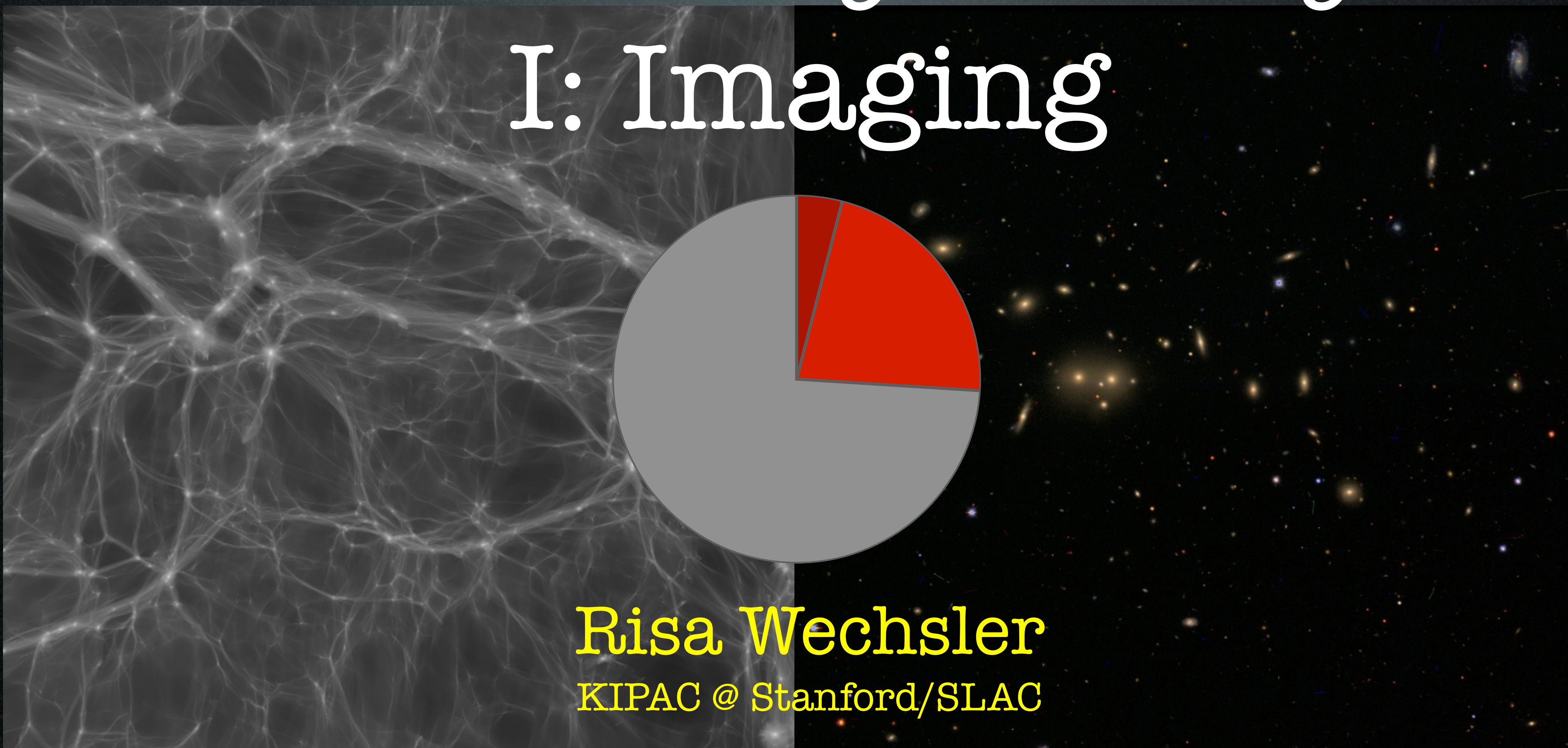
Large-Scale Structure from Galaxy Surveys

I: Imaging



Risa Wechsler

KIPAC @ Stanford/SLAC

SLAC SSI August 17, 2017

Cosmology in 2017:
A strange but well-established Standard Cosmological Model

★ inflation created initial density fluctuations

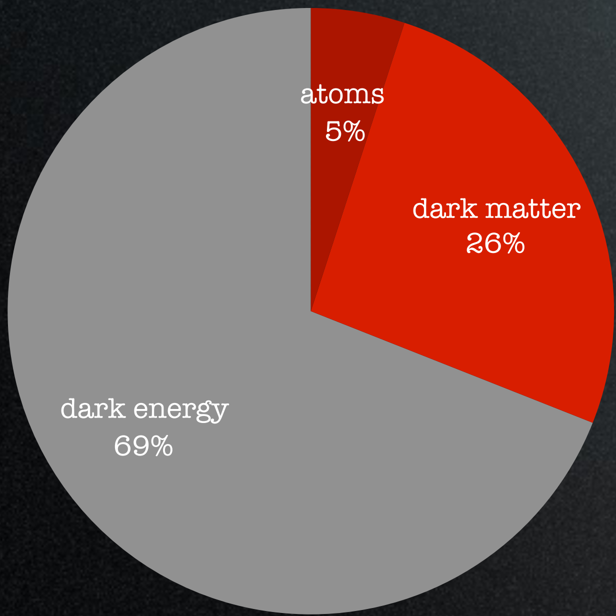
★ gravity is described by general relativity

★ mass in the universe is dominated by dark matter (~85%)

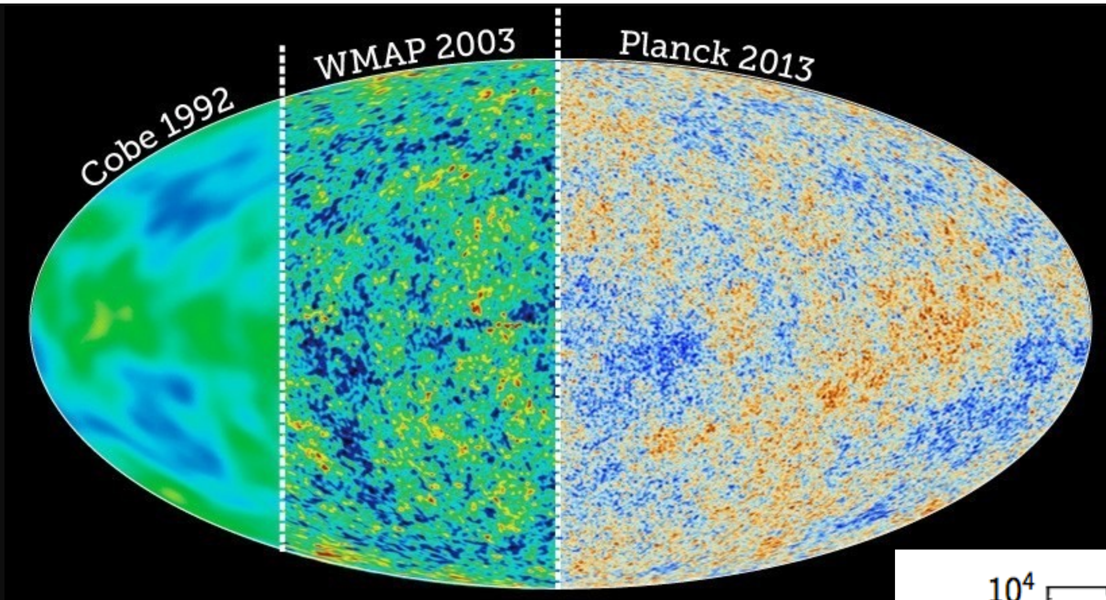
★ Universe is accelerating due to a cosmological constant

current cosmological model can be described by

~7 cosmological parameters --
amount of:
dark matter, baryons, dark energy
+ neutrinos (<0.1%)
expansion rate (H_0)
size of the fluctuations (A/σ_8)
how the fluctuations vary with scale (n)

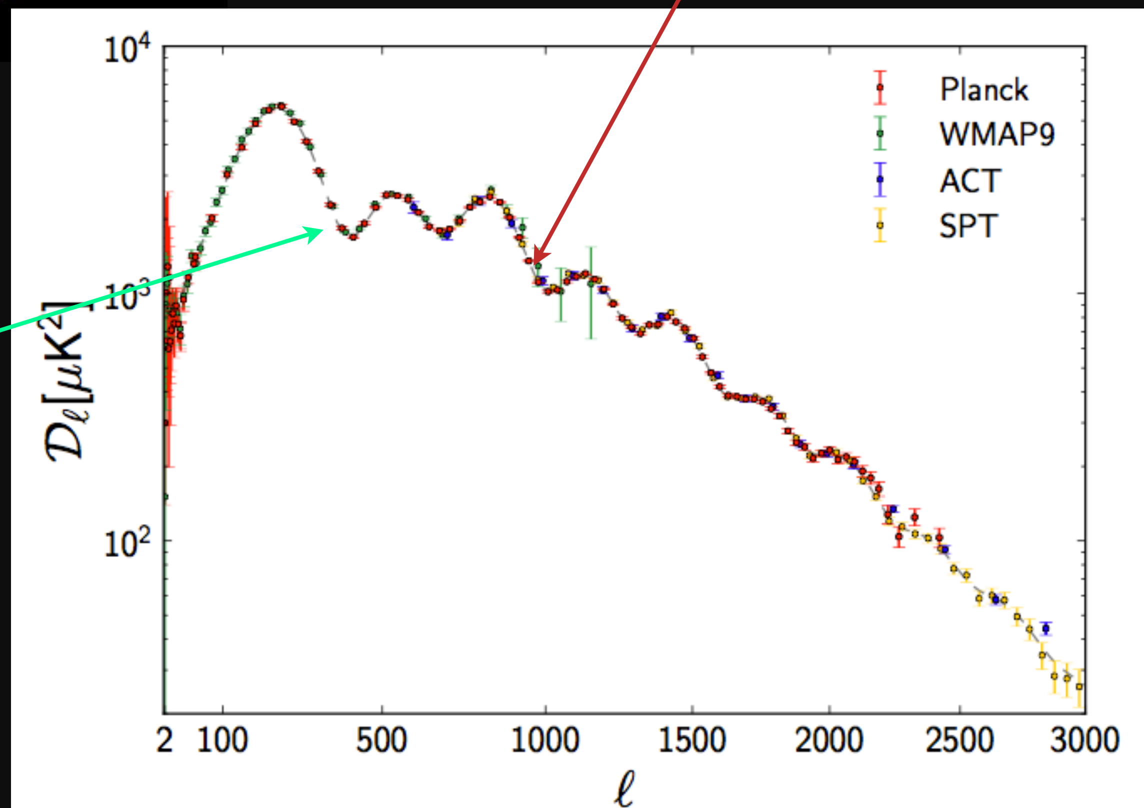


ΛCDM



data

theoretical model



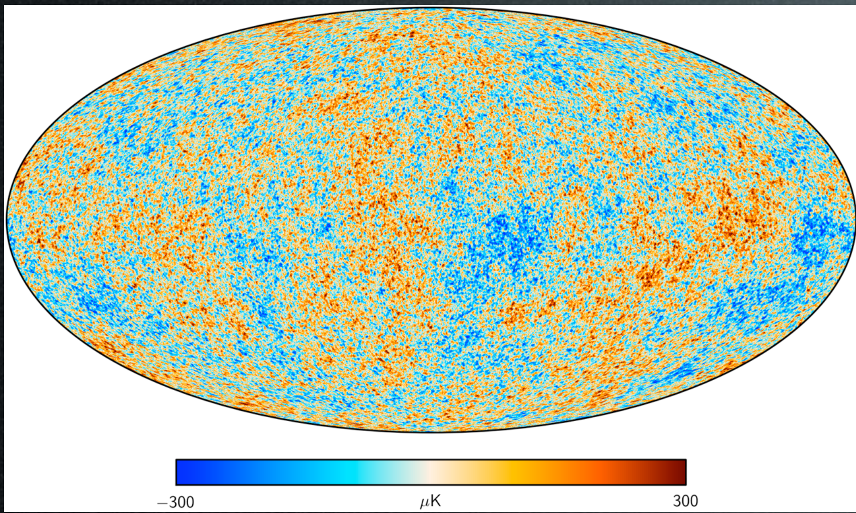
Measurements of the Cosmic Microwave Background give an incredibly precise picture of the Universe at 400,000 years old

The Cosmological Model Post-Planck 2015

Planck Collaboration XIII 2015 (1502.01589)

baryon density	$\Omega_b h^2$	0.02222 +/- 0.00023
matter density	Ω_m	0.308 +/- 0.12
Hubble parameter	H_0	67.8 +/- 0.9 km/s/Mpc
normalization of the power spectrum	σ_8	0.83 +/- 0.015
tilt of the power spectrum	n_s	0.968 +/- 0.006
optical depth	τ	0.066 +/- 0.016
tensor-to-scalar ratio	r	< 0.11
dark energy eq. of state	w	-1.006 +/- 0.045
sum of neutrino masses	Σnu	< 0.23 eV
spatial curvature	$\|\Omega_k\|$	< 0.005

all current data consistent with flat ΛCDM



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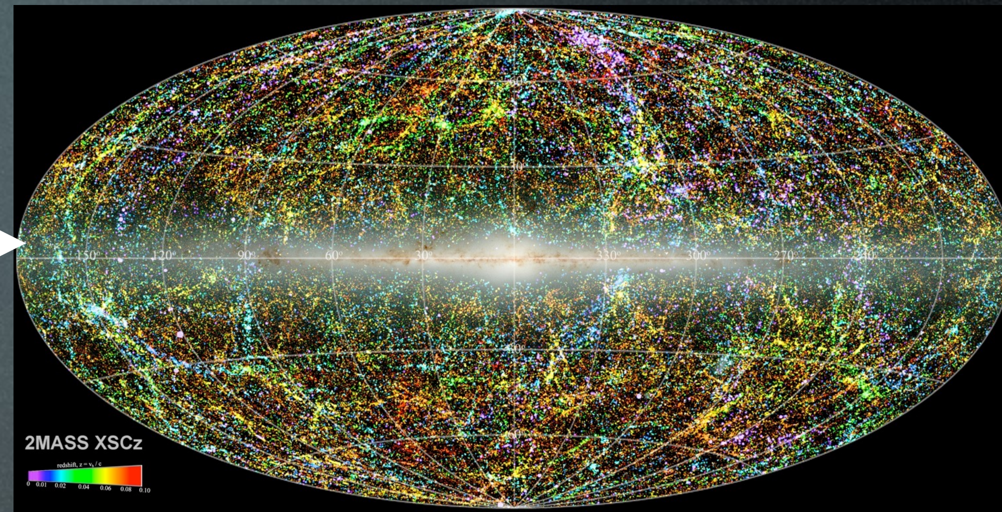


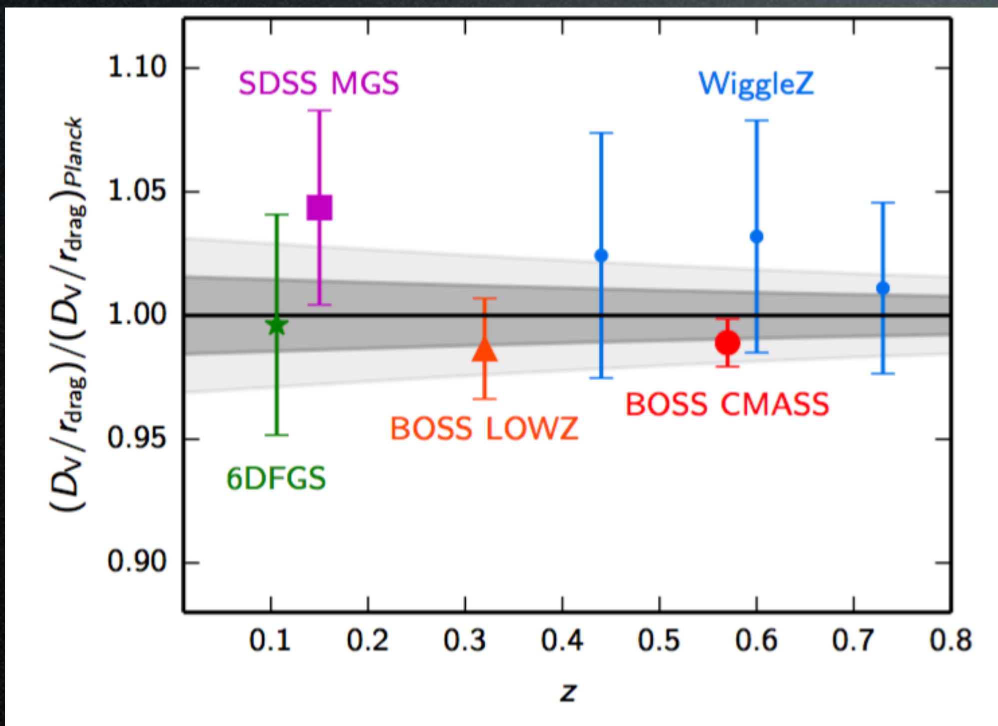
- ★ New generation of imaging and spectroscopic galaxy surveys will test this paradigm at much higher precision.
- ★ Does this picture still hold together at the next level of precision? Can we use galaxy surveys to learn what dark energy and dark matter are?

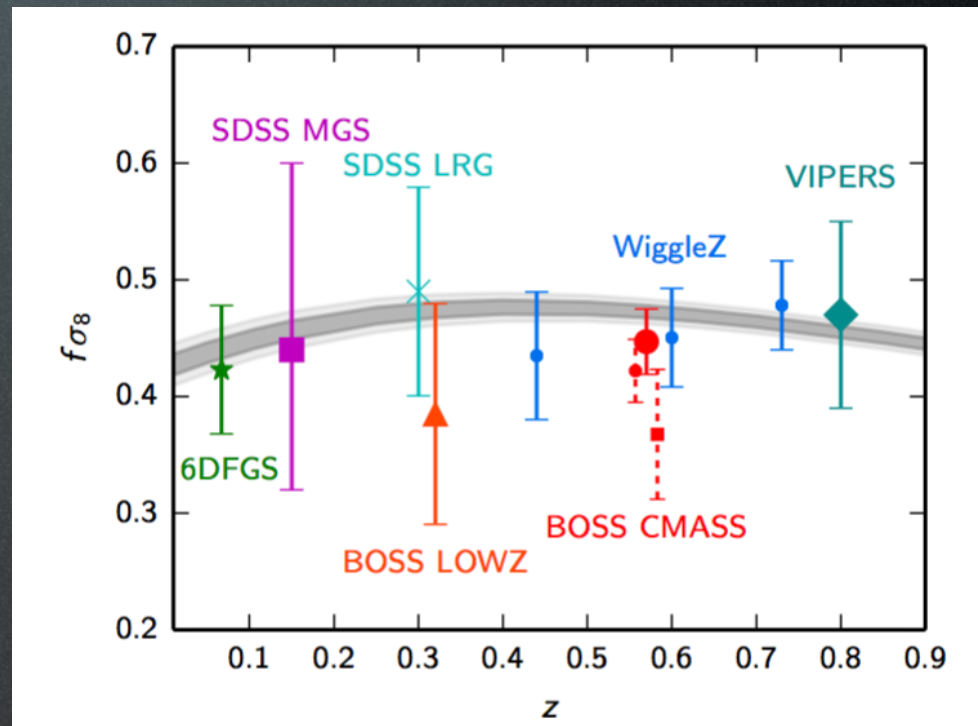
- How did the Universe begin?
    - can we directly measure the physics of inflation using galaxy surveys?
- What is the Universe made of?
    - what is the dark matter?
        - is structure formation on all scales consistent with the predictions of cold dark matter (CDM)?
    - what are the masses of the neutrinos?
        - can we measure the sum of the neutrino masses from their impact on cosmological structure formation?
- What is accelerating the Universe?
    - is it a new energy component?
        - if so, is it a cosmological constant, or something that changes with time?
    - is it a modification of gravity?
- How did galaxies form?
    - how is galaxy formation driven by and embedded in the formation of structure?
    - how does the process of galaxy formation impact the matter distribution?

Dark Energy and Beyond

- Geometry: Measure the expansion rate of the Universe
  - Standard Candle: Supernovae (the distance-redshift relation)
  - Standard Ruler: Baryon Acoustic Oscillations (BAO)
    - The distance-redshift relation $D_A(z)$
    - Directly measure the expansion rate $H(z)$
- Dynamics: Measure the rate at which structures grow in the Universe. Growth rate depends on the matter density --> dark energy density.
  - weak lensing
  - galaxy clusters
  - galaxy clustering including redshift space distortions (RSD)
  - ★ GR makes a specific prediction for the relation between the expansion rate and the growth of structure; measuring both allows a test of GR.
  - ★ Can combine measurements of power spectrum from surveys with CMB; measure sum of neutrino masses + inflation parameters, including tilt and running of power spectrum

Measurements of the CMB at 380,000 years can predict the expansion history and growth of structure measured in the last 5 billion years.





