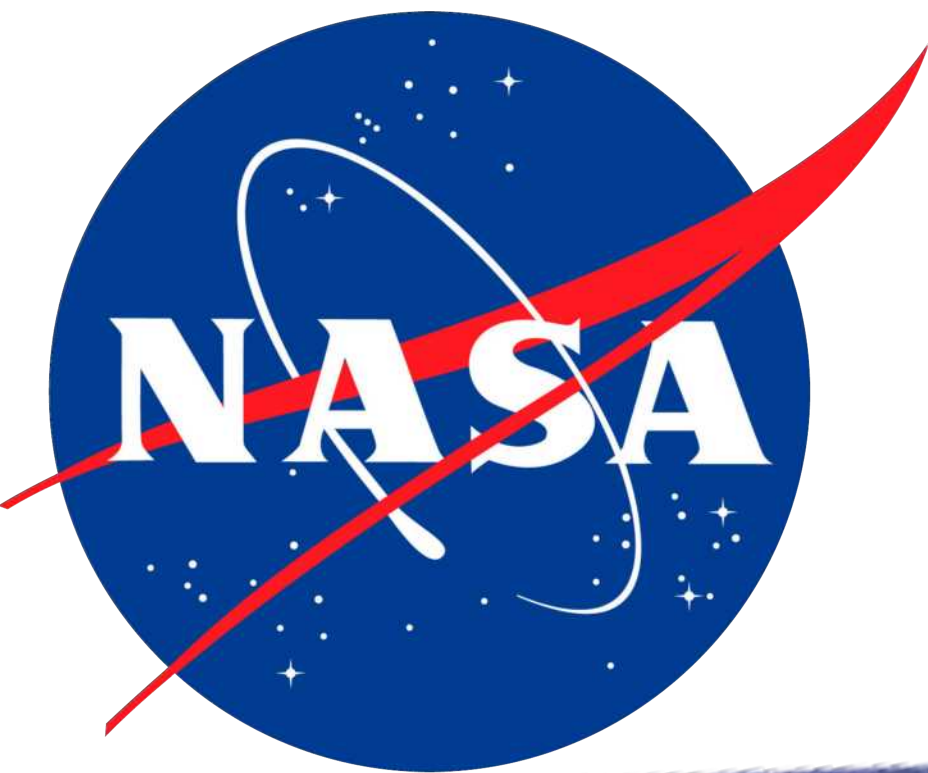
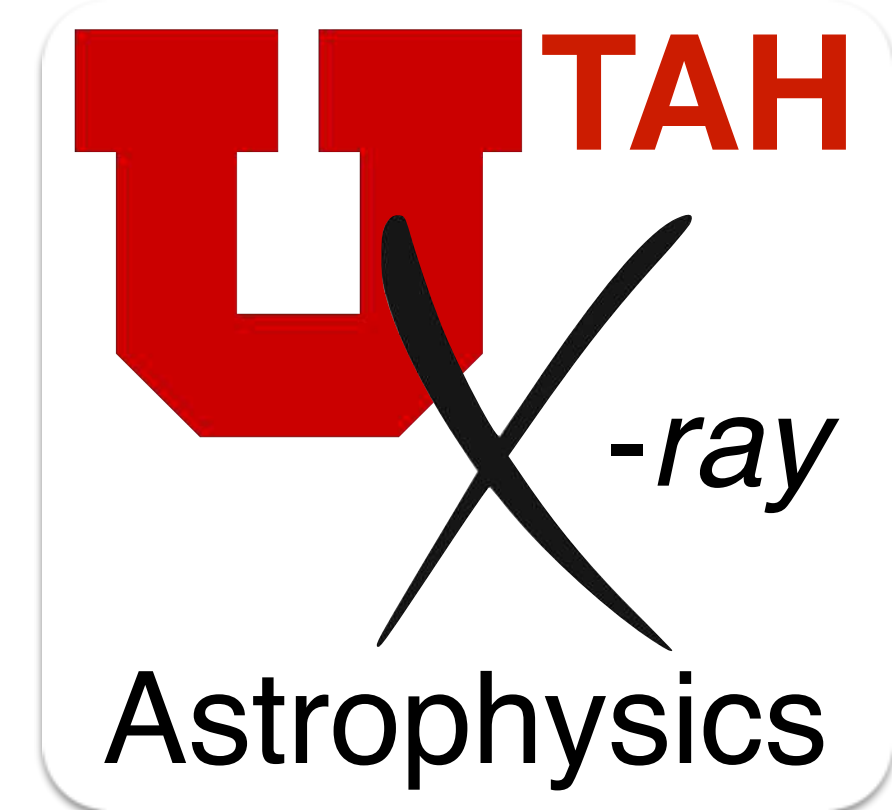


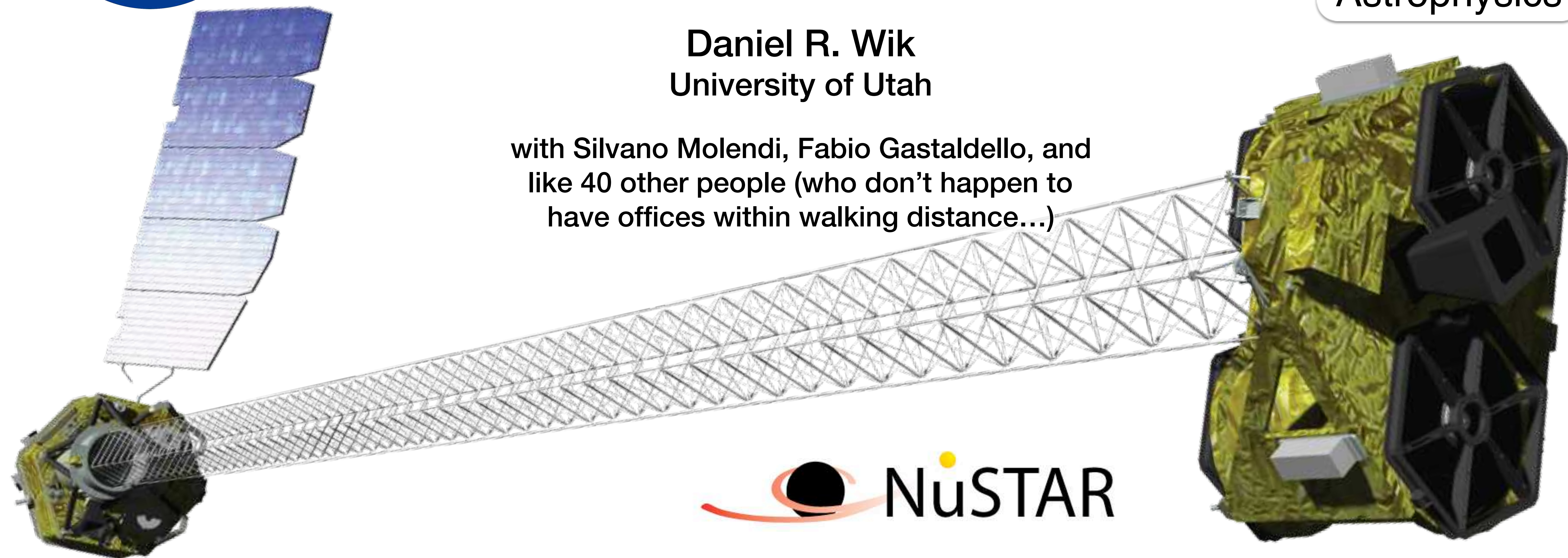


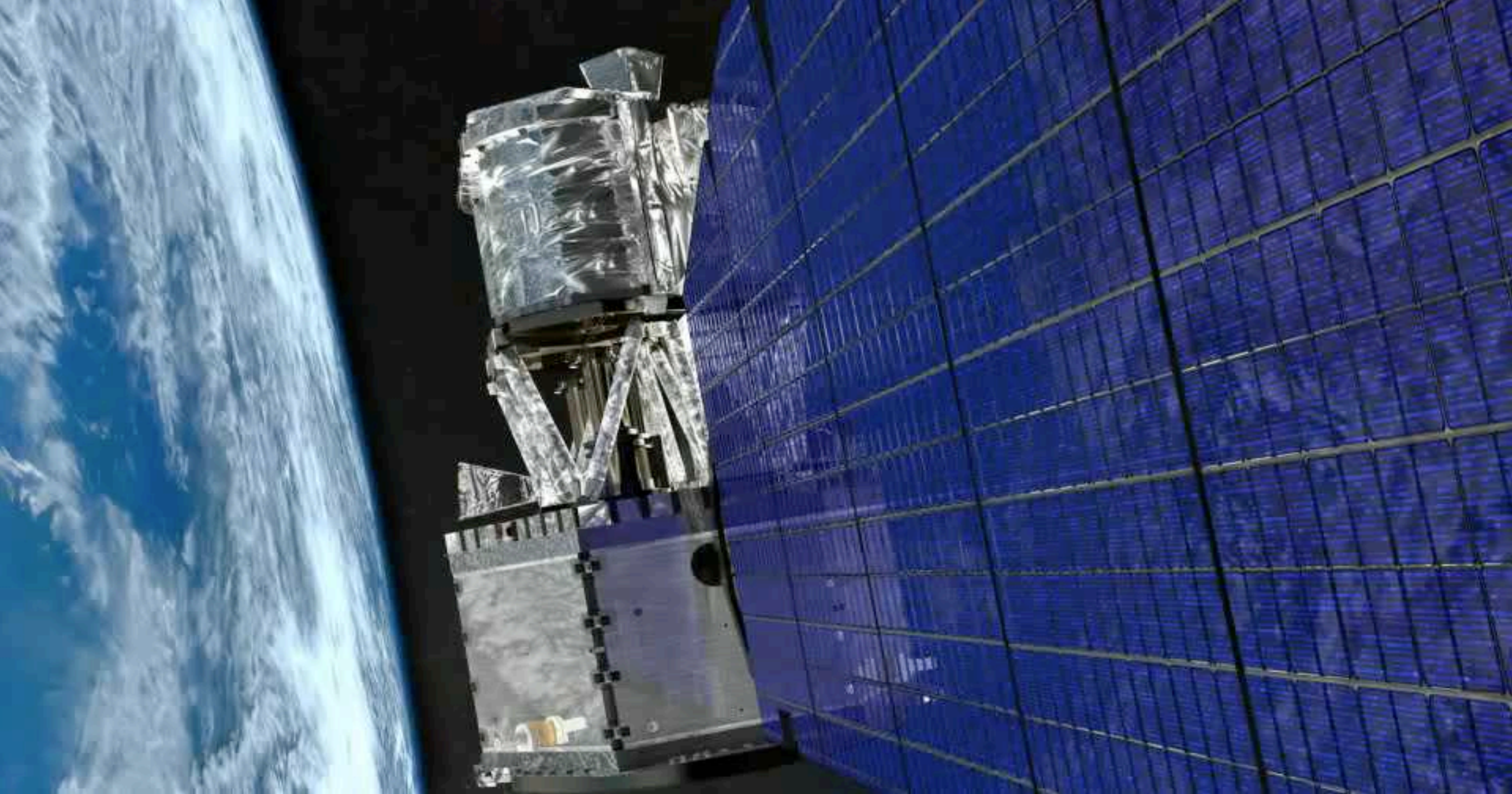
Stuck in the Weeds: Exploring the X-ray Universe with *NuSTAR*, the Hard Way



Daniel R. Wik
University of Utah

with Silvano Molendi, Fabio Gastaldello, and
like 40 other people (who don't happen to
have offices within walking distance...)



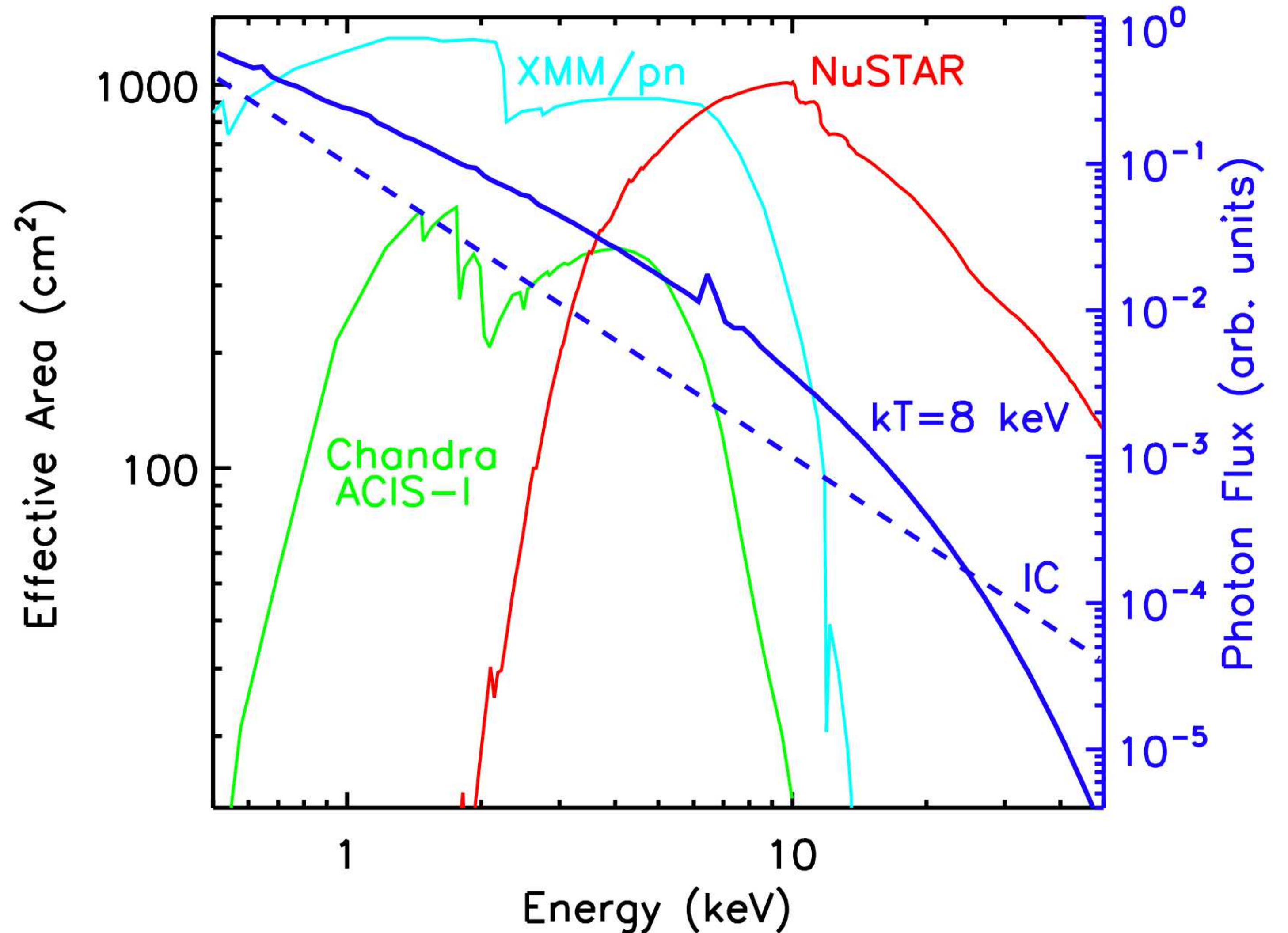


Why *NuSTAR*?

- 18''-1' angular resolution
- OK collecting area

But:

- high energy sensitivity
- low background



Characterizing the background and PSF enables the study of...

Stars
(Eta Car)

Supernova Remnants
(Cas A)

Dead Stars in
binaries

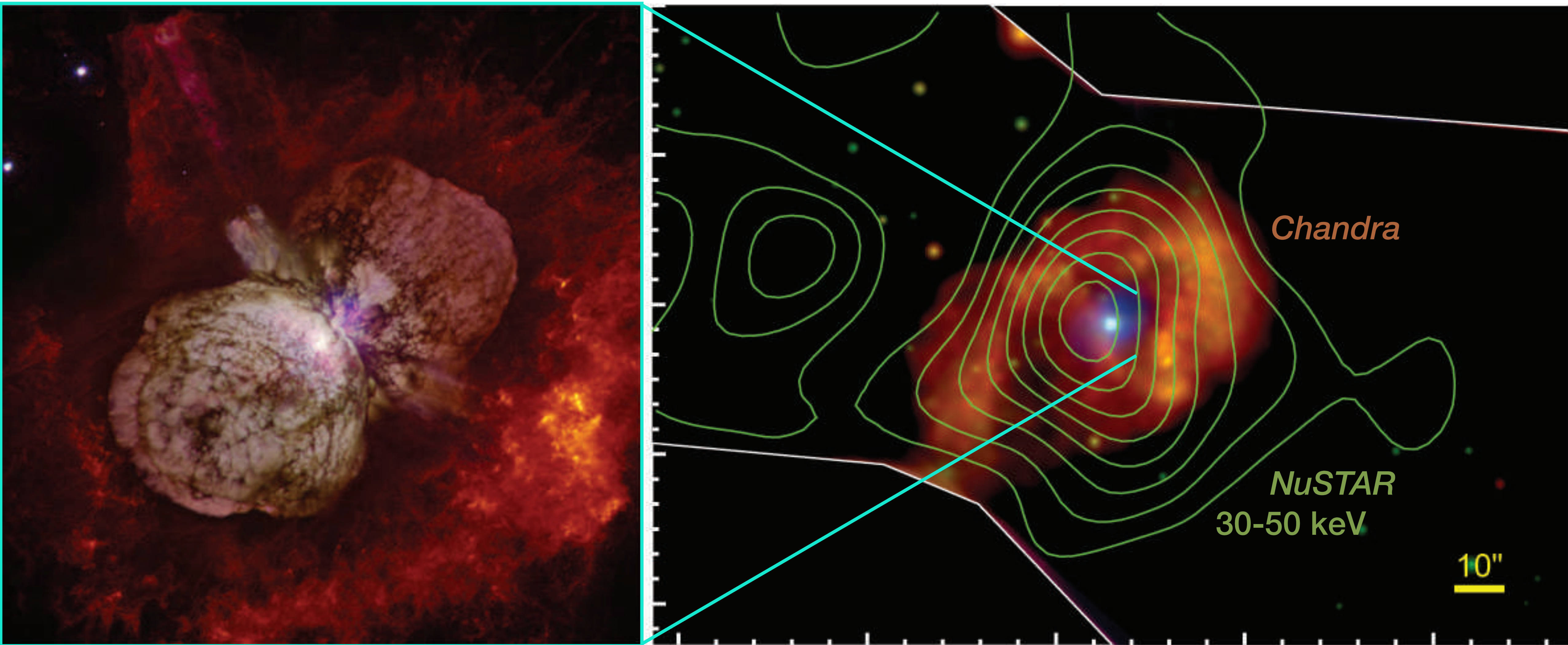
Supermassive
Black Holes

Galaxies
(NGC 253)

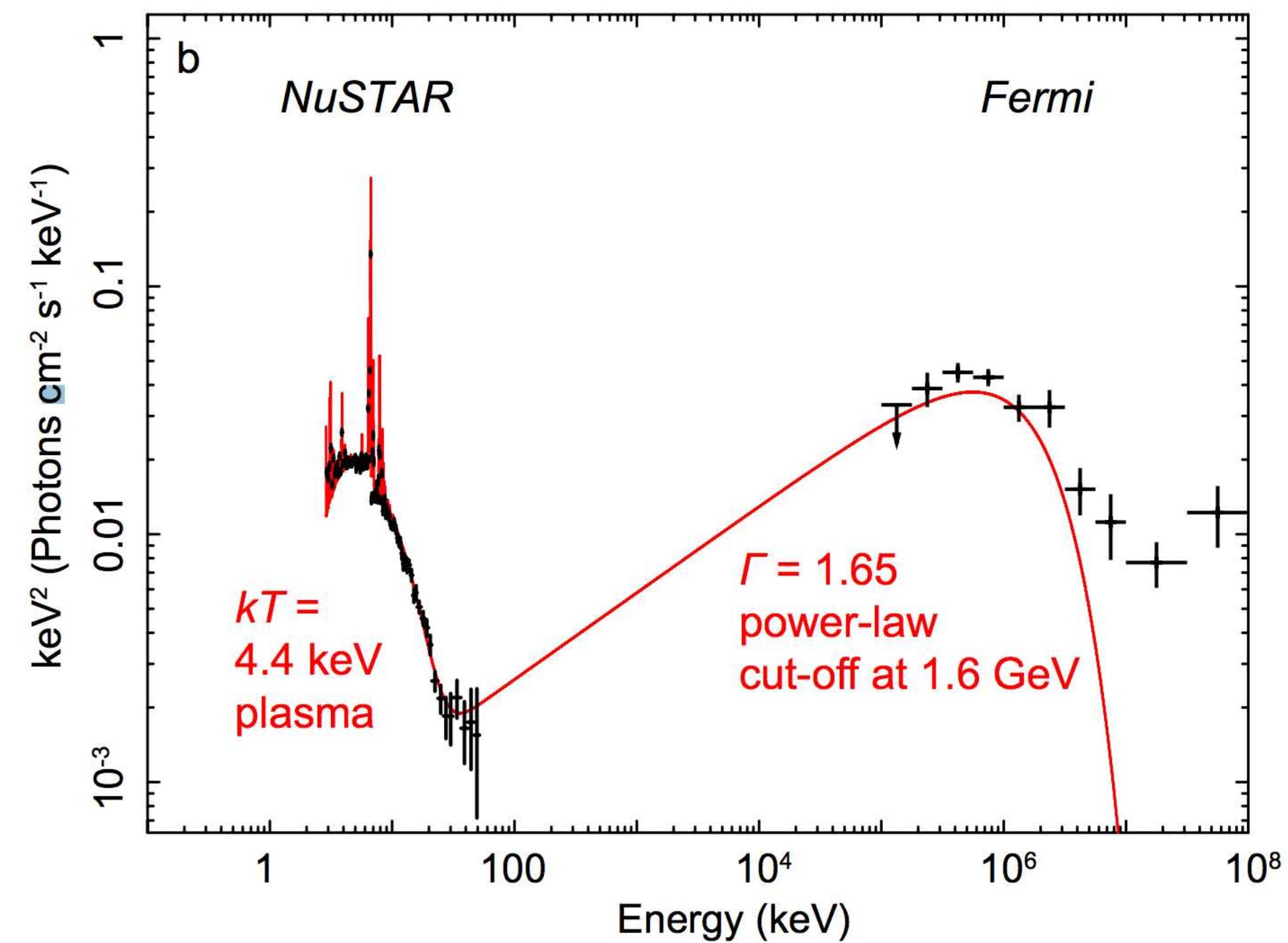
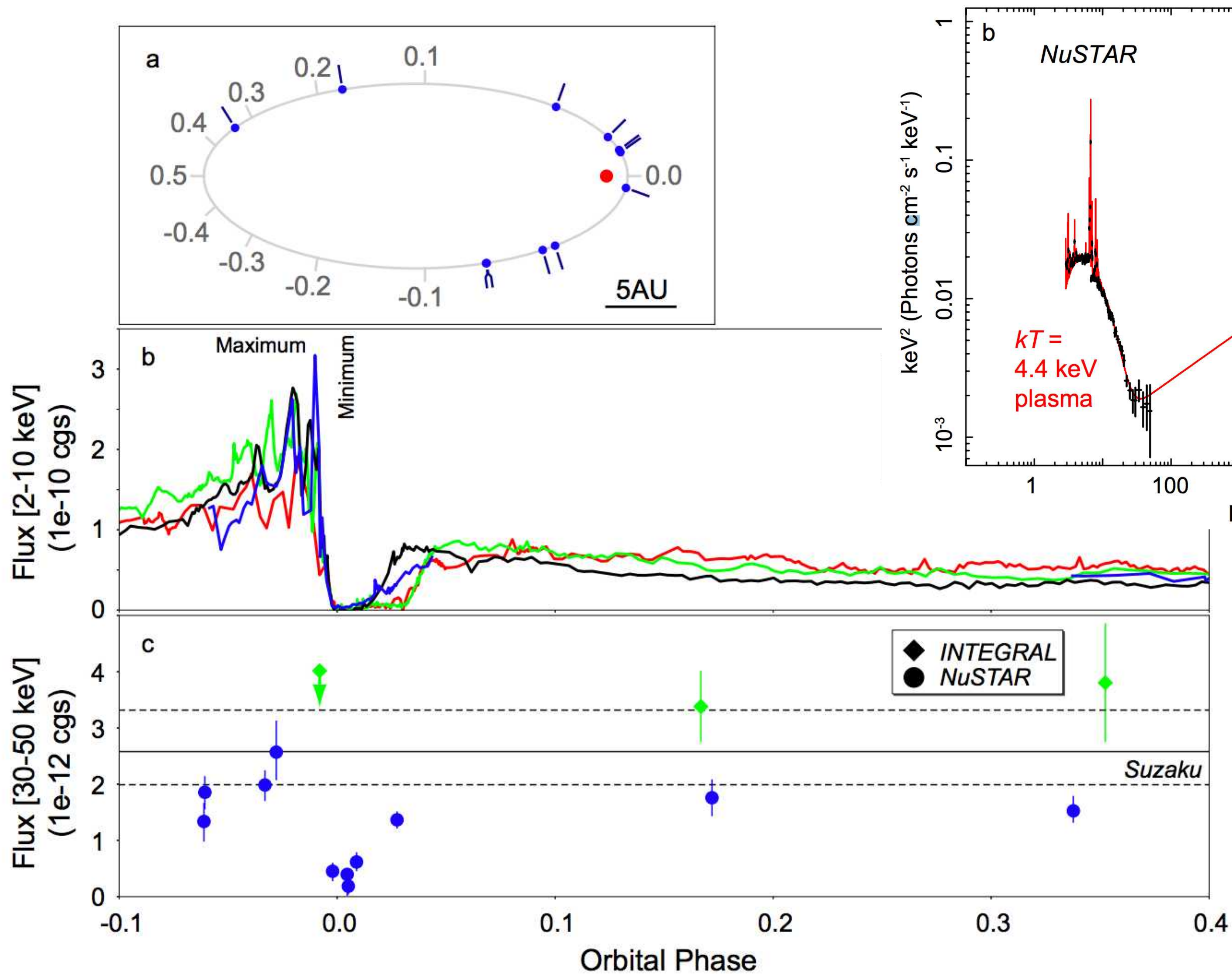
Sterile Neutrino
Dark Matter

Clusters of
Galaxies

High Energy X-rays identified with Eta Carinae

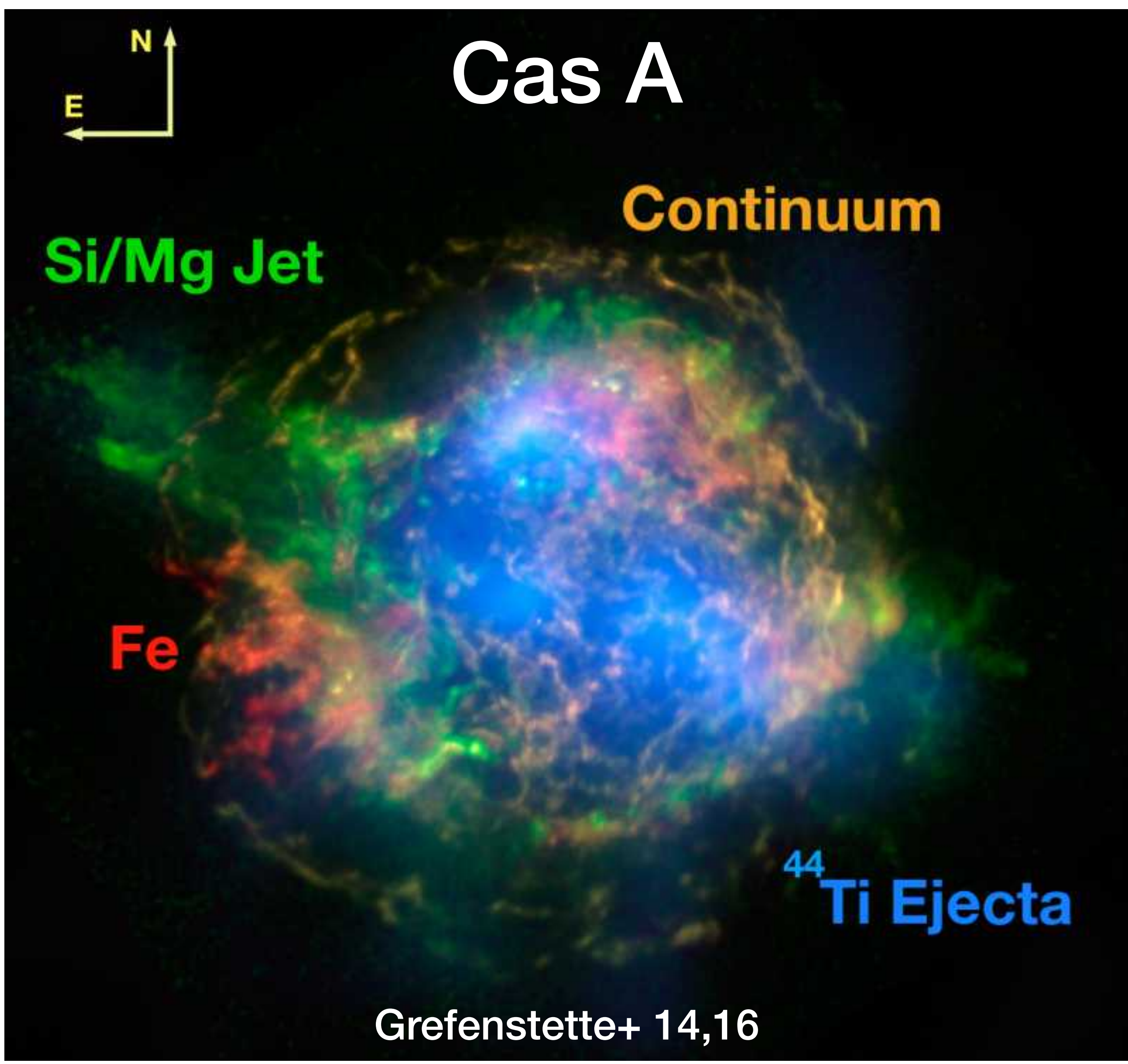
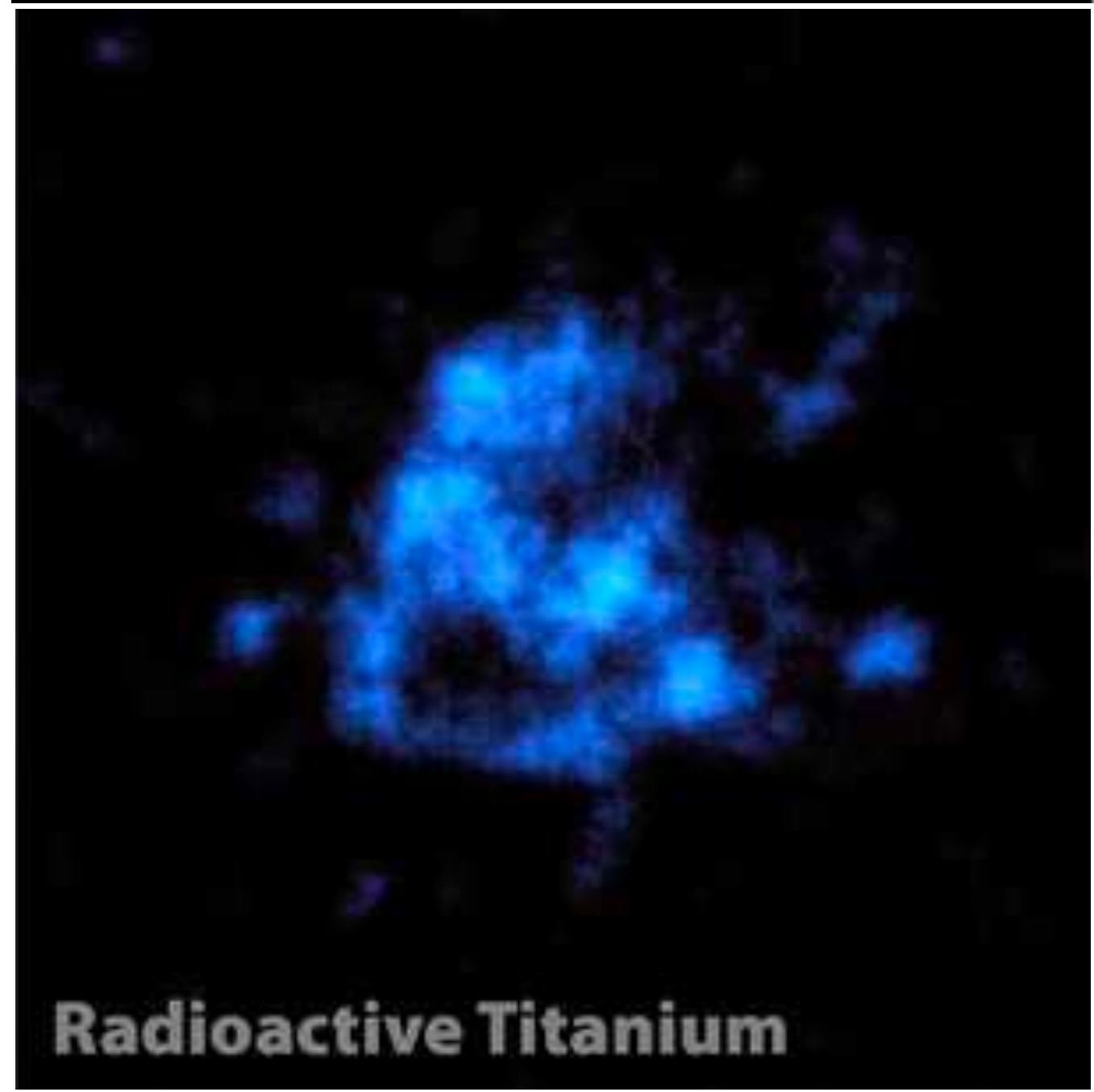
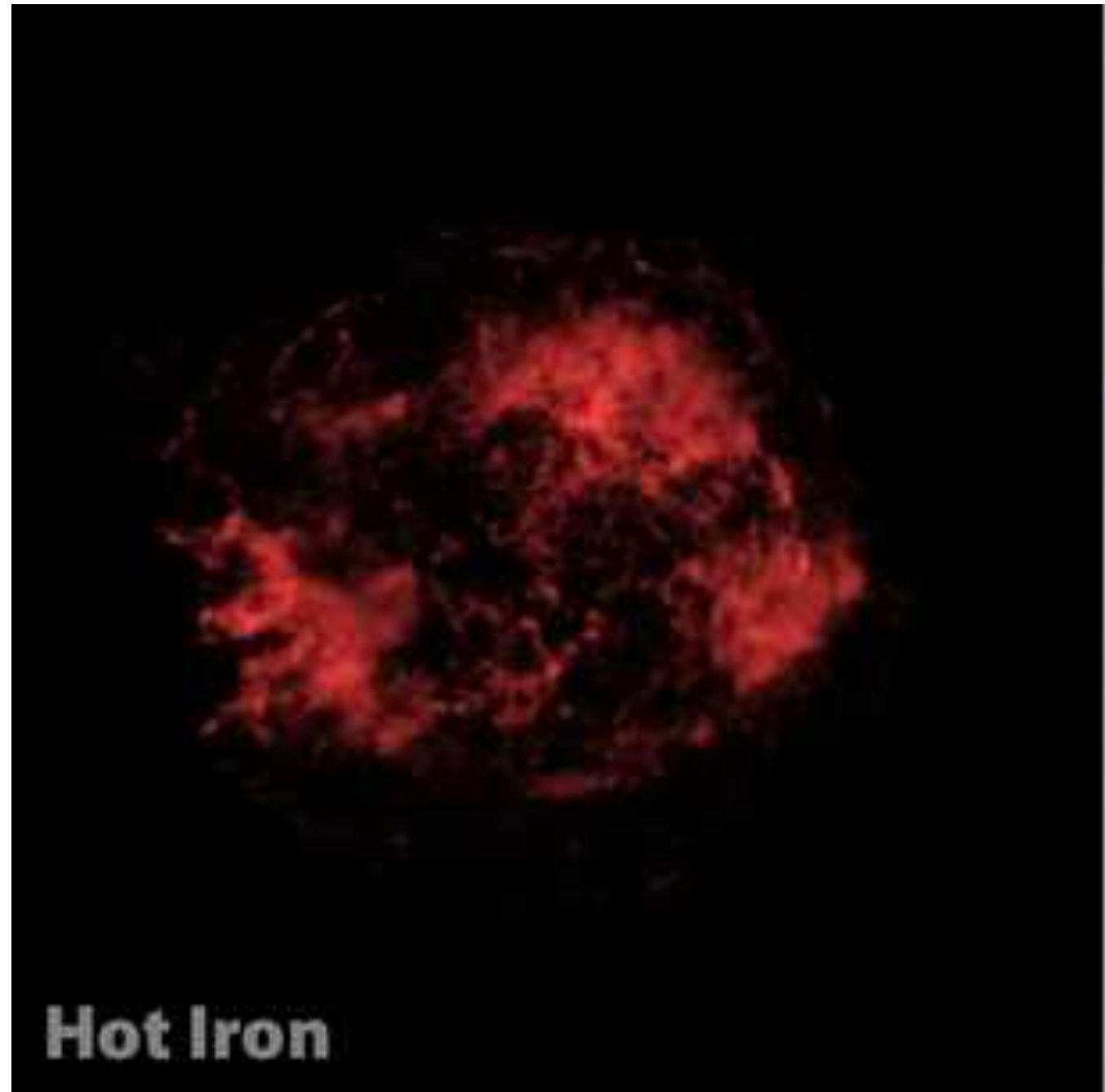


Hamaguchi+ 18

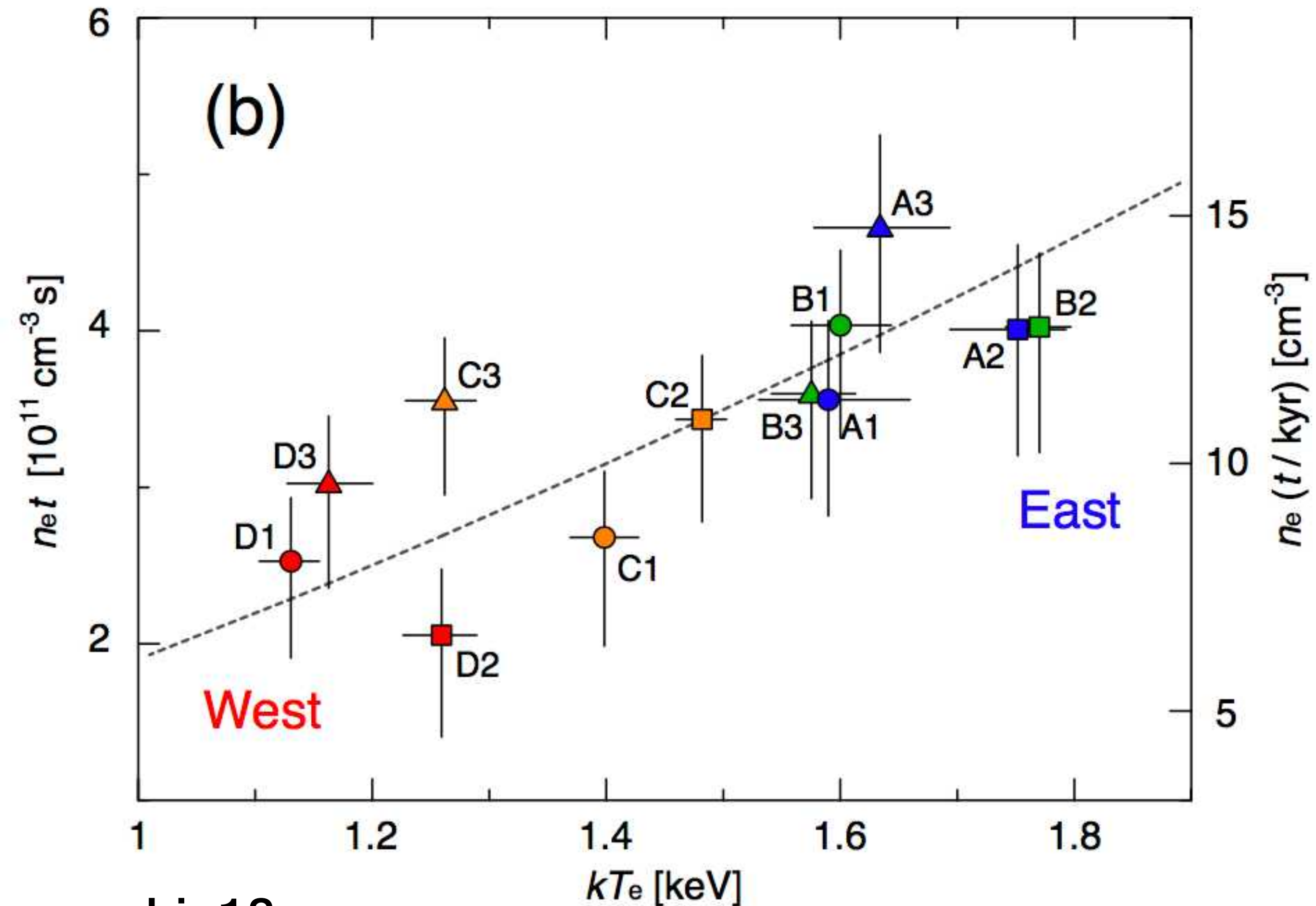
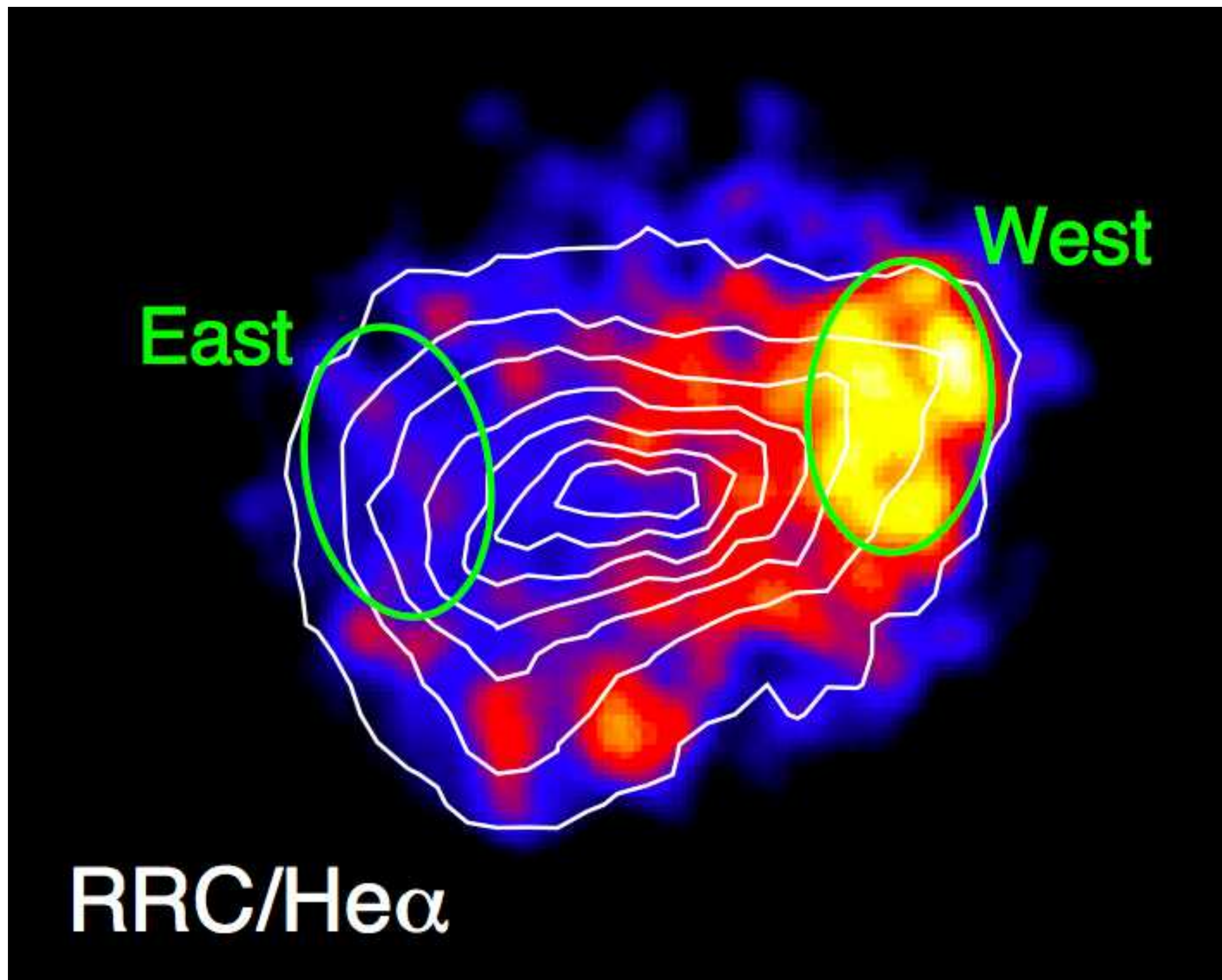


