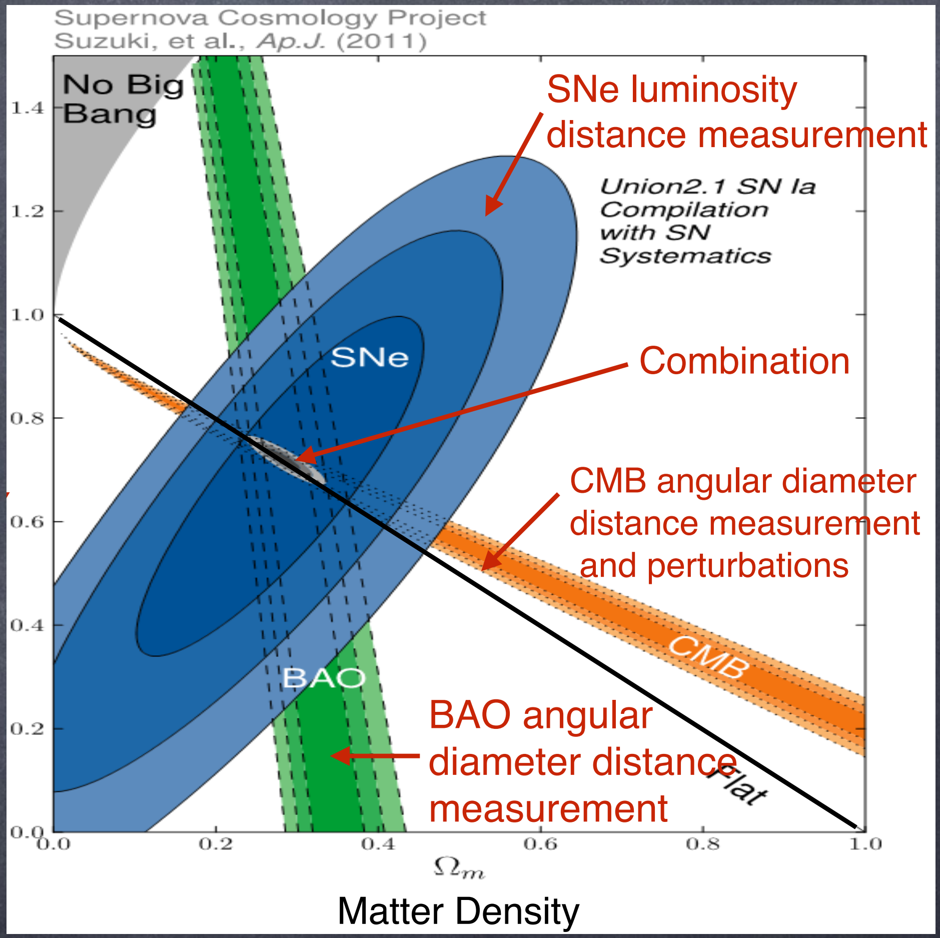
Early Science Results

- based on 140 sd deg SV data
- > 50 science result papers so far
  - milky way satellites, galaxy evolution, LIGO follow-up, cosmology, …

