Kinematics of the Narrow-Line Regions in Nearby AGN Based on IFU Observations

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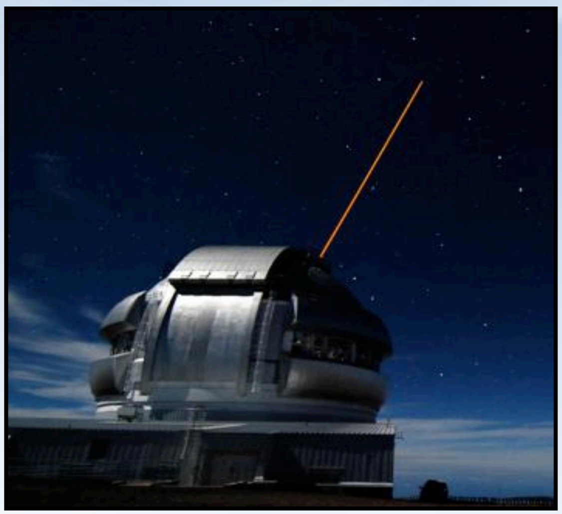
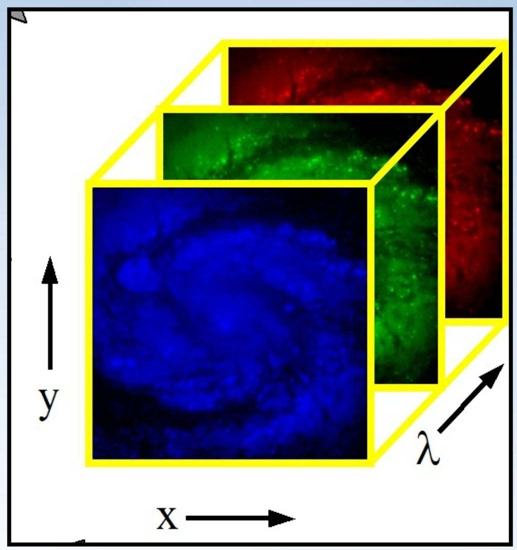
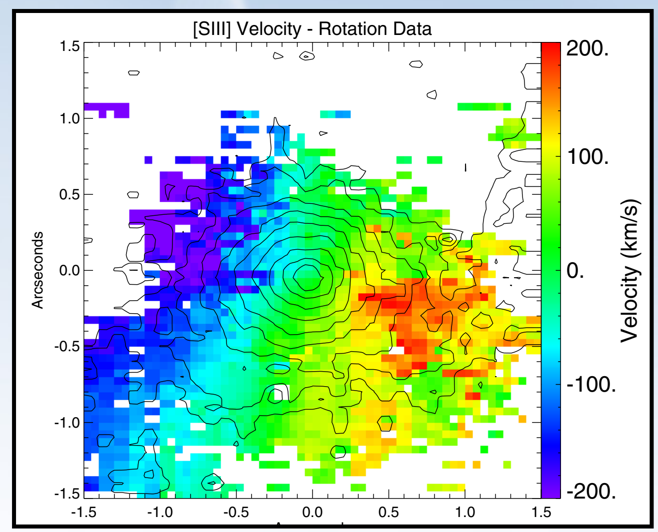
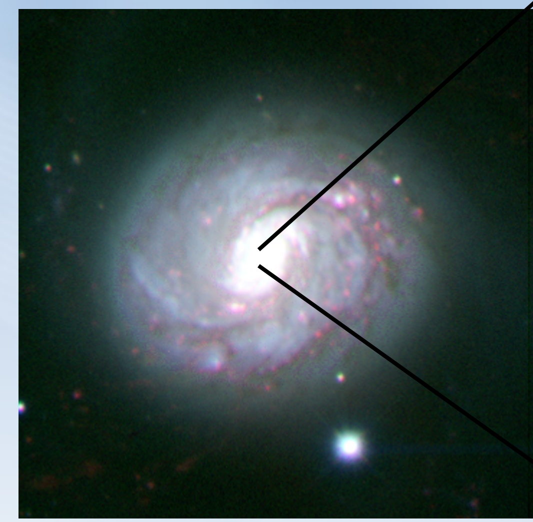
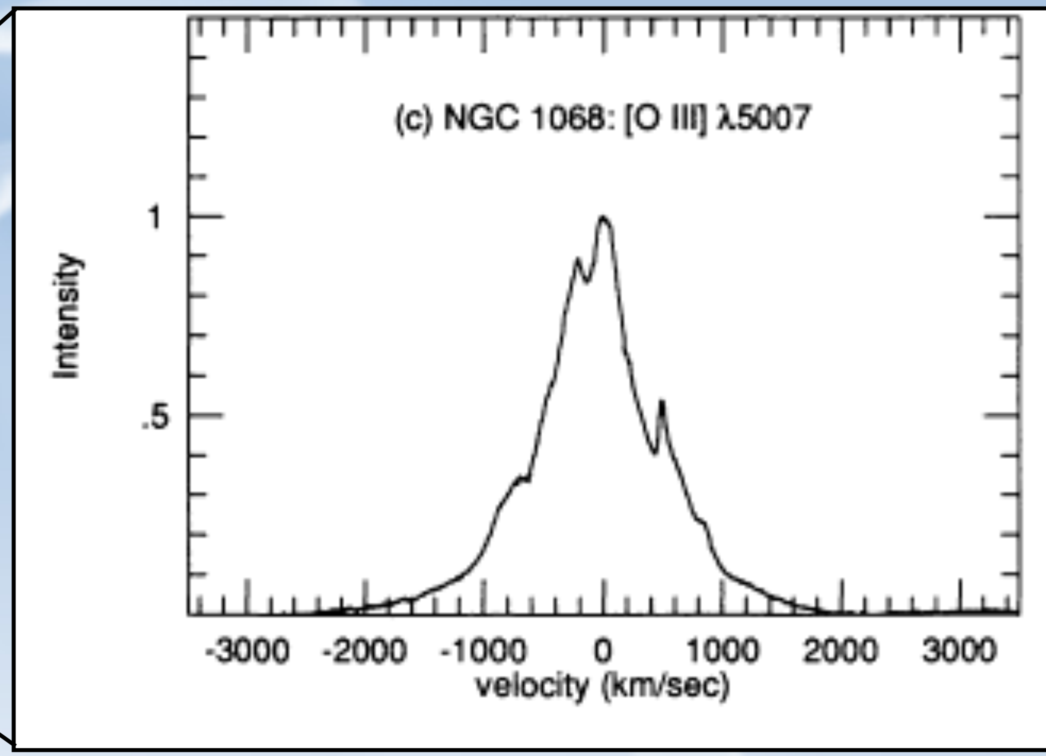






