Observational Cosmology II

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Fundamental Physics, Benasque

Cosmology Probes

- Cosmic Microwave Background Radiation
- Supernovae
- Ages
- Gravitational Lensing
- Large Scale Structure
  - Clustering
  - Abundances

Measuring the Universe

• Cosmological determinations depend normally on measuring distances that are integrals over the expansion rate of the universe H(z)

$$\mathbf{H(z) = H_o\, E(z) = \frac{\dot{a}}{a}}$$

$$\mathbf{E^2(z) = \Omega_M\,(1+z)^3 + \Omega_R\,(1+z)^4 + \Omega_K\,(1+z)^2 + \Omega_{DE}\,(1+z)^{3(1+w)}}$$

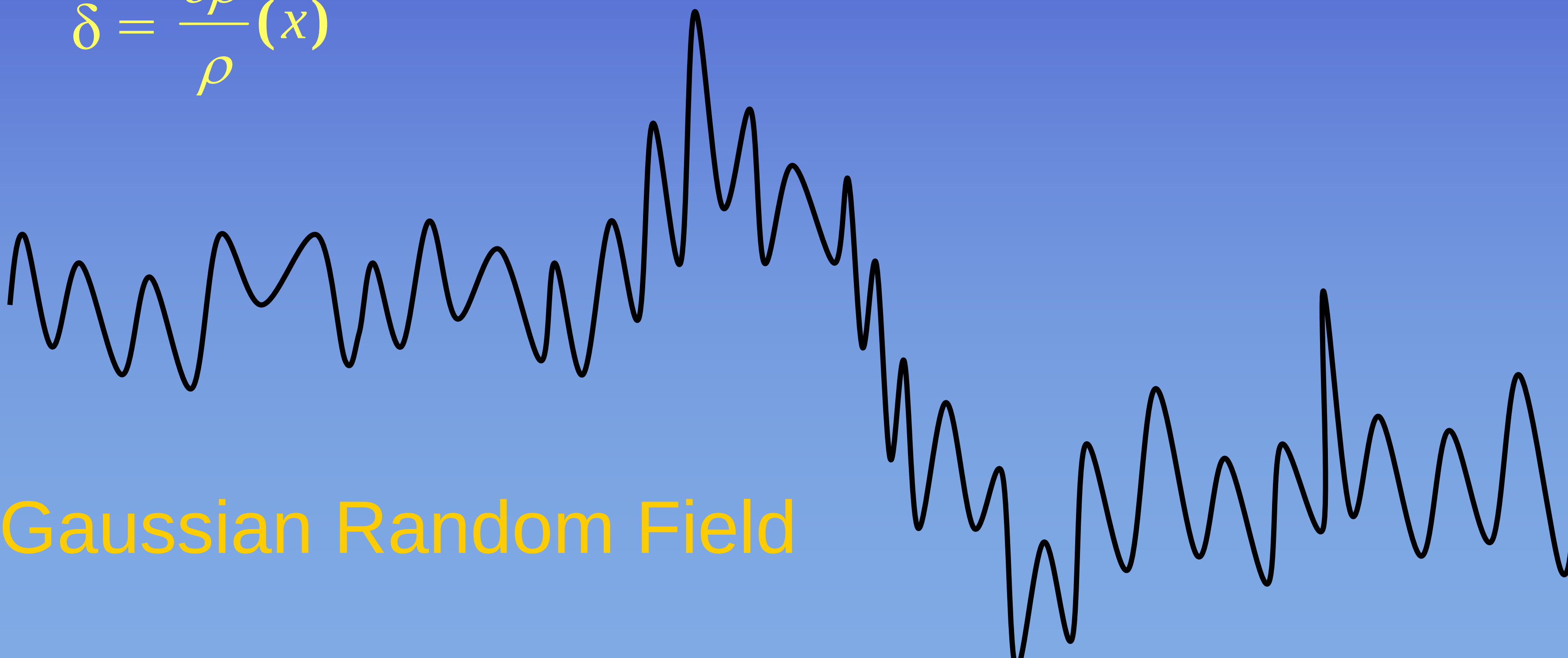
• Comoving distances: $\mathbf{d_c = \int \frac{dz}{H(z)}}$

Measuring the Universe

- Standard candles: $d_l = d_c\,(1+z)$
- Standard rulers: $d_a = \dfrac{d_c}{(1+z)}$
- Volume markers: $\dfrac{dV}{dz\,d\Omega} = \dfrac{d_c^2}{H(z)}$
- Rate of growth of structure: $D(z)$

Cosmology from objects abundances: Press-Schechter Formalism

$$\delta = \frac{\delta\rho}{\rho}(x)$$



Gaussian Random Field

Cosmology from objects abundances: Press-Schechter Formalism

- The probability of having a density δ in a density field δ_R smoothed by a window function W_R

$$P(\delta, t) = \left[\frac{1}{2\pi\sigma^2(R, t)}\right]^{1/2} \exp\left(-\frac{\delta^2}{2\sigma^2(R, t)}\right)$$

where

$$\sigma^2(R, t) = \int \frac{d^3k}{(2\pi)^3} \left|\delta_k(t)\right| W_k^2(R)$$

Press-Schechter Formalism

• Assume that regions with $\delta > \delta_c$ will form gravitationally bound objects with

• The fraction of bound objects with mass greater than M

$$\mathrm{F(M)} = \int_{\delta_c}^{\infty} \mathrm{P}(\delta, \mathrm{R})\, \mathrm{d}\delta = \frac{1}{\sqrt{2}\sigma(\mathrm{R})} \int_{\delta_c}^{\infty} \exp\left(-\frac{\delta^2}{2\sigma^2(\mathrm{R})}\right) \mathrm{d}\delta$$

• The mass function is then

$$\mathrm{N(M, t)\, dM} = -\left(\frac{\bar{\rho}}{\mathrm{M}}\right) \left(\frac{1}{2\pi}\right)^{1/2} \left(\frac{\delta_c}{\sigma}\right) \left(\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{dM}}\right) \exp\left(\frac{\delta_c^2}{2\sigma^2}\right) \mathrm{dM}$$

Press-Schechter Formalism

- However $\int_0^\infty \mathbf{f(M)\,dM} = \int_0^\infty \mathbf{dF} = \frac{\mathbf{1}}{\mathbf{2}}$

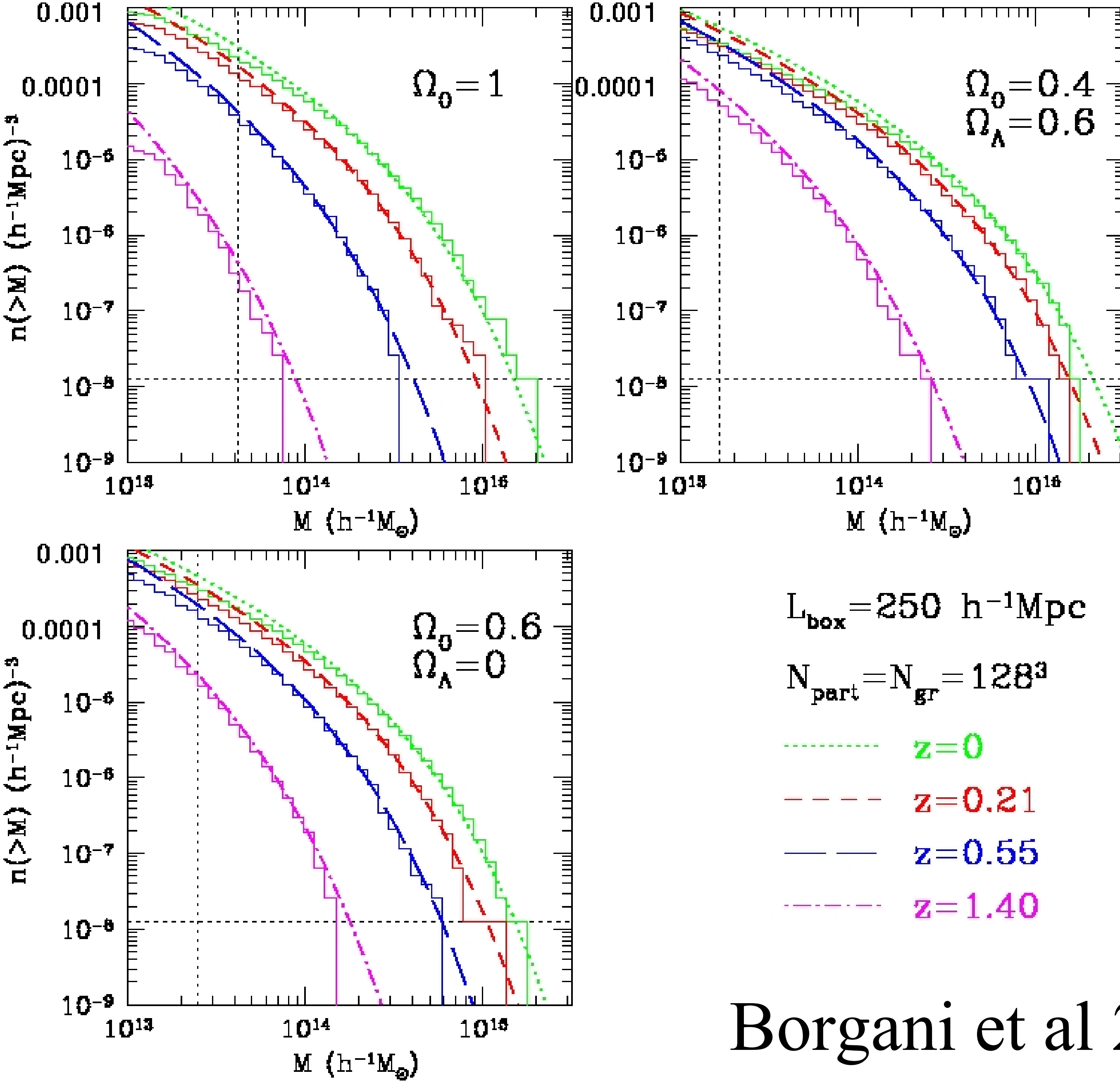
- Need to include objects with $\delta<\delta_c$ at filtered scale R, but with $\delta>\delta_c$ at some larger scale larger than R

$$\mathbf{F(M)} = \int_{\delta_\mathbf{c}}^\infty \mathbf{P}(\delta, \mathbf{R})\,\mathbf{d}\delta + \int_{-\infty}^{\delta_\mathbf{c}} \mathbf{C}(\delta_\mathbf{c}, \delta)\,\mathbf{d}\delta$$

Press-Schechter Formalism

- Modification Seth & Tormen, allowing for non-spherical perturbations

- Numerical simulations => fitting formulae (Jenkins et al 01)



Borgani et al 2001

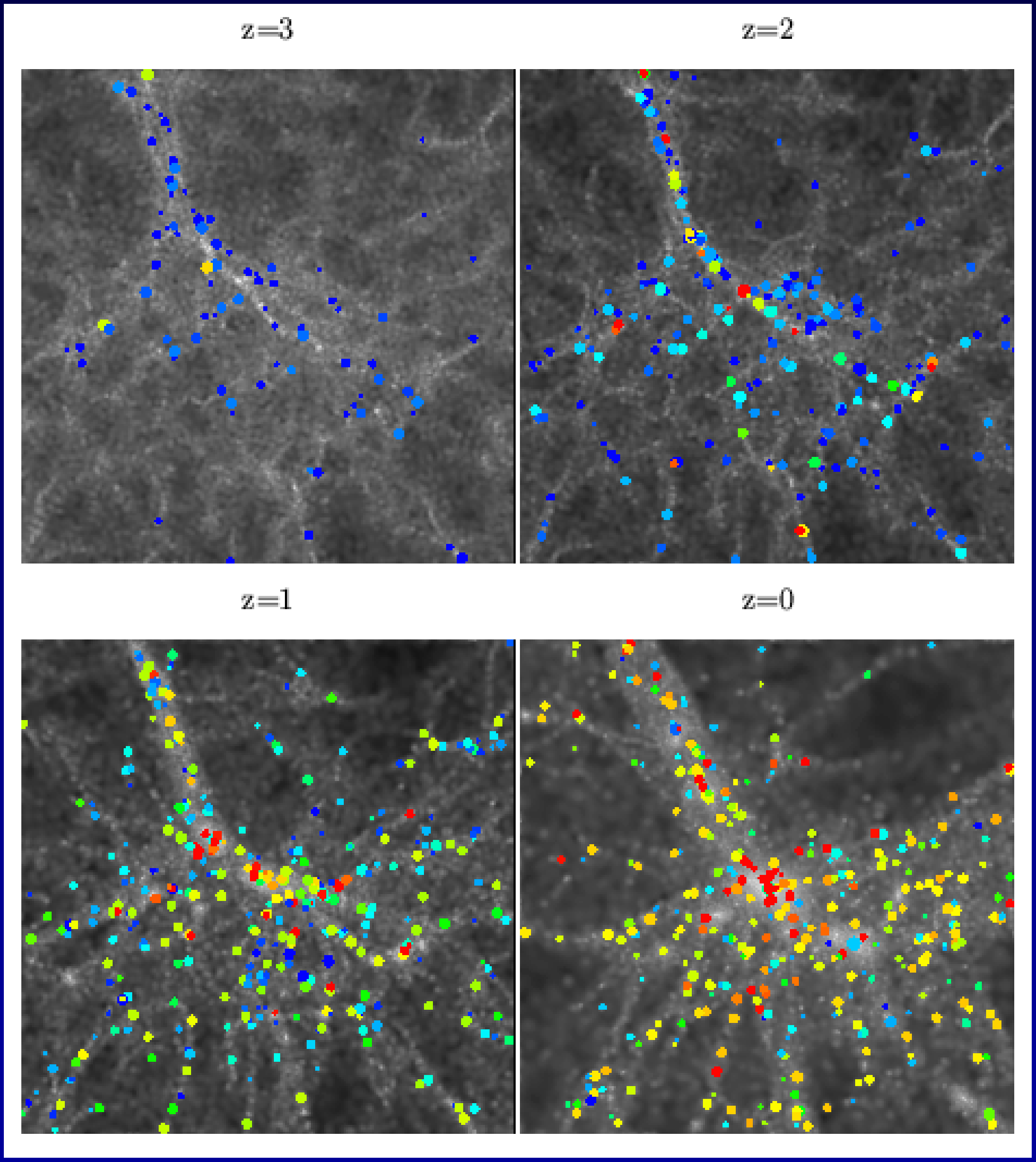
Press-Schechter Formalism

Caveats for applicability

- Bias: $\delta_g = b\ \delta_m$
- Selection Function: mass is not an observable

  Need a relation between Mass and observable

  $M = f(X) \Rightarrow dX/dM$



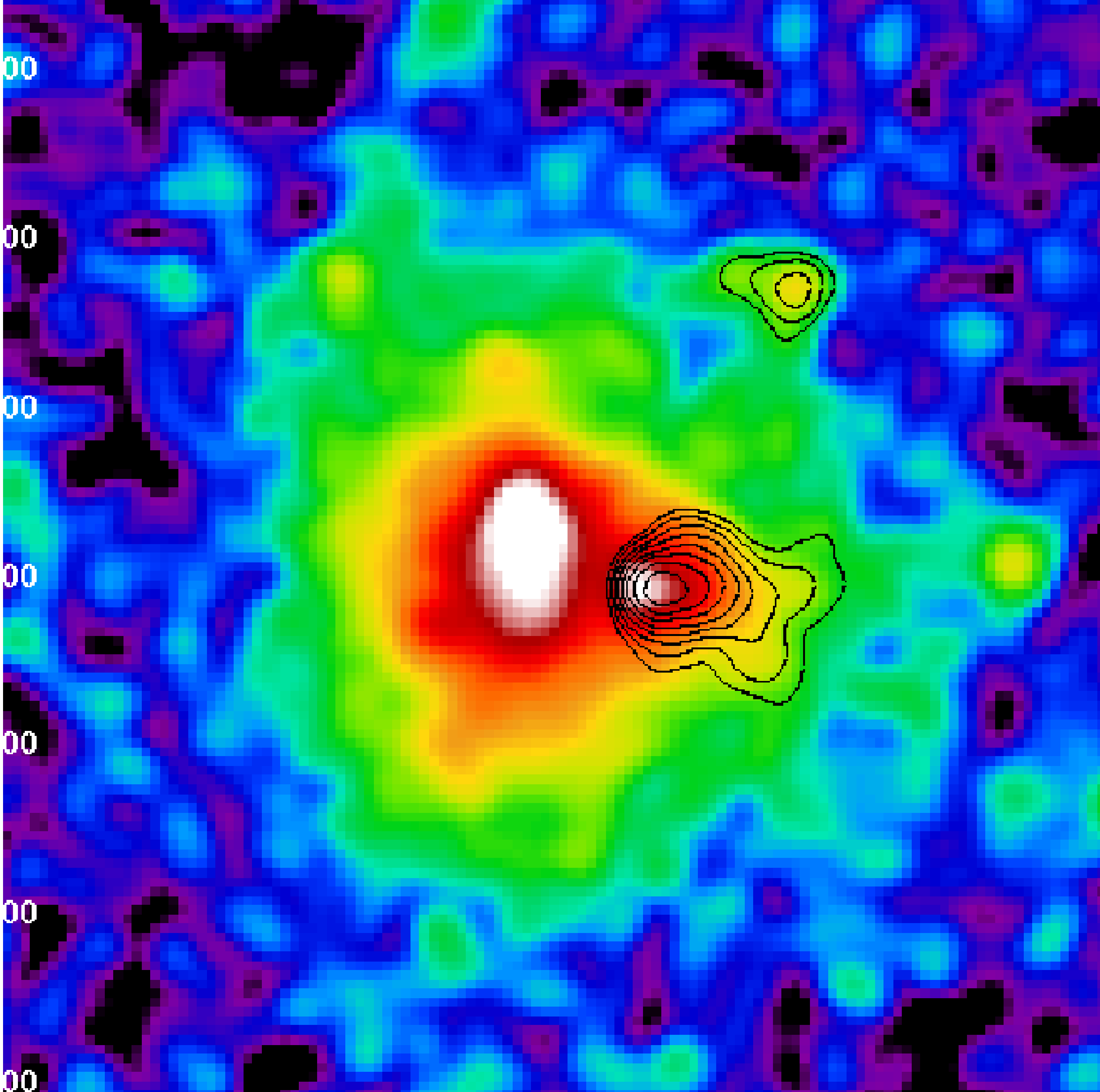
GIF simulations
Diaferio et al 2001

Cosmology with Galaxy Clusters

Galaxy Clusters Basic Components

Largest gravitationally bound structures in the Universe composed of:

- **Dark Matter**
- **Hot Gas**
- **Galaxies**



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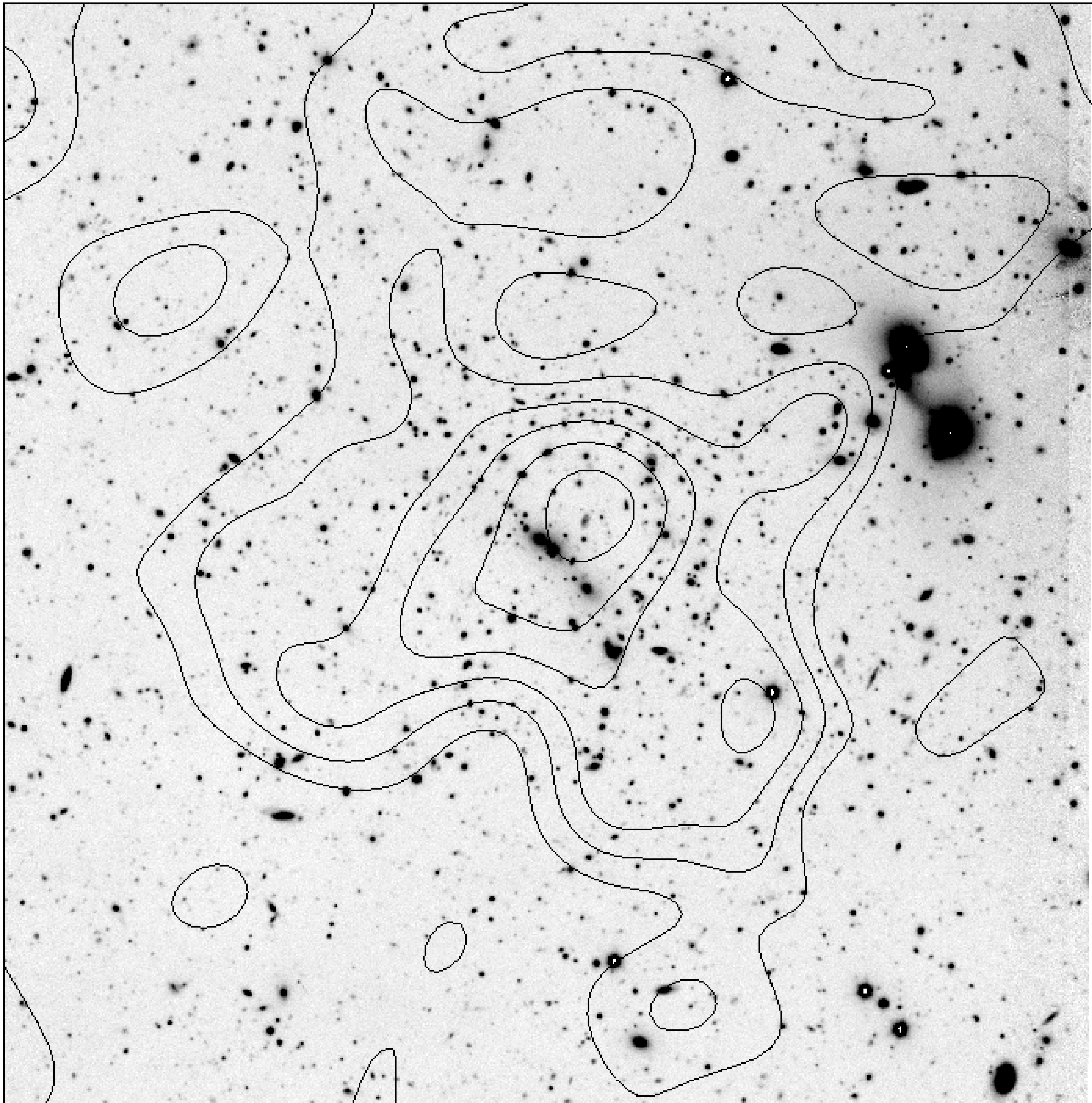
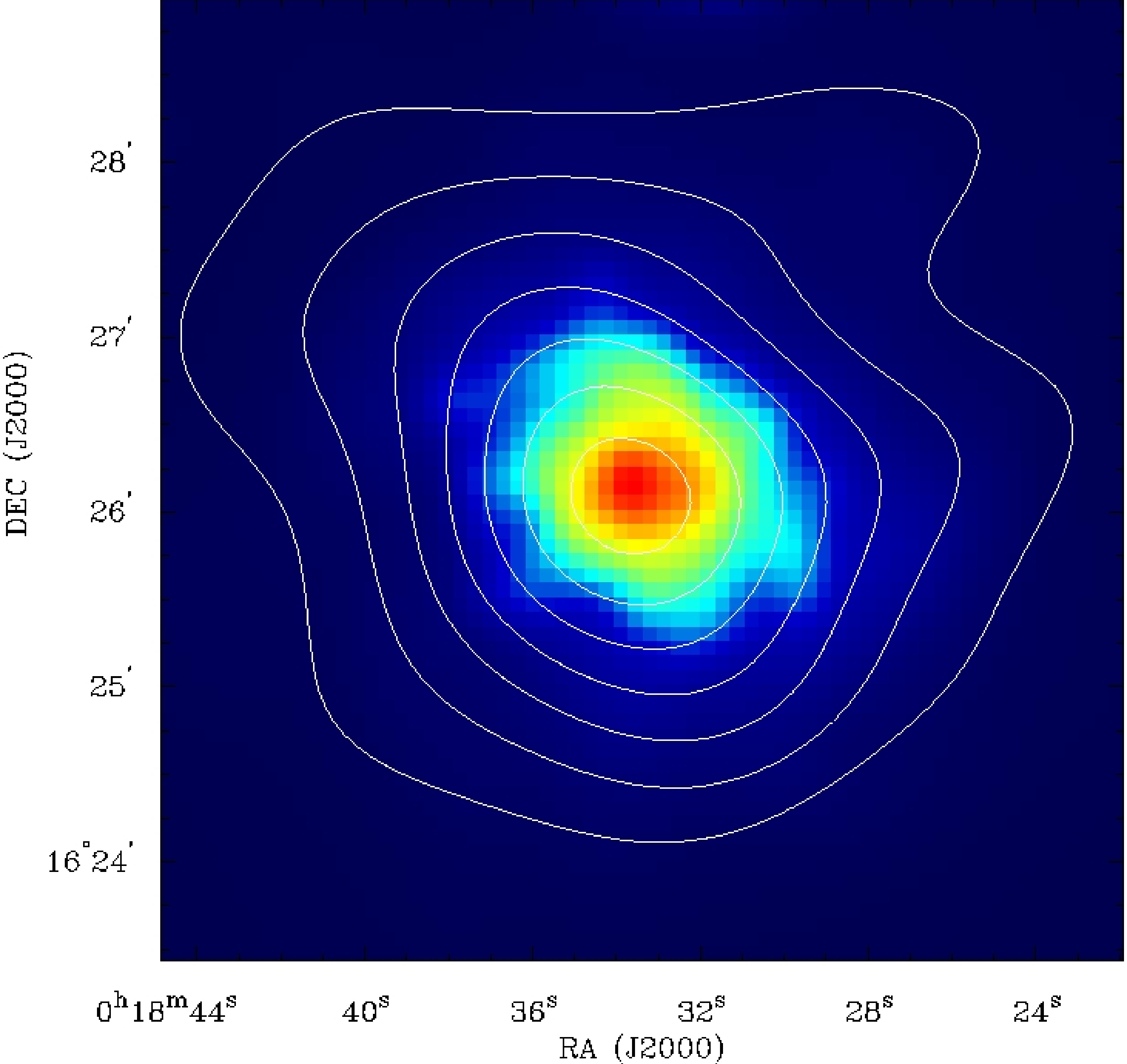
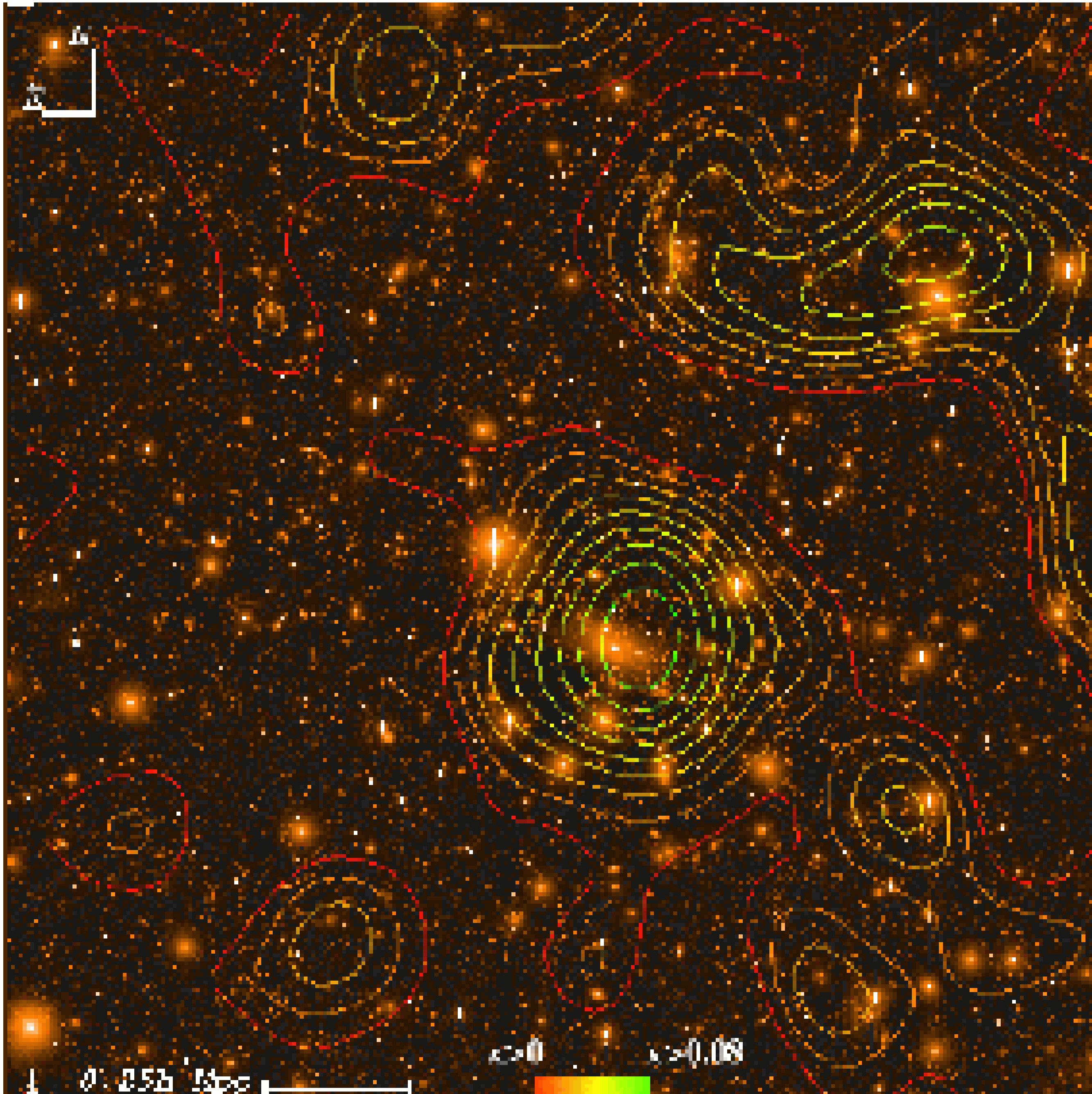



28′
27′
26′
25′
16°24′
DEC (J2000)
0h18m44s
40s
36s
32s
28s
24s
RA (J2000)



Cluster Formation Description

- Clusters of Galaxies form from gravitational collapse of high density peaks
- Cluster collapse dominated by dark matter with baryons following the potential wells dominated by dark matter
- During collapse the baryons suffer adiabatic compression and heating by gravitationally induced shocks, resulting in the formation of a hot intracluster medium
- For typical cluster masses ($\sim 10^{15}\ M_{\odot}$) the gas reaches temperatures of several $10^{7}\ {}^{o}K$ and becomes fully ionized.