Inverse Compton from the shock

Hamaguchi+ 18

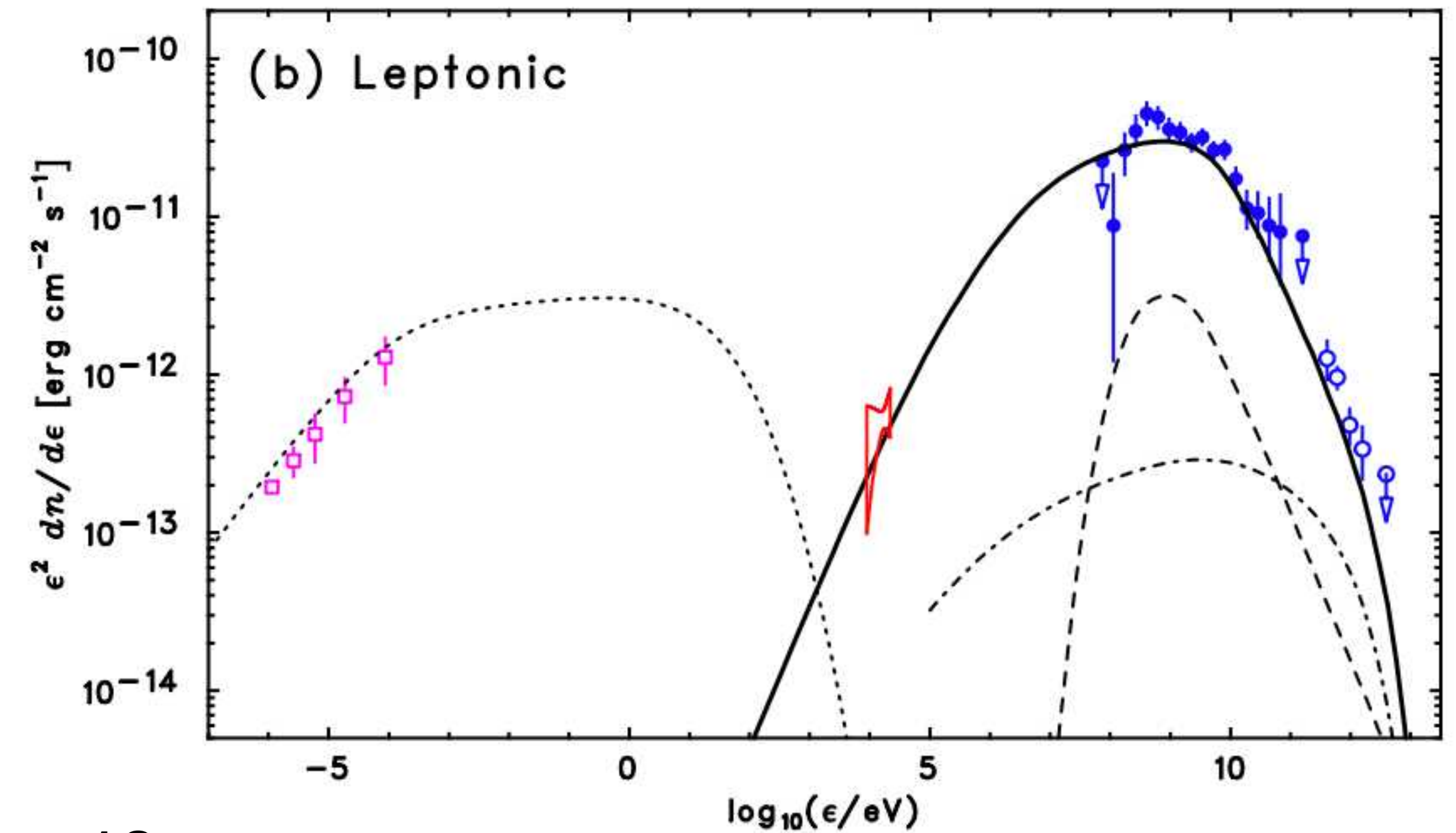
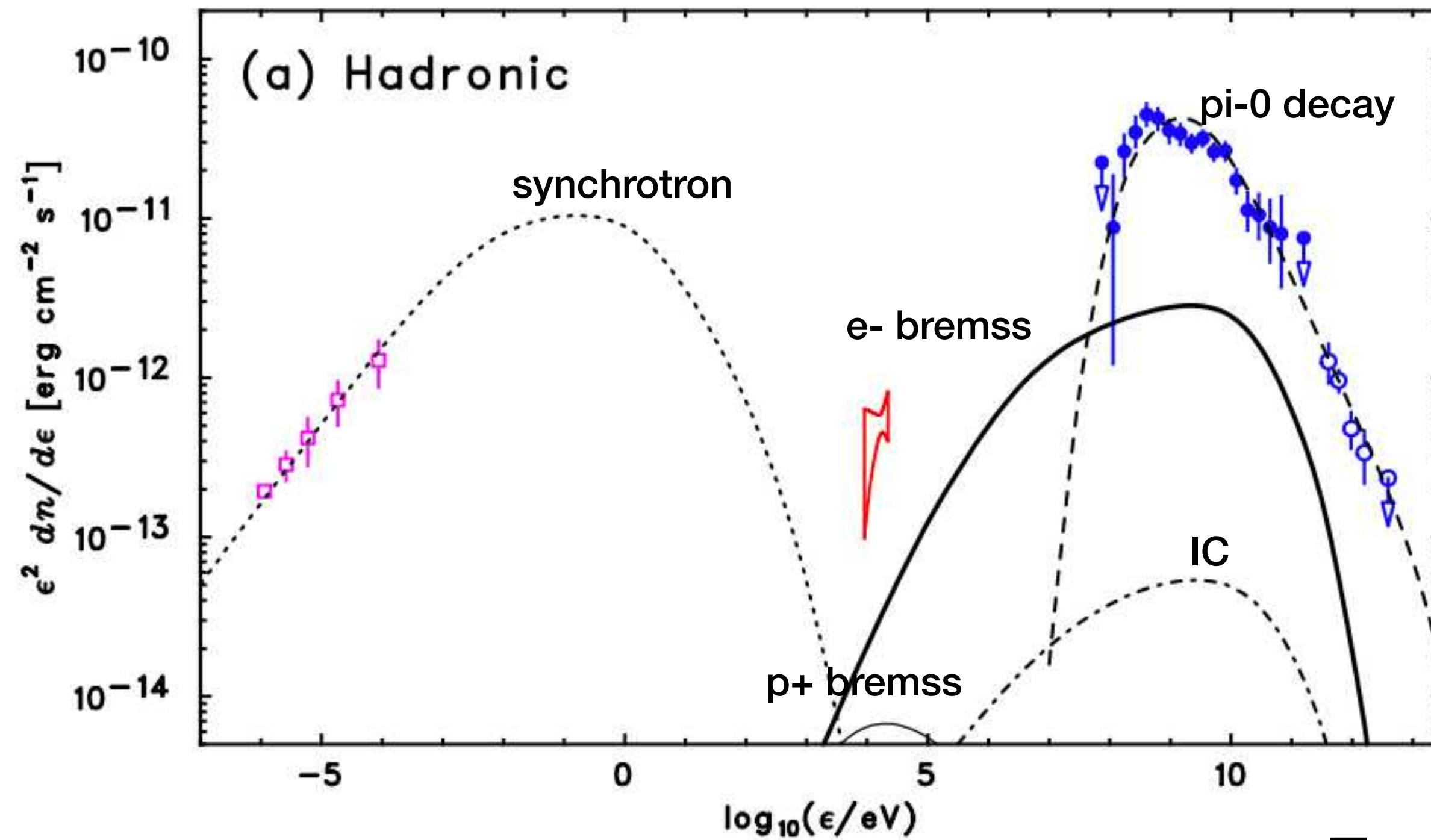
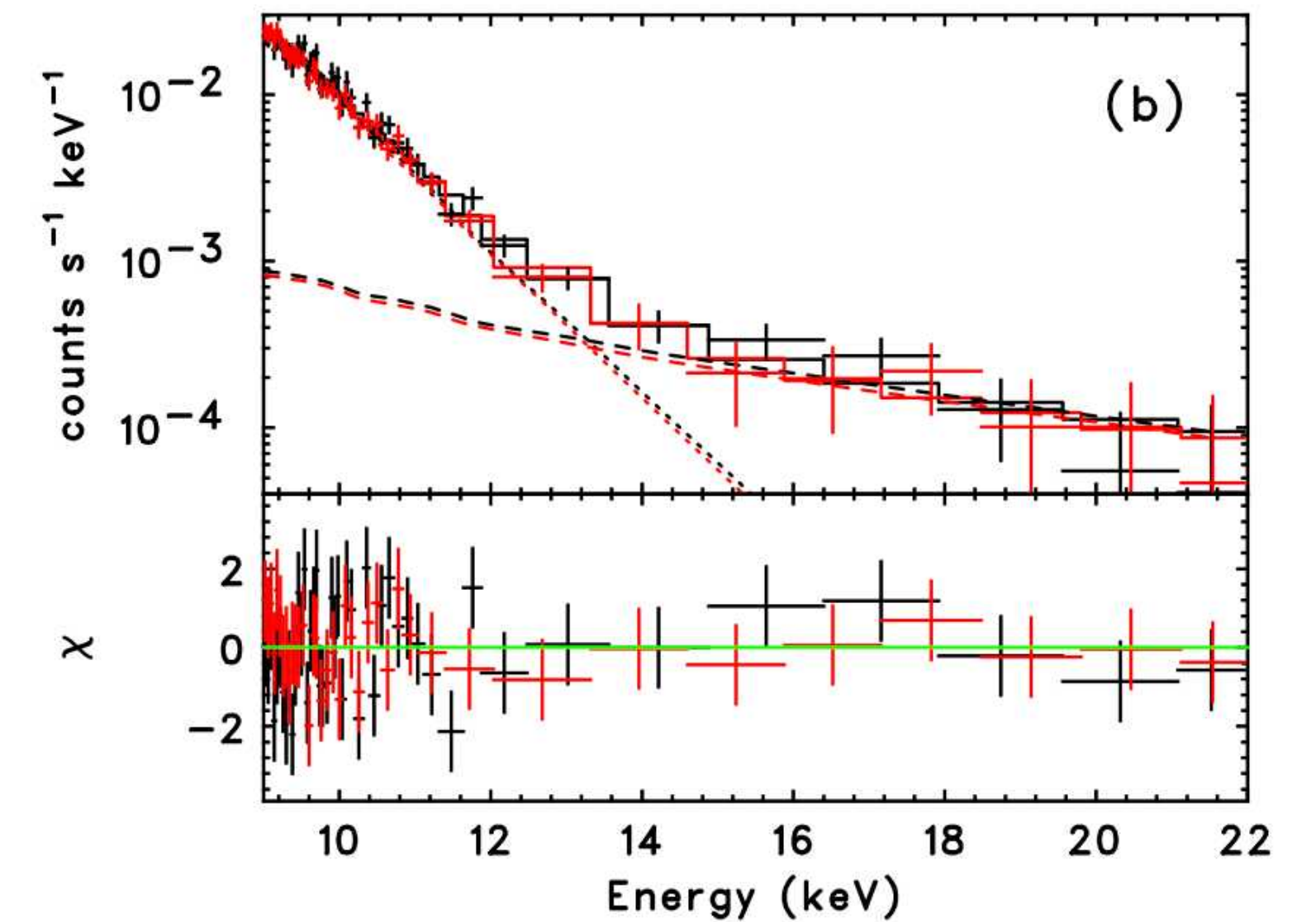


Supernova Remnant W49B: Physics of Shocks



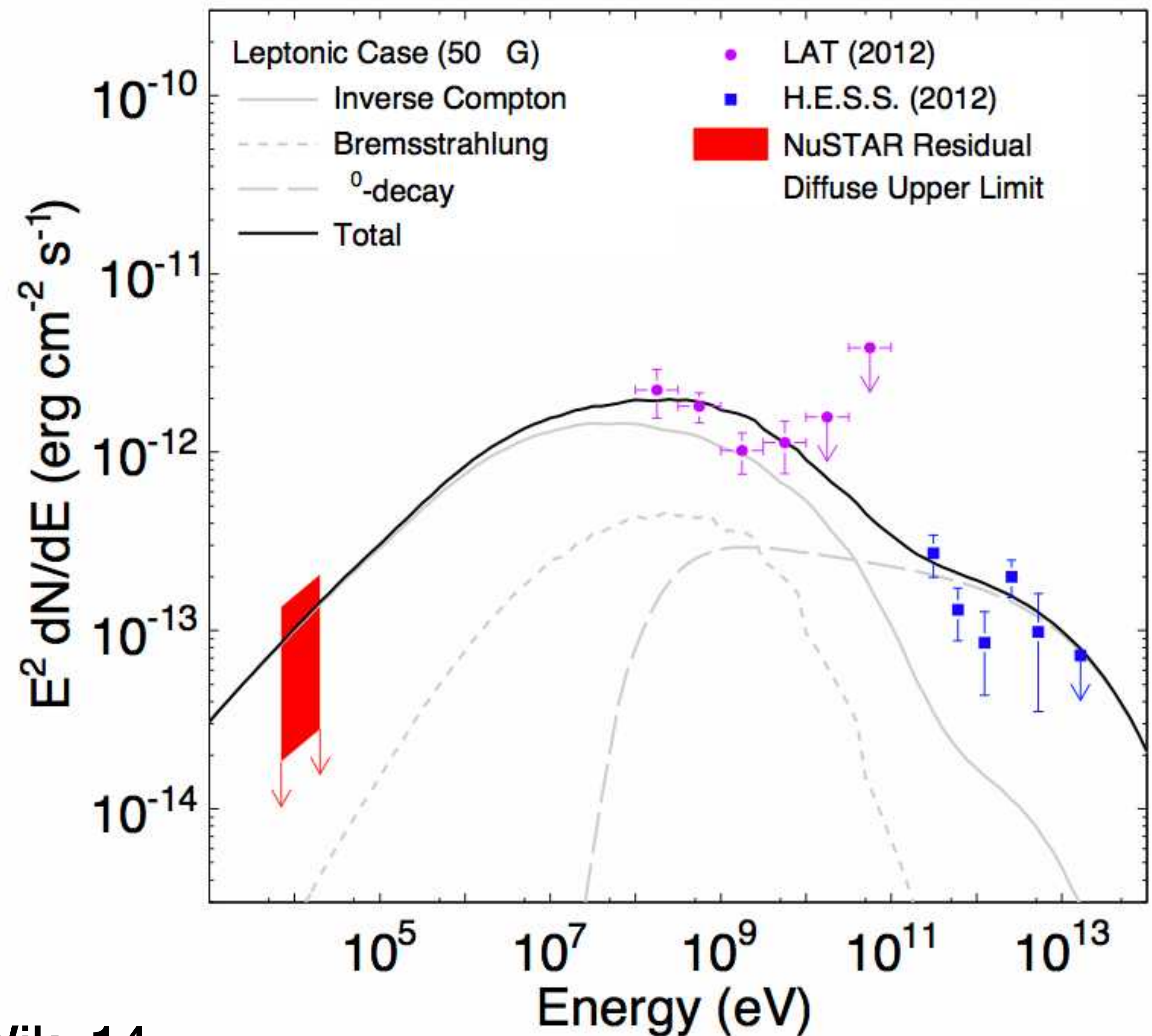
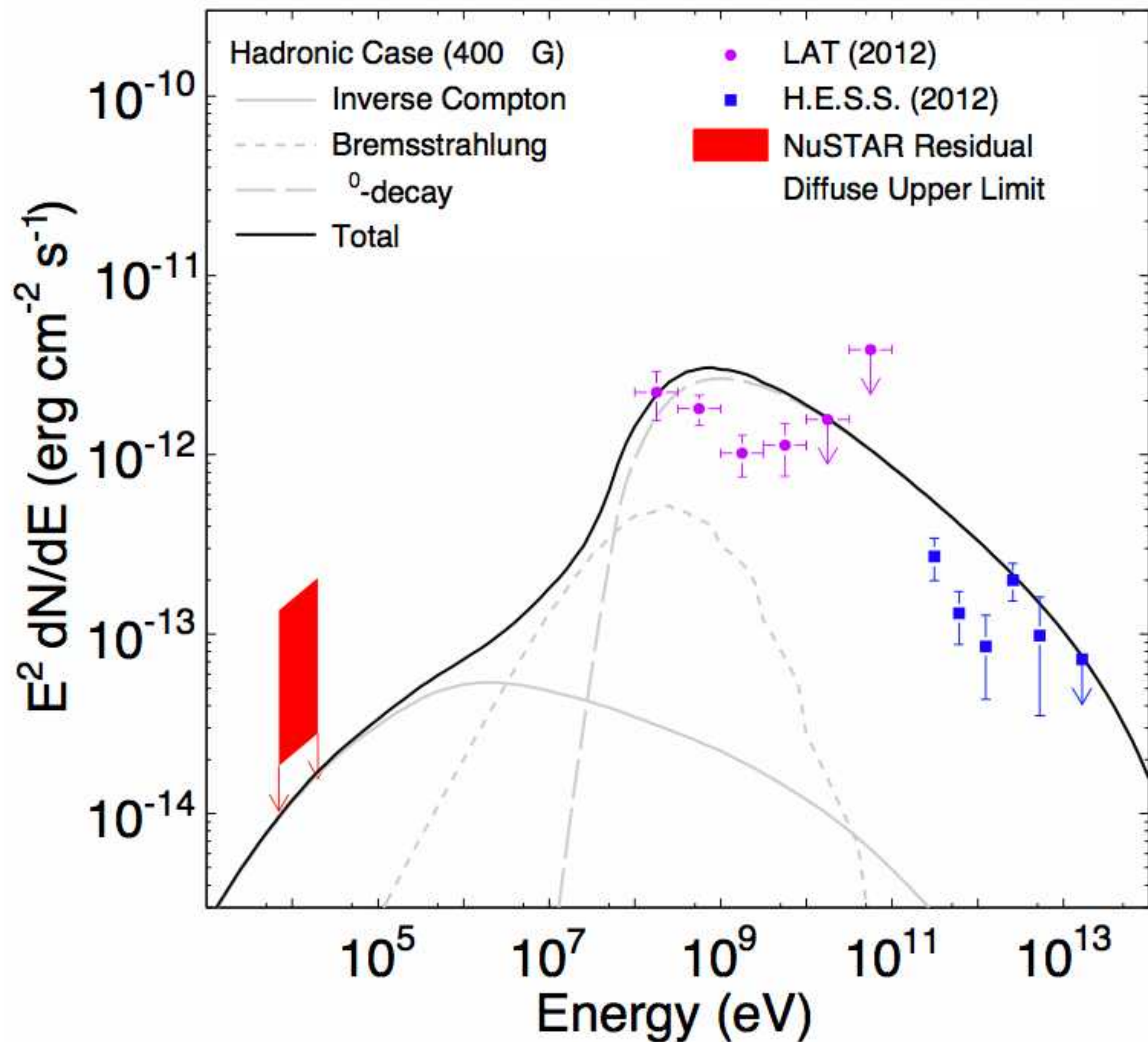
Yamaguchi+18

Supernova Remnant W49B: Physics of Shocks



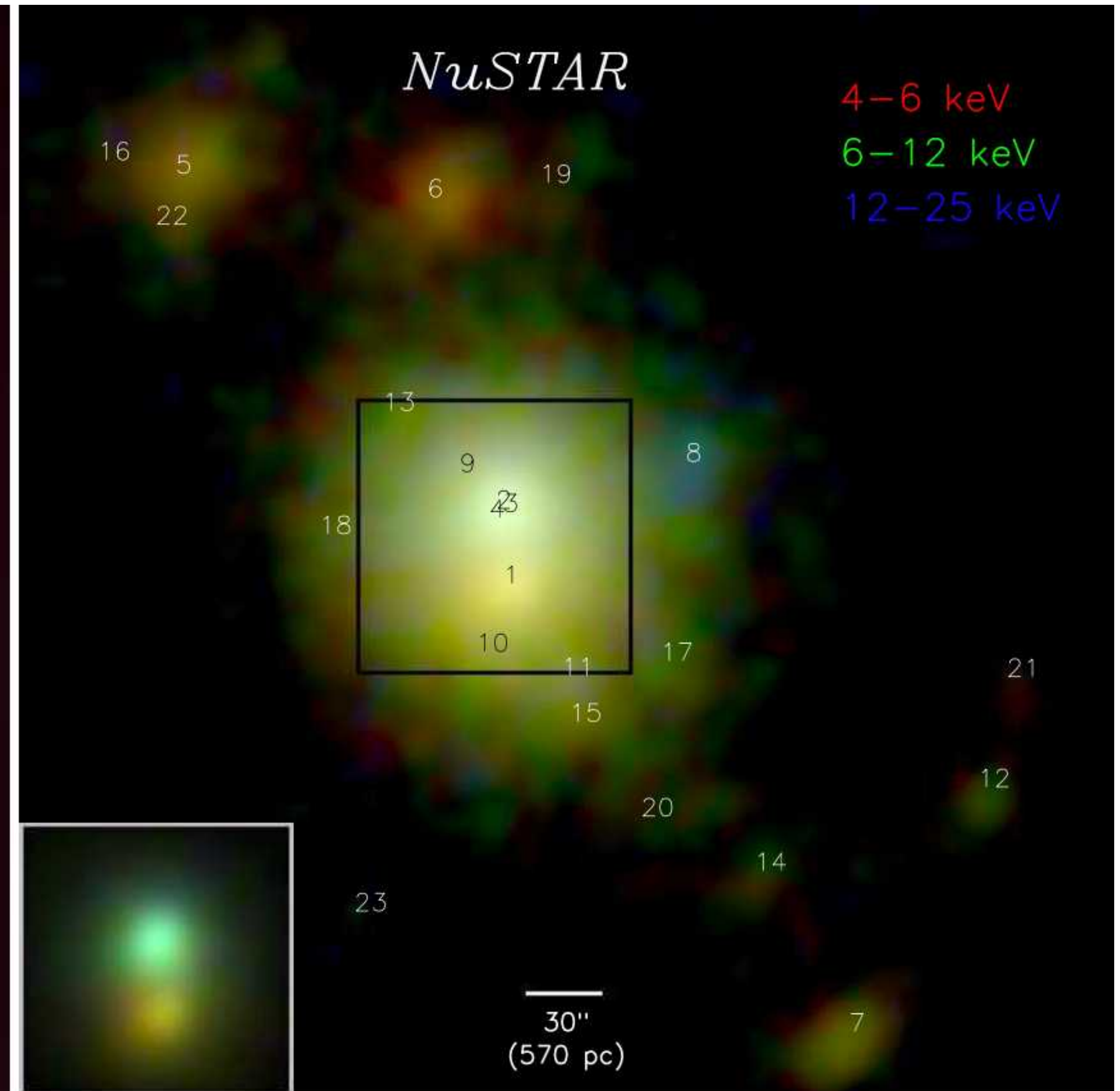
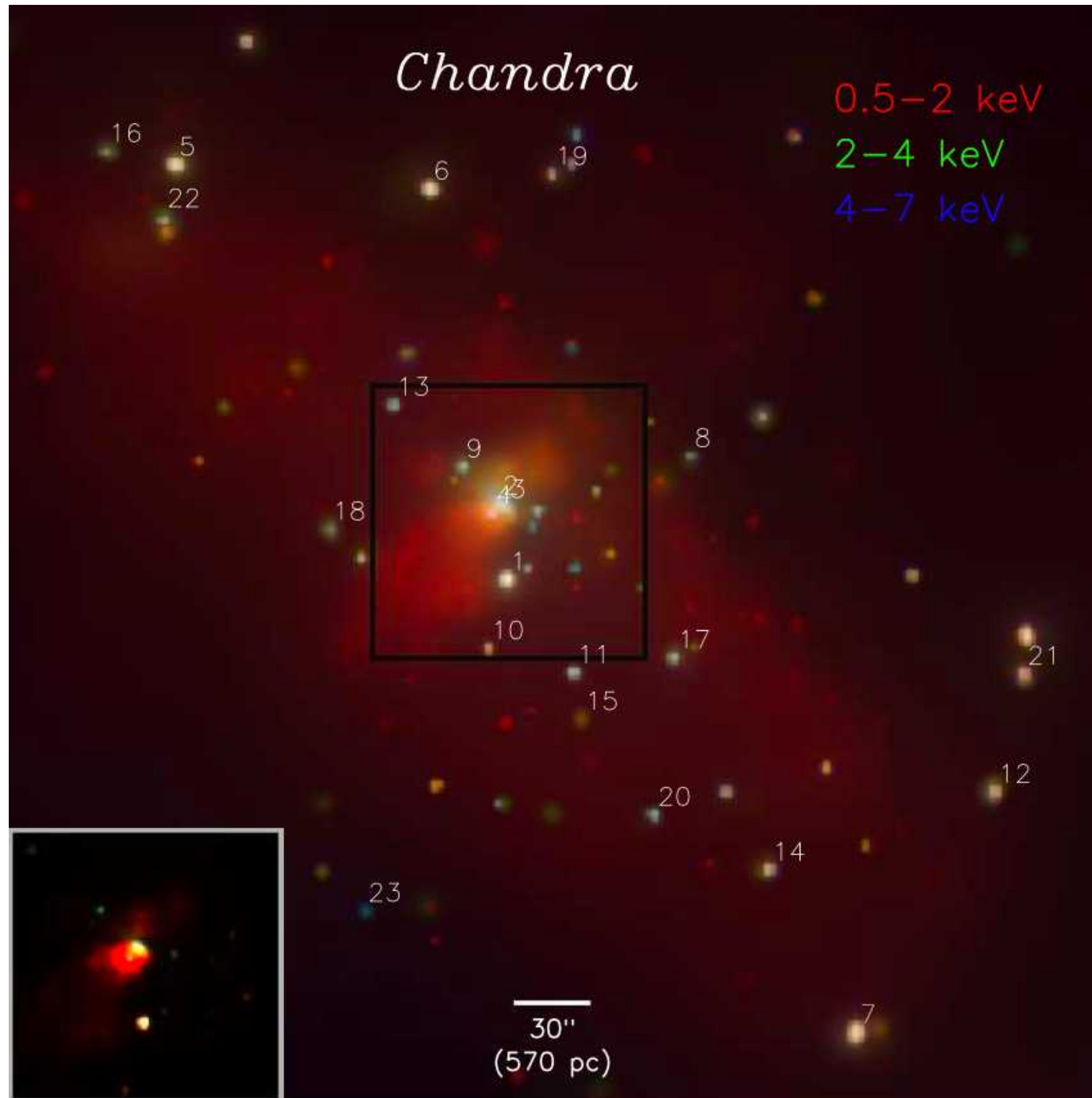
Tanaka+18

NGC 253: Effect of all SNRs



Wik+14

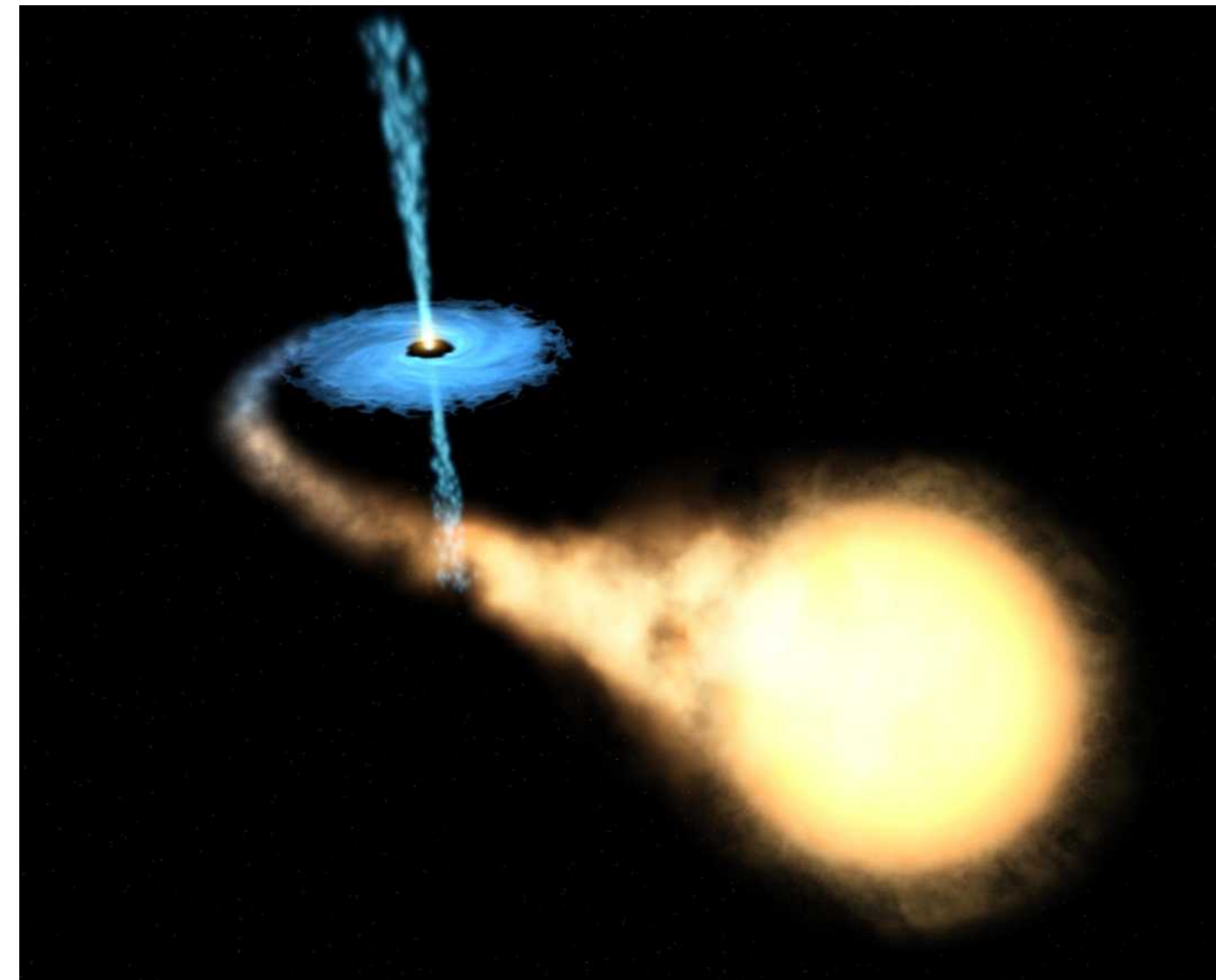
NGC 253: What we do detect: XRBs



X-ray emitting binaries

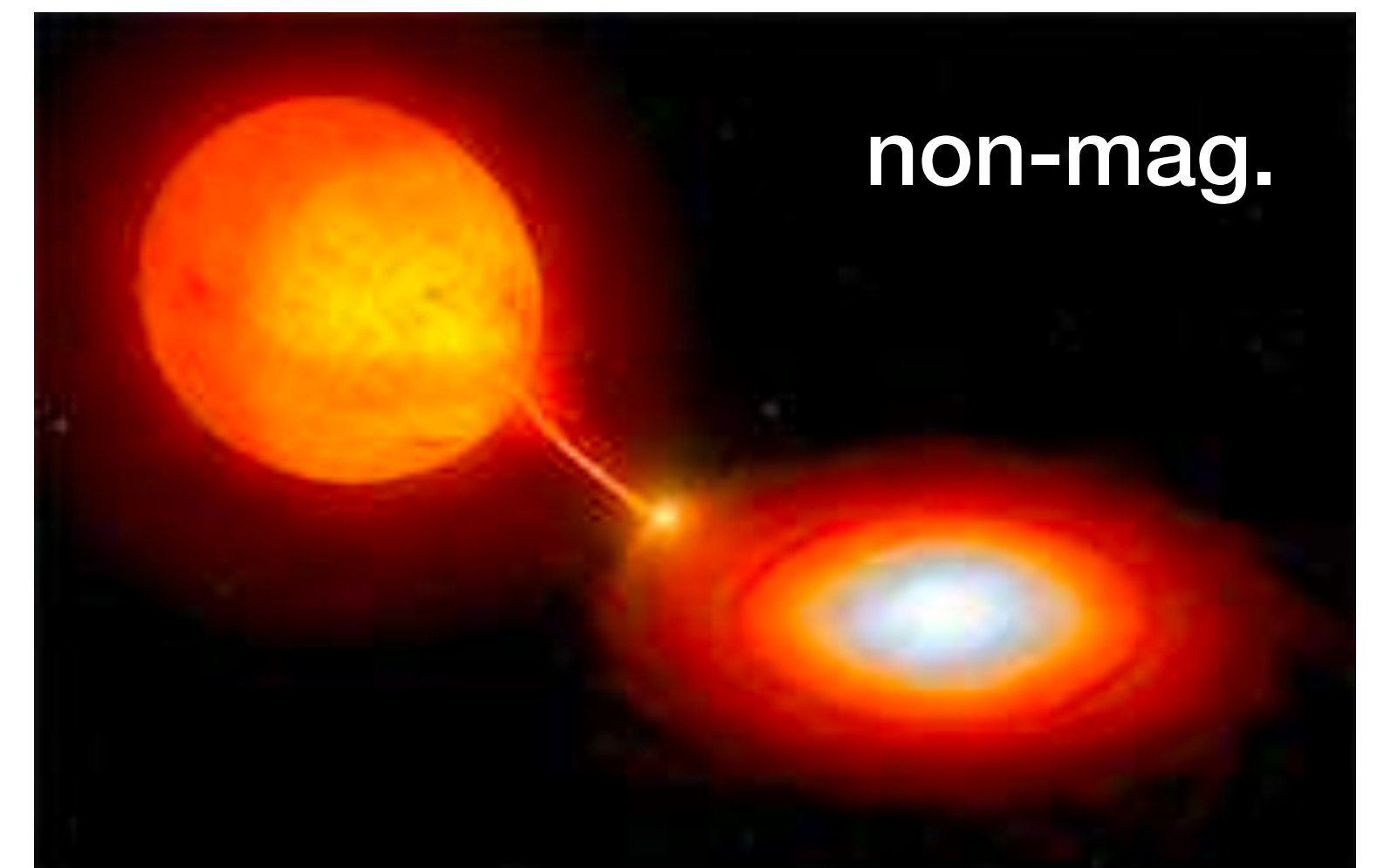


High Mass donor
BH or NS



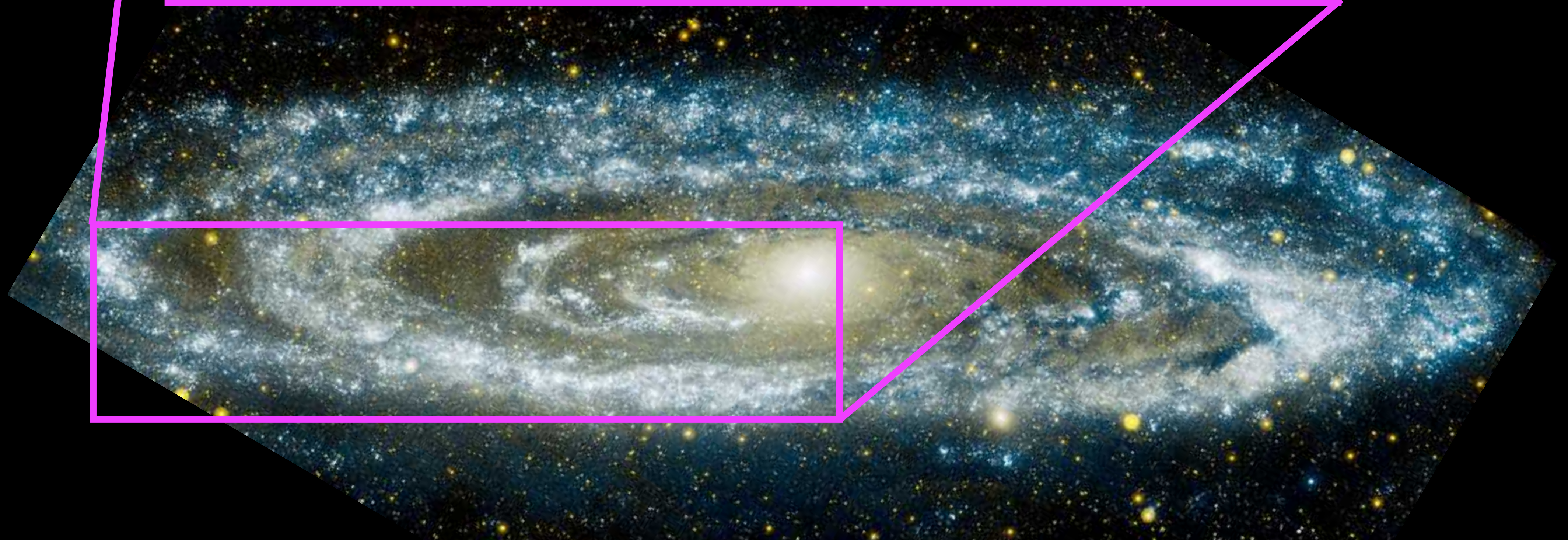
Low Mass donor
BH or NS

Cataclysmic Variables
white dwarf



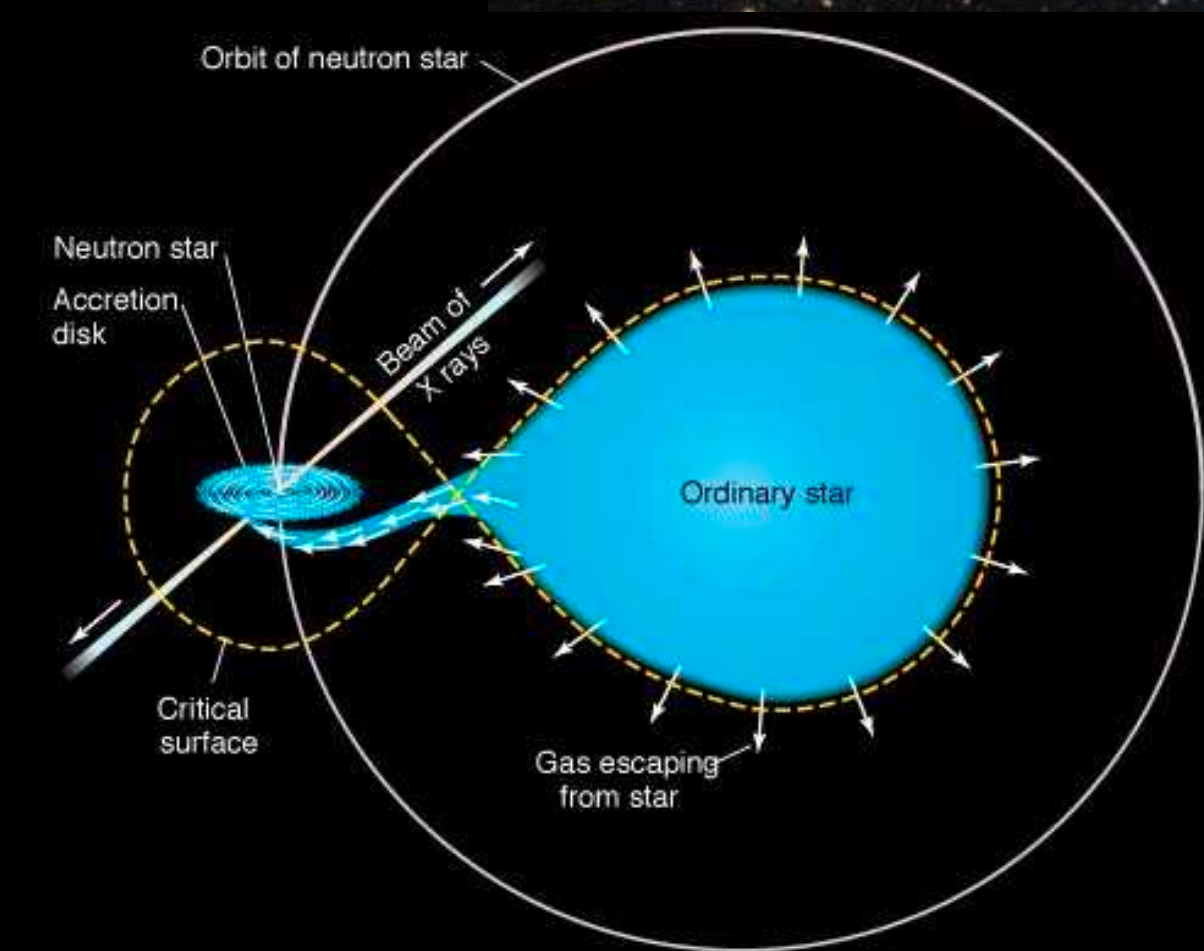
The Andromeda Galaxy, M31

Hubble footprint



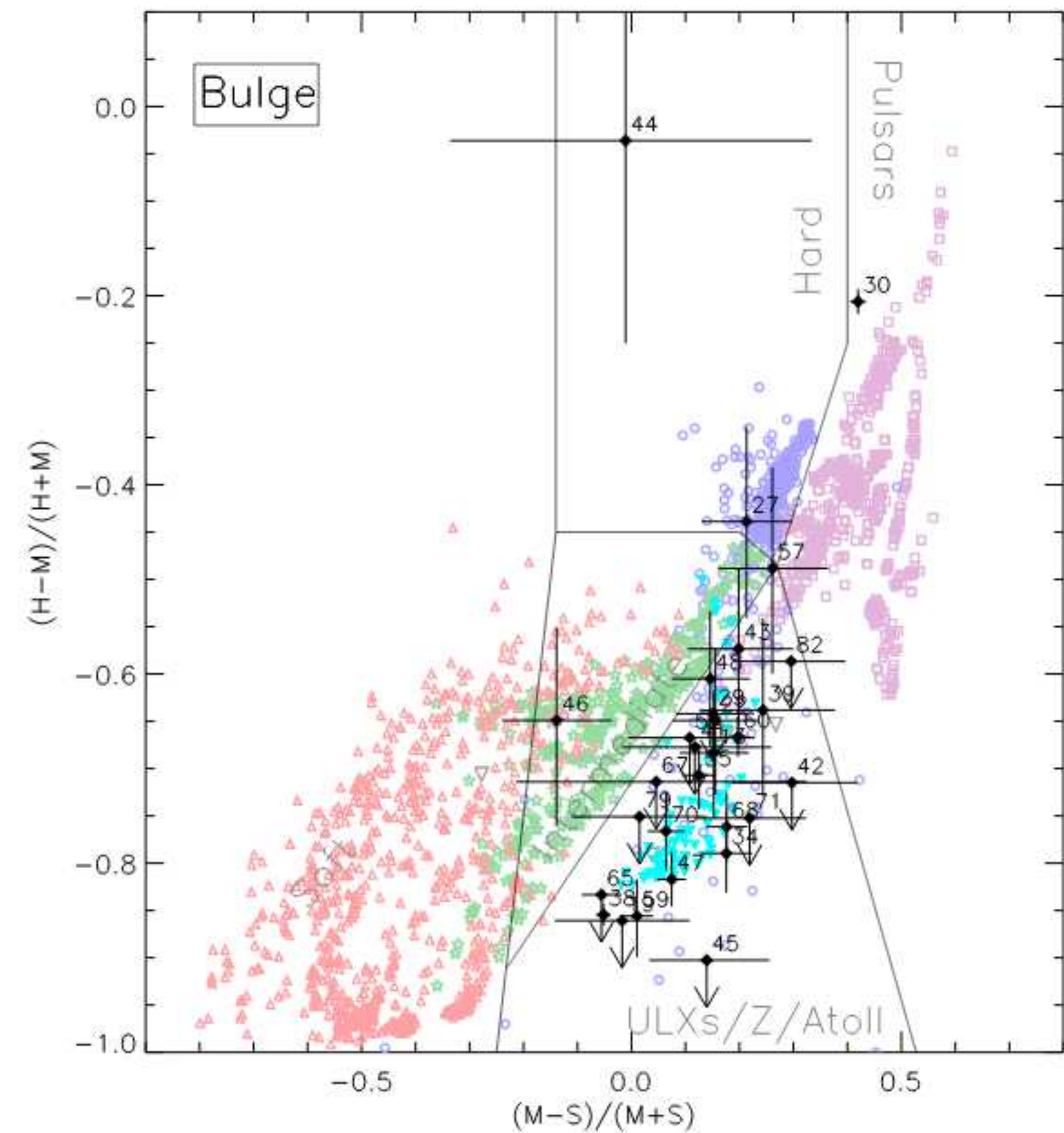
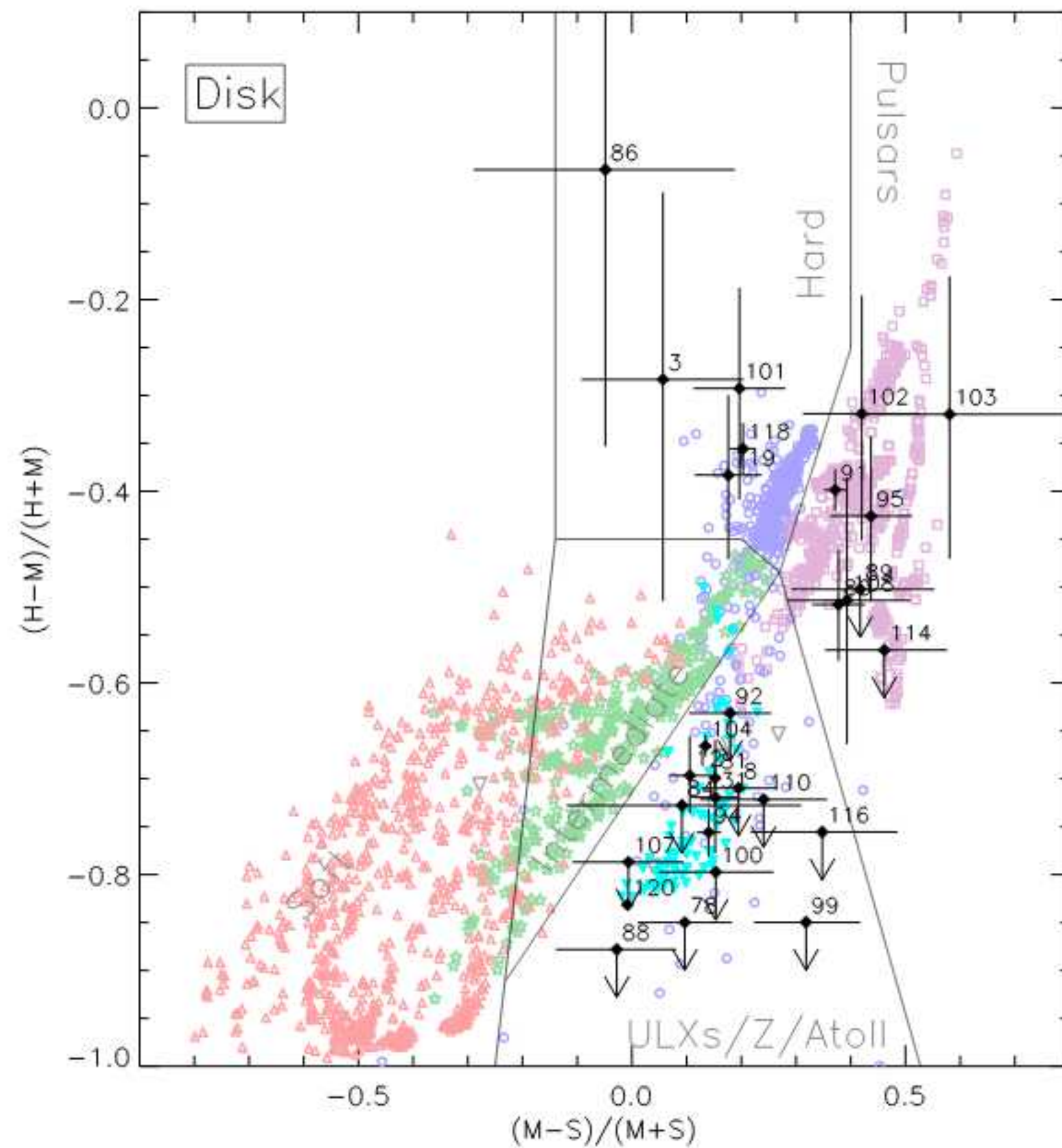
The Andromeda Galaxy, M31

