Cosmology in the 2020s

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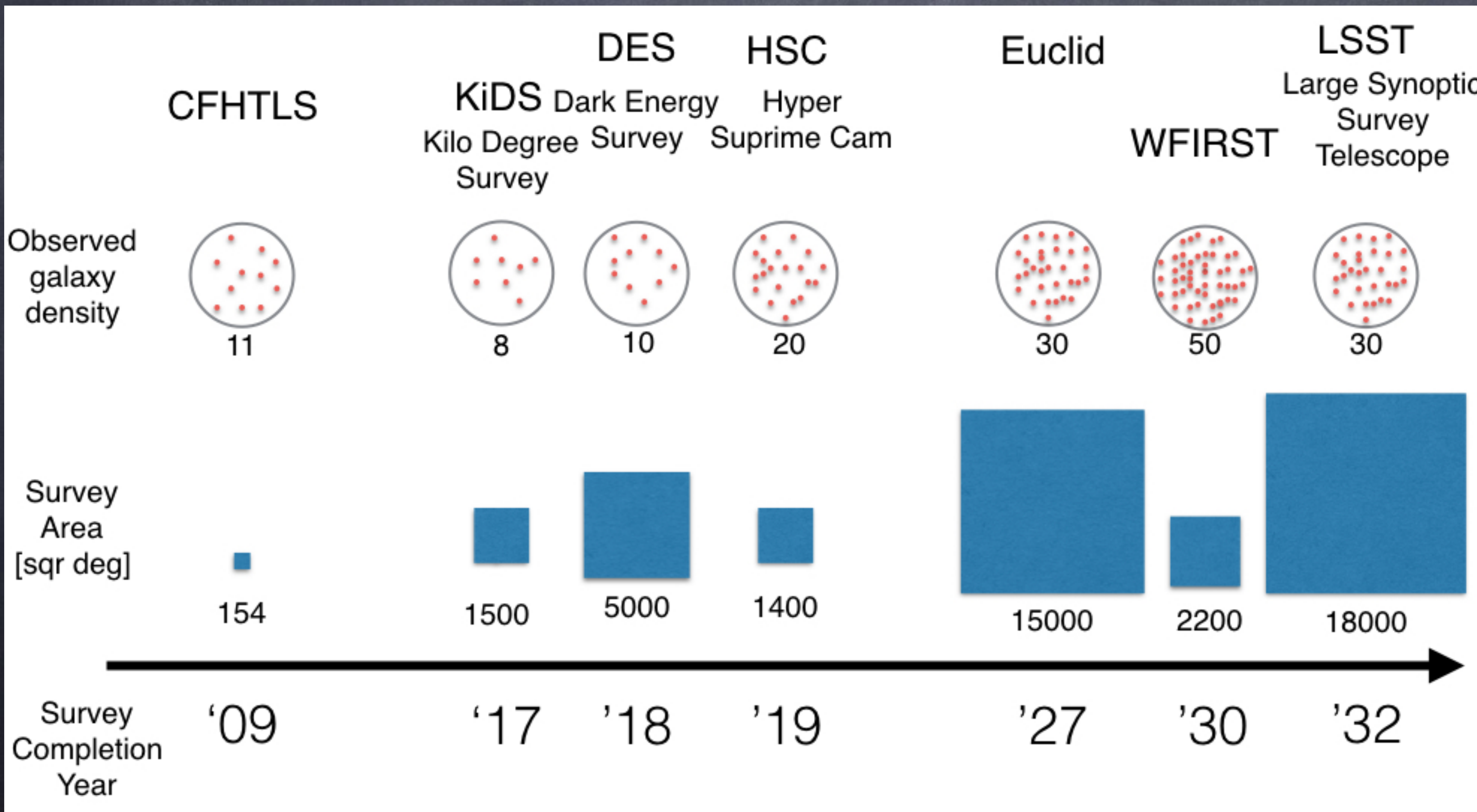
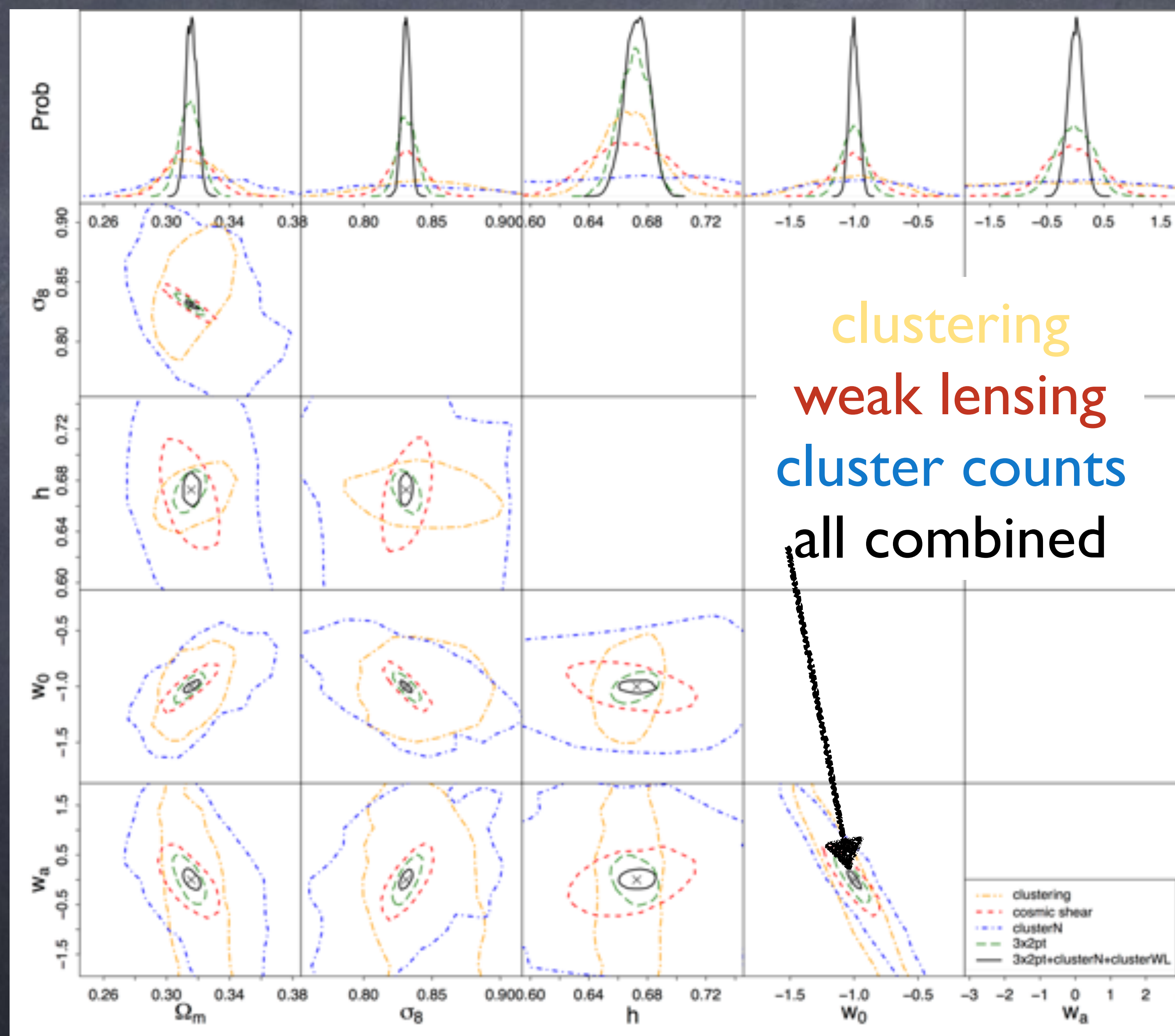
Photometric Dark Energy Surveys



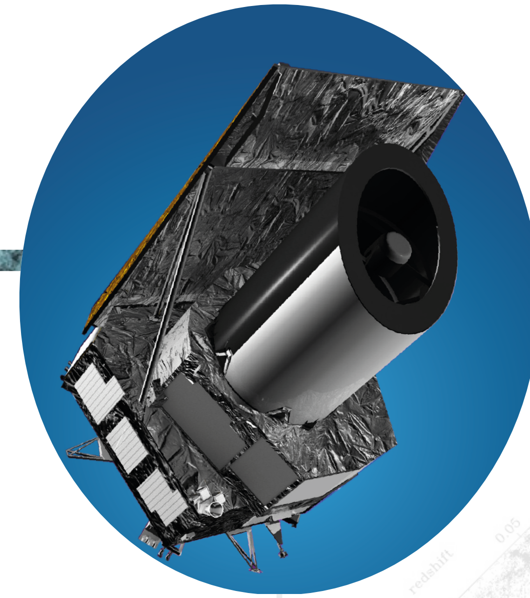
Cosmology from LSST: The Power of Combining Probes