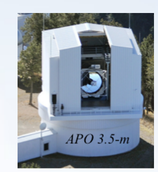
Before *HST*, the NLR was mostly unresolved.



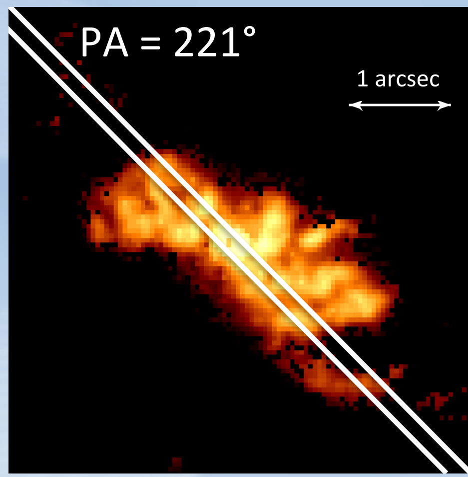


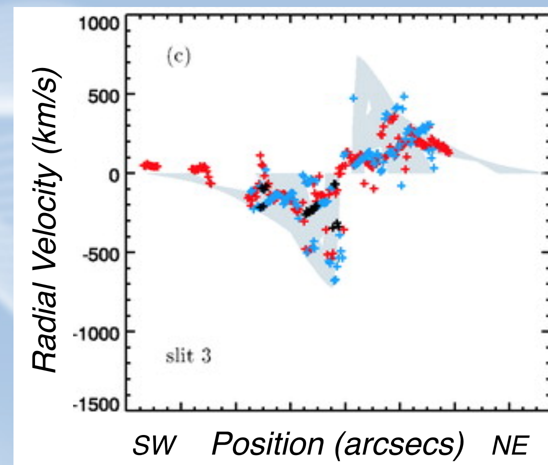
(Veilleux, 1991, ApJS, 75, 357)

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

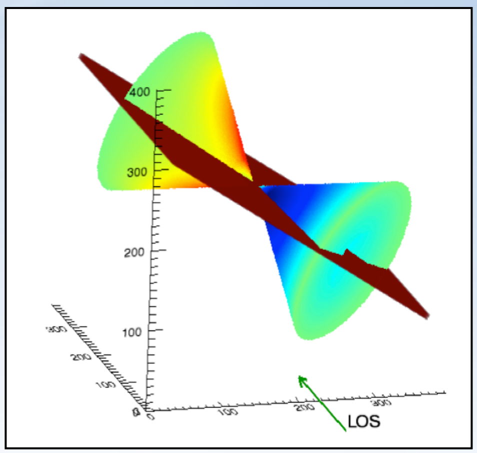


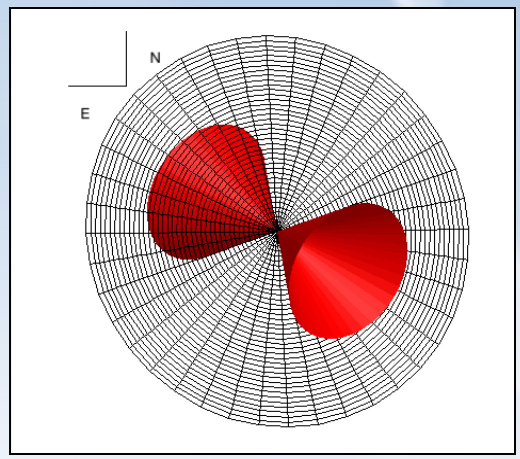
Using *HST's* STIS, we developed biconical outflow models.





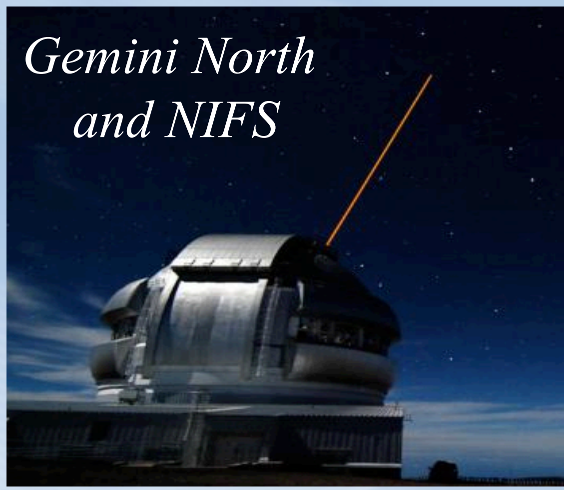
(Das+ 2005, AJ, 130, 945)