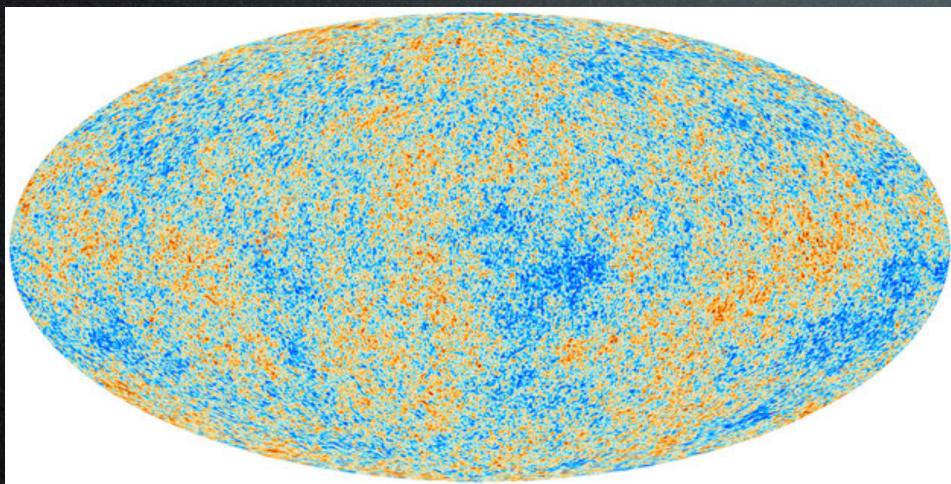
distance scale
(expansion history)

growth of structure

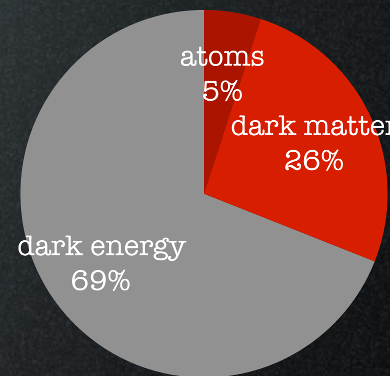
Planck Collaboration XIII 2015 —
predictions for late Universe data using a 6 parameter model

Predictions for structure formation

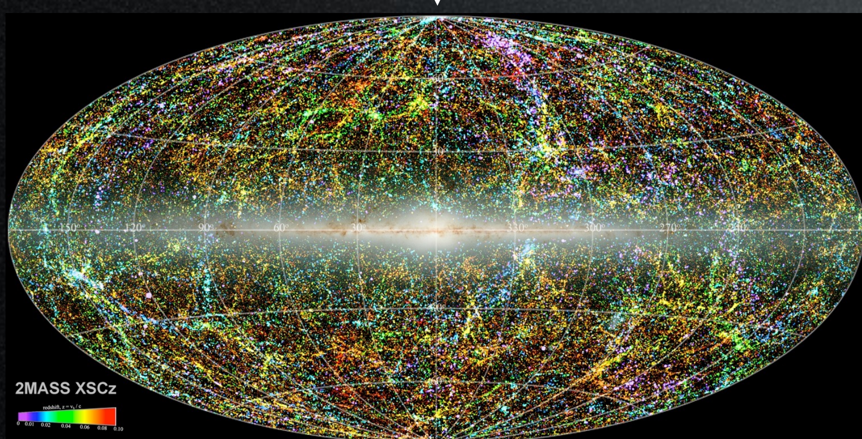
fluctuations are 10^{-5}



linear fluctuations



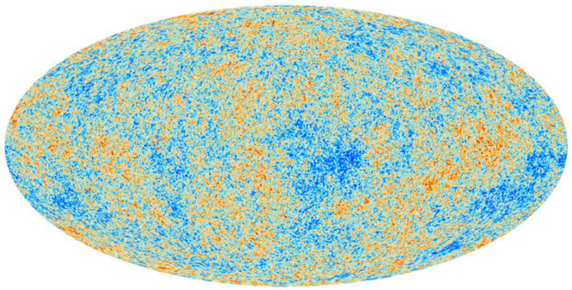
non-linear fluctuations

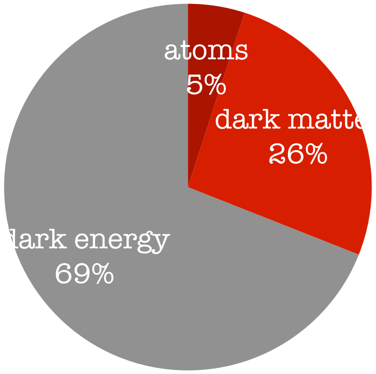


fluctuations are ~200
(gravitationally bound region)

evolution of fluctuations from the CMB to today's distribution of galaxies:
highly non-linear,
involves baryonic physics.

predictions
require numerical simulations





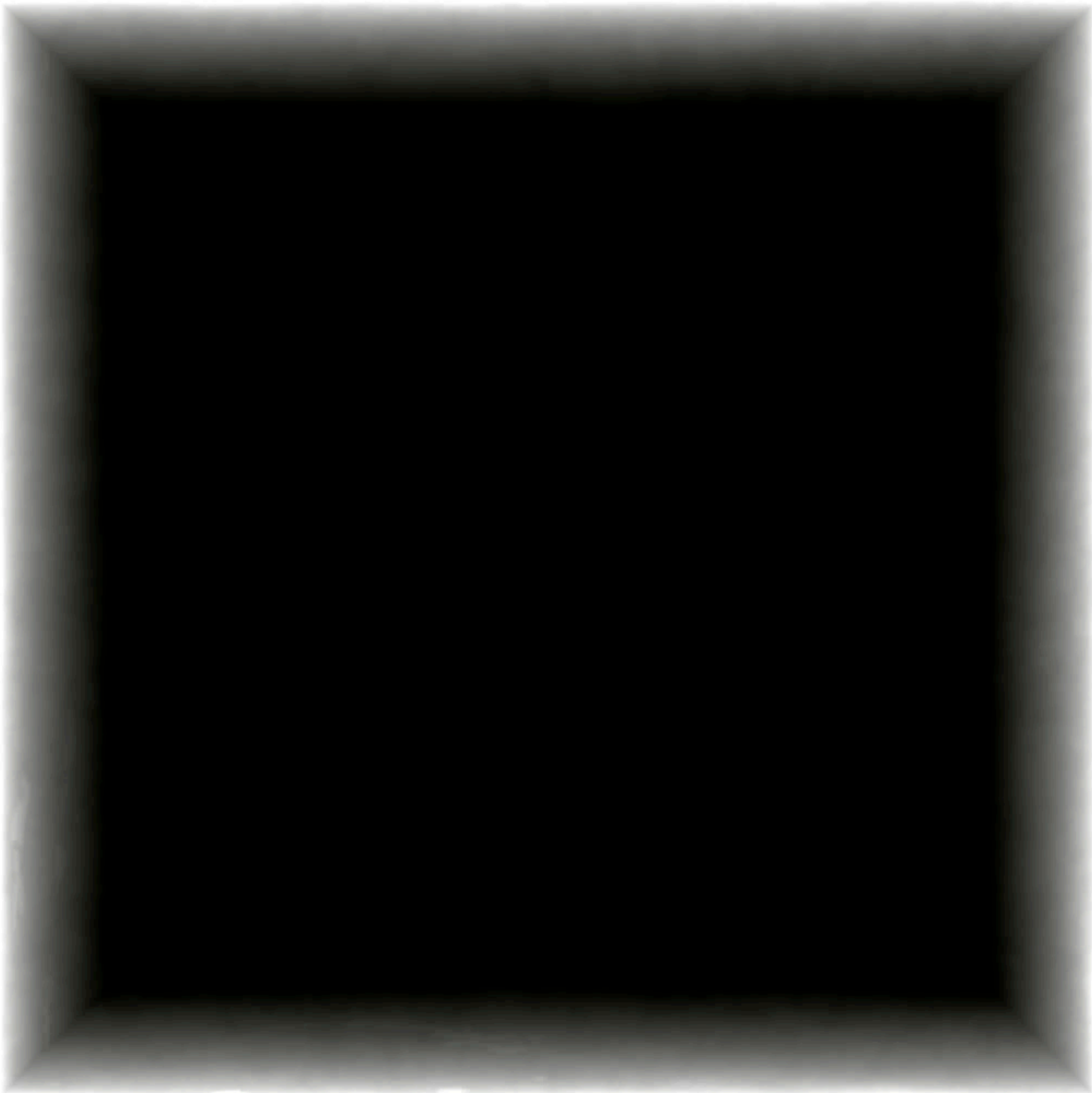
+

gravity

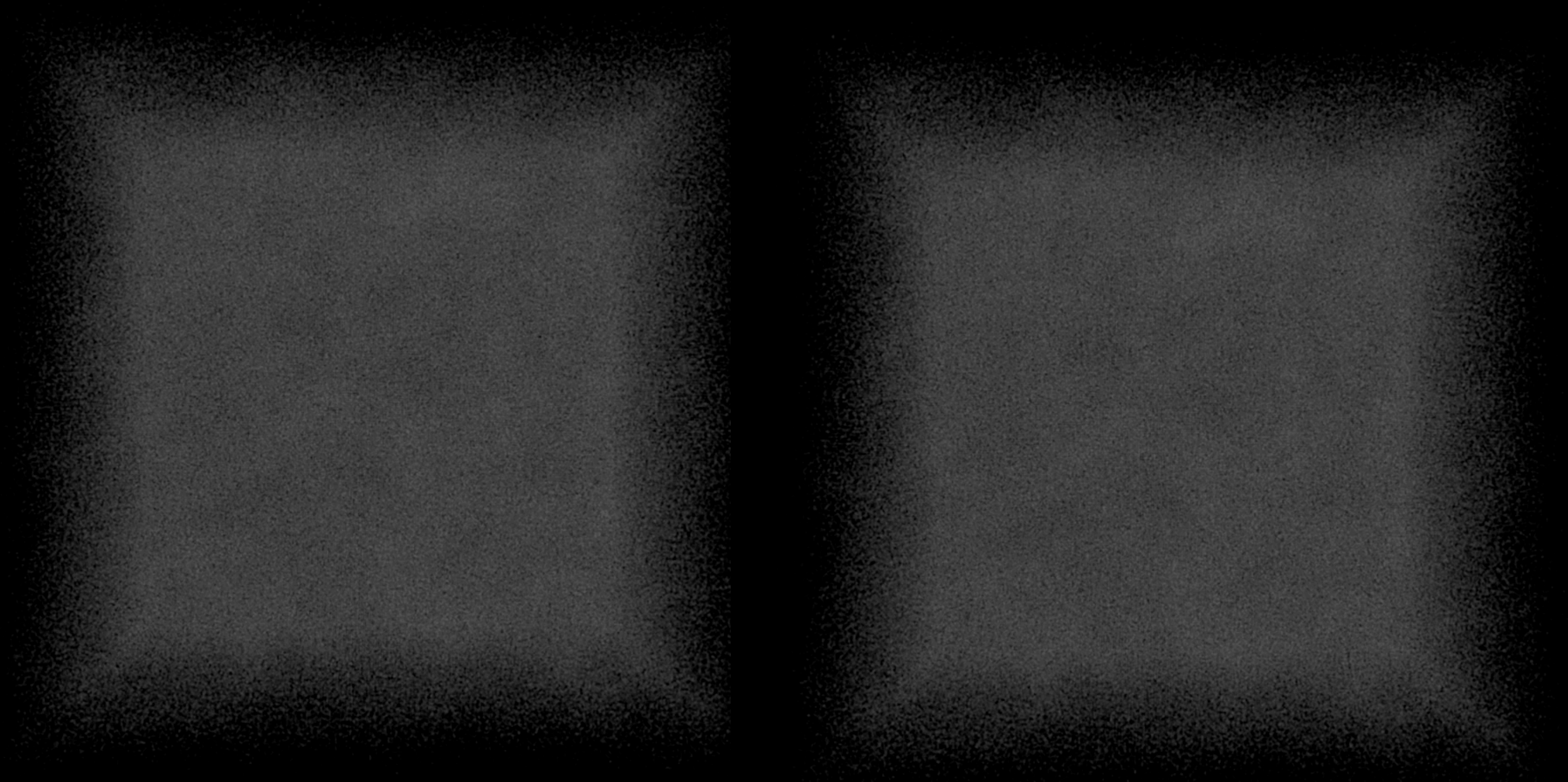
+

nature of dark matter

=

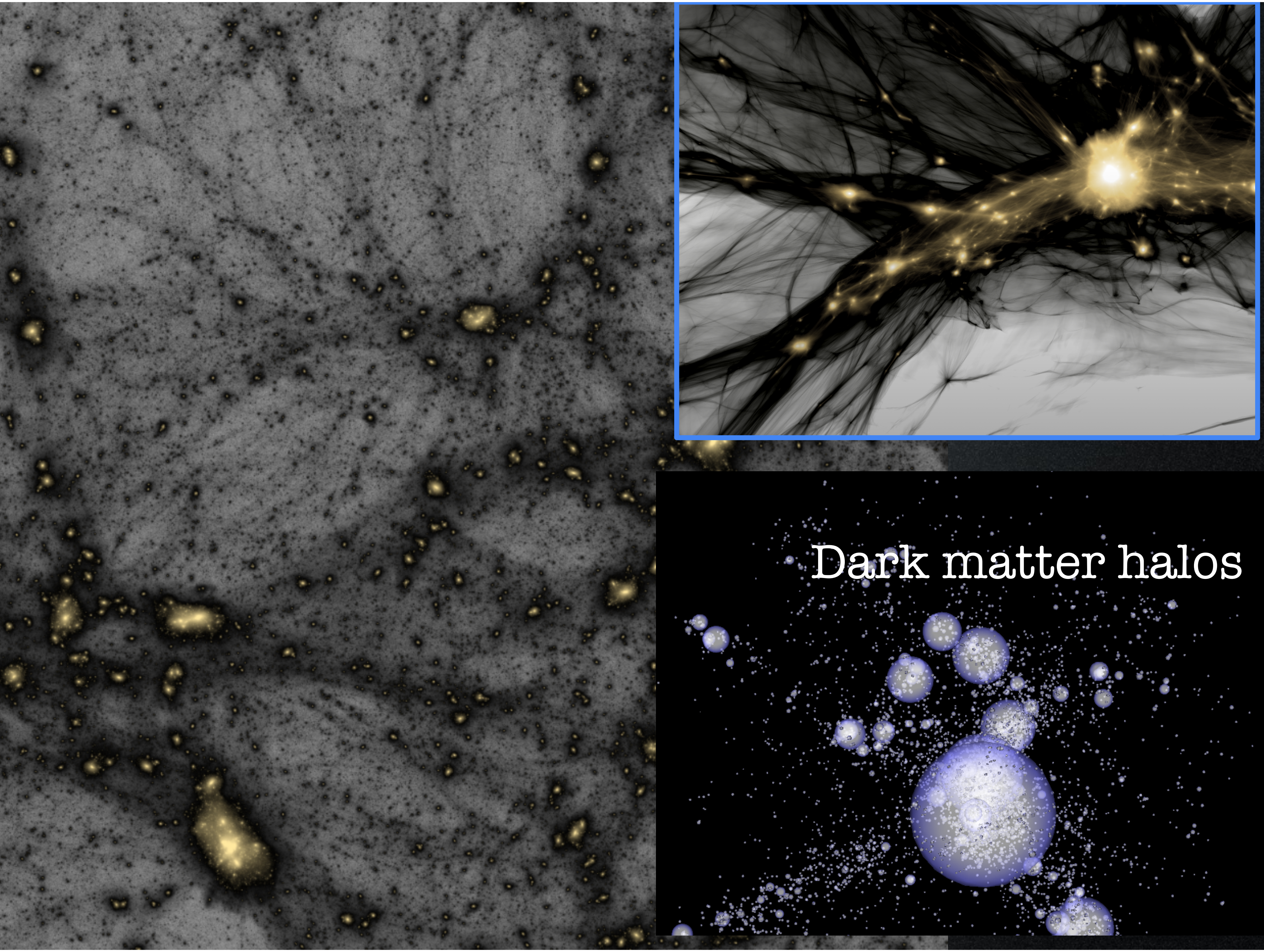


this distribution depends on cosmological parameters
& the nature of dark matter

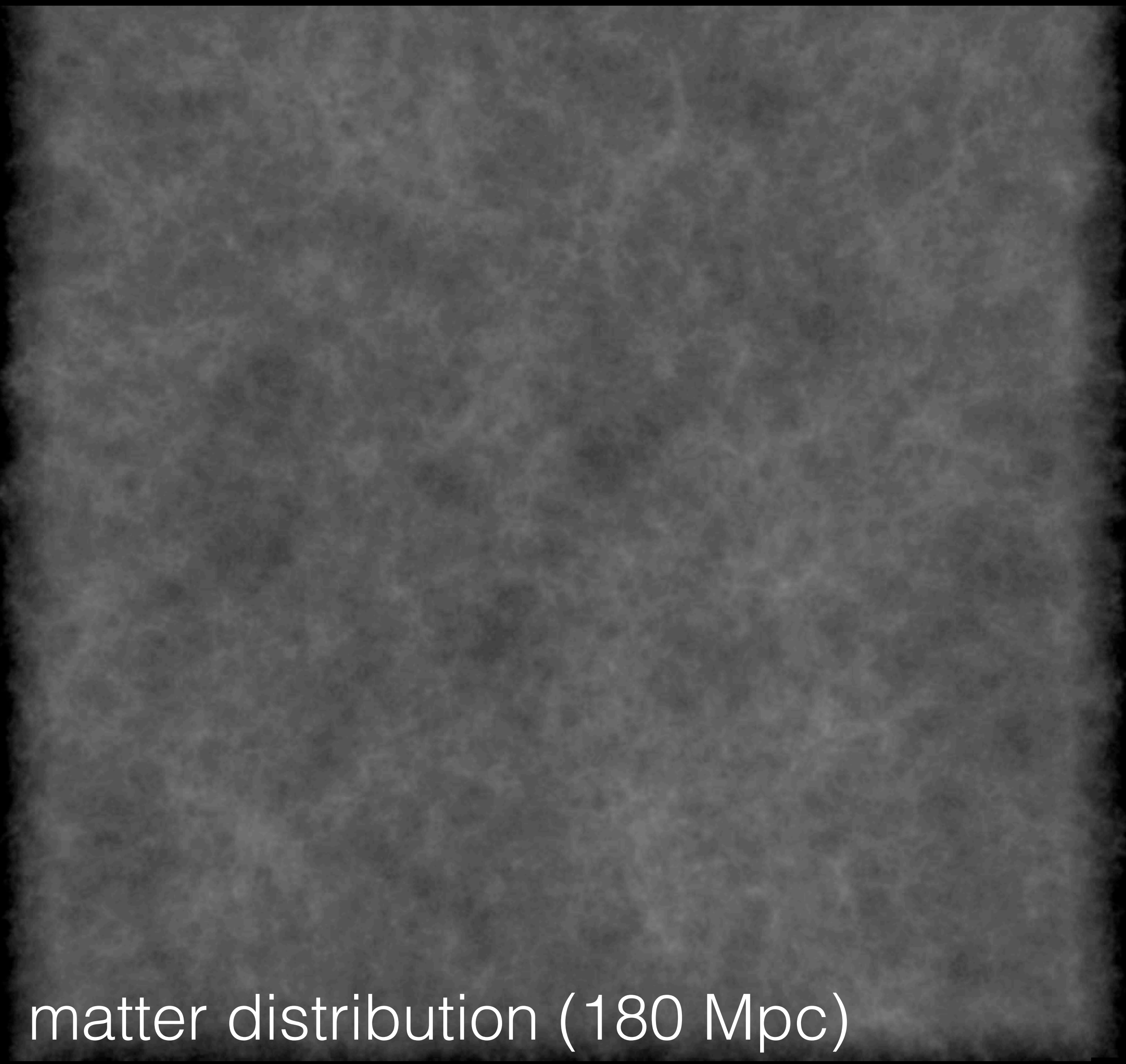


example: two Universes with same initial CMB power spectrum, but different values of the fluctuations today

movie, simulation: Ralf Kaehler, Yao-Yuan Mao, Risa Wechsler (Stanford/SLAC)

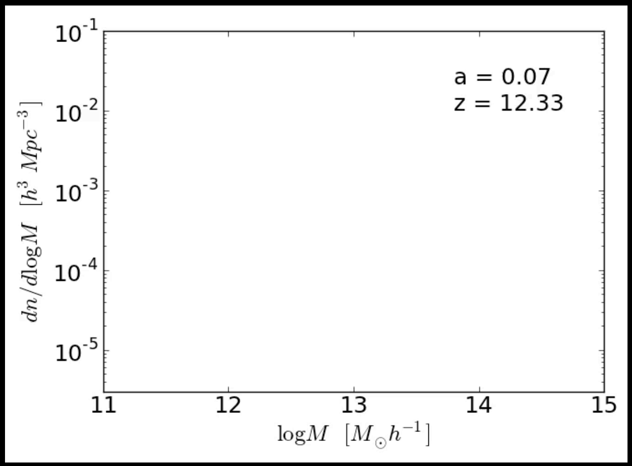

Dark matter halos

How does structure form?

