HIGH-RESOLUTION CHANDRA, HST, AND VLA OBSERVATIONS OF RADIO-LOUD SEYFERT GALAXIES

Dan Evans (Harvard University), Julia Lee (Harvard), Jane Turner (UMBC), Ralph Kraft (SAO), Stefano Bianchi (Roma Tre), Martin Hardcastle (U. Herts), Herman Marshall (MIT), Sarah Gallagher (UCLA), Kim Weaver (GSFC)

Ionized Environments in AGN

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

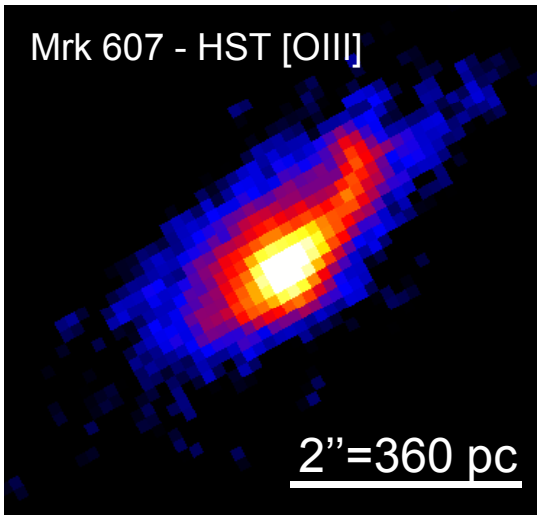
Multiphase ionized circumnuclear environments of Seyfert galaxies ideal places to measure the radiative and kinematic ionizing output of AGN

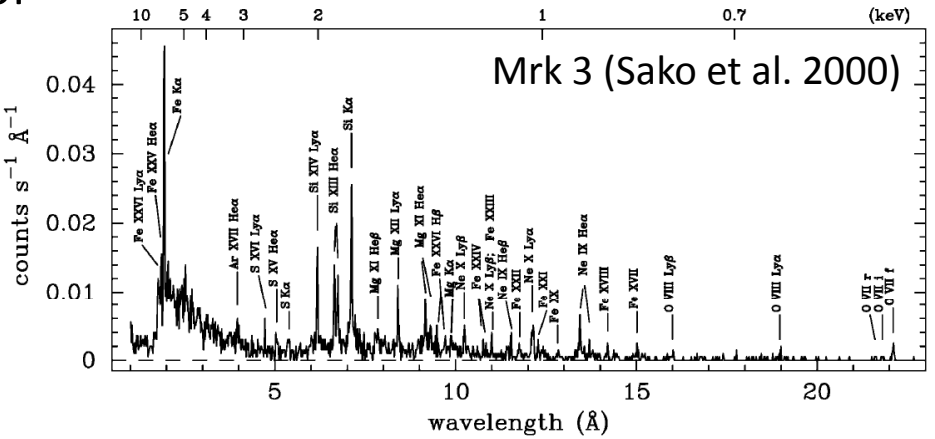
Seyferts show a range of jet/outflow properties, from truly radio-quiet sources to those with kpc-scale jets

- Approach:
  - HETG (and RGS) give detailed plasma diagnostics
  - Chandra and multiwavelength imaging to understand spatial relationships between AGN, jet, and gas, and construct ionization maps

Circumnuclear Environments in Seyferts

- NLR (sub-kpc) and ENLR (up to ~10 kpc) are regions of warm (T~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
- HETG and RGS observations show evidence for He-like triplets, narrow RRC features, indicative of photoionization

