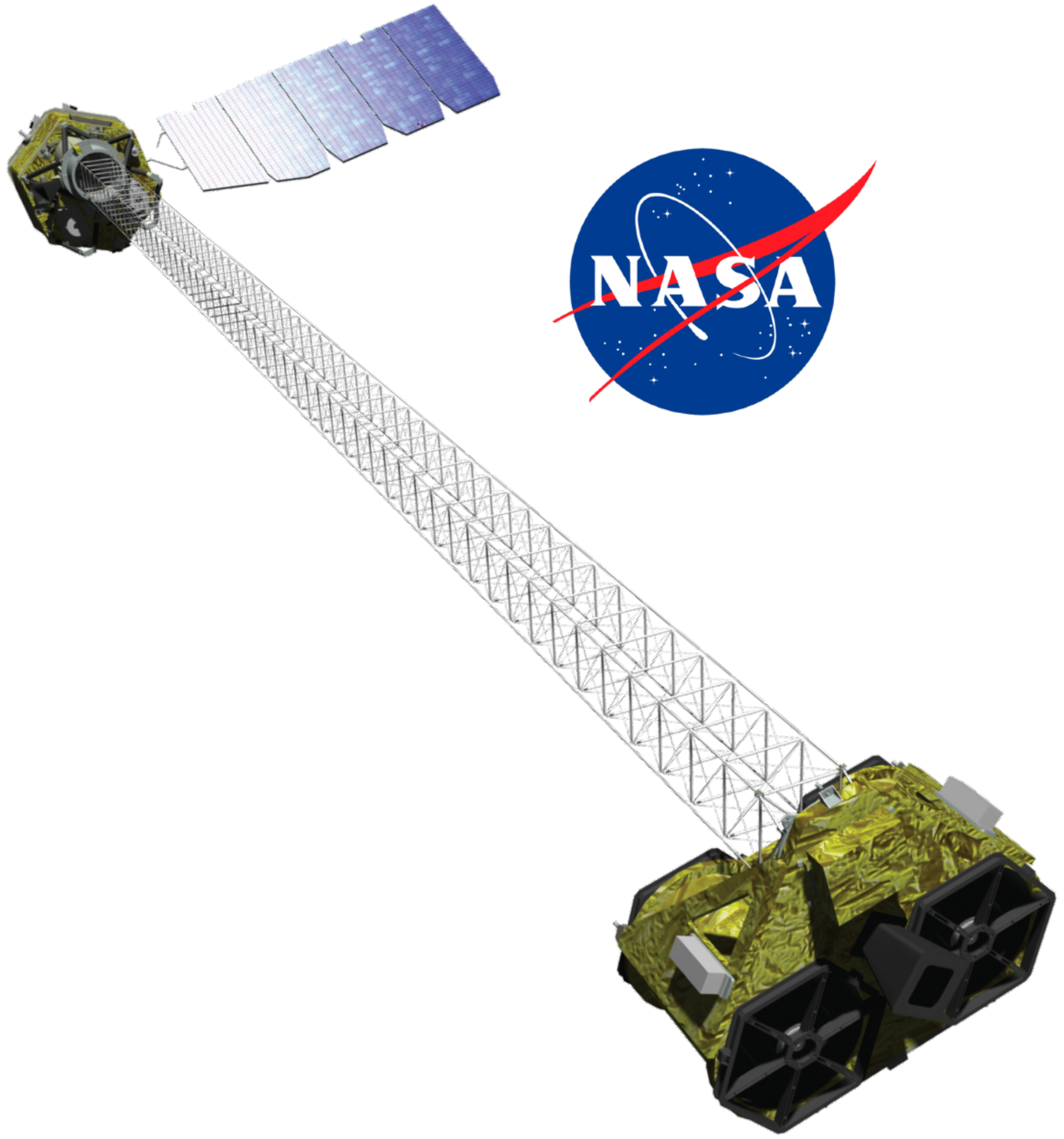
X-RAY ASTROPHYSICS
DEPARTMENT OF PHYSICS & ASTRONOMY

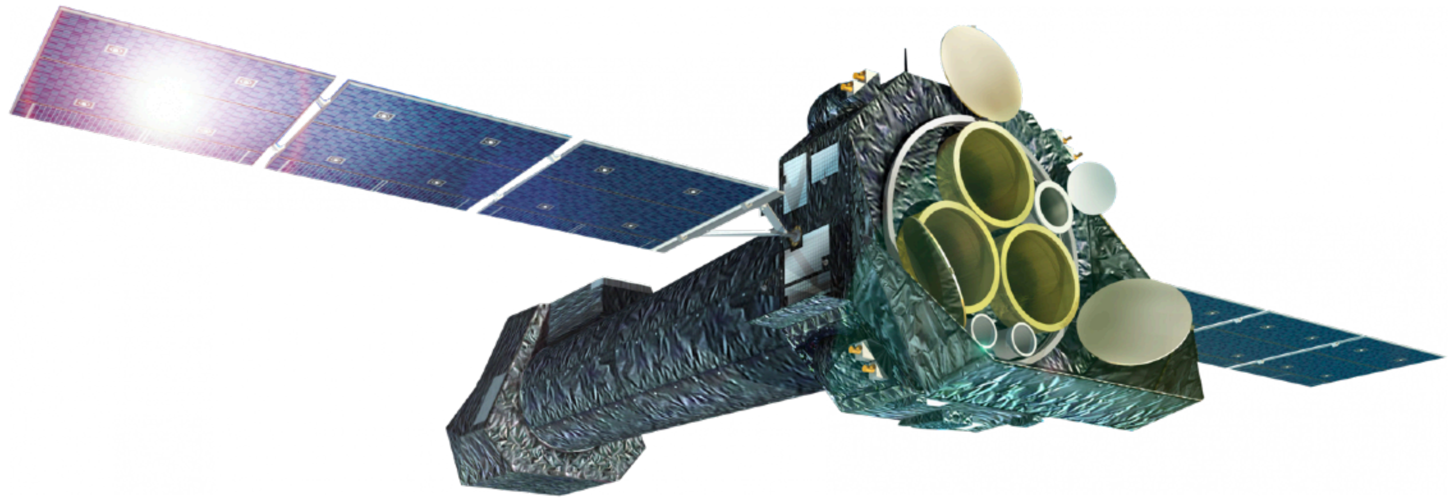
# Galaxy Cluster-based Evidence for Conflicting Calibrations between *NuSTAR* and *XMM-Newton/Chandra* at 3-10 keV Energies



CHANDRA X-RAY OBSERVATORY


Daniel R. Wik
(University of Utah)

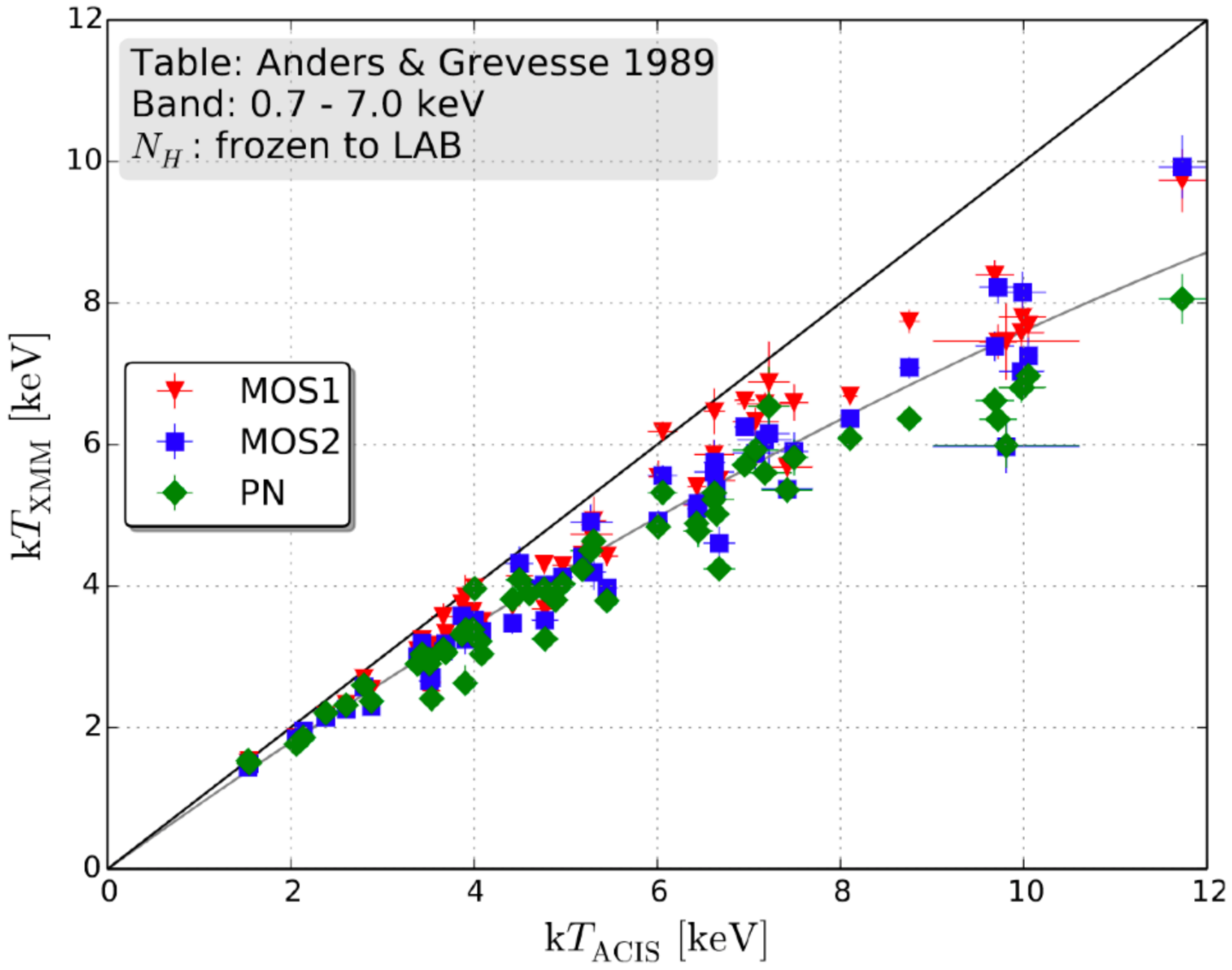

Based mostly on work from
Cicely Potter
(Utah)
and
Fiona Lopez
(Texas A&M)

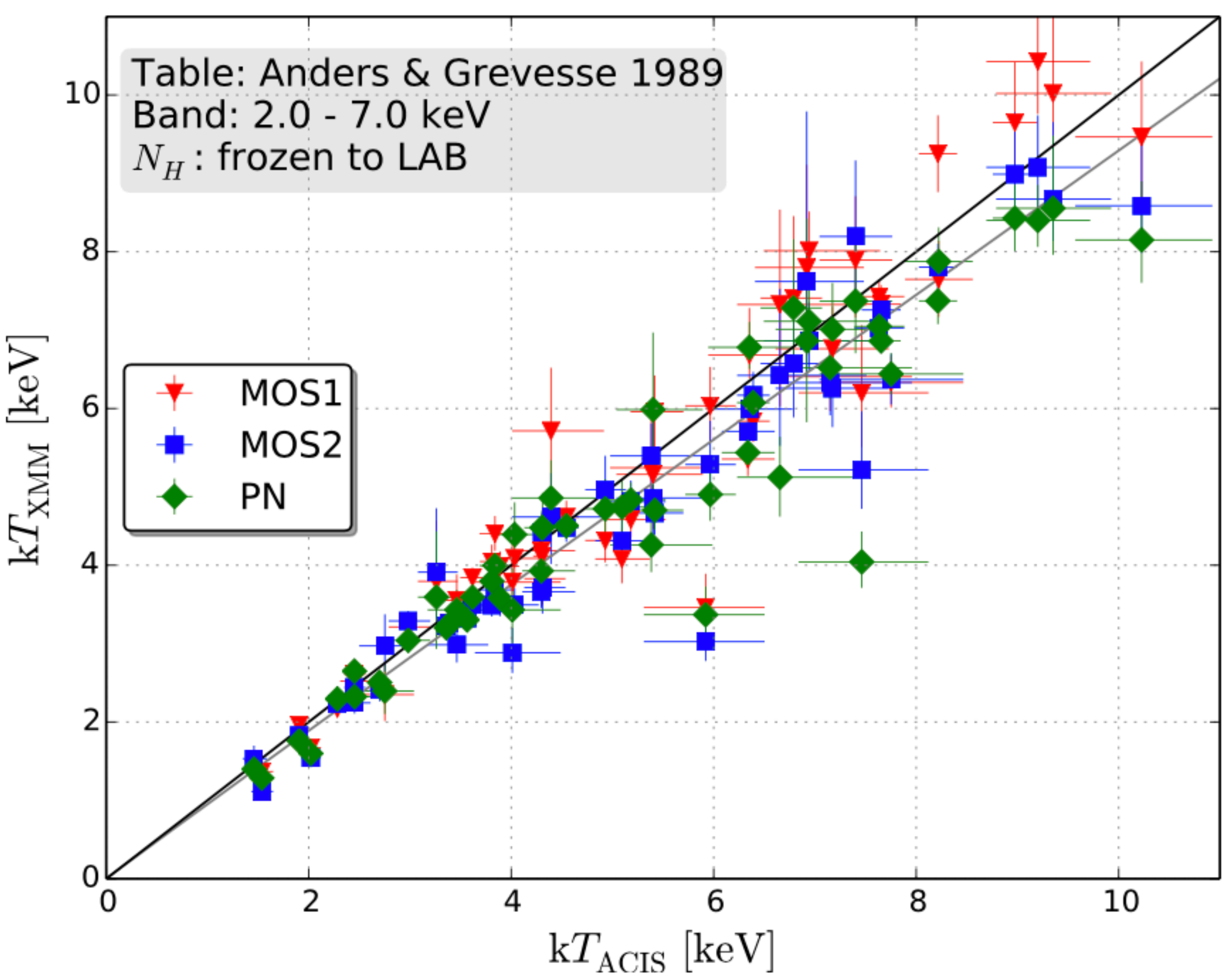


XMM-NEWTON

NuSTAR

# Galaxy Clusters: Temperature Discrepancy

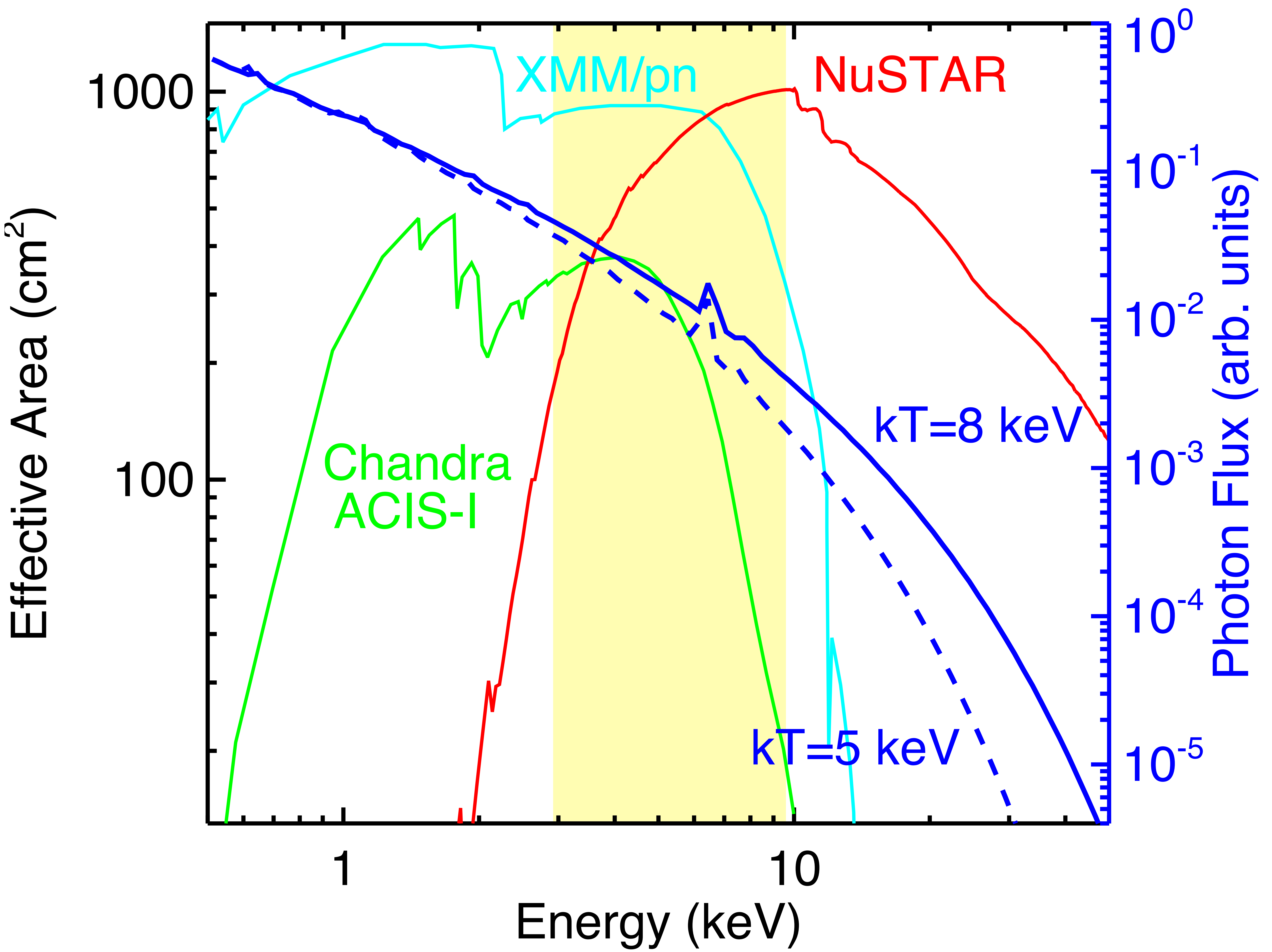



Schellenberger+ 2015

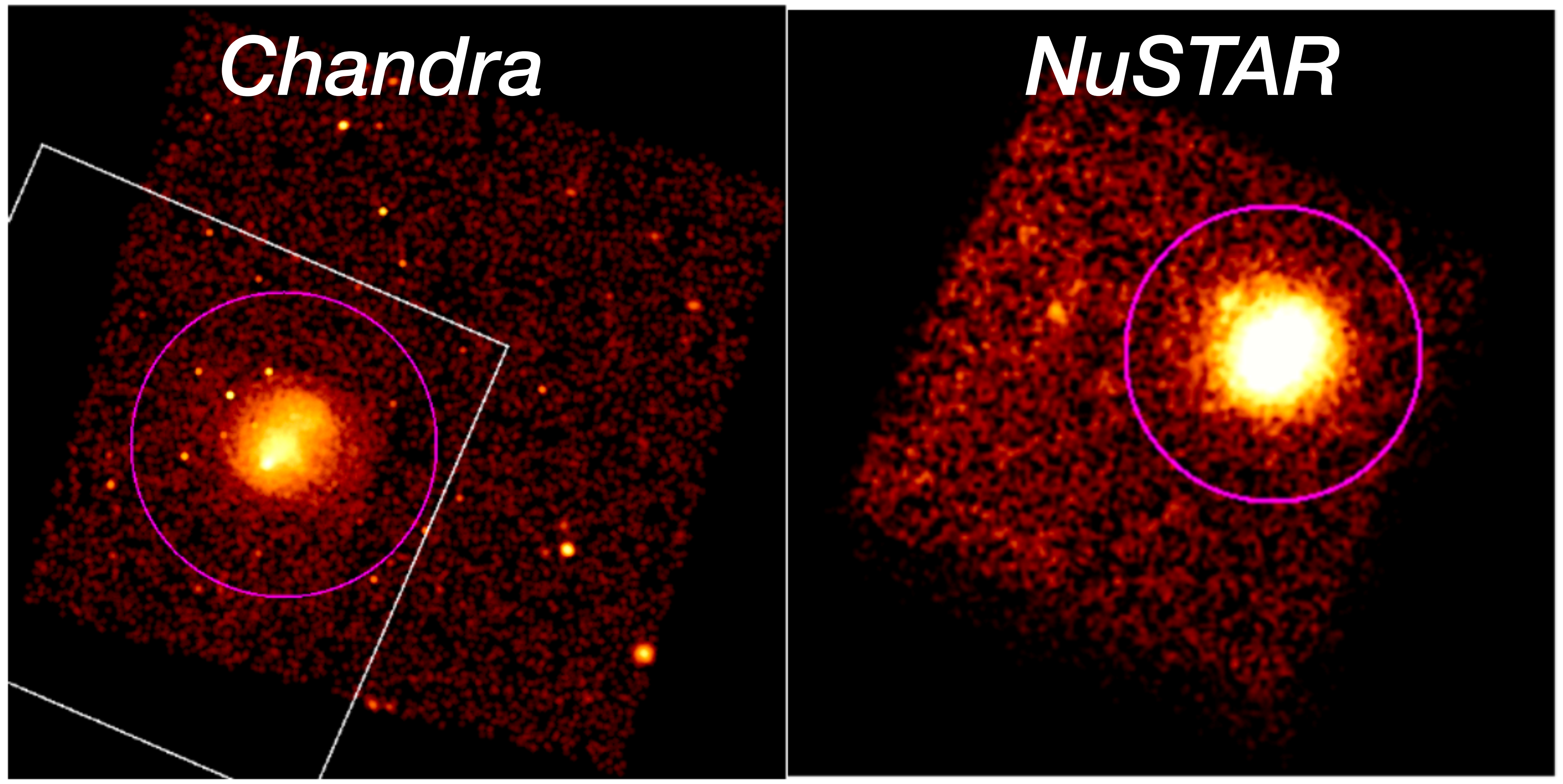
# *NuSTAR*'s Contribution

- Discrepancy is worst at the highest temperatures where *NuSTAR*'s sensitivity is most useful
- Even for low *kT*s, *NuSTAR* has a better handle on the exponential turnover of the bremsstrahlung continuum, which drives *kT* estimates
- In most cases, foreground absorption becomes almost negligible and lines have less impact on the continuum

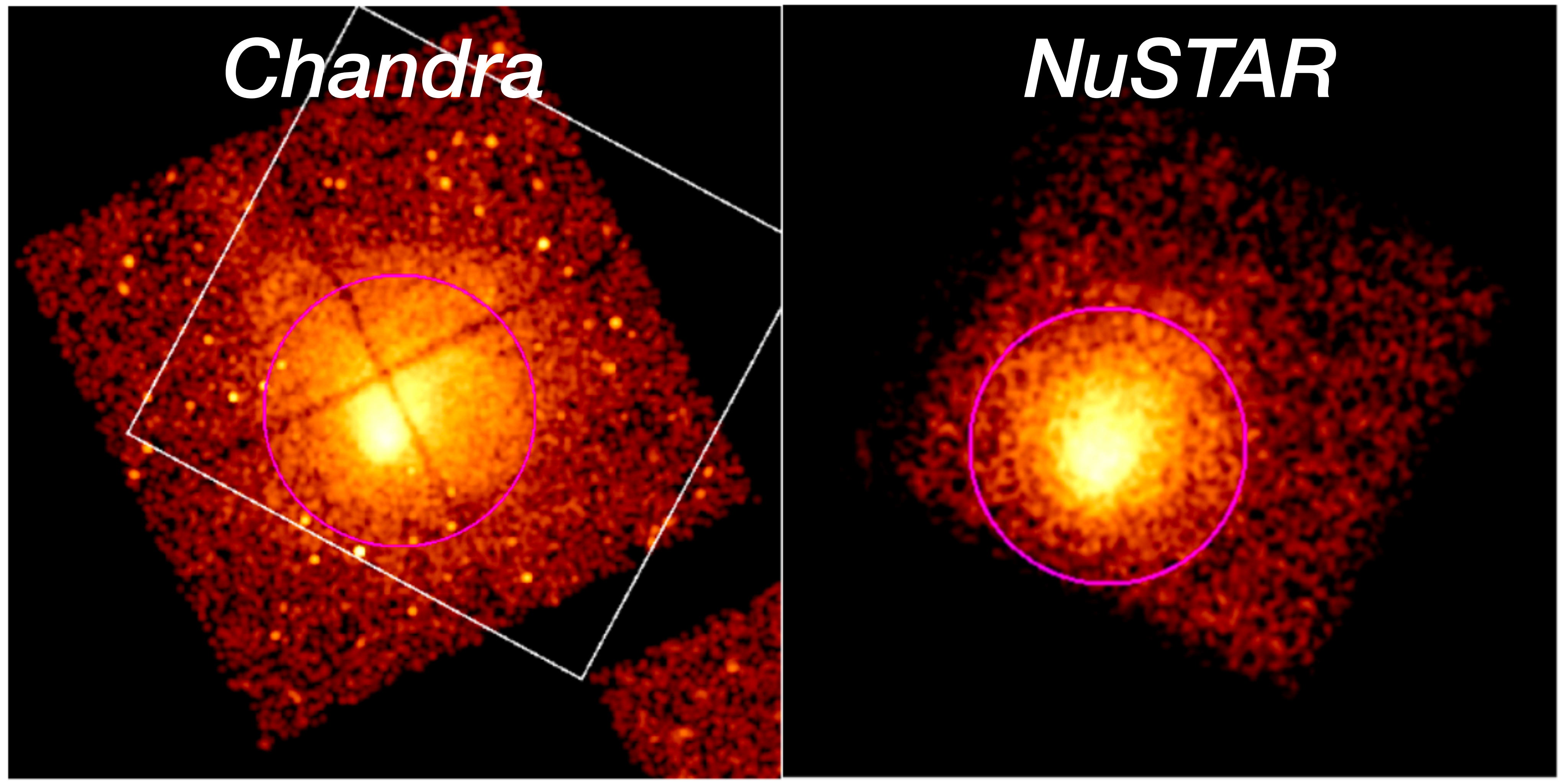


# Global *kT* Measurements (*Chandra* vs. *NuSTAR*)

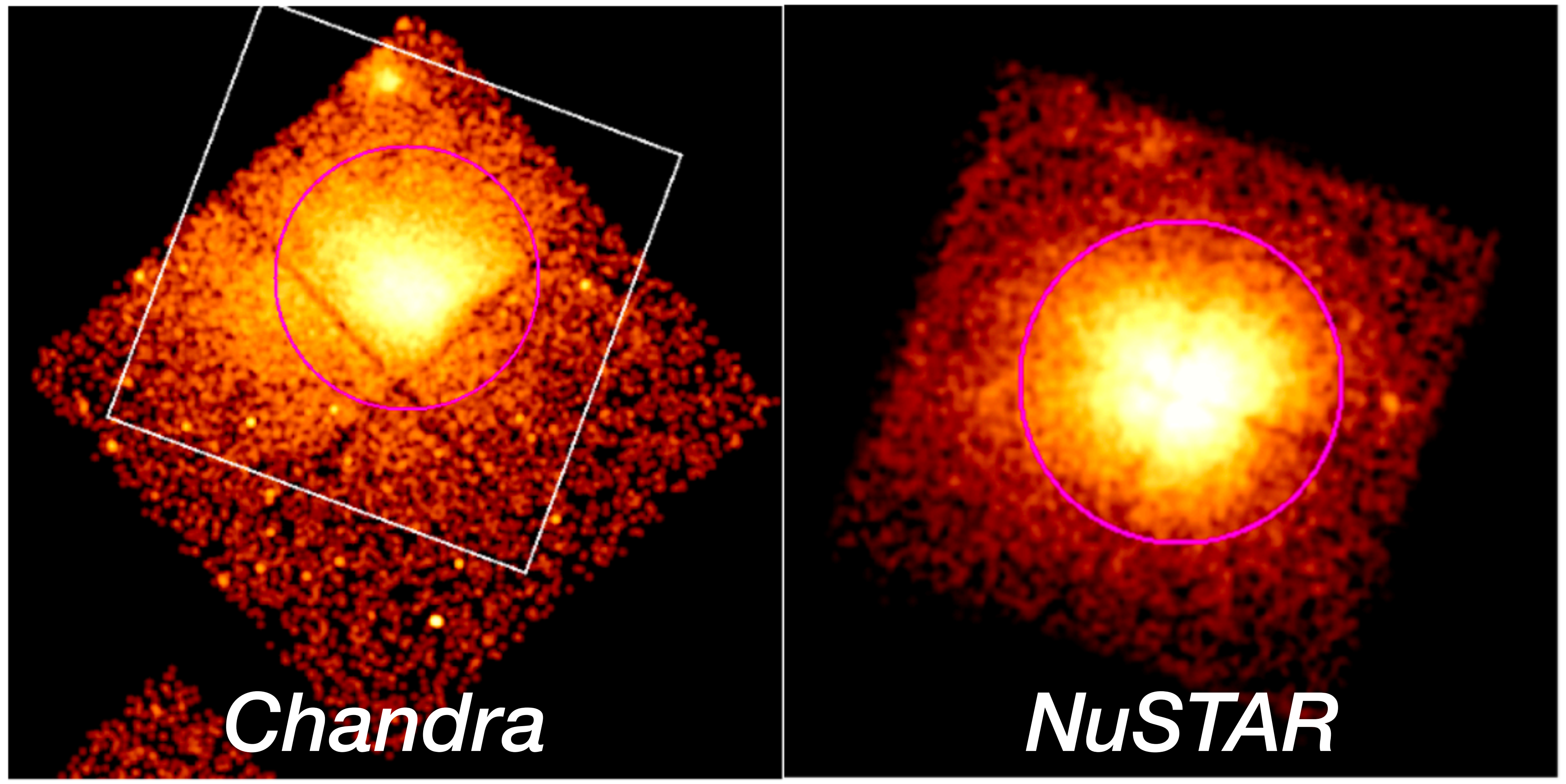
Wallbank+ 22




A2146




A665

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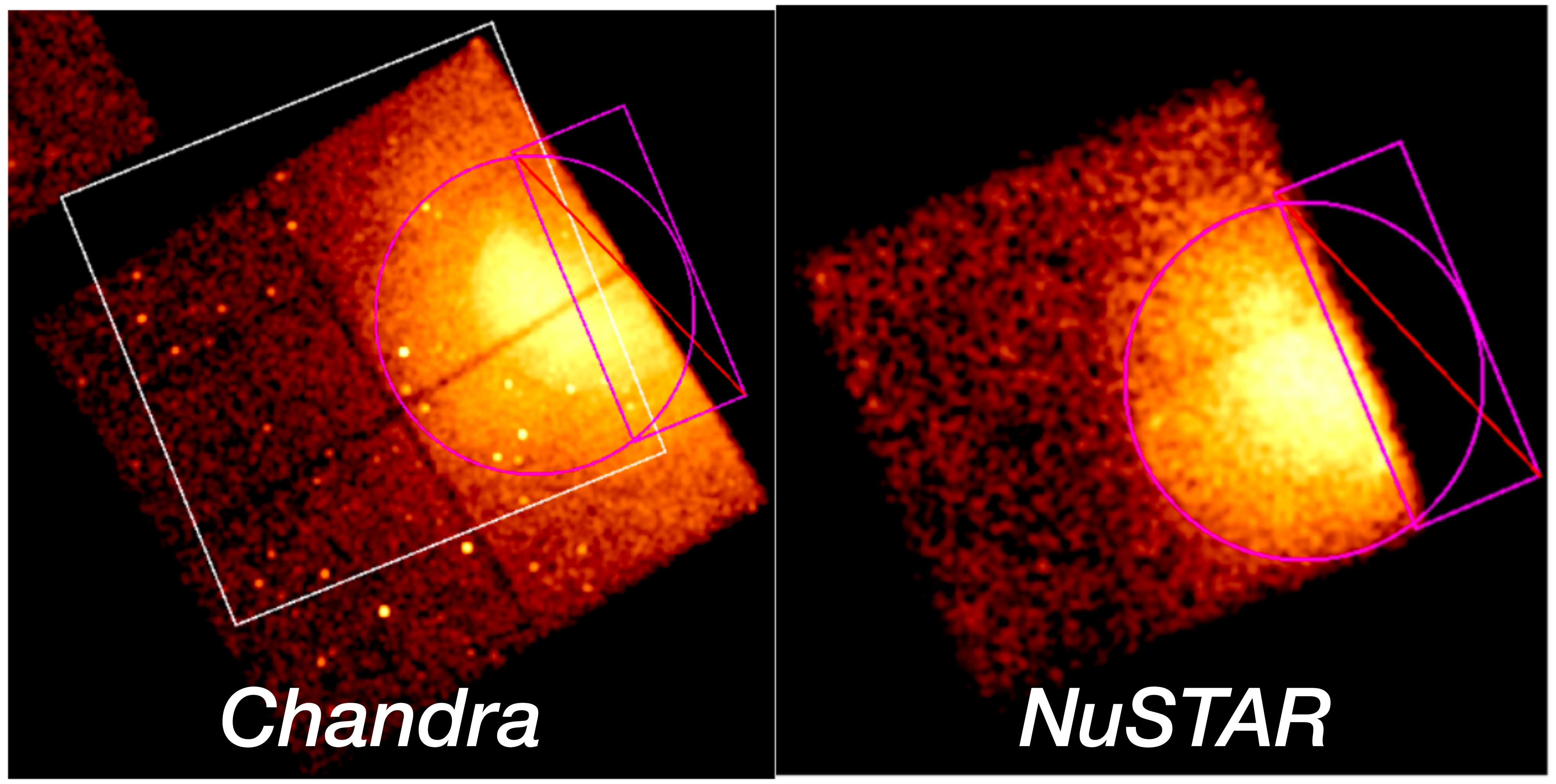
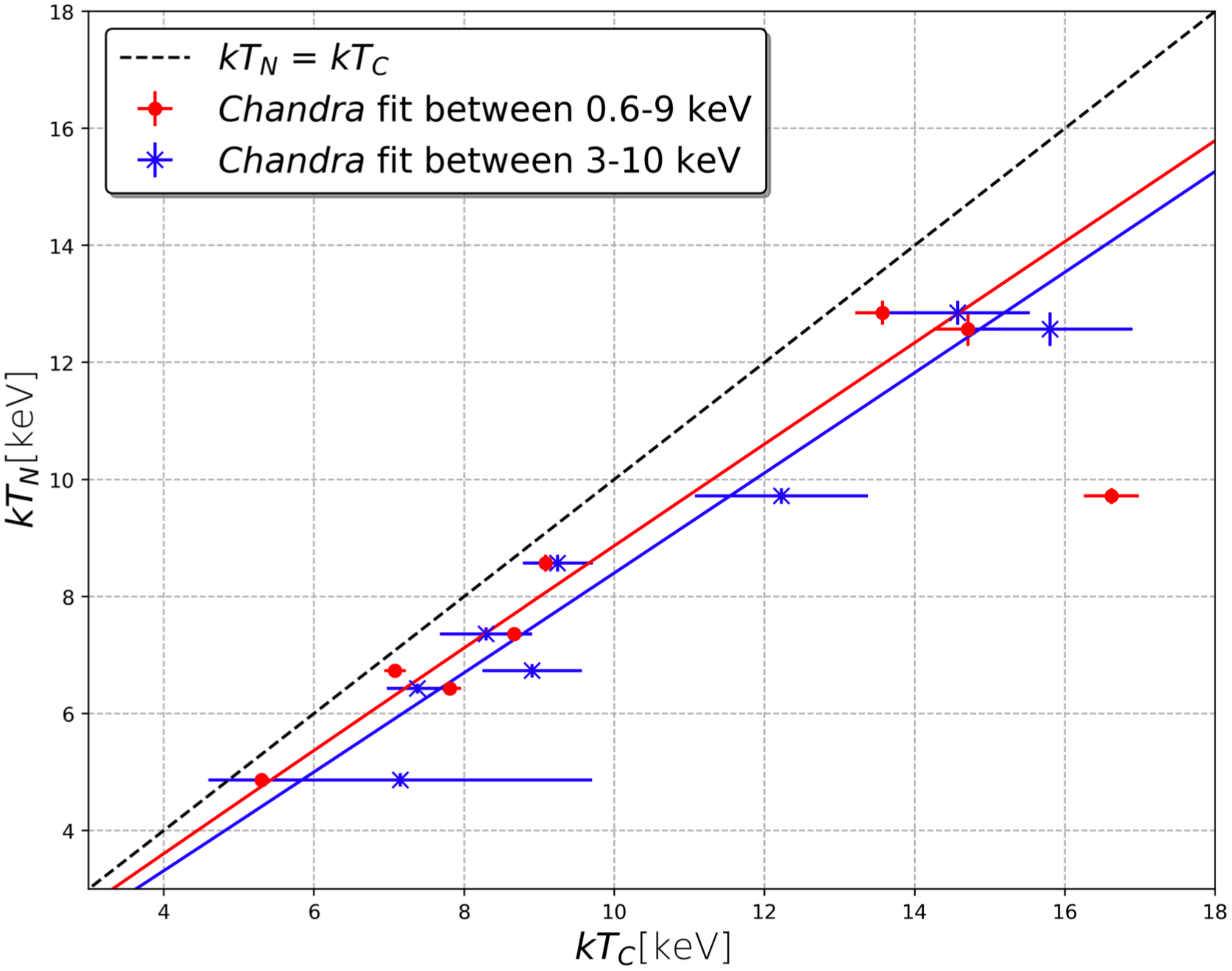



