Spatially Resolved HETG Spectroscopy of Ionization Cones in Seyfert Galaxies

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Ionized Environments in AGN

Understanding the relationship between accretion, radiation, and outflows is crucial for testing models of BH growth and galaxy formation

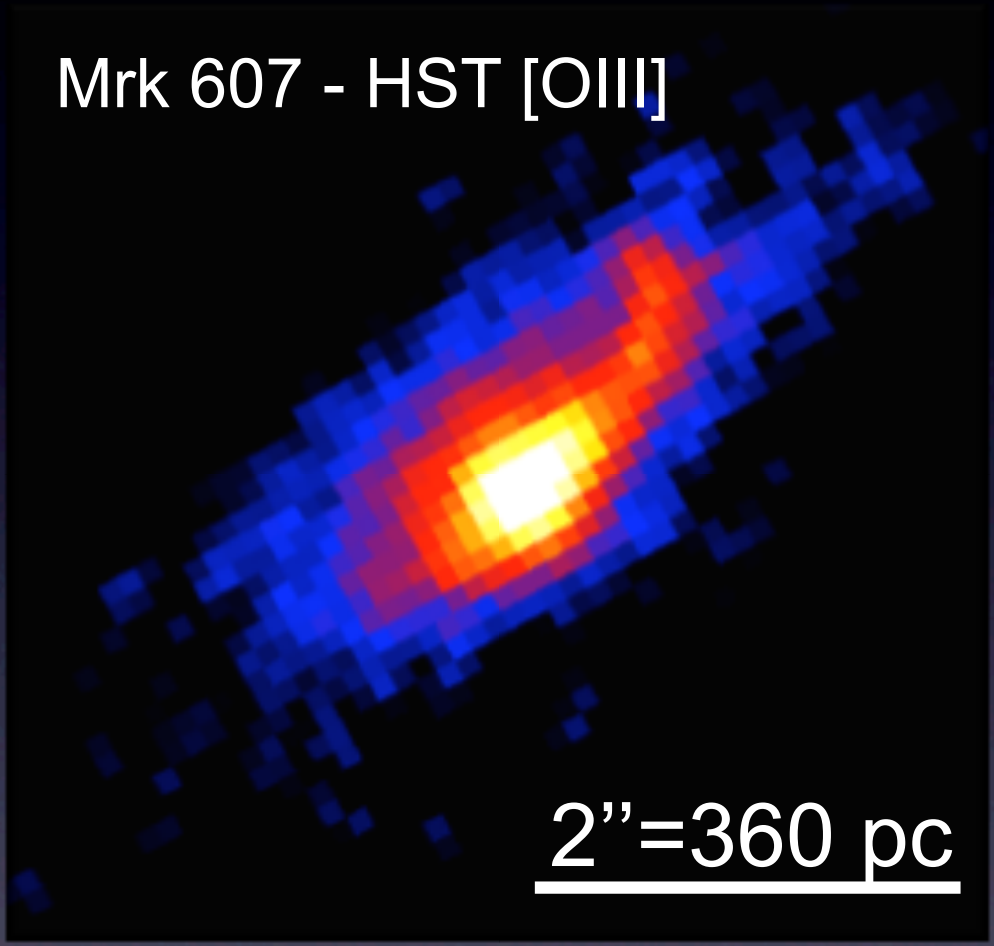
Multiphase ionized circumnuclear environments of Seyfert galaxies ideal places to measure <u>the radiative and kinematic ionizing output of AGN</u>

Seyferts show a range of jet/outflow properties, from truly radio-quiet sources to those with kpc-scale jets

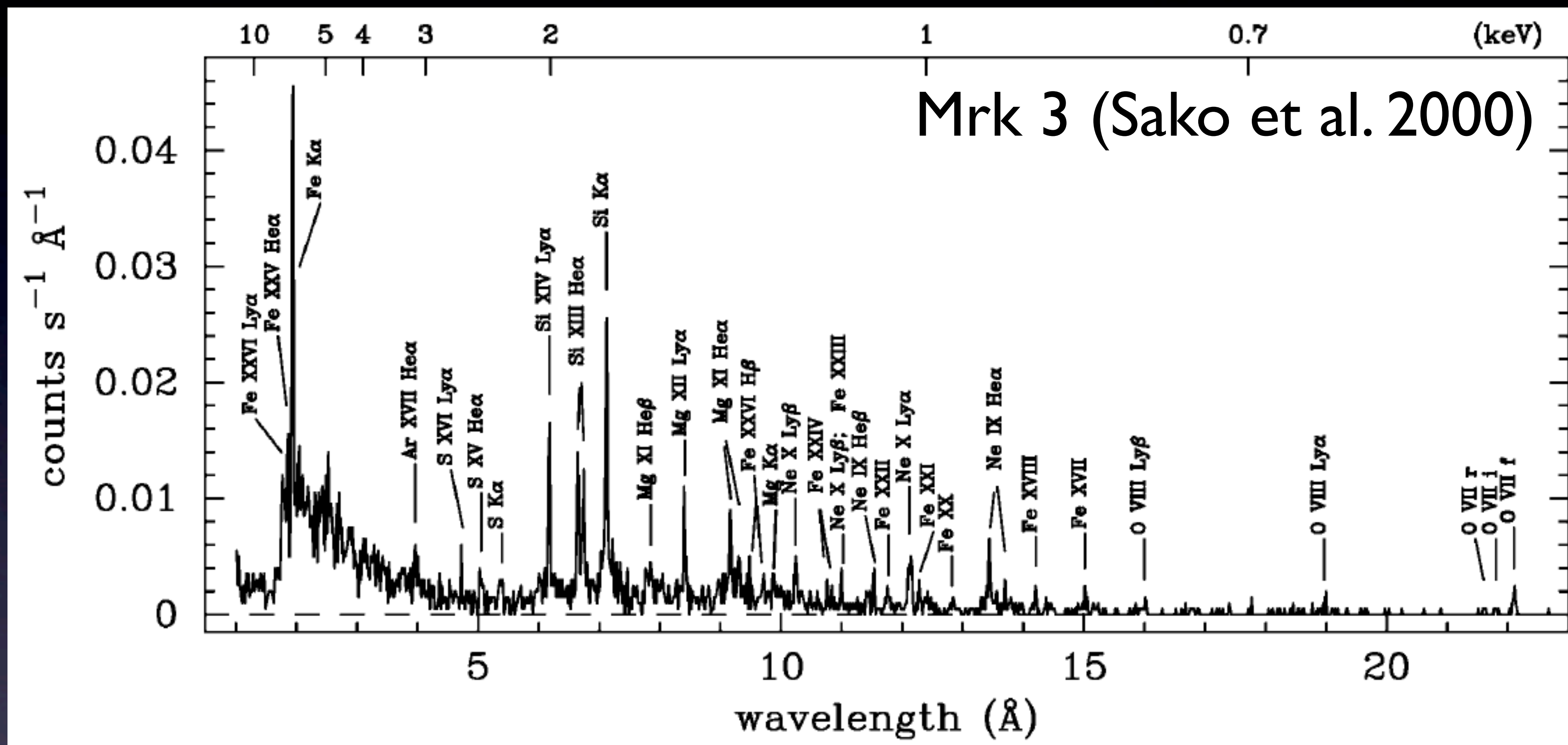
- HETG and RGS give detailed plasma diagnostics
- Chandra and multi-λ imaging to understand spatial relationships between nucleus, jet, and warm [OIII] gas and hot X-ray gas

Seyfert Circumnuclear Environments

- NLR (sub-kpc) and ENLR (up to ~10 kpc) are regions of warm ($T \sim 10^4$ K), ionized gas
- Seyfert 2 galaxies with little radio activity have smooth, collimated [OIII] gas distributions in the form of an ionization cone

