Inflows, Outflows, and Rotation in the Narrow-Line Regions of Seyfert Galaxies

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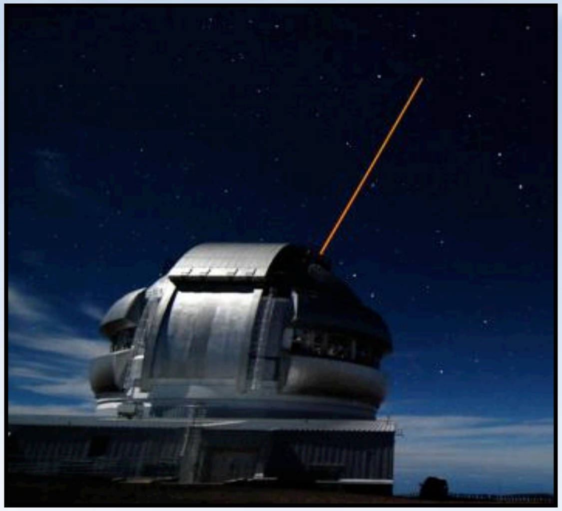
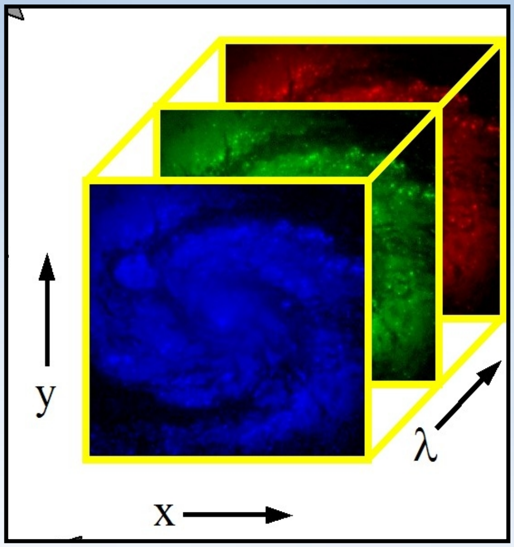
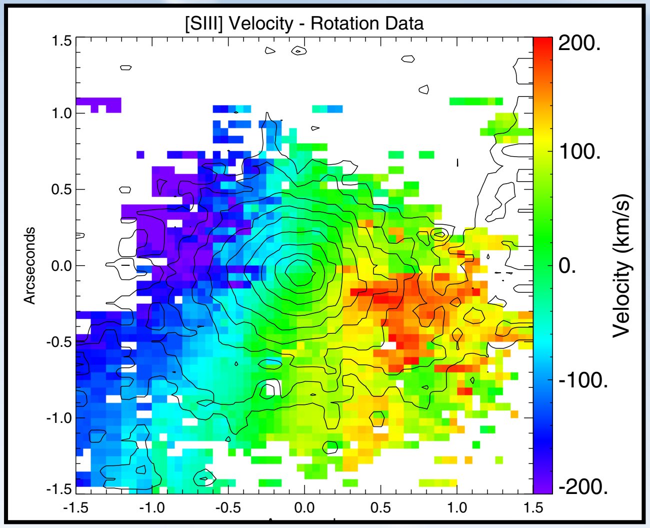
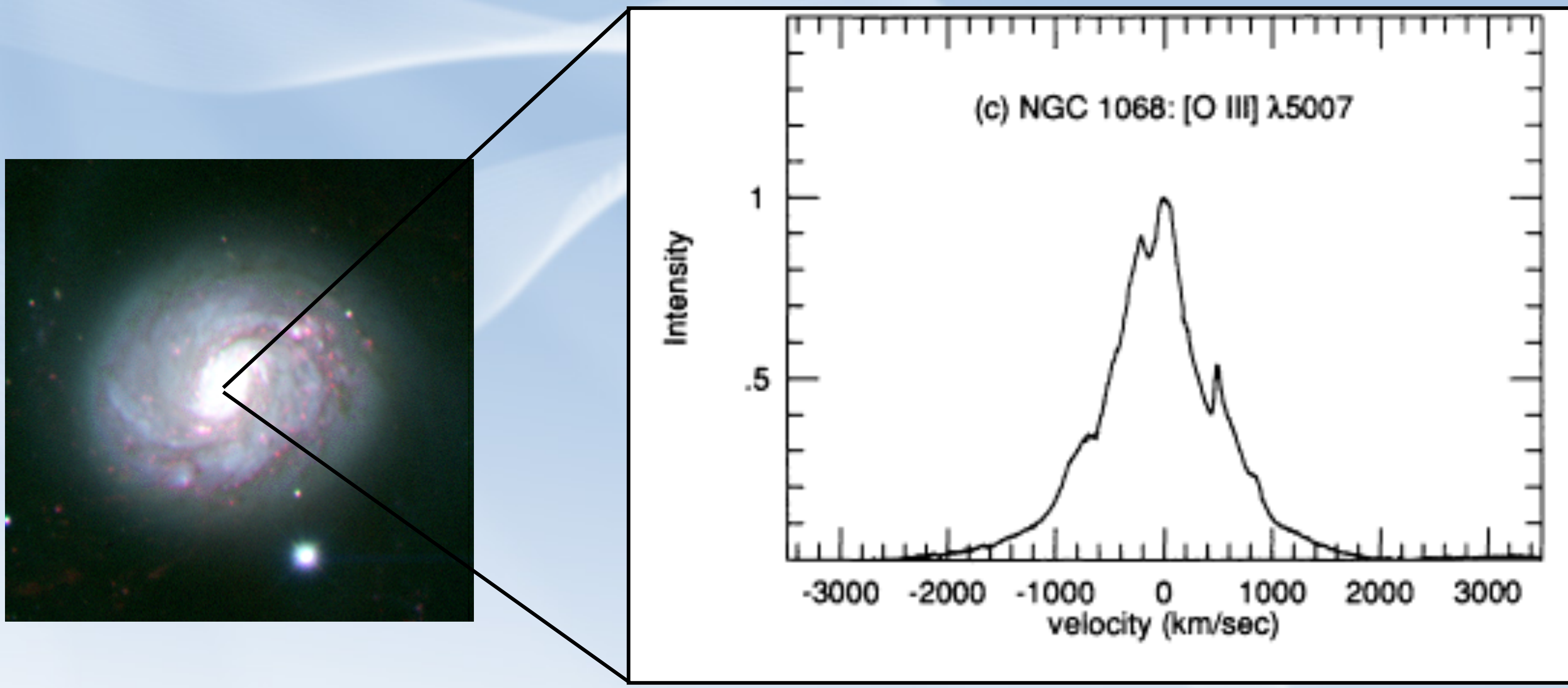






