The Multiwavelength Campaign on Mrk 509: Characterizing the UV and X-ray Outflow

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The Importance of AGN Outflows

- ★ **AGN & Black Hole evolution are intertwined with the evolution of the host galaxy.**
- ★ **Their radiative feedback influences the ionization of the IGM.**
- ★ **They may affect dispersal of heavy elements into the IGM and ICM.**
- ★ **We still aren’t sure how the outflows are created, what structure they have, or how much mass and energy they carry.**
- ★ **They are crucial to understanding the central engine:**
  - Accretion process
  - Total energy budget
- ★ **Low-redshift AGN are the nearest and brightest.**
  - ➢ We can study these at the highest angular resolution and best S/N.

X-ray/UV Campaign on Mrk 509 (Fall 2009)

- **XMM/Newton (Kaastra)**
  - 10 x 60 ks at 4-day intervals
- **INTEGRAL (Petrucci)**
  - 10 x 120 ks, matched to XMM
- **Swift (Kaastra)**
  - Simultaneous continuum monitoring in UV and X-ray w/ XRT & UVOT
  - 12 x 1 ks at 4-day intervals establishing baseline before XMM
- **Chandra + HST (Kaastra)**
  - 180 ks Chandra/LETGS: 10 & 12 Dec 2009.
  - 10 orbits HST/COS: 5 on 10 Dec 2009, 5 on 11 Dec 2009.