A754

# Global *kT* Measurements (*Chandra* vs. *NuSTAR*)



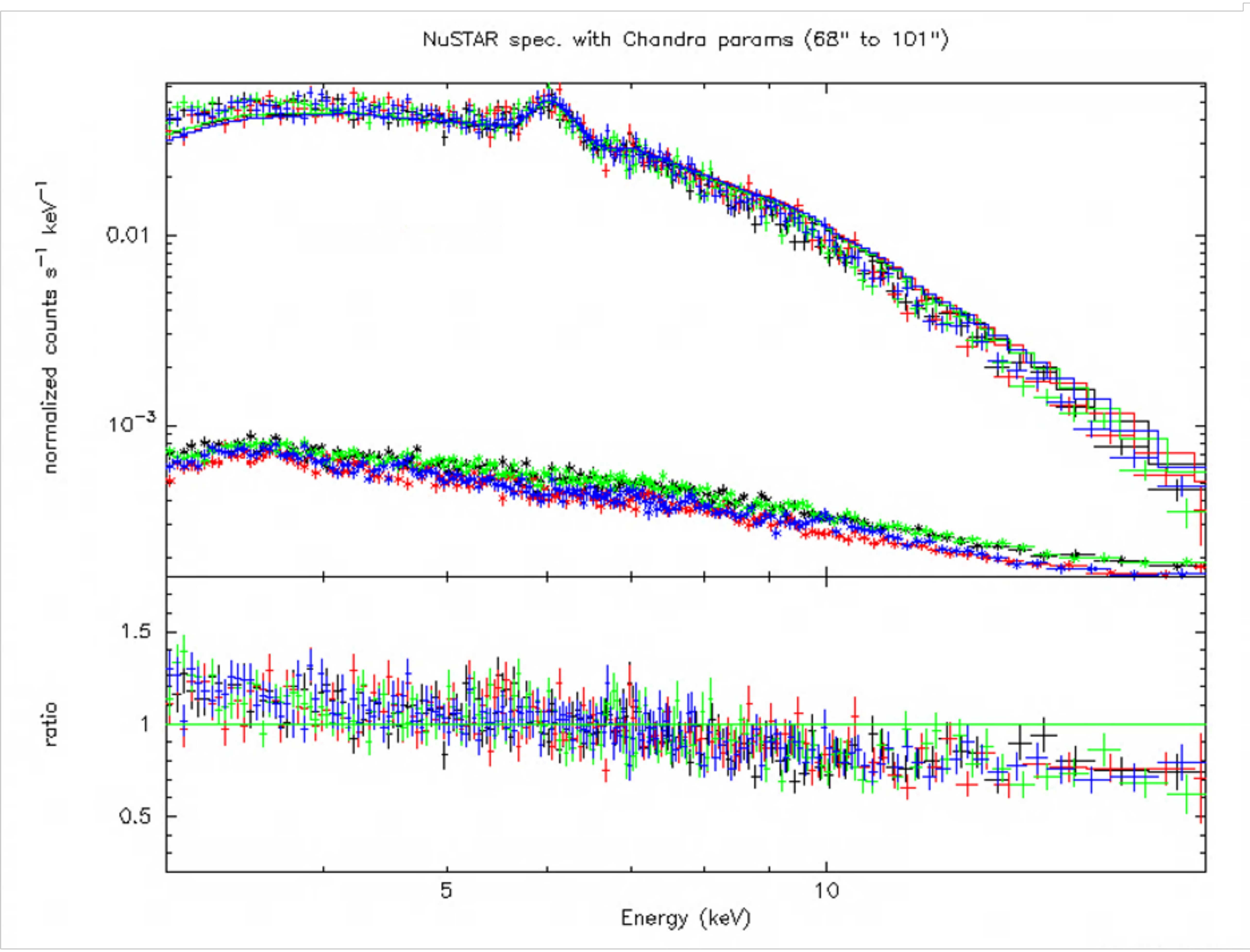

| Cluster Name | $kT_{C,(0.6-9)}$ keV | $kT_C$ keV | $kT_N$ keV |
|---|---|---|---|
| Abell 2146 | $7.08 \pm 0.14$ | $8.9 \pm 0.66$ | $6.72 \pm 0.11$ |
| Abell 2163 | $16.36 \pm 0.70^{\dagger}$ | $12.23 \pm 1.15$ | $9.72 \pm 0.13$ |
| Abell 2256 | $7.81 \pm 0.15$ | $7.38 \pm 0.41$ | $6.43 \pm 0.085$ |
| Abell 523 | $5.30 \pm 0.36$ | $7.15 \pm 2.55$ | $4.87 \pm 0.12$ |
| Abell 665 | $8.66 \pm 0.23$ | $8.29 \pm 0.62$ | $7.36 \pm 0.11$ |
| Abell 754 | $9.09 \pm 0.17$ | $9.25 \pm 0.47$ | $8.57 \pm 0.14$ |
| 1E 0657-56 | $13.57 \pm 0.36$ | $14.57 \pm 0.96$ | $12.85 \pm 0.20$ |
| RX J1347.5-1145 | $14.71 \pm 0.46$ | $15.80 \pm 1.09$ | $12.57 \pm 0.29$ |

For a *Chandra kT* of 10 keV, the *NuSTAR kT* is 11% or 16% lower

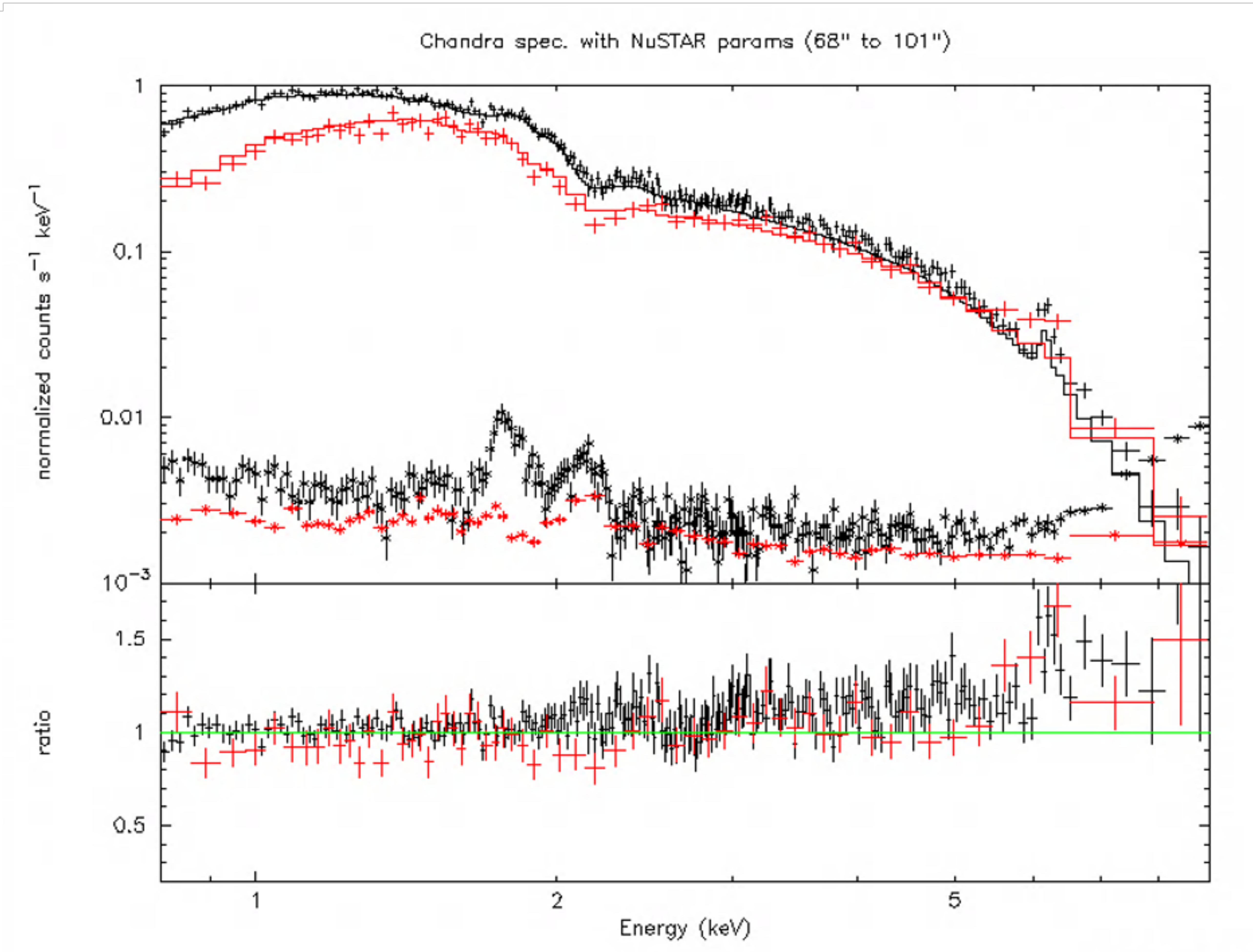
Physically, *NuSTAR* should be biased to *higher kT*s —> must be due to differences in calibration

Wallbank+ 22

# *NuSTAR* - *Chandra* Comparison

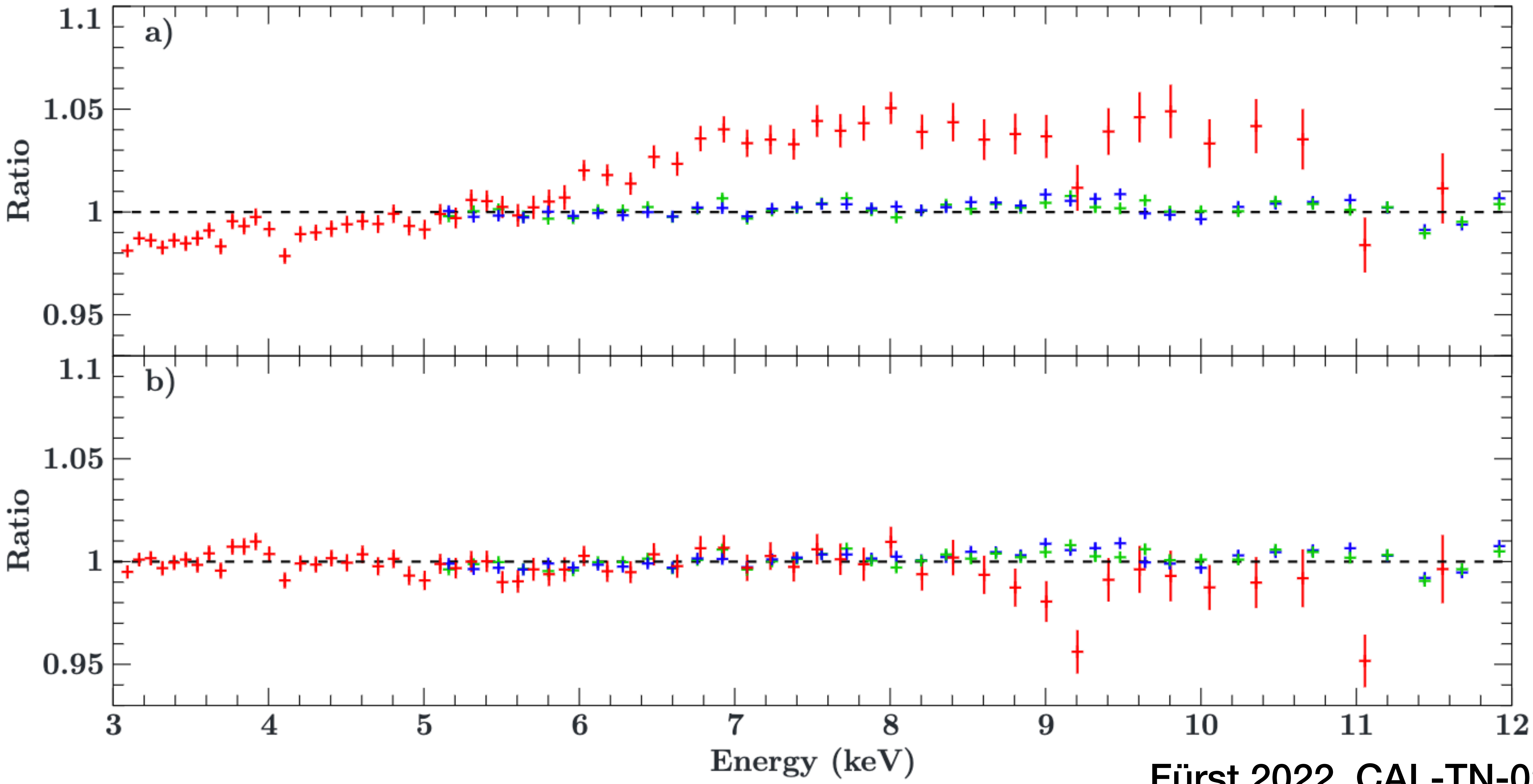



*NuSTAR* data with *Chandra* best-fit model
C-stat/dof: 3006/1567




*Chandra* data with *NuSTAR* best-fit model
C-stat/dof: 1105/964

# *NuSTAR - XMM-Newton* Comparison




Fürst 2022, CAL-TN-0230-1-3

# Cross-calibration with Relaxed Clusters

## Cicely Potter

*NuSTAR* Large Program (>100 ks each)

| Cluster | $kT$ (keV) | $z$ |
|---|---|---|
| Abell 2029 | 8.5 | 0.077 |
| Abell 478 | 7.3 | 0.088 |
| Abell 1795 | 6.1 | 0.062 |
| Abell 2199 | 4.4 | 0.030 |

Reanalysis of *Chandra/XMM-Newton* data in exact same regions

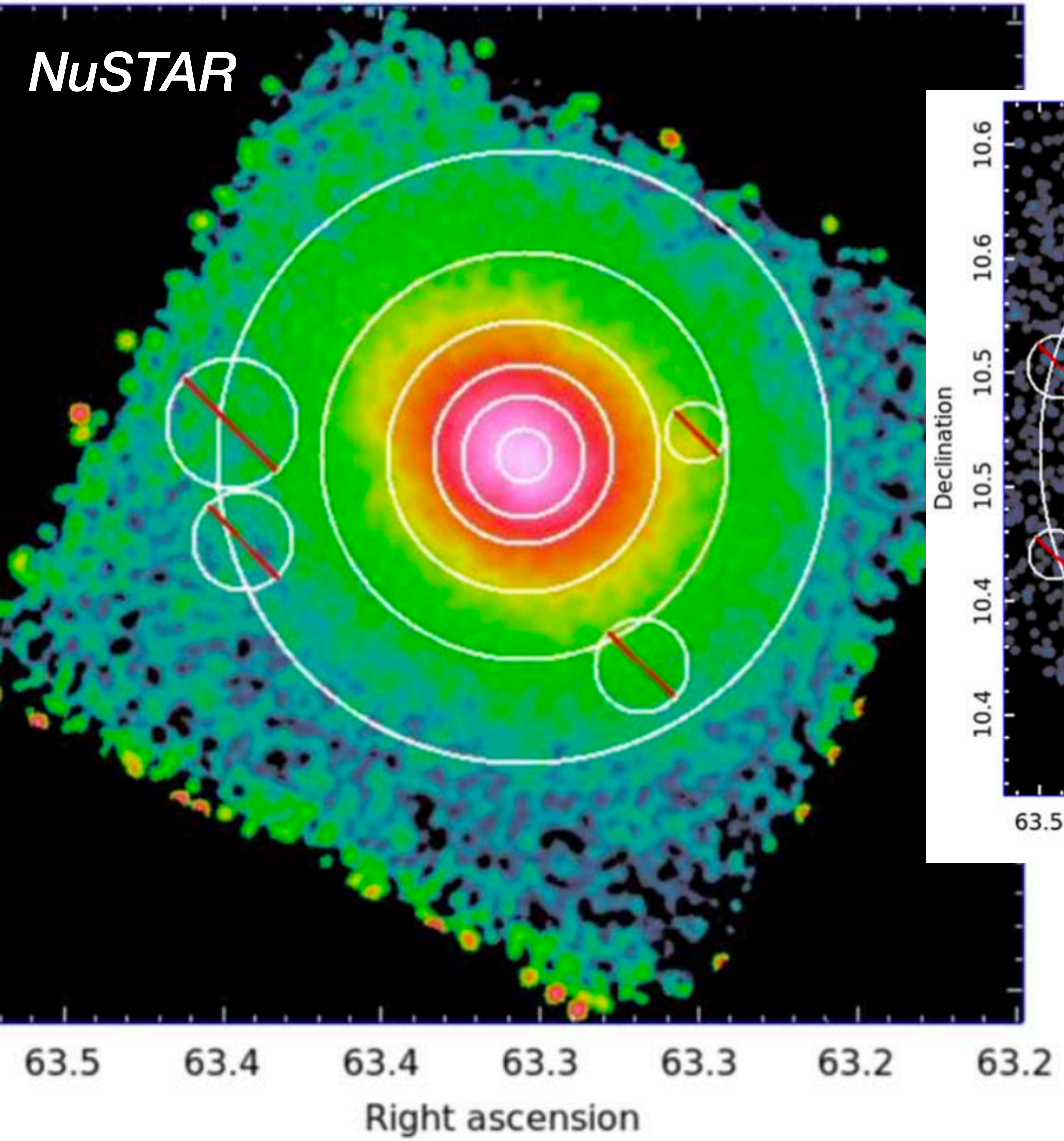
## Fiona Lopez

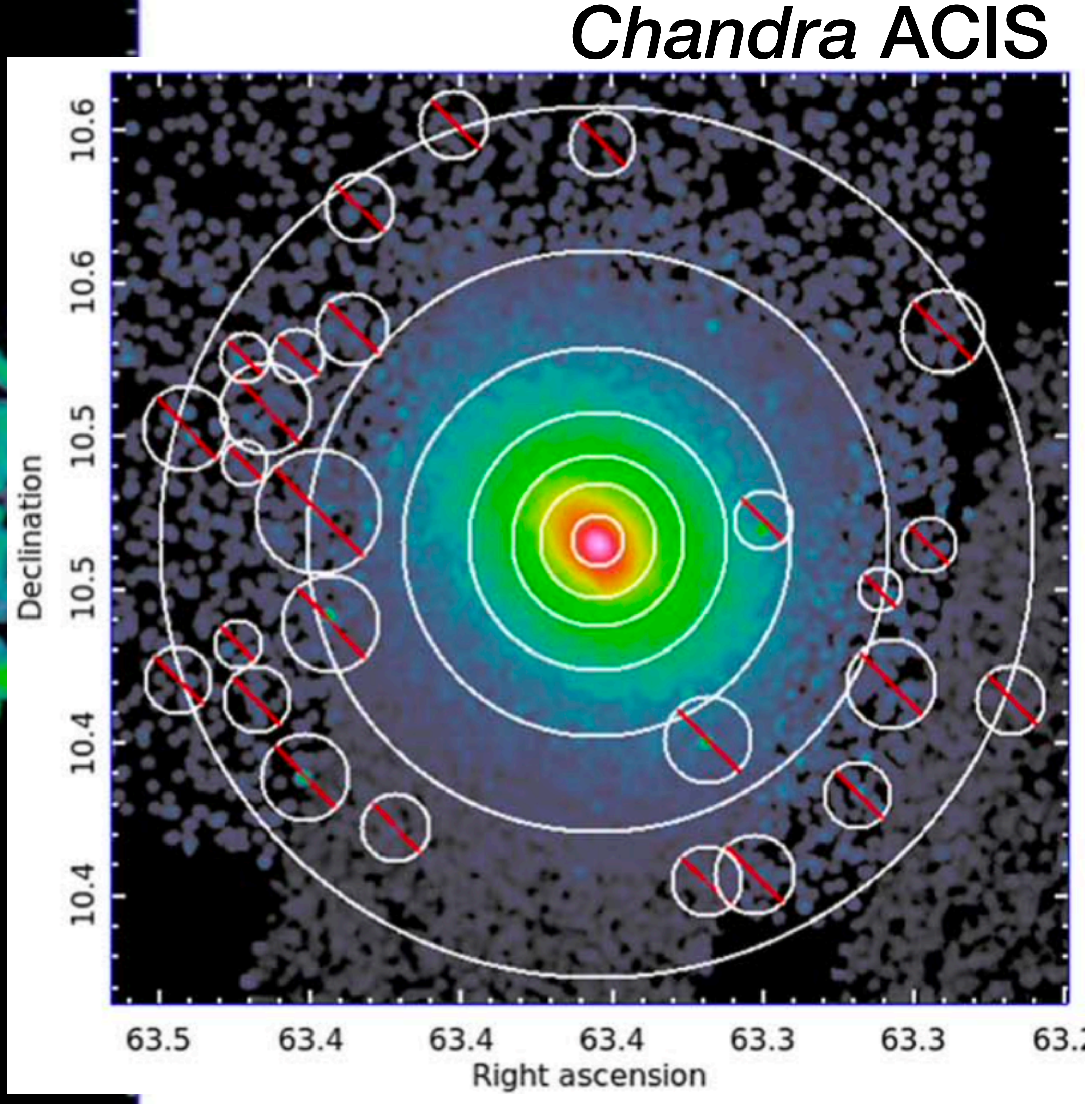
*NuSTAR* Cluster Snapshot C Program (20 ks each)

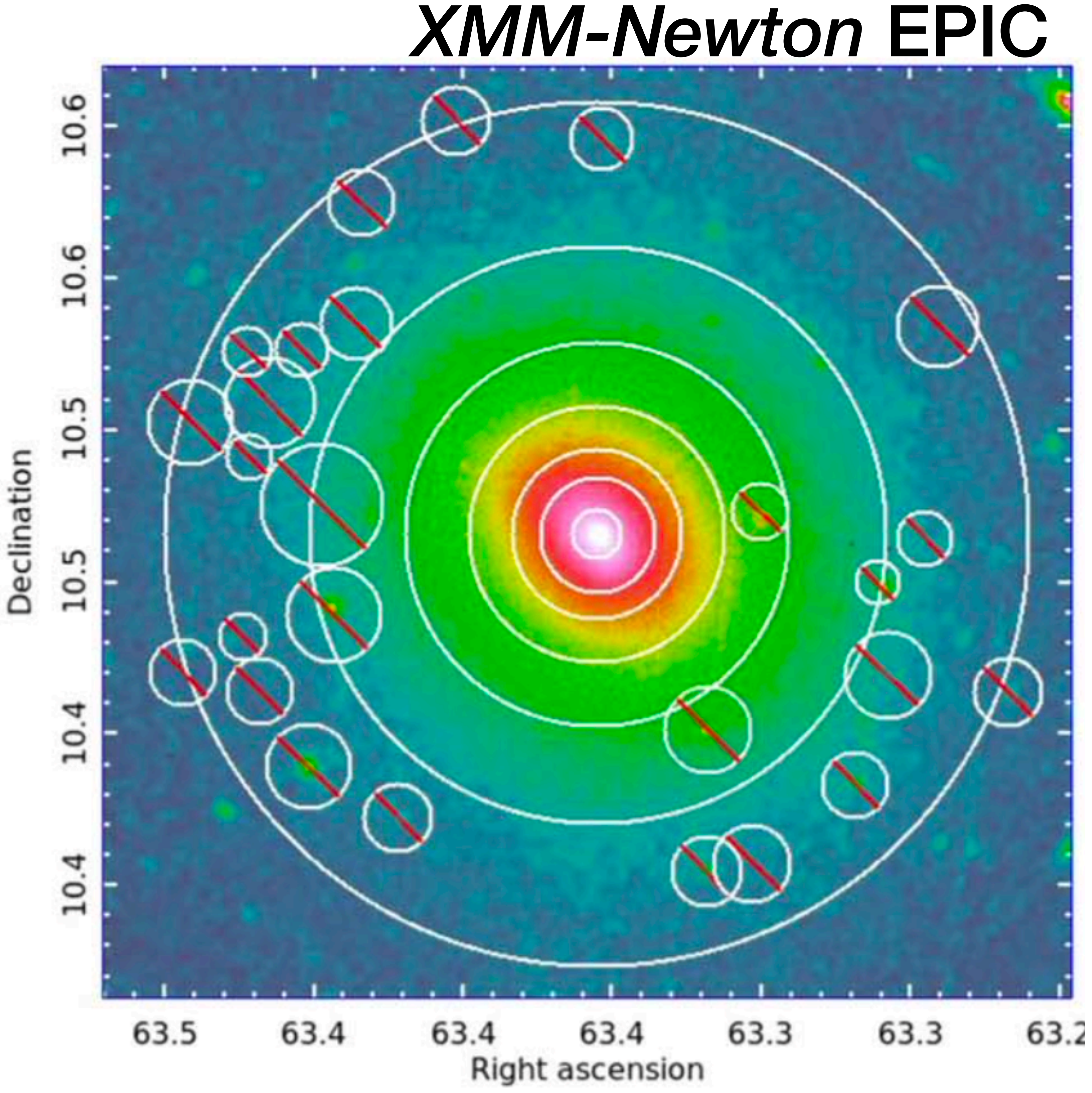
| Cluster | $kT_C$ (keV) | $\Delta kT_X$ (keV) | $\frac{T_C - T_X}{T_X}$ | $\Delta kT_N$ (keV) |
|---|---|---|---|---|
| RXC J1504 | $9.8 \pm 0.8$ | 0.2 | 0.53 | 0.8 |
| Abell 3571 | $8.1 \pm 0.1$ | 0.1 | 0.27 | 0.1 |
| Abell 3558 | $7.4 \pm 0.3$ | 0.1 | 0.35 | 0.2 |
| Abell 1651 | $7.1 \pm 0.3$ | 0.1 | 0.16 | 0.1 |
| Abell 3391 | $6.6 \pm 0.2$ | 0.1 | 0.19 | 0.2 |
| Abell 1650 | $6.4 \pm 0.1$ | 0.1 | 0.25 | 0.2 |
| Abell 3158 | $6.0 \pm 0.1$ | 0.1 | 0.18 | 0.1 |
| Abell 3112 | $5.5 \pm 0.1$ | 0.1 | 0.36 | 0.2 |
| Abell 1644 | $5.3 \pm 0.1$ | 0.2 | 0.15 | 0.2 |
| Abell 496 | $5.2 \pm 0.1$ | 0.1 | 0.18 | 0.2 |
| ~~Abell 3562~~ | ~~$5.0 \pm 0.3$~~ | ~~0.1~~ | ~~0.19~~ | ~~0.1~~ |

Extract same regions as in Schellenberger+ 2015 ($r < 3.5'$, excising cores)

