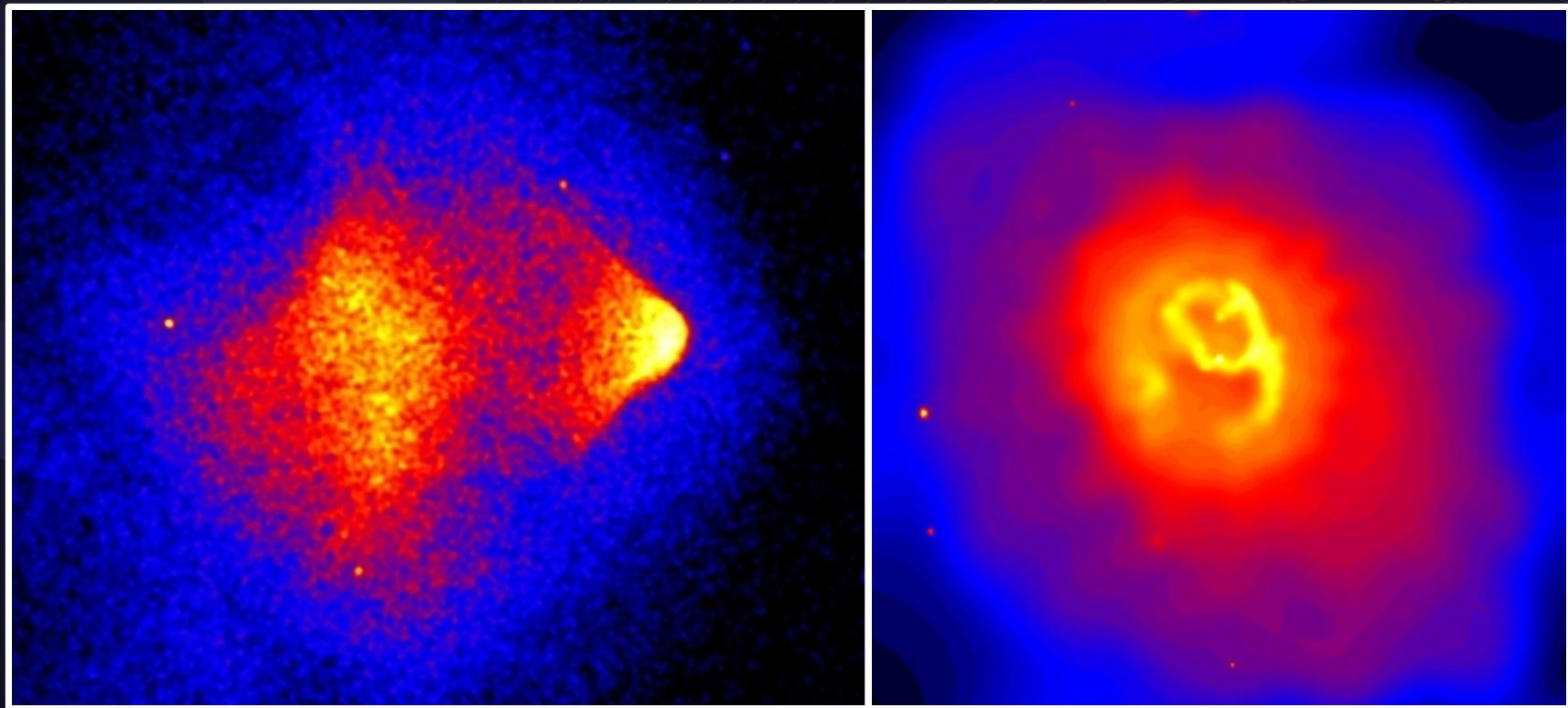


Galaxy Clusters: Relaxation and Feedback

Ken Cavagnolo
Michigan State University

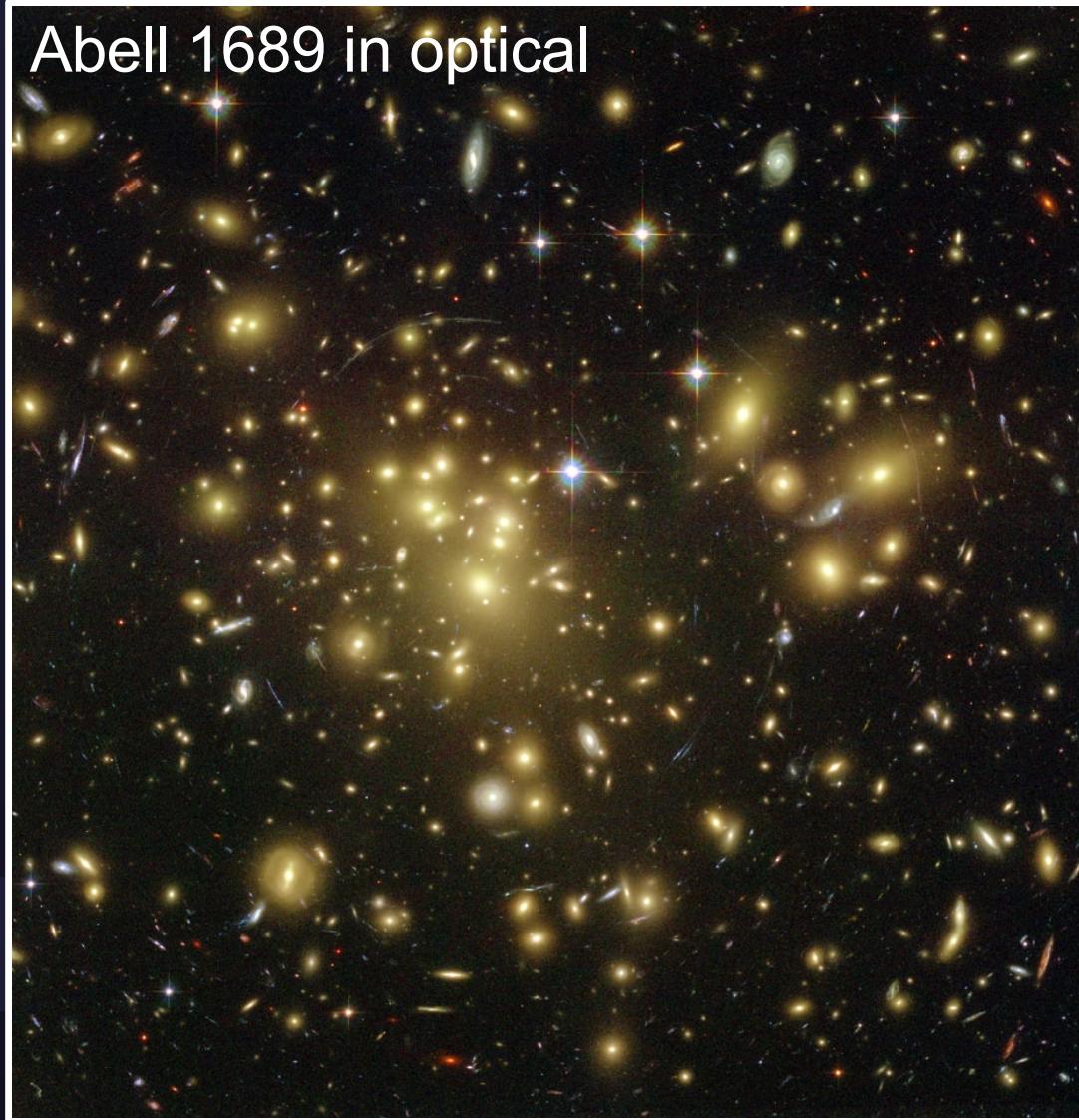


Collaborators at MSU

- Megan Donahue - Advisor
- Mark Voit - Co-advisor
- Ming Sun - Post-doc
- David Ventimiglia - Grad Student

Galaxy Clusters Refresher

Abell 1689 in optical

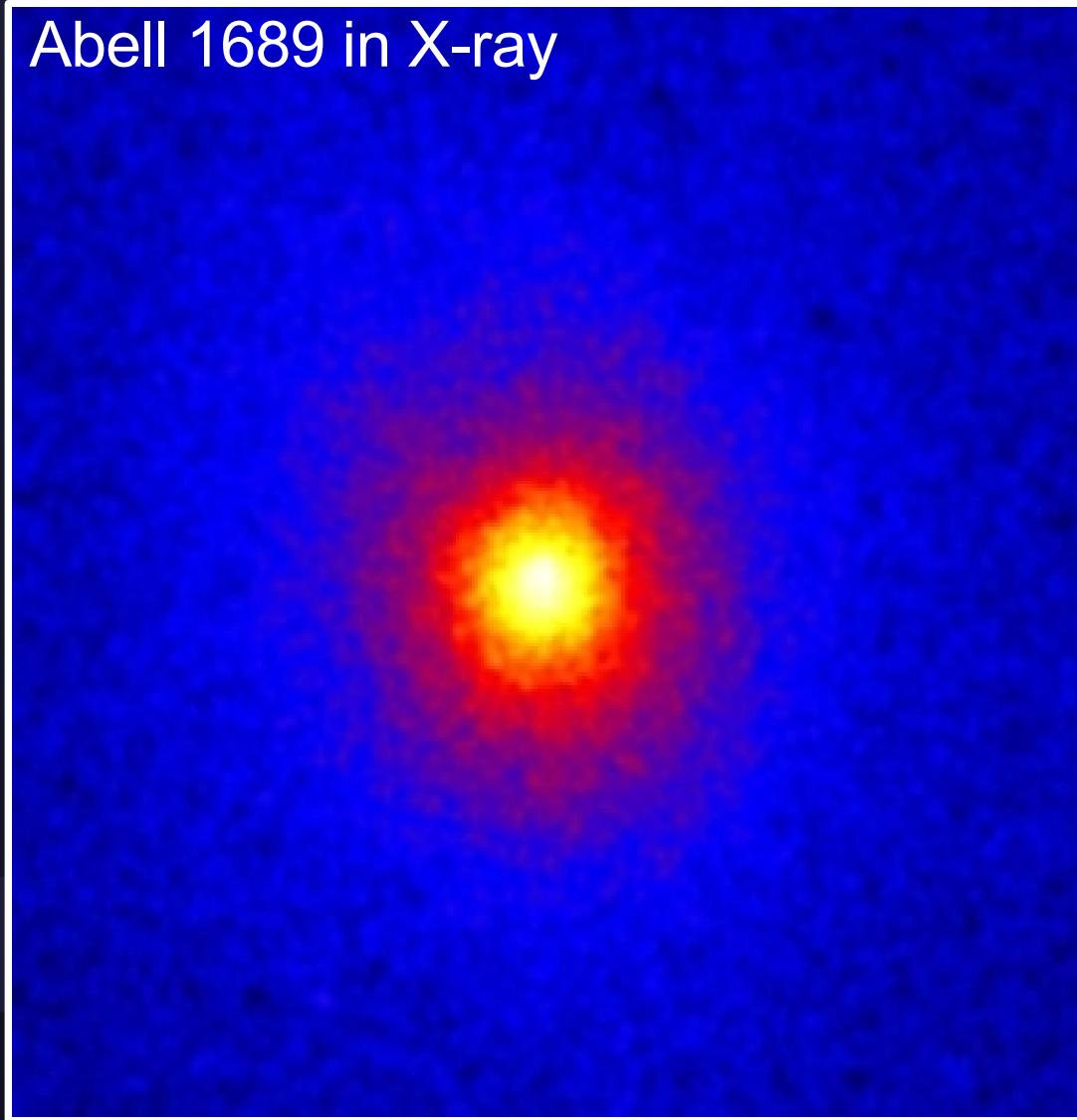


NASA / ACS Team / Benitez et al.

- 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

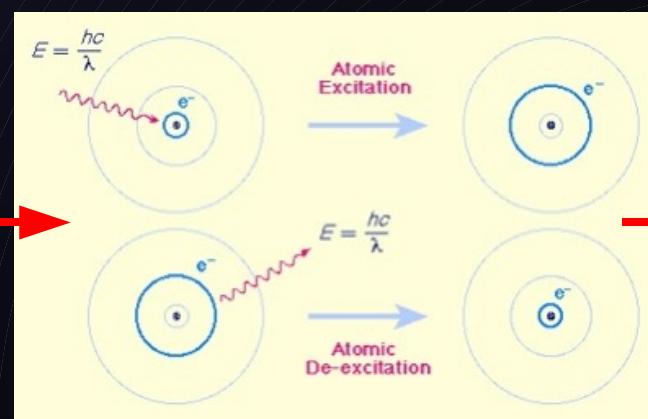
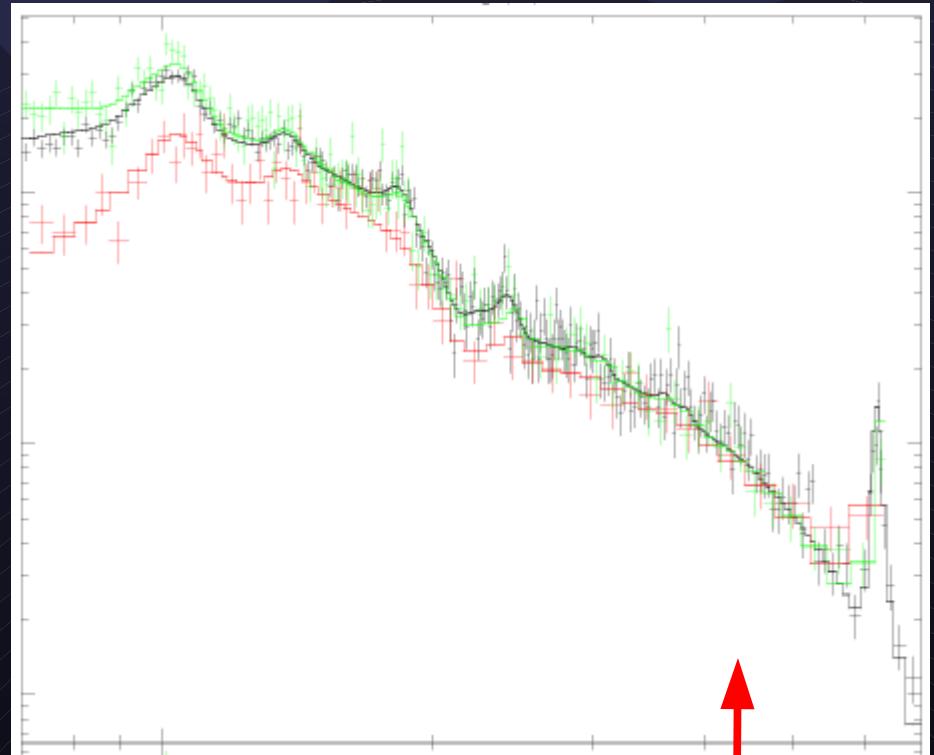
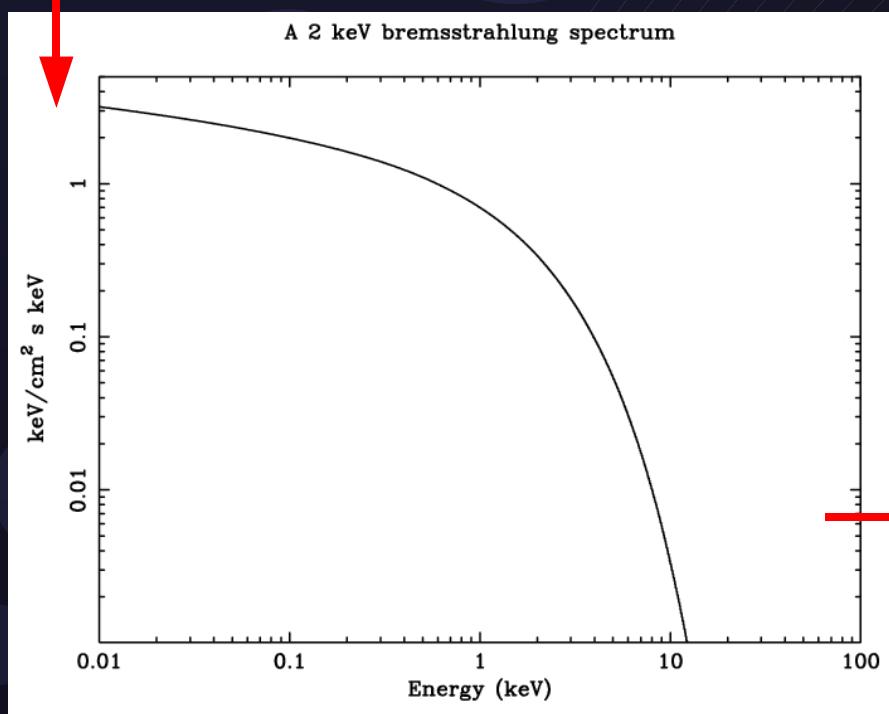
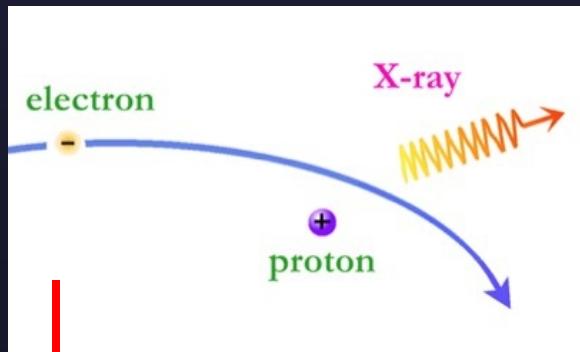
Abell 1689 in X-ray



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

Galaxy Clusters Refresher

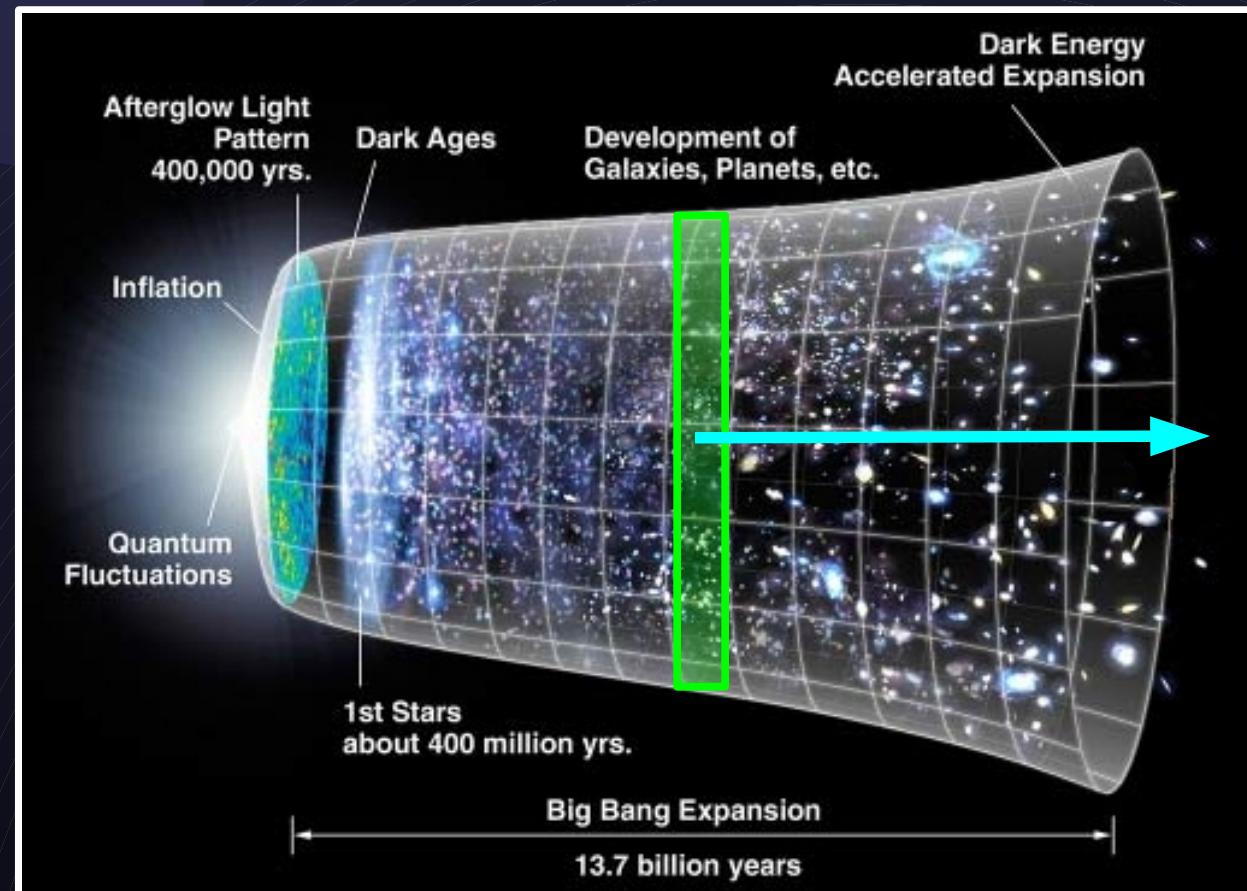
Dominant emission mechanism is thermal Bremsstrahlung



Chandra

Why study galaxy clusters?

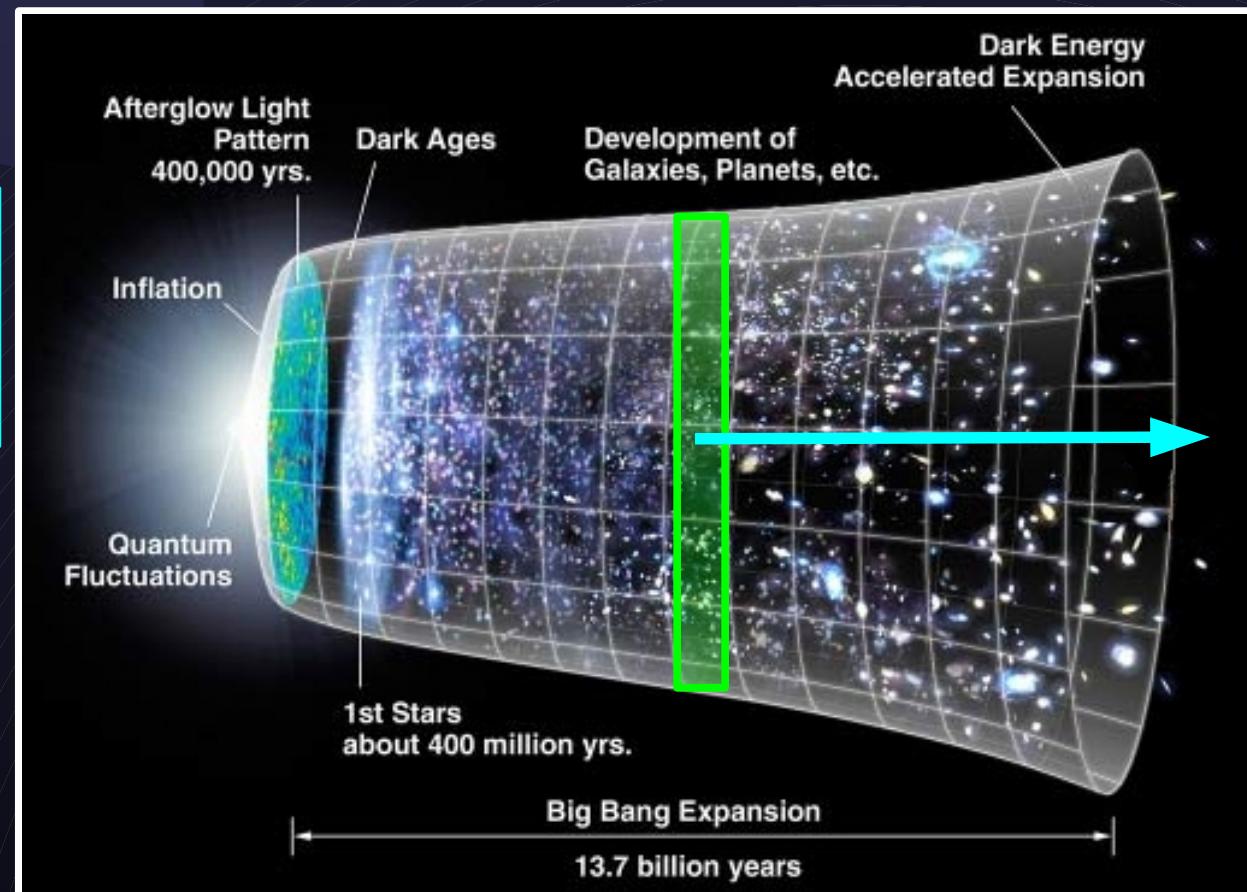
- Cosmology
 - Structure growth
 - Need more precise masses
- Galaxy Formation
 - Explain Hubble Sequence
 - Must understand feedback



NASA / JDEM

Why study galaxy clusters?

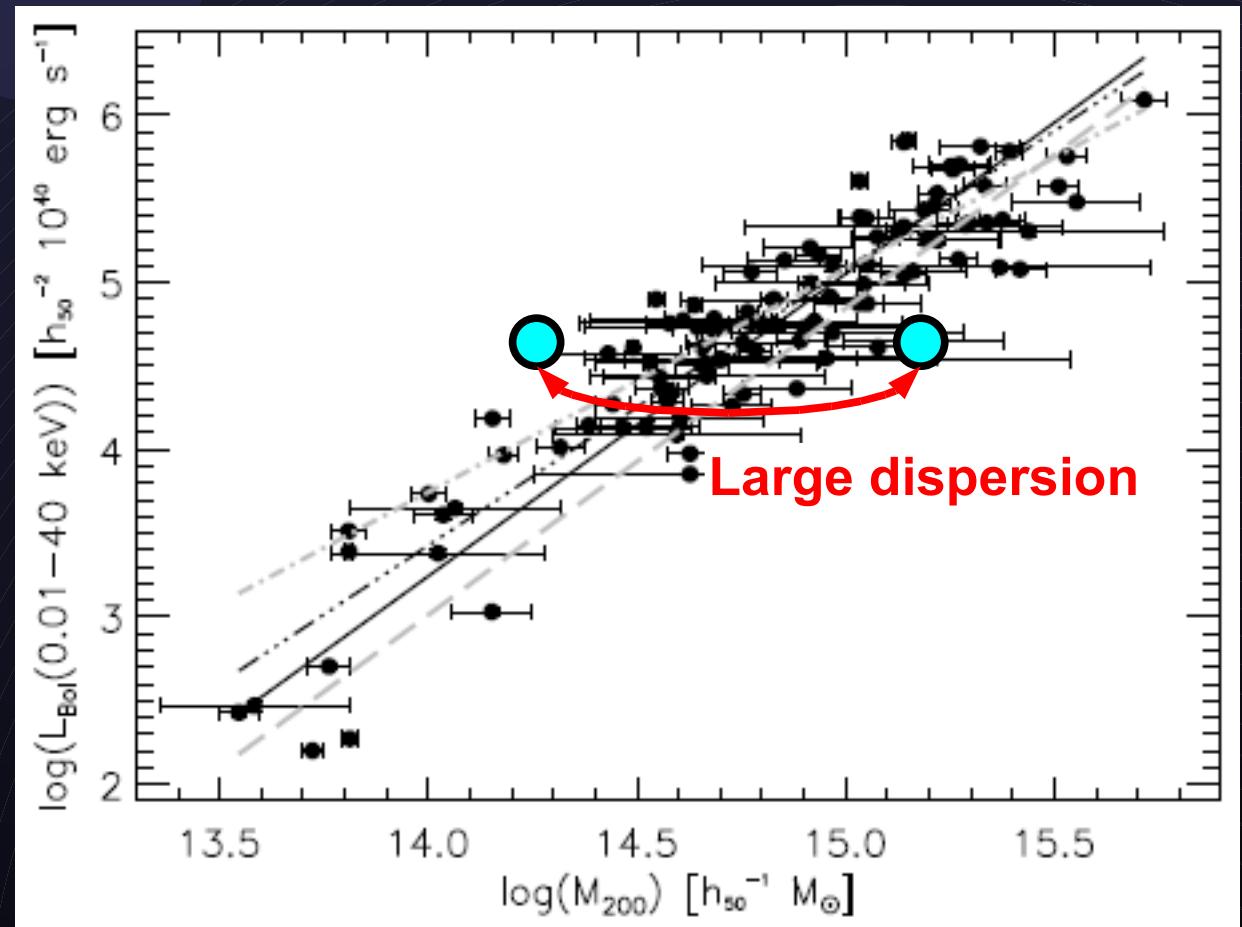
- Cosmology
 - Structure growth
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NASA / JDEM

