Cosmography with Galaxy Clusters
Shedding light on Dark Energy

Reinaldo R. de Carvalho (VST-Cen & INPE)

Francesco La Barbera (OAC/Italy)
Scott Dodelson (Fermilab/US)
Andre Ribeiro (Fermilab/US)
Marcelle Santos (Fermilab/US)
Roy Gal (Univ. of Hawaii/US)

Massimo Capaccioli (VST-Cen/Italy)
Lori Lubin (UC Davis/US)
Paulo Lopes (Univap/Brazil)
João Kohl (ON/Brazil)
Hugo Capelato (INPE/Brazil)

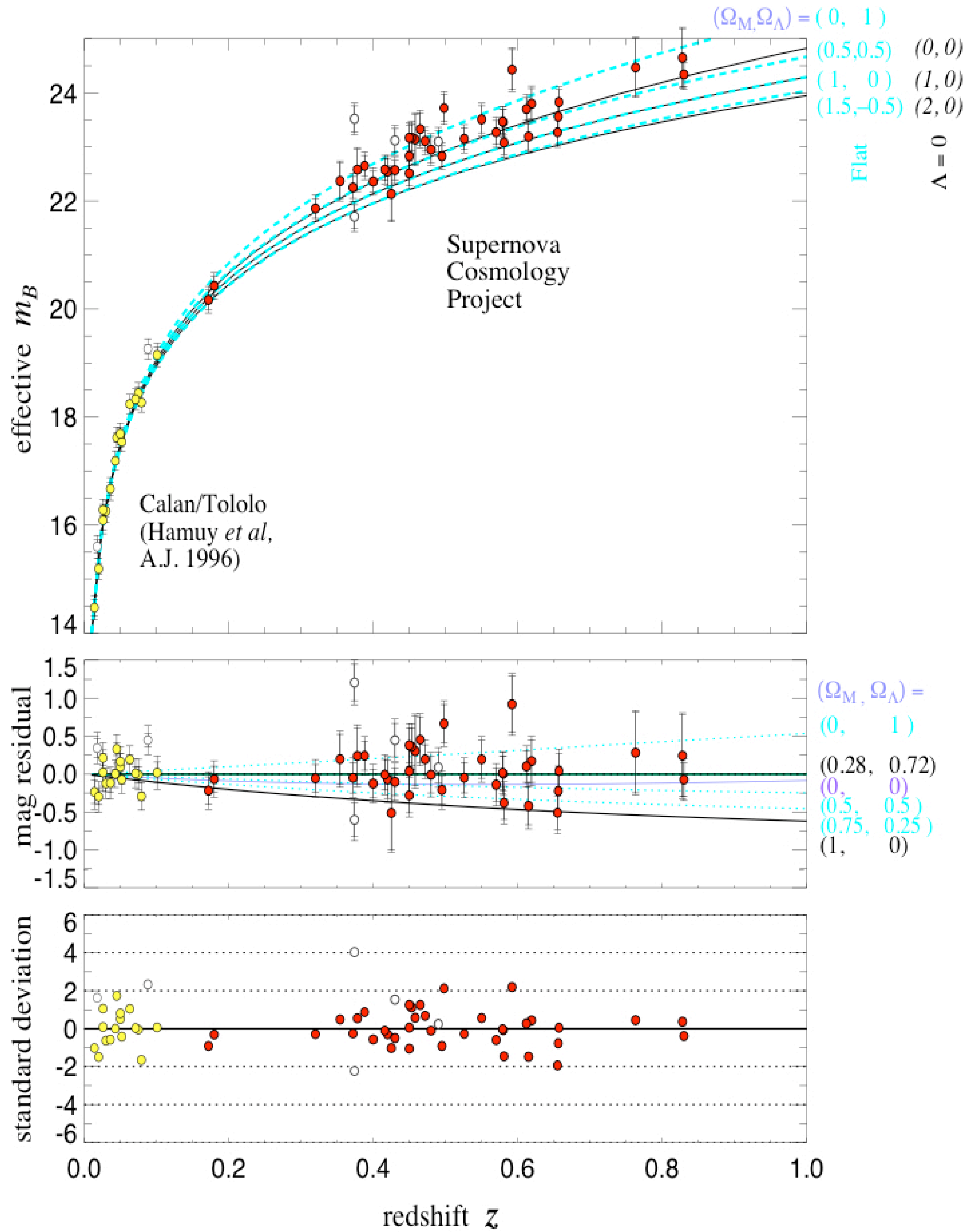
* - University of Naples is joining the project

Clusters of Galaxies

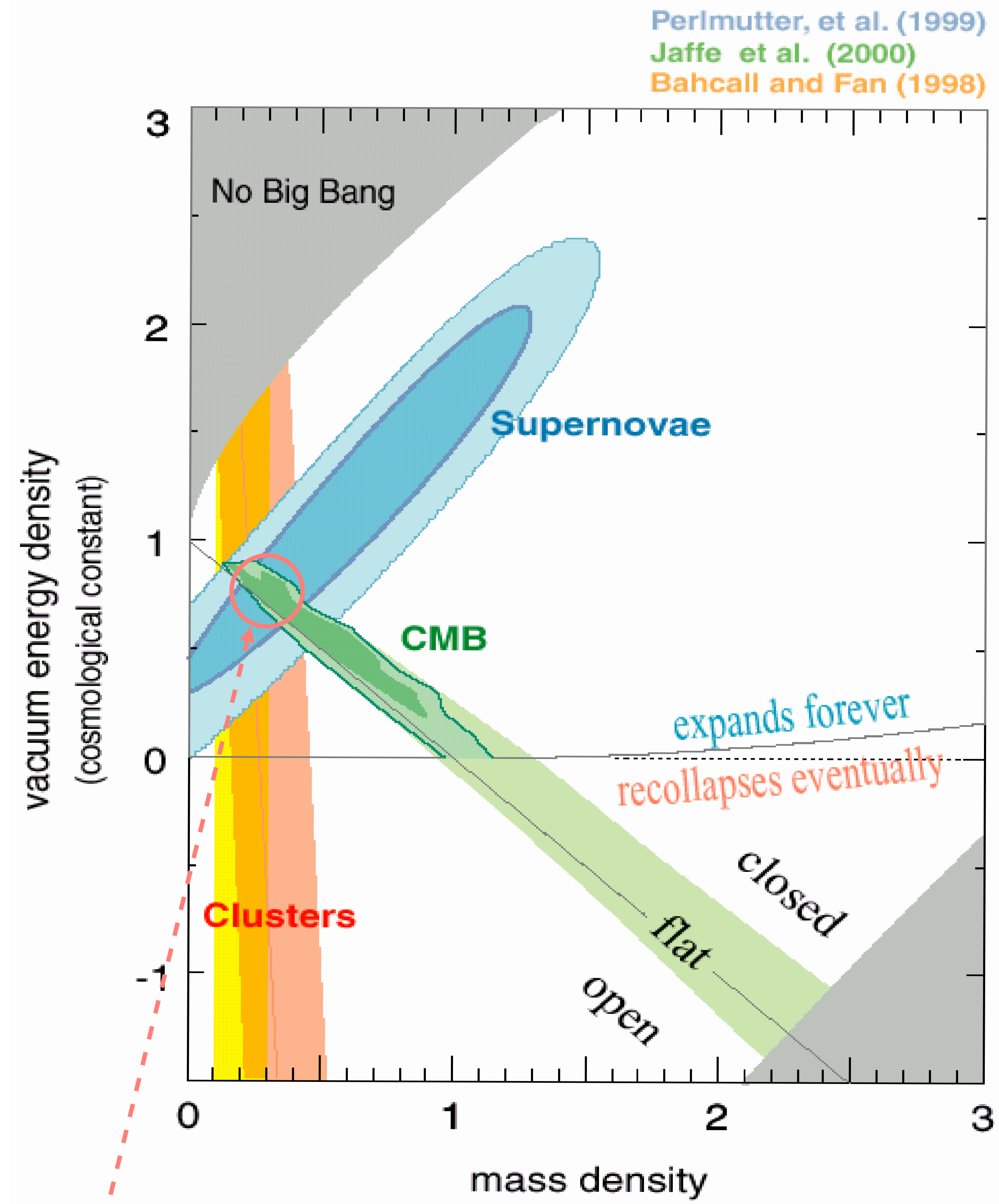
↓

Dark Energy

Supernovae indicating an accelerating expansion



Perlmutter, *et al.* (1998)



We are here:

$\Omega_\Lambda \approx 0.7 \quad \Omega_m \approx 0.3$

Key Issues

1. Is there Dark Energy?

   Will the SNe results hold up?

2. What is the nature of the Dark Energy?

   Is it Λ or something else?