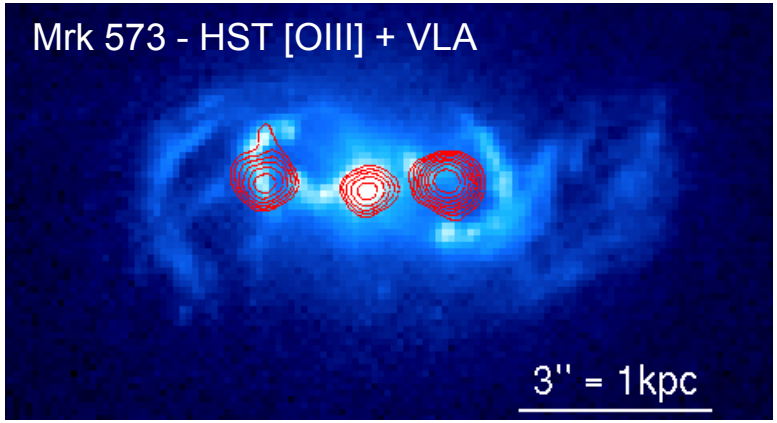


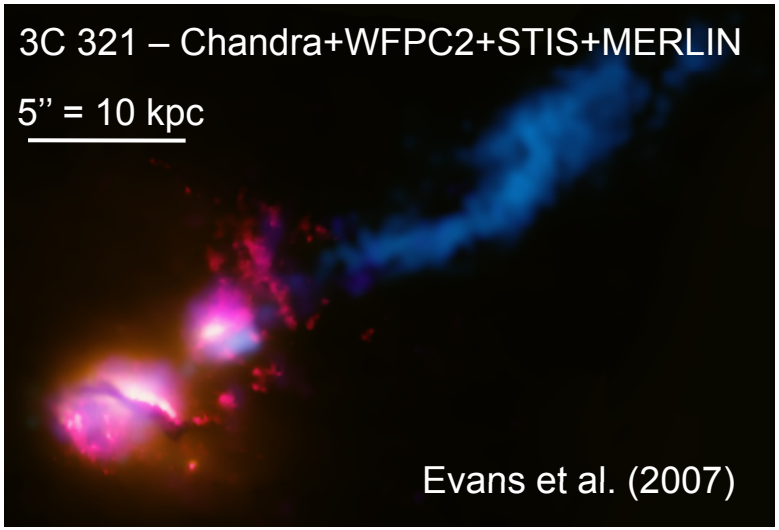


Radio-loud Seyferts

- Although Seyferts are radio quiet, 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?

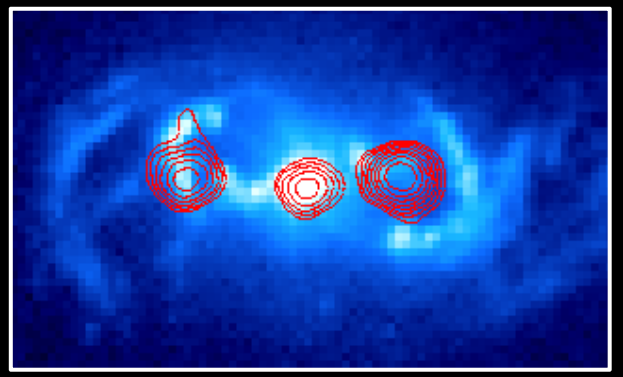
	Radio galaxies	Seyfert galaxies
Size/extent	10s kpc	~kpc
Jet velocity	Relativistic	Sub-relativistic
Shock velocity	1,000s km/s	100s km/s
Ambient medium	IGM/ICM	ISM





Ionization Mechanisms in Seyferts

- **How is the emission produced?**



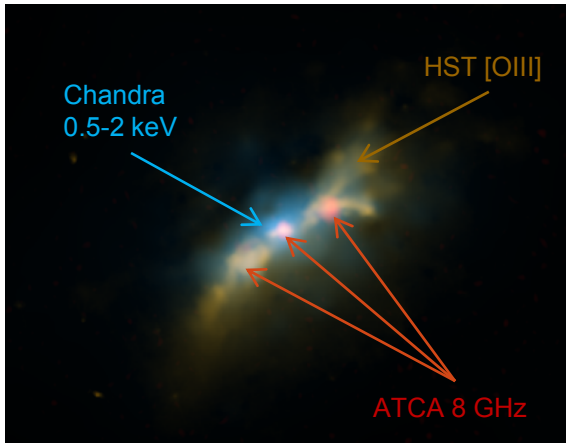
1. Line-emitting gas is shocked, collisionally ionized gas
2. Line-emitting gas is ionized by photons generated in situ in the hot shocked gas ('autoionizing' shock – see Dopita and Sutherland 1995). [Unlikely to be important for X-ray emission]
3. AGN photoionization dominates, though (weak) shocks 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
4. Radio jet plays no role at all; so-called 'pure' photoionization by AGN (e.g., Storchi-Bergmann 1996)

- **HETG observations, plus multi-λ imaging, can distinguish between these models**
- **Part of a large project to combine VLA, HST [OIII], and Chandra/XMM imaging and gratings spectroscopy of Seyferts**

Sample Selection

- 10 X-ray brightest sources from Schmitt et al. (2003) HST [OIII] catalog of Seyferts with:
  1. Seyfert 2 nuclei
  2. [OIII] ionization cones on scales >3”
  3. Range of jet properties (radio-quiet $\rightarrow 10^{40}$ ergs s^{-1}). Intermediate between XRB jets and radio-loud AGN
- Several already published, including NGC 2110 (Evans et al. 2006, 2007)
- Majority have HETG observations, some XMM RGS

