Dark Energy and Surveys

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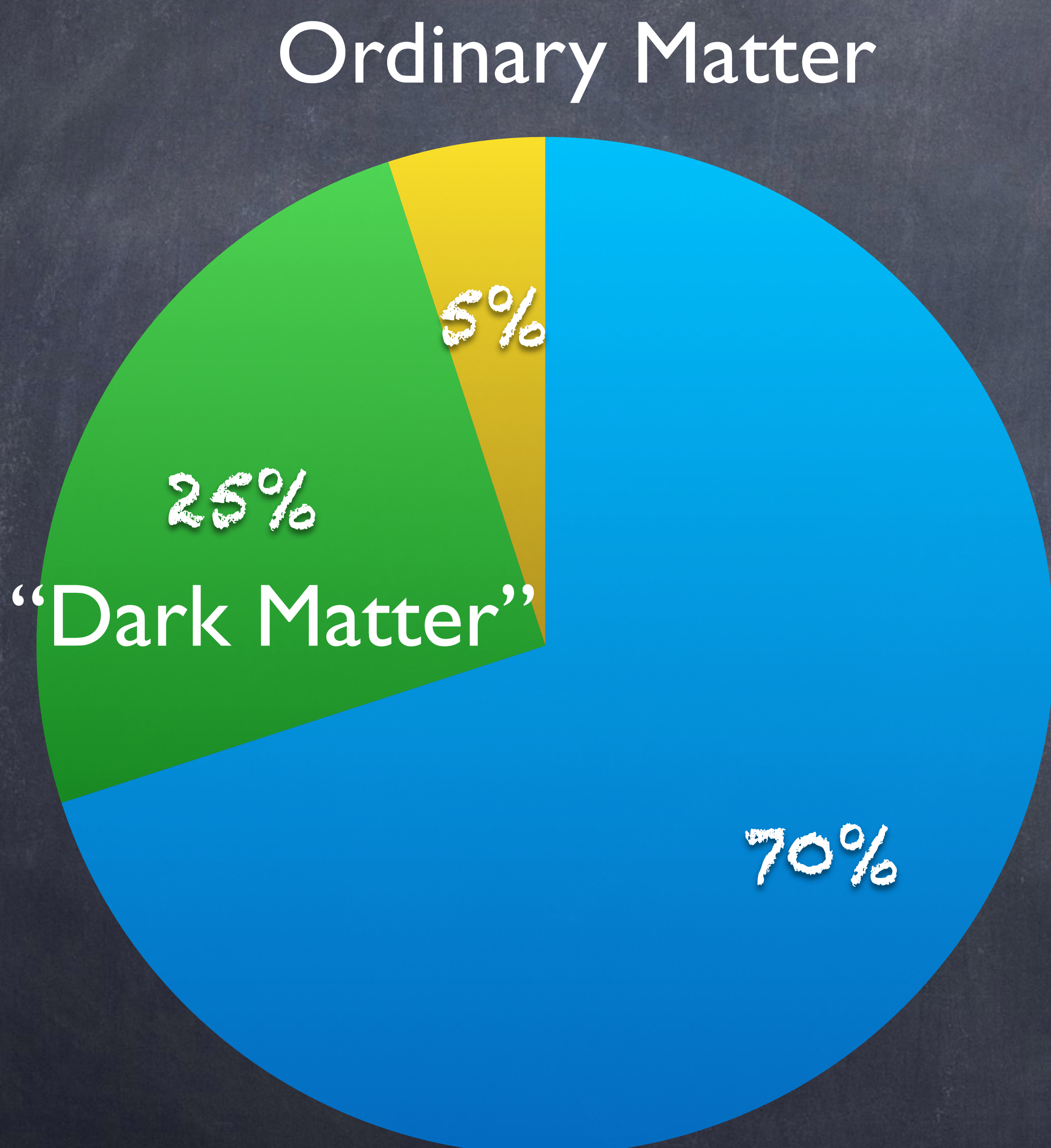
Our Simple Universe

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 not quite as simple - or we wouldn't be here]

Our Puzzling Universe



"Dark Energy"

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

acceleration first measured by SN 1998

next frontier: understand

Cosmic Acceleration

CMB + supernovae + large-scale structure:

homogeneity, isotropy, flatness + acceleration
impossible with GR + matter only

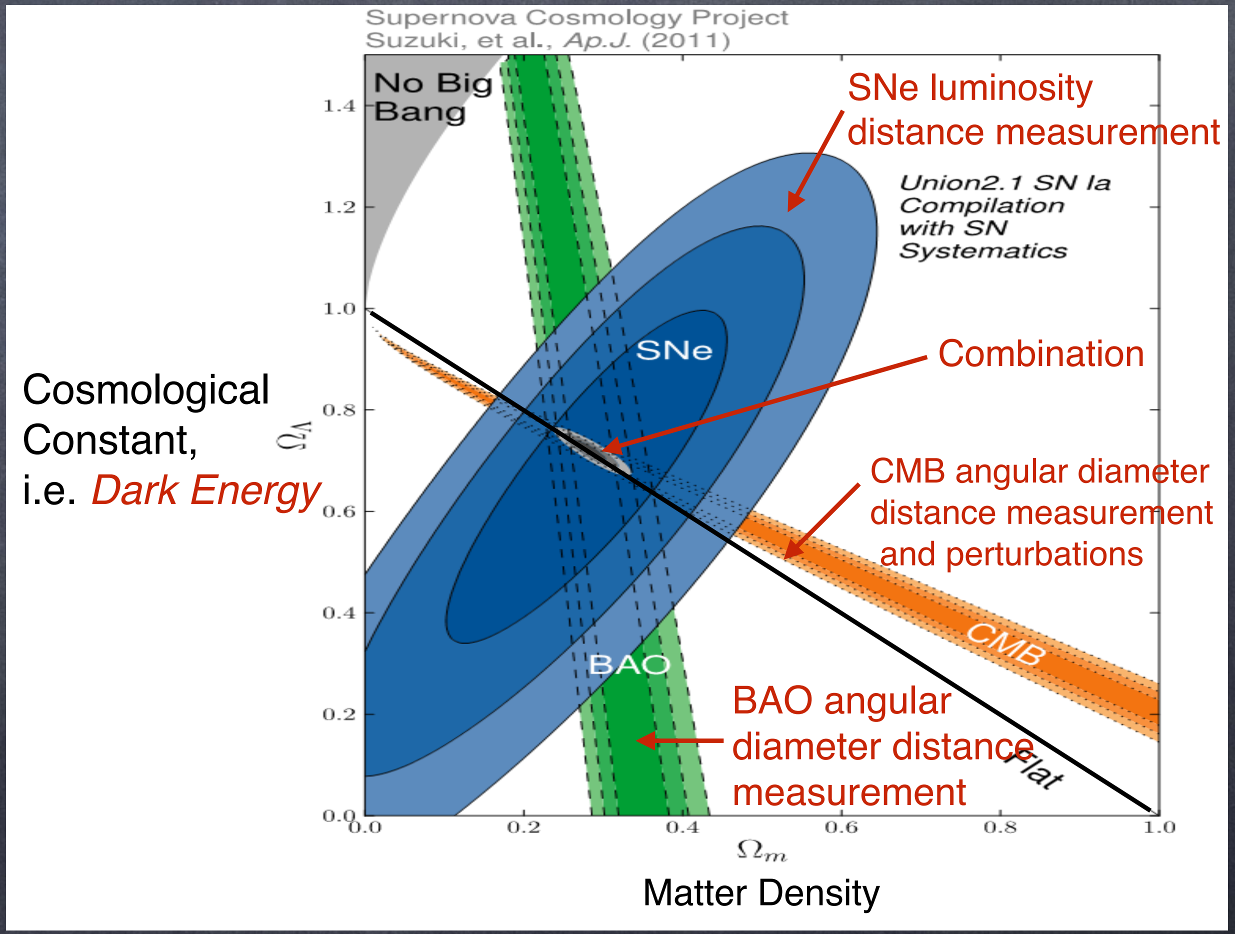
observations require a *repulsive* force

- cosmological constant Λ: w =p/ϱ=-1?
- dynamic scalar field, w(a)?

$$G_{\mu\nu} = 8\pi G \left(T_{\mu\nu} - \bar{\rho}_{\rm DE} g_{\mu\nu}\right)$$

- breakdown of GR?

dominates dynamics of late-time Universe



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: ghosts? instabilities?

Theory Space: Breaking GR

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Most can be cate

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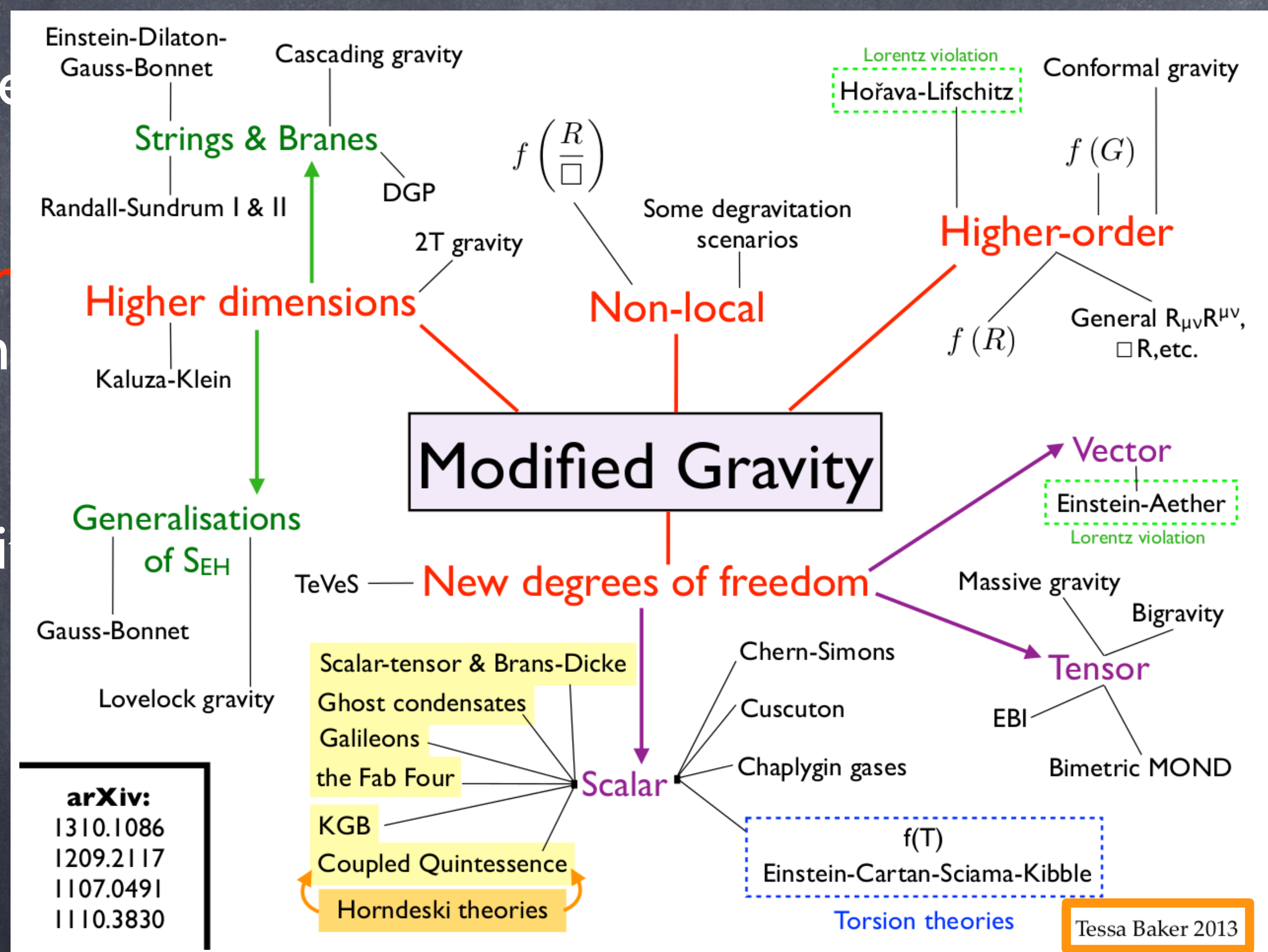
velock's theorem (1969)

