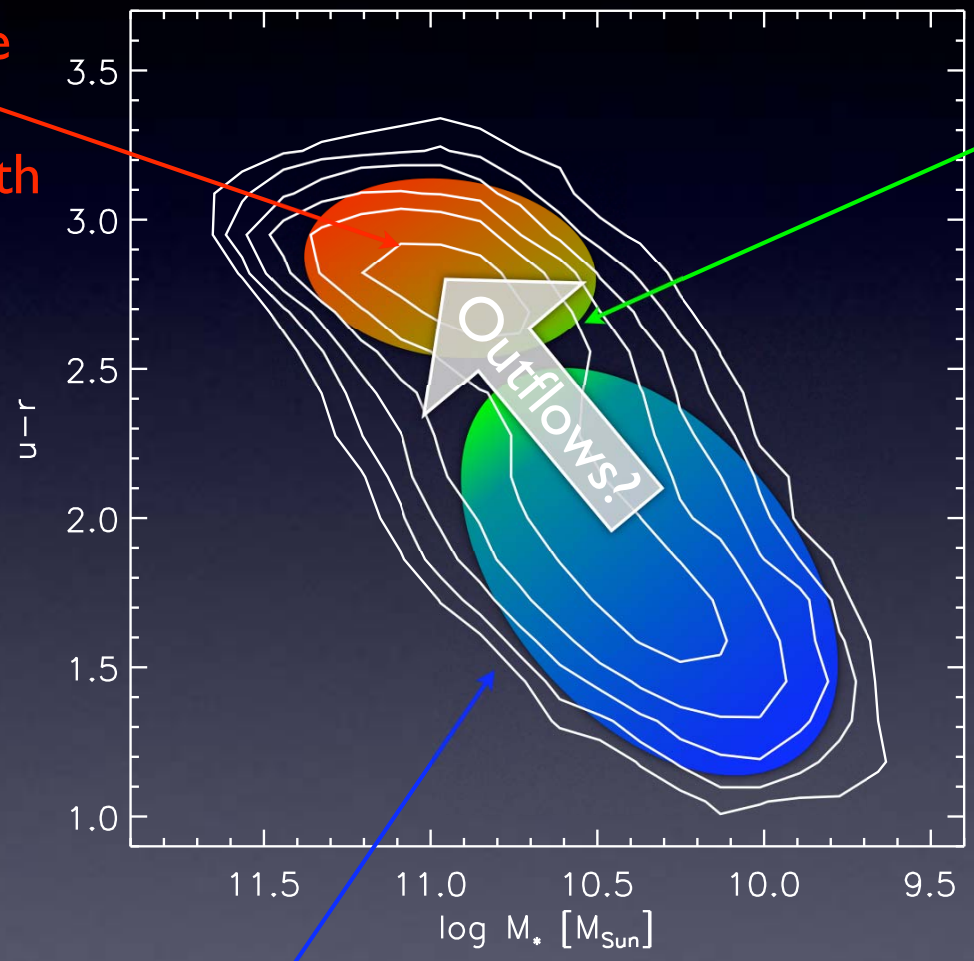
Spatially Resolved Chandra HETG Spectroscopy of the NLR Ionization Cone in NGC 1068

Dan Evans (MIT Kavli Institute),

Patrick Ogle (Caltech), Herman Marshall (MIT), Mike Nowak (MIT), Kim Weaver (GSFC), Stefano Bianchi (Roma Tre), Matteo Guainazzi (ESAC), Anna Lia Longinotti (MIT), Dan Dewey (MIT), Norbert Schulz (MIT), Mike Noble (MIT), John Houck (MIT), and Claude Canizares (MIT)

