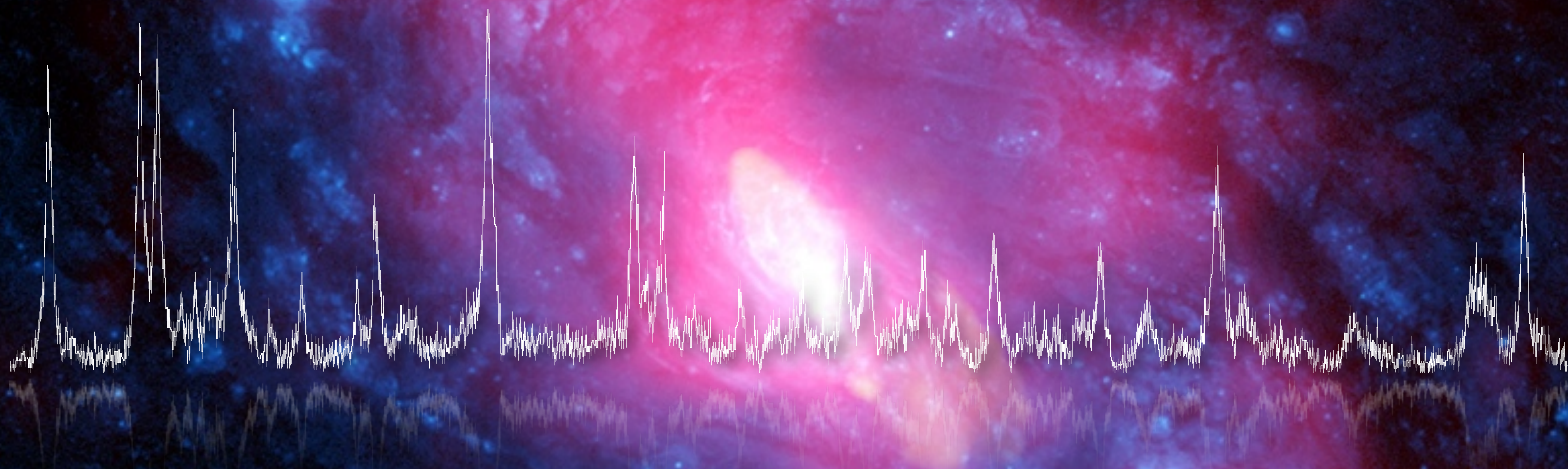
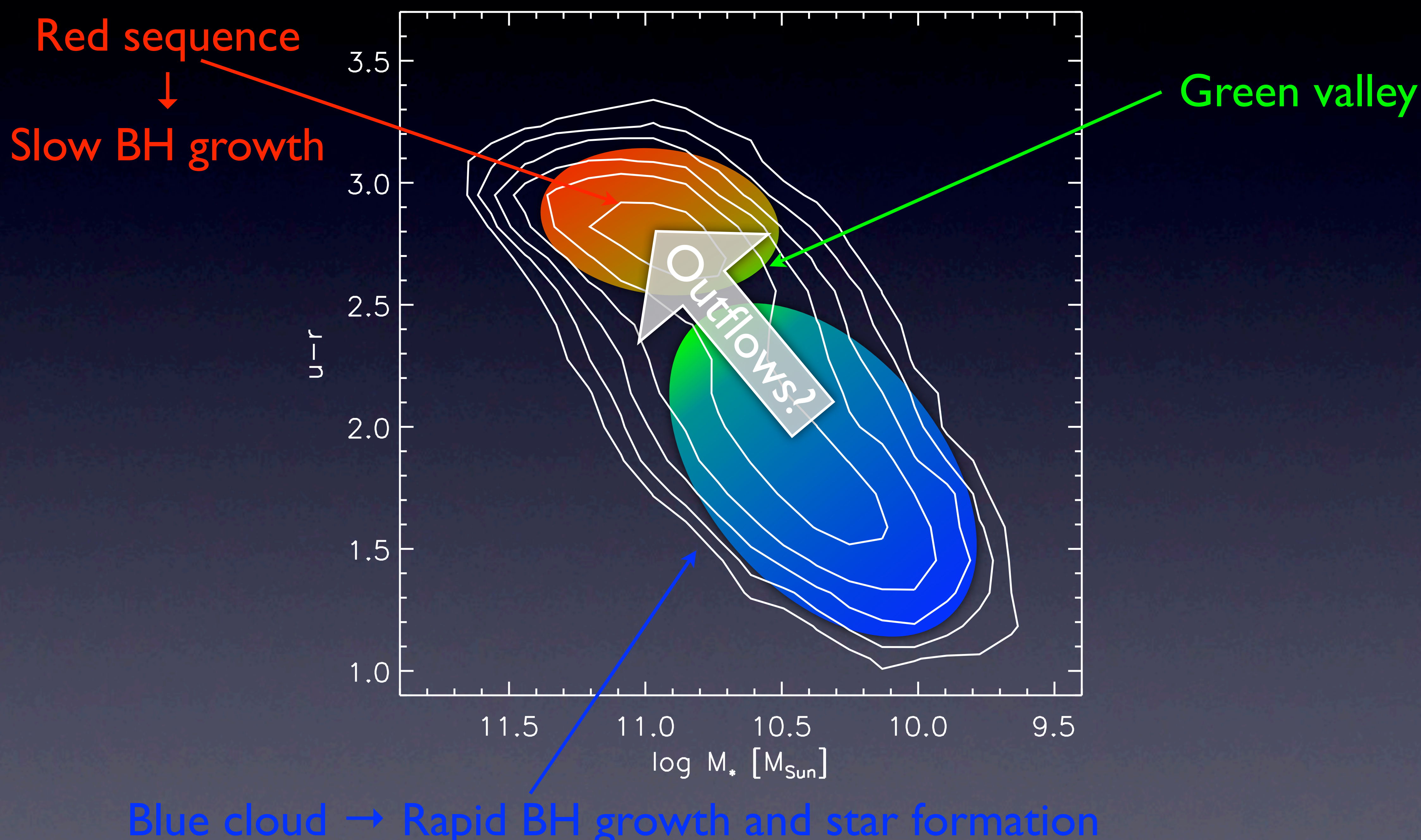
Do AGN Outflows Cease Star Formation? A New Technique Based on Ultradeep Chandra HETG Observations of NGC 1068



Dan Evans (MIT Kavli Institute & Harvard-Smithsonian CfA)

Patrick Ogle (Caltech), Herman Marshall (MIT), Mike Nowak (MIT), Kim Weaver (GSFC), Stefano Bianchi (Roma Tre), Kevin Schawinski (Yale) Matteo Guainazzi (ESAC), Anna Lia Longinotti (MIT), Jane Turner (UMBC), James Reeves (Keele), Mike Crenshaw (GSU), Martin Hardcastle (U. Hertfordshire), Dan Dewey (MIT), Norbert Schulz (MIT), Mike Noble (MIT), and Claude Canizares (MIT)

Galaxy Color-Magnitude Diagram



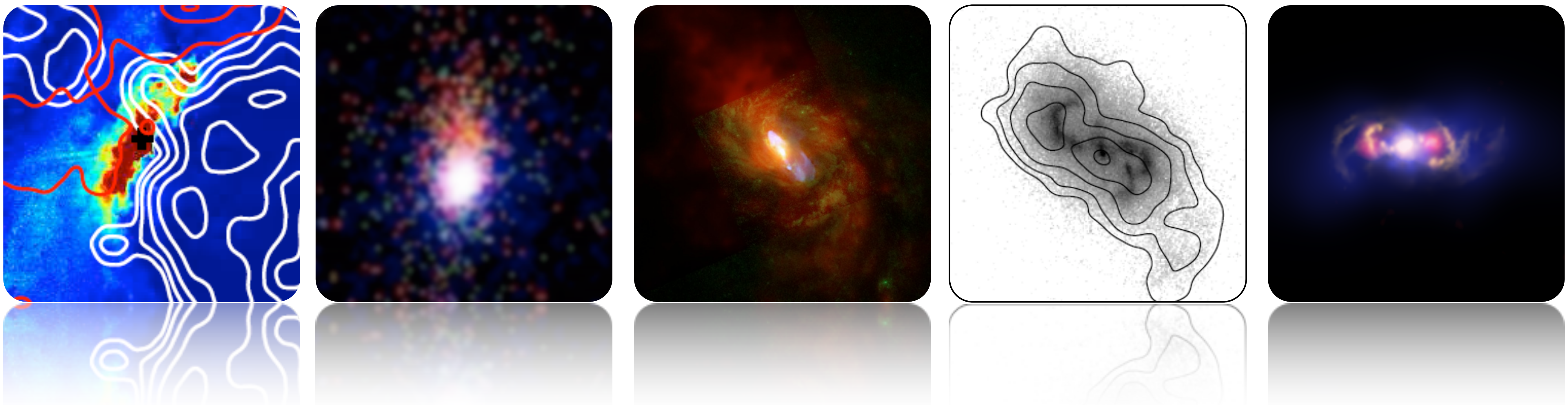
e.g. Smolcic et al. (2006), Faber et al. (2006), Hickox et al. (2009)

Q. Can the AGN actually deliver enough kinetic power to their environments to alter the evolution of the host galaxy in a meaningful way?

Q. How far does the outflow extend?

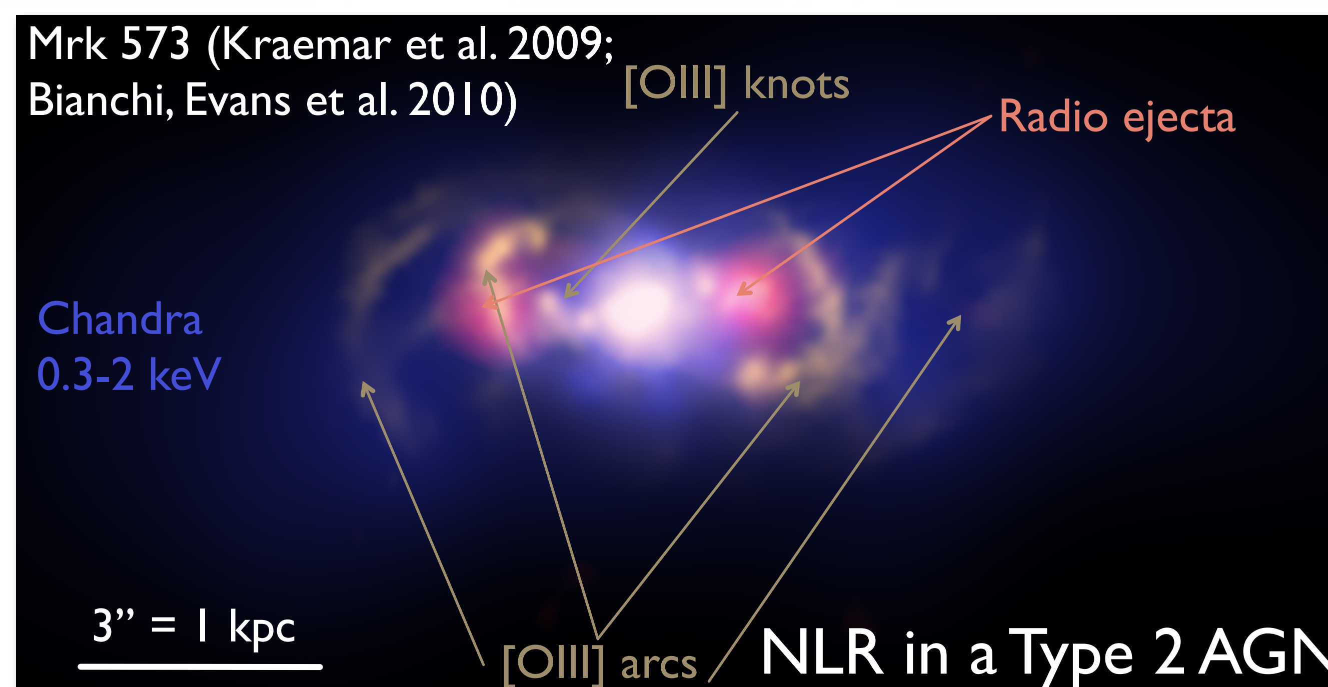
An excellent place to search for outflows is to study the ionizing effect of AGN on the kpc-scale NLR.