Subject to viabili



No favored alternative theory, theory space hard to summarize succinctly

Need unifying frameworks + phenomenology to compare to data

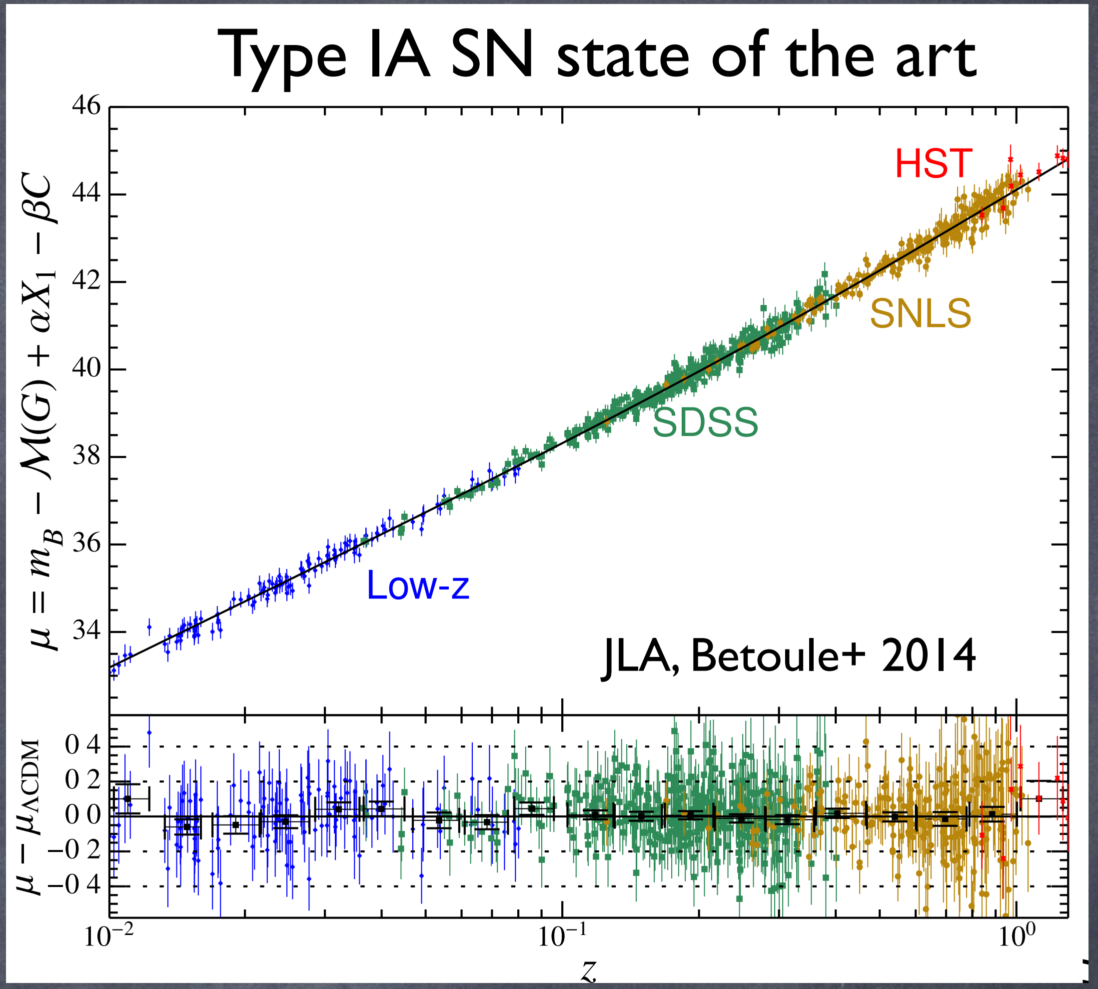
Testing Cosmic Acceleration

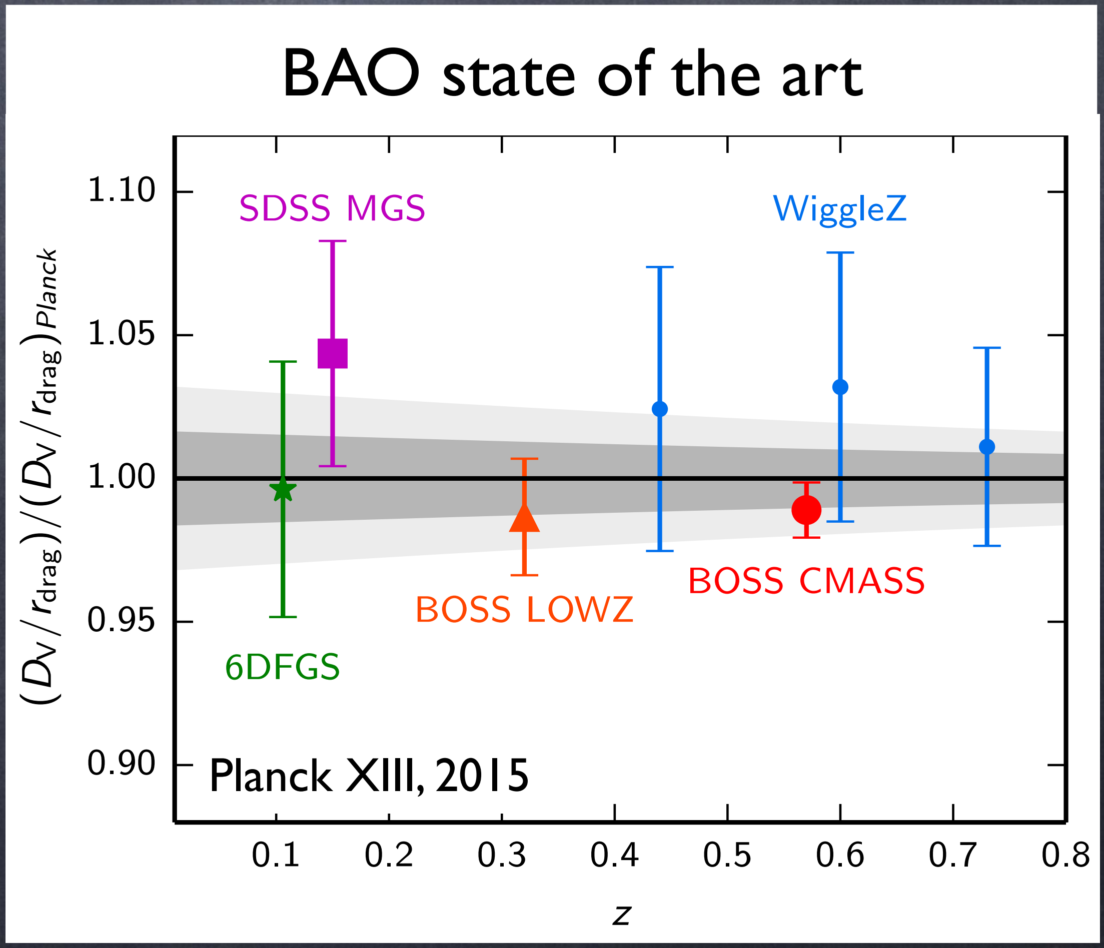
size of Λ difficult to explain

important to test GR over cosmological scales

Expansion history

- determines distances
- measured through supernovae, CMB peaks + baryonic acoustic oscillations (BAO)
- agreement with ΛCDM
- not much information on dark energy/gravity: at most w_0, w_a





Cosmic Structure Formation

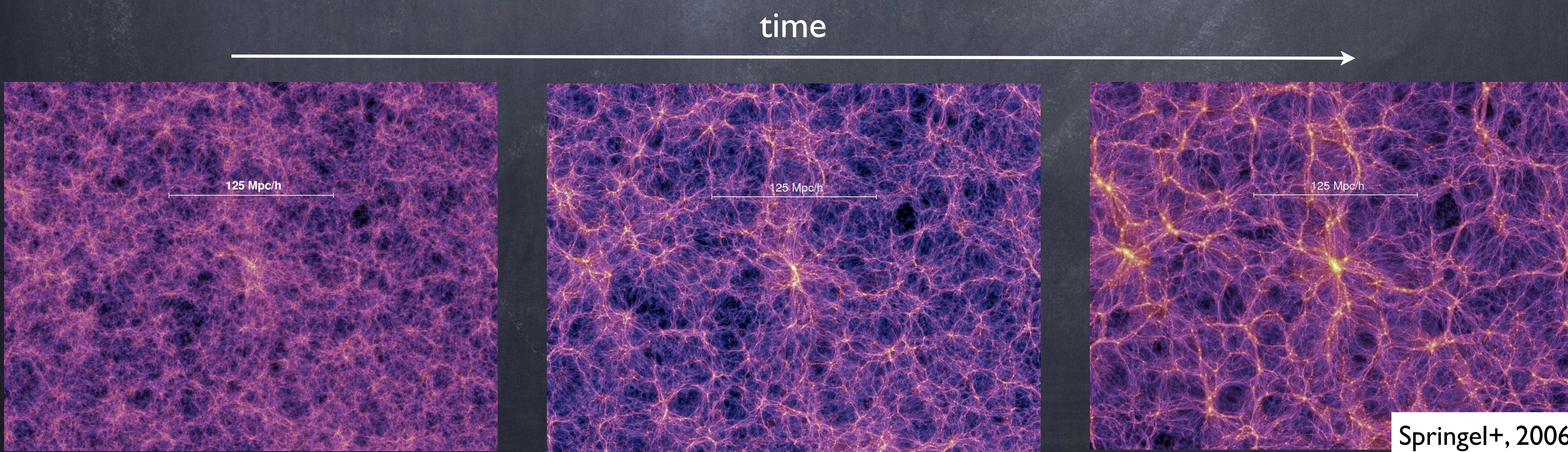
gravity drives **formation of cosmic structure**

much more information than expansion rate

linear level: perturbed Einstein equation

non-linear evolution: numerical simulations

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

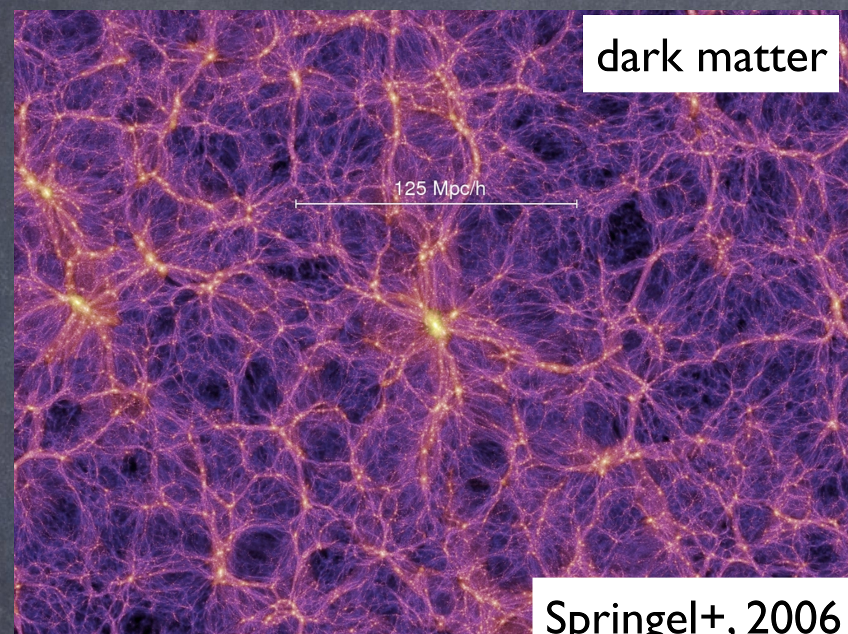


Springel+, 2006

How to compare with data?