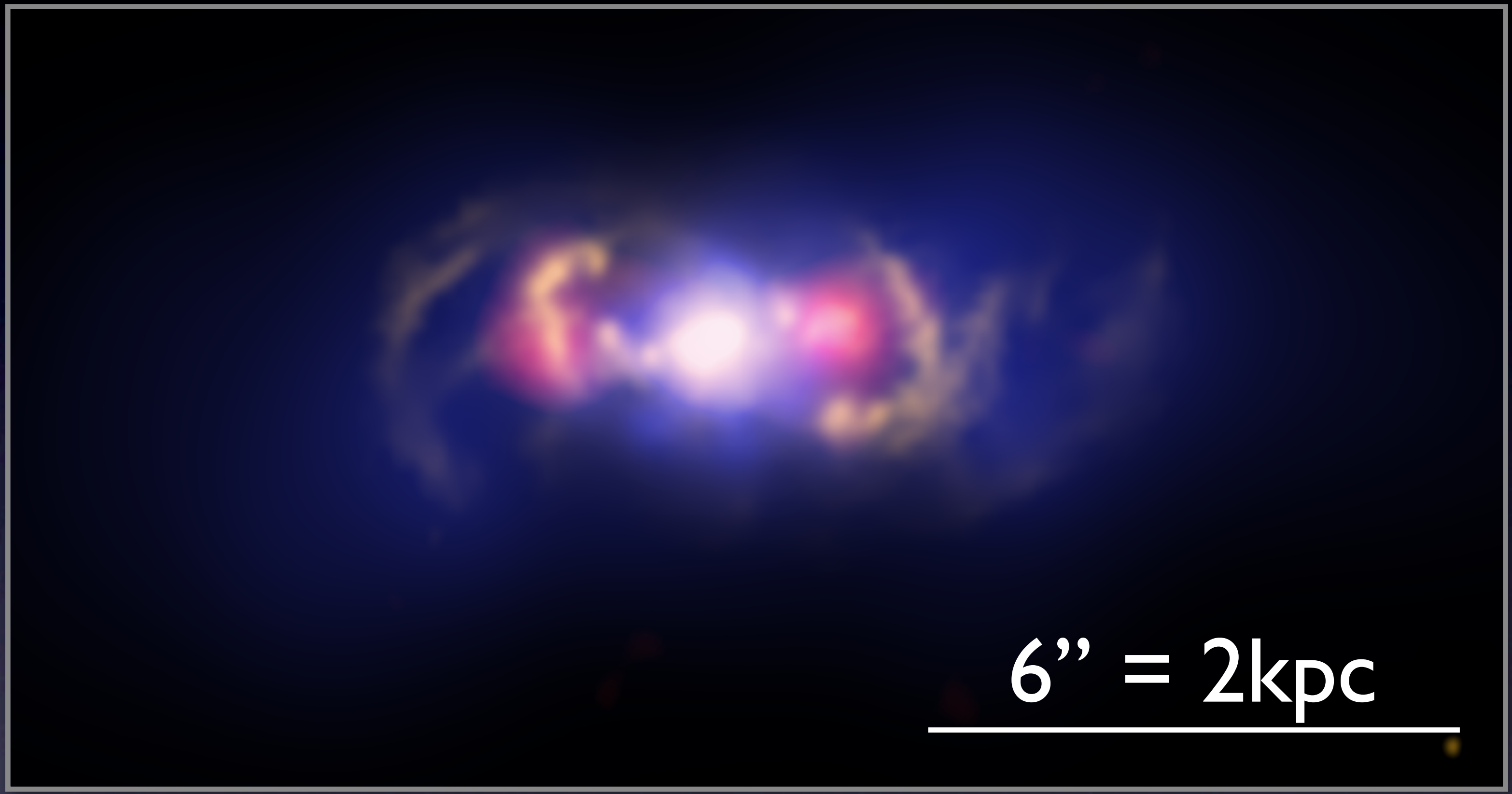


Seyfert Circumnuclear Environments

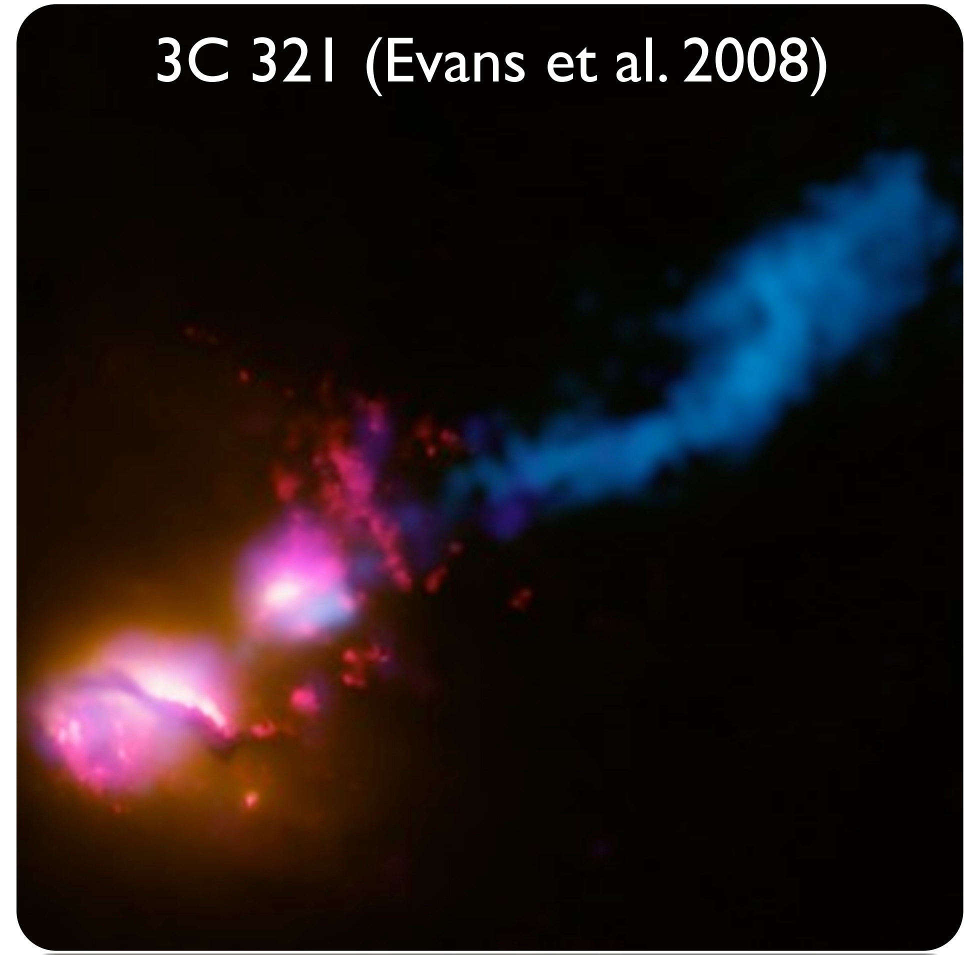


- HETG and RGS directly measure gas densities and ionization mechanisms
- Observations show evidence for He-like triplets, narrow RRC features, indicative of photoionization

Radio-Loud "Jetted" Seyferts

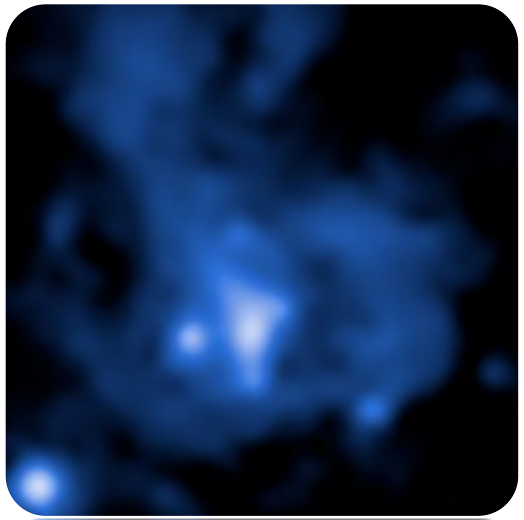
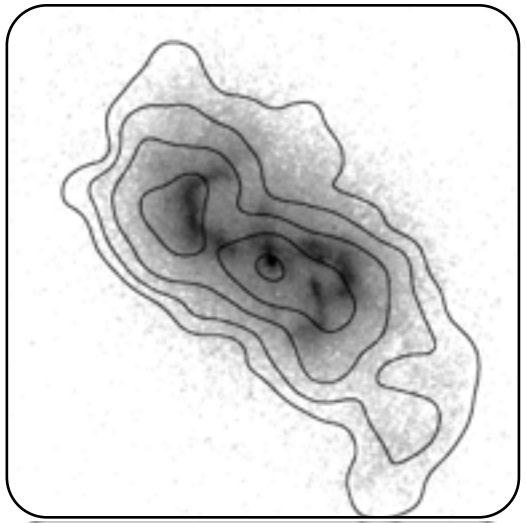


- Although Seyferts are "radio quiet" AGN, many are not radio silent
- 100s-pc scale radio jet may have strong influence on (E)NLR, often resulting in a disturbed environment, with prominent series of arcs, strands, and knots



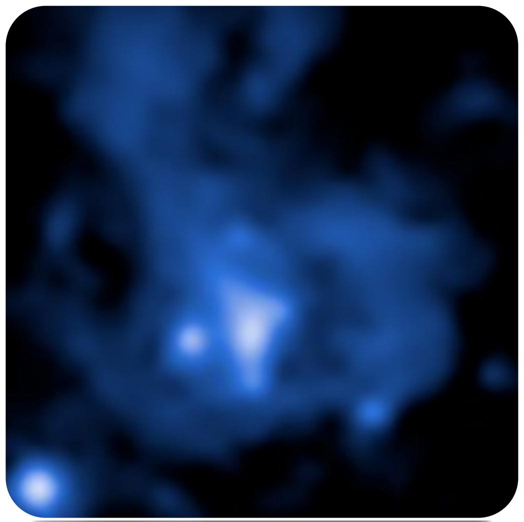
What parallels can be drawn between Seyfert jets and radio-galaxy jets?

