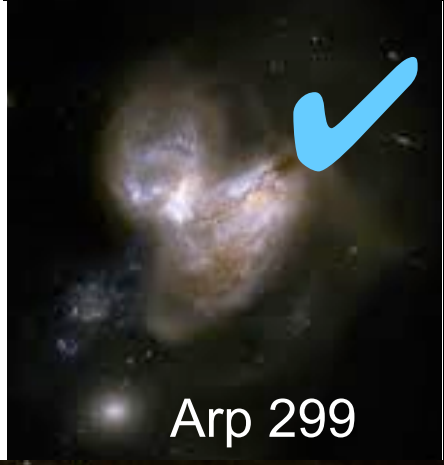
NuSTAR

Starburst Galaxies



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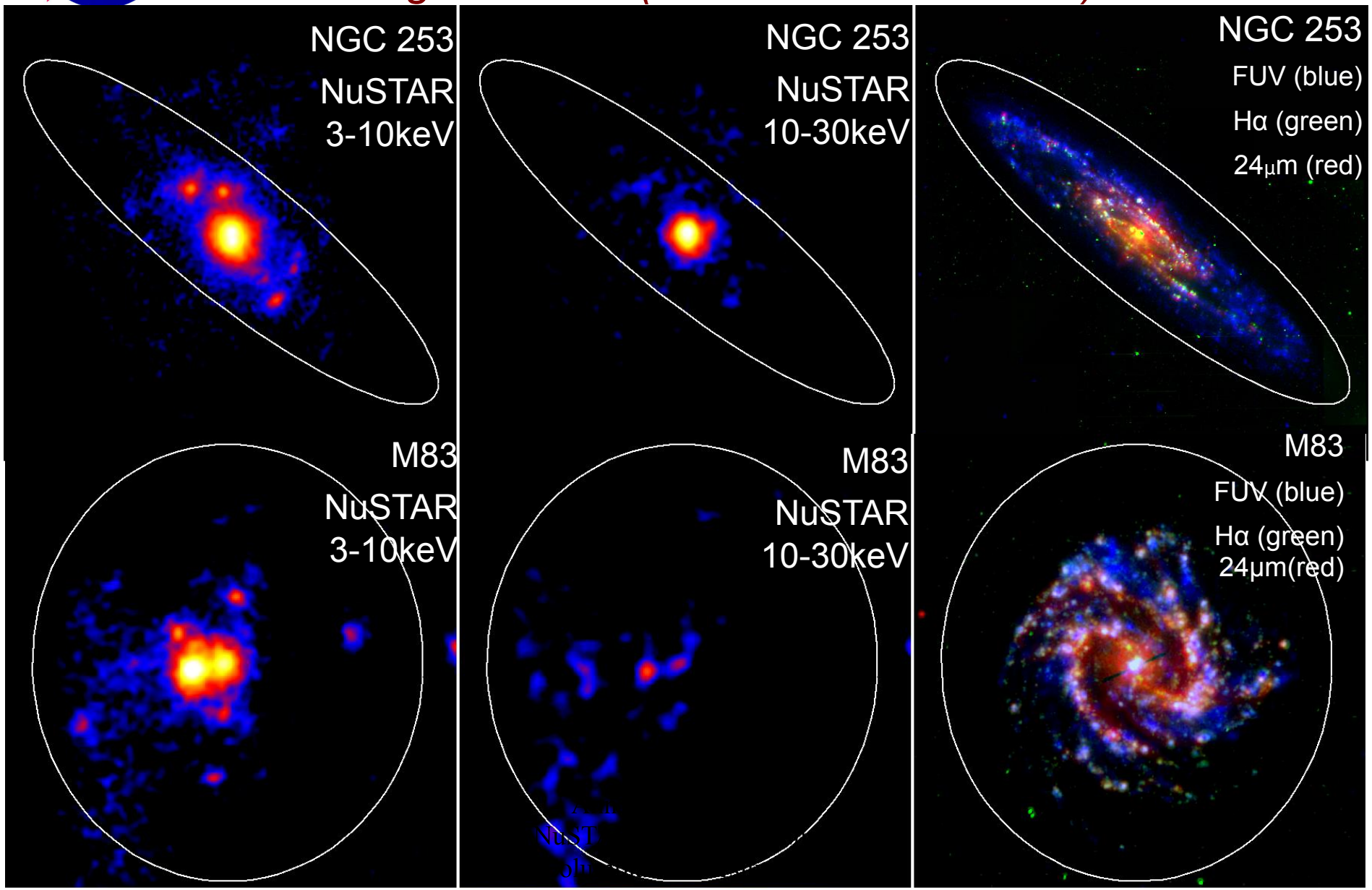
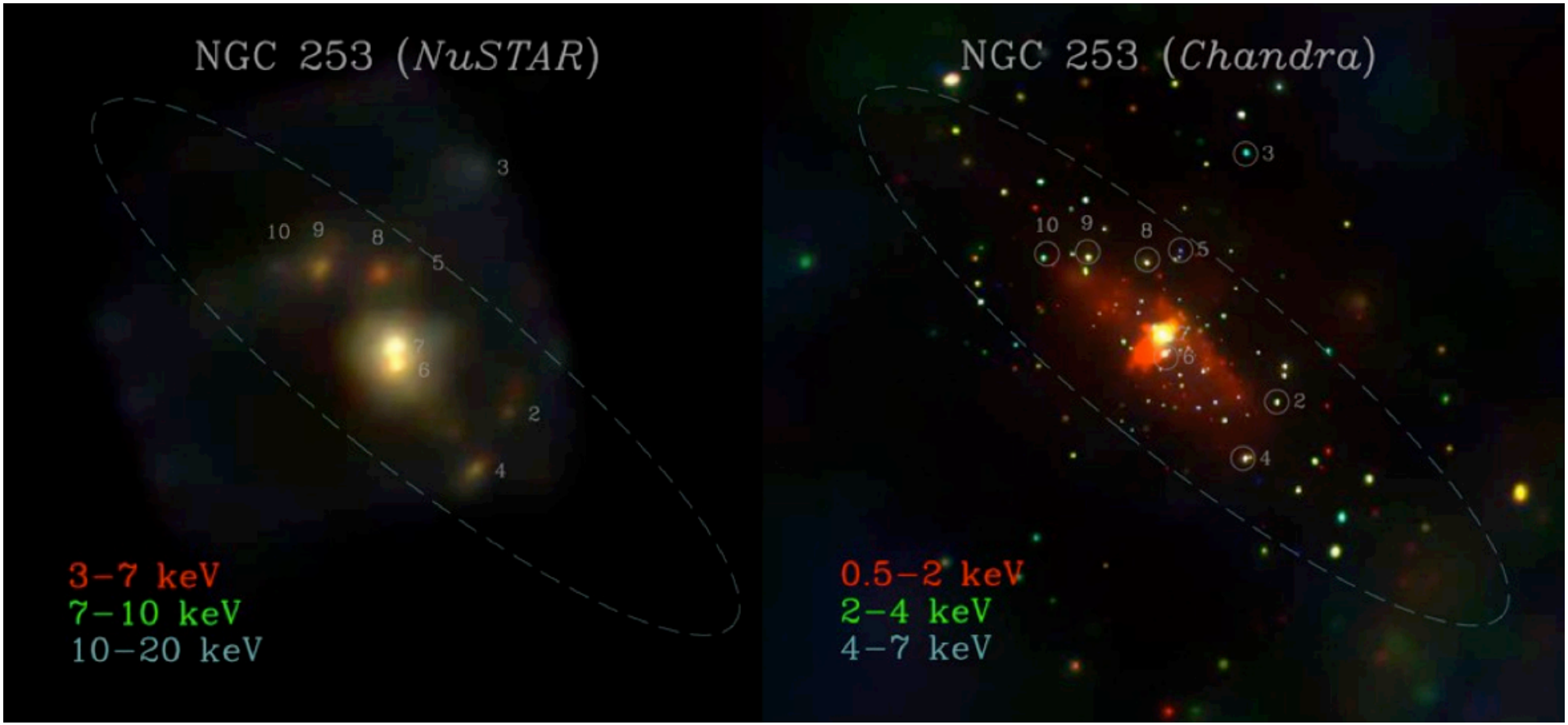
Hard (E>10 keV) observations of Starburst Galaxies

- Science goals:
  - Compact object (NS & BH) populations
  - Nuclear activity (AGN vs. starburst)
  - Diffuse emission from hot X-ray gas
  - Particle acceleration in SF regions
- All six galaxies have/will have concurrent *Chandra* coverage (P.I. Hornschemeier for five; PI for *Chandra* Arp 299 observations was A. Zezas).
- M83 has had three sets of *NuSTAR* observations, two concurrent with *XMM* exposures (PI K. Kuntz; Aug 2013, Jan 2014), one with *Chandra* (June 2014)

Spatially-Resolved Hard X-ray Images of Star-forming Galaxies (credit: Mihoko Yukita)

