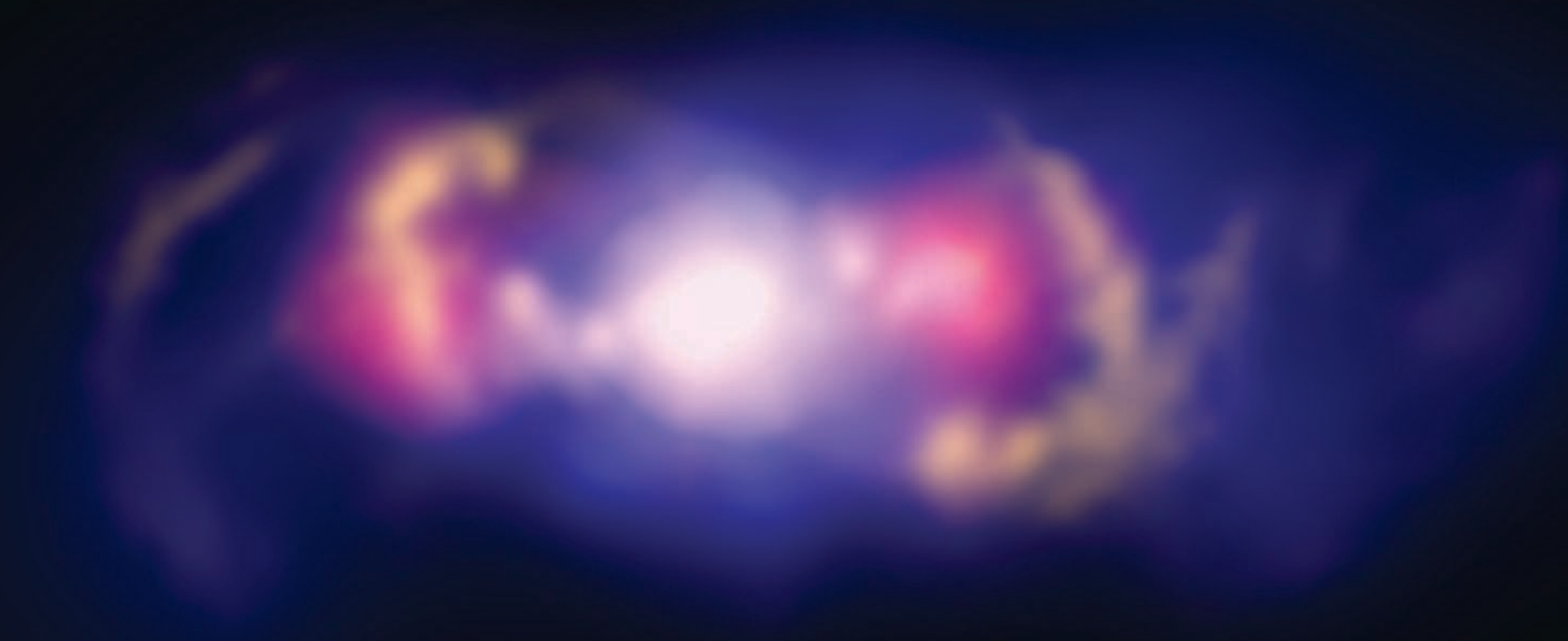
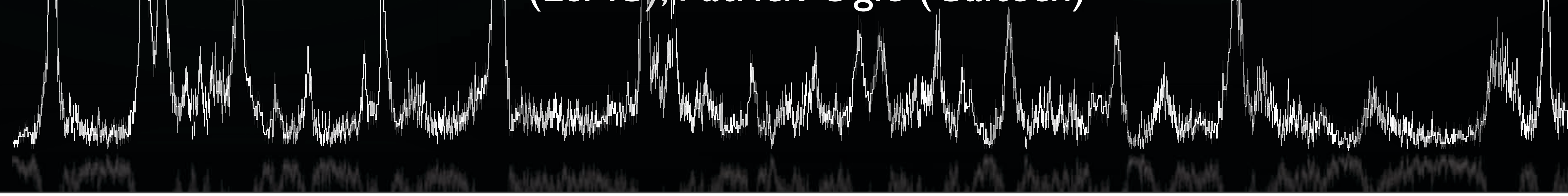
The Chandra Survey of Outflows in AGN with Resolved Spectroscopy (SOARS)

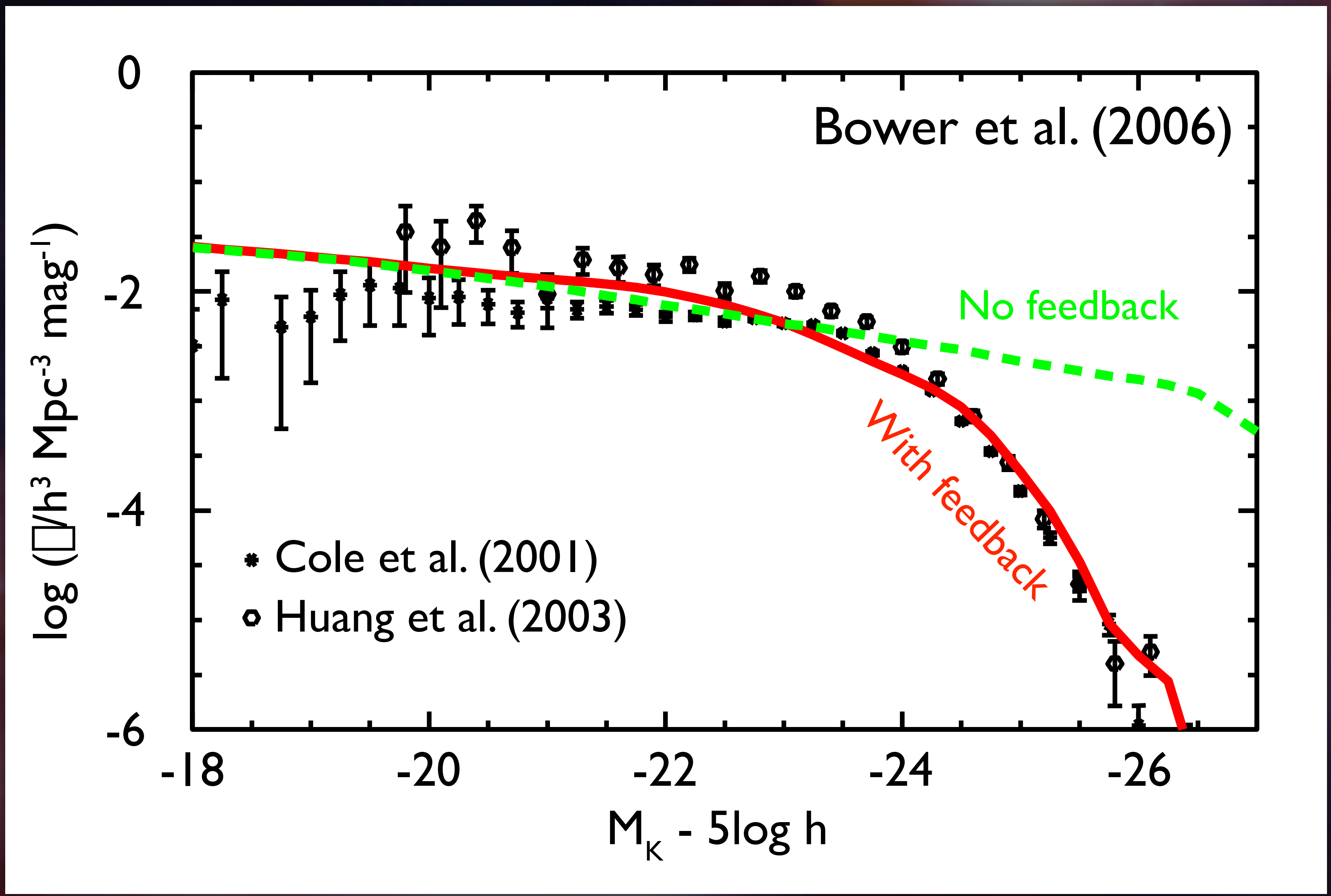


Dan Evans (CfA and Elon University)

Kevin Schawinski (Yale), Francisco Muller Sanchez (IAC/UCLA), Herman Marshall (MIT), Martin Ward (Durham), Ric Davies (MPE), James Reeves (Keele), Mike Crenshaw (GSU), Steve Kraemer (CUA), Kim Weaver (GSFC), Stefano Bianchi (Roma Tre), Matteo Guainazzi (ESAC), Patrick Ogle (Caltech)



Black Holes and Galaxy Formation

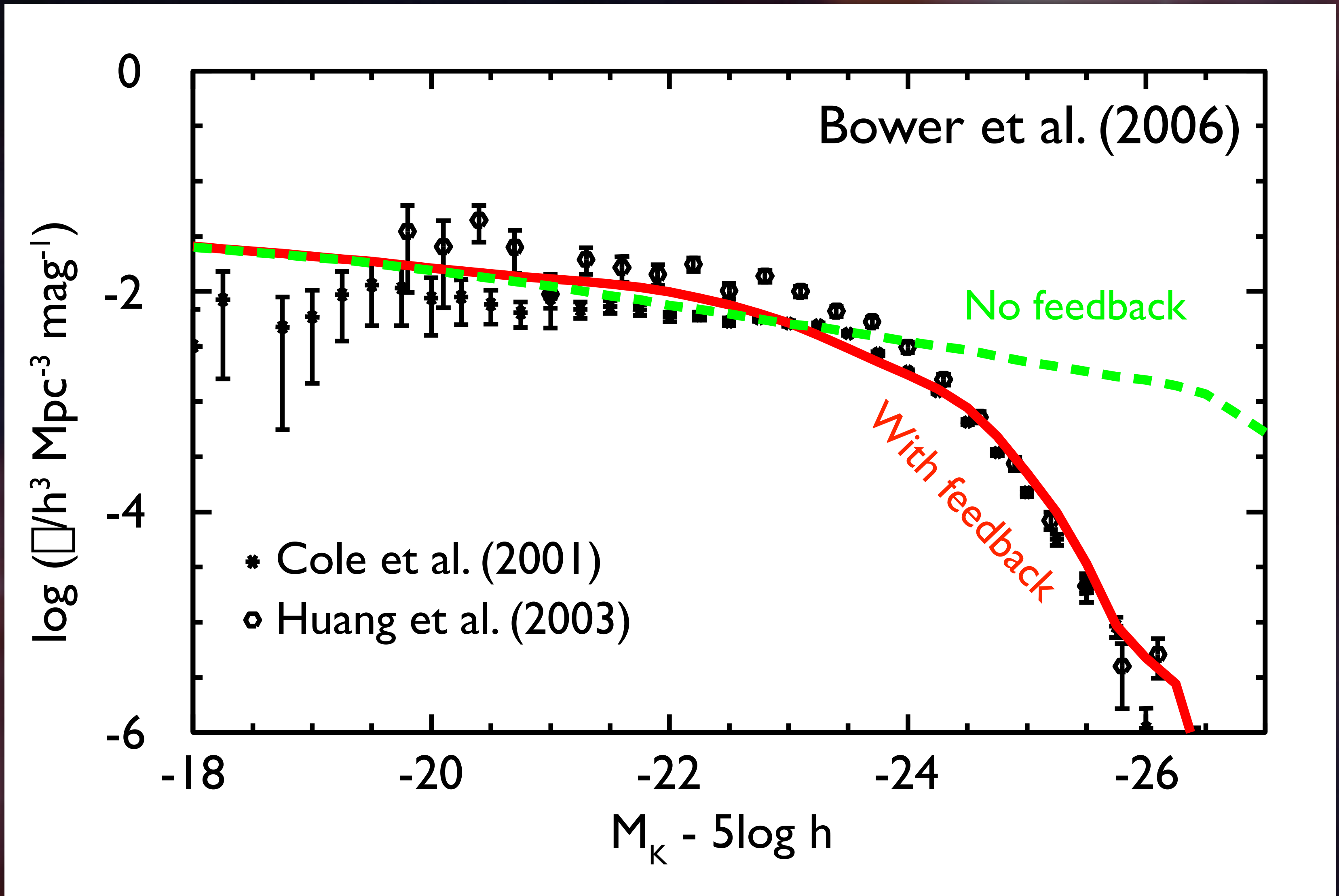


Sharp cutoff at the bright end of the galaxy mass function can be solved with AGN feedback

Thermal energy of a 10^{13} M□ halo = 10^{61} ergs

Credit: Richard Bower

Black Holes and Galaxy Formation

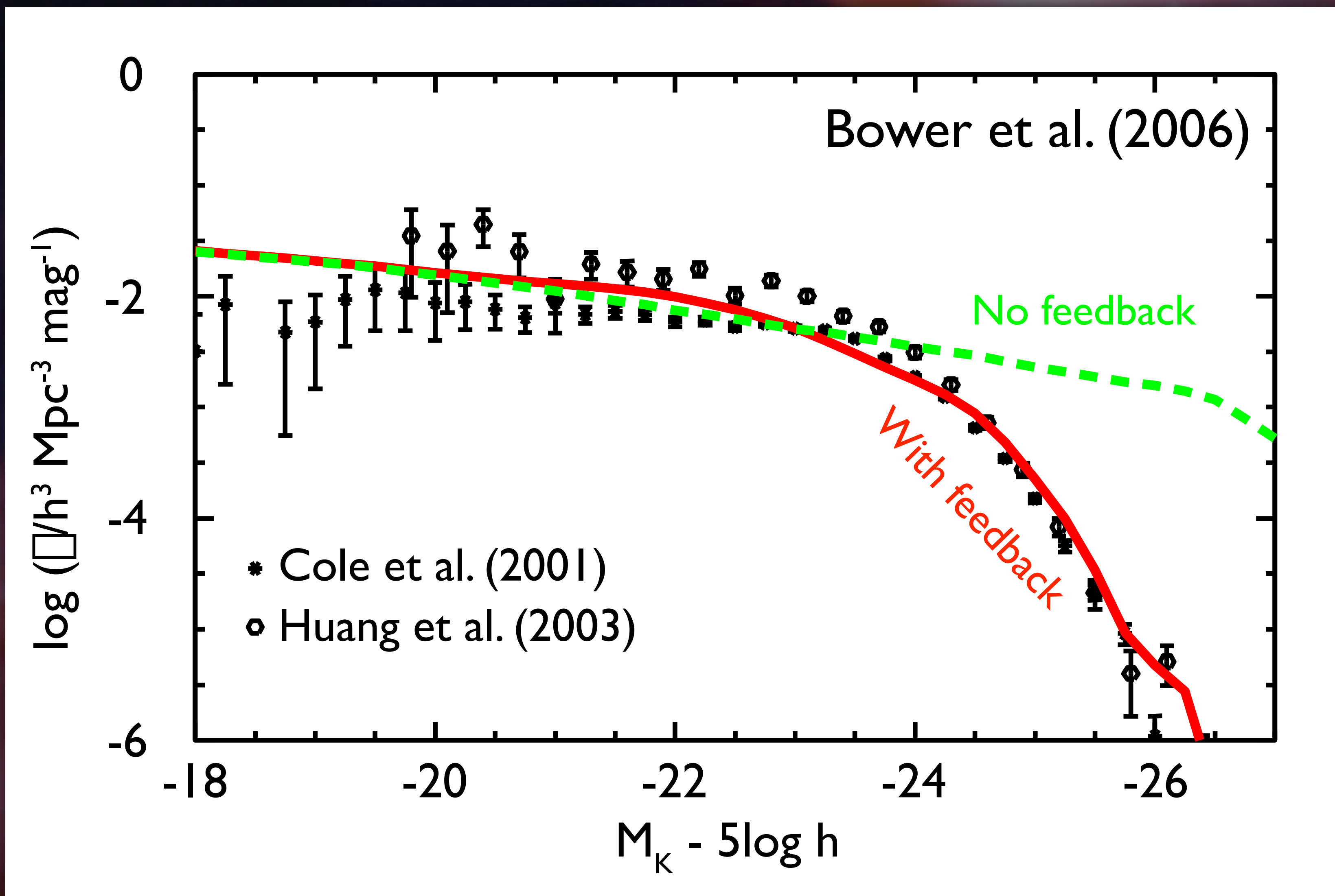


Sharp cutoff at the bright end of the galaxy mass function can be solved with AGN feedback