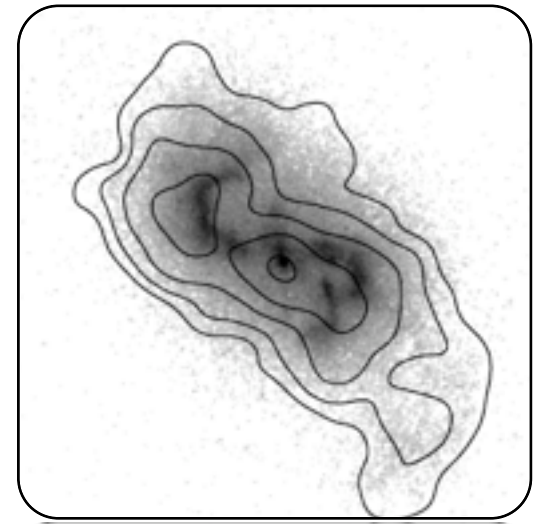
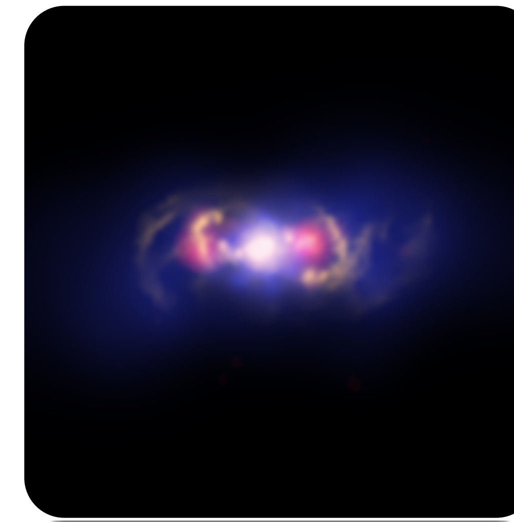
Ionization Mechanisms in Seyferts

1. Line-emitting gas is shocked and collisionally ionized (similar to radio galaxies)

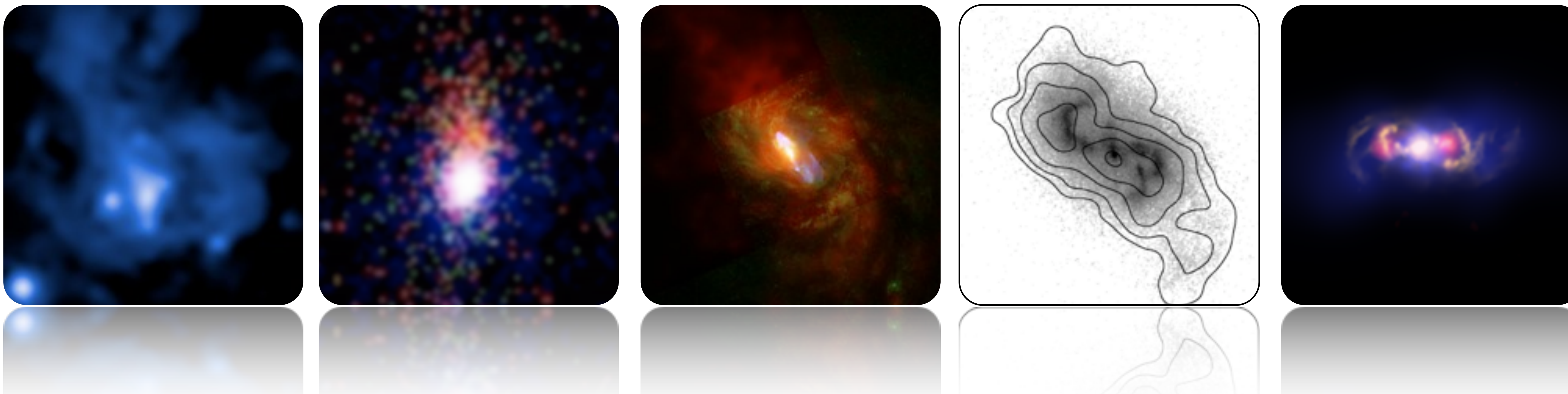
Ionization Mechanisms in Seyferts



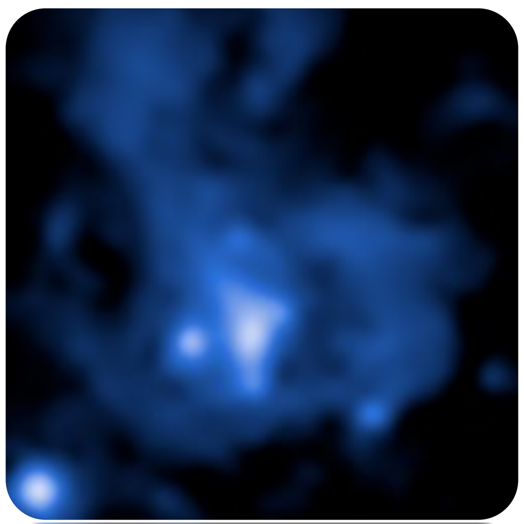
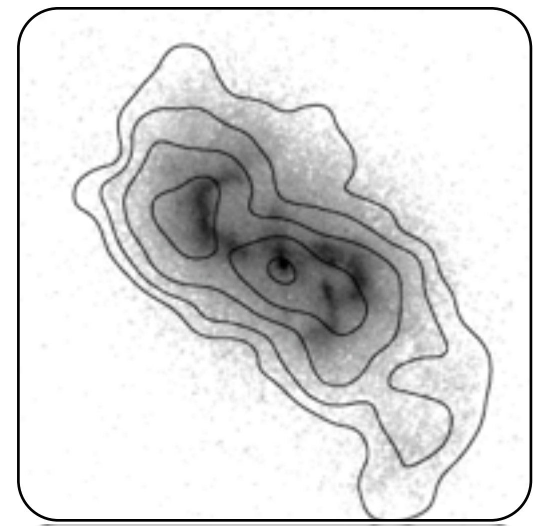
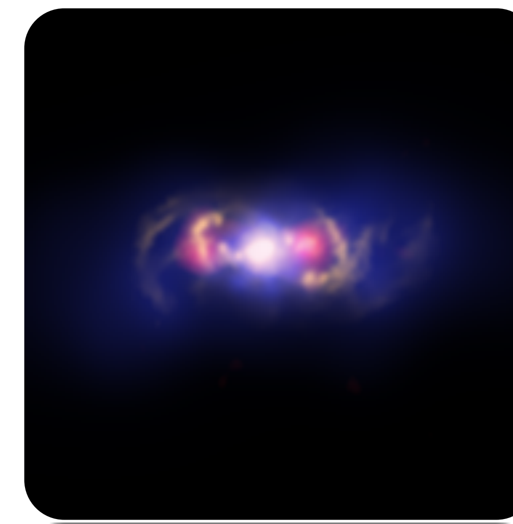
2. Line-emitting gas is ionized by photons generated in situ in the hot shocked gas ('autoionizing' shock – see Dopita and Sutherland 1995). [Unlikely to be important for X-ray emission]

Ionization Mechanisms in Seyferts

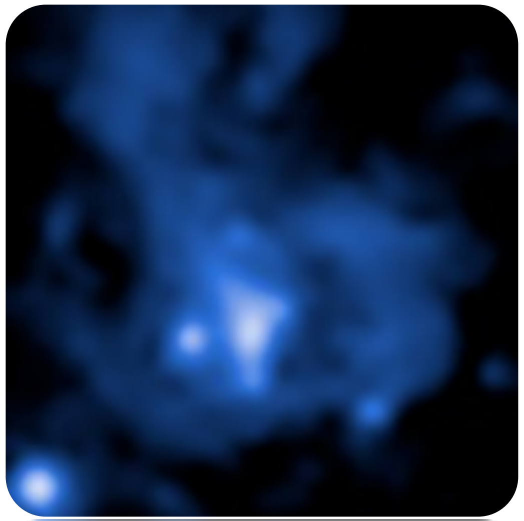
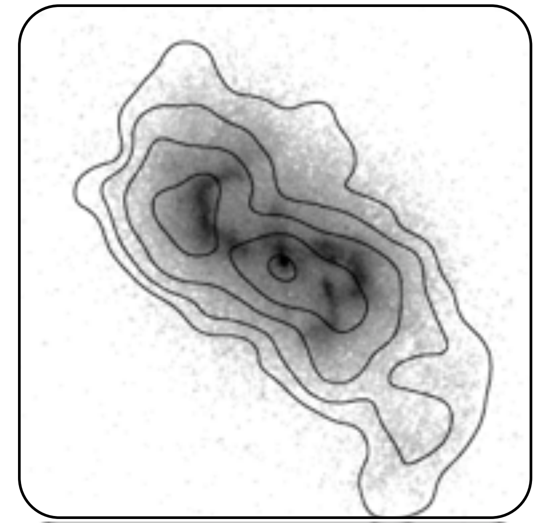
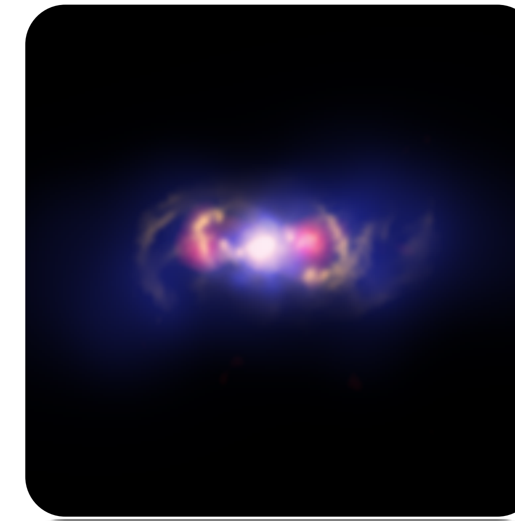


