Galaxy Clusters as Cosmological Probes

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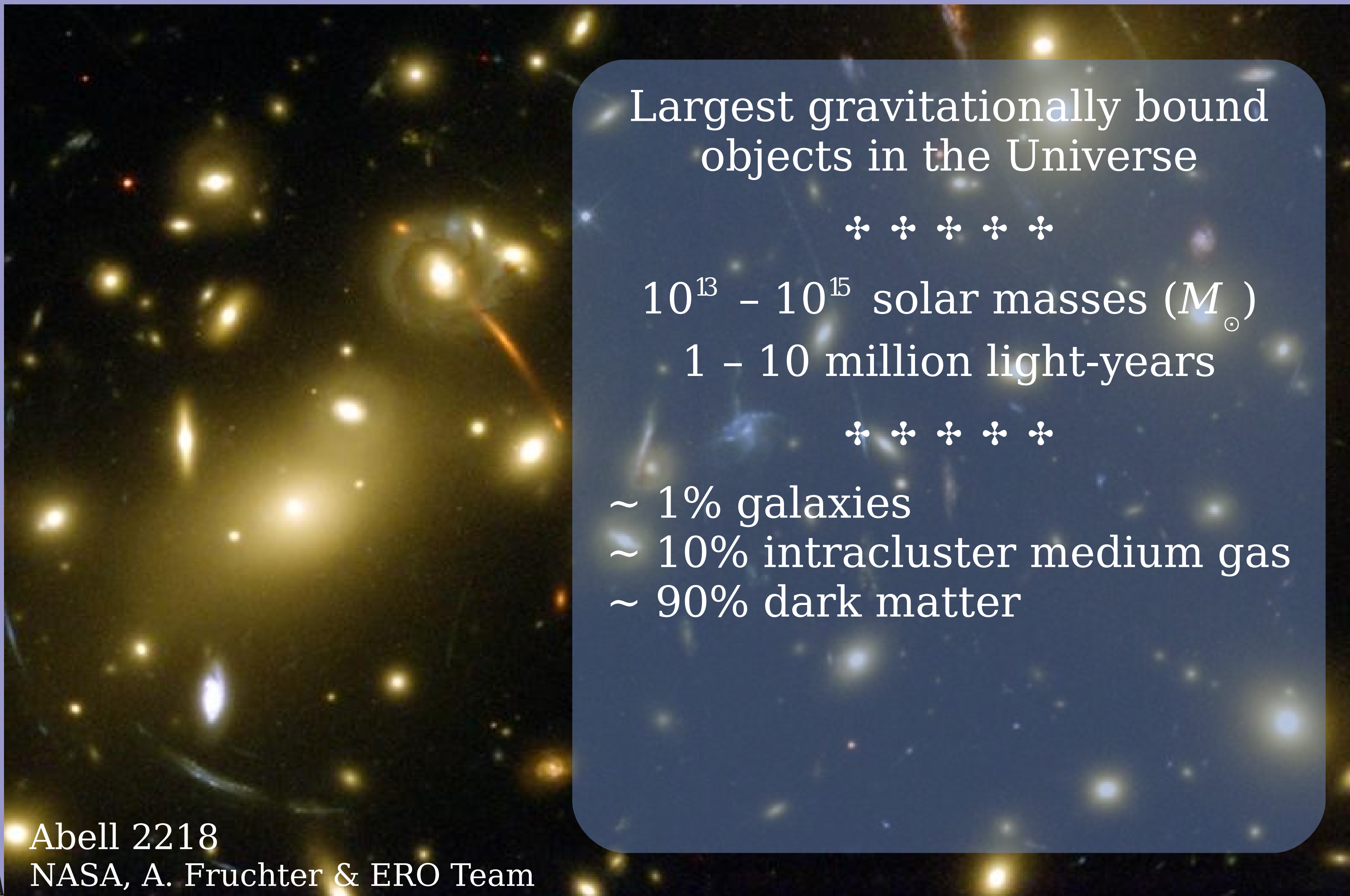
Outline

1. Galaxy clusters and their connection to cosmology
2. How clusters' physics affects their use as cosmological probes
3. Outlook for cluster cosmology

Clusters of galaxies



Largest gravitationally bound objects in the Universe

✣ ✣ ✣ ✣ ✣

10^{13} – 10^{15} solar masses ($M_\odot$)

1 – 10 million light-years

✣ ✣ ✣ ✣ ✣

~ 1% galaxies
~ 10% intracluster medium gas
~ 90% dark matter

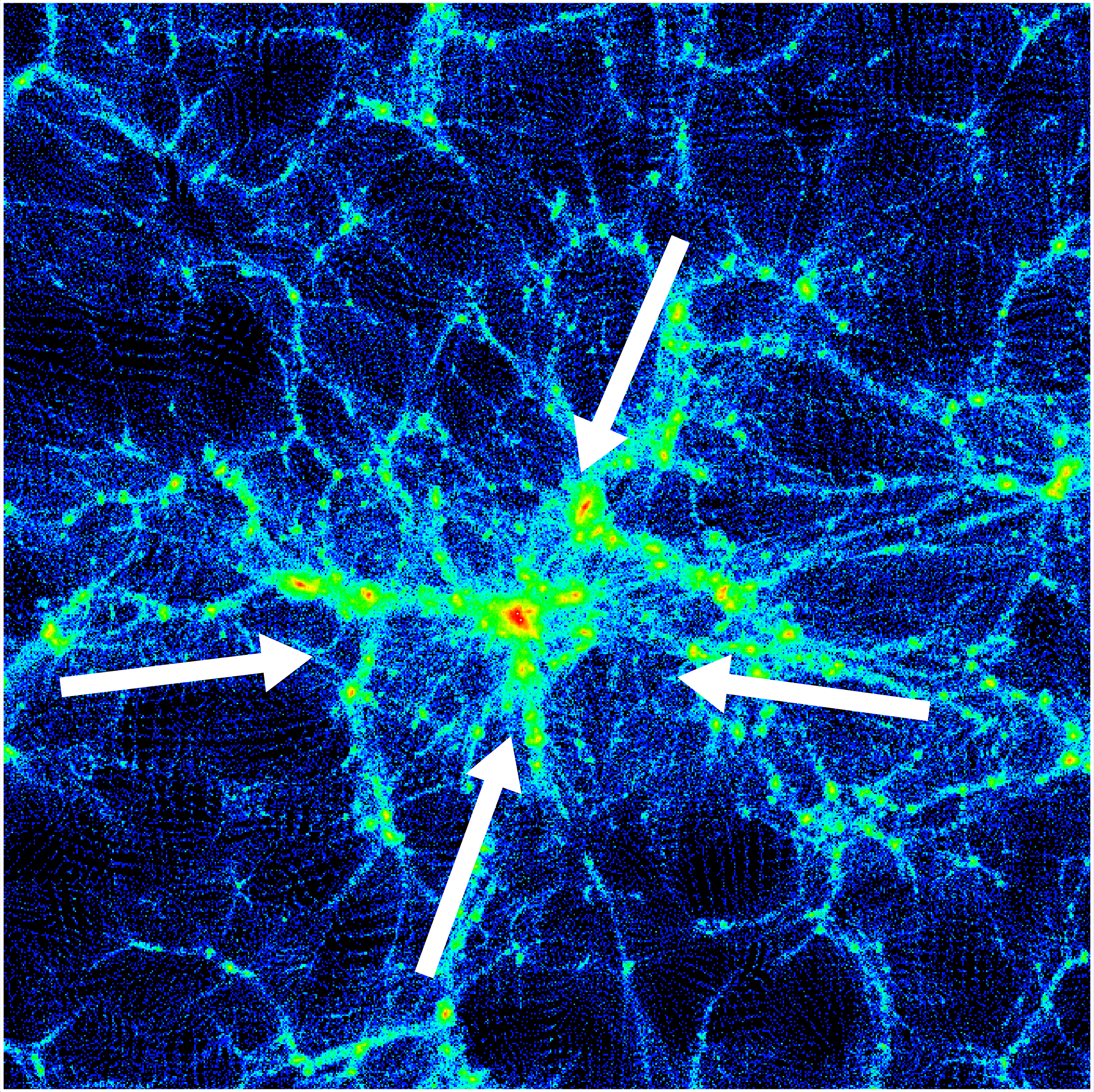
Abell 2218
NASA, A. Fruchter & ERO Team

Clusters in cosmological context

Clusters form through merging and accretion of smaller objects

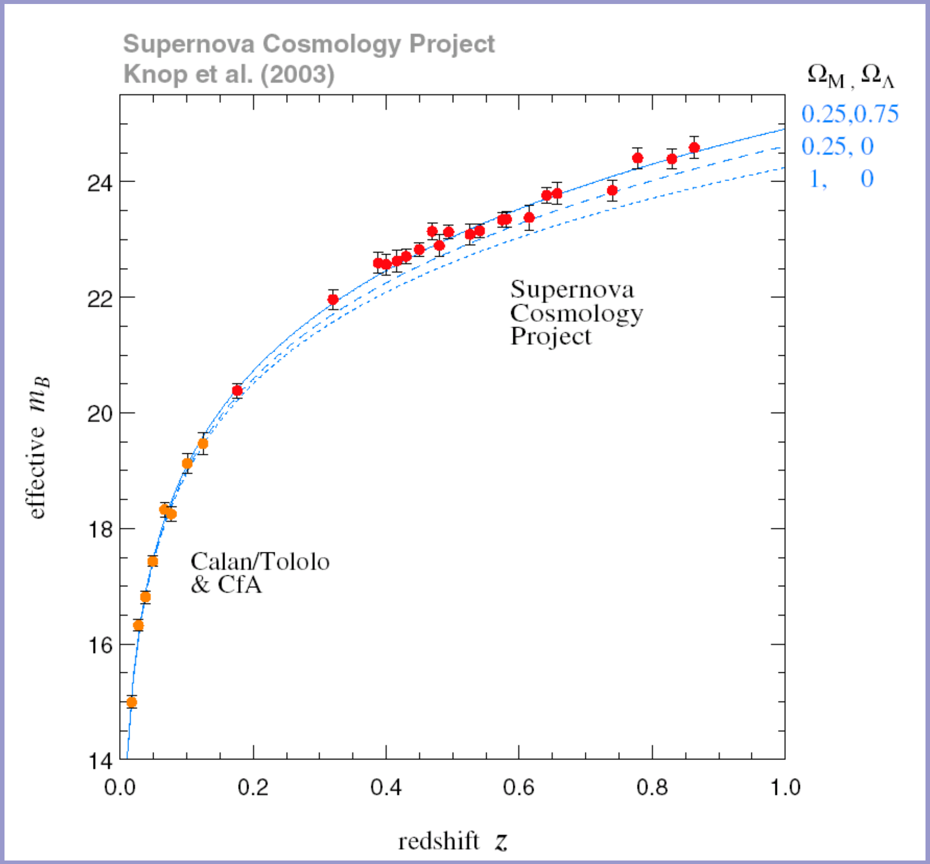
Filament-void network:
matter collects in filaments, then flows toward intersections