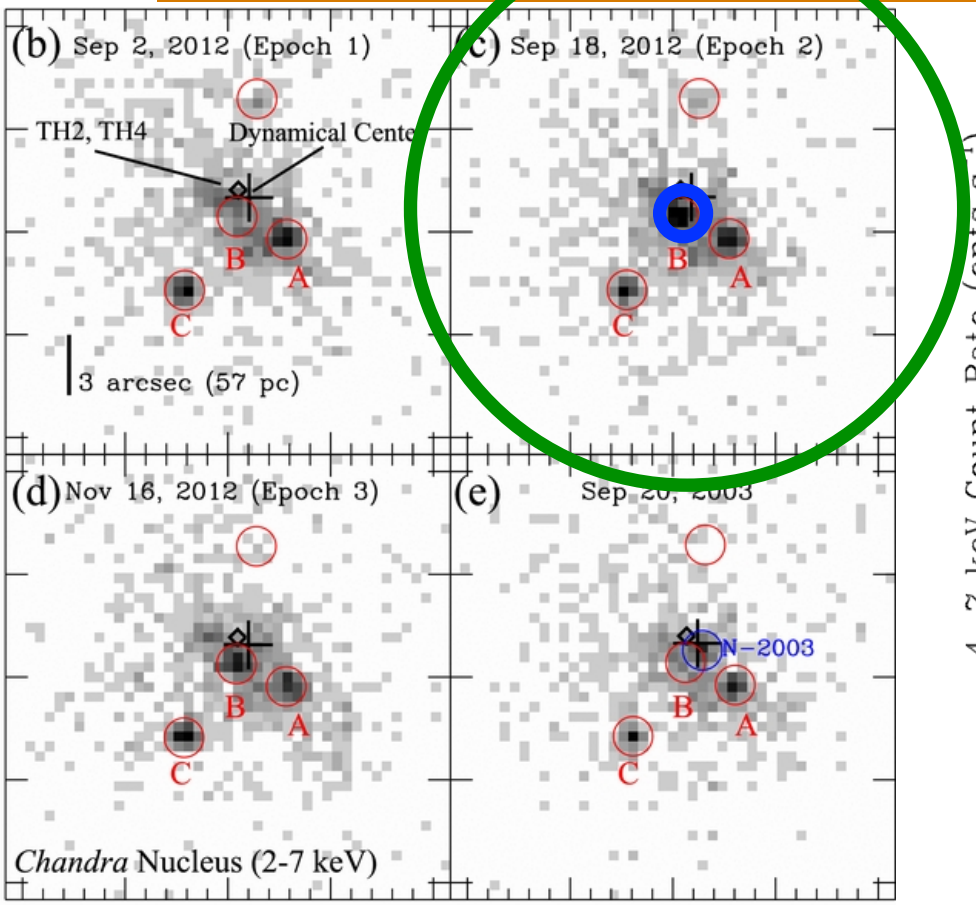


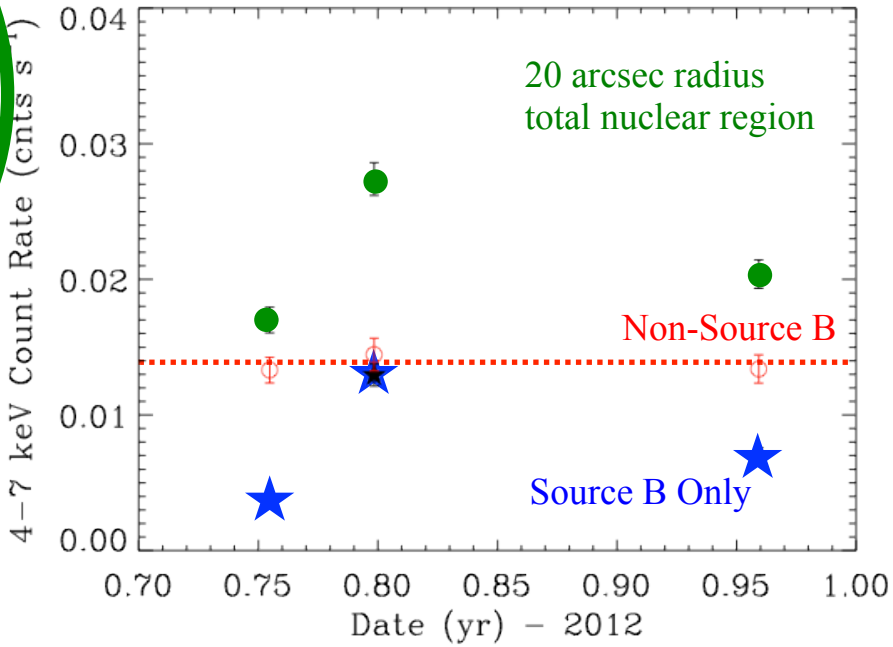
NGC 253



Nearby, can resolve (d ~ 3.9 Mpc)
Hosts a central starburst that drives a superwind
May host a low luminosity AGN

NGC 253: Hard X-ray emission dominated by luminous binaries from 3-30 keV (Lehmer et al. 2013)

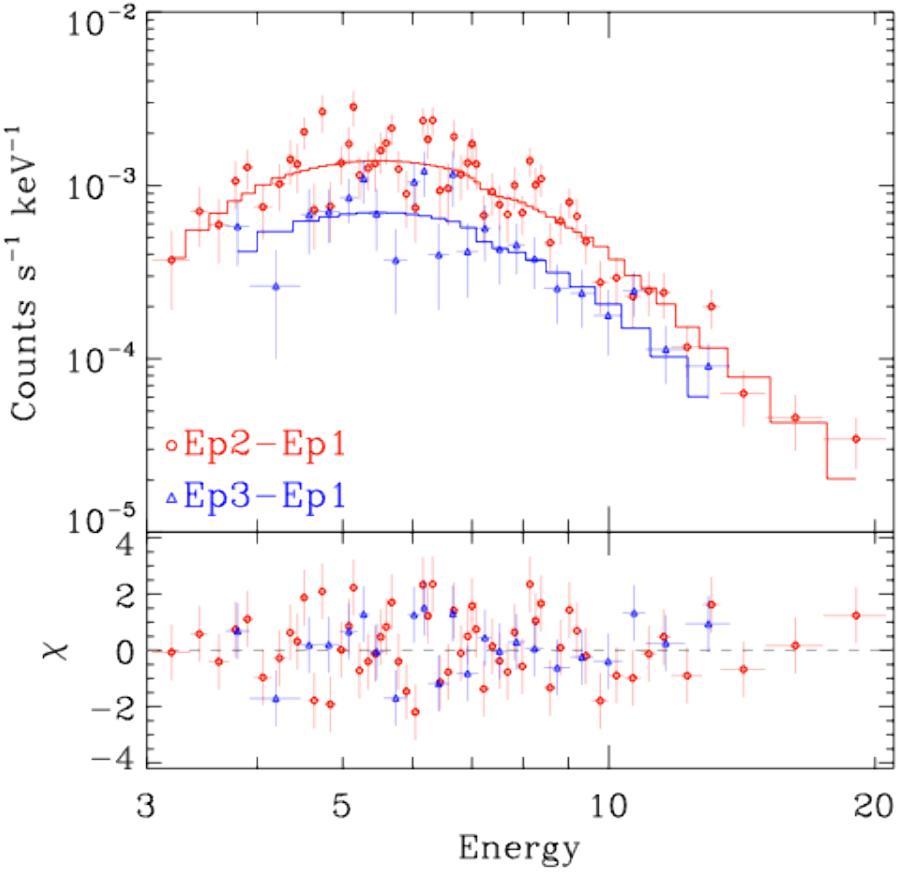




Source B drives the total variability in the inner ~20 arcsec. Can estimate *NuSTAR* spectrum of source B by differencing Epochs 2 and 3 from Epoch 1!

