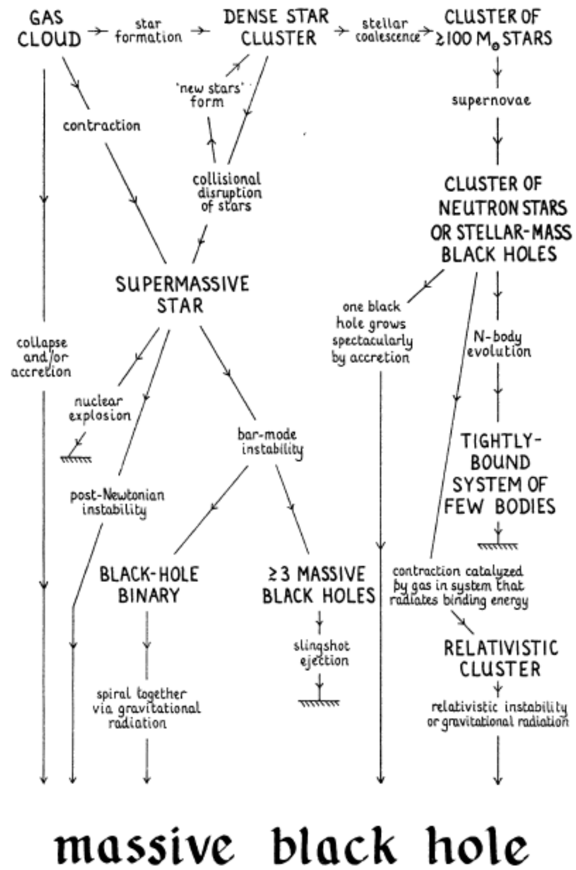
In a dense region all roads lead to a black Hole (Rees 1984 ARAA)



Deriving the Mass of SuperMassive Black Holes

- Stellar velocity fields
  - MW
  - Distant galaxies
- Gas motions
  - gas disks around nearby black holes
  - maser disks

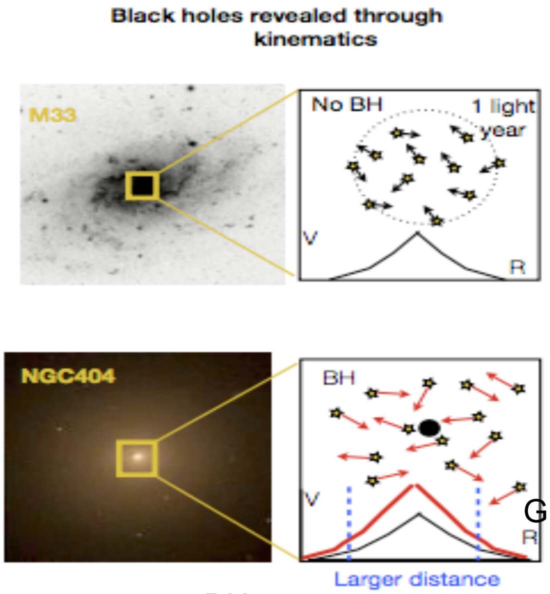
Next paper(s)

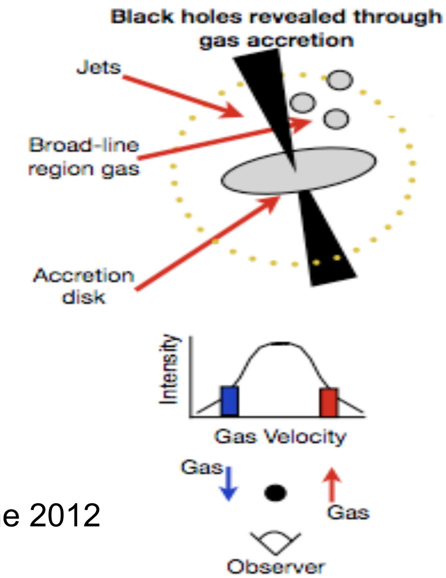
The Black Hole Mass in M87 from Gemini/NIFS Adaptive Optics Observations Gebhardt et al 2011 ApJ 729,119 also see Gebhardt, K., & Thomas, J. 2009, ApJ, 700, 1690

THE RELATIONSHIP BETWEEN LUMINOSITY AND BROAD-LINE REGION SIZE IN ACTIVE GALACTIC NUCLEI Kaspi et al 2005ApJ...629...61

Finding SMBHs

- Detect SMBHs via presence of an AGN (~10% today) OR
- Via dynamics (motion of stars or gas)... imply ~100% at M_{galaxy}>10^{10}M.





Greene 2012

stars near BH move more rapidly because of BH

broad emission lines-gas moving rapidly near BH

Some Scales (Rees 1984)

A central mass M has a gravitational radius

$$r_g = \frac{GM}{c^2} = 1.5 \times 10^{13}\ M_8 \text{ cm}, \qquad 1.$$

where M_8 is the mass in units of $10^8\ M_\odot$. The characteristic minimum time scale for variability is

$$r_g/c \simeq 500\ M_8 \text{ s}. \qquad 2.$$

A characteristic luminosity is the "Eddington limit," at which radiation pressure on free electrons balances gravity:

$$L_E = \frac{4\pi G M m_p c}{\sigma_T} \simeq 1.3 \times 10^{46}\ M_8 \text{ erg s}^{-1}. \qquad 3.$$

Related to this is another time scale

$$t_E = \frac{\sigma_T c}{4\pi G m_p} \simeq 4 \times 10^8 \text{ yr}.$$

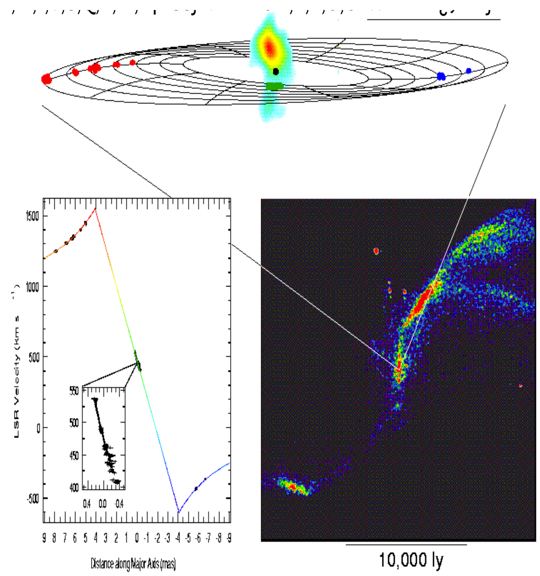
The time scale to grow a black hole if it Were accreting at the Eddington luminosity

The characteristic black body temperature if the Eddington luminosity is emitted at r_g

$$T_E \simeq 5 \times 10^5\ M_8^{-1/4}.$$

Examples of Astrophysical Black Holes

- We know that black holes come in 2 size scales
  - 5-20 M_{sun} ; the result of stellar evolution
  - 10^6-$10^{9.5}$ M_{sun} super massive black holes that reside in the centers of most massive galaxies
  - They may also come in another size scale; intermediate mass black holes with $50<M_{sun}<10^3$
- Detailed stellar evolution calculations indicate that for a star with roughly solar metallicity the maximum mass of the remnant black hole is ~20 M_{sun} so what about the recent GW event ?



Miyoshi et al

How Hot is a Black Hole??

Lets go back to the accretion disk spectrum- Longair 14.52-14.54

As matter flows inward the radiated luminosity is
$L=G\mathcal{M}M/\ 2R^2dR$ ($\mathcal{M}=dM/dt$)
Dividing by the area – get luminosity per unit area and equate this to the black body emission formula

$$G\mathcal{M}M/8\pi R^3=\sigma_{SB}T^4$$

correct dependence on M,$\mathcal{M}$ and R but wrong normalization

Have to account for: Boundary conditions at the inner edge of the disk

Get $T=[3G\mathcal{M}M/8\pi R^3\{1-\mathrm{sqrt}(R/R_{in}\}]^{1/4}$ where R_{in} is the innermost radius

How Hot is a Black Hole??

