A Cluster of Questions

The Crossroads

The Crossroads

S. P. Oh / **Astrophysicist**

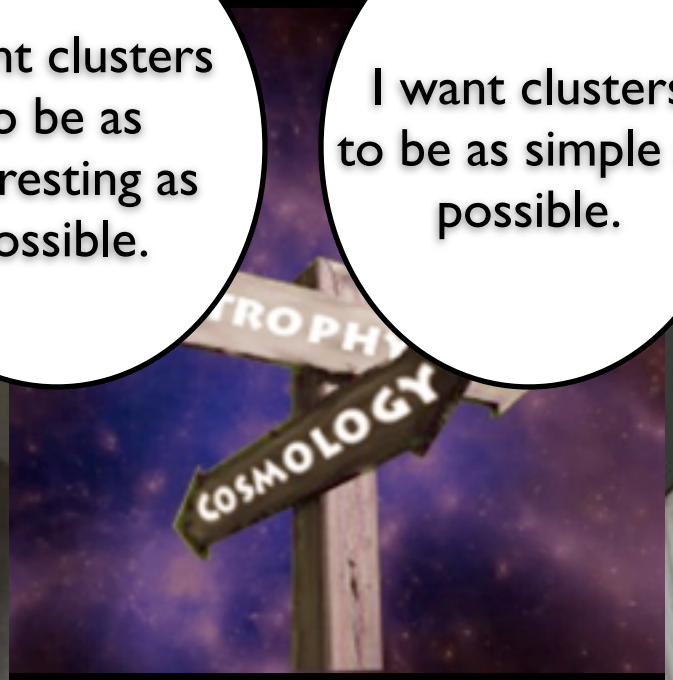
A. Evrard /

The Crossroads

I want clusters to be as simple as possible.

The Crossroads

I want clusters to be as interesting as possible.



I want clusters to be as simple as possible.

The Crossroads

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How well can we measure mass?

What is a “cluster of galaxies?”

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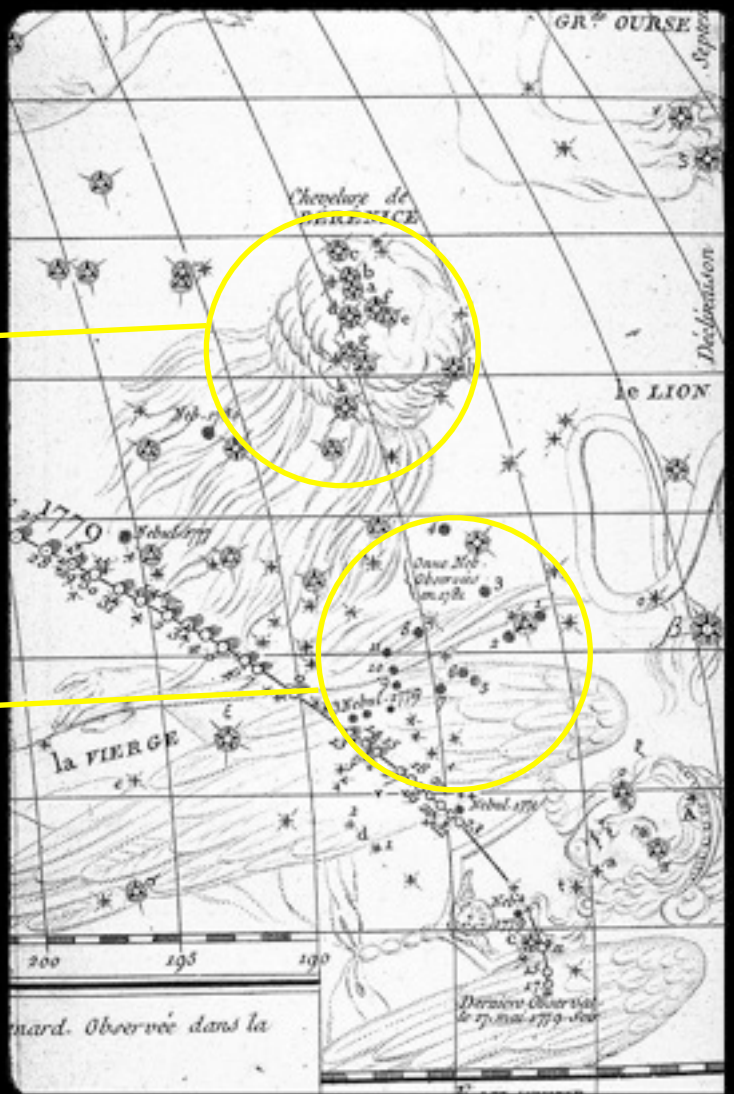
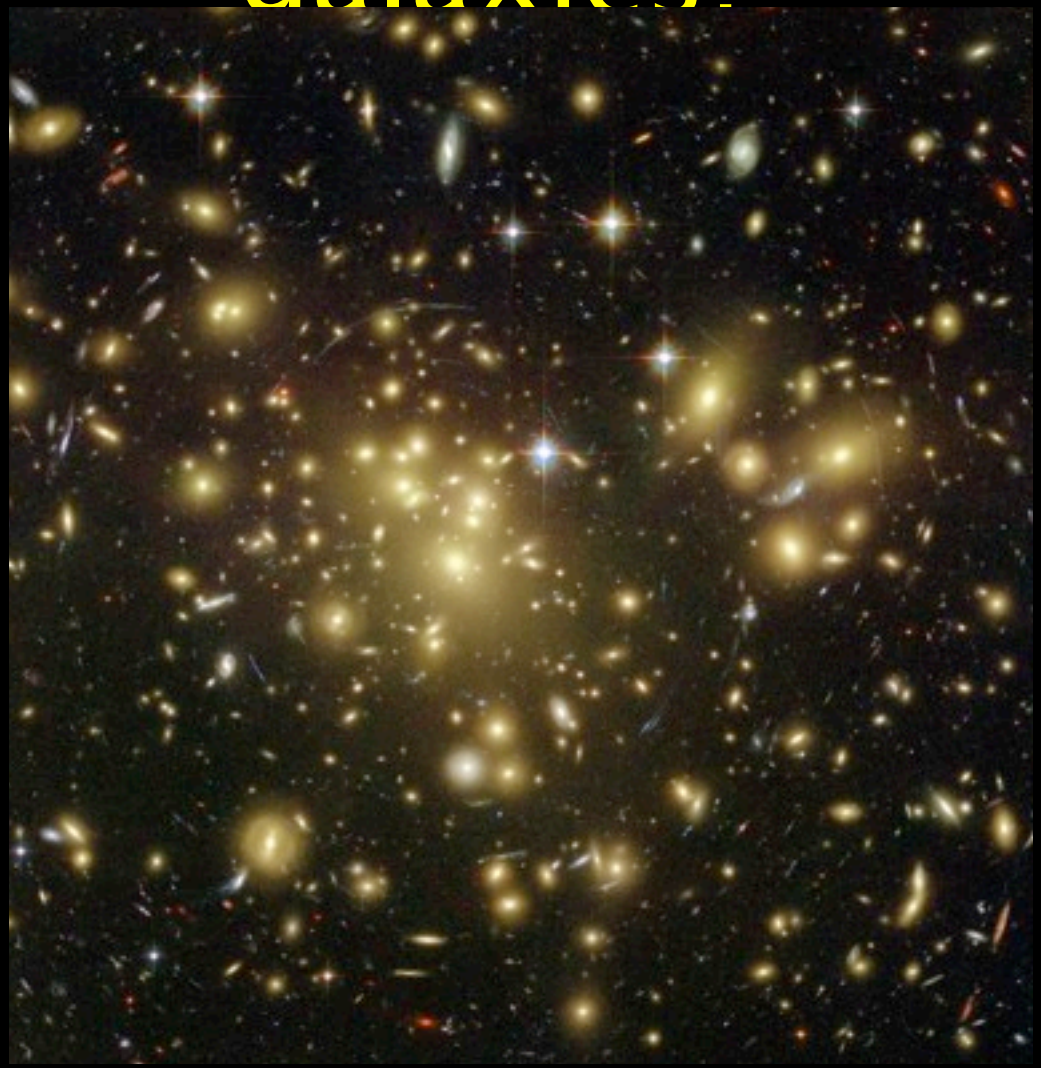


Coma Cluster

Virgo Cluster

Messier (1784)

What is a “cluster of galaxies?”



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S1D

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s_{1D} N_{200}

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s_{1D} N_{200} k_{lens}

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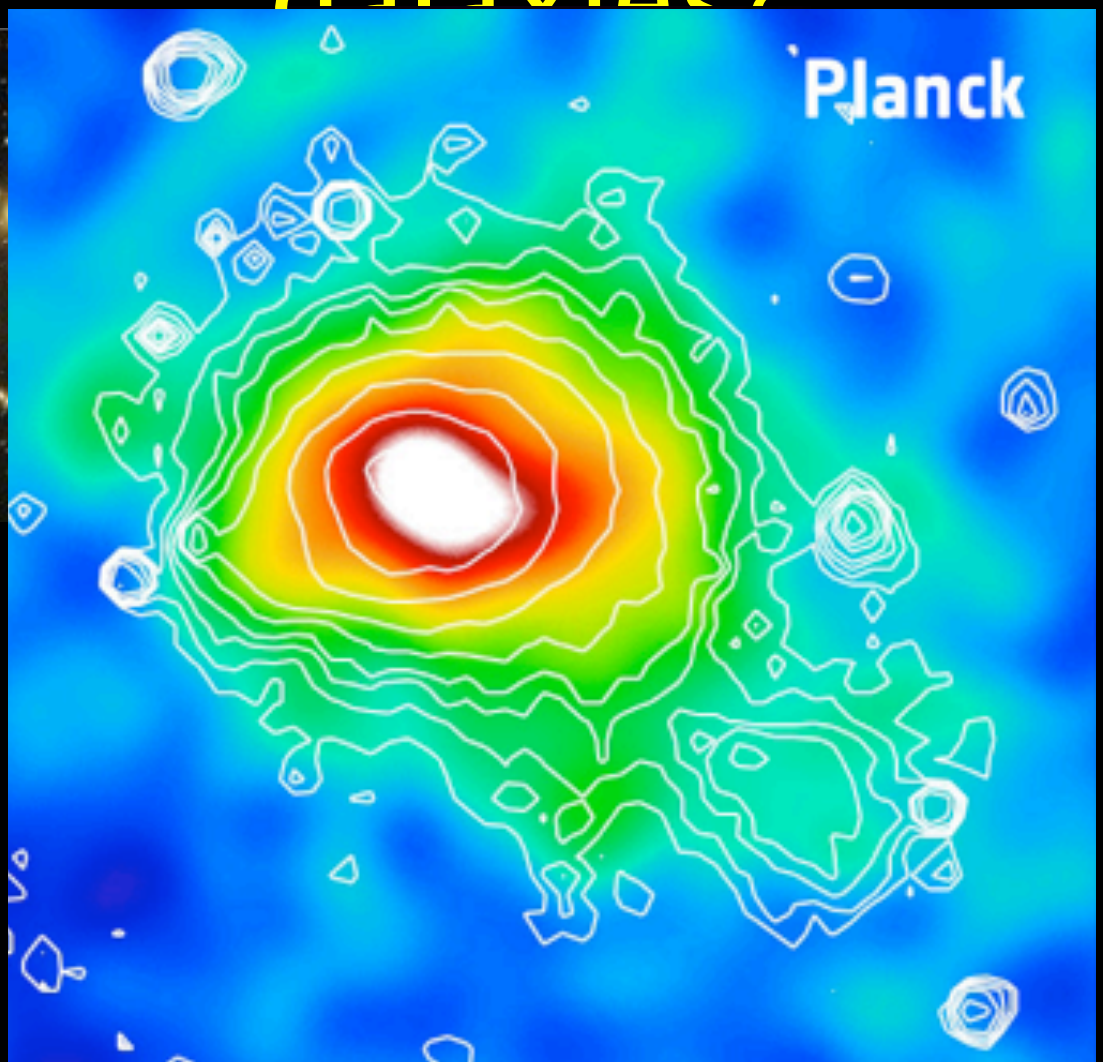
S_{1D} N_{200}



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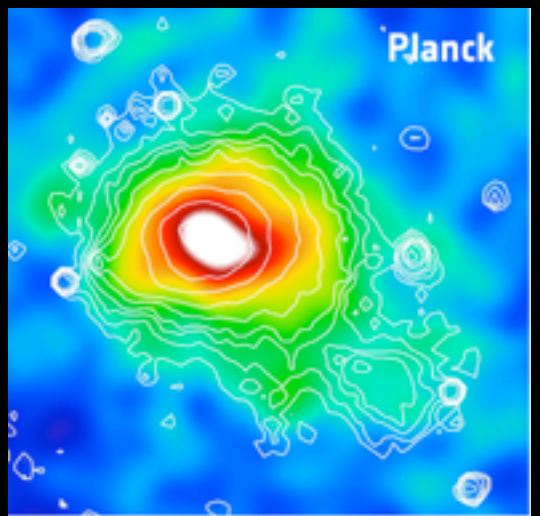

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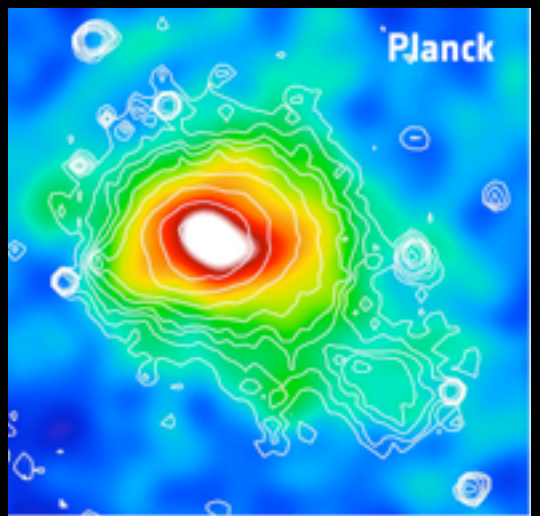

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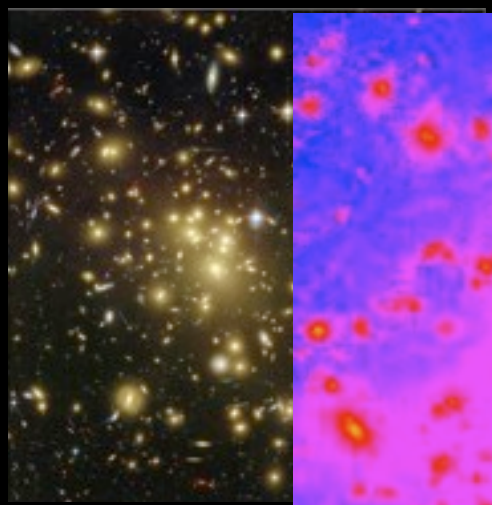

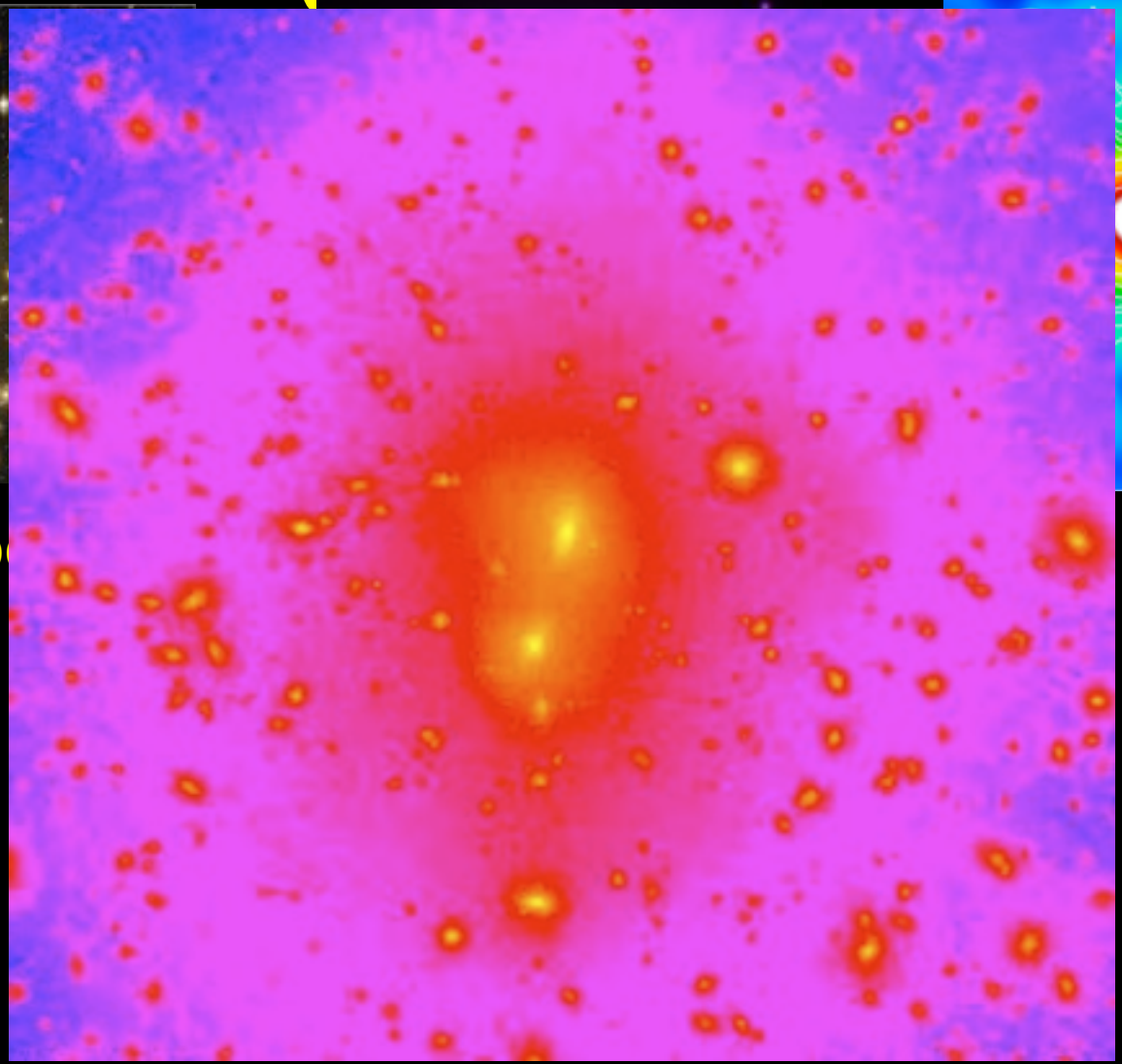

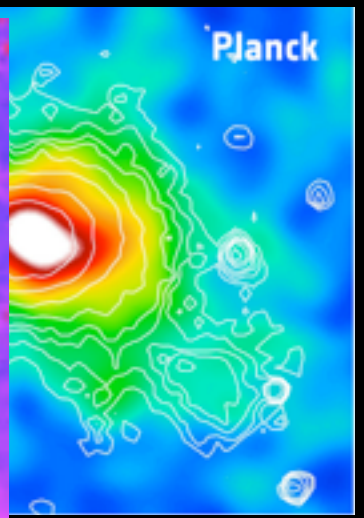

s_{1D} N_{20} Y_{SZ}

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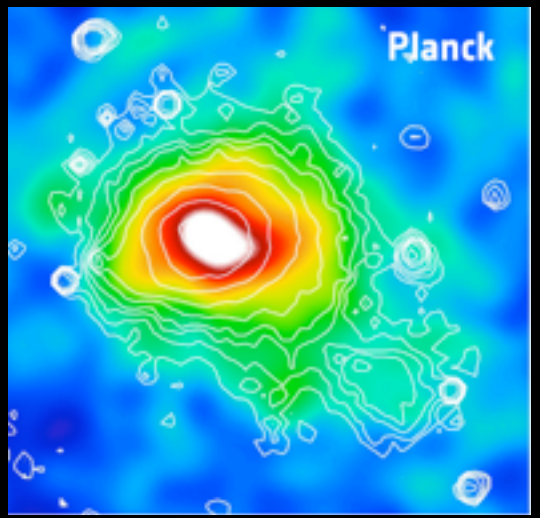

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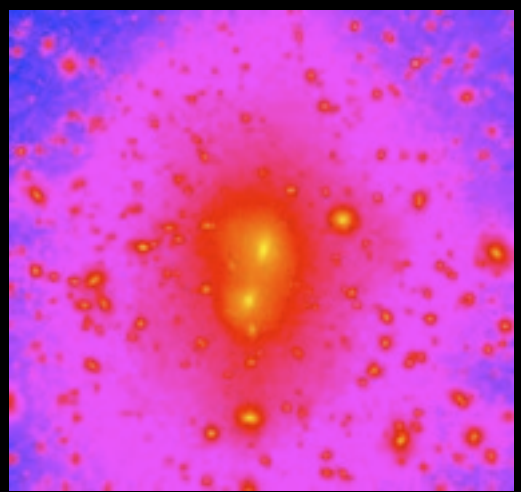