NuSTAR Spectral Constraints on Variable Source B

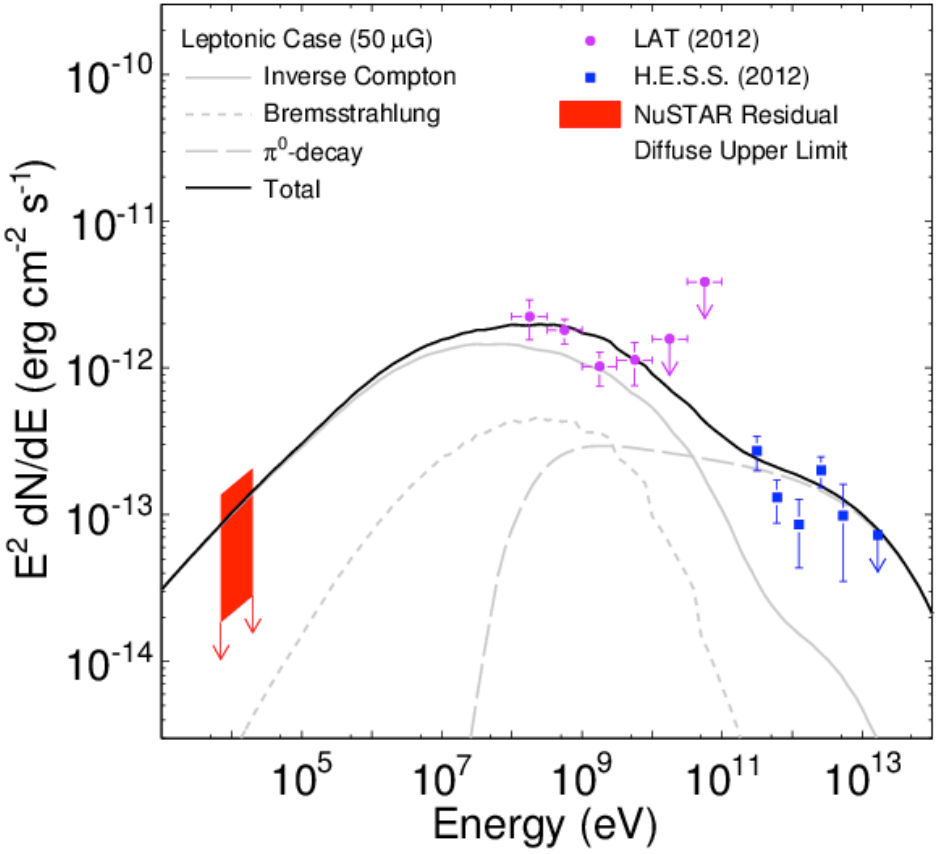
- Difference spectra were fit using an absorbed broken power-law model with $N_H = 1.6 \times 10^{23}$ cm^{-2}, $\Gamma_1 = 2.1$, $E_{break} = 7.9$ keV, and $\Gamma_2 = 3.9$.
- Expect LLAGN with very low accretion rates (M_{BH} ~5 × 10^6 $M_\odot$, L/L_{Edd} ~ 10^{-4}) to have very hard X-ray spectra of Γ = 1.4 (Younes et al. 2011)
- By comparison, ULXs have a range of Γ_1 = 1-3, E_{break} = 3-8 keV, and Γ_2 = 2-7 (e.g., Gladstone et al. 2009)



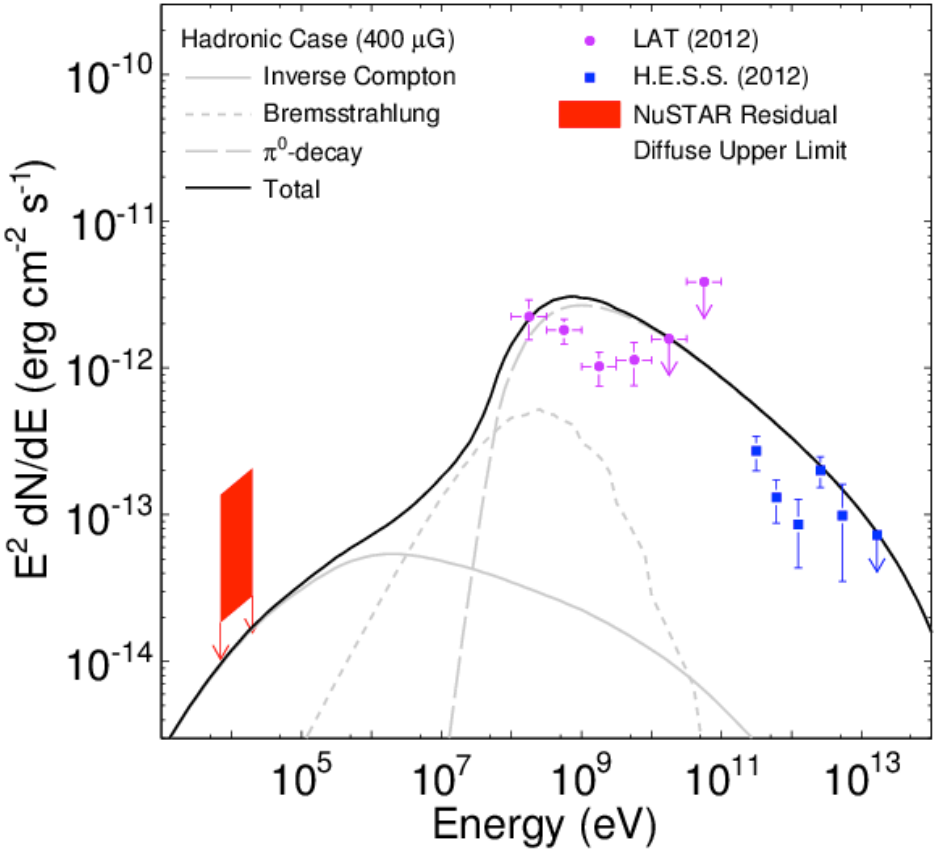
Source B is most likely a ULX and not an AGN. Have we determined that the black hole in NGC 253 is generally inactive during this starburst phase?

Fermi and H.E.S.S. detections may imply Inverse Compton – (Wik et al. 2014, submitted)