3. AGN photoionization dominates, though (weak) shocks still present: line-emitting gas is post-shock gas photoionized by AGN. Radio jet governs NLR morphology; overdensities have higher surface brightness in line emission

Ionization Mechanisms in Seyferts

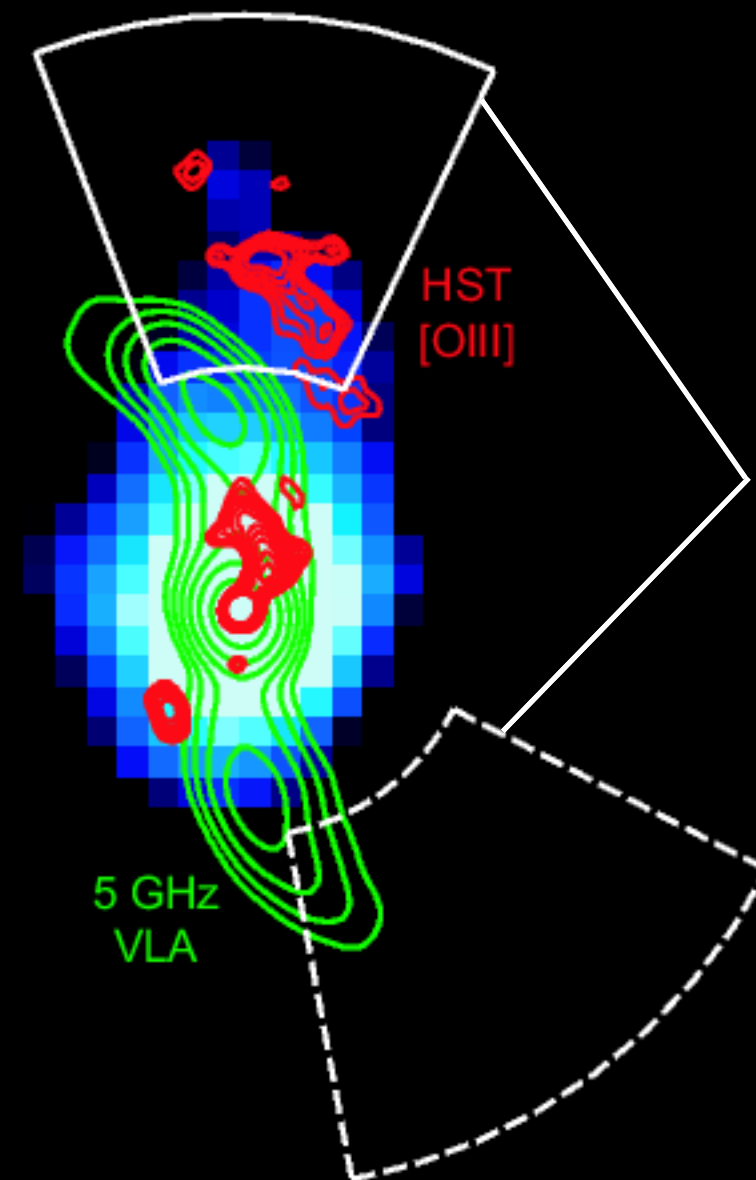
4. Radio jet plays no role at all; so-called ‘pure’ photoionization by AGN (e.g., Storchi-Bergmann 1996)

- Multi-λ imaging to understand spatial relationships and construct ionization maps
- Grating spectroscopy to perform plasma diagnostics (ionization state, density, etc)

NGC 2110 - Multi-λ + Imaging Spectroscopy

- Excellent spatial agreement between X-ray and [OIII] (Evans et al. 2006)
- Both clearly offset from radio, but extend along similar p.a.
- X-ray & [OIII] emission influenced by, but not directly associated with, radio jet?
- ACIS X-ray spectrum modeled by, e.g., two thermal plasma models (kT_1=0.3 keV; kT_2=5 keV)



Source, background spectral extraction regions

Chandra (0.5-1.5 keV) / VLA / HST [OIII]

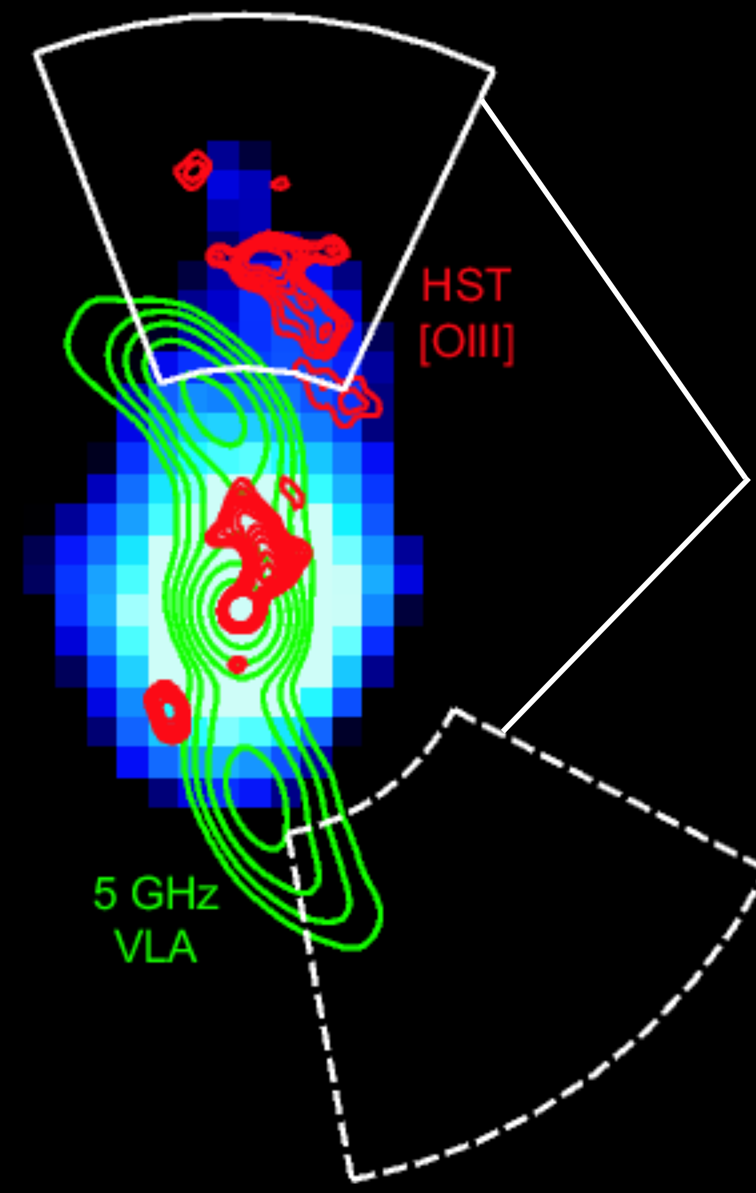
NGC 2110 - Multi-λ + Imaging Spectroscopy

Shock heating

- Minimum pressure of radio lobes, assuming ${}_{min}=2$ up to ${}_{max}=10^5$, is $\sim 10^{-10}$ Pa
- HST [OIII] and [SII] constraints (Ferruit et al. 1999) give pressure few 10^{-10} Pa
- Chandra spectrum, with plasma model, gives pressure few 10^{-10} Pa
- Energy imparted to gas $\sim 10^{39}$ ergs s^{-1}

Photoionization

- Consider extended X-ray luminosity, and assume ionization parameter and emissivity
- Nuclear luminosity required to photoionize similar to that measured
- This mechanism may be energetically viable.
- Also…