3. How does $w = p_X/\rho_X$ evolve?

   Dark Energy dynamics

The implications of Dark Energy are so important that the SNe Ia results must be confirmed by multiple independent methods with:

*** different systematic errors**
*** different cosmological parameter degeneracies**

Measurements of Dark Energy

Some Basic Approaches:

Cluster counting

- X-ray selection: Flux limited
- SZ surveys: redshift independence
- Lensing surveys: clean mass selection?
- **Optical surveys (!)**

Structure Formation

- Weak lensing power spectrum

Angular diameter distance

- Strong lensing statistics

Luminosity distance

- Type Ia SNe

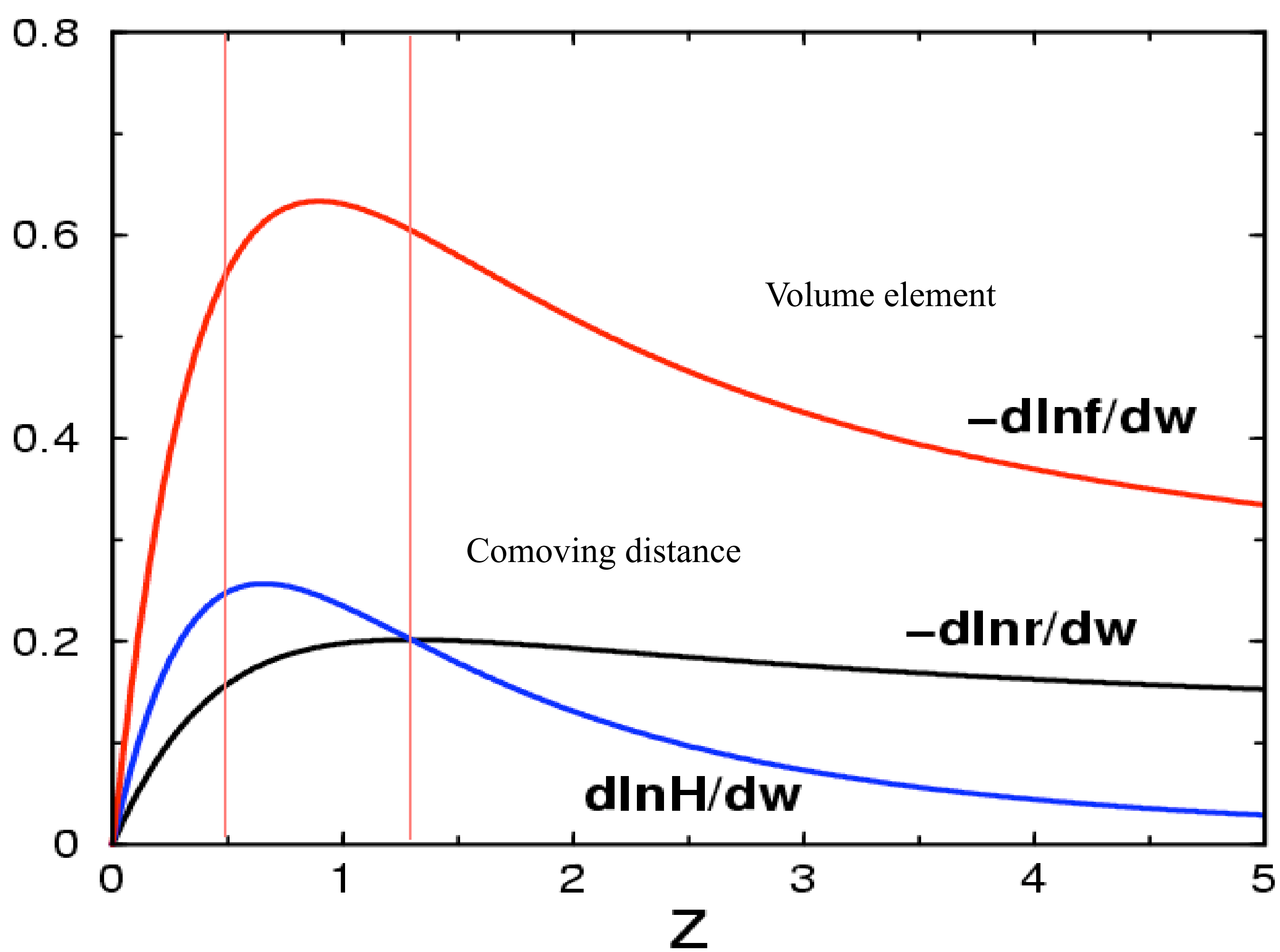
Sensitivity to Dark Energy equation of state

$$H^2 = \frac{8\pi G}{3}(\rho_M + \rho_X)$$

$$H(z)^2 = H_0^2 \left[\Omega_M (1+z)^3 + \Omega_X \exp[3\int_0^z (1+w(x))d\ln(1+x)]\right]$$

$$r(z) = \int_0^z \frac{dx}{H(x)}\,.$$

$$f(z) \equiv \frac{dV}{dz d\Omega} = r^2(z)/H(z)\,.$$



$$\frac{dr(z)}{dw} = -\frac{3}{2}\int_0^z \frac{\Omega_X H_0^2 (1+x)^{3(1+w)} \ln(1+x)\,dx}{H^3(x)}$$

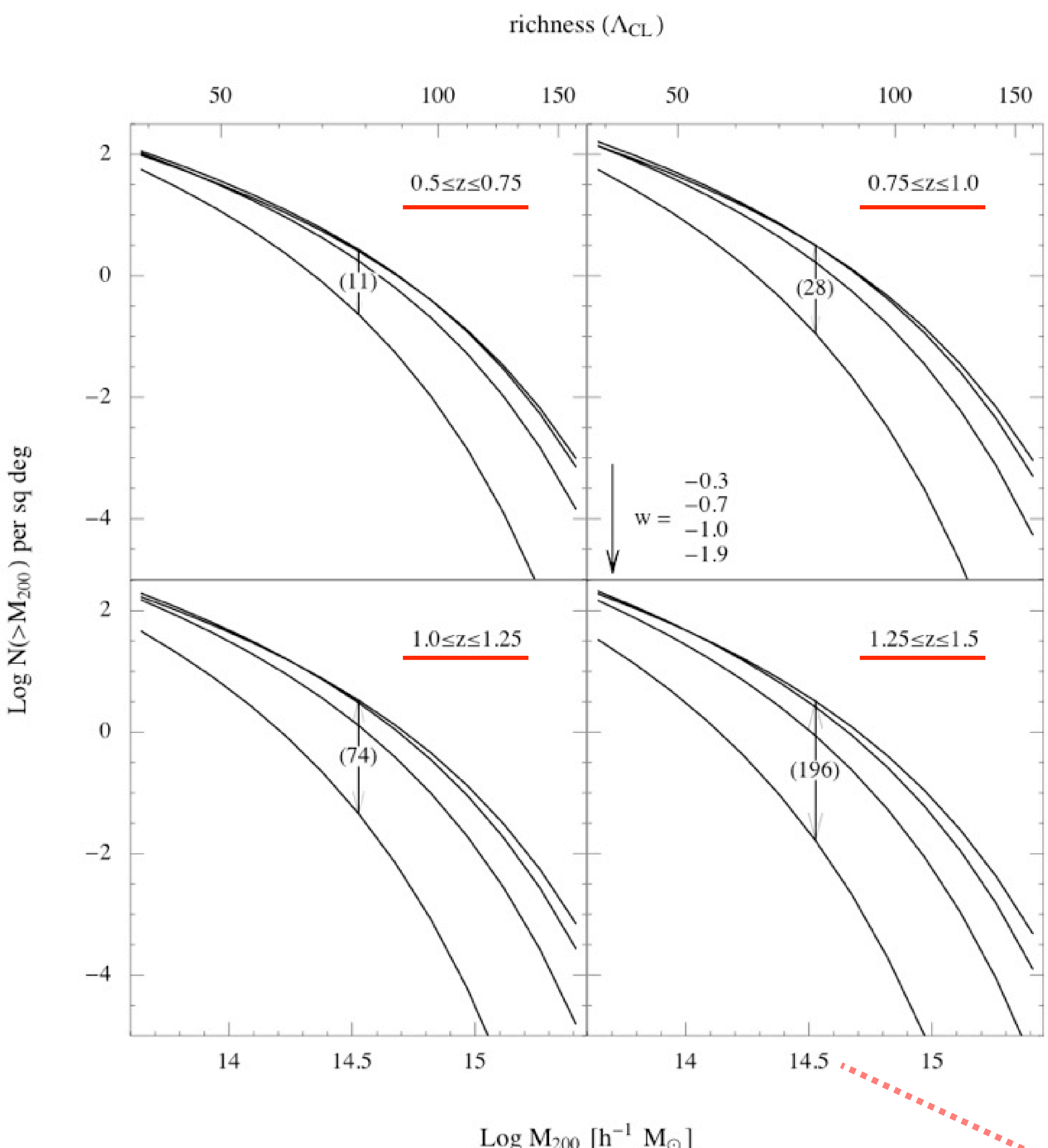
$$\frac{df(z)}{dw} = \frac{2r(z)}{H(z)}\frac{dr}{dw} - \frac{r(z)^2}{H(z)^2}\frac{dH}{dw}$$

$$\frac{dH(z)}{dw} = \frac{3}{2}\frac{\Omega_X H_0^2 (1+z)^{3(1+w)} \ln(1+z)}{H(z)}$$

Huterer & Turner 2001

Dark Energy

Cluster counting



800 Km/s

Munshi et al. (2004) measured N(>M) in the context of the PS formalism

$$\frac{dn}{dM}(z,M) = \sqrt{\frac{2}{\pi}}\frac{\rho_M}{M}\frac{\delta_c}{\sigma(M,z)^2}\frac{d\sigma(M,z)}{dM}\exp\left(-\frac{\delta_c^2}{2\sigma(M,z)^2}\right) \quad (4)$$

where $\sigma(M,z)$ is the rms density fluctuation on mass-scale M evaluated at redshift z and computed using linear theory, ρ_M is the present-day matter density, and $\delta_c \approx 1.68$ is the linear threshold overdensity for collapse.