Krause & Eifler 2017

+ supernovae + strong lensing

Euclid



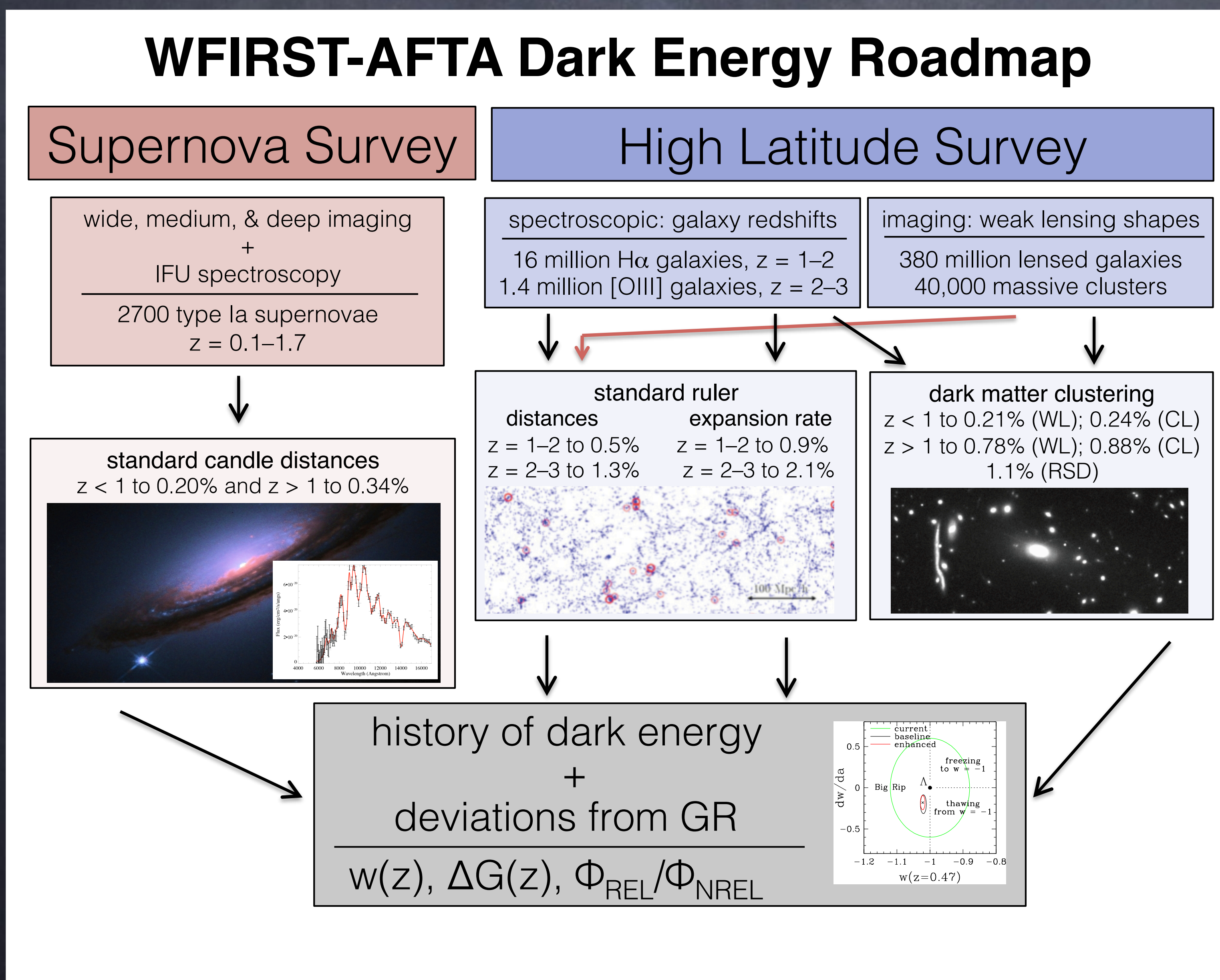
- **A single survey providing data for 5 different probes of dark energy**
  - Optimal use of a space observatory
  - Explore both geometry/expansion and clustering evolution/growth of structures
- **Design allow for a single visit to acquire imaging and spectroscopy on wide fields**
- **Main probes 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!*

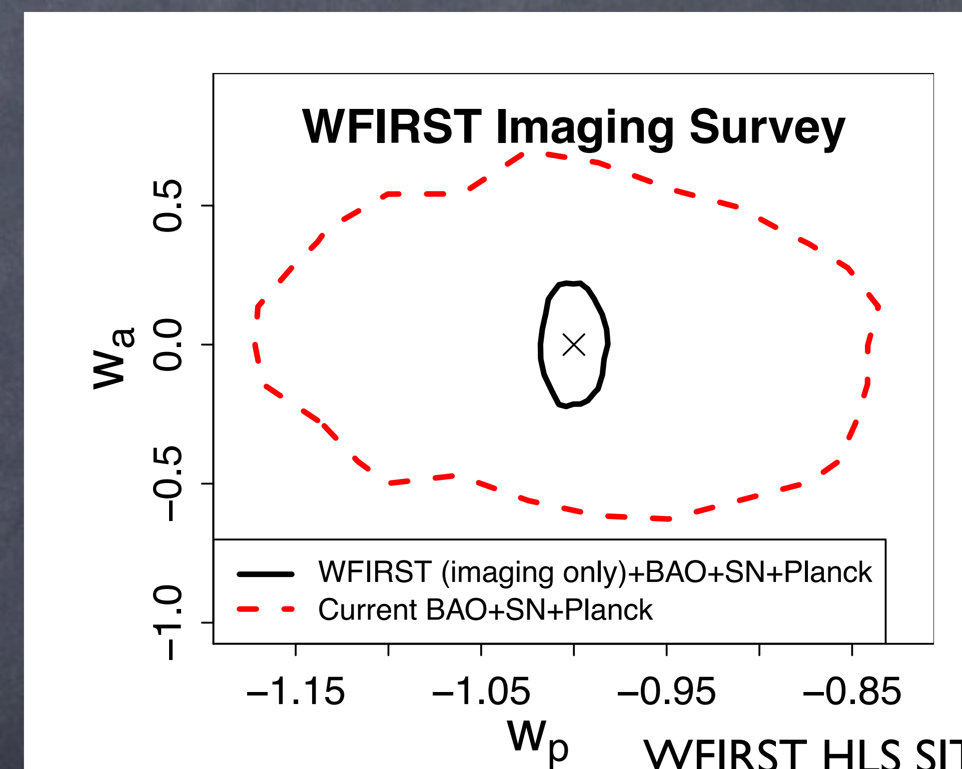
slide from K. Benabed's talk

WFIRST Wide-Field Infrared Survey Telescope

(aka the spy telescope)

one satellite, three cosmological surveys - launch ca. 2025

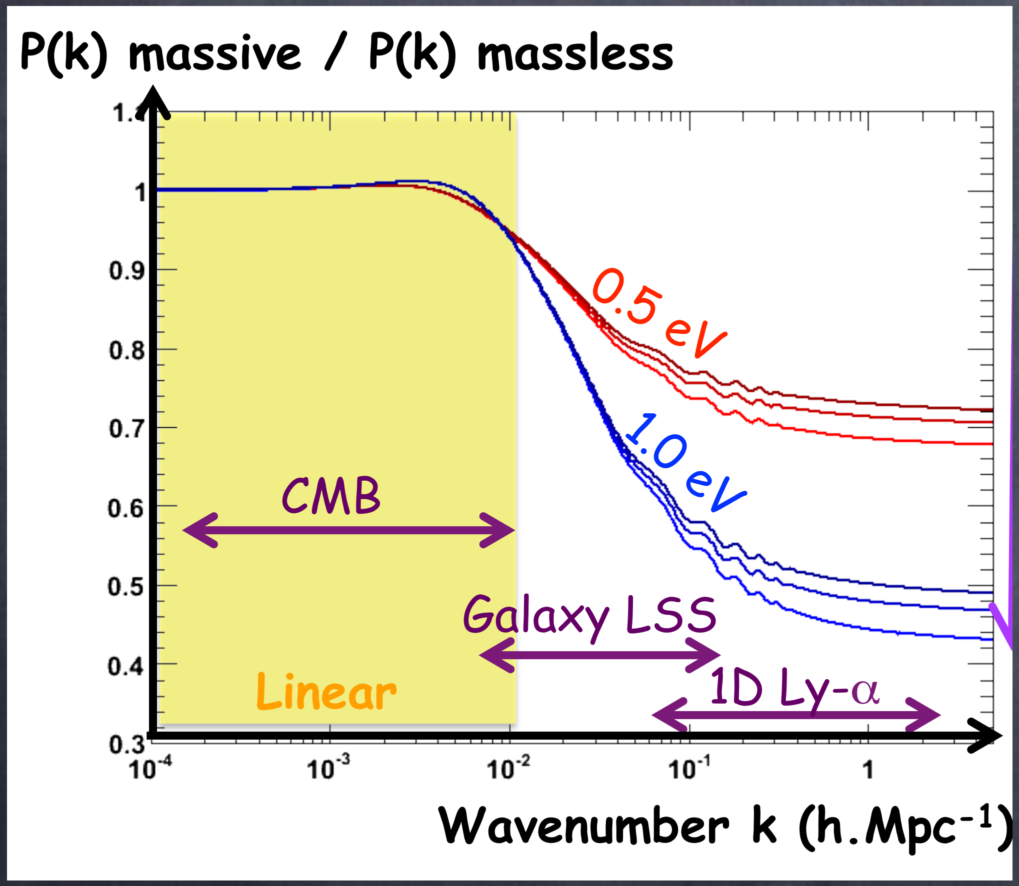




(credit: WFIRST SDT report, Spergel+ '15)