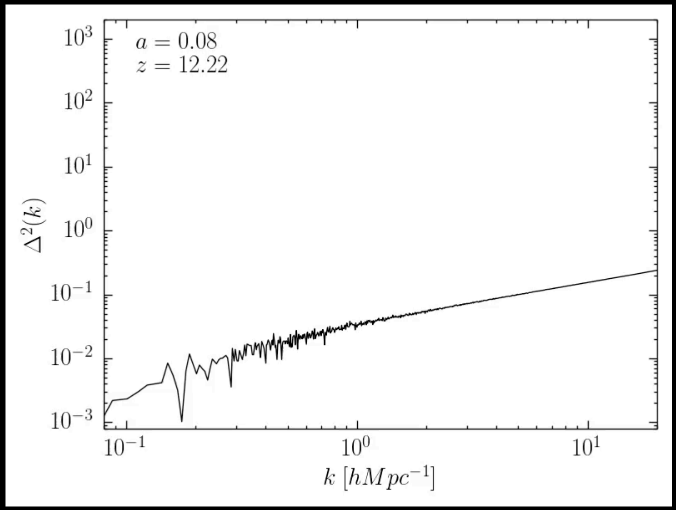


example statistics:

halo mass function

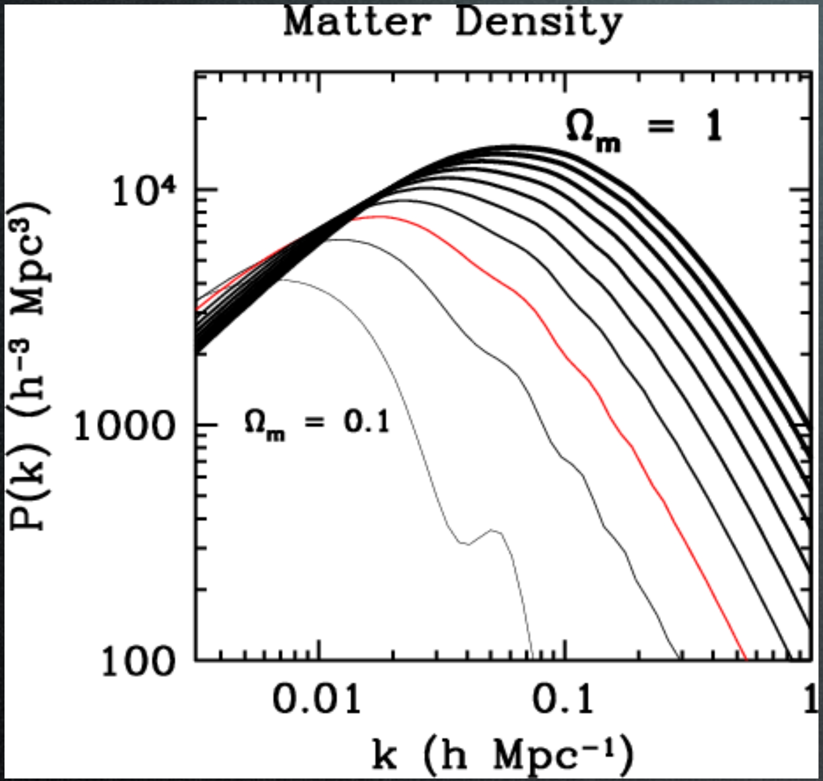


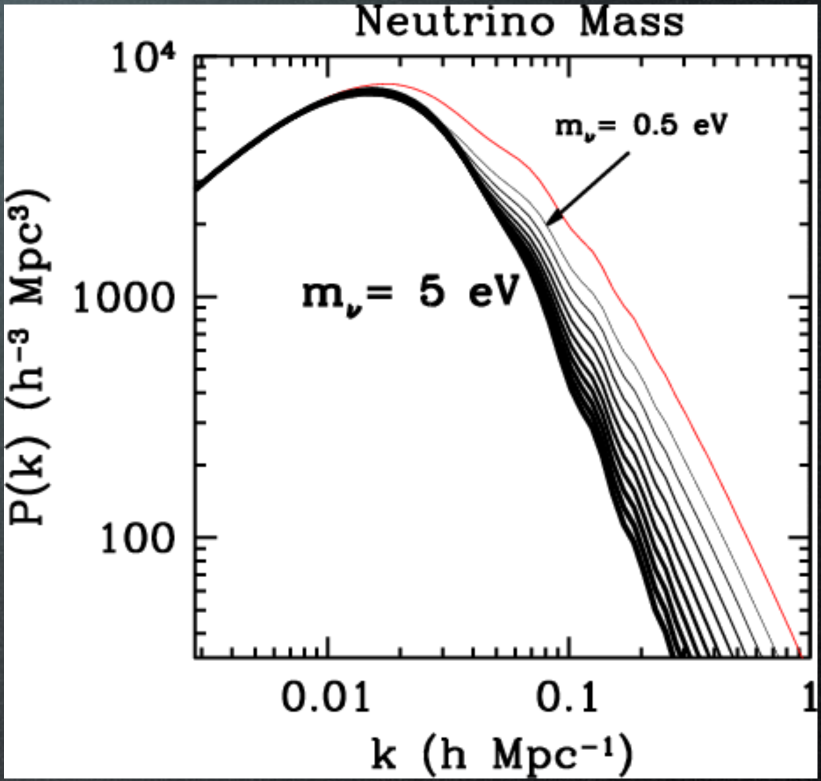
matter power spectrum



movie, simulation, statistics: Matt Becker, Ralf Kaehler, Yao-Yuan Mao, Rachel Reddick, Risa Wechsler (Stanford/SLAC)

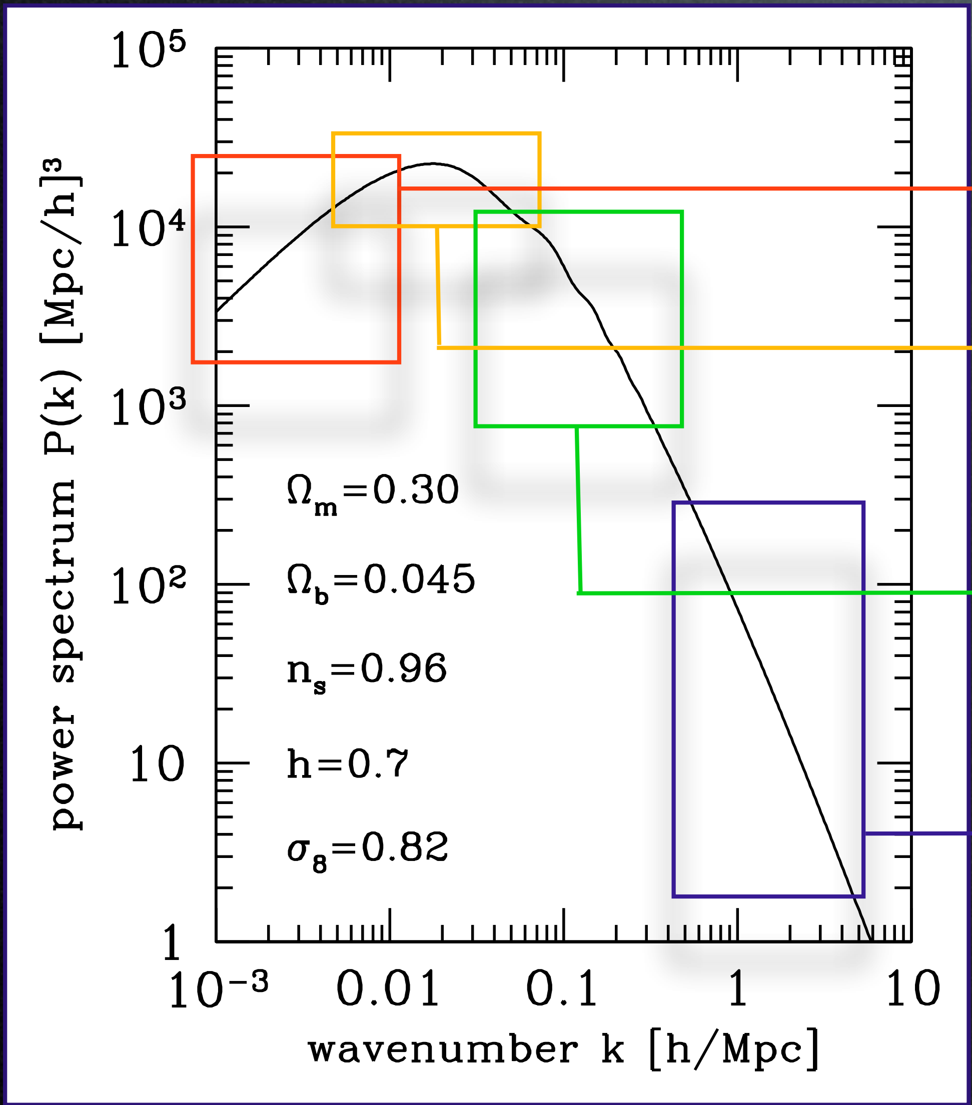
How do cosmological parameters impact the power spectrum?





- fluctuations start growing when the universe is matter dominated, so low matter density means less time for the fluctuations to grow
- scales that have entered the horizon while dark matter particles are relativistic get erased by “free streaming” (fast random particle velocities disperse the fluctuations out of dense regions)

What information does the power spectrum hold?



- primordial fluctuations from inflation.
- total matter density: when can fluctuations grow?
- baryon oscillations: our standard ruler.
- the temperature of dark matter (or relativistic particles).

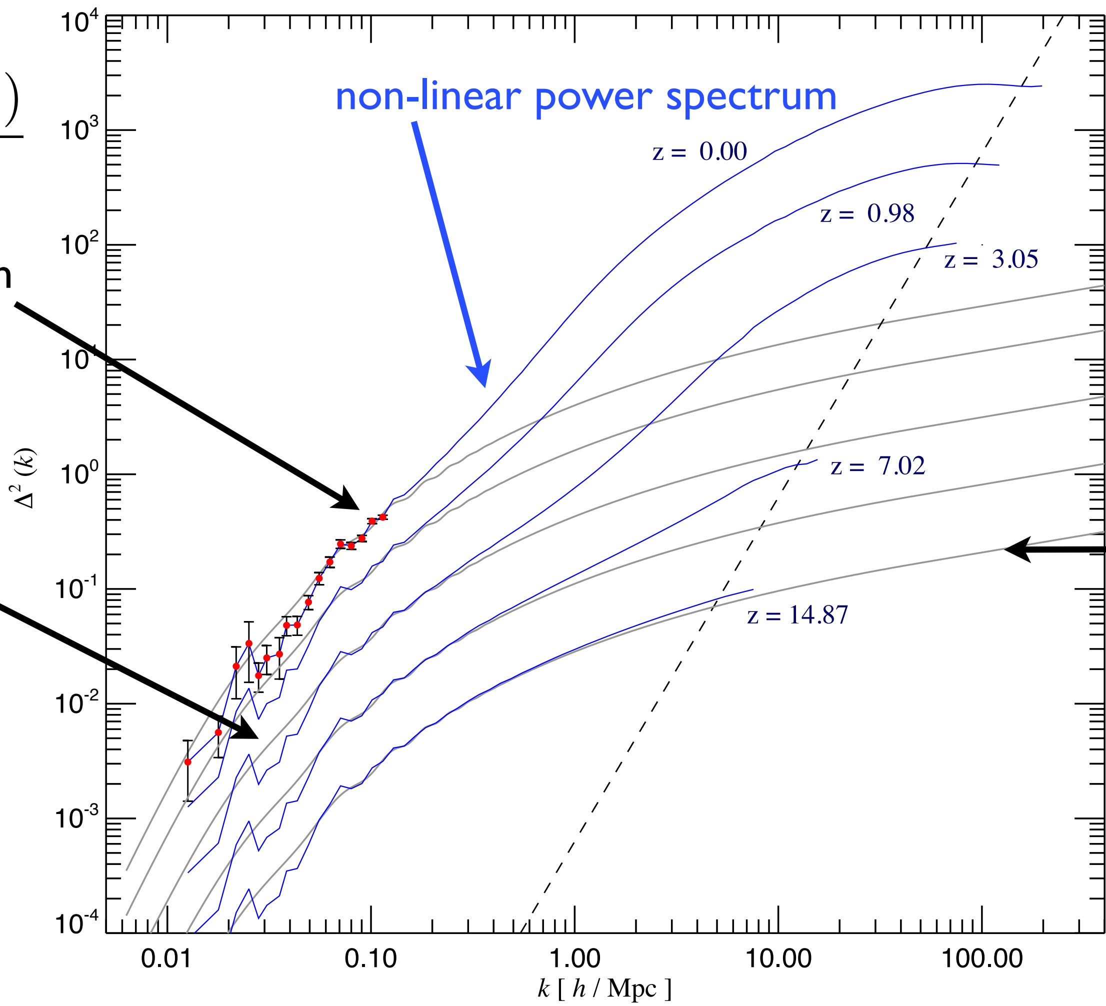
slide from J. Tinker

evolution of the matter power spectrum

$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

largest scales are still in the linear regime

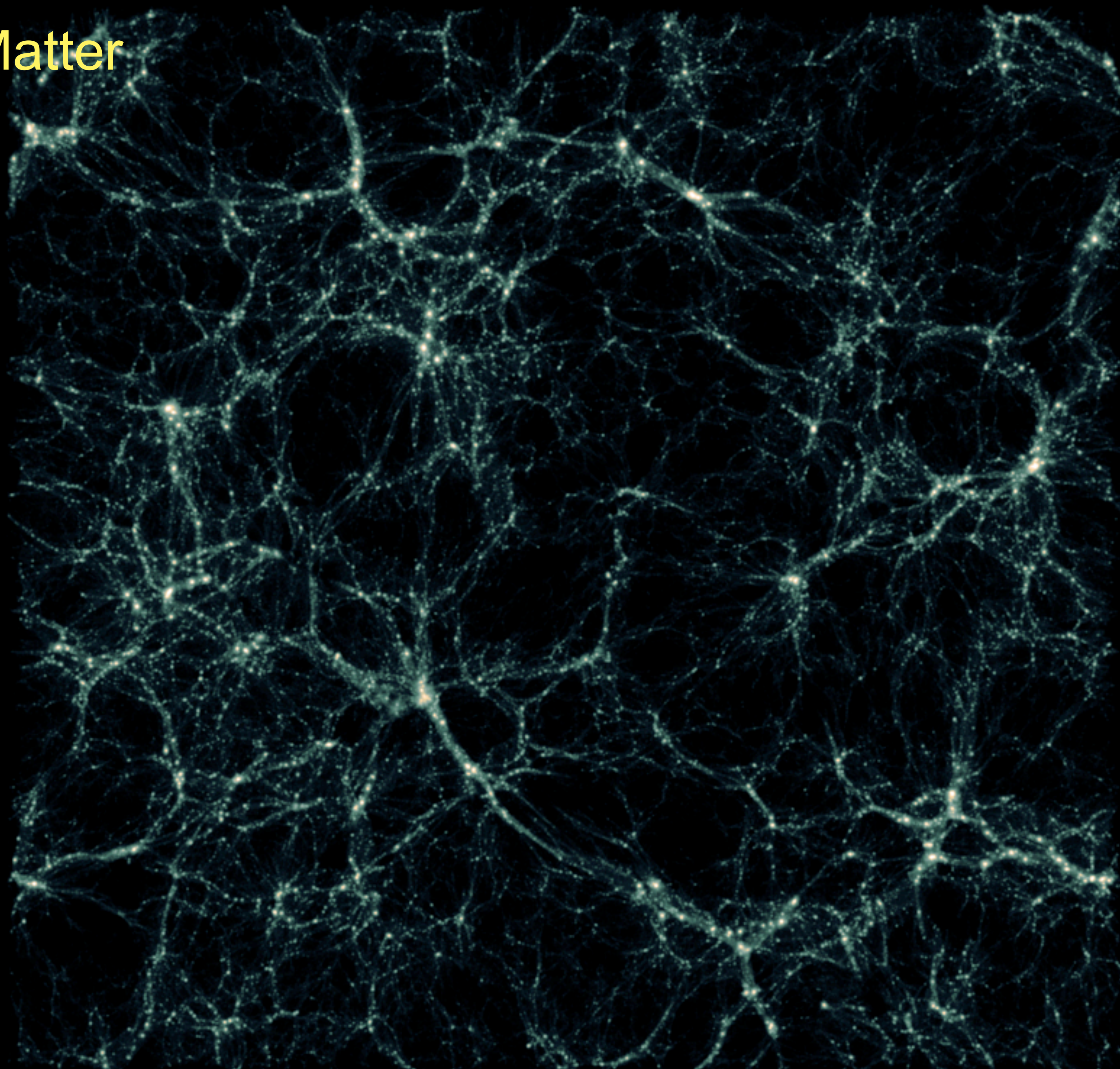
finite volume box; large modes have noise