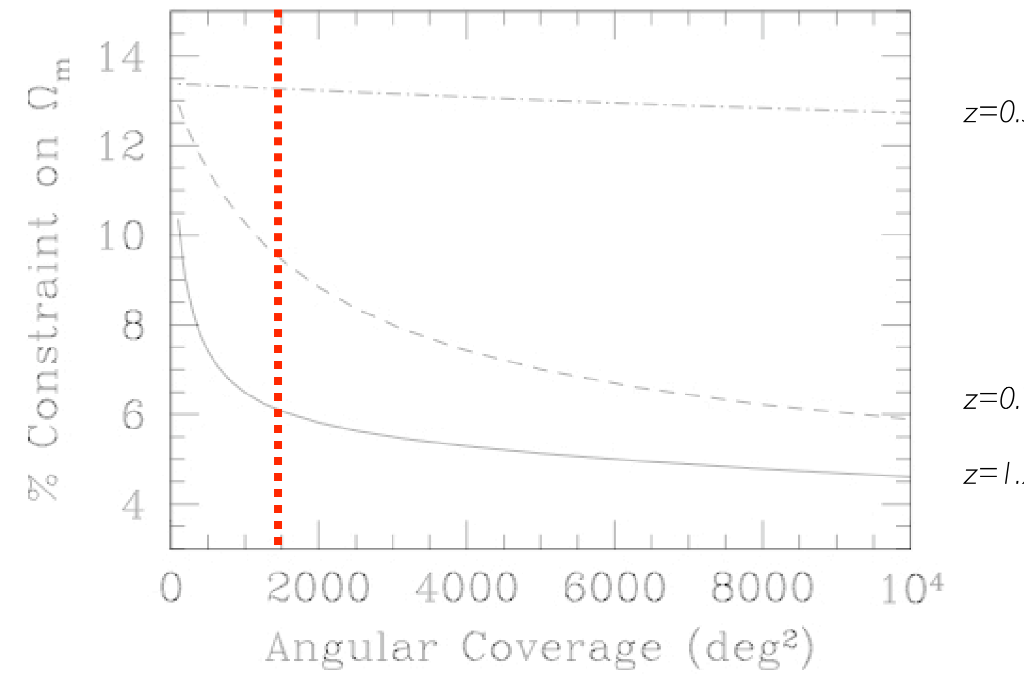
Soares-Santos et al (2008) used Sheth & Thormen (1999)

Dark Energy is not strongly affected by different expressions for the cluster mass function (Sheth & Thormen 1999; Jenkins et al. 2001).

Dark Energy

Cluster counting

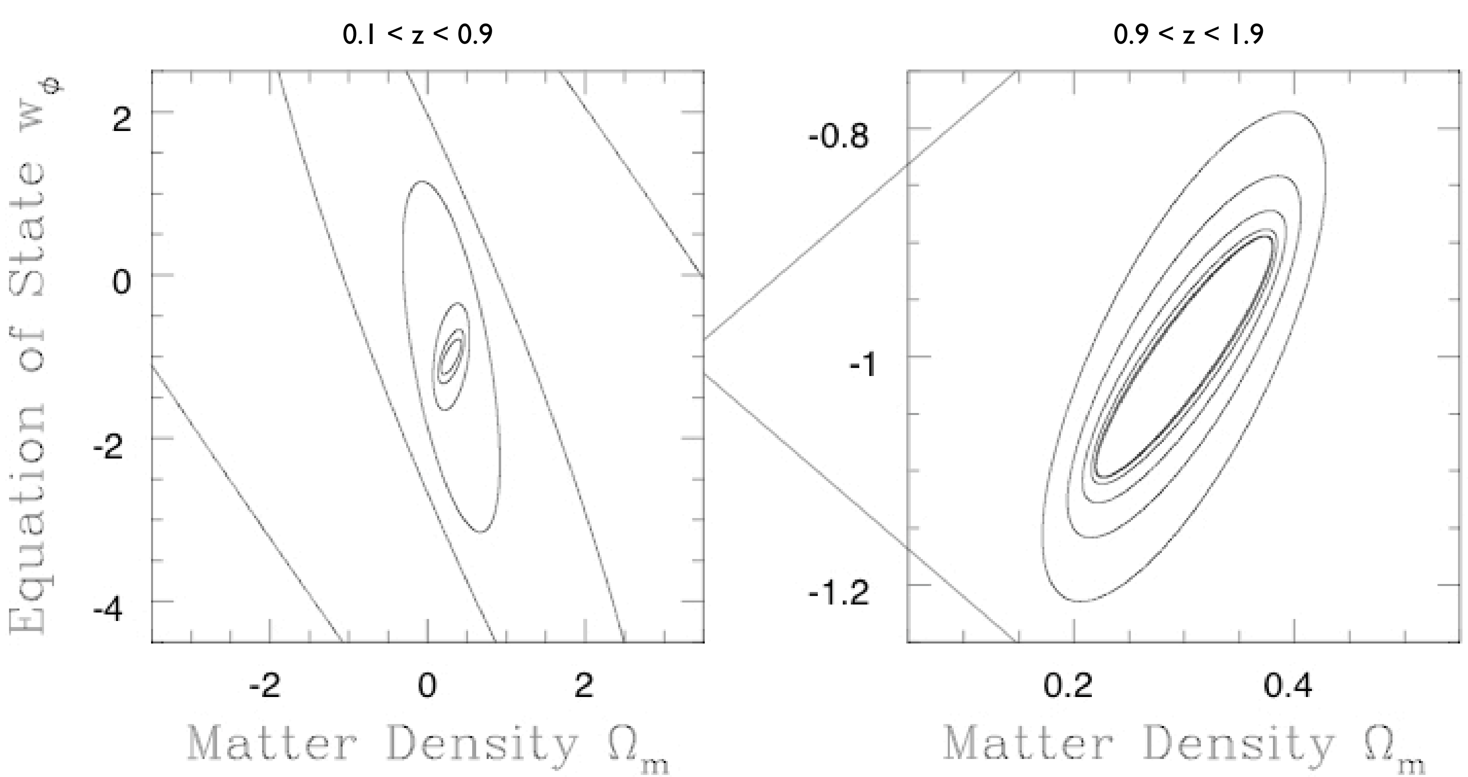
How large should be the area covered ?



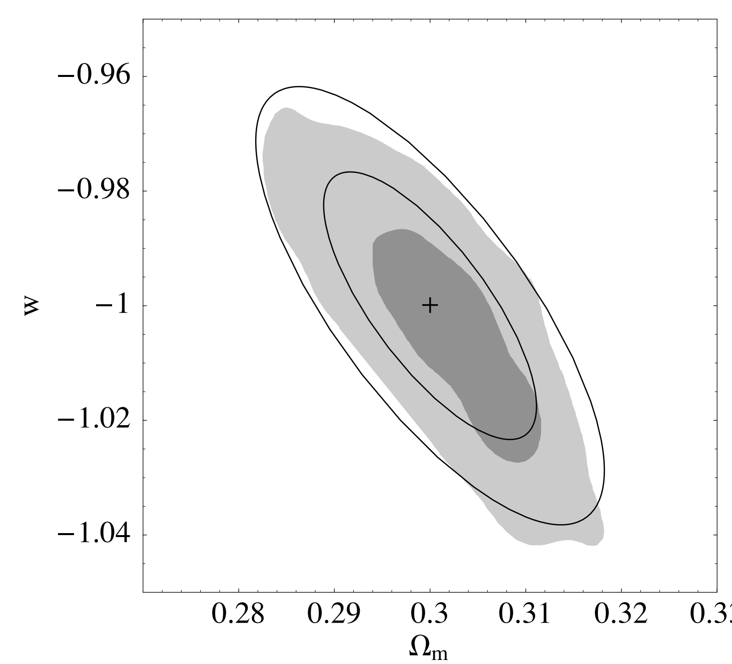
Levine et al (2002)

How well can we constrain ***w*** ?

