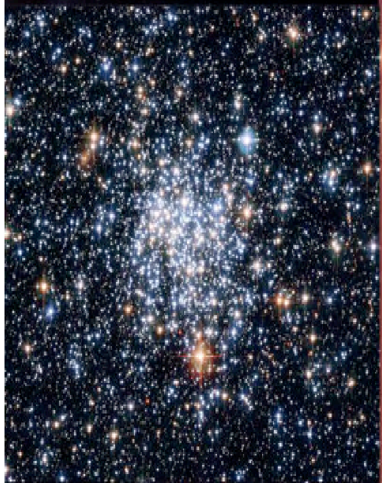
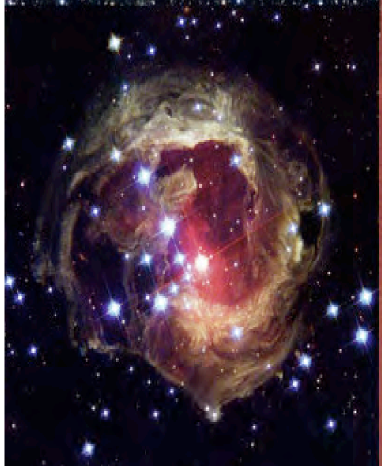
R·I·T





41st ESLAB Symposium.

The Impact of HST on European Astronomy

The primary aim of the 41st ESLAB symposium is to review the key contribution that HST has made in all areas of astronomy and emphasize their impact on European astronomical research

Supermassive Black Holes

David Axon

May 29-June 1, 2007, ESA, ESTEC, Noordwijk, The Netherlands

Thanks to

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- Andrew Robinson (RIT)
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- Dan Batcheldor (RIT)
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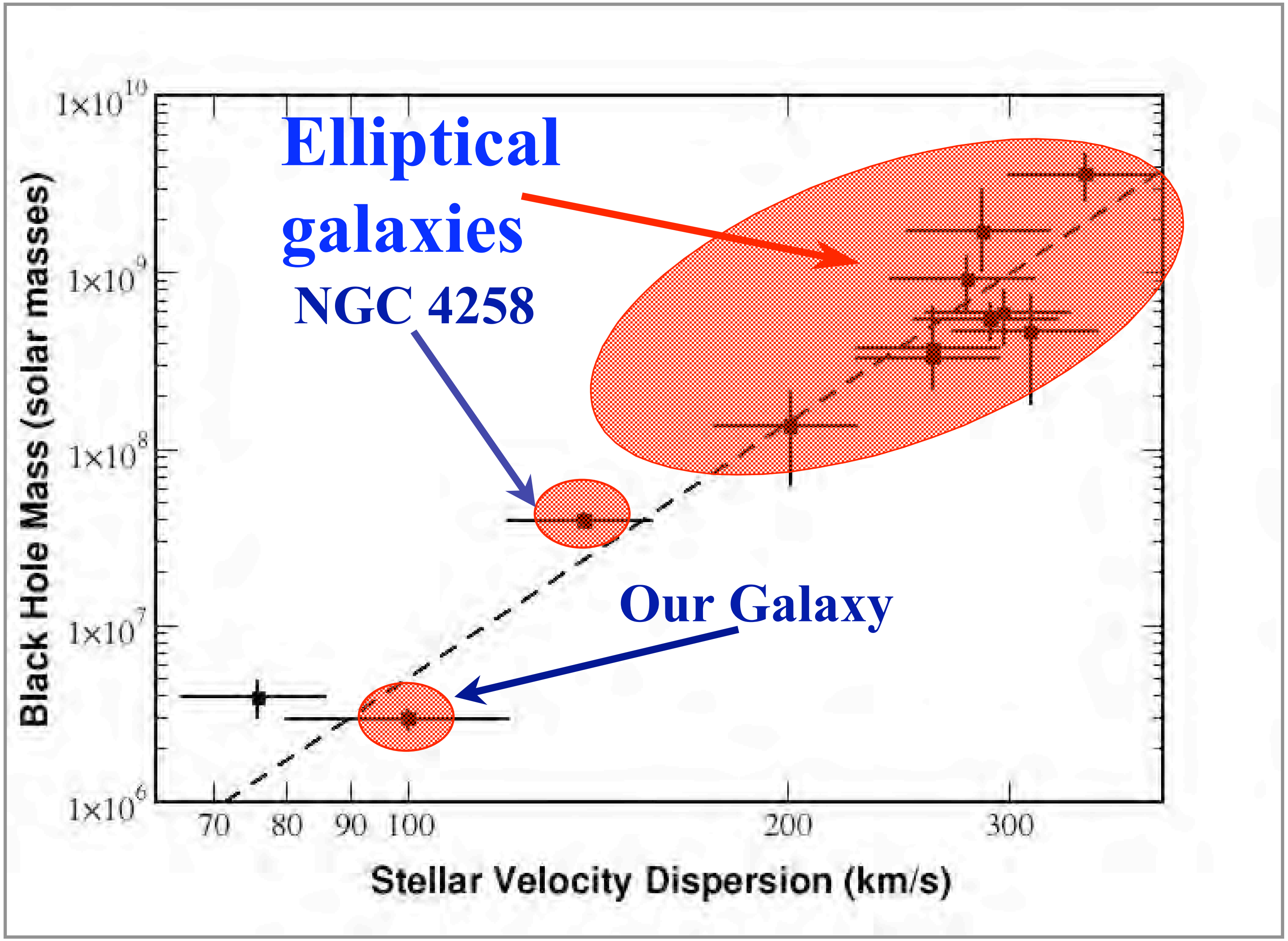
- David Merritt(RIT)
- Kambiz Fathi (IAC)
- Clive Tadhunter(Sheffield)
- Manuela Campanelli(RIT)
- Carlos Lousto(RIT)
- Roeland van der Marel (STScI)
- Holland Ford(Johns Hopkins)
- Ian McHardy(Southampton)
- Jack Gallimore(Bucknell)
- Alessia Gualandris(RIT)
- Yosef Zlowchower(RIT)

- Ross McLure(Edinburgh)
- Brad Peterson(OSU)
- Monica Valluri(Chicago)
- Alister Graham(Swinburne)

Outline

- Using gas dynamics to measure Black Holes in nearby galaxies
  - A gentle introduction
  - Issues for gas determinations -including Reverberation mapping
  - Issues for Stellar Dynamical determinations
- Beyond the local universe
  - the need for reverberation mapping
- BH mergers: Spin Flips, Kicks and 'naked QSOs'
- Black Hole Growth by Accretion- new insights into the fueling stream
- Conclusions

Massive black holes: The story so far…



Merritt & Ferarese (2000)

Is it really that simple and straightforward?

Use Gas/Stars as tracers to get velocity field V around the BH

- Inversion is not unique, is ϕ spherical, axially symmetric, triaxial? We want to reconstruct the 3D structure from its observed 2D projection on the sky!

Get grav. potential ϕ_{Stars} from the observed light distribution in galaxy nucleus

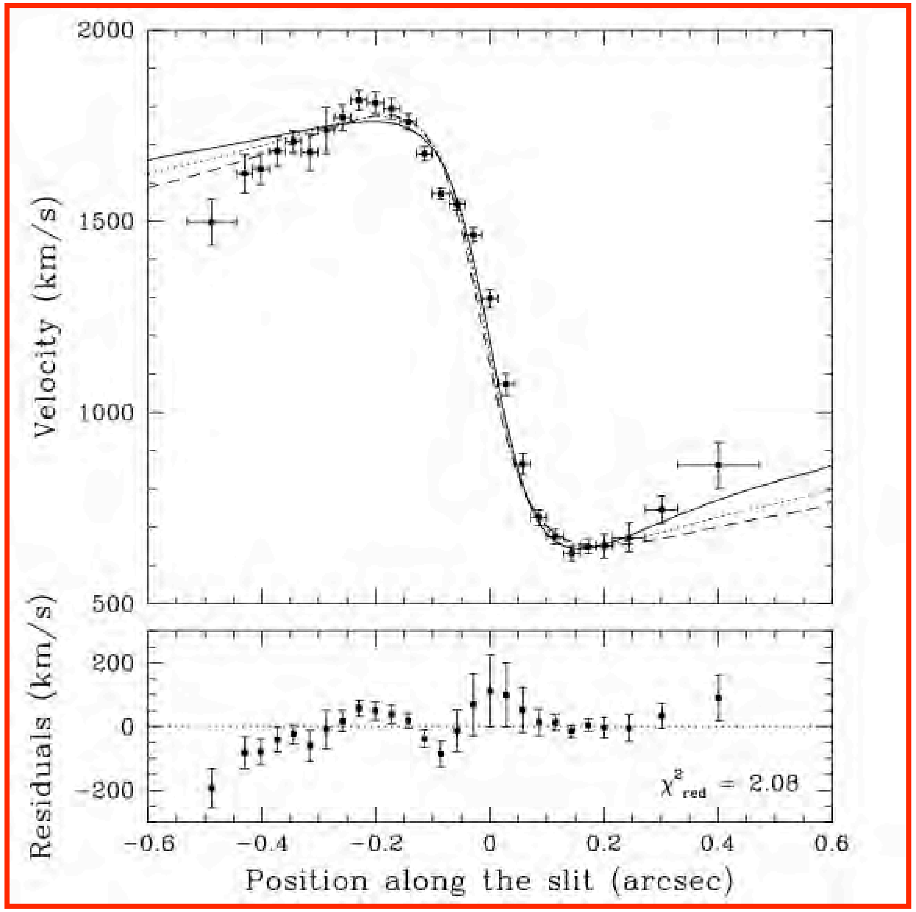
V is integrated along the line of sight, with a finite spatial resolution

Keplerian (and general) gas disks

- Finite slit size and pixel size
- Finite Spatial Resolution (Point Spread Function)
  - Galaxy at D = 10 Mpc (0.1" ~ 5 pc)
- Weight over the line surface brightness
- High leverage in unresolved central emission spike
- No justification for assuming gas settles in same plane at all radii e.g NGC4258, Cen A etc etc
- M/L not necessarily fixed to large scale values- cf talks by Boeker & de Zeeuw

M 87

First HST longslit spectra of a MBH



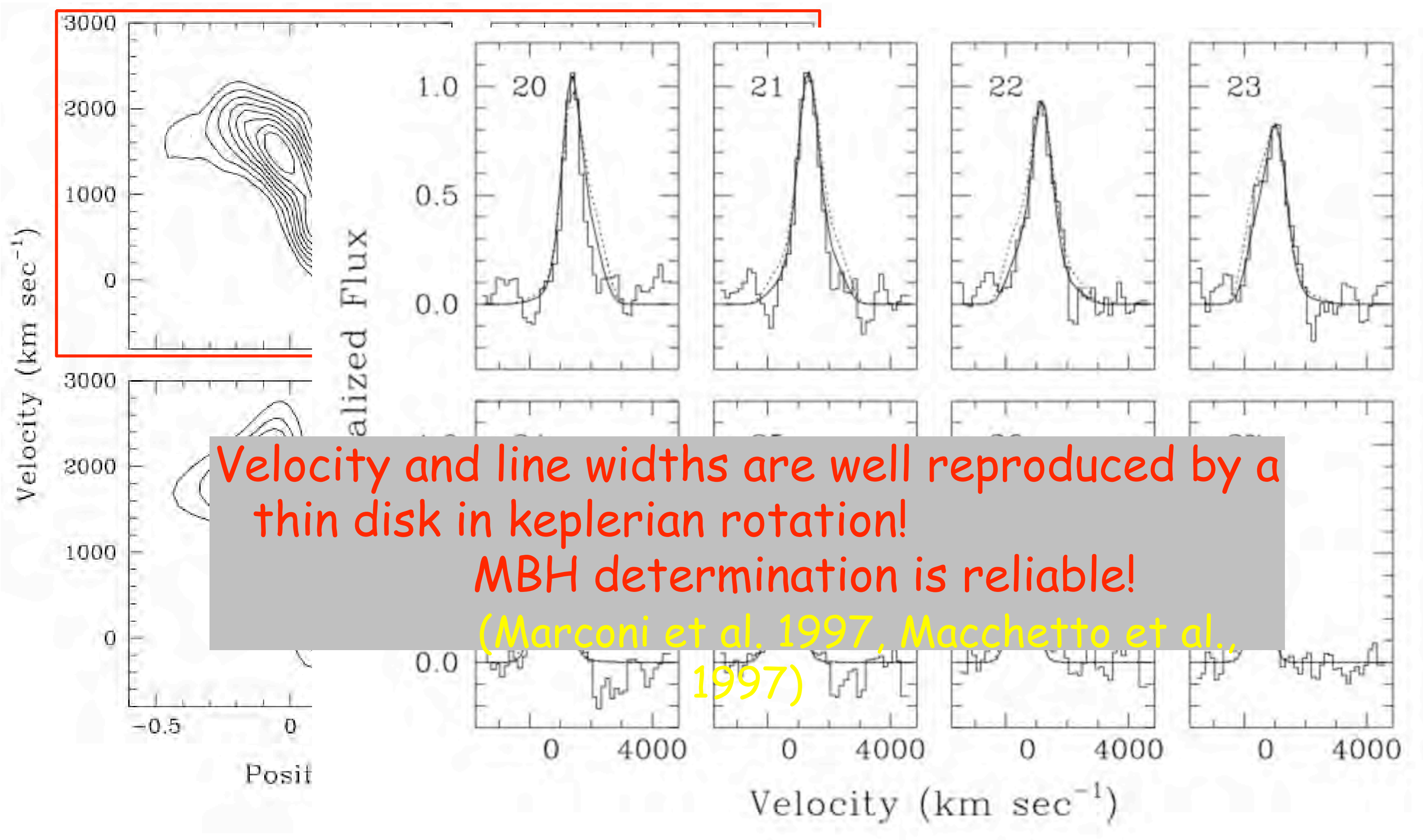
Macchetto, Marconi et al. (1997)

HST+FOC/f48 longslit rotation curve from [OII] λ3727Å emission line.

Thin Keplerian disk model works well!

$$M_{MBH}=(3.2\pm0.9)\times10^{9}M_{\odot}$$

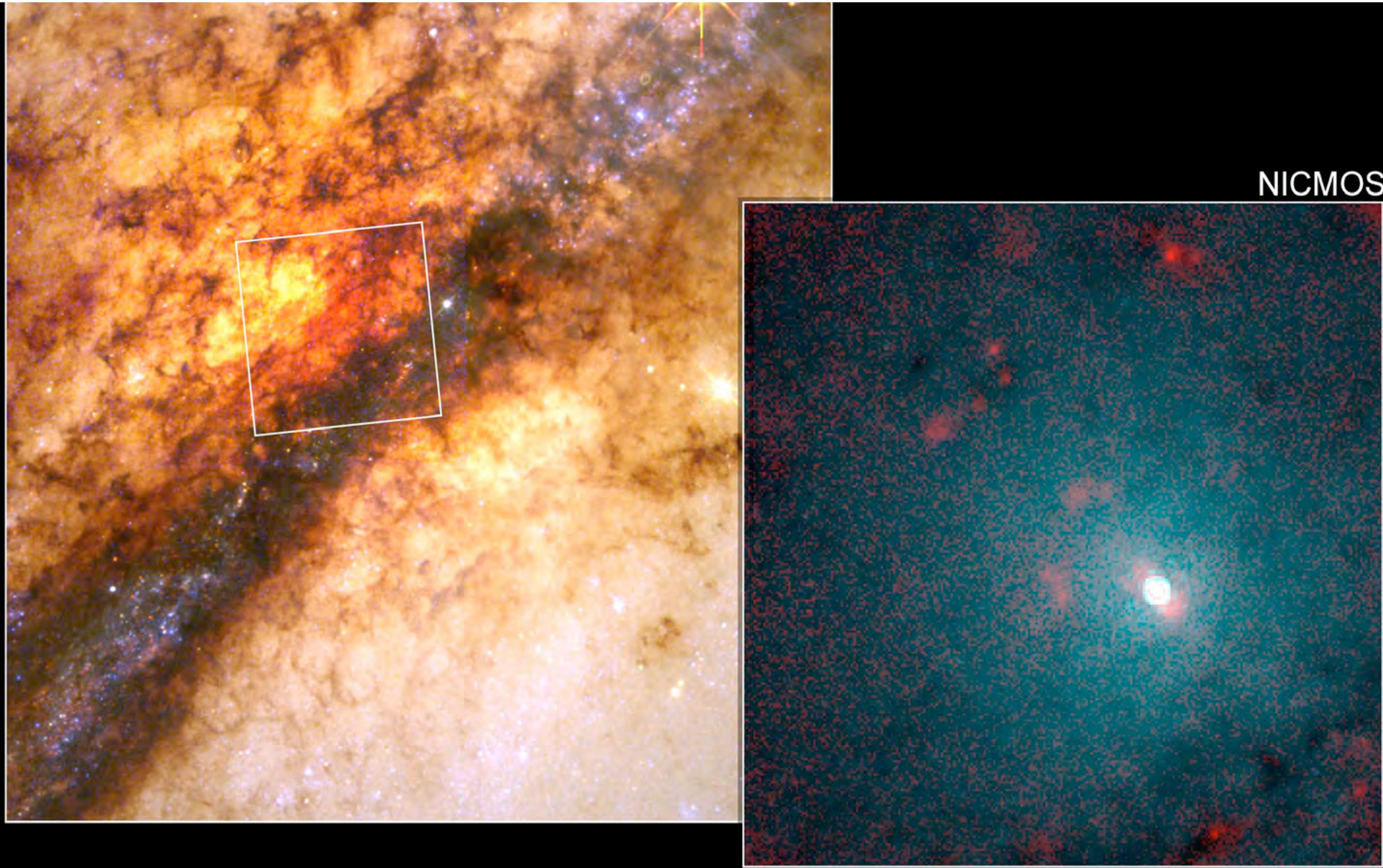
M 87: line widths



Velocity and line widths are well reproduced by a thin disk in keplerian rotation!

MBH determination is reliable!

(Marconi et al. 1997, Macchetto et al., 1997)



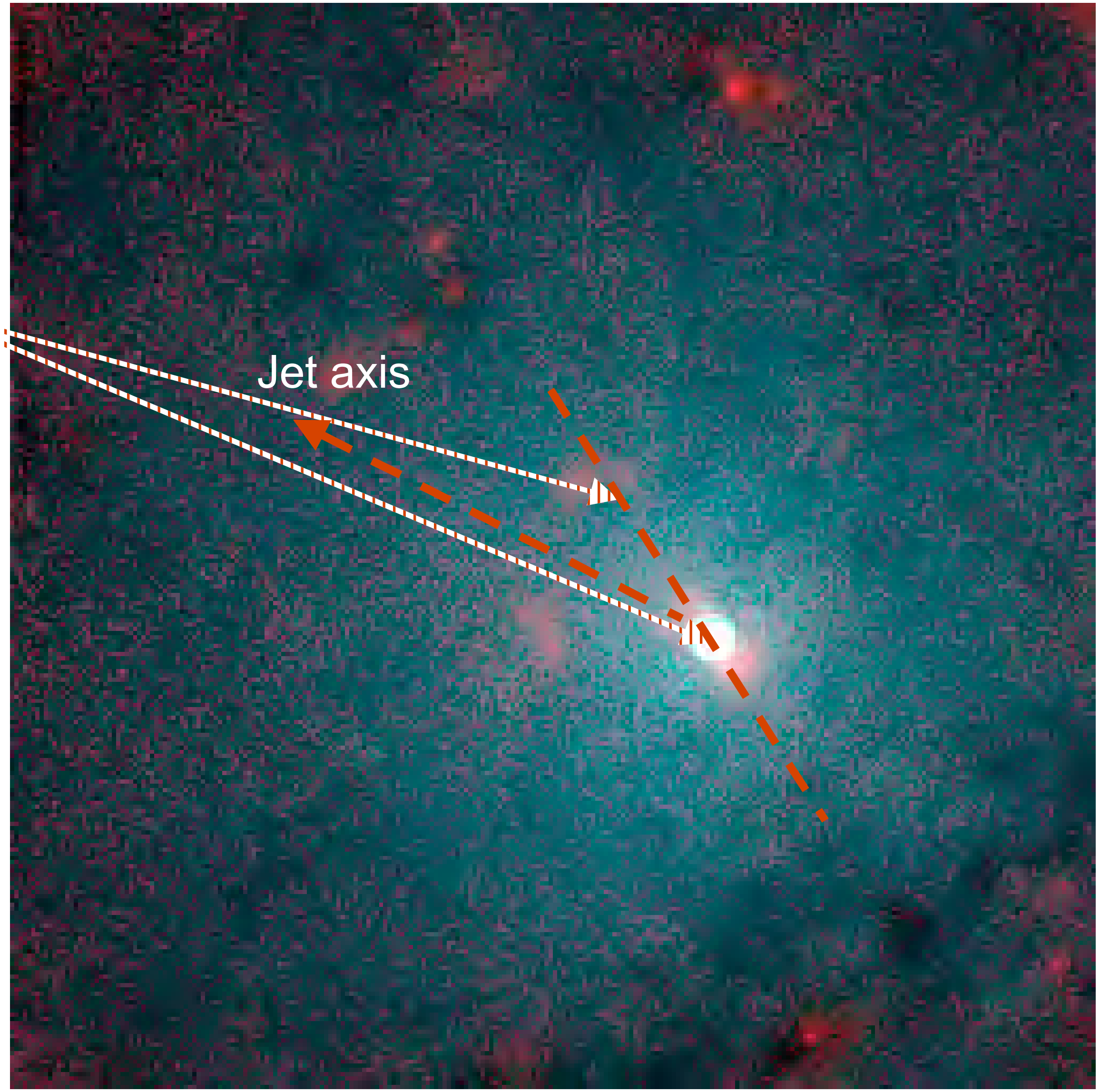
Centaurus A Nucleus

Hubble Space Telescope • WFPC2 • NICMOS

PRC98-14b • ST ScI OPO • May 14, 1998 • E. Schreier (ST ScI) and NASA

Paschen α Image (NIC2)

Elongated structure, ~ 1" x 2", PA~33deg (~ ⊥ to dust lane), not ⊥, not || to jet

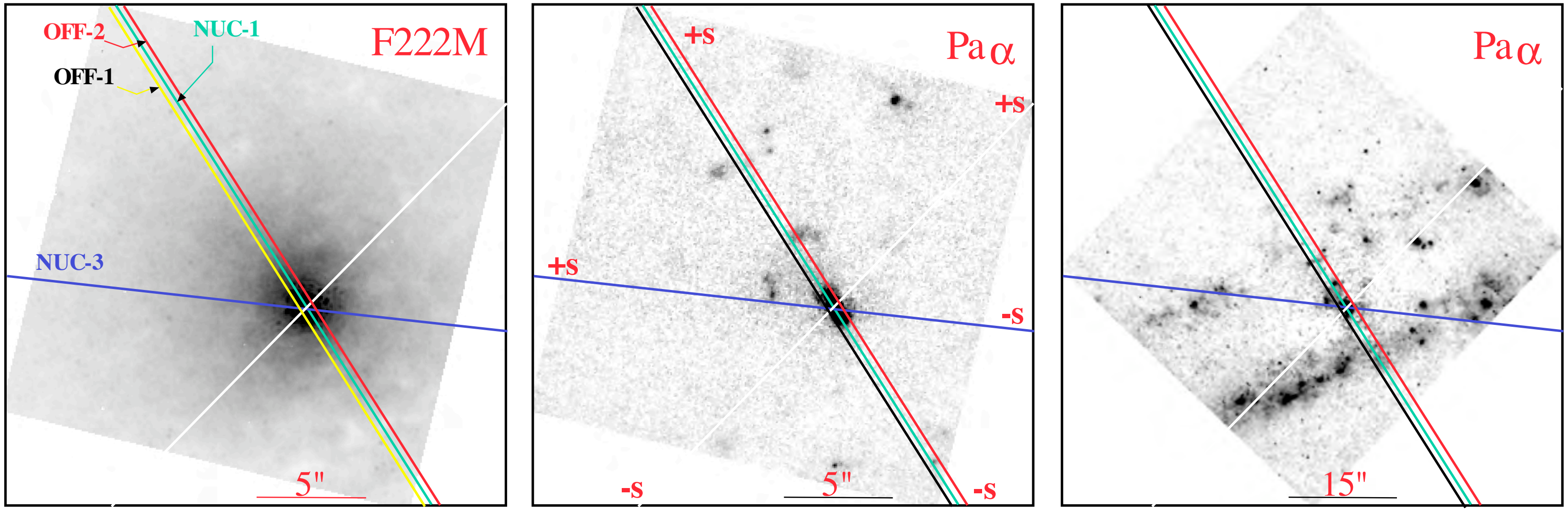


Interpretation:
20pc disk, inclined at ~60deg

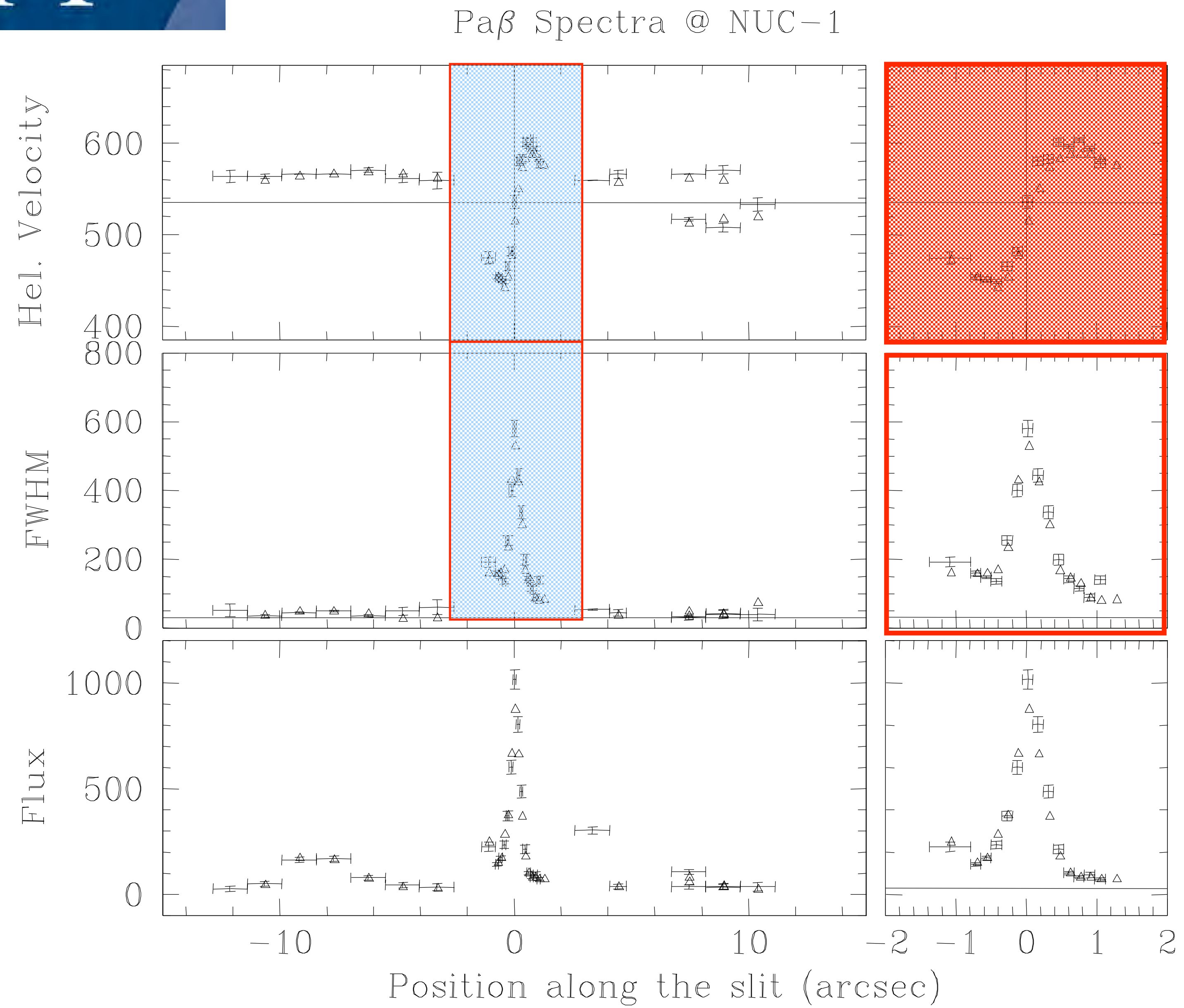
Schreier et al 1998

VLT -ISAAC IR-Spectroscopy

R=10,000
spatial resolution 0.3''

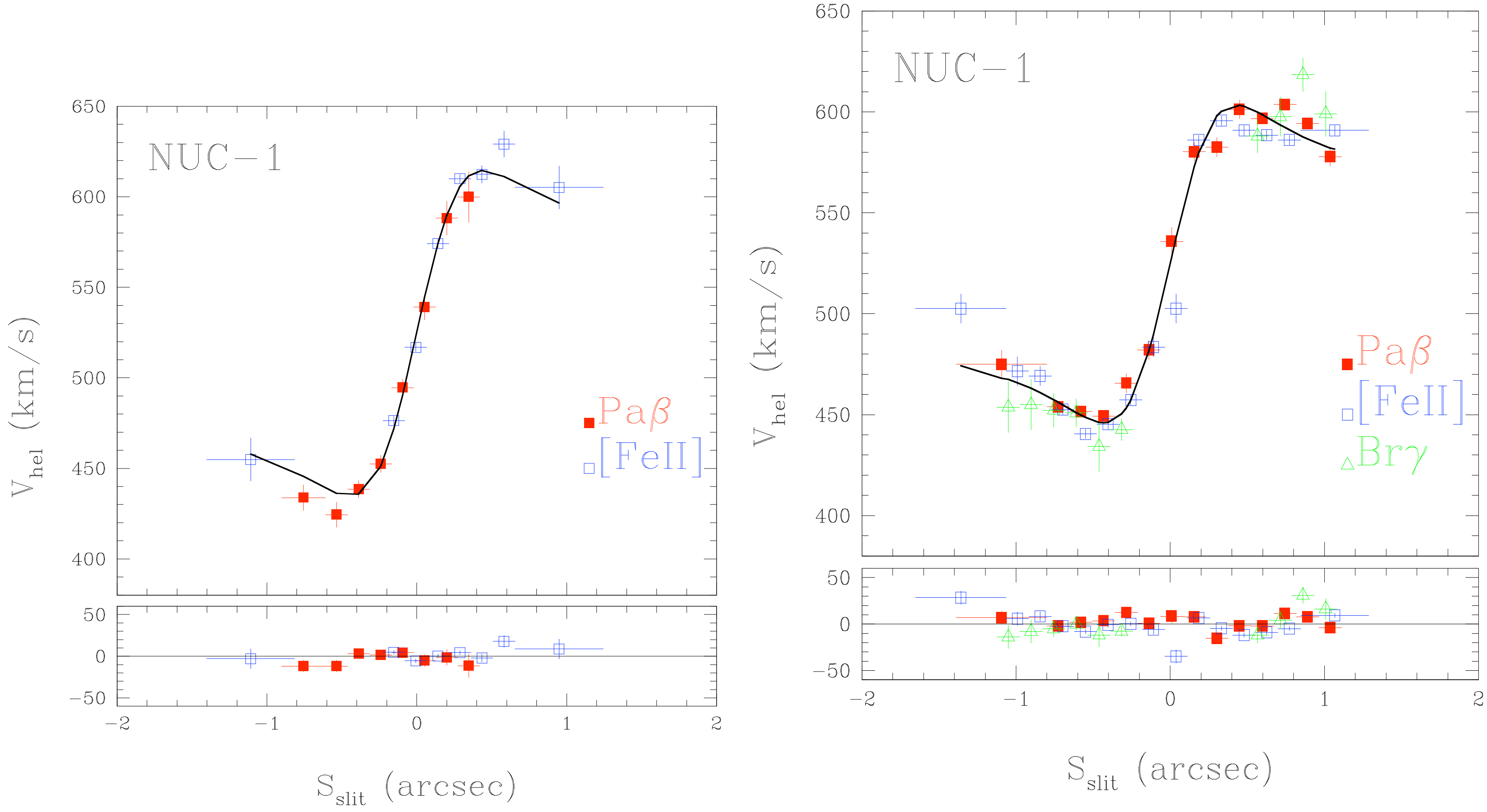


Marconi et al 2002 ApJ

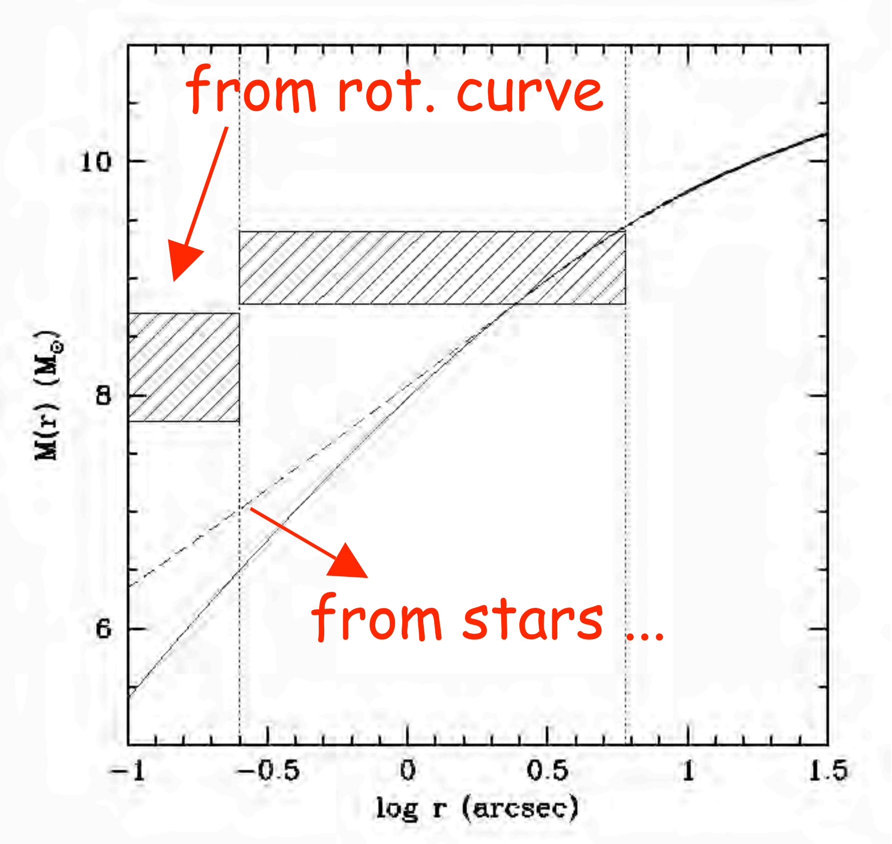


Paβ Spectra @ NUC−1
Hel. Velocity
FWHM
Flux
Position along the slit (arcsec)

Excellent fit to ionized gas velocity field with a Keplarian disc



Centaurus A



This mass is "dark"

- $M_{\odot}/L_{K\odot} > 200$

- Most likely interpretation is that of a BH!
- First extragalactic BH detection using near IR spectroscopy

Best Estimate

$$M_{BH} \sim 2\times10^{8} M_{\odot} \quad {}^{+3.0}_{-1.4}$$

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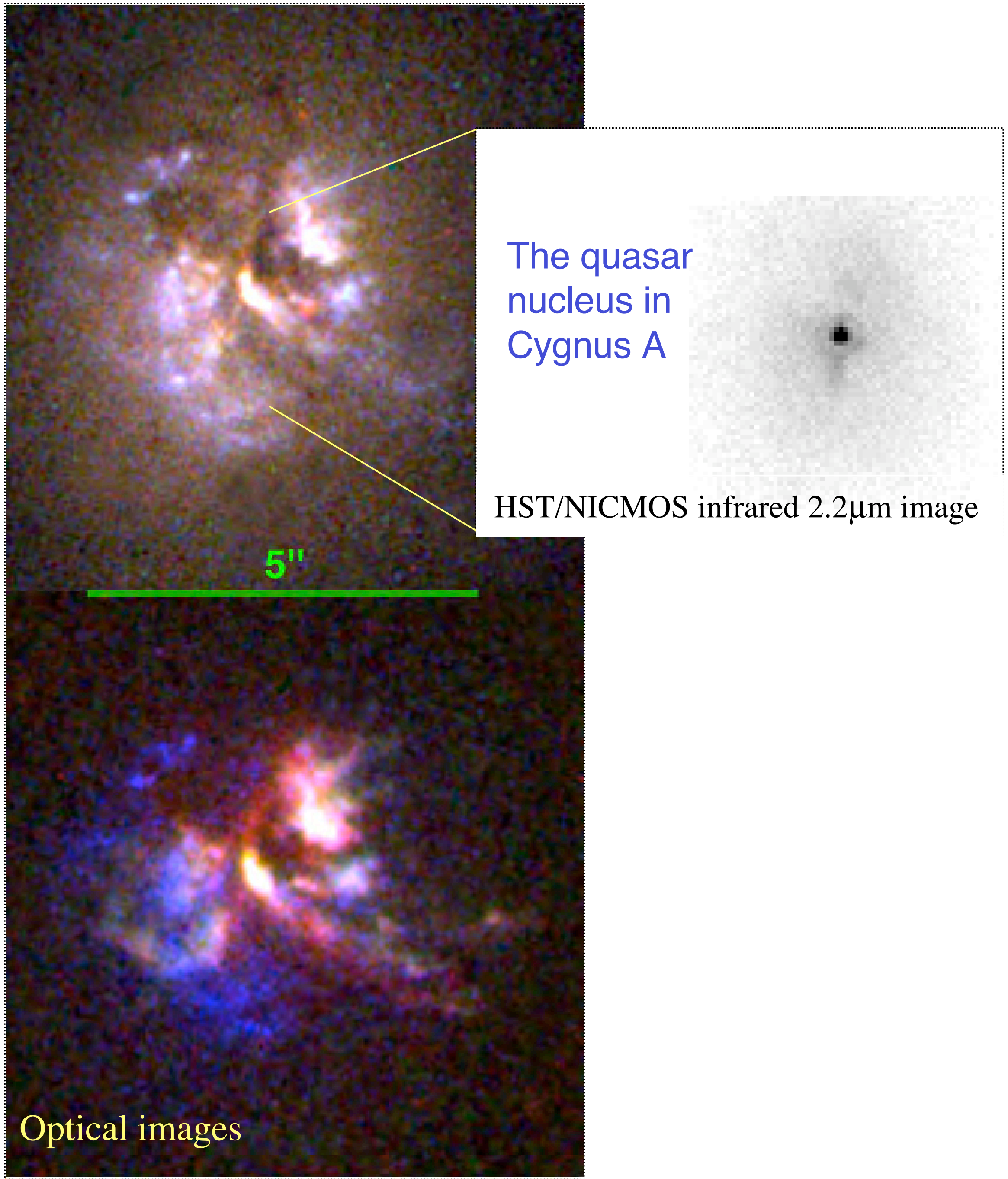
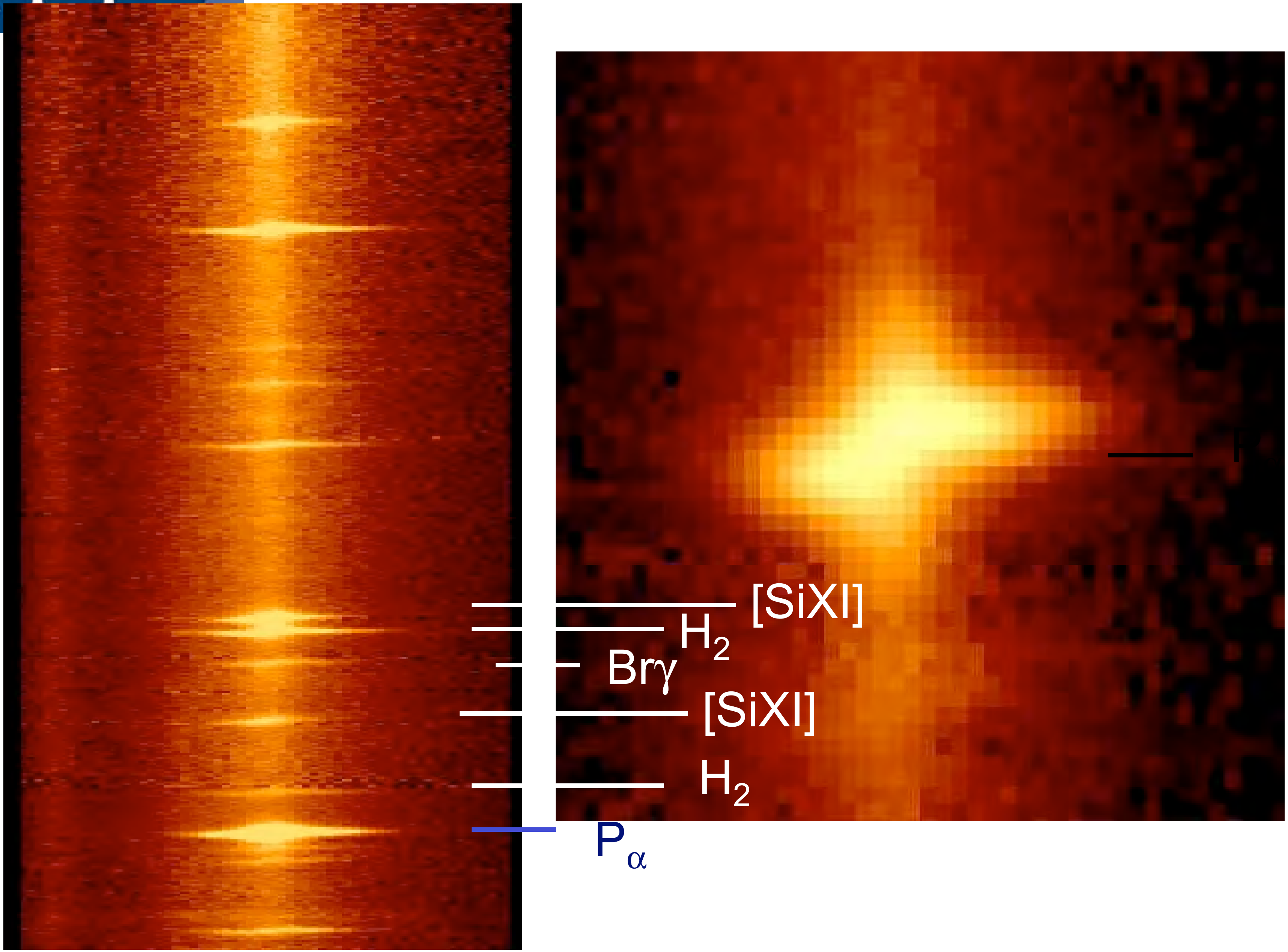
Cygnus A viewed by HST