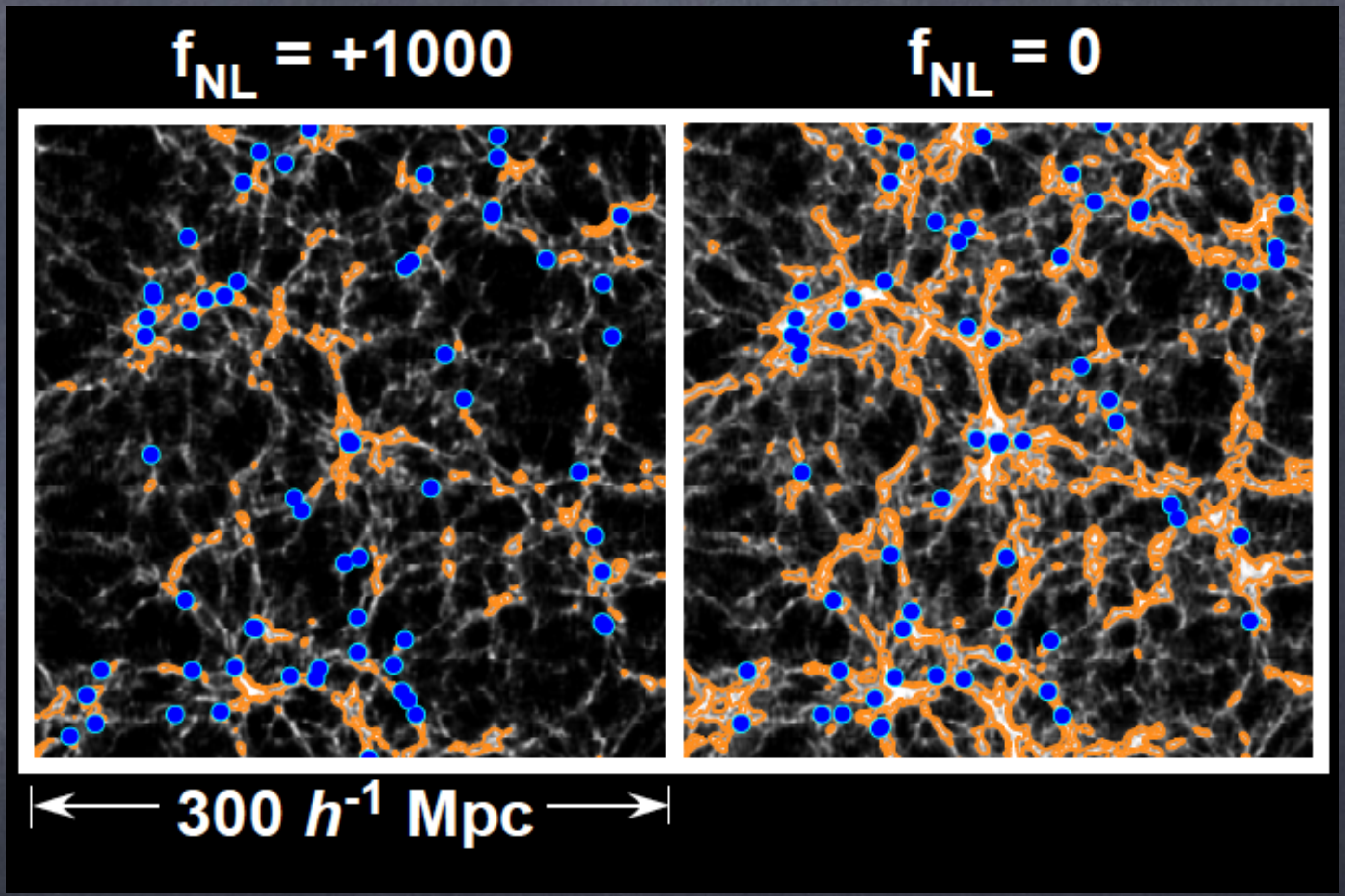
Beyond Dark Energy

Imprint of neutrinos



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

Distribution of Peaks

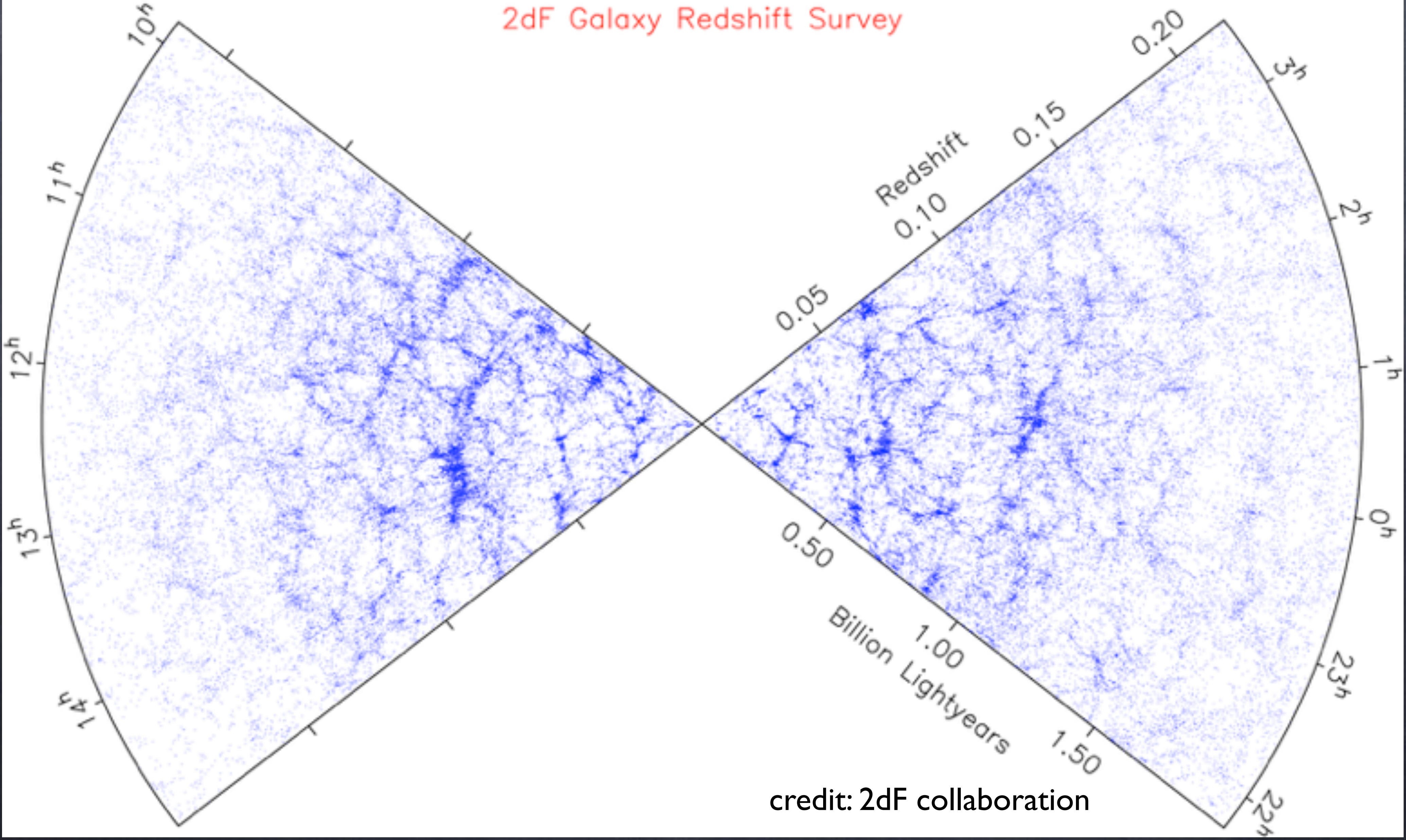


measure imprint of inflation on late-time structure
forecasts under way

Spectroscopic Dark Energy Surveys

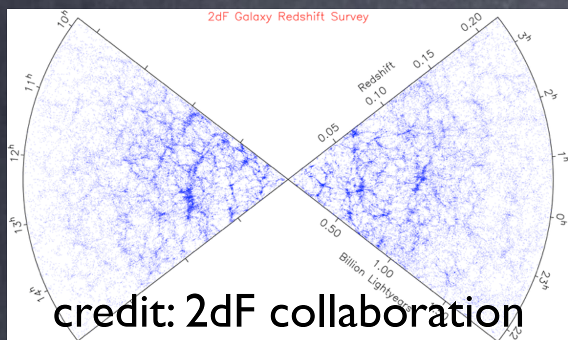
the early days: SDSS, 2-degree Field survey(2dF):

