Image of NGC 6240: Bush et al. 2008

Measuring Black Hole Masses in Nearby Galaxies with Laser Guide Star Adaptive Optics

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Outline

- Background on black hole mass measurements
- Examples of what's been done with AO to date
- Our own work, measuring black hole masses in NGC 6240, a collision between two disk galaxies
- Summary

Toolbox for Measuring BH Masses

- Many methods. None is universally applicable.
  - Individual stellar orbits (Galactic Center only)
  - Kinematics of masers rotating around a supermassive black hole
  - Spatially resolved Keplerian disk of stars or gas (e.g. spiral gals)
  - Full three-integral orbital modeling (early type galaxies)
    - Dynamically relaxed ellipticals, requires good understanding of stellar light/mass distribution
  - Reverberation mapping infers size of broad line region from time variability: unobscured AGNs
  - Inferring dynamics from width of various lines (Hβ, MgII, ...)
  - etc ...

What spatial resolution is needed, to see Keplerian orbits?

- To see Keplerian velocities, must be able to resolve the "Gravitational Sphere of Influence" of the black hole

$$R_g \sim \frac{GM_{BH}}{\sigma_*^2} \sim 1.1 \left(\frac{M_{BH}}{10^9 M_\odot}\right)\left(\frac{200\ km/s}{\sigma_*}\right)^2 pc \sim 35 \left(\frac{M_{BH}}{10^9 M_\odot}\right)^{0.5} pc$$

using the M-σ relation

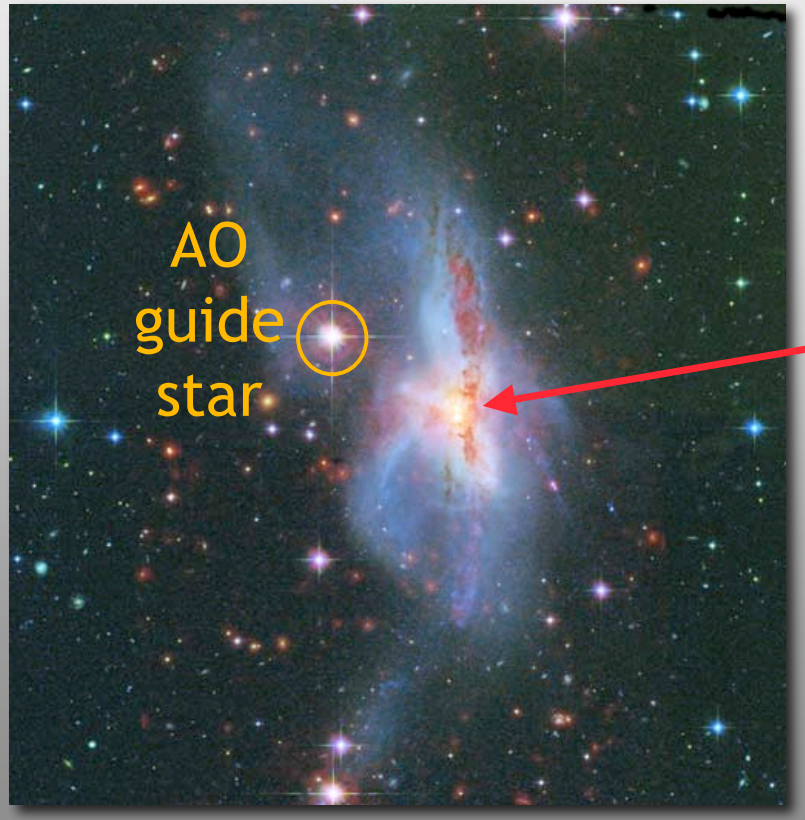
- $M_{BH} = 10^9\ M_\odot$ $R_g \sim 35$ pc
- $M_{BH} = 10^8\ M_\odot$ $R_g \sim 11$ pc
- $M_{BH} = 10^7\ M_\odot$ $R_g \sim 3.5$ pc

Some published AO-based black hole mass measurements in nearby galaxies

Galaxy	Method	Telescope	First author	Year
Cen A	stellar kinematics	VLT NACO	Häring-Neumayer	2006
NGC 1399	stellar kinematics	VLT NACO	Houghton	2006
NGC 3227	stellar kinematics	VLT SINFONI	Davies	2006
Cen A	gas kinematics	VLT SINFONI	Neumayer	2007
NGC 4486a	stellar kinematics	VLT SINFONI	Nowak	2007
9 Seyfert 1 galaxies	gas kinematics	Keck NIRSPEC	Hicks	2008
Fornax A	stellar kinematics	VLT SINFONI	Nowak	2008

NGC 6240:
Merger of two gas-rich spiral galaxies

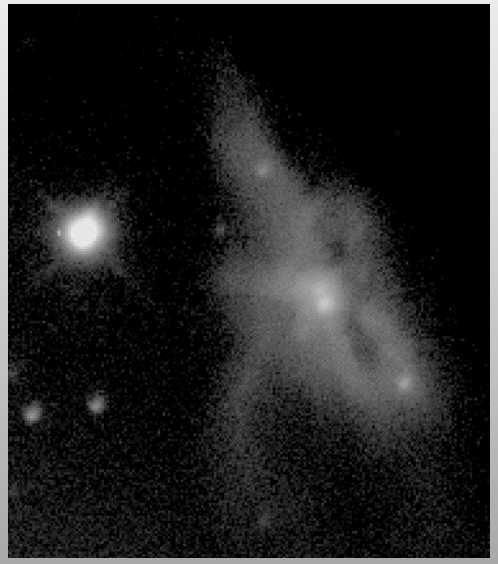
- A starburst galaxy (very intense star formation)
- Hosts 2 black holes, one from each galaxy



