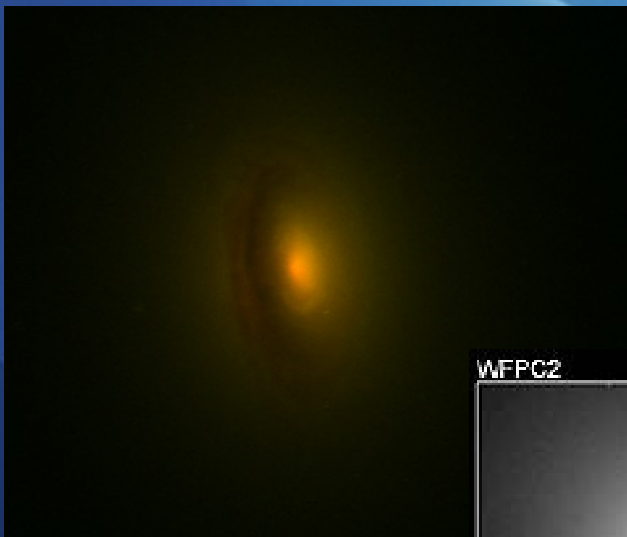
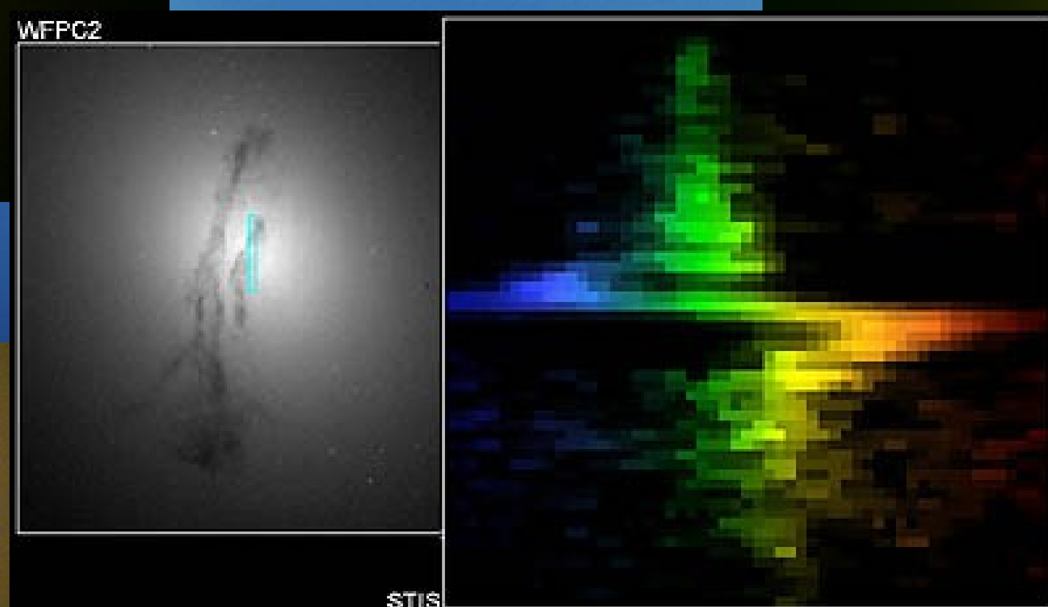
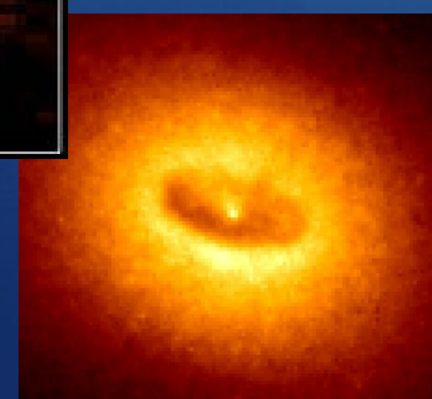
Supermassive Black Hole Demographics

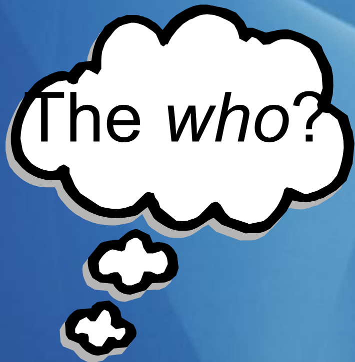
Dr. J. Pinkney







Collaborative research with the *Nuker* Team



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What is a Black Hole?

black hole (BH): 1. a region where matter has become so compact that even light cannot escape the pull of gravity.

$$v^2_{esc} = 2GM_{BH}/r \qquad (\sim c^2 \text{ on the event horizon})$$

$$r_{Schwarzschild} = 2GM_{BH}/c^2$$

Note the linear relationship between r_{Sch} *and* M_{BH} ...

$$r_{Sch}\ (\mathrm{km}) = 2.95\ M_{BH}\ (M_\odot)$$

Properties:

- Mass
- Charge
- Spin

Other properties are not independent, e.g., size ~ mass, area, volume, entropy (A/4).

Types of Black Holes

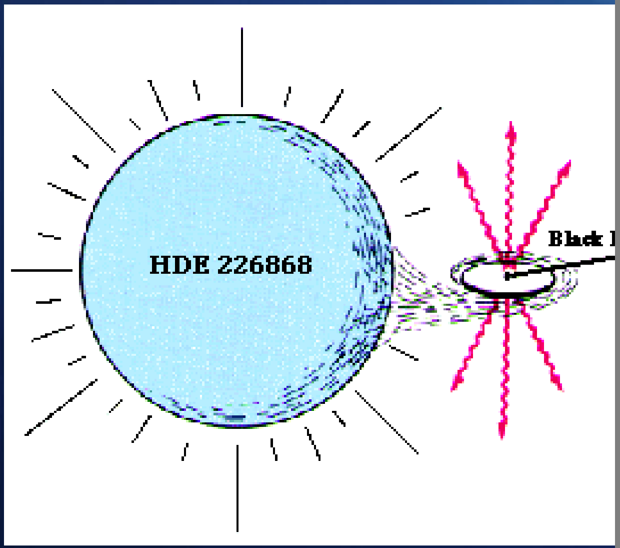
	Non-rotating	Rotating
Uncharged	Schwarzschild	Kerr
Charged	Reissner-Nordstrom	Kerr-Newman

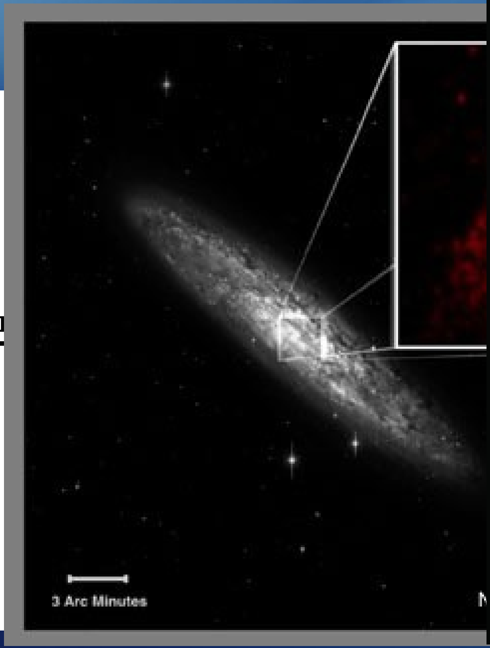
Observationally ...

stellar
(3-30 $M_\odot$)

intermediate
(100 - 10^4 $M_\odot$)

Supermassive
(10^5 - $10^{10} M_\odot$)

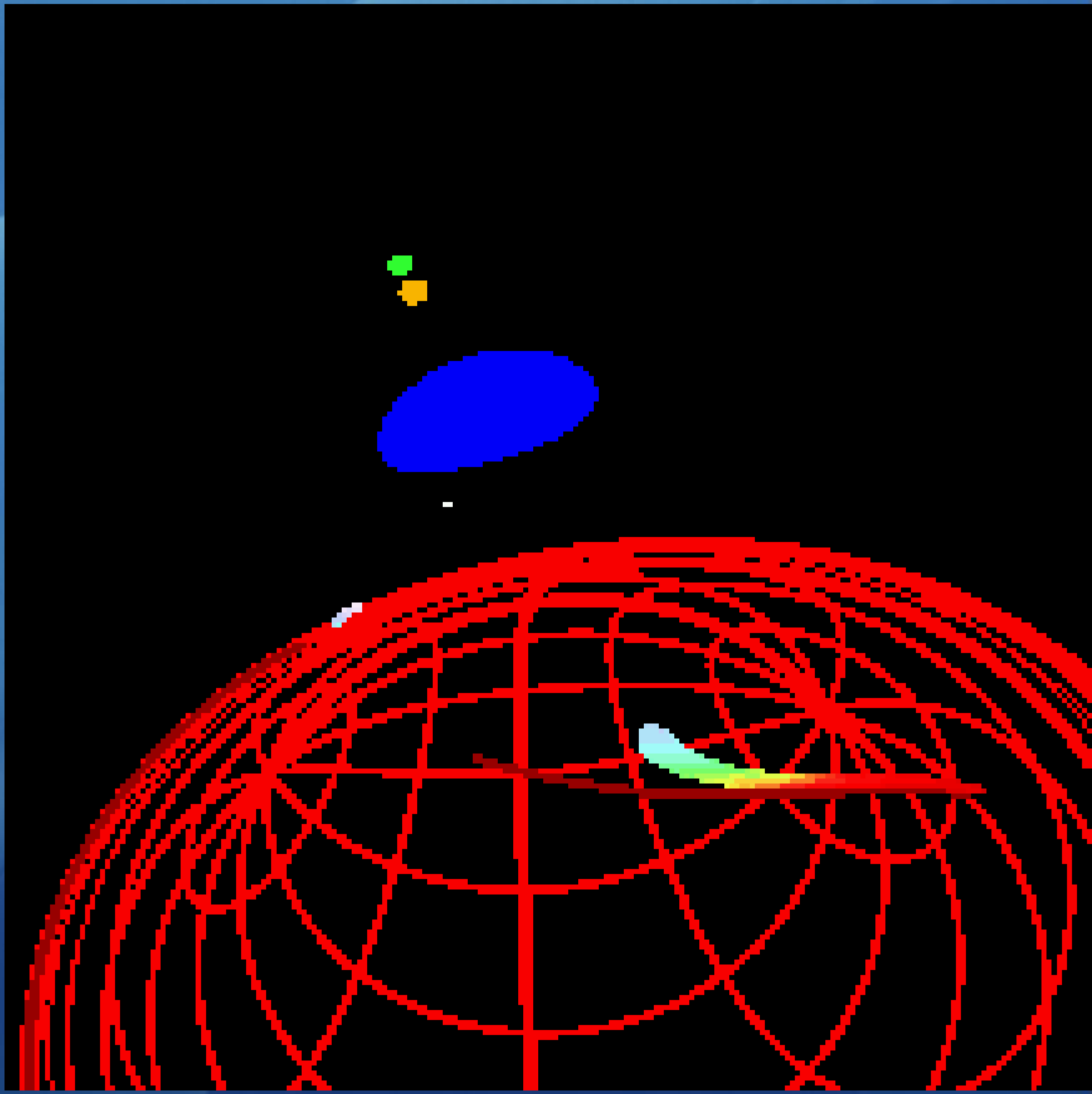




Black Hole Physics - Close up

General Relativity needed

- space warped
- time dilation
- gravitational redshifts



See: http://casa.colorado.edu/~ajsh/orbit.html

Black Hole Physics - Far away

Newtonian Mechanics will suffice

Radius of <u>Sphere of influence</u> of a black hole:

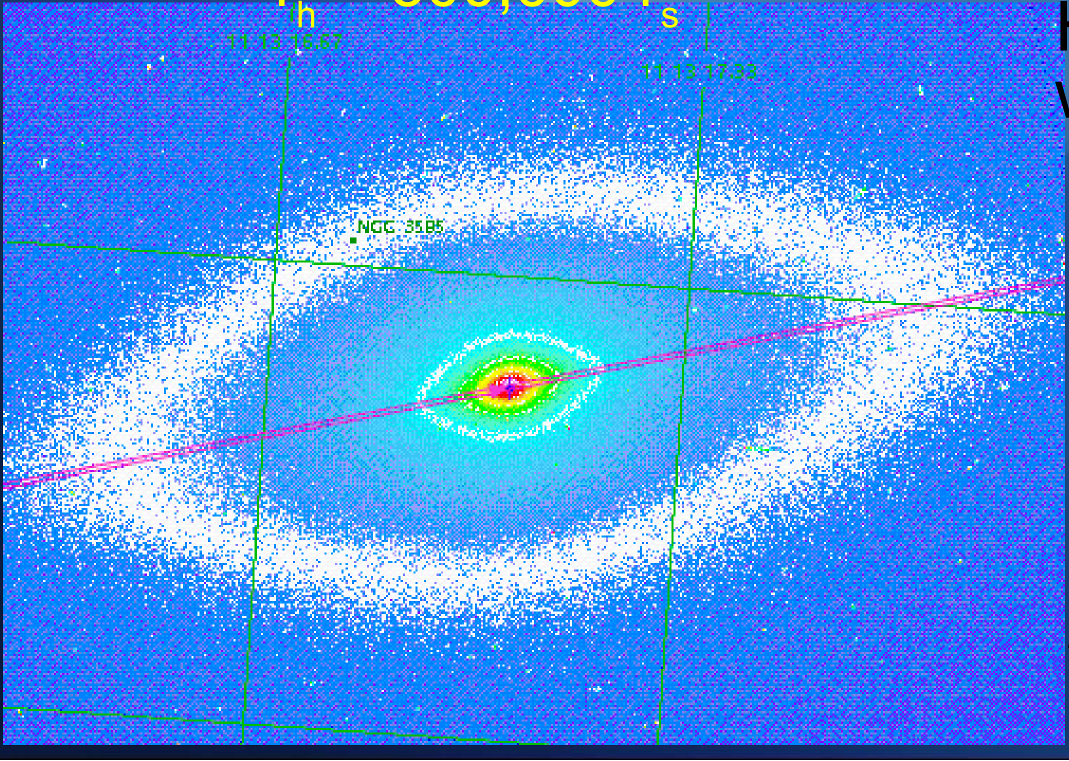
$$r_h \equiv \frac{GM_{BH}}{\sigma^2} = 10.8\ pc \left(\frac{M_{BH}}{2\times10^8\ M_{sun}}\right)\left(\frac{\sigma}{200\ kms^{-1}}\right)^{-2}$$

10.8 pc is 1” for D=2.2 Mpc (can resolve from ground)

10.8 pc is .1” for D=22. Mpc (can resolve with HST)

10.8 pc is 2.1 million AU, and r_s=4 AU for 2×10^8 Msun

$r_h \sim 500{,}000\ r_s$

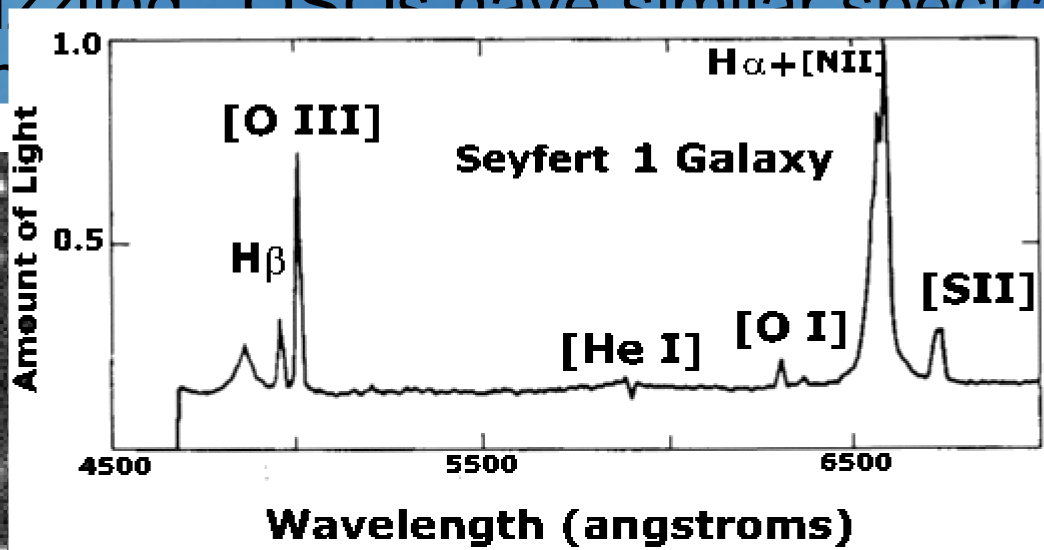


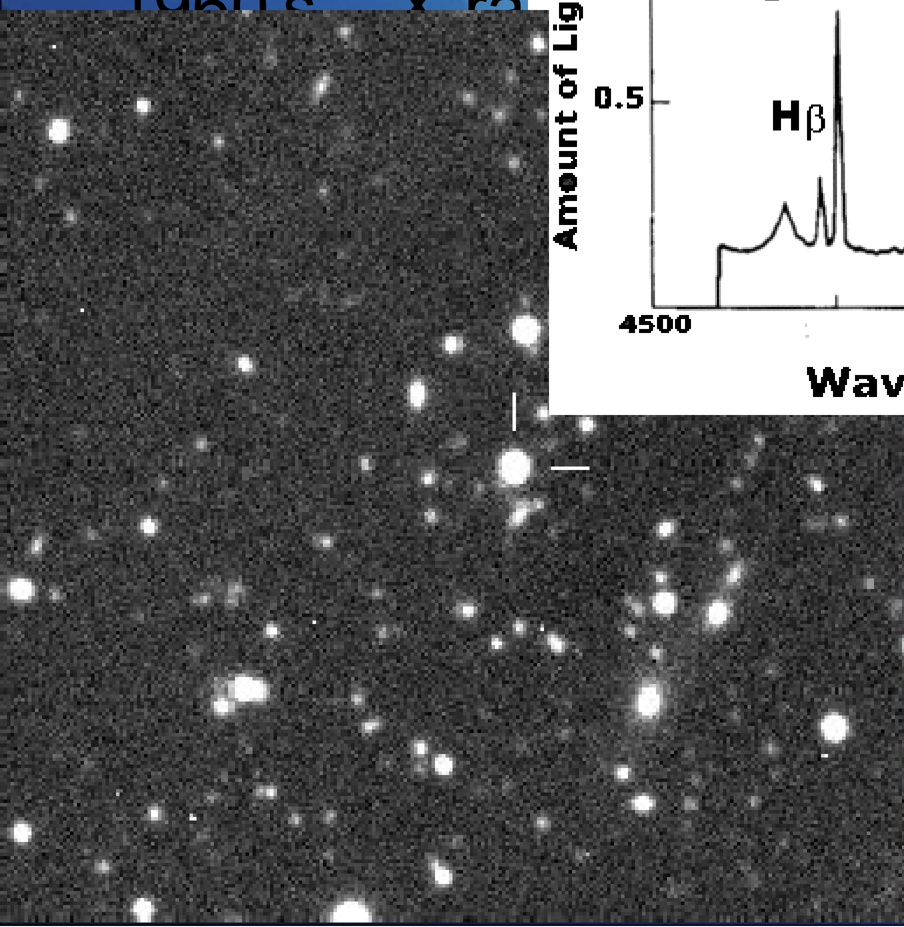
HST image of NGC 3585 with proposed STIS slit overlayed.