NuSTAR



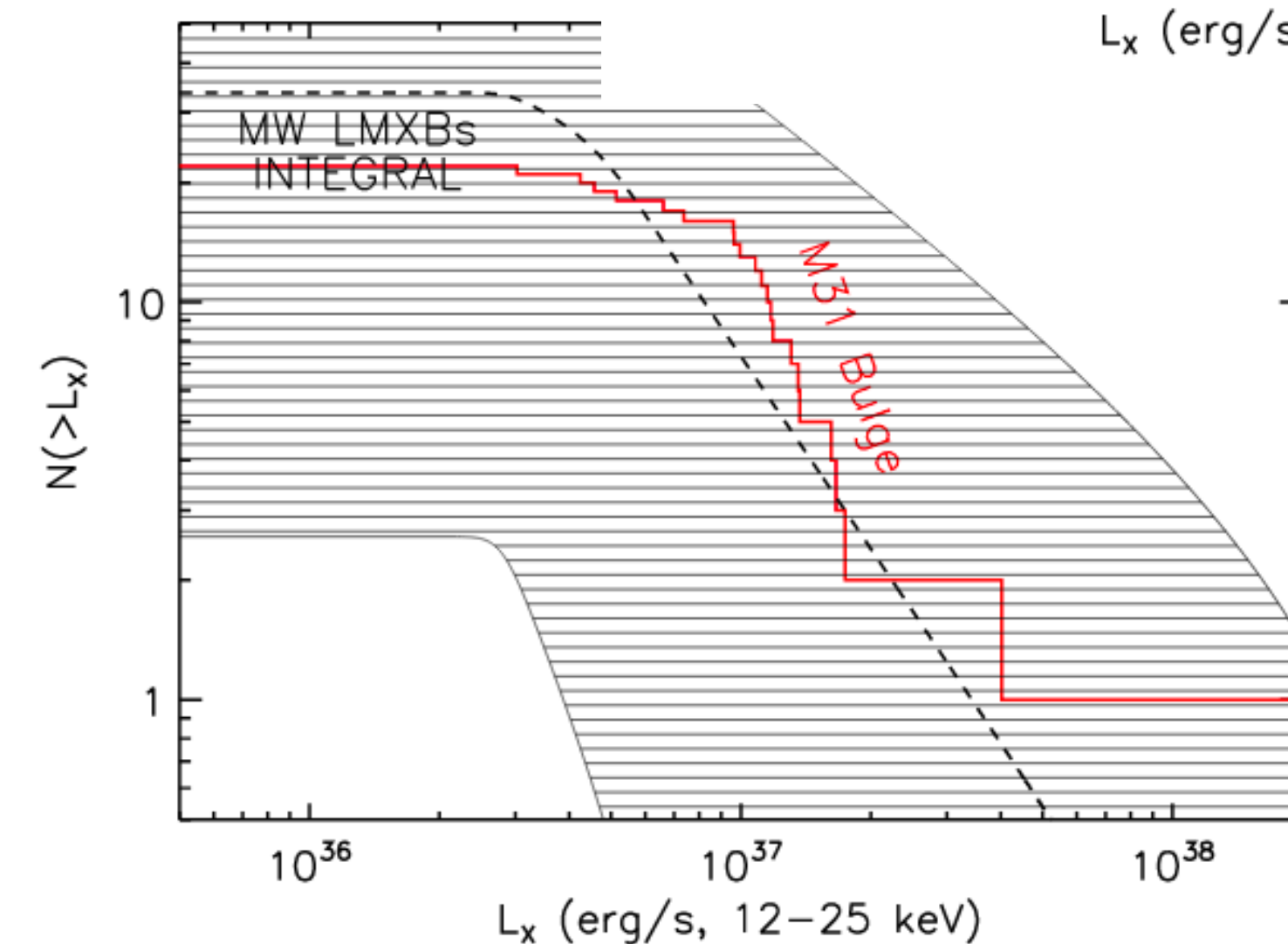
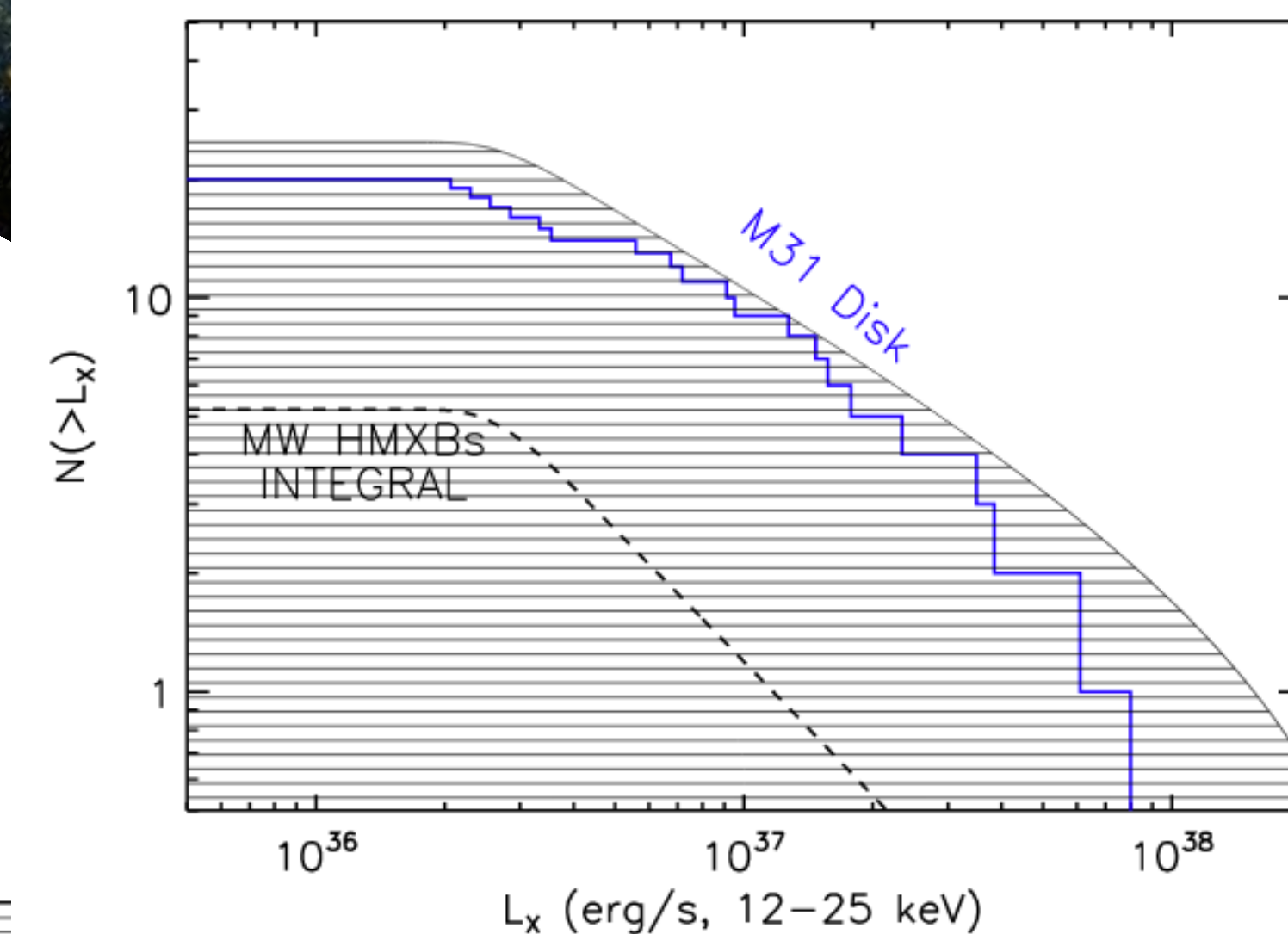
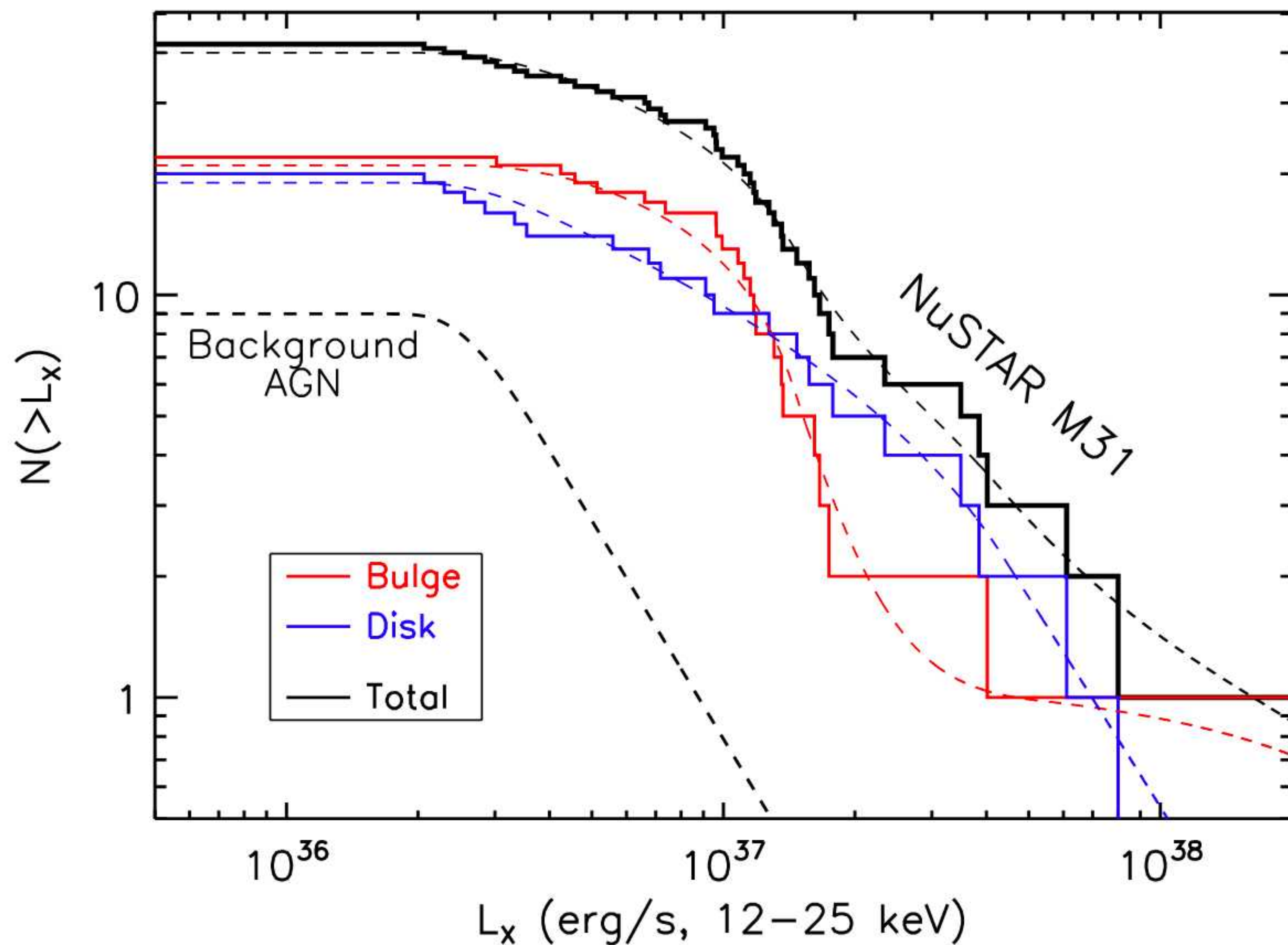
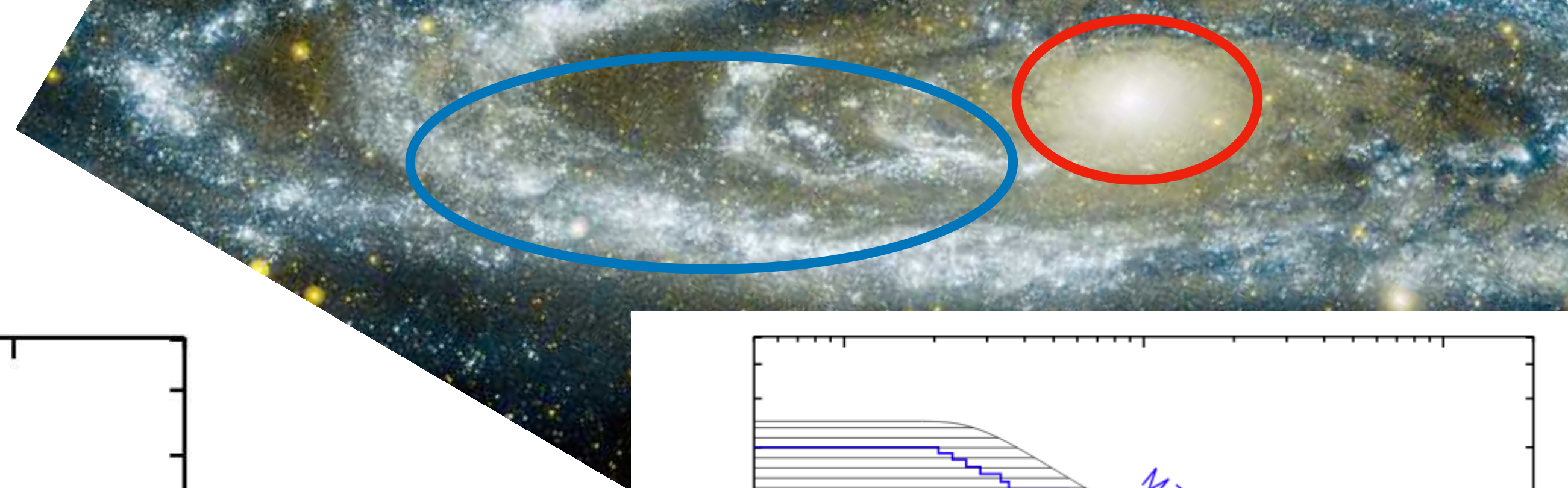
GALEX

M31 XRB CO Nature



Wik+ in prep

M31 XRB Population

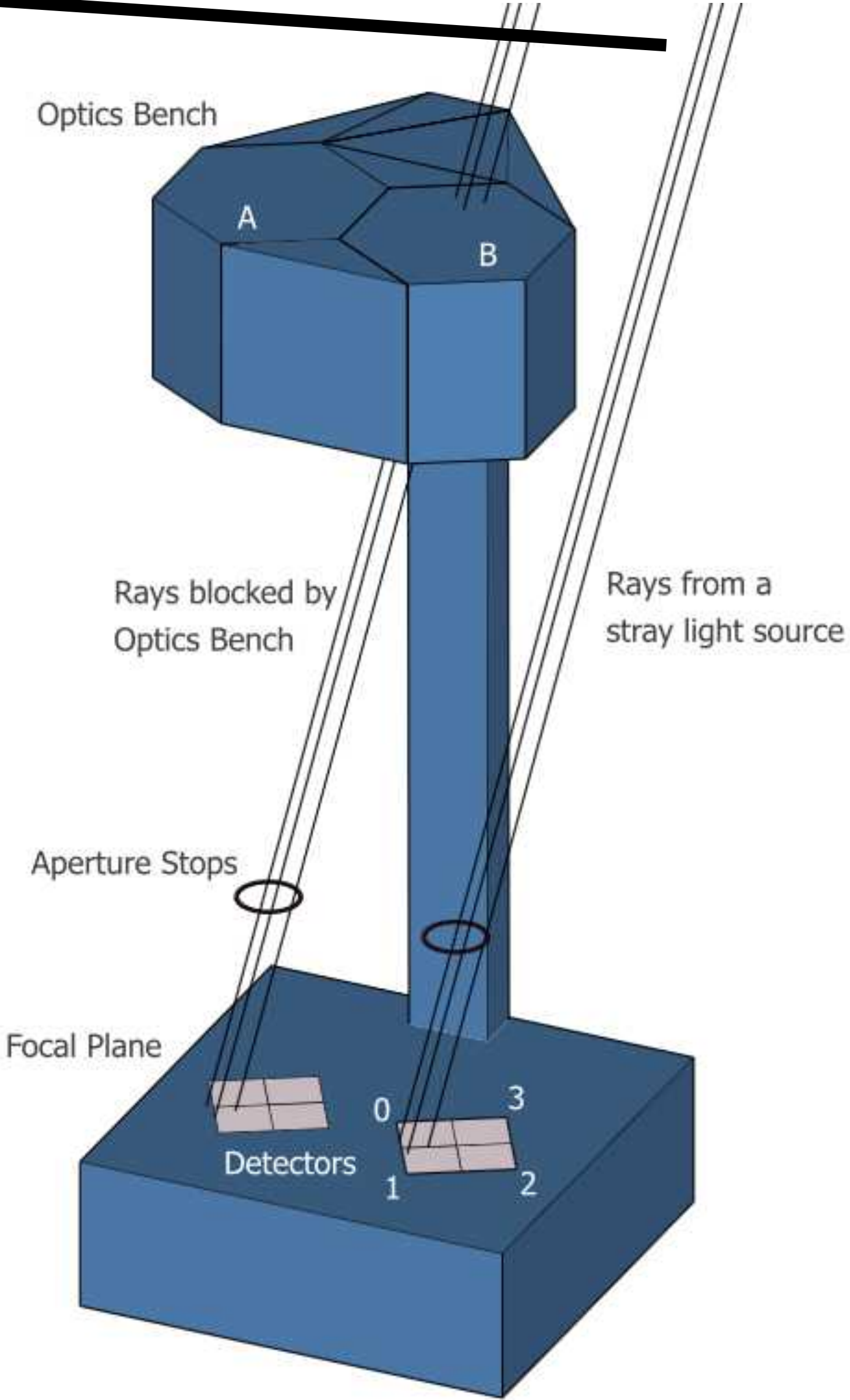
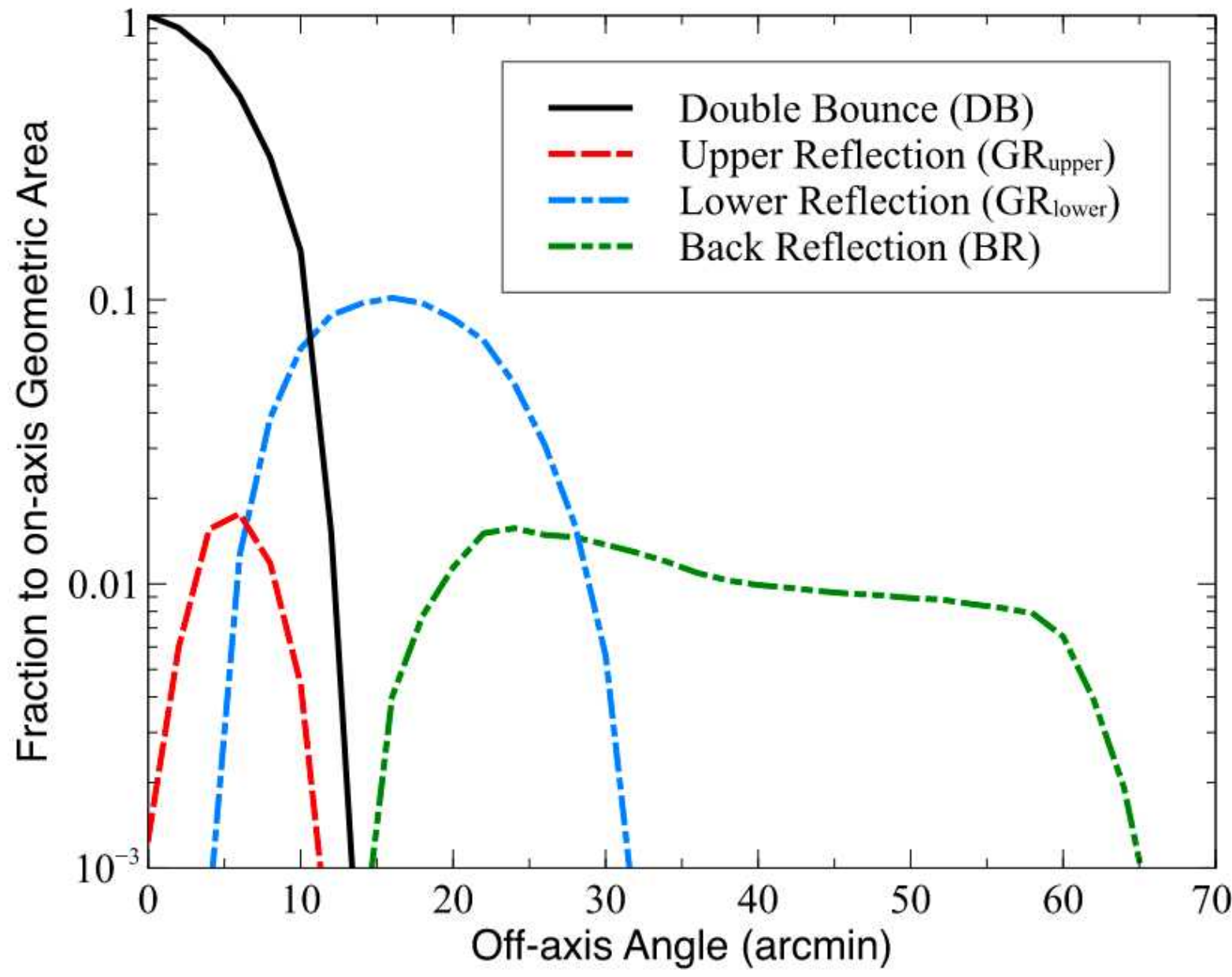
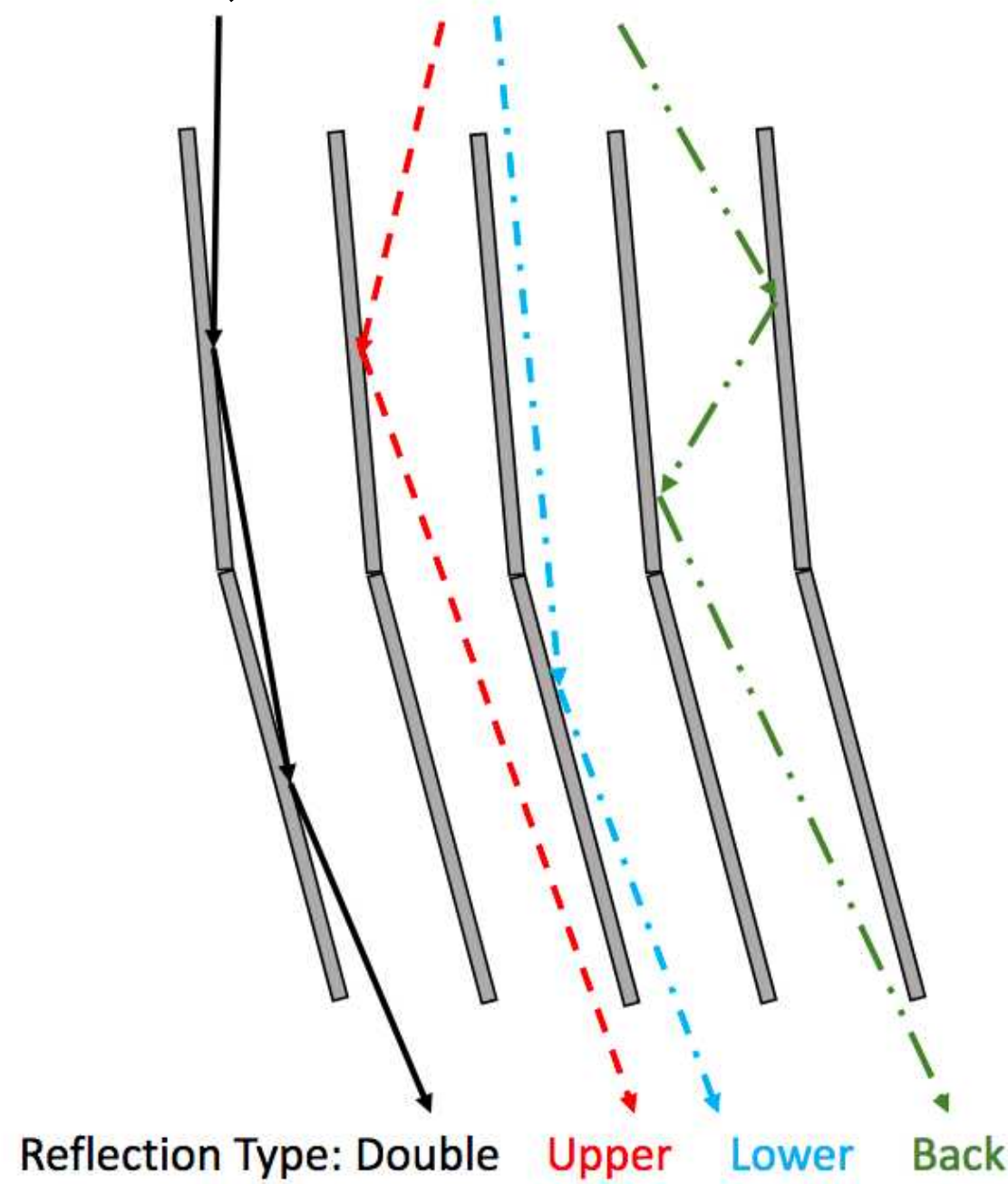
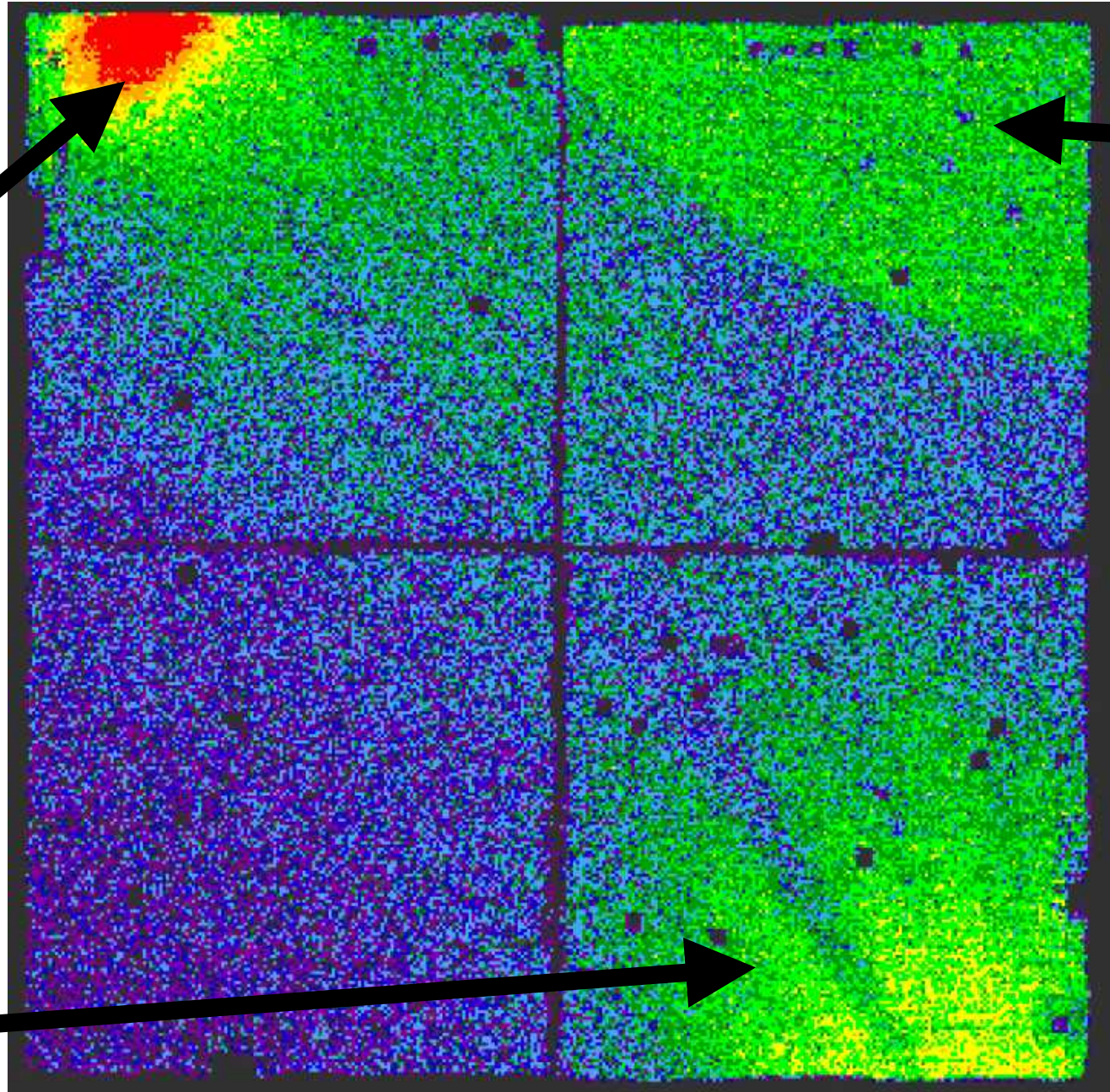


Wik+ in prep

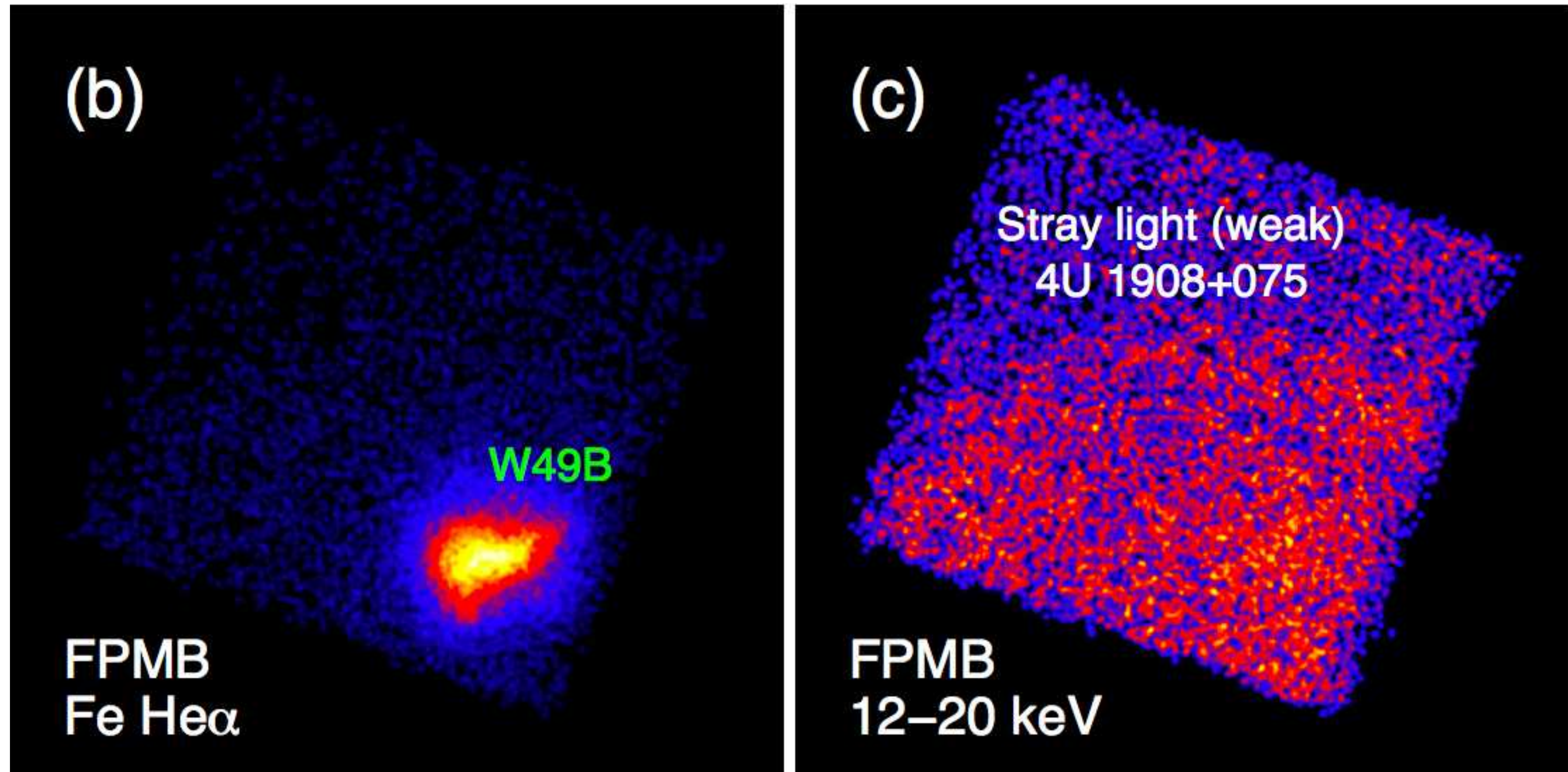
Interlude:

Why is this science “hard”?

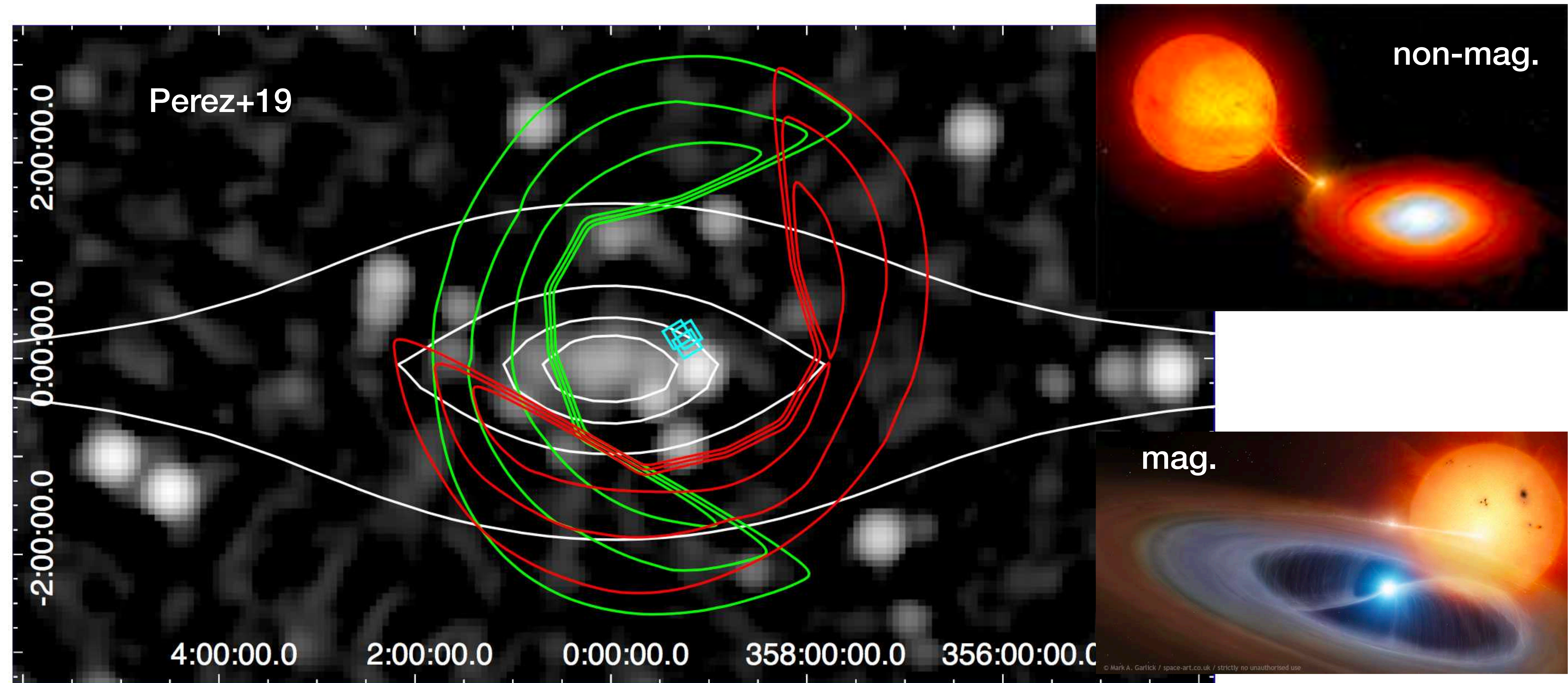
Overcoming technical challenges



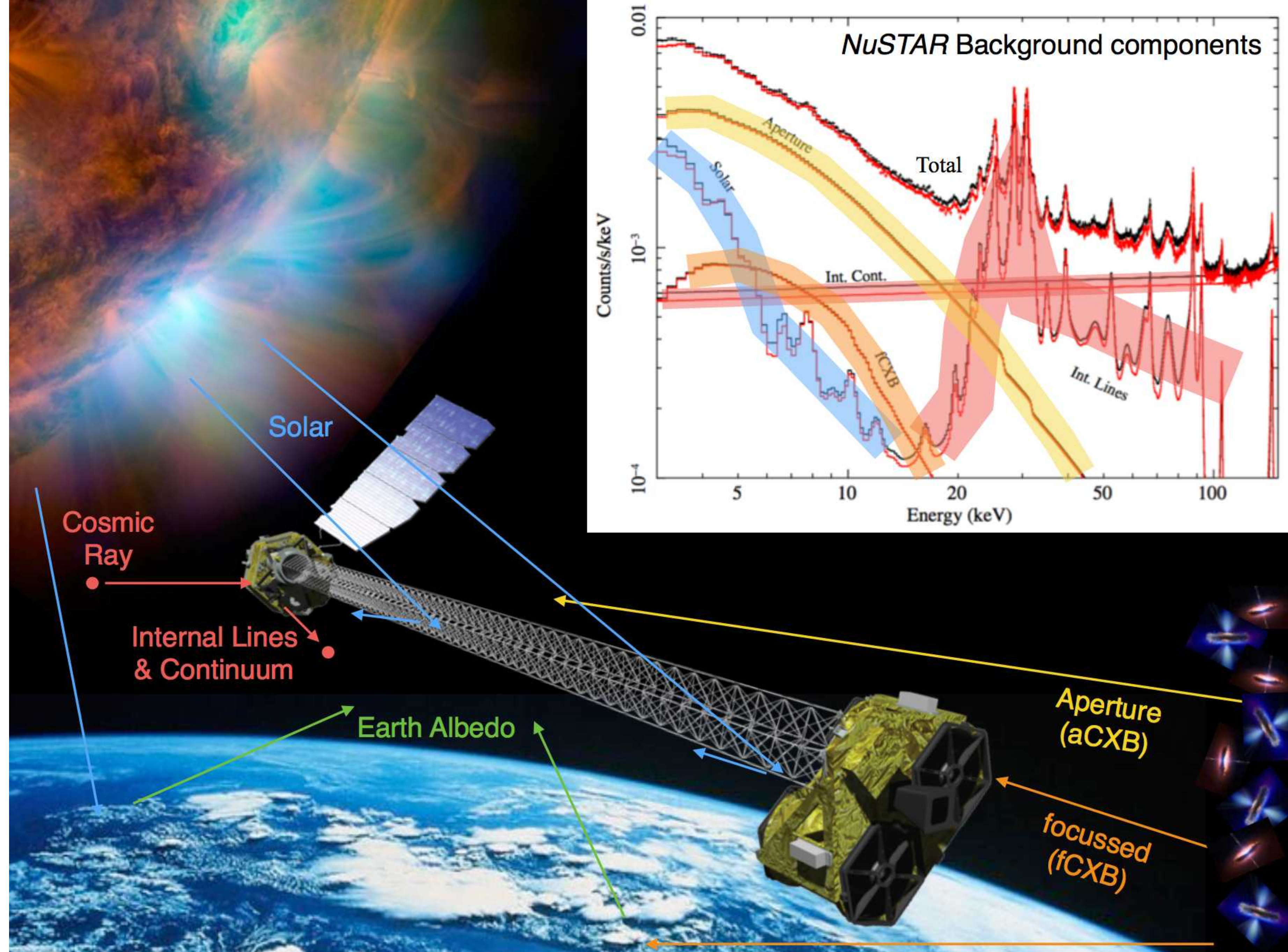
Galactic fields are crowded: stray light common



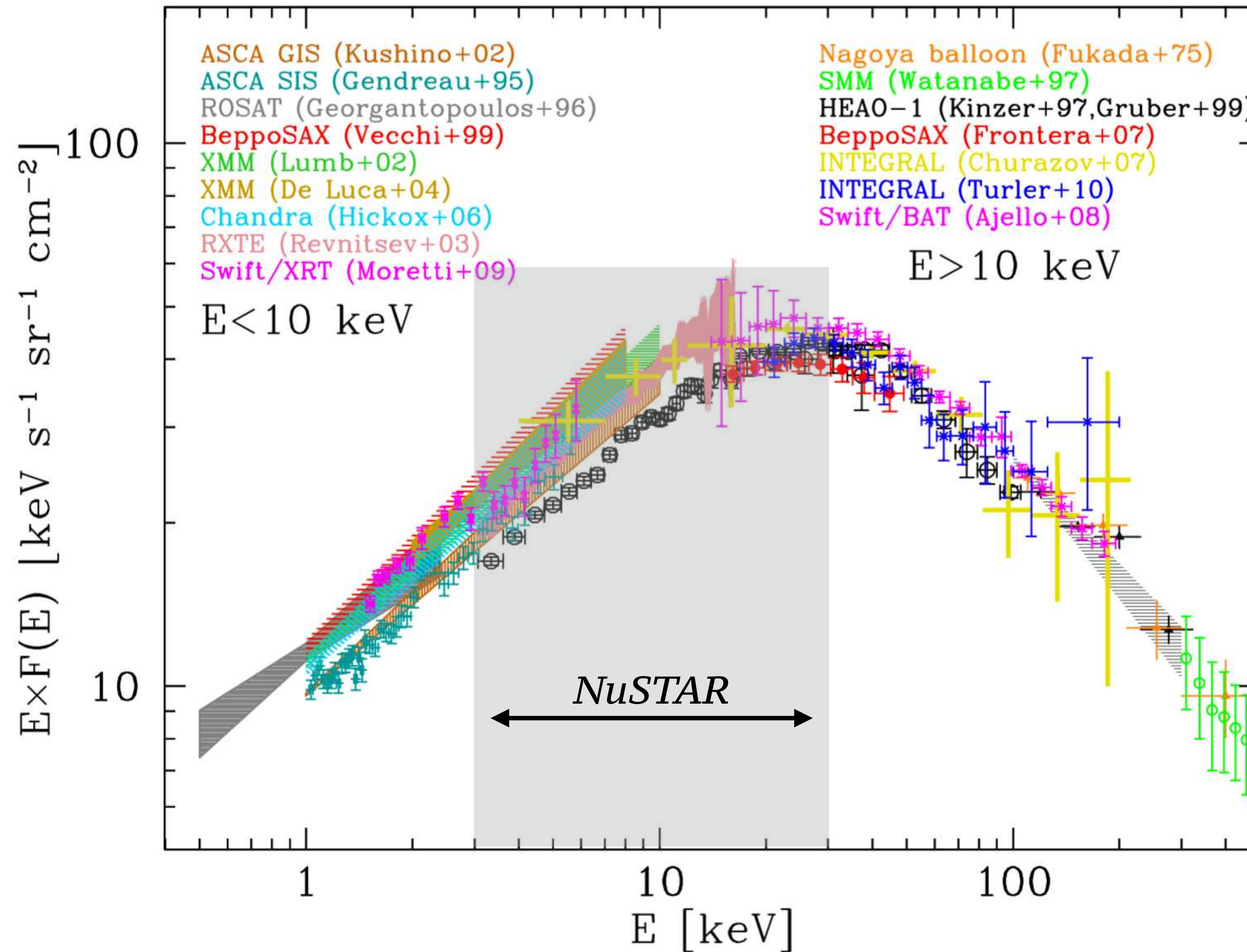
White dwarf binary population in the Galaxy