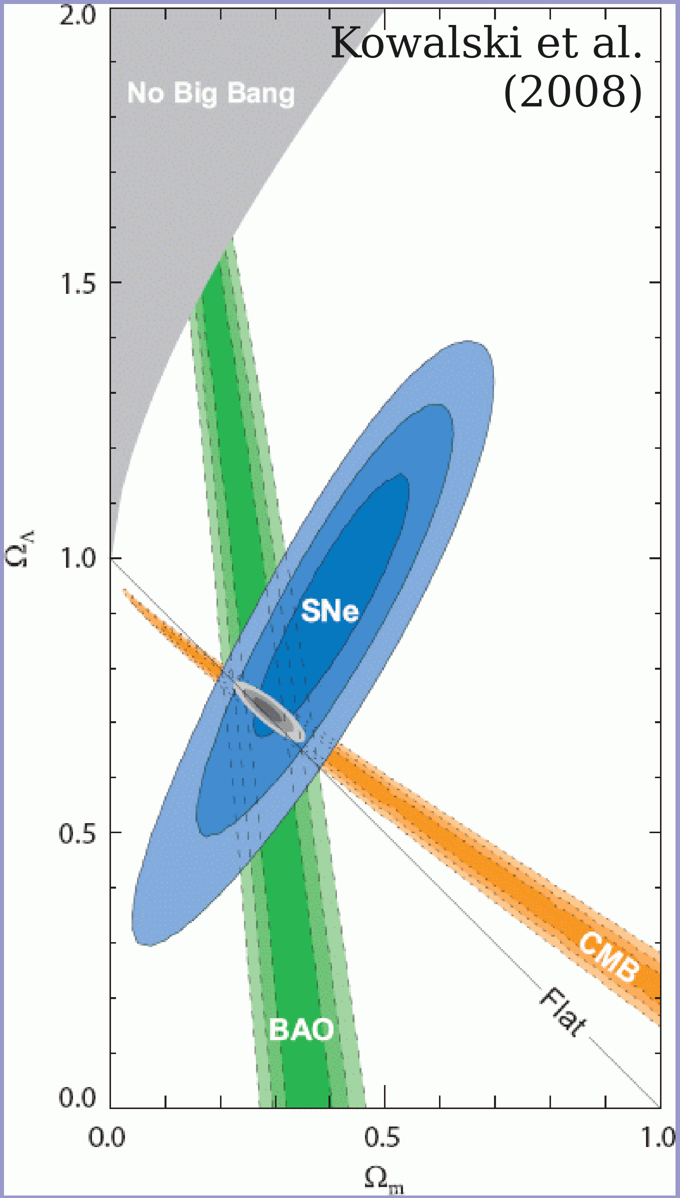
Rich clusters lie at the intersections



Dark energy

~ 70% of the energy density of the Universe today is in a form whose gravitational influence is *repulsive* – "dark energy"





Parametrize your ignorance

Friedmann equations

Expansion rate

$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\left[\frac{\rho_{m0}}{a^3}+\rho_{de}-\frac{k}{a^2}\right]$$

Rate of change of expansion rate

$$\frac{1}{a}\frac{d^2a}{dt^2} = -\frac{4\pi G}{3}\left[\frac{\rho_{m0}}{a^3}+\rho_{de}\left(1+3w\right)\right]$$

The **equation of state parameter** is defined as

$$w(t) \equiv \frac{P_{de}(t)}{\rho_{de}(t)\,c^2}$$

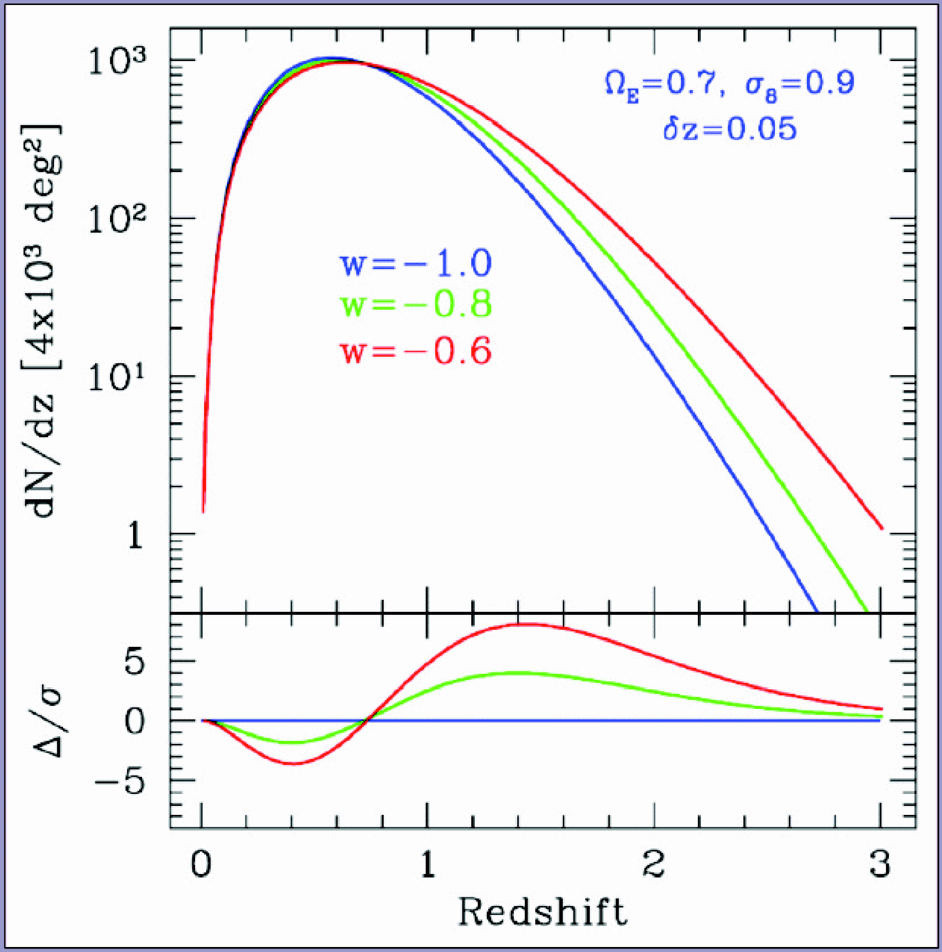
If $w < -1/3$, the expansion accelerates when ρ_{de} dominates.

Counting clusters for cosmology

Cluster abundance as a function of mass and redshift

$$\frac{d^2N}{dM\,dz} = \frac{dV}{dz}\,n(M,z)$$

$$n(M,z) \propto \frac{\rho_b}{\sigma M}\int_{\delta_c}^{\infty} d\delta\,\exp\left(-\frac{\delta^2}{2\sigma^2}\right)$$



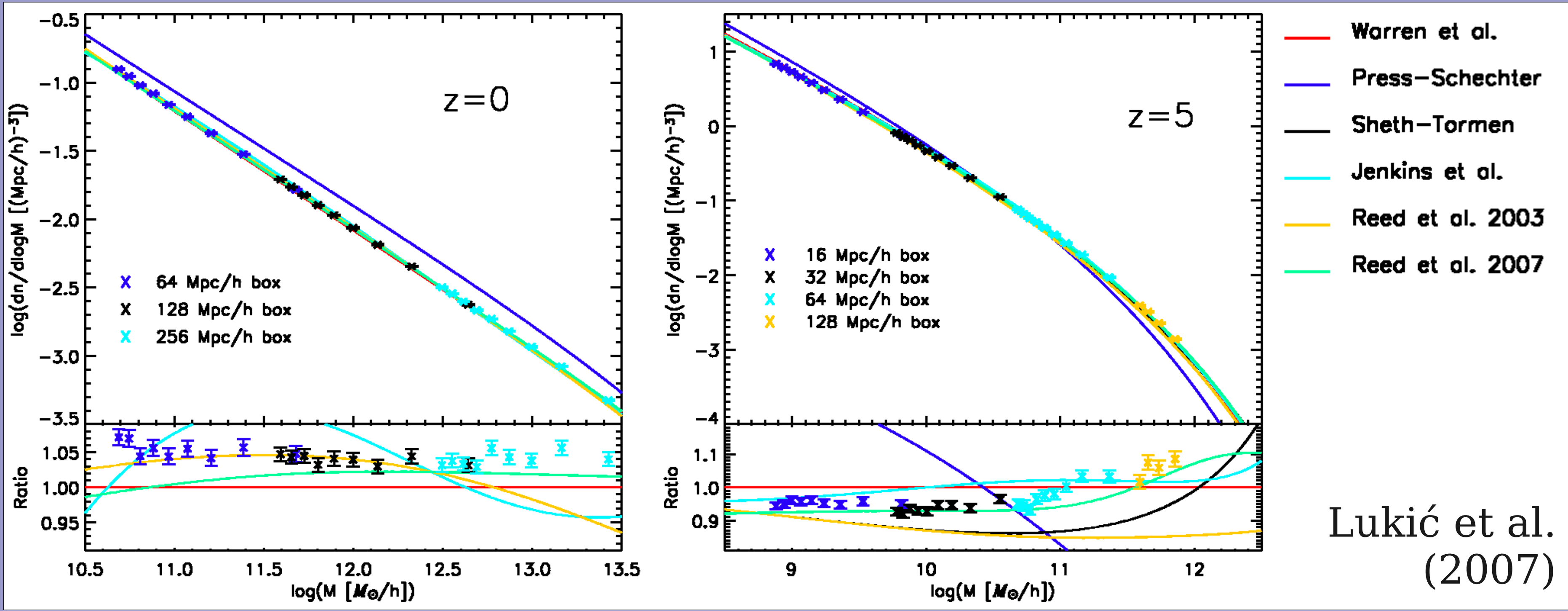
Mohr (2005)

Depends on:

- Volume-redshift relation *dV/dz*
- Linear growth factor ($\rightarrow \delta(z)$)
- Power spectrum ($\rightarrow \sigma(M,z)$)

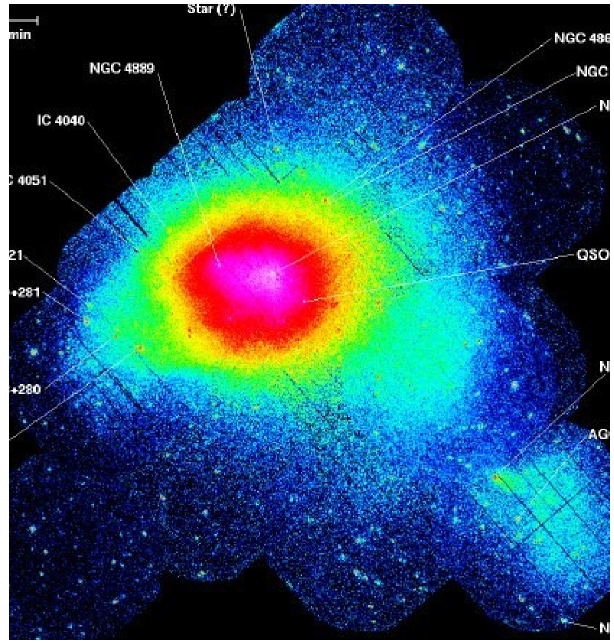
The dark matter halo mass function

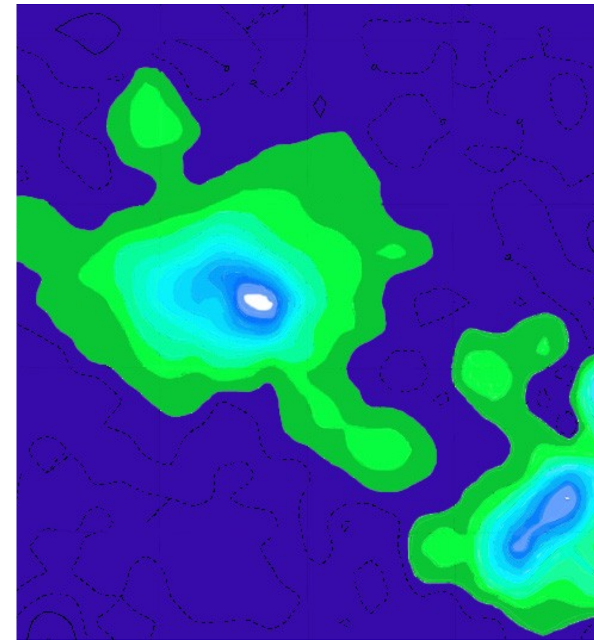
- **Accurately predicted by *N*-body simulations (e.g. Warren et al. 2006)**
  - Evolution follows mass variance evolution to first order
- **Theoretically understood using excursion sets (Lacey & Cole 1993, 4)**
  - Shape reflects Gaussian process probability of exceeding collapse threshold



Lukić et al. (2007)

