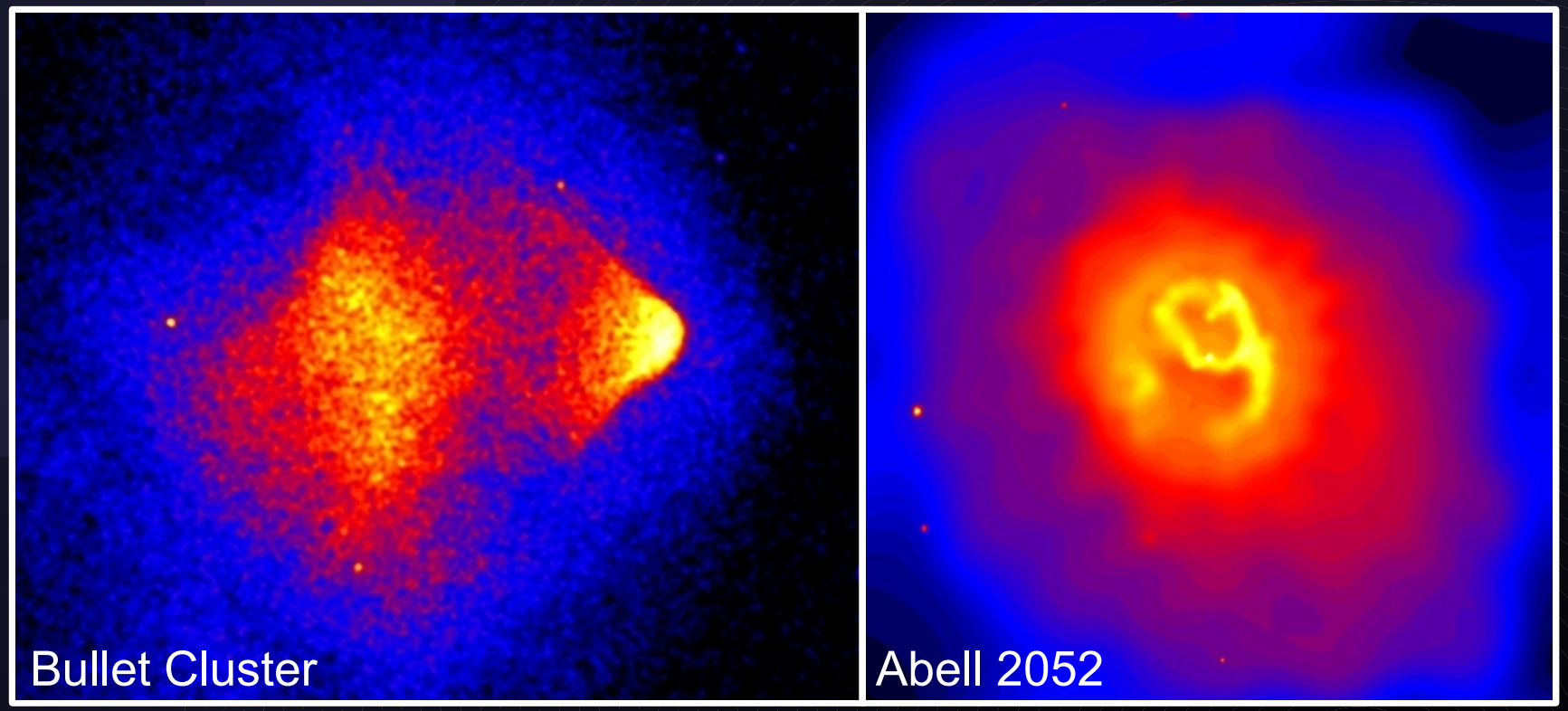
From Cosmology to Star Formation: An Hour with Galaxy Clusters

Ken Cavagnolo
Michigan State University



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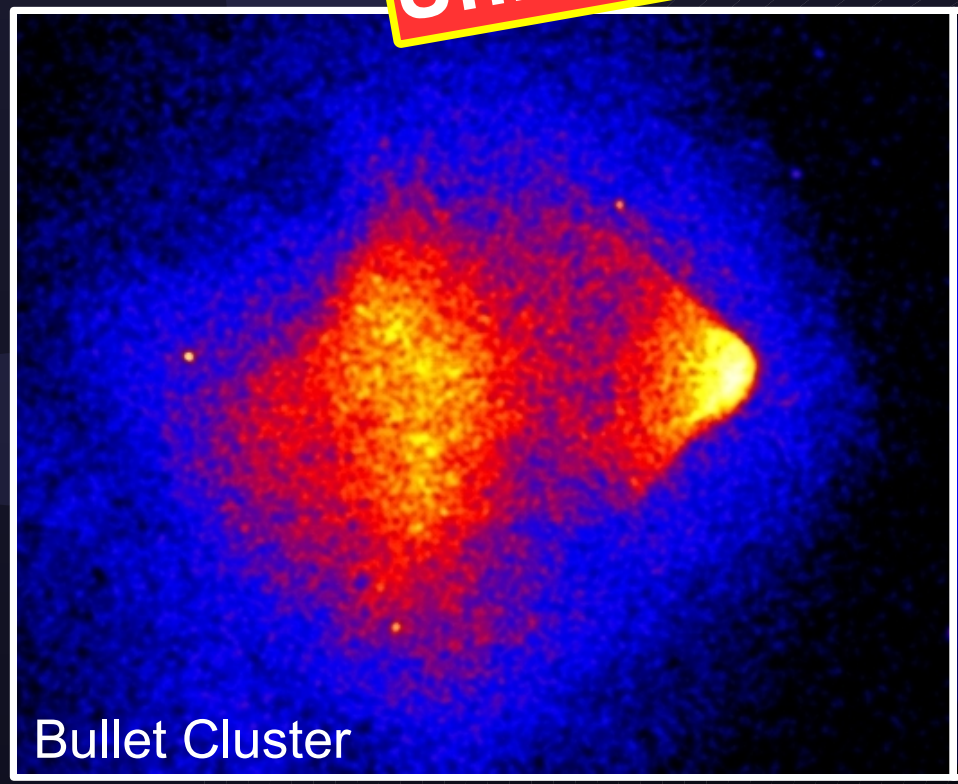
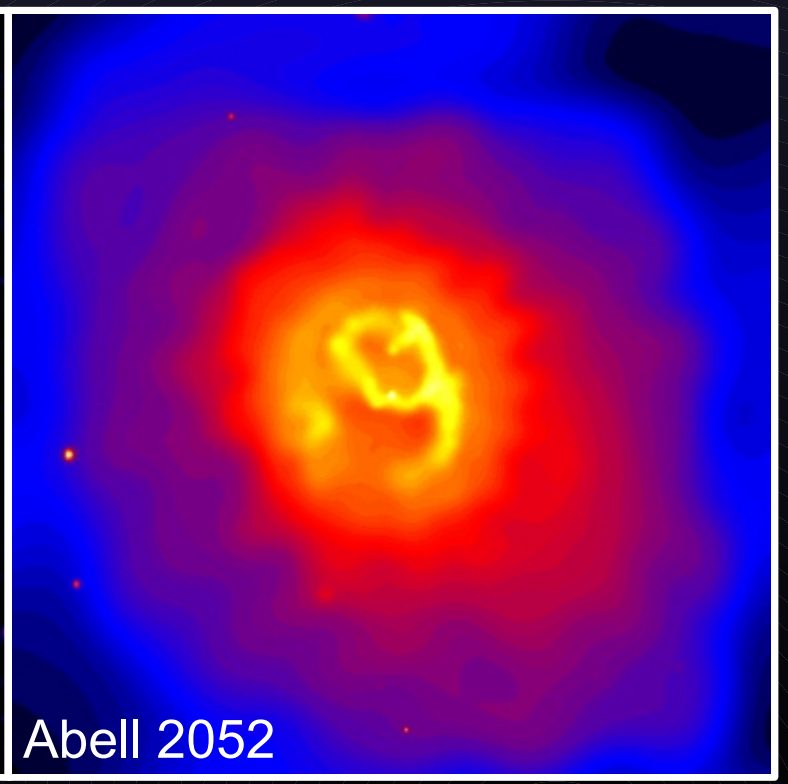


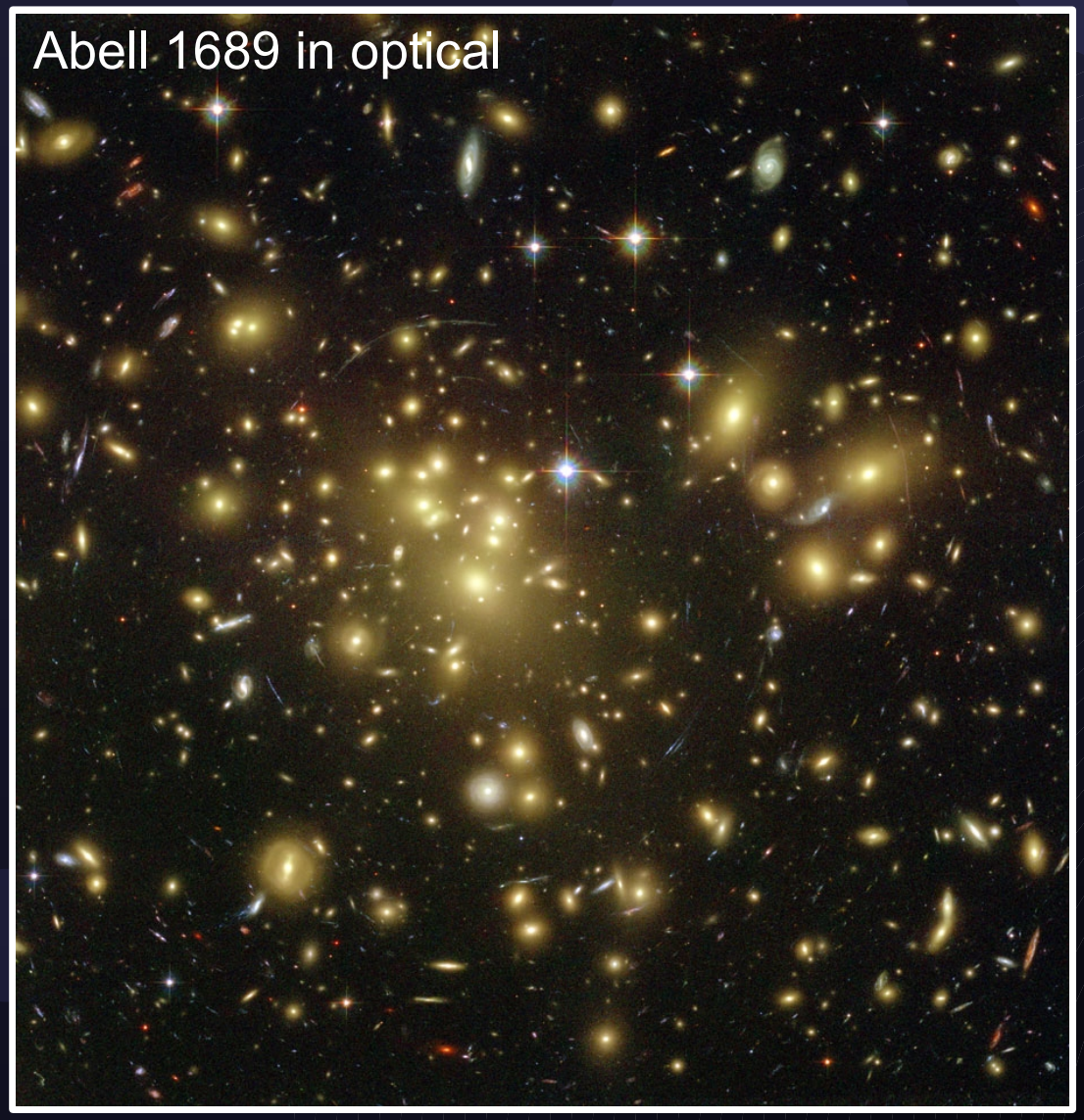


* in September

Collaborators

- Megan Donahue (Advisor)
- G. Mark Voit (Co-advisor)
- Ming Sun
- David Ventimiglia
- Brian McNamara

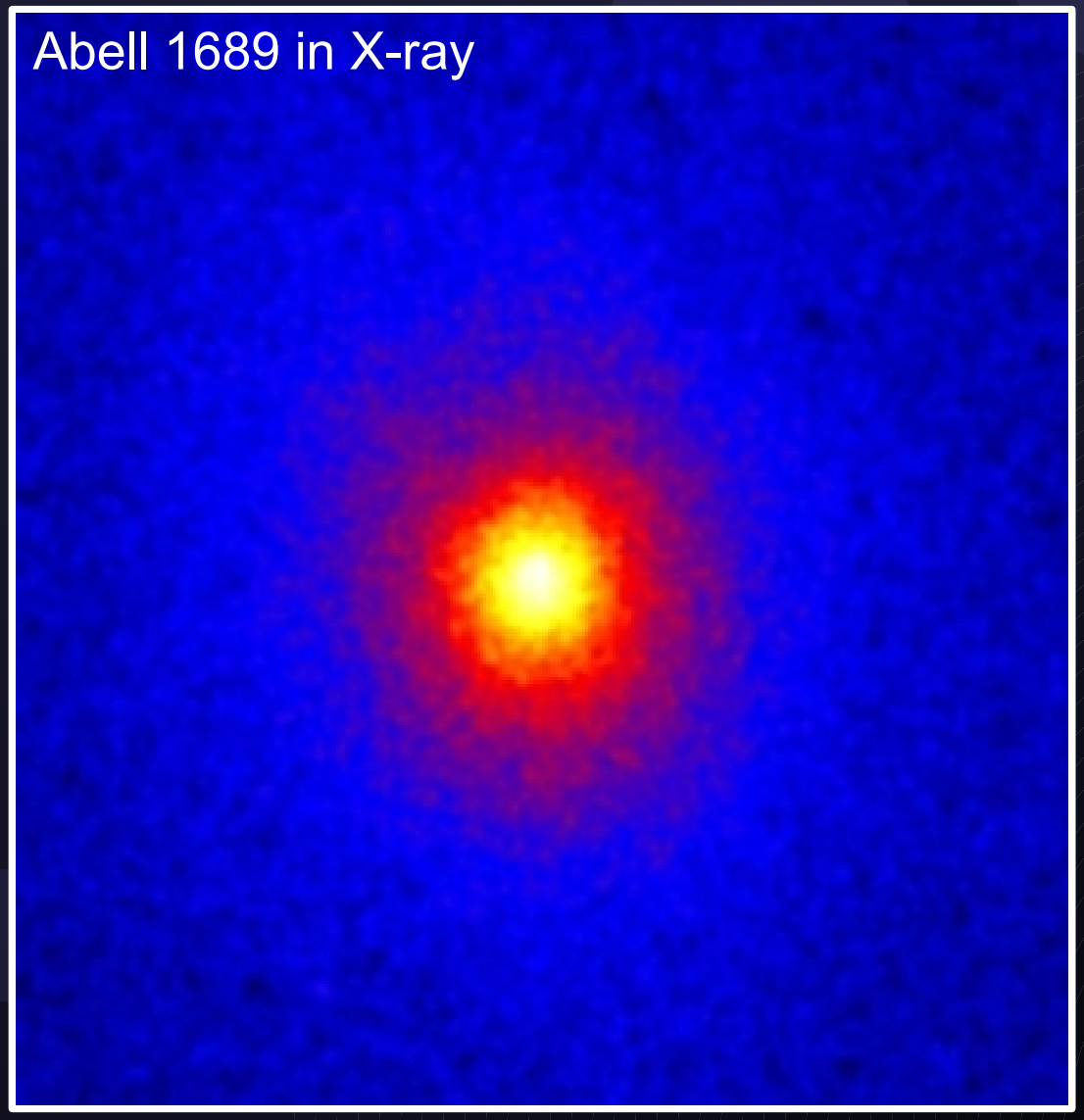
Galaxy Clusters Refresher



NASA / ACS Team / Benitez et al.

- 100's to 1000's of galaxies
- 70-80% dark matter
- 30-20% baryons
- Few Mpc in size
- 10^{13}-10^{15} $M_{\odot}$
- Stars and Galaxies aren't everything...

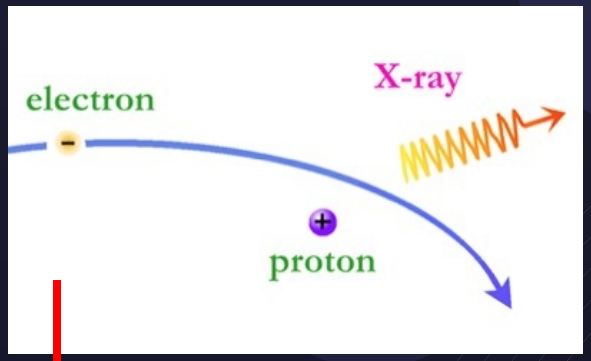
Galaxy Clusters Refresher

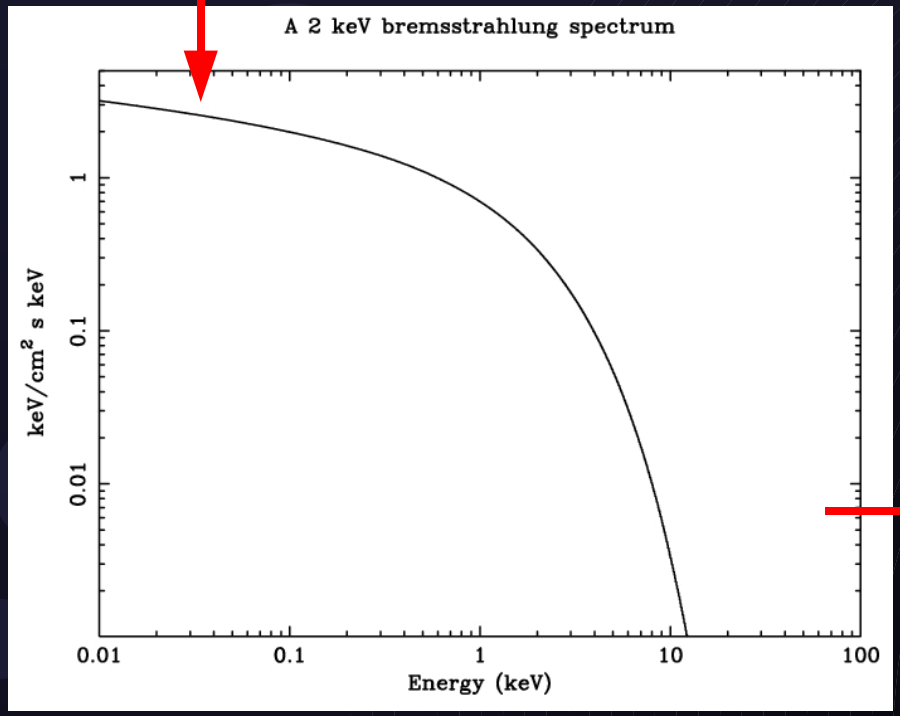


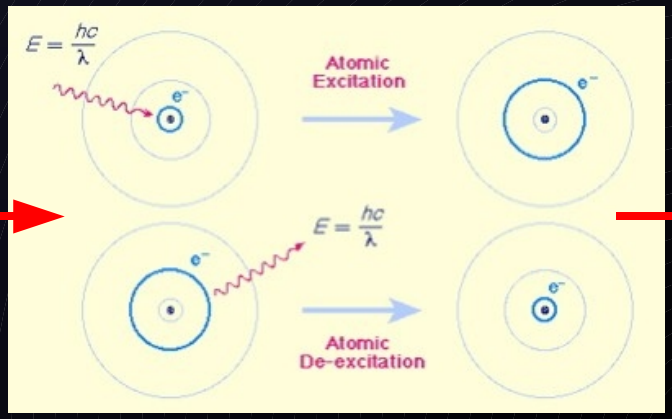
- Intracluster medium (ICM) is 60-90% of baryons
- Hot: ≥ 10 million K
- Diffuse: ≤ 10^{-1} cm^{-3}
- Luminous: 10^{42}-10^{45} ergs s^{-1}

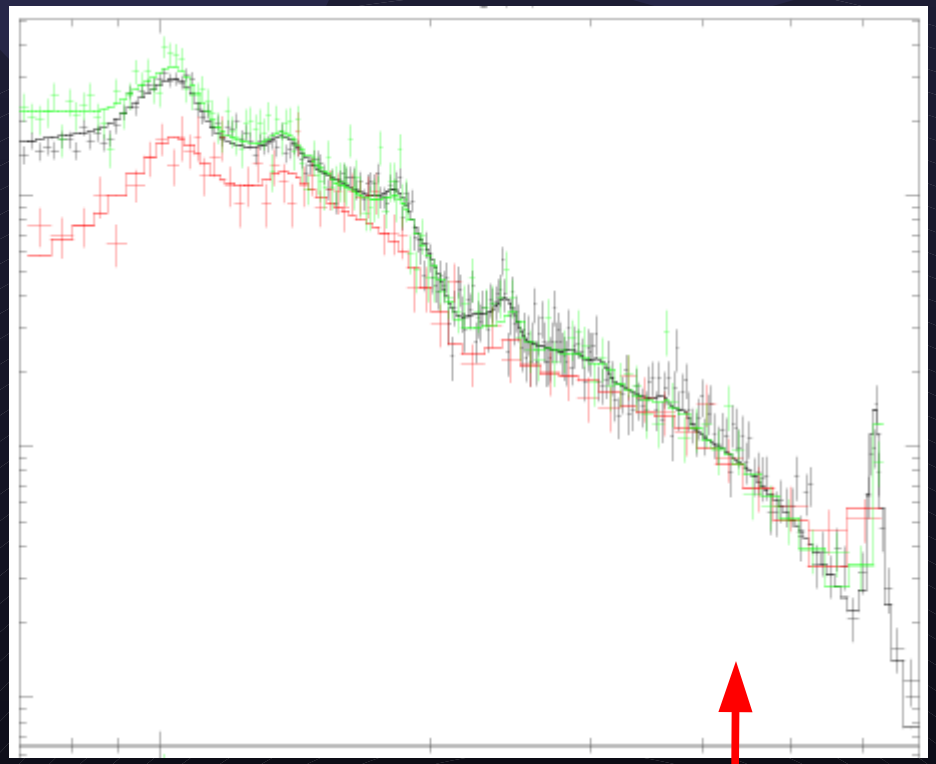
Galaxy Clusters Refresher

Dominant emission mechanism is thermal Bremsstrahlung





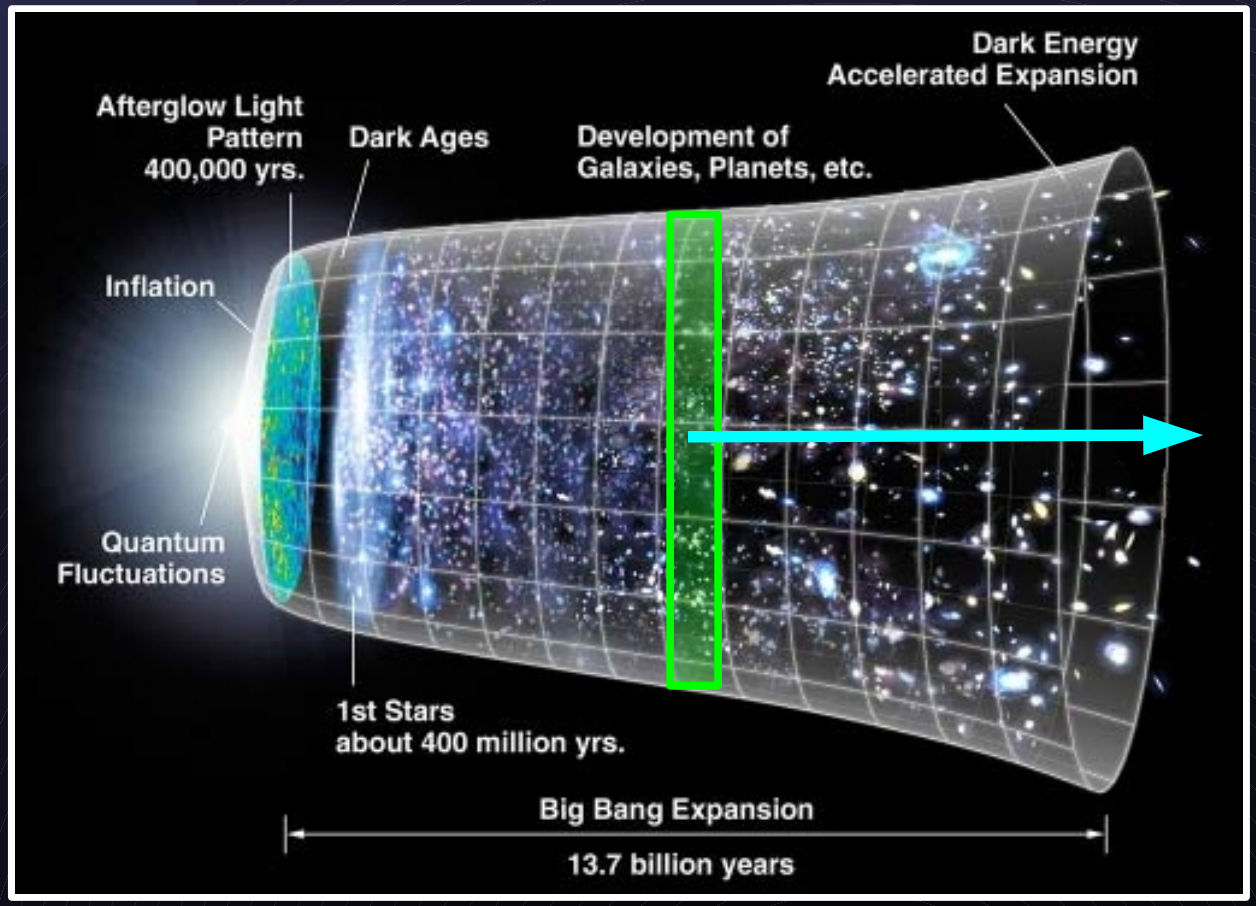




Chandra

Why study galaxy clusters?