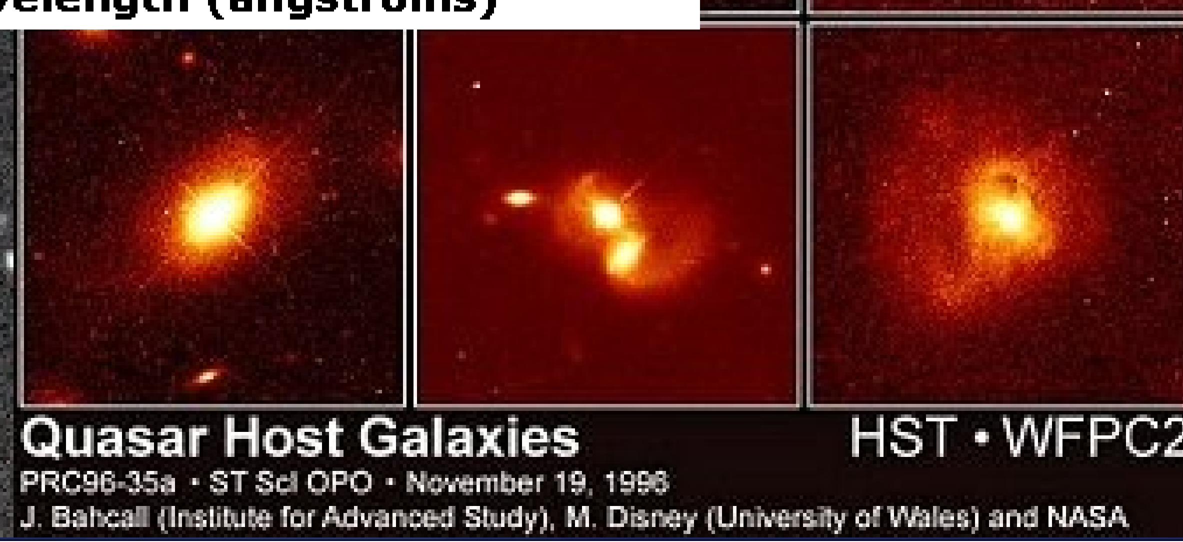
The search for supermassive black holes does not require a mastery of general relativity, just Newtonian physics.

SMBH Background – history of AGN

1943 – Seyfert studies emission line nuclei.
1932-1959 – radio astronomy detects AGN (unkn
Bright -- Milky Way -- Small, double-lobed – 3
1960 – 3C 48 identified with blue “star” (Sandage)
Spectra puzzling. QSOs have similar spectra.
1963 – M. Sch
1960's – X-ra



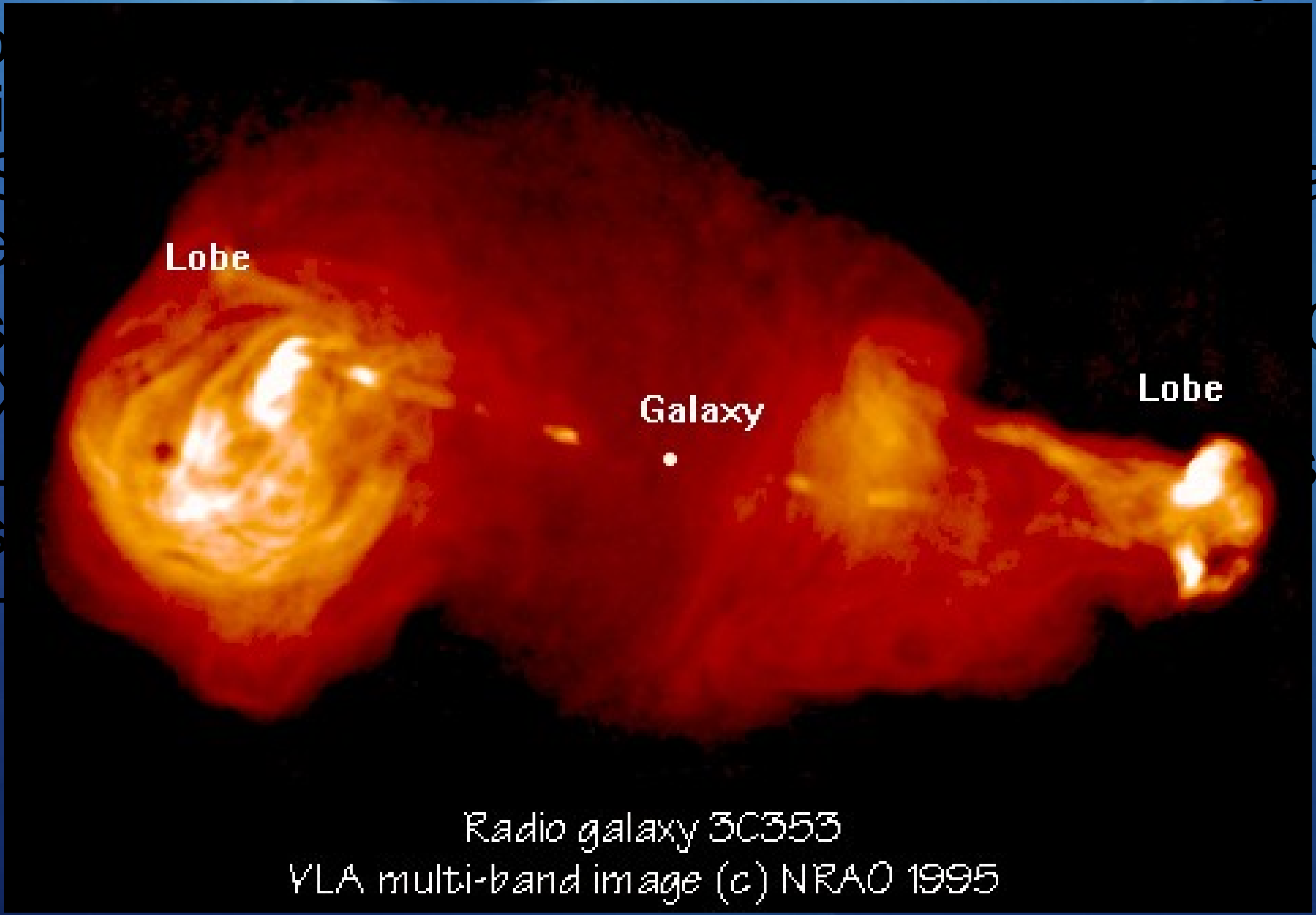




Supermassive Black Holes – Background. II

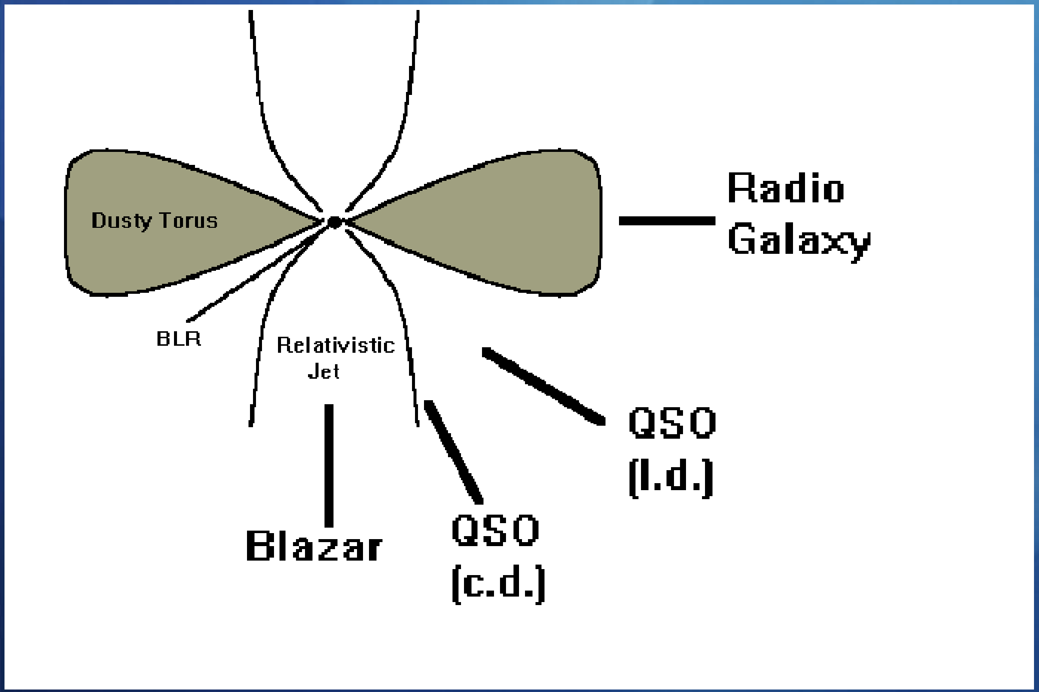
1963 – Greenstein & Schmidt propose that a $10^9\ M_\odot$ central
mass co ,
luminosi
1964 – S asars
could be

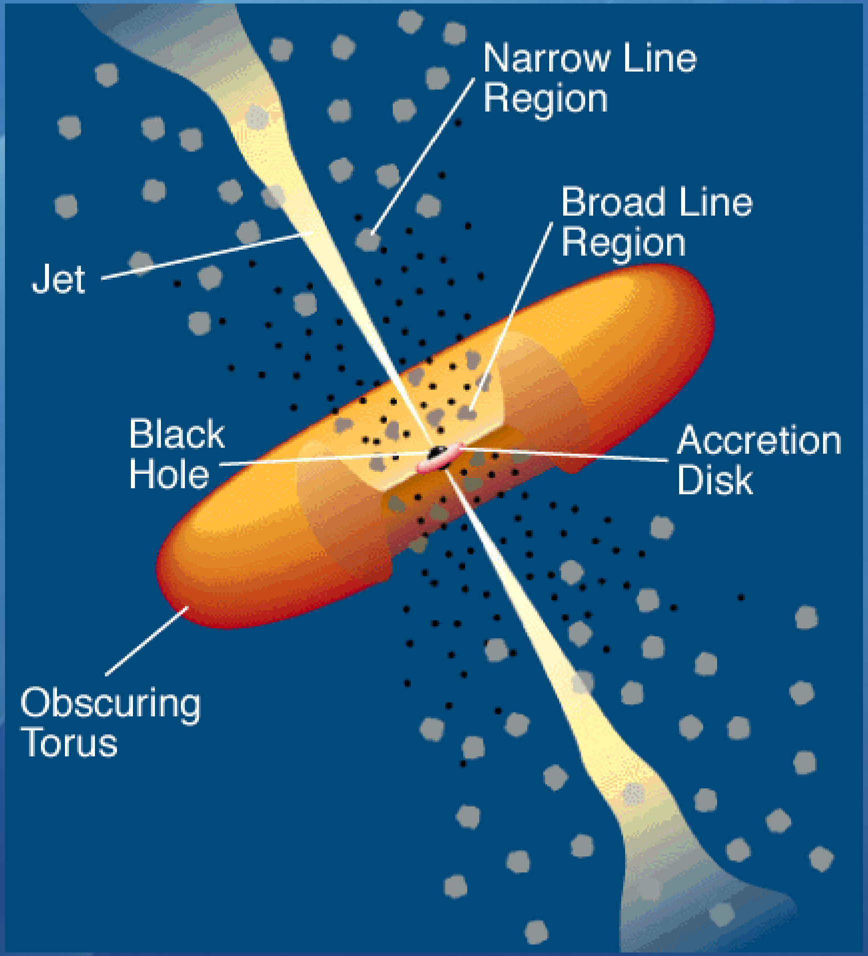
late 60's 001"
-- X
1969 – L should
exis
1970's –

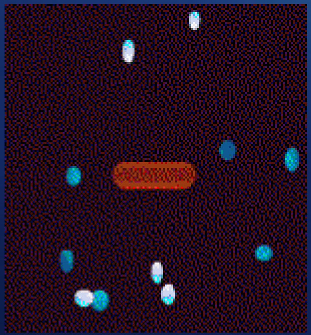


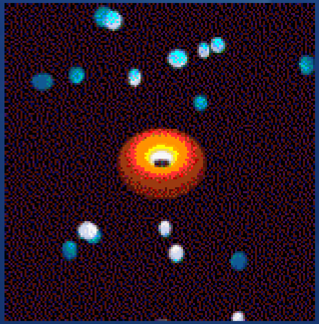
Supermassive Black Holes – Background. III

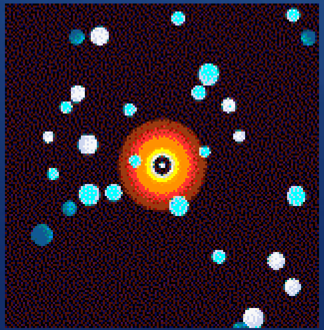
AGN, accretion Disks, and a unified model











Motivation for measuring SMBH masses.

Studies of *AGN* and *accretion disks*

- **Are all AGN caused by BH?**
- **How do jets form?**
- **Is the unified model true?**

Formation of SMBH, cosmology

- **Which came first ... SMBH, stars, bulges?**
- **What is the black hole *mass function*?**

Black Hole *demographics!**

- **Which galaxies have black holes?**
- **What properties of galaxies correlate with M_{BH}?**

*<u>demography</u>: the study of vital statistics in populations and subgroups of populations

Black Hole Demography* and the M_{BH} – sigma correlation ... some brief answers:

Which galaxies have a central SMBH?

Every one with a bulge!

What properties of galaxies correlate with M_{BH}?

1. Galaxy bulge mass. (Kormendy 1993, Kormendy & Richstone 1995)

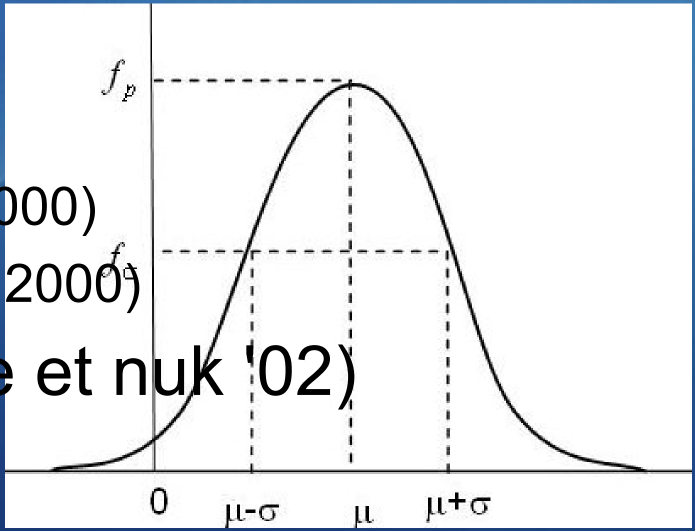
$$M_{BH} \sim 0.002\ M_{bulge}$$

2. Bulge velocity dispersion[1], σ "sigma".

$M_{BH} = 1.2\times10^8\ M_\odot\ (\sigma/200)^{3.75+-0.3}$ (Gebhardt et nuk 2000)

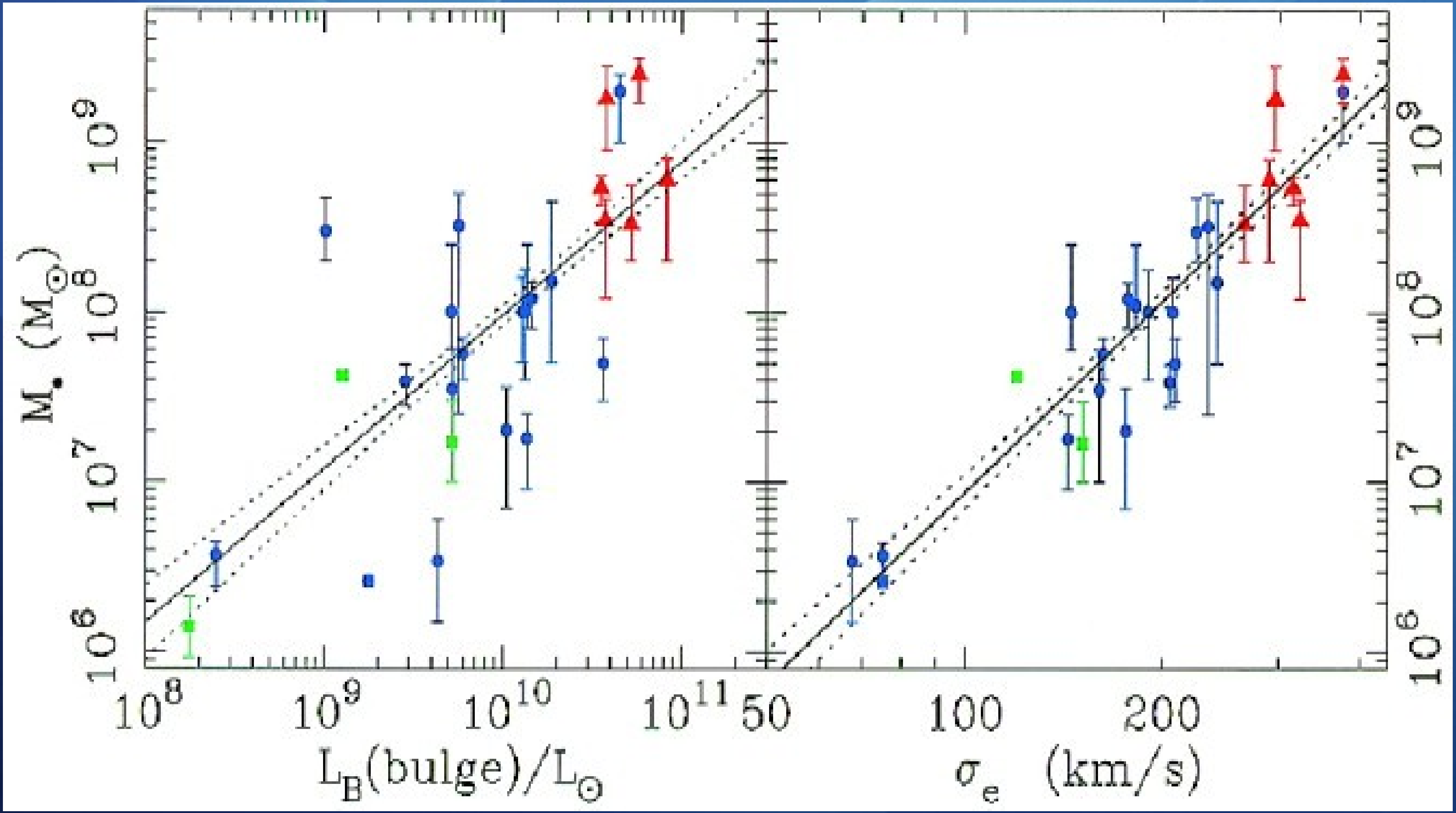
$M_{BH} = 1.2\times10^8\ M_\odot\ (\sigma/200)^{5.27+-0.4}$ (Ferrarese & Merritt 2000)

$M_{BH} = 1.34\times10^8\ M_\odot\ (\sigma/200)^{4.02}$ (Tremaine et nuk '02)



[1] *Velocity dispersion*: the 2nd moment of the line-of-sight velocity distribution. Approx. the sigma of a Gaussian fitted to the losvd.