Accretion on to a 10^9 M□ black hole = 10^{62} ergs

Credit: Richard Bower

Black Holes and Galaxy Formation

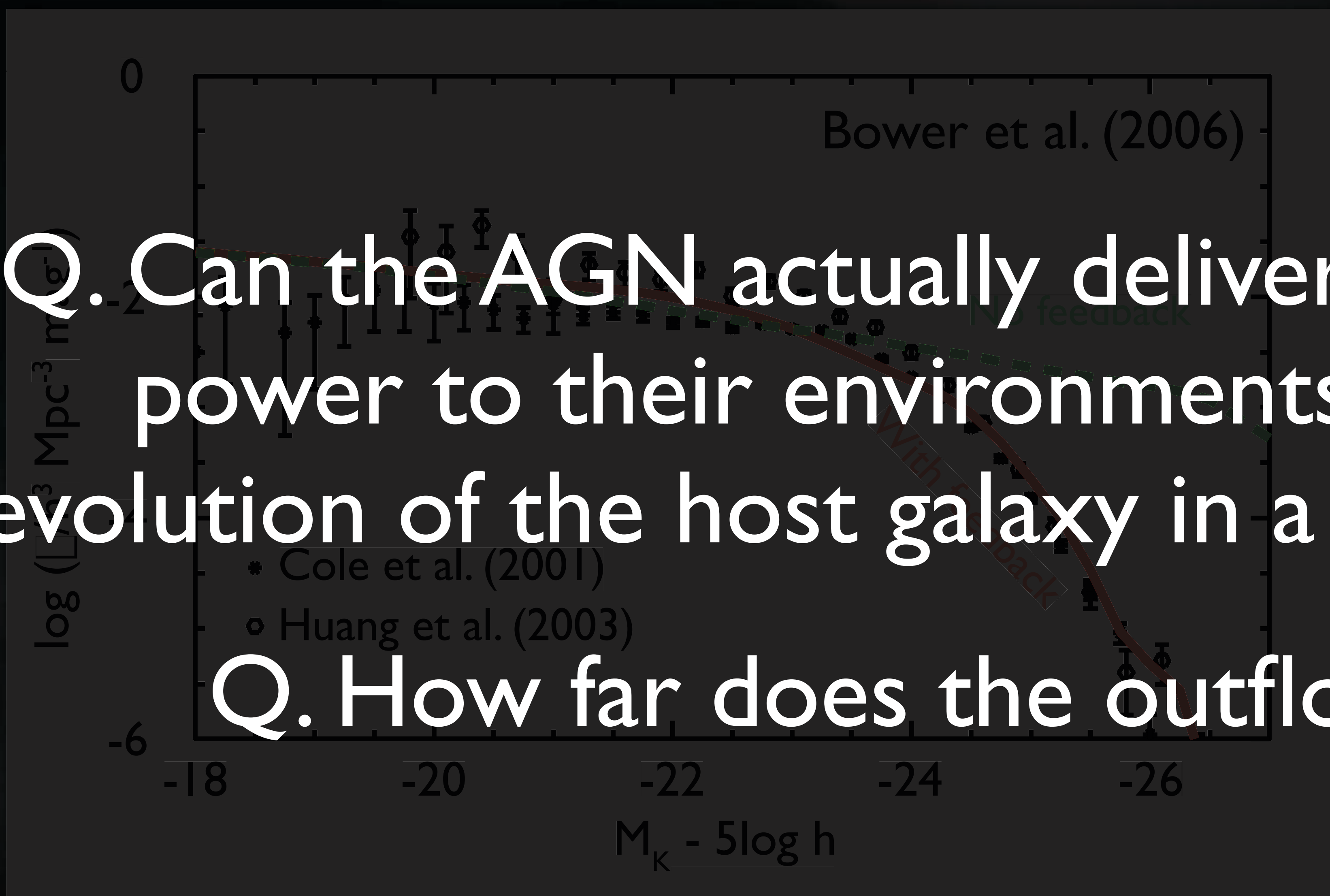


Sharp cutoff at the bright end of the galaxy mass function can be solved with AGN feedback

Accretion on to a $10^9\ M_\odot$ black hole = 10^{62} ergs

Credit: Richard Bower

Black Holes and Galaxy Formation



Sharp cutoff at ... can be solved ... feedback

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?

Accretion on to a 10^9 M black hole = 10^{62} ergs

Credit: Richard Bower

The Narrow-Line Region in AGN

Largest observable structure from soft X-rays to near-IR that is directly affected by both the ionizing radiation and dynamical forces from the SMBH.

CHEERS by J. Wang (Poster 6.1)

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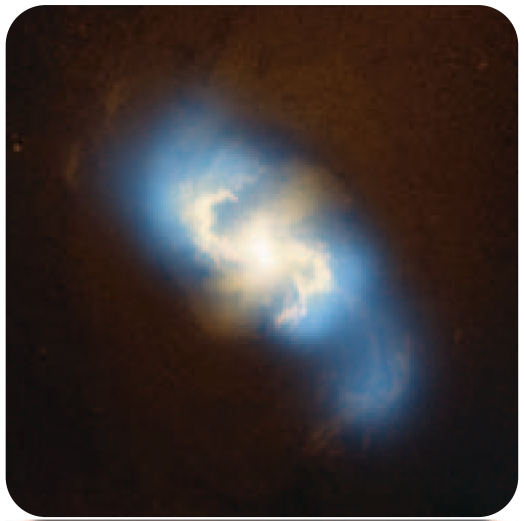
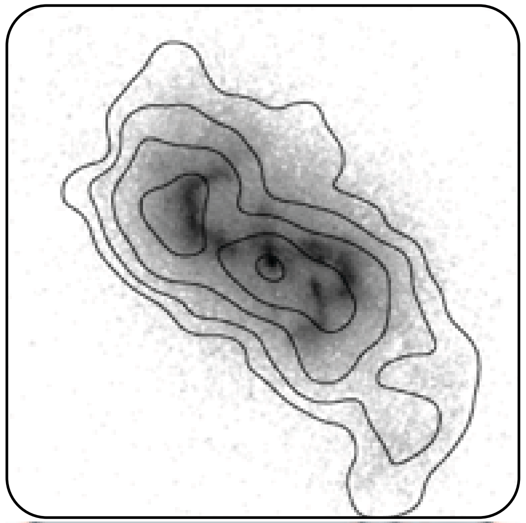
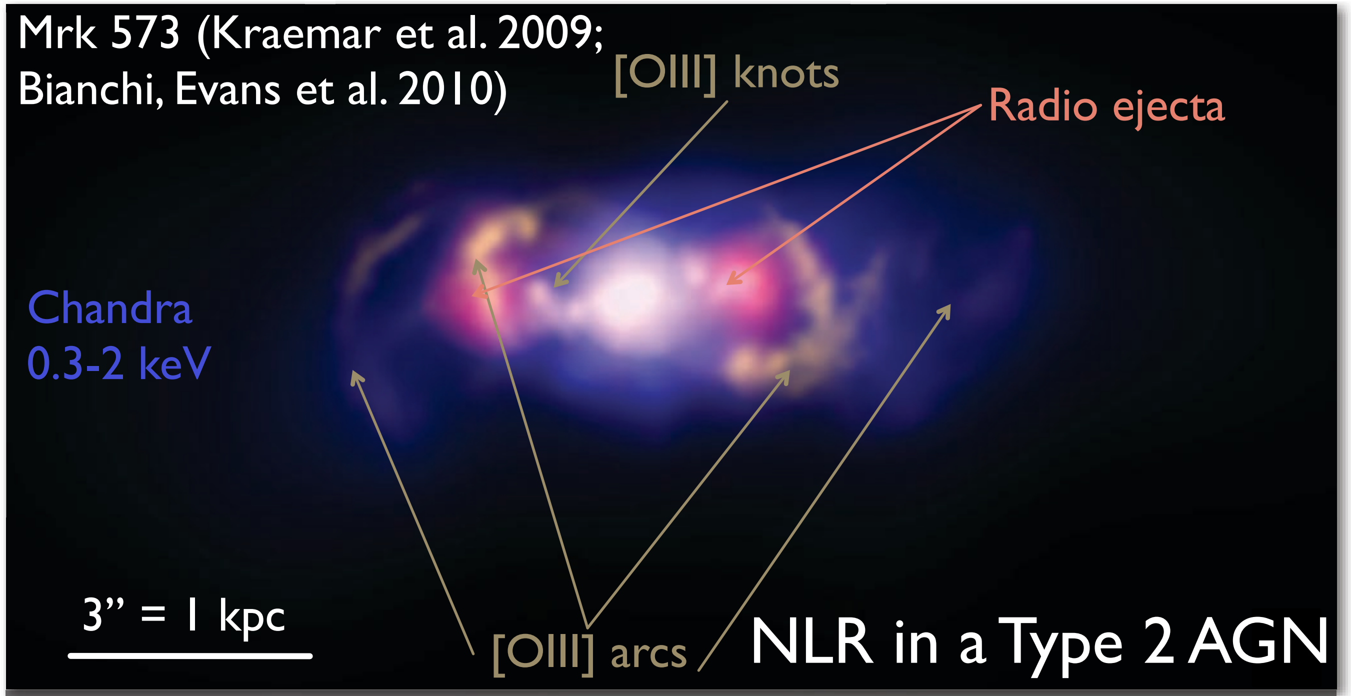


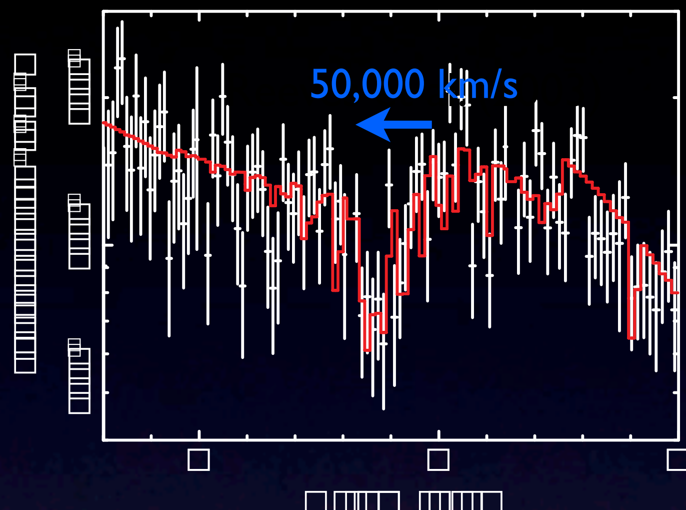

CHEERS by J.Wang (Poster 6.1)

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

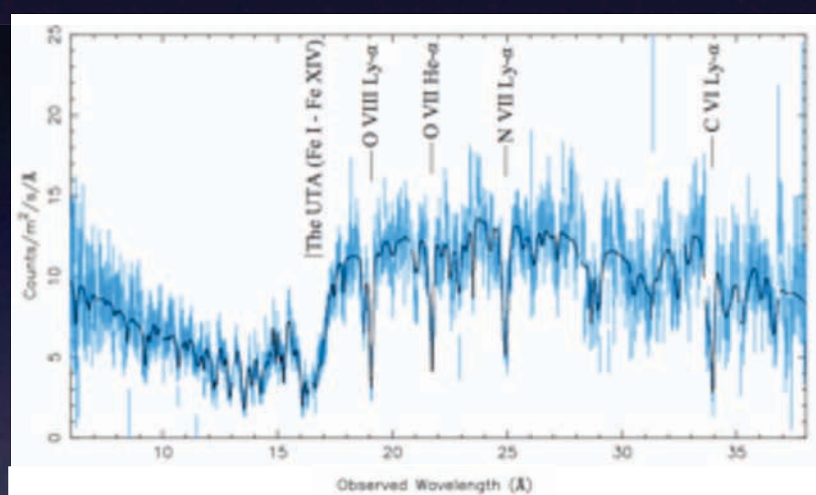
2. Some estimates of energy in the multiphase gas



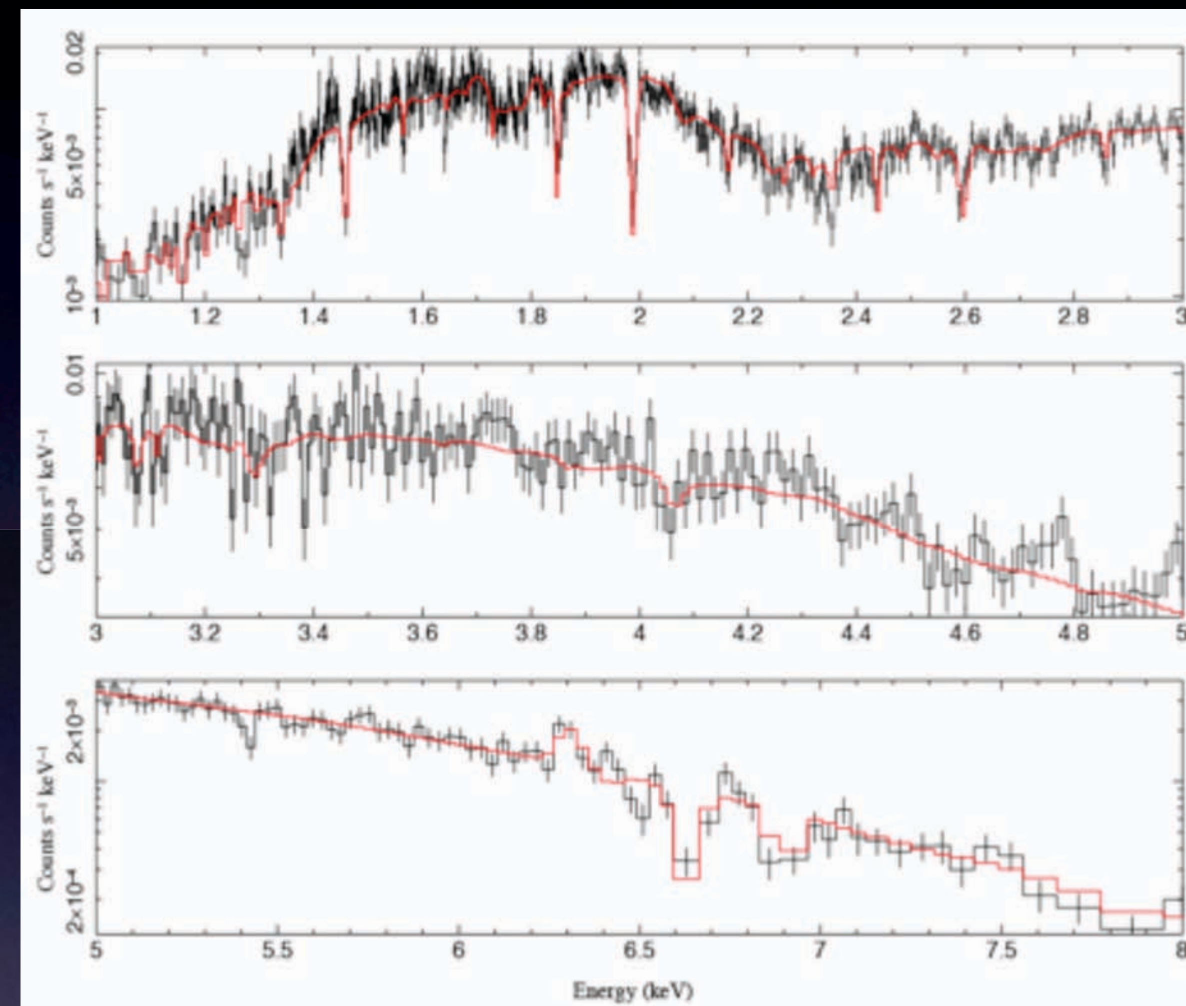
Searching For Outflows: X-ray Spectroscopy



PDS 456 - Reeves et al. (2003)