- Cosmology
  - Structure growth
  - Need more precise masses
- Galaxy Formation
  - Explain Hubble Sequence
  - Must understand feedback



NASA / JDEM

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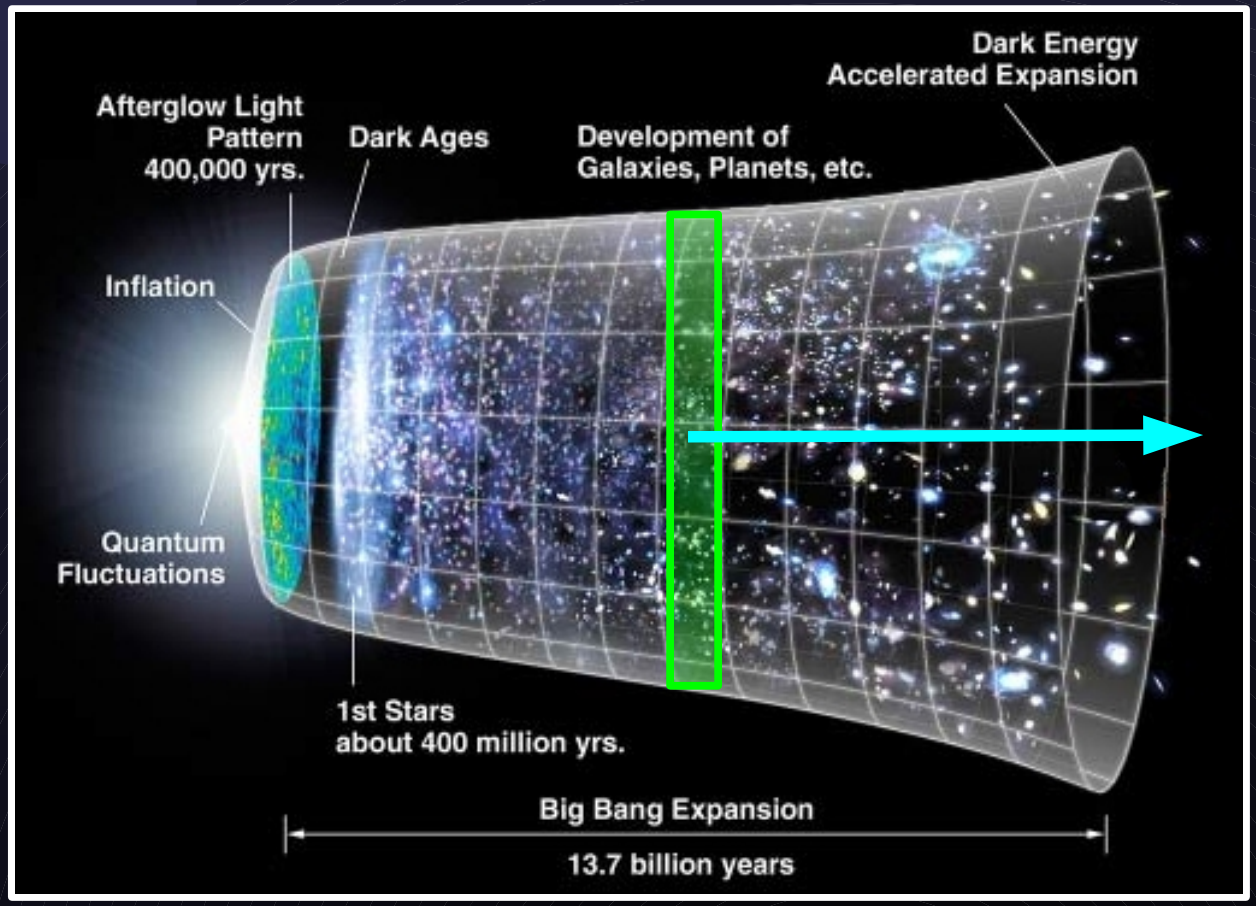
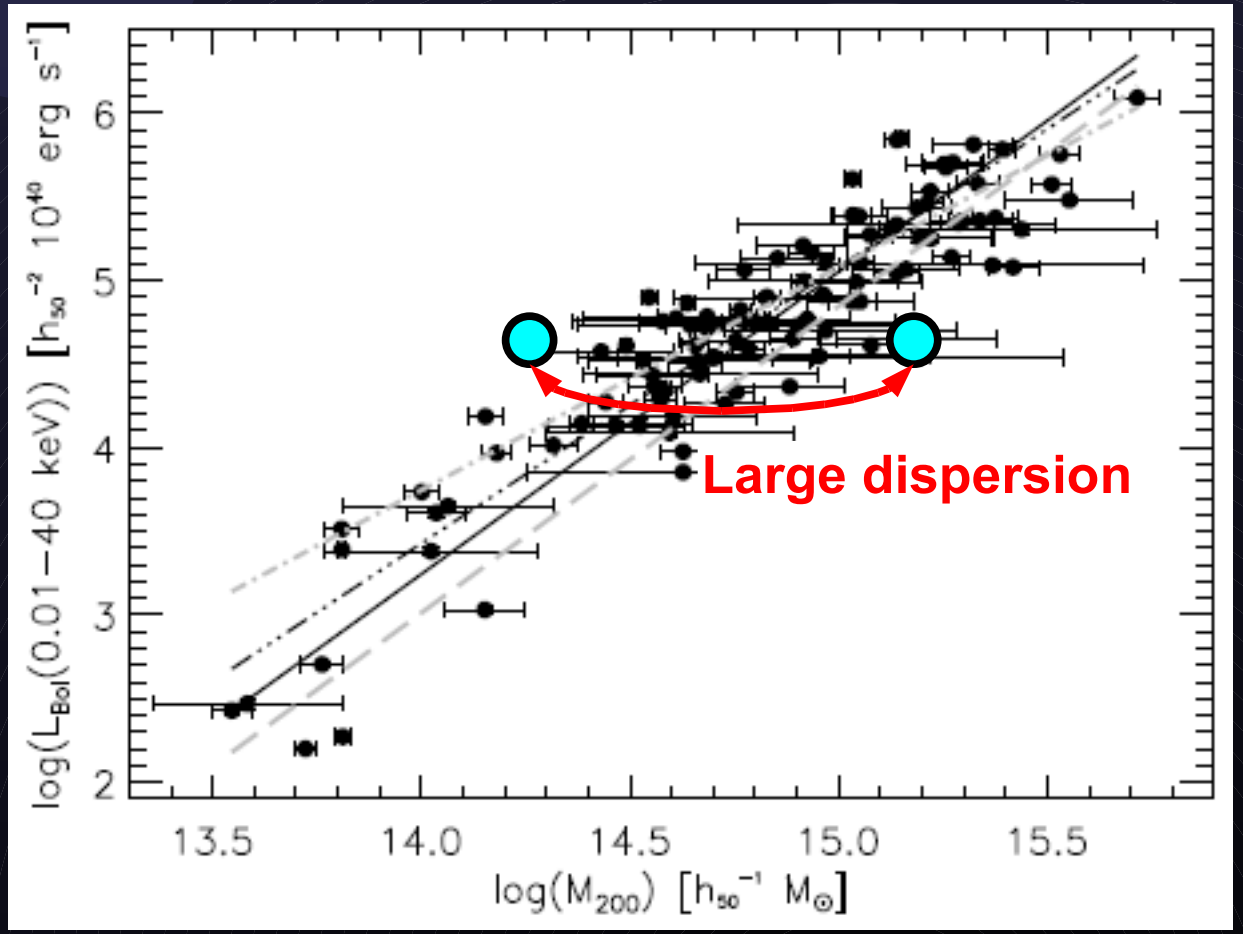


NASA / JDEM

Cosmological Importance of Relaxation

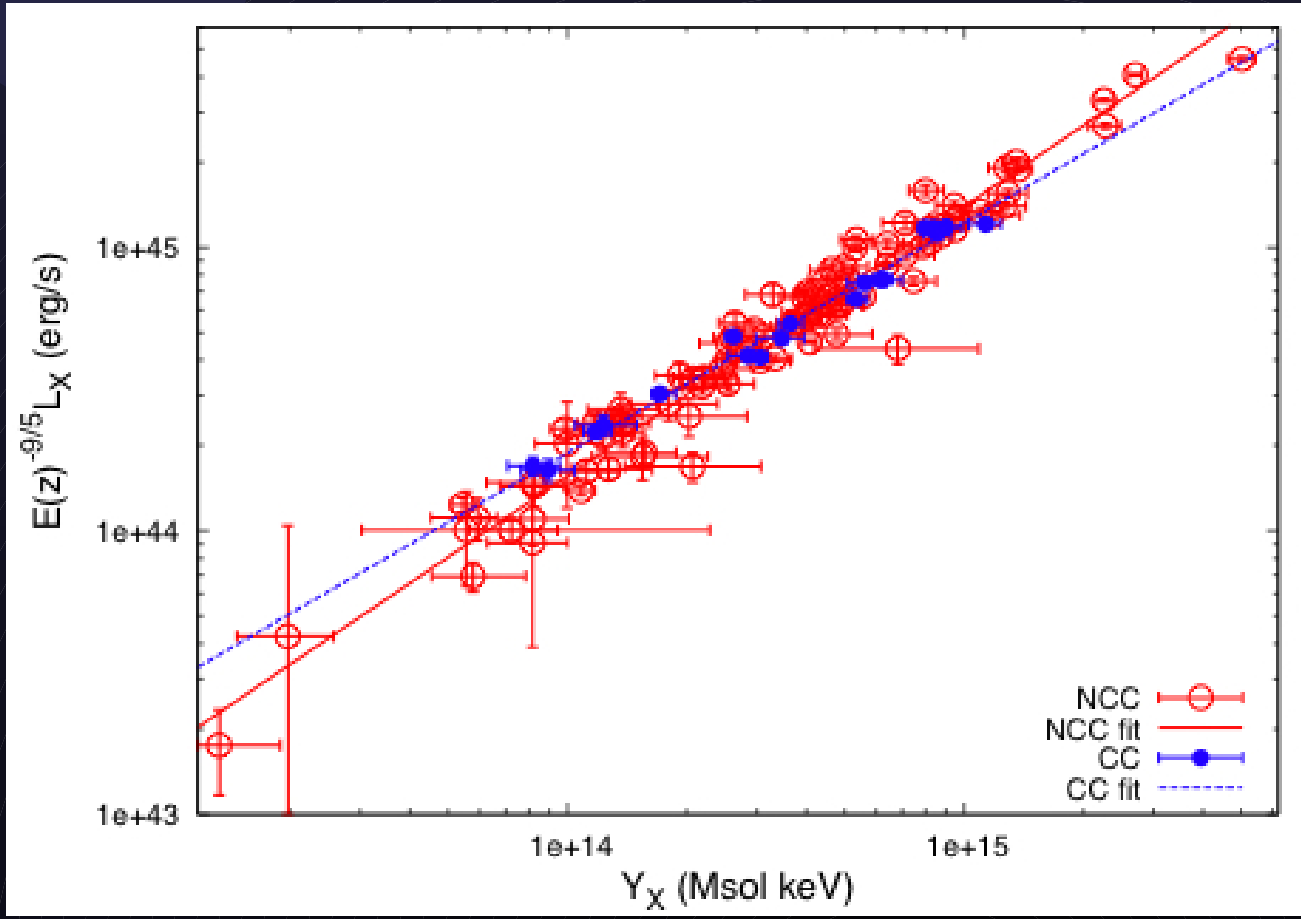
- Clusters expected to be self-similar
- Observables are mass surrogates, assuming equilibrium i.e. relaxation
- Heating and cooling alter scaling relations
- Precision cosmology requires knowledge of the scatter and how it evolves



Reiprich et al. 2001

Cosmological Importance of Relaxation

- Is this problem tractable?
- Quantify sub-structure through imaging analysis
- What about an aspect independent measure?
- Temperature skewing predicted by Mathiesen & Evrard 2001



Maughan 2007

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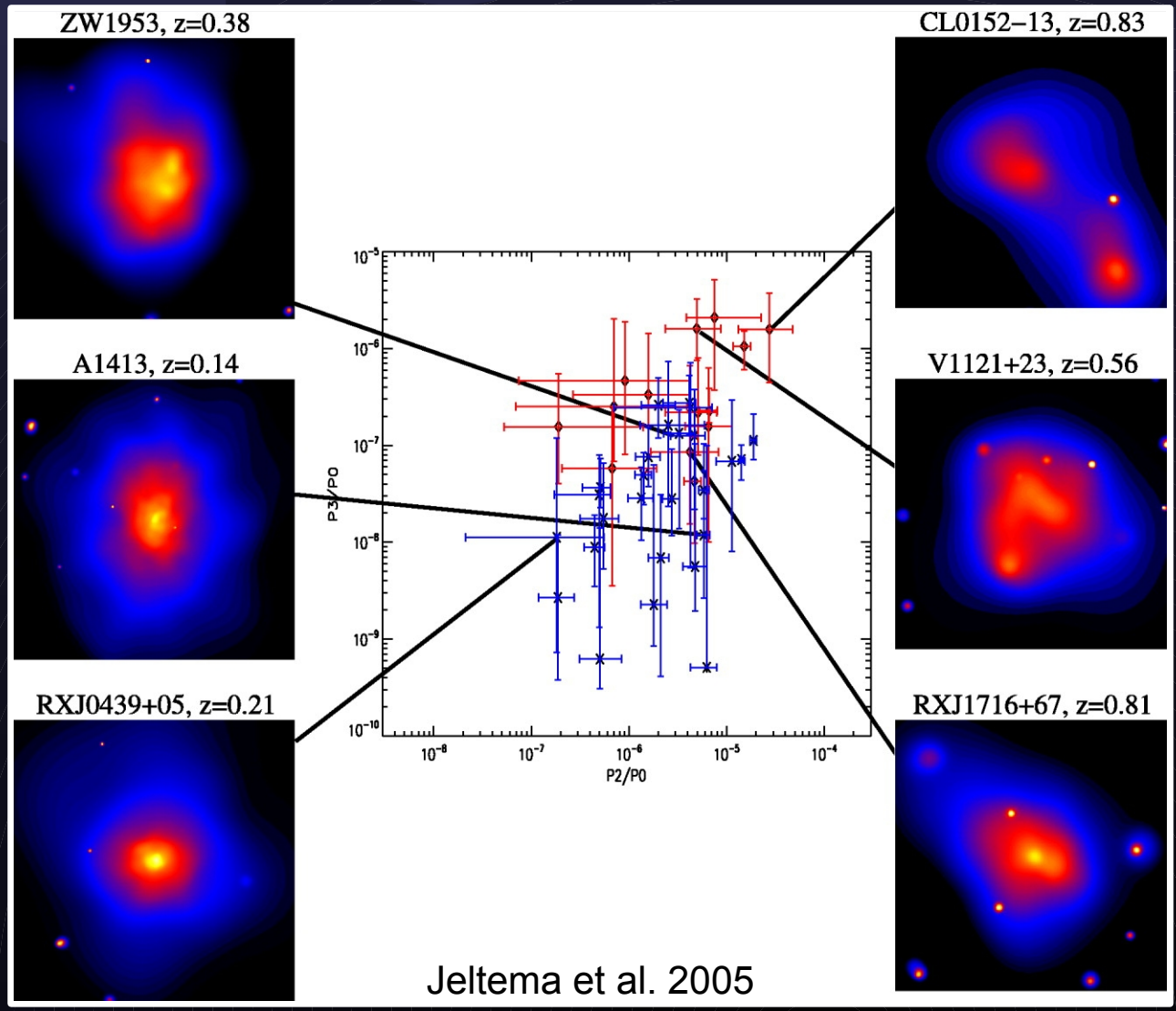

Jeltema et al. 2005

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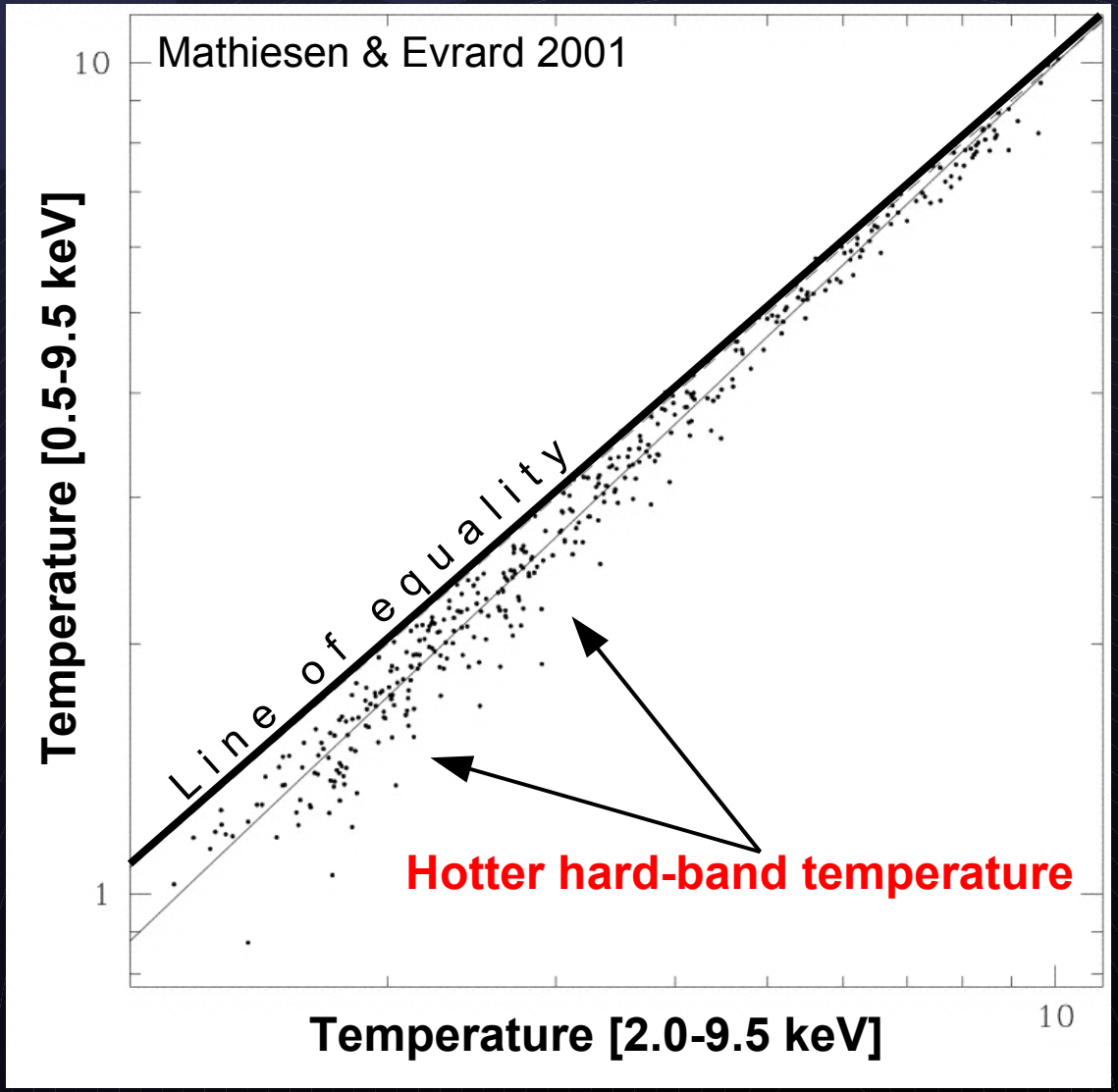
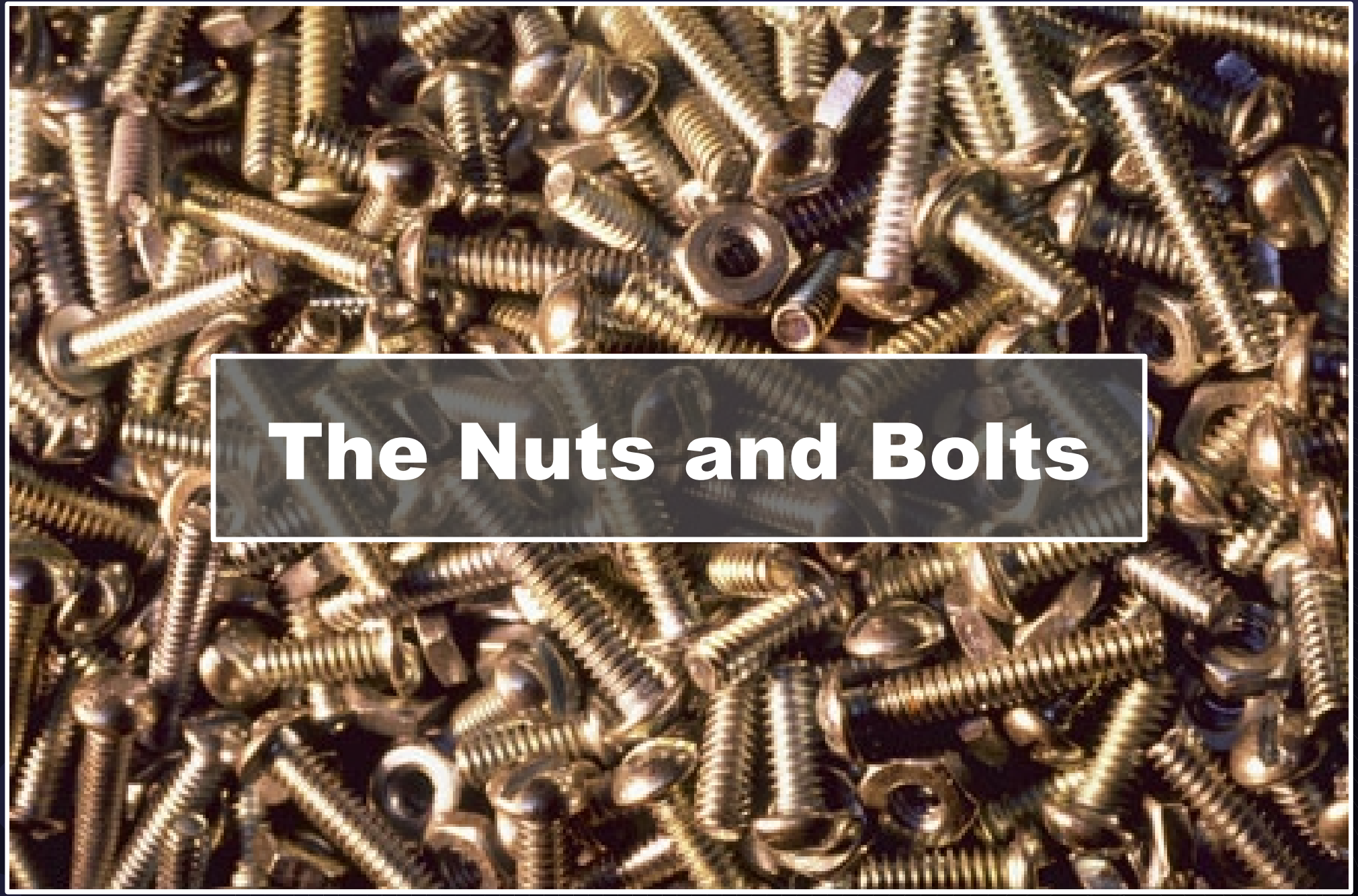