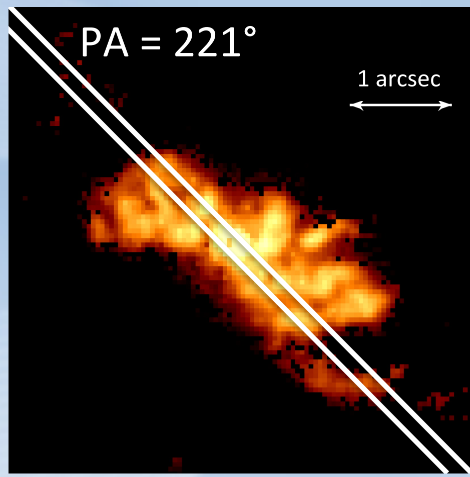
Before *HST*, the NLR was mostly unresolved.

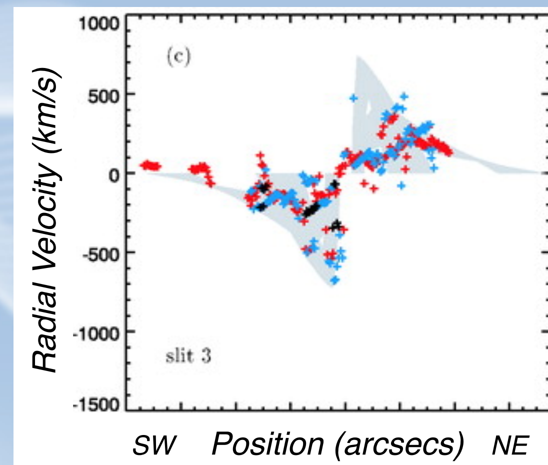


(Veilleux, 1991, ApJS, 75, 357)

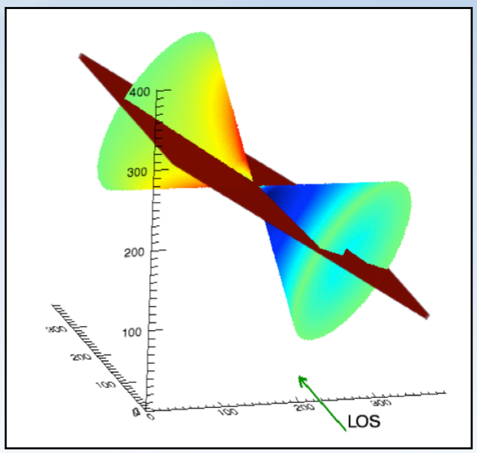
In the past, investigators claimed infall, rotation, outflows, parabolic orbits, etc.