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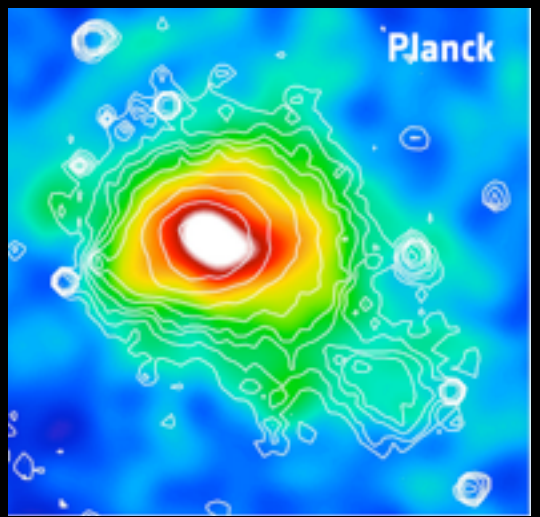

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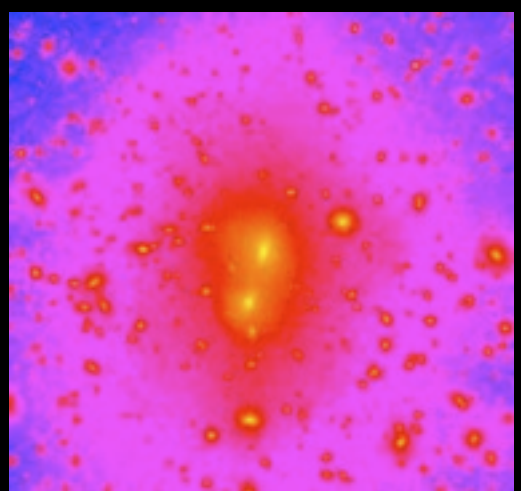

M_{500c}

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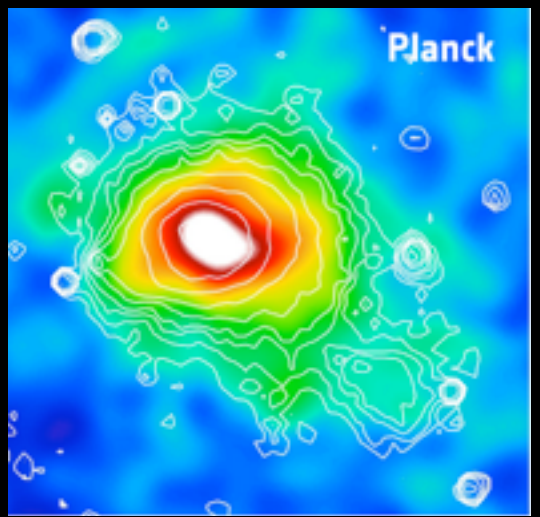

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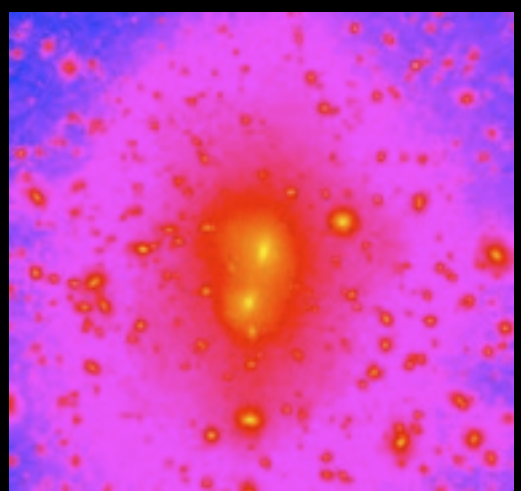

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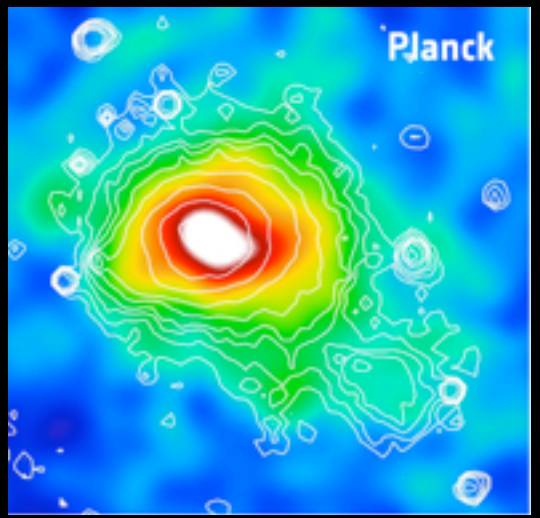

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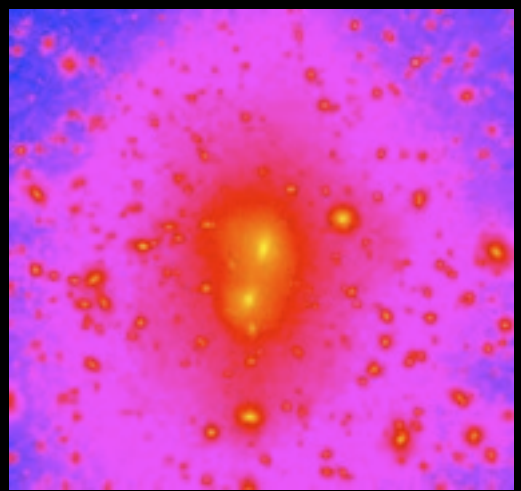

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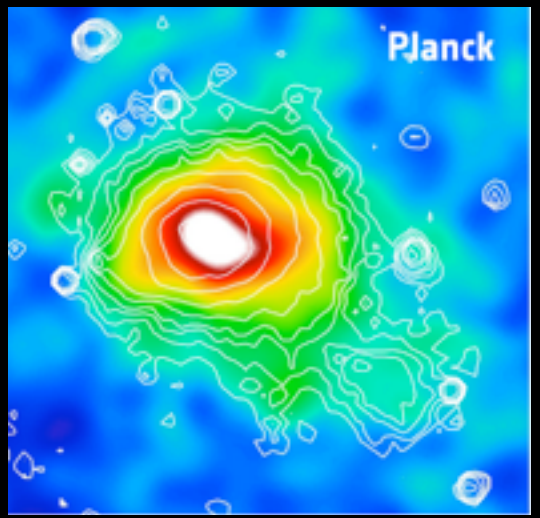

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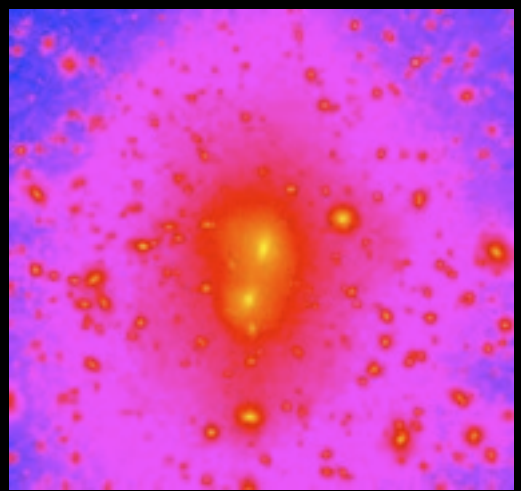

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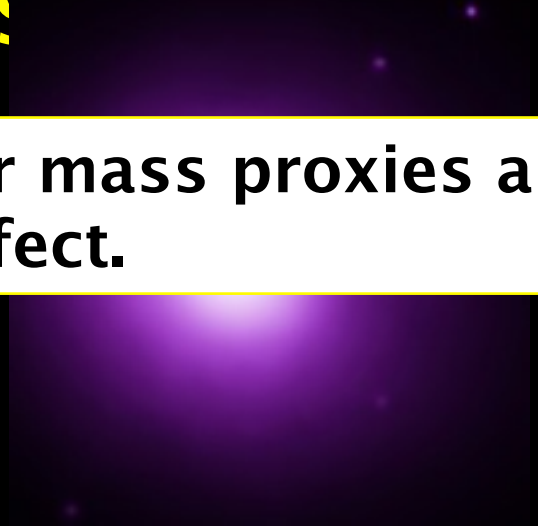

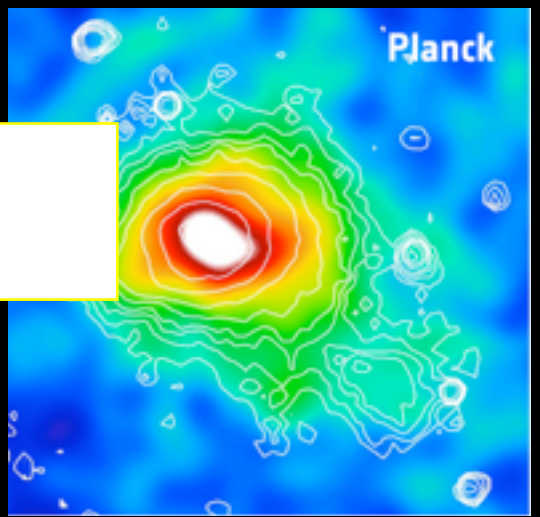

All our mass proxies are imperfect.

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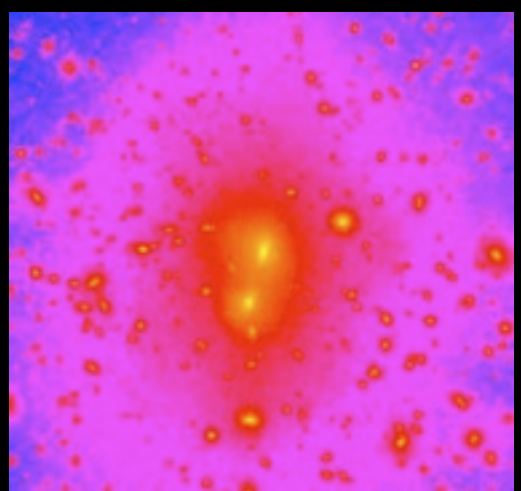

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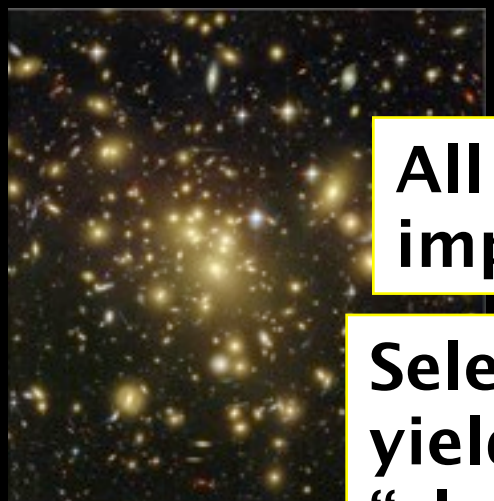

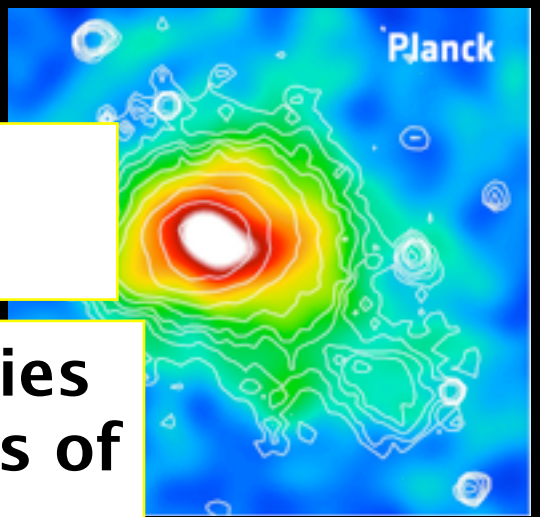

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Selecting on different proxies yields different populations of “clusters.”

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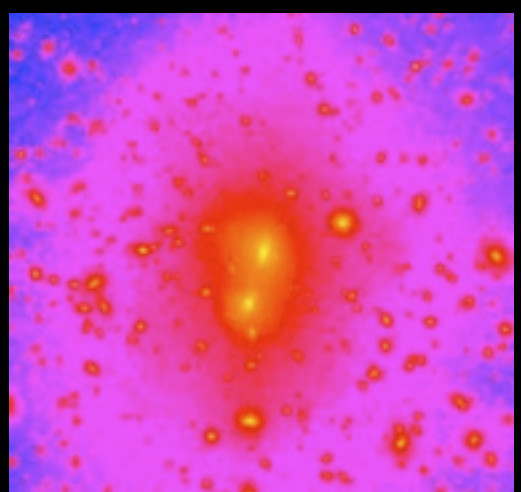

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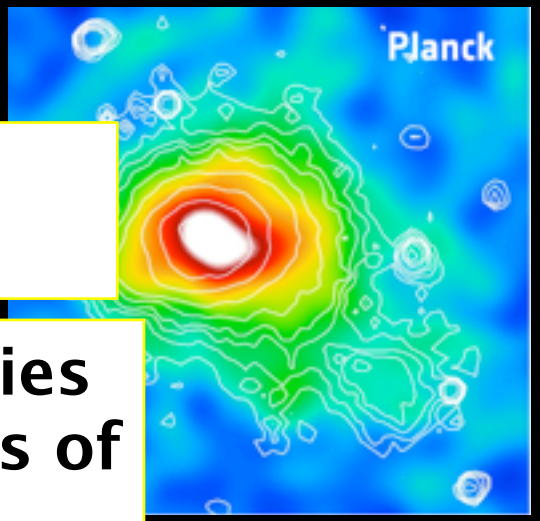

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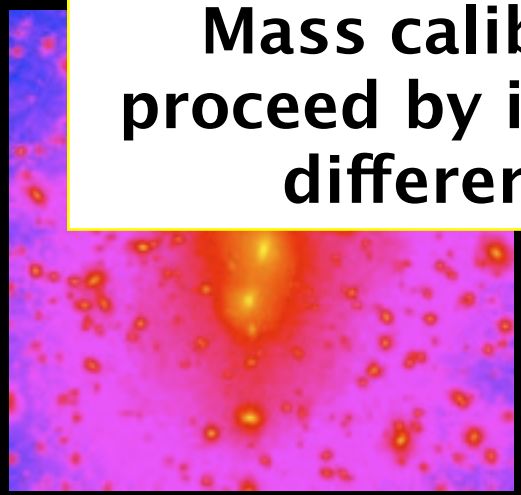

Mass calibration must proceed by intercomparing different proxies.

M_{500c} M_{200c} M_{200m} …

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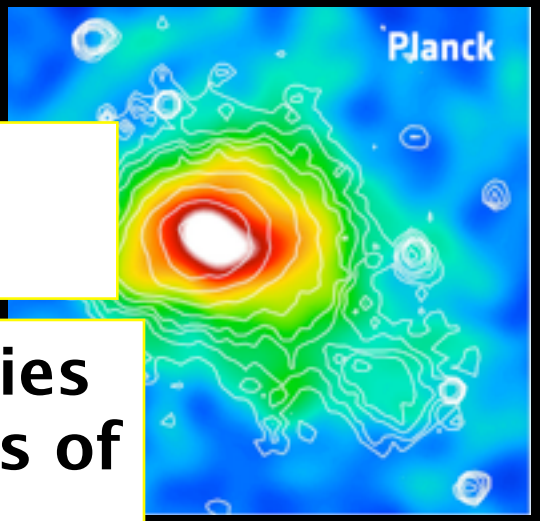

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S_{1D} N_{200} L_X T_X M_d T_X Y_{SZ}

Mass calibration must proceed by intercomparing different proxies.

Astrophysical understanding can help us parametrize our comparisons.

...

Which mass proxies are most reliable?

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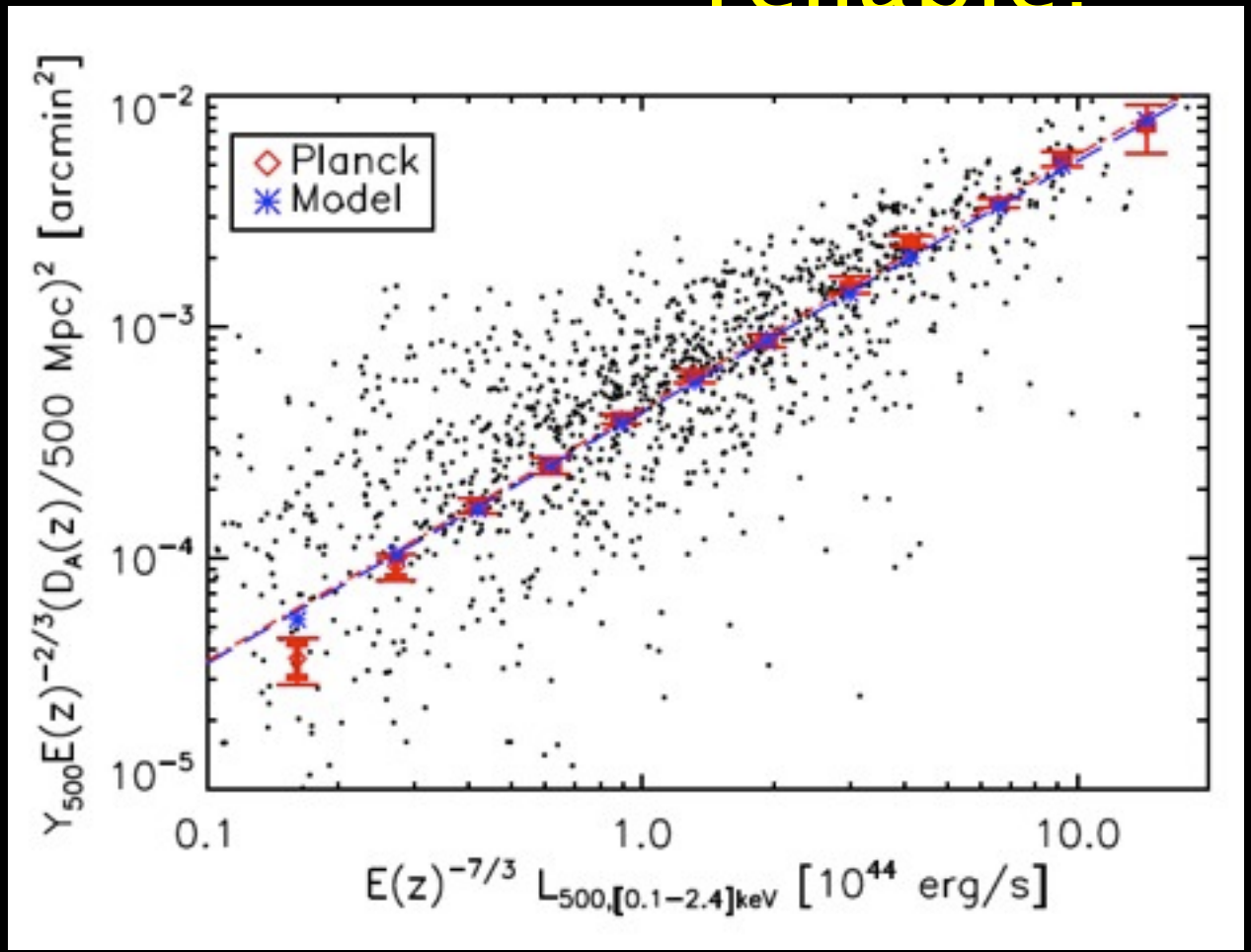
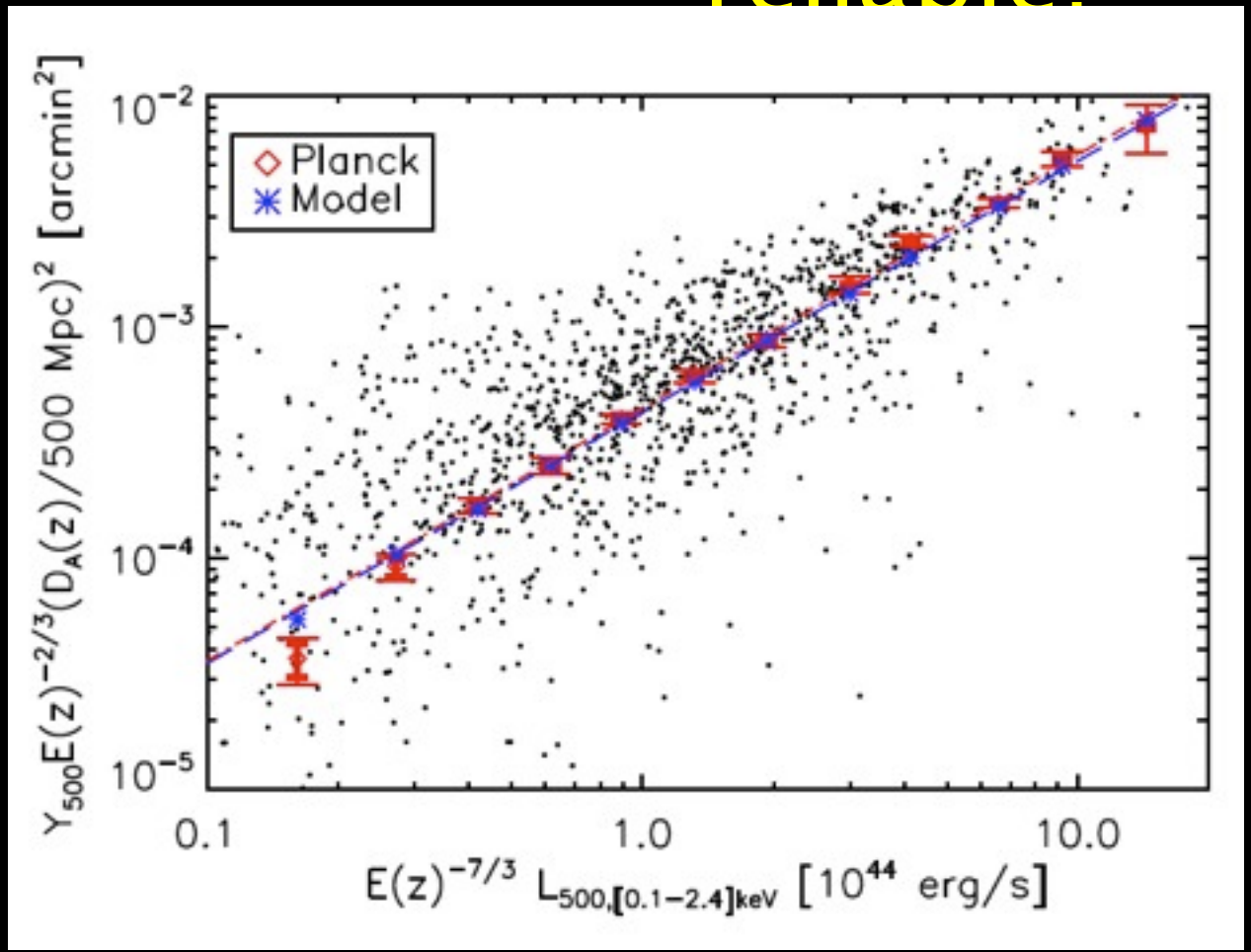


PLANCK Collaboration

Which mass proxies are most reliable?