Searching For Outflows: Multi-λ Imaging

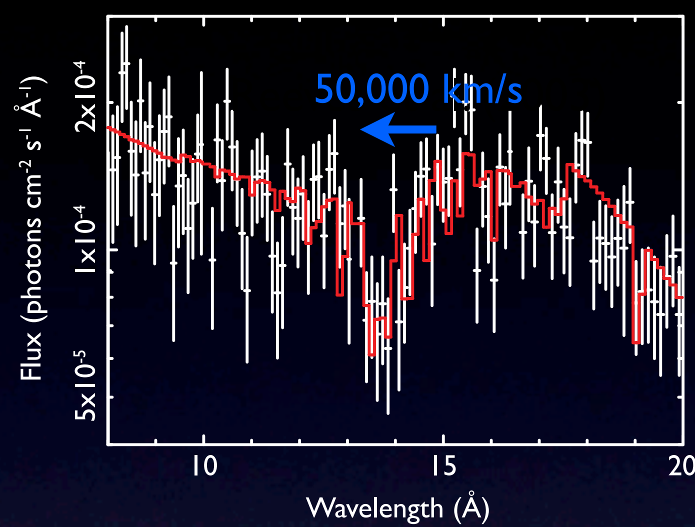


1. Spatial relationships between nucleus, jet, warm [OIII] gas and hot X-ray gas in kpc NLR

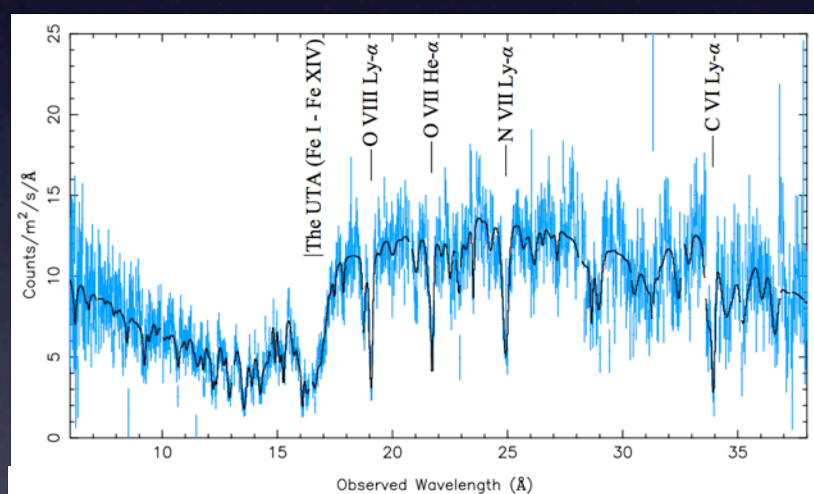
2. Some estimates of energy in the multiphase gas



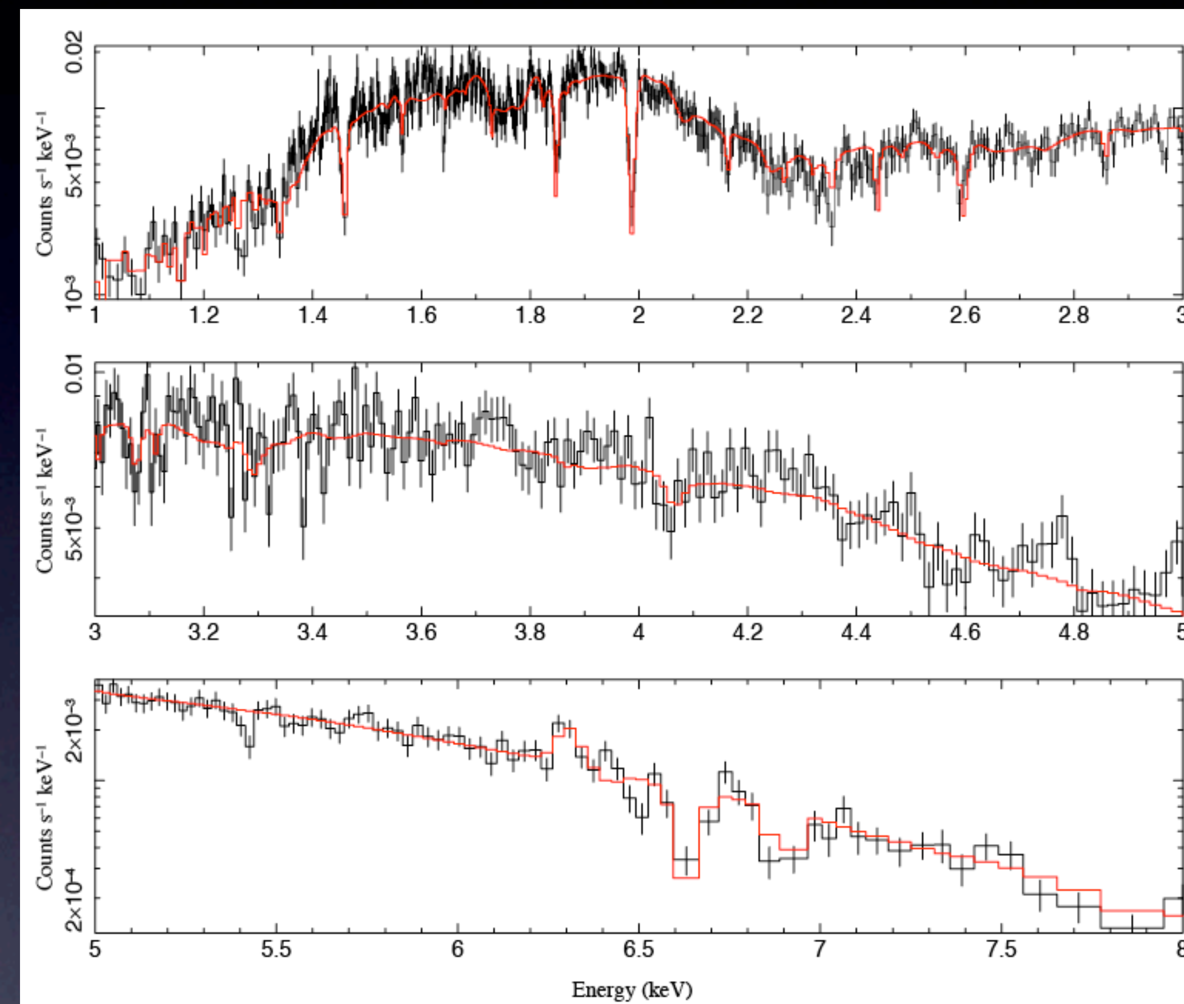
Searching For Outflows: Spectroscopy



PDS 456 - Reeves et al. (2003)



N3516 - Mehdipour et al. (2010)

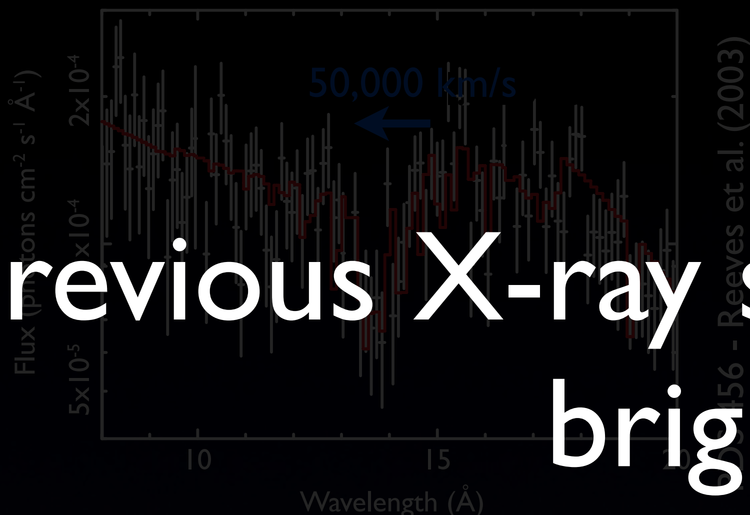


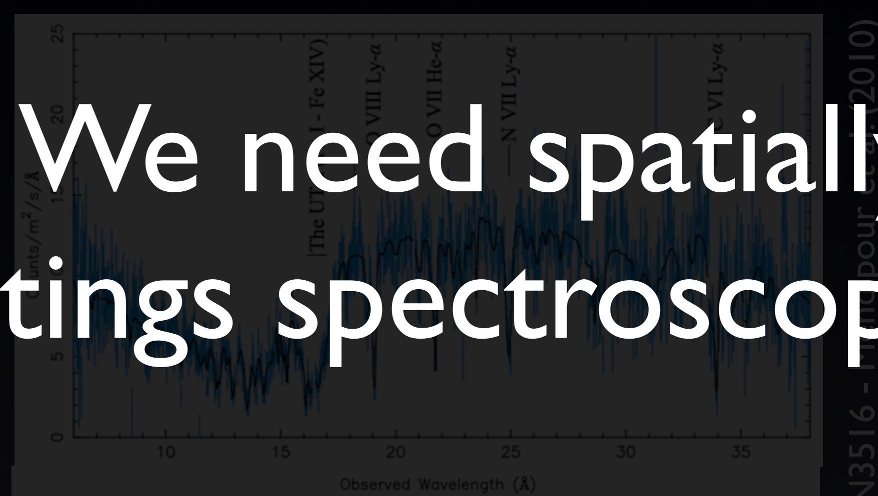
ESO 323 - Evans et al. (in prep.)

High-ionization X-ray gas has large columns and filling factors

→ may be dominant NLR component

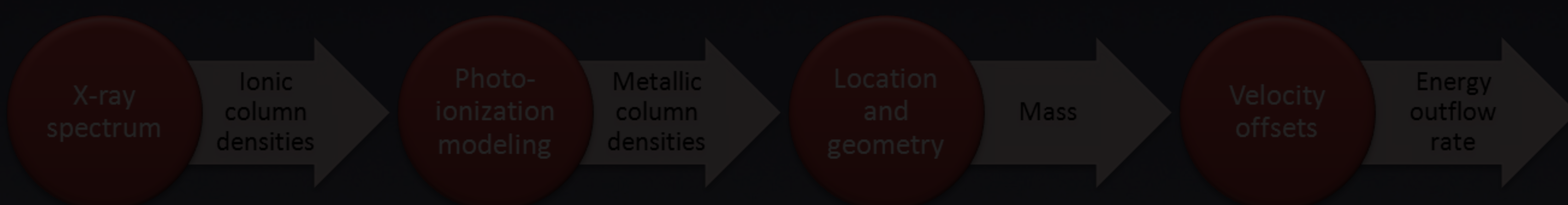
Searching For Outflows: Spectroscopy





All previous X-ray studies have been restricted to bright, Type 1 AGN.

We need spatially resolved, high resolution gratings spectroscopy of the entire NLR in Type 2 AGN.



High-ionization X-ray gas has large columns and filling factors → may be dominant NLR component