talk by E. Sanchez

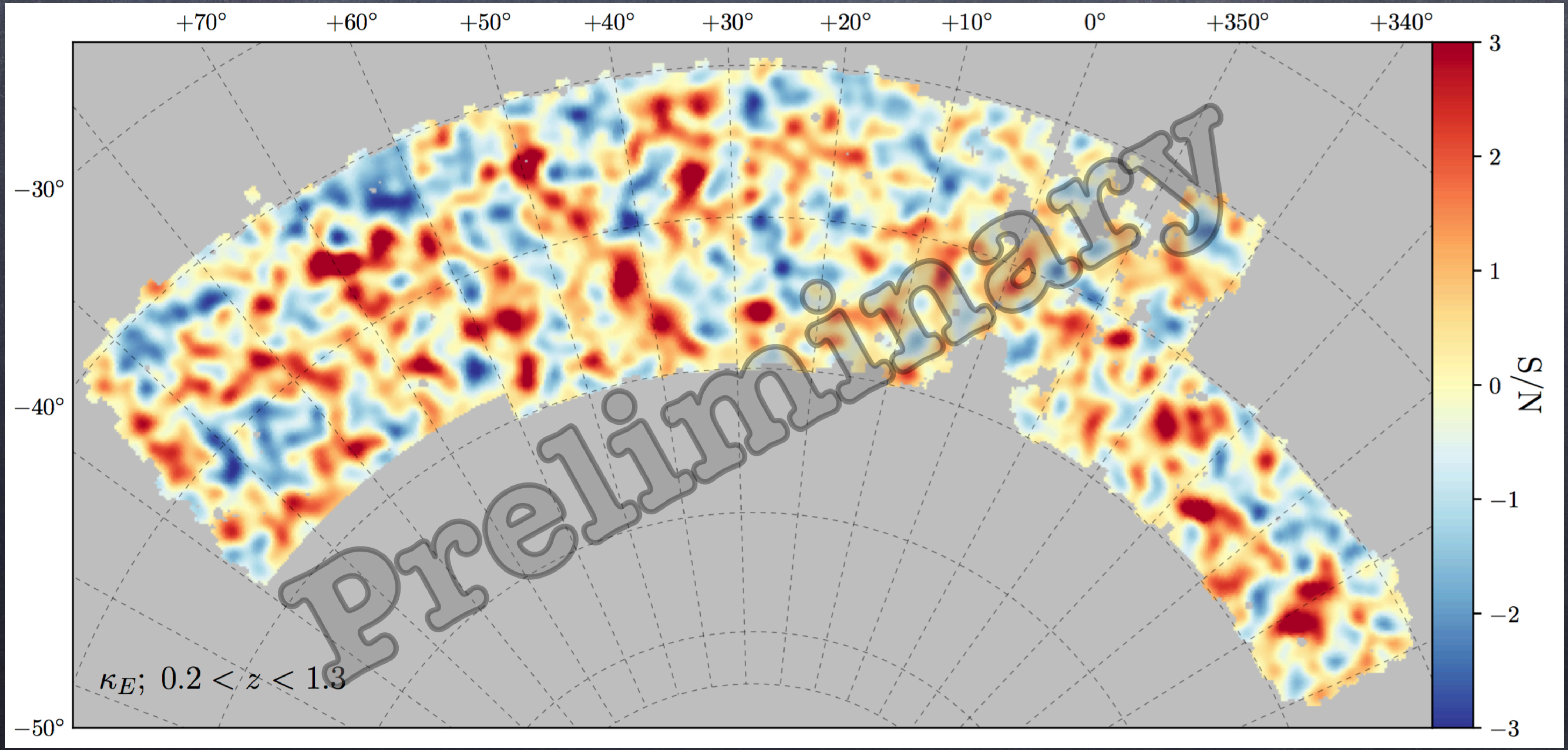
The Power of Combining Probes

- 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

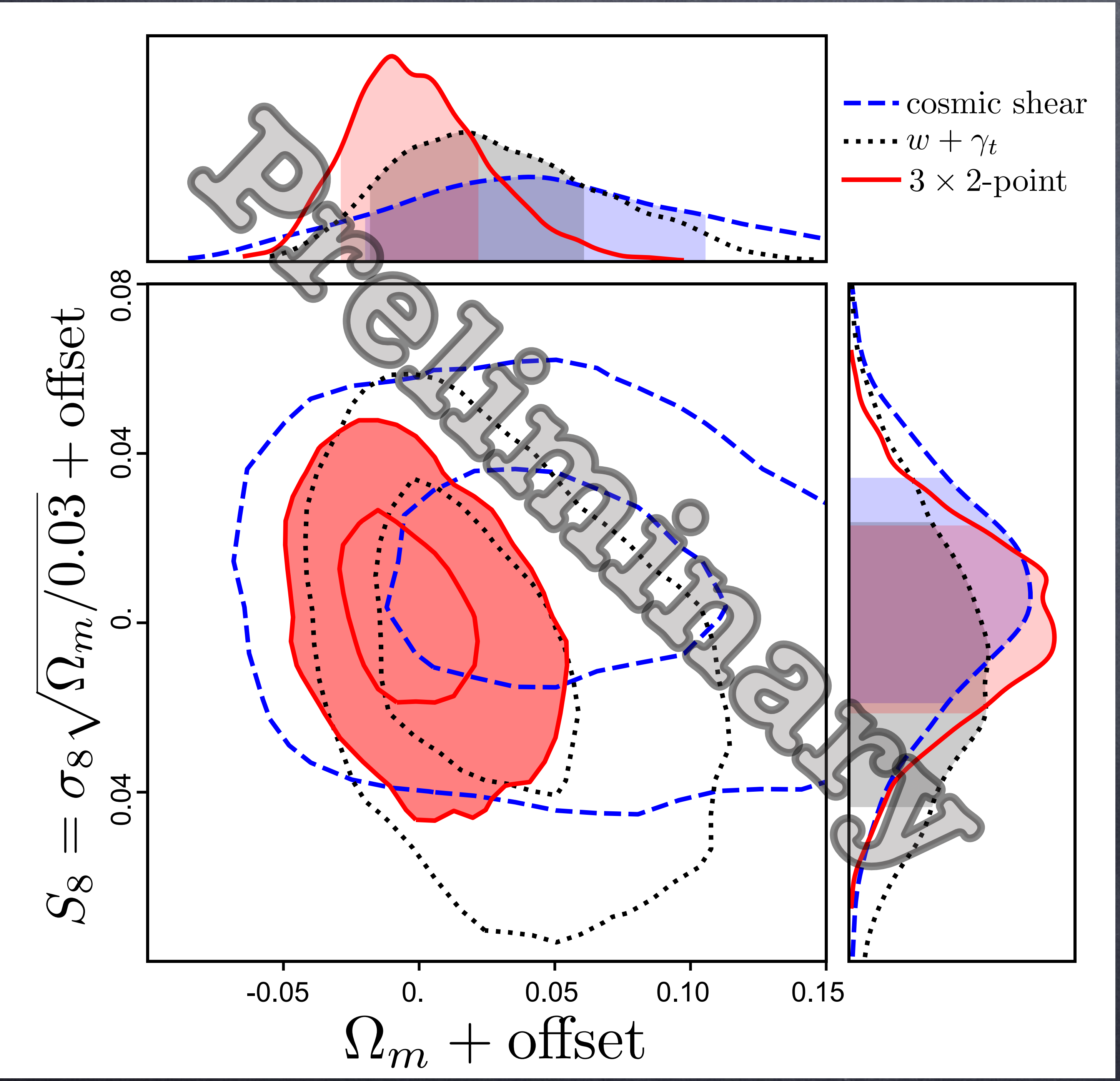


DES-Y1 Results

- shapes + redshifts of 35×10^6 source galaxies, covering 1321 sqdeg
- two independent {shape measurement algorithms, shape calibrations, photo-z validations, correlation function measurement pipelines, sets of cosmological simulations, analysis pipelines}
- two-staged blinding process: rescale catalogs, off-set parameter constraints