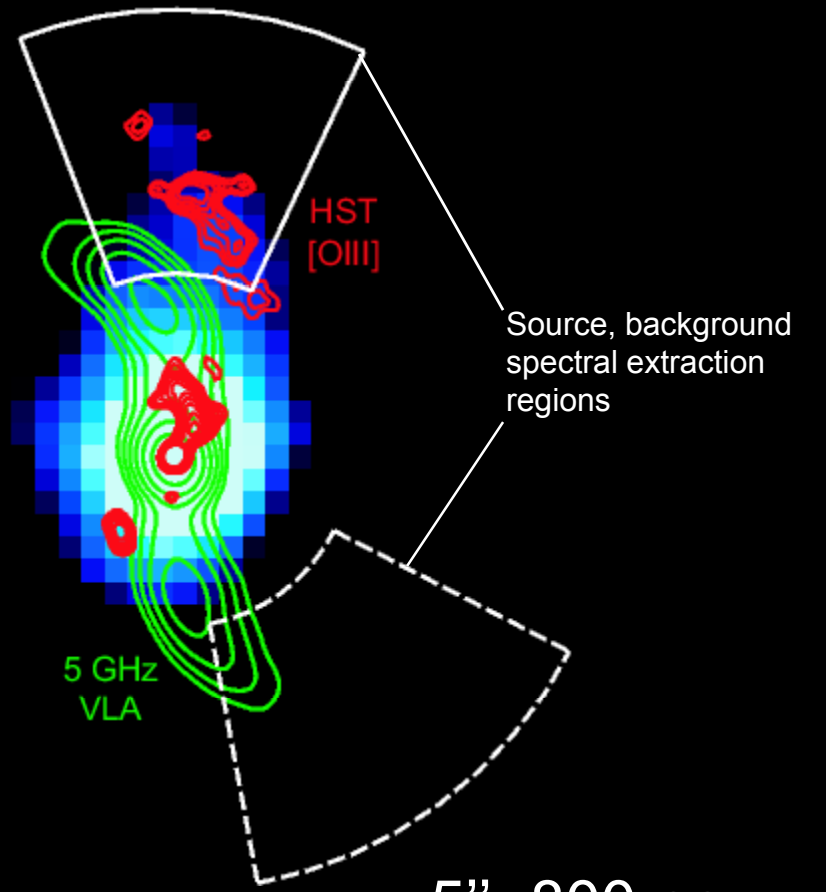
IC 5063 (Evans et al, in prep.)



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

NGC 2110 – Multi-λ + Imaging Spectroscopy

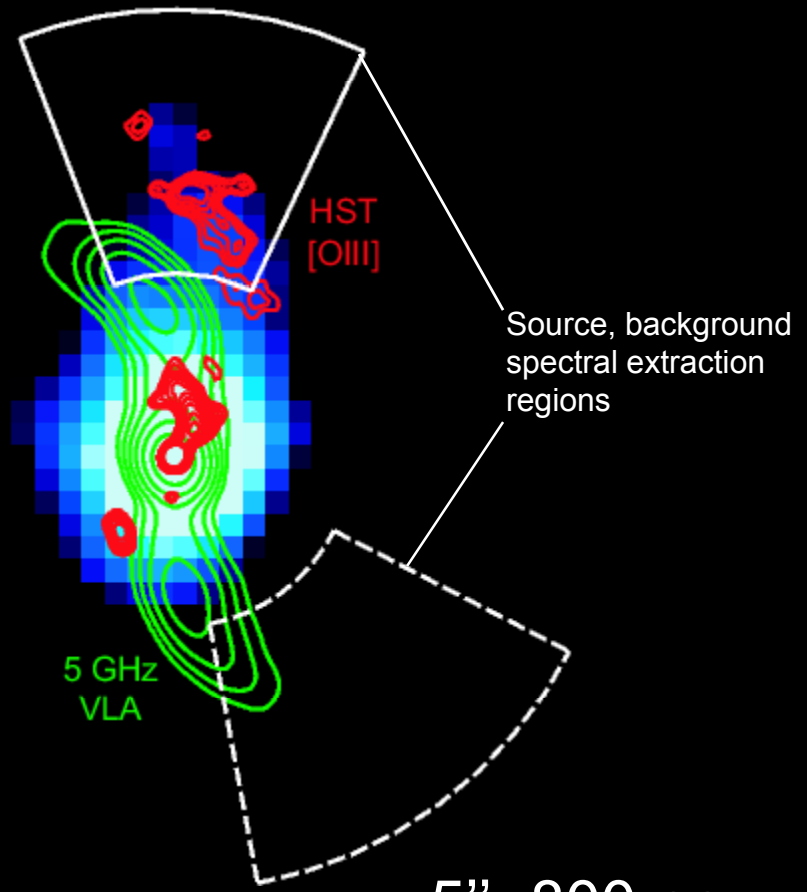
- Excellent spatial agreement between X-ray and [OIII] (Evans et al. 2006)
- Both clearly offset from radio, but extend along similar p.a.
- X-ray & [OIII] emission influenced by, but not directly associated with, radio jet?
- ACIS X-ray spectrum modeled by, e.g., two thermal plasma models (kT_1=0.3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