# *NuSTAR/Chandra/XMM-Newton* of Abell 478

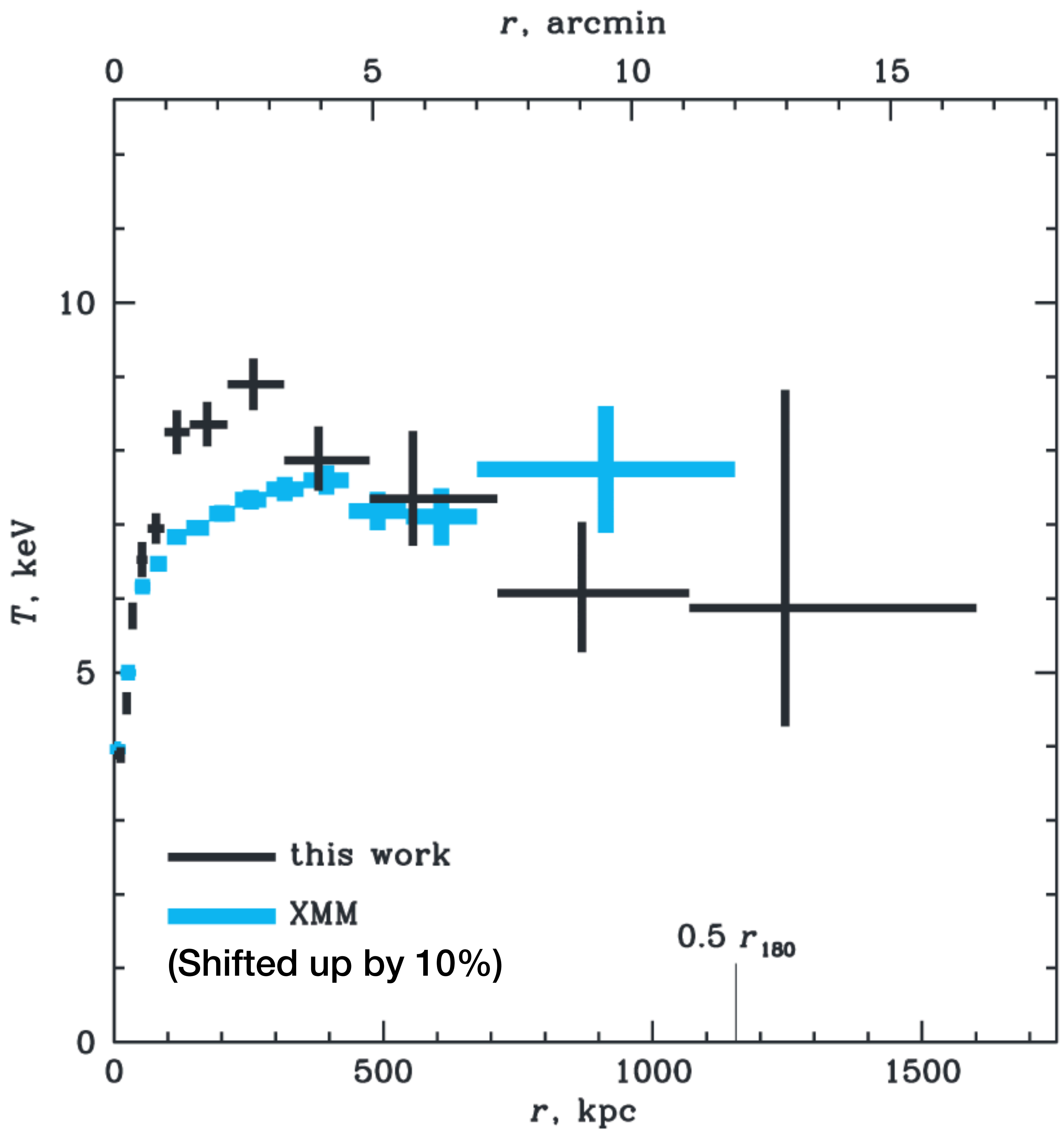


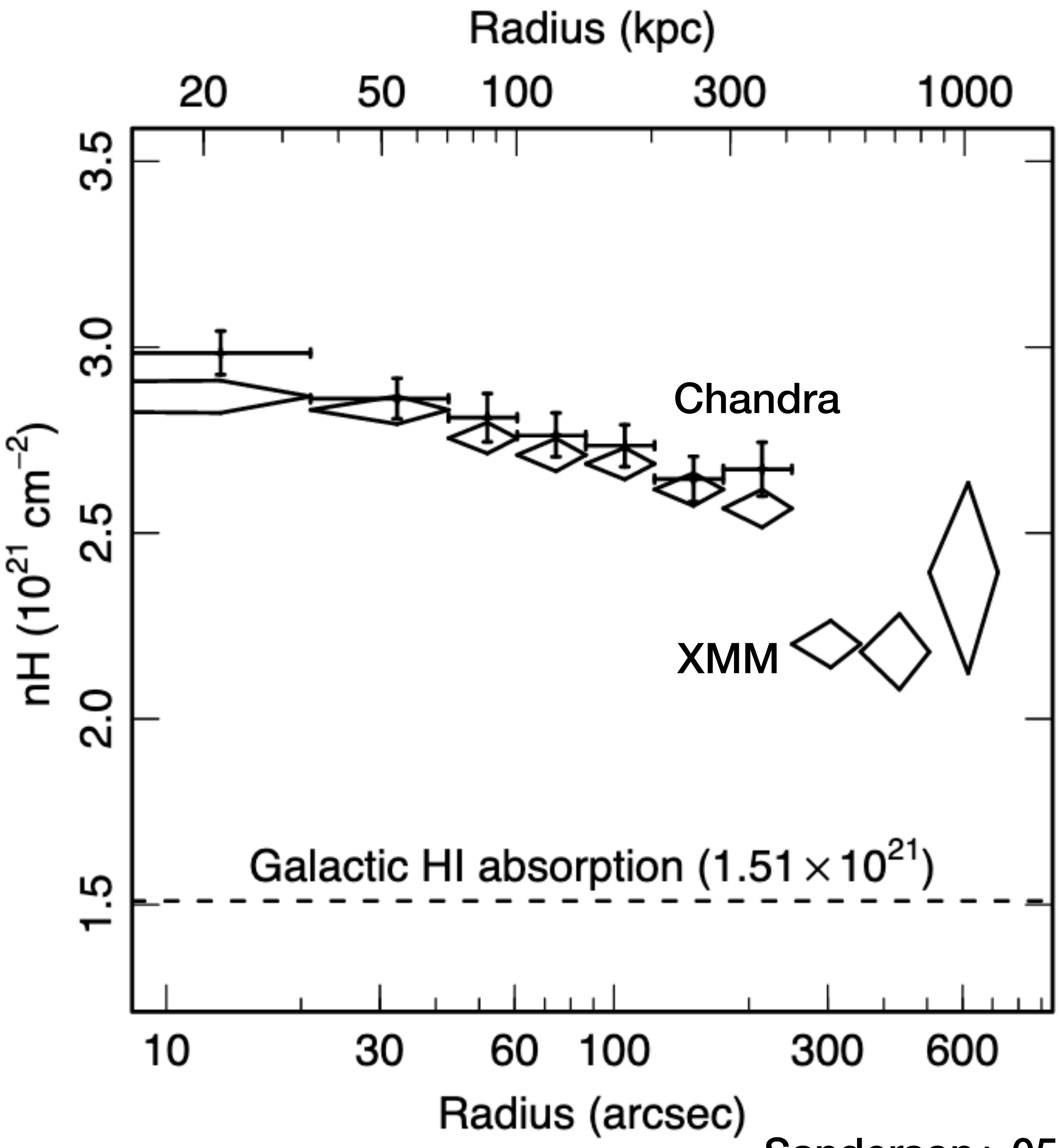




Potter+ 2023

# *Chandra* & *XMM-Newton kT* Profiles

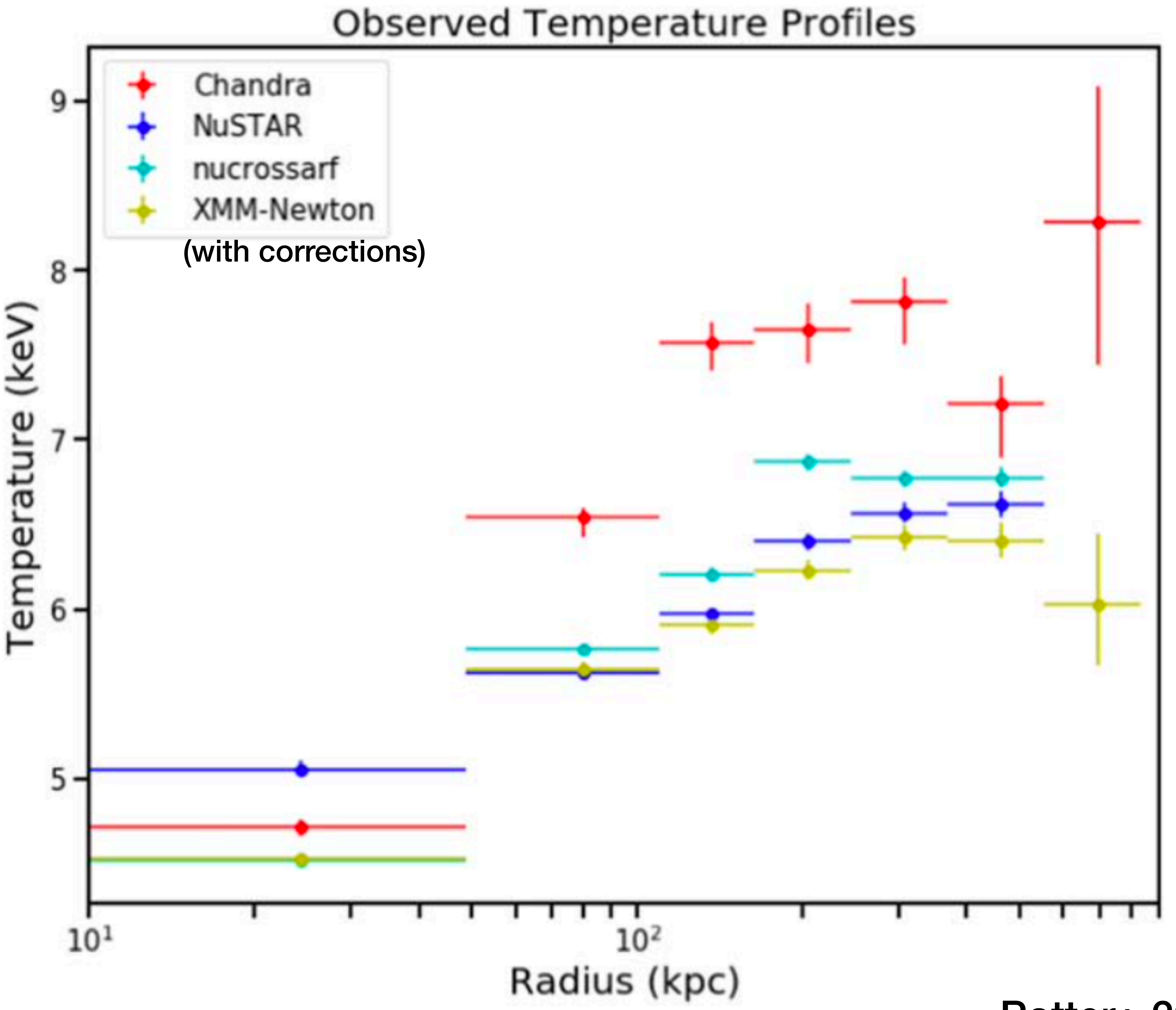



Vikhlinin+ 05, Pointecouteau+ 04




Sanderson+ 05

# Abell 478: Temperature Profiles



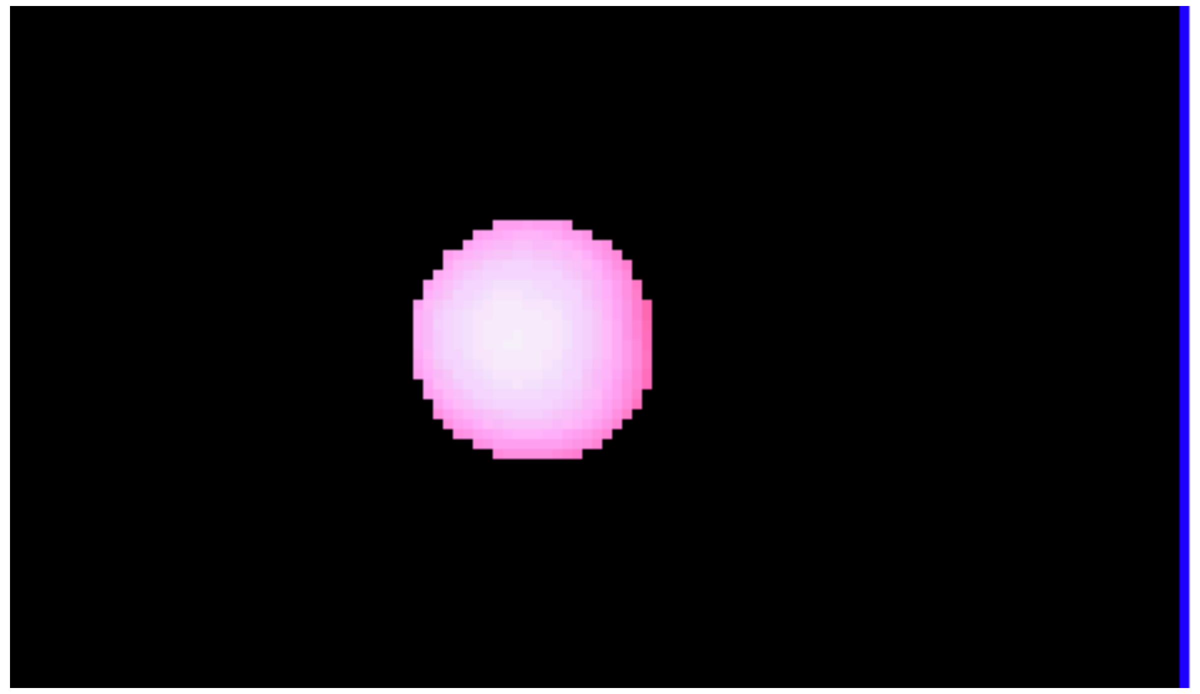

Potter+ 2023

# *NuSTAR* PSF Correction Using “Cross-ARFs”

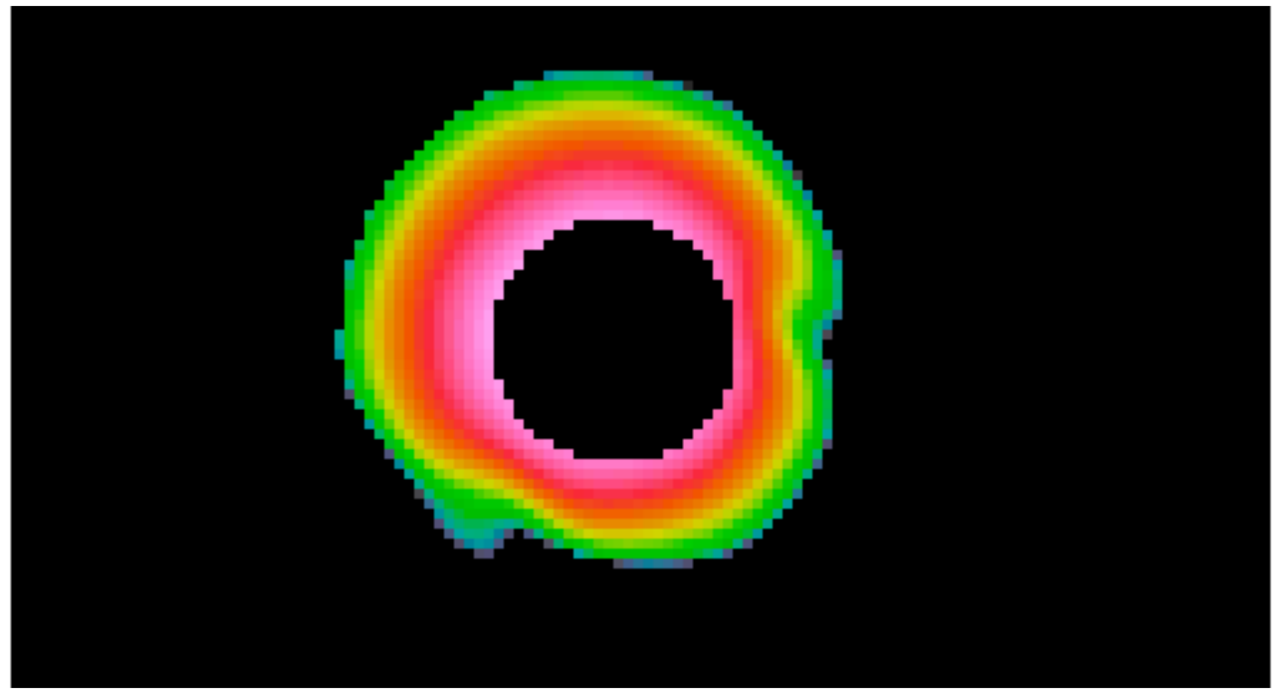
Systematic uncertainty of point source reconstruction is 3.4% (Creech+ 2024)

NuCrossARF

Equivalent to ARF produced by nuproducts

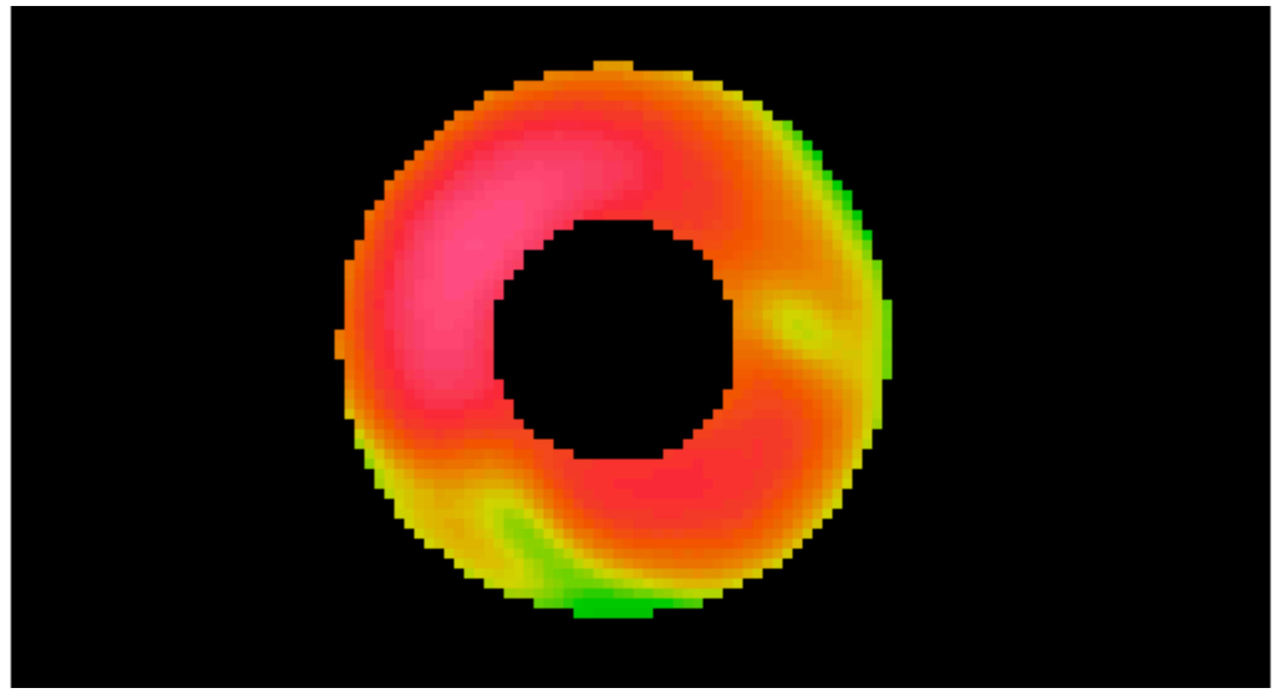


Emission inside Annulus 1, modulated by the PSF, creating a weighted ARF

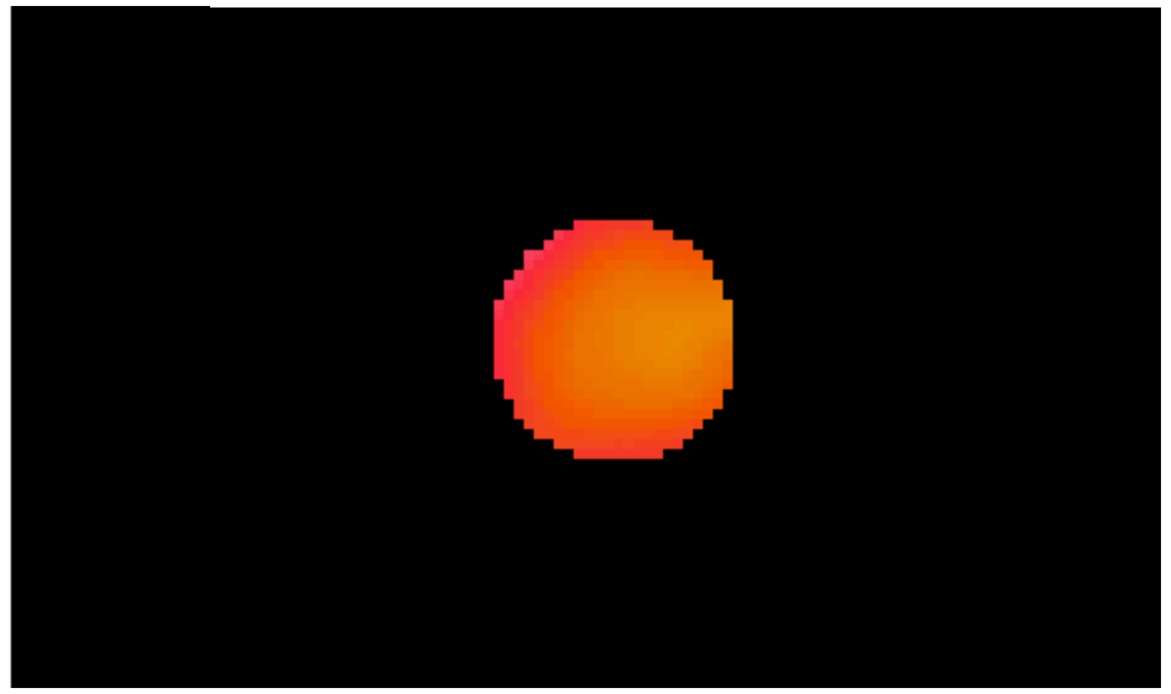


Emission scattered from Annulus 1 into Annulus 2 by the PSF, creating a weighted cross-ARF

Equivalent to ARF produced by nuproducts



Emission inside Annulus 2, modulated by the PSF, creating a weighted ARF



Emission scattered from Annulus 2 into Annulus 1 by the PSF, creating a weighted cross-ARF

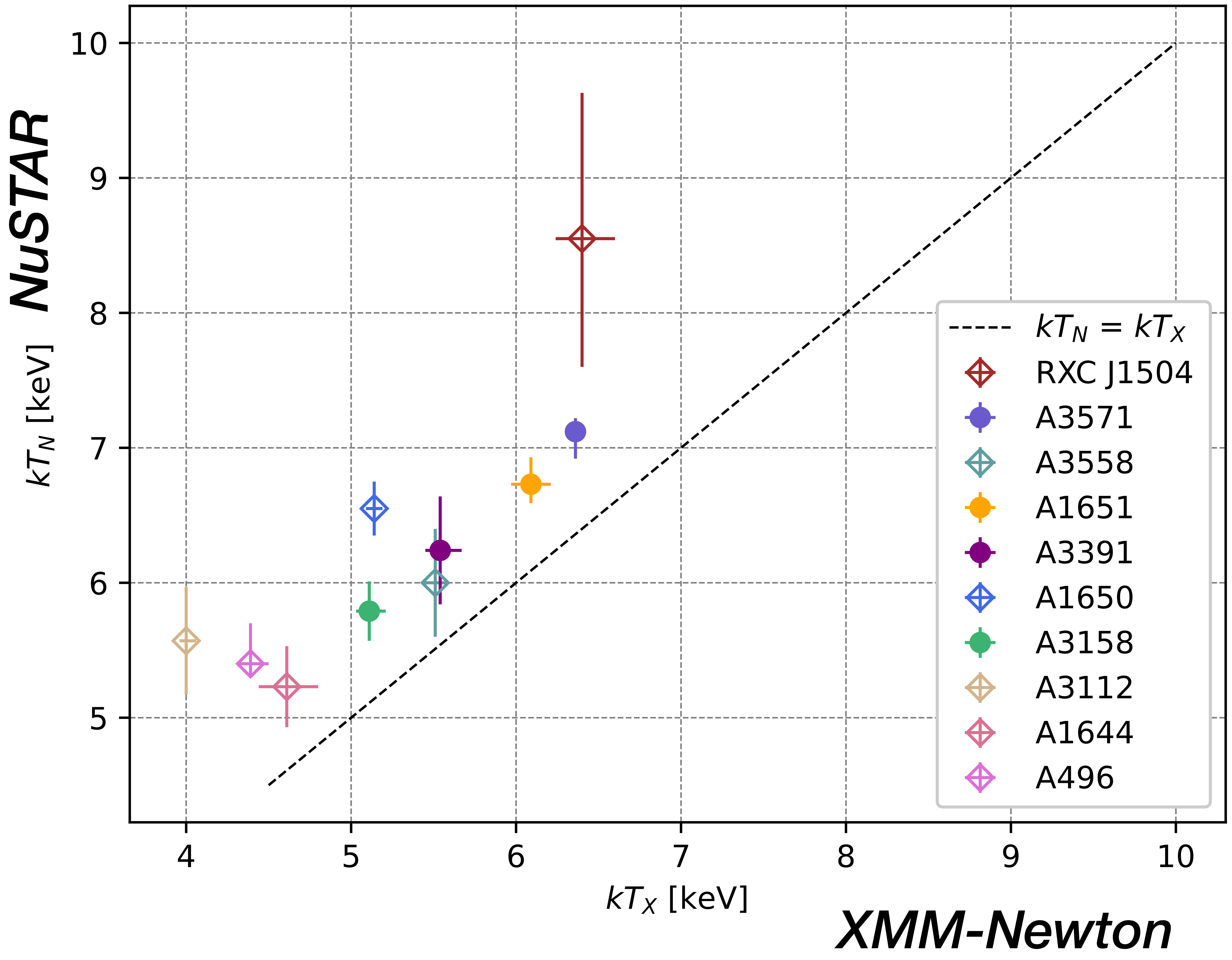
# Snapshot Cluster Temperatures

Lopez+ 2024

| Cluster Name | Redshift z | Gain Offset keV | $kT_c$ keV | $kT_X$ keV | $kT_N$ keV | $kT_{Ni}$ keV |
|---|---|---|---|---|---|---|
| RXC J1504 | 0.2172 | $-0.10 \pm 0.04$ | $9.81^{+0.80}_{-0.79}$ | $6.40^{+0.20}_{-0.16}$ | $8.55^{+1.09}_{-0.95}$ | $5.93^{+0.18}_{-0.33}$ |
| Abell 3571 | 0.0390 | $-0.09 \pm 0.02$ | $8.10^{+0.08}_{-0.08}$ | $6.36^{+0.06}_{-0.03}$ | $7.12^{+0.10}_{-0.20}$ | |
| Abell 3558 | 0.0484 | $-0.05 \pm 0.03$ | $7.42^{+0.27}_{-0.28}$ | $5.51^{+0.08}_{-0.08}$ | $6.00^{+0.40}_{-0.40}$ | $6.23^{+0.30}_{-0.30}$ |
| Abell 1651 | 0.0850 | $-0.09 \pm 0.04$ | $7.07^{+0.25}_{-0.25}$ | $6.09^{+0.12}_{-0.12}$ | $6.73^{+0.20}_{-0.14}$ | |
| Abell 3391 | 0.0561 | $-0.10 \pm 0.07$ | $6.62^{+0.22}_{-0.22}$ | $5.54^{+0.13}_{-0.09}$ | $6.24^{+0.40}_{-0.40}$ | |
| Abell 1650 | 0.0838 | $-0.10 \pm 0.04$ | $6.43^{+0.10}_{-0.10}$ | $5.14^{+0.05}_{-0.05}$ | $6.55^{+0.20}_{-0.20}$ | $5.88^{+0.90}_{-0.30}$ |
| Abell 3158 | 0.0592 | $-0.05 \pm 0.05$ | $6.01^{+0.10}_{-0.10}$ | $5.11^{+0.10}_{-0.08}$ | $5.79^{+0.22}_{-0.22}$ | |
| Abell 3112 | 0.0753 | $-0.10 \pm 0.03$ | $5.45^{+0.12}_{-0.09}$ | $4.00^{+0.06}_{-0.04}$ | $5.57^{+0.40}_{-.040}$ | $4.59^{+0.20}_{-0.20}$ |
| Abell 1644 | 0.0474 | $-0.06 \pm 0.05$ | $5.31^{+0.14}_{-0.13}$ | $4.61^{+0.19}_{-0.17}$ | $5.23^{+0.30}_{-0.30}$ | $5.24^{+0.20}_{-0.20}$ |
| Abell 496 | 0.0331 | $-0.07 \pm 0.03$ | $5.18^{+0.07}_{-0.07}$ | $4.39^{+0.11}_{-0.08}$ | $5.40^{+0.30}_{-0.10}$ | $3.82^{+0.10}_{-0.03}$ |

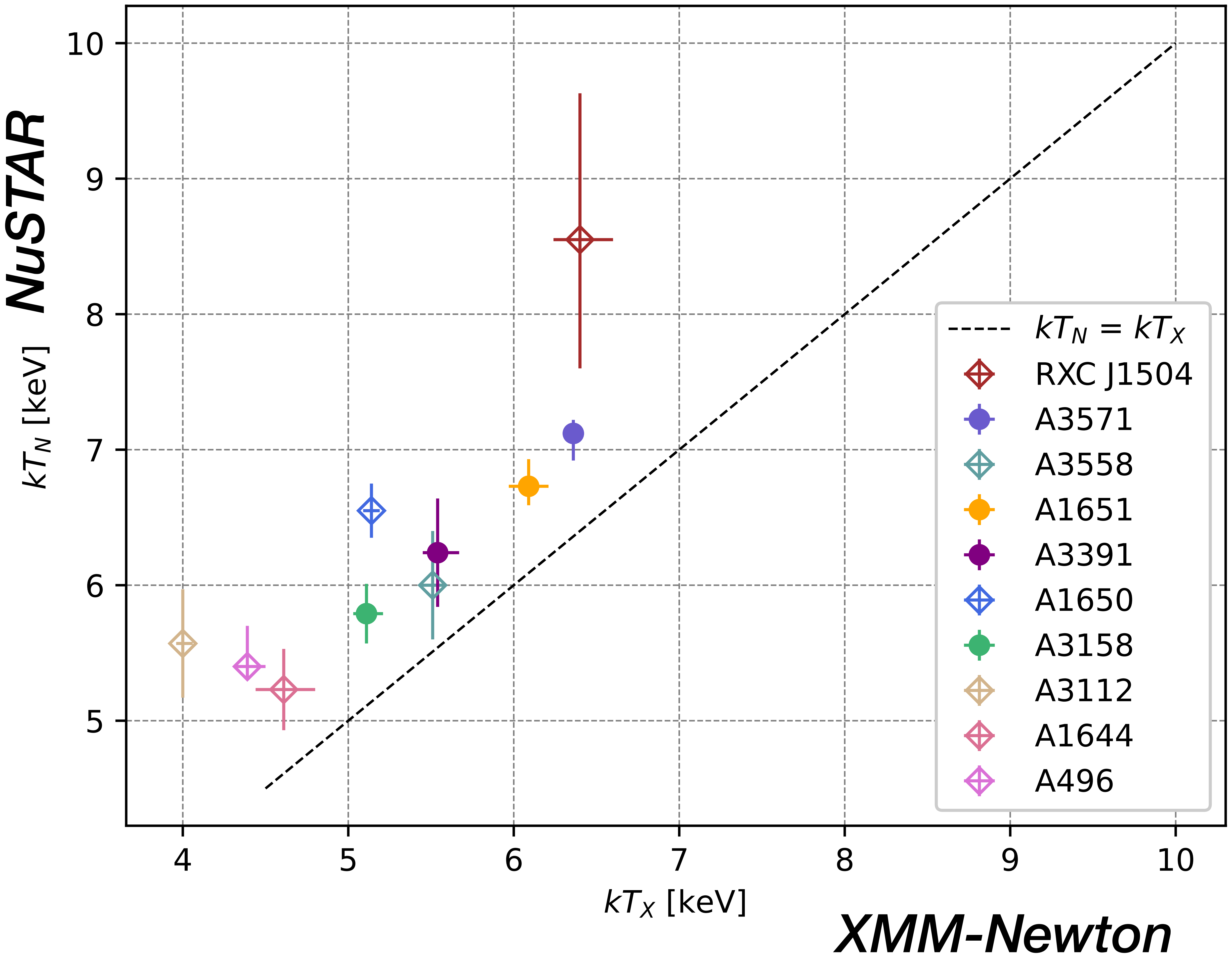
Schellenberger+ 2015

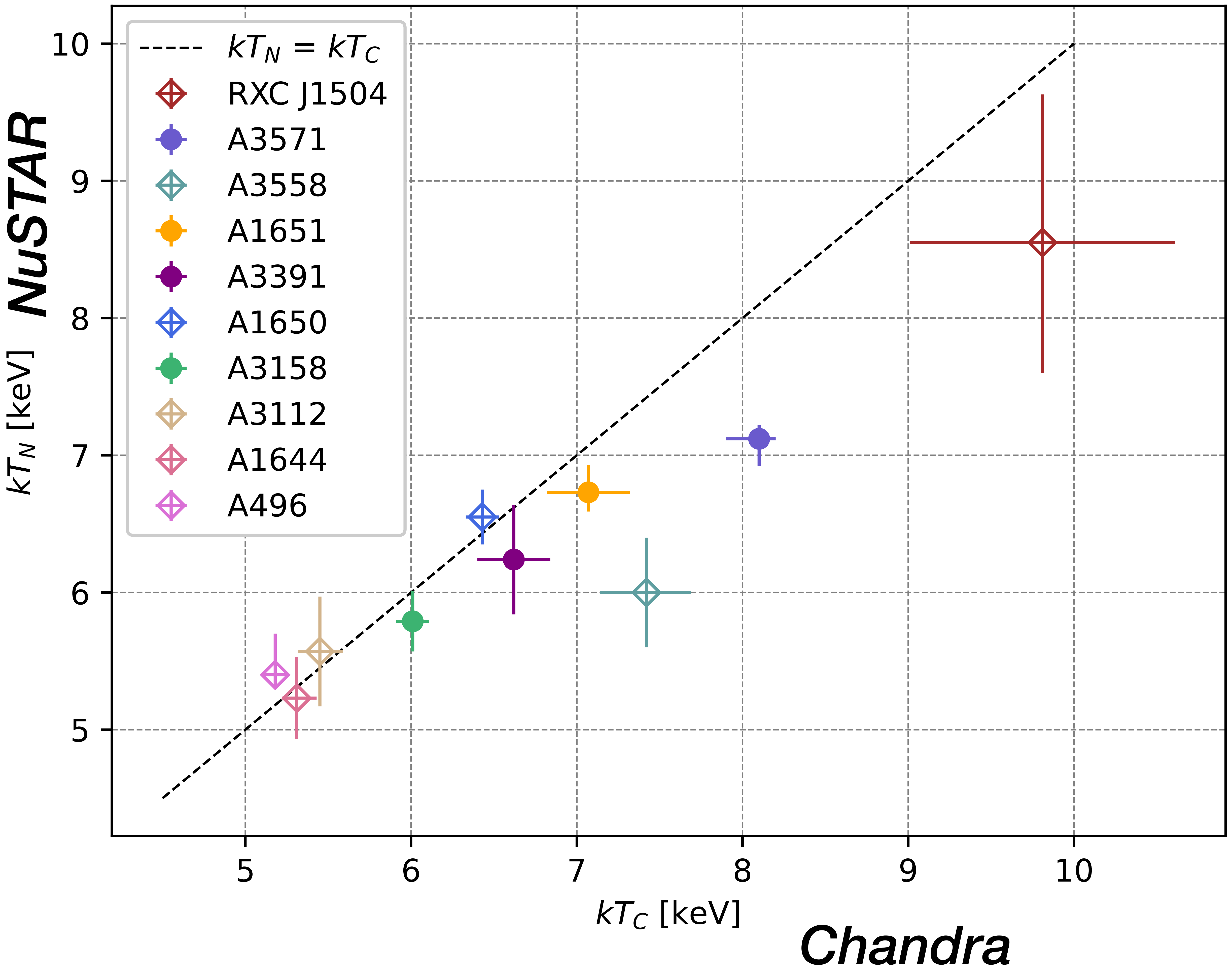
# Snapshot Cluster Temperatures




Lopez+ 2024 (*Chandra*/*XMM-Newton* kTs from Schellenberger+ 2015)

# Snapshot Cluster Temperatures




Lopez+ 2024 (*Chandra*/*XMM-Newton* kTs from Schellenberger+ 2015)

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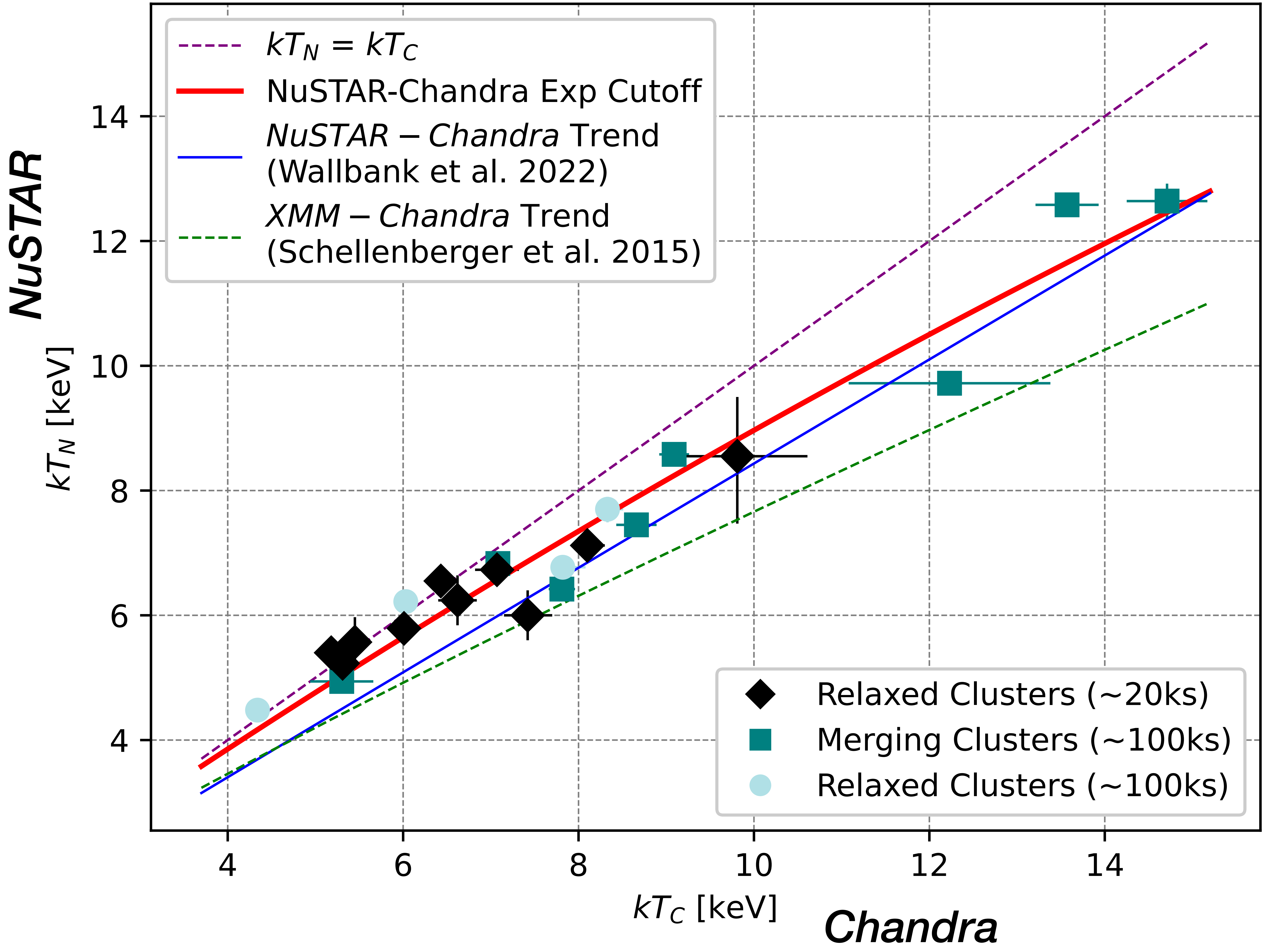
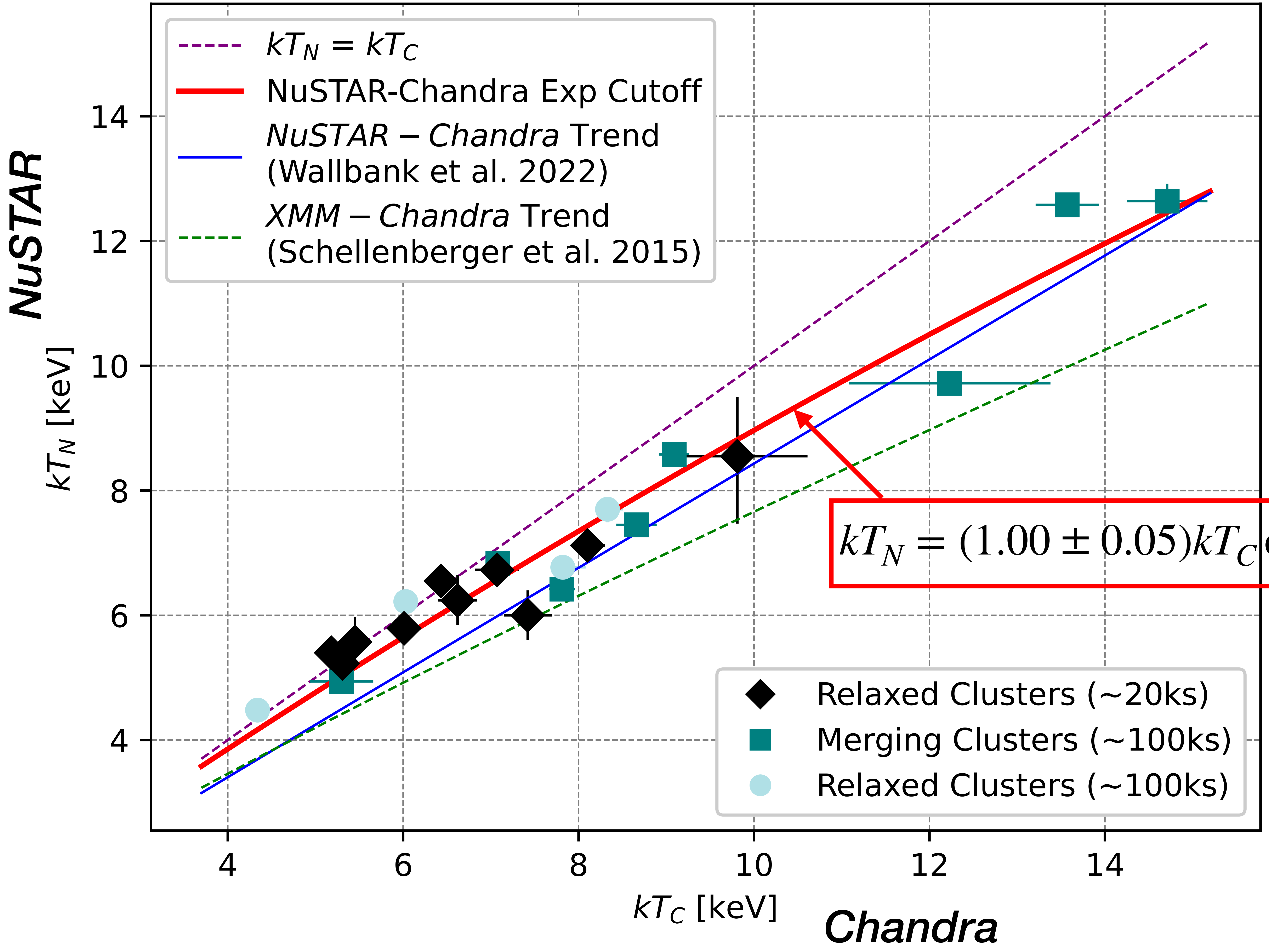



Lopez+ 2024

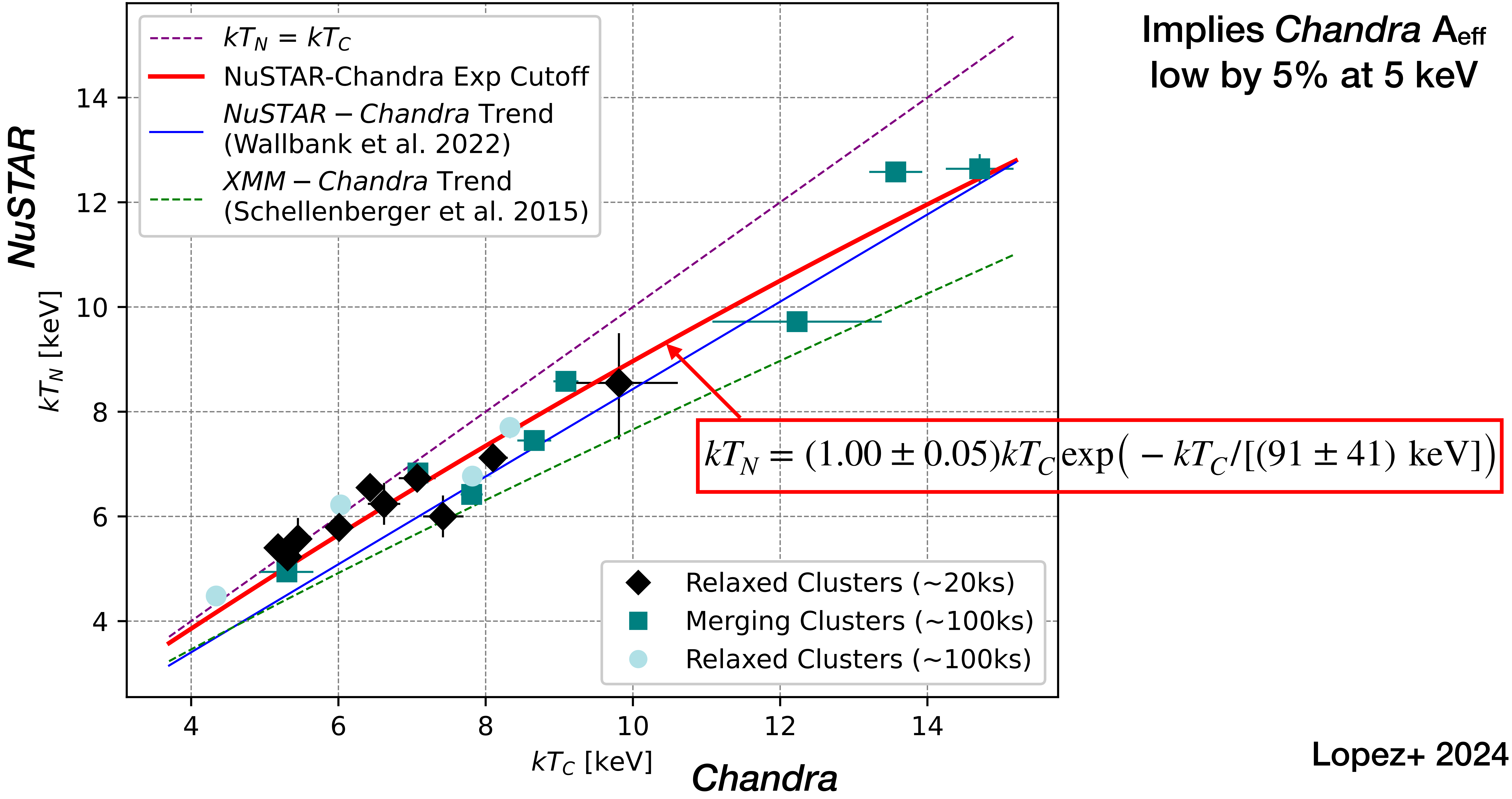
# Snapshot Cluster Temperatures




$$kT_N = (1.00 \pm 0.05) kT_C \exp\left( -kT_C / [(91 \pm 41)\ \mathrm{keV}] \right)$$