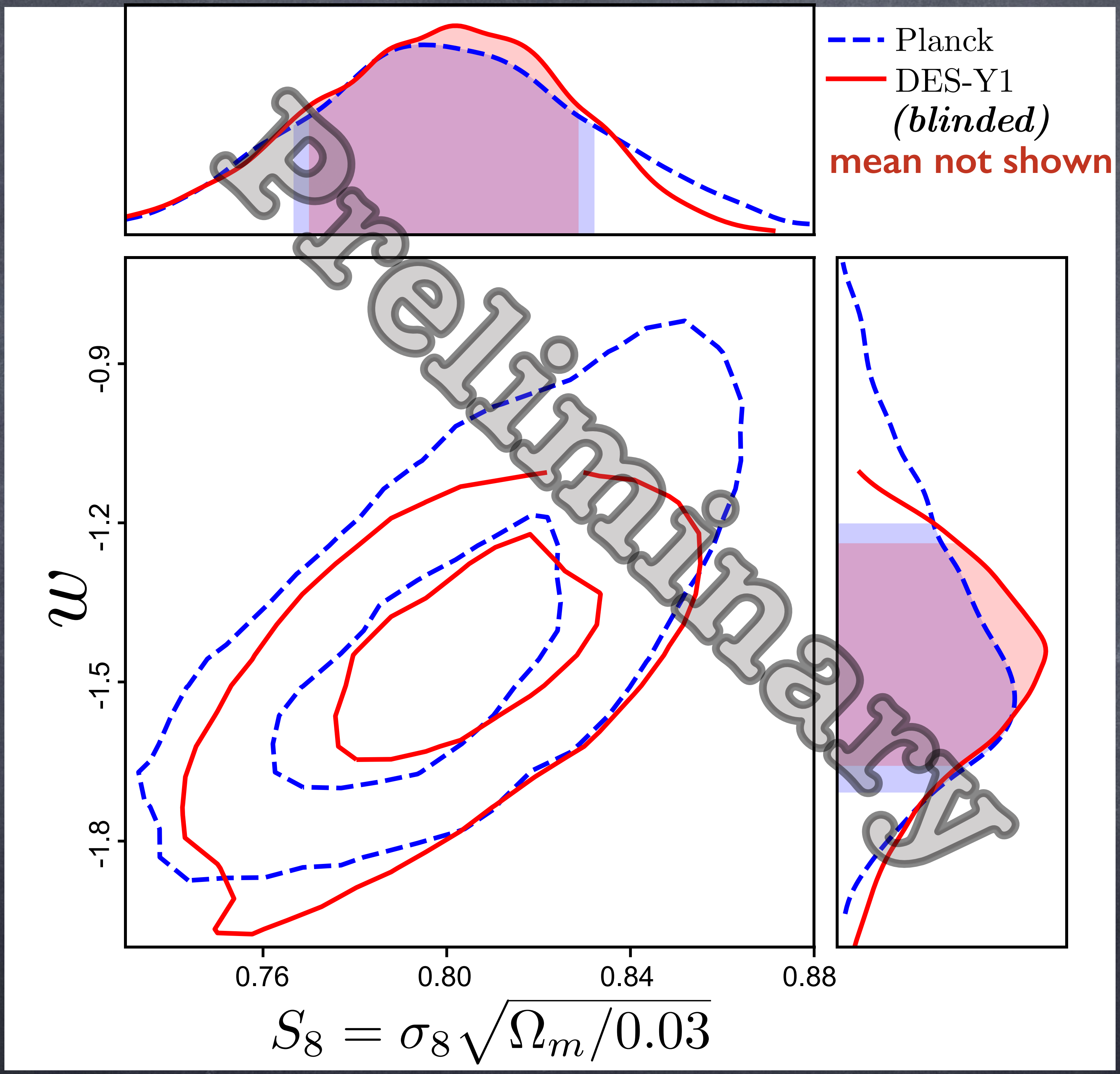


DES-Y1 Results



- DES-Y1 weak lensing: factor ~2 increase in constraining power
- consistent cosmology constraints from weak lensing and clustering
- DES-Y1 3x2pt: first joint analysis in configuration space

DES-Y1 Results: Dark Energy



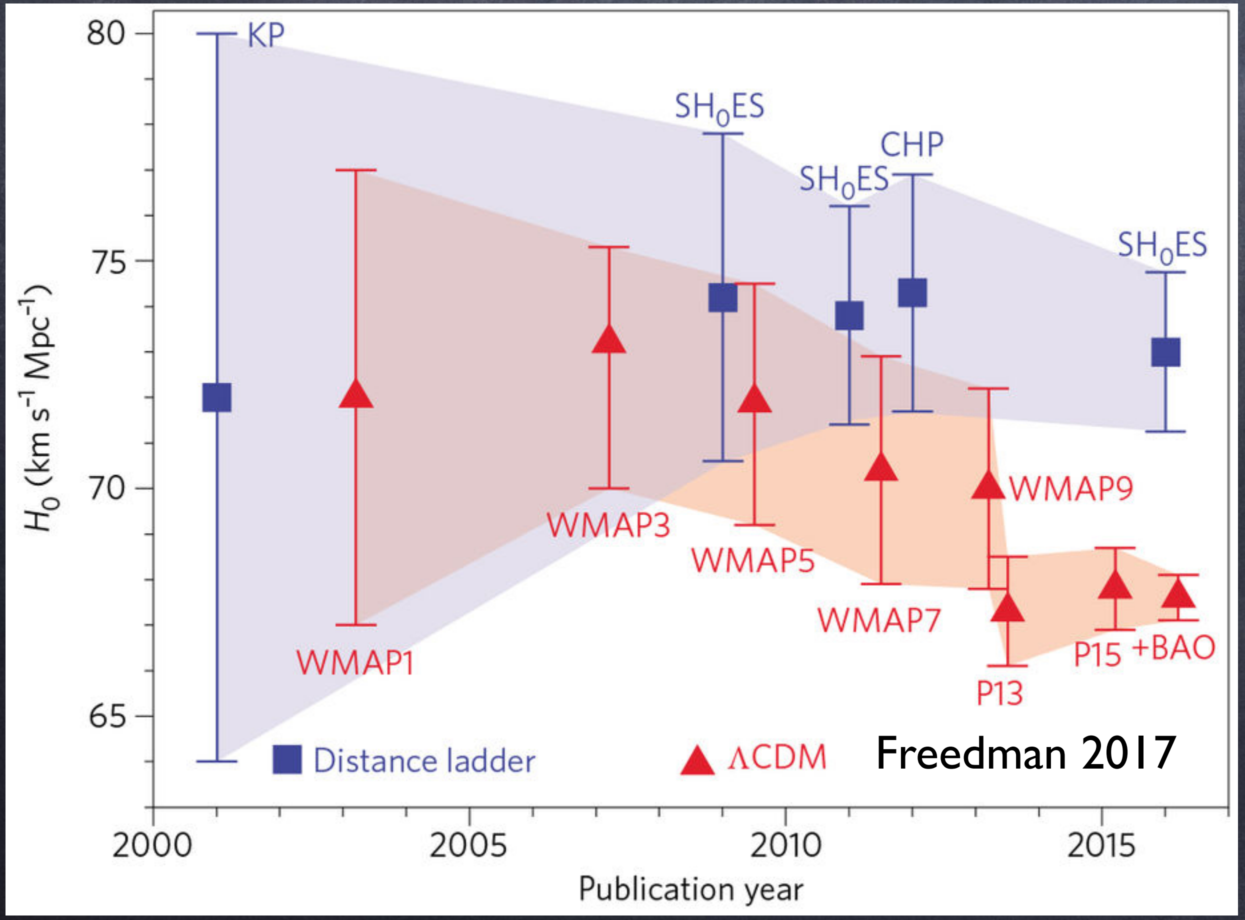
DES-Y1 dark energy constraining power competitive with Planck (high-z)!