Lets go back to the accretion disk spectrum- Longair 14.52-14.54

$T(R)=[3G\mathcal{M}M/8\pi R^3]^{1/4}(R/R_{in})]^{-3/4}$

Temperature at fixed number of R_s decreases as $M^{-1/4}$

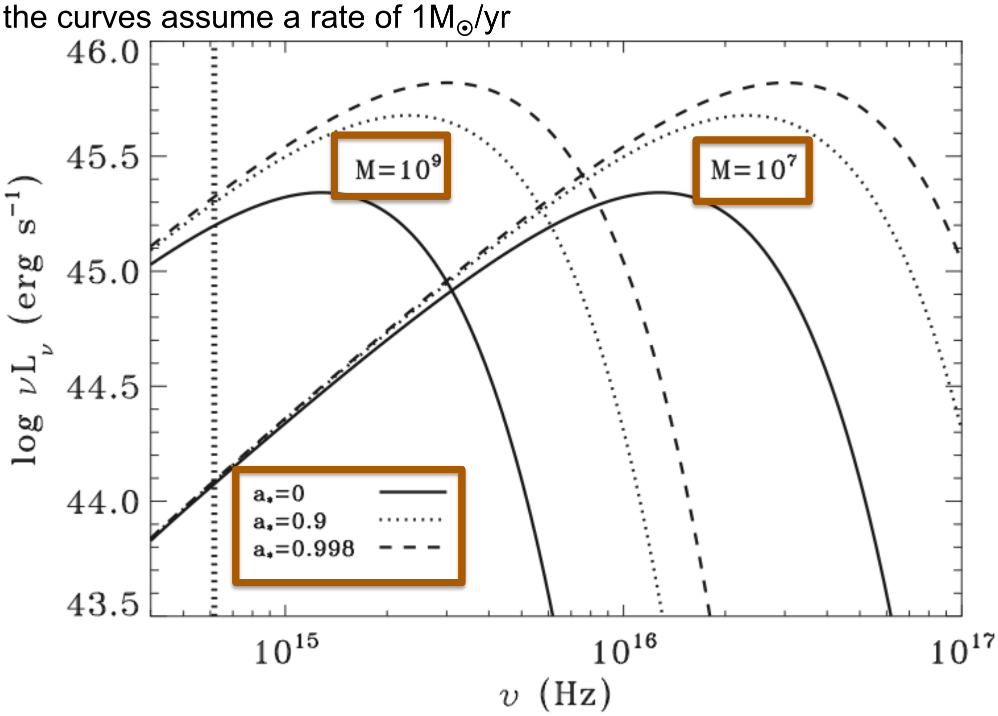
- **disks around more massive black holes are cooler at a fixed R/R_S and $\mathcal{M}/\mathcal{M}_{Edd}$**

now recasting in terms of the Eddington limit where $\mathcal{M}_{Edd}$ is the mass accretion rate for the Eddington limit and we assume that the conversion efficiency of mass into energy is 10% and M_8 is the BH mass in units of 10^8 M⊙

$$T=6.3\times10^5[\mathcal{M}/\mathcal{M}_{Edd}]^{1/4}[M/M_8]^{-1/4}(R/R_{in})]^{-3/4}k$$

Effect of BH Mass and Spin on Emitted Spectrum

all the curves assume a rate of $1M_\odot$/yr



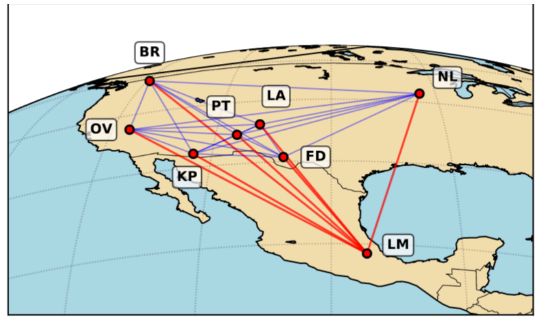
Best Image of SgrA*

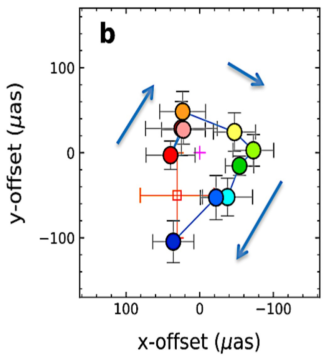
- (147±7μas)×(120±12μas), at position angle 88◦±7◦ (Ortiz-Léon 2016)
- This corresponds ~ 6.5 R_S for a 4×10^6 $M_\odot$ black hole.
- Detection of orbital motions near the last stable circular orbit of the massive black hole SgrA* -we are seeing S

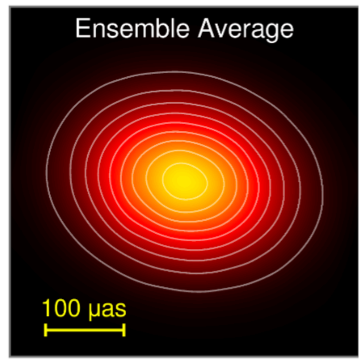
"face on"

- GRAVITY Collaboration 2018

arxiv.org/pdf/1810.12641.pdf







How Hot are Black Holes

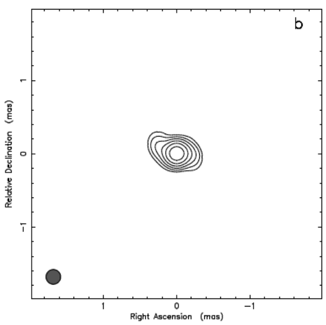
For a black body the spectrum peaks at E= 2.8kT

Expect disk emission in AGN accreting close to the Eddington limit to be strong in the ultraviolet - origin of the broad peak in quasar SEDs in the blue and UV

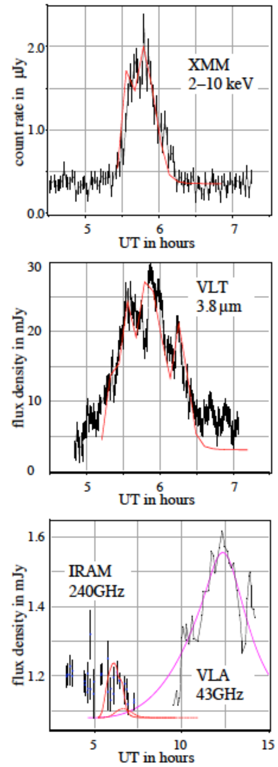
Stellar mass galactic black holes peak in the soft x-ray

The Center of the Milky Way

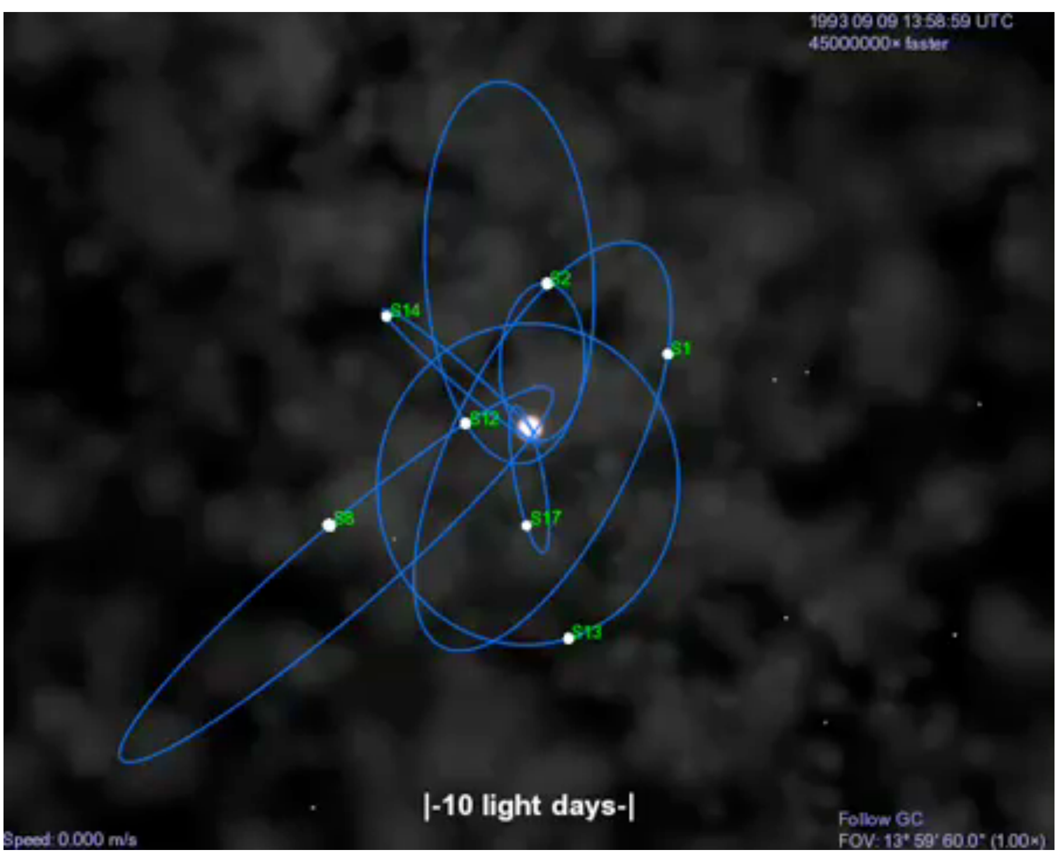
- The center of the MW is called Sagitarius A*(SgrA*) from the name of the radio source at the dynamical center of the MW.
- This is also the location of a weak, time variable x-ray (log L_x~34- 100x less than a typical xray binary) and IR source
- The radio source is very small (<0.0005"<$50R_s$ for $M=4x10^6M_\odot$ BH at d=8kpc)
- At SgrA* 1"=0.04pc=$1.2x10^{17}$ cm ,0.5mas=6AU