VLT-Isaac



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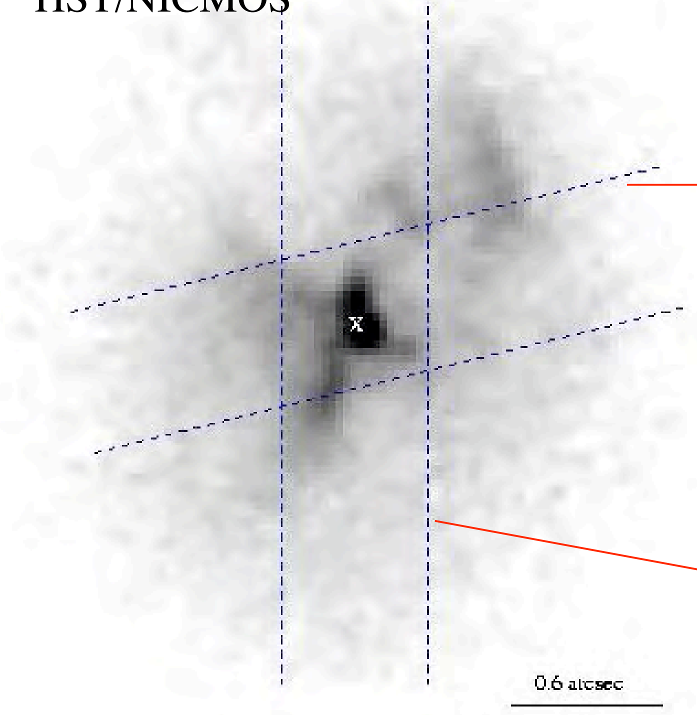
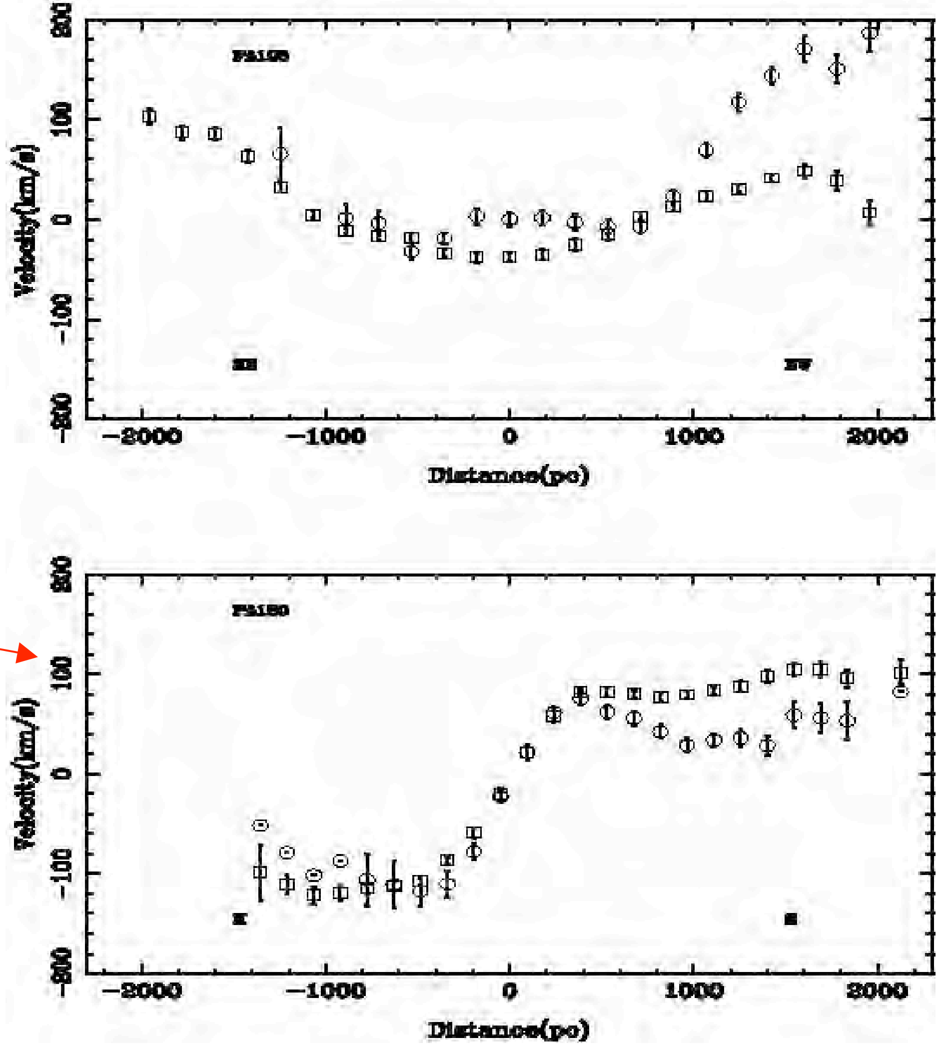
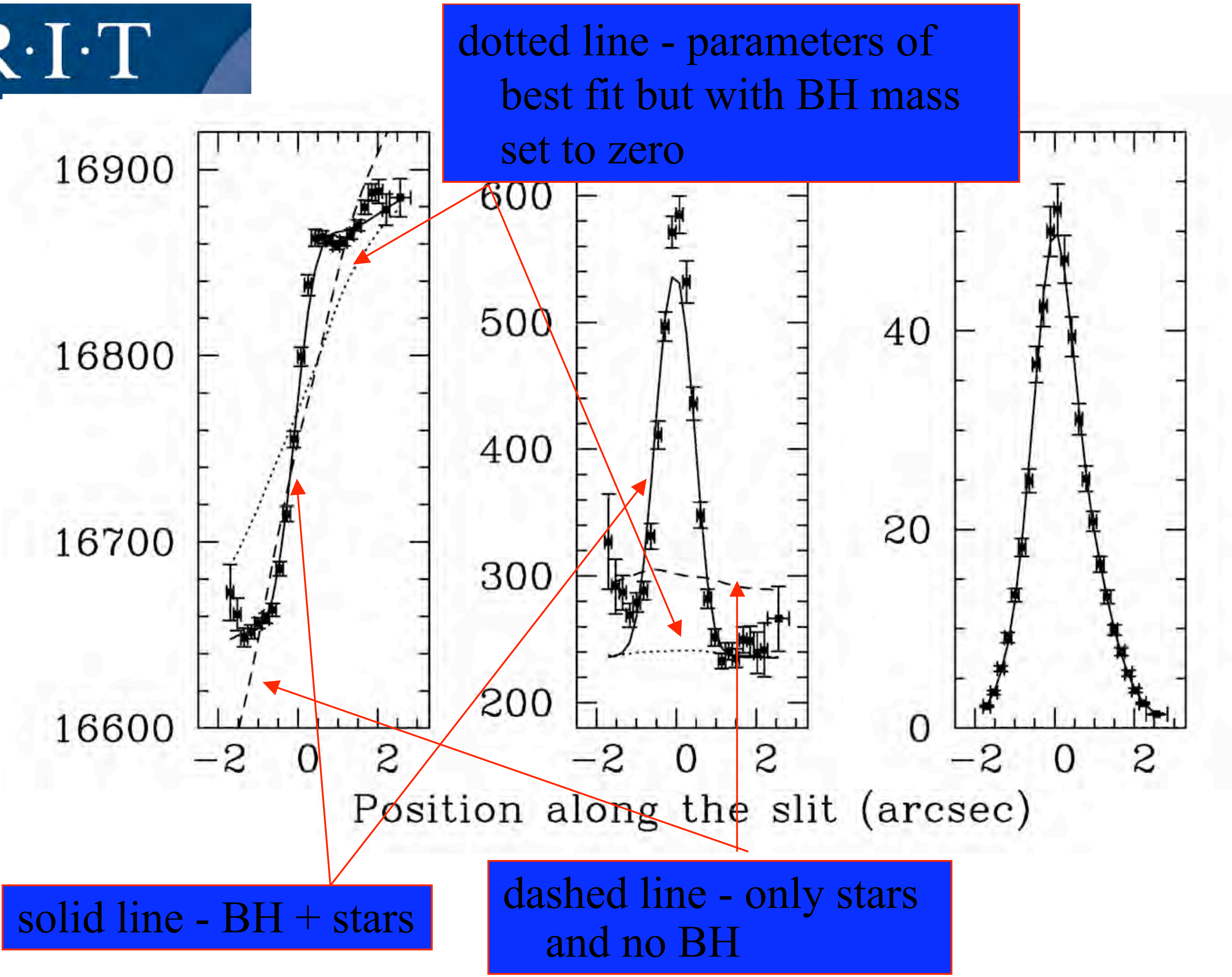
2.0 micron image
HST/NICMOS



Tadhunter et al. 2003



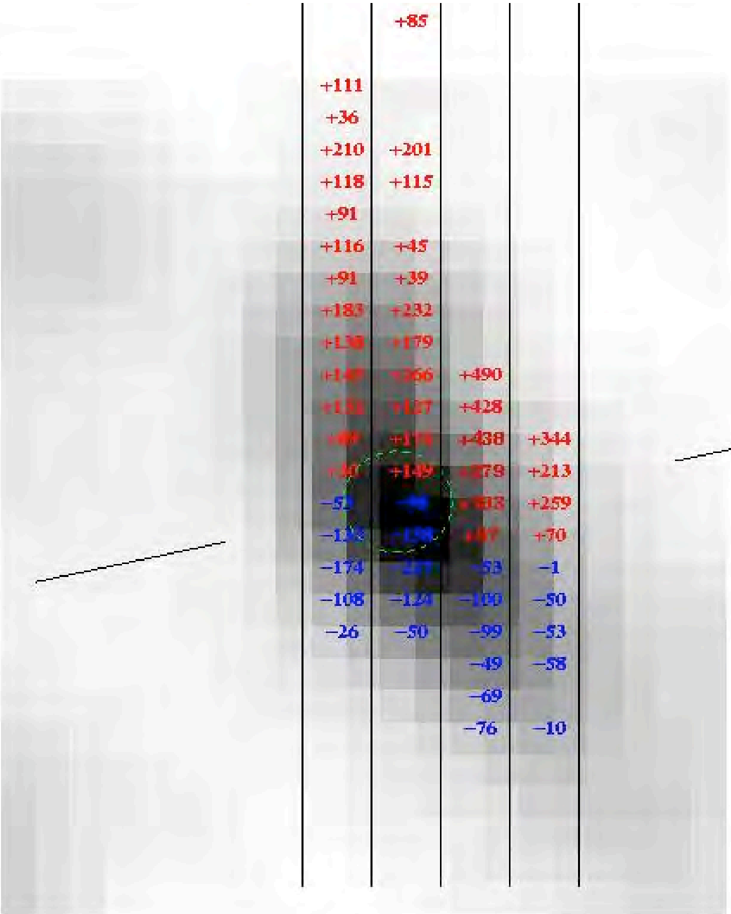
Evidence for a super-massive black hole in Cygnus A from Keck/NIRSPEC infrared data

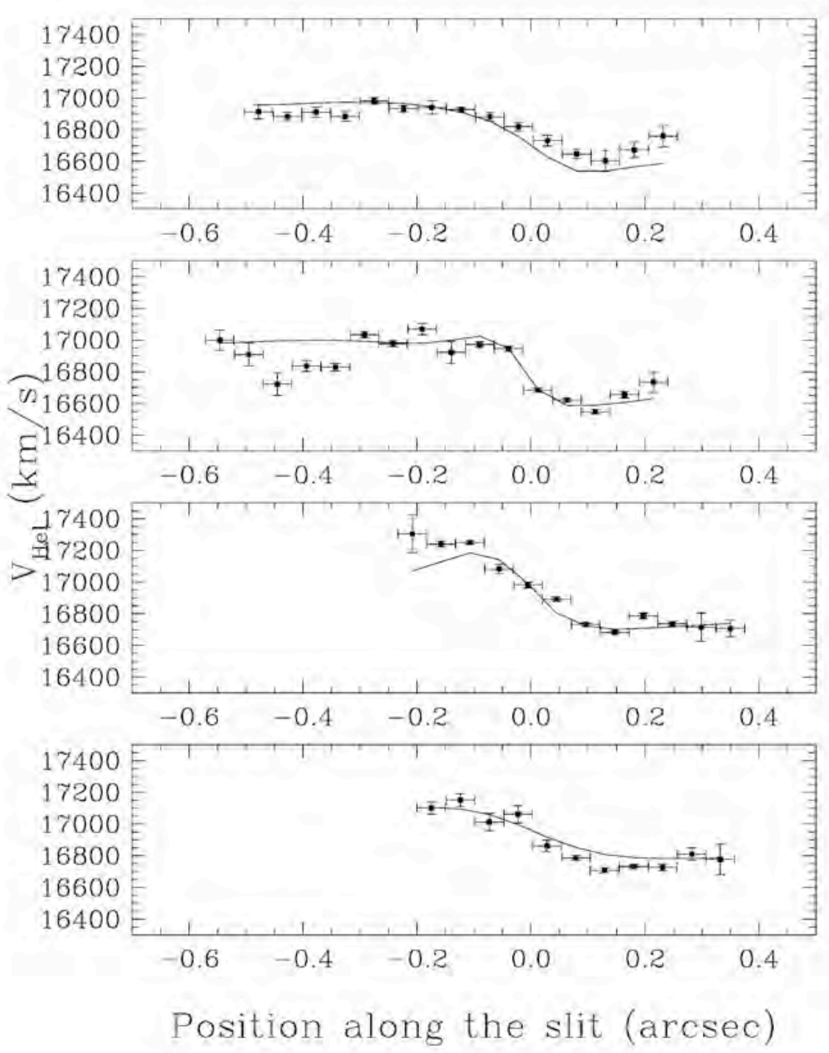


dotted line - parameters of best fit but with BH mass set to zero
16900
16800
16700
16600
600
500
400
300
200
40
20
0
−2
0
2
Position along the slit (arcsec)
solid line - BH + stars
dashed line - only stars and no BH

R·I·T

Model Fit to Cygnus A HST Data

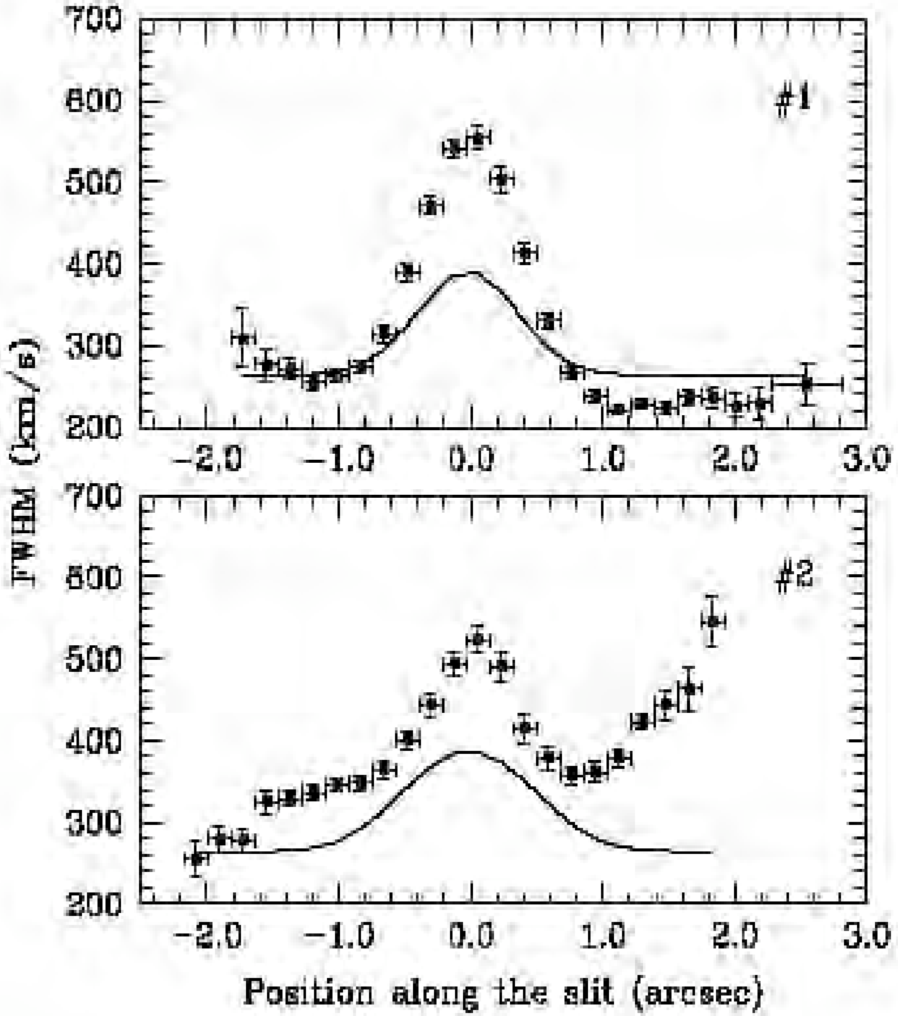




Evidence for a super-massive black hole in Cygnus A from HST/STIS data

Cygnus A

Tadhunter et al

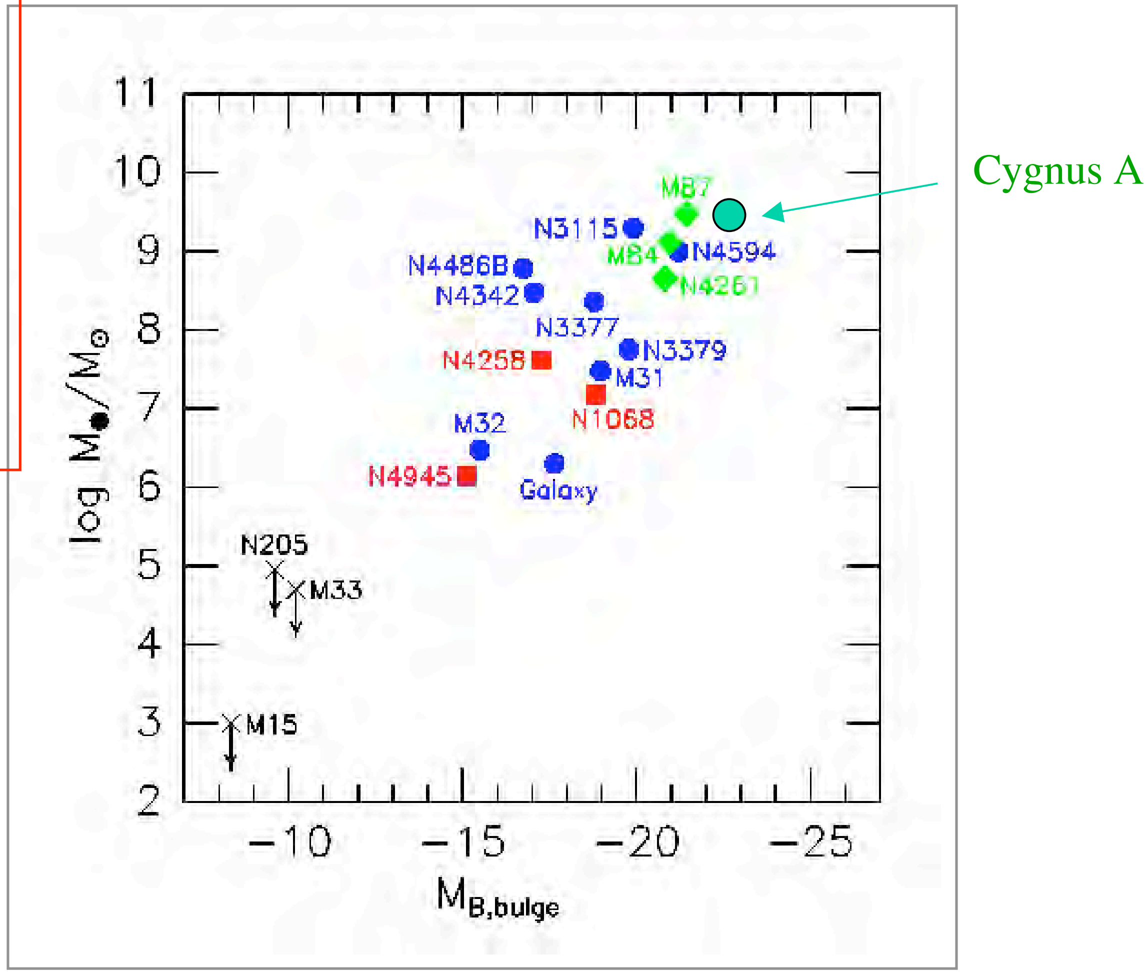


Need additional
220 km/s turbulent
broadening

Correlation between black hole mass and galaxy bulge mass/luminosity

Best Estimate

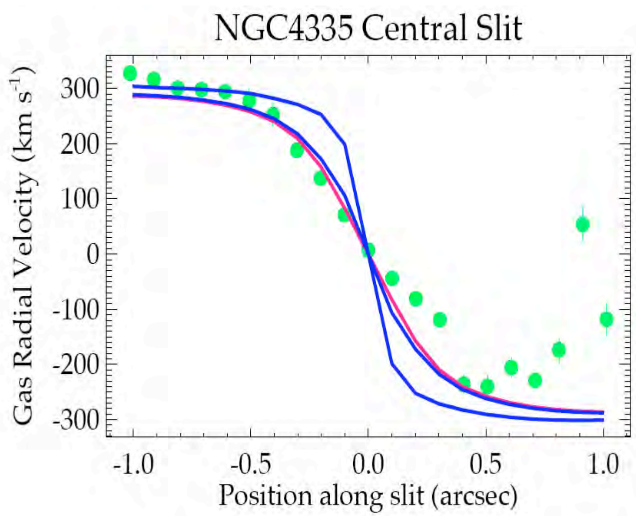
$$M_{BH} \sim 2.1\times10^{9\,+3.5}_{\;\,-1.3} M_\odot$$

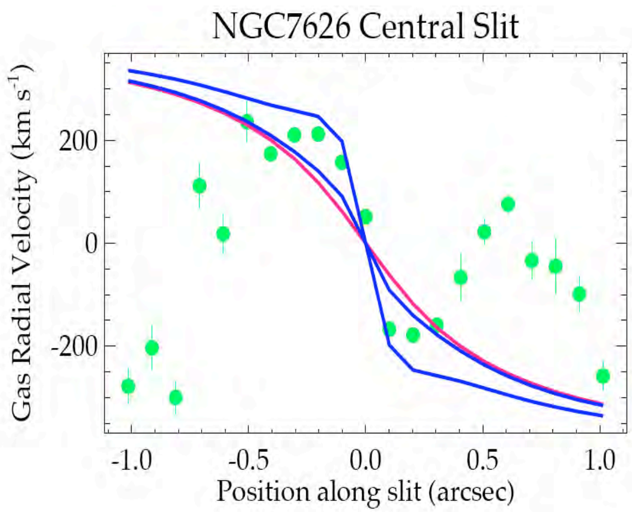


result consistent with idea that properties and power of radio jets in radio galaxies are determined more by accretion rate than by absolute masses of black holes

What Drives the Central Velocity Dispersion in Nearby Early-Type Galaxies?

❍ G. A. VERDOES KLEIJN, R. P. VAN DER MAREL, and J. NOEL-STORR





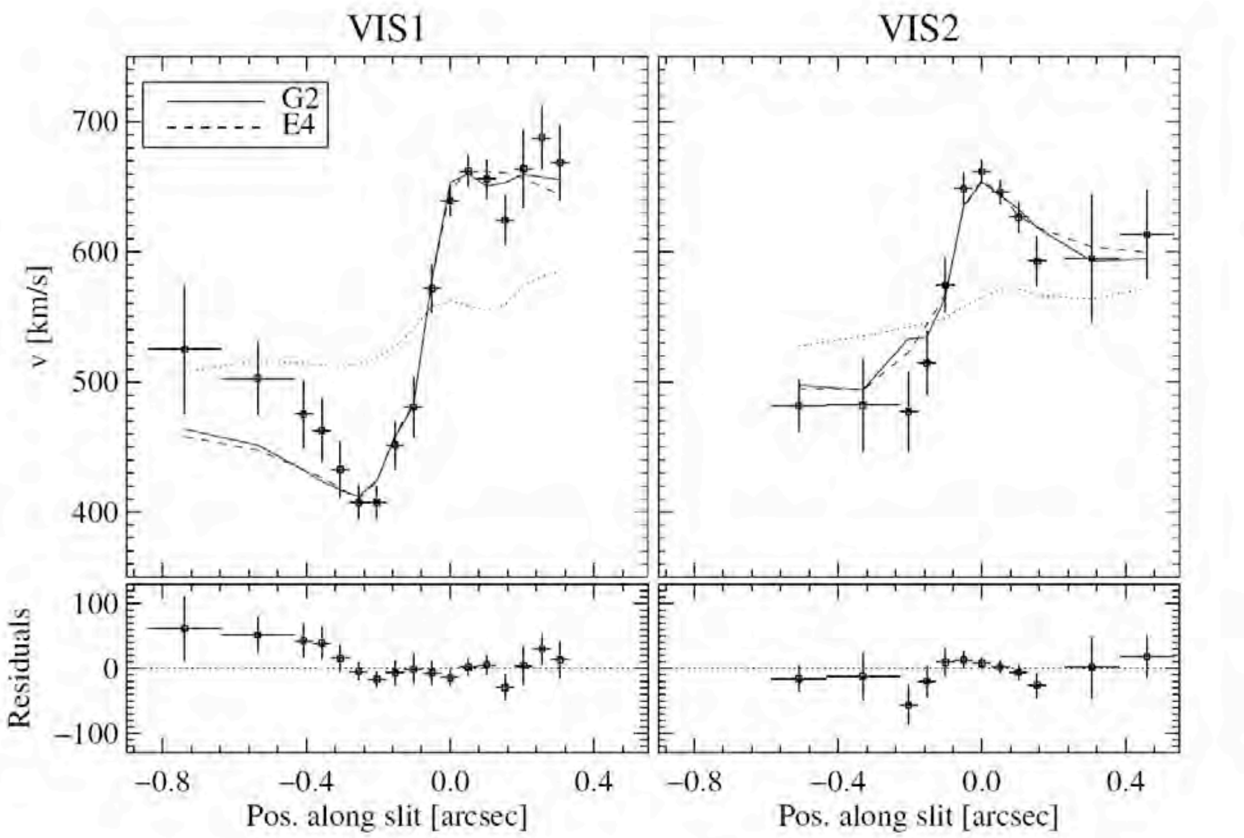
- modeling of gas and star in the nuclei of 16 active and 4 quiescent early-type galaxies to constrain the relative
- importance of gravitation and shocks/turbulence.
- The observed central gas velocity dispersion often exceeds the stellar velocity dispersion.
  - Modeling accounts for v_{gas} **but not σ_{gas}**
- This could be due to either the gravitational potential of a black hole or turbulent shocks in the gas.
- C.f -Similar 'excess dispersion seen in some spirals - Ho et al

Centaurus A - HST-STIS spectra!

STIS spectrum at [SIII] λ9535 Å

Lower signal-to-noise ratio than VLT data

Larger amplitude of rotation curve and larger FWHM at nucleus than VLT Data



$i = 25$

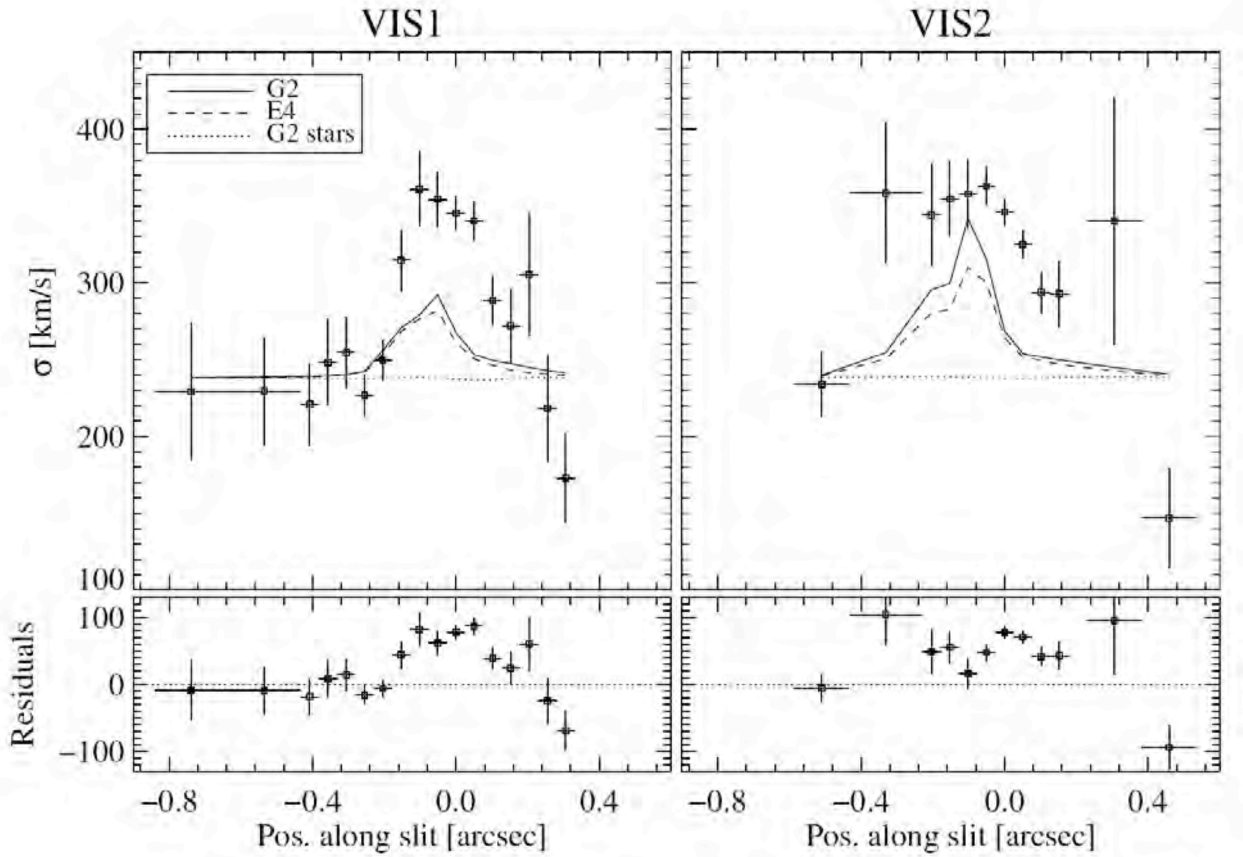
$$M_{\rm BH} = (1.1 \pm 0.1) \times 10^8 \ M_\odot$$

$i = 35$ Largest allowed

$$M_{\rm BH} = (6.5 \pm 0.7) \times 10^7 \ M_\odot$$

Marconi et al. 2006

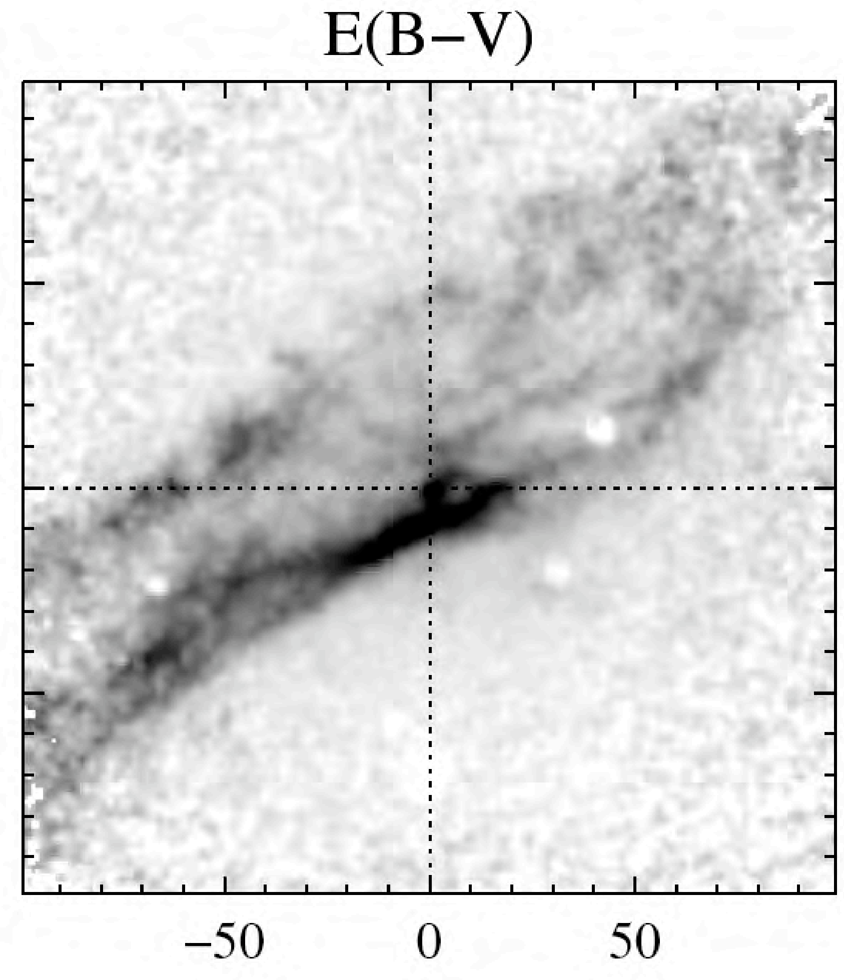
Centaurus A - HST-STIS spectra!



broad FHWM
Neccesary for BH
But not accurate
Measure of M_{BH}

- mismatch between observed and model velocity dispersion not necessarily indication of non-circular motions or kinematically hot gas.
- due to an inaccurate computation arising from too course a model grid, or adoption of an intrinsic brightness distribution which is too smooth

Centaurus A - HST-STIS spectra!