Demography: the M_{BH} – sigma correlation.



σ_e = luminosity-weighted velocity dispersion within half-light radius

Response to the M_{BH} – sigma correlation.

Theorists: SMBH mass is not just related to how much mass is present in the bulge, but also by how much the bulge has collapsed.

Therefore, the growth of the galaxy bulge and SMBH are very intimately related.

-> Revisit galaxy formation!
-> When was growth most rapid – time of quasars?!
-> Which came first, stars or SMBH? -> What are the seeds of SMBH?
-> Is there an even better predictor of BH mass?

Observers: get more data! Better define the relationship!
-> go after low mass galaxy bulges
-> go after high mass galaxies *
-> is there curvature? *
-> is there a 2nd parameter, i.e. does the scatter correlate with anything?
→ Use the M-sigma relation to estimate M's at higher z.

2009 Update to the M_{BH} – sigma correlation.

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A QU

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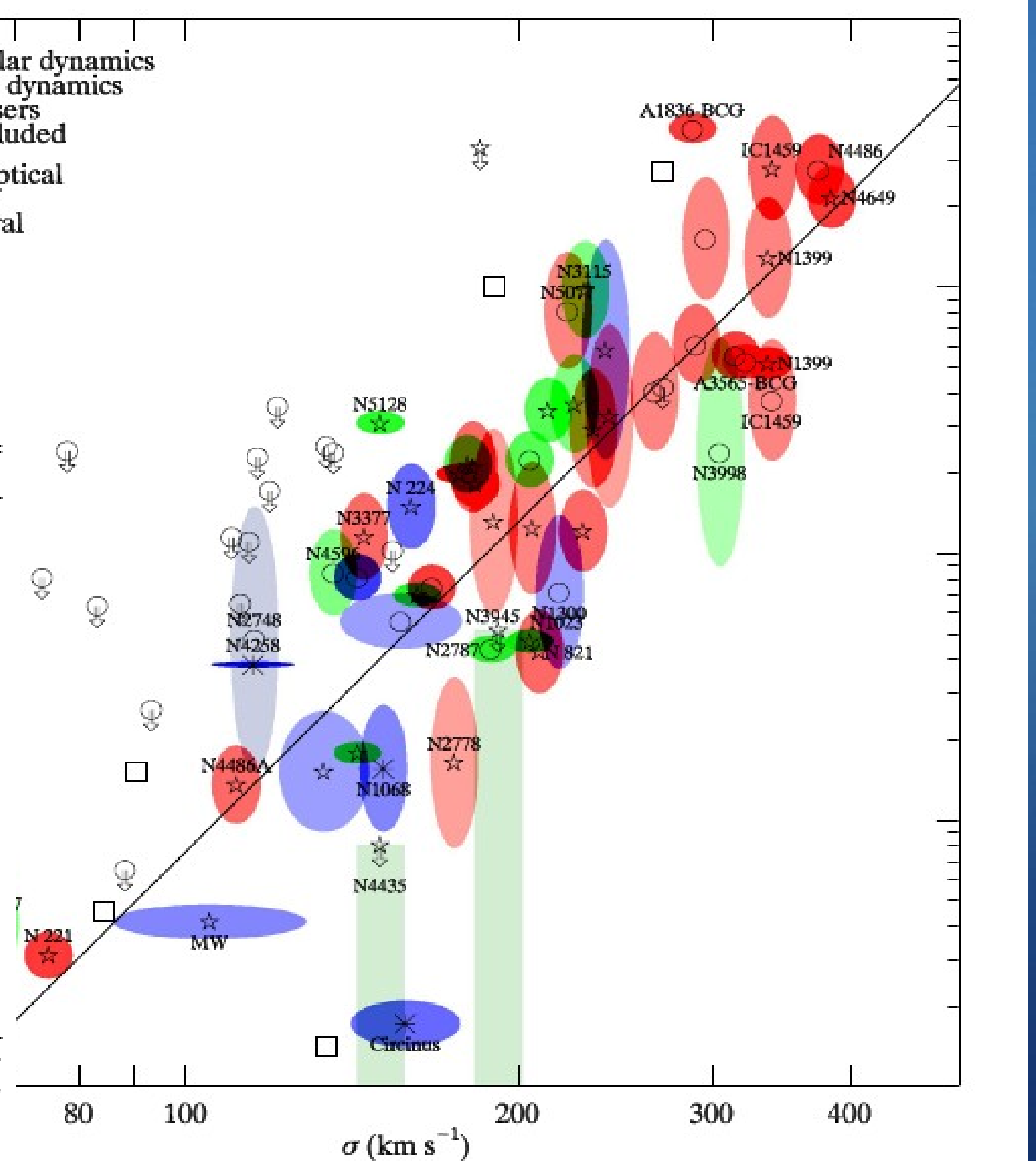
TABLE 4
M–σ RELATION FOR SUBSAMPLES

Subsample	N_m	N_u	α	β	ϵ_0
Full sample	49	19	8.11 ± 0.08	4.10 ± 0.43	0.45 ± 0.06
Early type	40	7	8.19 ± 0.081	3.73 ± 0.422	0.38 ± 0.065
Late type	11	12	8.00 ± 0.280	4.67 ± 1.563	0.55 ± 0.139
Ellipticals	27	2	8.22 ± 0.085	3.84 ± 0.432	0.31 ± 0.064
Non-ellipticals	24	17	8.01 ± 0.163	3.97 ± 0.886	0.54 ± 0.106
Stars and masers	33	3	8.11 ± 0.108	3.97 ± 0.568	0.49 ± 0.077
Gas dynamics	18	16	8.13 ± 0.109	4.19 ± 0.557	0.35 ± 0.085
$\sigma_e < 200$ km s^{-1}	25	17	8.07 ± 0.180	3.87 ± 0.964	0.51 ± 0.103
$\sigma_e > 200$ km s^{-1}	26	2	8.14 ± 0.151	4.08 ± 0.869	0.36 ± 0.075
Non-barred	43	7	8.20 ± 0.086	4.05 ± 0.439	0.43 ± 0.064
Barred	7	12	7.66 ± 0.117	0.97 ± 0.761	0.16 ± 0.082
Classical bulges	41	16	8.16 ± 0.089	4.02 ± 0.452	0.46 ± 0.068
Pseudo-bulges	10	3	7.96 ± 0.142	4.17 ± 0.885	0.25 ± 0.103

NOTE. — Results from fits to subsamples of our full sample, based on morphological type, BH mass-measurement type. N_m and N_u are the number of galaxies in each group with BH mass measurements and upper limits, respectively.



alaxies with dynamical measurements. The symbol indicates the method of BH mass measurement: stellar dynamical (*pentagrams*), gas dynamical (*circles*), masers (*asterisks*). Arrows indicate $3\sigma_{68}$ upper limits to BH mass. If the $3\sigma_{68}$ limit is not available, we plot it at 3 times the $1\sigma_{68}$ or at 1.5 times the $2\sigma_{68}$ limits. In our fitting, the limits are treated at their actual confidence levels. For clarity, we only plot error boxes for upper limits

Black Hole Demography

Other correlations with central SMBH mass.

Mbh vs Bulge Mass (Haring and Rix '04)

- **scatter around 0.3 dex**
- **used Jeans equation dynamical models**

Mbh vs Gravitational binding energy as traced by stellar light profile (Aller and Richstone '07)

- **scatter as low as Mbh-sigma**

Mbh vs pitch angle (Seiger et al. '08)

- **Total mass more concentrated for tighter spirals**
- **scatter around 0.3 dex for P< 37 degrees.**

Mbh vs concentration index (Graham et al 2001)

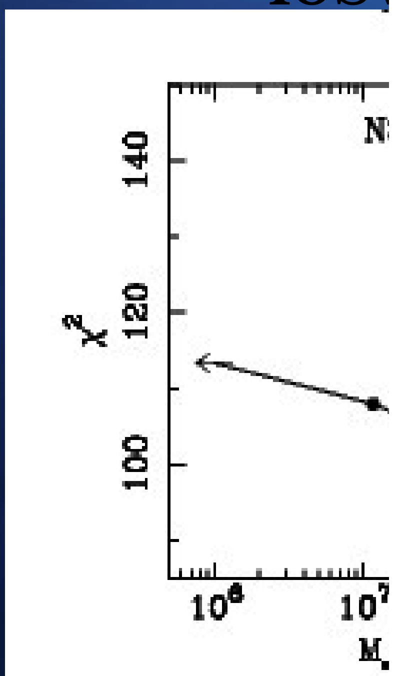
Multivariate quantities (eg r_e,I_e as 2nd param to sigma) (Aller and Richstone '07) - Didn't lower scatter in Mbh-sigma.

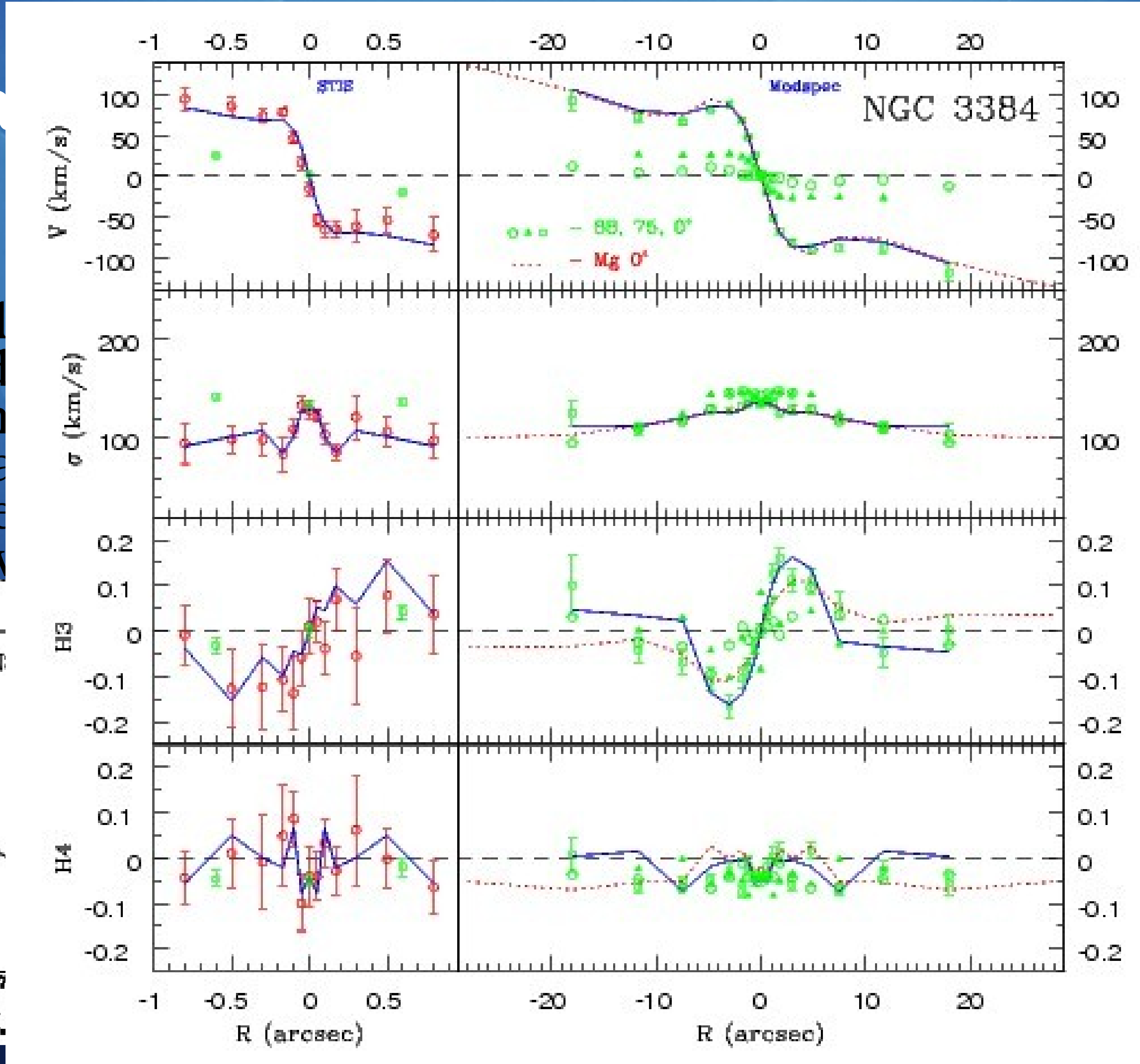
- Grav binding energy = -PE = $(M/L)^2(I_e)^2(R_e)^3$ gives low scatter

Curvature in relation instead of simple power law? (Wyithe & Stewart 2006)

Dyna

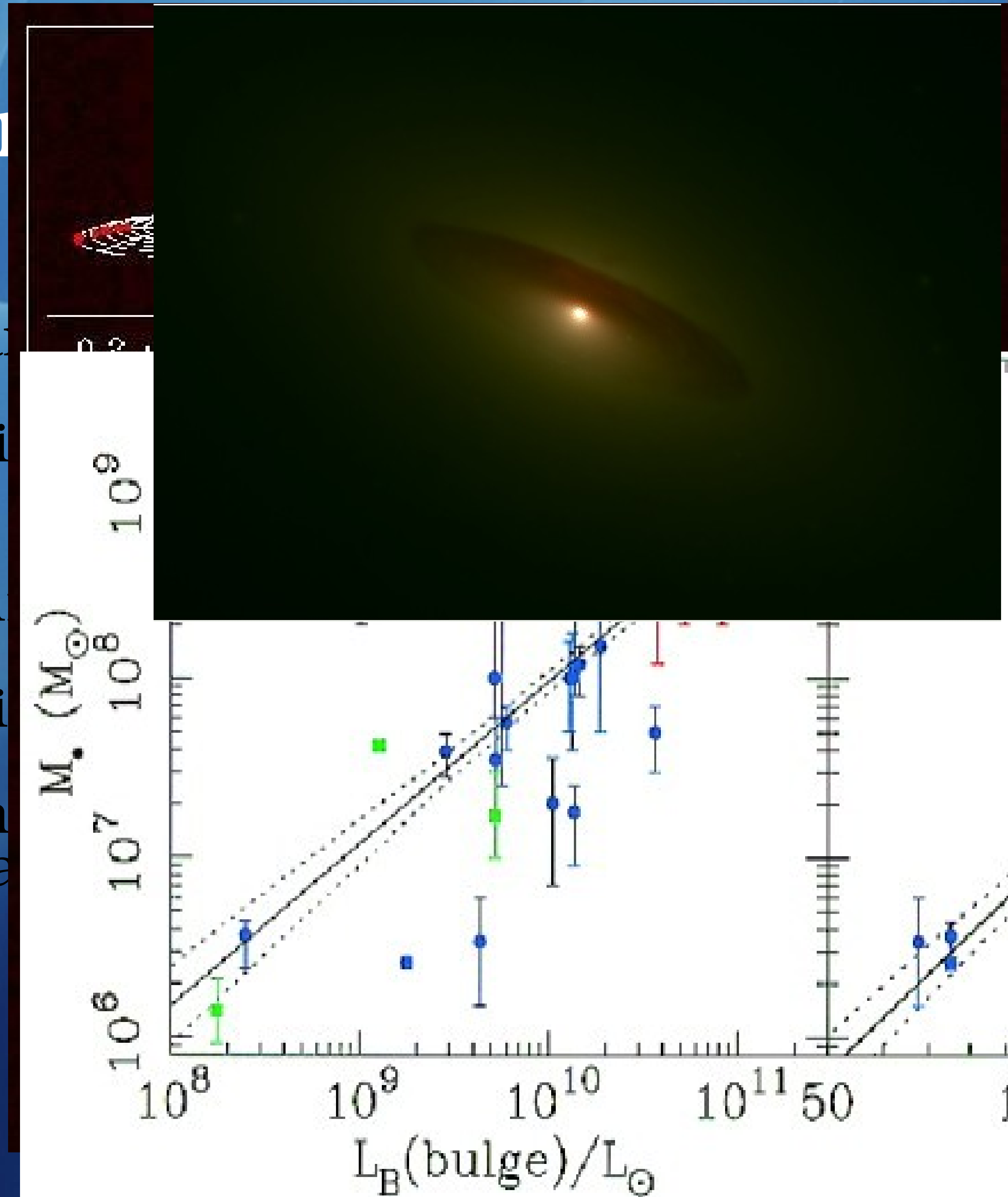
- Stellar d
  - Individ
  - Ensem
    - Ima
    - Spe
    - Iosy





Dynamical r

- Stellar dynamics
  - Individual stars
  - Ensembles of sta
- Gas dynamics
  - Masers <-- “Plati
  - Gas spheres
  - Gas disks
    - Imaging (grou
    - Spectroscopy
    - Model assumi circular orbits disk, under on
  - Reverberation ma



Applicability of the two main methods

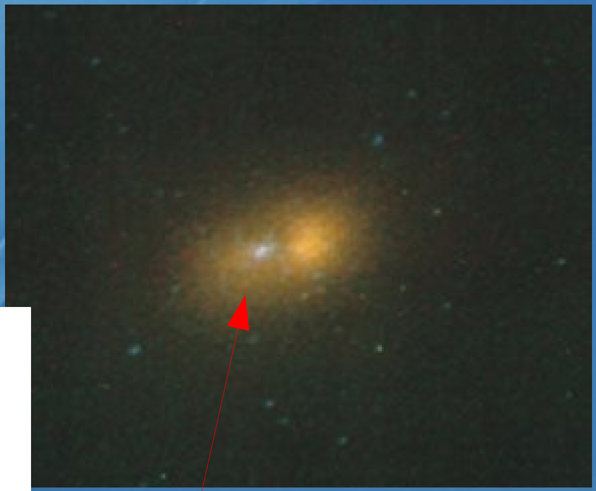
Stellar kinematics:
Dust interferes
AGNs interfere,   eg. M87
Mergers, severe non-axisymmetry bad.
→ Want ellipticals and early type bulges with minimal dust

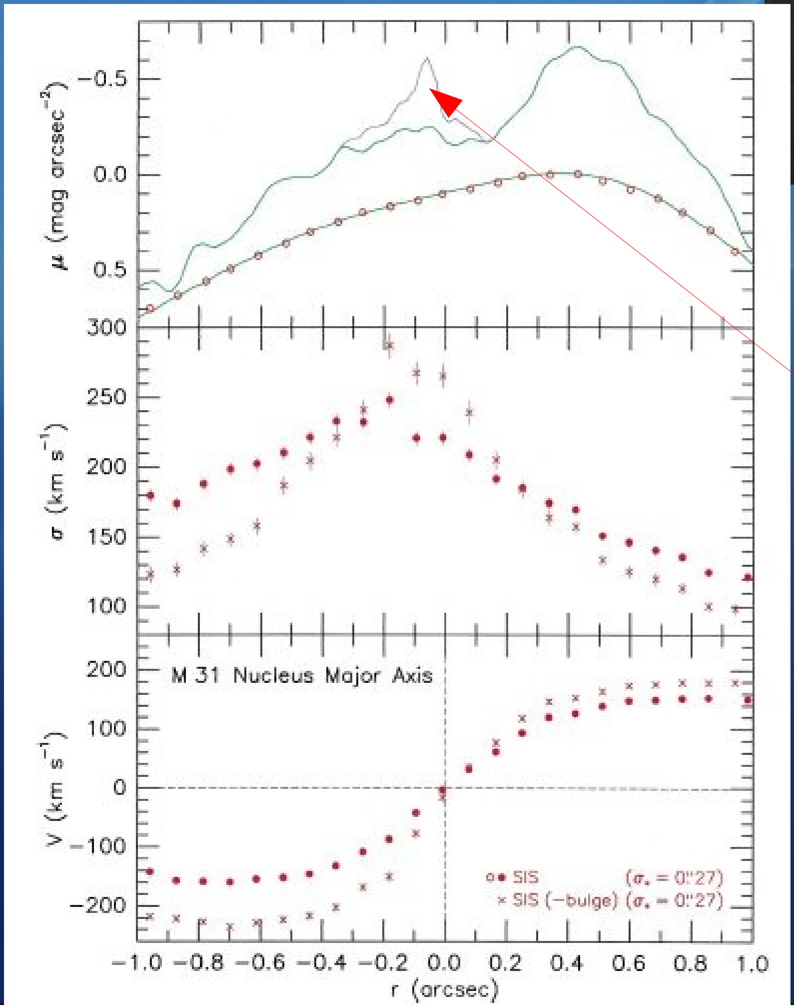
Gas disk method:
Dust useful indicator of *i* & planar gas.; – traces Halpha
AGN interfere. Broad lines, winds, radiation pressure
Non-circular motions – not settled into disk.
Gas not kinematically "cold" -- asymmetric drift.
→ Galaxies with an organized dust patterns are promising

Early results from stellar kinematics

M32 – Tonry et al. 1984

M31 – Dressler & Richstone; Kormendy and Bender (1999)



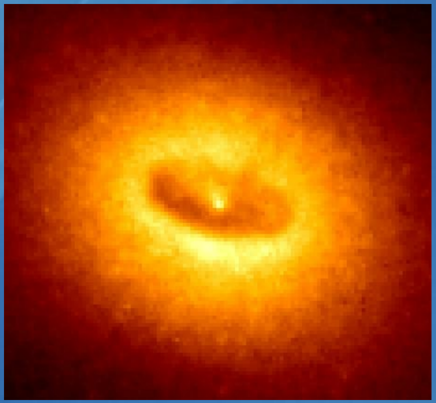


Blue nucleus!