Radio image of SgrA*



Radio, near IR and Radi light curves

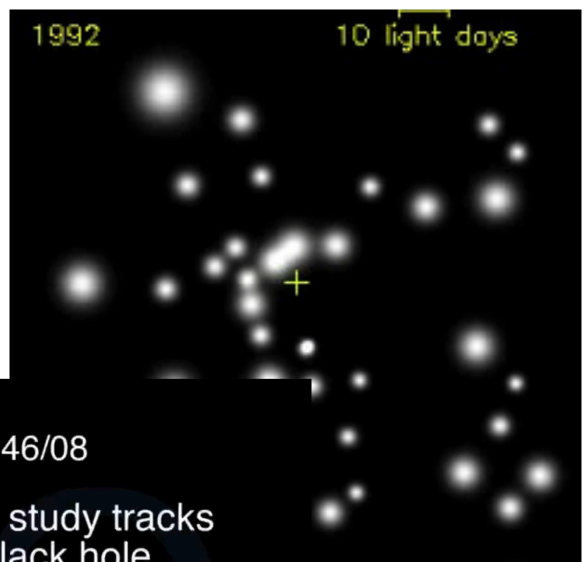


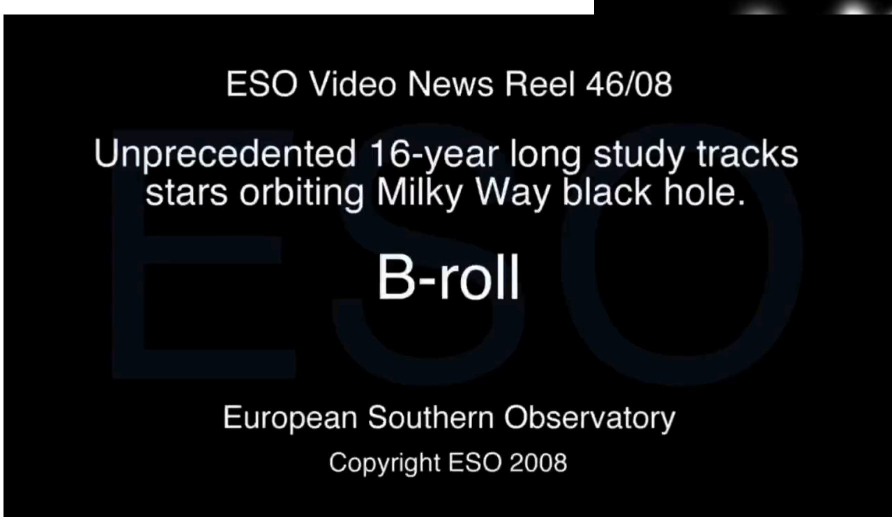
Some Problems with Sgr A*

- There is lots of gas for accretion in the galactic center from the ISM and stellar winds
- Yet the observed luminosity is very low ($L/L_{Edd} \sim 10^{-10}$)
- What happens to the accretion energy- where does the mass and energy go

- Sgr A* is similar to >95% of all massive galaxies- they have big black holes, but low luminosities

Motion of Stars Around the Center of the Milkyway- see http://www.youtube.com/watch?v=ZDxFjq-scvU http://www.mpe.mpg.de/ir/GC/

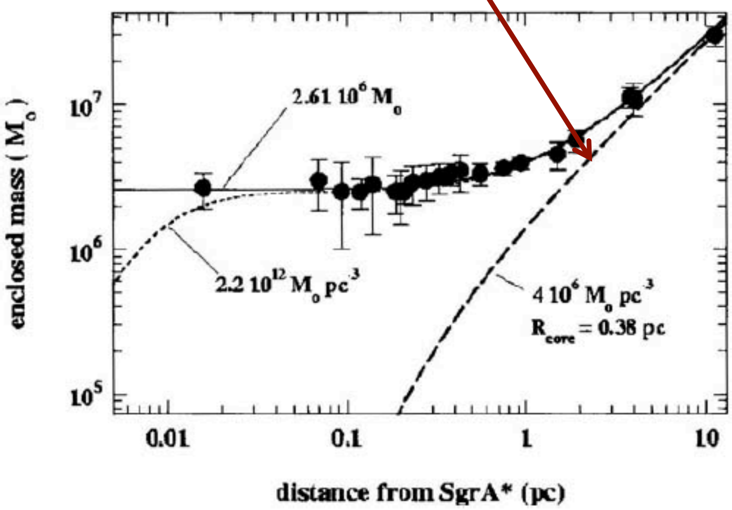




MW Center

Predicted mass from models of the Milkway

- Two teams led by R. Genzel and A. Ghez have measured the 3-D velocities of individual stars in the galactic center
- This allows a determination of the mass within given radii
- The inferred density of the central region is $>10^{12} M_{\odot}/pc^3$



•As shown by Genzel et al the stability of alternatives to a black hole (dark clusters composed of white dwarfs, neutron stars, stellar black holes or sub-stellar entities) shows that a dark cluster of mass $2.6 \times 10^6 M_{sun}$, and density $20 M_{sun} pc^{-3}$ or greater can not be stable for more than about 10 million years

Velocity Distribution of Stars Near the Center of the MW

A Supermassive Black Hole in the Milky Way 29

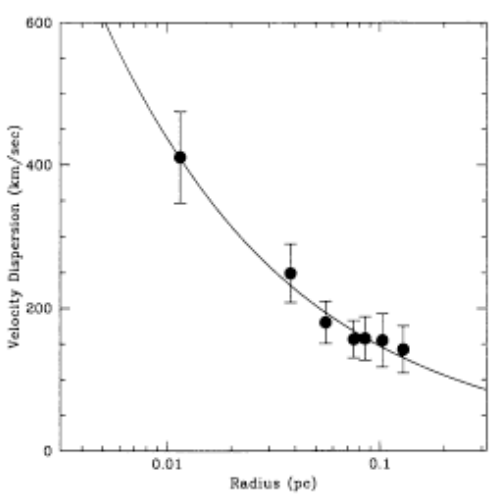


Figure 7. The projected stellar velocity dispersion as a function of projected distance from Sgr A* is consistent with Keplerian motion, which implies that the gravitational field is dominated by mass within 0.1 pc.