Model predicts SZ signal Y_{500} based on X-ray characteristics

PLANCK Collaboration

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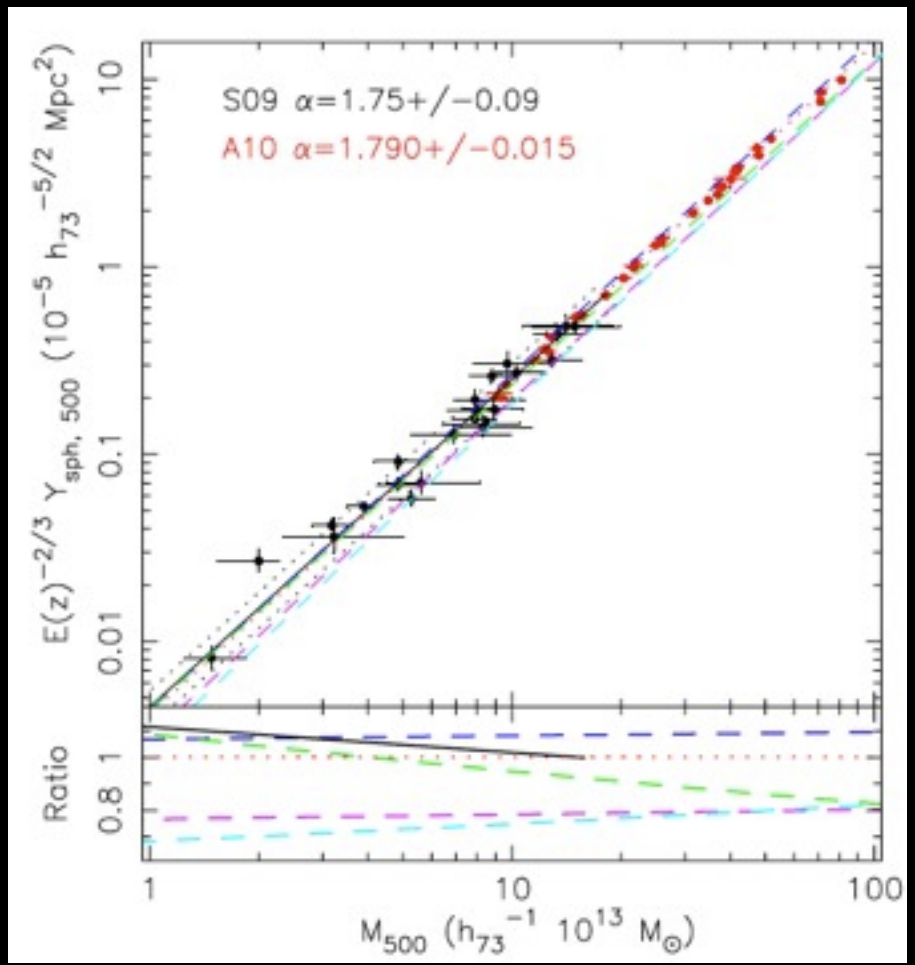

Sun+

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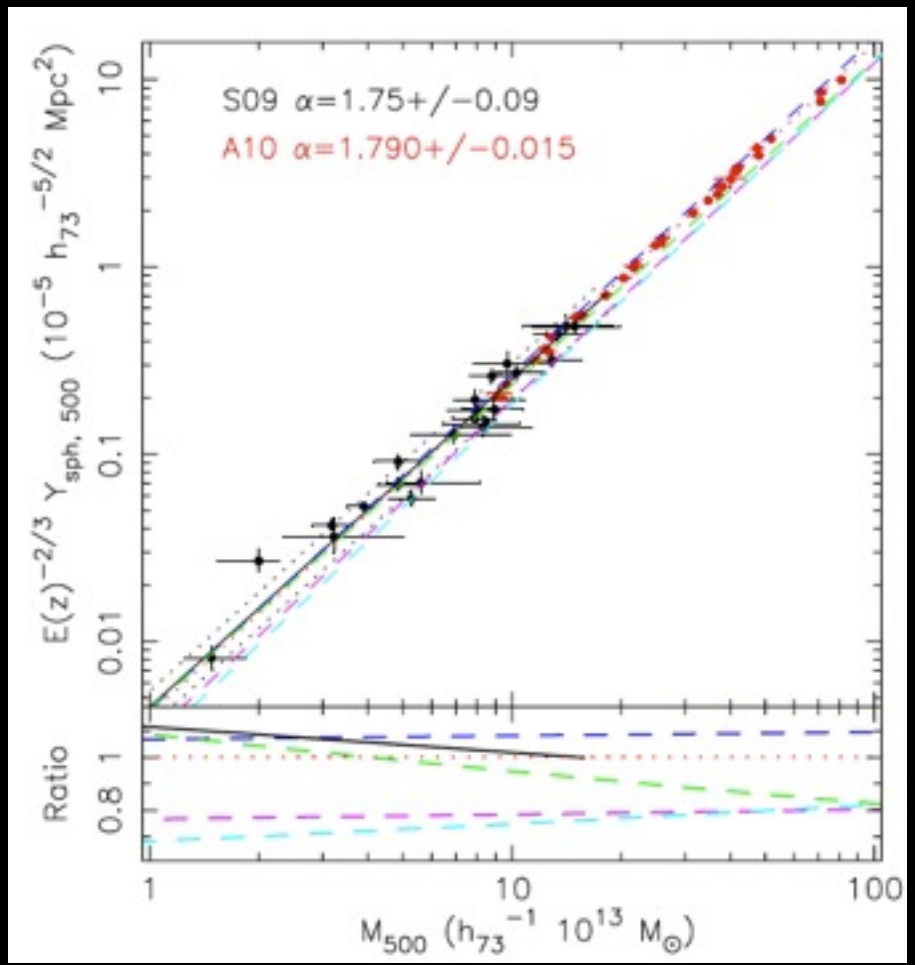


Relationship between $Y_X = M_g T_X$ and mass estimated from hydrostatic equilibrium is well-behaved over two orders of magnitude in mass

Sun+

How does scatter affect mass calibration?

Consider an approximate mass function $n(M) \propto M^{-\alpha}$

Suppose $\bar{S}_i(M) = S_{i0}(M/M_0)^{\beta_i}$ with lognormal scatter

Then: $\langle \ln M(S_{i0}) \rangle = \ln M_0 - \alpha \sigma^2_{\ln M_i}$

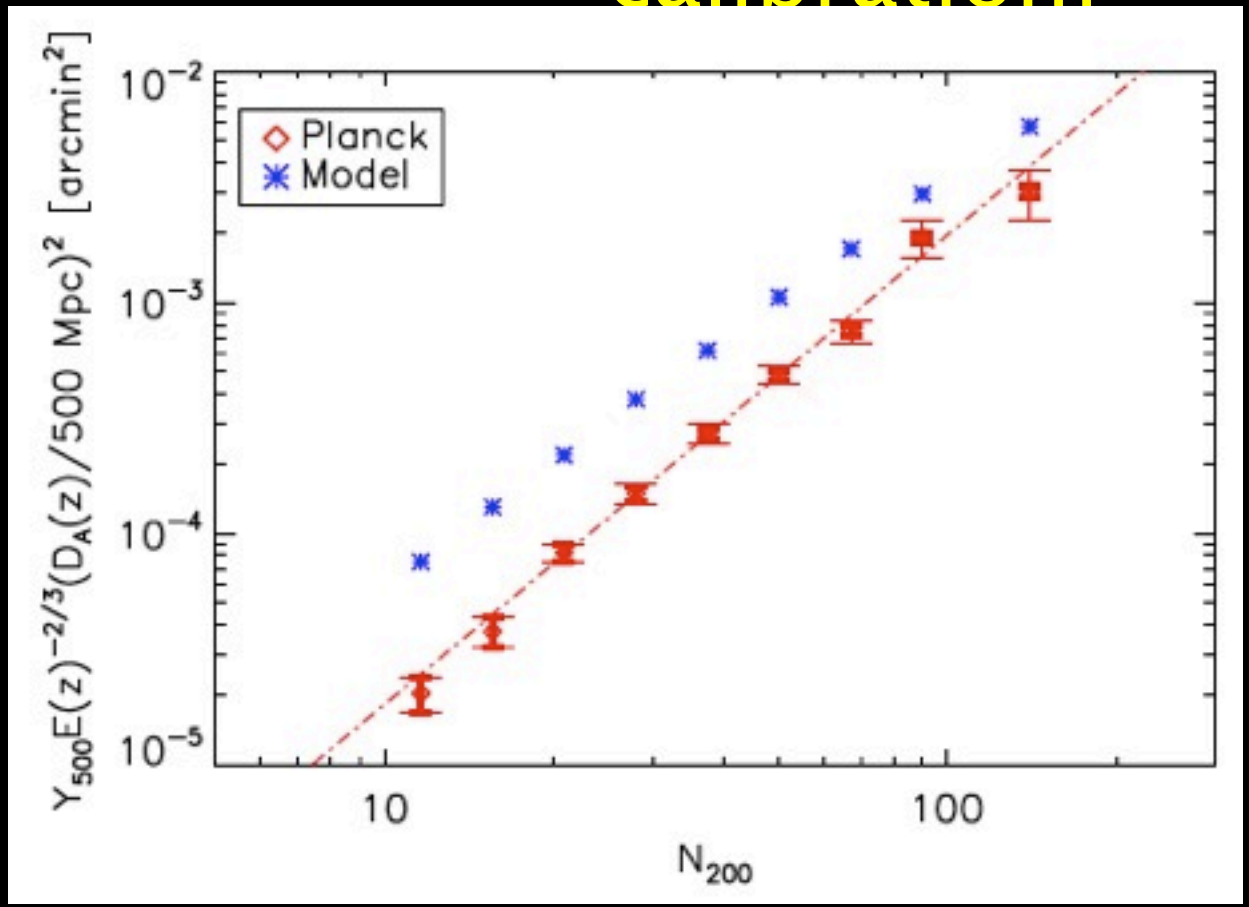
$$\langle \ln S_j(S_{i0}) \rangle = \beta_j [\langle \ln M(S_{i0}) \rangle + \alpha r_{ij} \sigma_{\ln M_i} \sigma_{\ln M_j}]$$

Where $\sigma^2_{\ln M_i}$ is the log mass variance at fixed S_i

And r_{ij} accounts for correlated scatter

Adapted from Allen, Evrard, & Mantz 2011

How does scatter affect mass calibration?



PLANCK Collaboration 2011

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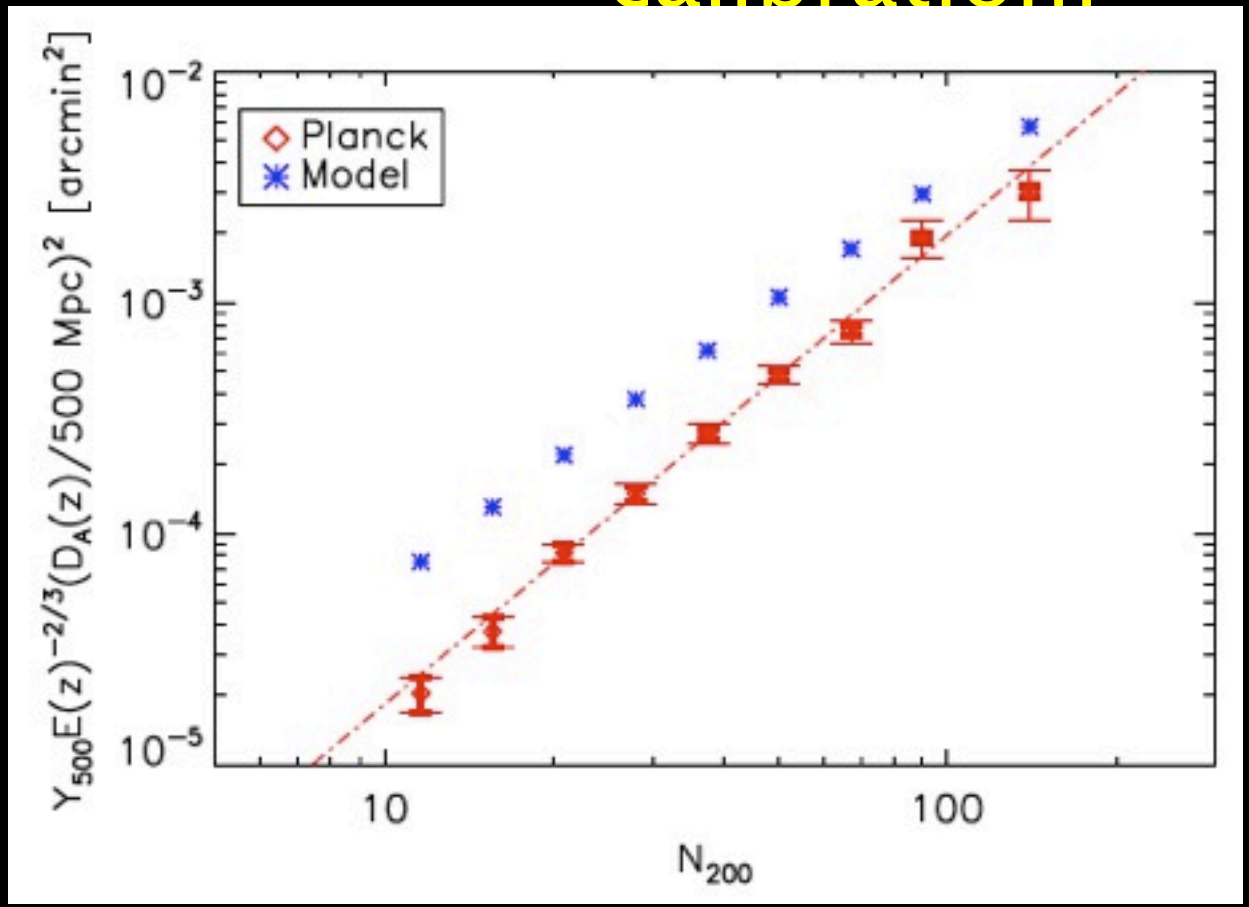
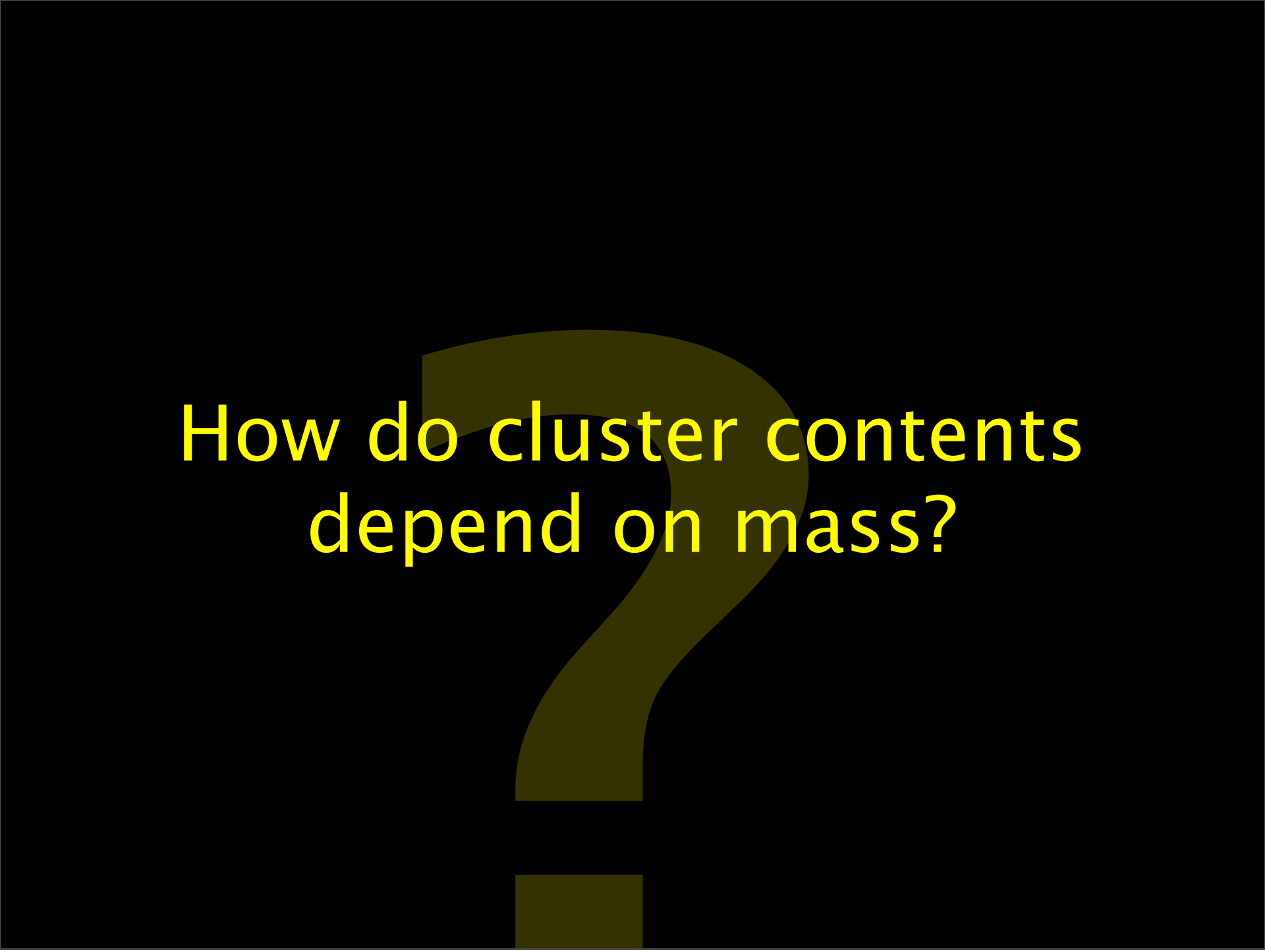


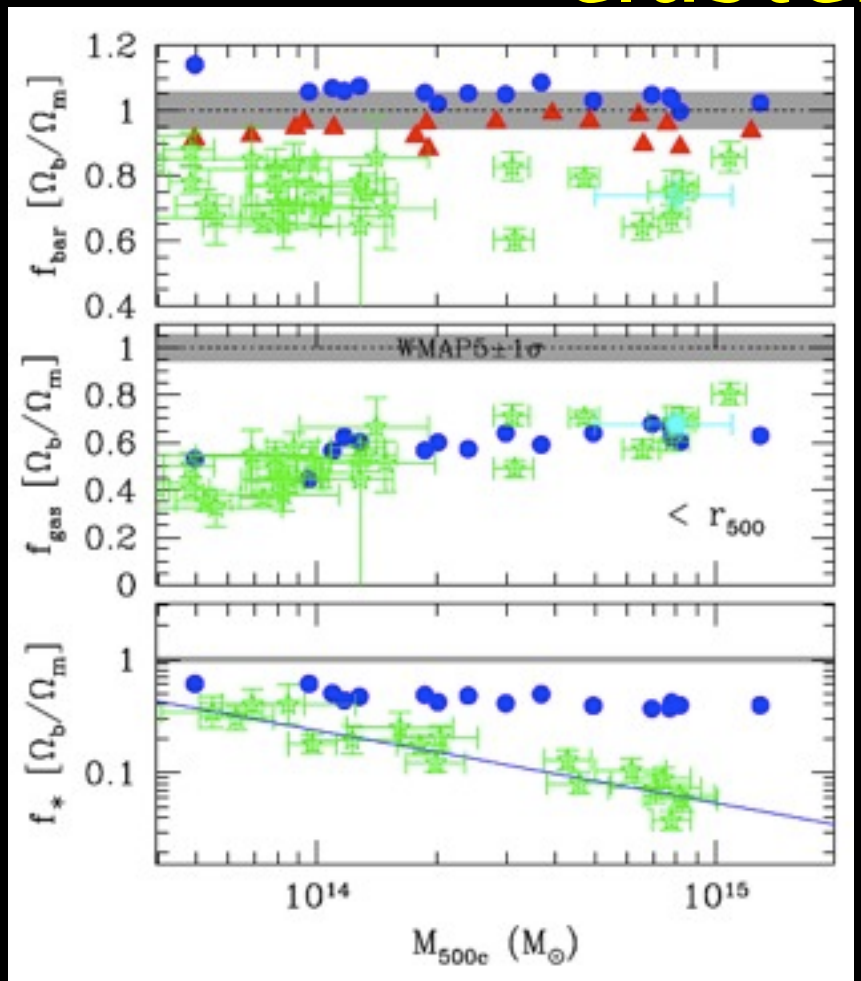
PLANCK Collaboration 2011

Scatter in Y-M relation for richness selected clusters is likely to be greater than scatter for SZ selected clusters

How do cluster contents depend on mass?