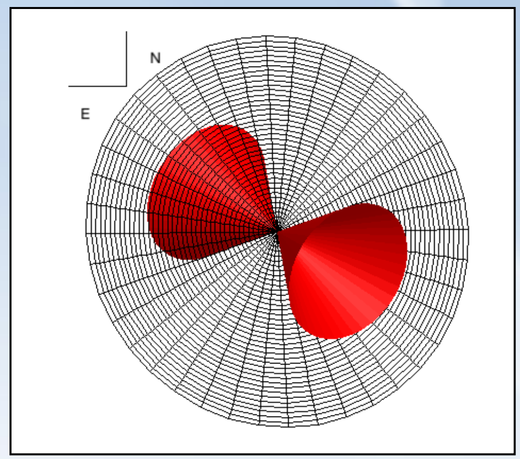
HST images resolved the NLR, and we used *HST*/STIS to study the kinematics with biconical outflow models.





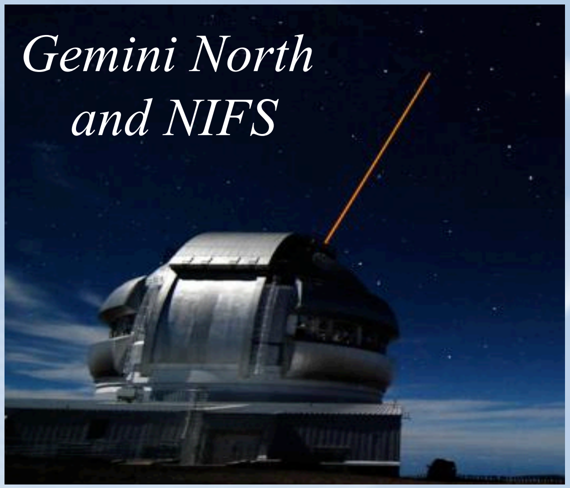
(NGC 4151: Das+ 2005, AJ, 130, 945)

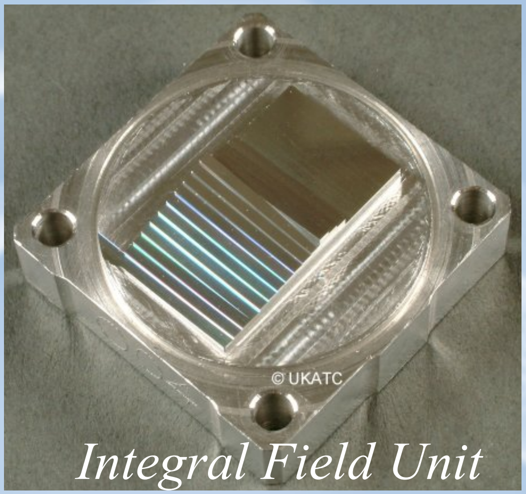


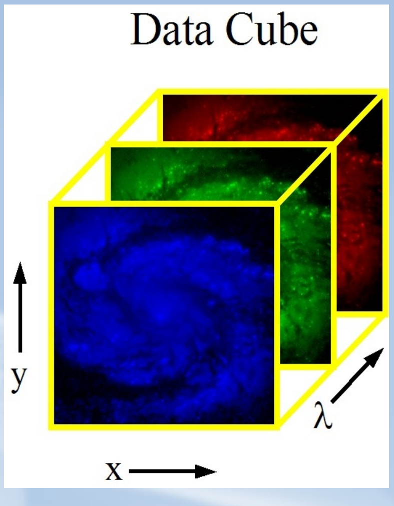


- However, a single long-slit spectrum may be misleading.
- Kinematic maps of the NLR are needed → IFUs.

IFUs (+ AO) can map the NLR kinematics.







- Integral Field Units (IFUs): image slicers, lenslets, and/or fibers obtain spectra over a field of view. Adaptive optics (AO) resolves NLR structure.
- Ex) *Gemini's* Near Infrared Field Spectrometer (NIFS):
  - $\lambda/\Delta\lambda \approx 5000$, ~ 0.1″ resolution, 0.9 – 2.4 μm coverage, 3″ x 3″ FOV.
    → 3600 spectra in one observation
  - Z band: [S III]; J band: [Fe II], Pβ; K band: Brγ, H_2, CO stellar.
- Other IFU Observations of AGN NLRs:
  - *Gemini* GMOS: Storchi-Bergmann+, Rupke+
  - *Keck* OSIRIS: e.g., Hicks+
  - *ESO VLT* SINFONI: e.g., Davies+

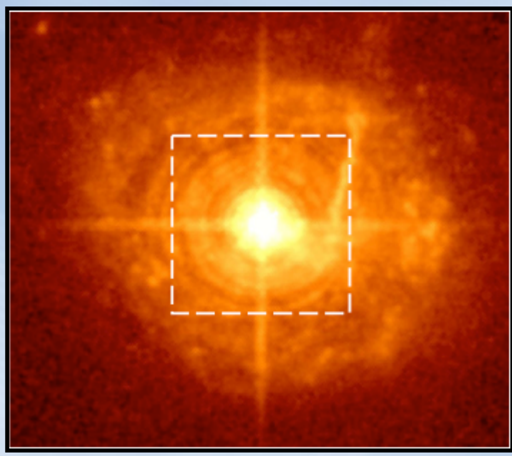
What can kinematic mapping of the NLR tell us?