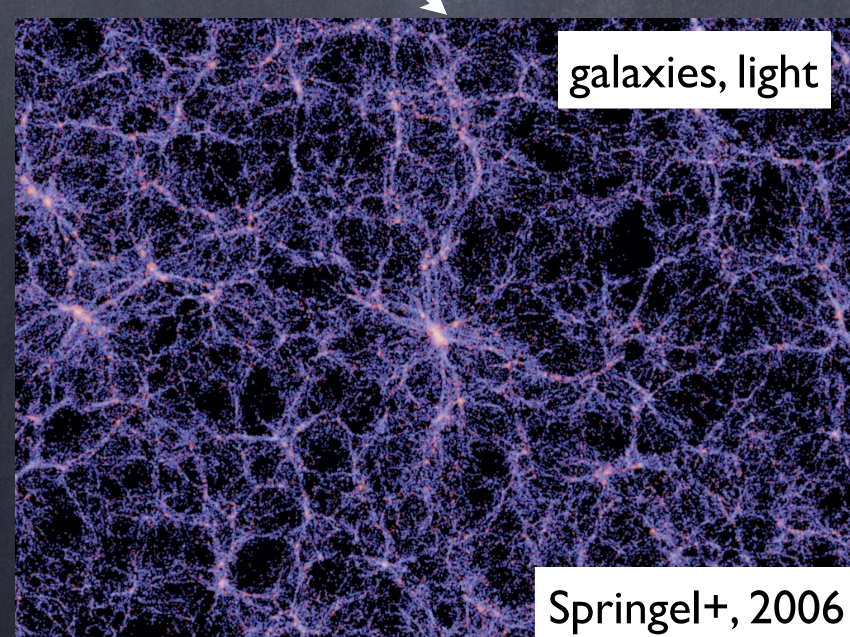
physics
+ model parameters

generate initial conditions, evolve



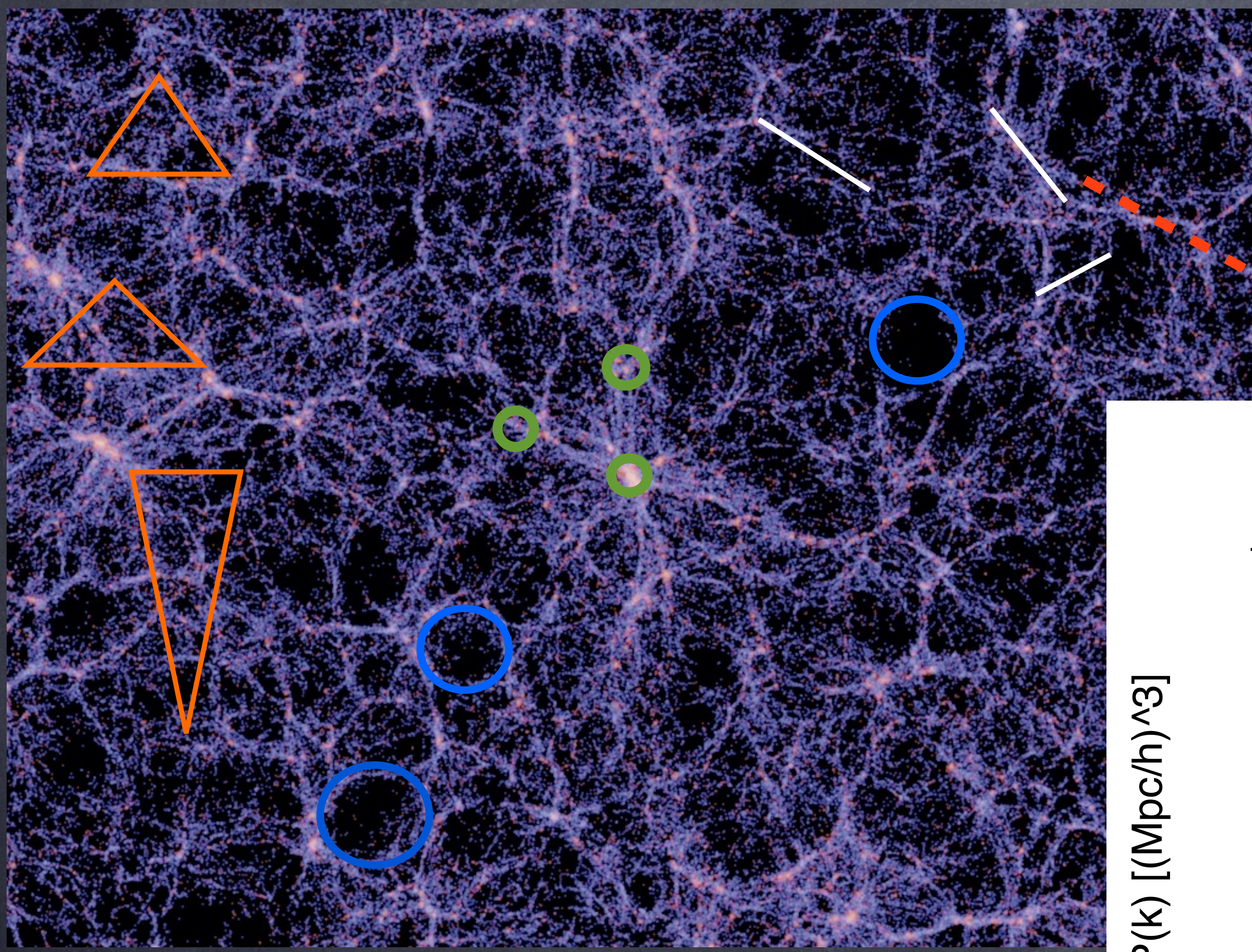
galaxy formation models

?

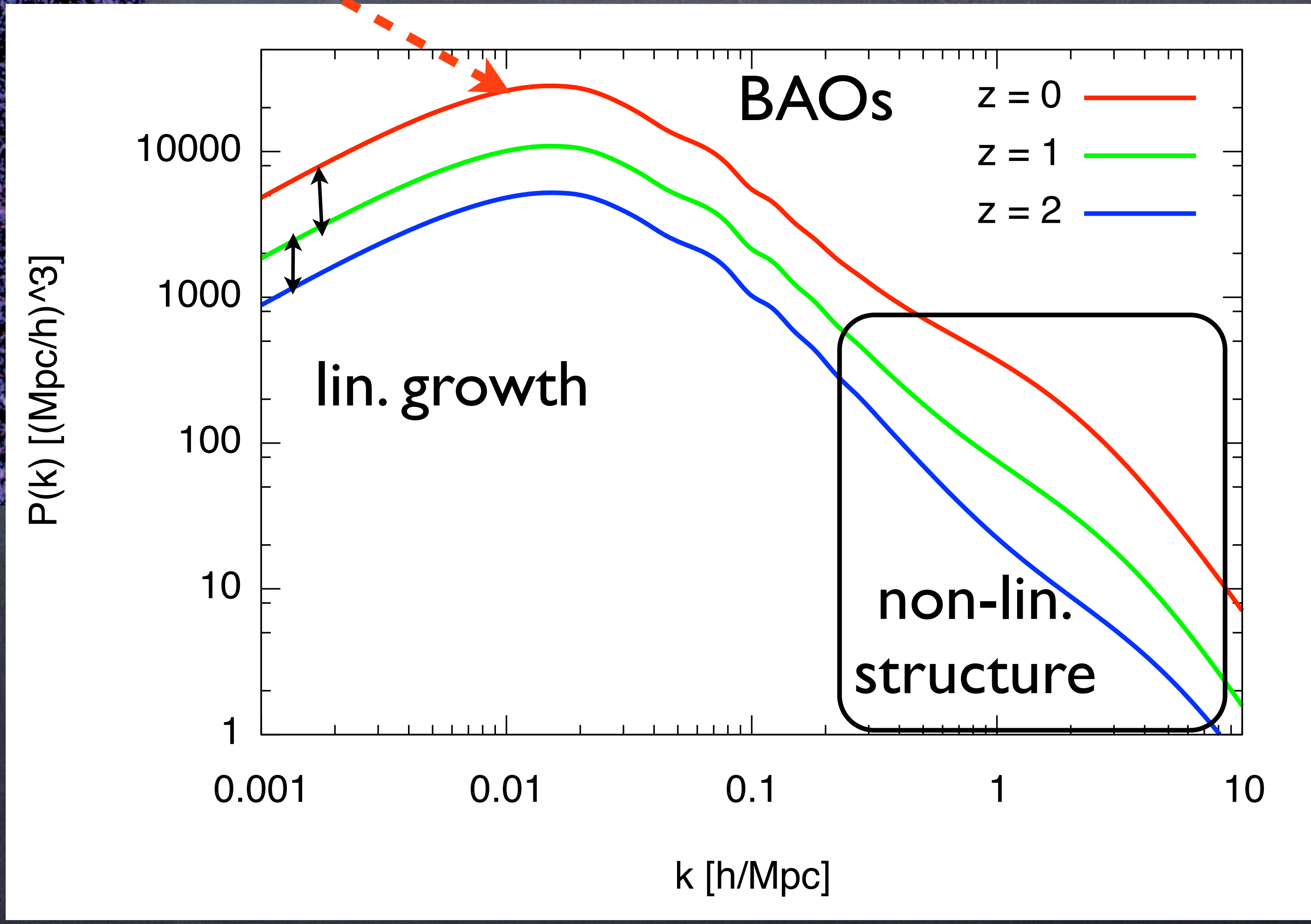


?

What to look for in the galaxy distribution?



need redshift, understand galaxy bias

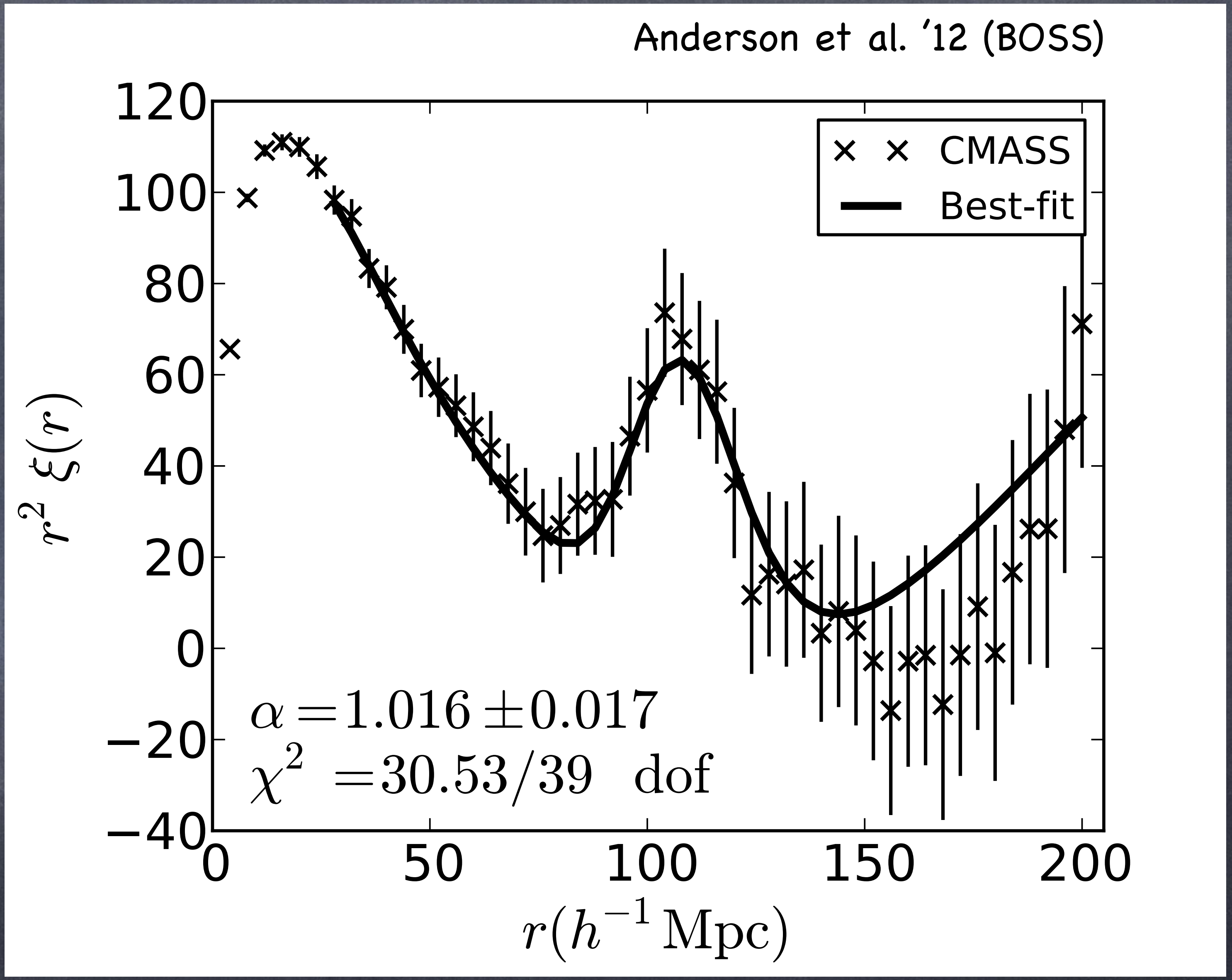


- clusters (over densities),
- voids (under densities)
- two-point correlations
- three-point correlations,...