Cosmological Importance of Relaxation

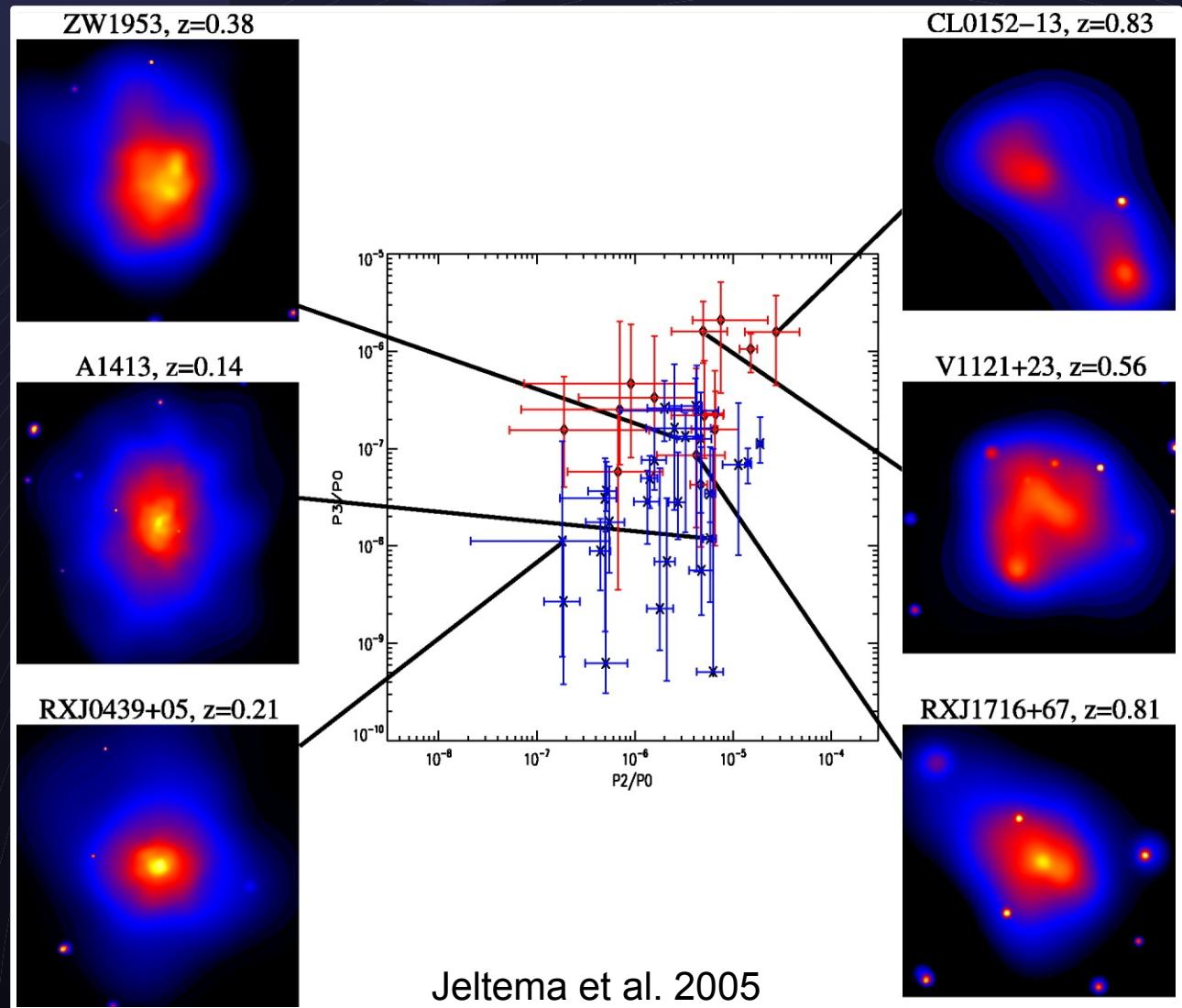
- Clusters expected to be self-similar
- Observables are mass surrogates, assuming equilibrium i.e. relaxation
- Heating and cooling alter scaling relations
- Precision cosmology requires knowledge of the scatter and how it evolves



Reiprich et al. 2001

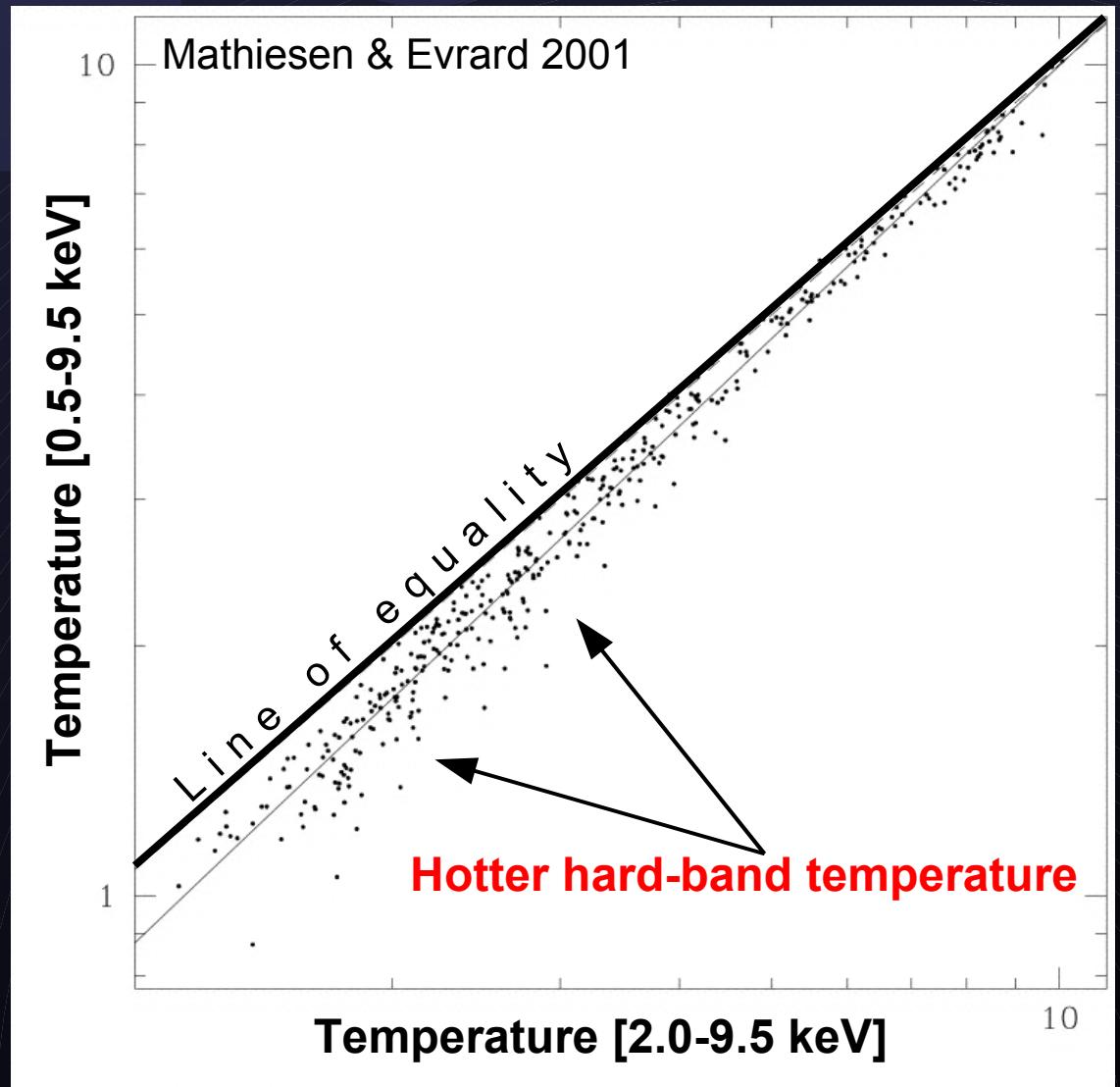
Cosmological Importance of Relaxation

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



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



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:

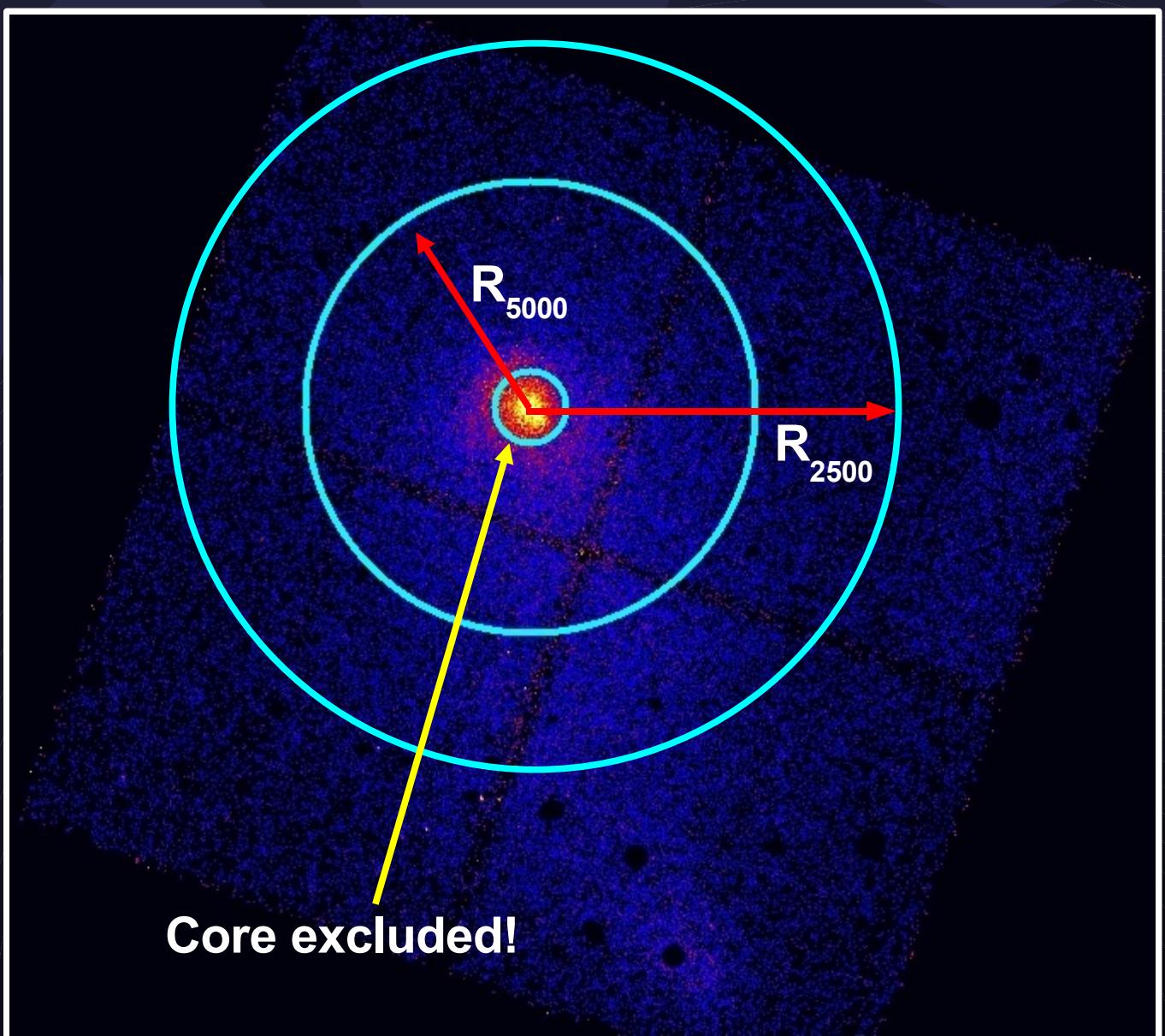
$$T_{HBR} = \frac{T_{2.0-7.0}}{T_{0.7-7.0}}$$



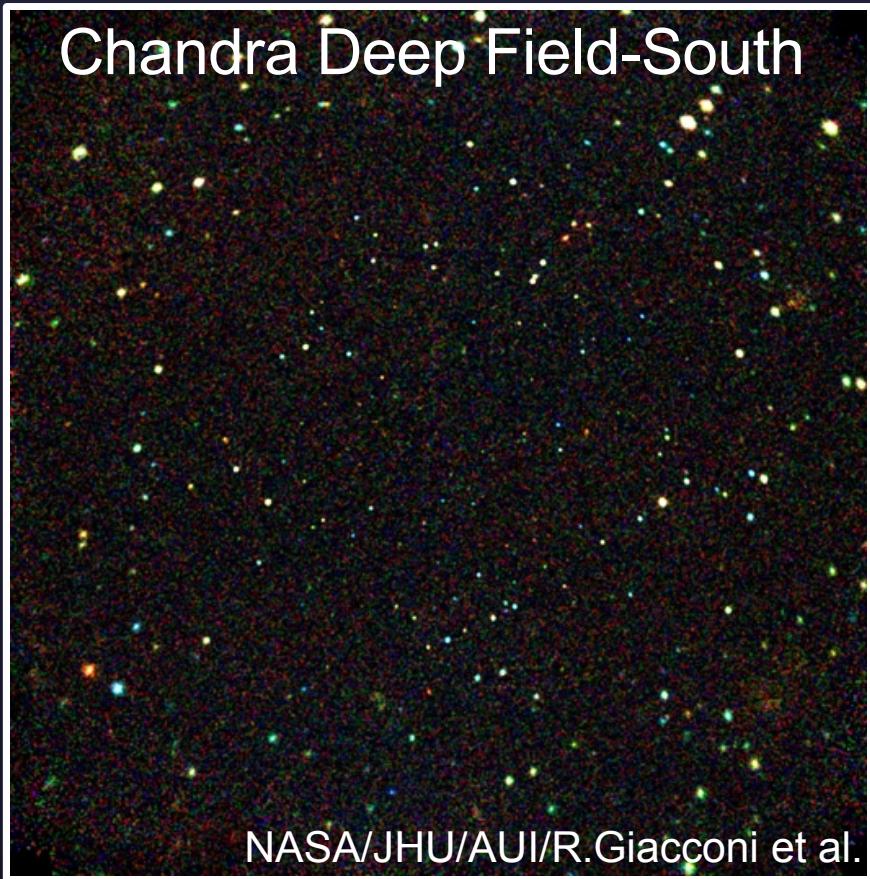
The Nuts and Bolts

“T_{HBR}” Data Analysis

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



Chandra Deep Field-South

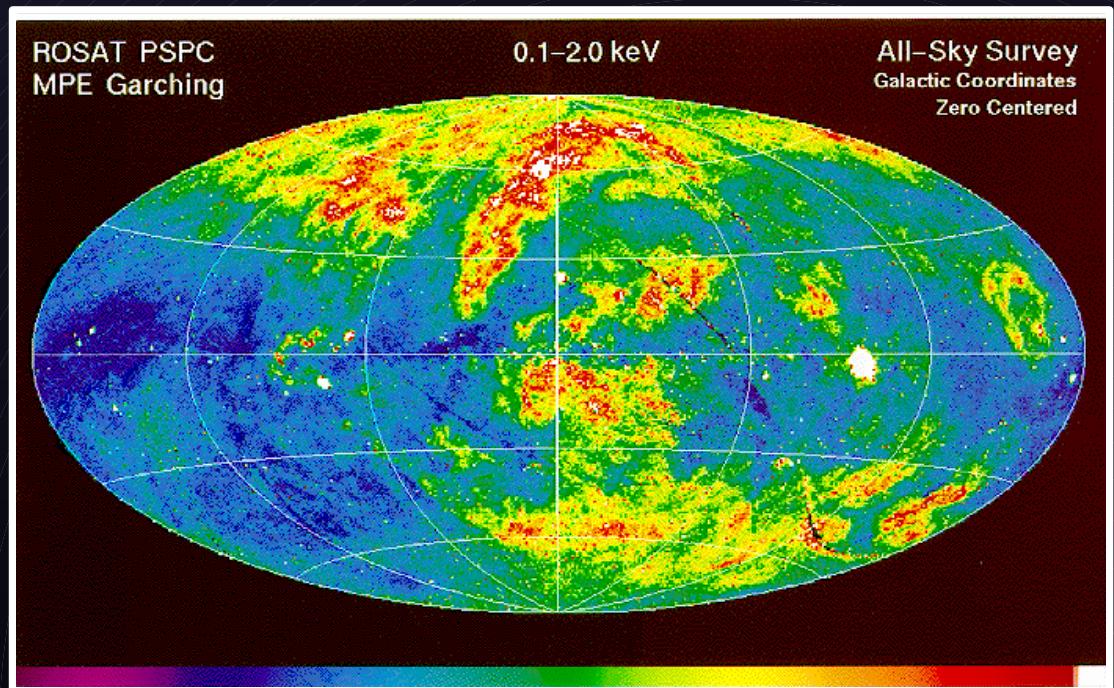


NASA/JHU/AUI/R.Giacconi et al.

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

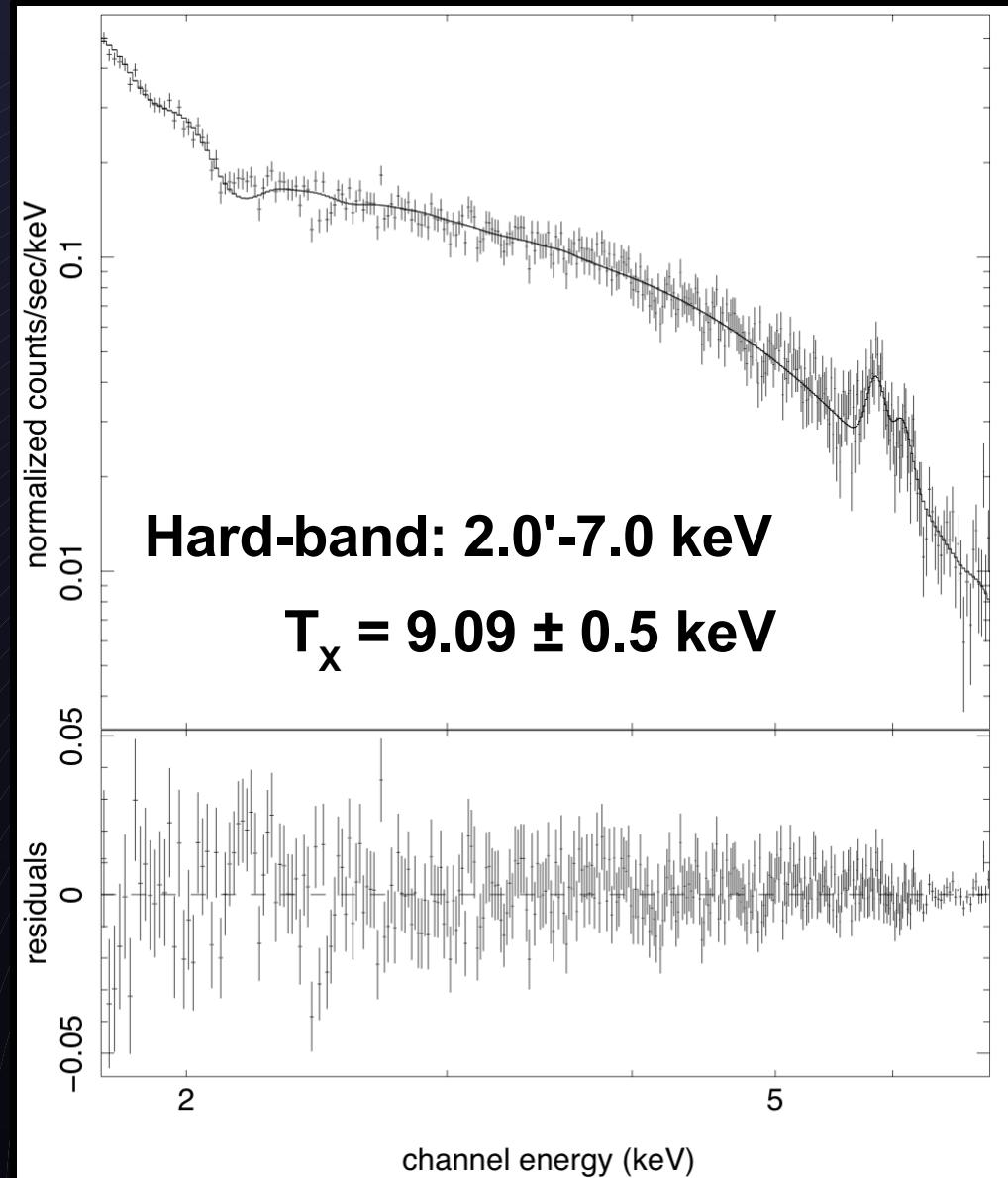
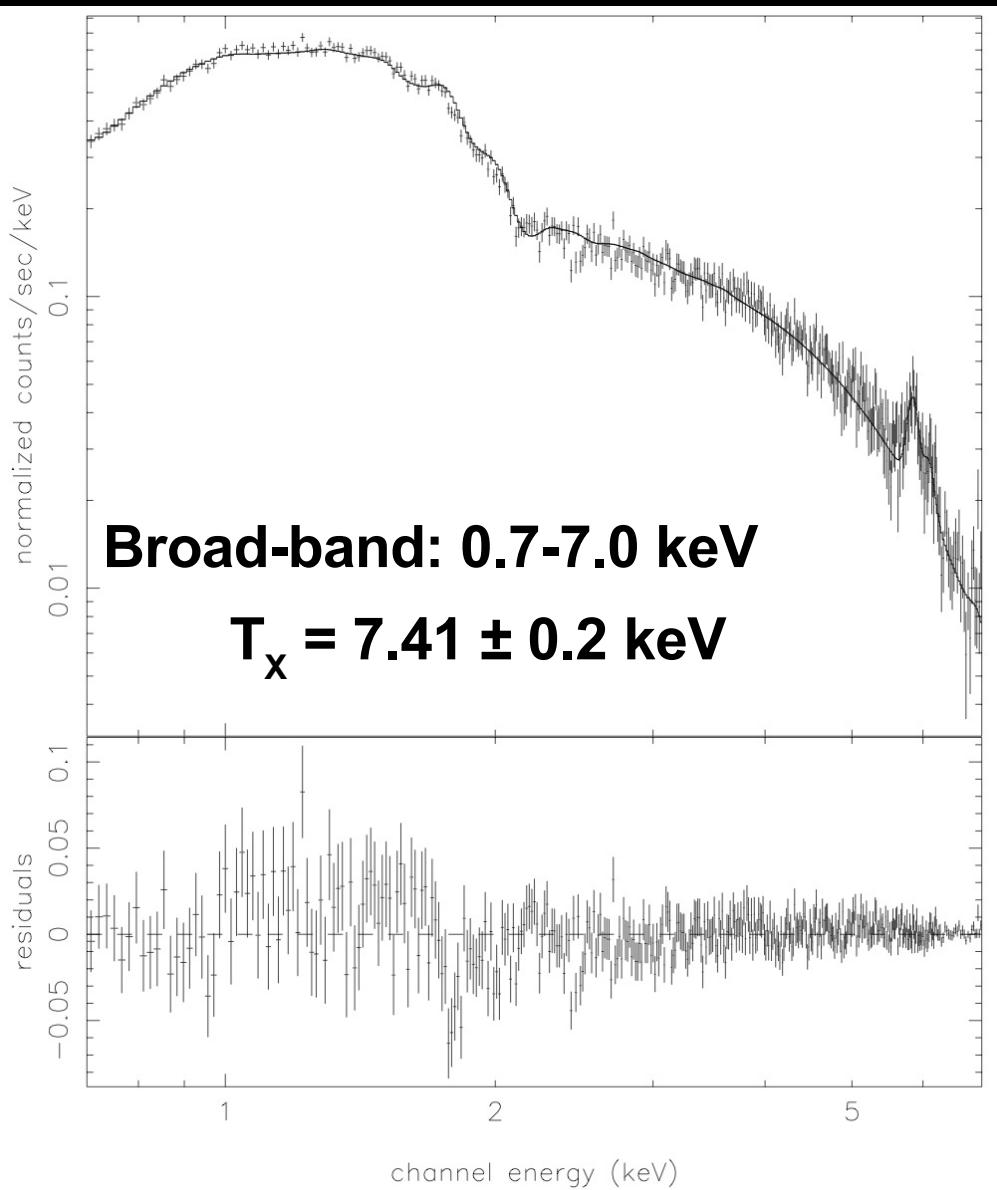
X-ray Background Consideration

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



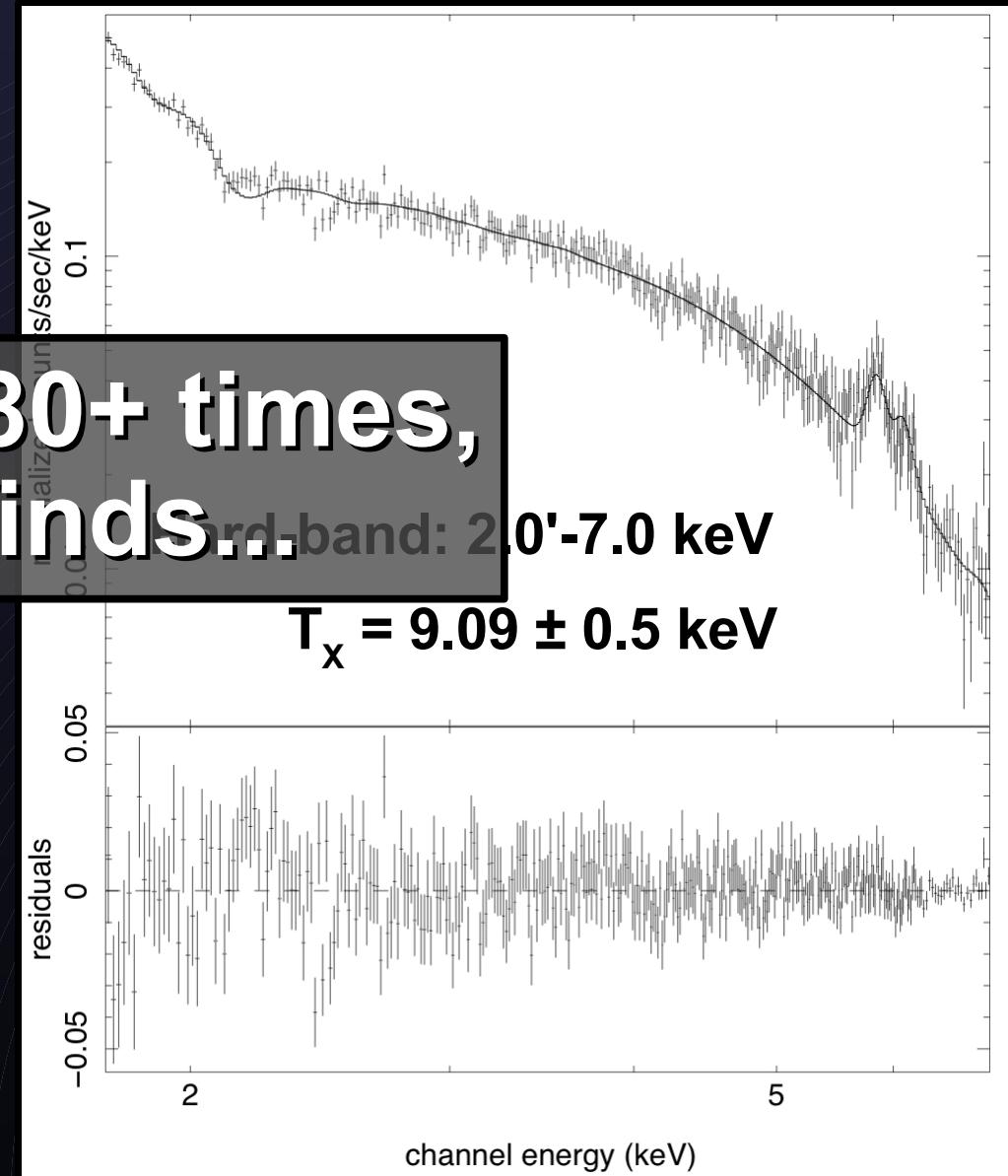
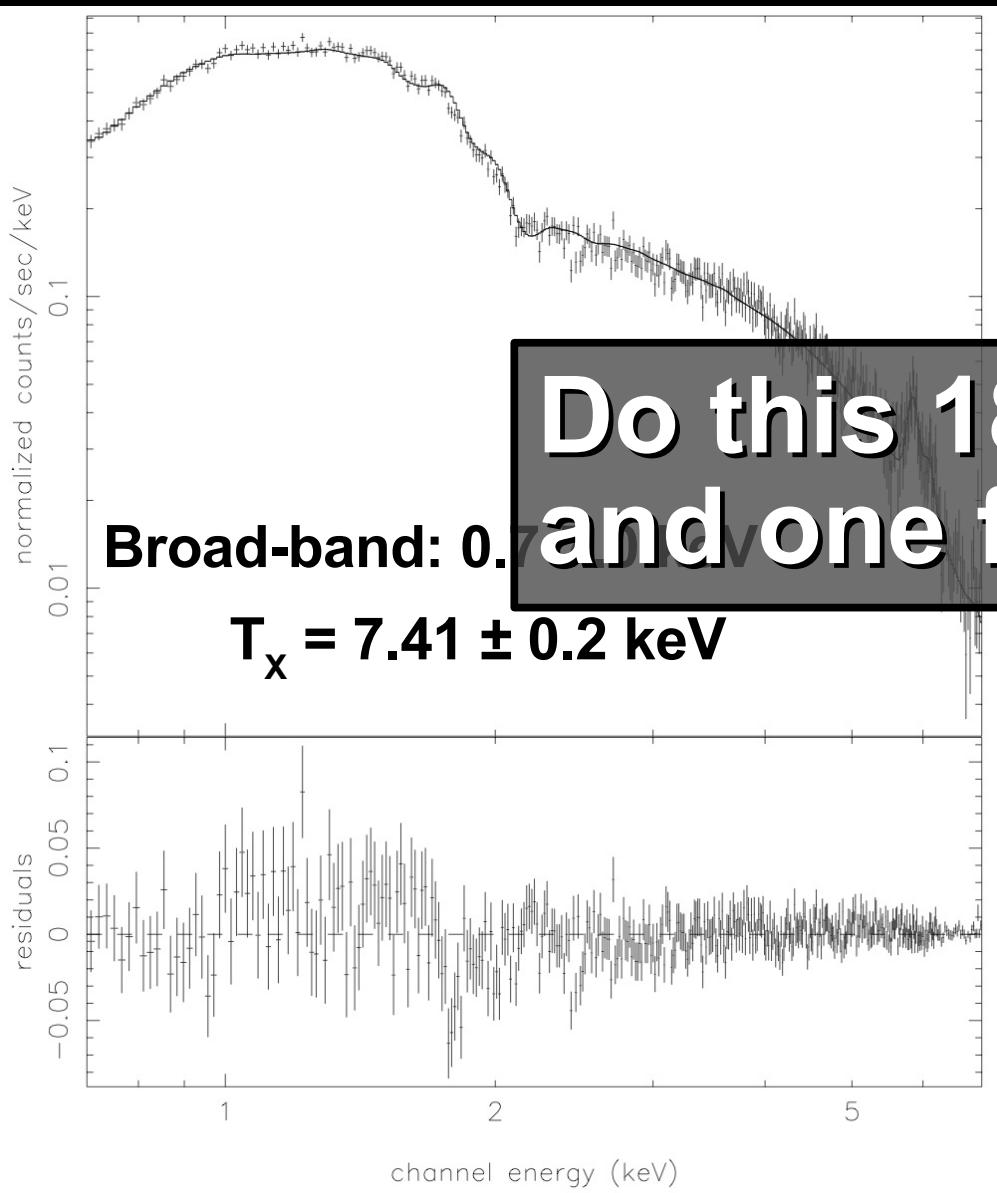
Inferring the gas temperature