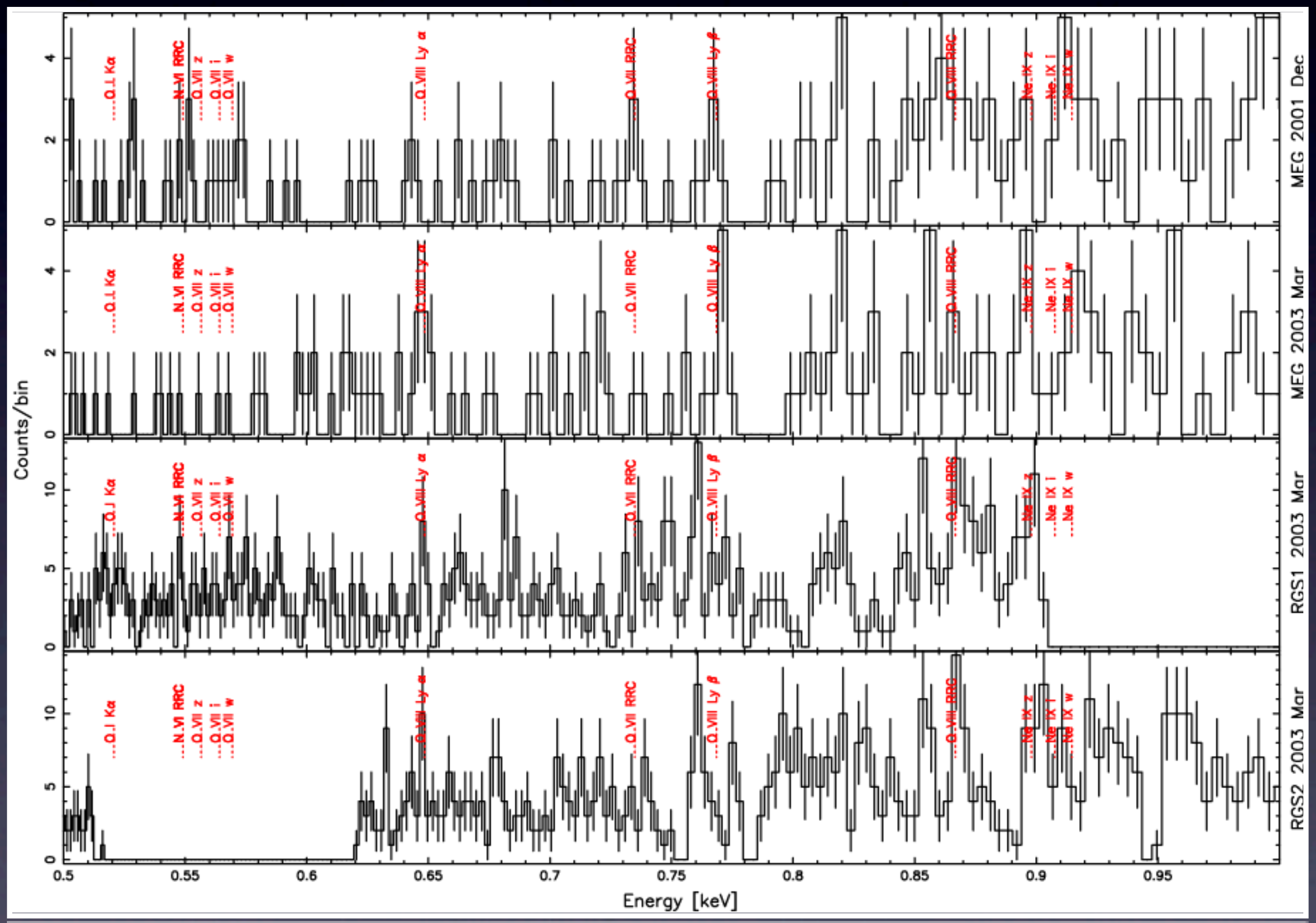
Source, background spectral extraction regions

Chandra (0.5-1.5 keV) / VLA / HST [OIII]

NGC 2110 - HETG and RGS Spectroscopy

250-ks HETG observations (150 ks AO-3, 100 ks AO-5) and 50-ks XMM RGS (Evans et al. 2007a)

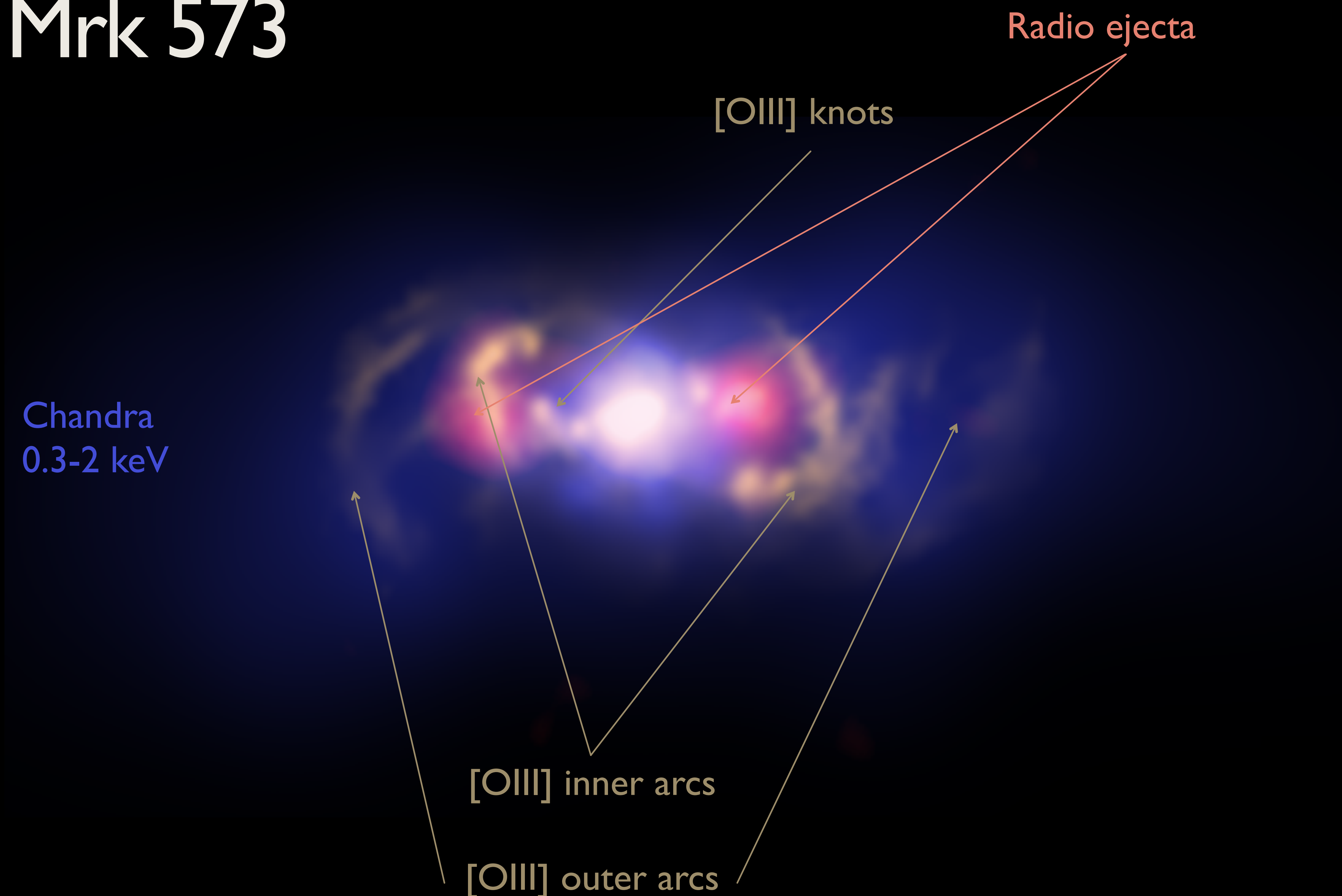
- Evidence for photoionization:
    1. Narrow O VIII RRC
    2. Forbidden OVII and Ne IX
    3. Low Fe L-shell strengths w.r.t. collisional ionization



- X-ray/[OIII]/radio morphology naturally explained by jet-environment interactions

Jet shapes the gas, but photoionization dominates?