Cosmology with Galaxy Clusters

- **Cluster Mass: best “observable”**
- **Cluster Observables:**
  - Richness: N_g
  - Velocity dispersion: z,σ
  - X-rays: $S_x \alpha \rho^2 T^{1/2}$, Tx
  - Lensing: ε => g, μ
  - Sunyaev-Zeldovich: $\Delta T \alpha \rho T$

Cosmology with Galaxy Clusters

• Clustering: clusters are highly biased tracers of the underlying mass distribution

power spectrum, correlation functions

• Abundances: count how many clusters are above a certain mass threshold imposed by your observable

mass function

• Baryon fraction: clusters are fair samples of the overall mass composition of the universe

$f_B = \Omega_B/\Omega_M \quad => \Omega_M = \Omega_B/f_B$

Cosmology with Galaxy Clusters

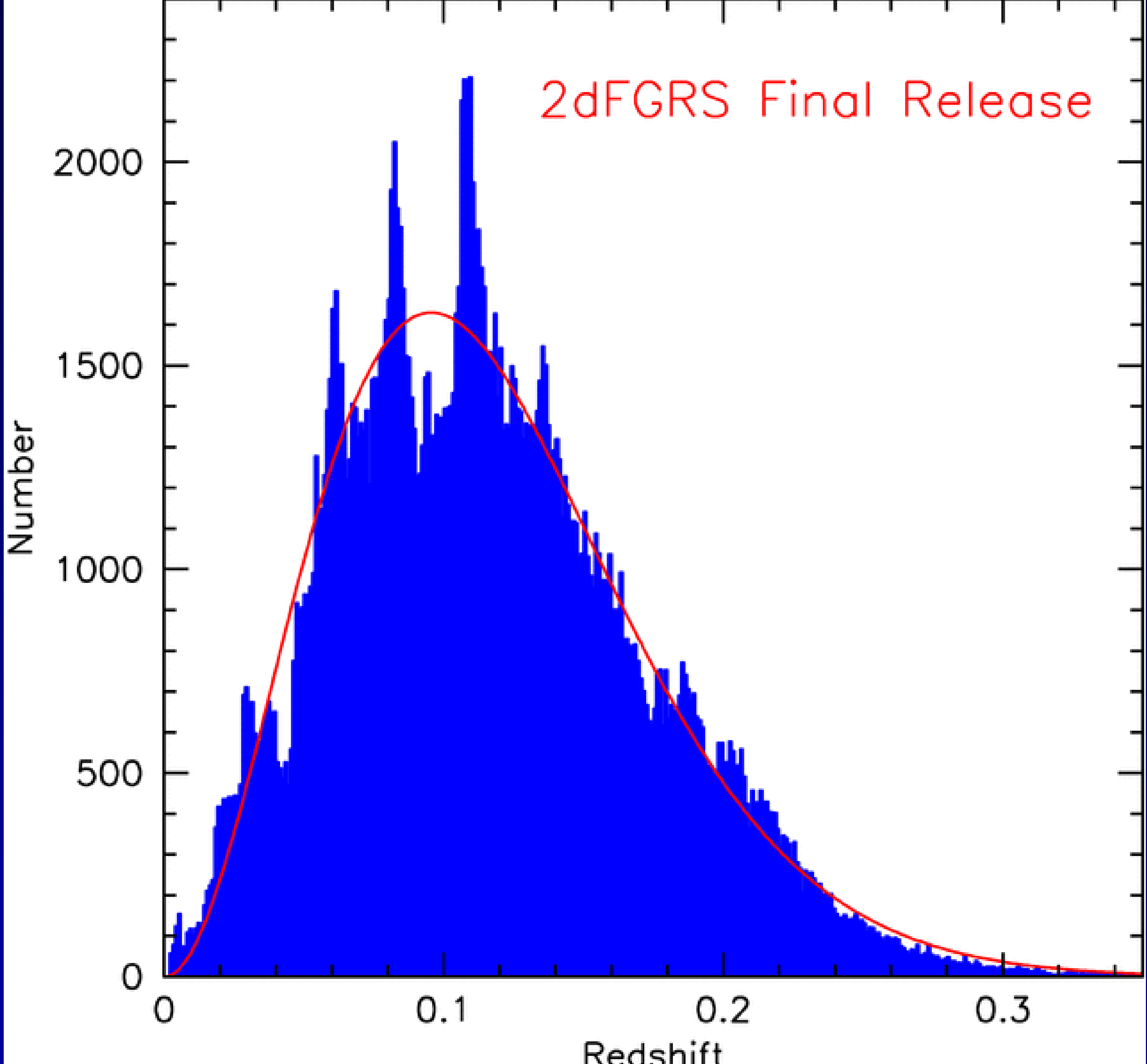
Cluster abundances

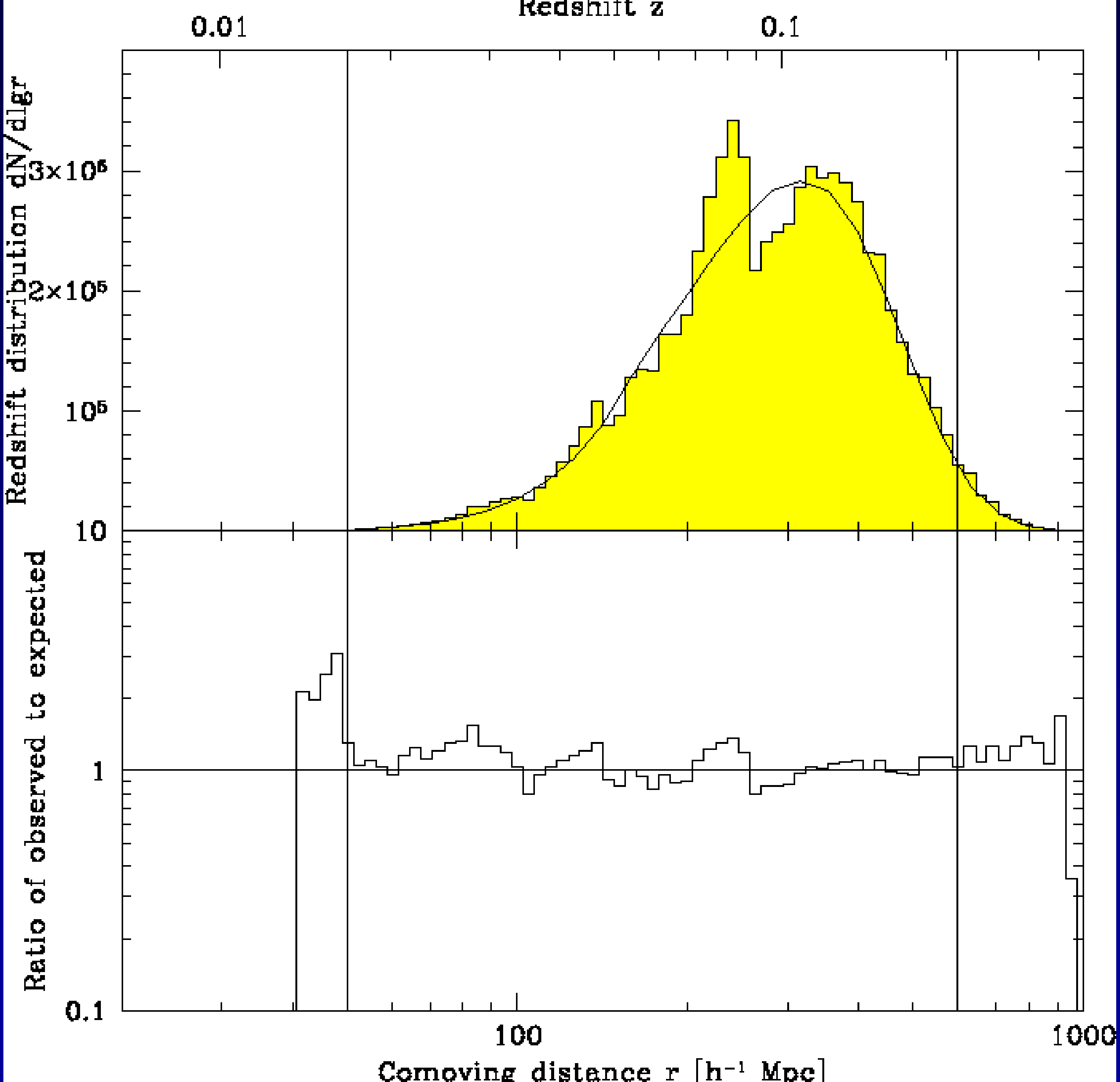
- Cluster surveys

Local: σ_8-Ω_M

Redshift distribution:

$$\frac{d^2N}{dzd\Omega}(z) = \frac{d^2V}{dzd\Omega}(z) n_{com}(z) = \frac{c}{H(z)} D_A^2 (1+z)^2 \int_0^\infty dM\, f(M,z) \frac{dn}{dM}(z)$$


2dFGRS Final Release
Number
2000
1500
1000
500
0
0
0.1
0.2
0.3
Redshift



Redshift z
0.01
0.1
Redshift distribution dN/dlgr
3×10^5
2×10^5
10^5
10
Ratio of observed to expected
1
0.1
100
1000
Comoving distance r [h^{-1} Mpc]

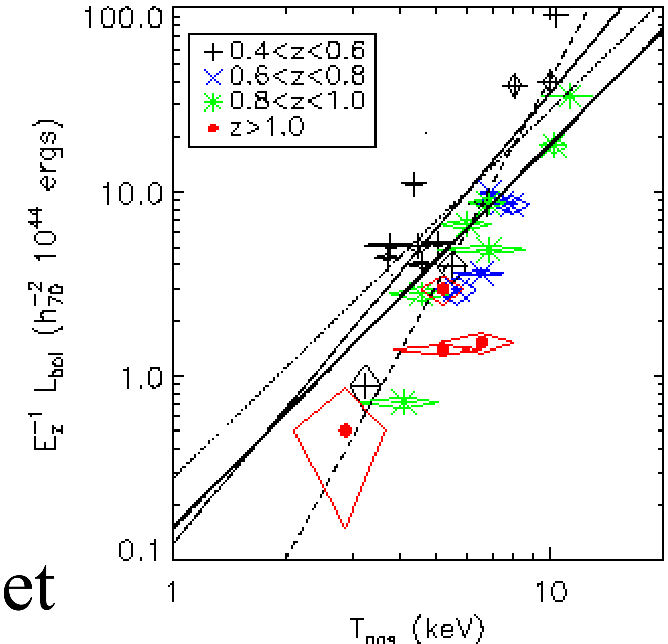
Cosmology with Galaxy Clusters

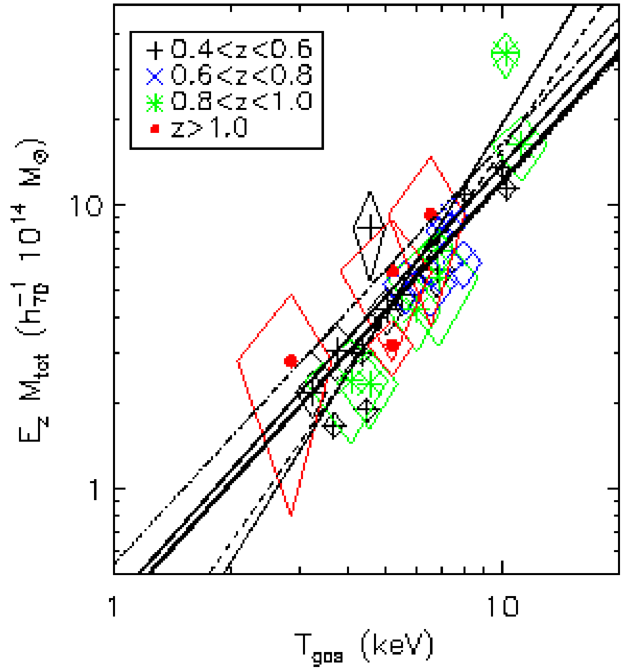
Cluster Redshift distribution dependences

- Volume
- Abundance evolution
- Mass selection function

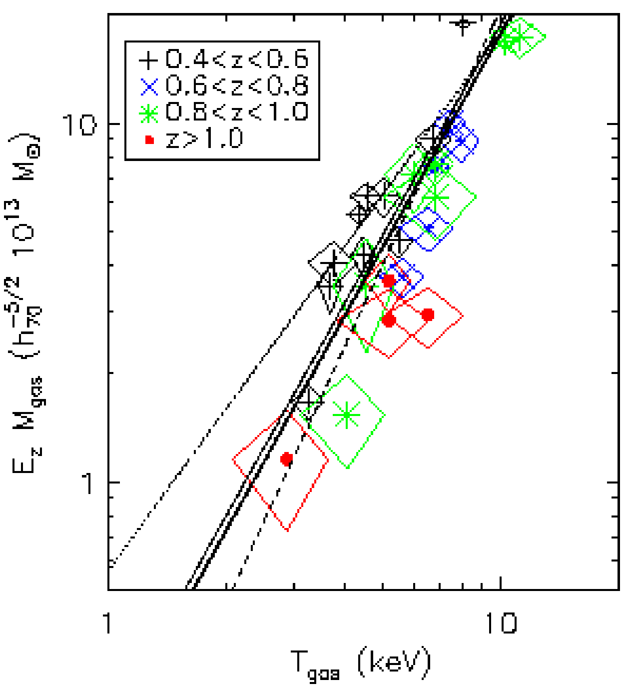
Cluster Scaling Relations

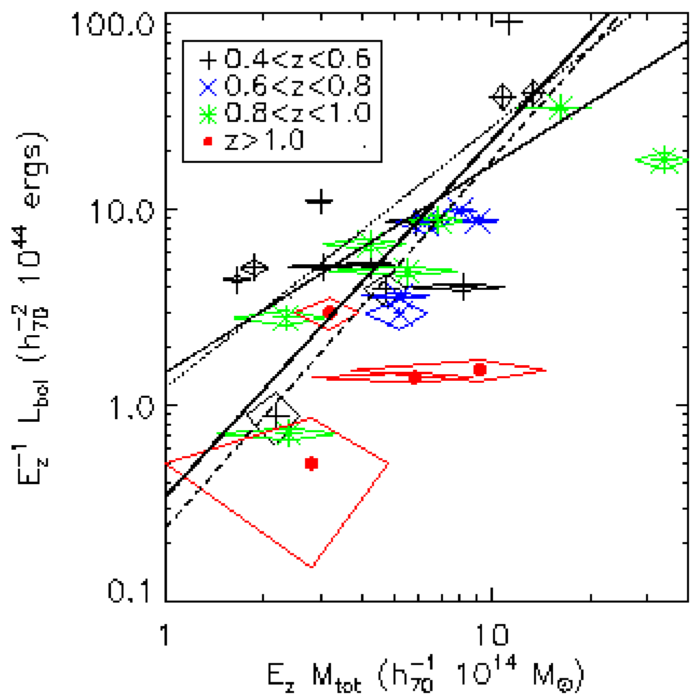
- If cluster gas properties determined only by gravitational collapse then clusters should be scaled versions of each other:
  - $L_x \alpha M \rho_{gas} T_x^{1/2}$
  - $L_x \alpha T_x^2 (1+z)^{3/2}$
  - $L_x \alpha M^{4/3} (1+z)^{7/2}$
  - $S \alpha T_x (1+z)^{-2}$
  - $T \alpha M^{2/3} (1+z)$
- Observationally these relations do not hold
  - $L_x \alpha T_x^3$



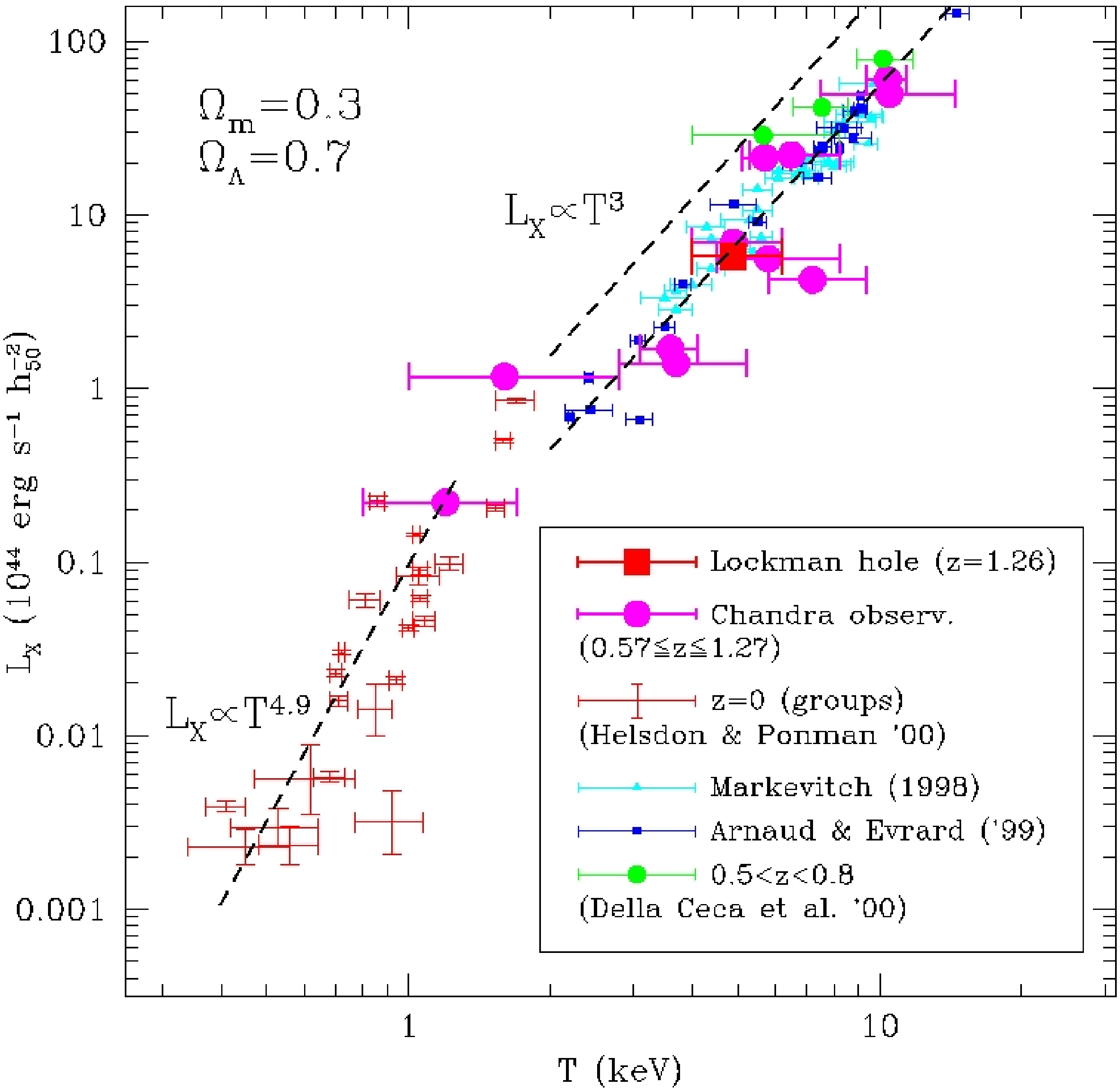


Ettori et al 2003





Borgani et al 2001



Cosmology with Cluster Surveys

Optical Selection: Overdensities

- Select by number of galaxies: clusters are selected as overdensities of galaxies compared to the field background

  - Easy selection
  - number of galaxies correlates with mass with large scatter

    $N_g \propto M^p$
  - projection effects: spurious systems
  - At high redshift the selection breaks down

Cosmology with Cluster Surveys

Velocity dispersion selection

- Select doing a spectroscopic survey
  - Very expensive selection
  - velocity dispersion should correlate well with mass $\sigma^2 \propto M/R$
  - interlopers
  - poor virialization

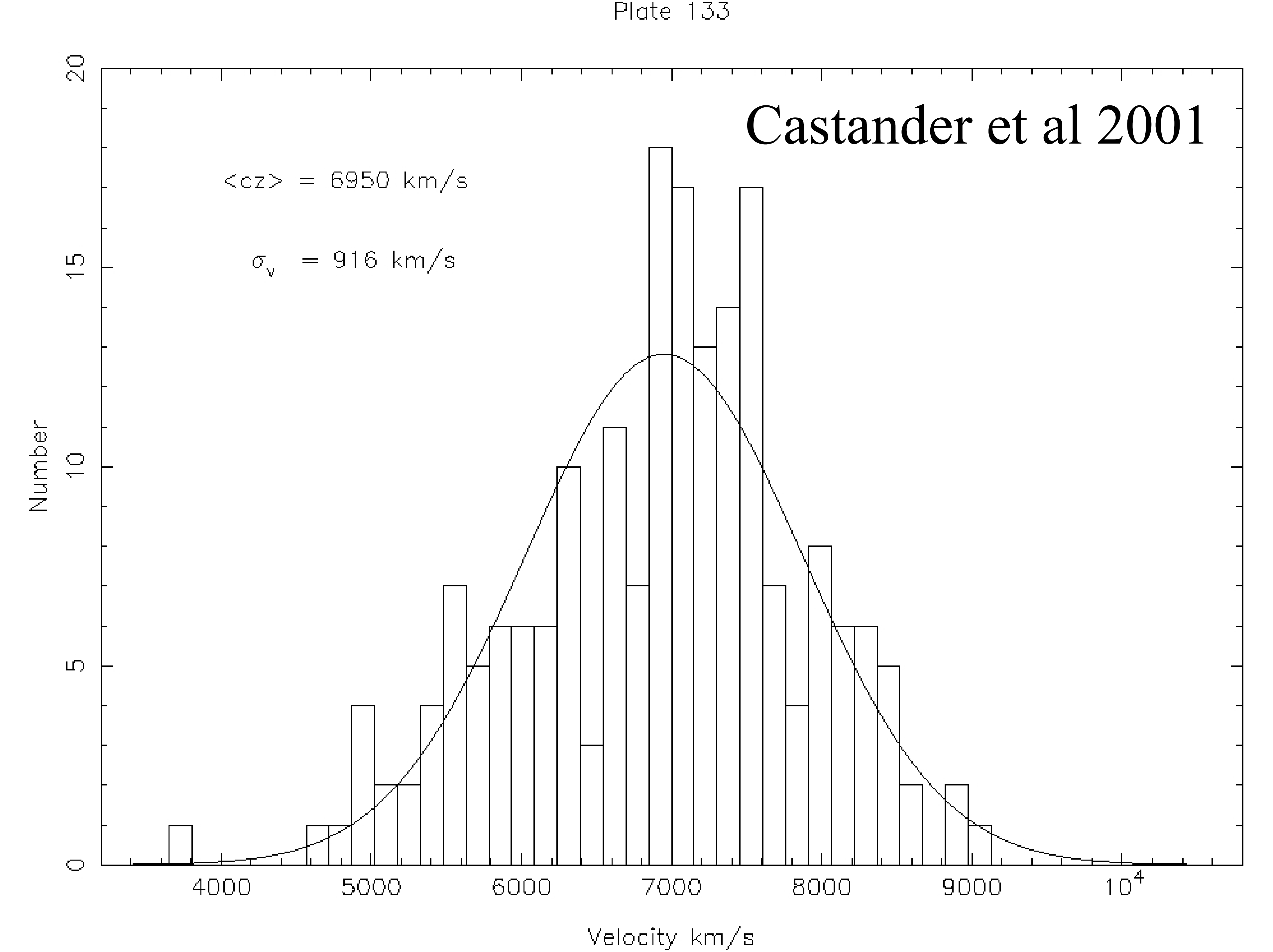


Plate 133
Castander et al 2001
<cz> = 6950 km/s
σ_v = 916 km/s
Number
Velocity km/s
0
5
10
15
20
4000
5000
6000
7000
8000
9000
10^4

Cosmology with Clusters Surveys

X-ray selection

- Clusters are selected by their X-ray flux
- In fact, as they are extended they are selected by surface brightness
- Lx α $\rho^2 T^{1/2}$
  - Easy selection
  - luminosity correlates with mass with some scatter: Lx α $M^{4/3}$
  - projection effects are reduced
  - At high redshift hard to detect

Cluster Physics Input

Hydrostatic Equilibrium

$$\frac{1}{\rho_{gas}} \nabla P_{gas} = -\nabla\Phi$$

Poisson's Equation

$$\nabla^2\Phi = 4\pi G \rho_{grav}$$

$$\rho_{grav} = -\frac{1}{4\pi G} \nabla \left(\frac{1}{\rho_{gas}} \nabla P_{gas} \right)$$

Equation of State

$$P_{gas} = \frac{\rho_{gas} k T_e}{\mu m_p}$$

Isothermal

$$\rho_{grav} = -\frac{kT_e}{4\pi G \mu m_p} \nabla^2 \ln \rho_{\rm gas}$$

Hydrostatic Equilibrium

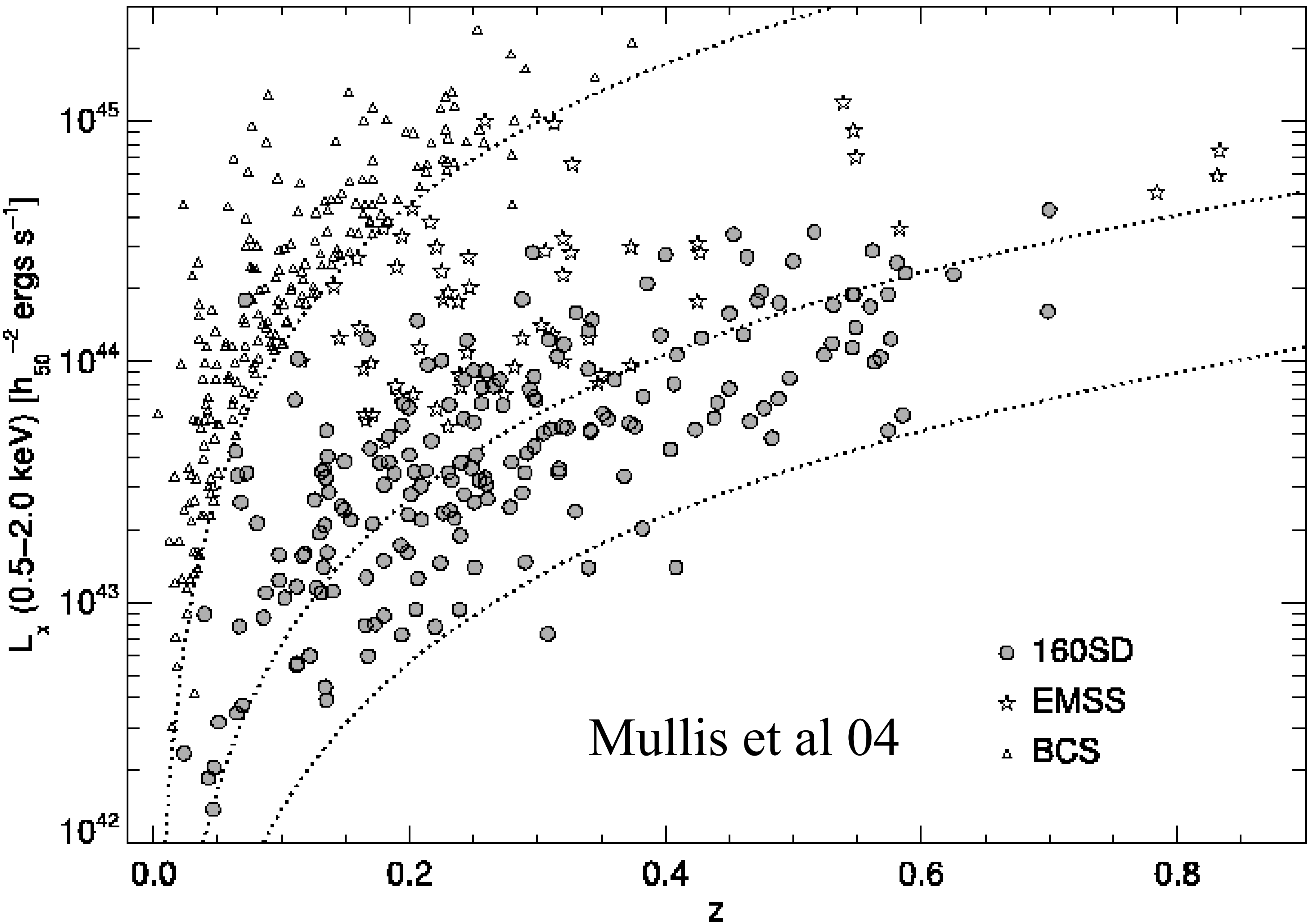
$$\frac{1}{\rho_{gas}} \nabla P_{gas} = -\nabla\Phi$$