Lopez+ 2024

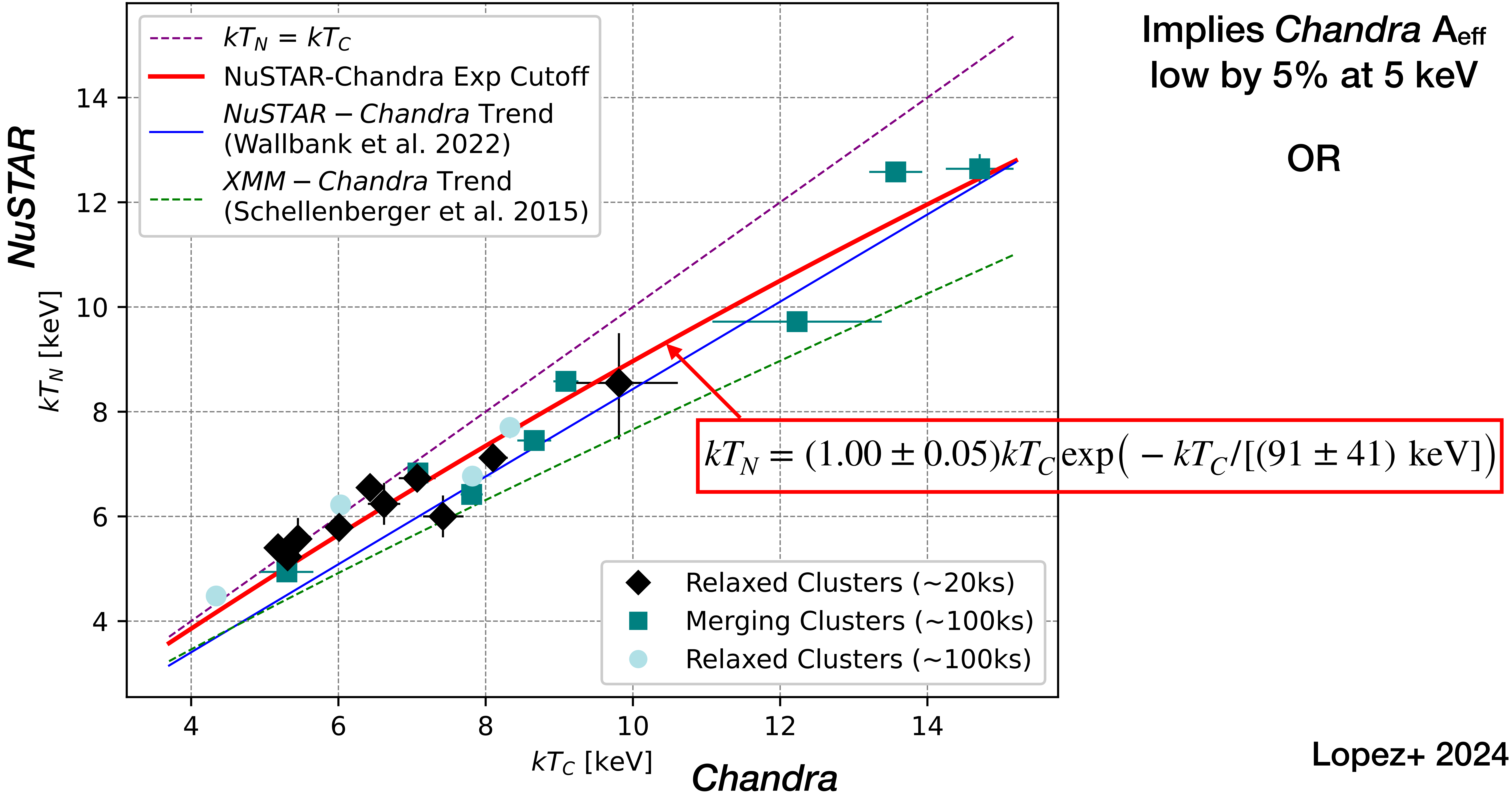
# Snapshot Cluster Temperatures




Implies *Chandra* $A_{\mathrm{eff}}$ low by 5% at 5 keV

Lopez+ 2024

# Snapshot Cluster Temperatures

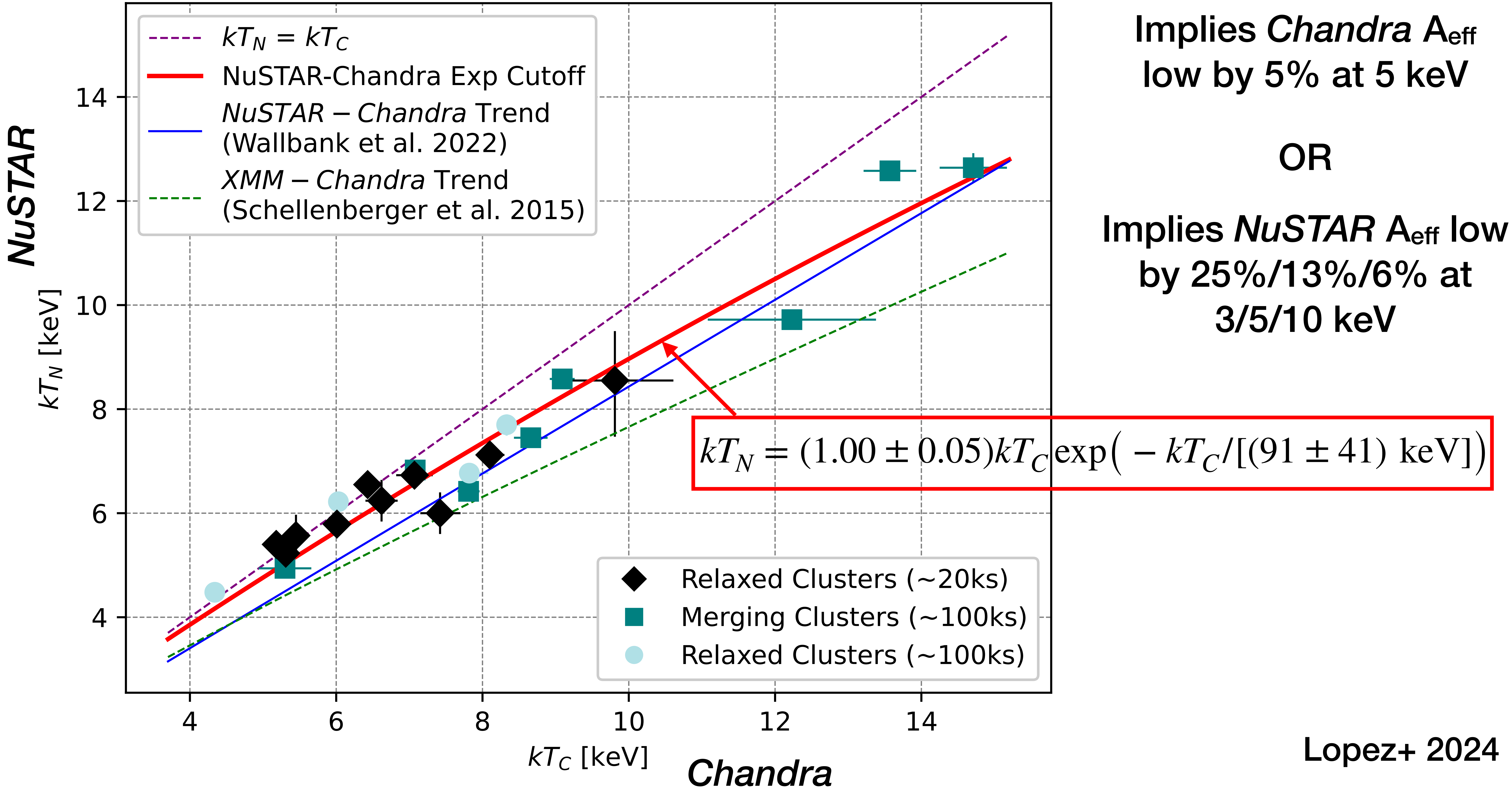



Implies *Chandra* $A_{eff}$ low by 5% at 5 keV

OR

Lopez+ 2024

# Snapshot Cluster Temperatures



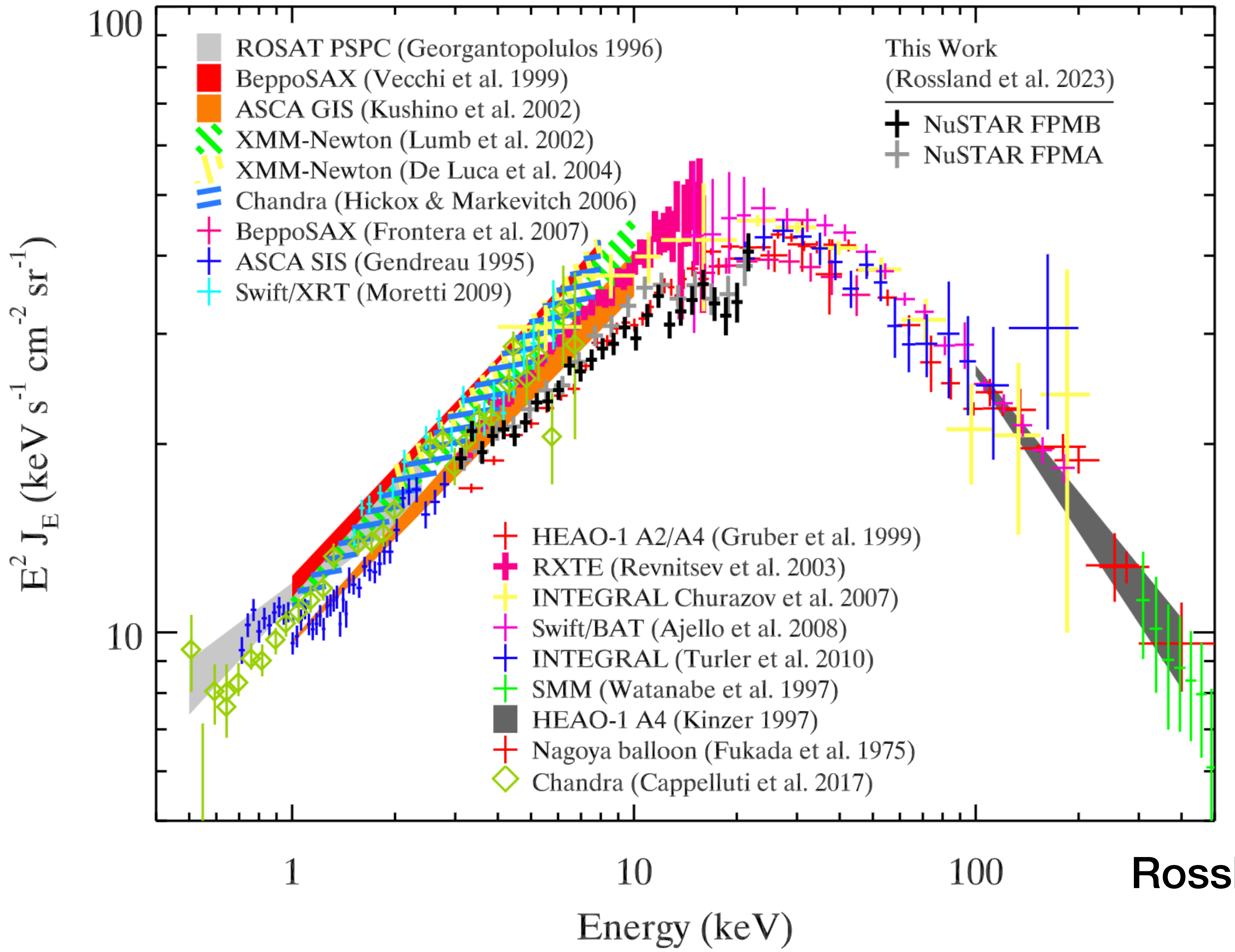

Implies *Chandra* $A_{eff}$ low by 5% at 5 keV

OR

Implies *NuSTAR* $A_{eff}$ low by 25%/13%/6% at 3/5/10 keV

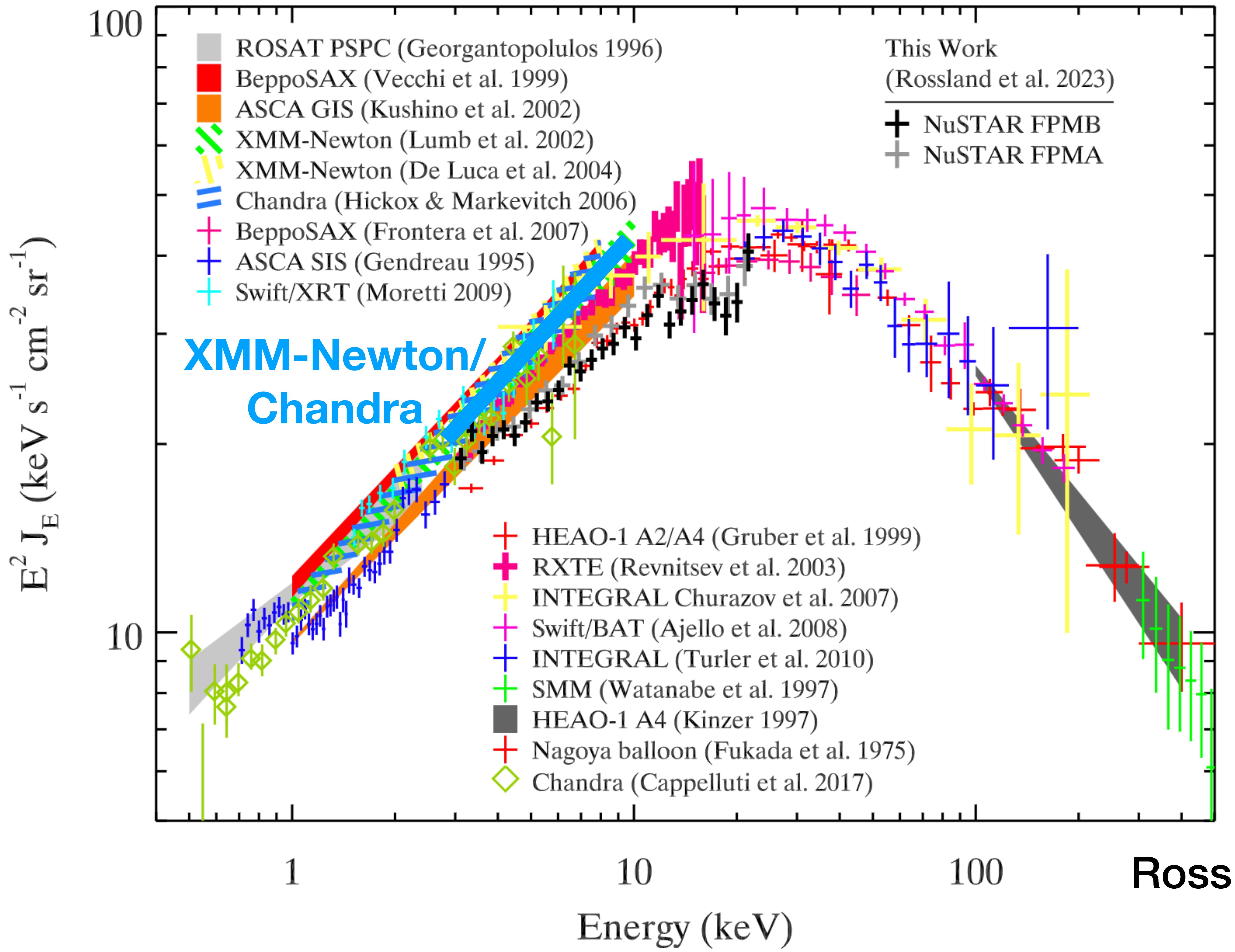
Lopez+ 2024

# CXB Measurement Consistent



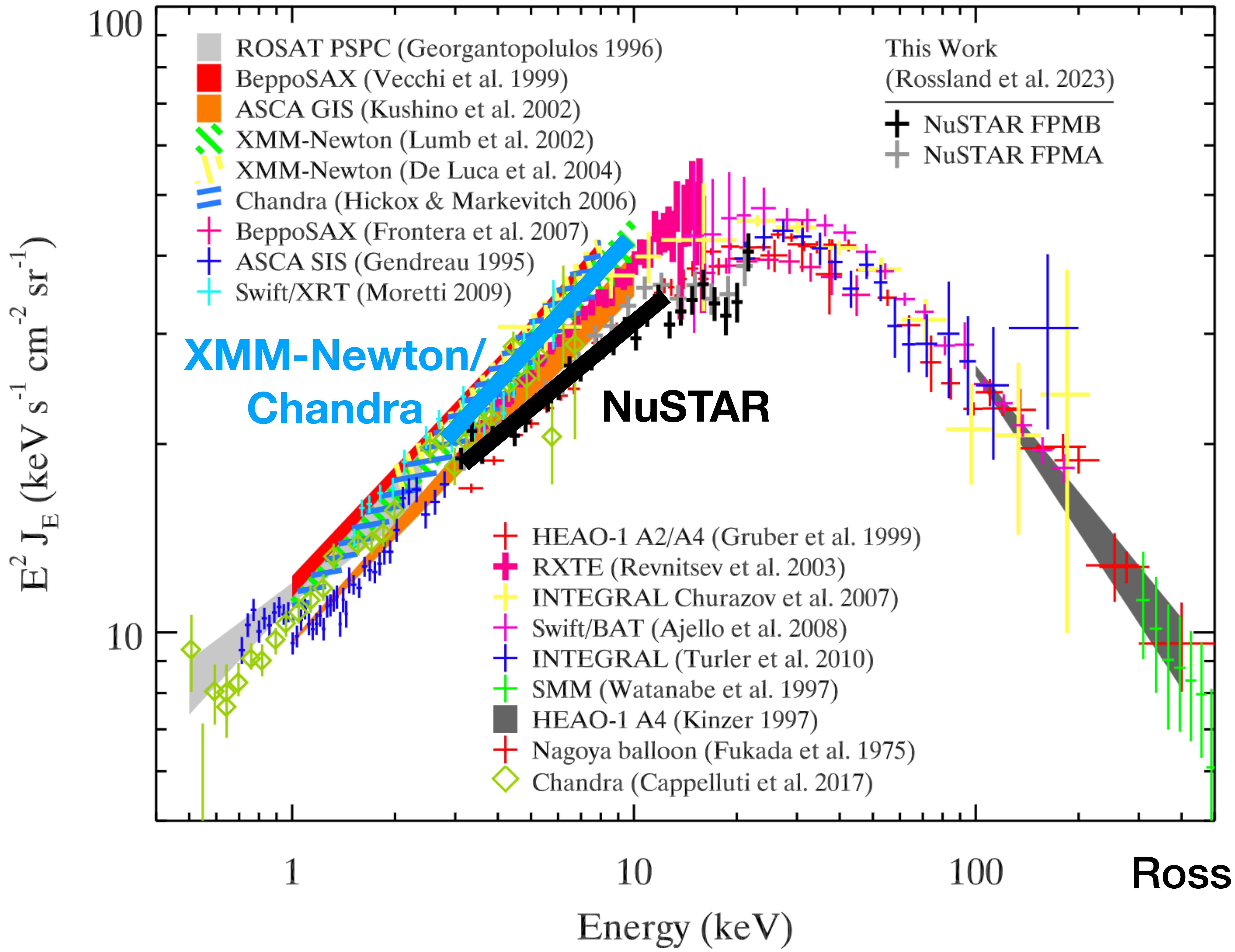

Rossland+ 2023

# CXB Measurement Consistent




Rossland+ 2023

# CXB Measurement Consistent



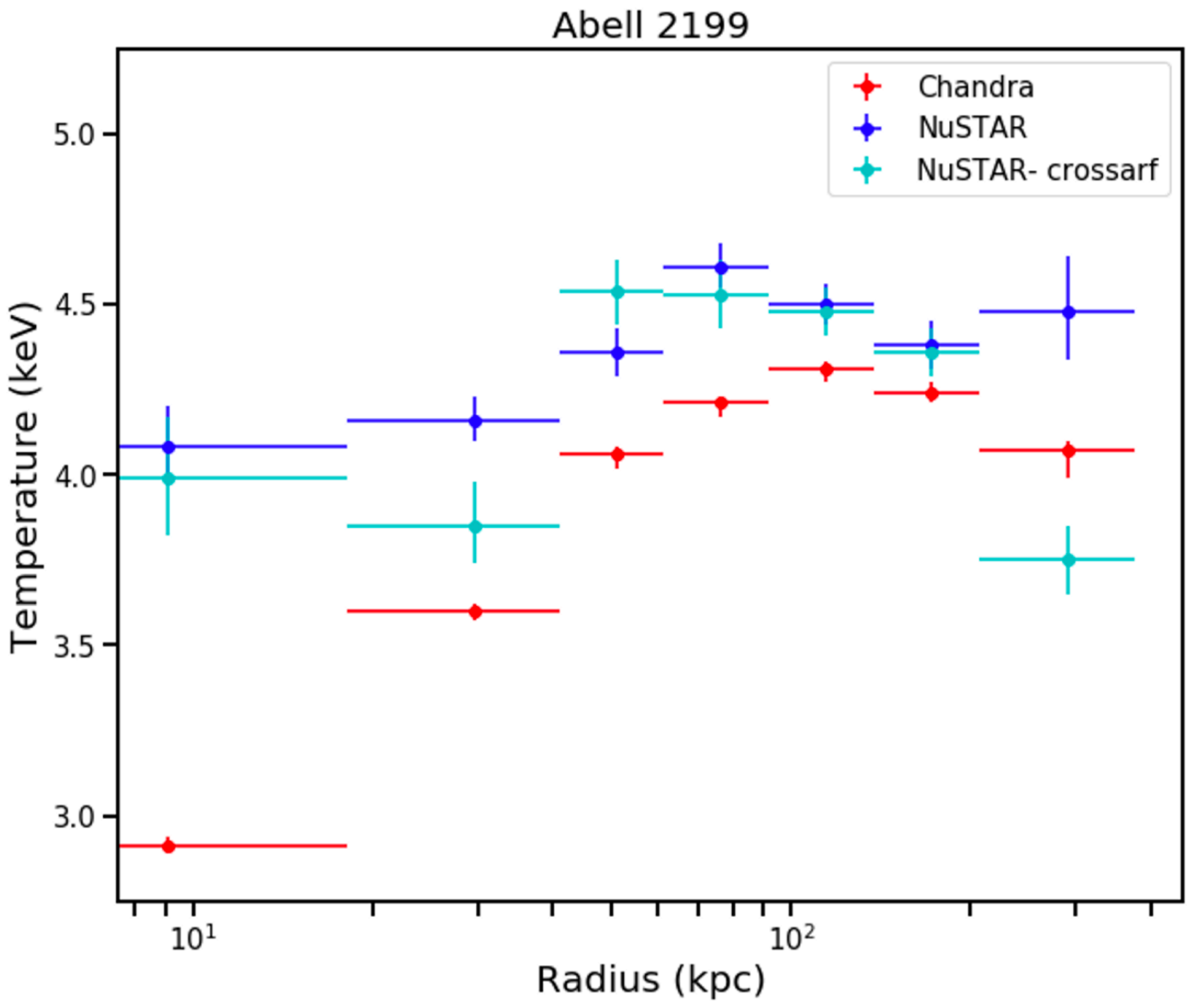

Rossland+ 2023

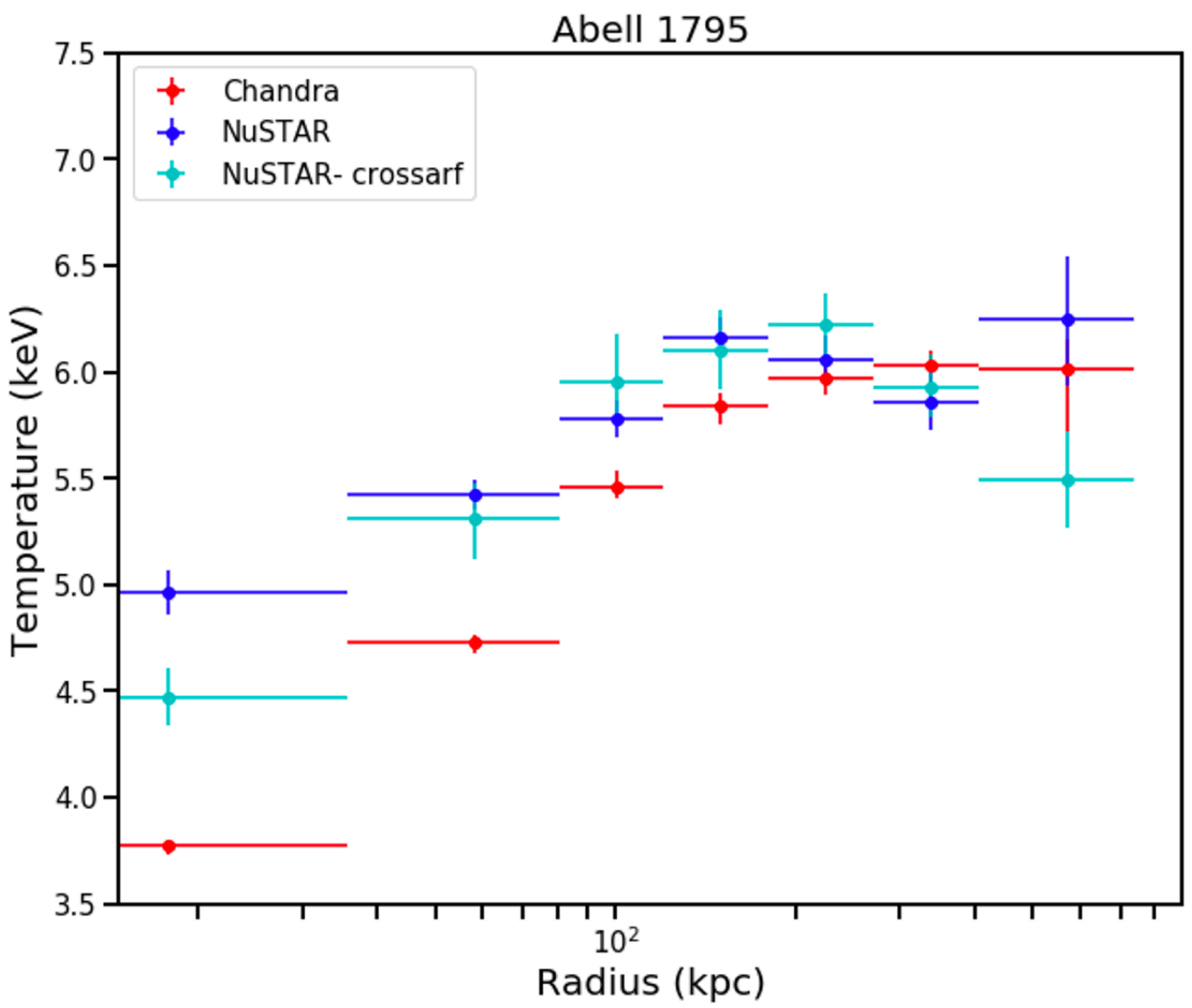

*NuSTAR* FPMA+B combined (Bgd-sub, exp-corrected)

