Title: The Shape of Clusters and Large-Scale Structure

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Abstract: The largest structures in the Universe -- Superclusters of Galaxies -- range in size from a few Mpc to the 'Great Walls' scale of hundreds of Mpc. What is the shape of these large structures -- are they filamentary in nature or are they flattened two-dimensional 'pancakes'? How do they form and evolve? Superclusters are typically dominated by clusters of galaxies, systems that serve as one of the most powerful tools in cosmology. What is the shape of clusters -- are they spherically symmetric or are they elongated? Are they aligned with each other on large scales? I present results that answer these fundamental questions, revealing the predicted shape and evolution of the large-scale structure in the Universe in the current popular cosmology. We show that the shape of clusters provides an interesting new tool in constraining cosmology, as well as provides clues to the formation and evolution of large-scale structure.

The Shape of Clusters and Large-Scale Structure

Neta A. Bahcall

Princeton University

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What is the Shape of Large-Scale Structure?

[Clusters, Superclusters]

Why important?

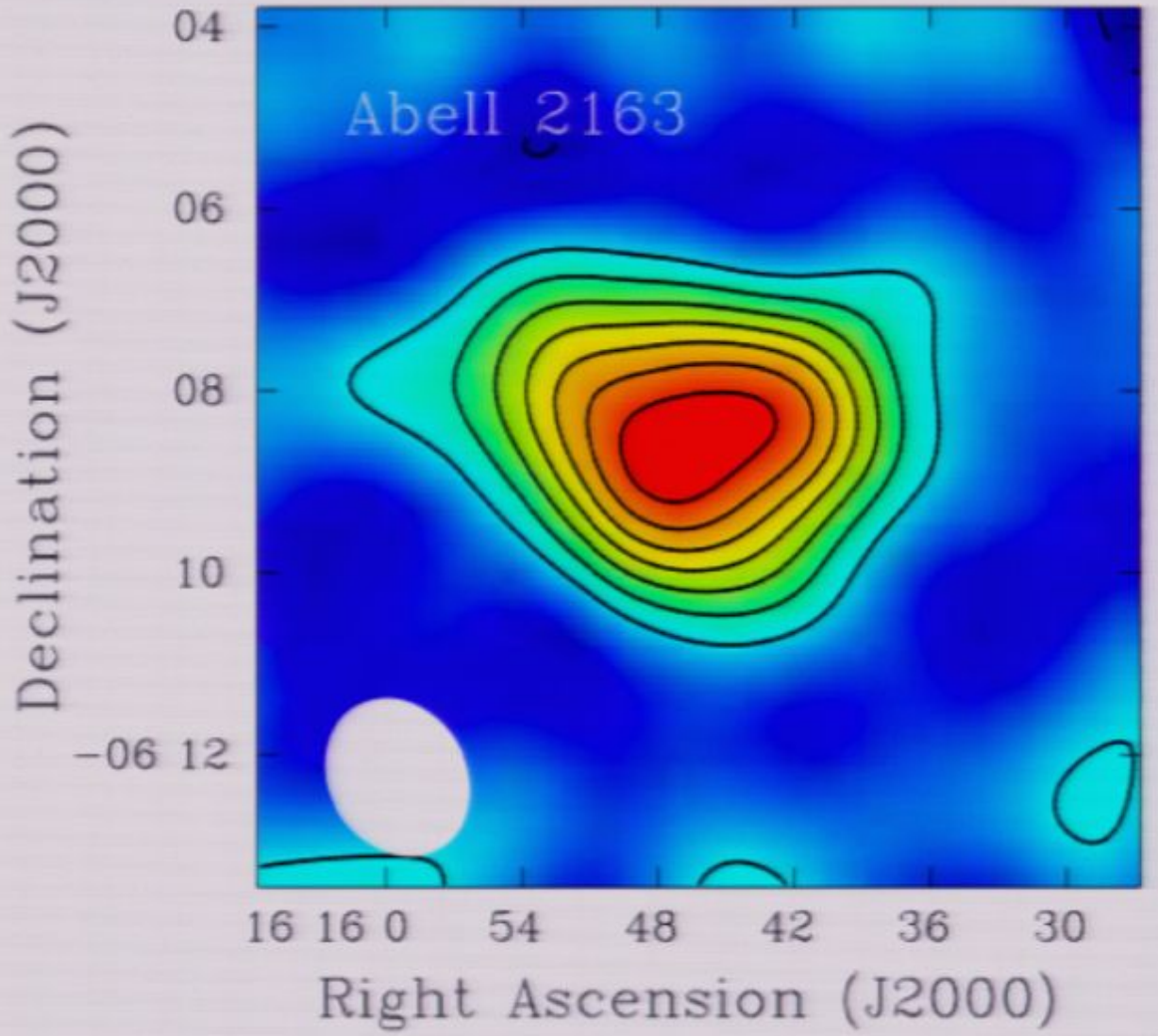
- What is the Universe like?
- Formation & Evolution of Structure
- Proper Use of Clusters
- Cosmology

Topics

- The Shape of Clusters
- Alignment of Cluster Pairs
- Evolution of Shape & Alignment
- New Tool in Cosmology:
  - ➔ ***Cluster Ellipticity***
- Superclusters: Filaments or Pancakes?

Hot Gas in Clusters

(X-rays;SZ)



Shape Impact

Clusters typically assumed spherical

Impact of Non-Sphericity:

- Selection Bias (in lensing; optical; X-ray; SZ)
  'pointed' clusters affect R_{cl}, V_{cl}, M_{cl}, n_{cl}(>threshold)
- Impacts H_o from Clusters (X-Rays + SZ)
  (H_o too low if 'pointed' clusters prefered)
- Other
- New Tool for Cosmology, Structure Formation

Cluster Shape

- Large-Scale Simulations of LCDM
  [1500^3 Mpc^3; Ω_m= 0.27; Dark-Matter; 1.2E11 Mo/p]
- 10^6 Clusters [$M_{180} > 2E13\ h^{-1}\ M_o$]
- z = 0 to 3
- Determine Cluster Best-Fit Ellipse
  (2nd-moment of particles)