Observing galaxy clusters





Optical/Infrared

Galaxies
Intracluster stars

Dark matter via
gravitational lensing

X-Ray

Thermal hot gas

Radio

Nonthermal particles

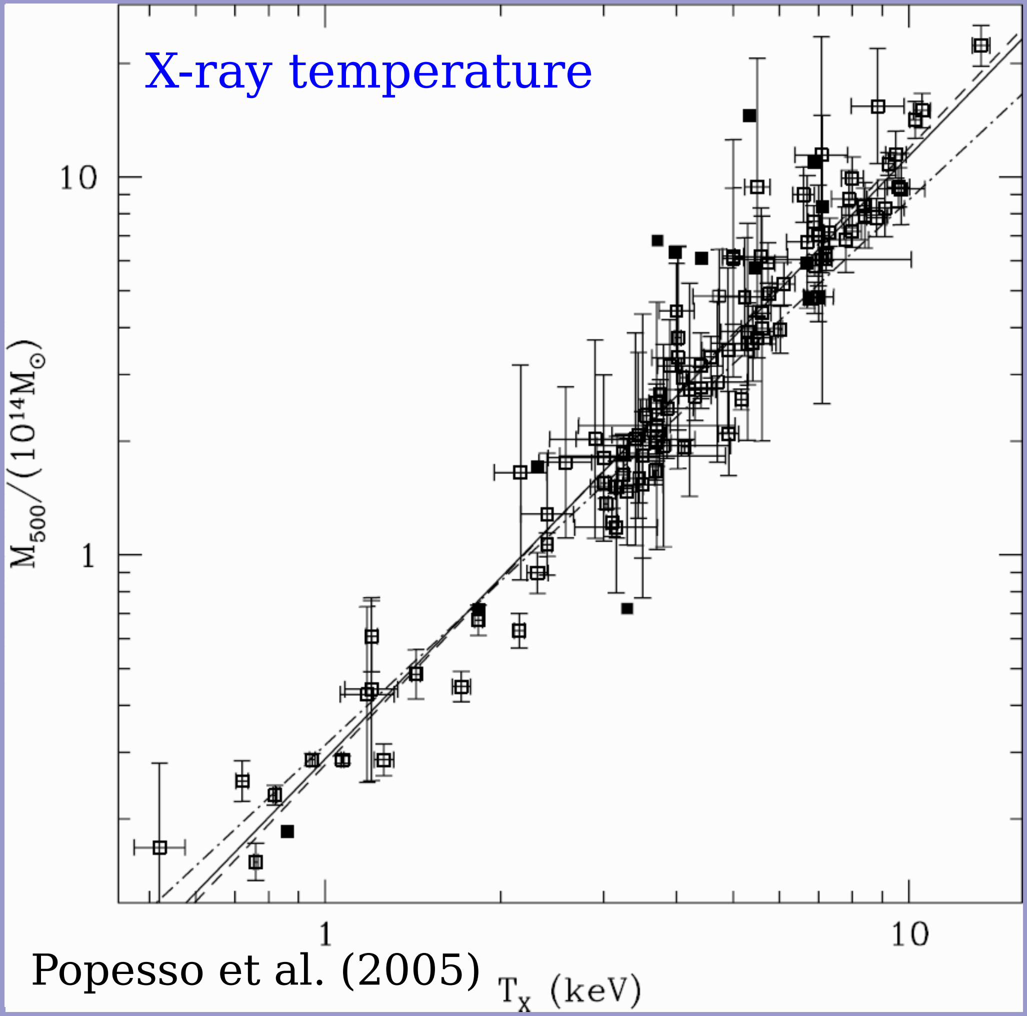
Thermal hot gas via
Sunyaev-Zel'dovich
effect (microwave)

Mass-observable scaling relations

For clusters, many things correlate with mass

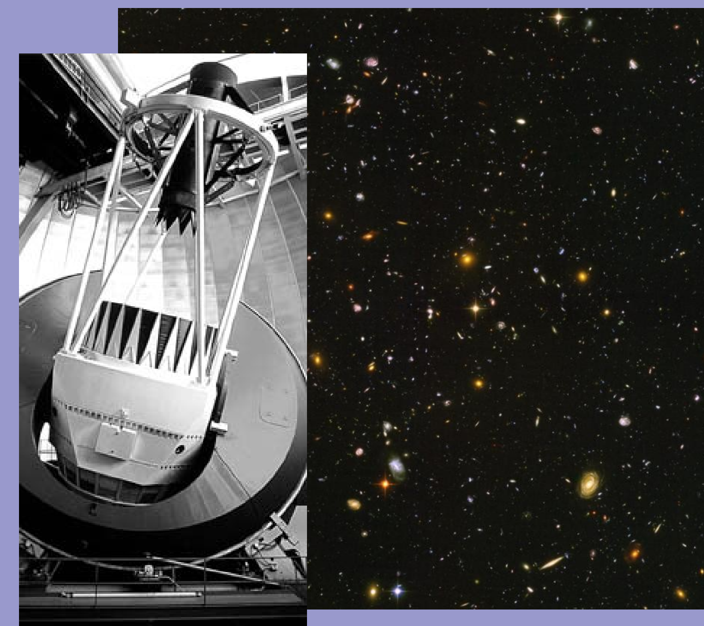
- X-ray luminosity
- X-ray temperature
- Sunyaev-Zel'dovich effect
- Isophotal size
- Infrared luminosity

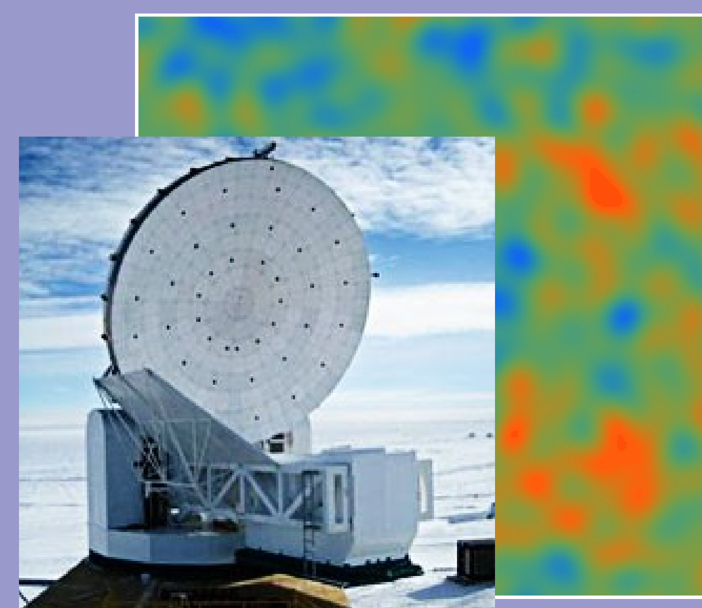
Massive clusters are a fairly regular population



Cluster surveys to measure dark energy

- **Dark Energy Survey (DES)**
  - Optical redshift catalog of ~ 10^7 galaxies to z ~ 1.4
  - 5000 deg^2 survey of southern sky
  - 500 Mpixel 4-color camera
- **South Pole Telescope (SPT)**
  - Microwave catalog of ~ 10^4 clusters
  - 4000 deg^2 survey at < 1' resolution
  - 3 – 5 frequencies (95 – 350 GHz)
- **Survey volumes ~ 1 Gpc^3**





Options for constraining cosmology

- **Direct *N*-body/gasdynamics + mock skies**
  - Directly form stars, AGN, etc. (perhaps with subgrid models)
  - Simulate observations, including light travel time and response
  - Compare with observations in “data space”
- ***N*-body + mass-observable relation***
  - Mass function from simulations
  - Assign observables based on observed scalings
- **Self-calibration*** (Levine et al.; Lima & Hu; Majumdar & Mohr)
  - Parametrize mass-observable relation
  - Fit parameters along with cosmology

* Need to know the form and evolution of the intrinsic scatter!

The intracluster medium (ICM)

Collisionally ionized plasma

- $n_e \sim 10^{-3}$ cm^{-3}
- $T \sim 10^7$ - 10^8 K (1 – 10 keV)

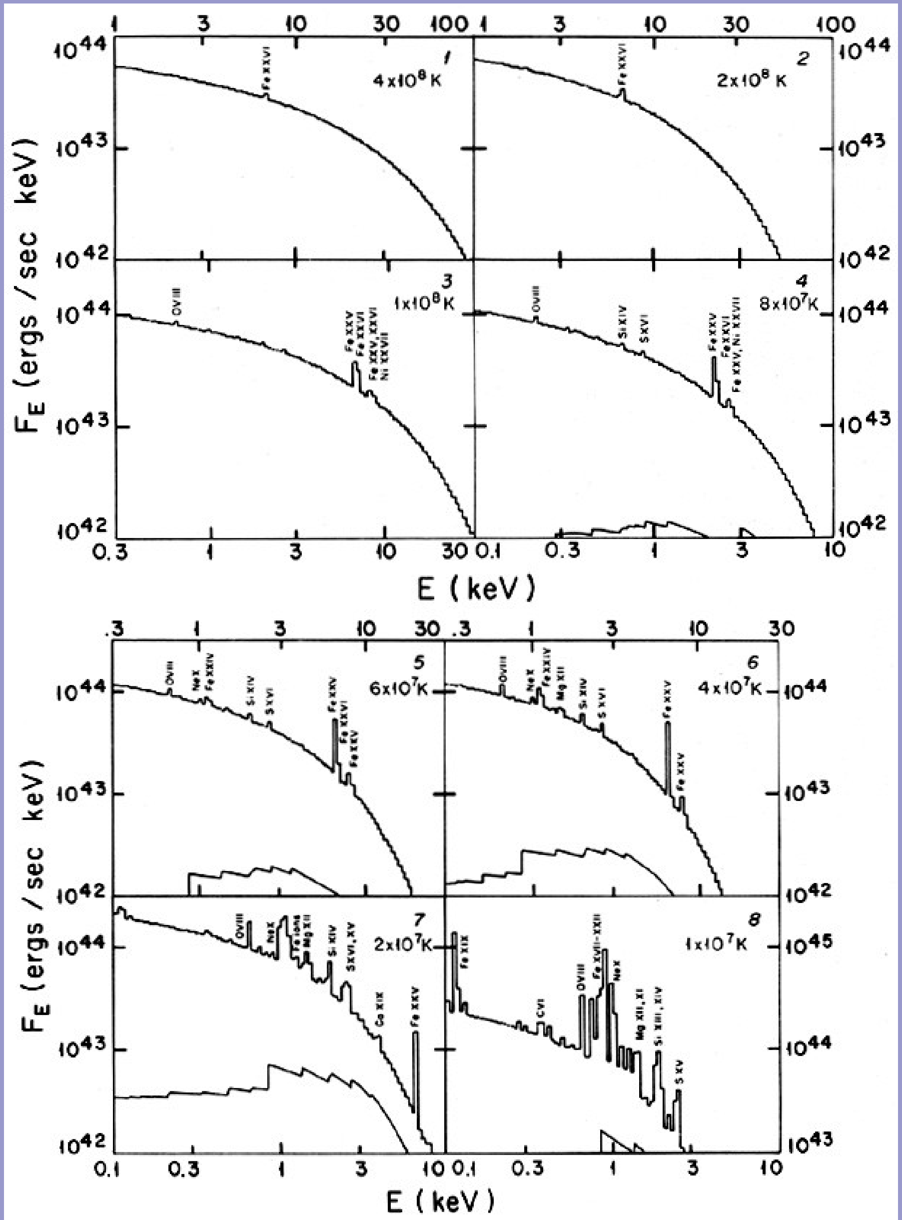
Heavy element abundance
~ 0.3 – 0.5 solar

Optically thin emission

- Thermal bremsstrahlung ($T > 10^7$ K)
- Recombination and line emission ($T < 10^7$ K)

Isobaric cooling time

$$t_{\rm cool} = 8.5\times10^{10}\left(\frac{n_e}{10^{-3}\,{\rm cm}^{-3}}\right)^{-1}\left(\frac{T}{10^8\,{\rm K}}\right)^{1/2}\ {\rm yr}$$



Model X-ray spectra (Sarazin & Bahcall 77)

Clusters are hydrostatic and spherical.