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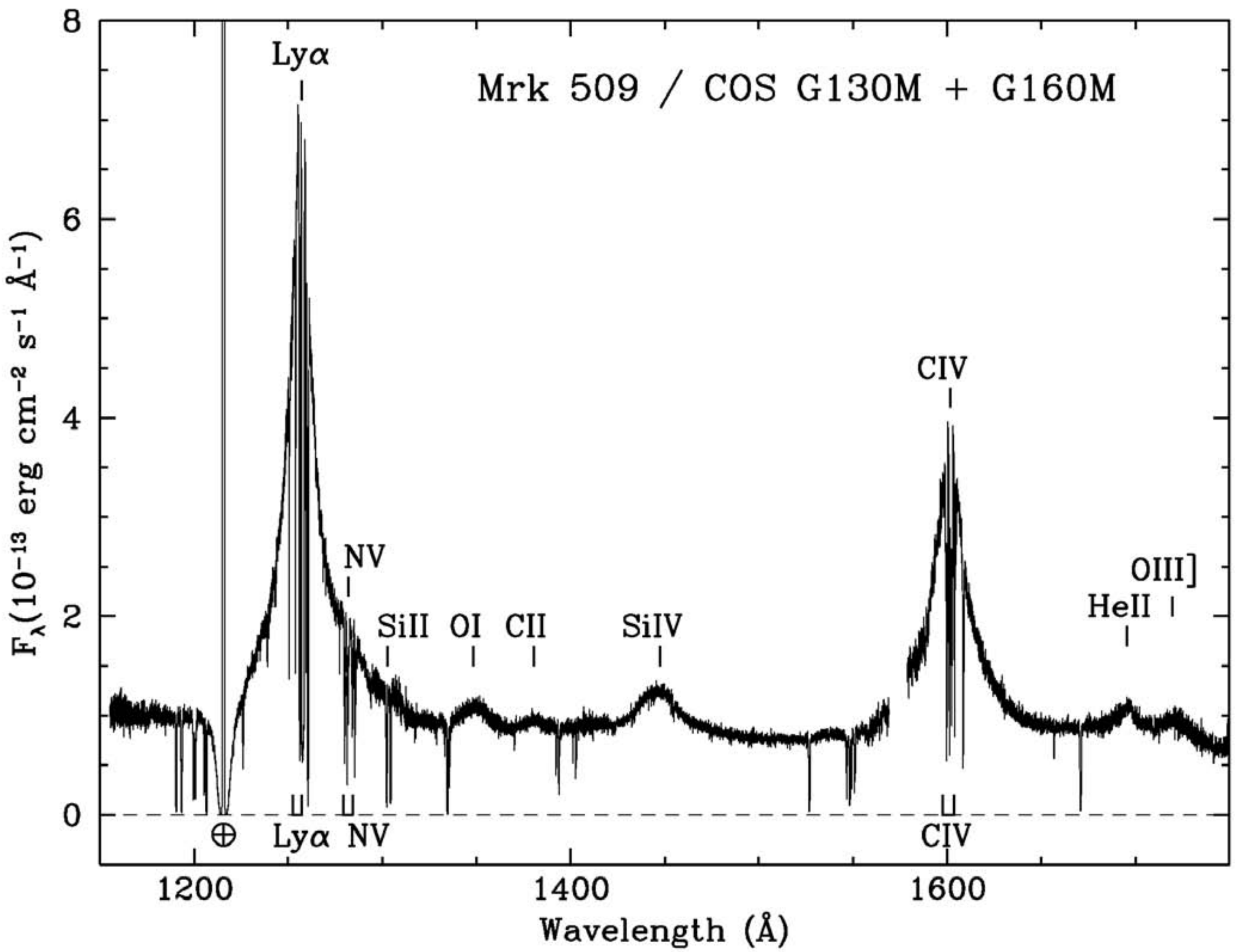
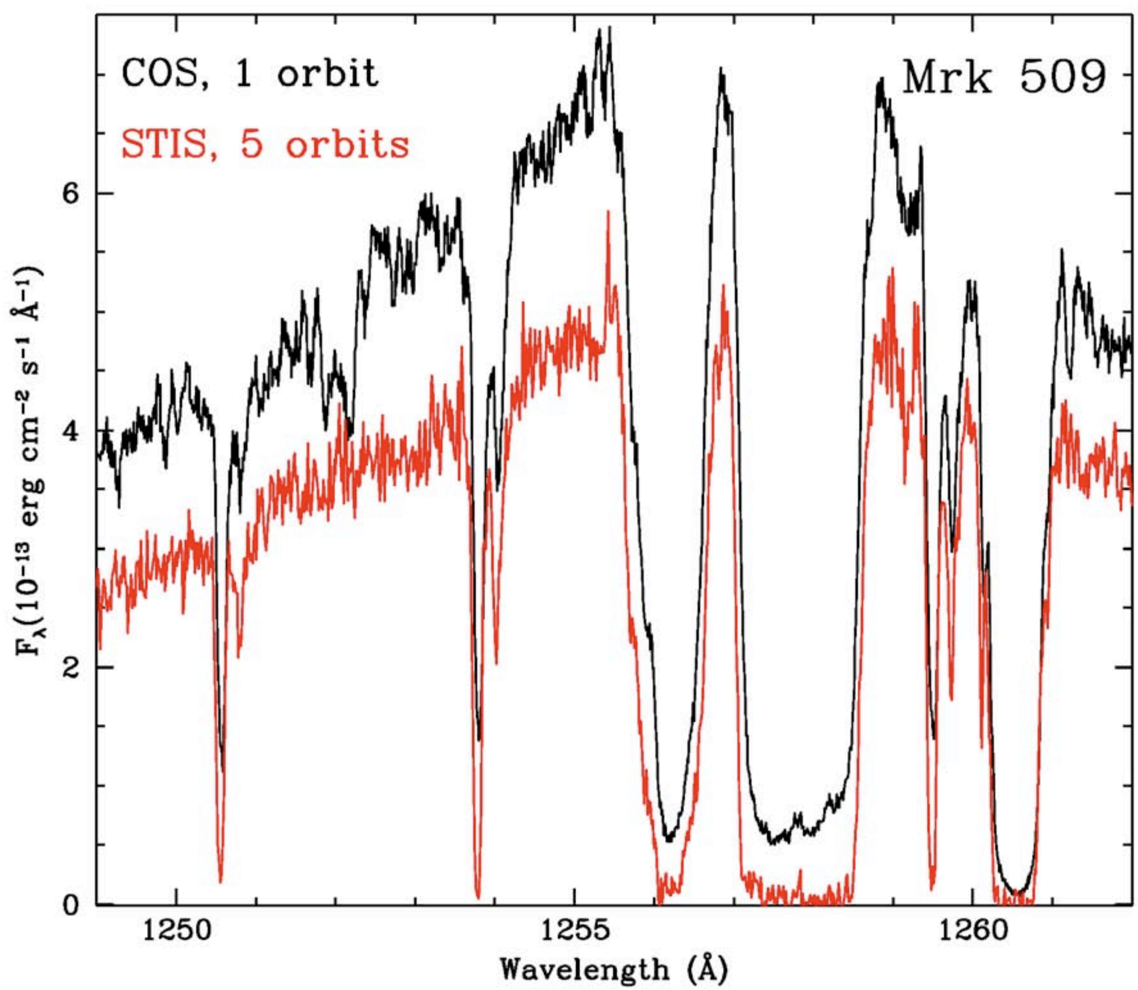
Scientific Goals for the X-ray/UV Campaign on Mrk 509

- ★ Measure time-dependent absorption in the outflowing gas to determine its density, location, mass flux, and kinetic luminosity.
- ★ In the UV, use velocity-resolved measurements of Li-like doublets to determine column density and covering factors for C and N in the outflowing gas.
- ★ Determine abundances of C, N, O, Ne, Si, S, and Fe over a broad range of ionization parameters.