Levine et al (2002) - over 1000□



Soares-Santos et al (2008) over 1500□



Dark Energy

Cluster counting

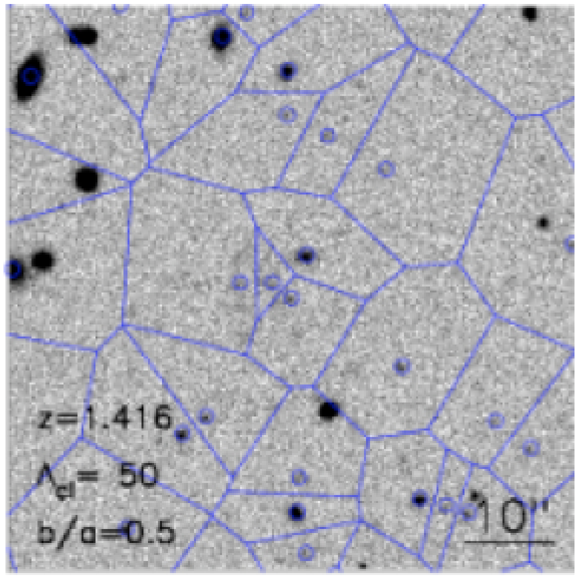
Detecting Clusters with Voronoi-Tesselation (Ramella et al. 2001)

-does not distribute the data in bins

-does not assume a particular source geometry intrinsic to the detection process

is sensitive to irregular and elongated clusters

-the area of the cell is the area a galaxy occupies in the plane



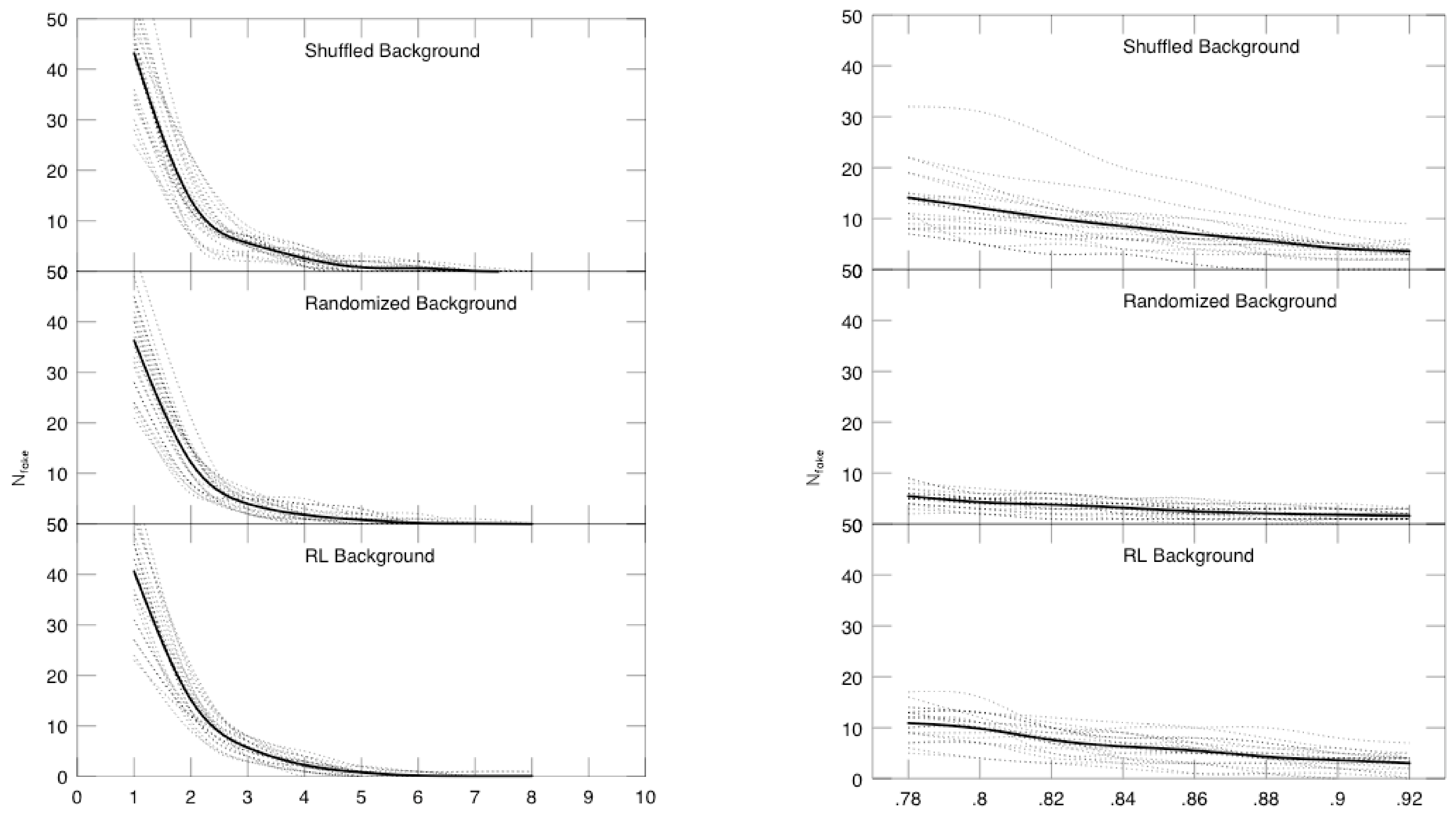
-clusters are identified at high-density regions composed by small adjacent cells

How do we set VT to search for clusters ?

Dark Energy

Cluster counting

- Density Threshold - search confidence level (scl)
- The probability that an overdensity is a random fluctuation (Kiang 1996) - rejection confidence level (rcl)



Nmin

scl

Cluster counting

Algorithm

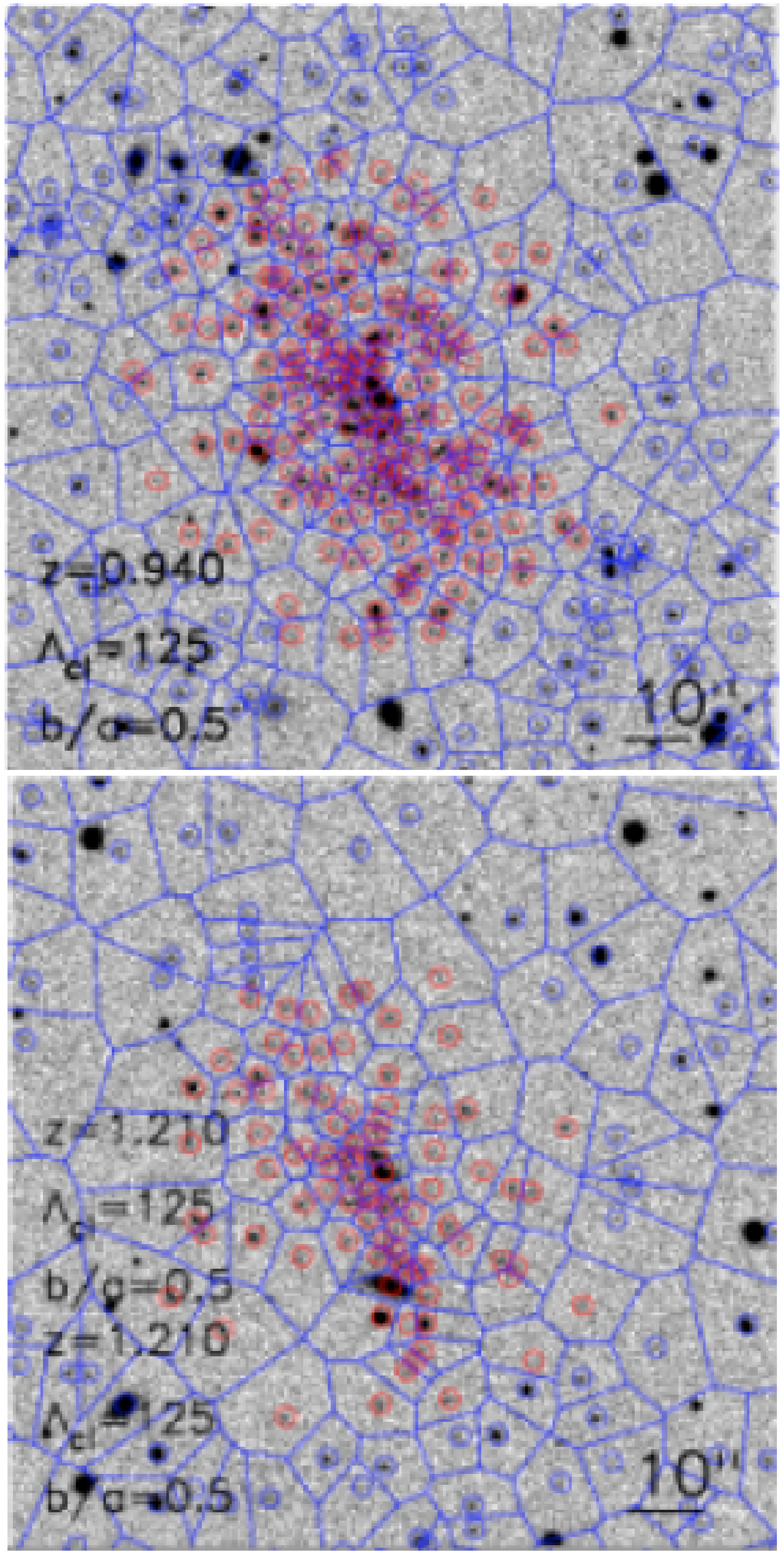
(i) The galaxy catalog is divided into different magnitude bins, starting at the bright limit of the sample and shifting to progressively fainter bins. The step size adopted is derived from the photometric errors of the catalog.

(ii) The VT code is run using the galaxy catalog for each bin. Hence, each magnitude slice will have a catalog of cluster candidates associated with it.