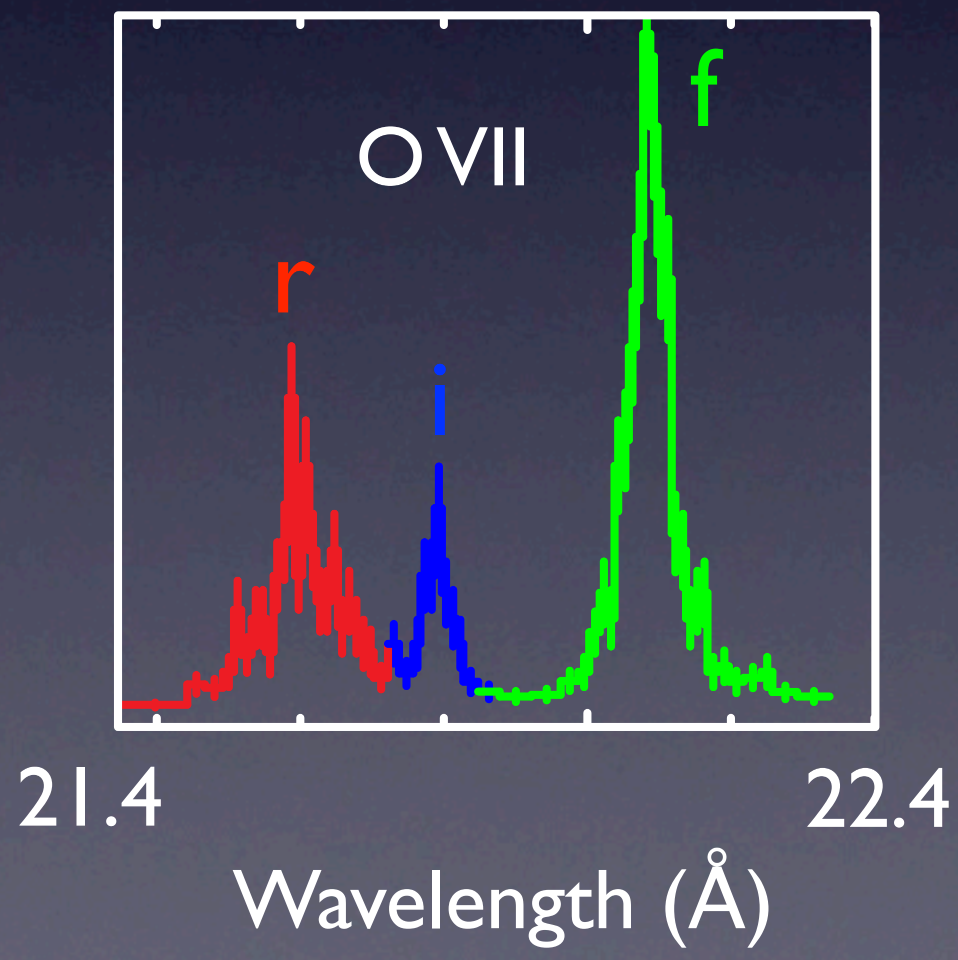
The Chandra SOARS Project

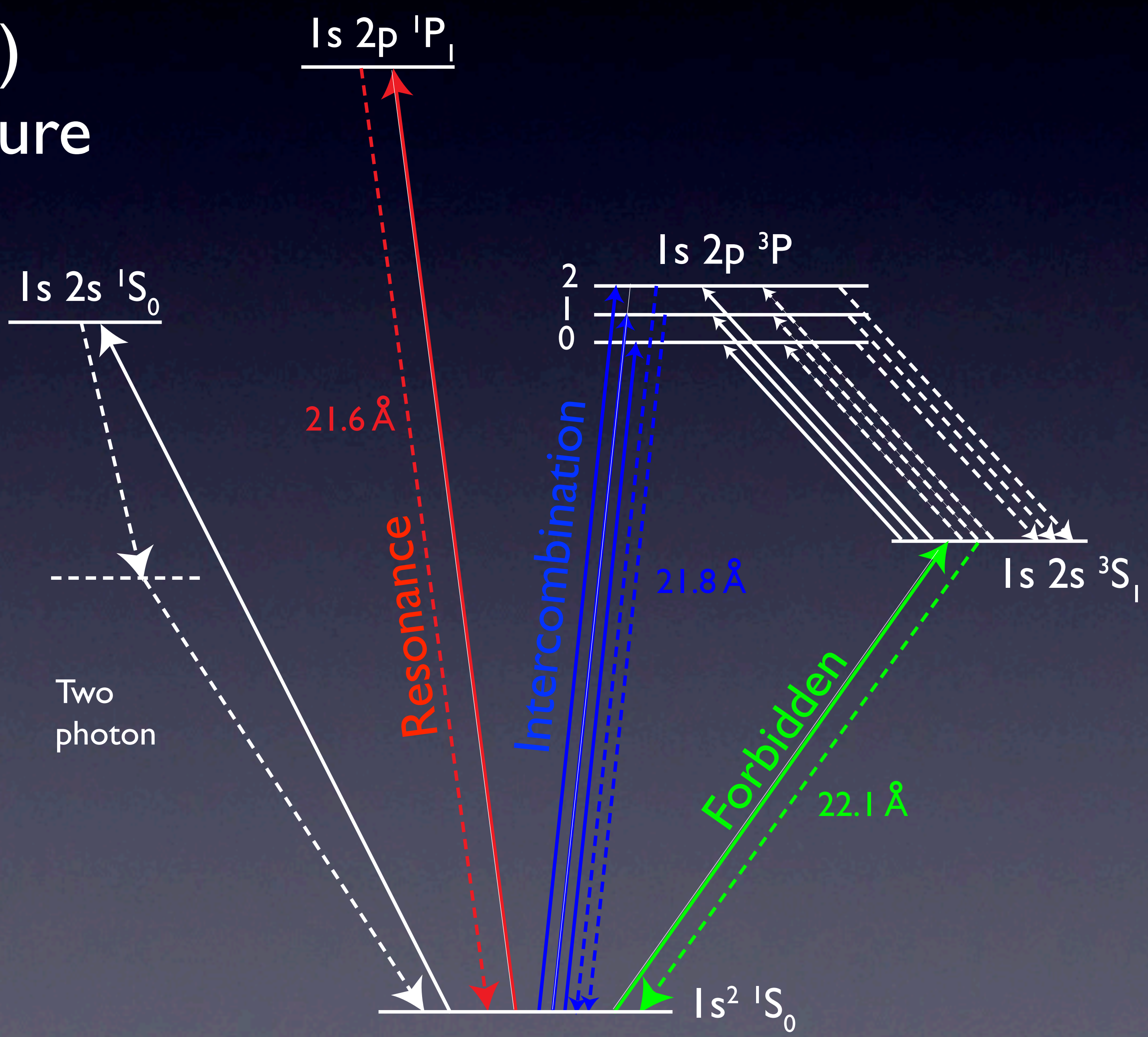
Survey of Outflows in AGN with Resolved Spectroscopy

- First spatially resolved X-ray study of kpc-scale NLR environments in type-2 AGN
- 1.5 Ms granted over multiple AOs; more on way
- Two unique advantages: high angular resolution (0.5" FWHM) and high spectral resolution (R~1000)

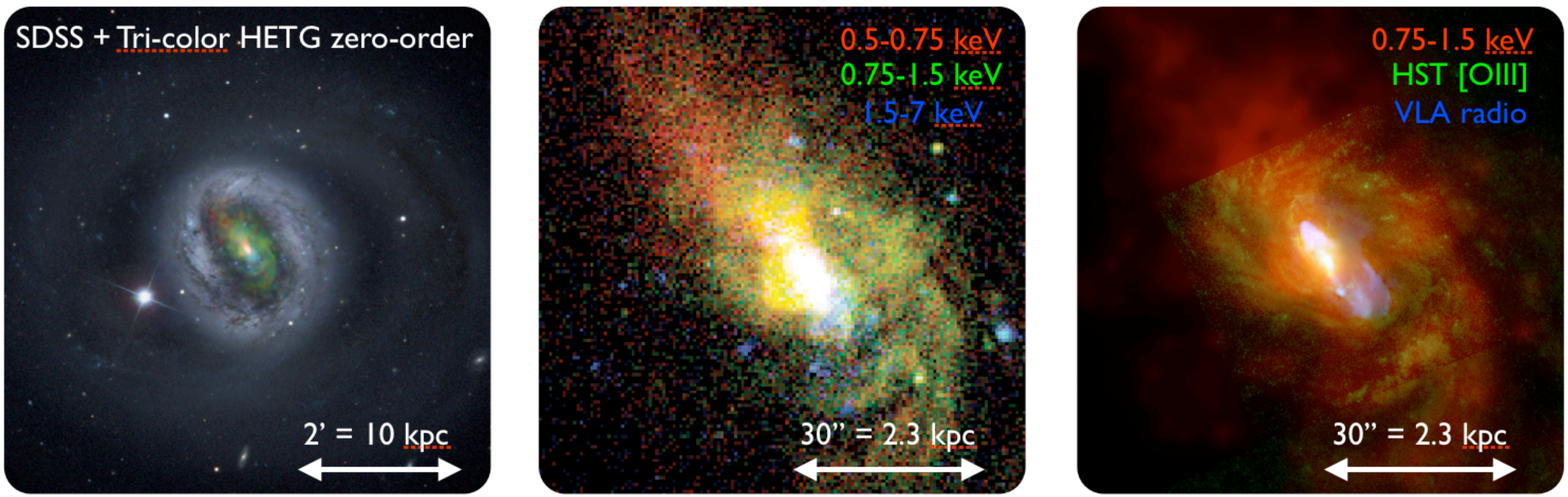
Chandra HETG and HST STIS spectroscopy

- Collisional ionization (jet) vs. photoionization (AGN radiation)
- Direct diagnostics of temperature and density



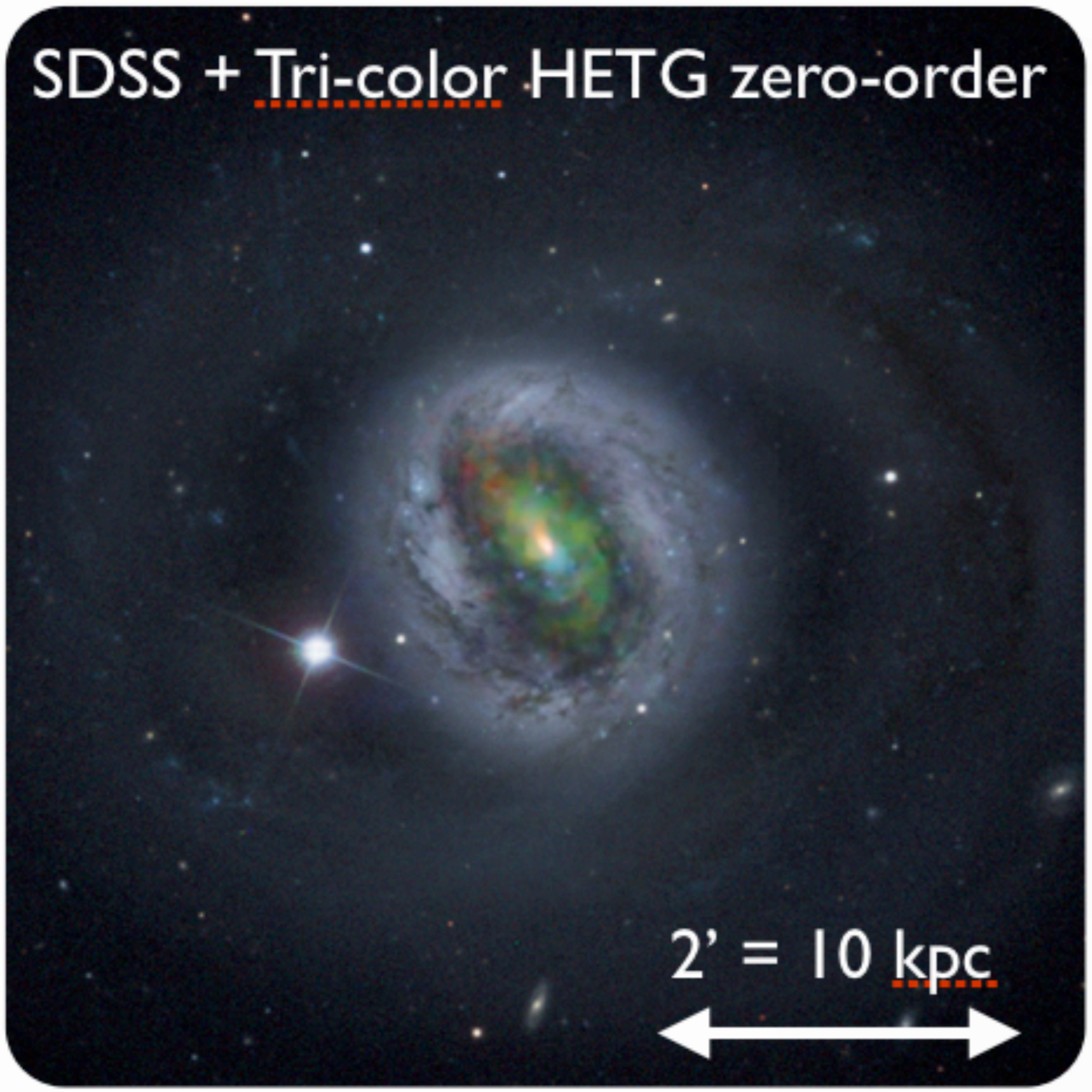


The Prototypical Example - a 440-ks Chandra HETG GTO Observation of NGC 1068 (Evans et al., in prep.)

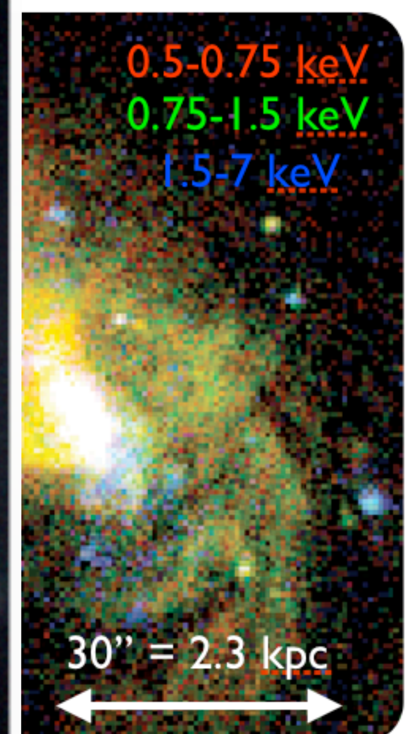


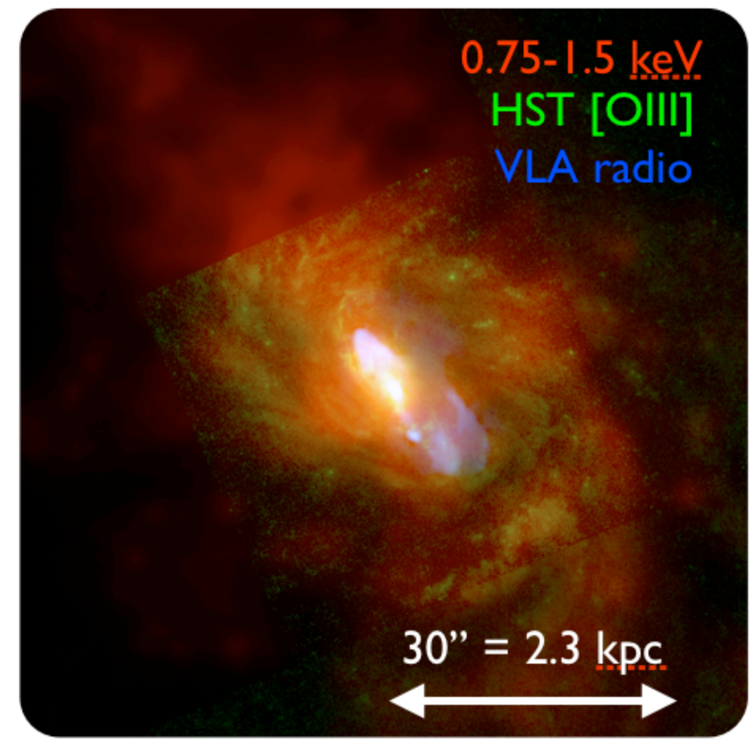
- Nearby: z = 0.003793, D_L = 16.3 Mpc, 1" = 80 pc ✔
- Compton-thick Seyfert 2 ✔
- Late type host galaxy ✔
- Black hole mass ~ $(8\pm0.3)\times10^6\ M_\odot$ (e.g., Lodato et al. 2003) ✔
- Accreting at or near Eddington limit (e.g., Kishimoto et al. 1999) ✔
- Prominent kpc-scale radio jet ✔

The Prototypical Example - a 440-ks Chandra HETG GTO Observation of NGC



et al. 2009)