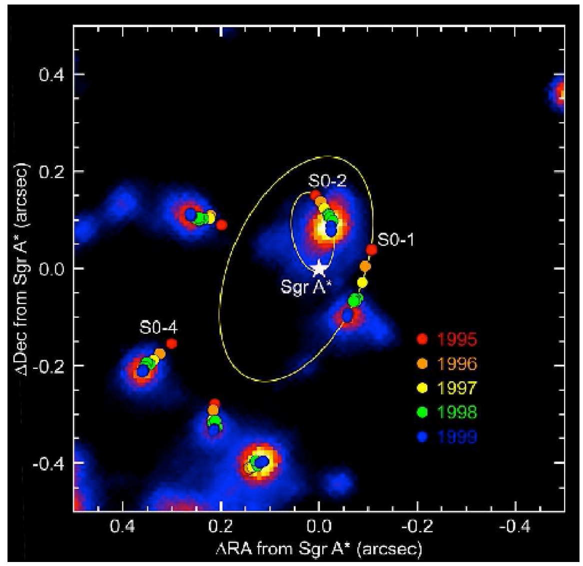
Ghez et al 1998

- While stars are moving very fast near the center (Sgr A*) the upper limit on its velocity is 15 km/sec

If there is equipartition of momentum between the stars and SgrA* then one expects

- $M_{SgrA*} > 1000 M_{\odot} (M_*/10 M_{\odot})(v_*/1500 km/sec(v_{sgrA*}/15 km/sec)^{-1}$

Where we have assumed that the star stars we see have a mass $10 M_{\odot}$ and a velocity of 1500 km/sec



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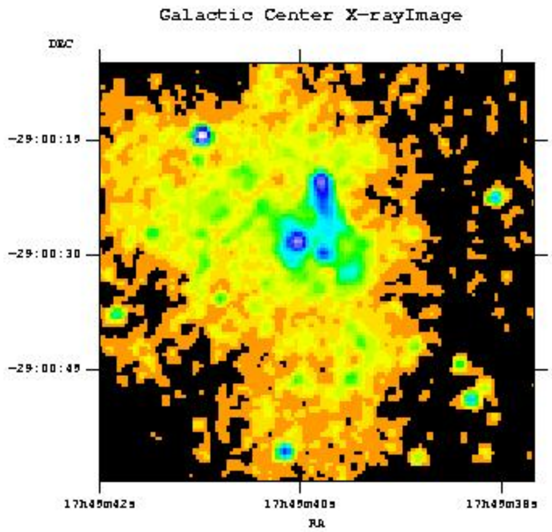
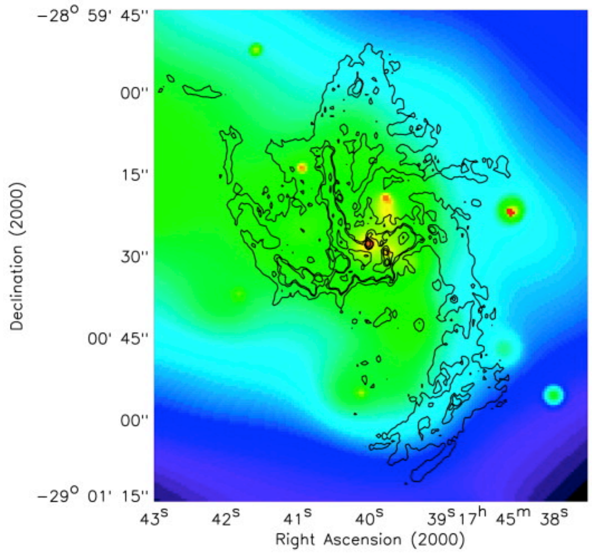
- Paper of interest

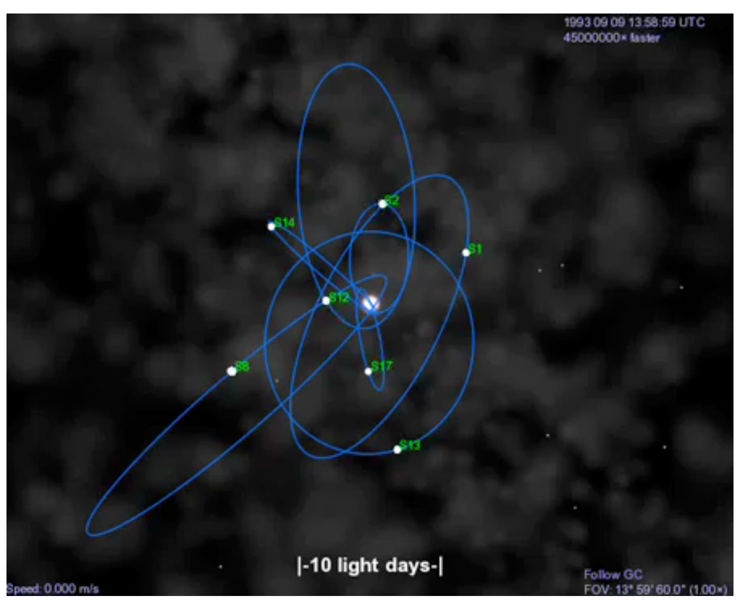
The Milky Way's Supermassive Black Hole: How good a case is it? A Challenge for Astrophysics & Philosophy of Science Andreas Eckart 1703.09118.pdf

Radio and X-ray Image of MW Center





Motion of Stars Around the Center of the Milkyway- see http://www.youtube.com/watch?v=ZDxFjq-scvU
http://www.mpe.mpg.de/ir/GC/



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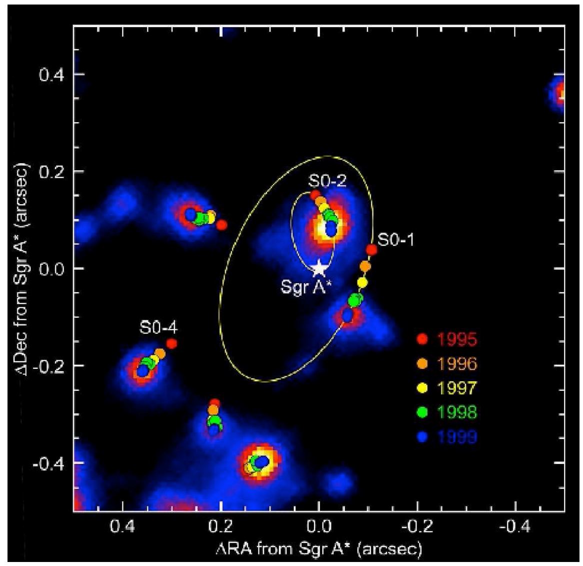
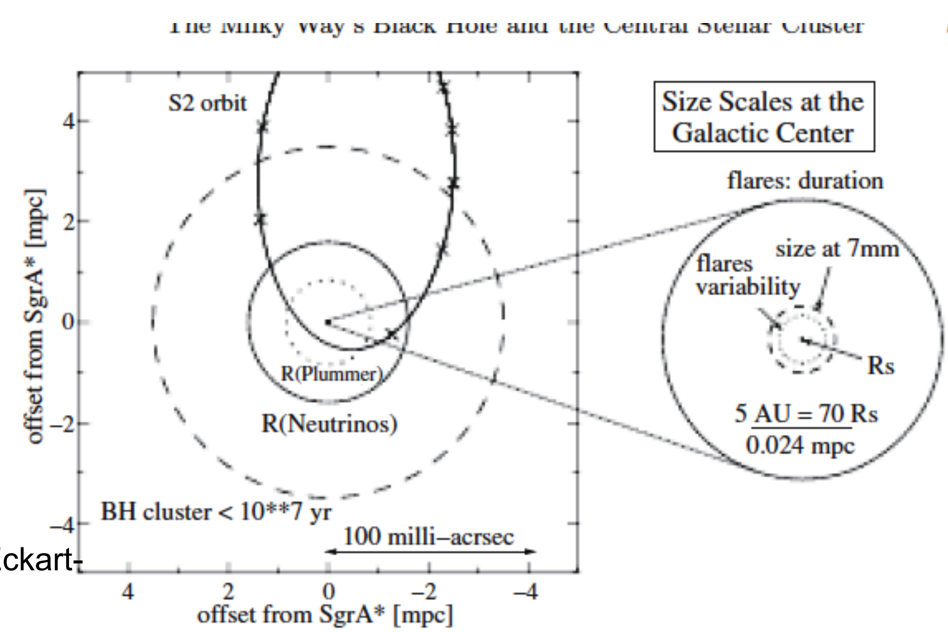
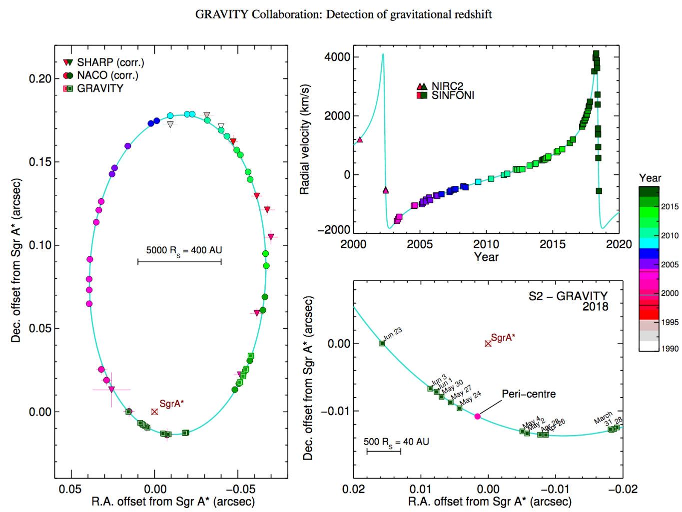