Stray light
from the
Cosmic X-ray
Background
(CXB)
dominates
other
components
from 3-20 keV

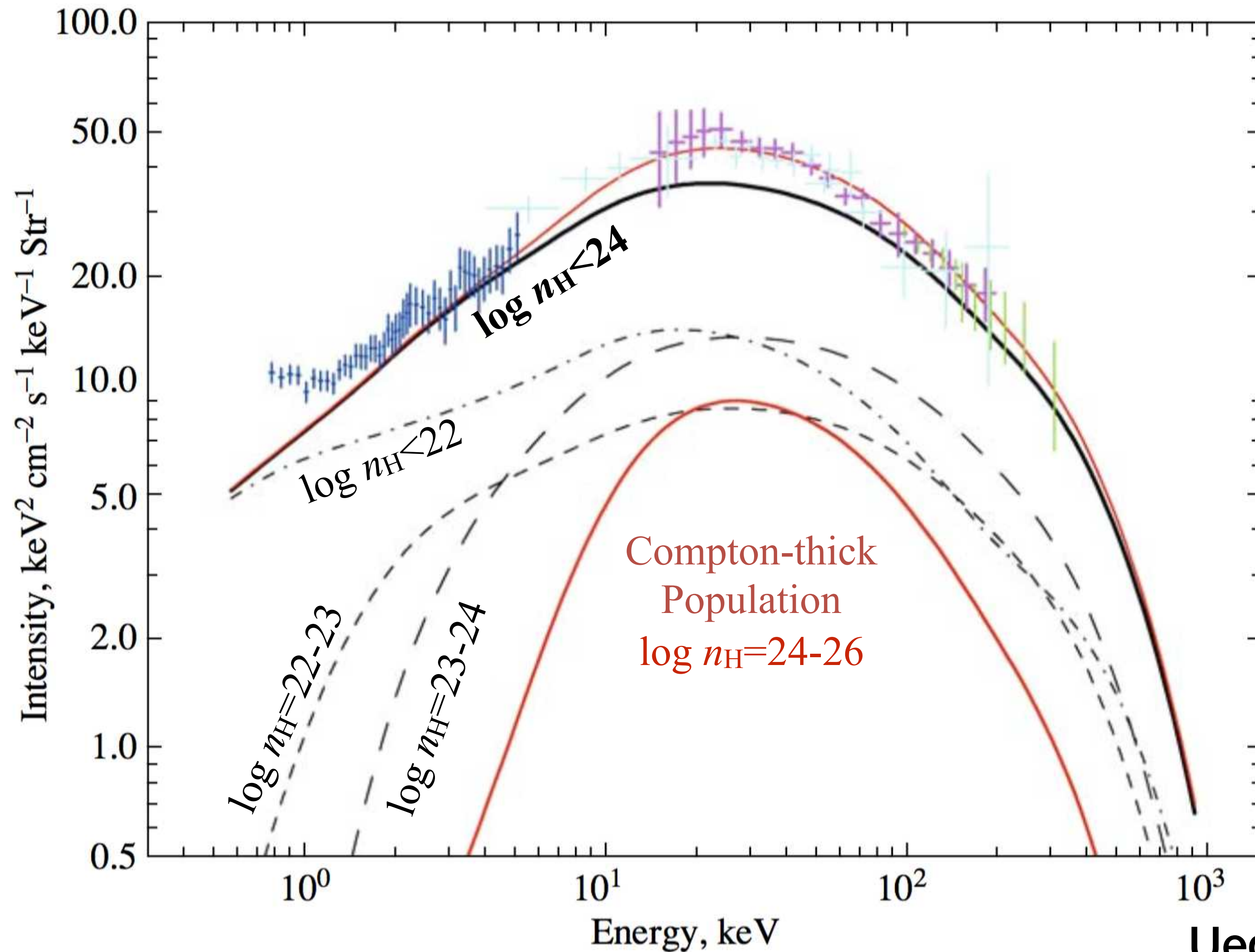


Cosmic X-ray Background (CXB)



Calibration
 uncertainties persist,
 affect AGN population
 synthesis models

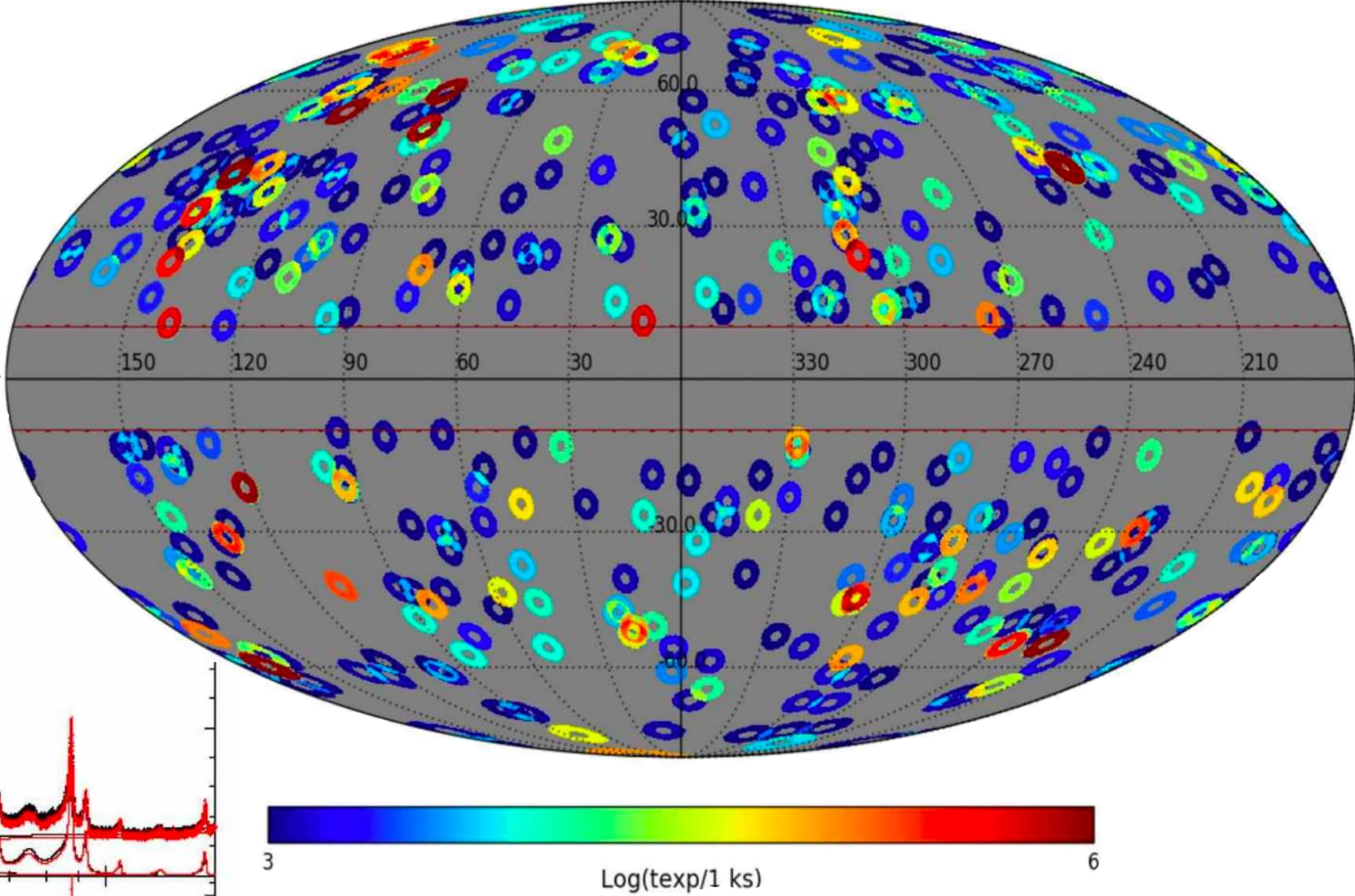
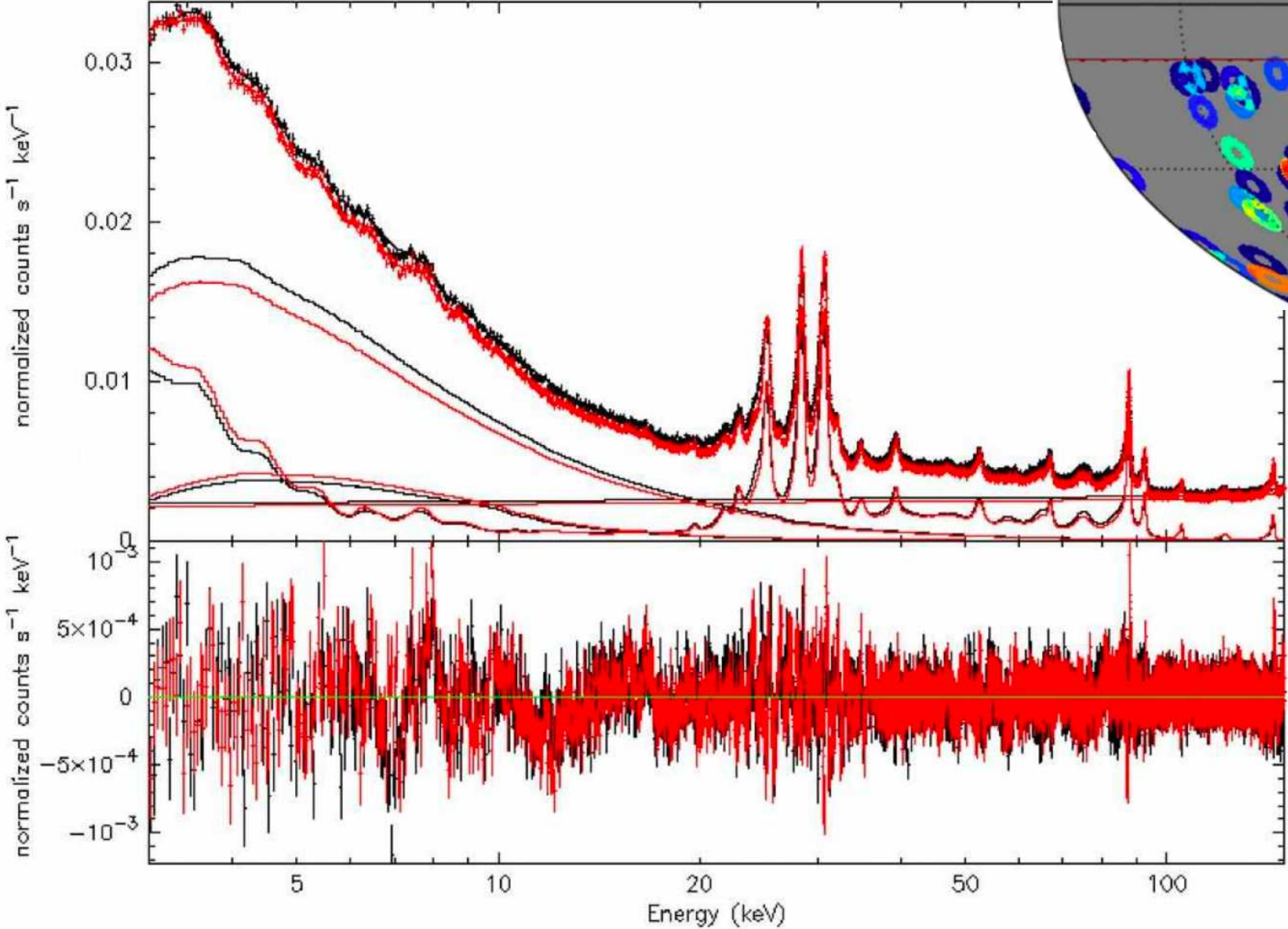
Absolute CXB measurement constrains AGN pop.



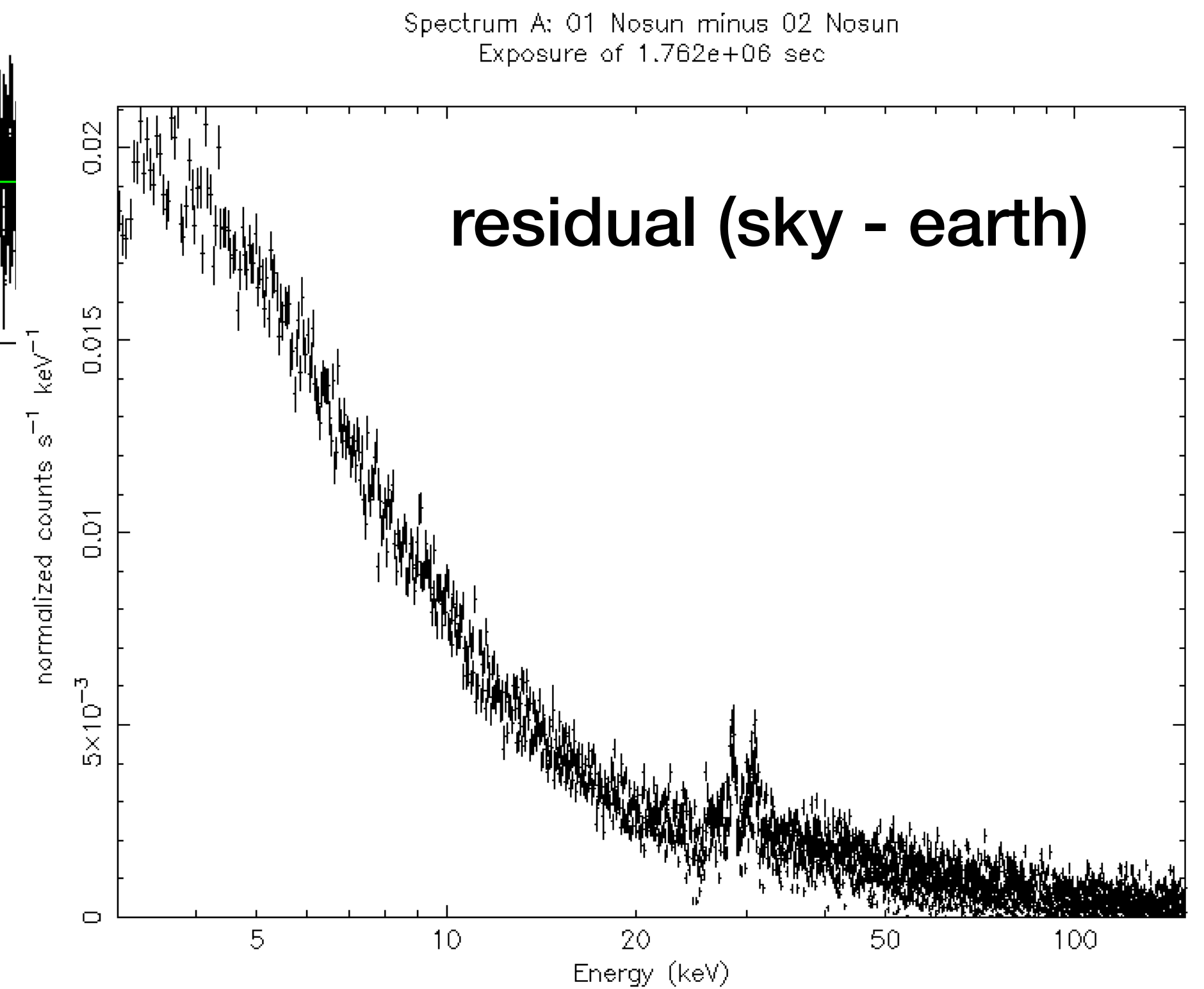
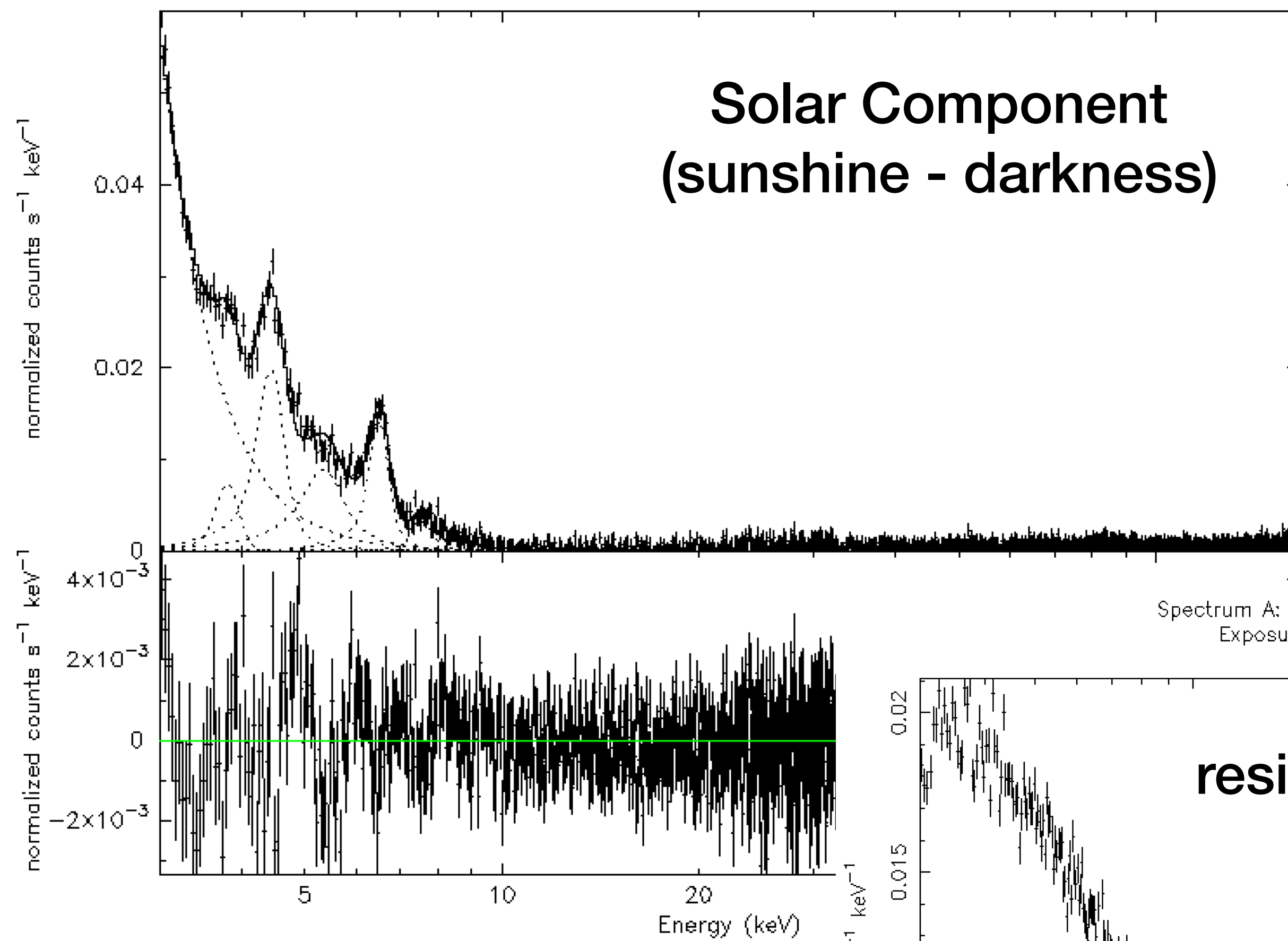
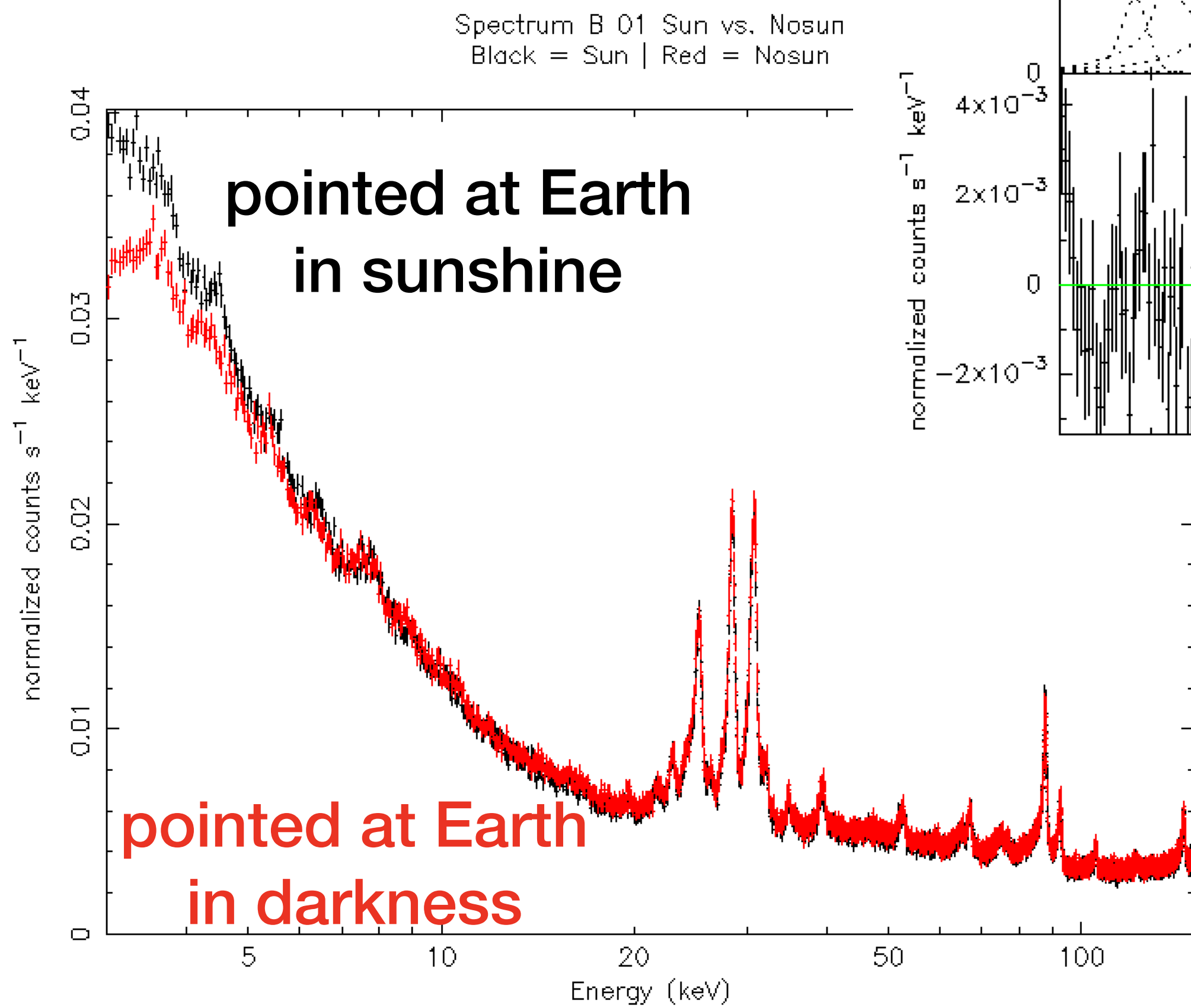
Ueda+ 2014



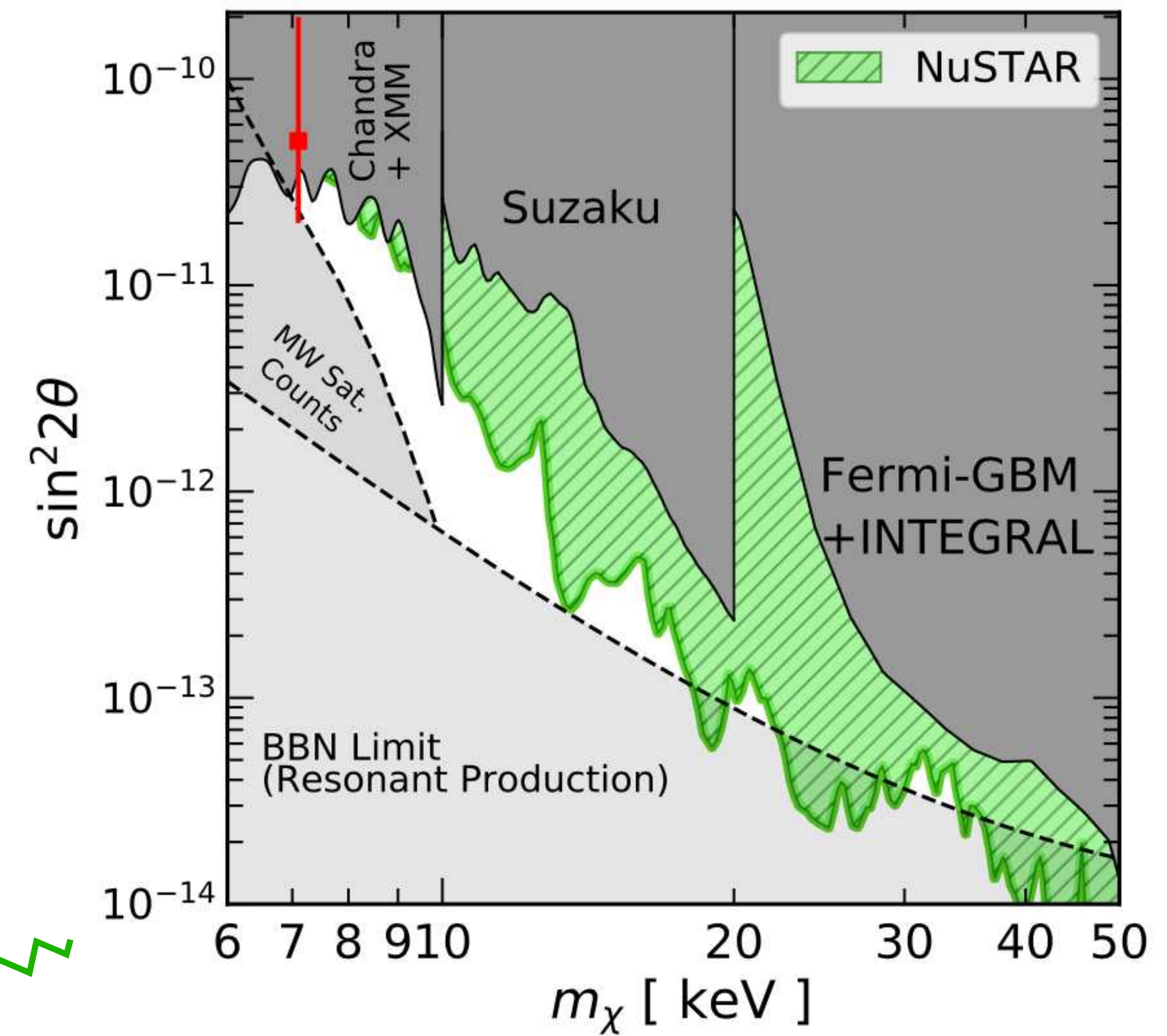
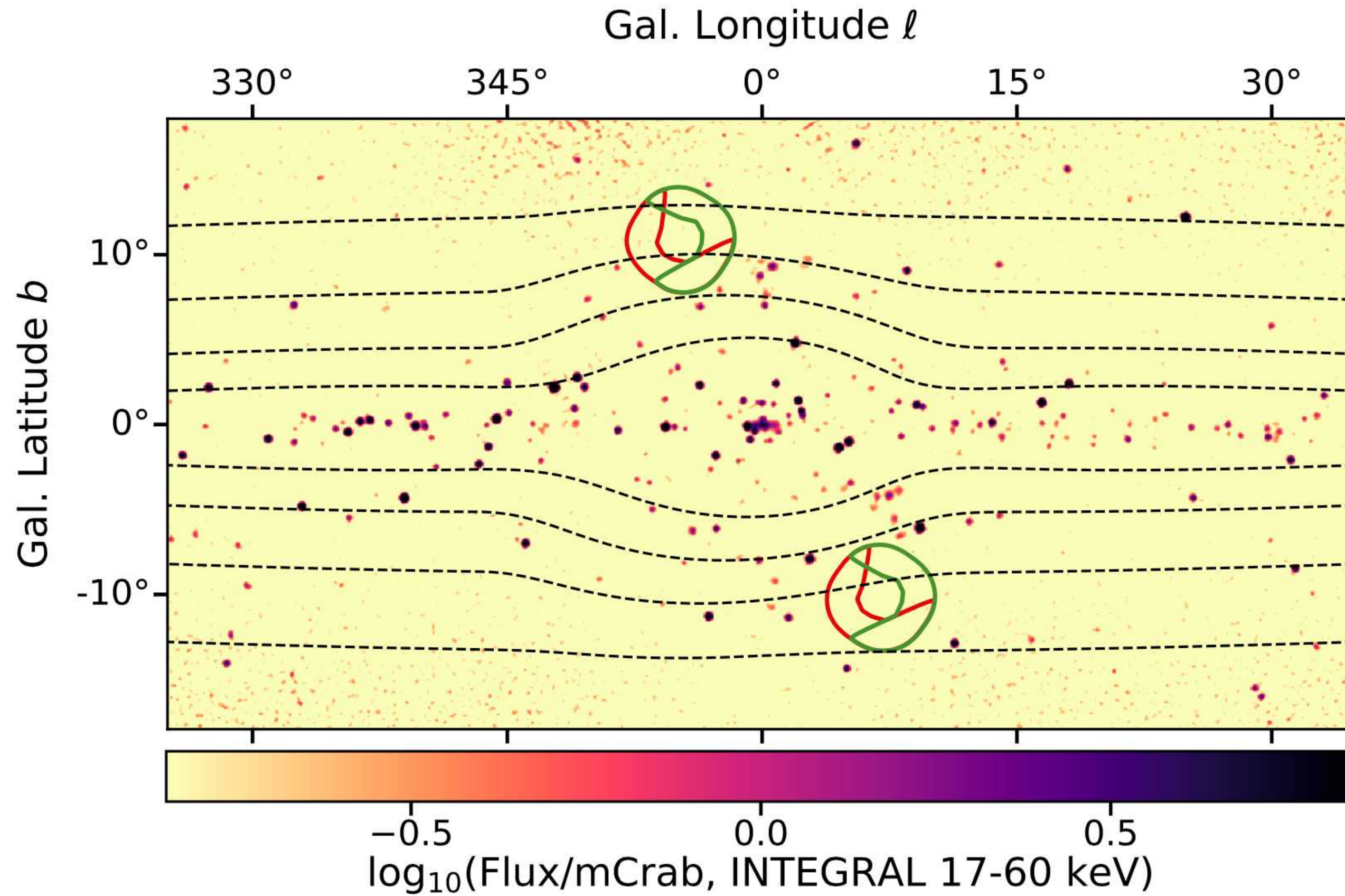
FPMA/FPMB
(Black)/(Red)



~50 Ms
to work with



Constraining sterile neutrino dark matter



Roach+19

Characterizing the background and PSF enables the study of...

Stars
(Eta Car)

Supernova Remnants
(Cas A)

Dead Stars in
binaries

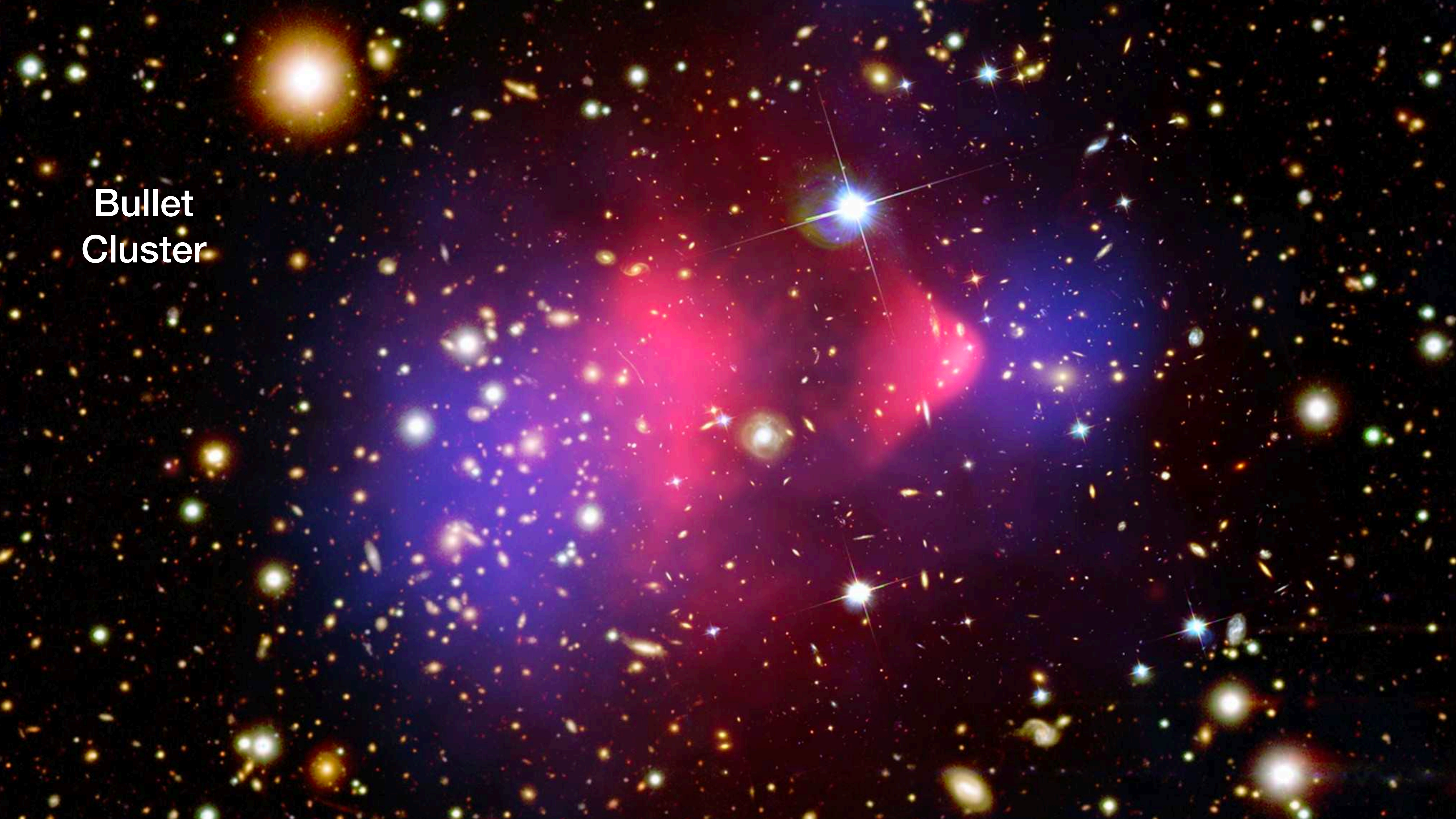
Supermassive
Black Holes

Galaxies
(NGC 253)

Sterile Neutrino
Dark Matter

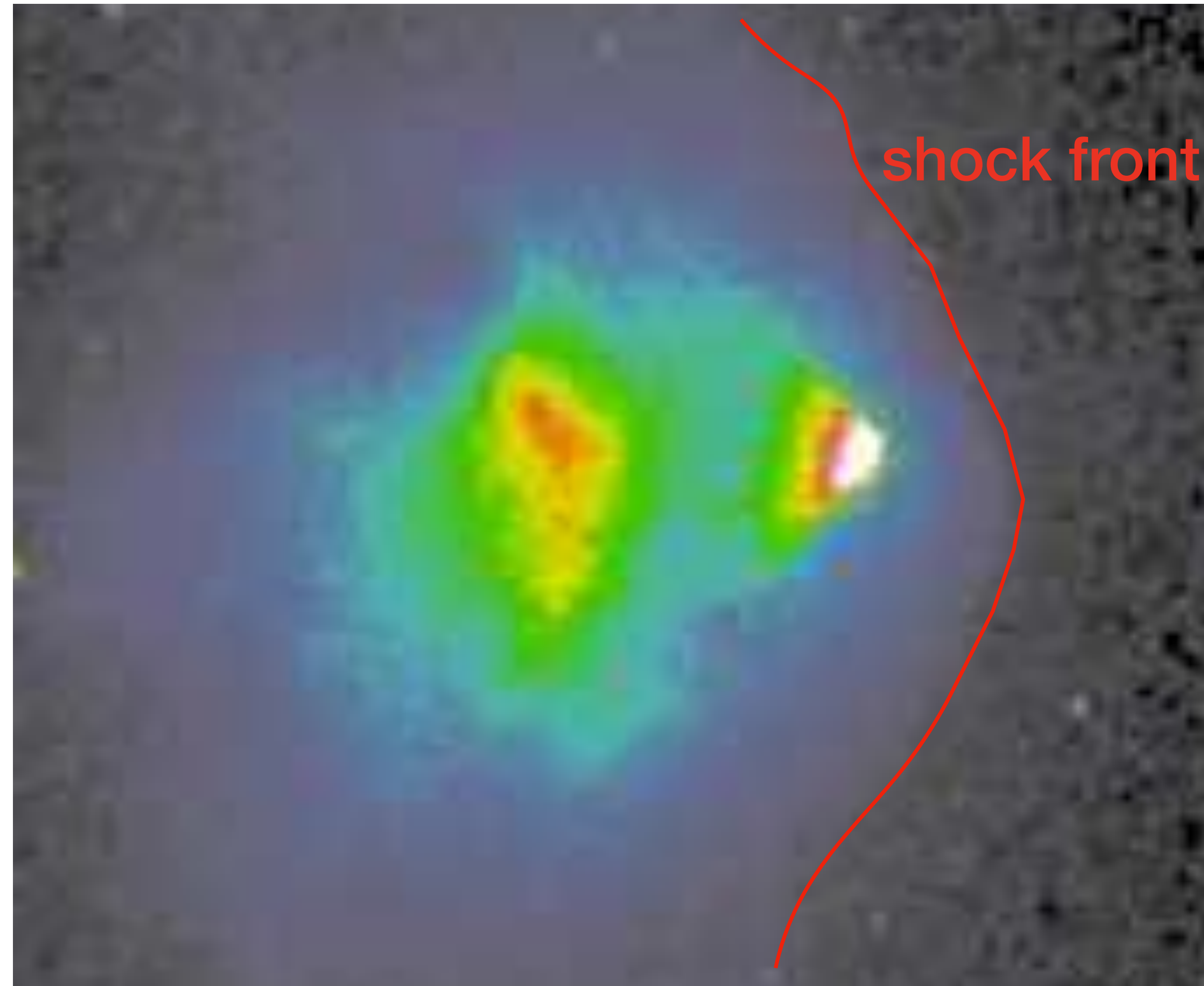
Clusters of
Galaxies

Bullet
Cluster

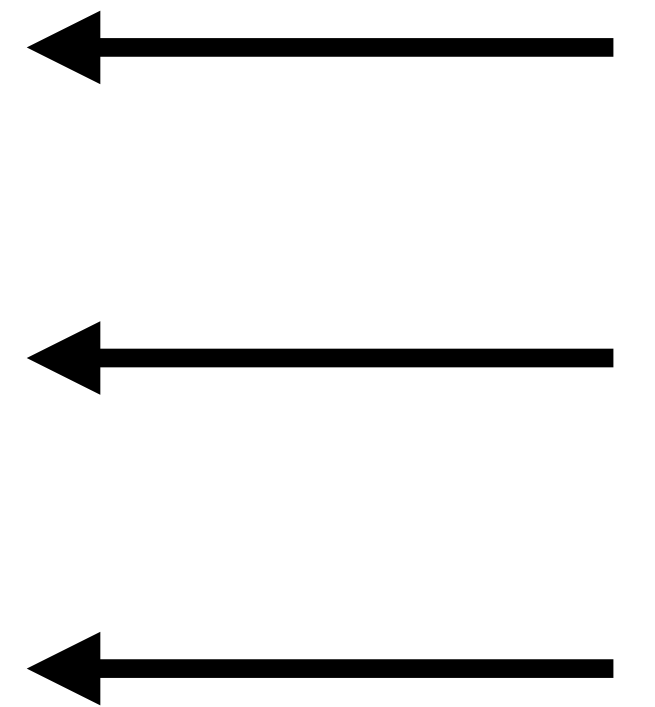


How are particles heated & accelerated during a merger?