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



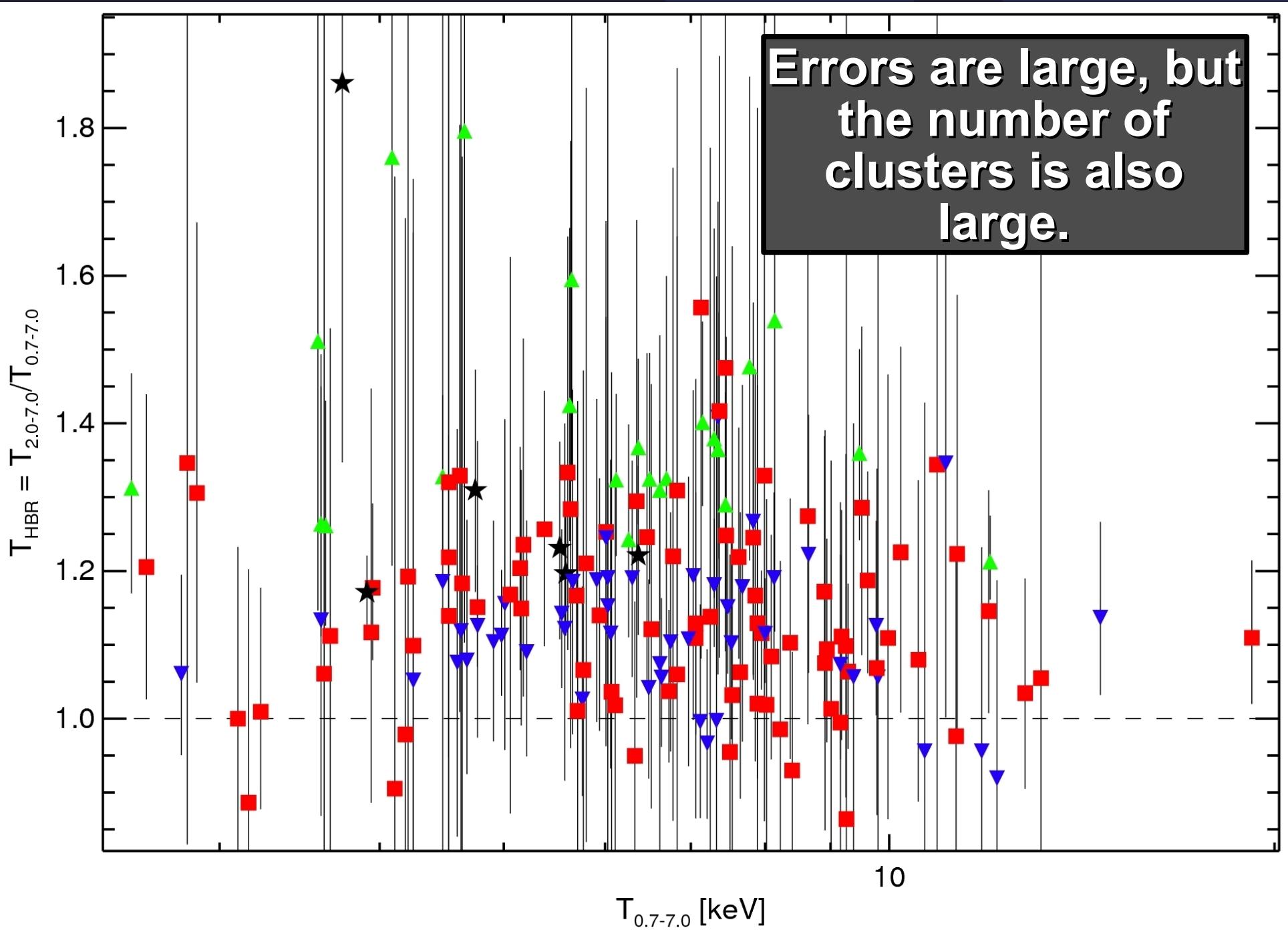
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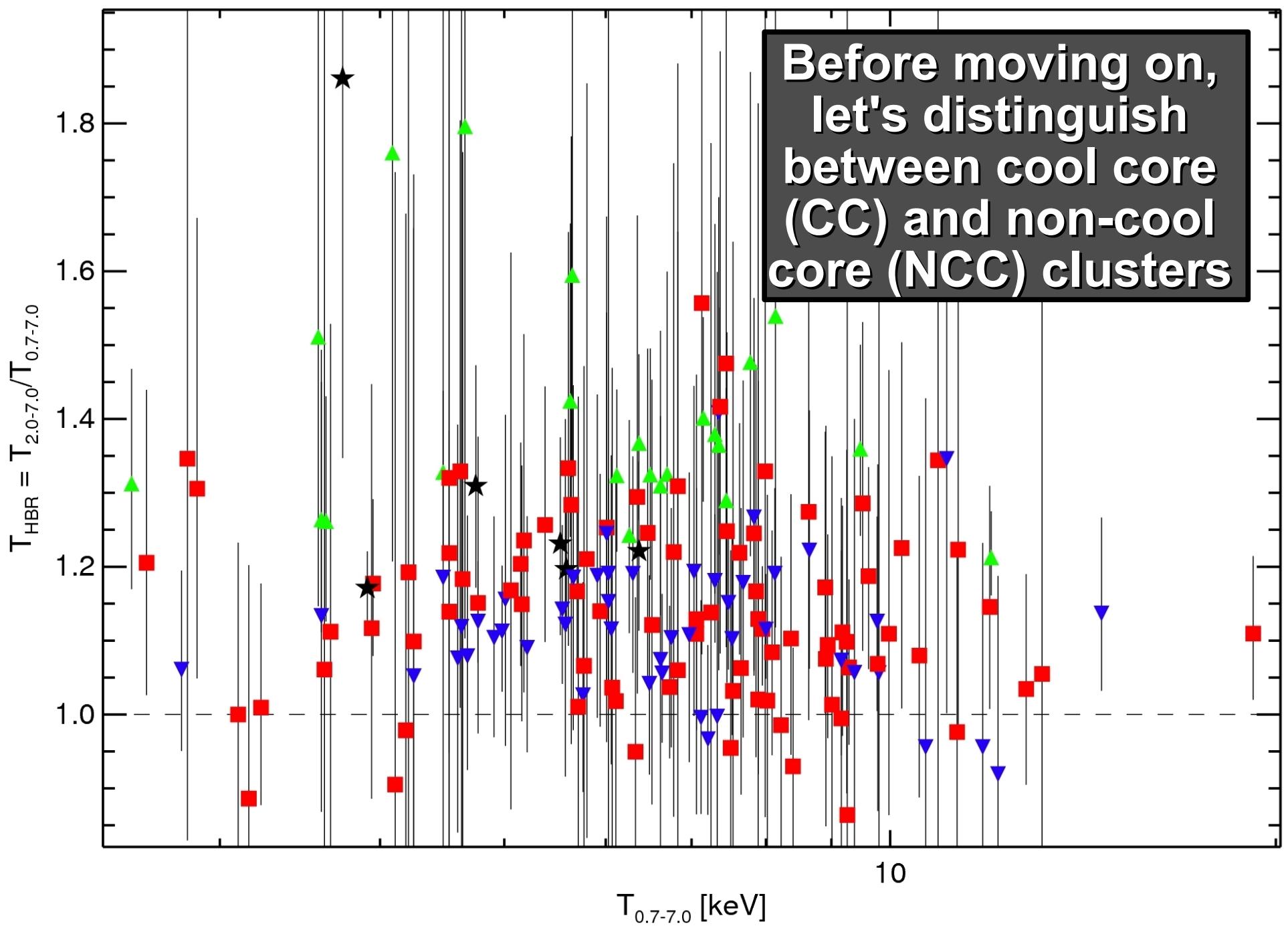
Do this 180+ times,
and one finds...

Net Skewing of T_{HBR}

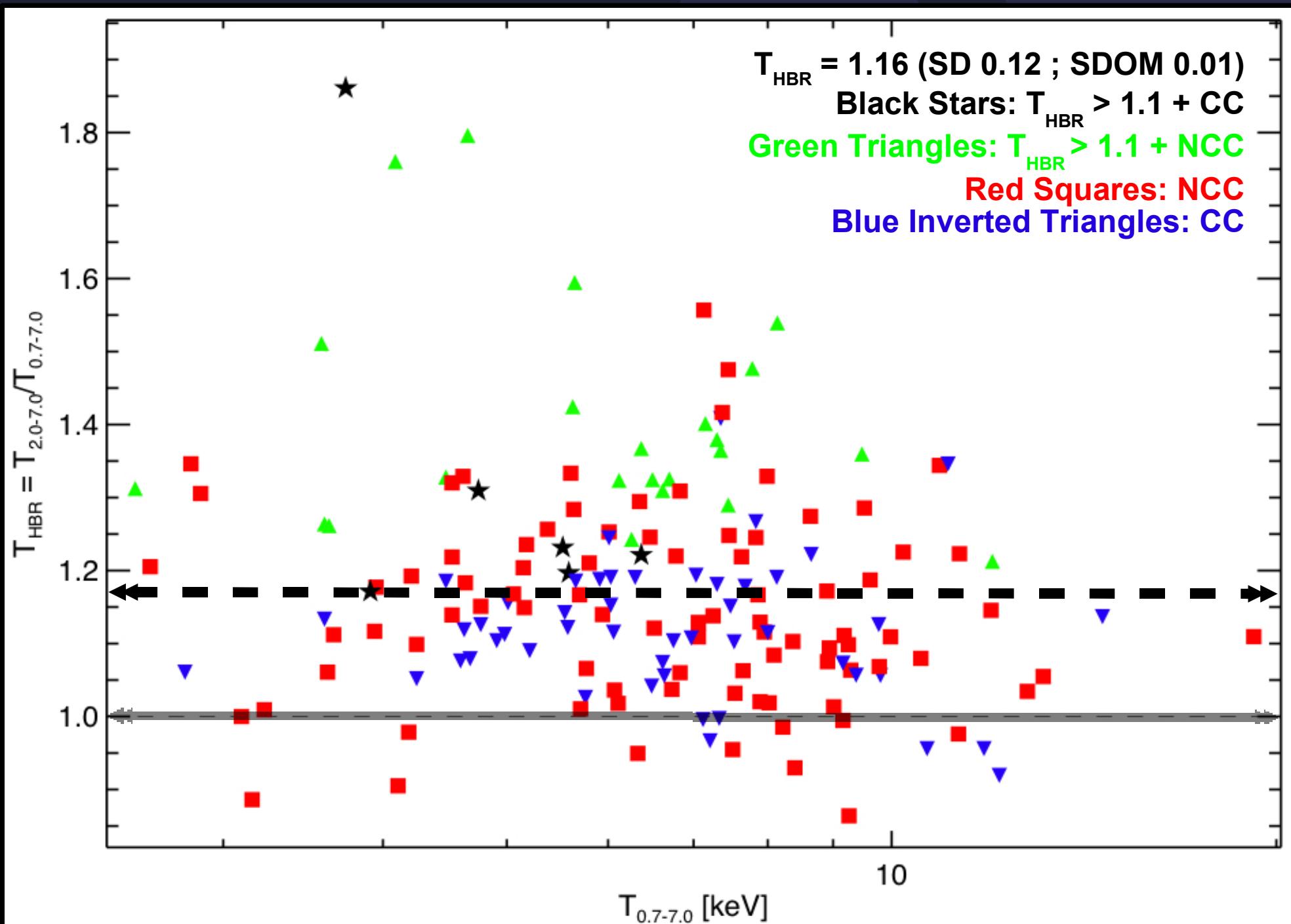


Net Skewing of T_{HBR}

Before moving on,
let's distinguish
between cool core
(CC) and non-cool
core (NCC) clusters

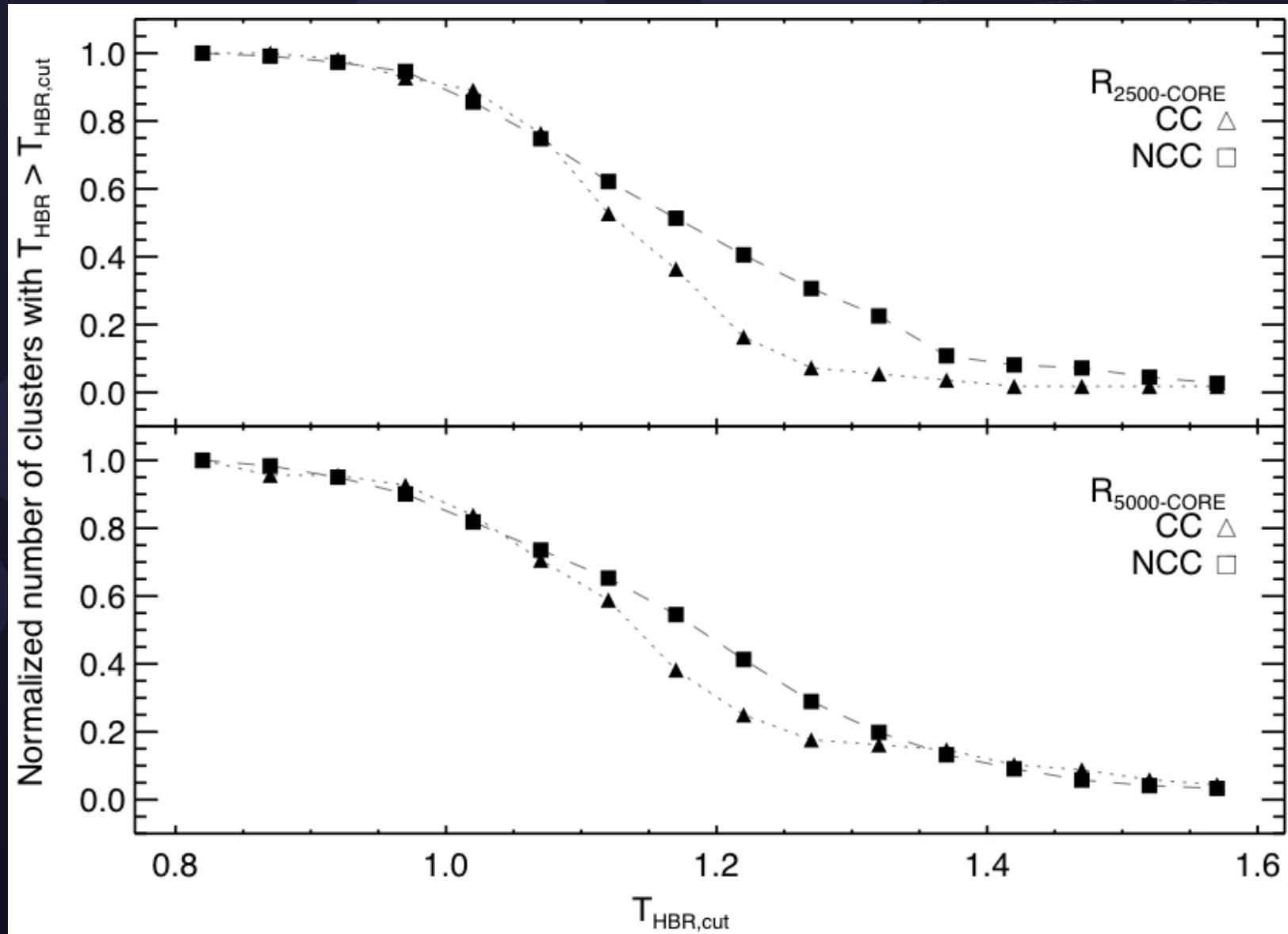


Net Skewing of T_{HBR}



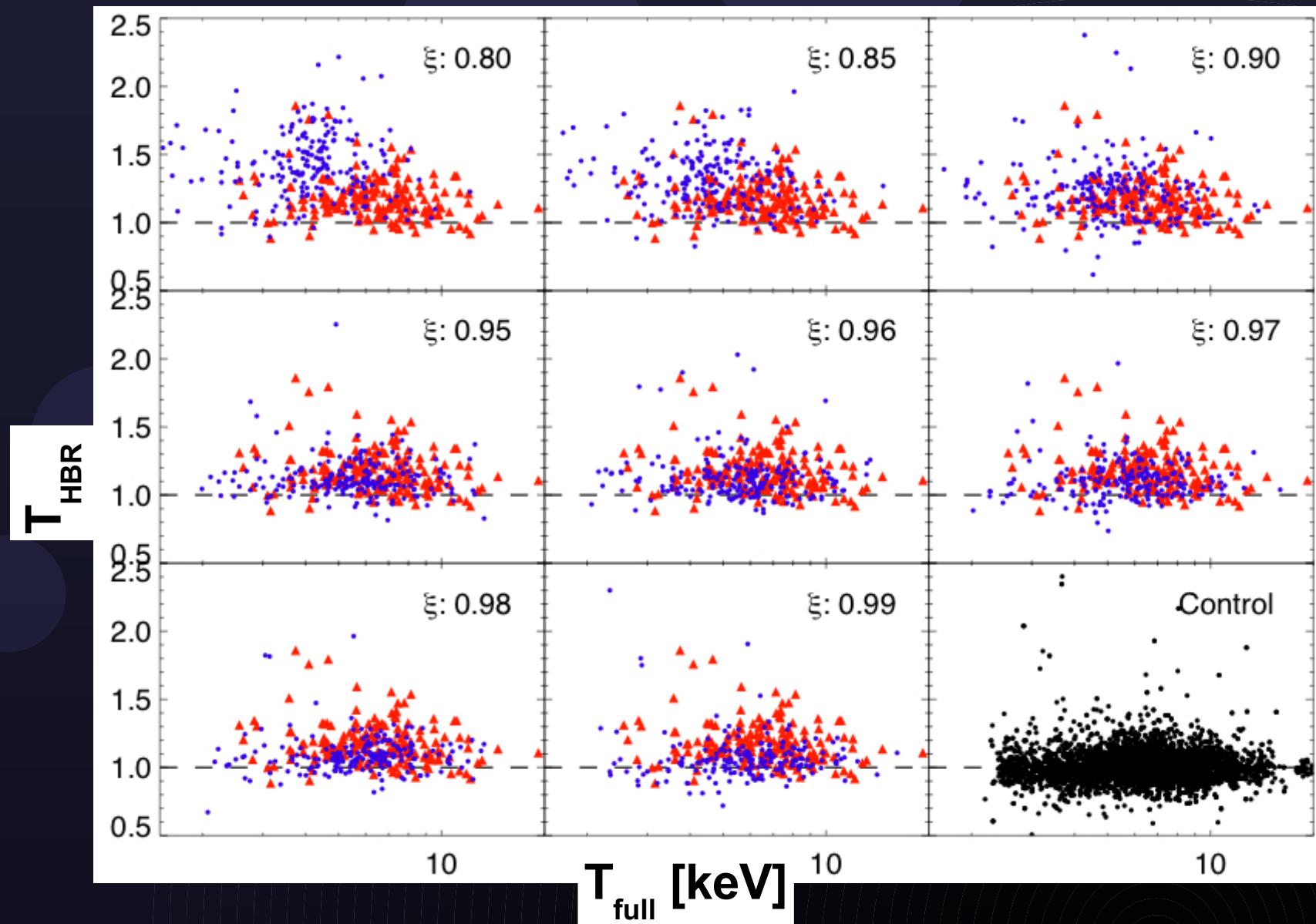
Culling out Cool Cores using T_{HBR}

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

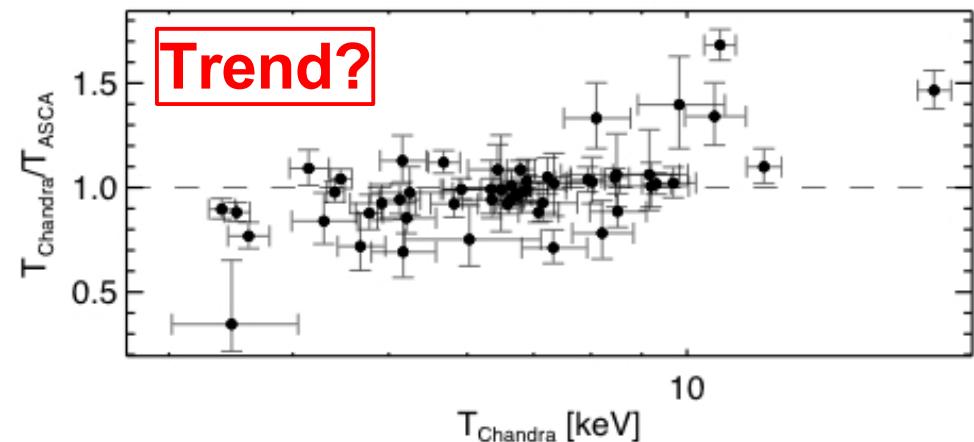
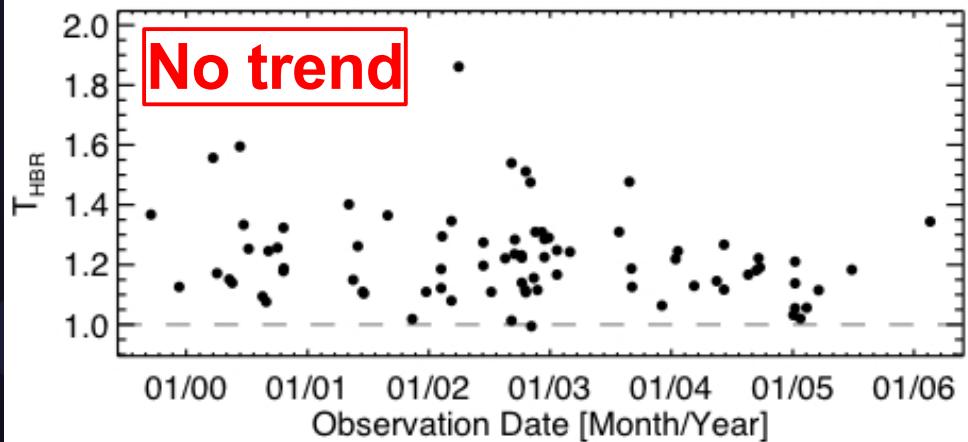
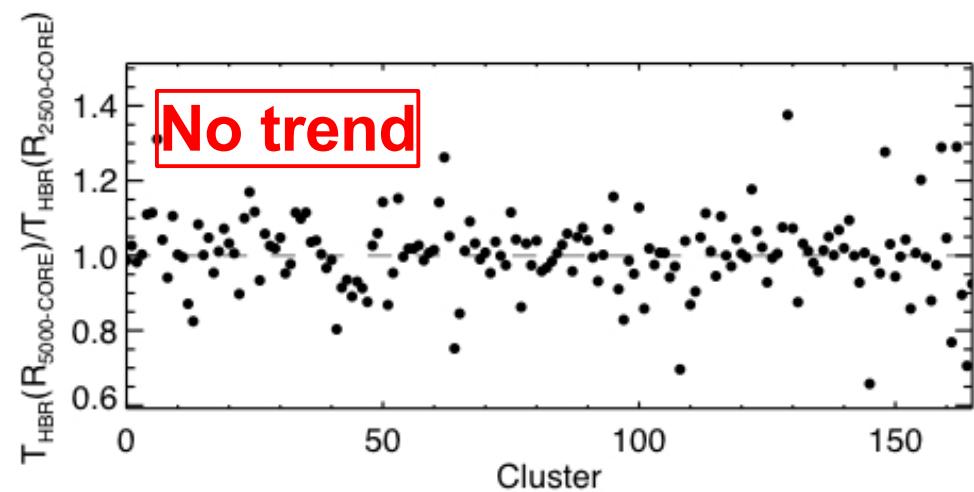
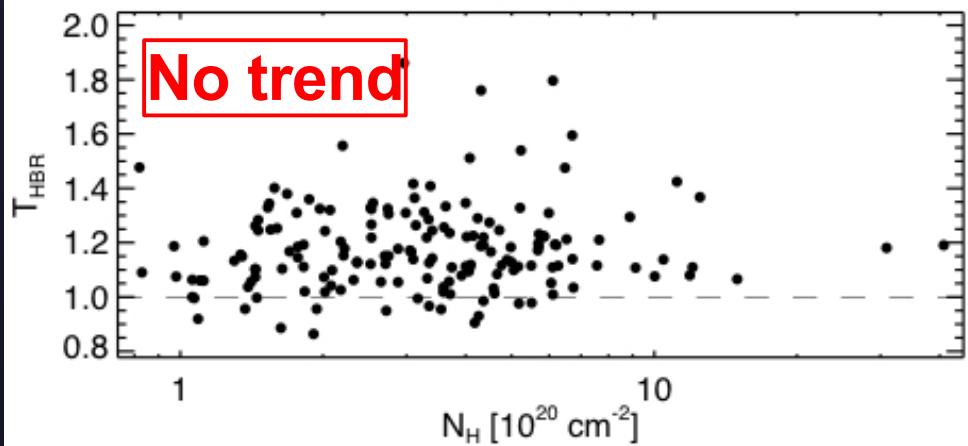
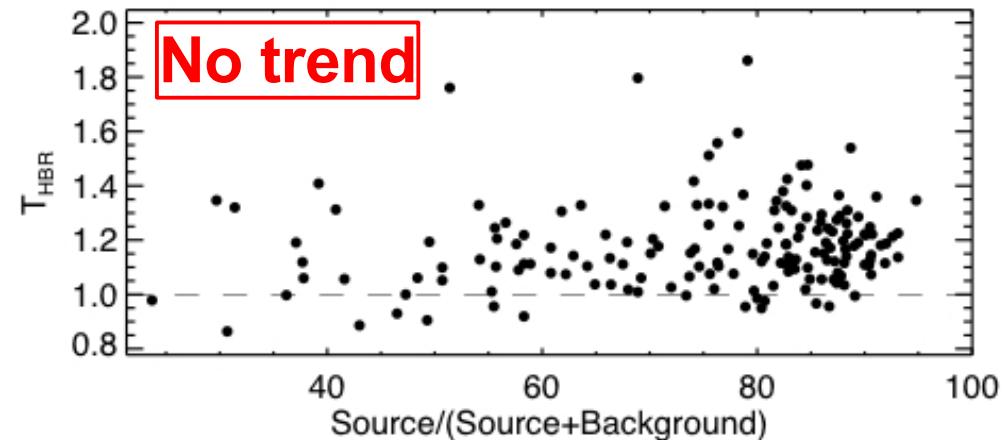
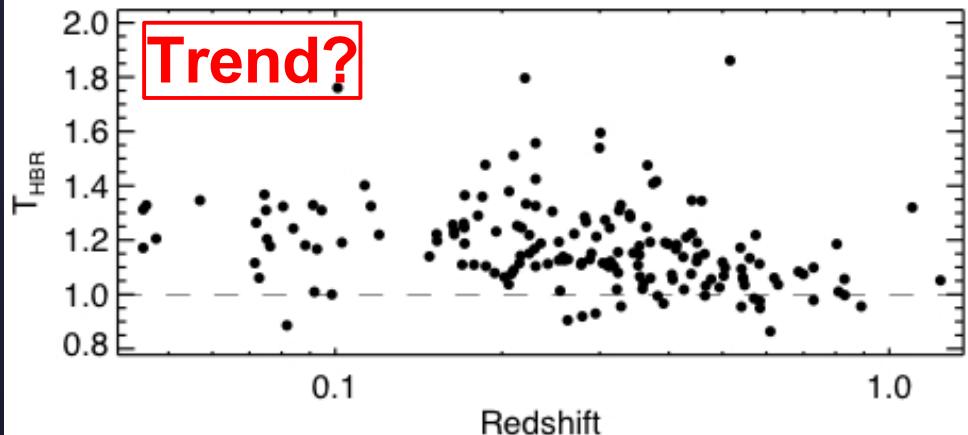