Temperature Inhomogeneity

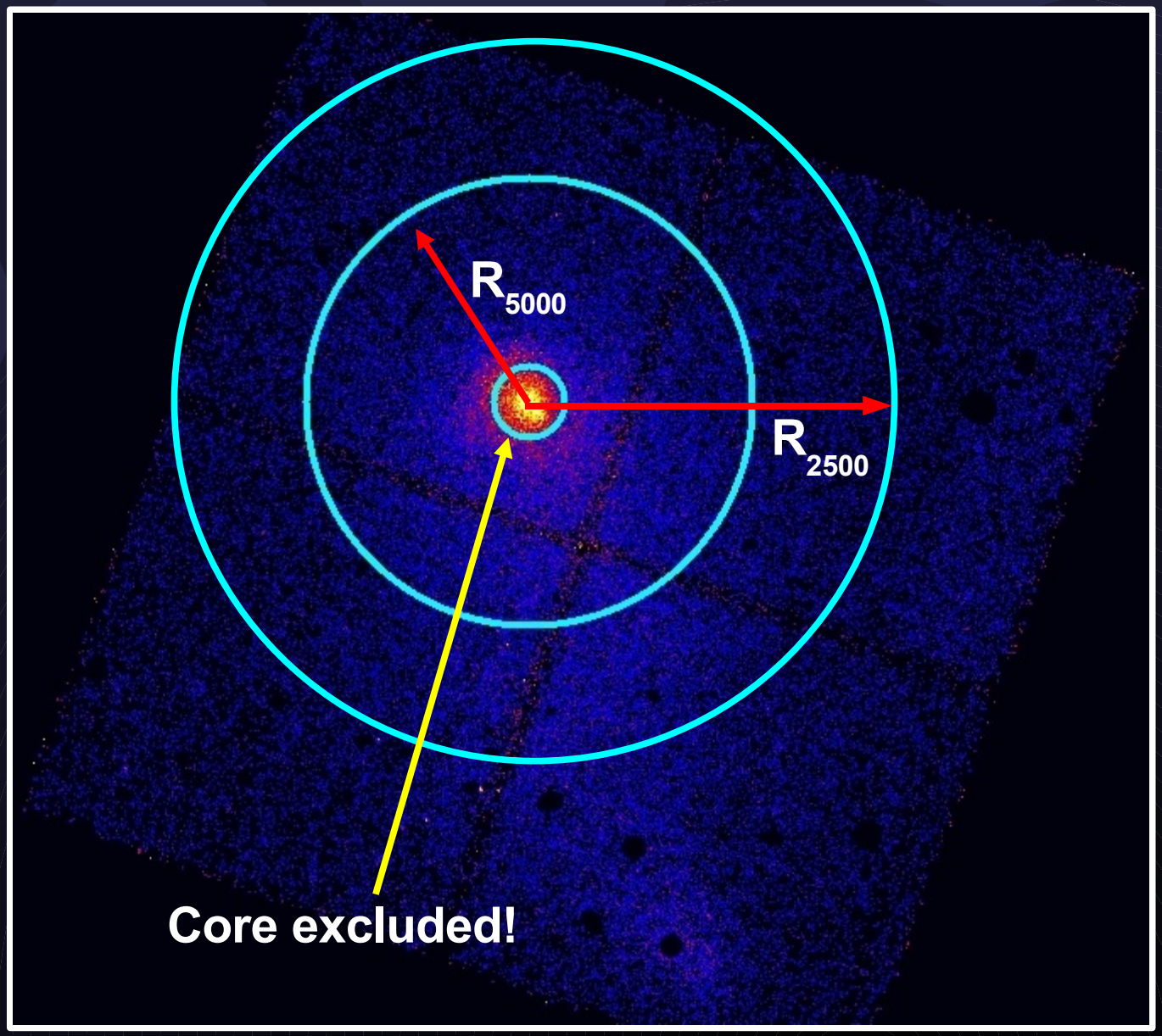
- How shall we quantify temperature skewing?
- Broad-band temperature: 0.7-7.0 keV band
- Hard-band temperature: 2.0-7.0 keV band
- 2.0 keV is in cluster rest frame
- Define Hard-band to Broad-band Ratio:

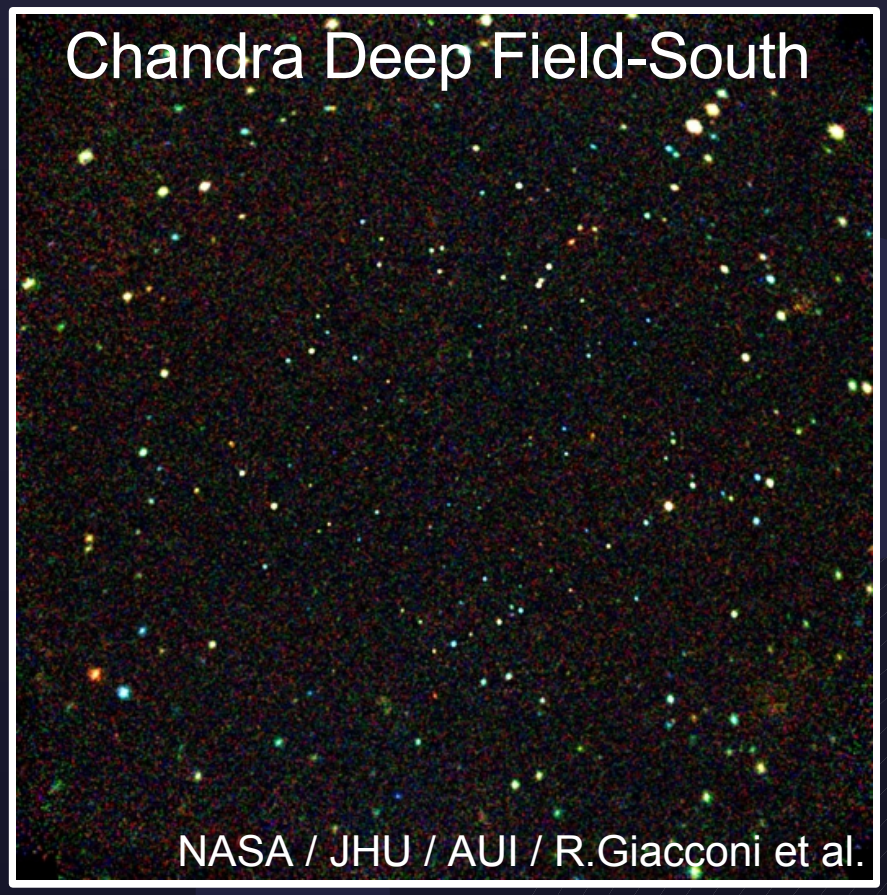
$$T_{HBR} = \frac{T_{2.0-7.0}}{T_{0.7-7.0}}$$


The Nuts and Bolts

"T_{HBR}" Data Analysis

- Collected clusters from Chandra Archive
- +11 Msec, 300+ obs
- Two apertures selected:
  - R_{5000}
  - R_{2500}
- Cores excised

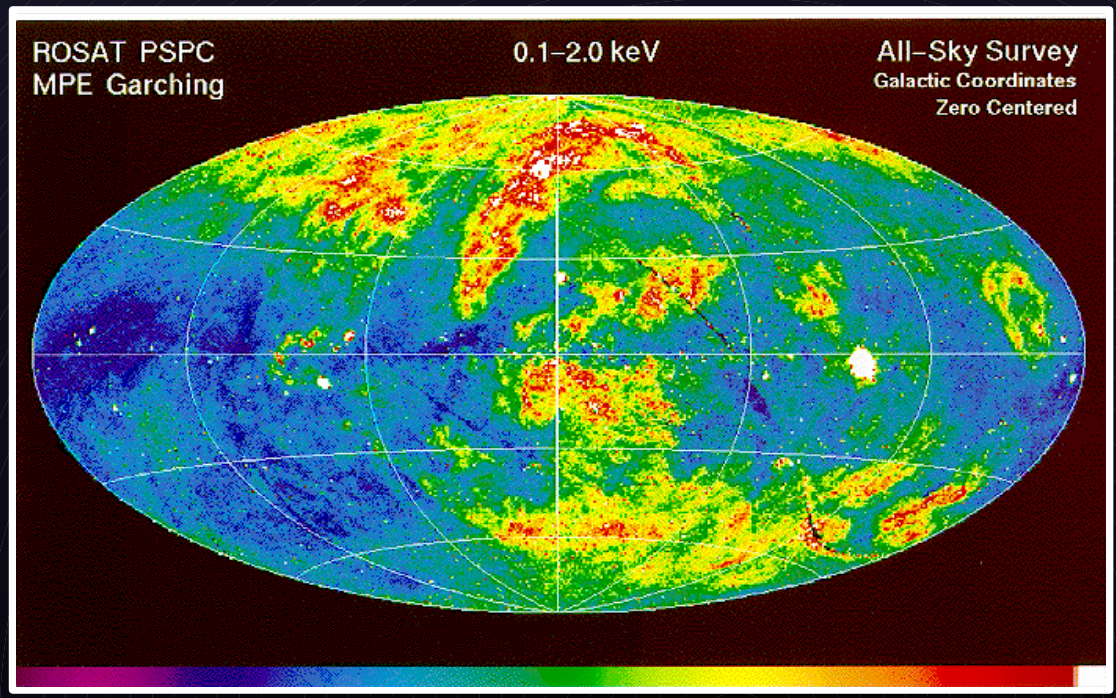




X-ray Background Consideration

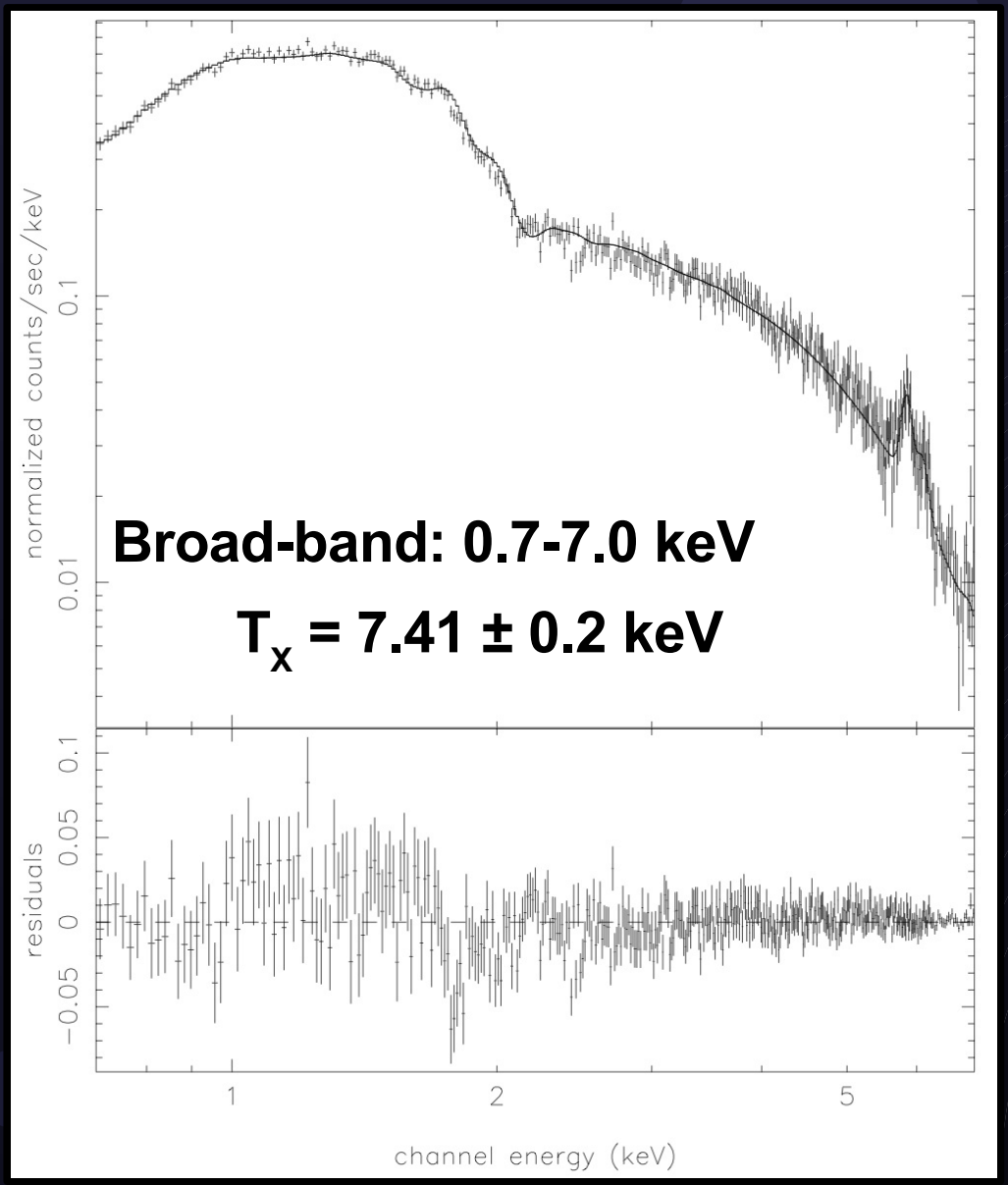
- Hard-particle background
- Important at E > 2 keV
- Correct spectral count rate

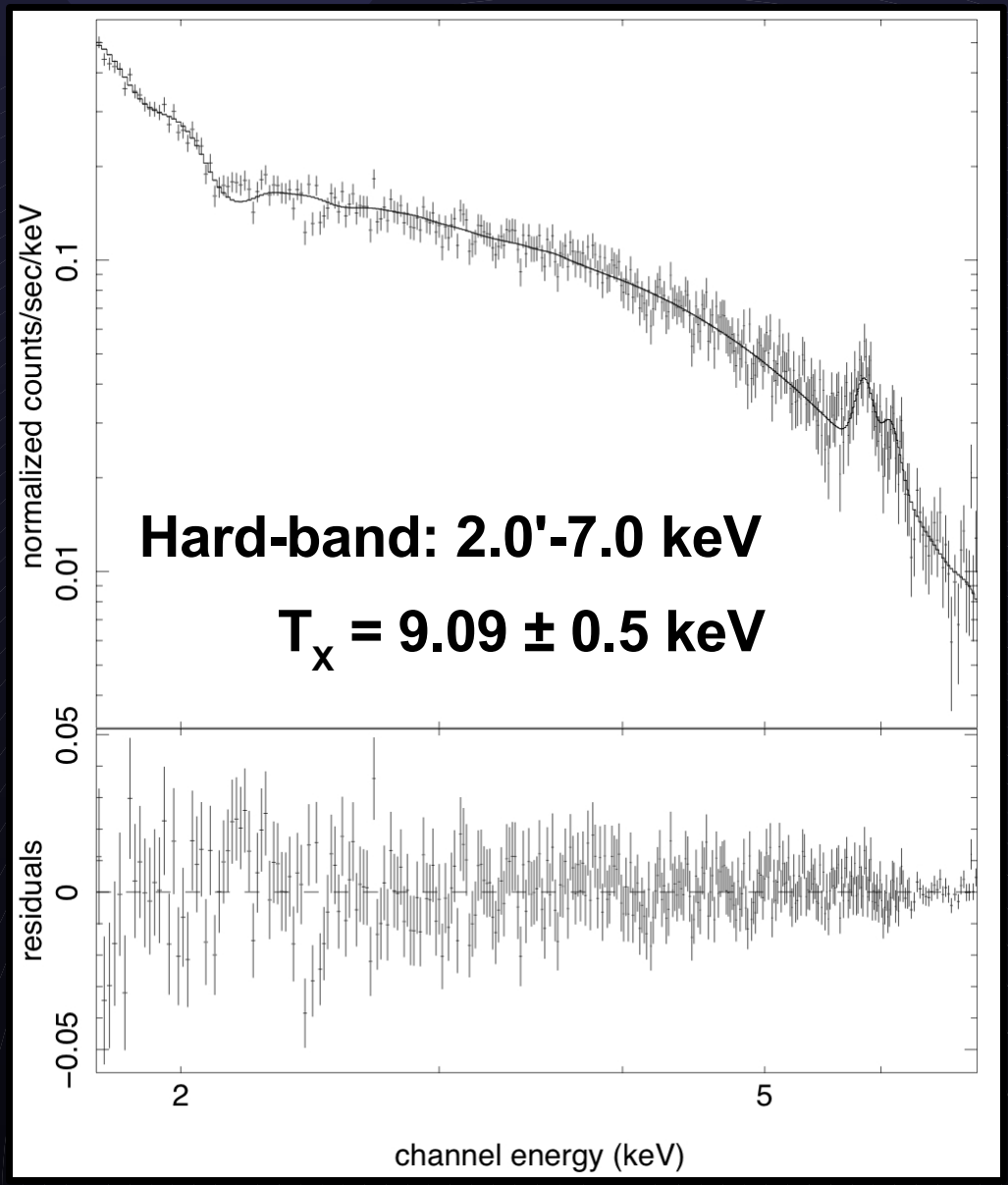
- Soft, local background
- Spatially varying
- Is problematic at E < 2 keV



Inferring the gas temperature

- Single-phase thermal plasma
- Fixed absorbing N_{HI}
- Metal abundance is free
- Soft background fixed and error added





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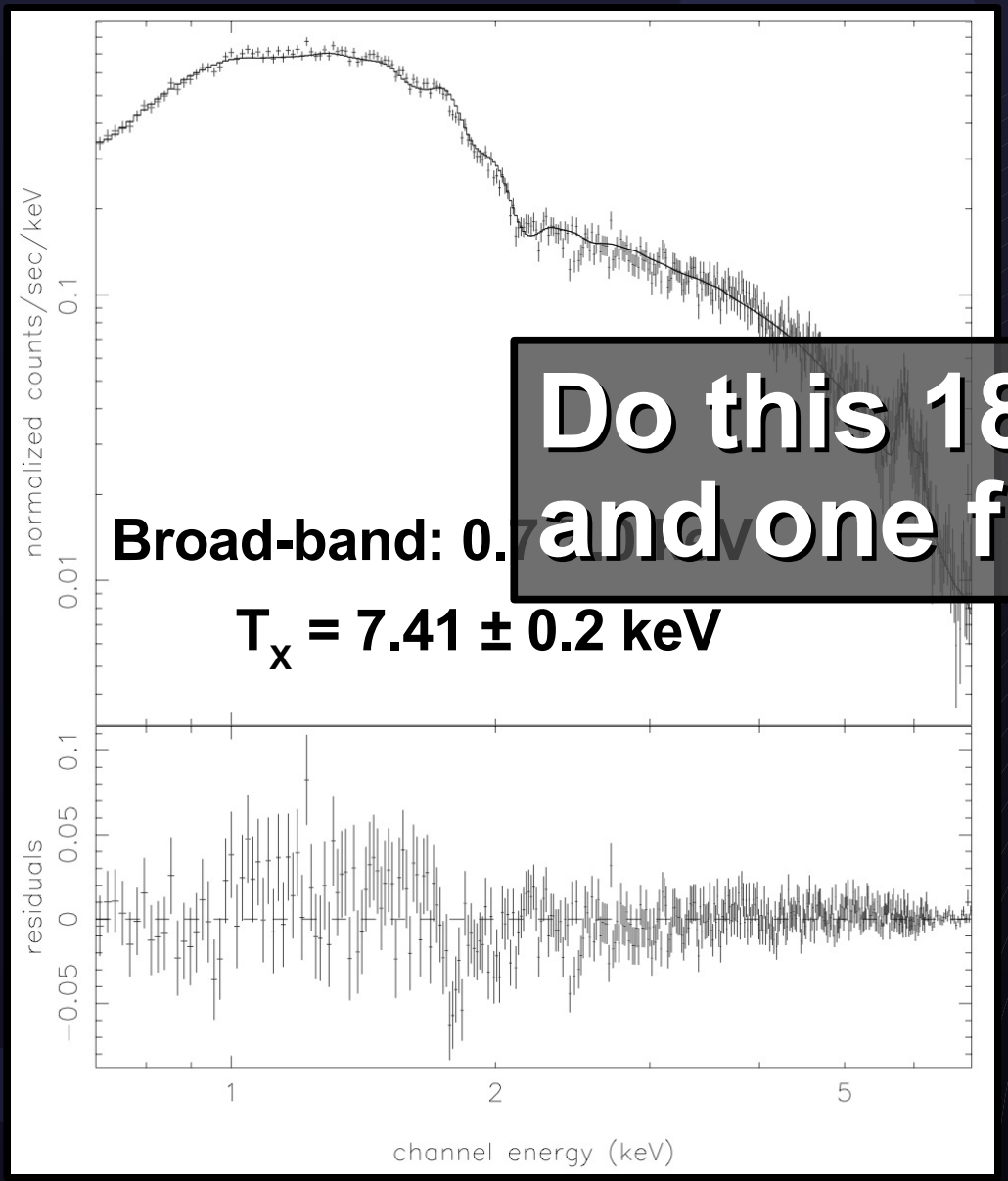
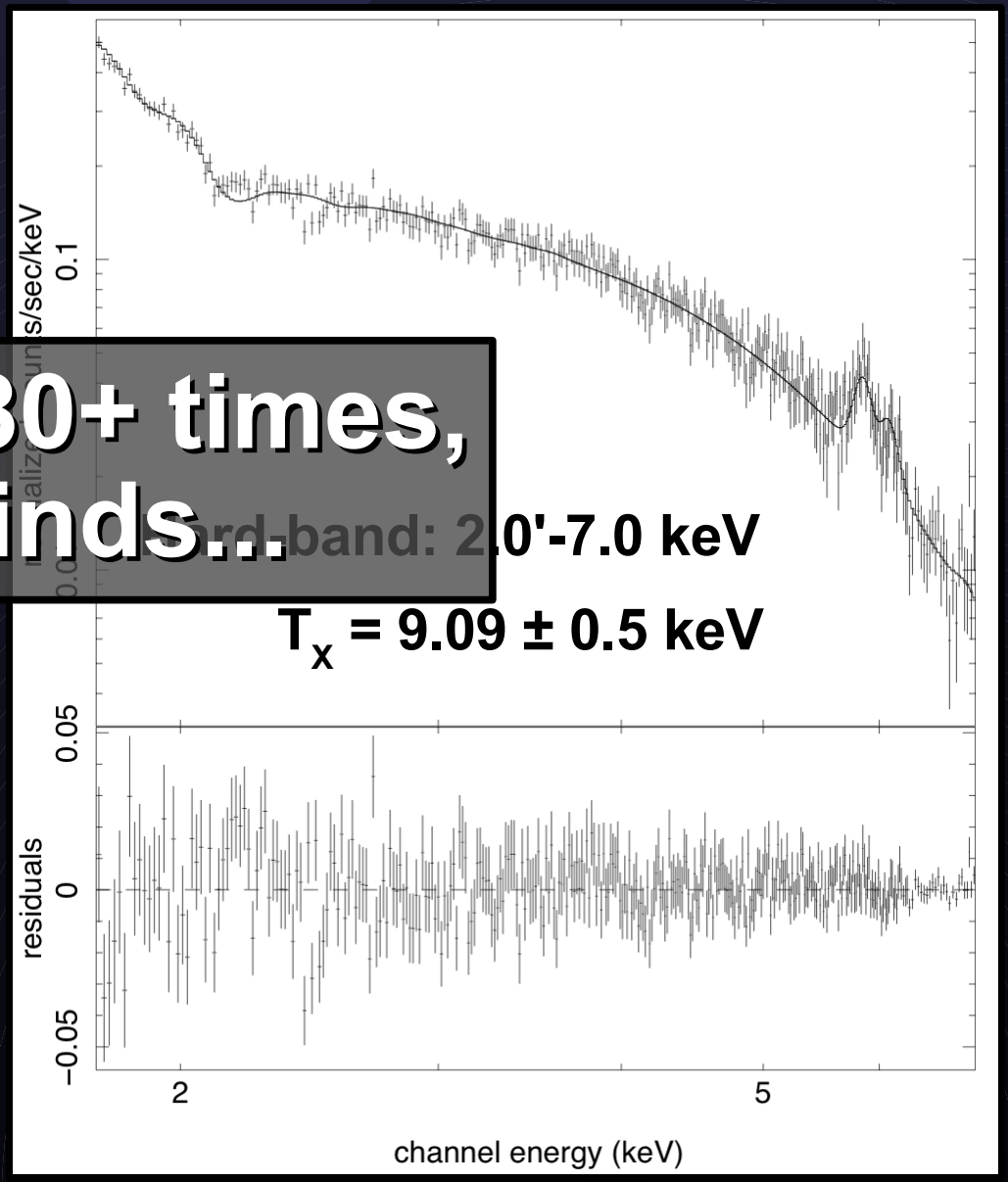