Are baryons missing from clusters?



Kravtsov+ 2009

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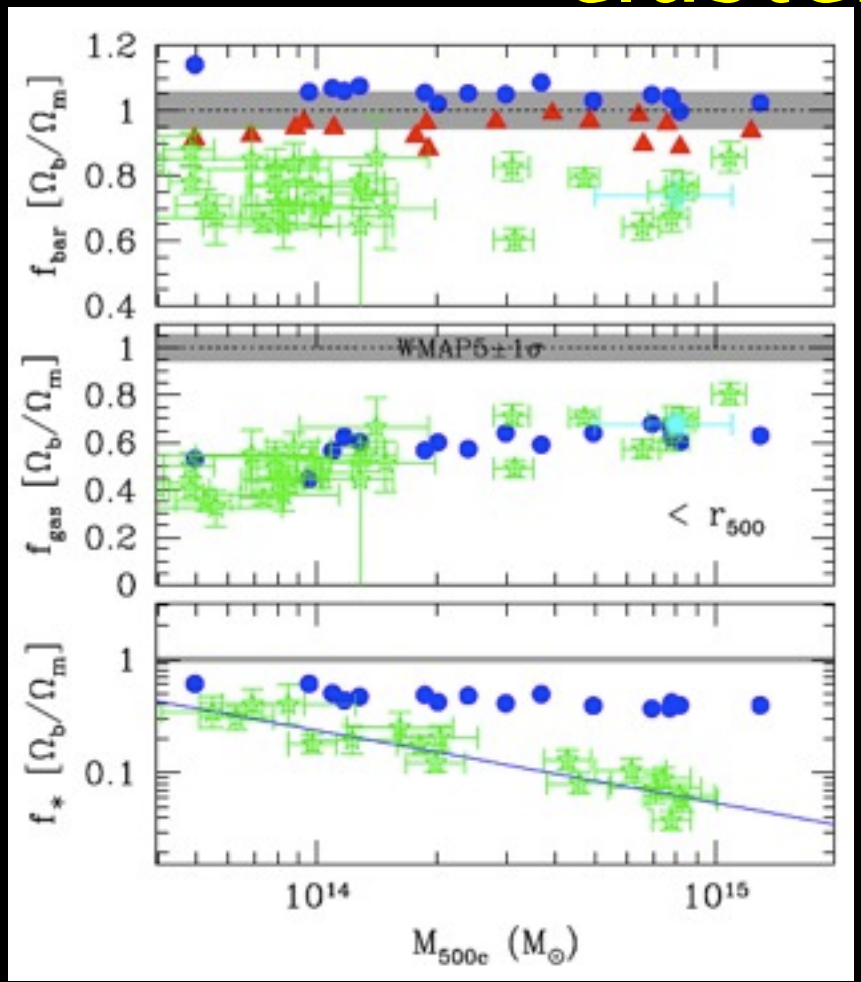
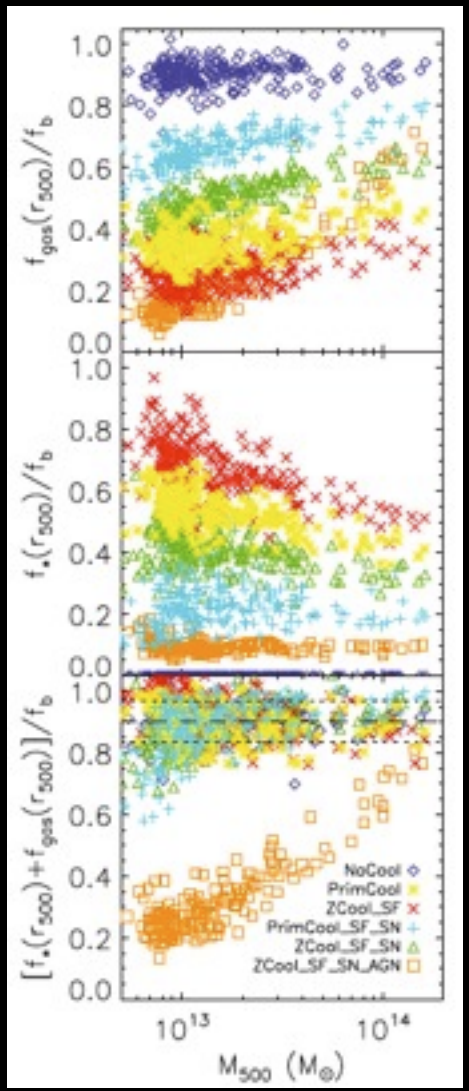


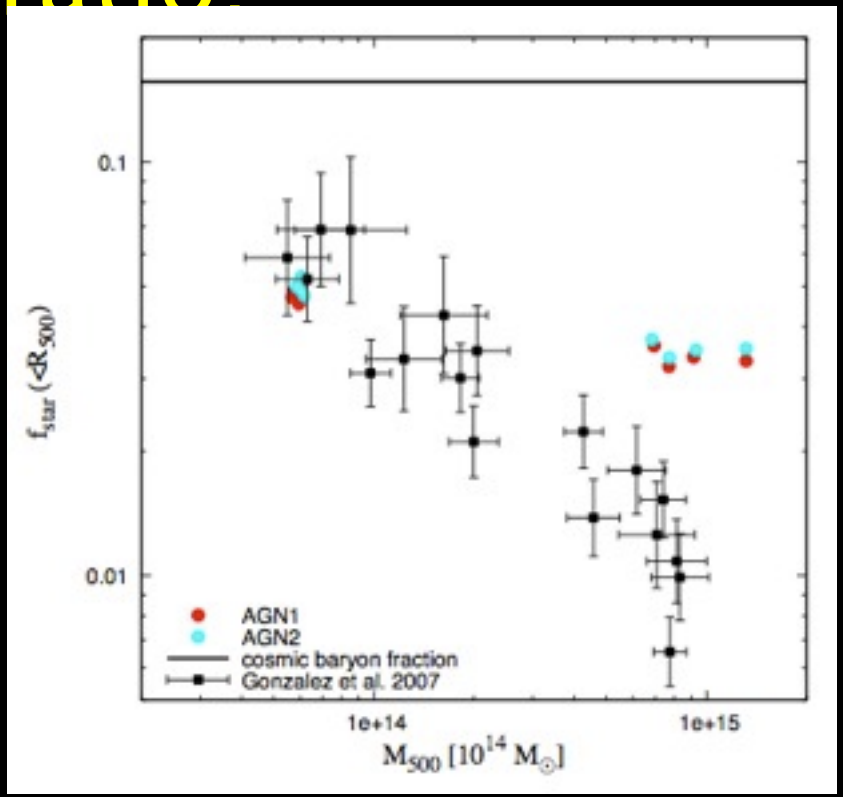
Observed baryon fraction in clusters appears to fall 2-3s short of cosmic mean

Kravtsov+ 2009

What determines the star-to-gas ratio?

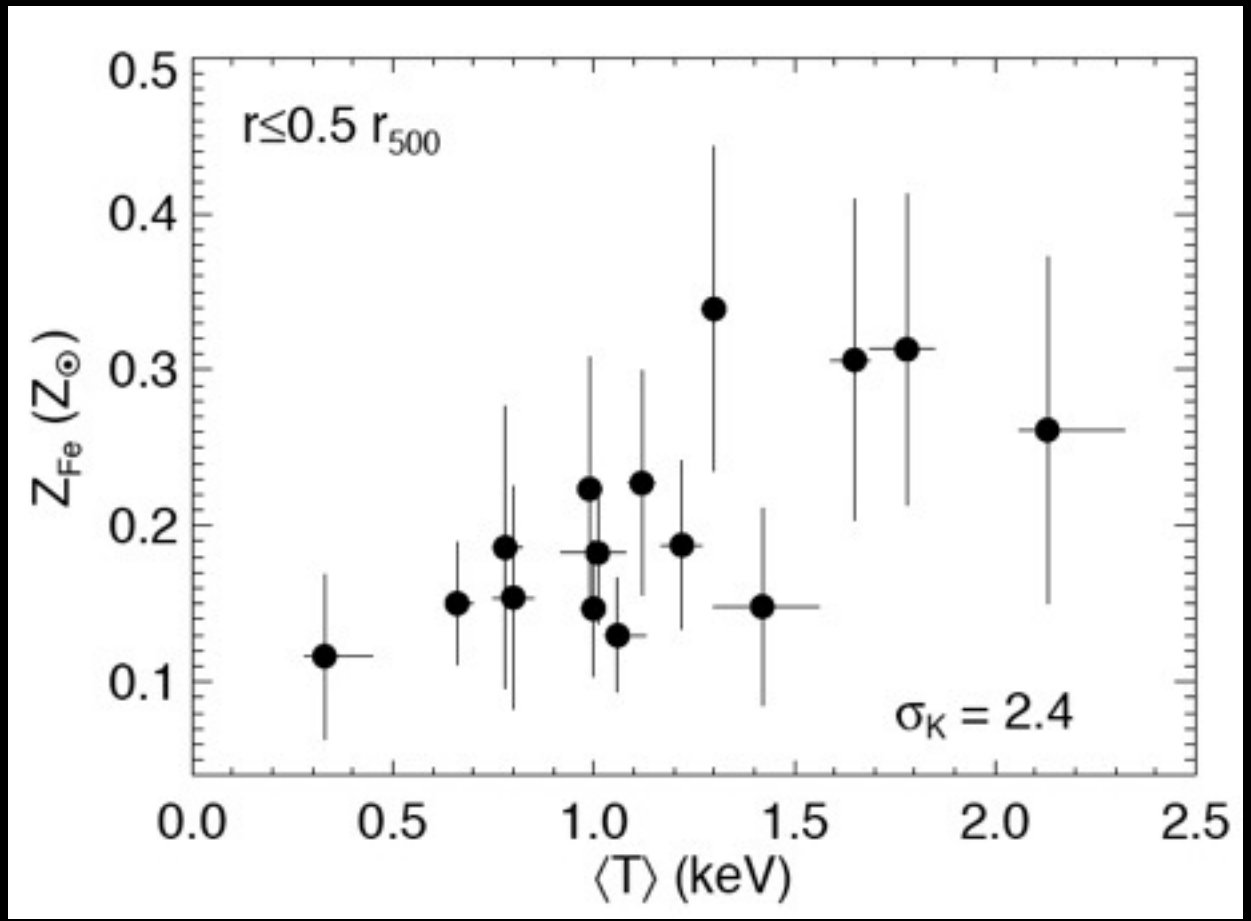


McCarthy+ 2011



Fabjan+ 2010

How does enrichment depend on mass?



Rasmussen & Ponman

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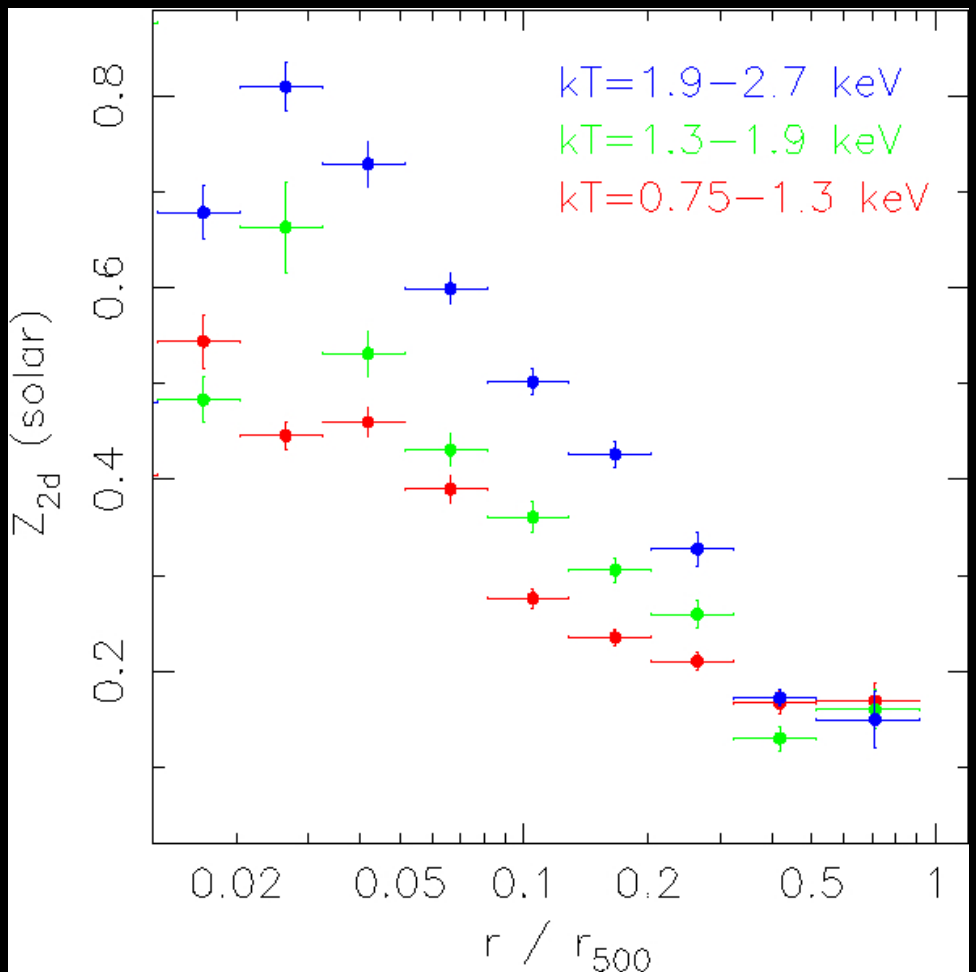

Sun 2011 (in

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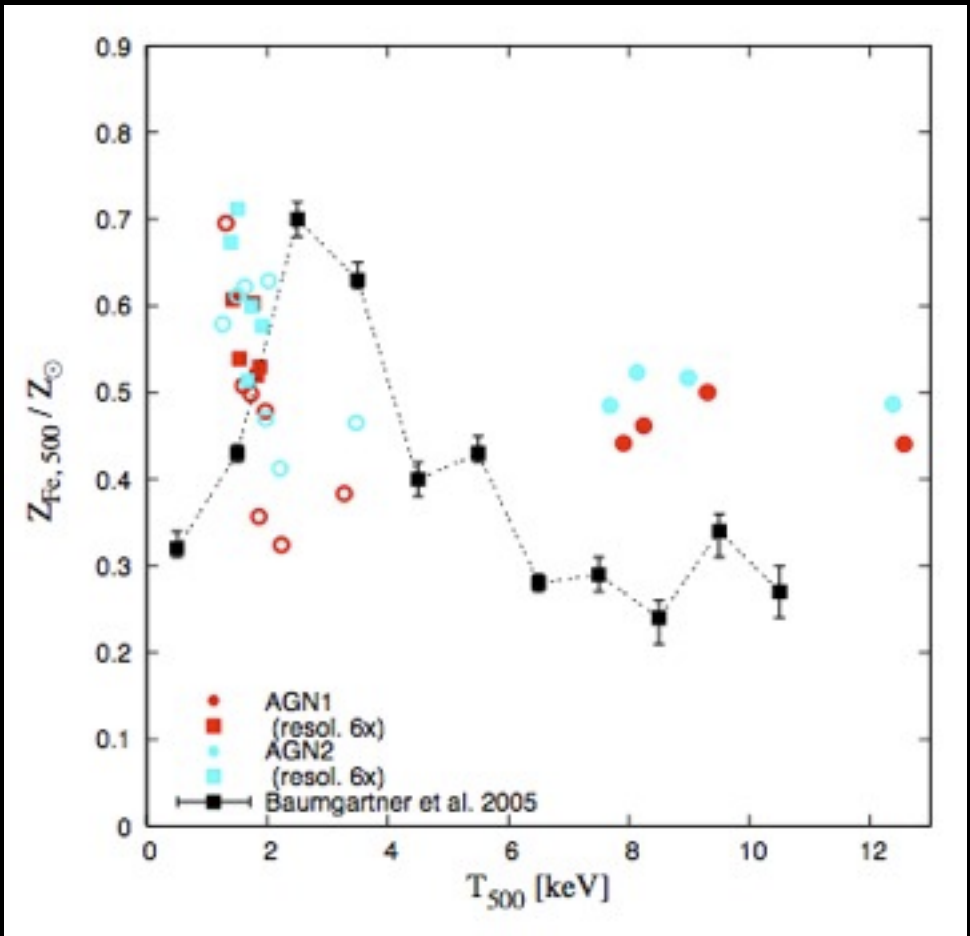

Fabian+

Simulations produce more ICM enrichment in groups than is observed

Why aren't groups and clusters self-similar?

Is preheating sufficient?

Is preheating sufficient?

Excess entropy in cluster core makes core gas less compressible, reducing f_{gas} and L_X

$$K = kTn_e^{-2/3} \propto P\rho^{-5/3}$$

If excess entropy is independent of halo mass, then reduction of f_{gas} and L_X is greater in lower-mass halos

Minimal preheating imposes floor K_{min} everywhere at an early time z_{heat}

Kaiser 1991
Evrard & Henry 1991

Is preheating sufficient?