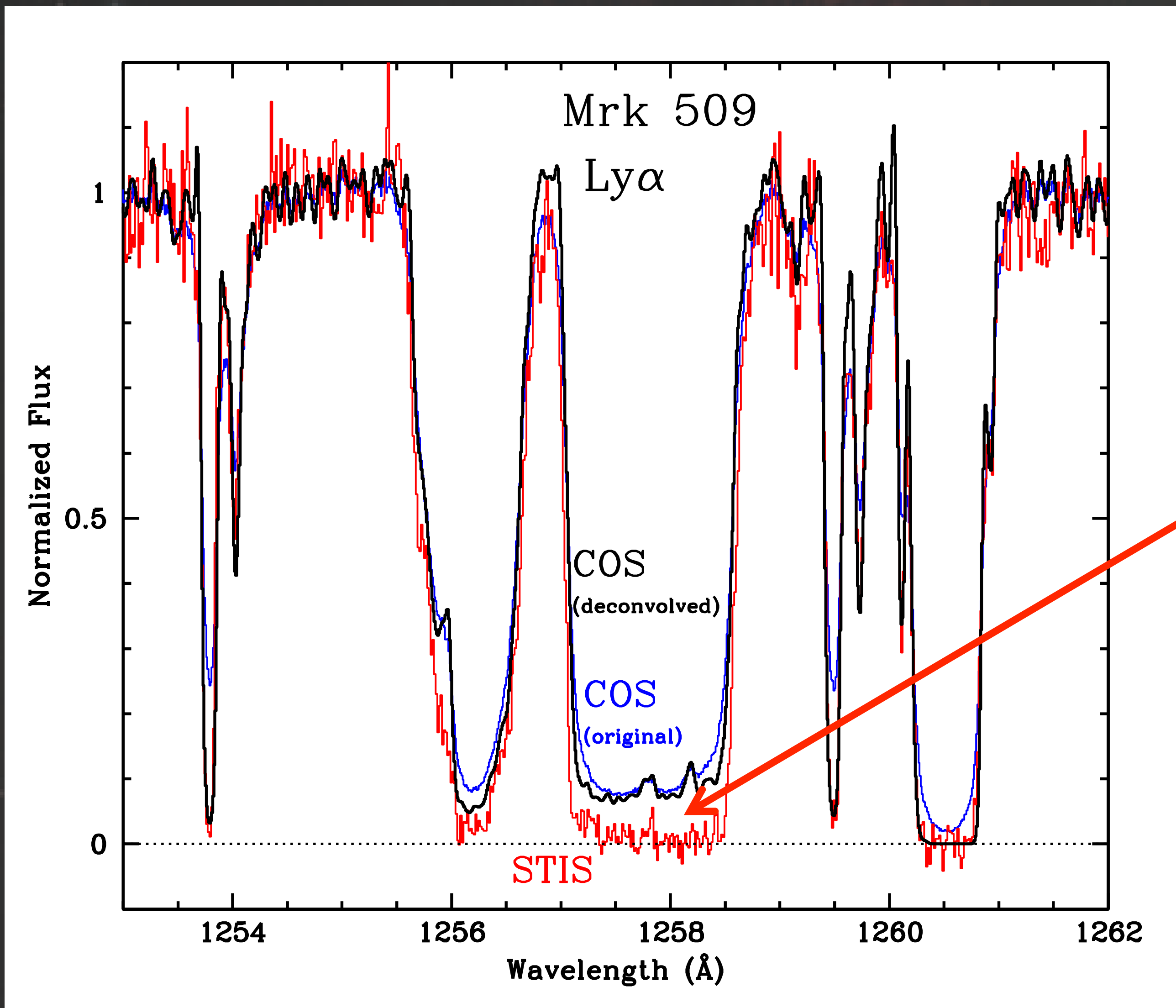
COS Merged Spectrum (5+5 orbits) of Mrk 509