Eckart

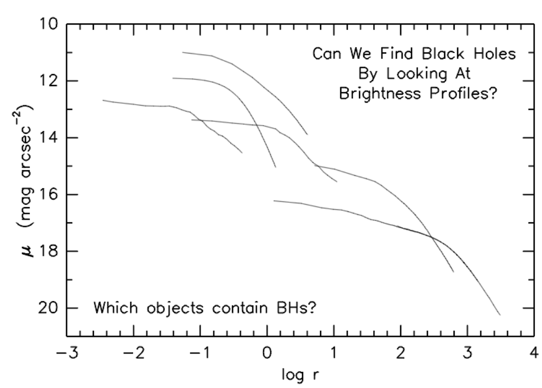
Enormous Improvements

- **Detection of the gravitational redshift in the orbit of the star S2 near the Galactic centre massive black hole★**
- GRAVITY Collaboration A&A V615, July 2018 L15
- "Near pericentre at 120 AU ≈ 1400 Schwarzschild radii, the star has an orbital speed of ≈7650 km s−1, such that the first-order effects of Special and General Relativity have now become detectable"



What About Other Supermassive Black Holes Longair 19.3

- At the centers of galaxies- so much more distant than galactic stellar mass black holes
- First idea: look for a 'cusp' of stars caused by the presence of the black hole- doesn't work, nature produces a large variety of stellar density profiles… need dynamical data
- 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)



Kormendy and Richstone (2003)

Longair 19.3. eq 19.8 and extensive discussion
Gebhardt et al 2011 ApJ 729,119 and Gebhardt, K., & Thomas, J. 2009, ApJ, 700, 1690

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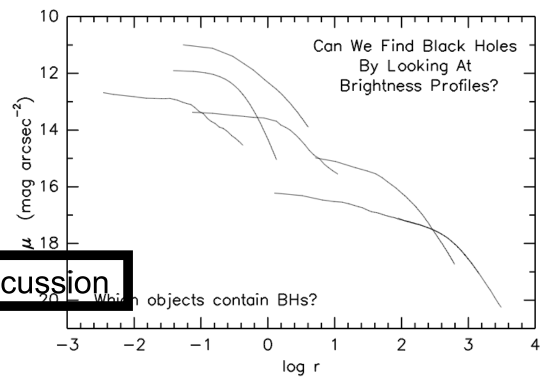


Kormendy and Richstone (2003)

Longair 19.3. eq 19.8 and extensive discussion

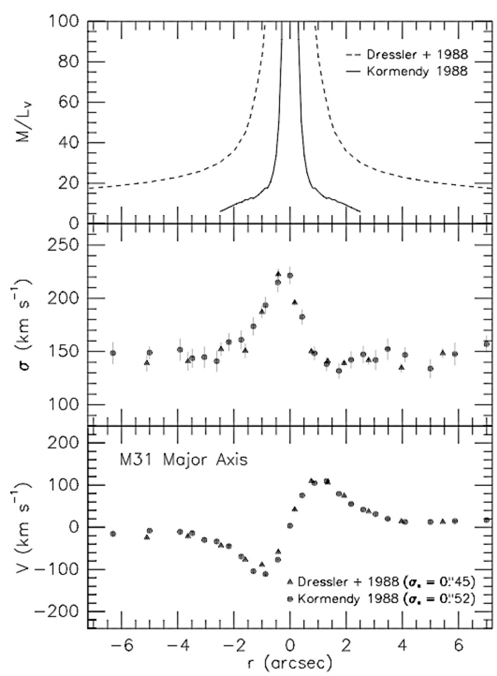
- In Jeans eq $\sigma_r, \sigma_\theta, \sigma_\phi$ are the velocity dispersion in r,θ and ϕ directions , ν is the density of a tracer
- V is the rotational velocity

Longair eq 19.8

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

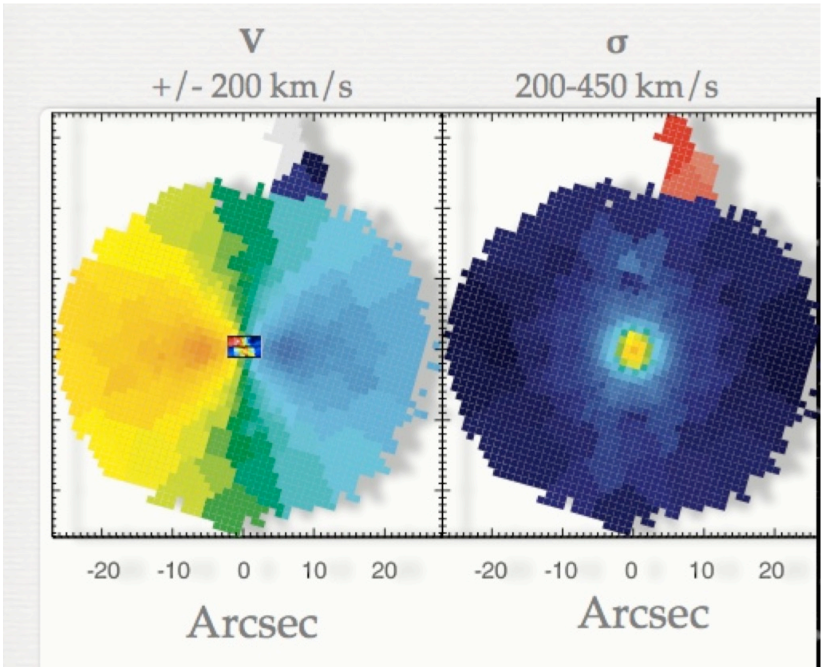
Example of data for the nearest galaxy M31

- Notice the nasty terms
- V_r is the rotation velocity σ_r σ_θ, 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