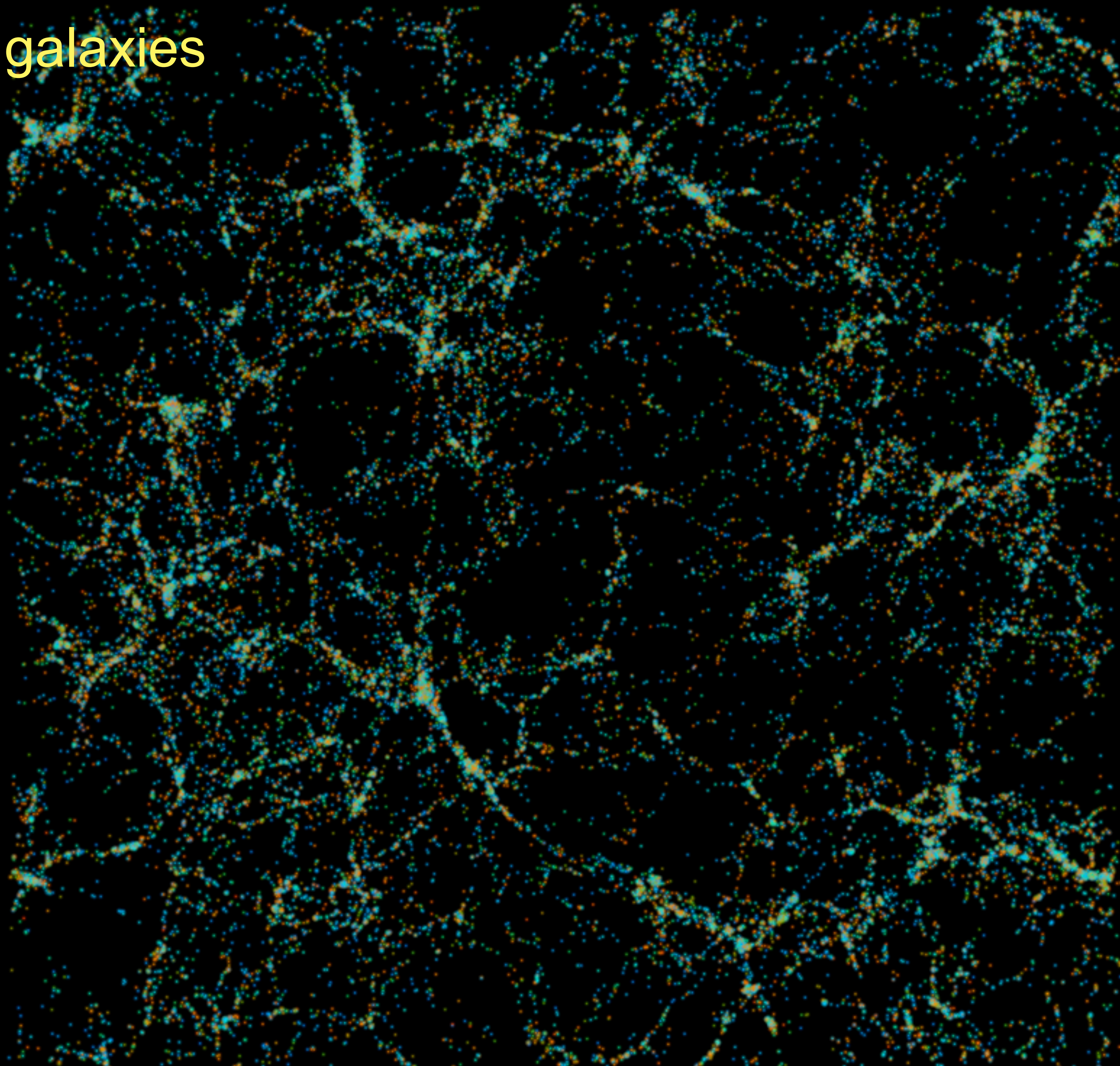
linear power spectrum

Springel et al 2005

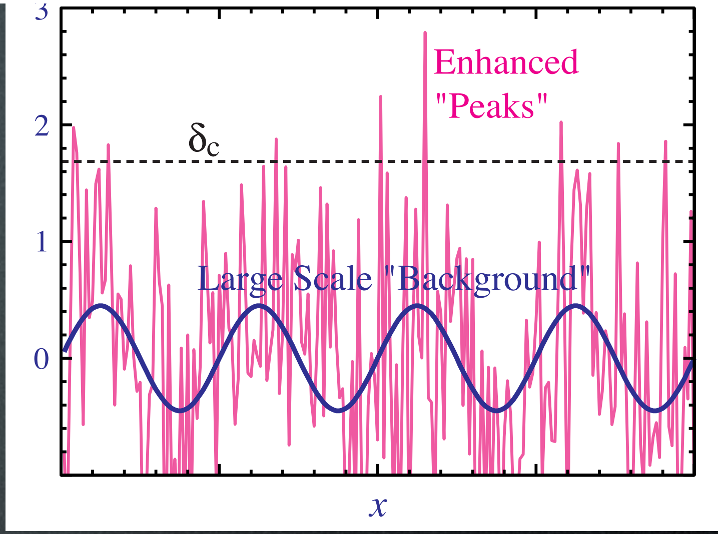
Dark Matter

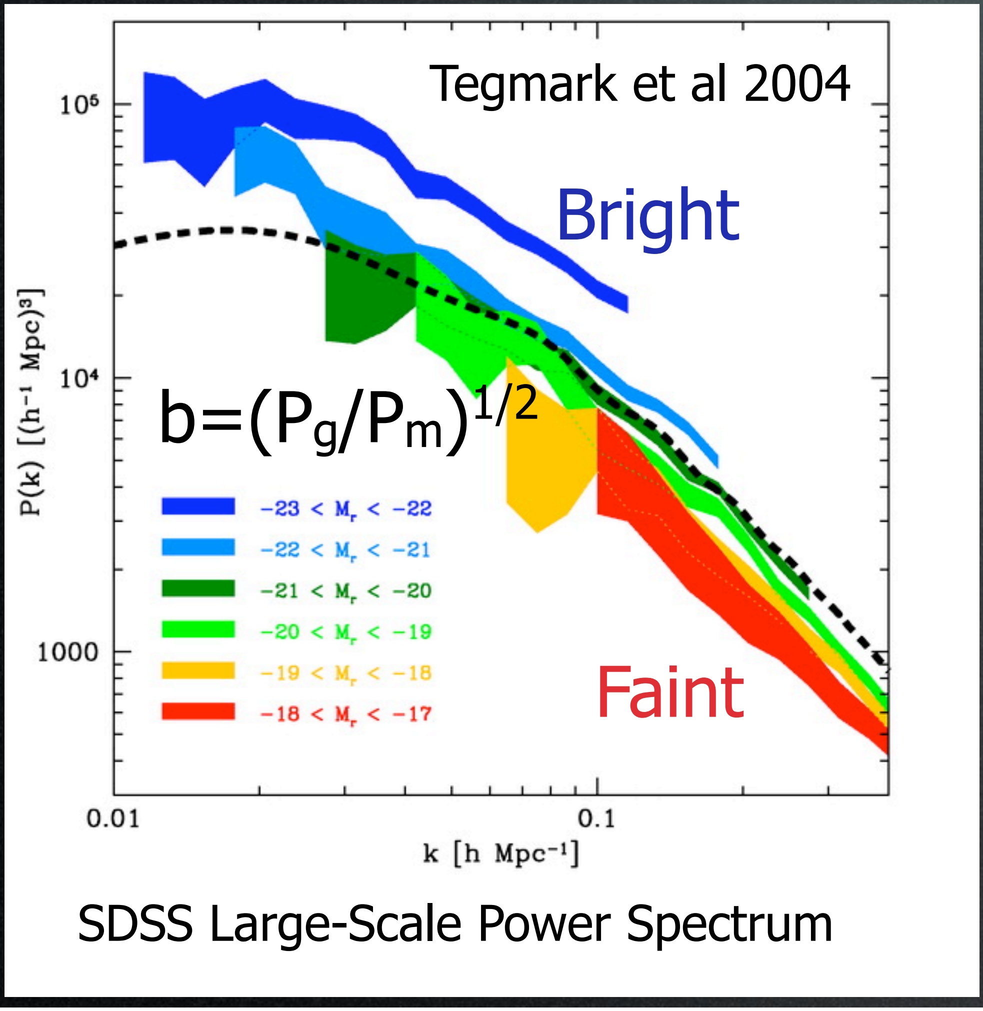


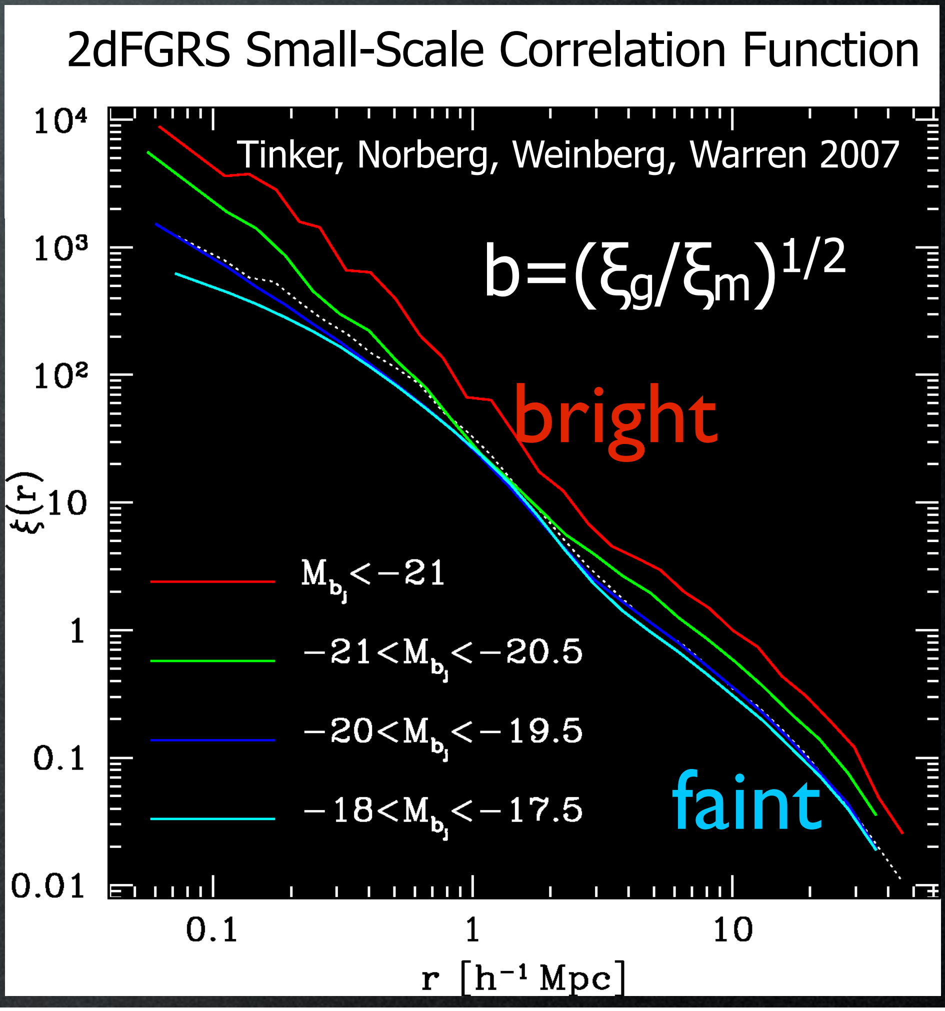
Visible galaxies



Galaxies are biased tracers



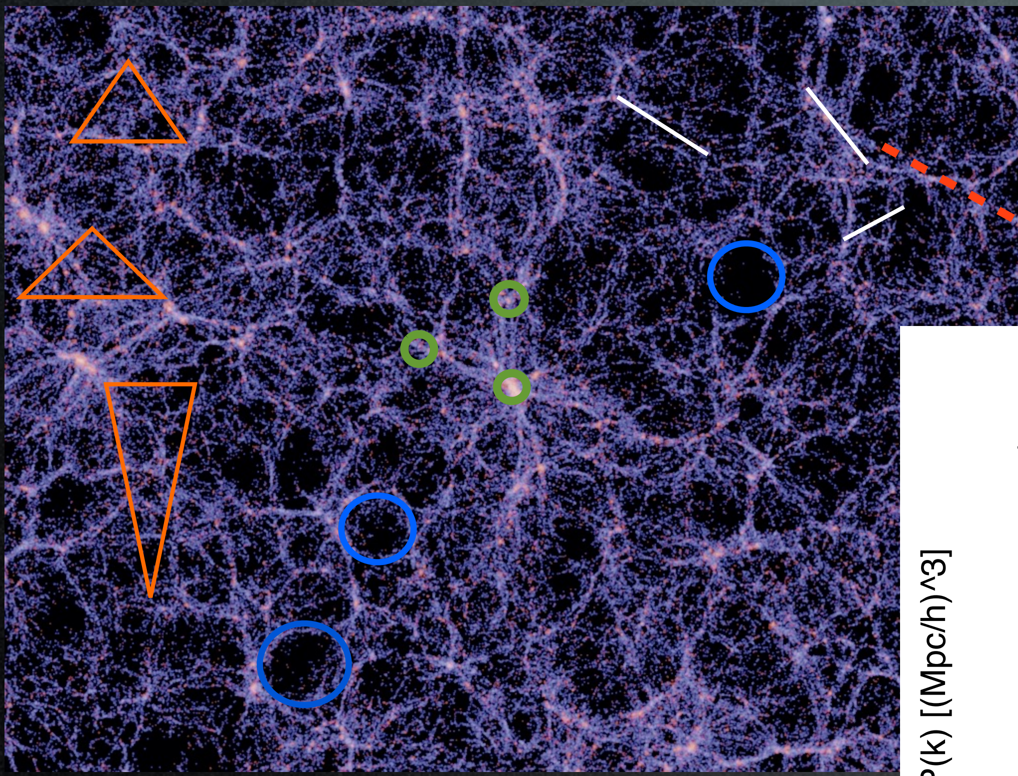




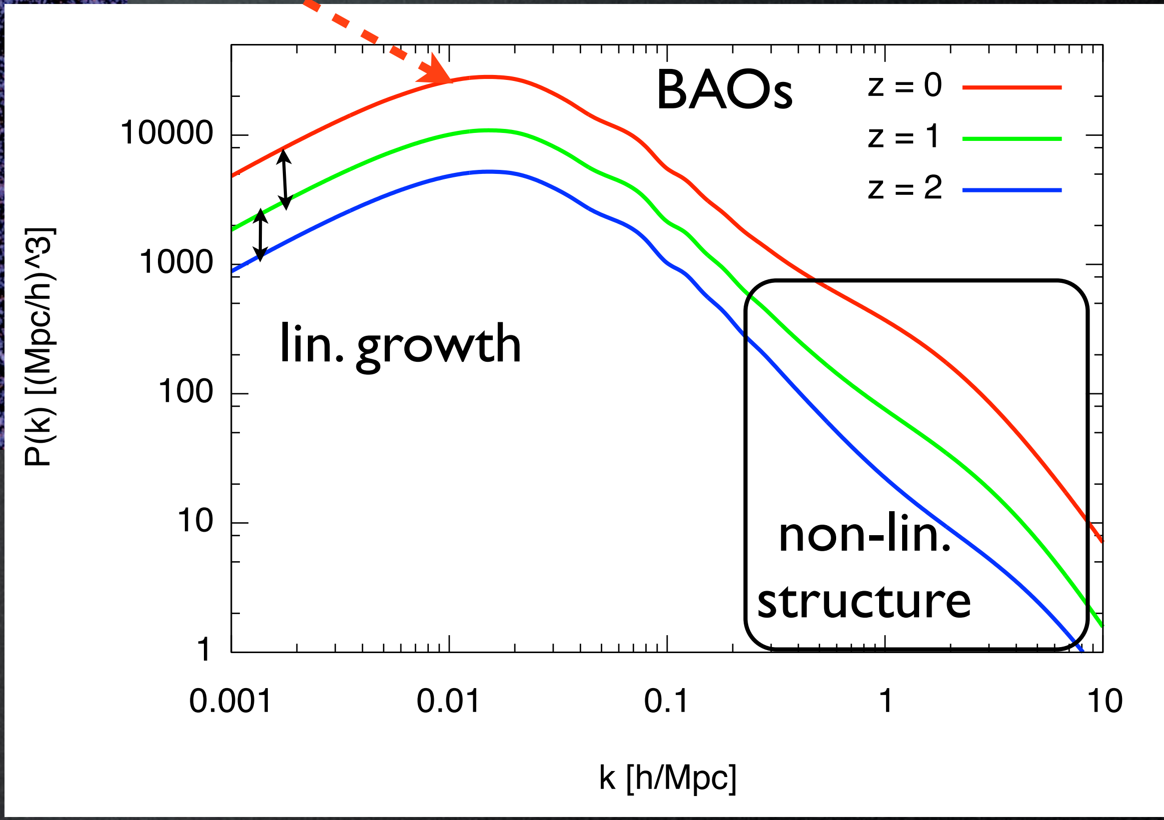
Measuring the matter distribution with galaxies

- Galaxies are biased tracers of the dark matter
- Halo bias is a function of mass — higher peaks are more biased
- Galaxy bias is a function of galaxy properties: which halos do they live in?
- On large enough scales, bias is roughly linear and scale-independent

What to look for in the galaxy distribution?



need to understand connection between galaxies and the underlying matter distribution (galaxy bias)



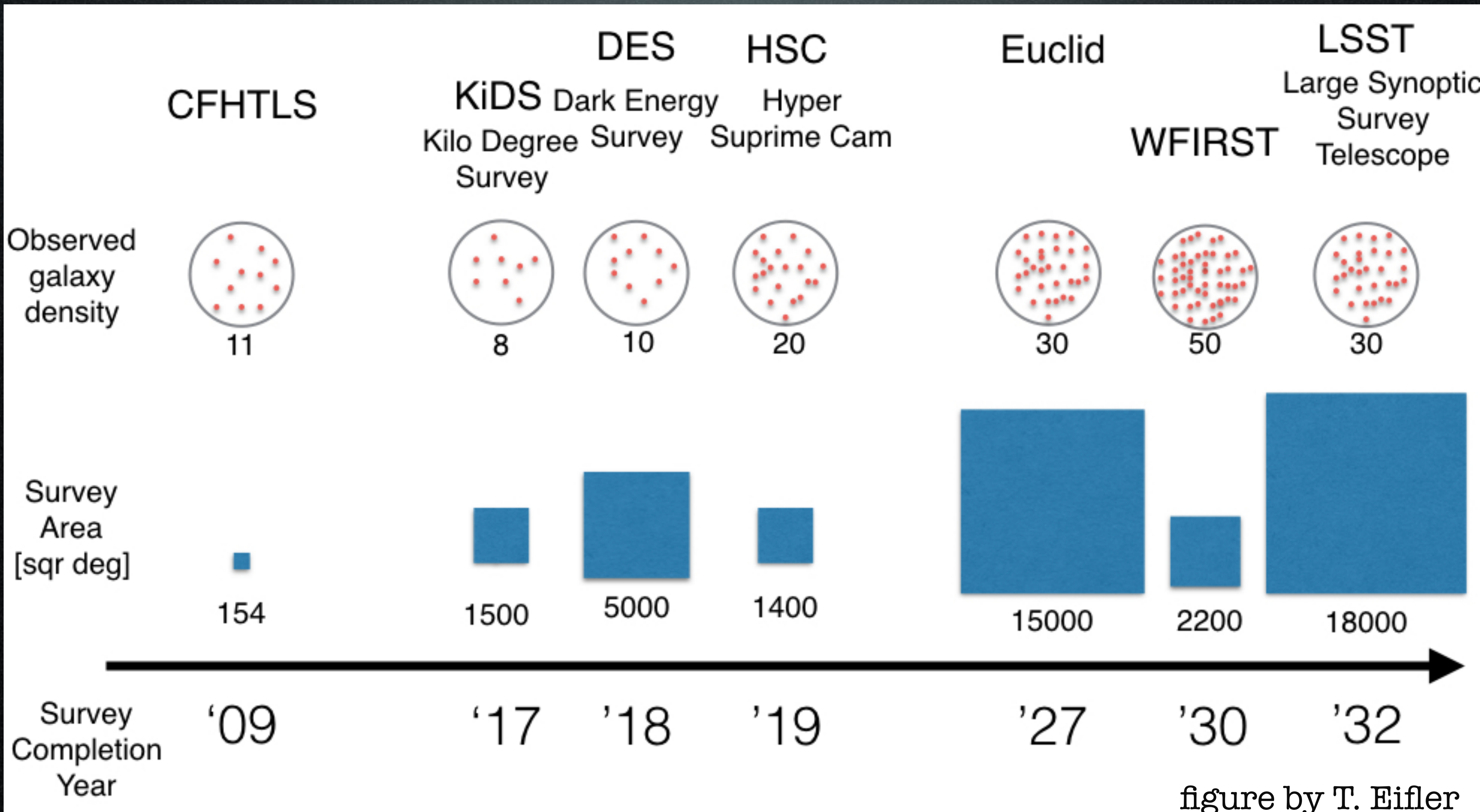
- clusters (overdensities)
- voids (underdensities)
- two-point correlations
- three-point correlations,...

slide modified from E. Krause

Imaging and Spectroscopic surveys

- 2+D mapping with imaging surveys (SDSS, DES, HSC, Euclid, LSST, WFIRST):
  - weak lensing (geometry+growth)
  - cluster abundance and clustering (mostly growth, some geometry)
  - galaxy clustering, including BAO (geometry+growth)
  - supernovae, strong lensing time delays (geometry)
- 3D mapping with redshift surveys (SDSS, BOSS, DESI, Euclid):
  - Baryon Acoustic Oscillations (BAO) (geometry)
  - Redshift-space distortions (RSD) (growth)
  - Significant additional information for dark energy, inflation, neutrinos from full galaxy power spectrum to small scales, if modeling can keep up with the data

Photometric Dark Energy Surveys



Dark Energy Survey

- New camera built for the existing Blanco telescope
- 5000 sq. degree imaging survey in the southern sky, 30 sq. degrees deep SN survey with additional multi-wavelength data and spectroscopic followup.
- 300 million galaxies, grizY to ~ 24, 3000 SN
- Y1 cosmology just released based on 1350 sq. degrees.
- Y3 complete, 5000 sq. degrees to ~ 40% depth

LSST

- 10 billion galaxies
- image half the sky, every 3 nights, for 10 years, 30TB / night
- 8.4 m telescope with new 3200 megapixel camera, being built at SLAC
- can detect objects ~ 100 times fainter than SDSS at the same distance
- Y1 already 18000 sq. degrees to r ~ 25.5 mag
- may discover as many as 100-200 new satellites of the Milky Way!

2022+

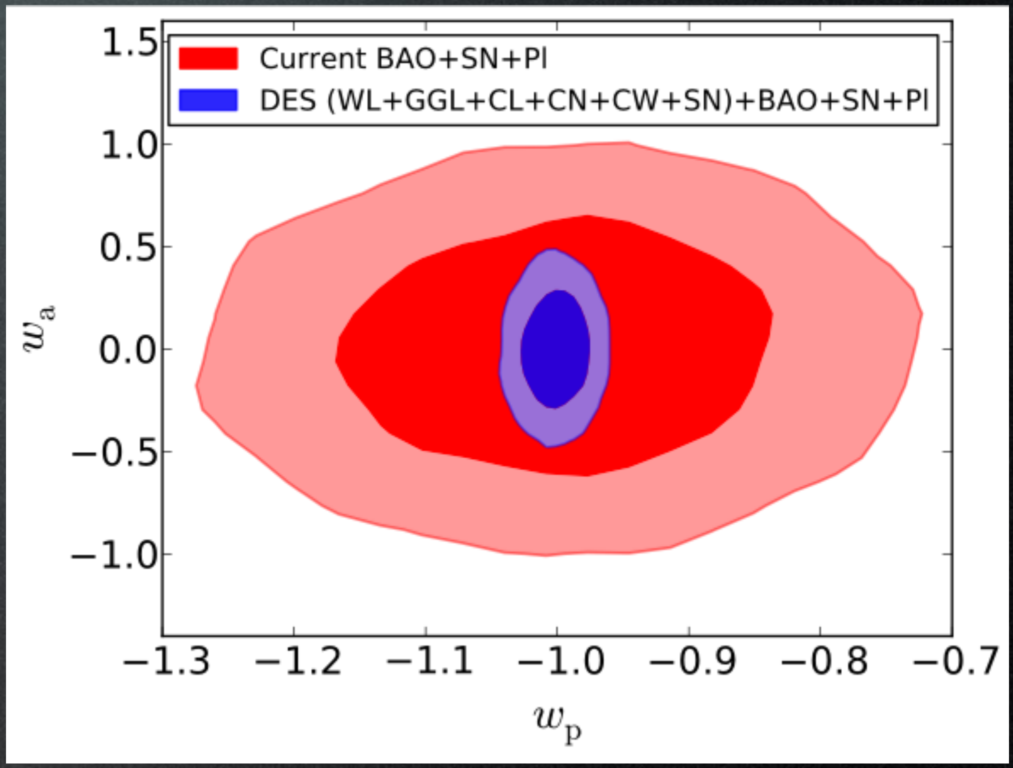
LSST Science Collaborations

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

Dark Energy Probes
(Imaging Surveys)

- Galaxy Clusters [Mantz]
  - DES: ~30K clusters to z~1
  - LSST: ~200K clusters to z ~ 1.2
- Weak Lensing [Schneider]
  - DES: Shape measurements of ~200M galaxies (peaking at z ~ 0.5)
  - LSST: Shape measurements of ~3.6B galaxies (peaking at z ~ 0.8)
- Galaxy Clustering
  - DES: 300 million galaxies to z ~ 1
  - LSST: 10 B+ galaxies to z ~ 1.5
- Supernovae [Kim]
  - DES: 3000 well-sampled SNe Ia to z ~1
- Strong Lensing [Marshall]
  - DES: ~30 QSO lens time delays
  - LSST: ~400 QSO lens time delays
- Cross-correlations
  - Galaxies x shear; galaxy lensing x CMB lensing
- Combined probes [Krause]

$$w(a) = w_0 + w_a(1 - a(t))$$



DES Y5 forecast by Krause & Eifler

Bias vs. cosmology

Goal is to probe the evolution of the matter power spectrum — can tell us especially about the matter density and the size of the fluctuations.

How do we break degeneracies between how galaxies populate matter distribution and the clustering of the matter distribution itself?

Combined probes, for example "3x2pt"

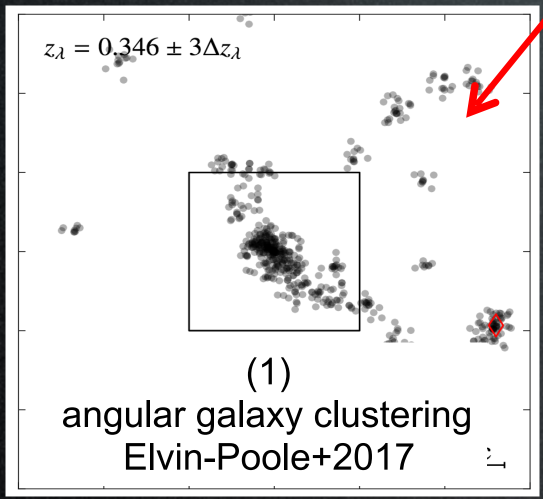
- galaxy-galaxy 2pt clustering
- shear-shear 2pt clustering
- galaxy-shear 2pt clustering

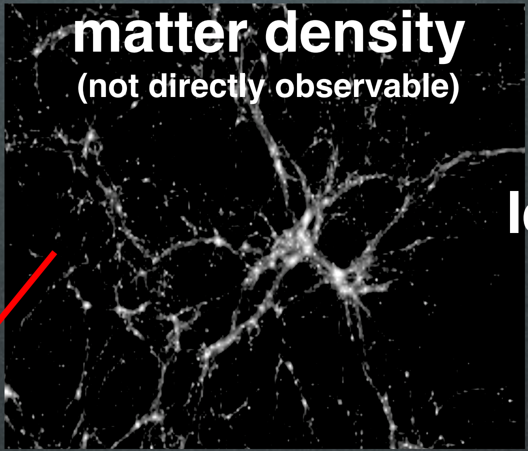
Other data combinations will (1) further break degeneracies and/or (2) provide independent checks, to test systematics

Combining these allows one to break degeneracies between galaxy bias, matter density, and size of fluctuations.