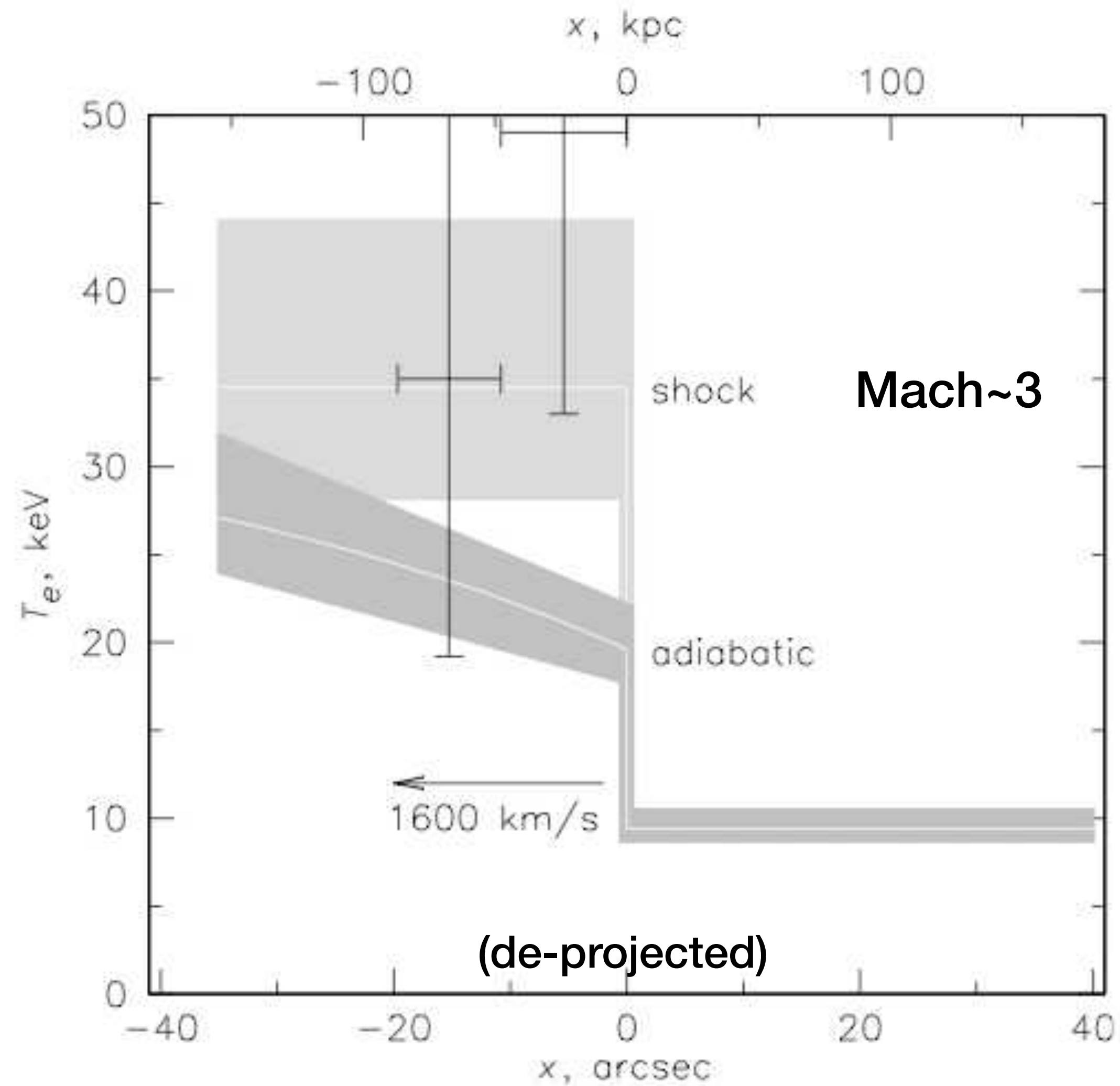
Bullet
Cluster



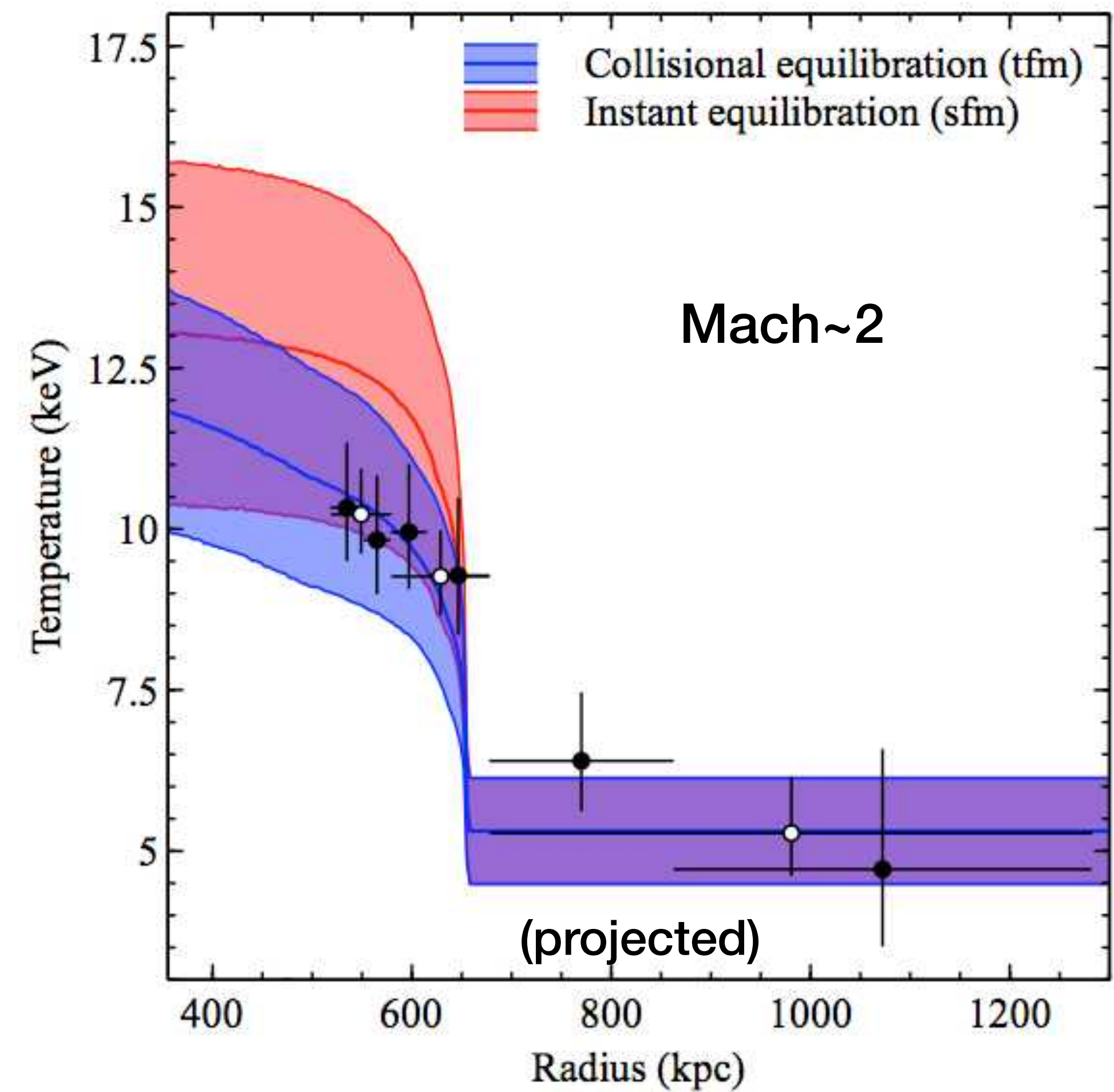
gas flow



Conflicting evidence so far: bow shocks

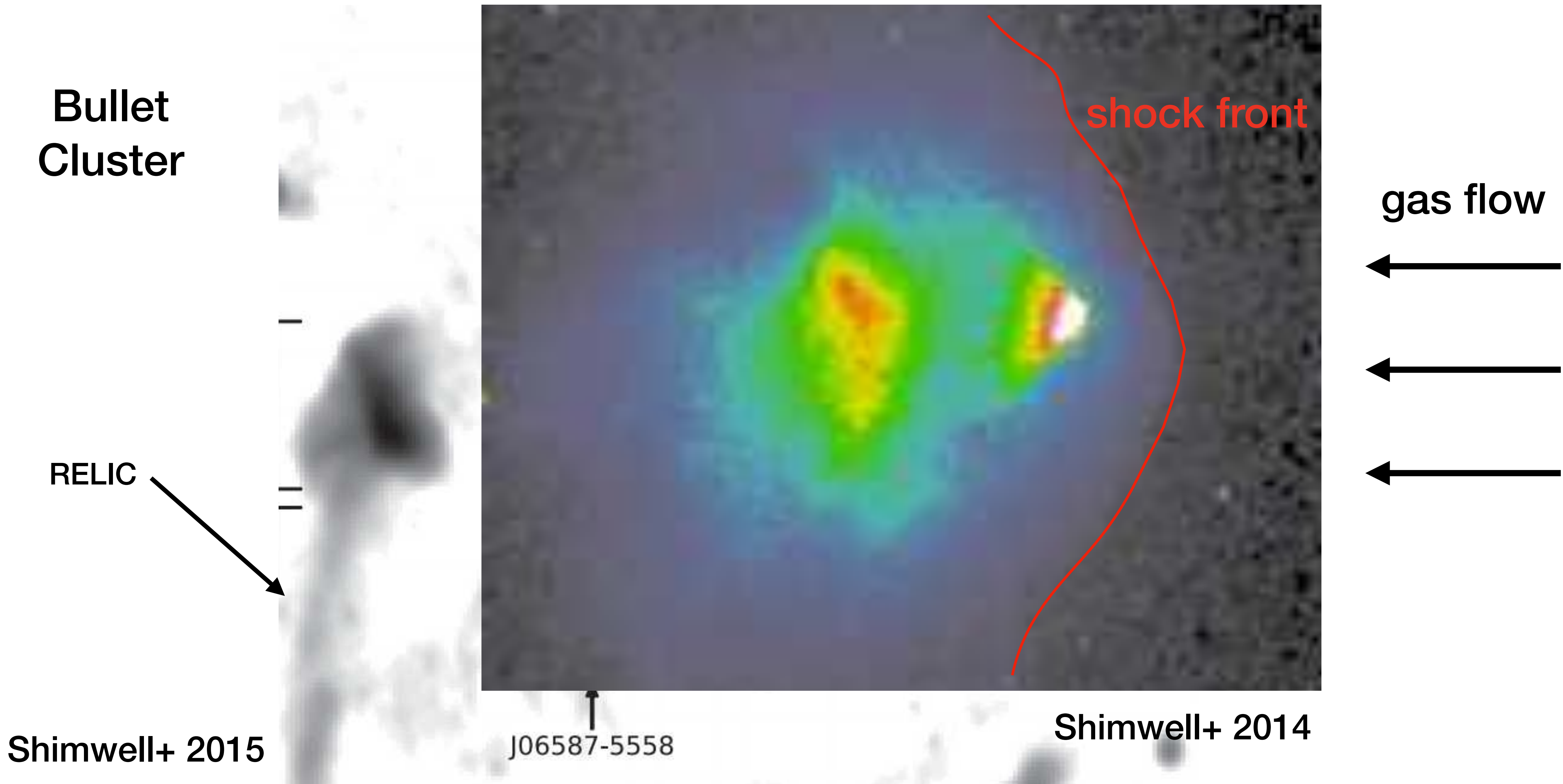


Bullet Cluster: Markevitch 2006

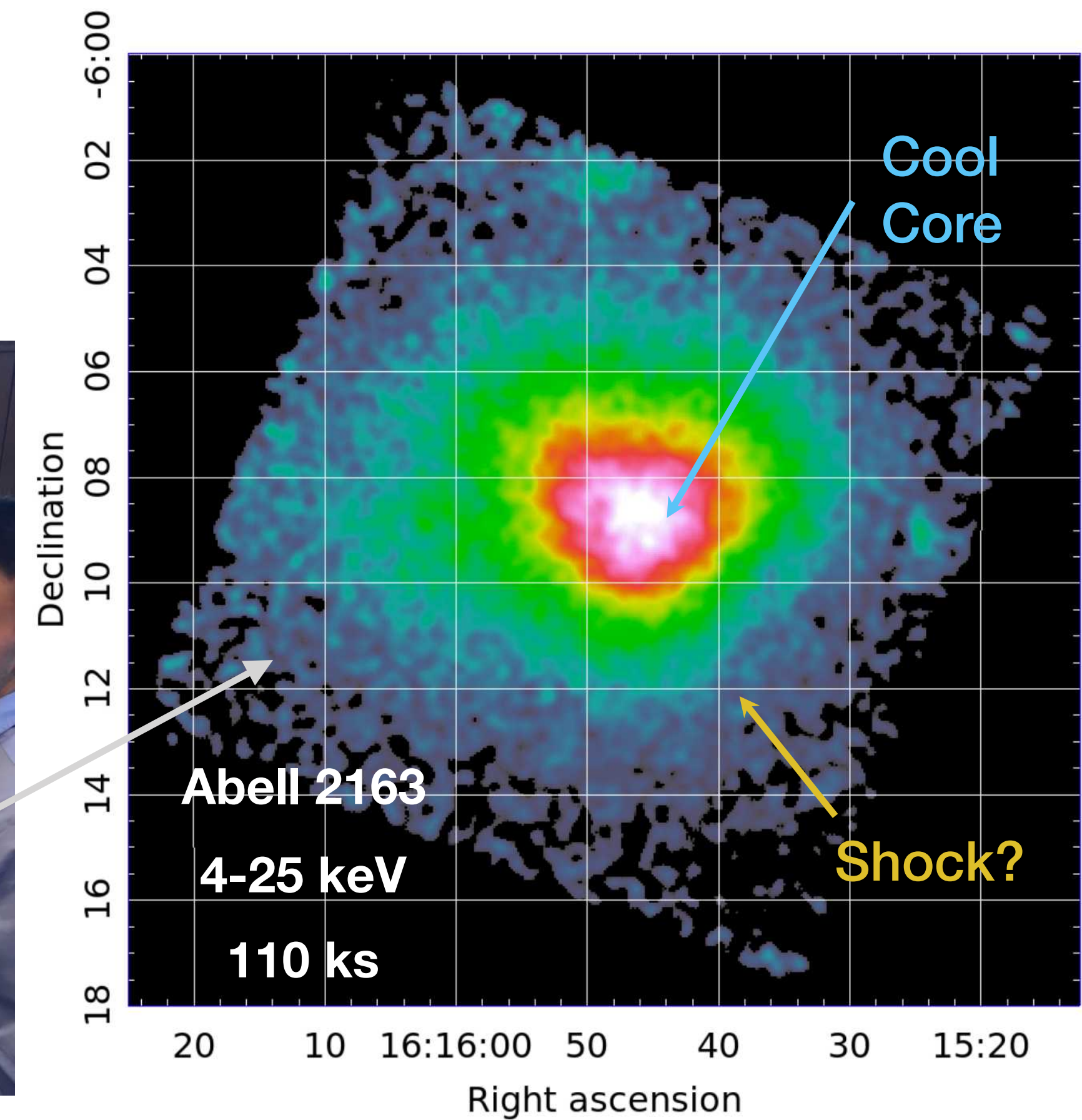
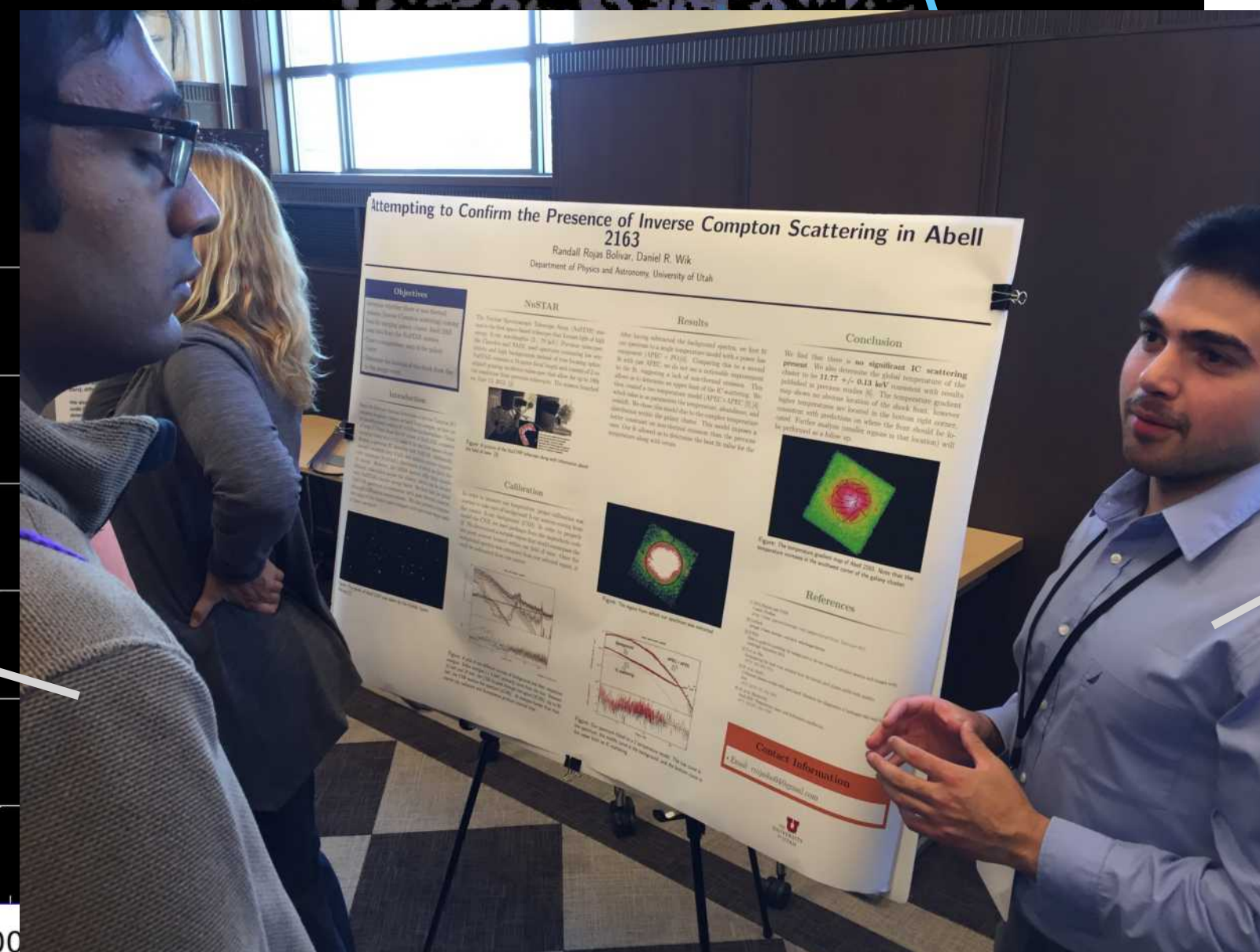
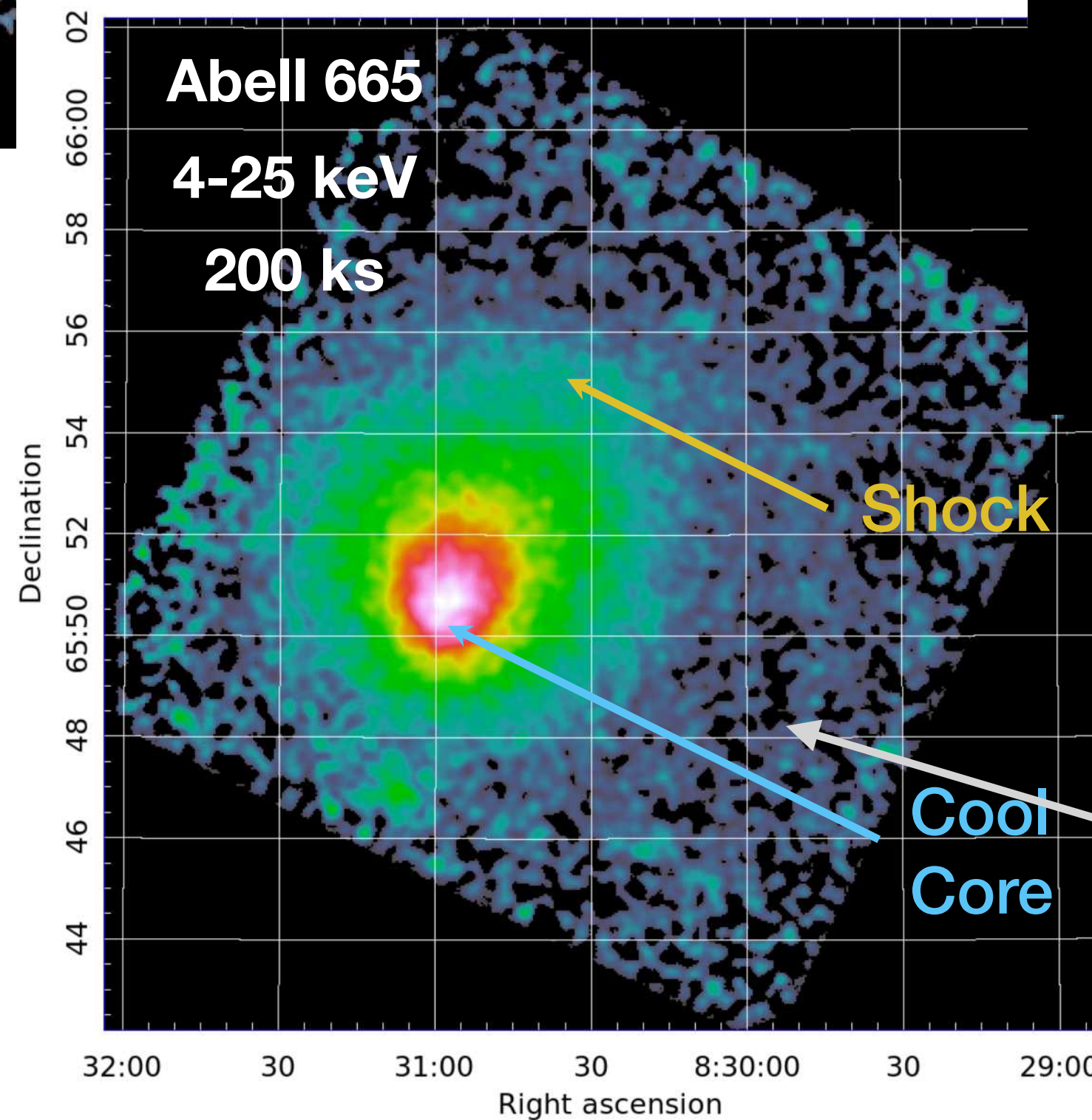
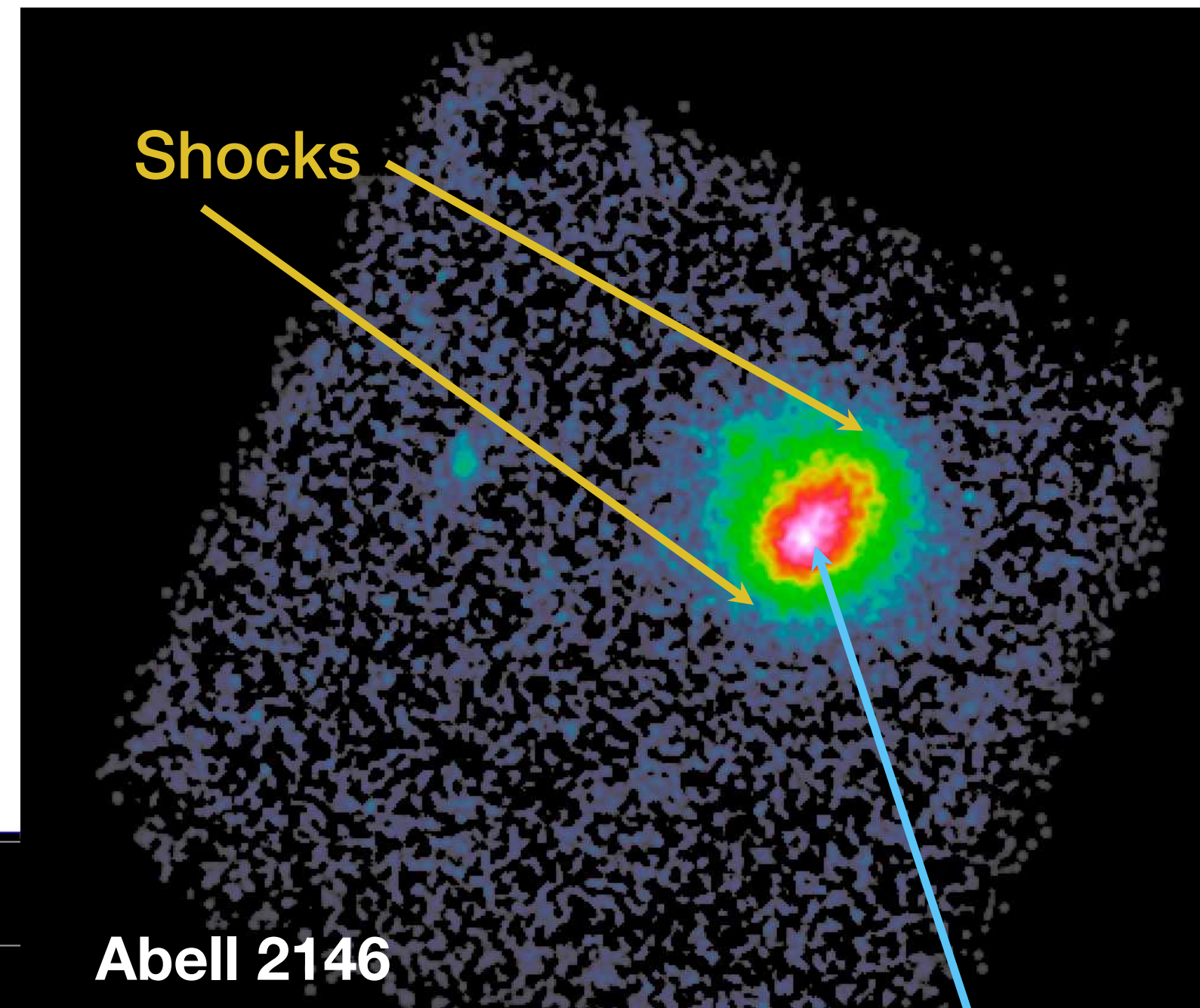
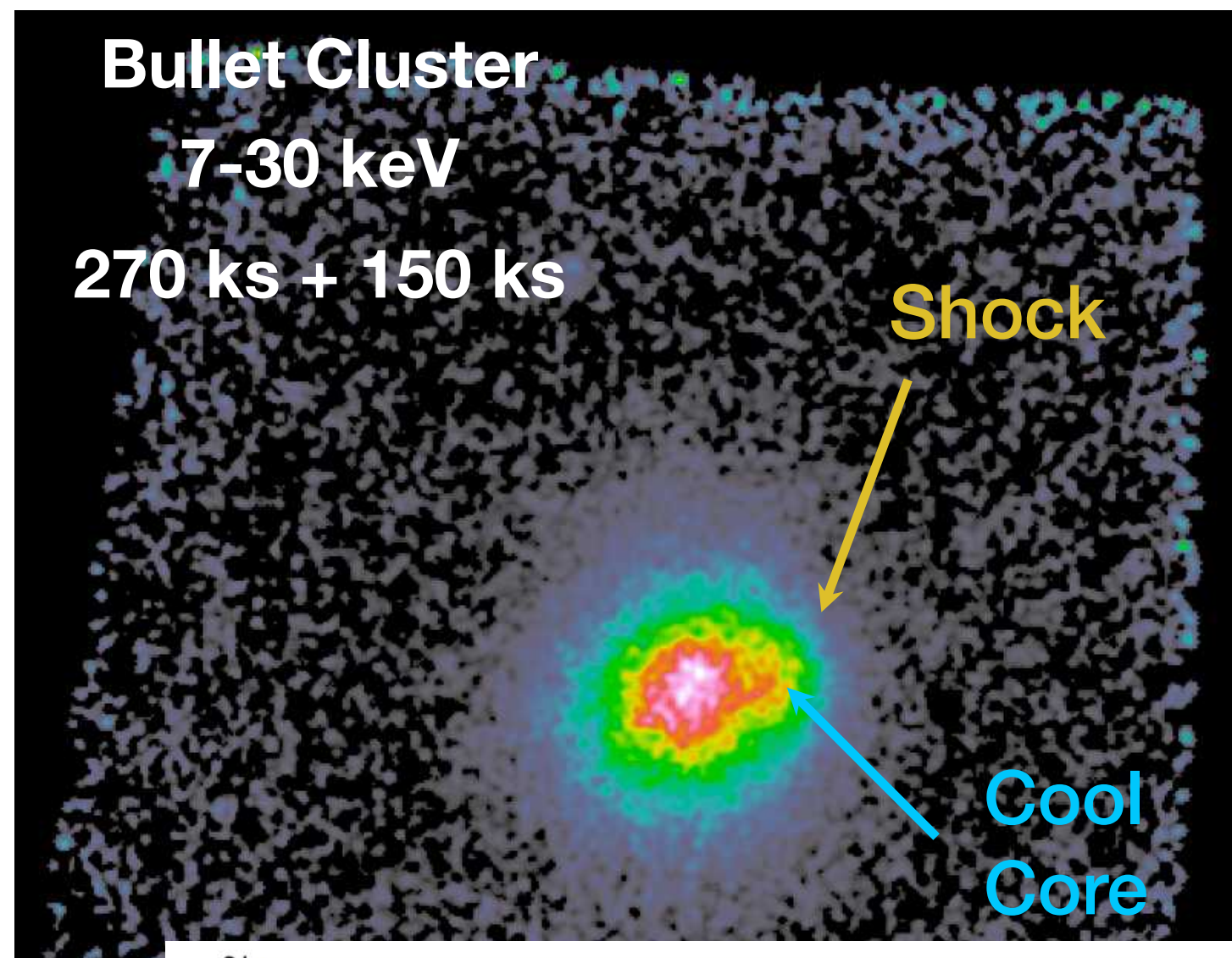


Abell 2146: Russell et al. 2012

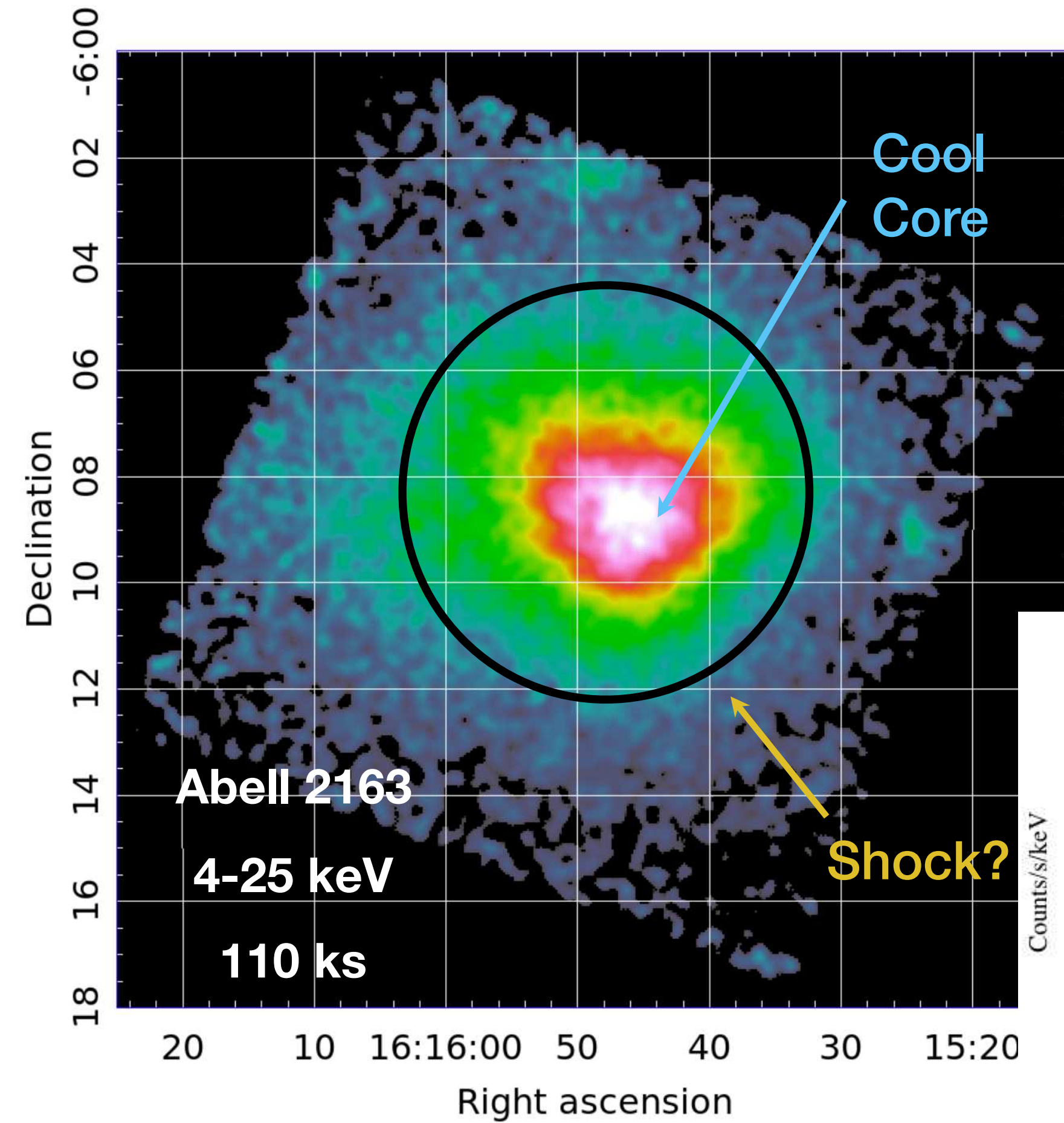
How are particles heated & accelerated during a merger?



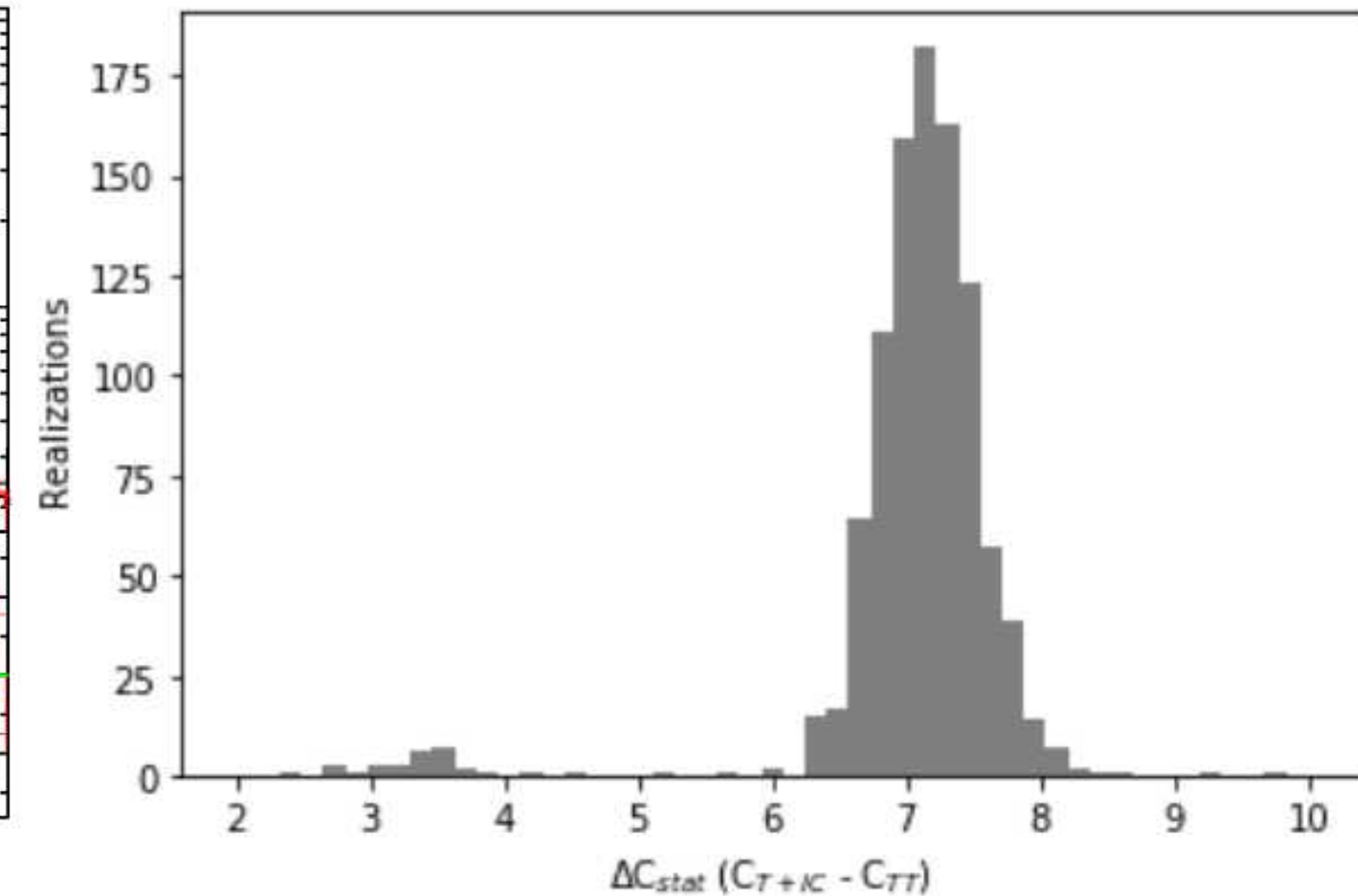
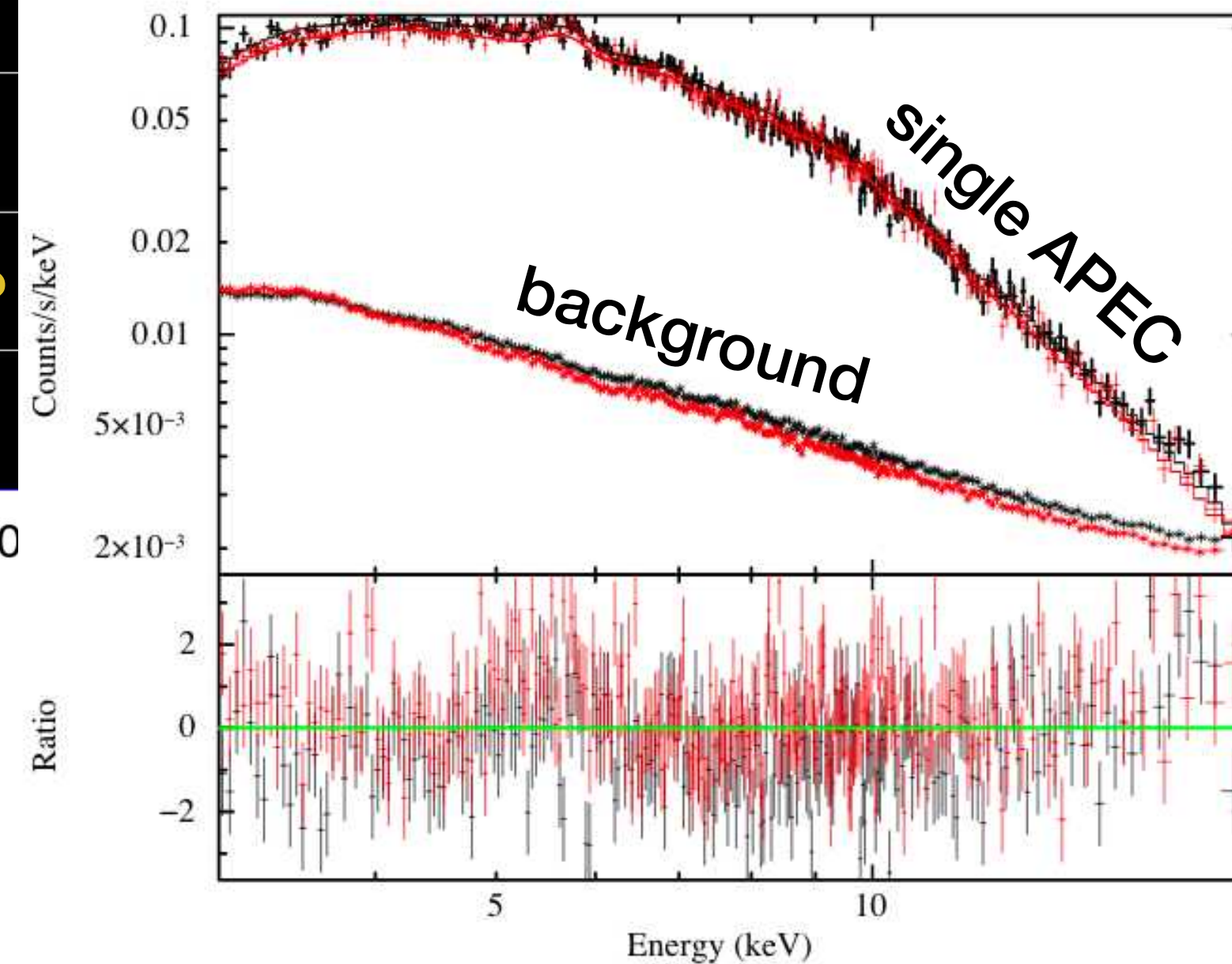
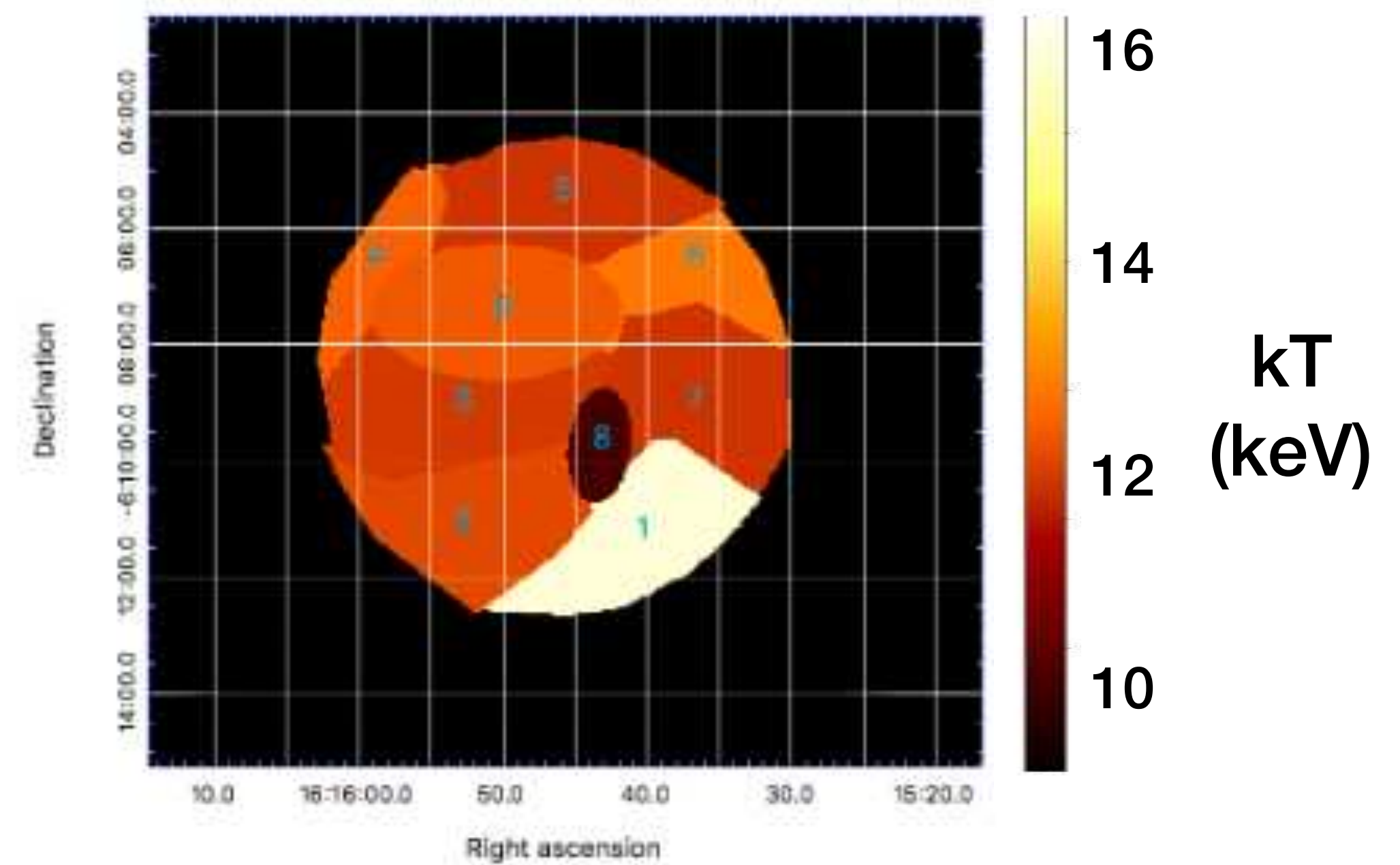
Clusters of Interest



Abell 2163

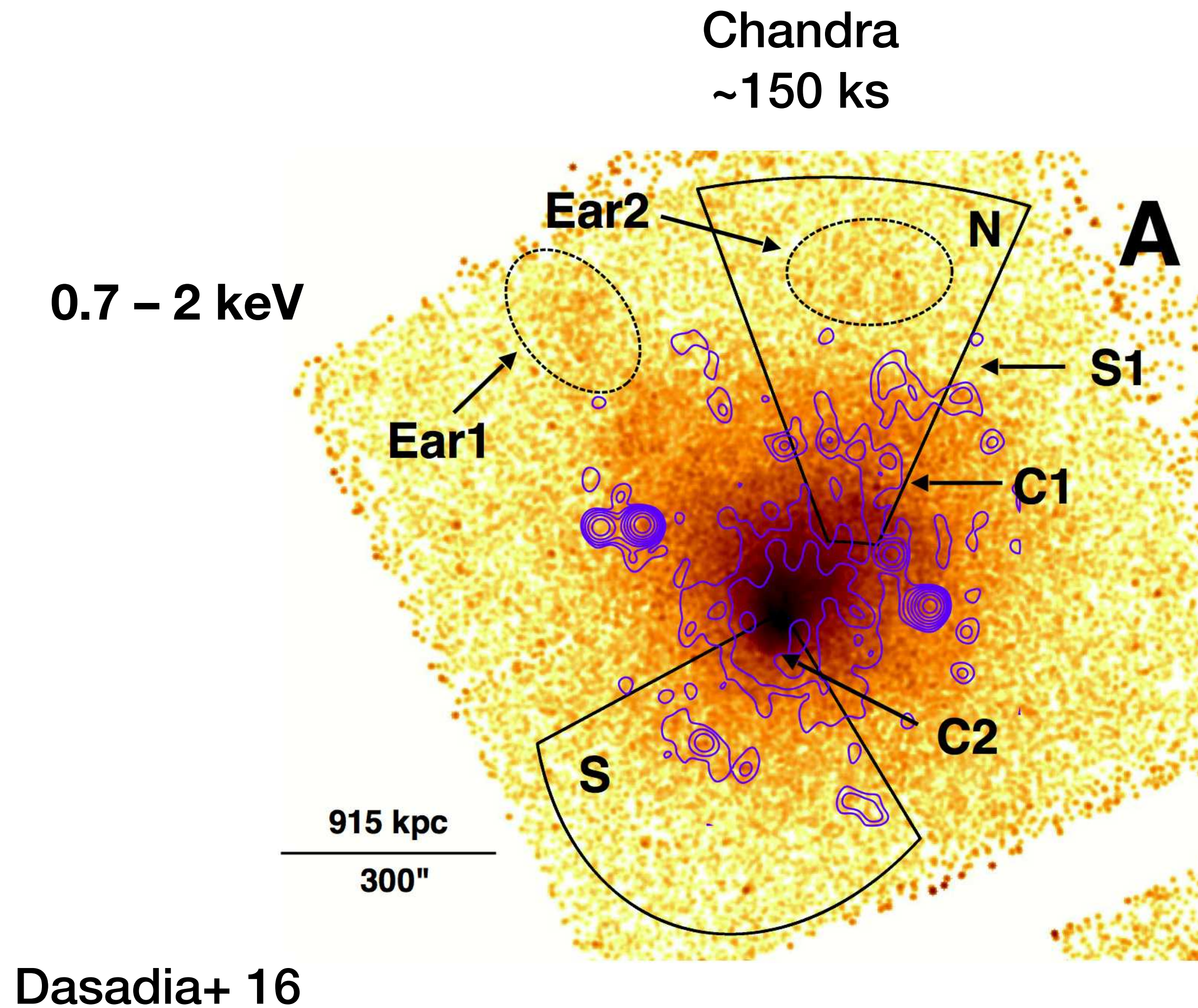


IC upper limit
corresponds to a lower
limit on B of
0.22 μG (T+IC) or
0.35 μG (T-map)

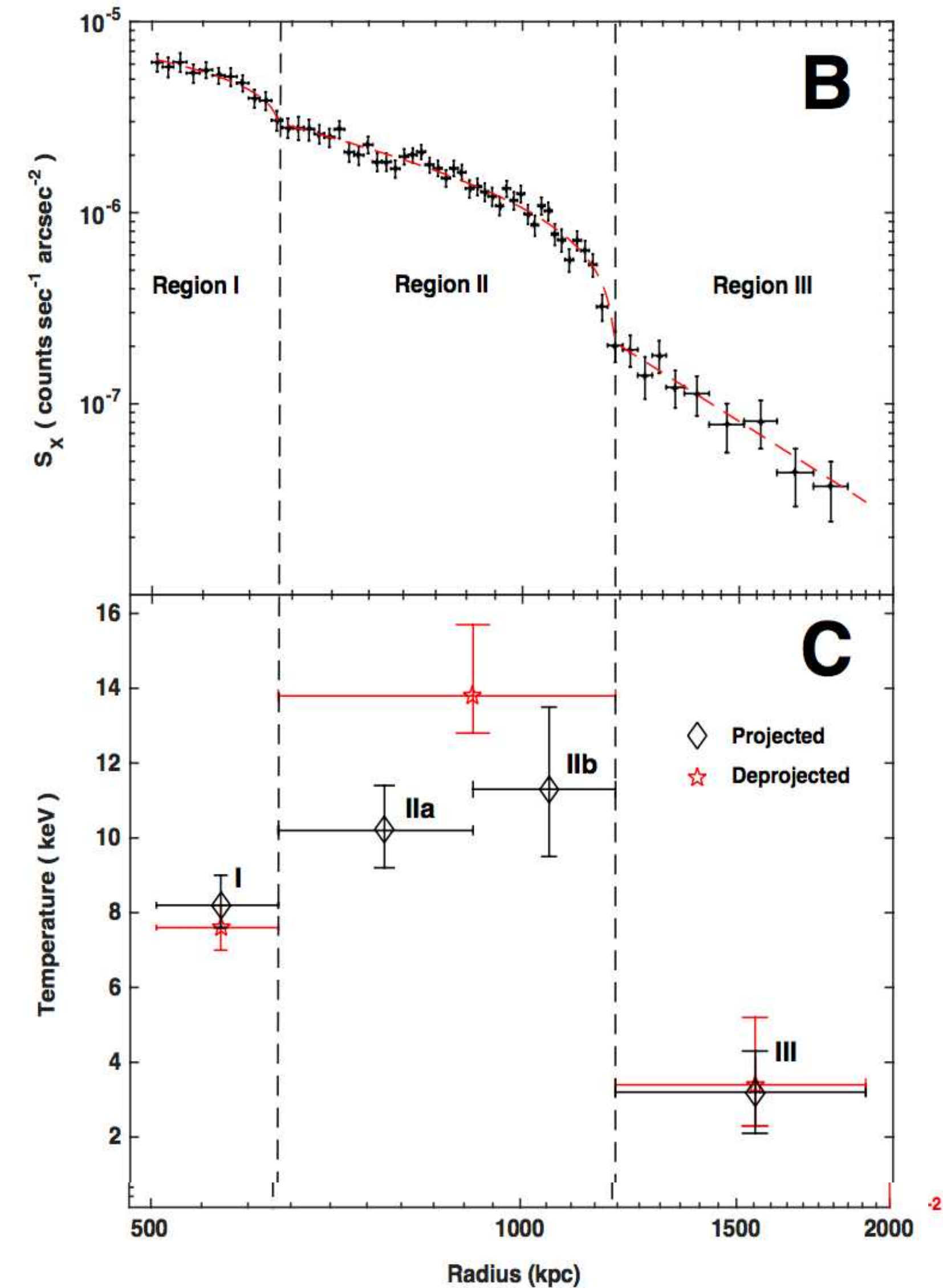


Rojas+ in prep.