LSS Probes of Dark Energy

Galaxy Clustering

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



LSS Probes of Dark Energy

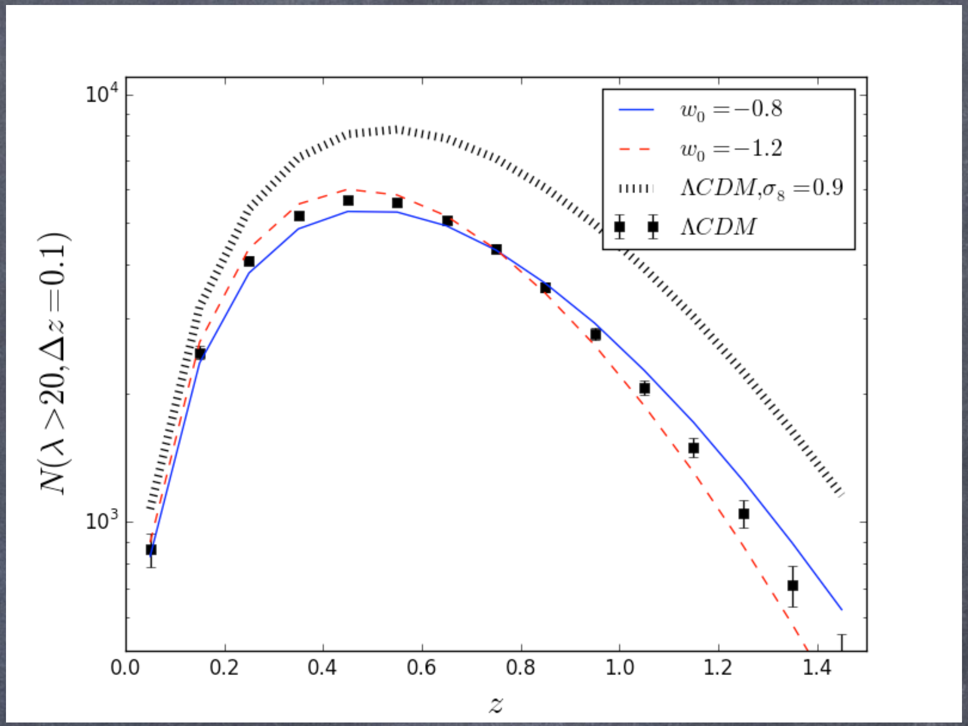
Galaxy Clusters

- measure number counts

$$N(\hat{M}, z, \Delta z) = \frac{dn}{dMdz}\Delta V(z, \Delta z)$$

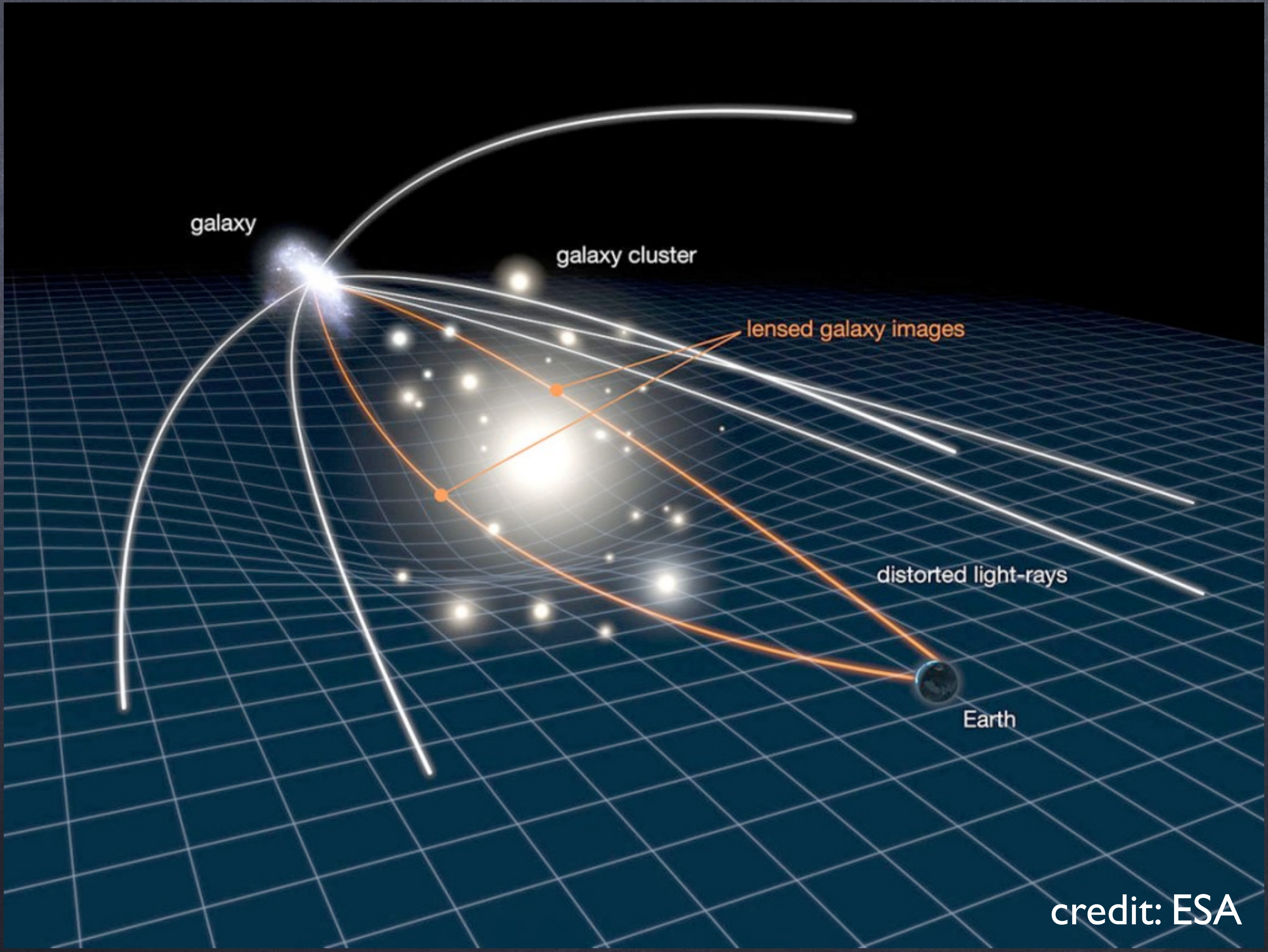
→ distribution of peaks, growth of structure, expansion history

- but need to identify clusters + member galaxies, infer masses!