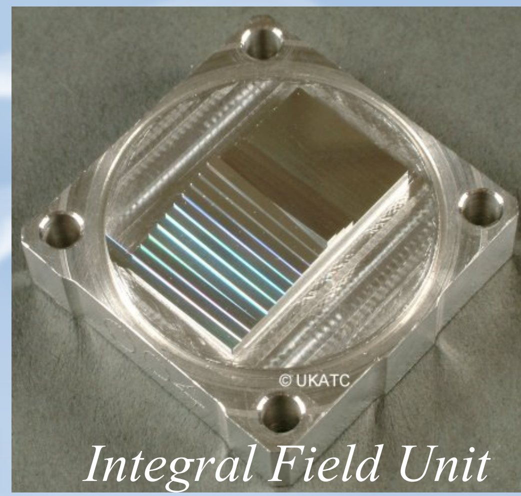


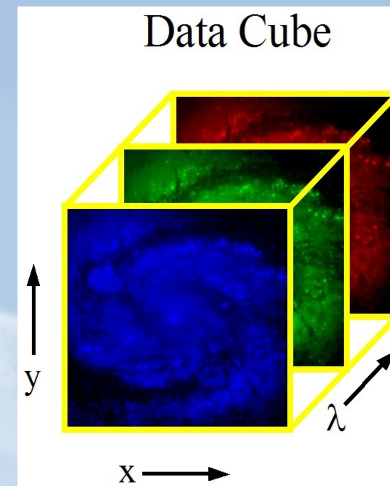


- A single long-slit spectrum is likely not enough.
- Kinematic maps of the NLR are needed.

IFUs (+ AO) can map the NLR kinematics.





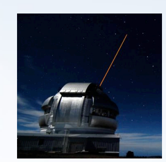


Gemini's Near Infrared Field Spectrometer (NIFS):

- Spectra at R ≈ 5000 covering 0.9 – 2.4 μm at ~ 0.1″ angular resolution over a 3″ x 3″ FOV.
- 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+



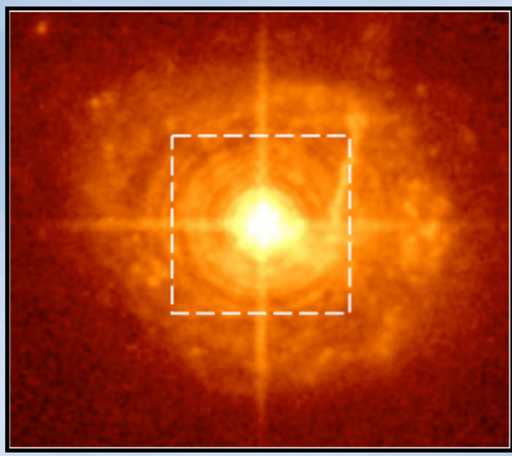
What can kinematic mapping of the NLR tell us?

- Is the gas in the NLR rotating, infalling, or outflowing?
  - **Yes.** Depends on geometry, ionization state, AGN luminosity, distance from SMBH, etc.
- How are AGN fueled on NLR scales (1 – 1000 pc)?
  - IFU K-band observations of warm H_2 are important. (ALMA observations of cold component needed as well.)
- What is the origin of NLR outflows?
  - Do IFU observations confirm our claims of in situ acceleration of local material?
- Can NLR outflows provide significant AGN feedback?
  - Need to characterize mass outflow rates and kinetic luminosities.

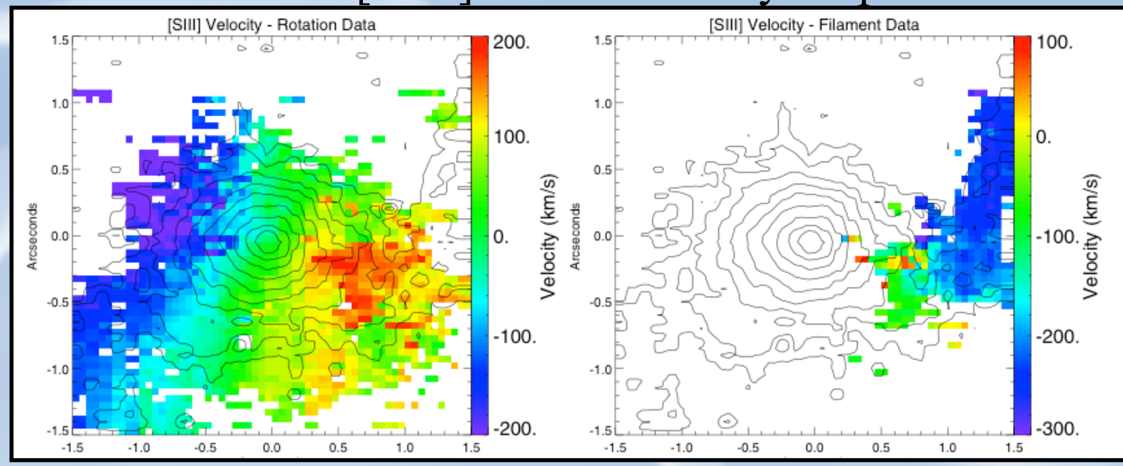
Let's look at some examples →

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

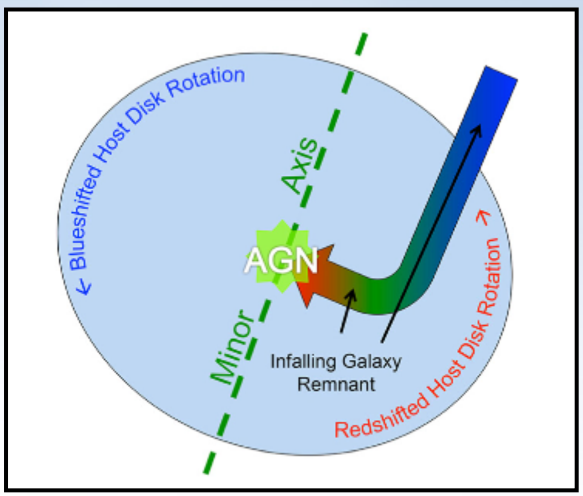
HST [O III] Image



NIFS [S III] Radial Velocity Maps



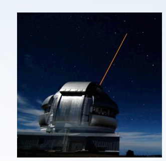
(Fischer + 2015, ApJ, 799, 234)