NOT!

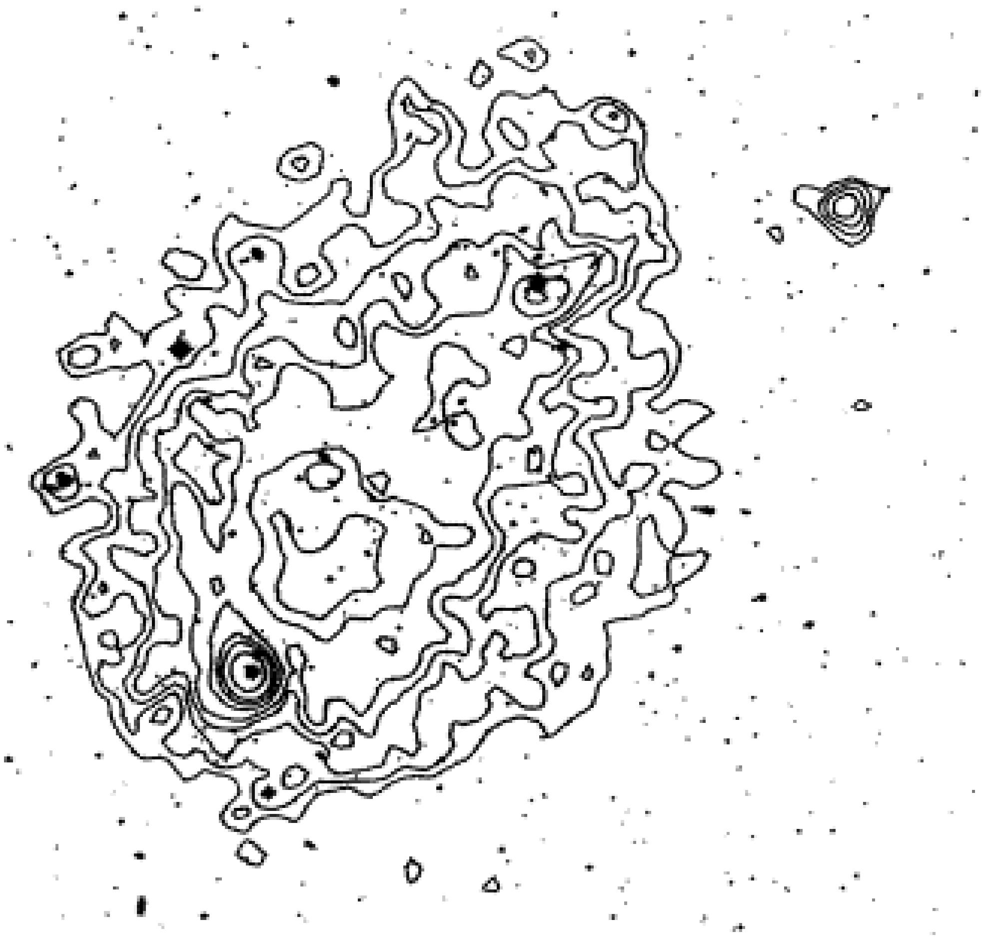
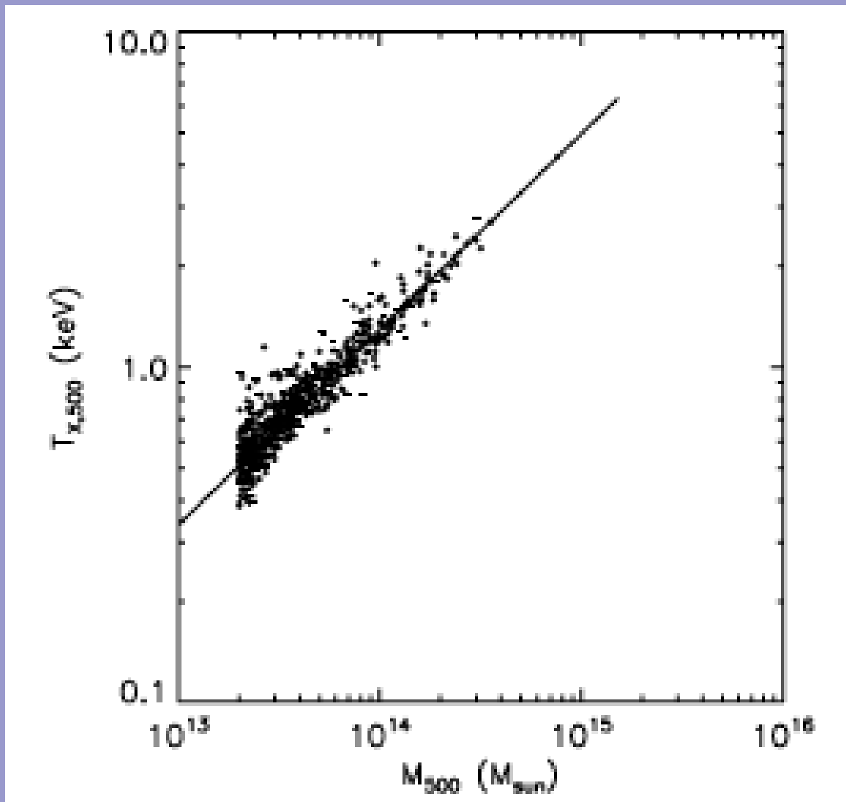


Figure 2: The X-ray iso-intensity contours of A1367 snow the elongatation or the central region ot the cluster and the ga.axy associated with 3C284 in the southeast.

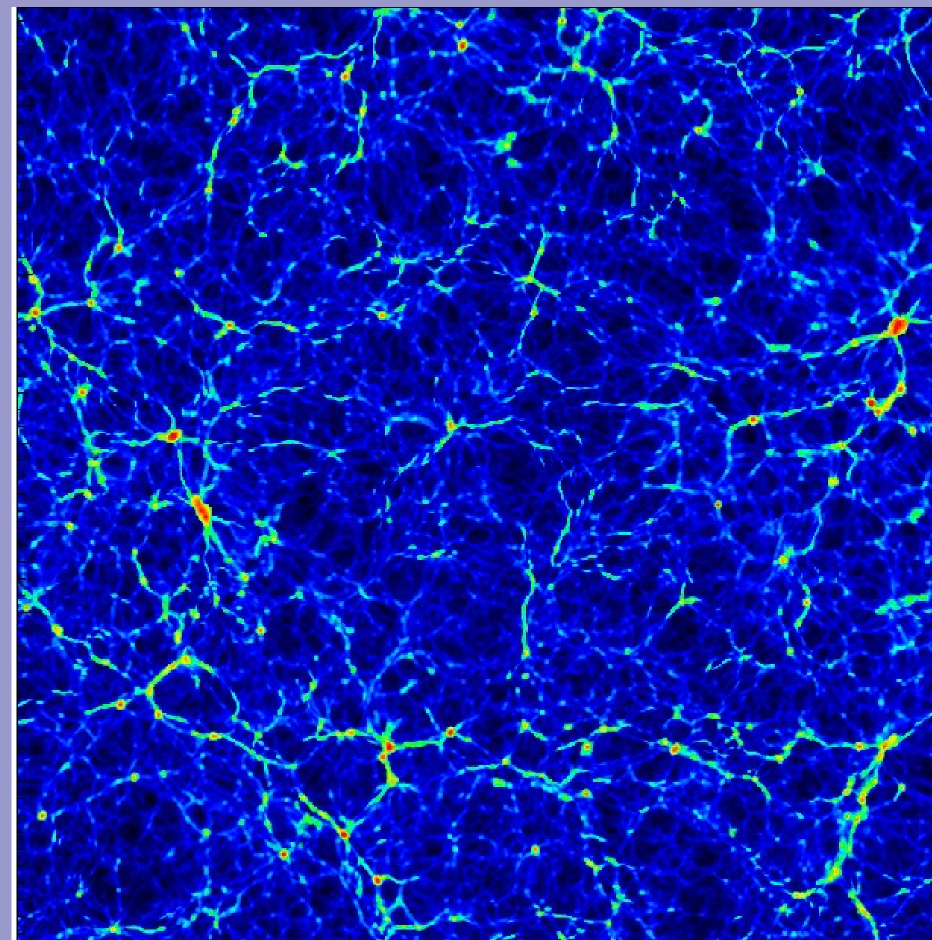
Einstein data
Jones & Forman (82)

Effects of cluster dynamics – *FLASH*

Yang et al. (2009, 2010)



X-ray mass-temperature relation
at redshift 0
~ 600 clusters with $M > 2\text{x}10^{12}\ M_{\odot}$

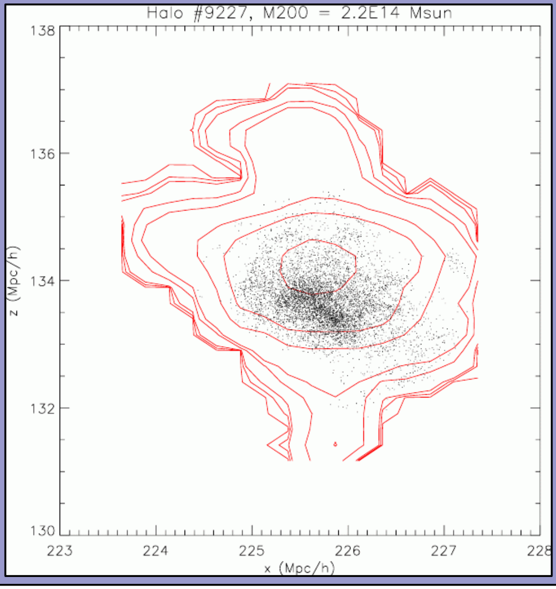


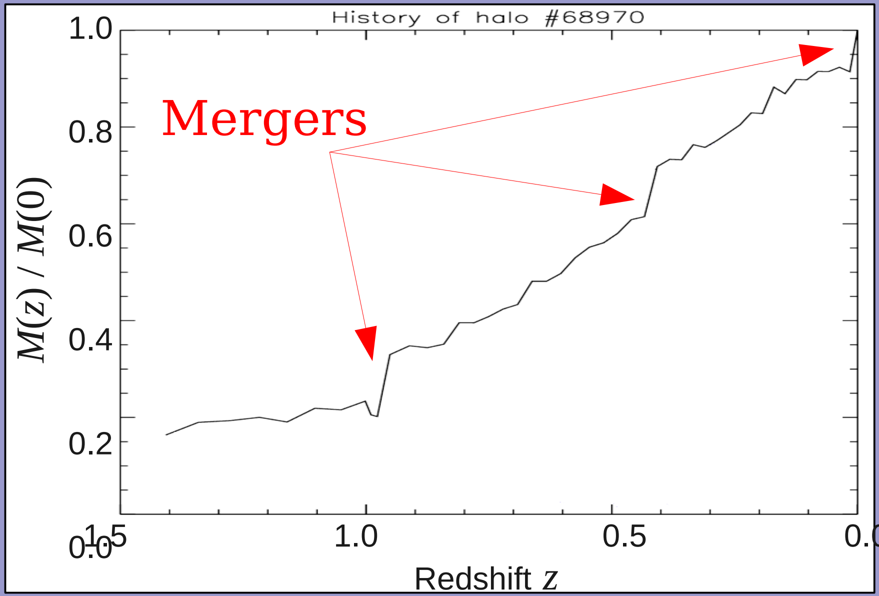
$256\ h^{-1}$ Mpc

ΛCDM cosmology: $\Omega_{m0} = 0.262$, $\Omega_{b0} = 0.0437$, $h = 0.708$, $\sigma_8 = 0.74$