Spherical Symmetry

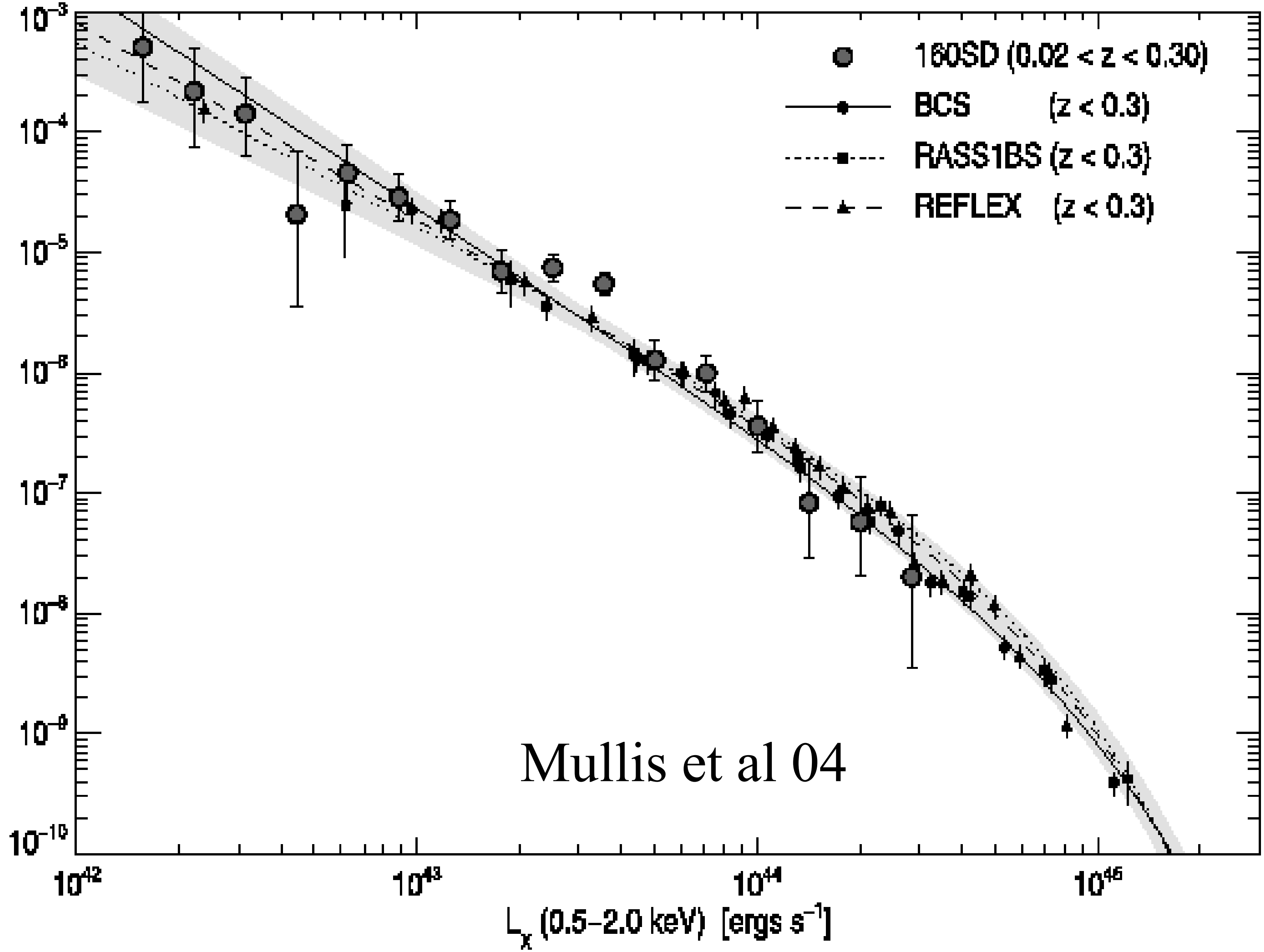
$$\frac{1}{\rho_{gas}} \frac{\mathrm{dP}}{\mathrm{dr}} = -\frac{\mathrm{d}\Phi}{\mathrm{dr}} = -\frac{GM(r)}{r^2}$$

Isothermal

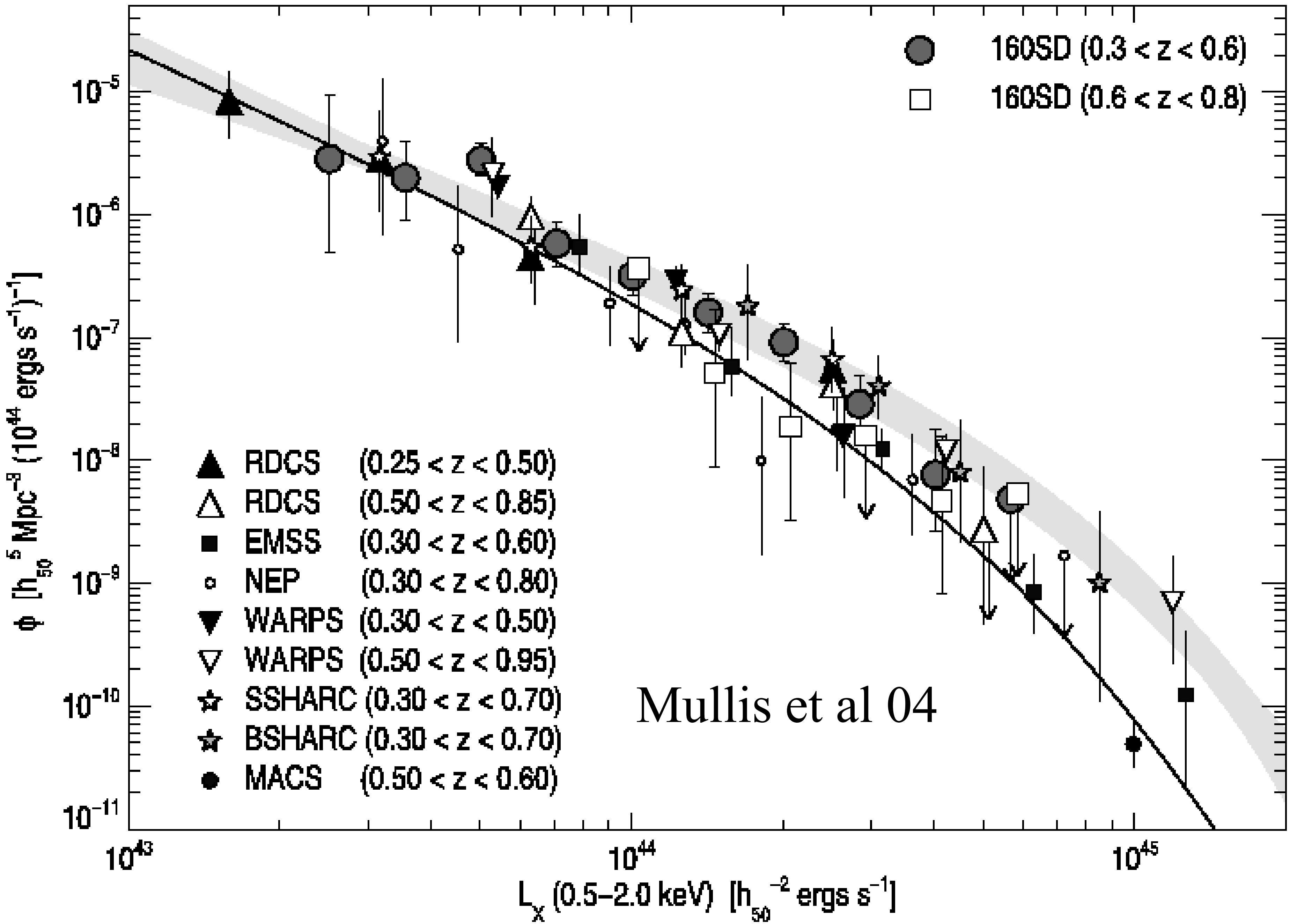
$$\frac{kT_e}{\mu m_p} \frac{\mathrm{d}\ln\rho_{\rm gas}}{\mathrm{dr}} = -\frac{\mathrm{d}\Phi}{\mathrm{dr}}$$



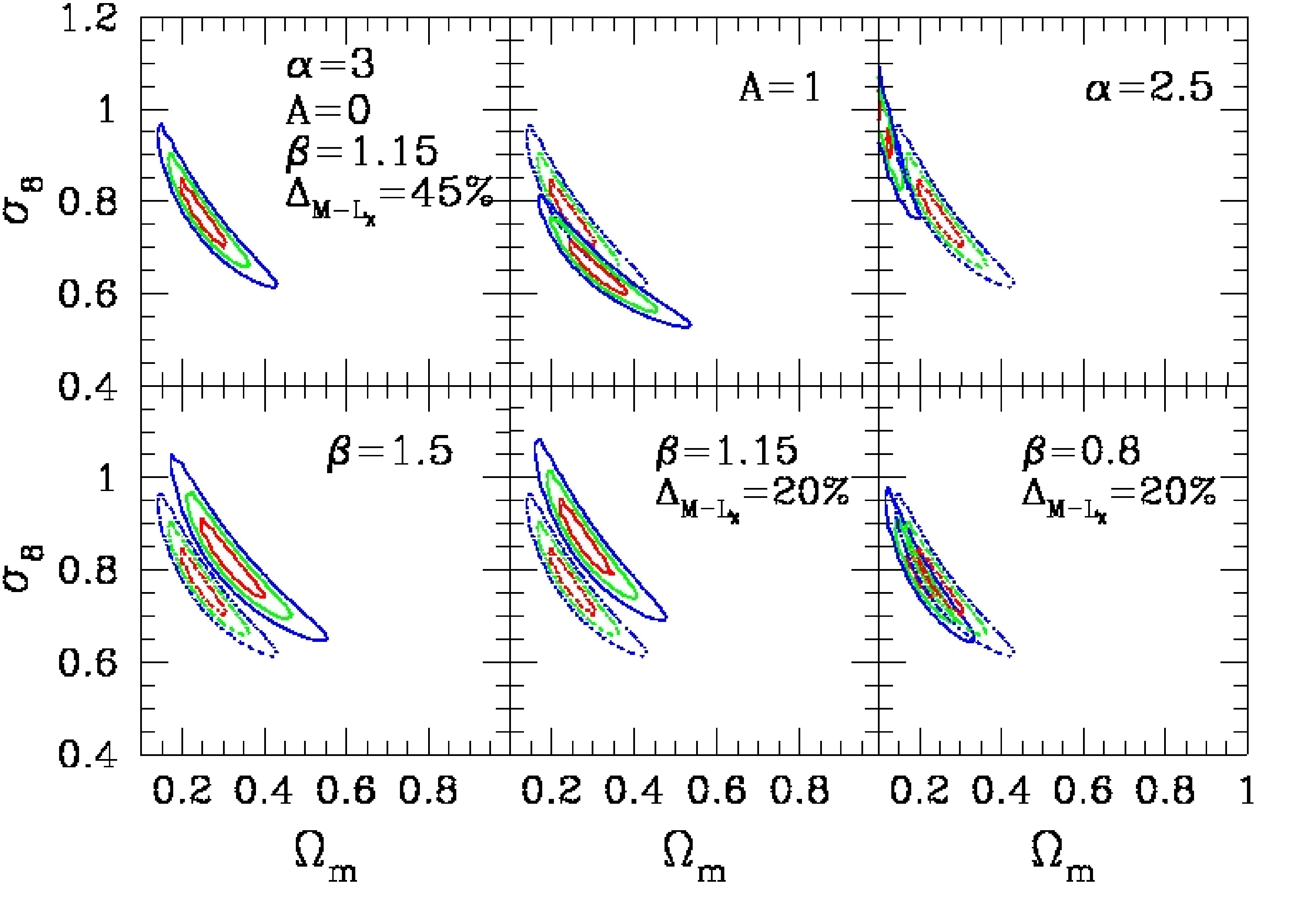
L_x (0.5–2.0 keV) [h_{50}^{-2} ergs s^{-1}]
10^{45}
10^{44}
10^{43}
10^{42}
0.0
0.2
0.4
0.6
0.8
z
160SD
EMSS
BCS
Mullis et al 04



160SD (0.02 < z < 0.30)
BCS (z < 0.3)
RASS1BS (z < 0.3)
REFLEX (z < 0.3)
Mullis et al 04
ϕ [h_{50}^{5} Mpc^{-3} (10^{44} ergs s^{-1})$^{-1}$]
L_X (0.5–2.0 keV) [ergs s^{-1}]


160SD (0.3 < z < 0.6)
160SD (0.6 < z < 0.8)
RDCS (0.25 < z < 0.50)
RDCS (0.50 < z < 0.85)
EMSS (0.30 < z < 0.60)
NEP (0.30 < z < 0.80)
WARPS (0.30 < z < 0.50)
WARPS (0.50 < z < 0.95)
SSHARC (0.30 < z < 0.70)
BSHARC (0.30 < z < 0.70)
MACS (0.50 < z < 0.60)
Mullis et al 04
ϕ [h_{50}^{5} Mpc^{-3} (10^{44} ergs s^{-1})$^{-1}$]
L_X (0.5–2.0 keV) [h_{50}^{-2} ergs s^{-1}]
10^{43}
10^{44}
10^{45}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}

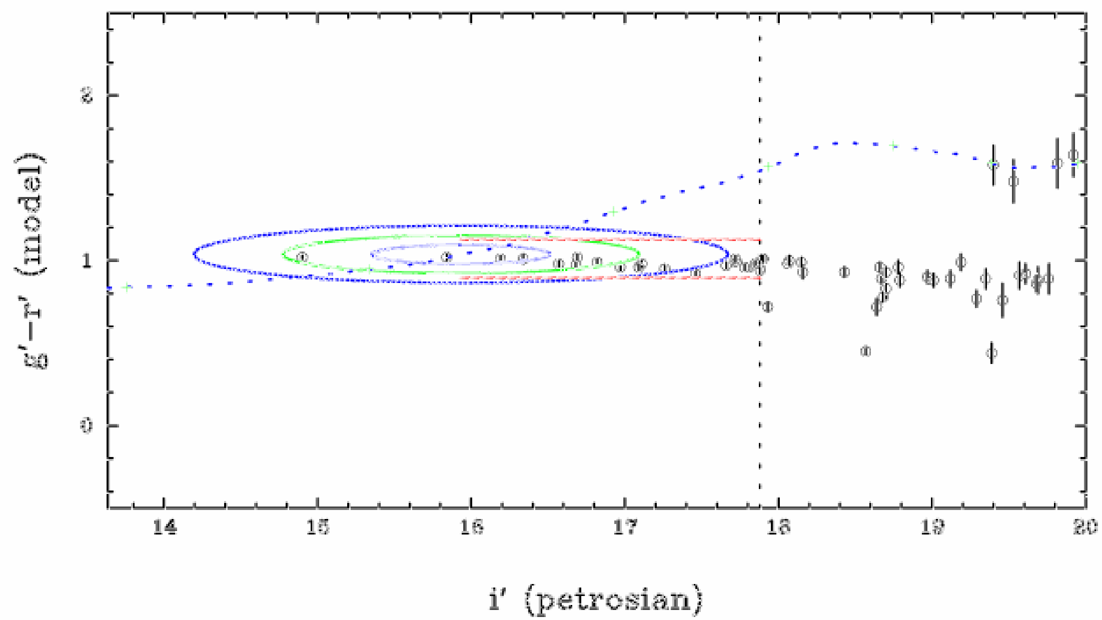
Borgani et al 2001

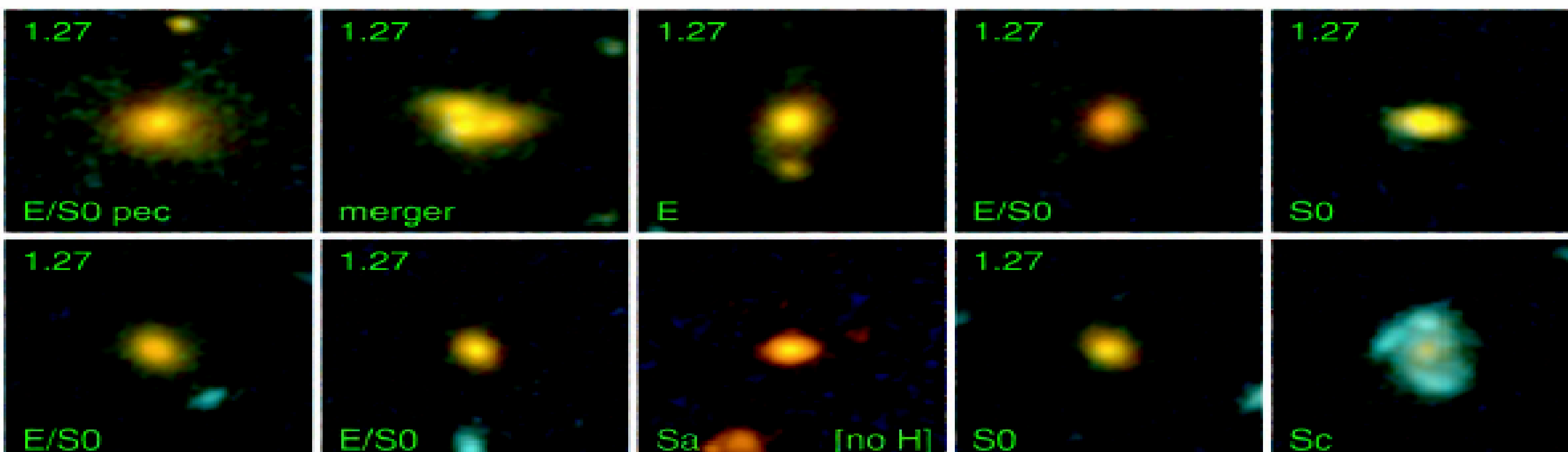


Cosmology with Clusters Surveys

Optical selection: Red cluster sequence

- Elliptical galaxies dominate the bright end of the galaxy population in a cluster
- They share very similar photometric properties (colours) and form a well defined sequence in colour-magnitude diagrams
  - Efficient selection
  - number of ellipticals correlate with mass with scatter: $N_E \alpha M^p$
  - provide a robust estimate of the cluster redshift


g′−r′ (model)
0
1
2
14
15
16
17
18
19
20
i′ (petrosian)


1.27
E/S0 pec
1.27
merger
1.27
E
1.27
E/S0
1.27
S0
1.27
E/S0
1.27
E/S0
Sa
[no H]
1.27
S0
Sc

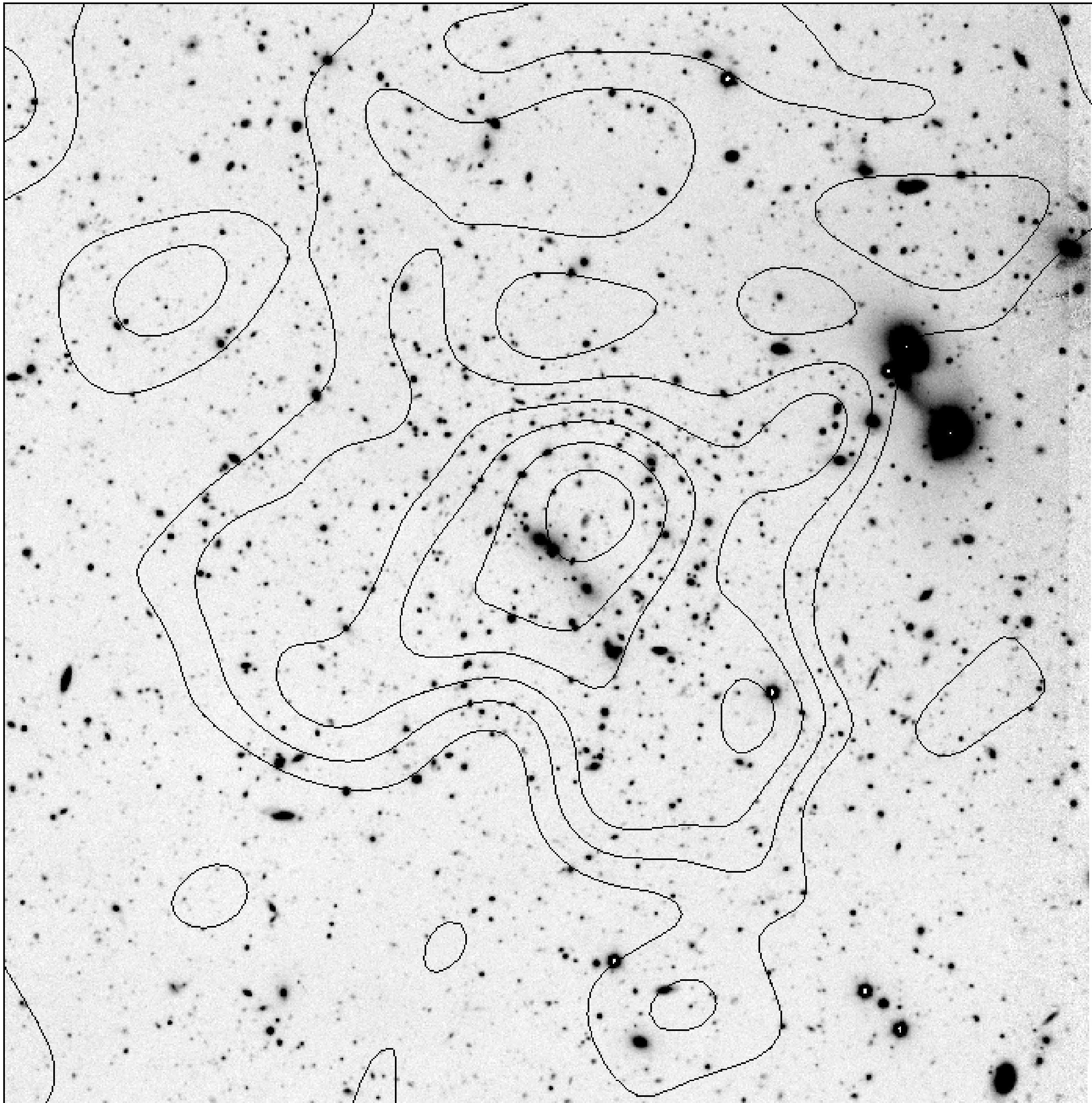
Cosmology with Clusters Surveys

Weak lensing selection

• Cluster can be selected by the lensing signatures imprinted on the background galaxy population

- Inefficient selection (noisy)
- directly select on PROJECTED mass

MS0016+16



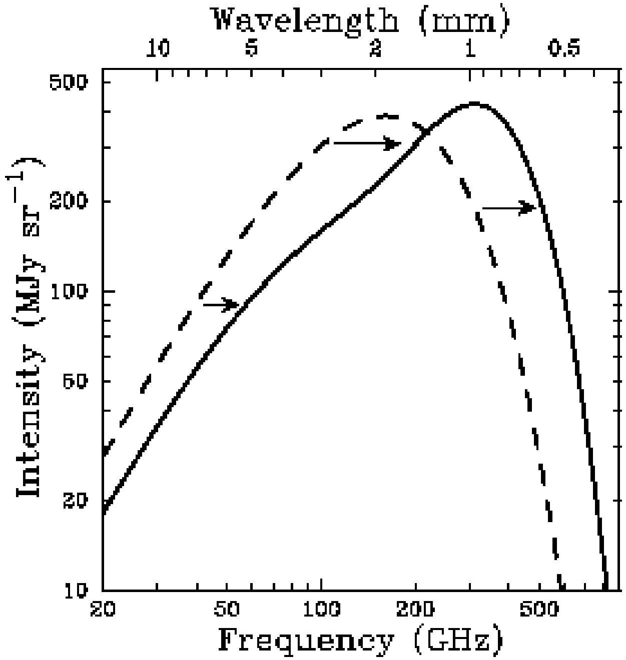
Cosmology with Clusters Surveys

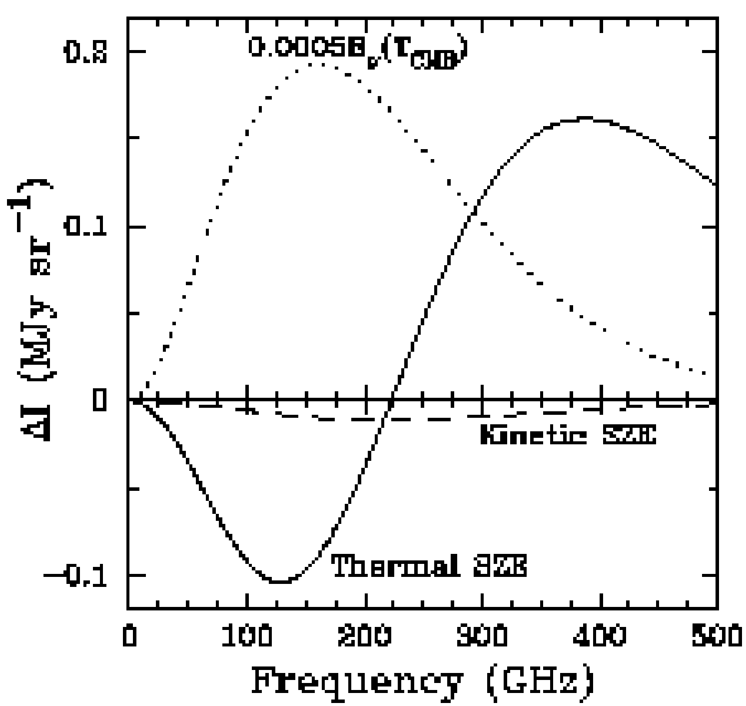
Sunyaev-Zeldovich selection

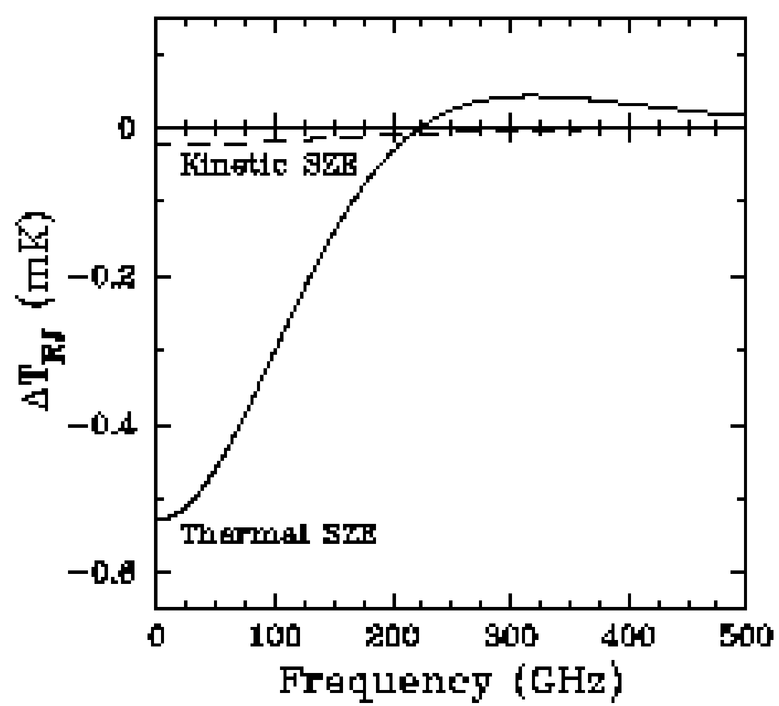
- The SZ effect is the change in the spectrum of the CMB radiation when it passes through the hot gas in a galaxy cluster: CMB photons are inverse Compton scattered

- $\Delta T/T \, \alpha \, \rho T$

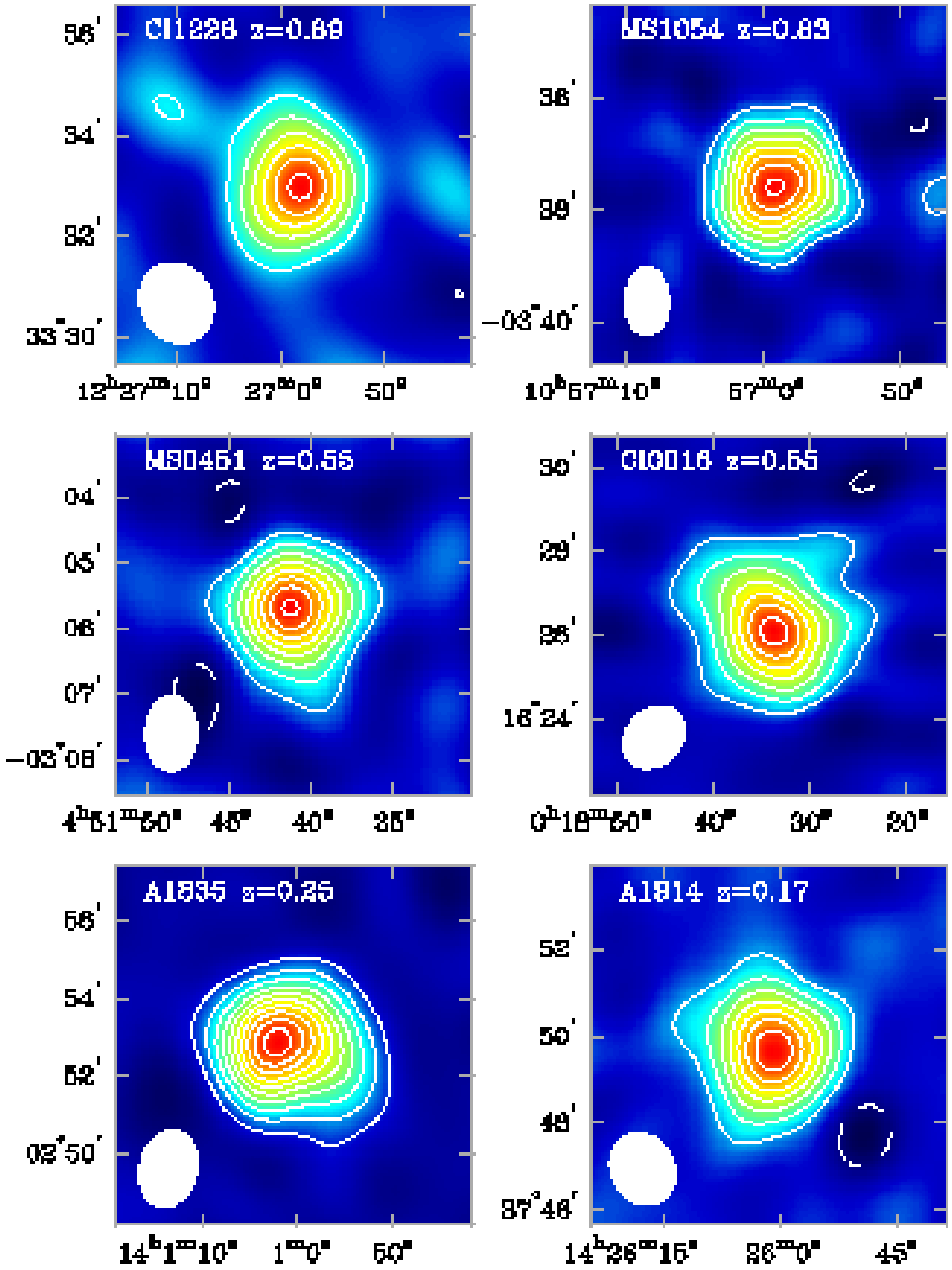
    - Challenging selection with current instruments
    - independent of redshift
    - the SZ signal correlates with mass with little scatter: $\Delta T/T \alpha$ M
    - confusion with CMB anisotropies if not enough resolution and spectral coverage