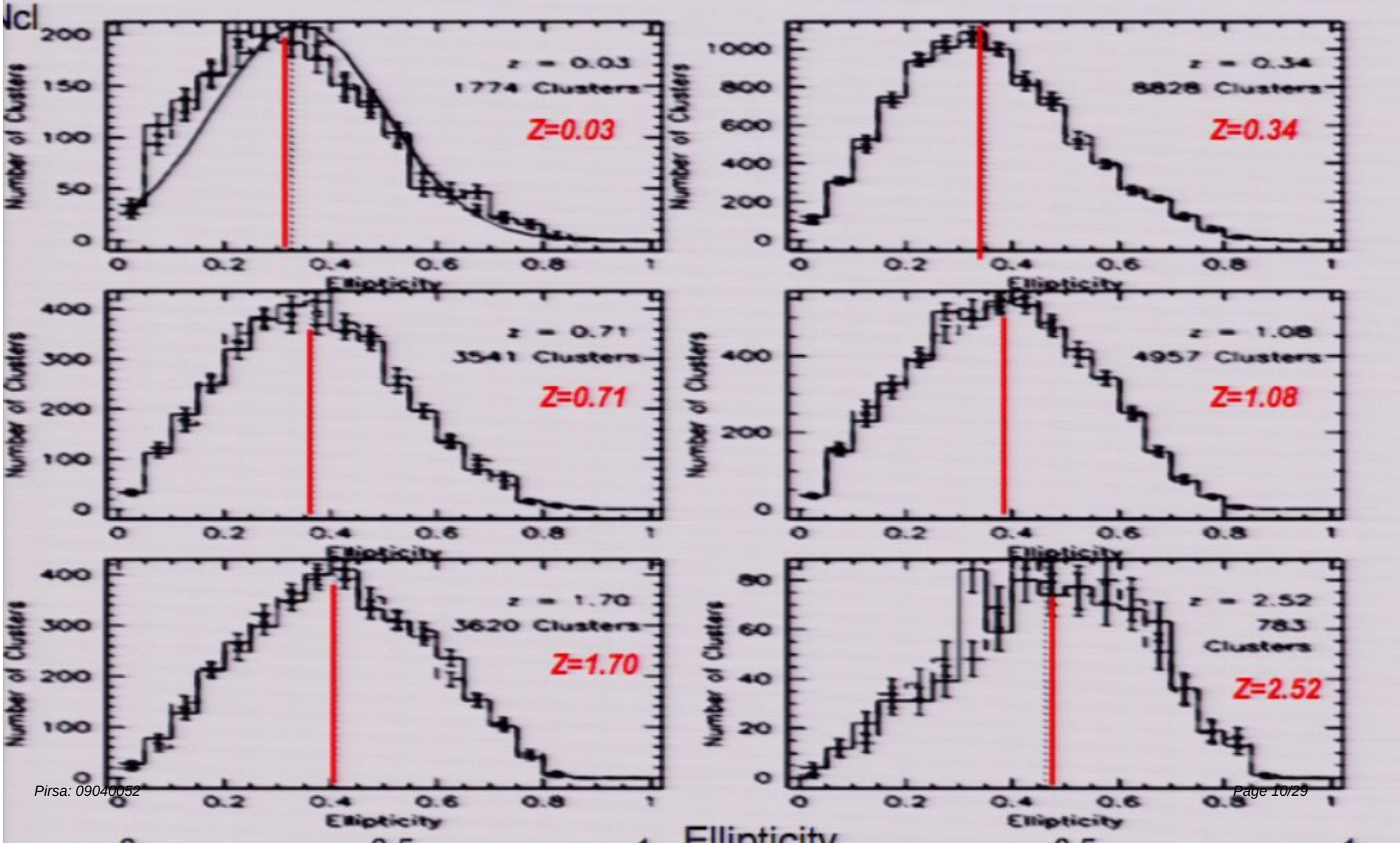
  $(I_{ij} = \sum X_i X_j)$ → *a1 > a2 > a3*

- $E = 1 - a2/a1$
- $E_{2D} = 1 - a2_{2D}/a1_{2D}$ *(projected)*

→ $\langle E \rangle \sim 0.3 - 0.5$

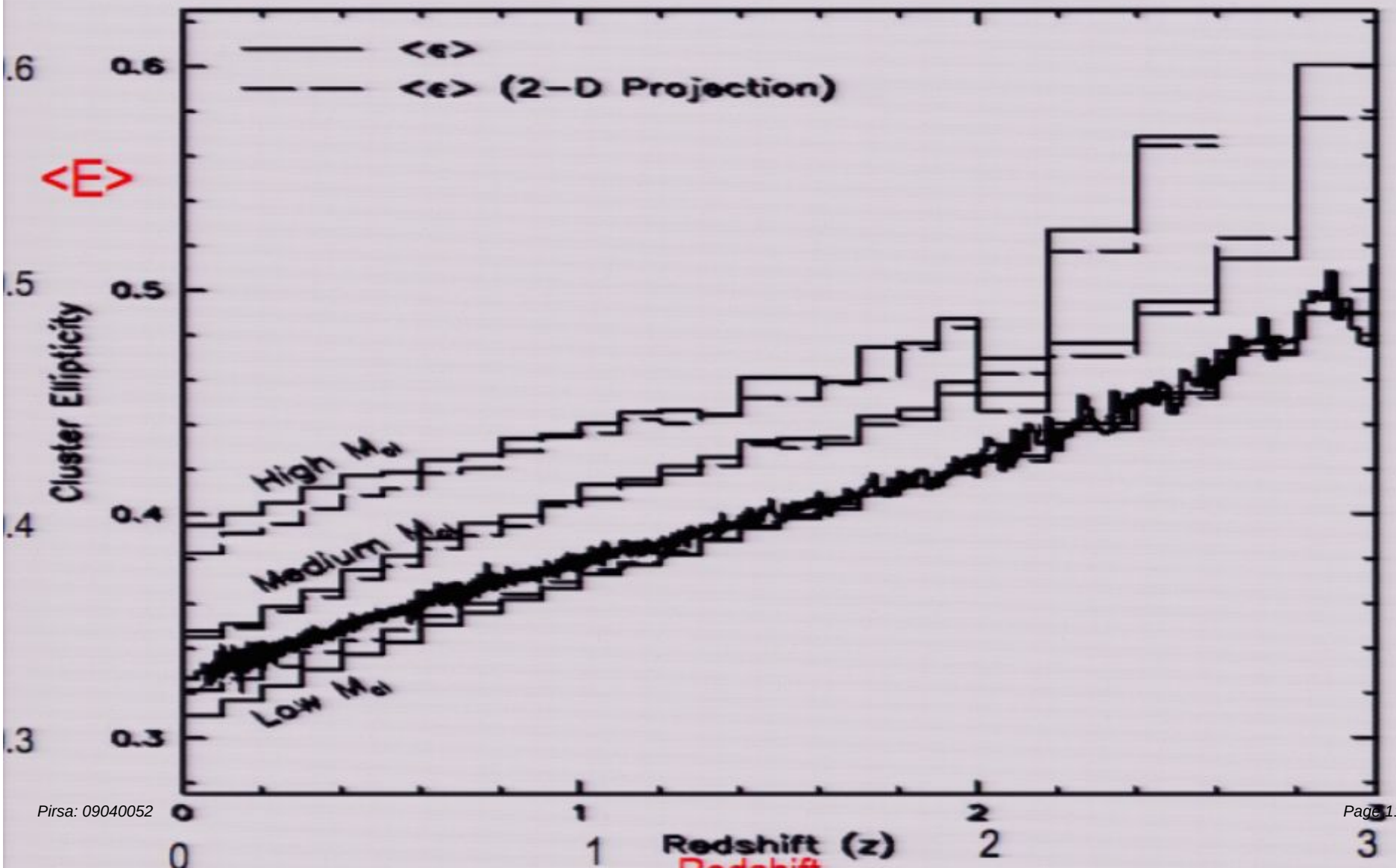
Cluster Ellipticity Distribution

(Hopkins, Bahcall, Bode 2005)