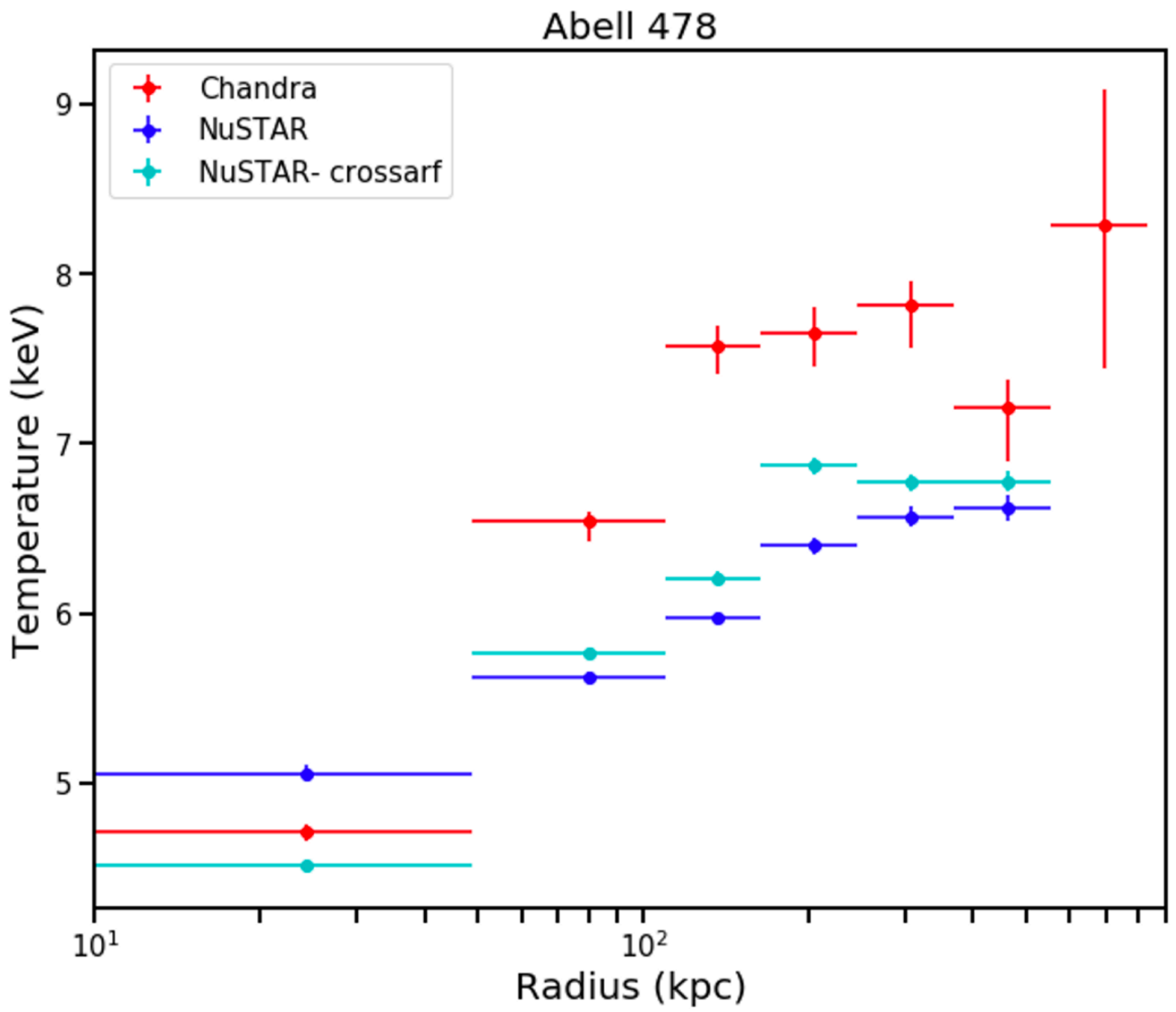
4-25 keV

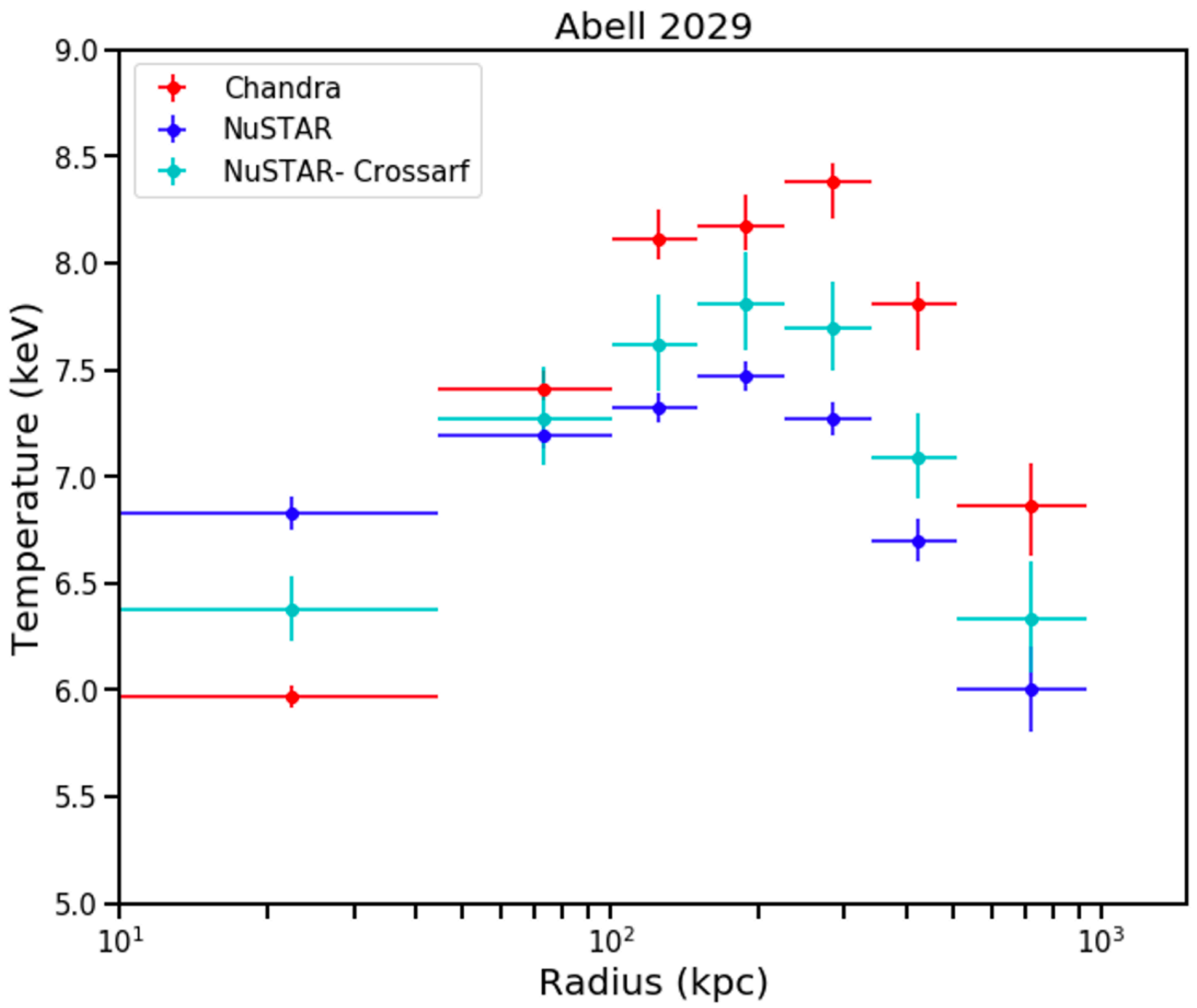
Potter+ in prep

## Deep observations of relaxed clusters
## Nominal Chandra ARFs



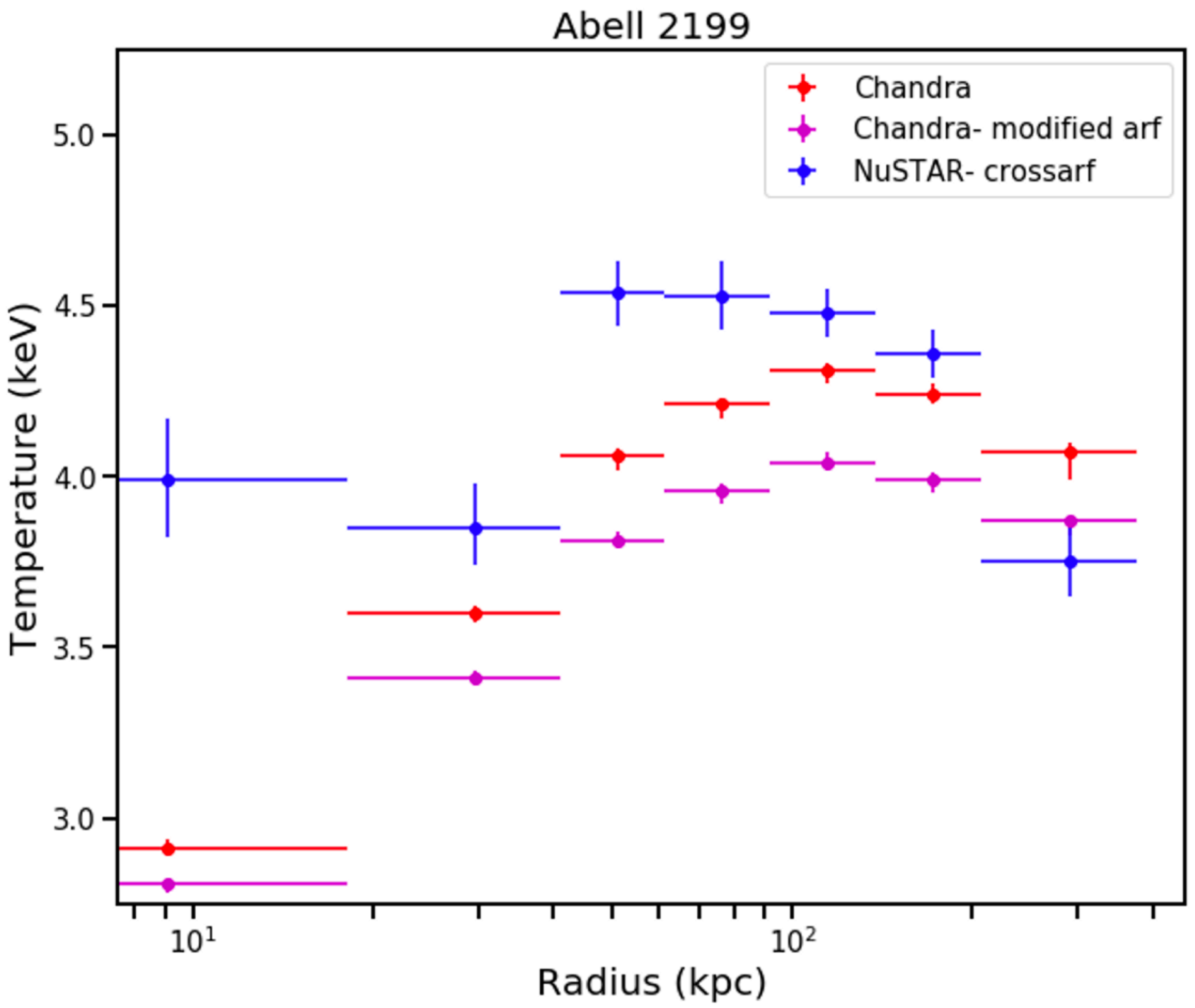



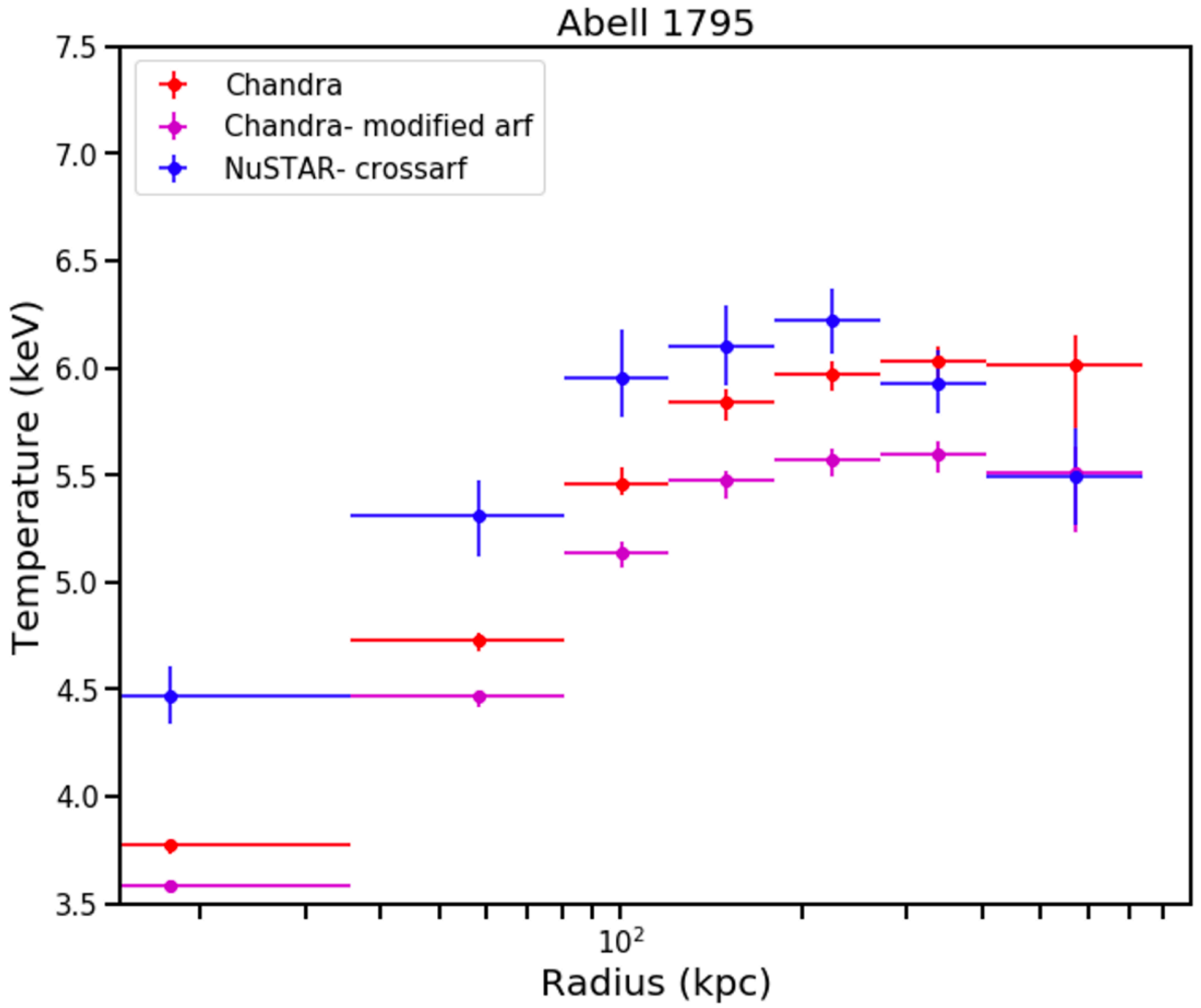



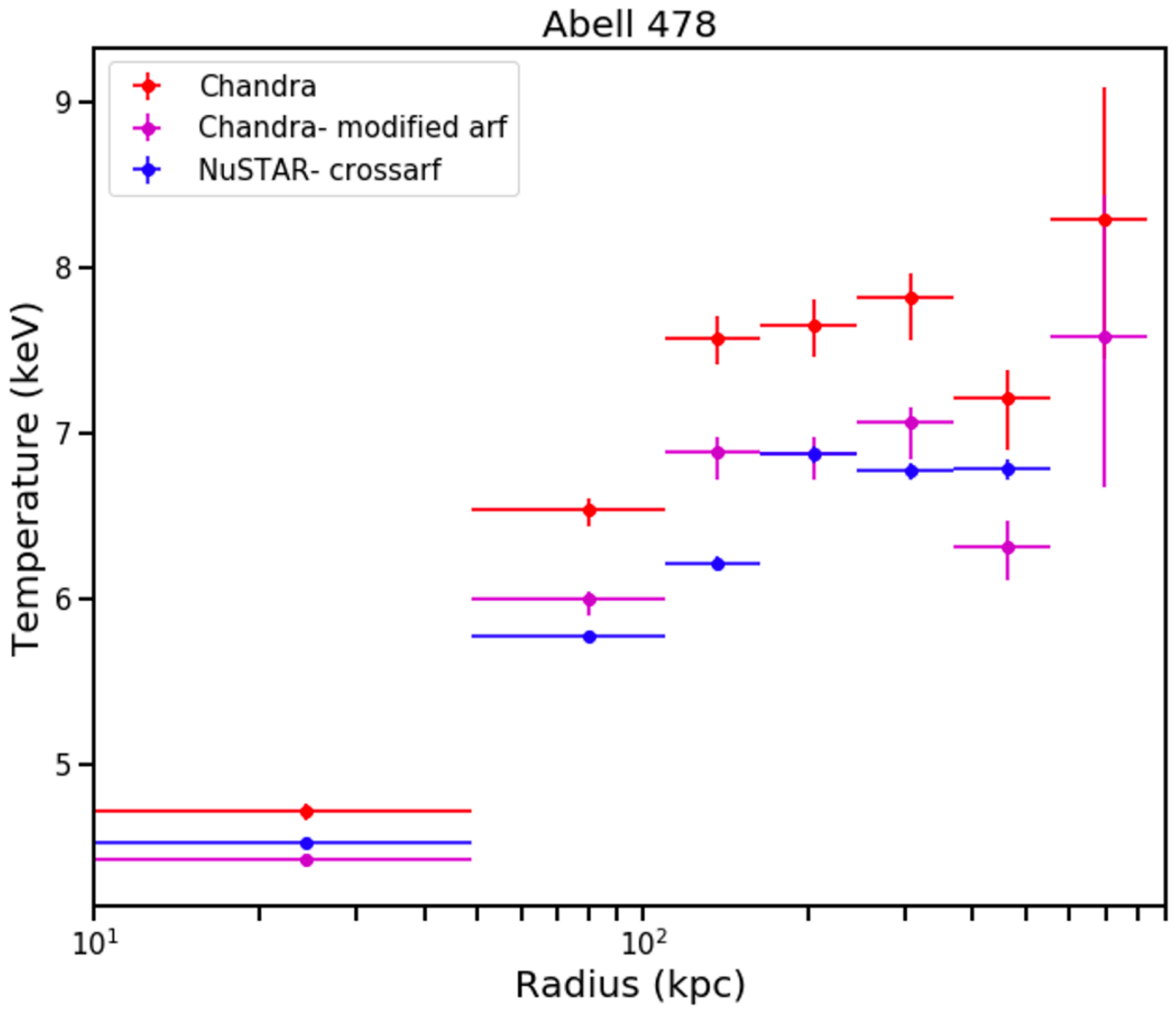



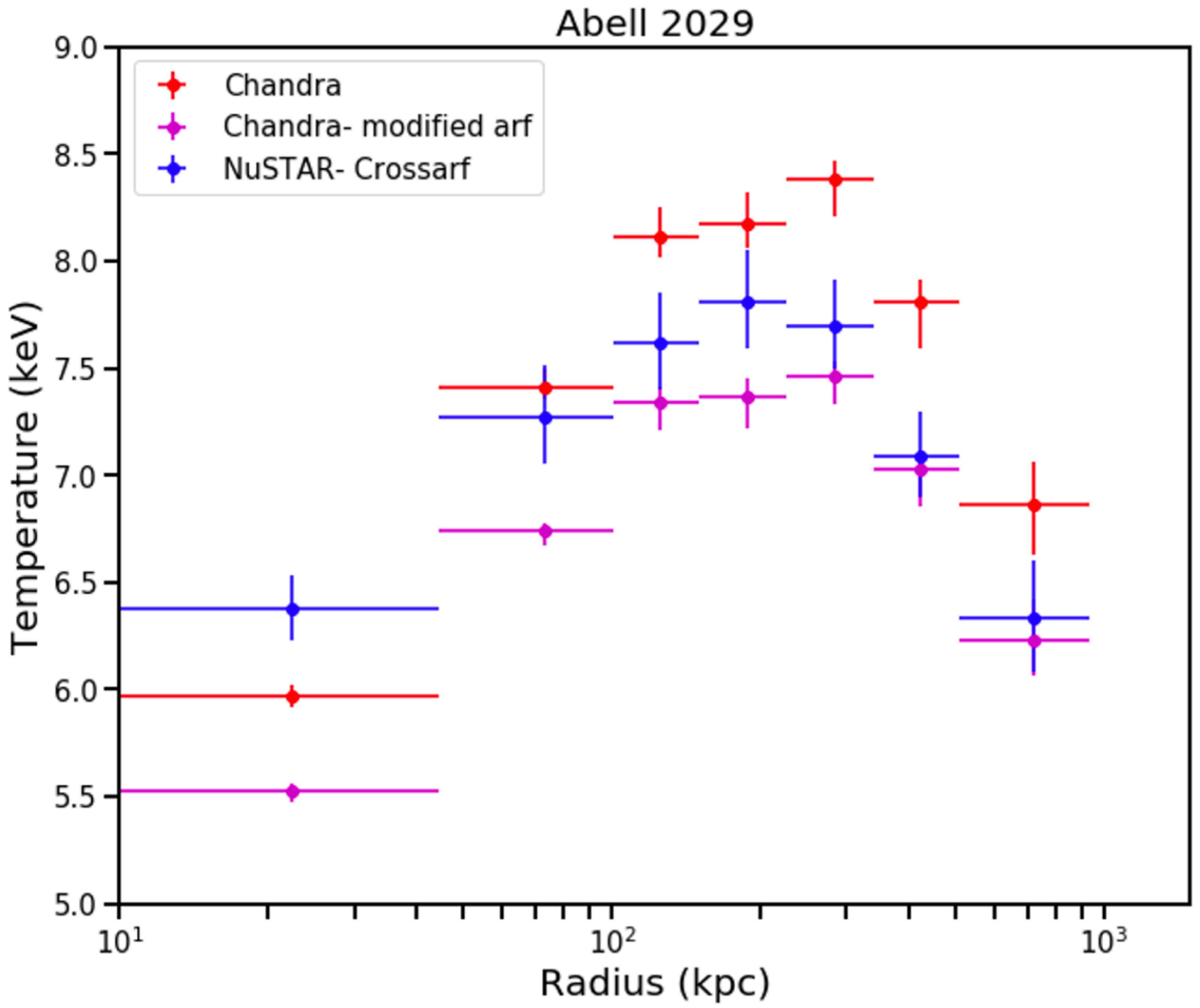

Potter+ in prep

## Deep observations of relaxed clusters
## Modified Chandra ARFs



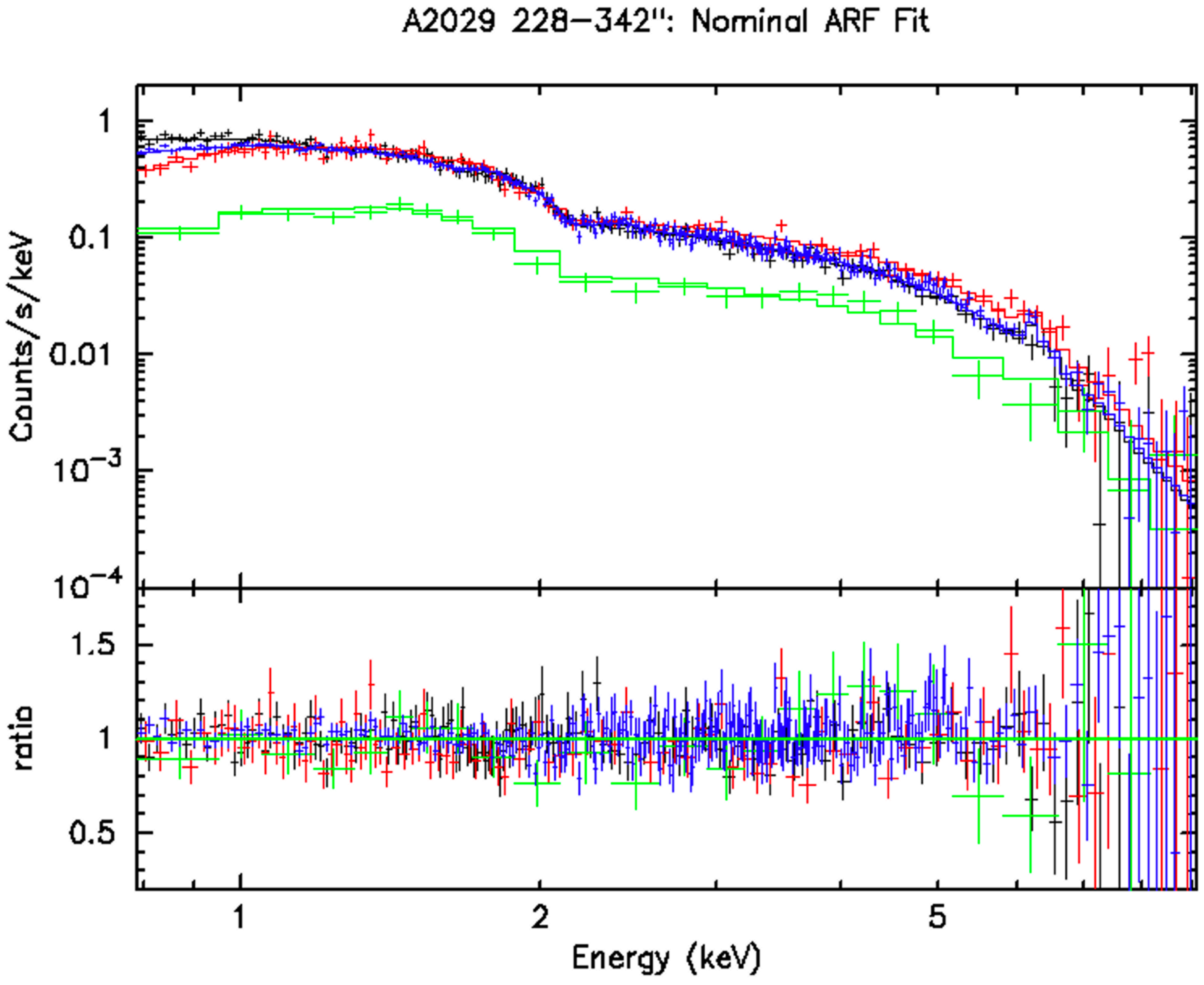



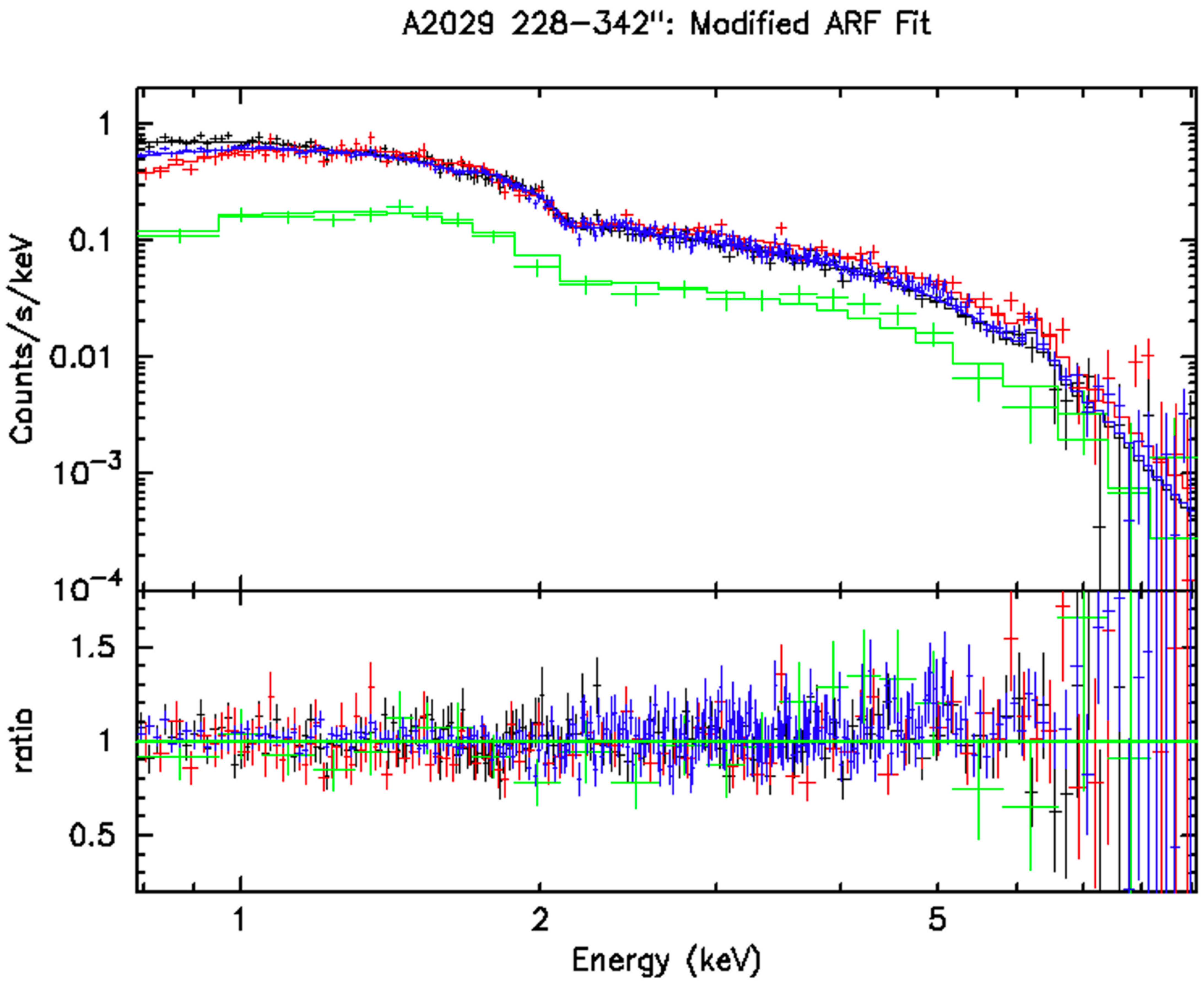

Potter+ in prep

# Abell 2029, 5th Annulus

## Nominal Chandra ARF

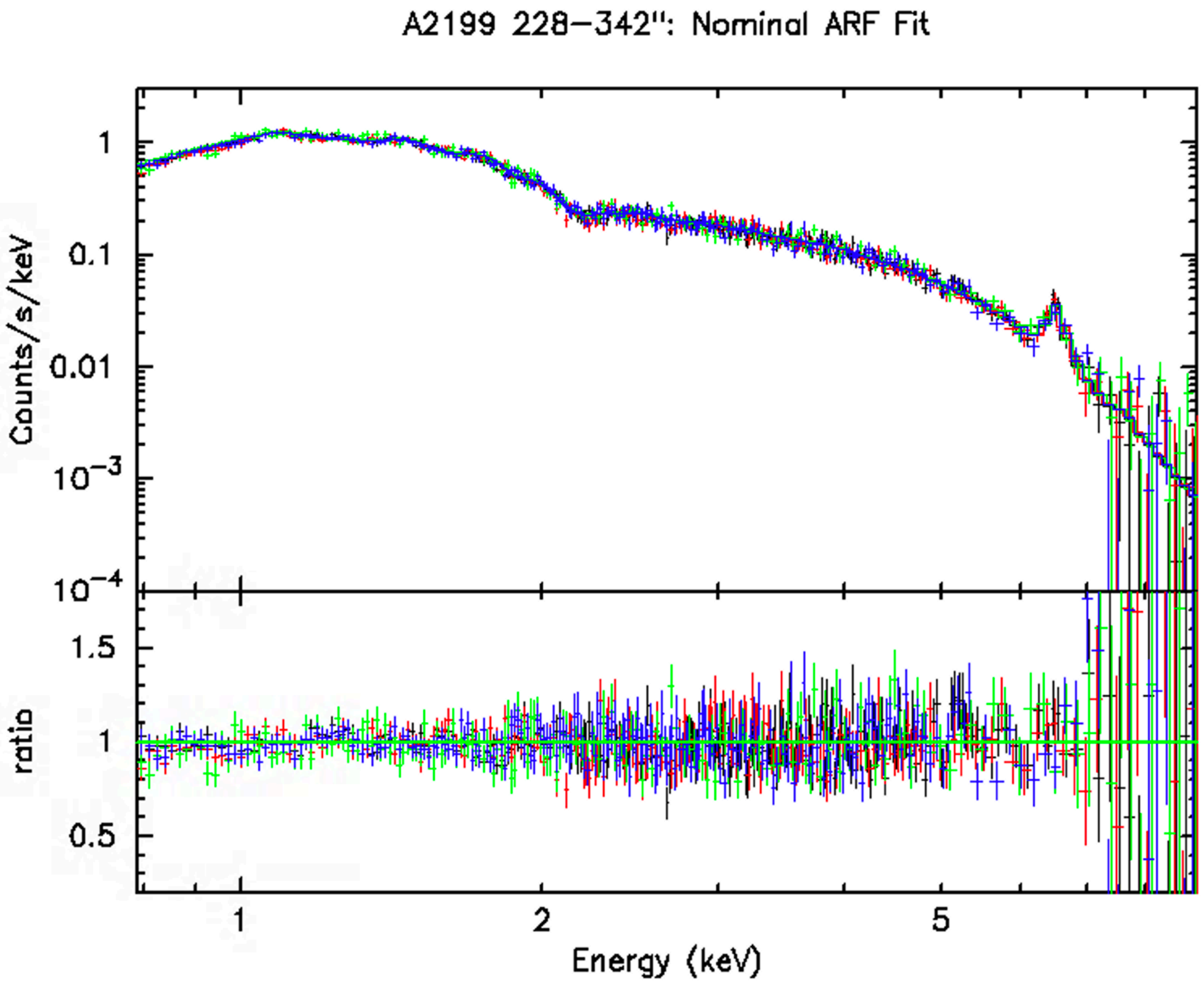



## Modified Chandra ARF

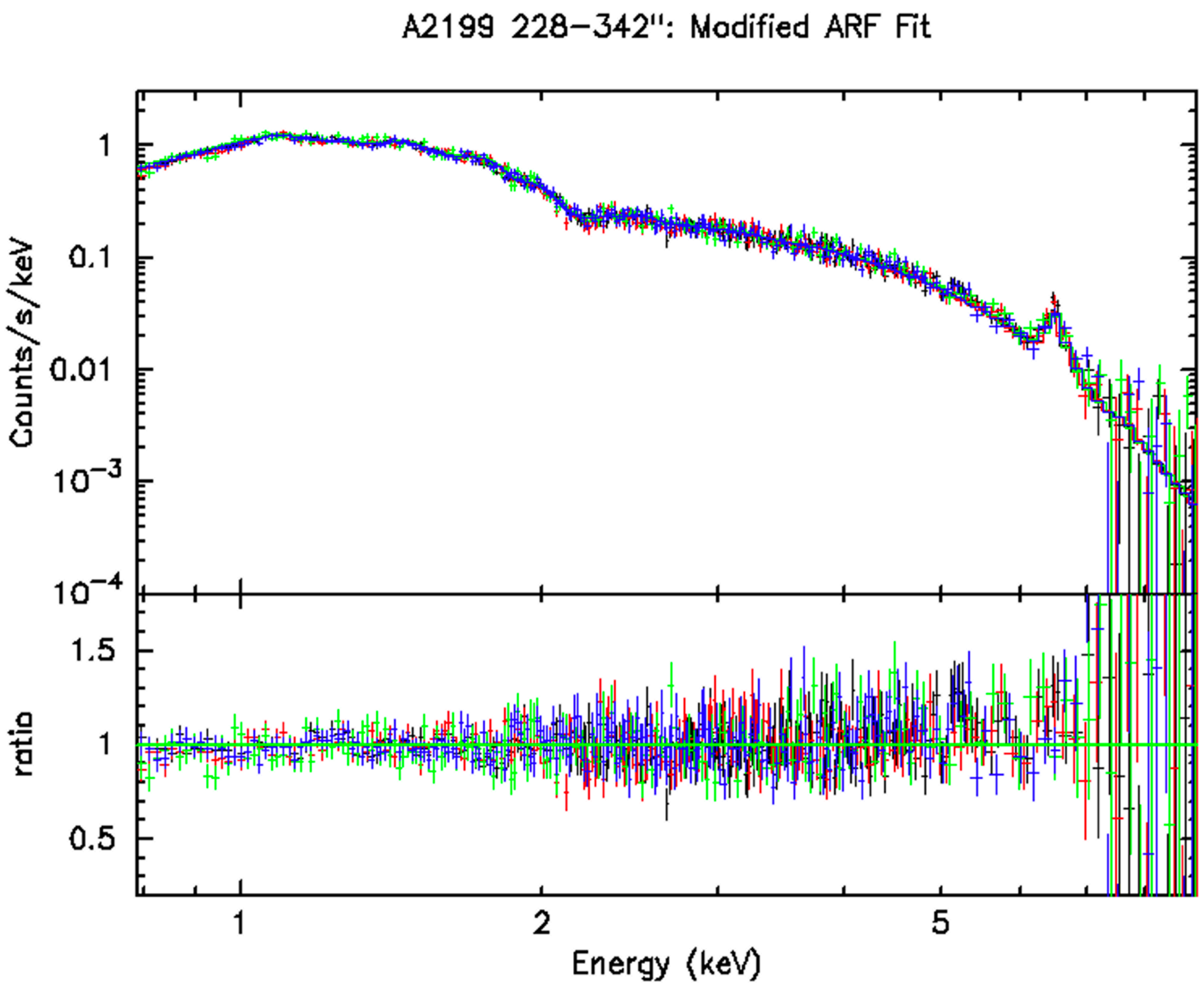


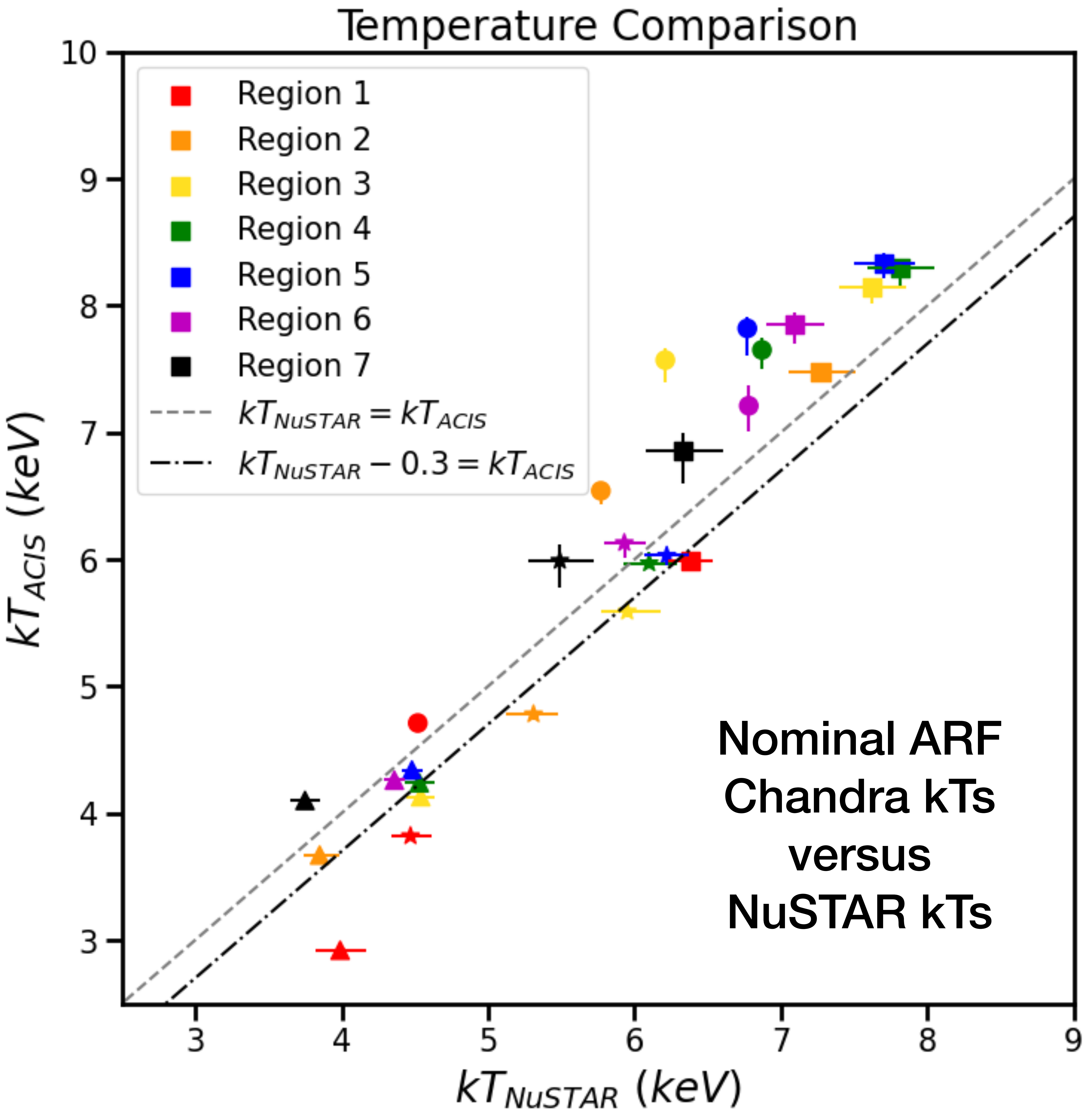
# Abell 2199, 5th Annulus

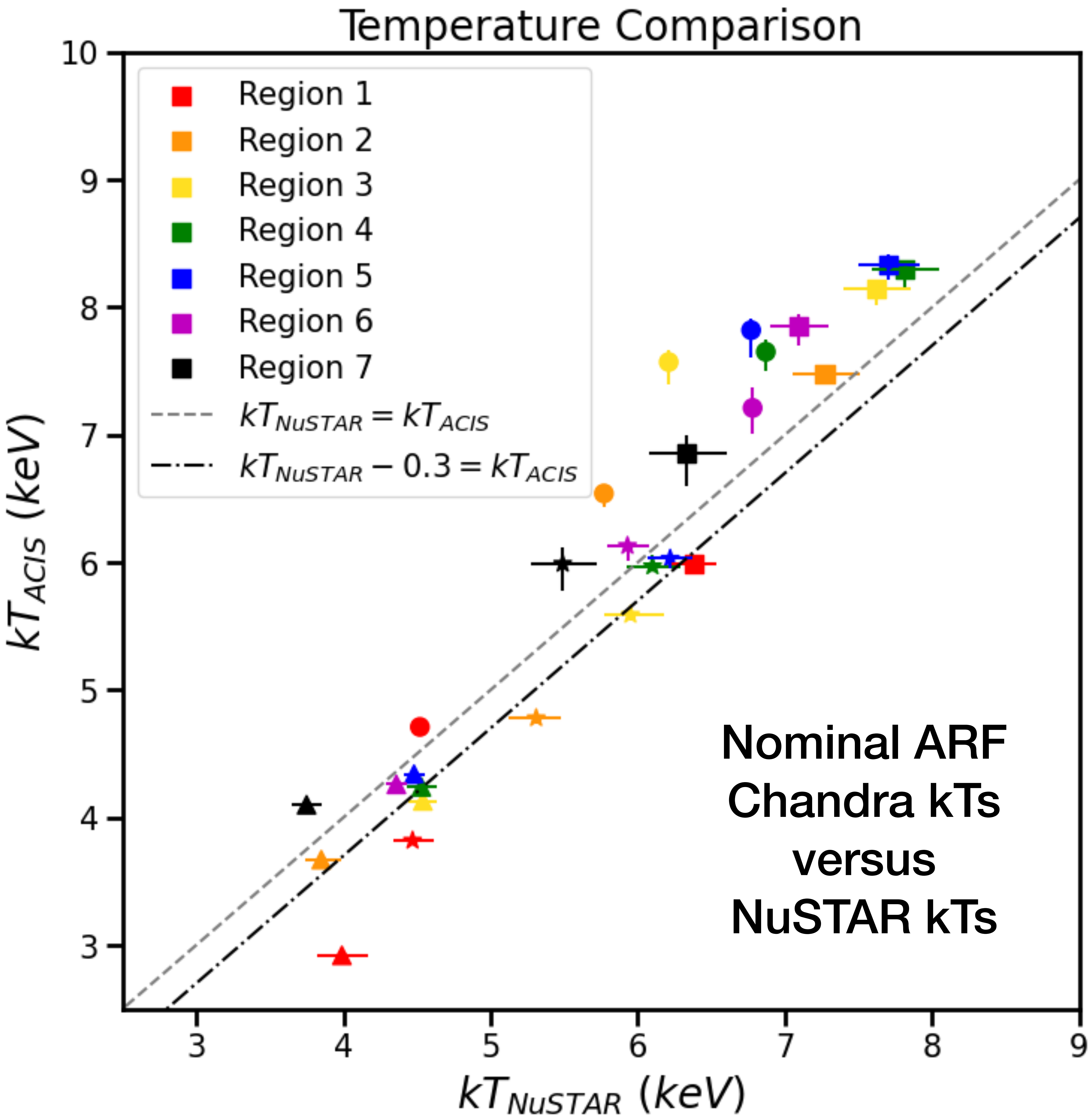
## Nominal Chandra ARF

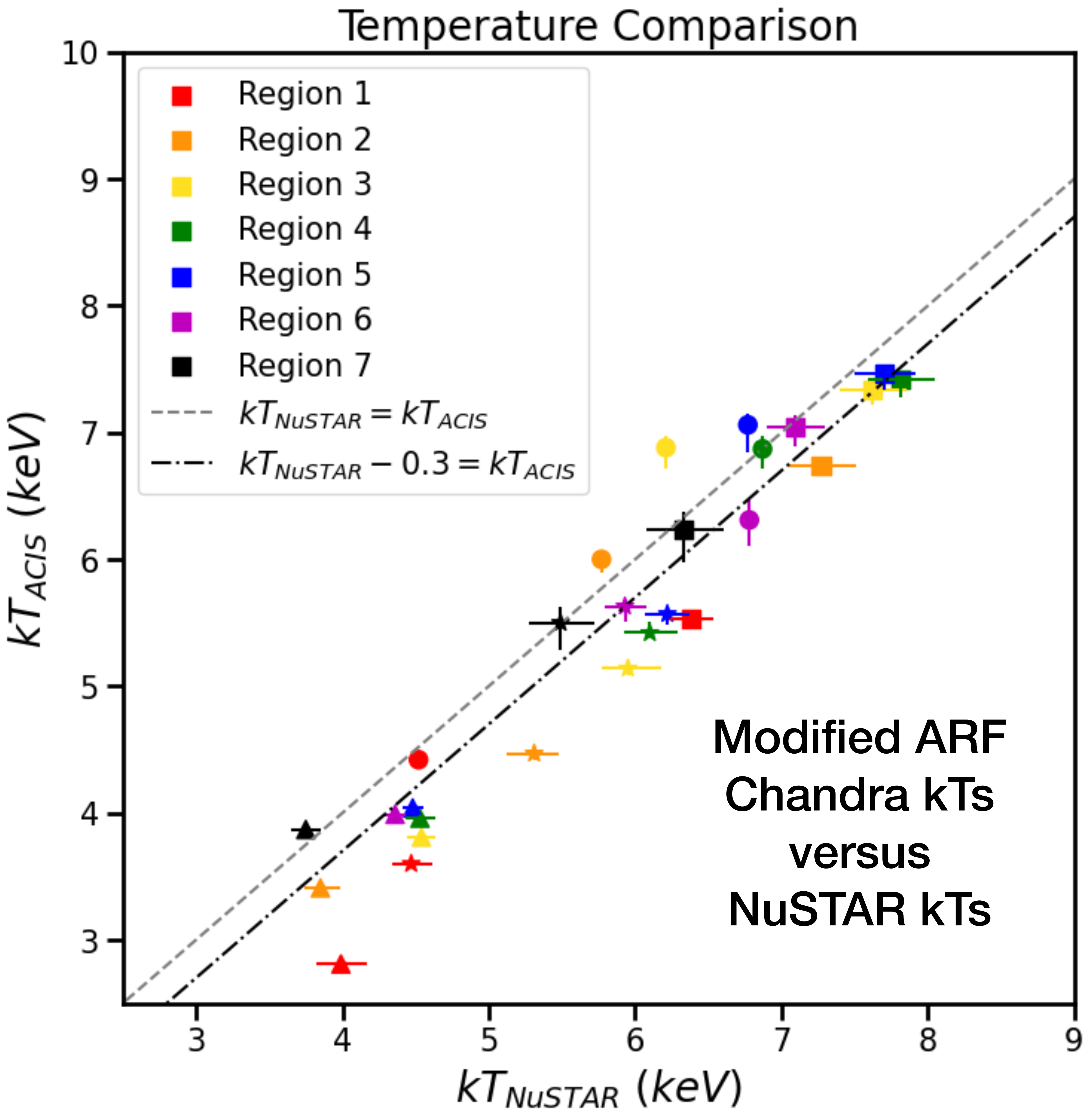



## Modified Chandra ARF



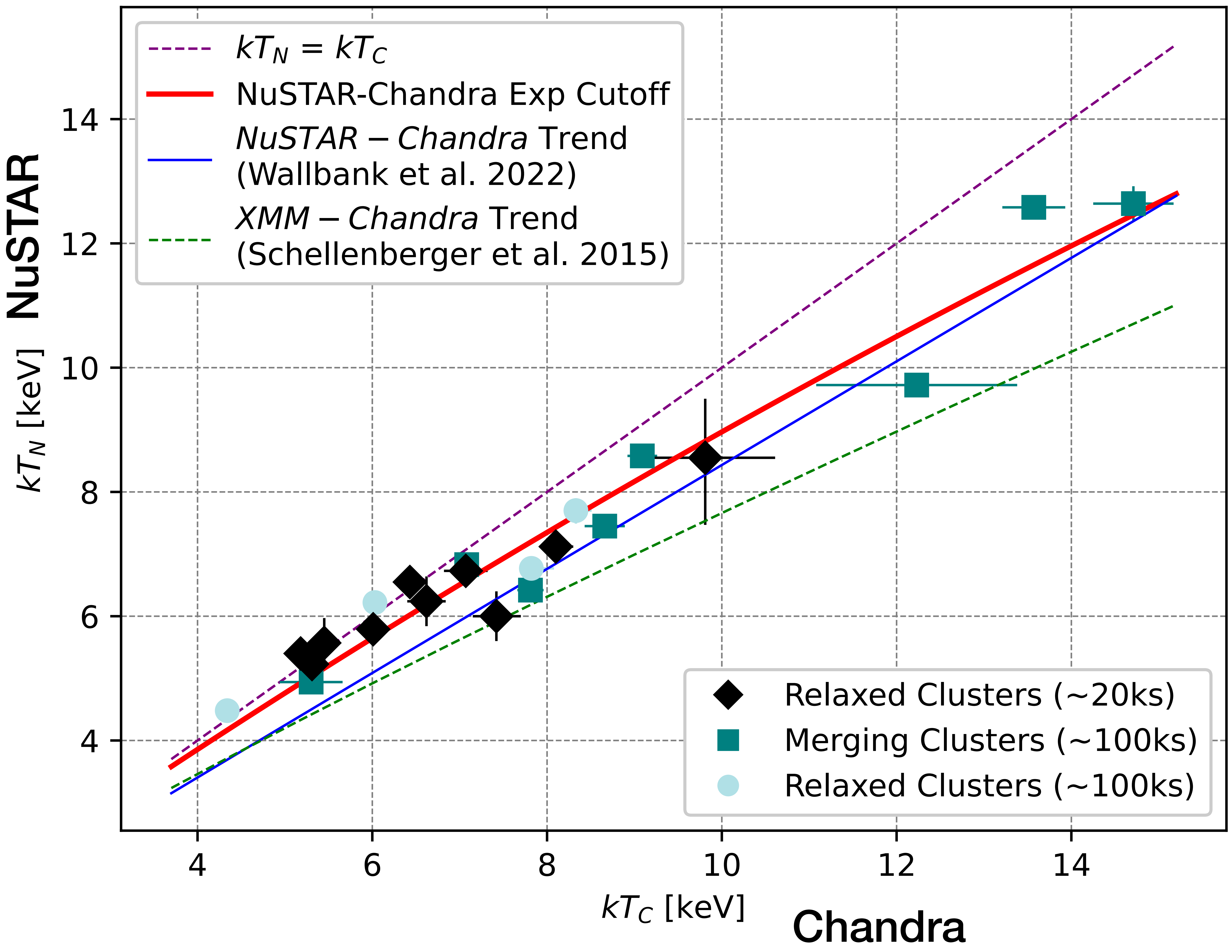

Temperature Comparison
Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
$kT_{NuSTAR} = kT_{ACIS}$
$kT_{NuSTAR} - 0.3 = kT_{ACIS}$
Nominal ARF
Chandra kTs
versus
NuSTAR kTs
$kT_{ACIS}$ (keV)
$kT_{NuSTAR}$ (keV)
10
9
8
7
6
5
4
3
3
4
5
6
7
8
9


Temperature Comparison
Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
$kT_{NuSTAR} = kT_{ACIS}$
$kT_{NuSTAR} - 0.3 = kT_{ACIS}$
$kT_{ACIS}$ (keV)
$kT_{NuSTAR}$ (keV)
Nominal ARF
Chandra kTs
versus
NuSTAR kTs

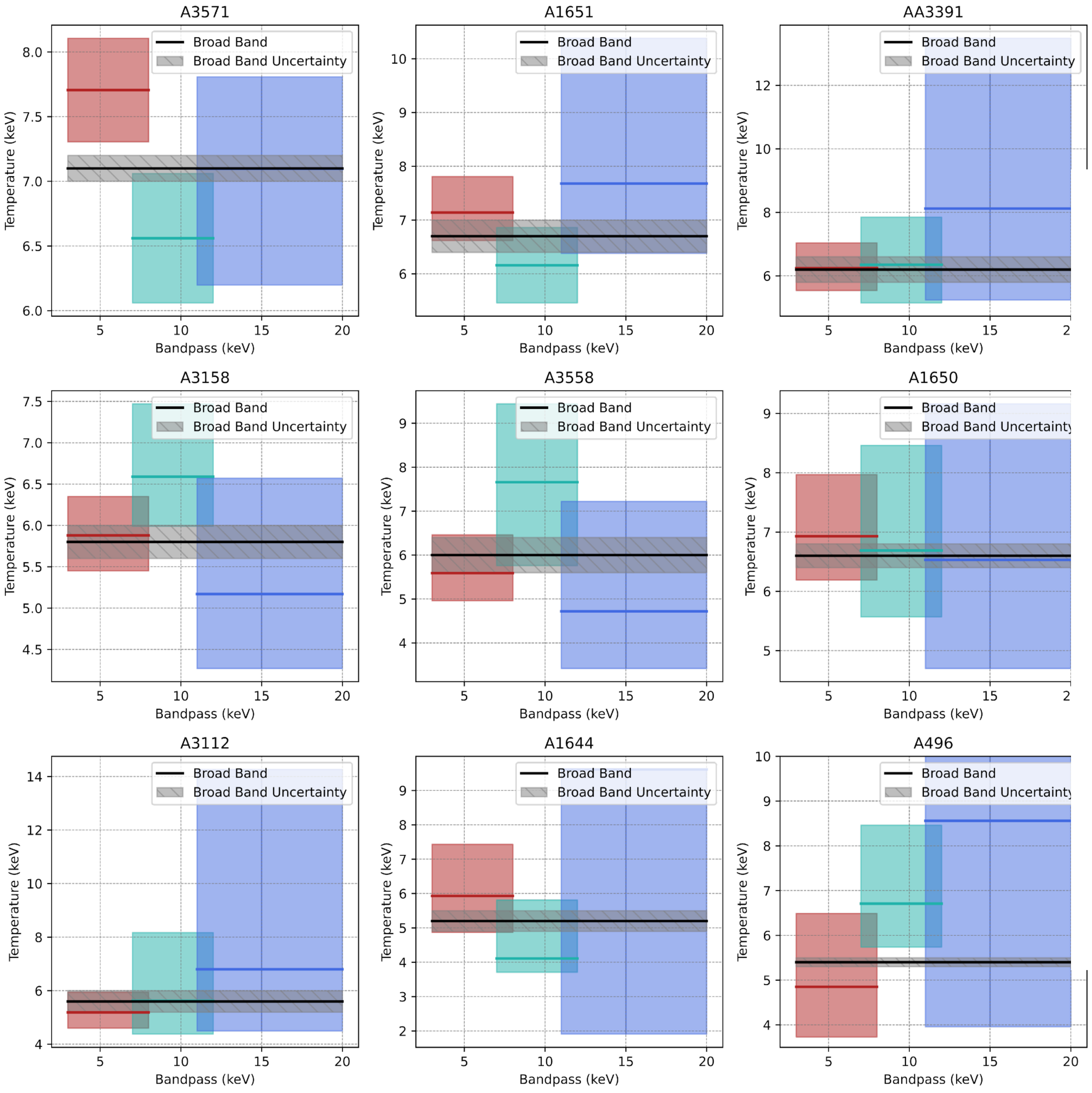