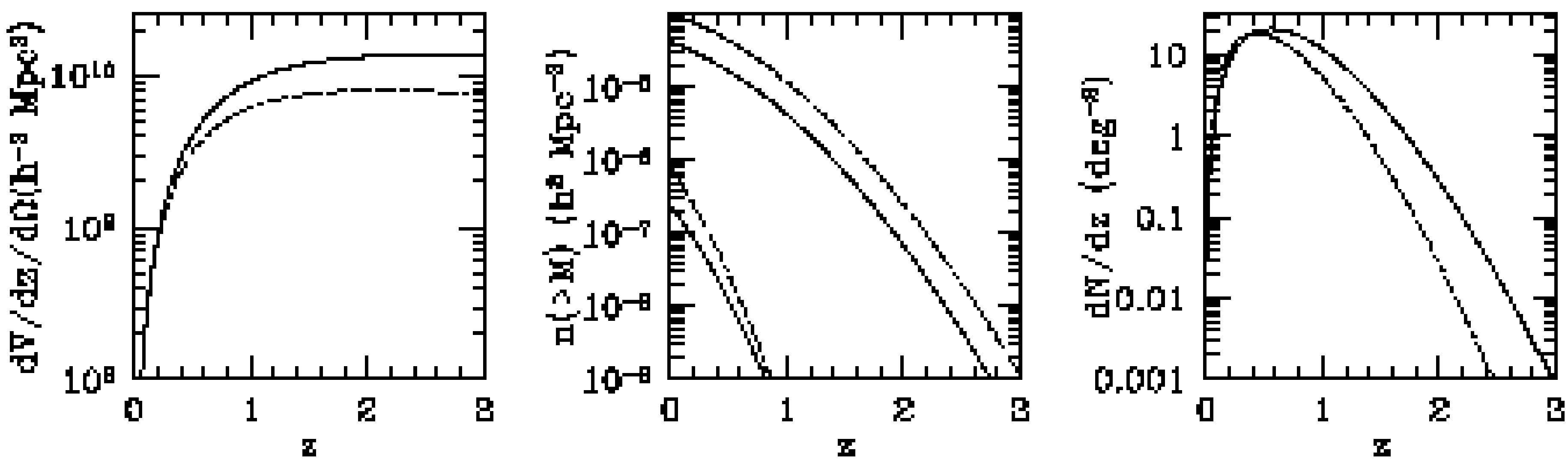

Wavelength (mm)
10
5
2
1
0.5
Intensity (MJy sr^{-1})
500
200
100
50
20
10
20
50
100
200
500
Frequency (GHz)


0.0005$B_\nu(T_{CMB})$
ΔI (MJy sr^{-1})
0.2
0.1
0
−0.1
Kinetic SZE
Thermal SZE
0
100
200
300
400
500
Frequency (GHz)


ΔT_{RJ} (mK)
0
−0.2
−0.4
−0.6
Kinetic SZE
Thermal SZE
0
100
200
300
400
500
Frequency (GHz)

Carlstrom et al 2004





Carlstrom et al 2004

Cosmology with Clusters Surveys

Summary conclusion

- Combination of current abundance evolution determinations indicate that $\Omega_M \sim 0.2\text{-}0.3$

Cosmology with Galaxy Clusters

Angular-diameter distance determination

- X-rays: S_X α D_A n_e2 $T^{1/2}$
- SZ: (ΔT/T) α D_A n_e T

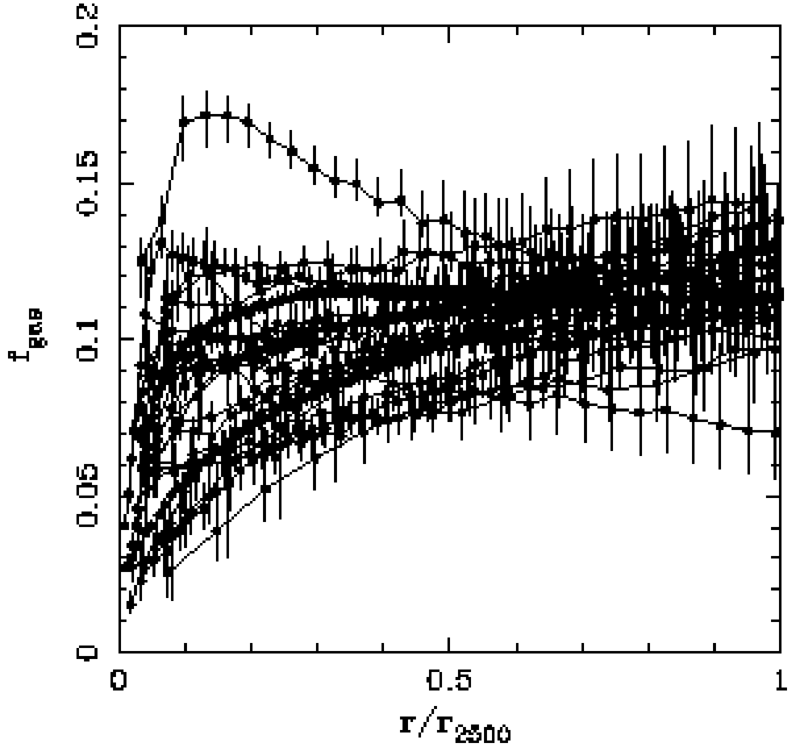
D_A α $(\Delta T/T)^2$ / S_X $T^{3/2}$

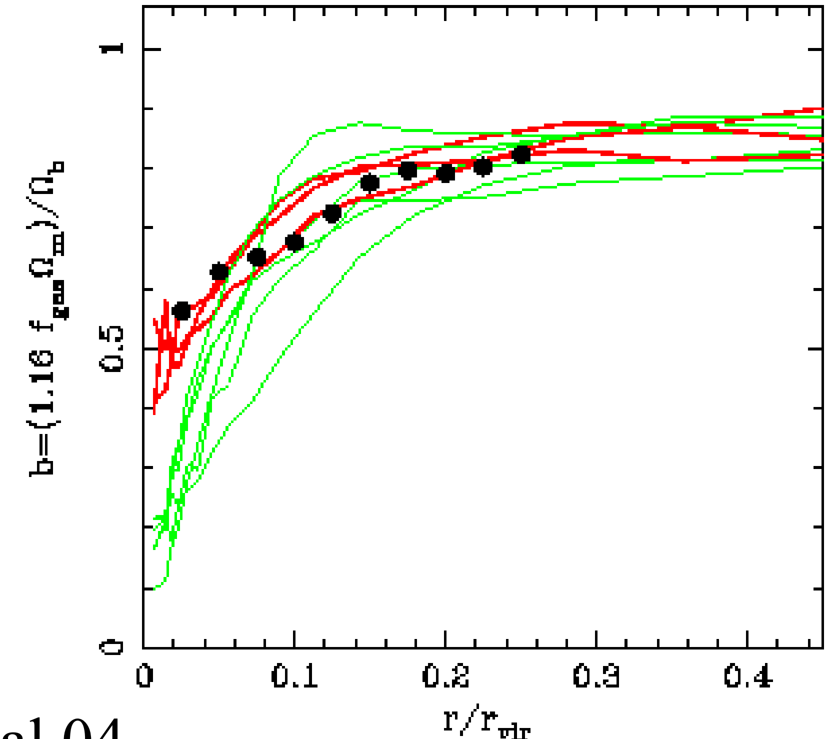
Cosmology with Clusters Surveys

Baryon fractions

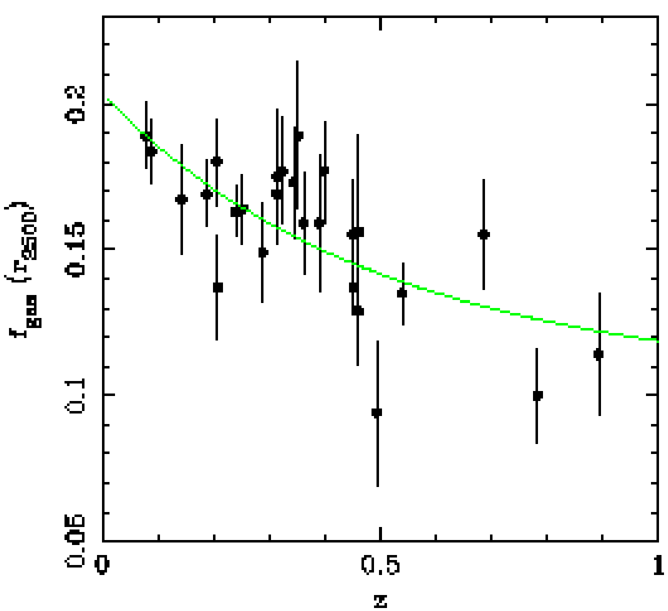
• Baryon fraction: clusters are fair samples of the overall mass composition of the universe

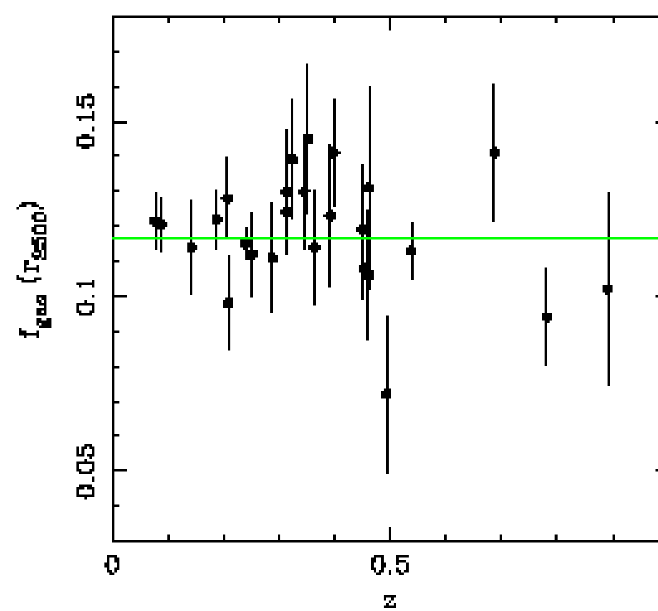
$f_B = \Omega_B/\Omega_M \quad => \Omega_M = \Omega_B/f_B$

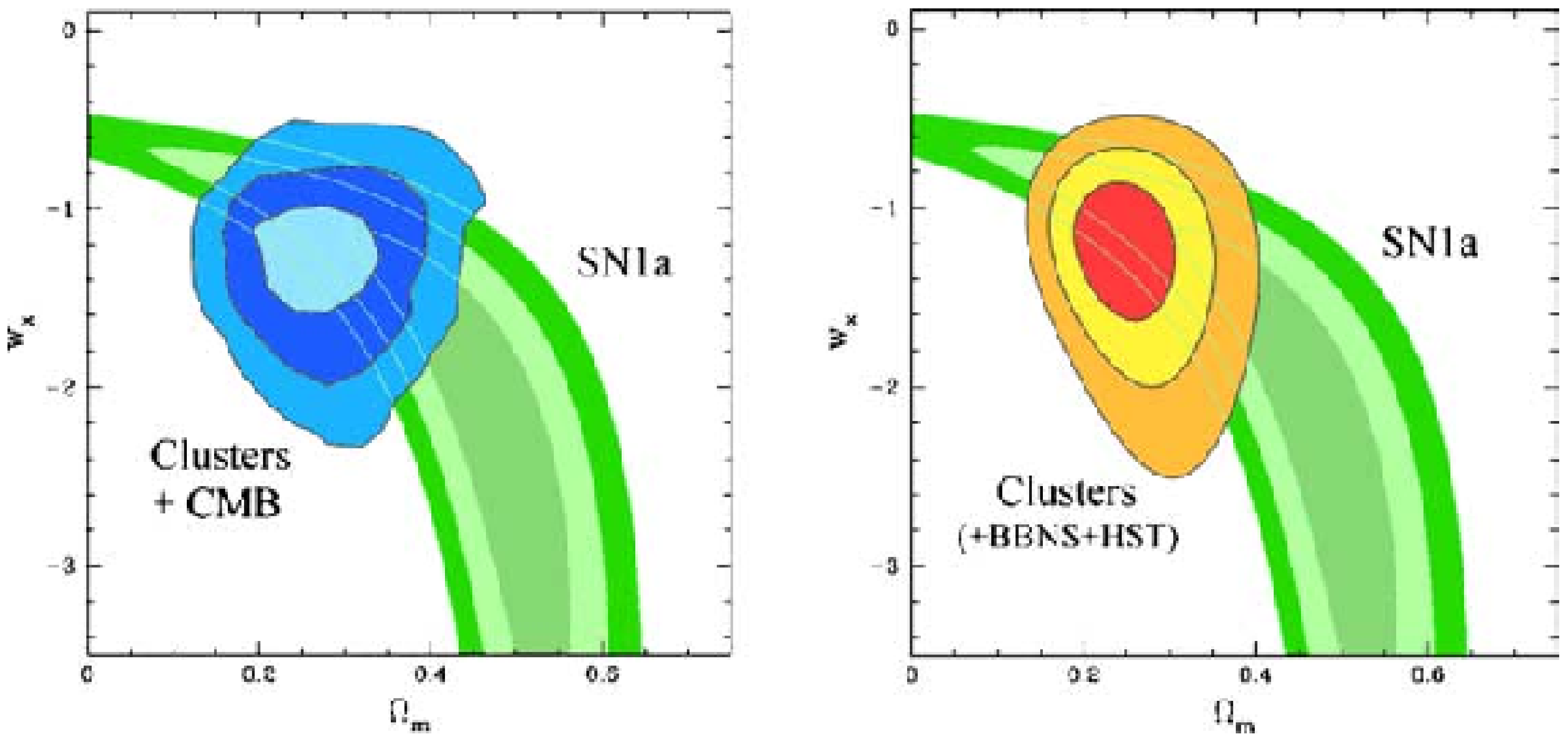




Allen et al 04





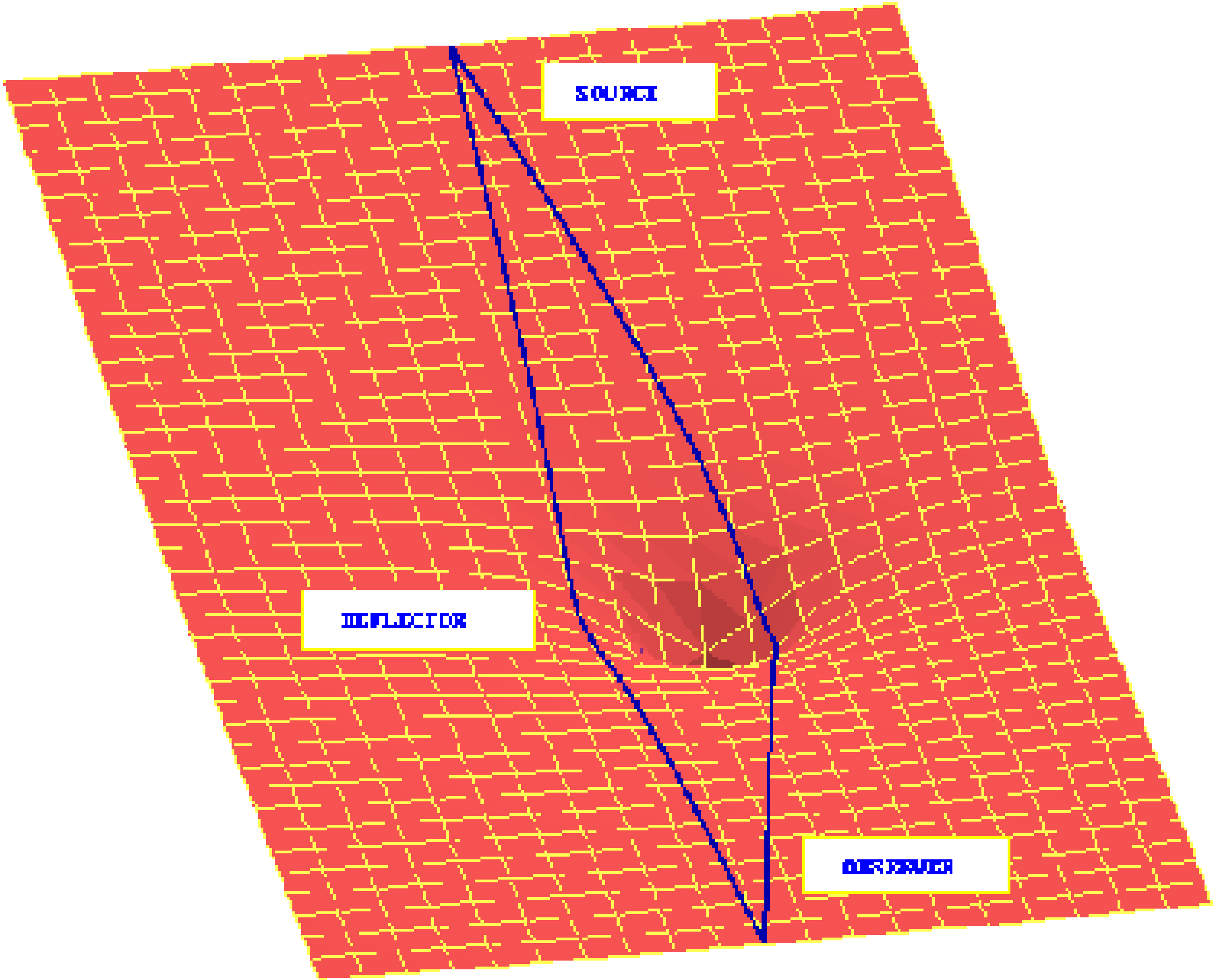


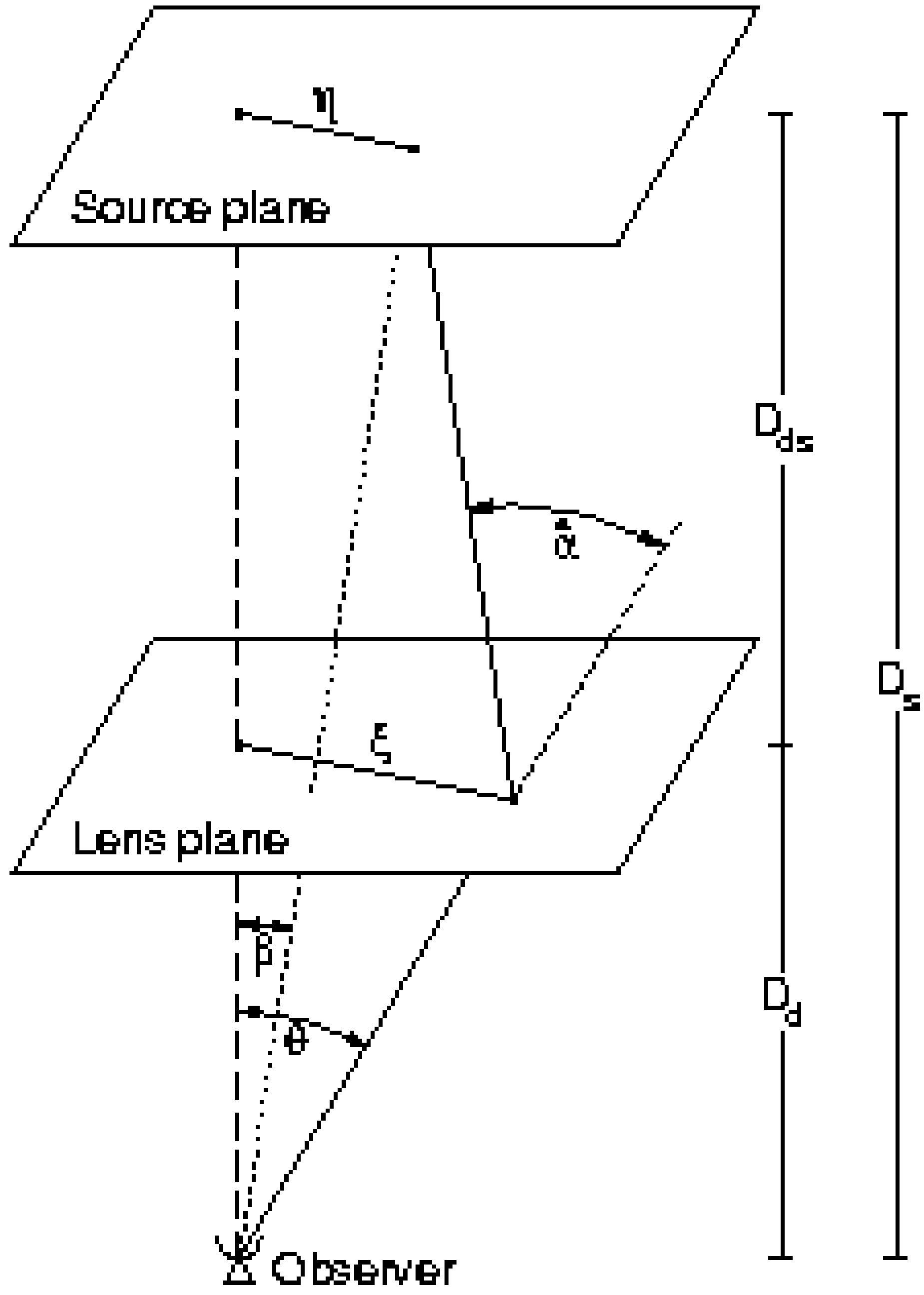
Allen et al 04

Gravitational Lensing

- Gravitational lensing is the deflection of light due to gravitational potentials

- Normally, three regimes are considered
  - Strong lensing
  - Weak lensing
  - Cosmic shear (Weak-weak lensing)


SOURCE
DEFLECTOR
OBSERVER



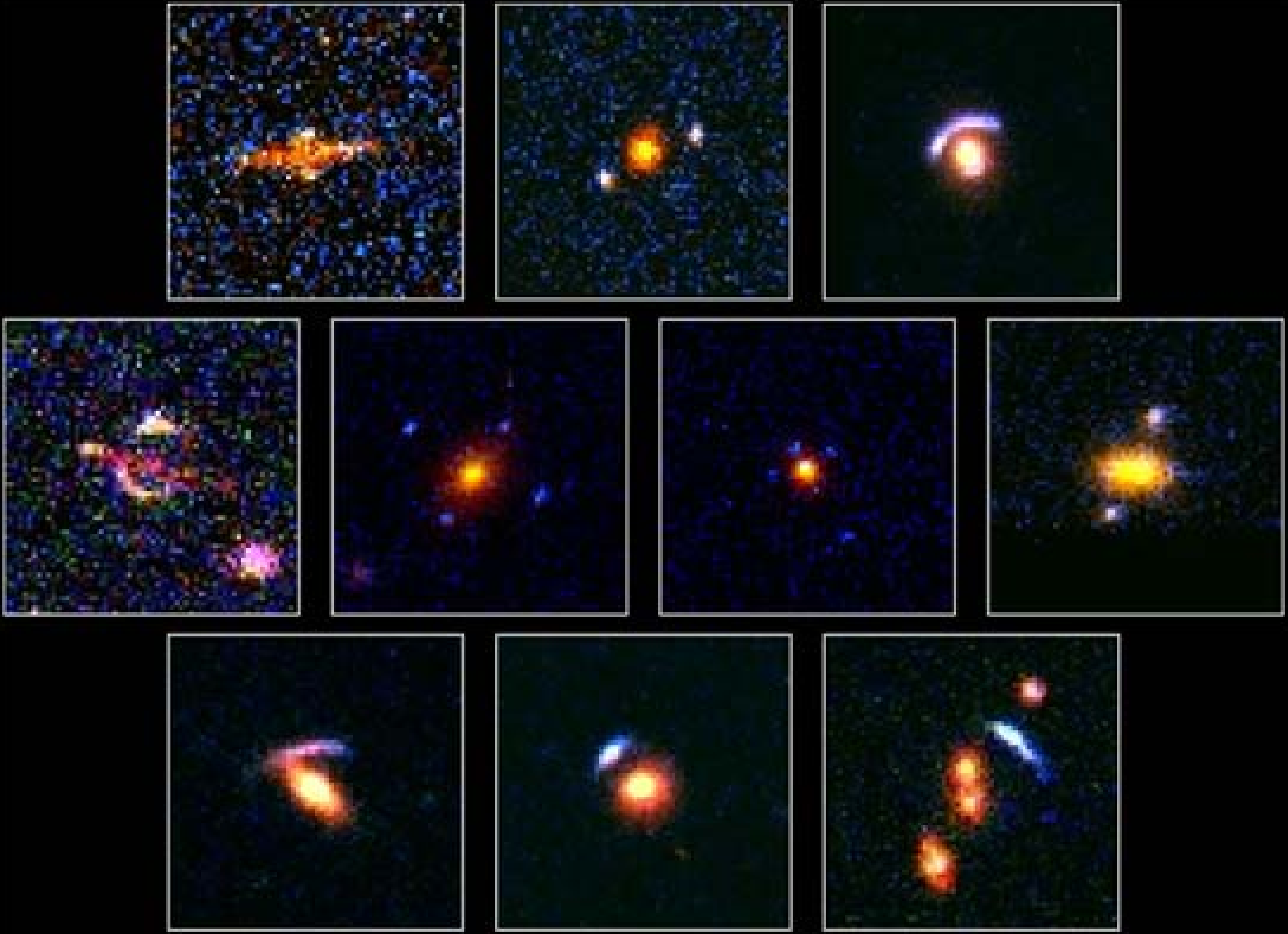
η
Source plane
D_{ds}
$\hat{\alpha}$
D_s
ξ
Lens plane
β
θ
D_d
Observer