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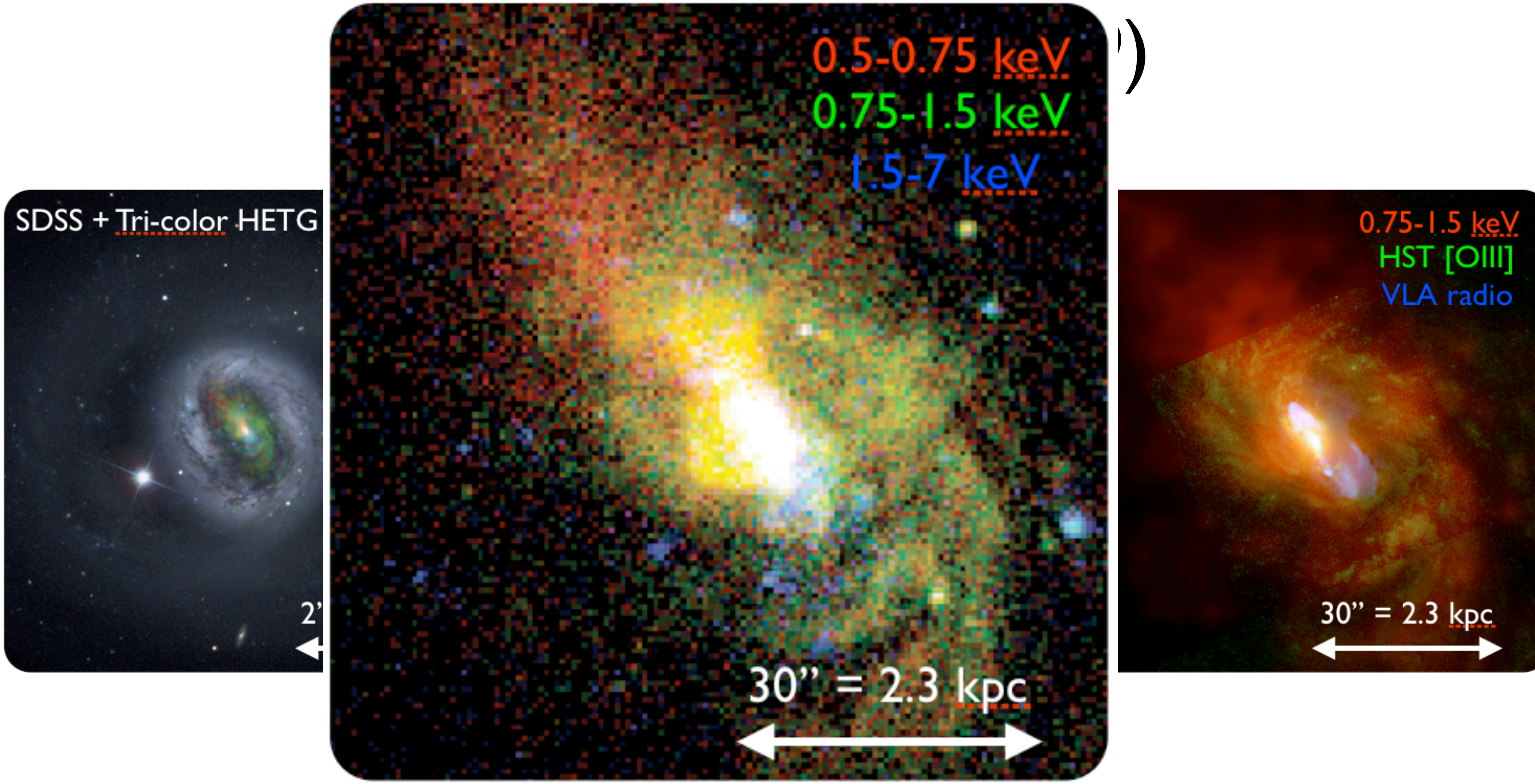
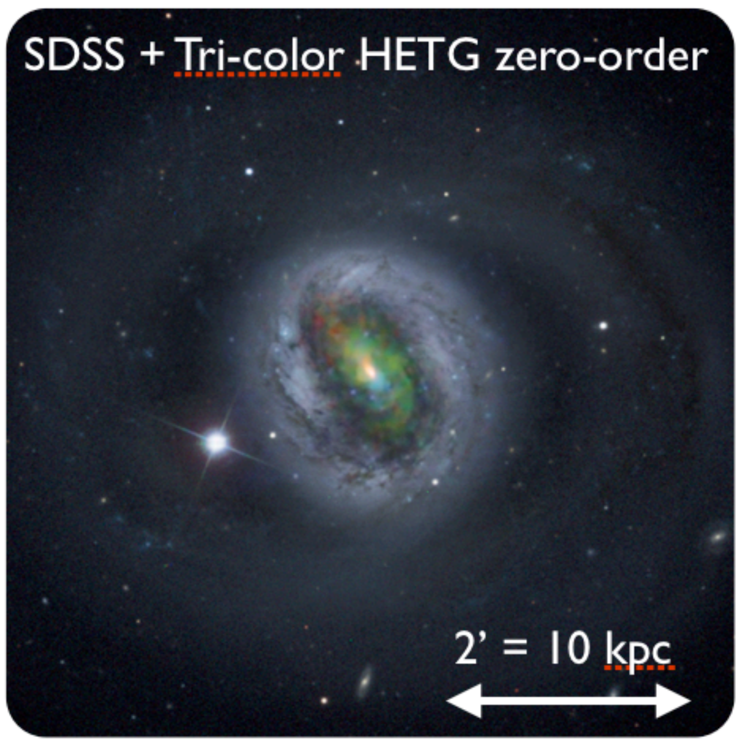
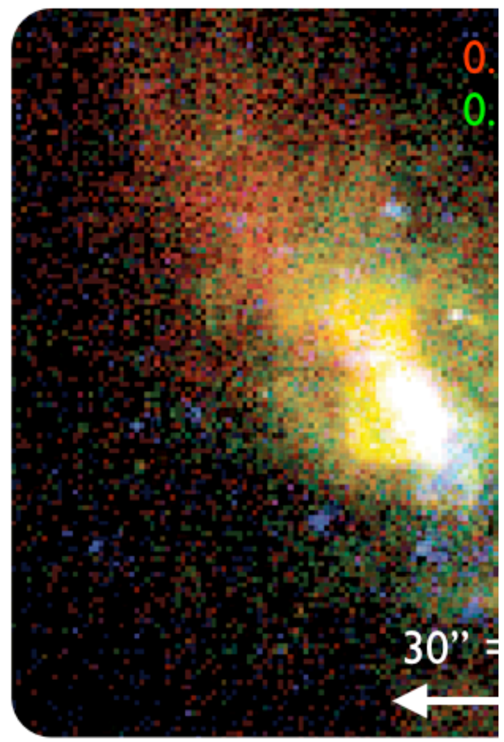
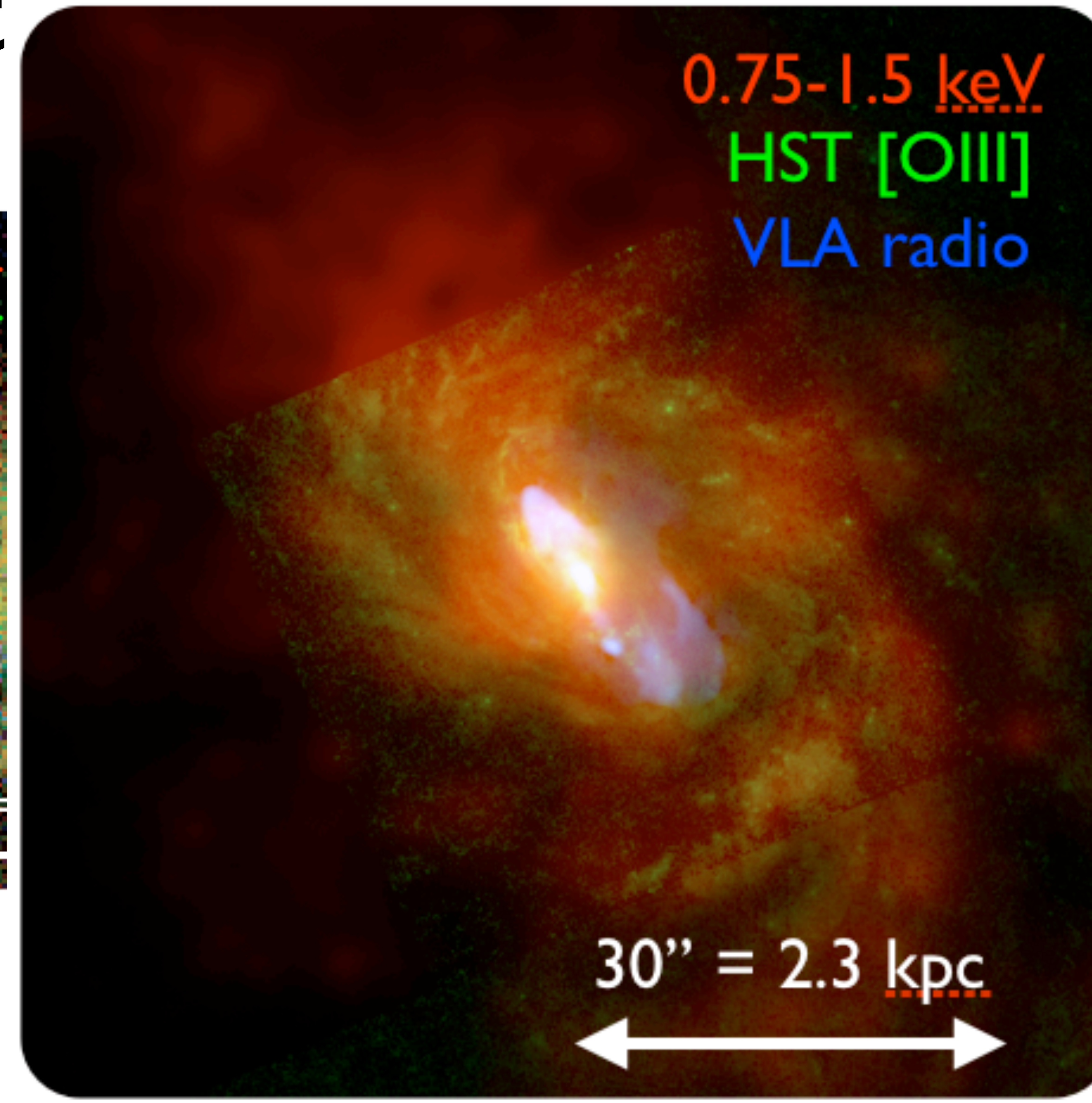
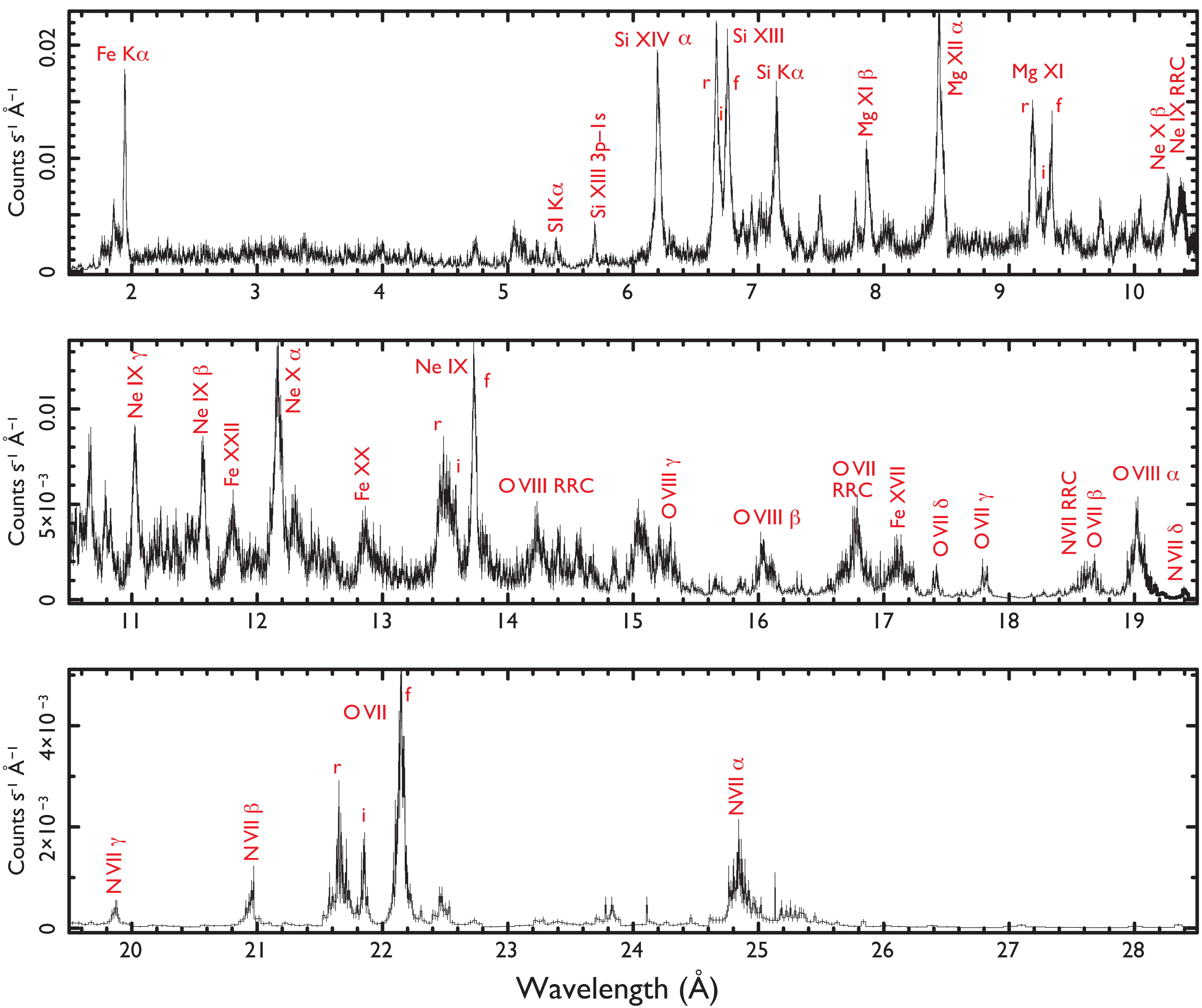


The Prototypical Example - a 440-ks Chandra HETG GTO Observation of NGC 1068 (Evans et