Three two-point functions

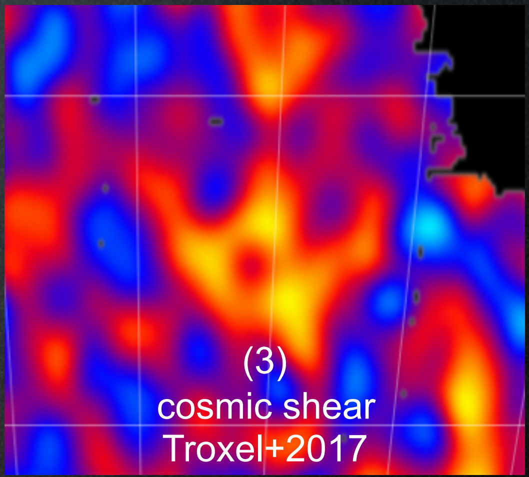
galaxy field





(2)
galaxy-galaxy lensing
Prat, Sanchez+2017

lensing convergence



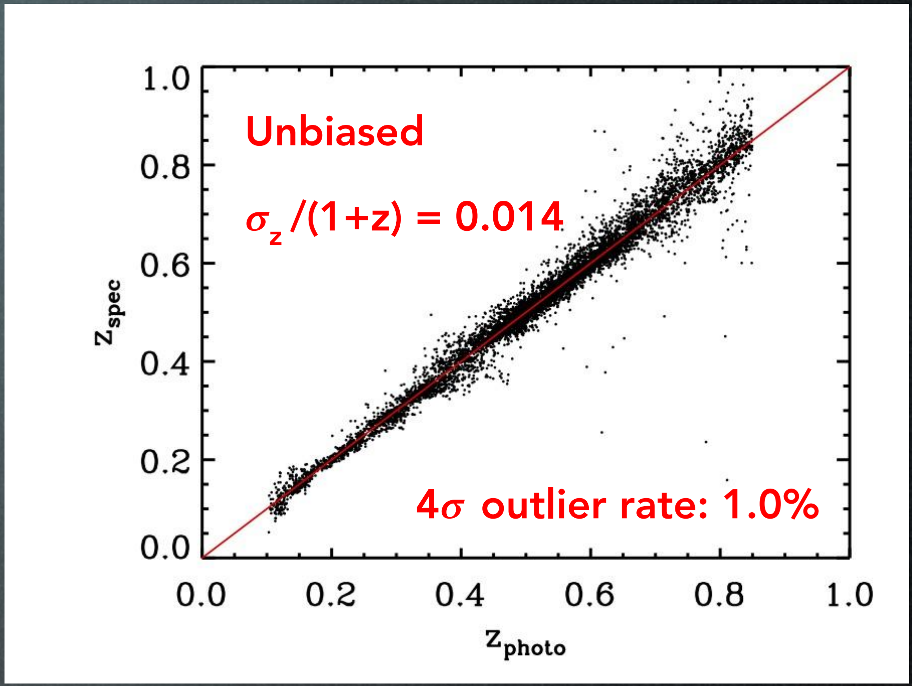
What galaxies to use?

- Key issue with photometric surveys: we don’t have precise redshift information
- Trade off between number density of galaxies and the precision and accuracy of their redshifts
- Bright galaxies have more precise photometric redshifts than faint galaxies
- Red galaxies have more precise photometric redshifts than blue galaxies

What galaxies to use?

- redMaGic — luminous red galaxies, selected based on distance from cluster red sequence
- designed for accurate and precise redshifts.
- approximately constant comoving density, approximately constant clustering bias
- selection has only two free parameters:
  - desired comoving density (sets distance from red sequence)
  - luminosity threshold of the galaxies
- Great photo-z performance dz = 0.02(1+z), achieved by throwing out lots of galaxies (can optimize this trade-off)

Lens galaxy selection

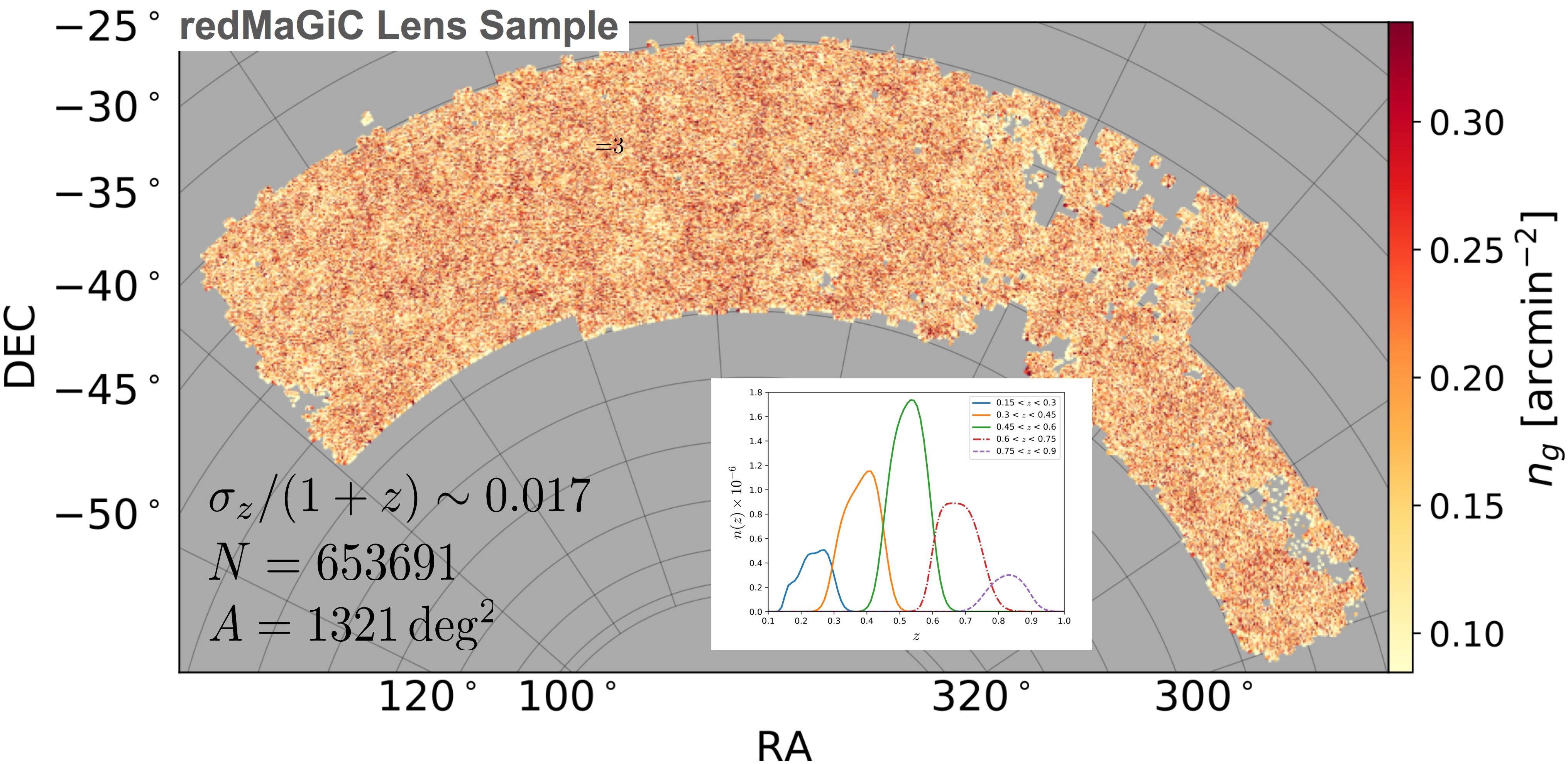


- High photo-z precision is important for:
  - calibration of **intrinsic alignments** from galaxy-galaxy lensing signal.
  - photo-z calibration of source distribution via cross-correlations.
  - better environment measures, e.g. robust void finding with photometric data

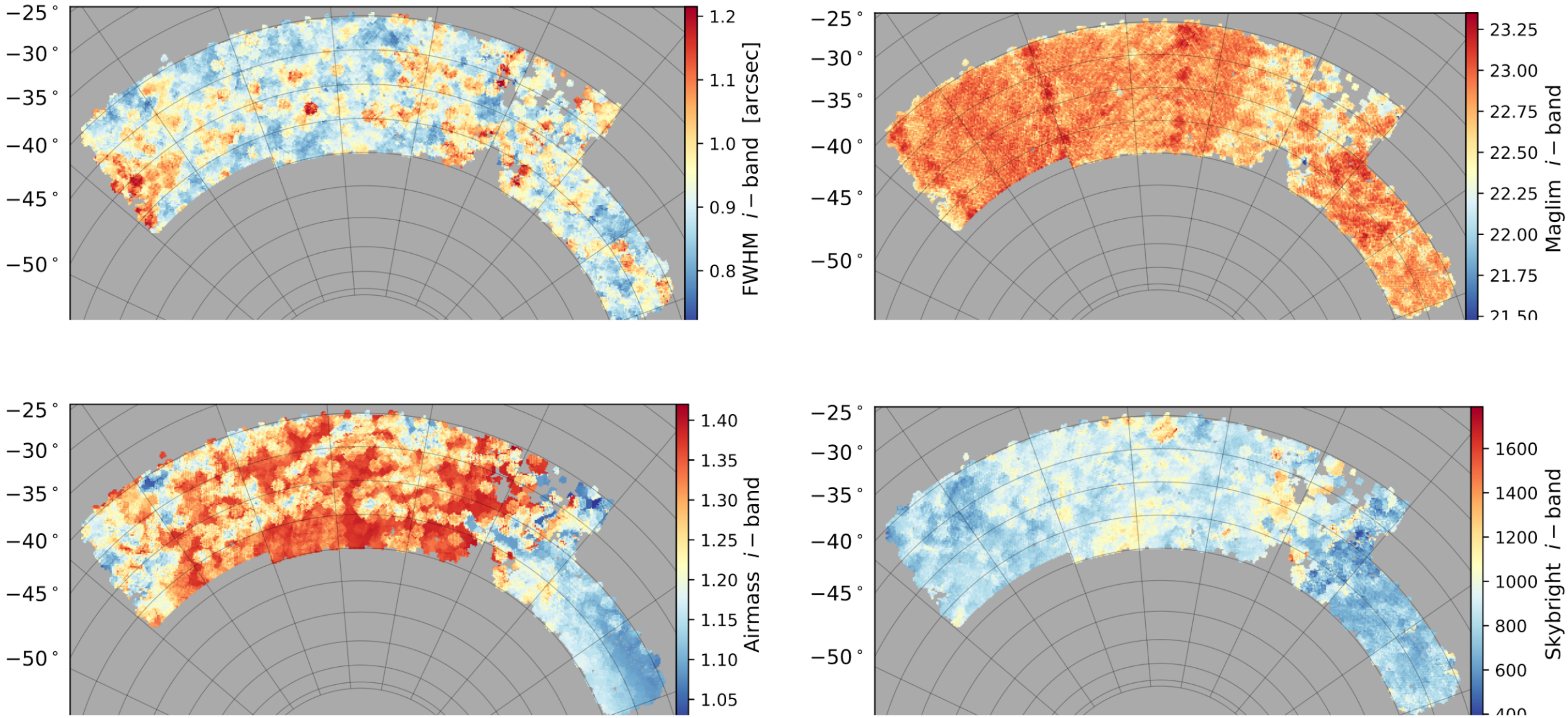
DARK ENERGY SURVEY

Galaxy Clustering for combined probes

J. Elvin-Poole, M. Crocce, A. Ross, et al.

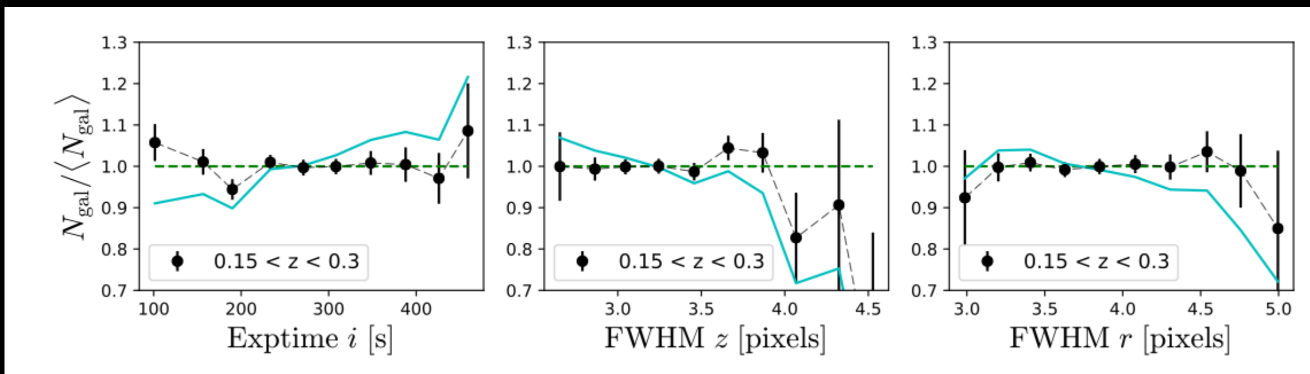


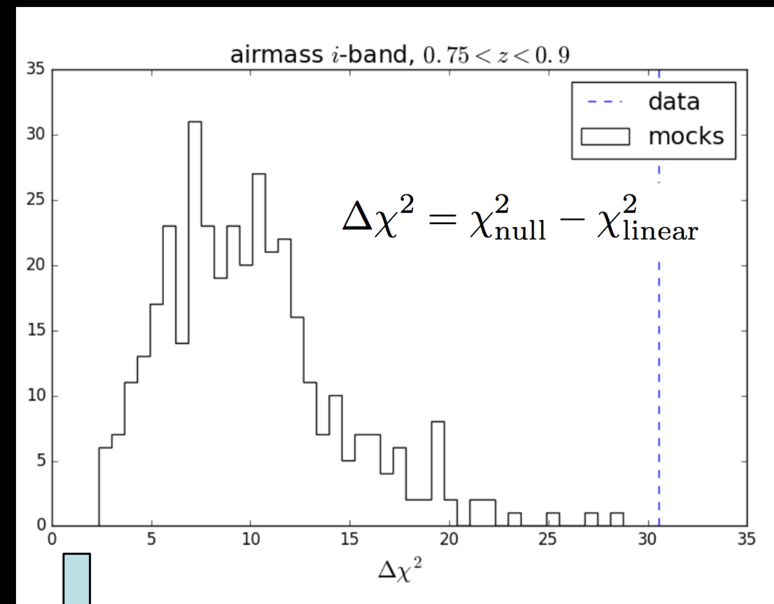
Observing conditions across the sky averaged over different exposures



These induce fake density fluctuations → Need to remove these modes.

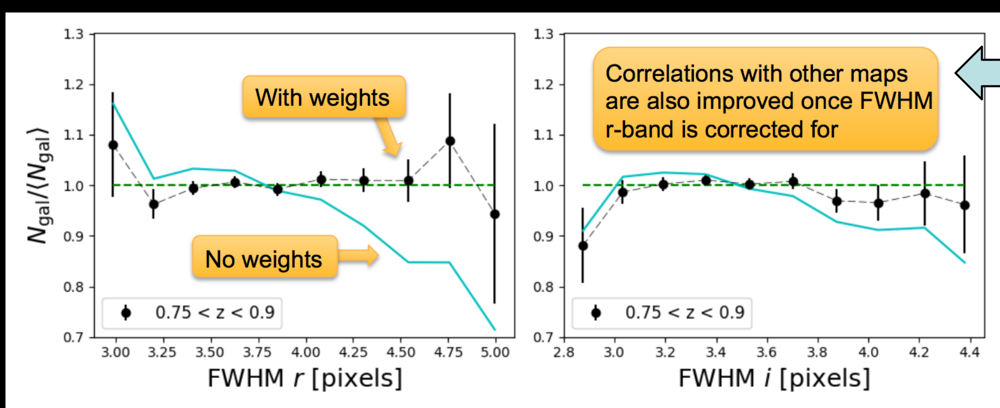
Removal of systematics by sample weighting

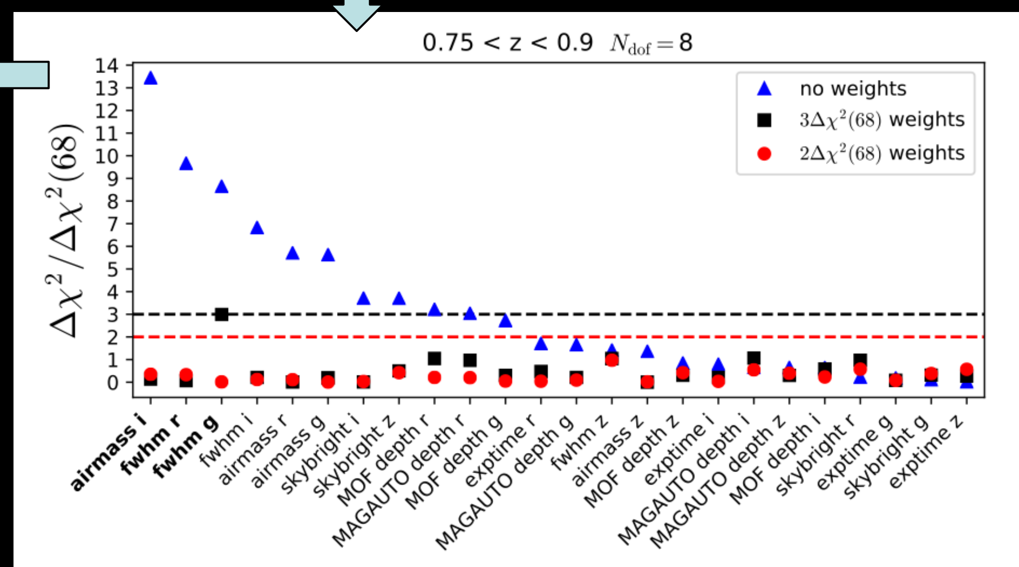




We estimate the significance using a large set of mocks

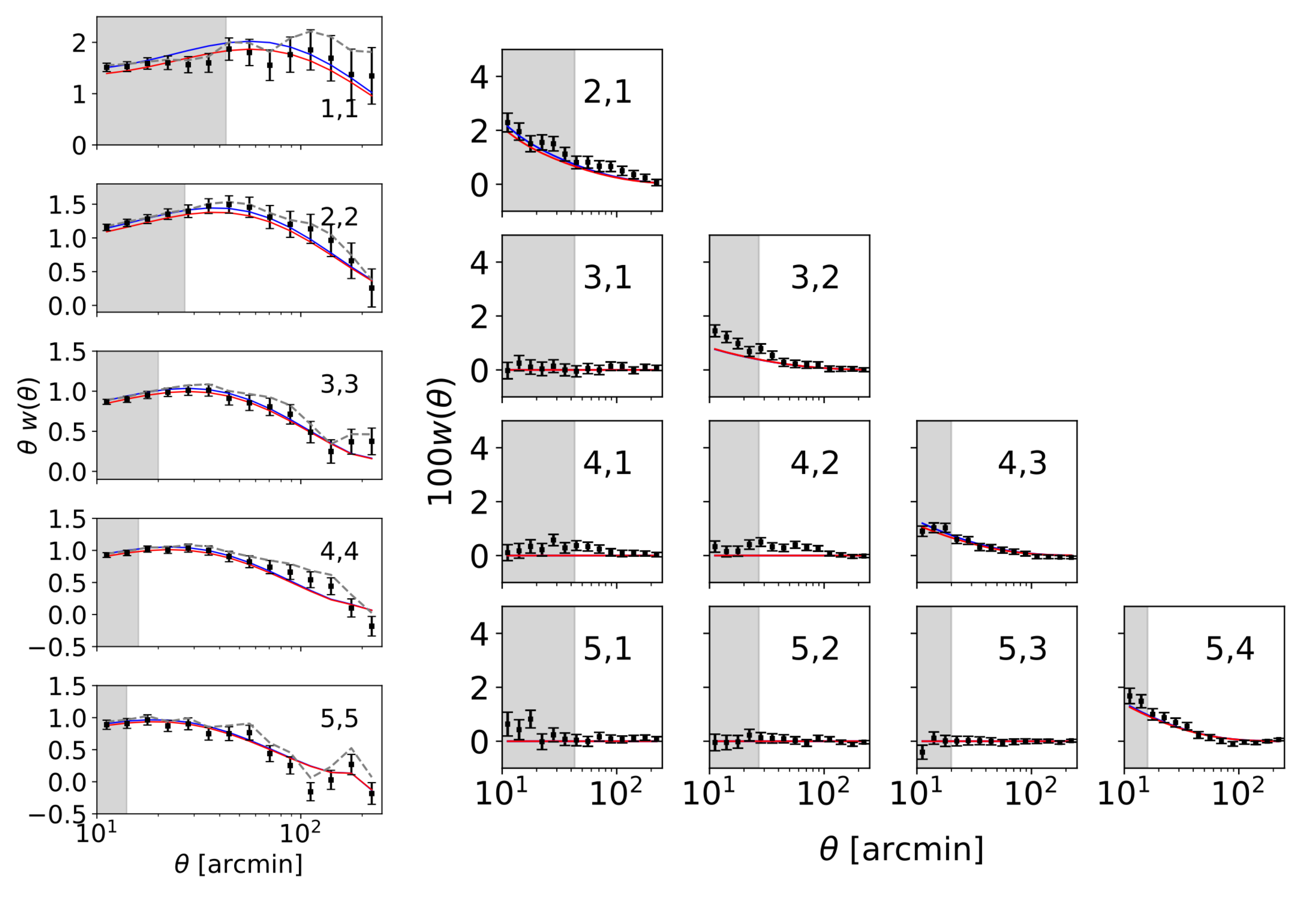
We weight the sample until residual correlations is below 2 / 3 sigma