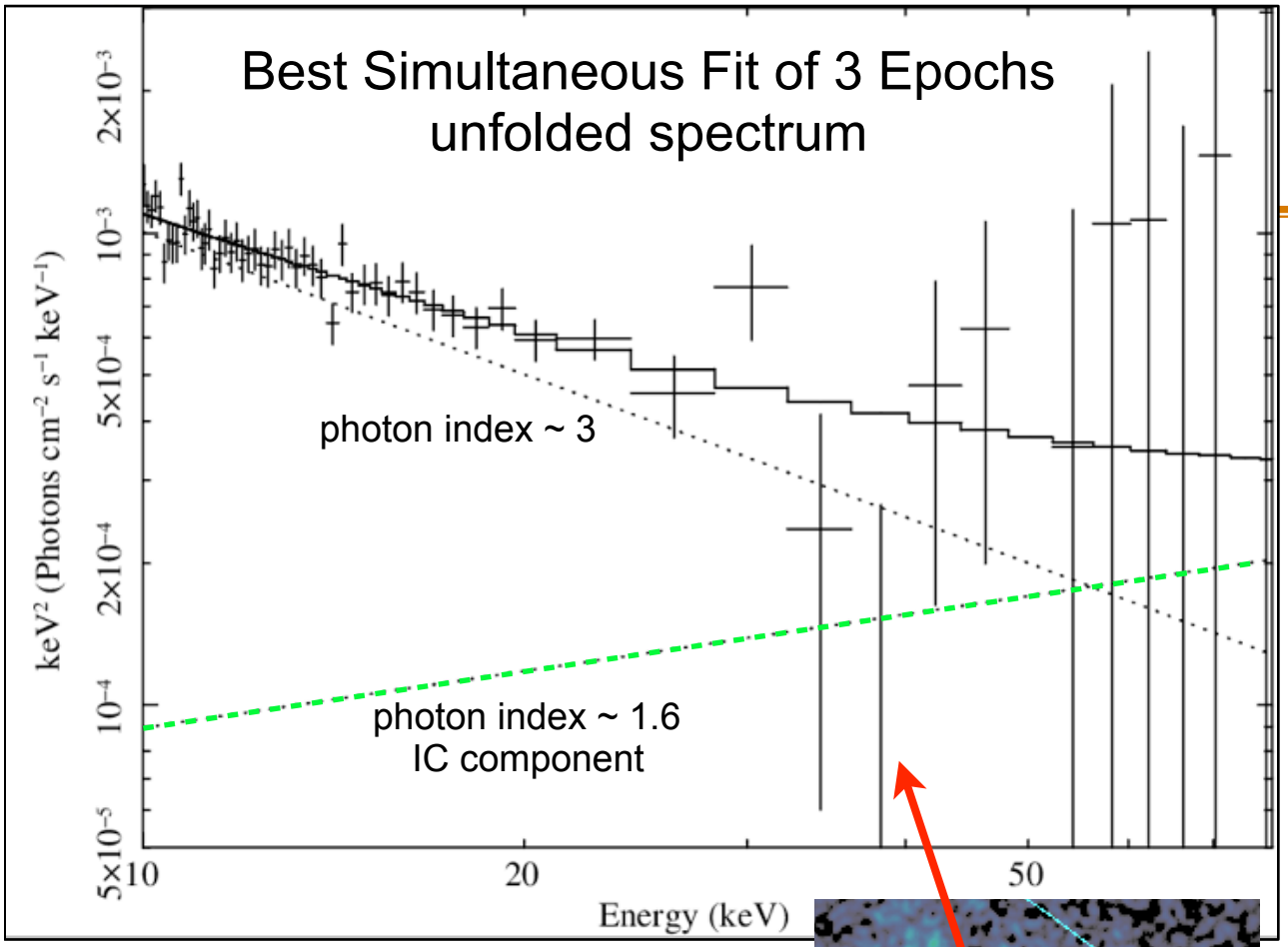
Leptonic

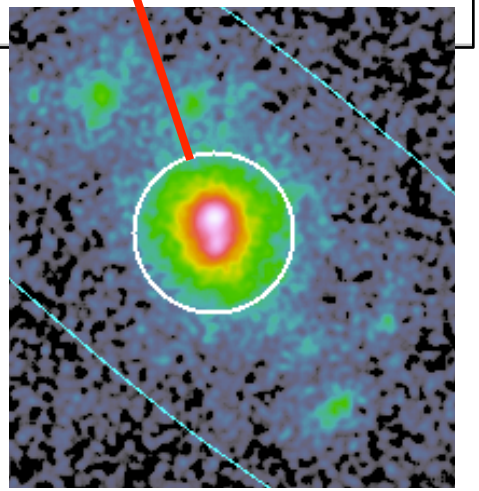


Hadronic



NGC 253





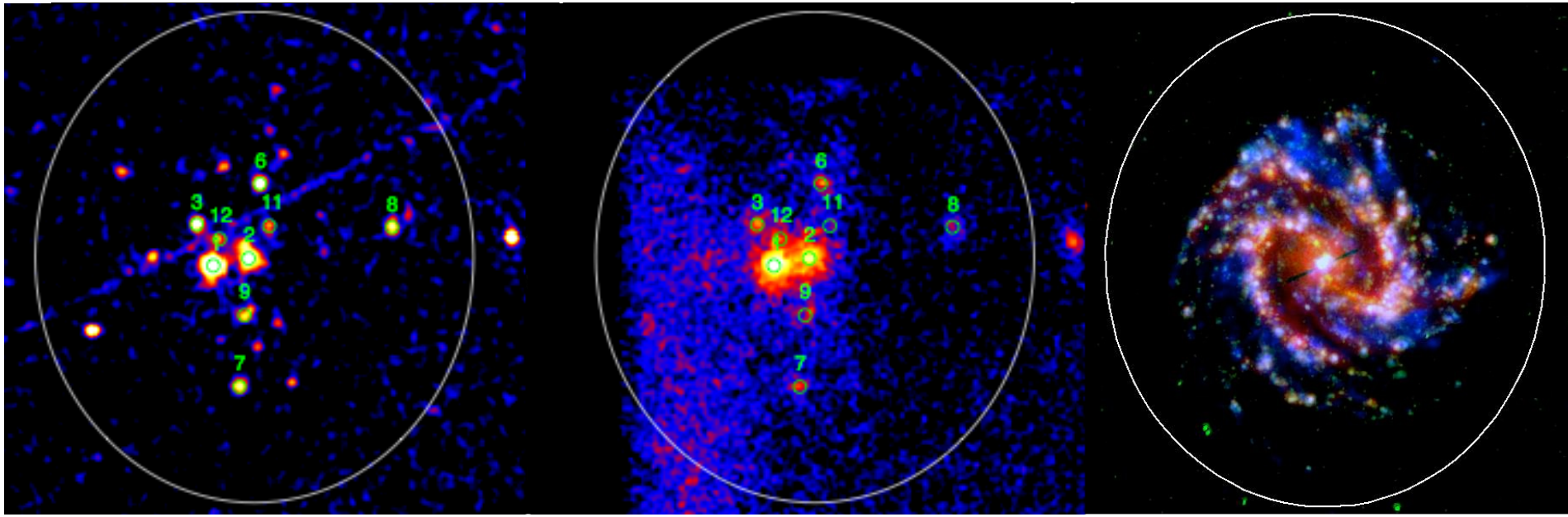
NuSTAR

NGC 253

M83 Point Sources (Yukita et al. 2014, in prep)

FUV (blue)
Hα (green)
24μm(red)

M83 *XMM* (4-10keV) *NuSTAR* (4-25keV)

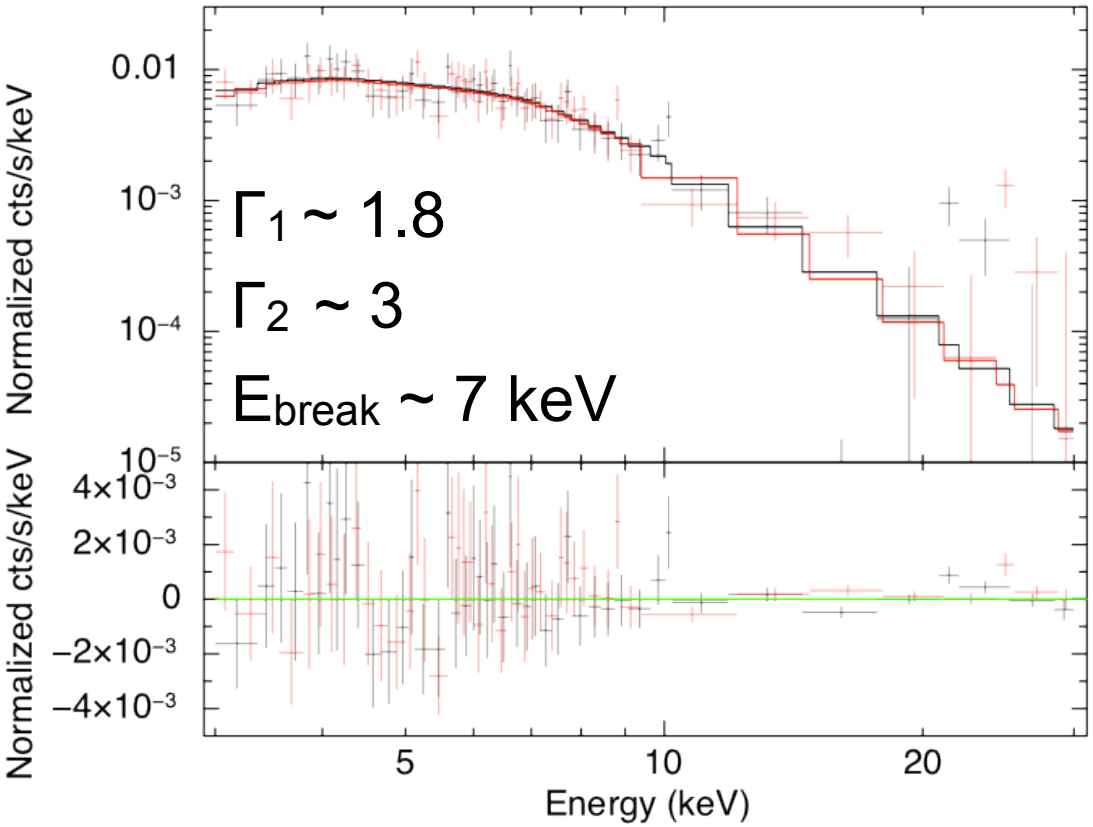


NuSTAR (160ks):
9 sources above 3 sigma (4-25 keV).

3-30 keV spectra of star-forming galaxies are SOFT (Yukita et al. 2014 in prep)

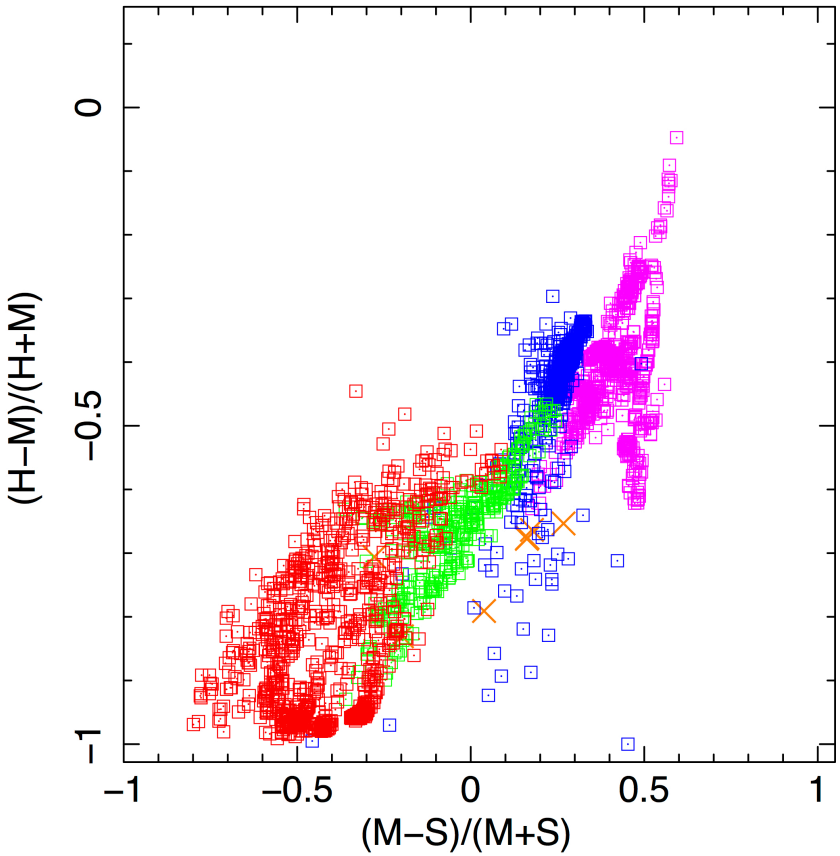
- *NuSTAR* observations of NGC 253 and M83 have detected hard X-ray emission from nuclear regions and several off-nuclear point sources.
- Both galaxies have an integrated galaxy-wide X-ray spectrum that rapidly declines at hard X-ray energies