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

Emission Mechanisms

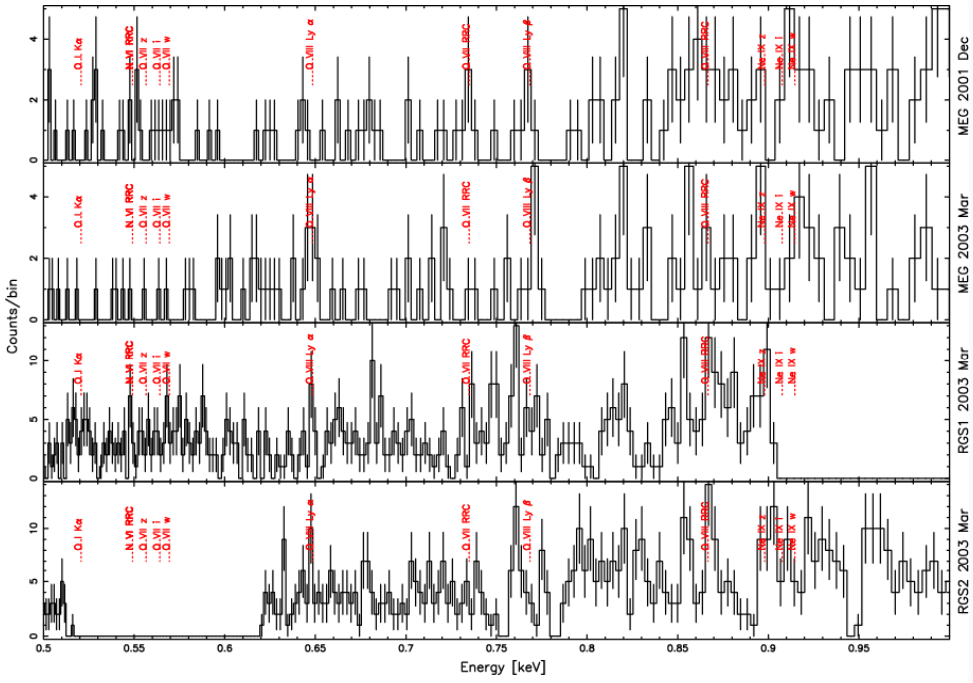
1. Shock heating
   - Minimum pressure of radio lobes, assuming $\gamma_{min}=2$ up to $\gamma_{max}=10^5$, is ~10^{-10} Pa
   - HST [OIII] and [SII] constraints (Ferruit et al. 1999) give pressure few 10^{-10} Pa
   - Chandra spectrum, with plasma model, gives pressure few 10^{-10} Pa
   - Energy imparted to gas ~10^{39} ergs s^{-1}
2. Photoionization
   - Consider extended X-ray luminosity, and use sensible values of ionization parameter and emissivity
   - Nuclear luminosity required to photoionize similar to that measured
   - This mechanism may be energetically viable. Also…