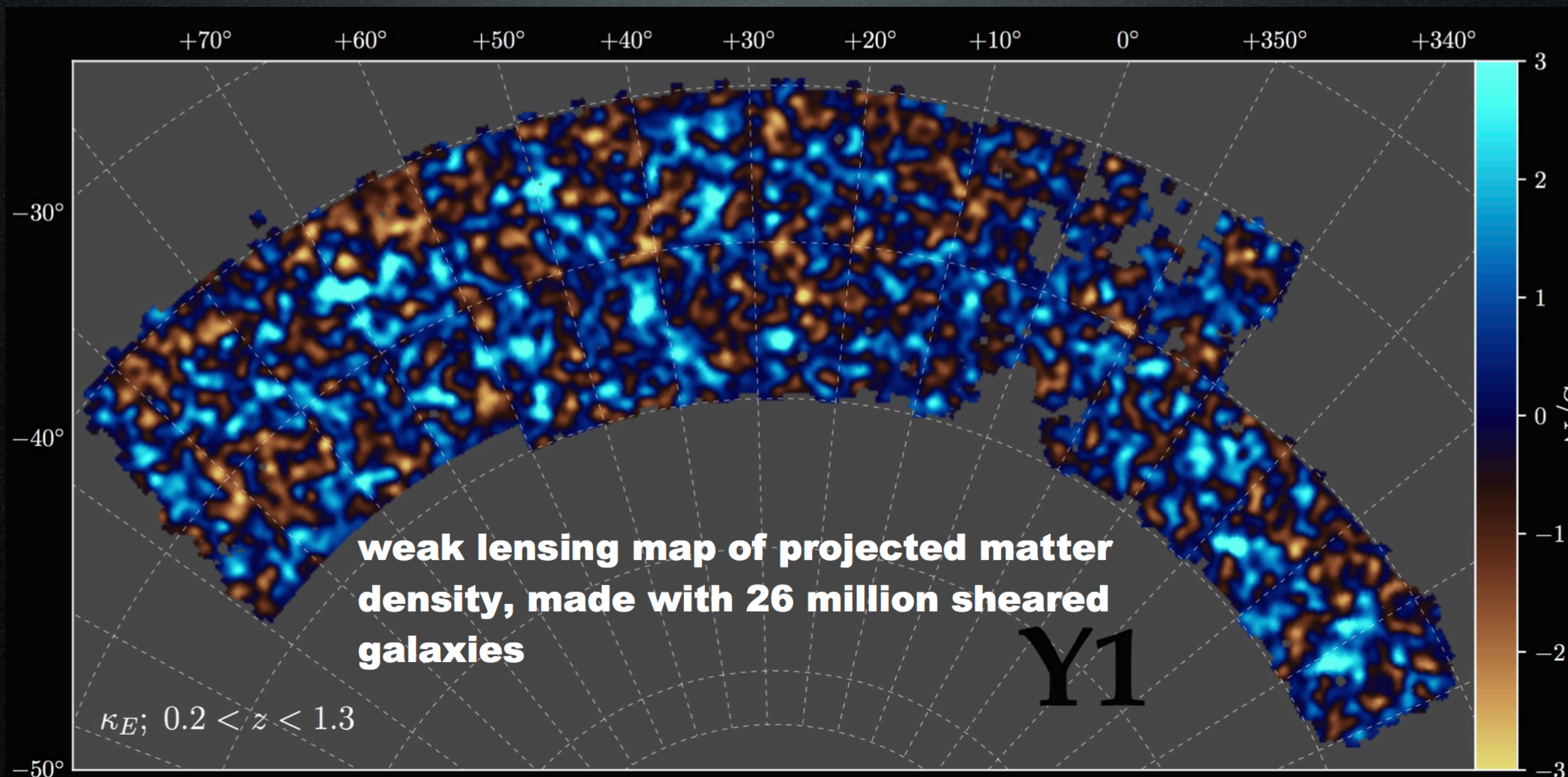


24 maps and 5 redshift bins (!).

Galaxy Clustering



Weak lensing mass map

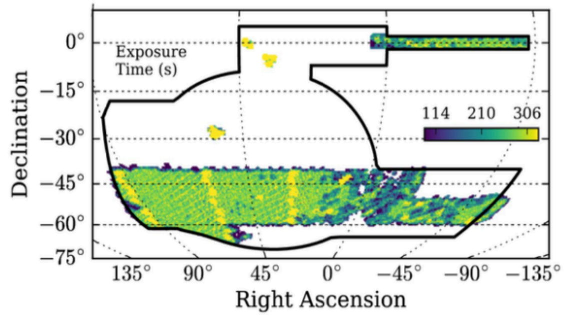


Systematics in these surveys depend on galaxies

- We are moving from a statistics-limited regime to a systematics-limited regime --> need accuracy, not just precision!
- Systematics in analysis
  - Accuracy of code and pipelines
  - Human bias
- Systematics in making the map from an imaging survey
  - Photometric redshifts
  - Shear calibration
  - Calibration, dust, star-galaxy separation, deblending, etc etc.
- Systematics in making robust predictions for a given model
  - Basic observables as a function of cosmology (non-linear structure formation, including impact of galaxy formation)
  - Covariance between observables
  - Modeling galaxy bias, including scale dependence
  - Intrinsic alignments

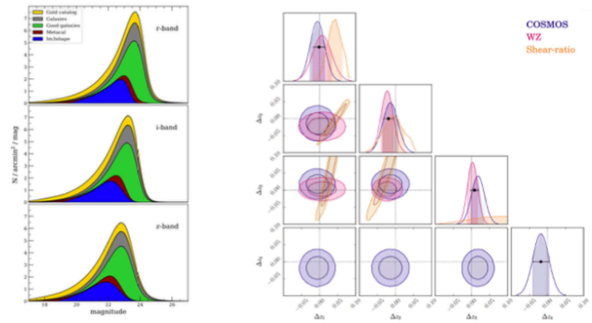
Increasing statistical power requires excellent systematics control.

Unprecedented size and depth of photometric data



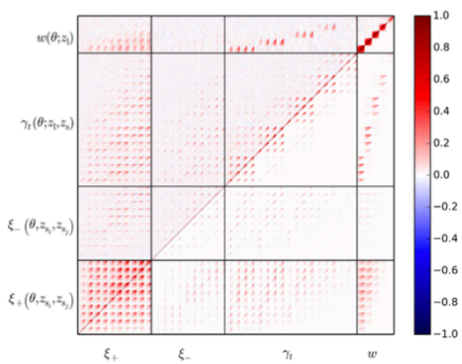
Drlica-Wagner, Rykoff, Sevilla+ released today

Two independent shape & photo-z catalogs and calibrations

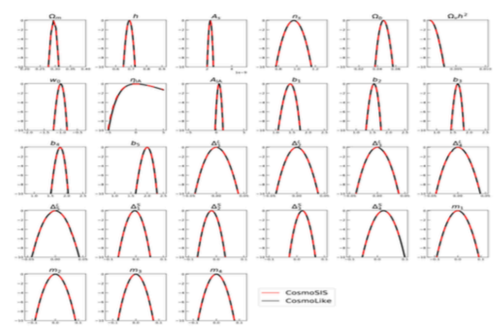


Zuntz, Sheldon+; Samuroff+; Hoyle, Gruen+ released today; Davis+, Gatti, Vielzeuf+, Cawthon+ in prep.

Full, validated treatment of covariance and nuisance parameters

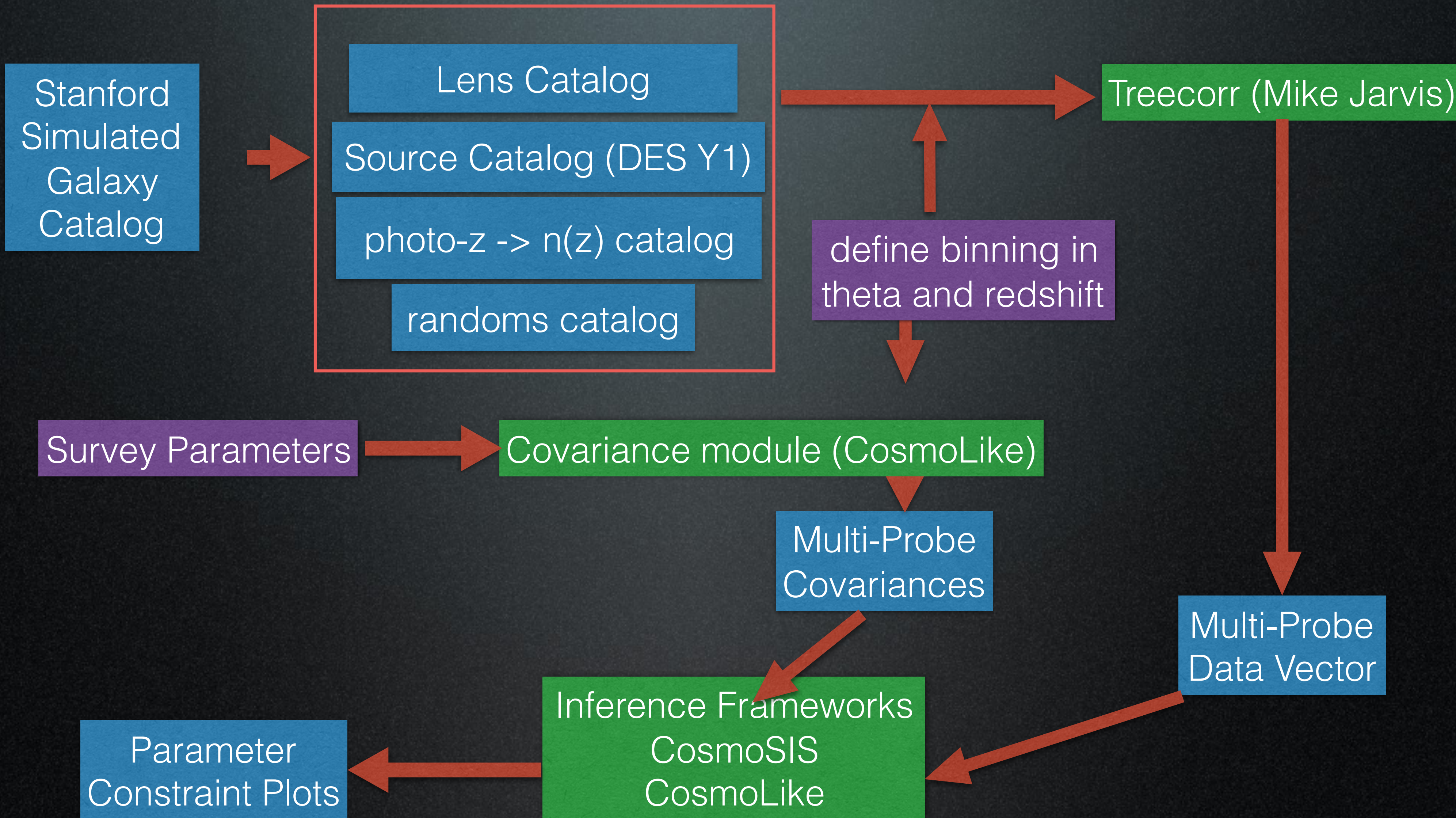


Theory and simulation tested, blind, analysis with two independent codes, CosmoLike and CosmoSIS



Krause, Eifler+2017; MacCrann, DeRose+ in prep

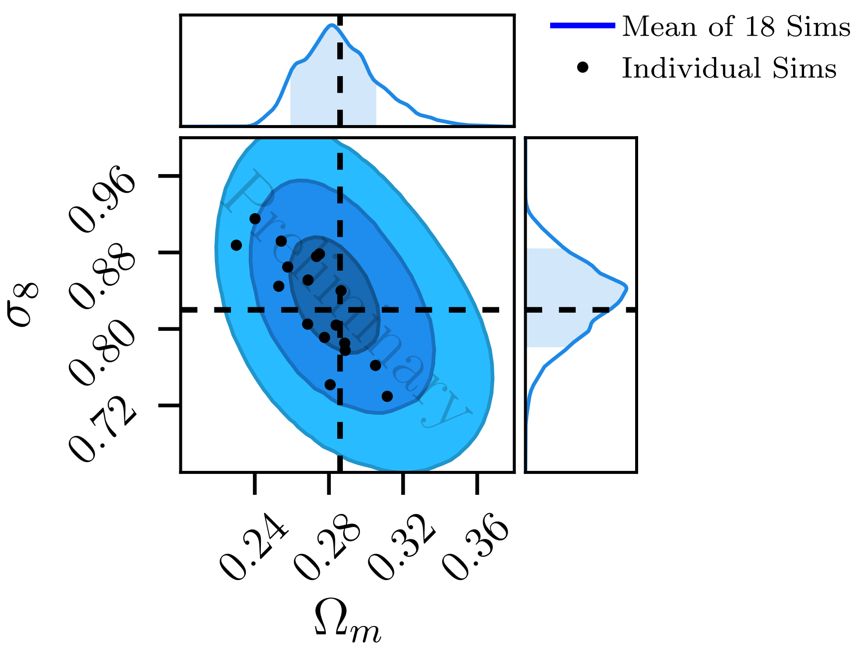
Catalog to cosmology



with Eifler, Krause, MacCrann, Troxel, Zuntz (DES + LSST DESC)

Catalog to cosmology

flagship analysis:
3x2pt: shear-shear, galaxy-shear, galaxy-galaxy
“redmagic" galaxy sample (well-controlled photo-zs)



Preliminary!!

run full analysis code on 18 simulated realizations of the DES Y1 footprint

DeRose & RW DES sims; analysis by McCrann, DeRose, Krause, Eifler

DES-Y1 Multi-Probe Cosmology
Systematics Modeling + Mitigation

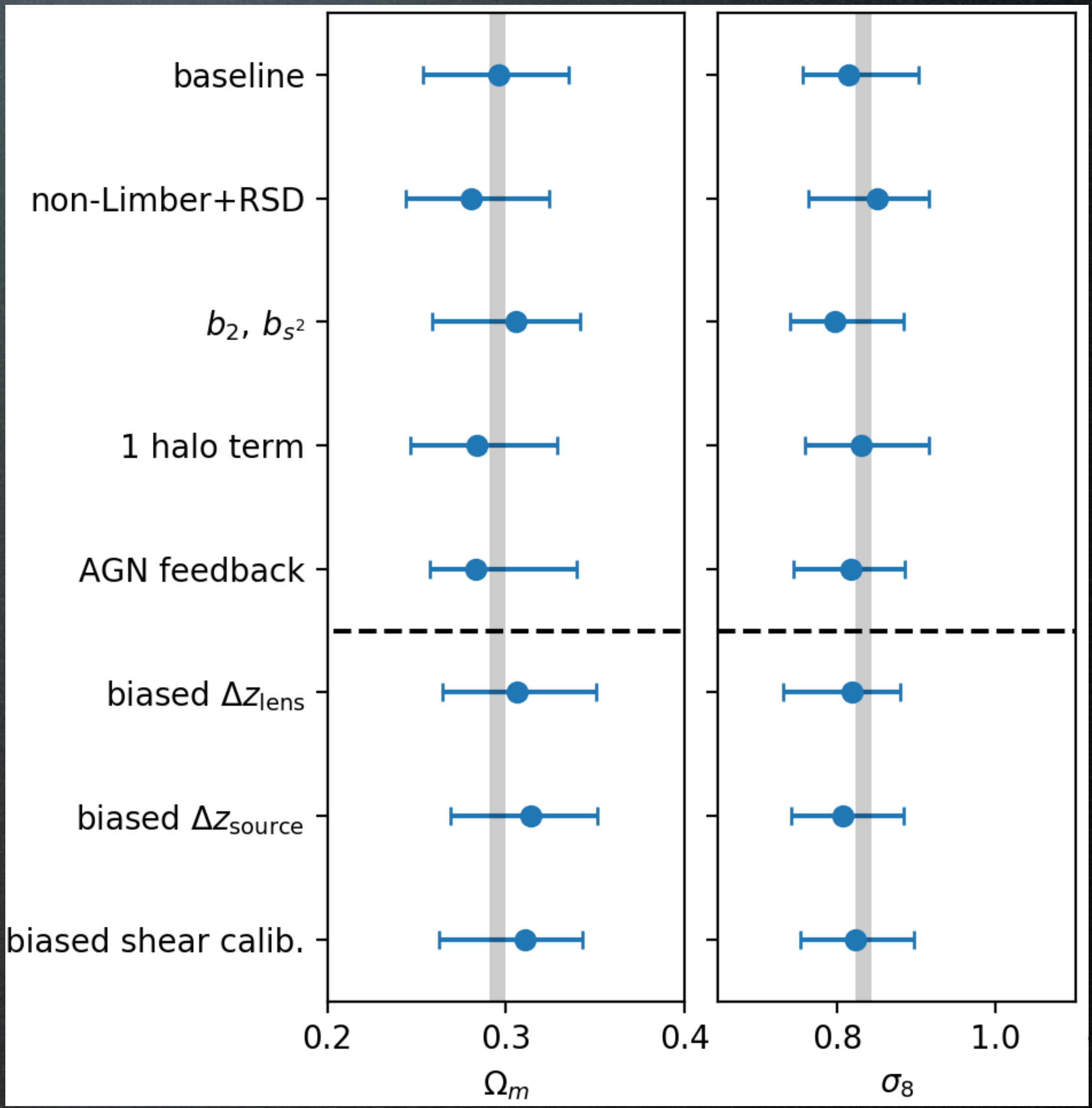
Krause et al 2017

minimize systematics impact through scale cuts

no marginalization required

marginalized systematics

check robustness wrt priors



simulated analyses, baseline model not centered on DES-Y1 cosmology

3x2pt analysis on DES Y1 data

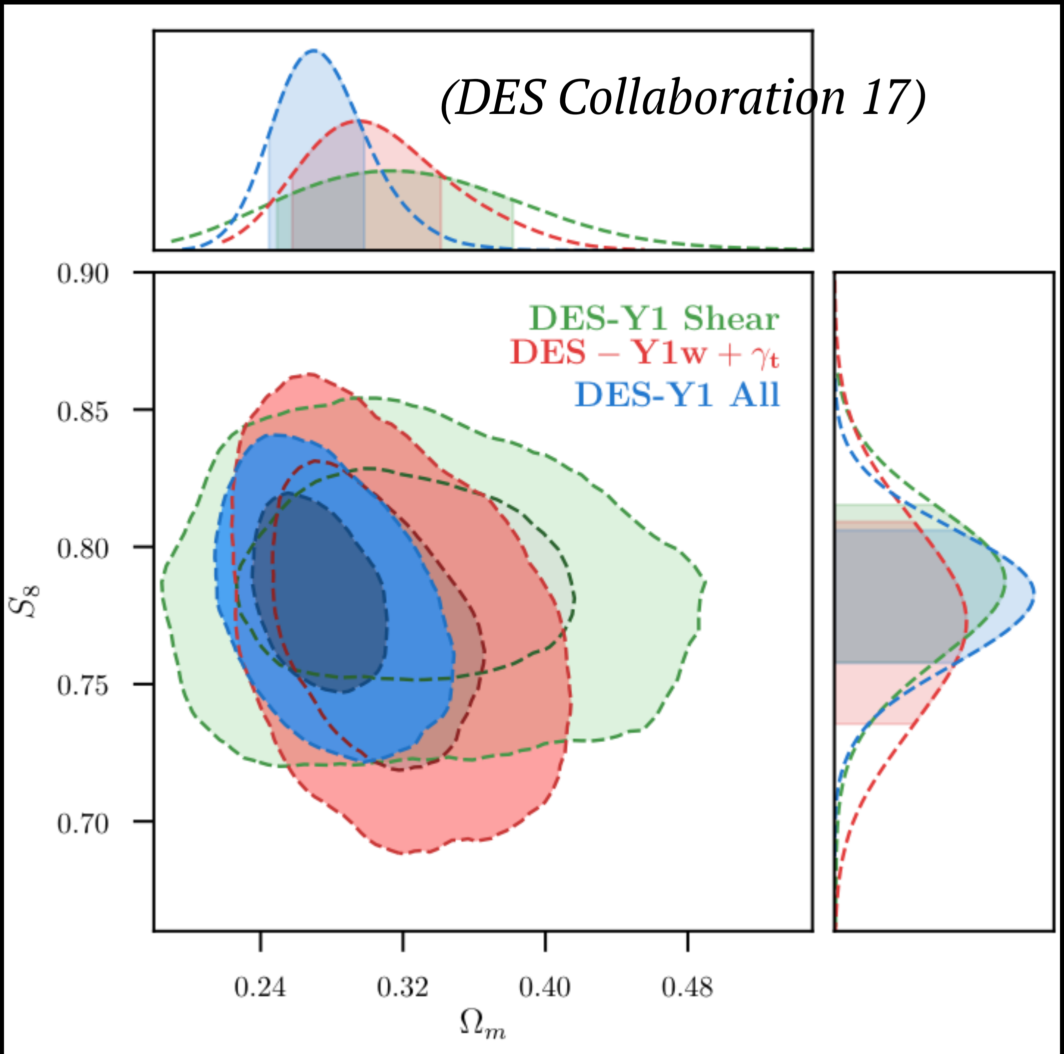
Parameter	Prior
Cosmology	
Ω_m	flat (0.1, 0.9)
A_s	flat $(5 \times 10^{-10}, 5 \times 10^{-9})$
n_s	flat (0.87, 1.07)
Ω_b	flat (0.03, 0.07)
h	flat (0.55, 0.91)
$\Omega_\nu h^2$	flat$(5 \times 10^{-4}, 10^{-2})$
w	flat (-2,-.5)
Lens Galaxy Bias	
$b_i (i = 1, 5)$	flat (0.8, 2.5)
Intrinsic Alignment	
$A(z) = A[(1+z)/1.62]^\alpha$	
A	flat (-5,5)
α	flat (-5,5)
Lens photo-z shift (red sequence)	
$\Delta z^i_{\text{Lens}} (i = 1, 5)$	Gauss (0.0, 0.01)
Source photo-z shift	
$\Delta z^1_{\text{source}}$	Gauss (-0.0037, 0.018)
$\Delta z^2_{\text{source}}$	Gauss (-0.0171, 0.015)
$\Delta z^3_{\text{source}}$	Gauss (0.020, 0.014)
$\Delta z^4_{\text{source}}$	Gauss (0.022, 0.022)
Shear calibration	
$m_i^{\text{METACALIBRATION}} (i = 1, 4)$	Gauss (0.013, 0.021)
$m_i^{\text{IM3SHAPE}} (i = 1, 4)$	Gauss (0.0, 0.035)

Analysis of shear-shear, galaxy-shear, galaxy-galaxy 2-pt statistics on 1000 sq. degrees of DES Y1 data.