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



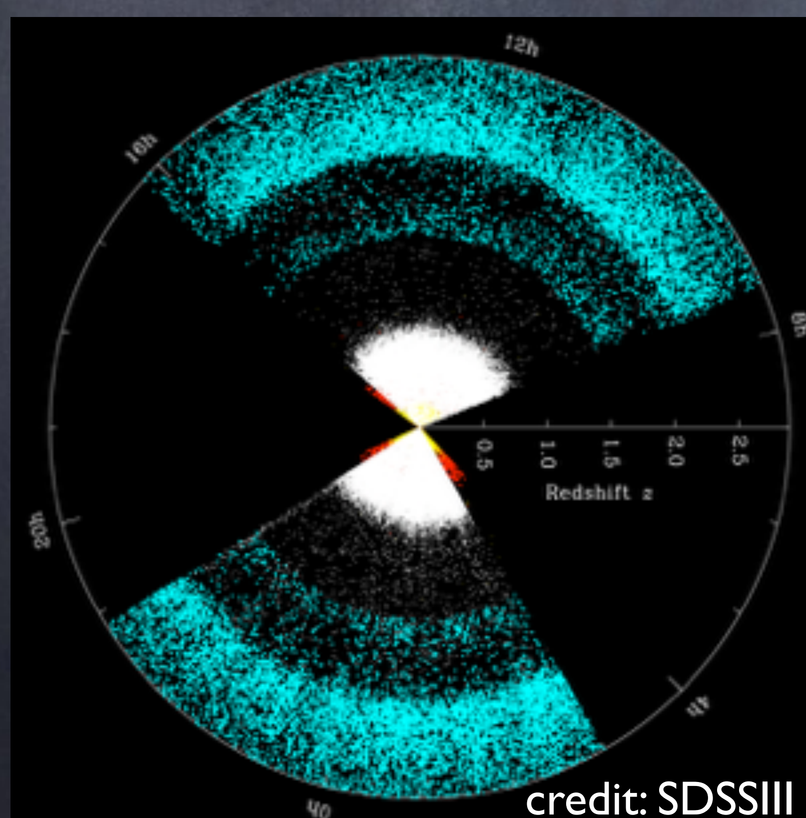
credit: 2dF collaboration

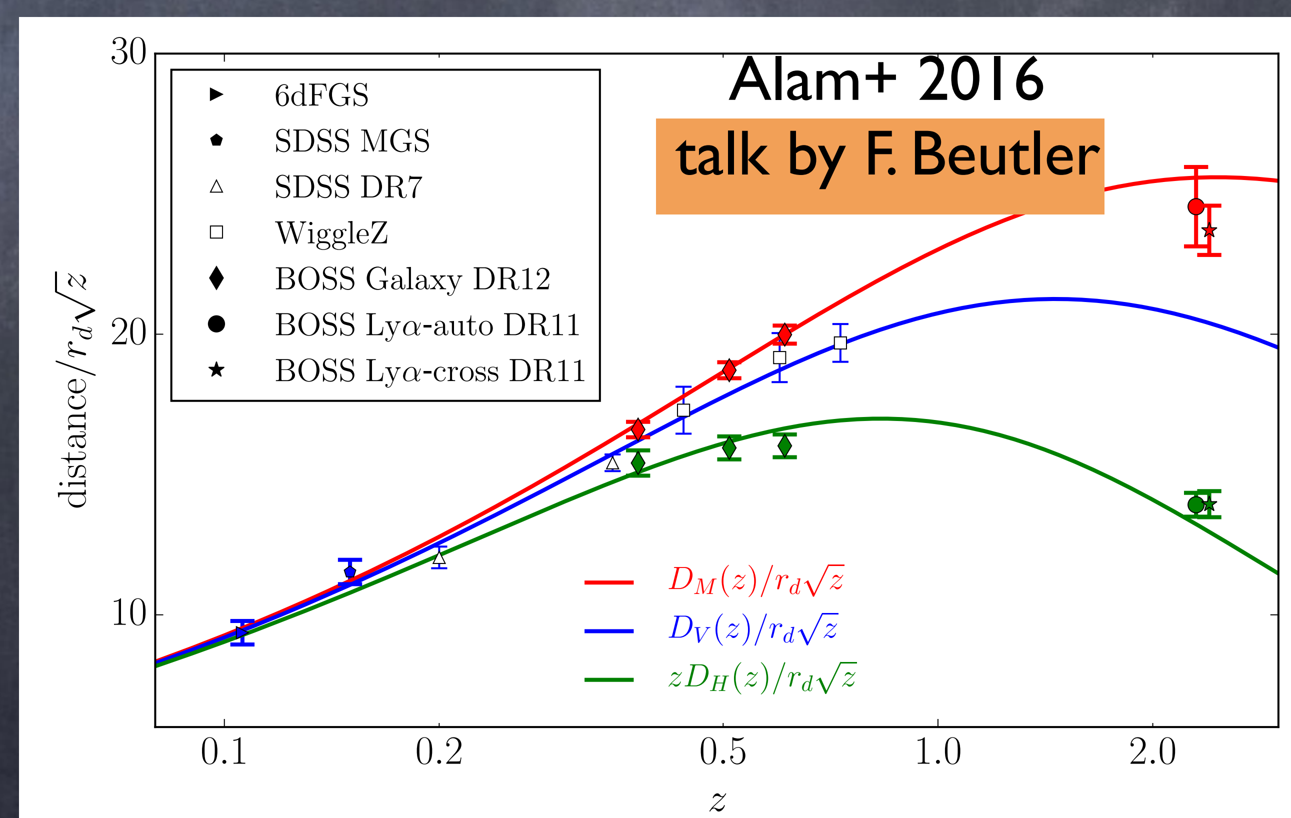
Spectroscopic Dark Energy Surveys



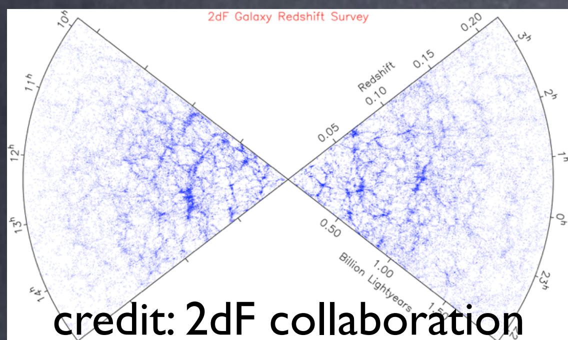
the present: BOSS, WiggleZ, …

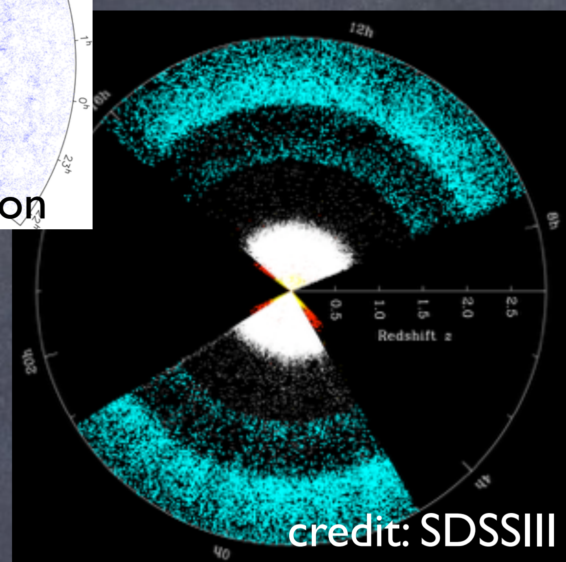
$\mathcal{O}(10^6)$ intermediate-redshift galaxies