Mrk 573

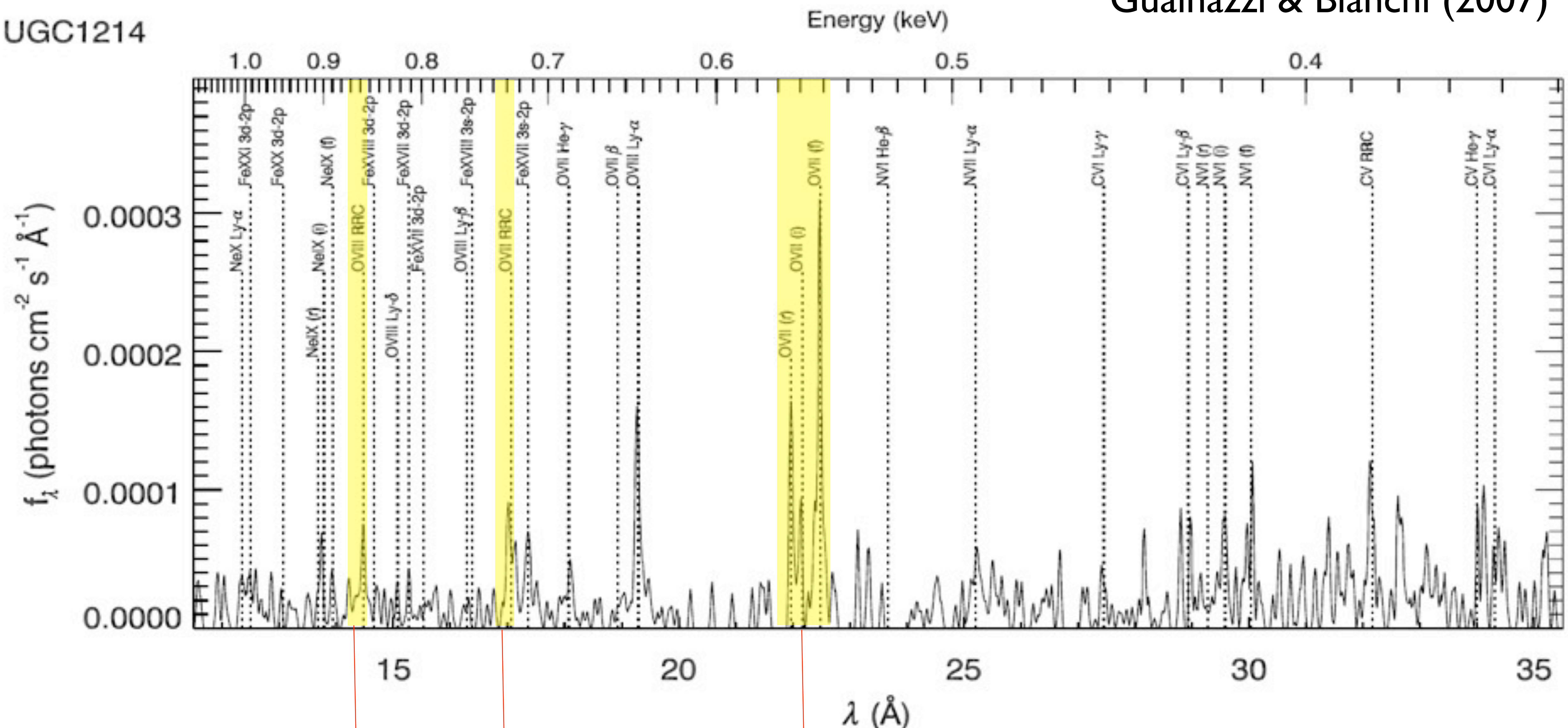


Bianchi et al., in prep.

3” = 1 kpc

XMM RGS spectrum of Mrk 573

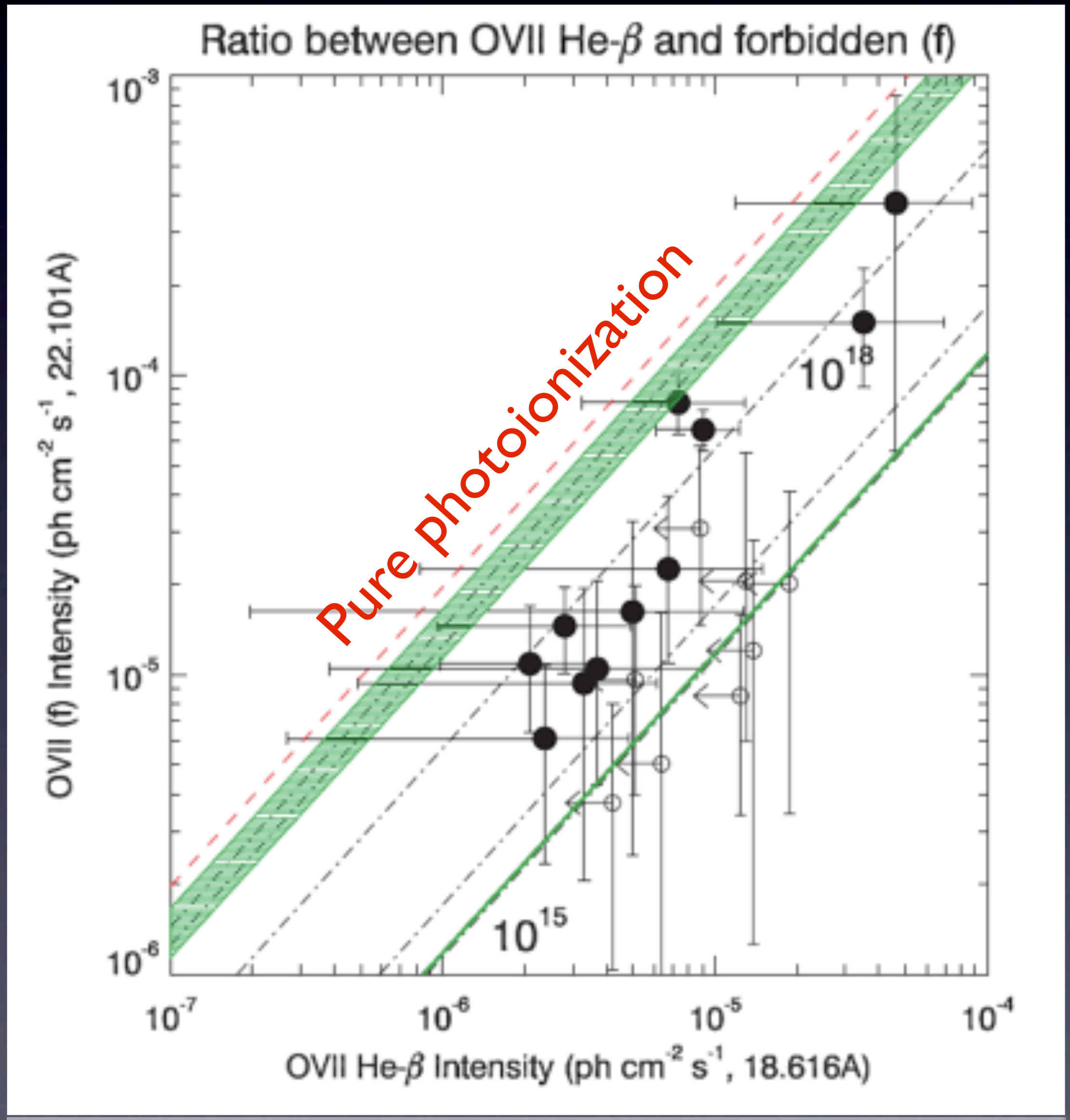
Guainazzi & Bianchi (2007)