Temperature Comparison
Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
$kT_{NuSTAR} = kT_{ACIS}$
$kT_{NuSTAR} - 0.3 = kT_{ACIS}$
$kT_{ACIS}$ (keV)
$kT_{NuSTAR}$ (keV)
Modified ARF
Chandra kTs
versus
NuSTAR kTs

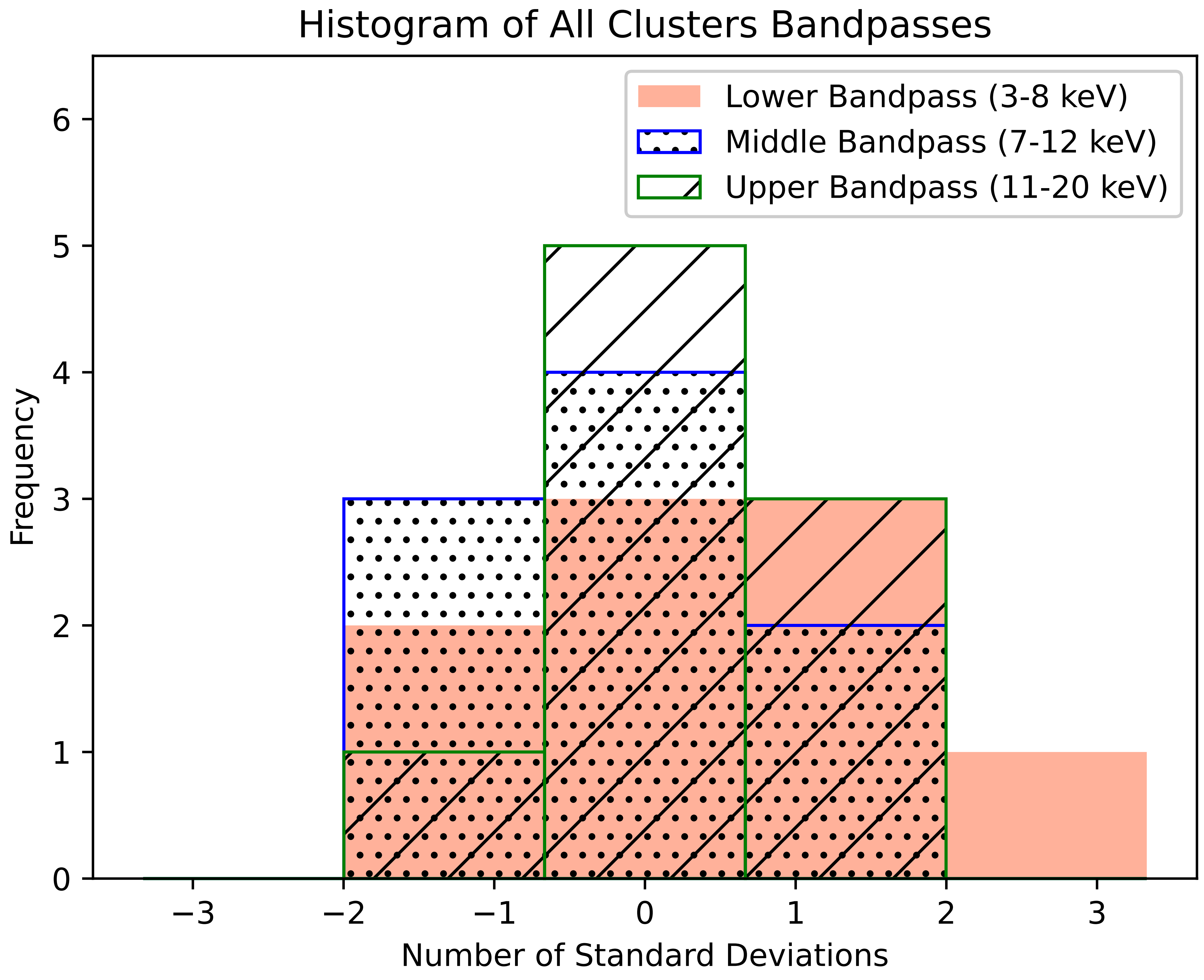
# In Summary

- *NuSTAR* kTs are systematically LOWER than *Chandra* kTs, which physically shouldn't happen
- *NuSTAR* kTs are systematically HIGHER than *XMM-Newton* kTs and comparable to *Chandra* kTs for cooler clusters
- Trend not sensitive to dynamical state, only overall temperature matters
- A correction to *Chandra*'s hard band effective area similar to *XMM-Newton*'s achieves better agreement with *NuSTAR*, although it's not perfect
- The XMM-Newton effective area correction may exacerbate disagreement with NuSTAR, but physical explanation plausible

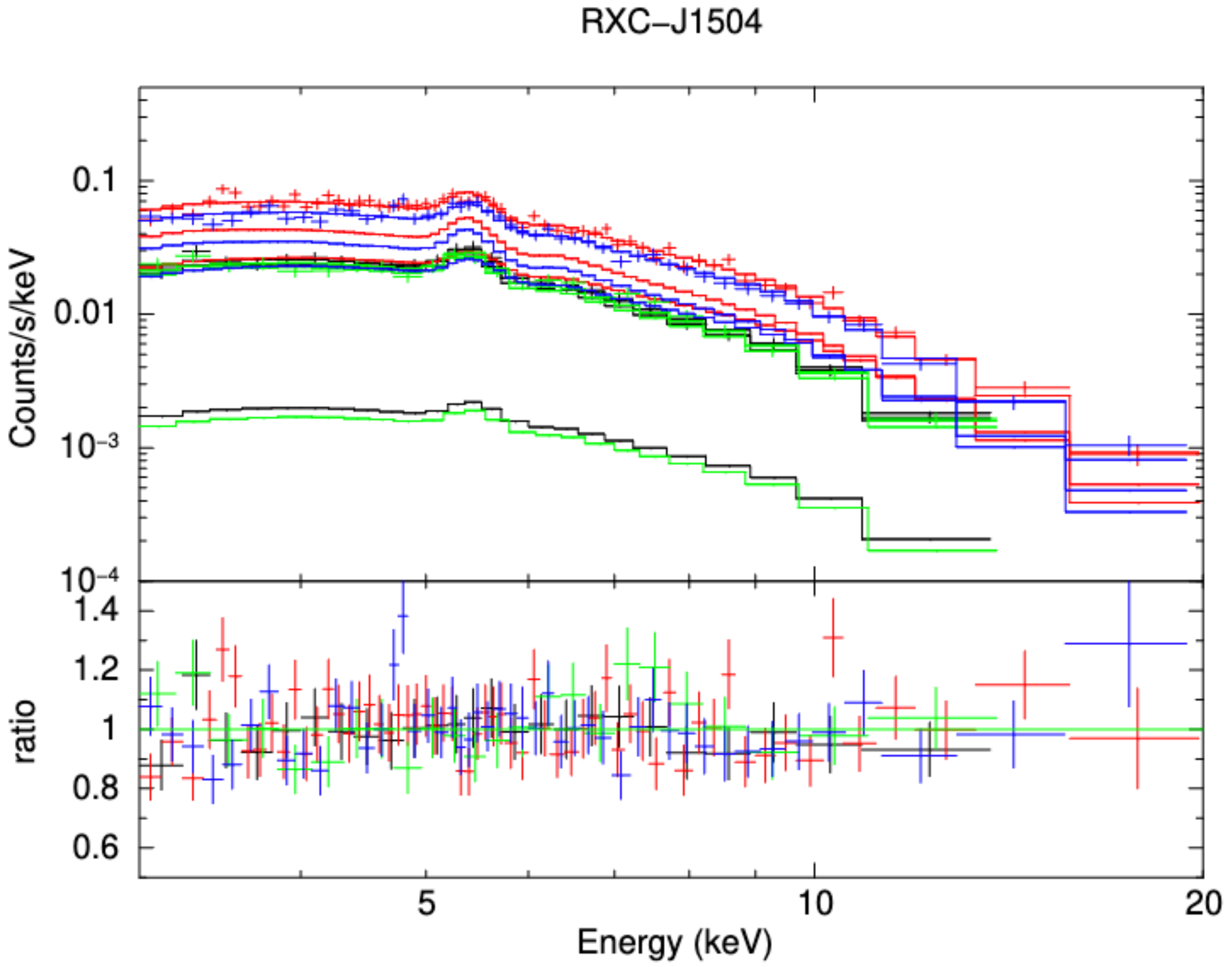


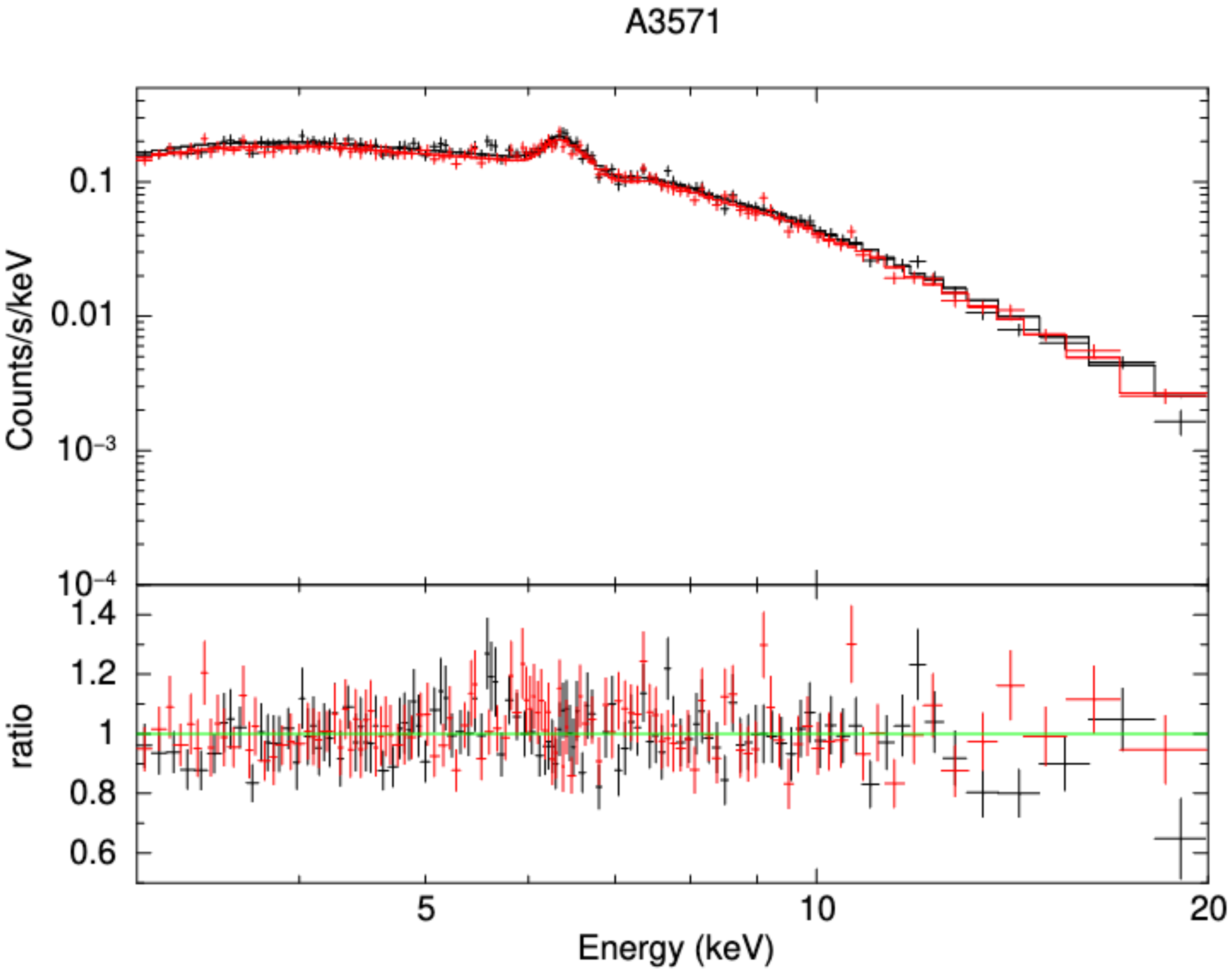
# Backup Slides


A3571
A1651
AA3391
A3158
A3558
A1650
A3112
A1644
A496
Broad Band
Broad Band Uncertainty
Temperature (keV)
Bandpass (keV)

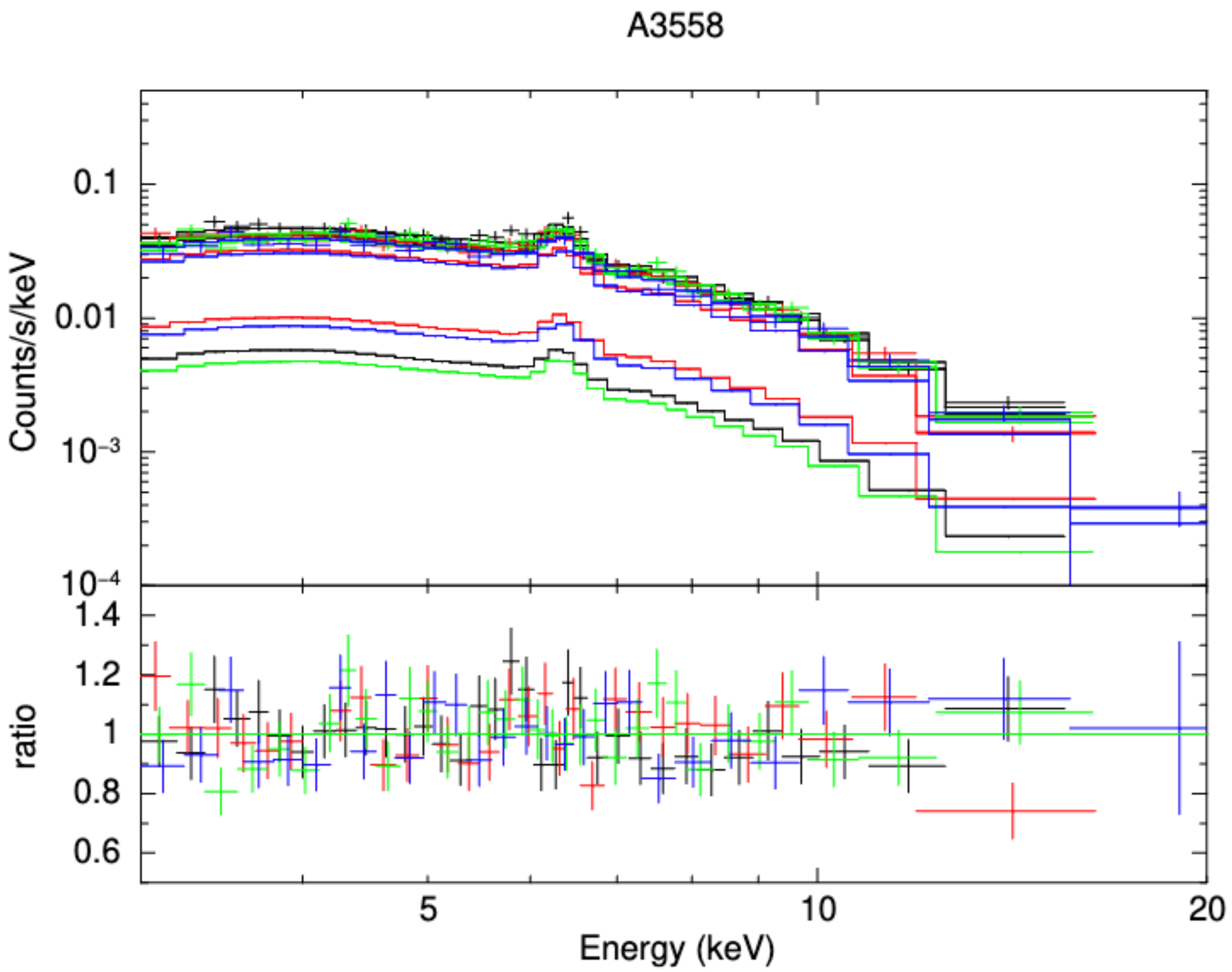

Histogram of All Clusters Bandpasses
Lower Bandpass (3-8 keV)
Middle Bandpass (7-12 keV)
Upper Bandpass (11-20 keV)
Frequency
Number of Standard Deviations

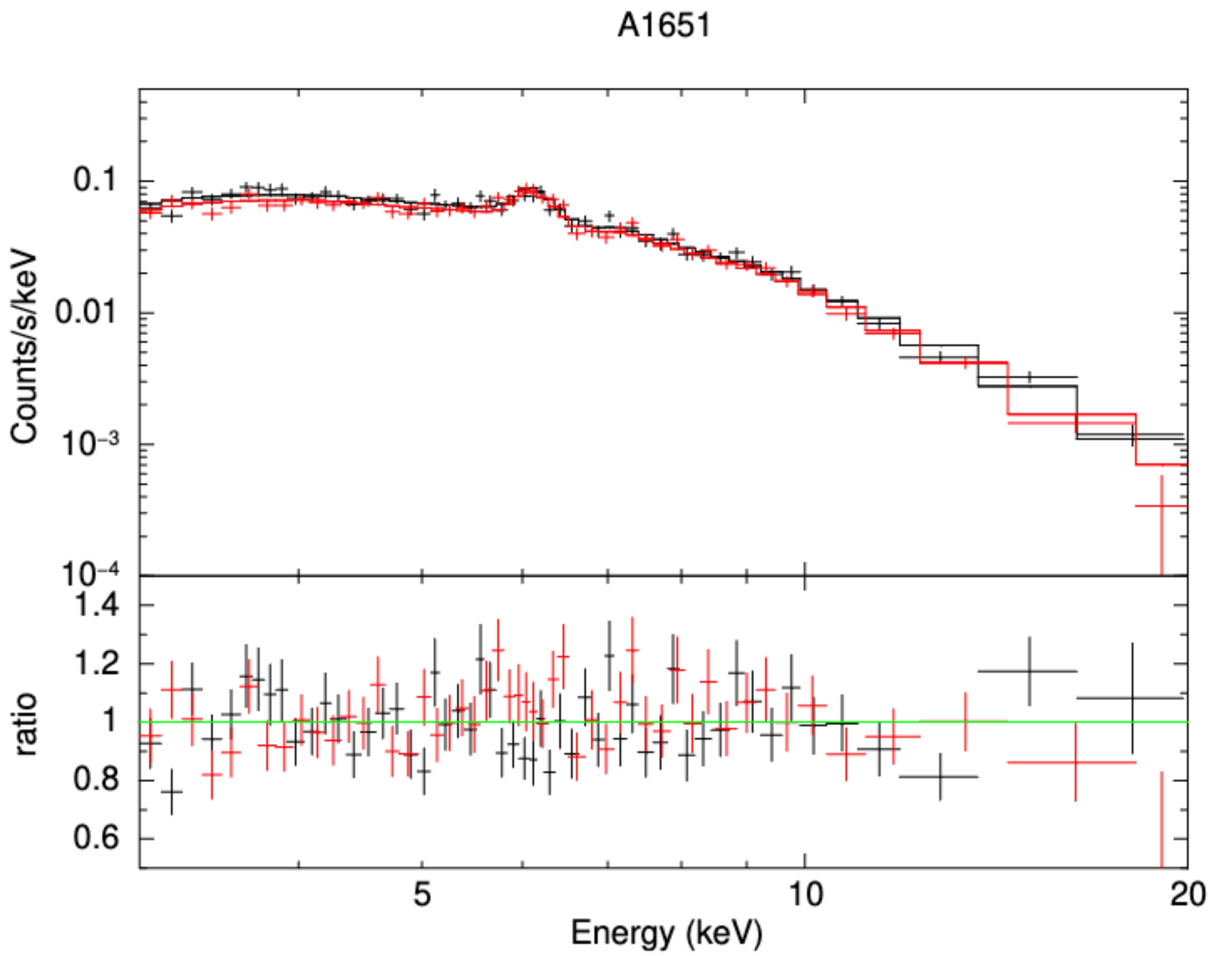
# Snapshot Spectral Fits



# Snapshot Spectral Fits



# Snapshot Spectral Fits

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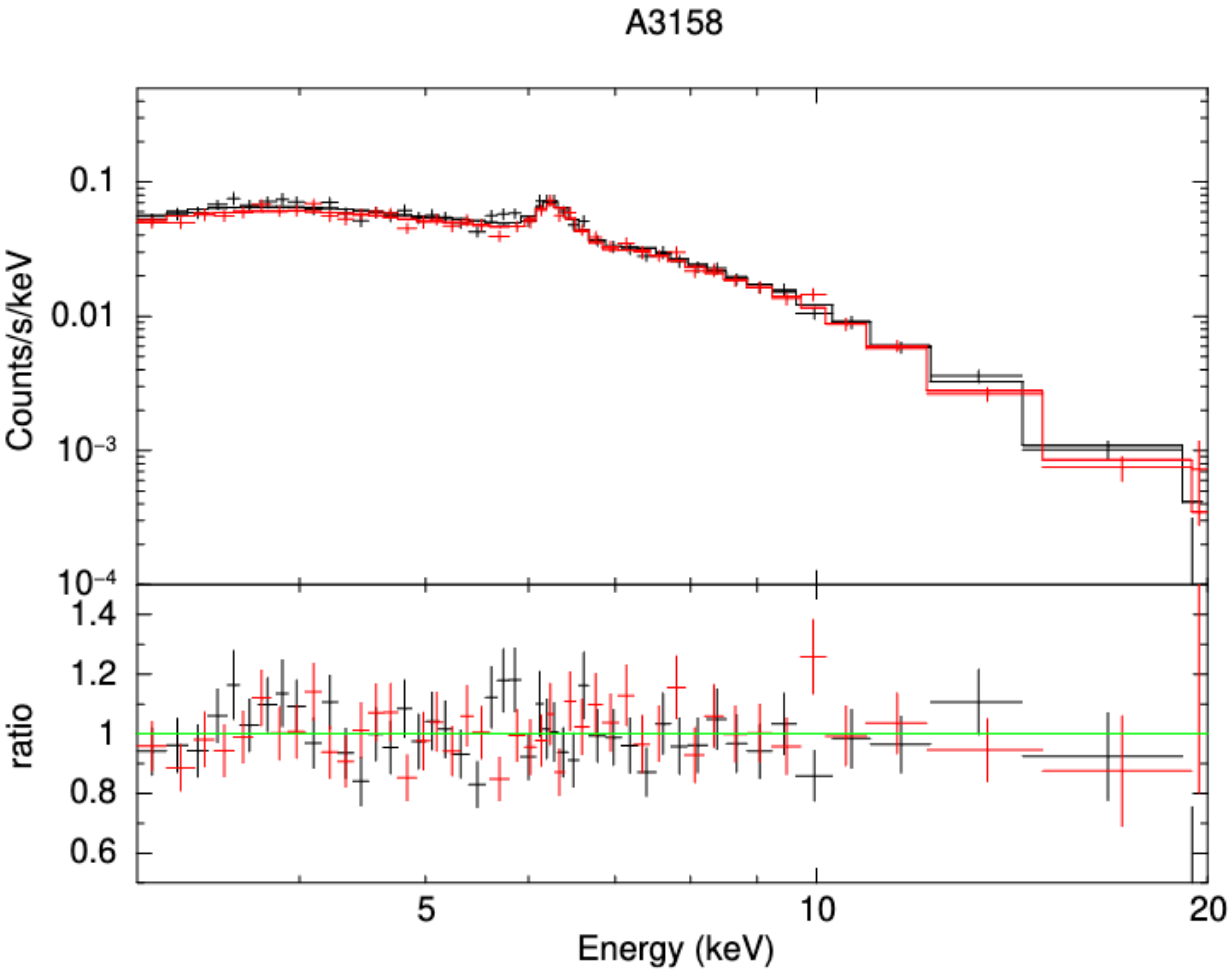