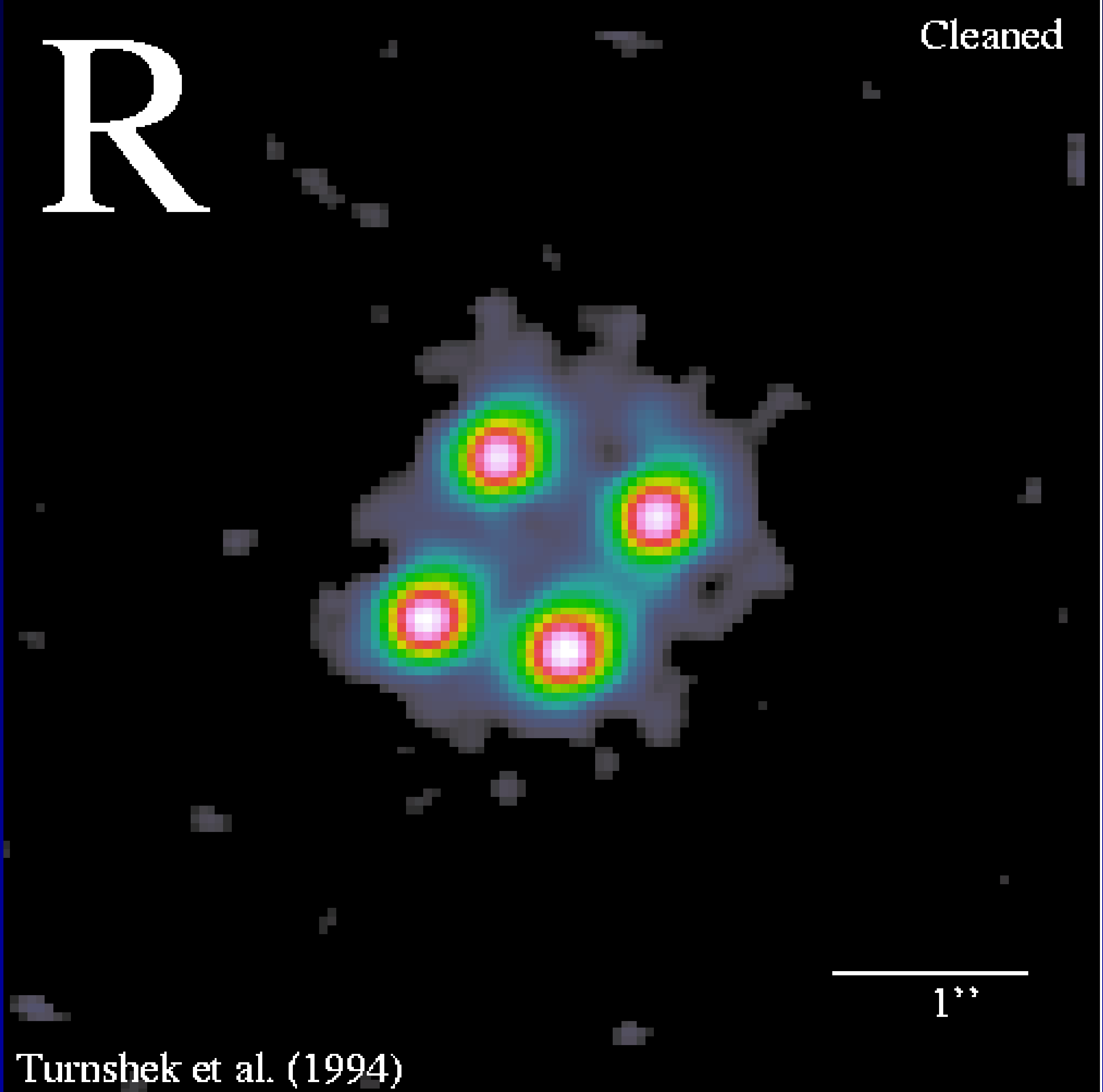
Gravitational Lensing

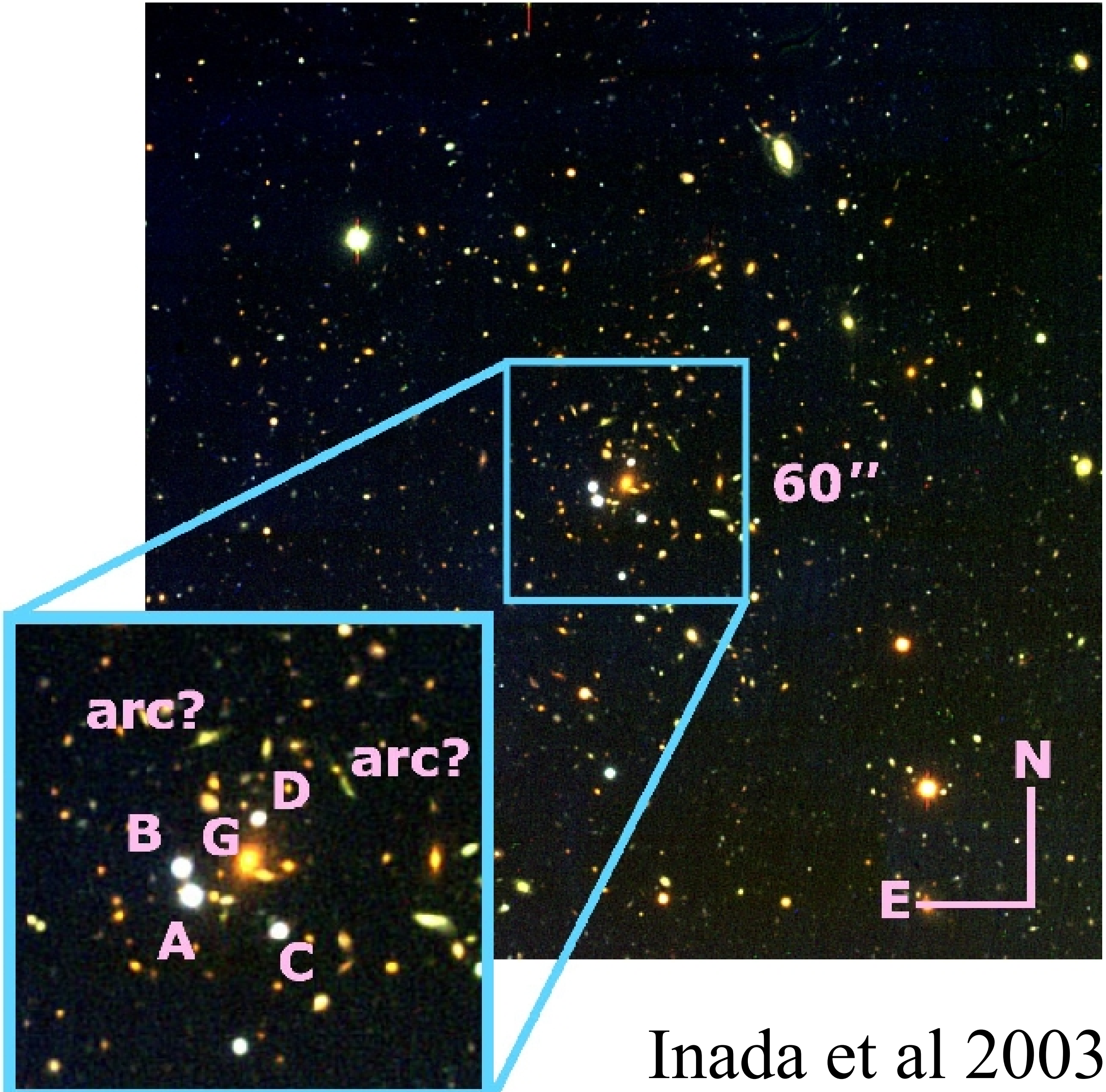
Strong Lensing

- Multiple images of the lensed background objects are produced

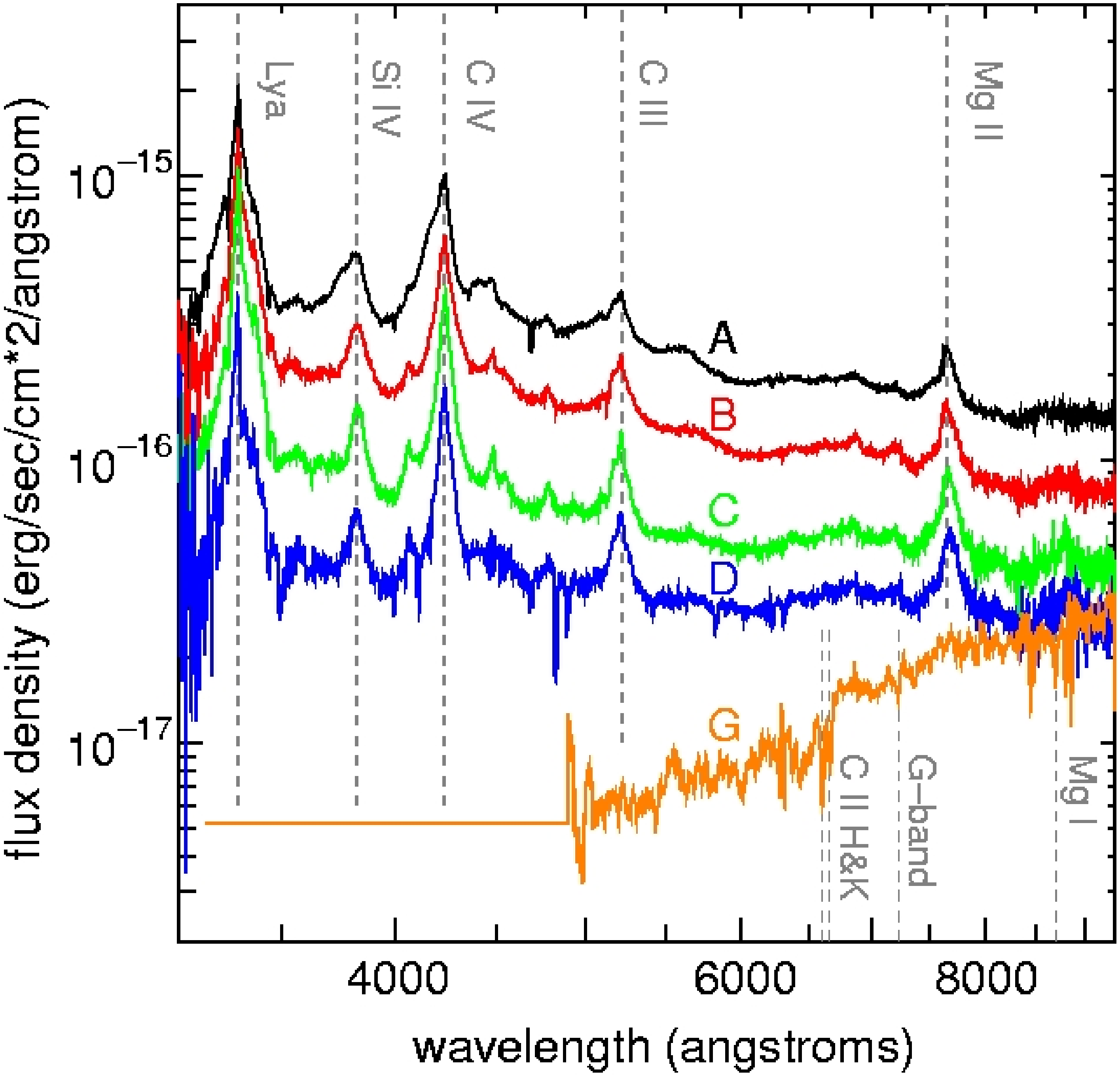
- Two types
  - Point sources (background QSOs) lensed by galaxies
  - Extended sources lensed by clusters



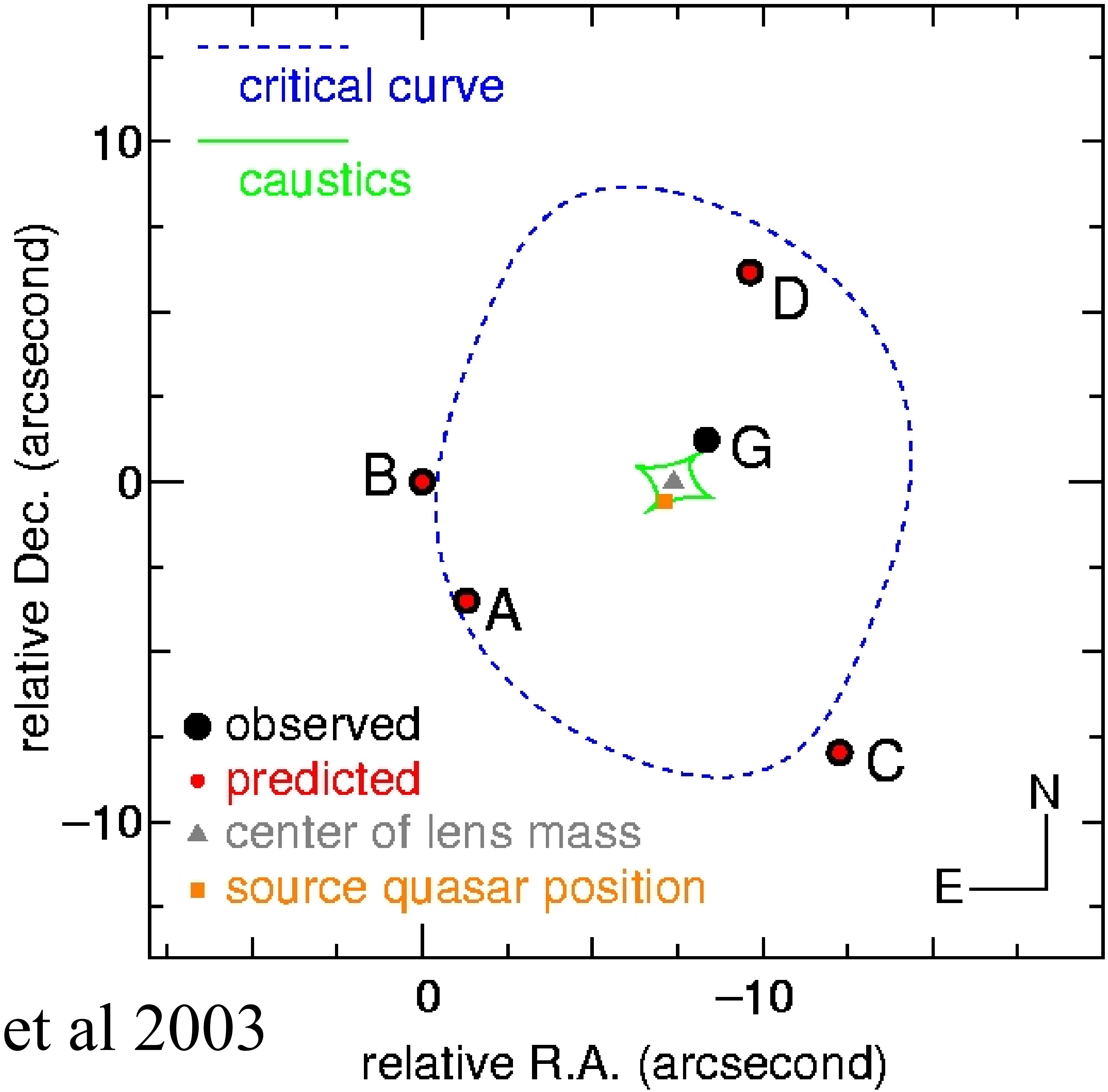

R
Cleaned
1''
Turnshek et al. (1994)



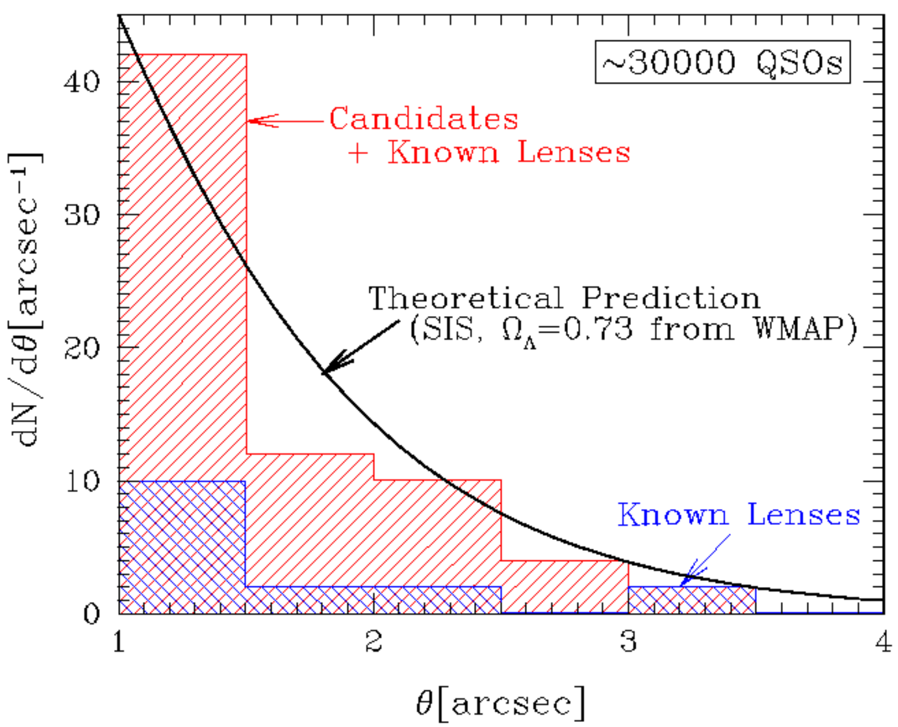
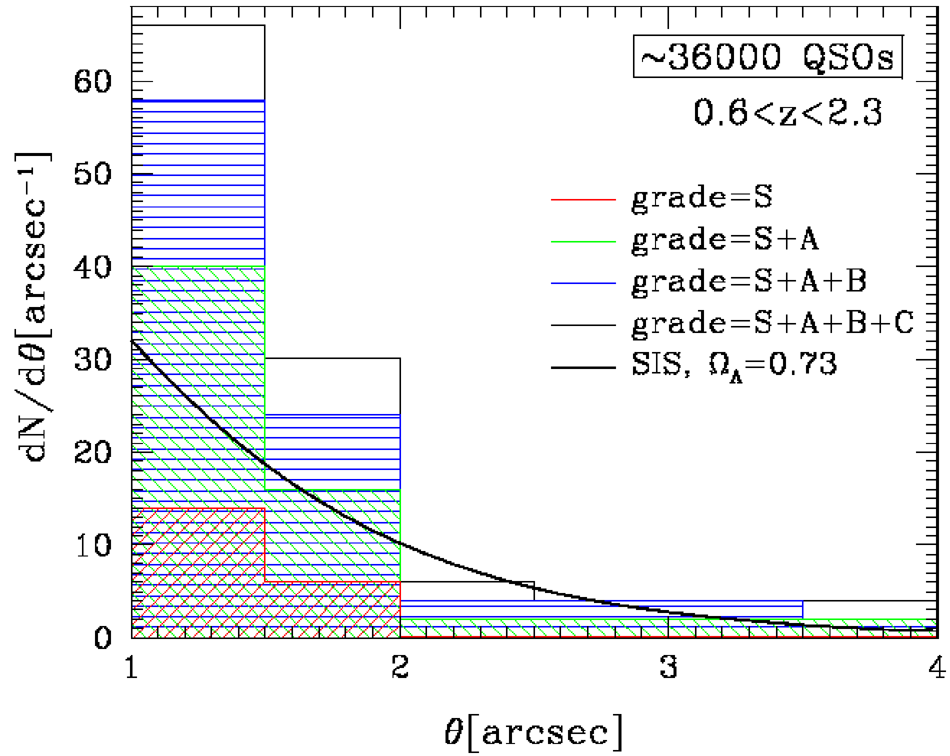
Inada et al 2003

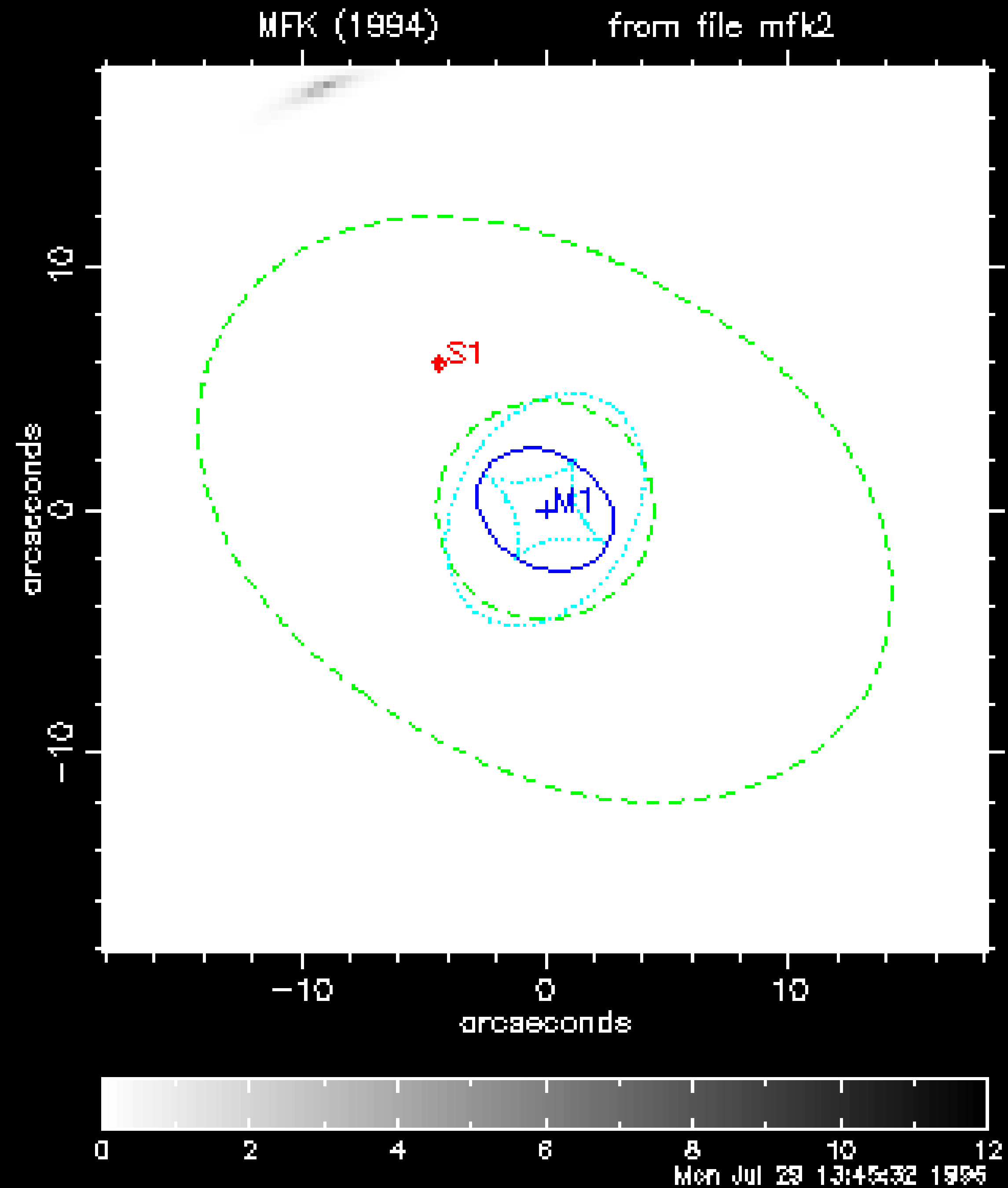


Inada et al 2003



Inada et al 2003


~30000 QSOs
Candidates
+ Known Lenses
Theoretical Prediction
(SIS, Ω_Λ=0.73 from WMAP)
Known Lenses
$dN/d\theta[\mathrm{arcsec}^{-1}]$
θ[arcsec]

~36000 QSOs
0.6<z<2.3
grade=S
grade=S+A
grade=S+A+B
grade=S+A+B+C
SIS, Ω_Λ=0.73
$dN/d\theta[\mathrm{arcsec}^{-1}]$
θ[arcsec]

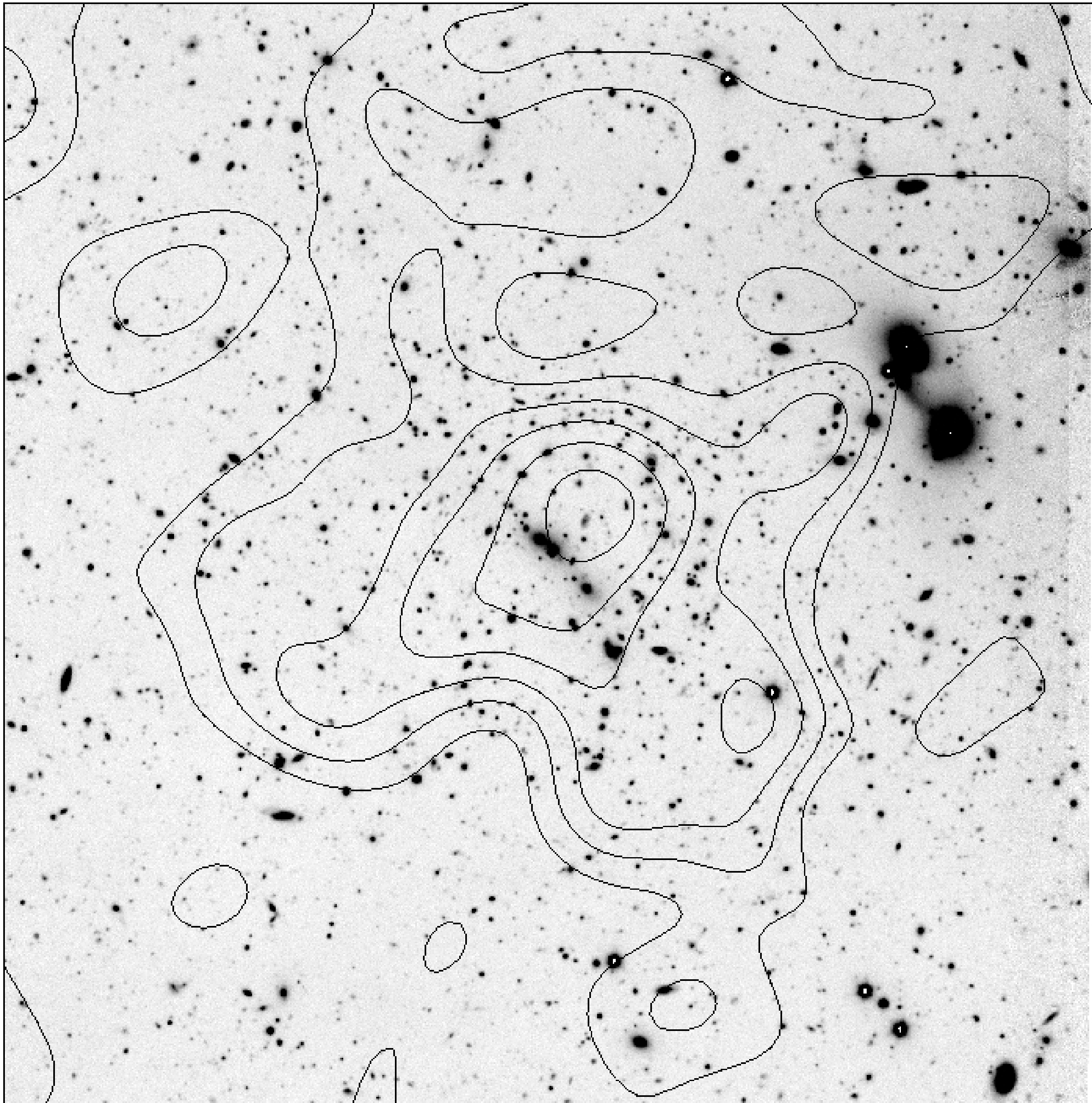

MFK (1994)
from file mfk2
10
0
−10
arcseconds
S1
M1
−10
0
10
arcseconds
0
2
4
6
8
10
12
Mon Jul 29 13:45:32 1996

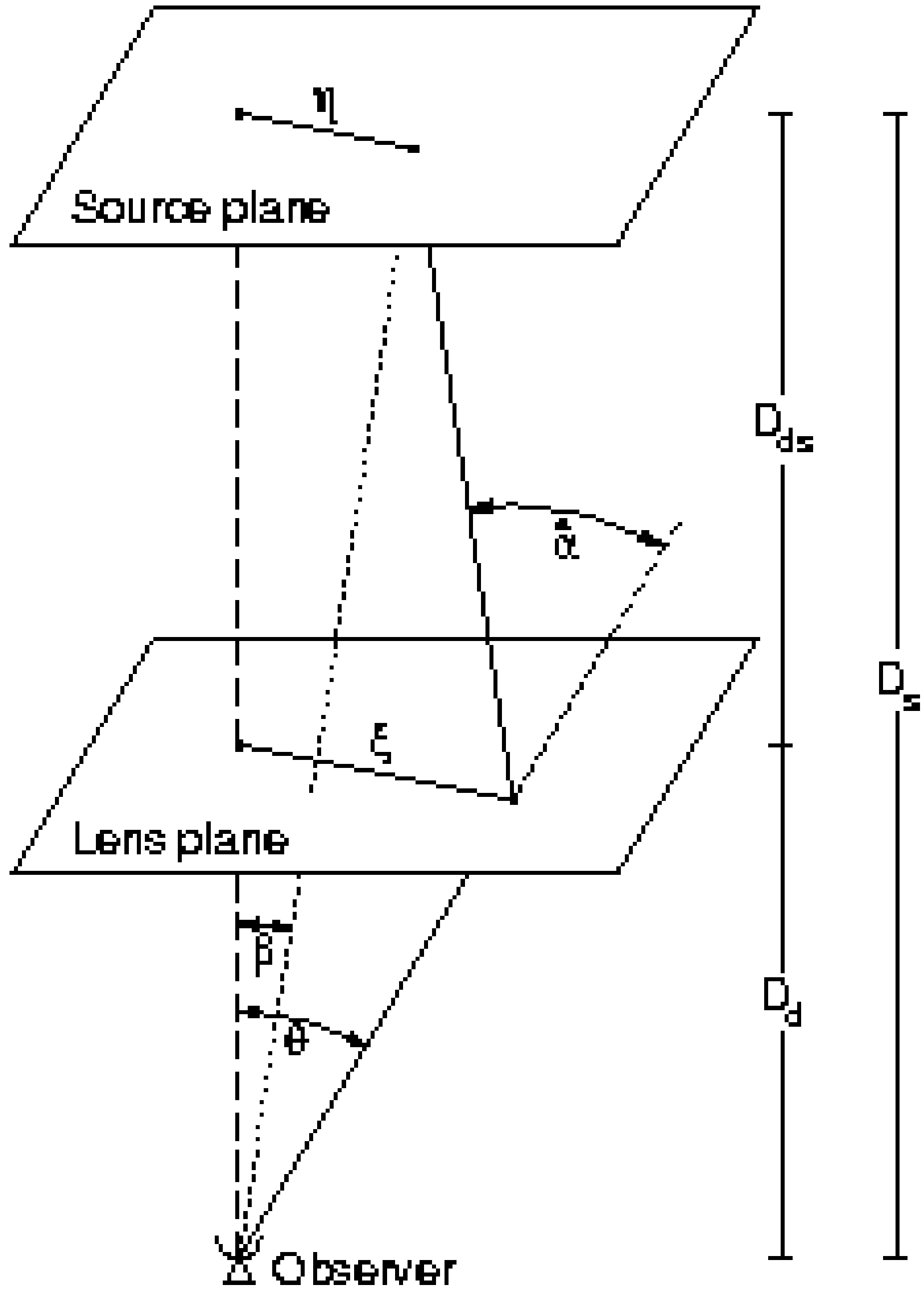
Gravitational Lensing

Weak Lensing

- Background galaxies are distorted and magnified/demagnified due to a large cluster gravitational potential

MS0016+16




η
Source plane
D_{ds}
$\hat{\alpha}$
D_s
ξ
Lens plane
β
θ
D_d
Observer

(Weak) Lensing equations

$$\vec{\eta} = \frac{D_s}{D_d}\vec{\xi} - D_{ds}\hat{\vec{\alpha}}(\vec{\xi}) \,.$$

$$\vec{\beta} = \vec{\theta} - \frac{D_{ds}}{D_s}\hat{\vec{\alpha}}(D_d\vec{\theta}) \equiv \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

$$\partial\vec{\beta} = \mathcal{A}\,\partial\vec{\theta}$$

$$\mathcal{A}(\vec{\theta}) = \left(\delta_{ij} - \frac{\partial^2\psi(\vec{\theta})}{\partial\theta_i\partial\theta_j}\right) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} ,$$

$$\Sigma(\vec{\xi}) \equiv \int dr_3\, \rho(\xi_1, \xi_2, r_3)$$

$$\kappa(\vec{\theta}) = \frac{\Sigma(D_d\vec{\theta})}{\Sigma_{cr}}$$

$$\Sigma_{cr} = \frac{c^2}{4\pi G}\,\frac{D_s}{D_d\,D_{ds}}$$

(Weak) Lensing equations

Lensing

- Observable: $\epsilon_i, m_i, a_i \rightarrow g_i, \mu_i \rightarrow \psi, M$

$$g_i = < \epsilon >$$

$$g_i = \frac{\gamma_i}{1-\kappa} \quad \left\{ \begin{array}{l} \kappa = \frac{1}{2}\left[\psi_{,11}(\theta) + \psi_{,22}(\theta)\right] \\ \gamma_1 = \frac{1}{2}\left[\psi_{,11}(\theta) - \psi_{,22}(\theta)\right] \\ \gamma_2 = \psi_{,12}(\theta) \end{array} \right.$$