N3115 - Kormendy

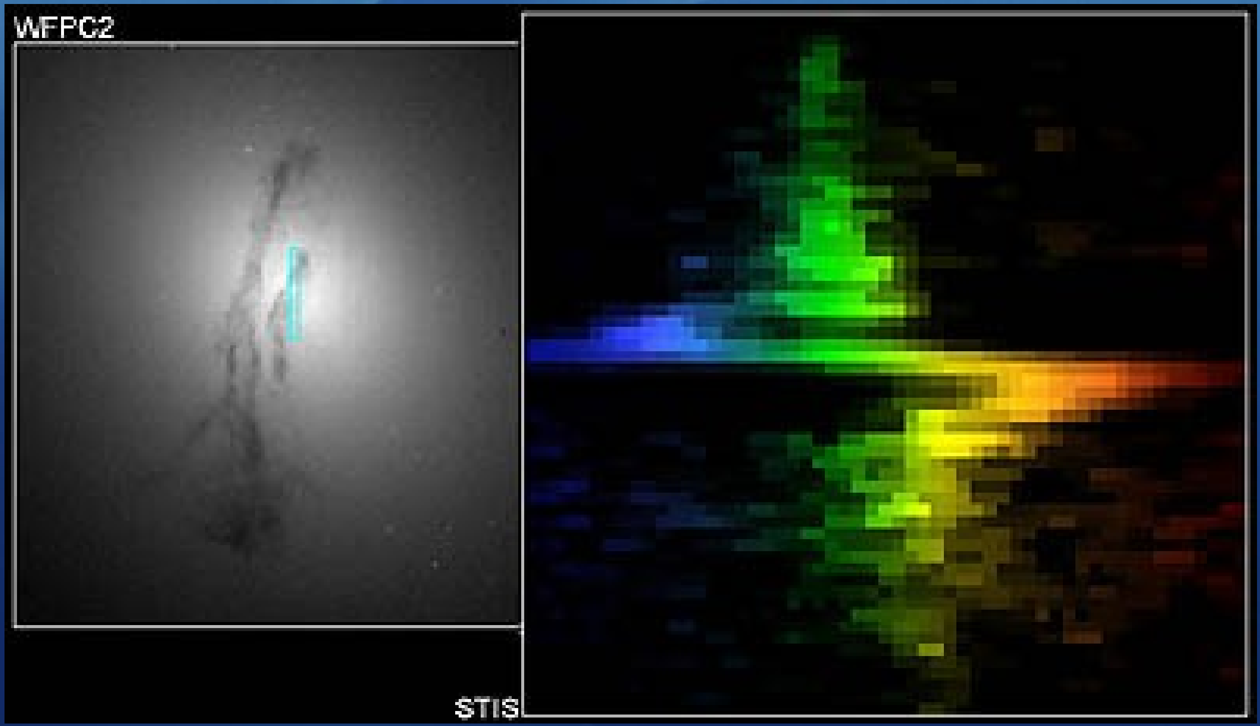
Early results from gas disk kinematics

M87 – Ford et al 1994

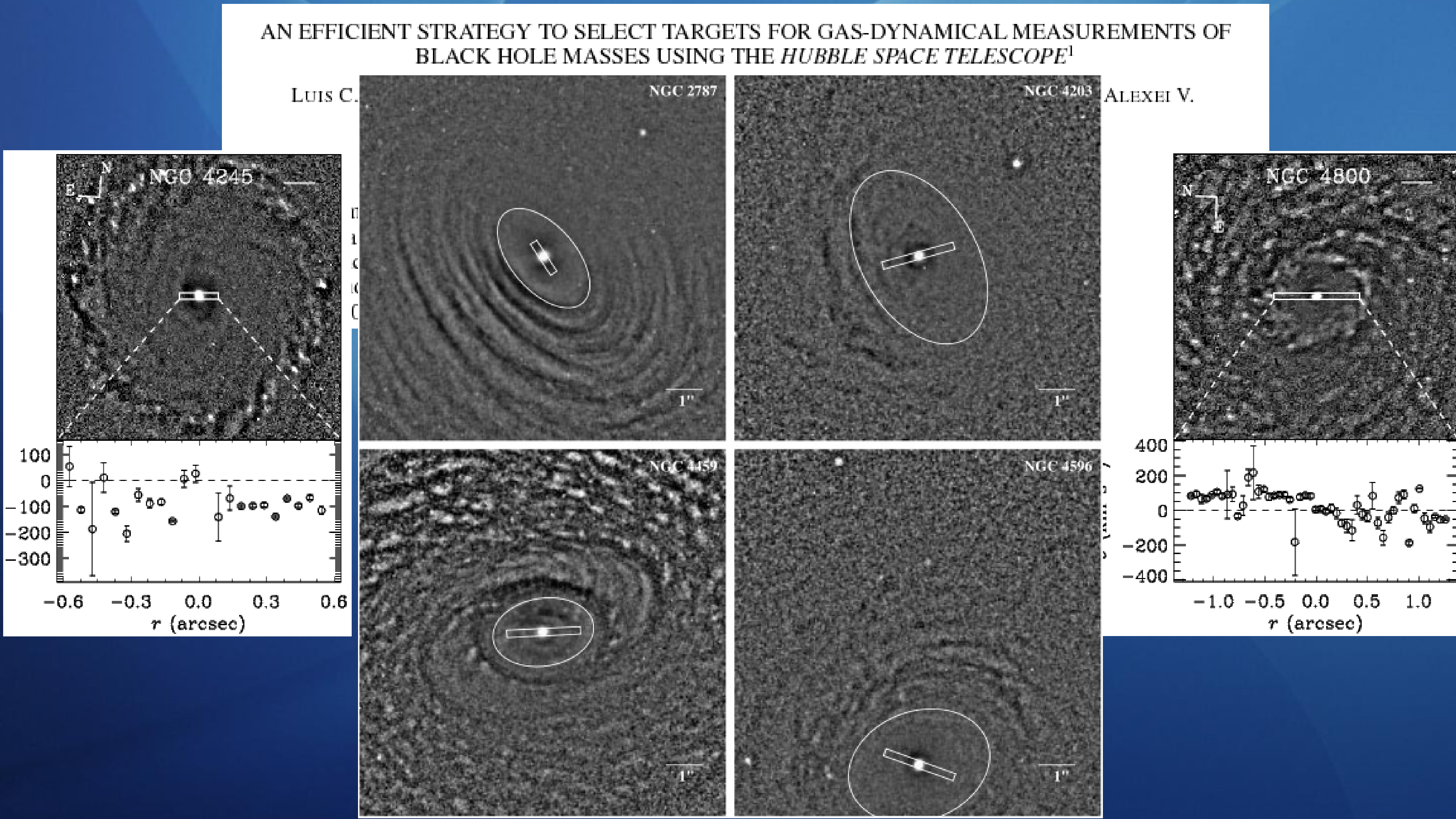


NGC 6251 – Ferrarese 1996

M84 – Bower et al 1998



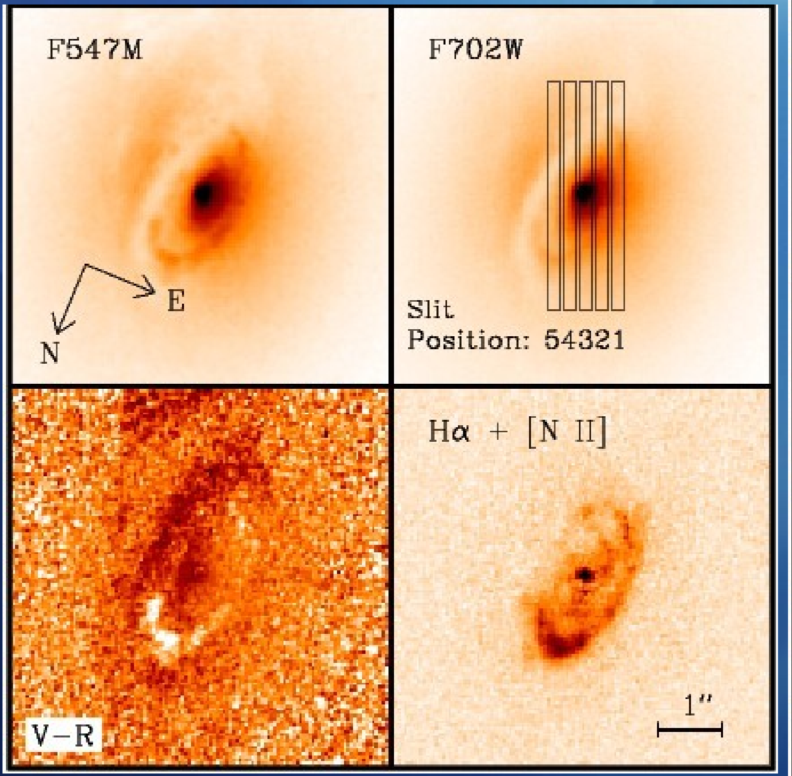
Lesson from the SuNNS survey

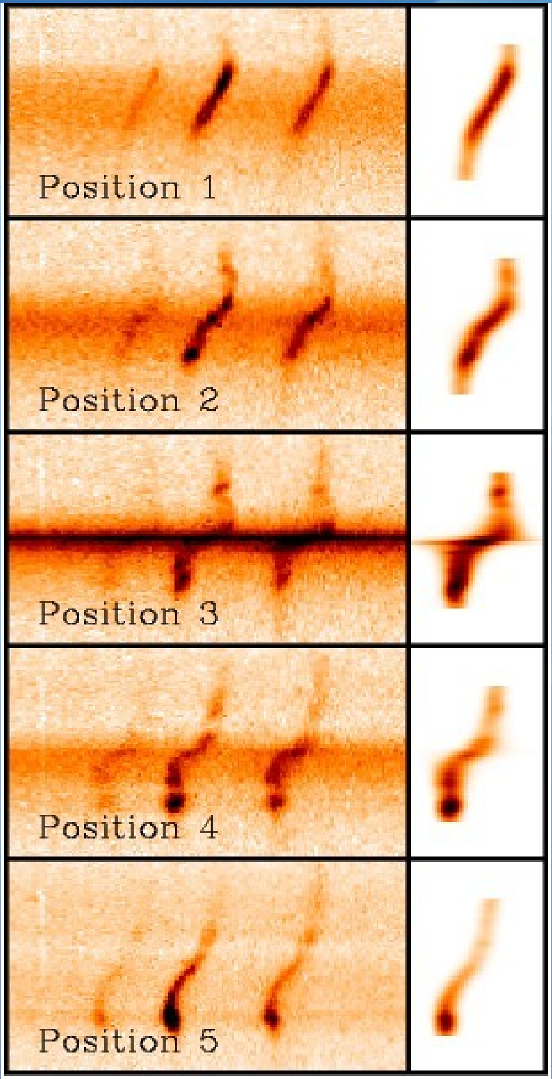


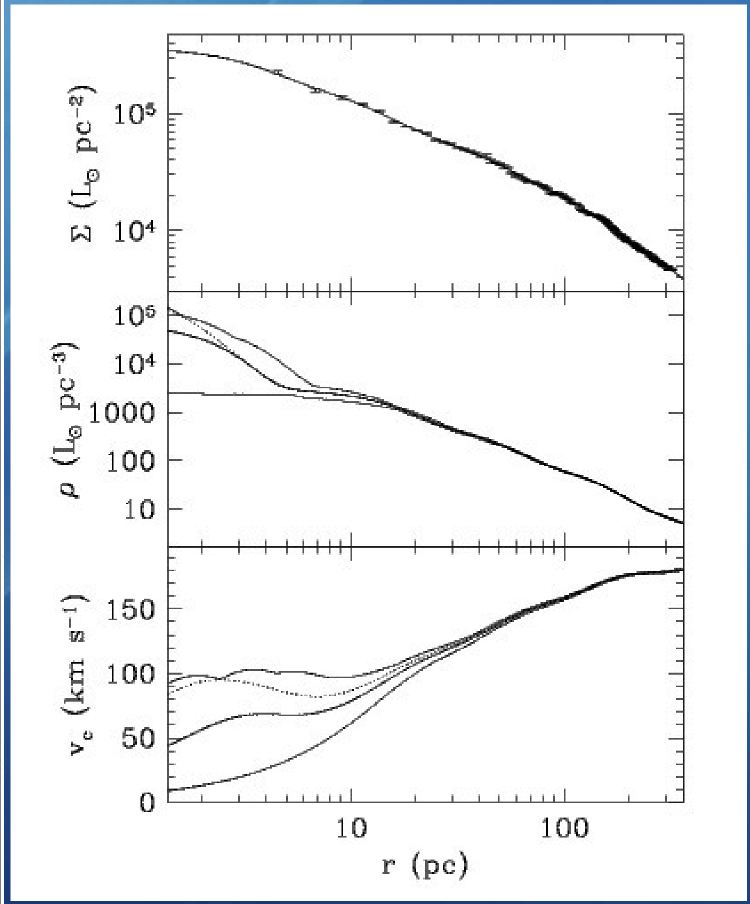
Only 15-20% of sample were amenable to gas disk analysis. Dust morphology important!!

Success Story: NGC 3245

(Barth et al 2001)







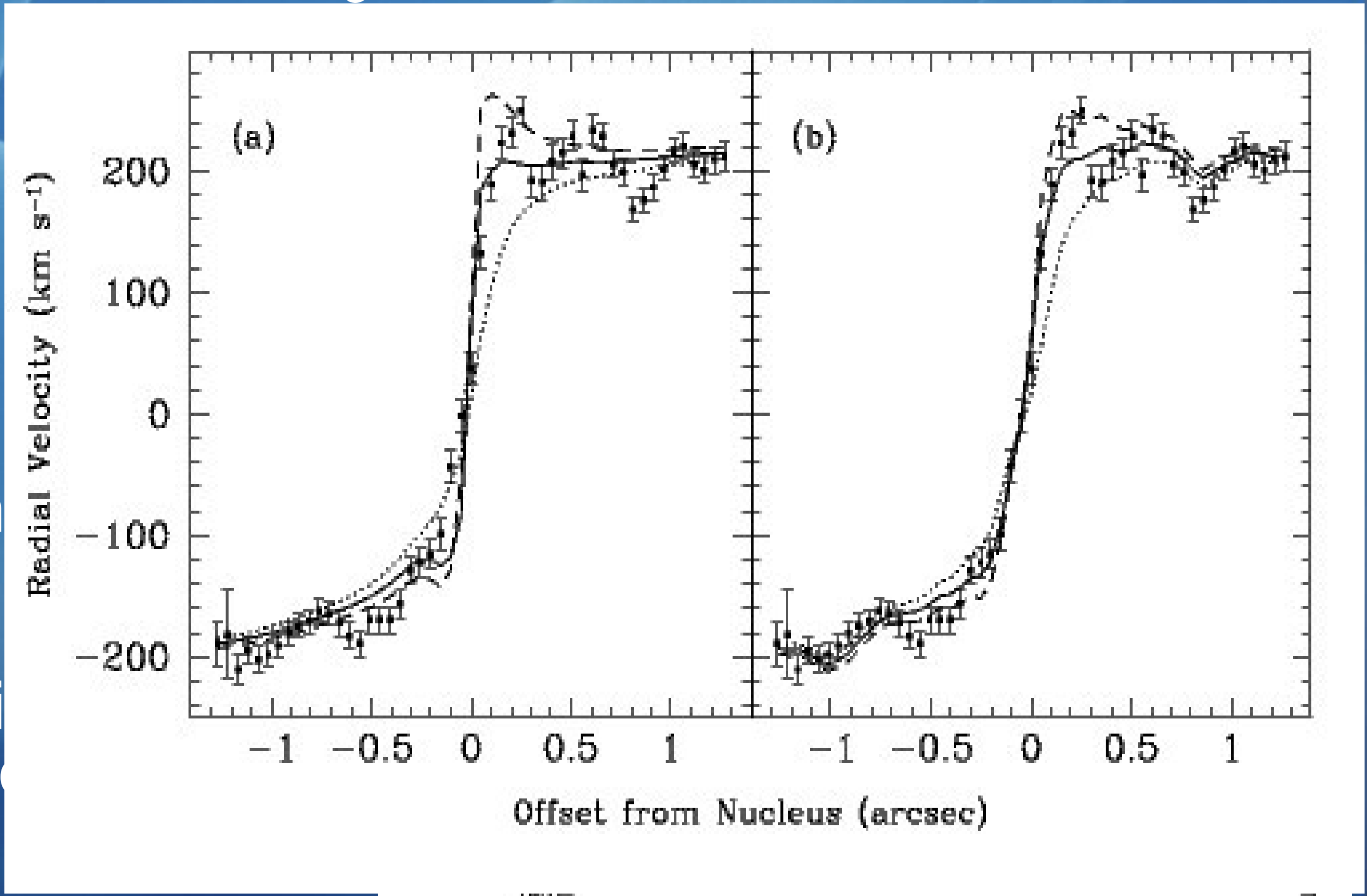
Success Story: NGC 3245

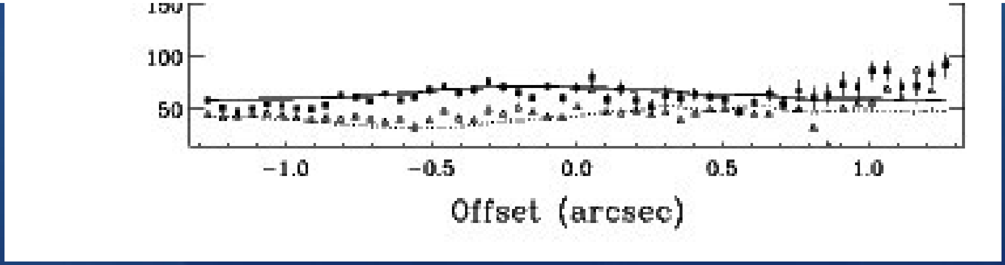
Barth et al (2001)