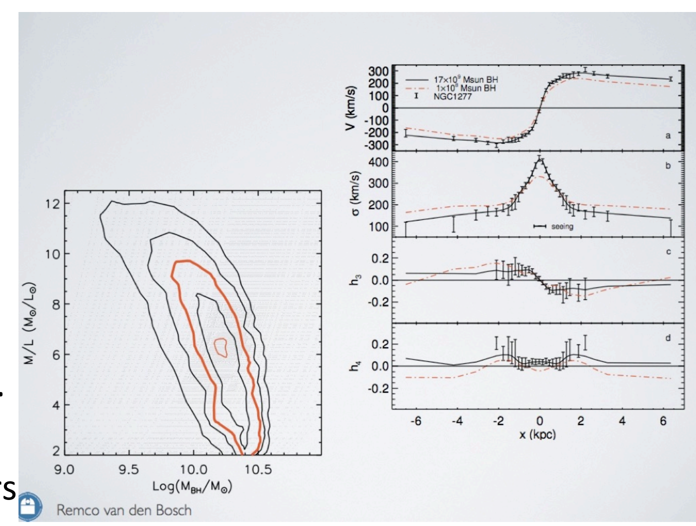
Modern Data

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

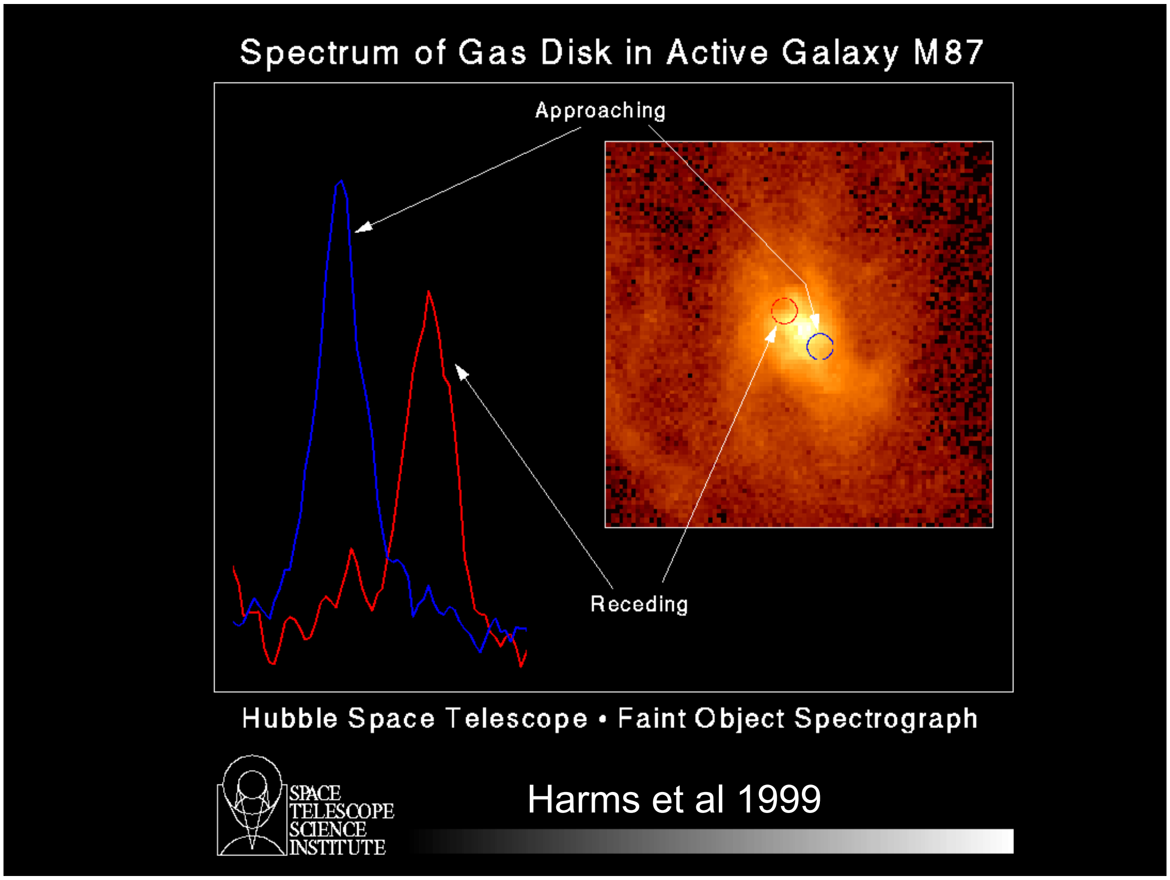


So How to Handle the Correlated Terms

- 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 hot much mass the stars have (make the variable the mass/light ratio of stars)

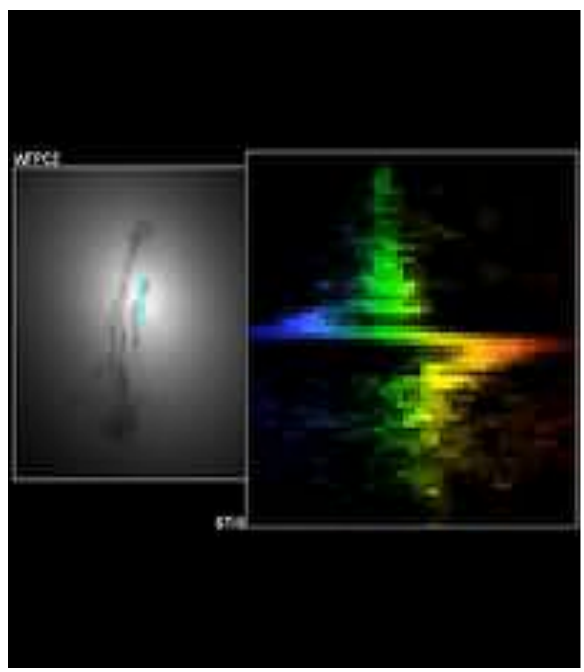


R. van den Bosch



Measuring the Mass of a SuperMassive Black hole

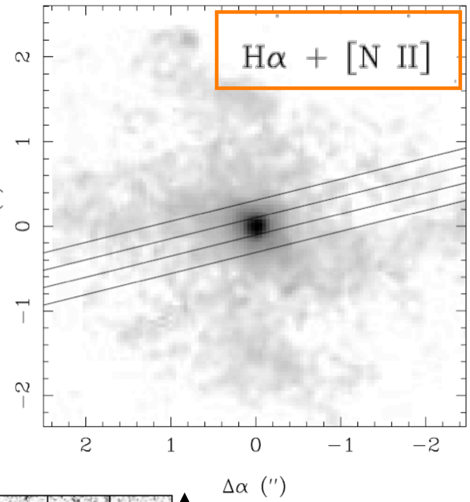
- Image of central regions and Velocity of gas near the center of M84 a nearby galaxy (Bower et al 1998) -
- The color scale maps the range of velocity along the slit, with blue and red color representing velocities (with respect to systemic) that are blueshifted and redshifted, respectively.
- The dispersion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



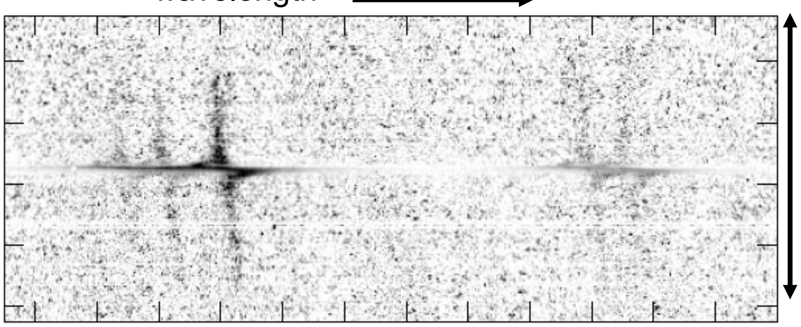
Measurement of Kinematics of Gas

- 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

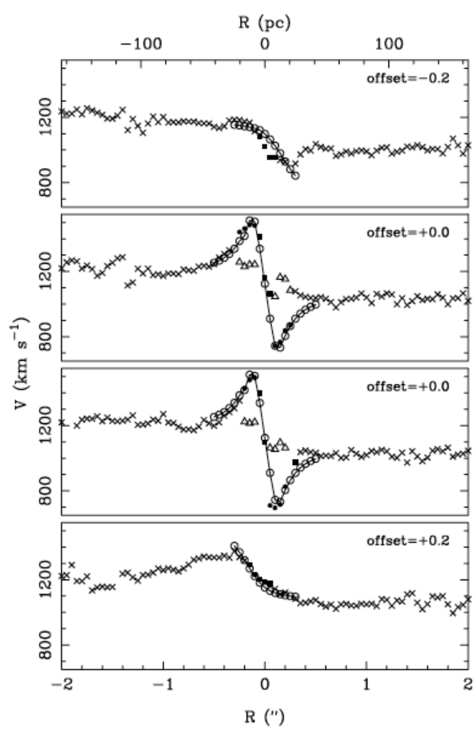
Analysis of Spectral Data for M84

- Mass of central object 1.5×10^9 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=6.6x10^{9}M