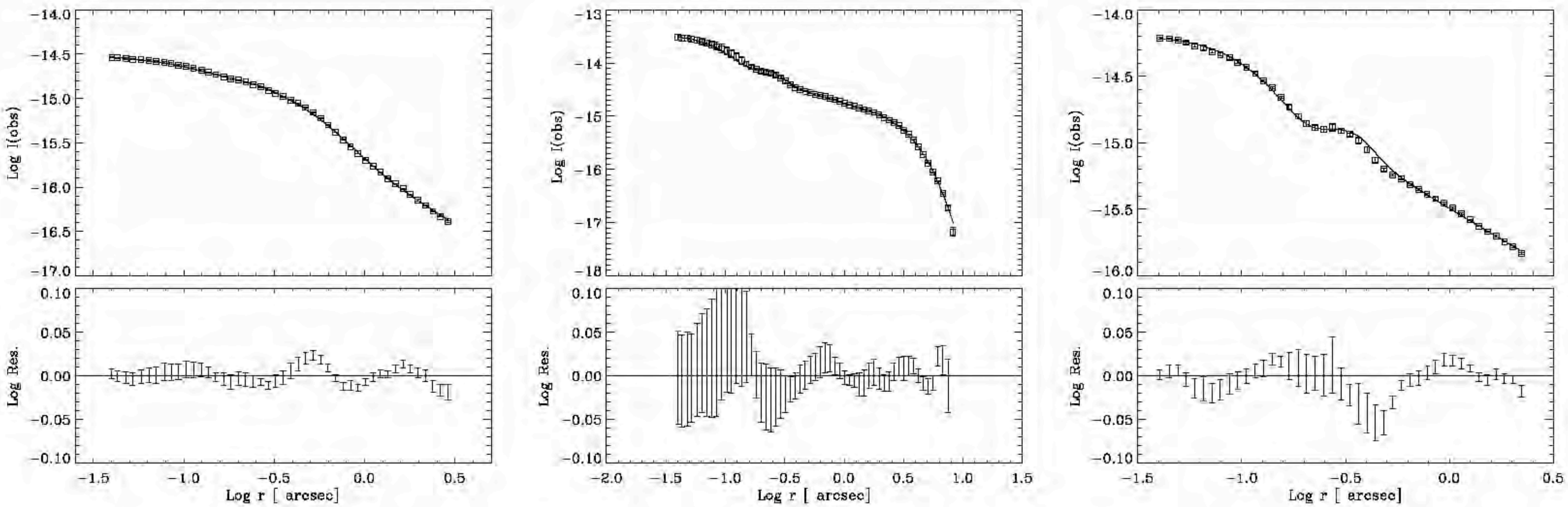
- first external galaxy for which reliable BH mass measurements from gas and stellar dynamics are available
- M_{BH} gas kinematical estimate is in good agreement with that from stellar dynamics (Silge et al. 2005)
- excellent agreement with correlation with M_{BH} v $L_{infrared}$
- But factor 2-4 above M_{BH}-σ.
- Easily understood- dustimpact on bulge-e.g. Wilkinson et al 1986

BH Masses in Spirals

Adapted from Ho 2005

Surface Brightness Fits

NGC 3310 NGC 4303 NGC 4258

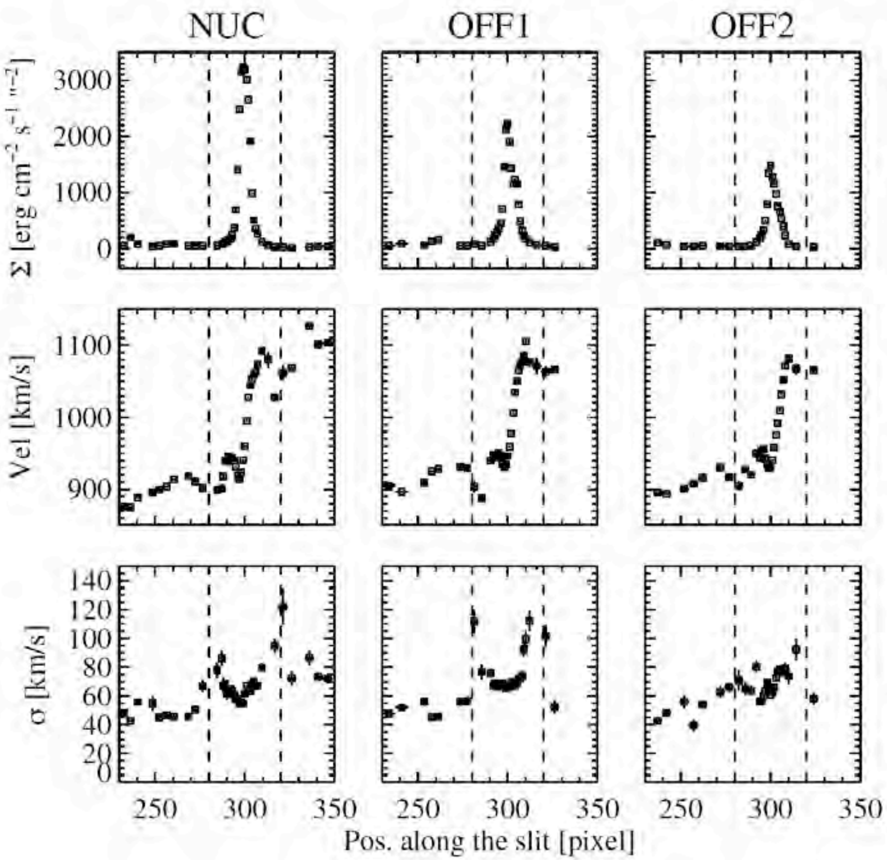


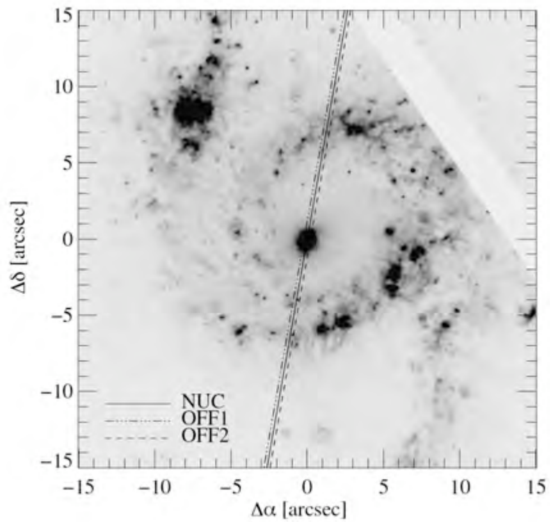
Oblate spheroid density distribution

$$\rho(m) = \rho_0 \left(\frac{m}{r_b}\right)^{-\alpha} \left[1 + \left(\frac{m}{r_b}\right)^2\right]^{-\beta} \qquad m^2 = x^2 + y^2 + z^2 / q^2$$

nuclear point source was added for NGC 4303 and NGC 4258 in order to account for the AGN emission.

NGC3310





- SBC starburst galaxy.
  - Presence of very young stars in the center; well studied
  - Distance ~17.4 Mpc
  - Inclination ~40

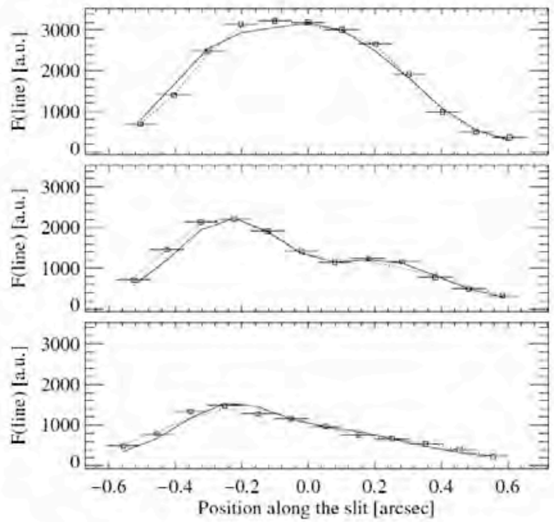
Fit line profiles with Gauss-Hermite series

$$L(v) = \frac{e^{-\frac{1}{2}y^2}}{\sigma\sqrt{2\pi}}\left[1 + \sum_{m=3}^{4} h_m H_m(y)\right] \qquad y = (\upsilon - \upsilon_0)/\sigma$$

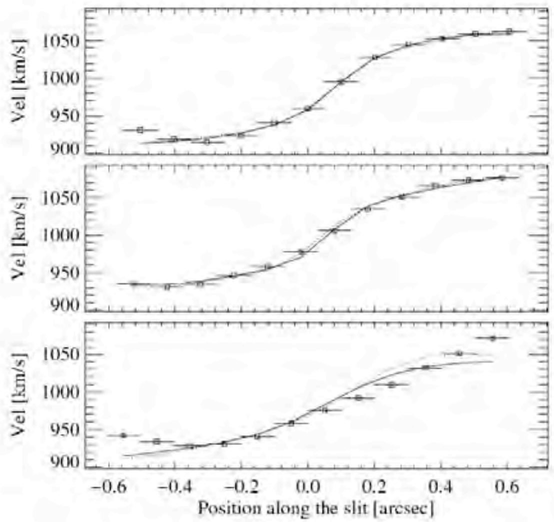
Pastorini et al, ApJ, 2007

NGC3310

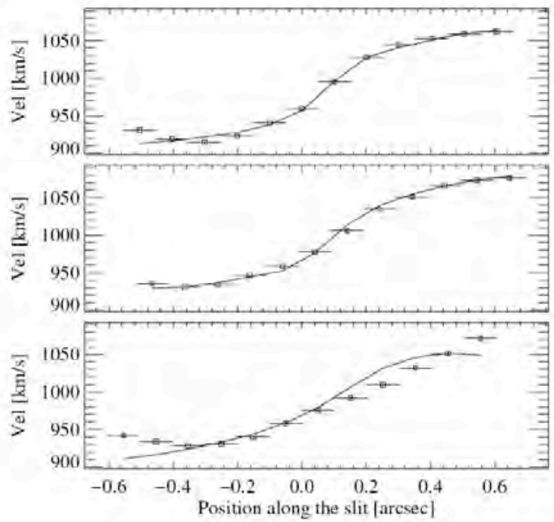
Flux

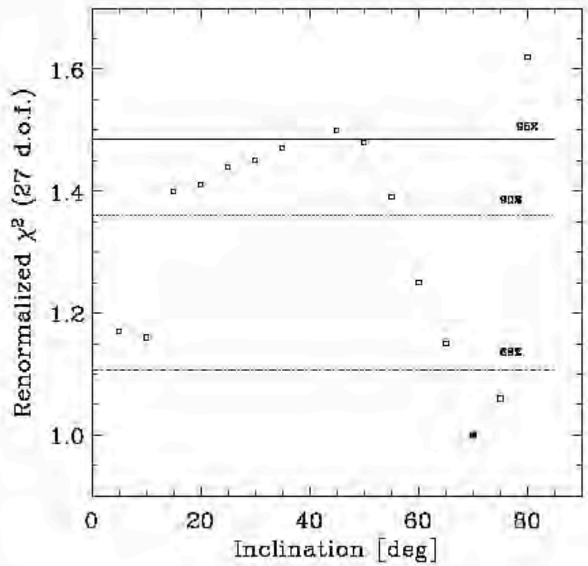


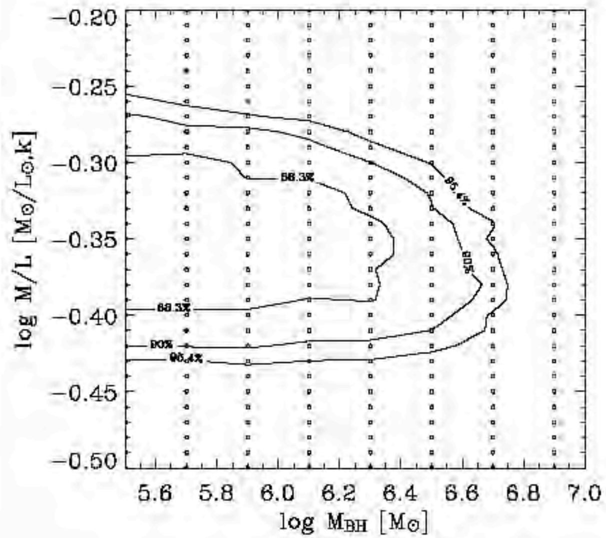
Rotation curve



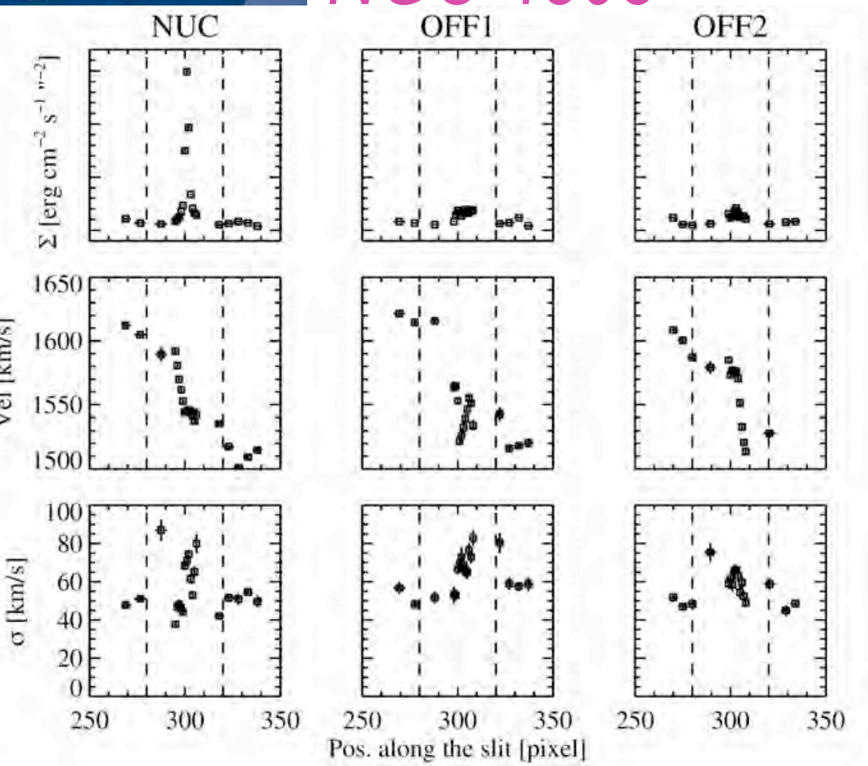
Best' inclination (i = 70 deg)

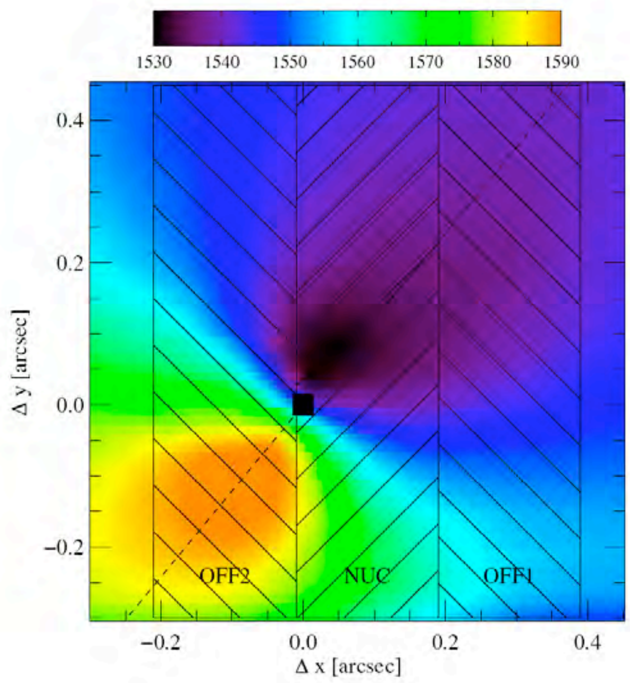


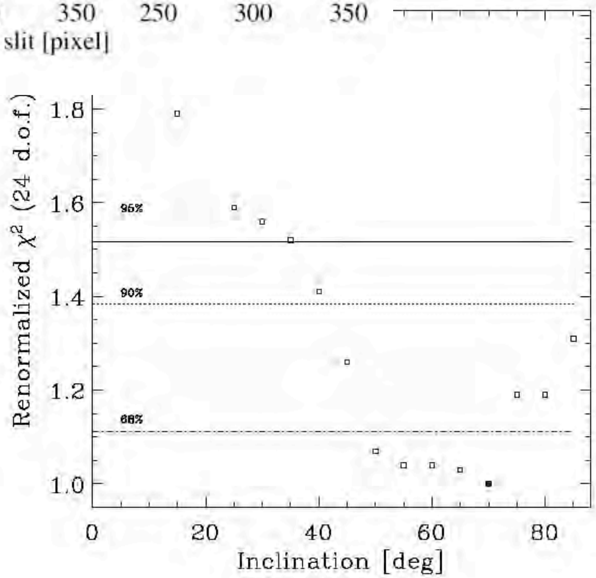


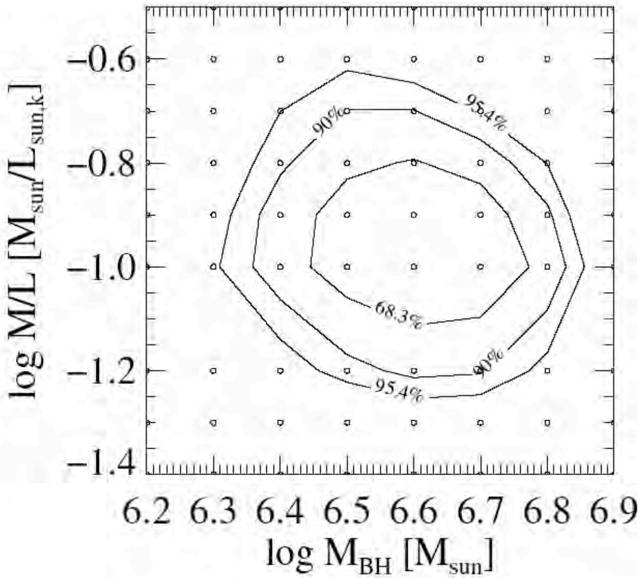


NGC 4303

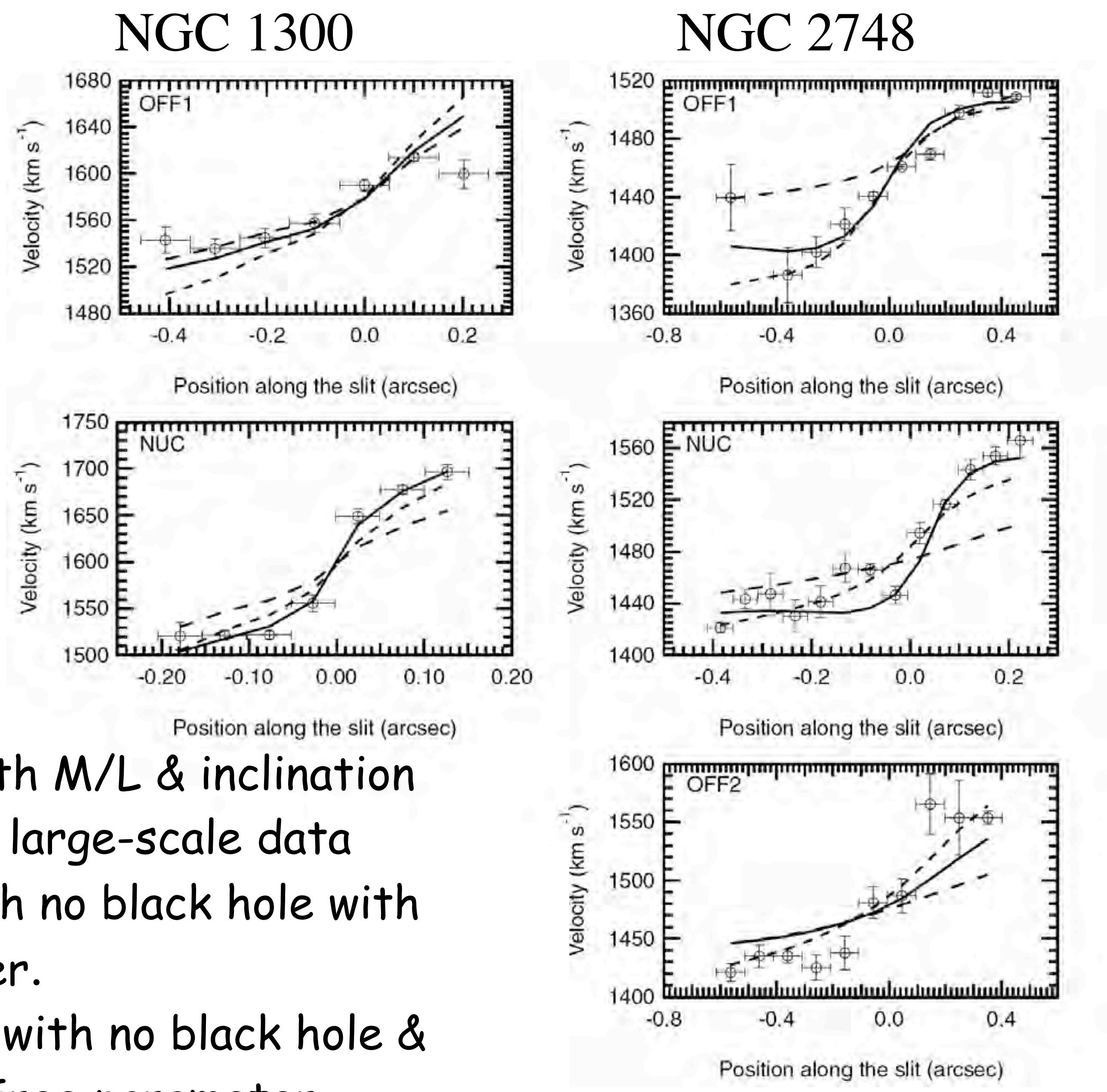








Pastorini et al, ApJ, 2007



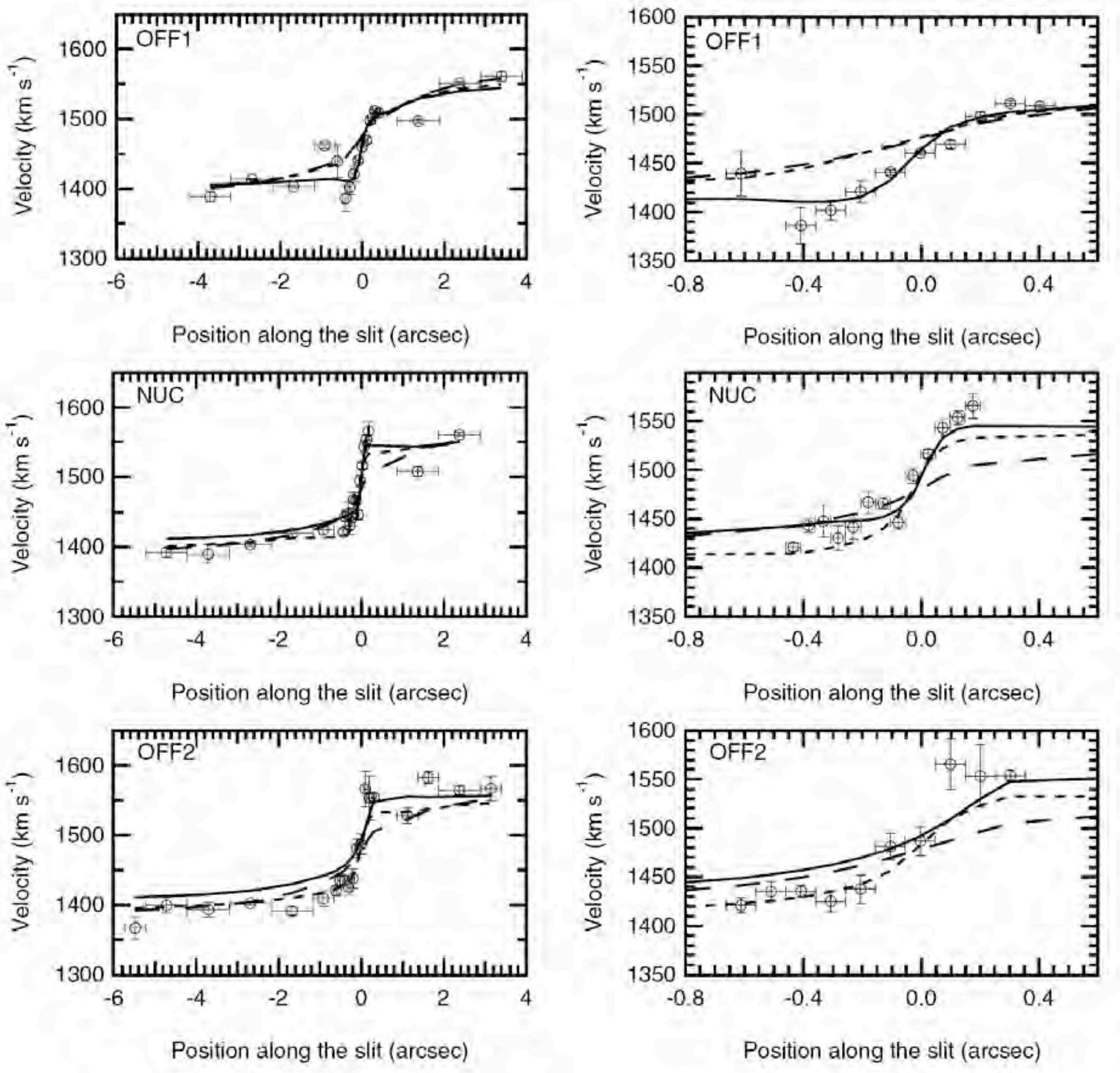
——— models with M/L & inclination fixed at values for large-scale data

- - - - models with no black hole with M/L free parameter.

— — - models with no black hole & inclination of disc free parameter.

Atkinson et al, ApJ, 2004

NGC2748



no black hole

coplanar disc

black hole

$5 \times 10^7 M_\odot$

slit angle to the line of nodes optimized

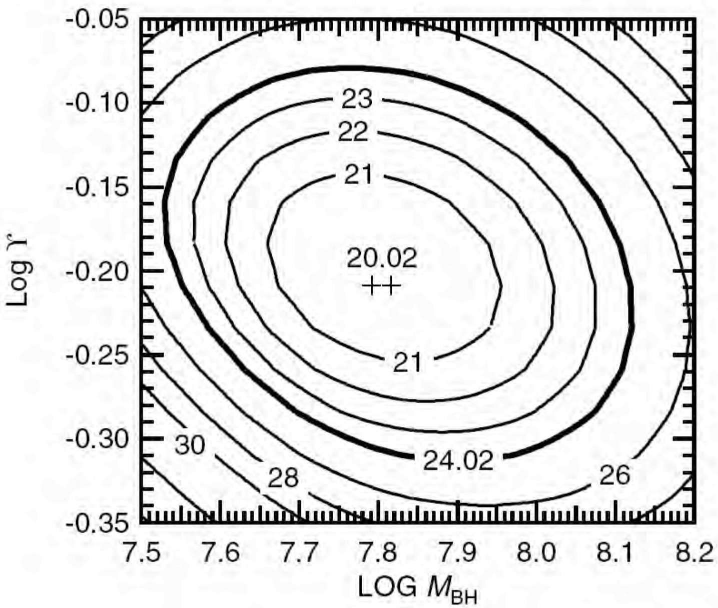
black hole

$4 \times 10^7 M_\odot$

Atkinson et al, ApJ, 2004

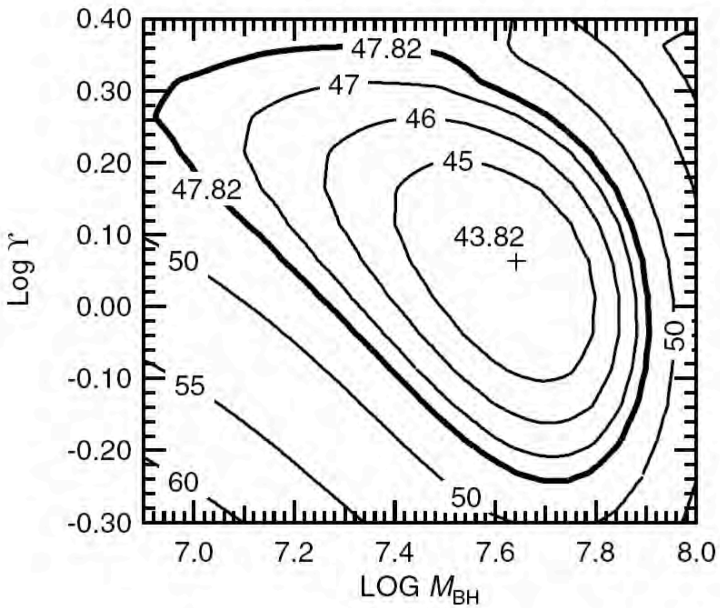
NGC 1300& NGC 2748

NGC 1300



$$M_{BH} = 6.6^{+6.3}_{-3.2} \times 10^{7} M_{\odot}$$

NGC 2748



$$M_{BH} = 4.4^{+3.5}_{-3.6} \times 10^{7} M_{\odot}$$

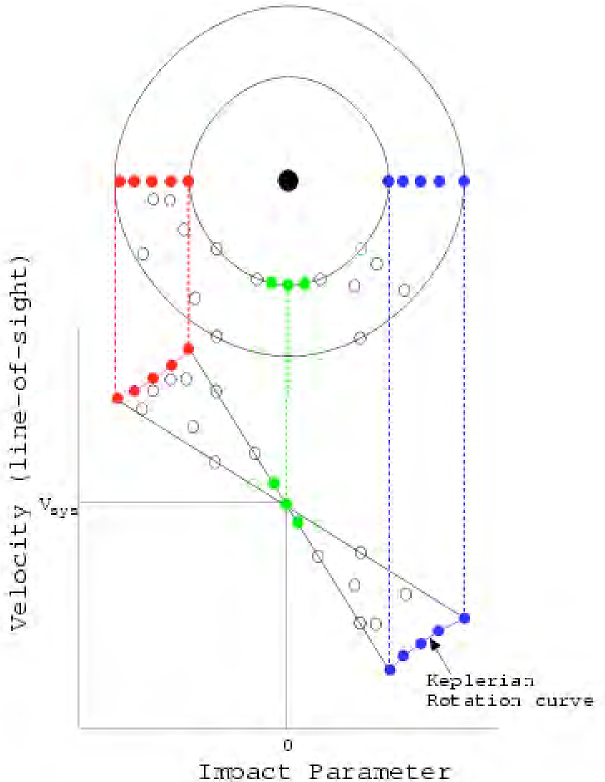
Chi Square fits: solid is 95% confidence level

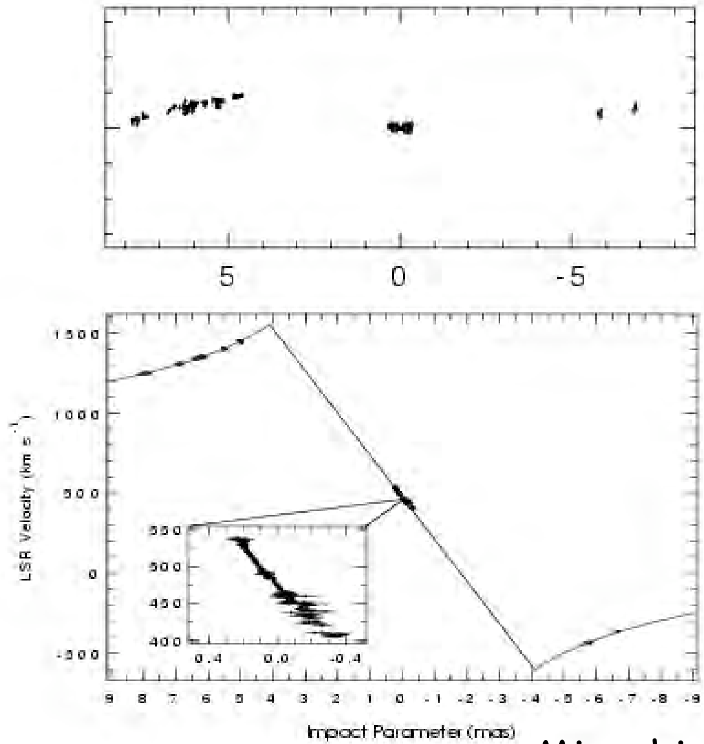
Atkinson et al, ApJ, 2004

NGC4258 :A Critical Yet difficult Case

Adapted from Ho 2005

NGC 4258 : Keplerian Velocity Profile





Miyoshi et al. 1995

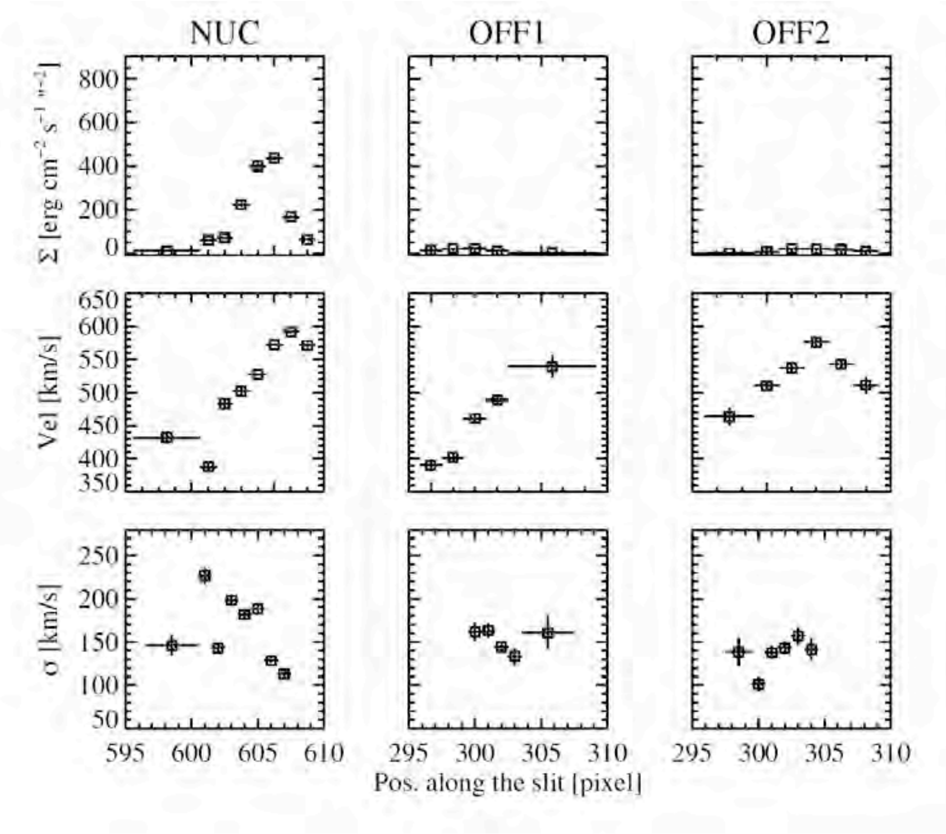
❍BH mass has been measured from kinematics of H_2O masers

M_{BH} = $4 \times 10^7\ M_\odot$

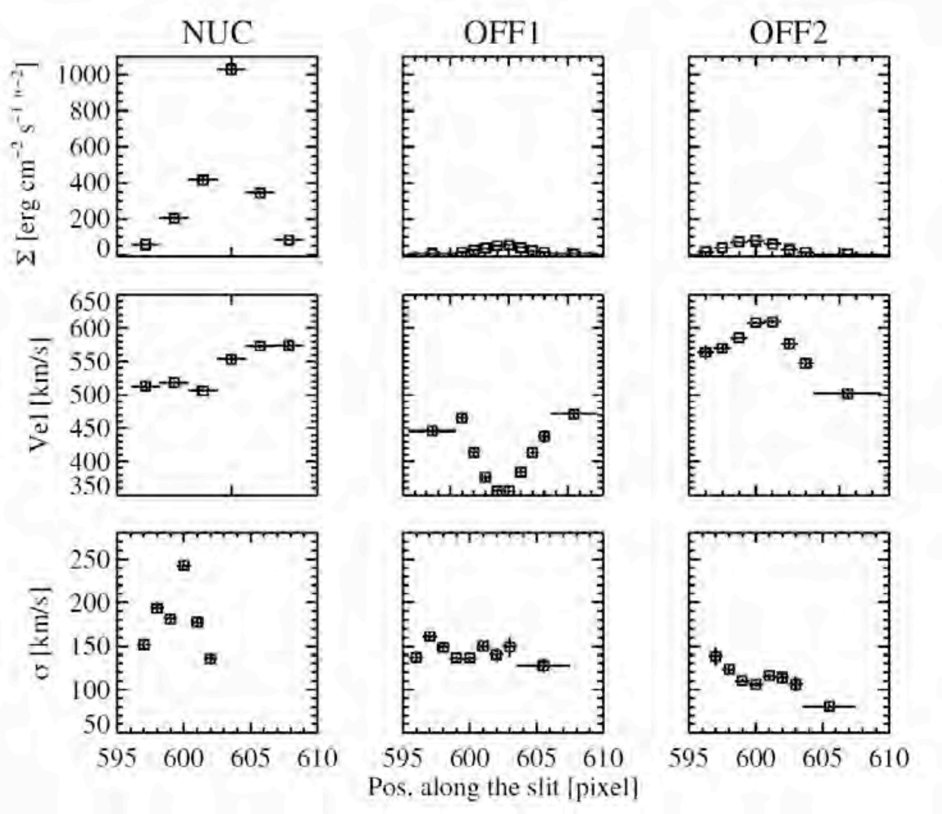
❍ Second best case for a SMBH after our galactic centre and is a crucial test for the stellar dynamical & gas kinematical methods!