Simulations and Systematics

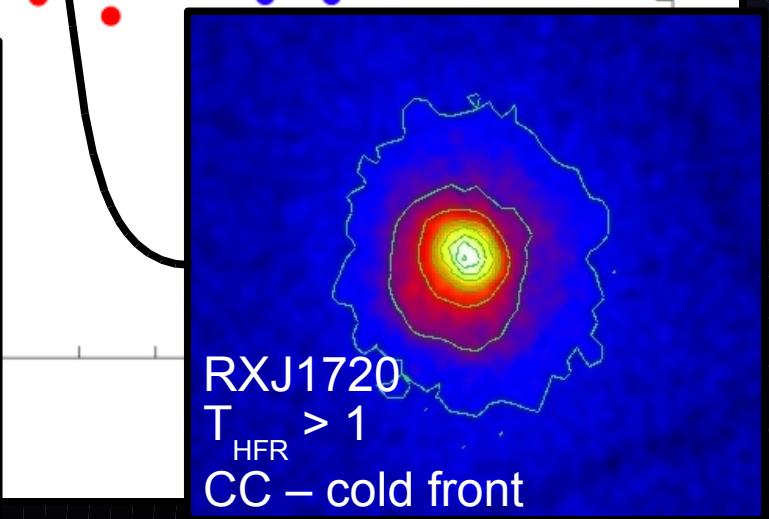
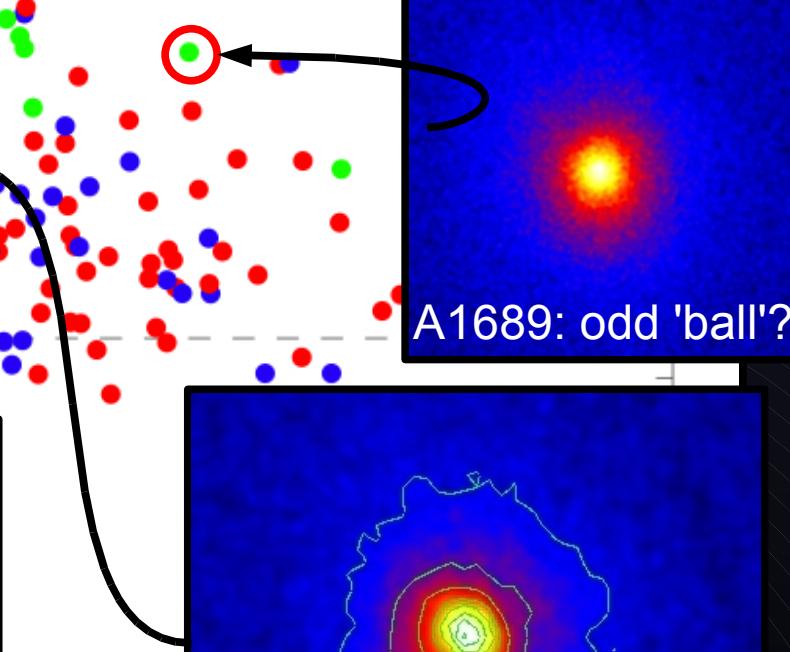
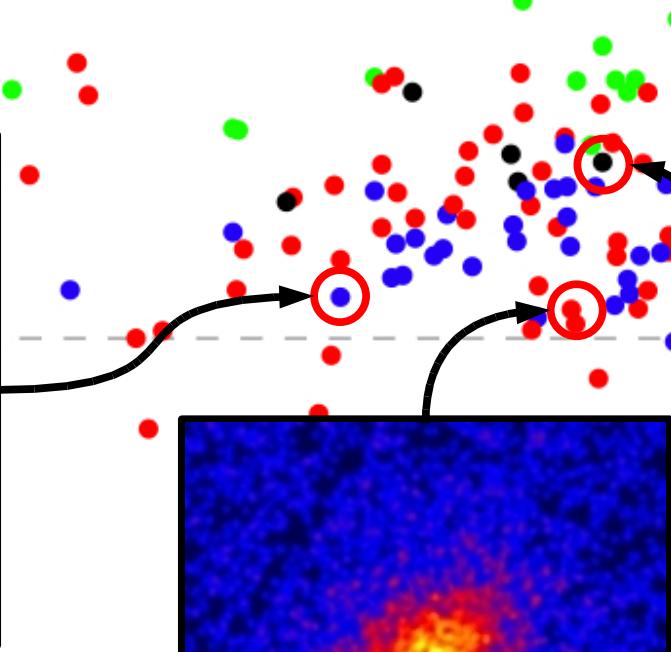
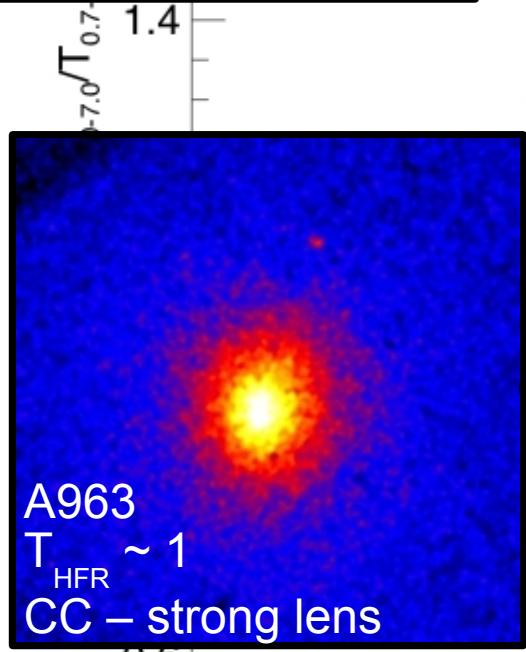
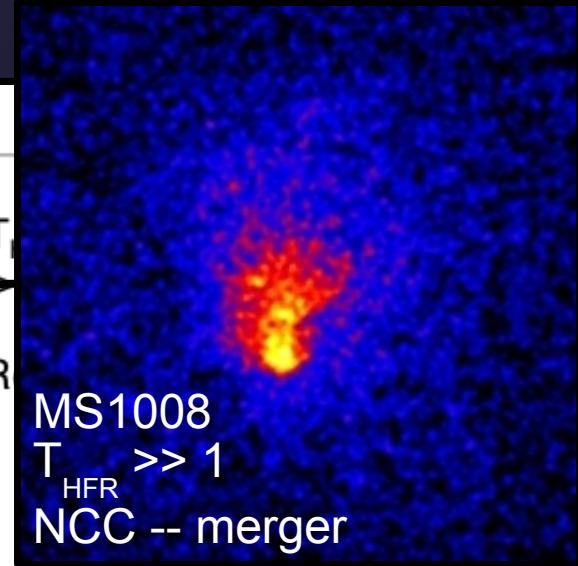
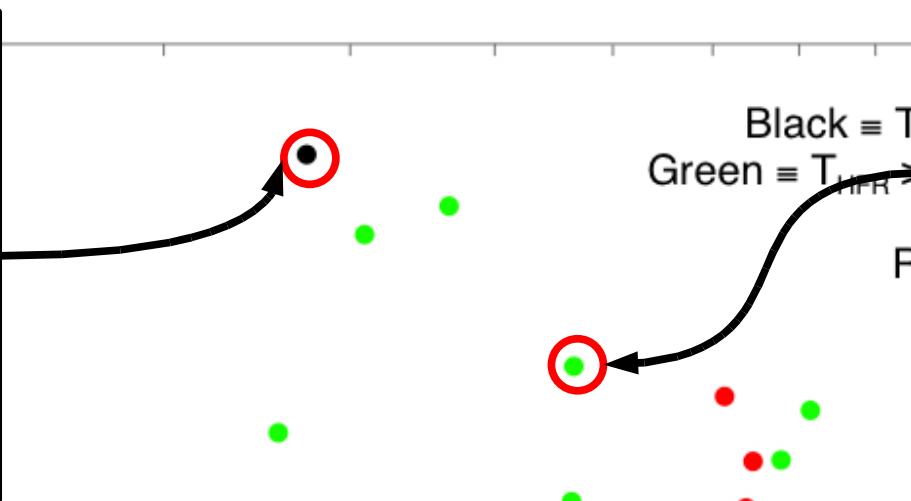
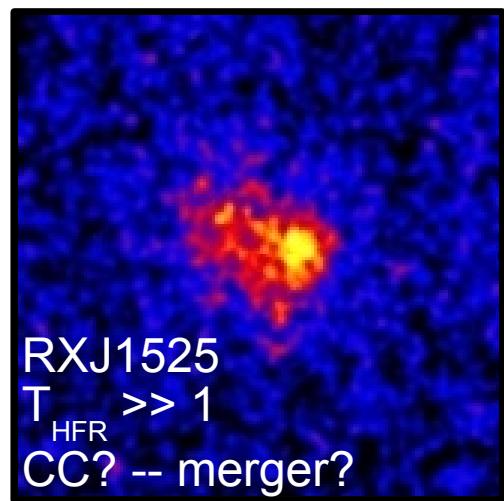
- Simulate two-phase gas
- Repeat spectral analysis
- Observe skewing in sims but not in control
- Dispersion in observation > control



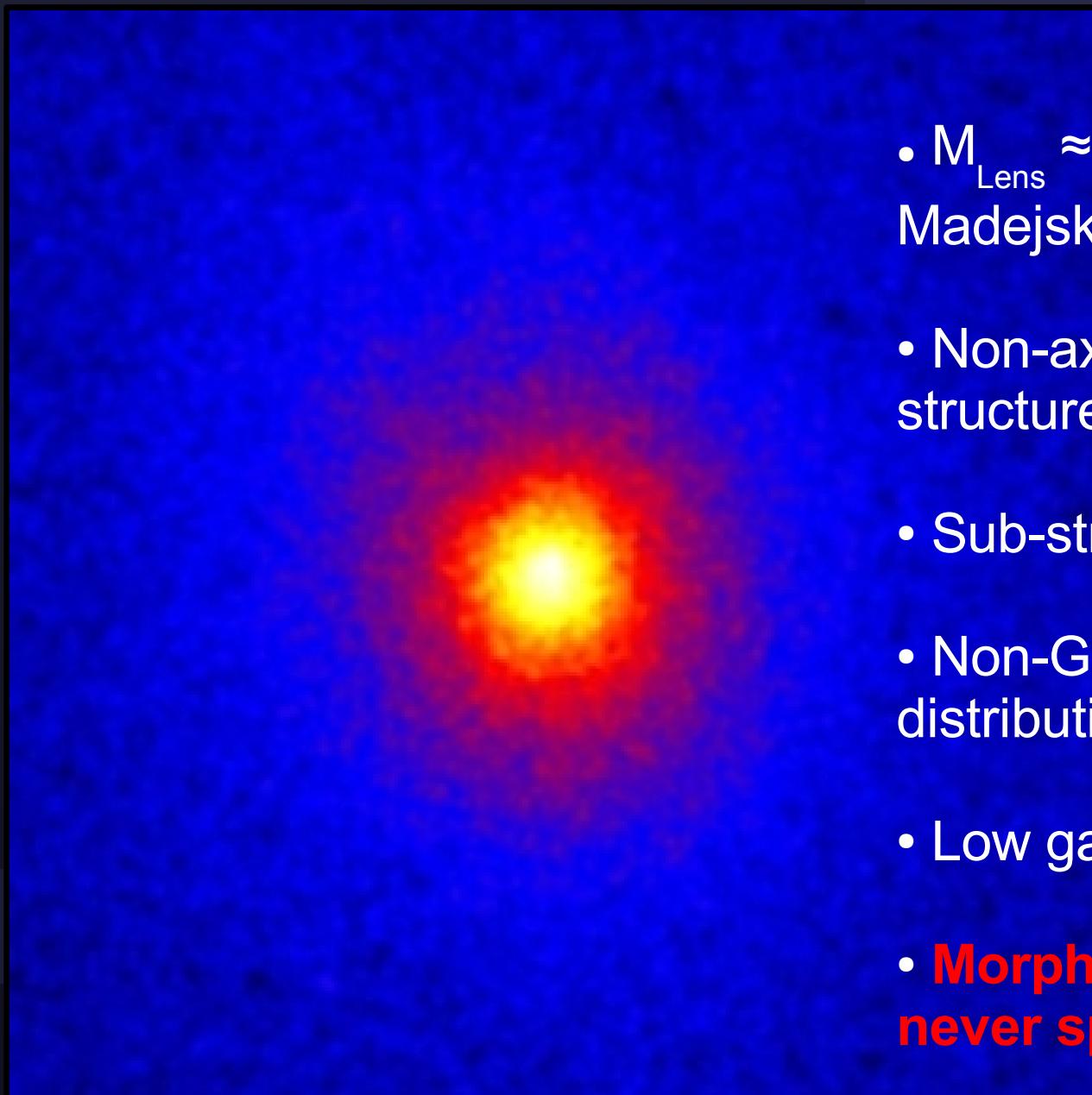
Simulations and Systematics



Putting It All Together



Abell 1689: not so relaxed



- $M_{\text{Lens}} \approx 2 \times M_{\text{X-ray}}$ (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”**

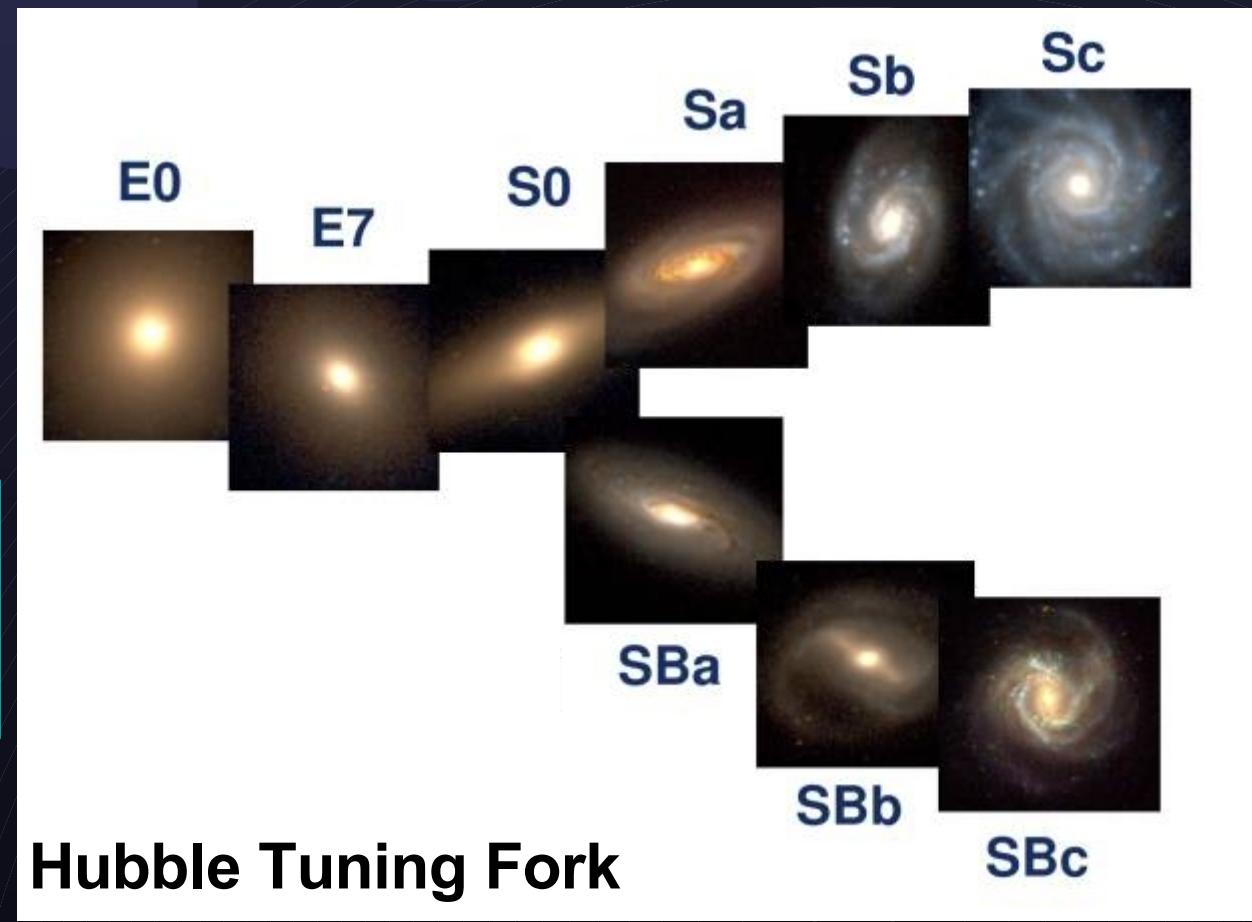
Cosmological Importance of Relaxation

- 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

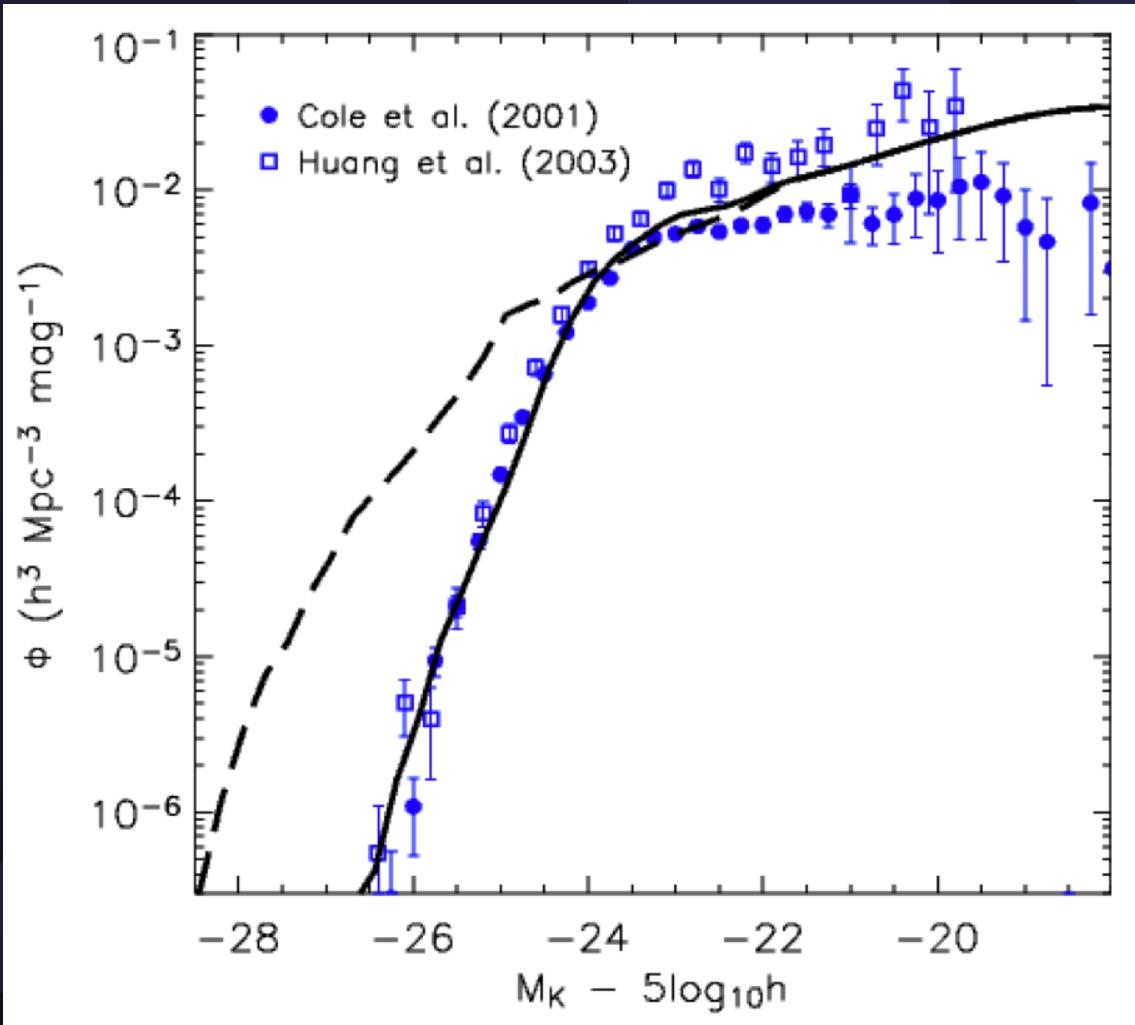
Now, what of the feedback issue...?

Why study galaxy clusters?

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



Importance of Feedback

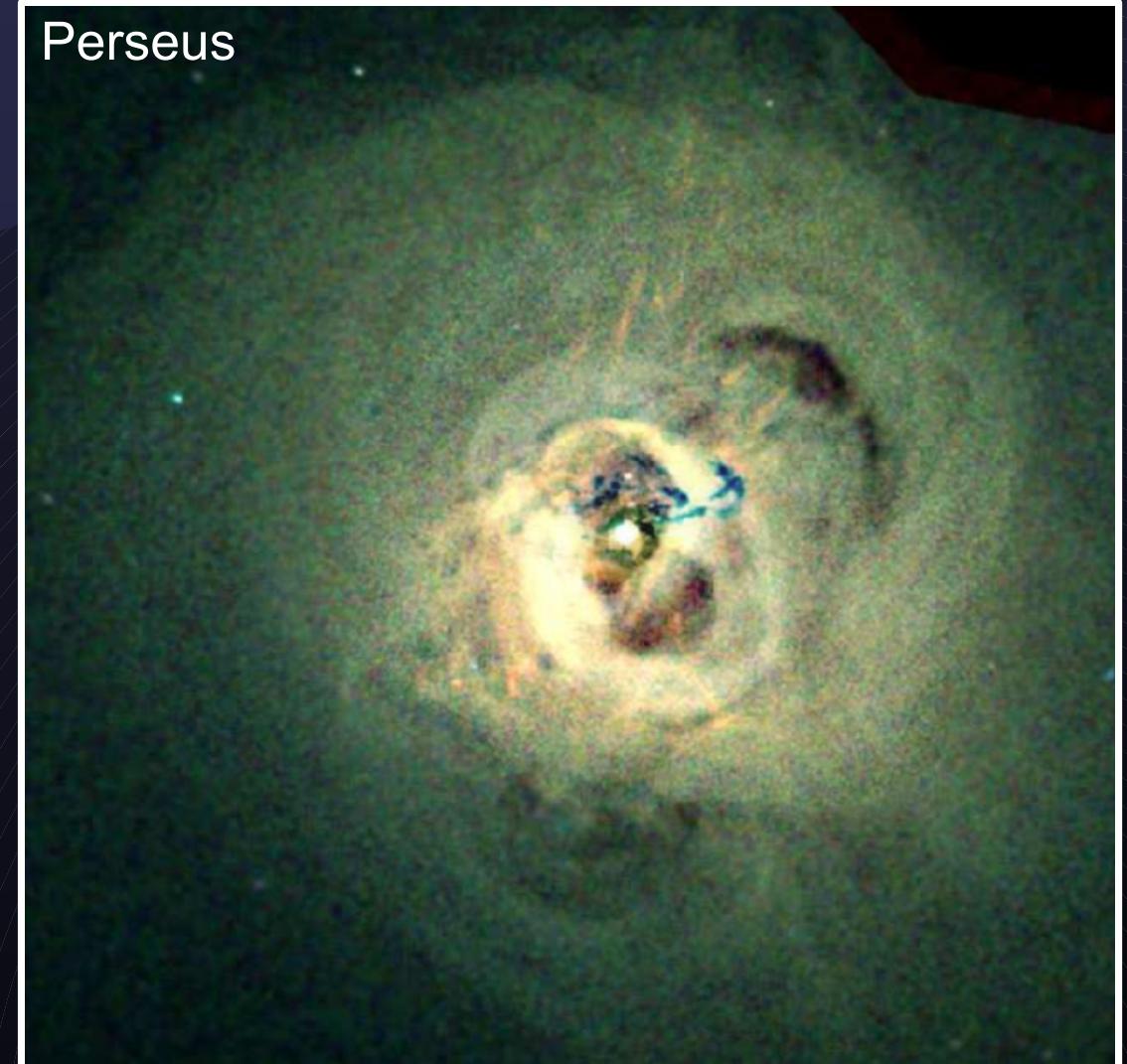


- Theory predicts:
 - Too many massive, blue galaxies
 - Too many dwarf galaxies
- The trouble with old ellipticals
 - Vigorous feedback at high-z
 - “Down-sizing” problem
- Central galaxy in groups and clusters are not growing unabated

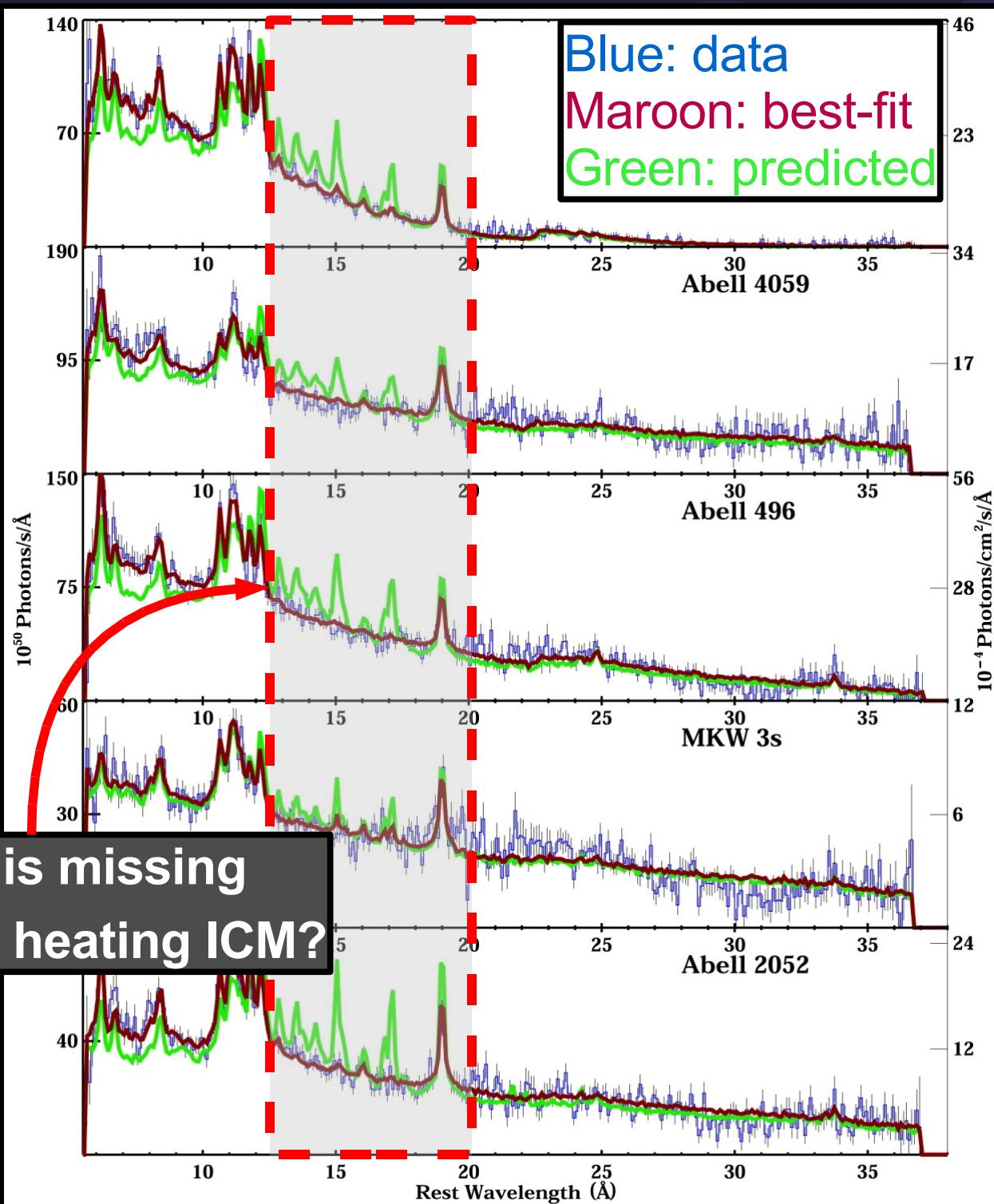
Croton et al. 2006

Importance of Feedback

- Central cooling time of ICM much shorter than Hubble age
- Expect massive flows of cool gas into core
- But star formation isn't rampant, why?
- Take a look at right...



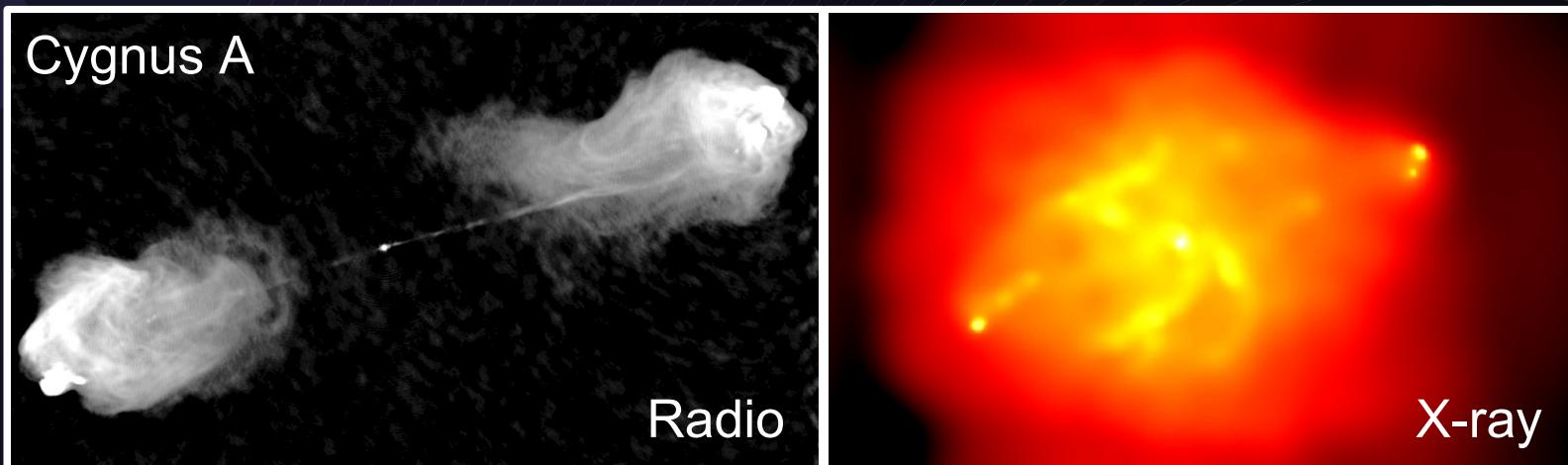
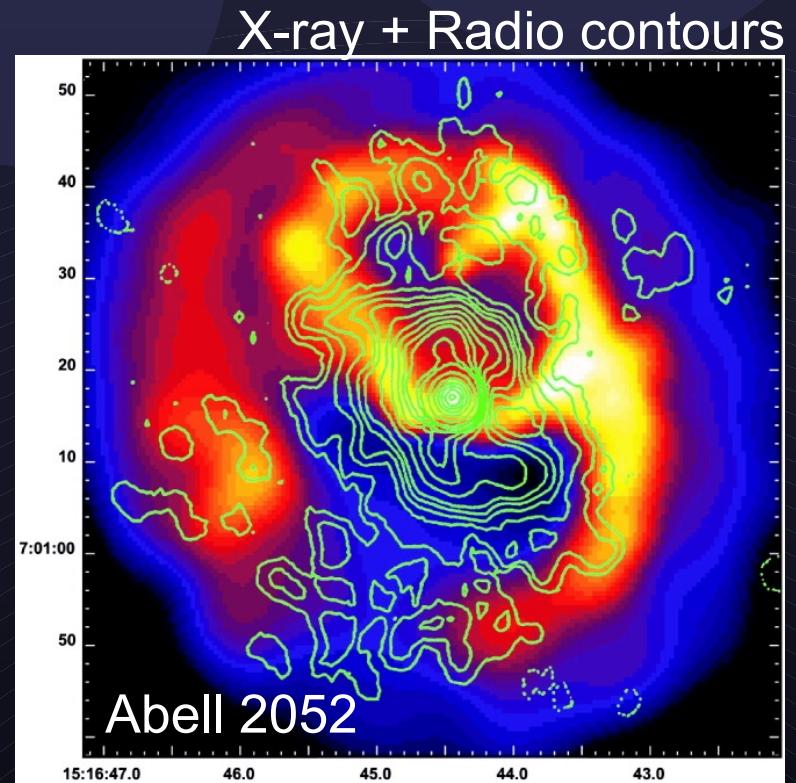
Cooling Trickles



- $T \leq \frac{1}{3}T_{\text{virial}}$ is missing
- Feedback heating ICM?

