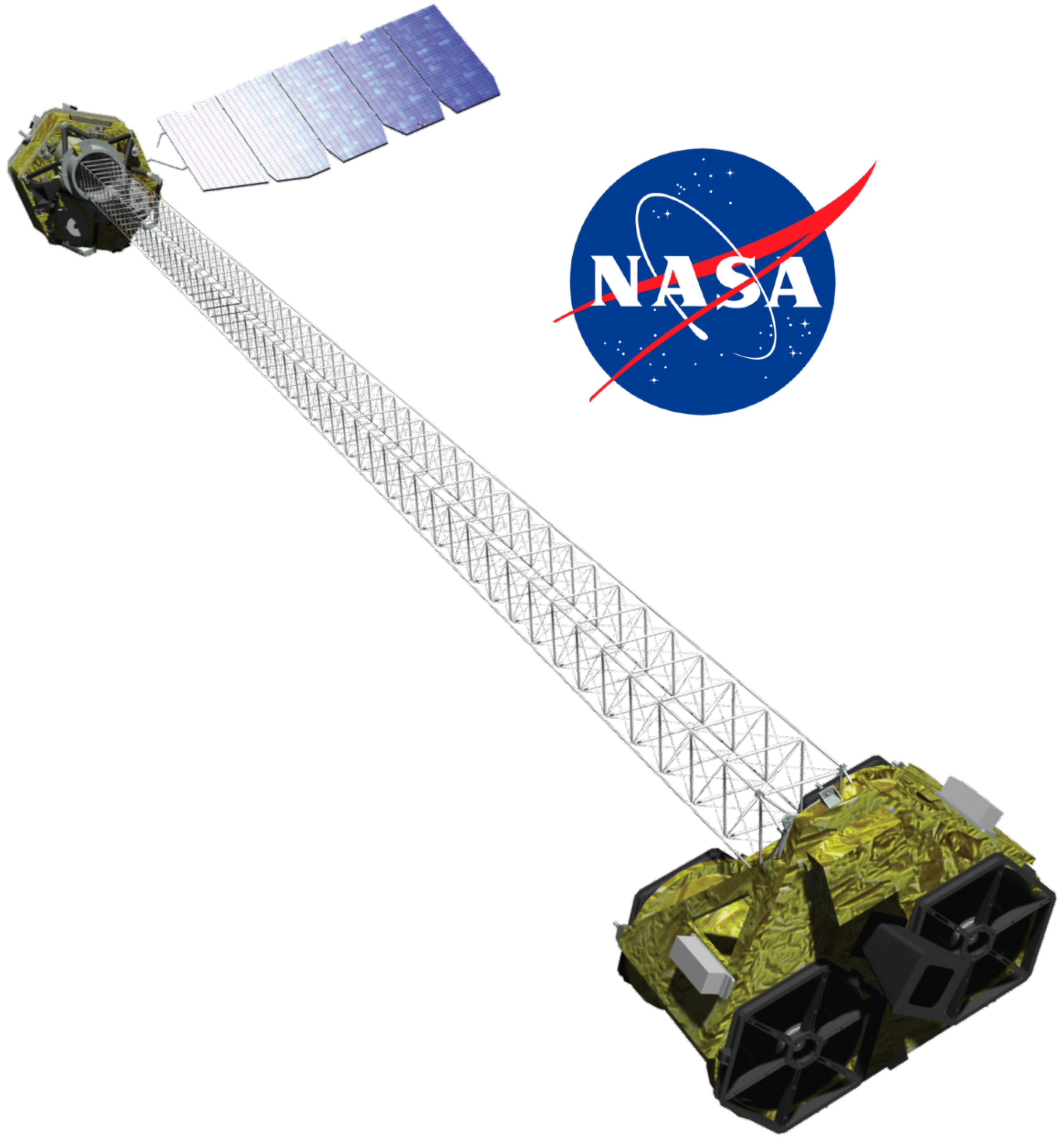
X-RAY ASTROPHYSICS
DEPARTMENT OF PHYSICS & ASTRONOMY

Galaxy Cluster Temperatures from *NuSTAR*, *Chandra*, and *XMM-Newton*

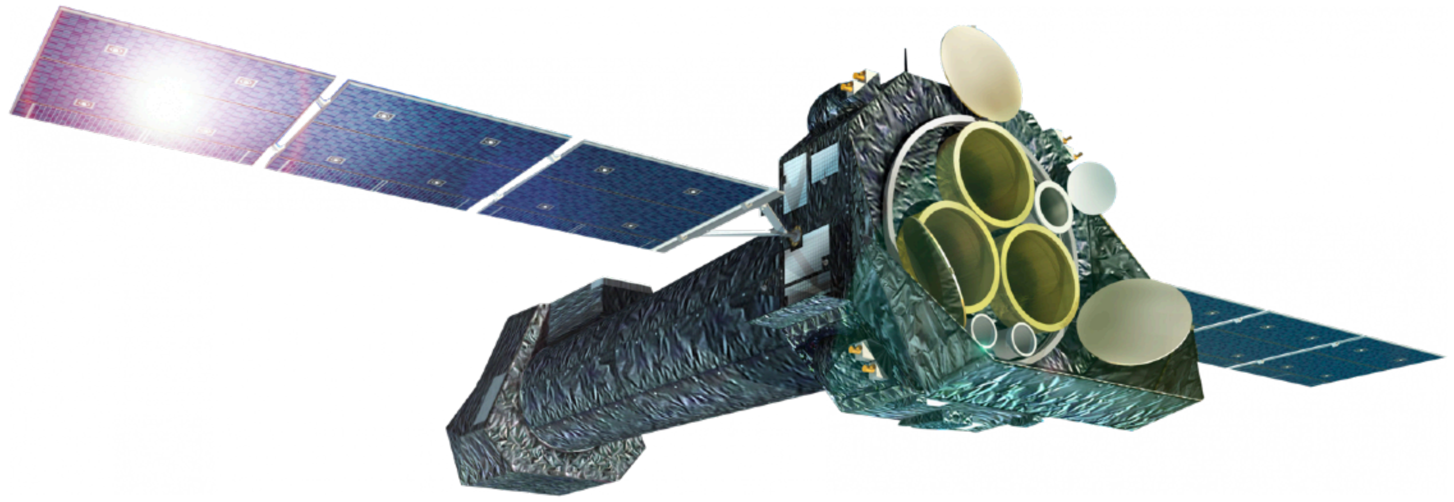


Daniel R. Wik
University of Utah

with Cicely Potter

AND
Gus Wallbank, Ben Maughan, Fabio Gastaldello, Gerrit Schellenberger, Randall Rojas-Bolivar, & Aysegul Tumer
as well as
Dominique Eckert, Brian Grefenstette, Kristin Madsen, Eric Miller, Allan Hornstrup, Silvano Molendi, NJ Westergaard, Greg Madjeski, Desiree Ferreira, Maxim Markevitch, & Richard Mushotzky

CHANDRA X-RAY OBSERVATORY

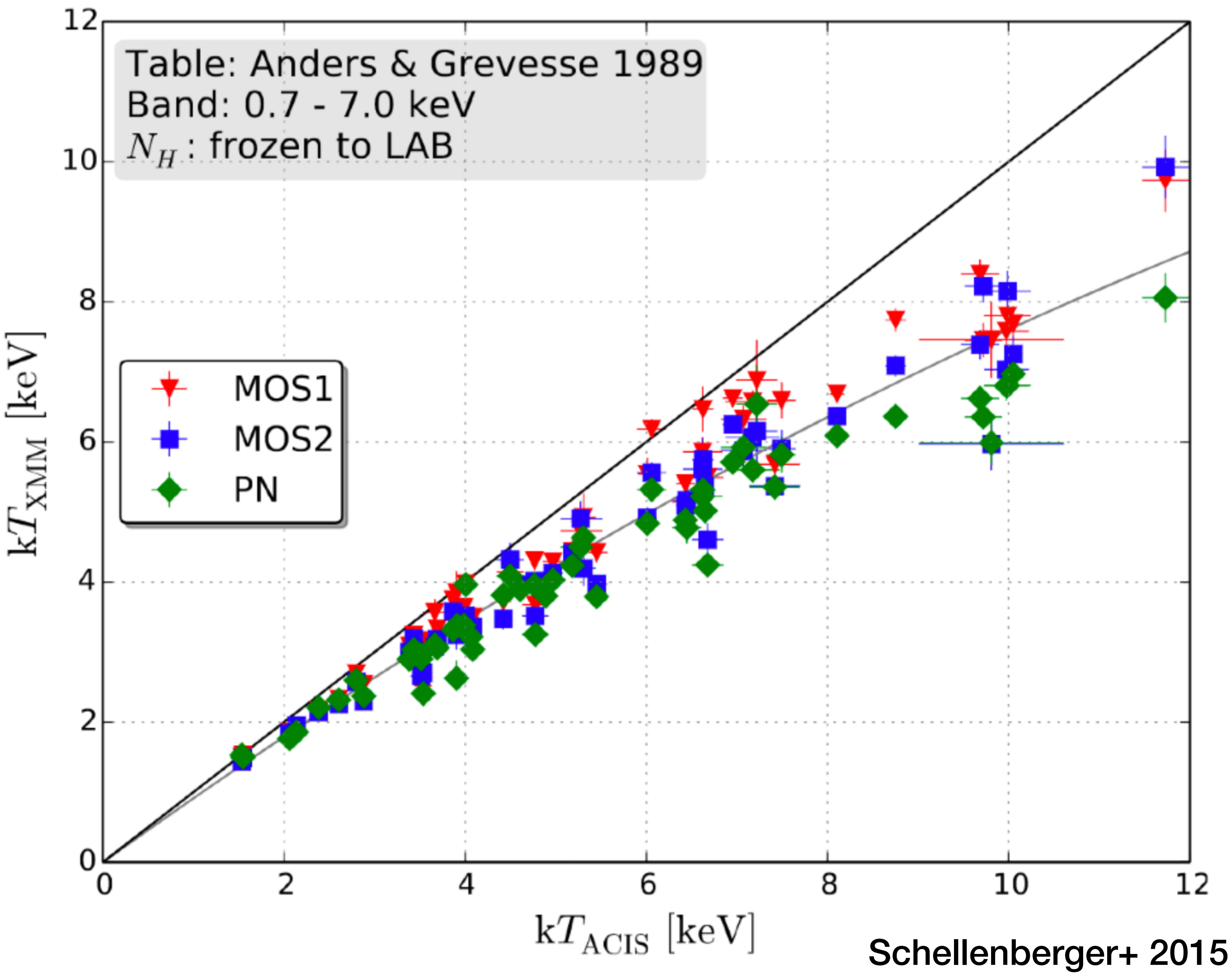


XMM-NEWTON

NuSTAR

Galaxy Clusters: Temperature Discrepancy

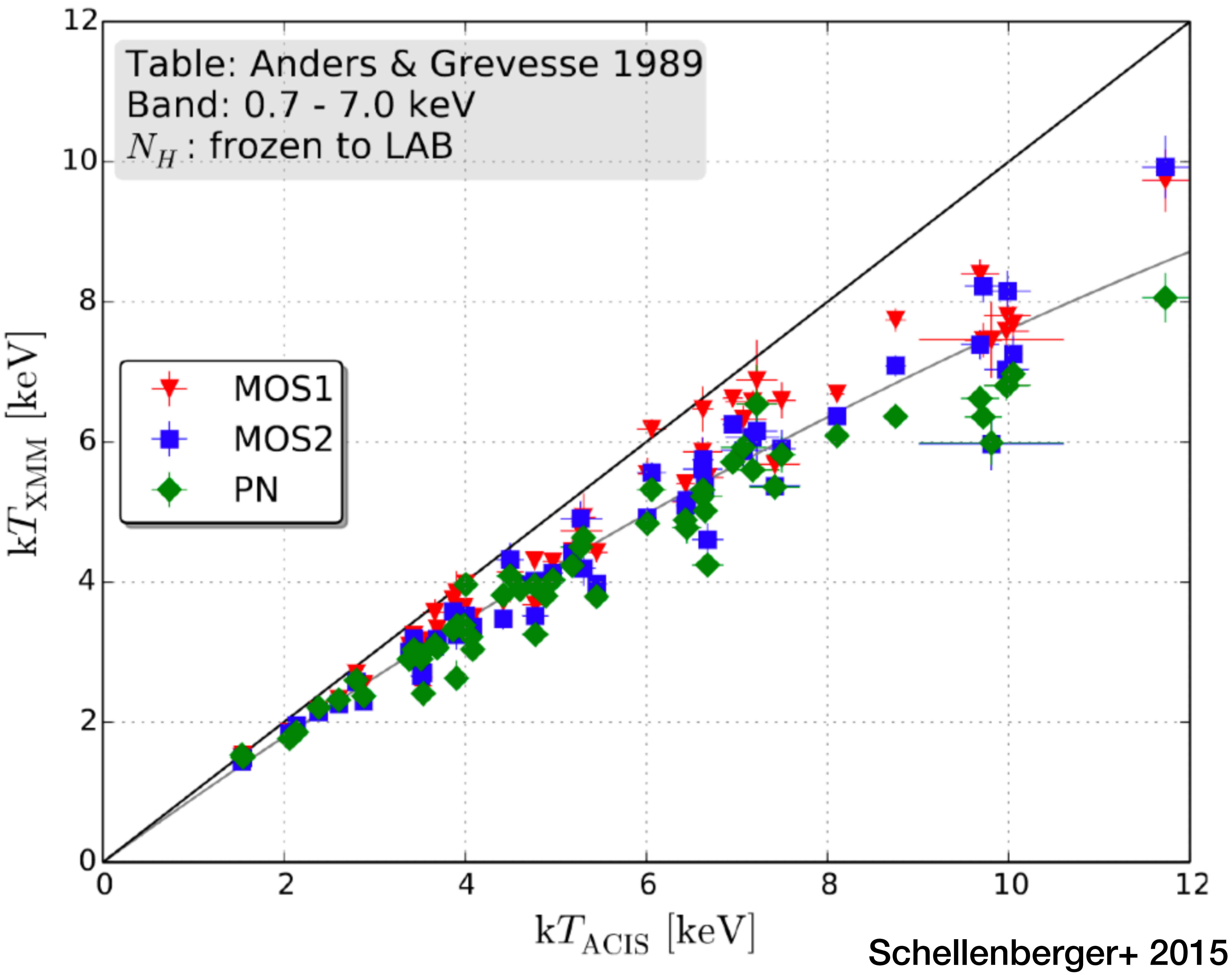
- *Chandra* full-band *kT*s are systematically higher than *XMM* full-band *kT*s, discrepancy increases with *T*
- *Chandra kT*s are consistent regardless of bandpass, while *XMM kT*s are not (agree with Chandra's at hard energies)
- *XMM* is inconsistent with itself (pn *kT*s lower than MOS *kT*s, no single *T* spectra even in a single instrument)



Schellenberger+ 2015

Challenges

- Signal highest at softer energies (less sensitive to kT, more sensitive to absorption and to a lesser extent abundances)
- Spatial variations, projection effects, sensitivity to the off-axis calibration (vignetting and PSF) all complicate analyses
- Clusters are faint



Schellenberger+ 2015

Hypothesis I: *Chandra* OK, *XMM-Newton* off

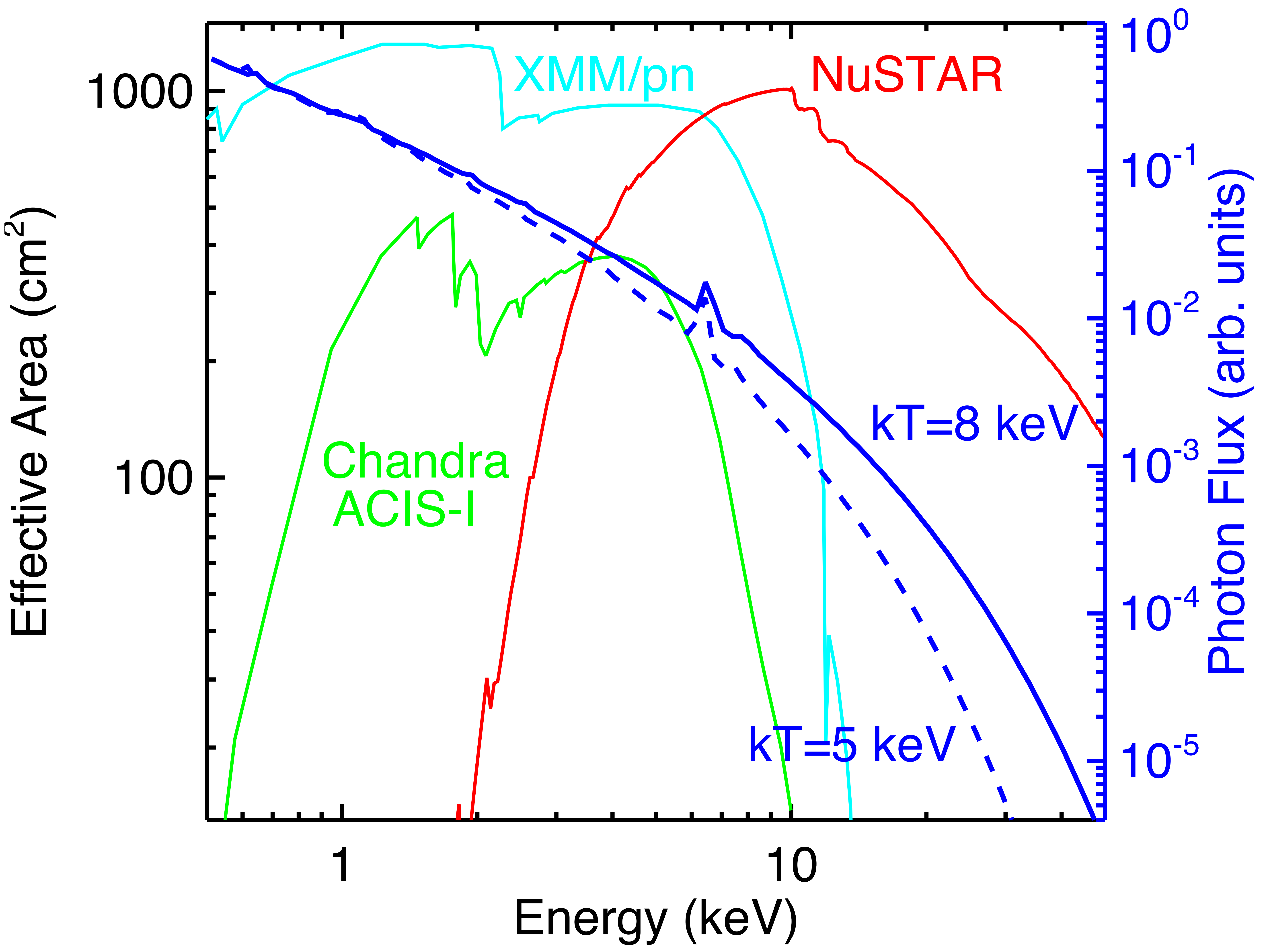
- *Chandra* self-consistent regardless of bandpass, *XMM-Newton* is not
- *XMM-Newton*'s 3 spectra-imaging telescopes give different answers
- Single temperature *XMM-Newton* fits that match hard band data in what should be roughly isothermal regions return excesses of ~20% in flux in the soft band

Prediction:

NuSTAR temperatures agree with both *Chandra* and *XMM-Newton* in the hard band, suggesting *Chandra* is well-calibrated and that *XMM-Newton* has issues at soft energies (but is correct at hard energies)

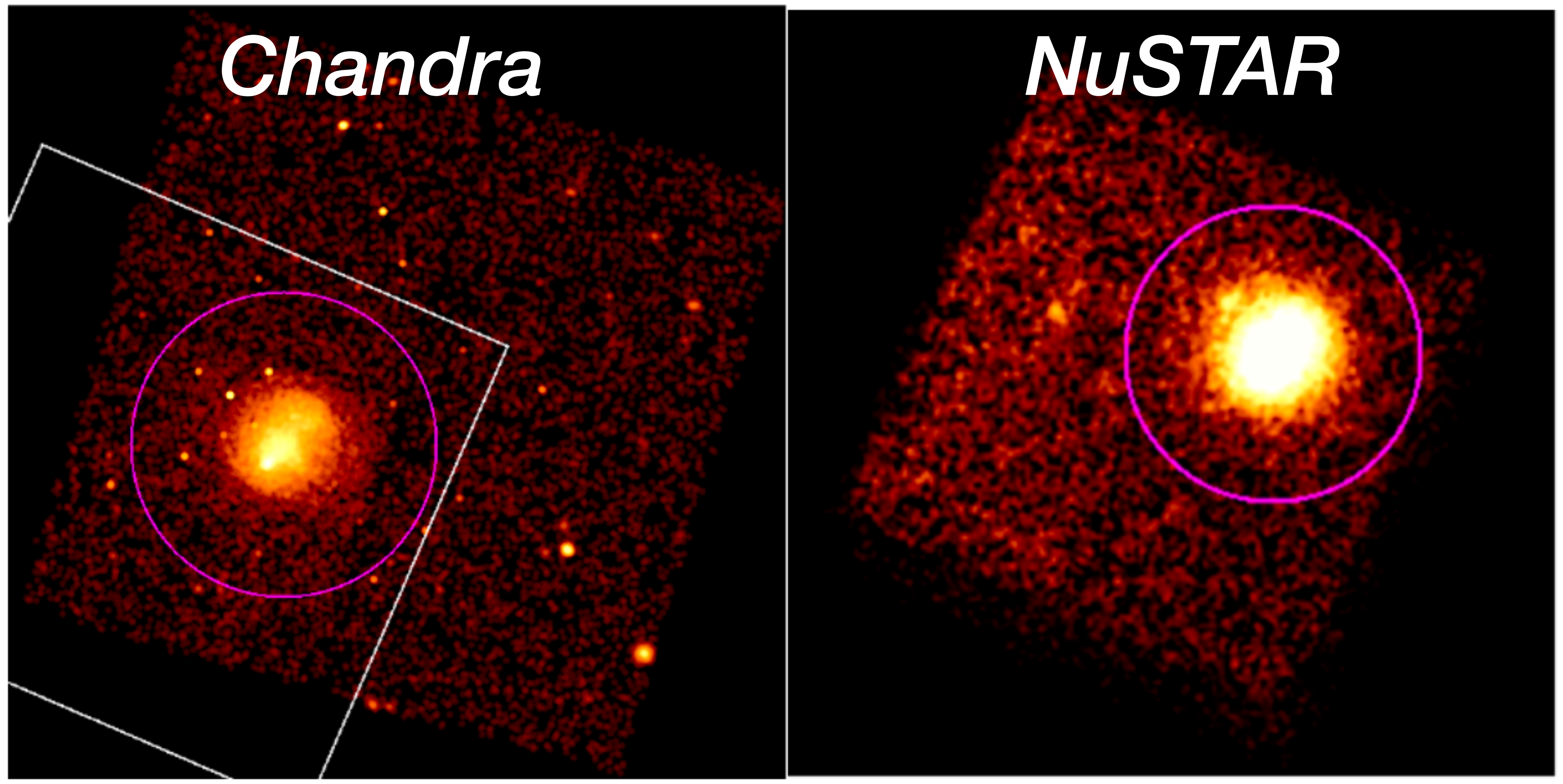
What's *NuSTAR*'s Contribution to this Issue?