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

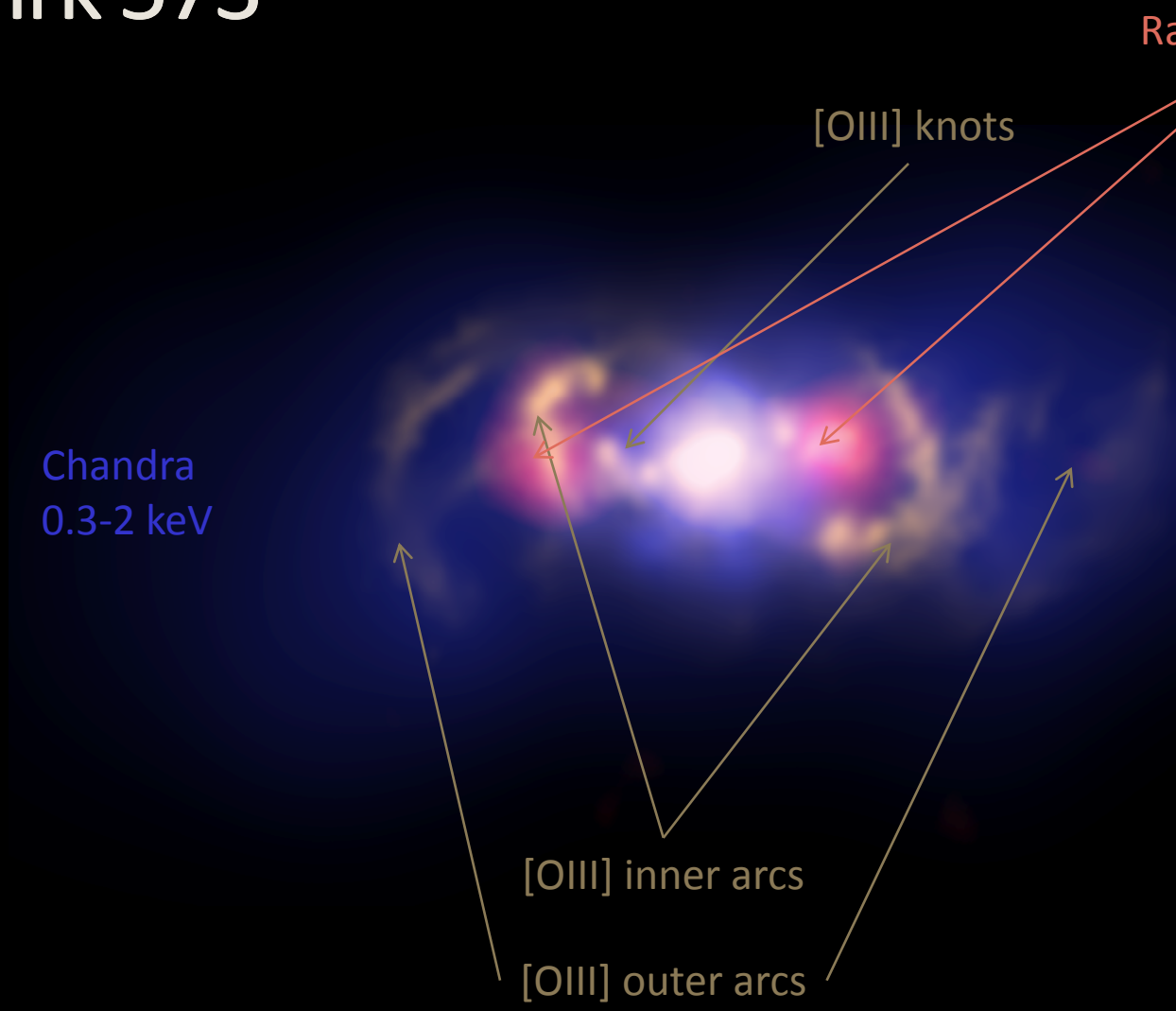
HETG and RGS Spectrum of NGC 2110

- 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 O VII and Ne IX
  3. Low Fe L-shell transition strengths w.r.t. collisional ionization predictions
- X-ray/[OIII]/radio morphology naturally explained by jet-environment interactions



- Photoionization and jet-environment interactions both important?