LSS Probes of Dark Energy

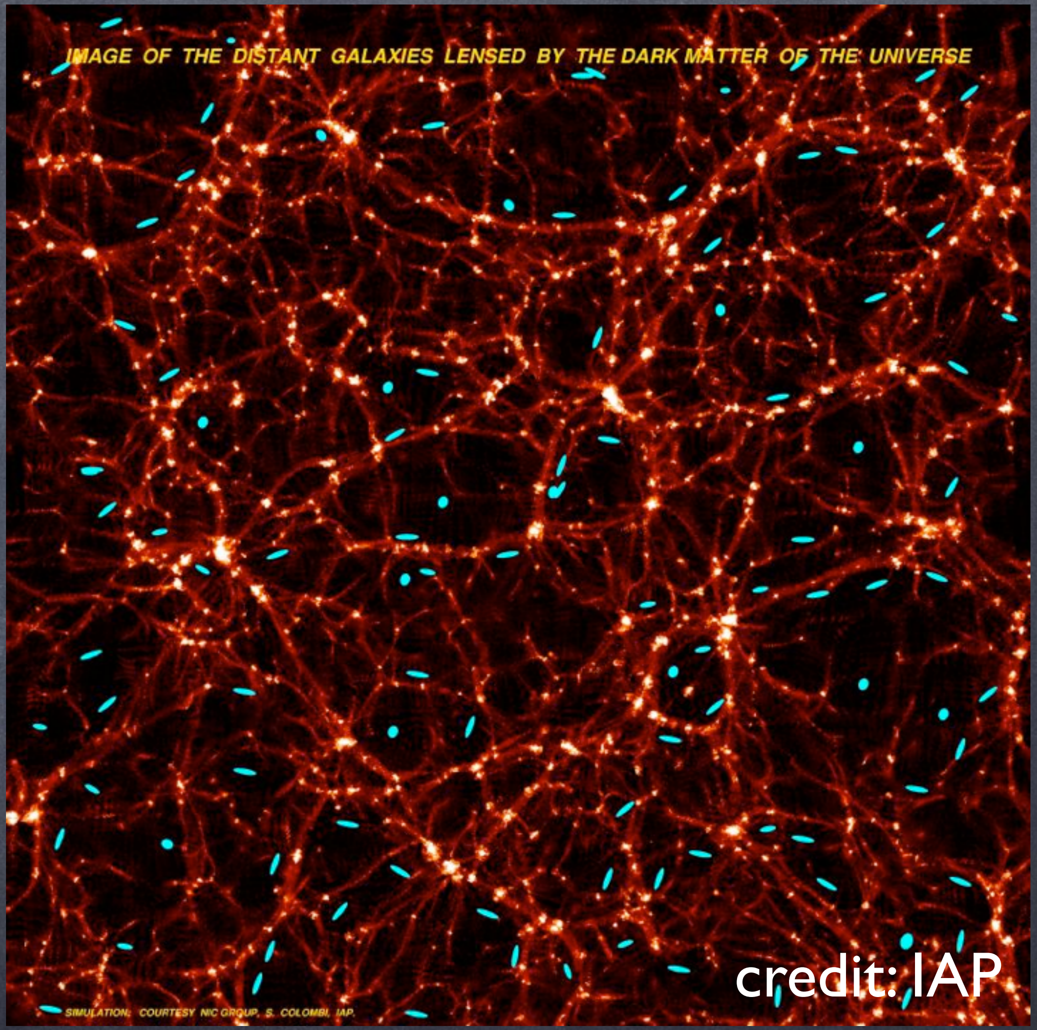
Weak Gravitational Lensing



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

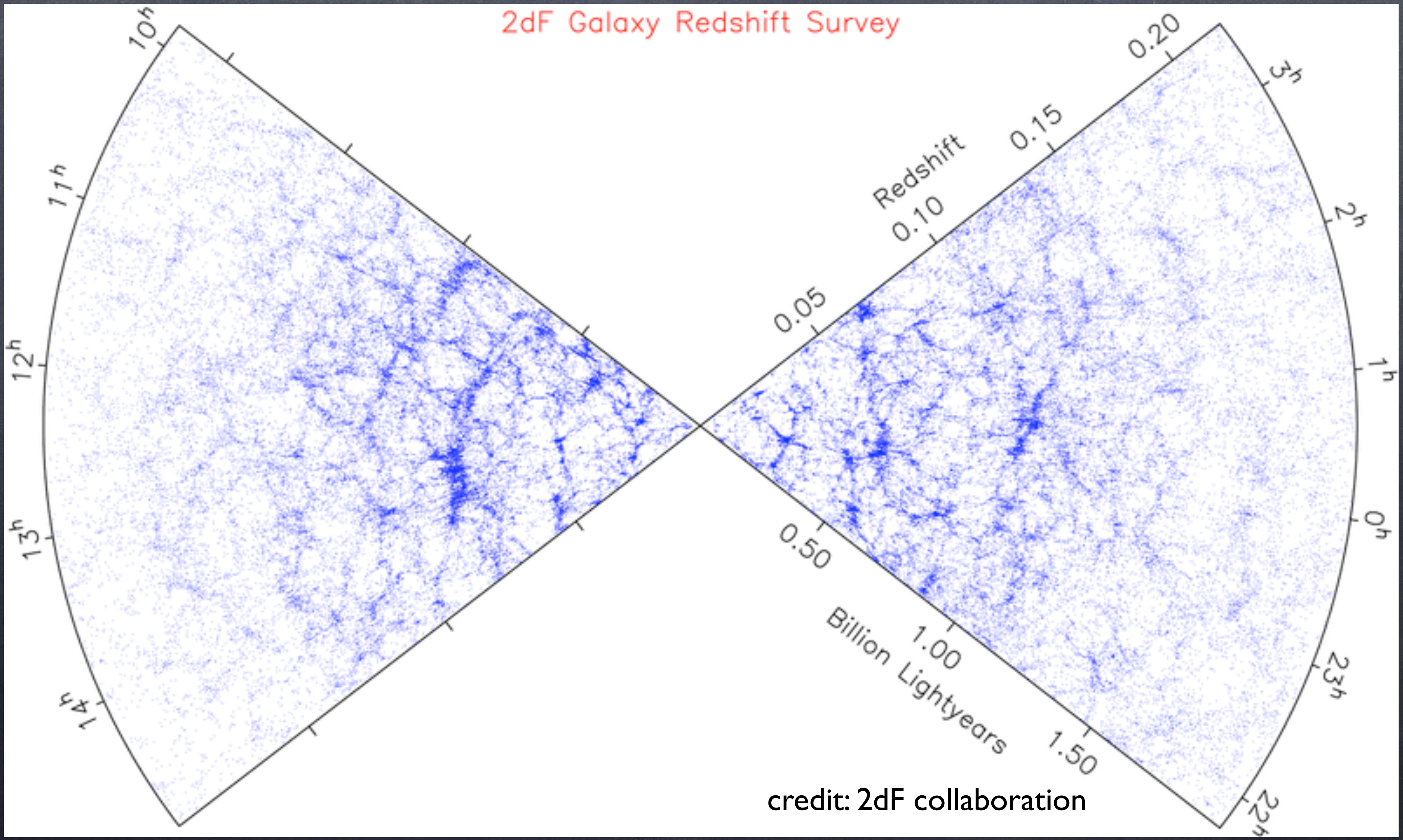
Weak Lensing

galaxy positions, shapes, types, redshifts

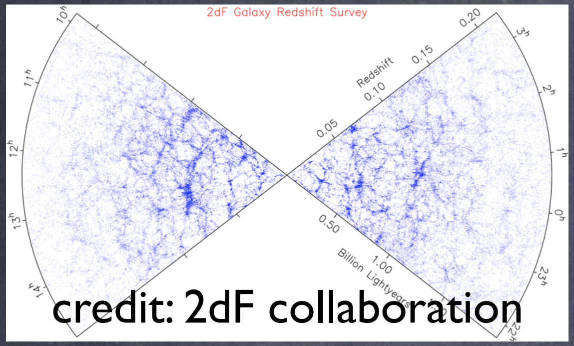
Spectroscopic Dark Energy Surveys

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

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

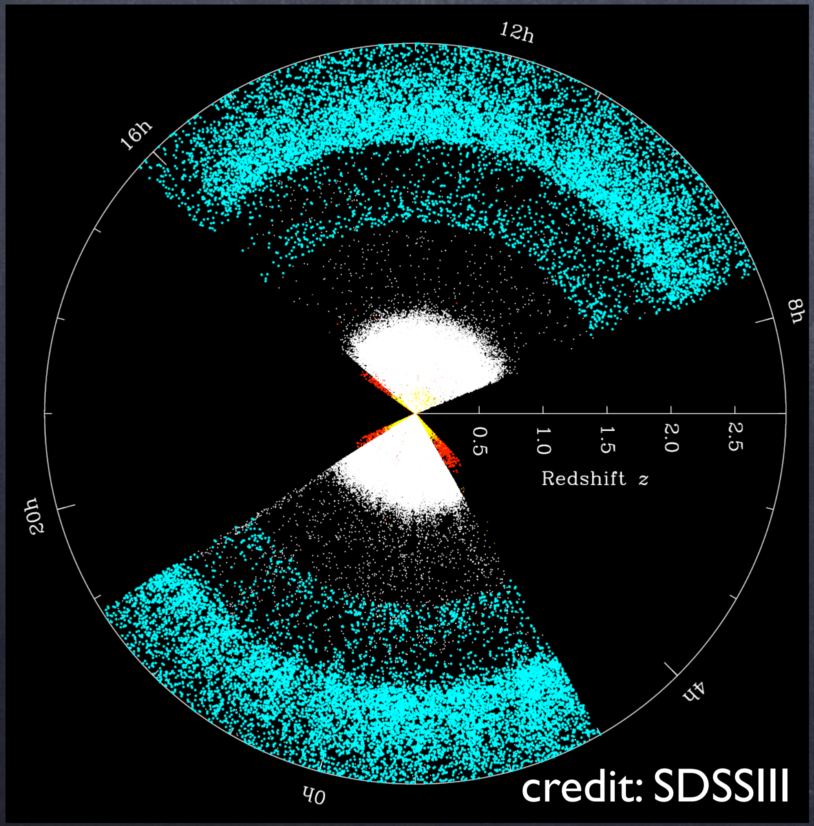


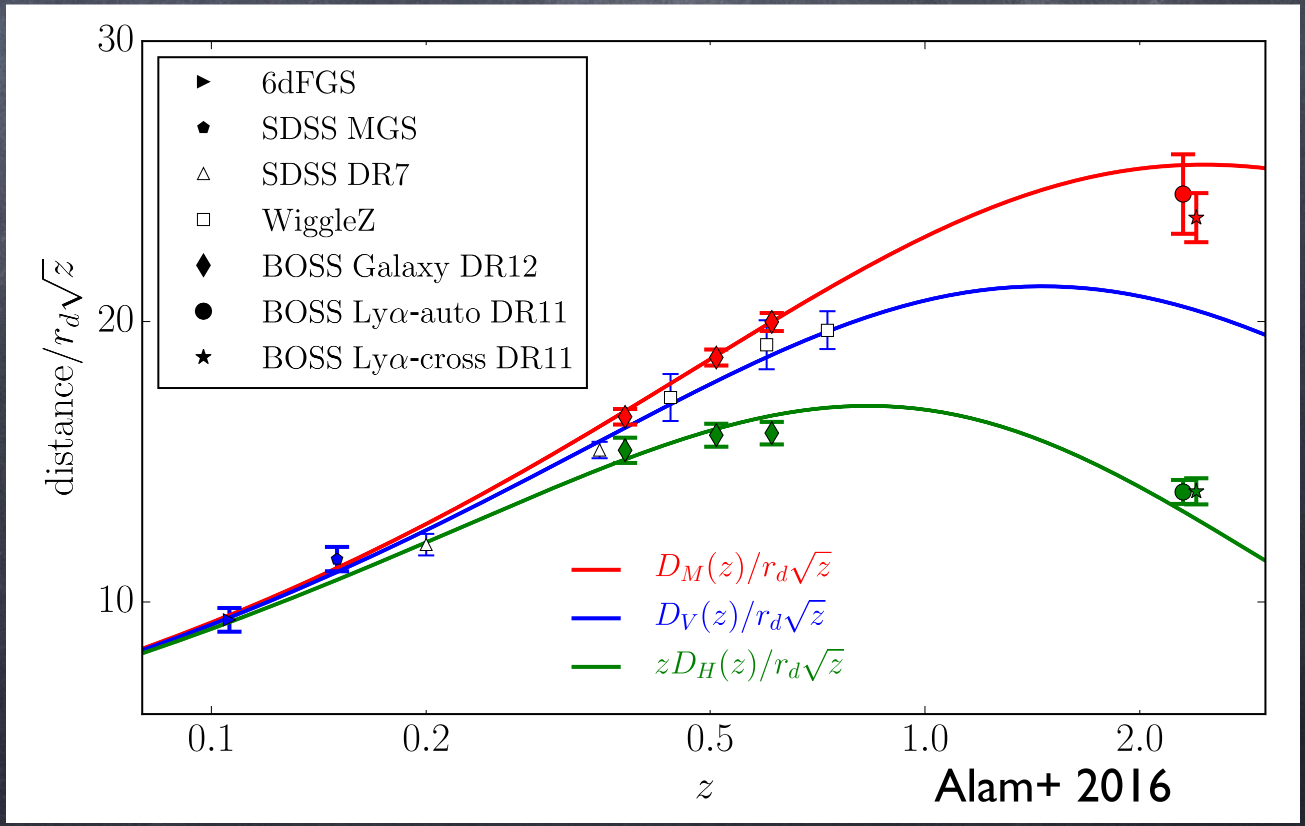
Spectroscopic Dark Energy Surveys



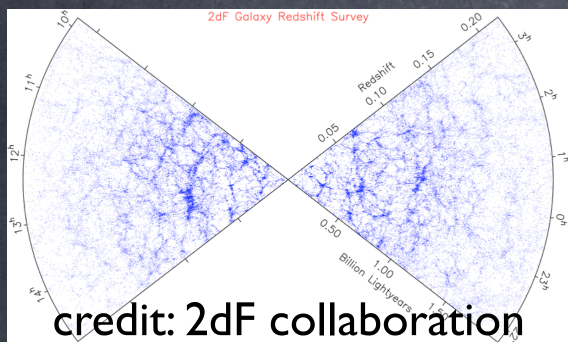
the present: BOSS, WiggleZ, …

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

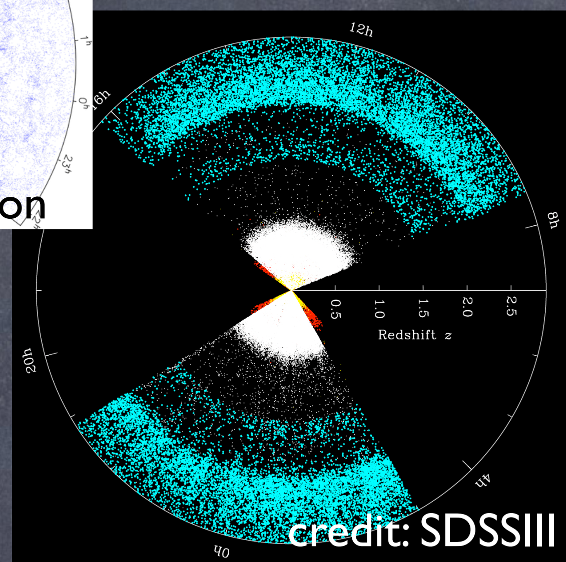




Spectroscopic Dark Energy Surveys



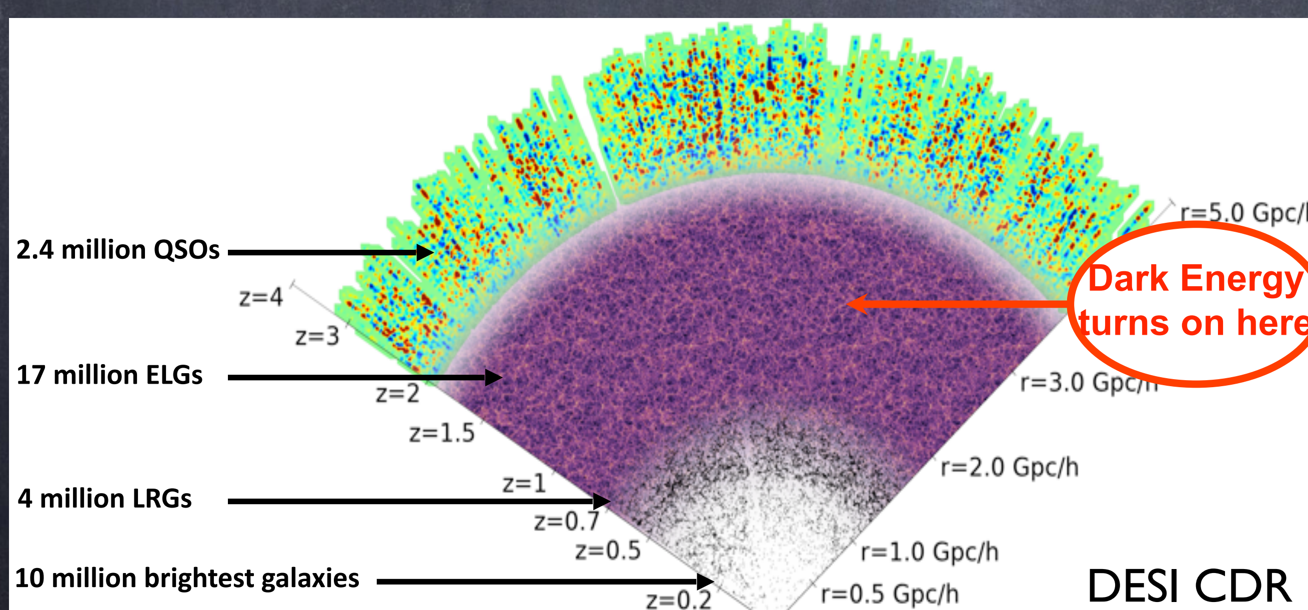
credit: 2dF collaboration



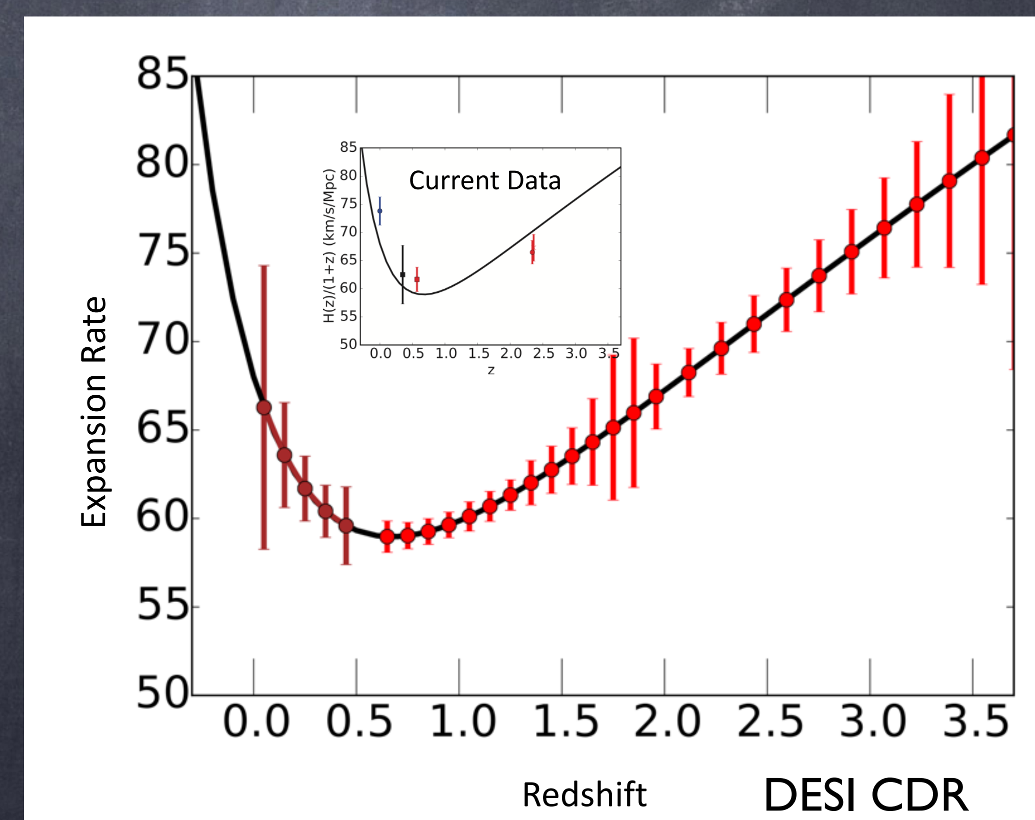
credit: SDSSIII

the future: Dark Energy Spectroscopic Instrument (DESI)

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



DESI CDR



DESI CDR

~Optical Dark Energy Surveys

Spectroscopic galaxy surveys

determine redshifts of select galaxies

Photometric galaxy surveys

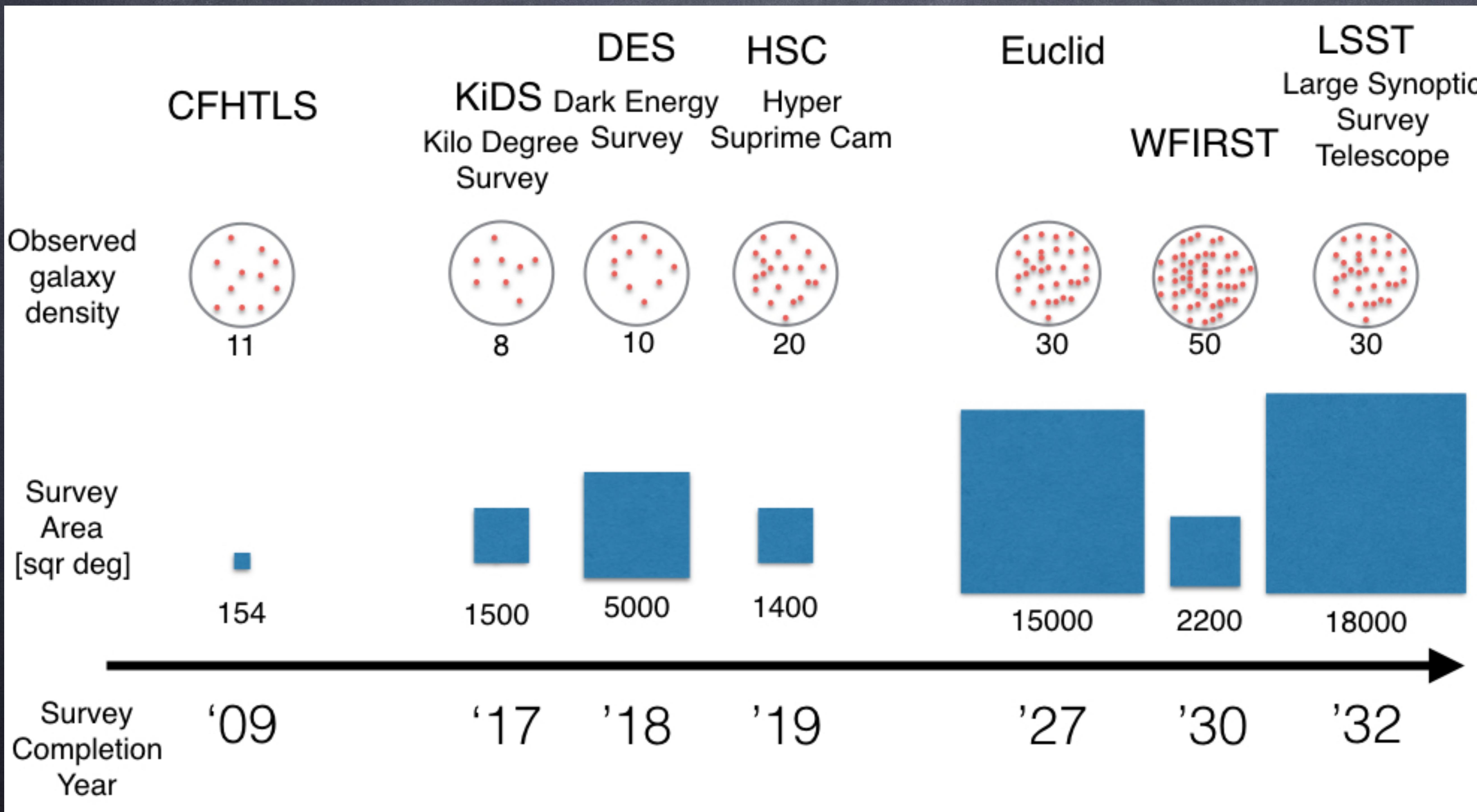
image all galaxies to lim. brightness, in multiple bands