Importance of Feedback

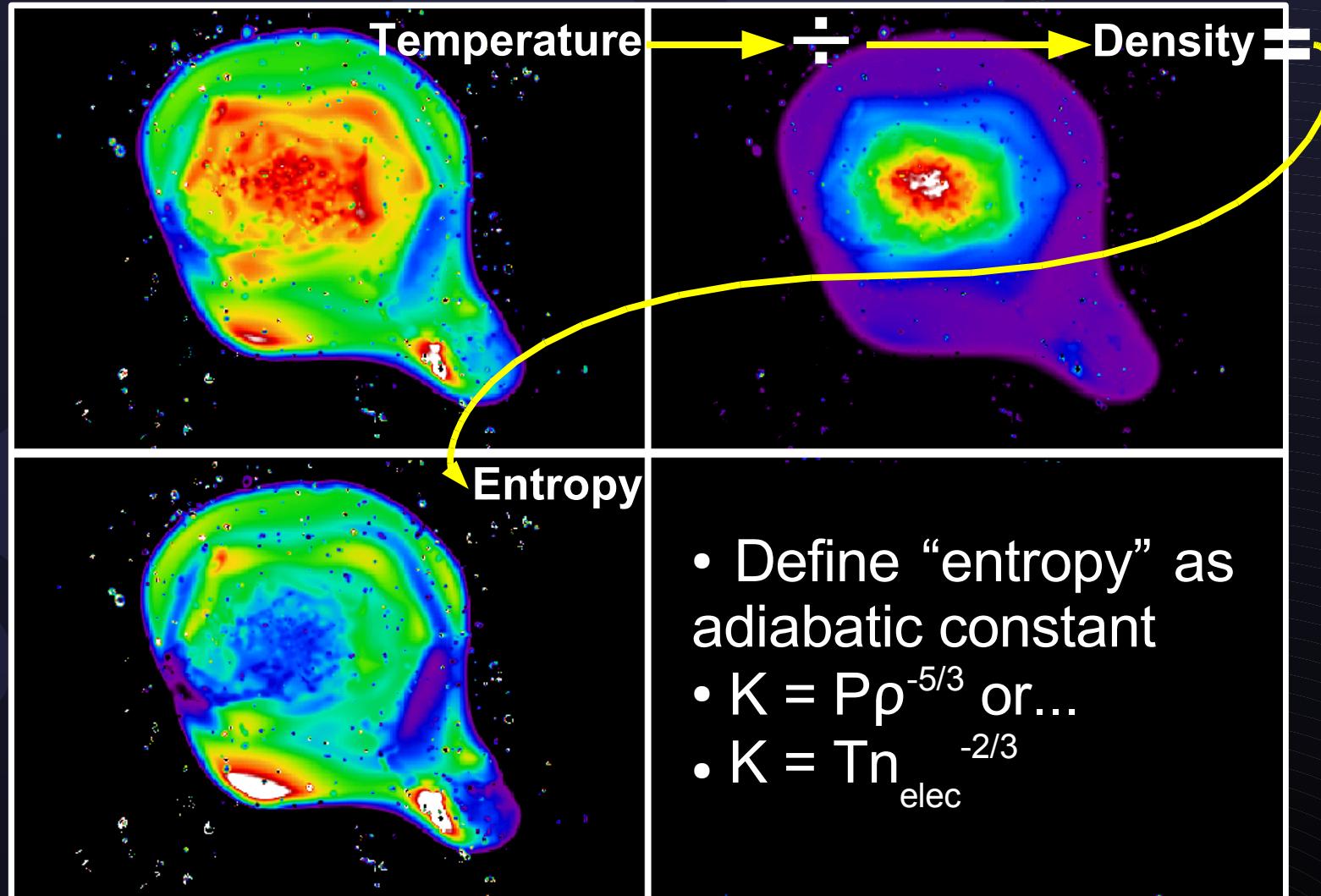
- Feedback heating now widely accepted
- Very, very modest star formation
- AGN are active
- Galaxy growth slowed
- How do we make sense of all this?
- **Our 'close to the data' approach:**
 - Study cooling ICM
 - Better understand feedback
 - Work toward self-regulation model
 - Focus on ICM entropy...



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
Schuecker et al. 2004

Properties of Entropy

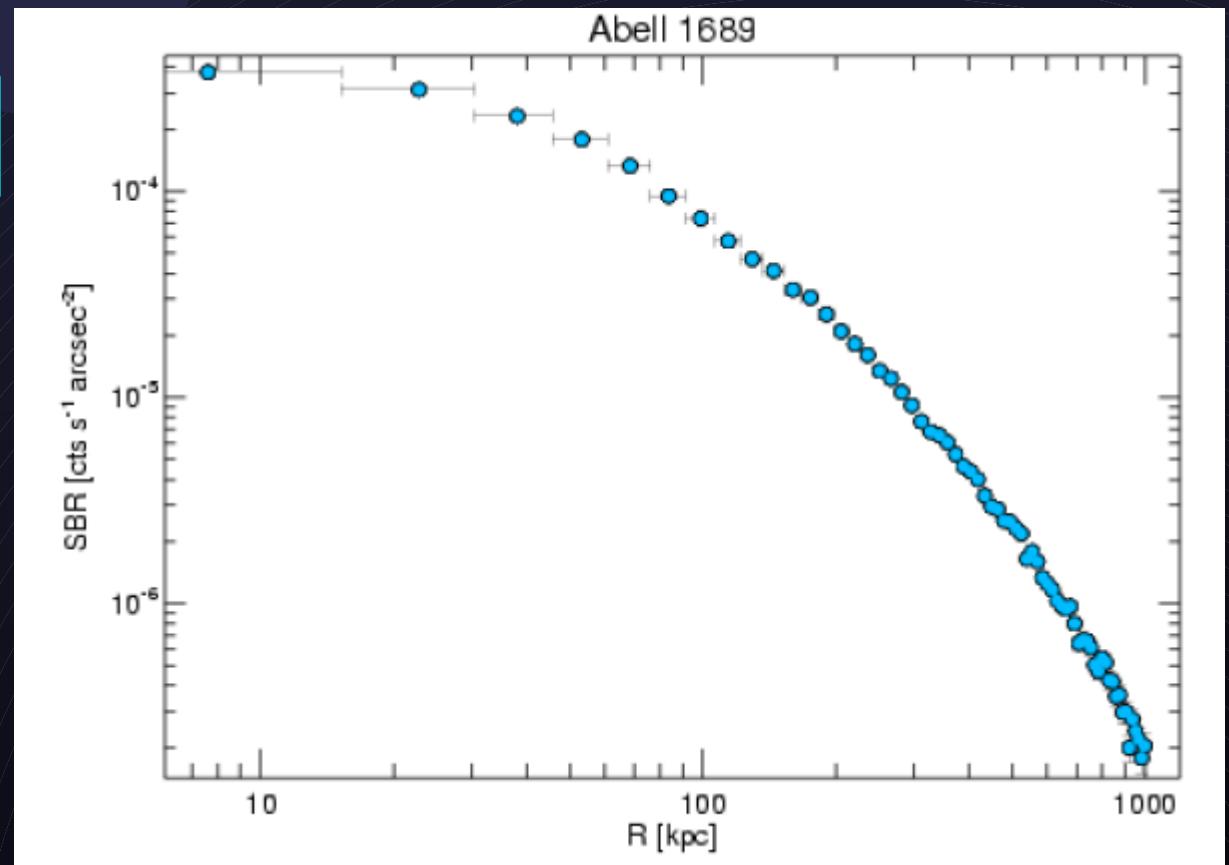
- In a gravity only Universe... radial entropy distribution follows power-law
- Potential wells are entropy sorting devices
- Departures from power-law indicative of past heating and cooling



**Chandra data reduction...
in a nutshell**

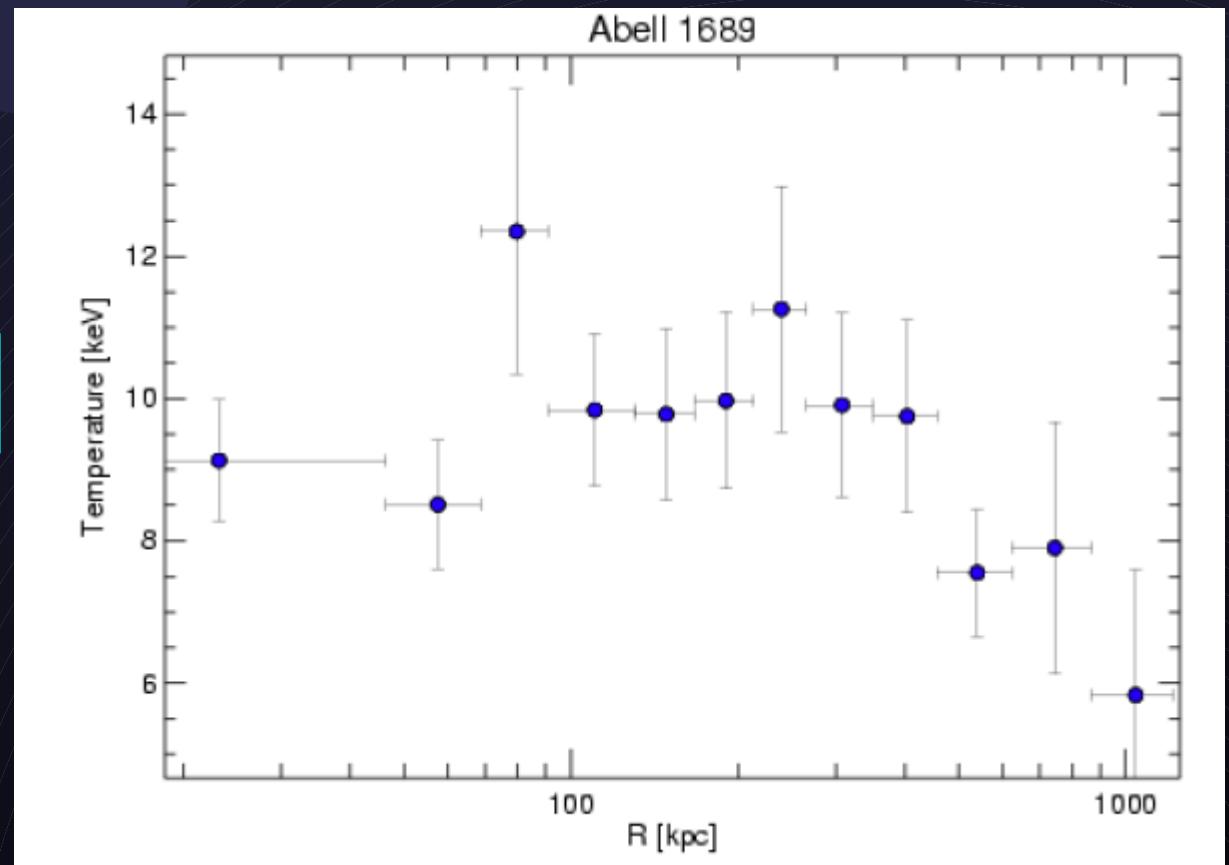
Chandra Data Reduction... in a nutshell

- 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



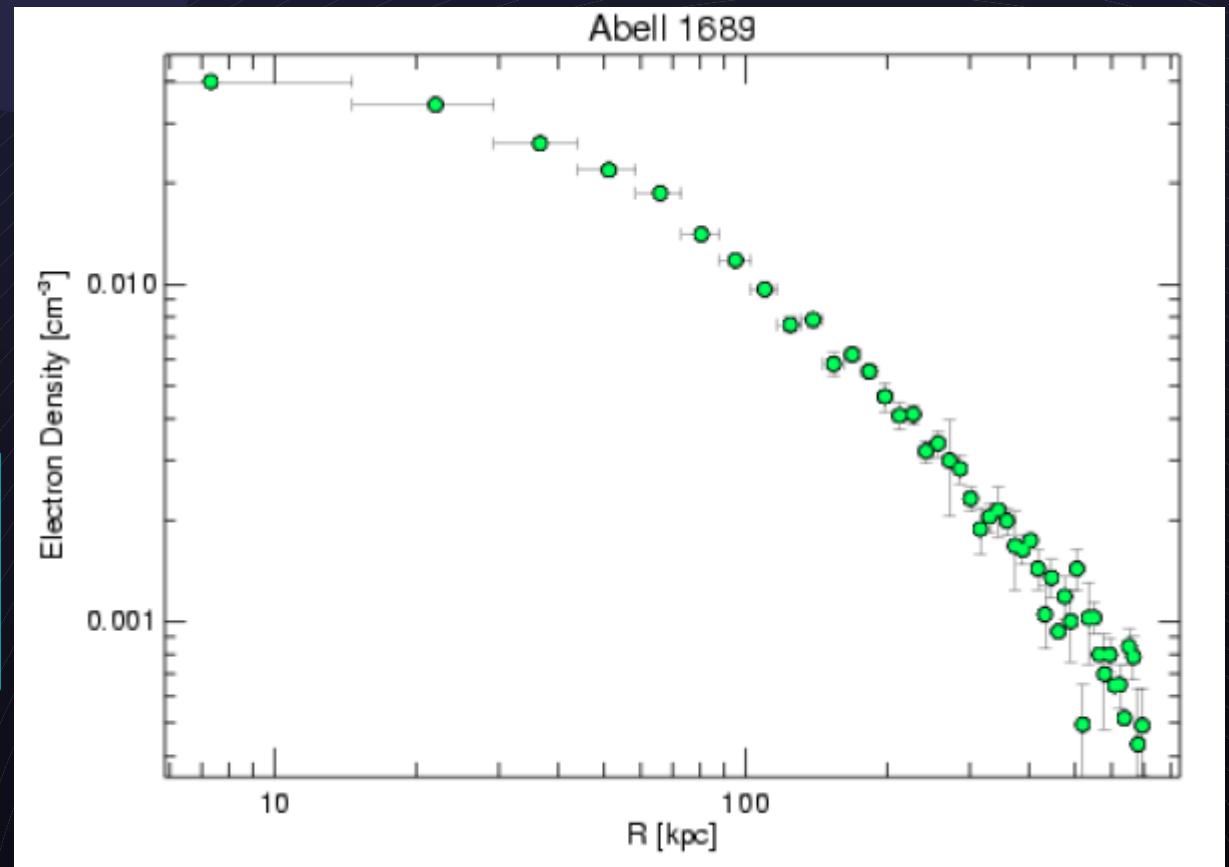
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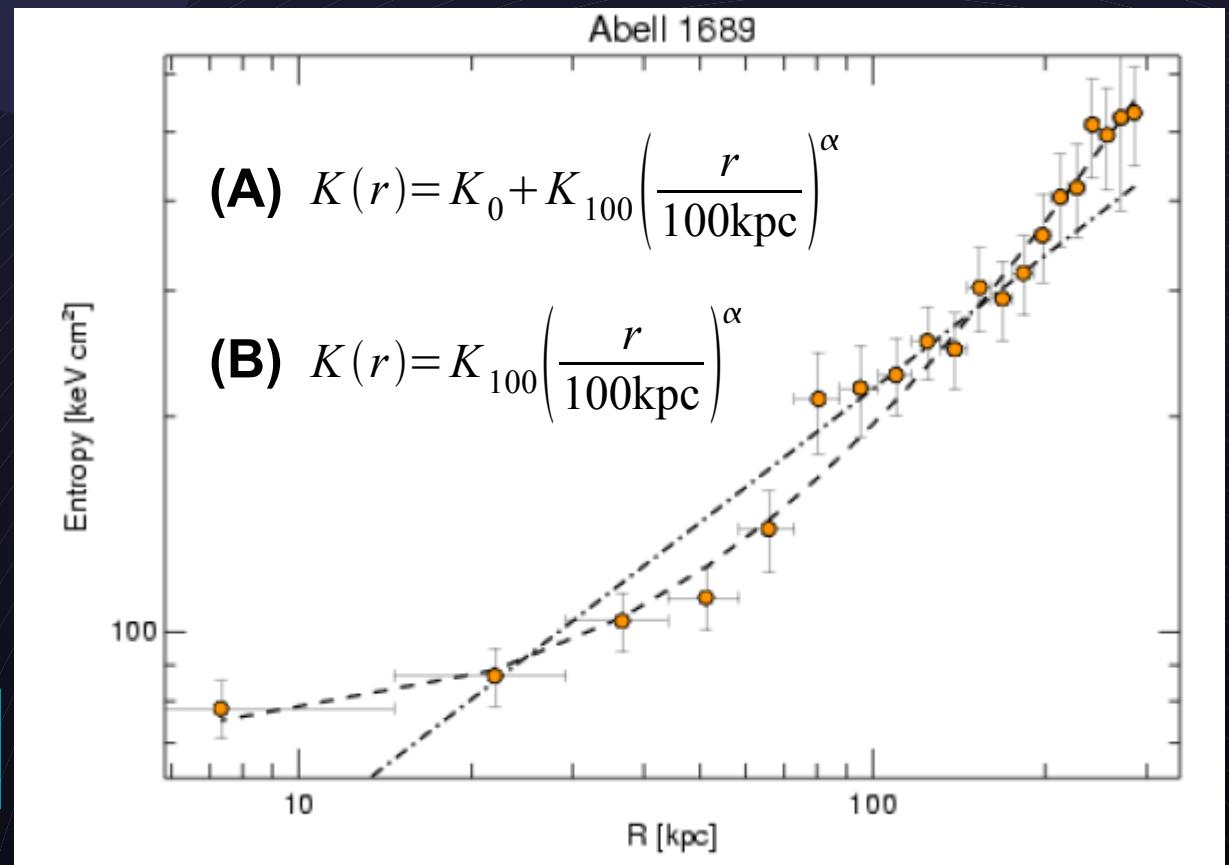
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Chandra Data Reduction... in a nutshell

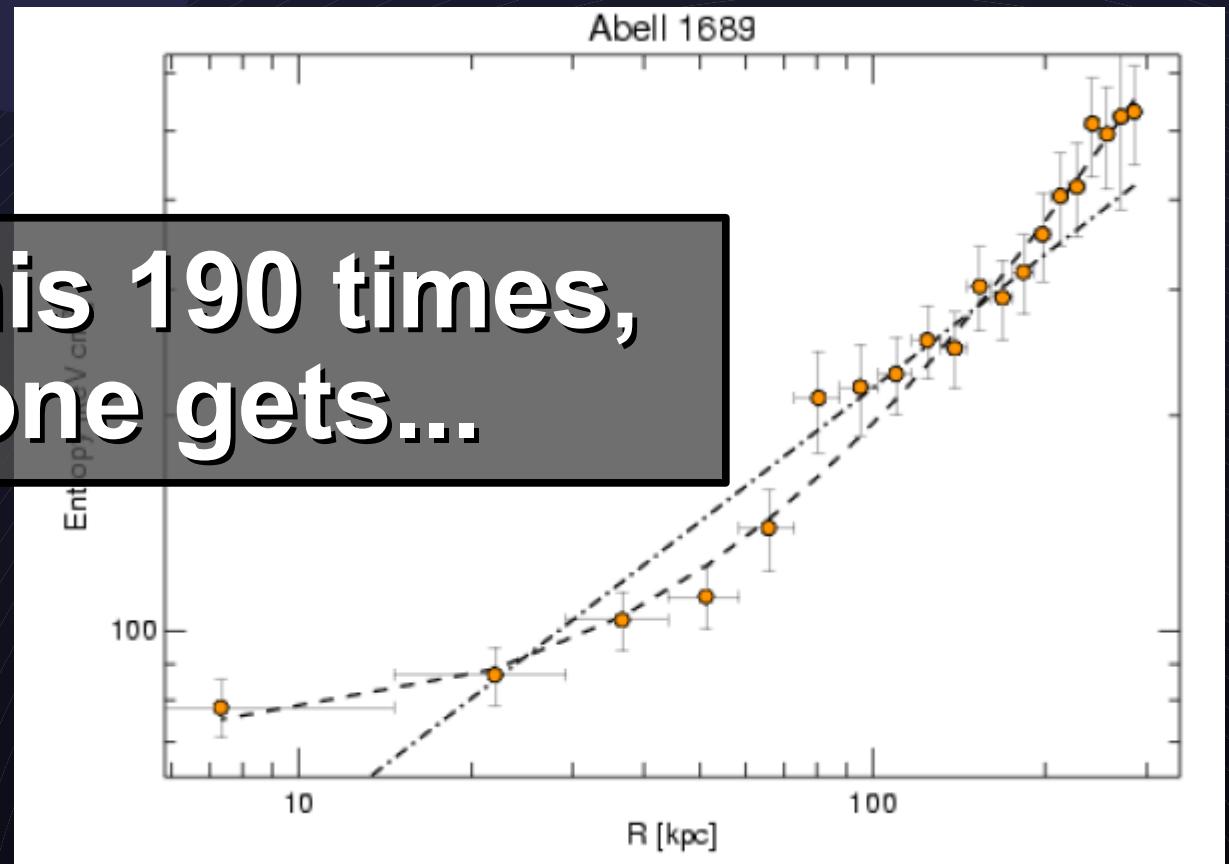
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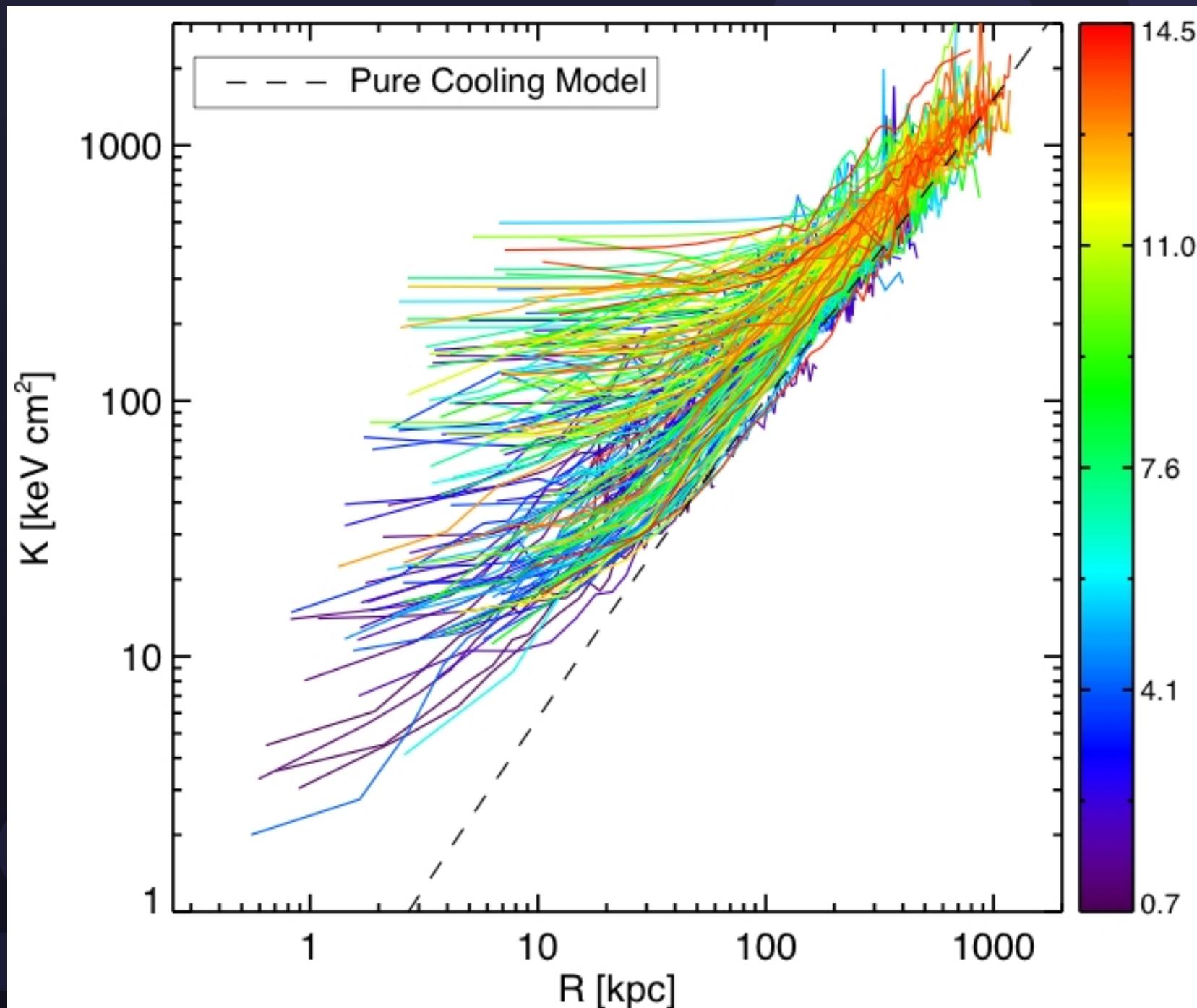
Chandra Data Reduction... in a nutshell

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Do this 190 times,
and one gets...



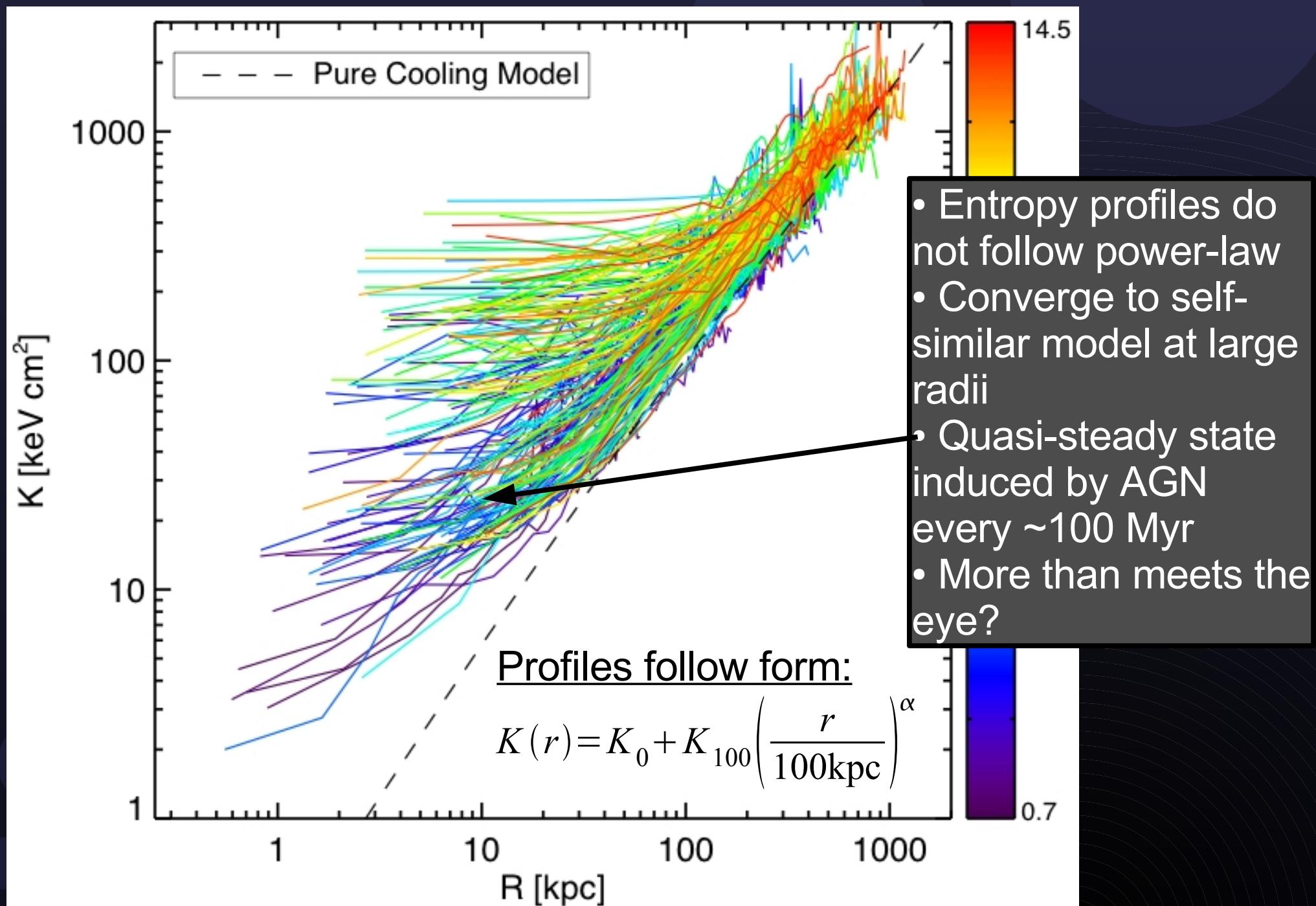
ACCEPT: Athenæum of Chandra Cluster Entropy Profile Tables



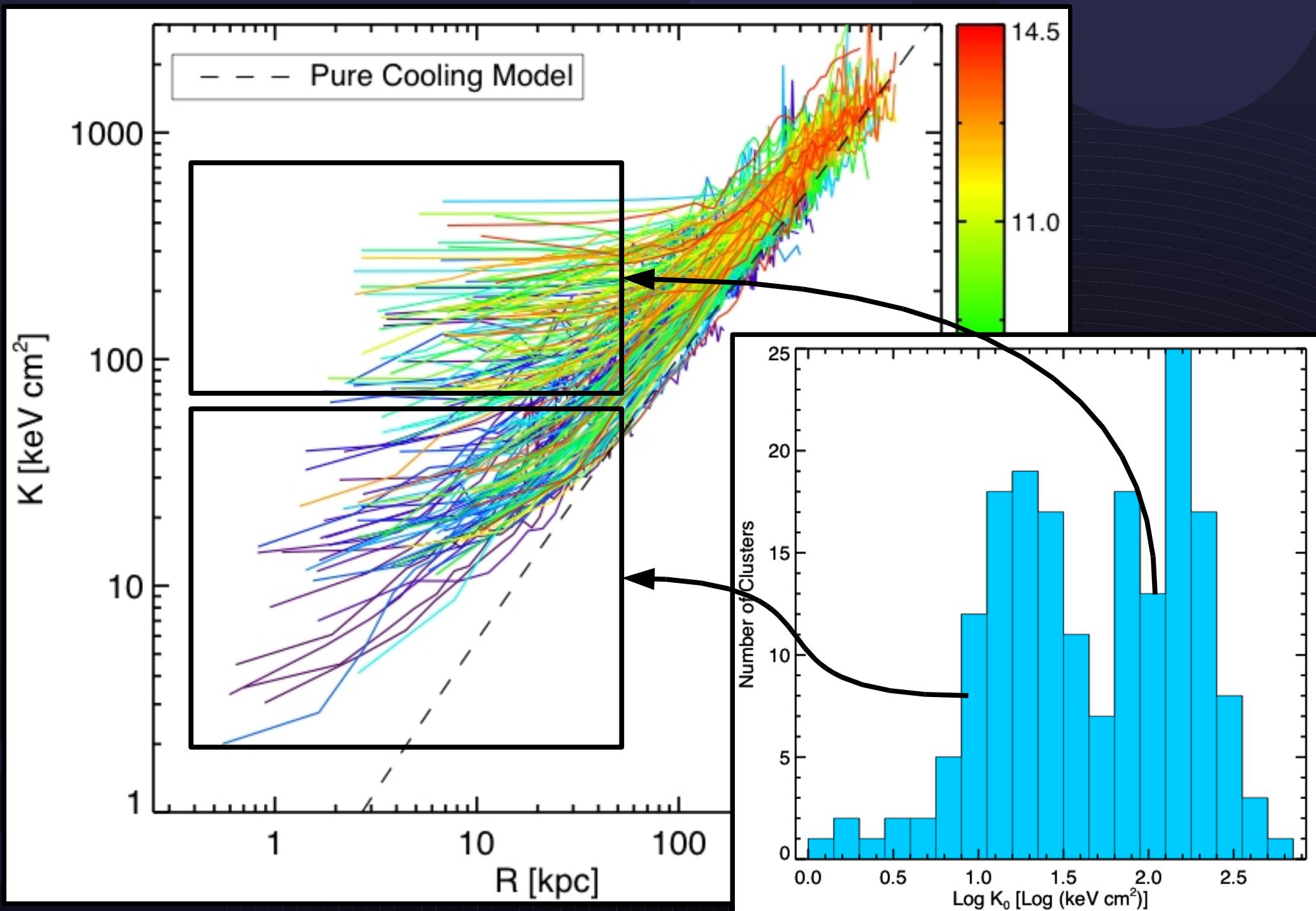
All results will
be publicly
available
online.