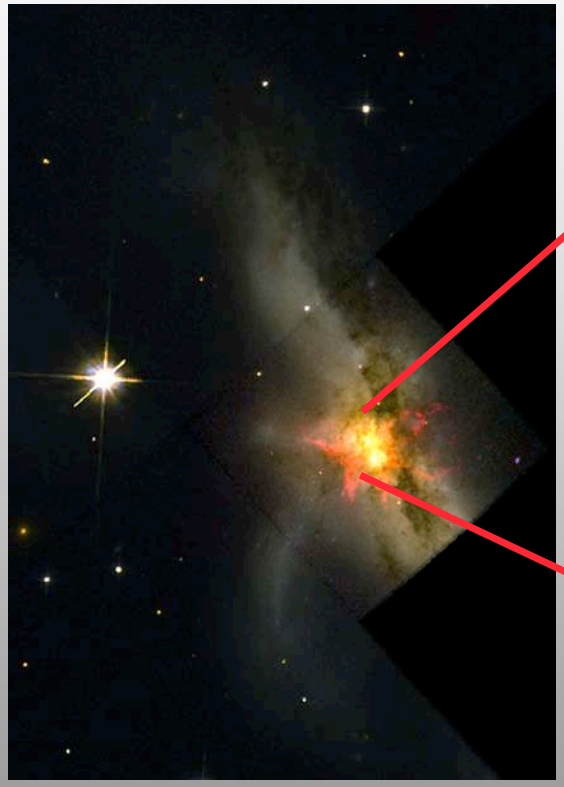
Spitzer and Hubble Space Telescopes

- Relatively nearby:
  ~100 Mpc
- Double nucleus
  (2 hard x-ray sources)
- Tidal tails due to
  merger (“bow-tie”)

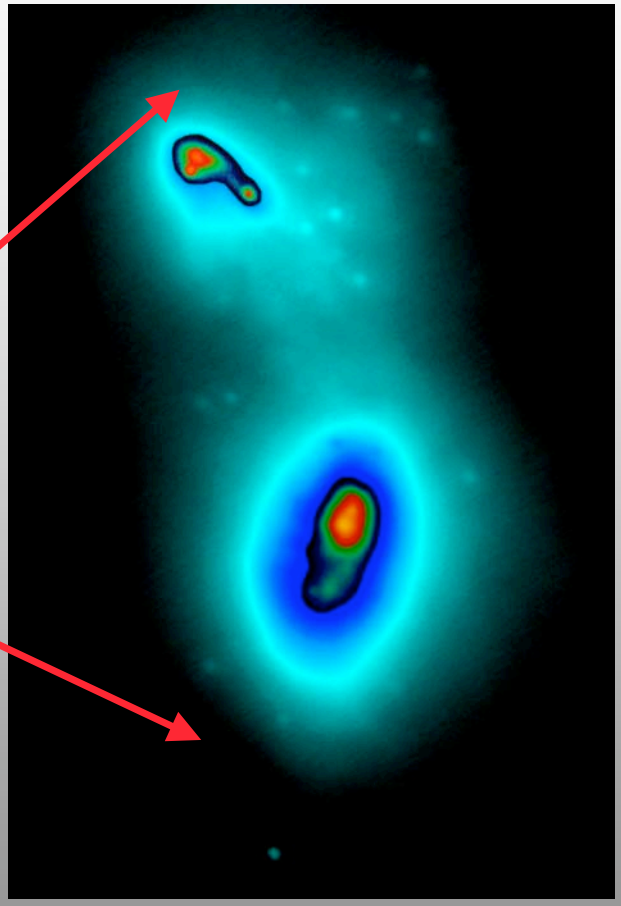
NGC 6240:
Merger of two gas-rich spiral galaxies