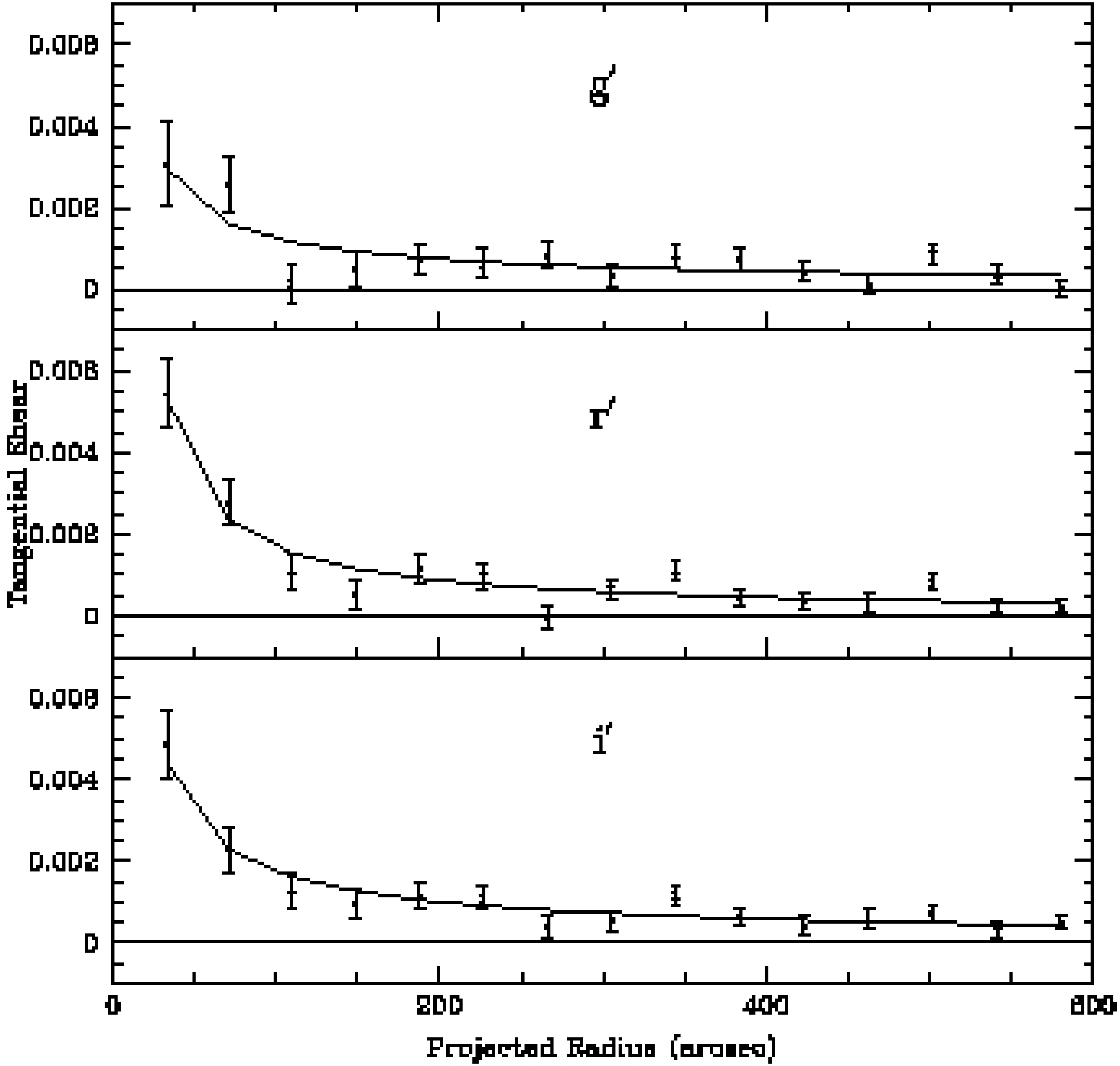
Gravitational Lensing

Weak weak lensing

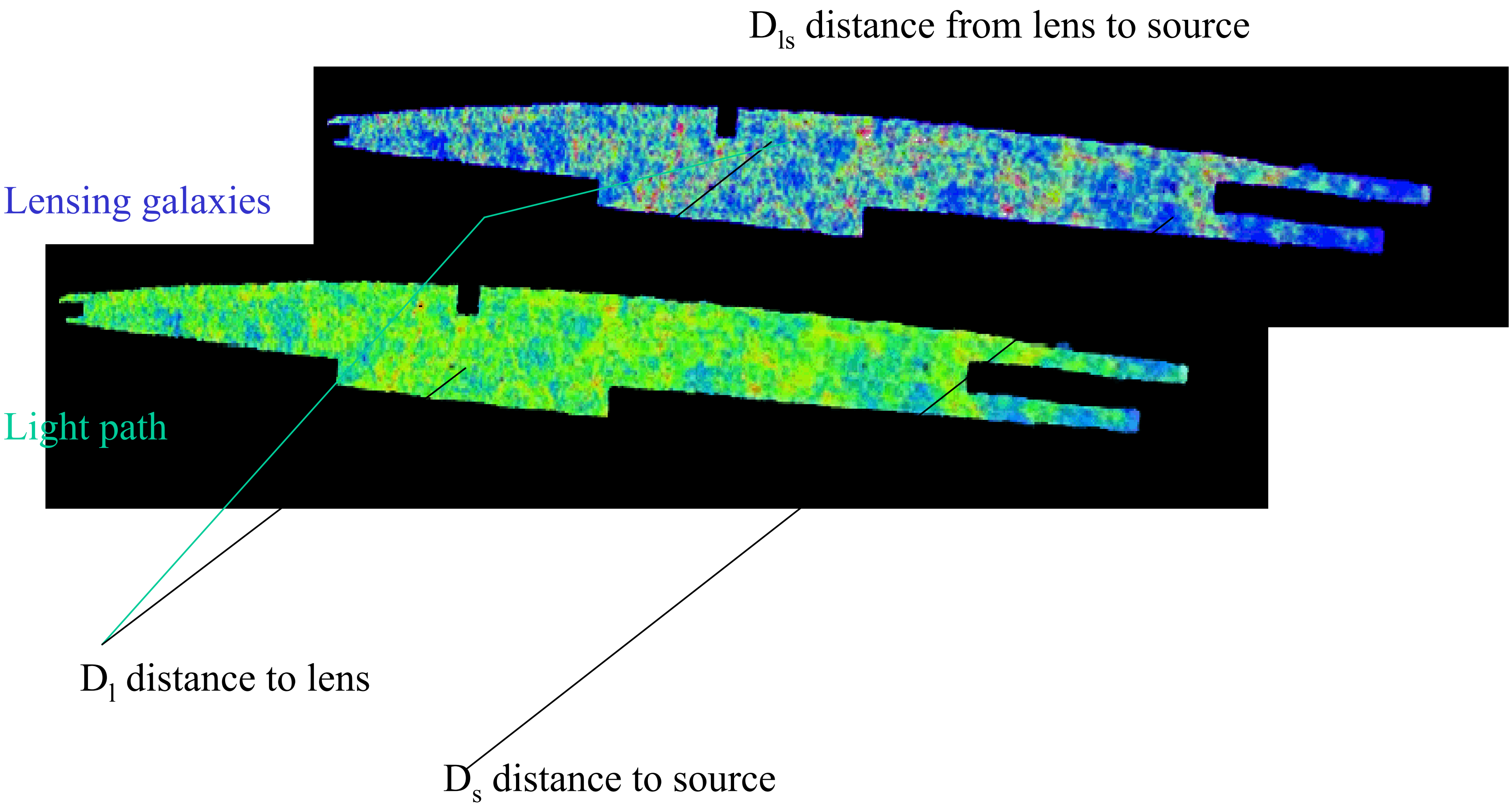
• Distortions produced in background galaxies due to foreground galaxies and/or large scale structures

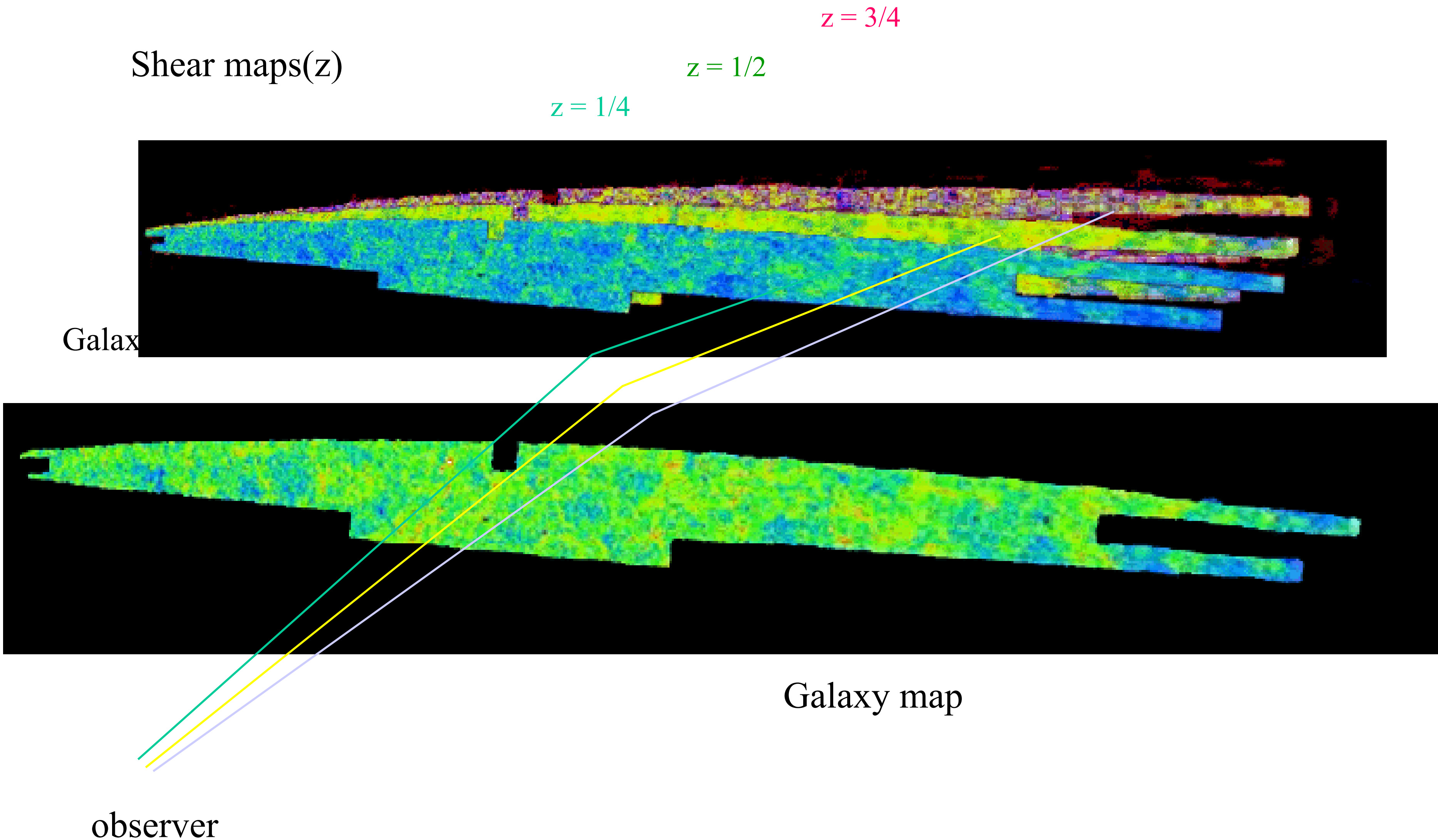
- Galaxy-shear correlations (galaxy-galaxy lensing)
- Shear-shear correlations (cosmic shear)

Fischer et al 2000



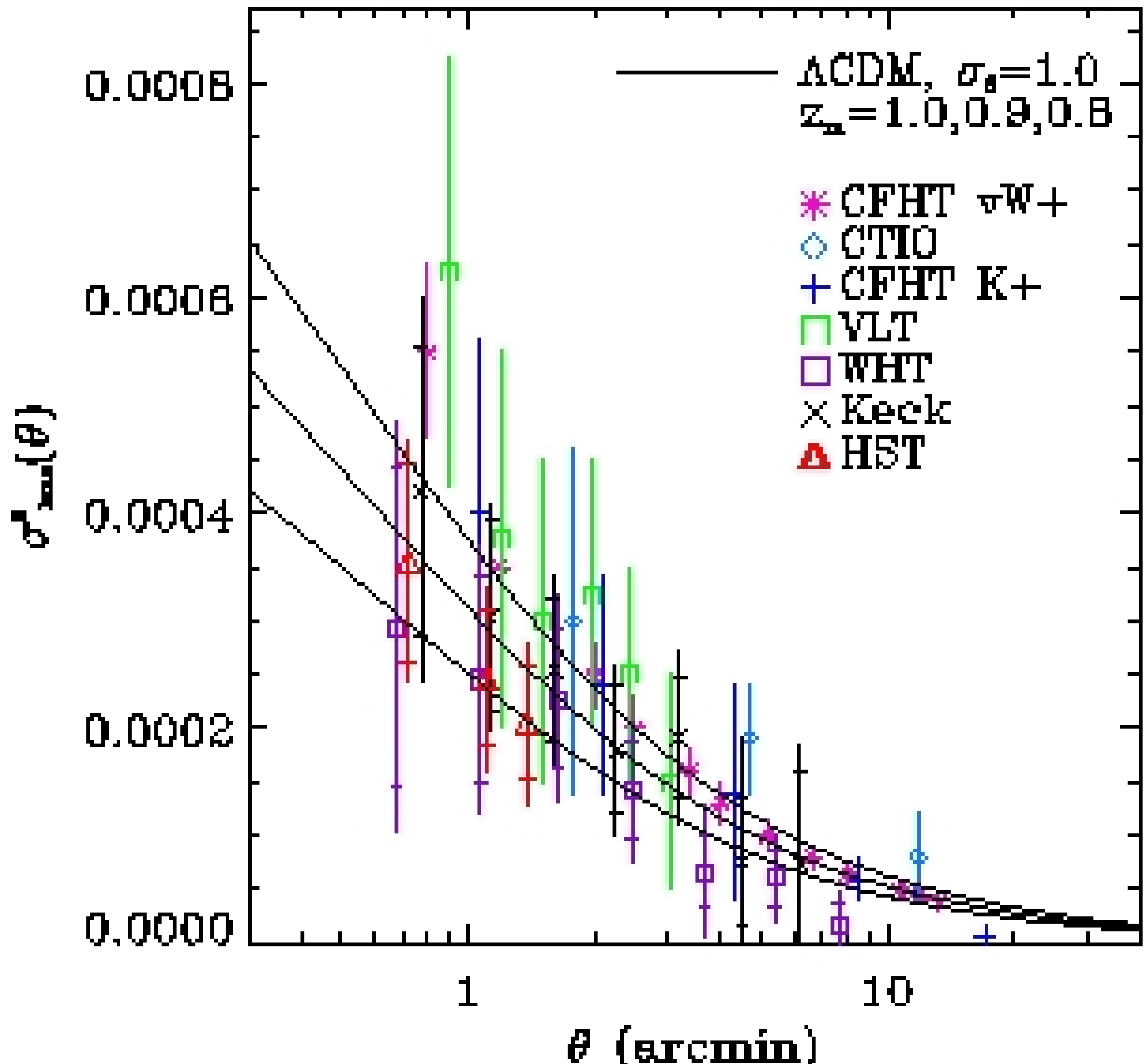
Background galaxy shear maps





z = 3/4
Shear maps(z)
z = 1/2
z = 1/4
Galax
Galaxy map
observer

van Waerbeke & Mellier 2003



Cosmology with LSS clustering

Evolution of density perturbations

- **Density perturbation** $\delta = \frac{\bar{\rho}}{\rho}$
- **Evolution** $\ddot{\delta} + \mathbf{H}\,\dot{\delta} - \frac{3}{2}\Omega_{\mathrm{M}}\mathbf{H}^2\delta = 0$
- **Growing mode solution: growth factor** $\delta = \mathbf{D}\,\delta_{\mathrm{o}}$

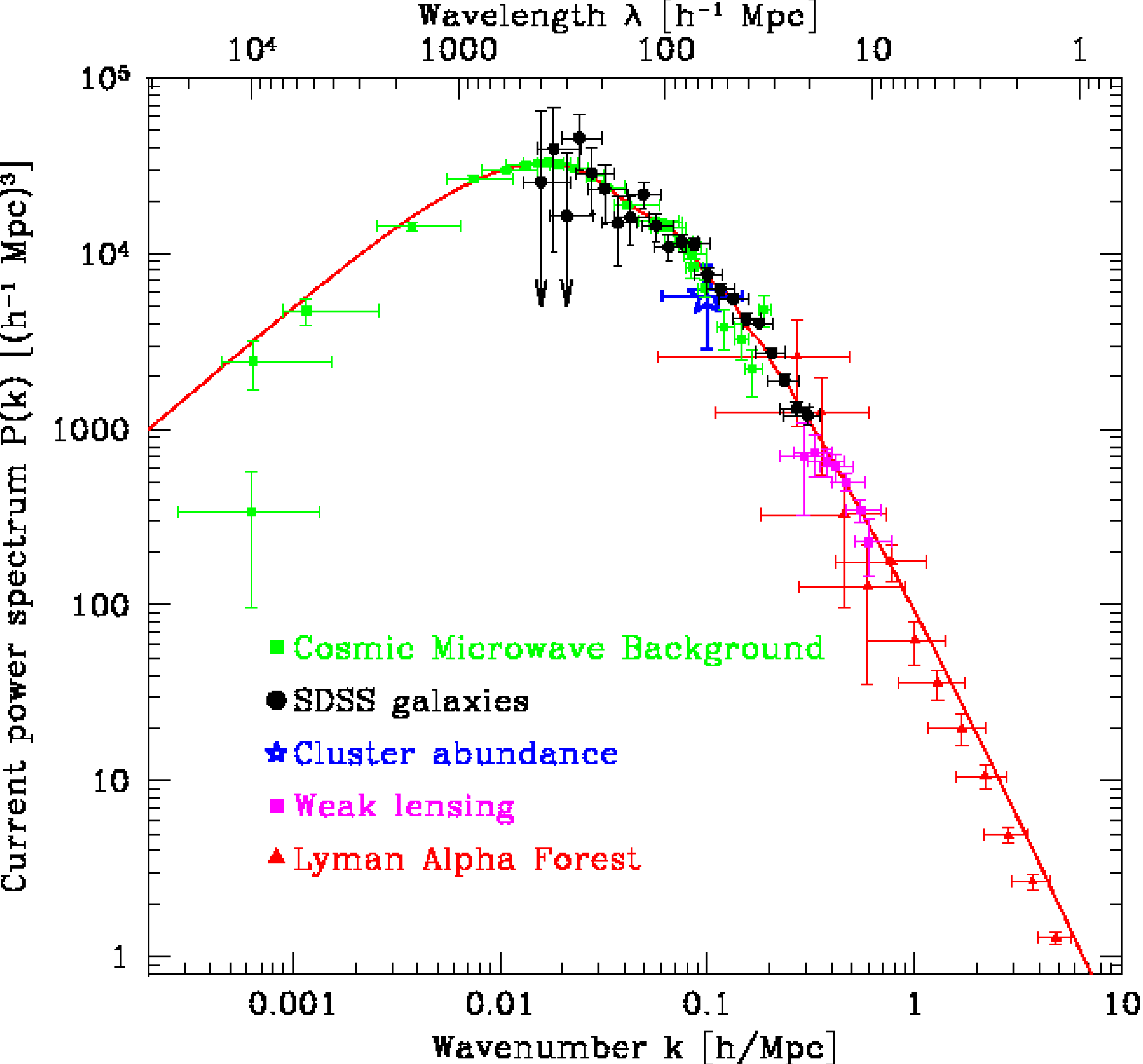
Cosmology with LSS clustering

Power spectrum

- **Fourier transform of density perturbation field**

$$\delta_{\mathbf{k}} = \frac{1}{\mathbf{V}} \int \mathbf{d}^3\mathbf{x}\, \delta(\mathbf{x})\, \mathbf{e}^{\mathbf{i}\,\mathbf{k}.\mathbf{x}}$$

- **Power spectrum** $|\delta_{\mathbf{k}}|^2 \propto \mathbf{k}^{\mathbf{n}}\, \mathbf{T}^2$



Tegmark et al 2003

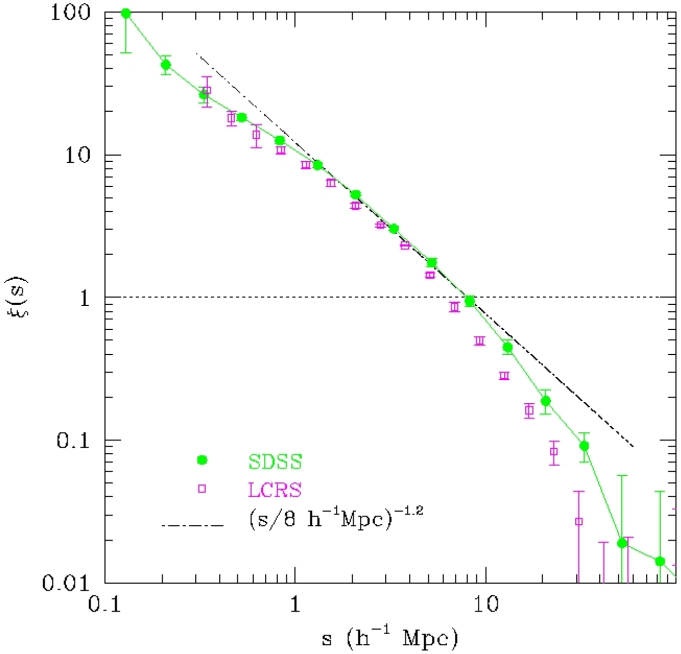
Cosmology with LSS clustering

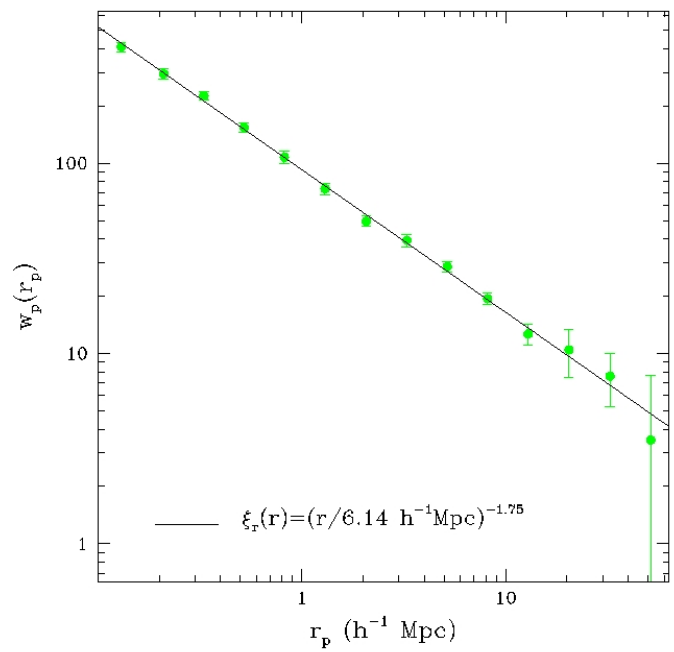
Correlation function

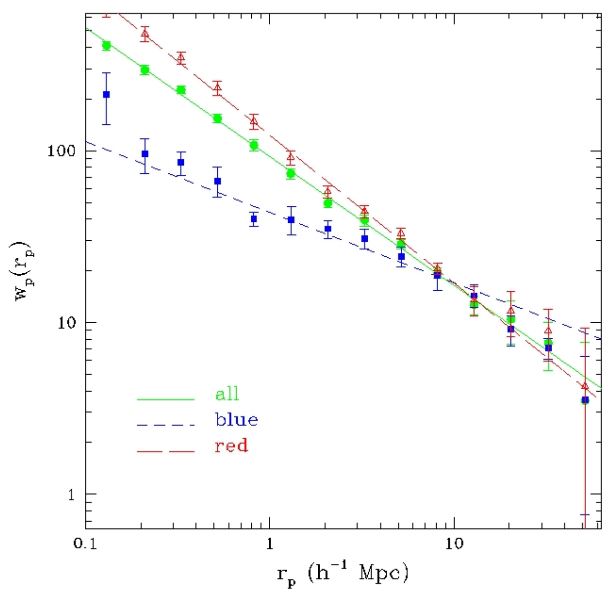
- Fourier transform of the power spectrum is the autocorrelation function

$$\xi(\mathbf{x}) = <\delta(\mathbf{x}')\delta(\mathbf{x}' - \mathbf{x})>_{\mathbf{x}'}$$

- Higher order correlations







Zehavi et al 2001

Cosmology with LSS clustering

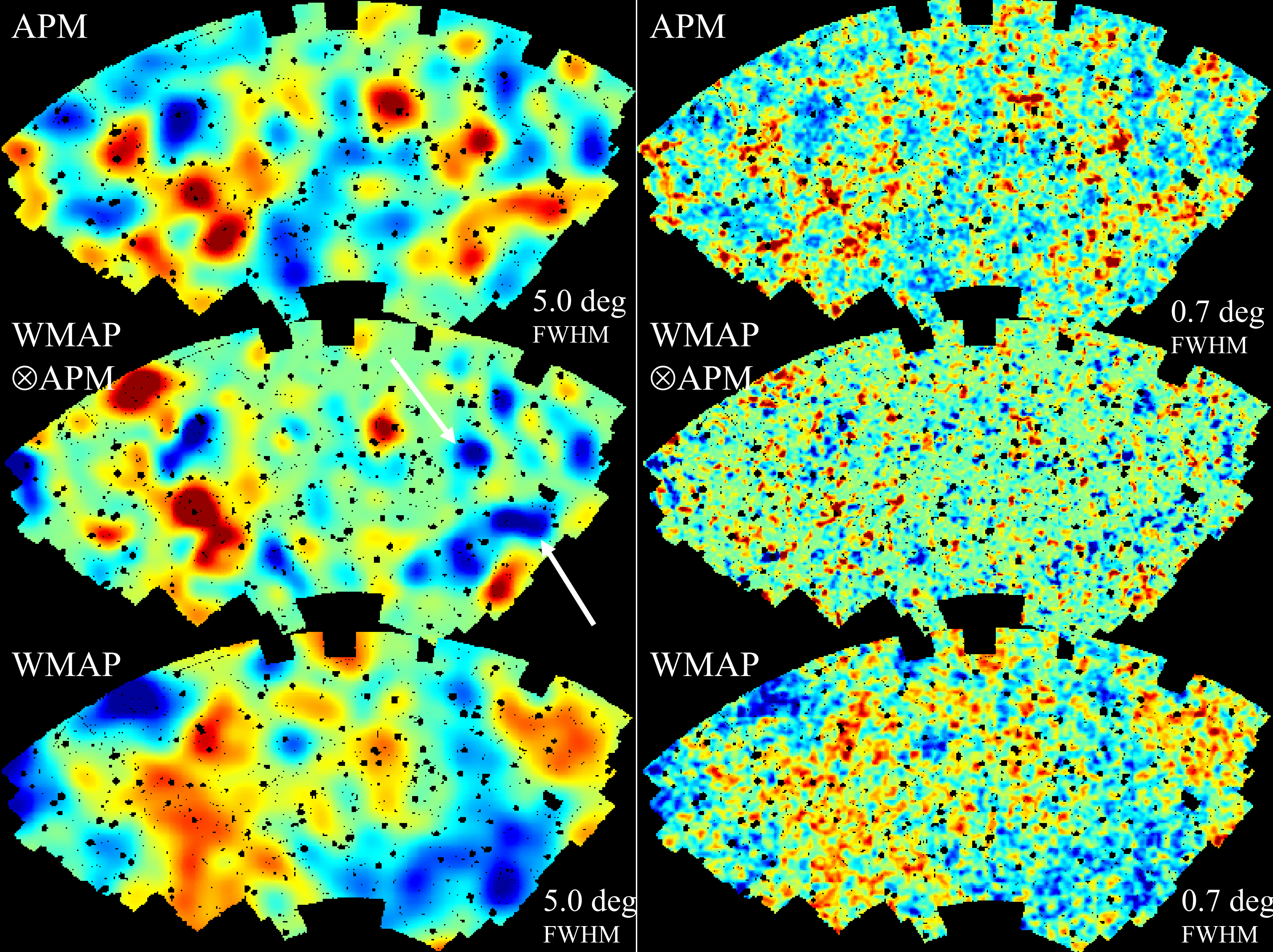
Baryon wiggles in galaxy distribution

Recently detected in the SDSS and 2dF surveys

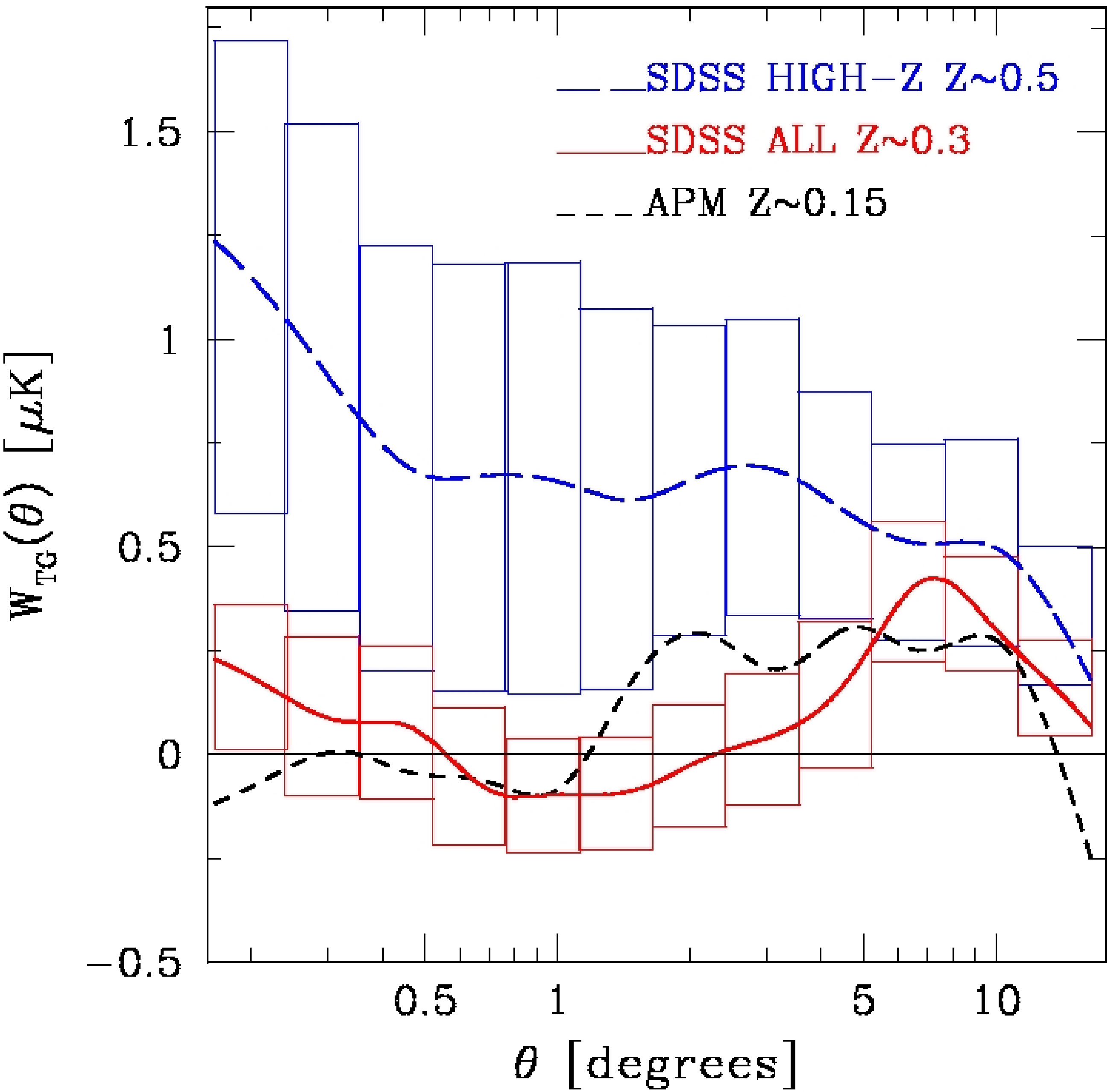
Cosmology with LSS clustering

Integrated Sachs-Wolfe effect

Recently detected cross-correlating WMAP with other “local” tracers, in particular the SDSS and APM surveys