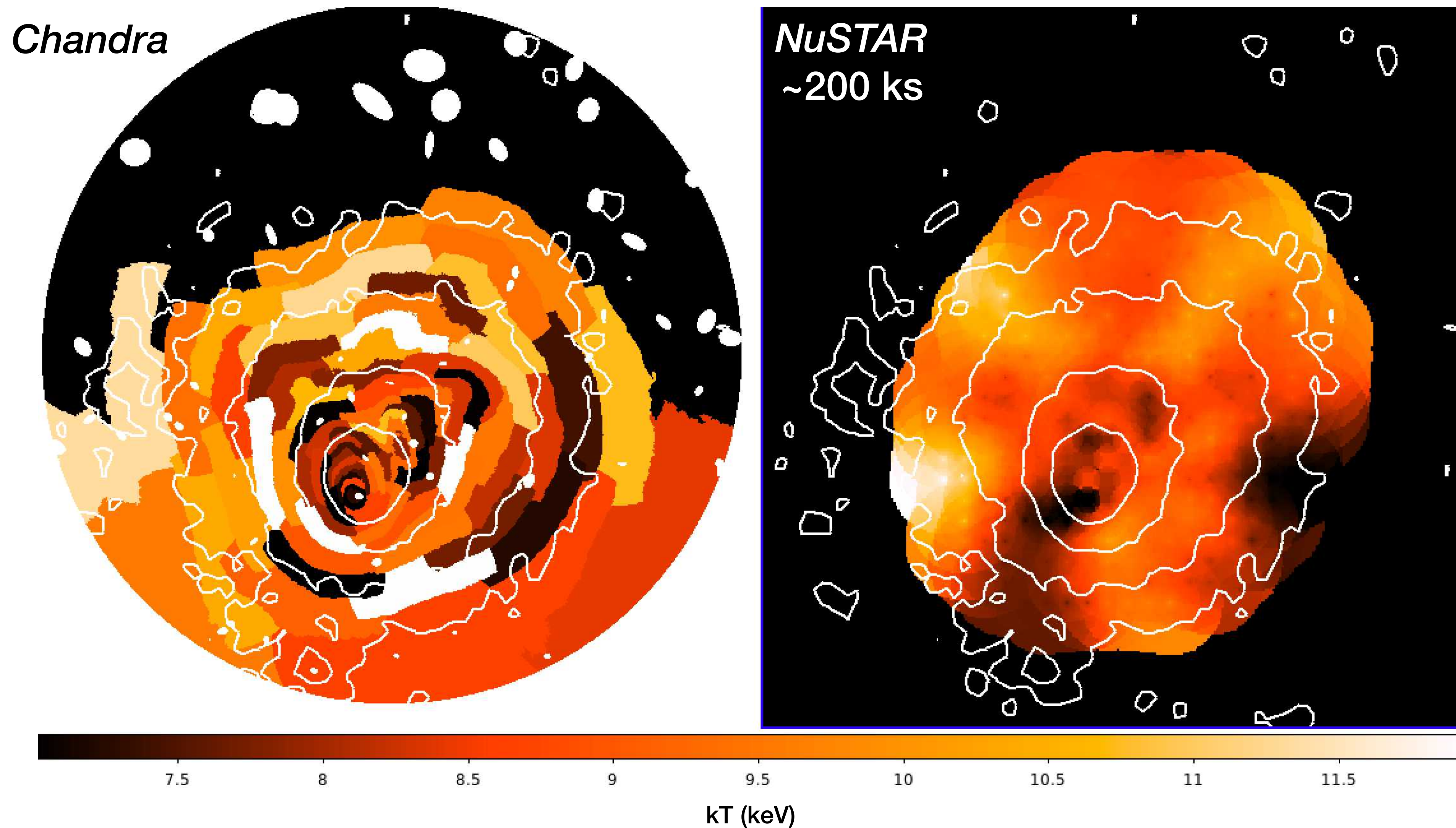
Abell 665: another Mach~3 shock



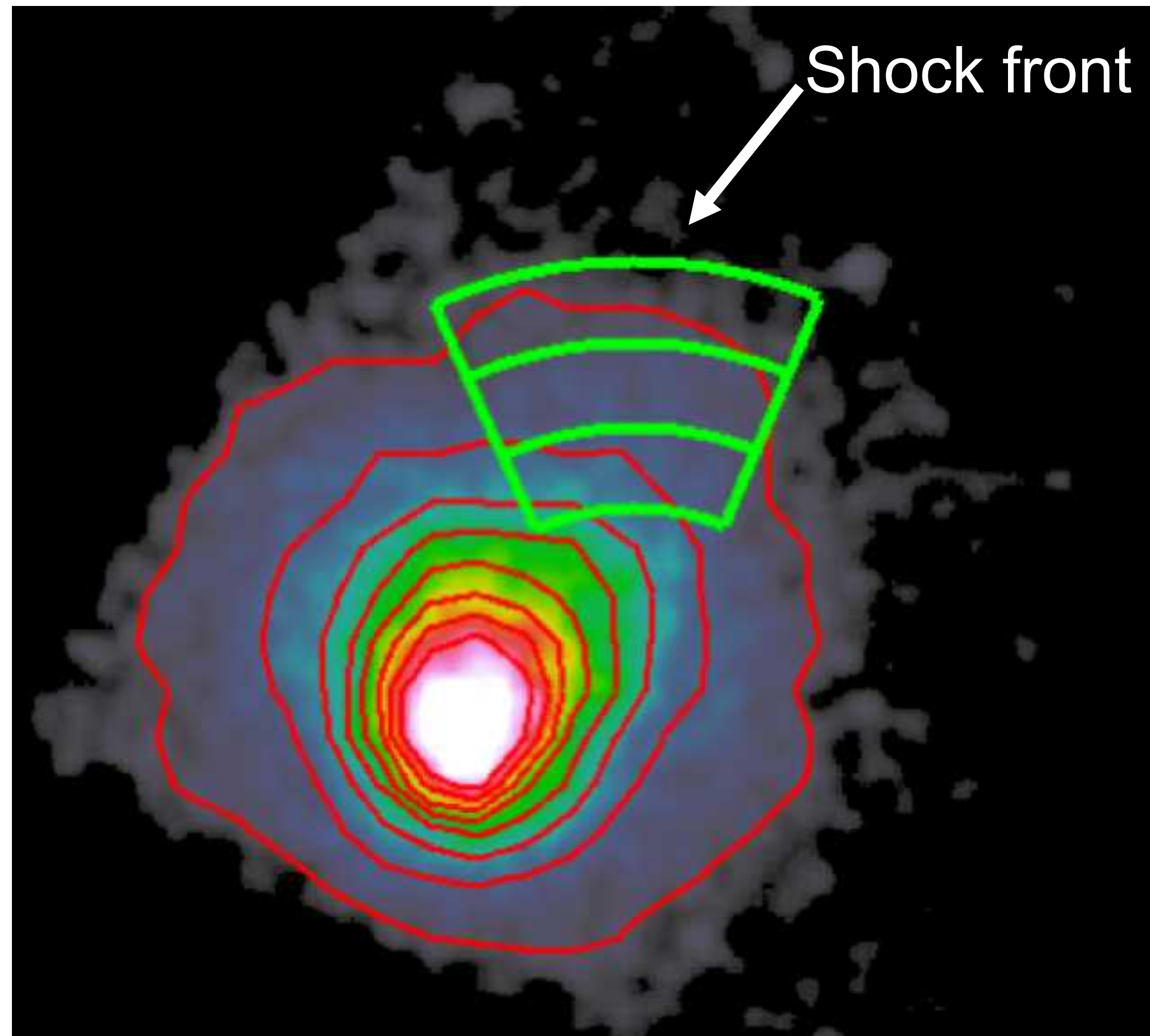
Dasadia+ 16



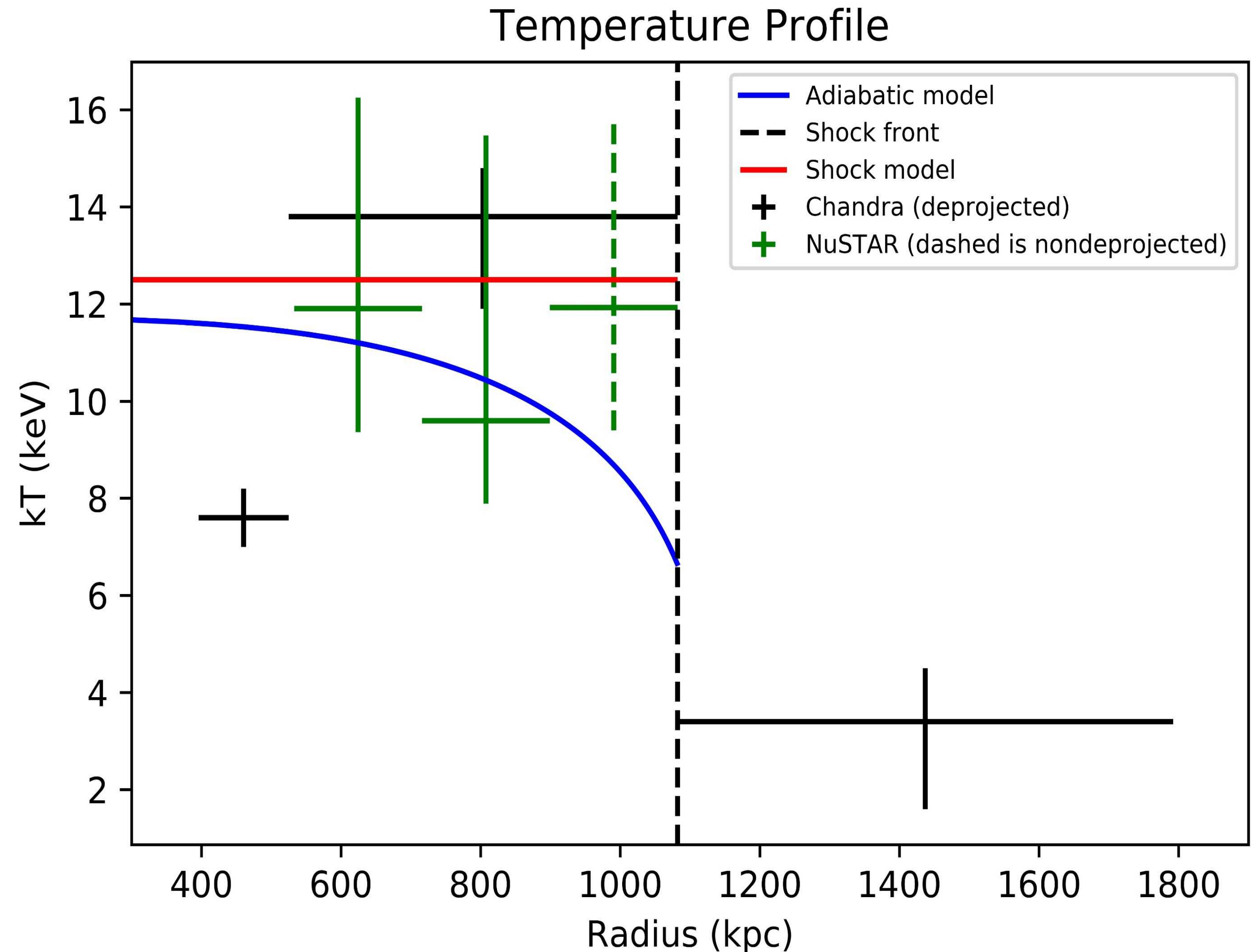
Abell 665: *Chandra*-only vs. *NuSTAR*-only



Suggestive, but need to add PSF modeling



Vankayalapati+ in prep.



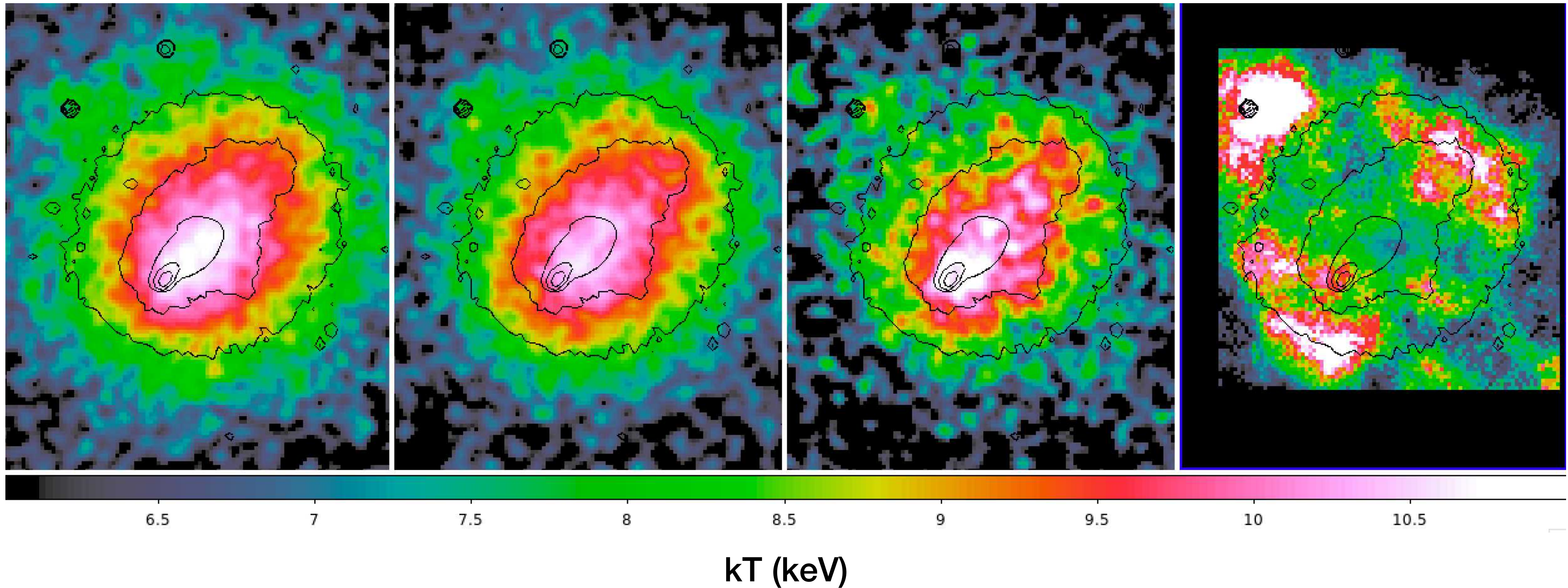
Abell 2146 *NuSTAR* Observation (260 ks)

3-5 keV

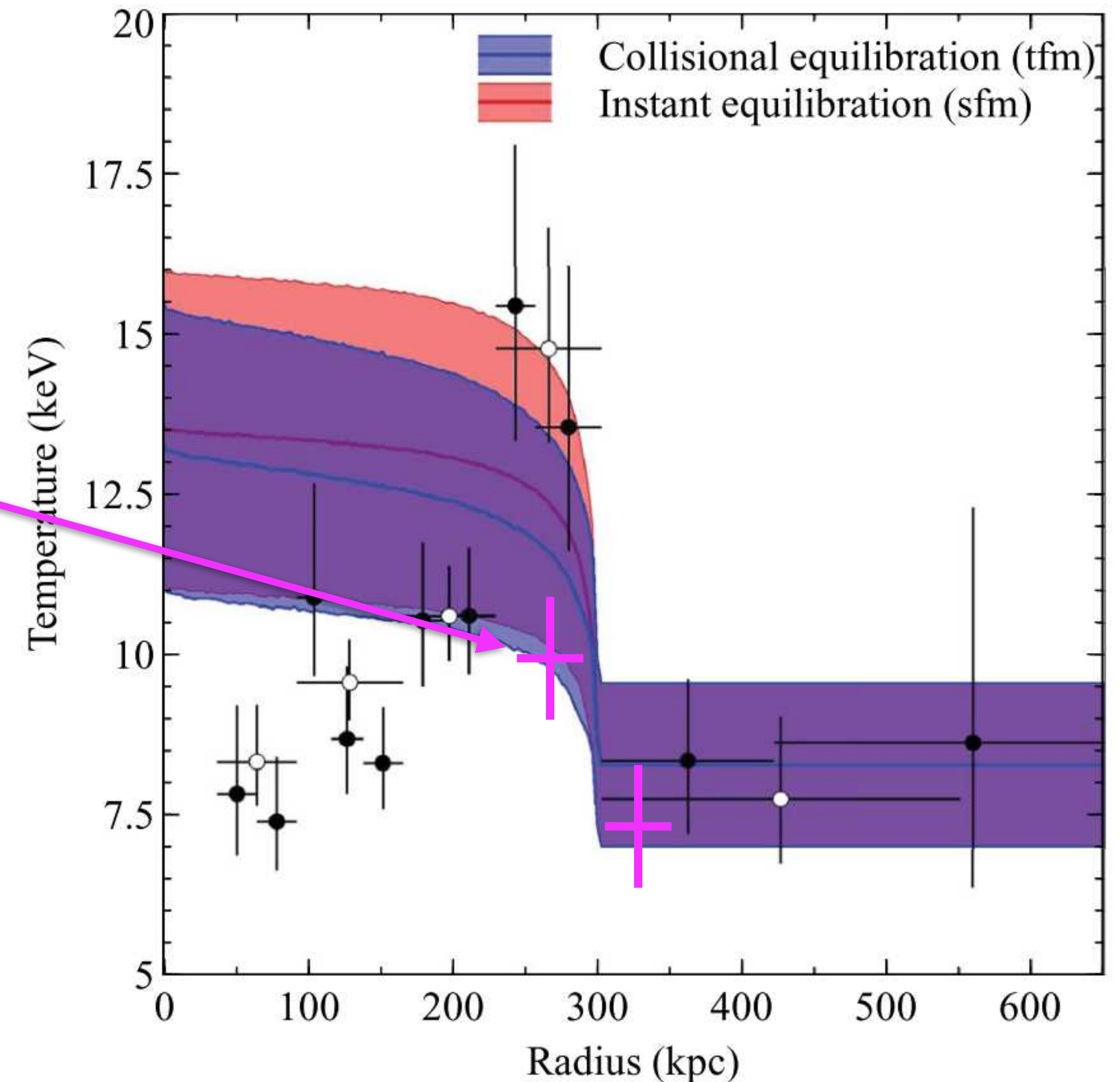
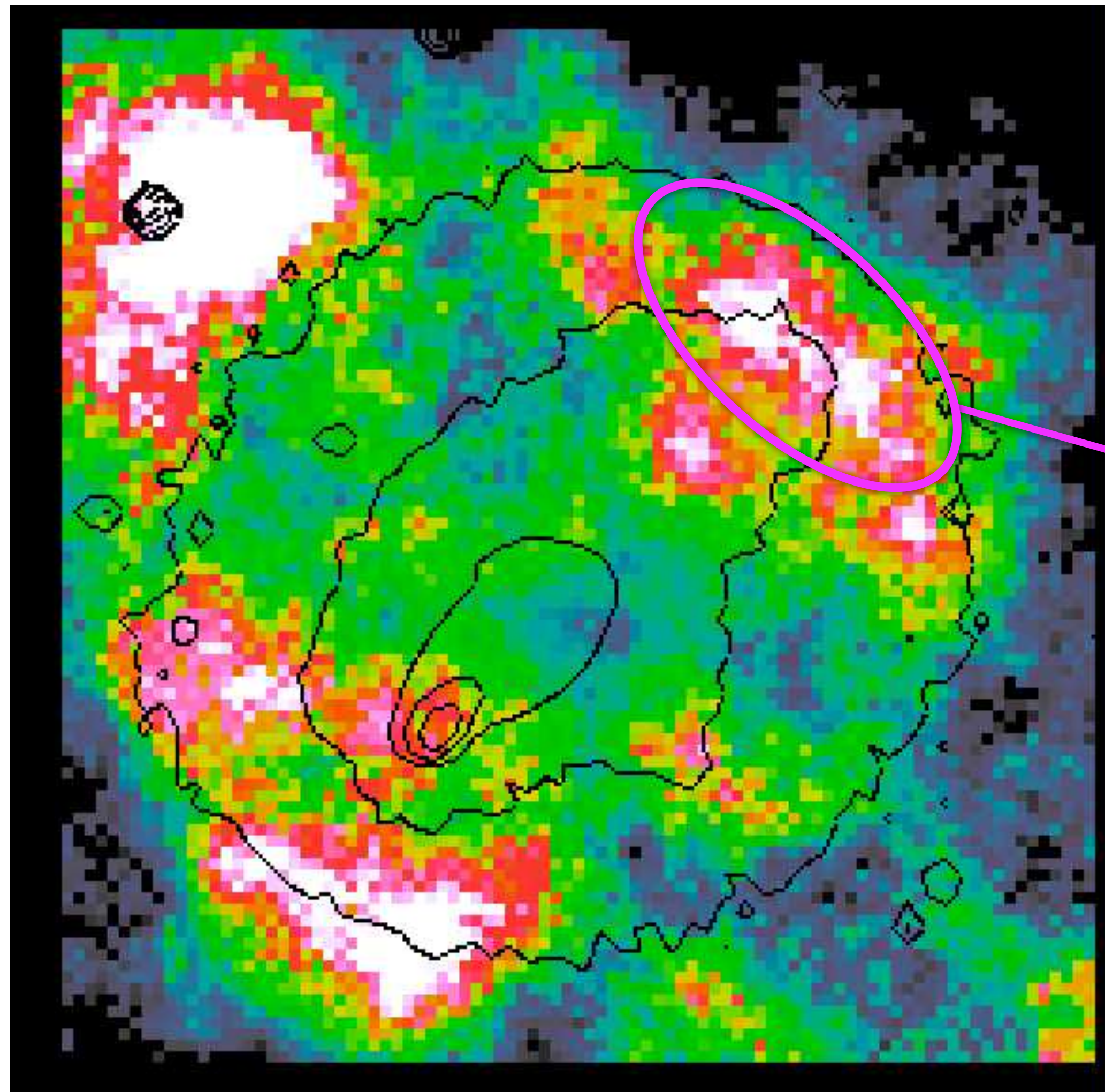
6-10 keV

10-20 keV

Temperature Map

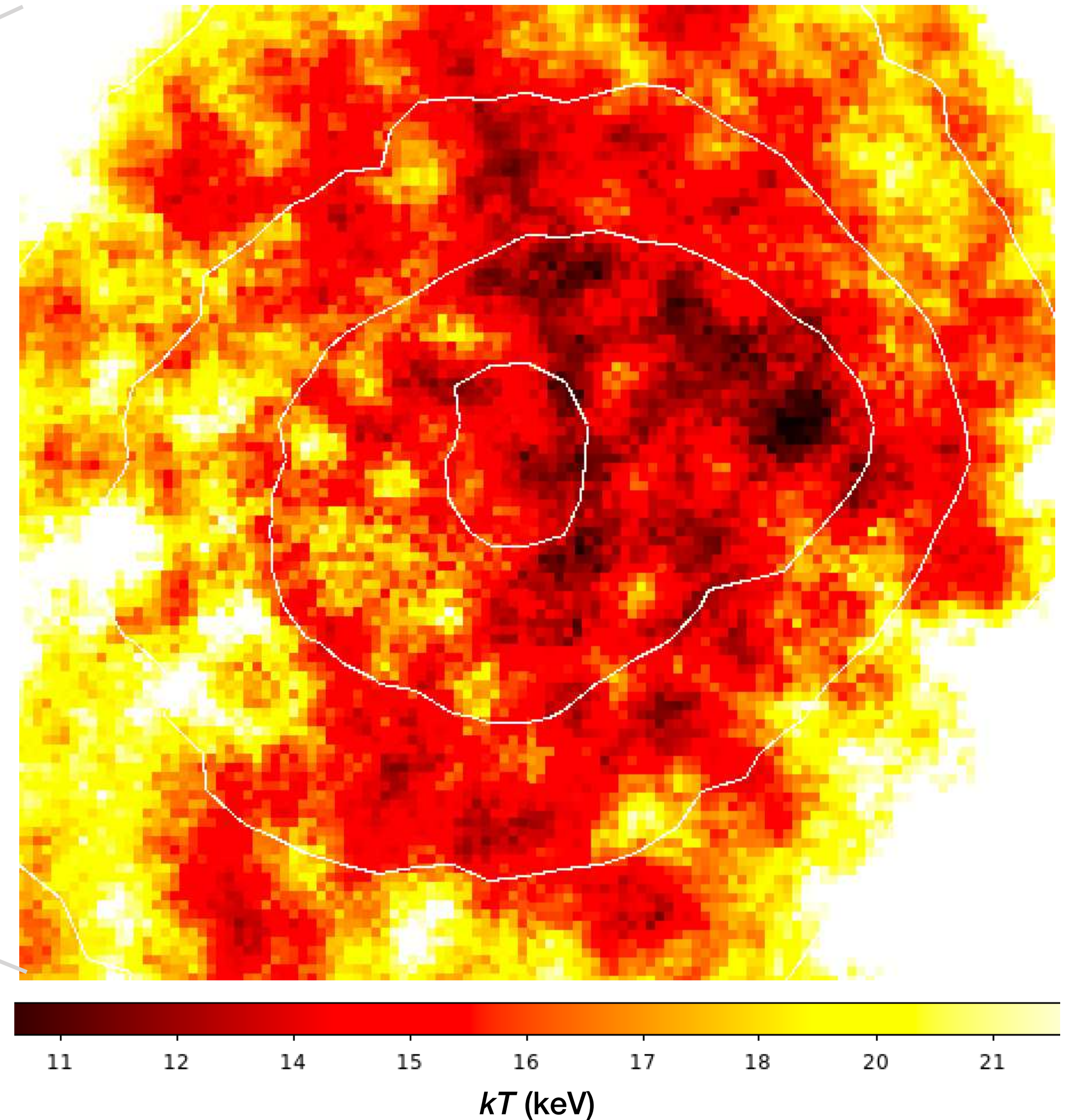
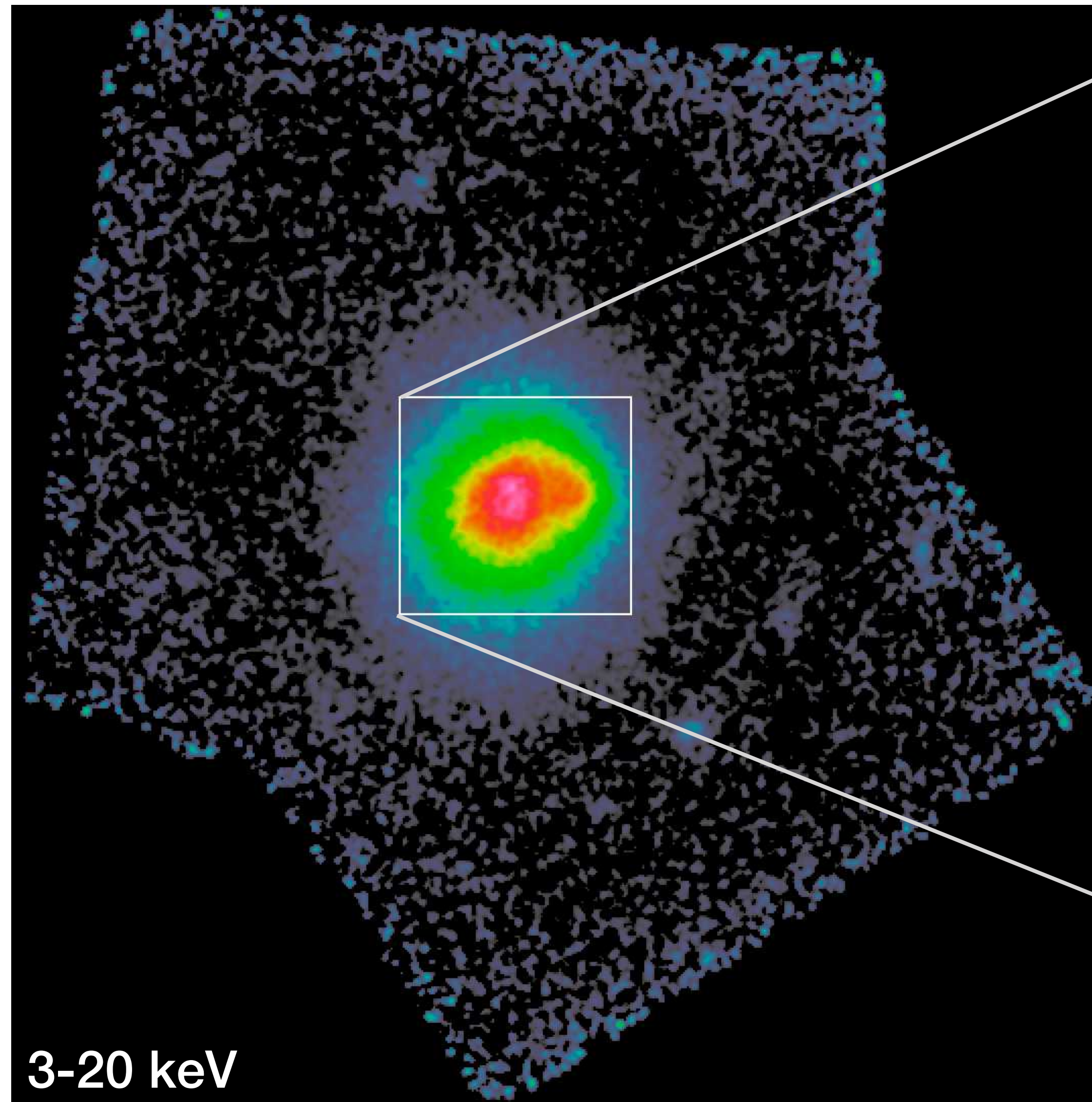


NuSTAR data reject high kT of upstream shock

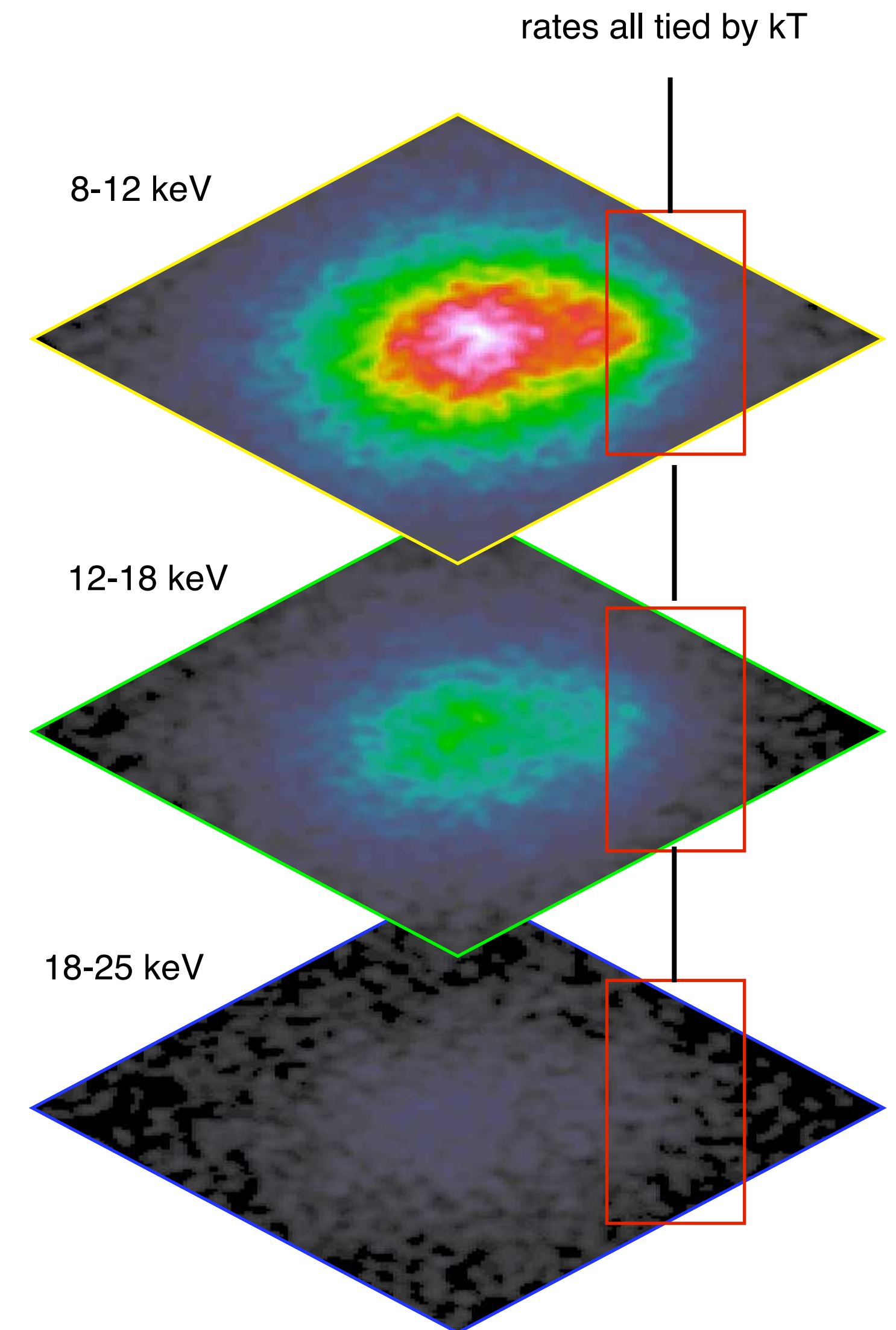
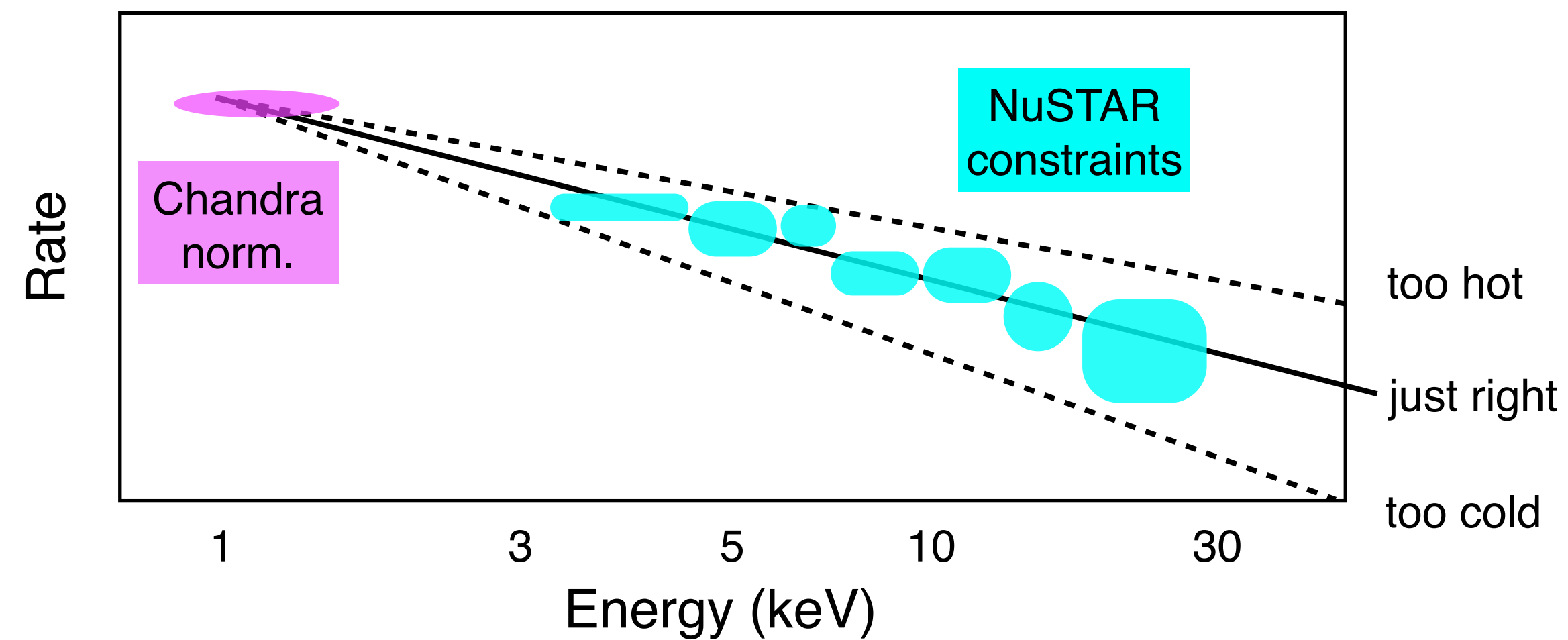
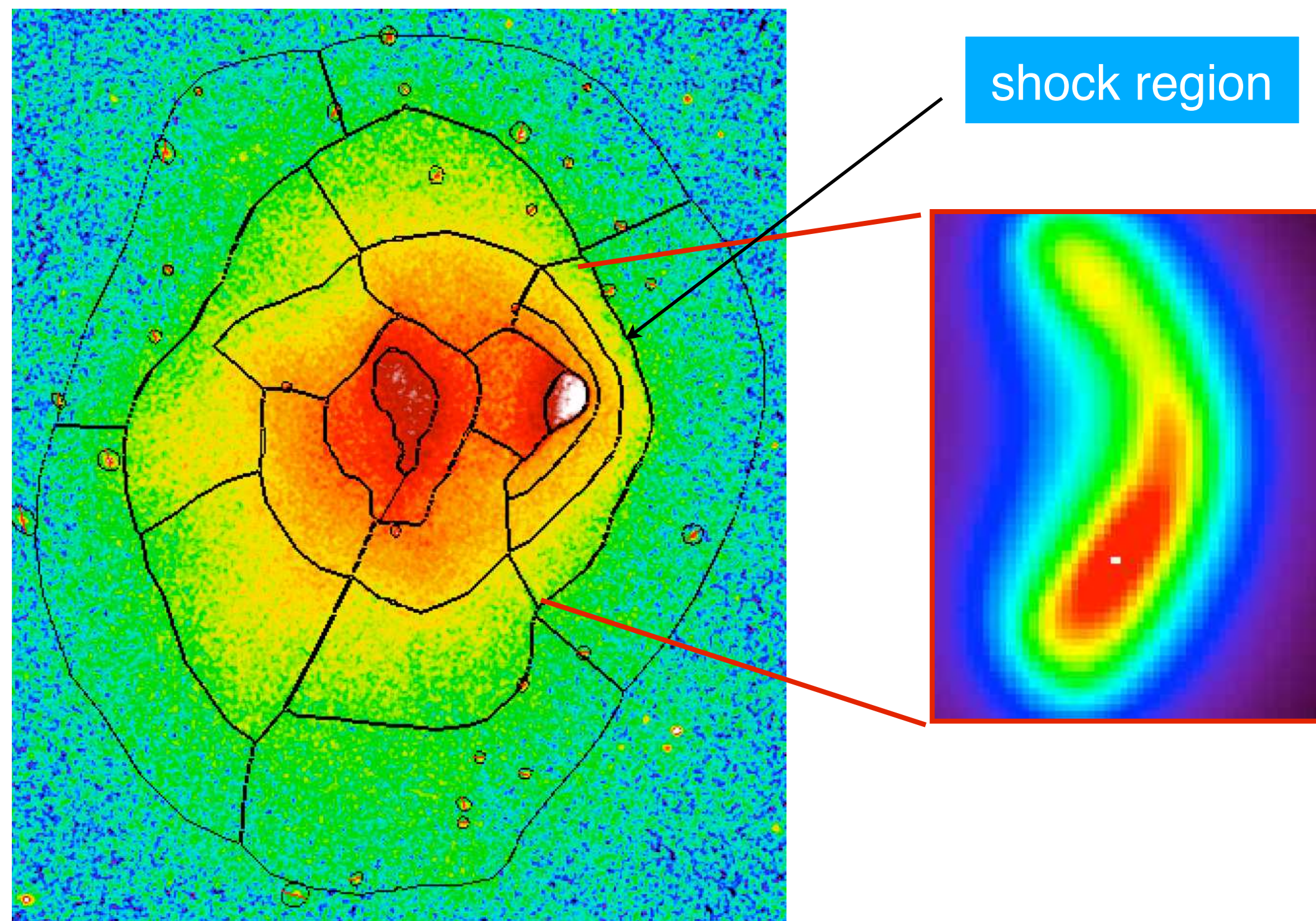