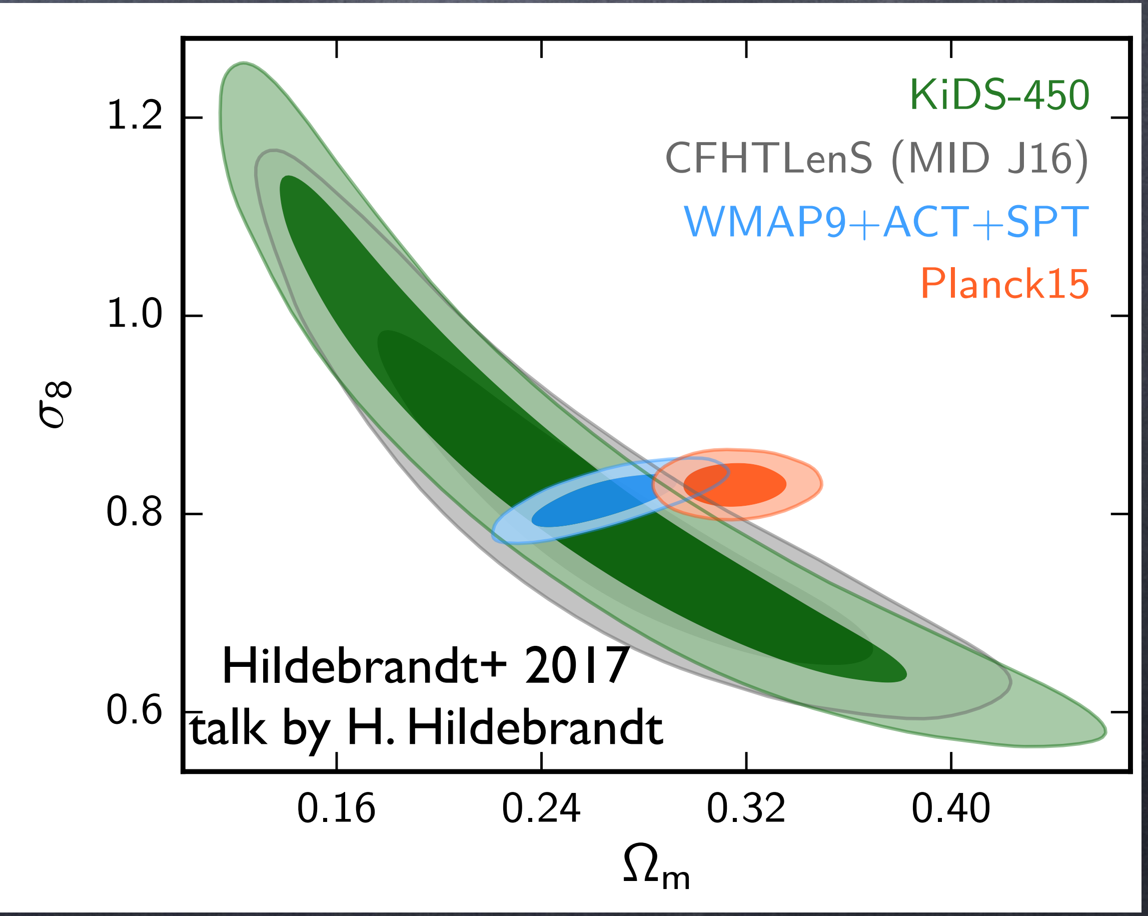
Dark Energy - July 2017

Planck CMB + ΛCDM: $\Omega_m = 0.316 \pm 0.009,\ \sigma_8 = 0.831 \pm 0.013$

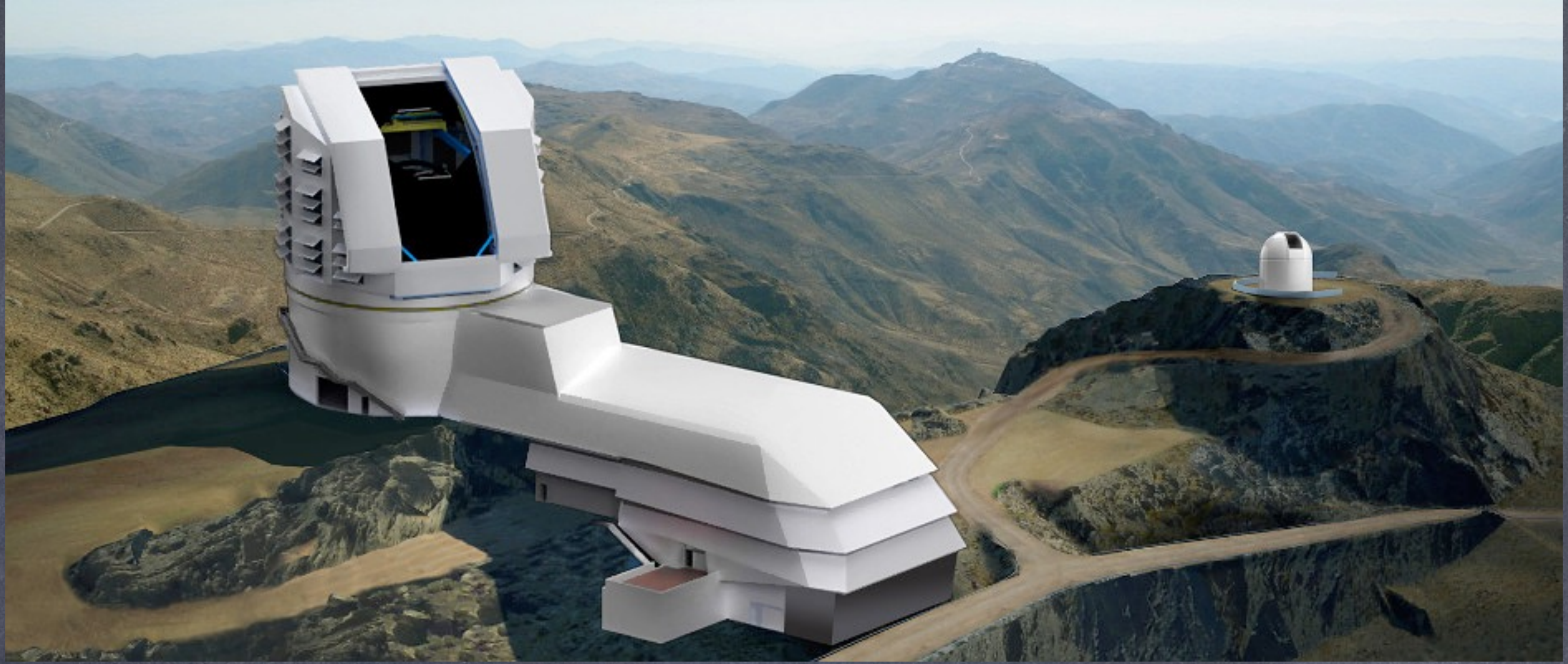
$$H_0 = 67.3 \pm 0.7\mathrm{km/s/Mpc}$$

- Expansion history (SN1a and BAO) agree at 1-2%
- Direct H_0 disagrees, e.g. $H_0 = 73.2 \pm 1.7\mathrm{km/s/Mpc}$ (Riess+2016)
- Growth of structure precision 5-10%
  many but not all measurements disagree with Planck + ΛCDM





Large Synoptic Survey Telescope



LSST: The Experiment

- largest planned LSS survey
- map visible sky every 3 nights
- high priority in P5, decadal survey
- construction started 2015
- commissioning first light 2019
- survey duration 2022-2032

LSST: Science Collaborations

- Solar System
- Stars, Milky Way, Local Volume