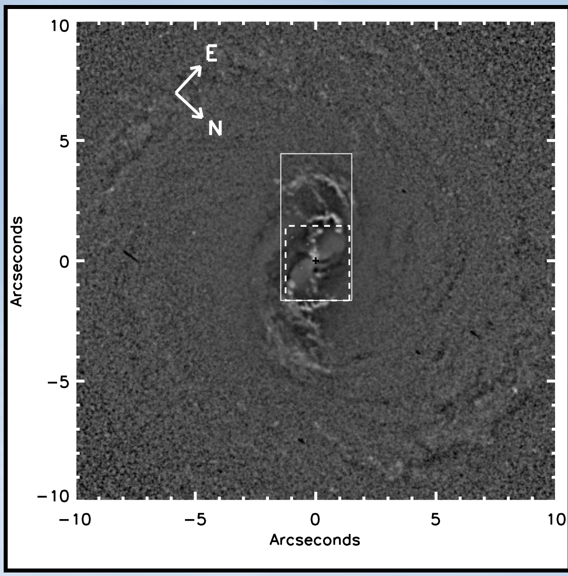
(Fischer + 2015)

→ *rotation* and *inflow*

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



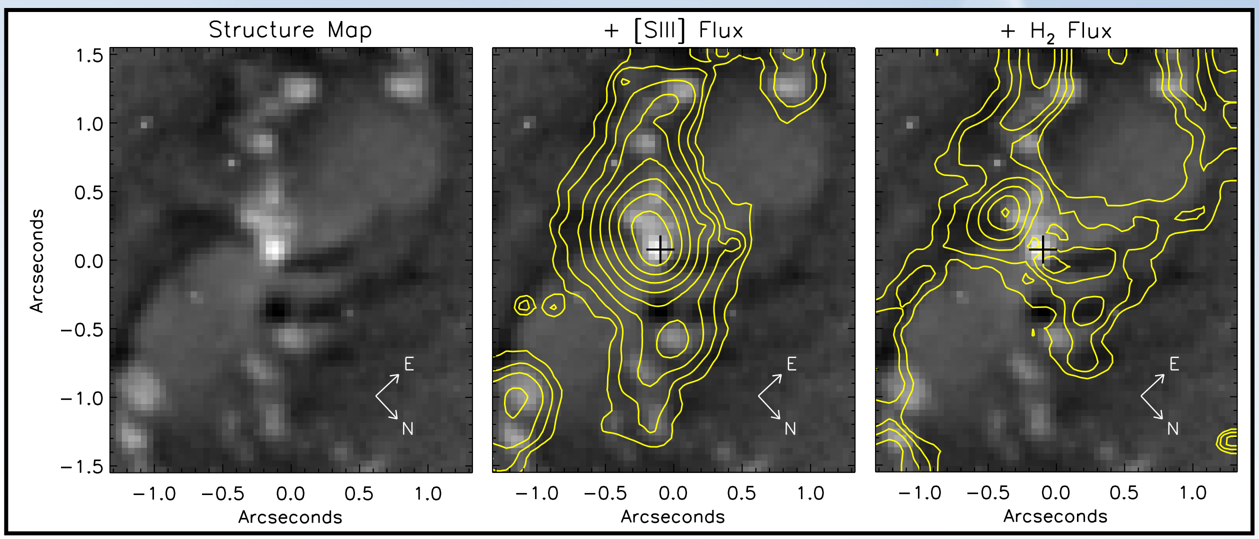
Mrk 573 (Seyfert 2): Dust spirals are lit up by AGN.

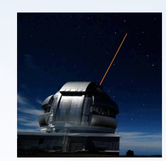


HST F606W (1″ = 340 pc)

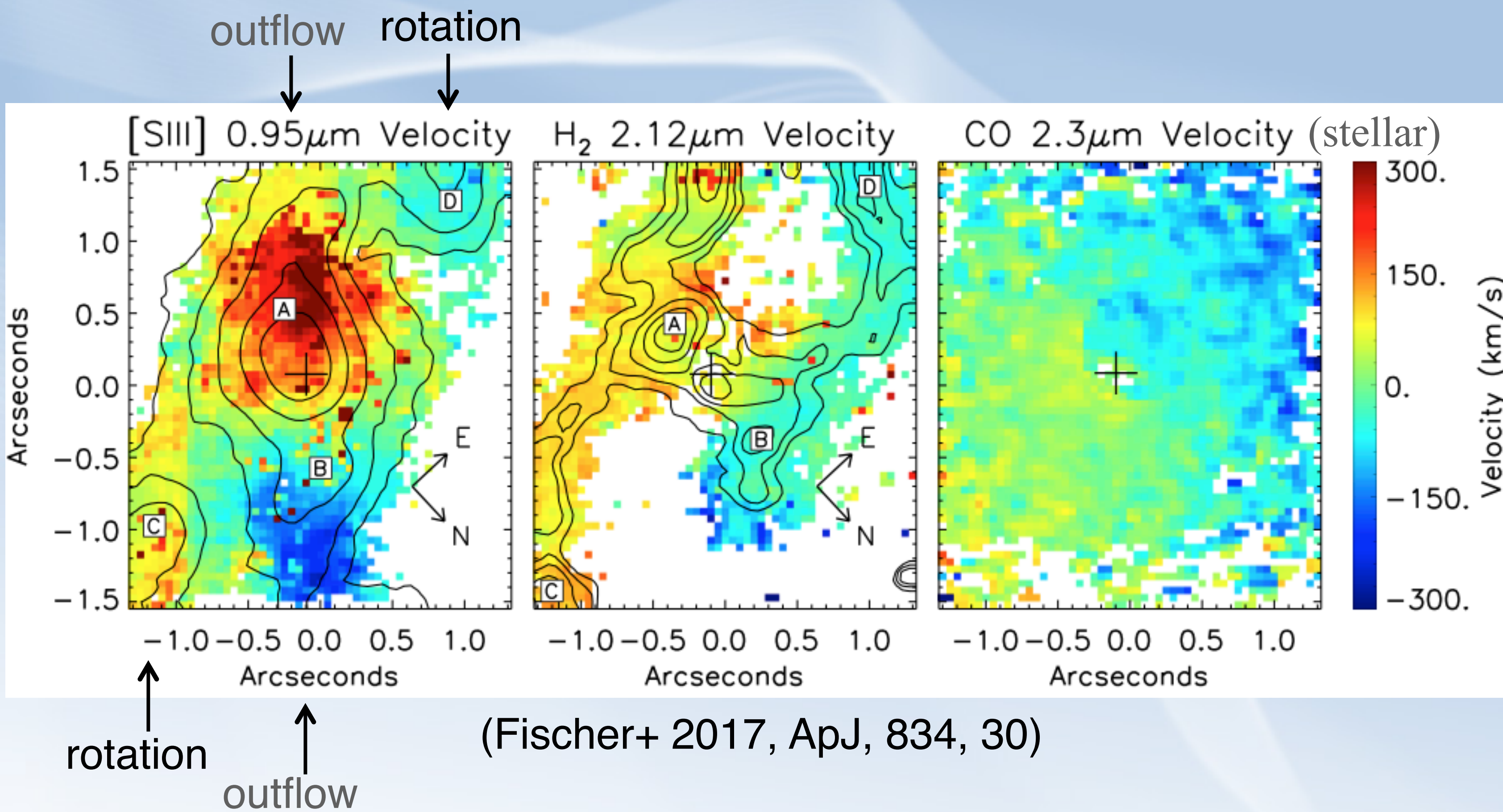
Dust spirals in NLR are ionized as they enter the ionizing (~vertical in figure).

