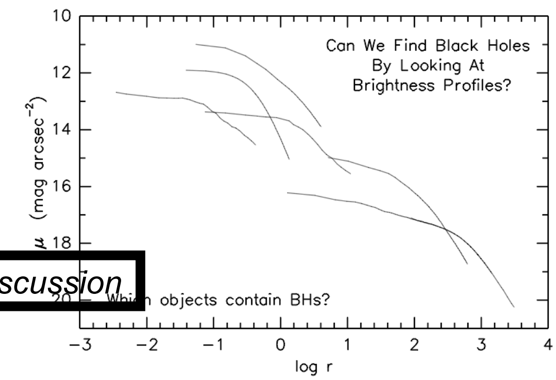
What About Other Supermassive Black Holes

- Dynamical data: use the collisionless Boltzman eq (conceptionally identical to the use of gas temperature to measure mass, but stars have orbits while gas is isotropic)



Longair 19.3. eq 19.8 and extensive discussion

Kormendy and Richstone (200

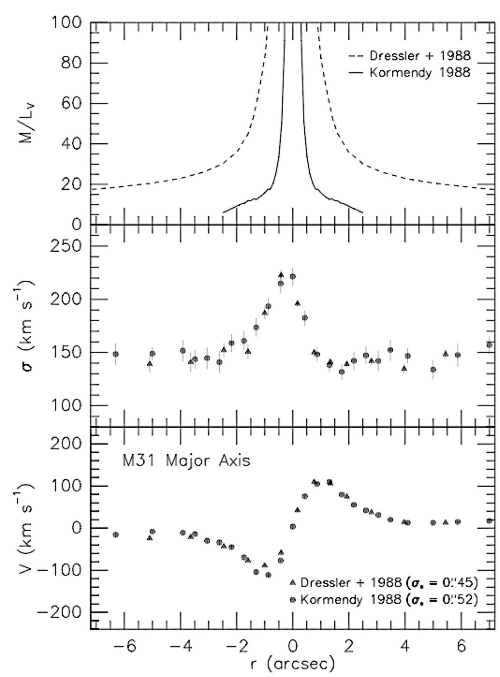
- In Jeans eq $\sigma_r, \sigma_\theta, \sigma_\phi$ are the velocity dispersion in r,θ and ϕ directions , ν is the density of a tracer
- V is the rotational velocity

Longair eq 19.8

$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G}\left[-\frac{d\ln\nu}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - \left(1-\frac{\sigma_\theta^2}{\sigma_r^2}\right) - \left(1-\frac{\sigma_\phi^2}{\sigma_r^2}\right)\right]$$

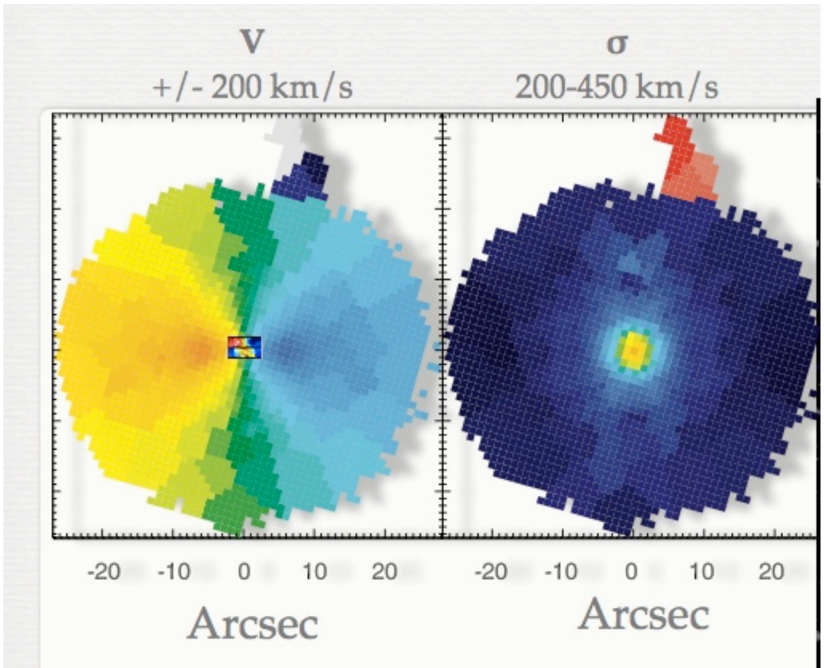
Example of data for the nearest galaxy M31

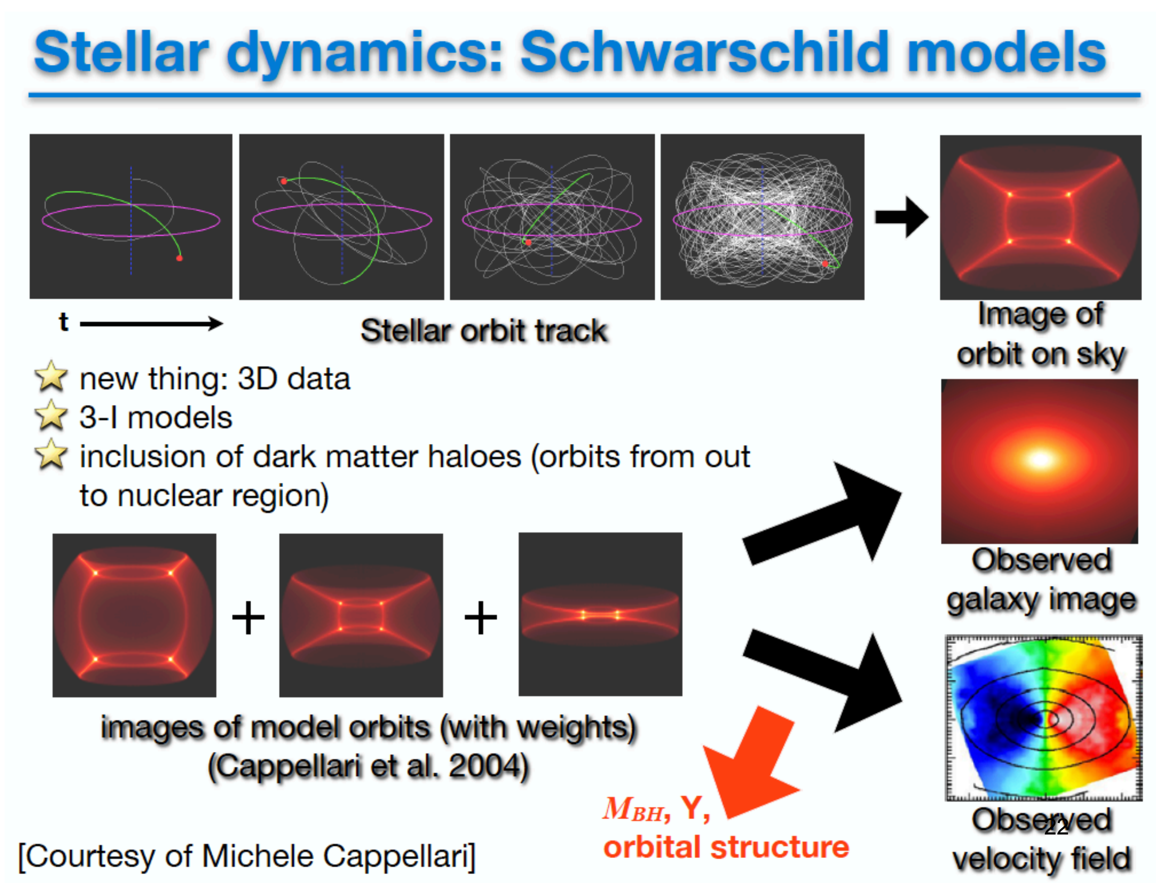
- Notice the nasty terms
- V_r is the rotation velocity σ_r $\sigma_{\theta,}$ σ_ϕ are the 3-D components of the velocity dispersion ν is the density of stars
- All of these variables are 3-D; we observe projected quantities !
- The analysis is done by generating a set of stellar orbits and then minimizing
- Rotation and random motions (dispersion) are both important.
- Effects of seeing (from the ground) are important- Hubble data



Modern Data

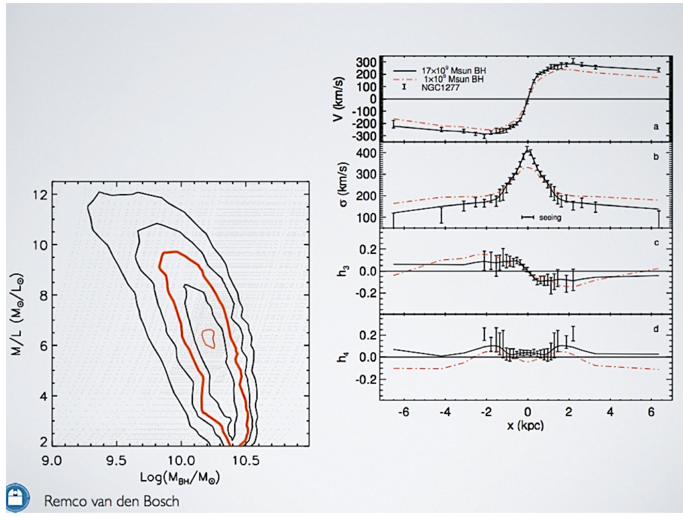
- 2 dimensional imaging spectra (R. van den Bosch)