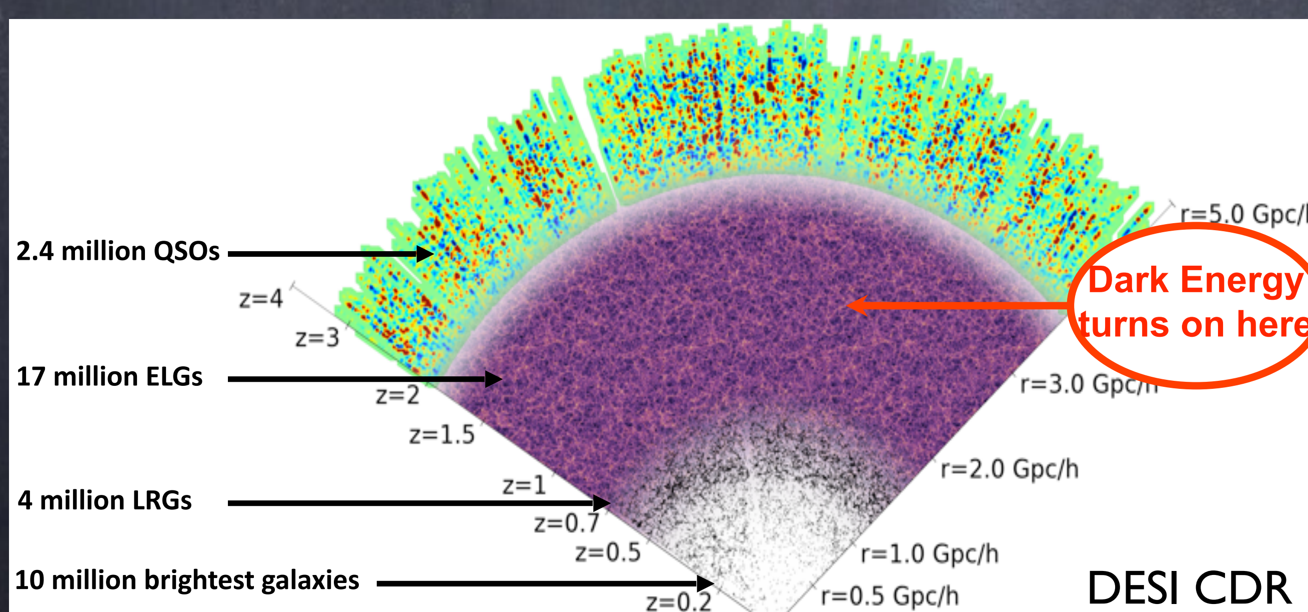
Spectroscopic Dark Energy Surveys

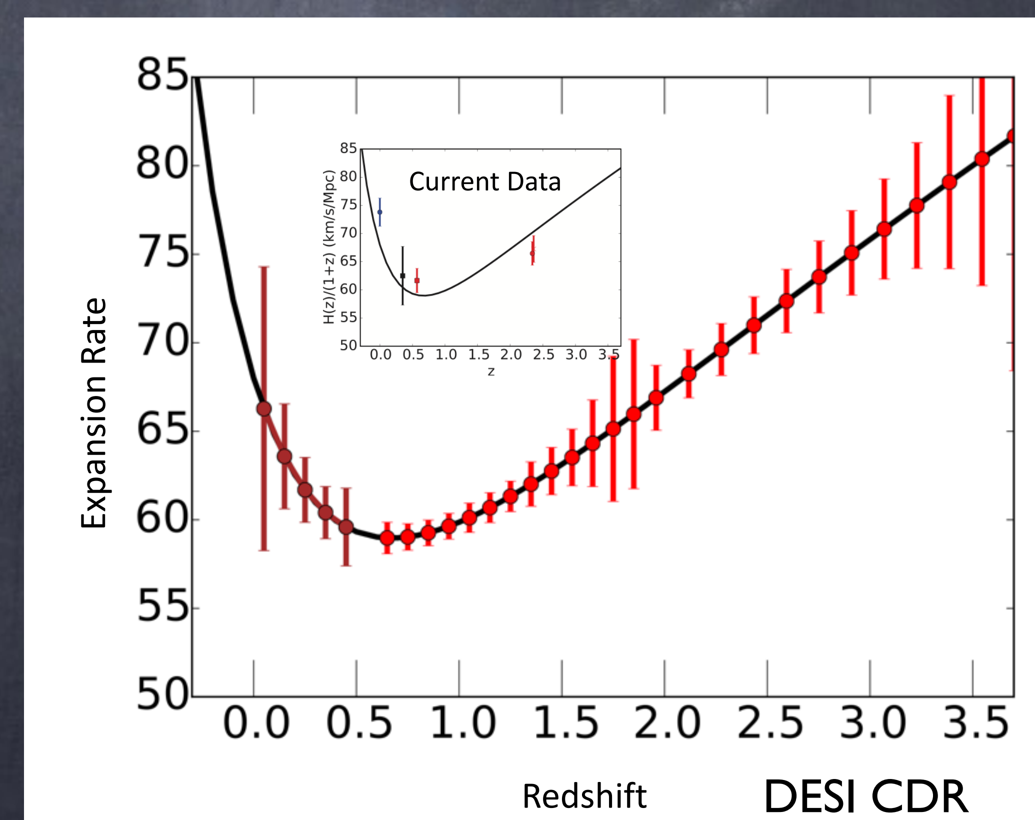




the future: Dark Energy Spectroscopic Instrument (DESI)

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





Cosmological Parameters from SSSI: Prerequisites

SSSI

- ”Stage IV”
  - DESI + 4MOST: broadband multi-tracer RSD power spectra
  - LSST: angular clustering, galaxy clusters, WL, SN, strong lensing
- Precision Cosmology
  - Statistical power needs to be matched by systematics control
  - Overlapping surveys are not independent
- Baseline Forecasts
  - account for cross-covariance between overlapping surveys
  - ~60 nuisance parameter (LSST), ~10/(spectroscopic survey)
  - open w_aCDM cosmology
  - Linearized modified gravity effects using (μ, Σ) parameterization (CosmoLike implementation by Miyatake & Eifler)

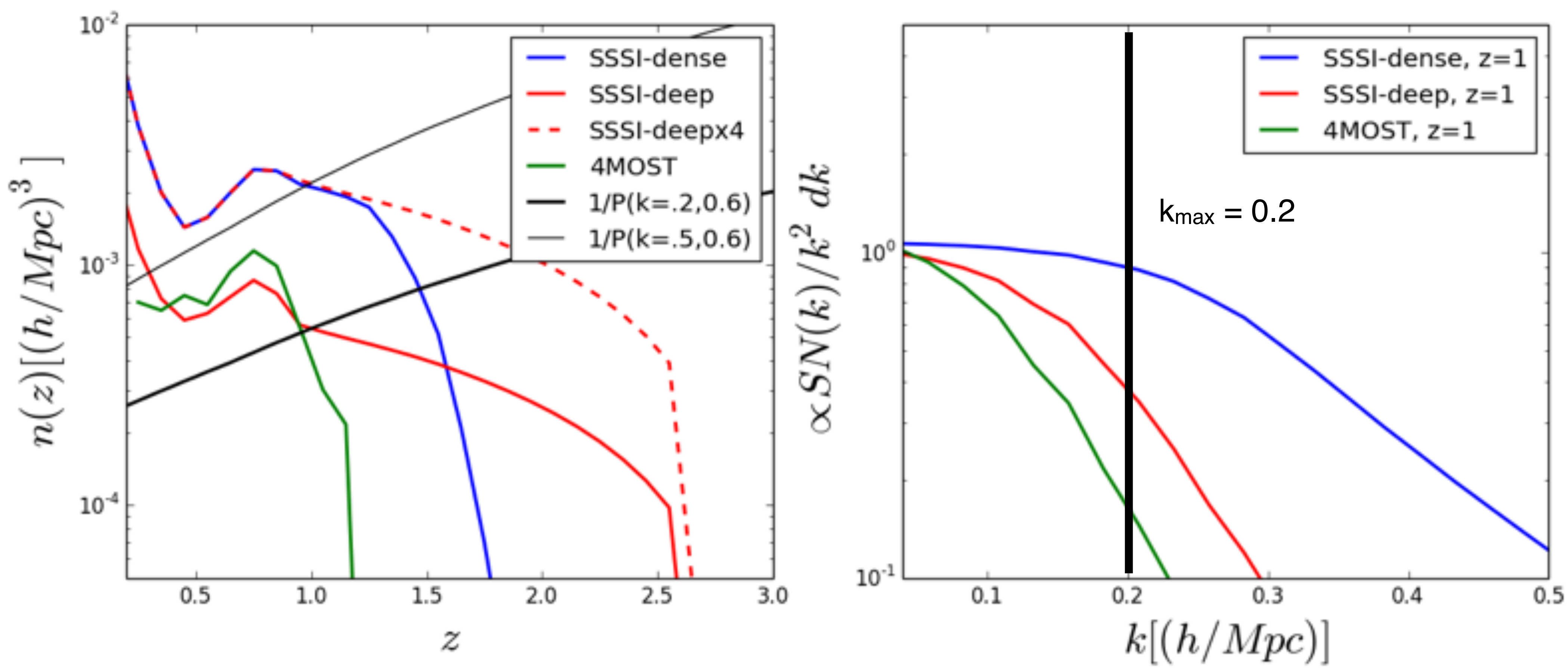
Cosmological Parameters from SSSI: SSSI Modeling

- **SSSI Baseline Scenarios**

  - SSSI-dense: 4xDESI-like density -> better sampling at large k

  - SSSI-deep: DESI-like + high-z sample -> extend redshift baseline

  - multi-tracer analysis with ELG, LRG, QSO samples



- **NB: 4MOST (12K sqdeg) already included in Stage IV forecasts**

Cosmological Parameters from SSSI: Constraints

	Stage IV	+SSSI *dense*, k_{max}=.2	+SSSI *dense*, k_{max}=.5	+SSSI *deep*, k_{max}=.2	+SSSI *deep*, k_{max}=.5	+SSSI *deepx4*, k_{max}=.2	+SSSI *deepx4*, k_{max}=.5
FoM	1089	1486	2430	1425	1972	1697	2860
$\sigma(w_a)$	0.082	0.070	0.050	0.071	0.060	0.062	0.051
$\sigma(\alpha_s)$	0.0028	0.0022	0.0016	0.0022	0.0019	0.0020	0.0013
$\sigma(\mu)$, $\sigma(\Sigma)$	0.019, 0.033	0.014, 0.027	-	0.015, 0.028	-	0.012 0.023	-

- **NB:**
- **Sta**

Cosmological Parameters from SSSI: Implications for Survey Design

SSSI

- **Best constraints from deep + densely sampled survey (deepx4)**
- **For downscaled version, deep or dense sample yield comparable constraining power**
  - **SSSI-dense, *if theory uncertainties can be controlled***
    - SSSI-dense*, to control theory uncertainties*
  - **SSSI-deep provides more leverage on general time dependence**