Abell 2146: Russell et al. 2012

Same method applied to the Bullet Cluster

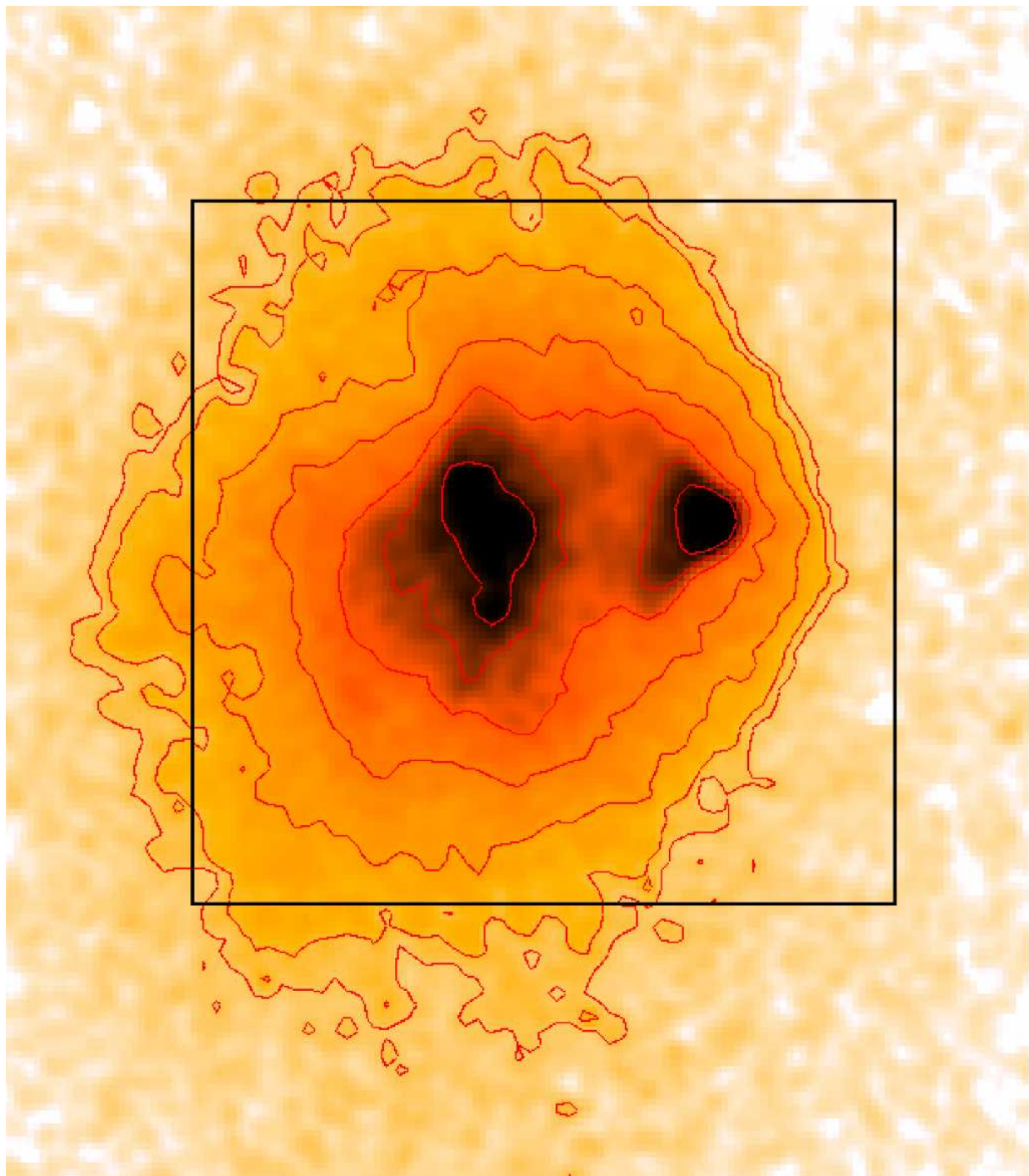


Need a new method

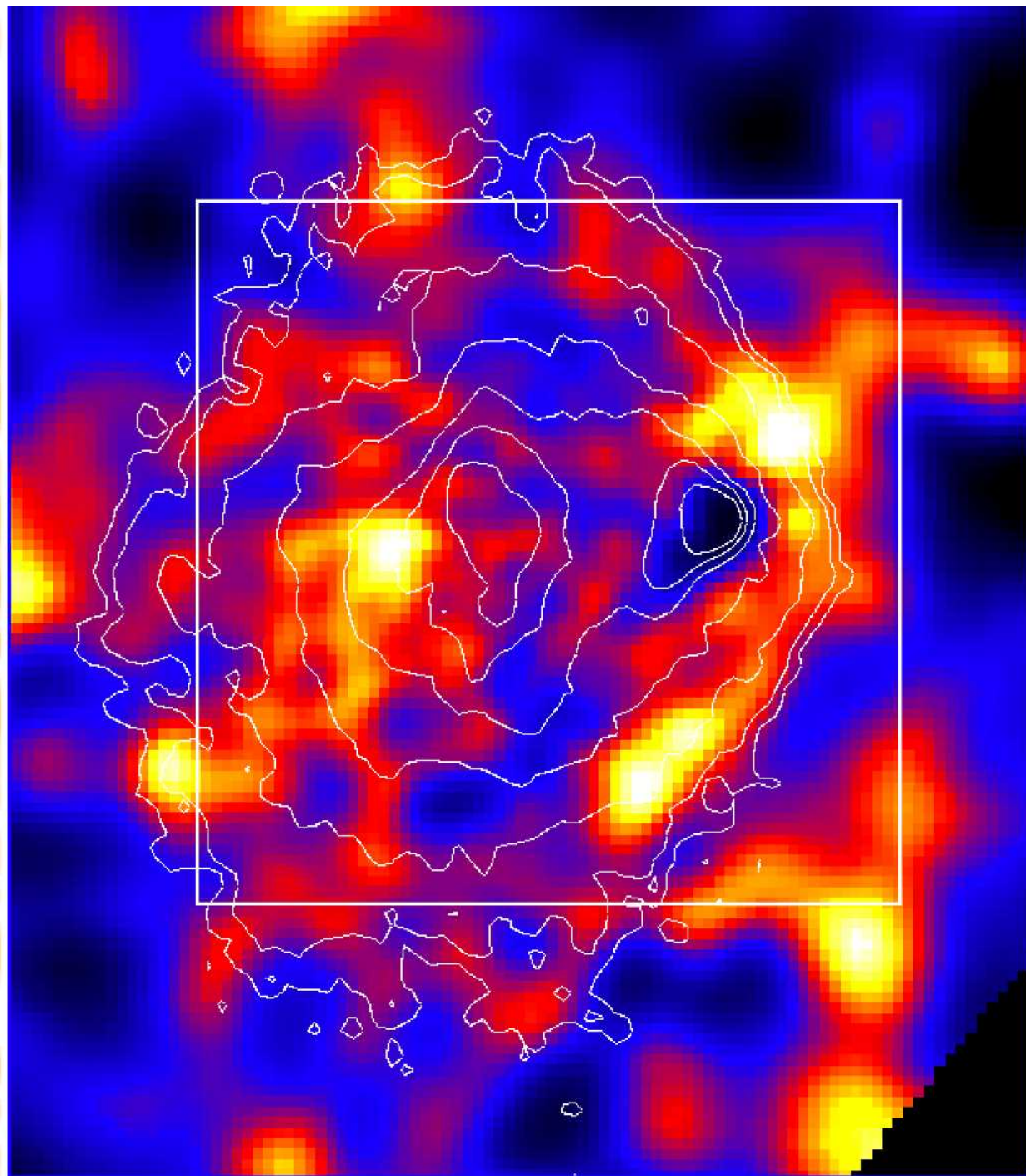


Bullet Cluster: resulting temperature comparison

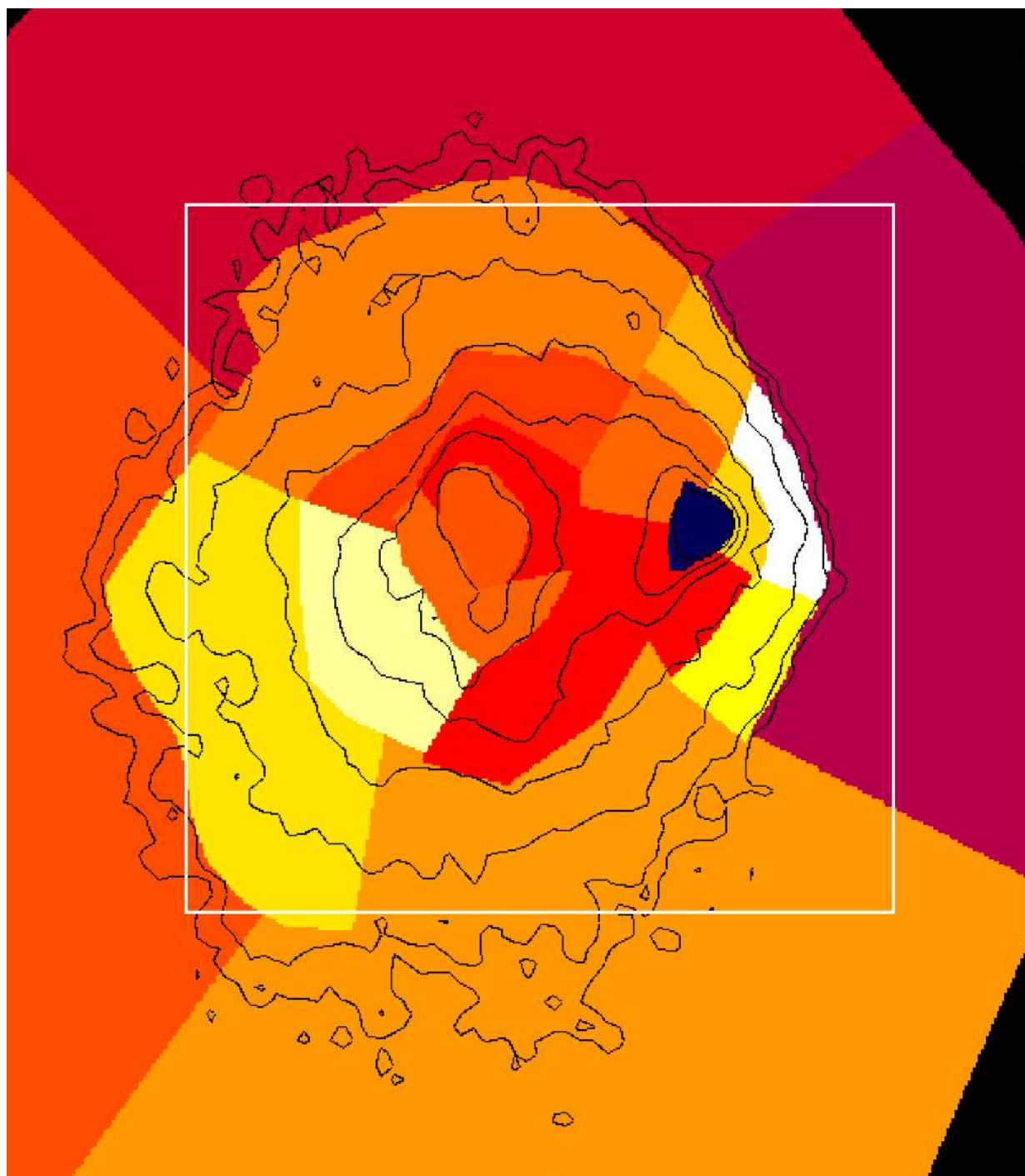
Chandra SB



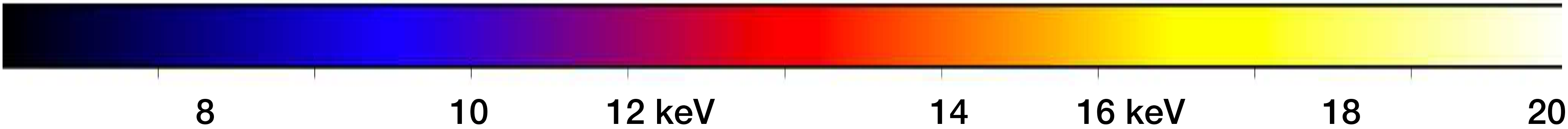
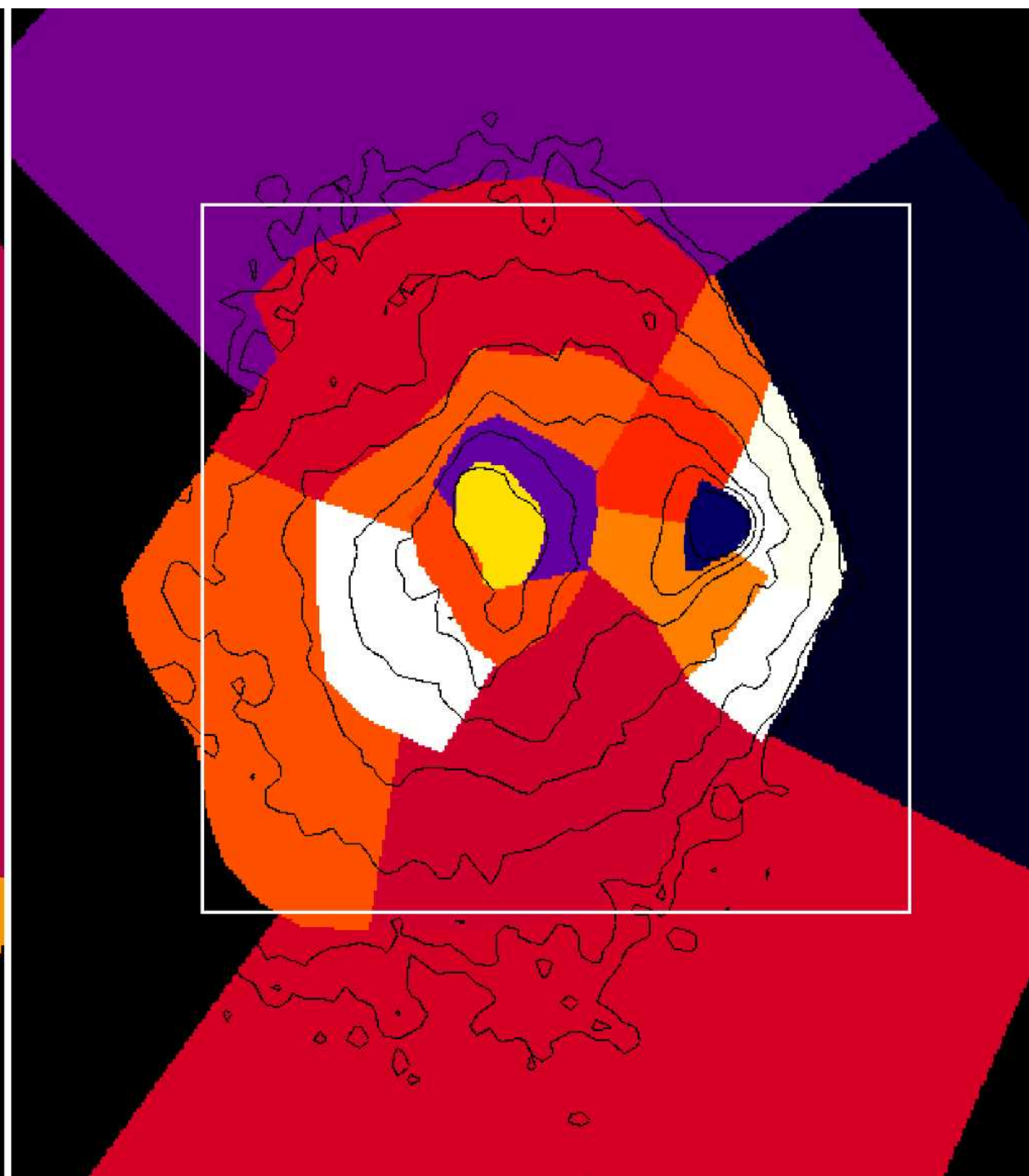
Chandra kT



Chandra kT

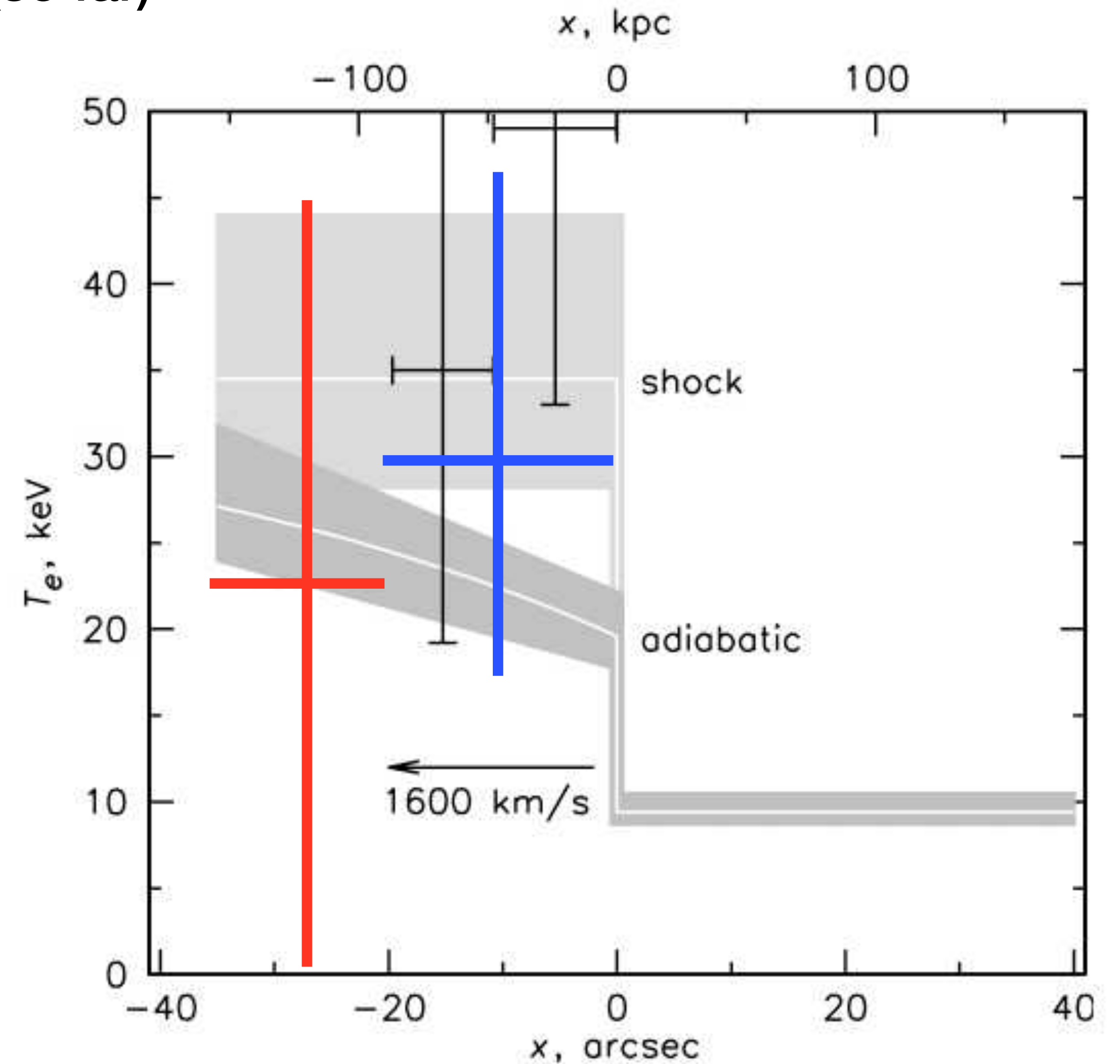
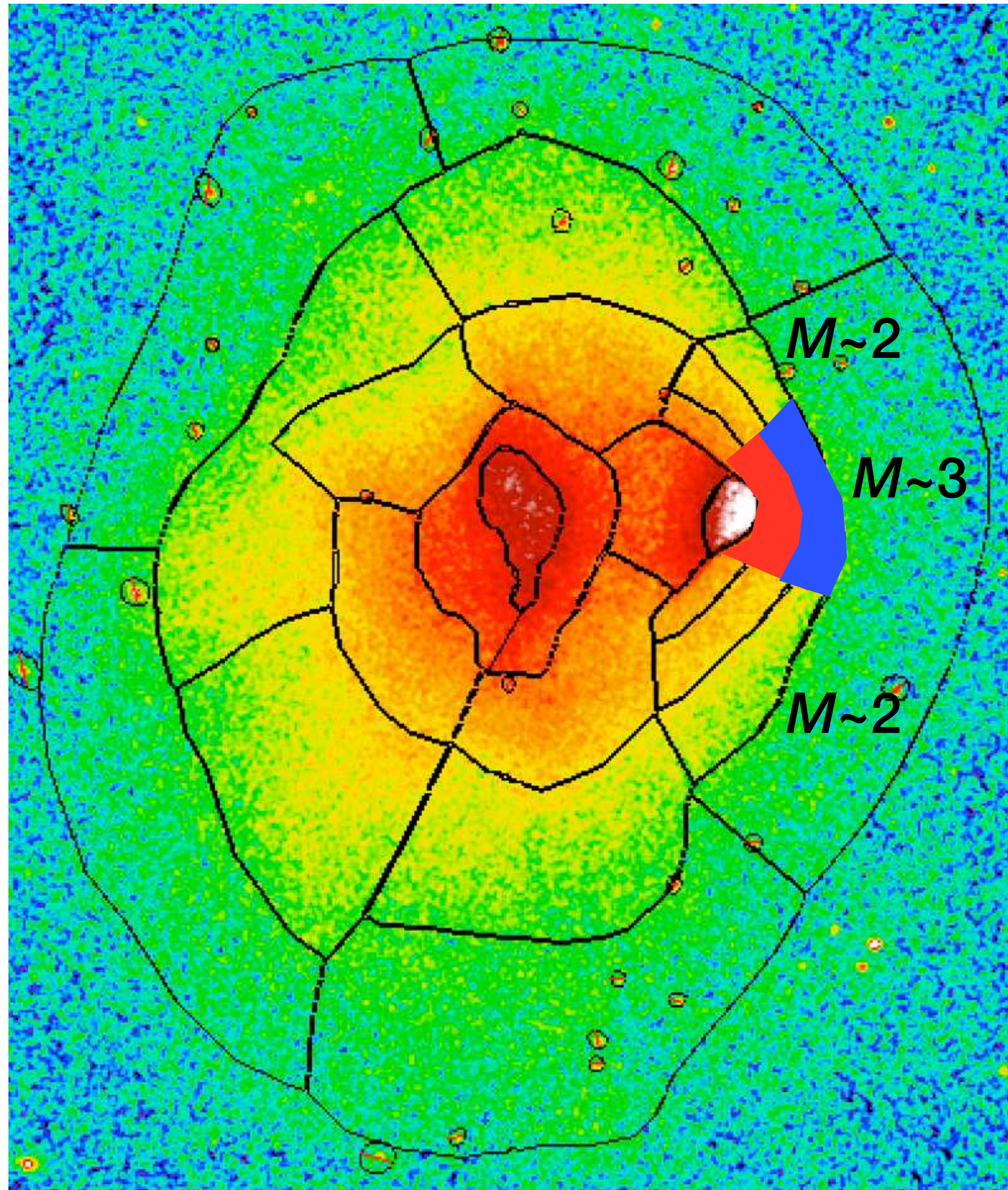


NuSTAR kT

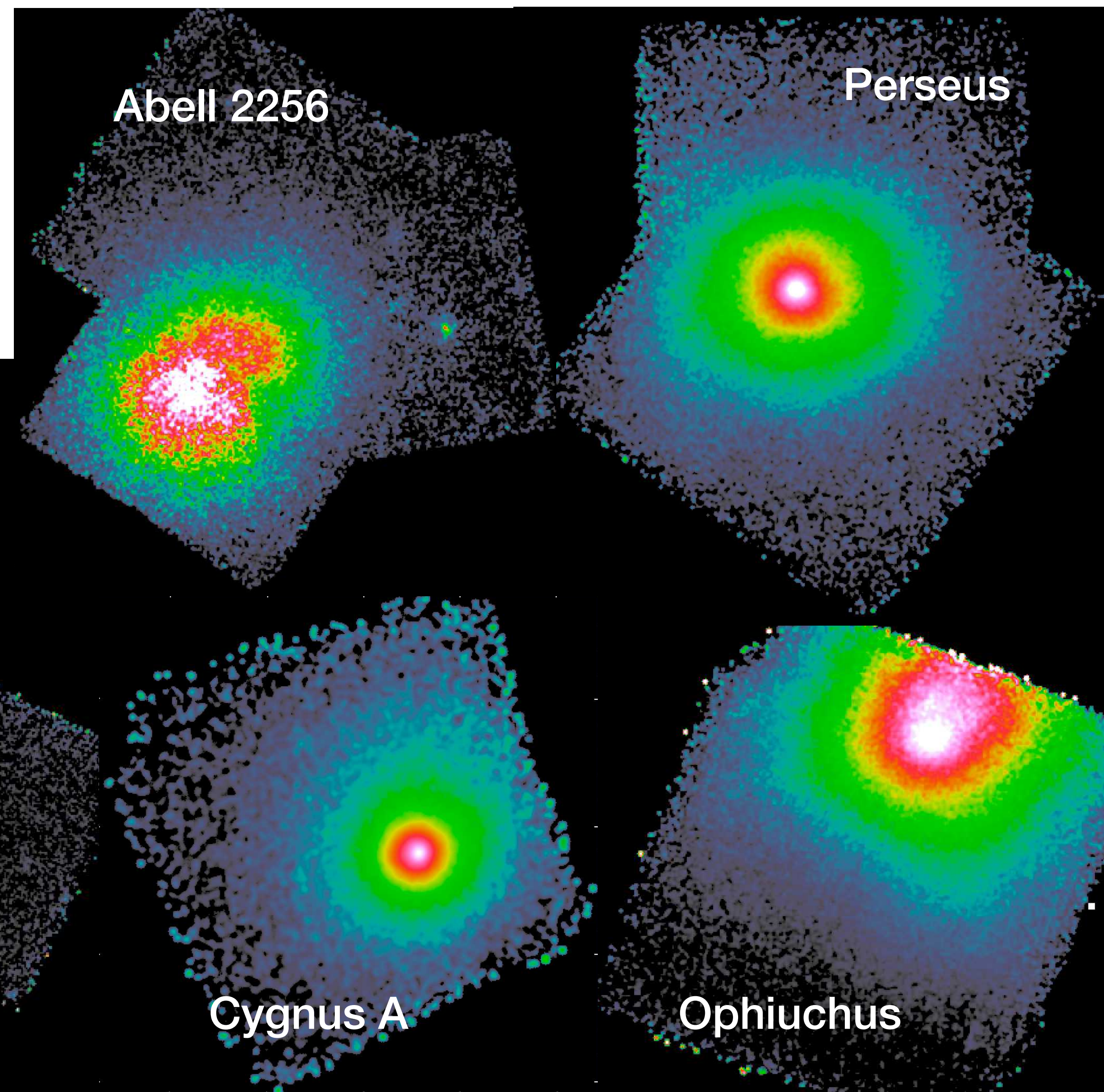
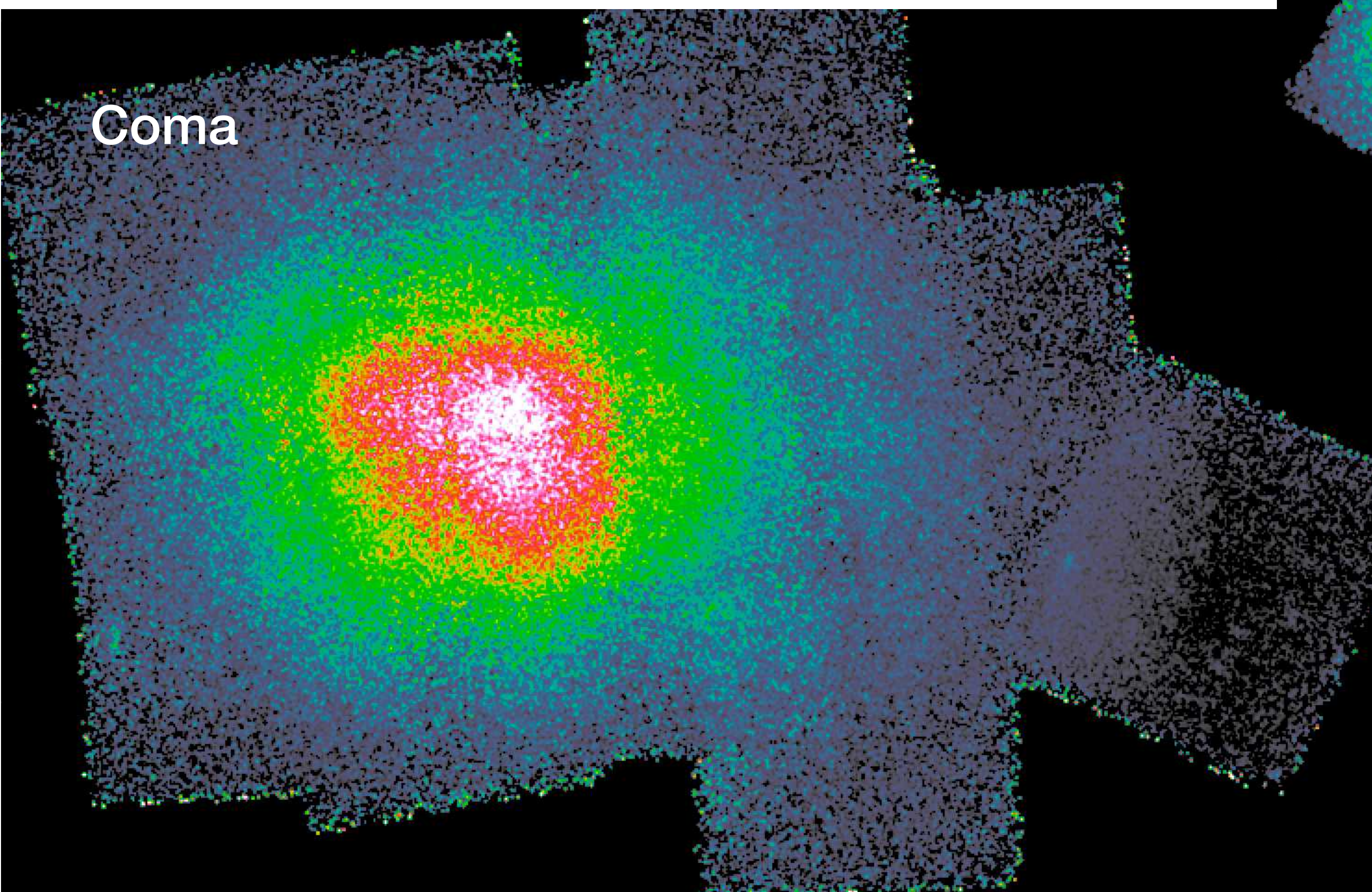


Insufficient statistics in the Mach~3 region

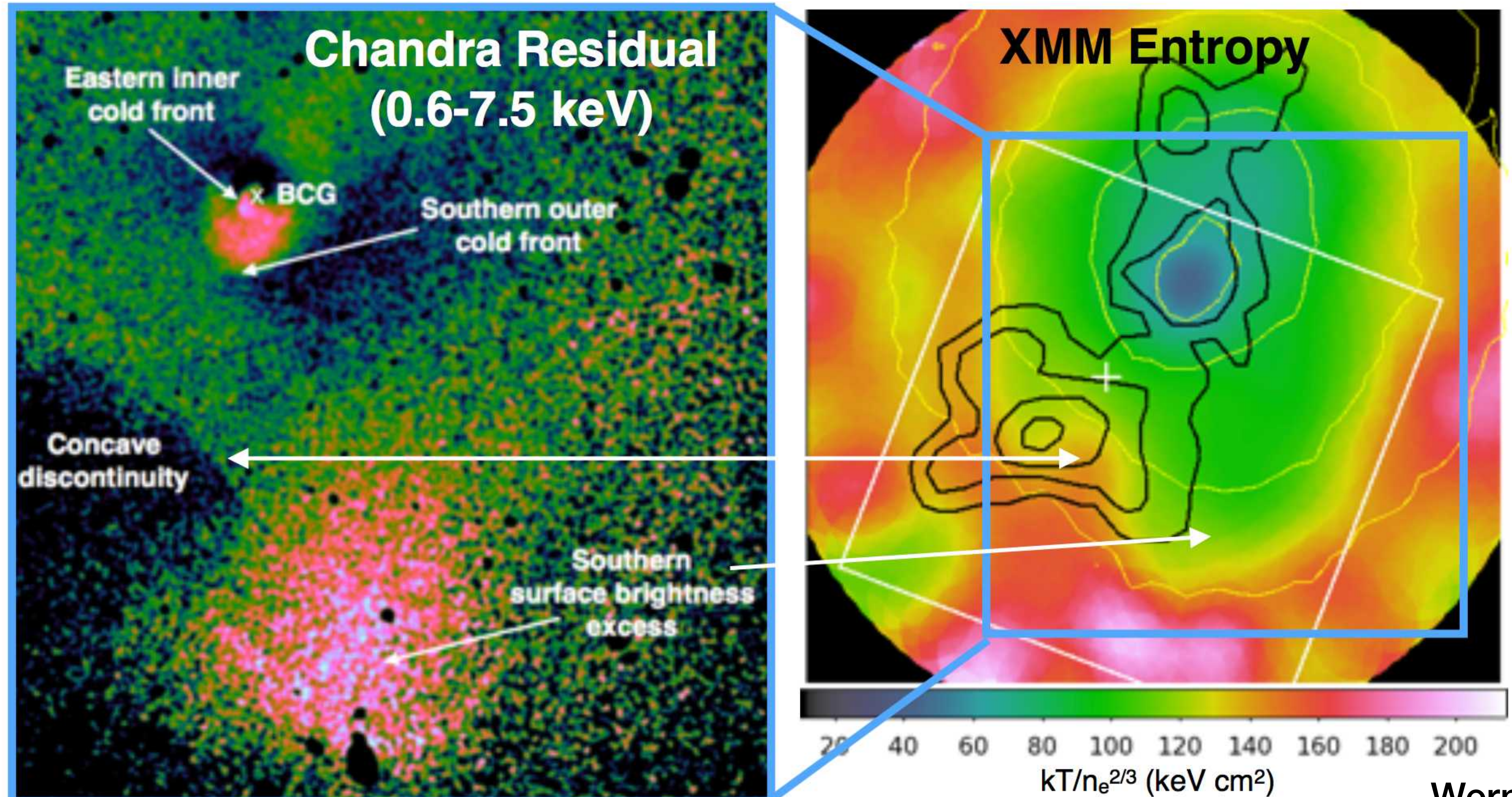
(so far)



NuSTAR observations of extended clusters

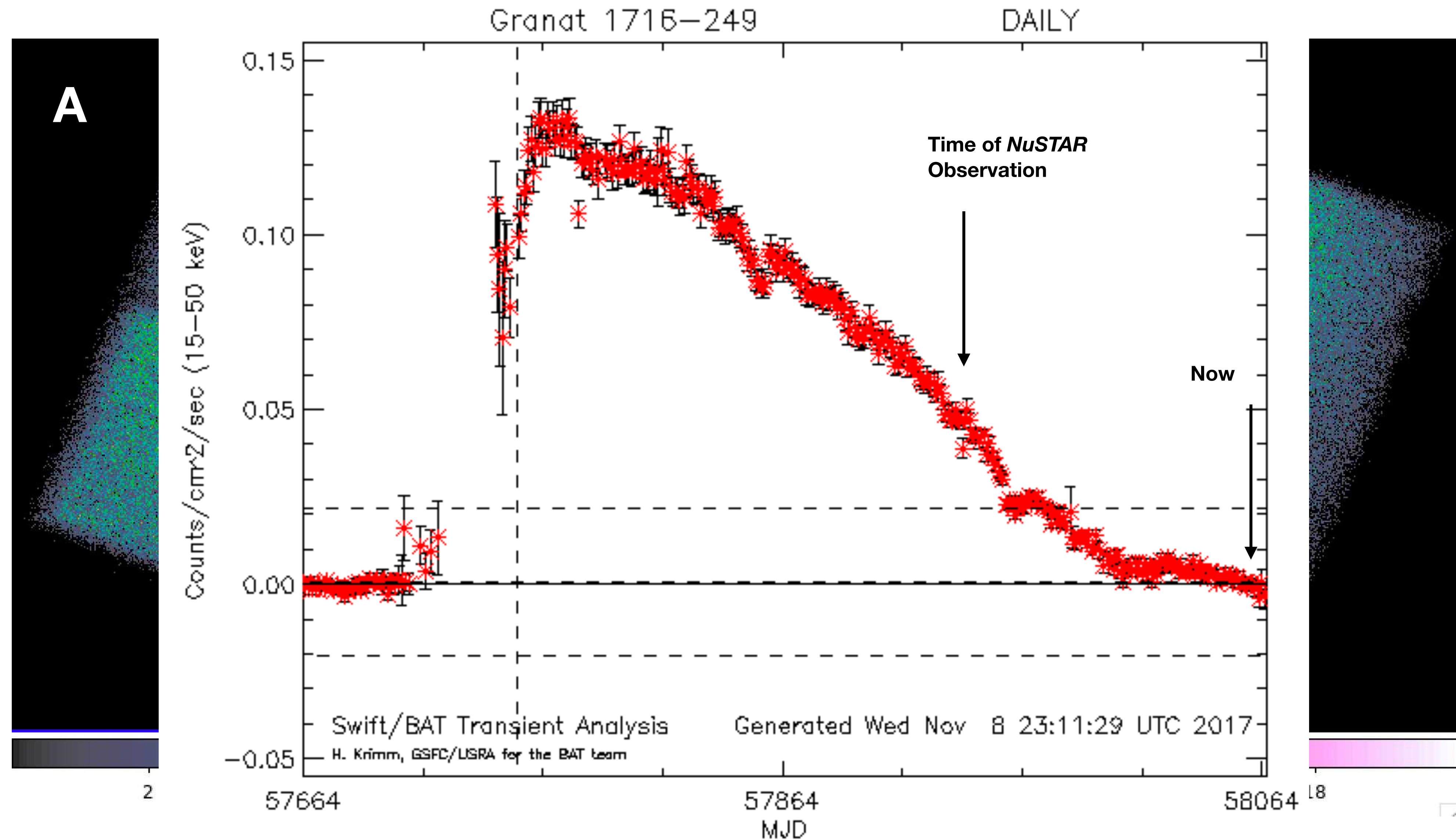


Ophiuchus Cluster Core: Merger-generated Mini-halo?

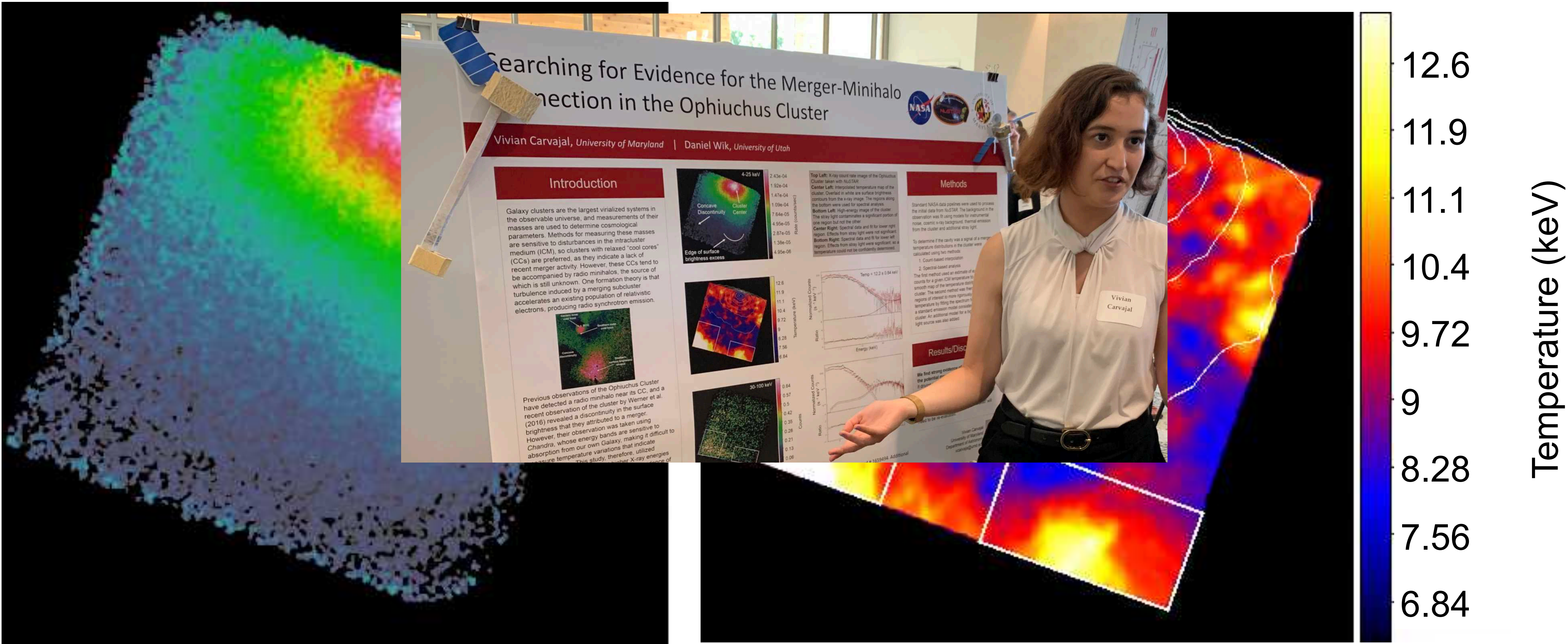


Werner+16

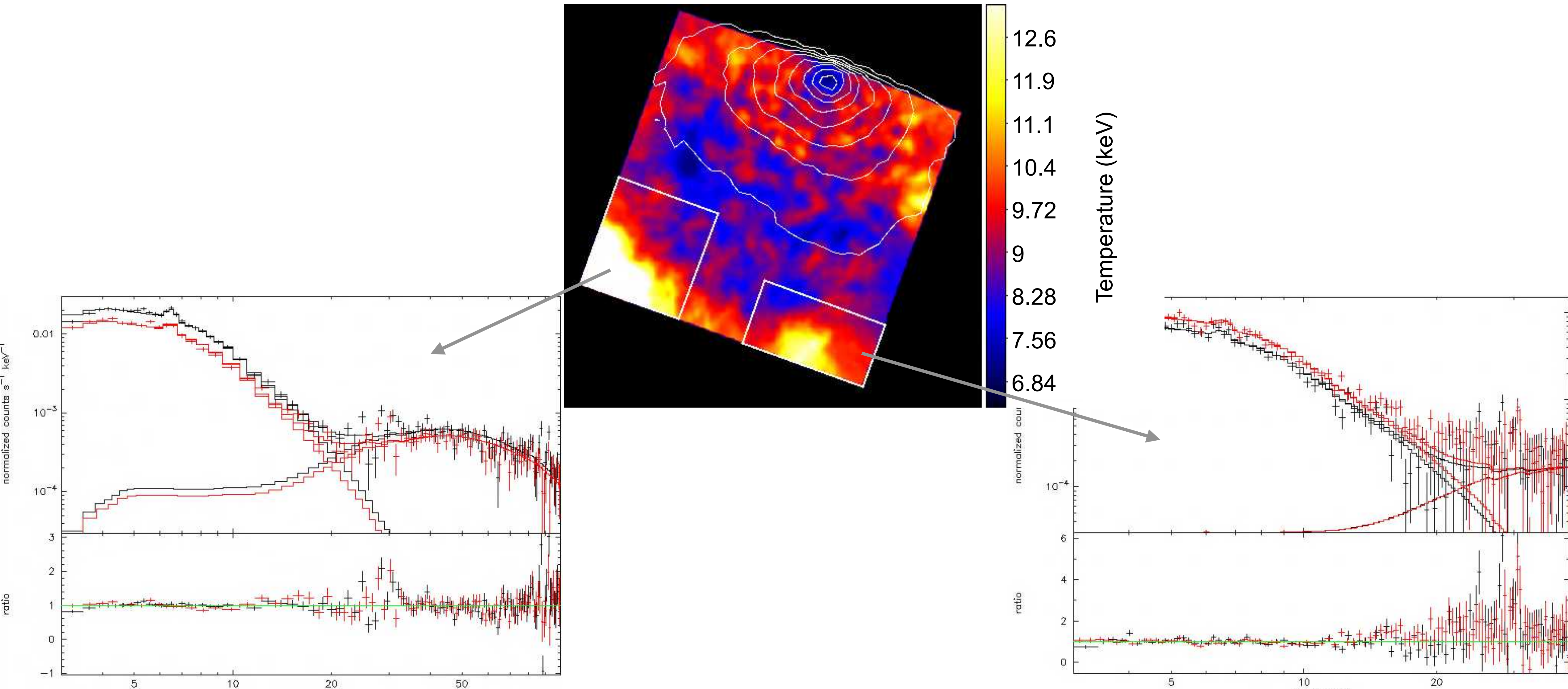
Ophiuchus Cluster Core: Merger-generated Mini-halo?