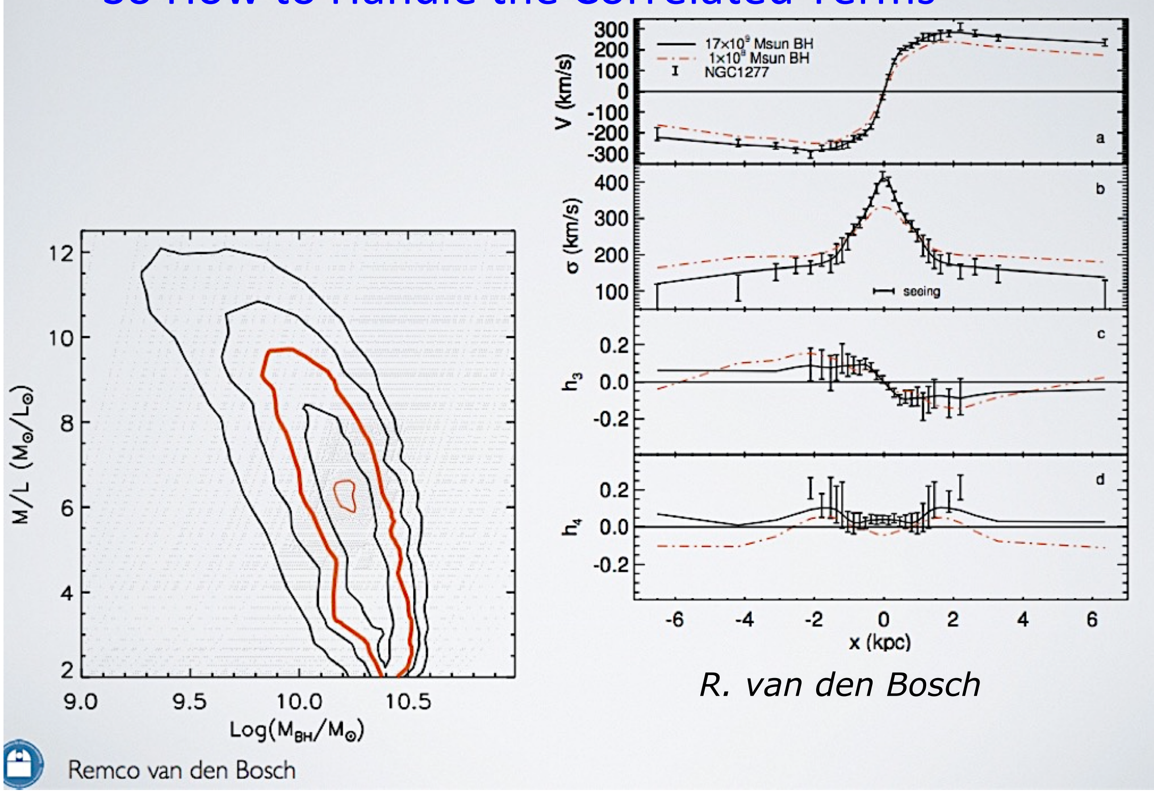
So How to Handle the Correlated Terms

- Construct a 'trial' potential : 3 sources of potential: stars, dark matter, black hole
- Vary the parameters (mass, shape of potential etc) until one gets good agreement with velocity field, distribution of stars.
- One of the big unknowns is how much mass the stars have (make the variable the mass/light ratio of stars)

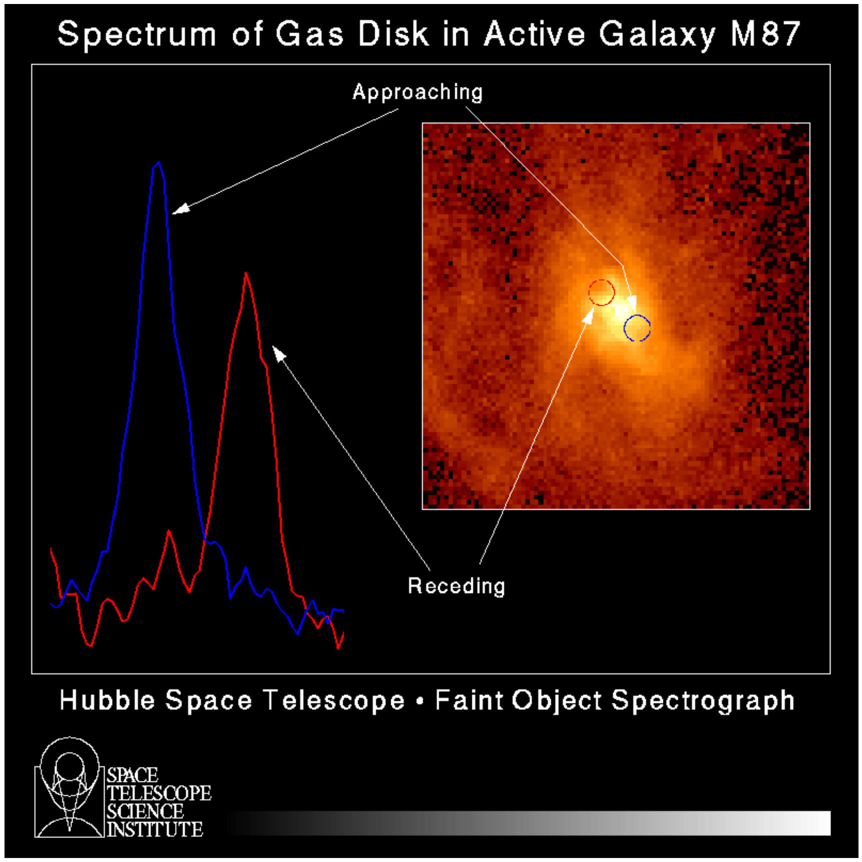


R. van den Bosch

So How to Handle the Correlated Terms

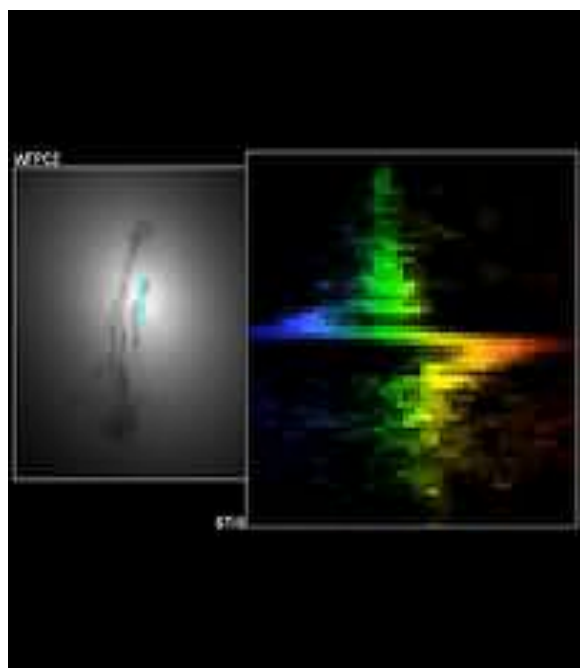


R. van den Bosch



Measuring the Mass of a SuperMassive Black hole

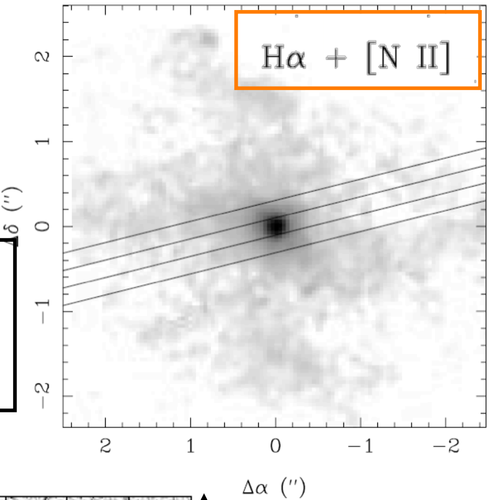
- Image of central regions and Velocity of gas near the center of M84 a nearby galaxy (Bower et al 1998) -
- The color scale maps the range of velocity along the slit, with blue and red color representing velocities (with respect to systemic) that are blueshifted and redshifted, respectively.
- The dispersion axis (horizontal) covers a velocity interval of 1445 km s-1, while the spatial axis (vertical) covers the central 3 arcsec;.



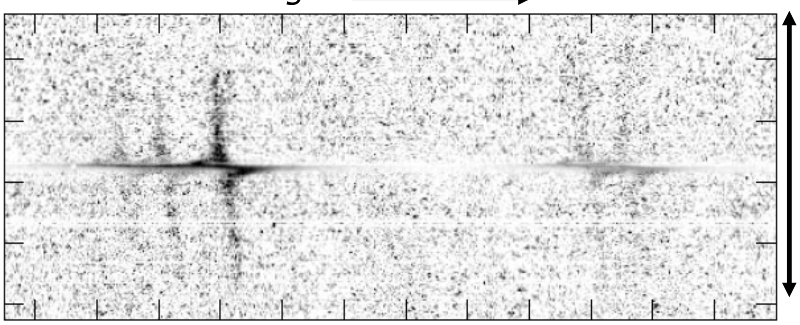
Measurement of Kinematics of Gas

- Image of optical emission line emitting gas around the central region of the nearby giant galaxy M84

HST STIS Observations of the Nuclear Ionized Gas in the Elliptical Galaxy M84
G. A. Bower, R. F. Green, D.



wavelength



Position on sky along slit

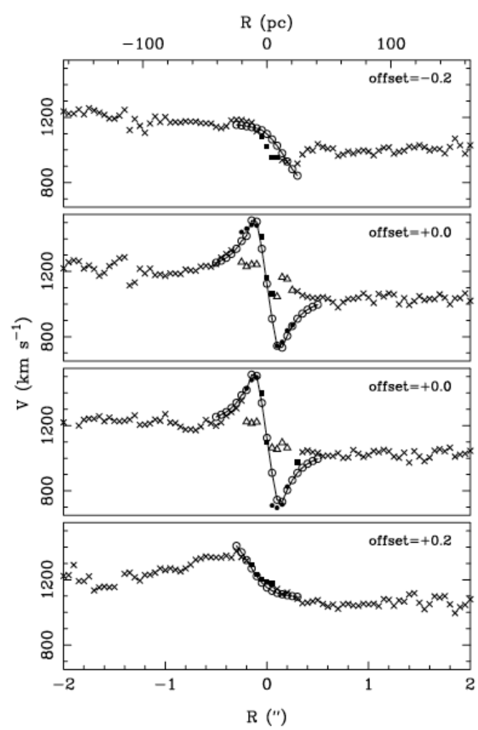
Analysis of Spectral Data for M84

- Mass of central object $1.5 \times 10^9\ M_{sun}$

TABLE 1
KEPLERIAN DISK MODEL PARAMETERS

Parameter	Best Fit	Uncertainty Range
Black hole mass ($M_\odot$)	1.5×10^9	$(0.9–2.6) \times 10^9$
Disk inclination (deg)	80	75–85[a]
Disk P.A. (deg)	83	80–85
Gas systemic velocity (km s^{-1})	1125	1100–1150
Intensity law	$I(r) \propto r^{-1}$	...
$I(r)$ inner radius (pc)	1	0.3–3
$V(r)$ inner radius (pc)	0.03	0.01–0.1
PSF σ (arcsec)	0.05	0.04–0.06

[a] Lower mass requires lower inclination.