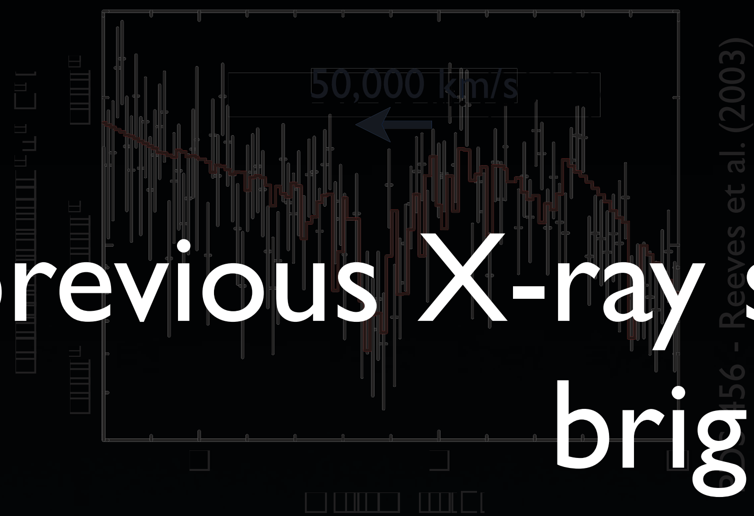


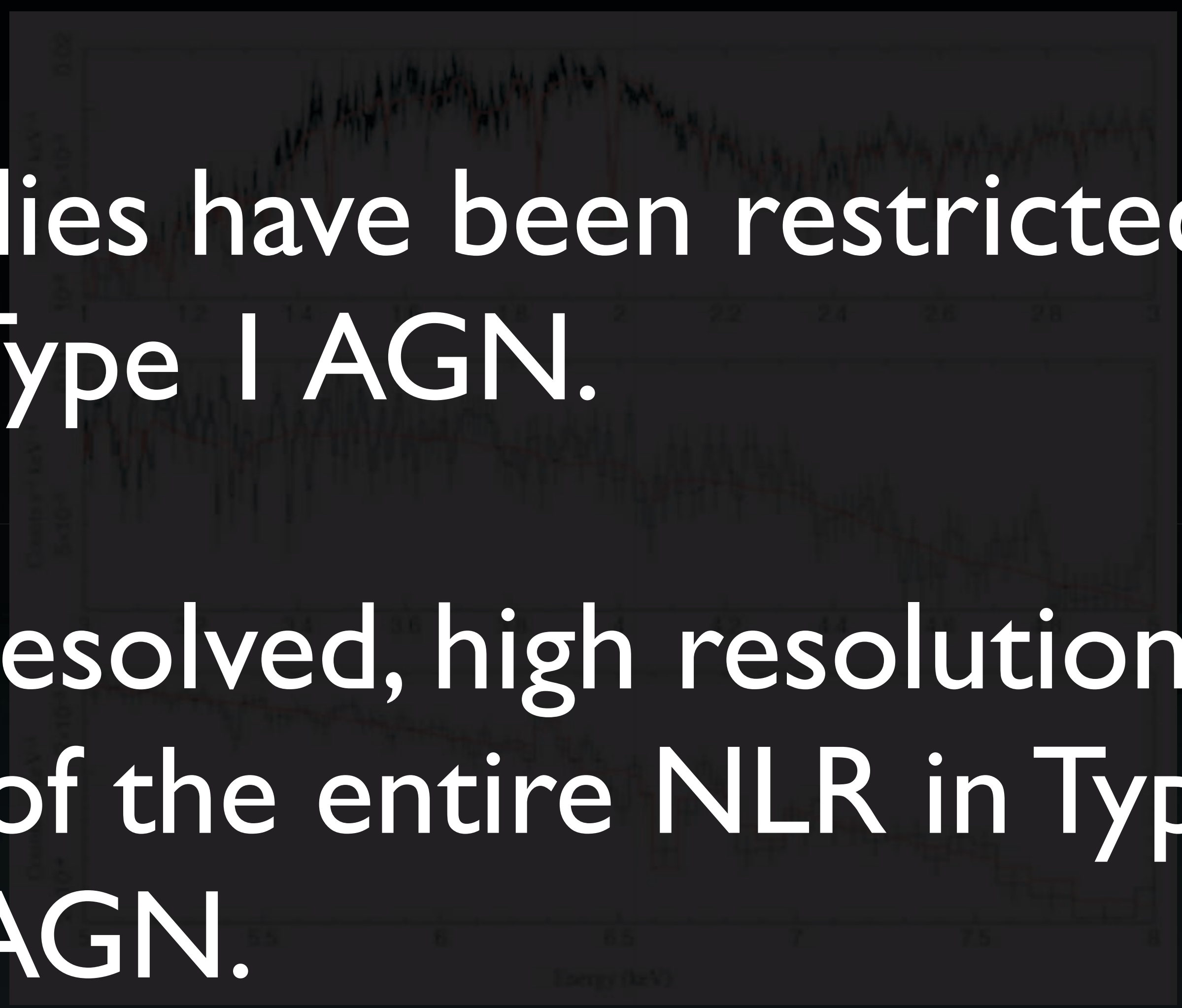
N3516 - Mehdipour et al. (2010)

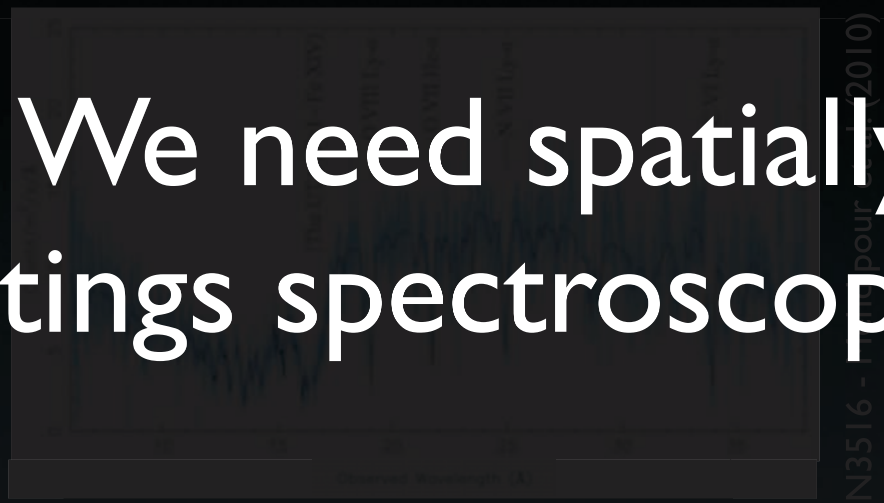


ESO 323 - Evans et al. (in prep.)

Searching For Outflows: X-ray 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.

X-ray spectrum → Ionic column densities → Photo-ionization modeling → Metallic column densities → Location and geometry → Mass → Velocity offsets → Energy outflow rate

The Chandra SOARS Project

Survey of Outflows in AGN with Resolved Spectroscopy

- First spatially resolved X-ray gratings study of kpc-scale NLR environments in type-2 AGN
- 1.9 Ms granted over multiple AOs (GO+GTO+Archival)

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(1) Spectroscopically disentangle collisional and photoionization

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① Spectroscopically disentangle collisional and photoionization

② Measure velocity offsets

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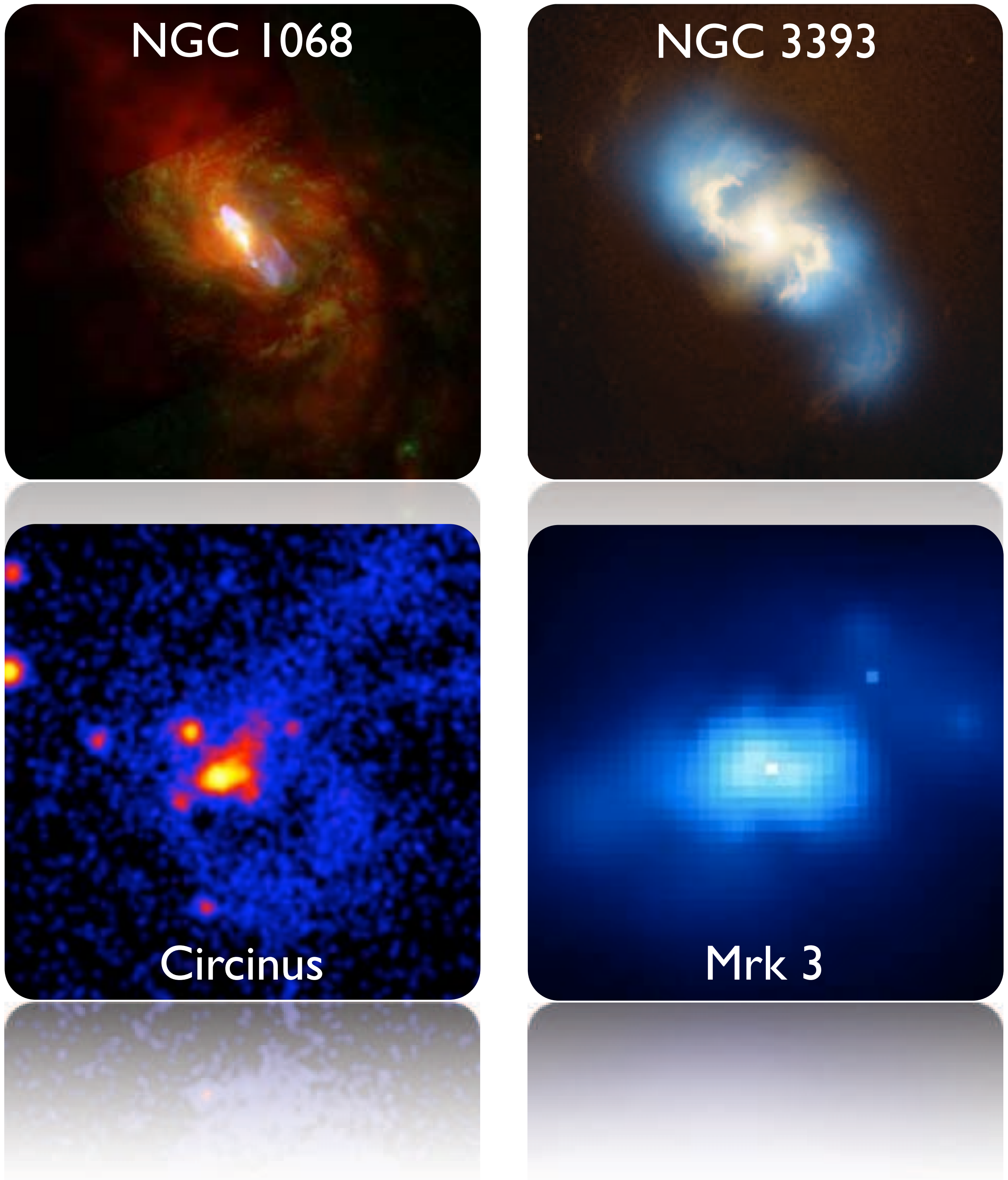
Survey of Outflows in AGN with Resolved Spectroscopy

- First spatially resolved X-ray gratings study of kpc-scale NLR environments in type-2 AGN
- 1.9 Ms granted over multiple AOs (GO+GTO+Archival)

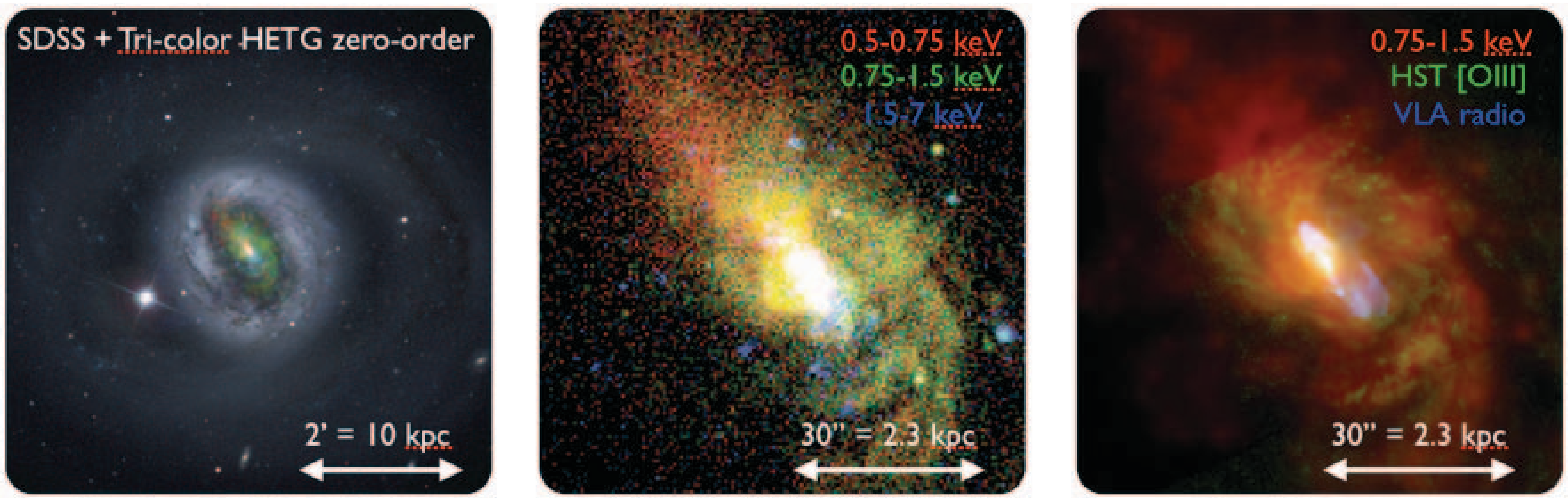
1. Spectroscopically disentangle collisional and photoionization
2. Measure velocity offsets
3. Determine how far AGN outflows propagate

The Chandra SOARS Project



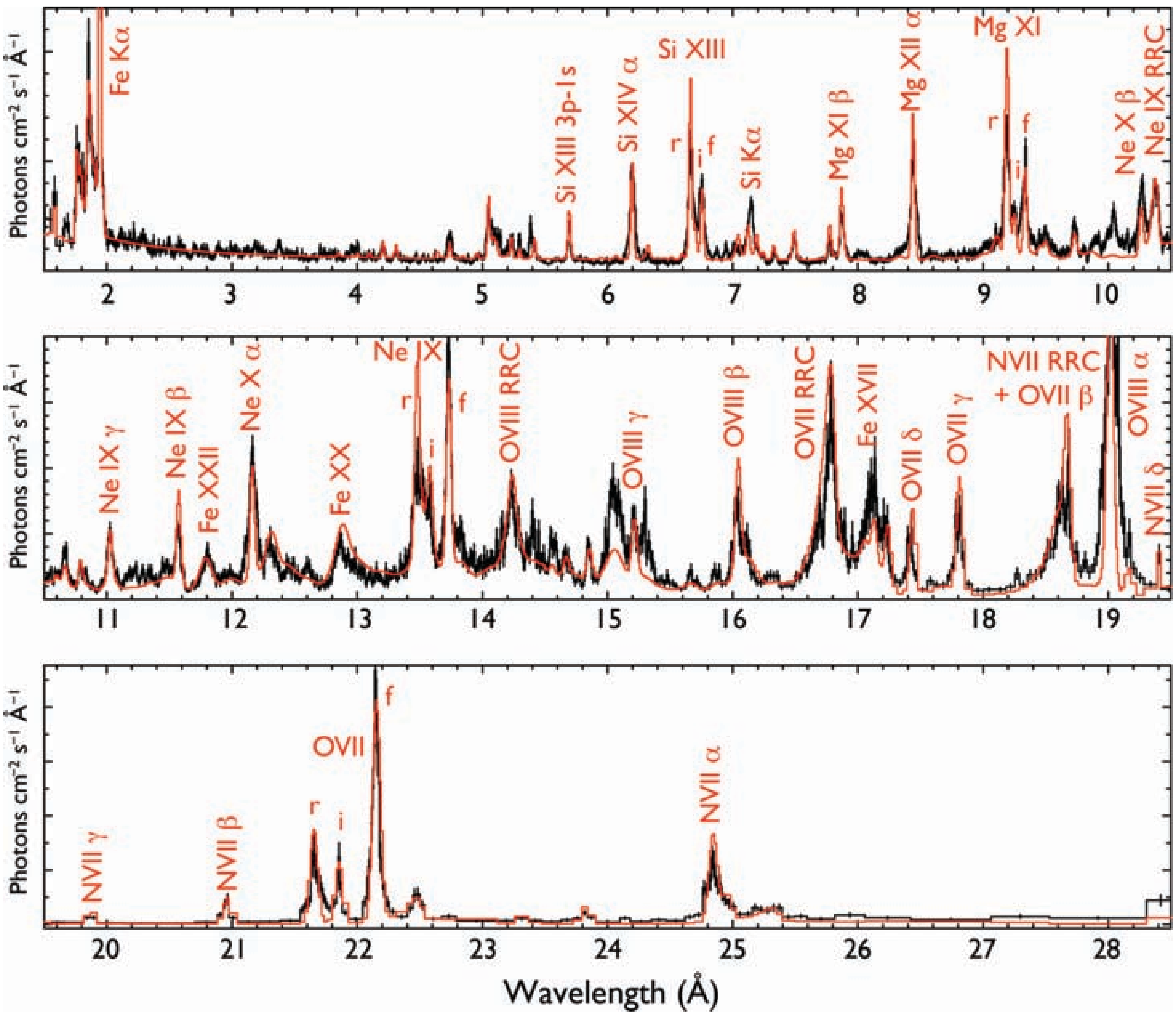
- **NGC 1068 (440 ks)**
  - $N_H > 10^{25}\ cm^{-2}$ (Evans et al. 2010)
  - HST: Das, Crenshaw & Kraemer (2007)
- **NGC 3393 (350 ks)**
  - Binary BH (Fabbiano et al. 2011)
  - $N_H \sim 2x10^{24}\ cm^{-2}$ (Fukazawa et al. 2011)
  - HST: Cooke et al. (2000)
- **Circinus (695 ks)**
  - $N_H \sim 2x10^{24}\ cm^{-2}$ (Yang et al. 2008)
- **Mrk 3 (400 ks)**
  - $N_H \sim 1.1x10^{24}\ cm^{-2}$ (Awaki et al. 2007)
  - HST: Crenshaw et al. (2010)

The Prototypical Example - a 440-ks Chandra HETG GTO Observation of NGC 1068 (Evans et al. 2011)



- Nearby: z = 0.003793, D_L = 16.3 Mpc, 1" = 80 pc ✔
- Compton-thick Seyfert 2 ($N_H > 10^{25}$ cm^{-2}) ✔
- Late type host galaxy ✔
- Black hole mass ~ 10^7 $M_\odot$ (e.g., Ludato et al. 2002) ✔
- Accreting at or near Eddington limit (e.g., Kishmoto et al. 1999) ✔
- Prominent kpc-scale radio jet ✔