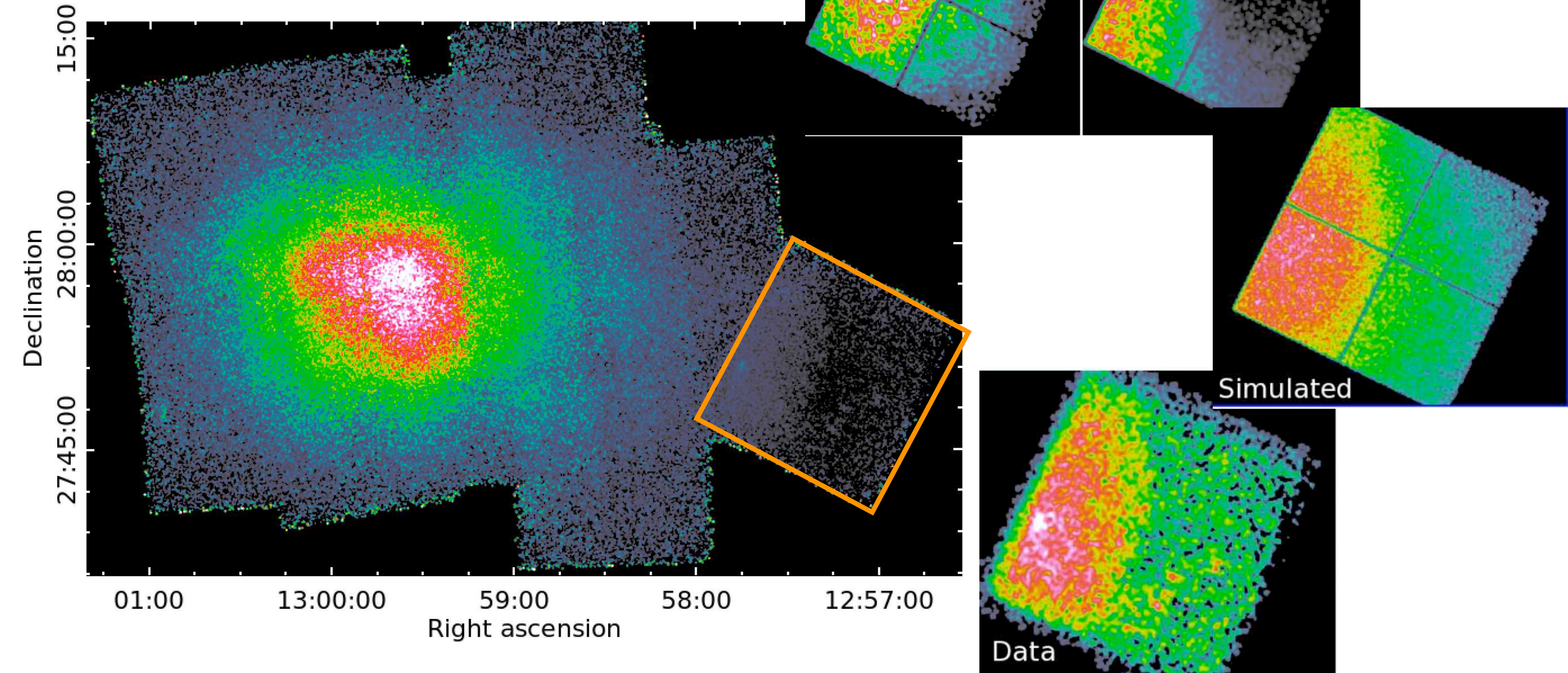
Ophiuchus Cluster Core: Merger-generated Mini-halo?



New, more subtle, stray light

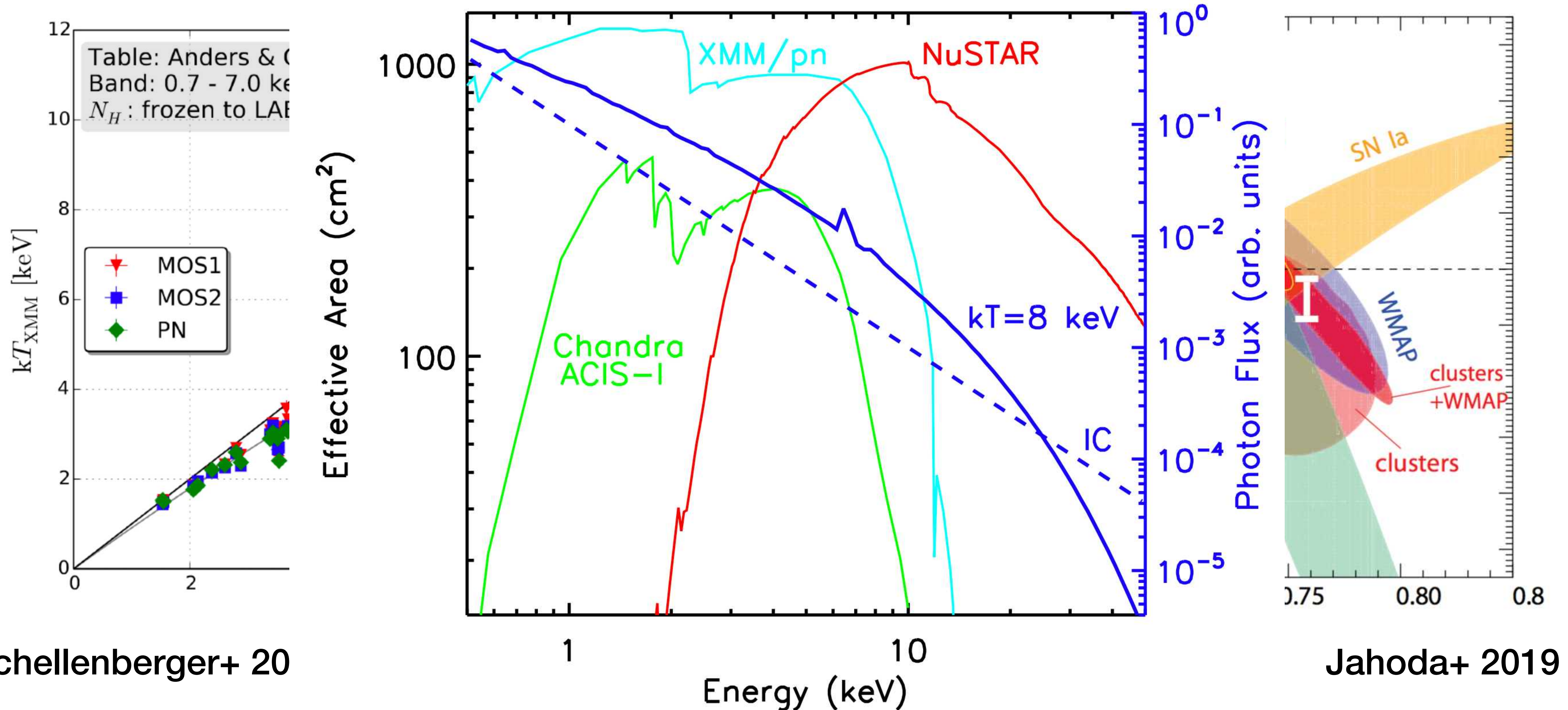


Coma Cluster



Potential to address calibration

limiting factor for cosmology

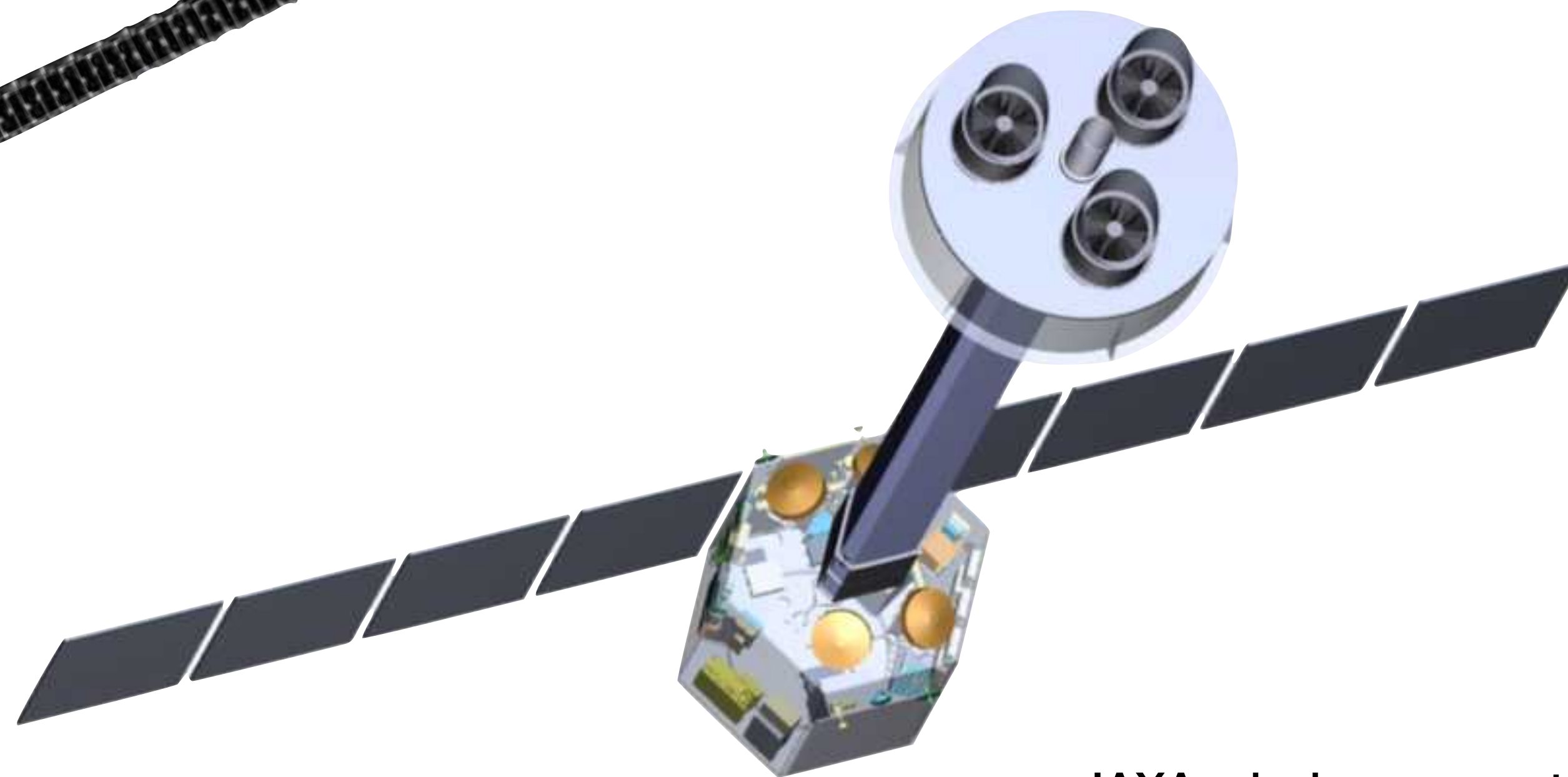


Schellenberger+ 20

Jahoda+ 2019

Future Proposed Hard X-ray Missions

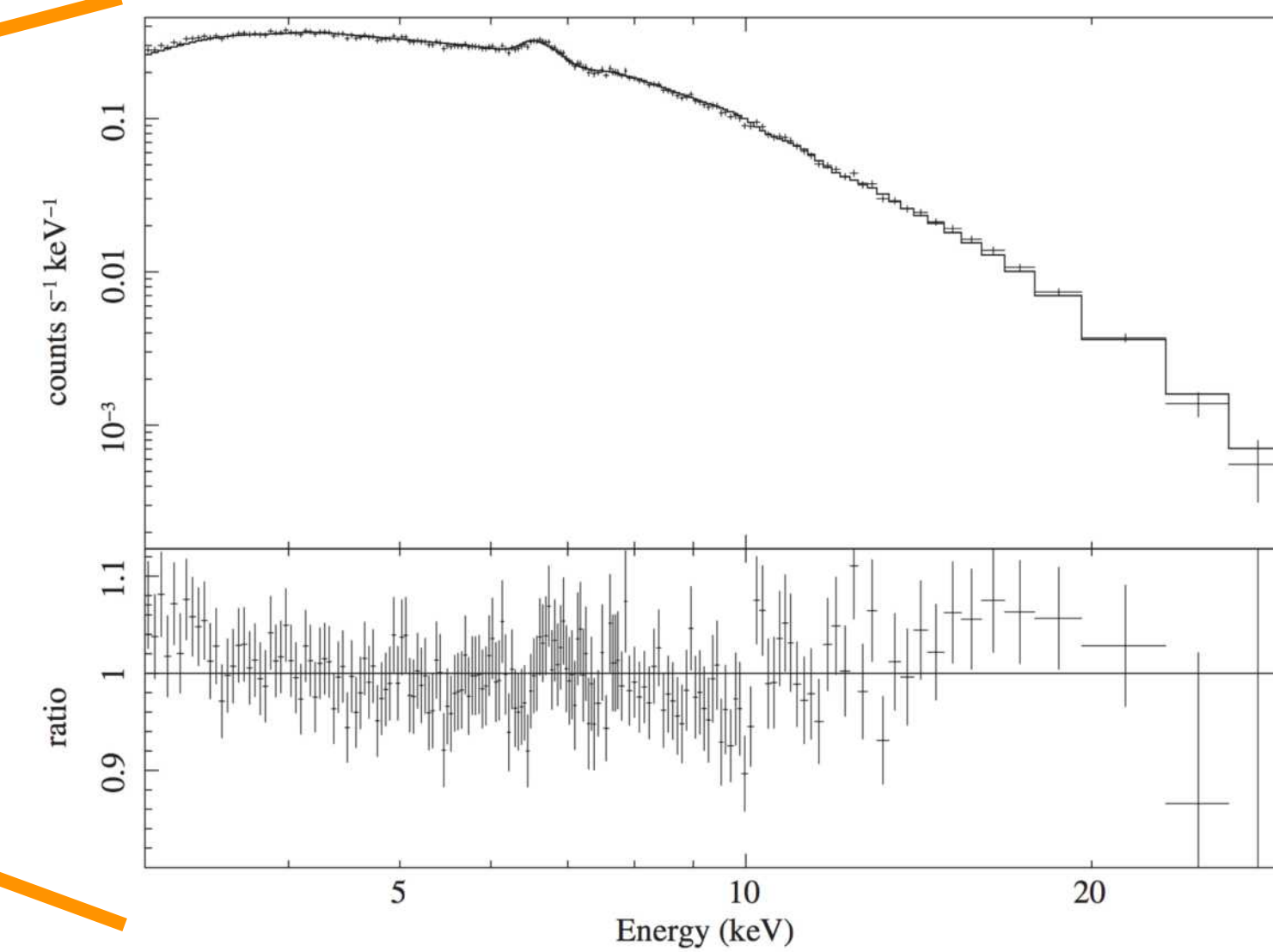
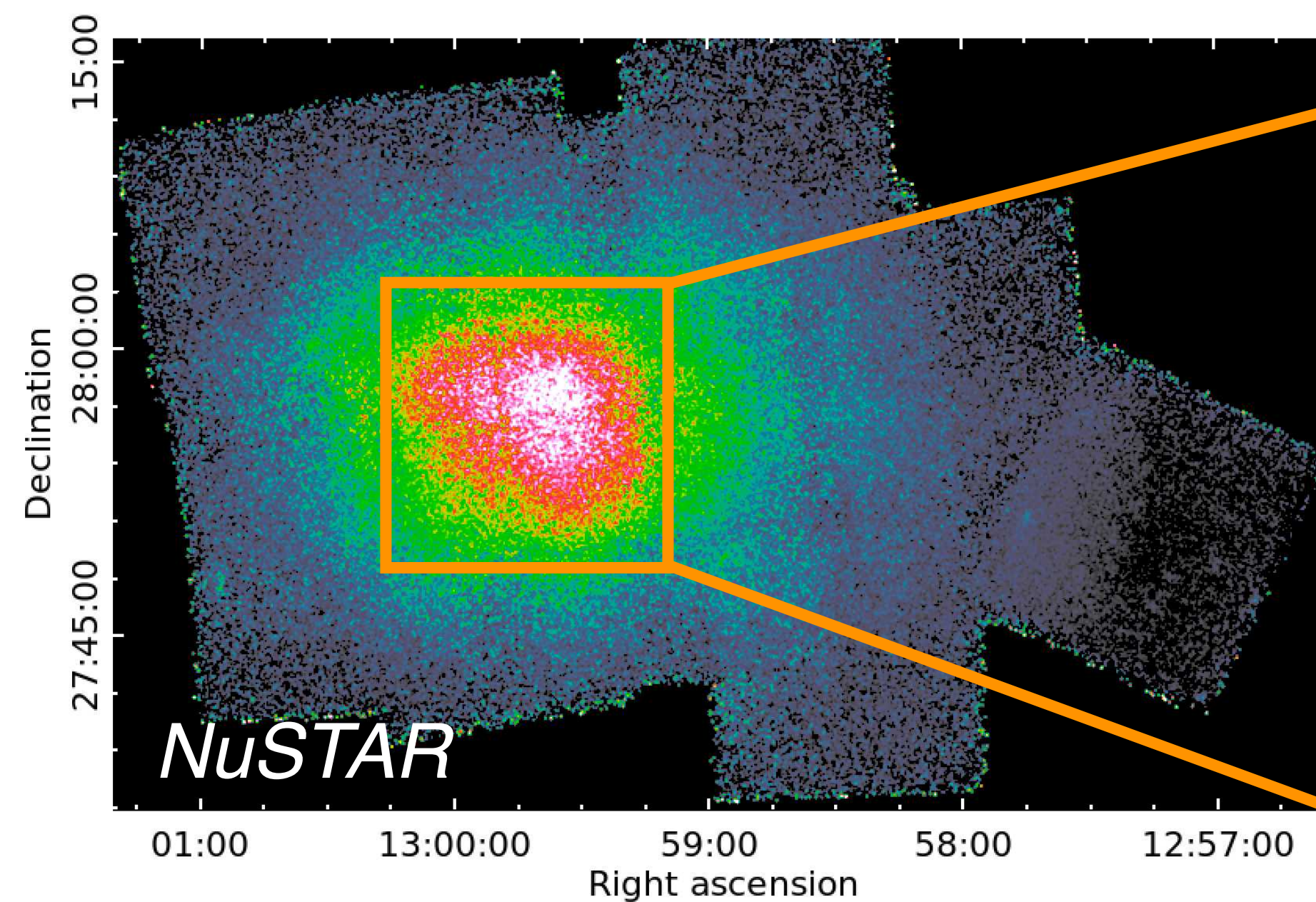
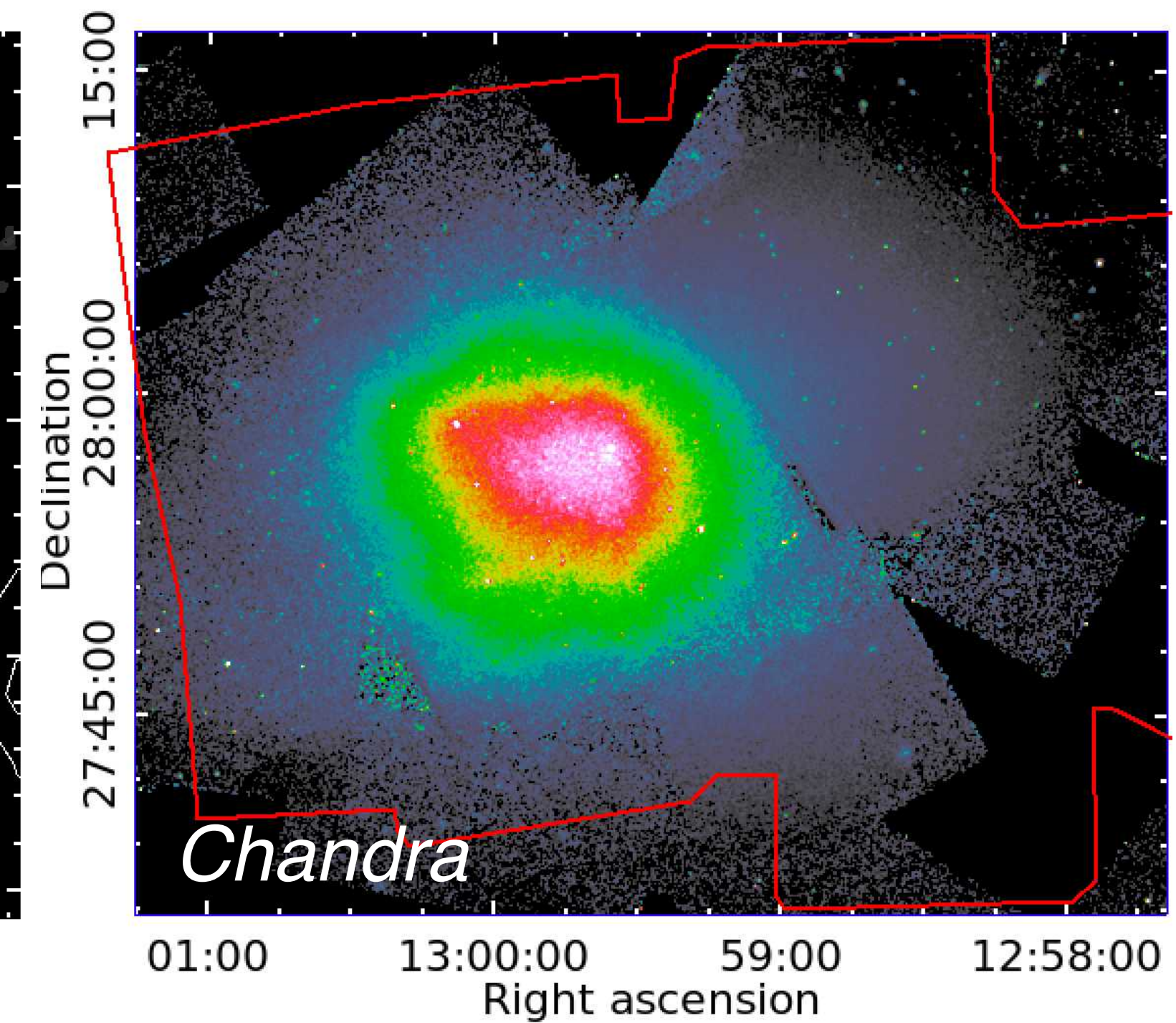
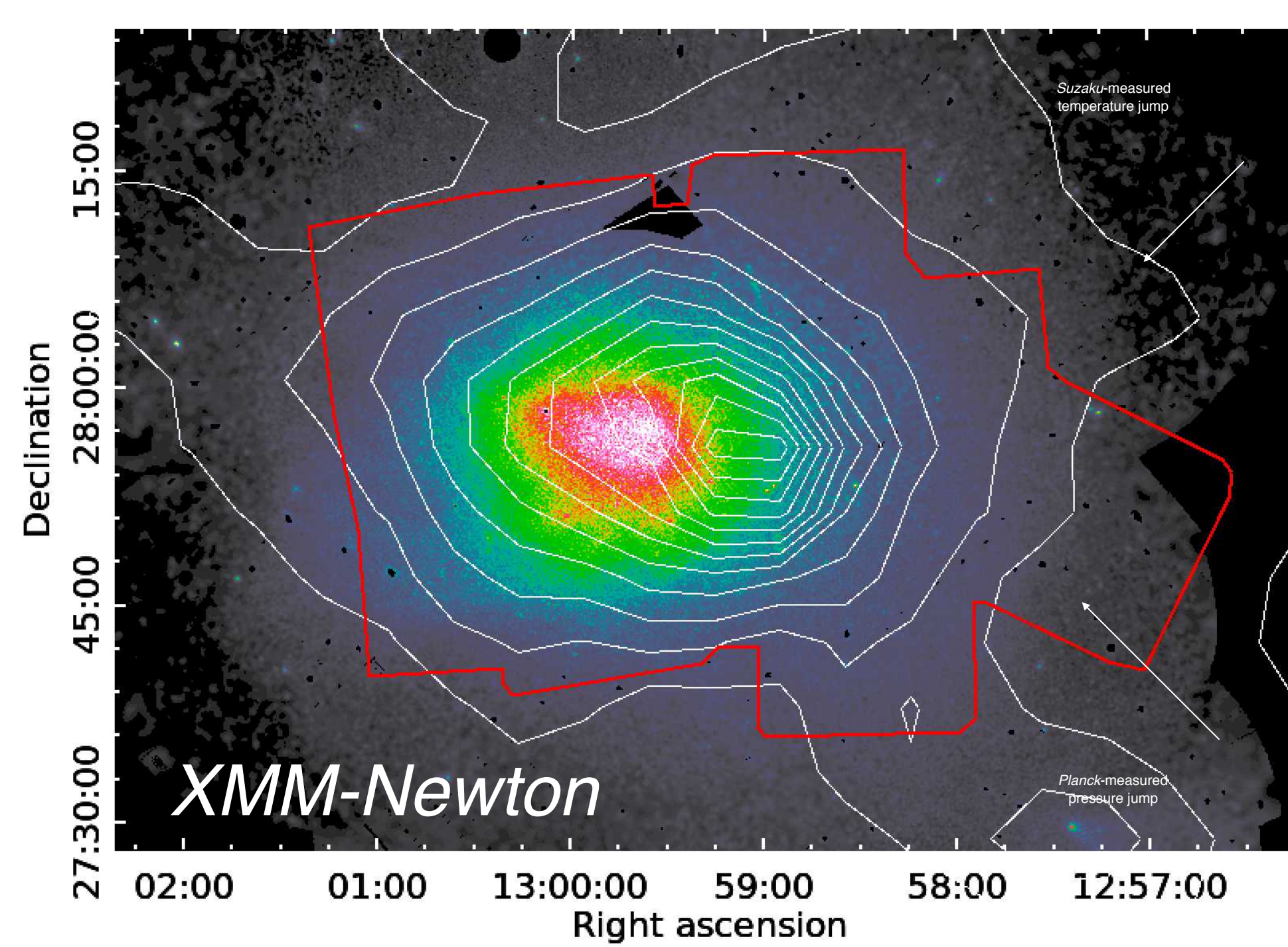
Make another *NuSTAR*, but better!
HEX-P: more area + 15" HPD
NASA Probe concept



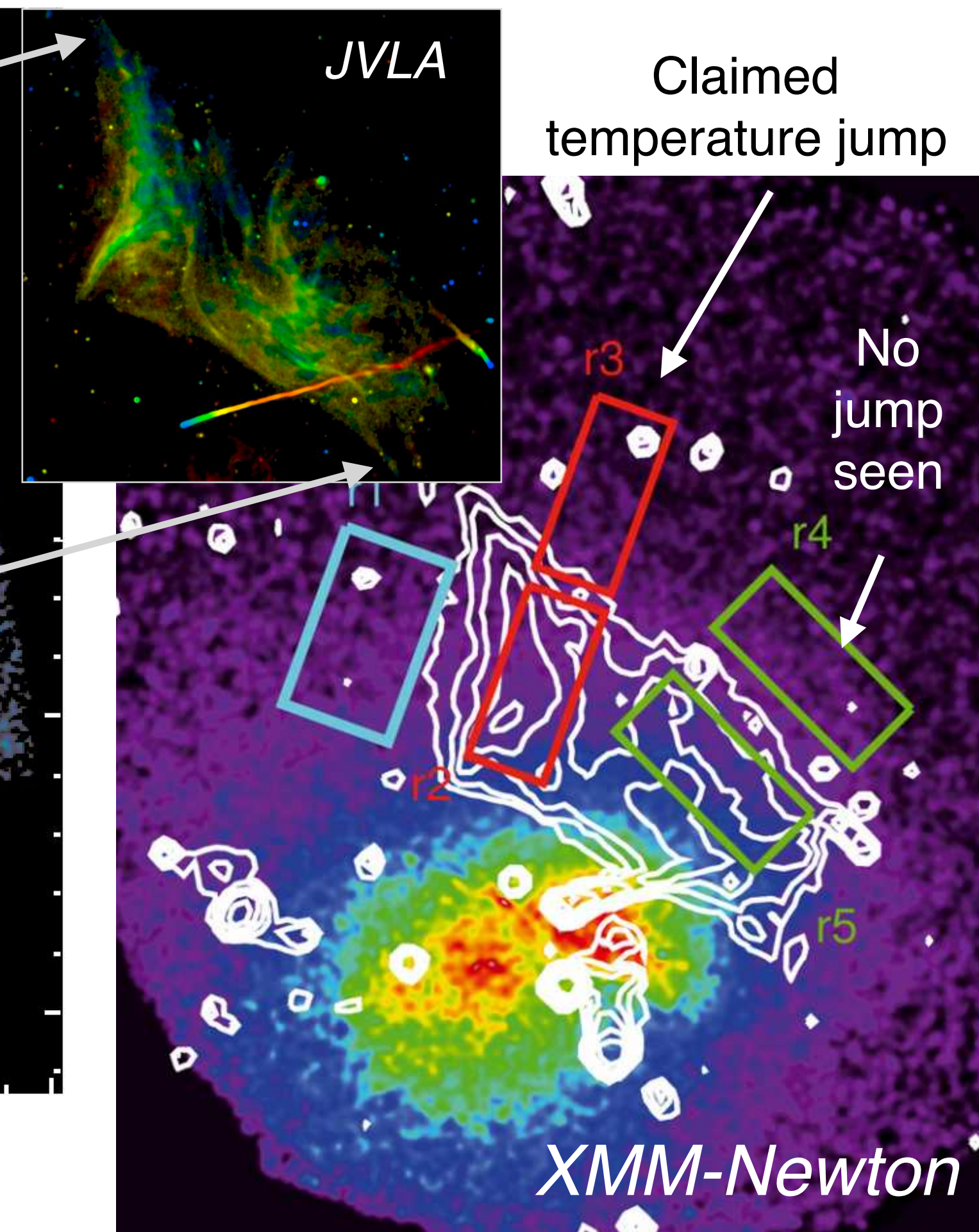
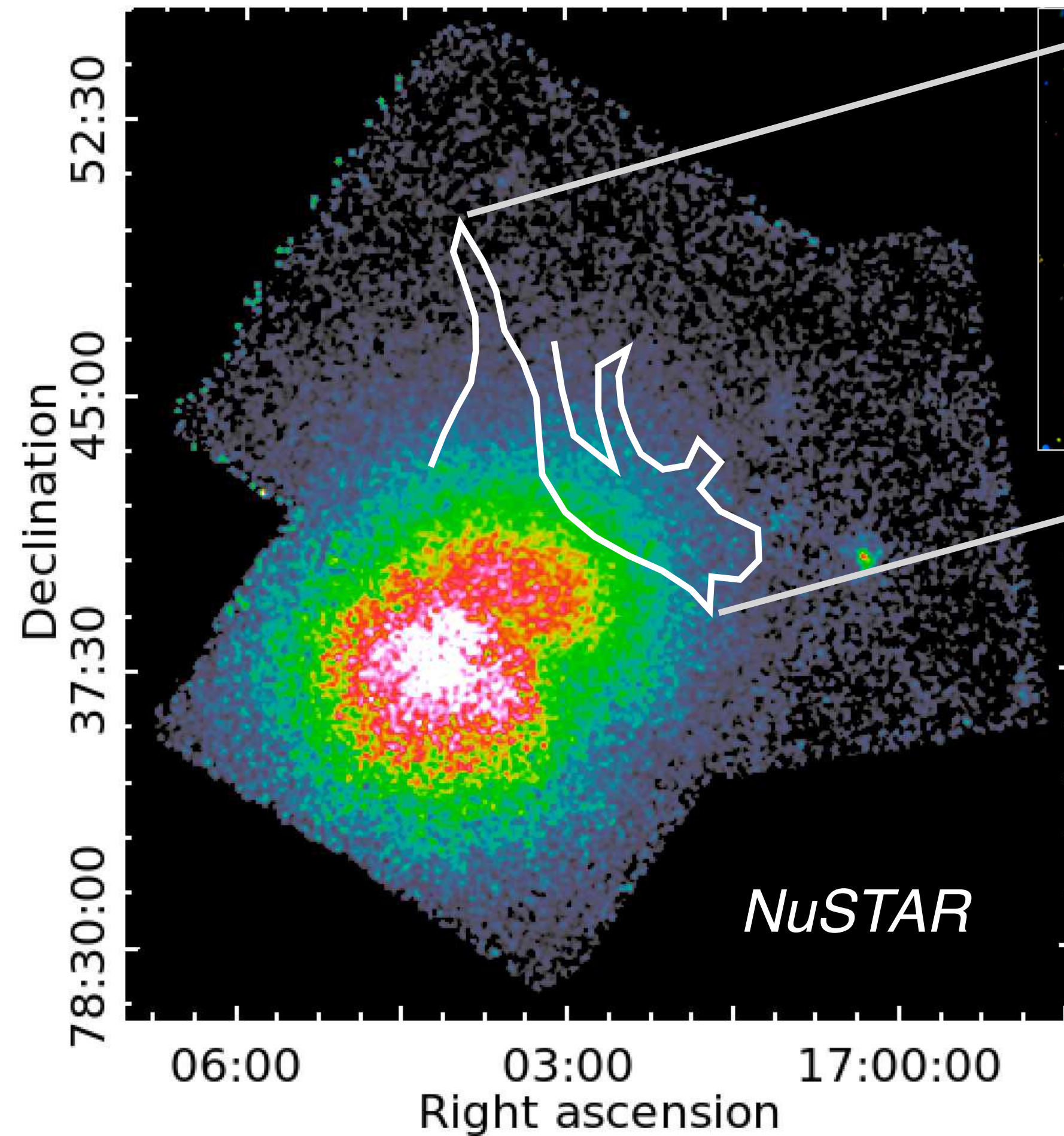
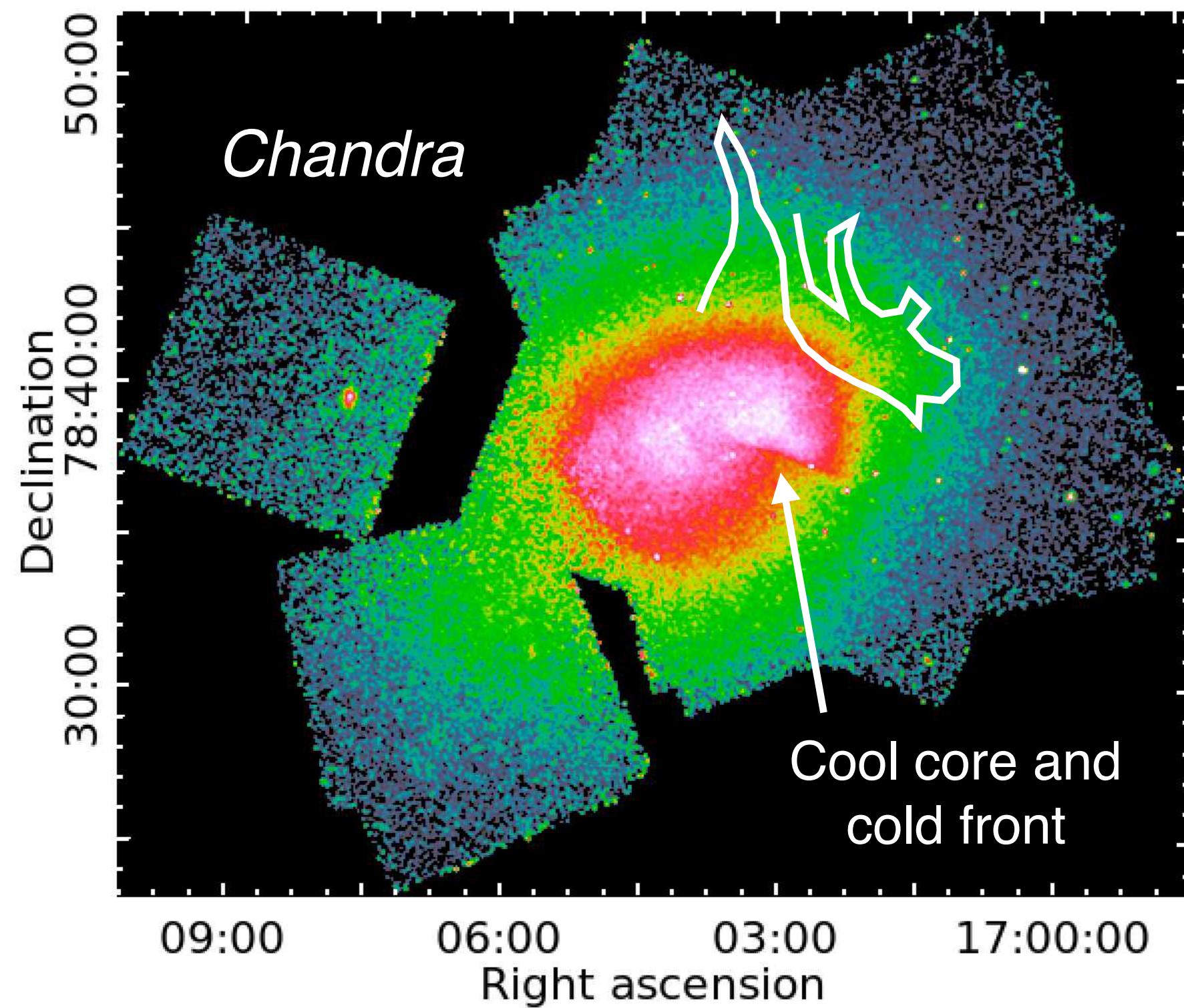
JAXA mission concept
Or use the *FORCE* Luke!
NuSTAR area with 15" HPD. Or Both.

Take aways

- *NuSTAR* is great for measuring, and spatially resolving, high temperature gas in galaxy clusters
- kT s largely agree, but *NuSTAR* tends to produce less extreme temperatures
- IC emission: no detections yet
 - Abell 2163: strong limits rule out previous IC estimates
 - A665, A2146: underway, no indications of IC
- Shock measurements: not yet definitive, but strong promise
 - Abell 665: somewhat favors electron shock-heating
 - Abell 2146 & Bullet cluster: more work needed, but may be limited by *NuSTAR*'s resolution



Abell 2256: kT (and IC?) features



Trasatti+ 2015

Ways this work can help with *XRISM* analysis

I'm trying to hire a person to do exactly this, right now!

If you or someone you know is interested in such work, please let me know!

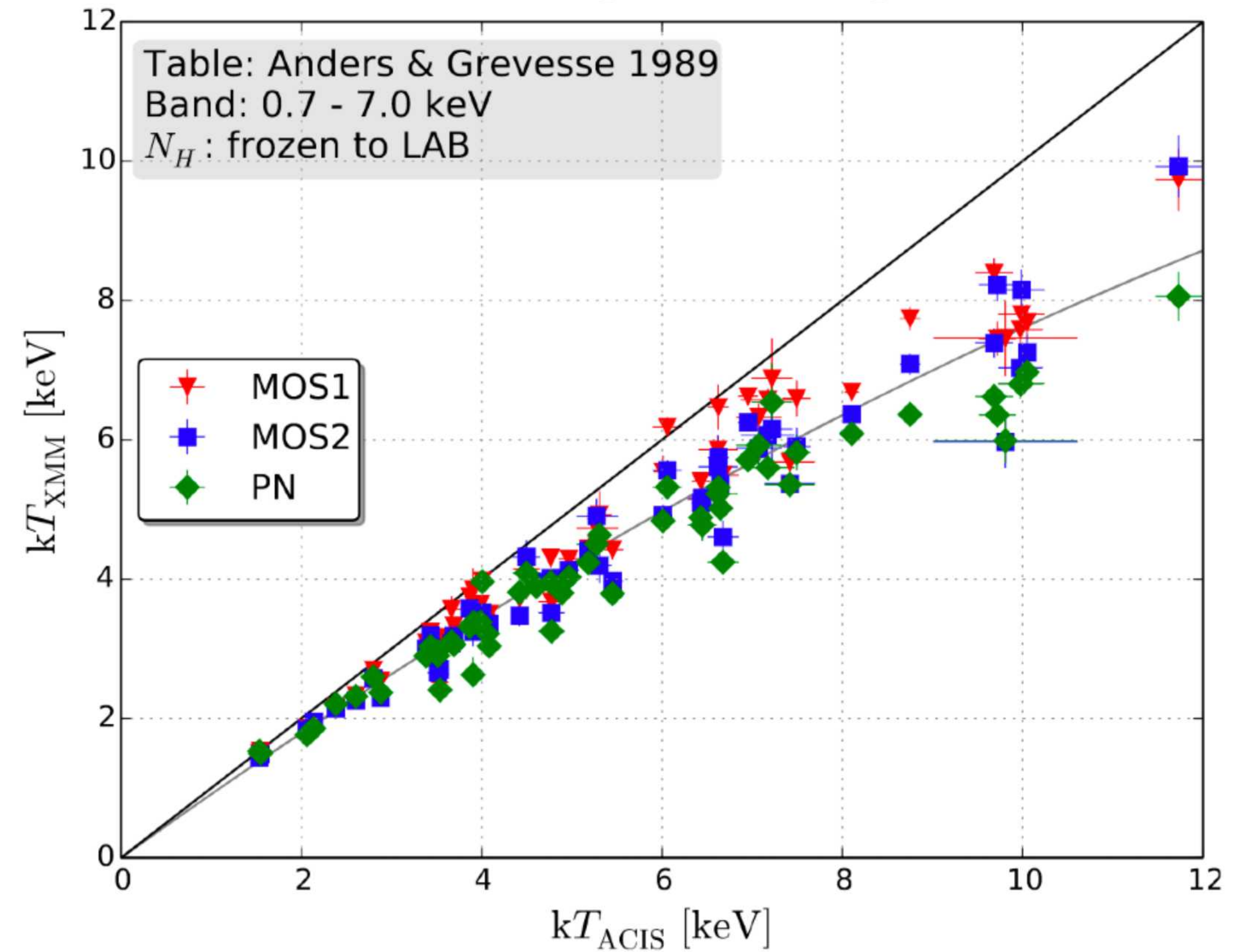
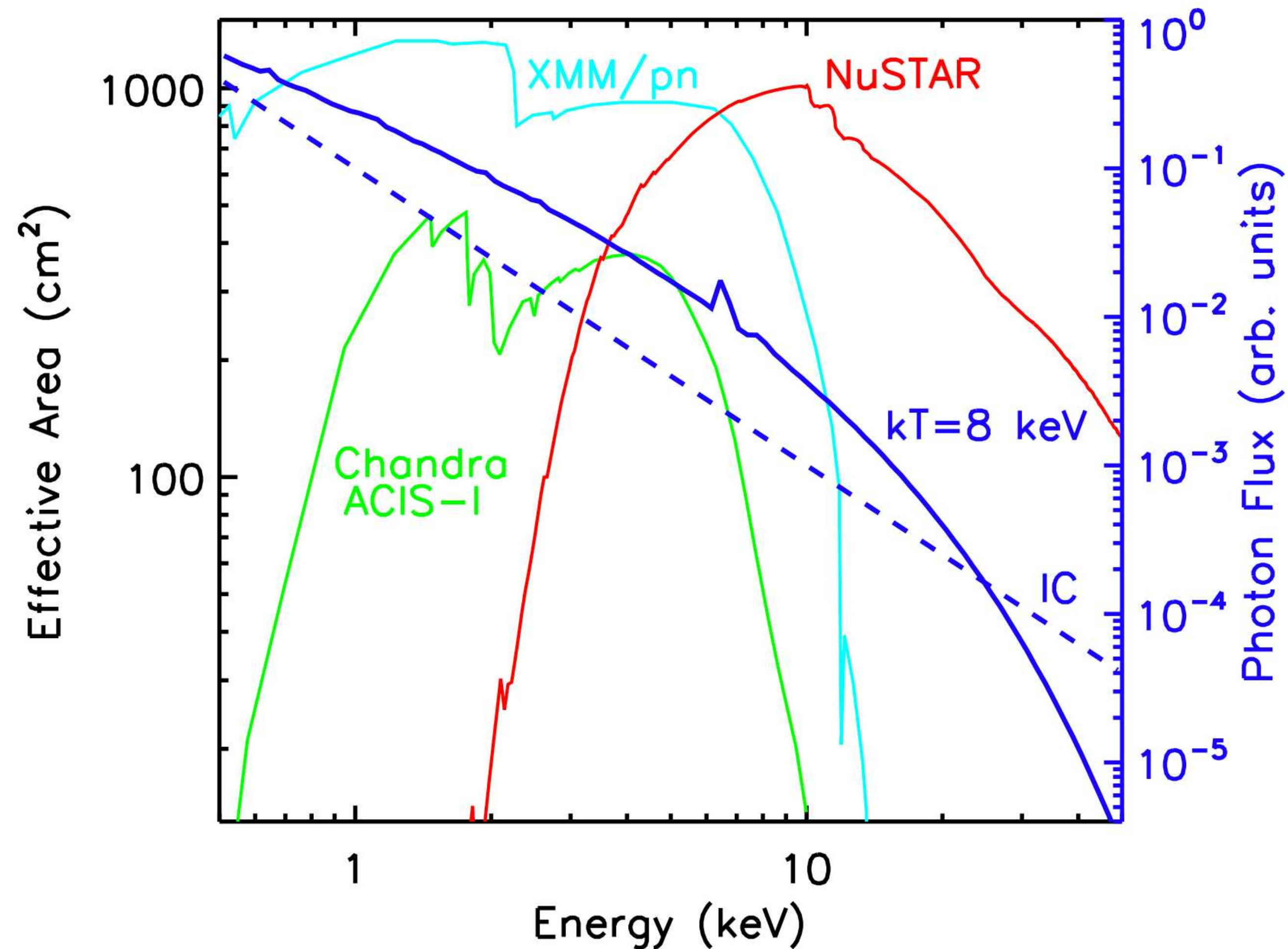
The NuSTAR-XRISM synergy is excellent:

- both have order 1 arcmin PSFs
- bandpasses overlap but combine for a much broader total bandpass
- both require similar tools/techniques to deal with PSF-mixing

Galaxy cluster science does not require simultaneous observations!

- assuming scattered light can be dealt with, current mosaics can be combined with future *XRISM* observations
- as *Hitomi* demonstrated so well, *NuSTAR*'s survival until *XRISM*'s launch is not guaranteed; better to begin deep, Legacy-class surveys of likely *XRISM* targets ASAP!

Systematics in galaxy cluster kT measurements



Schellenberger+ 2015