(iii) The centroid of a cluster candidate detected in different bins will change due to the statistical noise of the foreground/background galaxy distribution. Thus, the cluster catalogs from all bins are cross-matched, and overdensities are merged according to a given criteria

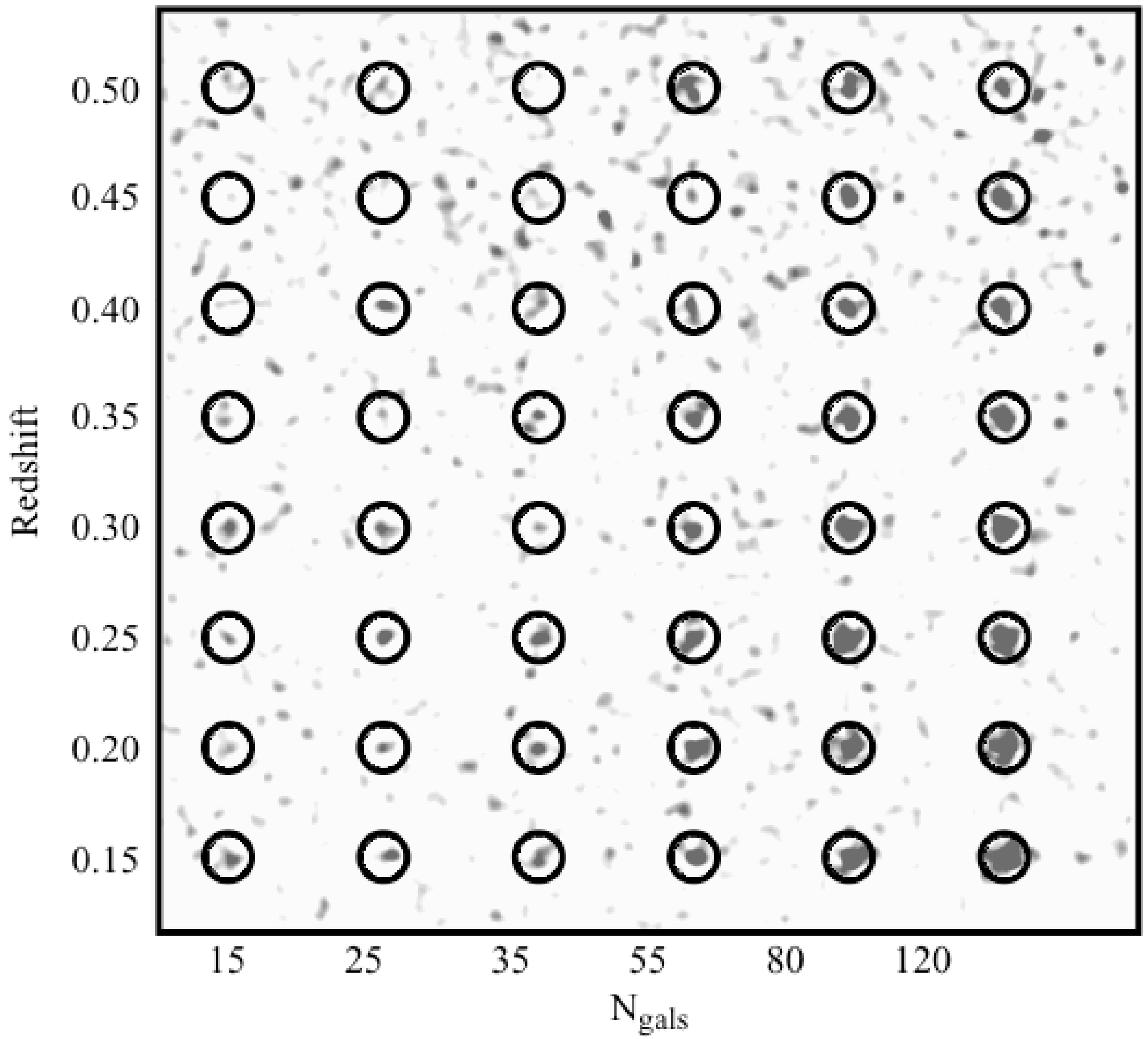
(iv) A minimum number (N_{min}) of detections in different bins is required in order to consider a given fluctuation as a cluster candidate. N_{min} acts as a final threshold for the whole procedure. After this step, the final cluster catalog is complete.

⇨ scl, rcl, and Nmin

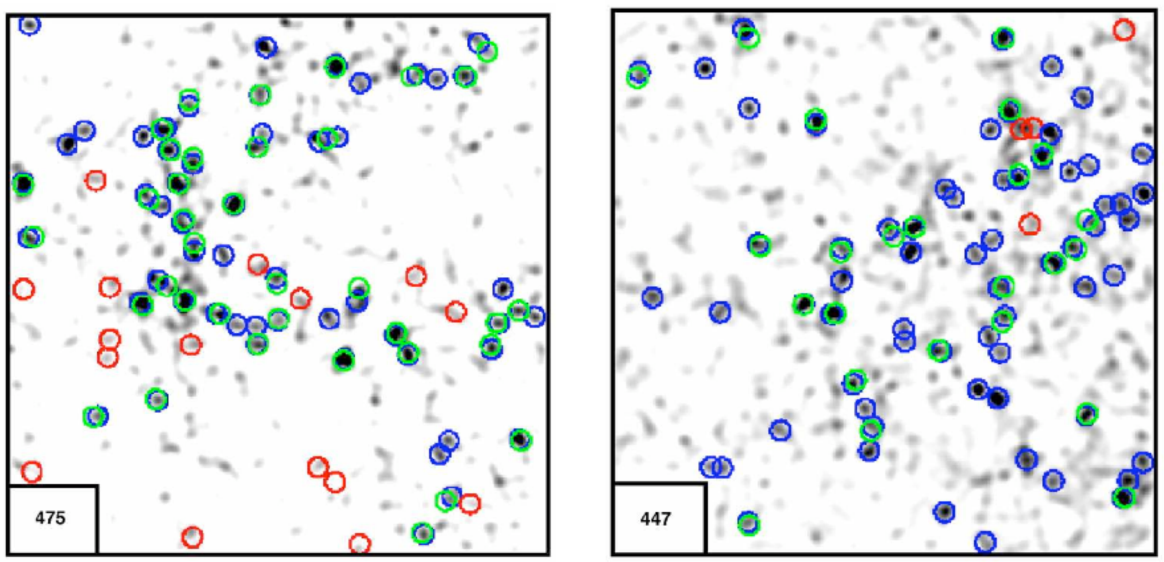


Cluster counting

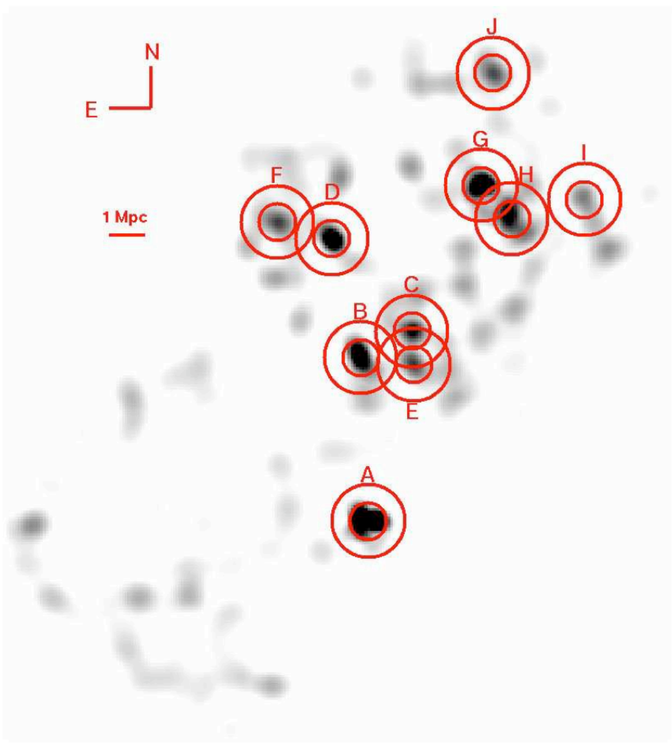
Adaptive Kernel - Gal et al. (2005)



Kernel size is set by simulations



Spectroscopy - clusters with Ngal > 30 & 0.07<z<0.20 shows how successful the method is