- Transients
- Galaxies
- Active Galactic Nuclei
- Informatics and Statistics
- Dark Energy

The LSST Dark Energy Science Collaboration

Prepare for and carry out cosmology analyses with the LSST survey

- five key cosmology probes, organized in Working Groups (WG)
  - Galaxy Clustering, Galaxy Clusters, Strong Lensing, Supernovae, Weak Lensing; Theory & Joint Probes
- “Enabeling Analyses” WGs: understand LSST system + systematics

lots of work until 2019, lots to learn from ongoing surveys!

The LSST Dark Energy Science Collaboration

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  - Galaxy Clustering, Galaxy Clusters, Strong Le
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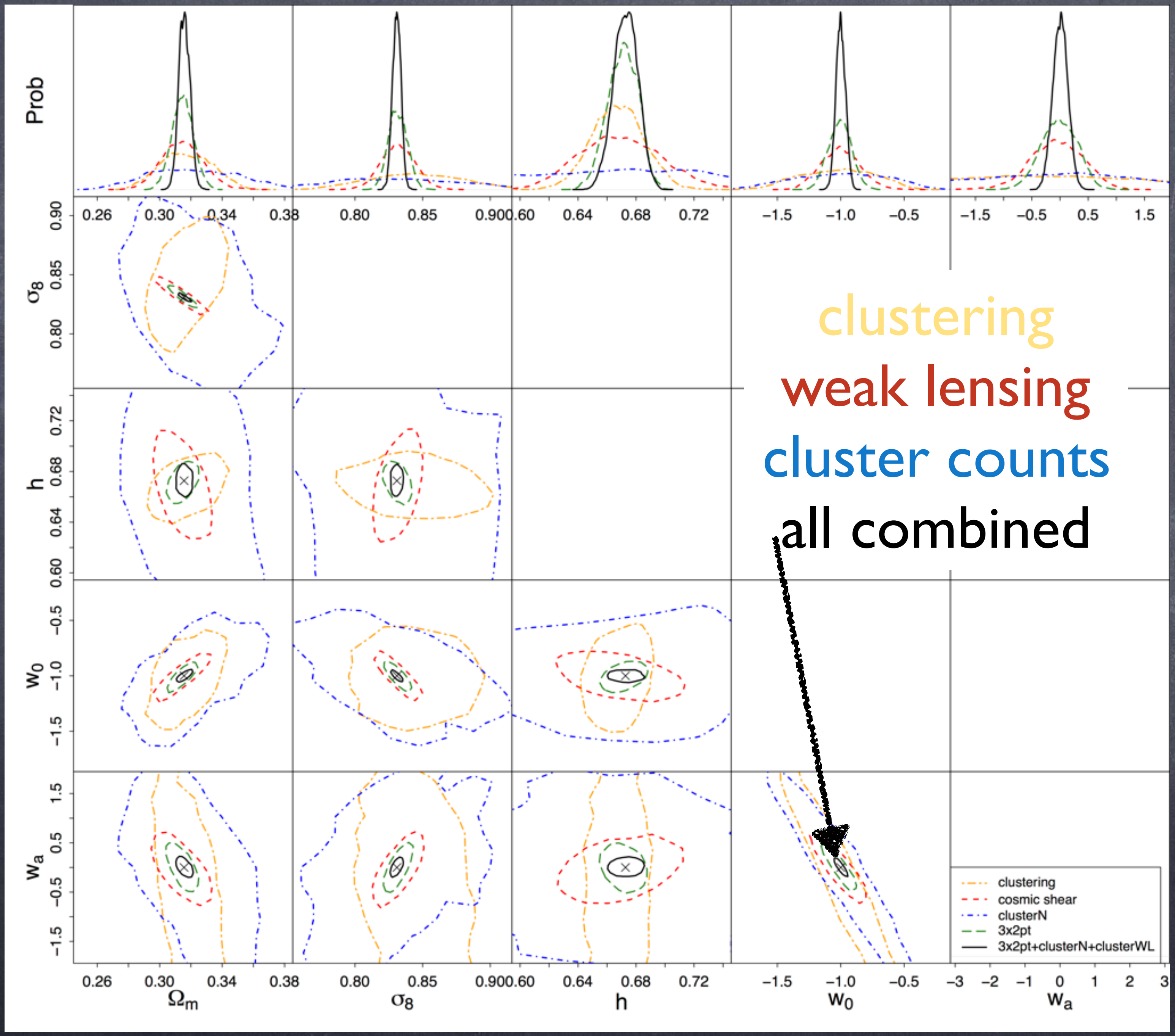
DESC cosmology likelihood, late 2015