NGC4258

Pastorini data



Archive

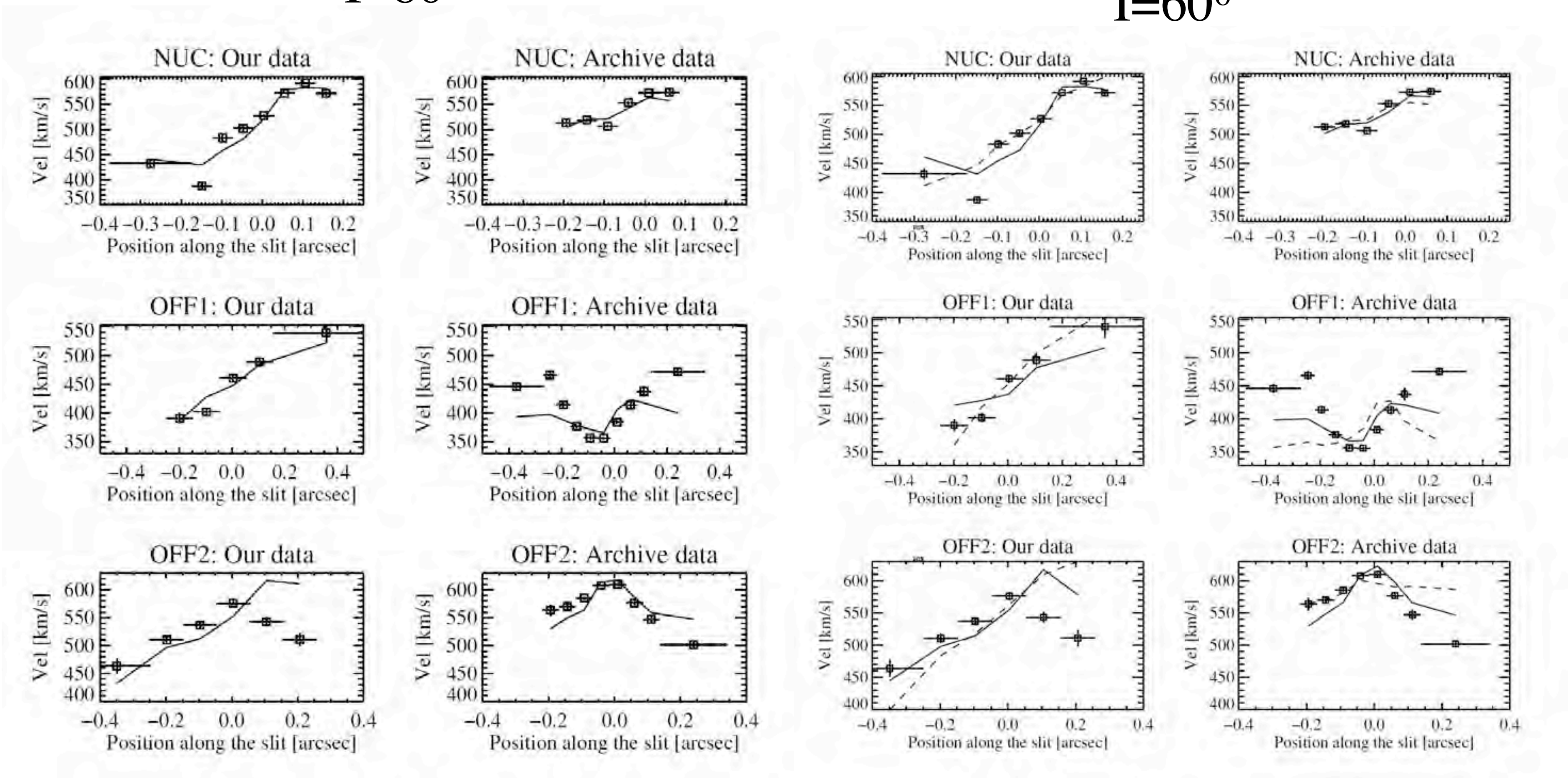


Pastorini et al, ApJ, 2007

R·I·T

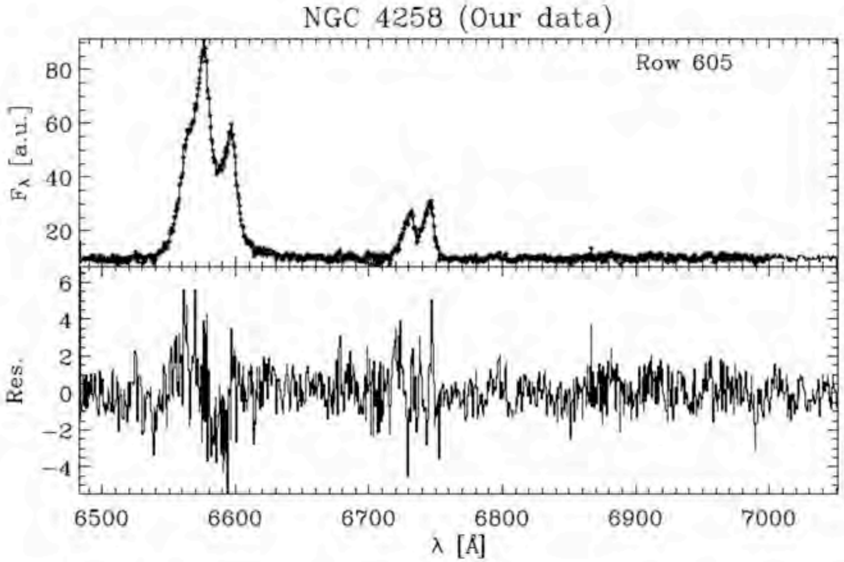
NGC 4258 .... no black hole

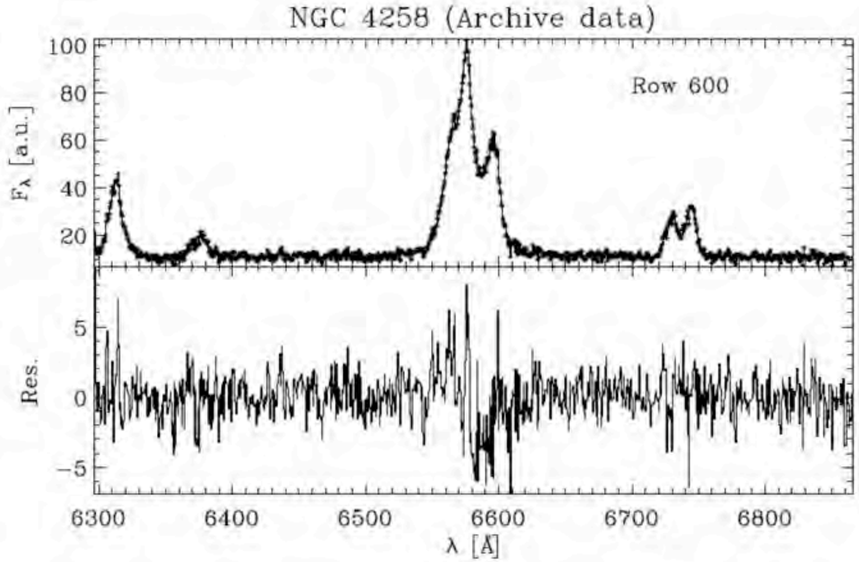
$I=80^0$ $I=60^0$

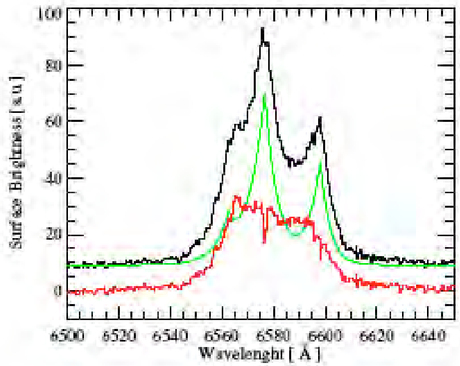


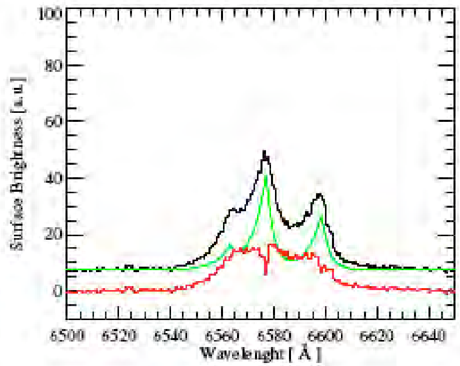
even if difference between two cases does not appear significative model without a BH provides an unphysically high value for stellar mass light ratio $M/L = 5.08\left[M_\odot / L_\odot\right]_H$

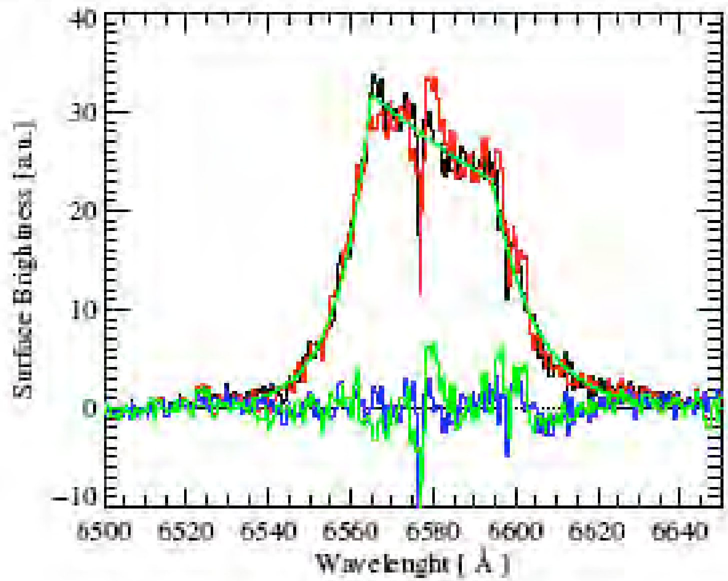
NGC4258


NGC 4258 (Our data)
Row 605
F_λ [a.u.]
Res.
λ [Å]
6500 6600 6700 6800 6900 7000


NGC 4258 (Archive data)
Row 600
F_λ [a.u.]
Res.
λ [Å]
6300 6400 6500 6600 6700 6800


Surface Brightness [a.u.]
Wavelenght [Å]


Surface Brightness [a.u.]
Wavelenght [Å]


Surface Brightness [a.u.]
Wavelenght [Å]
6500 6520 6540 6560 6580 6600 6620 6640

NGC 4258

$i(°)$	$\log M^a_{BH}$	$\log M/L^b$	V_{sys} (km/s)	$\theta(°)$	$(\chi^2_{rescaled})^c$
Fit of velocity ($\Delta v_0 = 33.74 Kms^{-1}$)^d					
5	9.69	-0.74	465.60	239.22	1.11
10	9.12	-1.21	466.31	239.84	1.09
15	8.78	-1.15	466.78	239.54	1.09
20	8.56	-2.10	461.66	238.51	1.10
25	8.37	-1.80	465.01	238.95	1.08
30	8.26	-1.92	464.67	238.98	1.07
35	8.15	-1.74	466.36	238.68	1.06
40	8.06	-1.83	465.47	238.35	1.05
45	8.03	-2.24	463.81	237.64	1.04
50	7.99	-2.22	465.32	237.07	1.03
55	7.97	-1.96	465.13	236.85	1.02
60	7.96	-2.30	467.98	237.04	1.00
65	8.00	-1.70	468.68	236.14	1.00
70	8.01	-1.64	472.64	236.69	1.00
75	8.09	-1.76	472.40	236.45	1.02
85	8.47	-2.07	497.09	244.23	1.12

[a] Units of $M_\odot$.

[b] Units of $M_\odot/L_{\odot,H}$.

[c] Rescaled χ^2 with errors computed as $\Delta v_i'^2 = \Delta v_i^2 + \Delta v_0^2$.

[d] Systematic error adopted to renormalize χ^2.

- M_{BH} = 7.9 x10^7 $M_\odot$ for i = 60°
- Twice as large as from CO observations
- Within ~1σ of maser results
  - Note: maser value is for smaller more compact inner disk, not resolved at HST resolution
- Upper limit to M/L < 1.8 $M_\odot/L_\odot$

Pastorini et al, ApJ, 2007

Results

NGC 3310-upper limit on the BH mass

$M_{star} \sim 7\times10^{7} M_{\odot}$[96% CL]   M/L=$0.47^{+0.04}_{-0.07}$ $M_{\odot}/L_{\odot}$

$M_{BH} < 4.2\times10^{6} M_{\odot}$[96% CL]

NGC 4303- requires BH?

$5.0^{+0.87}_{-2.26}\times10^{6} M_{\odot}$

[$6.0\times10^{5} M_{\odot} - 1.6\times10^{7} M_{\odot}$ taking into accout i>40^{0}]

NGC 4258- requires BH

$7.9^{+6.2}_{-3.5}\times10^{7} M_{\odot} \left(i = 60^{0}\right)$

[$2.5\times10^{7} M_{\odot} - 2.6\times10^{8} M_{\odot}$ taking into account allowed i range]

Comparison between M_{BH} estimates for spirals and BH-spheroid relations

(6 detections and 2 upper limits)

Galaxy	Type	D (Mpc)	log M_{BH}	log L_K	$\log \frac{MBH}{MBH(LK)}$ (Marconi)	σ_c	$\log \frac{MBH}{MBH(\sigma_c)}$ (Ferrarese)	σ_e	$\log \frac{MBH}{MBH(\sigma_e)}$ (Tremaine)
NGC1300	SB(rs)bc	18.8	7.8	10.0	0.6	90	1.3	87	1.1
NGC2748	SAbc	23.2	7.6	9.8	0.6	79	1.4	83	1.0
NGC3310	SAB(r)bc	17.4	<7.6	9.6	<0.9	101	<0.8	84	<1.0
NGC3516	S0	38.0	<7.3	10.7	<0.00	144	<-0.18	132	<-0.06
NGC4041	SA(rs)bc	19.5	<7.3	9.7	<0.4	92	<0.7	88	<0.6
NGC4303	SAB(rs)bc	16.1	6.6	10.2	-0.8	108	-0.3	84	0.0
NGC5252	S0	92.0	8.98	11.6	-0.02	192	0.7	190	1.0
NGC4258	SAB(s)bc	7.2	7.59	10.3	0.09	120	0.45	148	-0.19
Milky Way	SbI-II	0.008	6.60	10.2	-0.9	100	-0.2	100	-0.3
M81	SA(s)ab	3.9	7.84	11.0	-0.4	174	-0.1	165	0.0

The comparison between the BH spheres of influence and the spatial resolution of HST observations underlines the difficulties connected to the study of BH in late type spiral galaxies and indicates that higher spatial resolution is required for a significant step forward.

Virial Estimators
For Active Galactic Nuclei

Source	Distance from central source
X-Ray Fe Kα	3-10 R_S
Broad-Line Region	$200–10^4$ R_S
Megamasers	4×10^4 R_S
Gas Dynamics	8×10^5 R_S
Stellar Dynamics	10^6 R_S

In units of the Schwarzschild radius
$R_S = 2GM/c^2 = 3$ _ 10^{13} M_8 cm .

Mass estimates from the virial theorem:

$$M = f\,(r\,\Delta V^2/G)$$

where

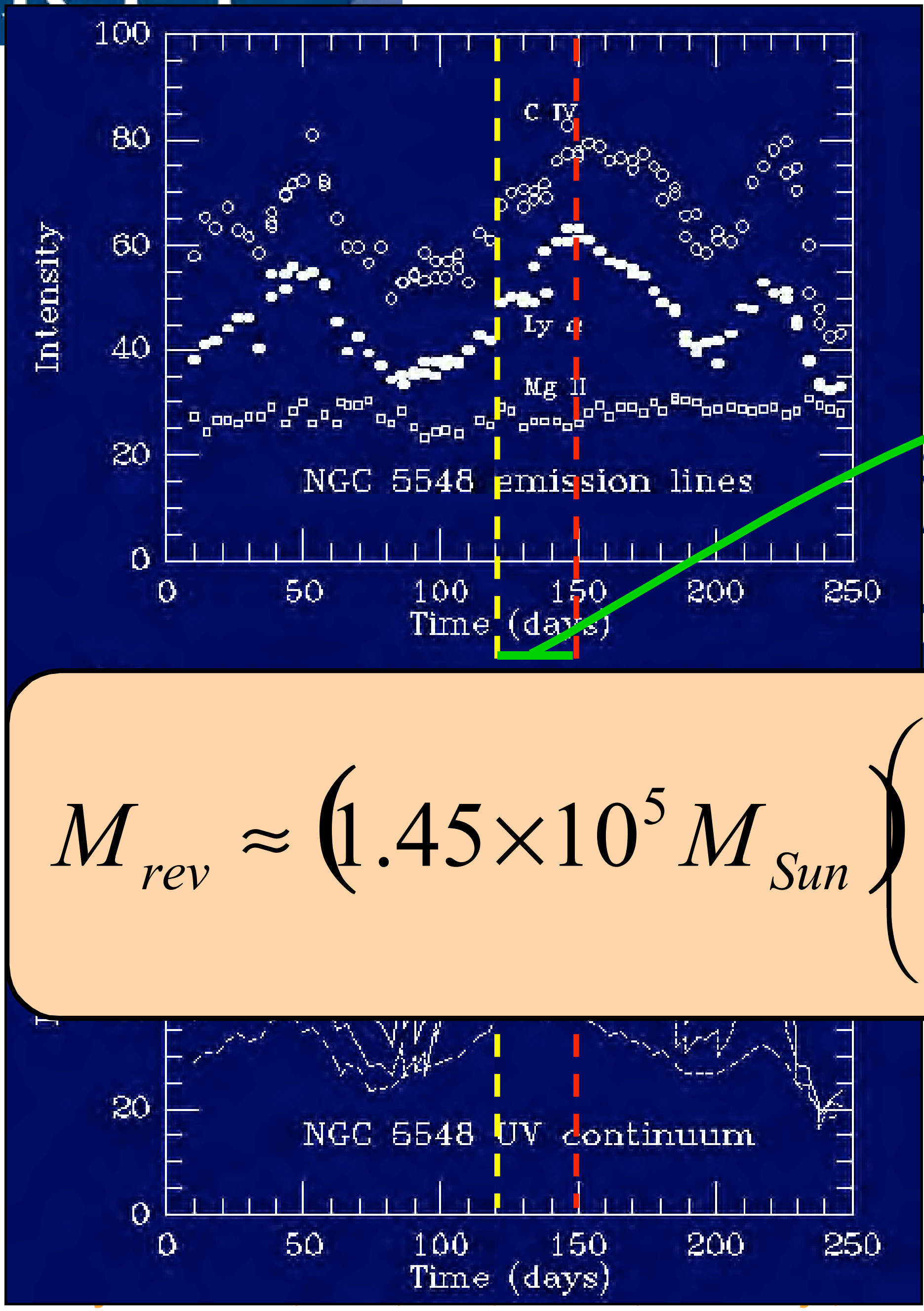
r = scale length of region

ΔV = velocity dispersion (emission-line width)

f = a factor of order unity, depends on details of geometry and kinematics

Credit:Brad Peterson

Reverberation Mapping



Time lag

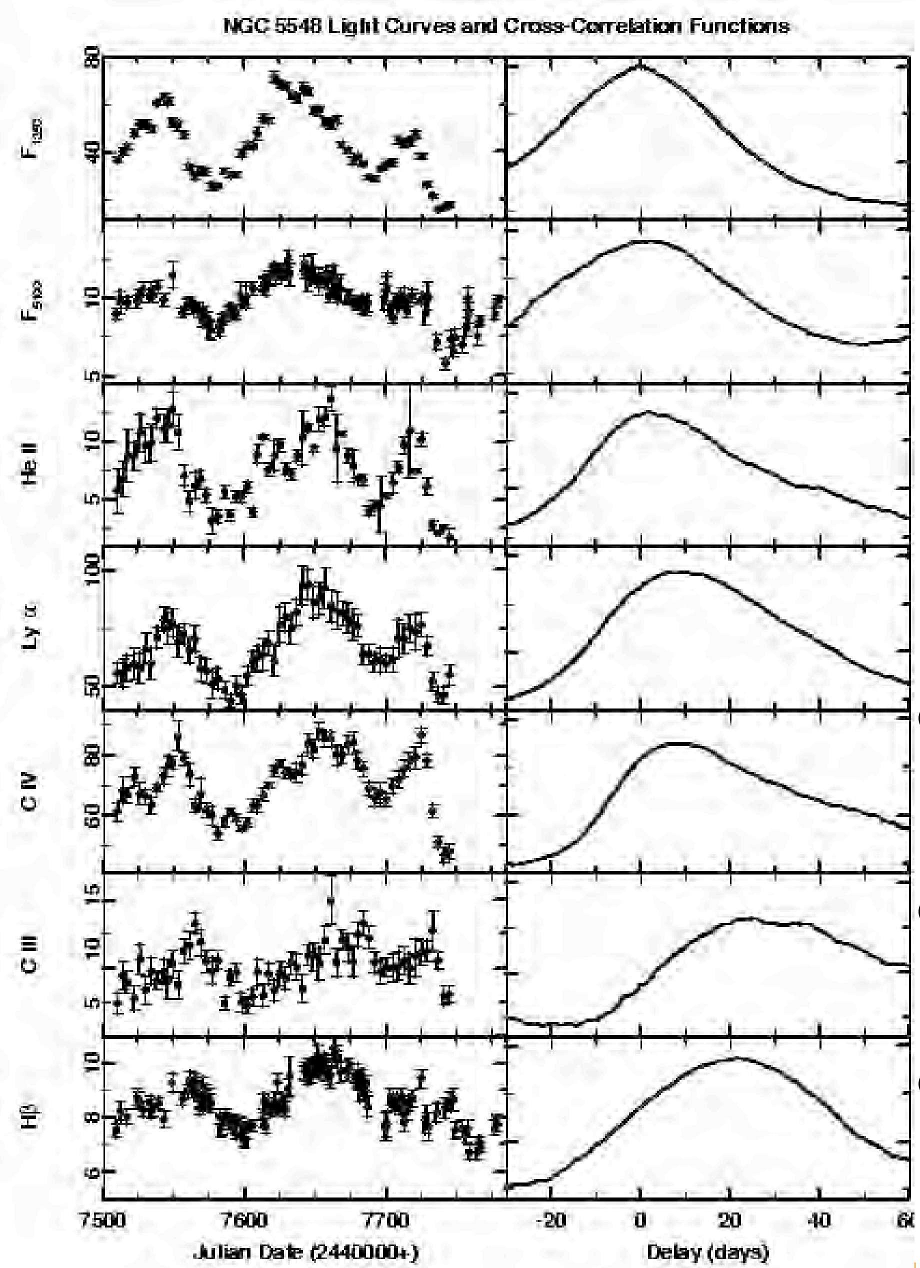
↓

BLR 'radius'

$$M_{rev} \approx \left(1.45\times10^{5} M_{Sun}\right)\left(\frac{c\tau_{BLR}}{1 lightday}\right)\left(\frac{FWHM}{1000 kms^{-1}}\right)$$

Virial mass

Peterson & Wandel (1999)



Reverberation Mapping Results

The relationship between the continuum and emission can be taken to be:

$$L(V,t) = \int \Psi(V,\tau)\, C(t-\tau)\, d\tau$$

Velocity-resolved emission-line light curve | "Velocity-delay map" | Continuum light curve

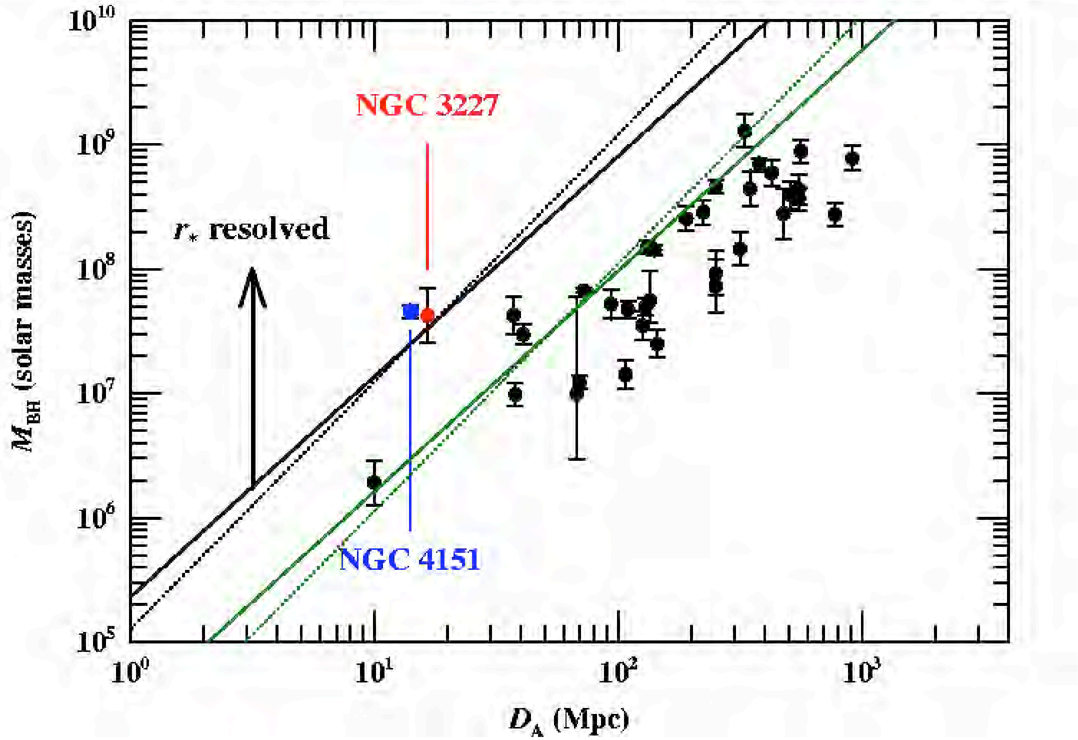
Kinematics & geometry of BLR can be tightly constrained by measuring the emission-line response to continuum variations-2D Transfer function

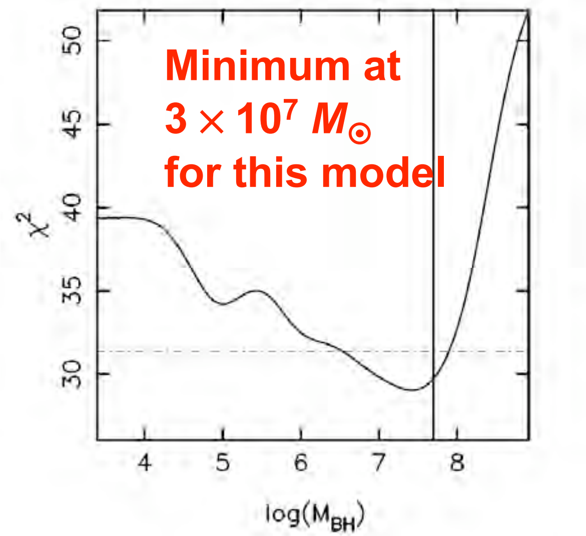
- most common to determine the cross-correlation function and obtain the "lag" (mean response time):
- Reverberation lags have been measured for 36 AGNs, mostly for Hβ, but in some cases for multiple lines.
- AGNs with lags for multiple lines show that highest ionization emission lines respond most rapidly ⇒ ionization stratification

Credit:Brad Peterson

Measuring AGN Black Hole Masses from Stellar Dynamics

Only two reverberation-mapped AGNs are close enough to resolve their black hole radius of influence $r_* = GM_{BH}/\sigma_*^2$ with diffraction-limited telescopes.





NGC 3227

Stellar dynamics $(7 - 20) \times 10^6 M_\odot$ (Davies et al. 2006)

Reverberation-based mass $(42 \pm 21) \times 10^6 M_\odot$ Peterson et al. 2004)

NGC4151

Stellar dynamics: $\leq 70 \times 10^6 M_\odot$ (Onken et al 2007

Highly uncertain- needs IFU Data

Reverberation: $(46 \pm 5) \times 10^6 M_\odot$ (Bentz et al. 2006)

Credit:Brad Peterson

SINFONI Study of gas in the Reverberation Mapped Galaxy NGC4593

Pastorini et al, 2007b $H_2 \ \lambda 2.1218\mu m$

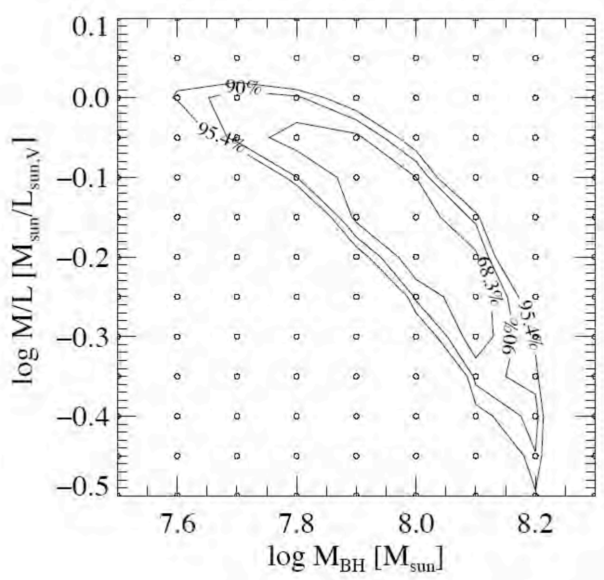
Two cubes

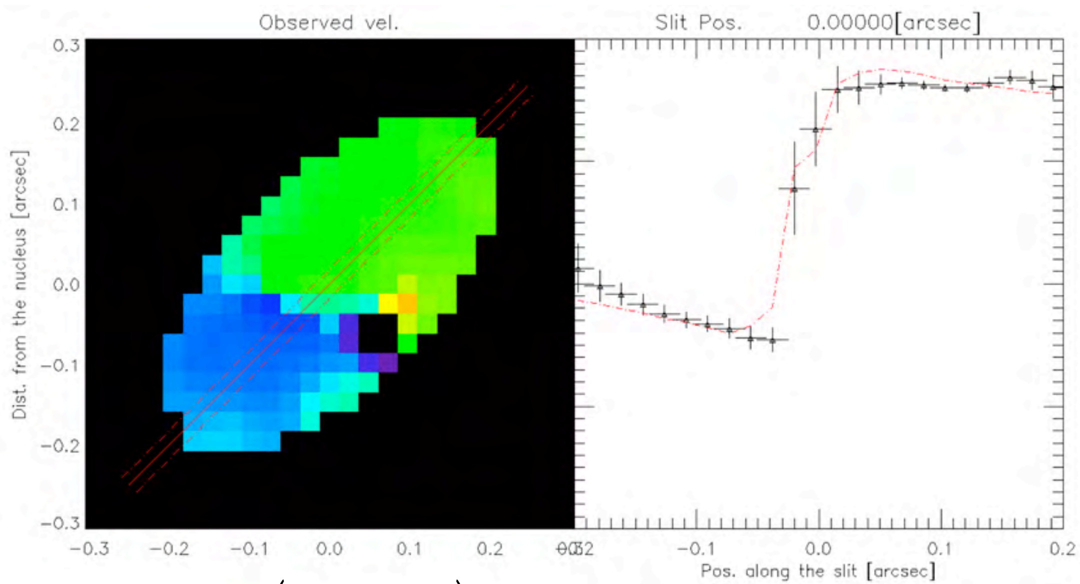
Natural Seeing – 2 arcsec

0.125×0.25 spatial resolution

AO – 0.2 arcsec

0.0125×0.025 spatial resolution





$$M_{BH}\left(SINFONI\right) = 7.08^{+5.82}_{-1.46} \times 10^{7} M_{\odot} \left(i = 36^{0}\right)$$

$$M_{BH}\left(Reverberation\right) = 9.8 \pm 2.1 \times 10^{6} M_{\odot} \left(\text{Delaney et al}\right)$$

Evidence That Reverberation-Based Masses Are Reliable

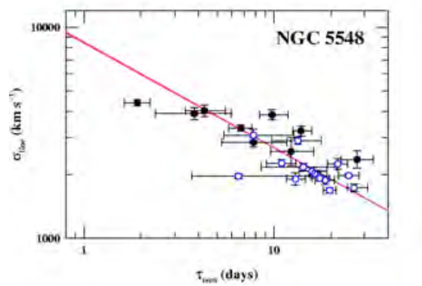
1. Virial relationship for emission-line lags (BLR radius) and line widths

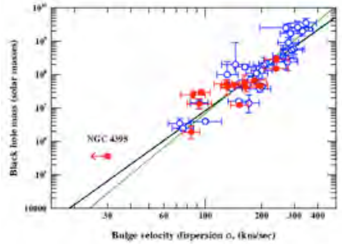
   $\Delta V \propto R^{-1/2}$

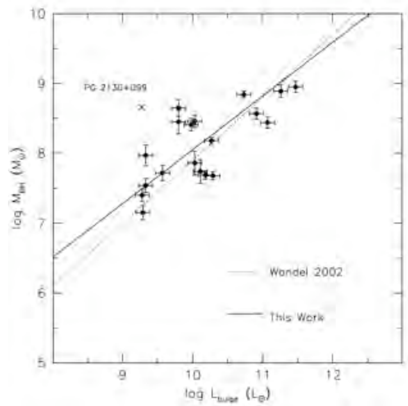
2. $M_{BH} - \sigma_*$ relationship

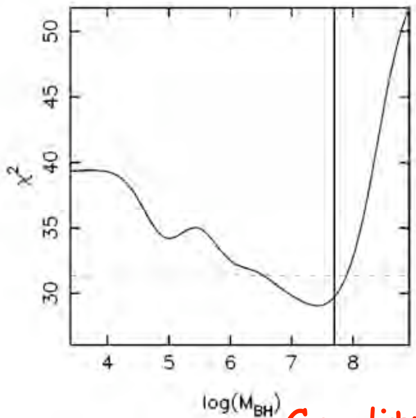
3. $M_{BH} - L_{bulge}$ relationship

4. Direct comparisons with other methods:
   - Stellar dynamical masses
     In the cases of
     NGC 3227
     and NGC 4151
   - Gas Dynamics
     NGC4593









Credit:Brad Peterson

The value of Integral Field Spectroscopy for SMBH mass estimates

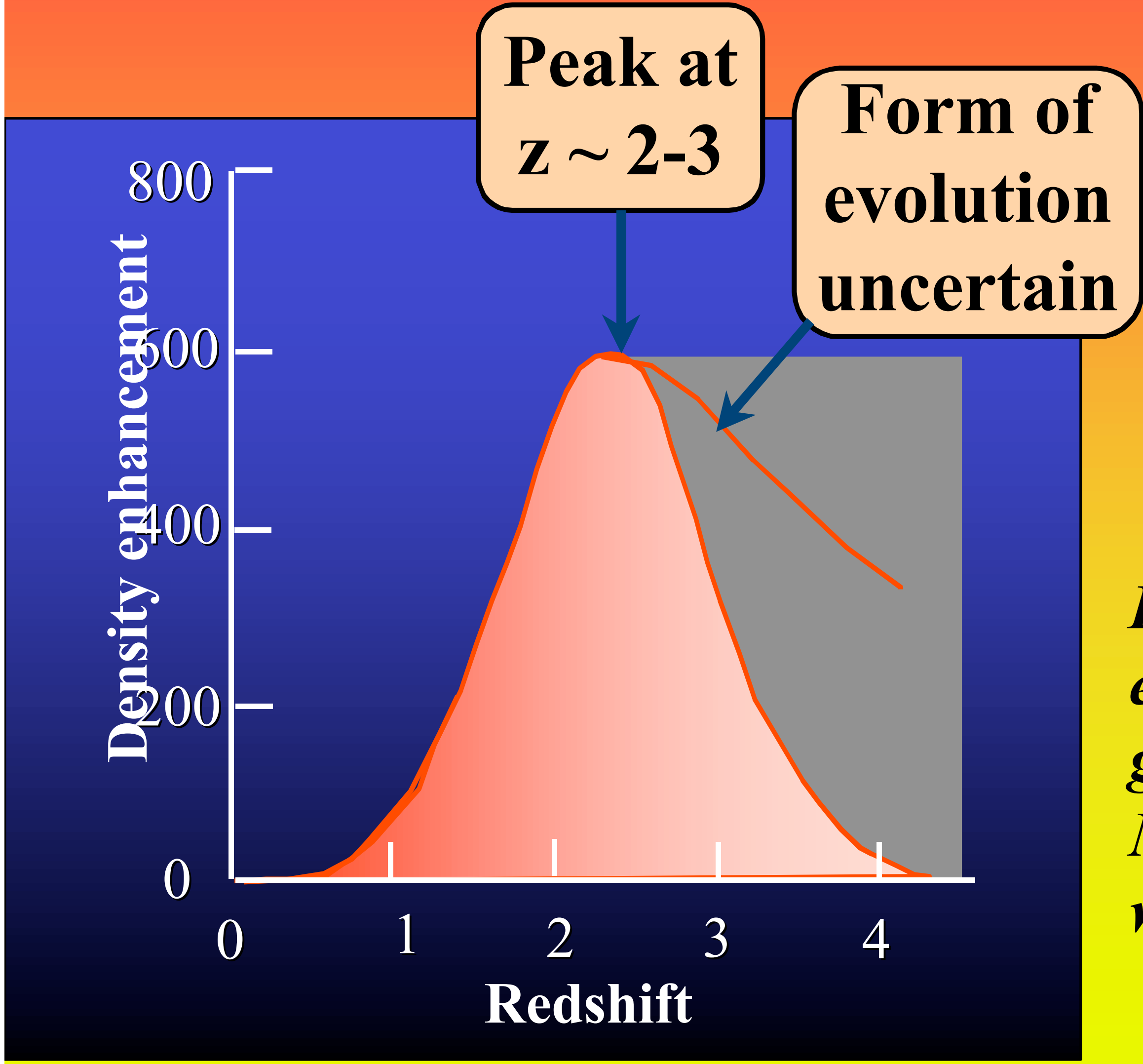
- High spatial resolution needed - to avoid all the nasty complication ideally need to resolve the sphere of influence - not achieved for spirals or most ellipticals studied so far
- Need High S/N - a significant problem for HST stellar dynamical studies (de Zeeuw, yesterday)
- IFU Data important for both gas and stellar dynamical methods
- - IFU is capable of producing measures of sigmaacross any chosen aperture
- - IFS provides an enormous number of dynamical data points to tightly constrain mass models
- Can make good progress by combining HST+IFU especially with AO
- Combine gas and stellar dynamical methods when possible

Conclusions

- Number of secure M_{BH} measurements from both gas and stars in ellipticals
- But issues for both methods- how good are the error bars?
- Gas certainly **sometimes** shows non-gravitational contributions
  - Complex motions seen on larger scale - the fueling chain even in M87
  - Gas warps important
  - Jet-cloud interactions due corrupt data in some places
- But there are radio galaxies in which σ_{gas} and v_{gas} well explained by unresolved rotation alone e.g M87, Cen A.

R·I·T

How has the Black Hole Distribution Changed with Time?



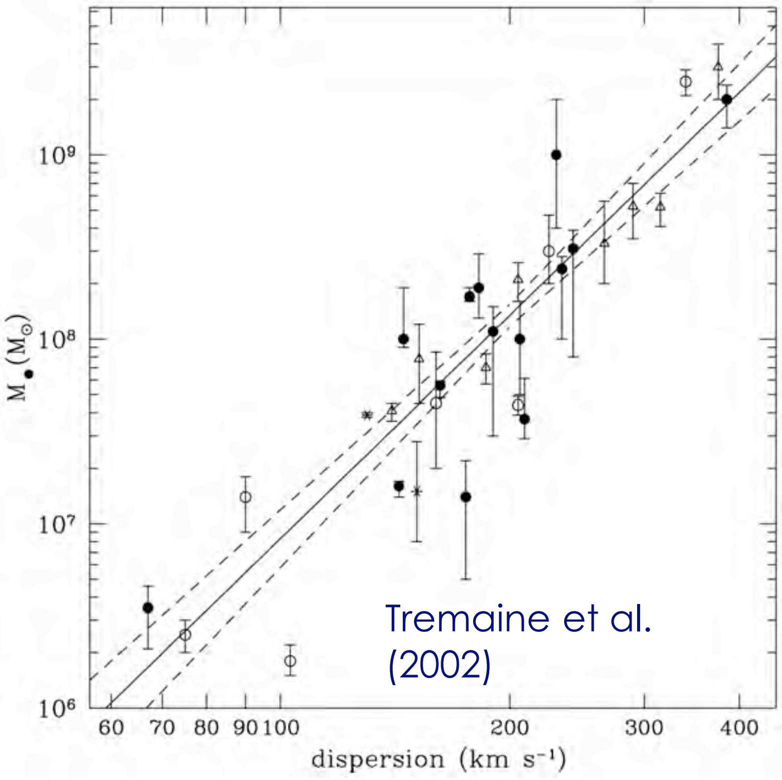
Radio galaxies, quasars and all types of active galaxy were much more common at large redshifts than they are in our locality.

If MBHs are the "central engine" of active galaxies, how does the MBH distribution change with redshift?