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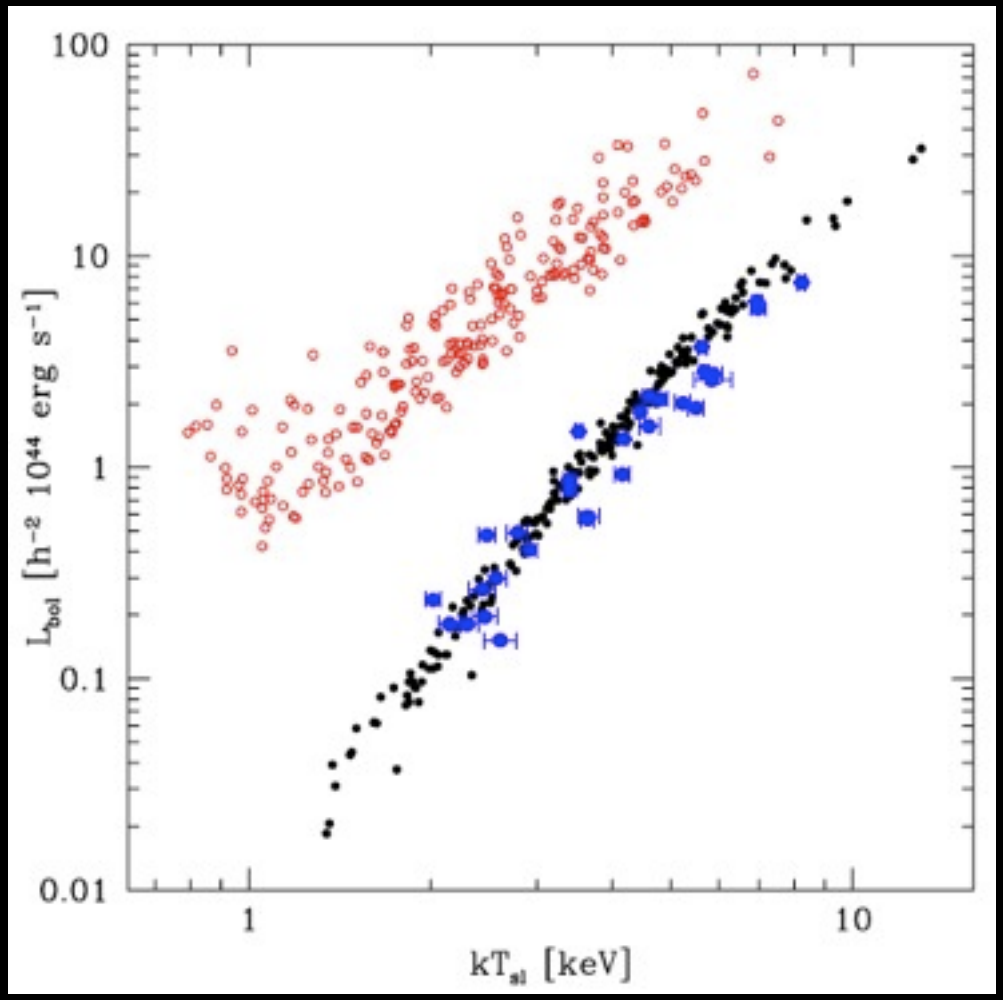

Minimal preheating of K_{min} = 200 keV cm^2 everywhere at z_{heat} = 4 is surprisingly successful

Stanek+ 2010

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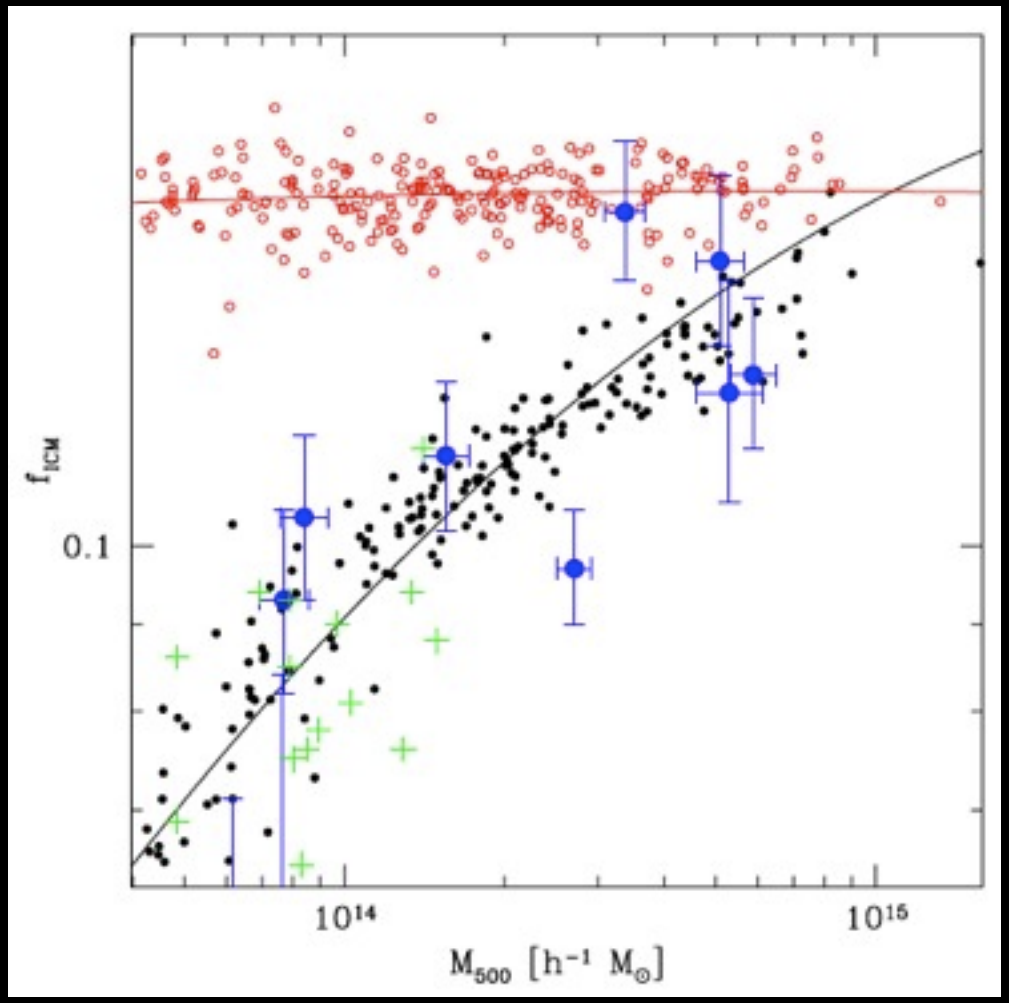

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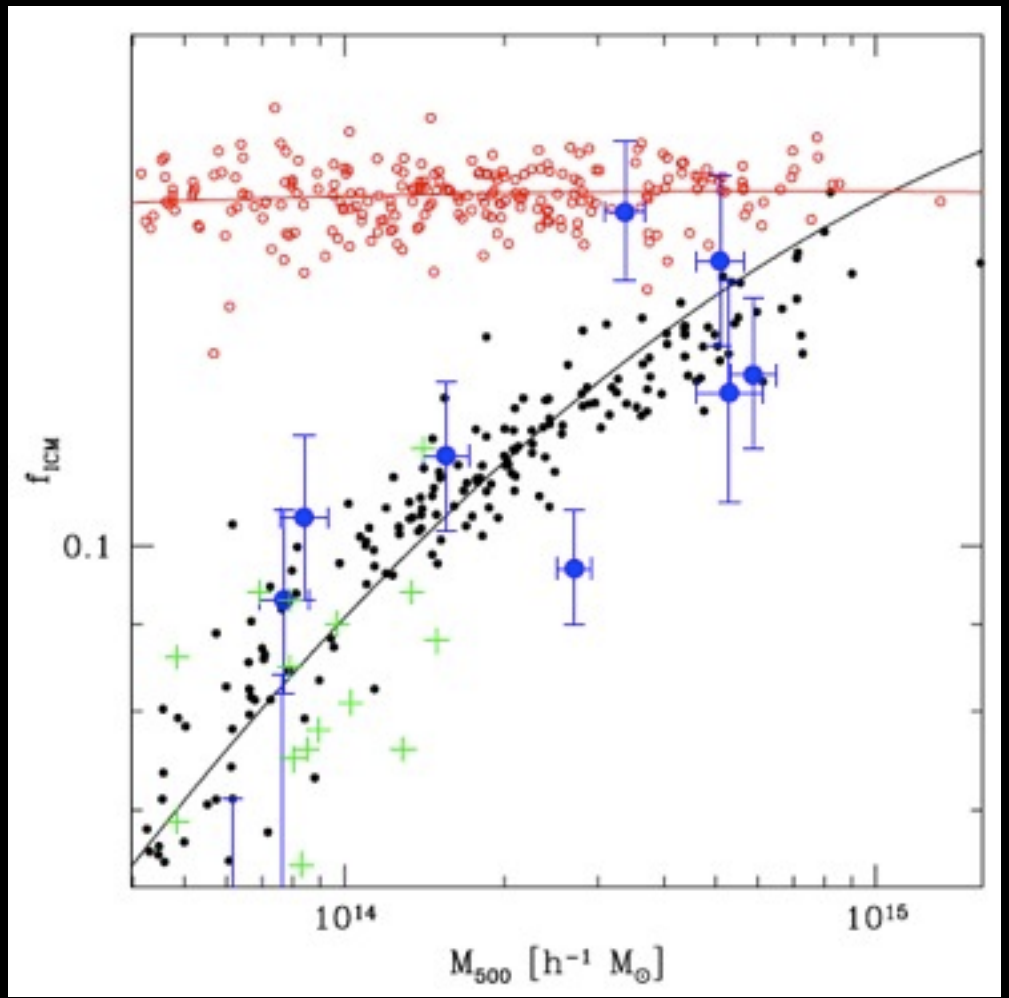

Stanek+ 2010

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But star formation is highly suppressed

What determines core entropy?

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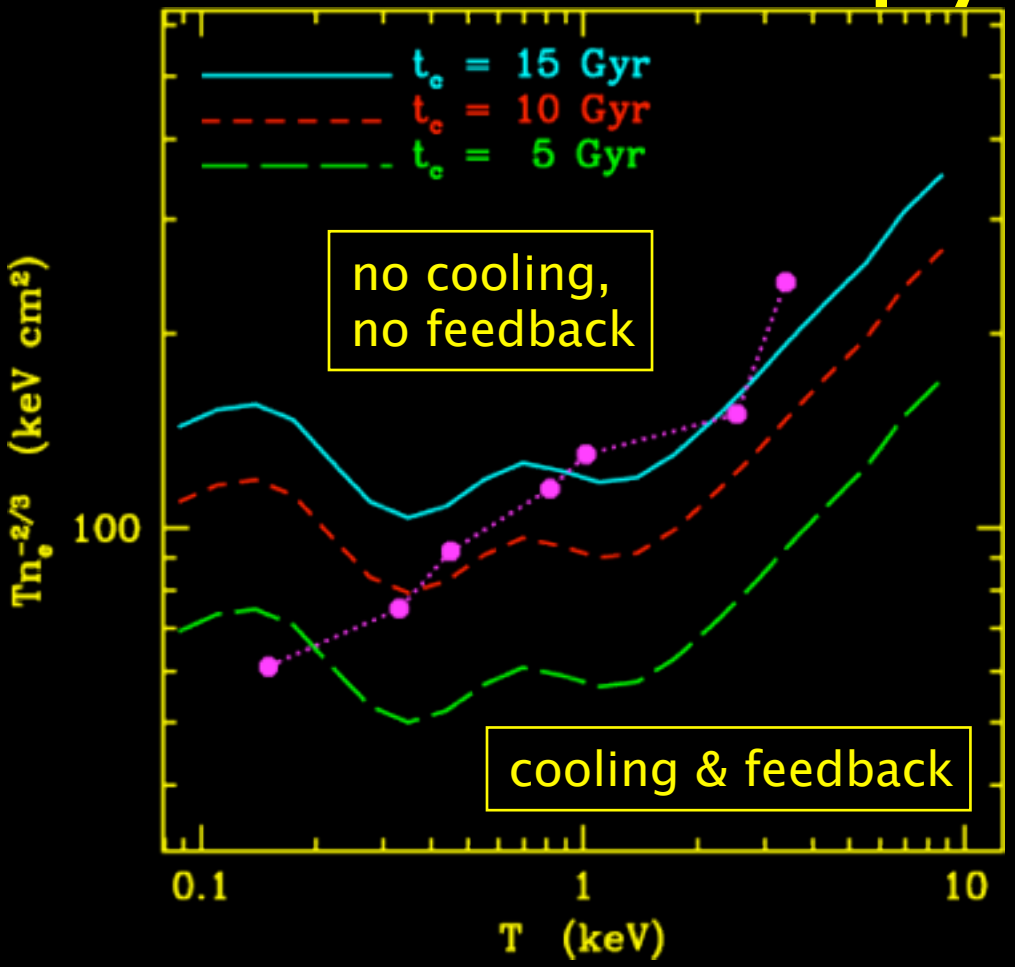
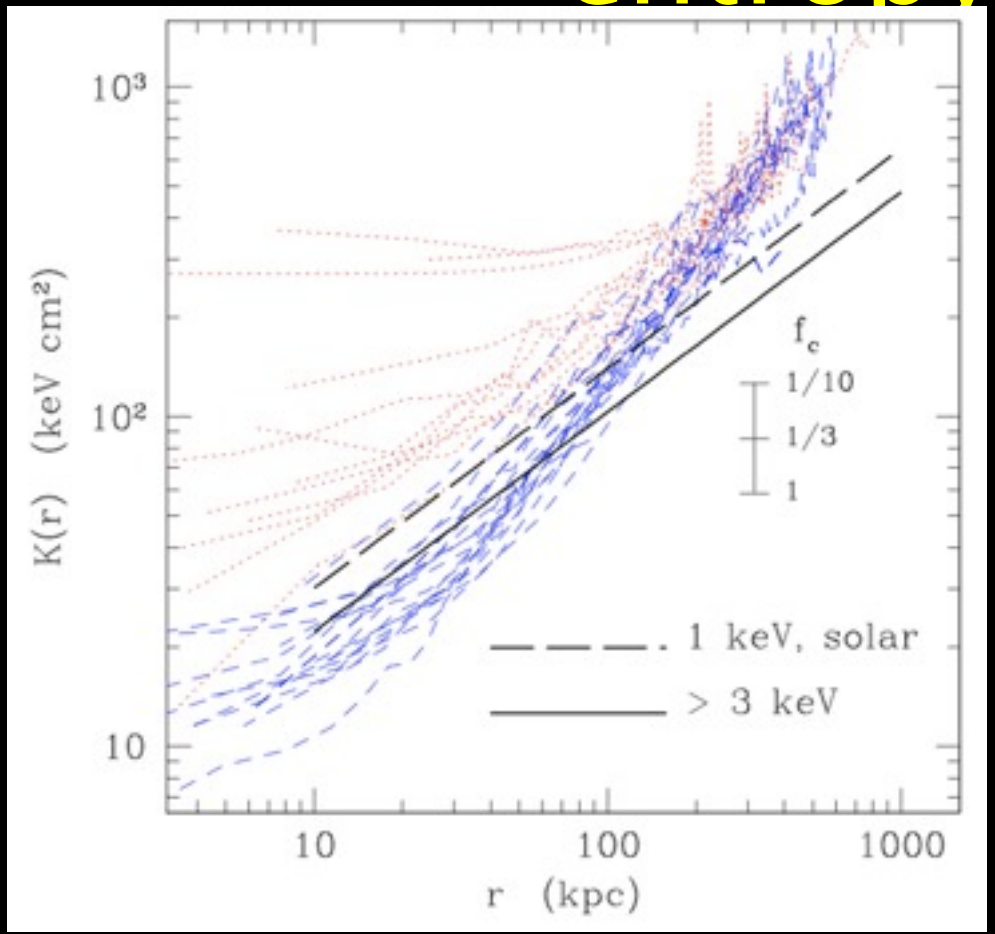


Gas with entropy < 150 keV cm^2 must either cool or feedback must keep it from cooling

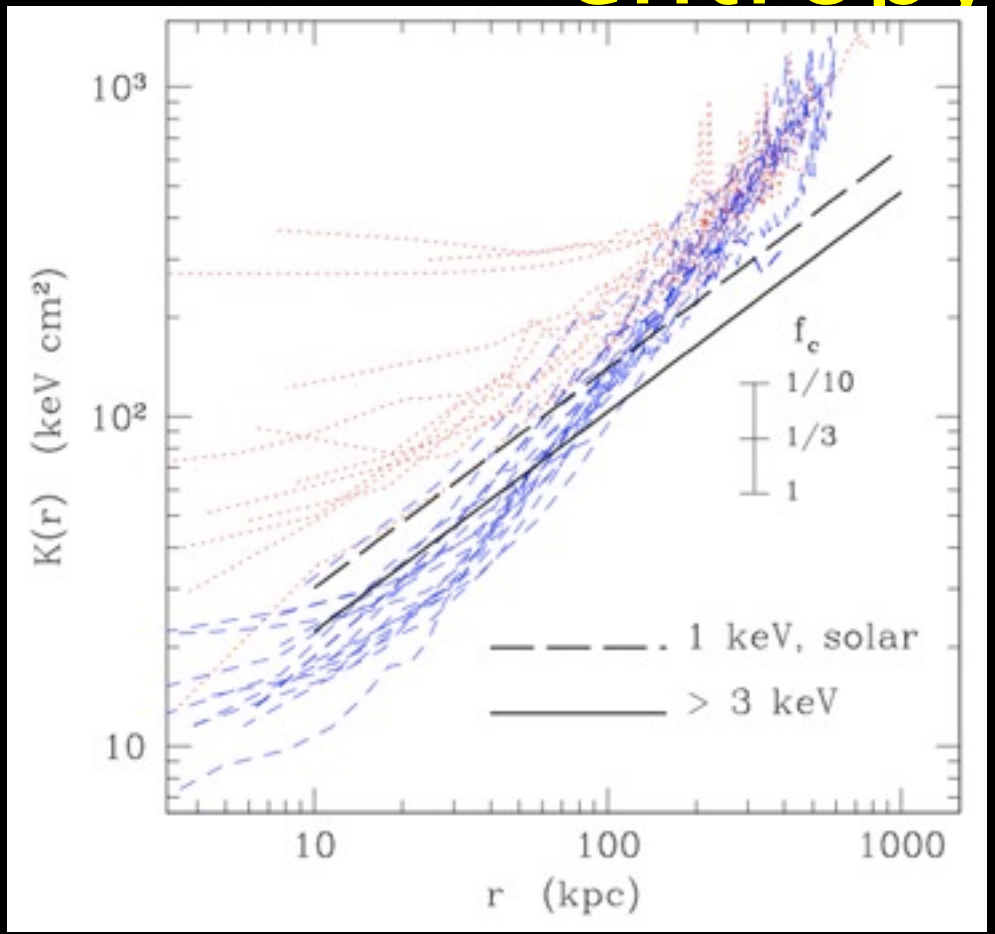
Voit & Bryan 2001

What determines core entropy?



Voit (2011)

What determines core entropy?



Critical threshold for cooling & feedback might be the locus of conductive balance

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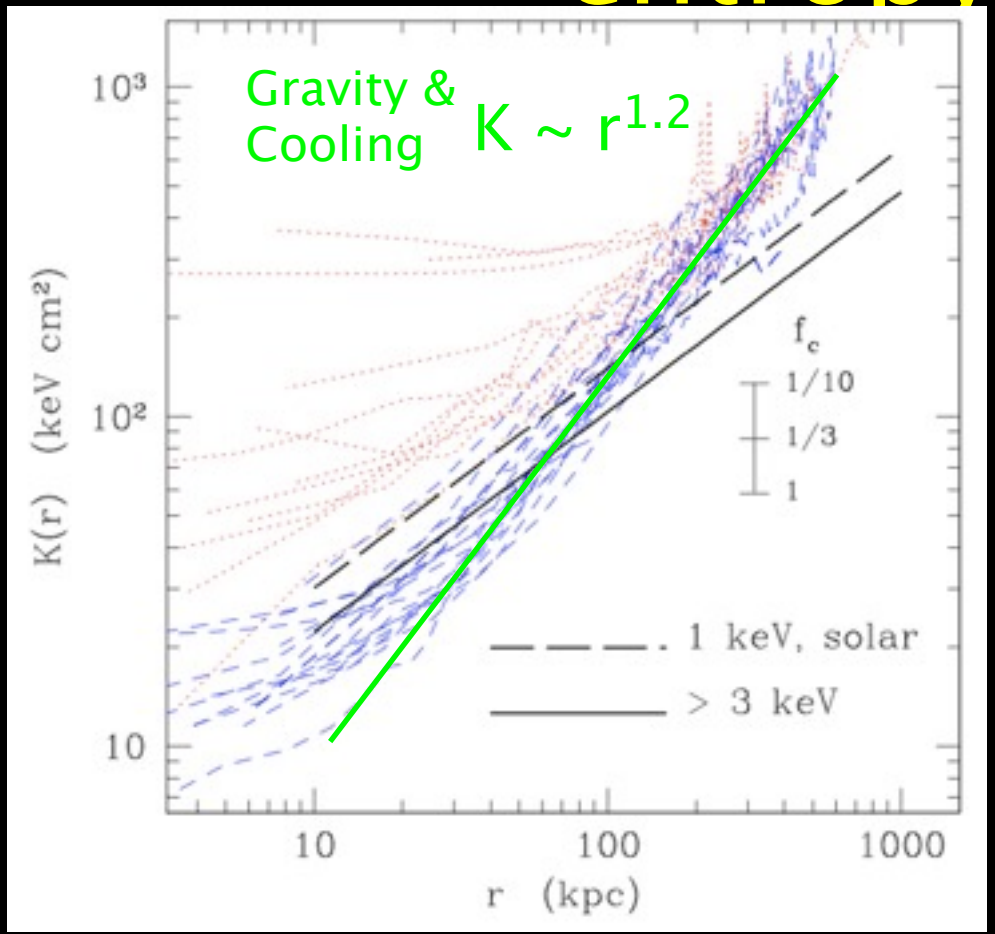