Lyα Region of Mrk 509



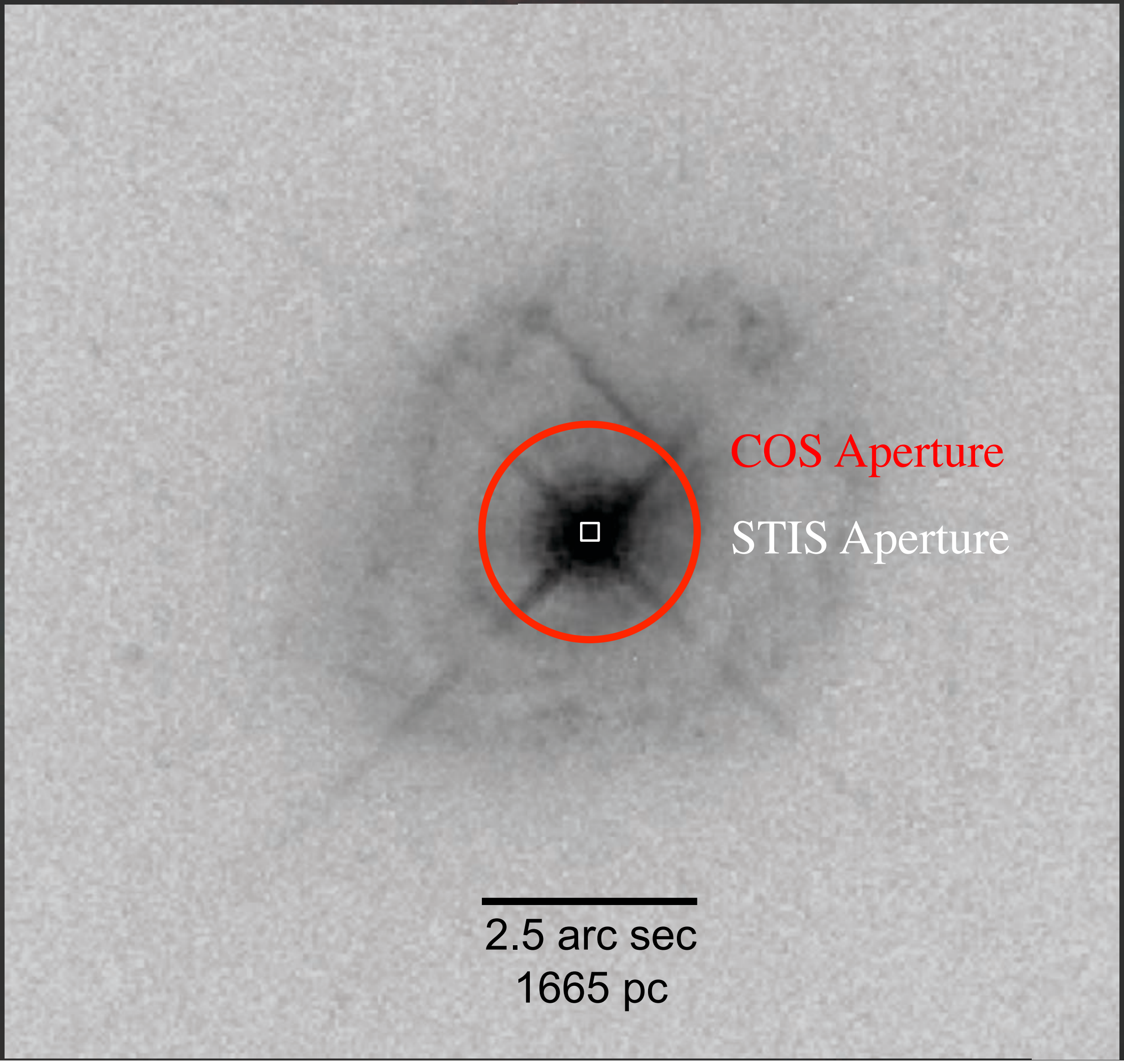
Deconvolved COS Spectrum Compared to STIS