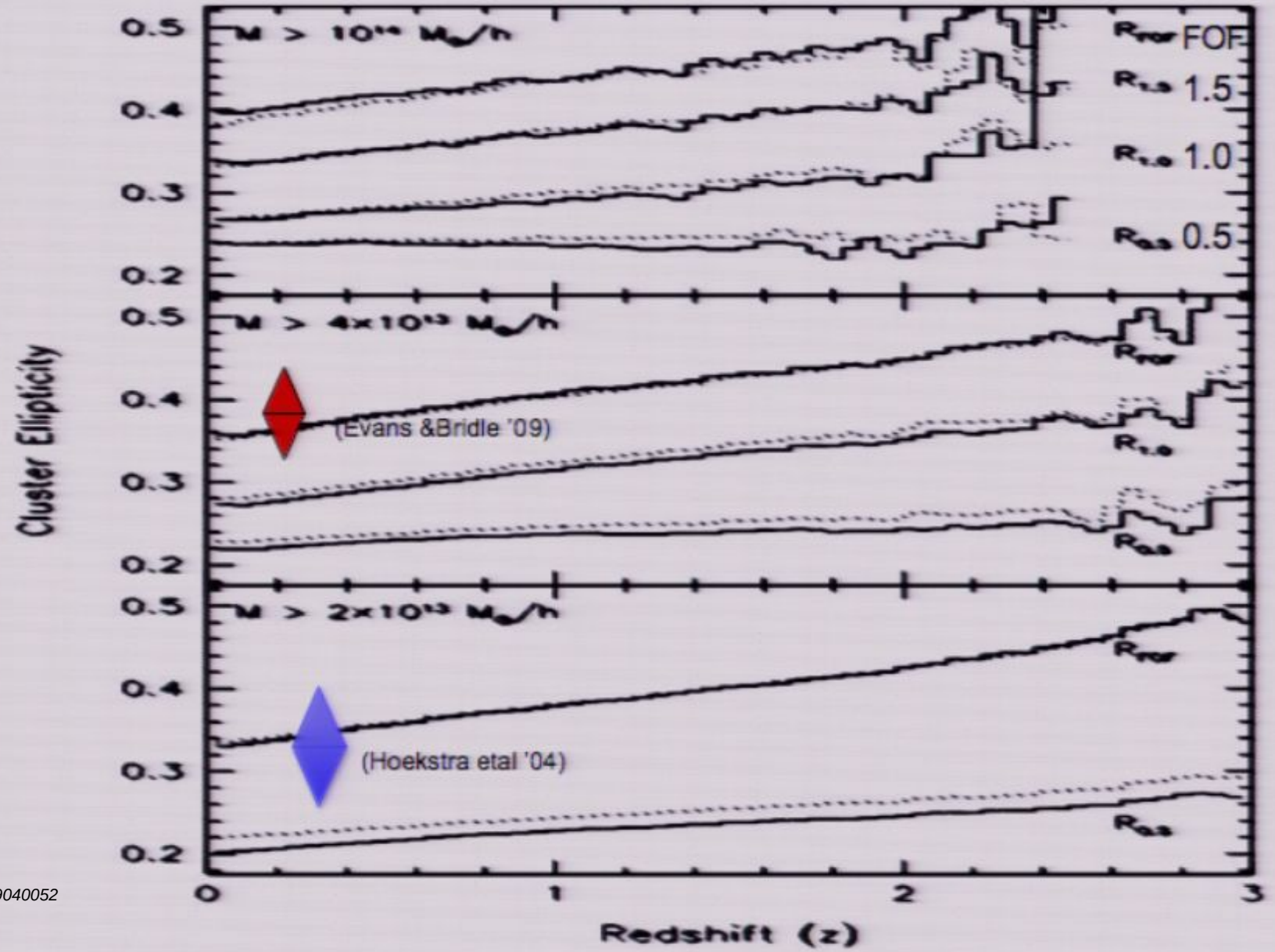
Evolution of Cluster Ellipticity

<E> versus Redshift and Mass



Mean Cluster Ellipticity

E_d versus z, R, M



Clusters Shape

- *Large Ellipticities:* $\langle E \rangle \sim 0.3 - 0.5$
  $a2/a1 \sim 0.5 - 0.7$

- $\langle E \rangle$ *increases with* M_{cl}, R_{cl}, z

  → $\langle E \rangle = 0.33 + 0.05z$

  → $\langle E \rangle \sim 0.3$ at $z \sim 0$
  ~ 0.5 at $z \sim 3$

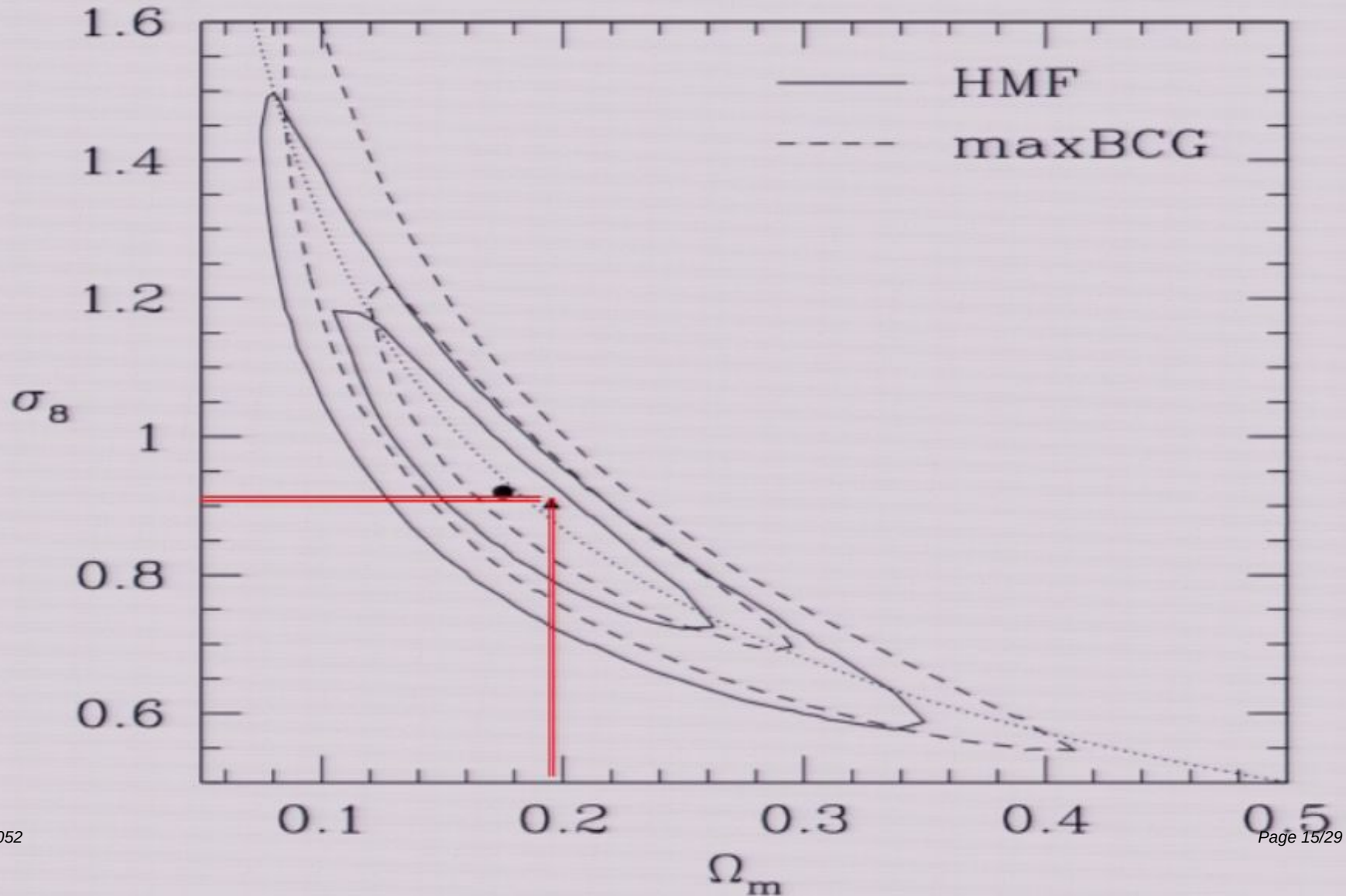
Cosmology

- Ω_m: Mass-Density of Universe
  ($\Omega_m = \rho_m / \rho_{critical}$)
- σ_8: Amplitude of Mass Fluctuations
  (on 8 Mpc scale)
- $\sigma_8 \, \Omega_m^{0.6} \sim 0.35 \pm 0.05$
  (From observed cluster abundance)