Mbh = 2.5E+8 +-0

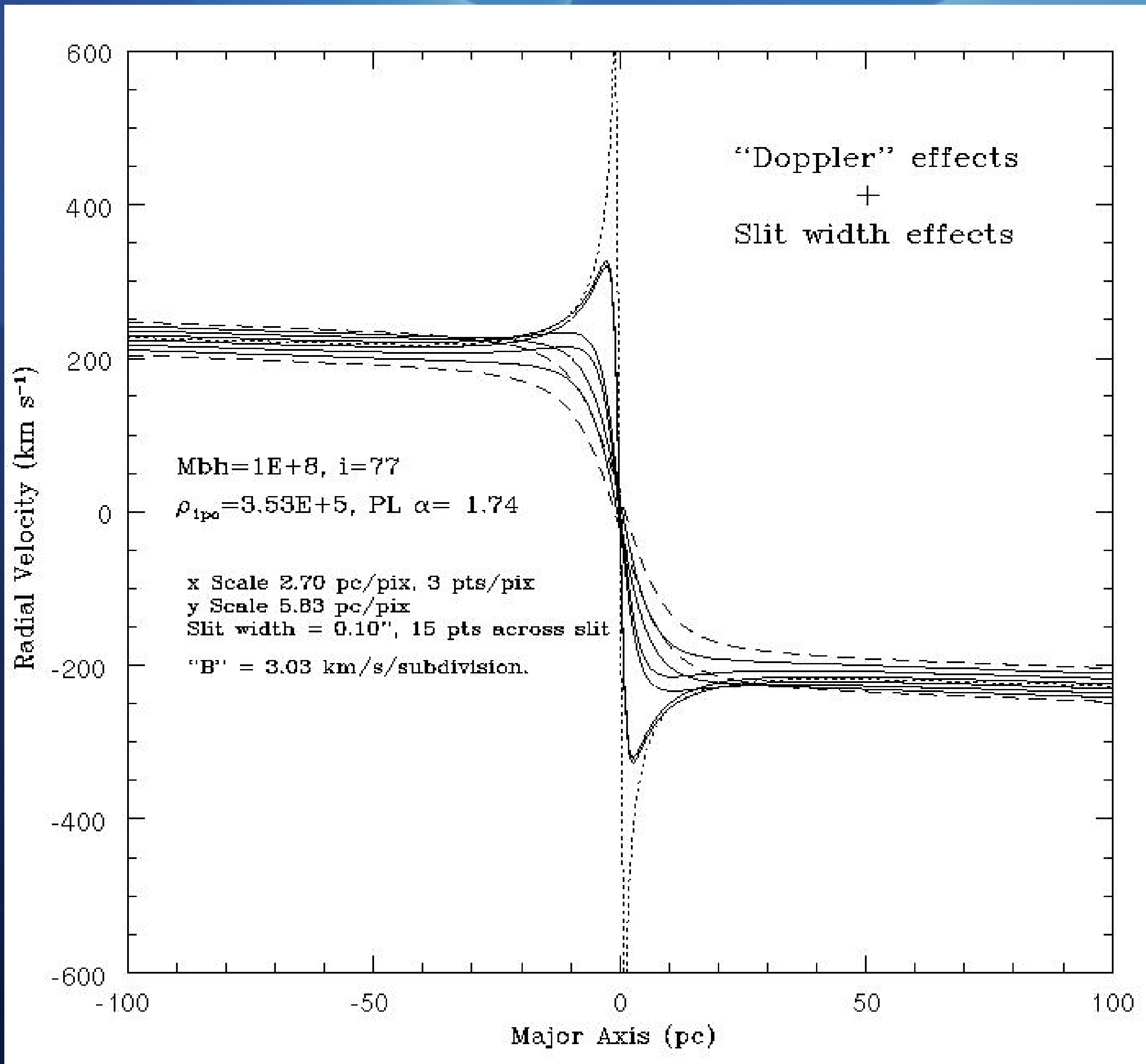
Broader lines than dispersion?

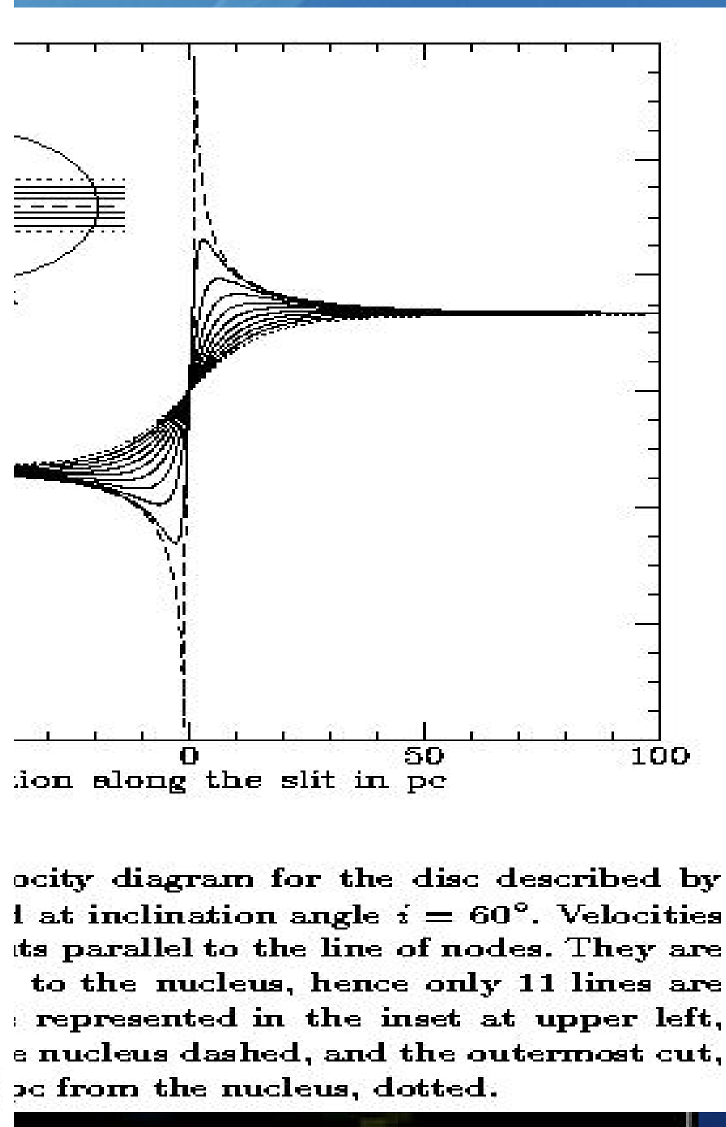
It helps to use an i function form (expe



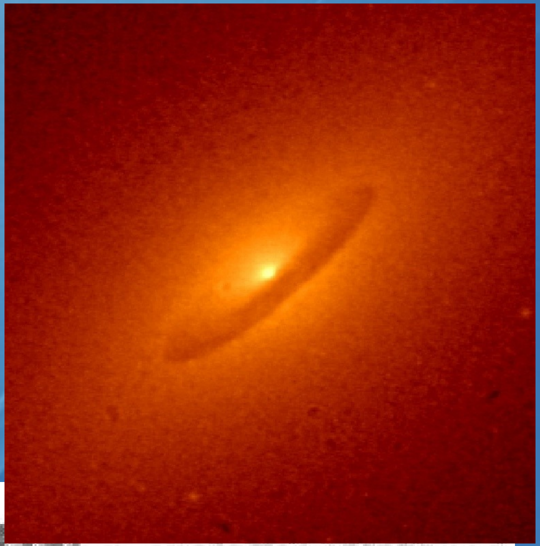


Complexities of gas kinematics with a long slit





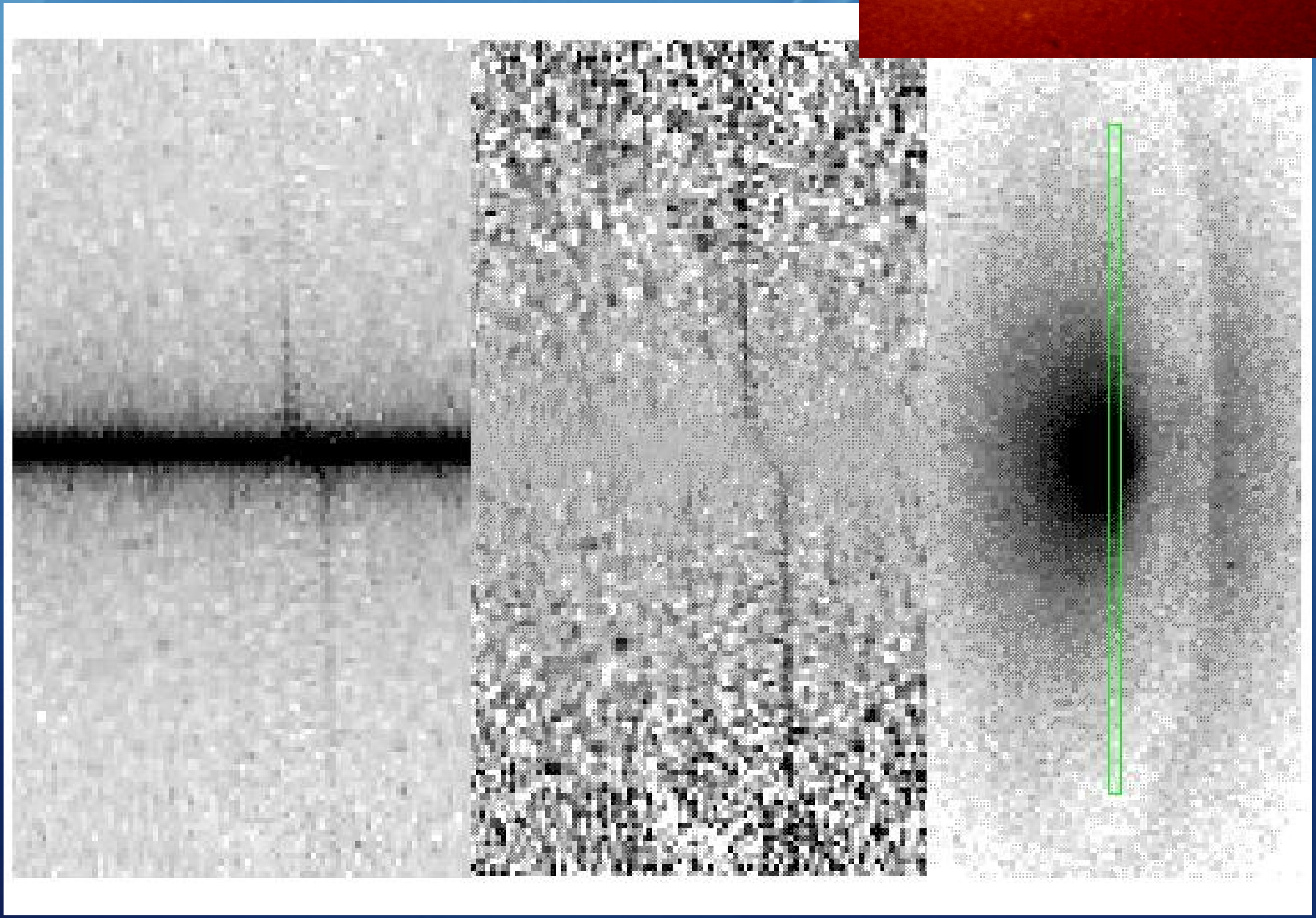
My work with NGC 4697



- Disky elliptical with organized dust disk
- Nearby D~11 Mpc
- Stellar kinematics gave a BH mass of 1.7×10^8

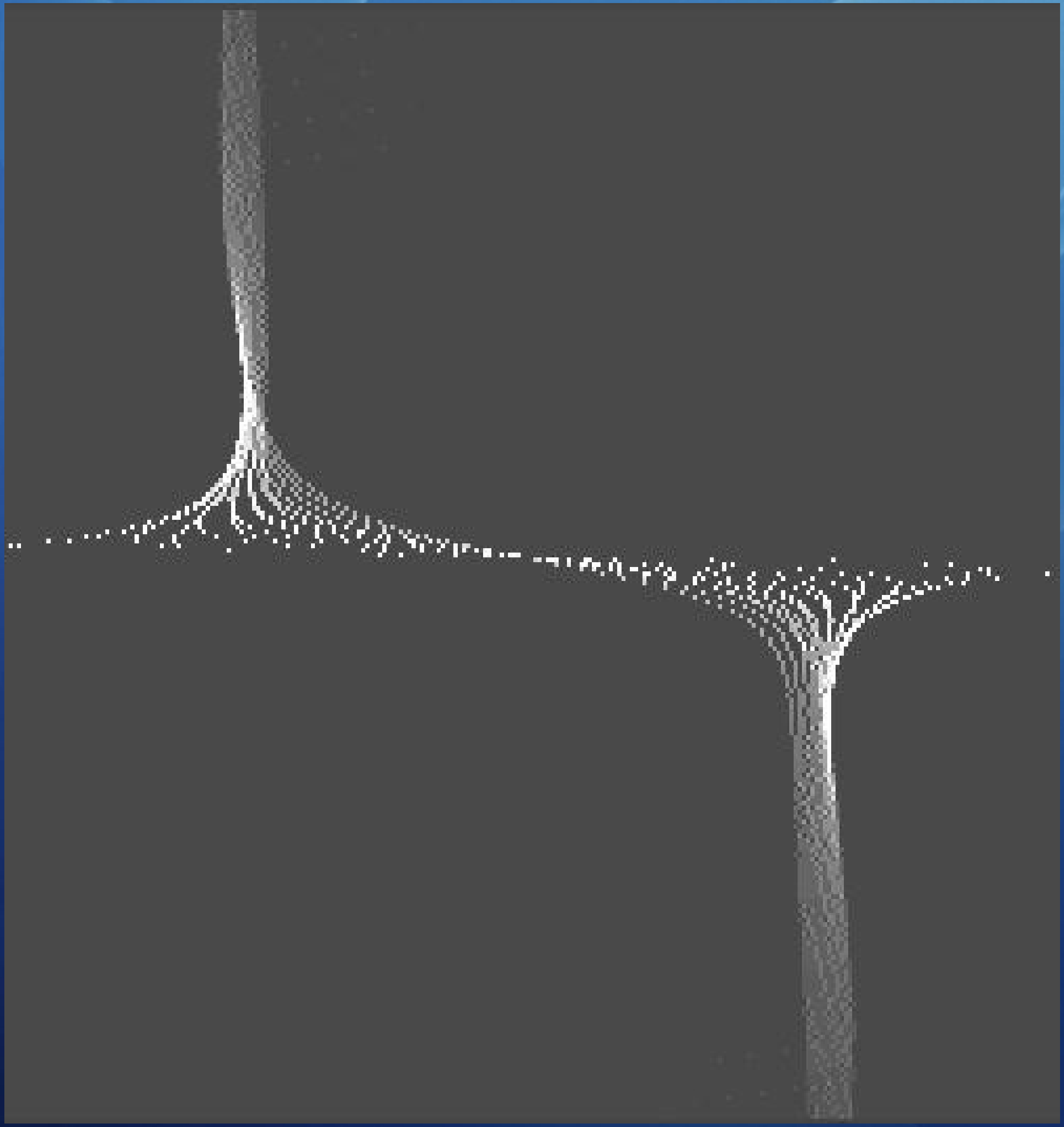
Comparison of methods possible!

STIS data



My work with NGC 4697

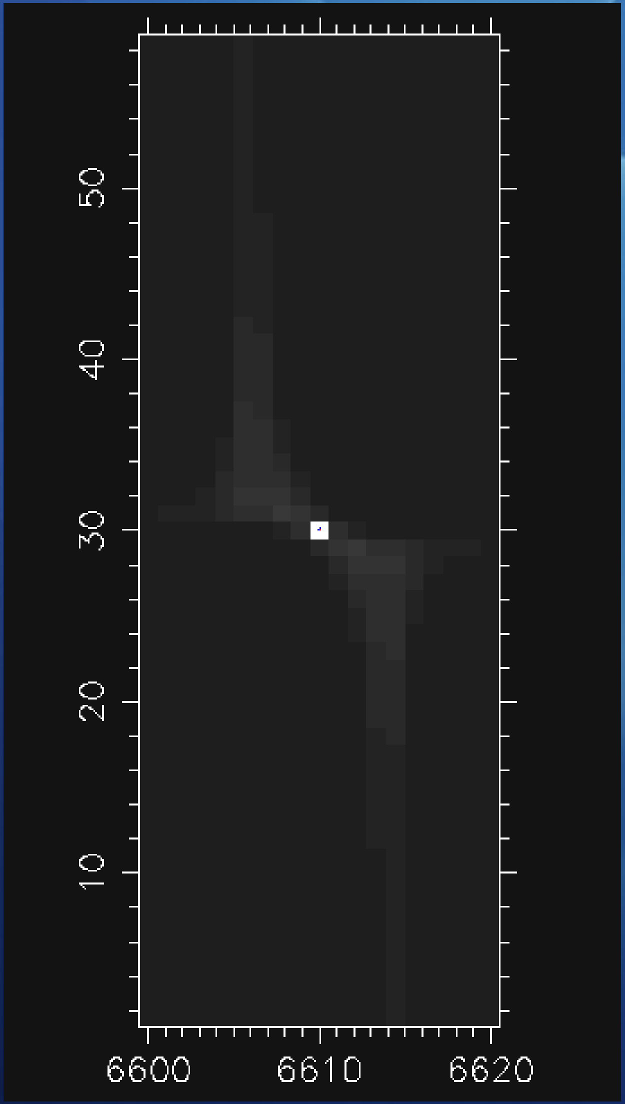
High-res model of 2D spectrum of gas disk seen thru slit.