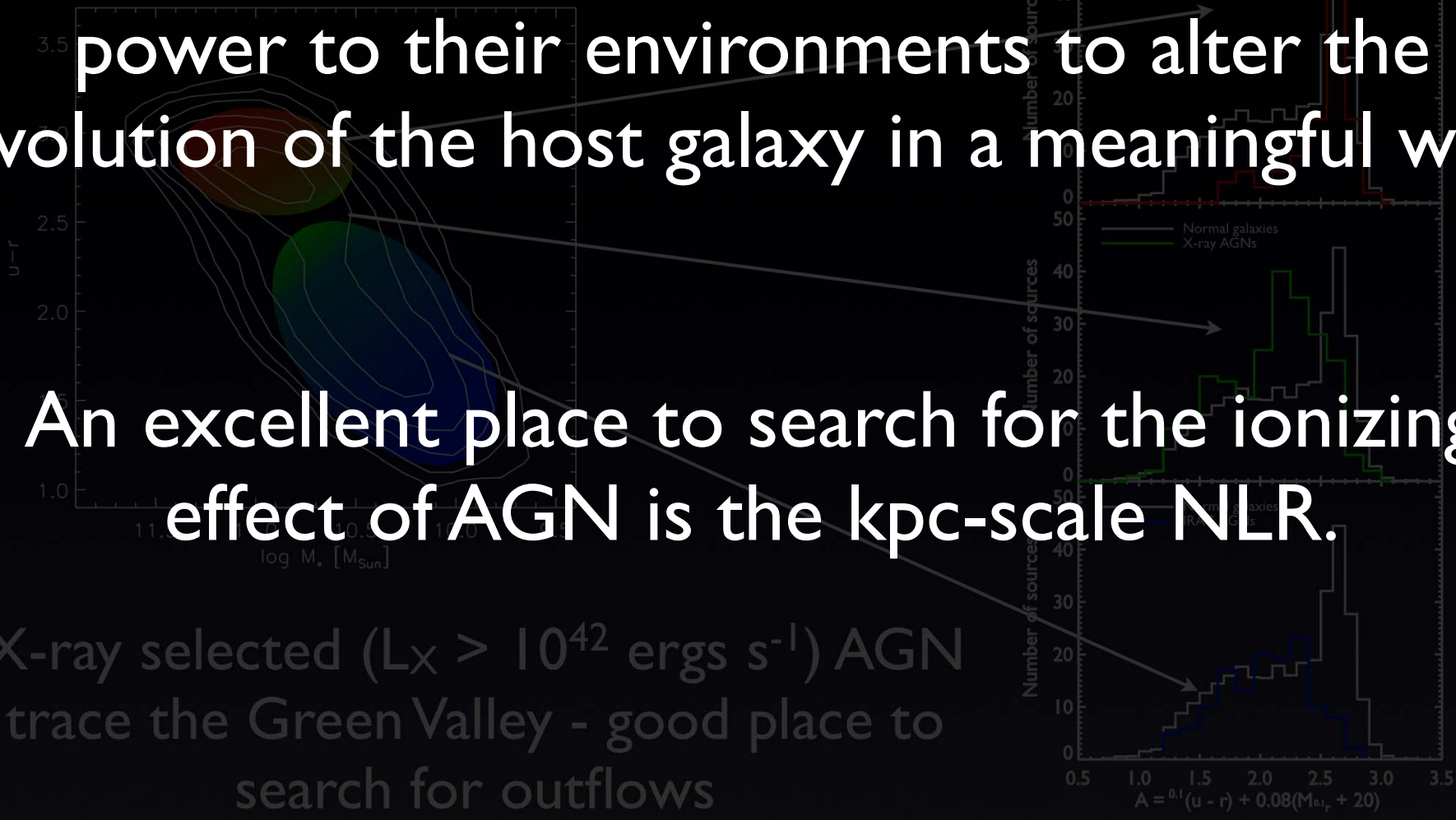
Galaxy Color-Magnitude Diagram



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

Galaxy Color-Magnitude Diagram

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



Hickox et al. (2009)

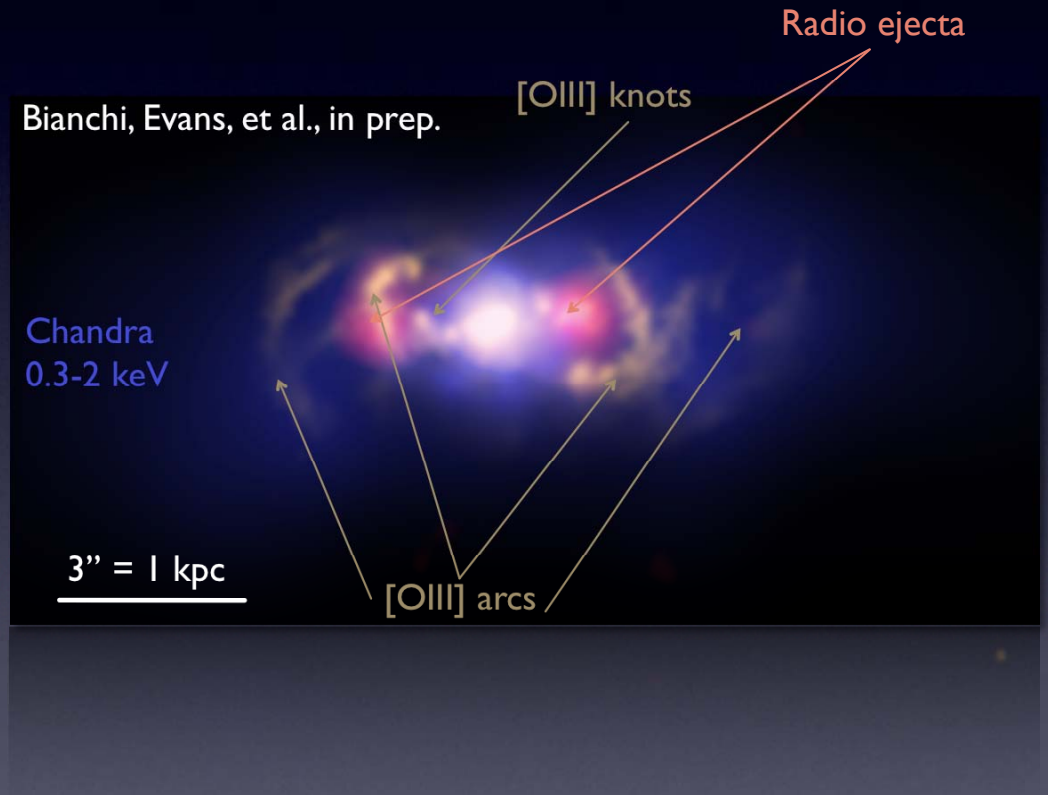
An excellent place to search for the ionizing effect of AGN is the kpc-scale NLR.

X-ray selected ($L_X > 10^{42}$ ergs s^{-1}) AGN trace the Green Valley - good place to search for outflows

Searching For Outflows

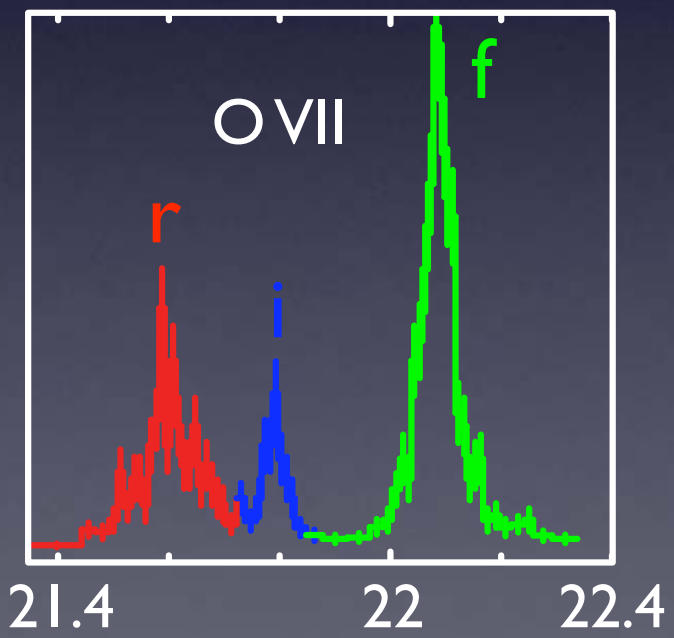
1. Multi-λ imaging of kpc-scale circumnuclear gas