→ $\sigma_8 \sim 0.9$ $\Omega_m \sim 0.2$
0.7 0.3
0.6 0.4

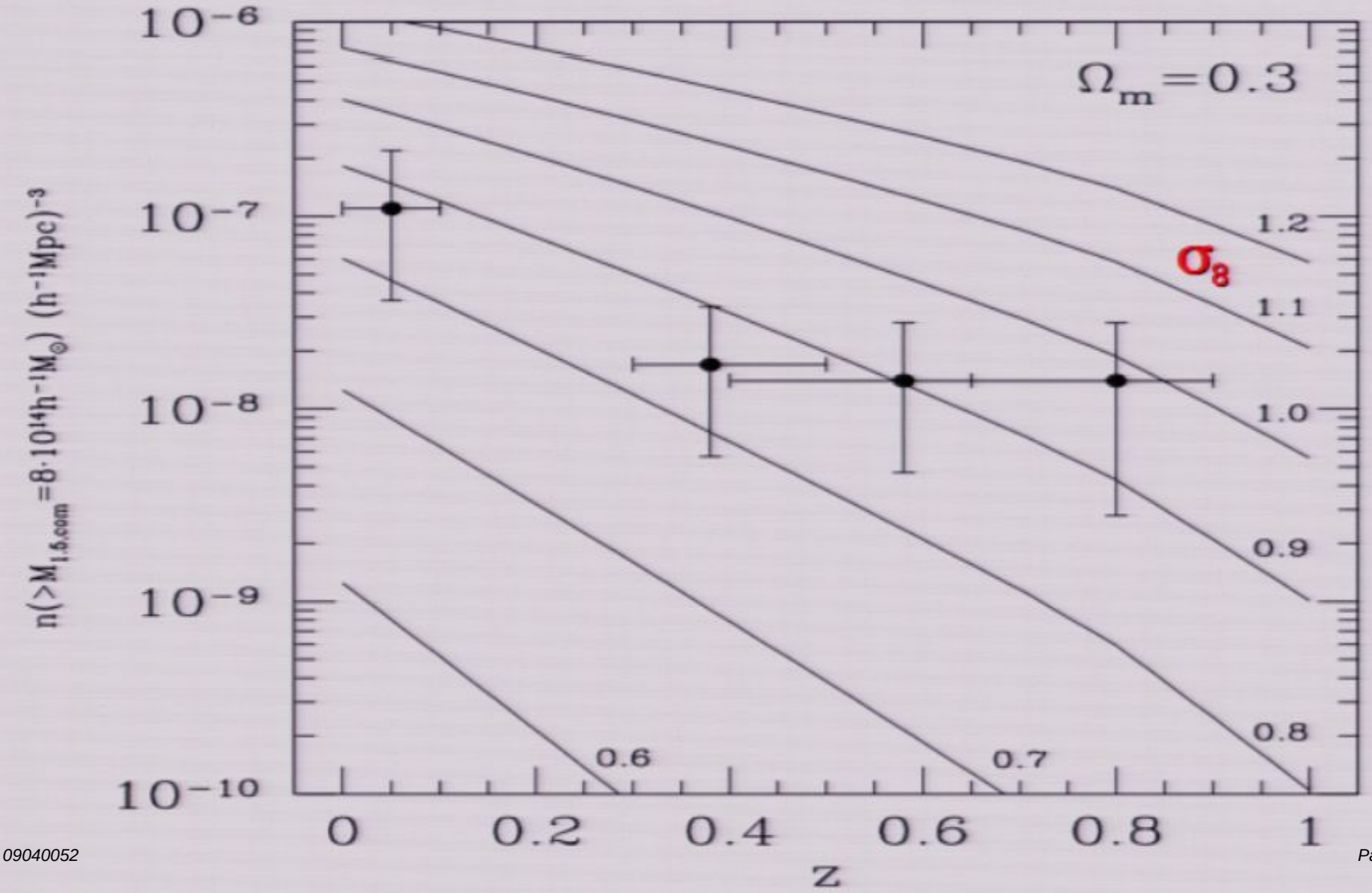
Amplitude σ_8 Not well determined

Ω_m - σ_8 (SDSS Clusters MF)
(Bahcall, Dong, Bode et al '03)



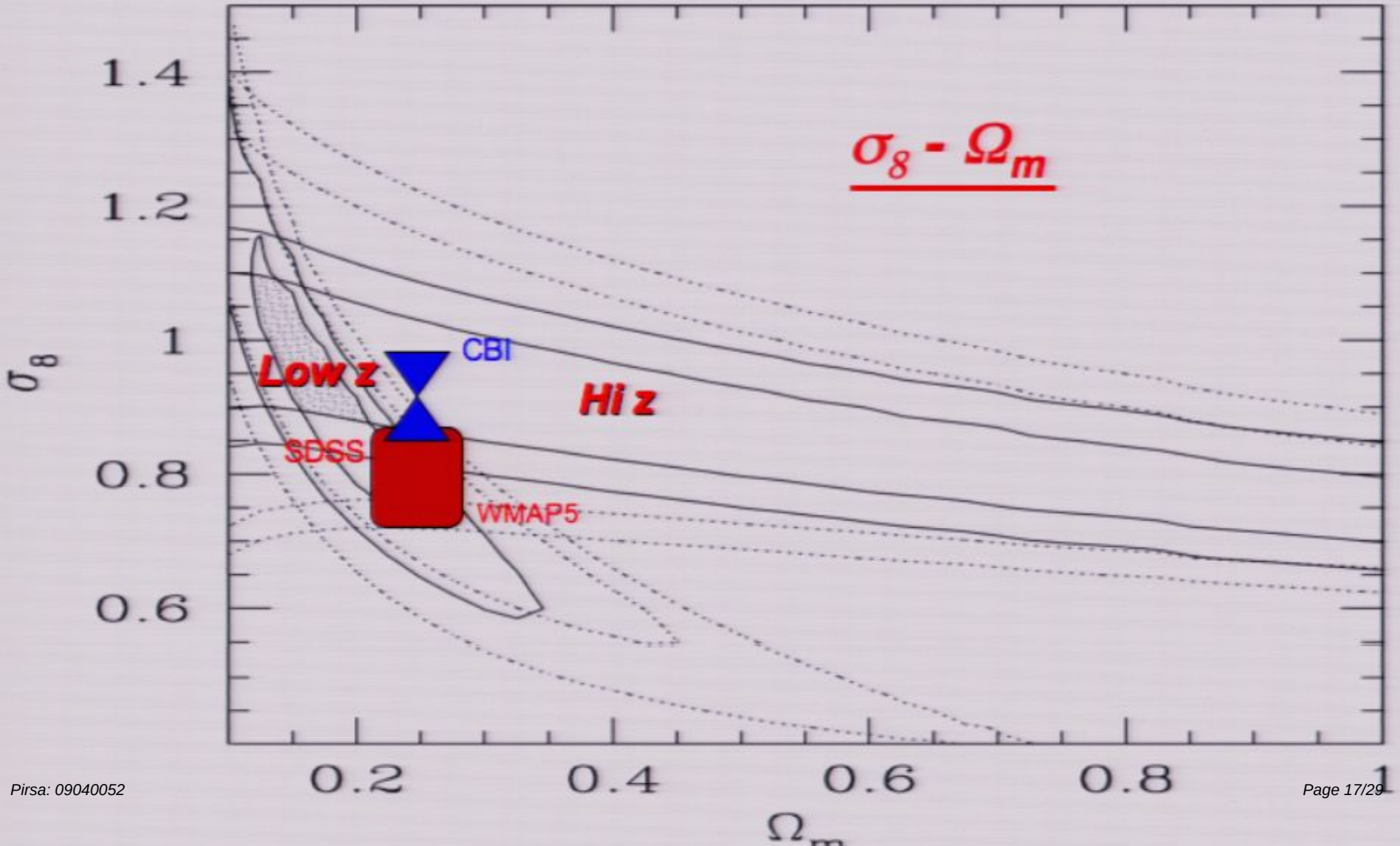
Cluster Abundance Evolution

→ σ_8 (Bahcall & Bode '03)