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 multiband imaging surveys:

300 million galaxies over 1/8 sky

4000 supernovae (time-domain)

New 570 Megapixel Dark Energy Camera on the Blanco 4-meter

5 bands (g,r,iz,Y), 10 tilings each

Stage III Survey using 4 complementary techniques:

I. Galaxy Clusters

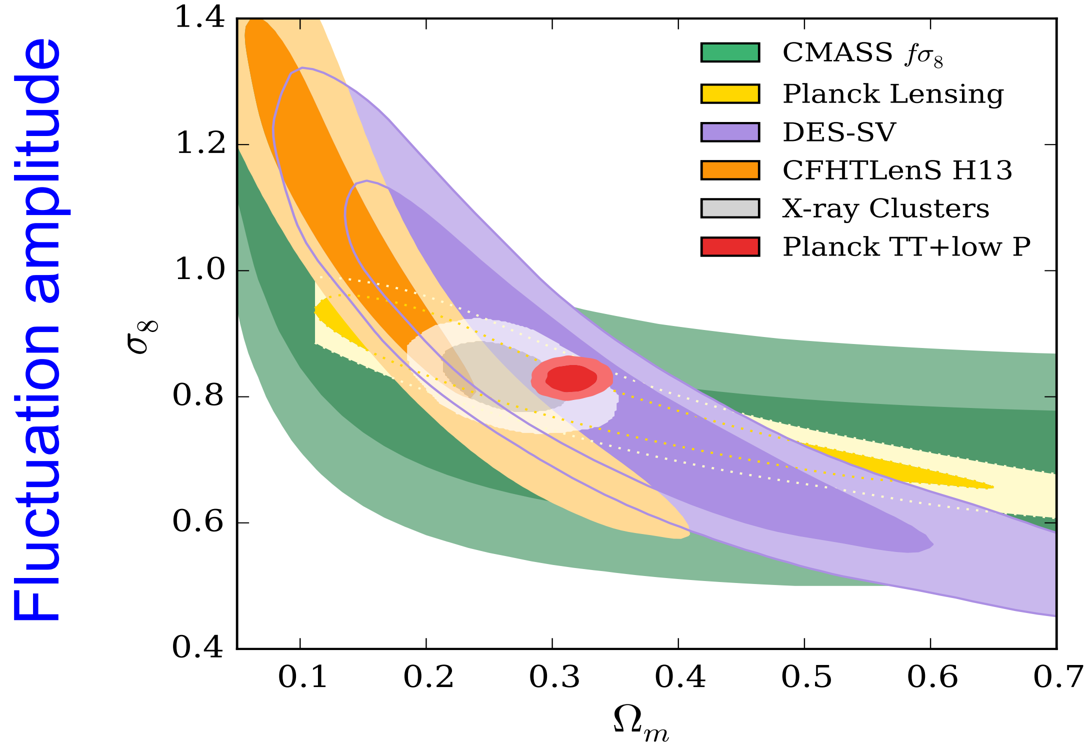
II. Weak Gravitational Lensing

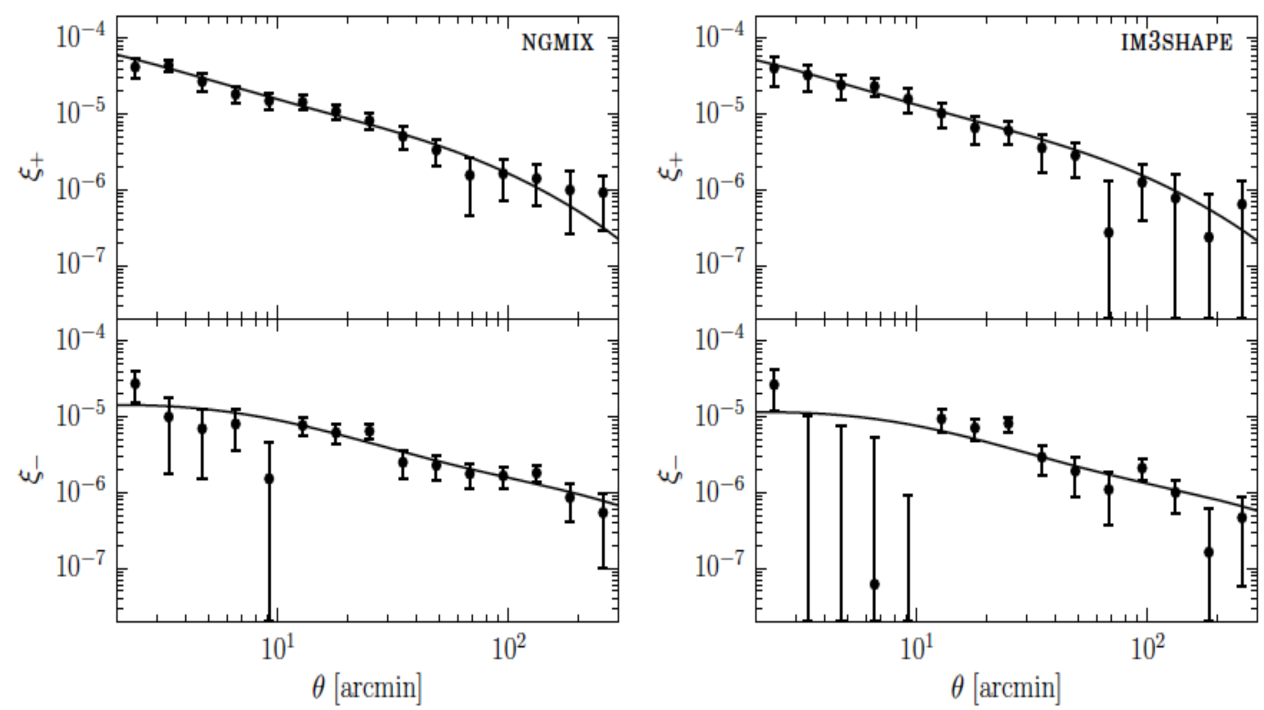
III. Galaxy Clustering

IV. Supernovae

DECam on the Blanco 4m at NOAO Cerro Tololo InterAmerican Observatory

DES: Weak Lensing with Science Verification Data





Cosmological parameters

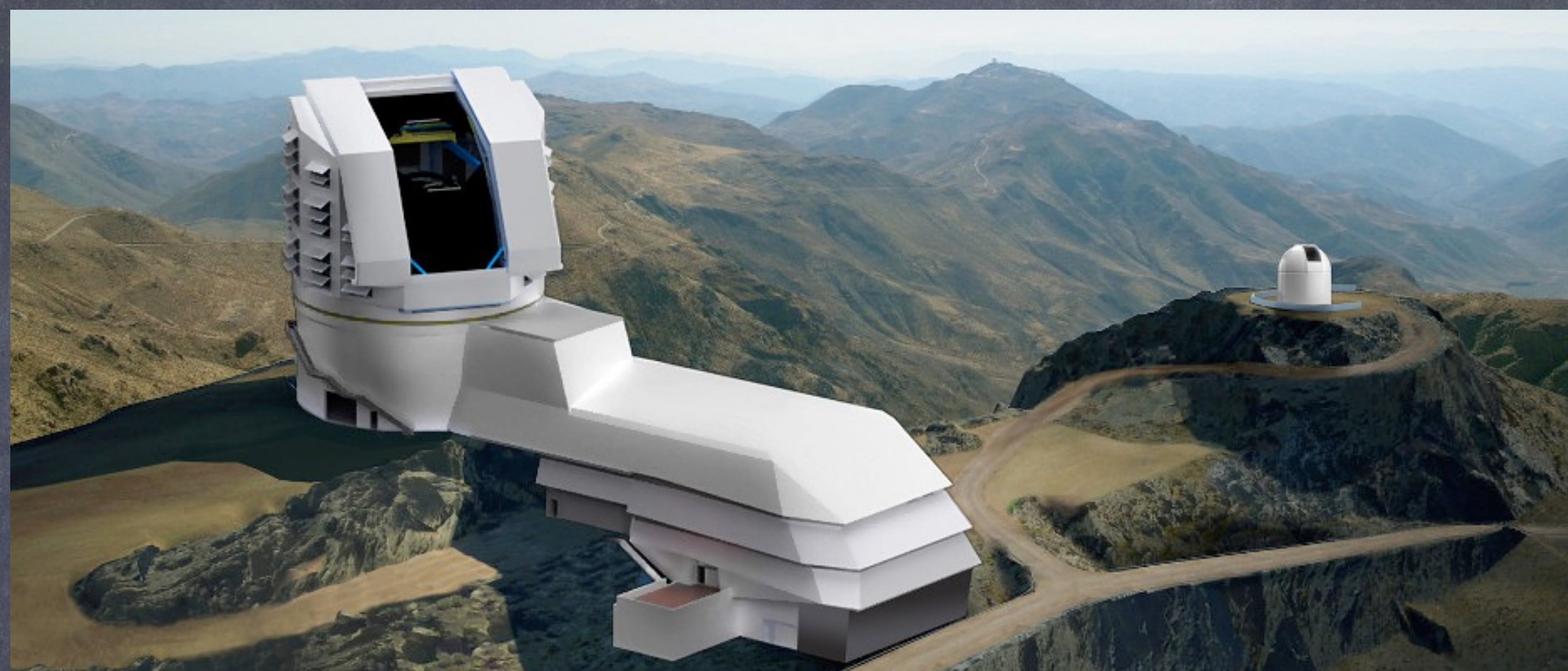
DES Collaboration+ 2016

2pt xi (+-) from two shear pipelines

Becker+ 2016

proof of concept - we understand the camera
5 years of data to come!

LSST
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

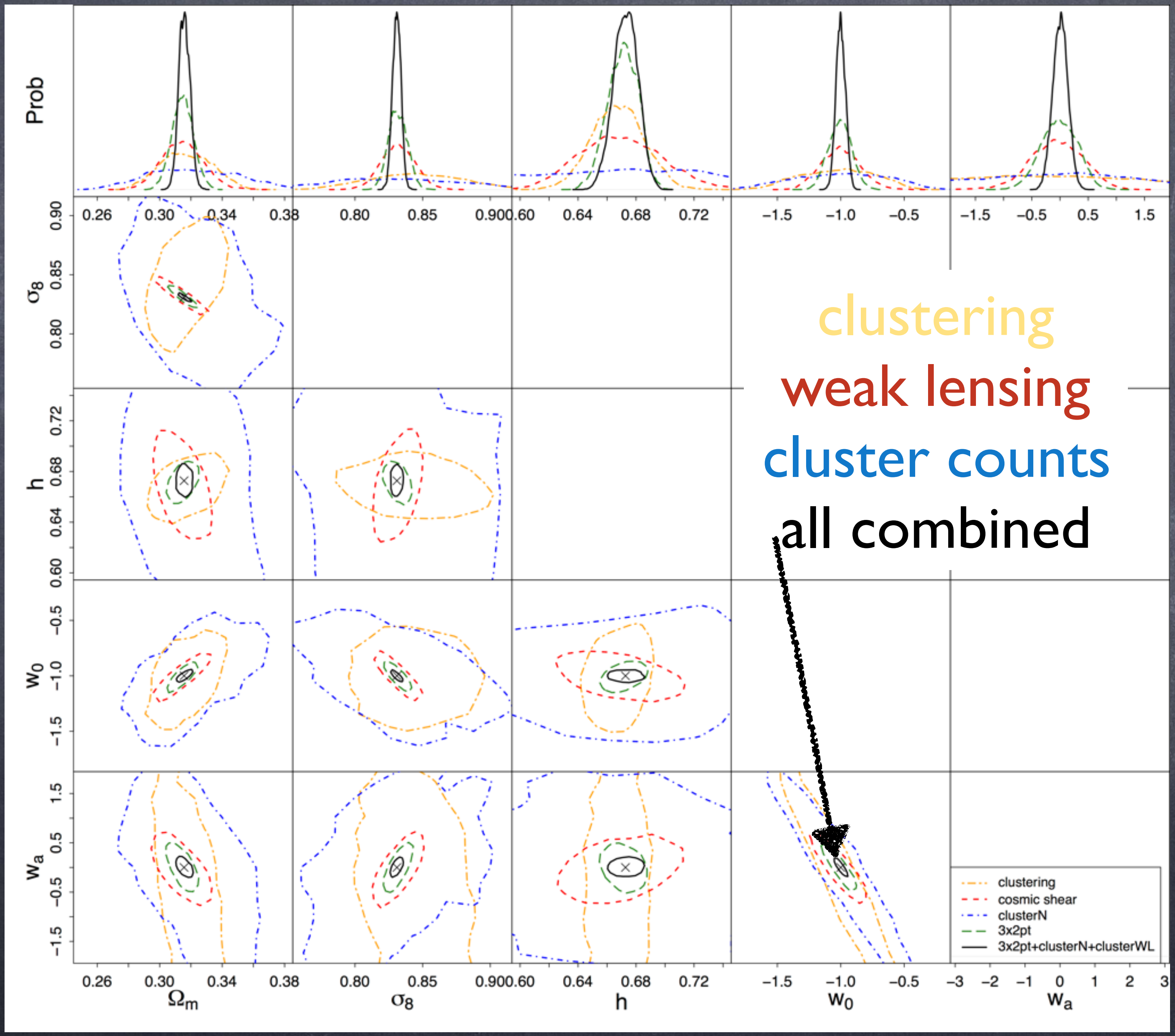
Prepare for and carry out cosmology anal