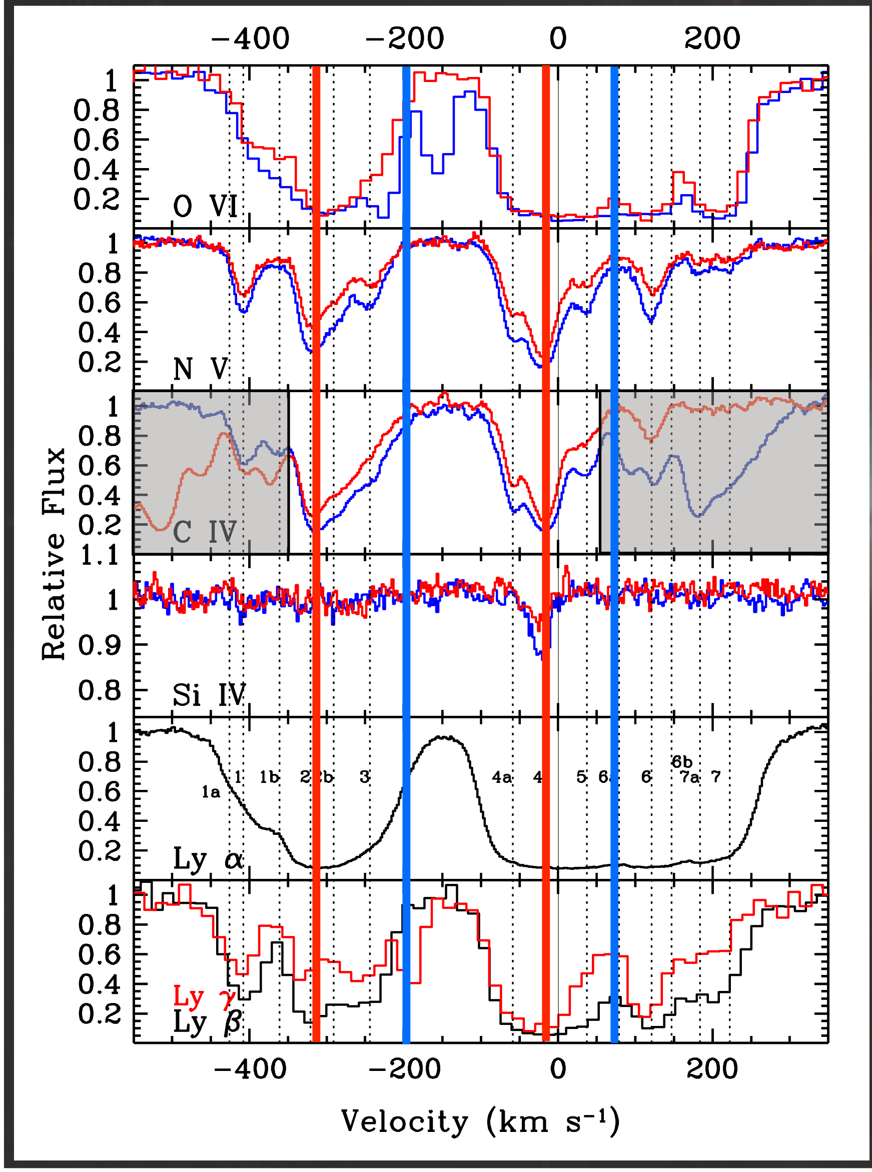
Red: STIS
Blue: Original COS
Black: Deconvolved COS

"Extra" light here is scattered light from a region <0.45" in diameter surrounding the nucleus.