Broad-band: 0.7-7.0 keV

$T_x = 7.41 \pm 0.2$ keV

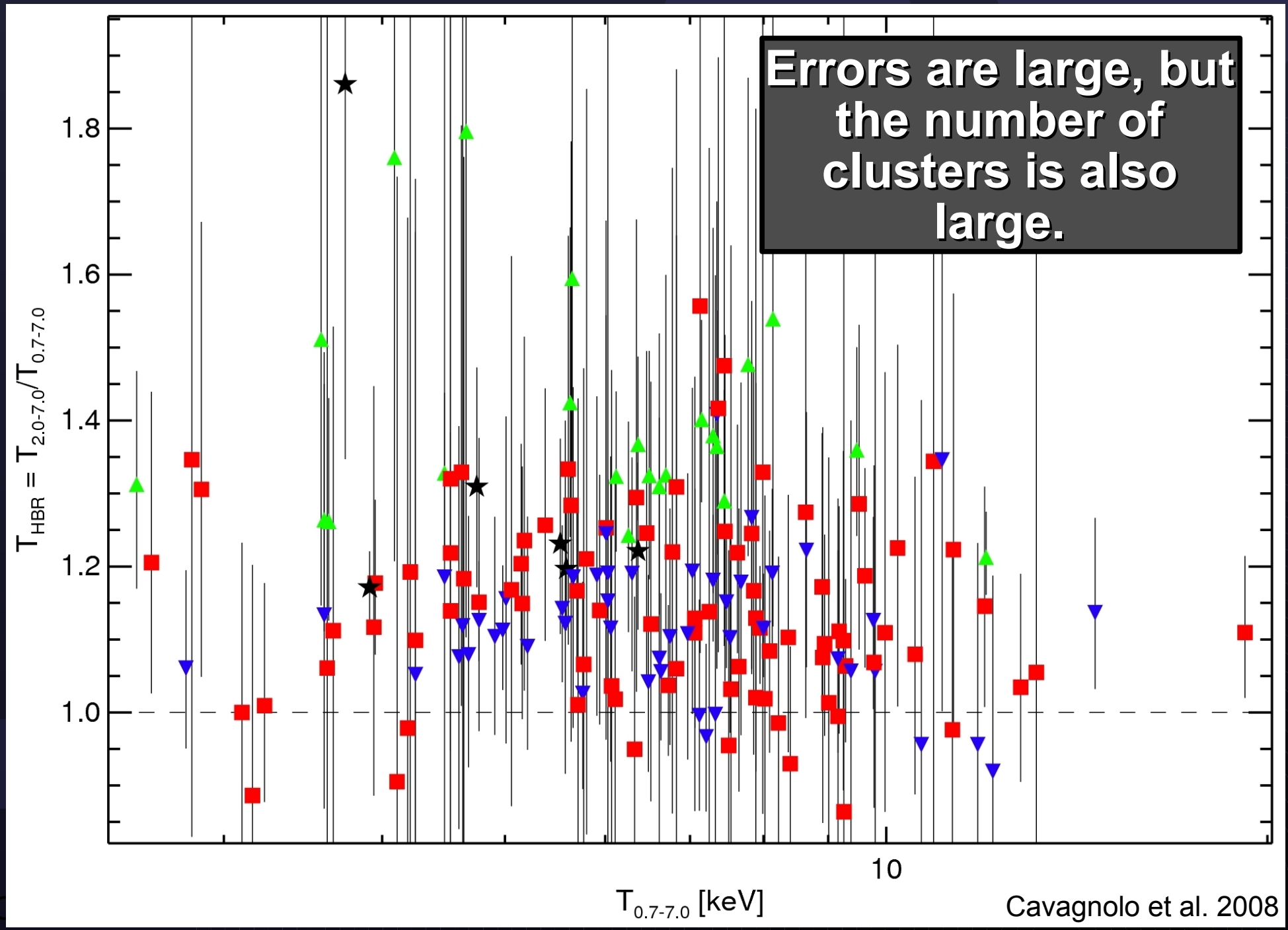


Broad-band: 2.0'-7.0 keV

$T_x = 9.09 \pm 0.5$ keV

Do this 180+ times, and one finds...

Net Skewing of T_{HBR}



Cavagnolo et al. 2008

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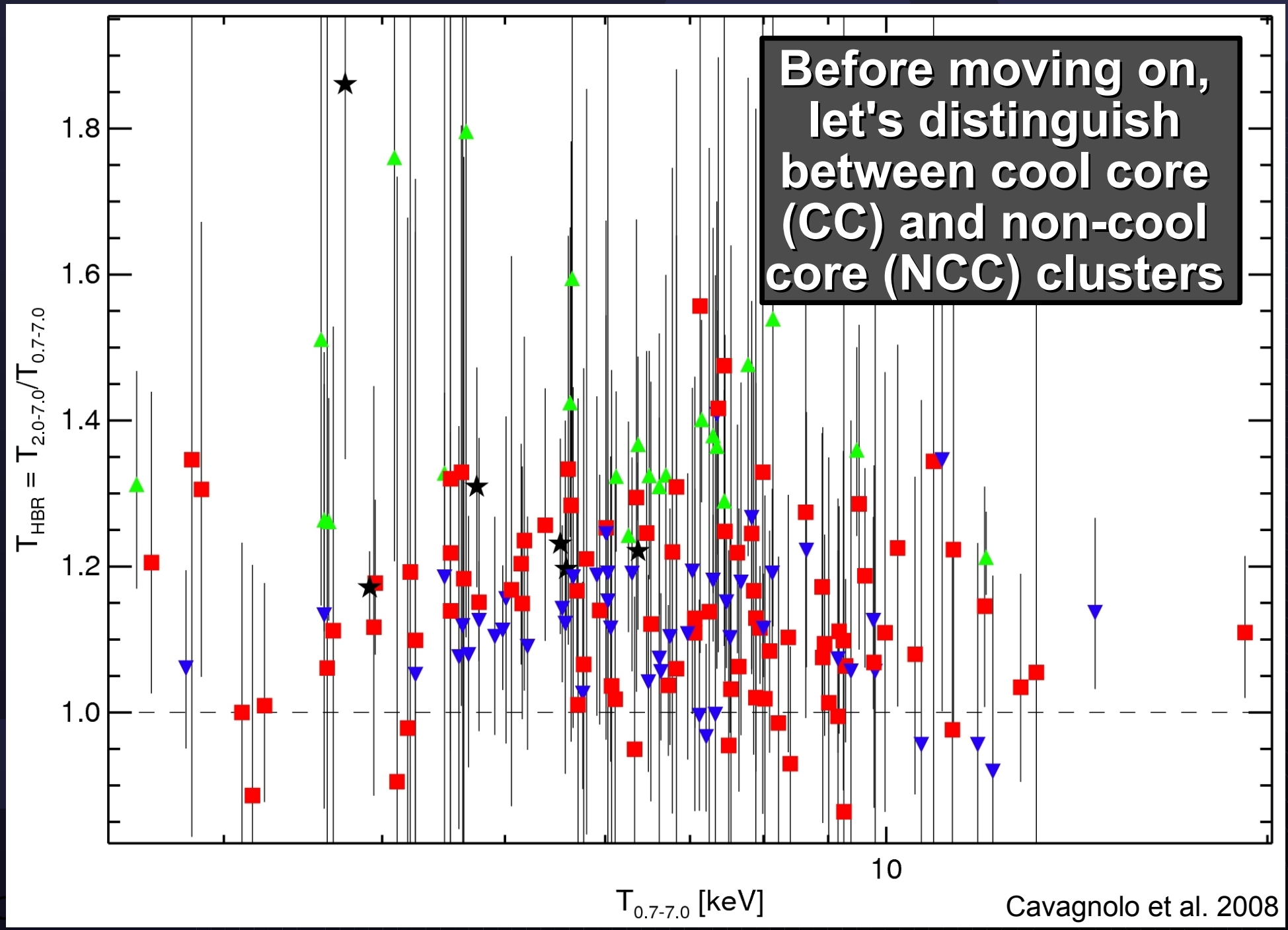

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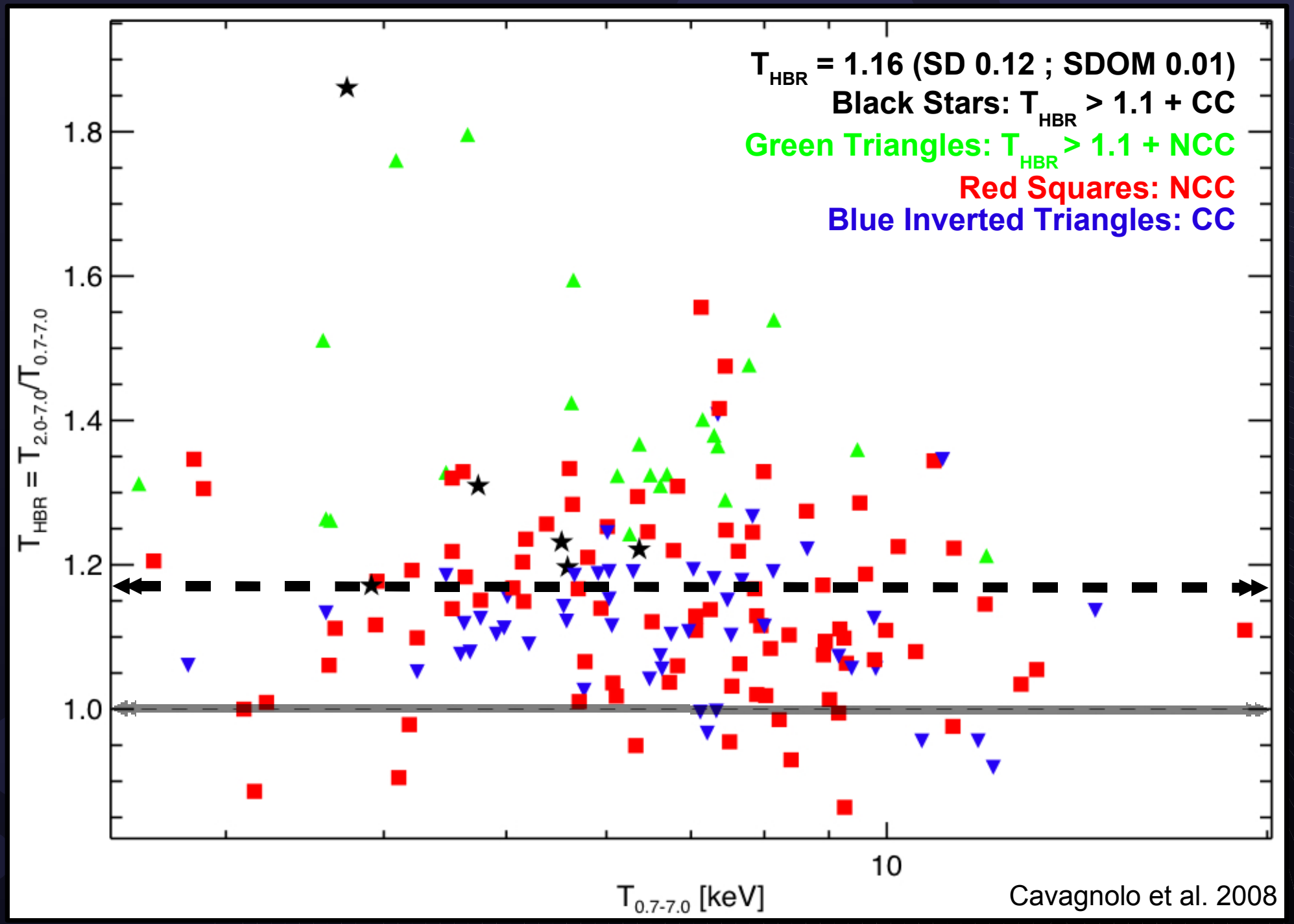
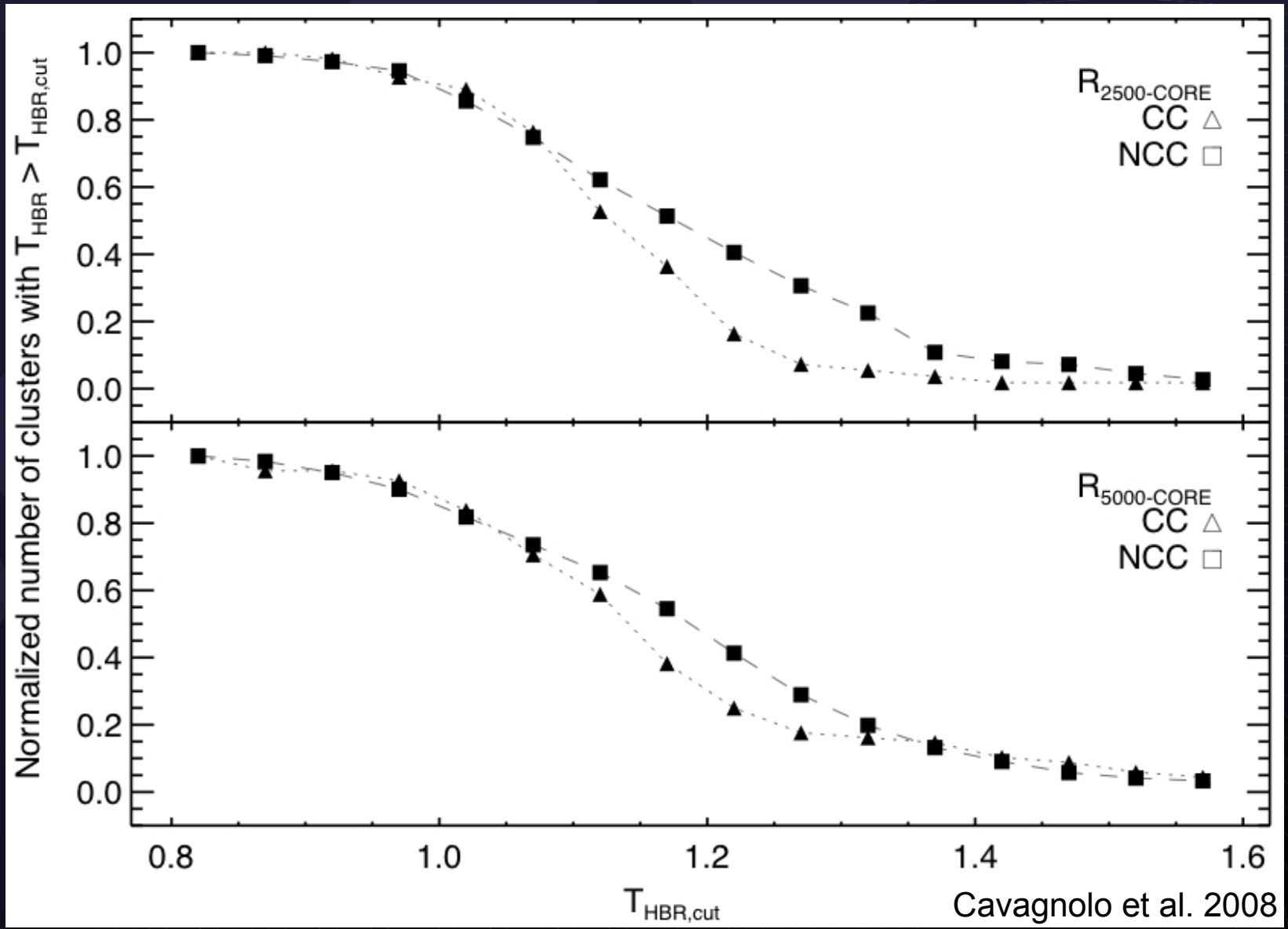


Cavagnolo et al. 2008

Culling out Cool Cores using T_{HBR}

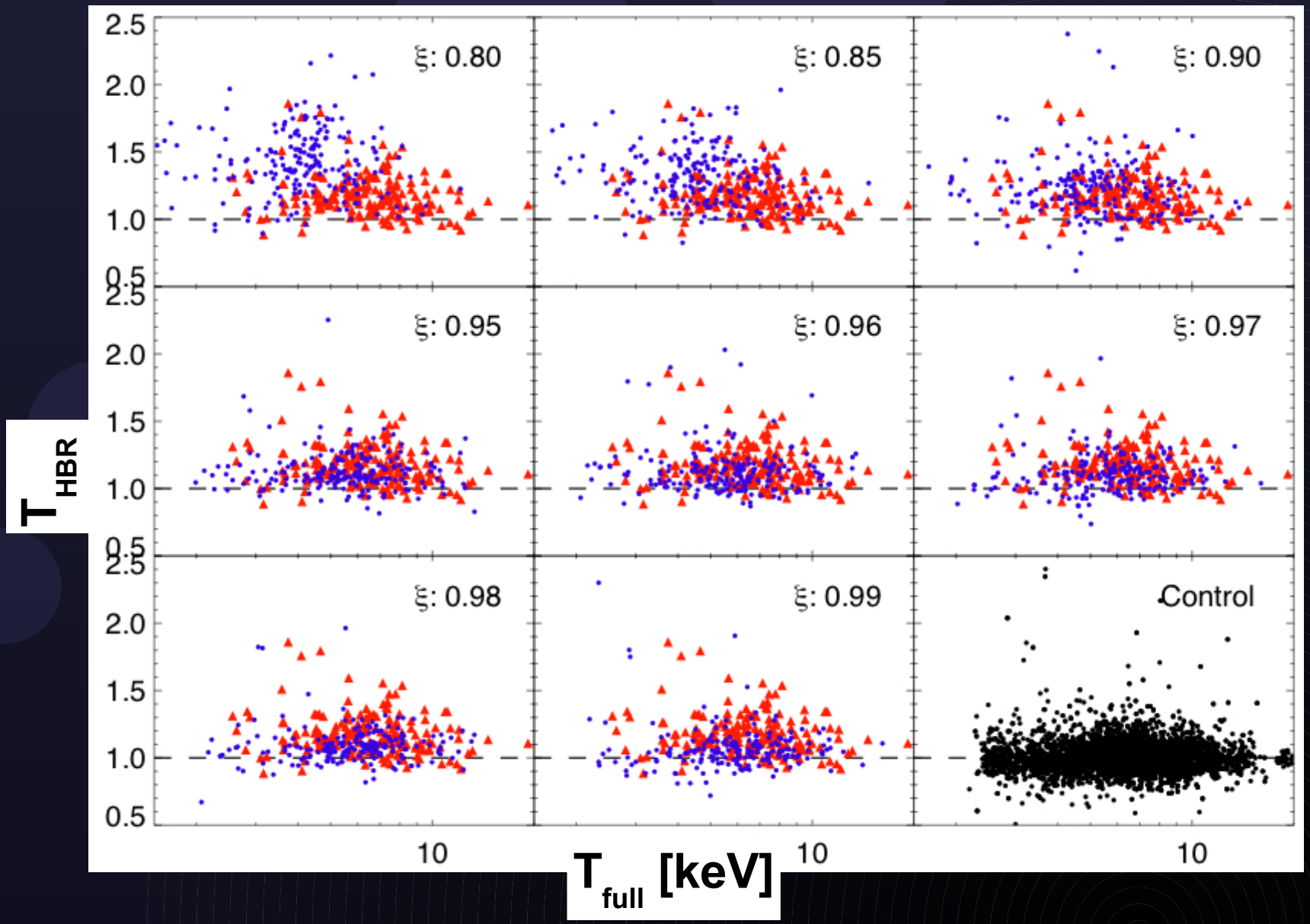
- Increasing values of T_{HBR} "prefer" non-cool cores
- Robust against choice of cool core definition



Cavagnolo et al. 2008

Simulations and Systematics

- Simulate two-phase gas
- Repeat spectral analysis
- Observe skewing in sims but not in control
- Dispersion in observation > control



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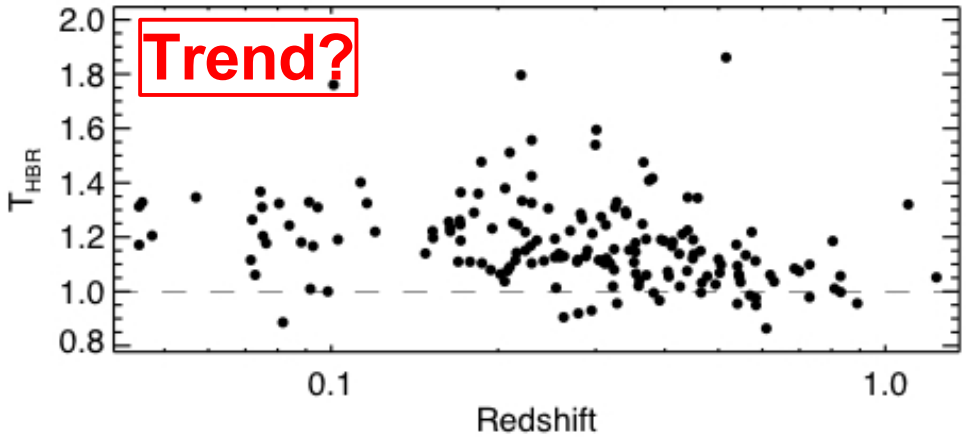
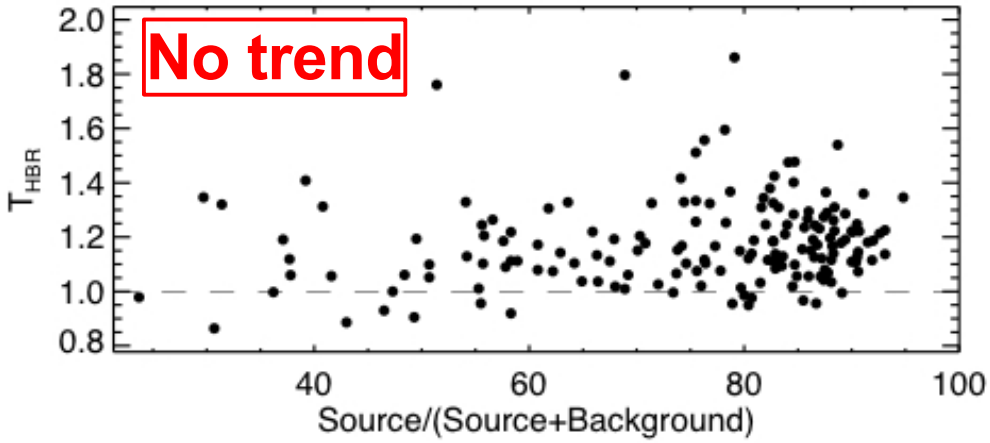
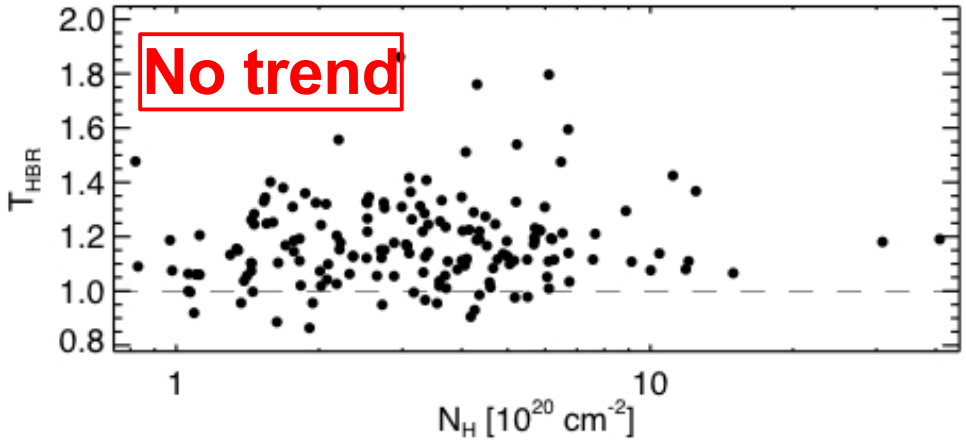
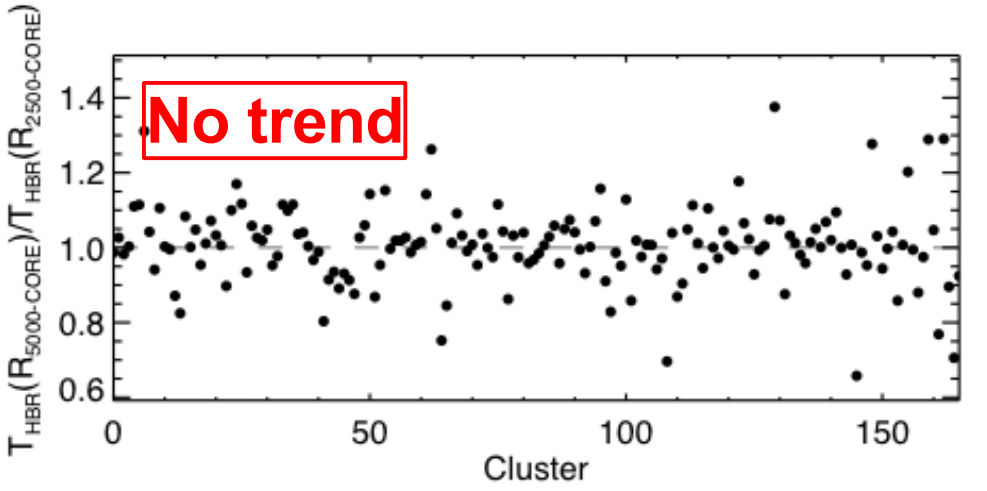
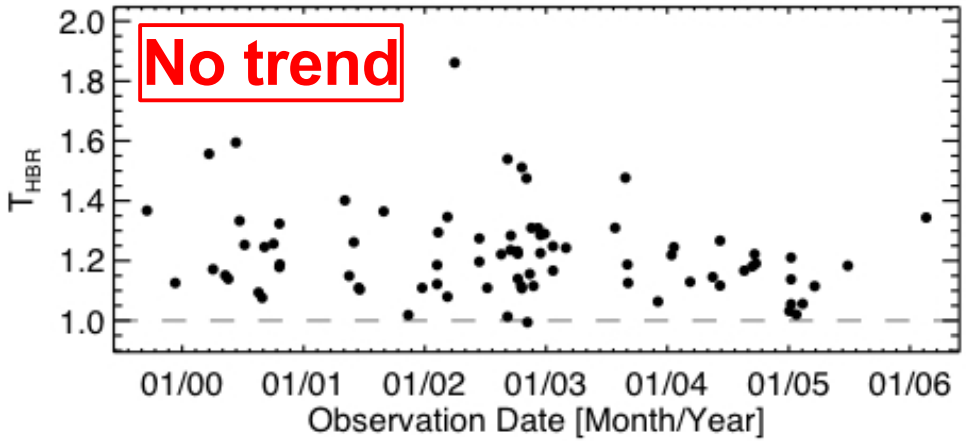
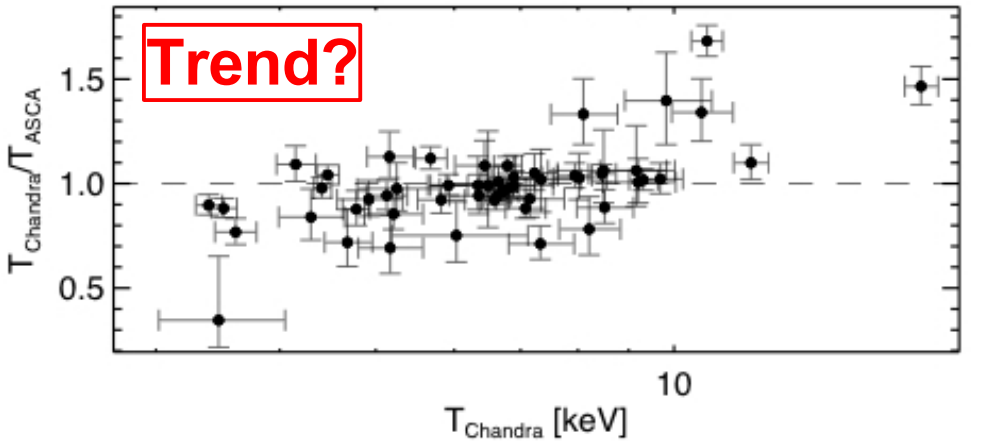