APM
5.0 deg
FWHM
WMAP
⊗APM
WMAP
5.0 deg
FWHM
APM
0.7 deg
FWHM
WMAP
⊗APM
WMAP
0.7 deg
FWHM

Fosalba et al 2003



Data Compilation

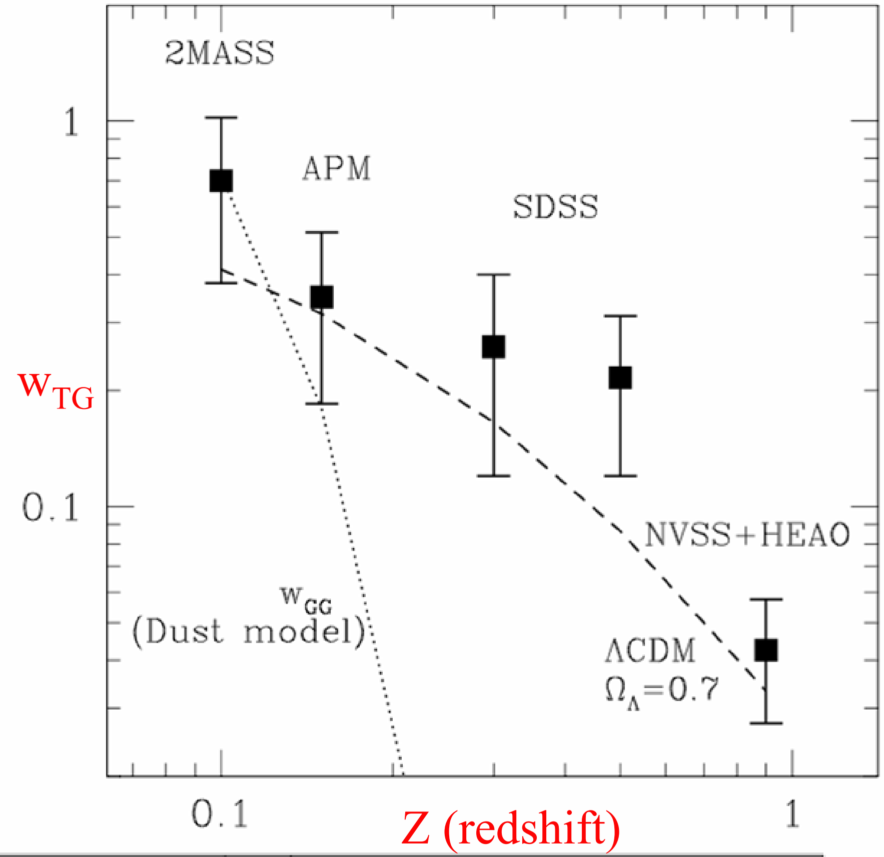
EG, Manera, Multamaki (astro-ph/ 0407022)

Coverage: *z= 0.1 - 1.0*

Area 4000 sqrdeg to All sky

Bands: *X-ray,Optical, IR, Radio*

Sytematics: *Extinction & dust in galaxies.*



$\bar{z}$	w_{TG}/b	b	catalog, Band
0.1	0.70 ± 0.32	1.1	2MASS, infrared ($2\mu m$)
0.15	0.35 ± 0.17	1.0	APM, optical (b_j)
0.3	0.26 ± 0.14	1.0	SDSS, optical (r)
0.5	0.216 ± 0.096	2.4	SDSS high-z, optical (r+colors)
0.9	0.043 ± 0.015	1-2	NVSS+HEAO, Radio & X-rays

TABLE I: Compilation of observed cross correlation w_{TG}/b (averaged for $\theta \simeq 4-10^\circ$.) of WMAP anisotropies with different catalogs. Error in w_{TG}/b includes 20% uncertainty in b.

WMAP team (Nolta et al., astro-ph/0305467) and Boughm & Crittenden (astro-ph/0305001). Radio Galaxies (NVSS) + X-ray HEAO (both at z =0.8-1.1)

APM (Fosalba & EG astro-ph/05468)

z=0.15-0.3

SDSS (Fosalba, EG, Castander, astro-ph/0307249) z=0.3-0.5

SDSS team (Scranton et al 0307335)

2Mass (Afshordi et al 0308260) z=0.1

Cosmology Probes: the future

- Cosmic Microwave Background Radiation
- Supernovae
- Ages
- Gravitational Lensing
- Large Scale Structure
  - Clustering
  - Abundances

Cosmology Probes: the future

- Cosmic Microwave Background radiation
  - WMAP 2nd year release
  - Ground-based / balloon experiments
  - Planck

Cosmology Probes: the future

- Supernovae
  - Essence
  - ESO Key-project
  - Carnegie (LCO)
  - SDSS-II
  - DES
  - LSST
  - SNAP

Cosmology Probes: the future

- Ages (expansion rate)
  - Gravitational lensing (time delays)
  - cluster X-ray – SZ combination

Cosmology Probes: the future

- Gravitational lensing
  - WLS
  - CFHLS
  - DES
  - LSST
  - SNAP

Cosmology Probes: the future

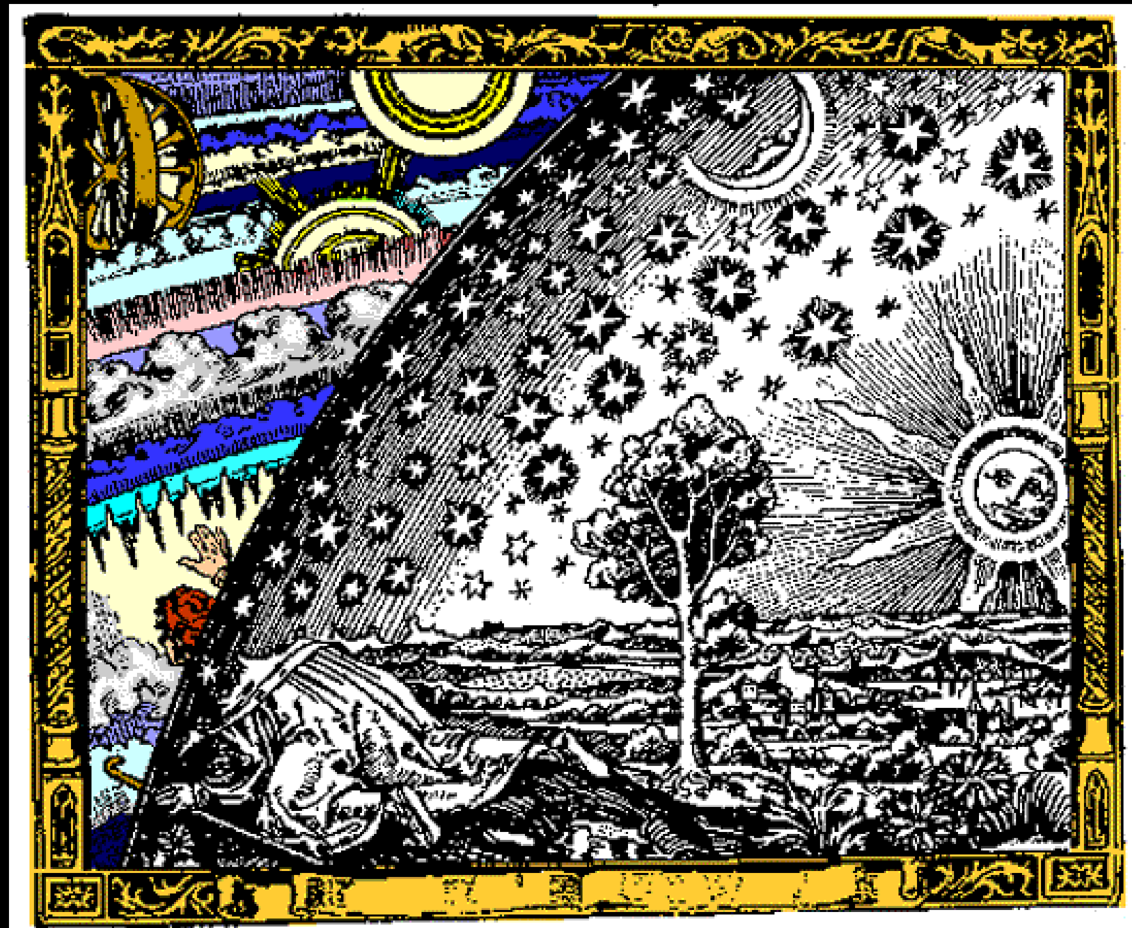
- Large Scale Structure: clustering
  - Several surveys: CFHLS, NOAO Deep Survey, VVDS, Deep-II,…
  - DES
  - LSST
  - SNAP

Cosmology Probes: the future

- Large Scale Structure: abundances
  - X-ray surveys: XMM-Newton & Chandra
  - RCS
  - SZ surveys: SPT
  - DES
  - LSST

IEEC

CSIC



The Science Case for the Dark Energy Survey

Institut de Física d'Altes Energies

IFAE

NCSA

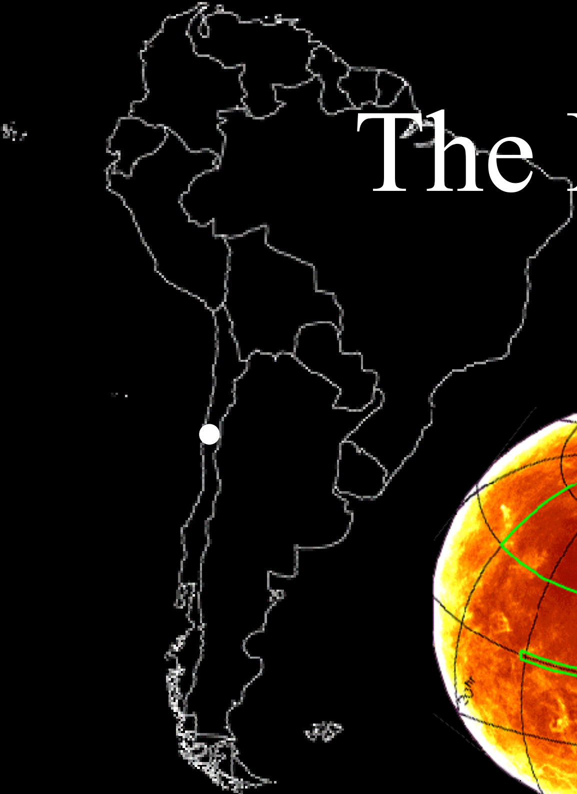
BERKELEY LAB

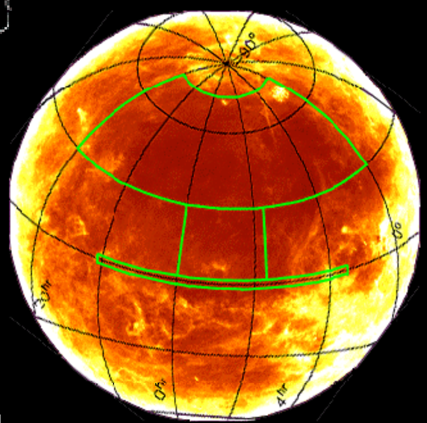
Announcement of Opportunity

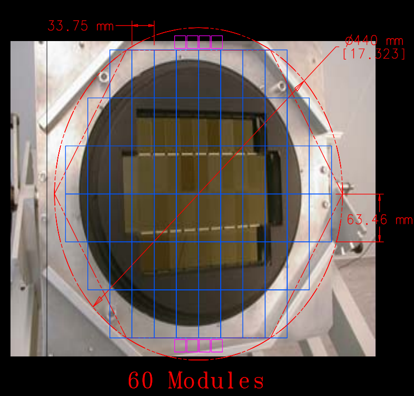
Blanco Instrumentation Partnership

- Develop a major instrument for Blanco 4m CTIO
- Submit a science, technical & management plan
- Community instrument
- Up to 30% of Blanco 4m for 5 years commencing in 2007 or 2008
- Letter of intent March 15, 2004
- Proposals August 15 2004

The Dark Energy Survey

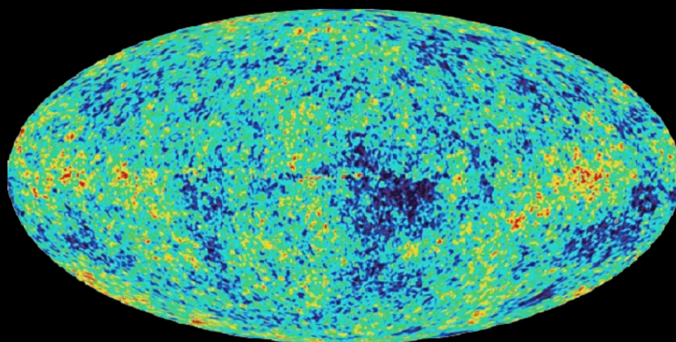




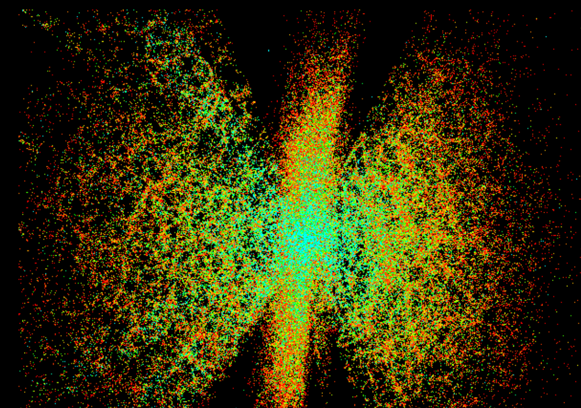


- We propose to make precision measurements of Dark Energy
  - Cluster counting, weak lensing, galaxy clustering and supernovae
  - Independent measurements
- by mapping the cosmological density field to z=1
  - Measuring 300 million galaxies
  - Spread over 5000 sq-degrees
- using new instrumentation of our own design.
  - 500 Megapixel camera
  - 2.1 degree field of view corrector
  - Install on the existing CTIO 4m

Cosmology Nowadays



WMAP measures the CMB radiation density field at z=1000



Sloan Digital Sky Survey measures the galaxy density field at z < 0.3

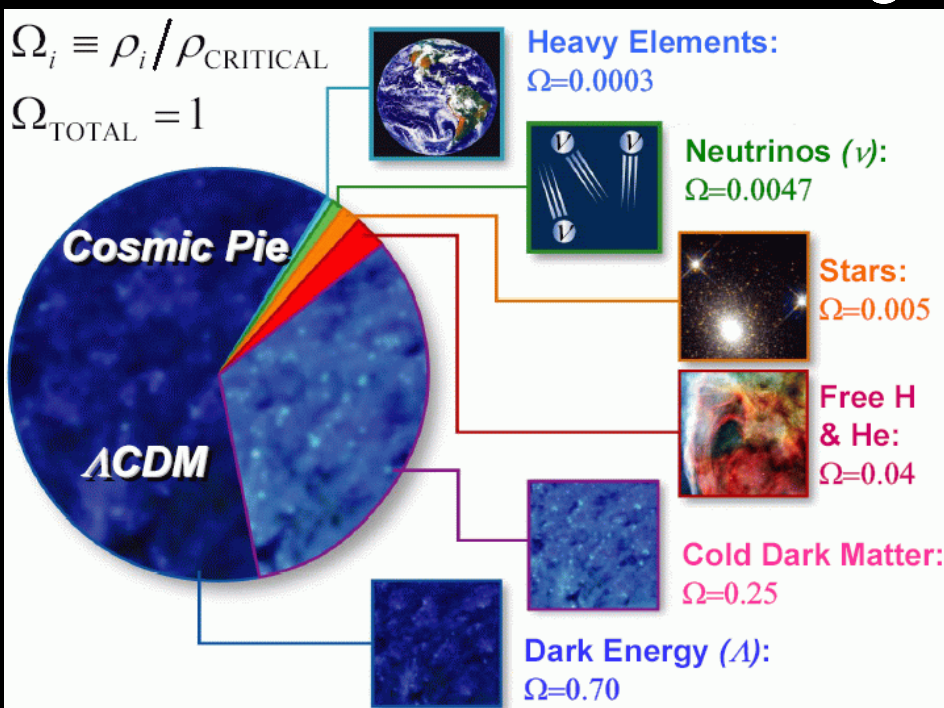
Combine to measure parameters of cosmology to 10%.
We enter the era of precision cosmology.

– Confirms dark energy (!)

2003 Science breakthrough of the year

The Big Problems: Dark Energy and Dark Matter

The confirmation of Dark Energy points to major holes in our understanding of fundamental physics



- Dark energy?

  Who ordered that? (said Rabi about muons)
- Dark energy is the dominant constituent of the Universe
- Dark matter is next

95% of the Universe is in forms unknown to us

1998 Science breakthrough of the year

Dark Energy

1. The Cosmological Constant Problem

   Particle physics theory currently provides no understanding of why the vacuum energy density is so small: $\rho_{DE}^{(Theory)} / \rho_{DE}^{(obs)} = 10^{120}$

2. The Cosmic Coincidence Problem

   Theory provides no understanding of why the Dark Energy density is just now comparable to the matter density.

3. What is it?

   Is dark energy the vacuum energy? a new, ultra-light particle? a breakdown of General Relativity on large scales? Evidence for extra dimensions?

The nature of the Dark Energy is one of the outstanding unsolved problems of fundamental physics.

Progress requires more precise probes of Dark Energy.

Measuring Dark Energy

- One measures dark energy through how it affects the universe expansion rate, H(z):

  $H^2(z) = H^2_0 \; [\, \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_K (1+z)^2 + \Omega_{DE} (1+z)^{3(1+w)} \,]$

  matter radiation dark energy

- Note the parameter w, which describes the evolution of the density of dark energy with redshift. A cosmological constant has $w = -1$.

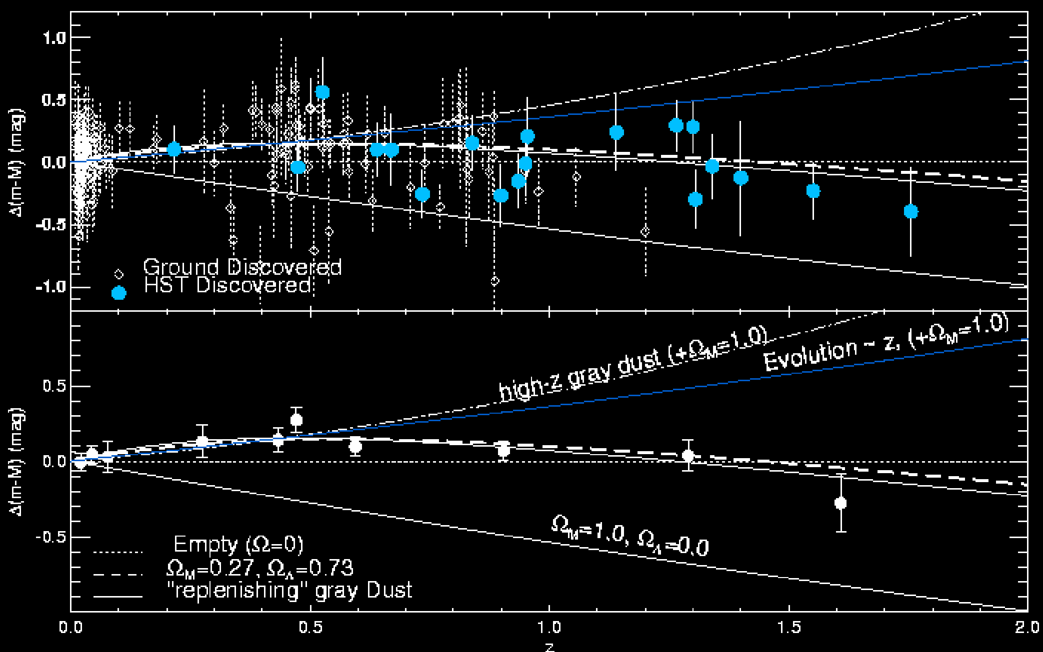
  w is currently constrained to ~20% by WMAP, SDSS, and supernovae

- Measurements are usually integrals over H(z) $\quad r(z) = \int dz/H(z)$
- Standard Candles (e.g., supernova) measure $\quad d_L(z) = (1+z)\, r(z)$
- Standard Rulers measure $\quad d_a(z) = (1+z)^{-1}\, r(z)$
- Volume Markers measure $\quad dV/dz d\Omega = r^2(z)/H(z)$
- The rate of growth of structure is a more complicated function of H(z)

DES Dark Energy Measurements

- New Probes of Dark Energy
  - Galaxy Cluster counting
    - 20,000 clusters to z=1 with $M > 2x10^{14}\ M_{\odot}$
  - Weak lensing
    - 300 million galaxies with shape measurements
  - Spatial clustering of galaxies
    - 300 million galaxies
- Standard Probes of Dark Energy
  - Type 1a Supernovae distances
    - 2000 supernovae

Supernova



- Type 1a Supernovae magnitudes and redshifts provide a direct means to probe dark energy
  - Standard candles

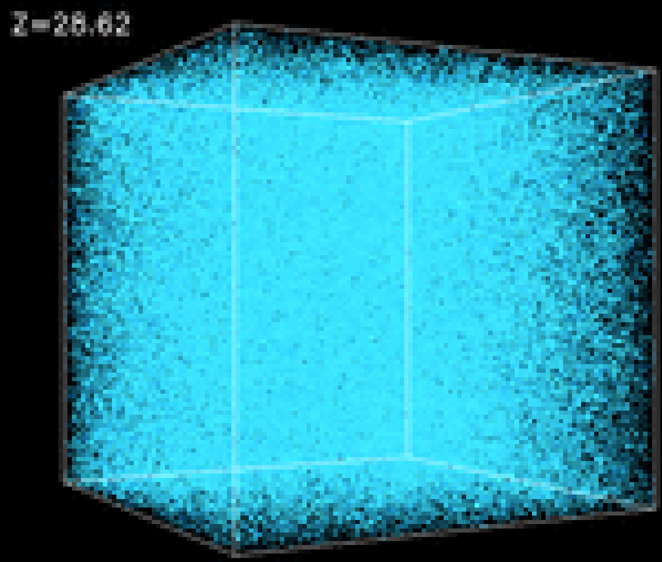
DES will make the next logical step in this program:
  - Image 40 sq-degree repeatedly
  - 2000 supernovae at $z < 0.8$
  - Well measured light curves

Current projects: SCP, Essence, CFHLS

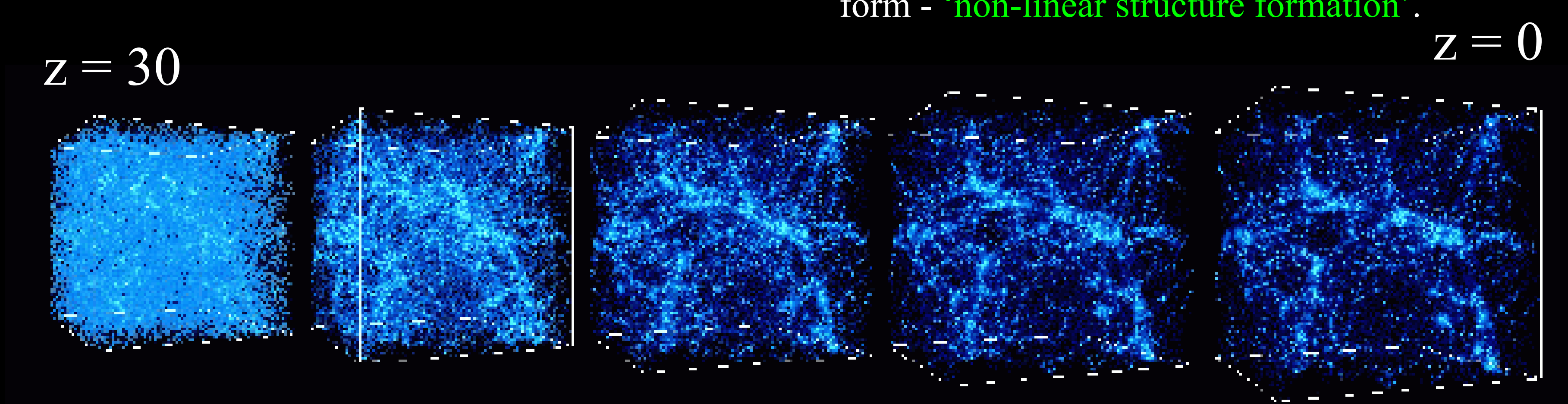
Proposed projects: SDSS, PanStarrs, LSST, SNAP

2000 — 2005 — DES — 2010 — 2015 — 2020

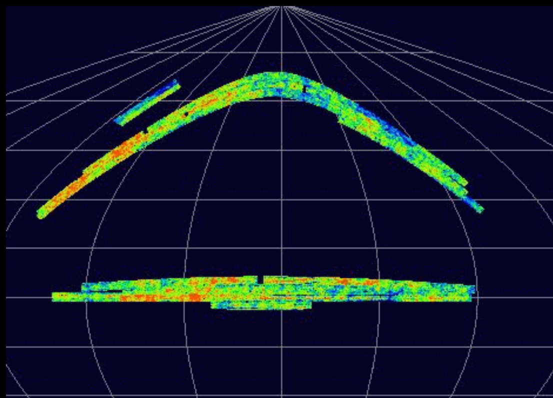
New Probes of Dark Energy

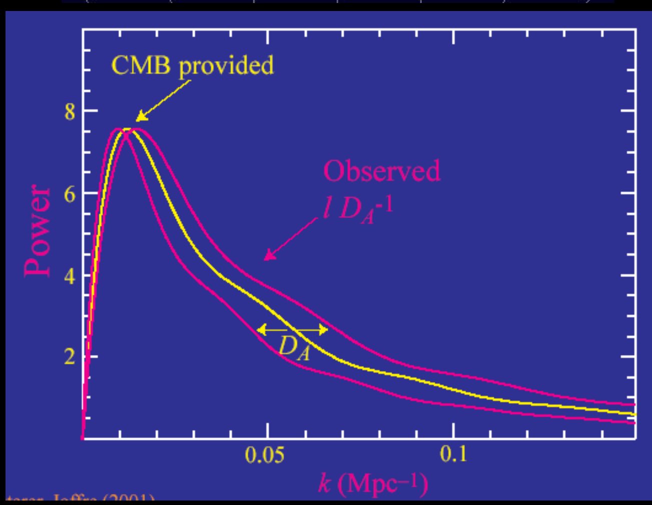


- Rely on mapping the cosmological density field
- Up to the decoupling of the radiation, the evolution depends on the interactions of the matter and radiation fields - ‘CMB physics’
- After decoupling, the evolution depends only on the cosmology - ‘large-scale structure in the linear regime’.
- Eventually the evolution becomes non-linear and complex structures like galaxies and clusters form - ‘non-linear structure formation’.