NGC 1068 - A Purely Photoionized + Photoexcited Plasma

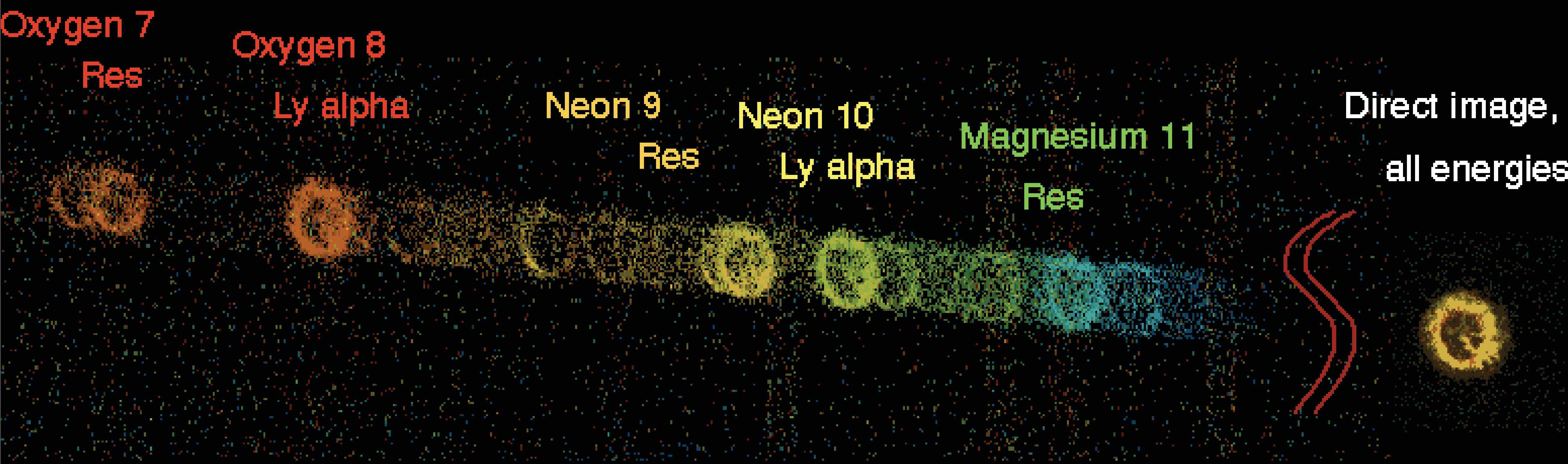


Evans et al. (2011); see also Kinkhabwala et al. (2002); Brinkman et al. (2002); Ogle et al. (2003); new work by Neetika Sharma

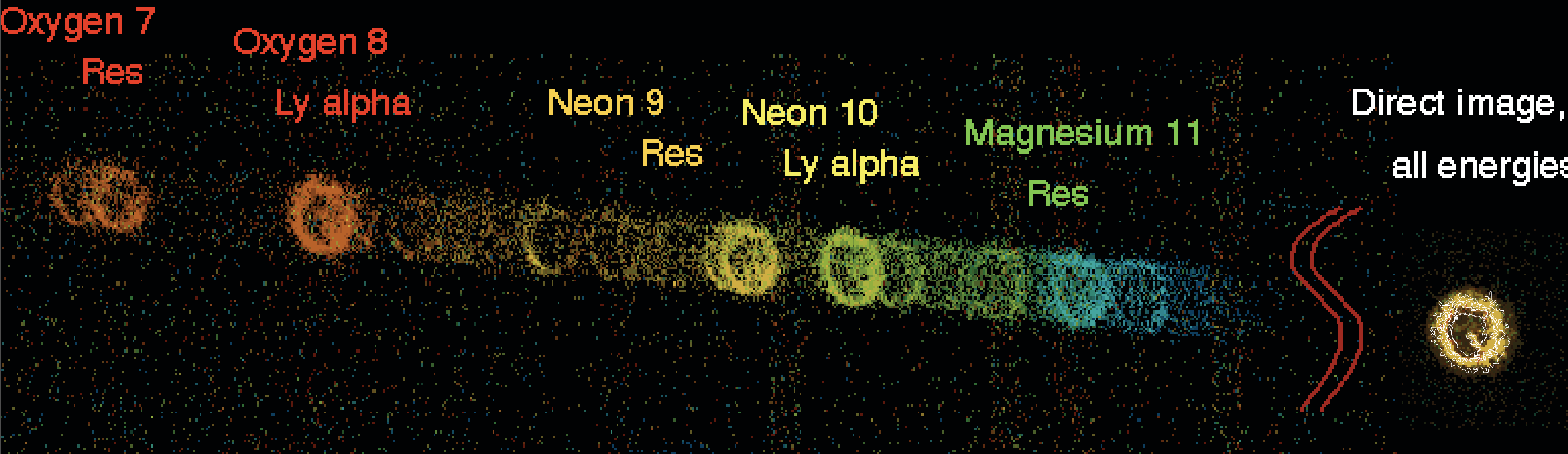
Ion	$N^{\rm rad}_{\rm ion}$ (cm^{-2})	kT_e[a] (eV)	EM[b] ($\times 10^{64}$ cm^{-3})
C v	8E17	2.5	6.7
C vi	9E17	4.0	1.8
N vi	6E17	3.0	6.5
N vii	6E17	4.0	1.7
O vii	1.1E18	4.0	1.5
O viii	1E18	4.0	0.32
Ne ix	3E17	*4*	*0.42*
Ne x	2.5E17	*4*	*0.097*
Mg xi	2E17	*4*	*0.31*
Mg xii	2E17	*4*	*0.092*
Si xiii	2E17	*4*	*0.13*
Si xiv	2E17	*4*	*0.042*