7 cosmological parameters
+ 20 nuisance parameters:
5x1 bias parameter per lens bin
2 intrinsic alignment parameters
5x1 photo-z shift parameter per lens bin
4x1 photo-z shift parameter per source bin
4x1 shear calibration bias parameter per source bin

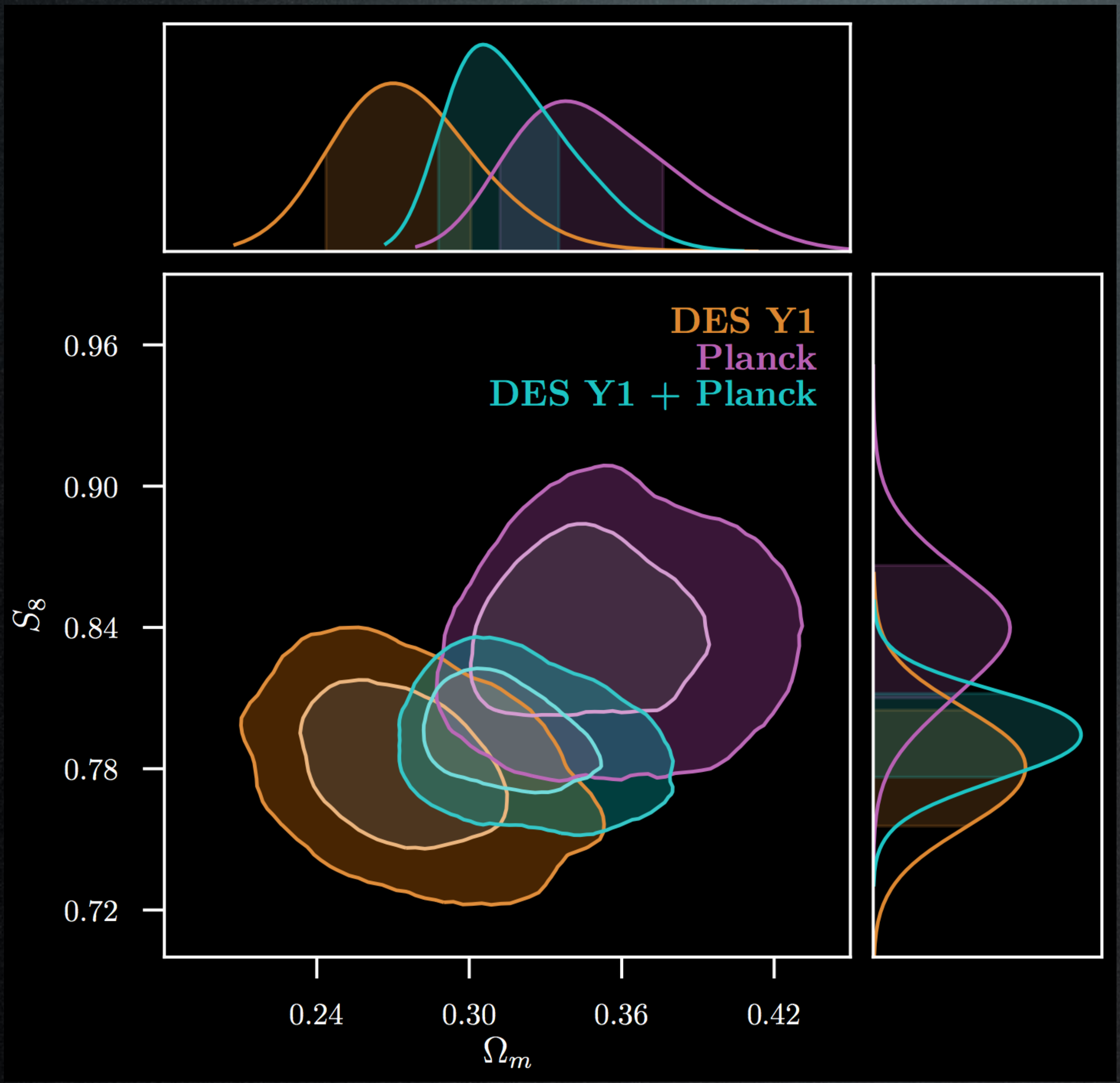
Photometric redshifts constrained two independent ways: using COSMOS multi-band data; clustering redshifts.

Multi-Probe Constraints: LCDM



- DES-Y1 weak lensing: factor ~2 increase in constraining power
- marginalized 4 cosmology parameters, 10 clustering nuisance parameters, and 10 lensing nuisance parameters
- consistent (Bayes Factor R = 2.8) cosmology constraints from weak lensing and clustering in configuration space

DES Y1 results



- DES and Planck constrain matter density and S_8 with equal strength
- Difference in central values 1-2σ in the same direction as earlier lensing results
- Bayes Factor 4.2 – no evidence for inconsistency
- Still consistent for joint low-z results + Planck, which is why we combine...

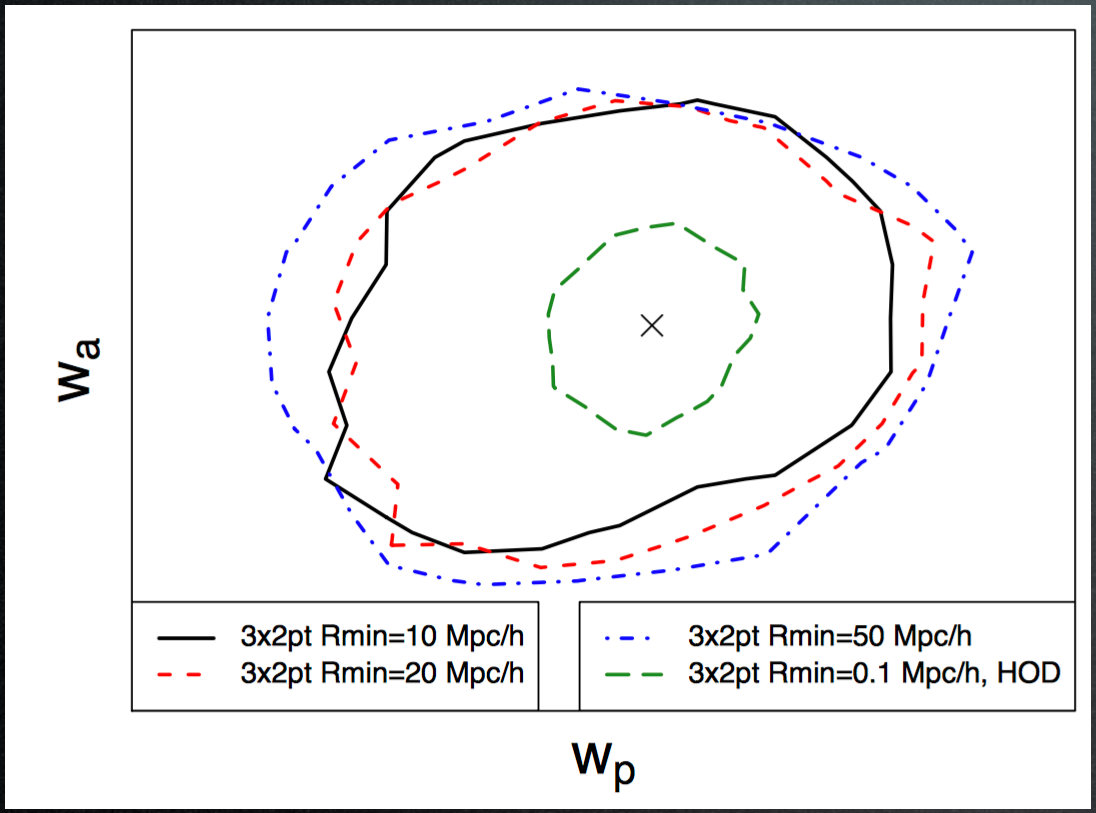
$$\Omega_m = 0.301^{+0.006}_{-0.008}$$

$$S_8 = 0.799^{+0.014}_{-0.009}$$

$$w = -1.00^{+0.04}_{-0.05}$$

Just 20%
of DES data!

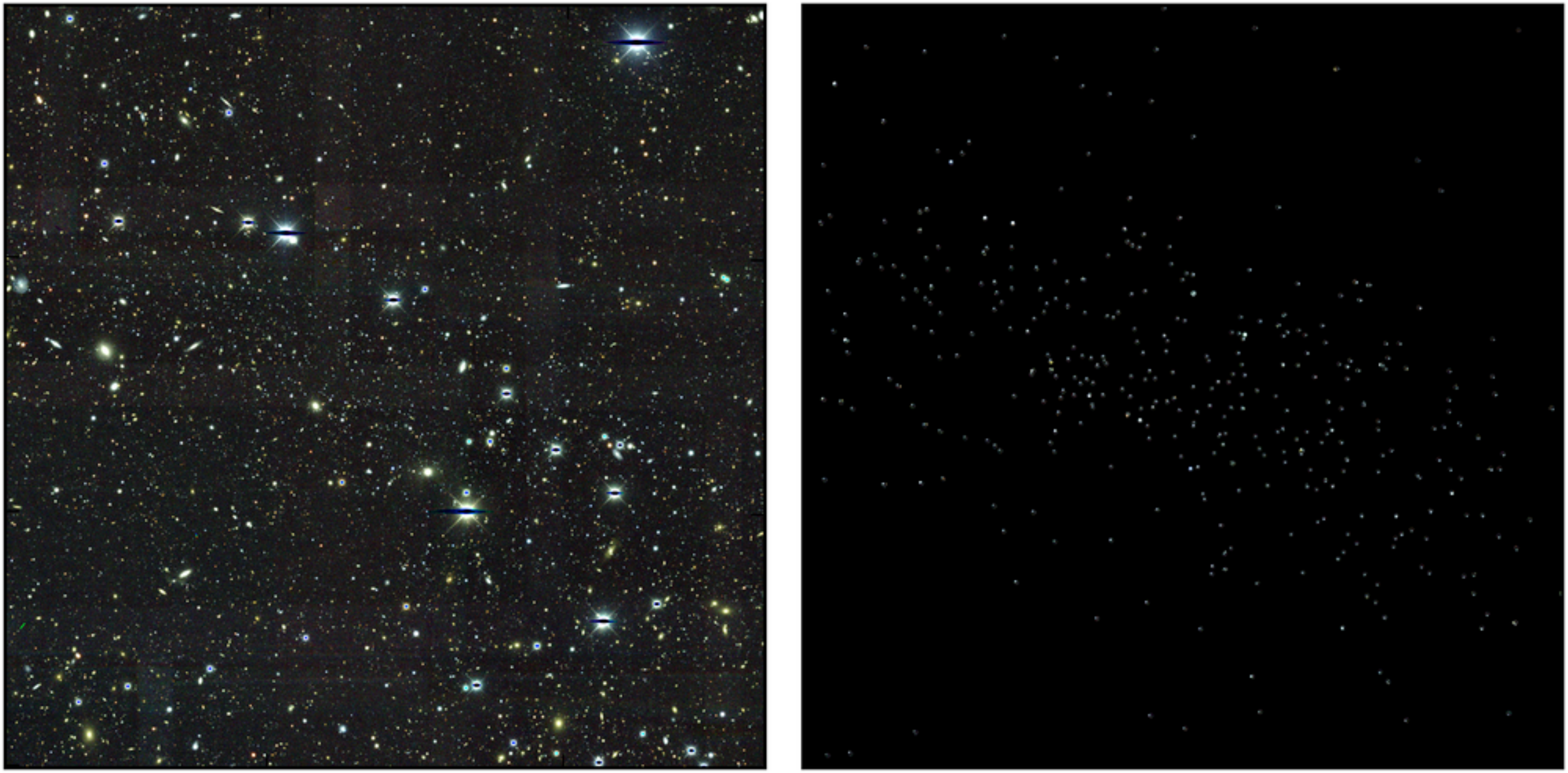
Significant future potential if we can push to smaller scales



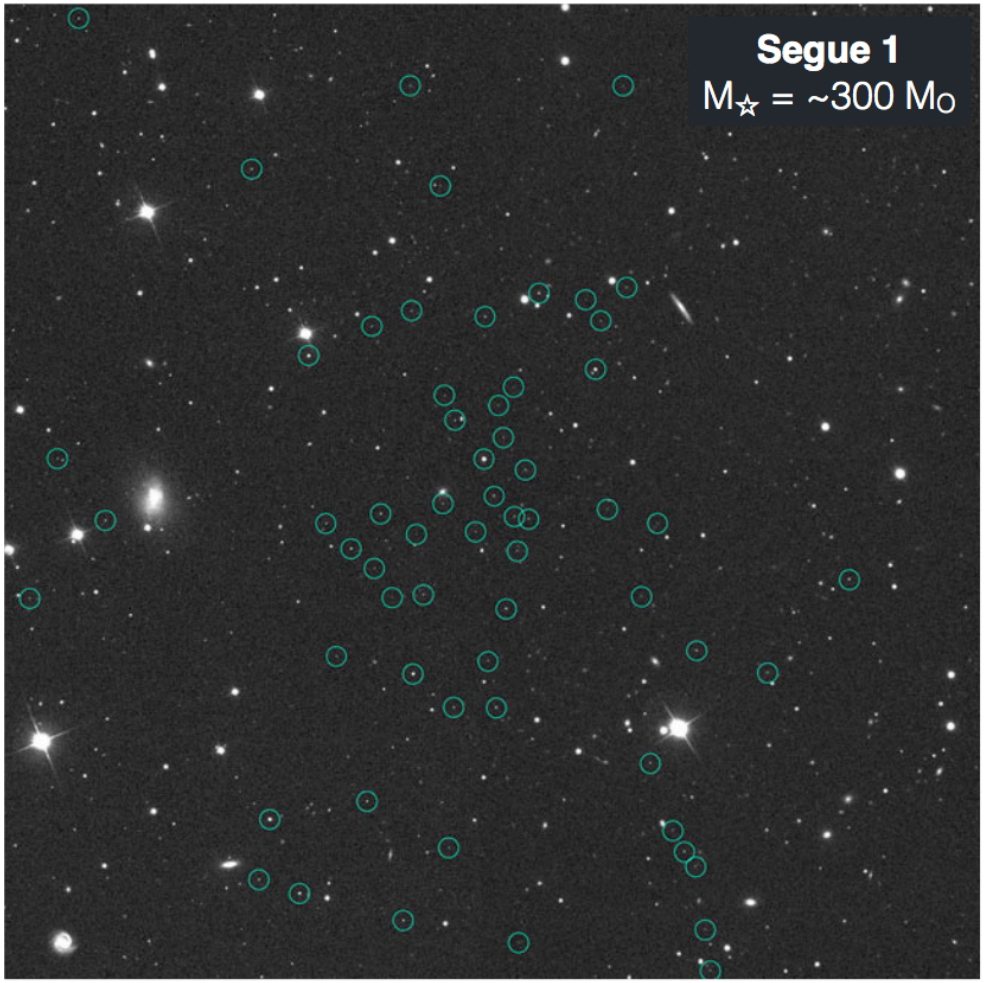
Pushing to small-scales requires more accurate modeling of non-linear galaxy clustering than is currently available

dark matter from large imaging surveys

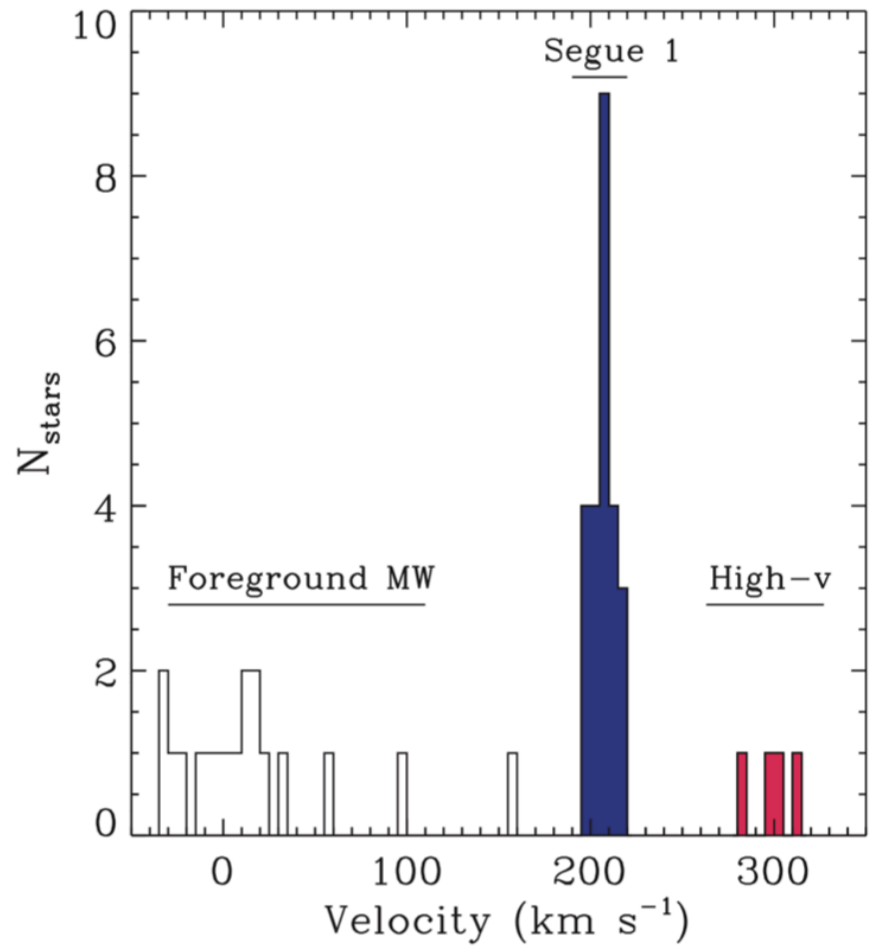
- Map of the mass produces a test of LCDM predictions
- Detection of dwarf galaxies tests small-scale power in CDM and provides targets for indirect detection
- Streams within the Milky Way can probe the shape the MW & test for substructure
- Strong lensing systems test small-scale power in CDM



Discovery of new dwarf satellites of the Milky Way!



Geha et al. 2009, ApJ, 692, 1464



Discovered as arcminute-scale statistical overdensities of **individually resolved stars**

Confirmed as **dark-matter-dominated** galaxies via spectroscopic follow-up (line-of-sight velocity dispersion)

Renaissance in discovery & understanding of MW satellites — 27 pre-2015, 27 new in 2015-16!