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

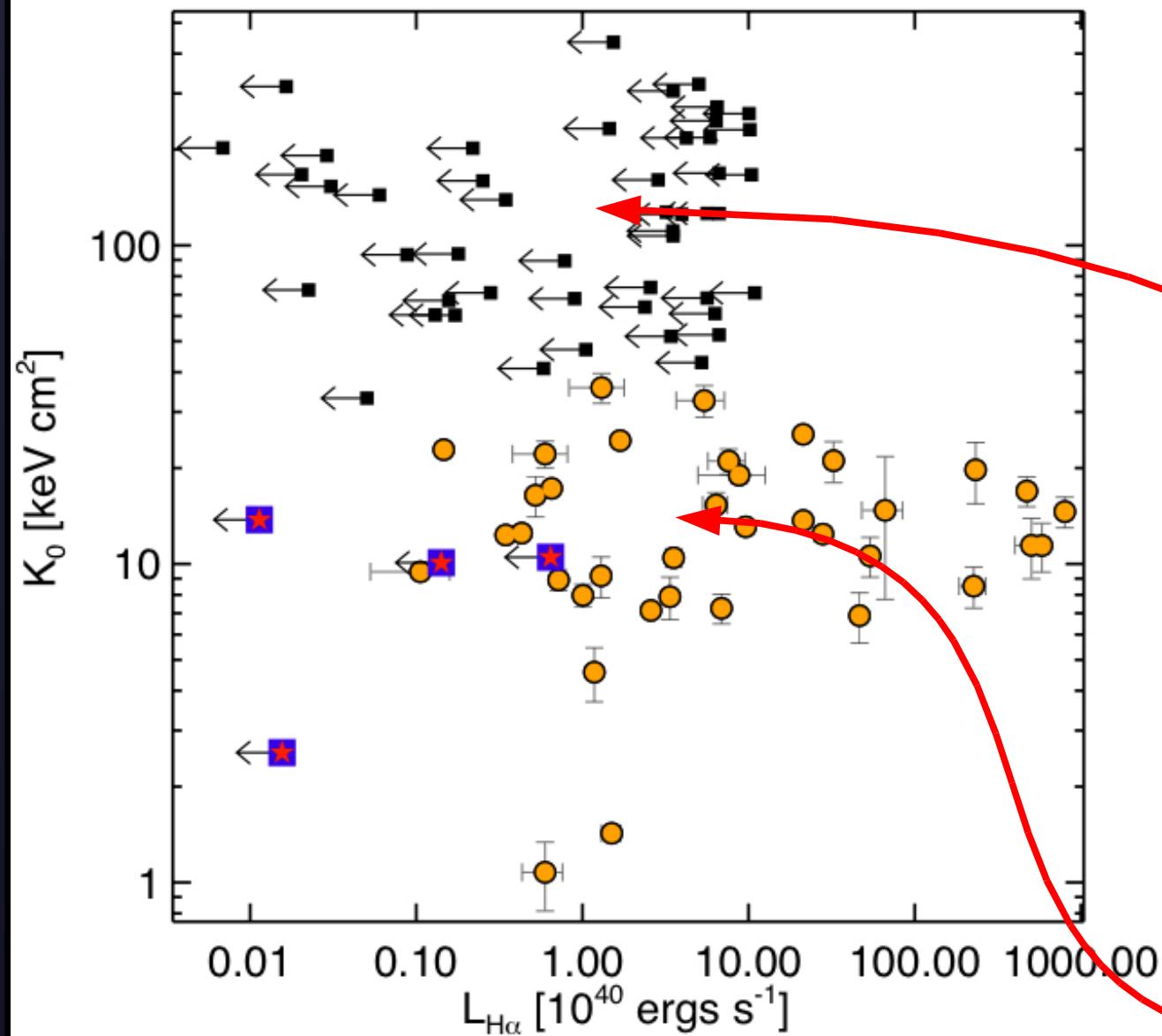
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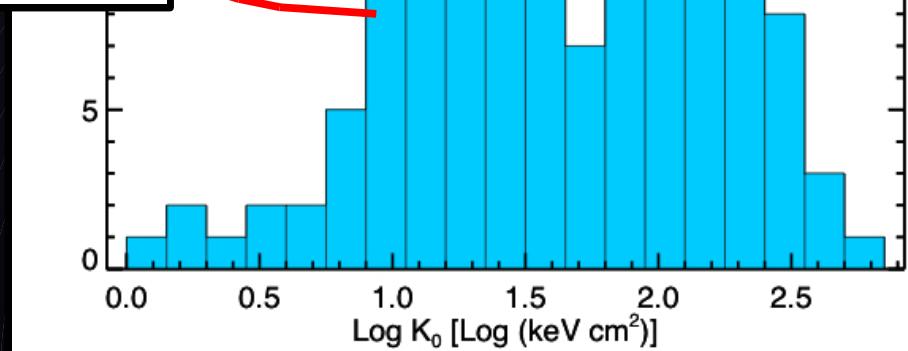
Bimodal entropy distribution



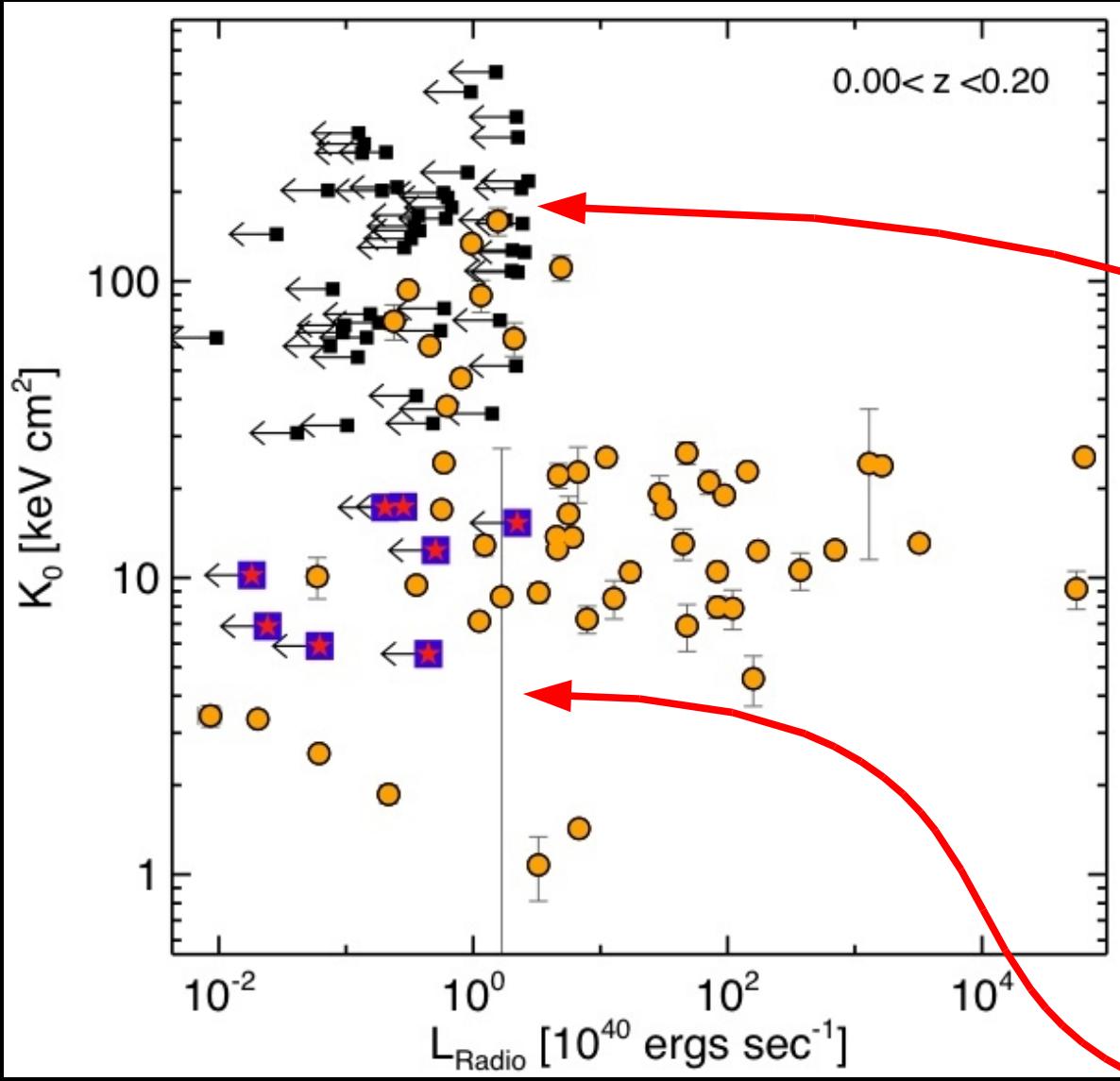
Assume H α as star formation indicator;
Star formation loves
low entropy



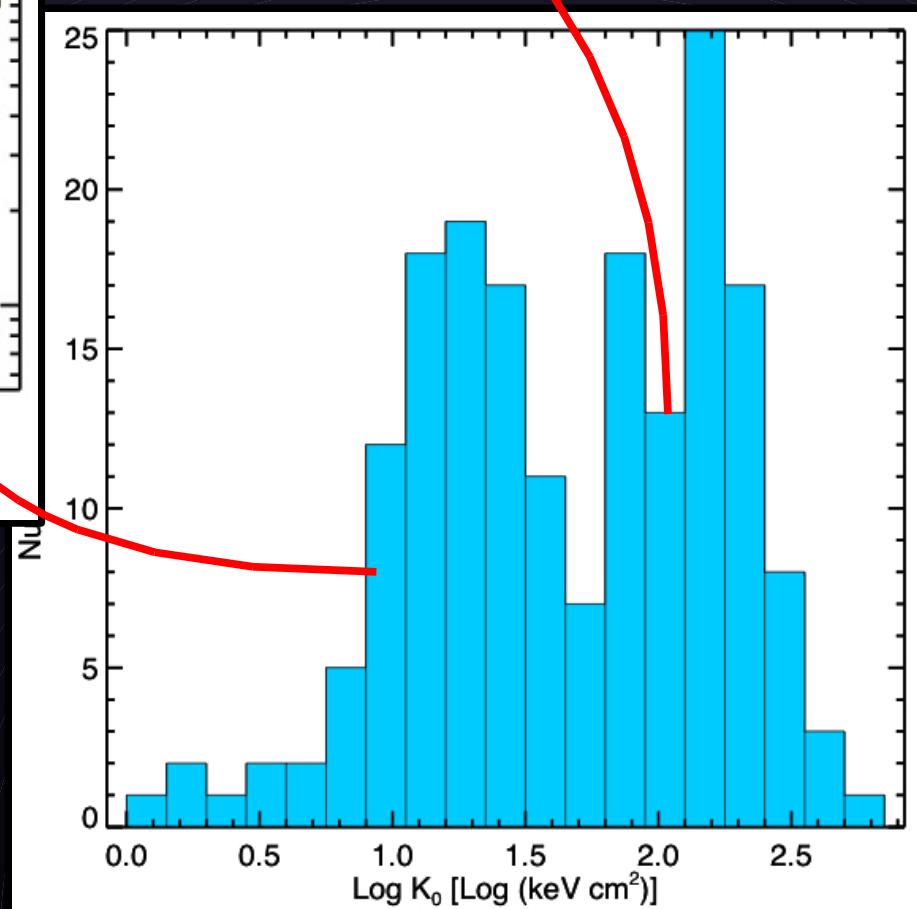
Conduction
interfaces can also
produce H α



Radio-loud sources
like low entropy too!

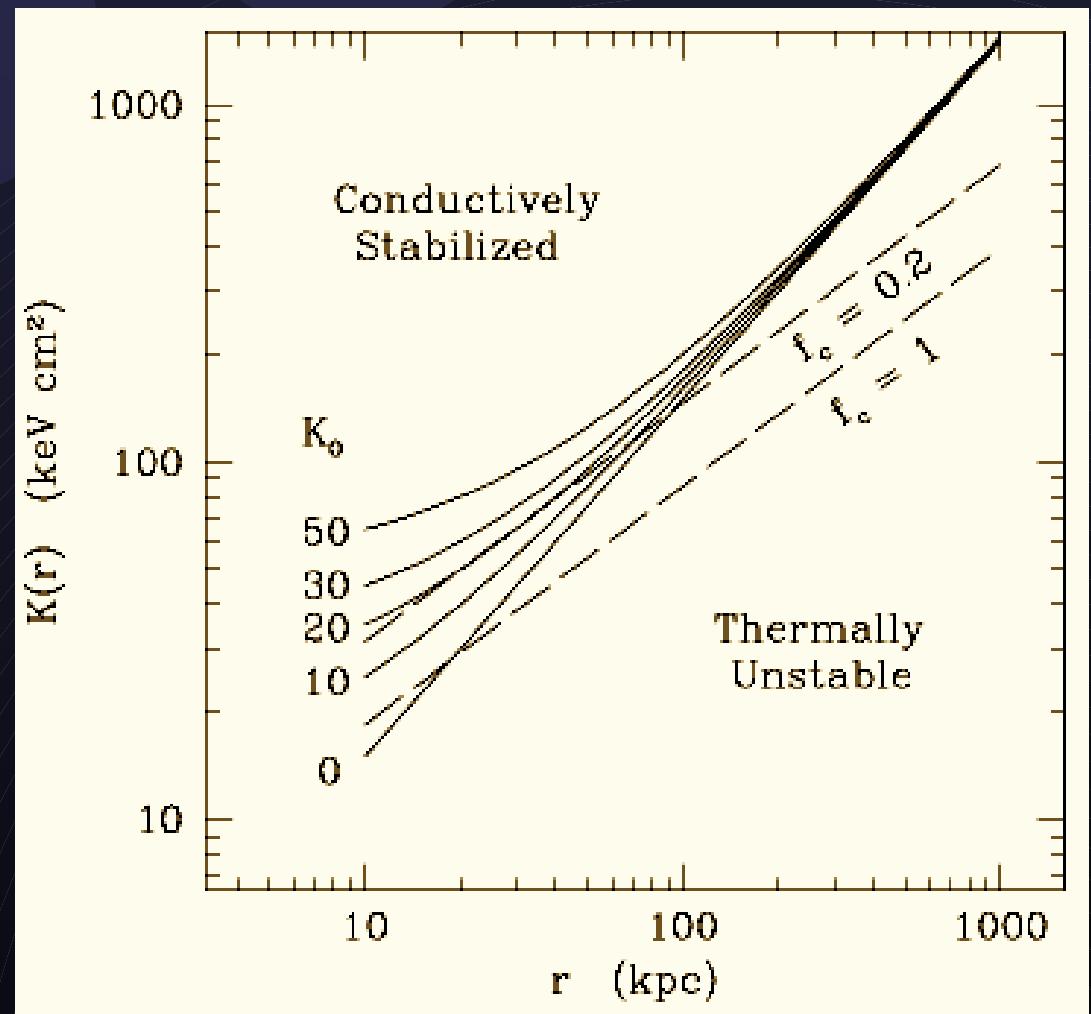


Most likely AGN, but might
also be relics, ghosts,
detached lobes, or
reaccelerated regions



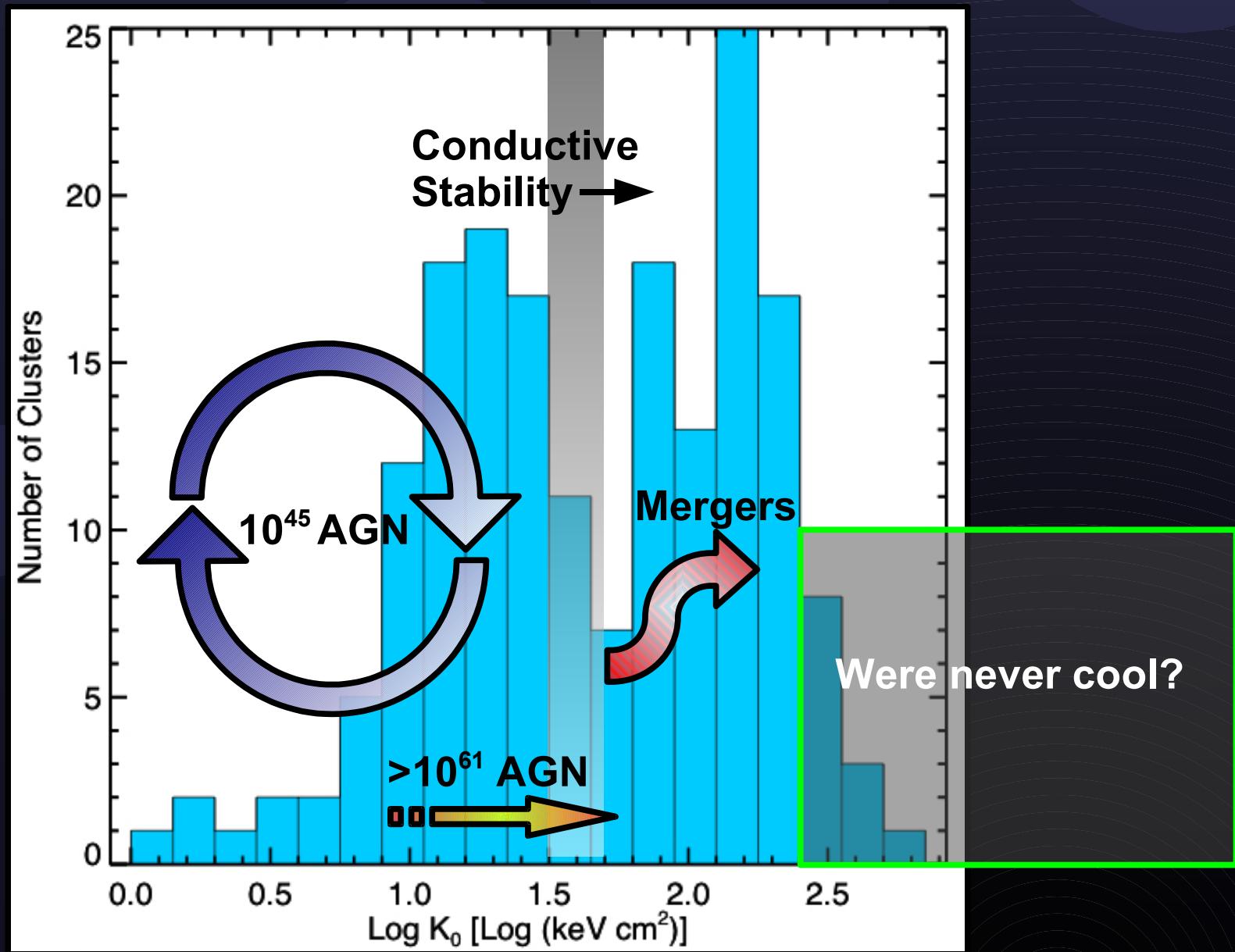
Conductive Stability

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



Voit et al., in prep.

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
- IMHO, CXO is one of the greatest pieces of scientific equipment ever built.

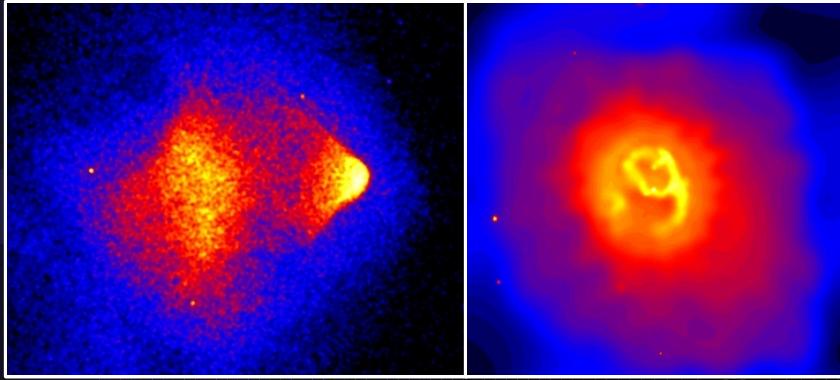
The road ahead

- Watch for papers in Mar-Apr... and Ming Sun's work on galaxy groups!
- Await results of simulation work
- Apply all scatter reduction techniques
- Entropy scaling relations
- Further explain bimodality
- Use multimodality for timescale tests
- Refine model for conductive stability
- Low entropy & no feedback
- High entropy & with feedback
- Low frequency radio survey?
- Radio dating?
- SZE study of high-z entropy?
- Test various pre-heating models
- 2D analyses
- Online searchable database

Intentionally left blank

Galaxy Clusters: Relaxation and Feedback

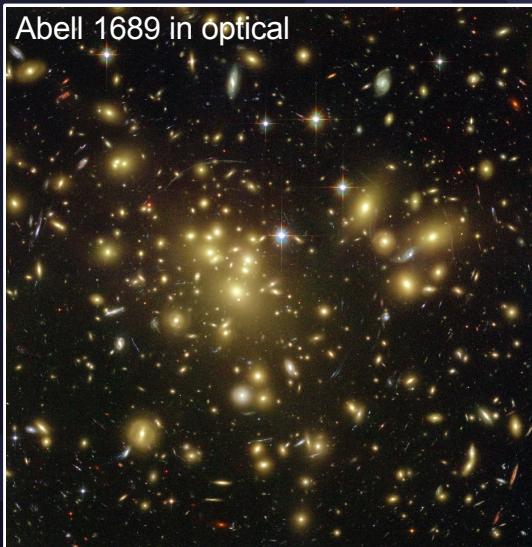
**Ken Cavagnolo
Michigan State University**



Collaborators at MSU

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Galaxy Clusters Refresher

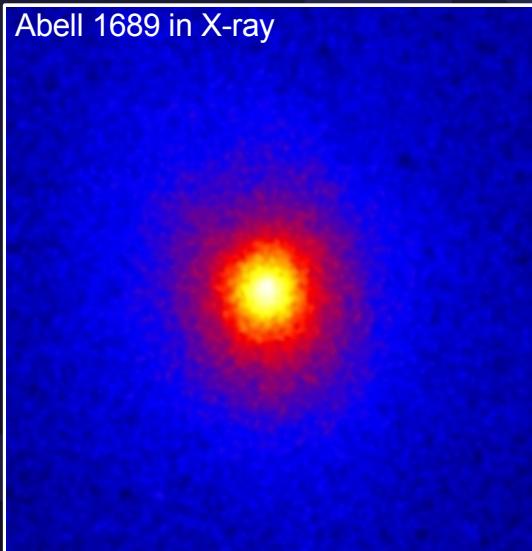


NASA / ACS Team / Benitez et al.

- 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

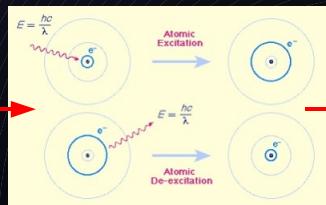
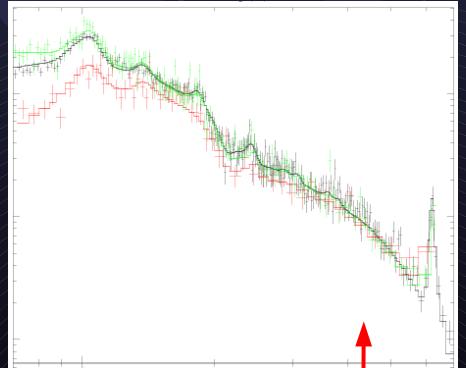
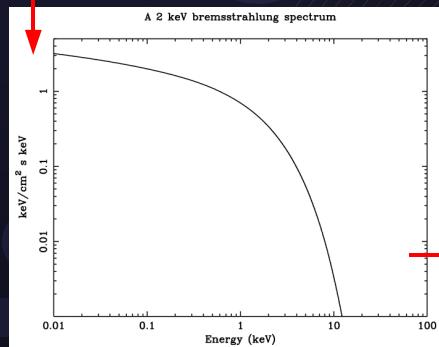
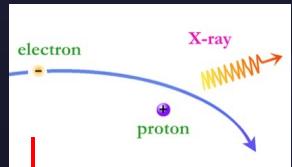
Abell 1689 in X-ray



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

Galaxy Clusters Refresher

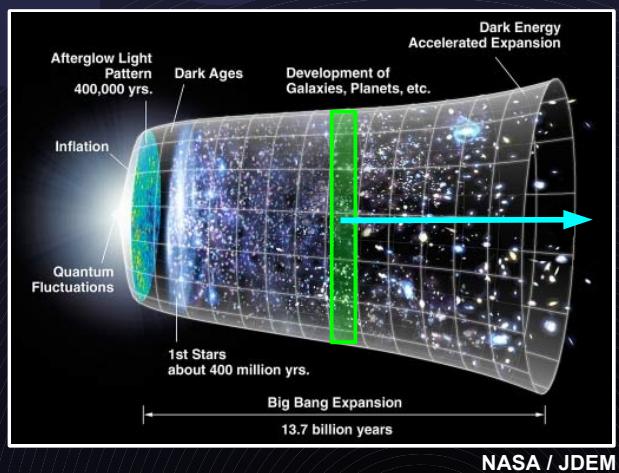
Dominant emission mechanism is thermal Bremsstrahlung



Chandra

Why study galaxy clusters?

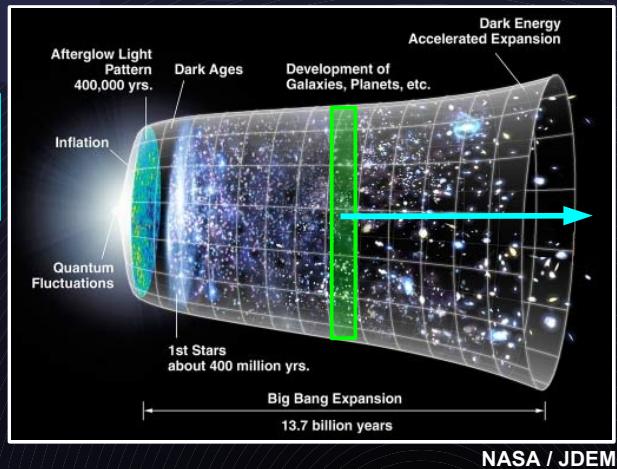
- Cosmology
 - Structure growth
 - Need more precise masses
- Galaxy Formation
 - Explain Hubble Sequence
 - Must understand feedback



NASA / JDEM

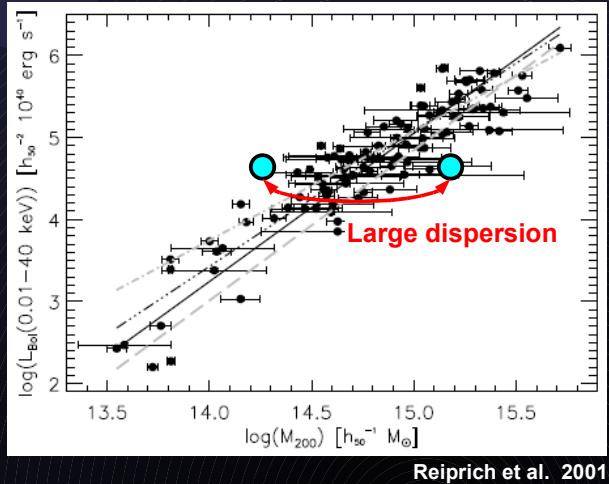
Why study galaxy clusters?