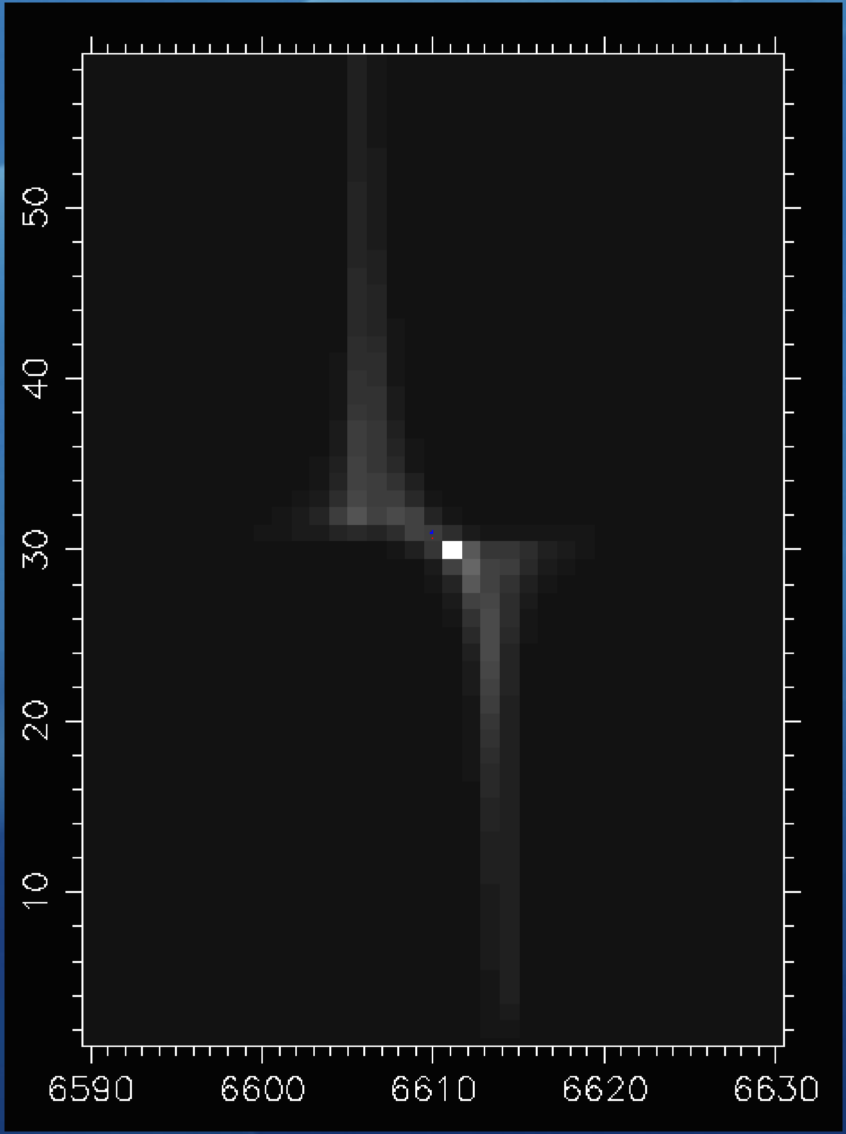


Rot = 2.7 deg
offset= 0.019"

My work with NGC 4697

STIS-res model of 2D spectrum of gas disk seen thru slit.



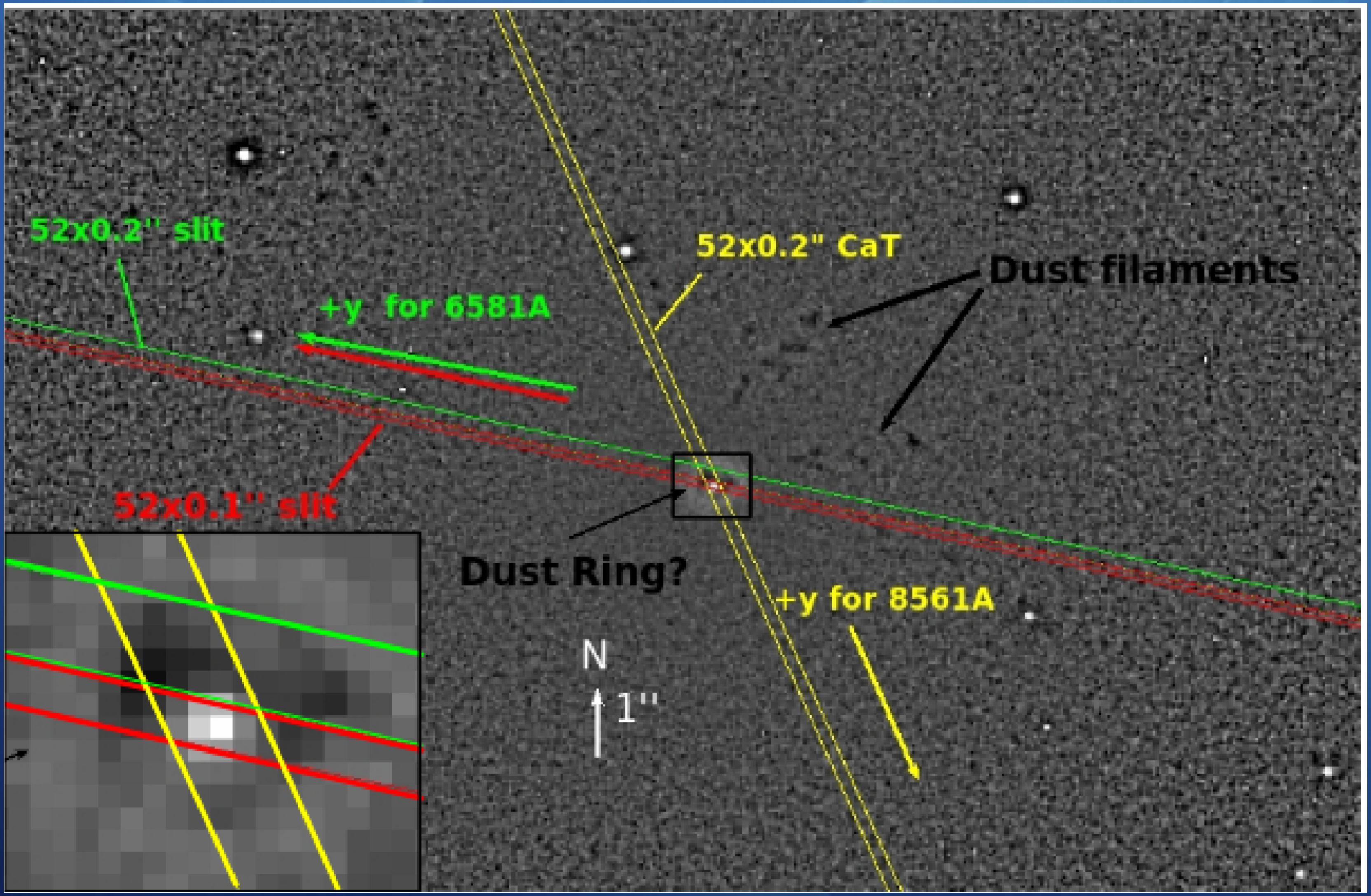


Mbh = 5x10^7

Mbh=5x10^7 + tilt,offset, gas dispers.

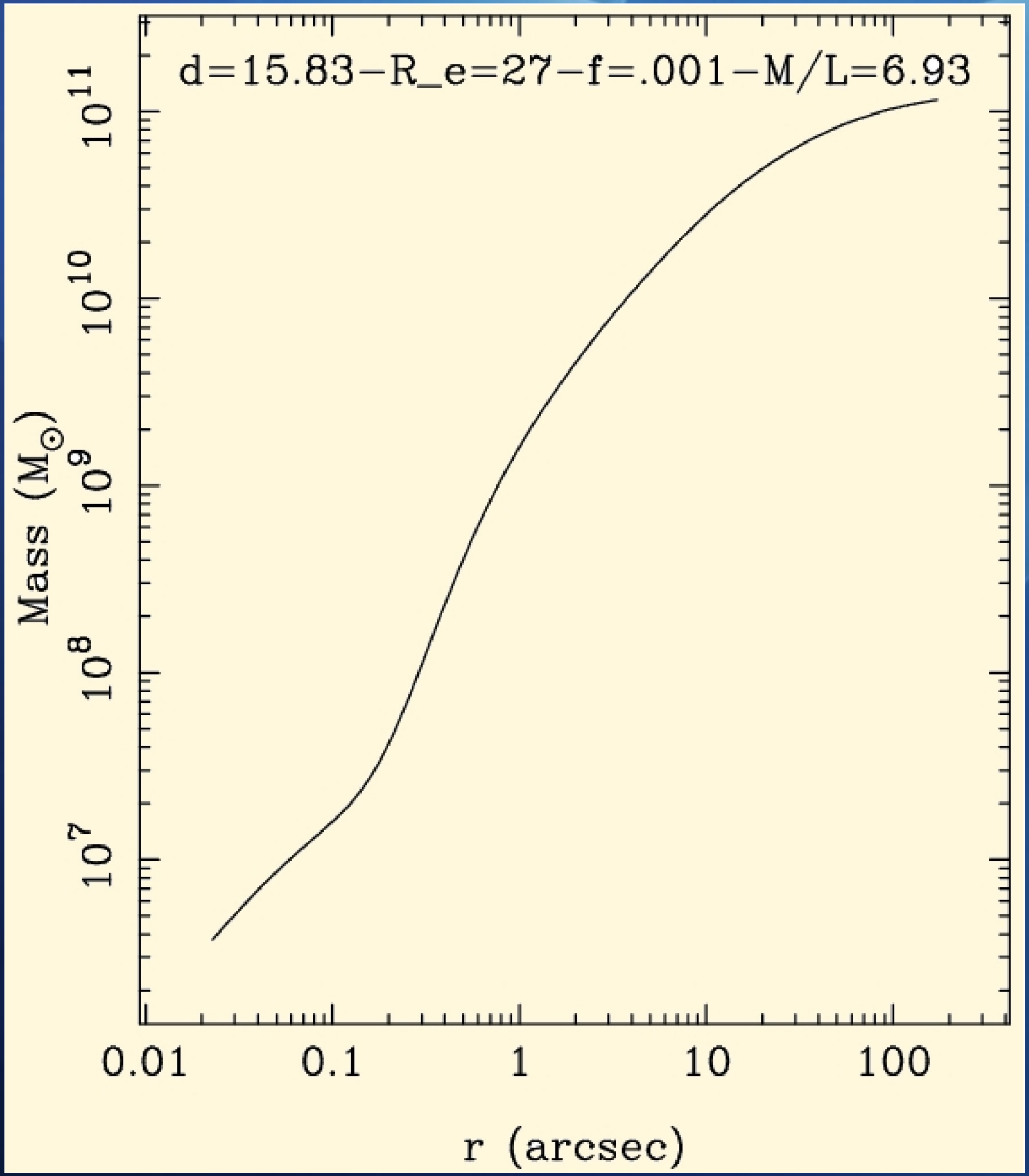
My work with NGC 4552

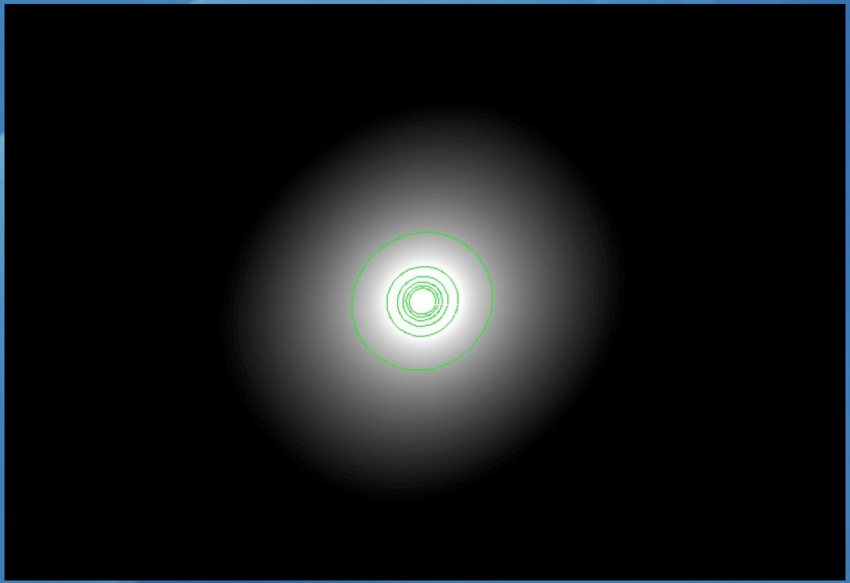
My work with NGC 4552



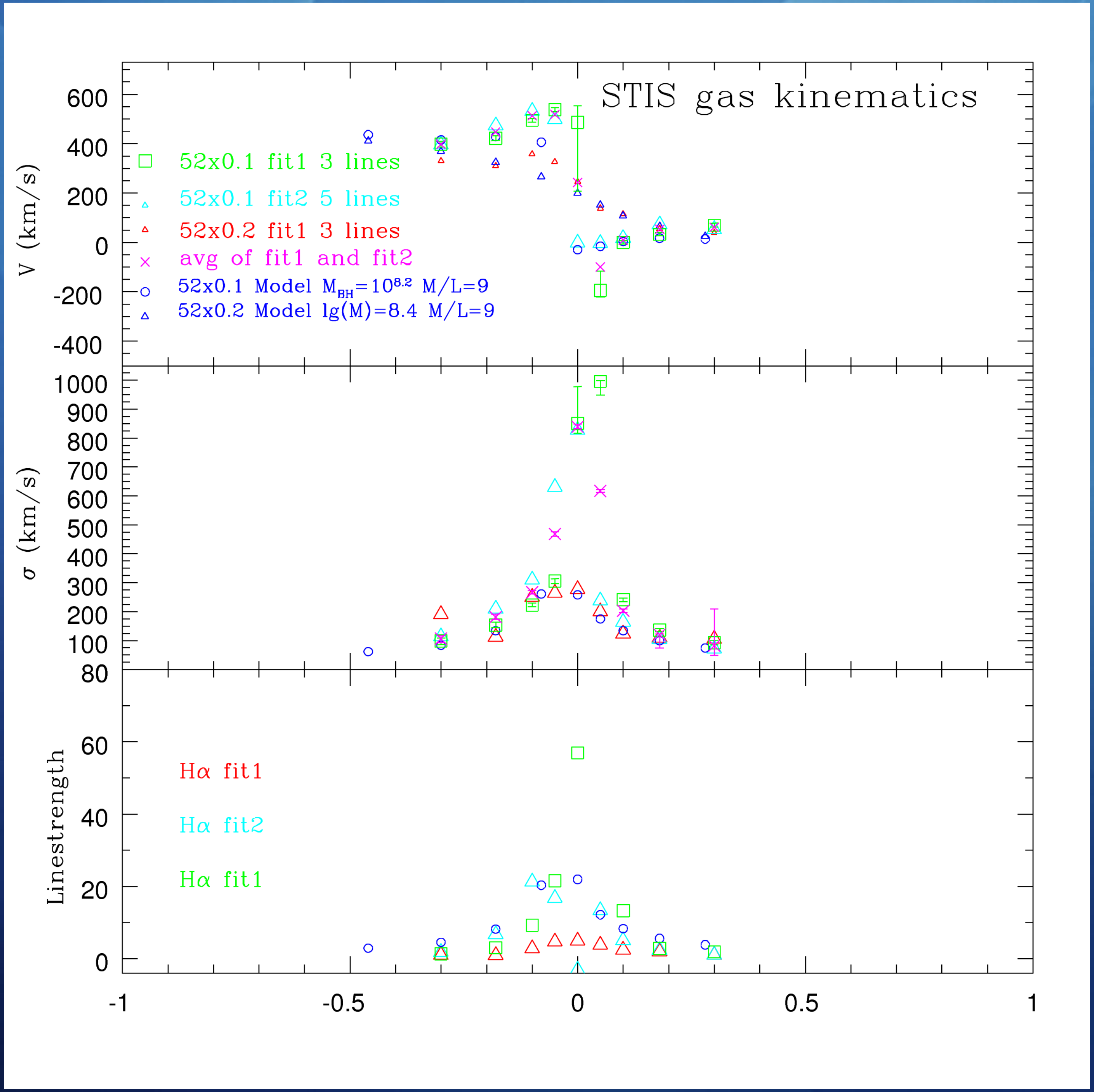
My work with NGC 4552

Enclosed mass profile comes from surface photometry.

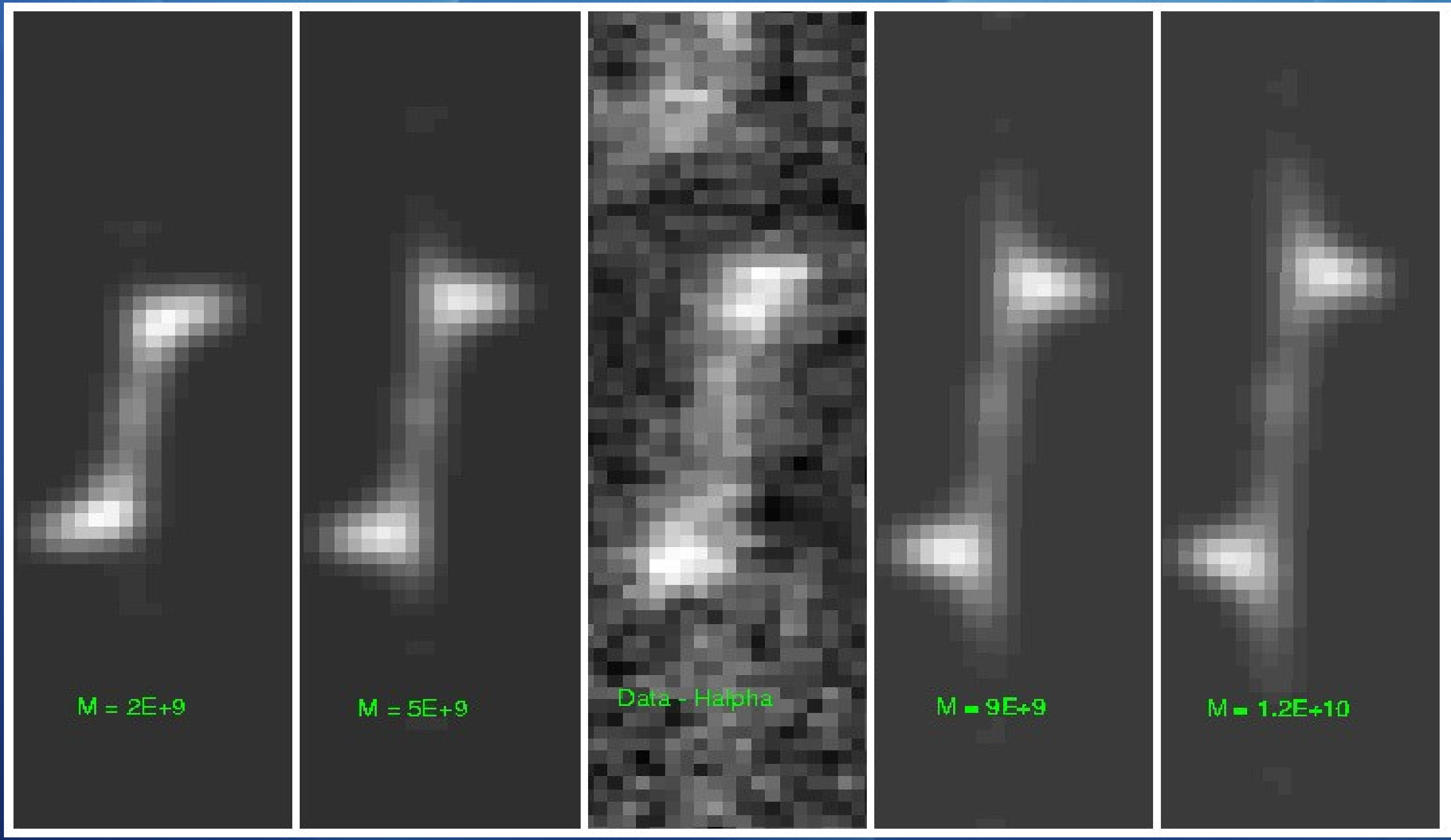




My work with NGC 4552



My work with NGC 4061



Conclusions on gas kinematics

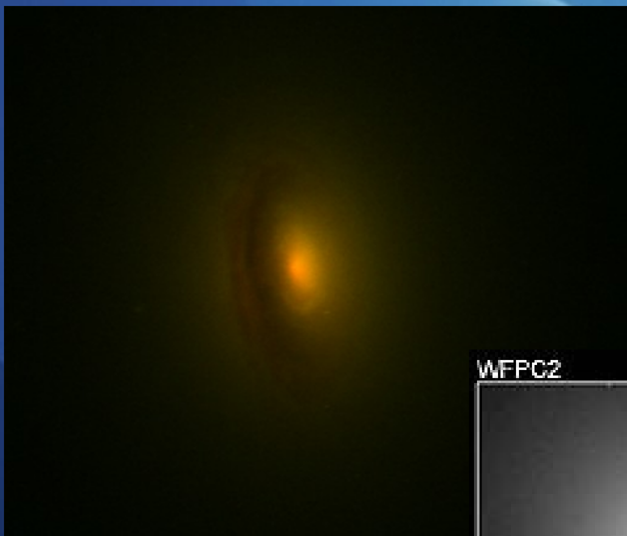
- Concerns about the gas disk method are well-founded
- Galaxies in which the gas disk method is applicable are rare
- Gas disk kinematics are giving masses which fall on the Mbh-sigma relation
- NGC 4697 will be an important check on systematic errors in the gas disk method