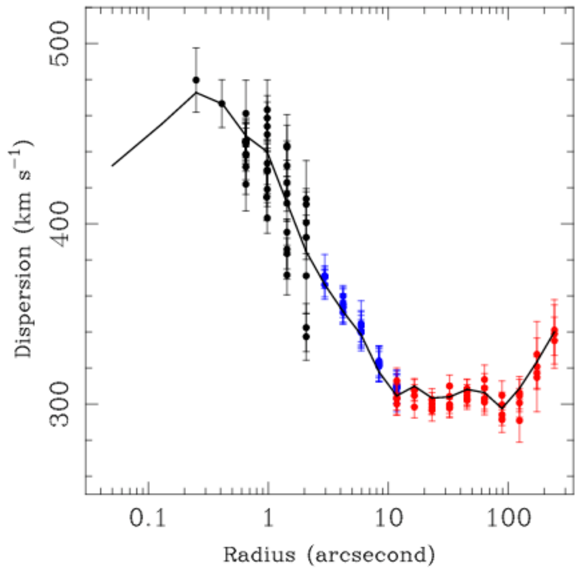
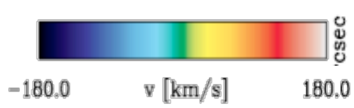


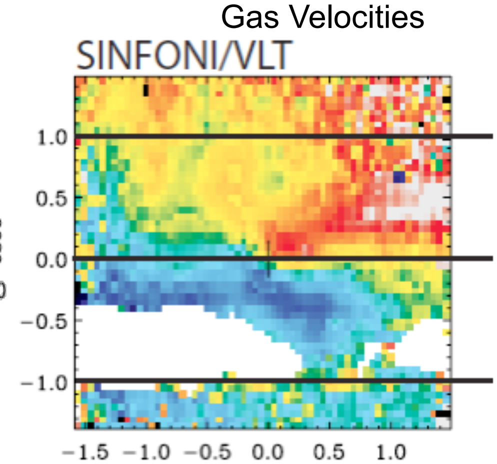
FIG. 5.— Velocity dispersion versus radius for M87. The black points are the NIFS data. The red points are the VIRUS-P data from Murphy et al. (2011), and the blue points are from the SAURON data. The multiple points at each radius represent the various position angles. The solid line is the best-fit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

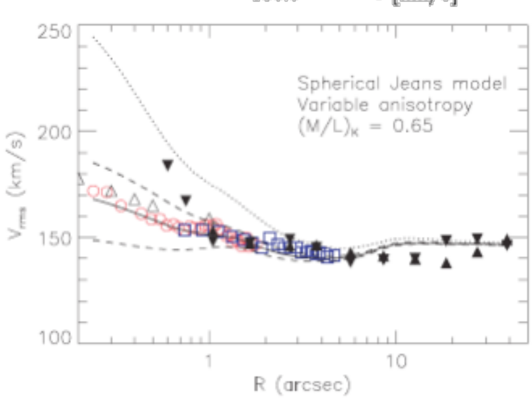
Centaurus -A

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

Gas Velocities







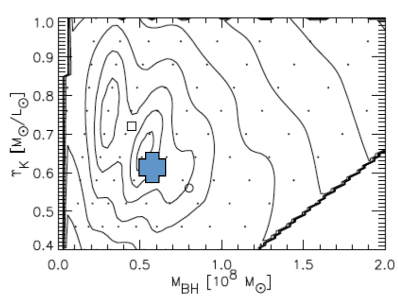


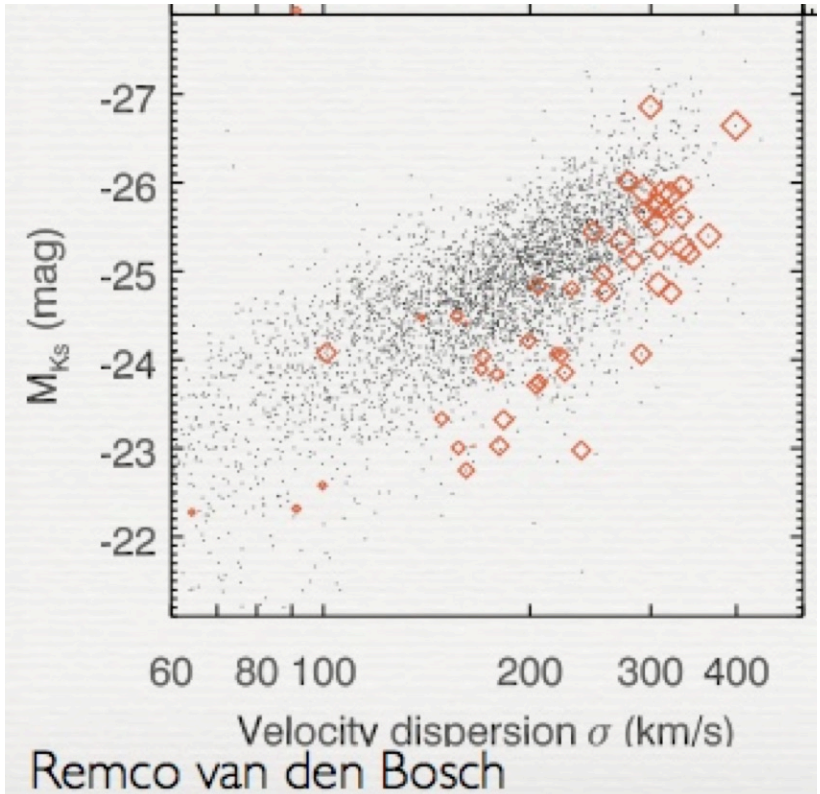
Figure 4: Spherical anisotropic Jeans model

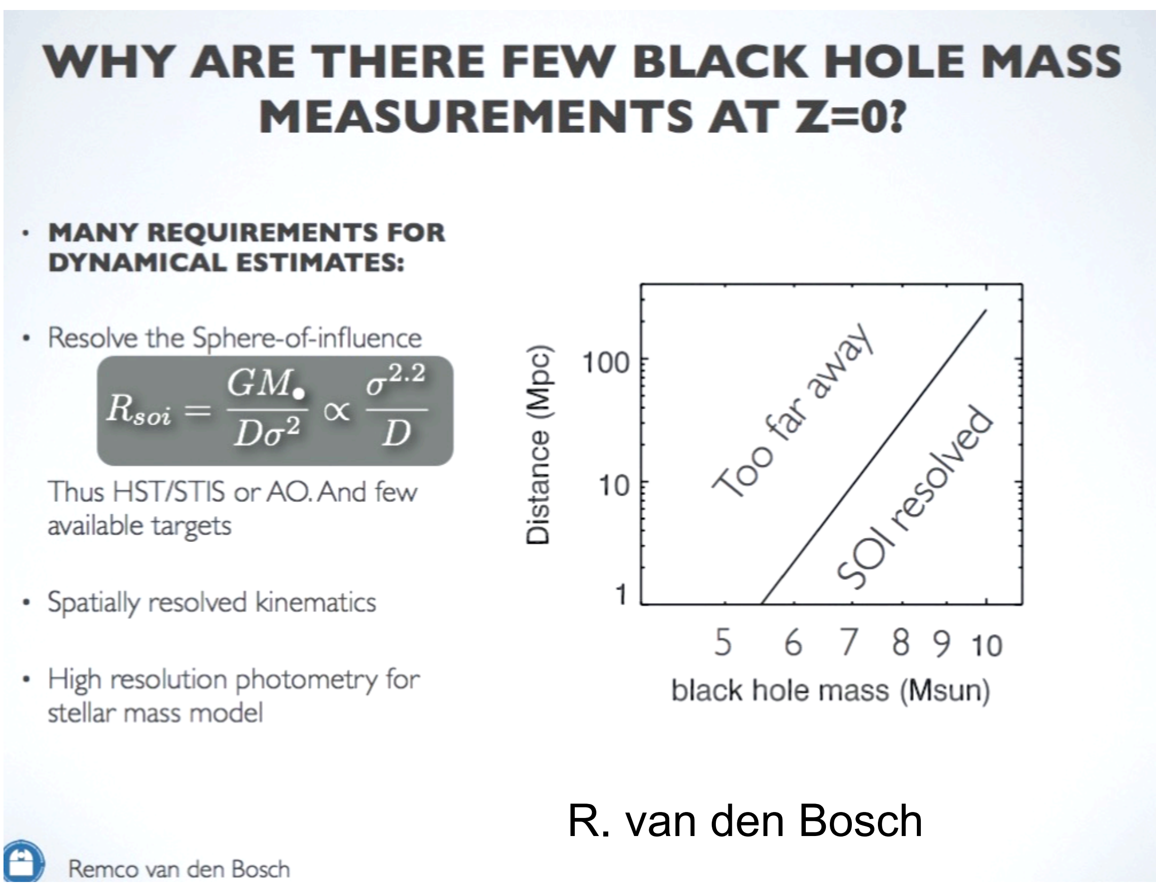
$$M_{BH} = (5.5 \pm 3.0) \times 10^7 M_\odot.$$