- 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

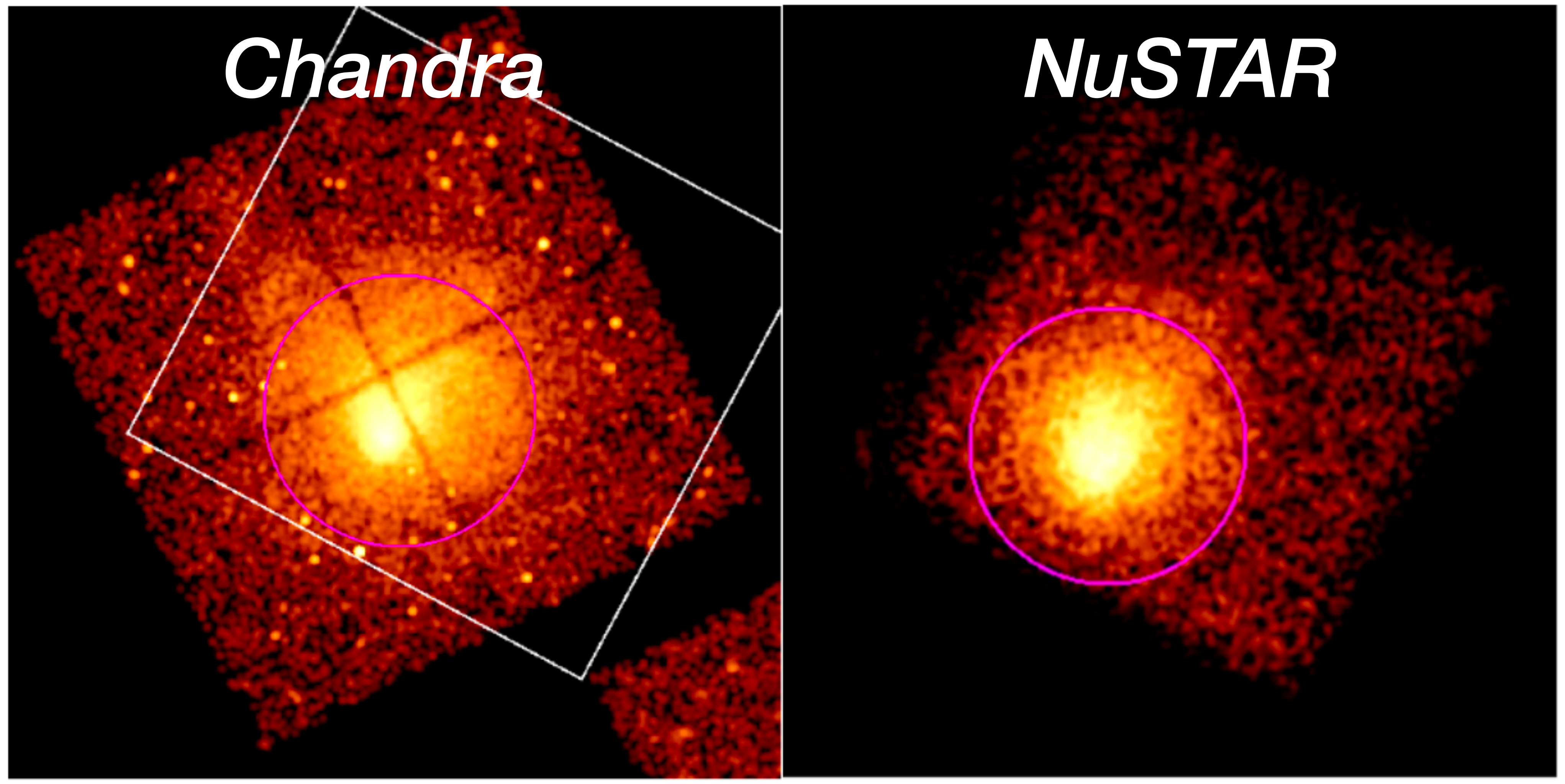


Global *kT* Measurements (*Chandra* vs. *NuSTAR*)

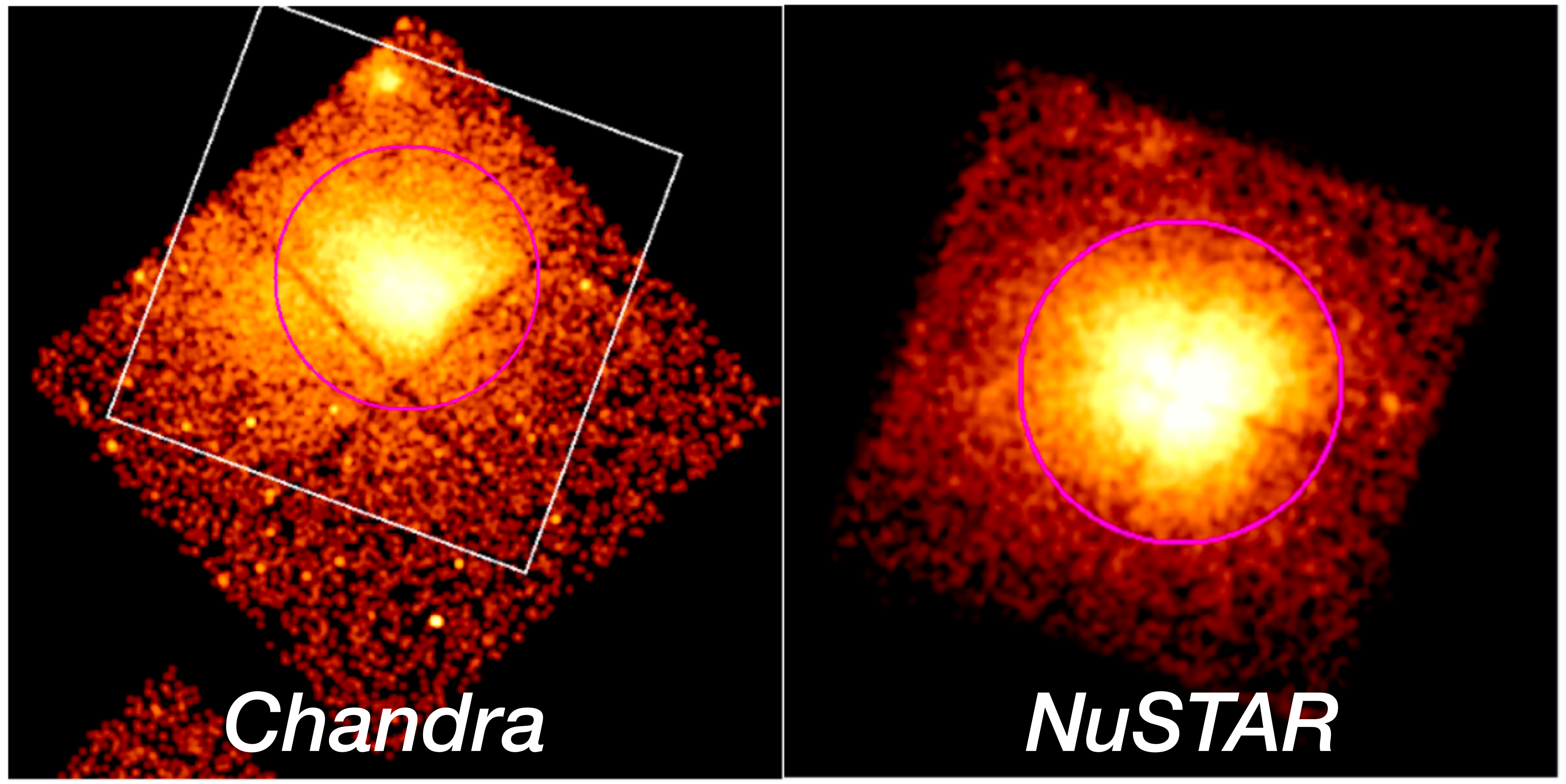
Wallbank+ 22



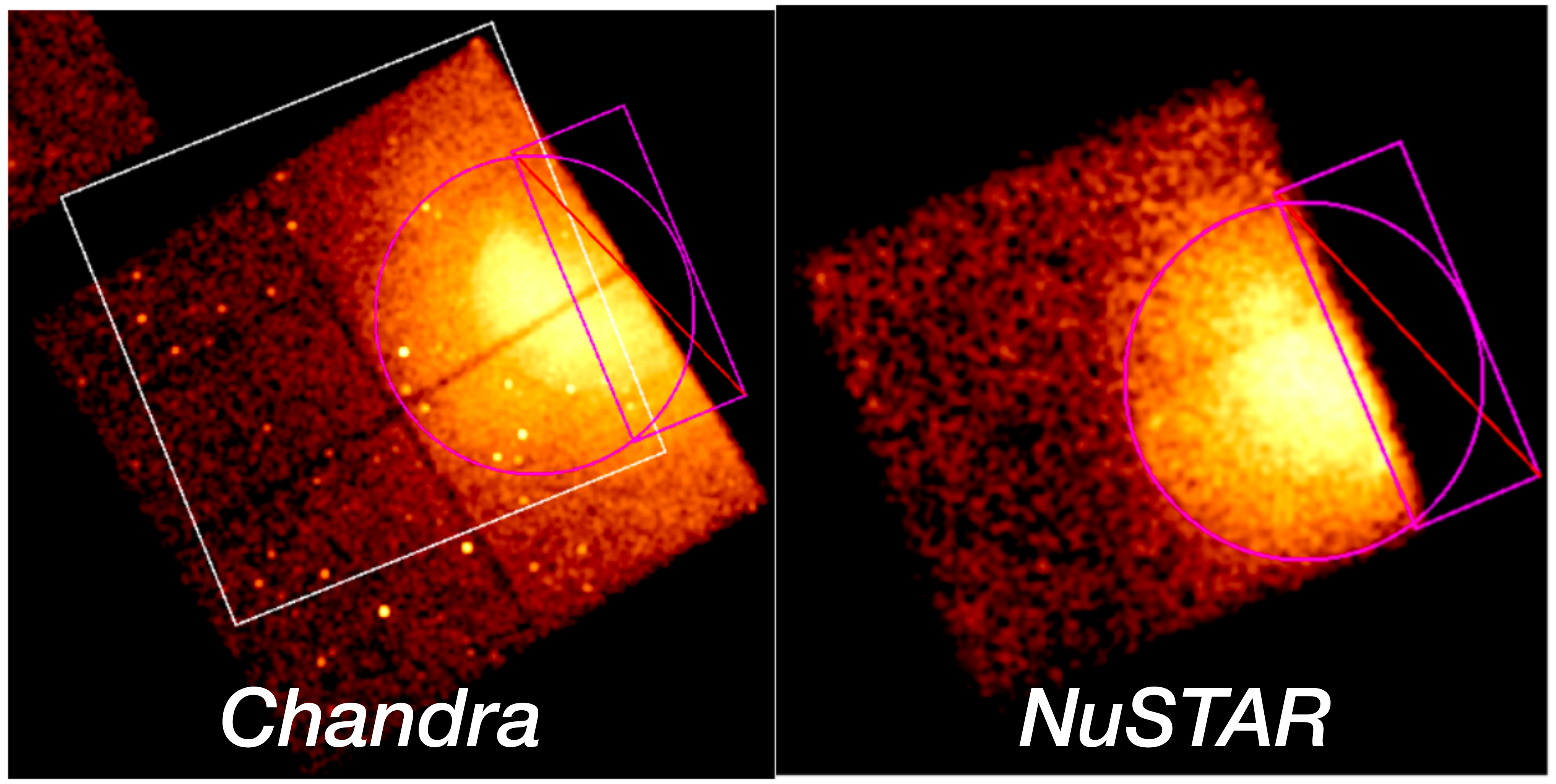
A2146



A665

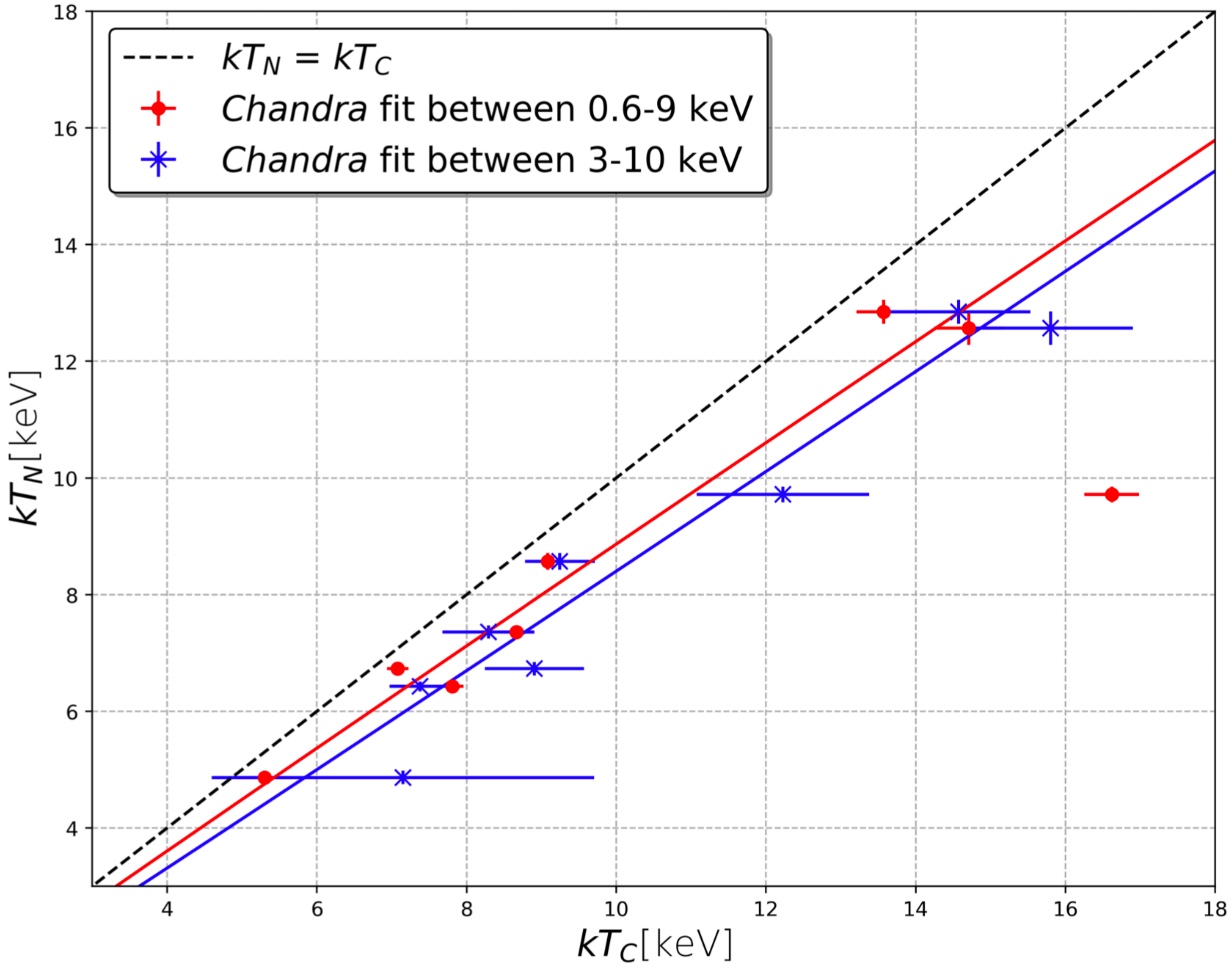


A2163



A754

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



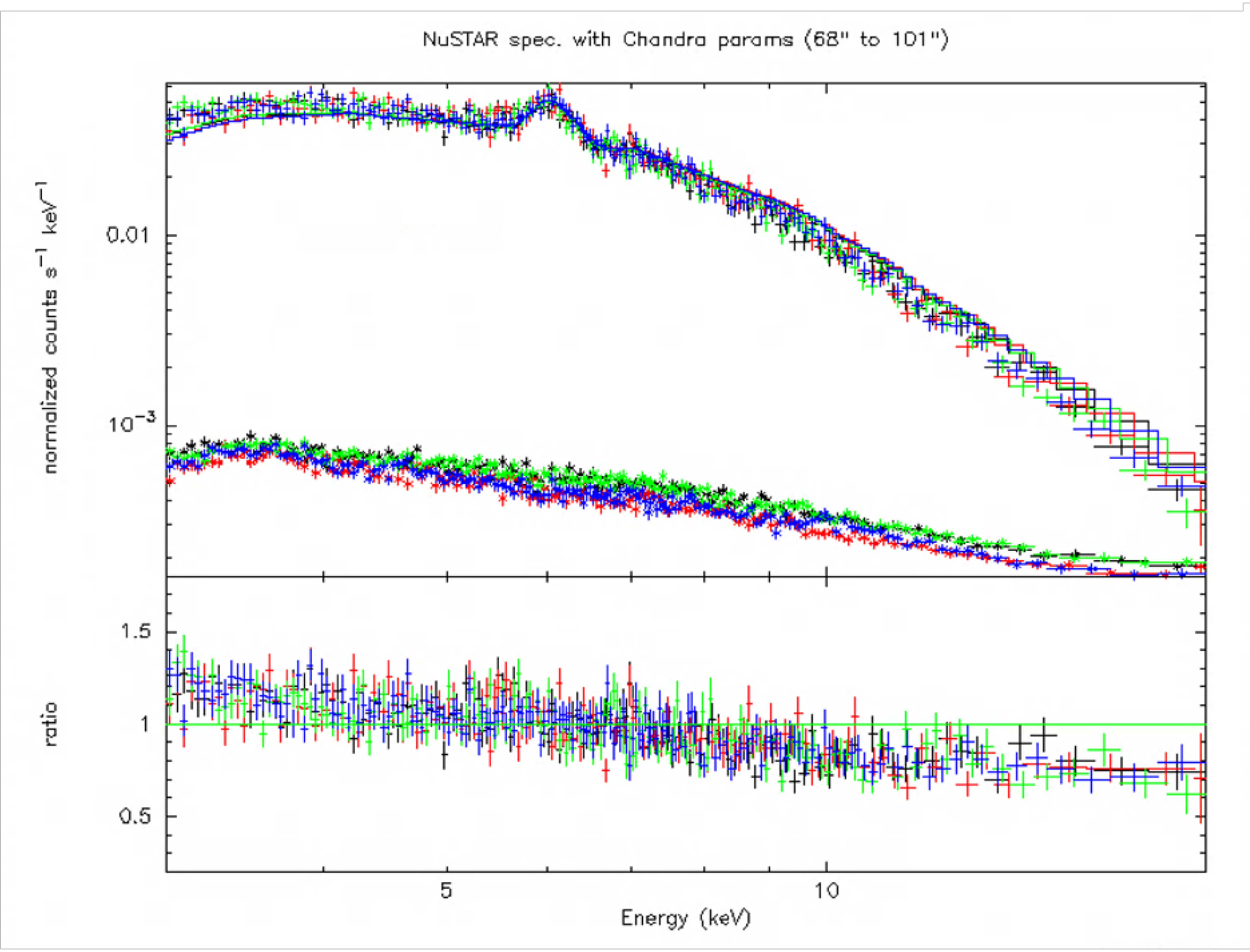
Cluster Name	$kT_{C,(0.6-9)}$ keV	kT_C keV	kT_N keV
Abell 2146	7.08 ± 0.14	8.9 ± 0.66	6.72 ± 0.11
Abell 2163	$16.36 \pm 0.70^{\dagger}$	12.23 ± 1.15	9.72 ± 0.13
Abell 2256	7.81 ± 0.15	7.38 ± 0.41	6.43 ± 0.085
Abell 523	5.30 ± 0.36	7.15 ± 2.55	4.87 ± 0.12
Abell 665	8.66 ± 0.23	8.29 ± 0.62	7.36 ± 0.11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

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

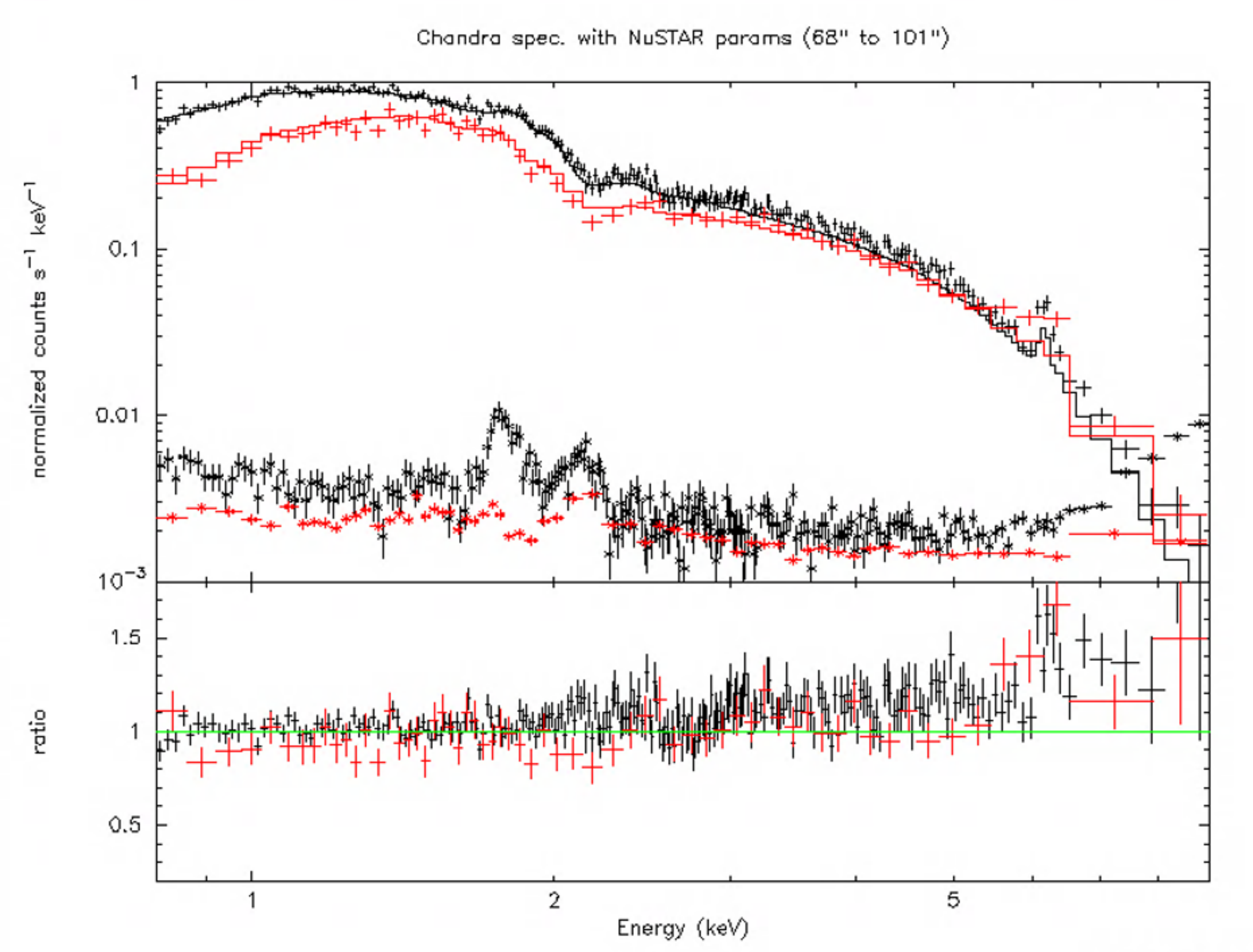
Physically, *NuSTAR* should be biased to *higher kT*s —> must be due to (mis)calibration