software implementation rapidly progressing
(talk by J. Neveu)

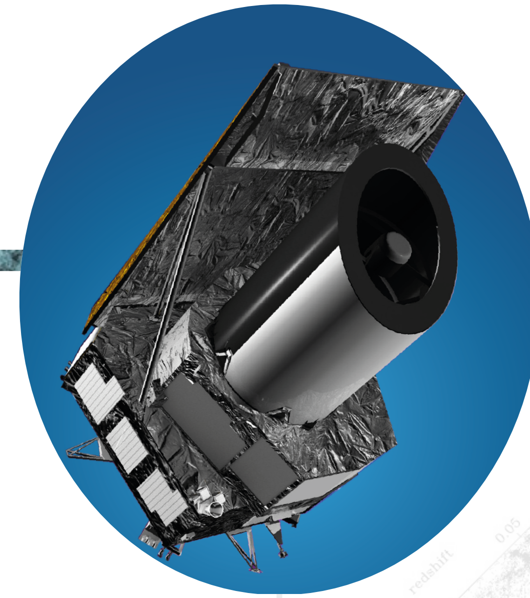
Cosmology from LSST: The Power of Combining Probes



Krause & Eifler 2017

+ supernovae + strong lensing

Euclid



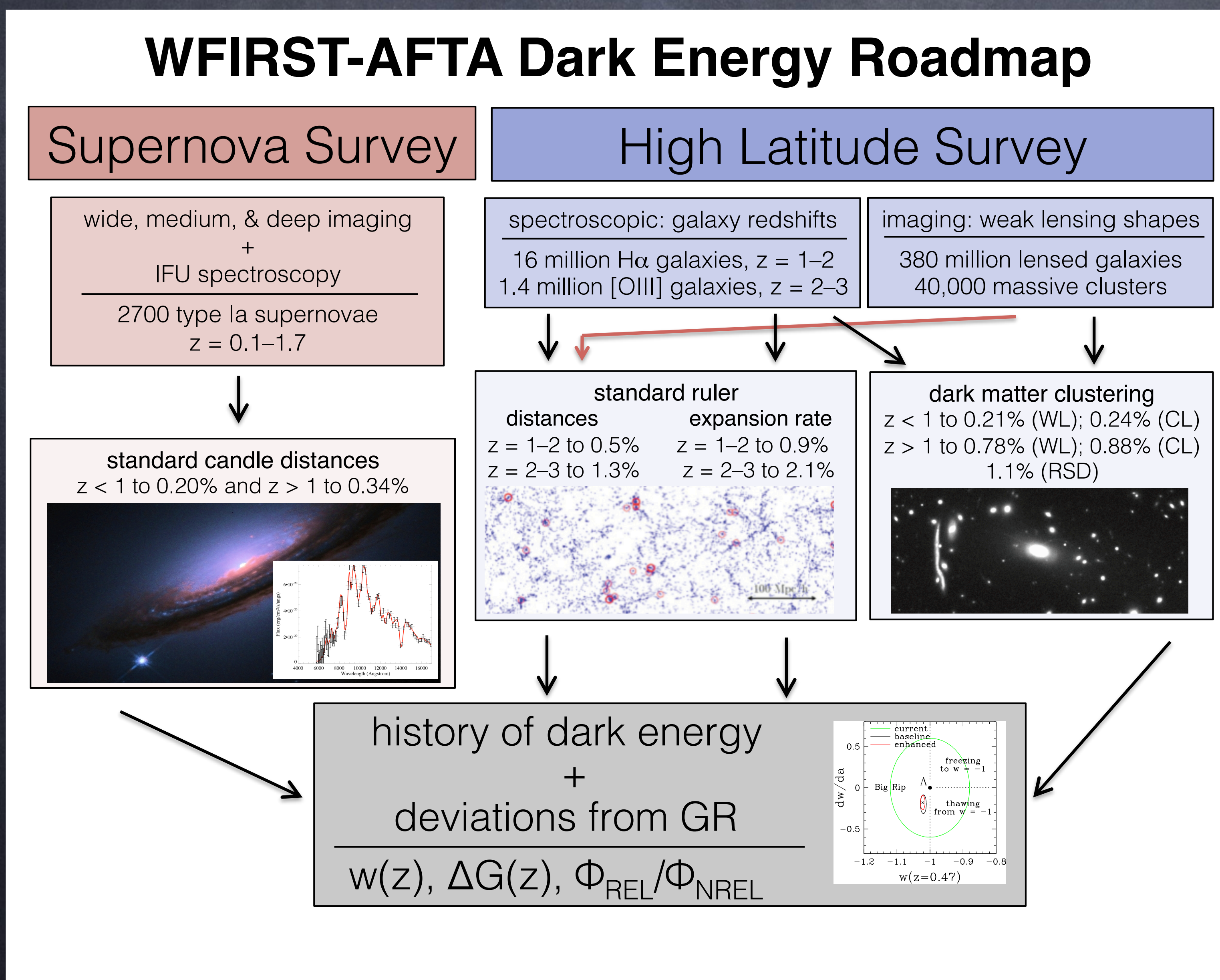
- **A single survey providing data for 5 different probes of dark energy**
  - Optimal use of a space observatory
  - Explore both geometry/expansion and clustering evolution/growth of structures
- **Design allow for a single visit to acquire imaging and spectroscopy on wide fields**
- **Main probes are Weak Lensing and BAO/RSD surveys**
  - ***WL: 1.5 10^9 galaxy shapes, shear & photo-z*** (u,g,r,i,z,Y,J,H, $\Delta z=0.05(1+z)$)
    - 15000 deg^2 , up to z=2
  - ***GC/RSD: 35 10^6 spectroscopic redshifts*** ($\Delta z=0.001(1+z)$)
    - 15000 deg^2 probing $0.7<z<1.8$
  - Great for DE
  - *Fantastic for ancillary astrophysics!*