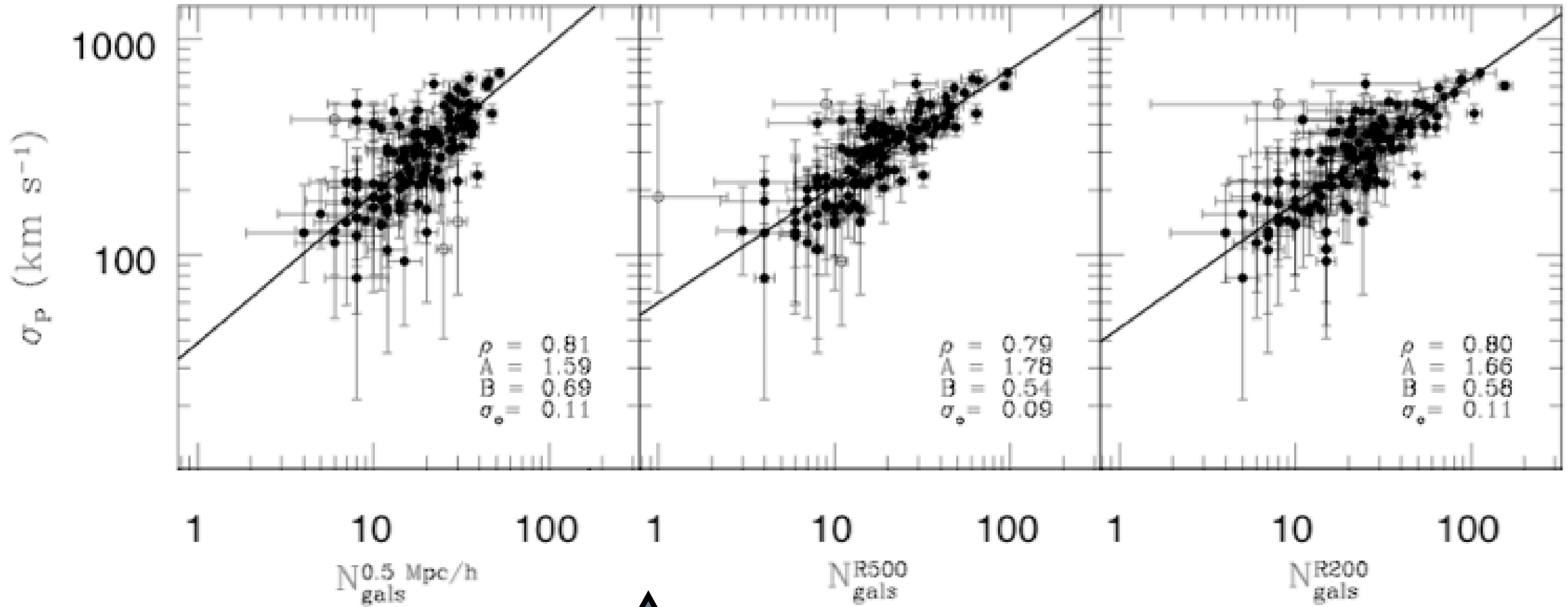


Spectroscopy - clusters with 0.7<z<1.20 selected by colors (r-i). Very successful at high-z as well.