Local Scaling Relations

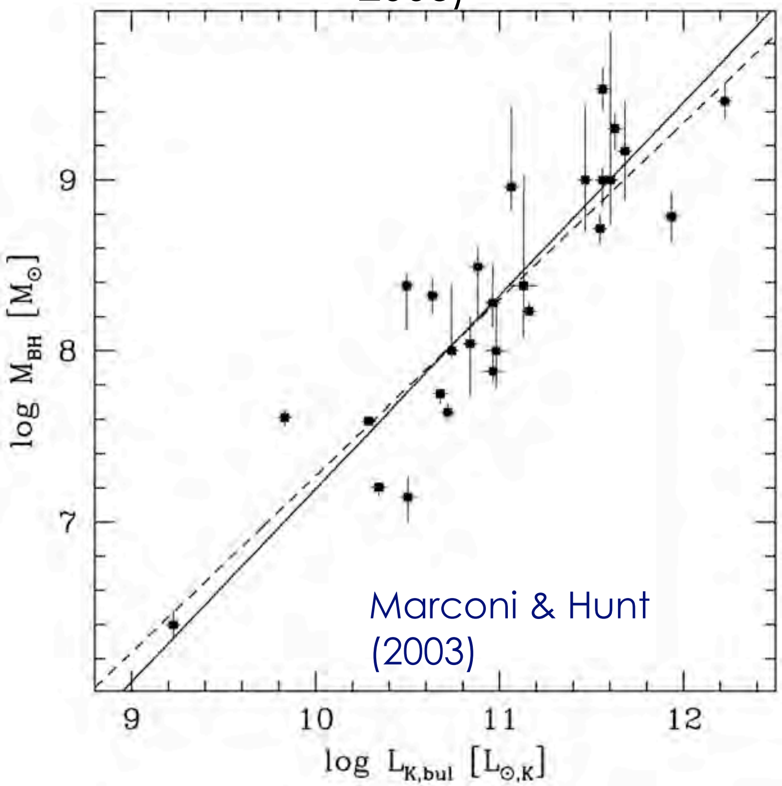
M_{BH}- σ relation

(Ferraresse et al. 2000; Gebhardt et al. 2000)

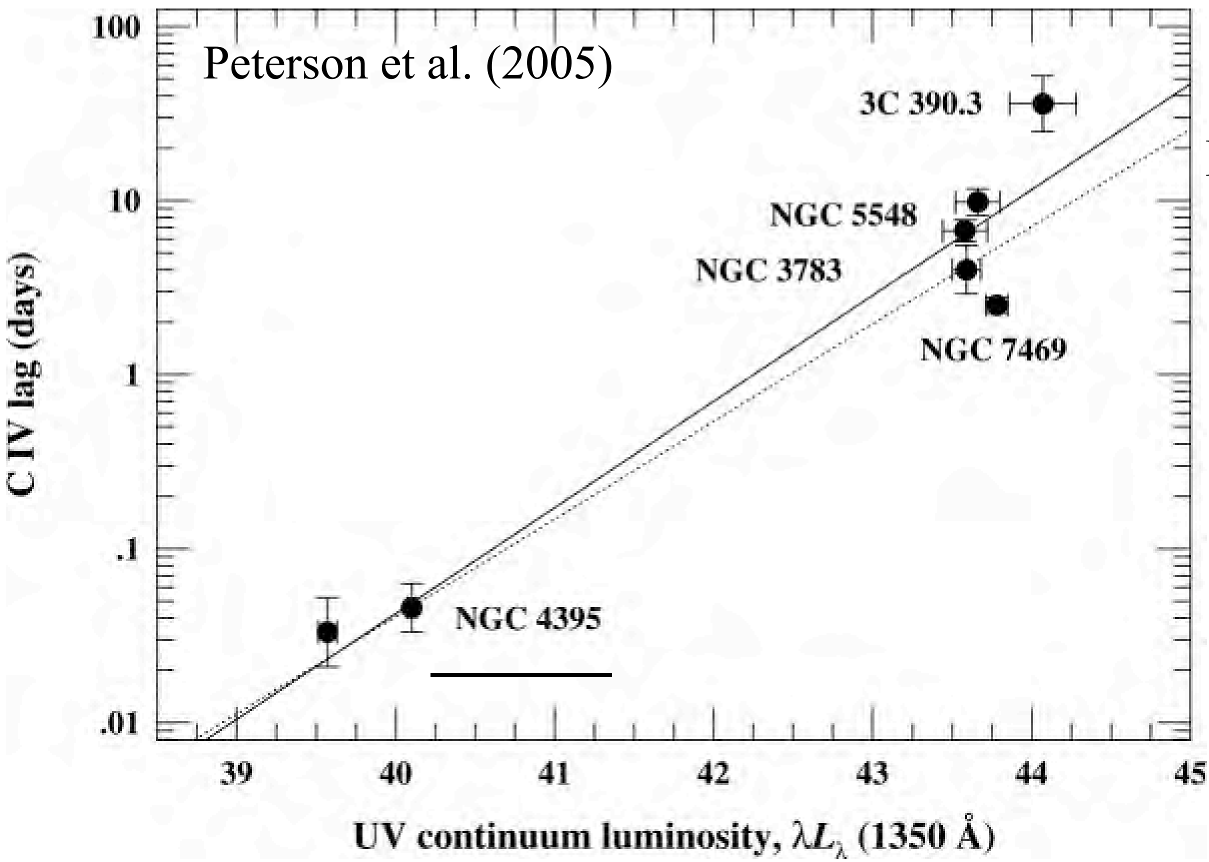


M_{BH} – L_{bulge} relation

(Magorrian et al. 1998; Marconi & Hunt 2003)



The R_{BLR} vs. L Relation for C IV



+ Kaspi et al. (2006)

Broad-line width *V* & size scaling with luminosity

$R \propto L^{1/2} \Rightarrow M_{BH}$

$R_{BLR} \propto L^{1/2}$ established over a range of **~10⁶**(!) in L

- UV varies more than optical
- $\tau \propto L_{opt}^{0.9} \propto (L_{UV}^{0.56})^{0.9} \propto L_{UV}^{0.5}$

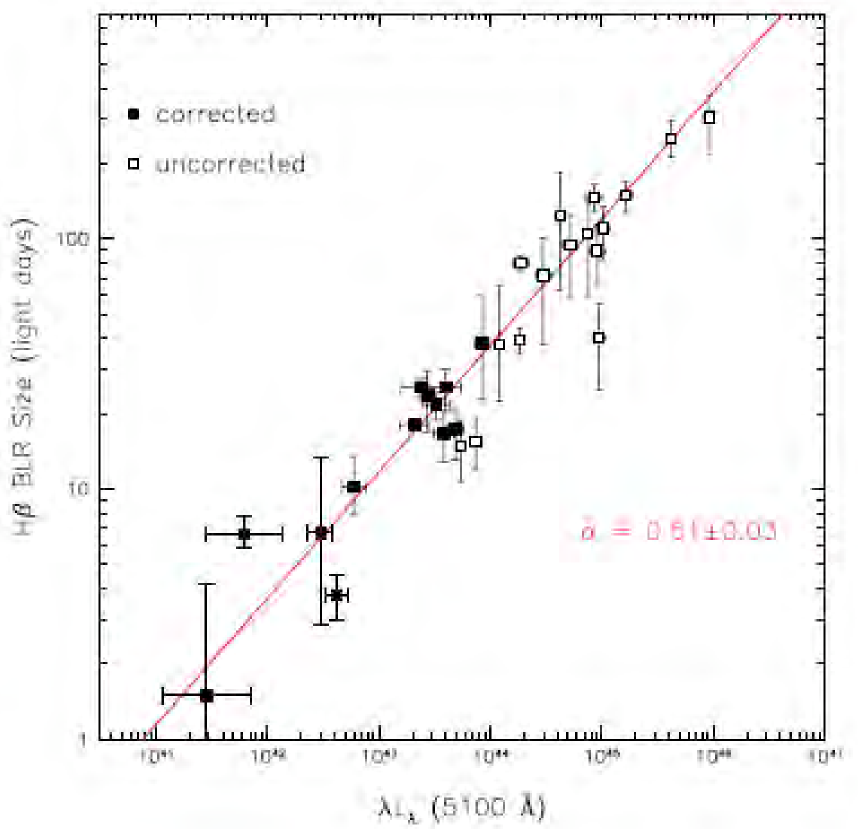
Estimating Black Hole Masses from Individual Spectra

Correlation between BLR radius R (= $c\tau_{cent}$) and luminosity L allows estimate of black hole mass by measuring line width and luminosity only:

$$M = f\,(c\tau_{cent}\,\sigma_{line}^2\,/G) \propto f\,L^{1/2}\,\sigma_{line}^2$$

Dangers:

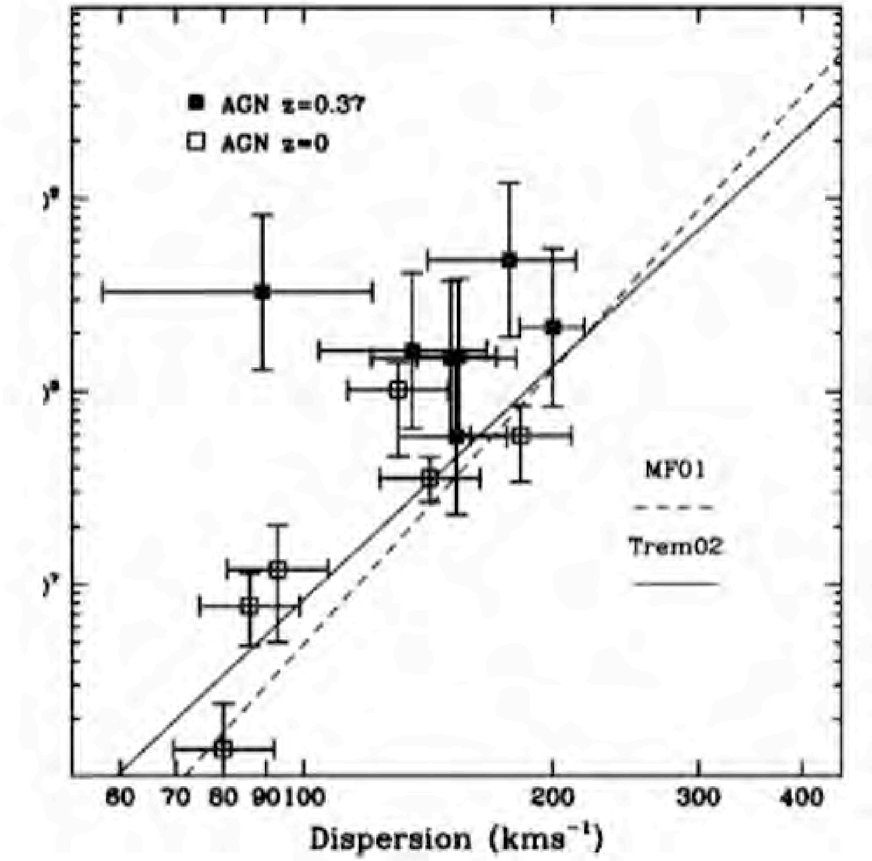
- blending (incl. narrow lines)
- using inappropriate f
  - *Typically, the variable part of Hβ is 20% narrower than the whole line*



Credit: Brad Peterson

Evolution with Z?

- Study M_{BH} – σ_* relationship (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002): $M_{BH} = (10^{8.13} M_\odot)(\sigma_*/200)^{4.02}$



Treu, Malkan, Blandford

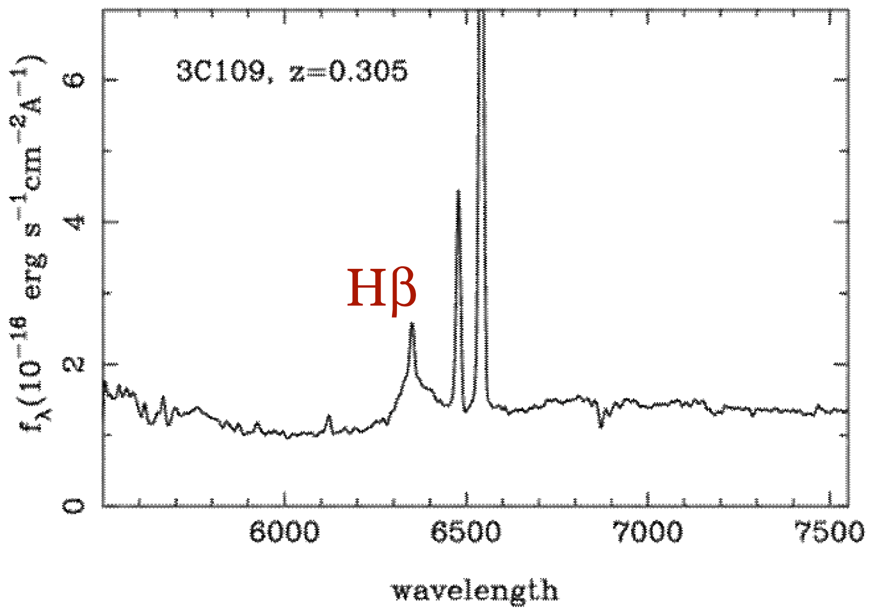
- OTHER GROUPS: Width of [O III] λ5007 line is indicator of σ (Nelson & Whittle 1996, Nelson 2000, Boroson 2003, Bonning et al. 2005): σ_* = FWHM of [O III] / 2.35. Needs confirmation for luminous QSOs.

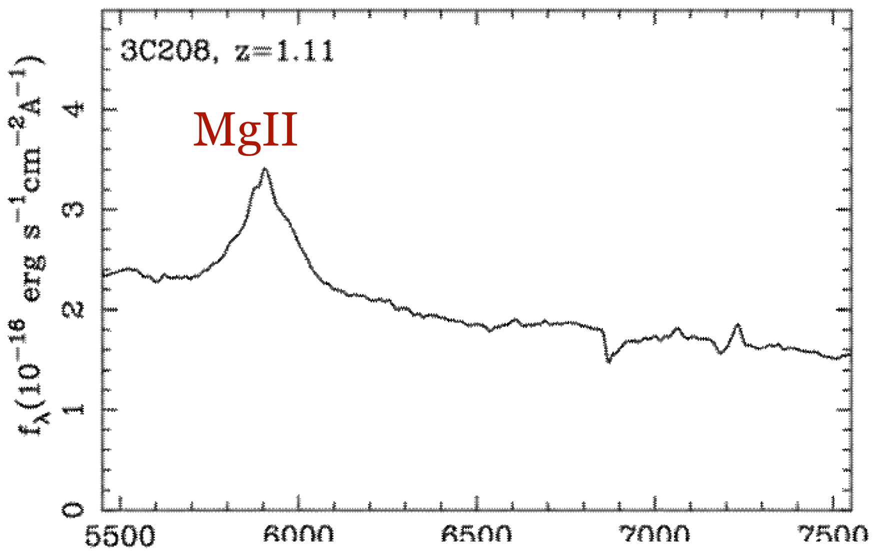
Black-hole mass: the 3CRR quasar sample

- Reverberation mapping gives BLR radius, scales as $R \propto L^{0.5}$ to $L^{0.7}$ (e.g., Kaspi et al. 2000, 2005; Bentz et al. 2006)
- Width of Hβ, Mg II, C IV gives $M_{BH} = (10^{7.69} M_{\odot}) v_{3000}^{2} L_{44}^{0.5}$

Issues about changing horses- Balmer lines at low Z-MgII at intermediate z -CIV at high z

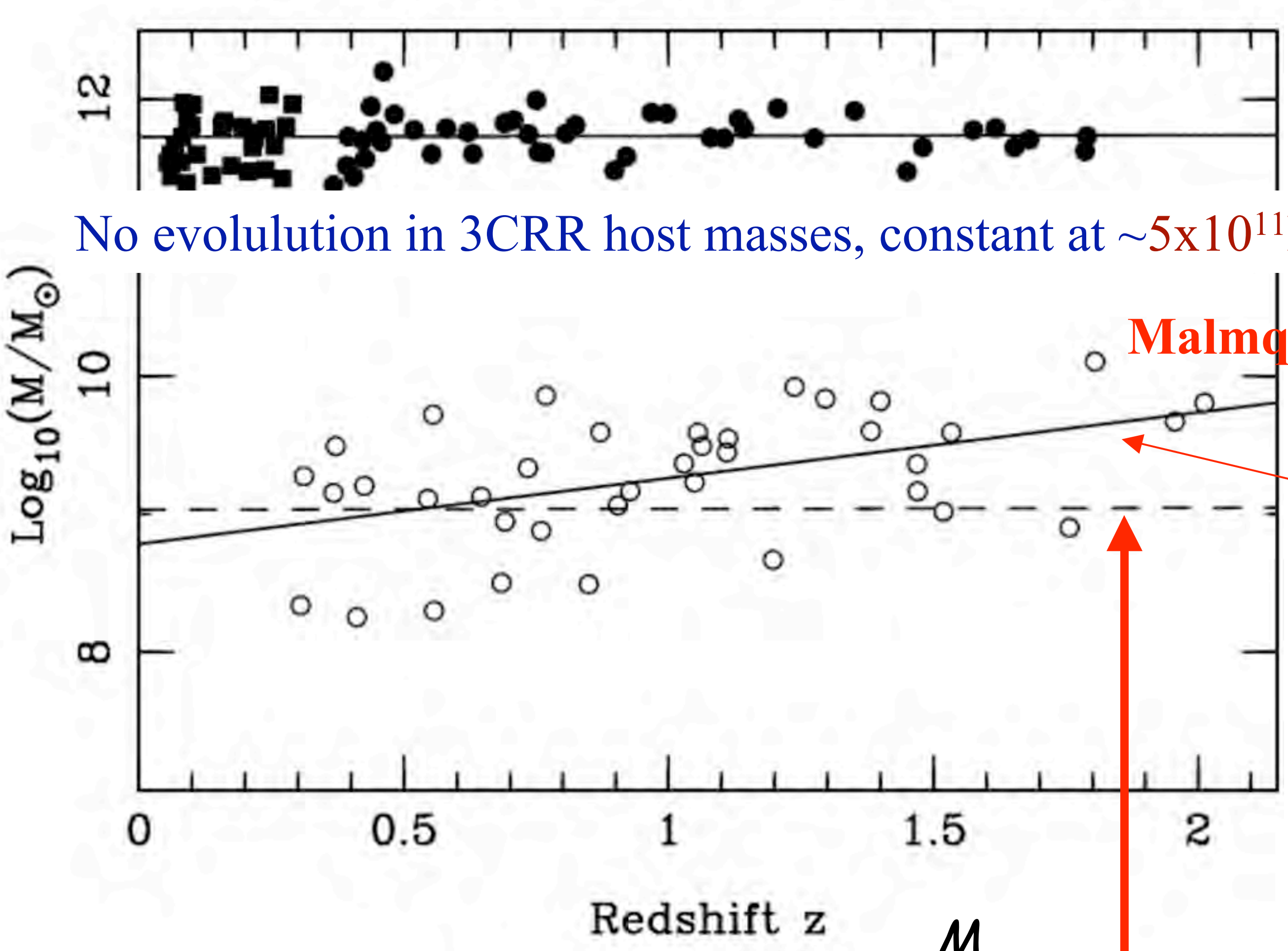
virial black-hole mass estimates for 38/40 3CRR quasars in the redshift interval 0<z<2





McLure et al. 2006, MNRAS, 368, 1395

Tracing the evolution of the M_{bh}:M_{sph} relation



No evolulution in 3CRR host masses, constant at ~$5\times10^{11} M_\odot$

(c.f. Best et al. 1998; Rocca-Volmerange et al. 2004)

Malmquist bias?

$$\frac{M_{BH}}{M_{SPH}} \propto (1+z)^{2.1\pm0.7}$$

Expected M_{bh}-z relation if $\frac{M_{BH}}{M_{SPH}} = 0.002$

Evolution of the black-hole masses significant at the ~3σ level

McLure et al. 2006, MNRAS, 368, 1395

Determining M_{BH} beyond the local universe

- Peak of quasar activity occurs at z = 2.5 - 3 & coincides with the time when the first deep potential wells assemble in plausible variants of hierarchical CDM models.
- 1) Black hole mass: CANNOT resolve the sphere of influence (0.1″ at z=1 is ~0.8 kpc)
- Scaling relationships based on virial relationship ($R_{BLR} \propto L$ (5100Å)$^{0.50}$ $M_{BH} \propto FWHM^2\, L$) poor surrogates for the real thing!
- Direct measurements of M_{BH} at z ~2. provides key to understanding these processes. Reverberation Mapping only possibility to directly measure black hole masses at this redshift.
- Enables linking of formation of the central black holes with dark matter halos in which the host galaxies assemble.
- Key objectives
  - Place constraints on accretion rates → important implications for MBH formation timescale
  - Comparison of BH masses with those in nearby galaxies → constrain possible evolutionary paths for quasars .

Collaborators: Marconi, Merritt, Capetti, Tadhunter, Maiolino

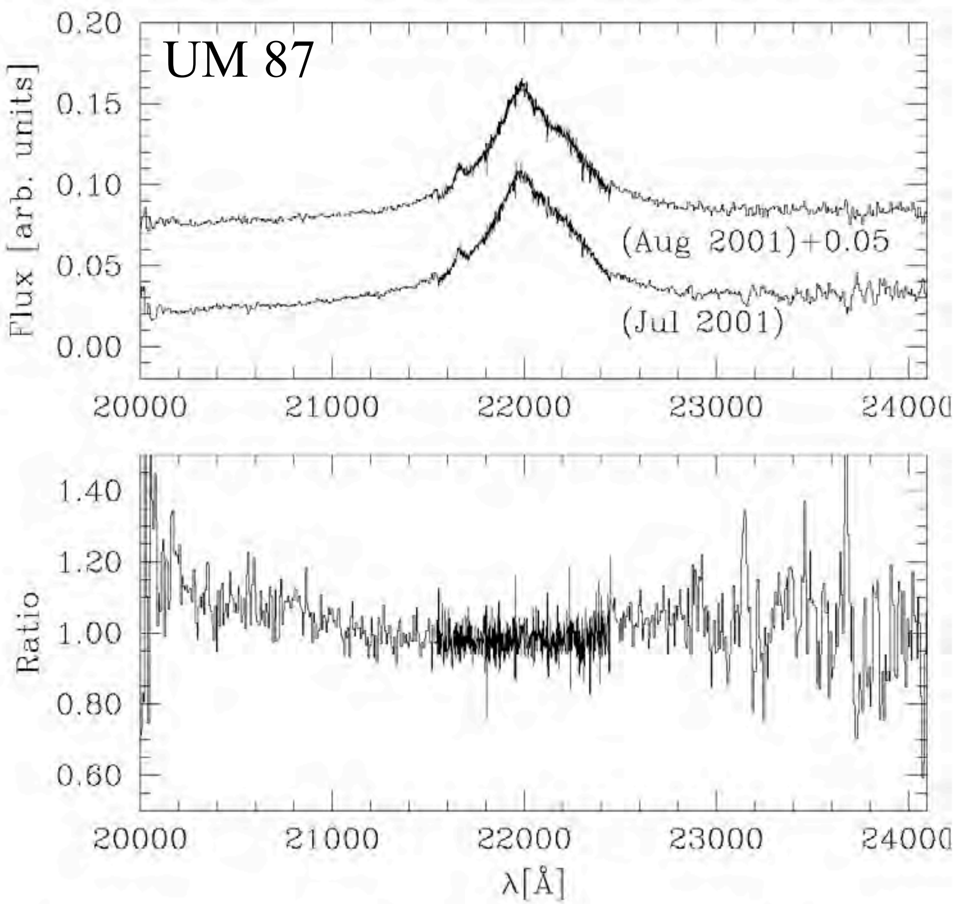
VLT reverberation mapping of QSO's at z ~2.5

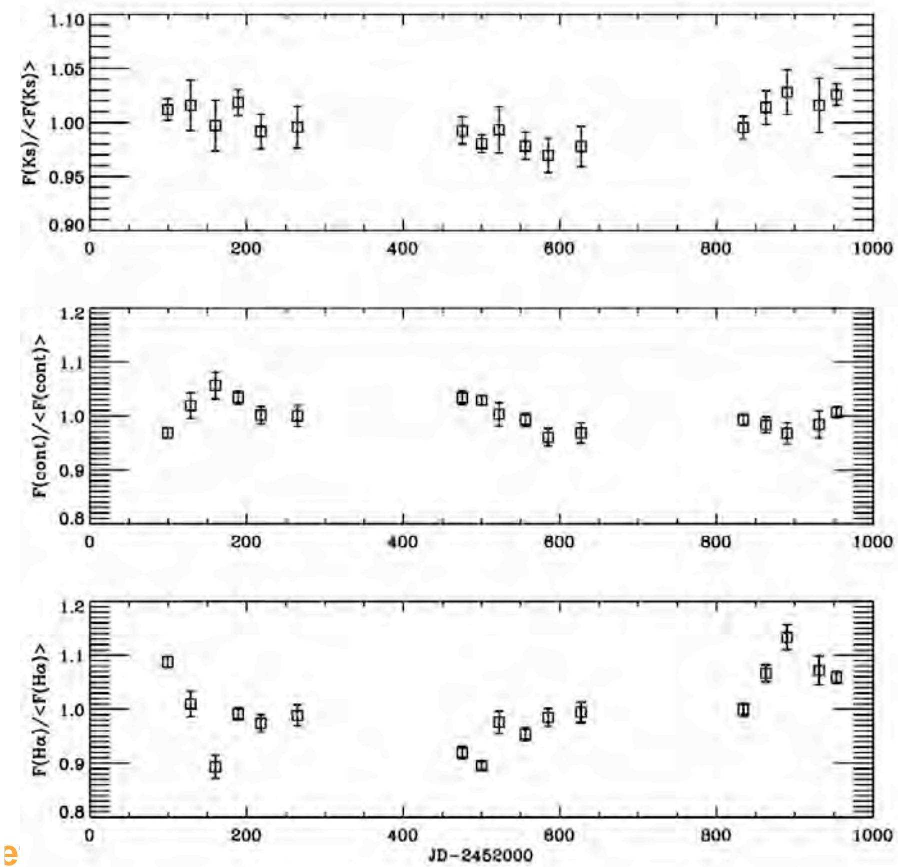
$$BLR\,Lag \simeq 670\ \mathrm{lt\ days}\ \ (1+\mathrm{z})\,\epsilon^{-1}\left(\frac{\mathrm{L}}{10^{46}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{\mathrm{FWHM}}{1000\,\mathrm{km\,s^{-1}}}\right)^{-2}$$

(ε ranging from 1-0.3)

→ z~2.5 observed BLR time lag 360-1200 days

3 years in most favourable case, 6-10 years in most unfavourable case





Theme: Direct Measurement of M_{BH}

Key Results

- oMarconi/Ferrarese
- oLocal M_{BH} - $\sigma(L_{bulge})$ pivotal role in much of contemporary work- (Scaling relations etc)
- oSound meaurements of M_{BH} from both Gas and Stars
- oNear.Mid IR measurements Gas/Stars important both to deal with Obscuration and to probe out in z(Reverberation- RM)

RM: Only way to directly measure M_{BH} beyond local universe

Impact of 8-m with AO/IFU S/N - constraints on M/L

Need 2D tranfer function for even 1 galaxy!

Issues

- oStill relatively few directly measured BH masses
- oStill need to carefully model M/L(R) -
- oAGN cricial if we are to understand M_{BH} host coevolution

Stars:Degeneracy in LOSVD analysis

Cannot be used easily for obscured galaxies and AGN

Disk contributions to σ

Gas Need AGN Lingering worries about NonGrav Motions

Ionized gas and molecular gas can have different Velocity Fields

Critical for M_{BH} - σ

Serious issue

Line emissivity in psf & disk i(r)

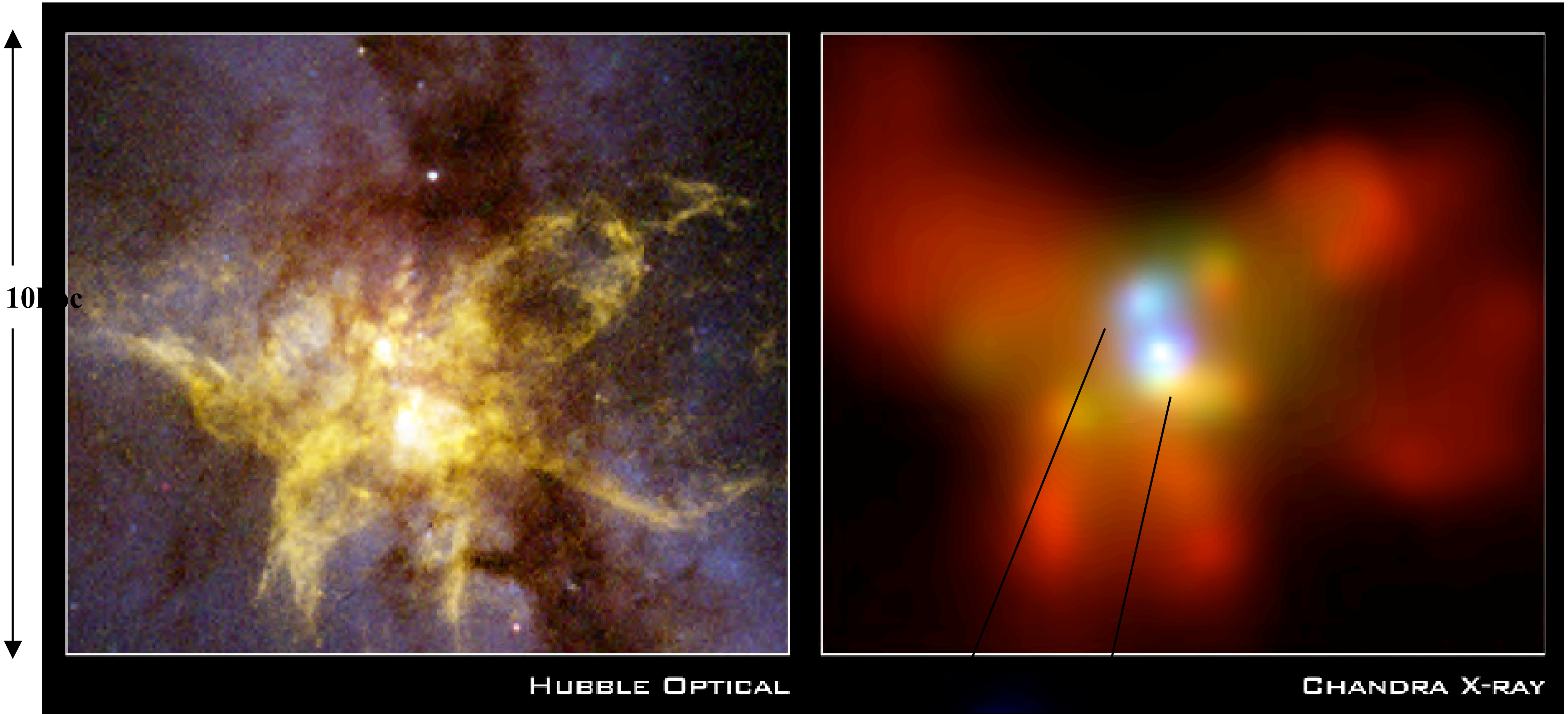
Theme 2: BH growth, Spin Flips & Kicks due to Mergers

- *Do binaries coalesce?*
- What is the spin and mass distribution of astrophysical black holes? *Why?*
- *What is the impact of gravitational-wave recoil?*

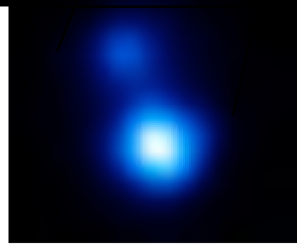
Credit Image:Whitmore

binary black hole system in NGC 6240

z=0.025



Gerssen et al 2004

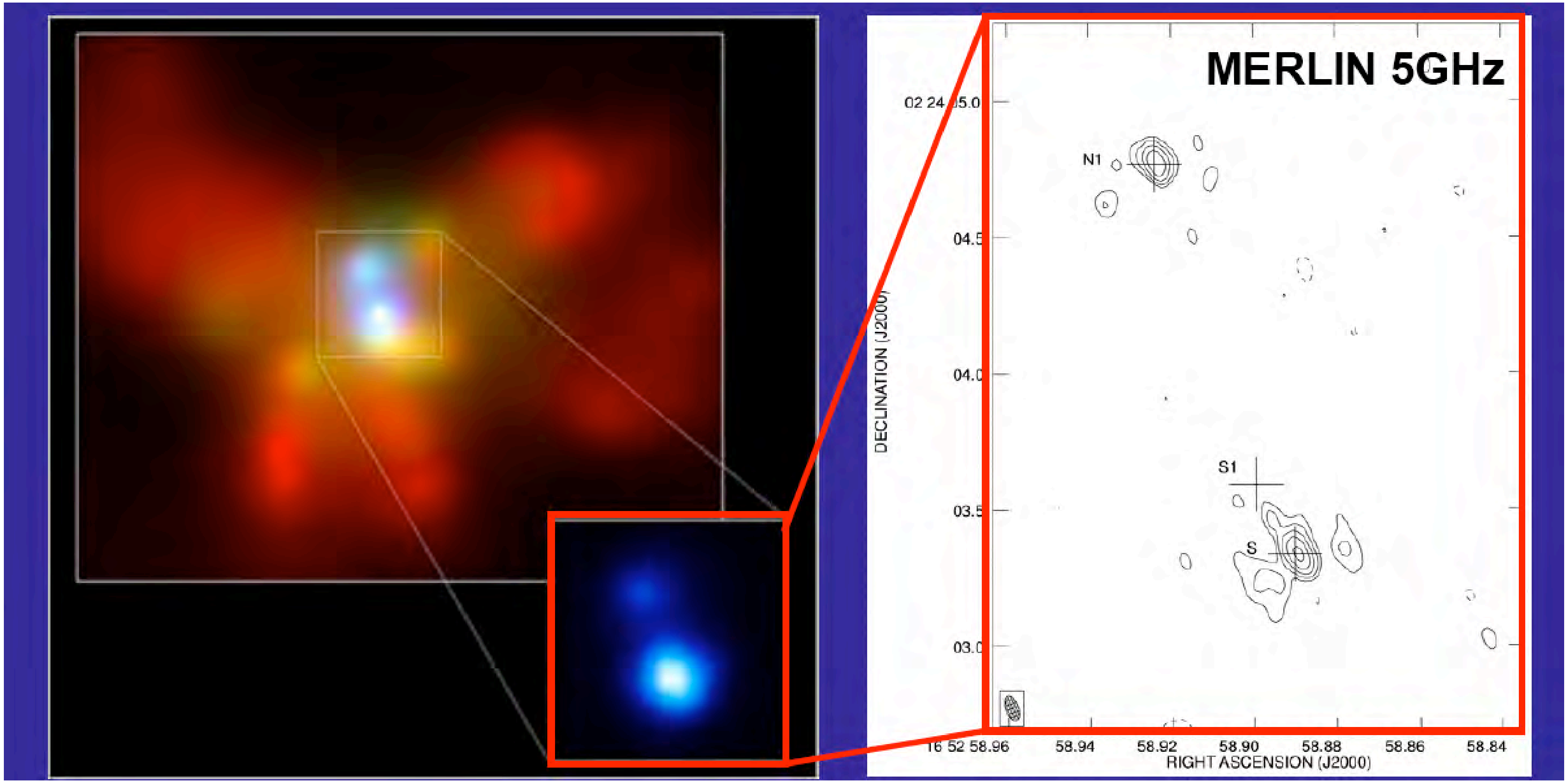


Komossa et al. 2003

NGC6240 2 AGN

X-rays

Radio



(Komossa et al 2003)

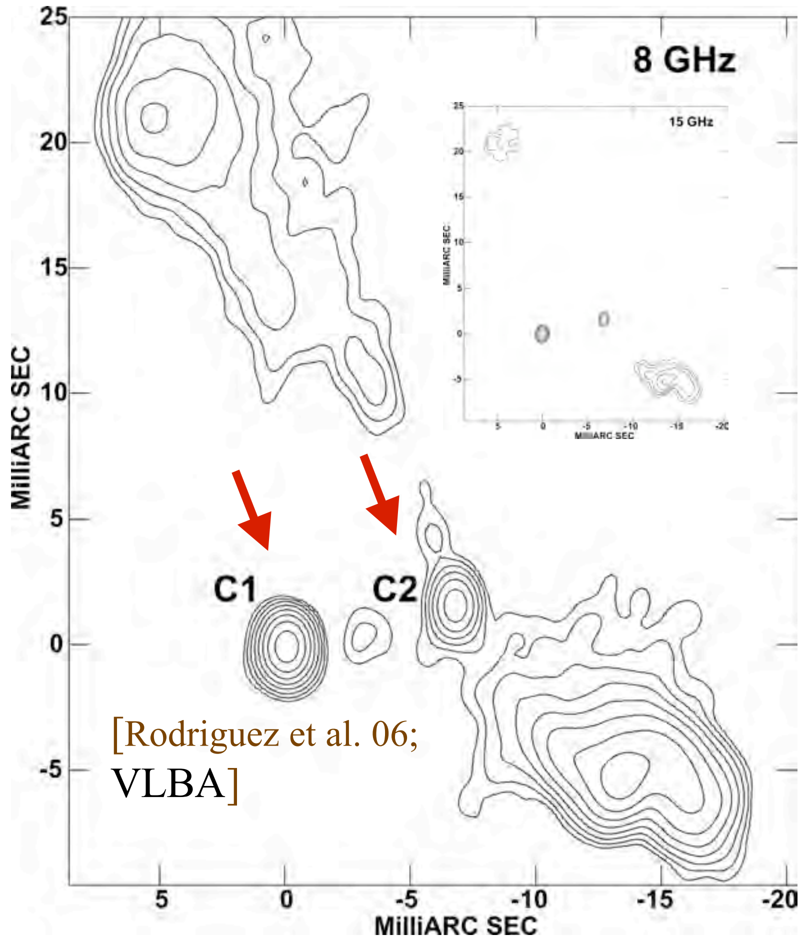
Beswick et al 2001

Gallimore& Beswick2004

obs. of BBHs: *spatially resolved sources*

two radio cores: 0402+379

- nearby radio galaxy (4C37.11) at z=0.06
- **two radio cores** C1,C2
- compact, variable & flat-spectrum
- interpreted as true nuclei rather than knots in jet
- projected separation: 7.3 pc !



[Maness et al. 04, Rodriguez et al. 06,]

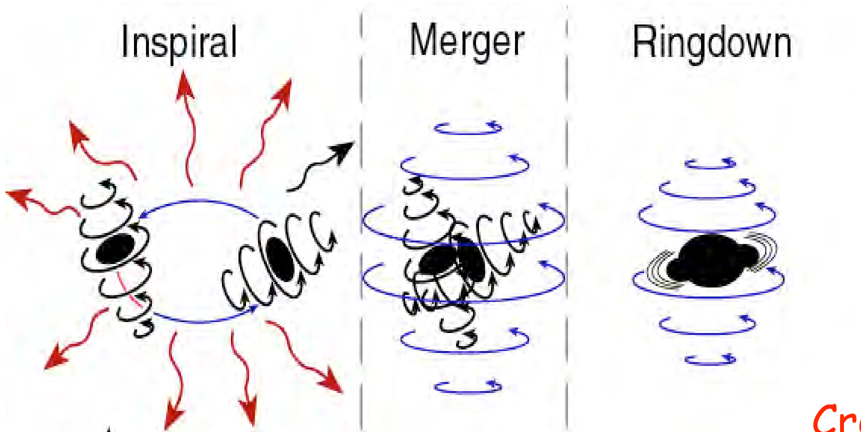
2005: Year of the Breakthrough(s)

Generalized Harmonics

Pretorius, PRL, **95**, 121101 (2005), [gr-qc/0507014]
Followed by Caltech/Cornell/AEI

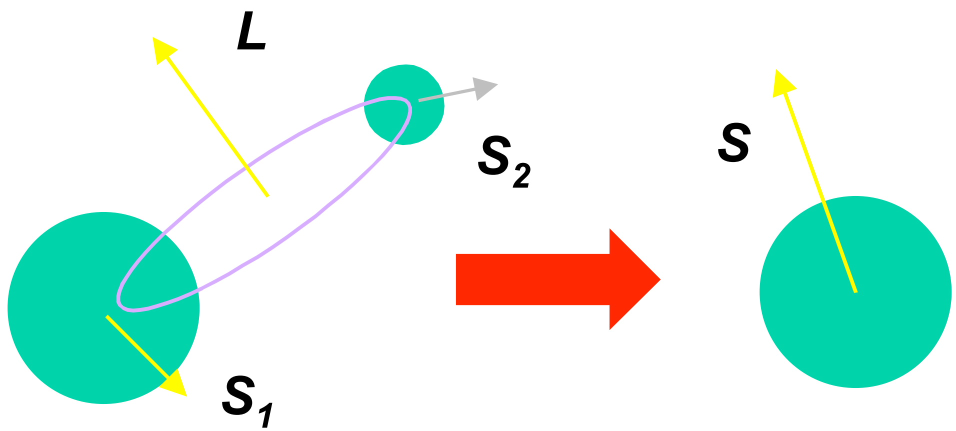
Moving punctures

Campanelli et al., PRL, **96**, 111101 (2006), [gr-qc/0511048]
Baker et al., PRL, **96**, 111102 (2006), [gr-qc/0511103]
Followed by PSU/Jena/FAU/AEI/LSU/
and applied to BH-NS binaries!