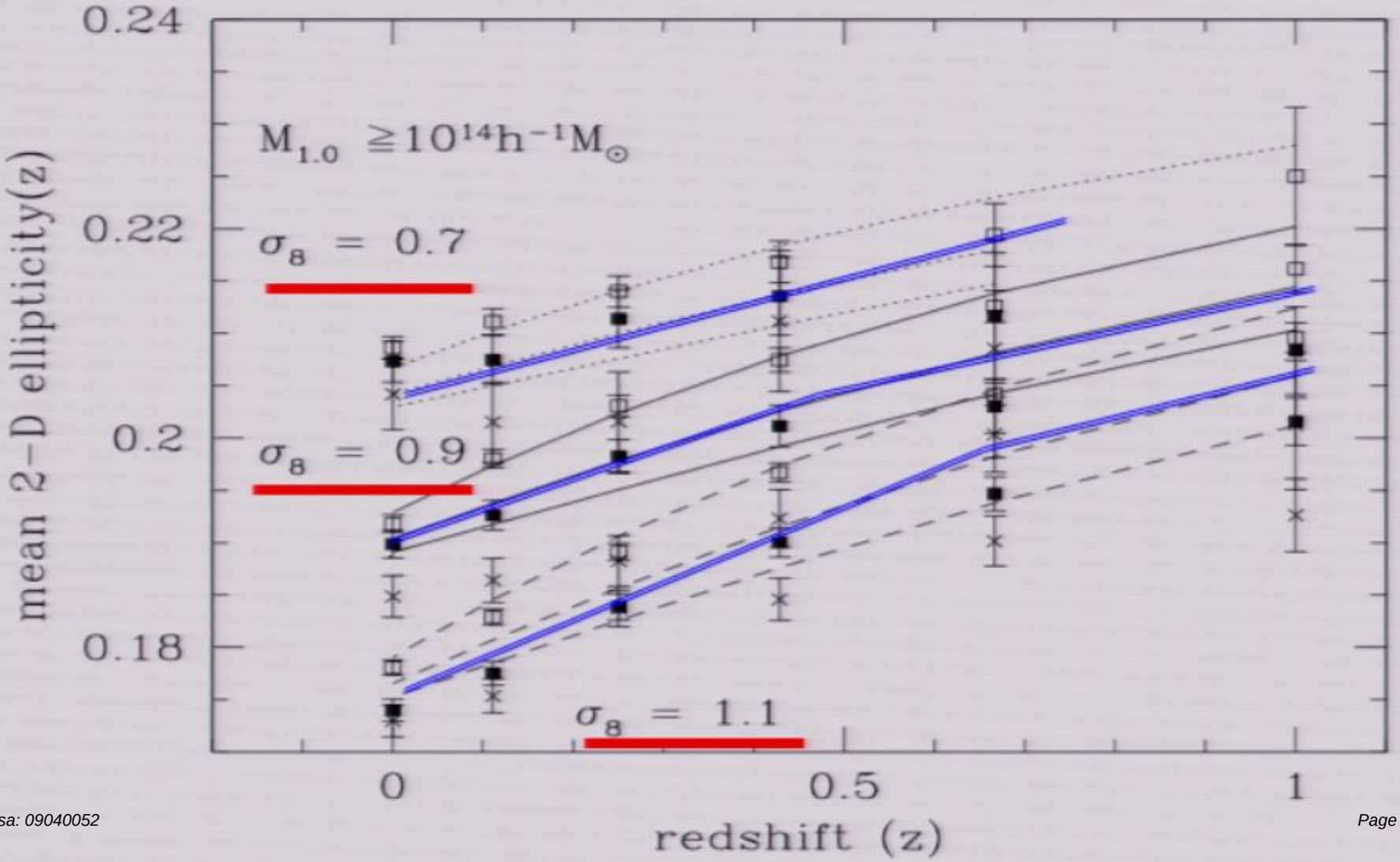


Cosmological Constraints (Bahcall & Bode)

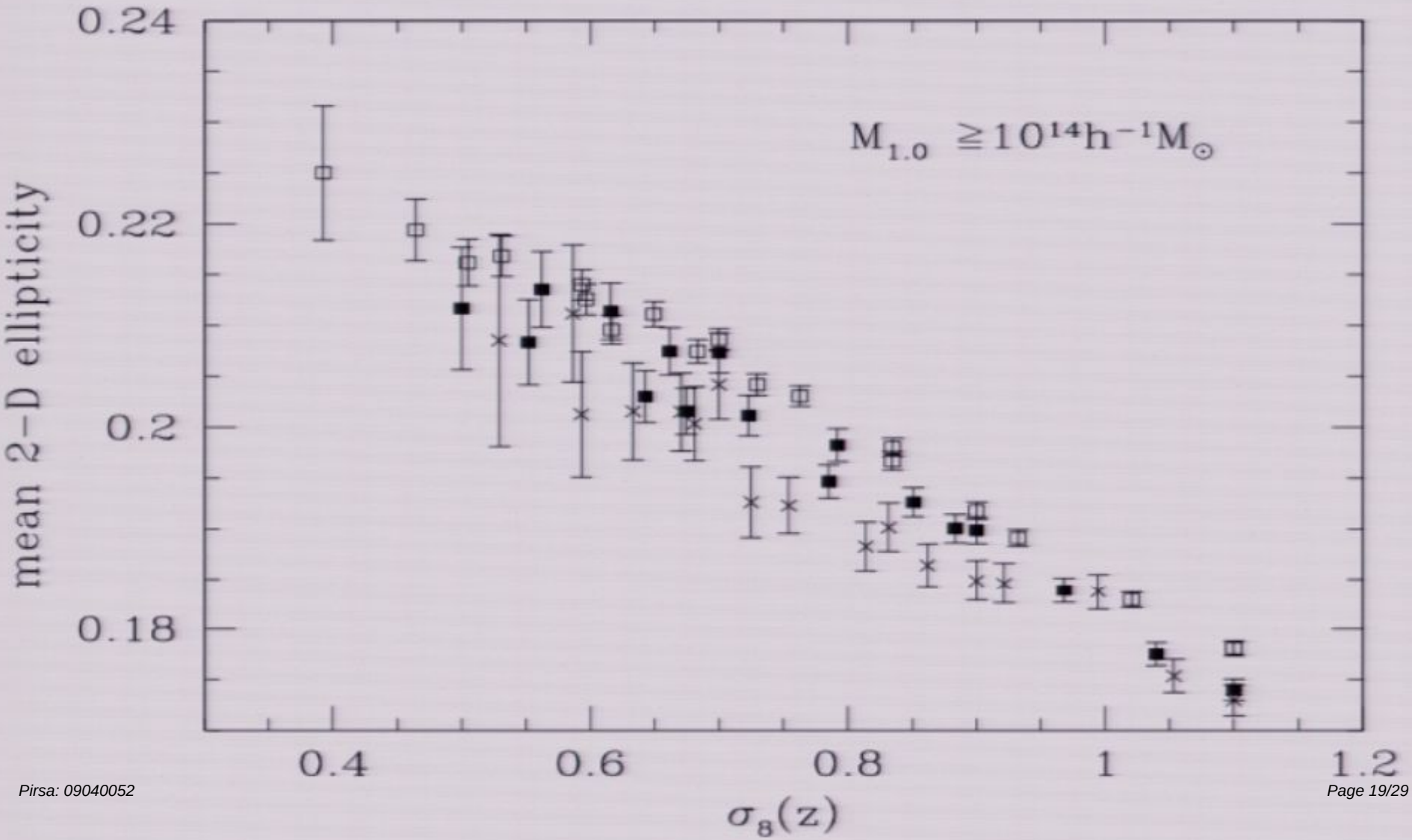
(from Low and Hi redshift cluster abundance)