HST WFPC2/F547M Image of Mrk 509

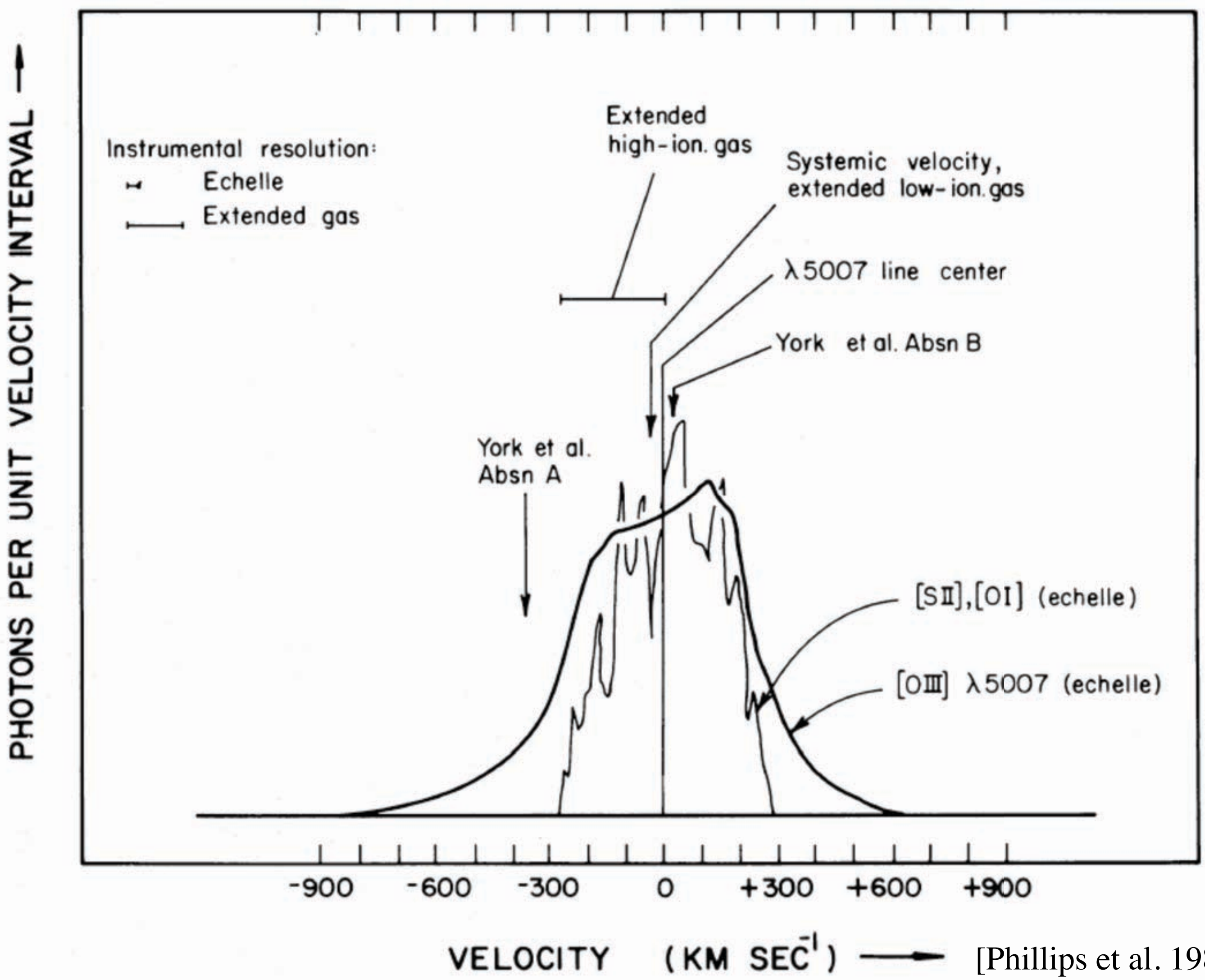


COS & FUSE UV Absorption lines in Mrk 509



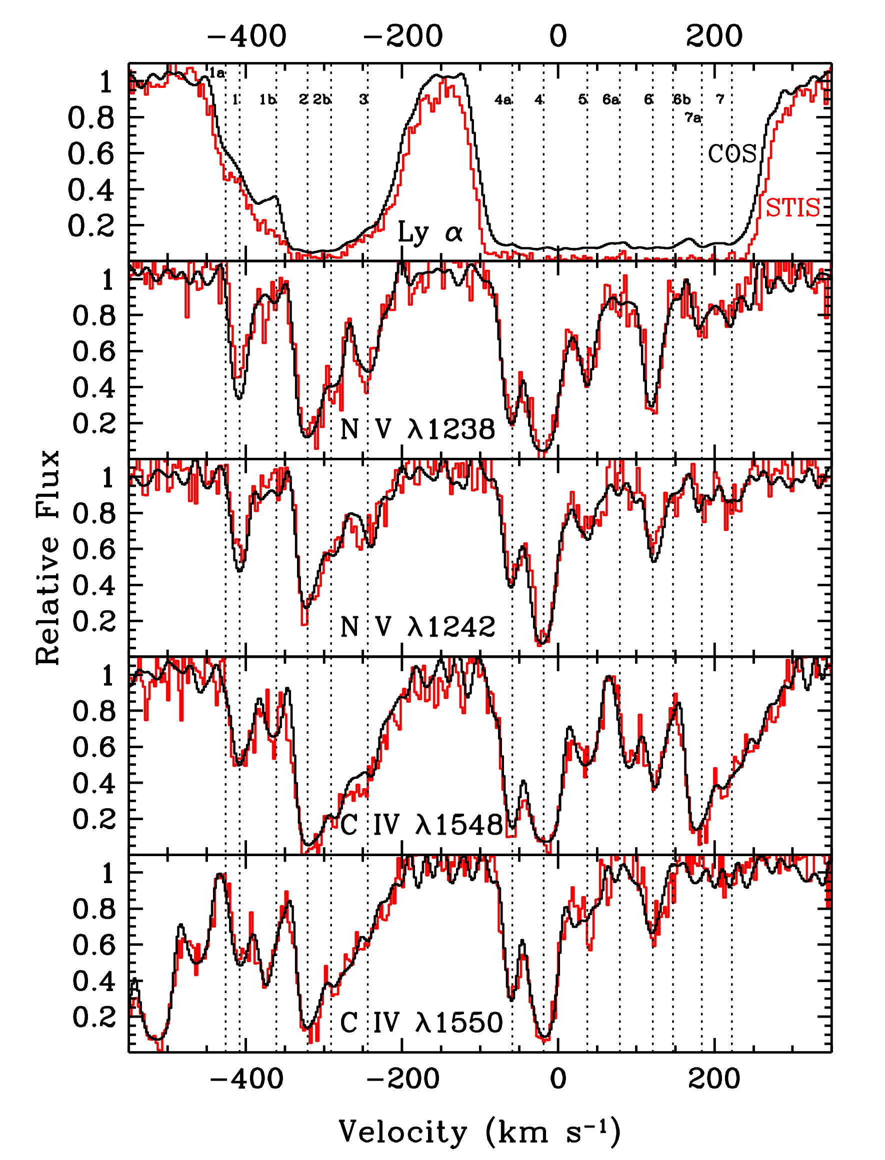
- O VI, Lyβ, and Lyγ from FUSE spectrum [Kriss+00]
- C IV doublet is split by only 500 km s^{-1}, so grey regions can't be used for optical-depth.
- Red lines mark the velocities of the components seen in the RGS spectrum.
- Blue lines mark the velocities of the components seen in the Chandra/LETGS spectrum.