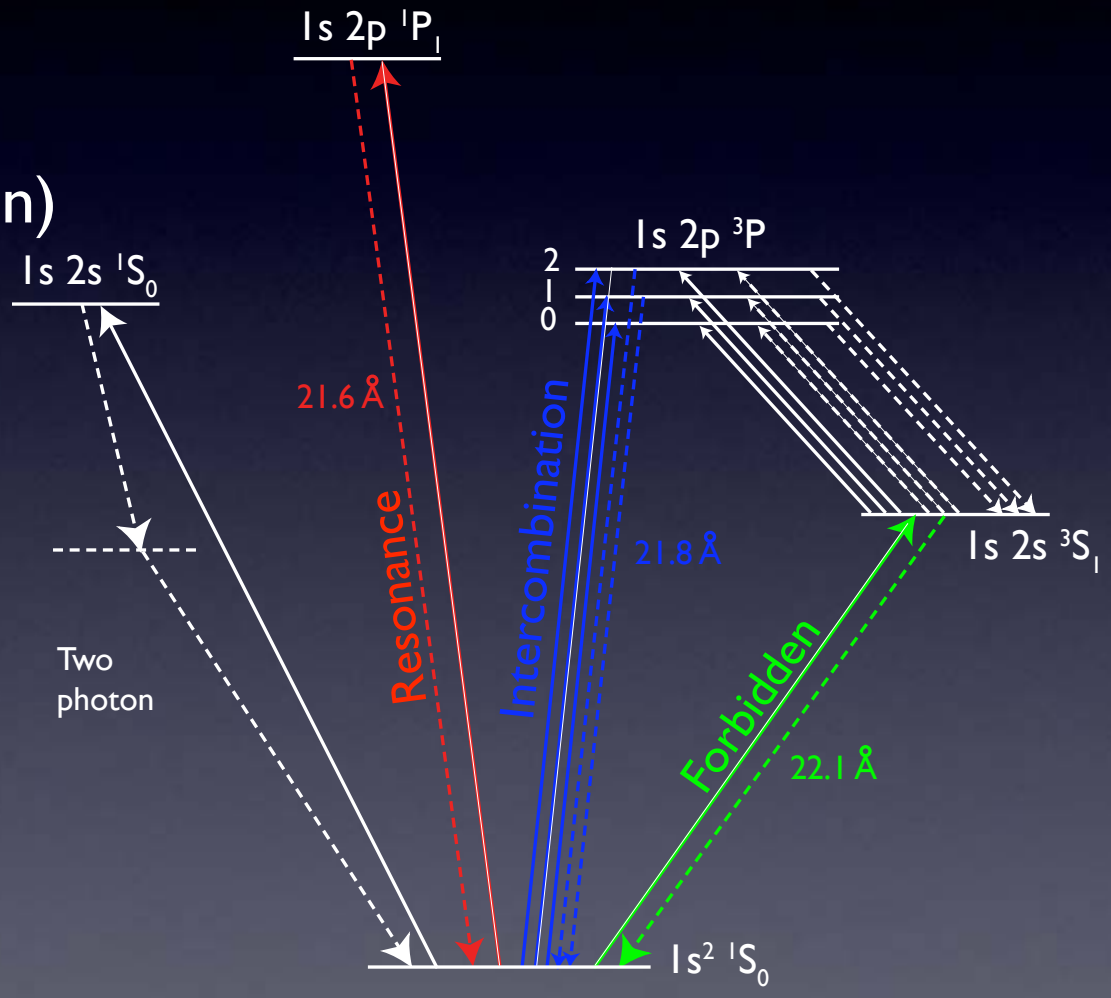
   - Spatial relationships between nucleus, jet, and warm [OIII] gas and hot X-ray gas



Searching For Outflows

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

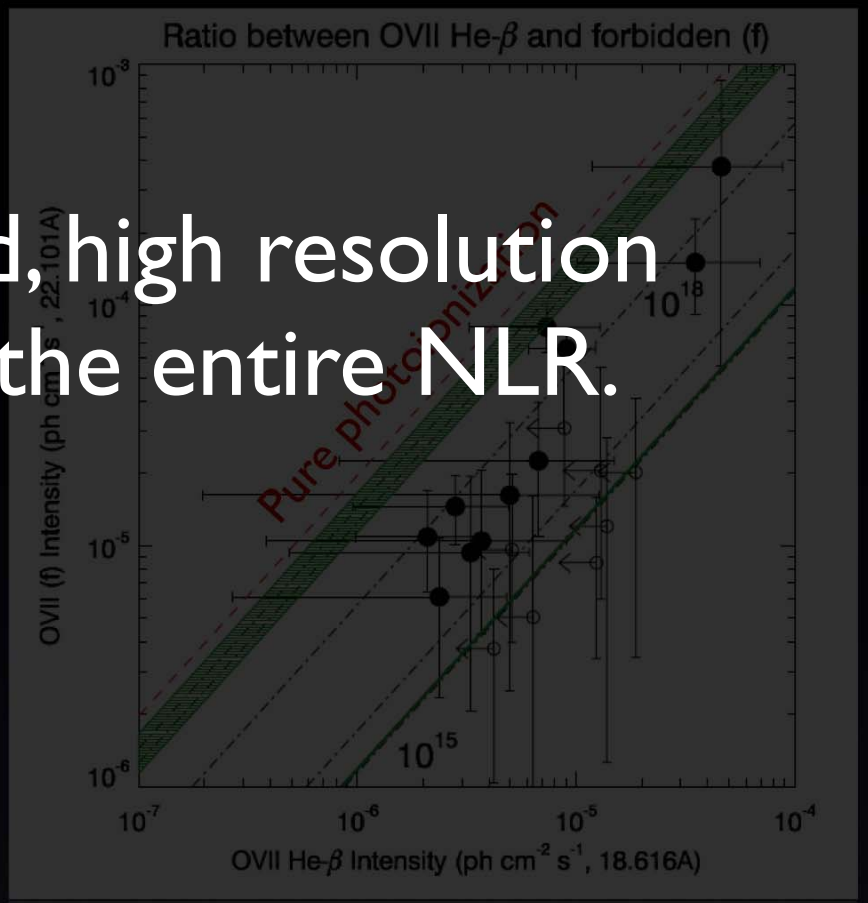




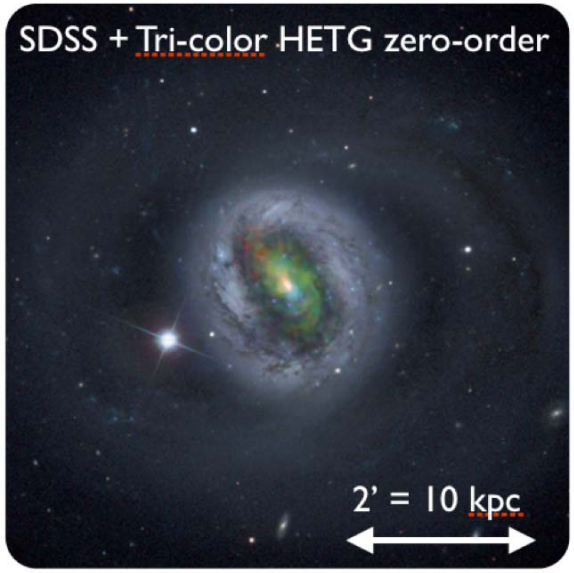
CIELO-AGN - Catalogue of Ionized Emission Line spectra in Obscured AGN