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





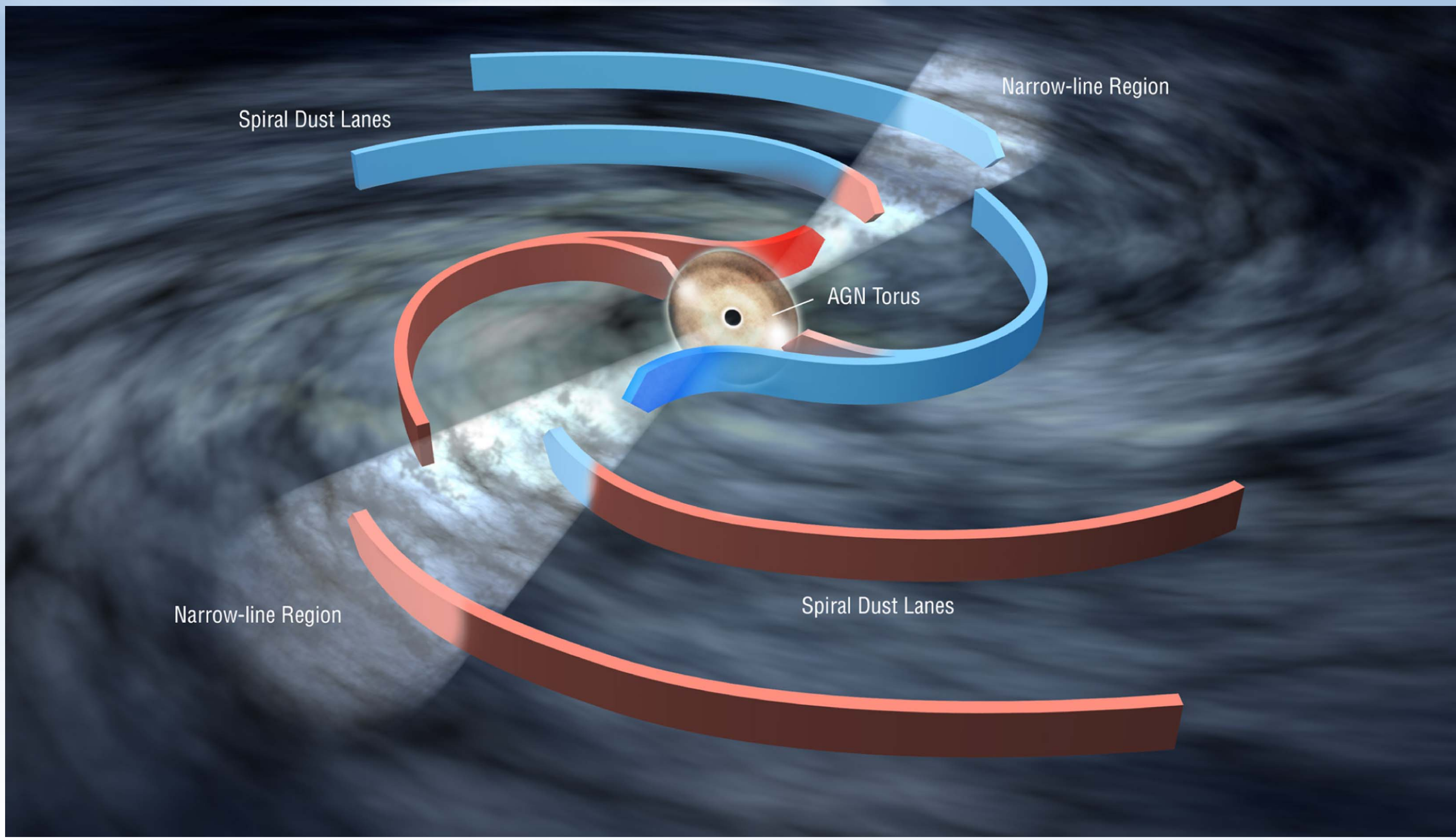
Mrk 573 NLR shows *in situ* acceleration of ionized and warm molecular gas from rotating dust/molecular spirals.