*Velocity of **gas** vs distance from center of emission along 3 parallel lines*

M87

- Velocity dispersion vs radius

Gebhardt et al 2011 (1"=80pc)

$M=6.6\times10^{9}M_{\odot}$

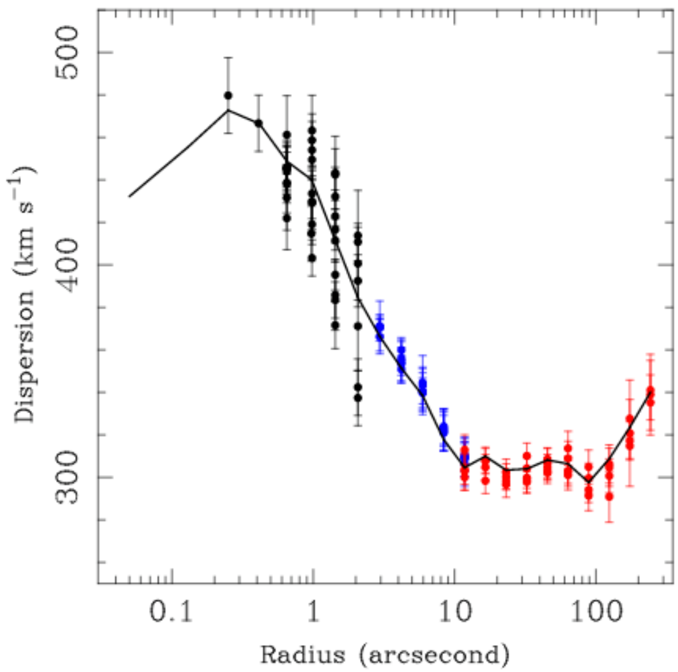
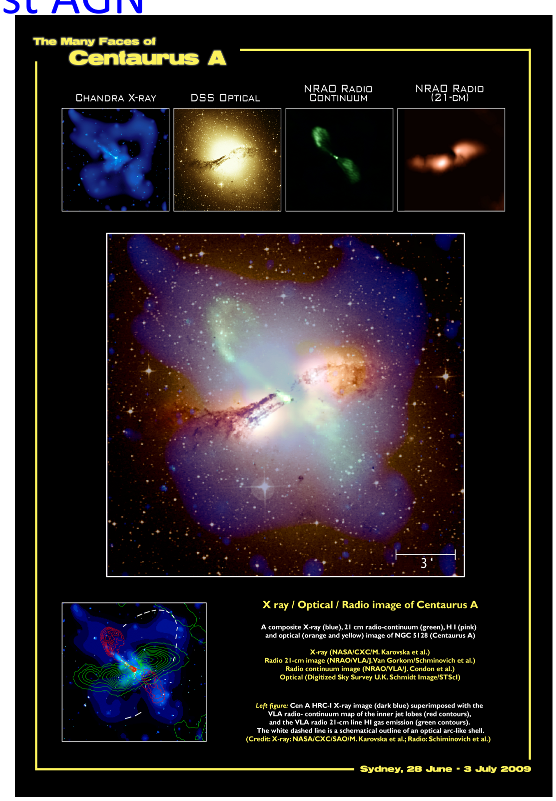


FIG. 5.— Velocity dispersion versus radius for M87. The black points are the NIFS data. The red points are the VIRUS-P data from Murphy et al. (2011), and the blue points are from the SAURON data. The multiple points at each radius represent the various position angles. The solid line is the best-fit model,

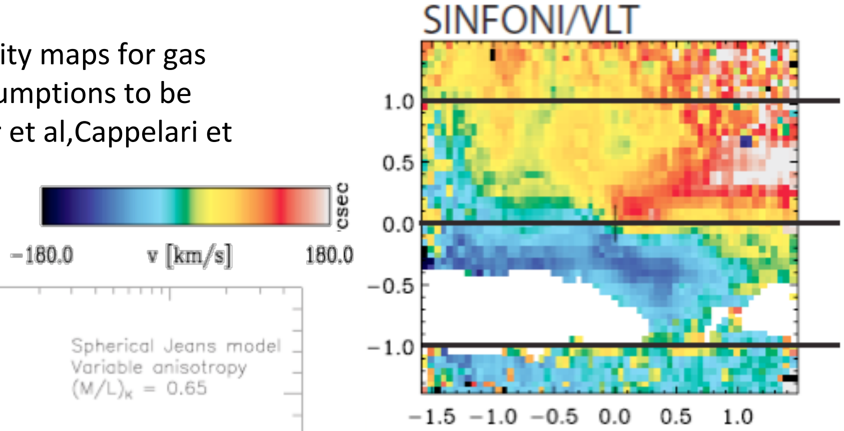
Centaurus-A The Nearest AGN



Centaurus -A

- 2 dimensional velocity maps for gas and stars allow assumptions to be checked (Neumayer et al,Cappelari et al)

Gas Velocities



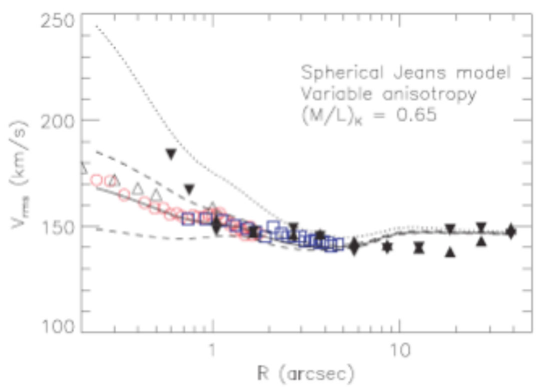
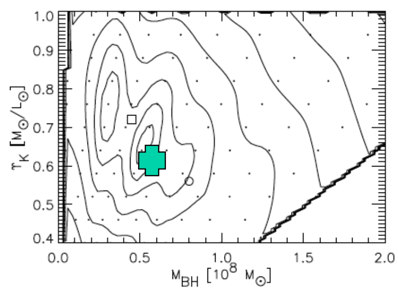


Figure 4: Spherical anisotropic Jeans model

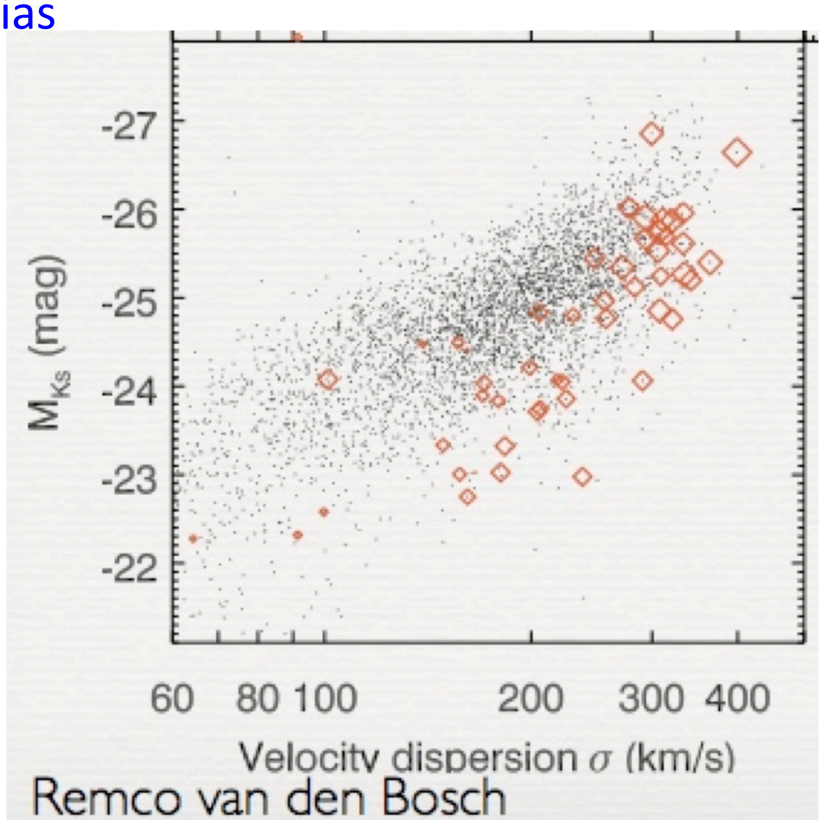
$$\boxed{M_{\rm BH} = (5.5 \pm 3.0) \times 10^7 M_\odot.}$$



Constraints from stars compared to those from Gas Velocities

Selection Bias

Red symbols are galaxies with measured BH masses from dynamics



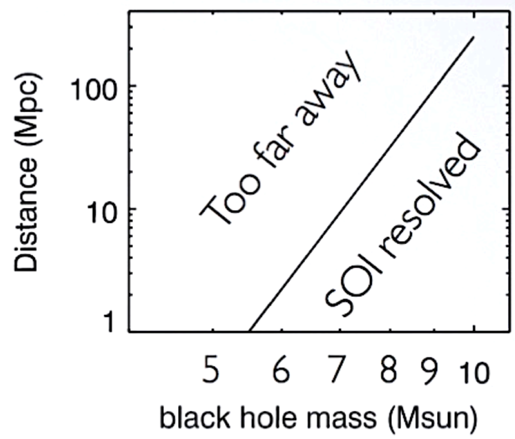
WHY ARE THERE FEW BLACK HOLE MASS MEASUREMENTS AT Z=0?