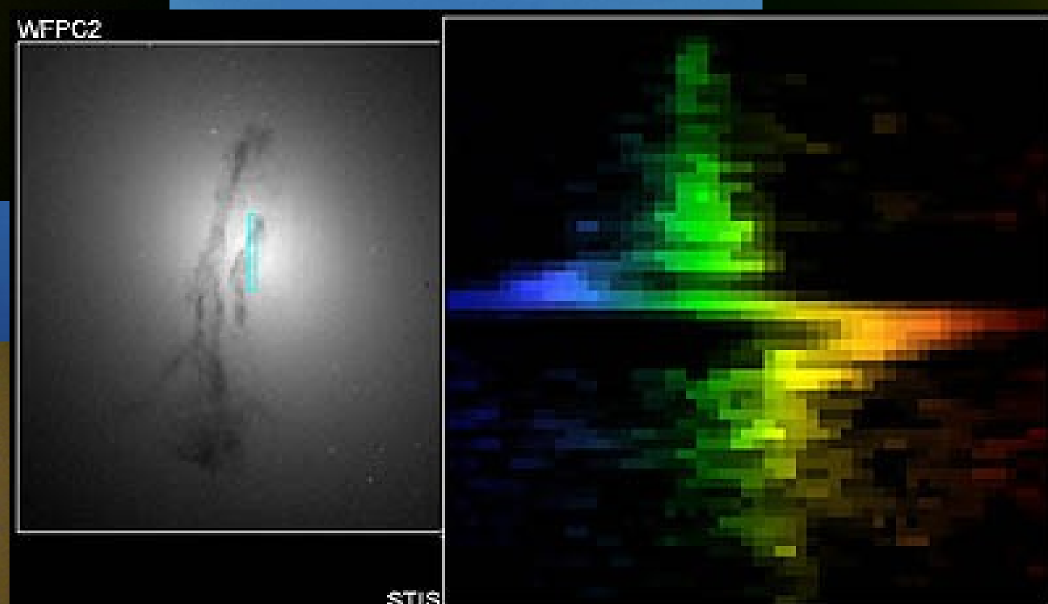
Future work:

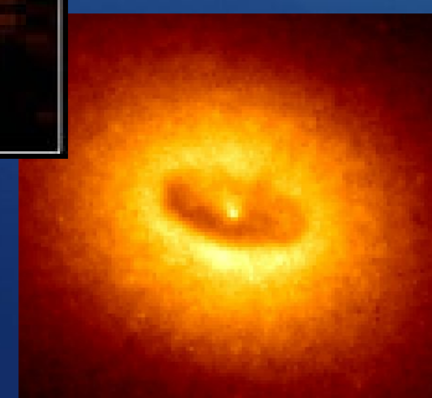
- Students working on galaxies with STIS gas data. (NGC 1961, NGC 2976, NGC 4864, etc.)
- Nuclear star clusters formed instead of BH?

Gas Kinematics and the Search for Supermassive Black Holes

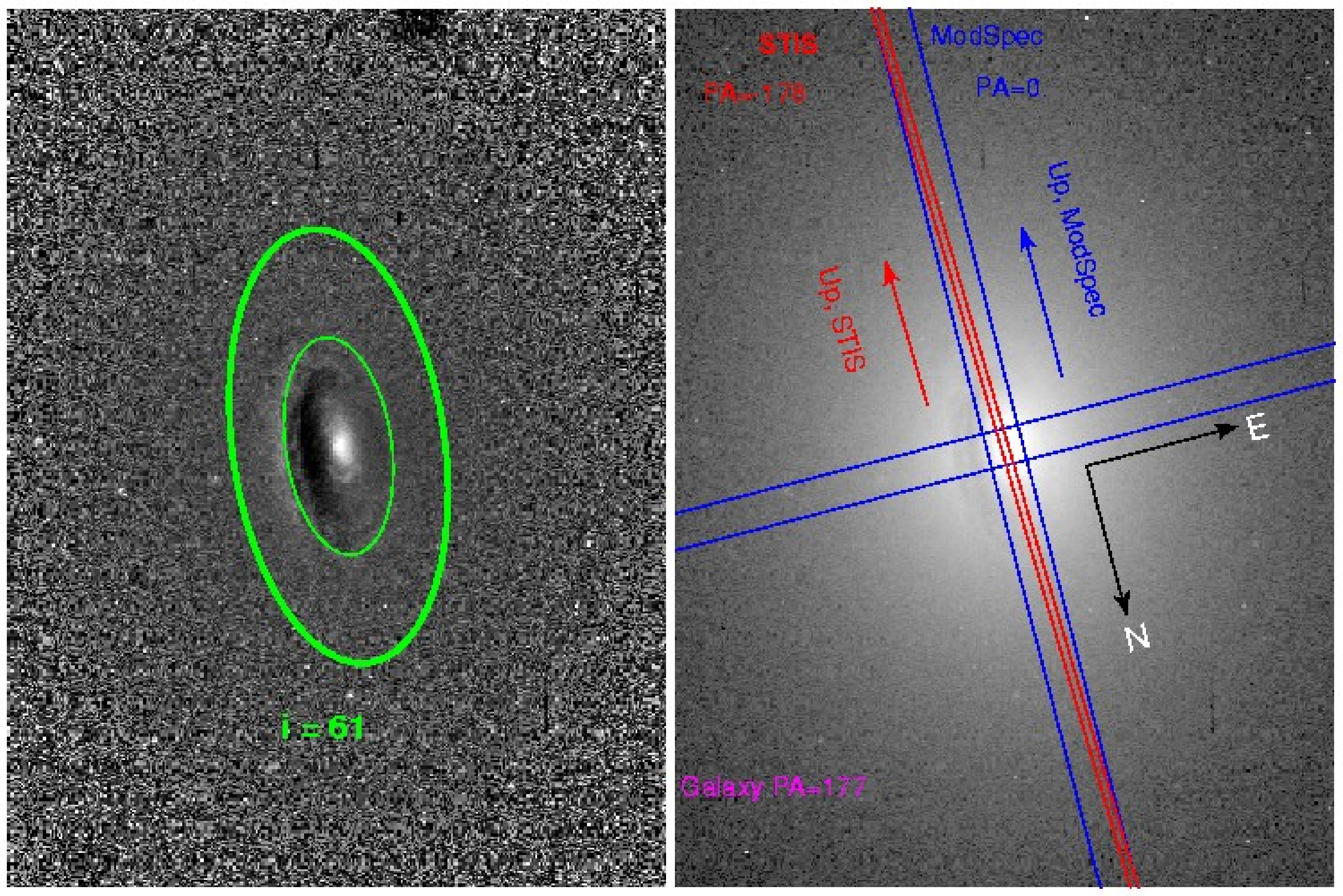
Dr. J. Pinkney





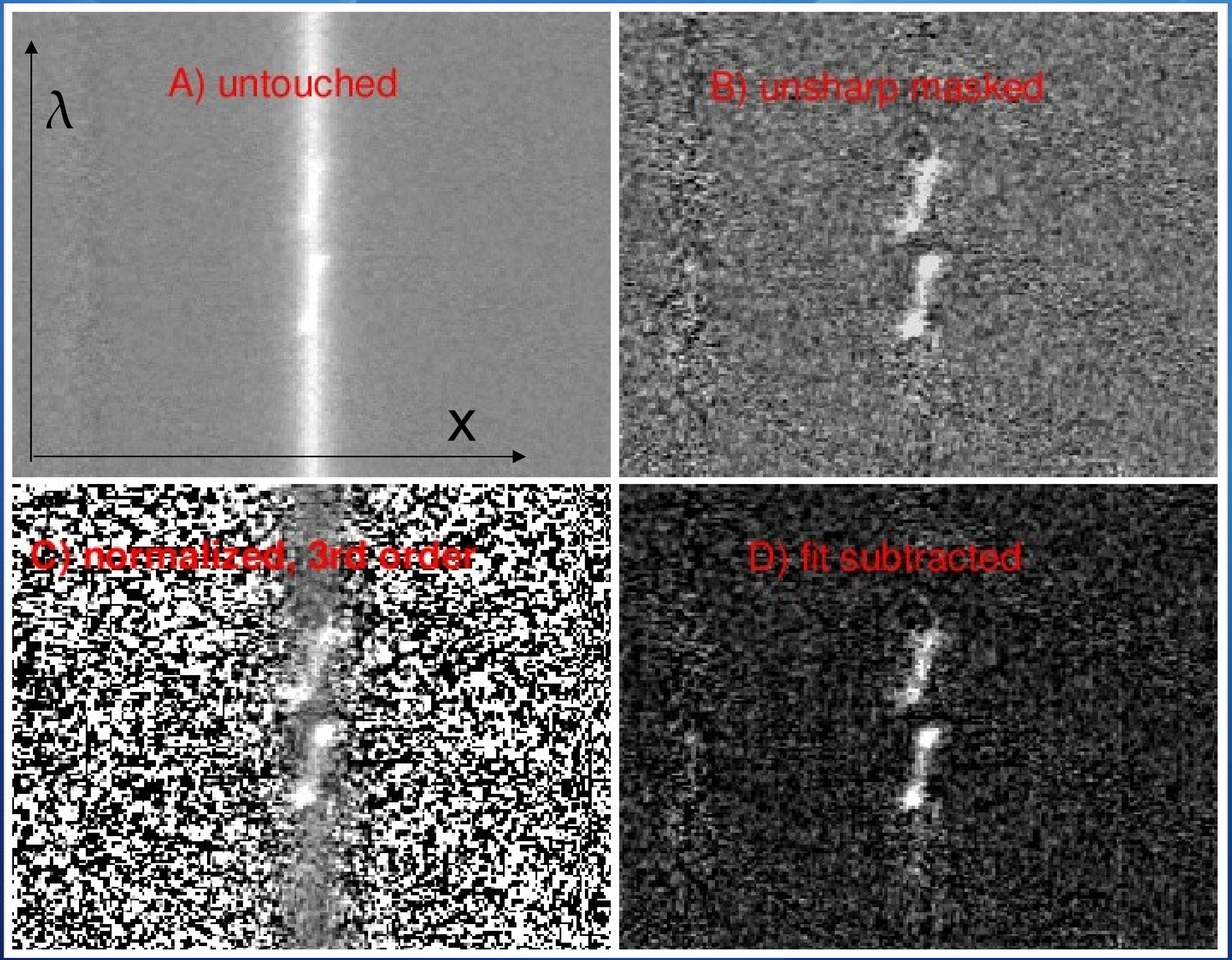


The NGC 4061 Story – longslit placement



The NGC 4061 Story – longslit Spectroscopy Results

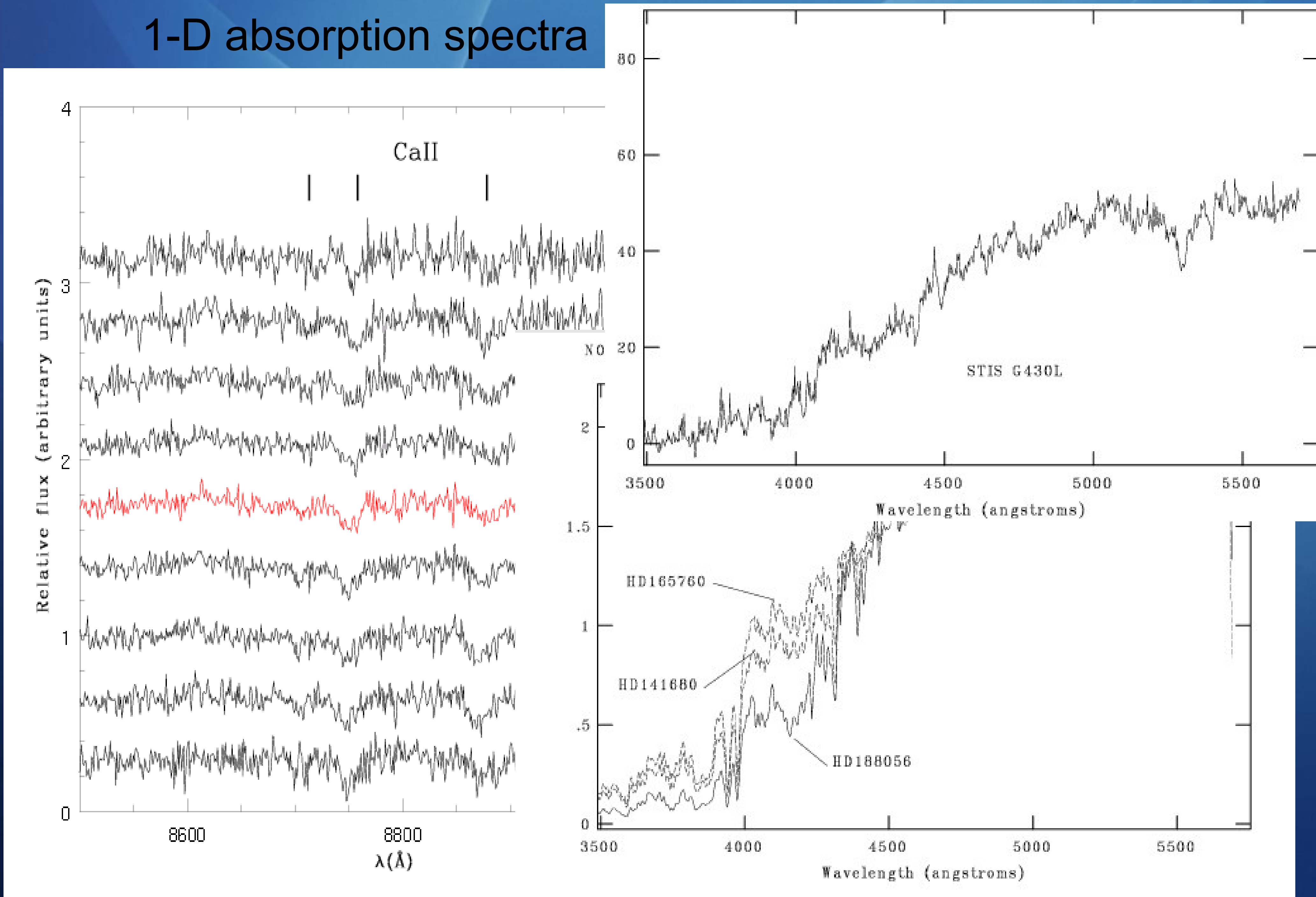
2D spectrum of Hα + [NII] lines.



Gas in rapid rotation at center!

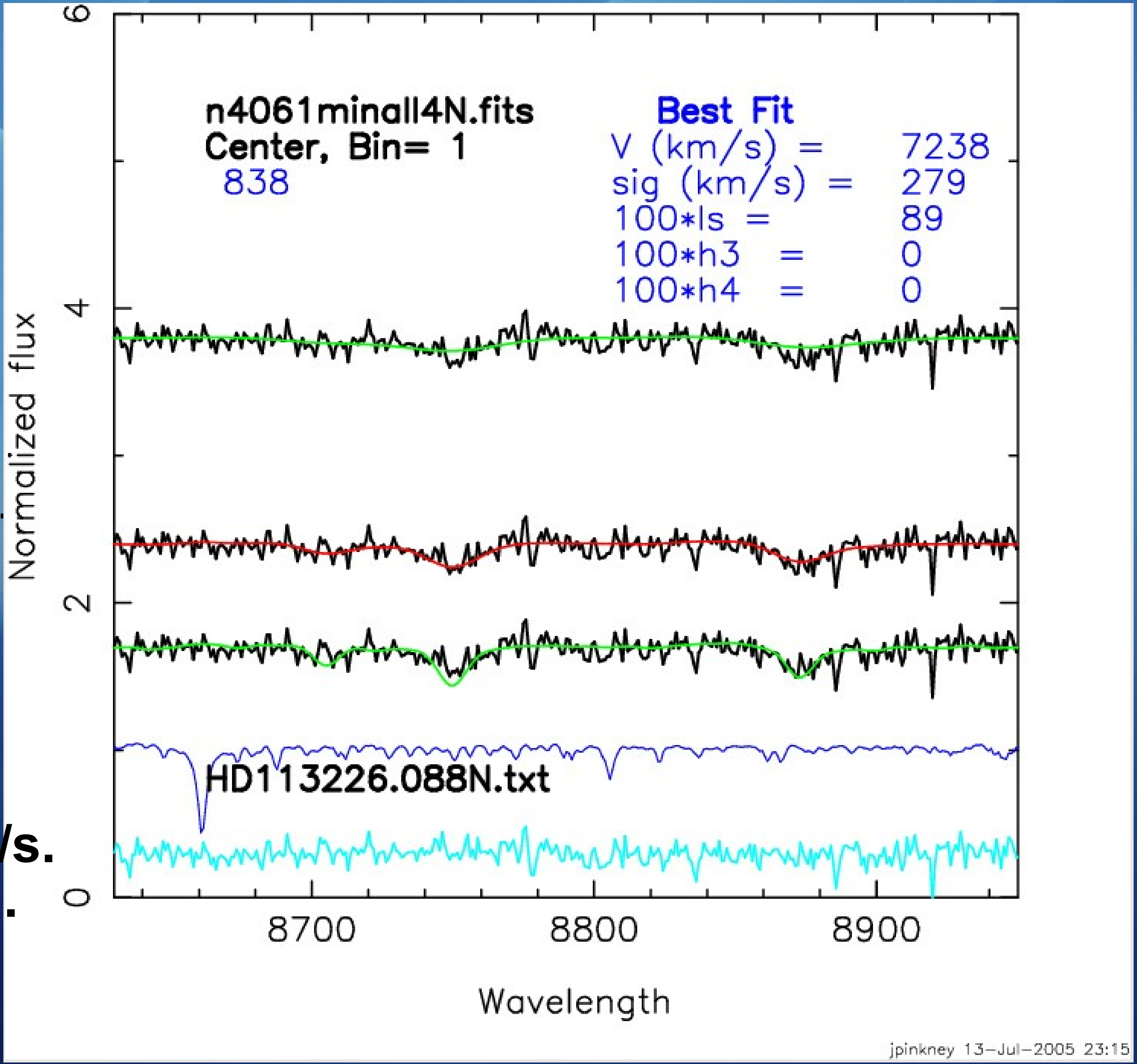
The NGC 4061 Story – longslit Spectroscopy Results

1-D absorption spectra



The NGC 4061 Story – measuring stellar kinematics

I use specallE for deriving kinematics (i.e., v vs R, σ vs R, etc) from both emission line and absorption line data.