Spectral-Line Imaging

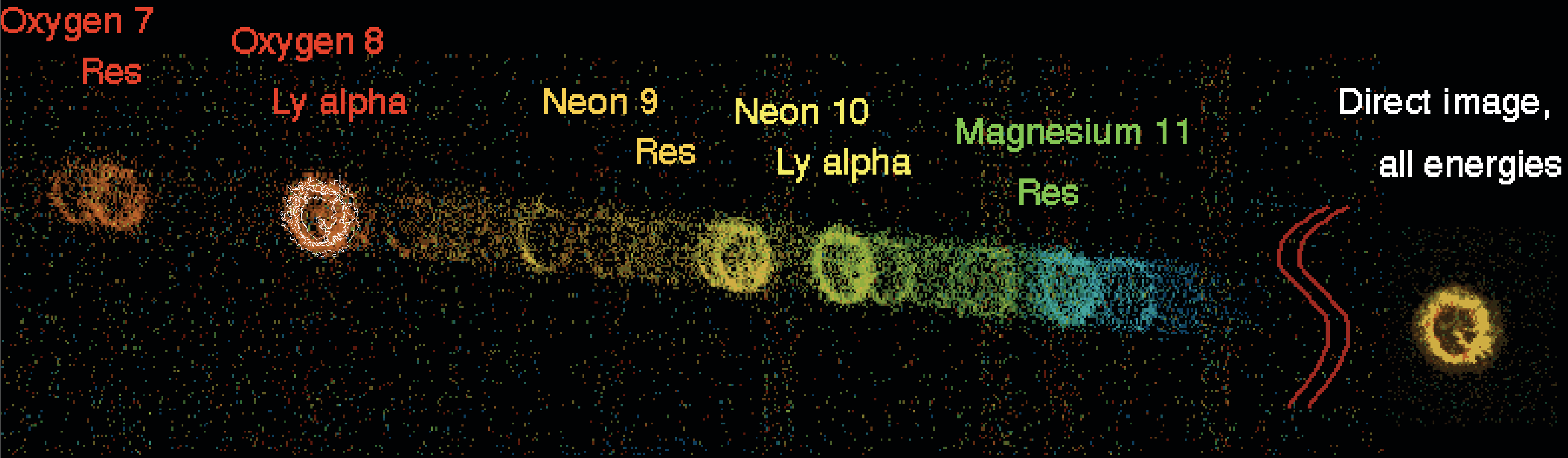
Spectral-Line Imaging



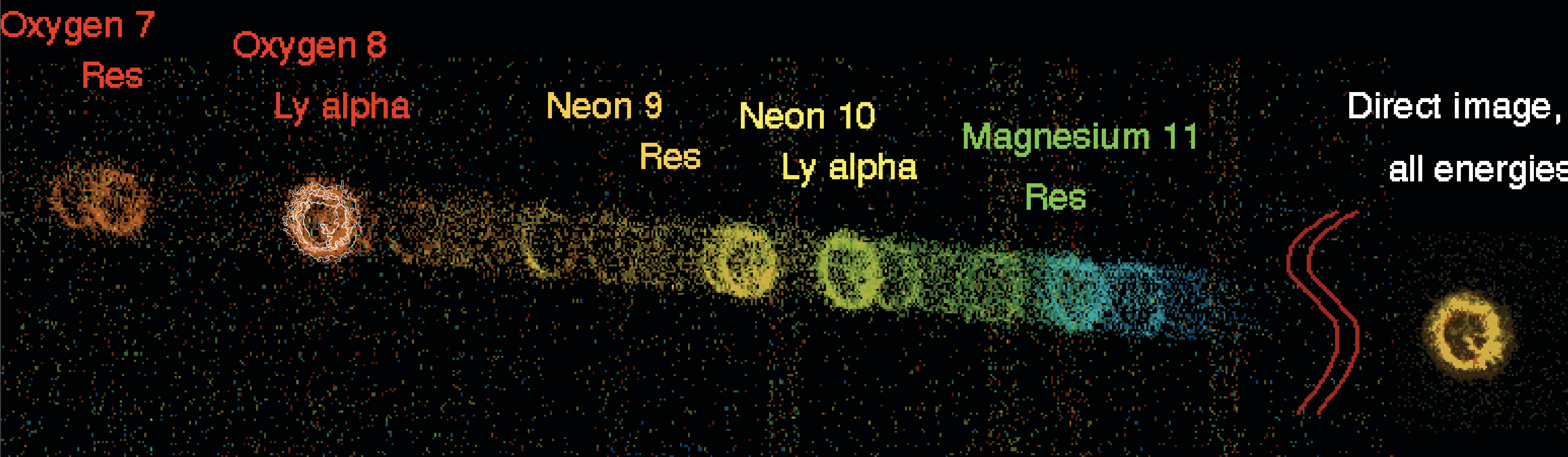
Spectral-Line Imaging

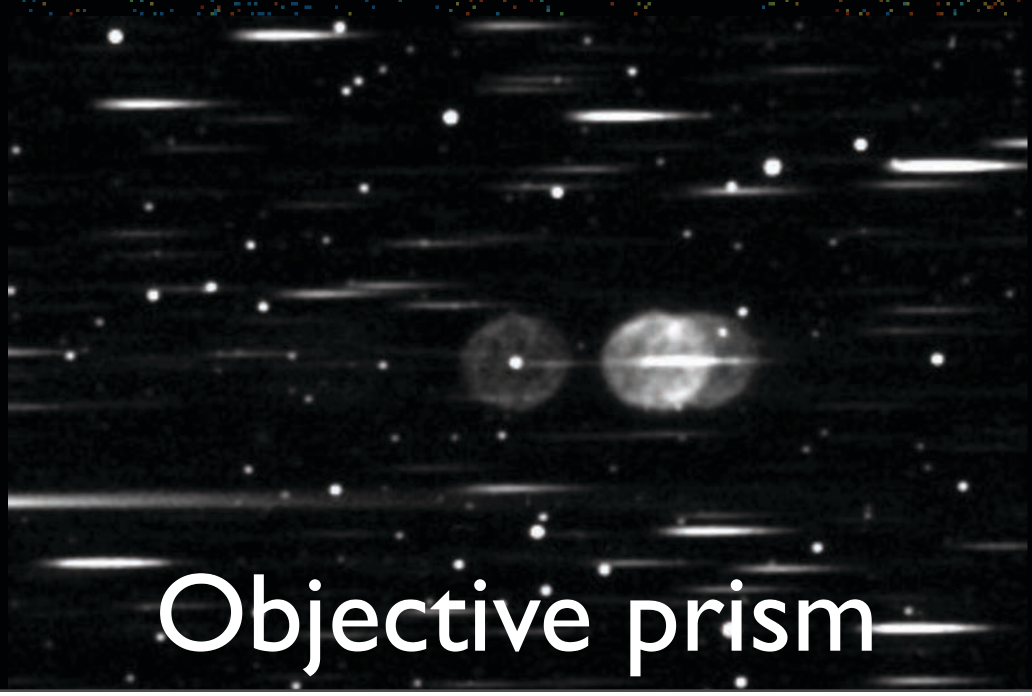


Spectral-Line Imaging

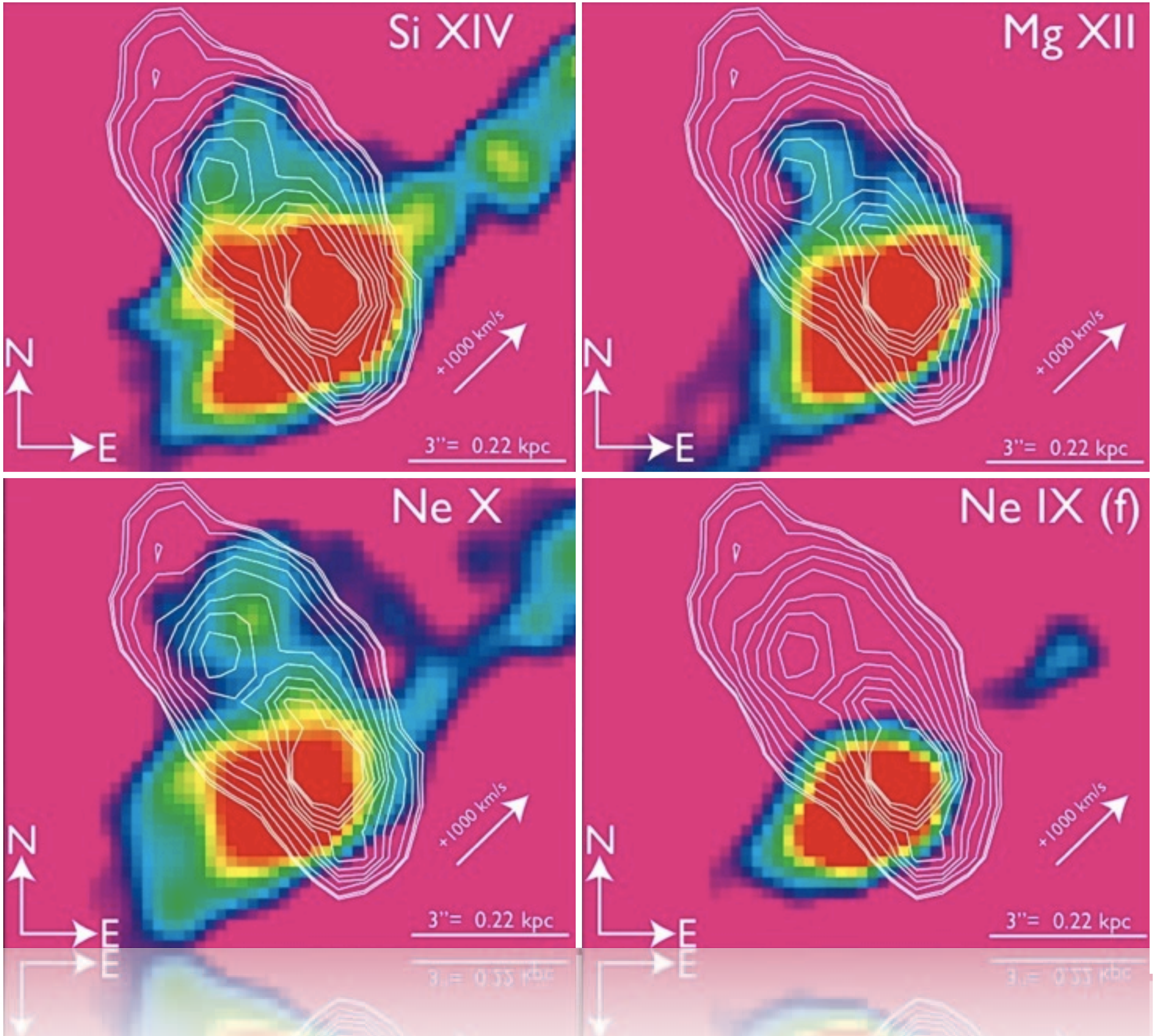


Spectral-Line Imaging

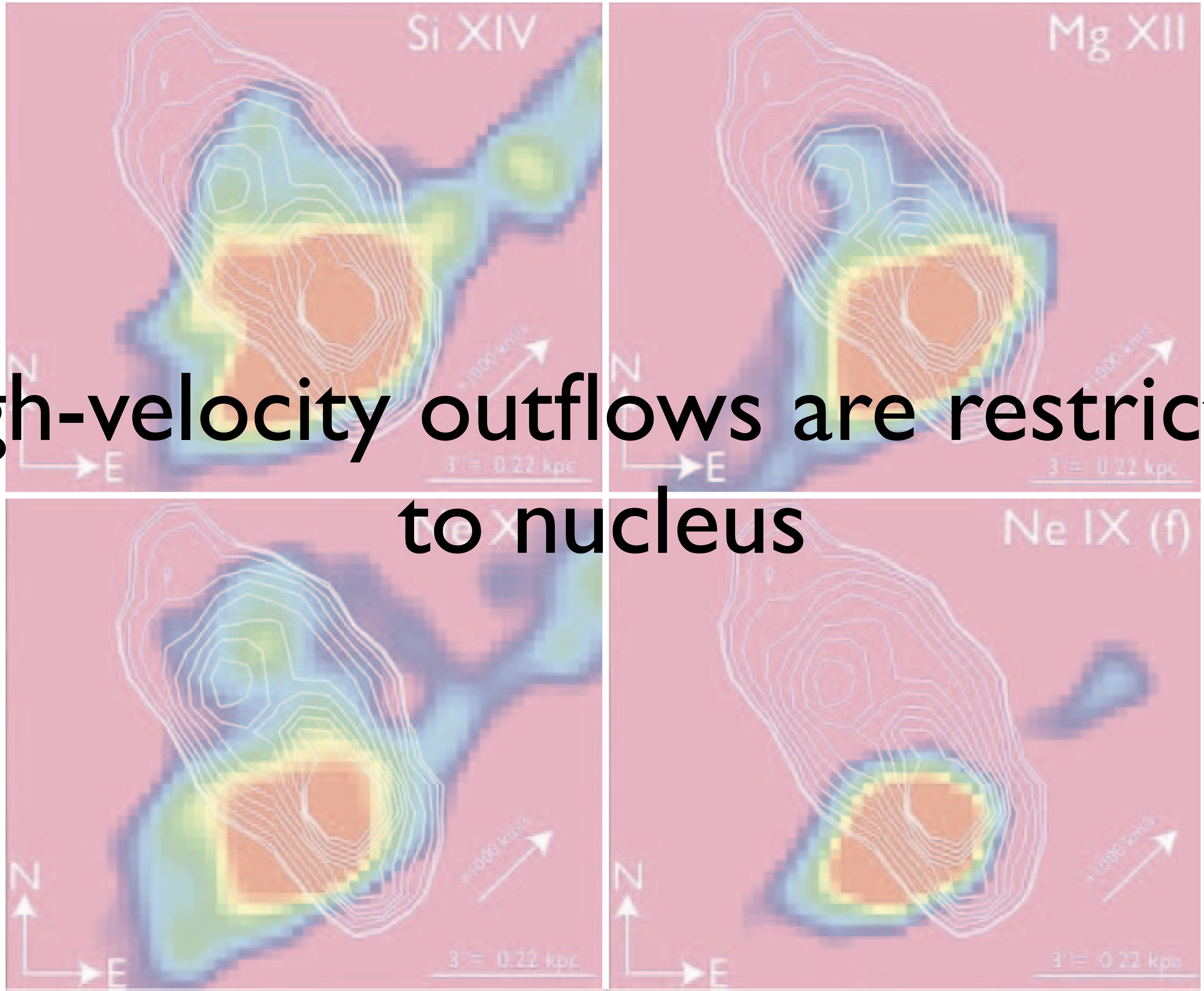




Spectral-Line Imaging

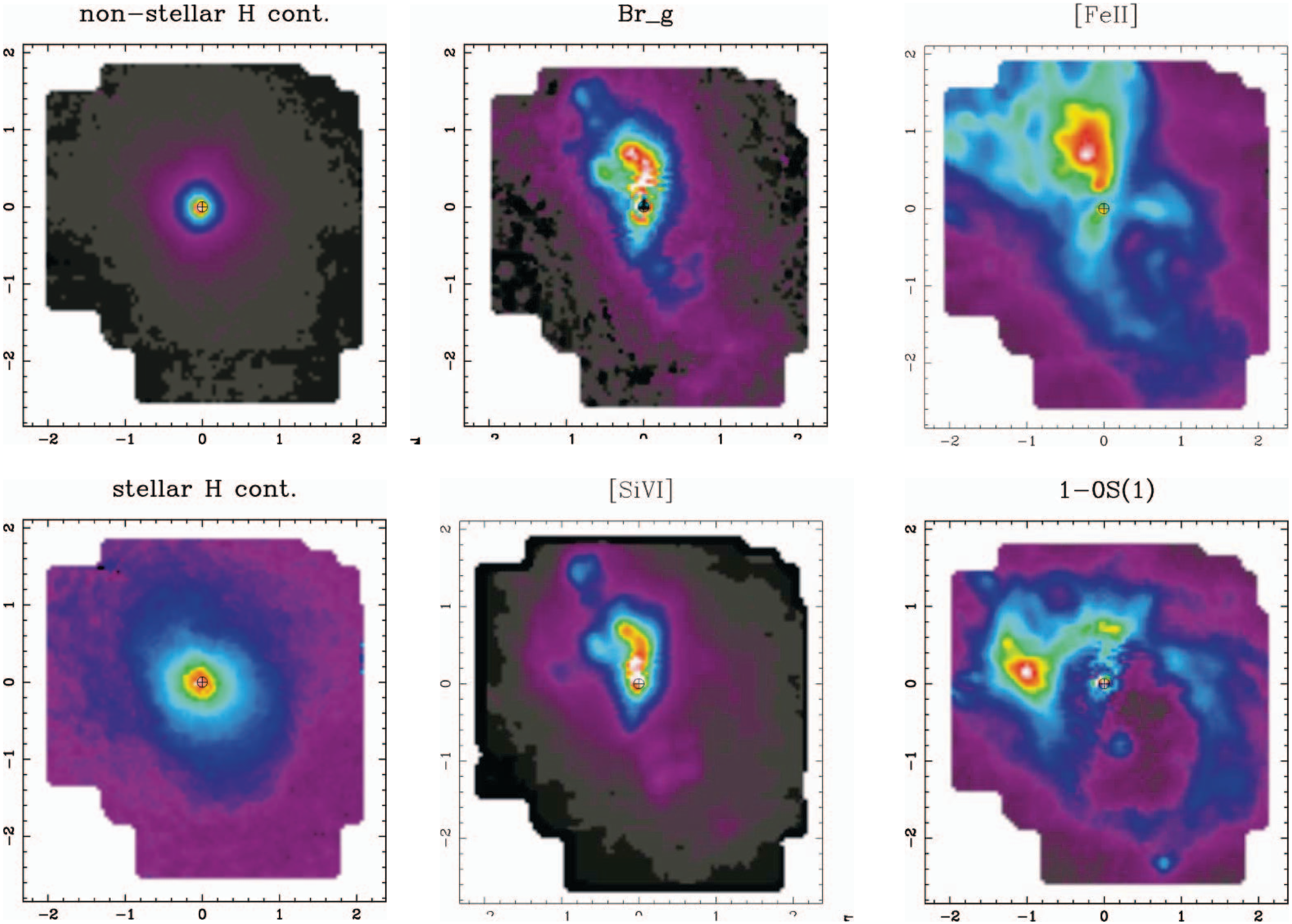


Spectral-Line Imaging



High-velocity outflows are restricted to nucleus

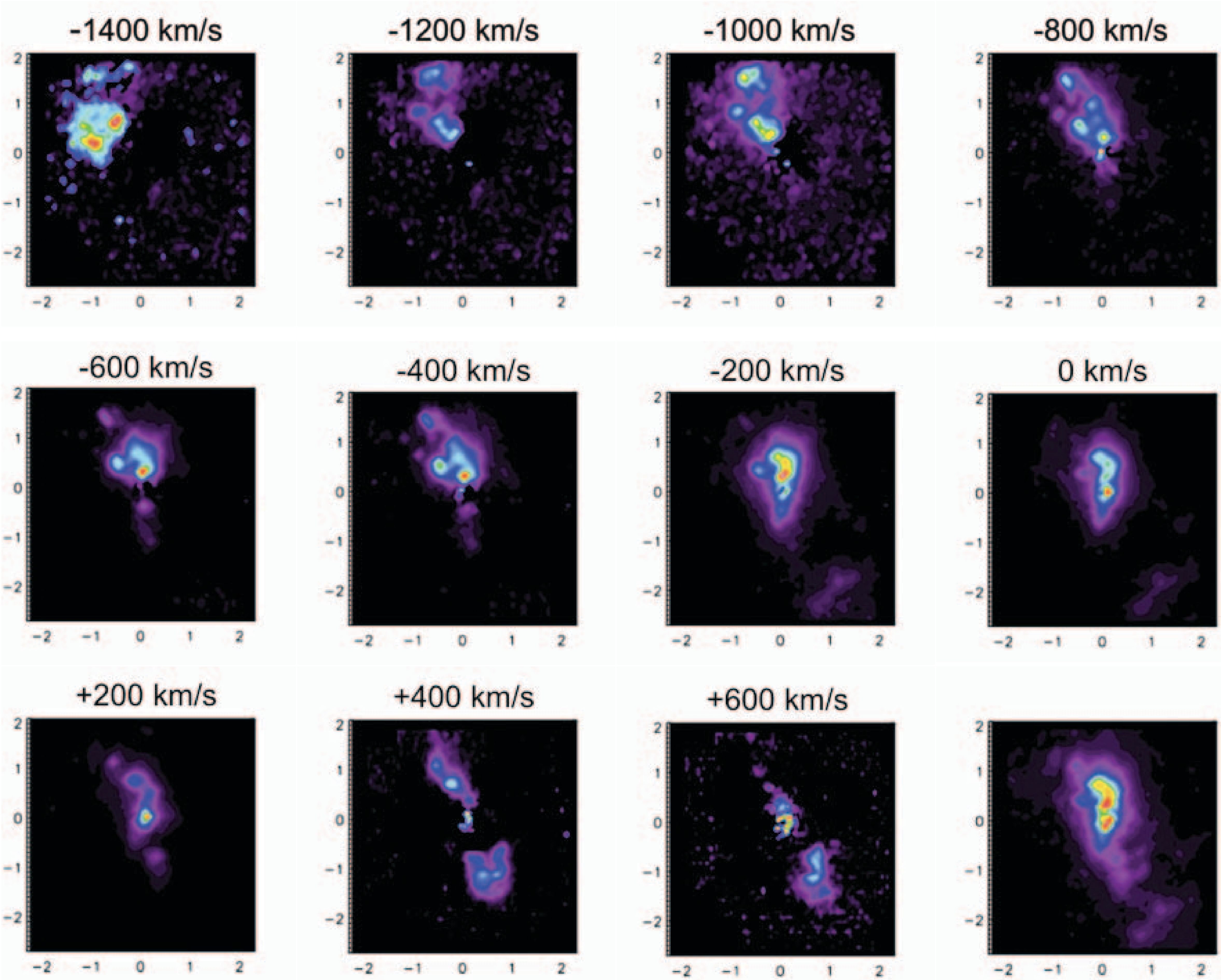
NGC 1068: SINFONI Maps



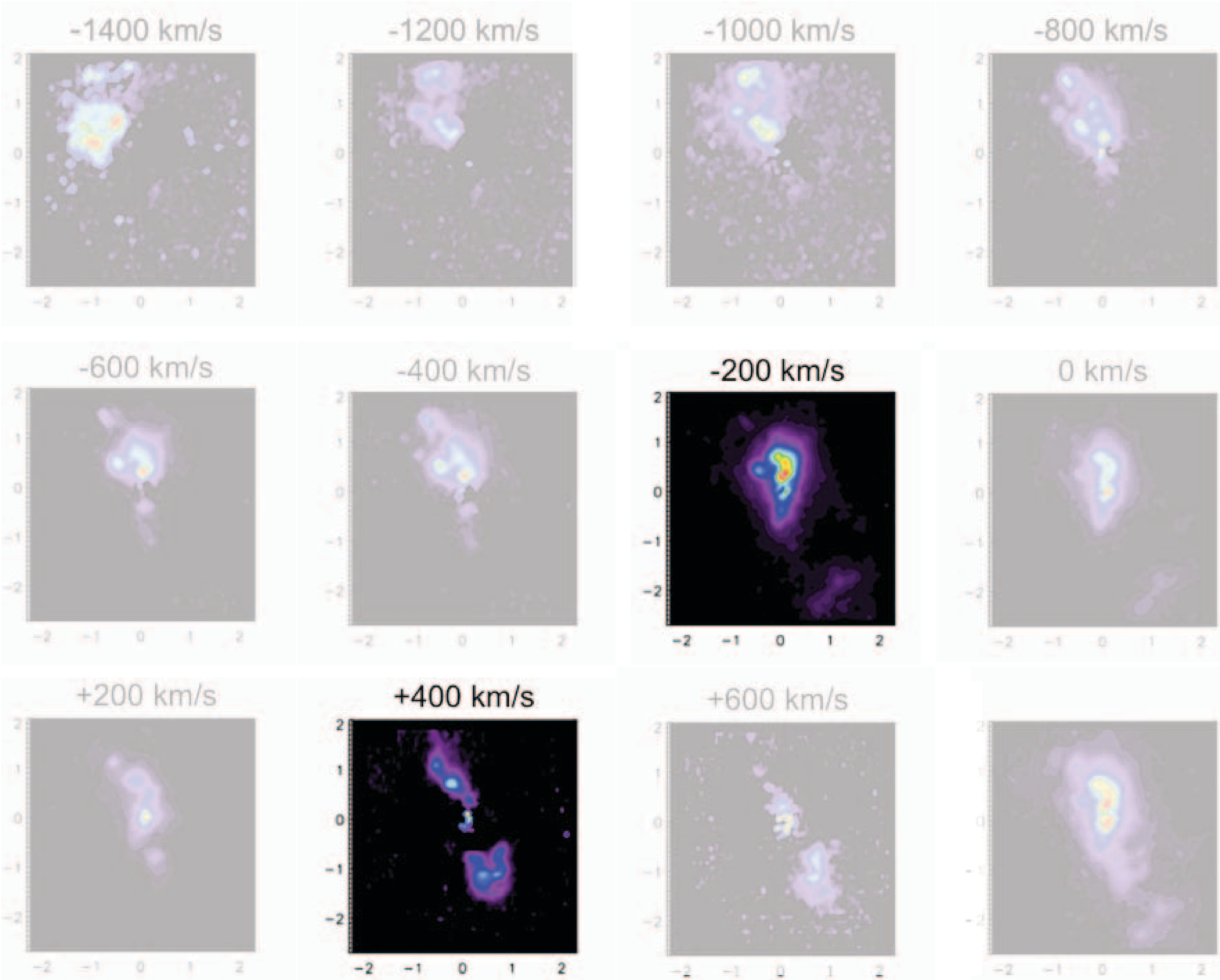
scales are in arcsec; the AGN location is marked at (0,0)

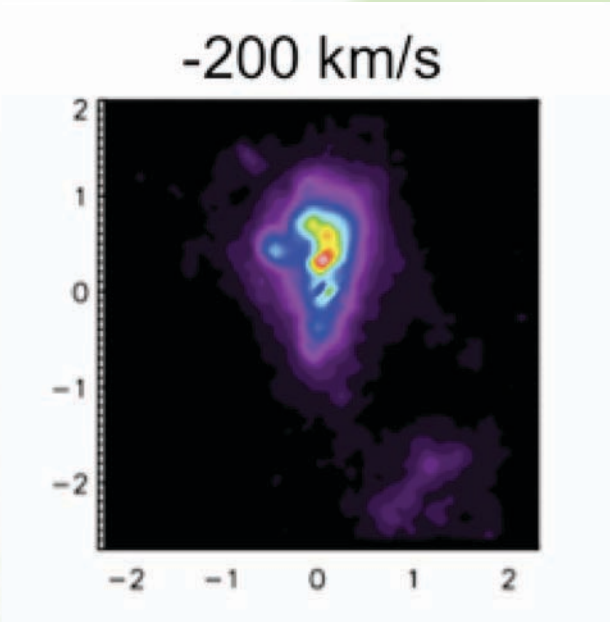
[Al IX] & [Ca VIII] are similar to [SiVI]

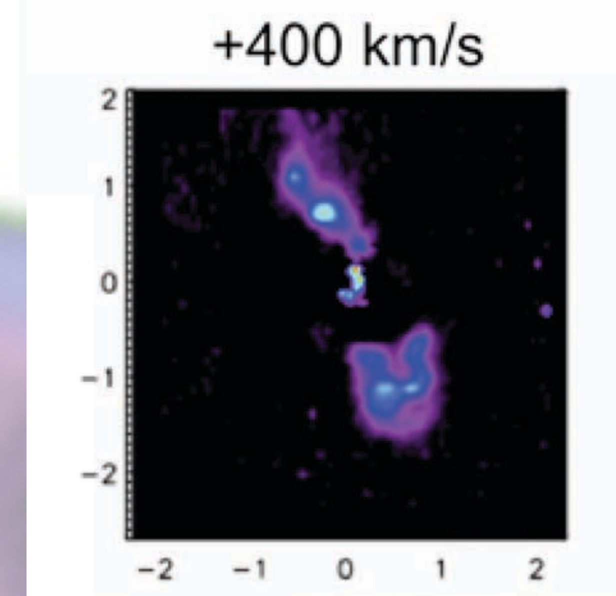
Muller-Sanchez et al. (2011)



Muller-Sanchez et al. (2011)