Wallbank+ 22

Chandra - *NuSTAR* Comparison

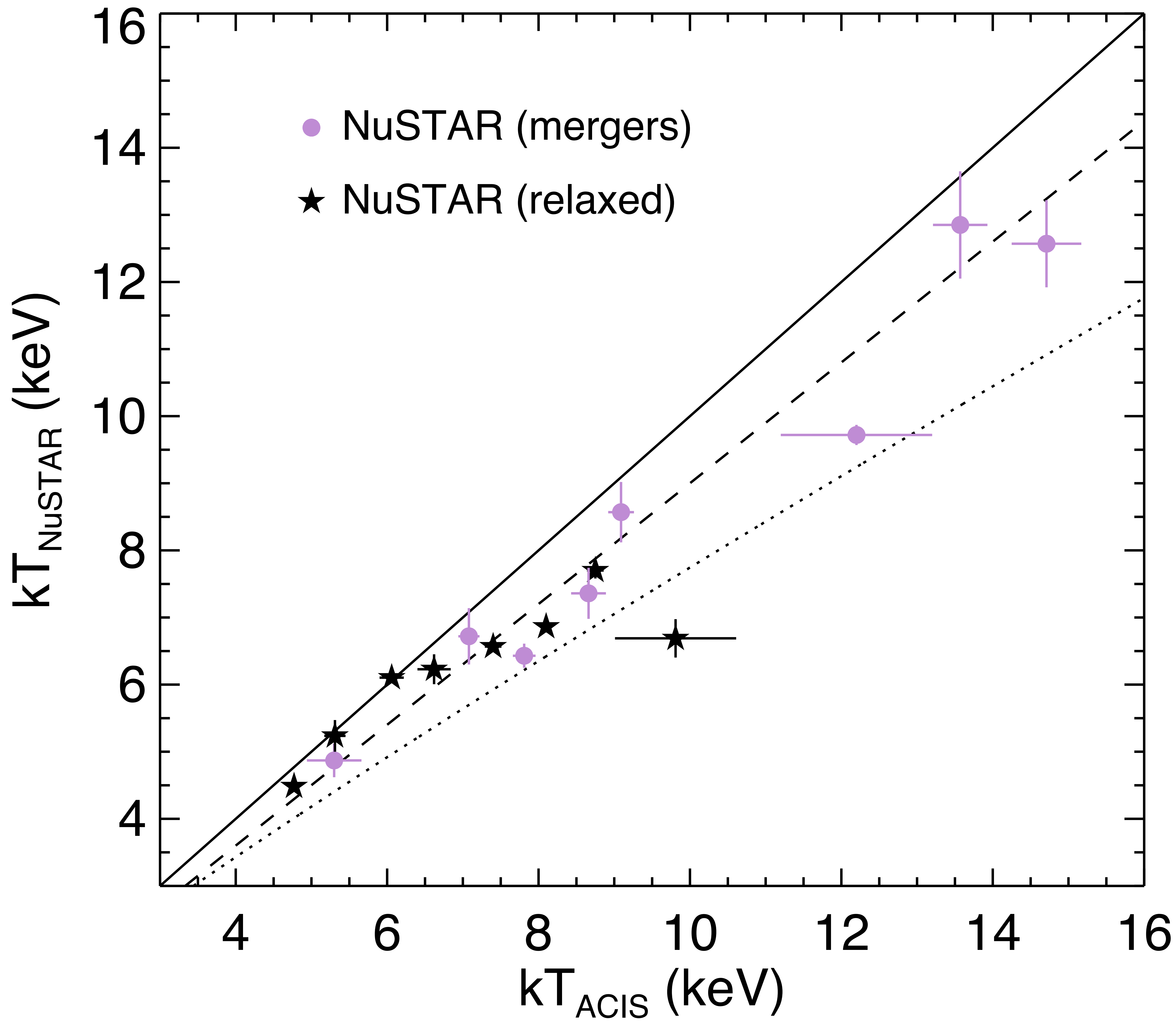


NuSTAR data with *Chandra* best-fit model
C-stat/dof: 3006/1567



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

Cross-calibration with Relaxed Clusters



***NuSTAR* Large Program (>100 ks each)**

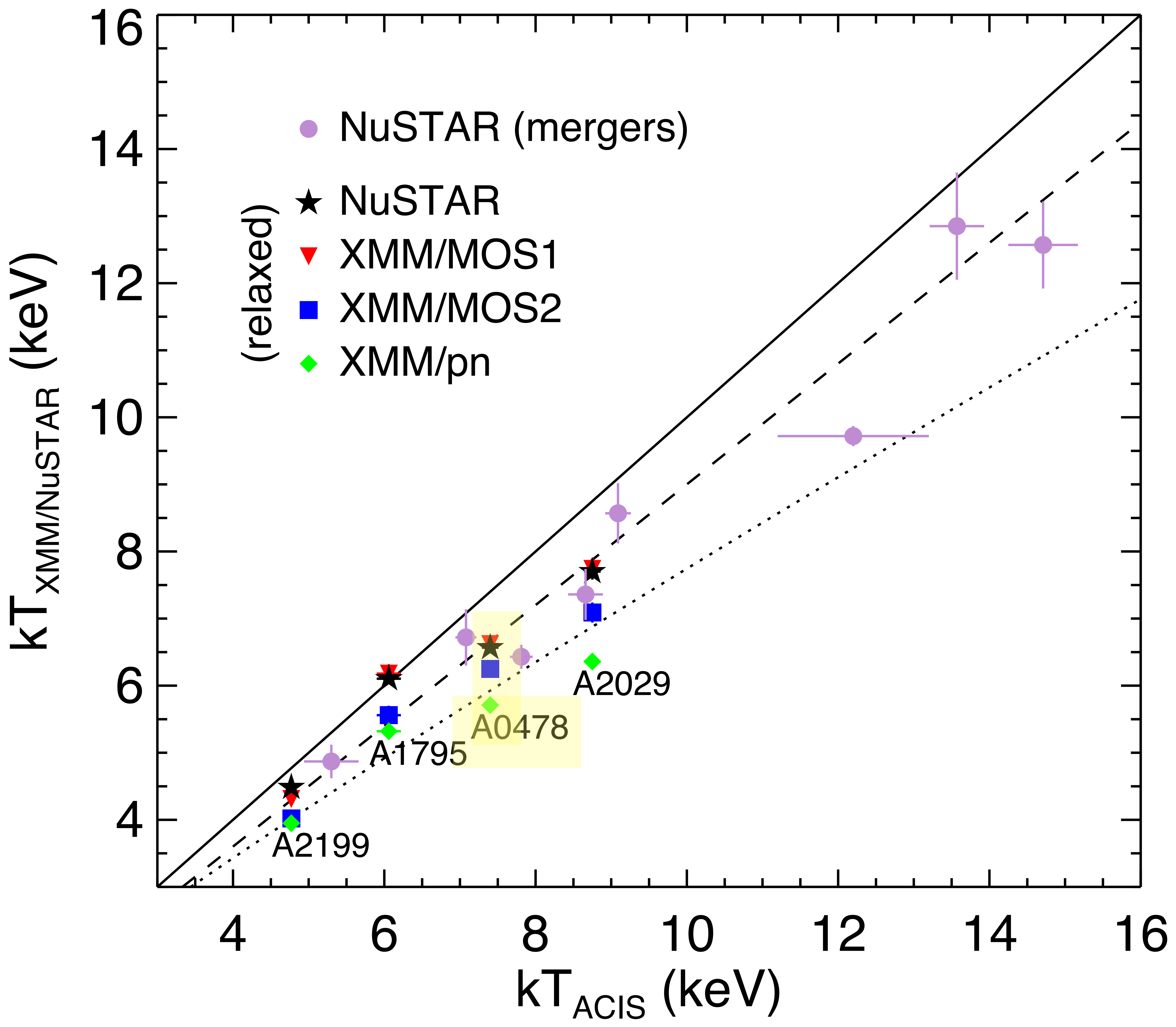
Cluster	kT (keV)	z
Abell 2029	8.5	0.077
Abell 478	7.3	0.088
Abell 1795	6.1	0.062
Abell 2199	4.4	0.030

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

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

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

Cross-calibration with Relaxed Clusters

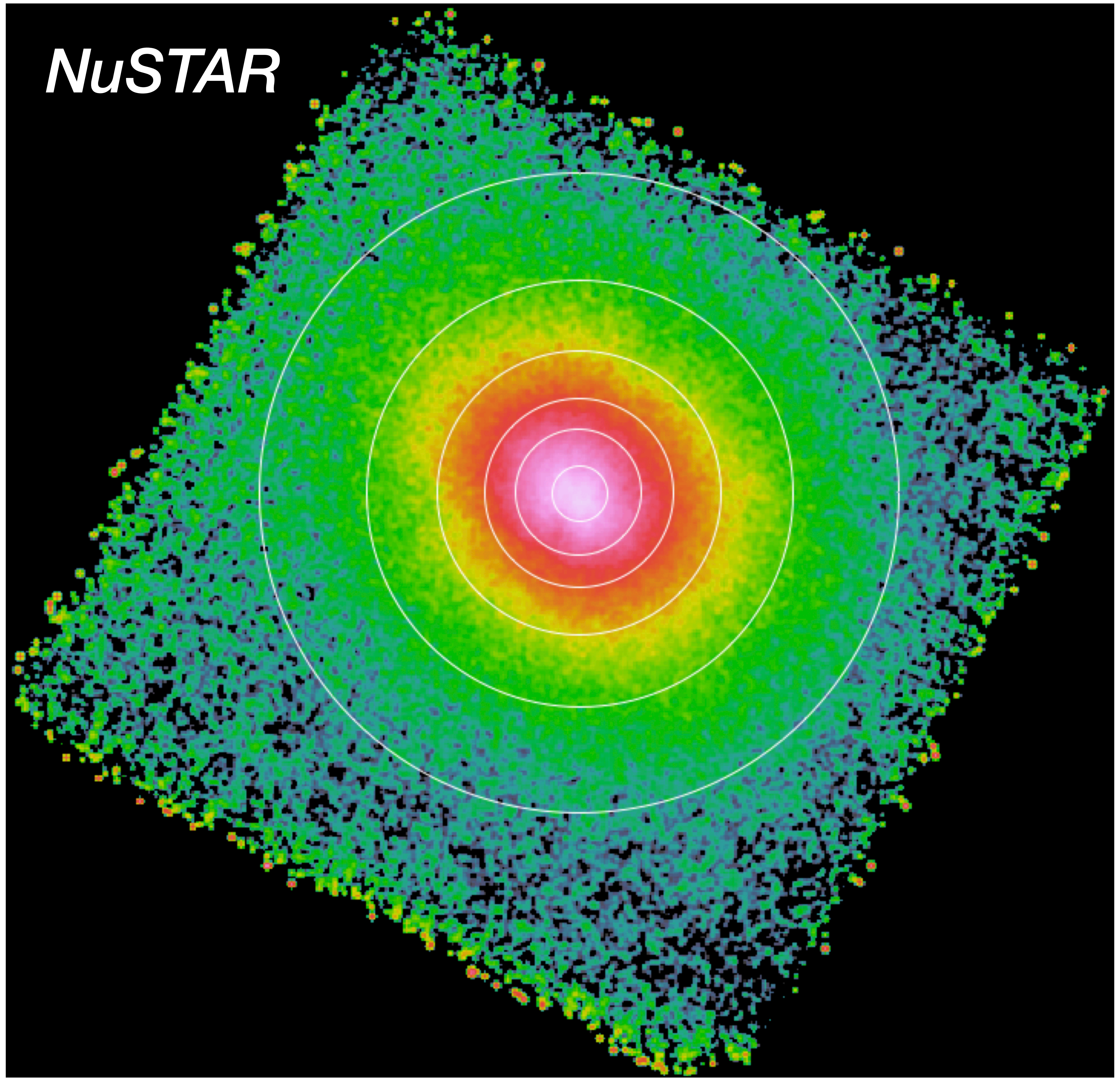


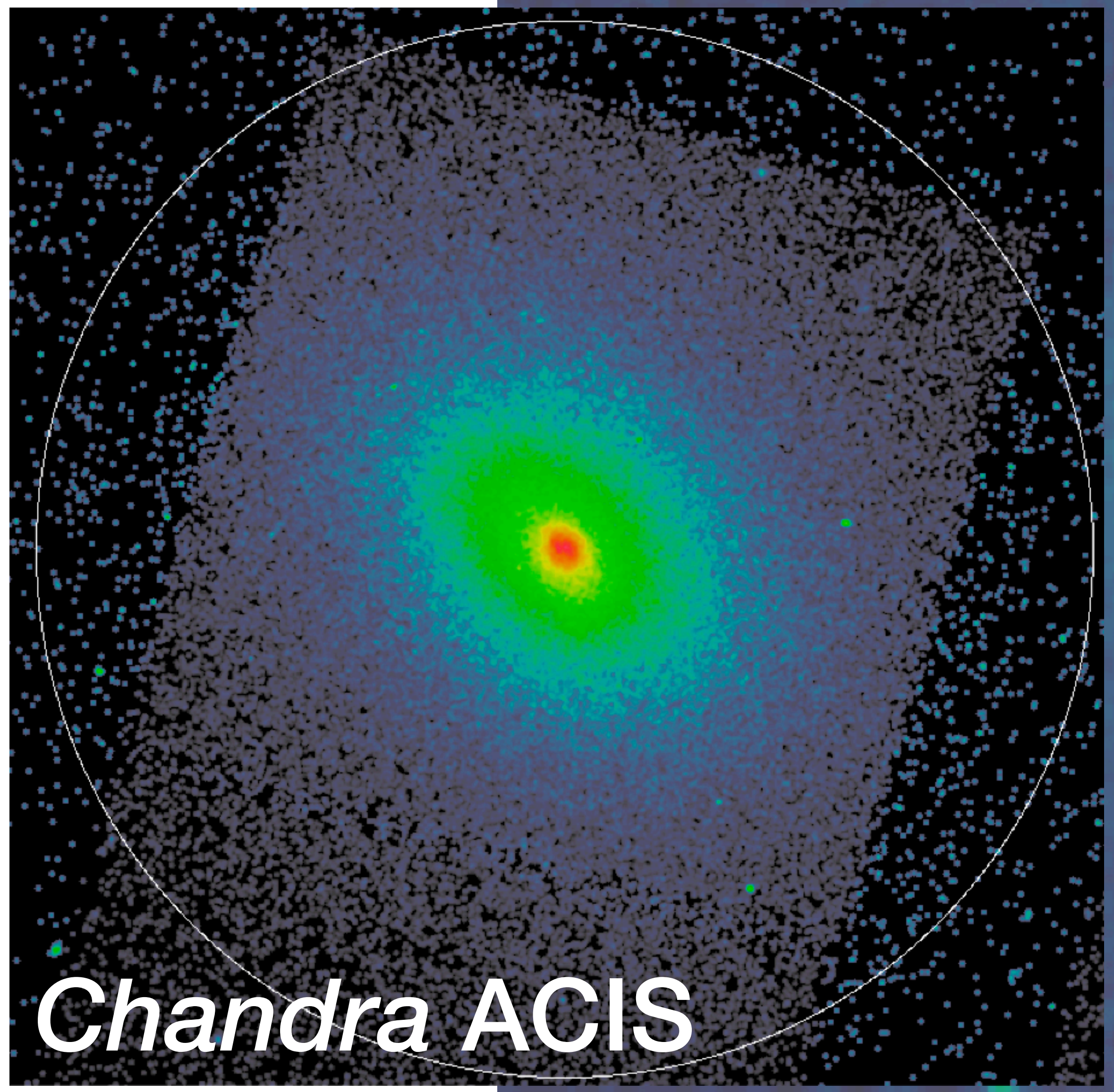
Large *NuSTAR* Program

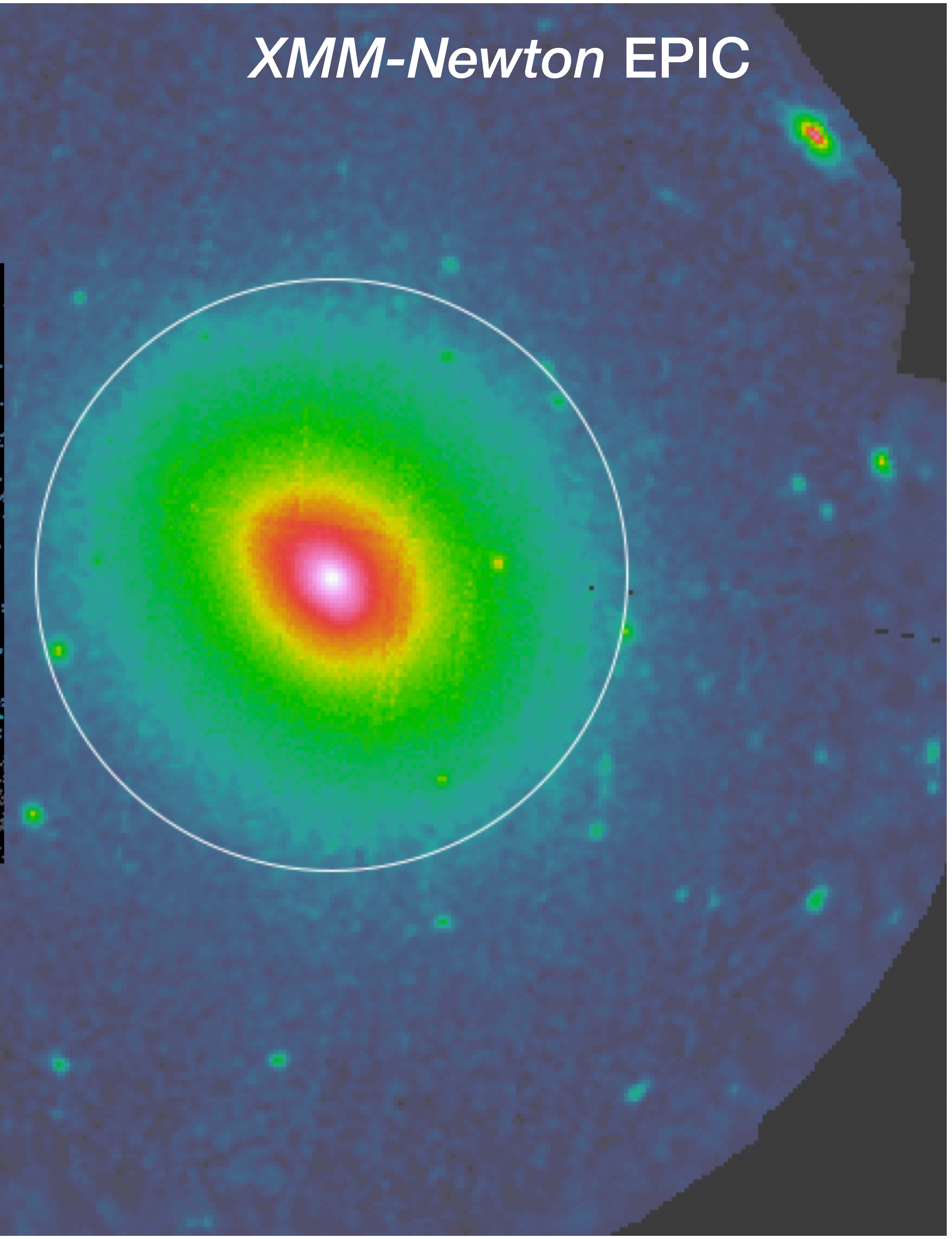
Cluster	kT (keV)	z
Abell 2029	8.5	0.077
Abell 478	7.3	0.088
Abell 1795	6.1	0.062
Abell 2199	4.4	0.030

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

NuSTAR/Chandra/XMM-Newton of Abell 478

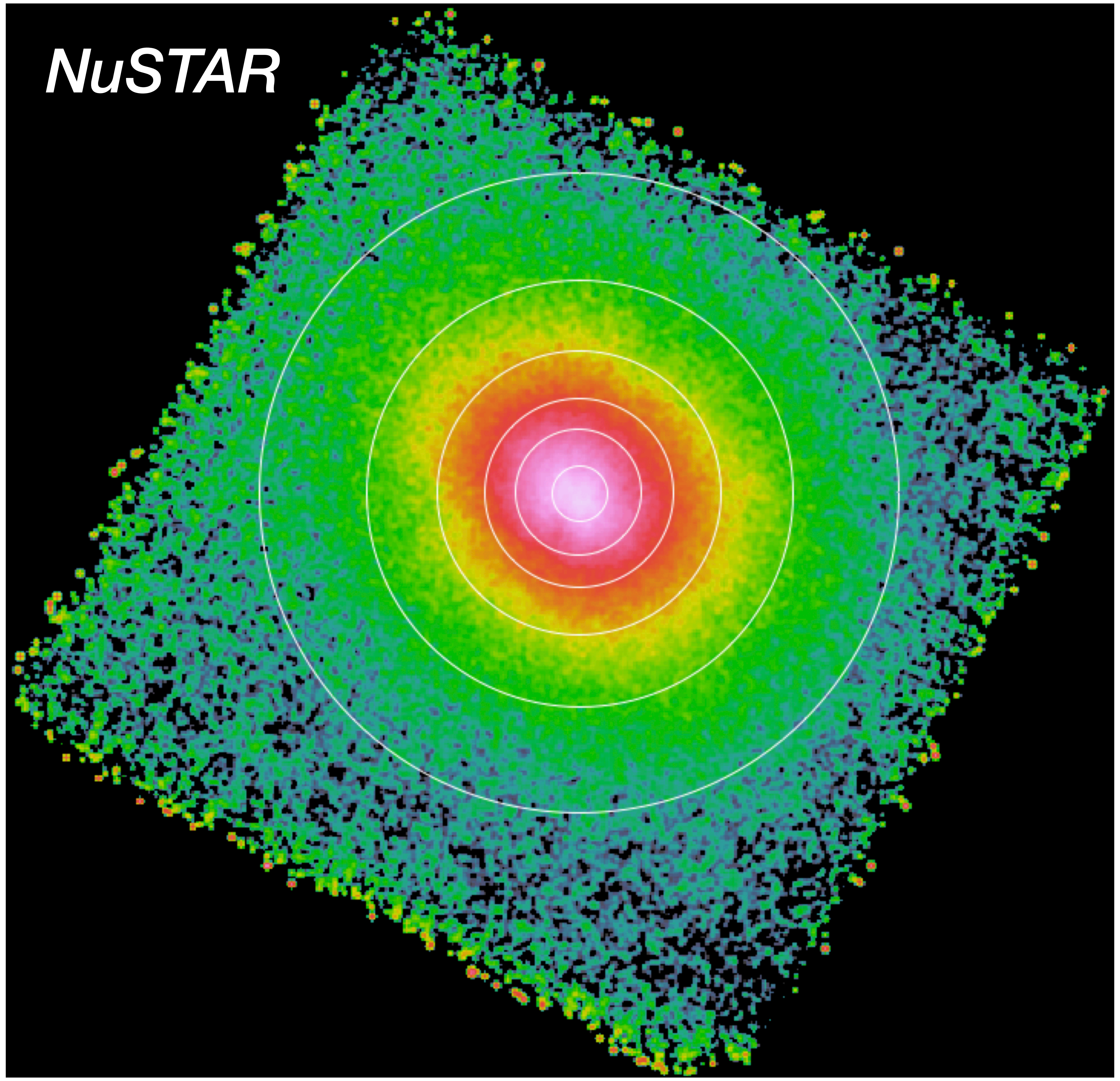






Potter+ in prep
(Submit next week or so)

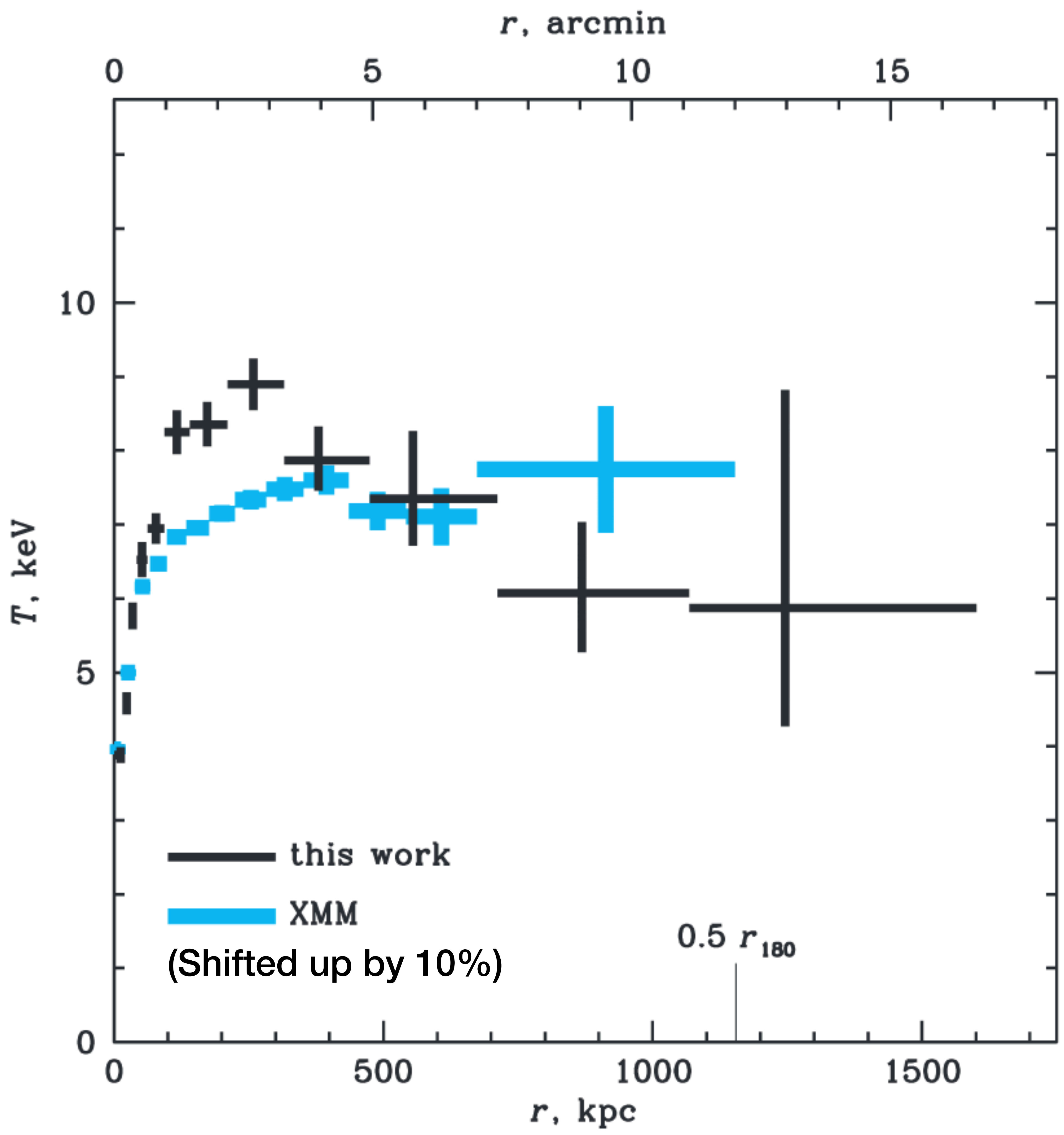
NuSTAR/Chandra/XMM-Newton of Abell 478



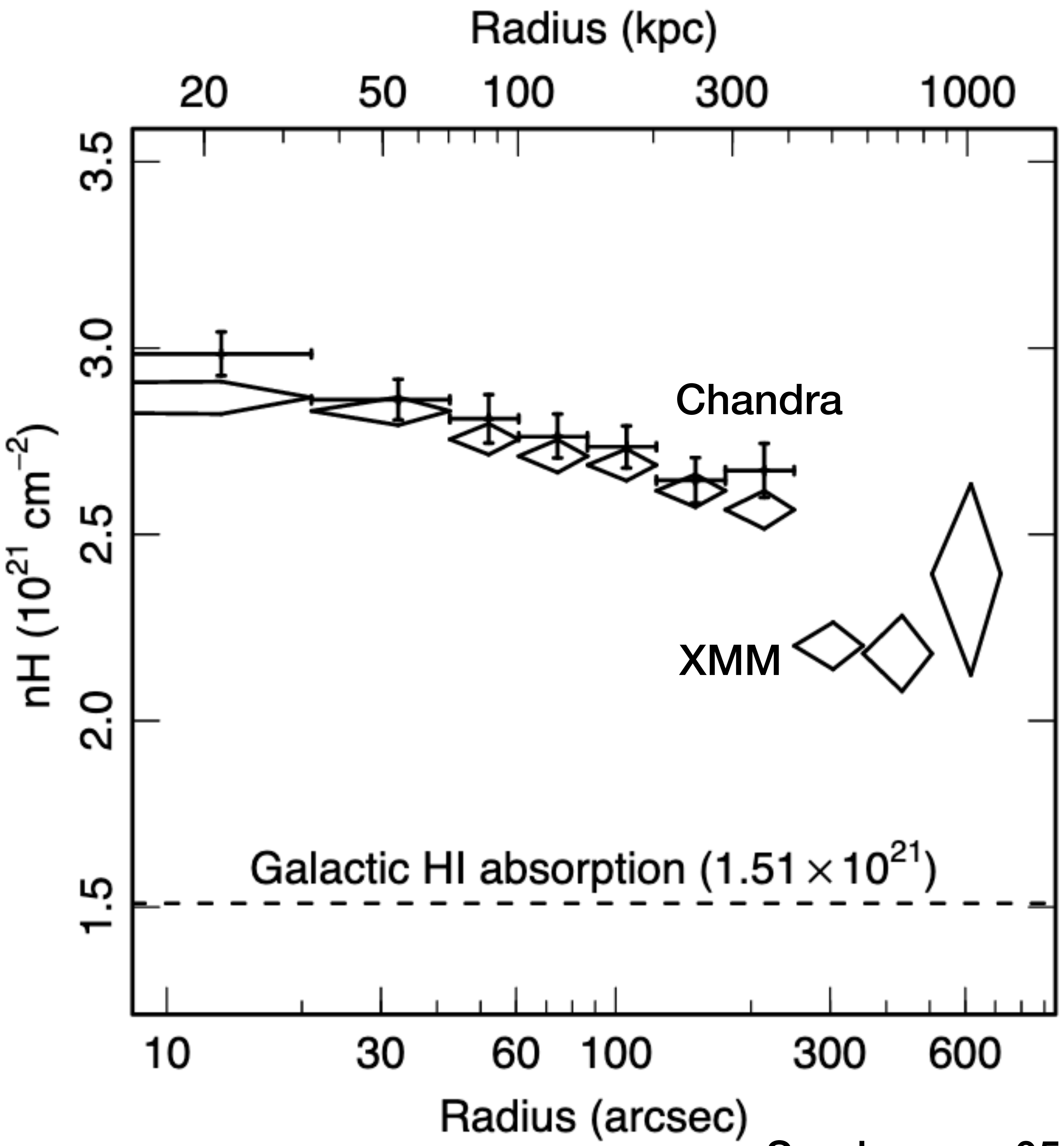
Potter+ in prep
(Submit next week or so)