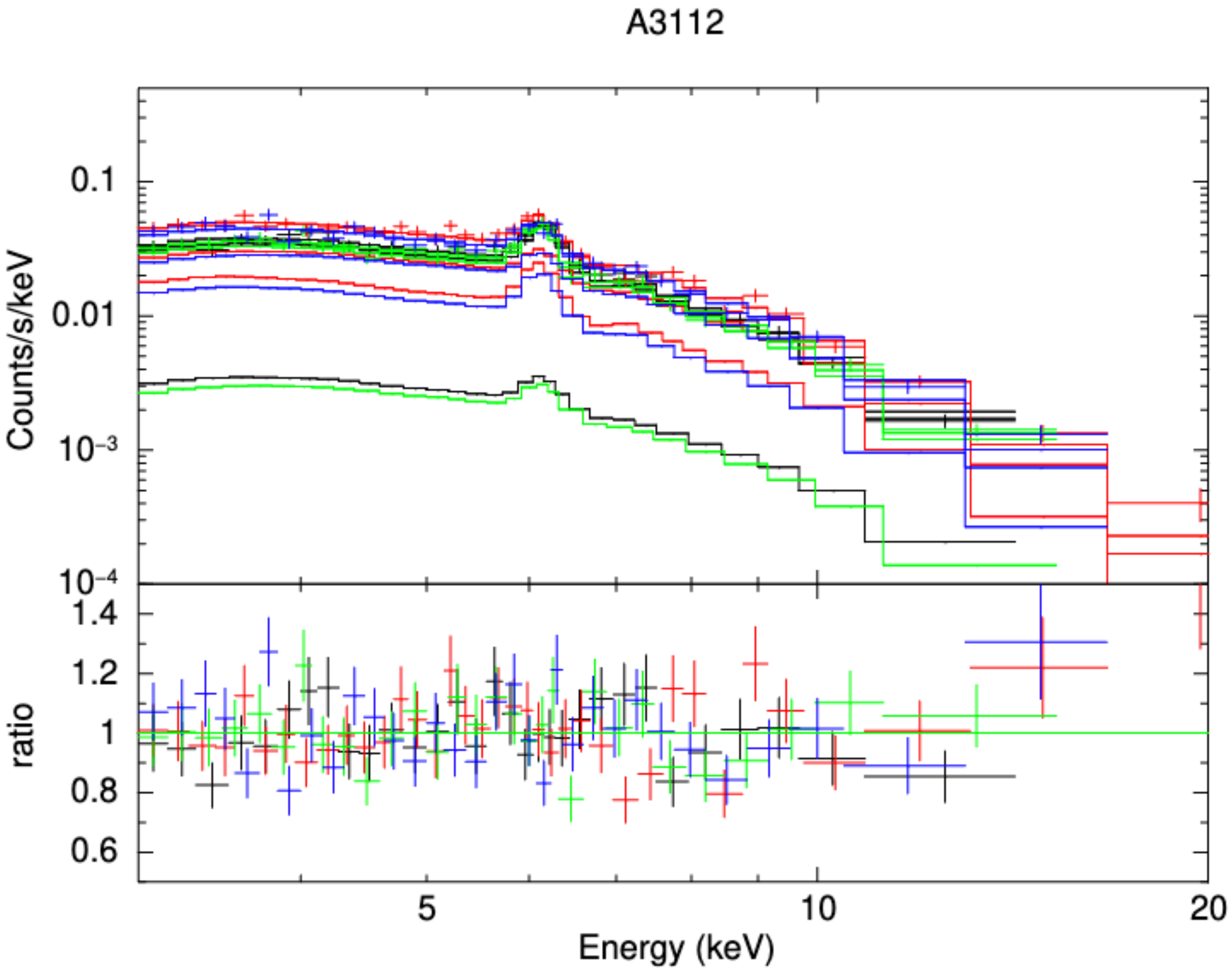

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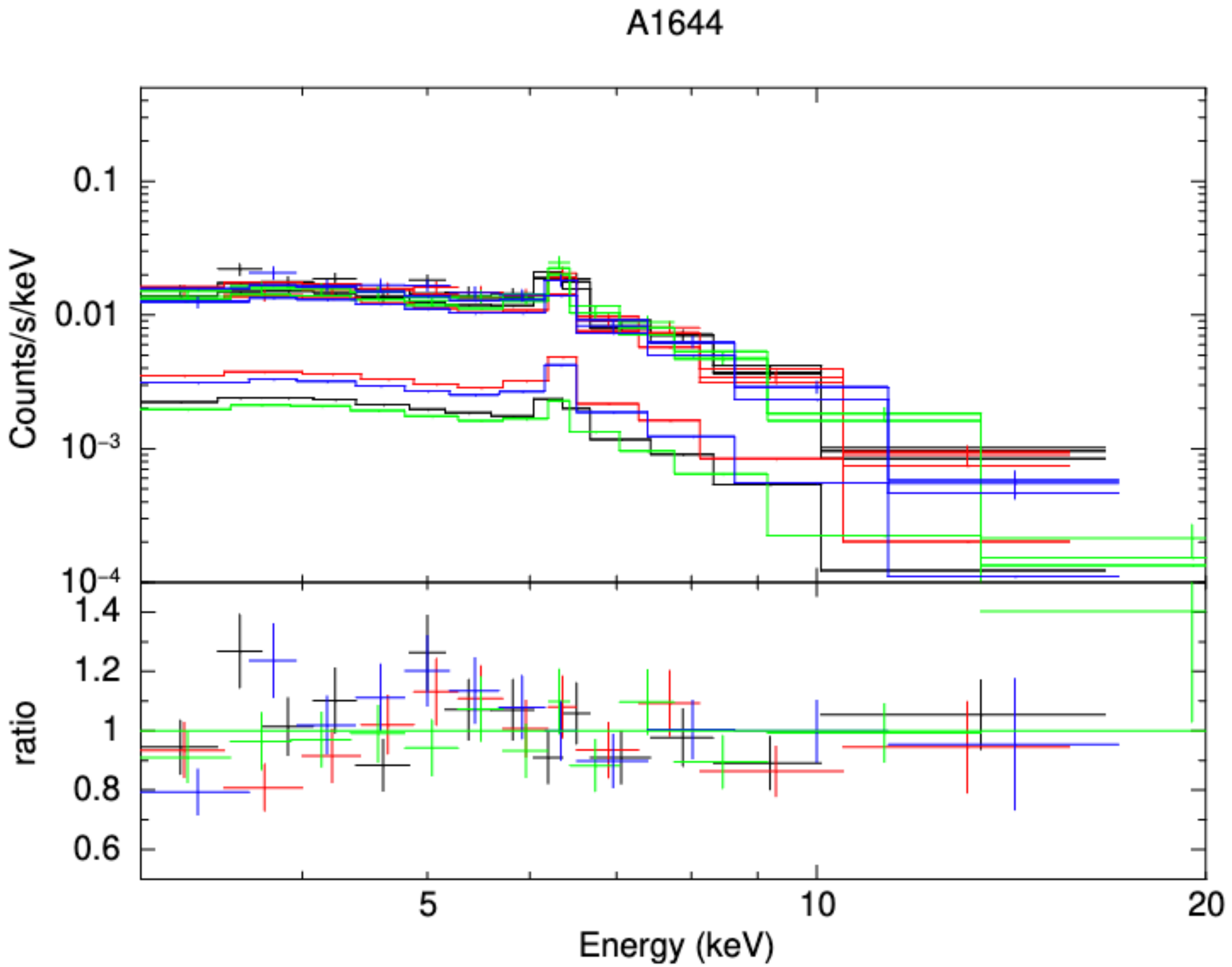
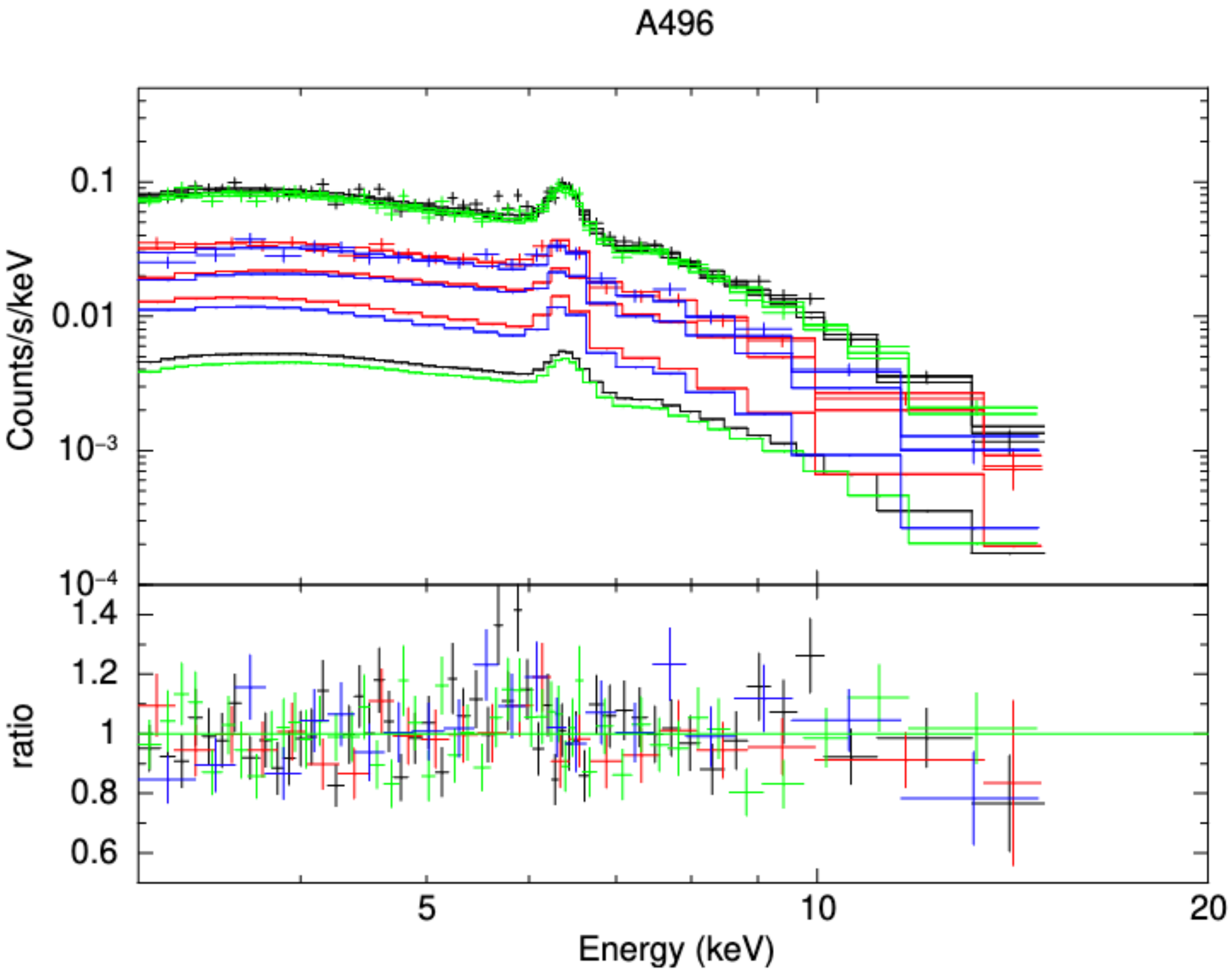
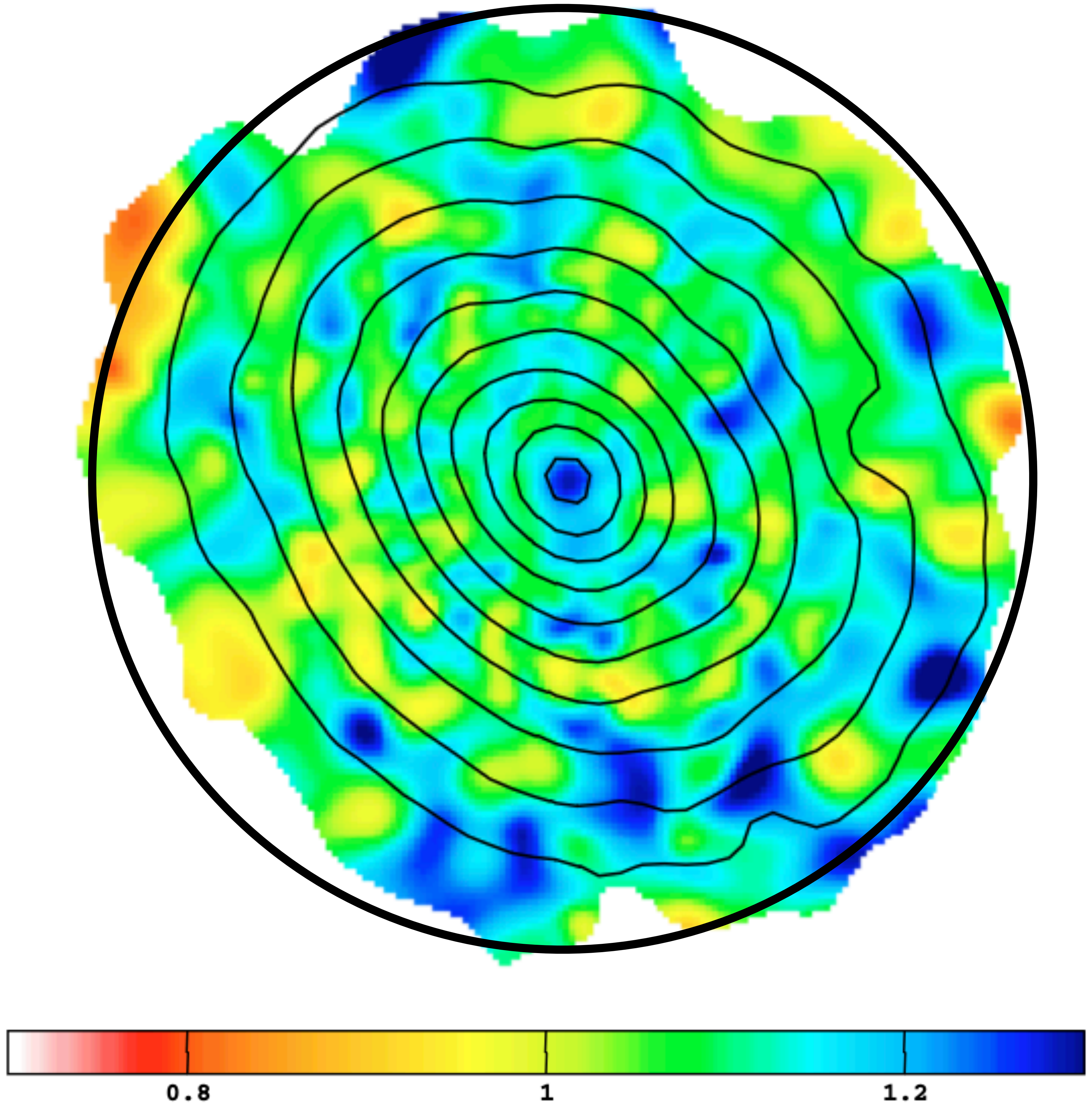
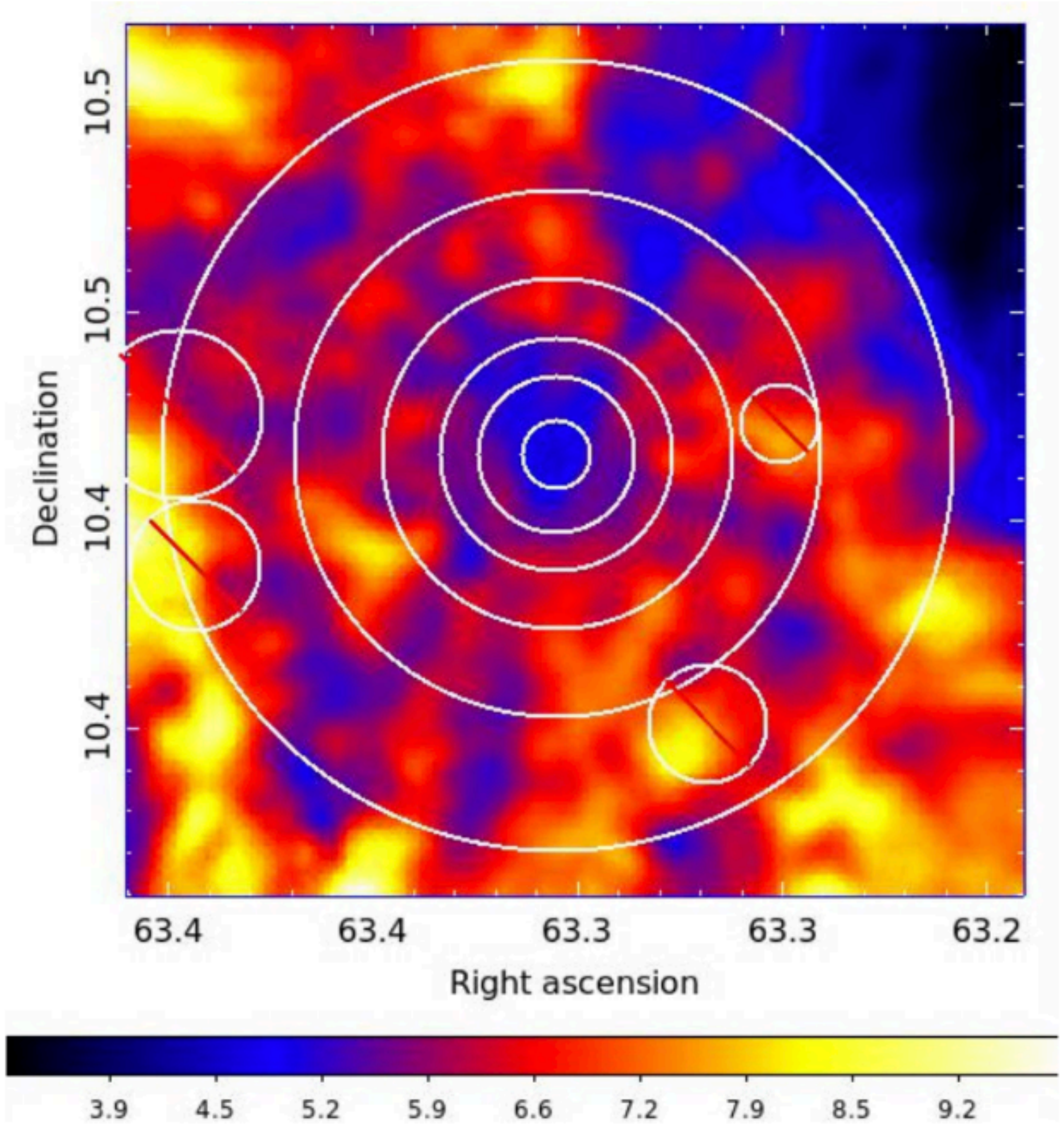


# Temperature Maps of A478

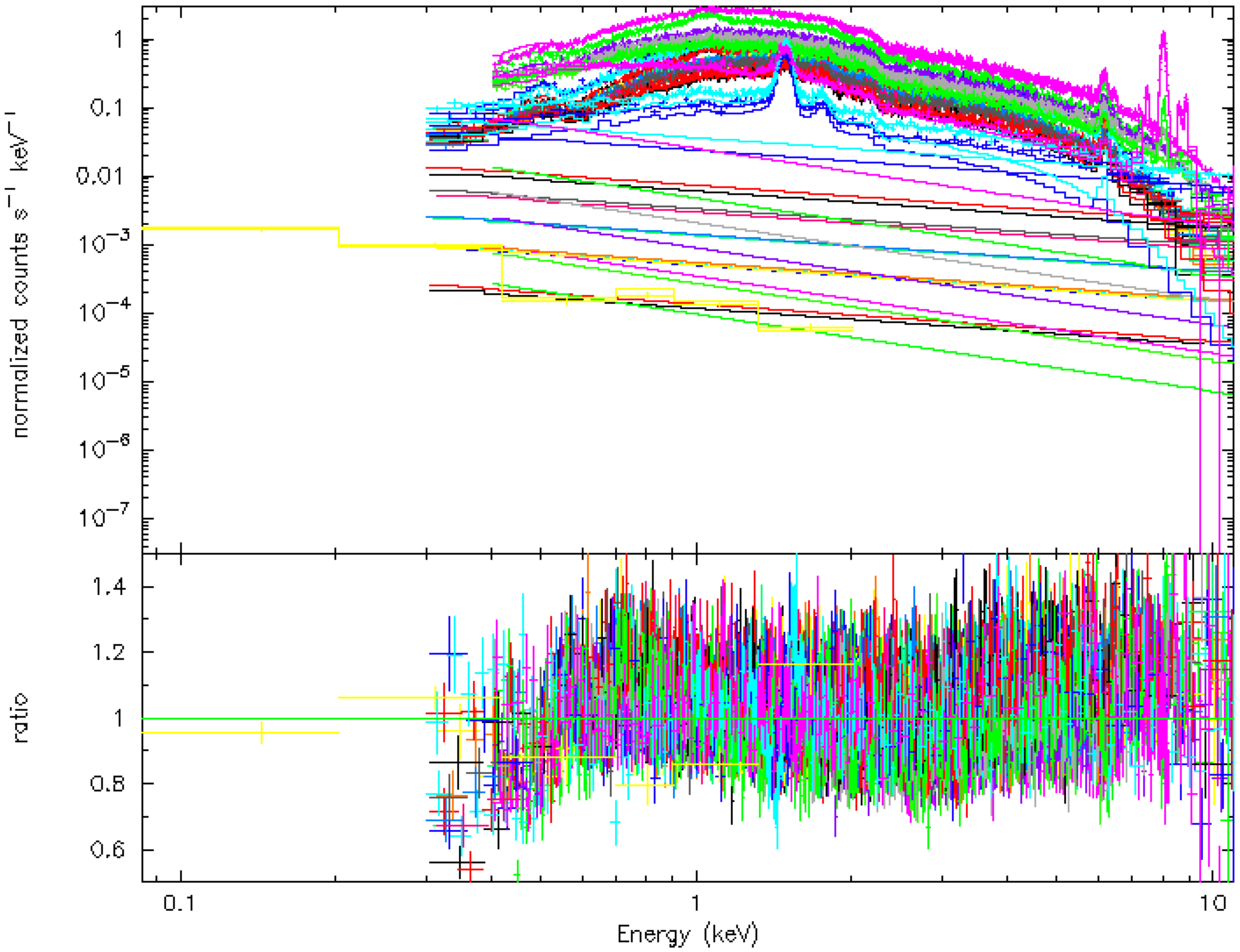



(<—hot) Hardness (cool—>)

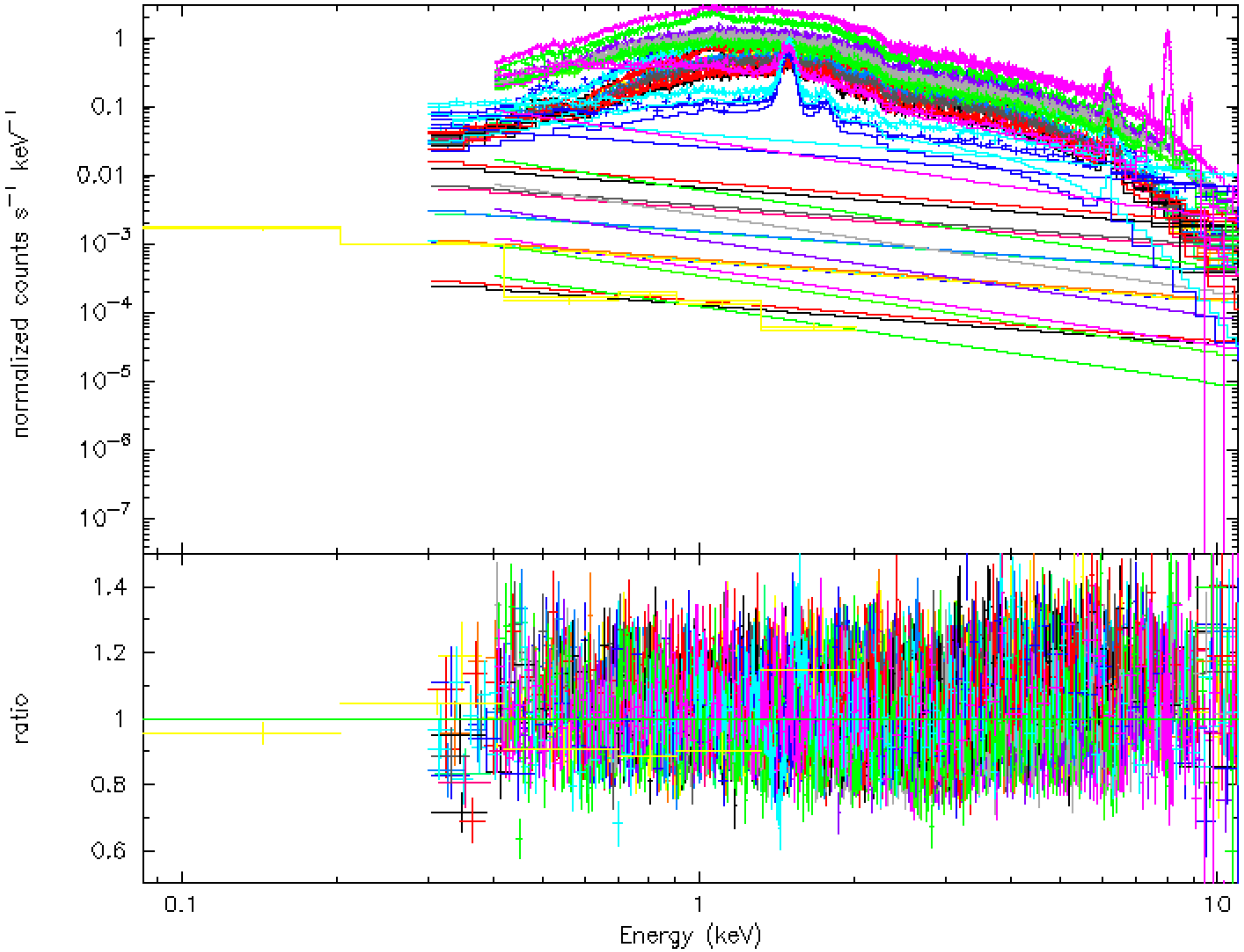


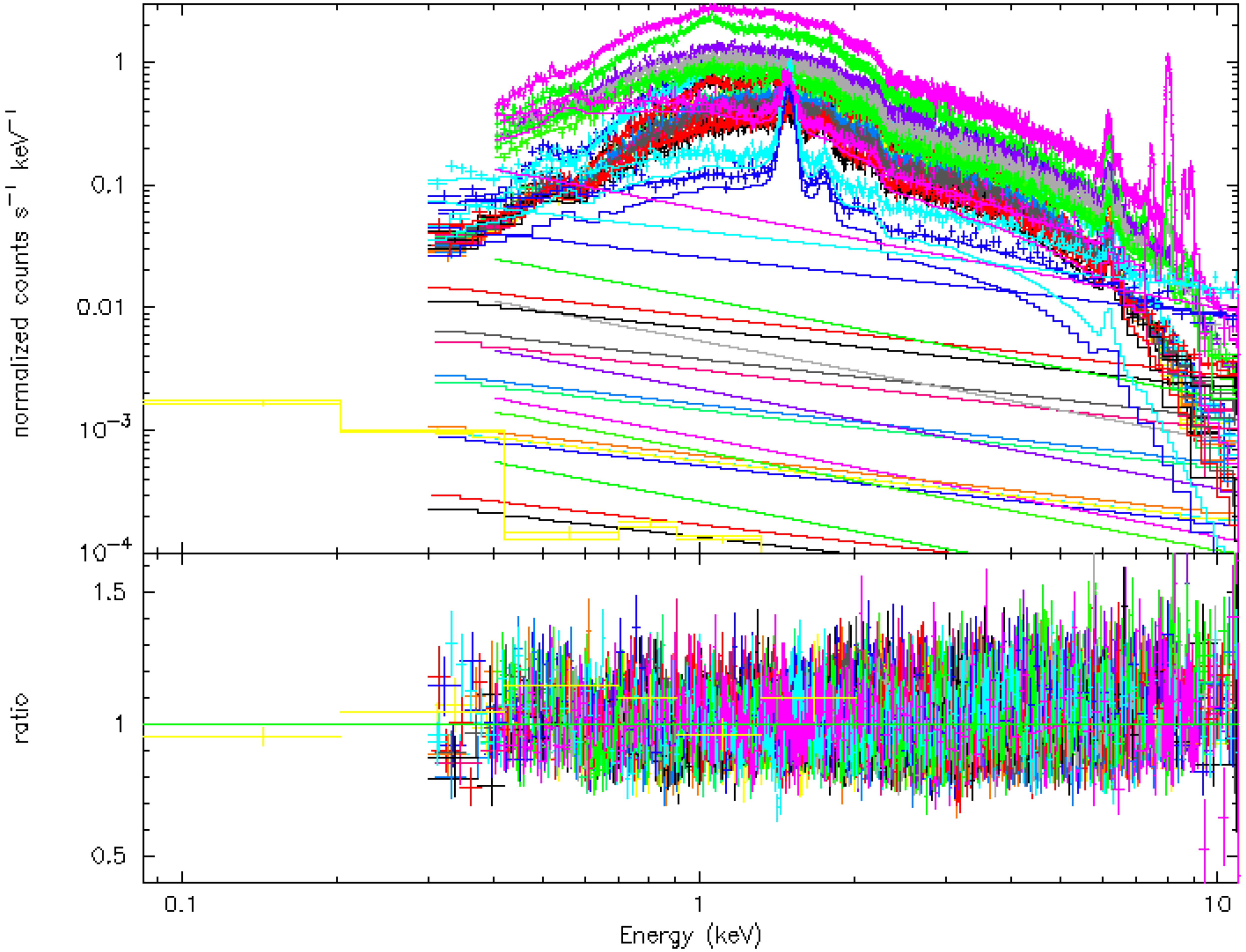

kT (keV)

# AnGr abund, wabs, no ARF correction

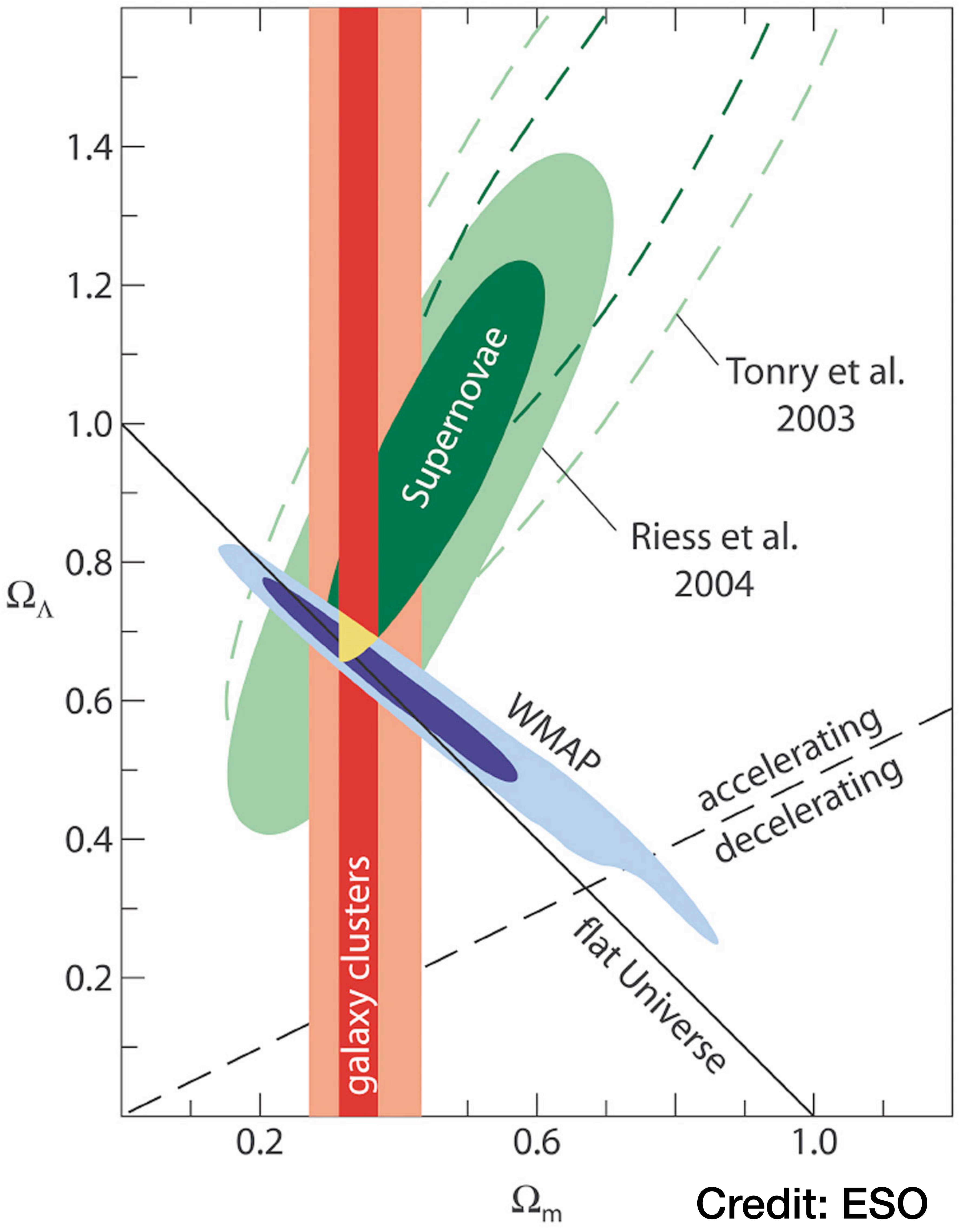


# Abund Wilm, before & after ARF correction



# Galaxy Clusters: Why Calibration?




Credit: ESO

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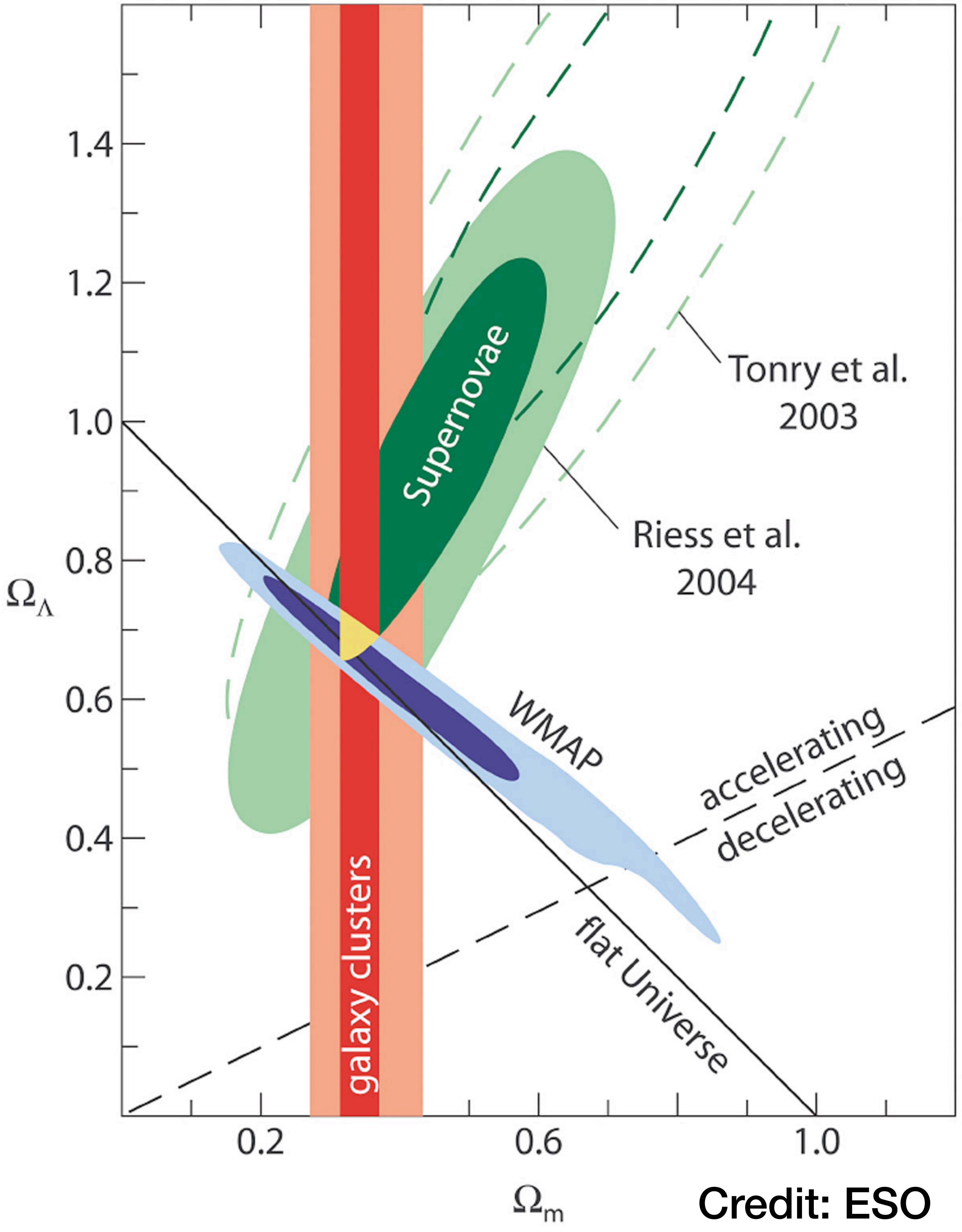


Credit: ESO

$$M(<r) = -\frac{kT(r)r}{G\mu m_p}\left[\frac{d\ln n_p}{d\ln r} + \frac{d\ln T}{d\ln r}\right] \propto T(r)r$$