- Is the gas in the NLR rotating, infalling, or outflowing?
- What is the origin of NLR outflows?
- Can NLR outflows provide significant AGN feedback?
- How are AGN fueled on NLR scales (1 – 1000 pc)?

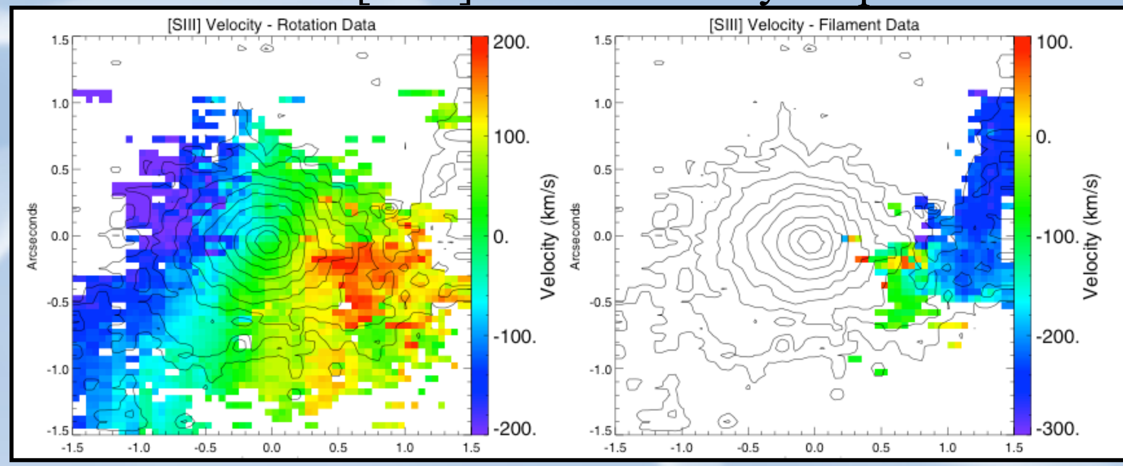
Let's look at some examples →

Mrk 509 (Seyfert 1) is being fueled by a minor merger.

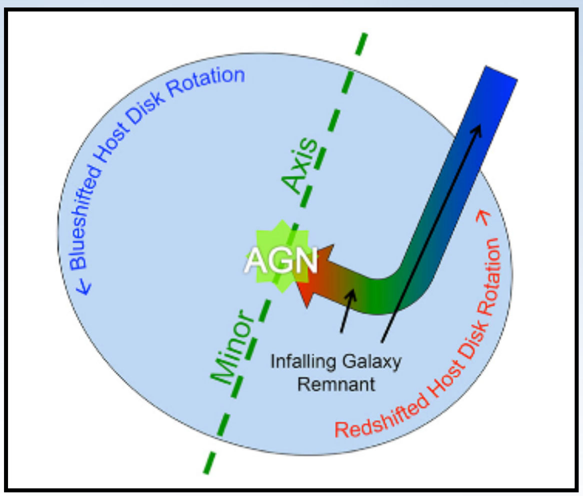
HST [O III] Image



NIFS [S III] Radial Velocity Maps



(Fischer + 2015, ApJ, 799, 234)

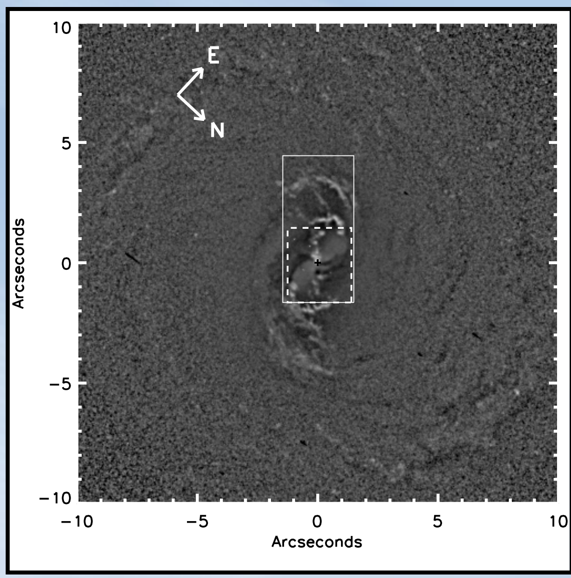


(Fischer + 2015)

→ *rotation* and *inflow*

- Liu, Arav, & Rupke (2015) also find *outflows* to ~1.2 kpc (~1.7″) using GMOS.
- Emission properties similar to those of UV absorption outflows.