Bechtol et al 2015, Koposov et al 2015, Drlica-Wagner et al 2015

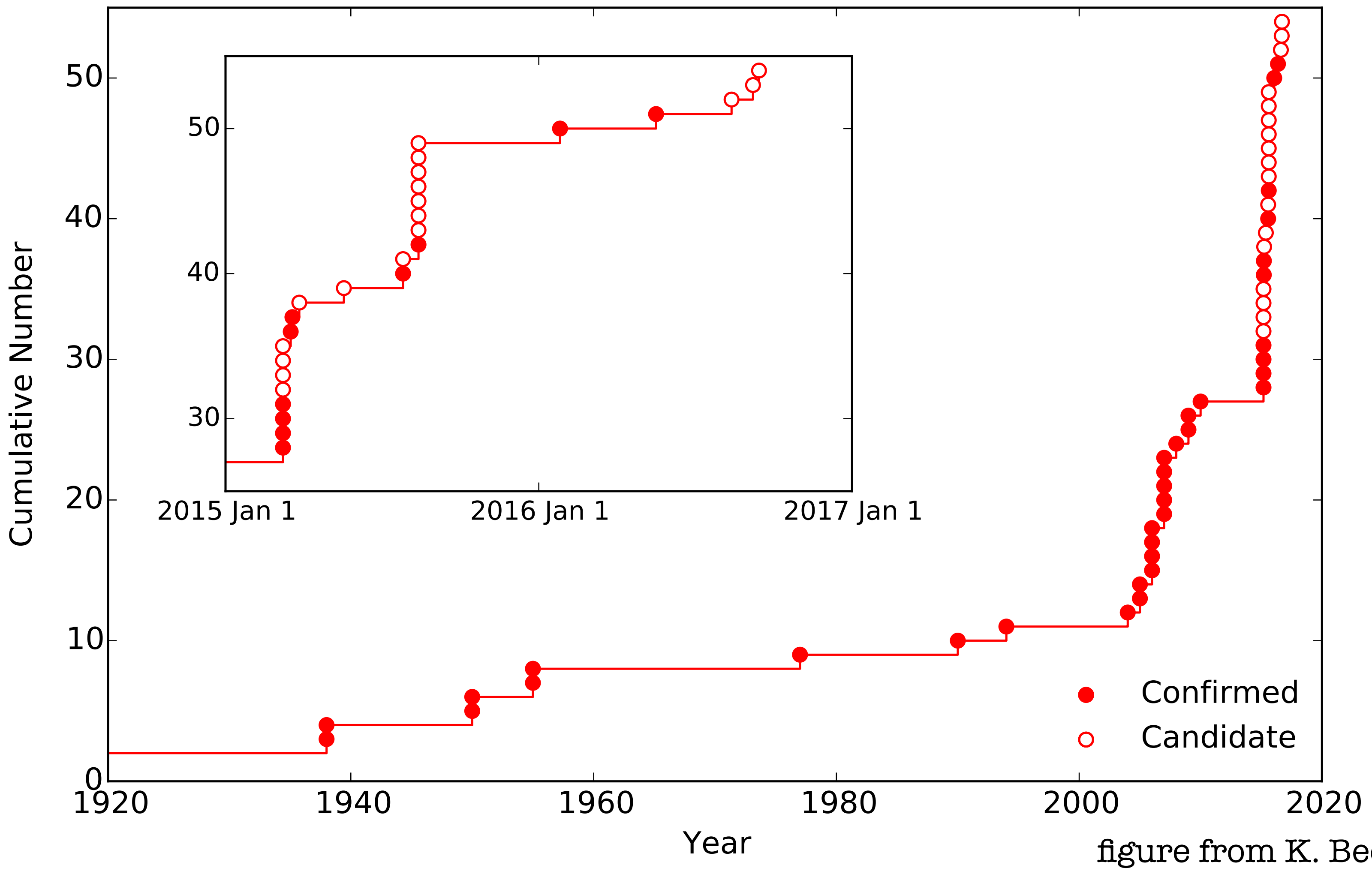
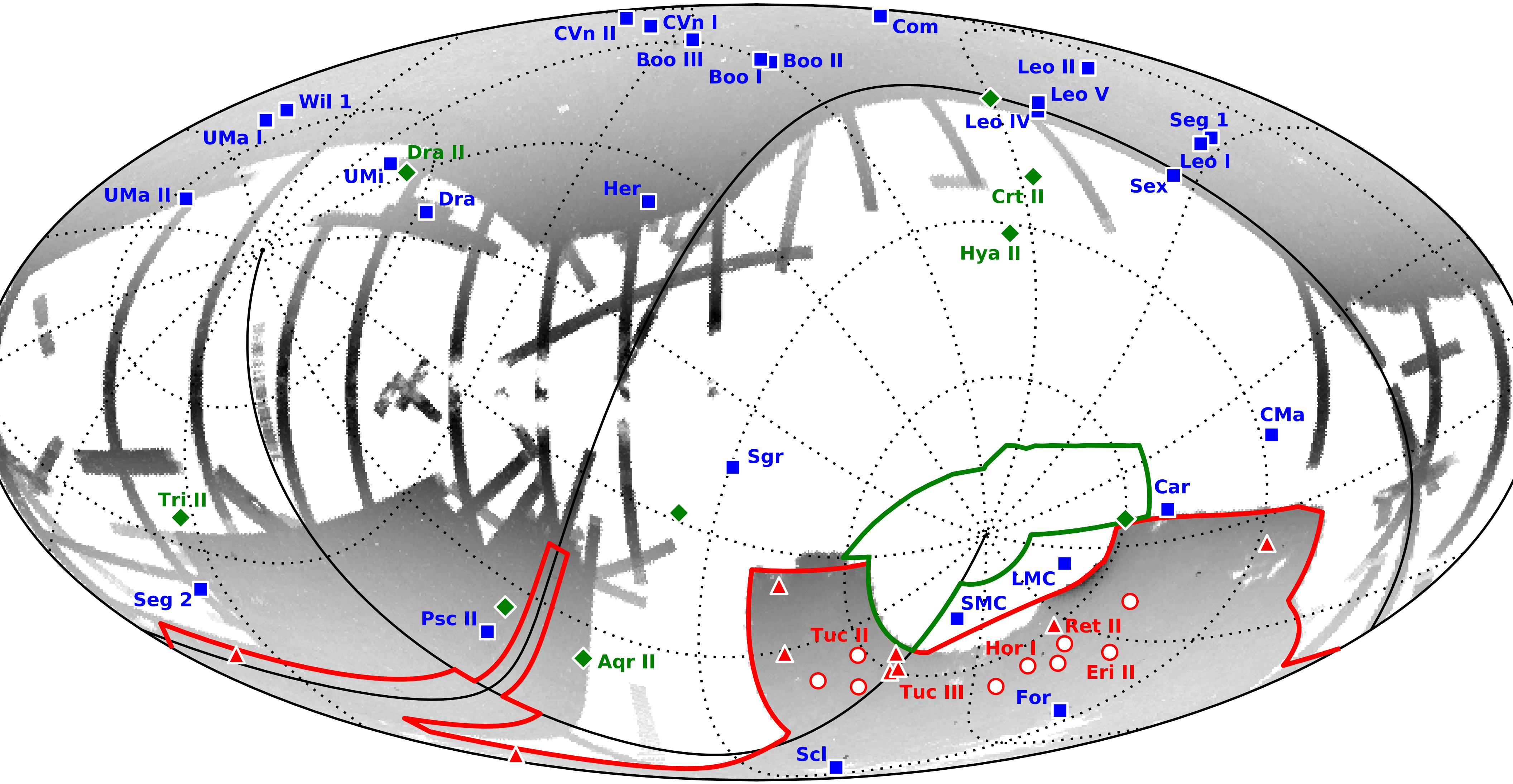


figure from K. Bechtol

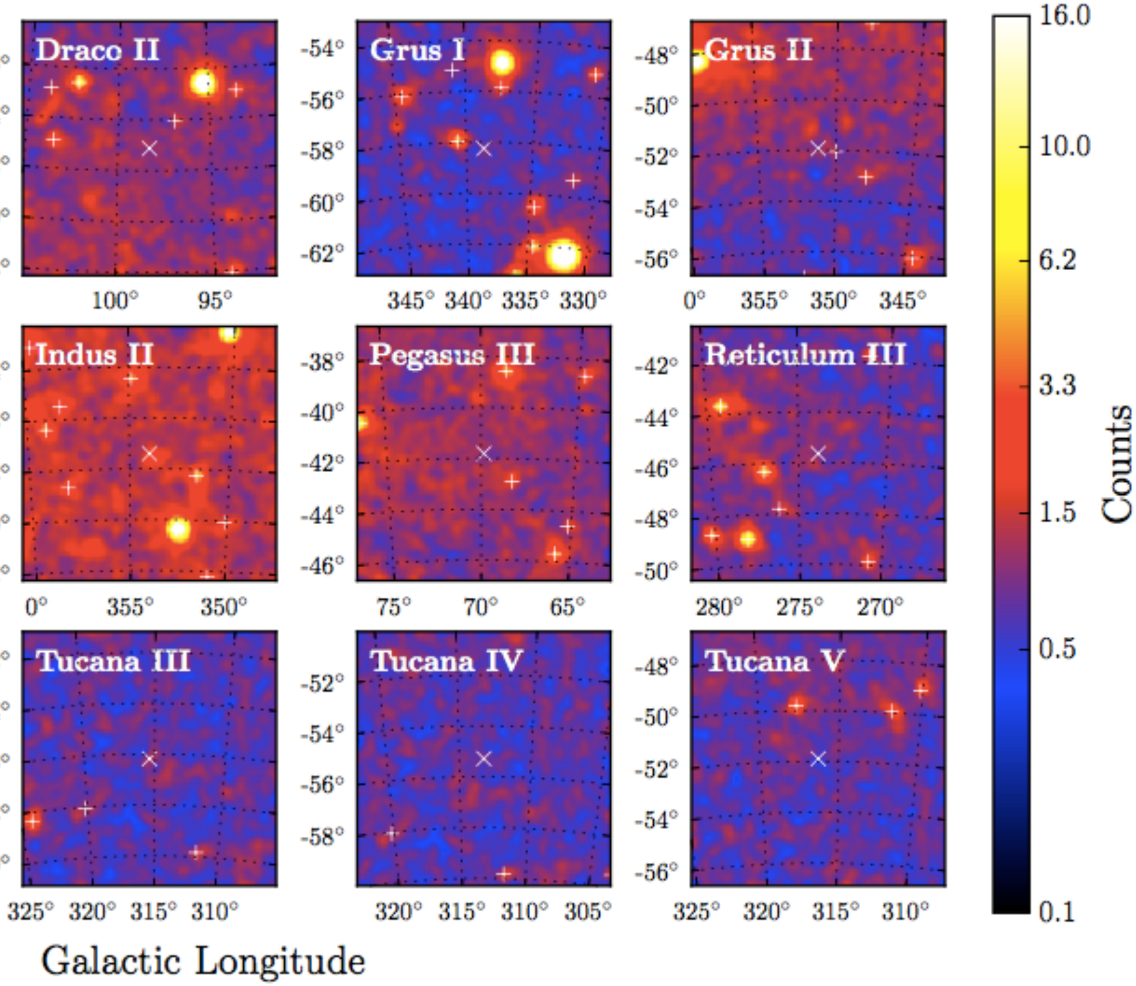
18 new satellites from DES + 3 more from Dark Energy Camera + 6 more in 2015-2016

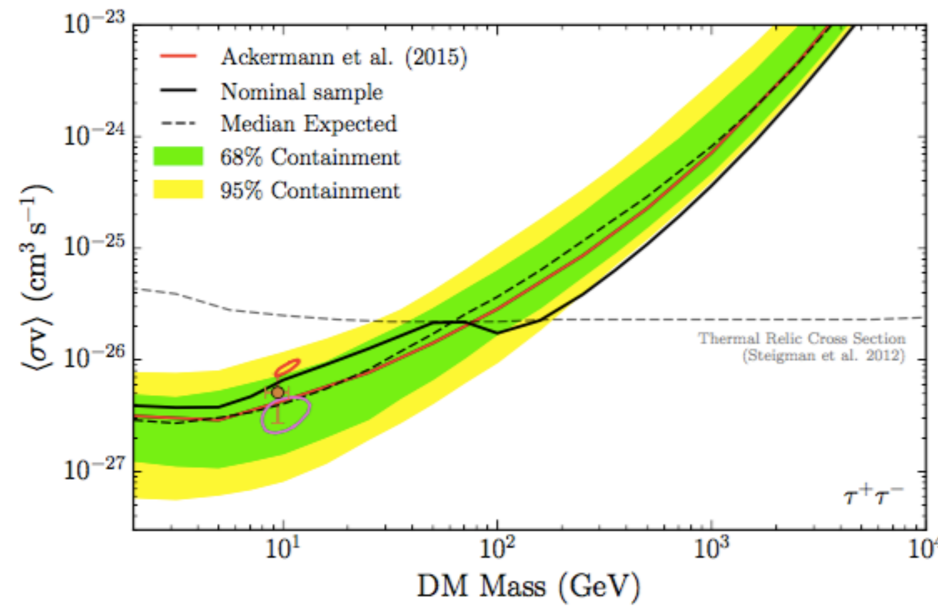


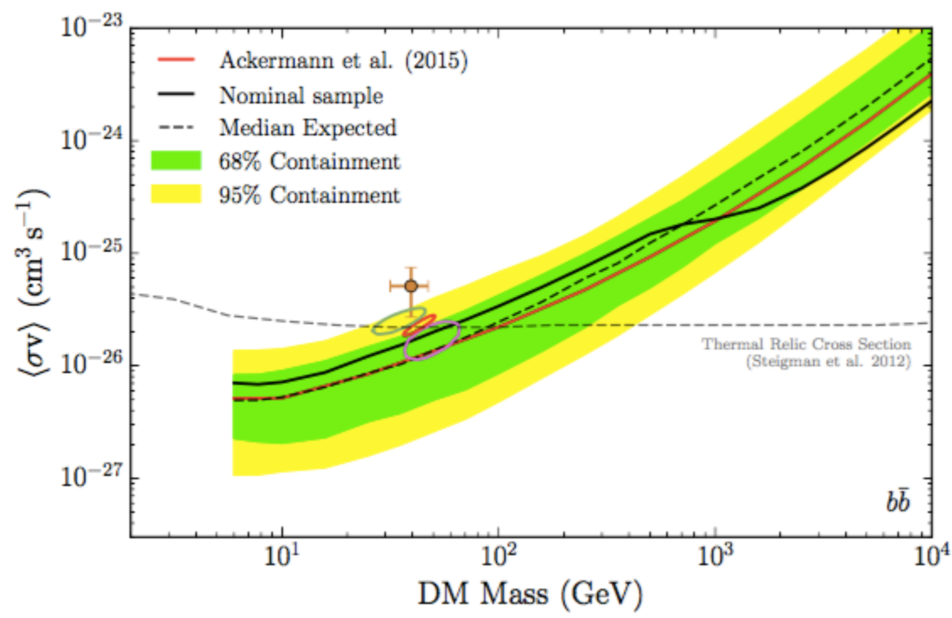
figures from K. Bechtol

18 new satellites from DES + 3 more from Dark Energy Camera + 6 more in 2015-2016

Search for Gamma Rays from Dark Matter annihilation in Dwarf Satellite Systems



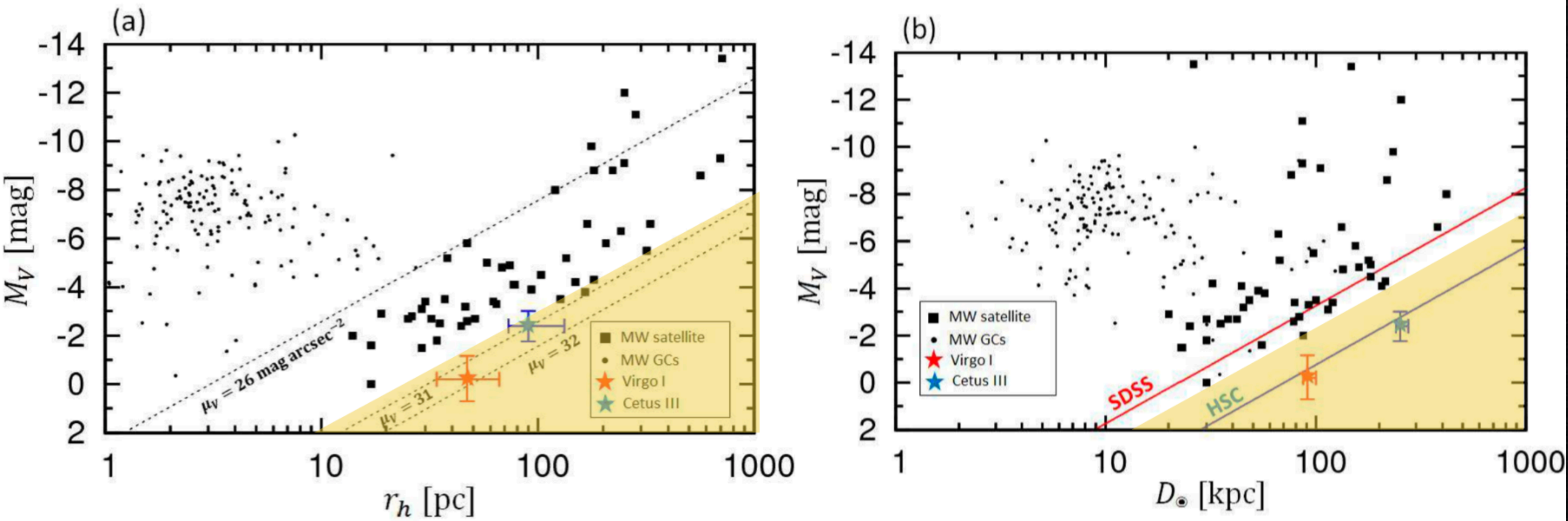




no globally significant excess
Albert et al 2016 (DES+Fermi-LAT)

Dwarf galaxies from future surveys

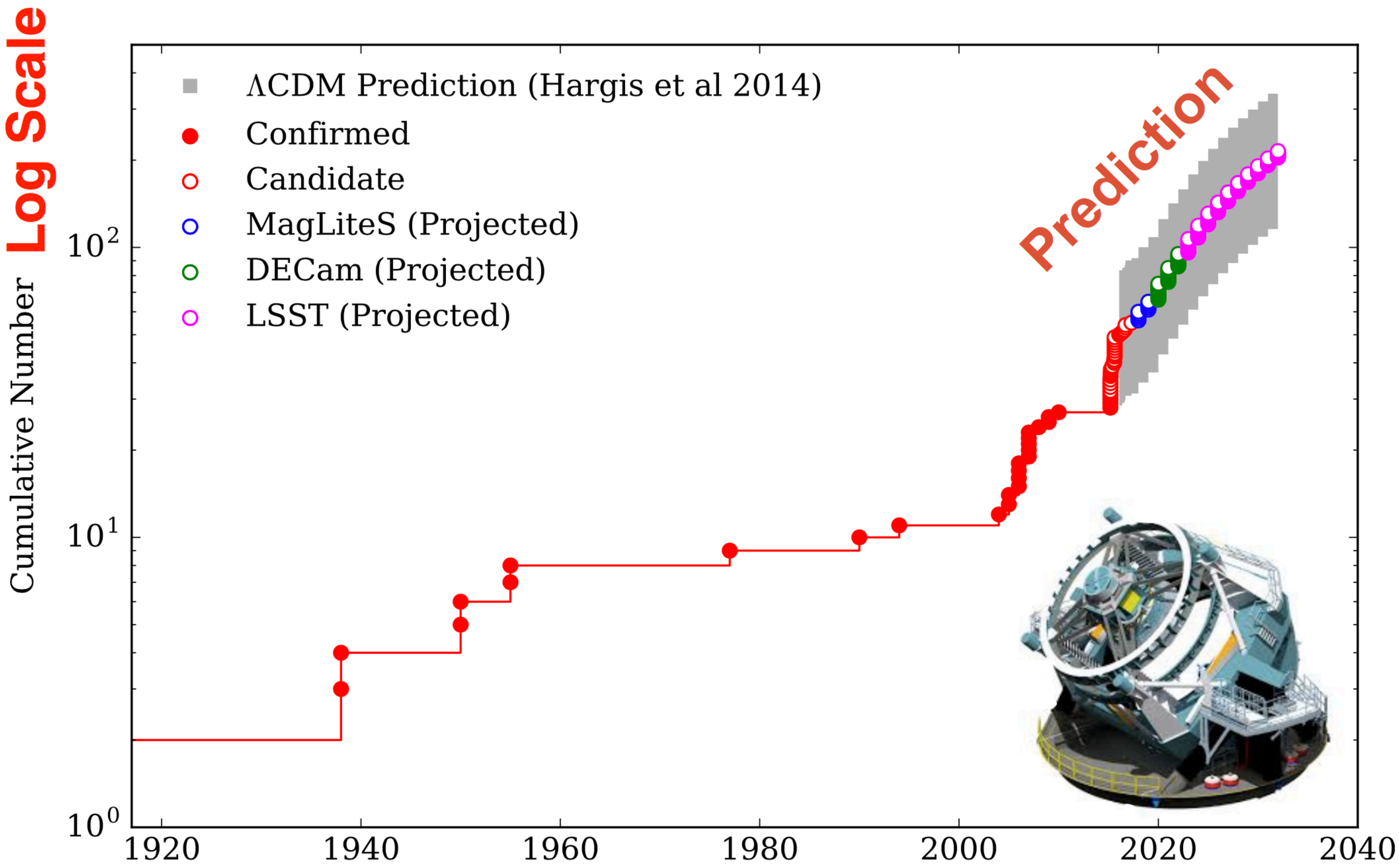
Two new ultra-faint galaxy candidates found in first 300 deg² of Hyper-Suprime Cam SSP data (<1% of 4π celestial sphere) that are likely undetectable in any previous survey



Homma et al. 2017

Similarly, we estimate that ~half of the ultra-faint galaxy candidates found with DES would not have been detected in a survey of SDSS depth

Bechtol et al. 2015, Drlica-Wagner et al. 2015


Log Scale
Cumulative Number
ΛCDM Prediction (Hargis et al 2014)
Confirmed
Candidate
MagLiteS (Projected)
DECam (Projected)
LSST (Projected)
Prediction
10^0
10^1
10^2
1920
1940
1960
1980
2000
2020
2040

Summary

- We are just beginning a new generation of imaging surveys
    - Year 1 results from DES show the power of future imaging surveys — weak lensing + clustering are consistent, and give constraints competitive with CMB.
    - Well-planned future program, includes HSC, Euclid, LSST, WFIRST
- As statistical power improves, need to worry more about:
    - Accurate predictions for key statistics as a function of cosmology
    - Modeling galaxy bias
    - Modeling intrinsic alignments
    - Precision & accuracy of photometric redshifts
    - Robust blinding methodologies
- Still exciting power from theoretical and methodological advances, including
    - Additional combinations of probes (e.g. peaks & troughs, gals+CMB)
    - Pushing measurements to smaller scales
    - More accurate image analysis (e.g. calibration, de-blending, shear, star-gal sep)
    - Improvements in photometric redshifts (algorithms, follow-up)