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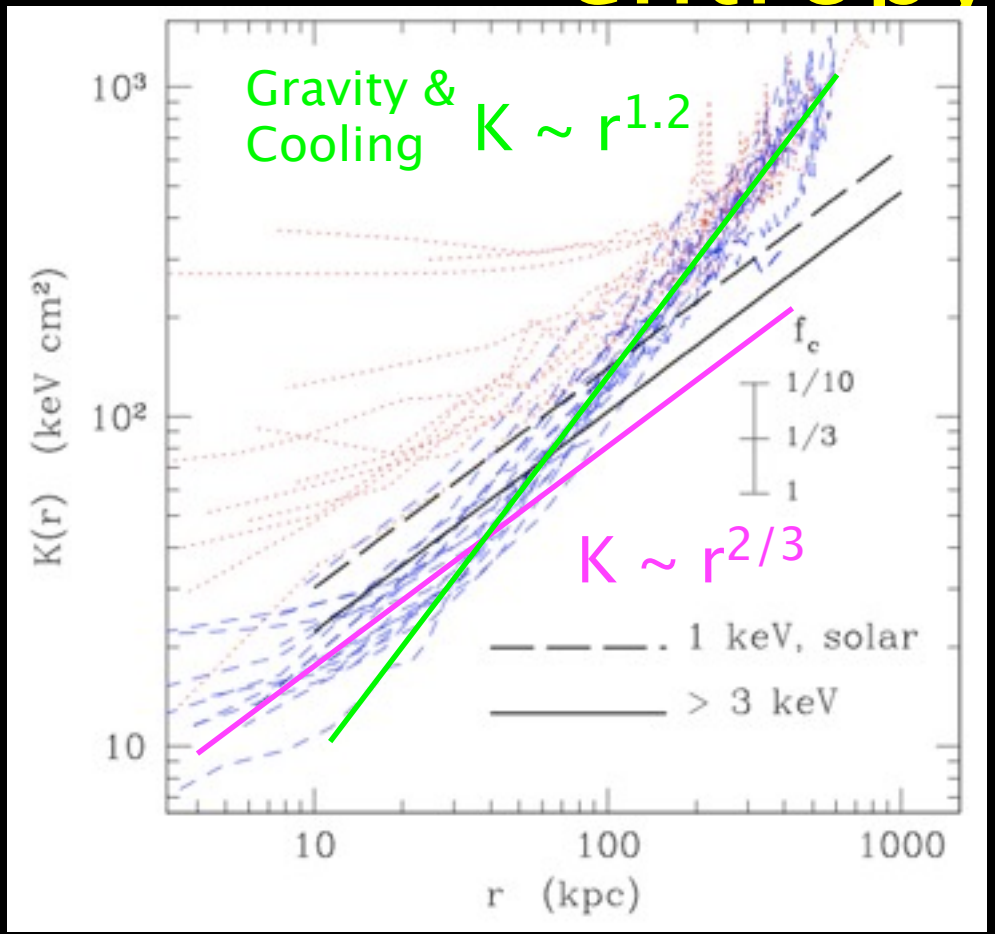

Voit (2011)

Critical threshold for cooling & feedback might be the locus of conductive balance

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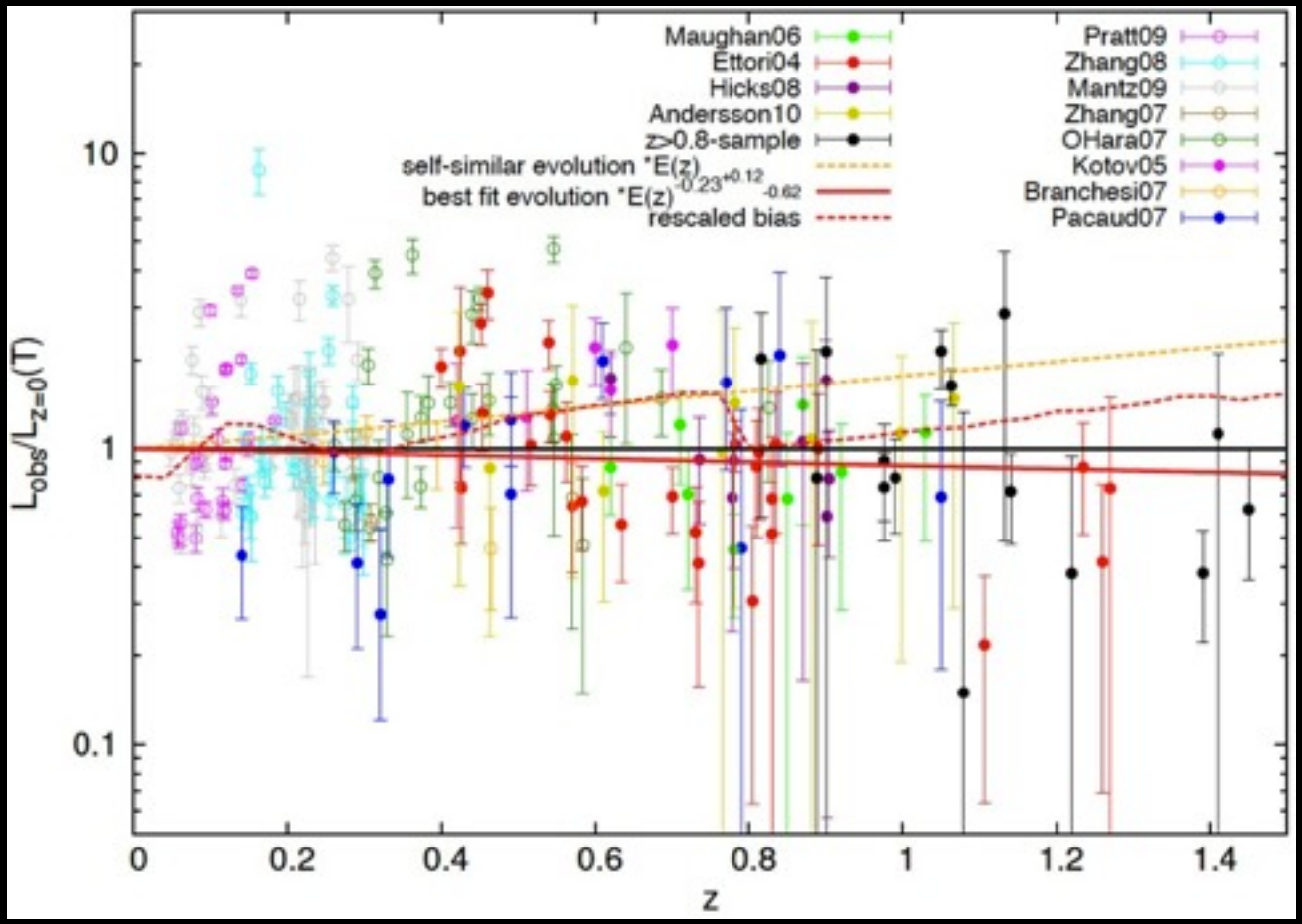

Reichert+ 2011 A&A, submitted

Evolution of L_X–T_X relation not self-similar.

X-ray cores may be less prominent at high redshift.

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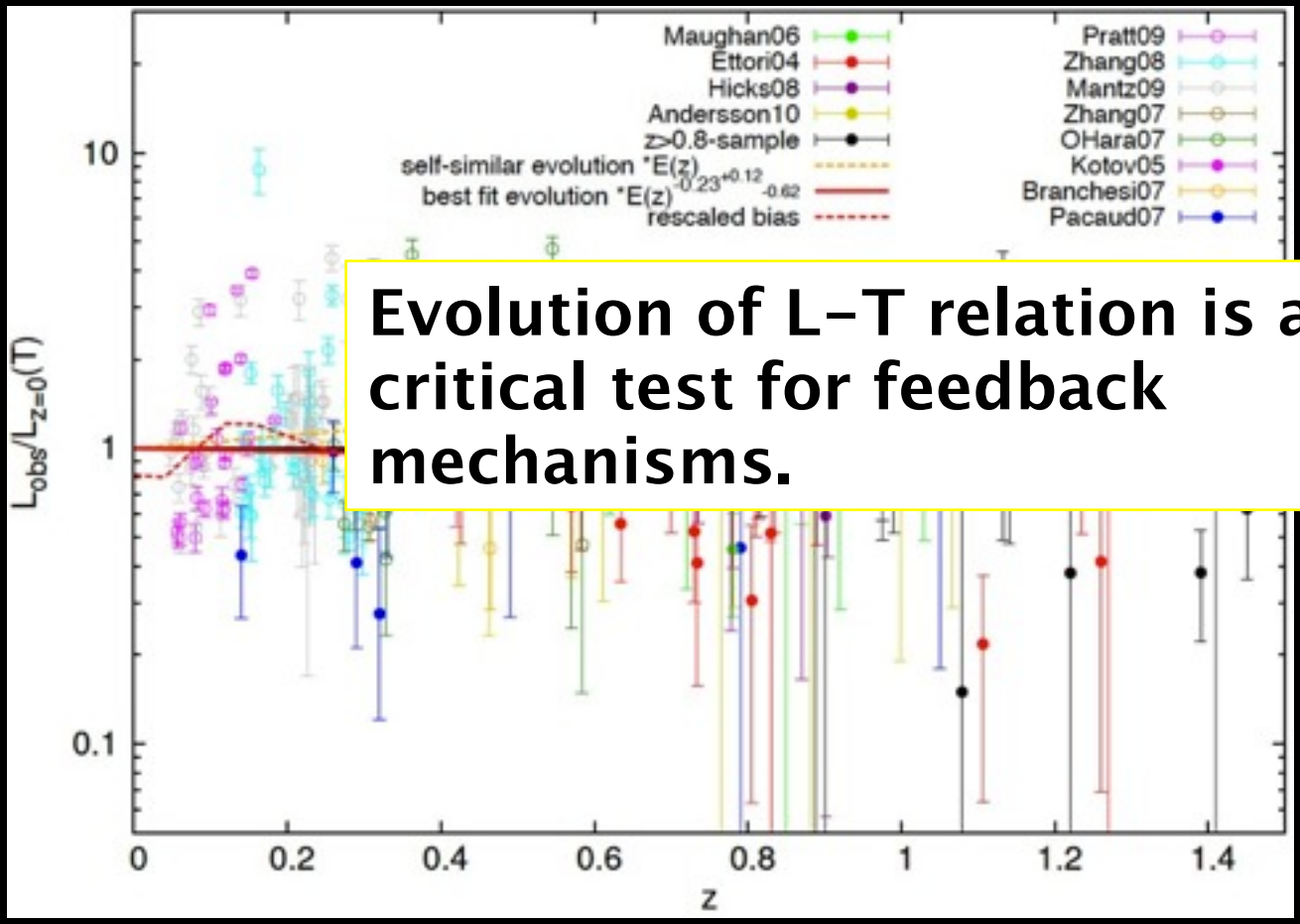

Evolution of L–T relation is a critical test for feedback mechanisms.

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Are clusters self-similar at large radii?

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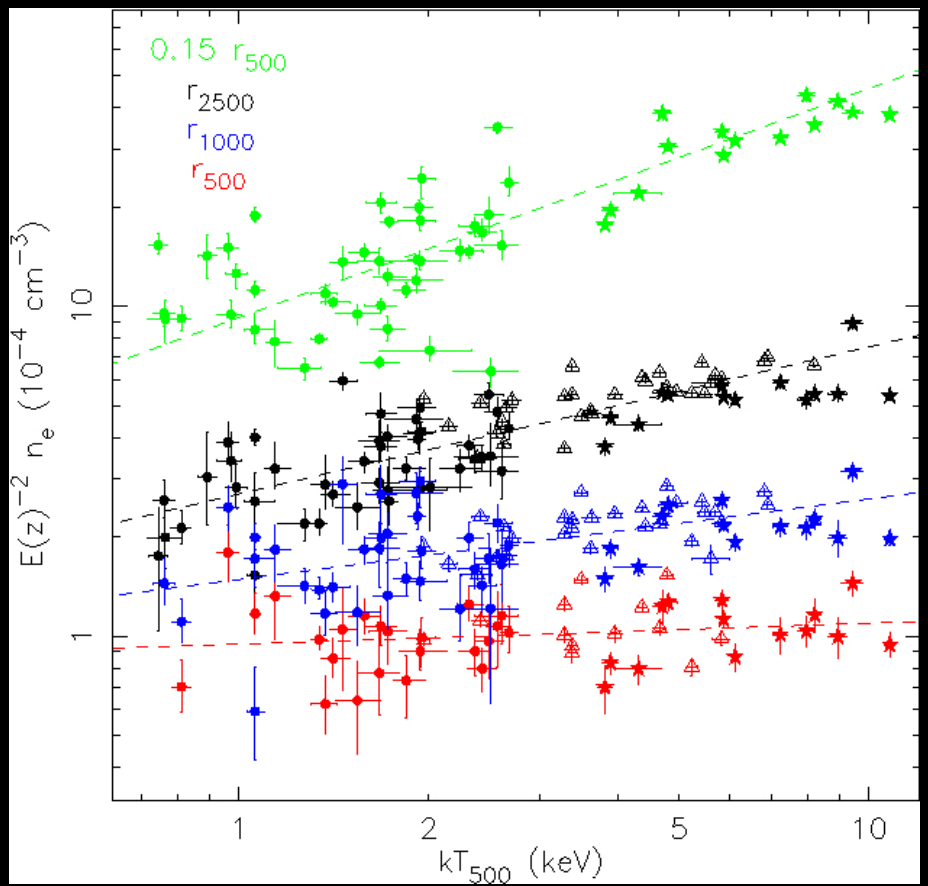
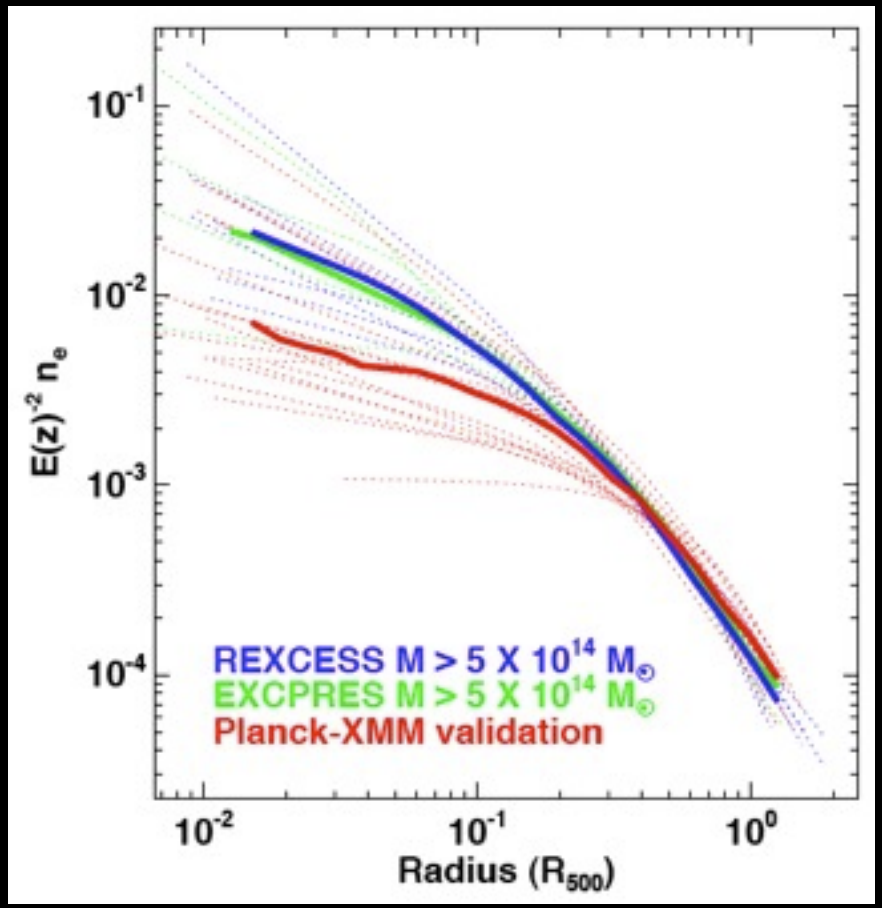


Sun 2011 (in

Are clusters self-similar at large radii?



PLANCK Collaboration

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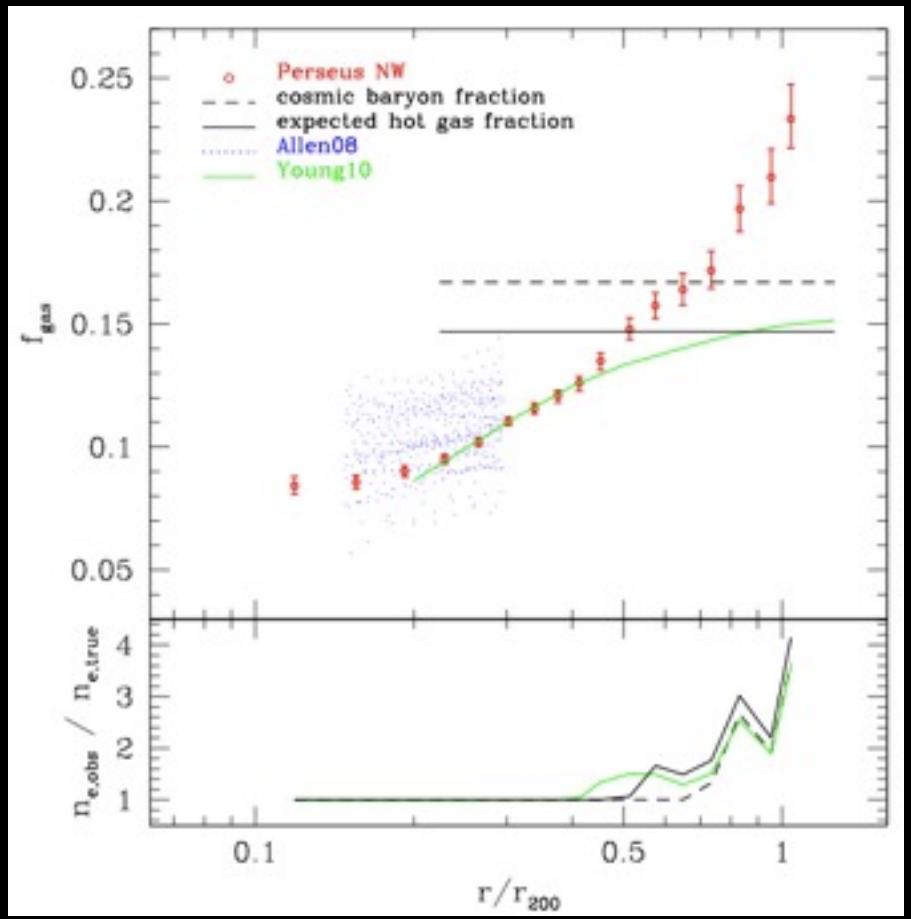
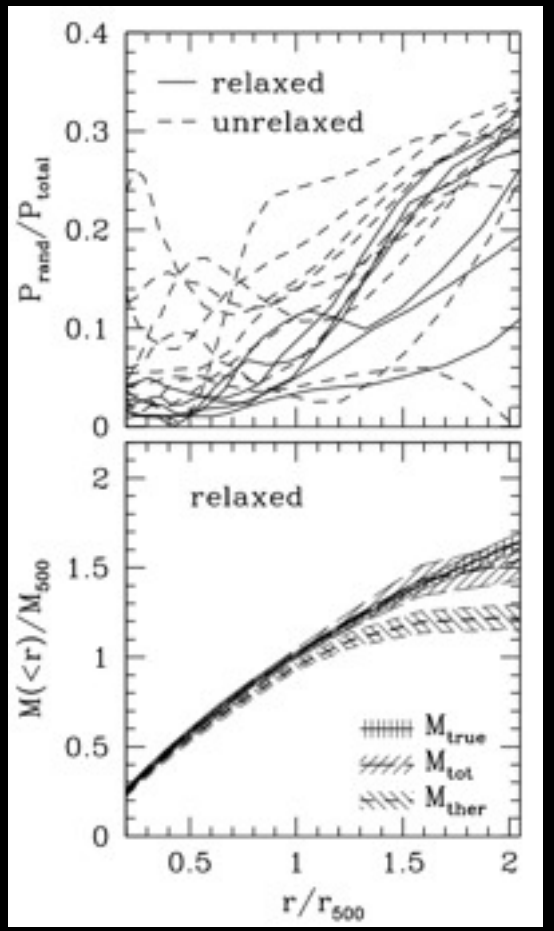
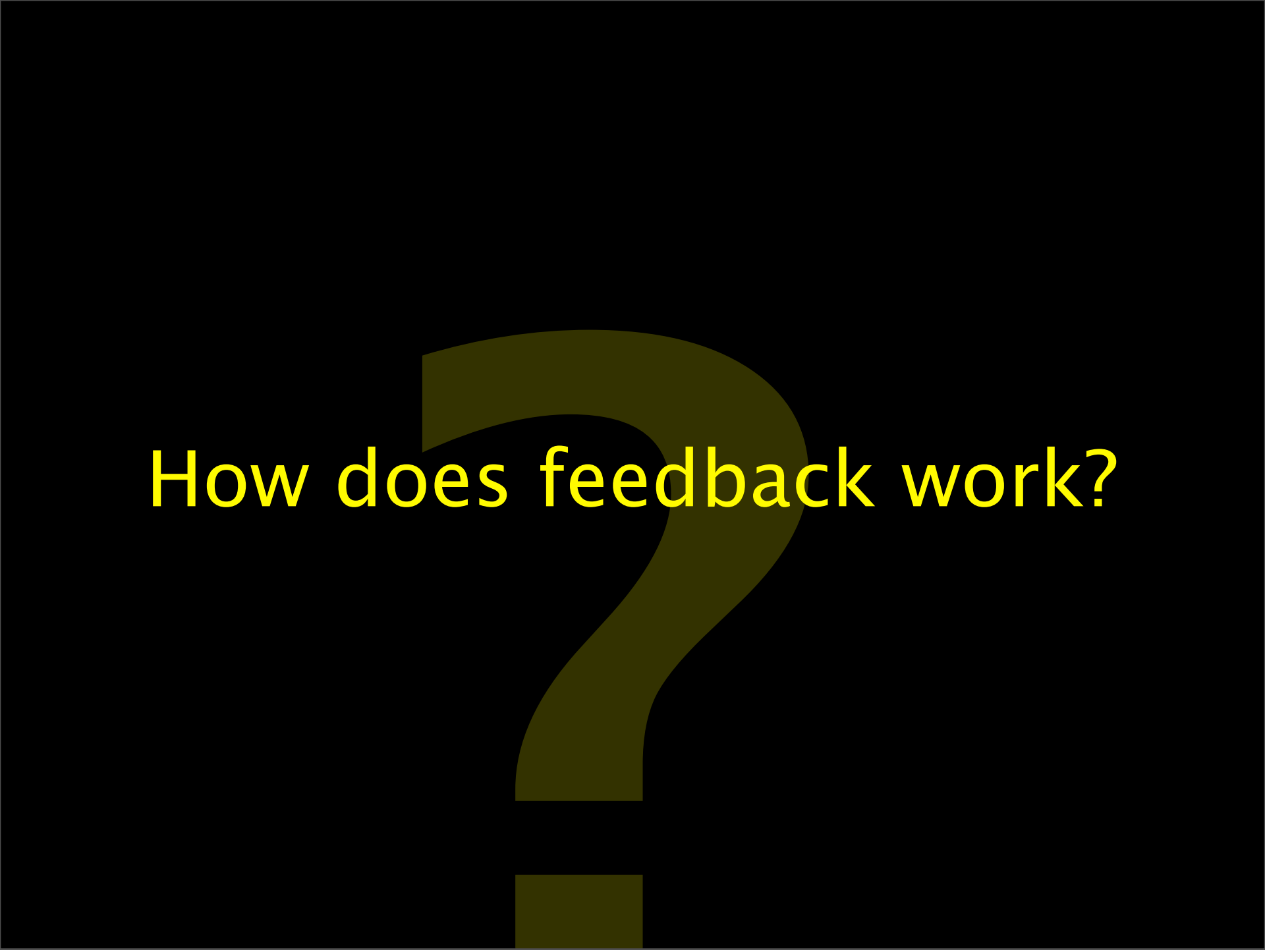


Simonescu+



Lau+ 2009

How does feedback work?