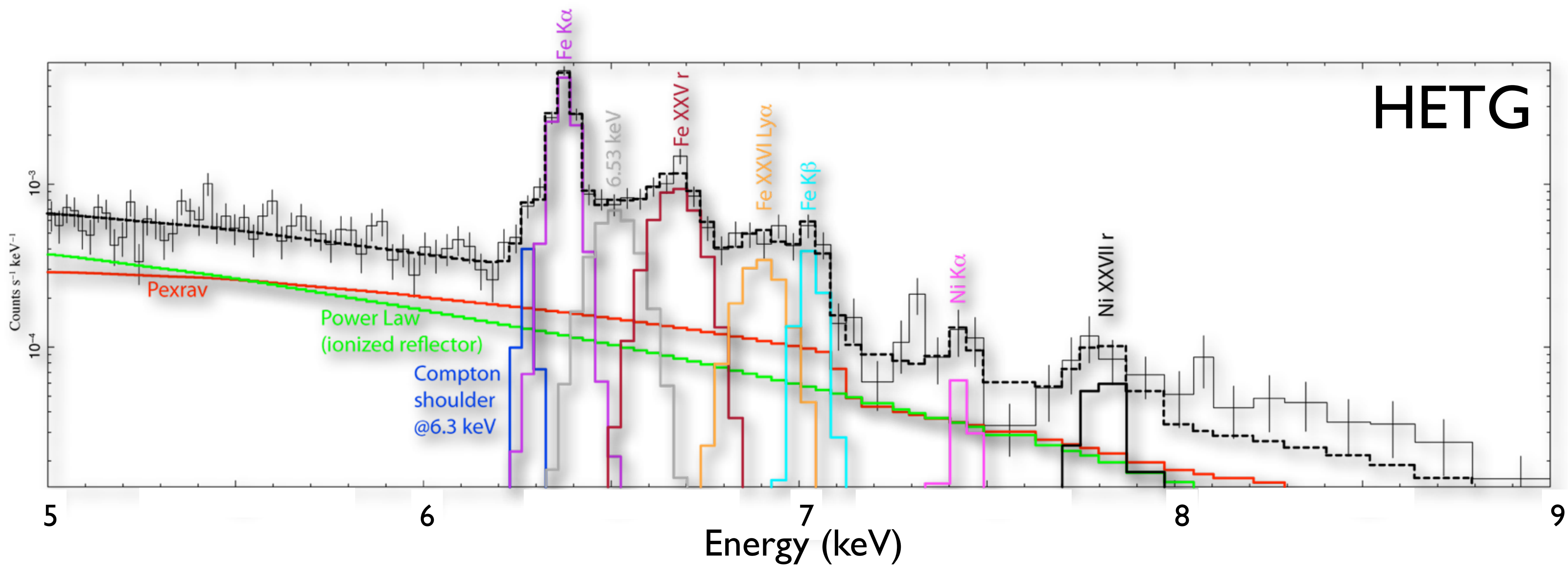


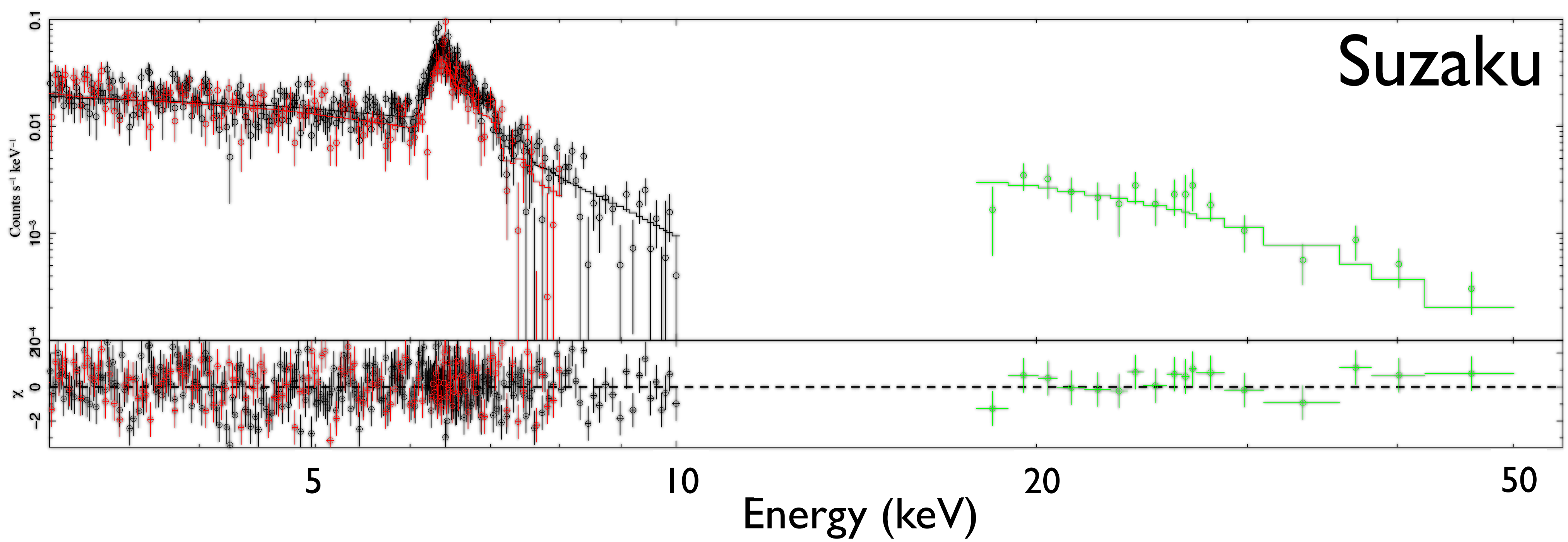




Evans et al. (2009); see also Kinkhabwala et al. (2002); Ogle et al. (2003)

Fe K Bandpass and Suzaku Spectrum



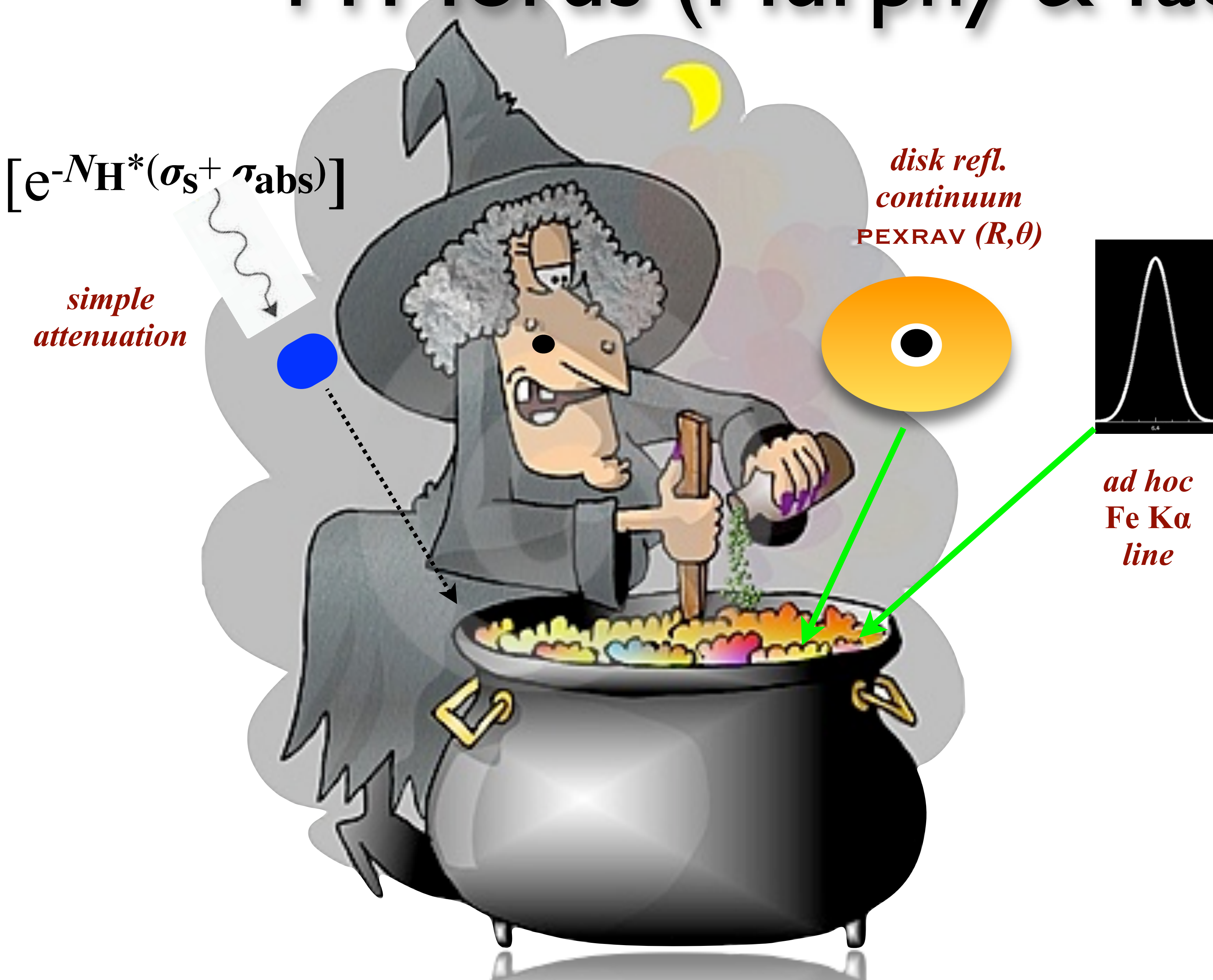


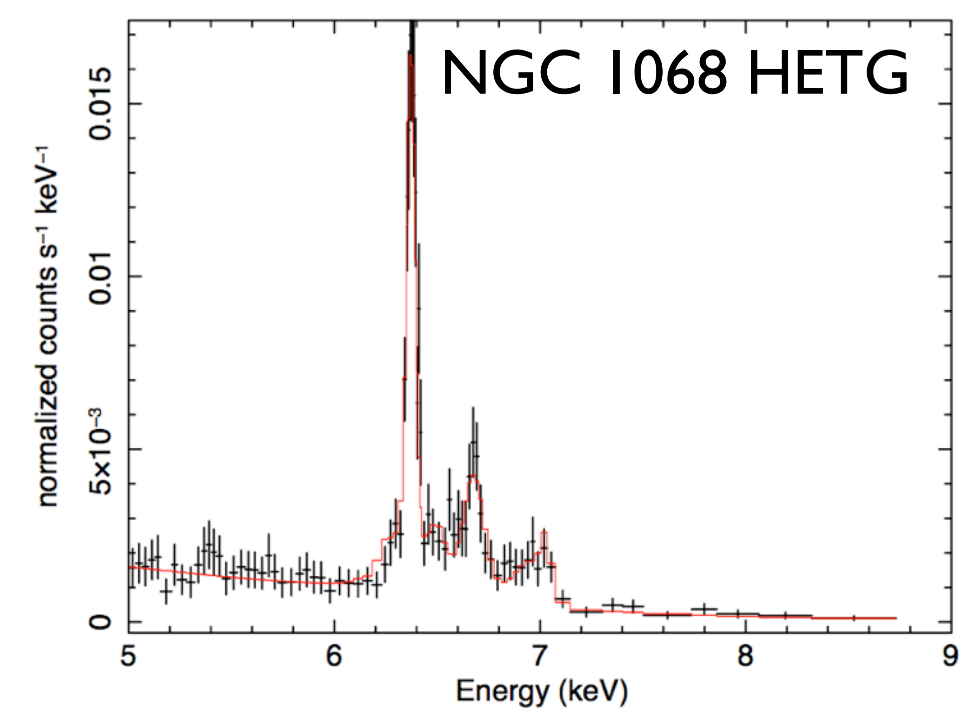
$\Gamma \sim 1.5\text{-}1.9$ (variable)

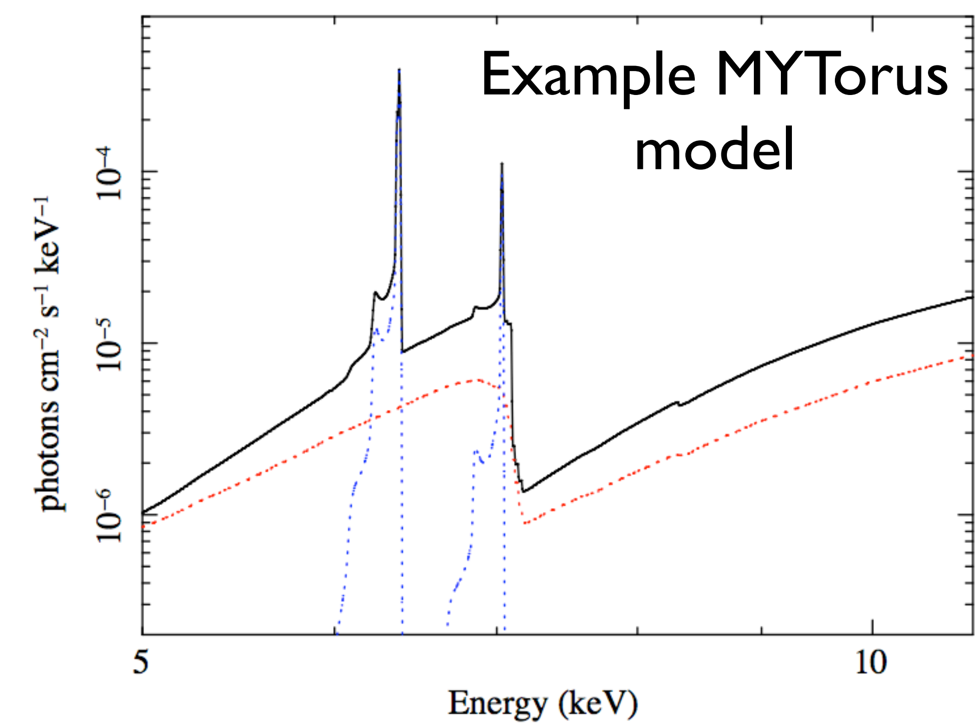
$N_H \sim 9\times10^{24}$ cm^{-2}

$L_{(2\text{-}10)} \sim 6\times10^{43}$ ergs s^{-1}

Self-consistent Torus/Reflection Modeling - MYTorus (Murphy & Yaqoob 2009)