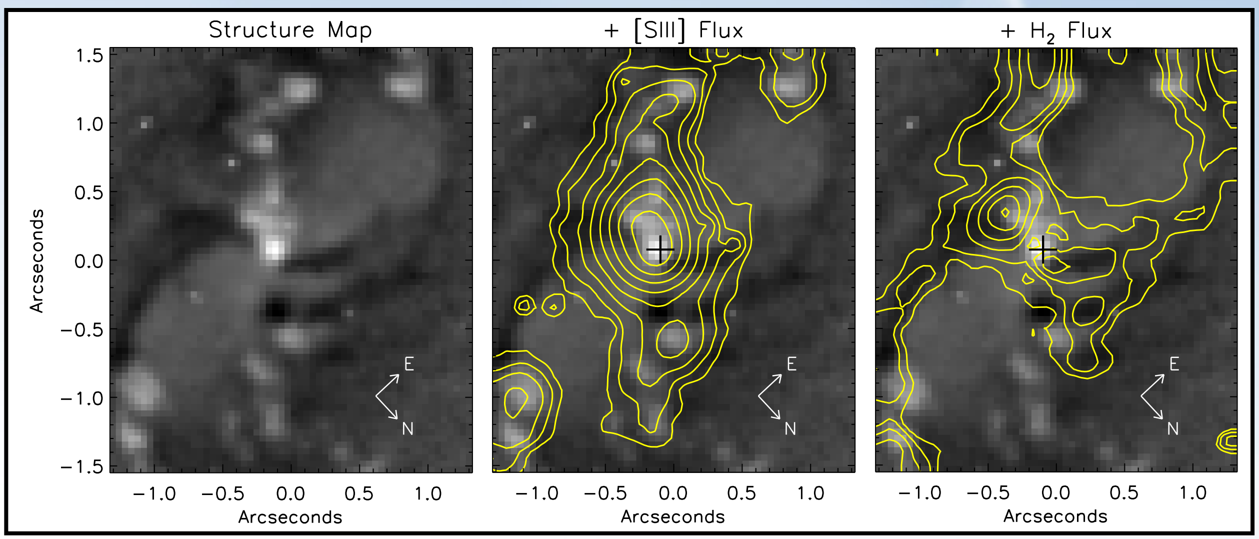
Mrk 573 (Seyfert 2): Dust spirals are lit up by AGN.



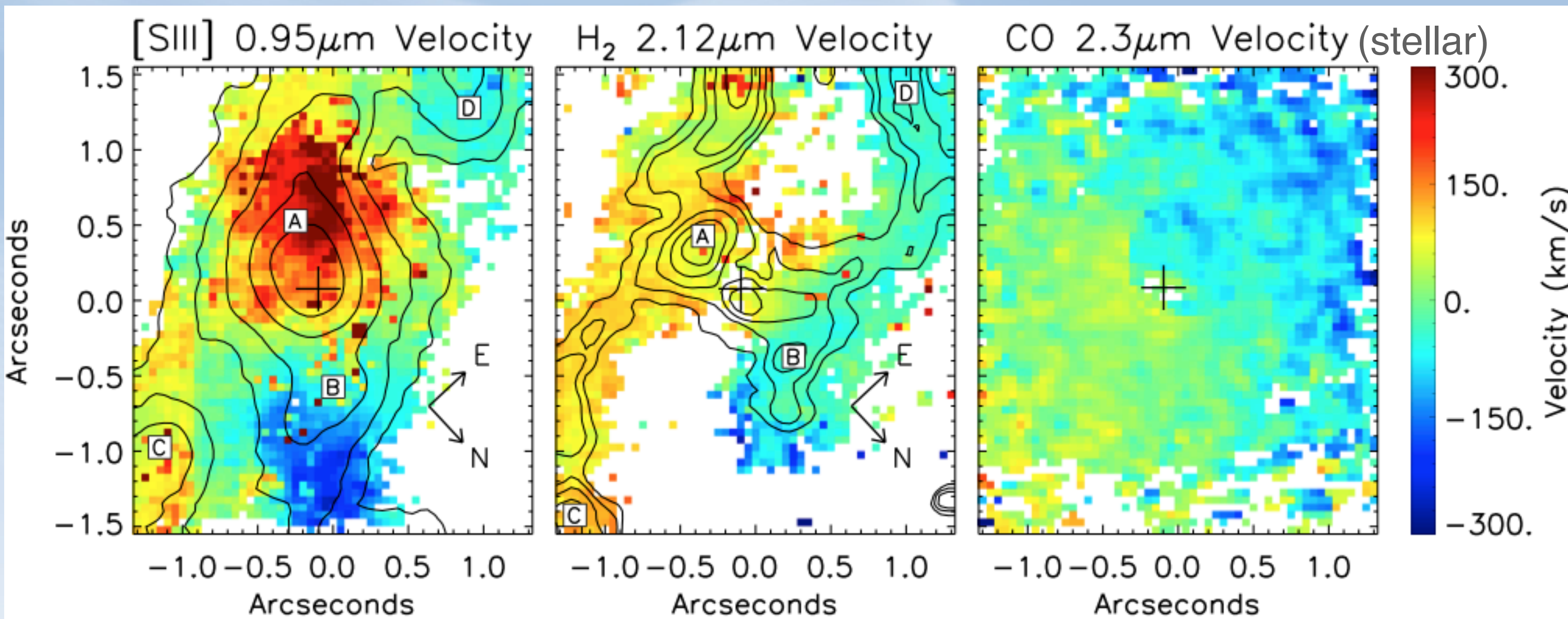
HST F606W (1″ = 350 pc)