Seeing-limited
visible image,
Lick Observatory

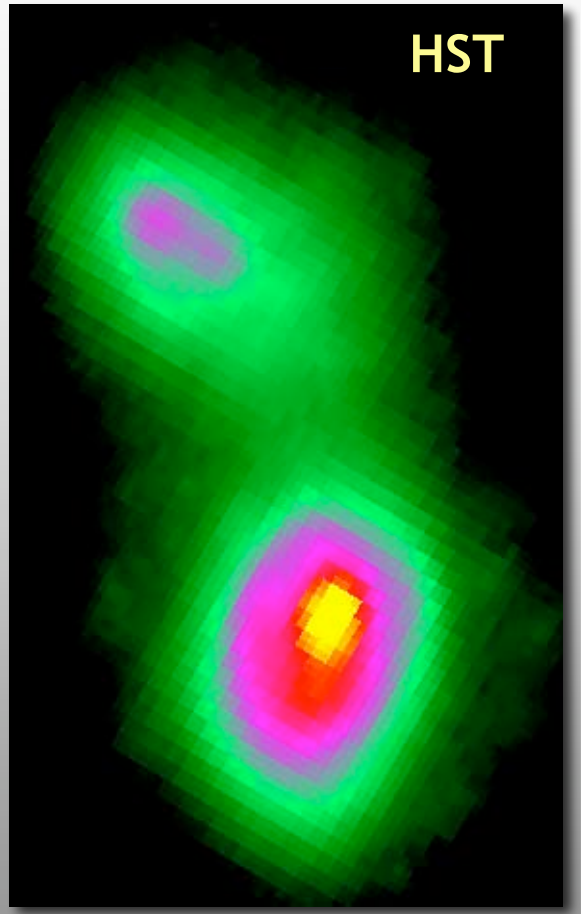


Hubble Space Telescope
0.45 μm, 0.81 μm, Hα



Near-infrared
2.2 μm image,
Keck adaptive optics

NGC 6240: Keck AO compared with HST NICMOS IR camera, K band



NIC2 camera, 2.2 μm

NIRC2 camera, 2.2 μm

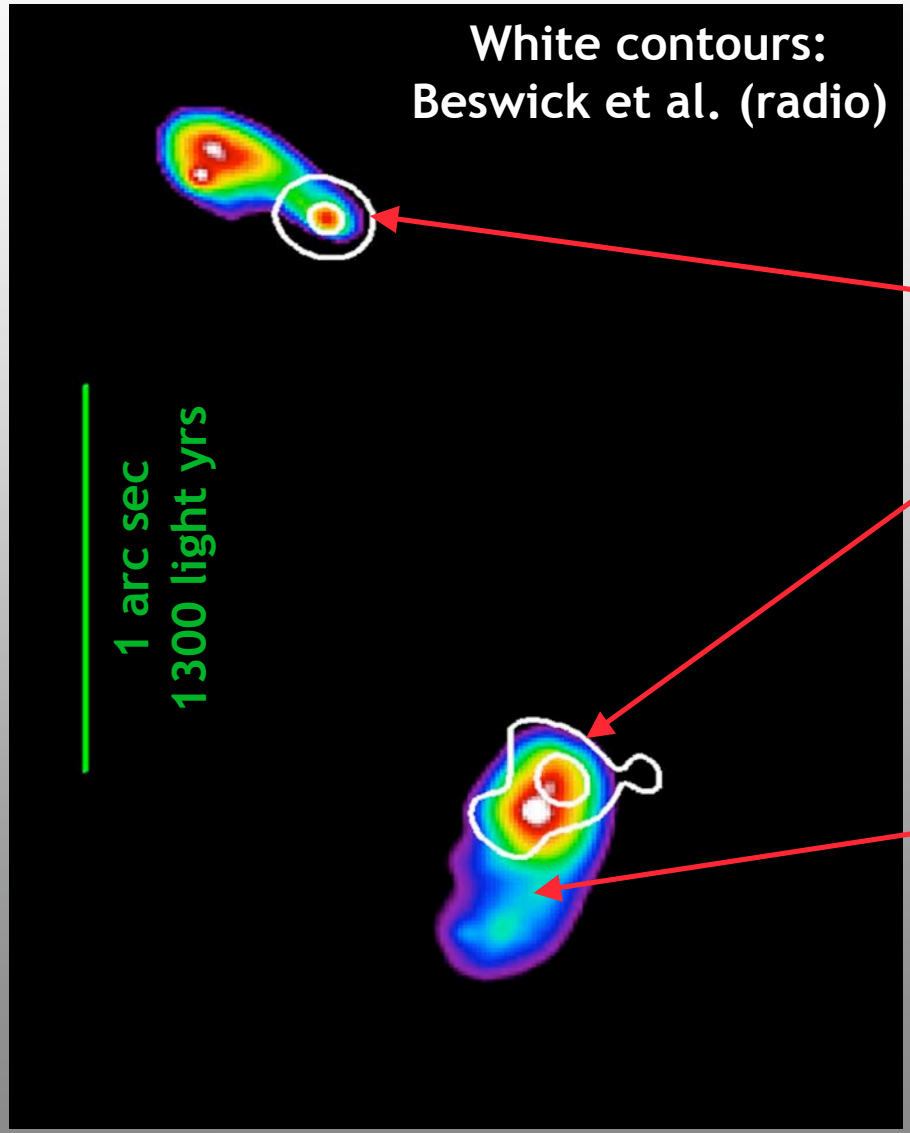
Each of these 30 "dots" is an unresolved star cluster

Ages 10-20 Myr

(Pollack et al. *ApJ* 2006)

Diffraction limit of 10m versus 2.4m telescope
⇒ 4X more angular resolution

Nonthermal radio sources indicate positions of black holes on Keck IR image

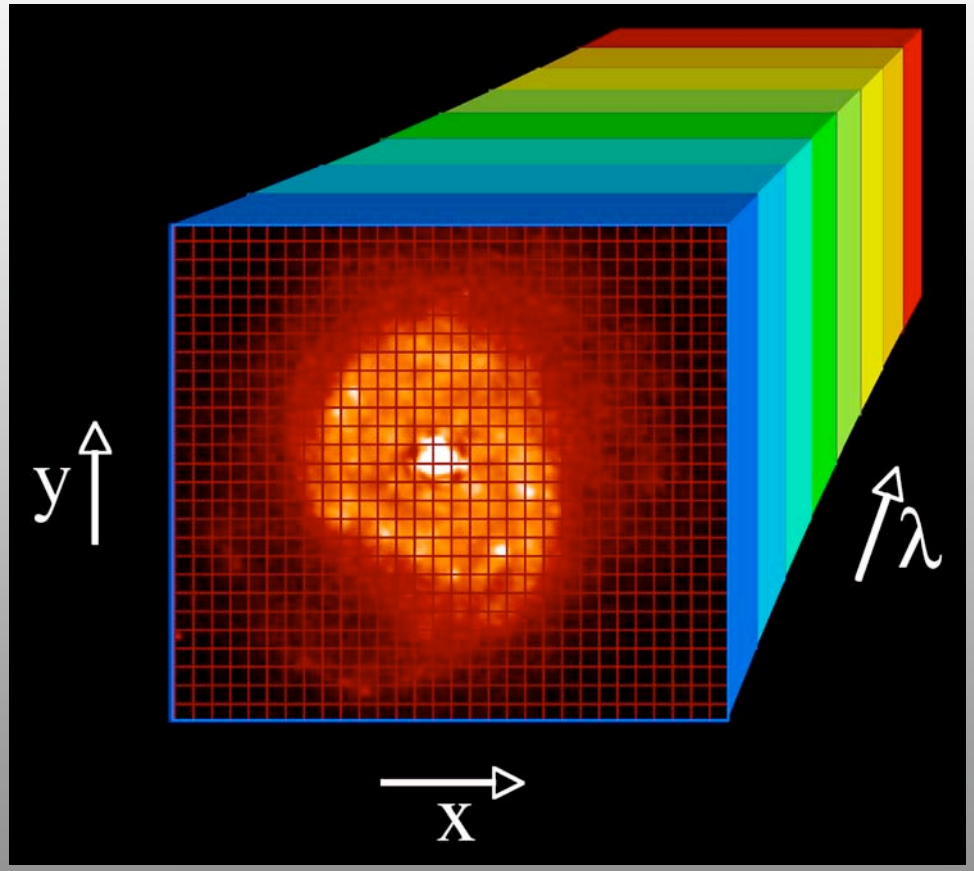


Radio contours

Keck AO infra-red images

Map out stellar velocities using an imaging spectrograph: OSIRIS

- Might expect Keplerian motion of stars around black hole (spiral galaxies)
- Fit to models with black hole and stellar disk