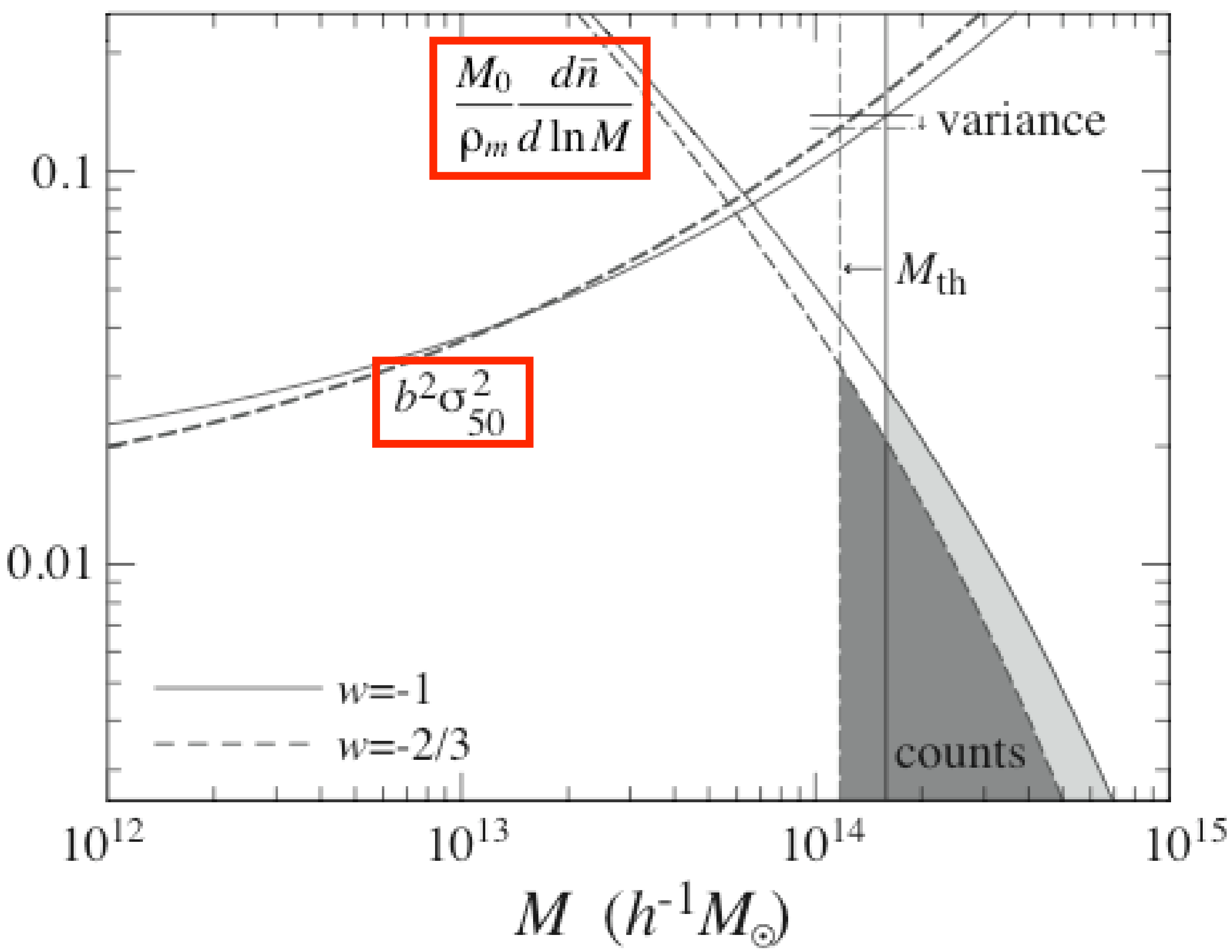
Dark Energy

Cluster counting Lopes et al. 2006,2008

Self calibration

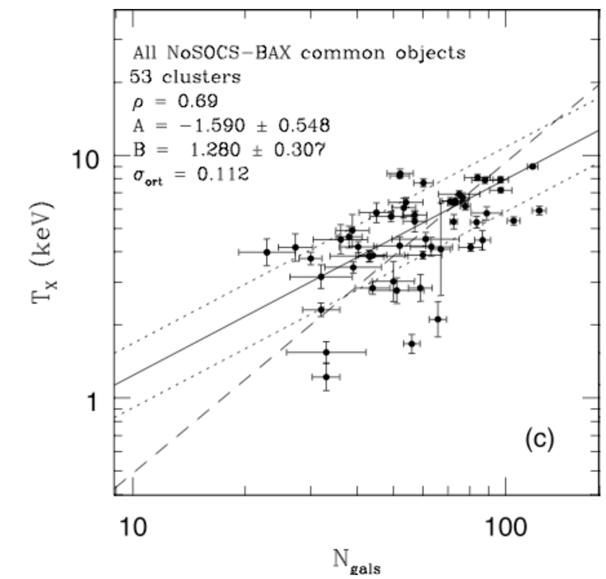


Mass - Observable



high-z

low-z



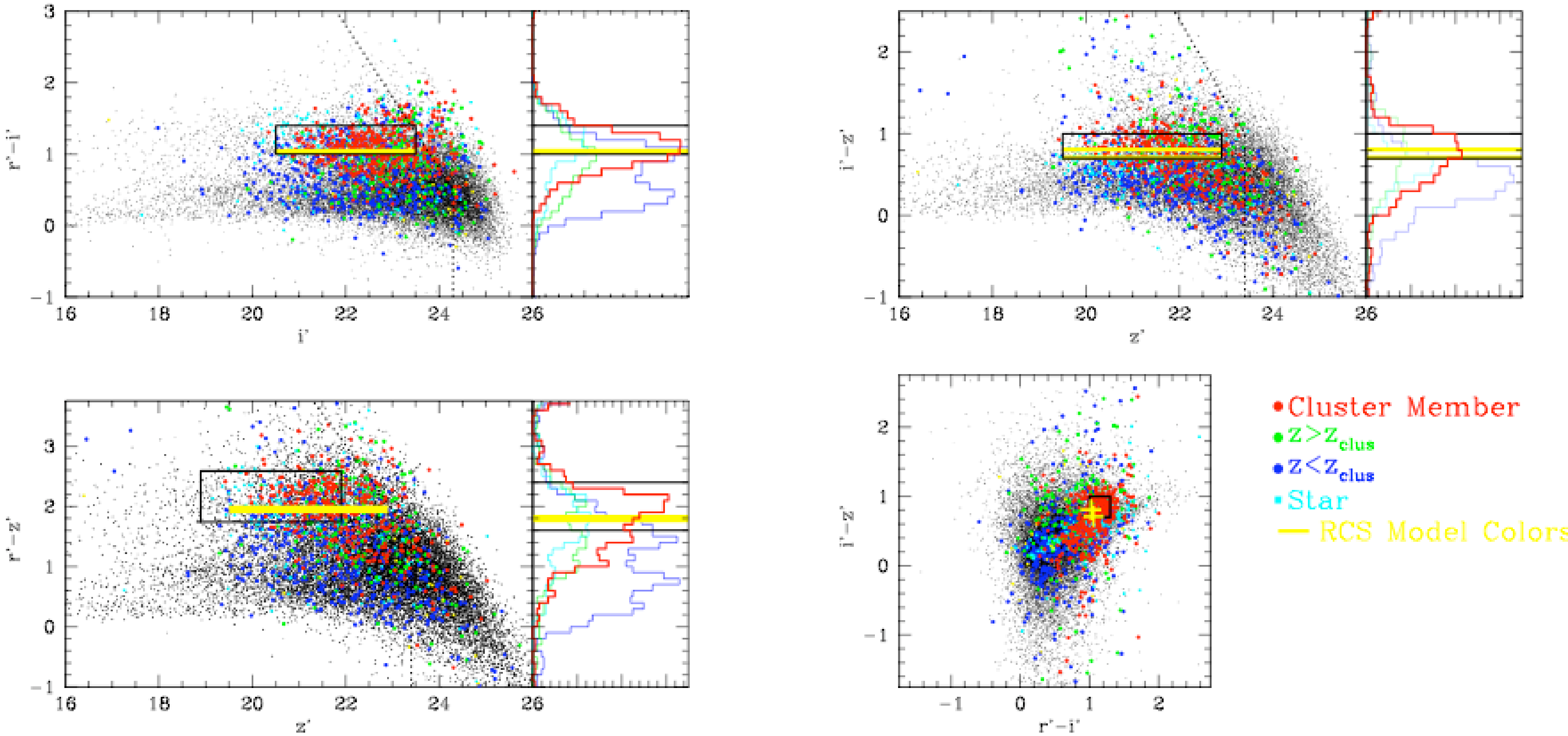
Lima & Hu 2004,2005

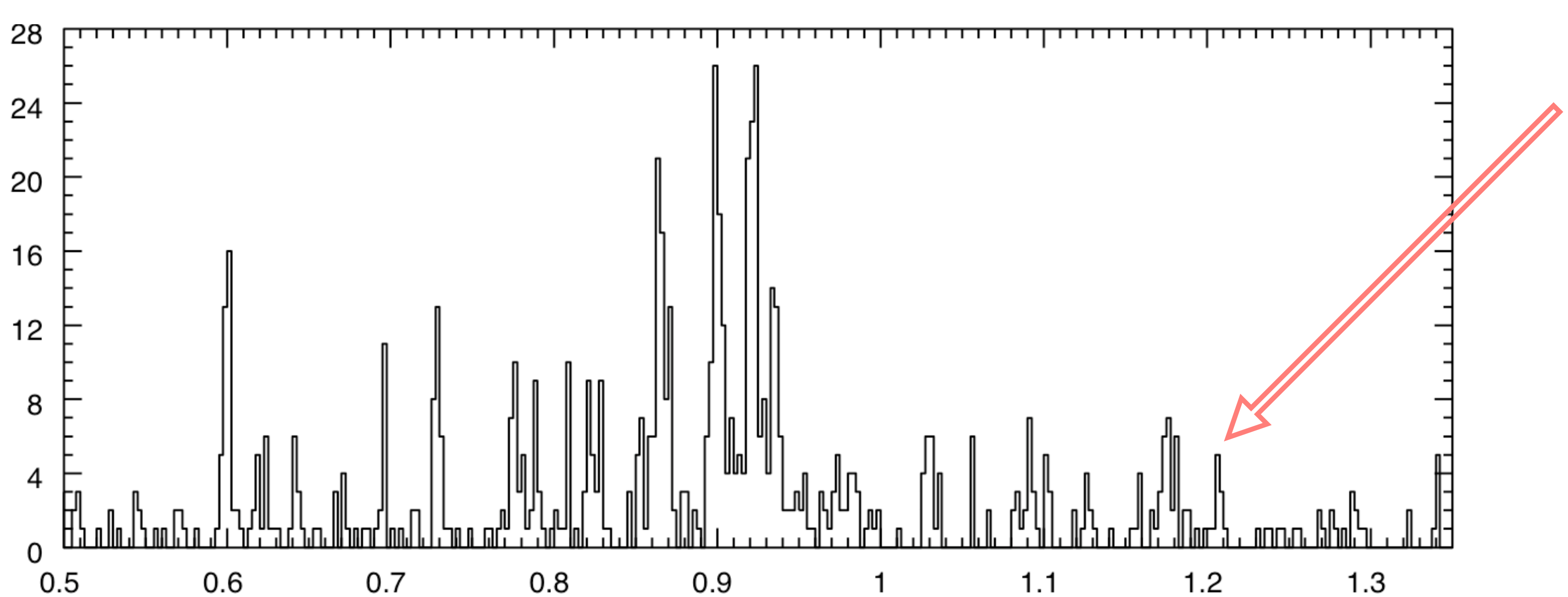
Dark Energy

Cluster counting

Deep Data from
Gal et al. 2004, 2005

LFC and ACS Data Redshifts for more than 1000 galaxies up to z~1.2





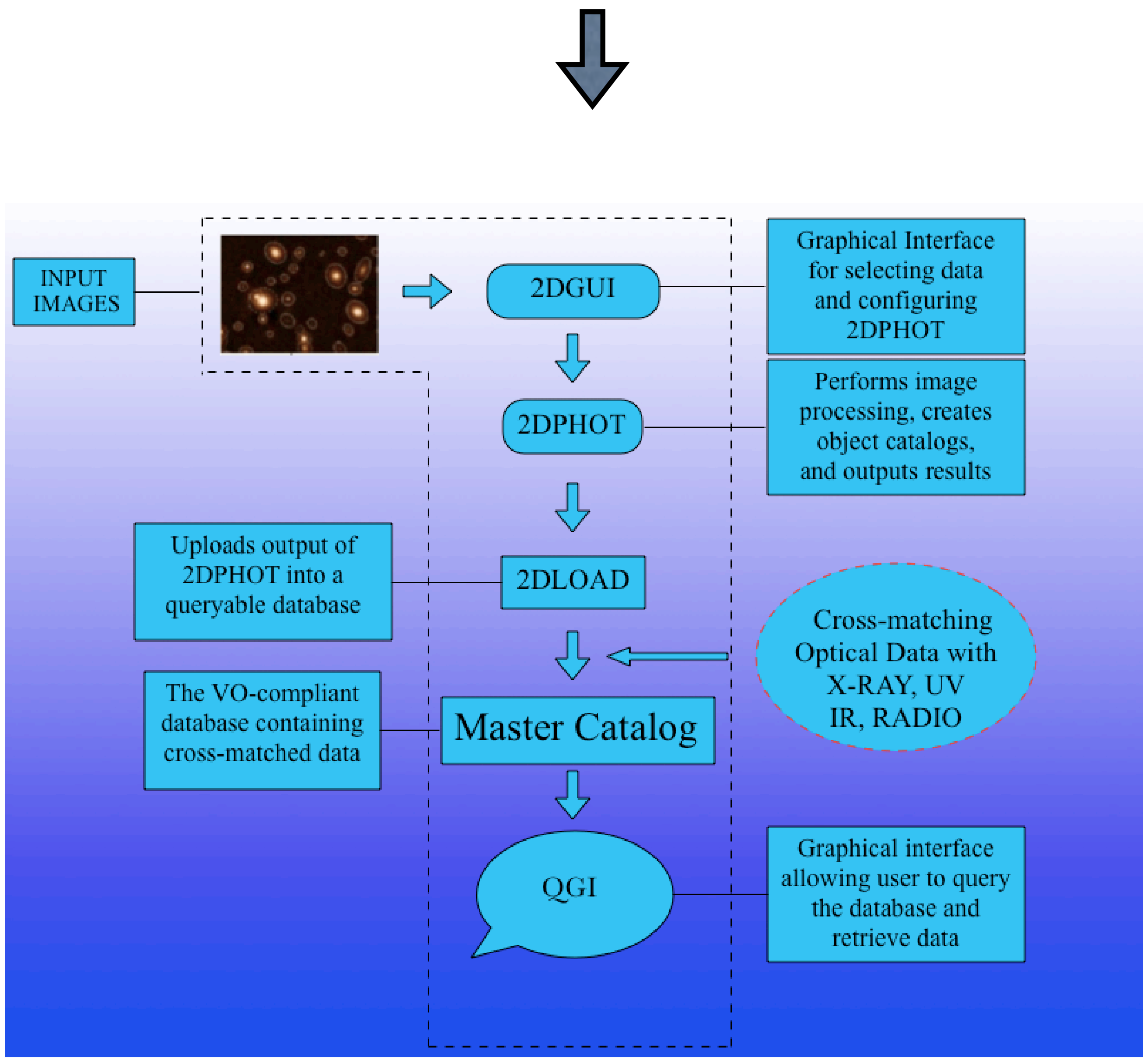
Poor cluster with 17 confirmed members

Cluster counting

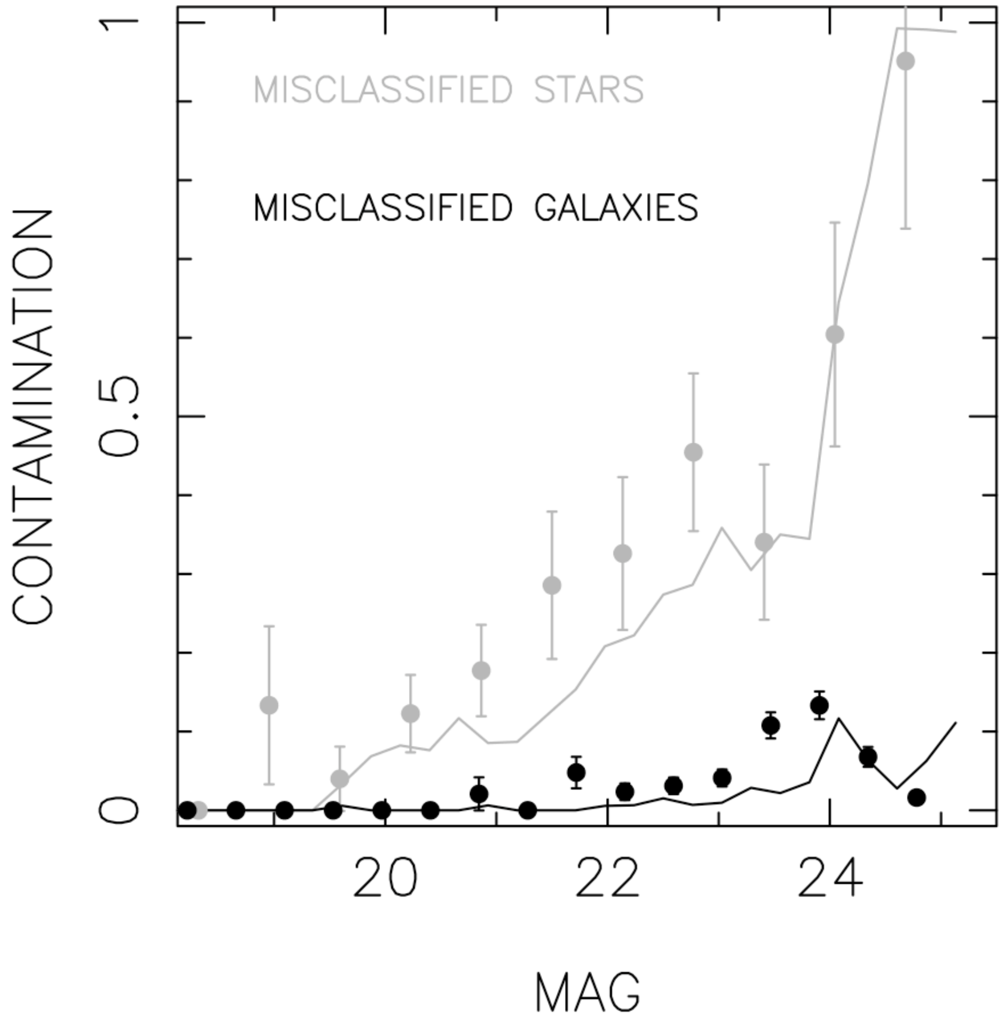
Realistic simulations (for KIDS images)

- Luminosity Function (L^* and α)
- Surface Density Profile (r_c and β)
- Ellipticity
- CM relation (slope and scatter)
- BO effect (f_B)

Soares et al. (2008)



La Barbera et al. (2008)

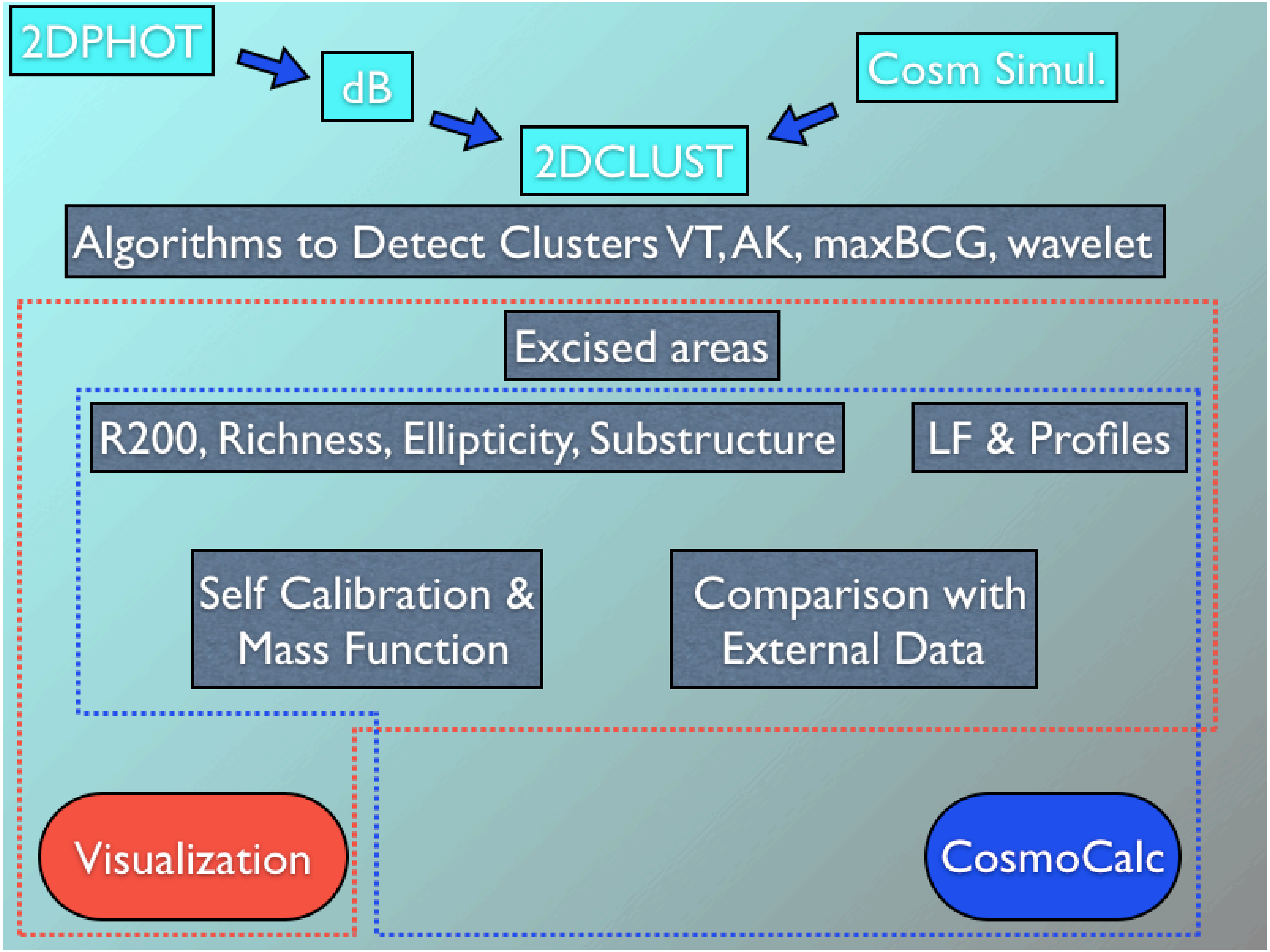


1 - Test the whole pipeline

2 - Assess how cluster finding algorithms are affected by different systematics

3 - Establish the forecasts for w based on the Fisher-Matrix scheme and self-calibration.

Cluster counting



Dark Energy

Cluster counting

KIDS - 1500□ over the sky, in 4 bands - $r_{AB} < 24.4$

Detecting Clusters using VT and Cut & Enhance (WG of SDSS/DES)

2DPHOT provides reliable s/g separation down to the limiting magnitude - Completeness and Contamination