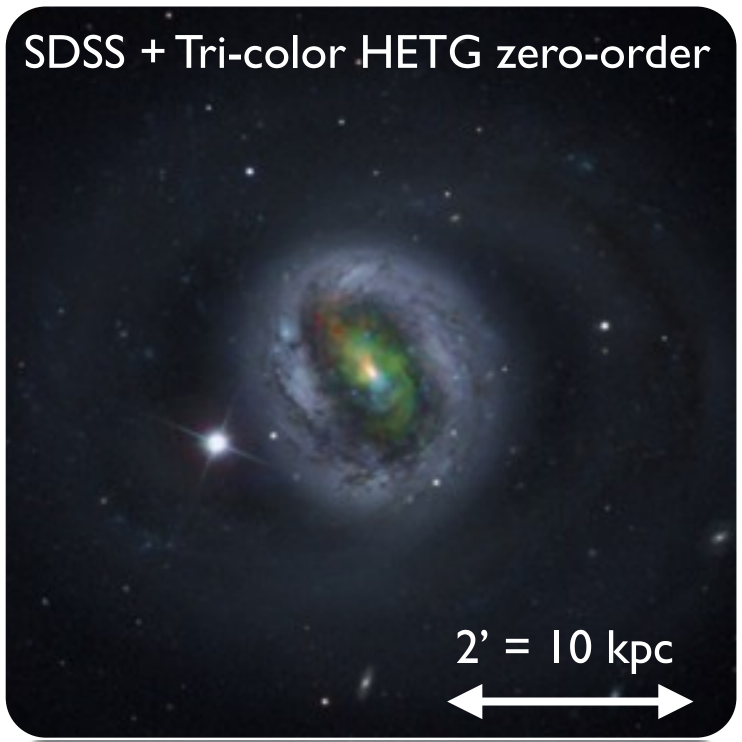


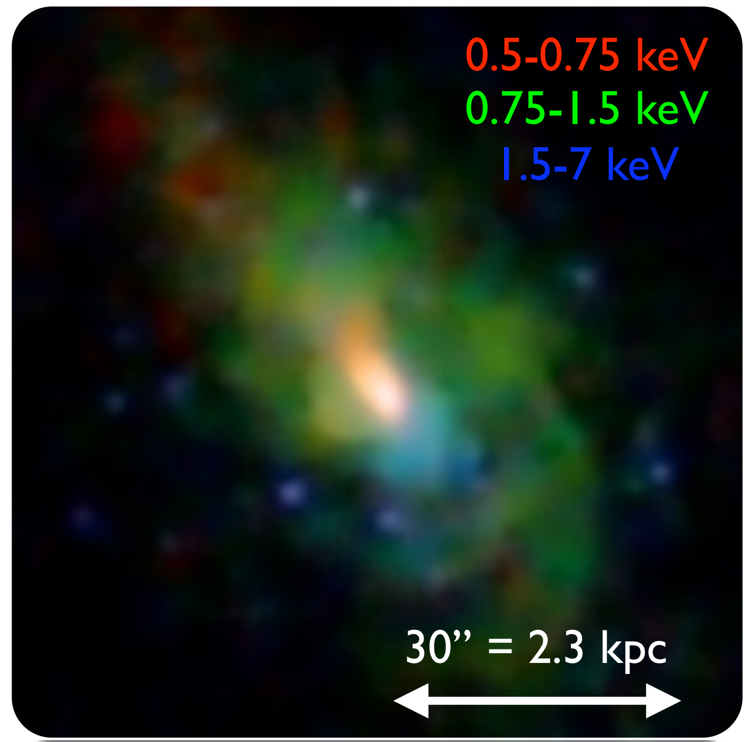
Narrow RRC features Strong OVII (f) → Photoionization dominates

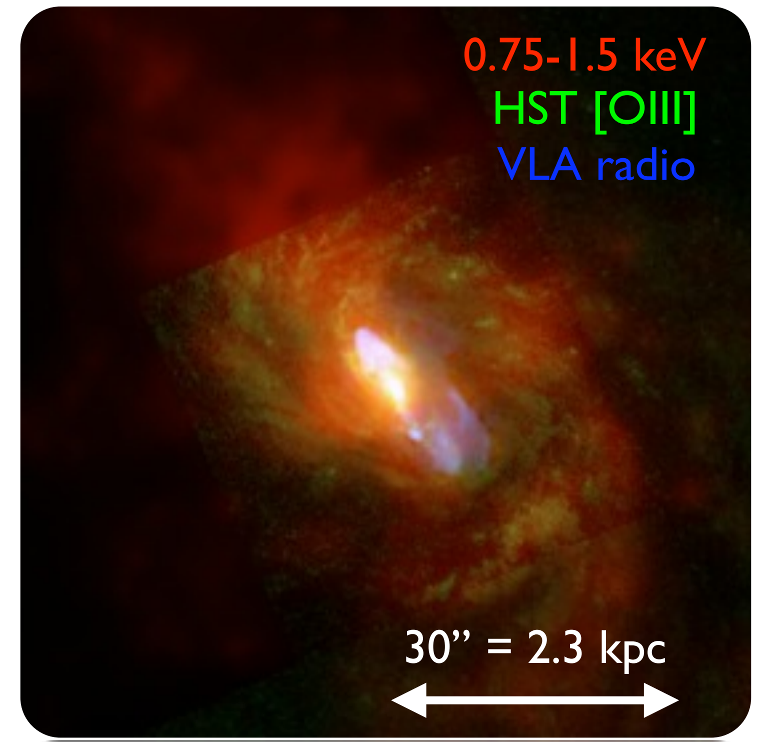
CIELO-AGN - Catalogue of Ionized Emission Line spectra in Obscured AGN

- XMM RGS spectra of 69 obscured Seyferts (Guainazzi & Bianchi 2007)
- Narrow RRCs in 36%
- Radiative decay from photoexcitation and recombination from photoionization are self-consistently calculated (PHOTOION)
- Resonant scattering plays an important role (not just pure photoionization)
- AGN radiation dominates