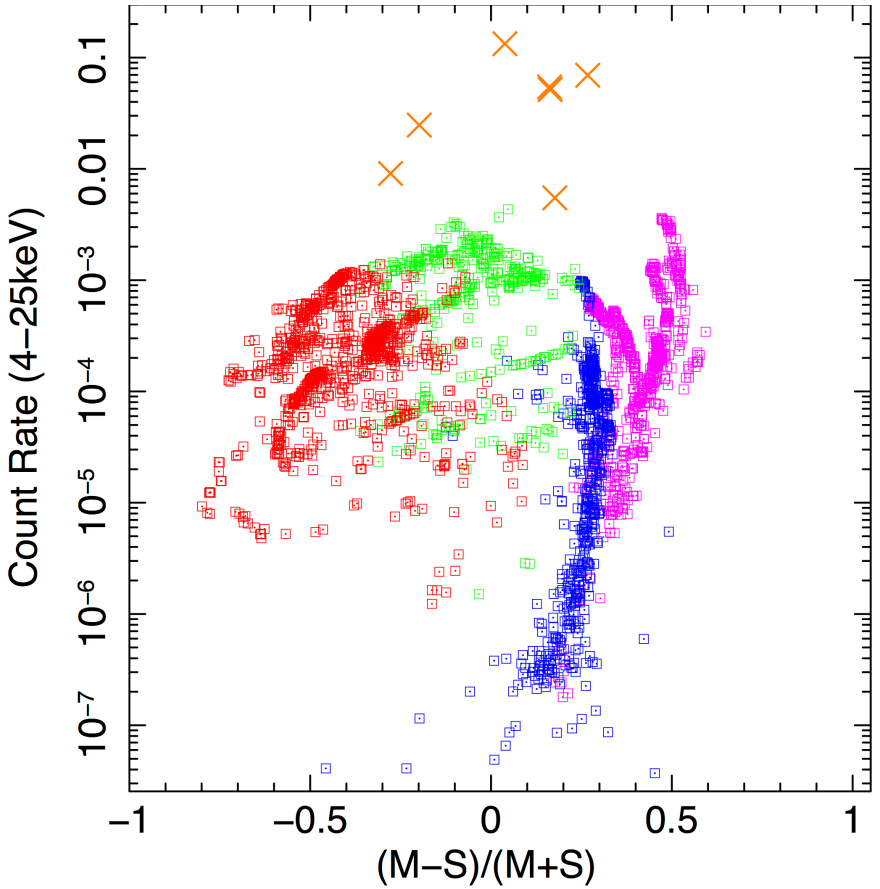
M83 Spectrum, NuSTAR 160 ks



Comparing Galactic & Extragalactic Binaries: Color-color & color-rate diagrams

(Wik et al submitted, Yukita et al., in prep, based on Kyanidis & Zezas in prep)





- *M83*
- *NGC 253*
- *Soft state BH binaries*
- *Intermediate state BH*
- *Hard state BH binaries*
- *Accreting pulsar*
- *NuSTAR ULXs*

Soft: 4-6 keV
Medium: 6-12 keV
Hard: 12-25 keV

Comparing Galactic & Extragalactic Binaries: Color-color & color-rate diagrams

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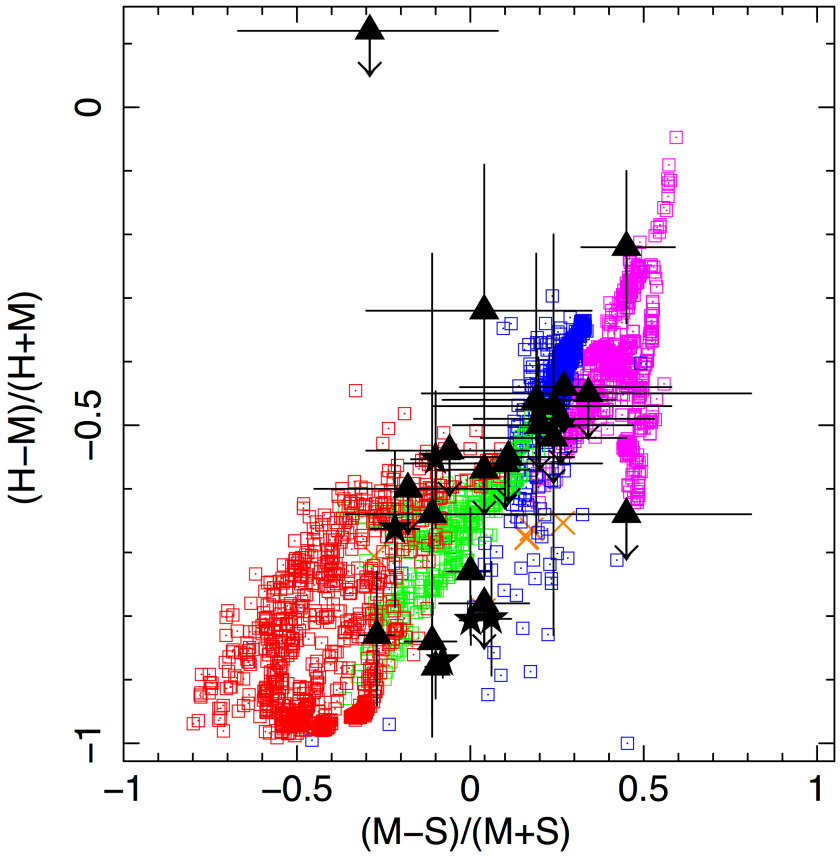