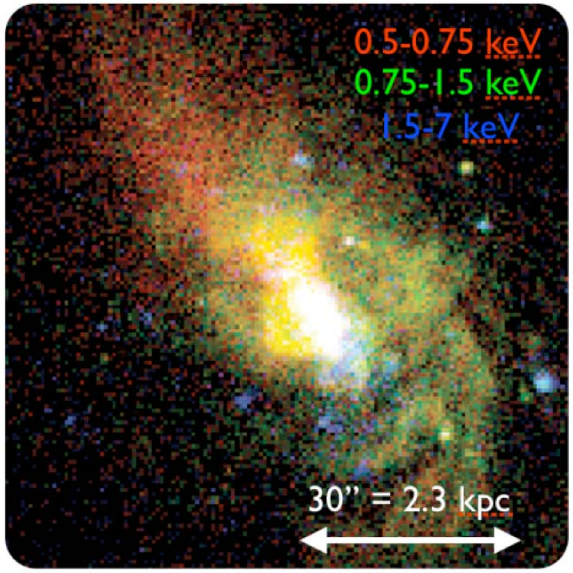
- XMM RGS spectra of 69 obscured Seyferts (Guainazzi & Bianchi 2007)
- Narrow RRCs in 36%
- Resonant scattering plays an important role (not just pure photoionization)
- AGN radiation dominates
- Dominated by point source

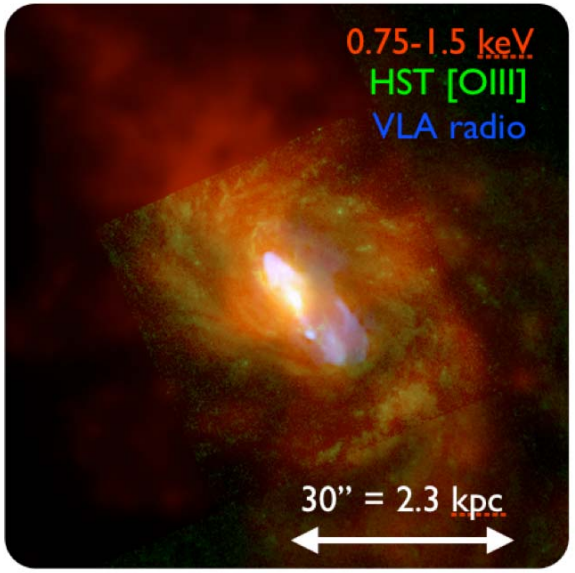
We need spatially resolved, high resolution gratings spectroscopy of the entire NLR.