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Cosmological Importance of Relaxation

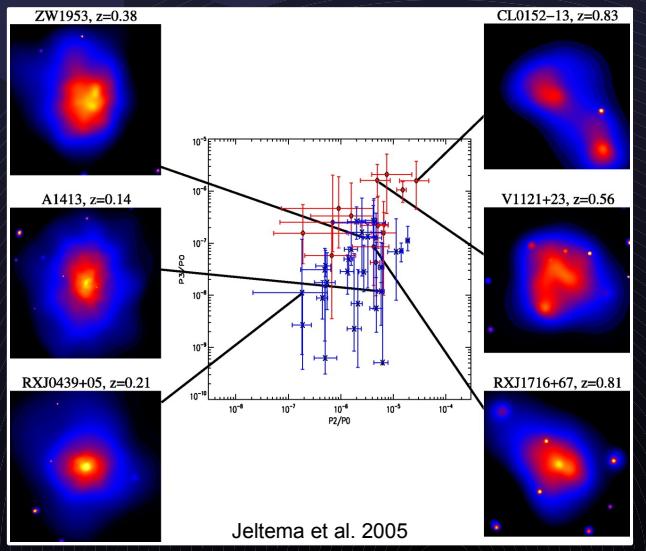
- Clusters expected to be self-similar
- Observables are mass surrogates, assuming equilibrium i.e. relaxation
- Heating and cooling alter scaling relations
- Precision cosmology requires knowledge of the scatter and how it evolves



Reiprich et al. 2001

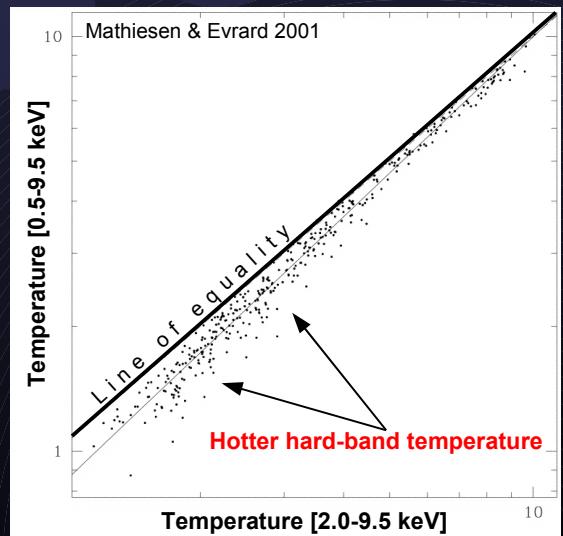
Cosmological Importance of Relaxation

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



Cosmological Importance of Relaxation

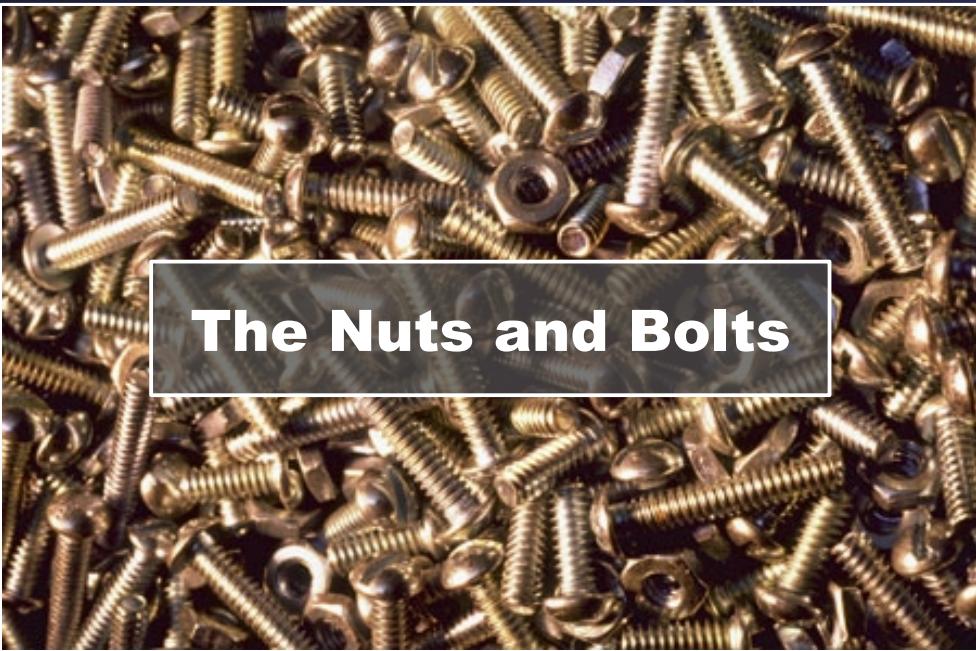
- Is this problem tractable?
- Quantify sub-structure through imaging analysis
- What about an aspect independent measure?
- Temperature skewing predicted by Mathiesen & Evrard 2001



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:

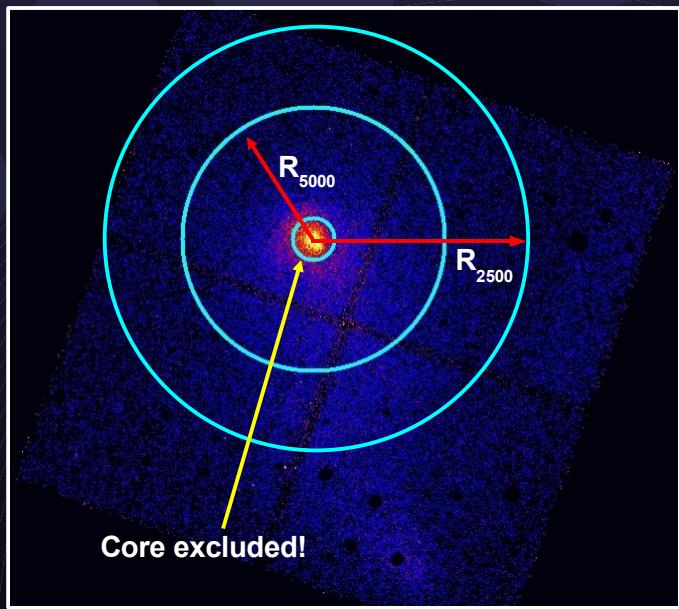
$$T_{HBR} = \frac{T_{2.0-7.0}}{T_{0.7-7.0}}$$



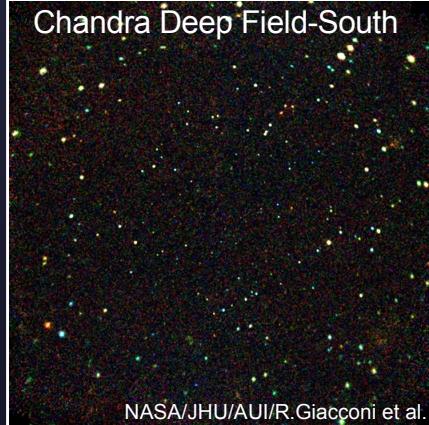
The Nuts and Bolts

“T_{HBR}” Data Analysis

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



Chandra Deep Field-South

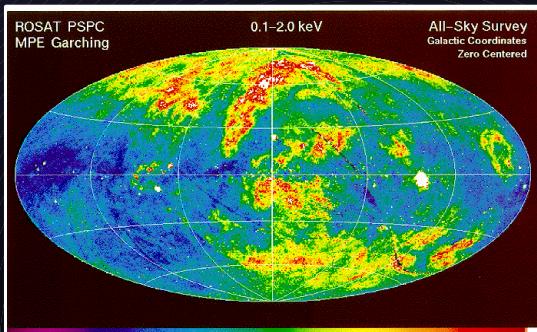


NASA/JHU/AUI/R.Giacconi et al.

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

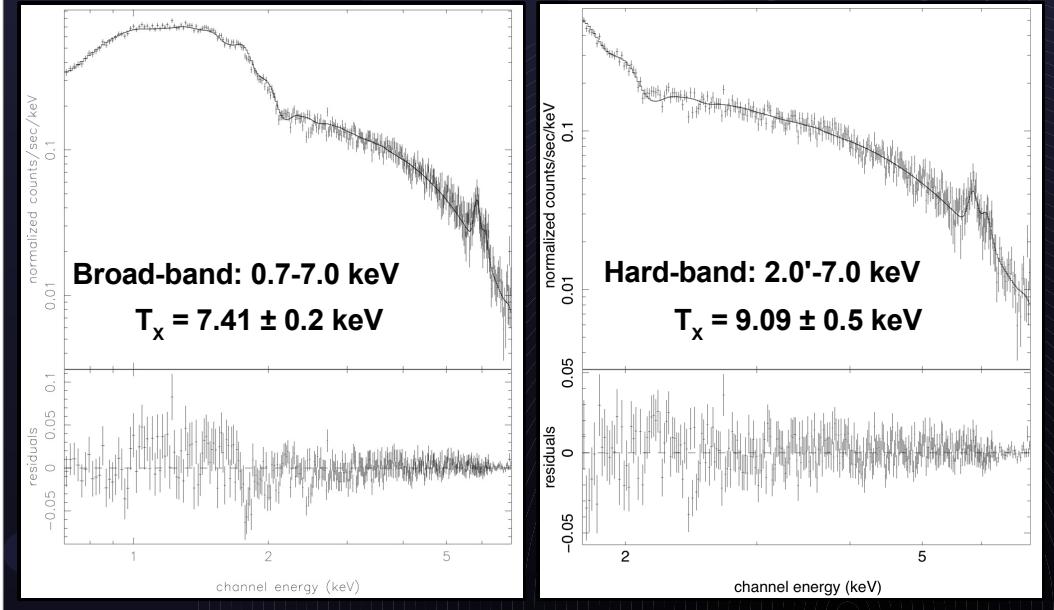
X-ray Background Consideration

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



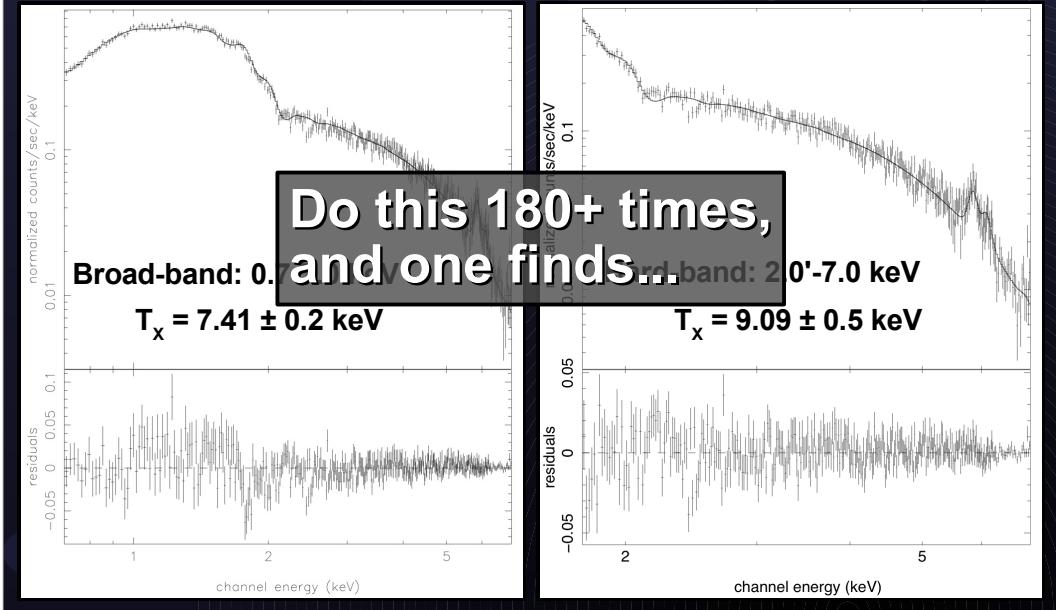
Inferring the gas temperature

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

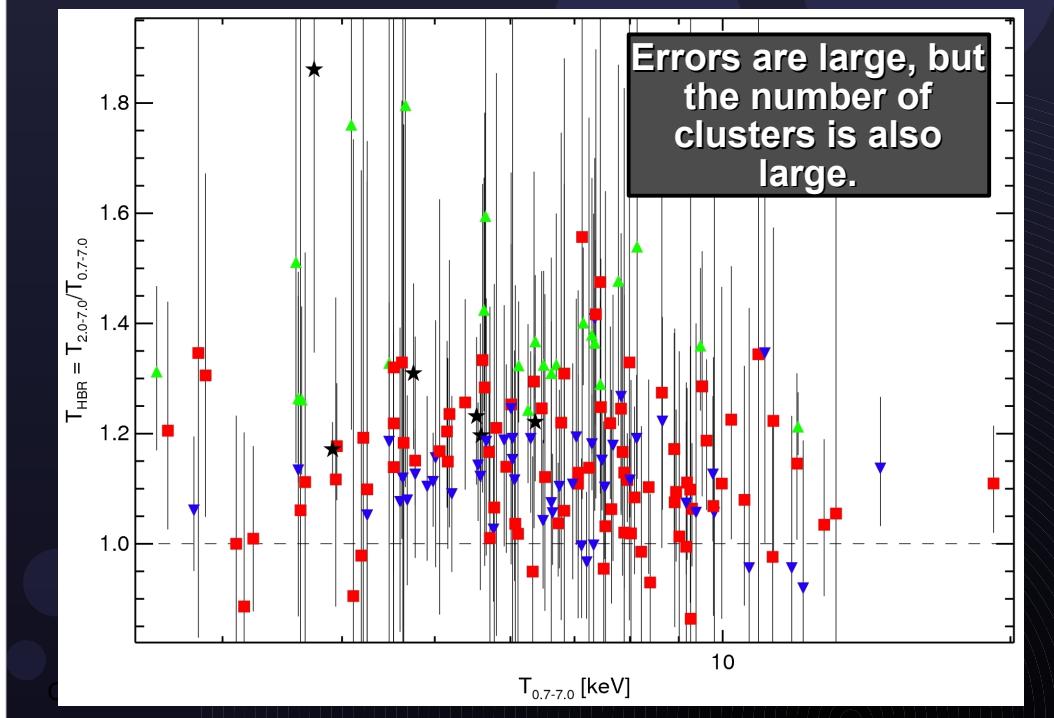


Inferring the gas temperature

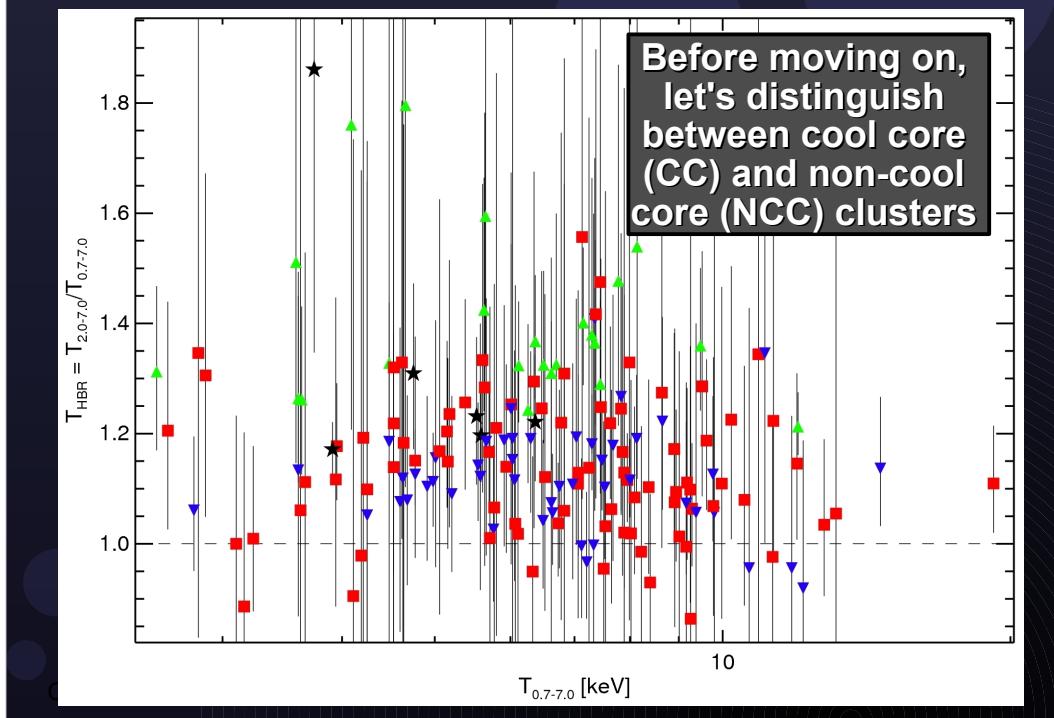
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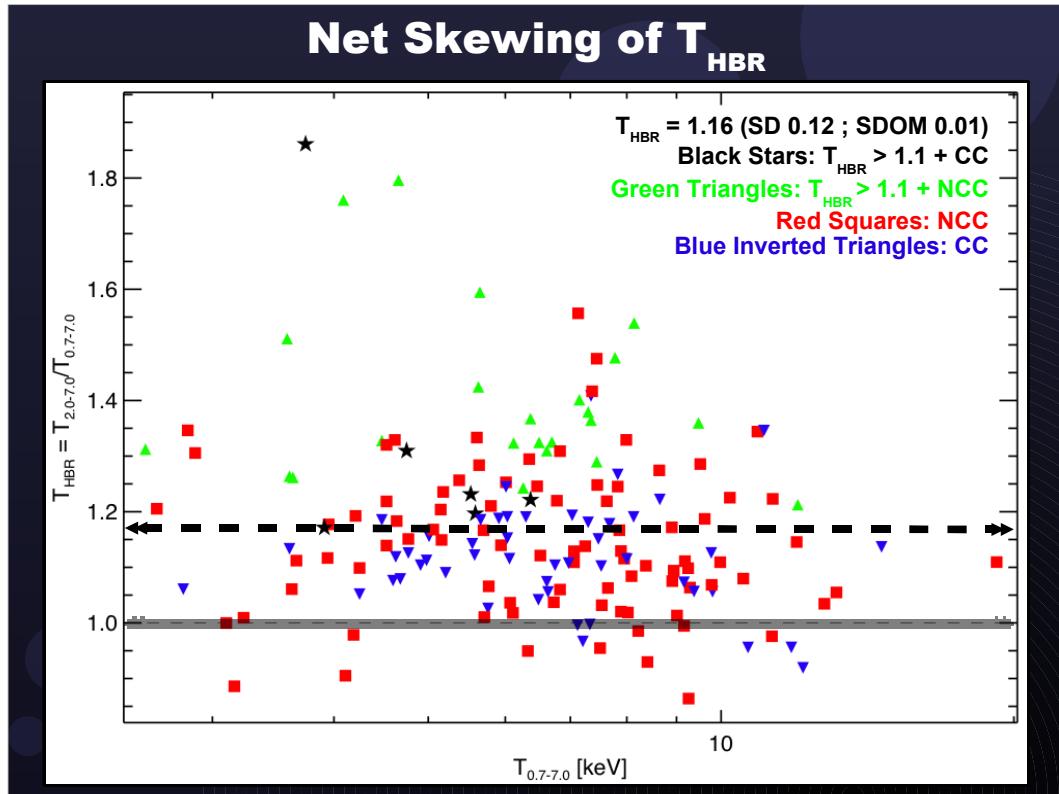


Net Skewing of T_{HBR}



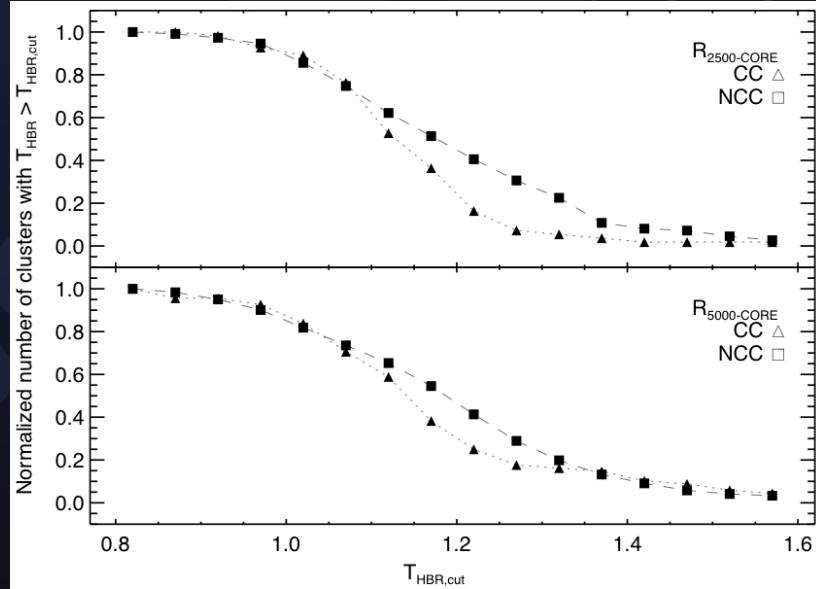
Net Skewing of T_{HBR}





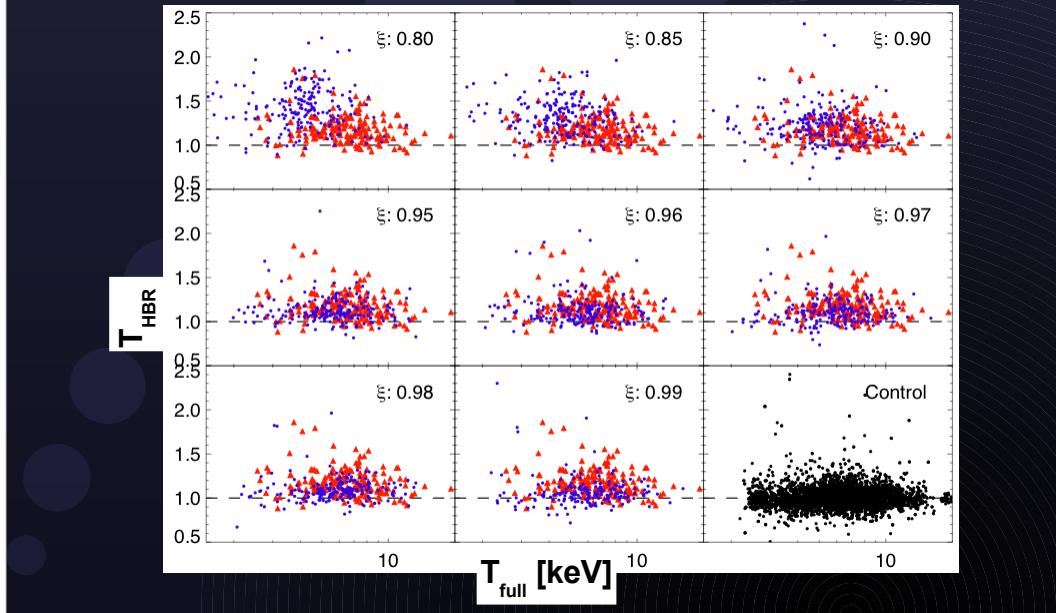
Culling out Cool Cores using T_{HBR}

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

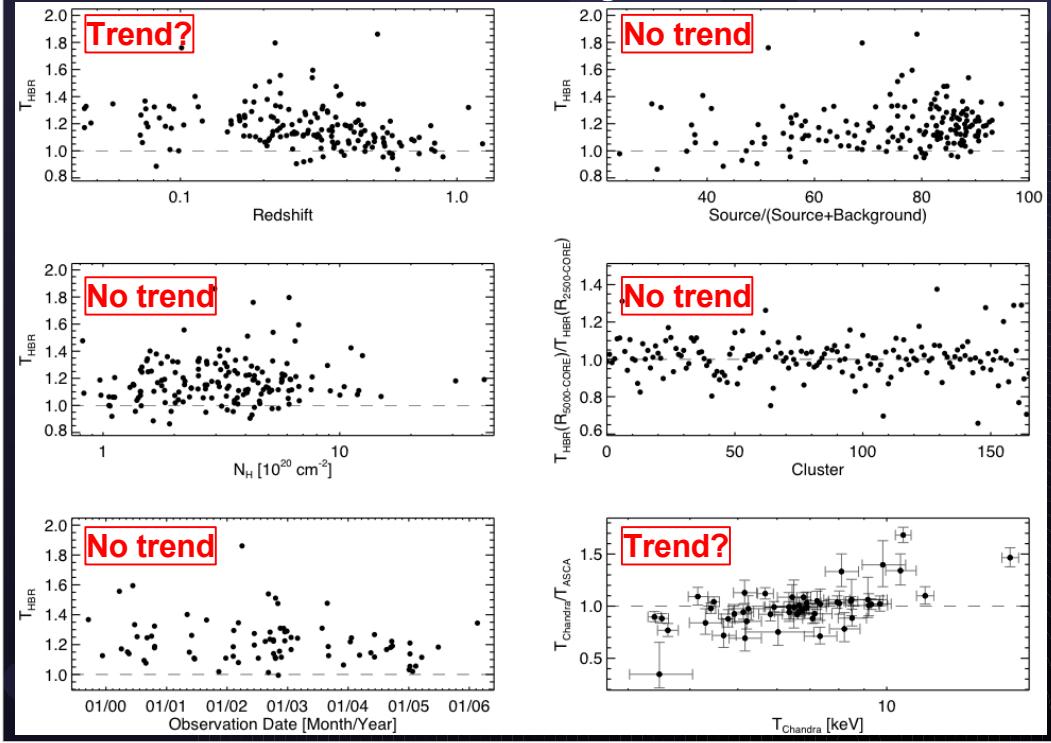


Simulations and Systematics

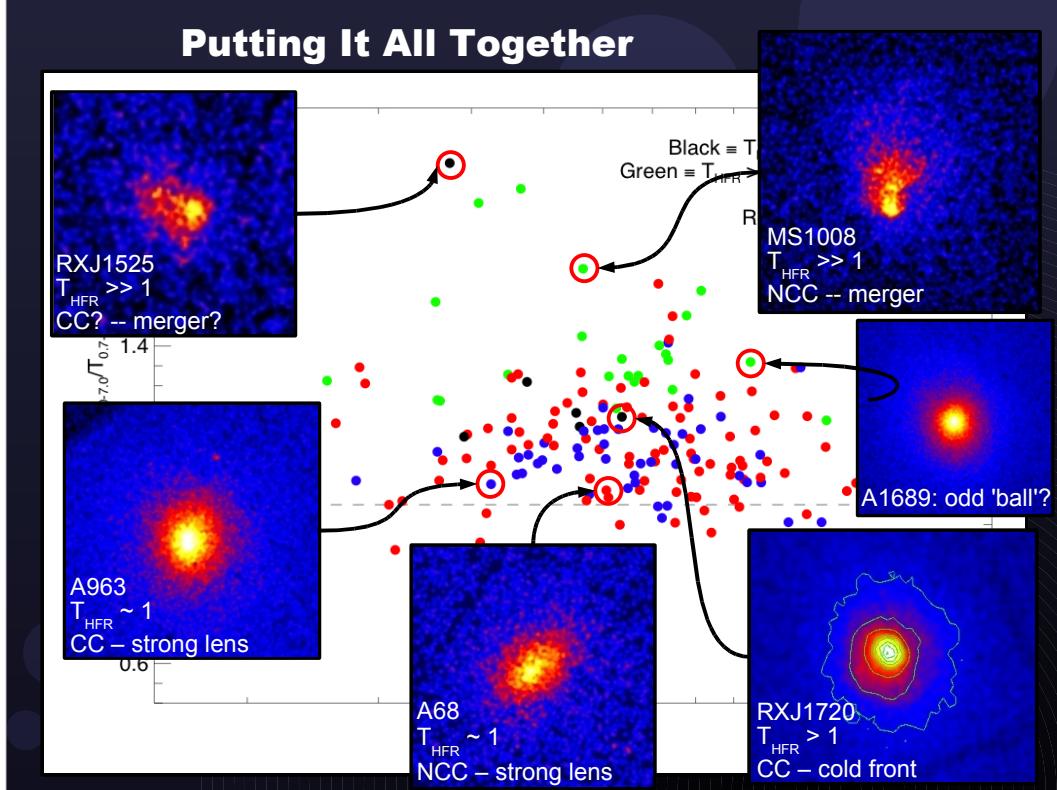
- Simulate two-phase gas
- Repeat spectral analysis
- Observe skewing in sims but not in control
- Dispersion in observation > control



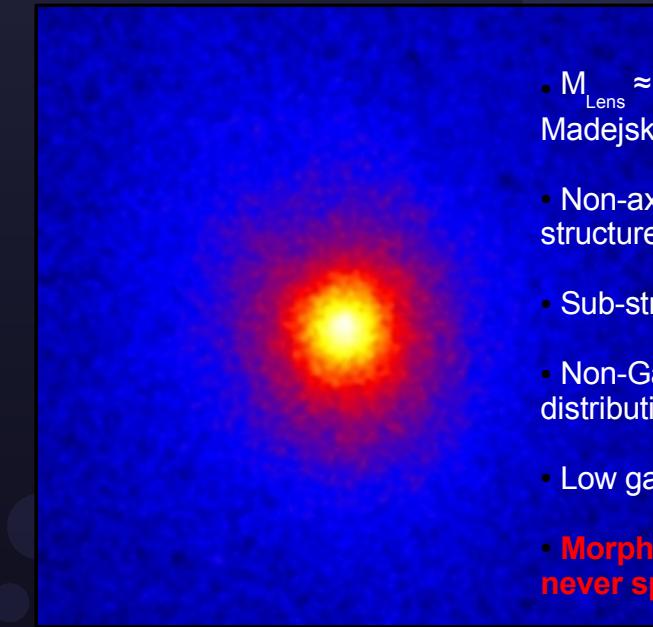
Simulations and Systematics



Putting It All Together



Abell 1689: not so relaxed



- $M_{\text{Lens}} \approx 2 \times M_{\text{X-ray}}$ (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

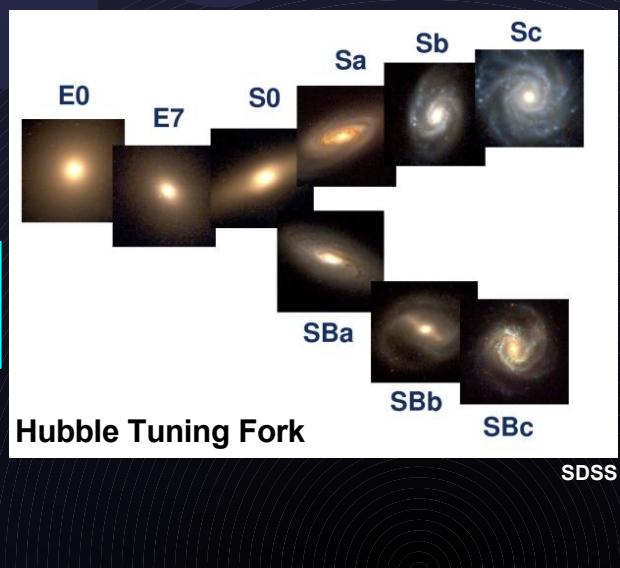
- Temperature inhomogeneity is a problem
- Appears to be something we can quantify
- Calibrate between temperature ratio and relaxation using N-body/SPH simulations
- Could be very useful tool for quantifying scatter in mass-observables

Now, what of the feedback issue...?