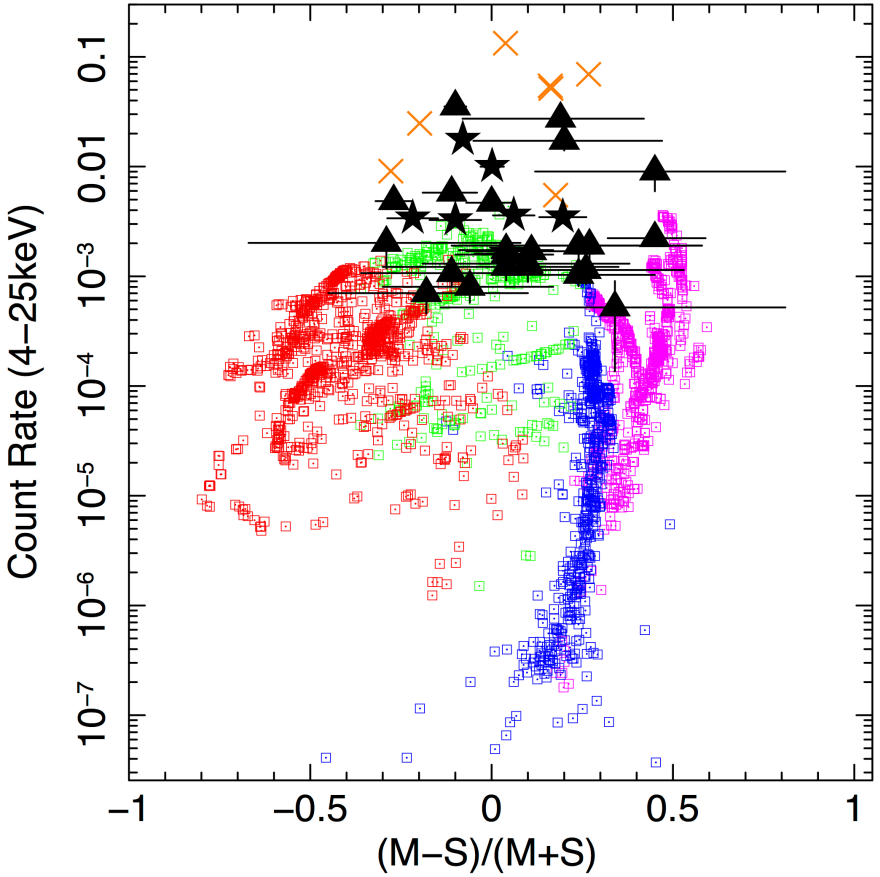

Soft: 4-6 keV
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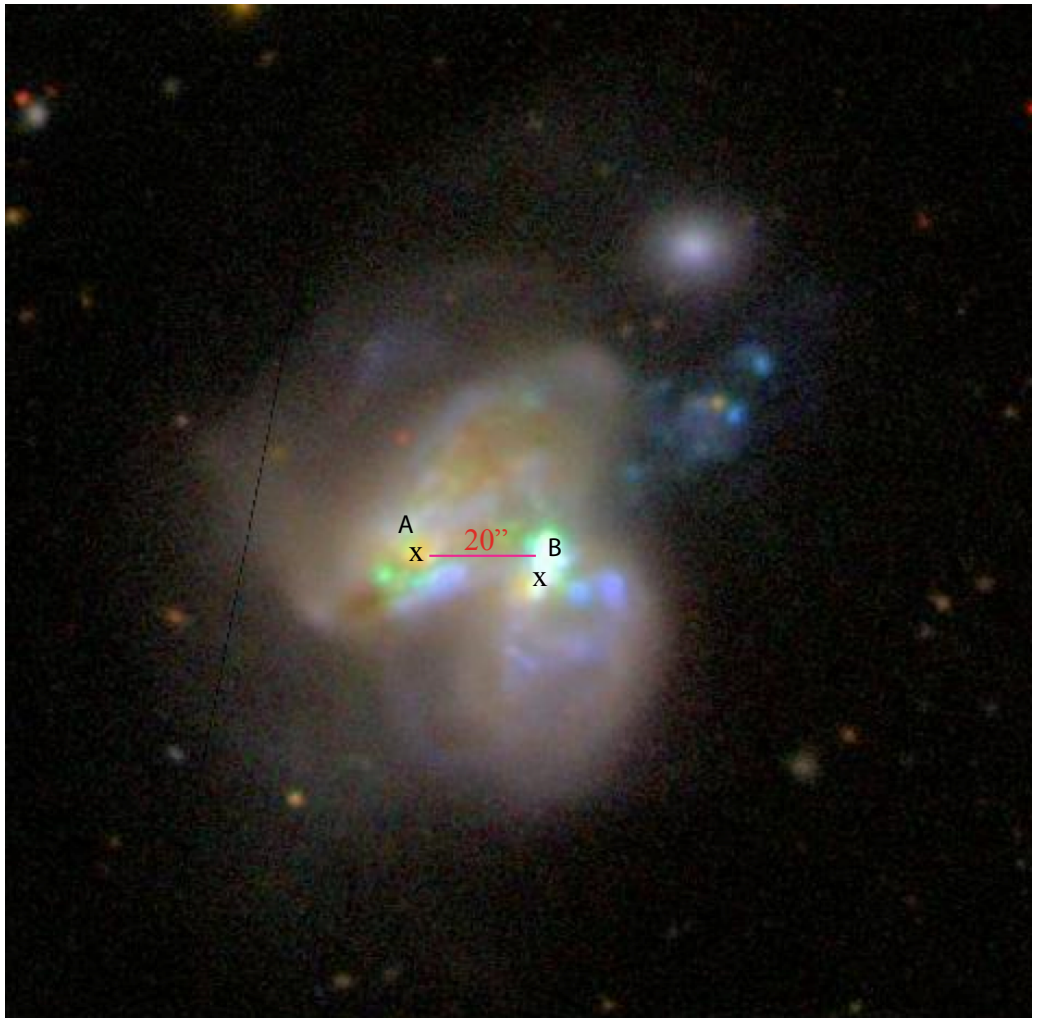
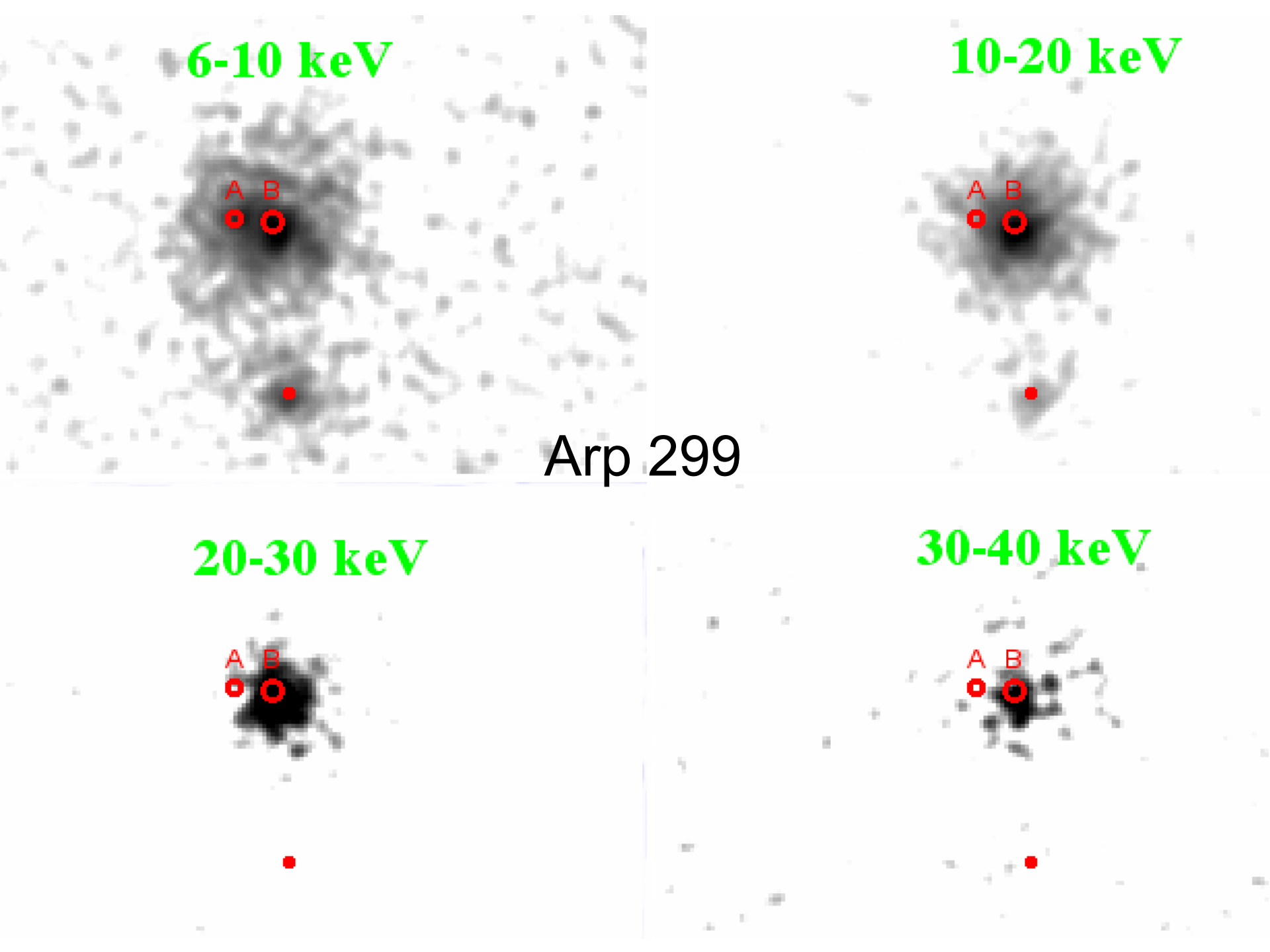
- M83
- NGC 253
- Soft state BH binaries
- Intermediate state BH
- Hard state BH binaries
- Accreting pulsar
- NuSTAR ULXs

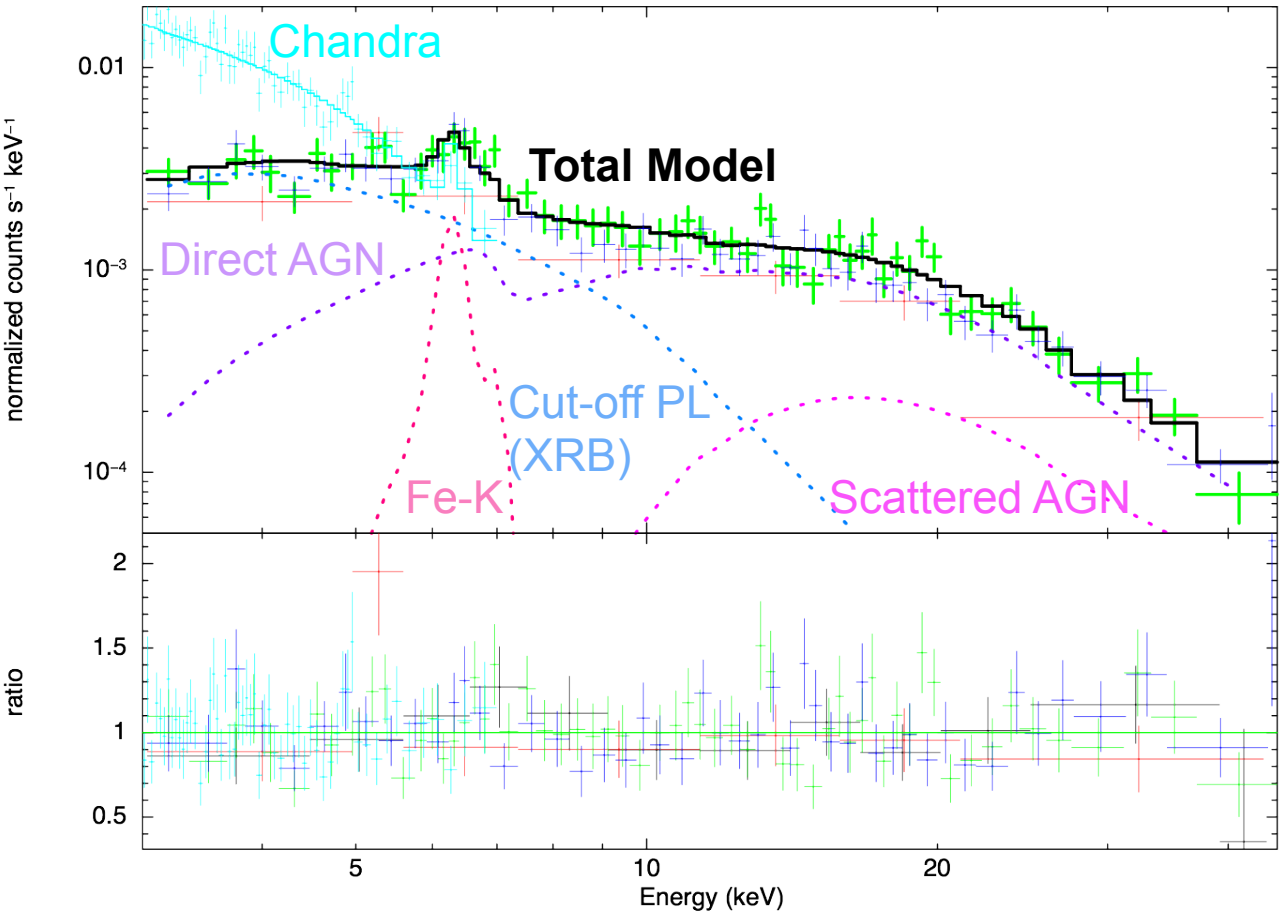
Arp 299, 70 ks NuSTAR observation

- LIRG with nuclear spectral characteristics similar to ULIRGs and LIRGs at high-z (Alonso-Herrero et al. 2009)
- Dramatic merger: Arp 299-B possible CTAGN