[O III] Line profile in the Nucleus



[Phillips et al. 1983]

Variability between the COS & STIS Spectra



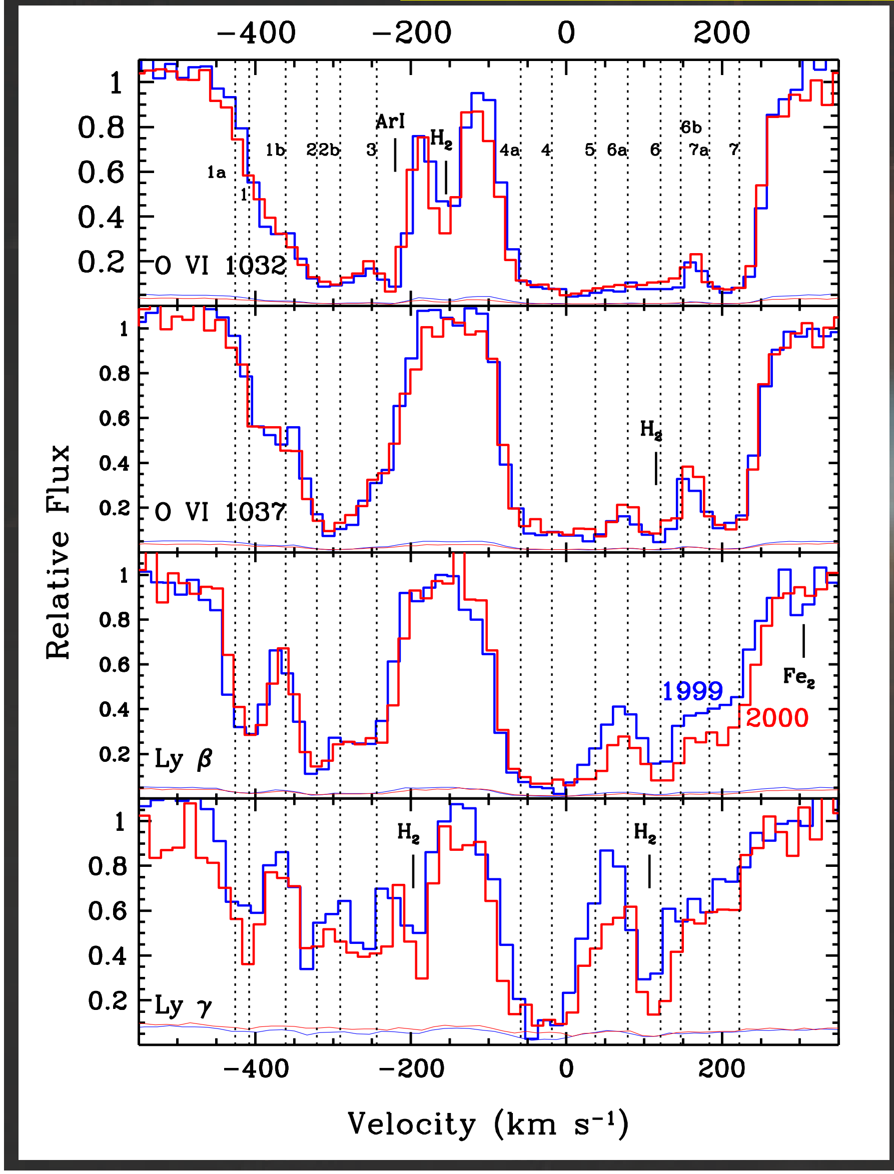
- STIS spectrum from 2001 [Kraemer+03].
- COS spectrum from 2009 [Kriss+11].