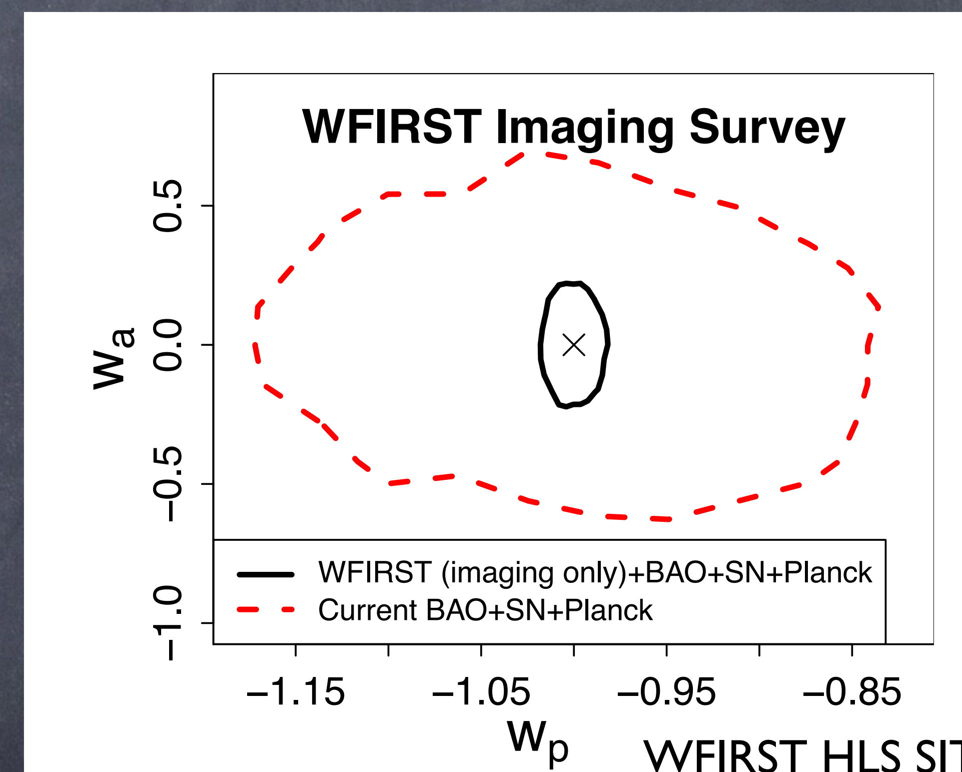
slide from K. Benabed's talk

WFIRST Wide-Field Infrared Survey Telescope

(aka the spy telescope)