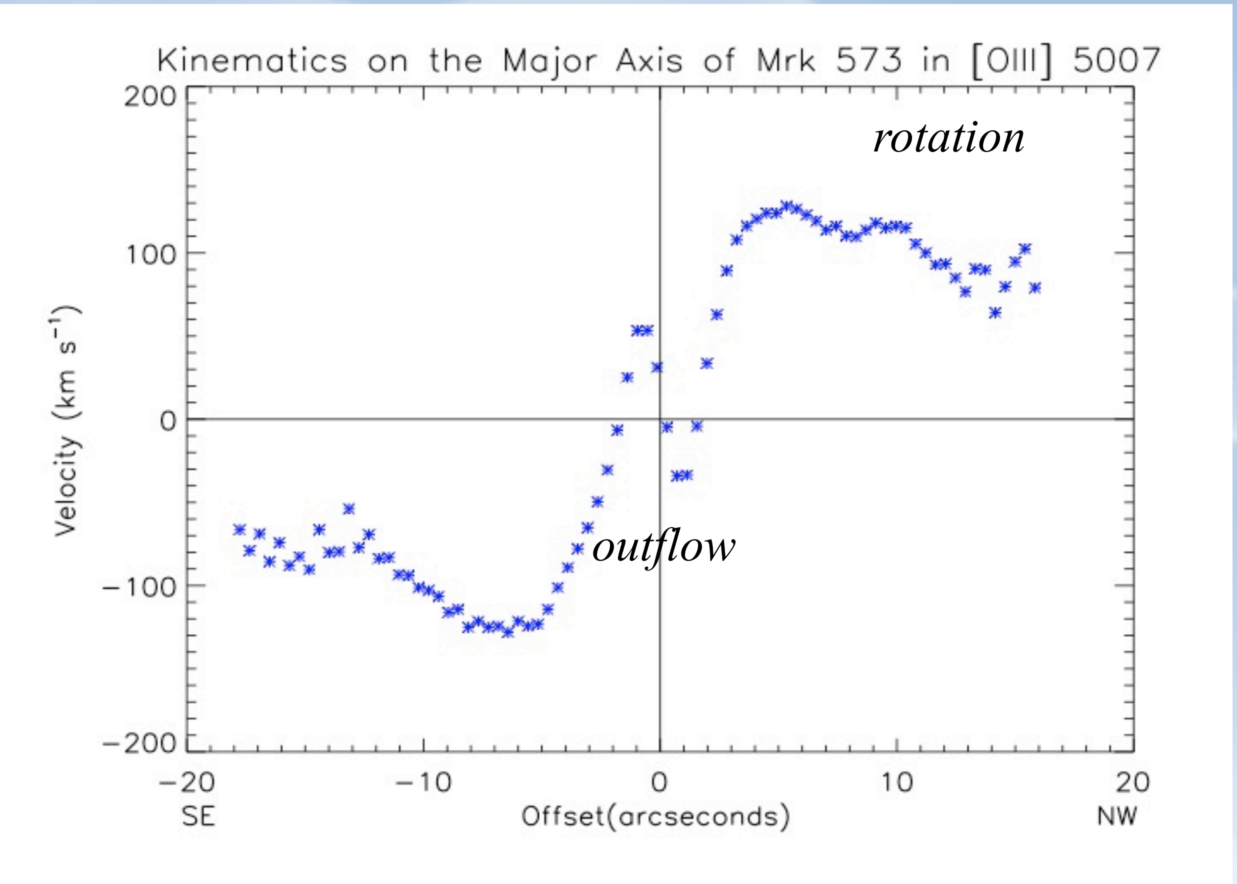
(Fischer+ 2017, ApJ, 834, 30)

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.

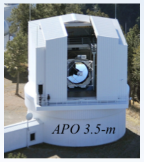


The extended NLR (ENLR) is rotating and extends out to ~17" (~ 6 kpc).



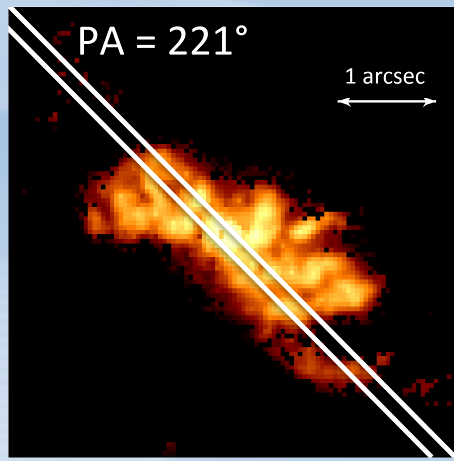
Apache Point Observatory DIS (Fischer+ 2017)

How significant are the outflows? →

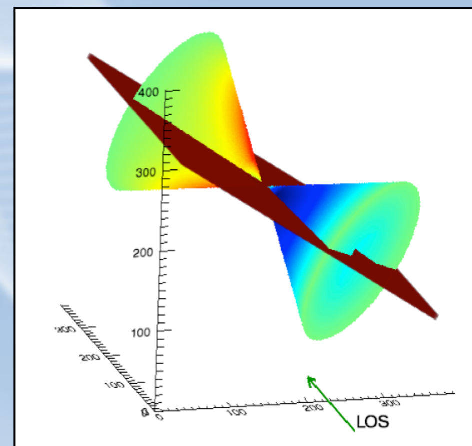


NGC 4151: Resolved mass outflow shows “in situ" acceleration.