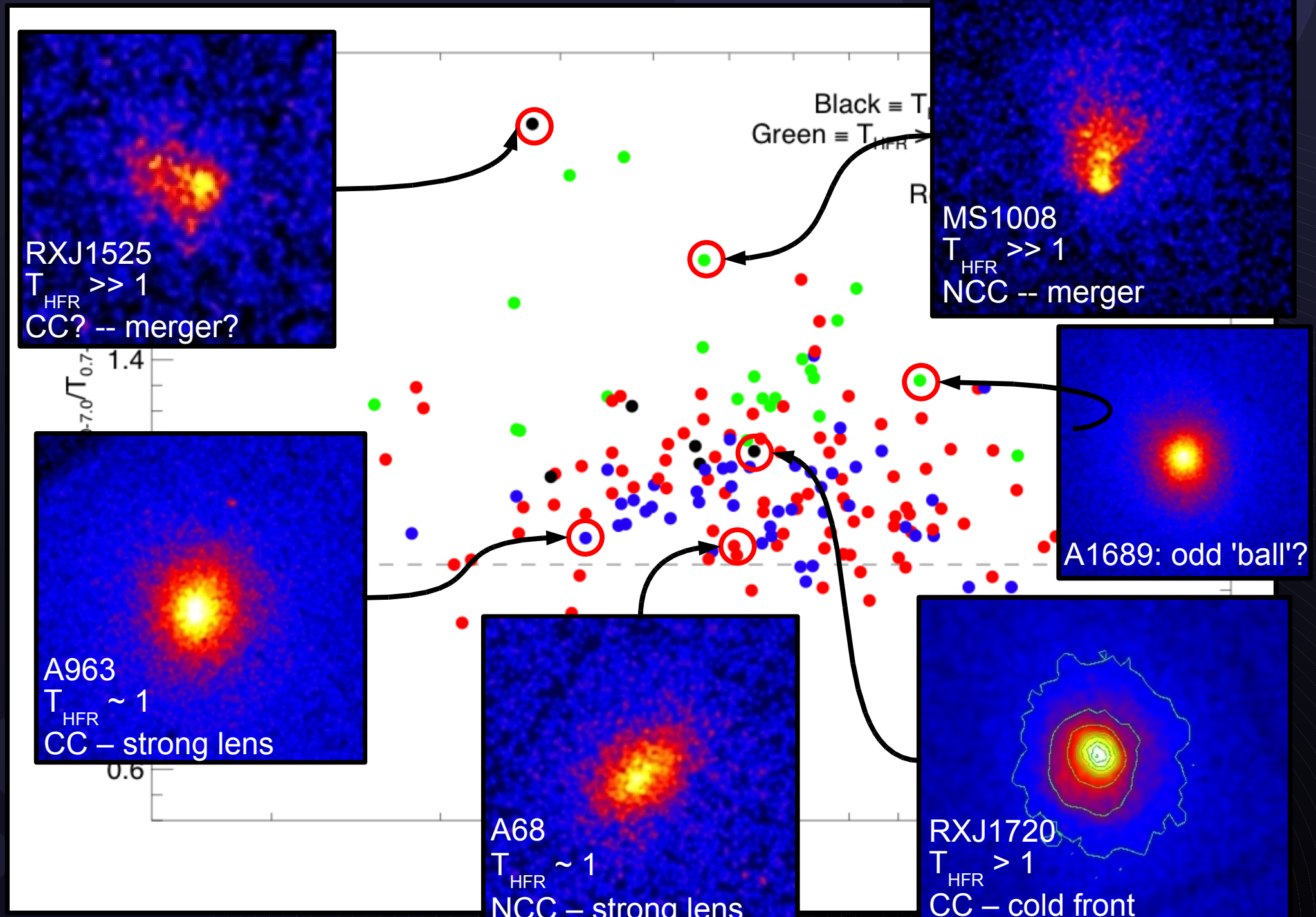




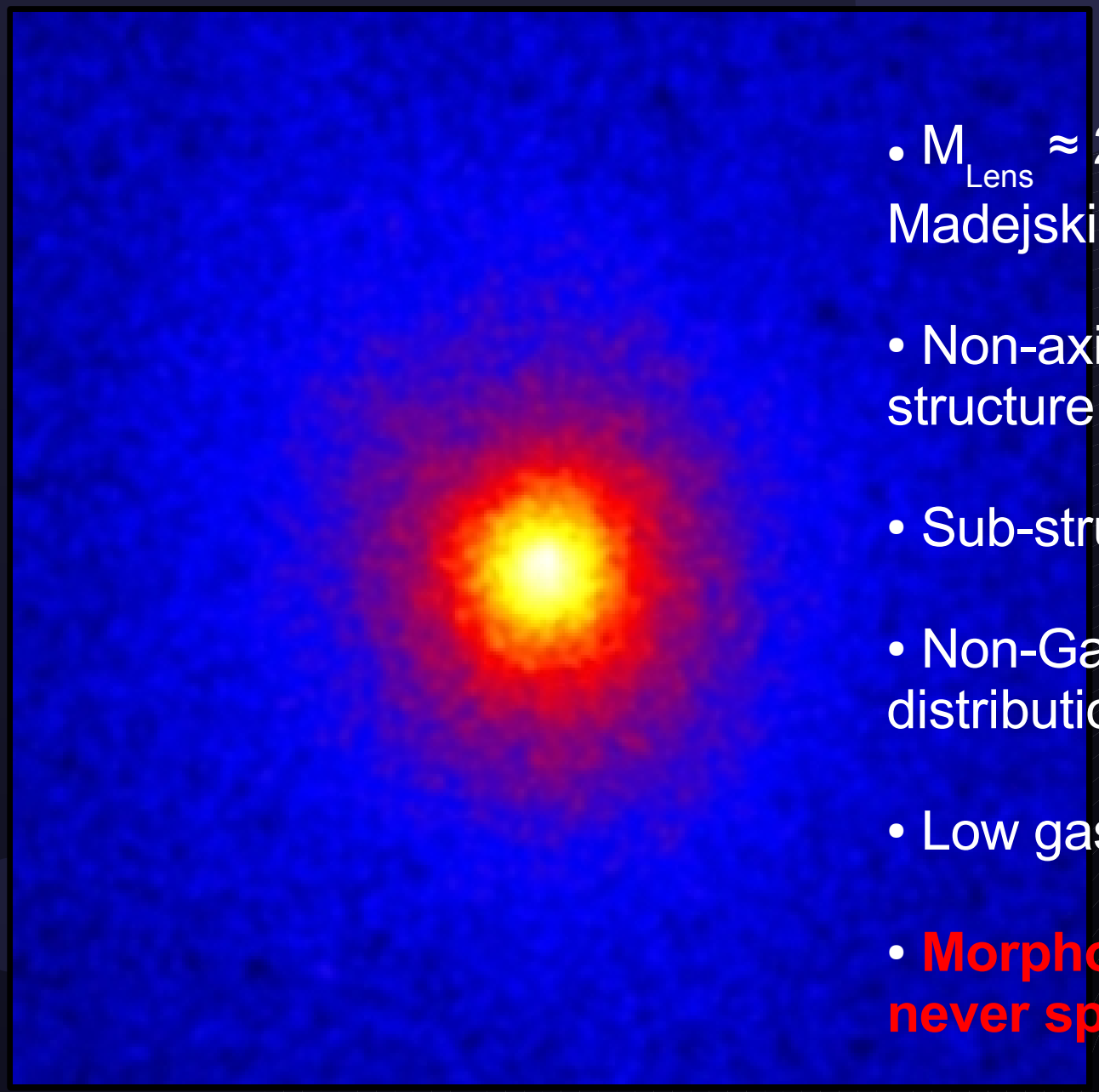




Putting It All Together



Abell 1689: not so relaxed



- $M_{Lens} \approx 2 \times M_{X\text{-}ray}$ (Andersson & Madejski 2004)
- Non-axisymmetric temperature structure (Andersson et al. 2006)
- Sub-structure in optical
- Non-Gaussian galaxy redshift distribution
- Low gas fraction: ~7% (XMM)
- **Morphological tests would never spot this as "unrelaxed"**

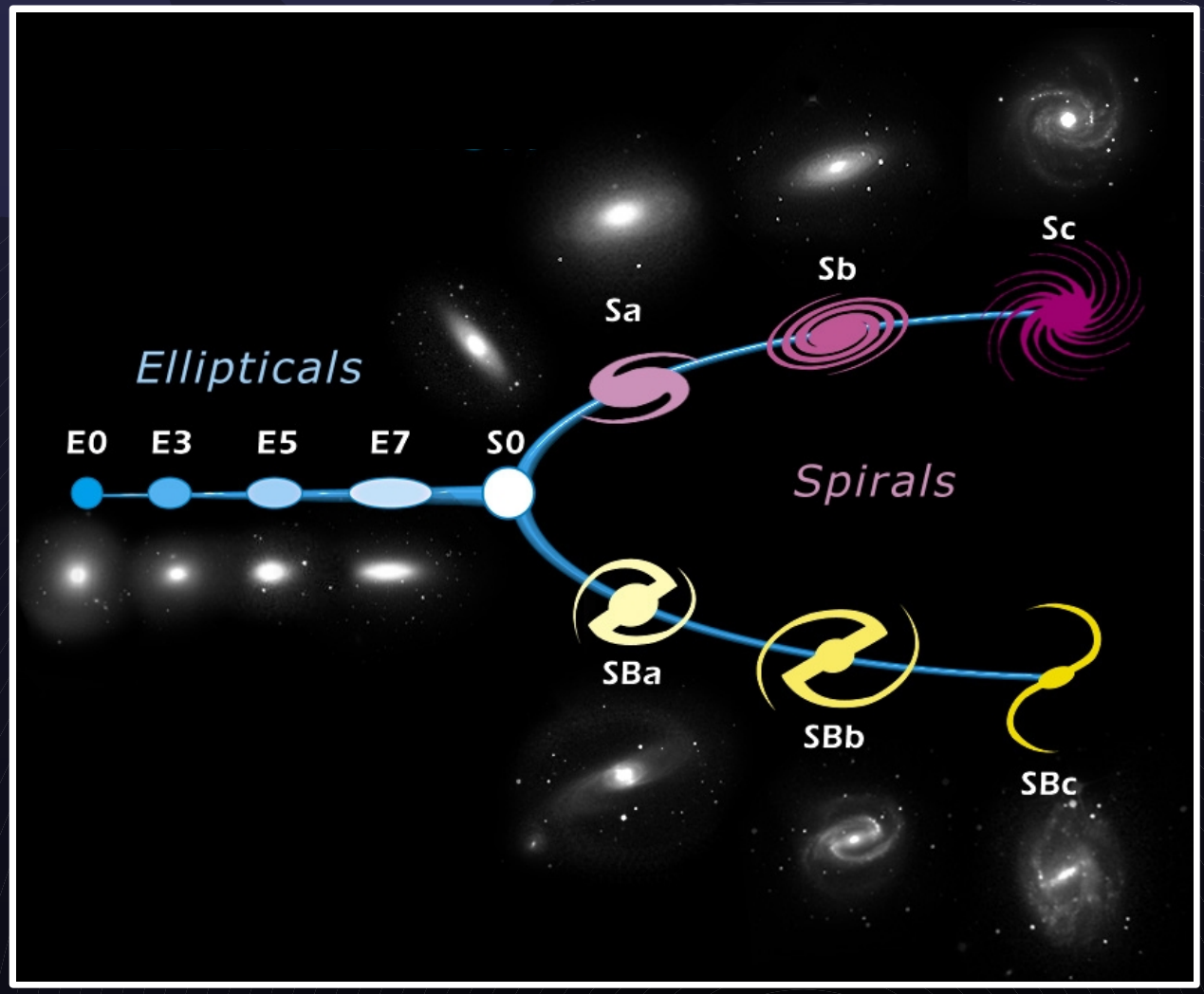
Cosmological Importance of Relaxation

- Temperature inhomogeneity is a problem
- Appears to be something we can quantify
- Calibrate between temperature ratio and relaxation using N-body/SPH simulations
- Could be very useful tool for quantifying scatter in mass-observables

Now, what of the feedback issue...?

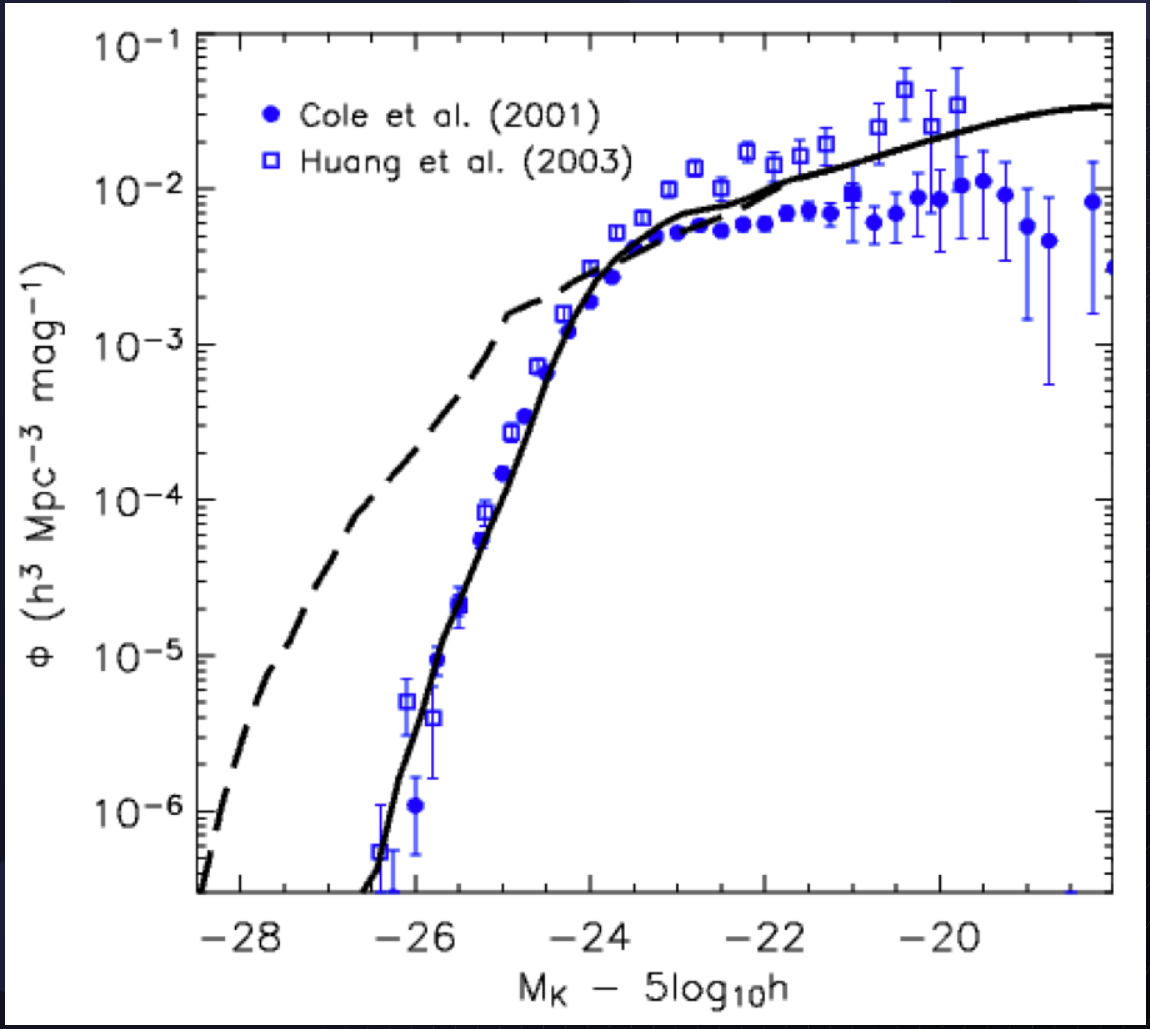
Why study galaxy clusters?

- Cosmology
  - Structure growth
  - Need accurate masses
- Galaxy Formation
  - Explain Hubble Sequence
  - Must understand feedback



NASA

Importance of Feedback

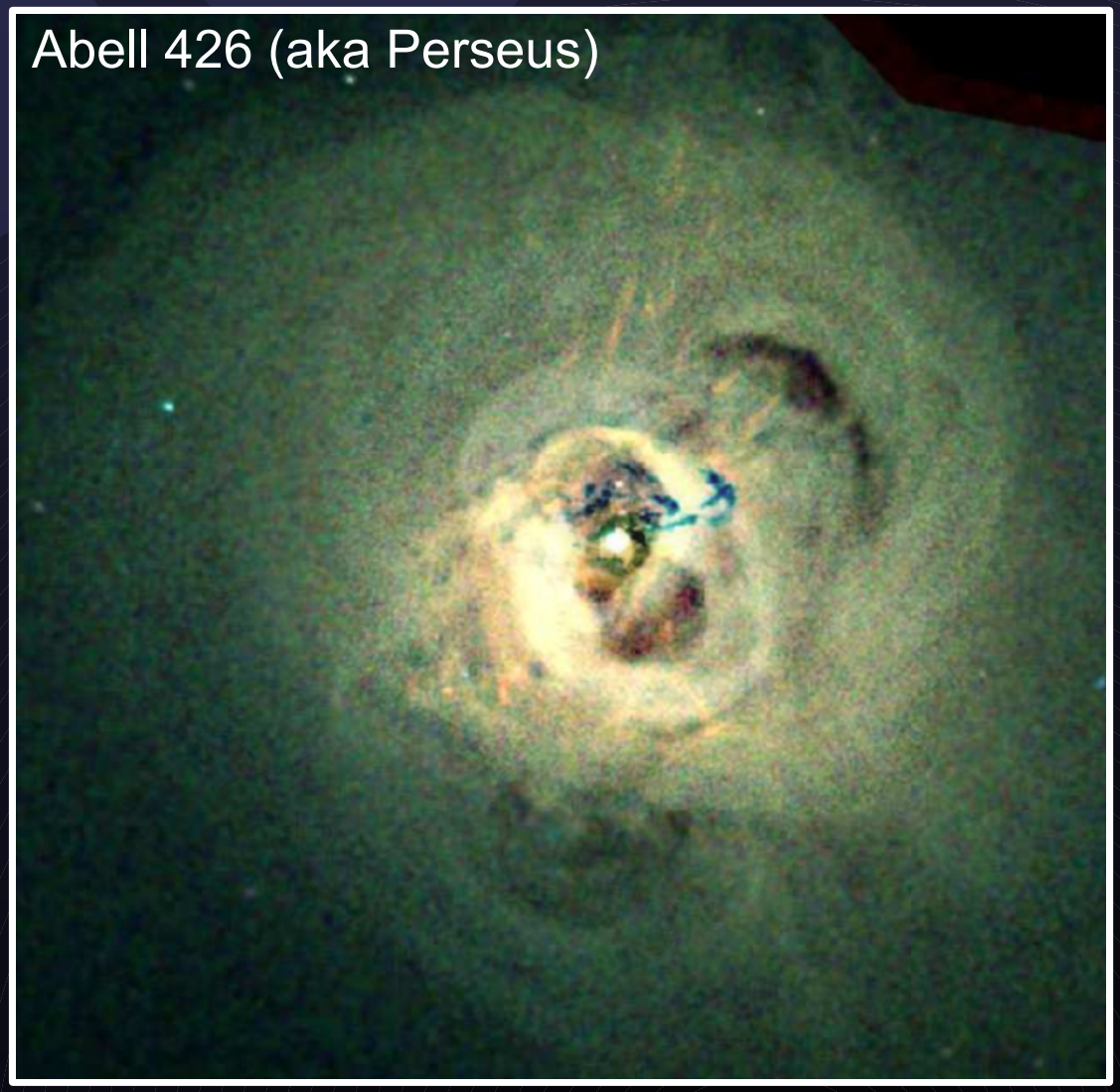


Croton et al. 2006

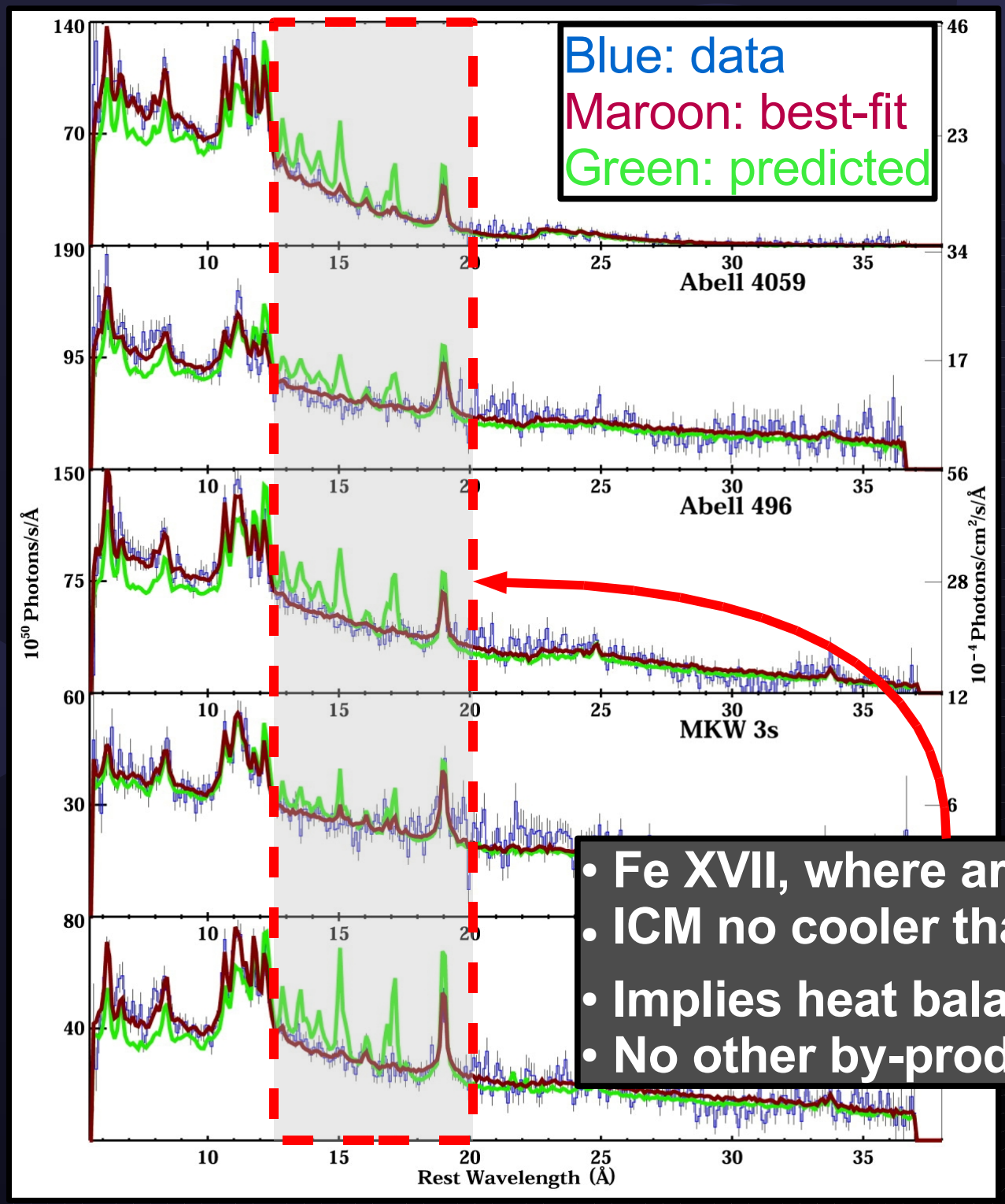
- GF theories predict:
  - Too many massive, blue galaxies
  - Too many dwarf galaxies
- The trouble with “red and dead” galaxies
  - Vigorous feedback at high-z
  - “Down-sizing” problem
- Central galaxy in groups and clusters are not growing unabated

Importance of Feedback

- Central cooling time of ICM much shorter than Hubble age
- Expect massive flows of cool gas into core
- Why the theoretical-observational disconnect?
- Take a look at right...