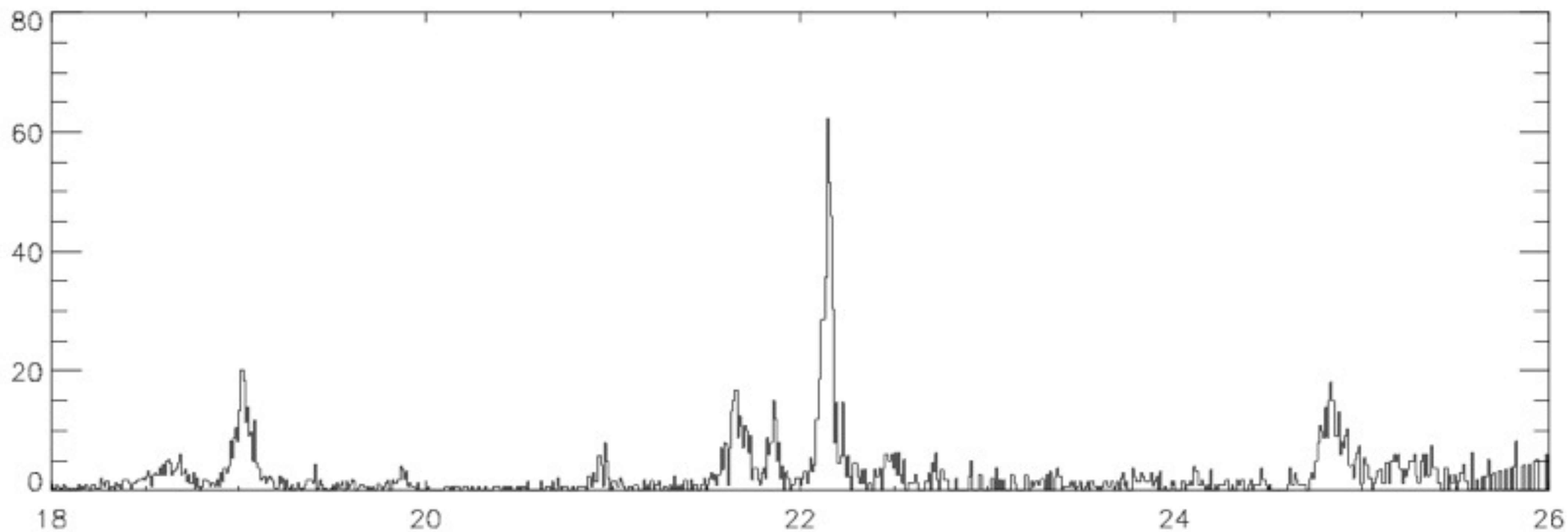




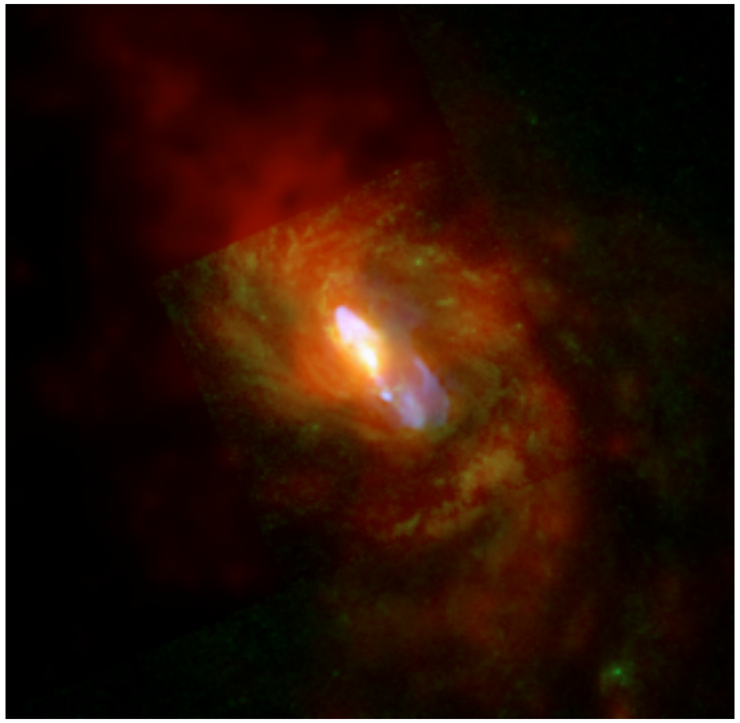
The Prototypical Example - NGC 1068

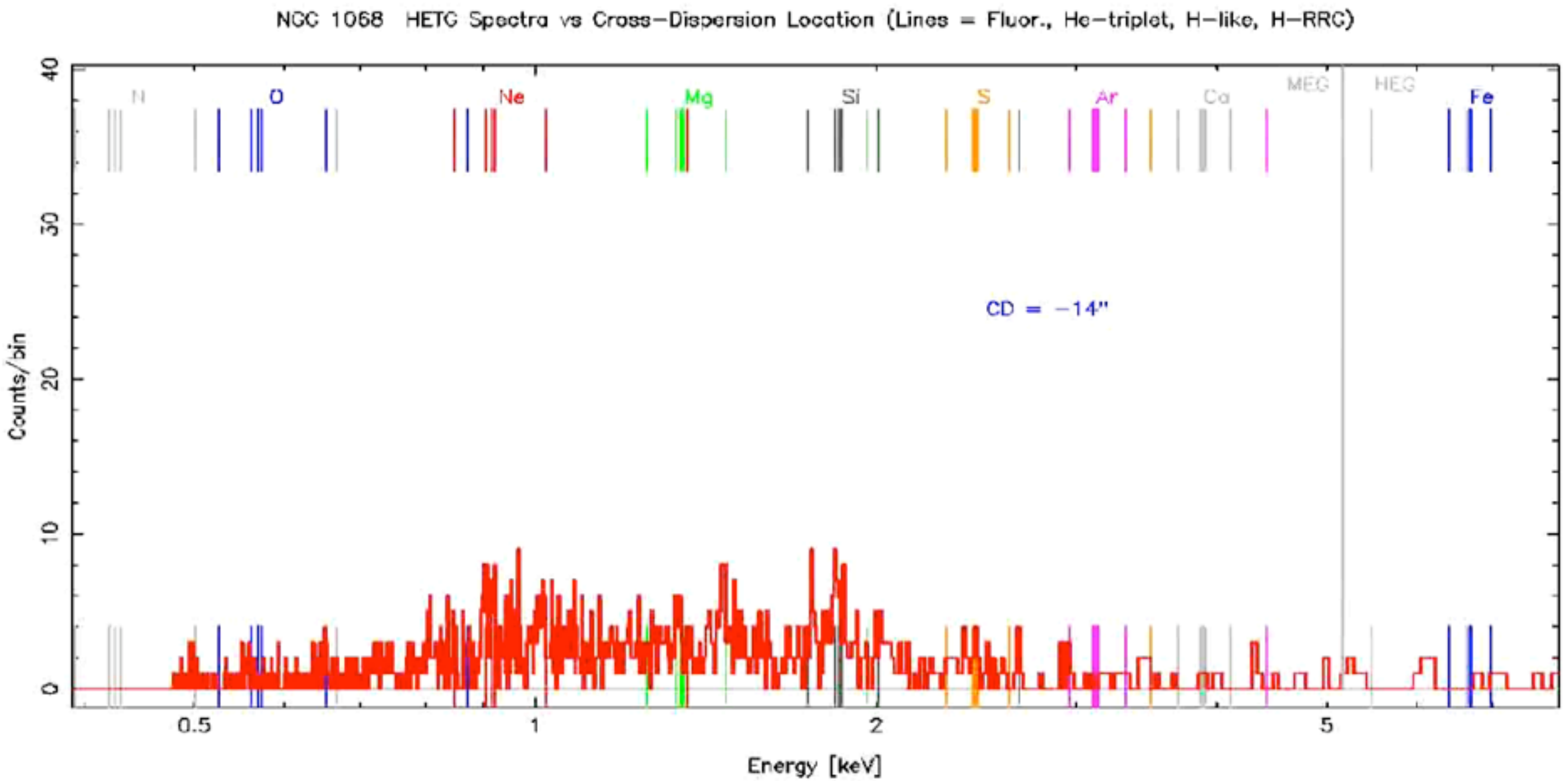
z=0.003793, D_L=16.3 Mpc, 1"=80 pc, Compton thick Seyfert 2

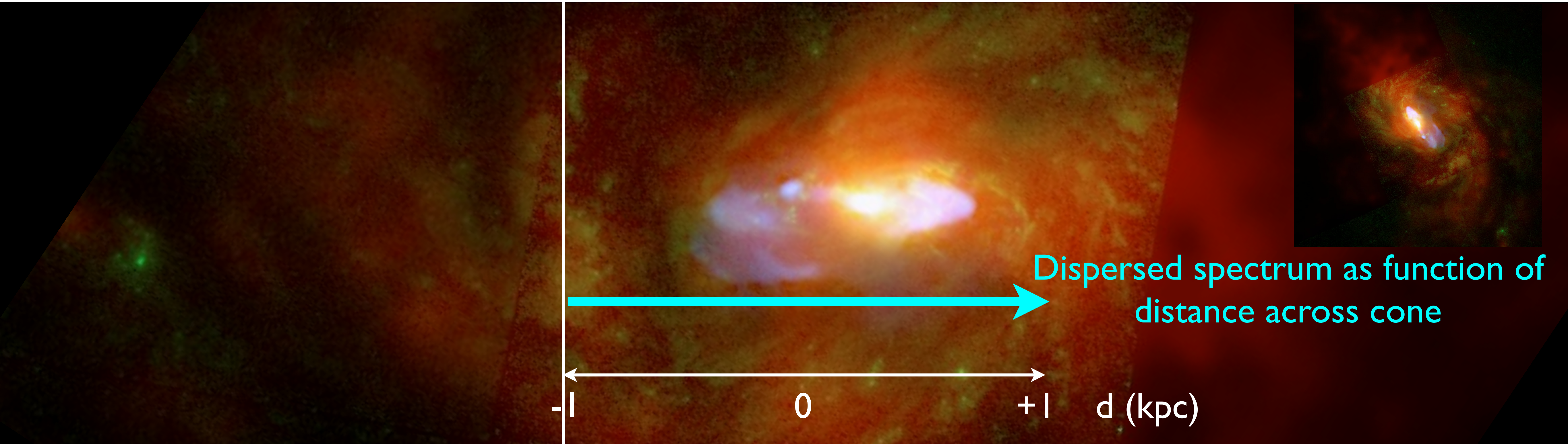
The Prototypical Example – NGC 1068

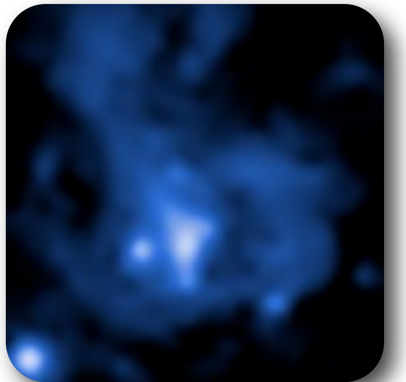


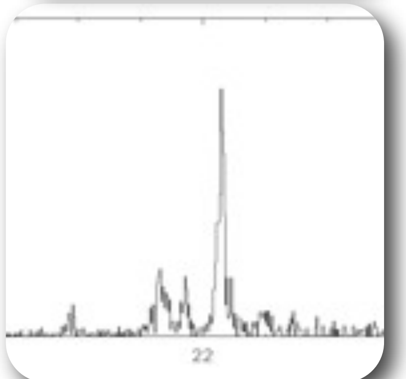
- Ogle et al. (HETG) and Kinkhabwala et al. (RGS) measured H-like and He-like N, O, Ne, Mg, Al, Si, S, narrow RRCs that indicate photoionization
- Fe XVII–XXIV L-shell transitions
- New 400-ks HETG GTO observation (PI Canizares) just performed (Evans et al., in prep.)

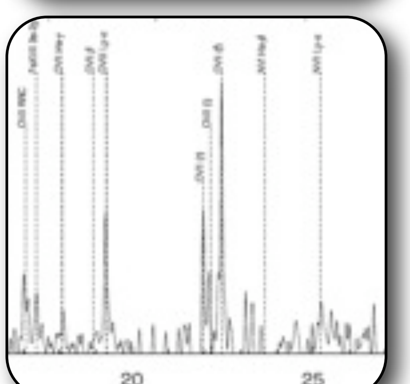



NGC 1068 HETG Spectra vs Cross-Dispersion Location (Lines = Fluor., He-triplet, H-like, H-RRC)
N
O
Ne
Mg
Si
S
Ar
Ca
MEG
HEG
Fe
CD = −14"
Counts/bin
0
10
20
30
40
0.5
1
2
5
Energy [keV]


Dispersed spectrum as function of distance across cone
-1
0
+1
d (kpc)







Summary

- The connection between accretion and jets/outflows is of key importance and is well addressed by X-ray observations (especially HETG)
- HETG plasma diagnostics plus multi-λ imaging powerful probes of ionized environments in Seyferts with outflows
- Photoionization dominates, but significant jet-environment rôle (feedback)
- Where is this going? Systematic intrinsic differences between radio-loud and radio-quiet AGN: accretion flow mode + BH spin governs jet formation? (Ask me for more info...)