- 6 annuli with roughly constant S/N, but keeping minimum widths for *NuSTAR* PSF
- Extract spectra from same regions in *Chandra* & *XMM-Newton*
- In *NuSTAR*, need to account for photons scattered between regions due to the large (~1’ HPD) PSF
- In *Chandra* & *XMM-Newton*, need to treat foreground absorption with care

Chandra & XMM-Newton kT Profiles

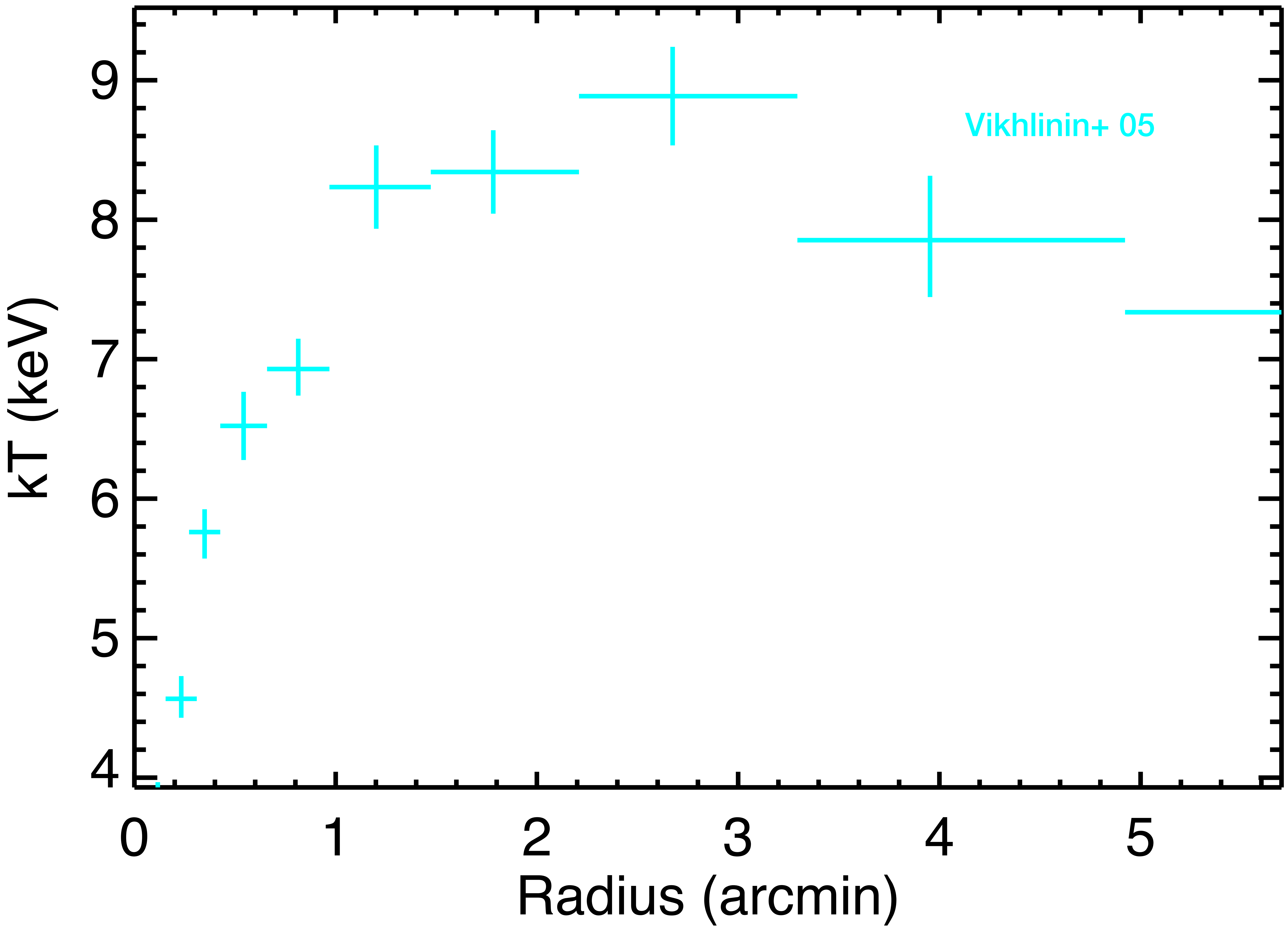


Vikhlinin+ 05, Pointecouteau+ 04

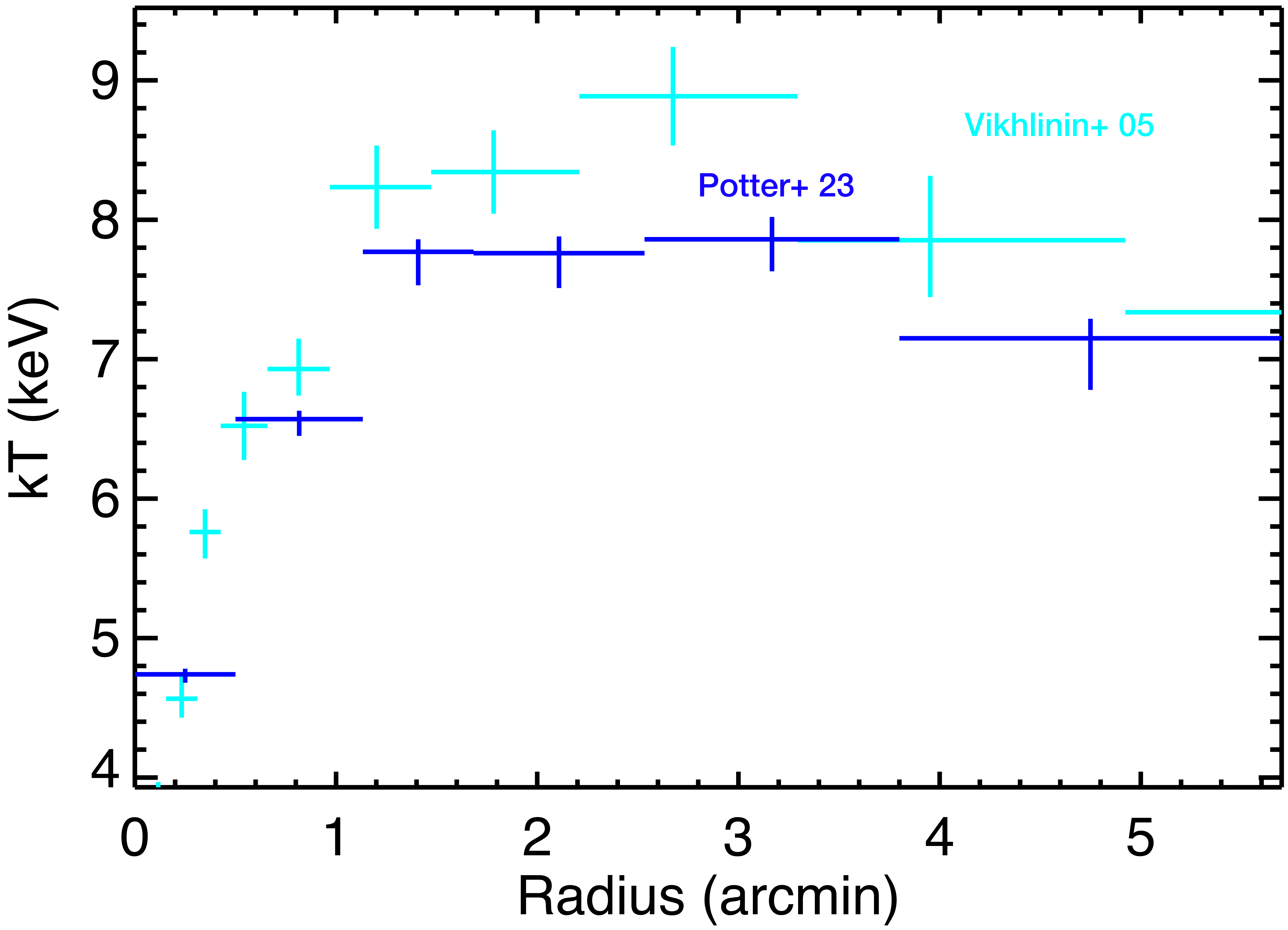


Sanderson+ 05

A478: *Chandra* kT Profiles



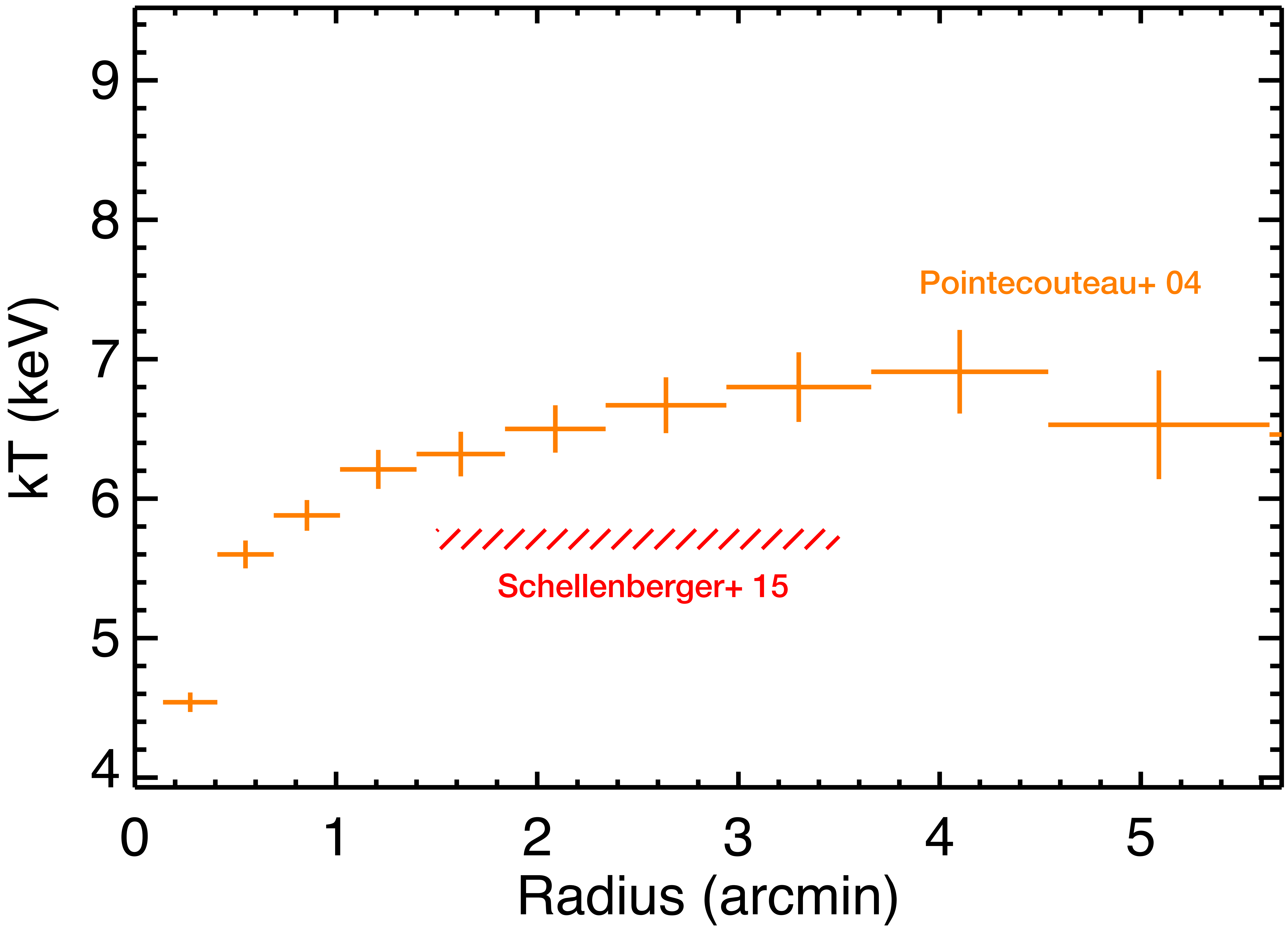
A478: *Chandra* kT Profiles



New fit includes ACIS-S observation and uses `TBabs` and `wilm` abundances

Also, calibration has been updated…
Hmm…
once or twice in the past 18 years

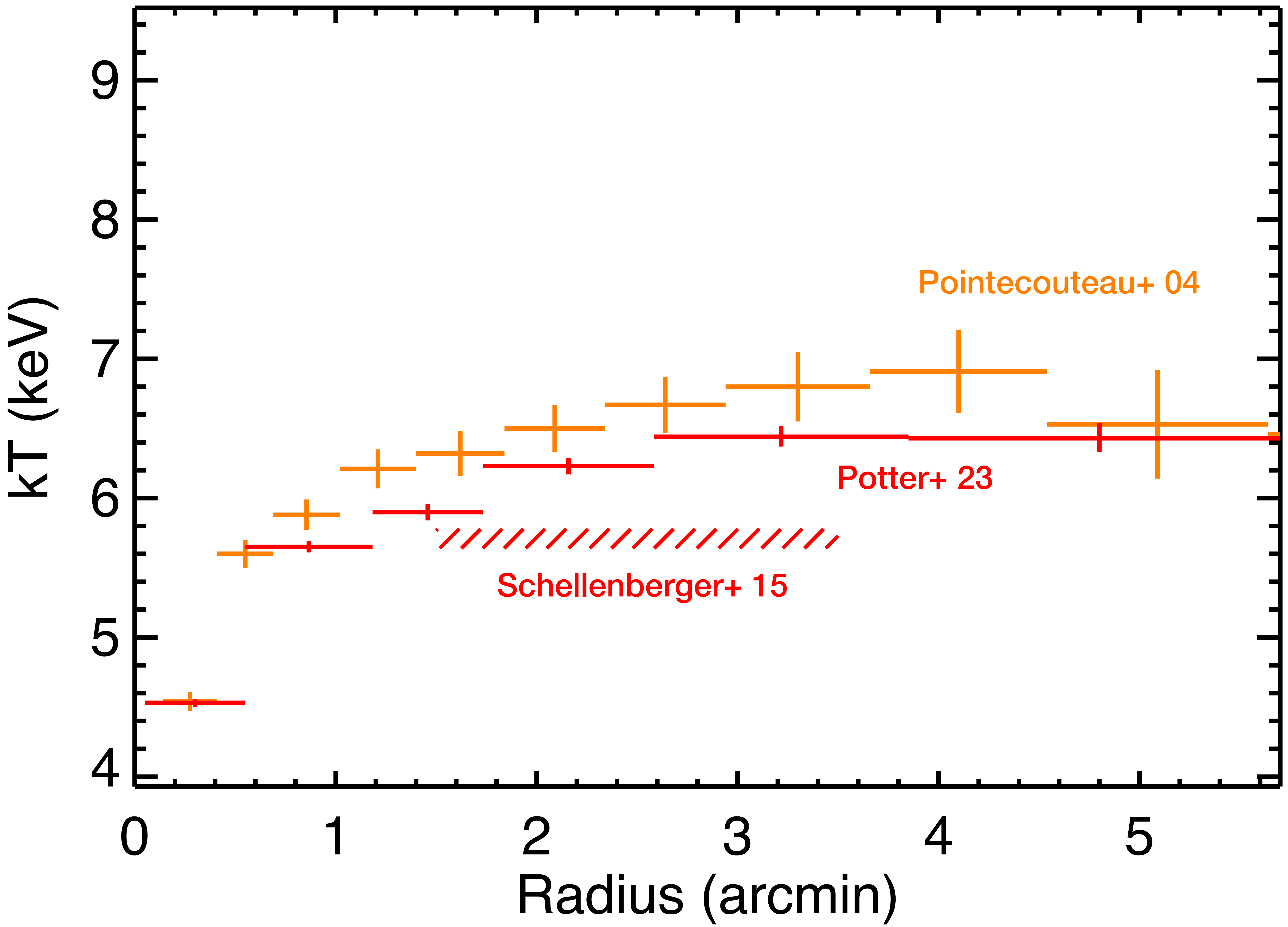
A478: *XMM-Newton* kT Profiles



Schellenberger kT for EPIC-pn

Pointecouteau kTs joint EPIC fit using `wabs` with free n_H

A478: *XMM-Newton* kT Profiles

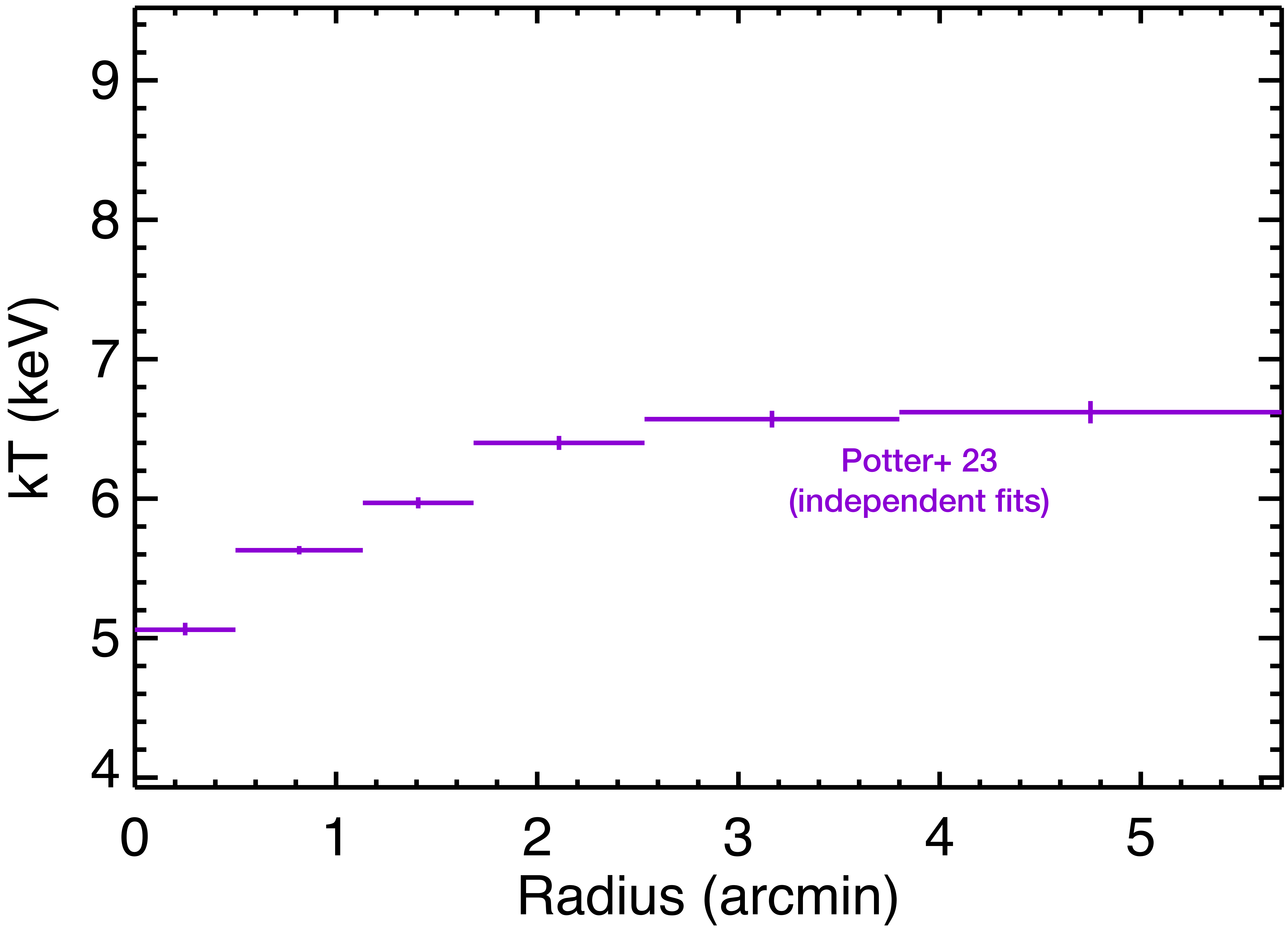


Schellenberger kT for EPIC-pn

Pointecouteau kTs joint EPIC fit using `wabs` with free n_H

Two ARF corrections:
`applyabsfluxcorr=yes`
`applyxcaladjusment=yes`
ESAS fitting using `TBabs` and `wilm` abundances with free n_H

A478: *NuSTAR* kT Profiles

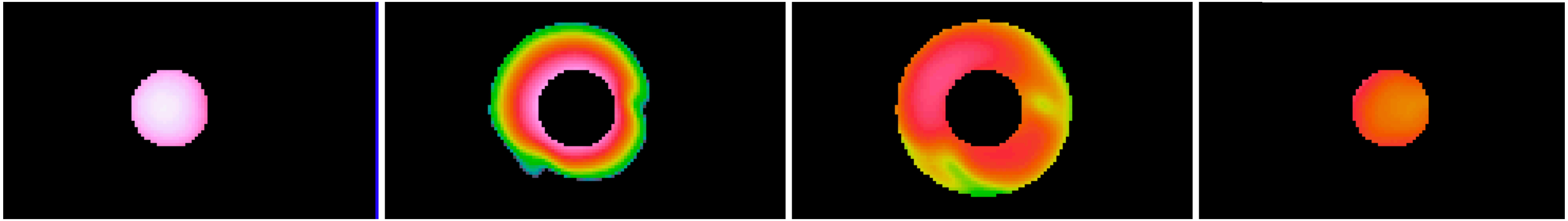


Region-by-region independent fitting using `TBabs` and `wilm` abundances with free n_H

NuSTAR PSF Correction Using “Cross-ARFs”