one satellite, three cosmological surveys - launch ca. 2025

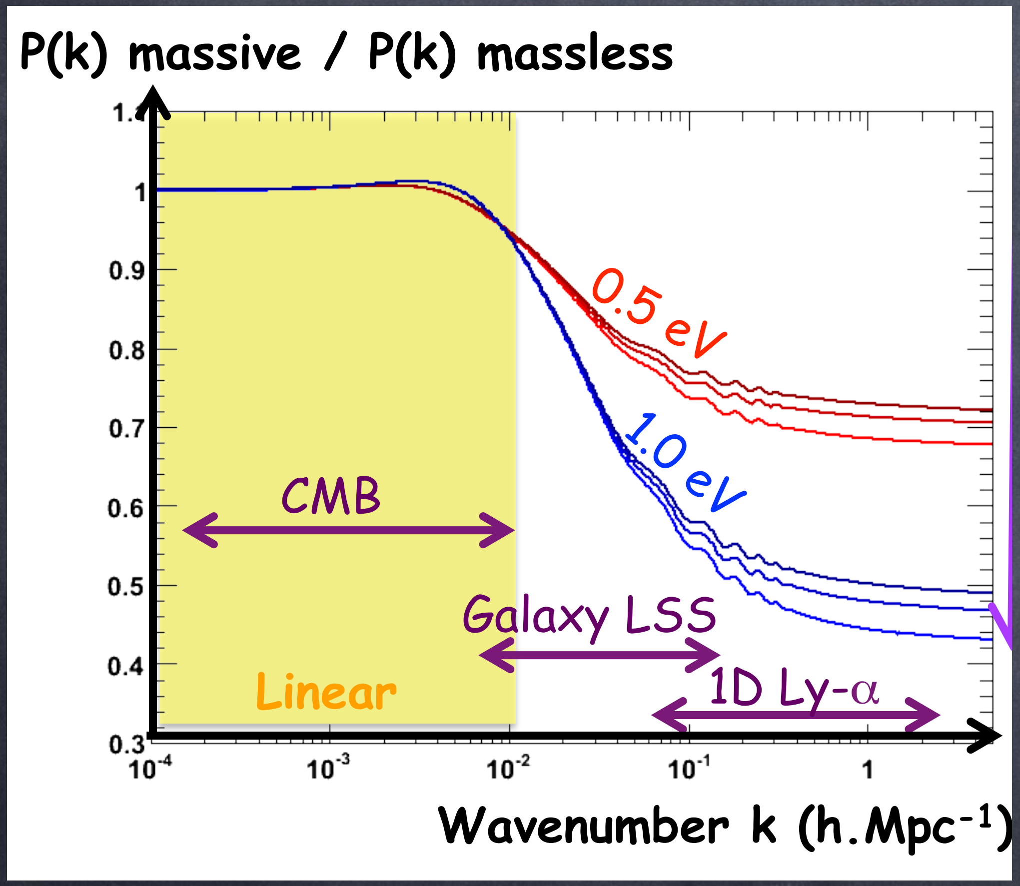




(credit: WFIRST SDT report, Spergel+ '15)

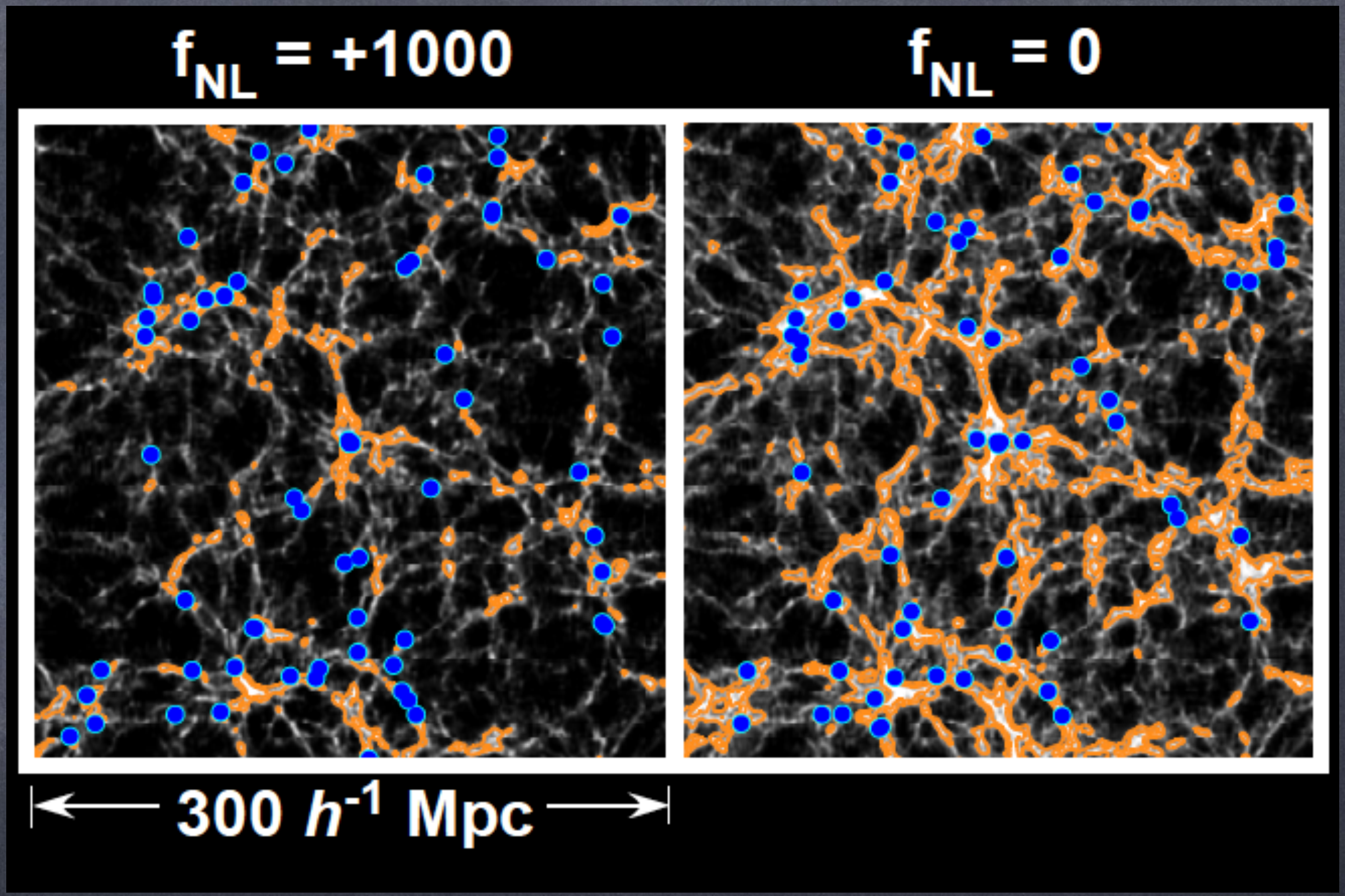
Beyond Dark Energy

Imprint of neutrinos



$$\mathrm{LSST}++:\ \Sigma(m_\nu) \sim 4\sigma$$
[normal hierarchy]

Distribution of Peaks



measure imprint of inflation on late-time structure
forecasts under way

Conclusions

- Existence of cosmic acceleration requires new fundamental physics
- 2020s decade of cosmological surveys: CMB-S4, DESI, LSST, WFIRST,…
- Cosmological constraints soon to be systematics limited
  - understand astrophysics
  - understand systematics
  - understand observables (voids, clusters, galaxies, etc…)
- Combine observables + surveys to understand/calibrate systematics
- Combine different surveys to robustly confirm/rule out ΛCDM
- Need collaboration across surveys, plan for analysis frameworks to combine observables from all surveys