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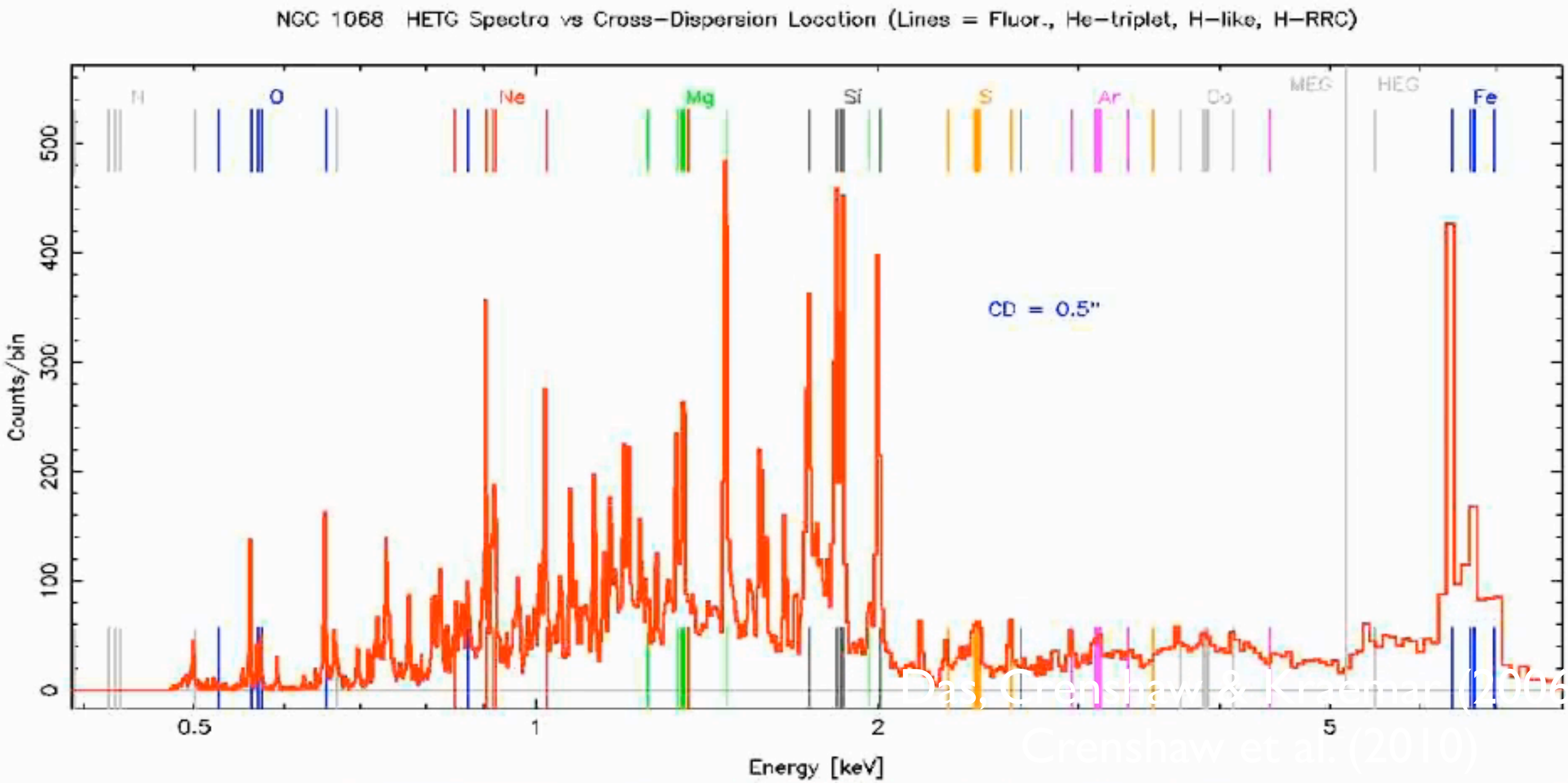
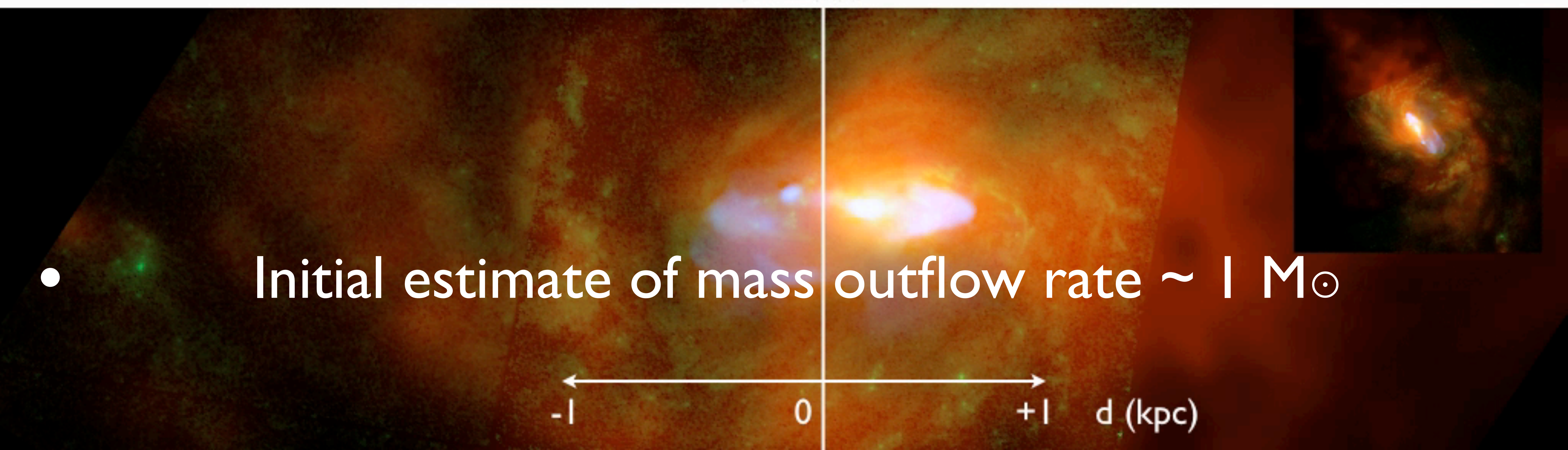


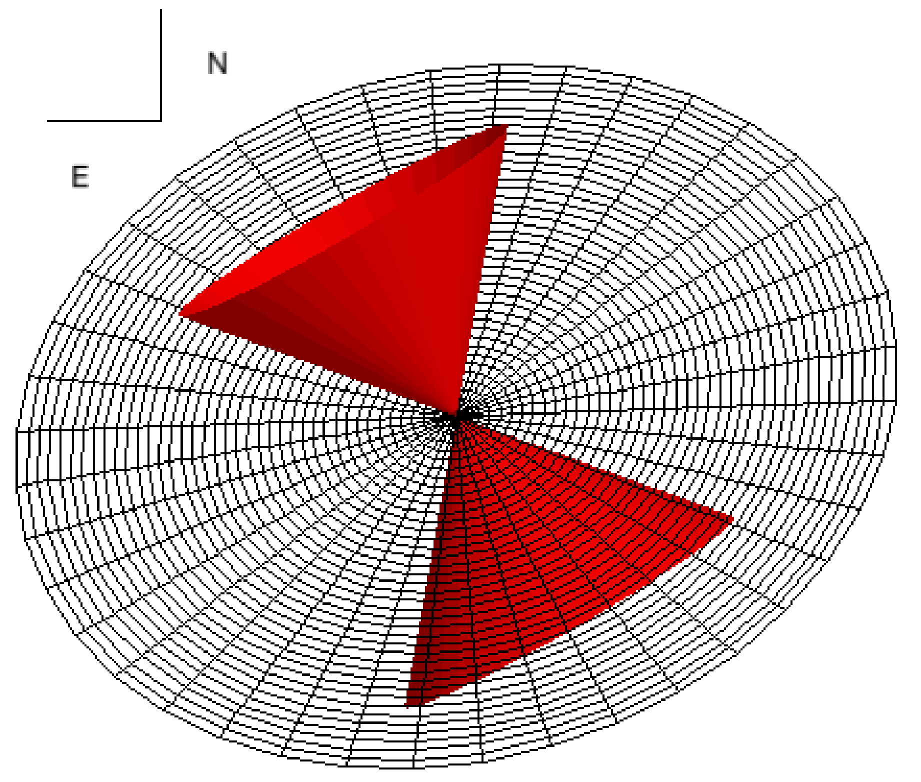
Das, Crenshaw & Kraemer (2006);
Crenshaw et al. (2010)



- Initial estimate of mass outflow rate ~ 1 M⊙

Preliminary results:

- ~500 km/s outflows detected in nuclear region
- All consistent with photoionization, rather than mechanical (jet) collisional ionization.



Das, Crenshaw & Kraemar (2006); Crenshaw et al. (2010)

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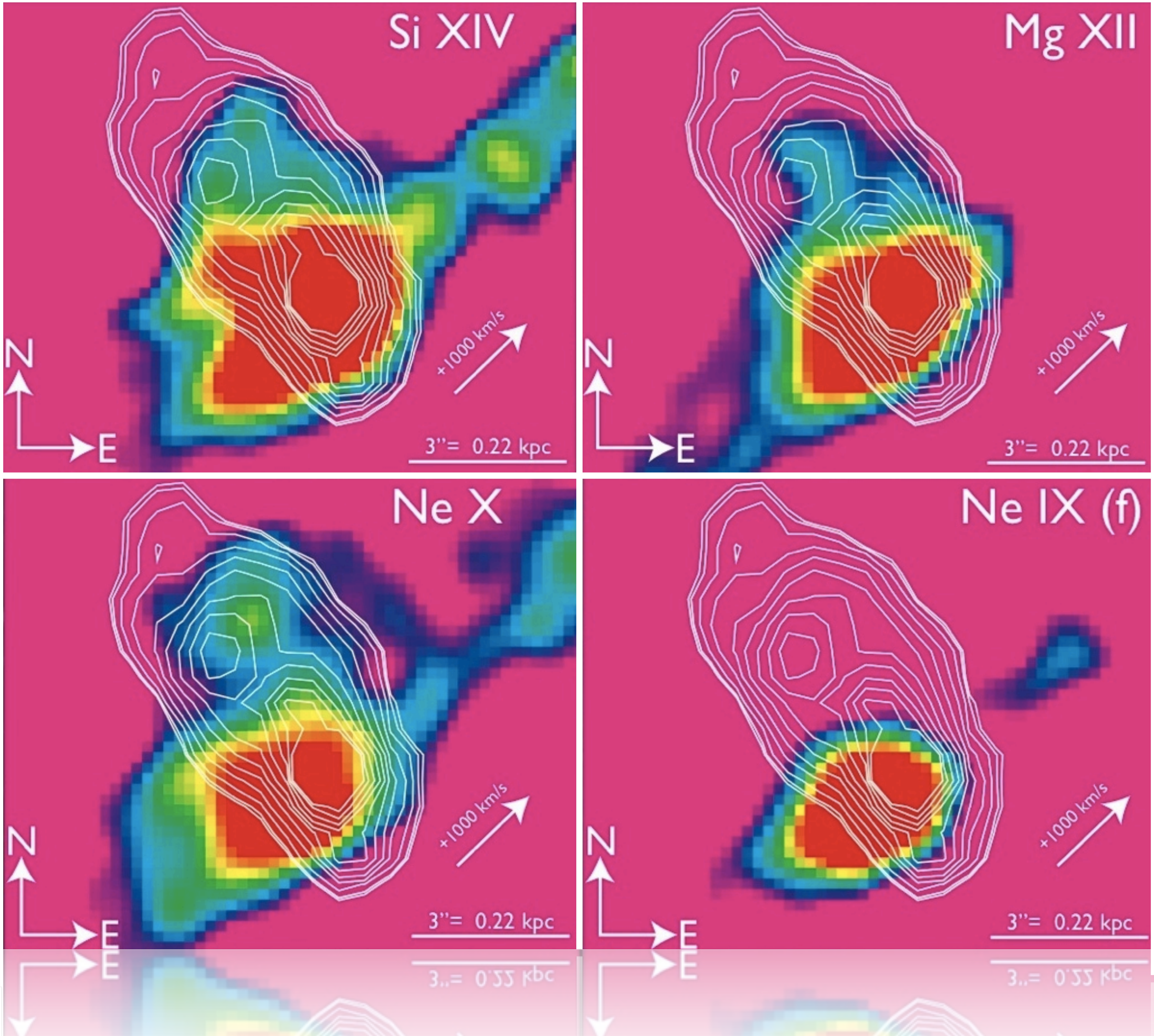
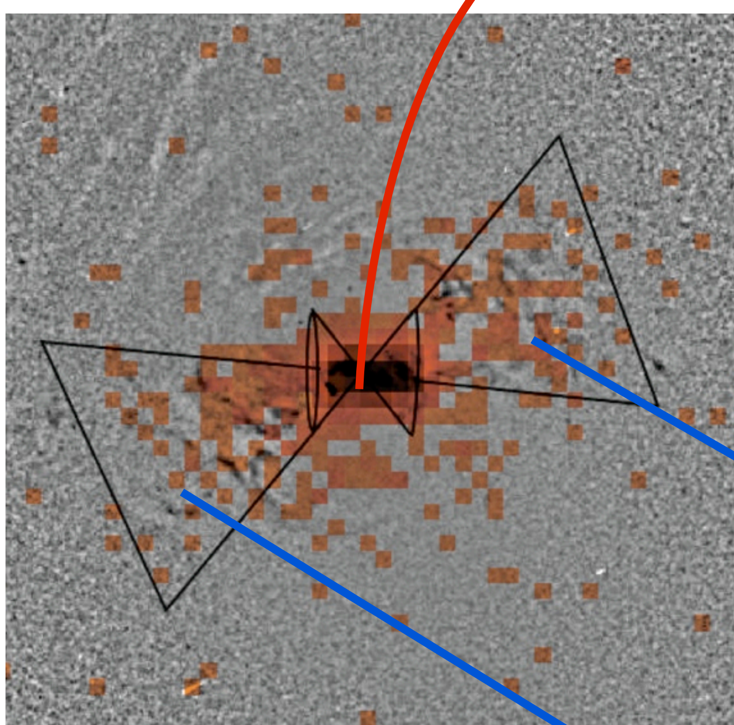
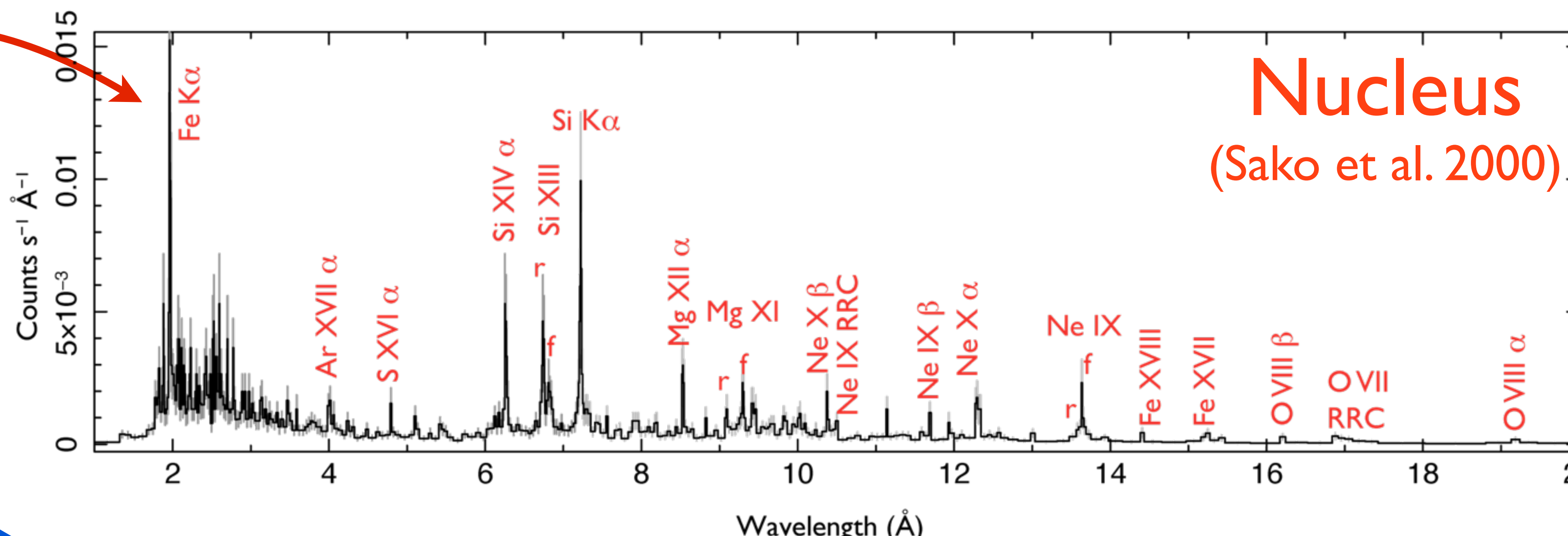
Spectral-Line Imaging