Equivalent to ARF produced by nuproducts

Equivalent to ARF produced by nuproducts



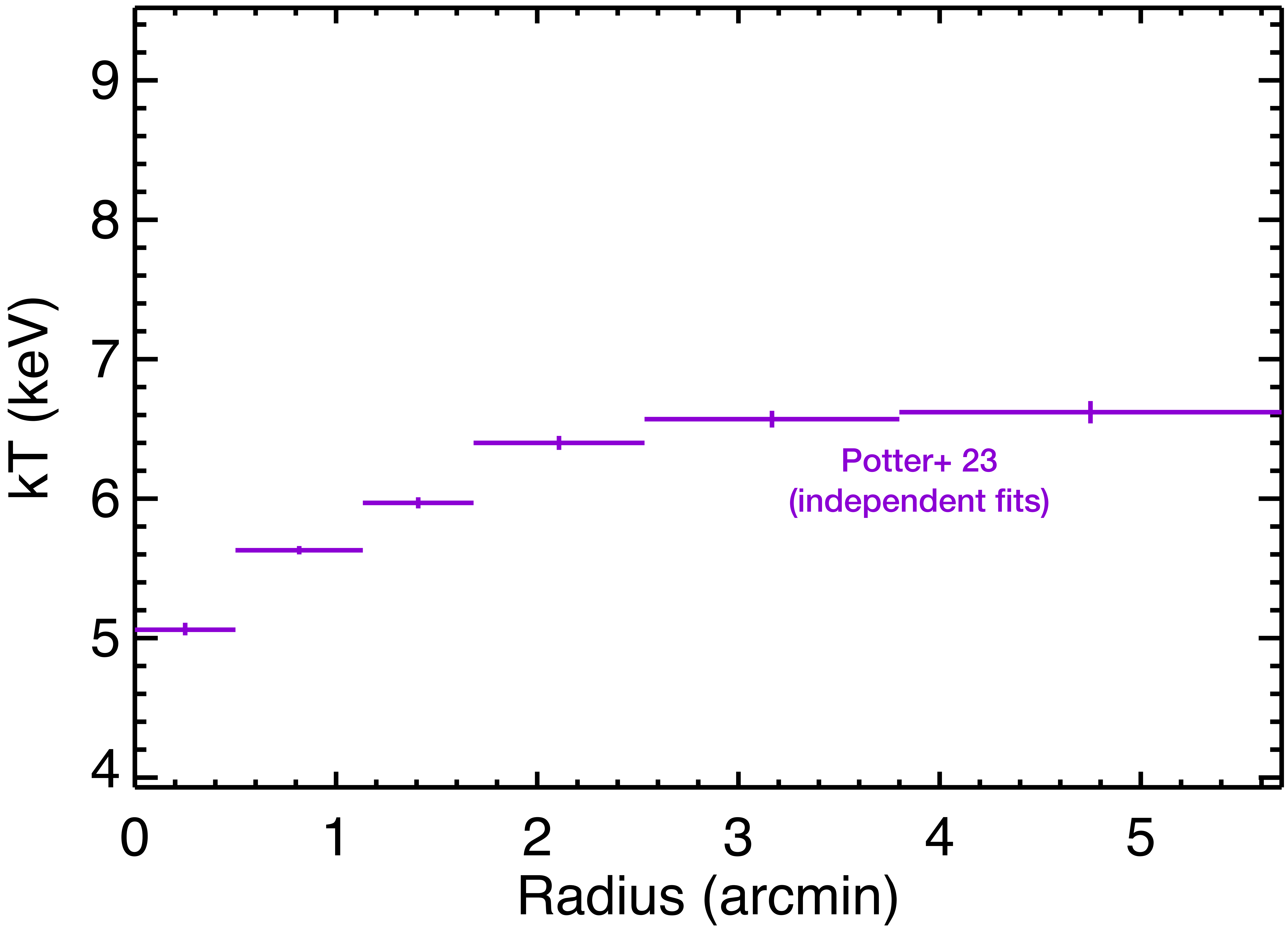
Emission inside Annulus 1, modulated by the PSF, creating a weighted ARF

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

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

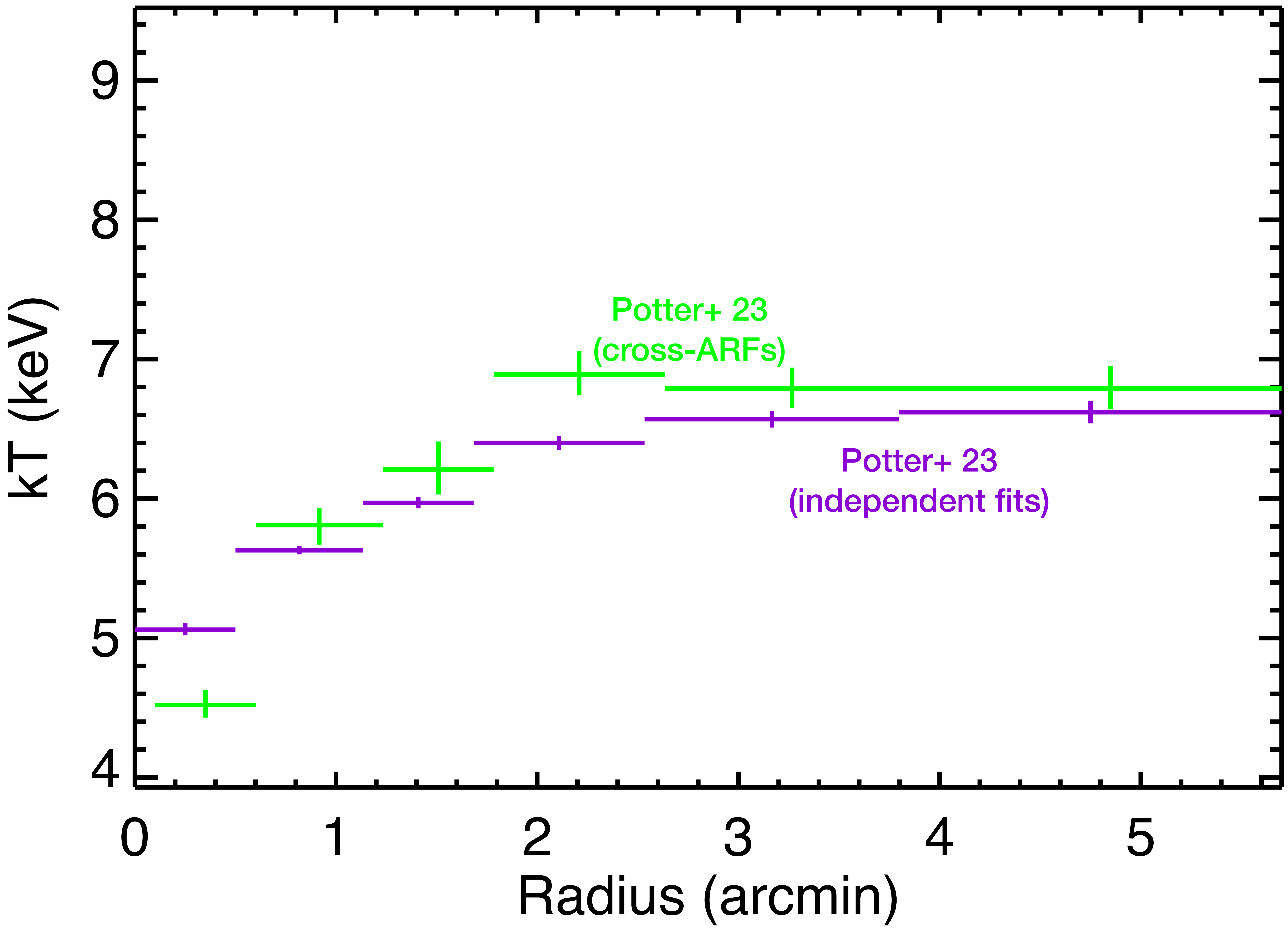
Emission scattered from Annulus 2 into Annulus 1 by the PSF, creating a weighted cross-ARF

A478: *NuSTAR* kT Profiles



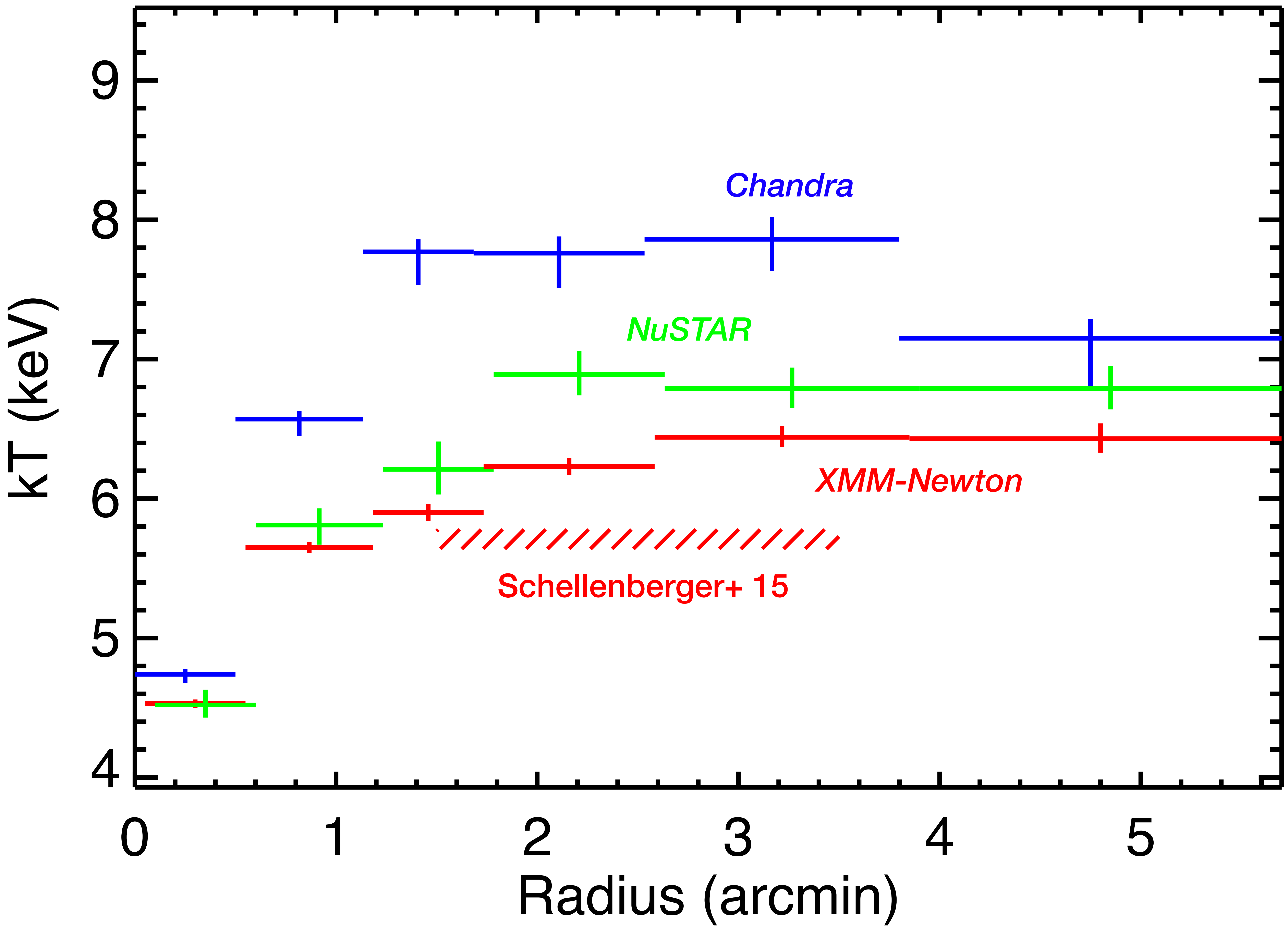
Region-by-region independent fitting using `TBabs` and `wilm` abundances with free n_H

A478: *NuSTAR* kT Profiles



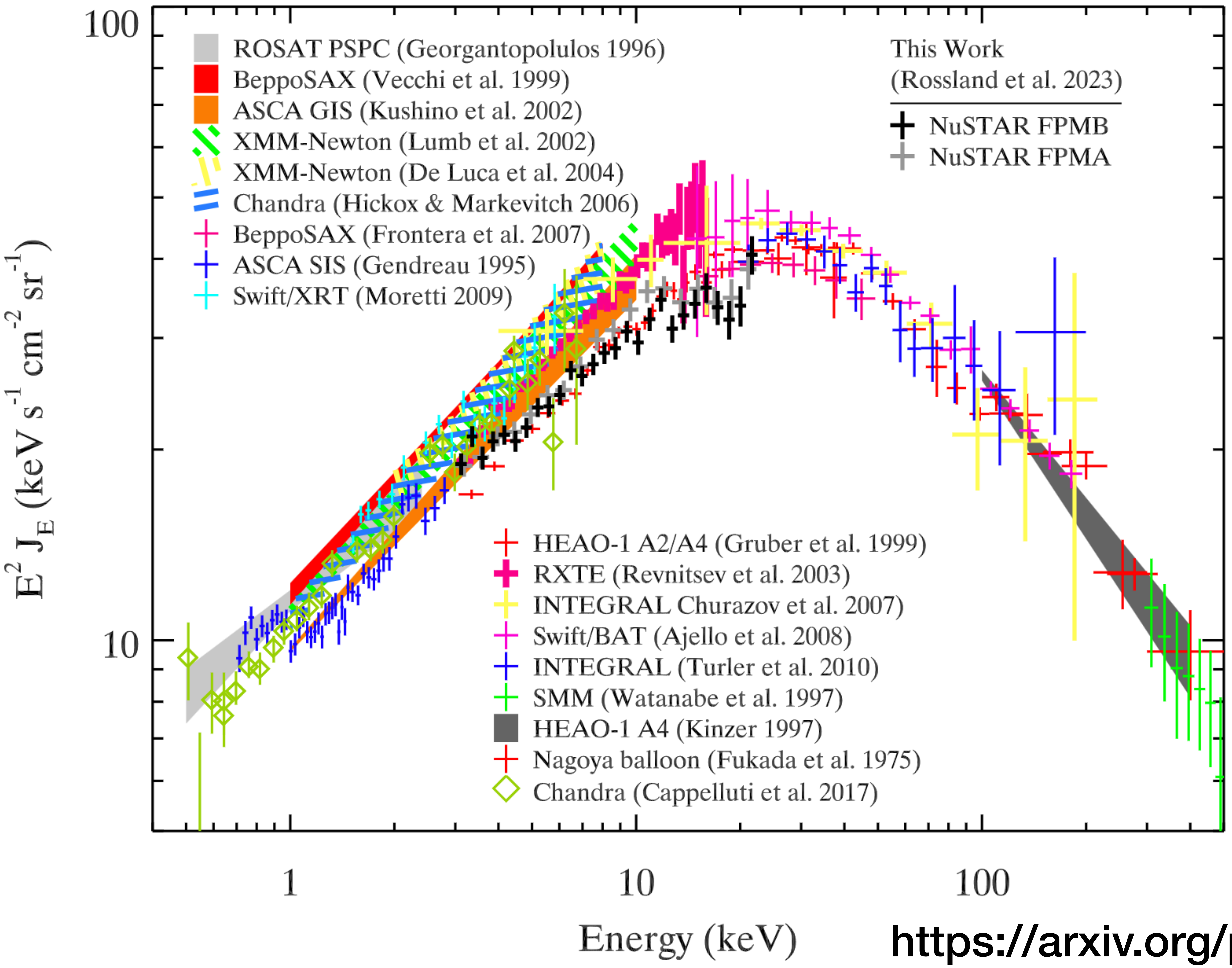
Region-by-region independent fitting using `TBabs` and `wilm` abundances with free n_H

A478: kT Profiles



Potter+ in prep
(Submit next week or so)

CXB Measurement Consistent



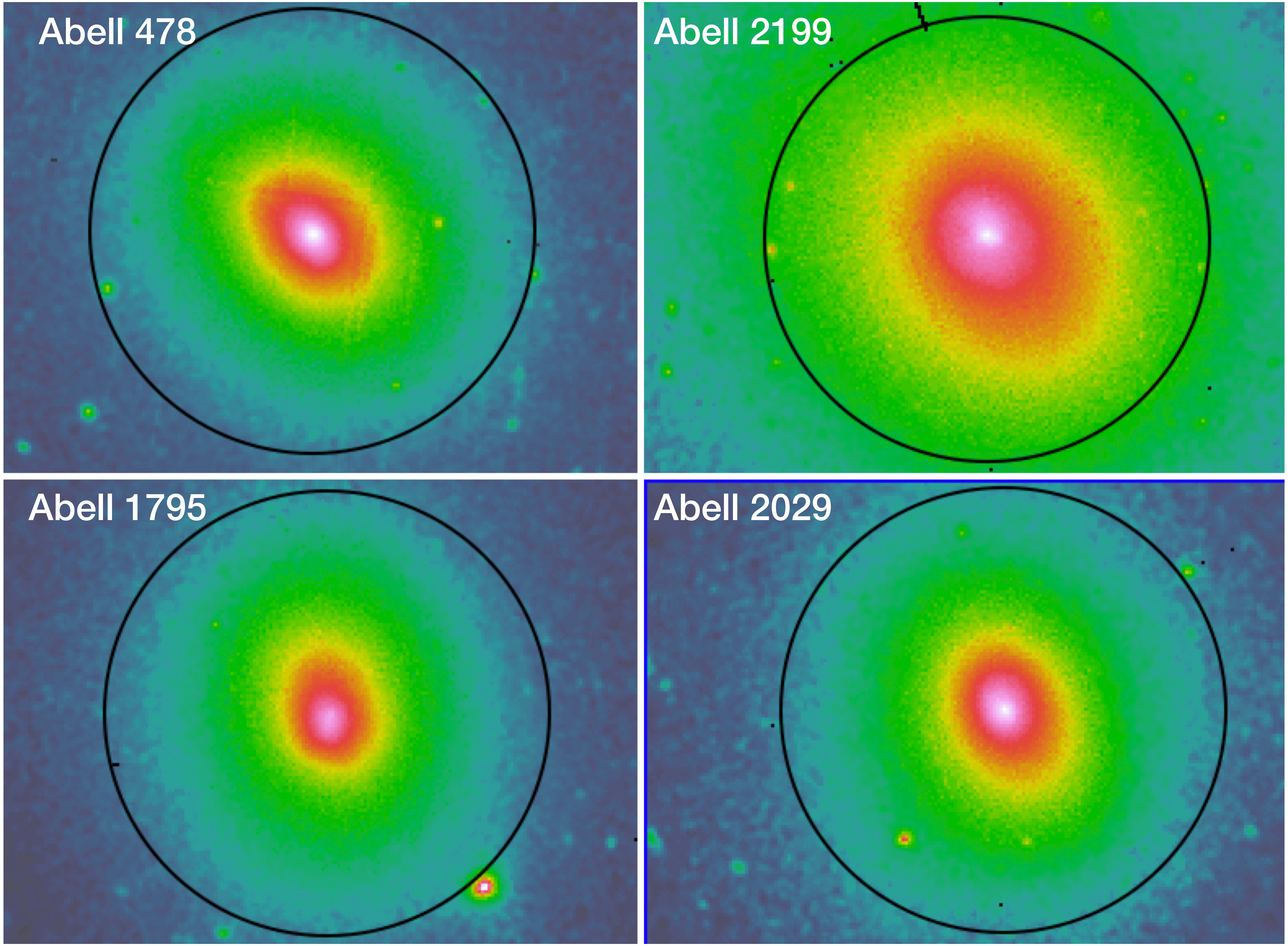
https://arxiv.org/pdf/2304.07962.pdf

Hypothesis II: *Chandra* off, *XMM-Newton* OK

- Expect *NuSTAR* kTs to be same or higher, never lower
- *Chandra* kTs all above *NuSTAR*'s kTs in A478 annuli
- *XMM-Newton* kTs all equal or below *NuSTAR* kTs

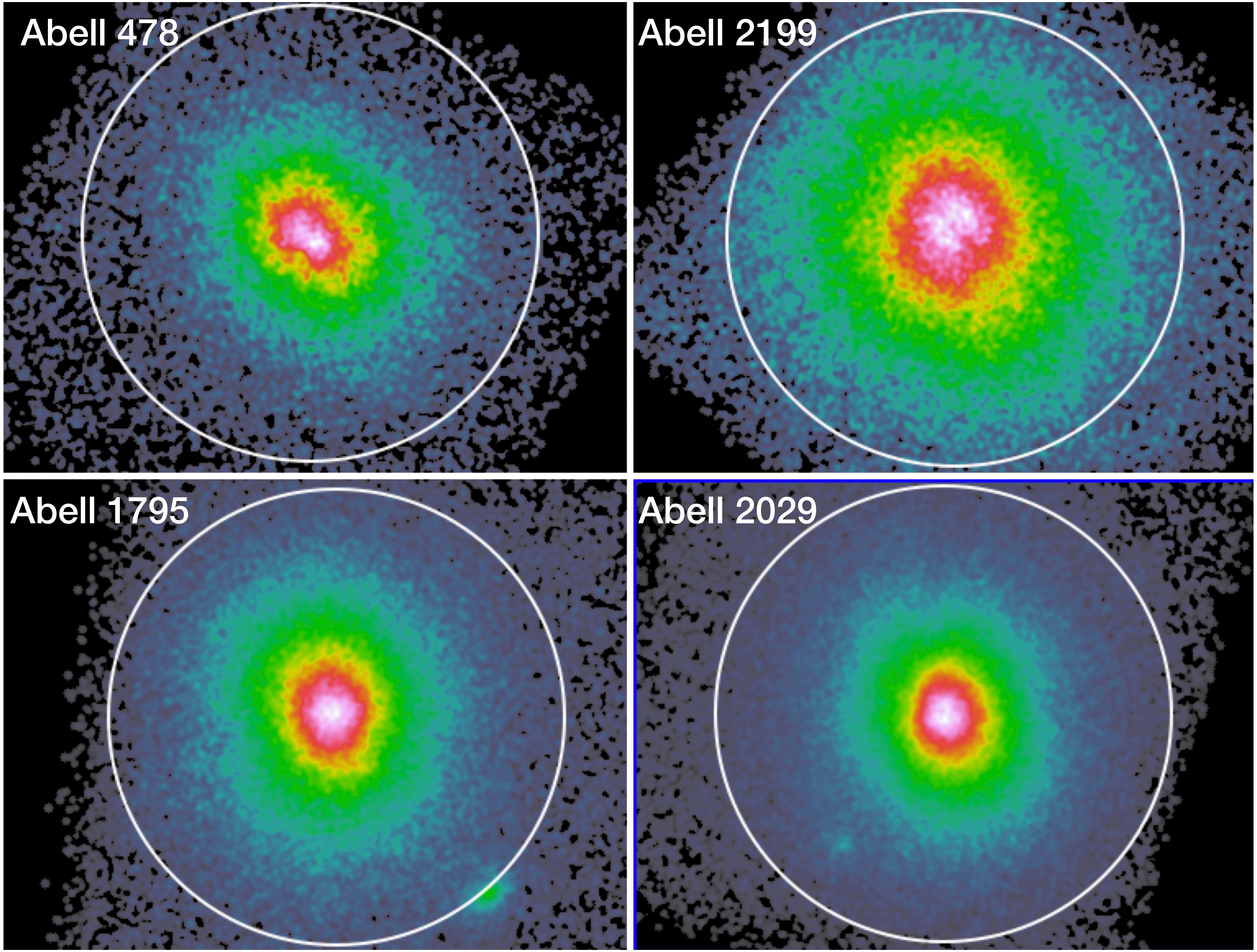
Prediction:

Same trend will emerge in analyses of 3 other deep observations of relaxed clusters



XMM-Newton EPIC combined
(Bgd-sub, exp-corr, adaptively smoothed)