Dust spirals in NLR are ionized as they enter the ionizing bicone (~vertical in figure).

Gemini NIFS contours show correspondence of [S III] with [O III] and H_2 with dust lanes.



Mrk 573 NLR shows *in situ* acceleration of ionized and warm molecular gas from rotating dust/molecular spirals.



(Fischer+ 2017, ApJ, 834, 30)

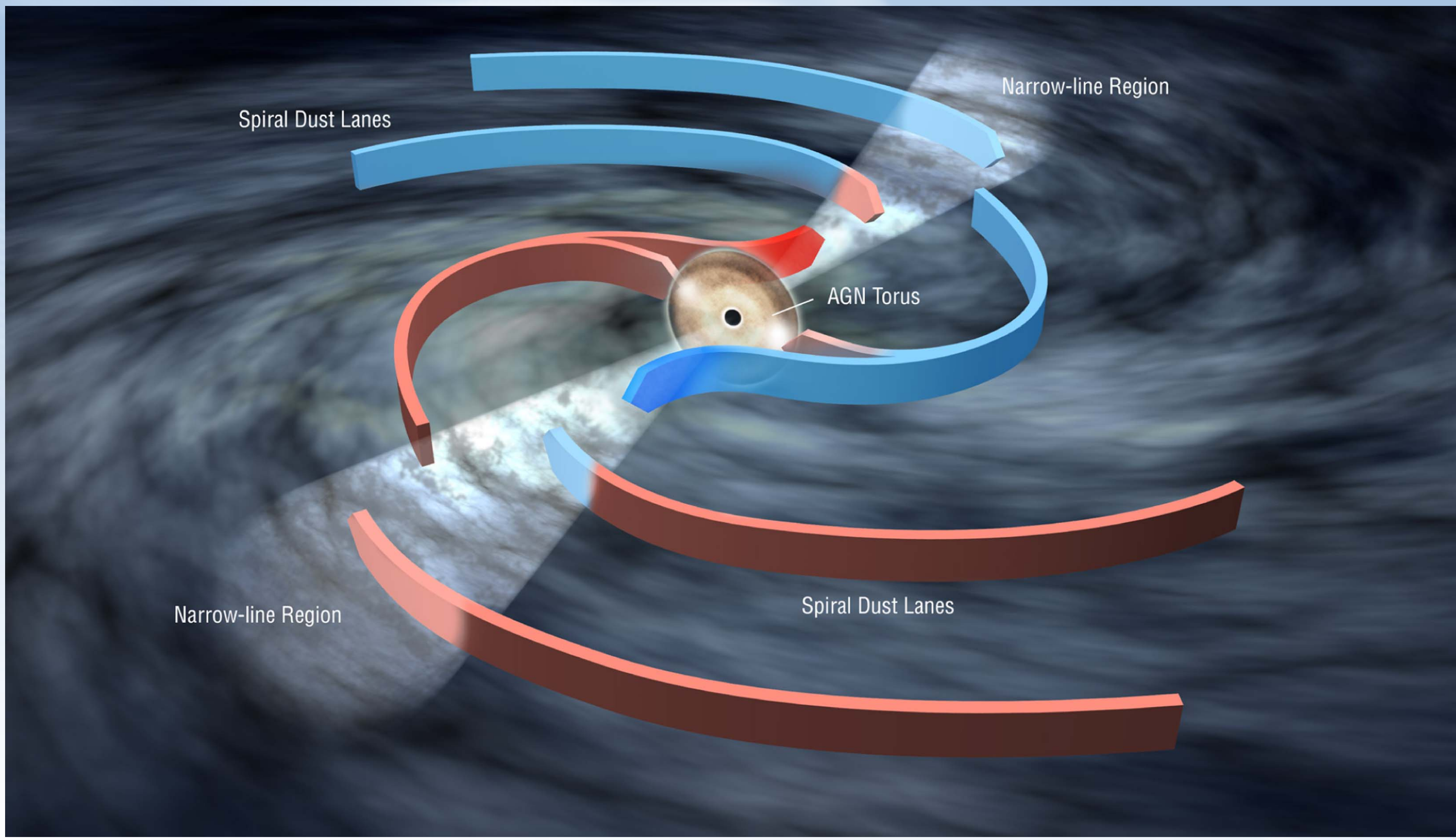
rotation (outer)
outflow (inner)

rotation (outer)
outflow (inner)