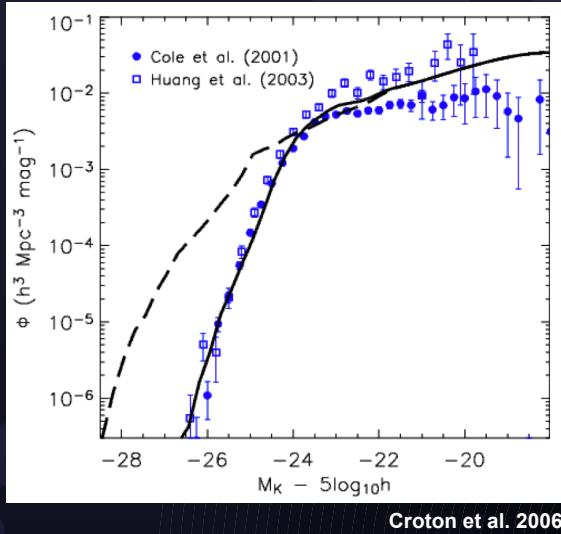
Why study galaxy clusters?

- Cosmology
 - Structure growth
 - Need accurate masses

- Galaxy Formation
 - Explain Hubble Sequence
 - Must understand feedback



Importance of Feedback



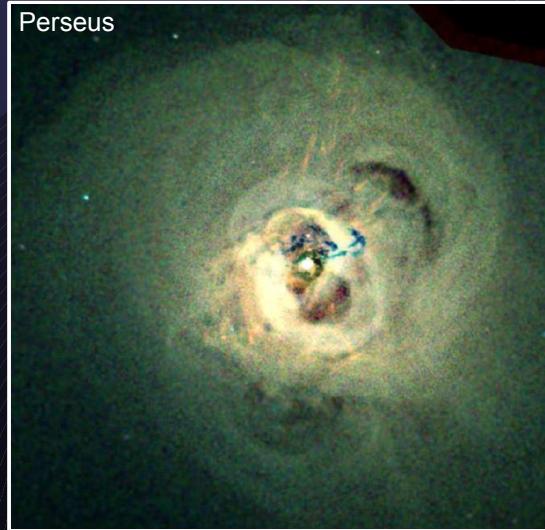
- Theory predicts:
 - Too many massive, blue galaxies
 - Too many dwarf galaxies

- The trouble with old ellipticals
 - Vigorous feedback at high-z
 - “Down-sizing” problem

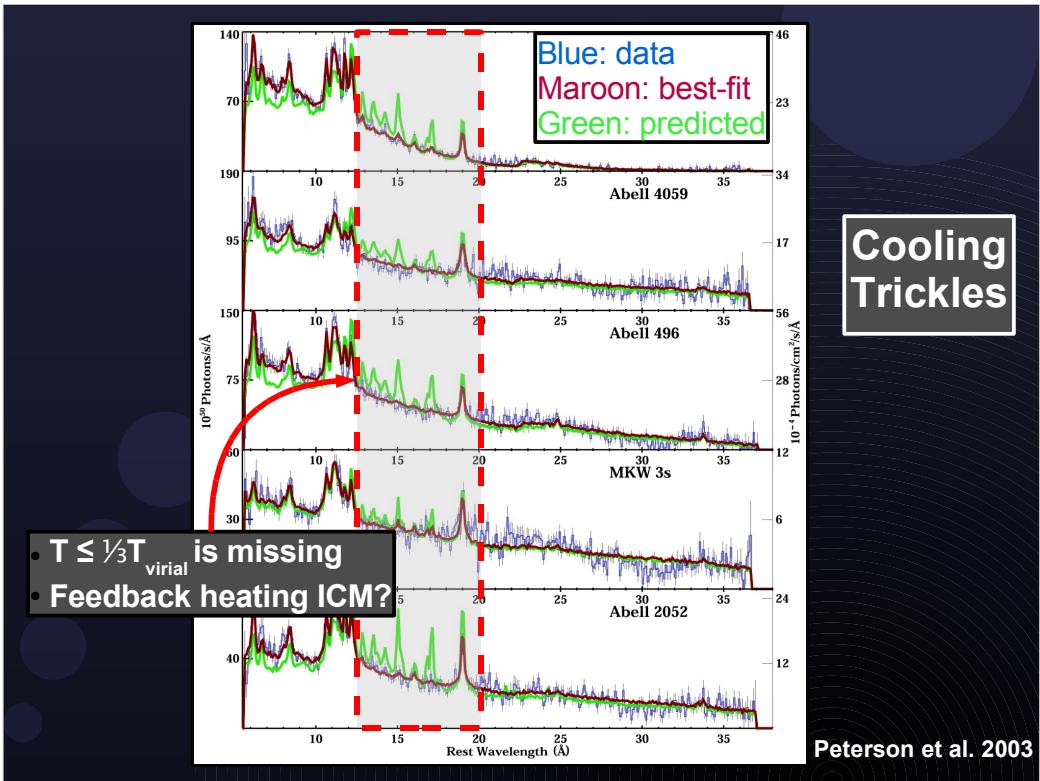
- Central galaxy in groups and clusters are not growing unabated

Importance of Feedback

- Central cooling time of ICM much shorter than Hubble age
- Expect massive flows of cool gas into core
- But star formation isn't rampant, why?
- Take a look at right...

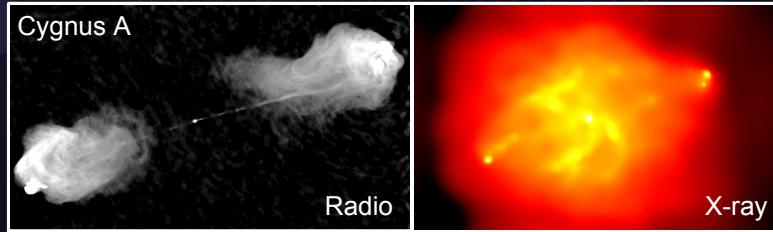
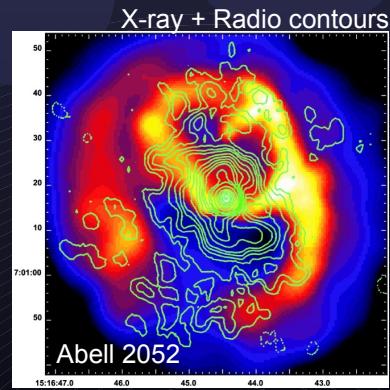


NASA / CXC / IoA / A.Fabian et al.



Importance of Feedback

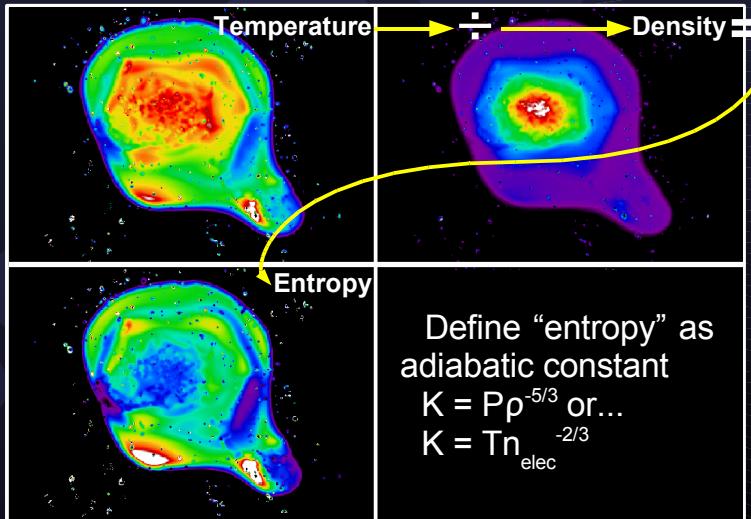
- Feedback heating now widely accepted
- Very, very modest star formation
- AGN are active
- Galaxy growth slowed
- How do we make sense of all this?
- **Our 'close to the data' approach:**
 - Study cooling ICM
 - Better understand feedback
 - Work toward self-regulation model
 - Focus on ICM entropy...



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
Schuecker et al. 2004

Properties of Entropy

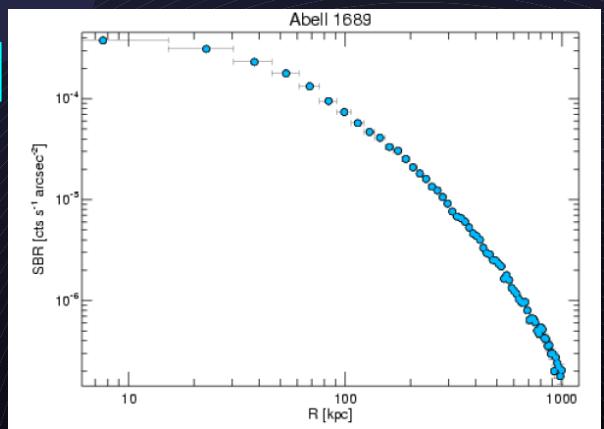
- In a gravity only Universe... radial entropy distribution follows power-law
 - Potential wells are entropy sorting devices
 - Departures from power-law indicative of past heating and cooling



**Chandra data reduction...
in a nutshell**

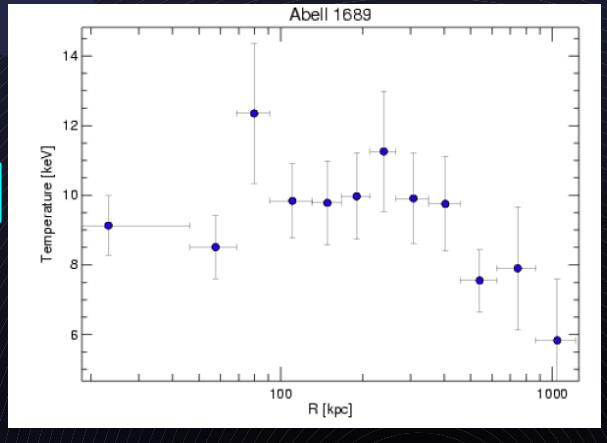
Chandra Data Reduction... in a nutshell

- 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



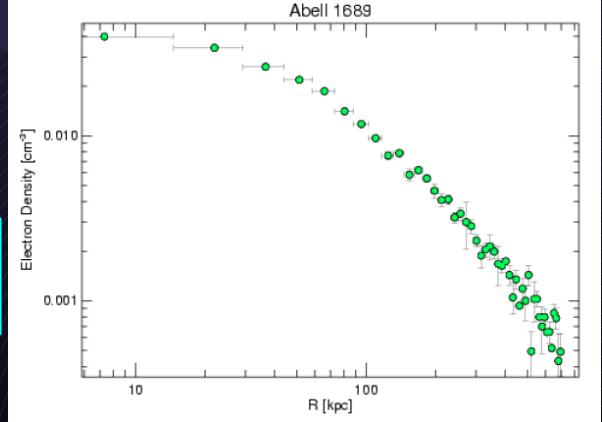
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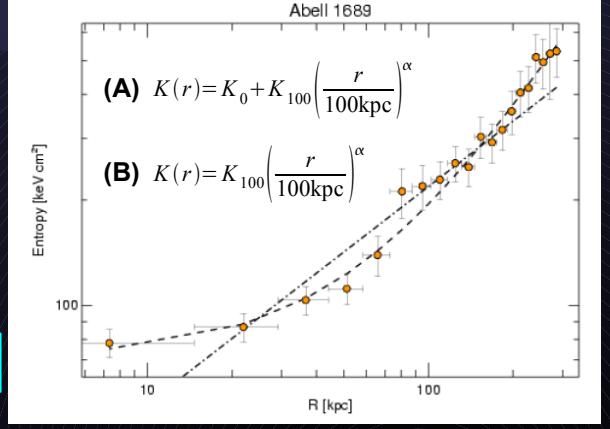
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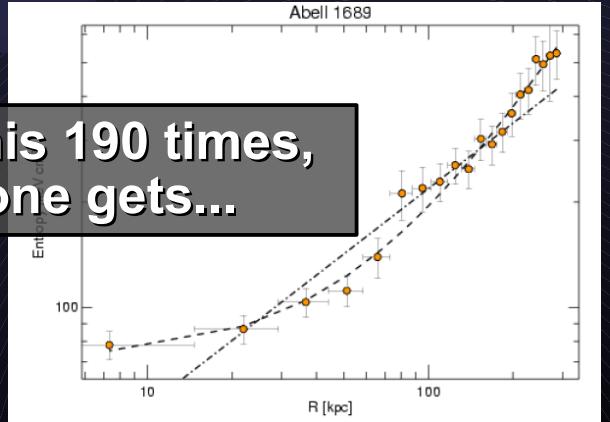
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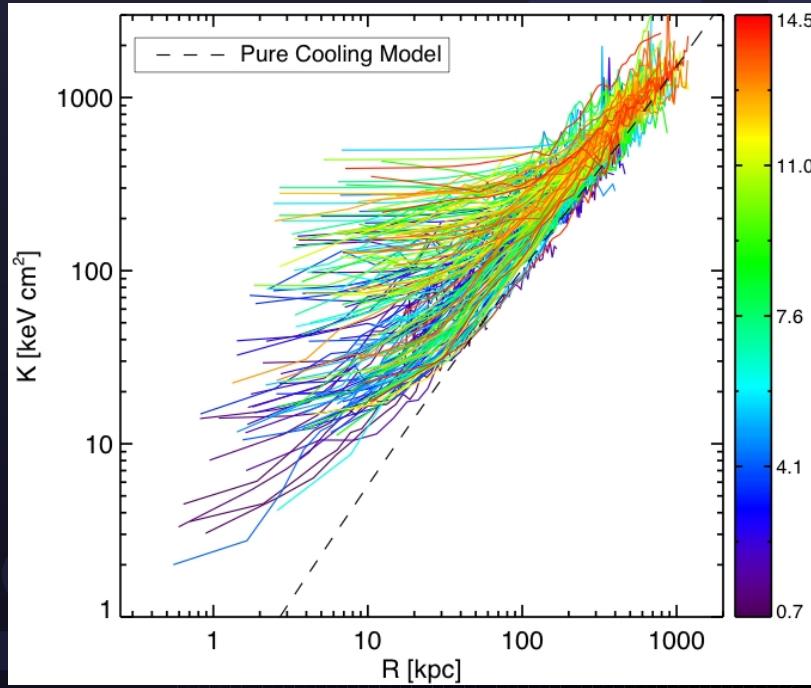
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Do this 190 times,
and one gets...



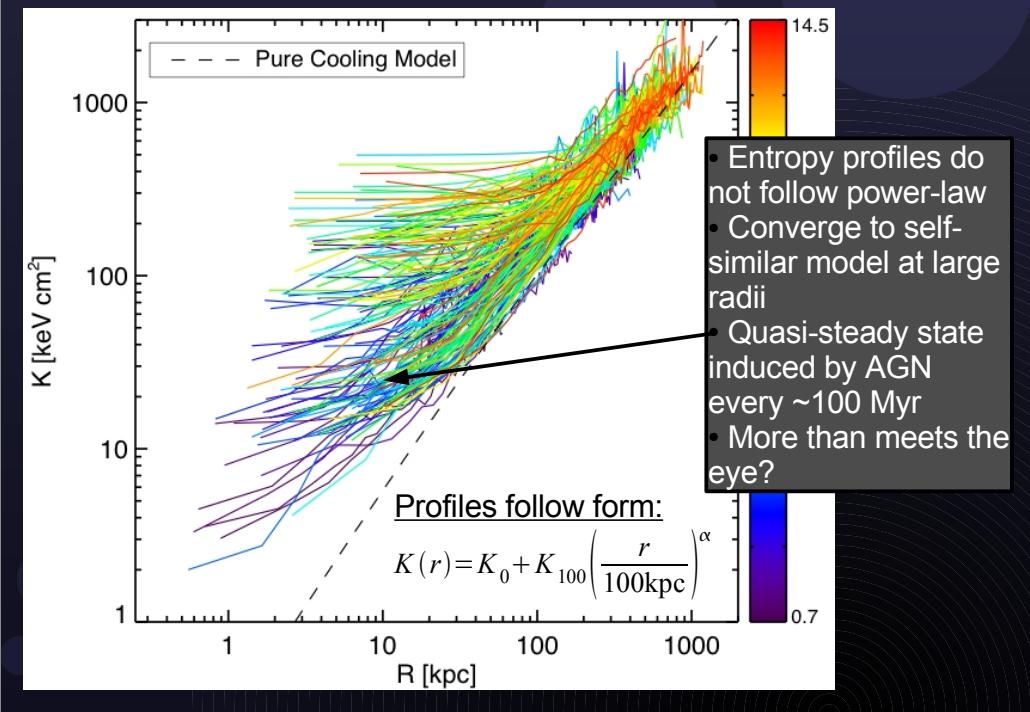
ACCEPT: Athenæum of Chandra Cluster Entropy Profile Tables

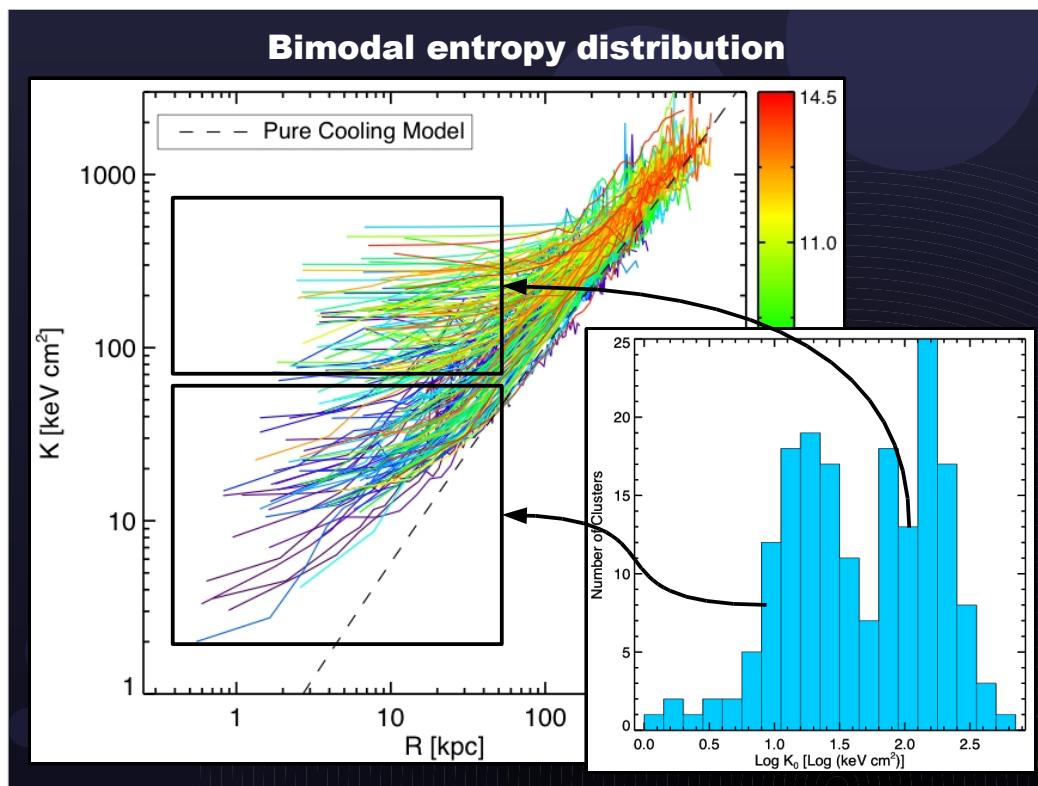


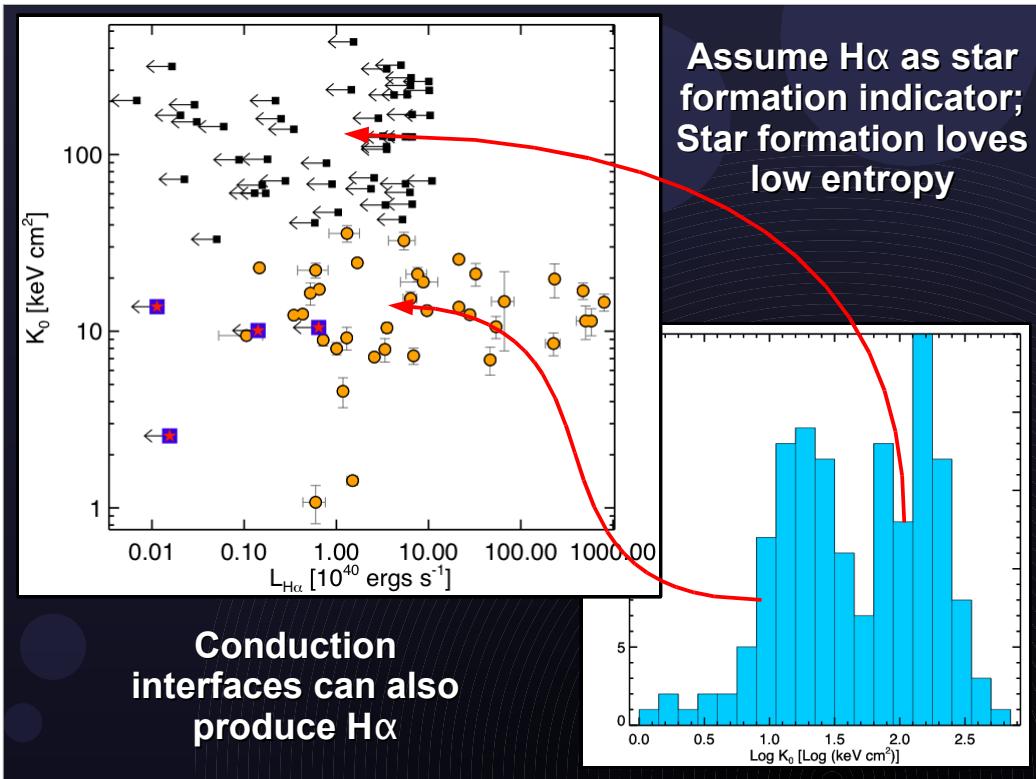
All results will
be publicly
available
online.

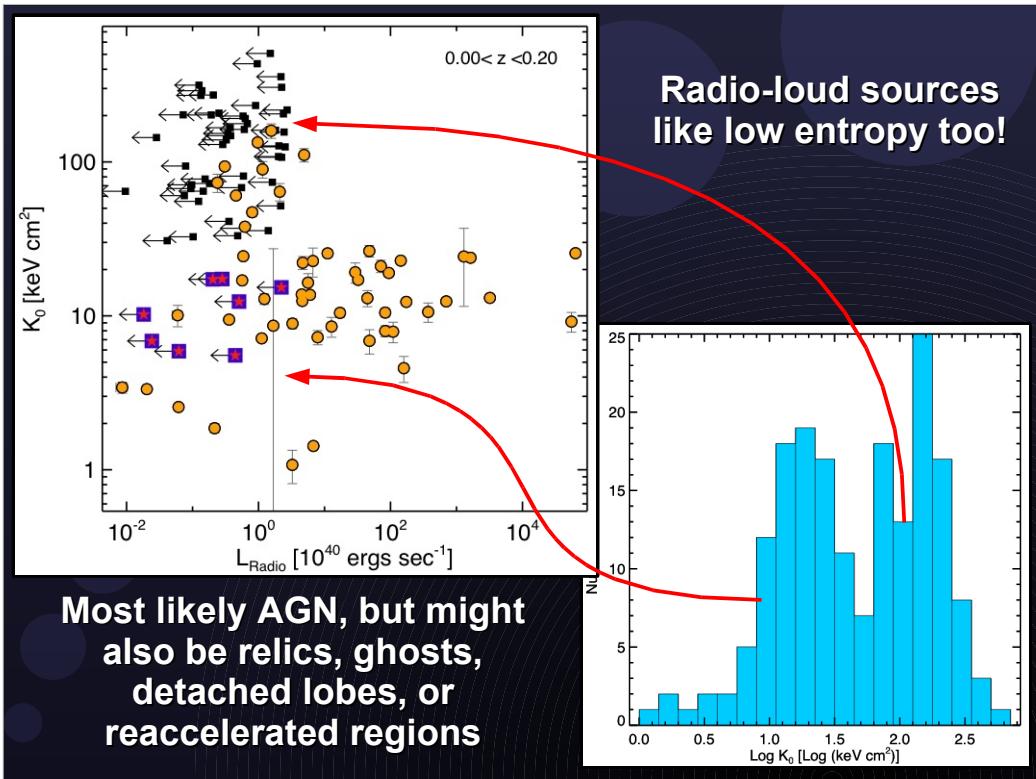
This includes
all profiles,
tables,
spectra,
reduced data,
figures, et
cetera.

ACCEPT: Athenæum of Chandra Cluster Entropy Profile Tables



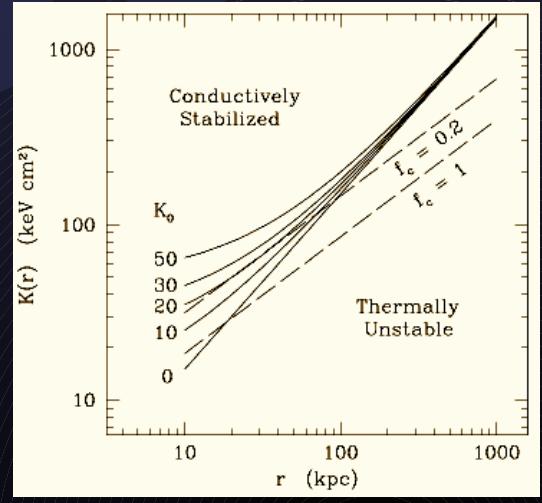






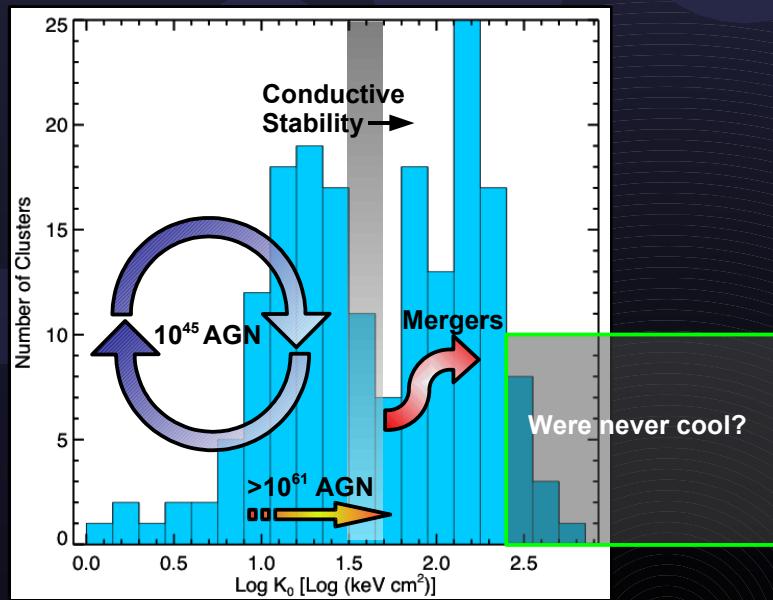
Conductive Stability

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



Voit et al., in prep.

Entropy lifecycle?



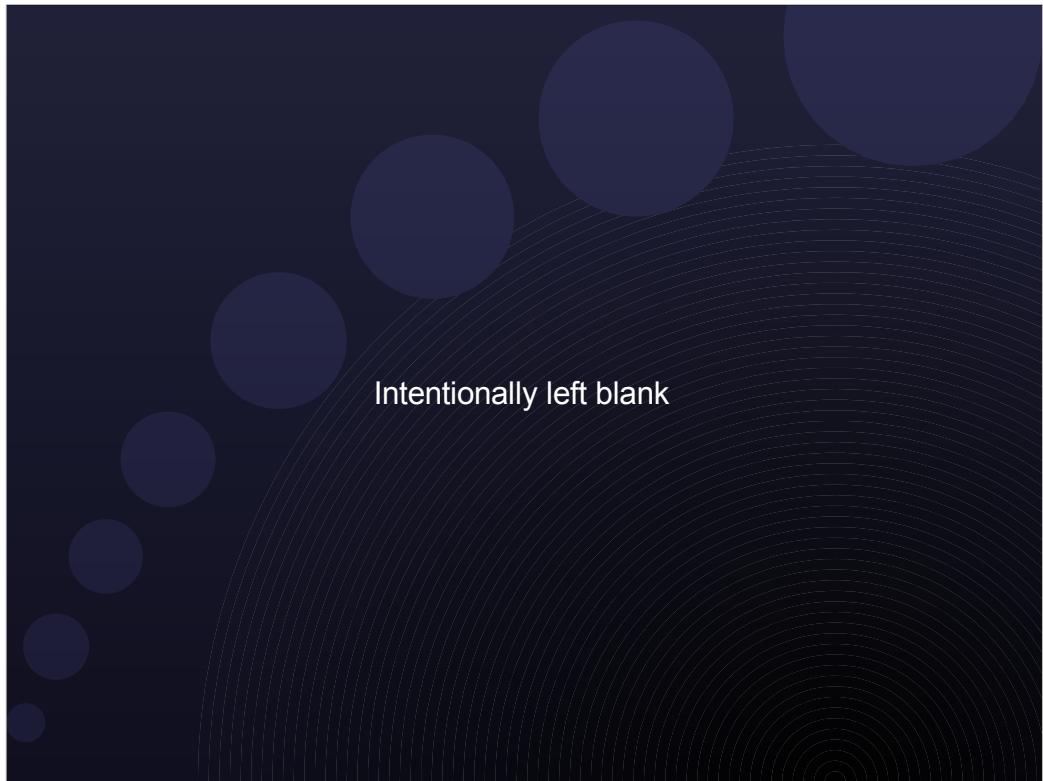
Conclusions

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
- IMHO, CXO is one of the greatest pieces of scientific equipment ever built.

The road ahead

- Watch for papers in Mar-Apr... and Ming Sun's work on galaxy groups!
- Await results of simulation work
- Apply all scatter reduction techniques
- Entropy scaling relations
- Further explain bimodality
- Use multimodality for timescale tests
- Refine model for conductive stability
- Low entropy & no feedback
- High entropy & with feedback
- Low frequency radio survey?
- Radio dating?
- SZE study of high-z entropy?
- Test various pre-heating models
- 2D analyses
- Online searchable database



Intentionally left blank