Measuring mass through Ngal and weak lensing, self-calibration technique

Study how galaxies evolve in high density regions since z ~ 1.2

$$w = p_X/\rho_X$$

Table 3: Dark energy projects proposed or under construction. Stage refers to the DETF time-scale classification.

Survey	Description	Probes	Stage
Ground-based:			
ACT	SZE, 6-m	CL	II
APEX	SZE, 12-m	CL	II
SPT	SZE, 10-m	CL	II
VST	Optical imaging, 2.6-m	BAO,CL,WL	II
Pan-STARRS 1(4)	Optical imaging, 1.8-m(×4)	All	II(III)
DES	Optical imaging, 4-m	All	III
Hyper Suprime-Cam	Optical imaging, 8-m	WL,CL,BAO	III
ALPACA	Optical imaging, 8-m	SN, BAO, CL	III
LSST	Optical imaging, 6.8-m	All	IV
AAT WiggleZ	Spectroscopy, 4-m	BAO	II
HETDEX	Spectroscopy, 9.2-m	BAO	III
PAU	Multi-filter imaging, 2-3-m	BAO	III
SDSS BOSS	Spectroscopy, 2.5-m	BAO	III
WFMOS	Spectroscopy, 8-m	BAO	III
HSHS	21-cm radio telescope	BAO	III
SKA	km^2 radio telescope	BAO, WL	IV
Space-based:			
JDEM Candidates			
ADEPT	Spectroscopy	BAO, SN	IV
DESTINY	Grism spectrophotometry	SN	IV
SNAP	Optical+NIR+spectro	All	IV
Proposed ESA Missions			
DUNE	Optical imaging	WL, BAO, CL	
SPACE	Spectroscopy	BAO	
eROSITA	X-ray	CL	
CMB Space Probe			
Planck	SZE	CL	
Beyond Einstein Probe			
Constellation-X	X-ray	CL	IV

Frieman, Turner, & Huterer (2008)