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

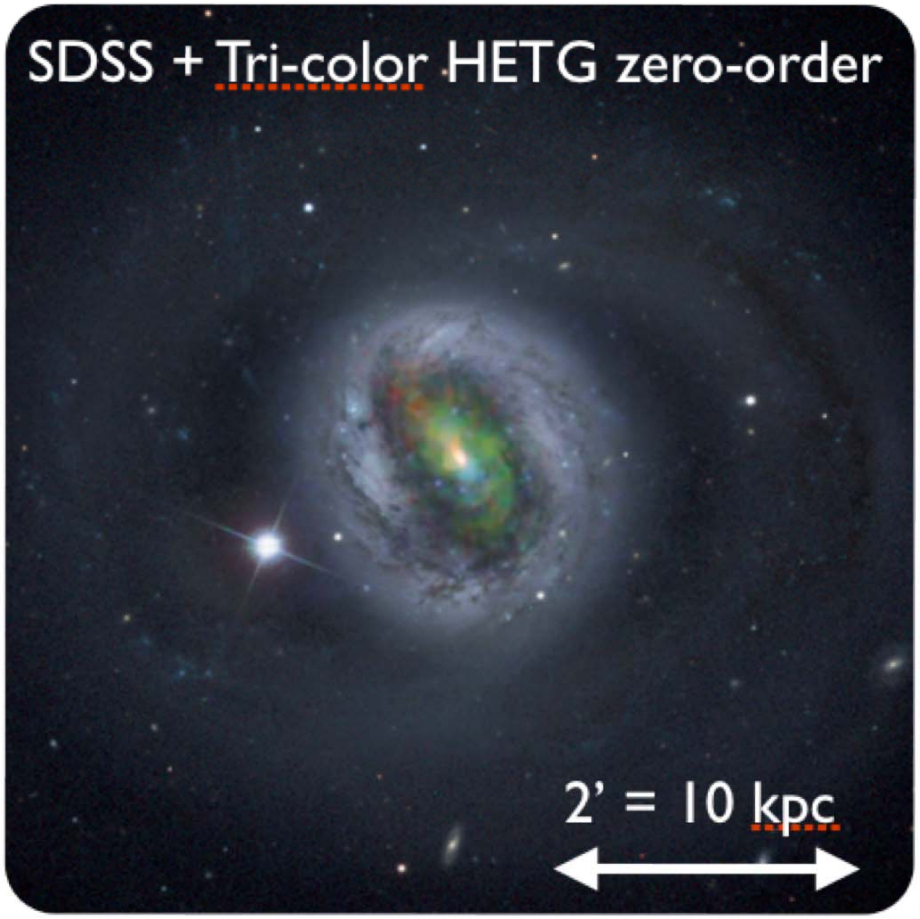


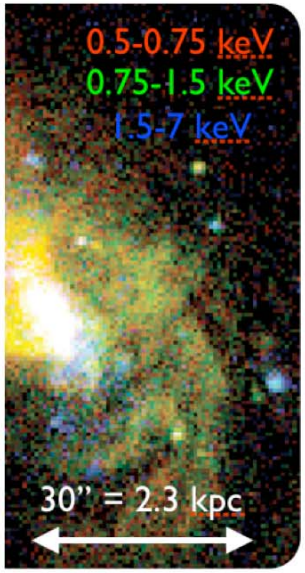


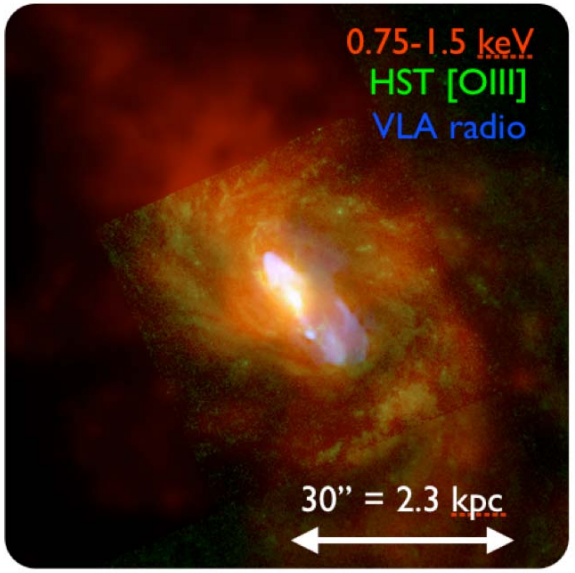


- Nearby: z = 0.003793, D_L = 16.3 Mpc, 1" = 80 pc ✔
- Compton-thick Seyfert 2 ($N_H > 10^{25}$ cm^{-2}) ✔
- Black hole mass ~ 10^7 $M_\odot$ (e.g., Ludato et al. 2002) ✔
- Accreting at or near Eddington limit (e.g., Kishmoto et al. 1999) ✔
- Prominent kpc-scale radio jet ✔

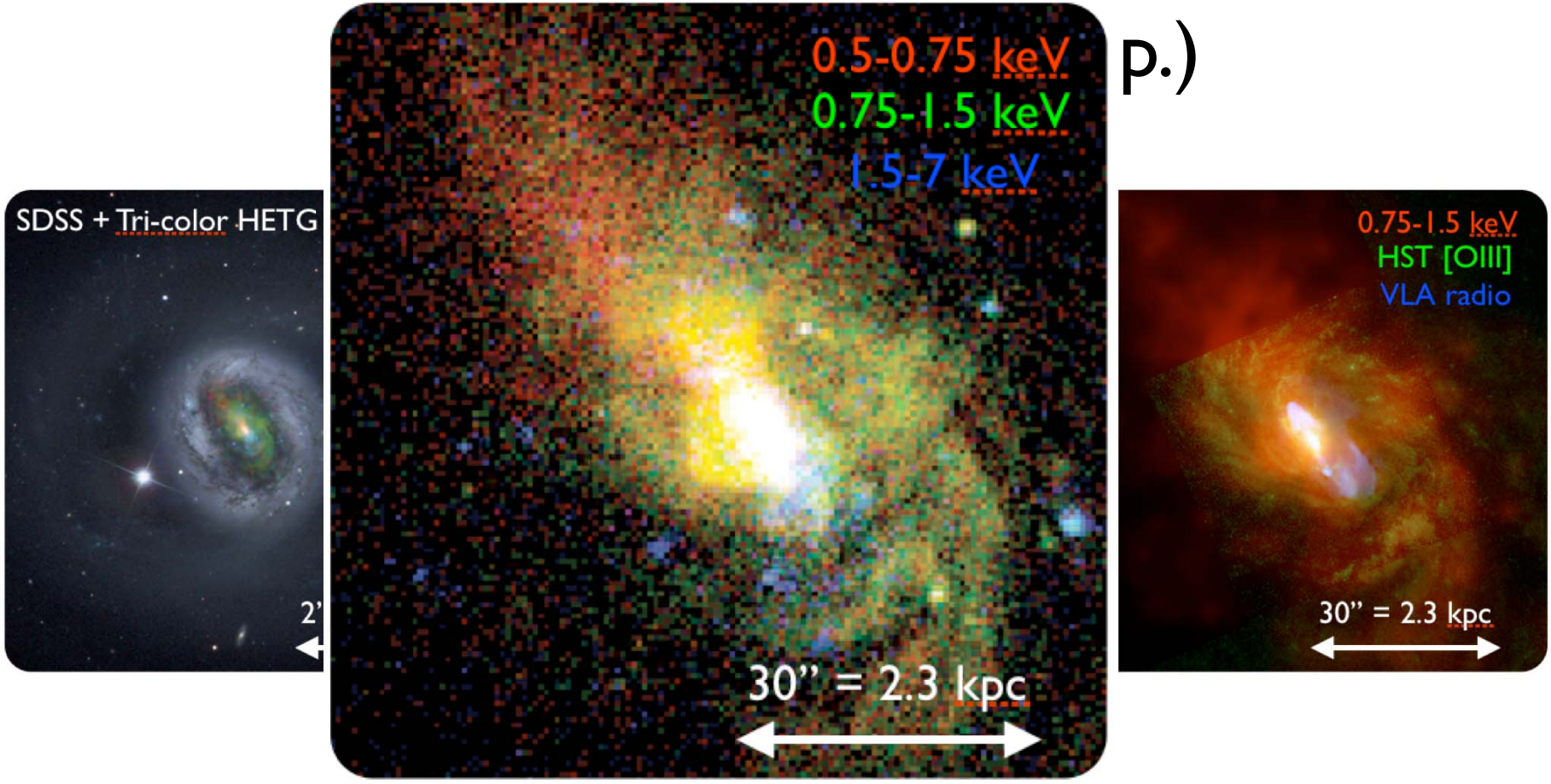
The Prototypical Example - a 440-ks Chandra HETG GTO Observation of NGC