Mrk 573

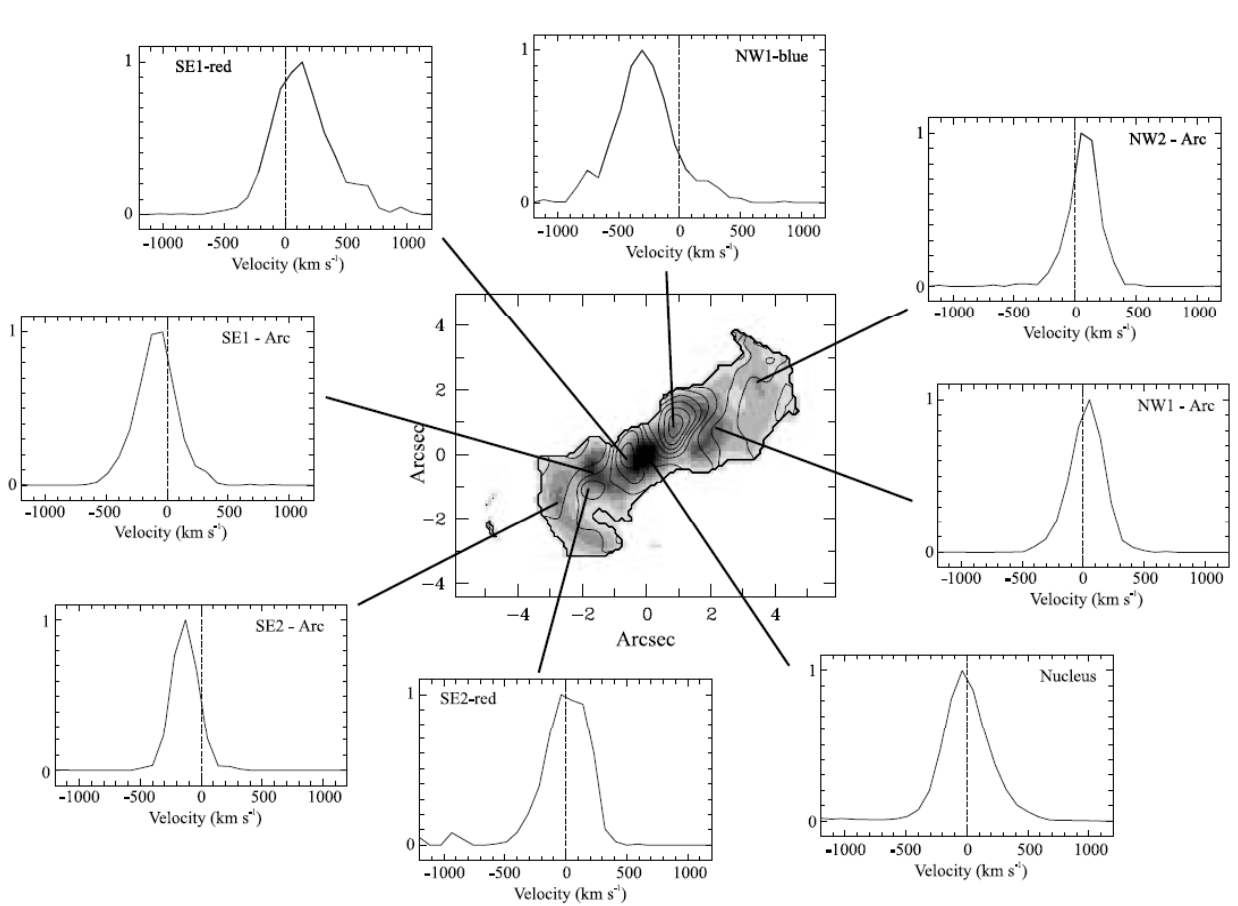


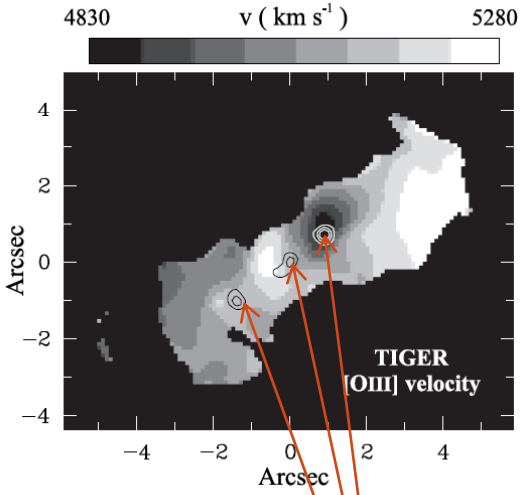
Bianchi et al., in prep.