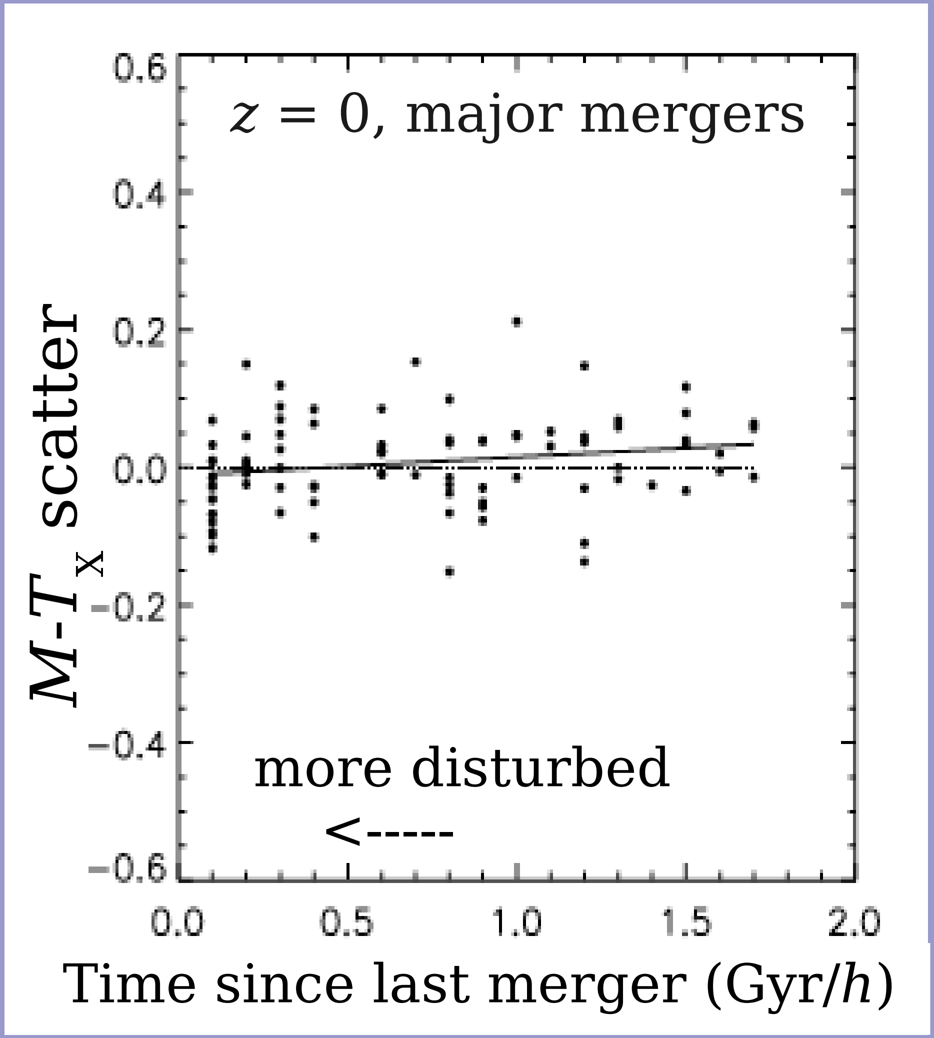
Dynamical state diagnostics

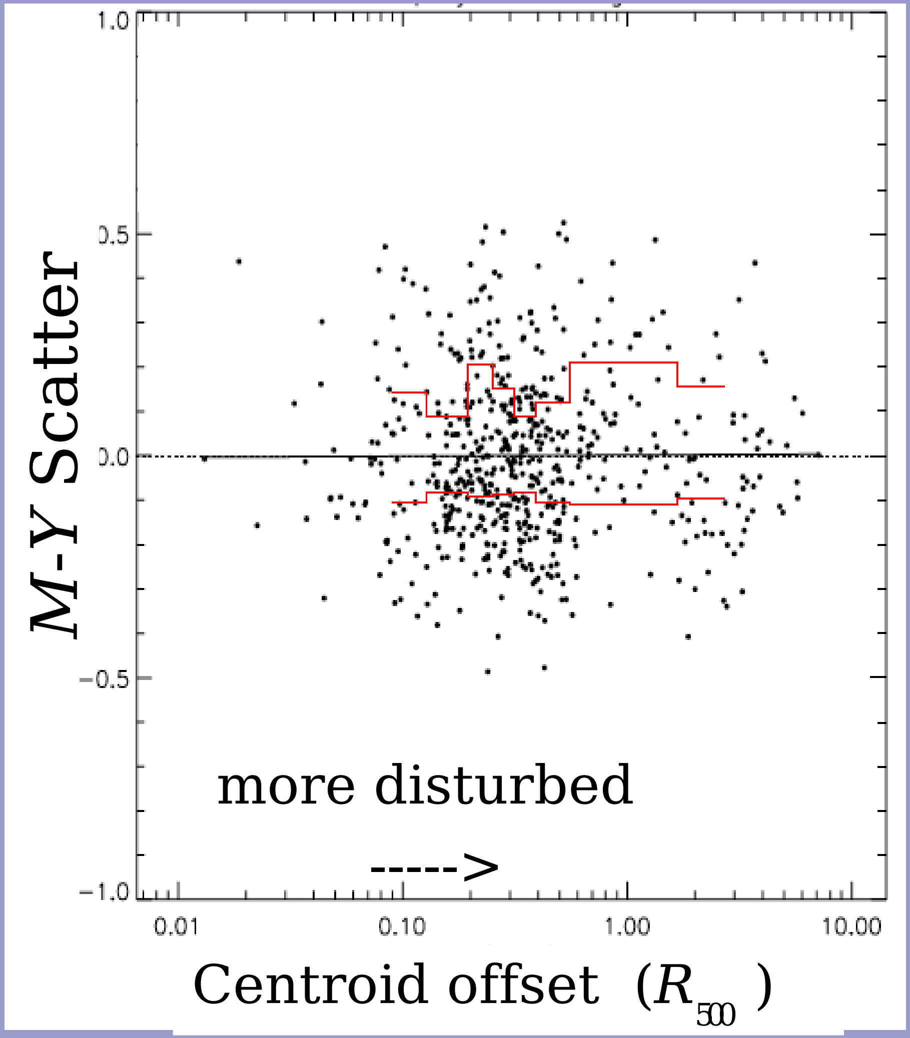
- **Centroid offset** (Mohr et al. 1995)
- **Multipole power** (Buote & Tsai 1995, 6)
- **Merger history** (Cohn & White 2005)
  - Use particle tags to trace halo progenitors
  - Identify merging events using
    - *Mass jump* – ratio of halo mass to mass of largest progenitor
    - *Mass ratio* – ratio of masses of two largest progenitors





Effects of cluster dynamics





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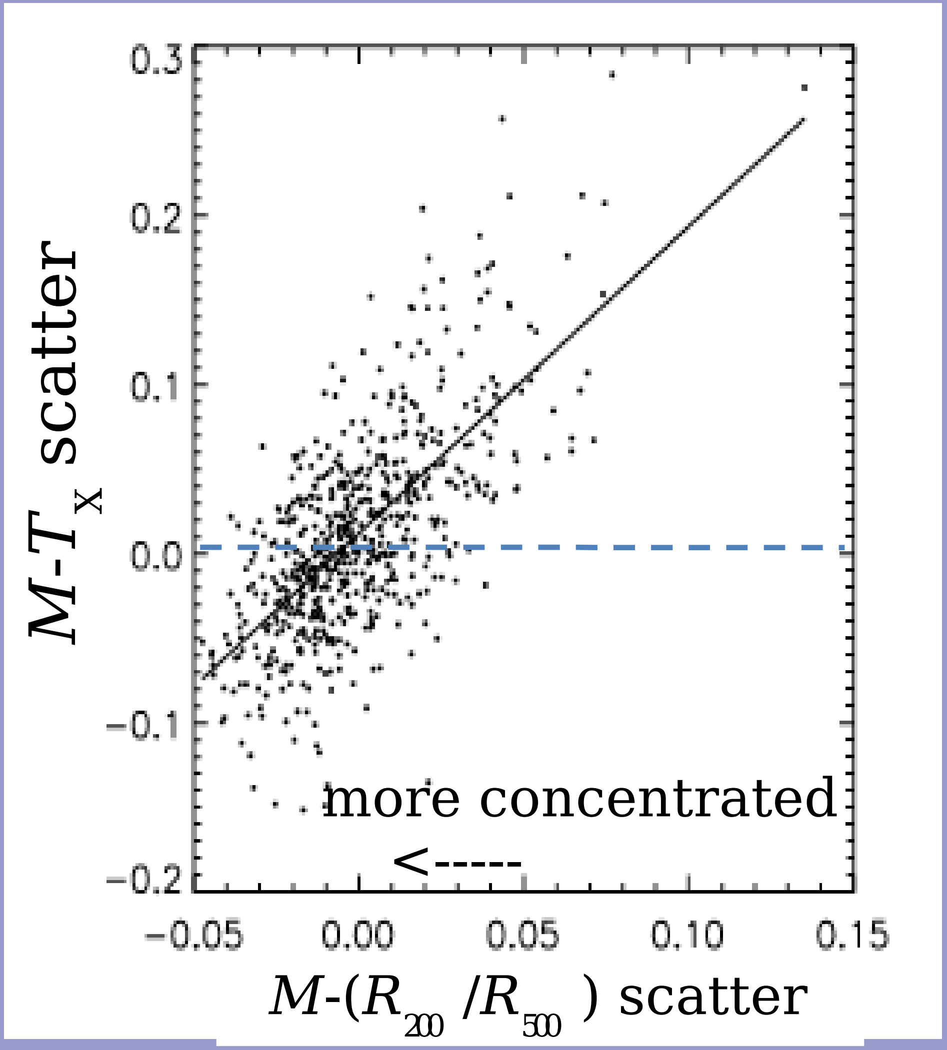
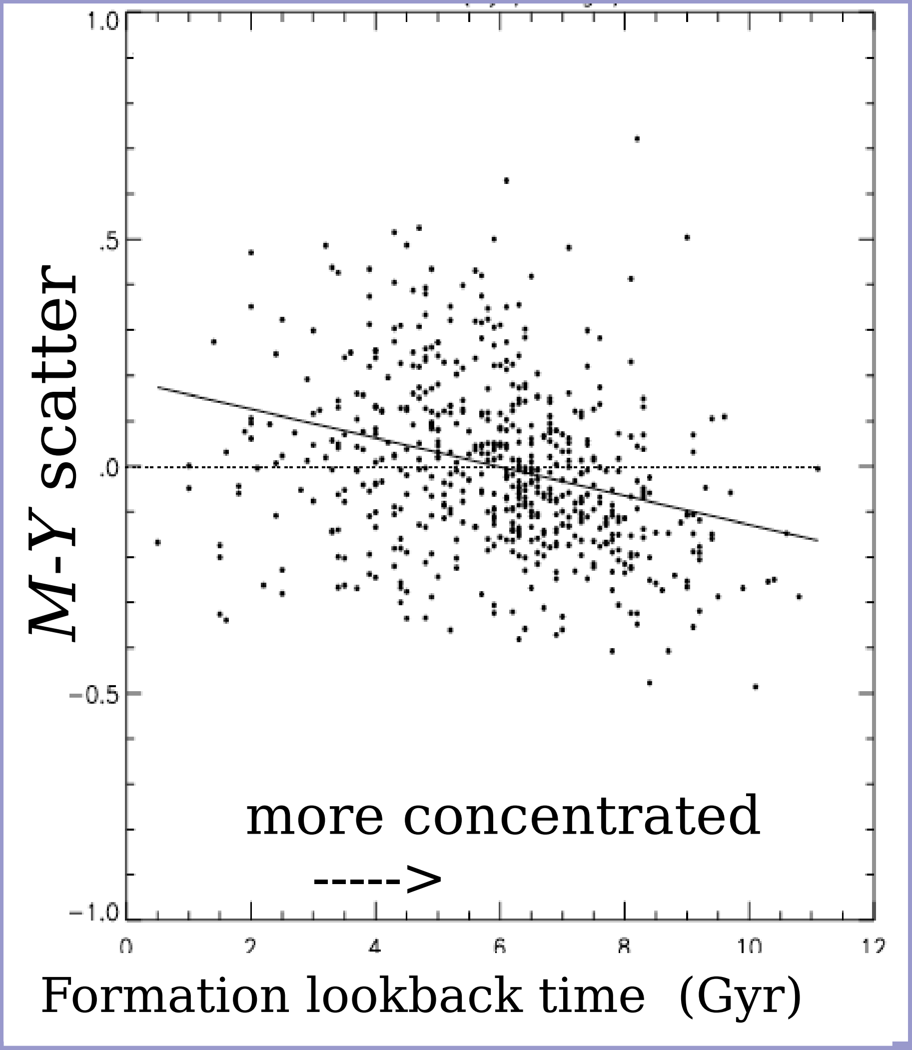
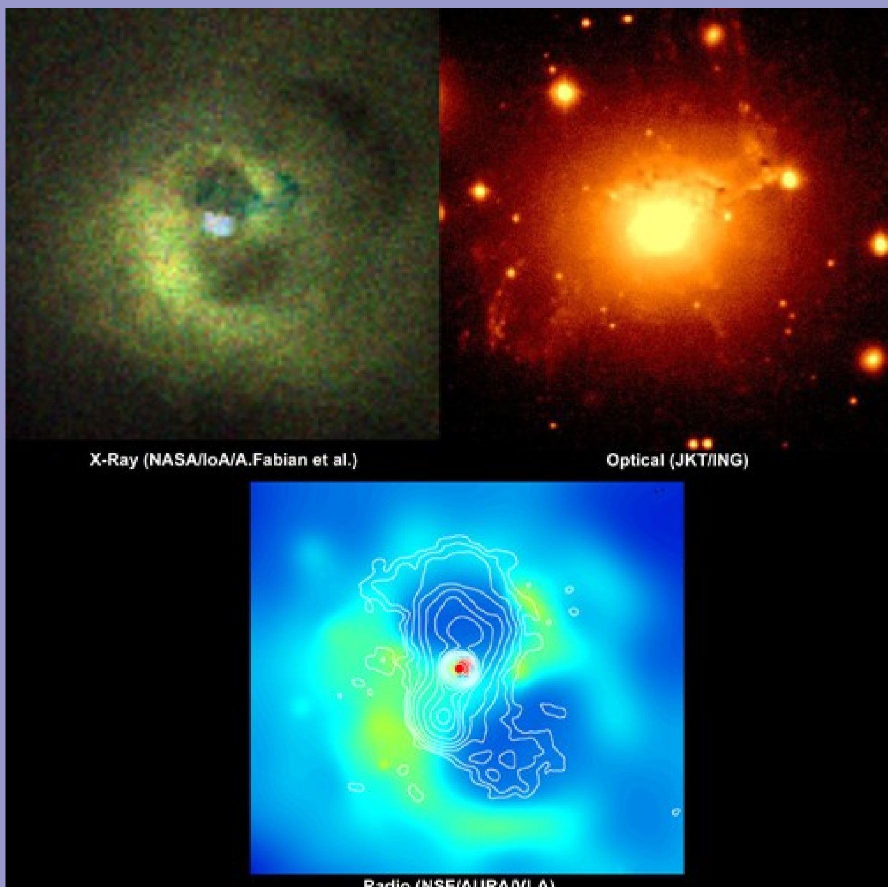