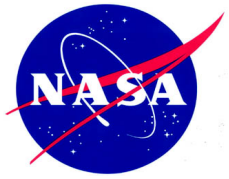

6-10 keV
A
B
10-20 keV
A
B
Arp 299
20-30 keV
A
B
30-40 keV
A
B

Isolating the hard X-rays from the Compton-Thick AGN in Arp 299 (Ptak et al 2014, submitted)



Cut-off power-law represents extranuclear flux (i.e., Arp 299-A and X-ray binaries)

MyTorus fit to full Arp 299 (1' region) spectrum



Isolating the hard X-rays from the Compton-Thick AGN in Arp 299

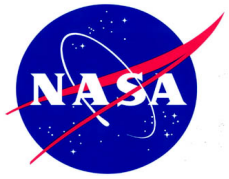
NuSTAR

(Ptak et al 2014, submitted)

- The Arp 299-B *NuSTAR* spectrum requires a column density of 4 x 10^{24} cm^{-2}. This implies an intrinsic 10-30 keV luminosity of 1.2 x 10^{43} ergs s^{-1}
  - ~ 5% L_{bol}
  - ~ 10% L_{Edd}
- In contrast the 10-30 keV luminosity of Arp 299-A must be < 1.2 x 10^{42} ergs s^{-1}. Roughly consistent with mid-IR spectrum (Alonso-Herrero et al 2013)
- *BeppoSAX* detection of Arp 299 (Della Cecca et al. 2002) was with F(10-30 keV) ~ 2X higher (~ 7 x 10^{-12} vs 4 x 10^{-12} ergs cm^{-2} s^{-1}) . Koss et al. (2013) BAT flux ~ consistent with *NuSTAR*.

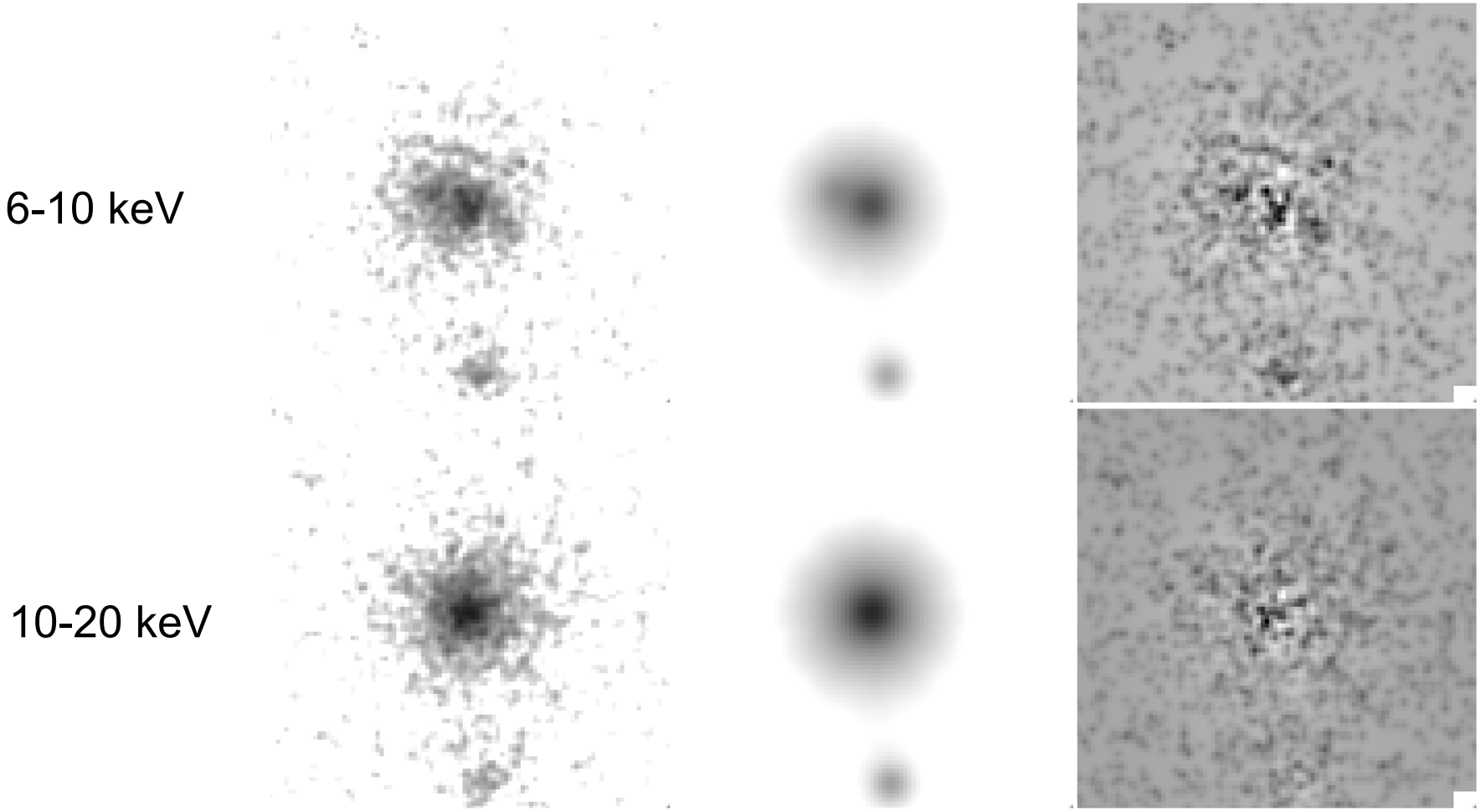
Summary

- NGC 253
  - Nuclear ULX and likely not AGN dominating hard X-ray flux during 3 *NuSTAR* observations (Lehmer et al. 2013)
  - Detailed modeling of XRBs and IC component presented in Wik et al. 2014 submitted.
- Arp 299
  - Any AGN in Arp 299-A and XRBs in Arp 299 are contributing little to E>10 keV emission (Ptak et al. 2014 submitted)
- M83
  - once again XRBs are soft above 10 keV
  - Same story so far with ULXs observed by *NuSTAR*
- Current/Upcoming *Chandra-NuSTAR* observations:
  - May 2014 - M83
  - June 2014 - NGC 3310
  - September 2014 - NGC 3256
  - January 2015 – M82 (~ 1 Ms invested on 2014 SN 1a)