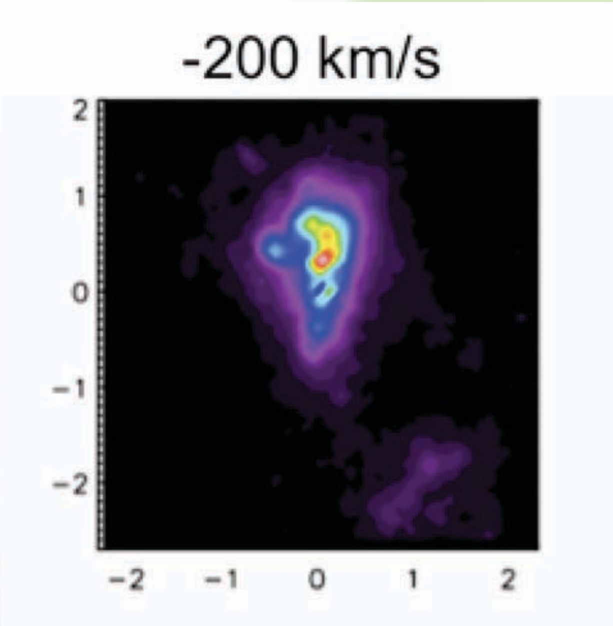

-1400 km/s
-1200 km/s
-1000 km/s
-800 km/s
-600 km/s
-400 km/s
-200 km/s
0 km/s
+200 km/s
+400 km/s
+600 km/s

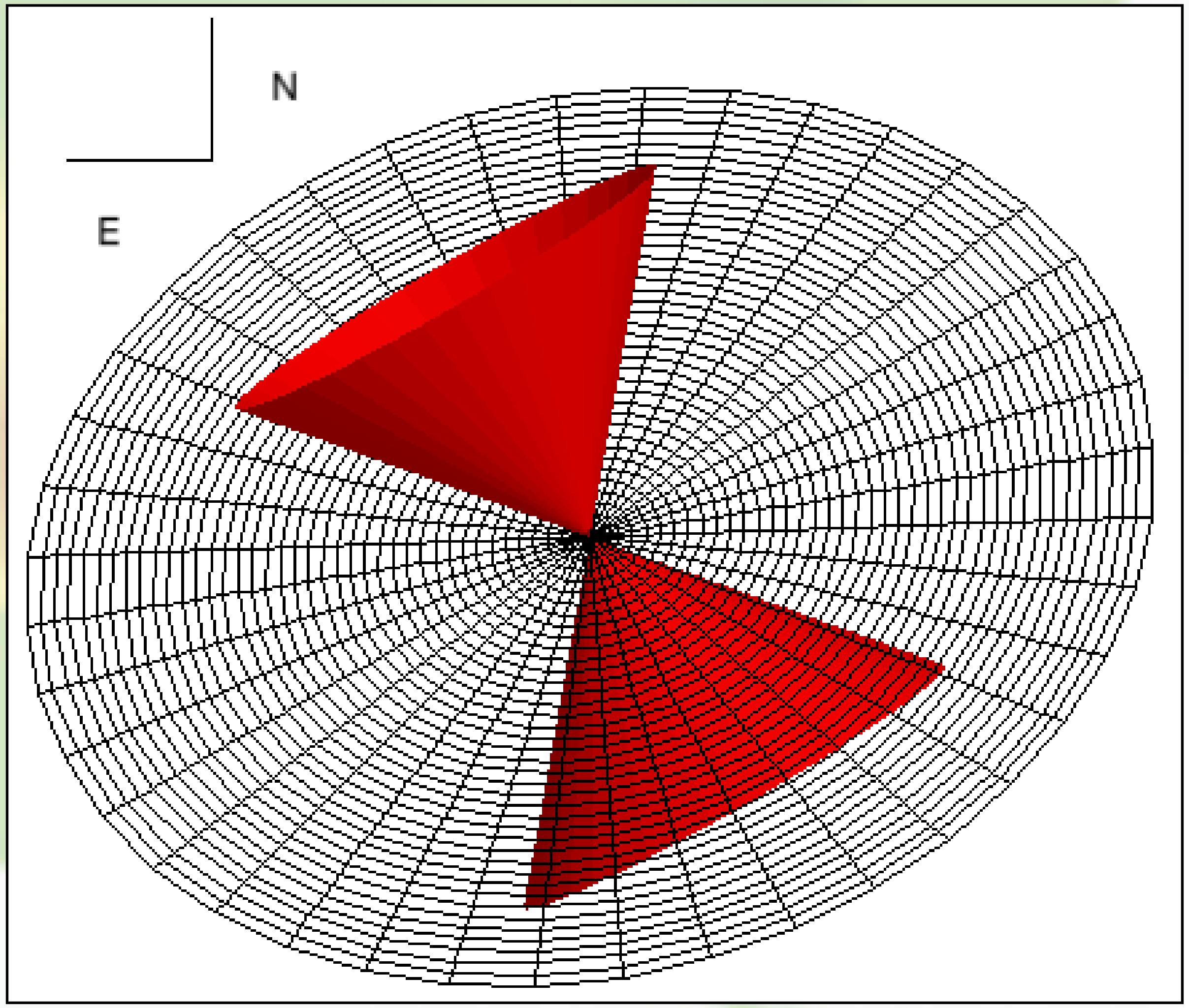




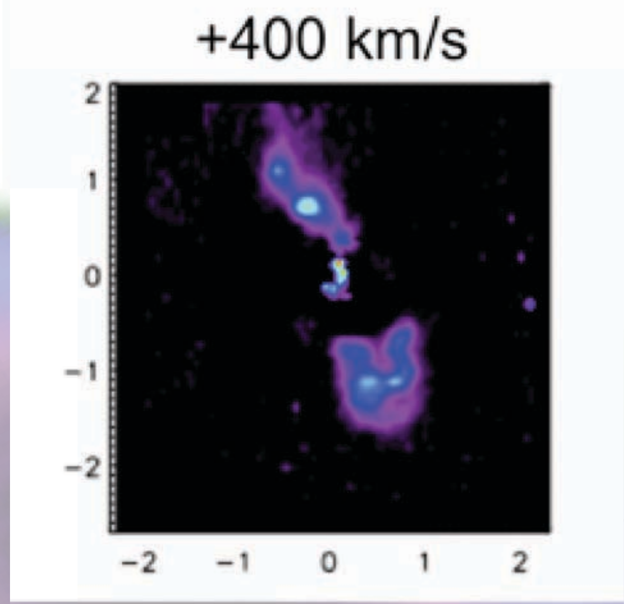
Mass loss rate ~ $9M_{\odot}$/yr

GMOS Program posters by A. Muller on NGC 2110 (Poster 4.1), G. Couto on Arp 102B (Poster 4.2), talk by Thaisa Storchi Bergmann tomorrow at 2pm.





Das, Crenshaw & Kraemer (2006, 2007); Crenshaw et al. (2010)



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Low vs. High Ionization Maps

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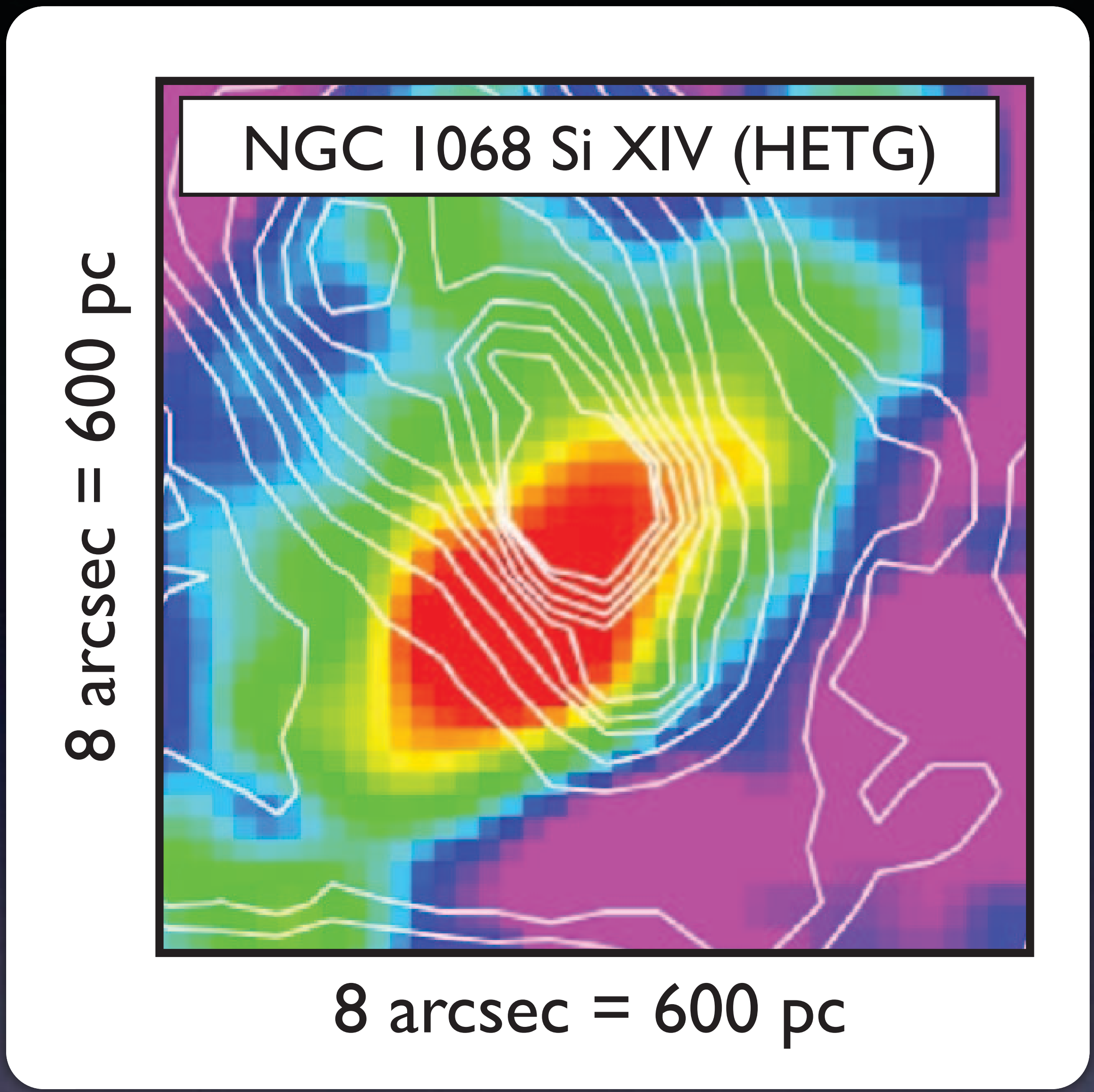
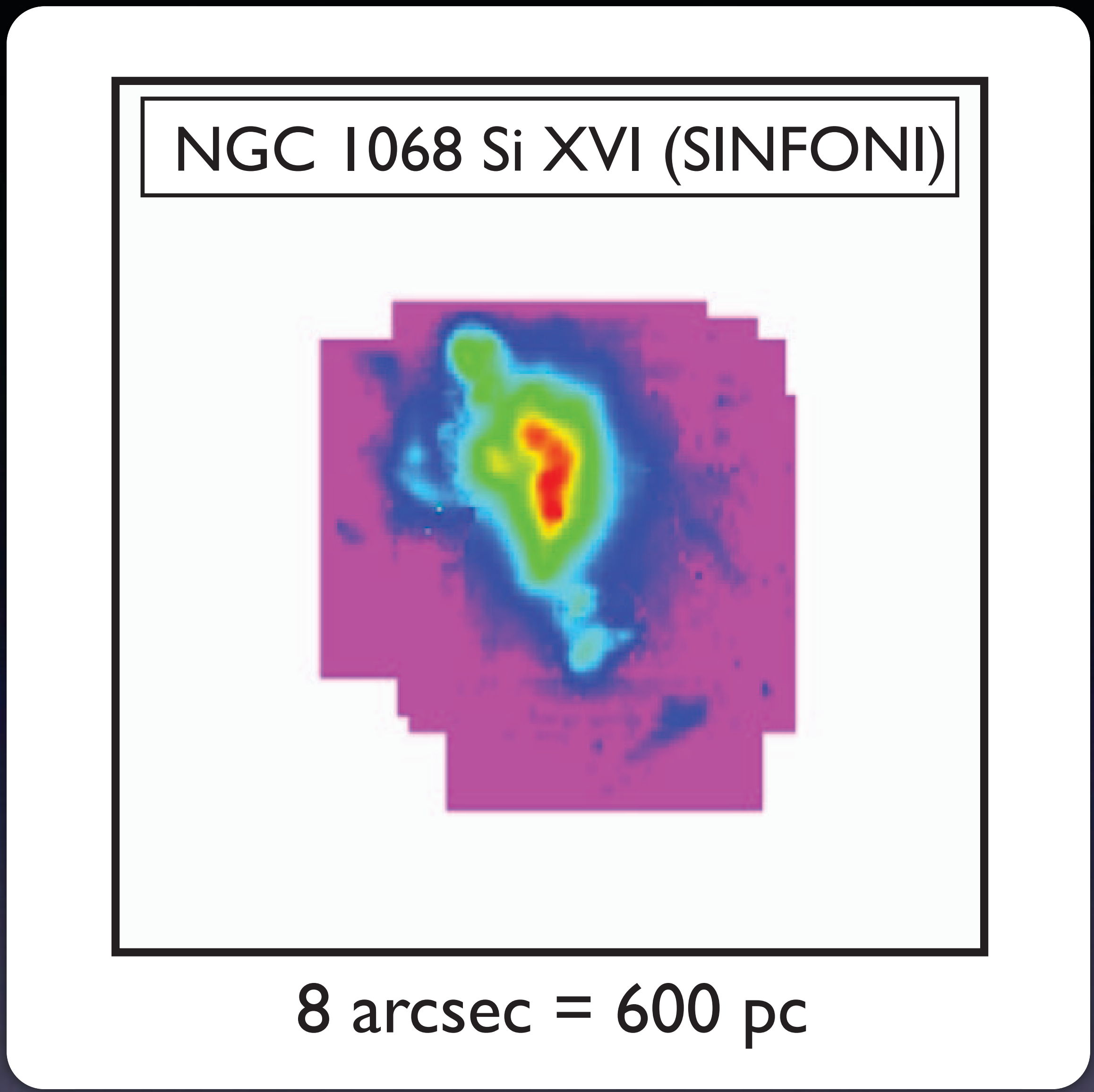
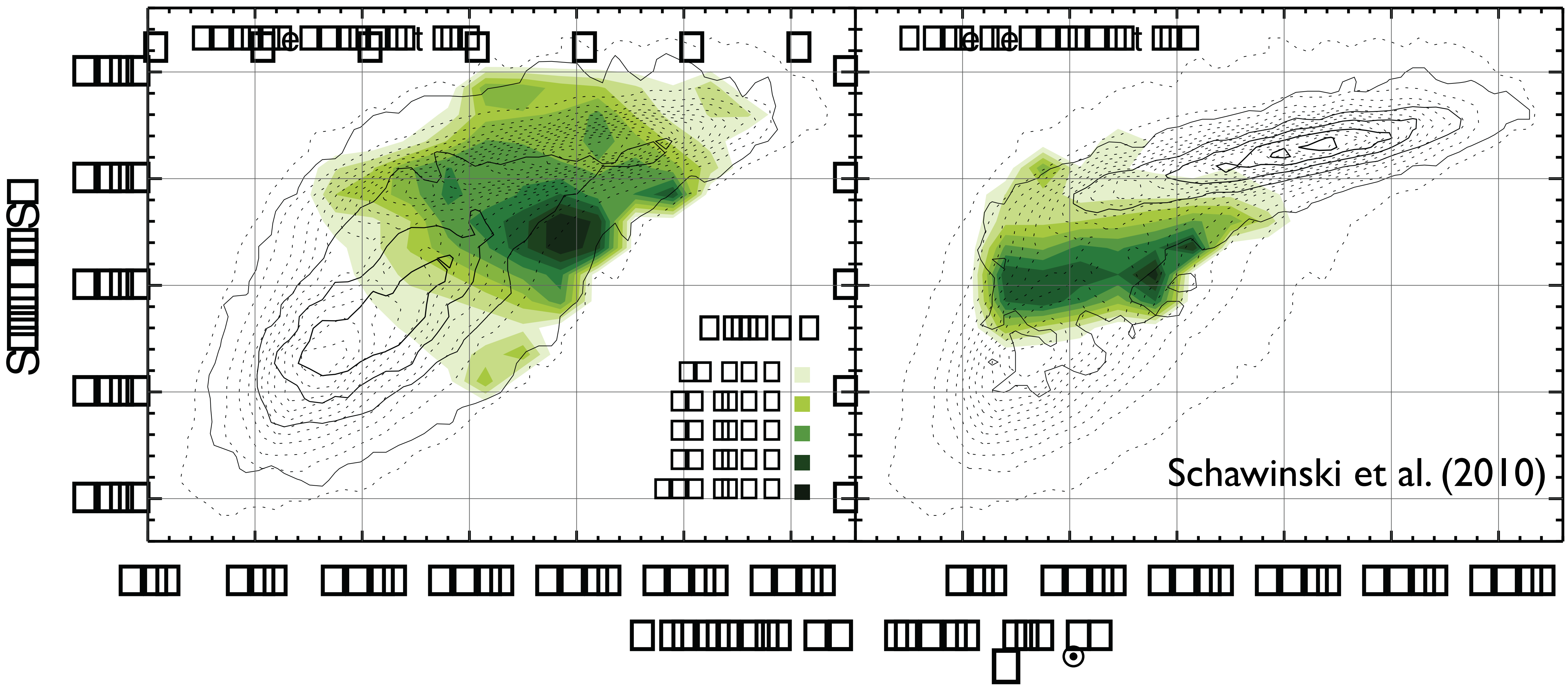