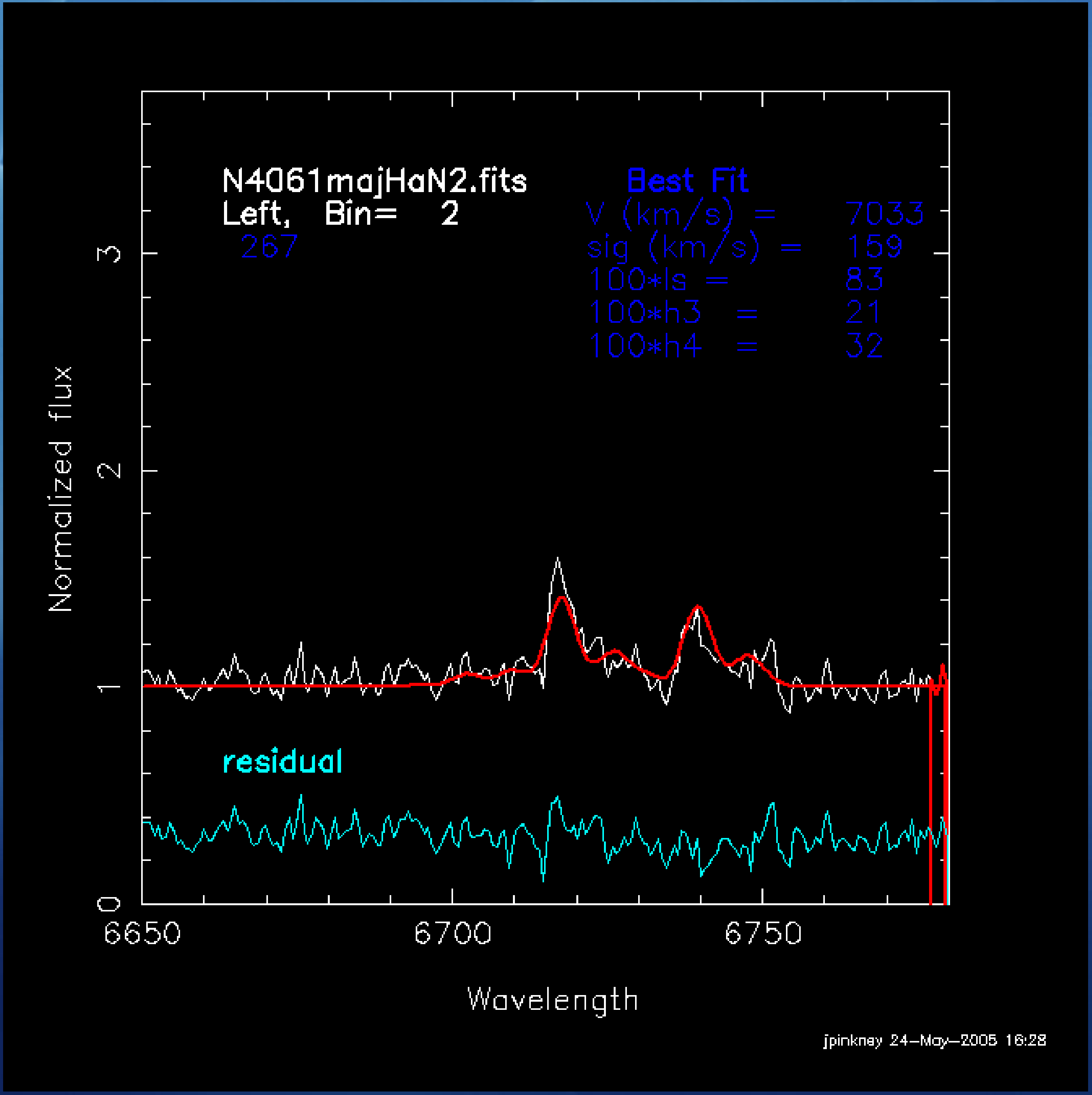


Aha! Sigma is NOT 477 km/s!! More like 280 km/s. Huchra is human.

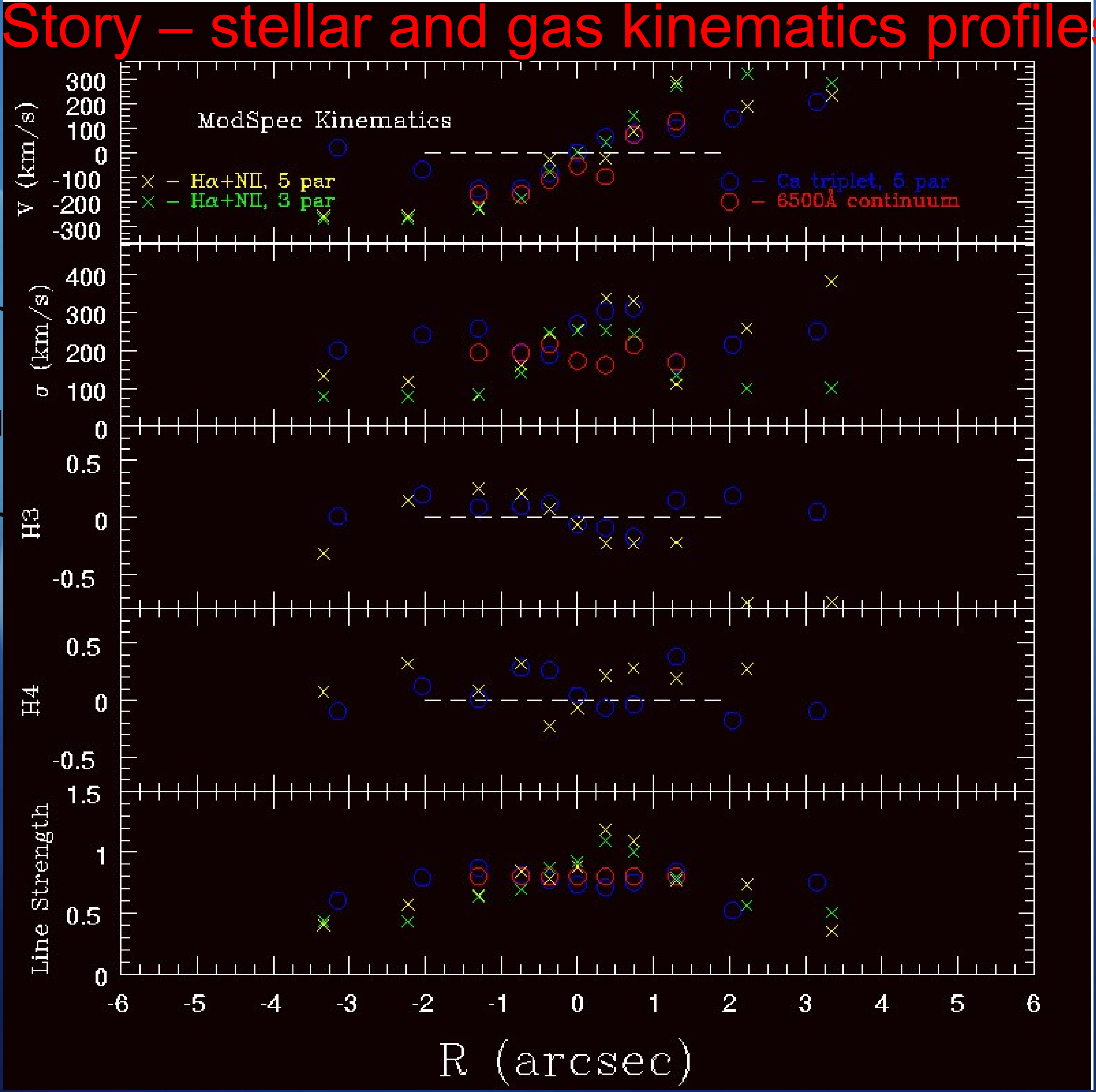
SpecallE -- fitting emission lines

I can fit up to 4 G-H polynomials to lines.
I can fit independent line strengths to each em line.

I can subtract absorption spectrum before fitting emission lines; this boosts the Halpha line.



The NGC 4061 Story – stellar and gas kinematics profiles



rotation in stars ar
gas
dispersion is abou
290 km/s
The gas is rotation
ally supported, not
he stars

No, I can't tell from
his plot alone if a
BH is present.

The NGC 4061 Story – measuring BH masses from spectra

Emission-line spectra

1. Reduce and combine spectra
2. Extract 1D spectra at many positions
3. Find V and sigma from line profiles at each position and compare to models

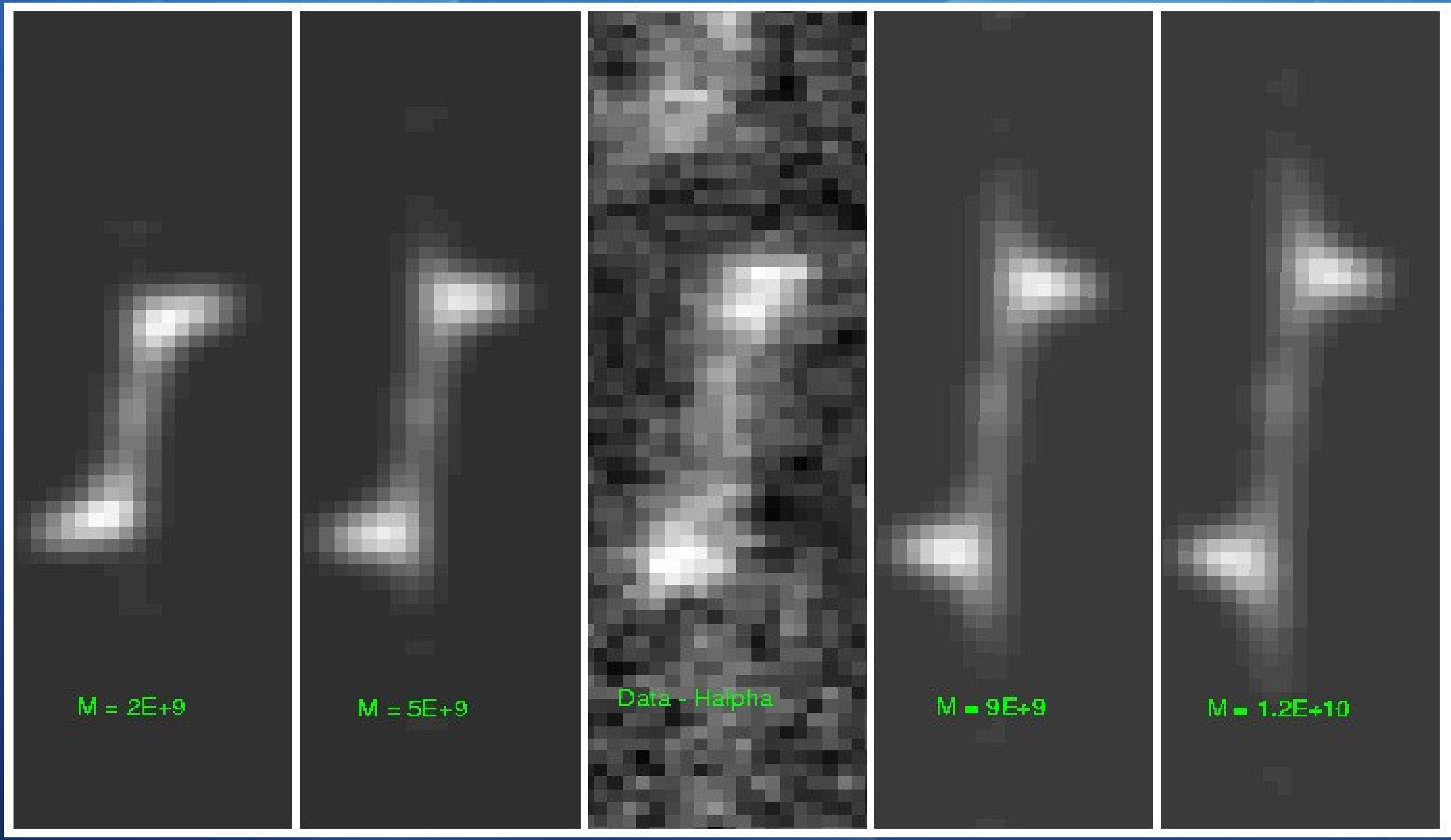
   OR

3. Compare 2D spectra directly to 2D models.
4. Models assume gas moves in circular orbits in a disk and require ...
   a) stellar mass distribution
   b) inclination of gas disk
   c) distance
   d) slit width
   e) seeing/PSF
   f) emission line surf. brightness distrib.

Absorption-line spectra

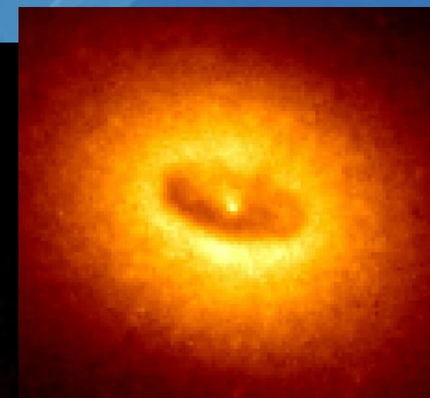
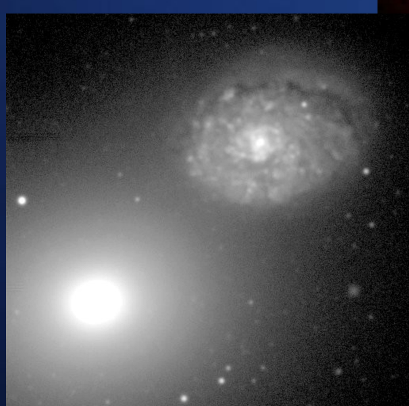
1. Reduce and combine spectra
2. Extract 1D spectra at many positions
3. Measure broadening functions to make stellar templates match the 1D spectra.
4. Make LOSVD's for each position
5. Adopt structural constraints for model
   a) spherical
   b) 2-integral, flattened
   c) 3-integral, anisotropic, etc
6. Draw orbits from an "orbit library" to match the photometry and kinematics
7. Use chi^2 to find best fit M_{BH}, M/L, etc.

“DiskslitG” – modeling gas kinematics



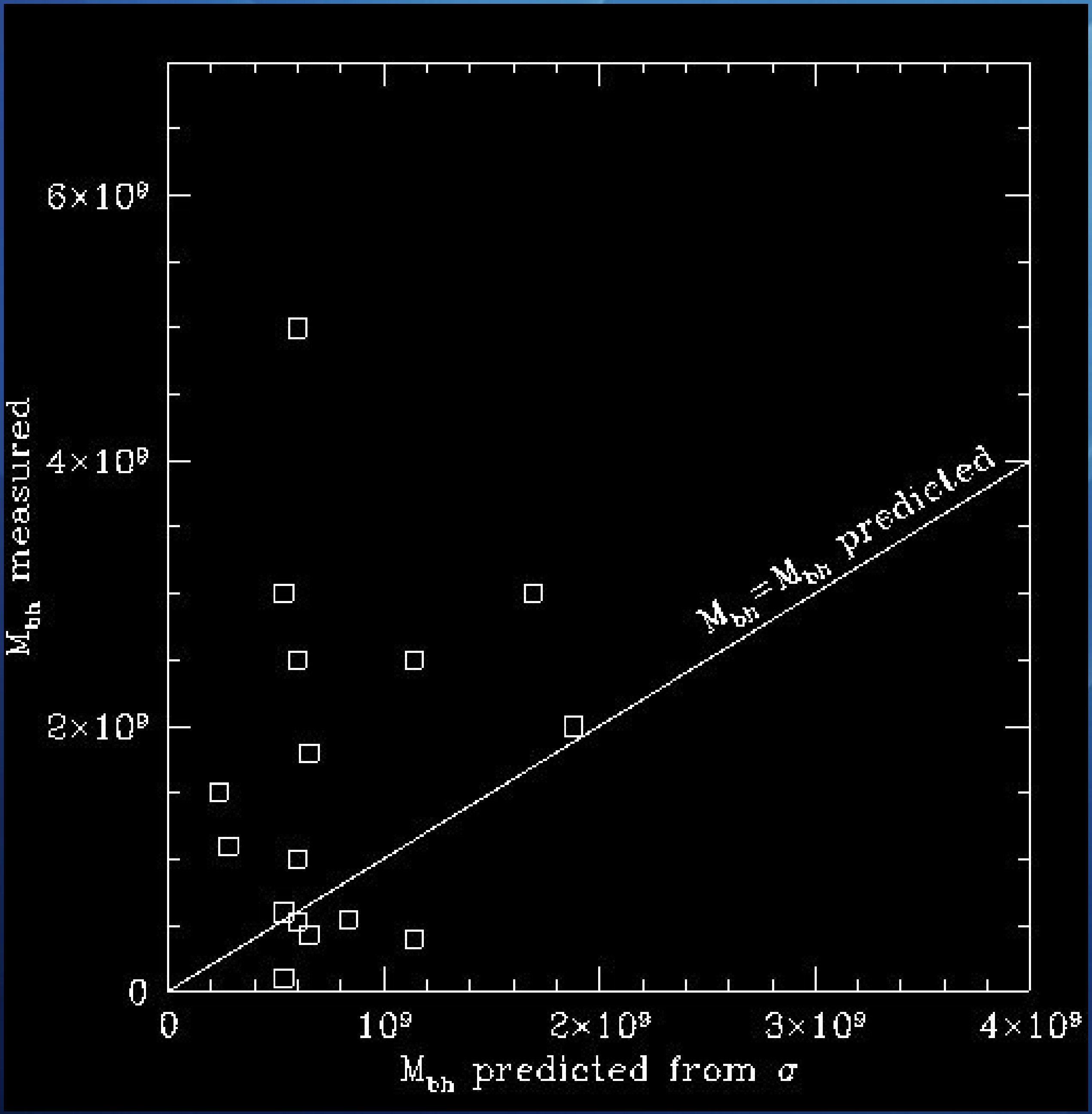
The emission lines are matched best by adding a 5-10$\times 10^9$ $M_\odot$ black hole to the stars!




Extra Stuff

The NGC 4061 Story – discrepancy with M-sigma



11 galaxies with M >1e+9 or sigma > 285 km/s.

Three galaxies have 2 measurements for the same sigma.