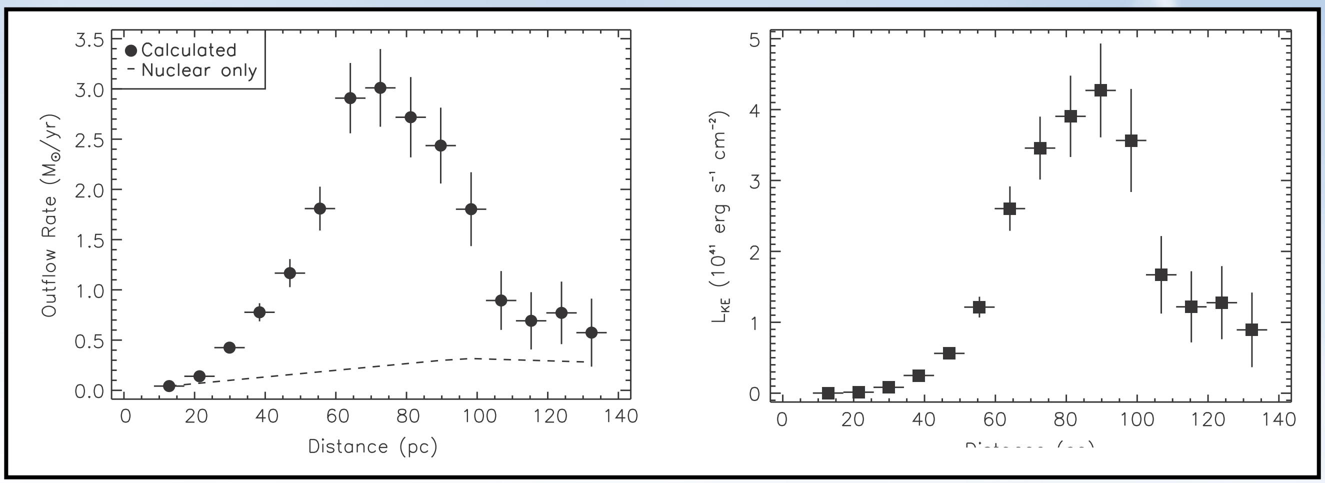
HST [O III] image, STIS slit



Biconical outflow model

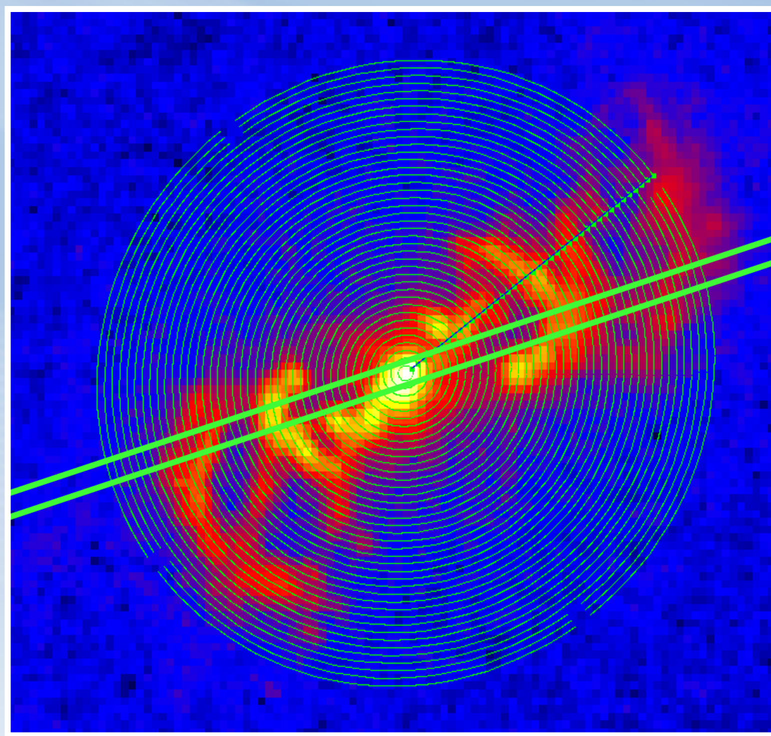


Images, spectra and photoionization models provide resolved outflow rates.