- five key cosmology probes, organized in
  - Galaxy Clustering, Galaxy Clusters, Strong Le
    Theory & Joint Probes
- “Enabeling Analyses” WGs: understand

DESC cosmology likelihood - late 2015
to be implemented within Science WGs

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

Cosmology from LSST: The Power of Combining Probes



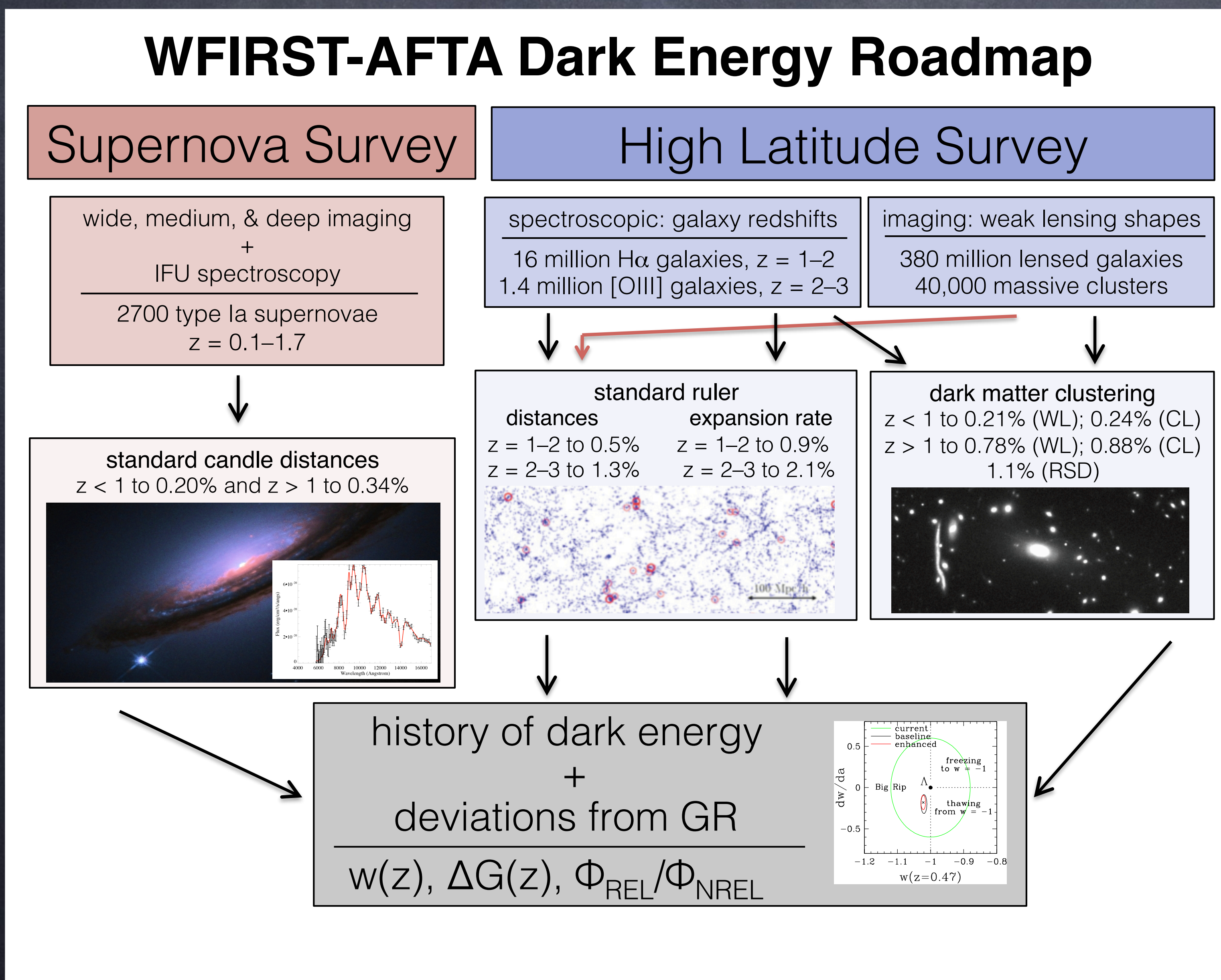
Krause & Eifler 2016

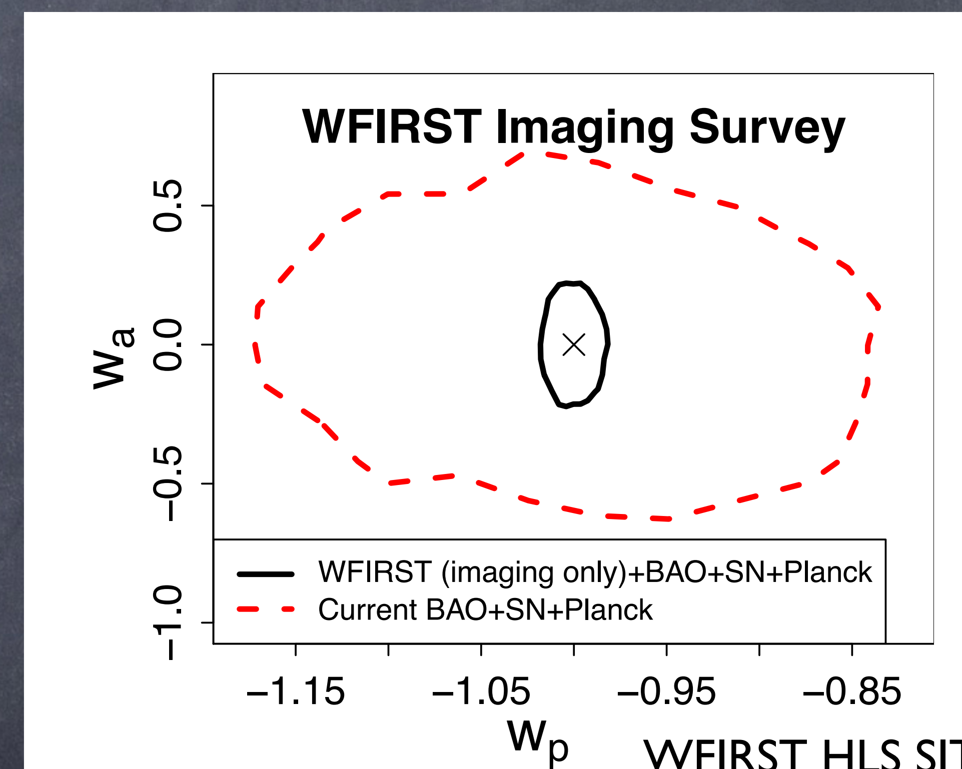
+ supernovae + strong lensing

WFIRST Wide-Field Infrared Survey Telescope

(aka spy telescope)

one satellite, three cosmological surveys - launch ca. 2025

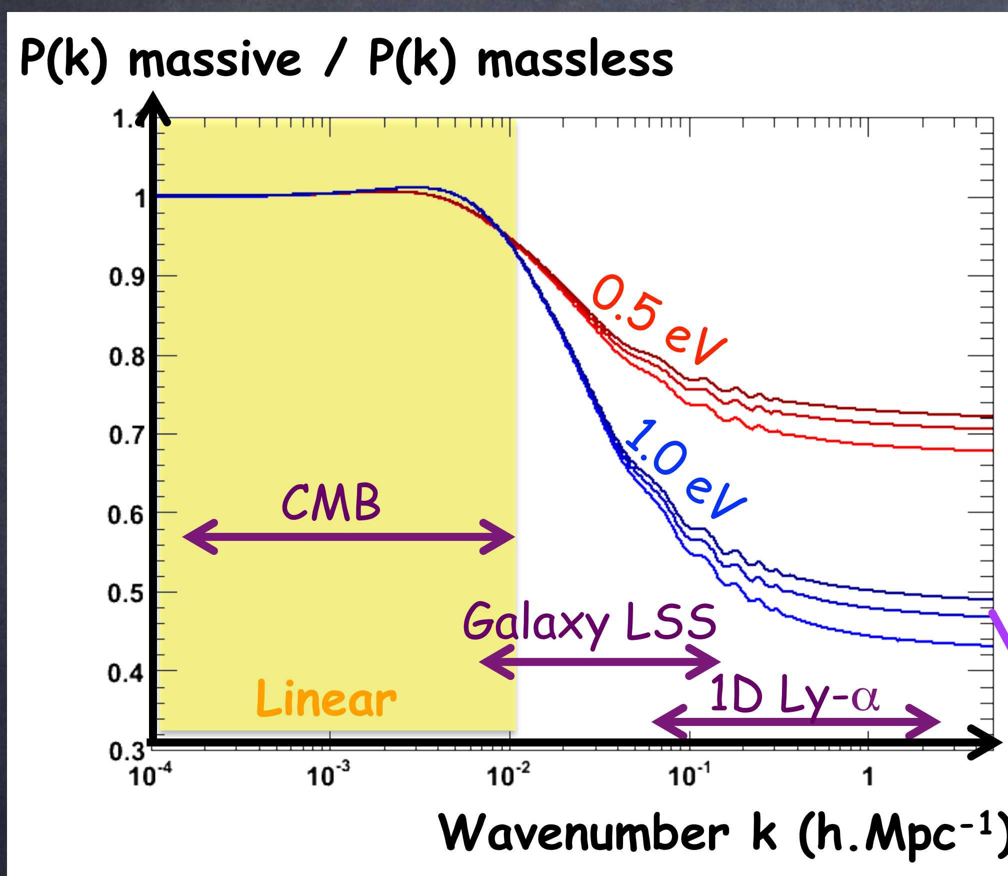




(credit: WFIRST SDT report, Spergel+ '15)

Beyond Dark Energy

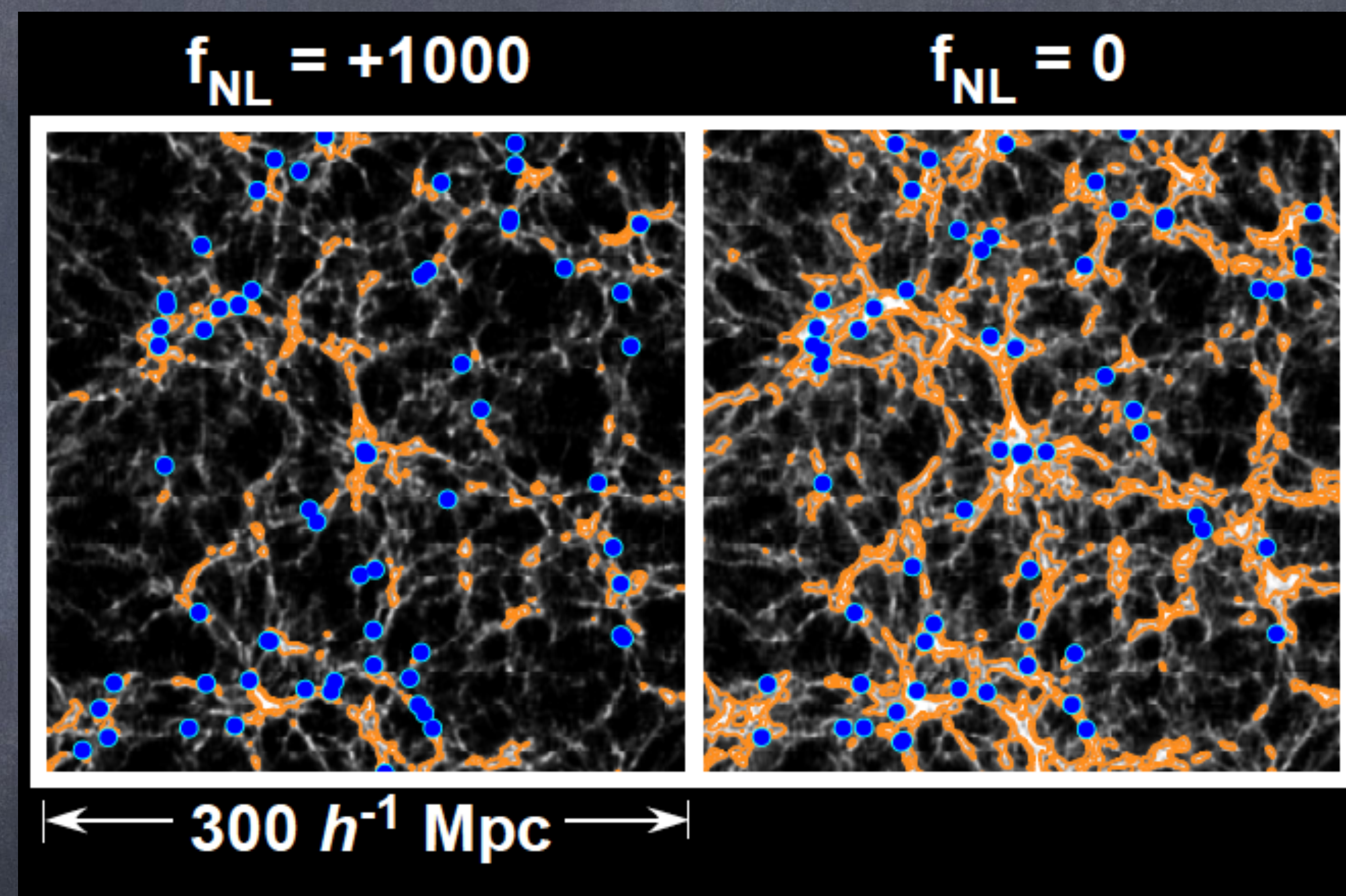
Imprint of neutrinos



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

[normal hierarchy]