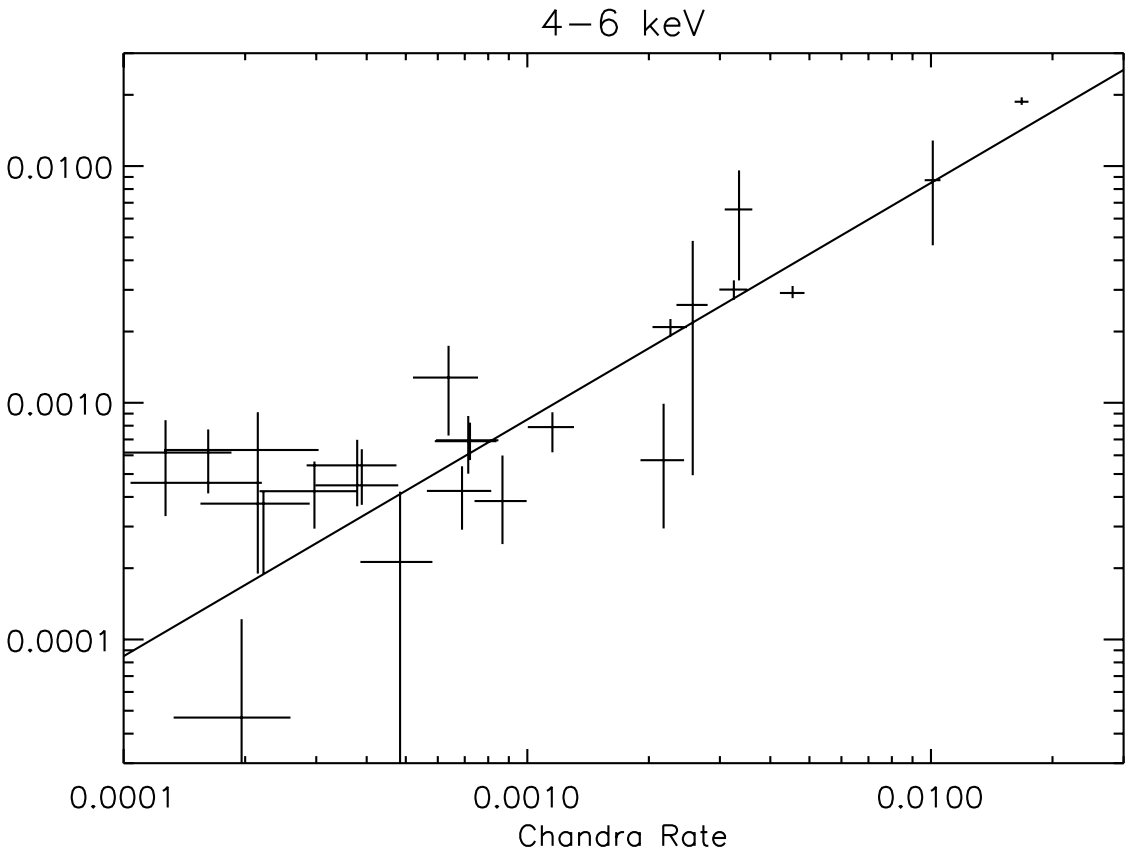


Backups

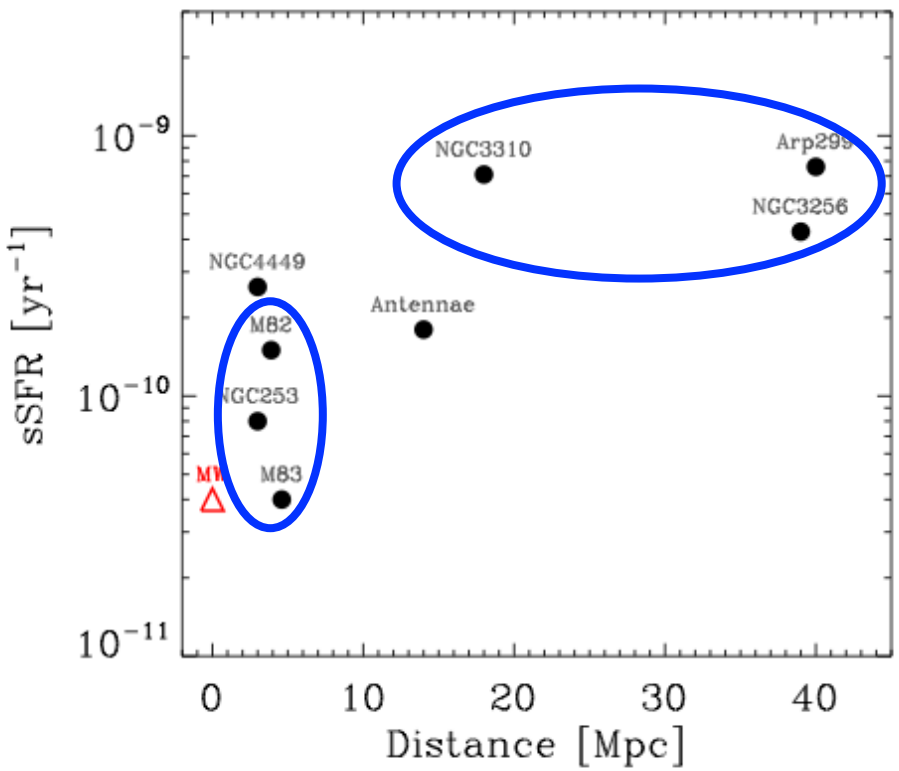
Arp 299 Spatial Fitting

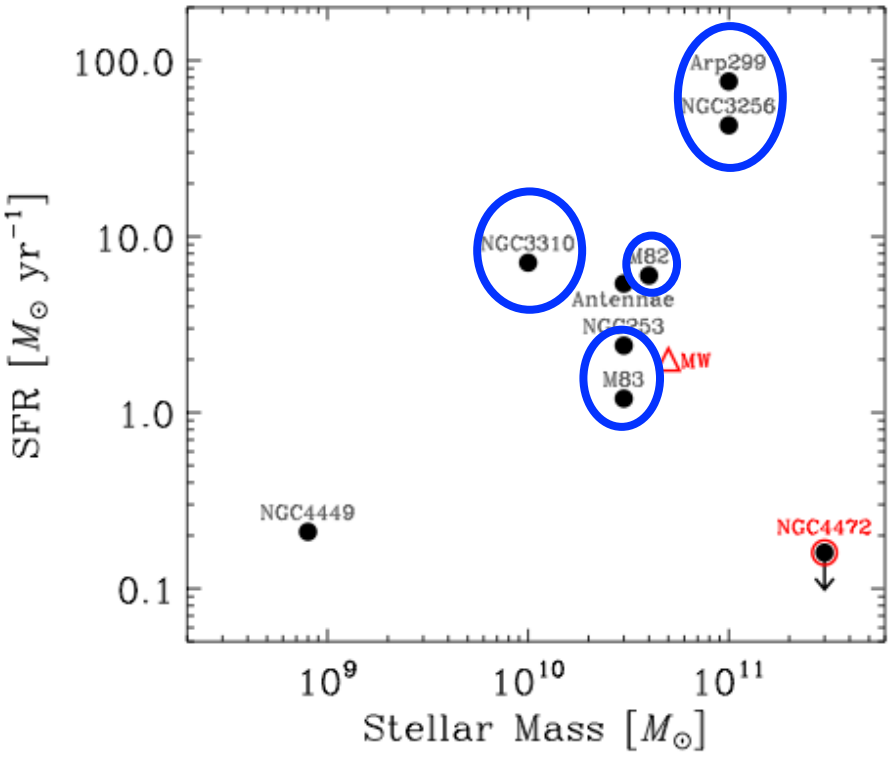


NGC 253 Sanity Check

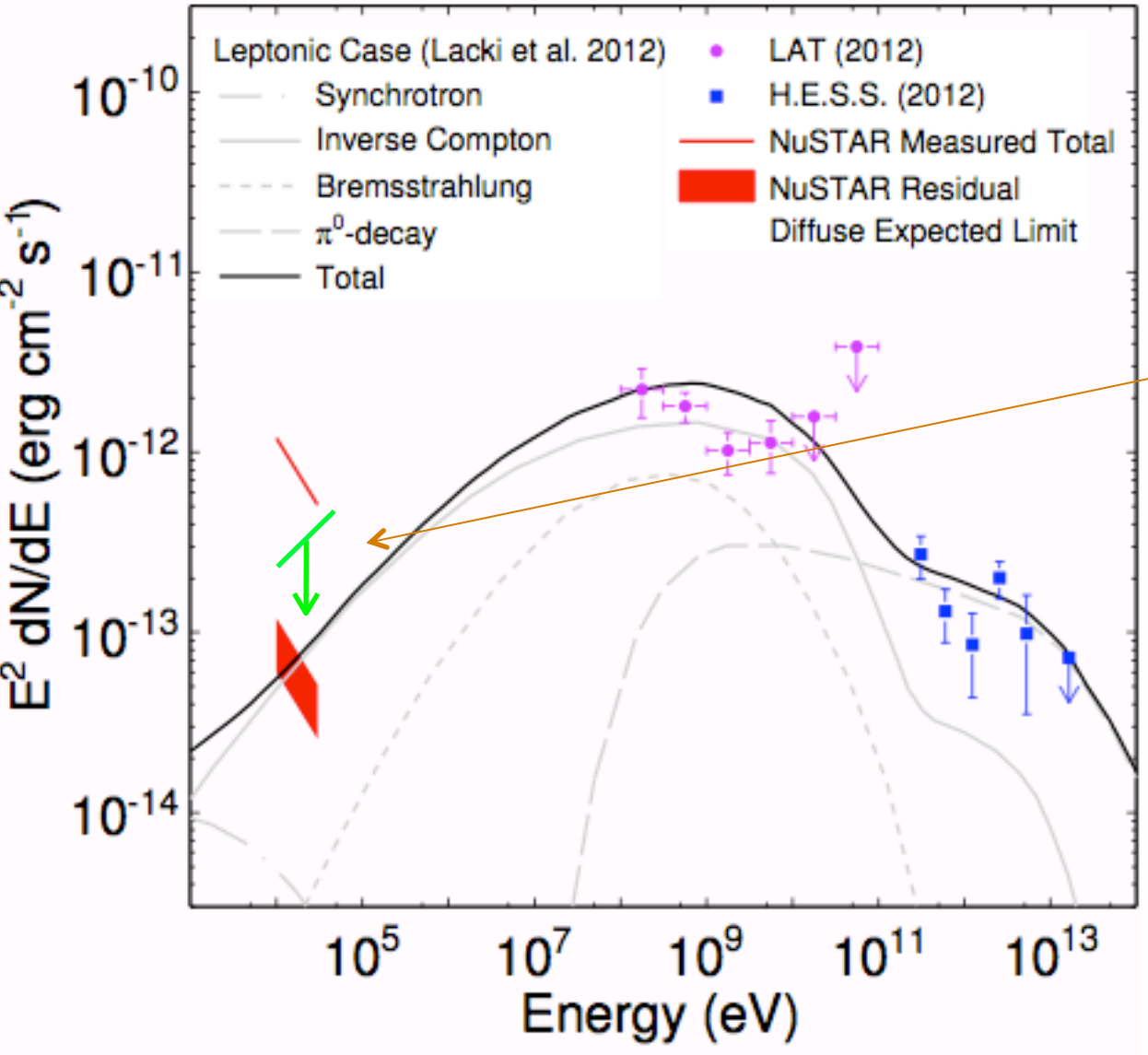


Survey sample





NGC 253



Work in progress: improving IC component upper limit through iterative spatial and spectral fitting