- **MANY REQUIREMENTS FOR DYNAMICAL ESTIMATES:**
- Resolve the Sphere-of-influence

$$R_{soi} = \frac{GM_{\bullet}}{D\sigma^2} \propto \frac{\sigma^{2.2}}{D}$$

Thus HST/STIS or AO. And few available targets

- Spatially resolved kinematics
- High resolution photometry for stellar mass model



R. van den Bosch

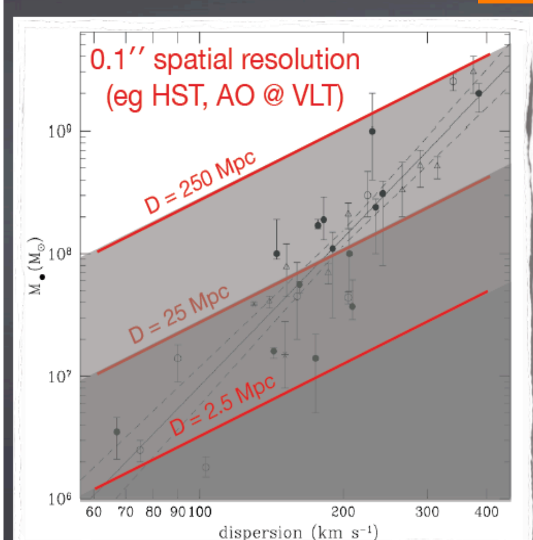
Remco van den Bosch

Direct BH mass measurements

BH sphere of influence

$$r_{BH} = \frac{G\,M_{BH}}{\sigma_\star^2} = 10.7\,\mathrm{pc}\left(\frac{M_{BH}}{10^8\,M_\odot}\right)\left(\frac{\sigma_\star}{200\,\mathrm{km/s}}\right)^{-2}$$

$$\theta_{BH} = \boxed{0.11''}\left(\frac{M_{BH}}{10^8\,M_\odot}\right)\left(\frac{\sigma_\star}{200\,\mathrm{km/s}}\right)^{-2}\left(\frac{D}{\boxed{20\,\mathrm{Mpc}}}\right)^{-1}$$



BHs are directly detectable with spatially resolved kinematics ONLY in the local universe

Need to calibrate indirect BH mass estimators like for the cosmological distance ladder

Marconi

The BIG Picture

Based on ground seeing

2015ApJS..218...10V
 van den Bosch, Remco C. E.;et al .
Hunting for Supermassive Black Hole
Nearby Galaxies With the Hobby-Ebe
Telescope

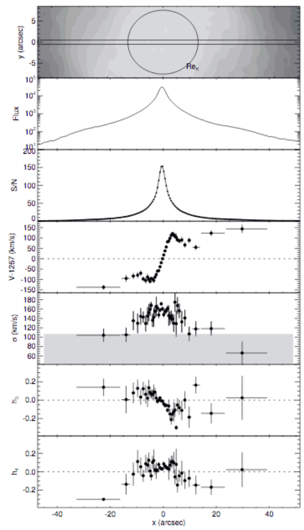
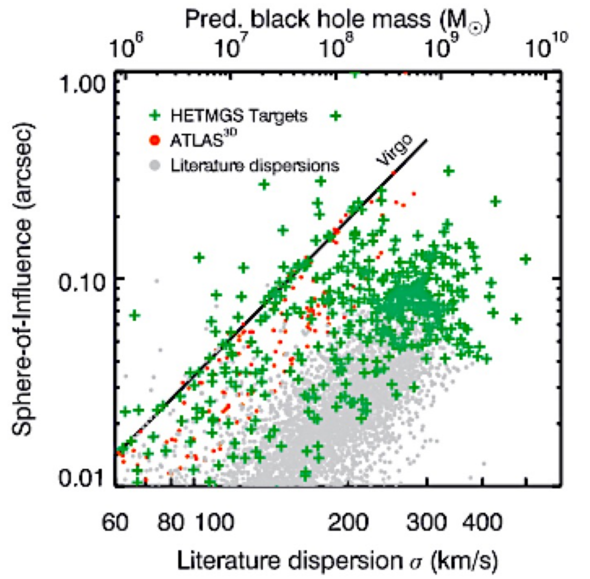


Figure 5. Example of the resolved stellar kinematics using exposure 262031 of NGC2950. The kinematics are measured in bins that are combined to



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NGC4258- Rotation of Maser Disk

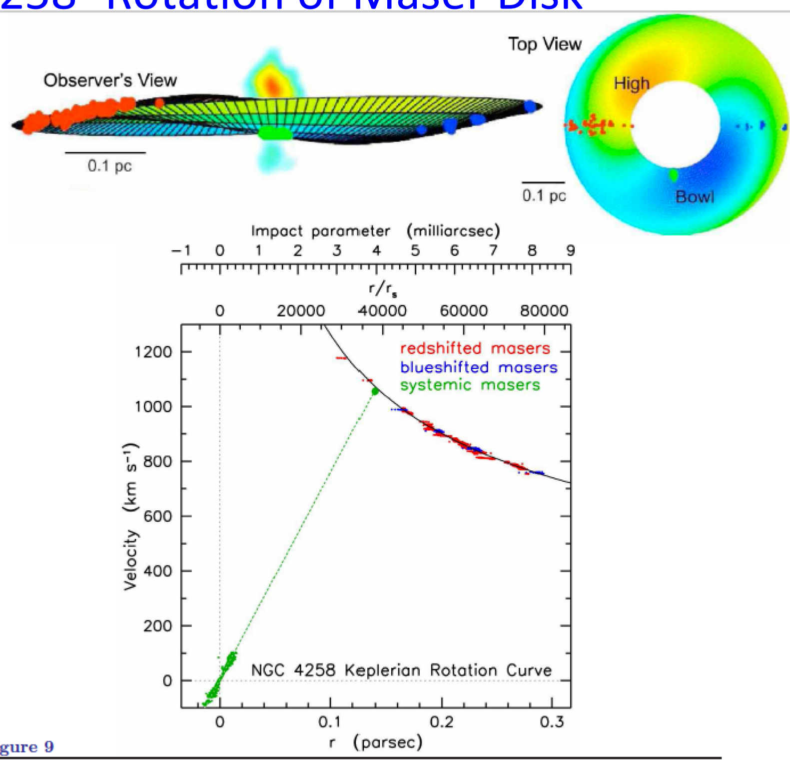
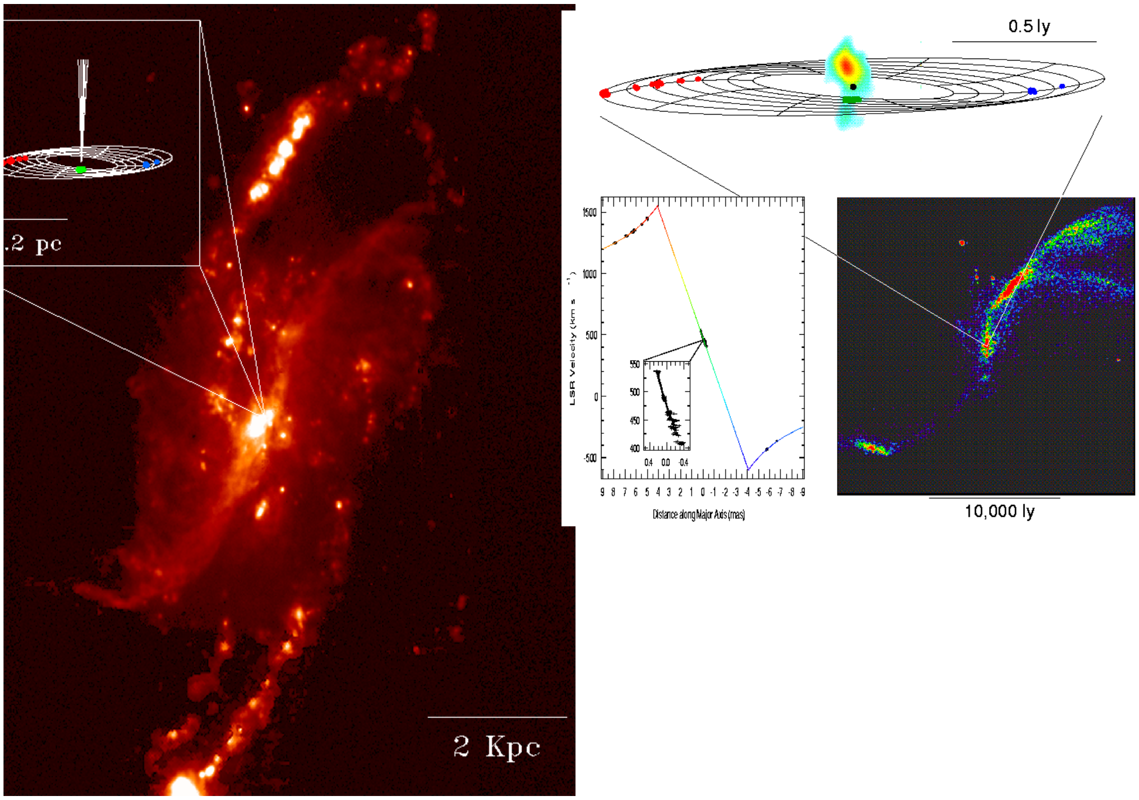
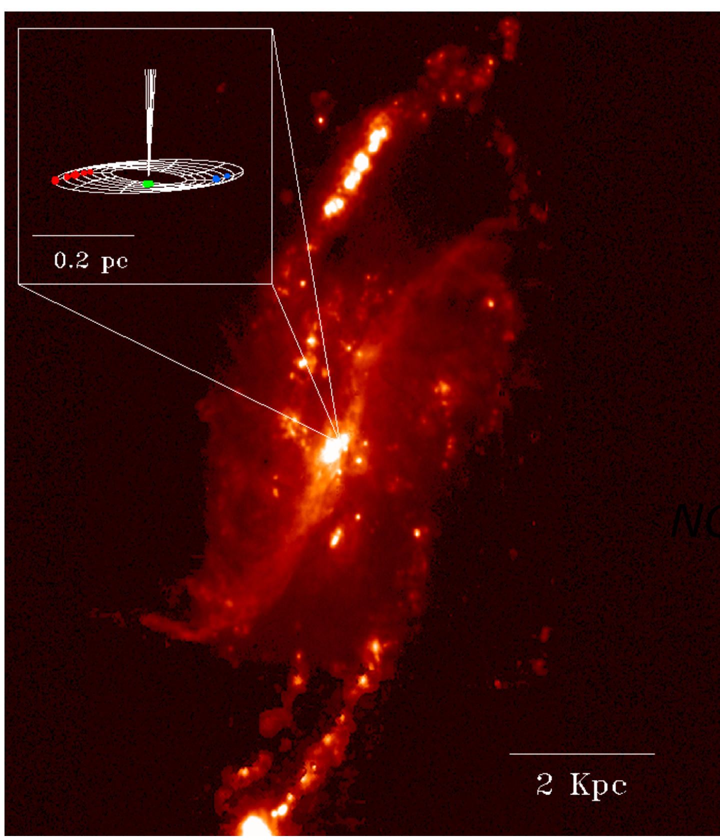