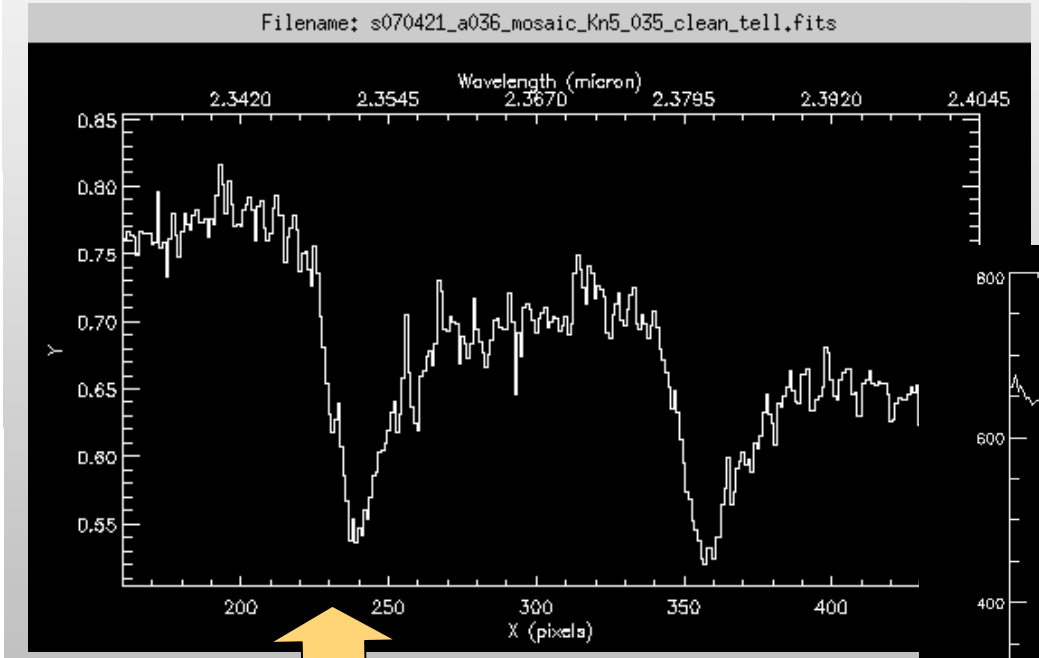


A spectrum at every pixel

OSIRIS PI: James Larkin, UCLA

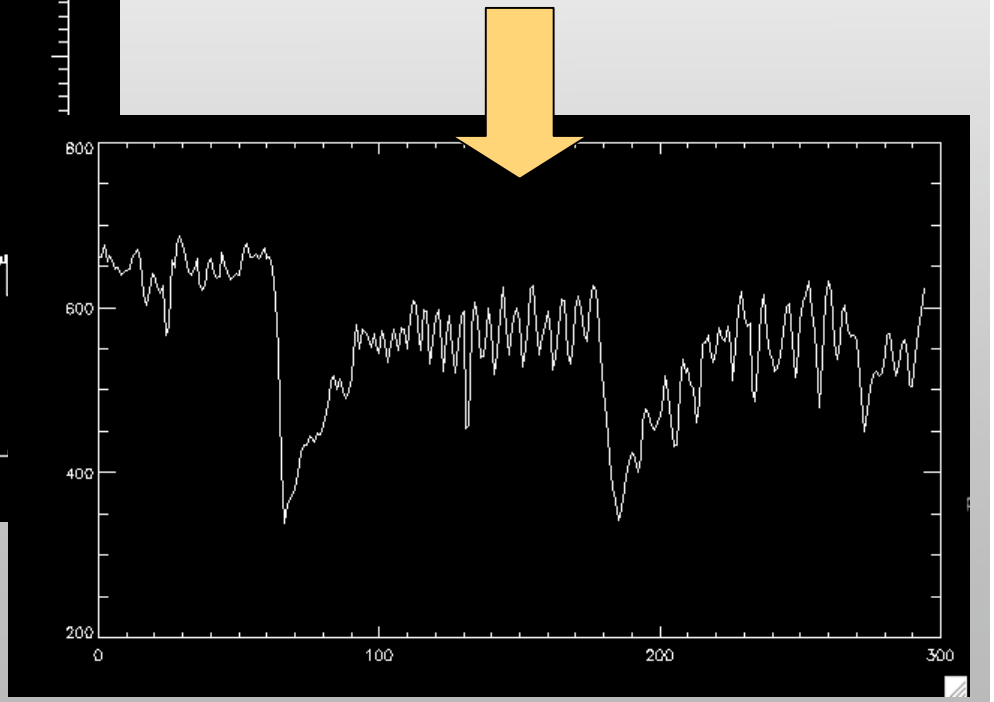
Fit Velocities to Spectrum at Every Pixel

- Fit Gaussian-broadened template to CO absorption bandheads (2.3 - 2.4 μm). Stellar features.

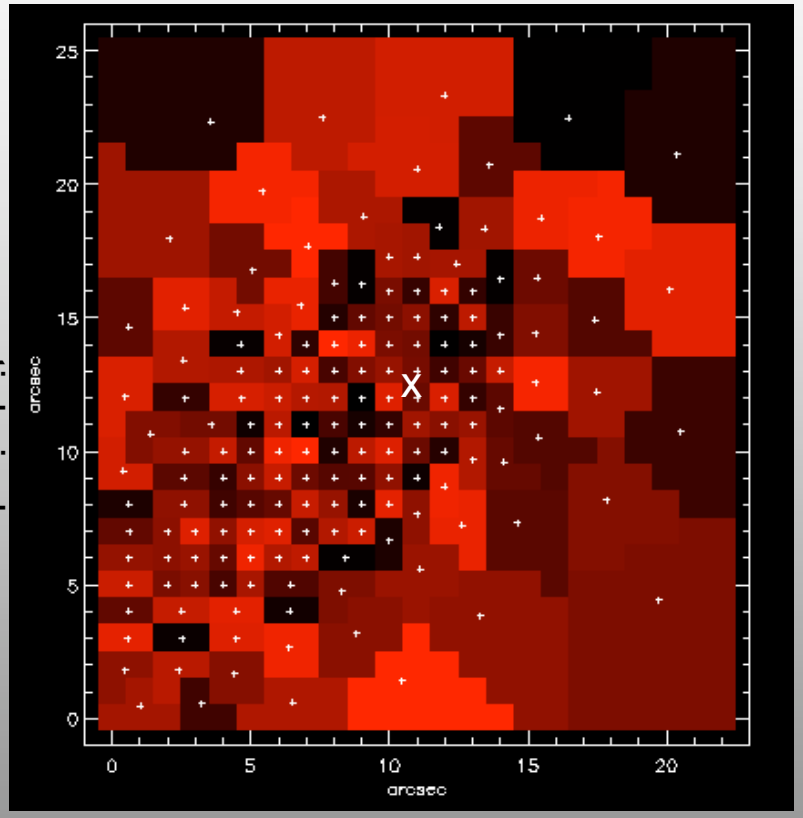


Our Data

Template (K5 supergiant)