NASA / CXC / IoA / A.Fabian et al.



Cooling Trickles

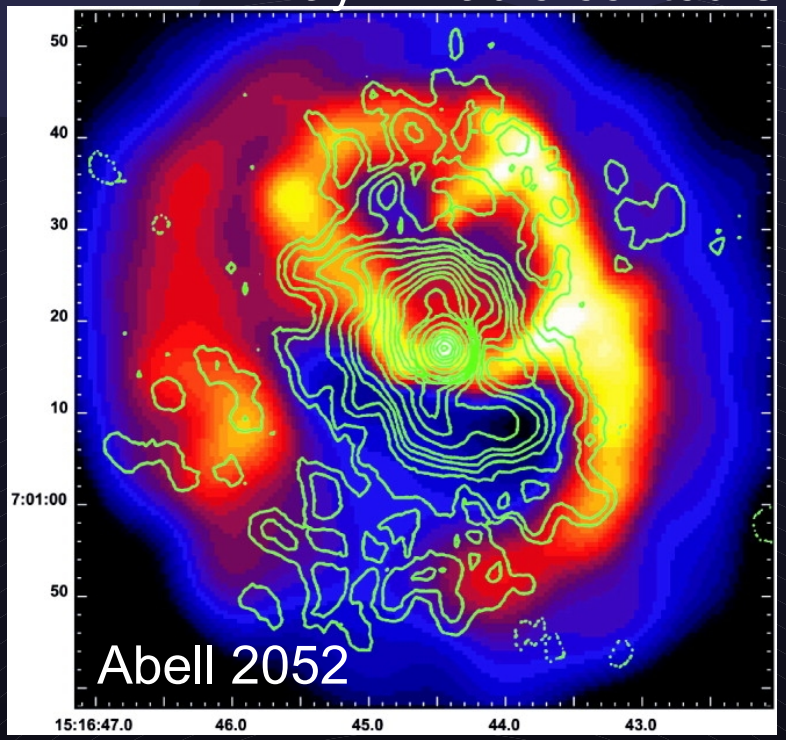
- Fe XVII, where art thou?
- ICM no cooler than $T_X \leq \frac{1}{3} T_{virial}$
- Implies heat balance
- No other by-products either

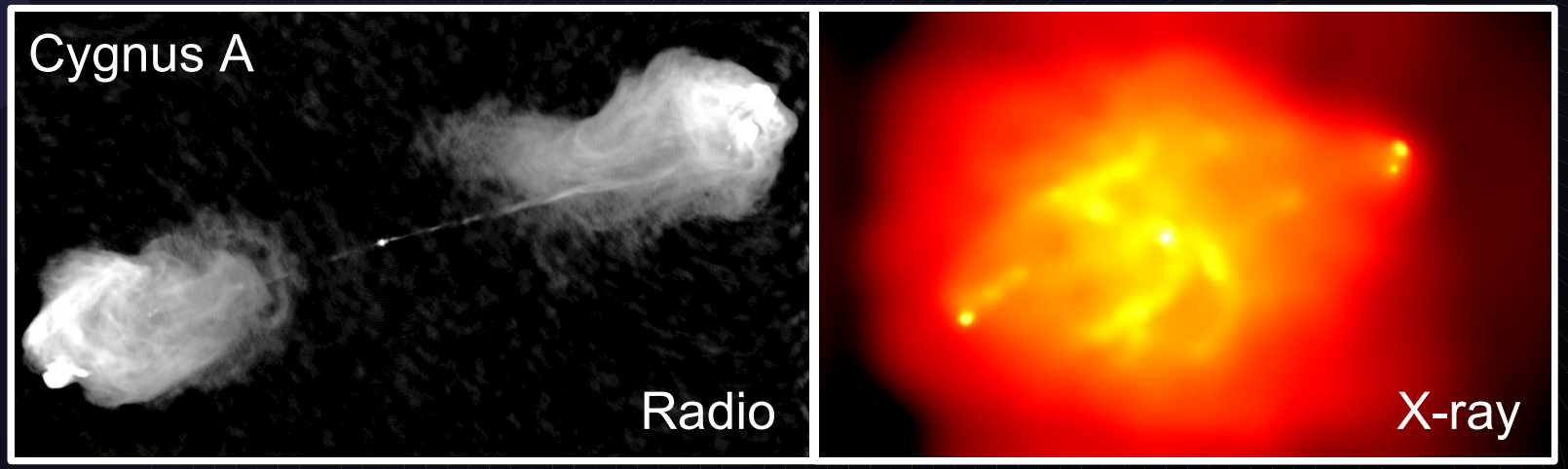
Peterson et al. 2003

Importance of Feedback

- Feedback heating now widely accepted
- Very, very modest star formation
- AGN are active
- Galaxy growth slowed
- How do we make sense of all this?
- **Our 'close to the data' approach:**
  - **Study cooling ICM**
  - **Better understand feedback**
  - **Work toward self-regulation model**
  - **Focus on ICM entropy...**

X-ray + Radio contours



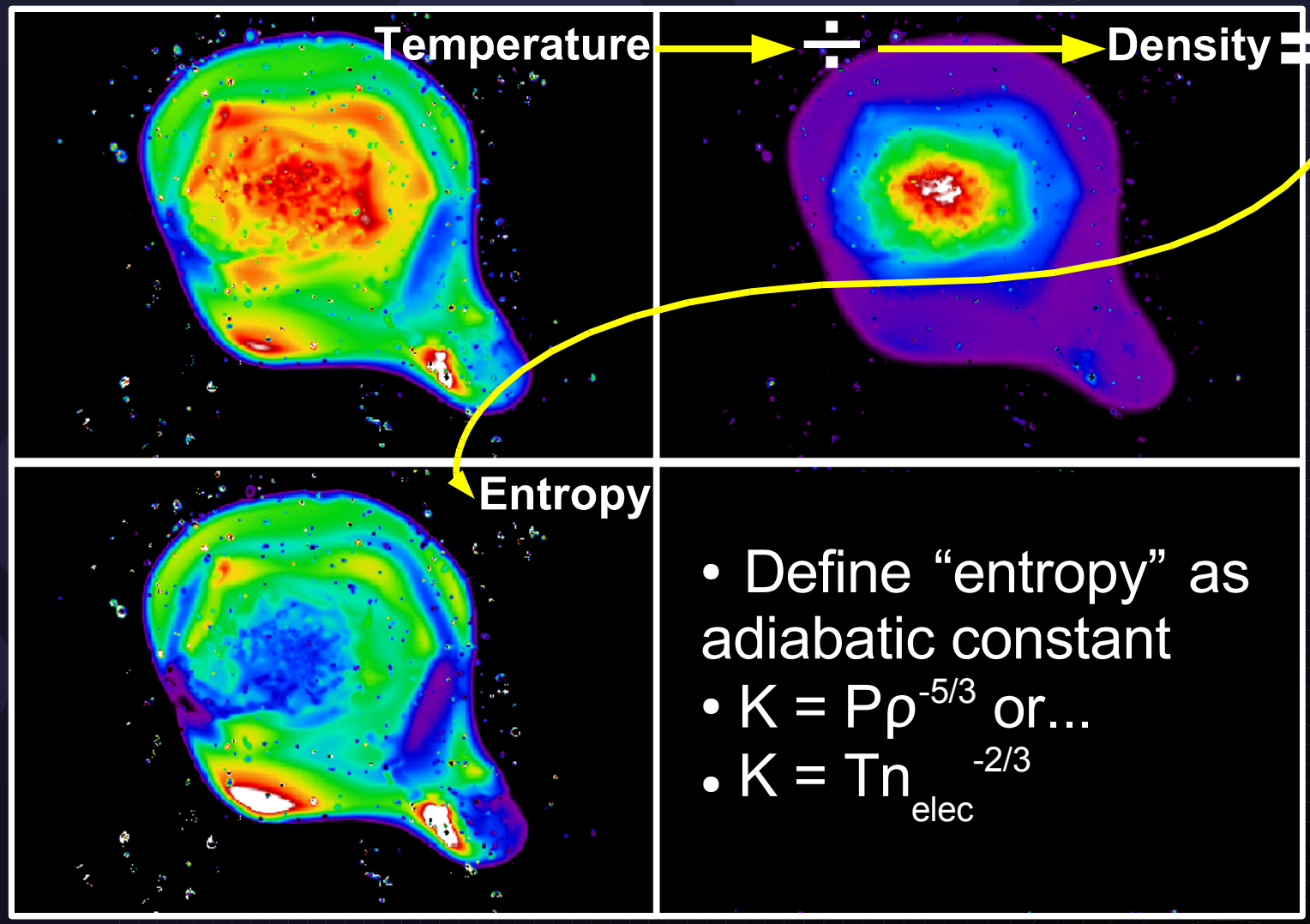


ICM Entropy

- Like PB&J, temperature and density are better together
- Fundamental property of ICM
- Dark matter halo and entropy structure dictate X-ray observables
- Entropy is beholden to thermal history

Entropy from Observables

Coma Cluster



- Define “entropy” as adiabatic constant
- $K = P\rho^{-5/3}$ or...
- $K = Tn_{elec}^{-2/3}$

Schuecker et al. 2004

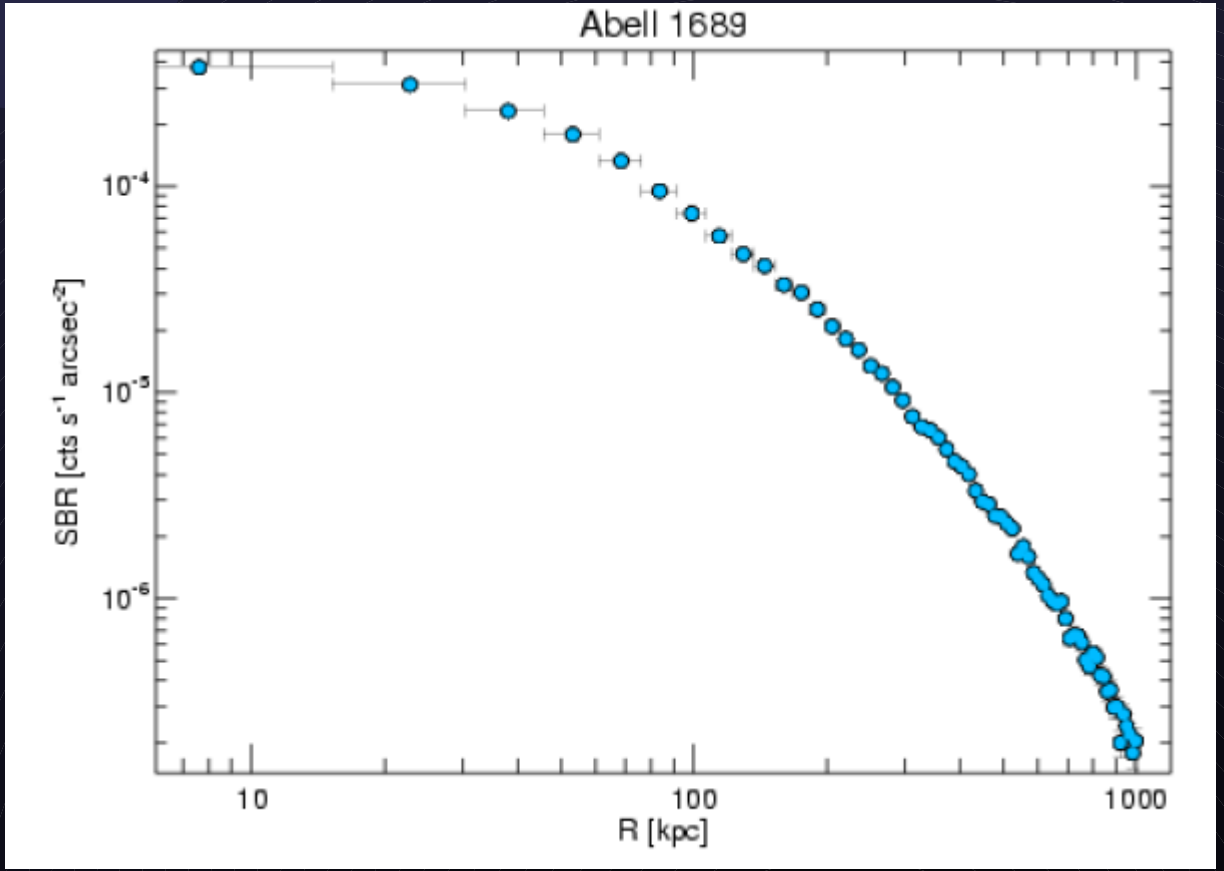
Properties of Entropy

- In a gravity only Universe... radial entropy distribution follows power-law
- Potential wells are entropy sorting devices
- Departures from power-law indicative of past heating and cooling

Chandra data reduction... in a nutshell

Chandra Data Reduction... in a nutshell

- Standard reduction
- Extract surface brightness profiles
  - Background subtracted
  - Exposure corrected
  - Point source cleaned
- Extract and fit temperature profile
- Deproject surface brightness
- Monte Carlo the errors
- Convert to electron density profile
- Calculate entropy profile
- Fit entropy models
- Profit?



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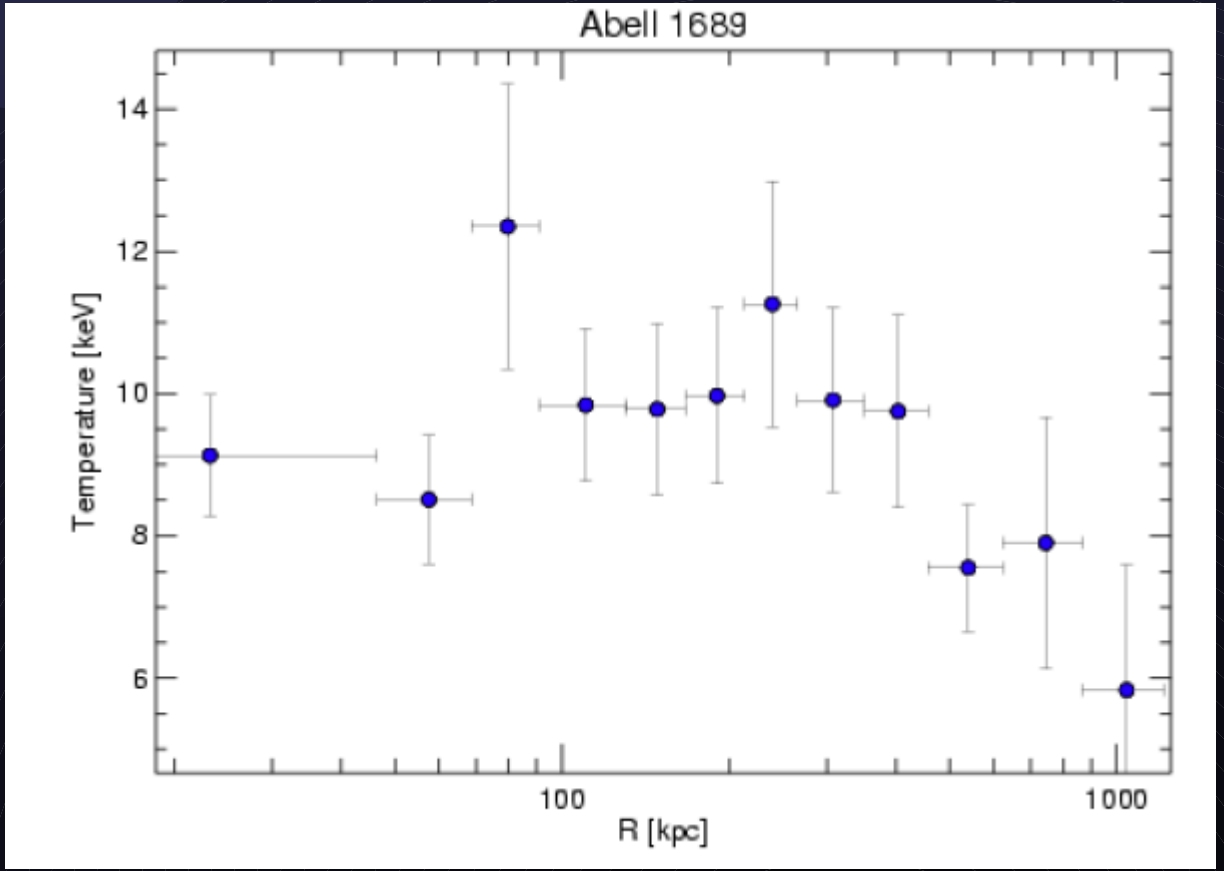

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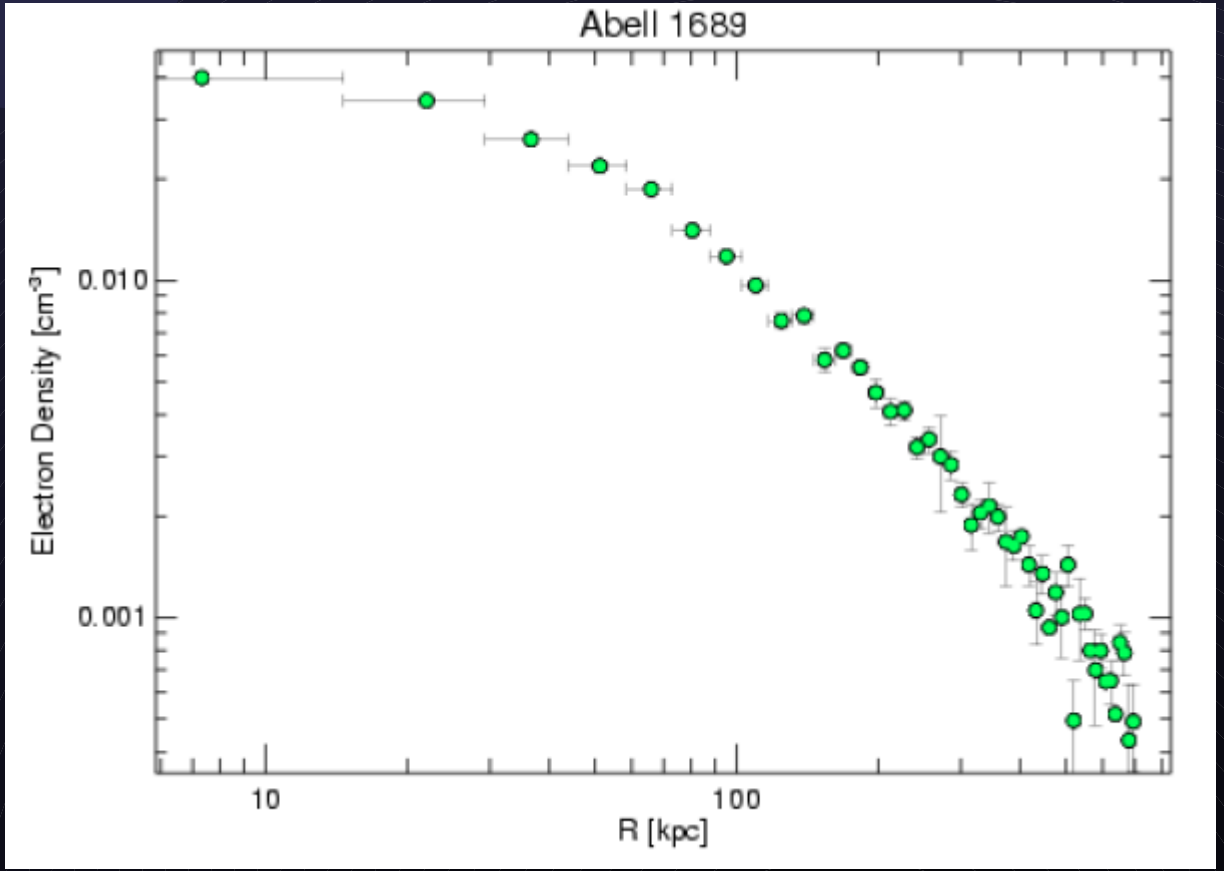

Chandra Data Reduction... in a nutshell

- Standard reduction
- Extract surface brightness profiles
  - Background subtracted
  - Exposure corrected
  - Point source cleaned
- Extract and fit temperature profile
- Deproject surface brightness
- Monte Carlo the errors
- Convert to electron density profile
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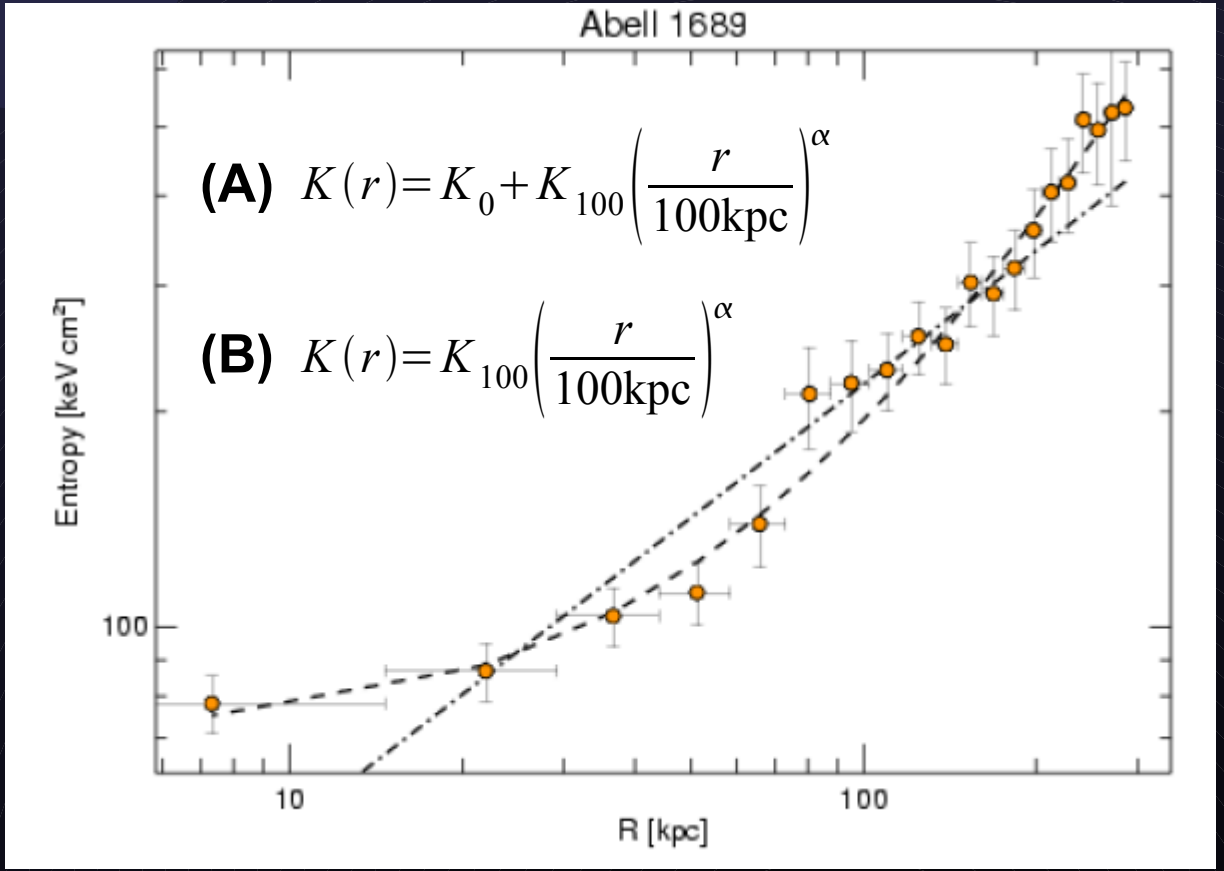