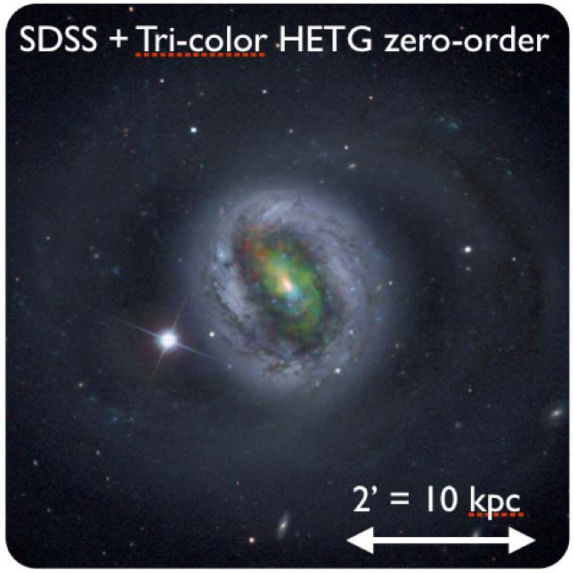


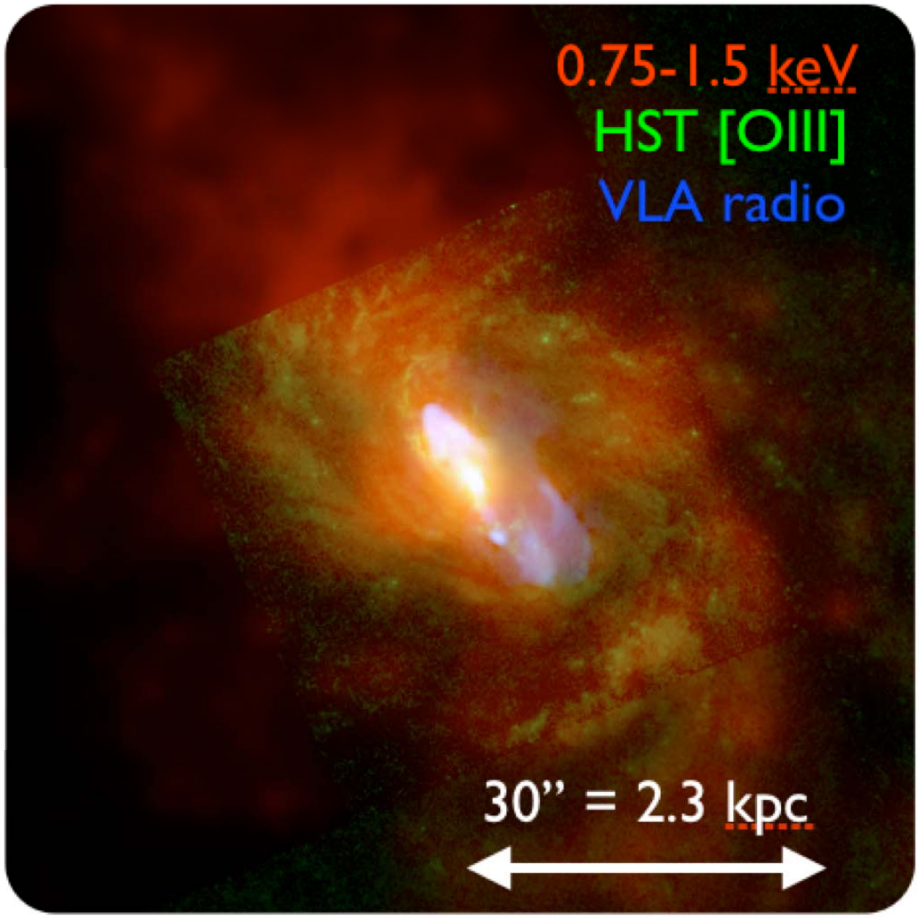
The Prototypical Example - a 440-ks Chandra HETG GTO Observation of NGC

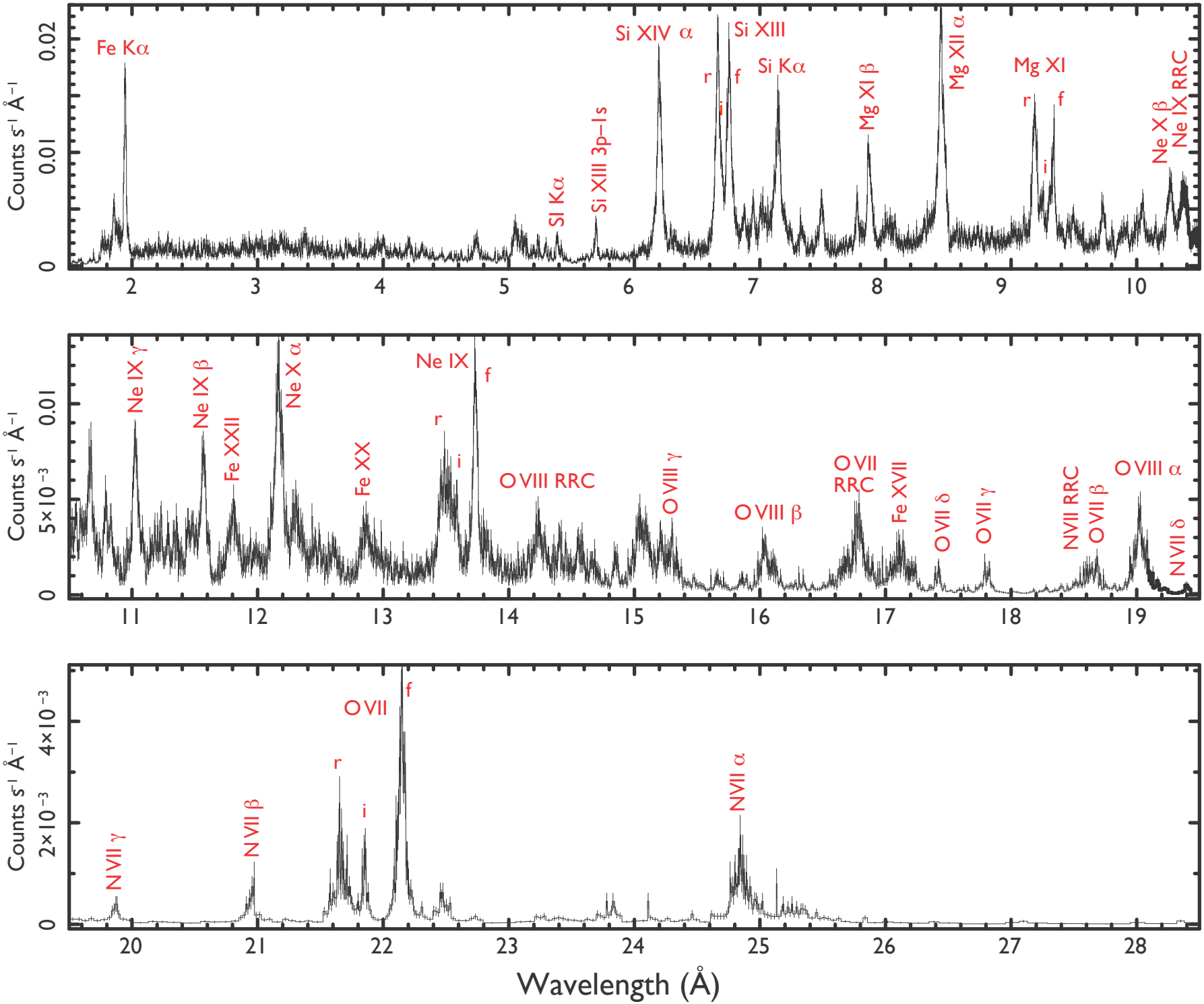


p.)