Cluster Ellipticity → σ_8
(Ho, Bahcall, Bode '06)



Cluster Ellipticity → $\sigma_8(z)$
(Ho, Bahcall, Bode 07)



Alignment of Clusters
(Hopkins, Bahcall, Bode 05)

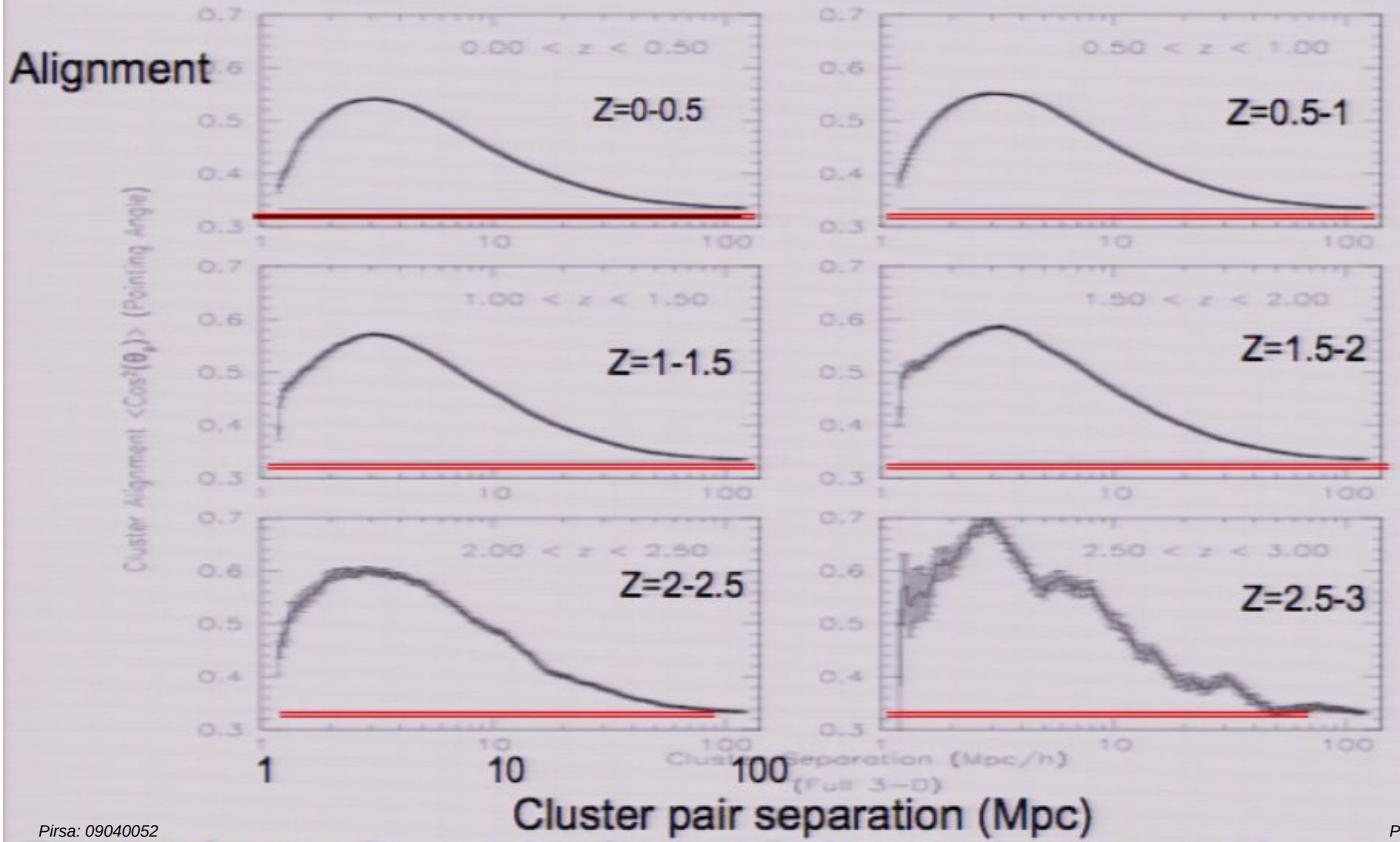


Fig. 8.— Same as Figure 6, but for the 3-D alignment function using the pointing angle method.

Cluster Alignment Function
(Hopkins, Bahcall, Bode '05)

- Alignment of Clusters to ***~100 Mpc***
- Alignment increases with cluster ***Mass***
- Alignment increases with ***Redshift***
- Alignment happens ***along Filaments***

  ➔ ***Clusters start highly elliptical and aligned; both decrease with time!***

- Predictions can be tested against observations

Large-Scale Structure; Superclusters

Superclusters

- *Filaments? 'Pancakes'? Properties?*

- *Defined: Clusters of Clusters*
- *Select using F.O.F. of Clusters (= Percolation)*
- *Function of Percolation Length L*

  $b = L/r_{cc} \sim 0.15 - 0.5;$

  $L \sim 3 - 10$ Mpc, $z \sim 0$, $M_{cl} > 1.75E13\ M_o$
- *Use LCDM Simulations*

Superclusters Map
(Wray, Bahcall, Bode, etal '06)

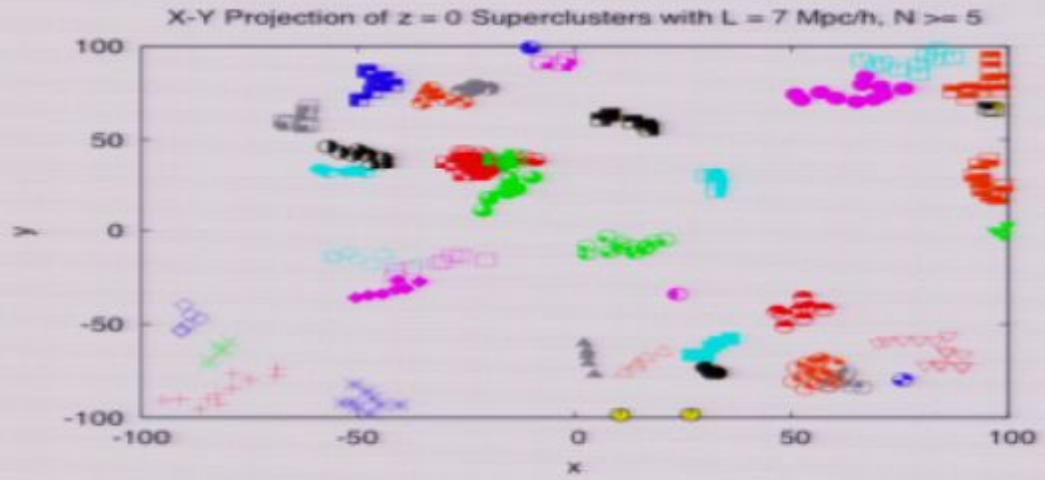


Fig. 1.— Clusters identified as supercluster members at redshift zero, for $L = 7h^{-1}$ Mpc and minimum multiplicity 5. Clusters represented by similar points are members of the same supercluster. See the text (§2.3) for further description.