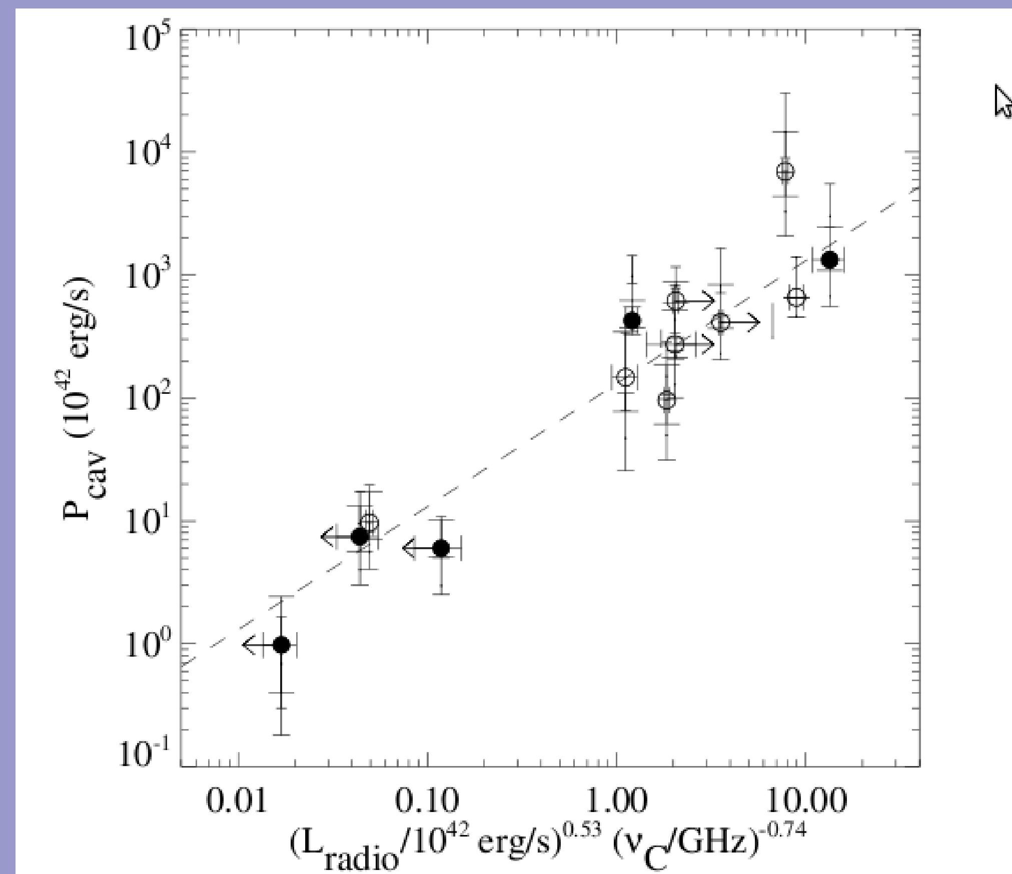


The ICM is "adiabatic."

NOT!



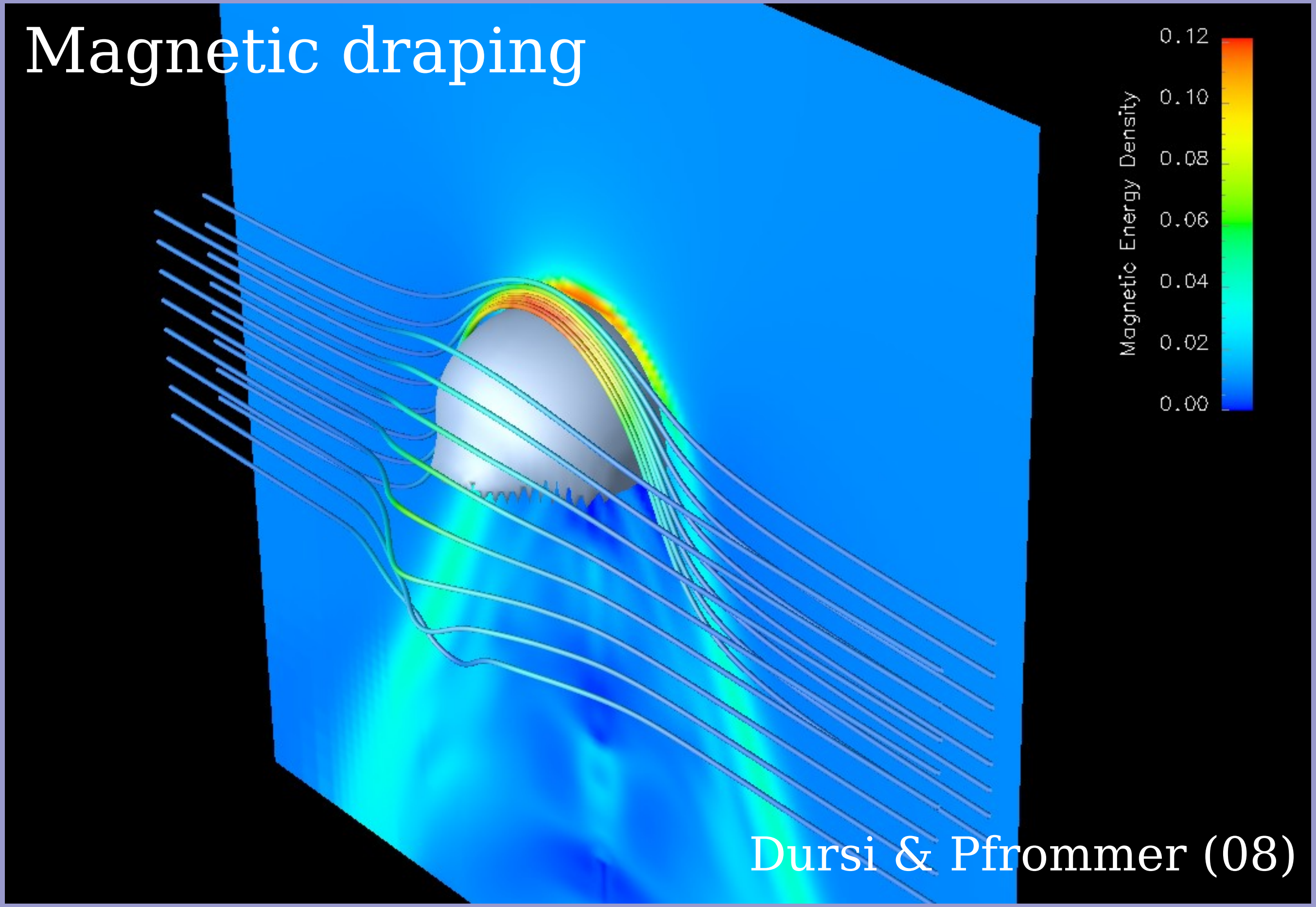
Perseus A (z = 0.018)



Birzan et al. (08)

Magnetic fields are dynamically unimportant.

NOT!



Even a weak field ($\beta \sim 1$ - 10) can stabilize magnetized bubbles against destruction by fluid instabilities

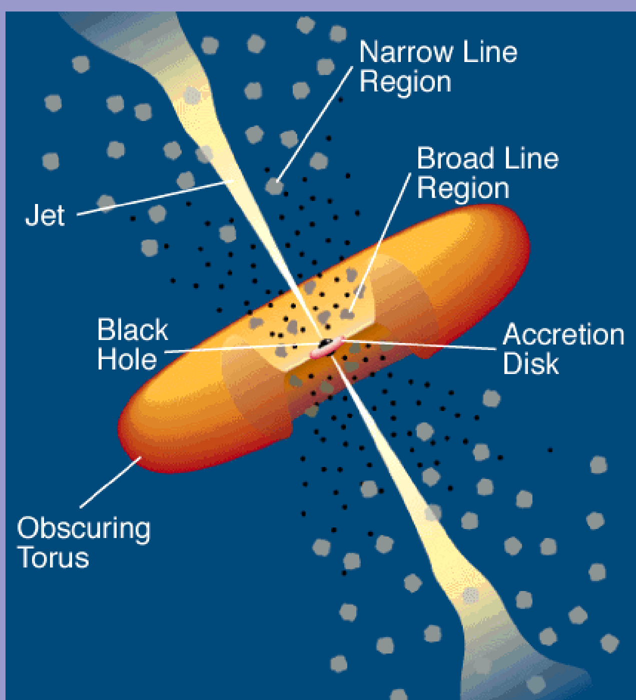
Direct simulation?