Credit:David Merritt

Spin Addition



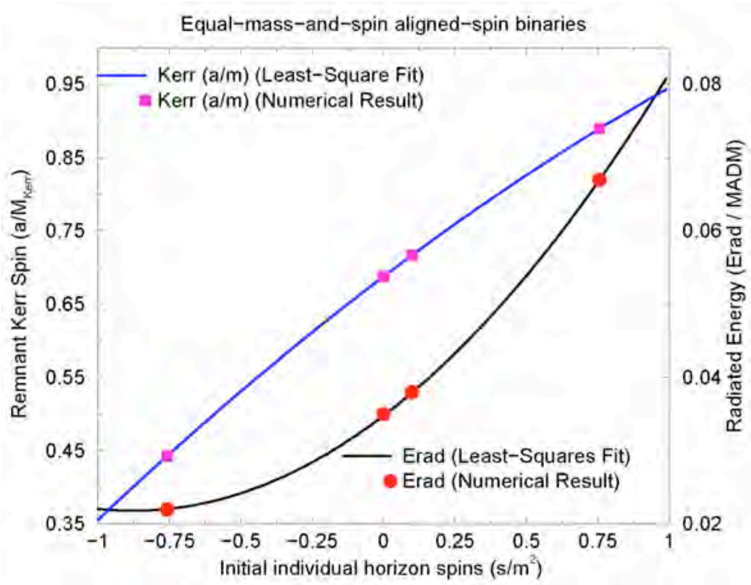
Conservation of angular momentum implies

$\boldsymbol{S}_1 + \boldsymbol{S}_2 + \boldsymbol{L} = \boldsymbol{S} + \boldsymbol{J}_{rad}$.

The final spin ***S*** is typically dominated by ***L***.

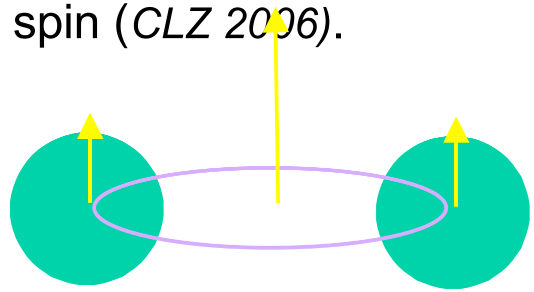
(Campanelli, Lousto, Zlowchower, Krishnan, Merritt2007)

(Hughes & Blandford 2003)



Maximal spin-up appears to be $a/M \approx 0.95$.

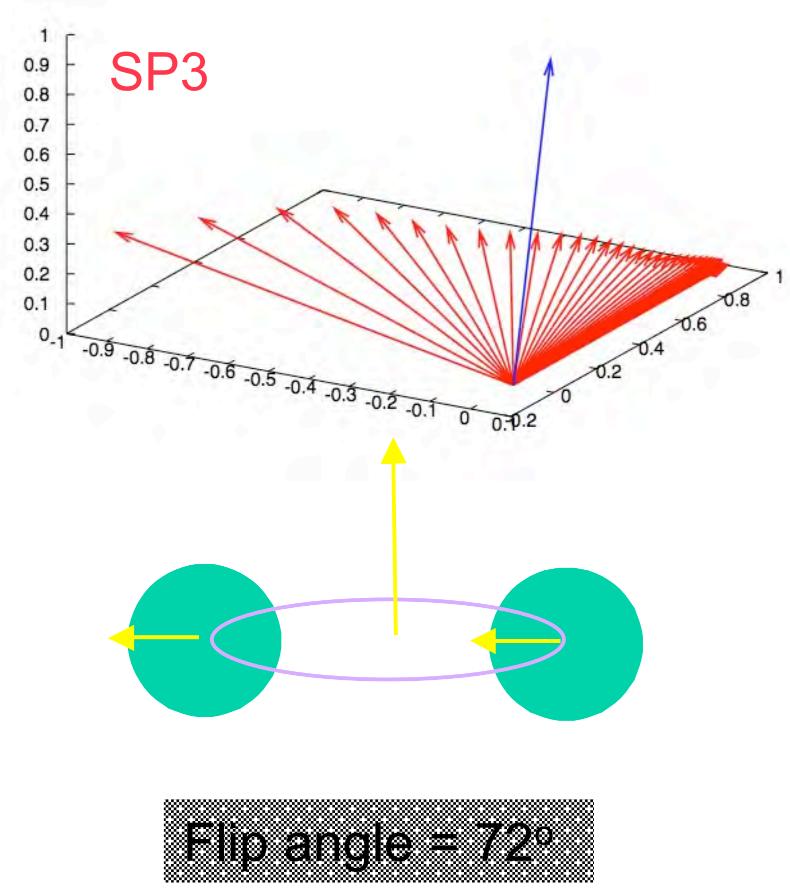
A “hang-up” occurs when spins are aligned, increasing the GW losses and reducing the final spin (*CLZ 2006*).

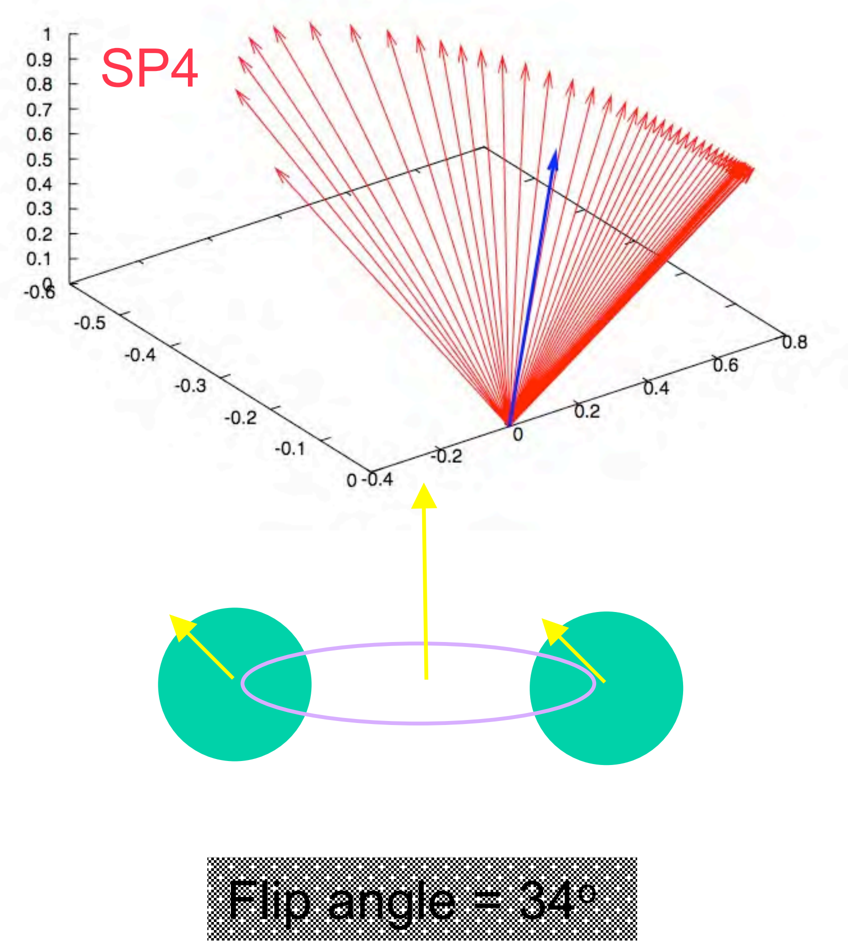


 Credit:David Merritt

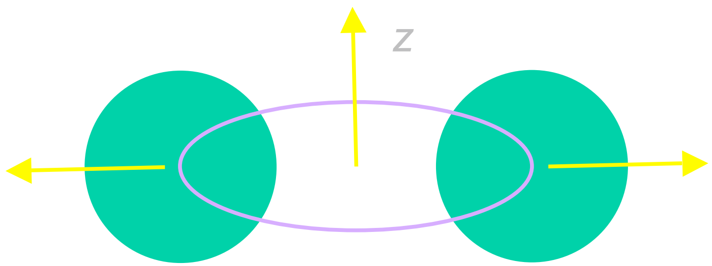
Spin Flips

(CLZKM 2007)





Spin Flips



• Seyfert jet directions show ****no**** correlation with the orientation of the large-scale gas disk.

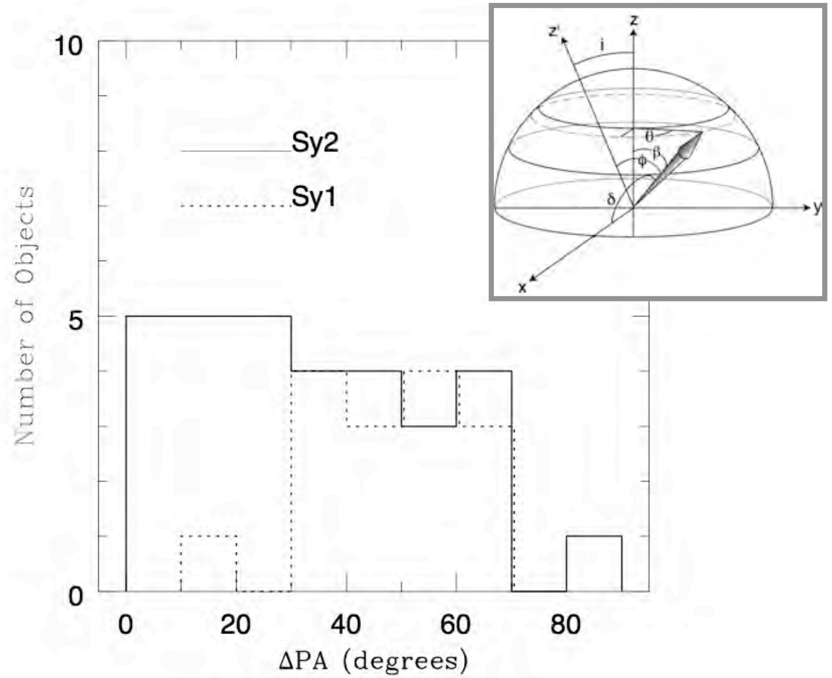
Ulvestad & Wilson (1984)

….

Schmitt et al. (1997)

Kinney et al. (2000)

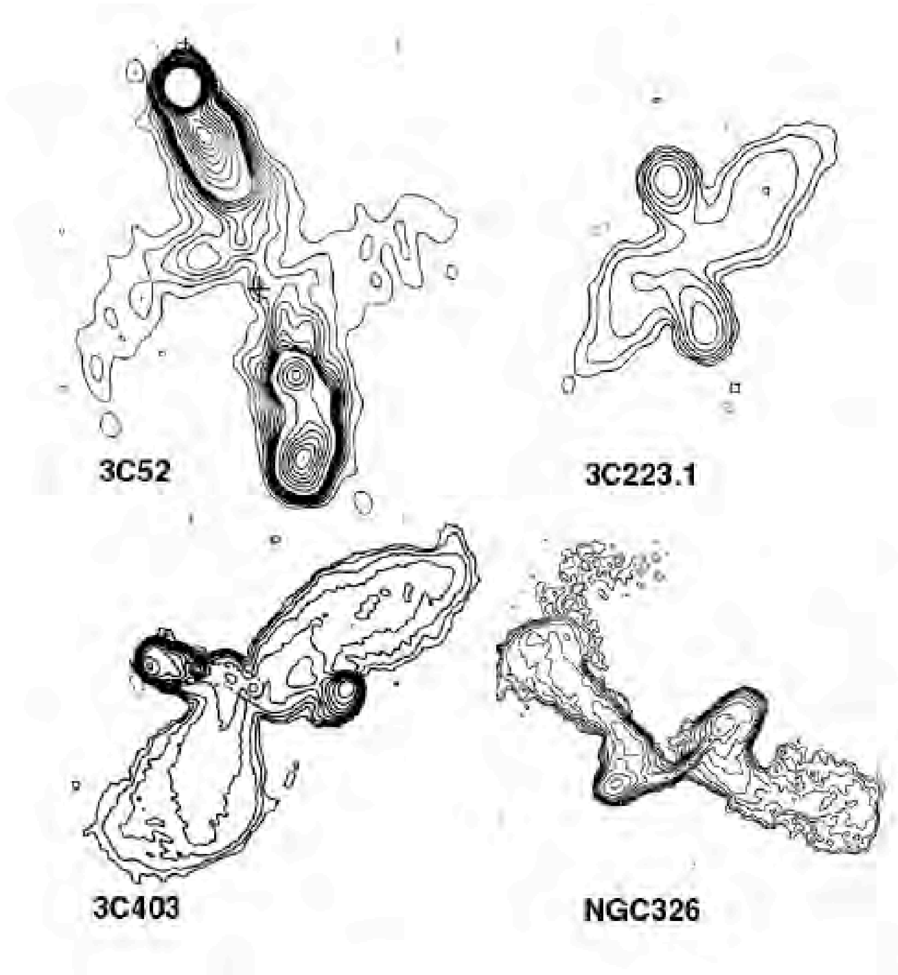
….



Credit:David Merritt

X-shaped Galaxies

- Re-orienting a supermassive black hole via external forces is hard
- -there is almost no way to do it short of absorbing a second supermassive black hole, whose infall imparts angular momentum (spin + orbital) to the larger hole (Merritt & Ekers 2002).

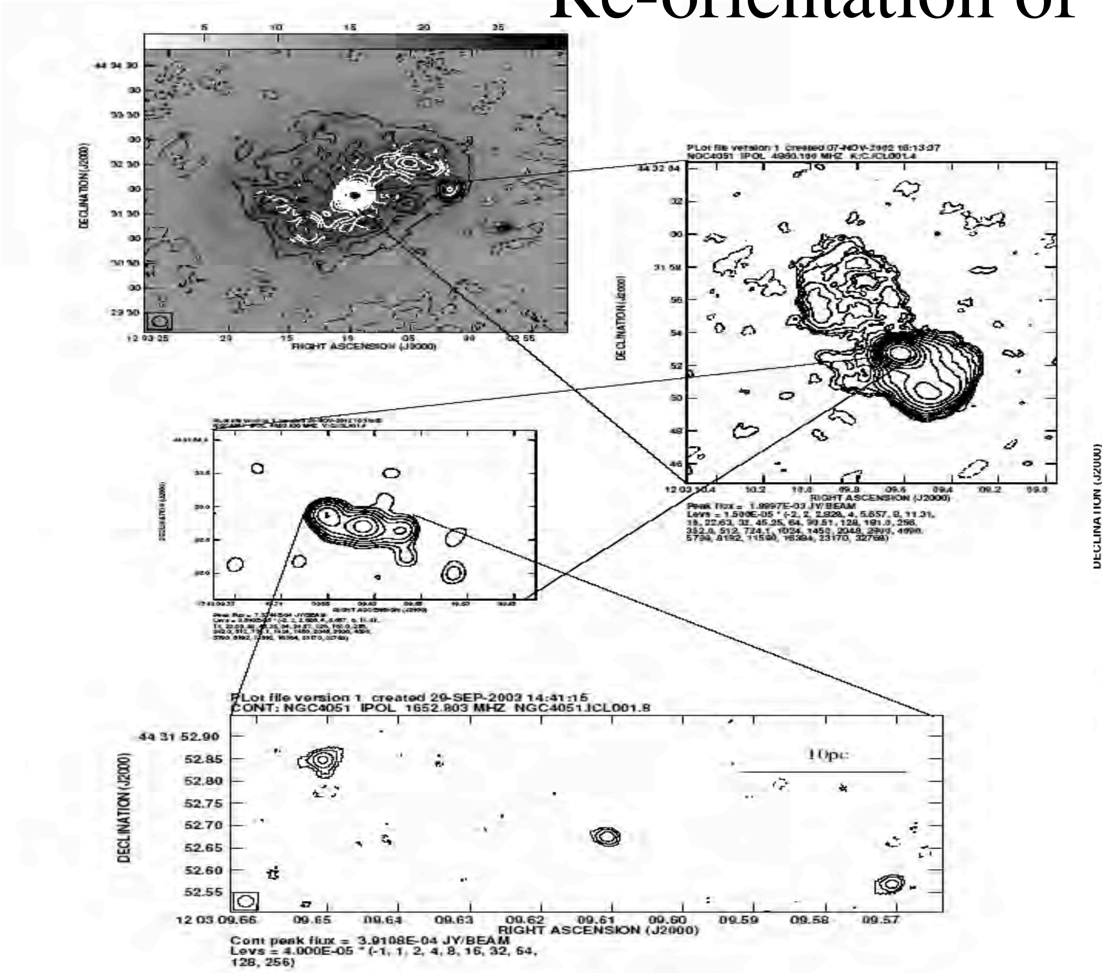


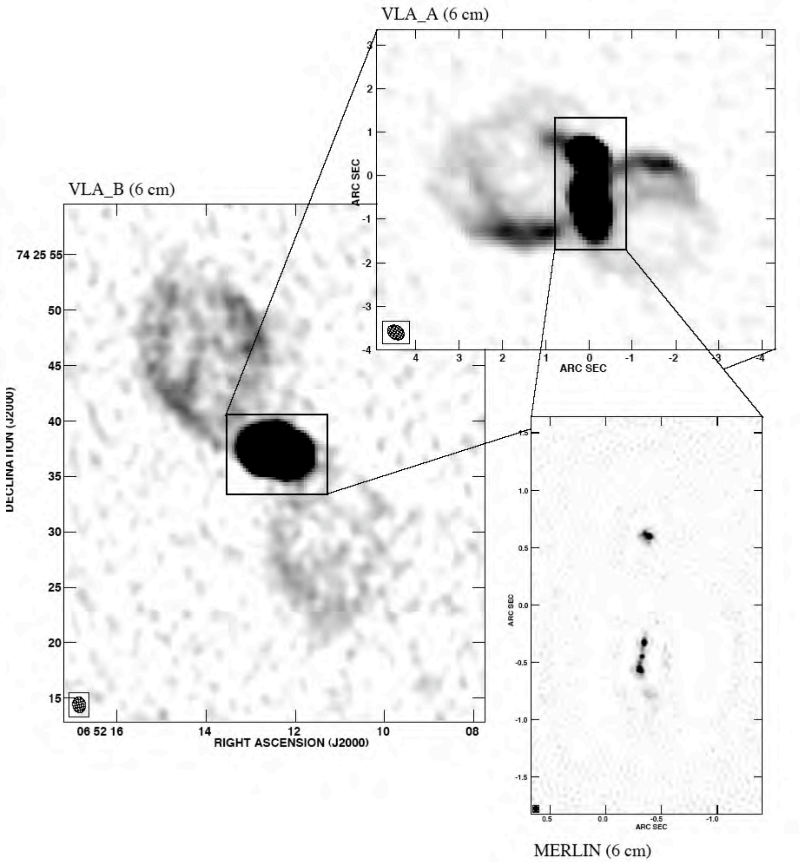
- Dennett-Thorpe et al 2002
- Merritt & Ekers 2002.

R·I·T

Multiple Epoch of Activity in Seyferts

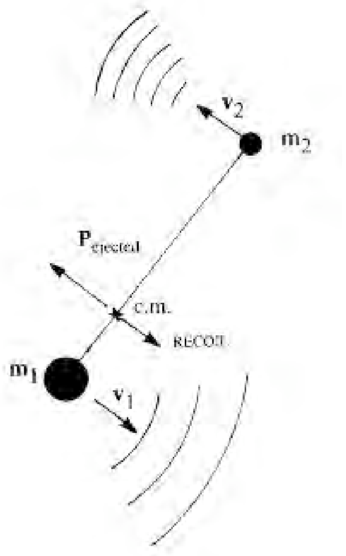
Re-orientation of supermassive black holes





NGC 4051 McHardy, Axon et al in prep
Gallimore et al 2006

Mkn 6 Kukula,Axon et al 1996
Kharb et al 2006

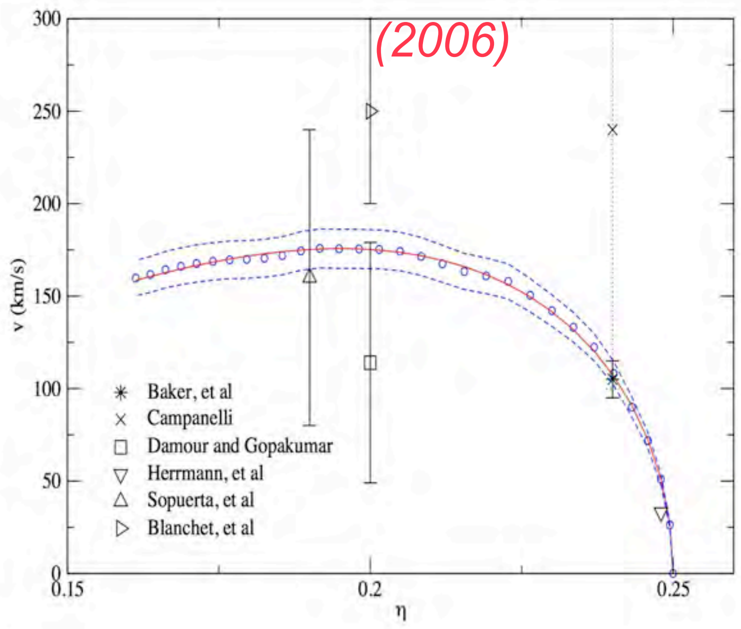


Rocket Effect

Redmount & Rees (1989):

"…recoil speeds hundreds of times larger [than in the non-spinning case], hence larger than galactic escape velocities, might be obtained from the coalescence of rapidly rotating holes…This effect…might be largest for two holes of equal mass"

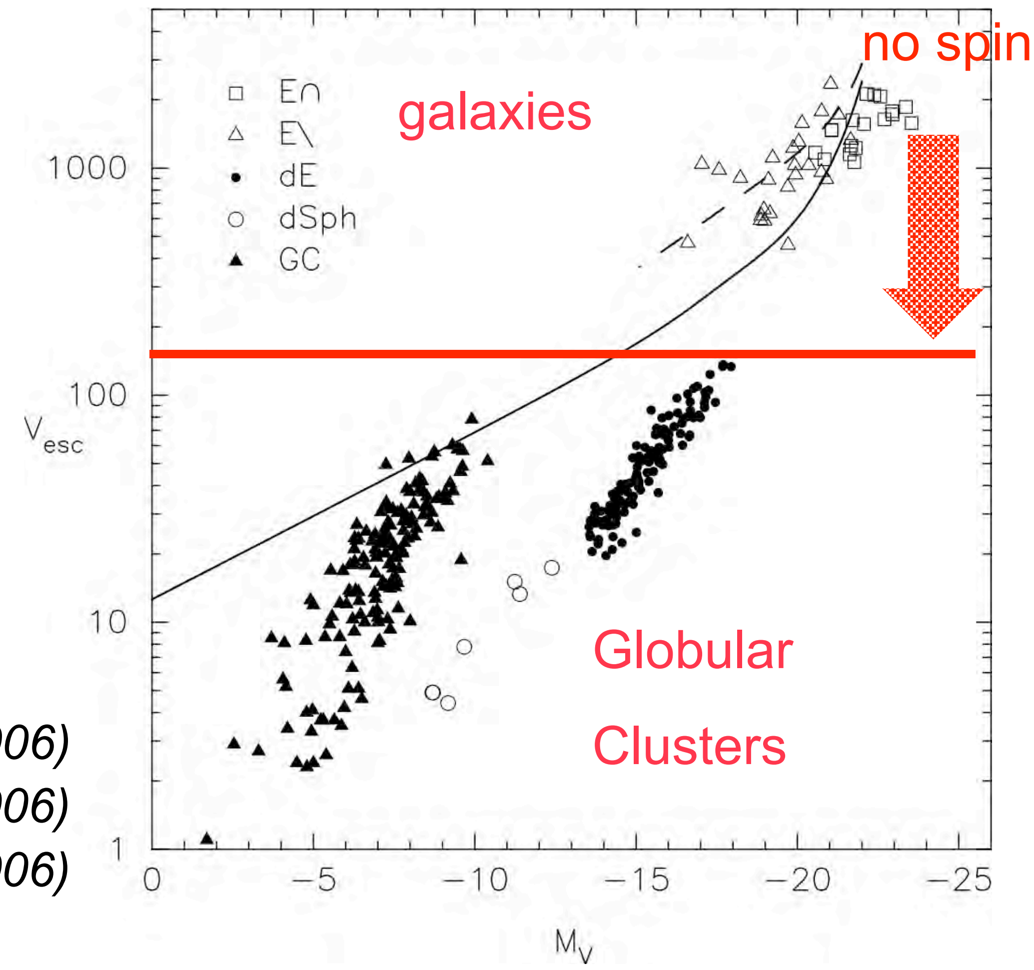
Galaxy Escape Velocities



Baker et al. (2006)

Sopuerta, Yunes & Laguna (2006)

Herrmann, Shoemaker & Laguna (2006)



Credit:David Merritt

Rocket Effect

(non-zero spins)

Koppitz et al. (2007):

$m_1 = m_2 \;\; a_1 = 0.58 \;\; a_2/a_1 = -(0,1/4,1/2,3/4,1)$

$V = 128$ km s^{-1} $(1 - a_2/a_1)$ ≤ 256 km s^{-1}

Herrmann et al. (2007):

$m_1 = m_2 \;\; a_1 = -a_2 = (0.2,0.4,0.6,0.8)$

$V = 475\, a$ km s^{-1} ≤ 392 km s^{-1}

Campanelli et al. (2007):

$m_1 = 2m_2 \;\; a_1 = 0.89 \; a_2 = 0$ $V = 454$ km s^{-1}

$m_1 = m_2 \;\; a_1 = -a_2 = 0.5$ $V = 1830$ km s^{-1}

Gonzalez et al. (2007):

$m_1 = m_2 \;\; a_1 = -a_2 = (0.73,0.80)$ $V = 2500$ km s^{-1}

Tichy & Marronetti (2007):

$m_1 = m_2 \;\; a_1 = a_2 = 0.80$ ≤ 2500 km s^{-1}

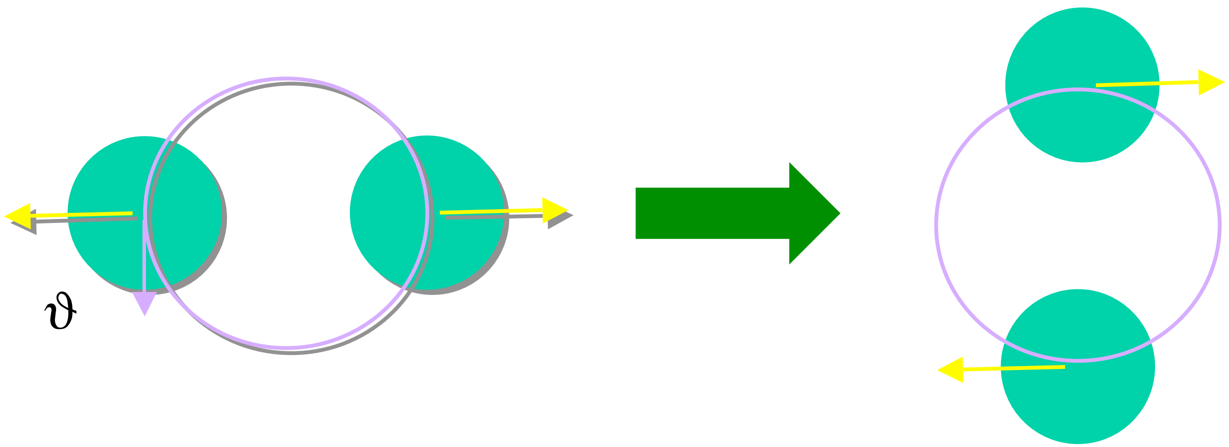
Baker et al. (2007):

$m_1/m_2 = 2/3 \;\; a_1 = a_2 = (0,\pm 0.2)$ ≤ 392 km s^{-1}

Credit:David Merritt

Recoil: Dependence on Orbital Phase

Kidder 1995



max. recoil when:

$m_1=m_2$,

$a_1=-a_2=1$,

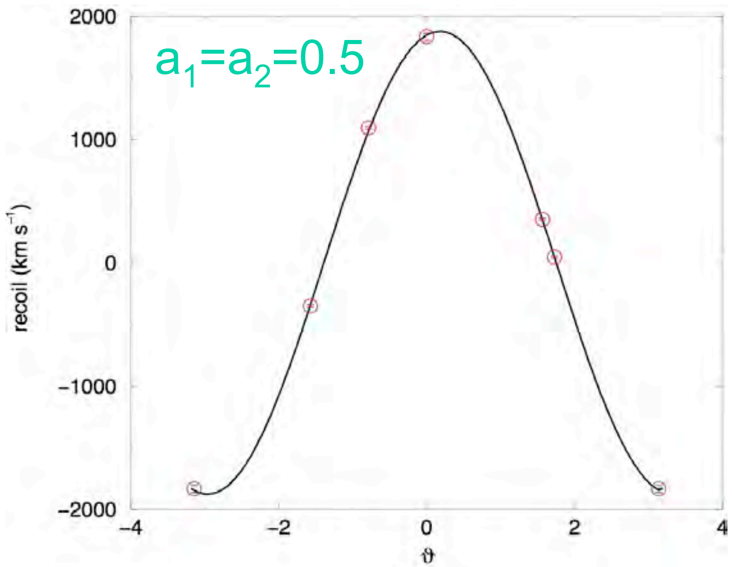
a parallel to orbital plane

CLZM (2007):

Kick depends on *initial* orientation of BH spin *wrt initial* velocity vector.

$$V_z = 1875 \text{ km s}^{-1} \cos(\vartheta-\vartheta_0)$$

$\Rightarrow$ 4000 km s^{-1} for $a_1=a_2=1$!

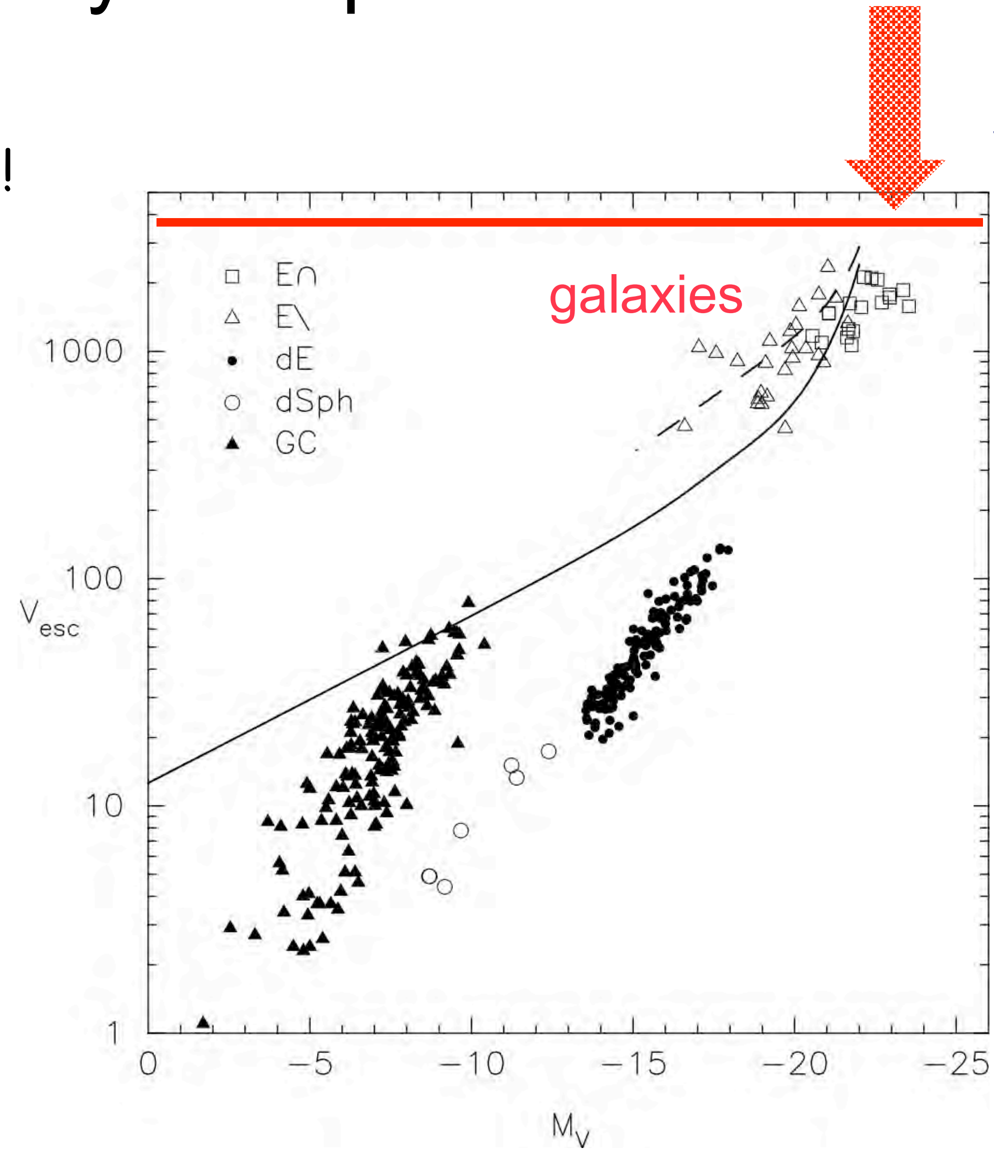


Credit:David Merritt

Galaxy Escape Velocities

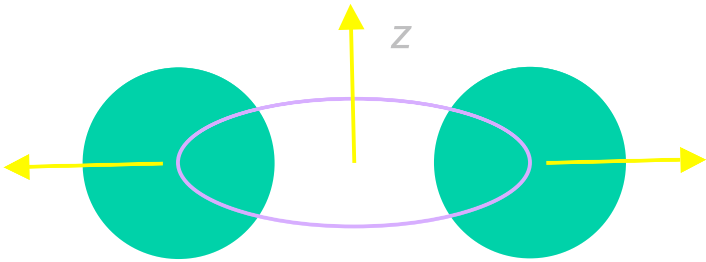
V_{recoil}^{max} ~ 4000 km/s !

spin!



Credit:David Merritt

Recoil Velocity Distributions

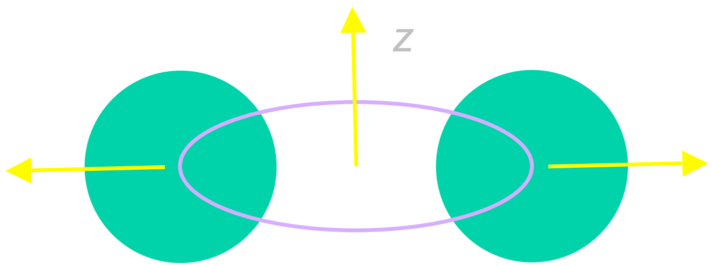


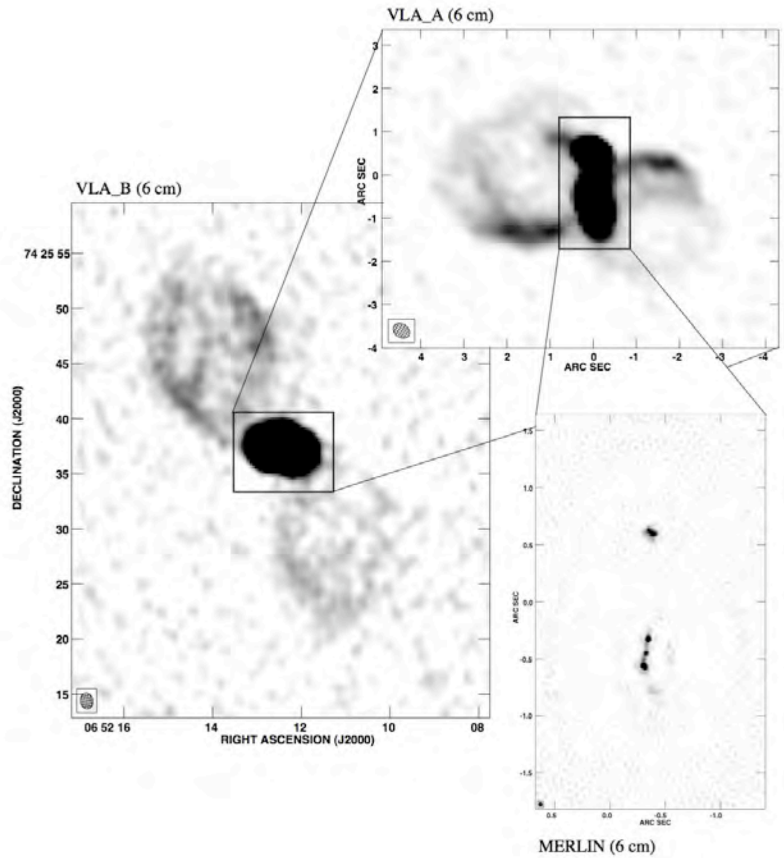
Bogdanovic, Reynolds & Miller (2007):

Torques from accreting gas will align spins of both BHs with the orbital angular momentum vector.

∴ Large kicks should be rare.

Recoil Velocity Distributions





But:

- Many individual AGN show evidence of (multiple) large changes in jet direction over time.