Cosmology with a ~billion spectra

Deep, wide, dense spectroscopic survey

- Most detailed map of galaxy distribution

  enables splits by environment

  cross-correlation science

- Measure galaxy power spectrum really, really well

  non-linear scales for $z<1.5$

  linear scales for $1.5<z<3.25$

  power spectrum as function of galaxy type

- Unprecedented signal-to-noise in higher-order statistics

Cosmology with a ~billion spectra

- Measure galaxy power spectrum really, really well

  non-linear scales for z<1.5

  linear scales for 1.5<z<3.25

  power spectrum as function of galaxy type

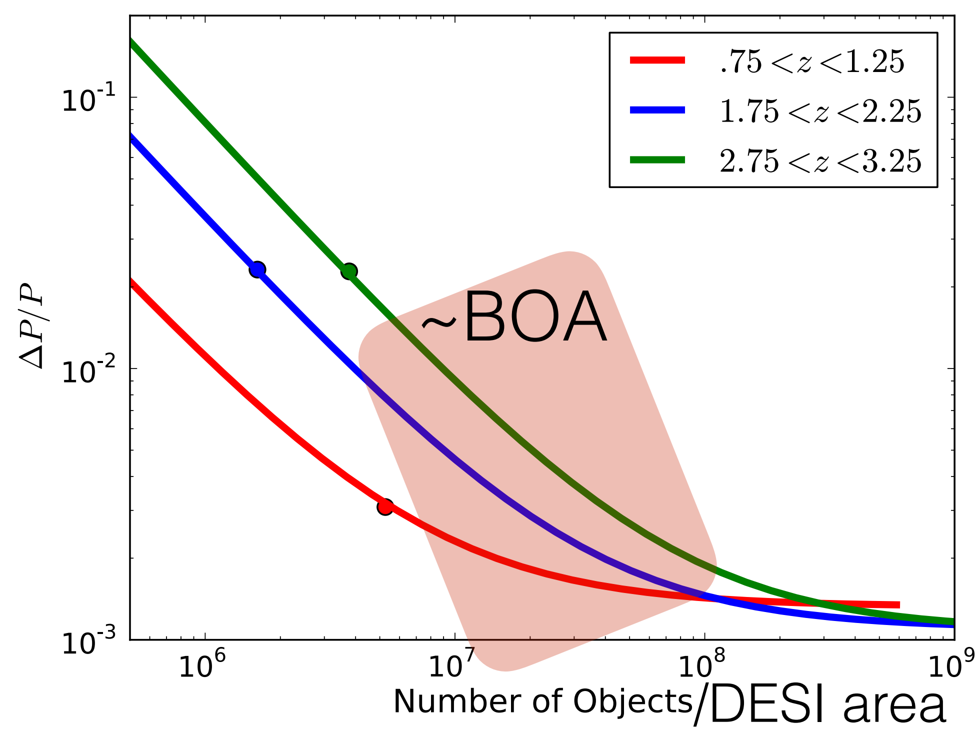


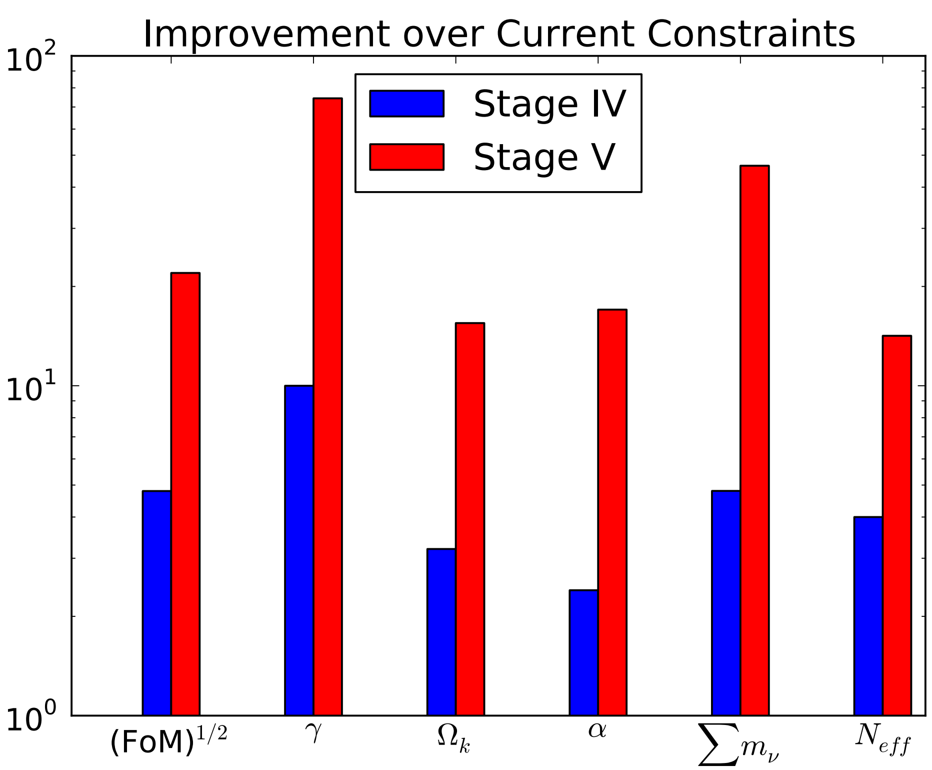
Figure 1. *Fractional error in the power spectrum on linear scales ($k = 0.2hMpc^{-1}$) that quantifies inhomogeneities for various redshifts as a function of the number of objects surveyed. The dots are projections for DESI: at $z = 1$ DESI will be within a factor of 3 of the ultimate error, but at higher redshift, there is at least of factor of ten more information to be mined by future surveys. LSST will measure many more objects but will have imperfect radial information so therefore less effective information per object.*

cosmic visions report

Cosmology with a ~billion spectra

- Cosmology parameters from RSD power spectrum

  lots of information left in the sky



5.4 High Resolution Spectroscopy of a Billion Objects

A most ambitious project would be one that obtained high resolution spectra of a large fraction of LSST objects. Such a *Billion Object Apparatus* (BOA) would come close to attaining the parameter improvements depicted in the right panel of Fig. 1 and open up many avenues for new discoveries. Here we outline some

from cosmic visions report

assumes k_{max} = 0.5 h/Mpc

Cosmology with a ~billion spectra

- Cosmology parameters from RSD power spectrum
- Parameter space may evolve with Stage III, Stage IV results

  -> and with theory developments!
- Requires precise models for BAO scale, galaxy power spectrum to k~0.5 h/Mpc

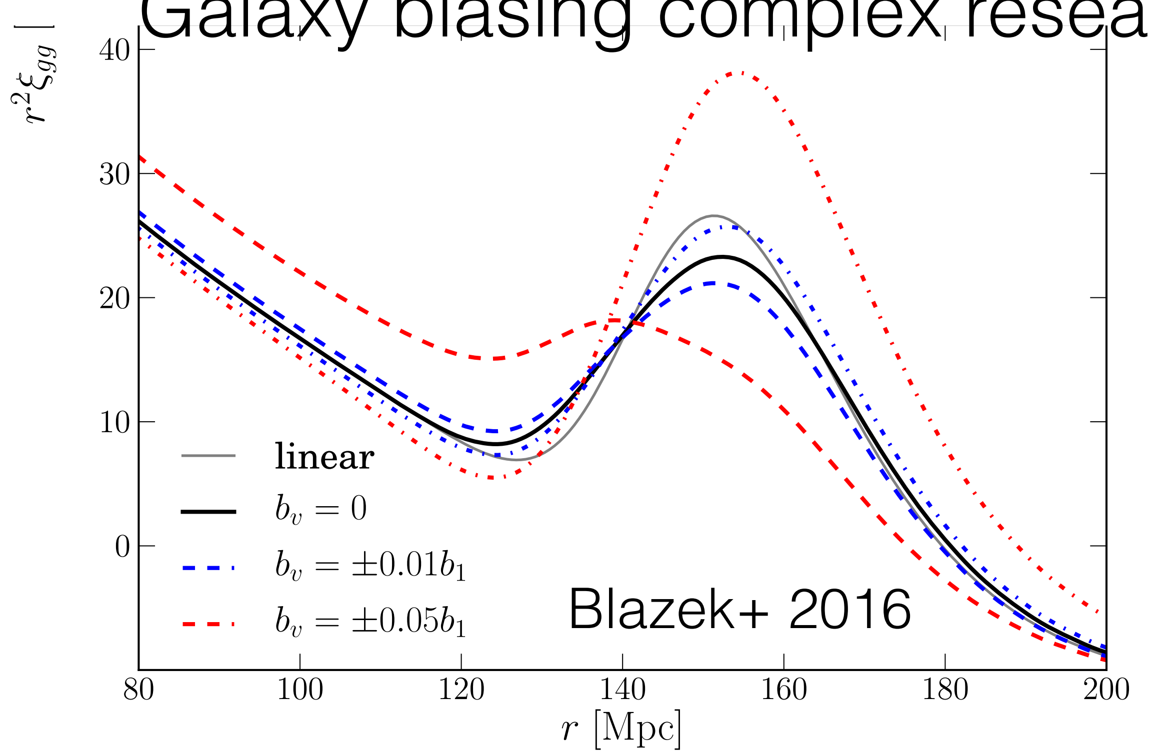
Cosmology with a ~billion spectra

- Cosmology parameters from RSD power spectrum
- Parameter space may evolve with Stage III, Stage IV results

  -> and with theory developments!
- Requires precise models for BAO scale, galaxy power spectrum to k~0.5 h/Mpc

Linear bias won't get us there!