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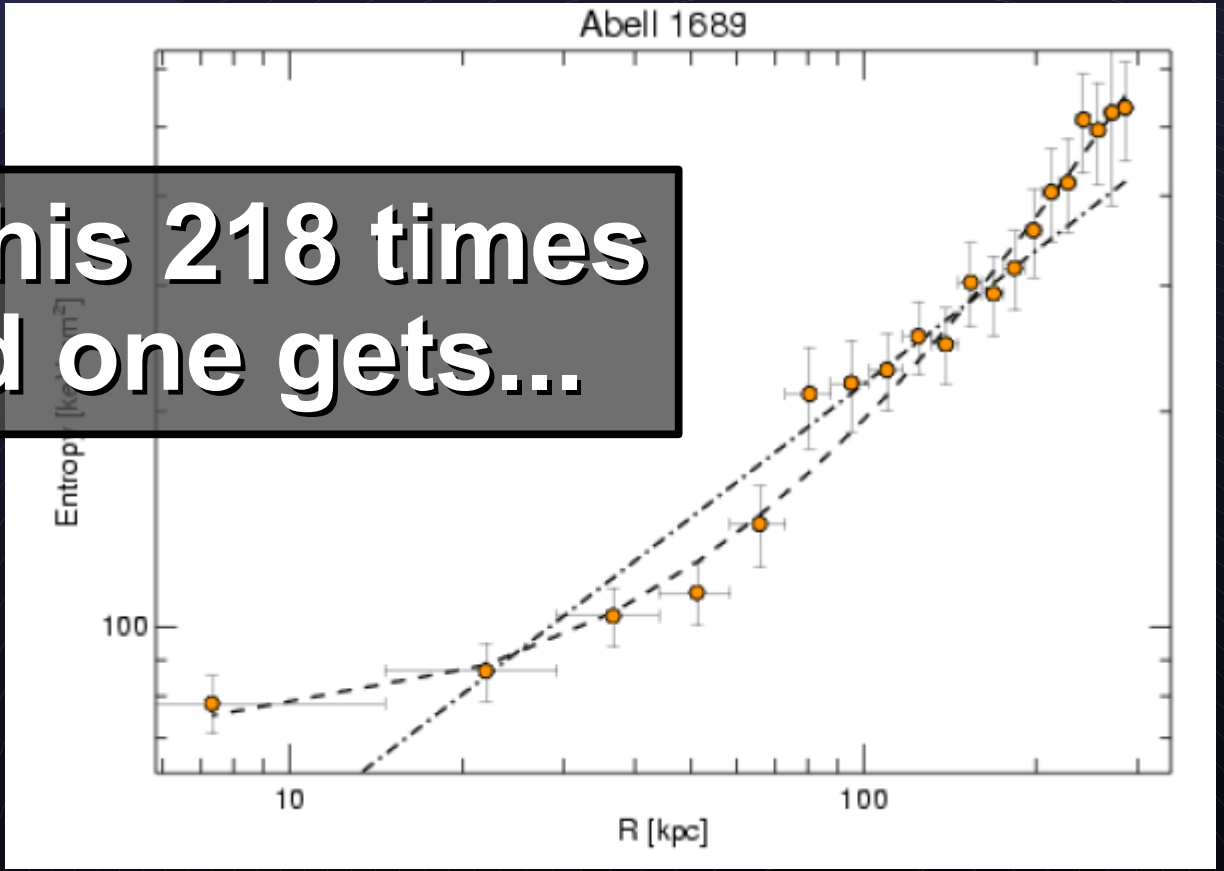
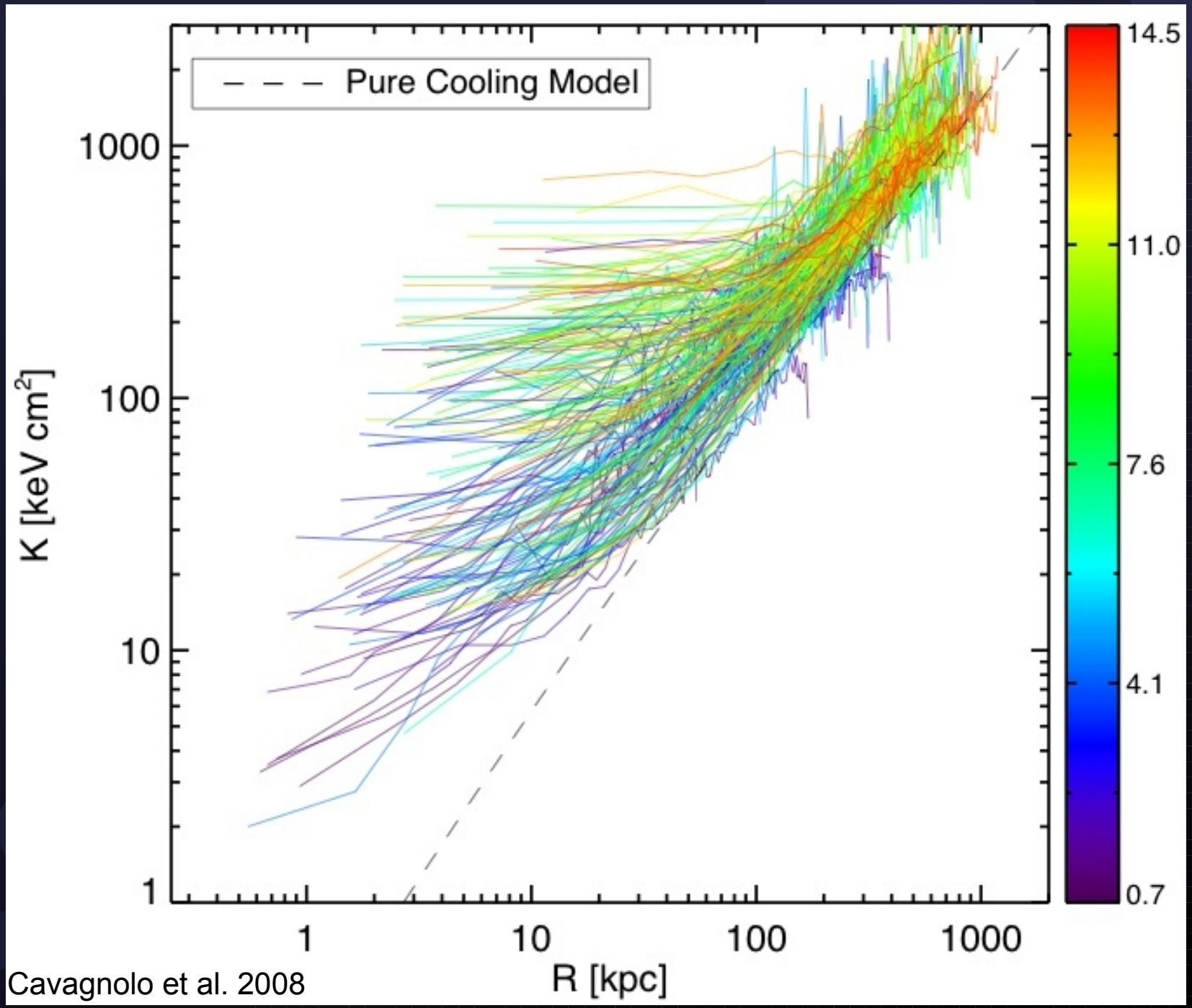
Do this 218 times and one gets...



ACCEPT : Archive of Chandra Cluster Entropy Profile Tables

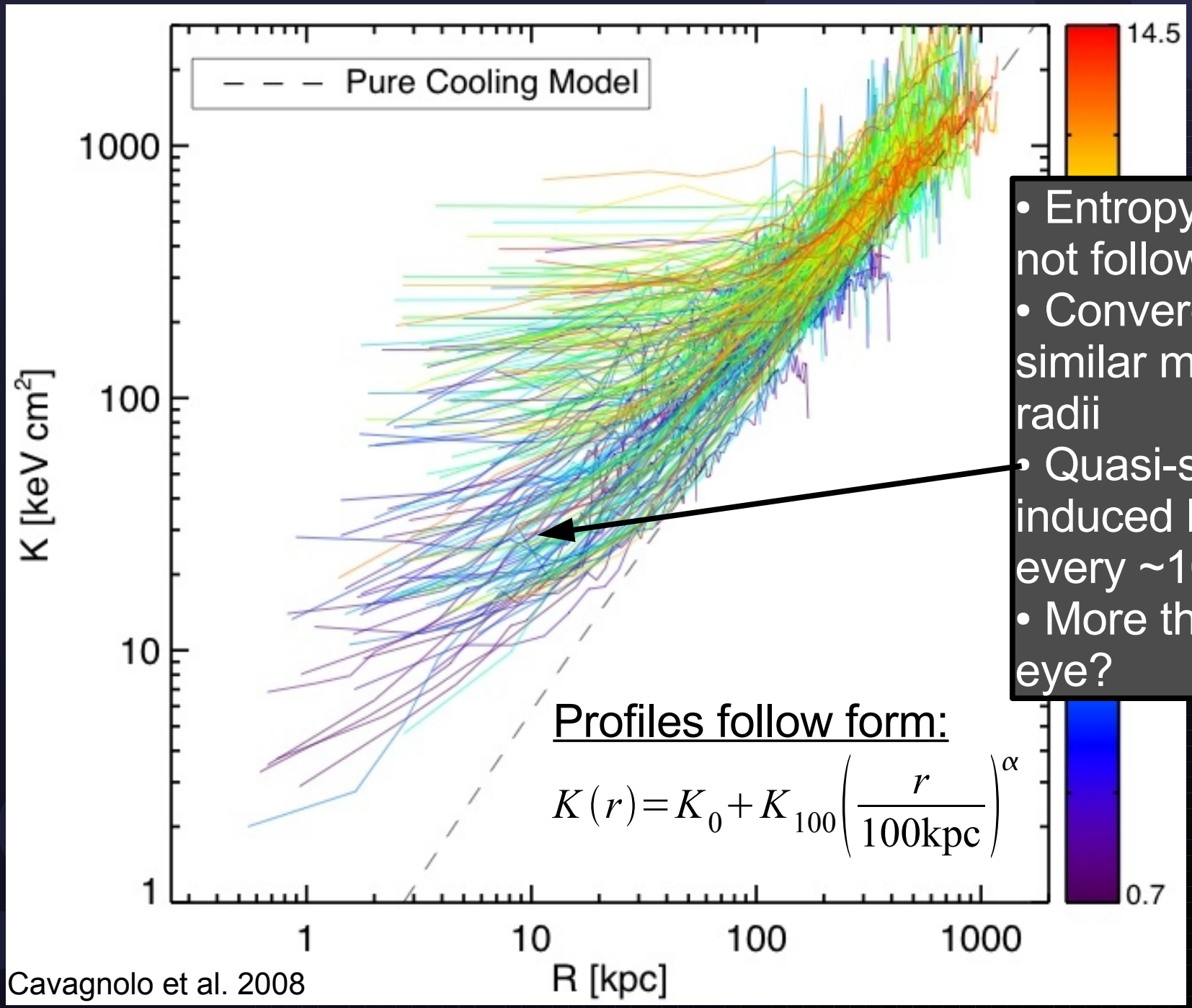


Cavagnolo et al. 2008

All results will be publicly available online.

This includes all profiles, tables, spectra, reduced data, figures, et cetera.

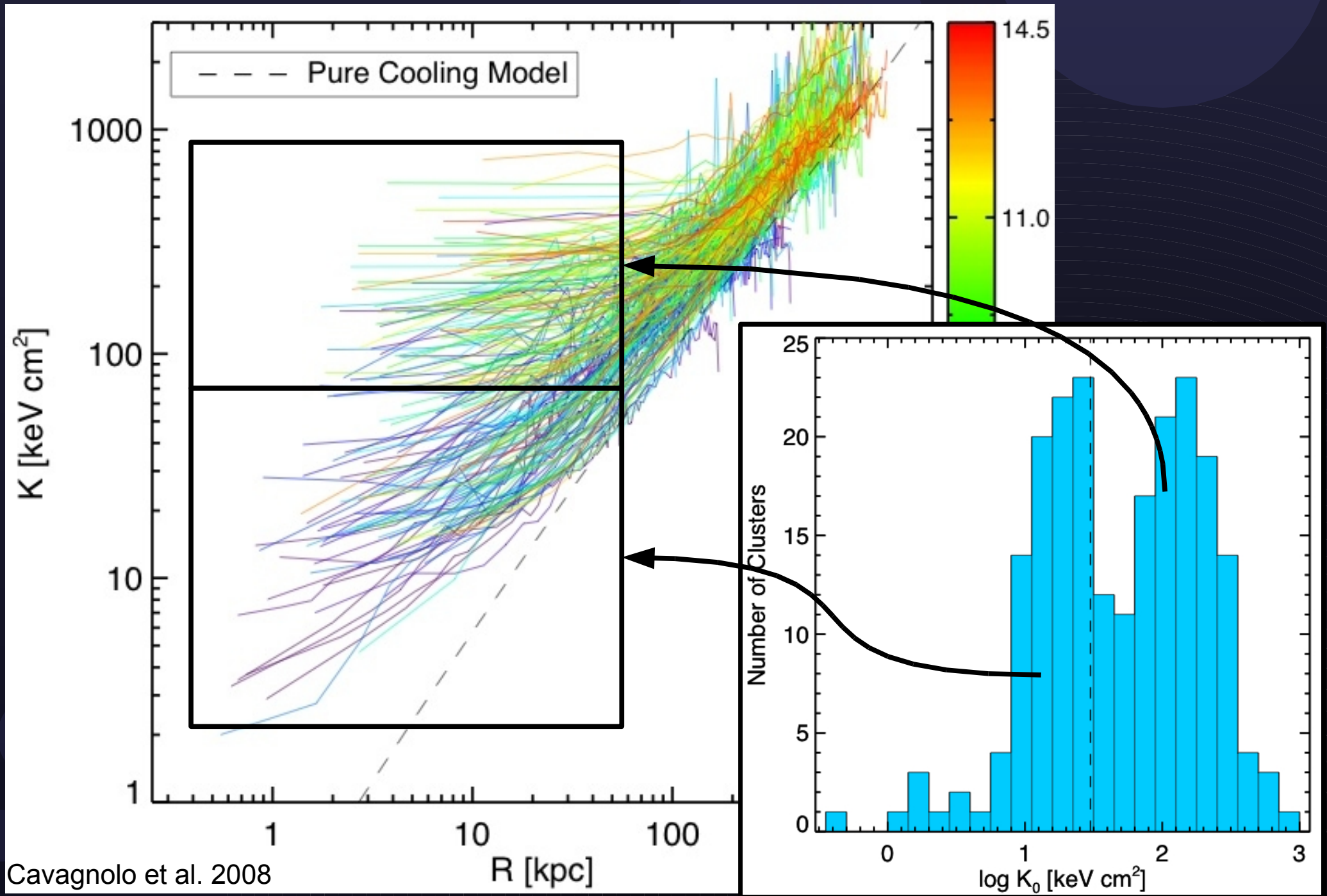
ACCEPT : Archive of Chandra Cluster Entropy Profile Tables



- Entropy profiles do not follow power-law
- Converge to self-similar model at large radii
- Quasi-steady state induced by AGN every ~100 Myr
- More than meets the eye?

Cavagnolo et al. 2008

Bimodal entropy distribution



Cavagnolo et al. 2008

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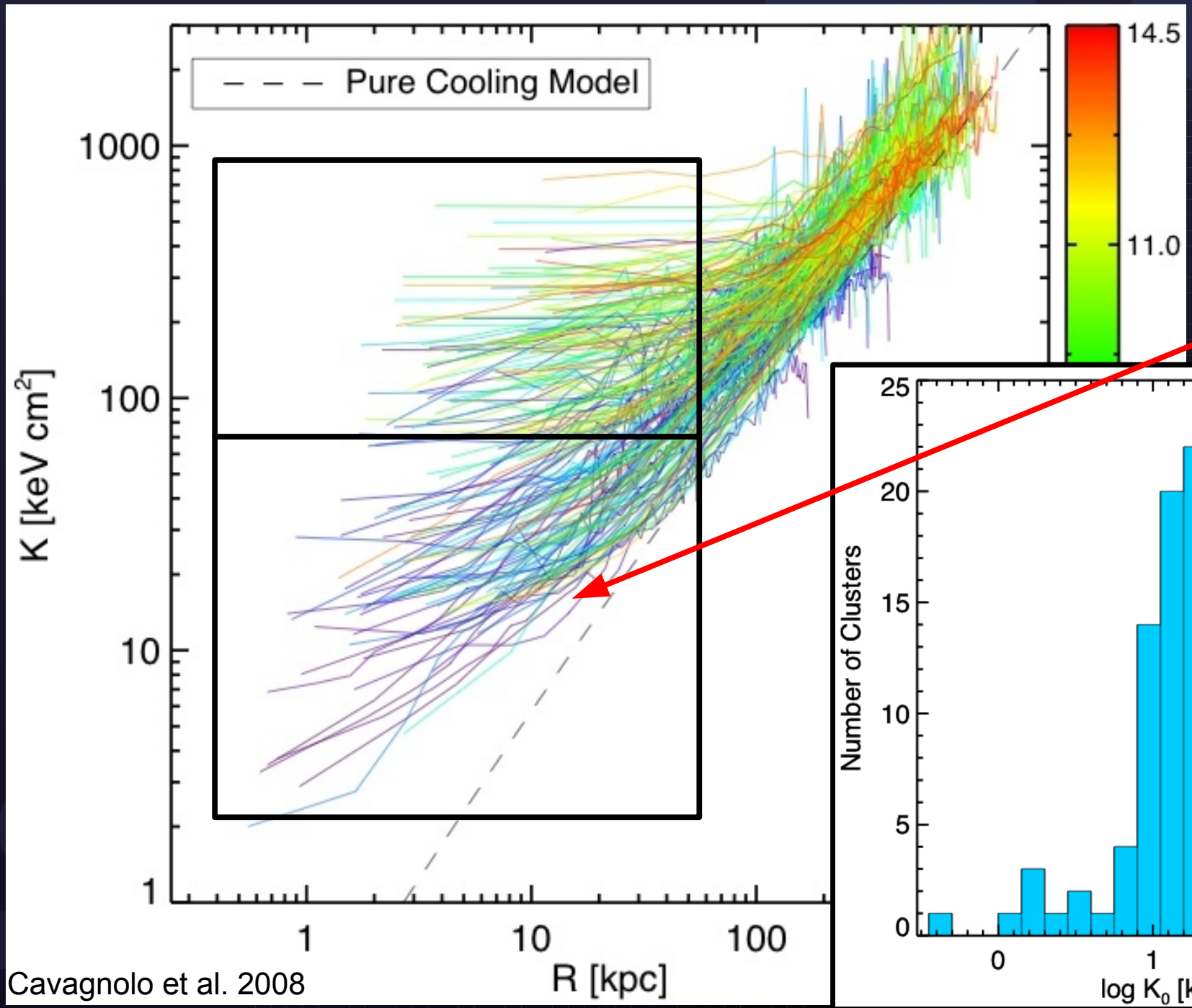
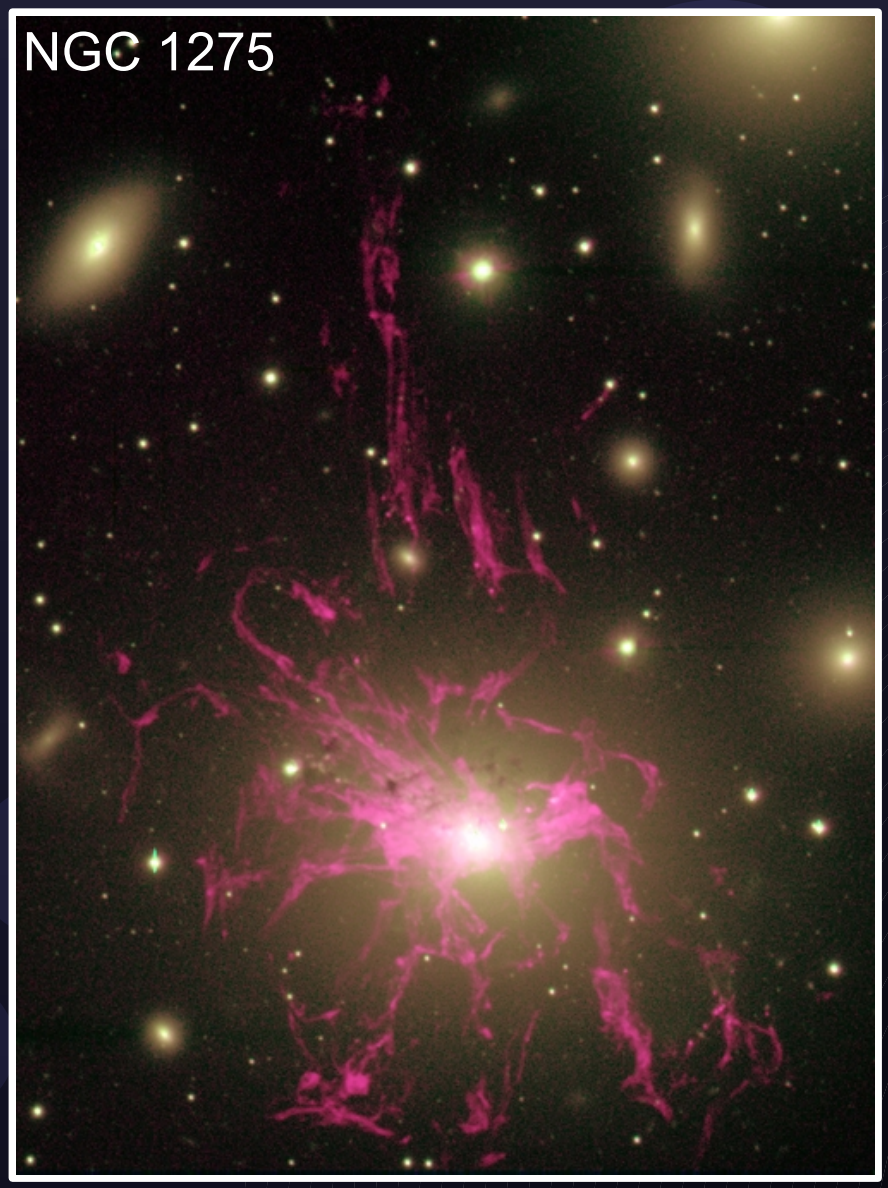