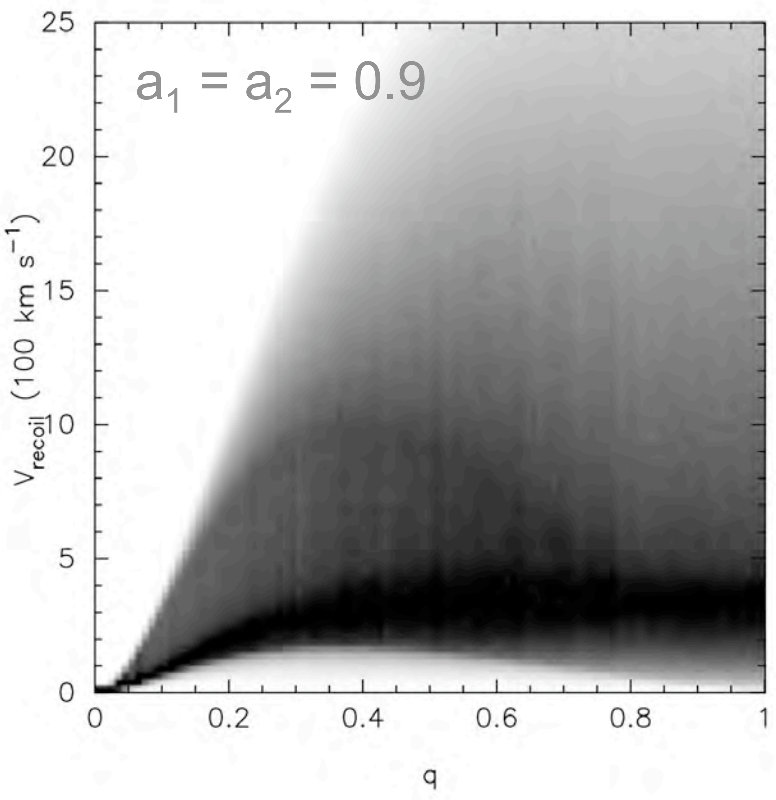
Gallimore et al. (2006)
Kharb et al. (2006)
Dennet-Thorpe et al. (2001)

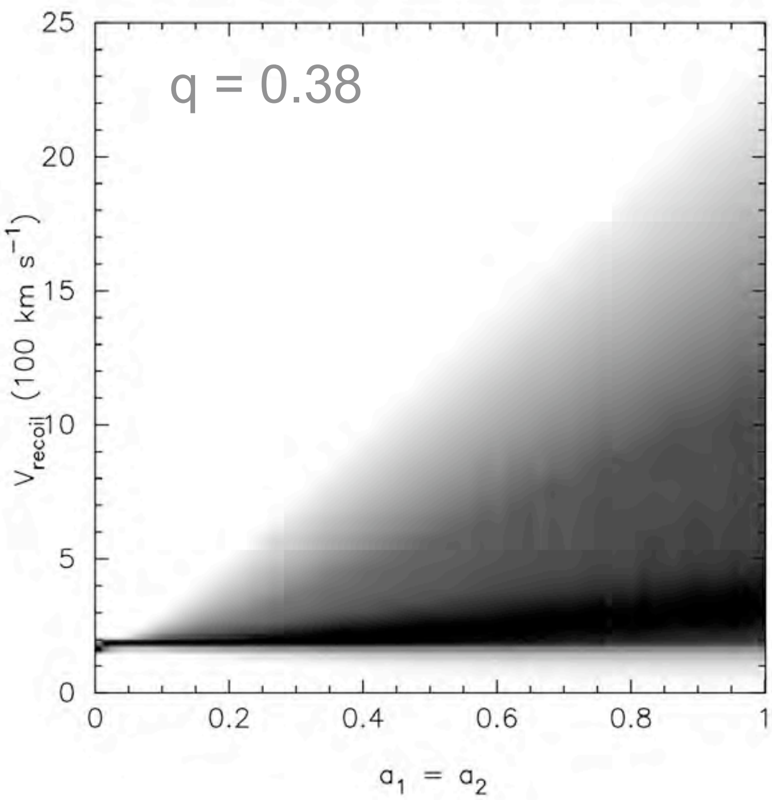
Mrk 6

 Credit:David Merritt

Recoil Velocity Distributions

$$V_{recoil} \propto \left(m_1/m_2\right)^2 \qquad V_{recoil} \propto spin$$



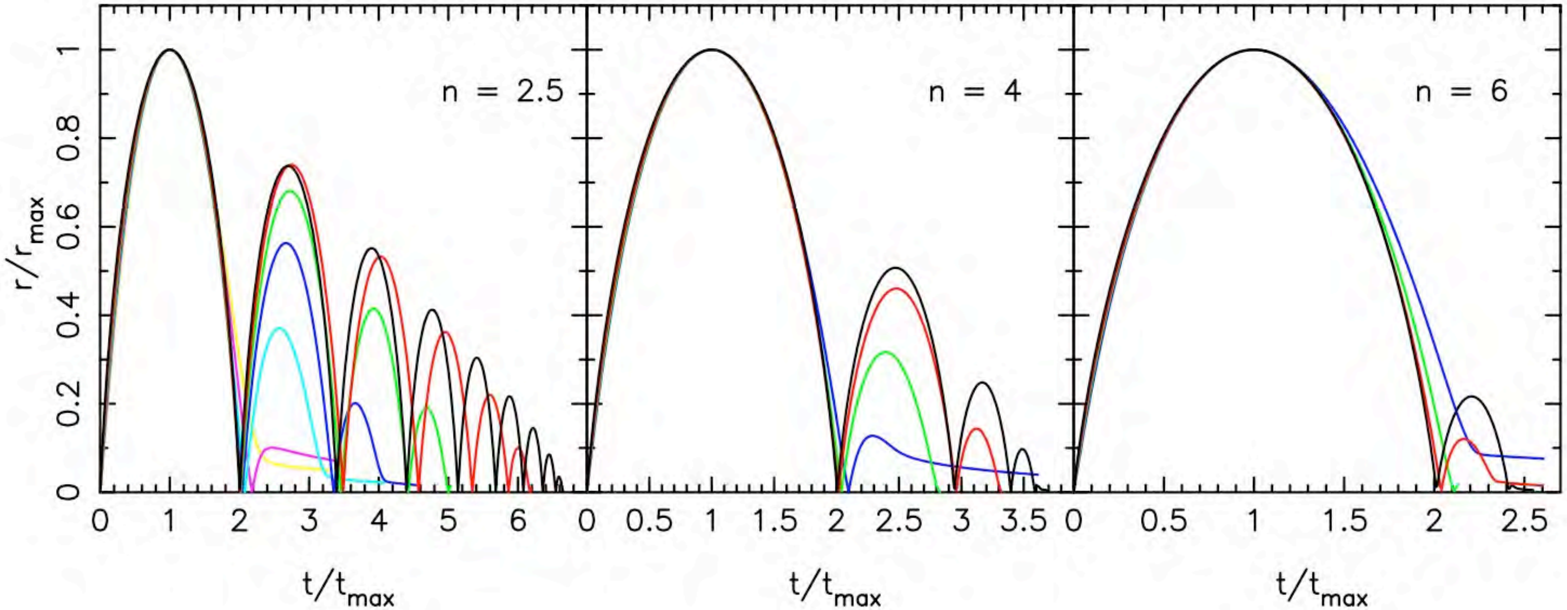


Credit:David Merritt

Orbital Evolution of Kicked SMBHs

Damped Oscillator

N-body on Grape Cluster



faint galaxy

bright galaxy

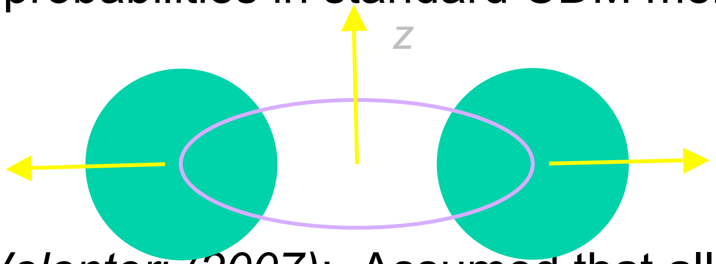
V/V_e = 0.9, 0.8, 0.7, …

n = Sersic index

Gualandris & Merritt 2007

Recoil Velocity Distributions

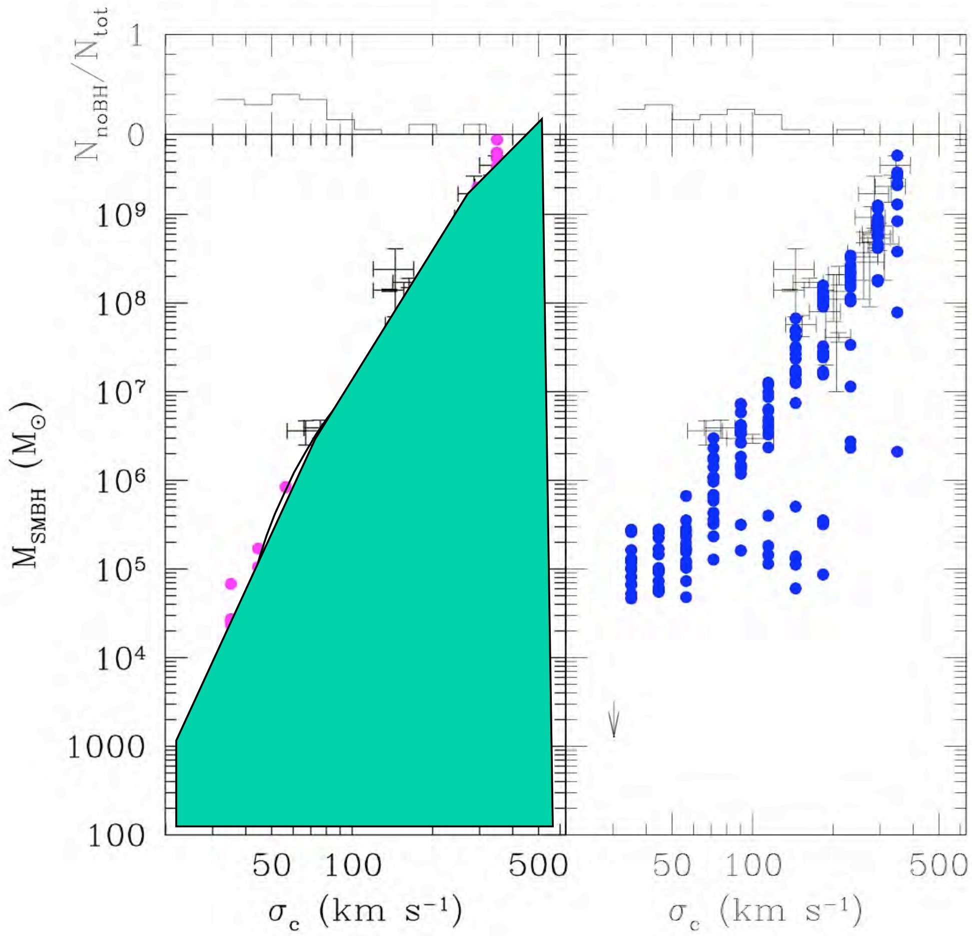
Madau & Quartert(2004): BBHs without spin and computed ejection probabilities in standard CDM merger model.



Volonteri (2007): Assumed that all BBHs have the above spin-orientation, and computed ejection probabilities in standard CDM merger model.

Result: SMBHs would be ejected fairly often.

Is M_{BH} v σ a upper envelope after all?



R·I·T

Observational Consequences

- Recoiling BH can retain the inner part of its accretion disk-truncation radius depends on V_{recoil} (Loeb 2007 astro-ph/0703722)
- Sufficient residual fuel to continue in AGN phase for ~10^6 years
- See AGN displaced from galaxies centers - in the case of the largest predicted kicks - ejected entirely (c.f. HE450- 2958, Magain et al 2006, Merritt et al 2006)
- Broad Emission Lines shifted from the recession velocity of the parent galaxy
  - Robinson, Axon & Stirpe 2007-Diversity Sample
  - Salviander et al 2007-3000 QSO from SDSS (Dr5) 0.1 < z < 0.81- factor of 10 more objects but low S/N

- Accretion disk remains bound to recoil BH inside radius where $V_{orbital} = V_{recoil}$

$$R_b = \left(10^{18.1}\,cm\right) M_8 V_{1000}^{-2}$$ [Loeb 2007]

Implies: truncates IR emitting part of Disk but keeps UV/X-ray and optical zones

Ionizing radiation from disk stays switched on

NLR ionization stucture has time to respond to hole motion- photoinization calcuation (robinson)

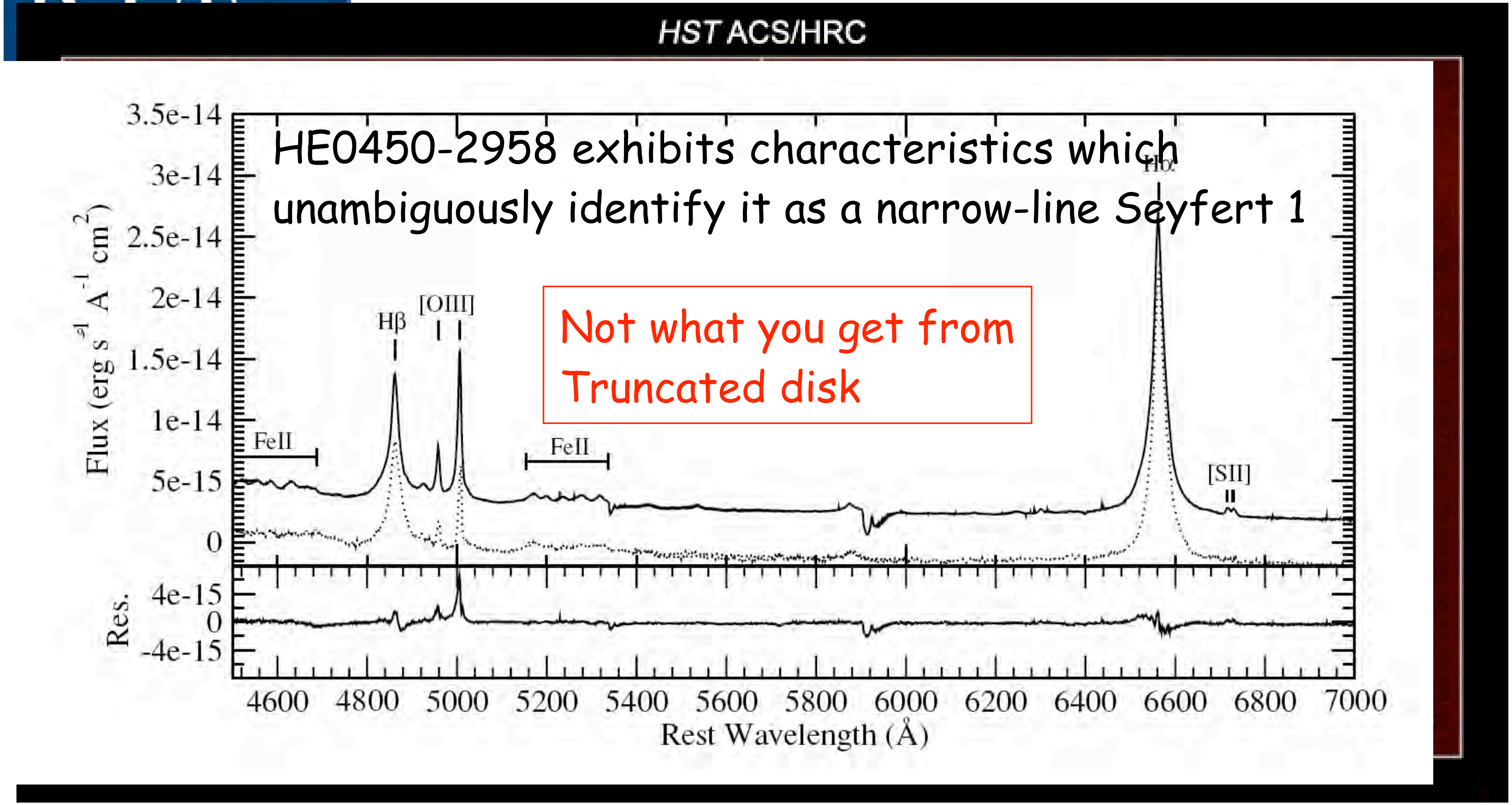
Time Scales

$$M_b = \left(10^{8.0} M_\odot\right) \alpha_{-1}^{-4/5} M_8^{3/2} \underbrace{\left(dM/dt\right)_0}_{\text{accretion rate}}^{7/10} V_{1000}^{-5/2}$$

$$t_{AGN} = \left(10^{8.0} yr\right) \alpha_{-1}^{-4/5} M_8^{3/2} \underbrace{\left(dM/dt\right)_0}_{\text{accretion rate}}^{-3/10} V_{1000}^{-5/2}$$

Dynamical Ages:

- Large radio source: **$t \sim 7.8 \times 10^8$** (v/0.01c) yr
- Small radio source: **$t \sim 3.2 \times 10^5$** (v/0.01c) yr
- Dynamical time scale of the disk on the few hundred pc scale **$t \sim 10^7$ yr**
- **In Seyferts kpc scale radio jets have to be very young < 10^6 yr (Axon, Capetti et al)**

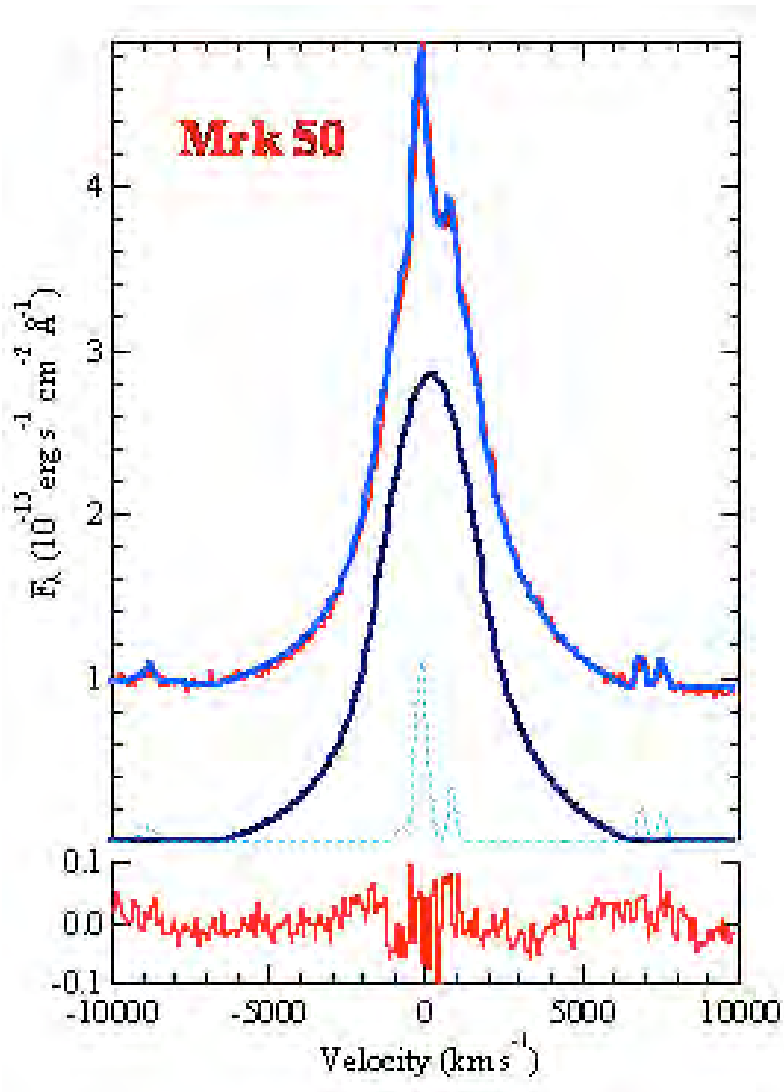


Merritt et al objection 1: predicated on old $|V_{recoil}|$

Merritt et al objection 2: M_{BH} over estimated-host spiral

Broad-line profile diversity

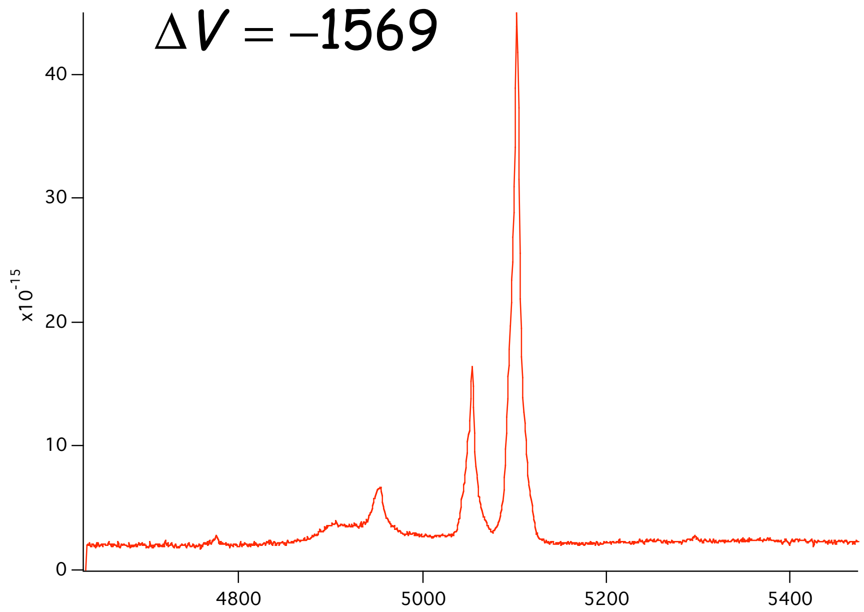
Robinson,Stirpe,Axon 2007

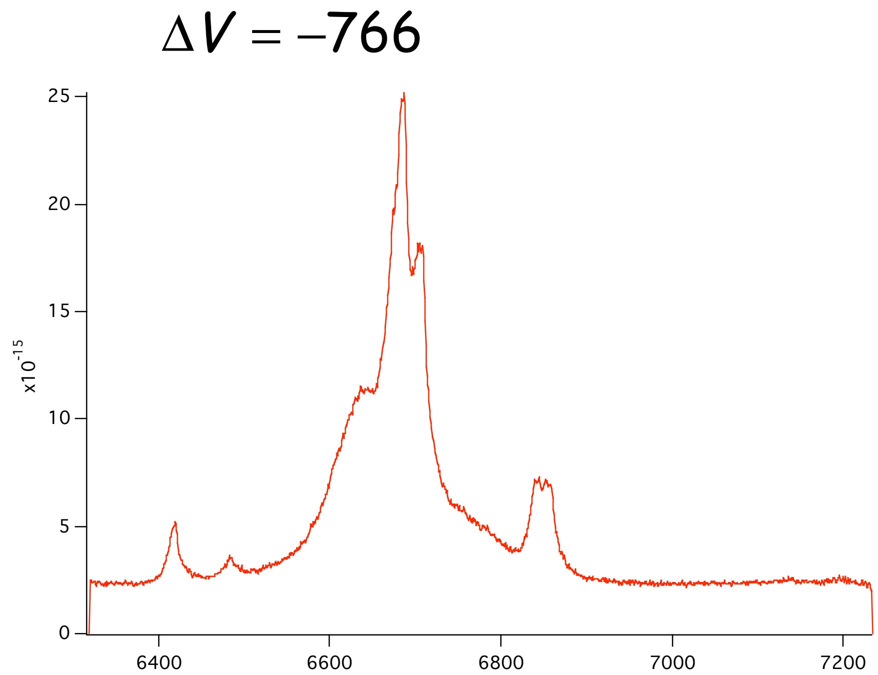


Model fit to Hα profile of Mrk 50

- Hα profiles for ~150 radio quiet AGN
- Most are well fit by a model incorporating –
  - single change in curvature from wings to core
  - anisotropy factors giving wing/core asymmetry
- Change in curvature can be attributed to steepening of BLR emissivity distribution
  - perhaps a transition from matter-to radiation-bounded clouds
- Diversity in shape partly caused by variation in velocity at which curvature changes

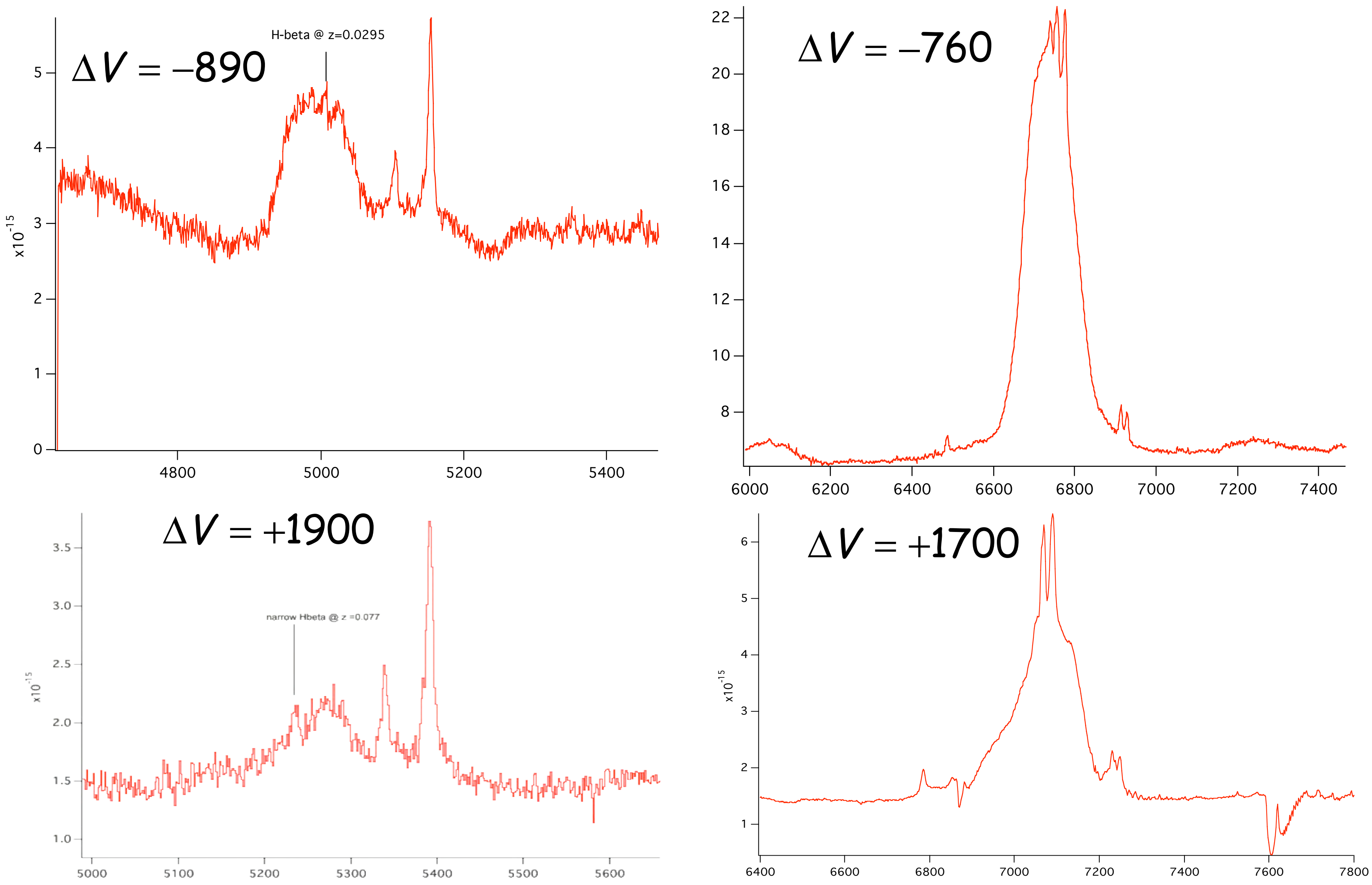
Mrk 6



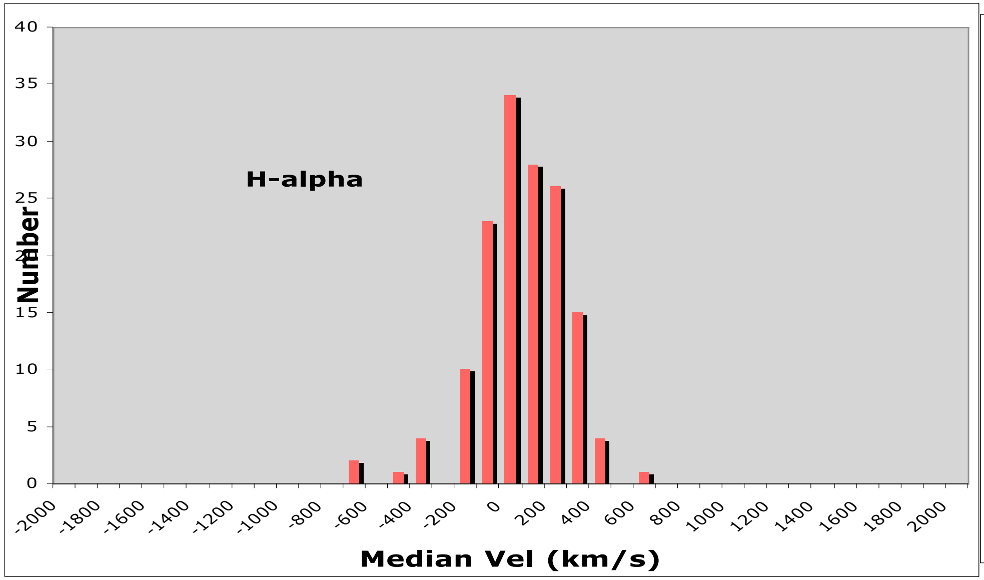


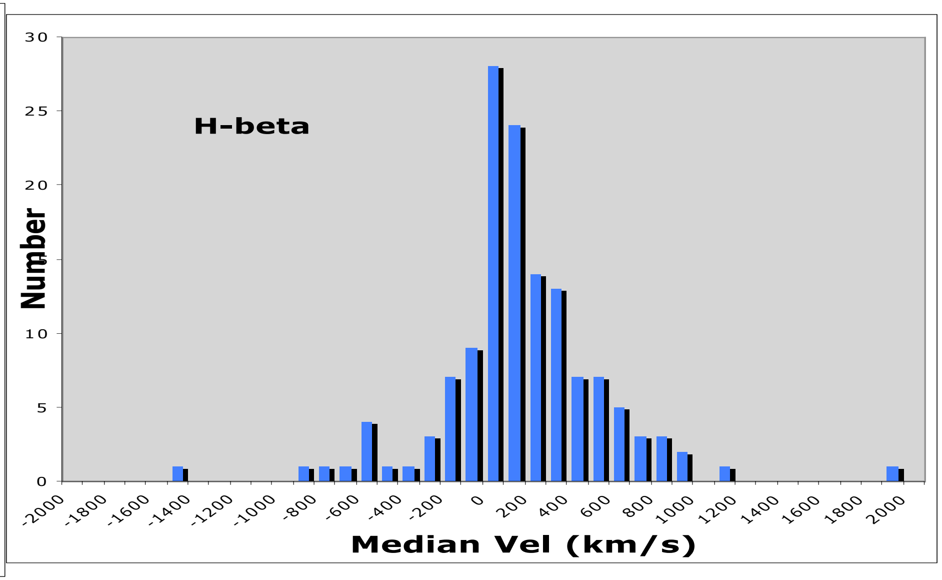
- Hbeta- fit FeII template
- Model both Hbeta and Halpha BLR with Robinson/Marconi broken power law profile. Allows clean seperation of BLR/NLR
- Salviander et al simply discard objects with FeII and asymmetric lines - leaving 70 candidate QSO-Bias?

Large Red and Blue shifts are seen

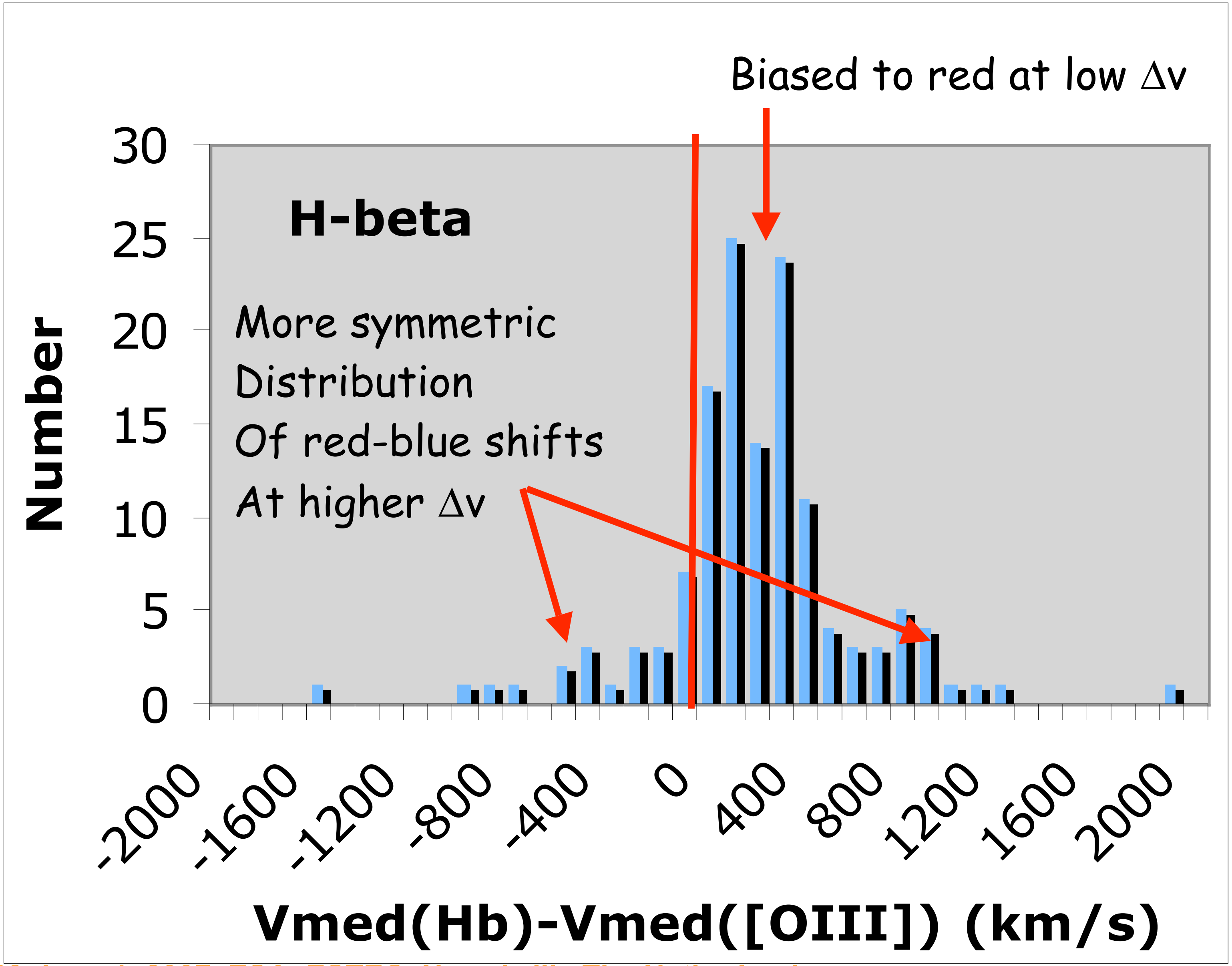


Distribution of BLR shifts

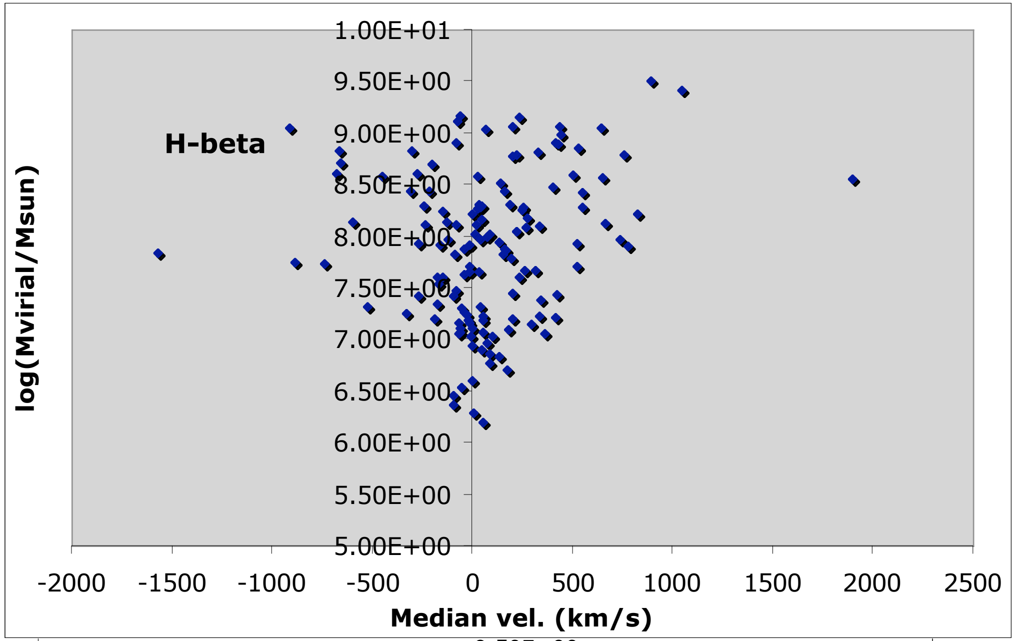


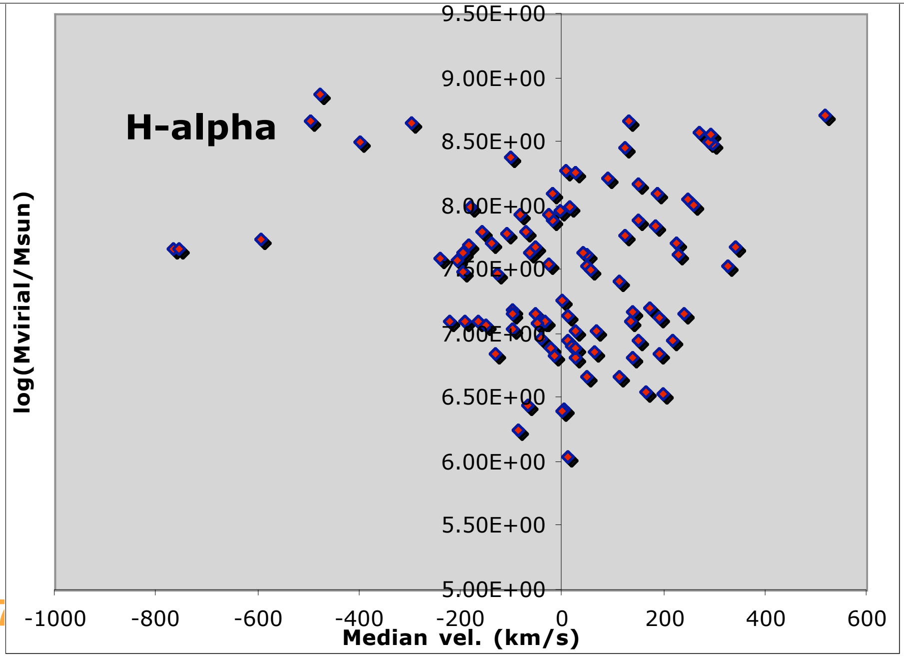


- Hβ distribution broader
- Lower s/n
- FeII residuals?
- etc


Biased to red at low Δv
H-beta
More symmetric
Distribution
Of red-blue shifts
At higher Δv
Number
30
25
20
15
10
5
0
-2000
-1600
-1200
-800
-400
0
400
800
1200
1600
2000
Vmed(Hb)-Vmed([OIII]) (km/s)

BLR-NLR Velocity Shifts v Virial Mass





No Clear Trends

R·I·T

Theme3: How do black holes accrete gas?