3'' = 1 kpc

Chandra, HST, and VLA Observations of Radio-Loud Seyfert galaxies

TIGER 3D (x, y, λ) Spectroscopy

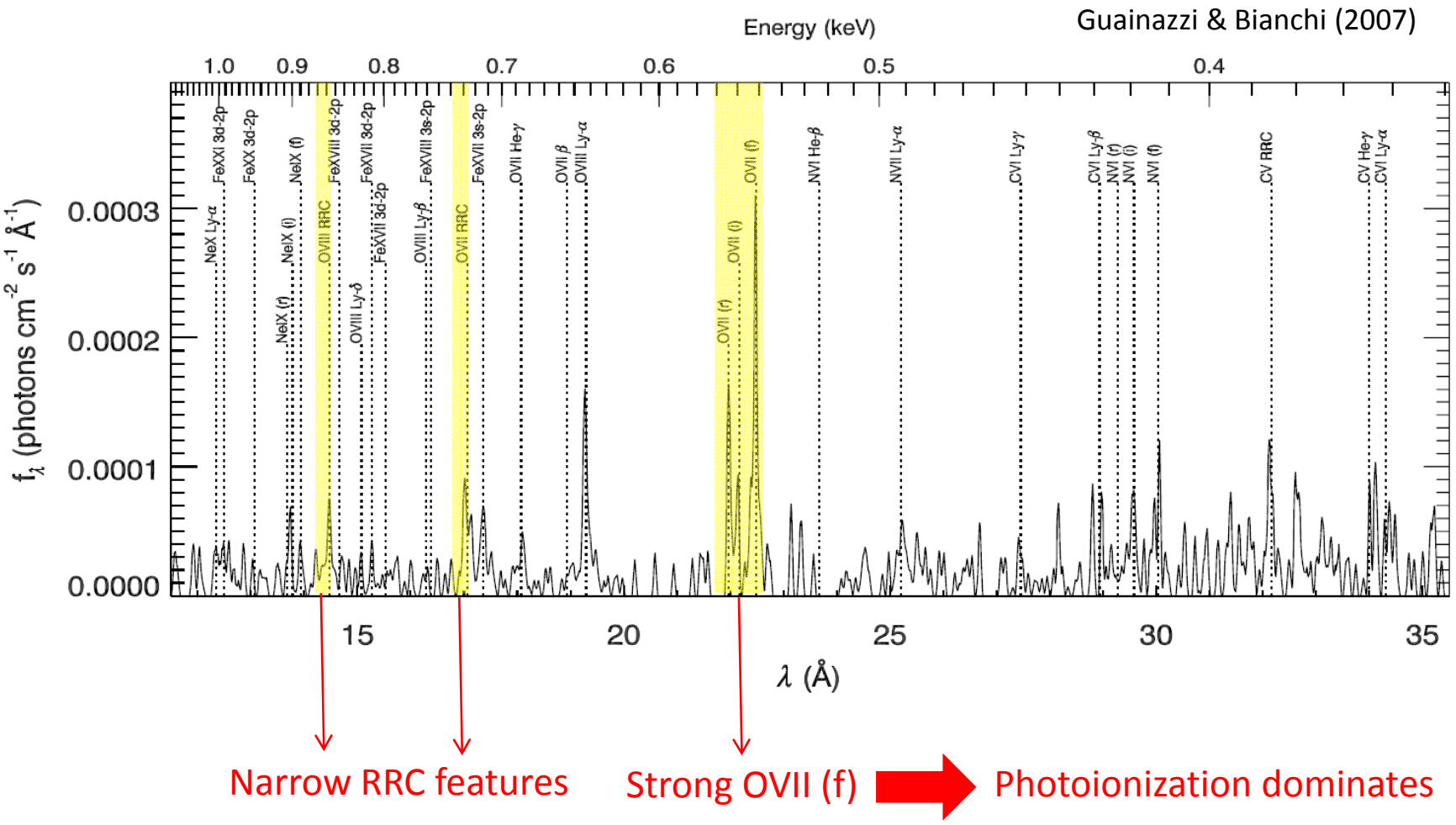


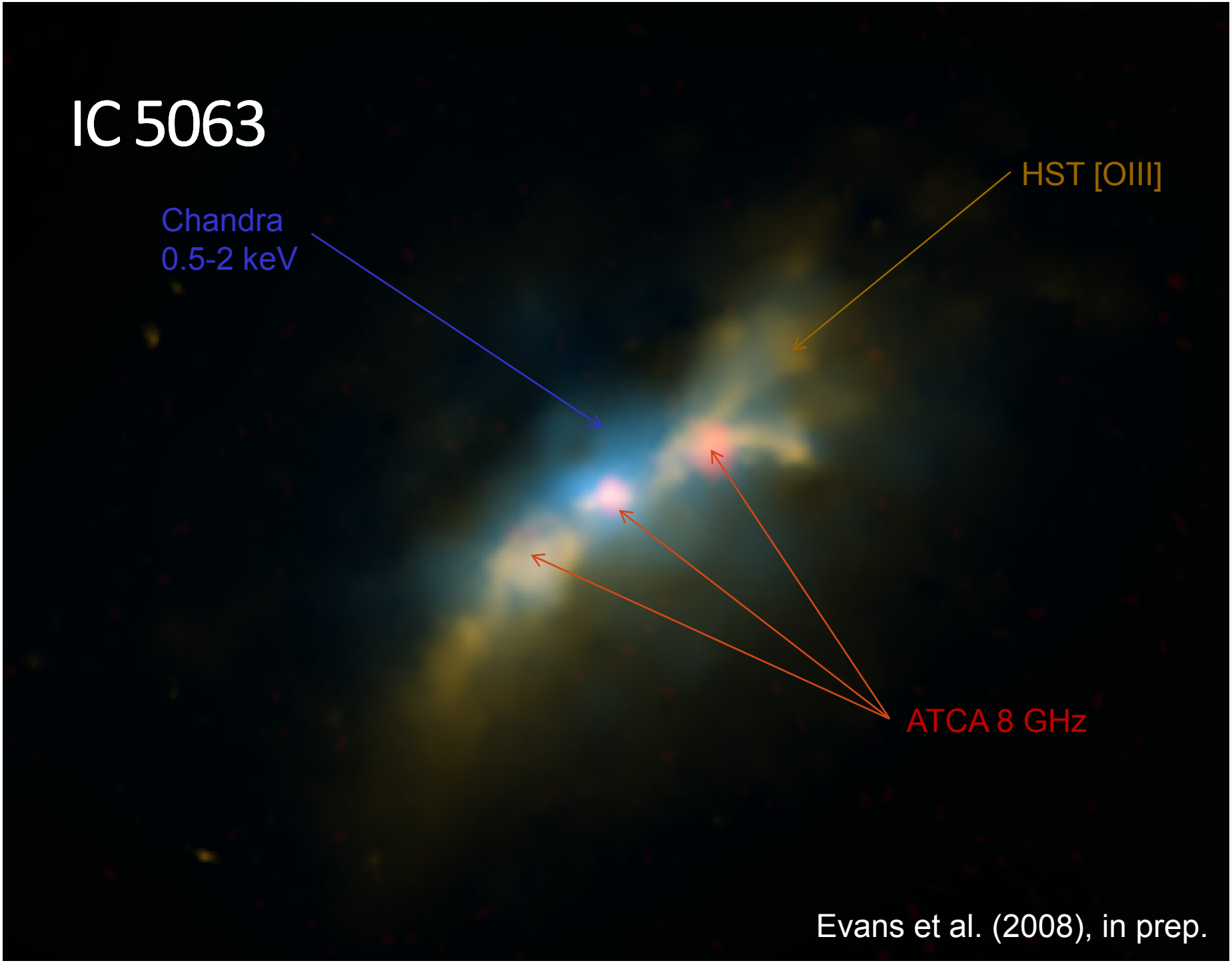


Radio ejecta

[OIII] λ5007 emission-line map with [OIII] isovelocity contours overlaid (Ferruit et al. 1999)