Short central cooling time; << 1 Gyr

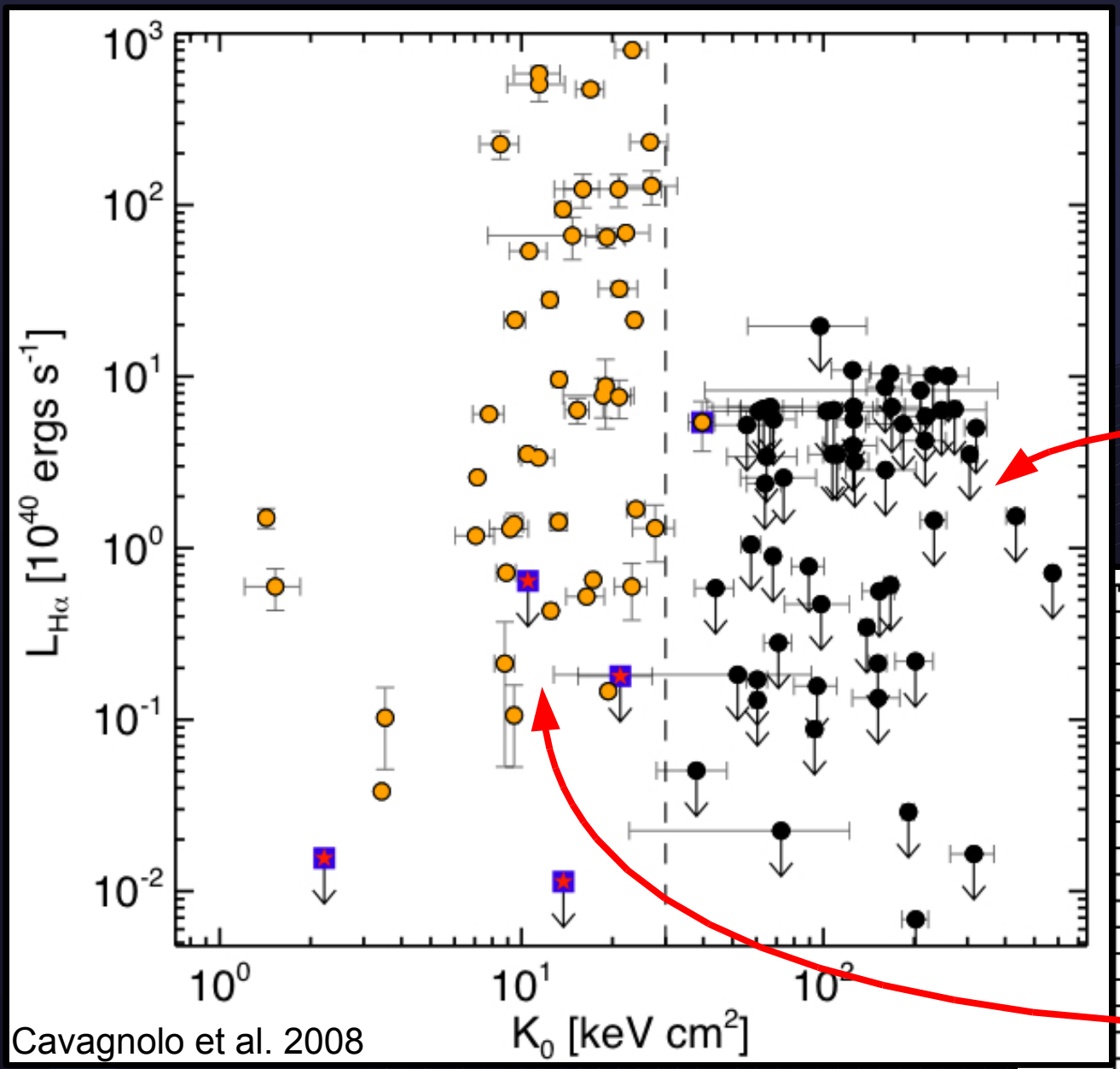
Cavagnolo et al. 2008

Signs of Feedback



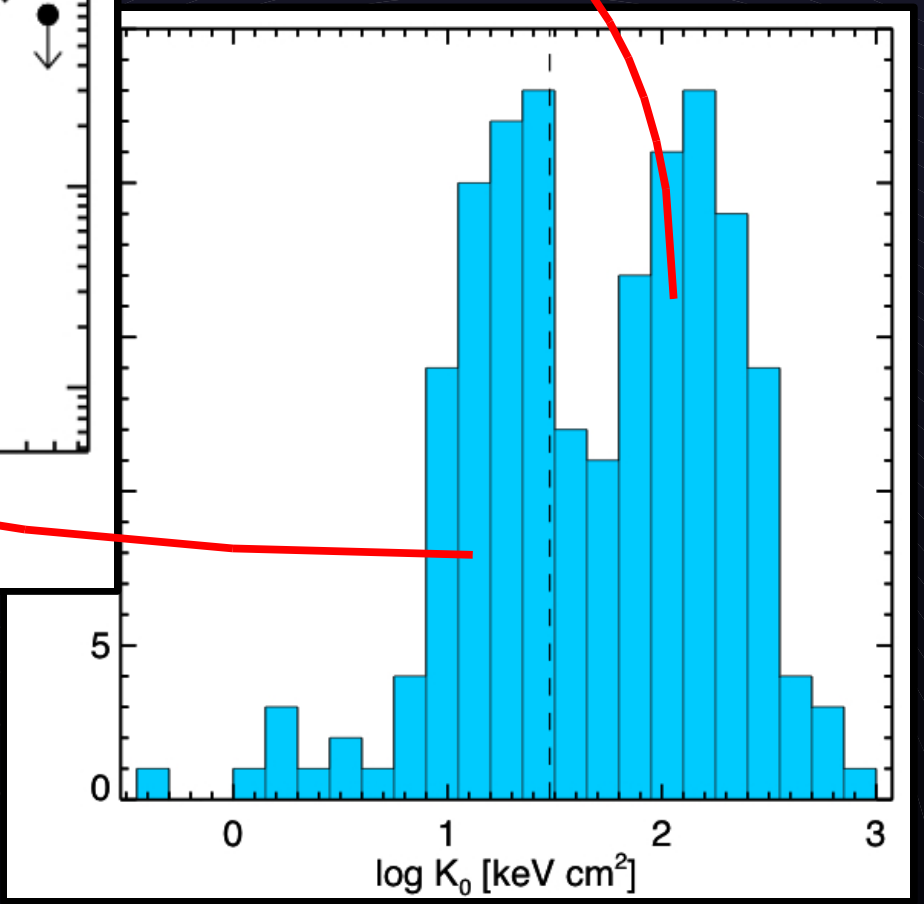
Conselice / Caltech / WIYN / NOAO / AURA / NSF

- Does star formation "know" about K_0?
- Select robust tracer like Hα
  - UV ionizing radiation from O and B stars
  - Turbulent mixing layers?
  - Conduction interfaces?
- Assume Hα traces SF
- Scour the literature; what turns up...



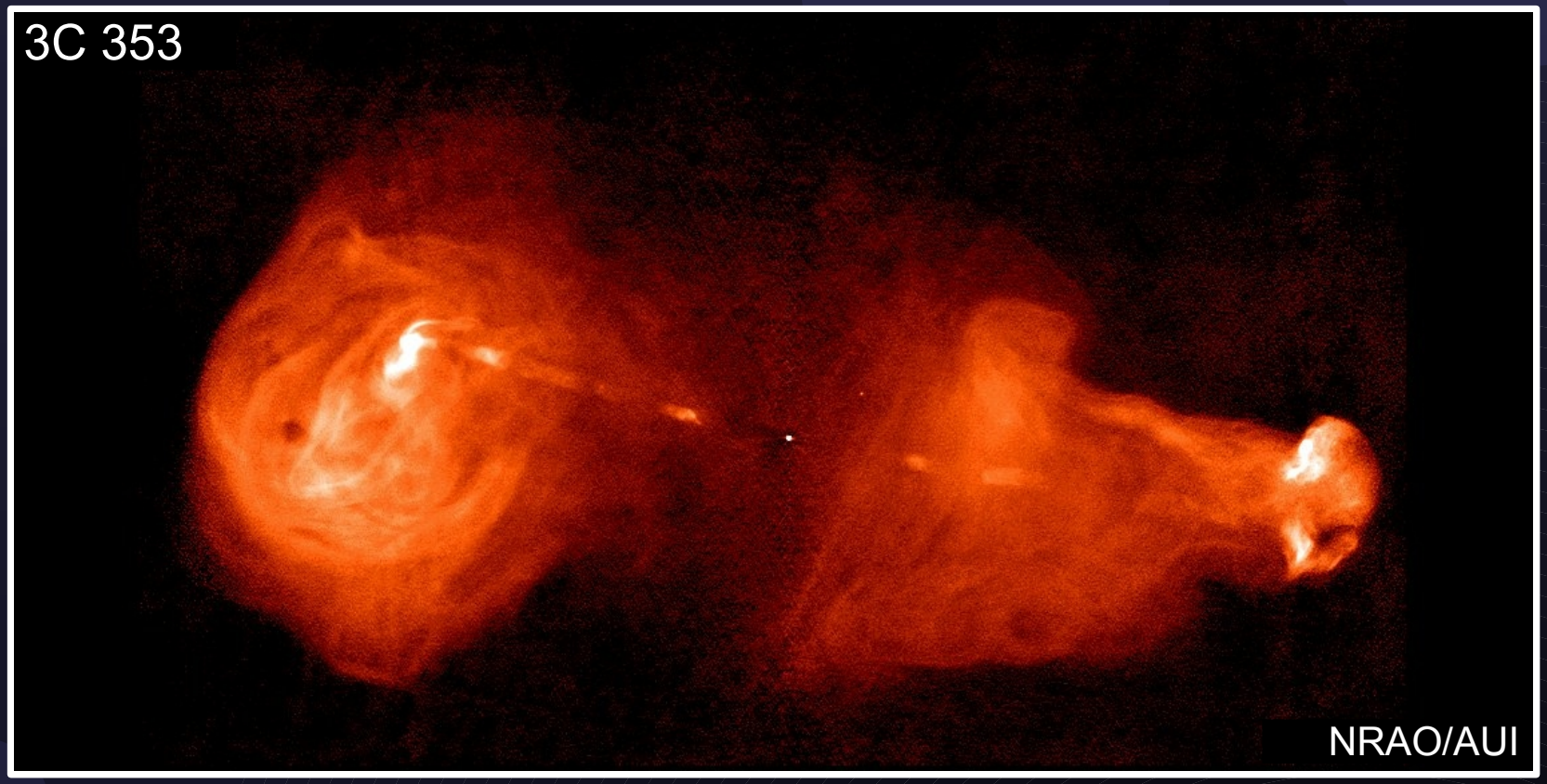
Cavagnolo et al. 2008

Star formation loves low entropy

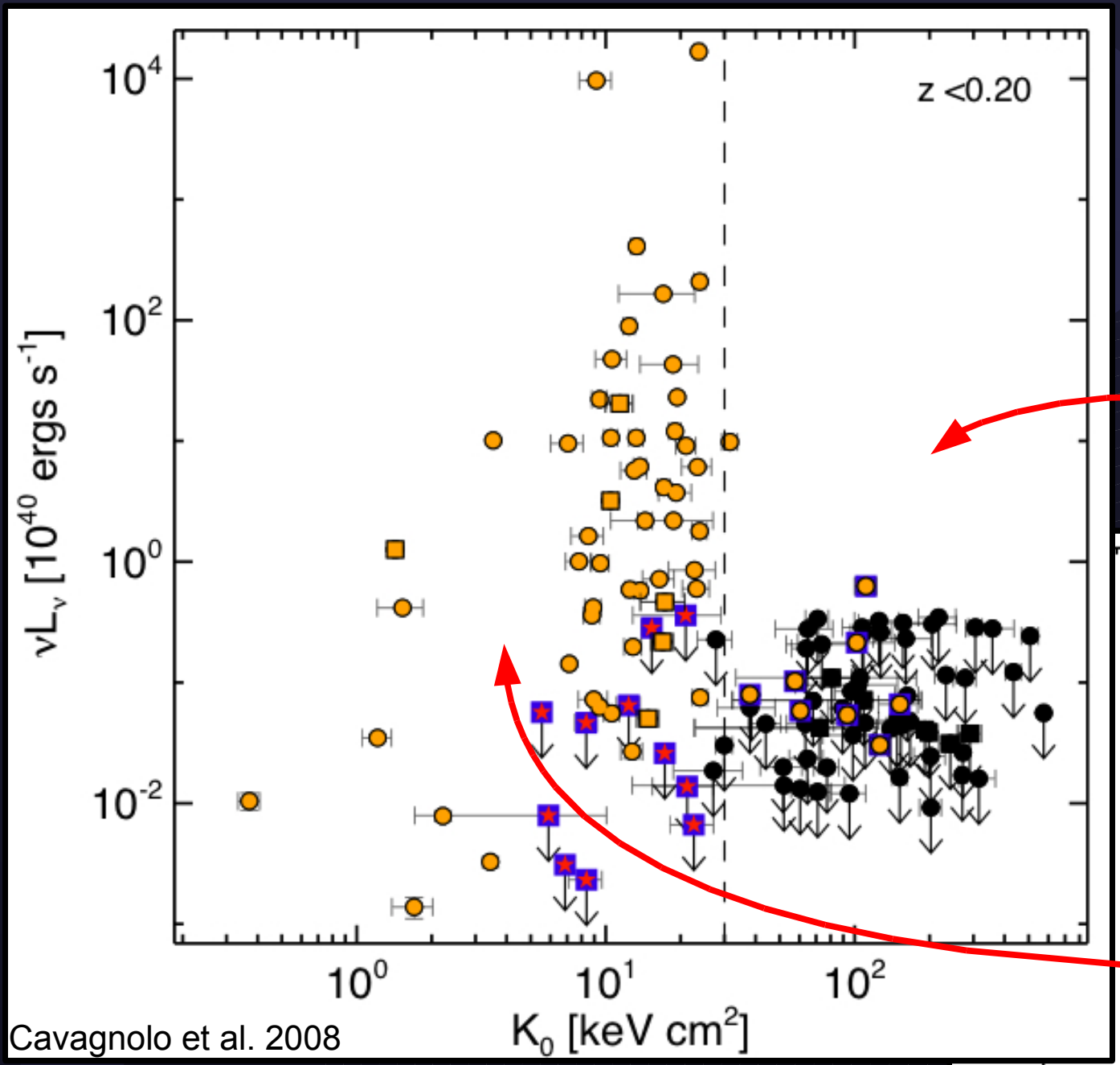


Thermal instabilities form below entropy threshold?

Signs of Feedback

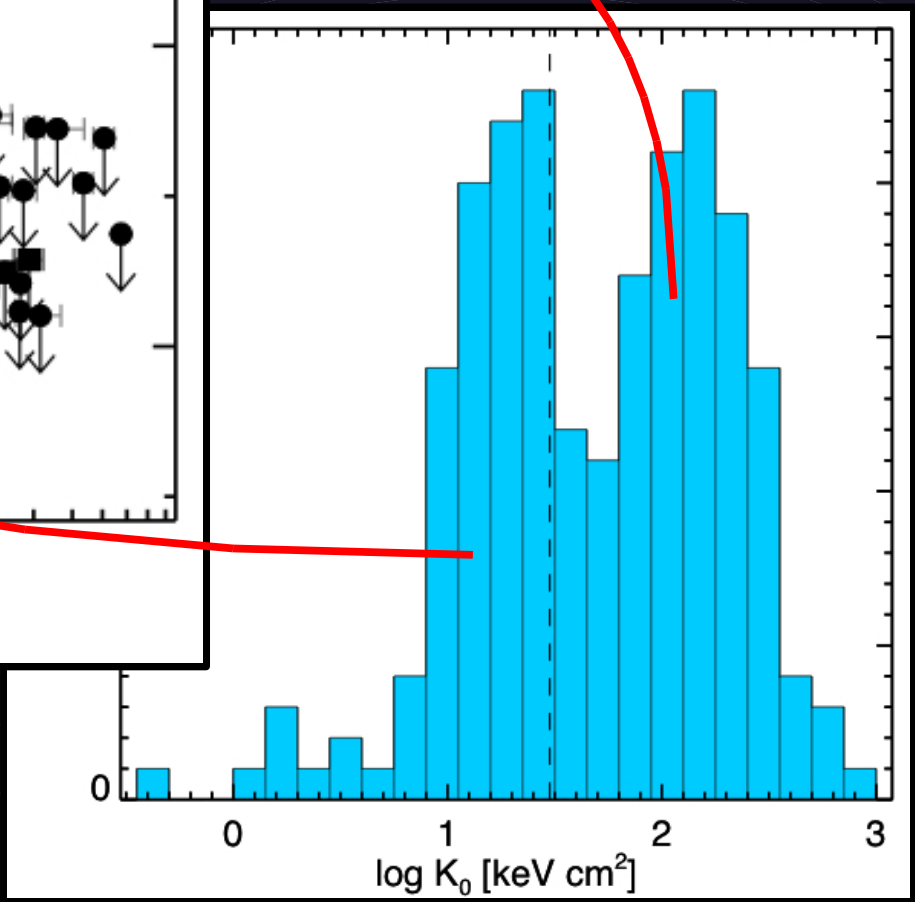


- Do AGN “know” about K_0?
- Select robust tracer like radio
- Skirt some resolution issues with $z<0.2$ cut



Cavagnolo et al. 2008

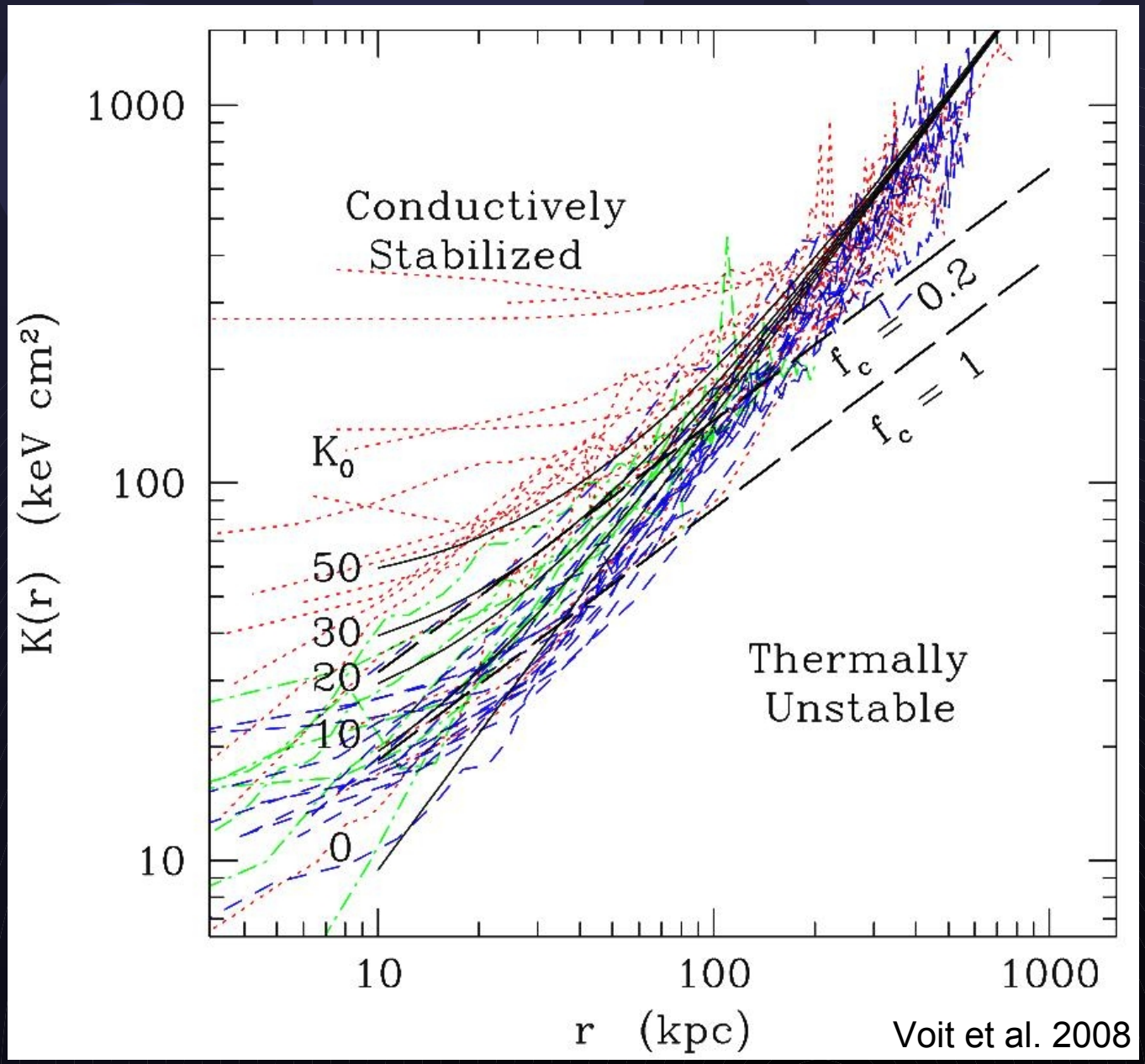
Radio sources like low entropy too!



Radio and Hα share similar entropy threshold; common mechanism?

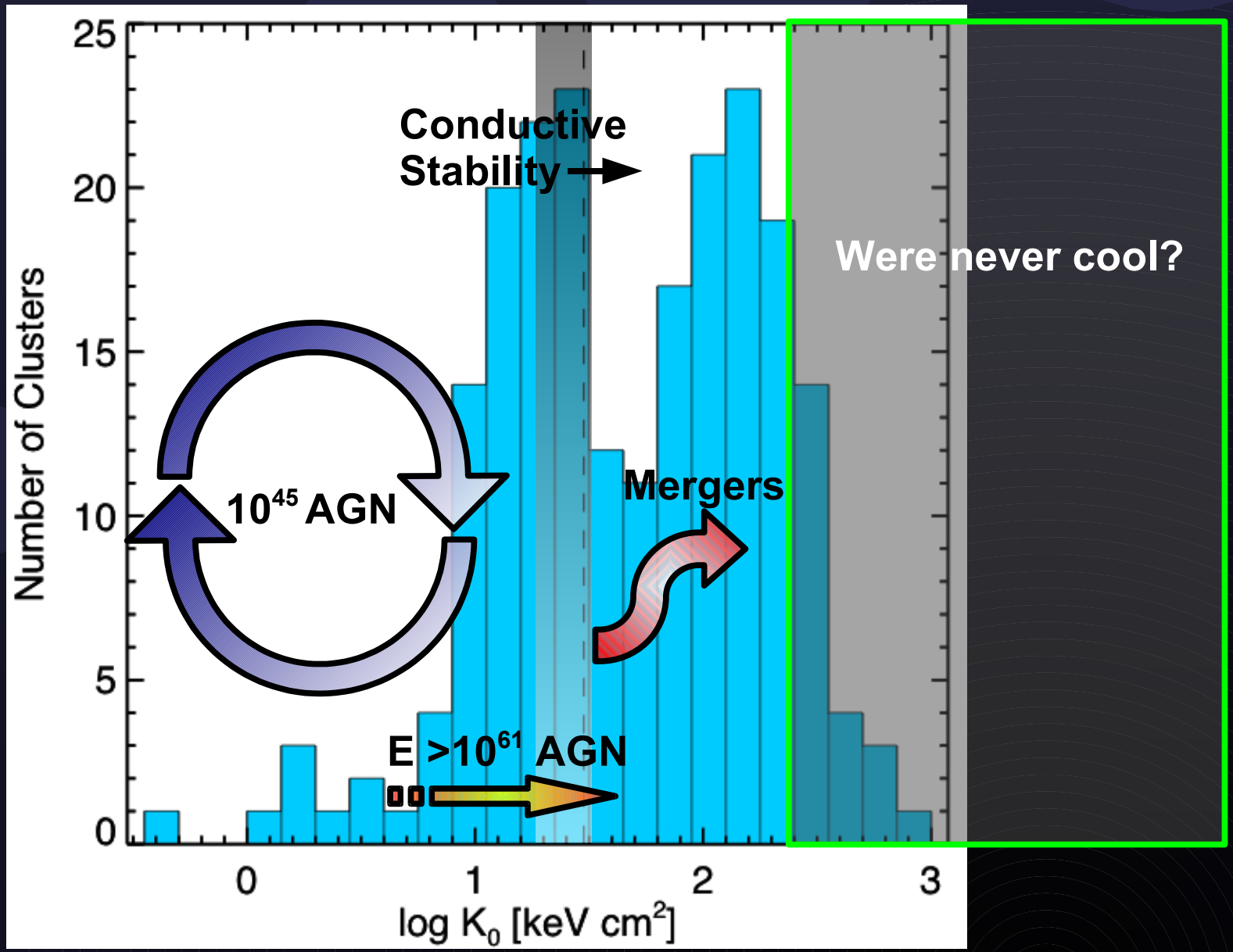
Conductive Stability

- When does a multi-phase medium form?
- $K_0 \leq$ 20-30 keV cm^2 appears to be threshold
- Conduction can't wipe out thermal instability below threshold
- Are we closer to understanding feedback?



Voit et al. 2008

Entropy lifecycle?



Conclusions

We've found...

- Hard-band to broad-band temperature ratio correlates with cluster dynamic state
- Low entropy environs promote feedback
- Characteristic entropy threshold for feedback activity
- Lots of work left to do...

The road ahead

- Entropy scaling relations
- Further study bimodality
- Study timescales with multimodality
- Work to refine conduction model
- Low entropy & no feedback
- High entropy & with feedback
- Sound waves, cosmic rays, and more
- ICM metal distribution
- Study BCG coronae
- Low frequency radio survey?
- Radio dating?
- SZE study of high-z entropy?
- Test various pre-heating models
- Await results of simulation work
- 2D analysis
- Online searchable database

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