Figure 9

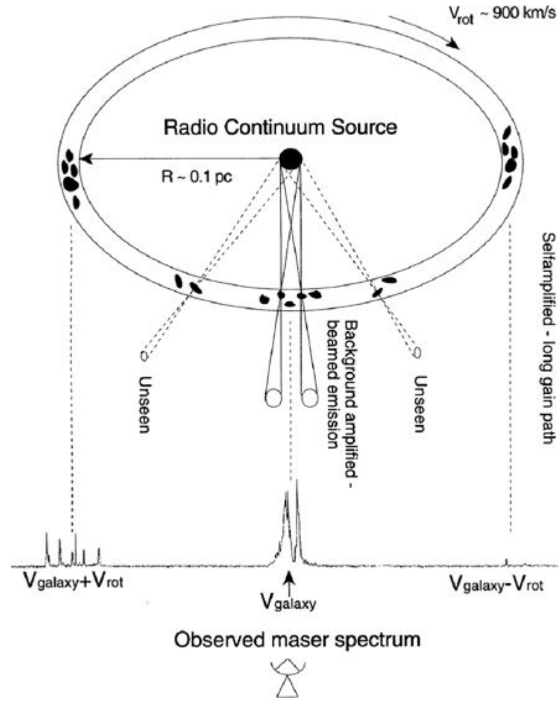
(*top*) Schematic views of the almost-edge-on, warped maser disk of NGC 4258 (from Moran 2008) with warp parameters from Herrnstein et al. (2005) and including the inner contours of the radio jet.


.2 pc
2 Kpc
0.5 ly
Distance along Major Axis (mas)
10,000 ly


0.2 pc
2 Kpc

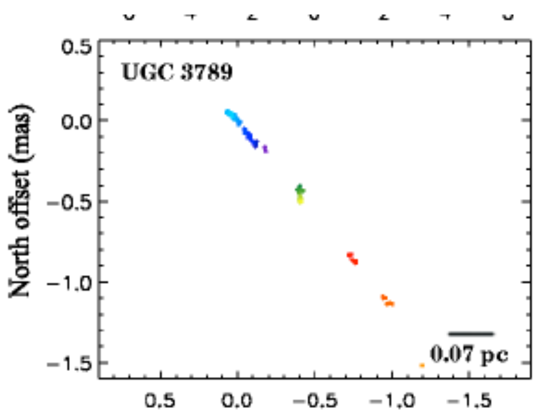
NGC4258

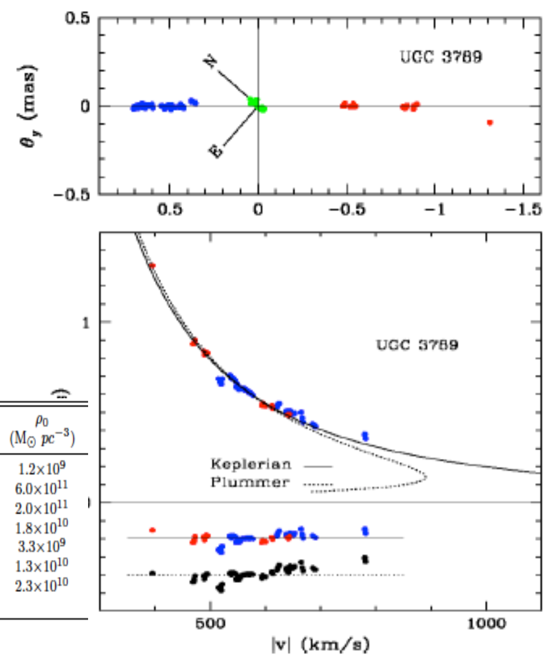
Maser Geometry Longair pg 619



megamasers in the nuclear regions of NGC 4258 (Greenhill *et al.*, 1995b), illu

Other Masers

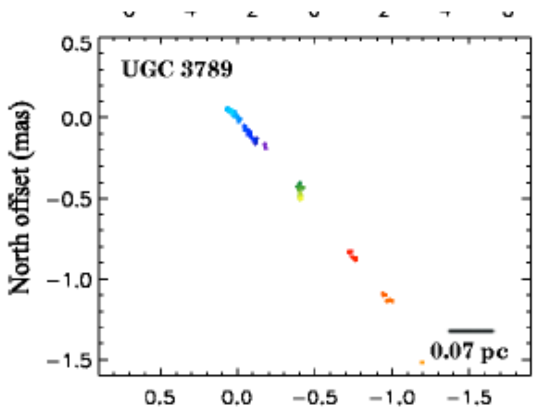


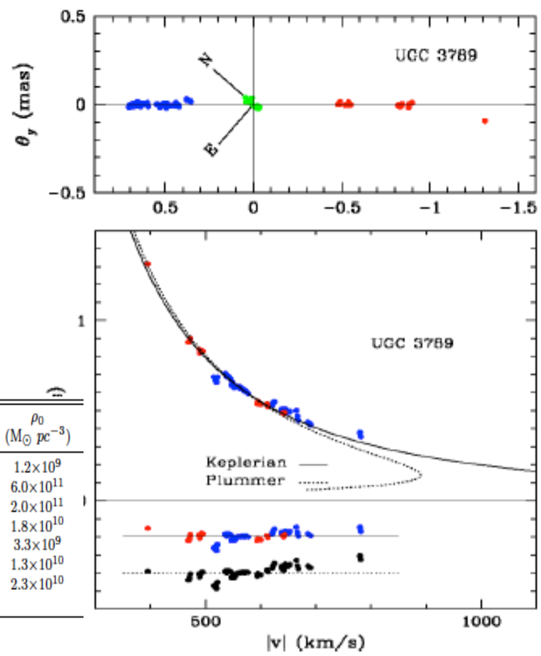


Name	Dist. (Mpc)	BH mass (10^7 $M_\odot$)	Disk Size (pc)	P.A. (°)	Incl. (°)	r_c (pc)	ρ_0 ($M_\odot$ pc^{-3})
NGC 1194	52	6.4±0.3	0.53-1.30	157	85	0.250	1.2×10^9
NGC 2273	26	0.76±0.04	0.028-0.085	153	84	0.015	6.0×10^{11}
UGC 3789	50	1.12±0.05	0.09-0.32	41	> 88	0.024	2.0×10^{11}
NGC 2960	71	1.14±0.05	0.13-0.36	−131	89	0.055	1.8×10^{10}
NGC 4388	19	0.84±0.02	0.24-0.29	107	–	0.090	3.3×10^9
NGC 6264	136	2.84±0.04	0.23-0.78	−85	90	0.083	1.3×10^{10}
NGC 6323	105	0.93±0.01	0.13-0.30	10	89	0.046	2.3×10^{10}

Kuo et al 2010

Other Masers





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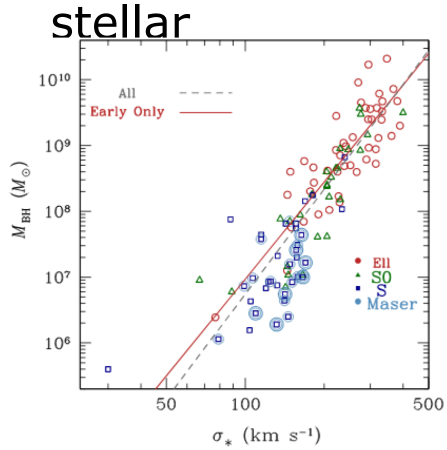
Kuo et al 2010

Updated Mega Maser Sample

- Masers allow probing lower mass black holes in lower mass galaxies than stellar



Galaxy (1)	D (2)	Type (3)	M_{BH} (4)	σ^* (5)	M_{tot} (6)	M_{1kpc} (7)	Meth (8)
Mrk1029	124.0	3p	6.28± 0.13	2.12± 0.05	10.57± 0.05	10.08± 0.06	maser
NGC1320	49.1	3p	6.74± 0.16	2.15± 0.05	⋯	⋯	maser
J0437+2456	66.0	3p	6.45± 0.03	2.04± 0.05	10.57± 0.22	10.04± 0.04	maser
ESO558−G009	102.5	3p	7.22± 0.03	2.23± 0.05	⋯	⋯	maser
UGC6093	150.0	3p	7.41± 0.02	2.19± 0.05	11.21± 0.05	10.19± 0.08	maser
NGC5495	93.1	3p	7.00± 0.05	2.22± 0.05	⋯	⋯	maser
NGC5765b	113.0	3p	7.64± 0.05	2.21± 0.05	⋯	⋯	maser
IC2560	41.8	3	6.64± 0.06	2.15± 0.03	⋯	⋯	maser
NGC1068	15.9	3p	6.92± 0.25	2.18± 0.02	10.42± 0.58	10.63± 0.06	maser
NGC1194	58.0	2	7.85± 0.05	2.17± 0.07	10.81± 0.08	10.19± 0.09	maser
NGC2273	29.5	3p	6.93± 0.04	2.10± 0.03	⋯	⋯	maser
UGC3789	49.9	3p	6.99± 0.09	2.03± 0.05	⋯	⋯	maser
NGC2960	67.1	2p	7.03± 0.05	2.22± 0.04	10.98± 0.03	10.40± 0.03	maser
NGC3079	15.9	3p	6.40± 0.05	2.16± 0.02	10.38± 0.05	9.85± 0.09	maser
NGC3393	49.2	3p	7.20± 0.33	2.17± 0.03	⋯	⋯	maser
NGC4258	7.3	3	7.58± 0.03	2.06± 0.04	10.52± 0.04	10.00± 0.05	maser
Circinus	2.8	3p	6.06± 0.10	1.90± 0.02	⋯	⋯	maser
NGC4388	16.5	3p	6.86± 0.04	2.00± 0.04	10.43± 0.05	9.73± 0.06	maser
NGC6264	147.6	3p	7.49± 0.05	2.20± 0.04	11.01± 0.09	9.92± 0.08	maser
NGC6323	113.4	3p	7.00± 0.05	2.20± 0.07	11.03± 0.09	9.97± 0.05	maser