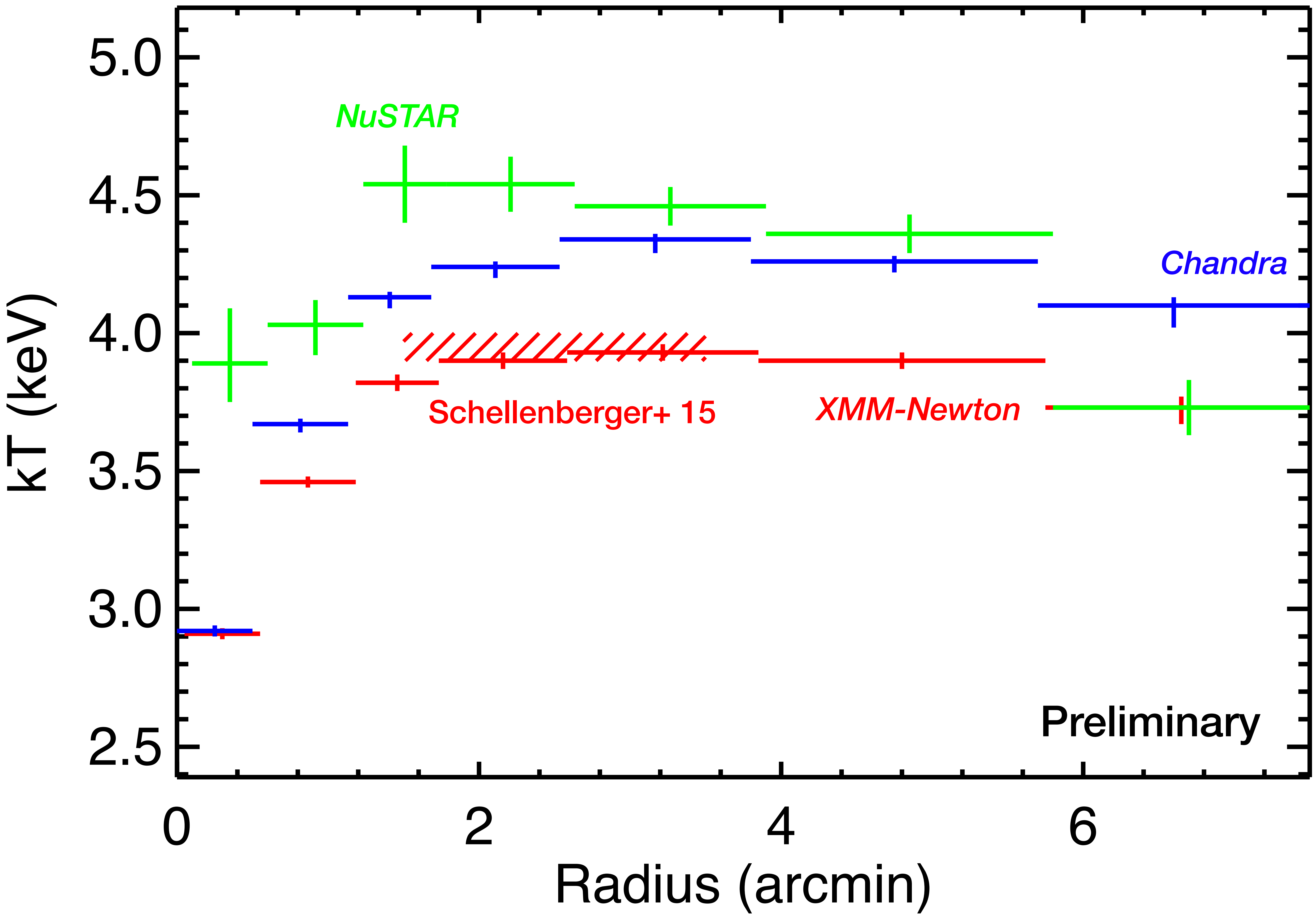
0.4-7.2 keV



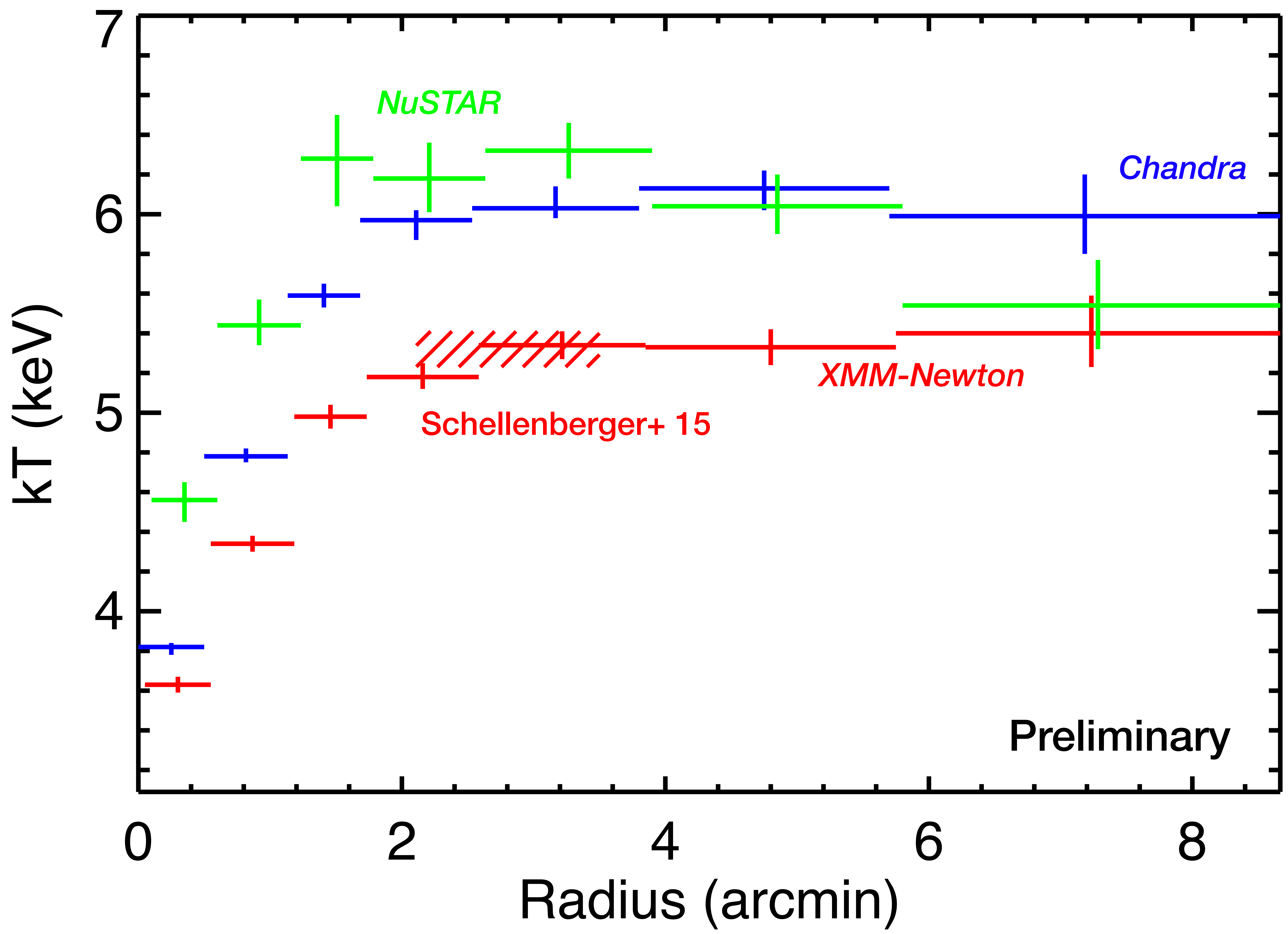
4-25 keV

NuSTAR FPMA+B combined (Bgd-sub, 8” smoothing)

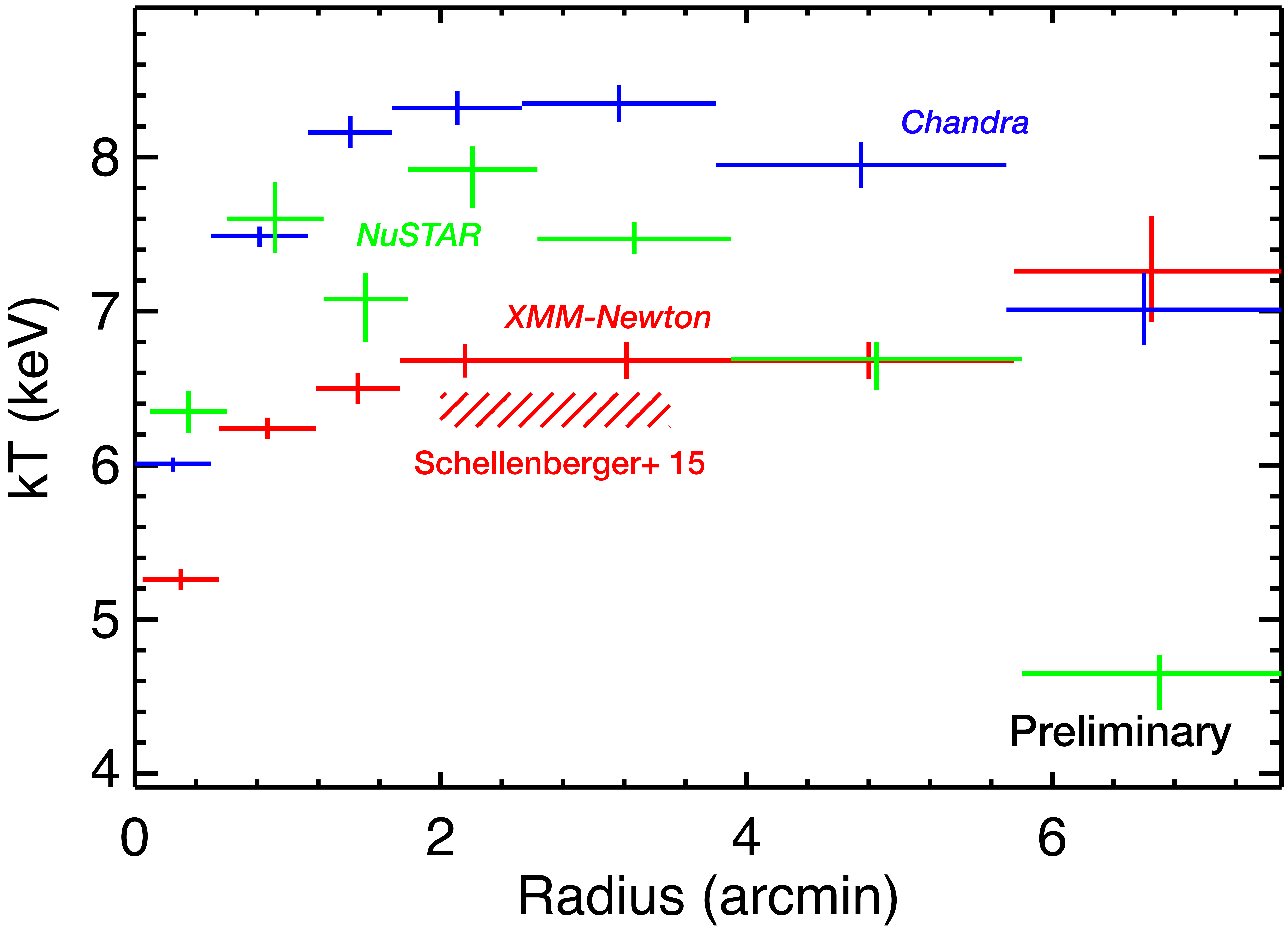
A2199: kT Profiles

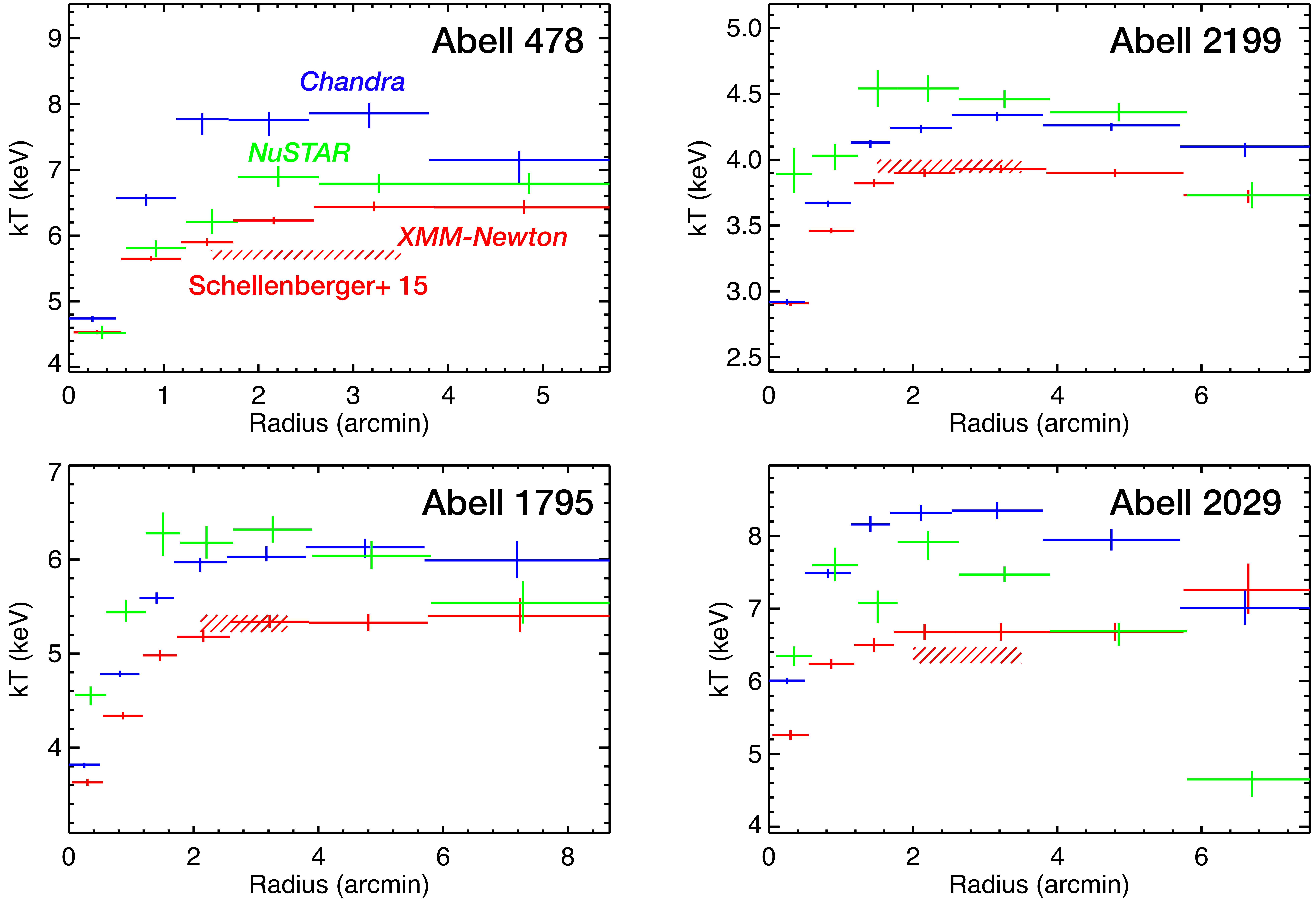


A1795: kT Profiles



A2029: kT Profiles




Abell 478
Chandra
NuSTAR
XMM-Newton
Schellenberger+ 15
kT (keV)
Radius (arcmin)
Abell 2199
kT (keV)
Radius (arcmin)
Abell 1795
kT (keV)
Radius (arcmin)
Abell 2029
kT (keV)
Radius (arcmin)

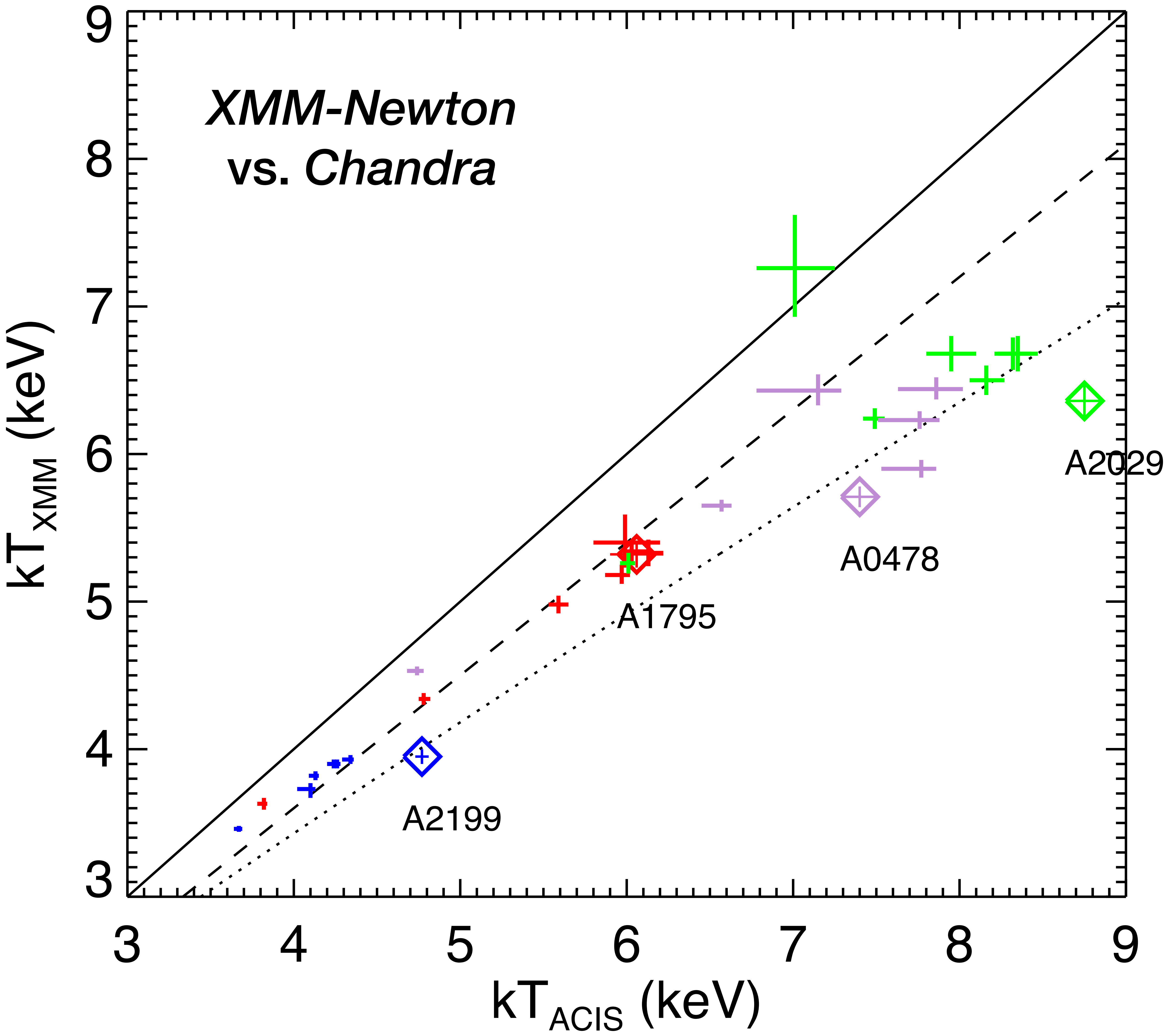
Hypothesis III: ???

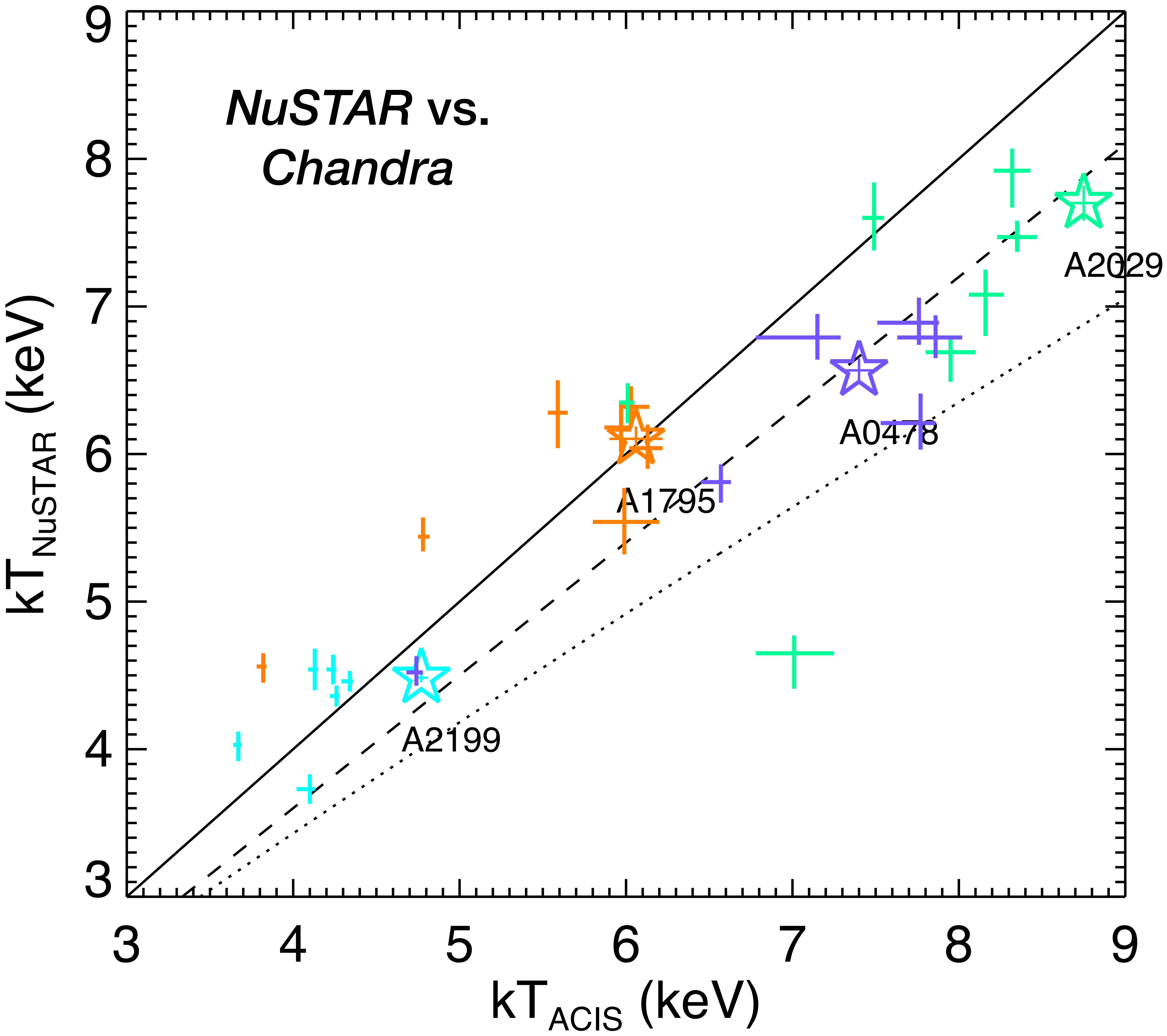
- *NuSTAR* analysis ongoing, refinements may support Hypothesis II, but may not
- Cooler clusters show better agreement all around, especially between *NuSTAR* and *Chandra*, but hotter clusters do not

Prediction:

Happy to hear yours!