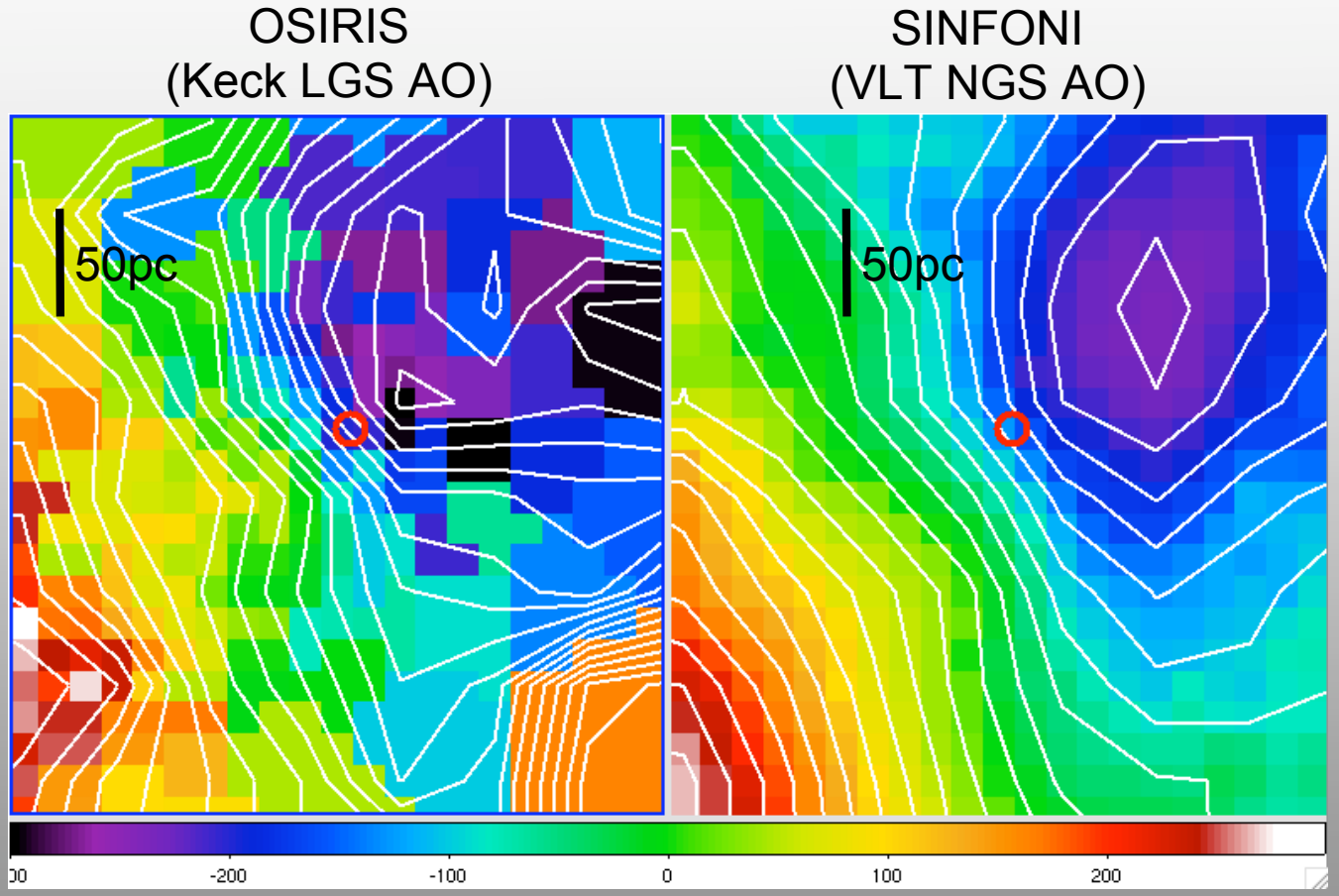


Velocity fields from IFU Spectra



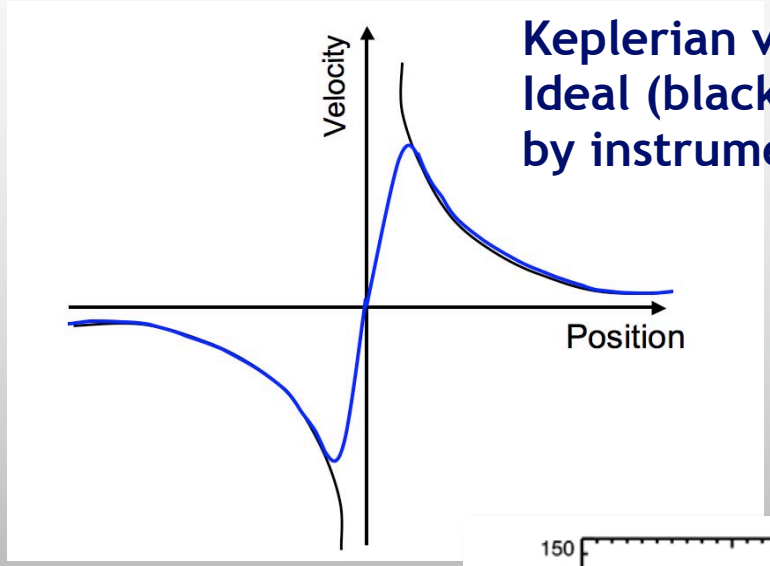
- Adaptive 2-d Voronoi binning to equalize S/N of each spectrum (Cappellari & Copin 2003)
  - Useful technique in velocity field observations; combine spectra spatially in an intelligent way
  - Each bin constructed to achieve a minimum S/N while maintaining compact bin size
- Target S/N is 20.