blue circles are maser BH masses

Masses 2019

- ALMA now has the sensitivity and angular resolution to measure dynamics 'close enough' to the black hole (Combes et al 2019, 1811.00984,Davis et al 2018) and can reach low masses

left panel- no BH
middle wrong inclination

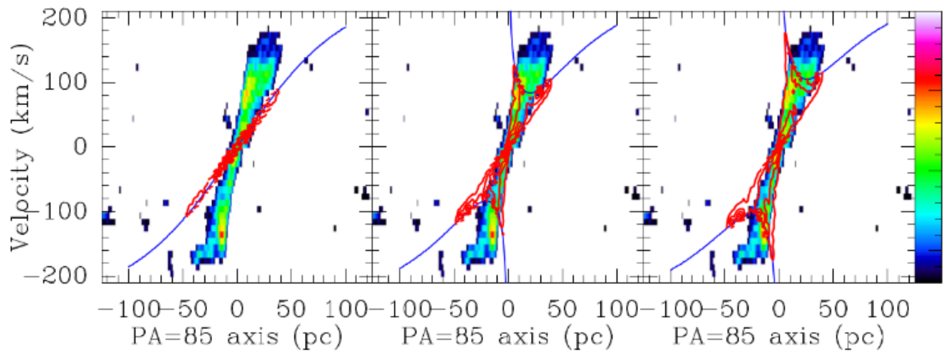
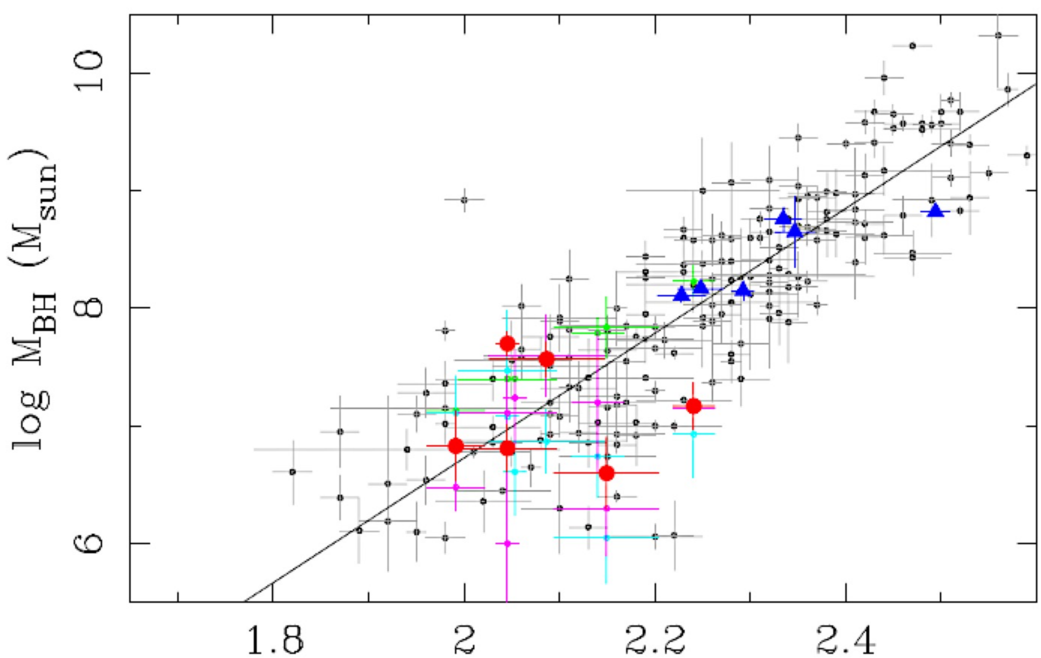


Fig. 10. Position-velocity diagram of the CO(3-2) line in NGC 1672, with a linear color scale (TM1 only). Superposed in red are the contours of the model without any black hole and torus inclination of 66° (left panel), with a black hole as derived from the M_{BH}-σ relation (Table 6) of 2.5 x 10^7 $M_\odot$ with i= 66° (middle panel), and the best fit: a black hole of 5.0 x 10^7 $M_\odot$, with i= 66° (right panel). The mass model is that based on the galfit decomposition, and the predicted circular velocity is reproduced in blue lines (Fig 9).

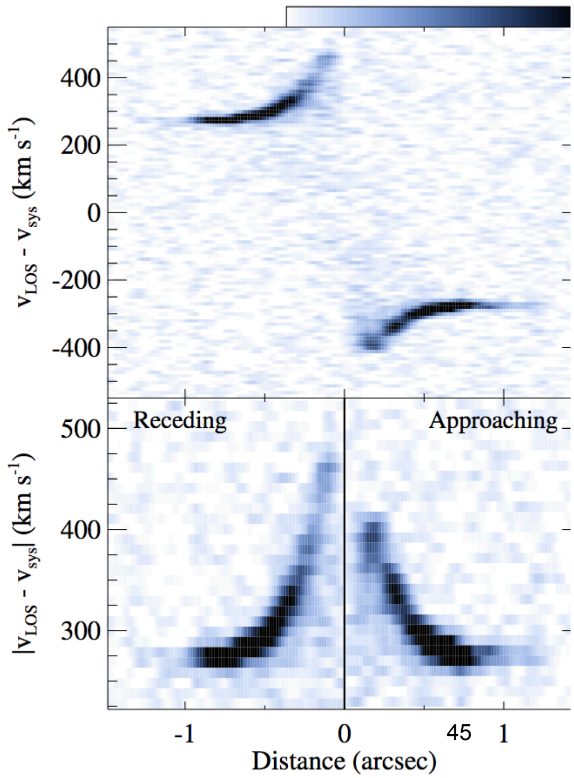
Masses 2019



CO points in red and blue

log σ (km/s)

ALMA CO Observations of NGC3258



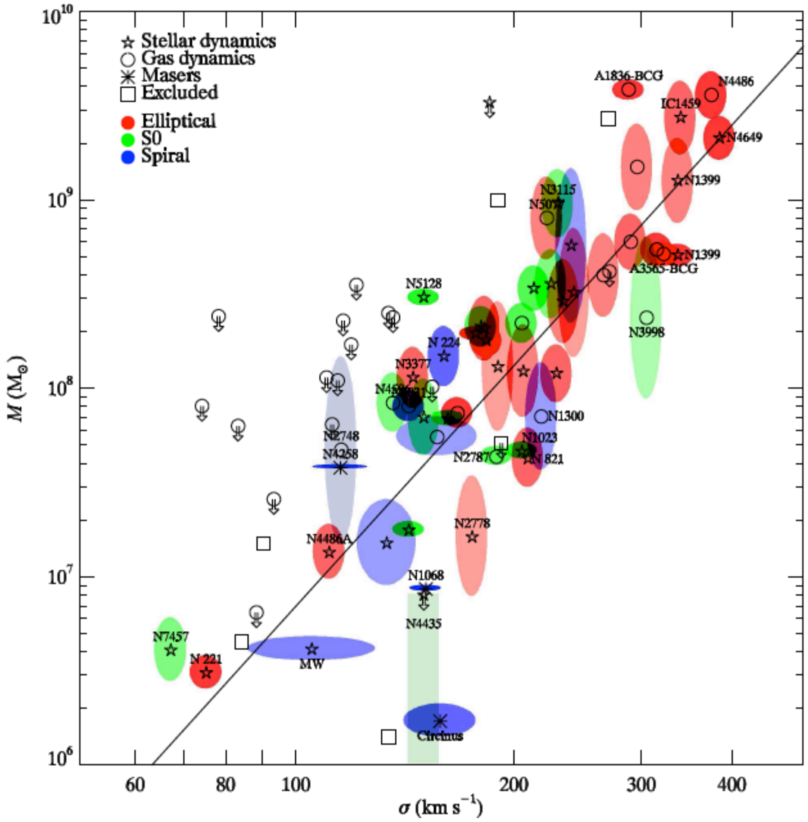
Status of Dynamics

- ~80 'normal' galaxies with secure BH masses
- ~40 with reasonable estimates (see De Nicola et al 2018)
- But limited to local universe (~250 Mpc) until ELTs and JWST

- Nearby Galaxies with **Dynamical Masses for their Central Black Holes** (Gultekin 2009)
- scaling of the mass of the black hole with the velocity dispersion of the stars in the bulge of the galaxy

M_{BH}~$10^{-3}/M_{bulge}$

- Galaxies know about their BH and vice versa

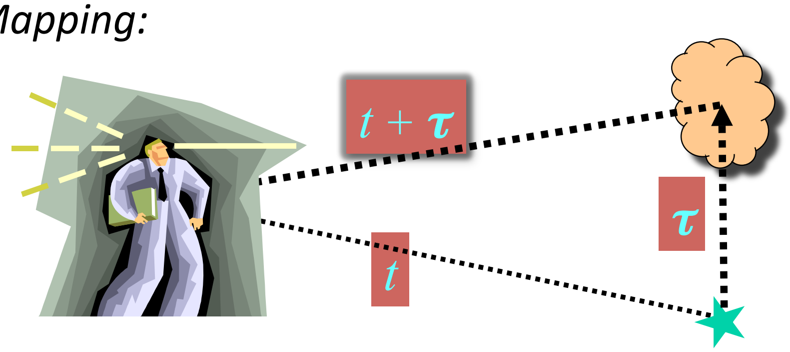


Virial Mass Estimates/Reverberation Mapping- Longair 20.5

$$M_{BH} = f\ v^2\ R_{BLR}/G$$

Reverberation Mapping:

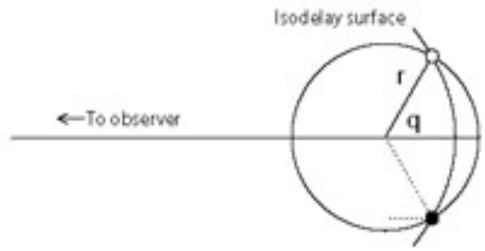
- $R_{BLR} = c\,\tau$
- v_{BLR}



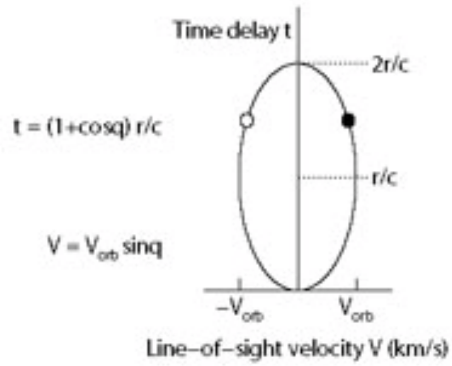
Line width in variable spectrum

What About AGN in General??