- Variations in Component #1 of N V set a lower limit for the density of $n_e > 160$ cm $^{-3}$.

- Given a photoionization model with log $\xi = 0.67$ (Kraemer+03), we get an upper limit on the distance of $r < 250$ pc.

- *Lack* of variability in Components 2–7 gives an *upper* limit on the density and a *lower* limit of $r > 100–200$ pc.
(See poster by Doug Edmonds.)

Variability between the FUSE Spectra



- FUSE spectra from 1999-11-06 [Kriss+00] and 2000-09-05 [Kriss+11].
- Variations in Lyβ and Lyγ in Components 5 and 6 set a lower limit on the density in all of these components of $n_e > 6$ cm^{-3}.
- Given a photoionization model with log ξ = 0.71(Kraemer+03), we get an upper limit on the distance of r < 250 pc.

Interpretation of the Absorption Components

- **Components 1-3 are part of the AGN outflow, although the UV gas is lower ionization than the X-ray.**
- **Similarly, Components 4a, 5-6 are associated with the lower-velocity portion of the X-ray outflow, but again, lower ionization than the X-ray gas.**
- **Component 4 is the ISM+Halo of the host galaxy.**
- **Component 7 at ≈200 km s^{-1}, is infalling to Mrk 509. We suggest that it might be similar to an HVC.**
  - Thom et al. (2008) find that HVC Complex C in the Milky Way has log n ≈ −2.5, dimensions 3x15 kpc, distance of 10 kpc, and a total mass of 8.2×10^{6} *M*.
  - For Component 7 in Mrk 509, for solar abundances, the total hydrogen column is $\sim 4\times10^{18}$ cm^{-2}. If this is similar to Complex C, its size is 1.3 kpc, and its distance from the center of Mrk 509 is 19 kpc.

Implications for Feedback

- Most feedback models require a total energy input from the active nucleus of $\gtrsim$5% of L_{bol} to significantly influence the evolution of the host galaxy.

- The density and distance limits for Component #1 allow us to evaluate the mass flux and kinetic luminosity:

  - $\dot{M}_{out} = 4\pi\ \Delta\Omega\ r\ N_H\ \mu m_p\ v_{out} = 3\pi(r/250\ \mathrm{pc})(N_H/1.0\times10^{19}\ \mathrm{cm}^{-2})(v/400\ \mathrm{km\ s}^{-1}) < 0.12\ M_\odot \mathrm{yr}^{-1}$

  - $L_k = ½\ \dot{M}_{out}\ v_{out}^2 < 6.4\times10^{39}\ \mathrm{erg\ s}^{-1}$

  - We measure $L_{bol} = 6.4\times10^{45}\ \mathrm{erg\ s}^{-1}$ (which requires $\dot{M}_{acc} \sim 1.1\ M_\odot \mathrm{yr}^{-1}$), so

  - $L_k/L_{bol} < 1\times10^{-6}$

What would constitute a significant outflow?

We need sufficient mass flux and velocity so that

$$L_k = \tfrac{1}{2}\,\dot{M}_{out} v_{out}^2 \;>\; 5\%\, L_{rad} = 5\%\,\eta\,\dot{M}_{acc} c^2$$

If $\dot{M}_{out} \sim \dot{M}_{acc}$, then

$$v_{out}^2 > 2 \times 5\%\,\eta\,c^2$$

Since $\eta \sim 0.1$,

$$v_{out} > 0.1\,c$$

Summary

- ★ **Mrk 509 shows 14 intrinsic absorption components in the UV spectrum.**
- ★ **The absorbers are both blue shifted and redshifted.**
- ★ **At least 2 of these are kinematically associated with X-ray absorbers:**
  - One or more (Components #1, 1a, 2, 2a, 3) are associated with the blue-shifted outflow from the nucleus.
  - Another (Component #4) may be associated with the halo or ISM of the host galaxy.
- ★ **The UV absorbers have lower ionization and lower column density gas than that causing the X-ray absorption.**

  ⇒UV-absorbing gas is due to higher density clumps embedded in an X-ray absorbing wind?

- ★ **Limits on the density and distance of the absorbers show that their kinetic luminosity is insufficient to cause significant feedback.**