Velocity maps from OSIRIS and SINFONI



- Use smoother, lower spatial resolution SINFONI data to remove large-scale motions of the two colliding galaxies
- Result: clear signature of black hole

Residual Velocity Profile Shows Keplerian Stellar Orbits



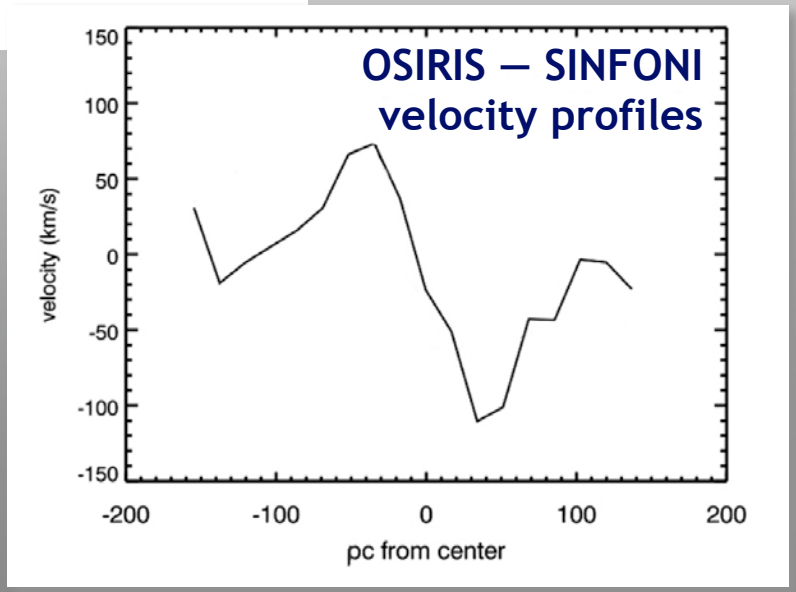
Keplerian velocity profile: Ideal (black) and smoothed by instrument PSF (blue)