Spatial Clustering of Galaxies





Cooray, Hu, Huterer, Joffre 2001

- The distribution of galaxy positions on the sky reflects the initial positions of the mass
- Maps of galaxy positions are broken up in photometric redshift bins
- The spatial power spectrum is computed and compared with the CMB fiducial power spectrum.
- The peak and the baryon oscillations provide standard rulers.
- DES will
  - Image 5000 sq-degrees
  - Photo-z accuracy of $\delta z < 0.1$ to $z = 1$
  - 300 million galaxies

PanStarrs

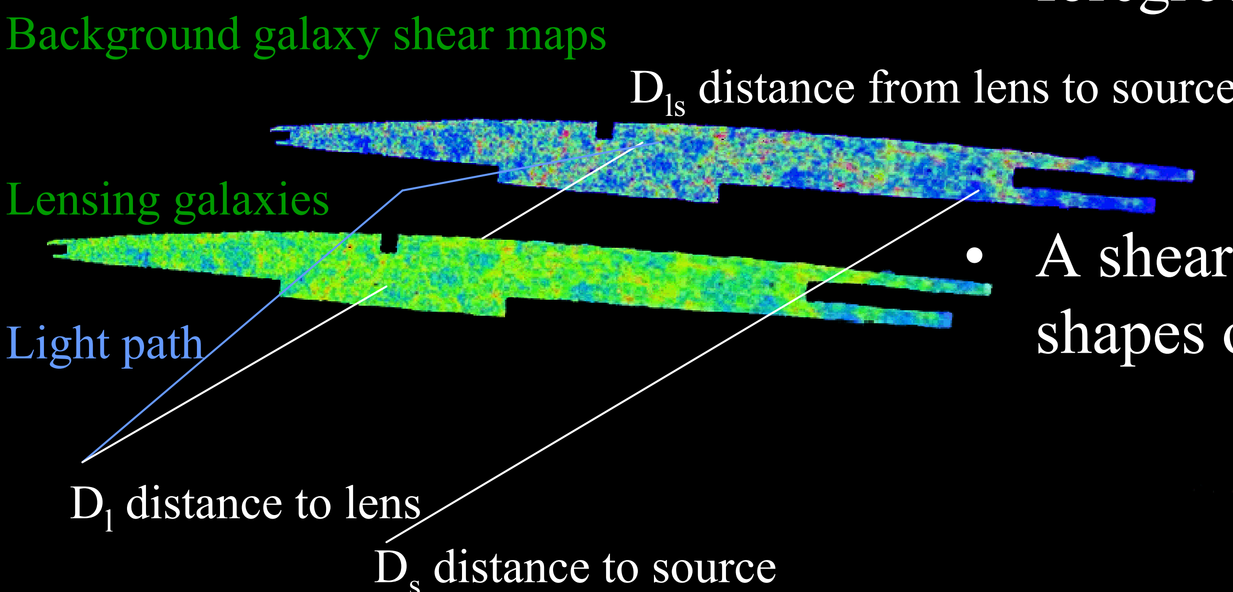
SDSS WMAP Planck LSST SNAP

2000 2005 DES 2010 2015 2020

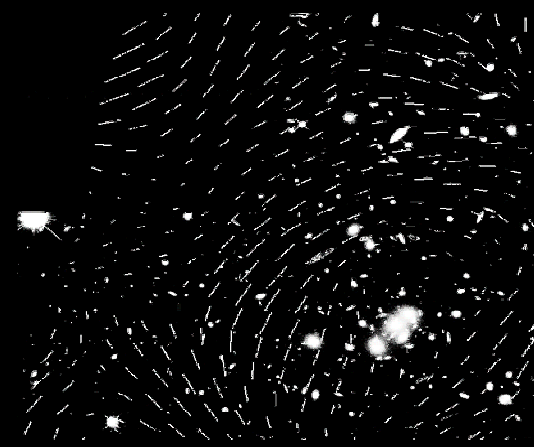

Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

Weak Lensing

- Weak lensing is the statistical measurement of shear due to foreground masses

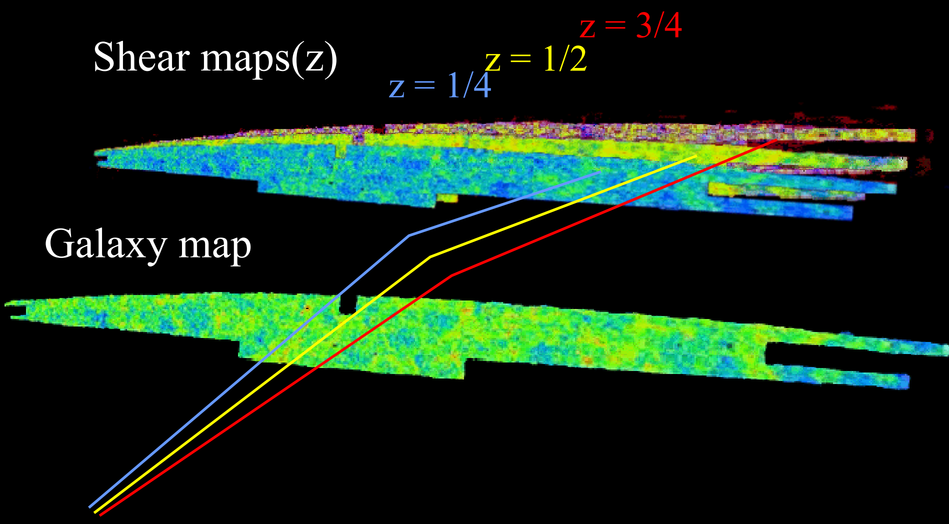


- A shear map is a map of the shapes of background galaxies

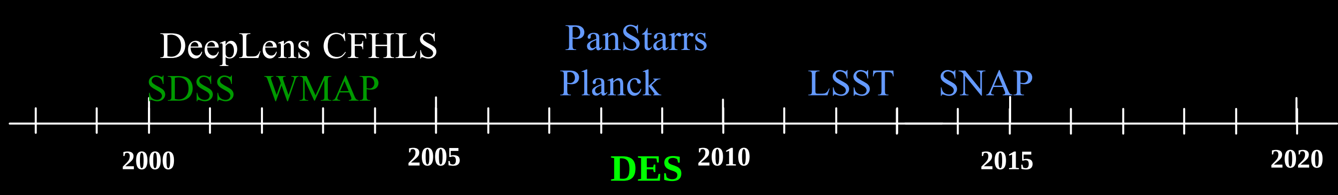


Weak Lensing

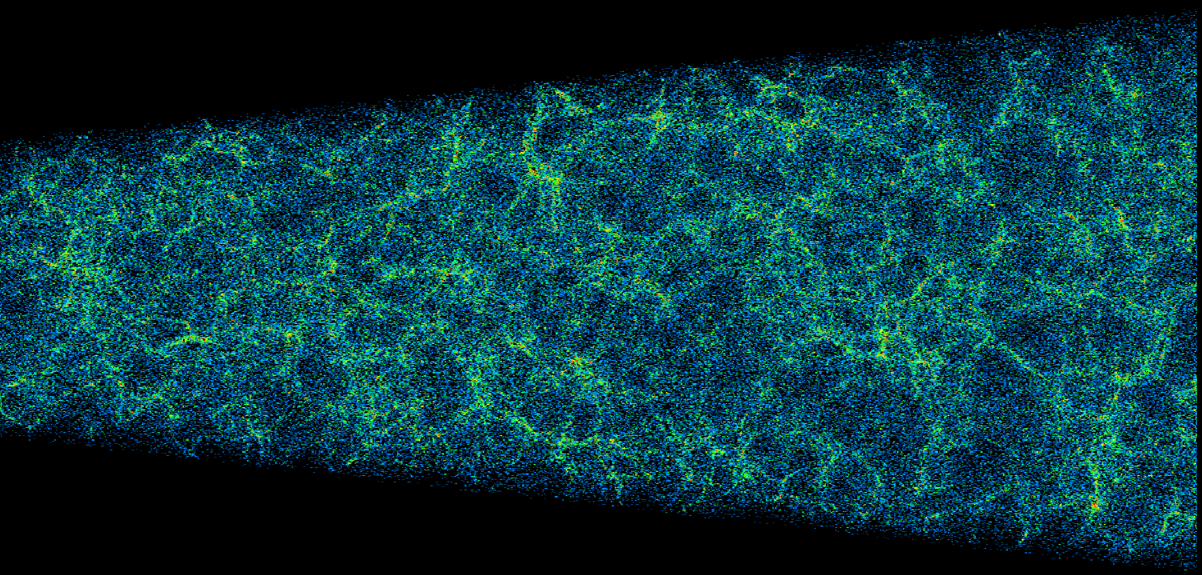
- The strength of weak lensing by the same foreground galaxies varies with the distance to the background galaxies.
  - Measure amplitude of shear vs. z
  - shear-galaxy correlations
  - shear-shear correlations



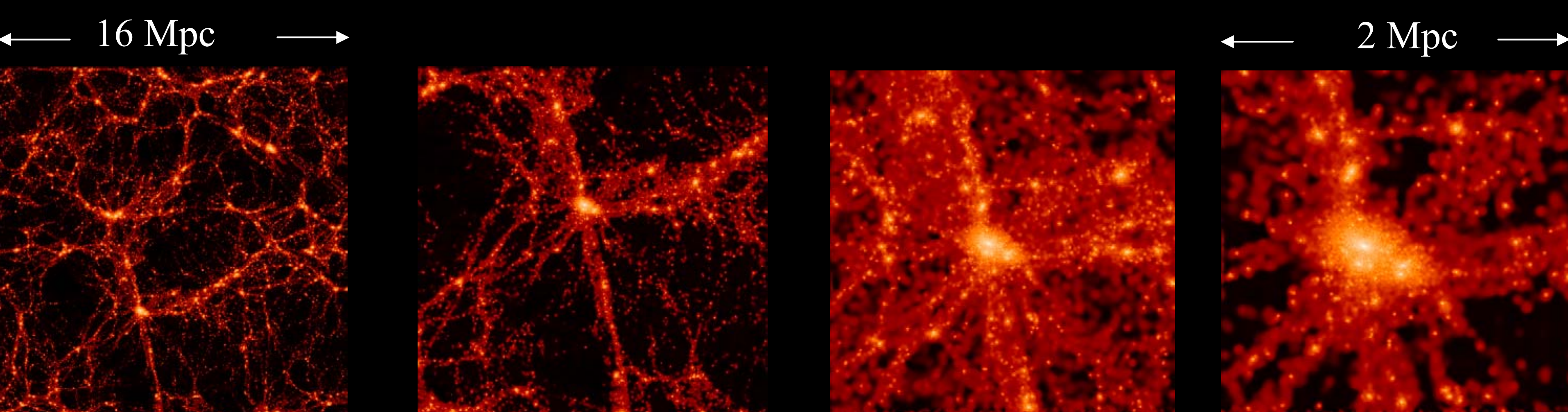
- DES will
  - Image 5000 sq-degrees
  - Photo-z accuracy of $\delta z < 0.1$ to $z = 1$
  - 10-20 galaxies/sq-arcminute



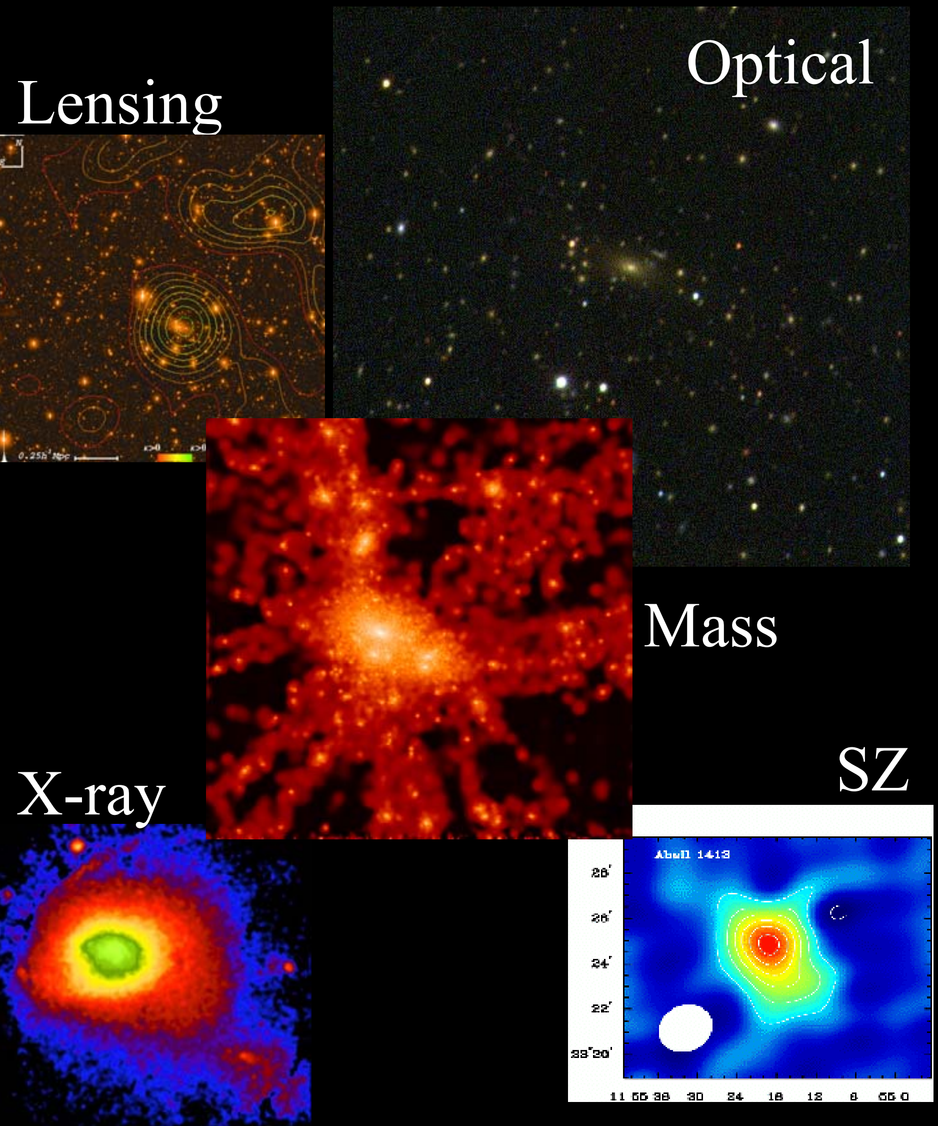
Peaks in the Density Field



- Clusters of galaxies are peaks of the density field.
- Dark energy influences the number and distribution of clusters and how they evolve with time.

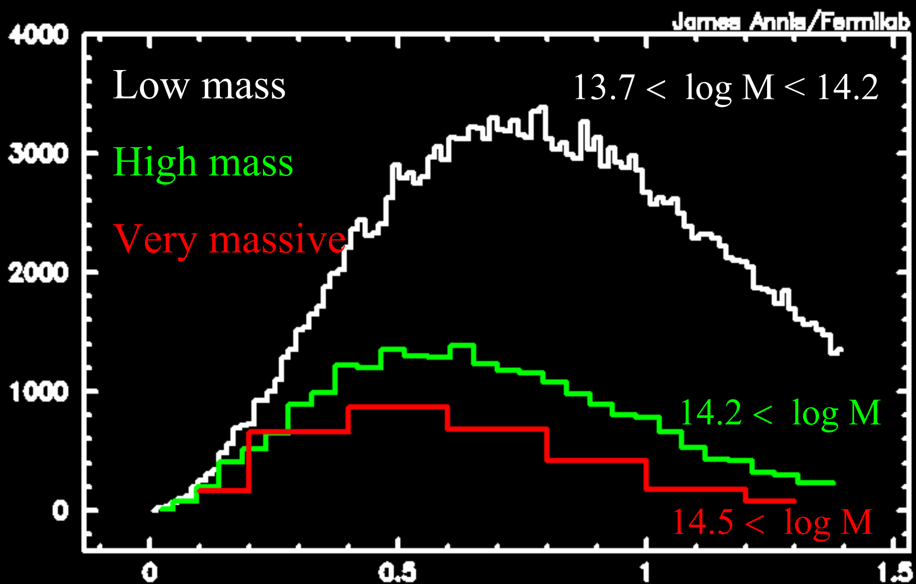


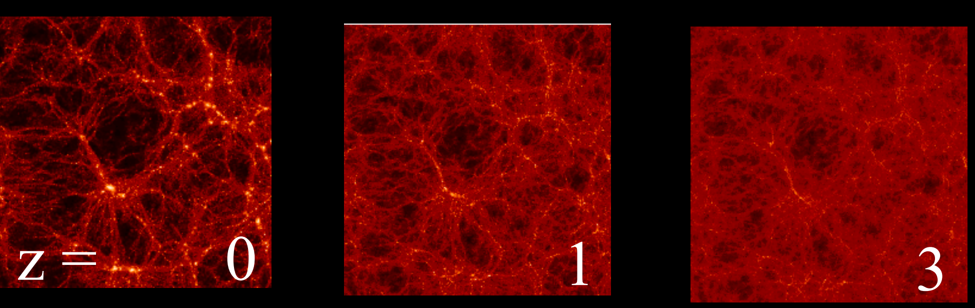
Cluster Masses



- Our mass estimators
  - Galaxy count/luminosity
  - Weak lensing
  - Sunyaev-Zeldovich
    - The South Pole Telescope project of J. Carlstrom et al.
    - DES and SPT cover the same area of sky
- Self calibration
  - Mass function shape allows independent checks
  - Angular power spectrum of clusters
  - Allows an approach at systematic error reduction

Cluster Counting



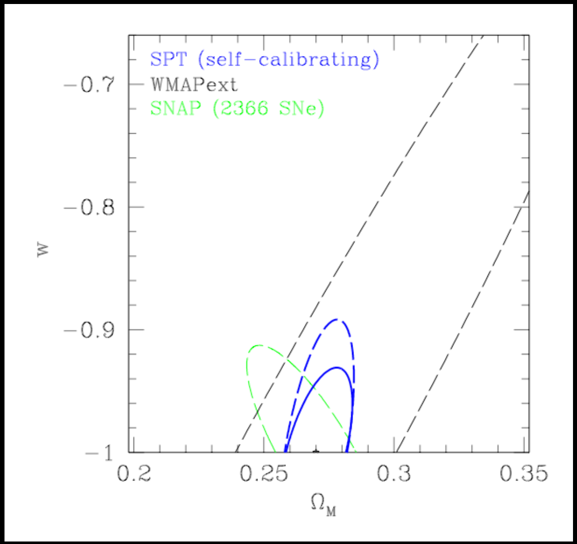


- Locate peaks in the density field using cluster finders
  - Red sequence methods
  - SZ peaks
- DES will
  - Image 5000 sq-degrees
  - Photo-z accuracy $\delta z = 0.01$ to $z = 1$
  - 20,000 massive clusters
  - 200,000 groups and clusters

We aim at ~5% precision on Dark Energy

Cluster Counting

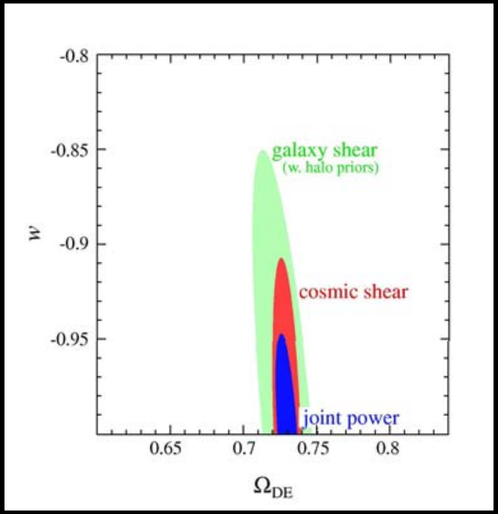
w



Ω_M

Weak Lensing

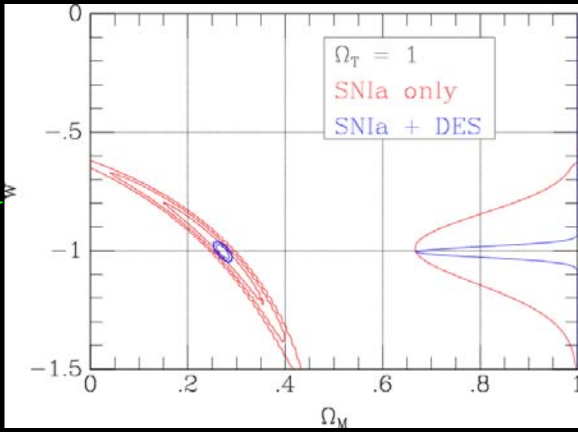
w



Ω_{DE}

Supernova

w



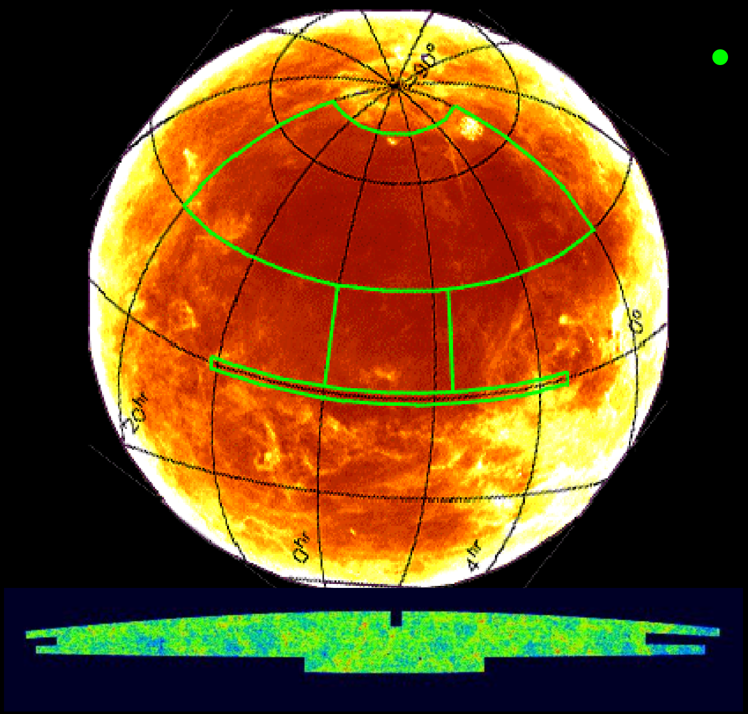
Ω_M

δ w ~ 5% and $\delta\ \Omega_{DE}$ ~ 3%

The Planck satellite will provide tighter input CMB measurements, and the constraints will improve slightly.

Joint constraints on w and w_a are promising: initial results suggest $\delta w_a \sim 0.5$.

The Dark Energy Survey



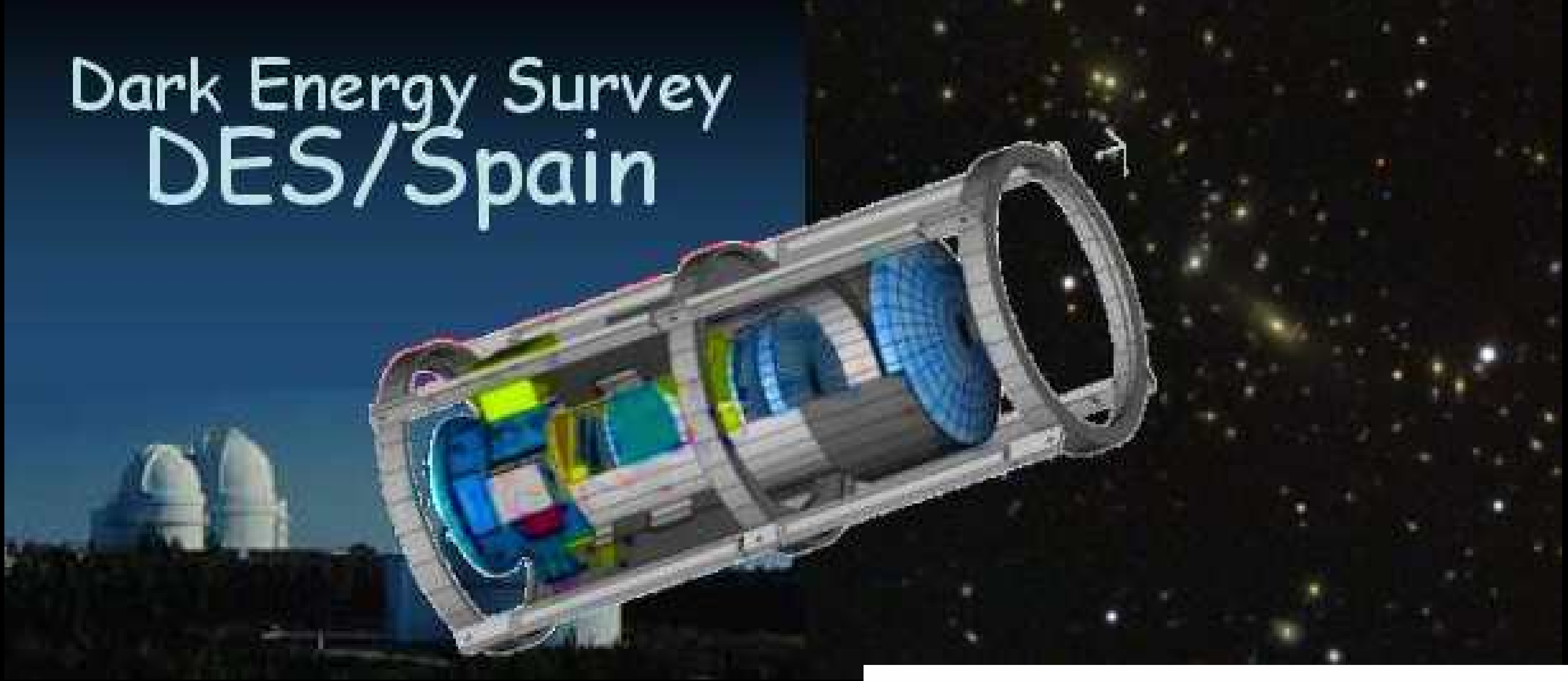
5000 sq-degrees

Overlapping SPT SZ survey

4 colors for photometric redshifts

300 million galaxies

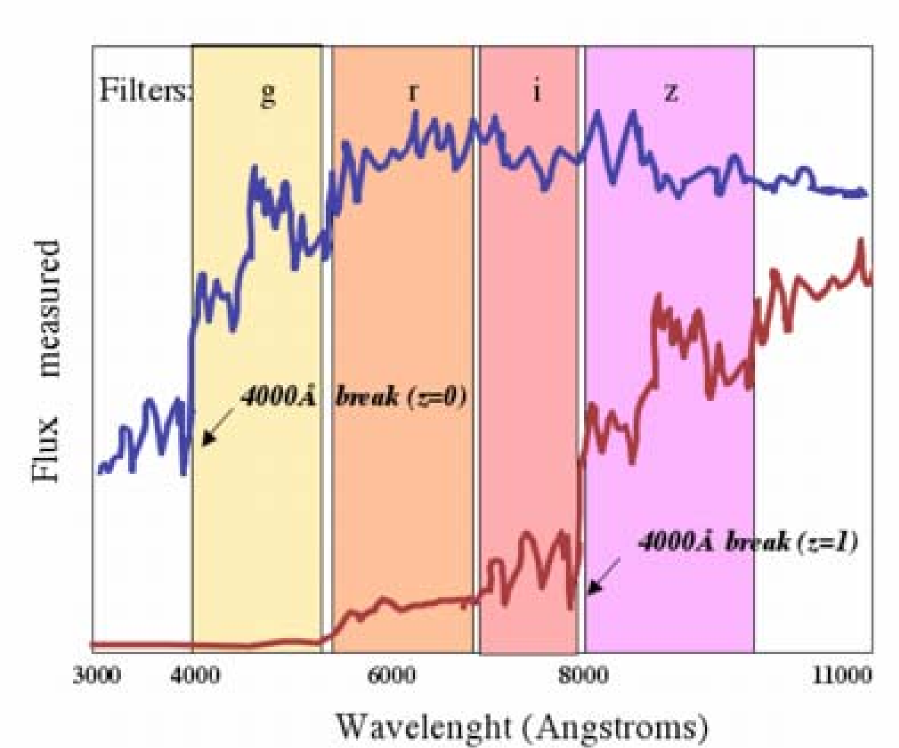
- We propose the Dark Energy Survey
  - **Construct a 500 Megapixel camera**
  - Use CTIO 4m to image 5000 sq-degrees
  - Map the cosmological density field to z=1
  - Make precision measurements of the effects of Dark Energy on cosmological expansion:
    - Cluster counting
    - Weak lensing
    - Galaxy clustering
    - Supernovae



Photometric redshifts

CCDs more sensitive on red (z-band)

5000 sqr degrees to z=1 matches SPT CMB data



Key projects (systematics!):

-Cluster Abundaces (SZ effect)

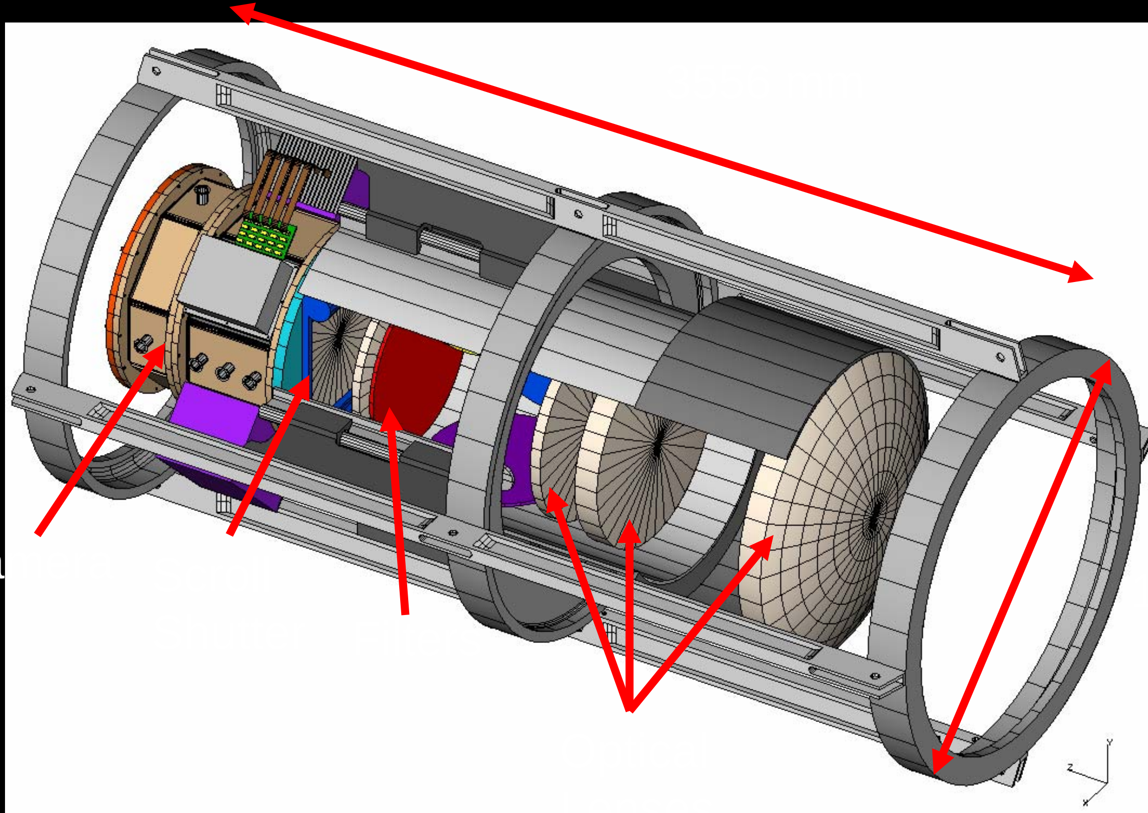
-Galaxy clustering evolution (Acustic peaks)

-Weak and strong lensing (Cluster mass)

-SNIa

DE: Dark Energy Instrument @Fermilab

IFAE &IEEC/CSIC



- CCD testing -> SNAP/LSST
- FE Elec & DAQ
- Simulations: science
- Data (Grid/Pipes)

575 mm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