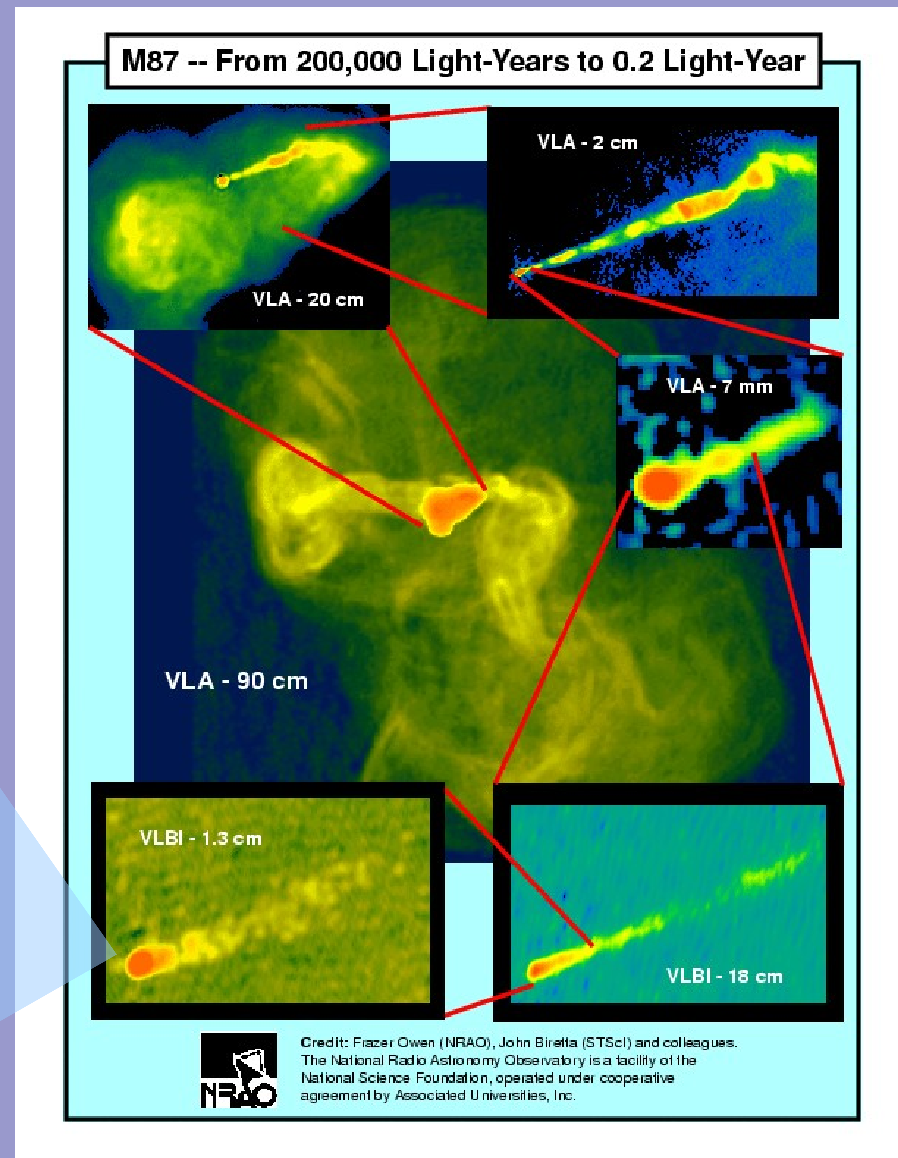
FORGET IT!

Cluster size ~ 1 Mpc

Accretion disks ~ 100 AU

⇒ Dynamic range ~ 2 x 10^9





What can we afford?

Time to solution: 1 month = 2.6 x 10^6 sec

⇒ Operations at 1 Pflop/s sustained: 2.6 x 10^{21}

Operations per resolution element update: ~ 100 – 1000

⇒ Resolution element updates: 2.6 x 10^{18}

⇒ Uniform resolution elements on a side in 3D: 40,000

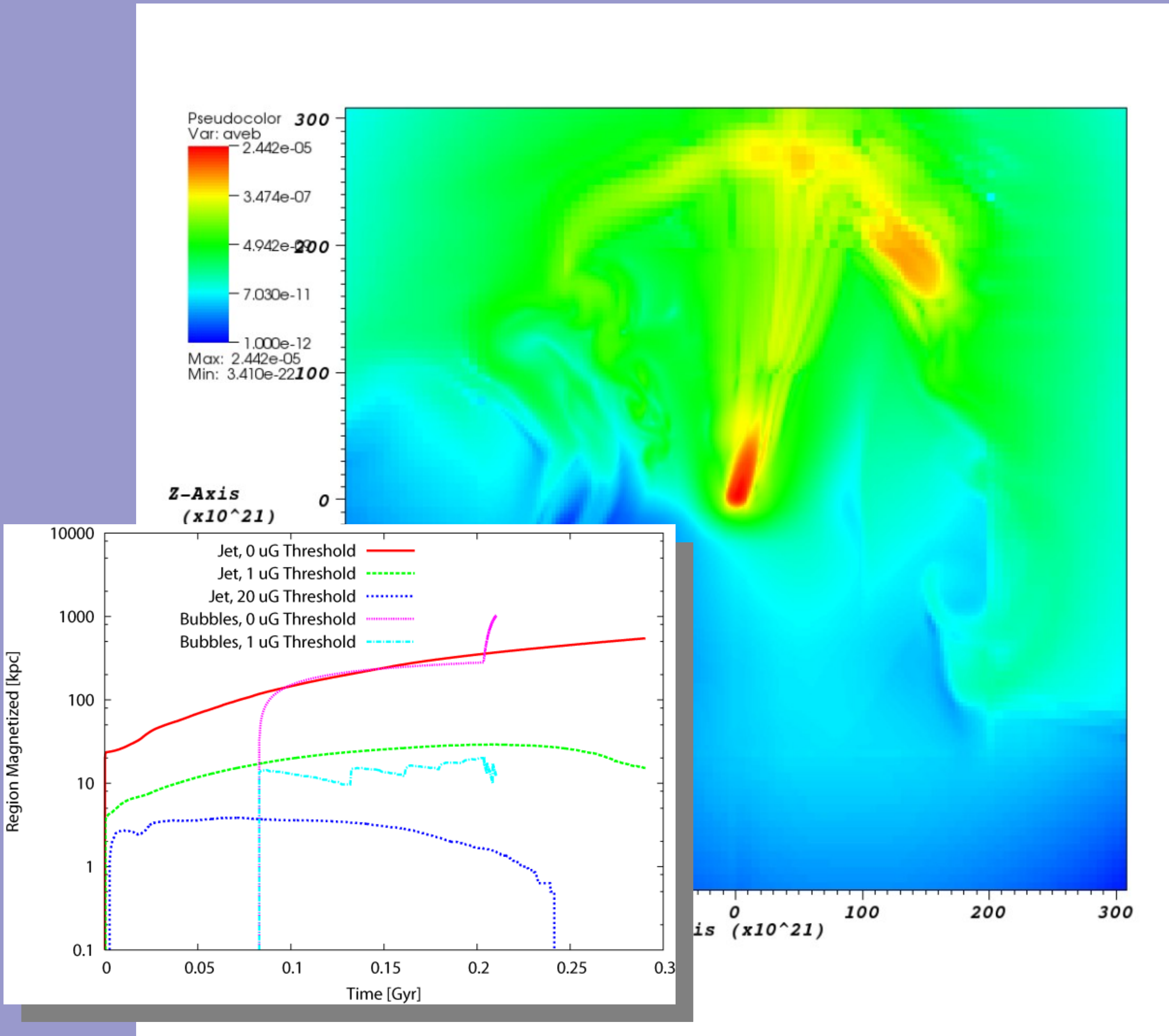
AMR/SPH gain over uniform grid: ~ 1000

⇒ Achievable dynamic range at petascale: 4 x 10^7

Cosmological simulations with realistic modeling of molecular clouds (~ 1 pc) achievable at petascale

Modeling of AGN accretion disks requires exascale (2020+)

Sustained 1 Pflop/s
Online June 2011

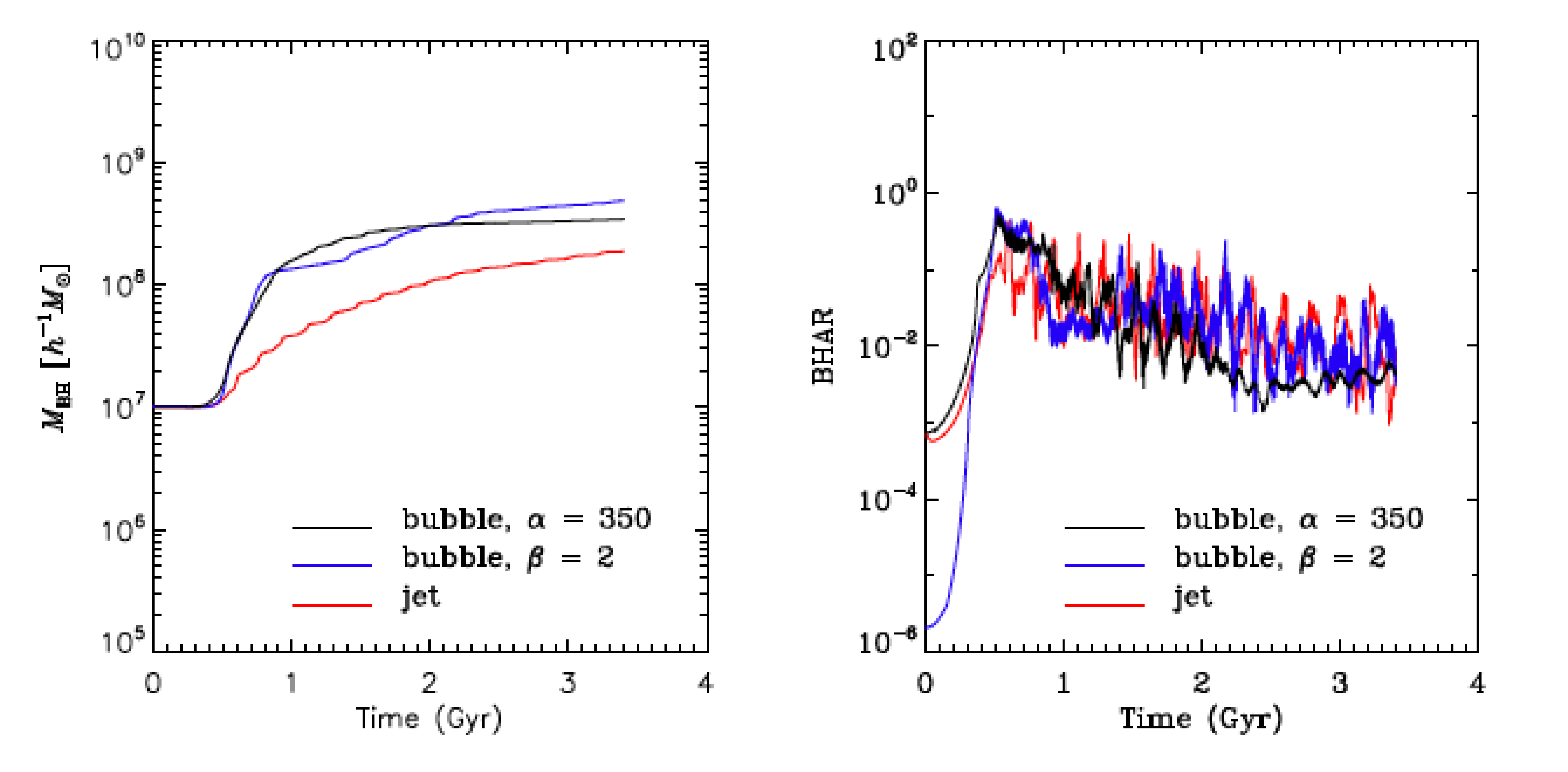


Magnetized AGN jet in model cluster

Sutter, Ricker, & Yang (09)