kinetic energy

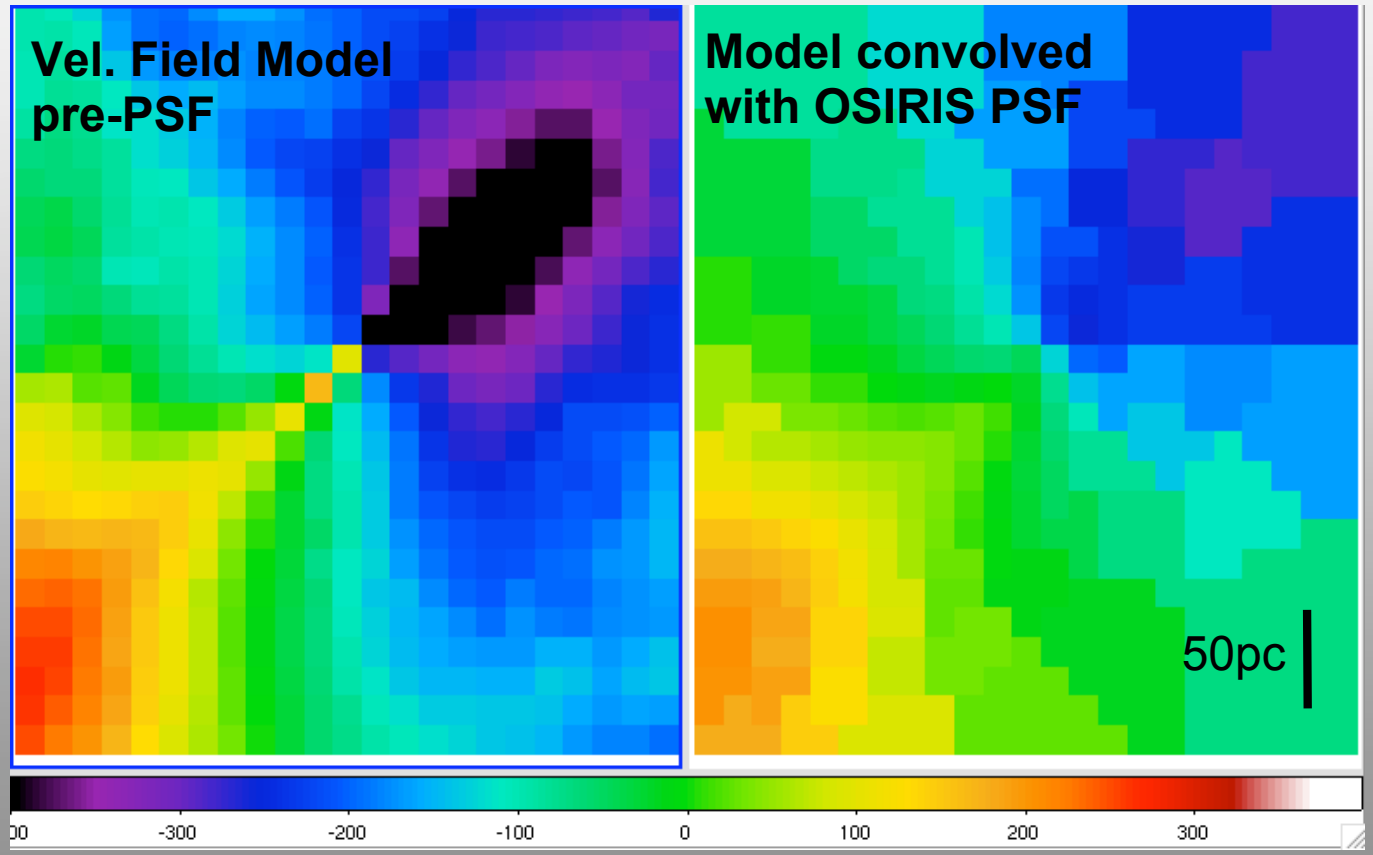
gravitational potential energy

$$mv^2 \cong \frac{GmM}{r}$$

$$v \cong \sqrt{\frac{GM}{r}}$$



Convolve Point Spread Function with Models to Compare with OSIRIS Data

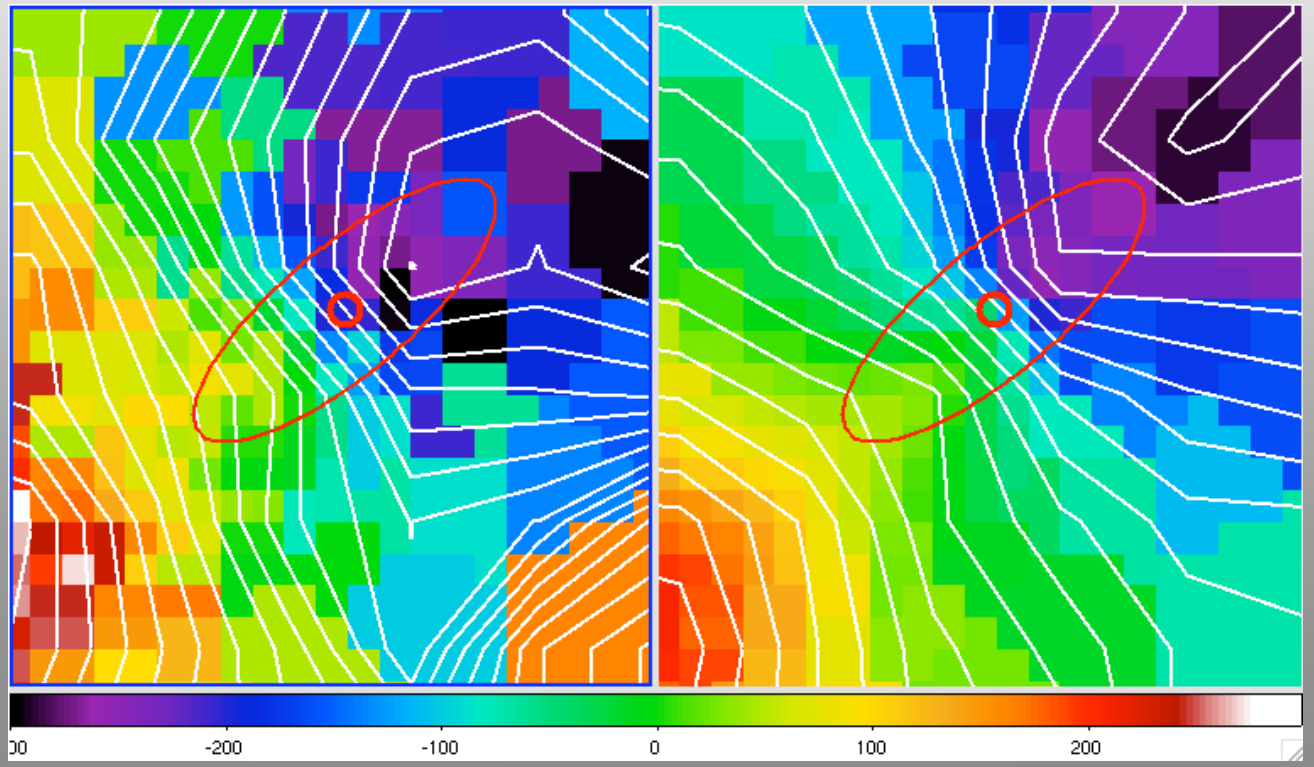


Best-fit model

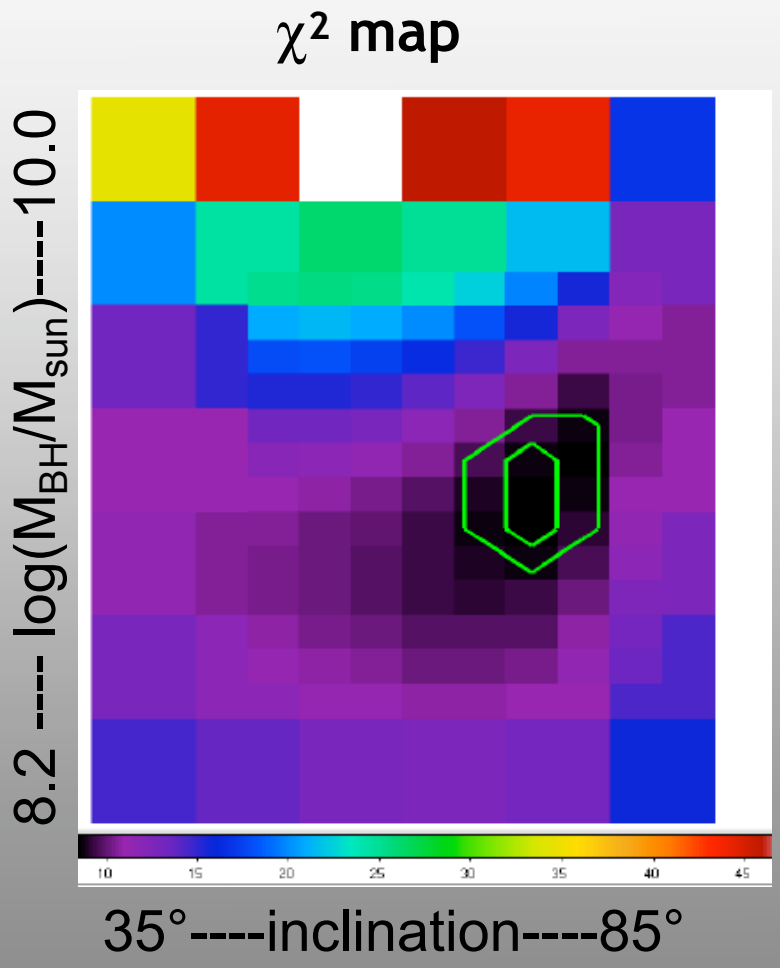
- $M_{BH} = 1.0^{+0.3}_{-0.2} \times 10^9 M_{sun}$, incl. = 75°, 30% Strehl