SOARS Synergies with Optical Surveys

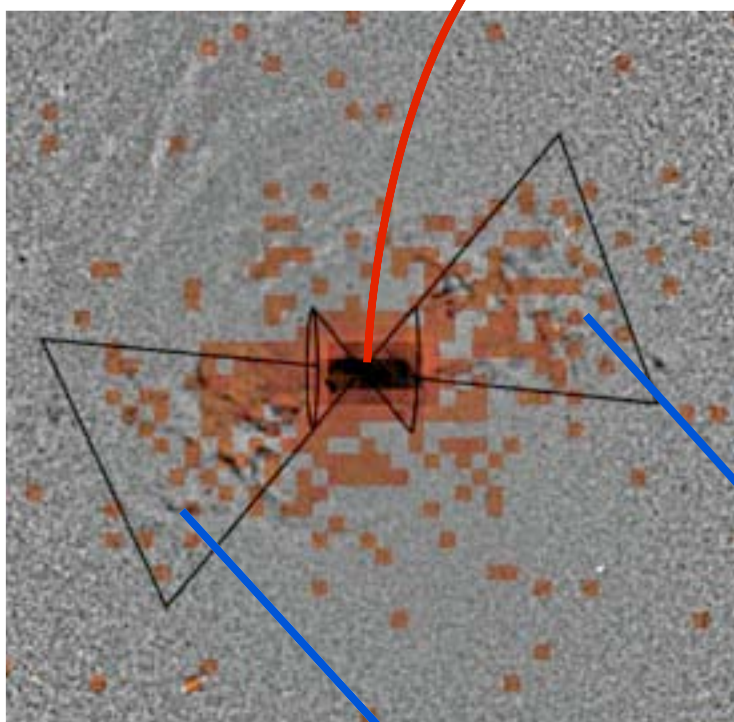


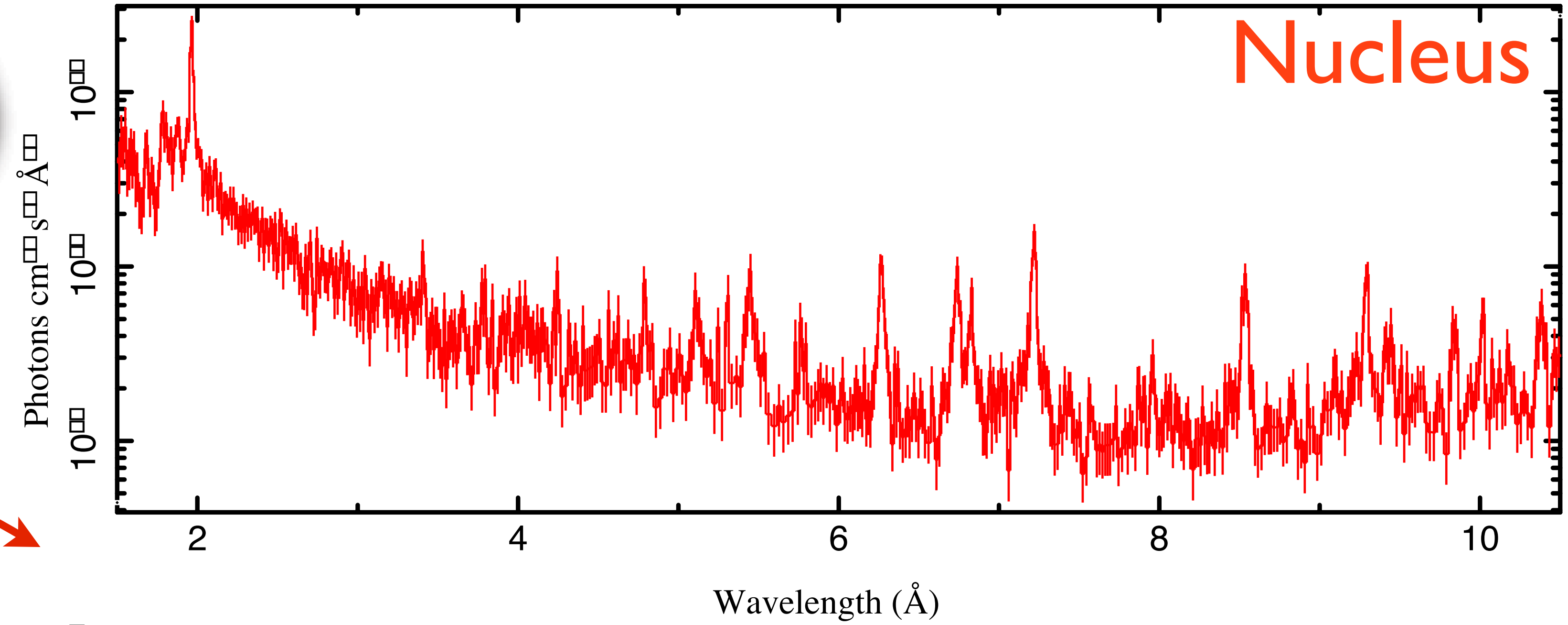
Early-type AGN are **genuinely migrating at fixed mass from the blue cloud to the low mass end of the red sequence**

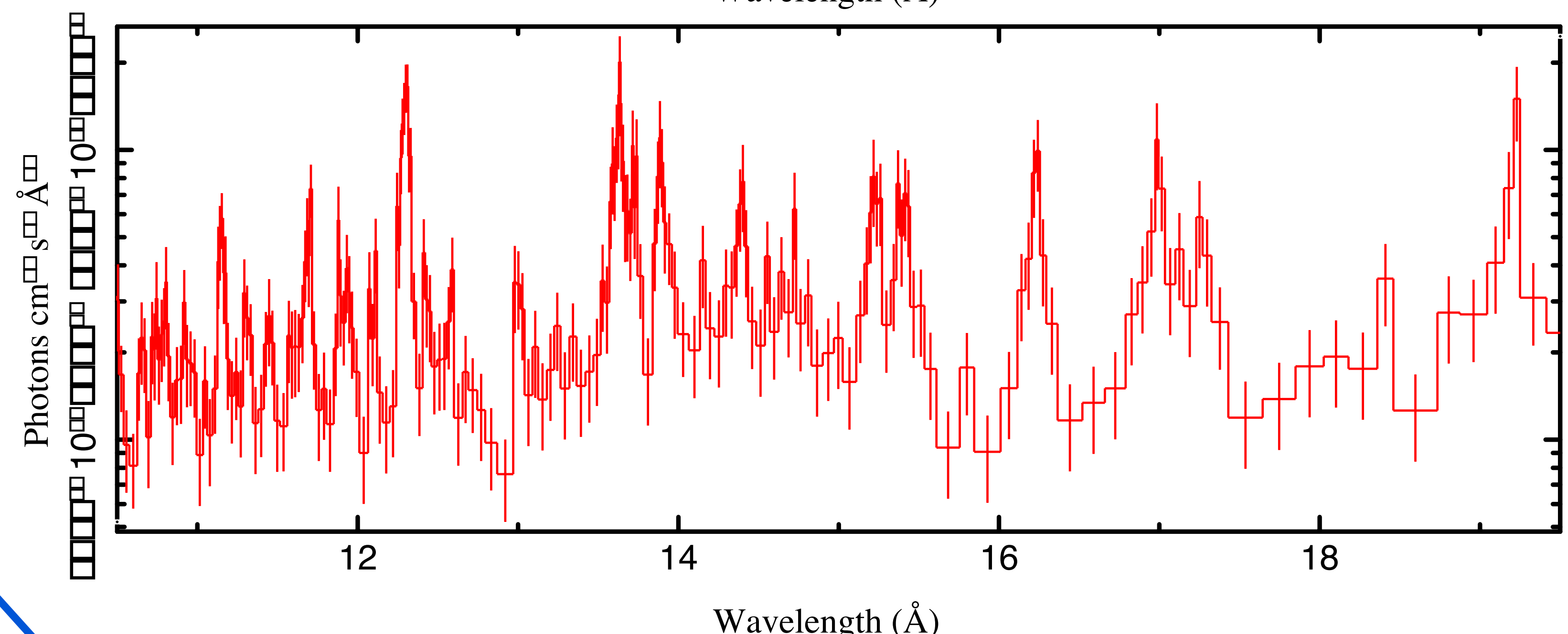
Late-type AGN have massive, highly stable stellar disks. Green host galaxy colors are **unlikely to be due to outflows**

Mrk 3 (400 ks)