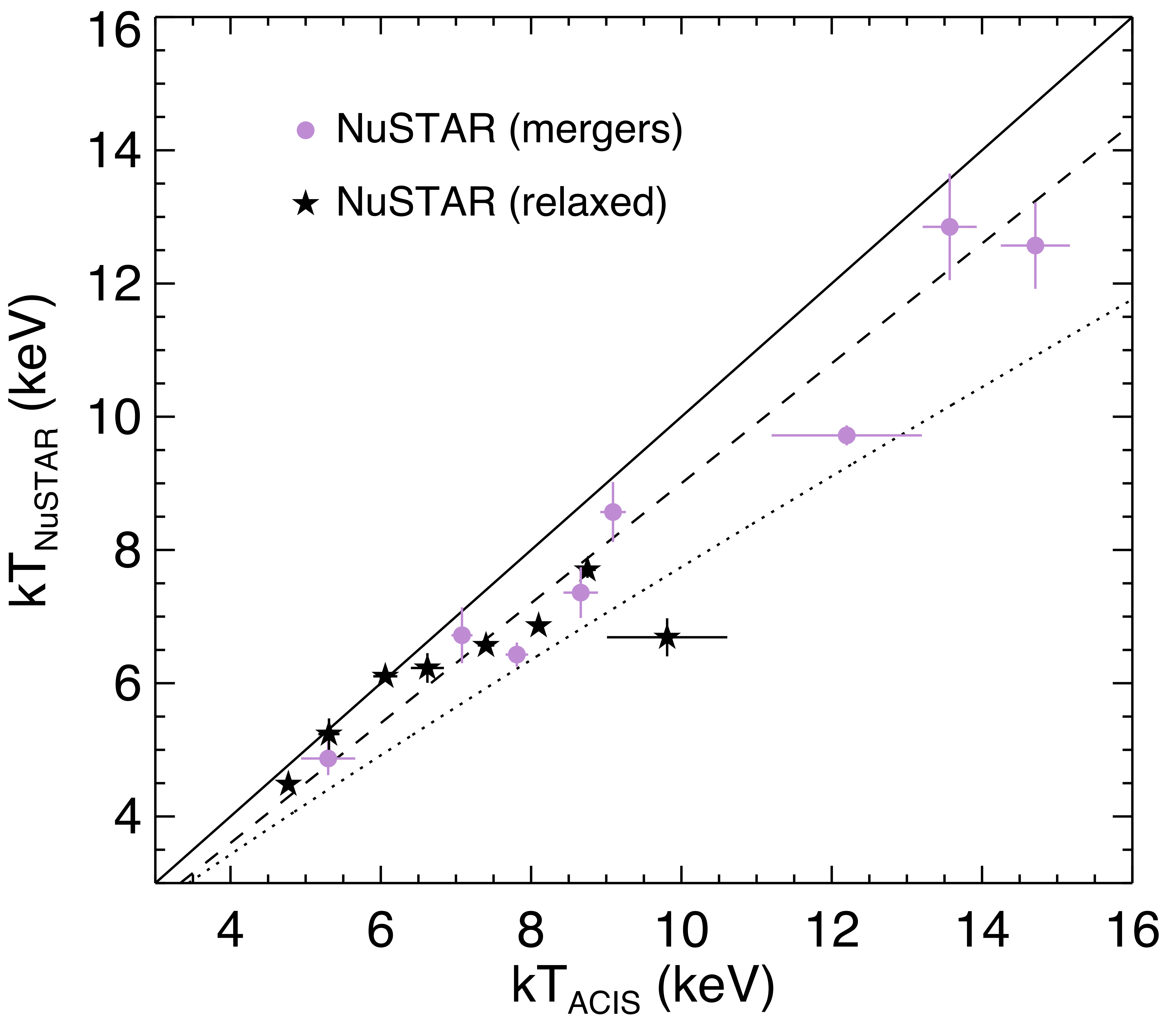
kT Trends from Annuli Measurements



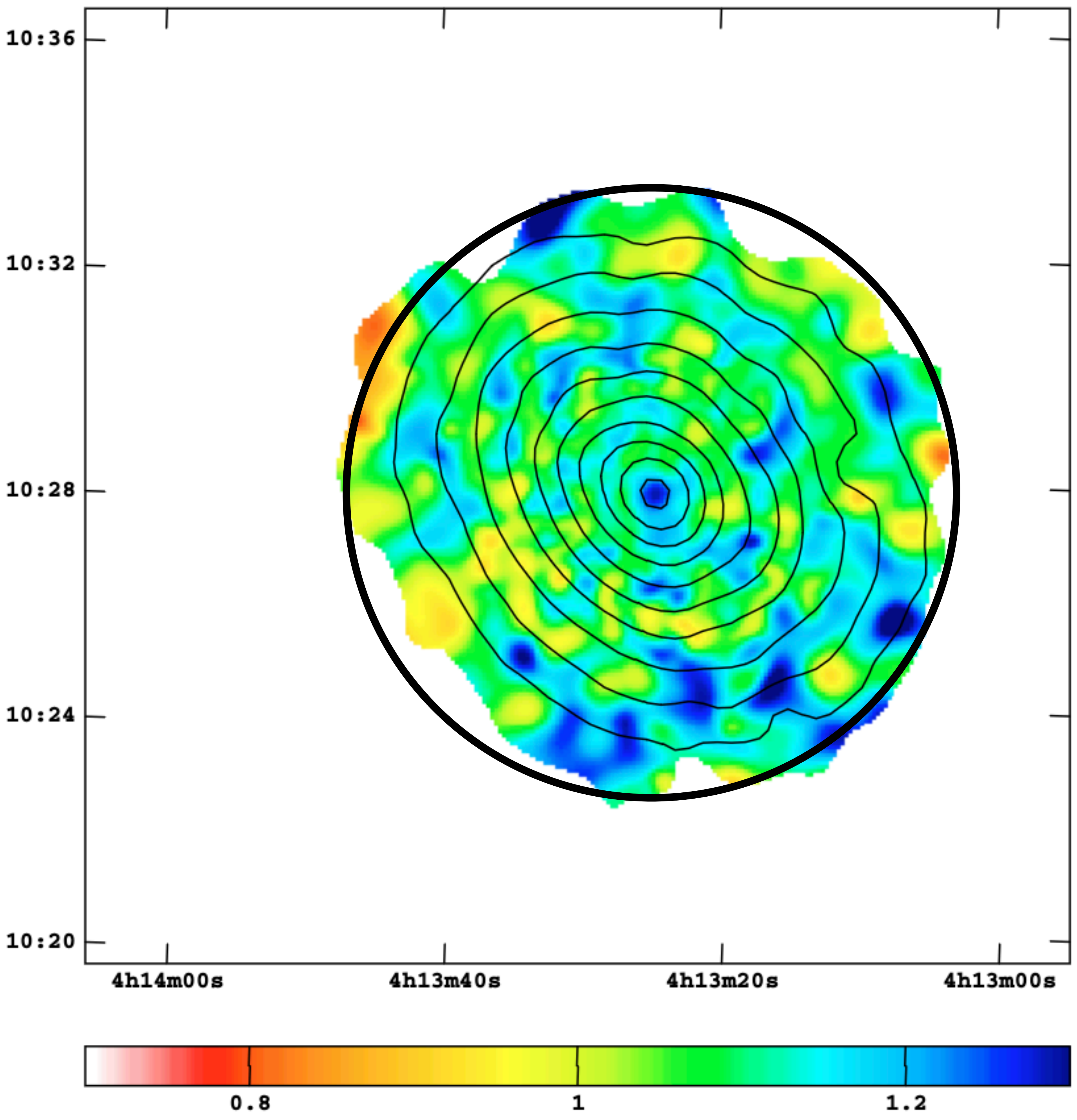


In Summary

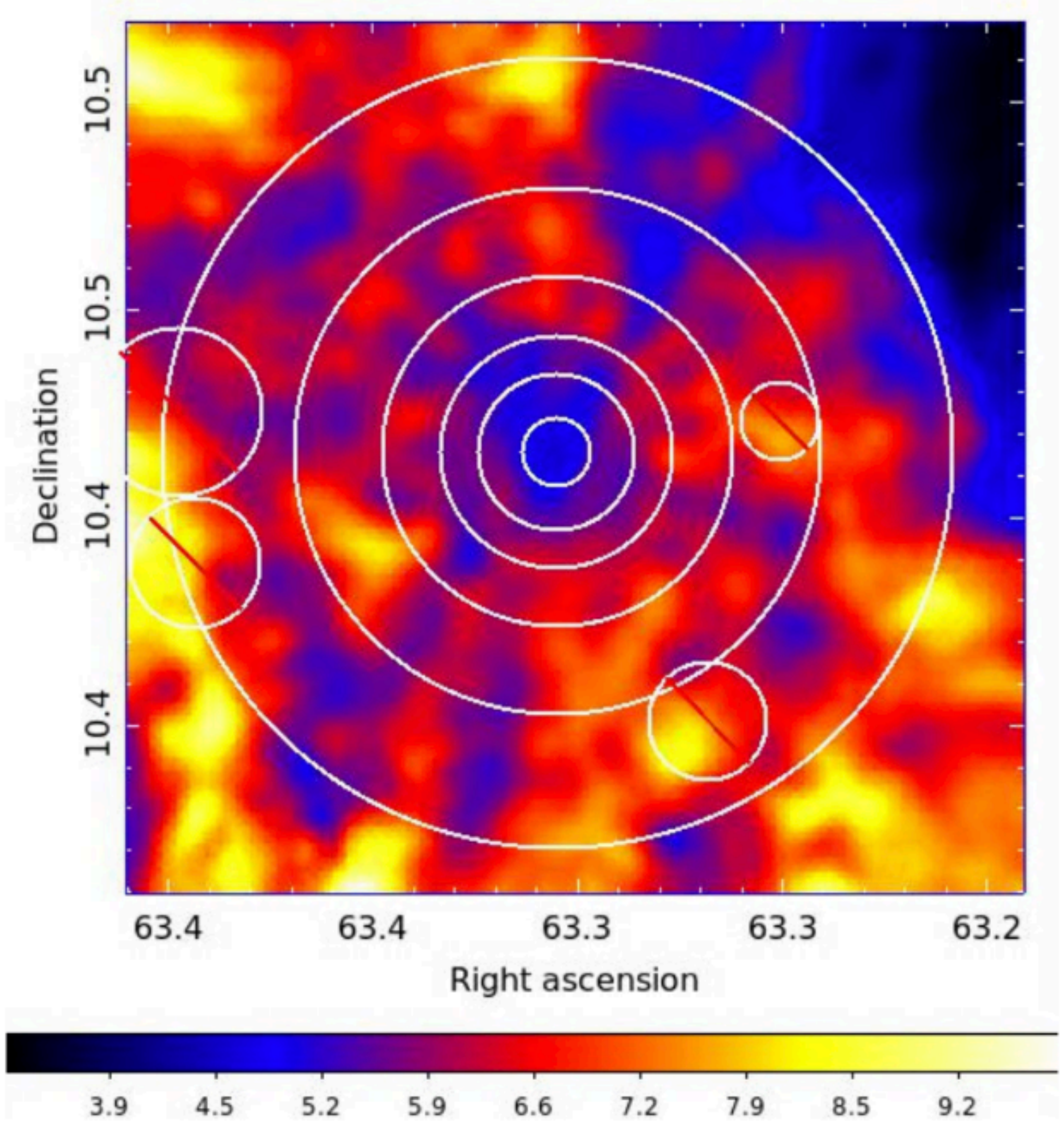
- *NuSTAR* kTs are often LOWER than *Chandra* kTs, which physically shouldn't happen
- *NuSTAR* agrees better with *XMM-Newton* for hot clusters and with *Chandra* for cooler clusters (maybe)
- The most recent updates to the EPIC effective areas work well
    - Corrections (by construction) bring MOS/pn into agreement with self and with *NuSTAR* in hard band
    - These corrections ALSO allow better soft proton characterization in ESAS fits
- Relaxed clusters have more regular and smaller temperature trends, allowing more straightforward cross-calibration, but idiosyncrasies hard to avoid



Temperature Map Comparison

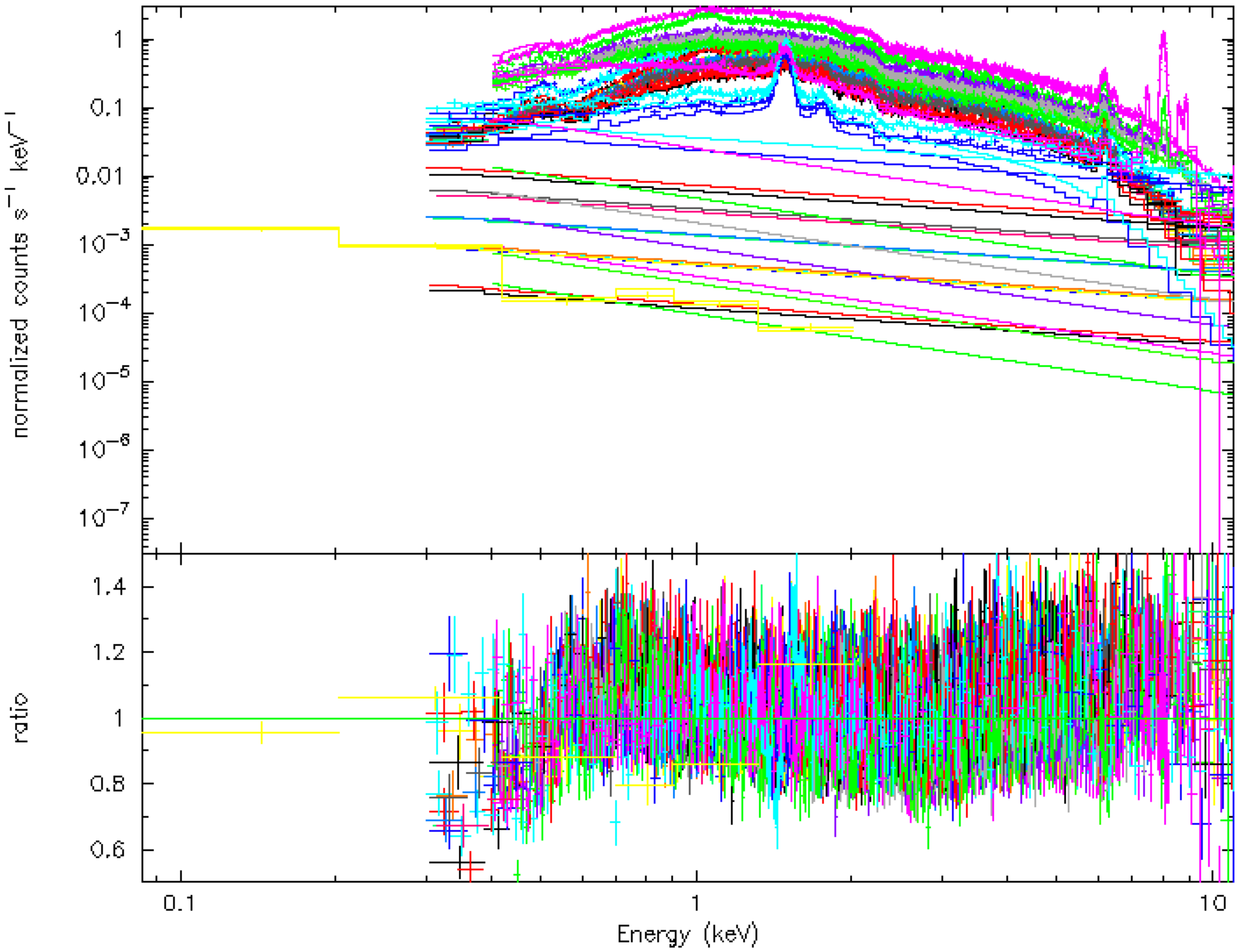


(<—hot) Hardness (cool—>)



kT (keV)

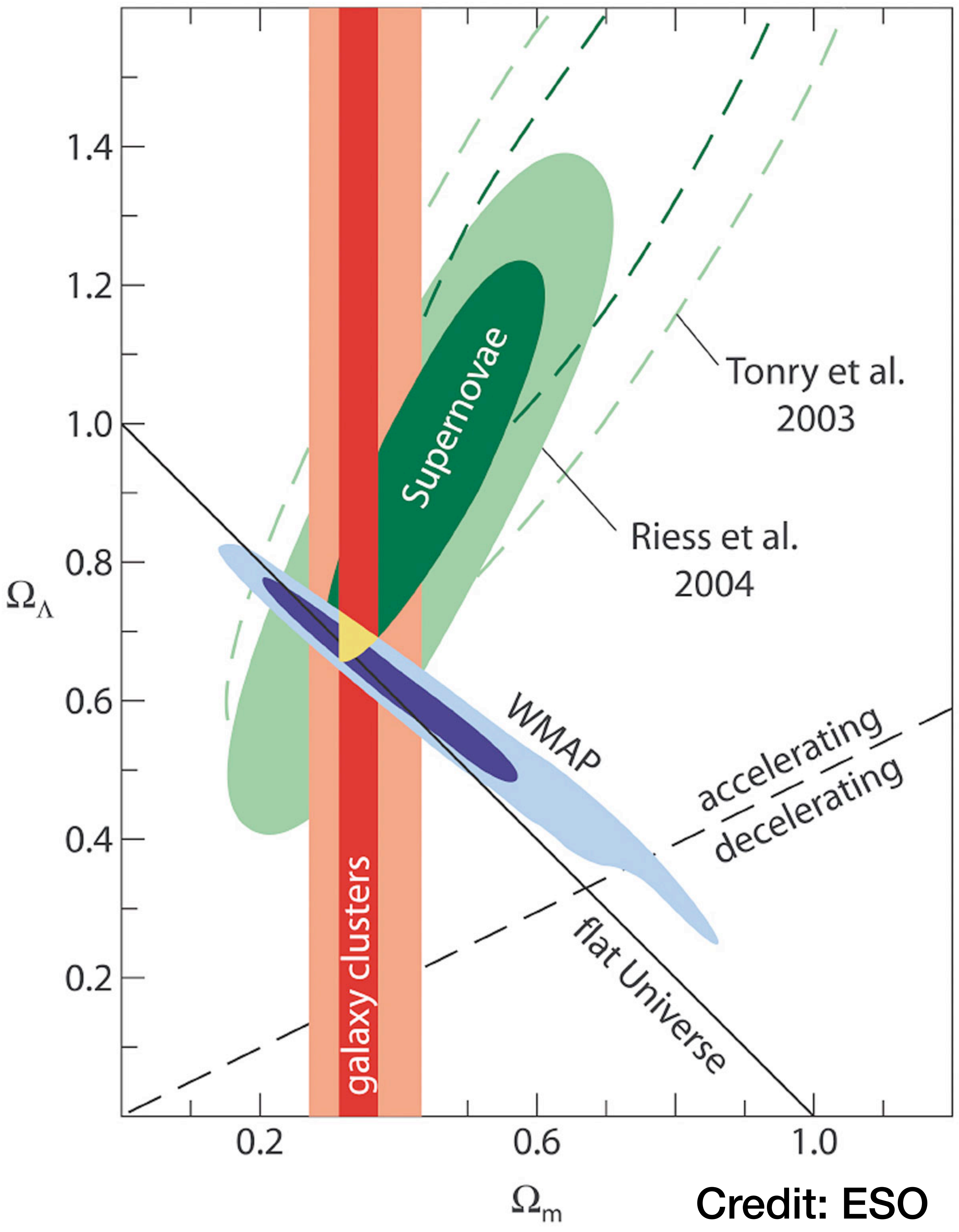
AnGr abund, wabs, no ARF correction



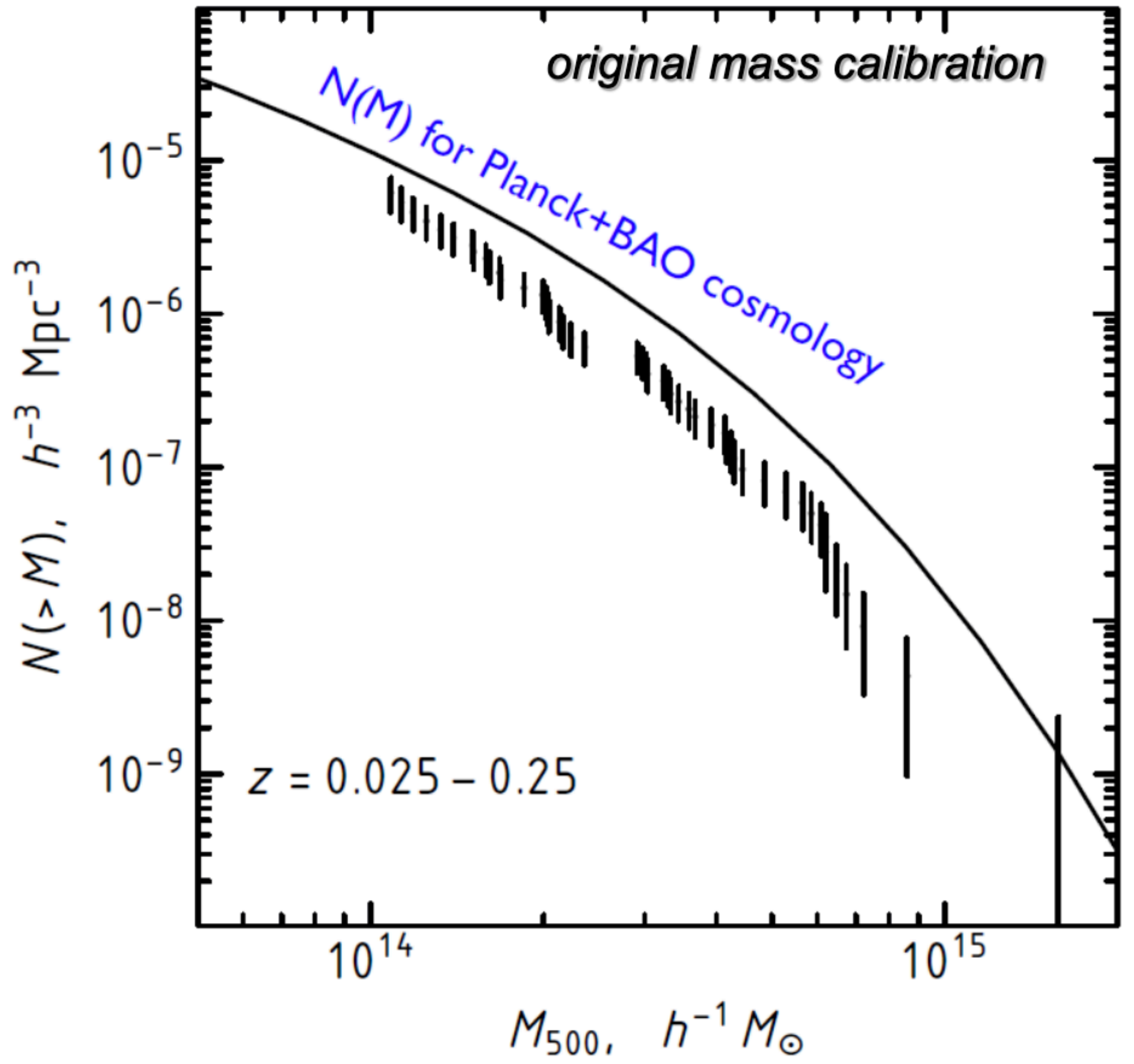
Abund Wilm, before & after ARF correction

Galaxy Clusters: Why Calibration?

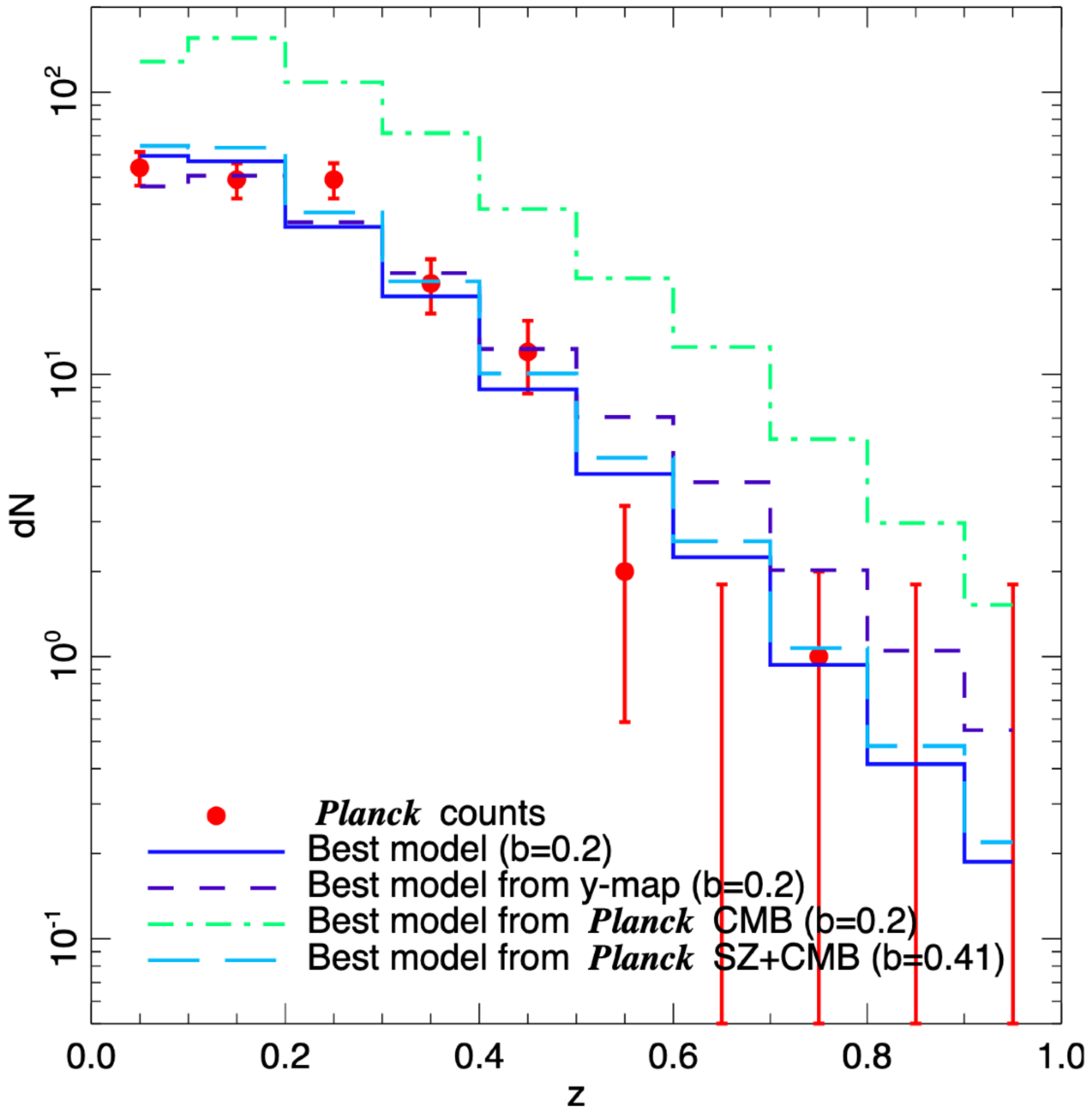
$$M(<r) = -\frac{kT(r)r}{G\mu m_p}\left[\frac{d\ln n_p}{d\ln r} + \frac{d\ln T}{d\ln r}\right] \propto T(r)r$$