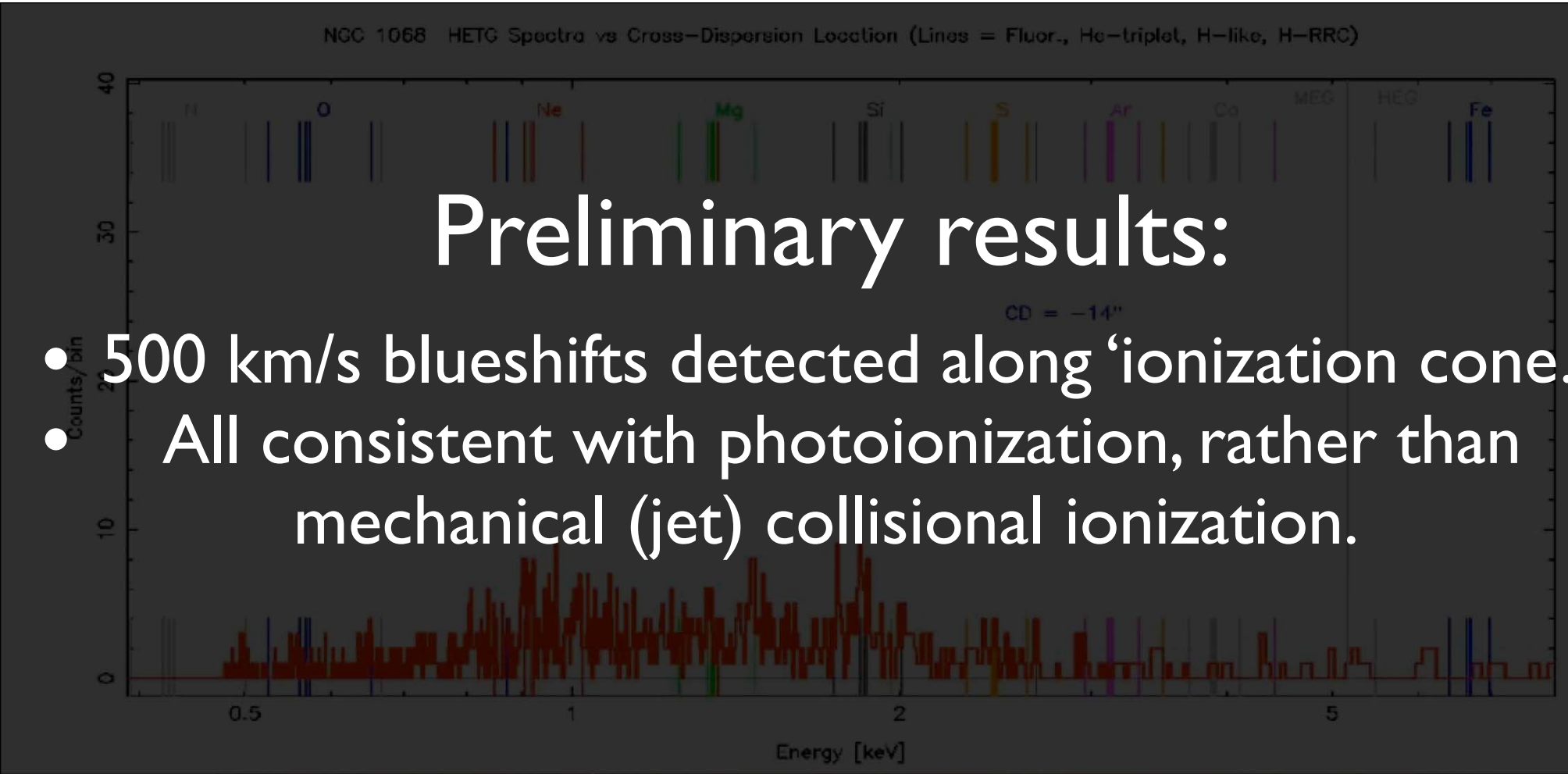
The Prototypical Example - a 440-ks Chandra HETG GTO Observation of NGC 1068 (Evans et a






Fe Kα
Si XIV α
Si XIII
r
i
f
Si Kα
Mg XII α
Mg XI
Mg XI β
Si I Kα
Si XIII 3p–1s
Ne X β
Ne IX RRC
Ne IX γ
Ne IX β
Fe XXII
Ne X α
Fe XX
Ne IX
O VIII RRC
O VIII γ
O VII RRC
O VIII β
Fe XVII
O VII δ
O VII γ
N VII RRC
O VII β
O VIII α
N VII δ
O VII
N VII γ
N VII β
N VII α
Counts s⁻¹ Å⁻¹
0
0.01
0.02
5×10⁻³
2×10⁻³
4×10⁻³
Wavelength (Å)

Spatially Resolved Spectroscopy: A Unique Experiment

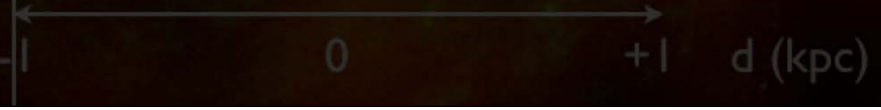


Preliminary results:

- 500 km/s blueshifts detected along 'ionization cone.'
- All consistent with photoionization, rather than mechanical (jet) collisional ionization.