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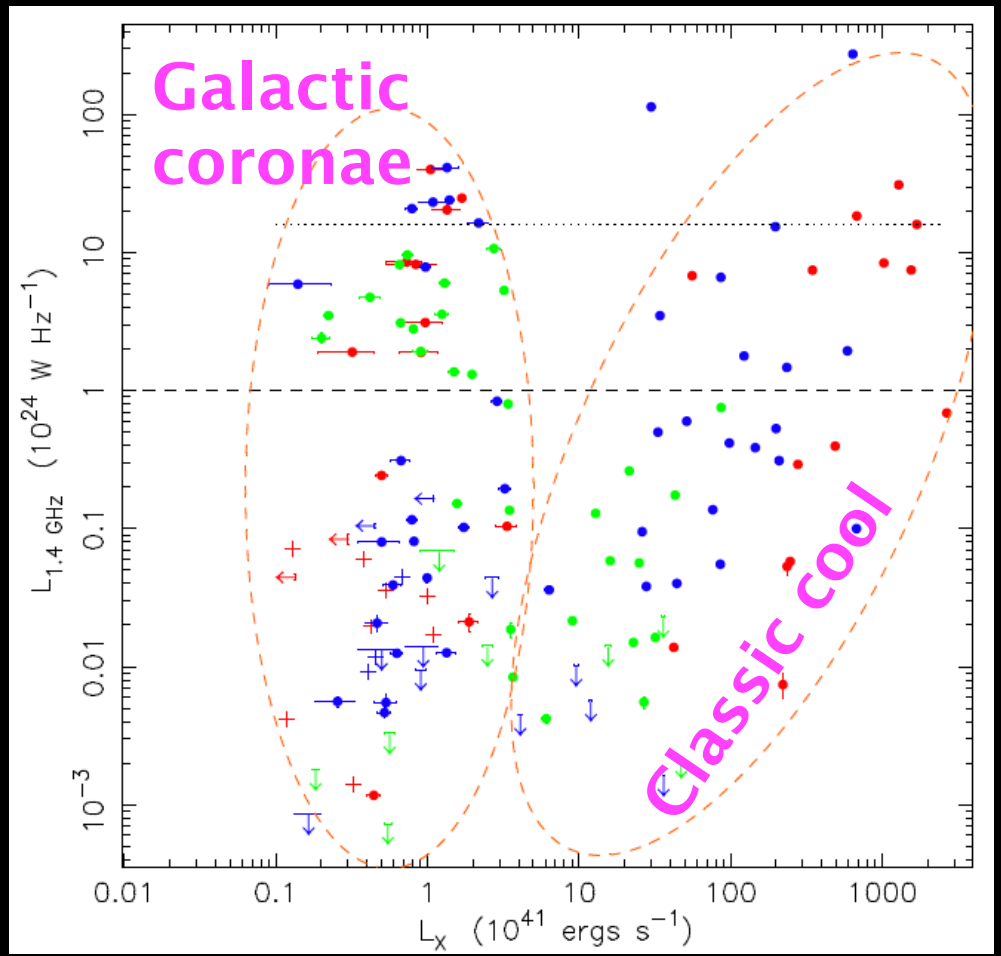

Only objects with low-entropy gas in the center have strong central radio sources

Sun 2009

How is AGN feedback thermalized?

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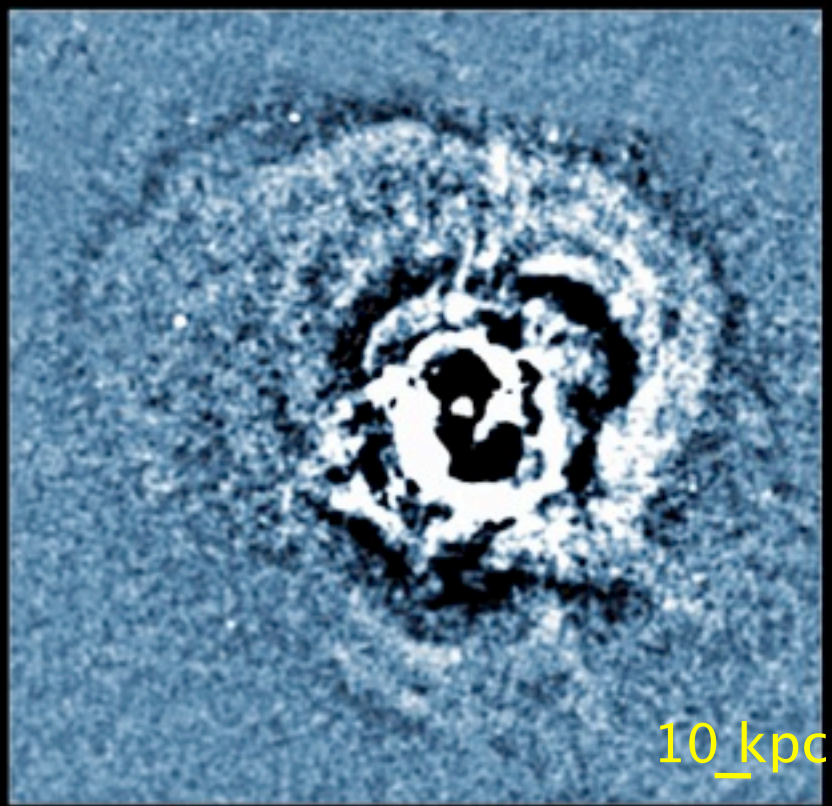
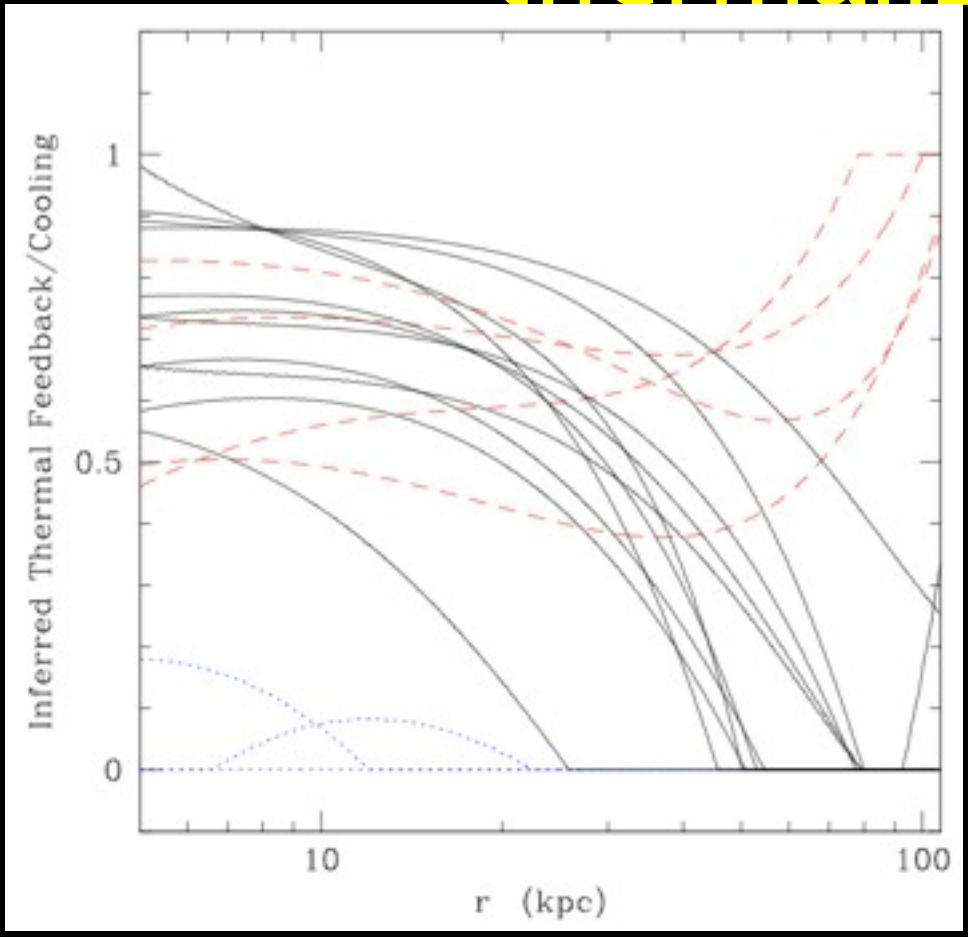


Fabian+ 2005

Identifying a single mechanism that can balance cooling from 1-100 kpc is difficult

How is AGN feedback thermalized?



Voit 2011

Hybrid models with AGN heating at < 30 kpc and thermal conduction at >30 kpc look promising

Ruszkowski & Begelman 2002
Voigt & Fabian 2004
Guo+ 2008

What if conduction is anisotropic?

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Buoyancy instabilities driven by anisotropic conduction can rearrange a cluster's magnetic field

Parrish+ 2009

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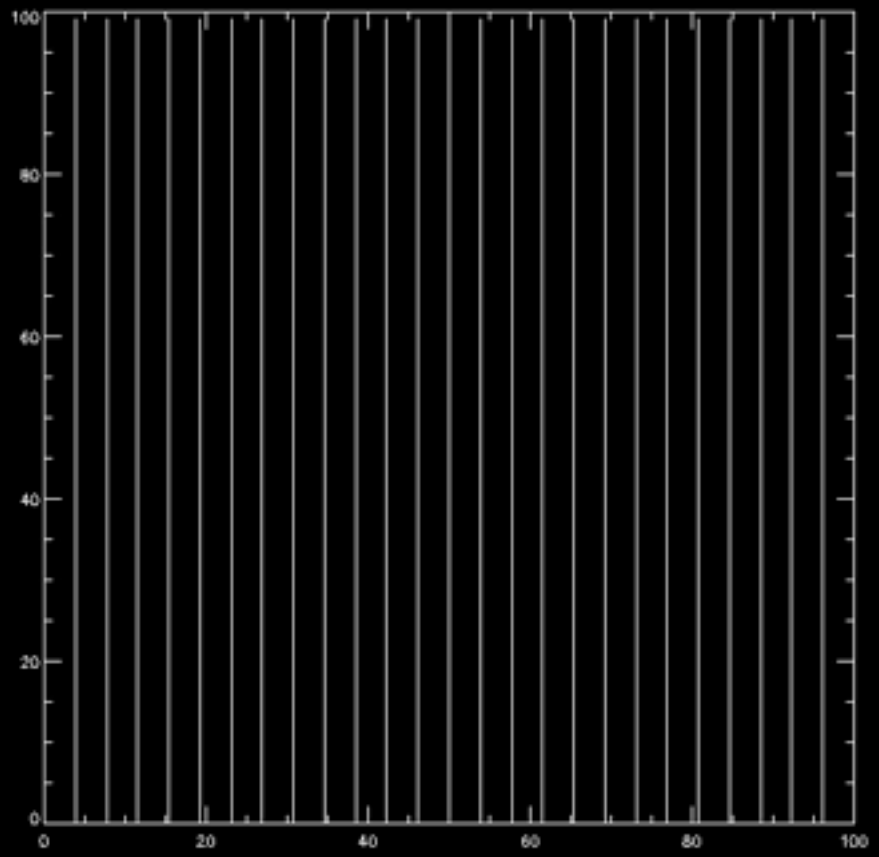

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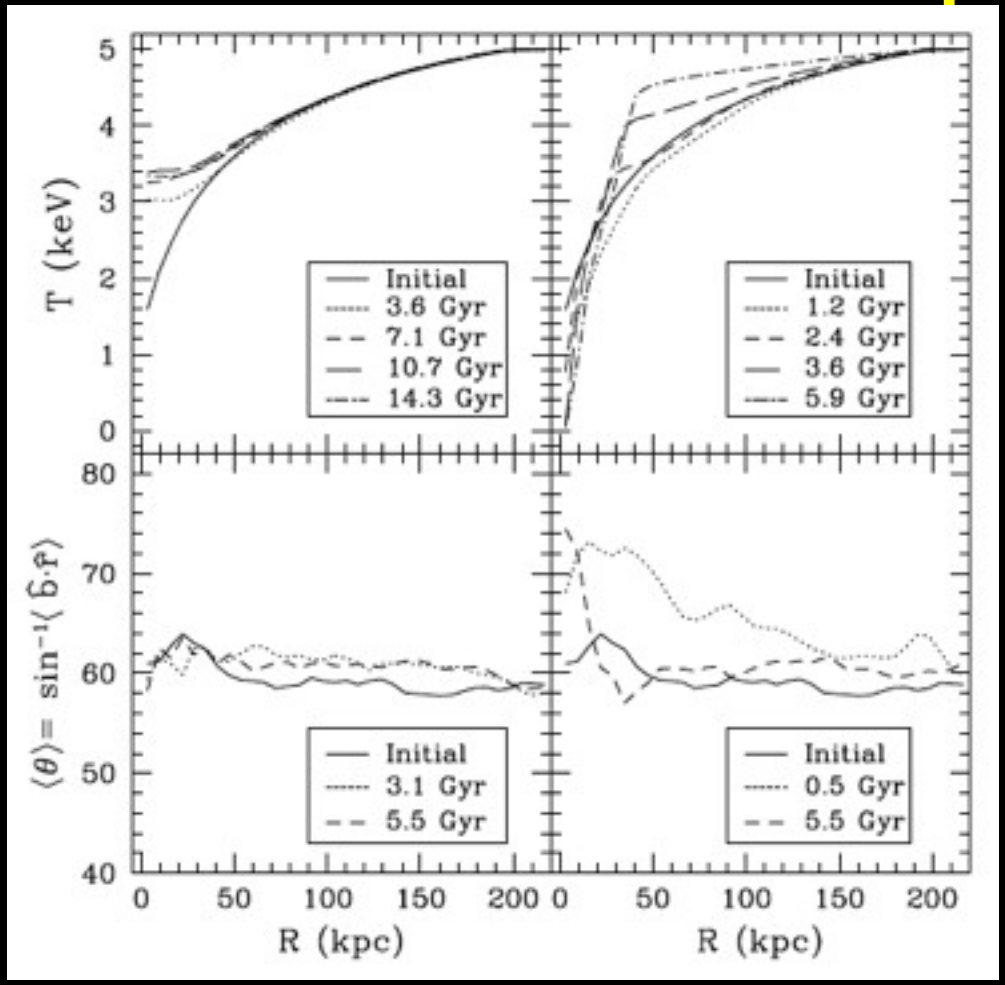

Competition between turbulence and buoyancy instabilities may regulate conductivity and produce core bimodality

Parrish+ 2010
Ruszkowski & Oh 2010

Why are stars forming in cluster cores?

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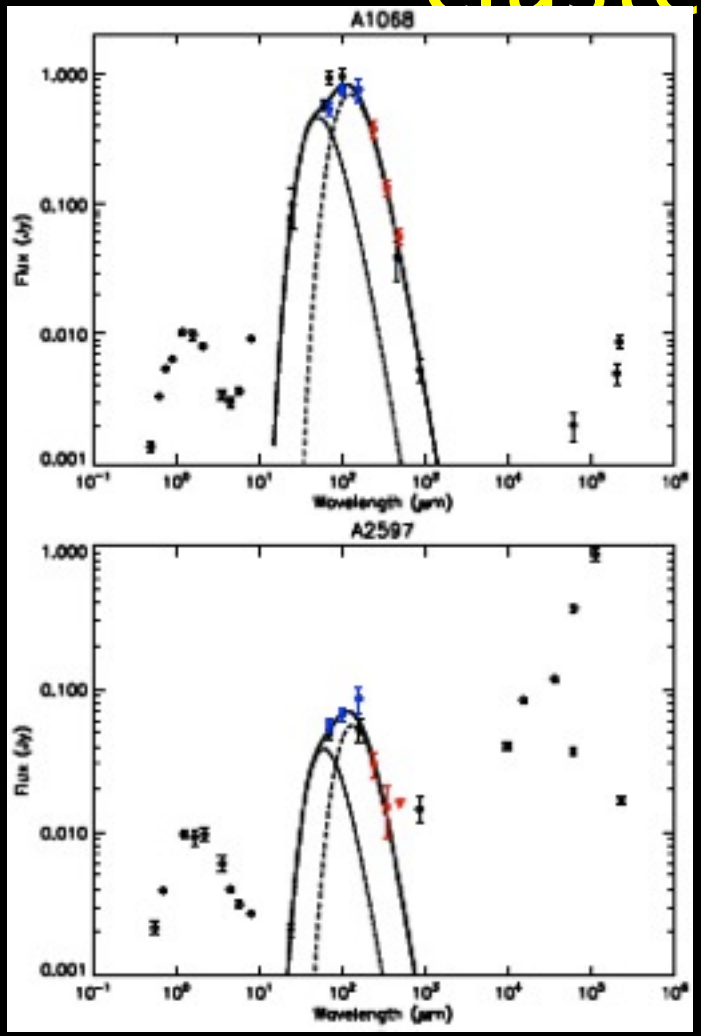
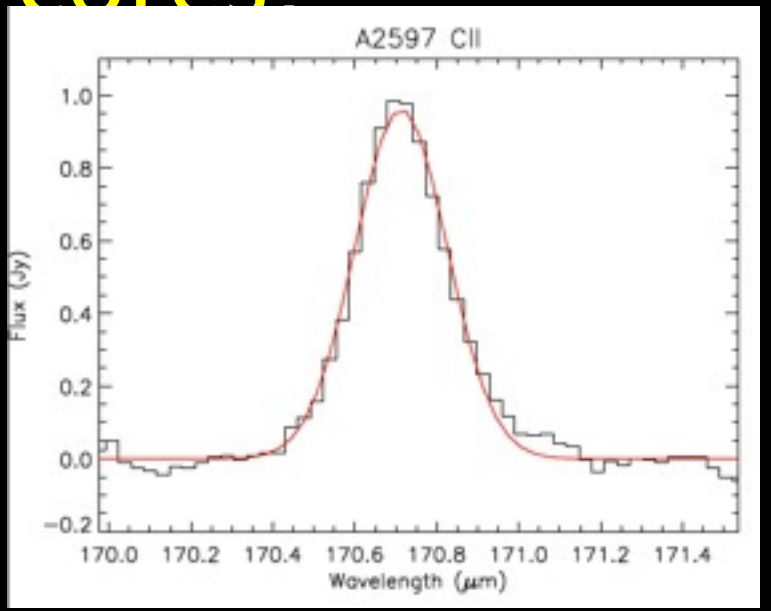
NGC 1275

Central cluster galaxies with cool cores have long been known to host star formation and emission-line nebulae

Why are stars forming in cluster cores?