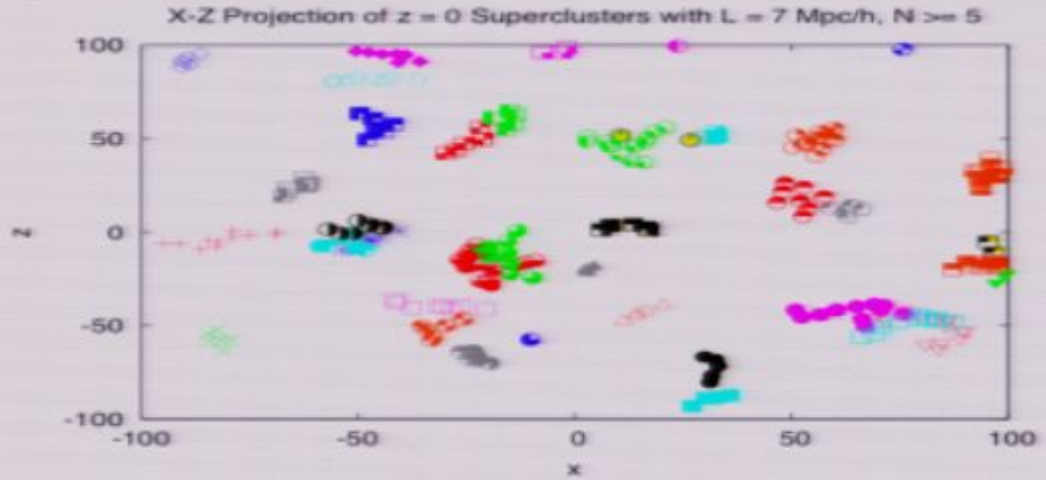
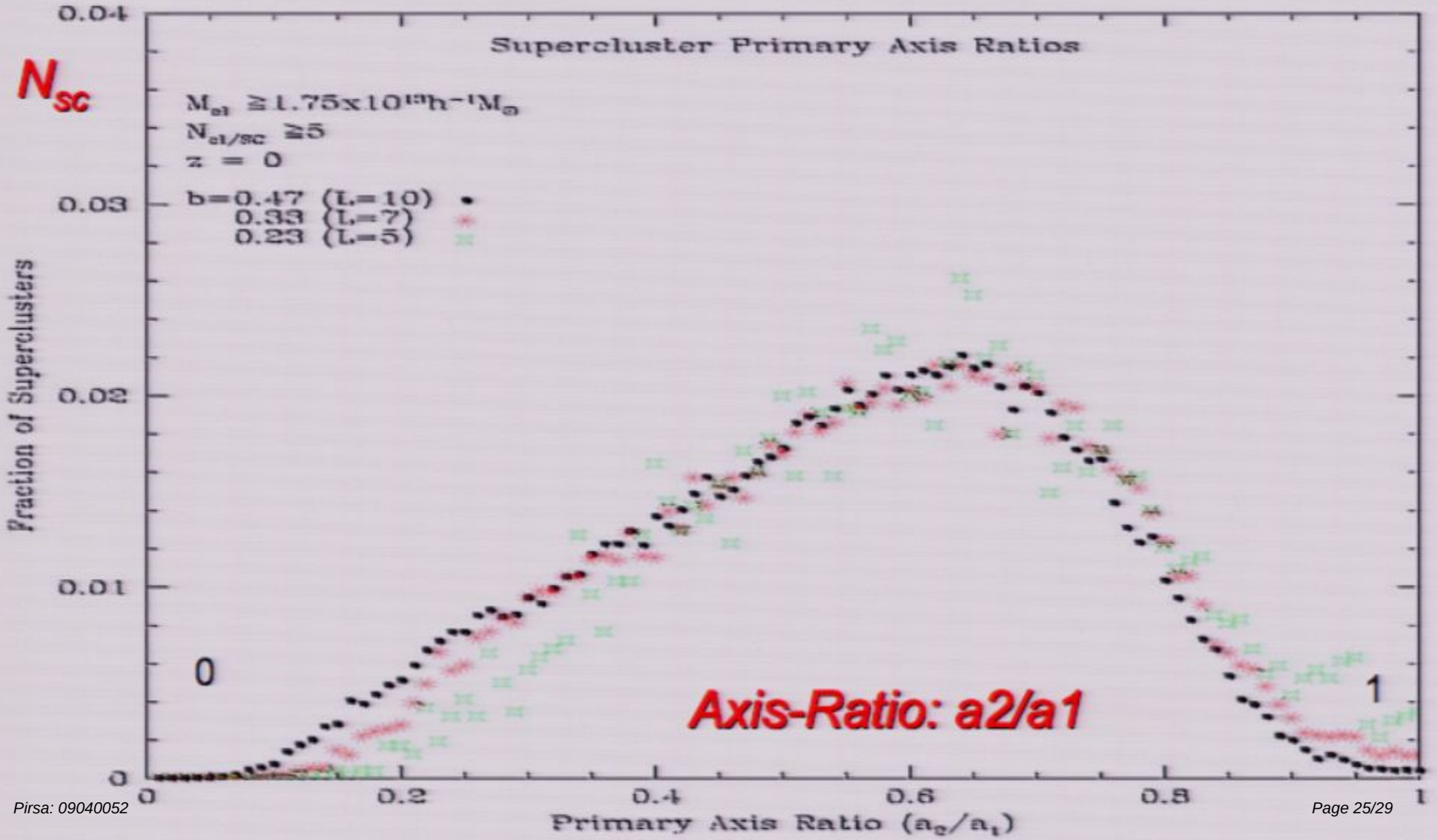
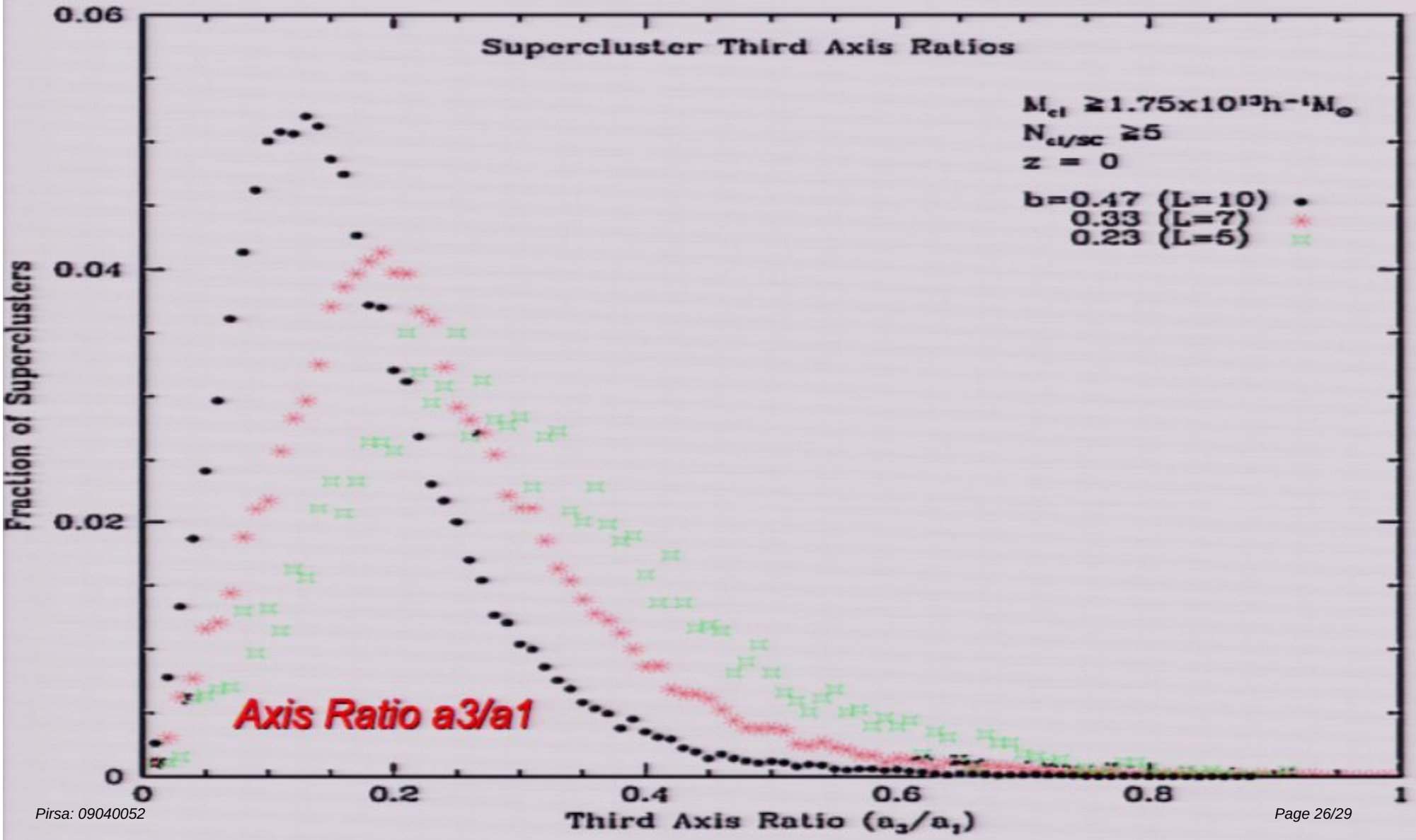