Galaxy biasing complex research area - here's just one example:



Relative velocity effect (Tseliakhovich & Hirata 2010) gives rise to galaxy velocity bias terms, shifts BAO scale (Dalal +2010, Yoo+2011,…)

Cosmology with a ~billion spectra

- Cosmology parameters from RSD power spectrum
- Parameter space may evolve with Stage III, Stage IV results

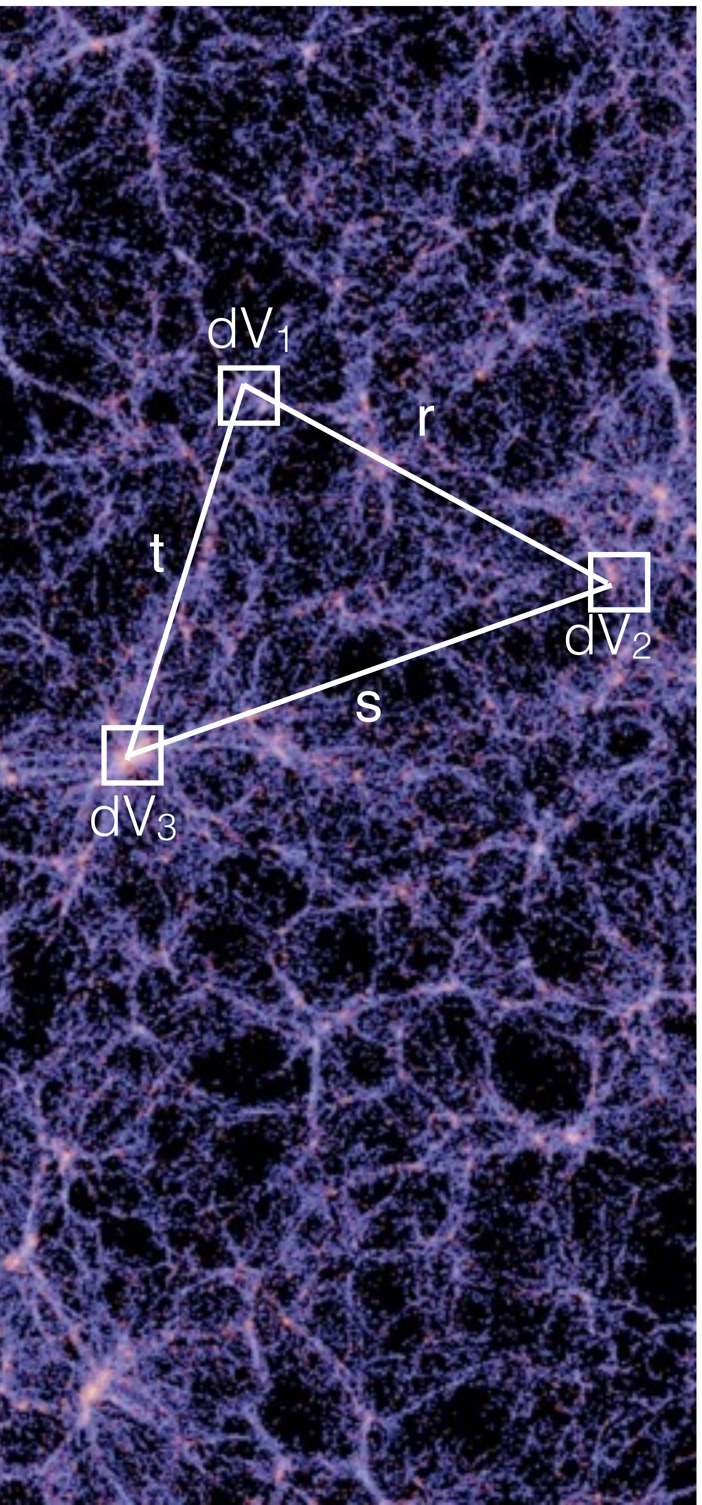
  -> and with theory developments!
- Requires precise models for BAO scale, galaxy power spectrum to k~0.5 h/Mpc
- high number density of BOA enables validation of bias models

  precise P(k) measurements beyond k = 0.5 h/Mpc

  P(k) as function of galaxy type

  Bispectrum, and higher-order statistics

Cosmology with a ~ billion spectra: Bispectrum



- Probability of finding three galaxies at separation (r,s,t) is given by the two, and three point correlation function

$$P_3(r,s,t) = \bar{n}^3 \left(1 + \xi(r) + \xi(s) + \xi(t) + \zeta(r,s,t)\right) dV_1 dV_2 dV_3$$

- B($\mathbf{k_1}$,$\mathbf{k_2}$) is the Fourier transform of **ζ(r,s,t)**,or in terms of density contrast

$$\langle \delta(\mathbf{k}_1)\delta(\mathbf{k}_2)\delta(\mathbf{k}_3)\rangle = (2\pi)^3 B(\mathbf{k}_1,\mathbf{k}_2)\delta^D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)$$

Cosmology with a ~ billion spectra: Bispectrum

- With one billion galaxies, can measure *a lot* of triangles!
- S/N per triangle is low, need suitable bins/data compression
- in cosmic variance limit, cumulative S/N scales as

$$S/N(B) \propto k_{\rm max}^6 P(k_{\rm max}) \approx k_{\rm max}^4$$

- high galaxy density of BOA will enable precision Bispectrum measurements, including multi-tracer Bispectra!
- (S/N in projected Bispectra much lower, need spectra)

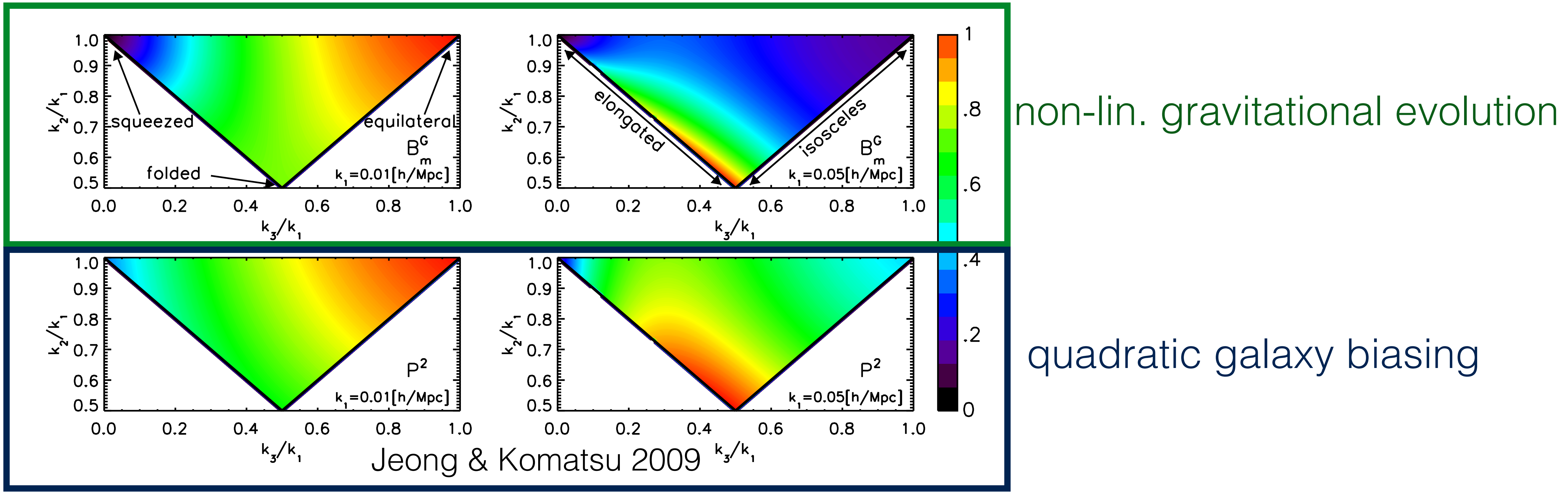
Cosmology with a ~ billion spectra: Bispectrum

- A toy model bispectrum

$$B_g(k_1,k_2,k_3) = b_1^3 B_m(k_1,k_2,k_3)$$ **non-lin. gravitational evolution**

$$+b_1^2 b_2\left[P_m(k_1)P_m(k_2) + (2\,\text{cyclic})\right]$$ **quadratic galaxy biasing**

$$+b_1^3\,(\text{primordial Bispectrum})$$ **inflation**



Jeong & Komatsu 2009

Cosmology with a ~ billion spectra: Bispectrum

Test galaxy bias models through configuration dependence of contributions to galaxy Bispectrum

- e.g., relative velocity bias (earlier example)
  - Yoo+11, Slepian+15 predicted configuration dependence
  - Slepian+ 2016: $b_v < 0.01$ from CMASS 3pt function
- BOA Bispectra will constrain Stage V bias models

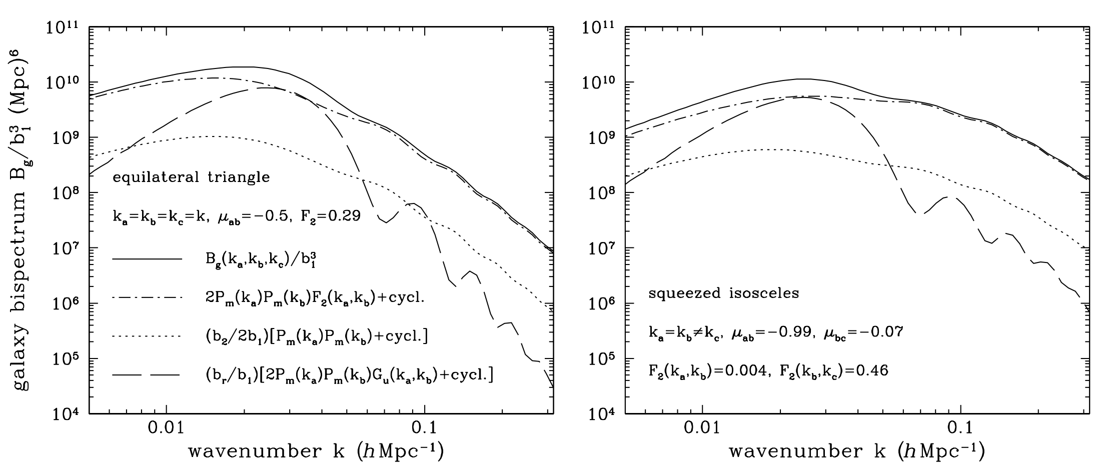


Figure 3. Scale-dependence of the full galaxy bispectrum for two triangular shapes. Three different components contribute to the full galaxy bispectrum in eq. (3.10): The nonlinear evolution of the matter density distribution (dot-dashed), the nonlinear bias (dotted), and the relative velocity effect (dashed). The cubic term in eq. (3.10) is omitted to avoid clutter. The full galaxy bispectrum is shown as solid lines. The bias parameters $b_2/b_1 = 0.1$ and $b_r/b_1 = 0.01$ are assumed.