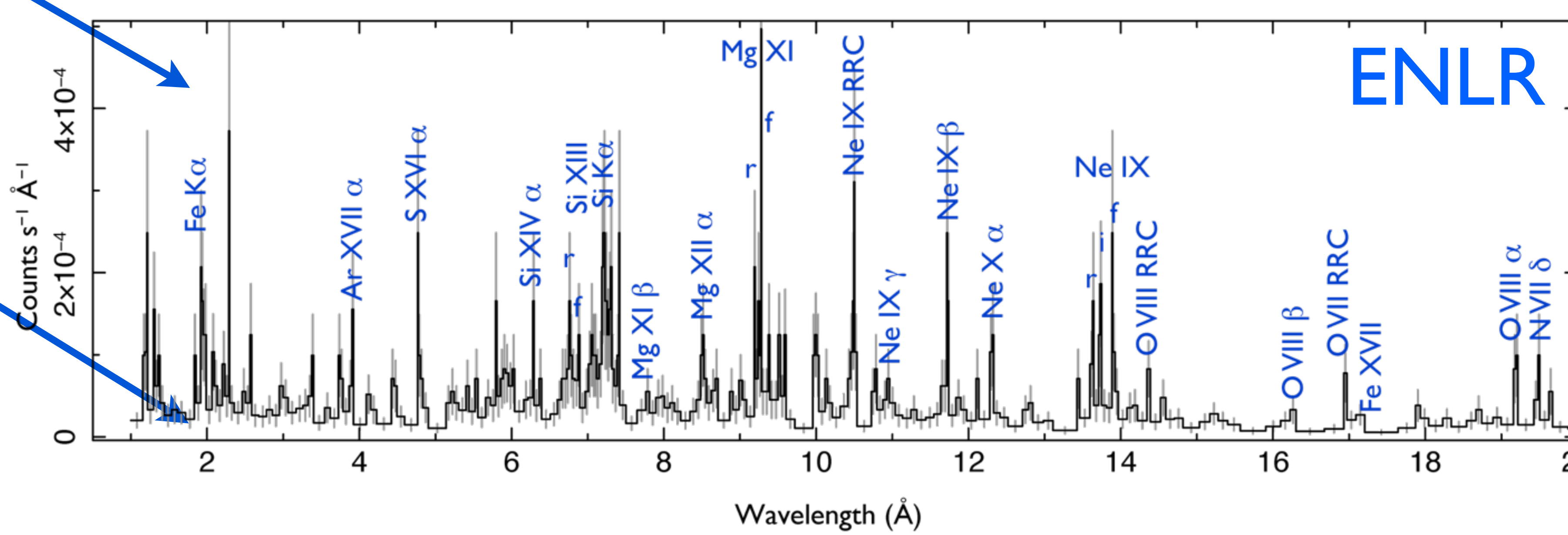


Next Up: Mrk 3

The Prototypical Early-Type Seyfert 2



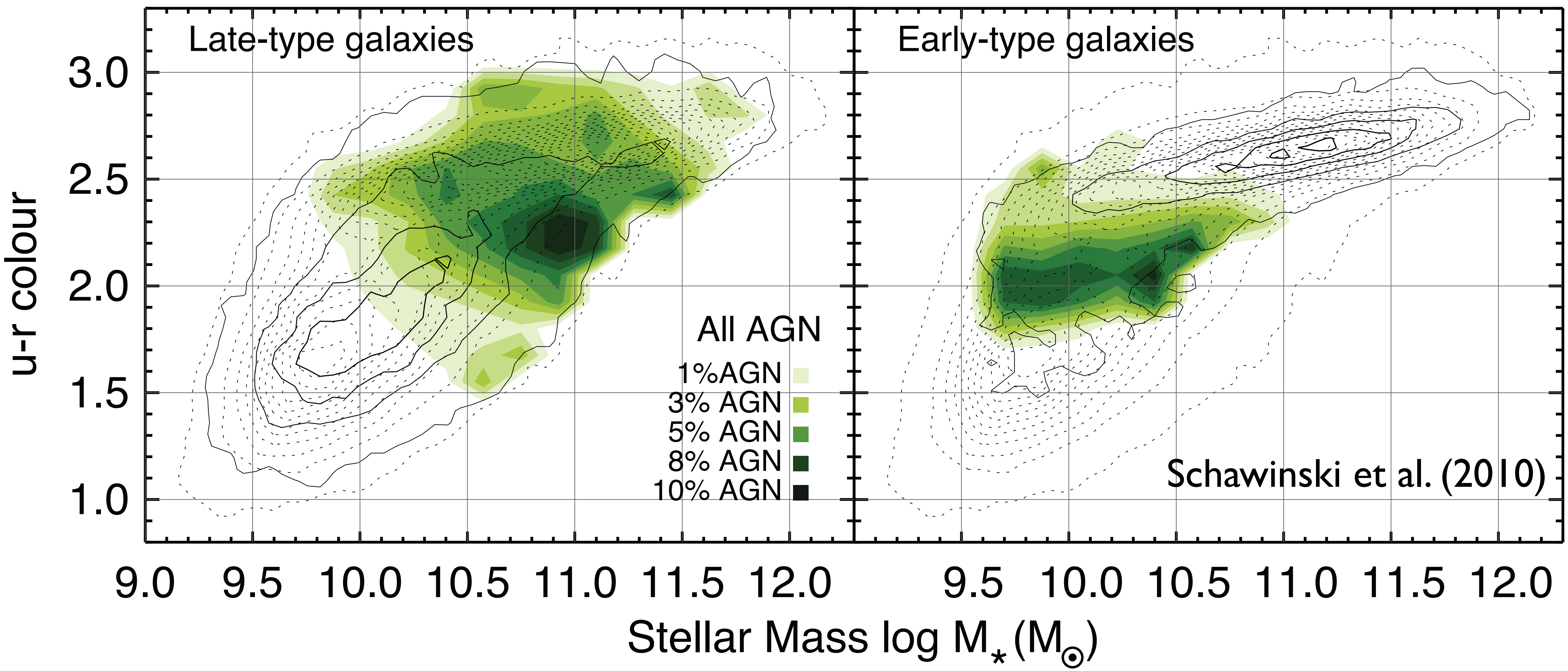




HST structure map
(H. Schmitt)
+
Bicone geometry
(Crenshaw et al. 2010)
+
0.5-2 keV X-ray

300 ks just awarded in AO-12!

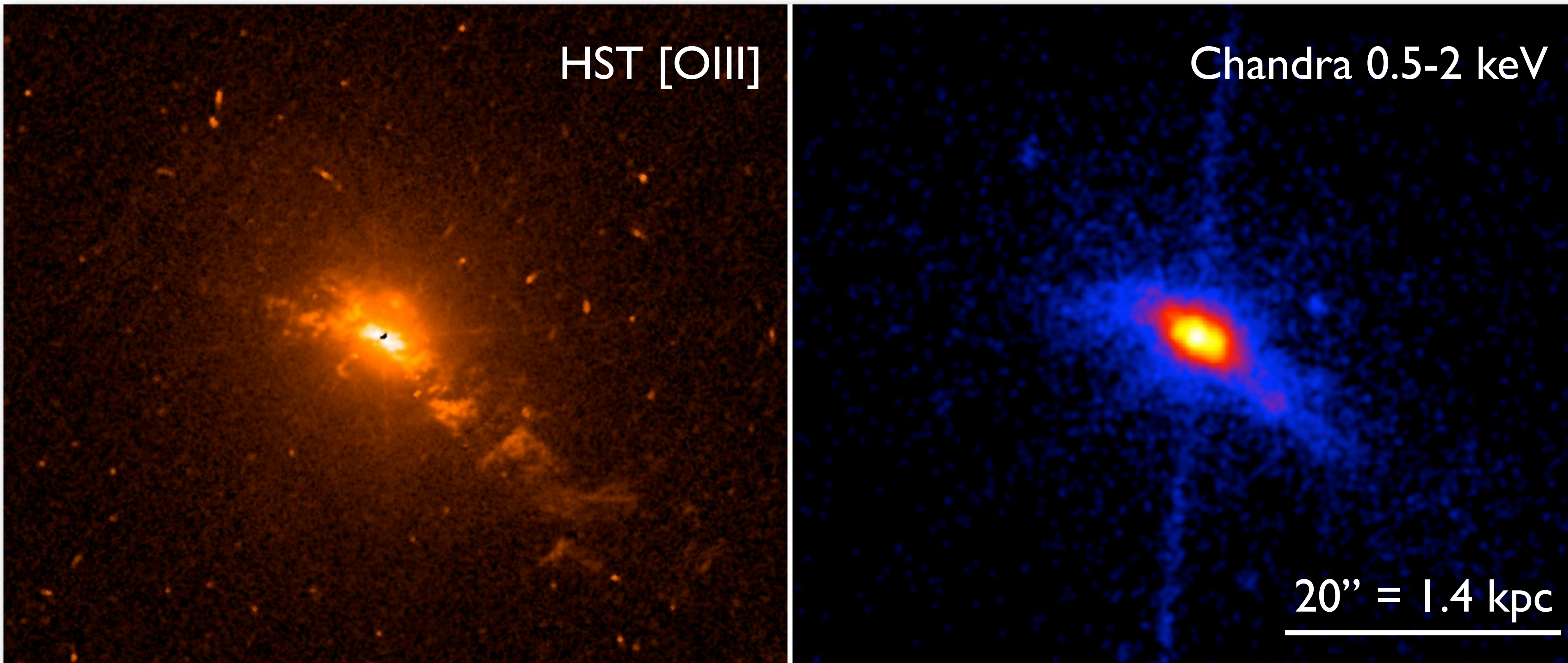
Synergies with Optical Surveys



Early-type AGN are **genuinely migrating at fixed mass from the blue cloud to the low mass end of the red sequence**

Late-type AGN have massive, highly stable stellar disks. Green host galaxy colors are **unlikely to be due to outflows**

NGC 4151 (400 ks) - Kraemer et al. (in prep.)