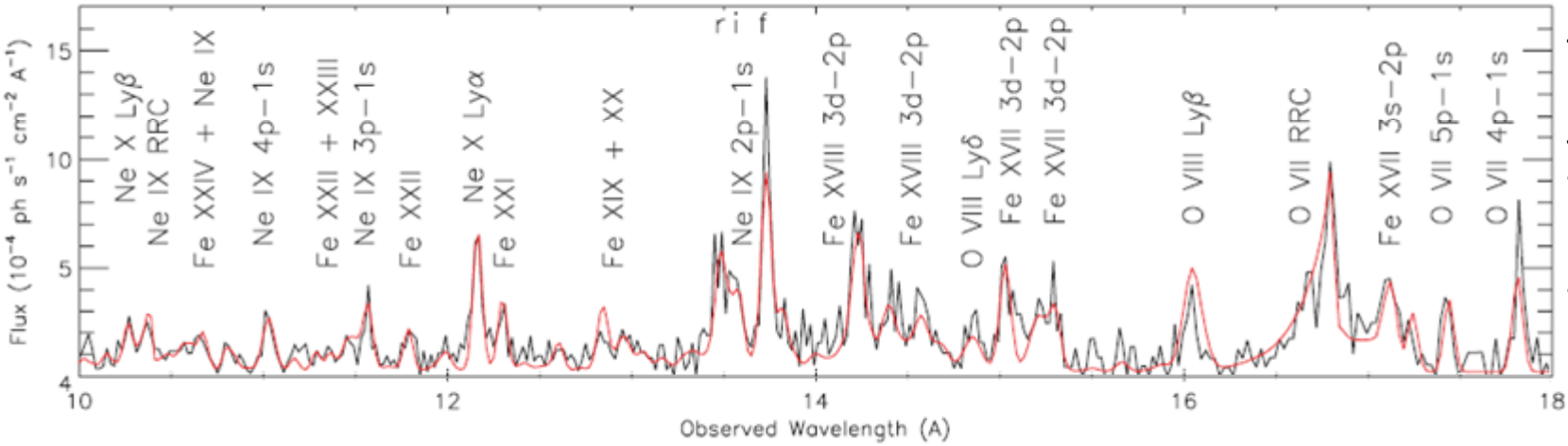
XMM RGS spectrum of Mrk 573





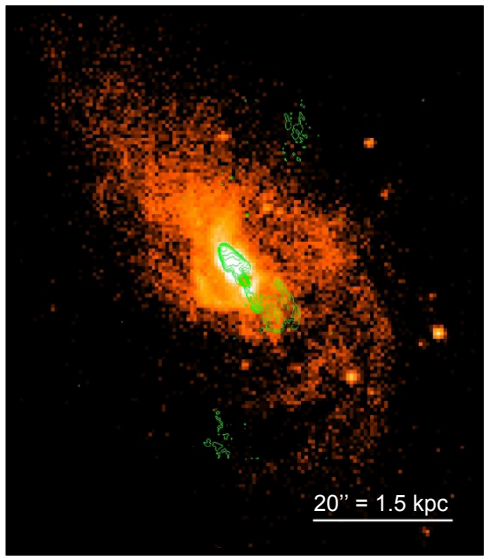
Chandra, HST, and VLA Observations of Radio-Loud Seyfert galaxies

The Prototypical Example – NGC 1068



Ogle et al. (2003)

- H-like and He-like N, O, Ne, Mg, Al, Si, S, narrow RRCs indicate photoionization
- Fe XVII–XXIV L-shell transitions
- HETG spectrum of off-nuclear gas consistent with photoionization
- 400 ks HETG GTO observations coming this fall



SUMMARY

- Chandra HETG plasma diagnostics plus multi-λ imaging are powerful probes of ionized environments in Seyferts with outflows: in principle distinguish between collisional ionization and photoionization
- Seyfert galaxies are radio-quiet, but many are not radio silent.Continuum in radio power (XRBs → RL Seyferts→ Radio galaxies)
- Radio jet may have strong influence on (E)NLR, often resulting in a disturbed environment, with series of arcs, strands, and knots
- Initial results suggest that AGN photoionization dominates, but a significant contribution from jet-environment interactions is also present.
- Detailed diagnostics of several AGN (e.g. NGC 1068) possible with deep HETG observations. Key for next generation of spectrometers