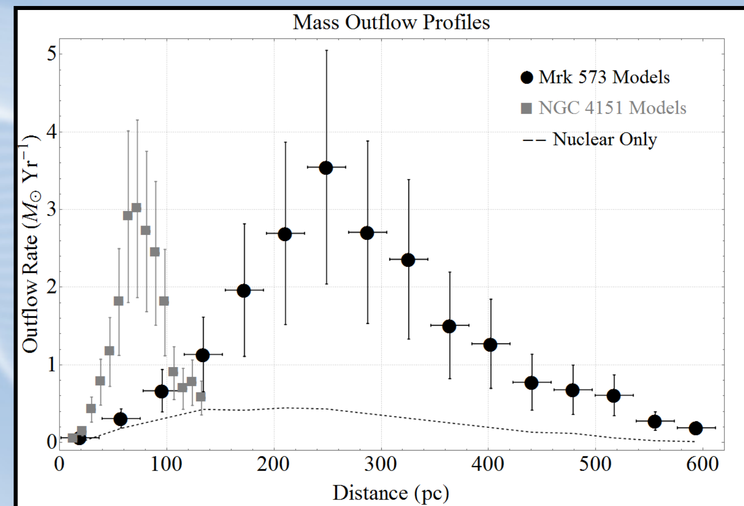


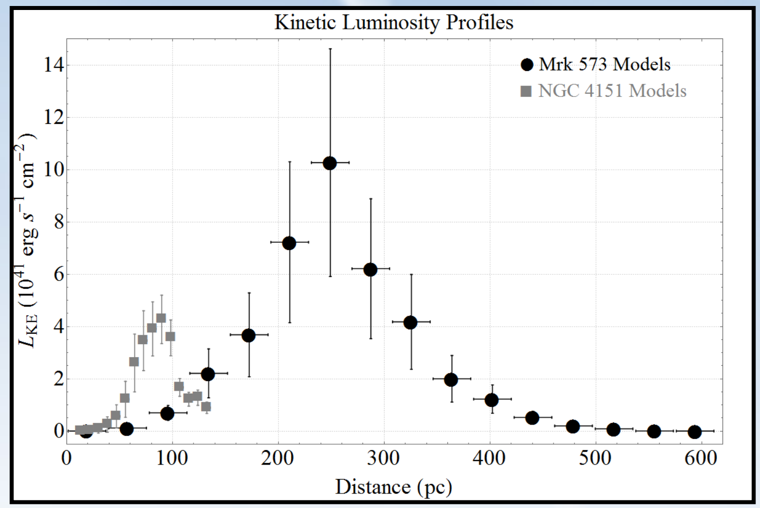
(Crenshaw+ 2015, ApJ, 799, 83)

Mrk 573 shows similar outflow rates on larger scales.

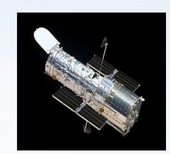


(Revalski+ 2017, in prep.)

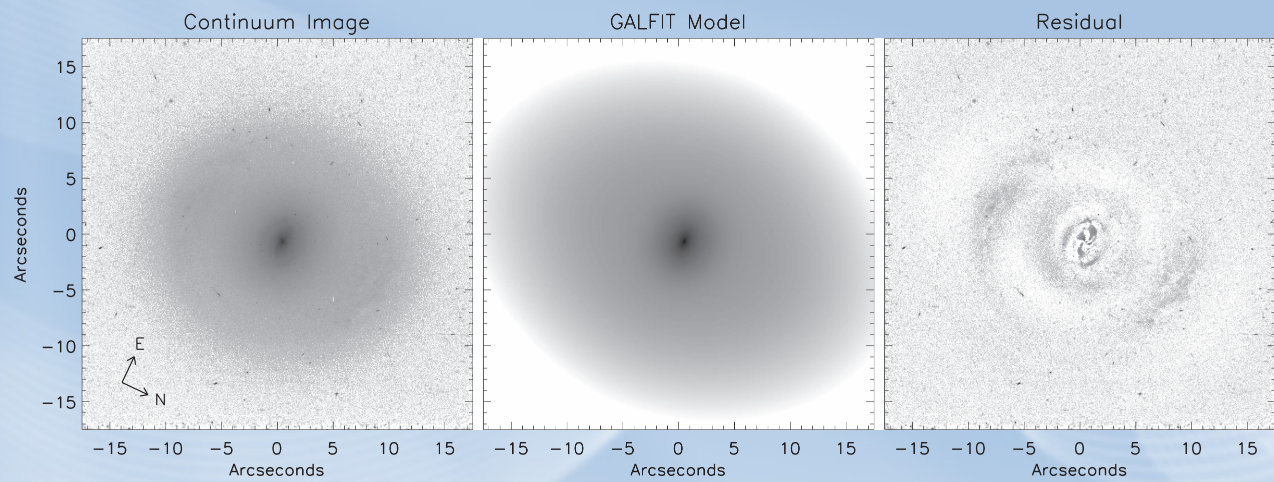


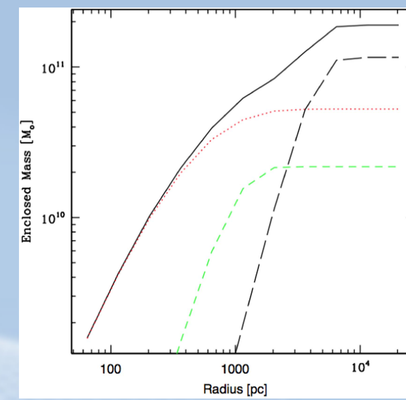


NGC 4151: $\log(L_{bol}) \sim 43.9$
Mrk 573: $\log(L_{bol}) \sim 45.2$



How far do the emission-line clouds travel in Mrk 573?

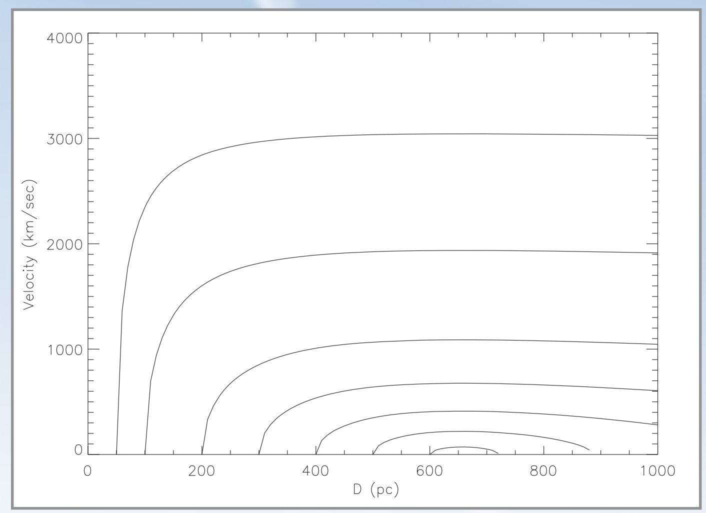




Enclosed mass profile and photoionization models give equation of motion (radiative driving and gravitational decelerations):

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

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



(Fischer+ 2017)

Questions

- Is the picture of in-situ acceleration of ionized gas from dust/ molecular spirals generally correct?
- Are NLR outflows extensive or powerful enough to clear the bulges of moderate-luminosity AGN?
- Are NLR outflows important for regulating the growth of SMBHs?
- What *spatially resolved* mass outflow rates and kinetic luminosities are important for AGN feedback?
- What are the pathways for fueling AGN? Can these be traced with kinematic maps of warm H_2 (even with *JWST*) or do we need *ALMA*?