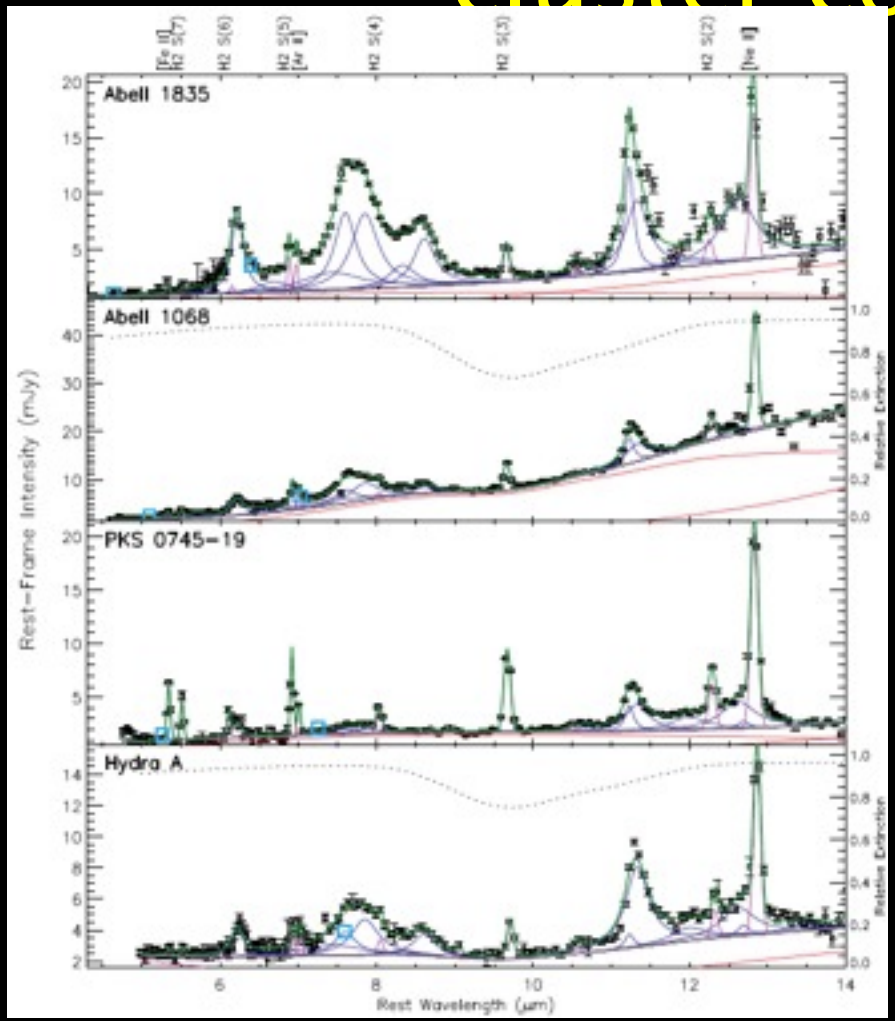
Edge+ 2010



Edge+ 2010

Herschel & Spitzer are revealing large amounts of cold dusty gas in star-forming BCGs

Why are stars forming in cluster cores?



Donahue+ 2011

Dust emission from star-forming BCGs, including PAHs (!), closely resembles that of normal star-forming galaxies

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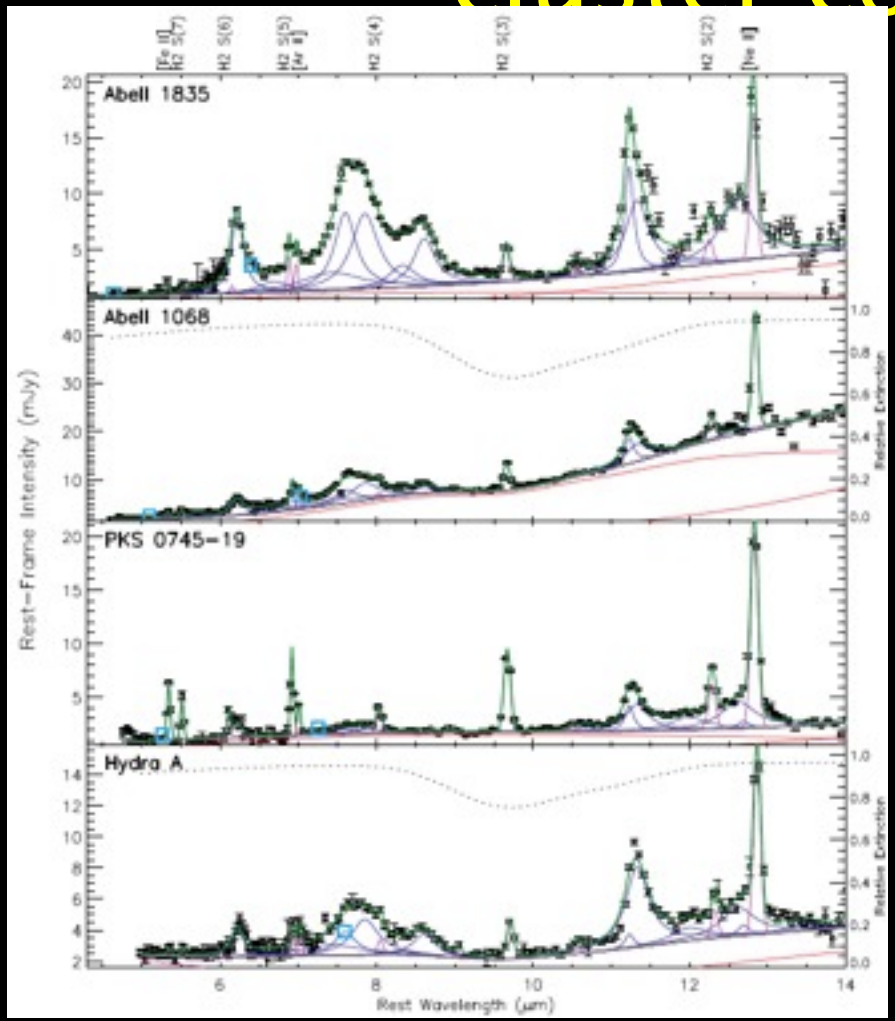
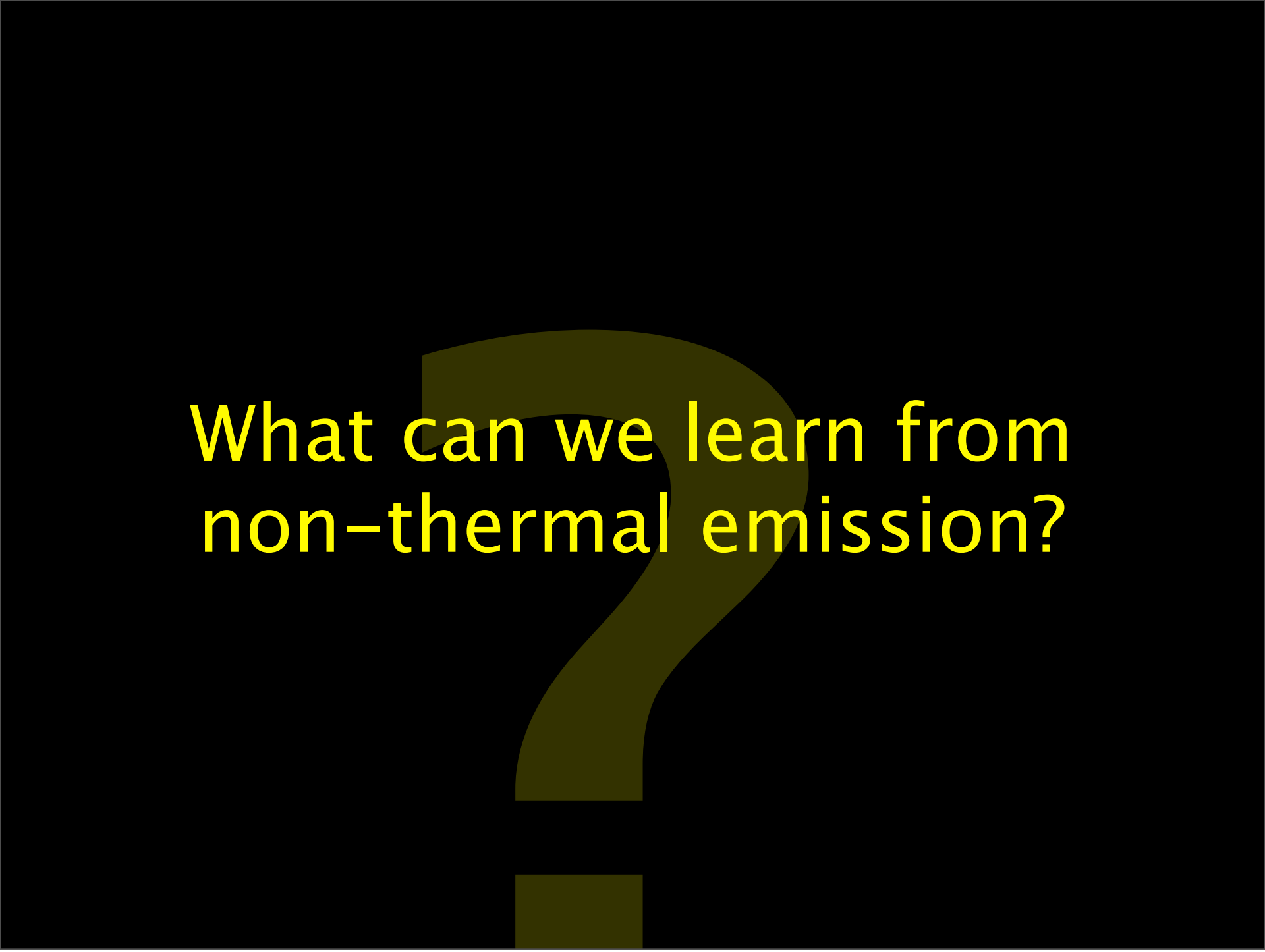


Donahue+ 2011

Dust emission from star-forming BCGs, including PAHs (!), closely resembles that of normal star-forming galaxies

Only rarely does the star-formation rate in a BCG exceed the stellar mass-loss rate

What can we learn from non-thermal emission?



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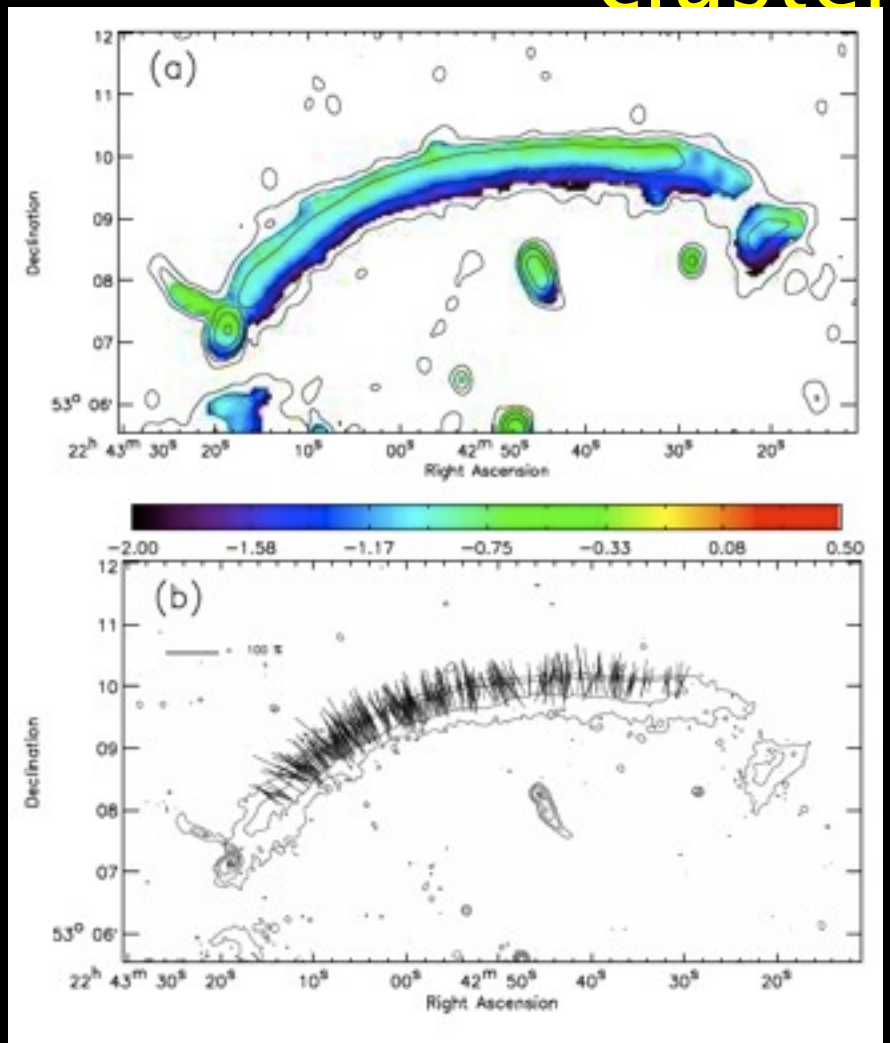

van Weeren+

Diffusive shock acceleration in cluster mergers can produce energetic cosmic rays

How are radio halos related to relaxation?

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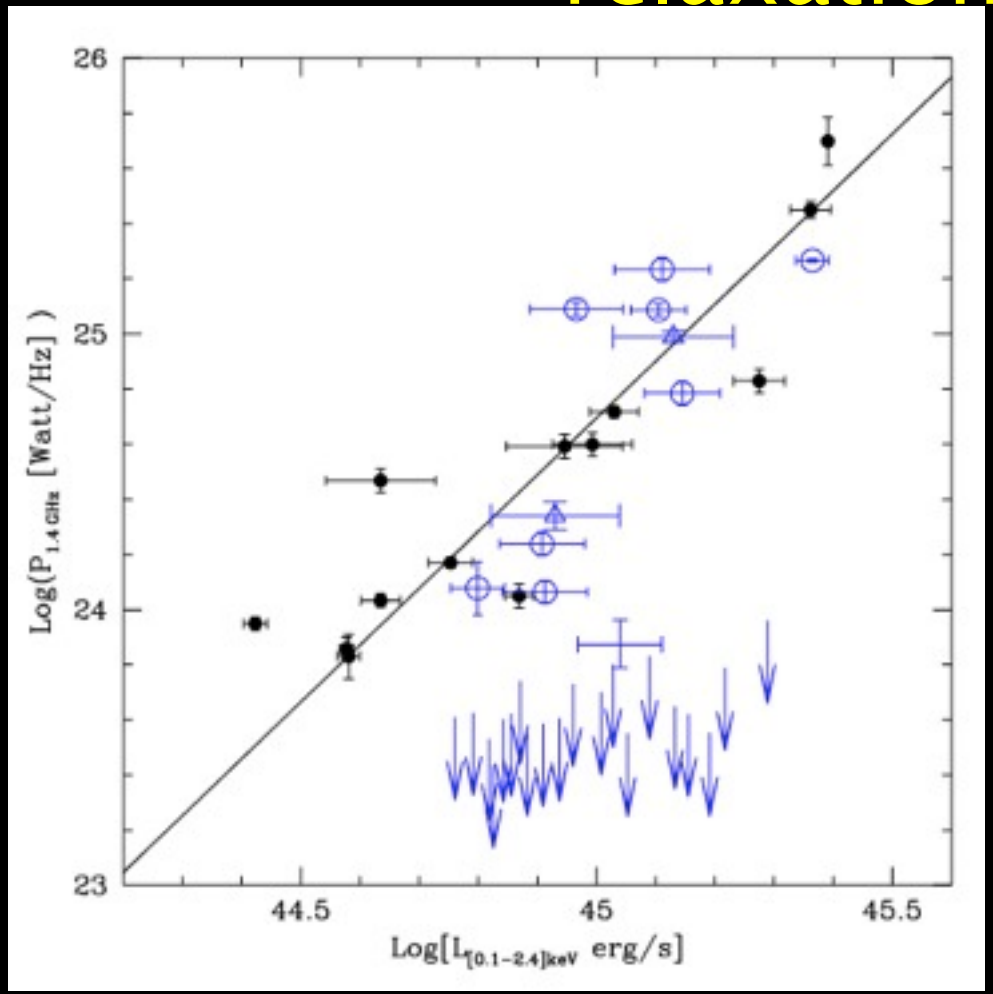

Cluster mergers can produce giant radio halos that disappear within ~ 1 Gyr as the cluster relaxes

Brunetti+ 2009

What is the ICM cosmic-ray pressure?

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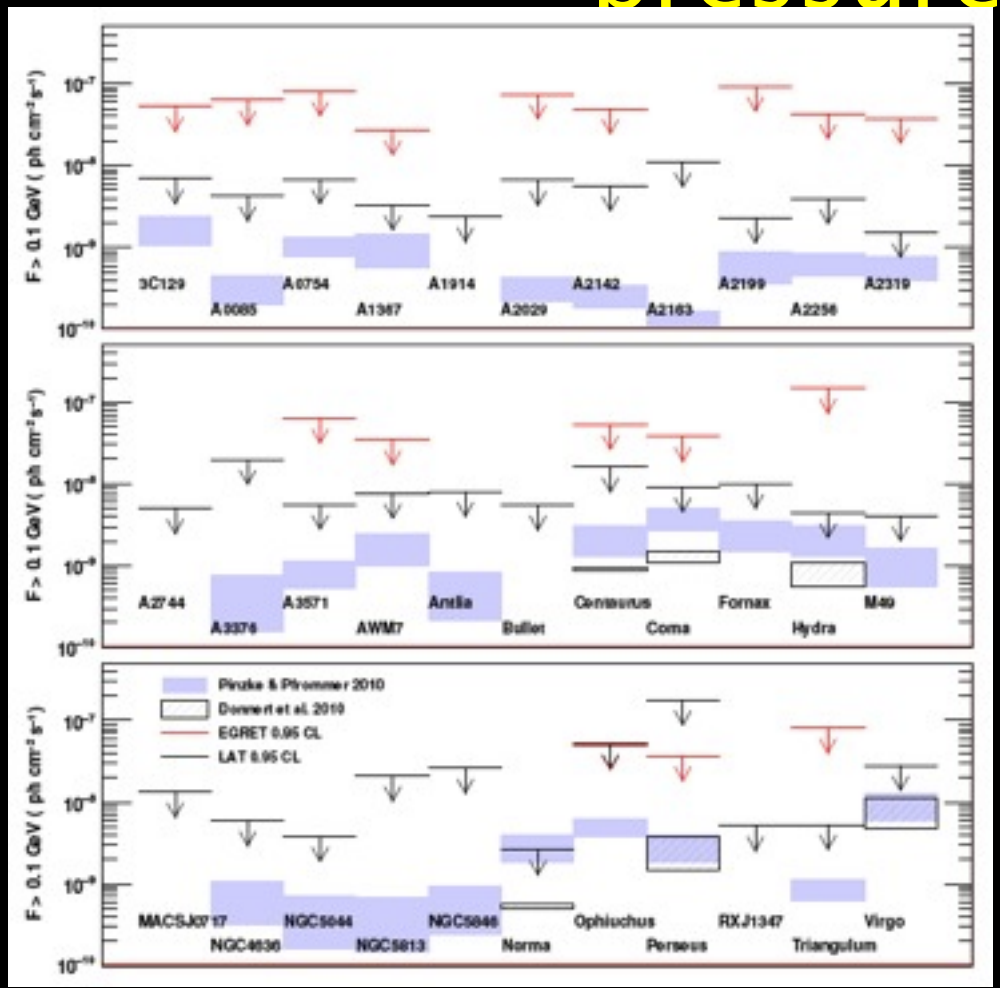

Fermi limits on hadronic cosmic-ray pressure are approaching <5-10% of thermal pressure

Ackermann+ 2010

How well can we measure mass?

- What is a "cluster of galaxies?"
- Which mass proxies are most reliable?
- How does scatter affect mass calibration?

Why aren't groups and clusters self-similar?

- Is preheating sufficient?
- What determines core entropy?
- How do core properties evolve?
- Are clusters self-similar at large radii?

What is non-thermal emission telling us?

- How are particles accelerated in clusters?
- How are radio halos related to relaxation?

How do cluster contents depend on mass?

- Are there baryons missing from clusters?
- What determines the star-to-gas ratio?
- How does enrichment depend on mass?

How does feedback work?

- What triggers feedback?
- How is AGN feedback thermalized?
- What if conduction is anisotropic?
- Why are stars forming in cluster cores?