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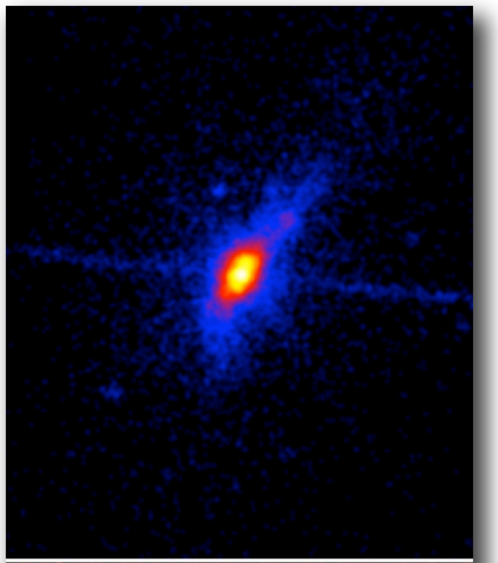
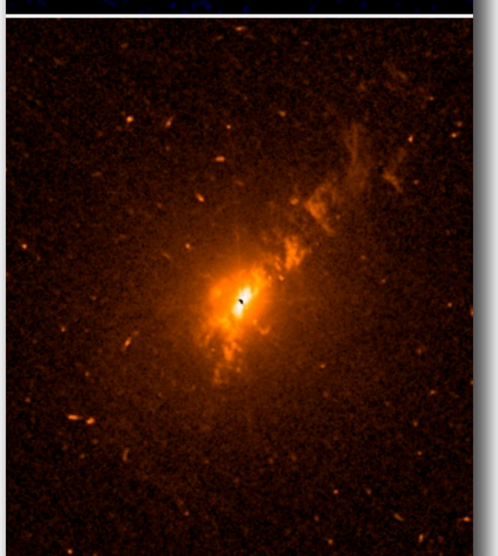
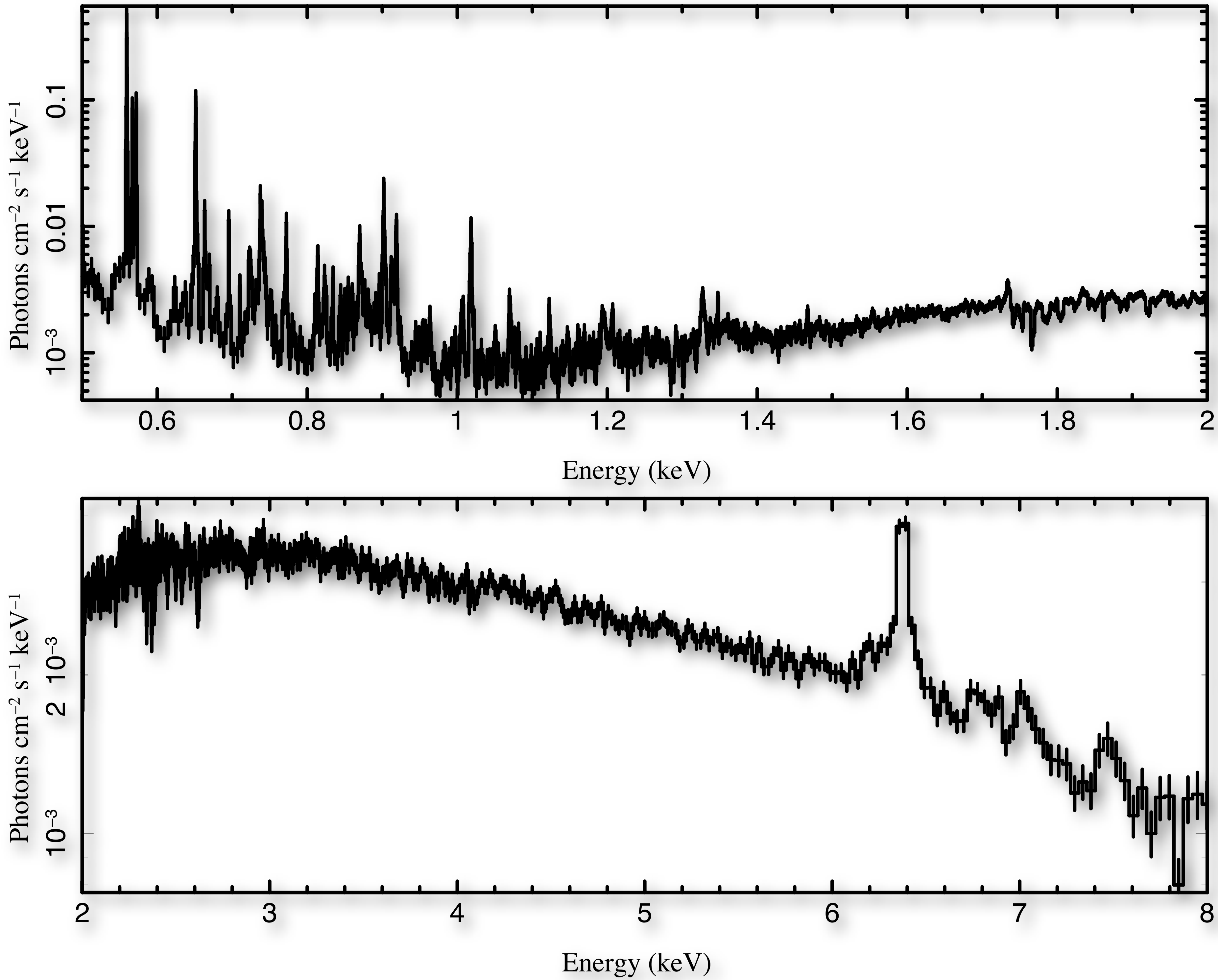
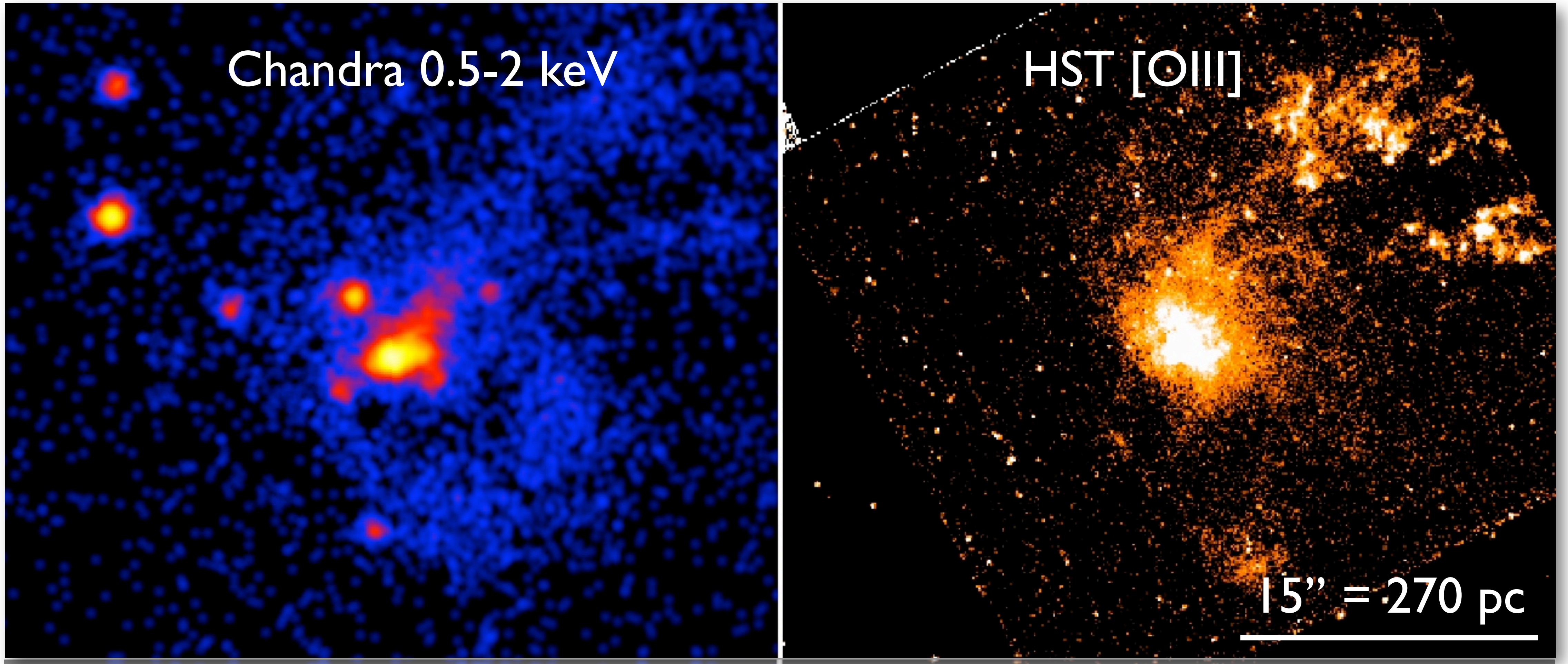


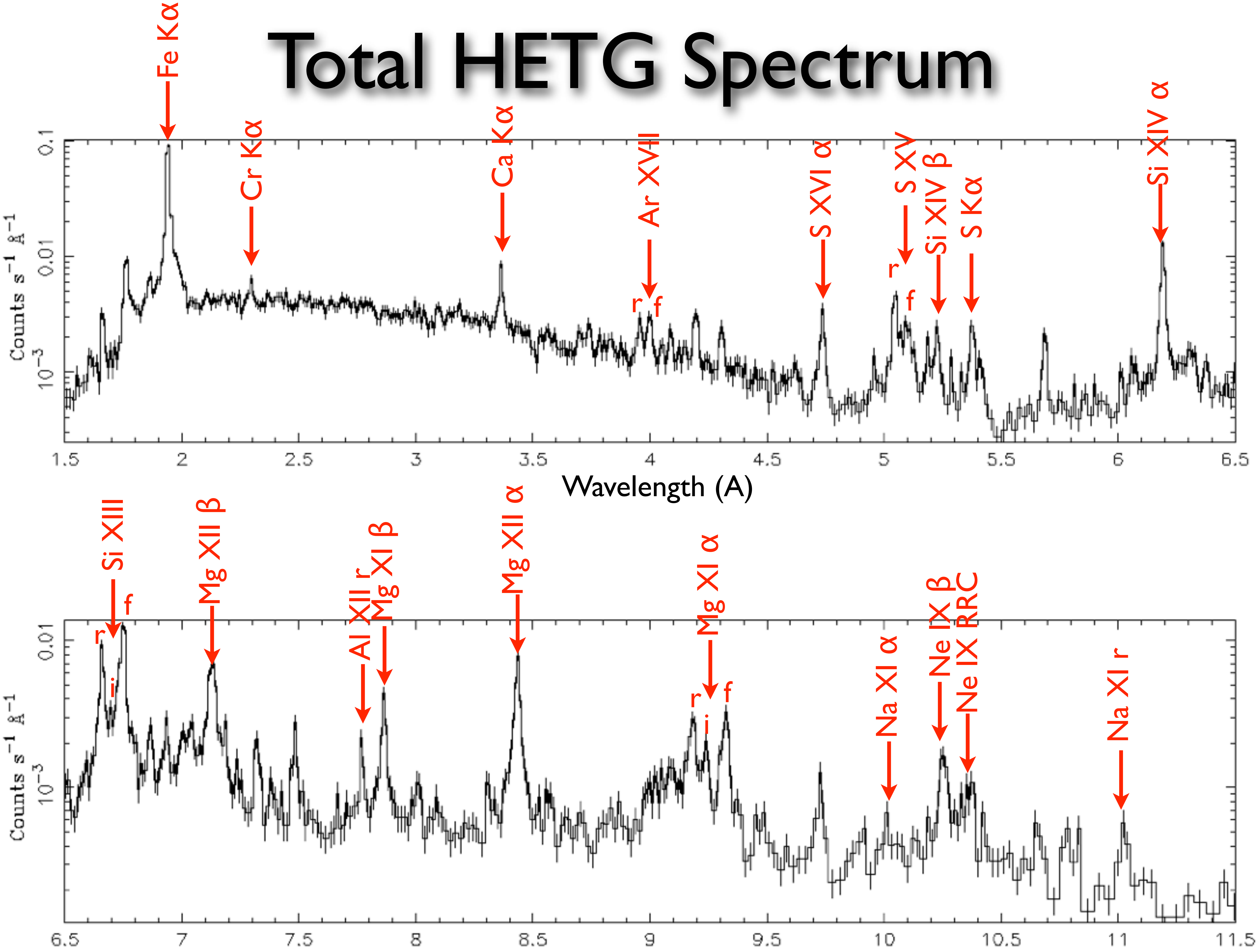


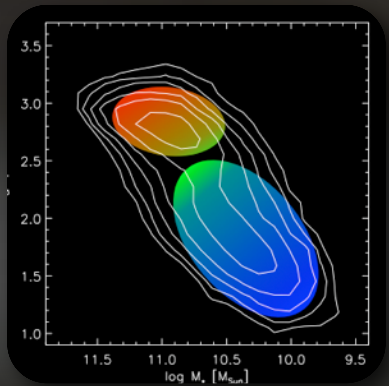


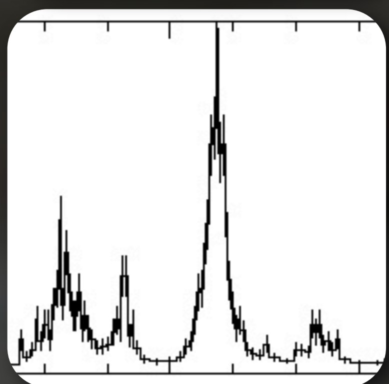
Circinus Galaxy (660 ks - close to SN1996cr!)
PI: Franz Bauer

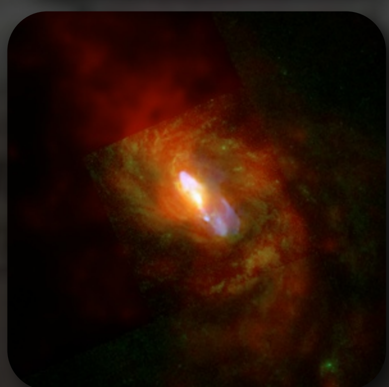


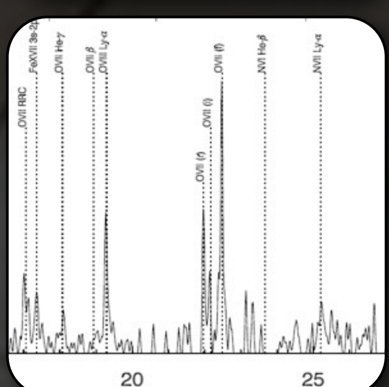
Total HETG Spectrum











Summary

Roadmap towards understanding energy transport in AGN:

- NGC 1068 has a 10^7 M⊙ black hole, which is accreting at or near its Eddington limit: it is an ideal laboratory to examine the role of AGN outflows and feedback on black-hole growth.
- Multiwavelength imaging shows that the radio jet, [OIII] and X-ray emission are spatially related.
- Spatially resolved, high-resolution Chandra HETG spectra show that the NLR is entirely photoionized, with no indication of collisional ionization from the jet: i.e., the AGN radiation field dominates the energetics.
- Outflows are detected in the nucleus, with velocities > 500 km/s.
- How do early- and late-type galaxies migrate from blue to red?
- Key to extend these observations to other nearby sources, not least, Mrk 3