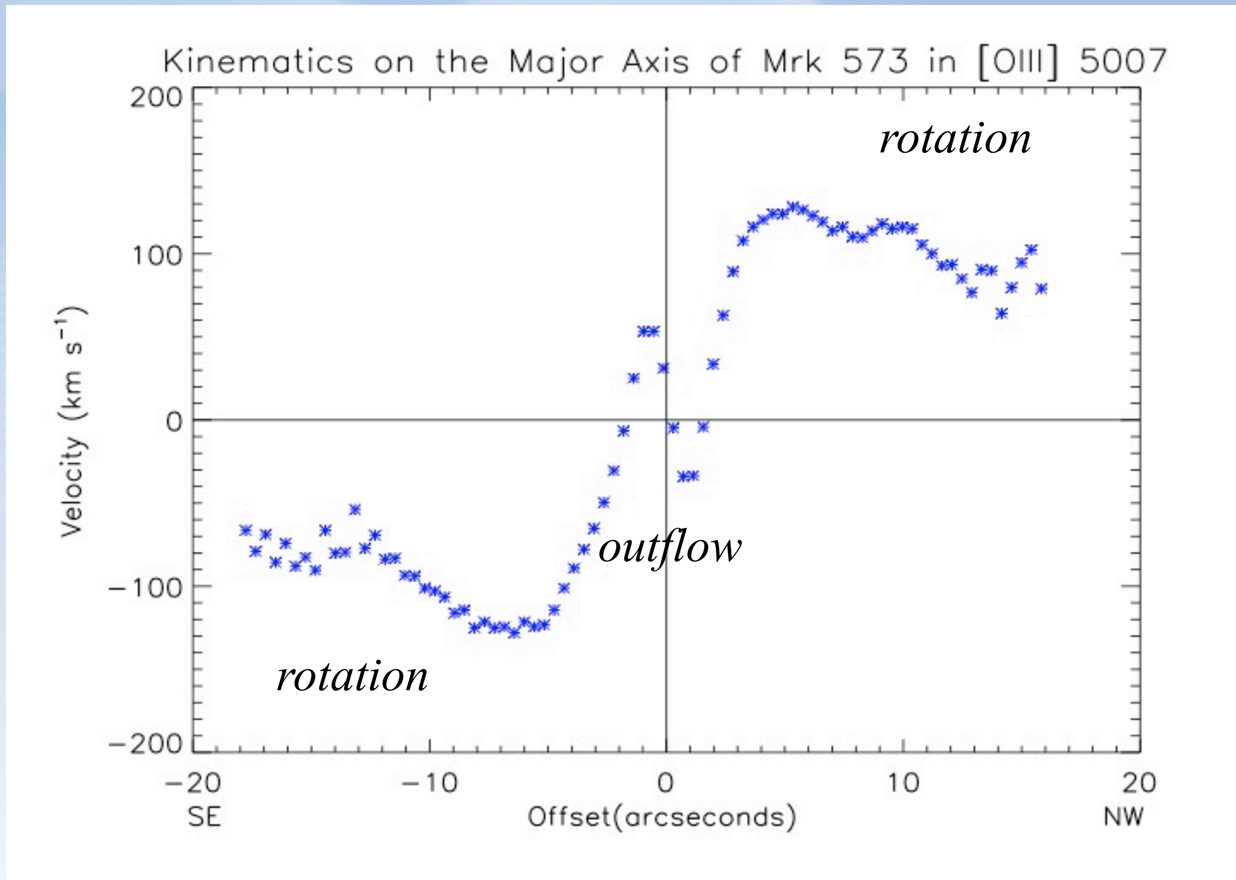
rotation

Outflows extend to ~750 pc, beyond which the ionized gas is rotating.
→ Not sufficient to clear the entire bulge

As the *inner* dust spirals enter the radiation bicone, gas is ionized and accelerated away from the AGN.



The extended NLR (ENLR) is rotating and extends out to ~17" (~ 6 kpc).