Observed vel. field

Model vel. field



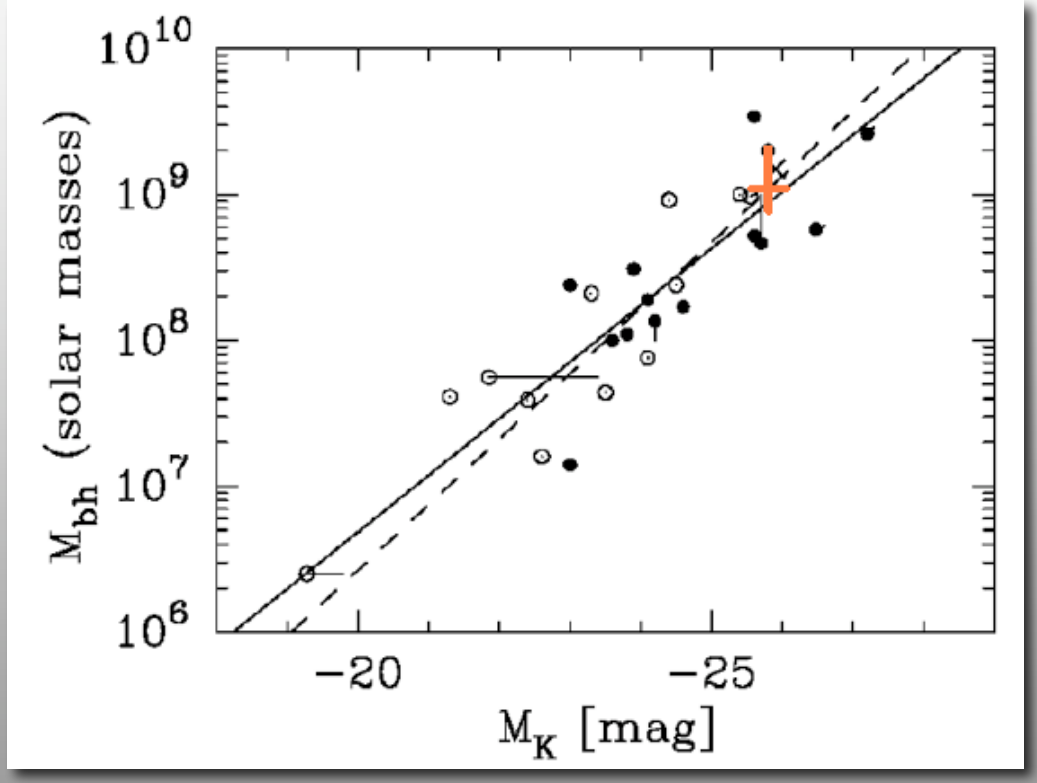
What parameters enter the fit?



- $M_{BH} = 1.0^{+0.3}_{-0.2} \times 10^9 M_{sun}$
- 1σ and 3σ contours shown in green, varying over all PSF choices
- These errors take into account velocity fitting errors and PSF choice errors
- Errors not yet accounted for:
  - Template choice
  - Idealized thin Keplerian disk
  - Dynamical mass = mass enclosed in 17 pc

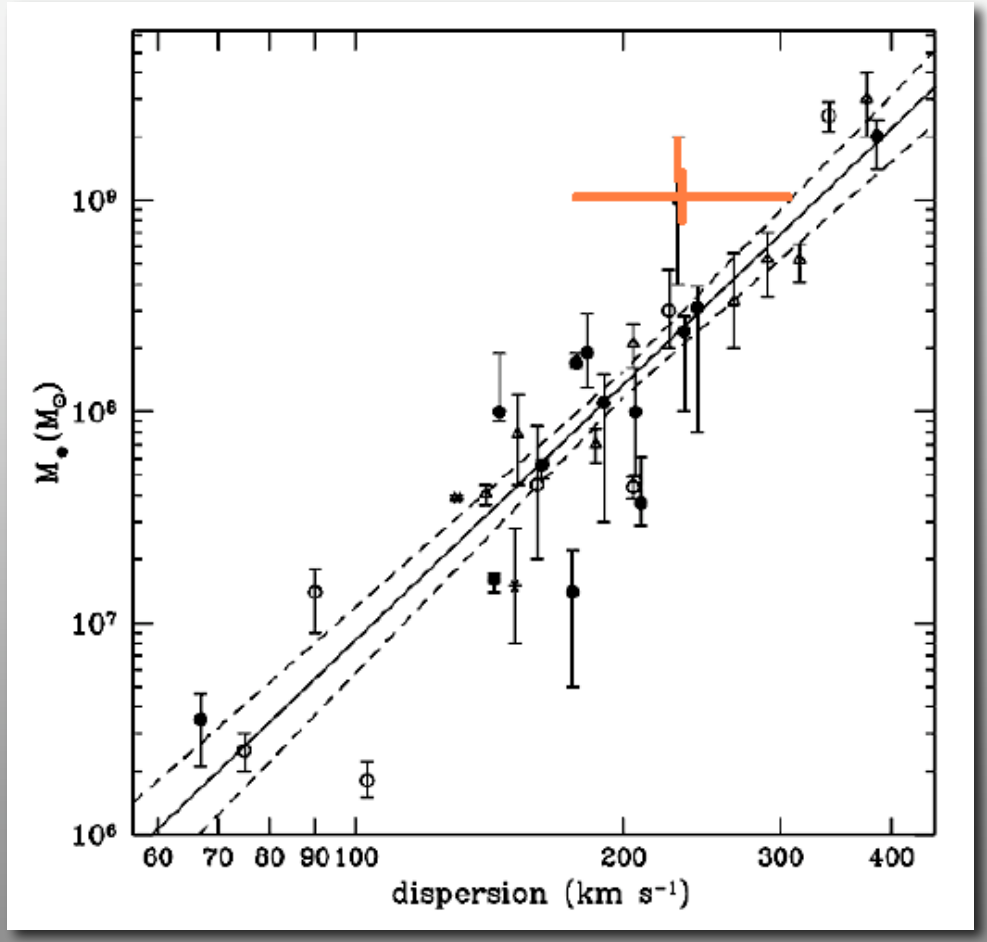
Comparing to Scaling Relations: Total Mass

- With 2MASS Ks photometry of total system, can put NGC 6240 on M_{BH}-L_{bulge} rel'n
- Good agreement suggests total mass may evolve into bulge



Plot: A. Graham 2007

Comparing to Scaling Relations: M-σ



Plot: Tremaine et al 2002

- Difficult to place on M_{BH} - σ relation because bulge is not relaxed yet
- Hence σ varies based on where you measure it
- We see 150-300 km/s near south BH (may be low because our stars are young; recently formed in disk)
- Tecza et al. (2000) measure 236 km/s integrated over whole 0.8”x0.7” region

NGC 6240: Summary

- We have located the positions of the two black holes
- High spatial resolution of Keck adaptive optics allowed us to identify ~30 new nuclear star-forming clusters, ages 10-20 Myr. Formed in most recent encounter between the two galaxies.
- Spatially resolved spectroscopy at the diffraction limit: map stellar velocity structure around black hole
- South black hole mass is ~ 10^9 $M_\odot$
- The 2 black holes are still deeply embedded in dust, not (yet?) at stage where AGN feedback destroys or ejects the gas and dust.