- The 'glare' of the black hole makes measuring the dynamics of stars and gas near the black hole very difficult

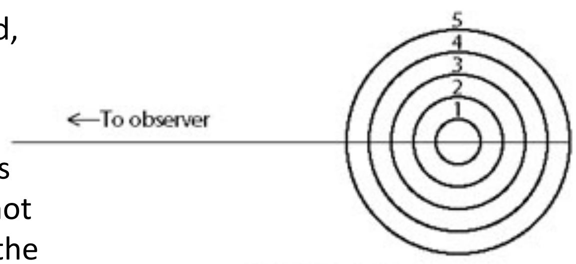


- Technique: reverberation mapping (Peterson 2003)
  - The basic idea is that there exists gas which is moderately close to to the Black Hole (the so-called broad line region- more later) whose ionization is controlled by the radiation from the black hole
  - Thus when the central source varies the gas will respond, with a timescale related to how far away it is

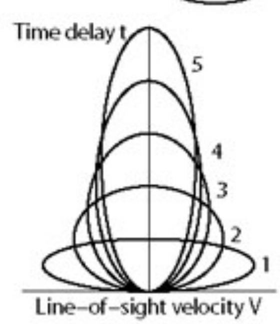


The Geometry

- Points (r, θ) in the source map into line-of-sight velocity/time-delay(τ) space (V, τ) according to $V = -V_{orb} \sin(\theta)$, where V_{orb} is the orbital speed, and $\tau = (1 + \cos(\theta))r / c$.



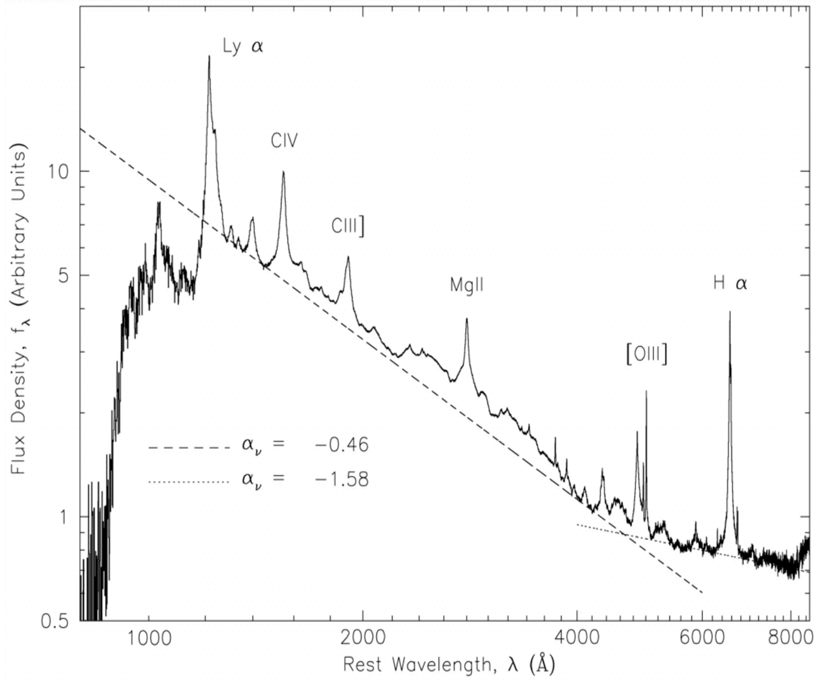
- The idea is that the broad line clouds exist in 'quasi-Keplerian' orbits (do not have to be circular) and respond to the variations in the central source. Lower ionization lines are further away from the central source.
- So



$$M_{BH}=frV^2/G$$

f is a parameter related to geometry- and the orbits of the gas clouds

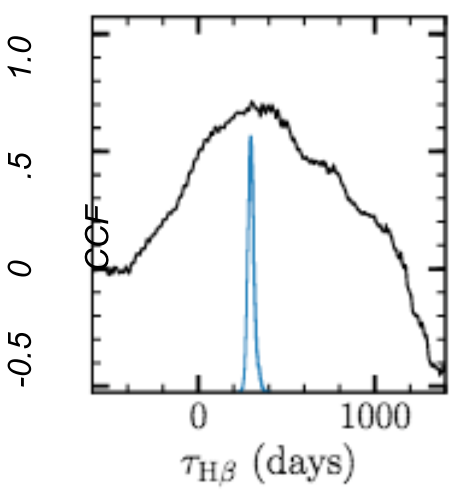
- AGN (type I) optical and UV spectra consist of a 'feature less continuum' with strong 'broad' lines superimposed
- Typical velocity widths (s, the Gaussian dispersion) are ~2000-5000km/sec
- The broad range of ionization is due to the 'photoionzation' of the gas- the gas is not in collisional equilibrium
- At short wavelengths the continuum is thought to be due to the accretion disk

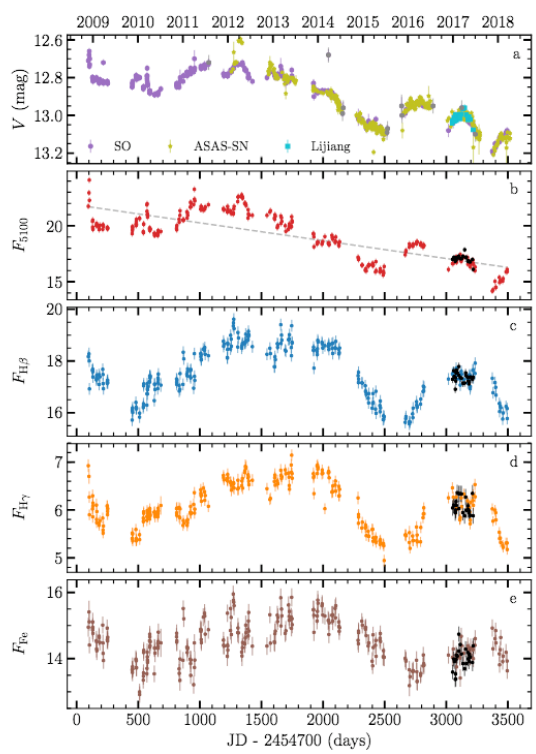


Van den Berk et al 2001

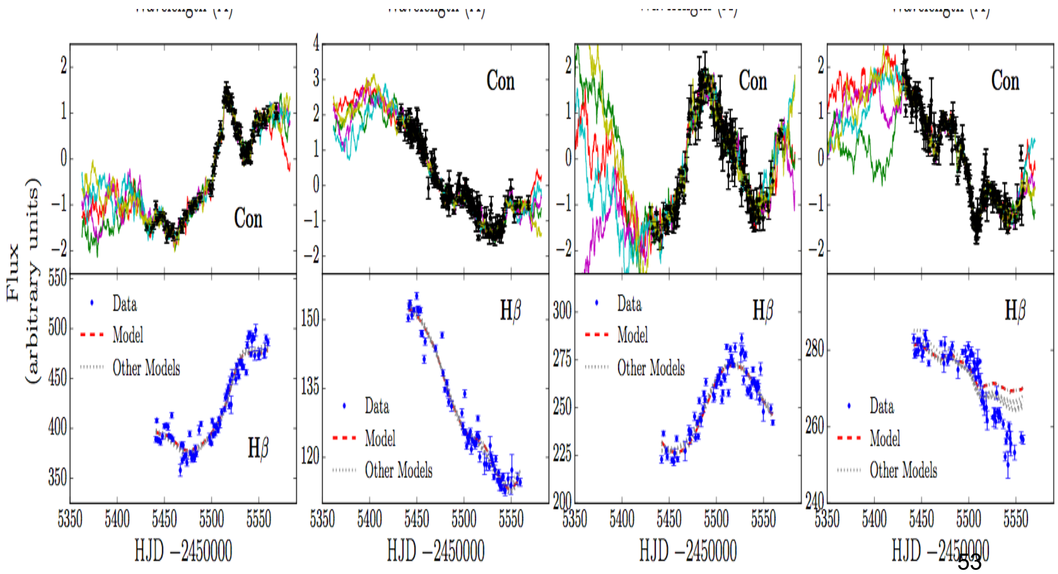
Data for Reverberation Analysis

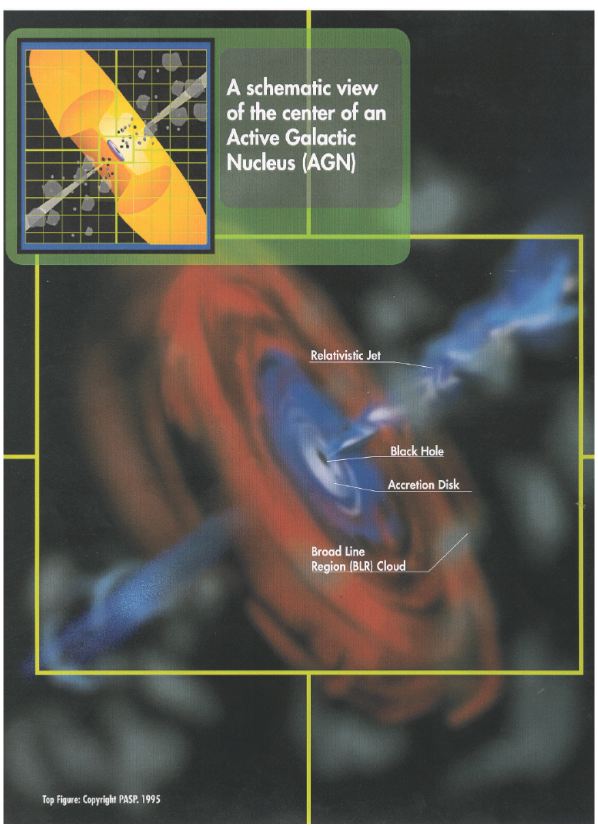
Zhang et al 2018 data for 3c273 and cross correlation of Hβ and continuum- clear lag of 146d