Fig. 2.— Same parameters as Fig. 1, but a different projection.

Superclusters Axis-Ratio: a_2/a_1
(Wray, Bahcall, Bode etal)



Superclusters Axis-Ratio: a_3/a_1



Filaments or Pancakes?
(Wray, Bahcall, Bode, etal '06)

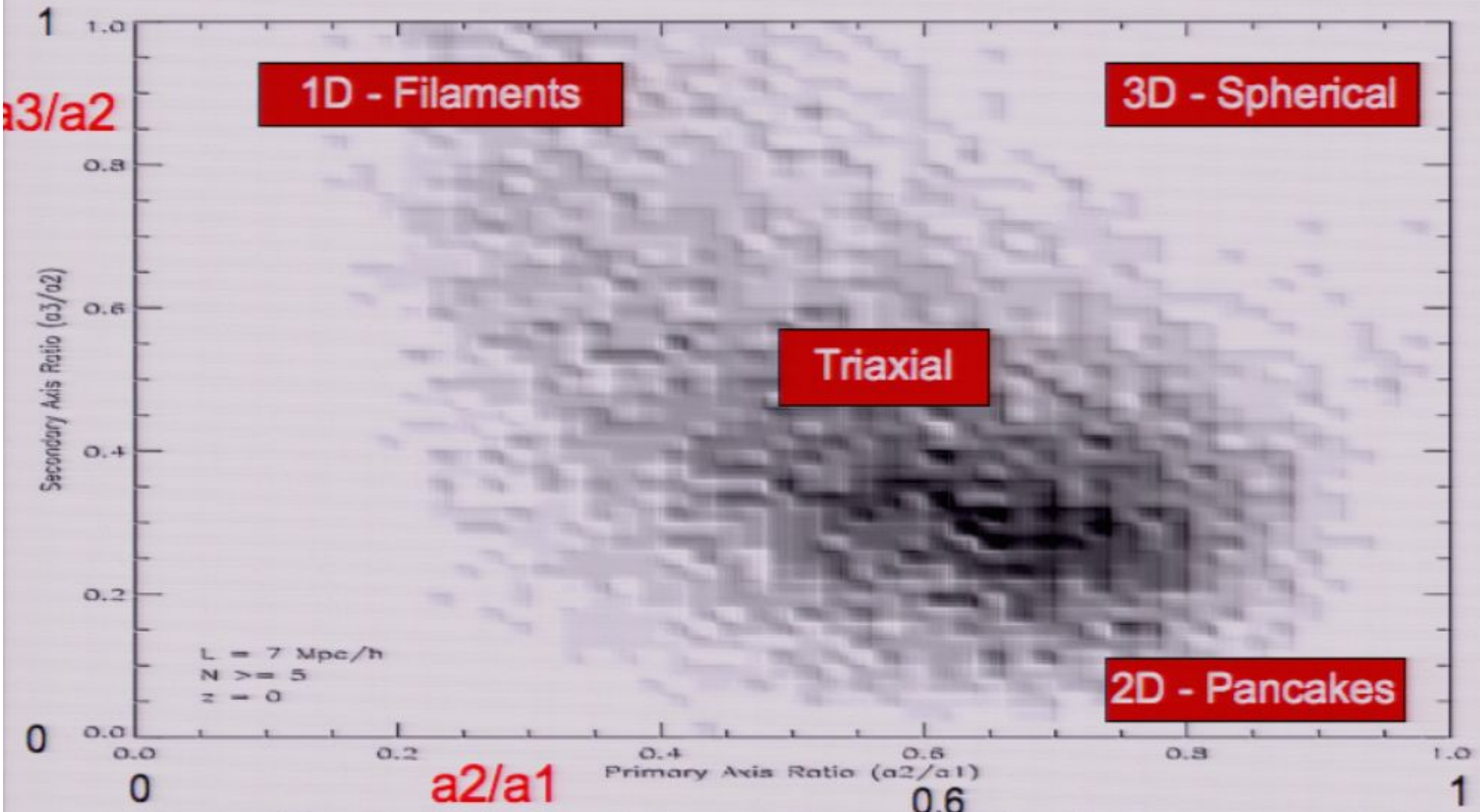


Fig. 9.— Bivariate distribution of primary and secondary axis ratios for low-z superclusters found with linking length $L = 7h^{-1}$ Mpc. See the text (§3.4) for interpretation.

Conclusions

Superclusters

- Supeclusters are *Triaxial*
  - > More so at ealier times
- Size: reaching *~200h^{-1} Mpc*
- Shape: *<a2/a1> ~ 0.6, <a3/a1> ~ 0.1-0.2*

e.g., *~ 100 x 60 x 10-20 Mpc* (z ~ 0)

➔ *Nearing 'Pancakes' at z ~ 0*

Conclusions

Clusters

- Clusters are *Triaxial*
  - > More so at earlier times
- *$\langle E_{cl} \rangle \sim 0.3$ to 0.5* (z ~ 0 to 3)
- Strong Cluster *Alignment to ~100 Mpc*
- Alignment and Ellipticity *increase with z*
- *New Tool in Cosmology:*

$\langle E_{cl} \rangle \rightarrow \sigma_8, \Omega_m$