Credit: ESO

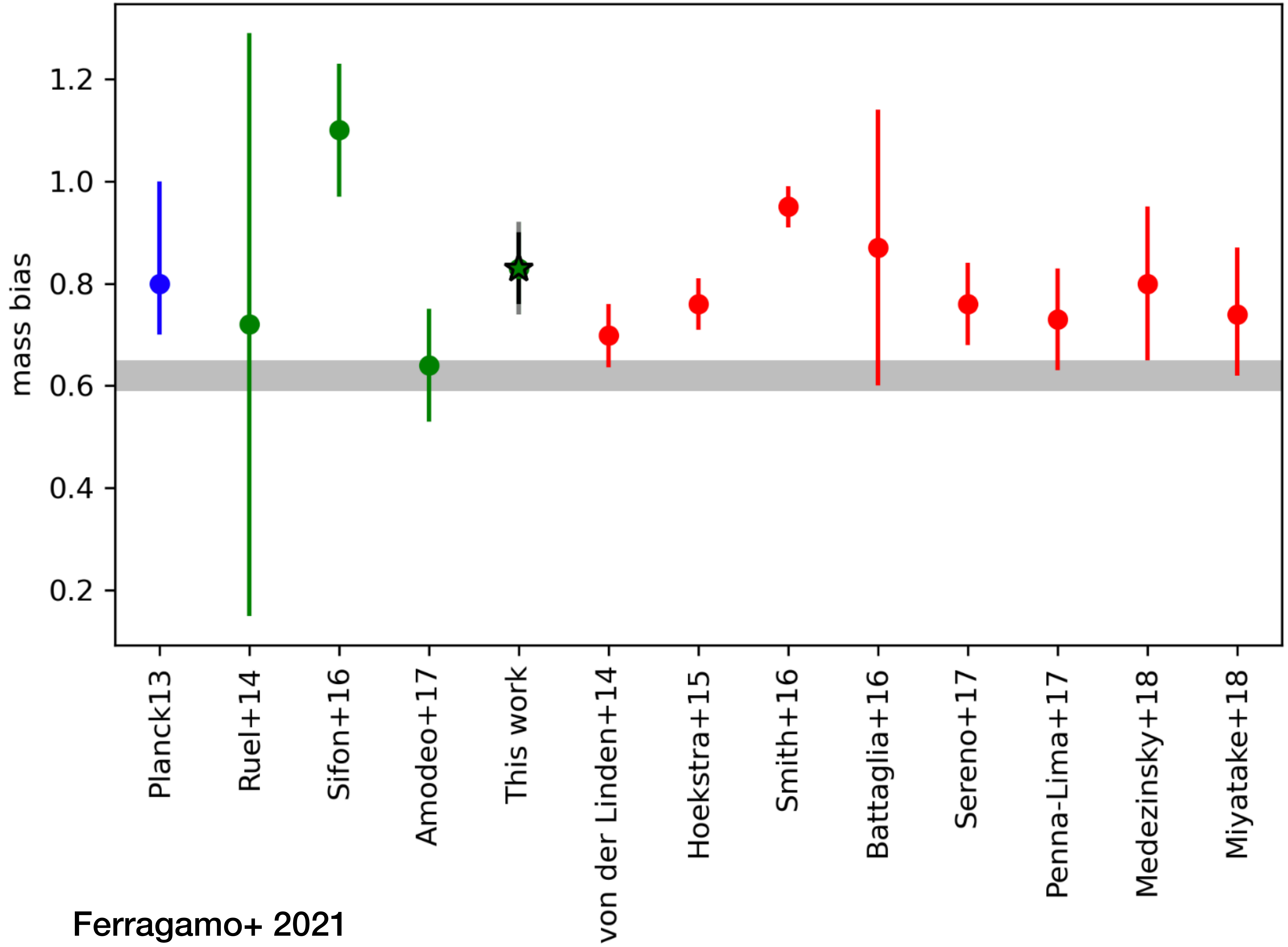


Vikhlinin+ 2009

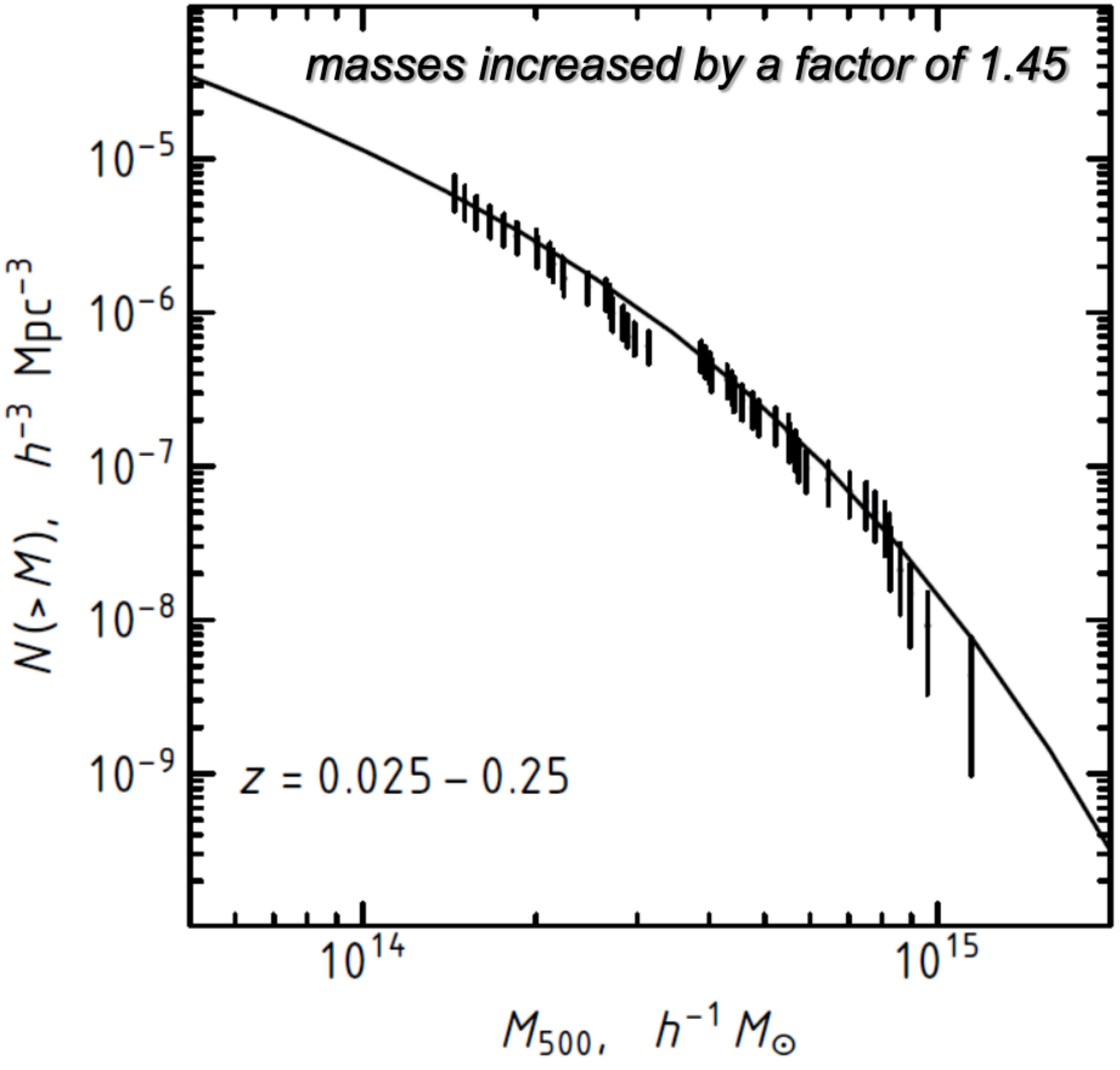


Planck collab. 2014 (XX)

Galaxy Clusters: Why Calibration?

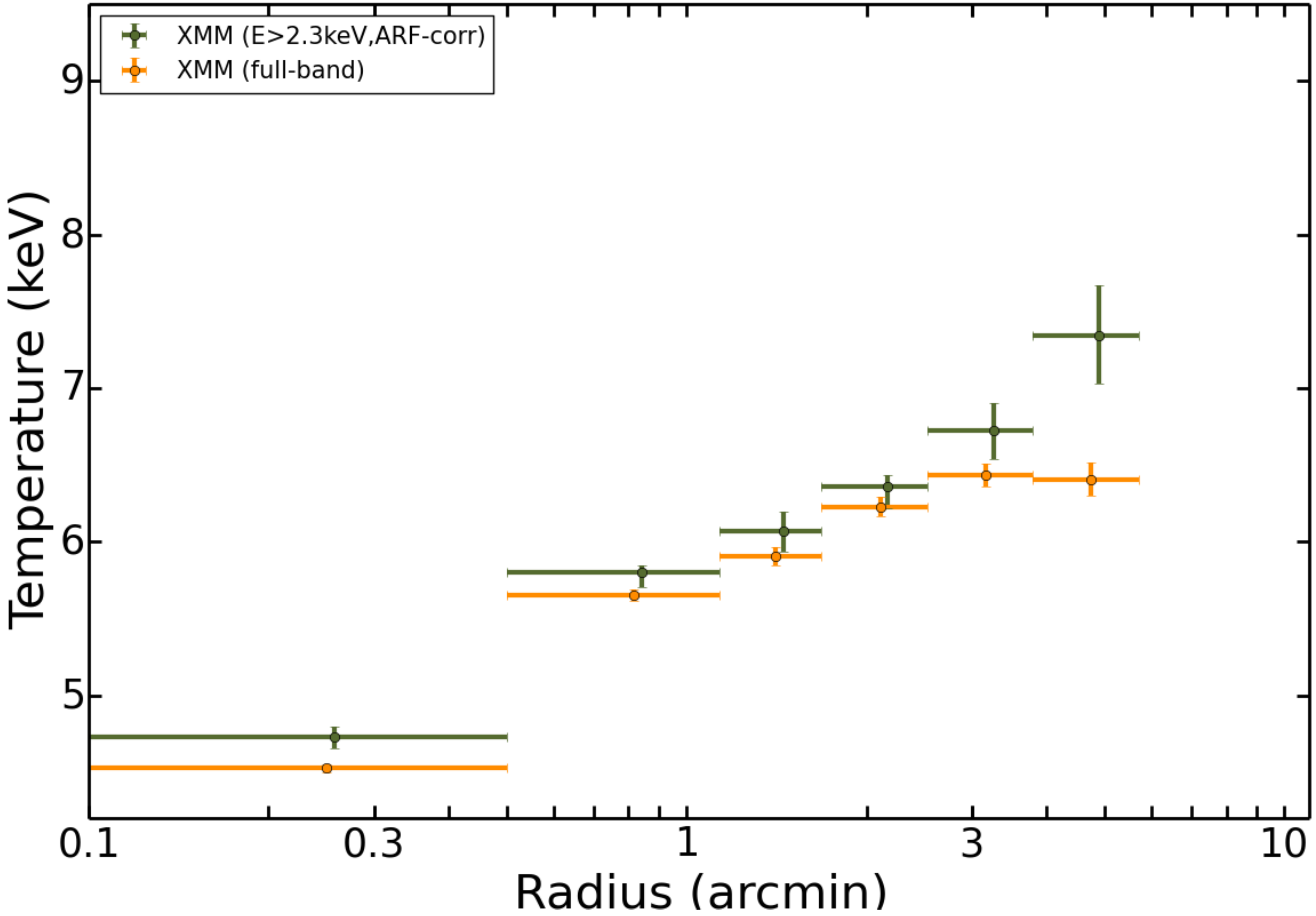


Ferragamo+ 2021

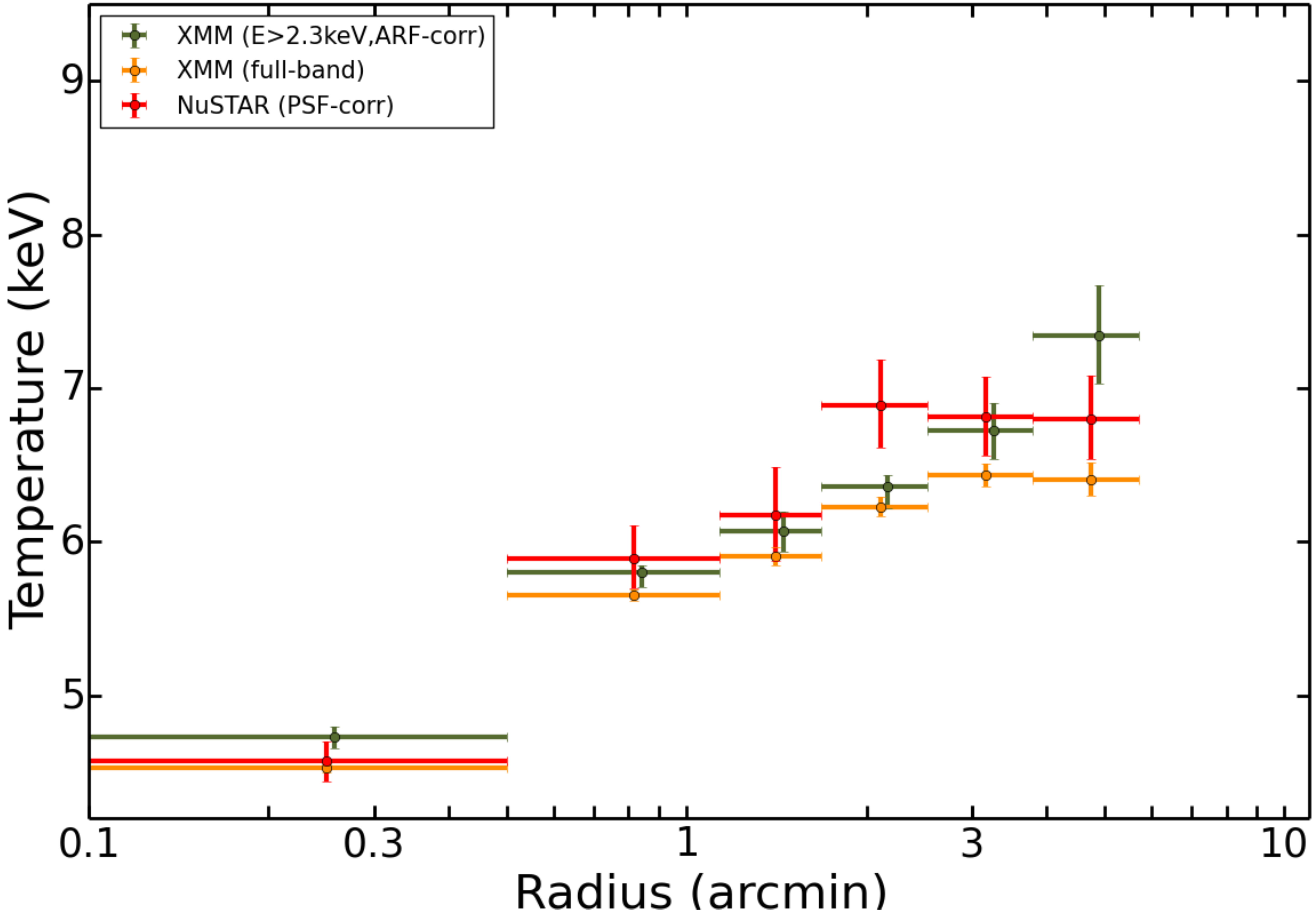


Vikhlinin+ 2009
(Borrowed from 2016 KICP Workshop slide by Kravtzov)

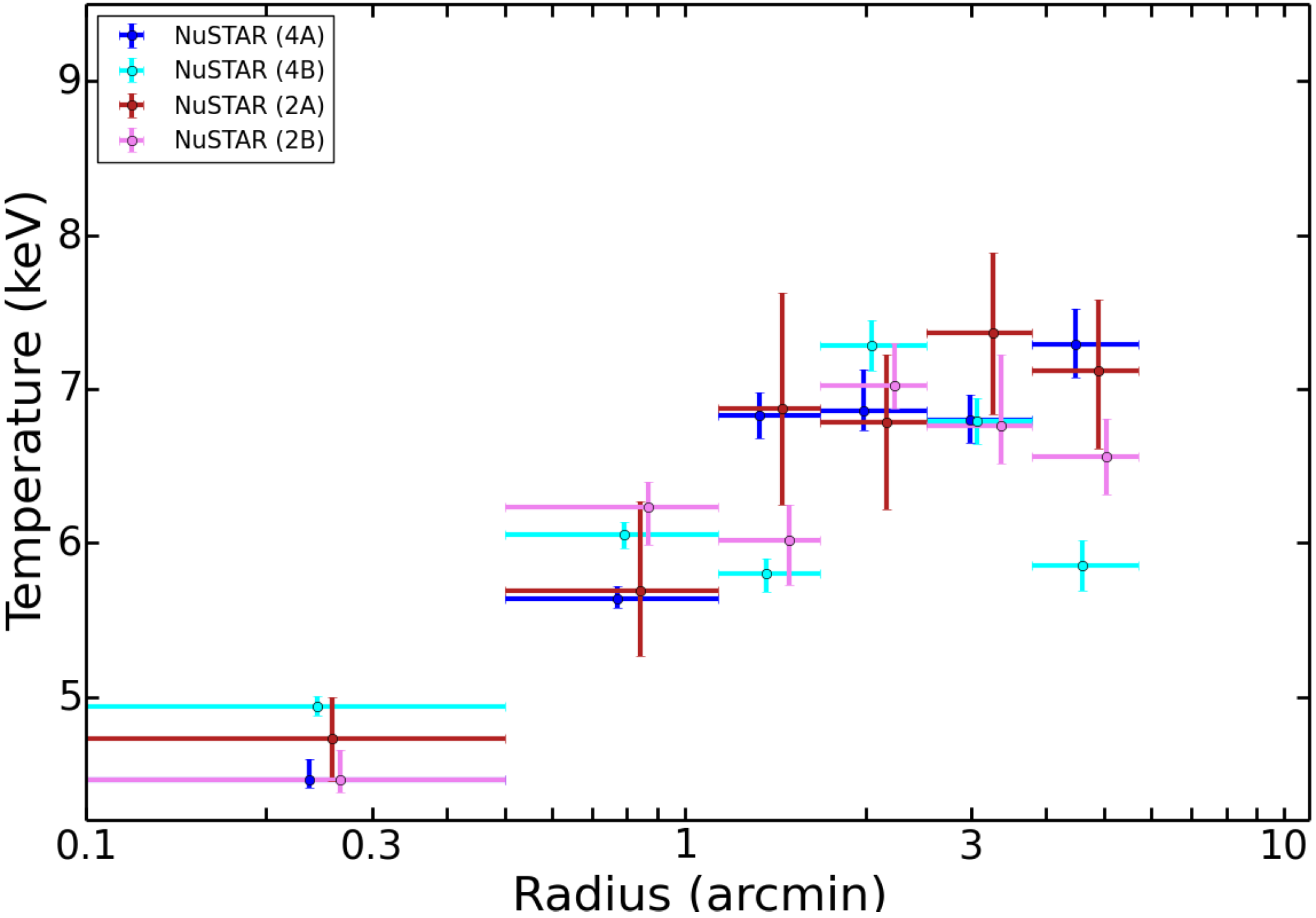
XMM-Newton Self Consistency



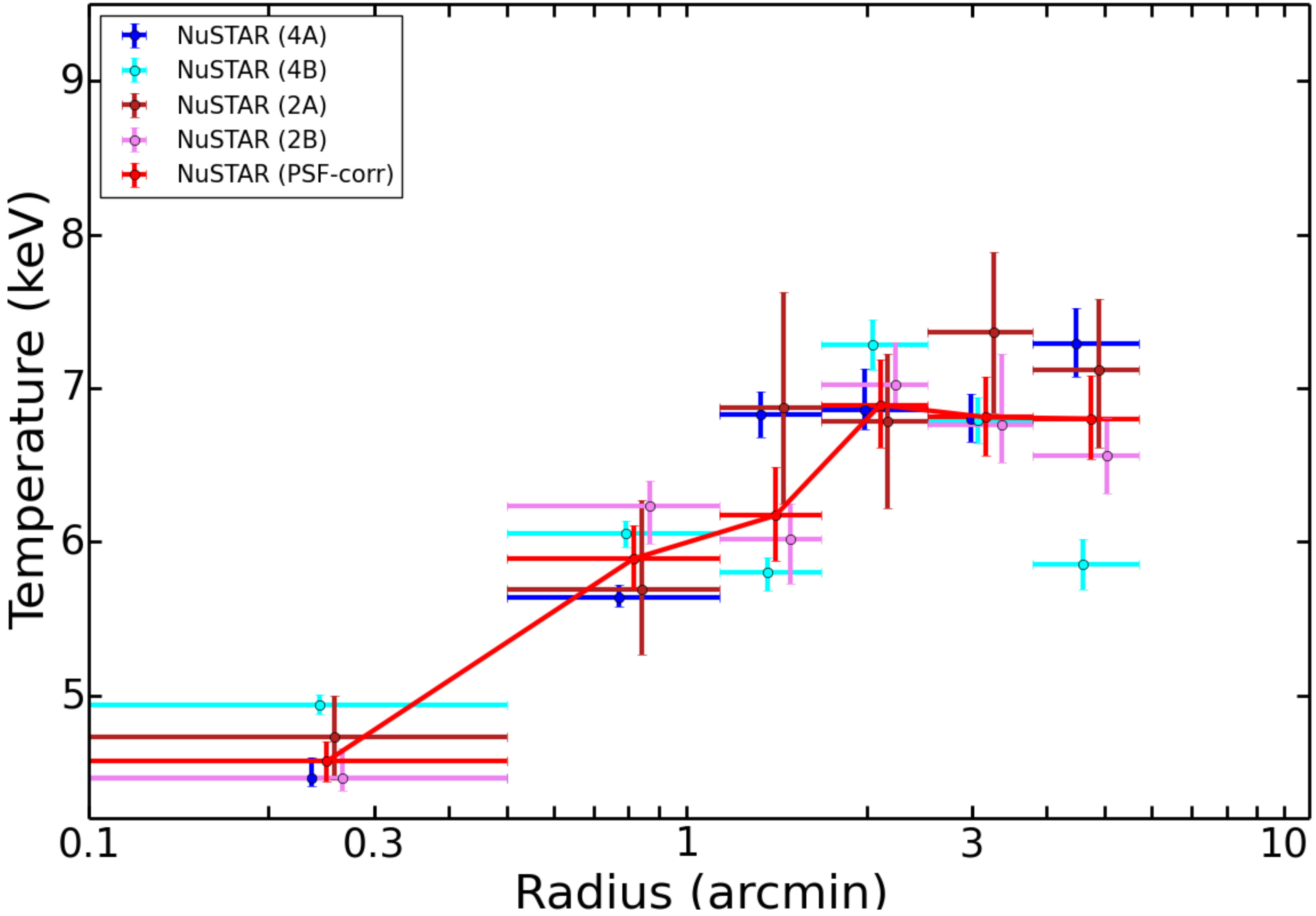
XMM-Newton Self Consistency



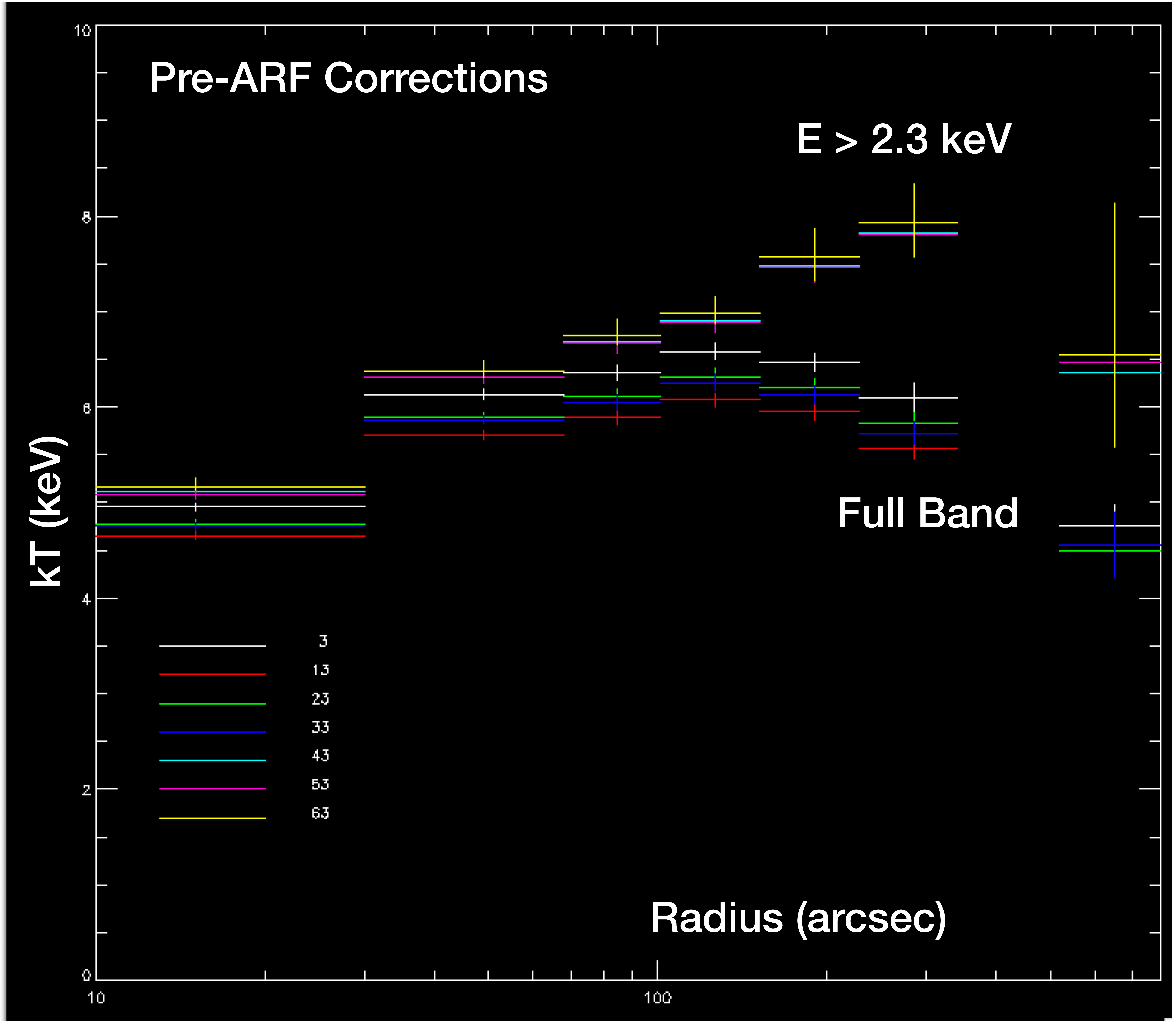
NuSTAR PSF correction systematics



NuSTAR PSF correction systematics



XMM-Newton Self-inconsistency Pre-ARF corrections



Scattered & Stray Light