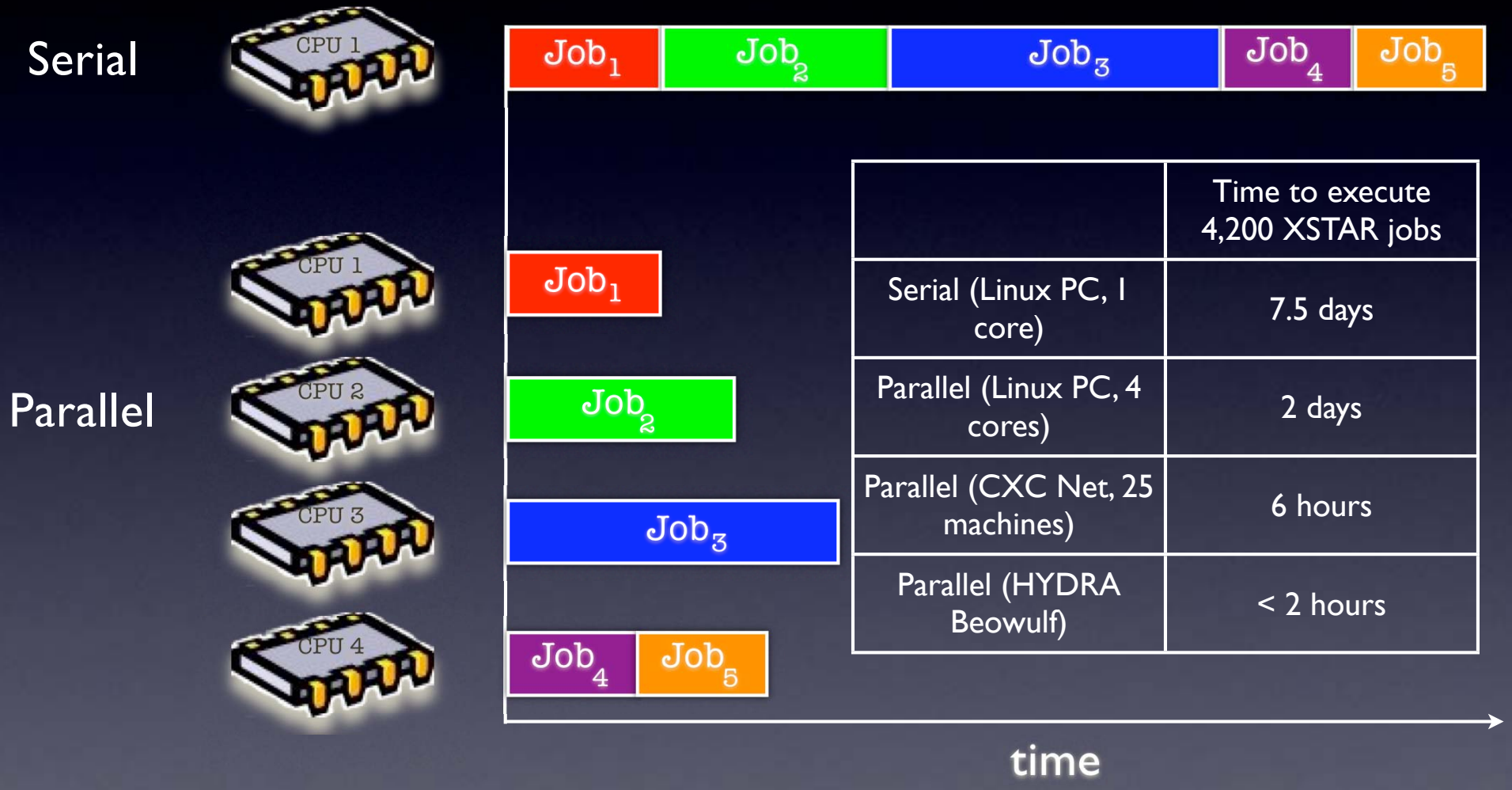
More to do:

- Determine mass outflow rate and power.
- Detailed photoionization models along cone.



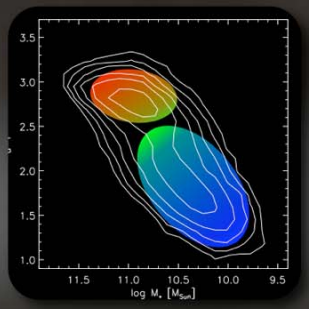
Parallelizing XSTAR (warmabs, photemis, etc.)

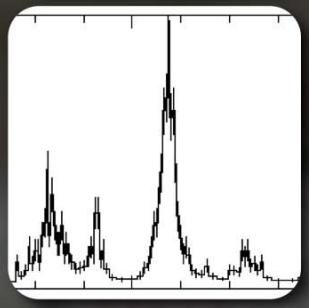
Code by Mike Noble (MIT)

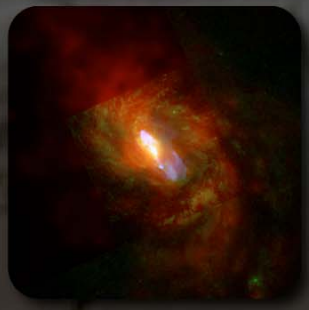


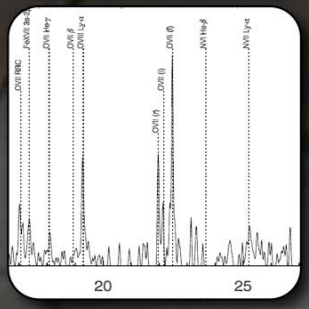
	Time to execute 4,200 XSTAR jobs
Serial (Linux PC, 1 core)	7.5 days
Parallel (Linux PC, 4 cores)	2 days
Parallel (CXC Net, 25 machines)	6 hours
Parallel (HYDRA Beowulf)	< 2 hours

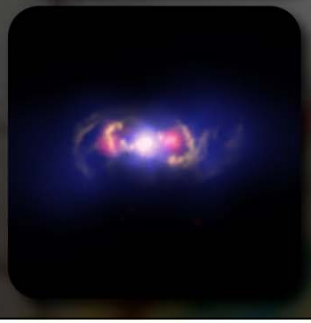
http://space.mit.edu/cxc/software/slang/modules/pvm/











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 along the NLR ionization cone, with velocities > 500 km/s up to several kpc from the nucleus.
- Further work will include detailed photoionization modeling of the HETG spectra between -1 and +1 kpc, in 40 pc bins.