Yoo, Dalal & Seljak 2011

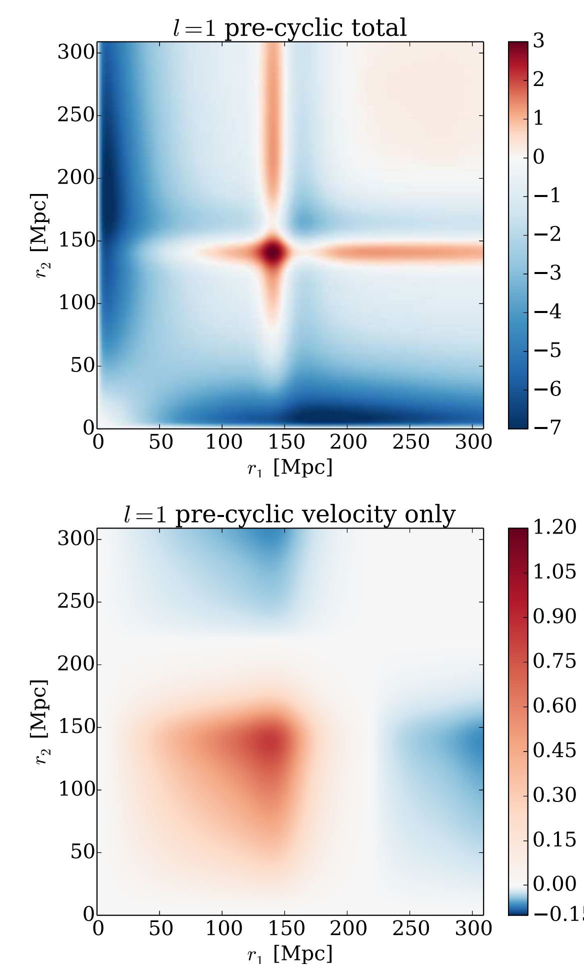


Figure 8. The top panel shows the P_1 coefficient with $b_v = 0$ (equation (53)). The middle panel shows the total P_1 coefficient with velocity term included. The bottom panel shows the P_1 coefficient due to b_v alone. Note that the relative velocity subtly enhances the number of triangles with two sides $\sim r_s$ by carefully comparing the top two panels; this is made clear in the bottom panel. We have used $b_1 = 1, b_2 = 0.1, b_v = 0.01$ and weighted by $r_1^2 r_2^2/10^4$ Mpc^4.

Slepian & Eisenstein 2015

Cosmology with a ~ billion spectra: Bispectrum

$$B_g(k_1,k_2,k_3) = b_1^3 B_m(k_1,k_2,k_3)$$ **non-lin. gravitational evolution**

$$+b_1^2 b_2 \left[P_m(k_1)P_m(k_2) + (2\,\text{cyclic})\right]$$ **quadratic galaxy biasing**

$$+b_1^3\,(\text{primordial Bispectrum})$$ **inflation**

- High S/N Bispectra may uncover new physics
  - Measuring amplitude of primordial non-Gaussianity templates will distinguish between single/multi-field inflation, constrain slow roll

    $\sigma(f_{\rm NL}^{\rm local}) < 1$ <- driven by scale-dep. bias, z< 1.5

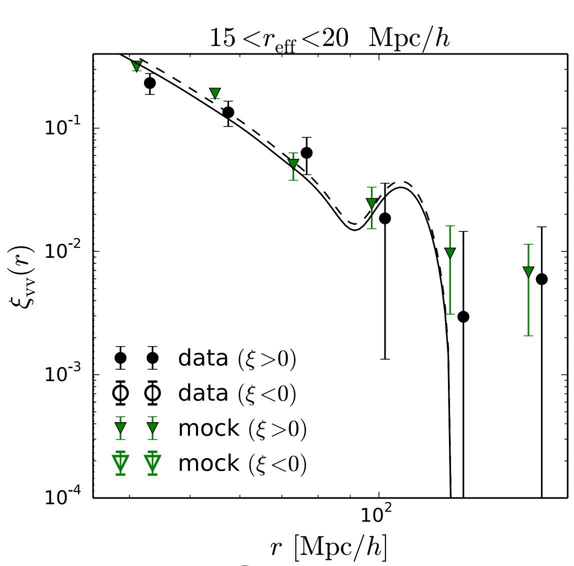
    $\sigma(f_{\rm NL}^{\rm equal}) \sim \text{a few}$ <- driven by high-z coverage

    $\sigma(f_{\rm NL}^{\rm orth}) \sim \text{a few}$

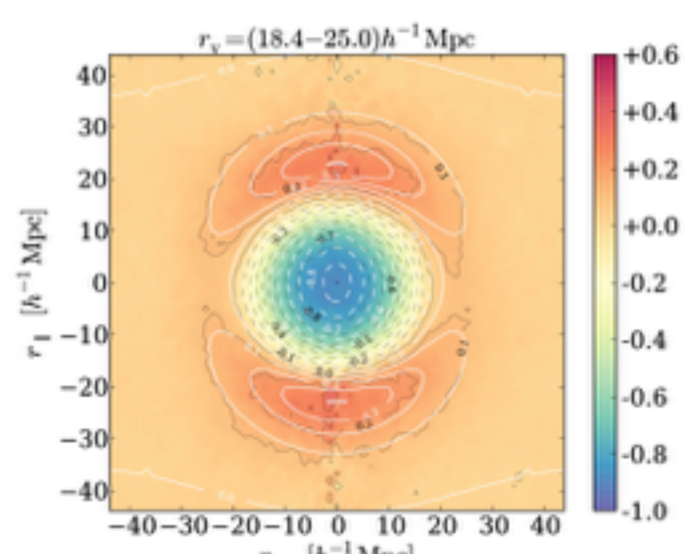
    preliminary!
  - Anisotropic non-Gaussianity, search for features -> Cora's talk
  - Plenty of room, *and S/N*, for new ideas :)

Cosmology with a ~ billion spectra: Void Cosmology

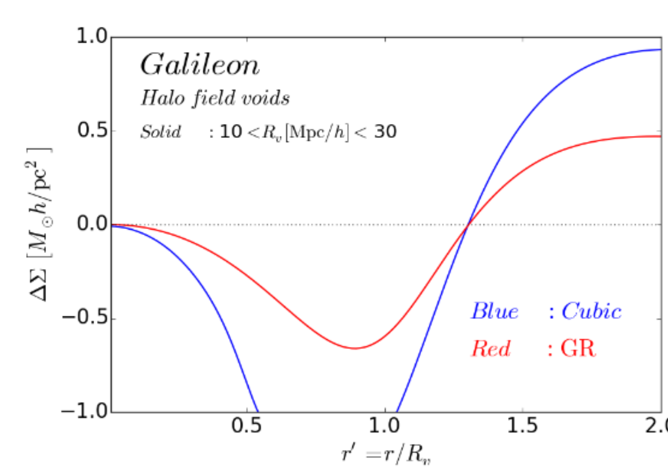
- Voids enable tests of GR in lowest density environment
- Finding voids requires high-density spectroscopic galaxy catalog
- rapidly developing cosmological probe
    - recent measurements of void clustering(Clampitt+2016), velocity field around voids (Hamaus+2015,2016), void lensing (Melchior +2015, Clampitt+2015, Gruen+2016)
    - much recent progress on models+phenomenology, but concrete parameter space needs more development



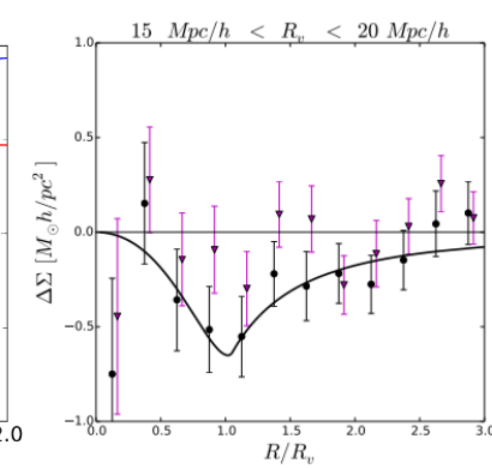
Clampitt+2016



Hamaus+2015



Barreira+2015



Clampitt+2015

Cosmology with a ~ billion spectra

- Parameters from Galaxy Power Spectrum

  lots of information left in the power spectrum

  need to understand galaxies really, really well

- Bispectrum, and higher-order statistics

  galaxy bias, new physics

- Tests of GR, enabled by high galaxy density
  - void cosmology
  - screening tests -> Phil Bull's (morning) talk

Theorists, please join the spectroscopy discussion