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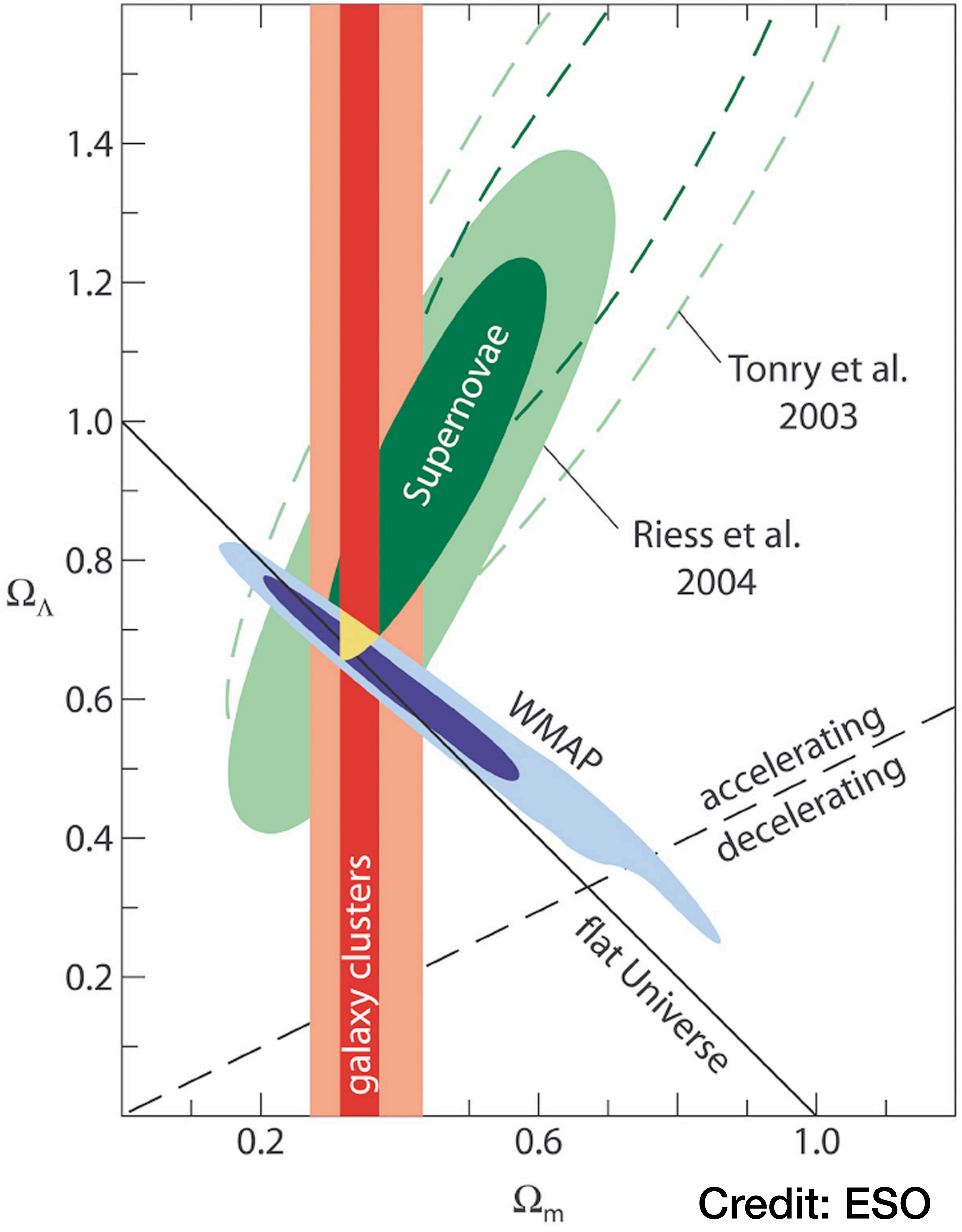


Credit: ESO

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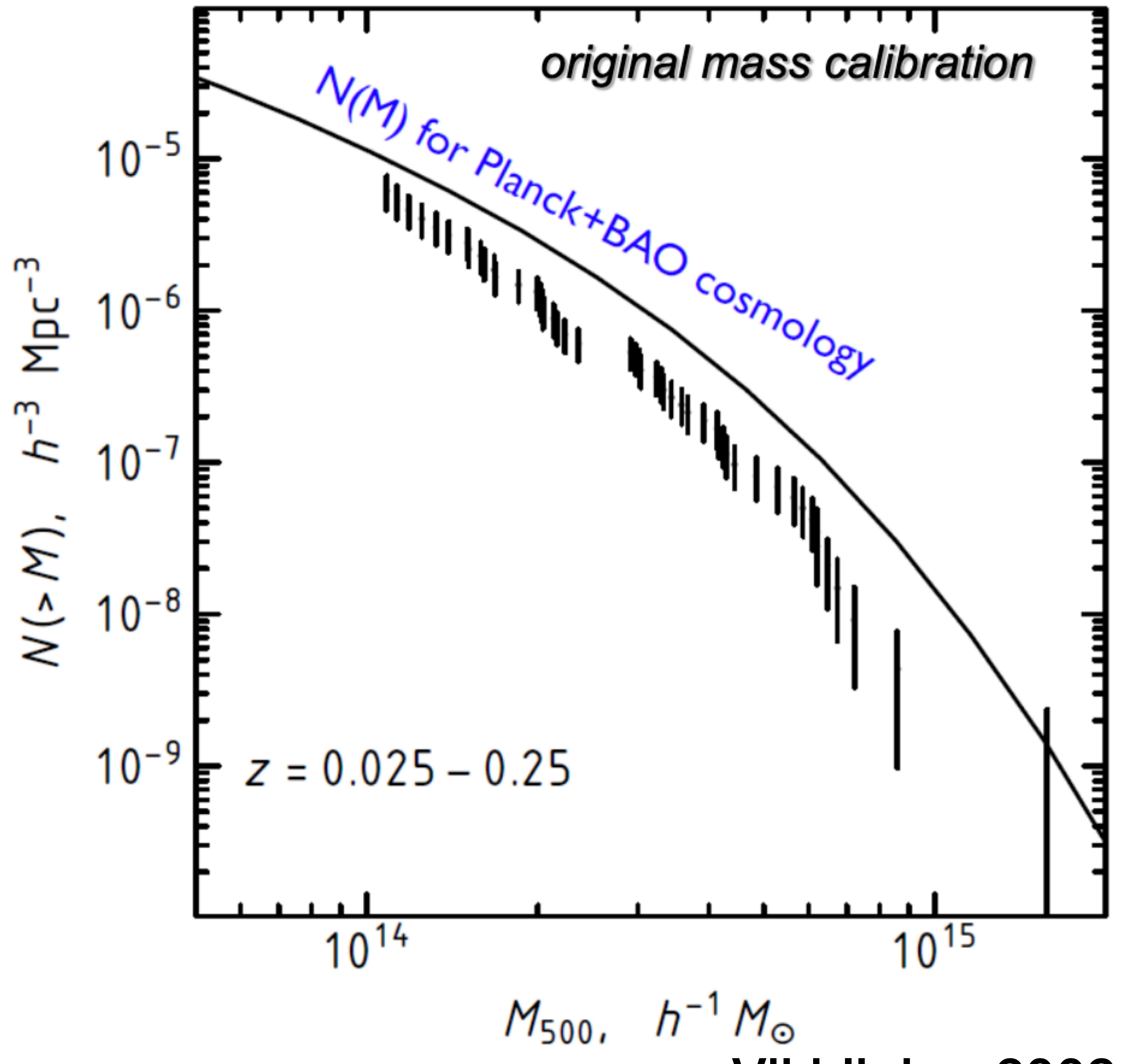


Vikhlinin+ 2009

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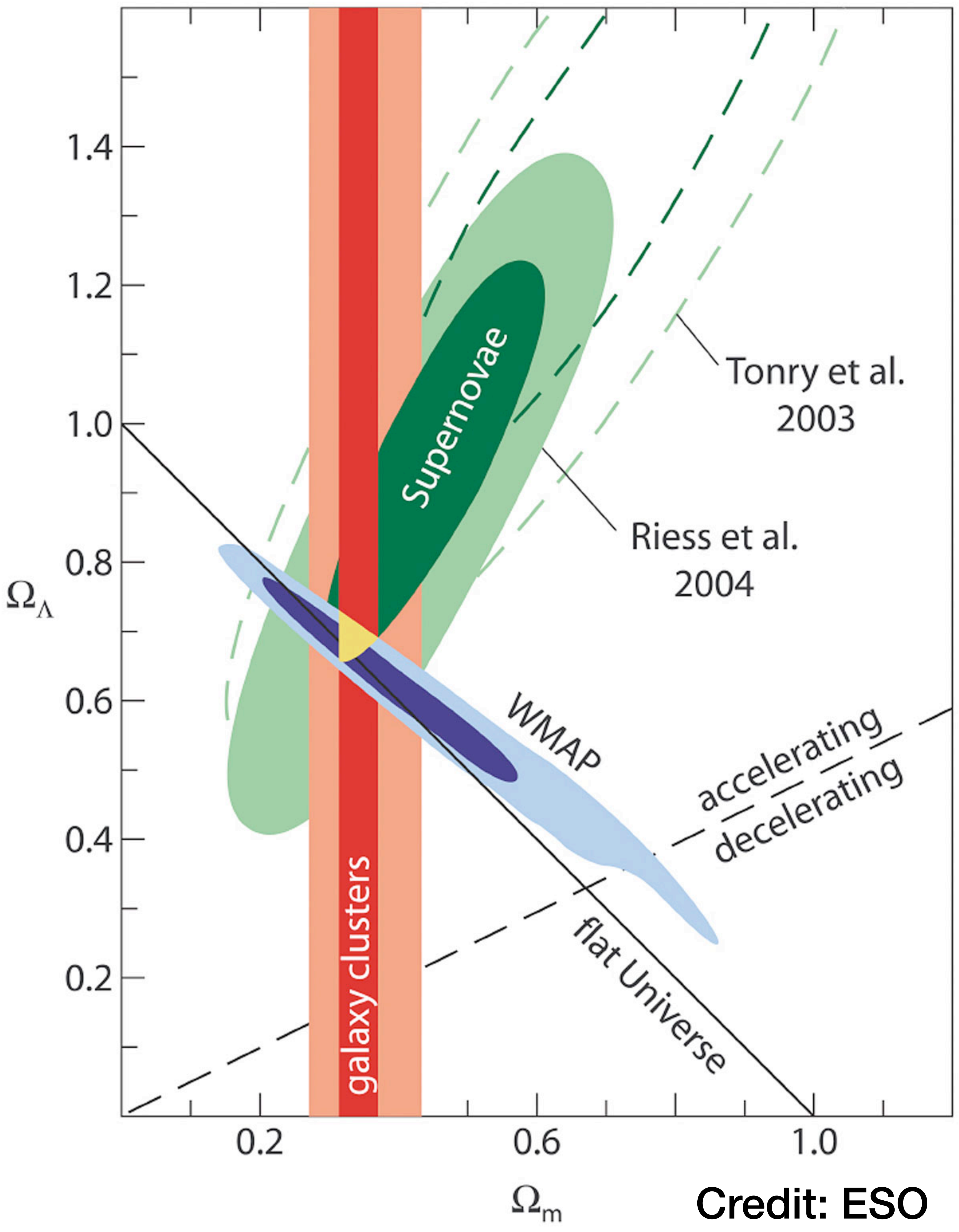
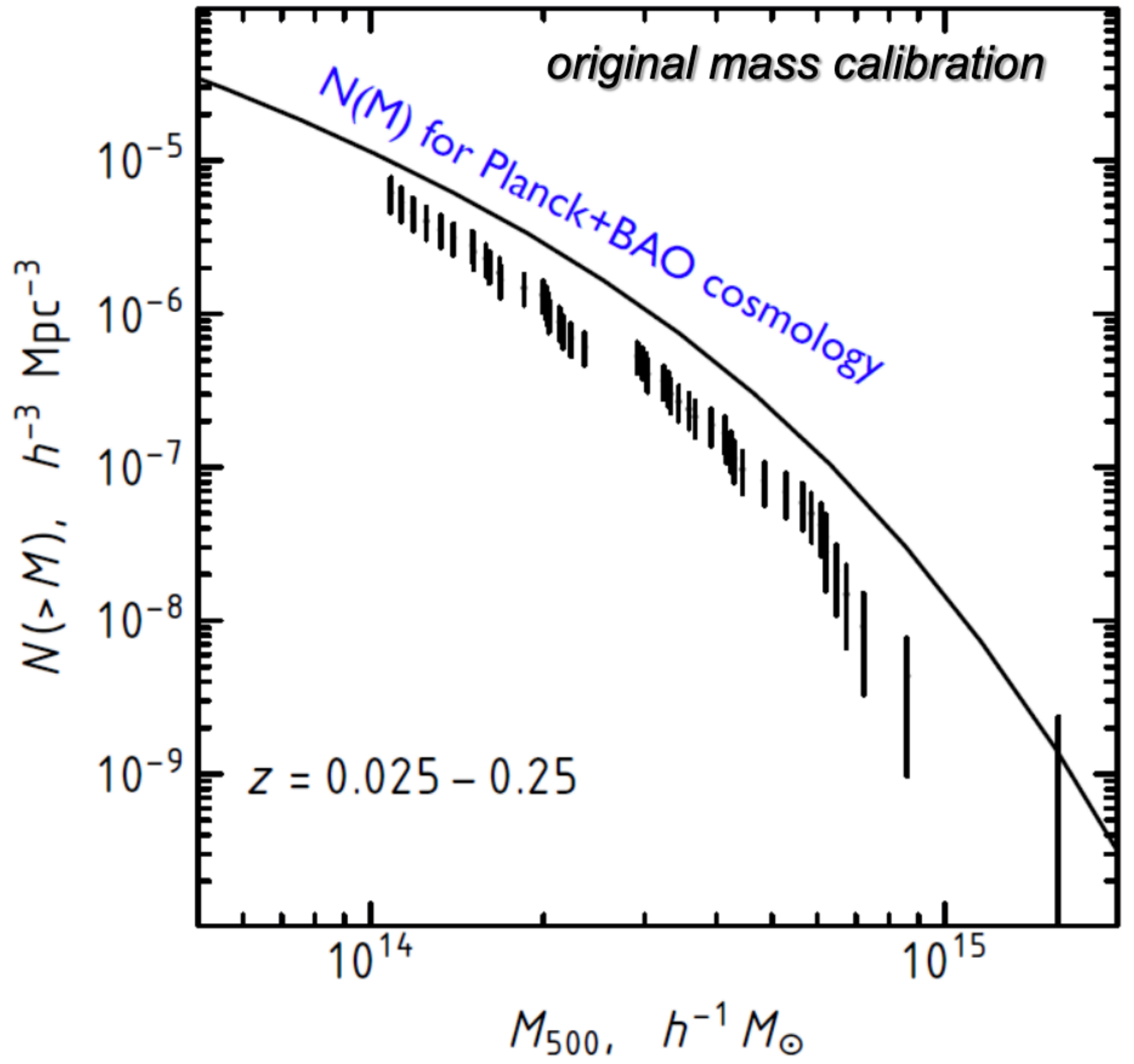
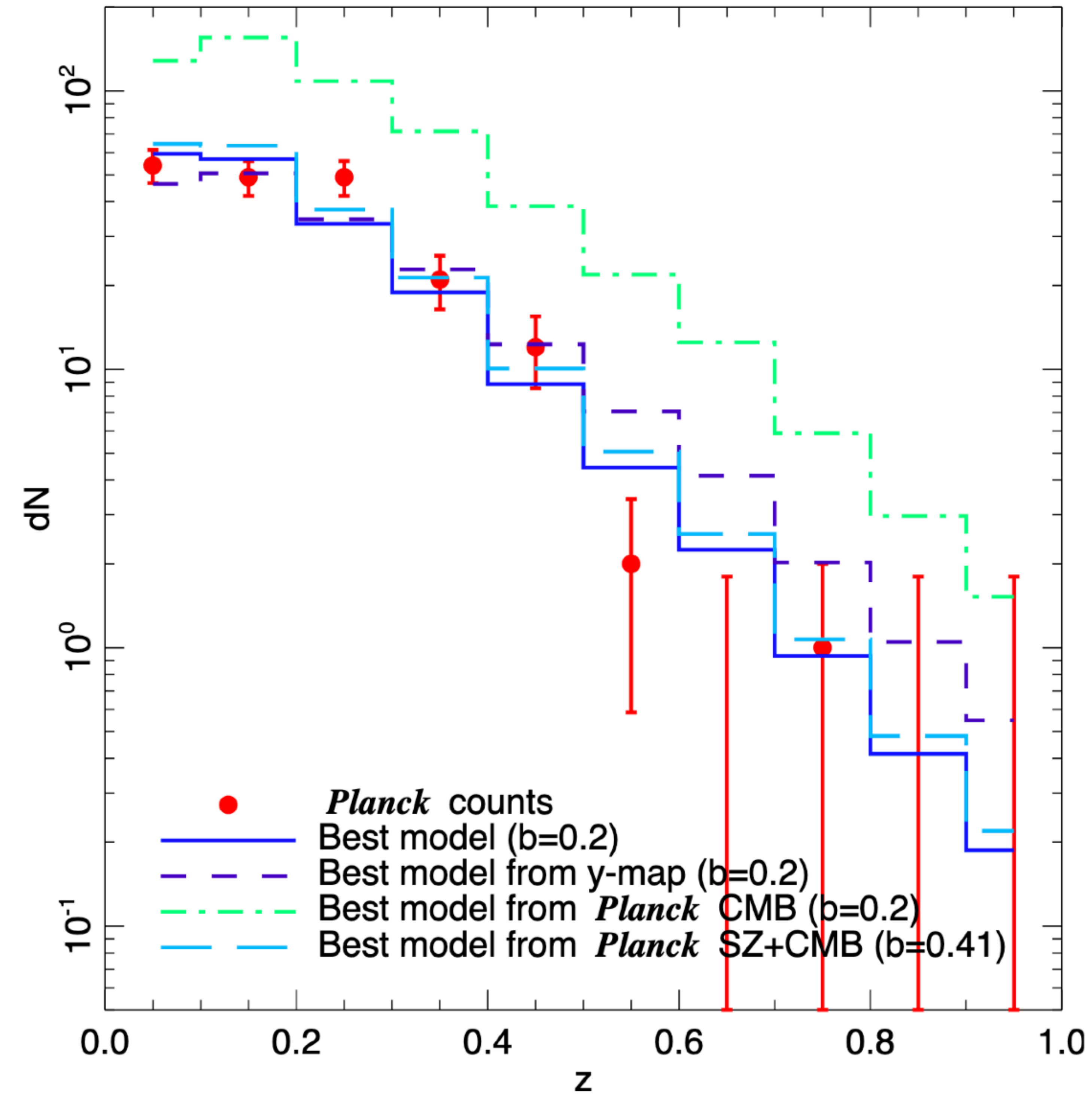



Credit: ESO

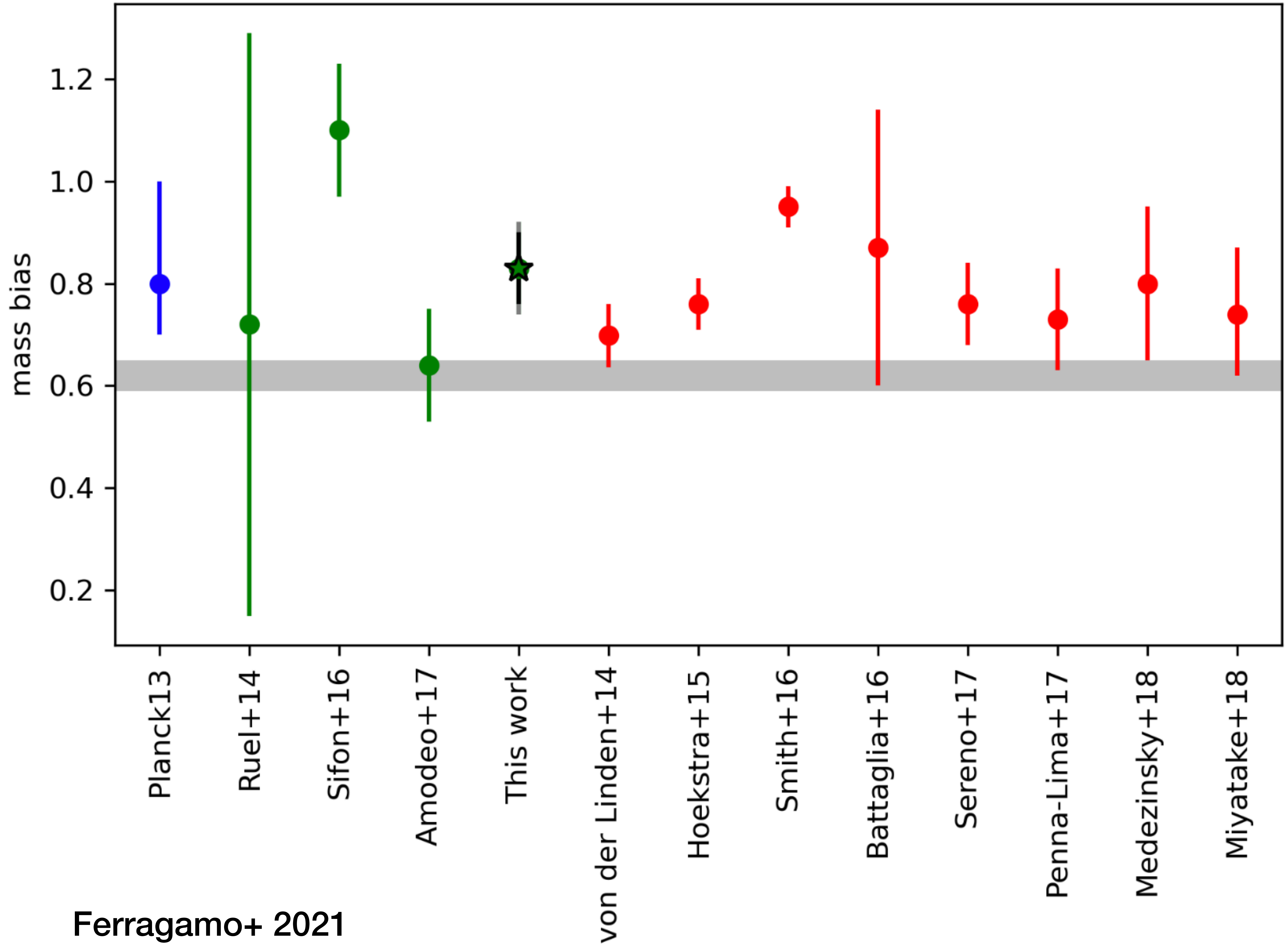



Vikhlinin+ 2009



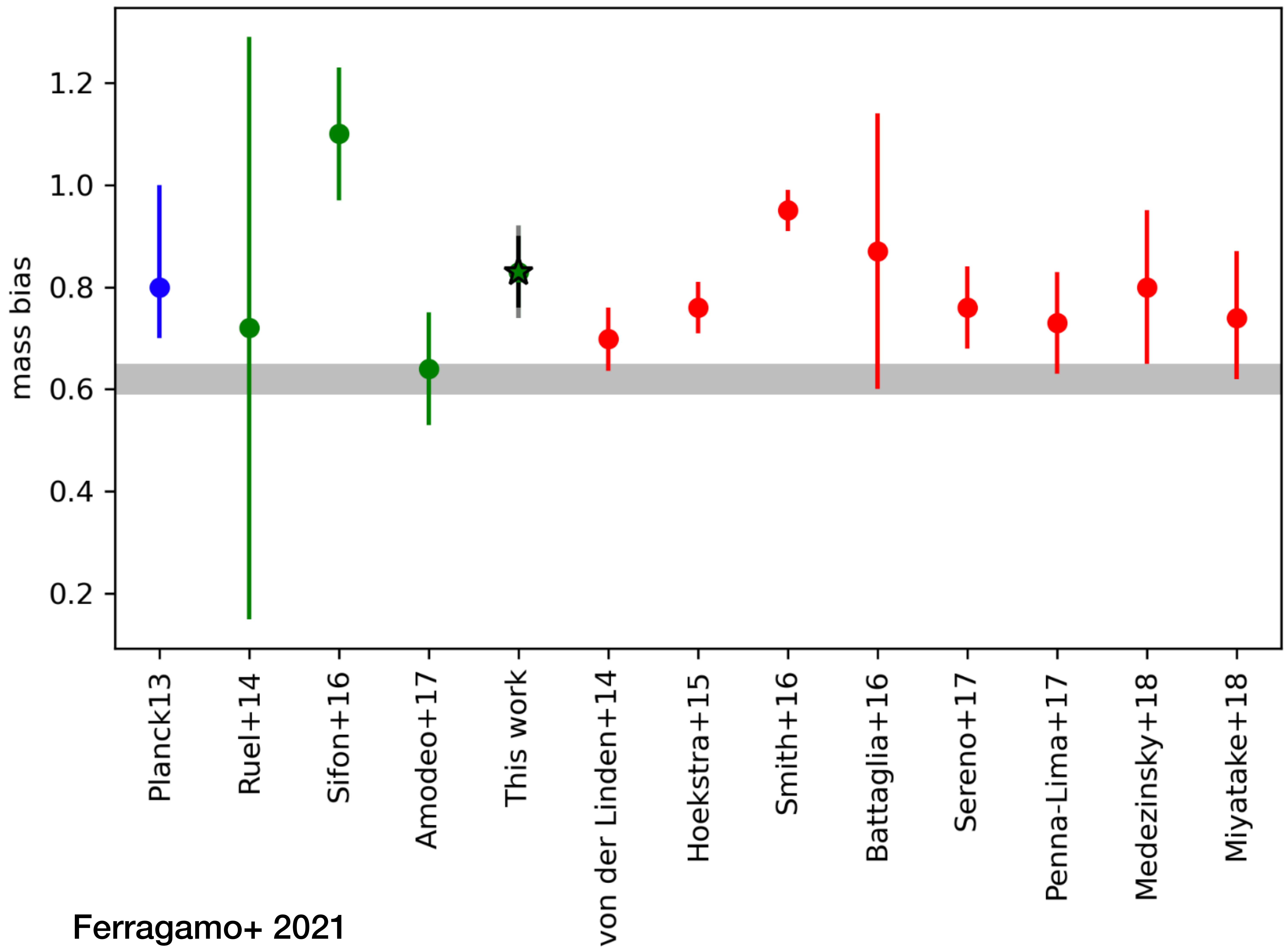

Planck collab. 2014 (XX)

# Galaxy Clusters: Why Calibration?

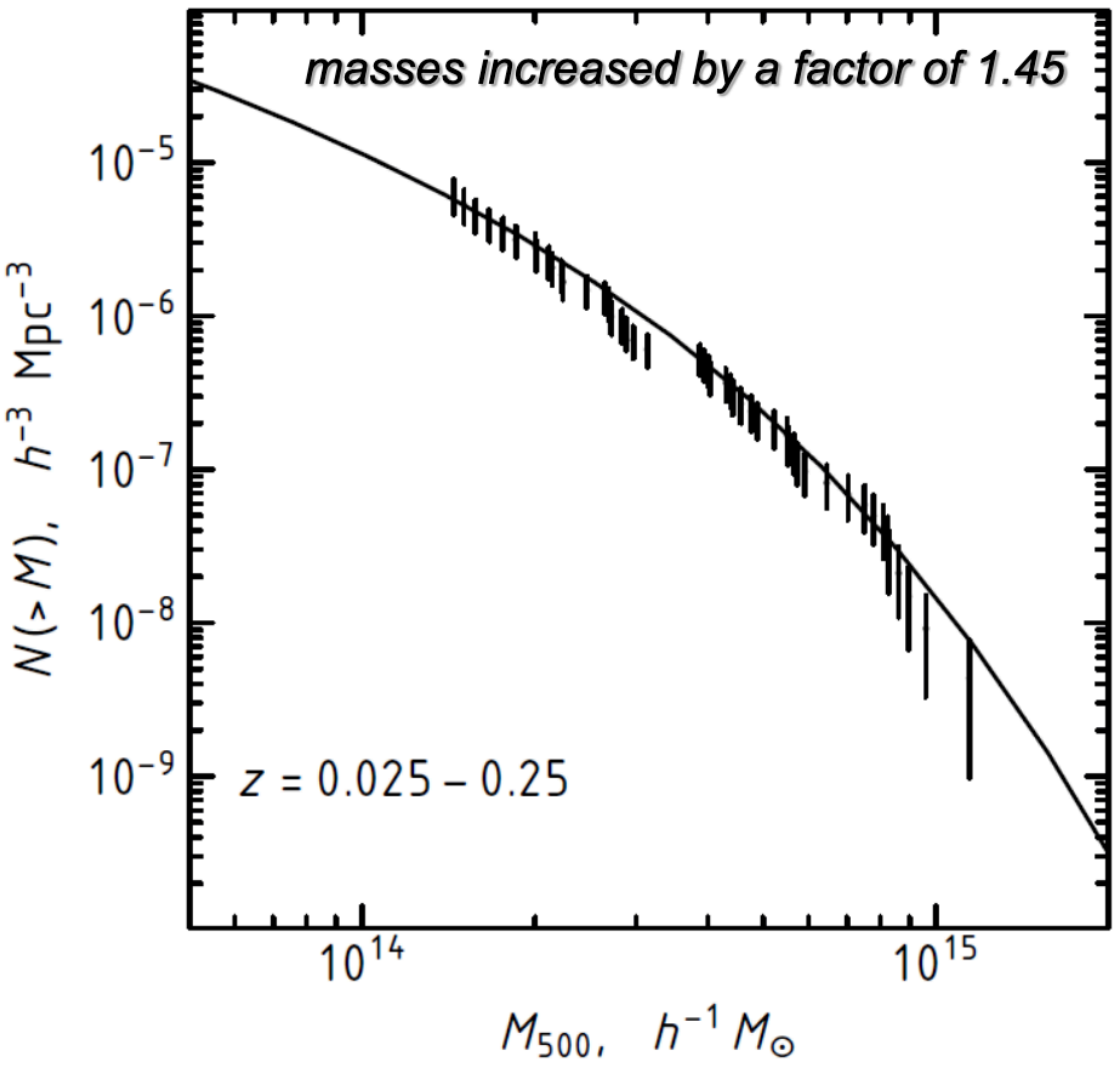



Ferragamo+ 2021

# Galaxy Clusters: Why Calibration?

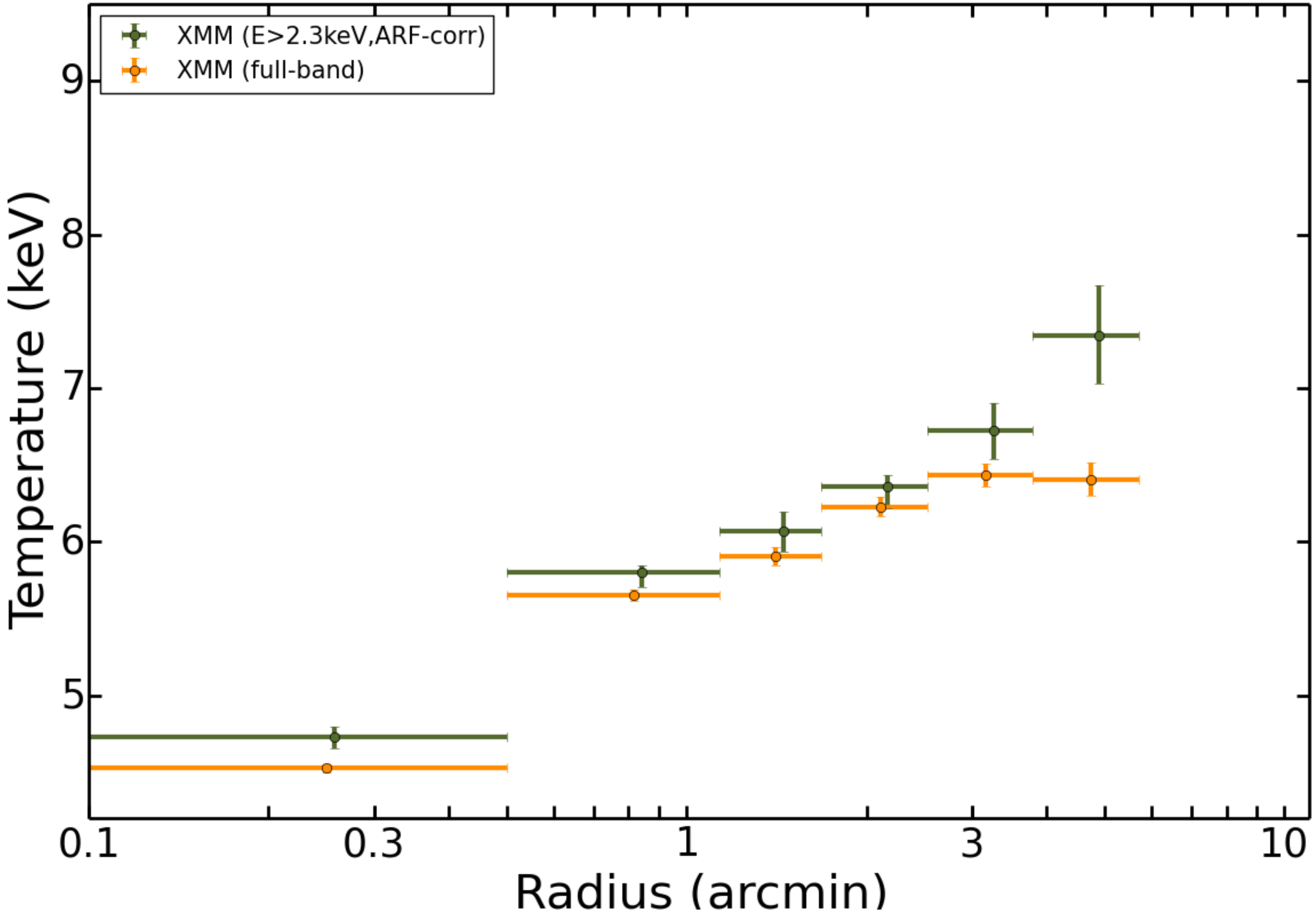



Ferragamo+ 2021




Vikhlinin+ 2009
(Borrowed from 2016 KICP Workshop slide by Kravtzov)

# *XMM-Newton* Self Consistency



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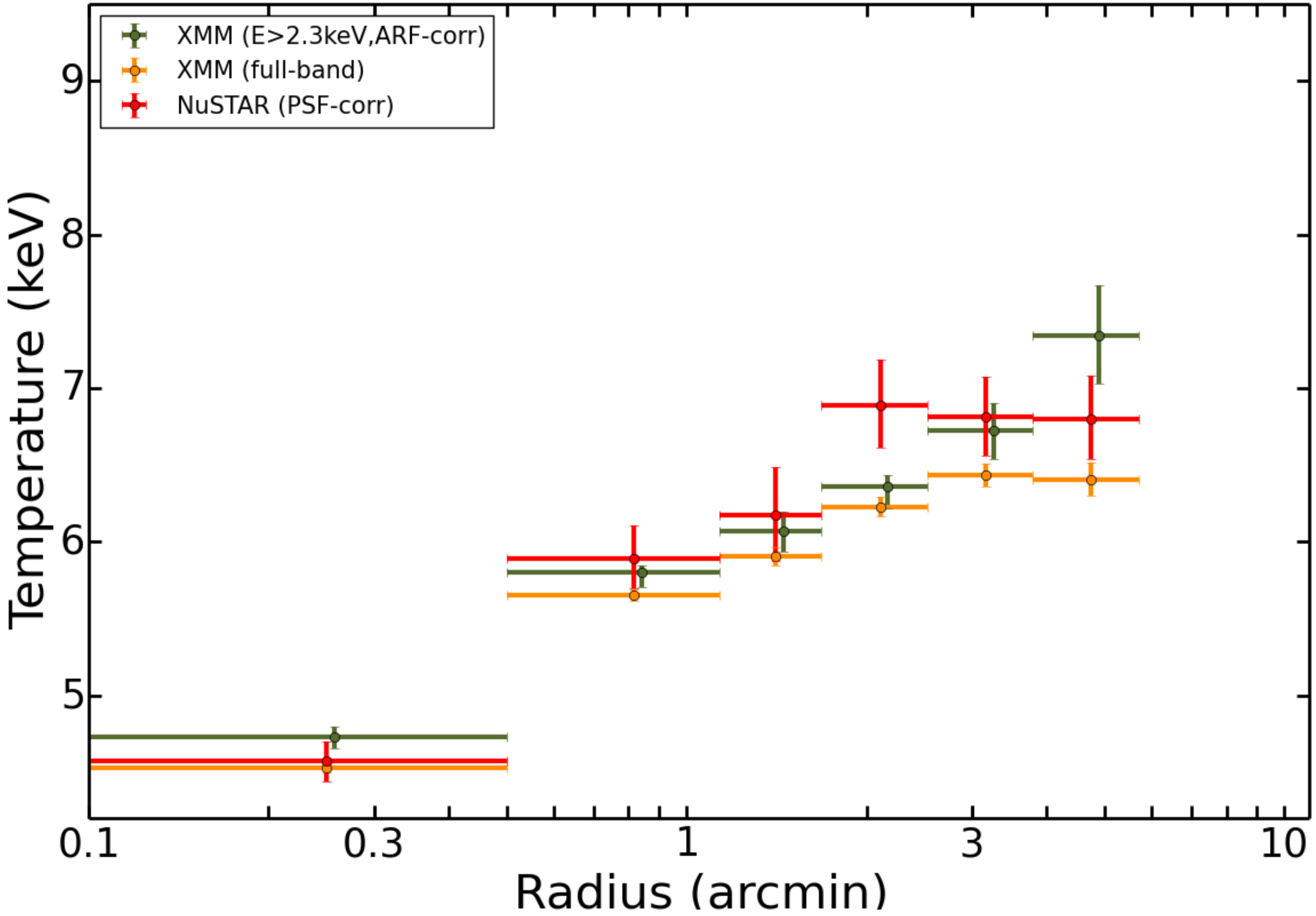

# Scattered & Stray Light