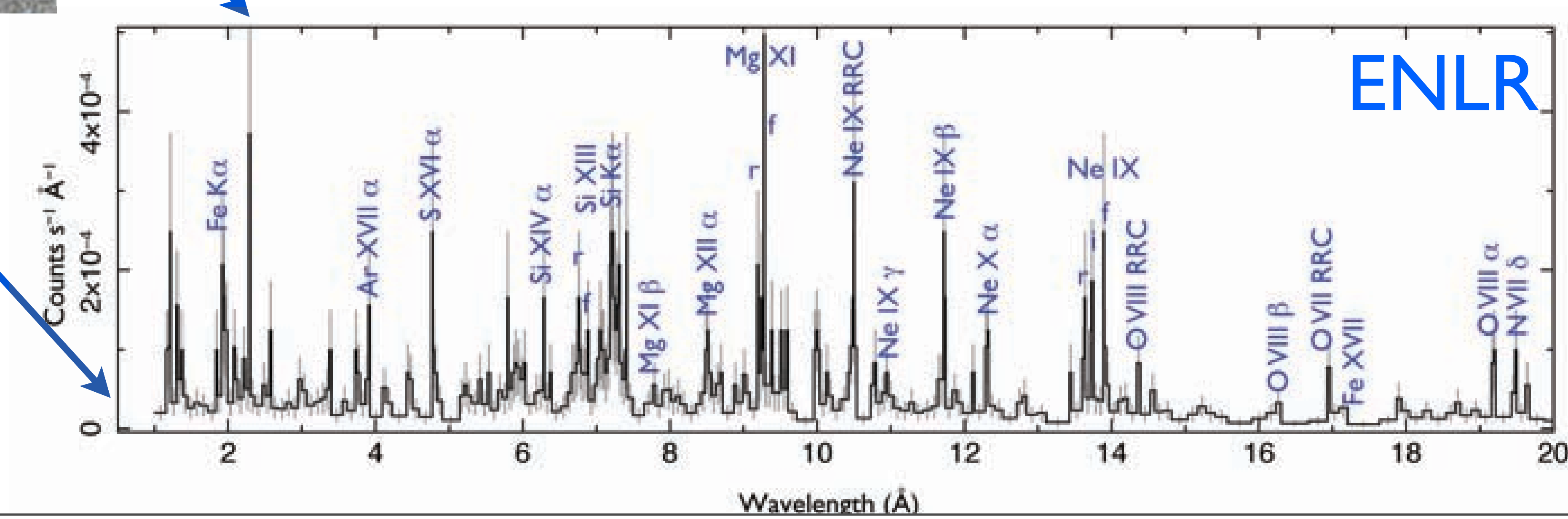
The Prototypical Early-Type Seyfert 2

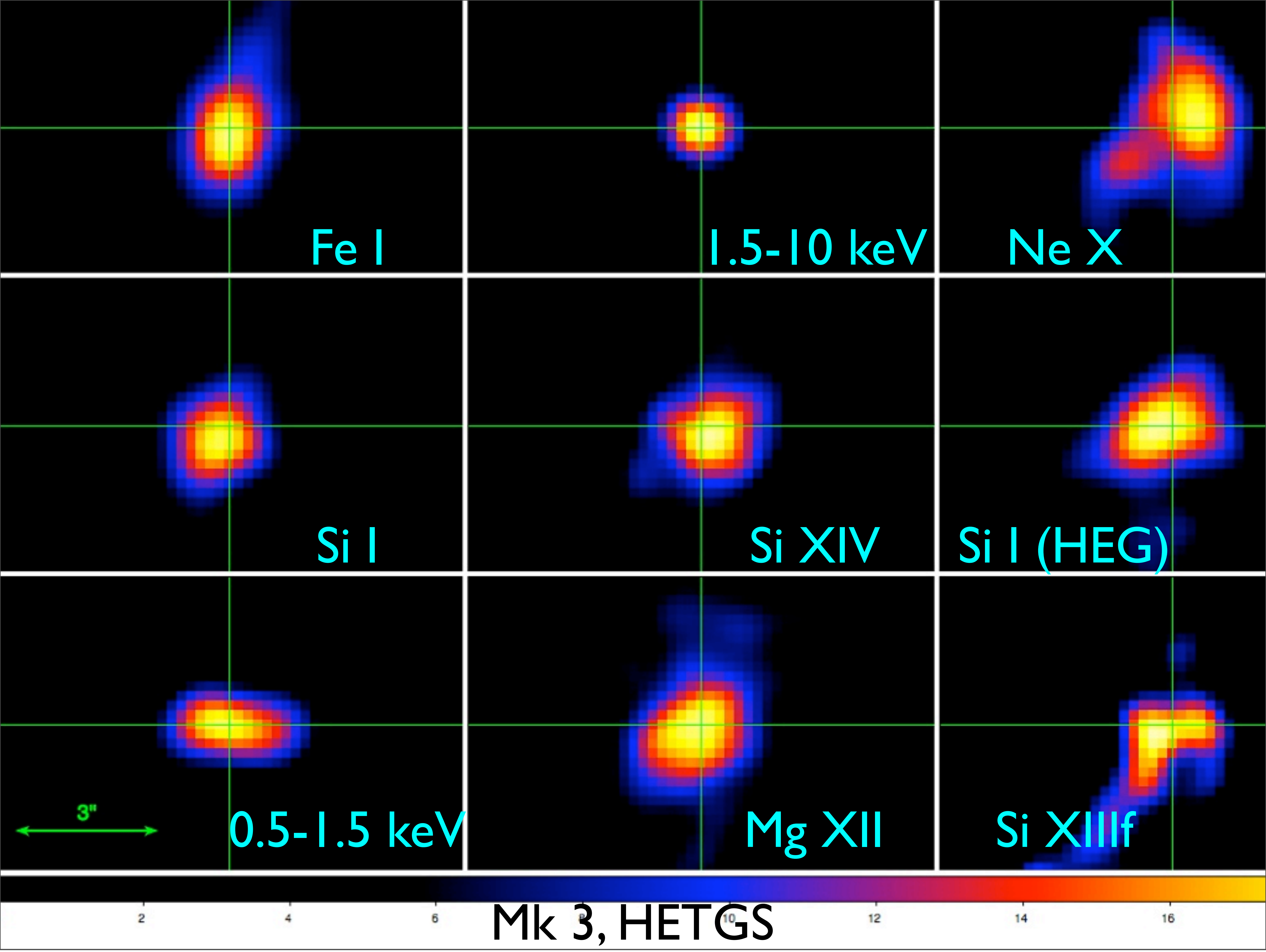




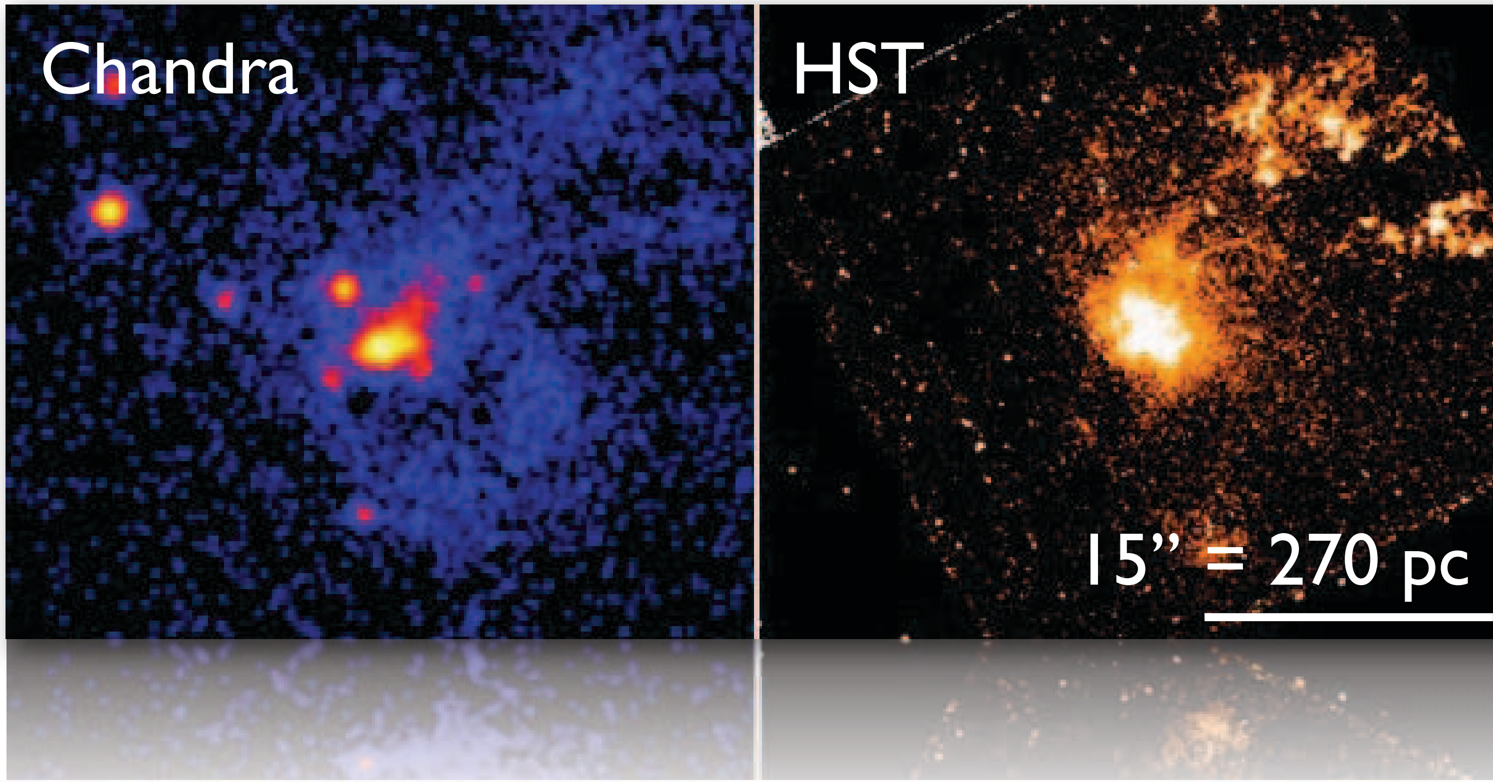


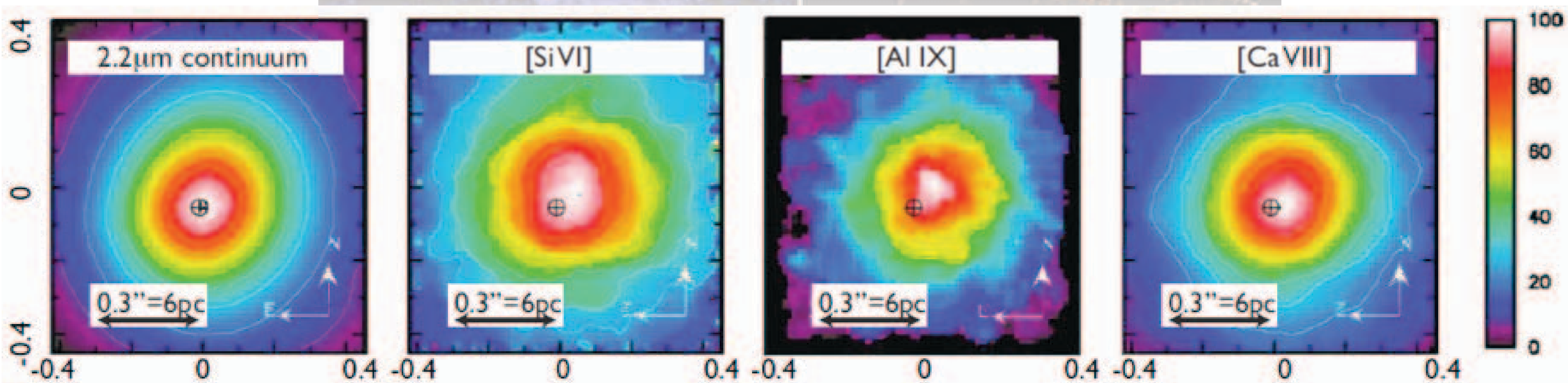
HST structure map
(H. Schmitt)
+
Bicone geometry
(Crenshaw et al. 2010)
+
0.5-2 keV X-ray




Fe I
1.5-10 keV
Ne X
Si I
Si XIV
Si I (HEG)
3"
0.5-1.5 keV
Mg XII
Si XIIIf
2
4
6
8
10
12
14
16
Mk 3, HETGS

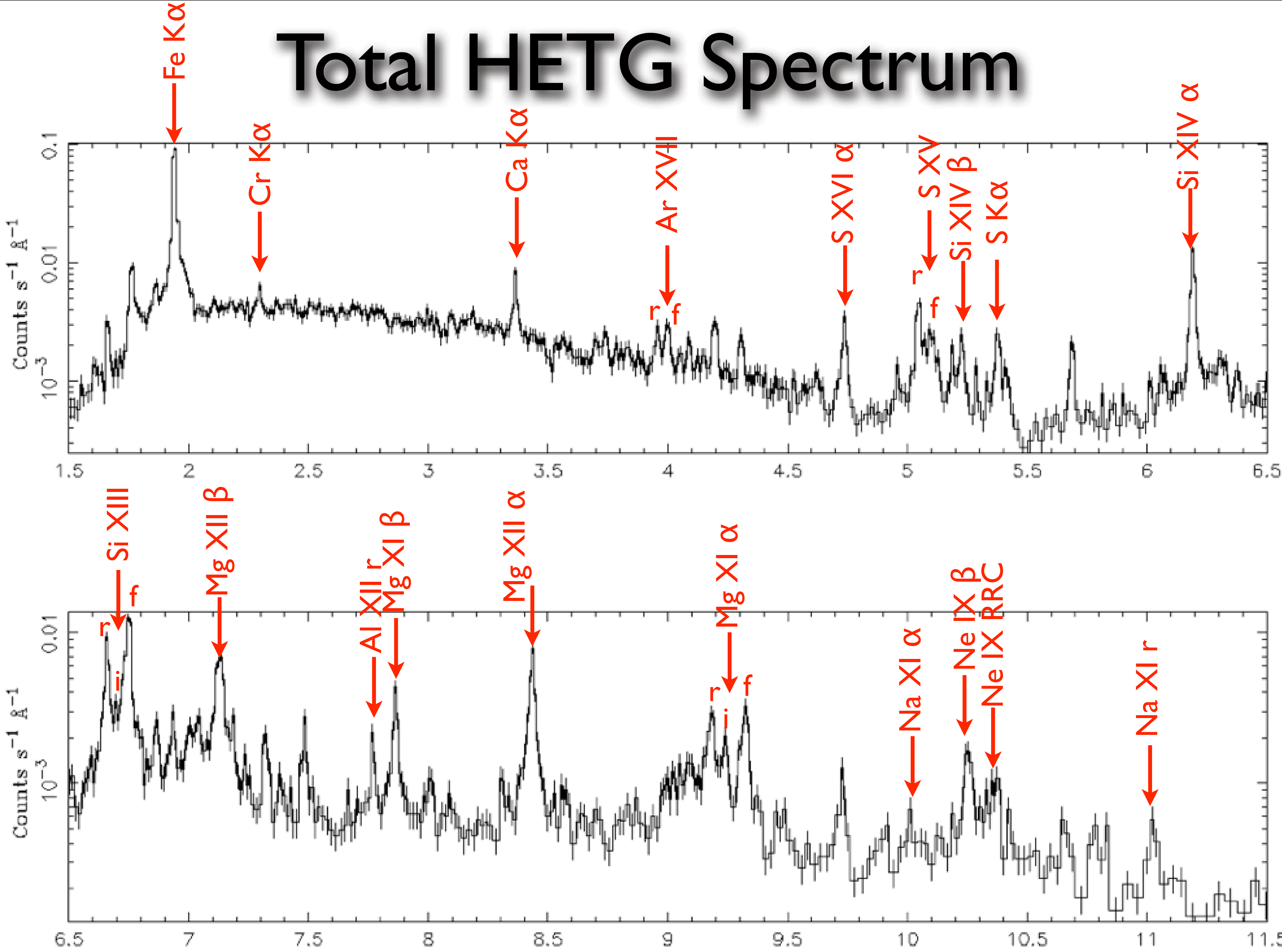
Circinus Galaxy (695 ks)

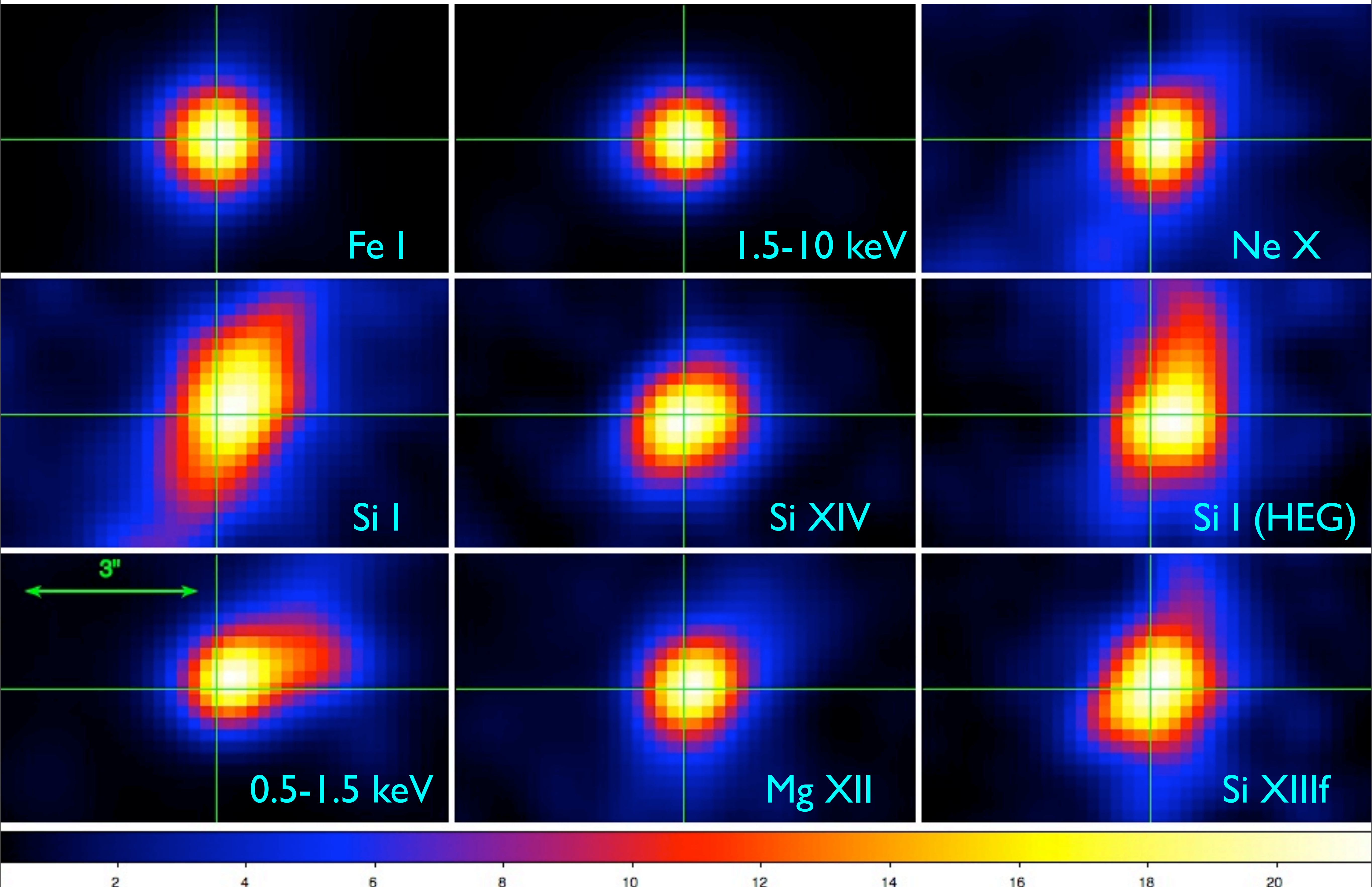




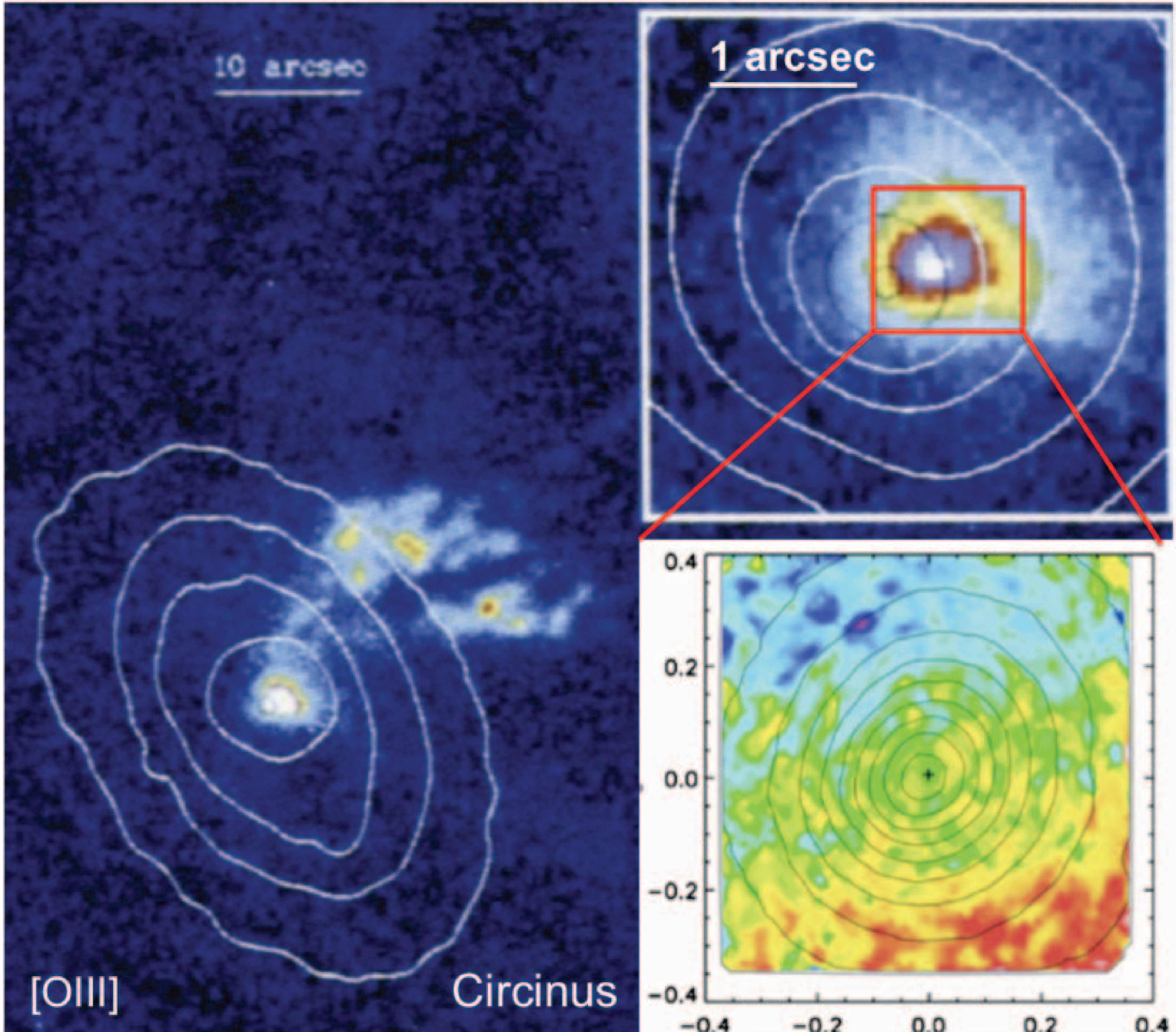
Mueller-Sanchez et al. (2006, 2011)

Total HETG Spectrum

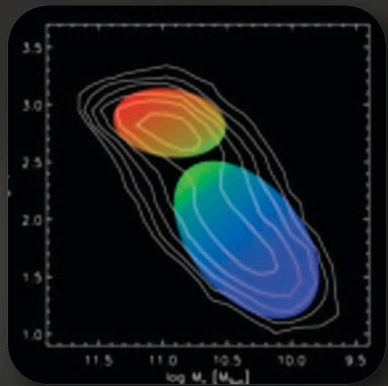


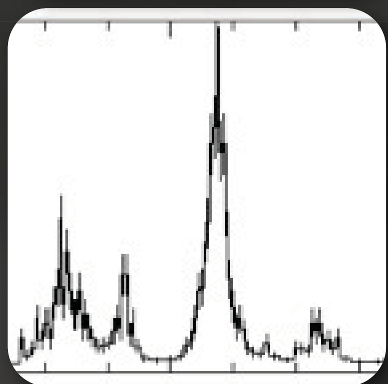


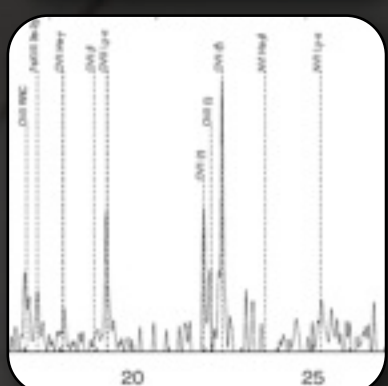
Circinus Galaxy, HETGS


10 arcsec
1 arcsec
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
[OIII]
Circinus


Pembroke
Allenstown
Suncook







Summary

SOARS - a better understanding energy transport in AGN:

- 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 restricted to the nucleus in NGC 1068, with velocities ~ 500 km/s.
- Potential evidence for outflows in Mrk 3
- NGC 3393 data in AO-13
- How do early- and late-type galaxies migrate from blue to red?