Distribution of Peaks



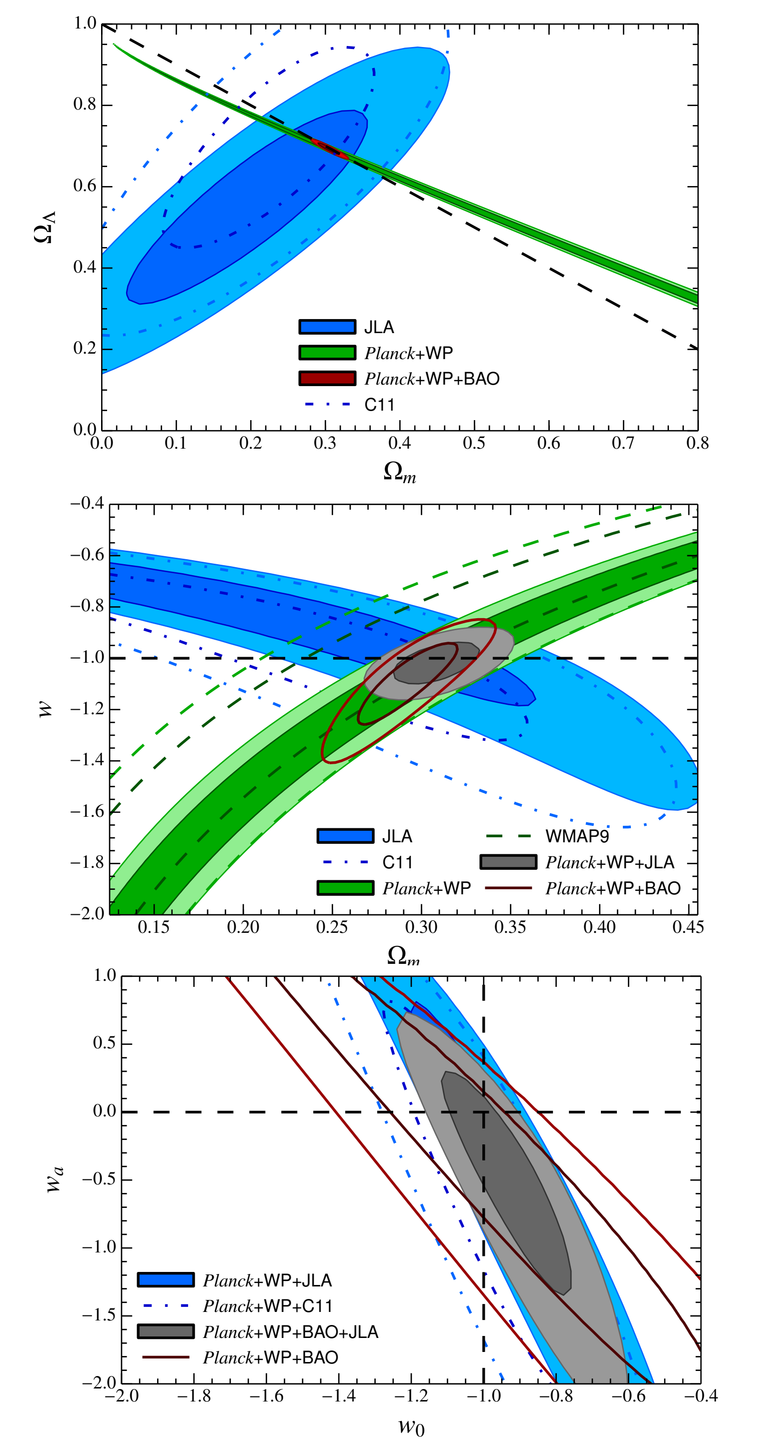
measure imprint of inflation on late-time structure

forecasts under way

The Power of Combining Probes

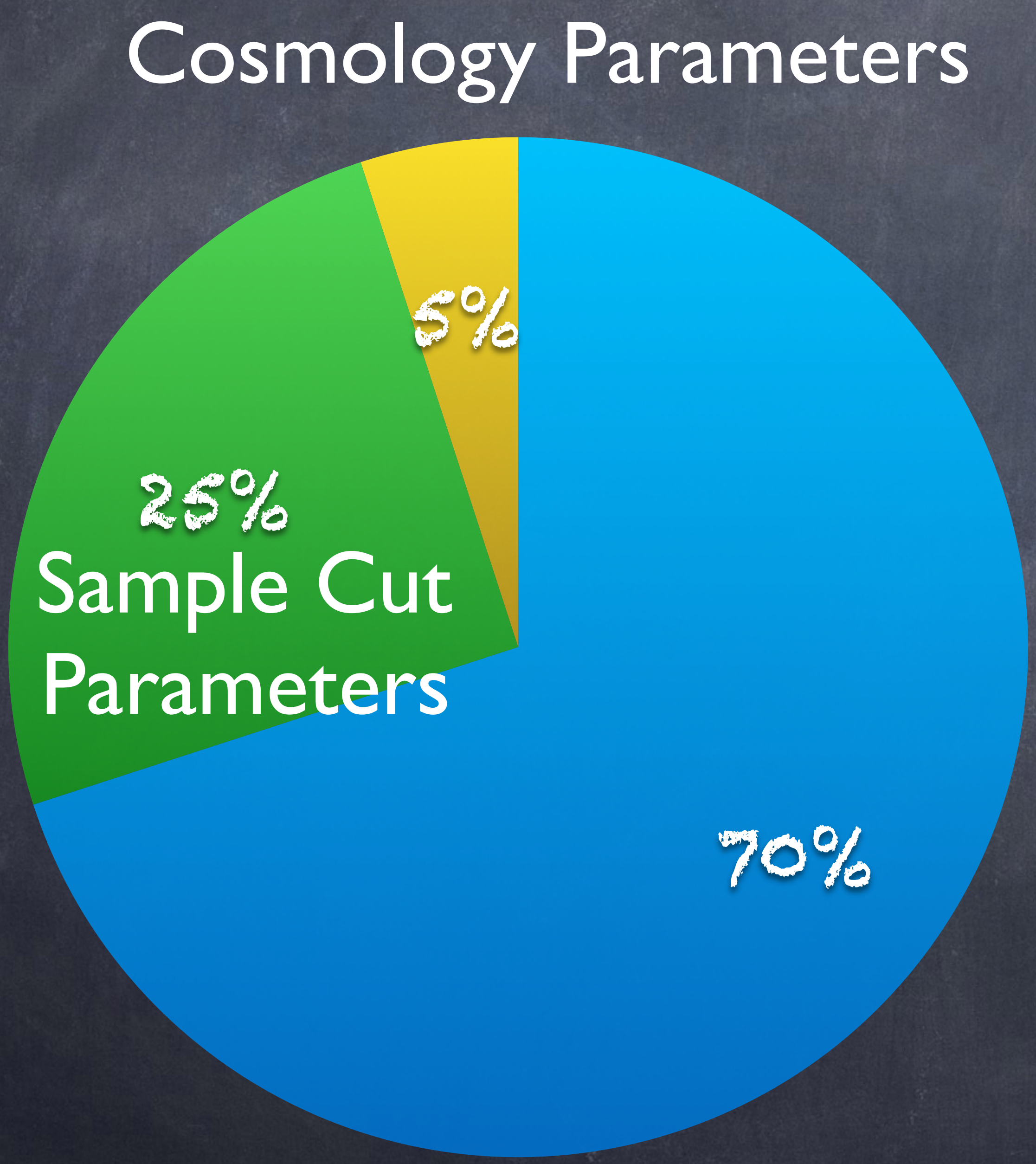
- Best constraints obtained by combining cosmological probes
    - independent probes: multiply likelihoods

- 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



Betoule et al. 2014

Cosmology Analysis Parameters

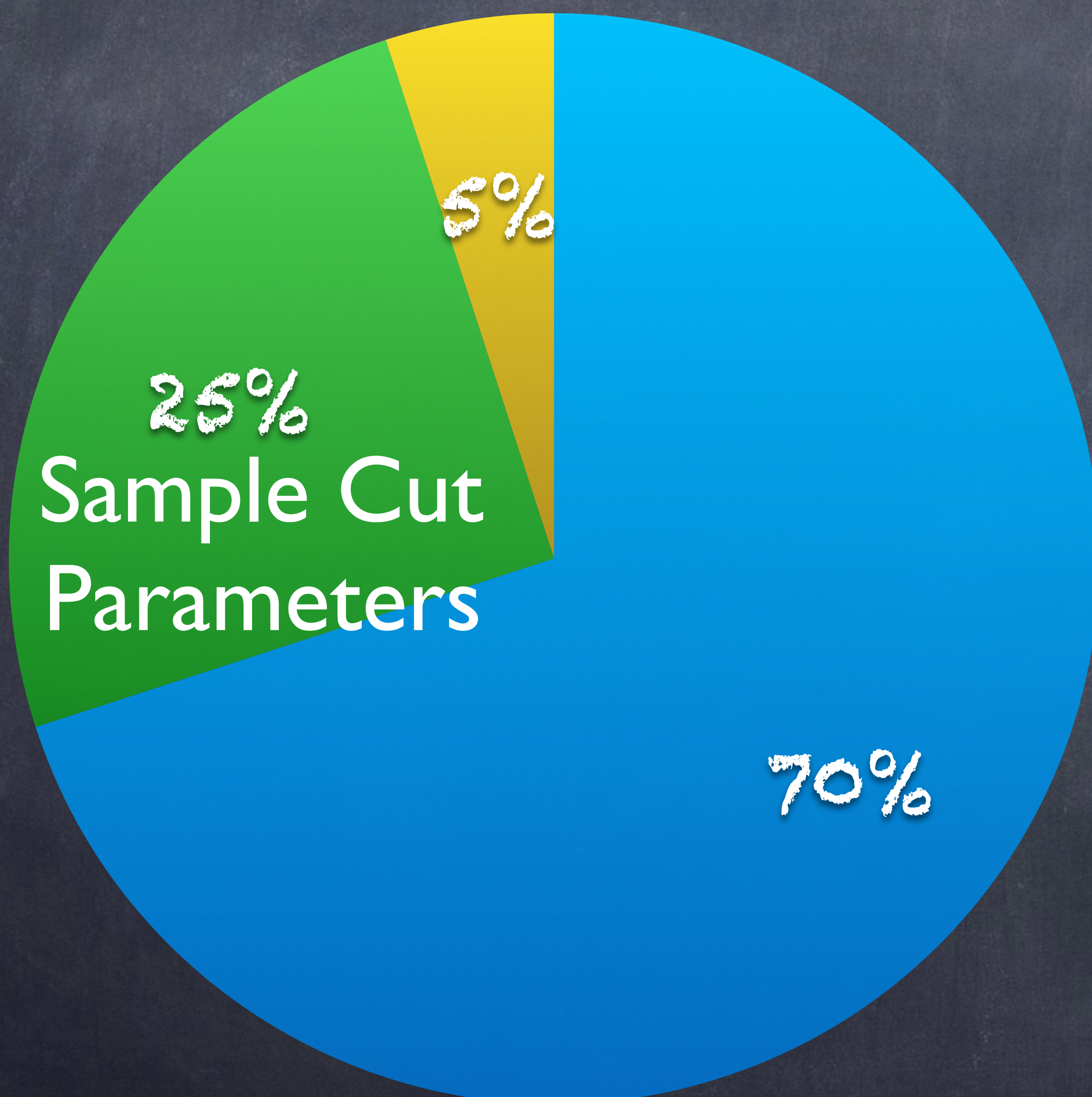


"Systematics Parameters"

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

Cosmology Analysis Parameters

Cosmology Parameters



"Systematics Parameters"

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

sample cuts + systematics highly interconnected

→ 95% systematics…

Cross-Correlations to the Rescue

We have only one experiment/Universe to observe

- can control the instrument/camera, choice of observables
- systematics affect different observables differently
- understand and calibrate systematics
  - compare object-by-object with better data

    photo-zs vs. spectroscopy; shear estimate from higher resolution imaging
  - statistically through cross-correlation

    galaxy shear x CMB lensing -> shear calibration (e.g., Schaan+ 2016);

    positions of spectroscopic galaxies x weak lensing -> galaxy bias
- check consistency of results across surveys and observables
- combine data for most stringent constraints

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