- *What are the geometry and radiative efficiency of the accretion flow as a function of the accretion rate?*
- *Which fraction of the infalling mass is expelled in outflows?*

one of the main unsolved questions in AGN research

Mechanisms for mass accretion triggering/feeding:

(1) galaxy interactions can send gas inwards (Hernquist 1989; Barnes & Hernquist 1992);

(2) non-axisymmetric kpc to hundred pc scale morphologies – e. g. bars – can promote gas inflow from galaxy disk towards the nucleus (e.g. Shlosman 1989, 1990, 1993);

(3) hundred of pc scales gaseous spirals can also send gas to feed the SMBH (Pogge & Martini 2002, Maciejewski 2004);

(4) sub-pc scale (unresolved) accretion disks (e.g. Sakura & Sunyaev 1973; Collin 1990-2000; Narayan 2000s)

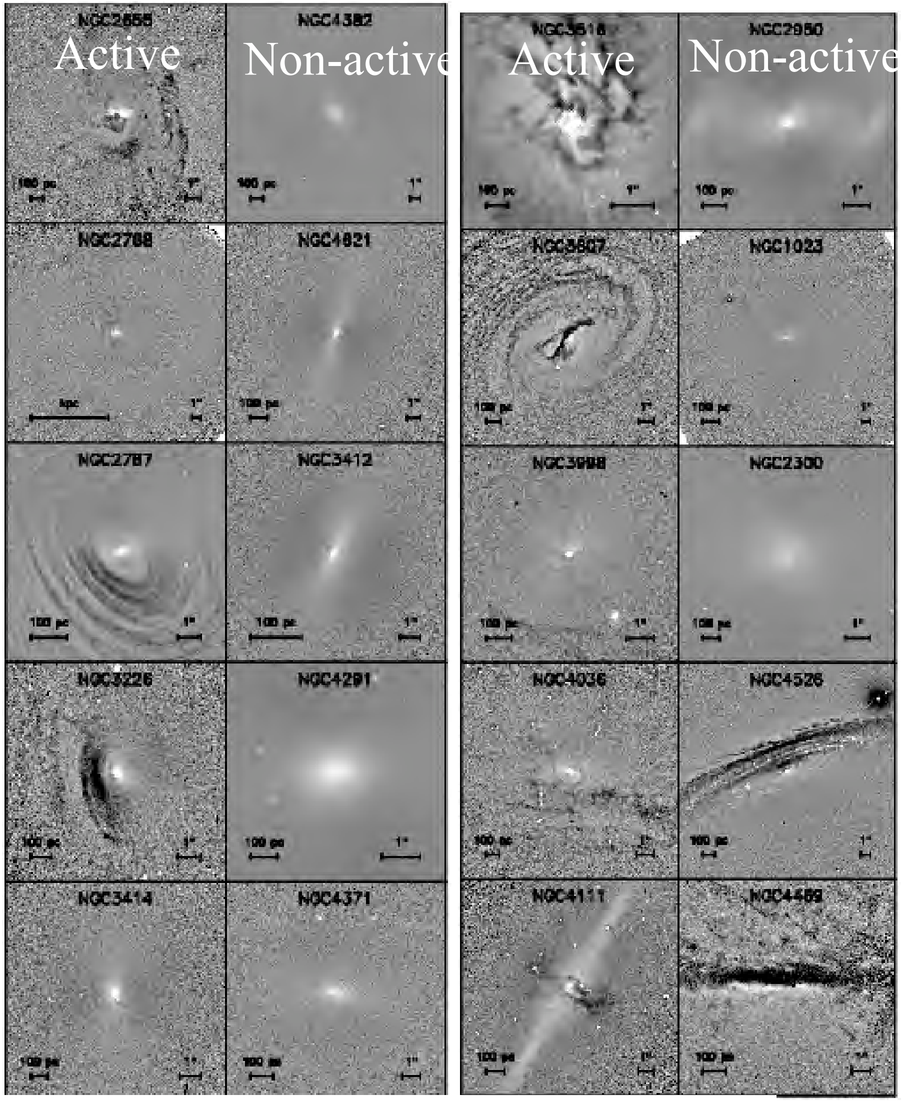
Feeding on 100 pc scales: morphology

Observations: AGNs have more circumnuclear gas and dust

- Van Dokkum & Franx (1995), HST radio-loud early-type galaxies have more dust than radio-quiet
- Pogge & Martini, 2002; Martini et al. 2003, HST Seyfert galaxies present dusty filaments and spirals in the nuclear region
- Xilouris & Papadakis (2002), HST among early Hubble types, active galaxies present more dust structure than non-active galaxies
- Ferrarese et al. (2006) HST: dust in early-type galaxies; signatures of star formation in most regular/compact dust structures;
- Lauer et al. (2005), HST: dust in early-type galaxies is correlated with nuclear activity
- Prieto et al. 2005 near-IR VLT adaptative optics images of the nuclear region (<300 pc) of LINER/Seyfert 1 galaxy NGC1097 reveal several spiral arms which seem to be channels for gas and dust to reach the SMBH at the nucleus

Lopes, Storchi-Bergmann & Martini 2007

HST Structure maps for 34 early-type galaxies pairs (T<0)



Dust structures are more frequent in active than in non-active galaxies (100% vs 27%): feeding material on its way in

~50% of non-active galaxies present nuclear stellar disks, absent in active galaxies; may be more, as disks at low inclination are hard to separate from bulge

Lopes, Storchi-Bergmann & Martini 2007

Feeding on 100 pc scales: gas kinematics

Theory

Maciejewski (2004-2006): nuclear (< 1 kpc) gaseous spirals originate as a response to non-axisymmetry in galactic potential resulting in streaming motions in gas up to 0.03 $M_\odot$ yr^{-1}, at accretion rates needed to power local Active Galactic Nuclei.
Kinematic signatures still missing!

Observations

- Peletier, Emsellem, Fathi et al. 2007: SAURON observations of gas kinematics reveal streaming motions due to a bar; not yet many active galaxies

- Storchi-Bergmann, Fathi, Axon, Robinson, Marconi 2006-2007 Gemini IFU observations to look for streaming motions along nuclear spirals in AGN hosts. Sample extracted from Lopes et al. 2007 (structure maps).

Observational (tricky) constraints: inclination should allow measurement of kinematics, presence of emitting gas, low-activity to avoid too much outflow. **NEW: Already found two cases: NGC1097 and NGC6951**

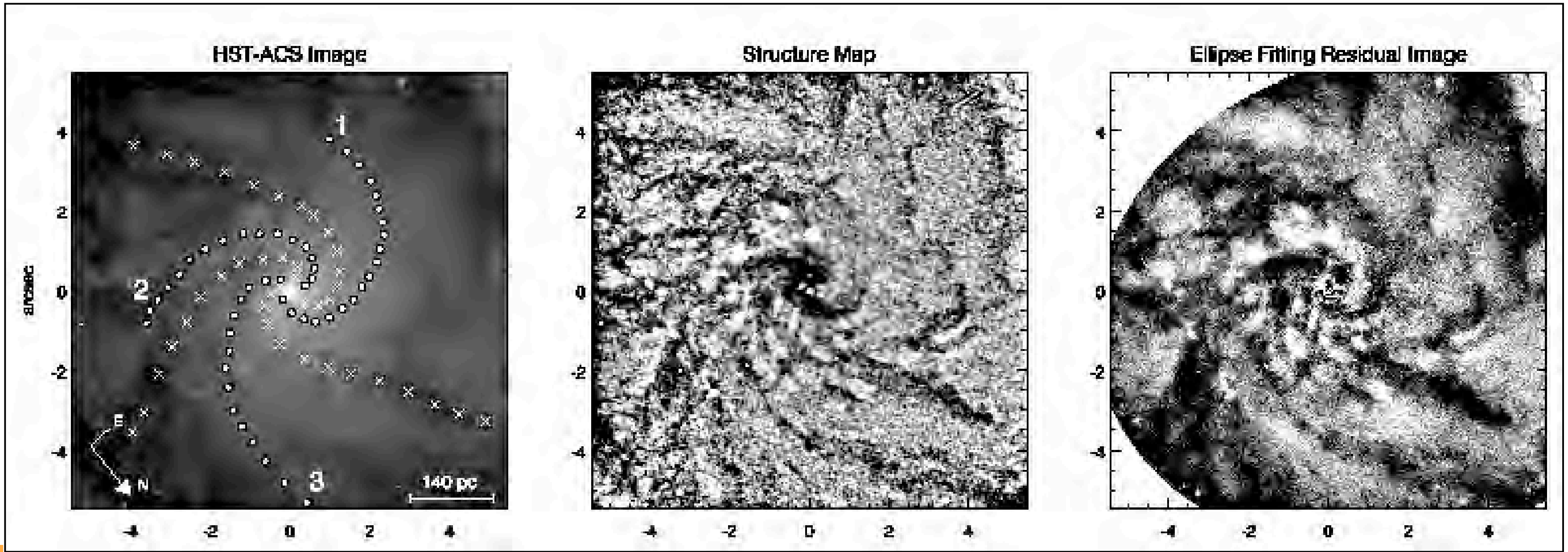
R·I·T

NGC 1097

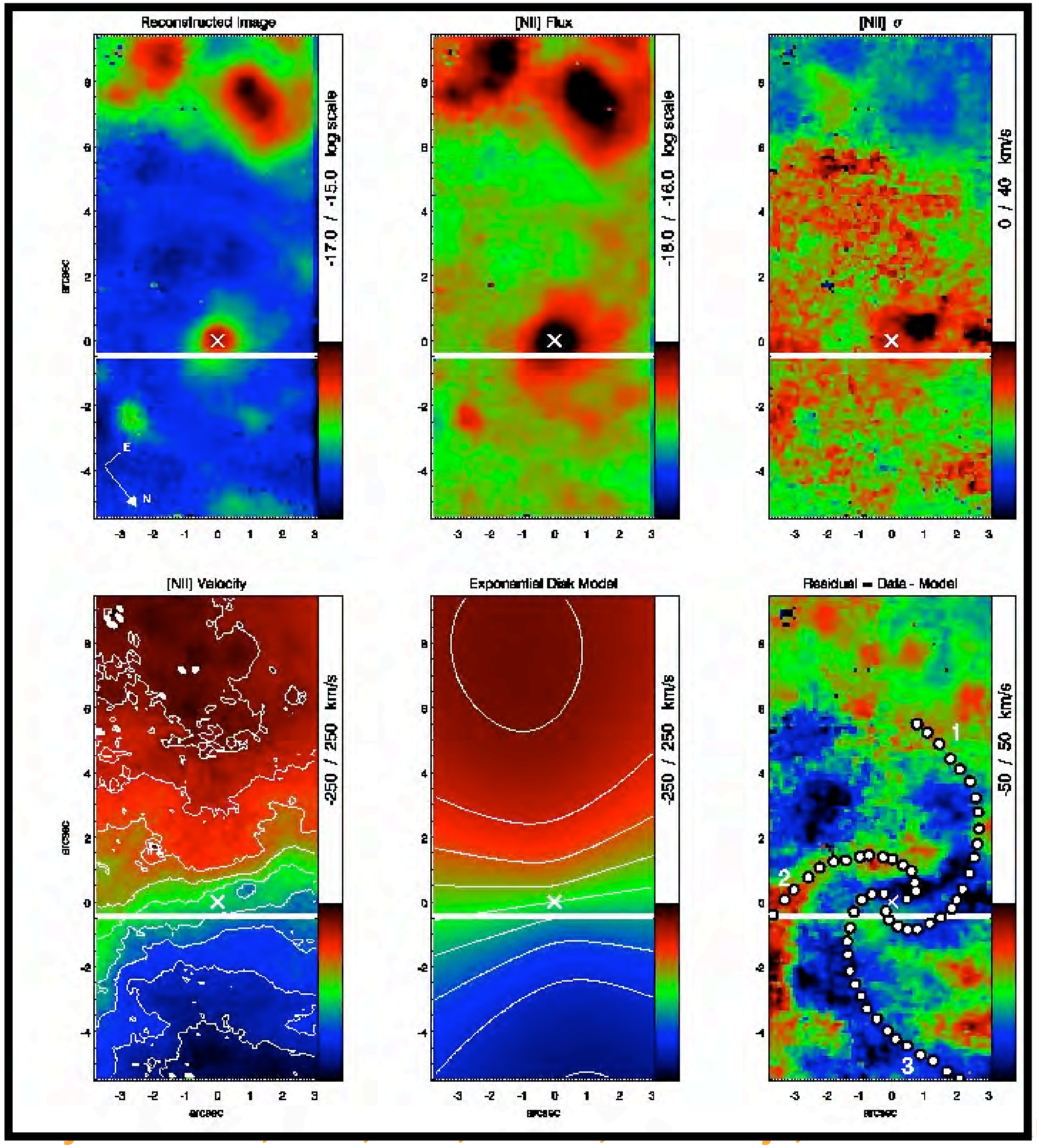
Luminous (M_B=-21.2) SBb galaxy at 17 Mpc with nuclear ring (700 pc); LLAGN with double-peaked Balmer lines (Storchi-Bergmann et al. 1993-2003)

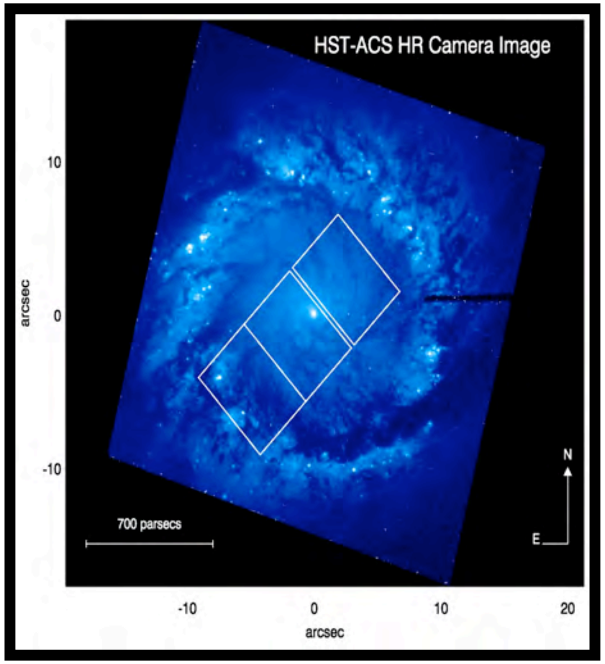
- HST ACS FR656N images of inner 500 pc: gas/dust filaments Prieto et al. 2005; Fathi et al. 2006)

Fathi et al. 2006:



Fathi et al. 2006: Gemini IFU GMOS spectra of H_ region covering 7″×15″(3 fields; 3000 spectra) _





Results:

1) Distorted rotation: residuals relative to circular rotation of ~50 km/s delineate spiral arms (dots); (2) redshifts in the near side, blueshifts in the far side

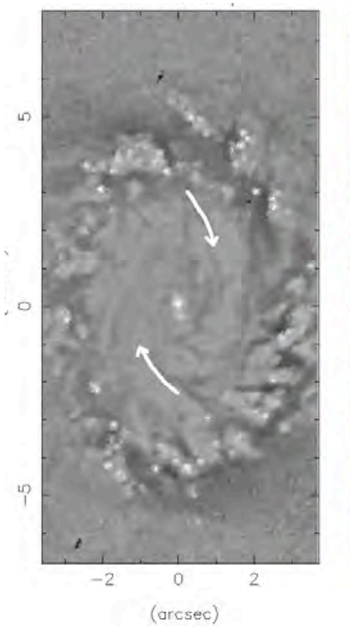
_ streaming motions along spiral arms towards the nucleus

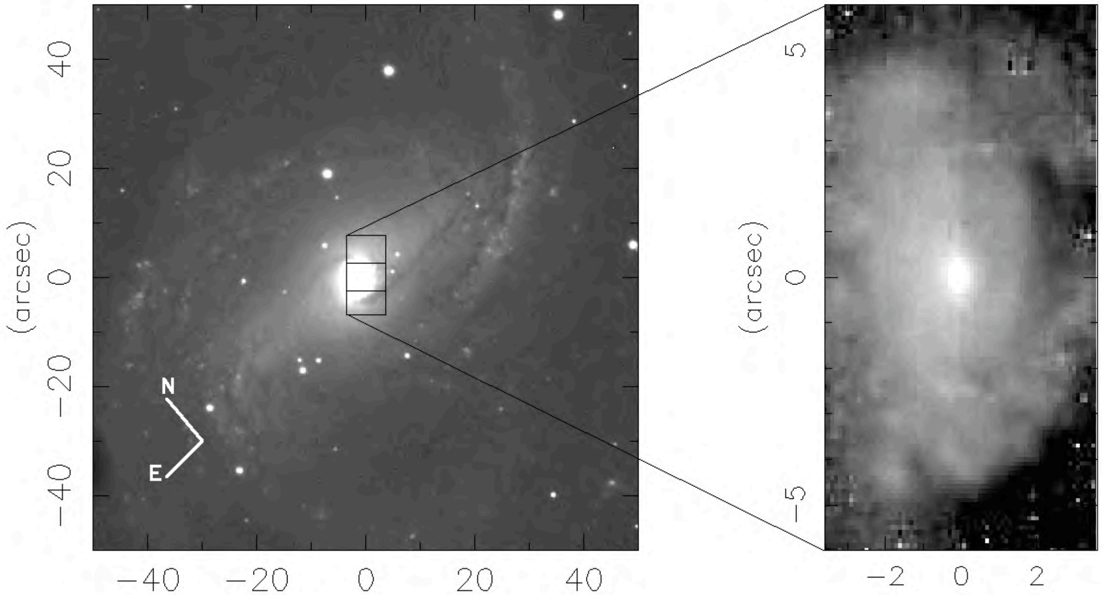
NGC6951

SABbc galaxy at 24 Mpc with LLAGN (LINER/Sy 2) , with star-forming ring at ~ 500 pc from nucleus

• Has radio, CO and HCN emission

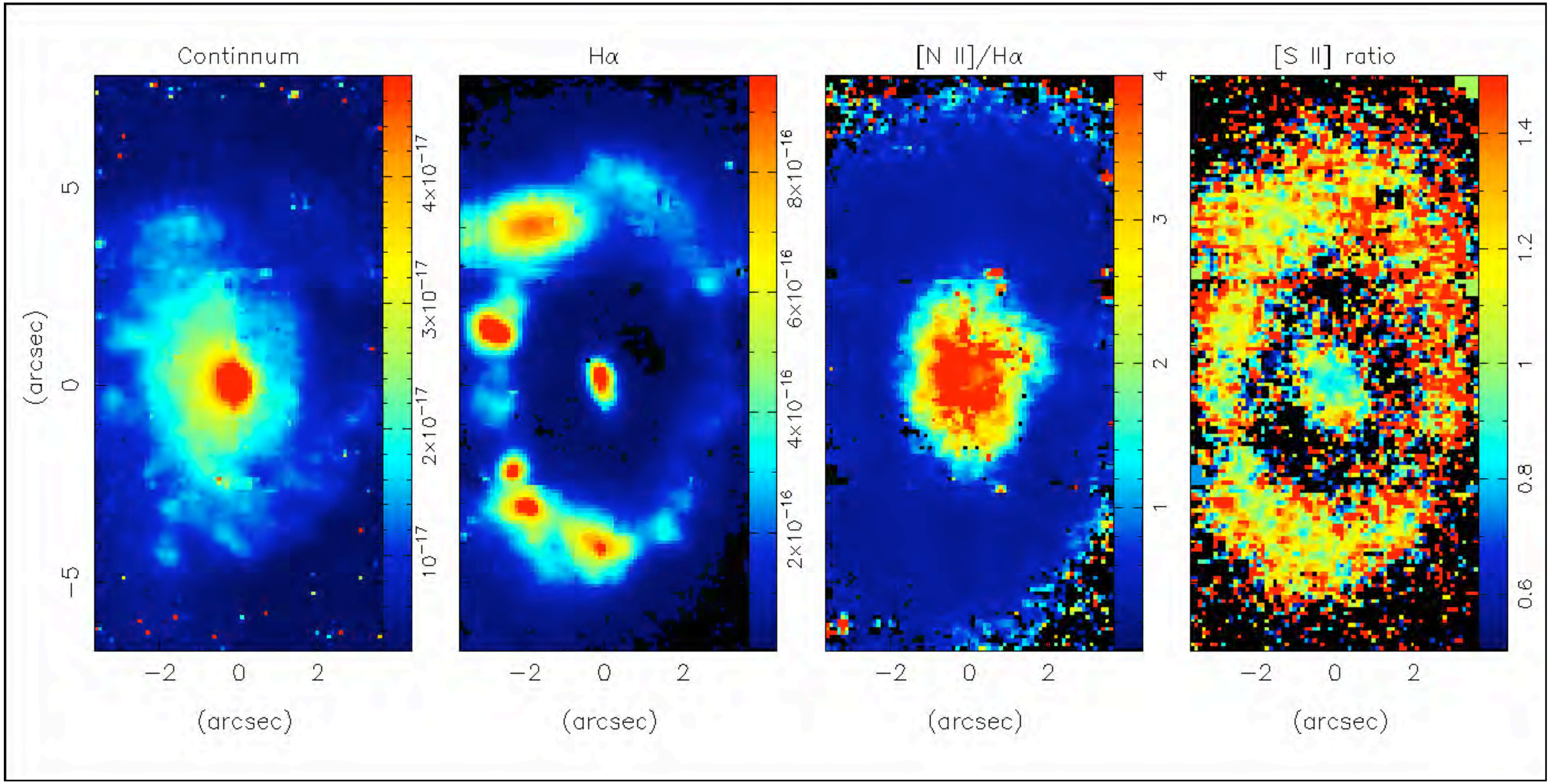
Structure map shows nuclear spirals

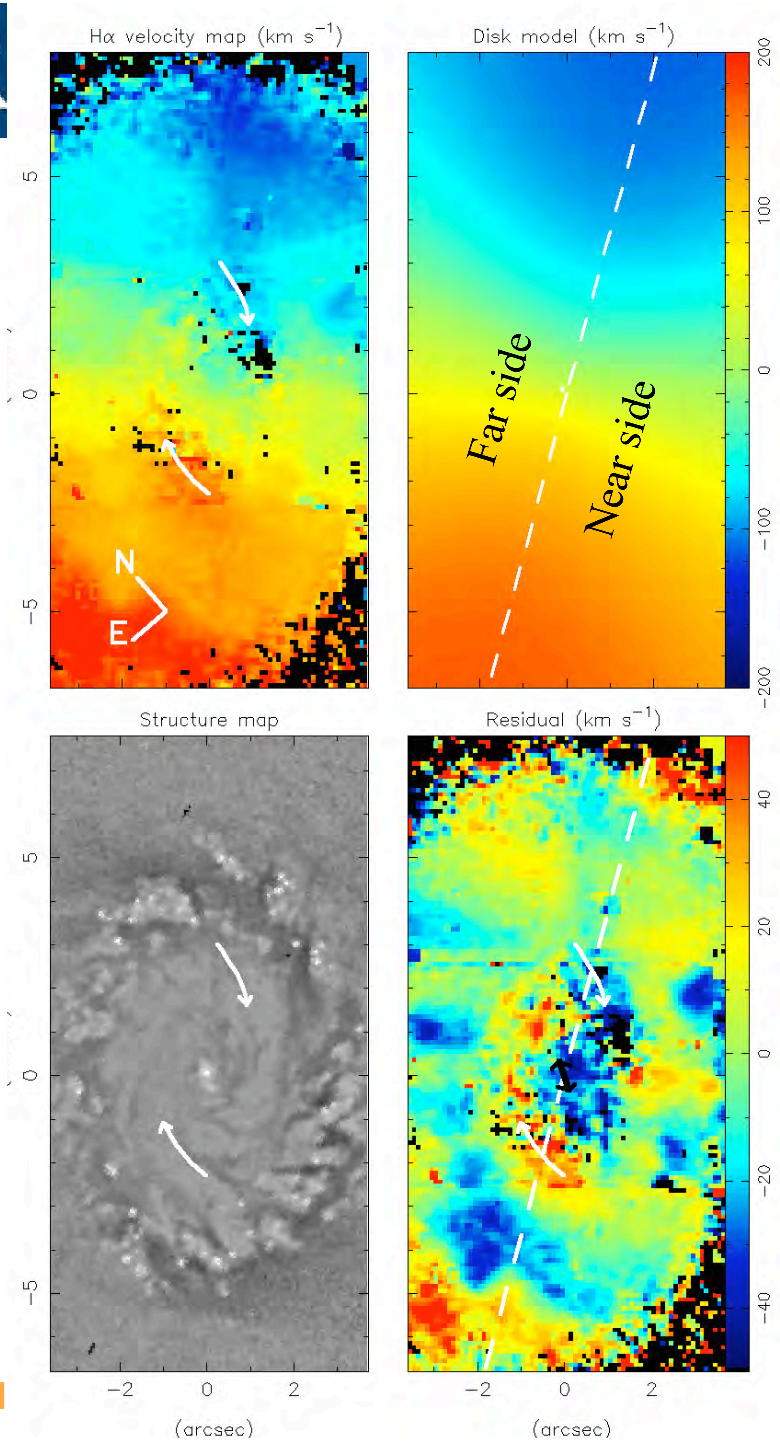




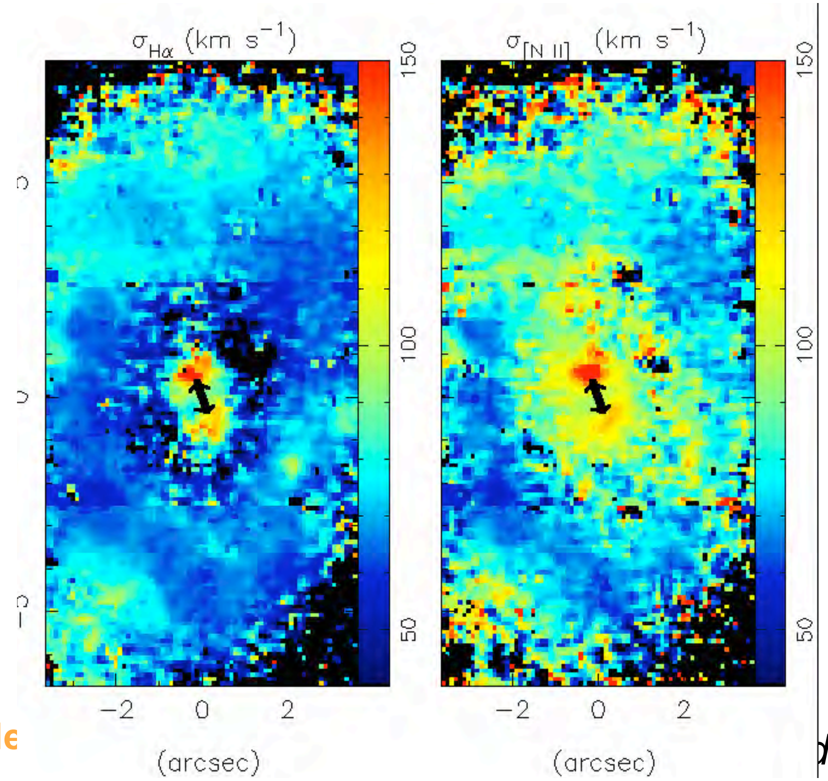
NGC 6951 fluxes and line ratios:

Storchi-Bergmann et al. 2007:





- Streaming motions along nuclear spirals
- Spirals seen in HCN (Krips et al. 2007)
- Residuals include outflow produced by radio jets (Saikia et al. 2002)



Implications

First time that streaming motions in nuclear spirals have been mapped (previously only large scale spiral arms: e.g. Visser 1980; Tilanus & Allen 1991; Emsellen, Fathi et al. 2005);

Nuclear spirals ubiquitous in active galaxies → material on its way in to feed the SMBH (more kinematic studies are being done);

- Timescales: @ 50 km/s, gas at ~100 pc from nucleus will reach center in a few 10^6 yrs (≡dynamical/free-fall timescale)

- Calculation of mass inflow rate (in ionized gas!):

$$\frac{dM}{dt} = \rho \times v \times \sigma \times f \cong 10^{-3} M_{\odot} yr^{-1}$$

⇒ Of order of nuclear accretion rate (derived from AGN luminosity for RIAF structure)

BUT: ionized gas may be only "tip of the iceberg"; neutral and molecular gas may dominate inflow (nuclear molecular mass ~ $10^7 M_{\odot}$ in NGC6951)

R·I·T

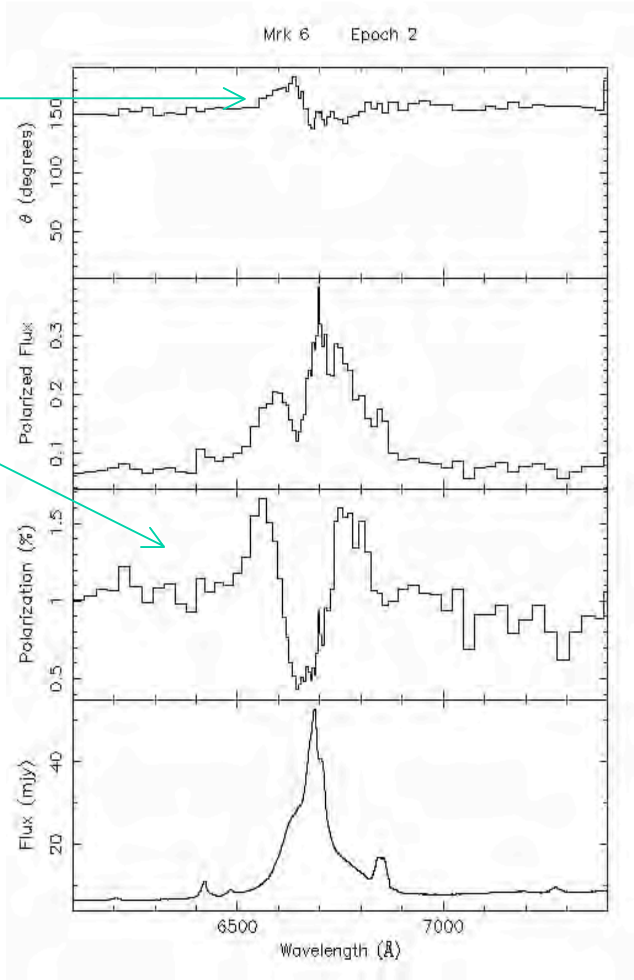
Feeding mechanisms on sub-parsec scales:
What goes onto the accretion disks?

Robinson, Axon, Young & Smith 2007

Adapted from Ho 2005

Objects with p, θ structure across broad Hα

- Double PA rotation
  - Sense of swing reverses from blue-red
  - Amplitude 30–70°
  - Centred on continuum PA
- Peak-trough-peak variation in p
  - Depolarization in core
  - Flanked by peaks in wings
- PA swing requires
  - Rotation in scattering plane and…
  - Spatial discrimination between red- & blue-shifted line-emission
- BLR resolved by scattering region (near-field scattering)



Goodrich & Miller 1994; Martel 1996; Corbett et al. 1998, 2000; Cohen & Martel 2001; Smith et al. 2002

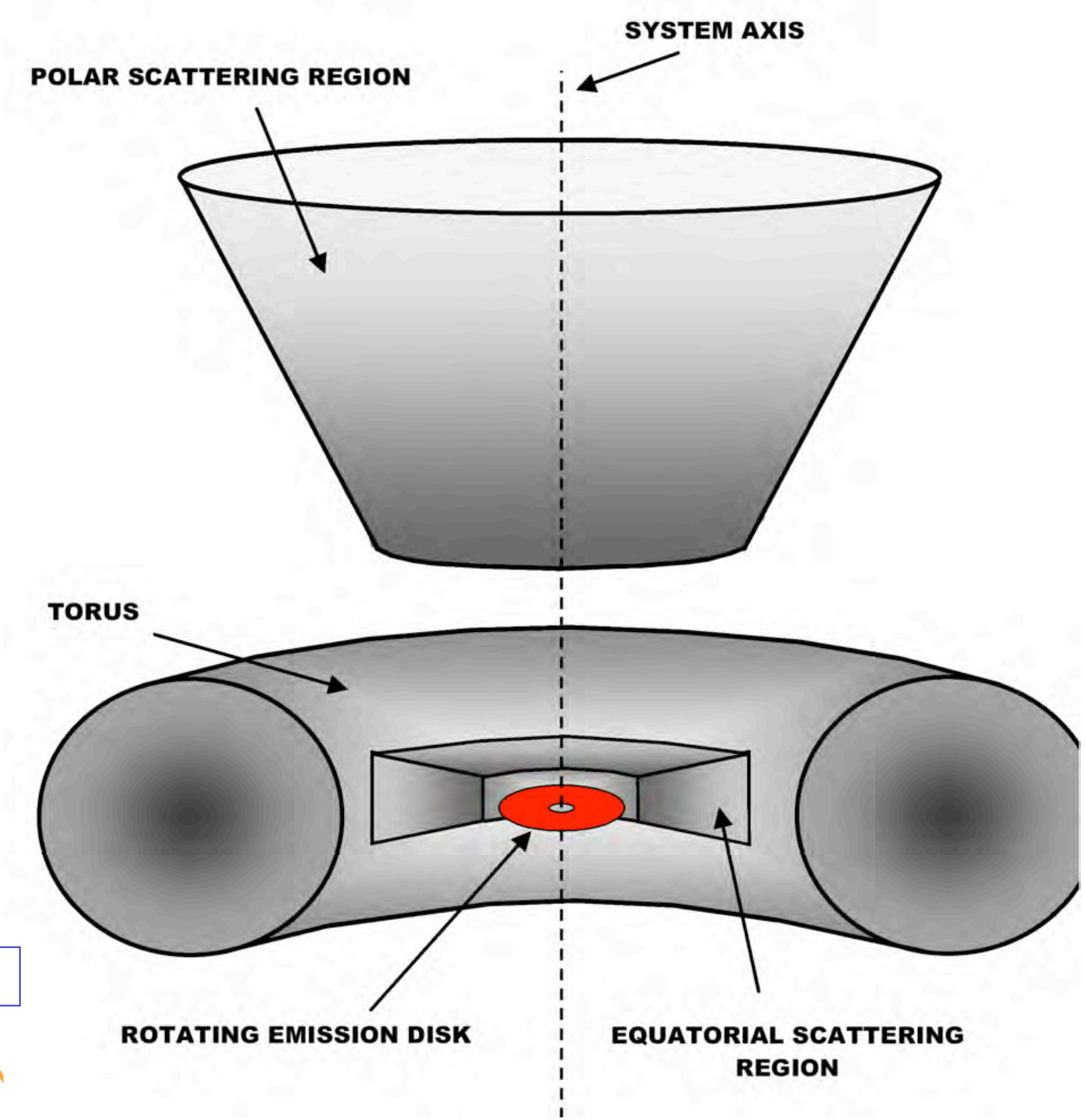
Other examples:

NGC4151; Mrk 509; Akn 120; (3C445)

Generic scattering model for Seyferts

Basic idea:

All Seyferts contain both equatorial and polar scattering regions → observed polarization properties determined by orientation

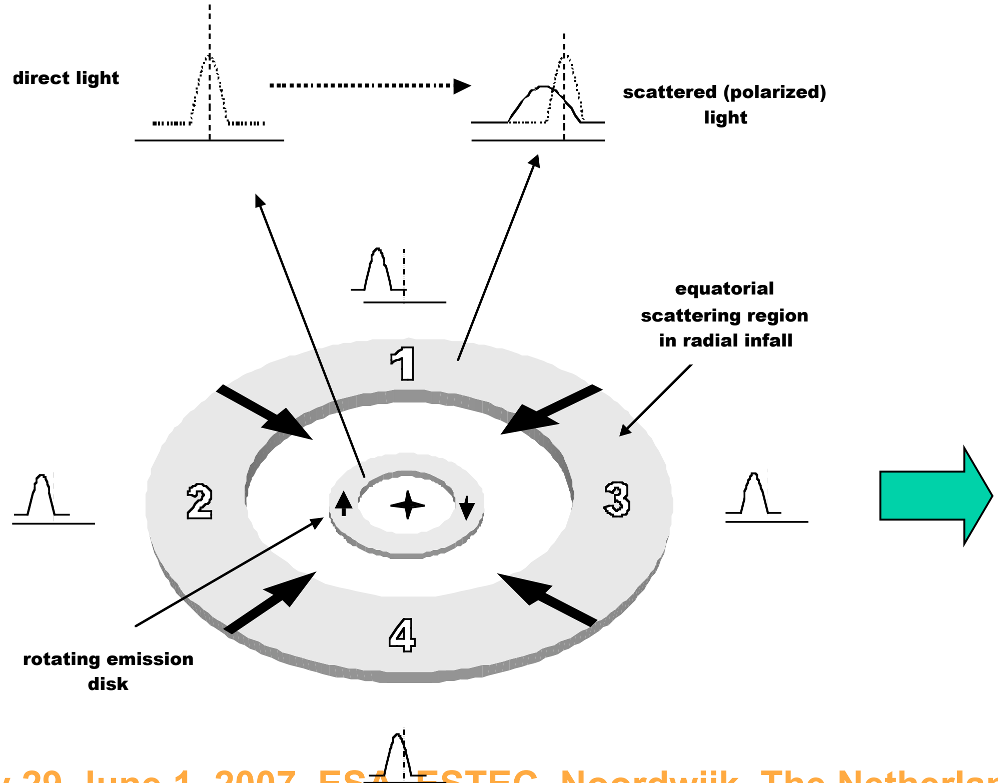


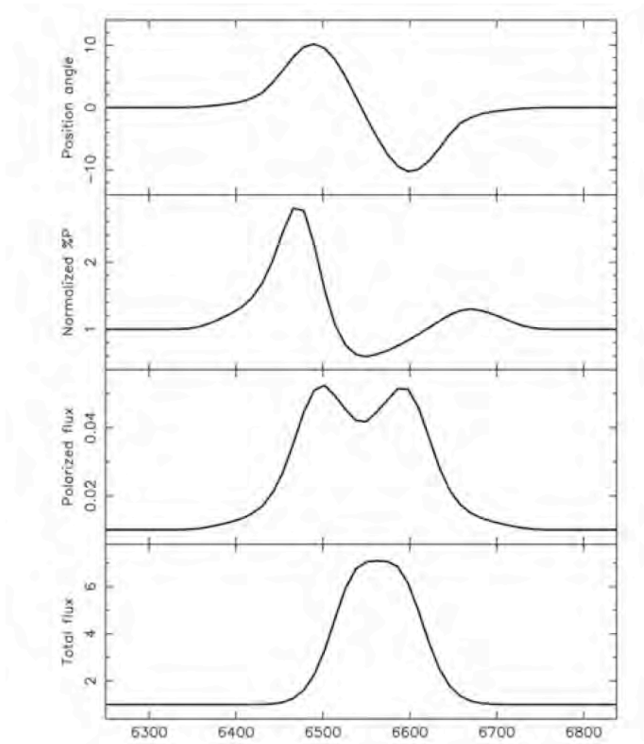
Young 2000, MNRAS 312, 567

Kinematics of the Equatorial Scattering zone

- Bulk motions appear as asymmetries in polarization spectrum
  - E.g., Radial inflow produces blue asymmetry
- Such asymmetries are present in some objects

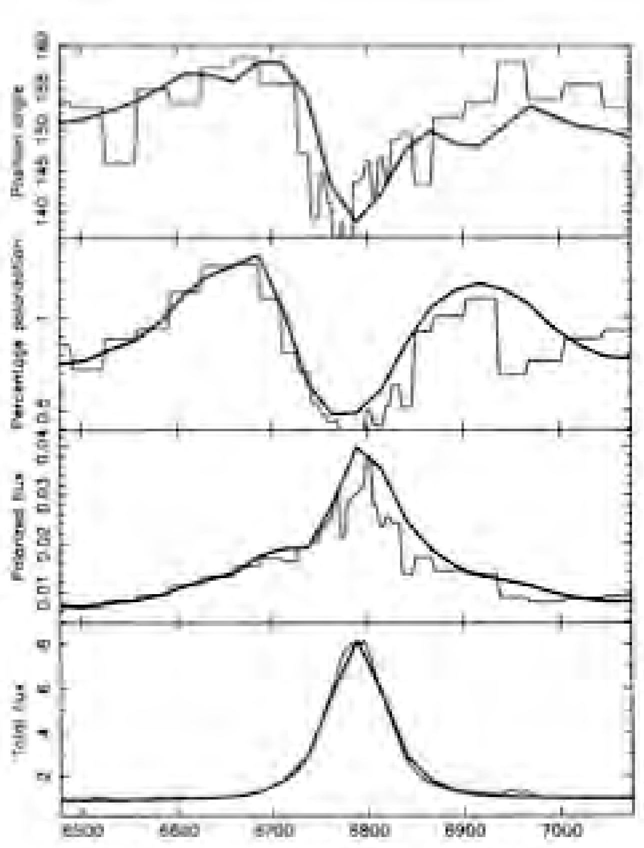
- Is the equatorial scattering region part of an outer accretion flow?
  - Does it trace mass transfer between the torus and the accretion disk?





Radial motions in Mrk 509?

Mrk 509 – Hα polarization



model → equatorial scattering region has bulk inward radial velocity ~ 900 km s^{-1} (Young 2000)

- *Mass inflow rate through inner edge of scattering region:*

$$\dot{m} \sim 4\pi r_{es}^2 \cos\theta_{es} n_e m_H / x$$

from scattering model

H ionization fraction unknown

$$\dot{m} \sim \left(2\times10^{-7}\ M_\odot\ yr^{-1}\right)/x$$

Bolometric luminosity → accretion rate ~ 0.3 $M_\odot$ yr^{-1}

Scattering electrons ionized atmosphere of neutral accretion flow?

Conclusions: AGN feeding

Nuclear gaseous spirals/filaments: strong correlation with activity_the actual fuel flowing in;

- kinematic signature of inflow along nuclear spirals; two cases observed so far. Difficulties: inclination, enough ionized gas emission in the nuclear spirals; outflows complicate gas kinematics;

- spectropolarimetry of some Seyfert 1 (e.g. Mrk. 509) shows that scattered lines are blueshifed and can be plausibly modelled as infall onto the BLR on sub-parsec scales