Effects of cooling and AGN feedback

Yang et al. (2009)



Effects of cooling and AGN feedback

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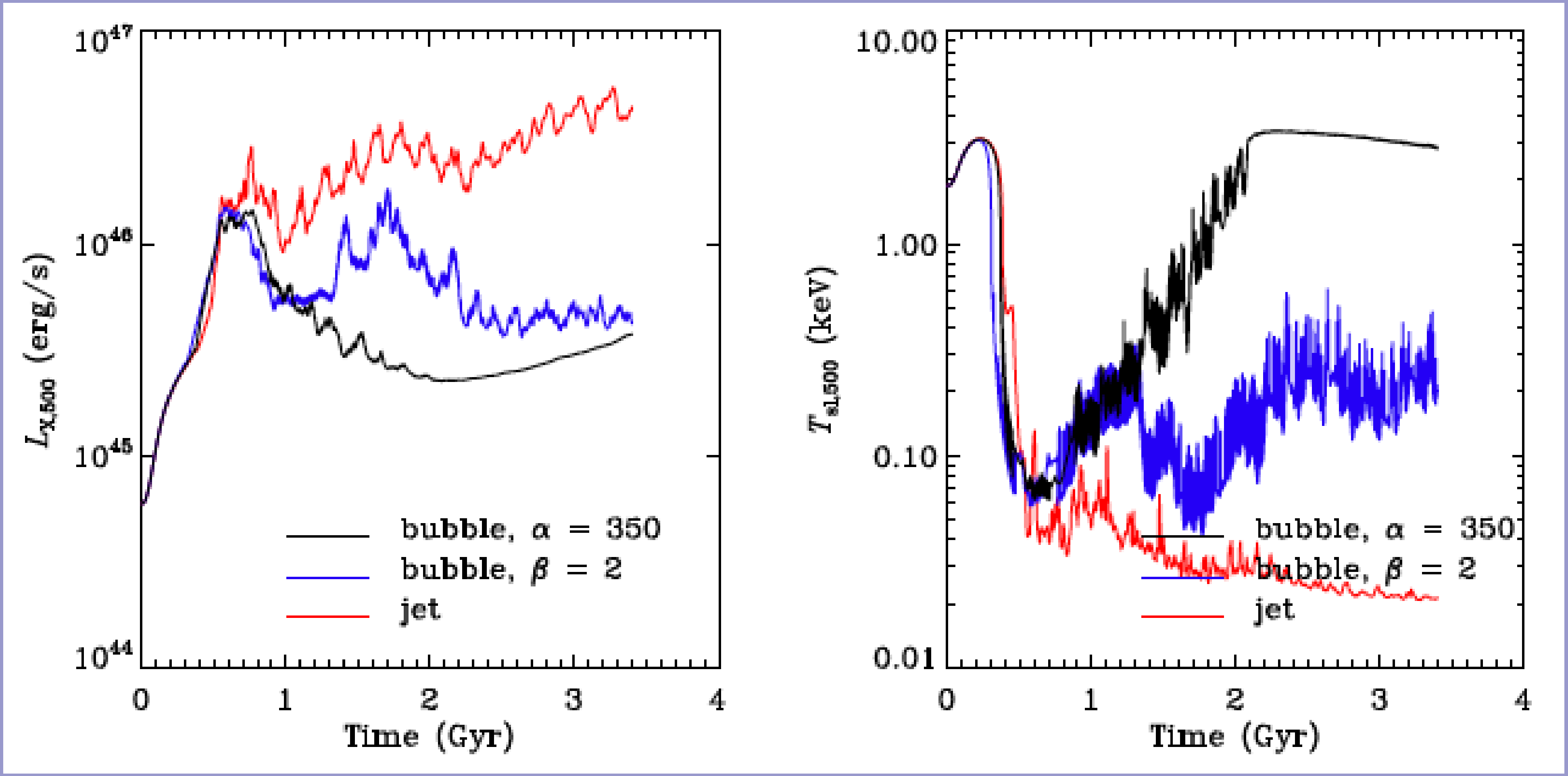


Additional cluster physics

- Anisotropic thermal conduction (Quataert, Parrish, Sharma, Chandran)
  - Modified convective instability criteria?
- Electron-ion nonequilibrium (Takizawa, Rudd, Nagai)
- Nonzero viscosity (Fabian)
  - Weak turbulence?
- Cosmic ray pressure (Miniati, Pfrommer, Skillman, et al.)

Conselice et al. (2001) – Hα filaments surrounding central galaxy (NGC 1275) in Perseus Cluster

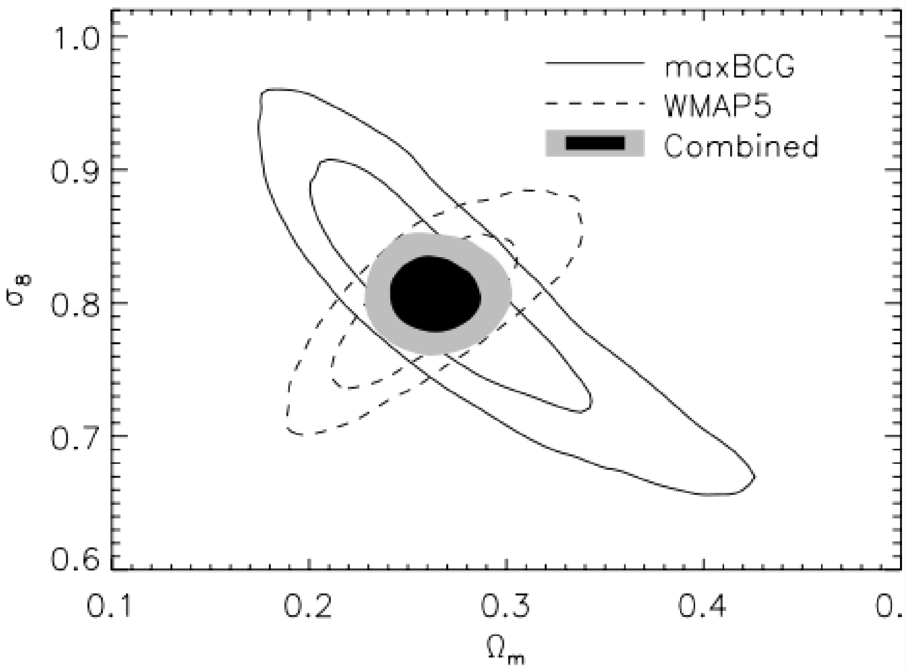
Current cluster constraints

maxBCG clusters from SDSS – optical richness-mass relation

Table 4
Best-fit Model

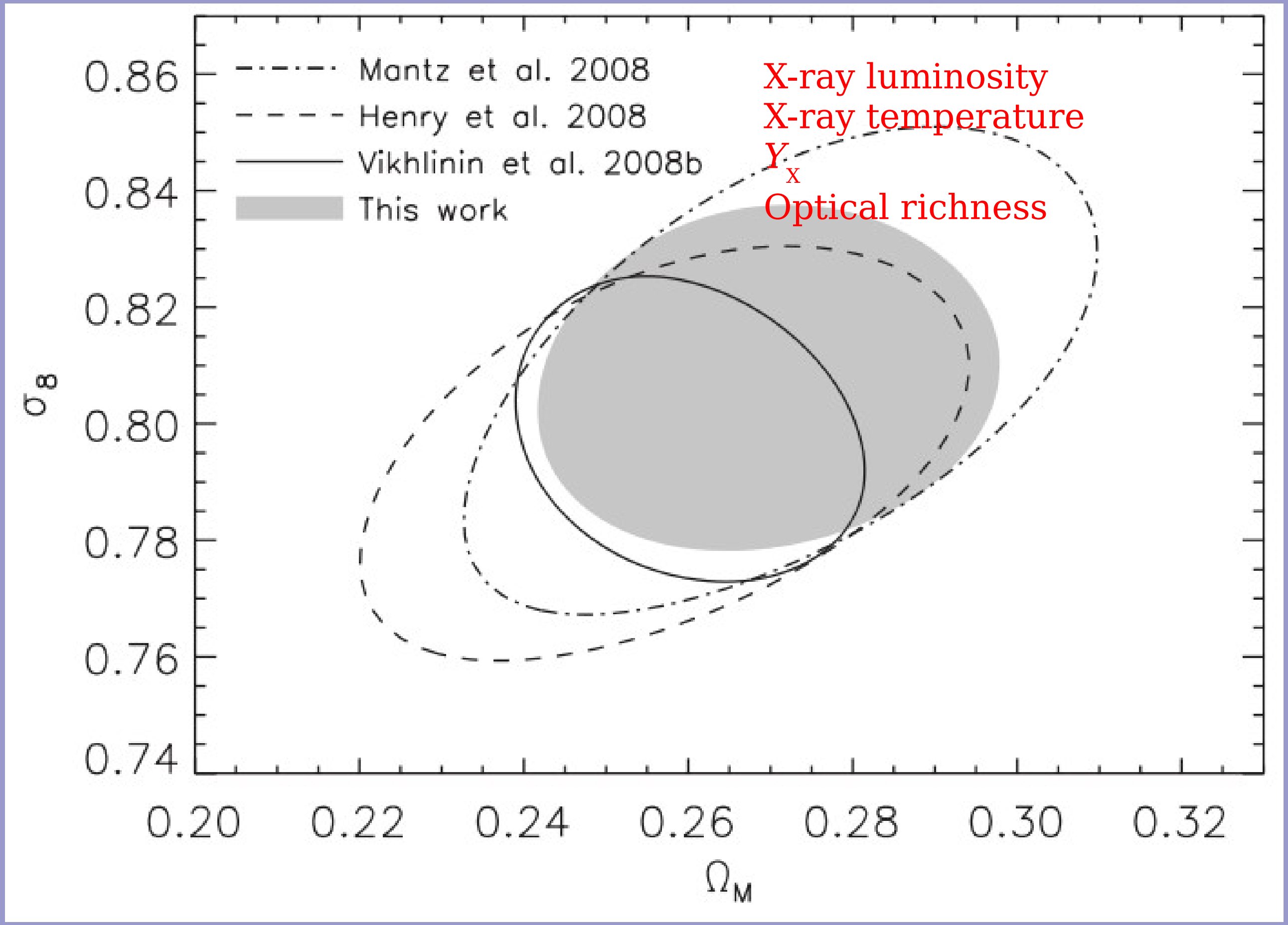
Parameter[a]	MaxBCG	MaxBCG+WMAP5[b]
σ_8	0.804 ± 0.073	0.807 ± 0.020
Ω_m	0.281 ± 0.066	0.269 ± 0.018
$\langle \ln N_{200} \| M_1 \rangle$	2.47 ± 0.10	2.48 ± 0.10
$\langle \ln N_{200} \| M_2 \rangle$	4.21 ± 0.19	4.21 ± 0.13
$\sigma_{N_{200}\|M}$	0.357 ± 0.073	0.348 ± 0.071
β	1.016 ± 0.060	1.013 ± 0.059

Notes.
[a] The masses M_1 and M_2 are set to $1.3 \times 10^{14} M_\odot$ and $1.3 \times 10^{15} M_\odot$, respectively.
[b] These values are obtained by including the WAMP5 prior $\sigma_8(\Omega_m/0.25)^{-0.312} = 0.790 \pm 0.024$. See Section 4.3 for details.



Rozo et al. (2010)

The power of multiple observables



Rozo et al. (2010)

Conclusions

Understanding the baryonic physics in galaxy clusters is key to using them as precision cosmological probes.

This understanding will be based (partly) on models + direct simulation for the next decade at least.

If we can use models + direct simulation to inform self-calibration, clusters may contribute dark energy constraints comparable to other probes.