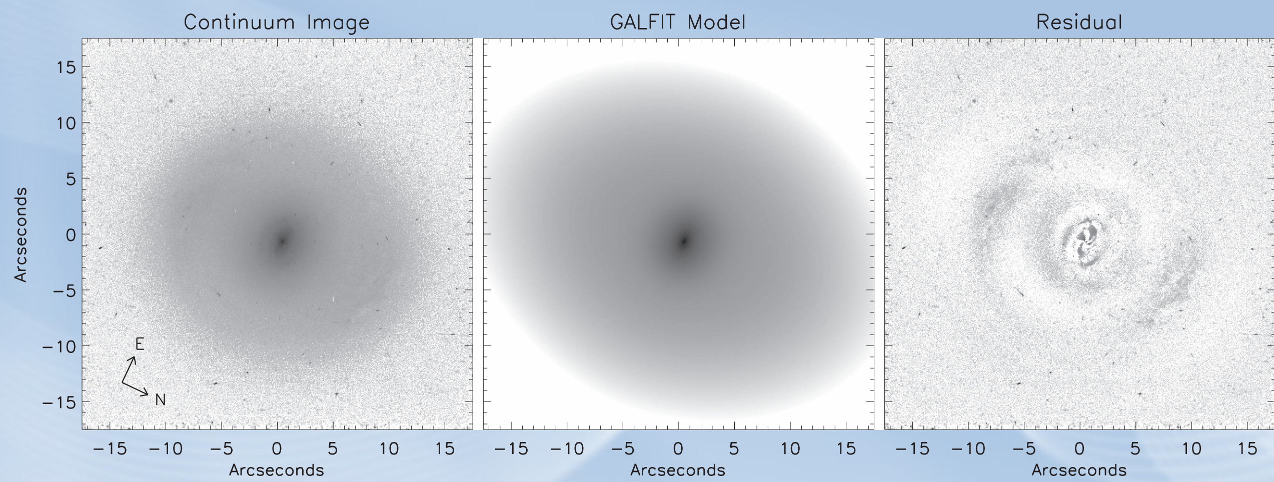
Apache Point Observatory DIS (Fischer+ 2017)

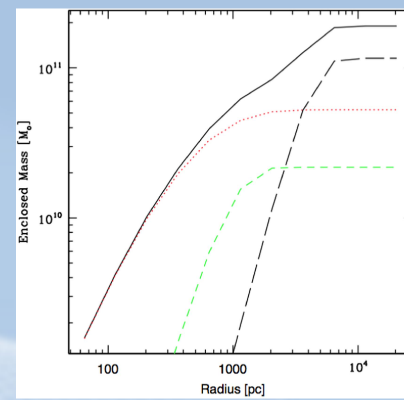
Conclusions (somewhat preliminary)

- Is the gas in the NLR rotating, infalling, or outflowing?
  - **Yes.** Depends on geometry, ionization state, AGN luminosity, distance from SMBH, etc. *(Gnilka talk, Machuca poster)*
- What is the origin of NLR outflows?
  - Primarily *in situ* acceleration of local material - e.g., rotating dust/molecular spirals (*Fischer et al. 2017)*
- Can NLR outflows provide significant AGN feedback?
  - Need *spatially resolved* mass outflow rates and kinetic luminosities over a range of luminosities. *(Revalski talk, Fischer talk)*
- How are AGN fueled on NLR scales (1 – 1000 pc)?
  - Along nuclear dust spirals/bars seen in *HST* images? Need kinematic maps of warm H_2 (*JWST?*) and likely cold molecular gas (*ALMA*).

Mrk 573: Composite X-ray, Optical, Radio

Dynamics of the emission-line clouds in Mrk 573

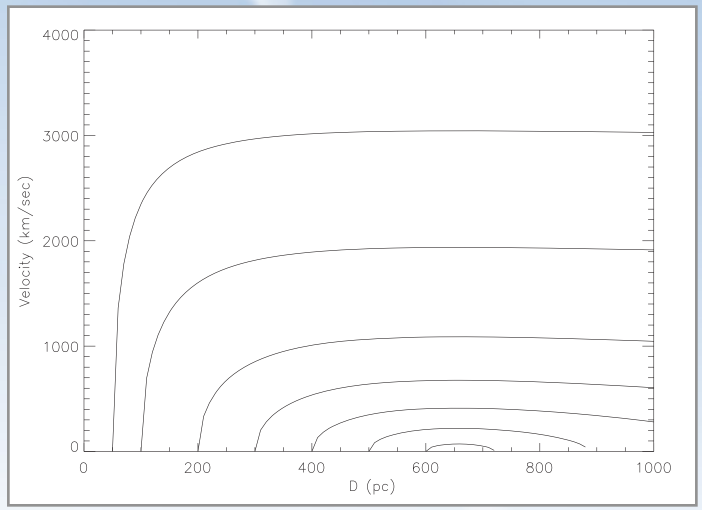




Enclosed mass profile and photoionization models give equation of motion (radiative driving and gravitational decelerations):

$$v(r) = \sqrt{\int_{r_1}^{r} \left[6840 L_{44} \frac{\mathcal{M}}{r^2} - 8.6 \times 10^{-3} \frac{M(r)}{r^2} \right] dr},$$

→ Nearly all of the clouds originated near dust/molecular gas lanes and traveled only tens of parsecs from their origins.



(Fischer+ 2017)