- Time series of continuum and Hβ emission line





Source	Distance from central source
X-Ray Fe K^{α}	3-10 R_S
Broad-Line Region	600 R_S
Megamasers	4×10^4 R_S
Gas Dynamics	8×10^5 R_S
Stellar Dynamics	10^6 R_S

A Quick Guide to Photoionized Plasmas- Reminder

- Fundamental idea photon interacts with ion and electron is ejected and ion charge increased by 1
- $X^{+q}+h\nu \Rightarrow X^{+(q+1)}+e^-$
- Ionization of the plasma is determined by the balance between photionization and recombination
- Photoionization rate is proportional to the number of ionizing photons x number of ionsxthe cross section for interaction and the recombination rate to the number of ions x number of electrons x atomic physics rates

• Steady state ionization determined not by temperature, but by balance between photo-ionization ($\sim F_E$ spectrum) and recombination (n_e):

$n_q \int F_E \sigma^{PI}(E)dE = n_{q+1} n_e \alpha(T_e)$

• $\boxed{\text{Ionization } n_{q+1}/n_q \propto F/n_e \propto L/n_e r^2 \equiv \xi}$

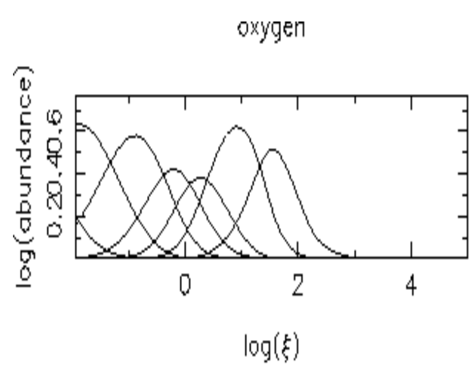
ξ is the ionization parameter (also sometimes called U)

$$\xi = L/n_e r^2$$

if know ξ from spectrum, measure L and derive r from timing analysis have a solution

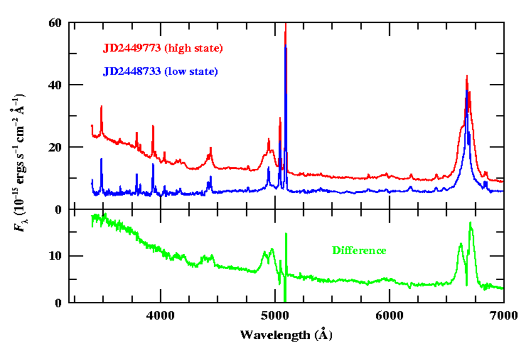
In Other Words

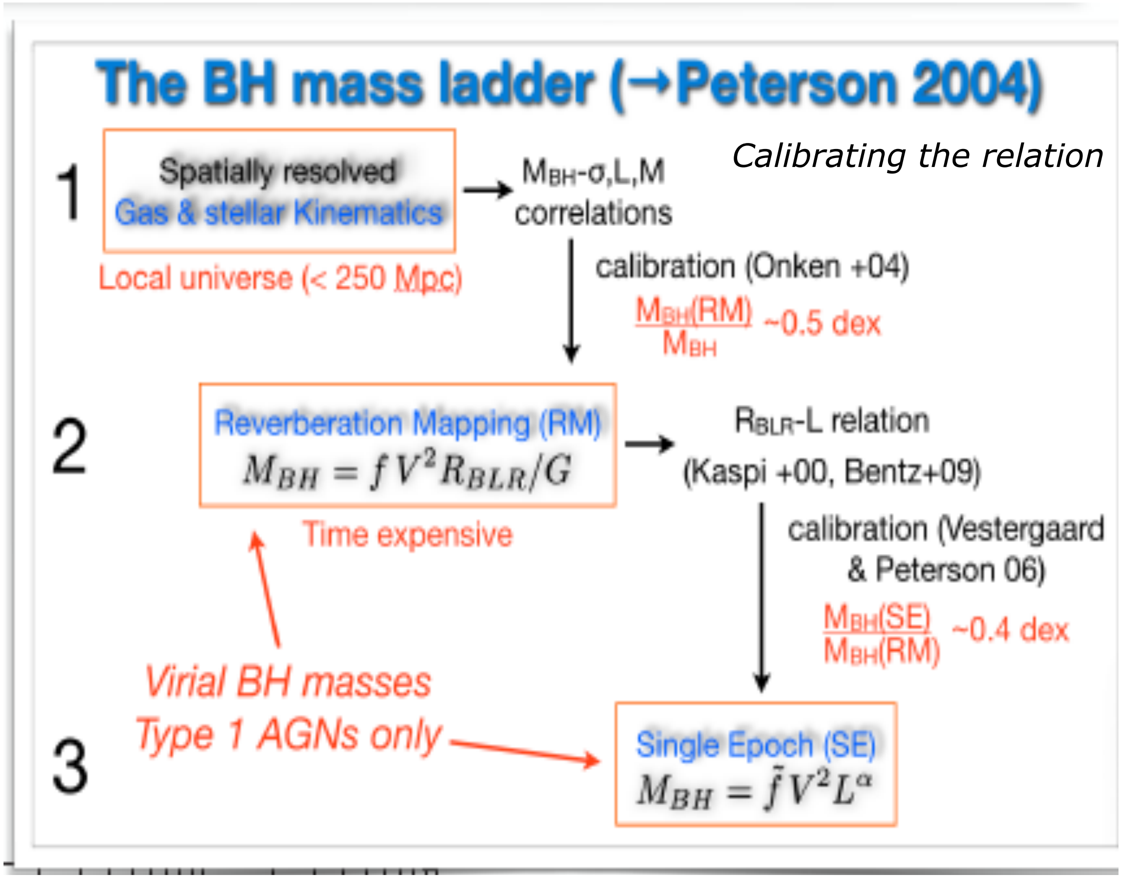
- For each ion:
  - Ionization = recombination
  - ~photon flux ~electron density
- For the gas as a whole
  - Heating = cooling
  - ~photon flux ~electron density
- => All results depend on the ratio photon flux/gas density or "ionization parameter"
- Higher ionization parameters produce more highly ionized lines (higher flux or lower density)



Neutral <------------>fully stripped

Peterson (1999)

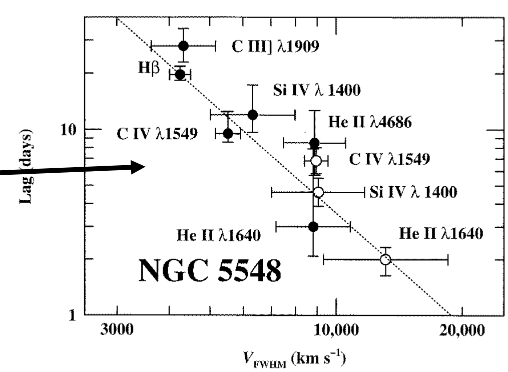




What is Observed??

- The higher ionization lines have a larger width (rotational speed) and respond faster (closer to BH)
- Line is consistent with idea of photoionization, density ~r^{-2}

  and Keplerian motions dominate the line shapes (v ~ $r^{-1/2}$)



- Such data exist for ~70 sources
- At present M_{BH} estimated to

within a factor of a few: M ∝ FWHM^2 L$^{0.5}$

More detailed analysis shows a variety of orbits from near-circular elliptical orbits to inflowing or outflowing trajectories.

The structure of the gas is consistent with a thick disk more or less face-on (see Gravity result on 3C273 Nature 563, 657)

Dotted line corresponds to a mass of 6.8x10^7 M$_\odot$
Peterson and Wandel 1999
For the latest see Pancoast et al 2019ApJ.871.108
and Williams et al 2018ApJ...866...75W

Spatially Resolved BLR !!!

- Gravity data for 3C273

"a spatial offset (with a spatial resolution of 10^{-5} arcsec (~0.03 pc) ..between the red and blue photo-centres of the broad Paschen-α line ..perpendicular to the direction of its radio jet. This spatial offset corresponds to a gradient in the velocity of the gas and thus implies that the gas is orbiting the central supermassive black hole. .. well fitted by a broad-line-region model of a thick disk of gravitationally bound material orbiting a black hole of 3×10^8 solar masses...

- In reverberation mapping experiments, M_{BH} is obtained by combining Balmer-line time-delay measurements with the gas velocity obtained from the line profile. This requires the use of a velocity-inclination factor $f = GM_{BH}/(v^2 R_{BLR})$, GRAVITY data favor f=4.7+/-1.4 .. reverb typical finds (Williams et al) f~4.3 and the broad line width is dominated by bound motion in the gravitational potential of the black hole.
- Zhang et al 18.11.03812 "The time lag of variations in Hβ relative to those of the 5100 A continuum is 146.8+8.3−12.1 days , which agrees very well with the Paschen-α region measured by the GRAVITY at The Very Large Telescope Interferometer; $M_{BH}/M \approx 2.0 \times 10^{-3}$