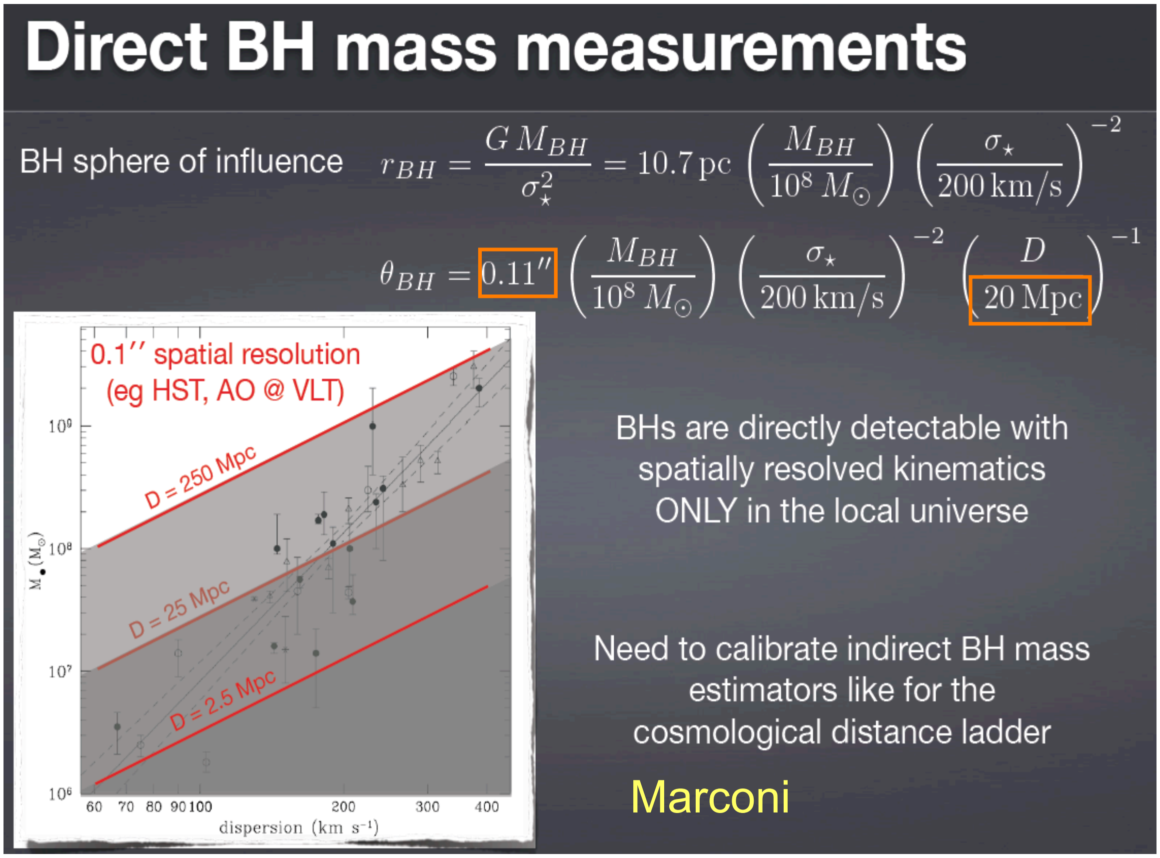
Constraints from stars compared to those from Gas Velocities

Selection Bias

Red symbols are galaxies with measured BH masses from dynamics







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

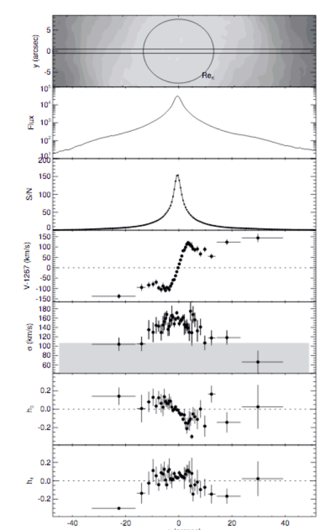
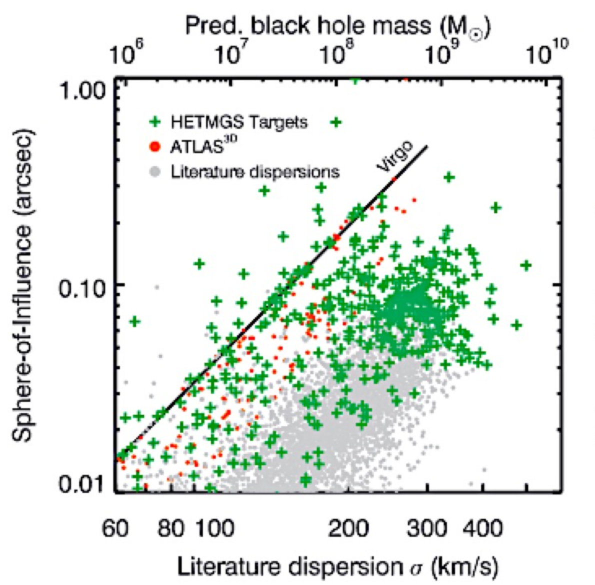


Figure 5. Example of the resolved stellar kinematics using exposure 262031 of NGC2950. The kinematics are measured in bins that are combined to



R. van den Bosch

NGC4258- Rotation of Maser Disk

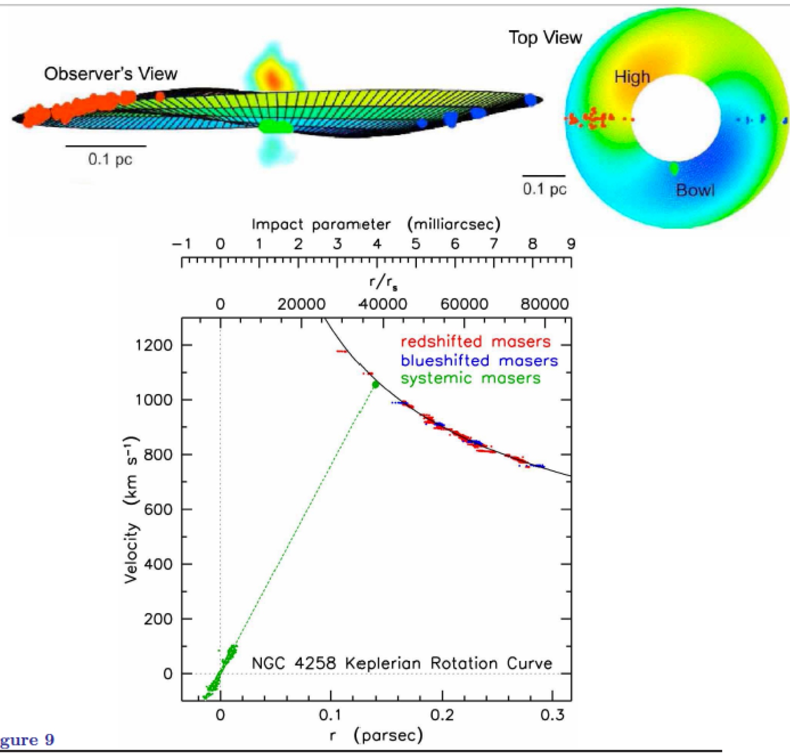
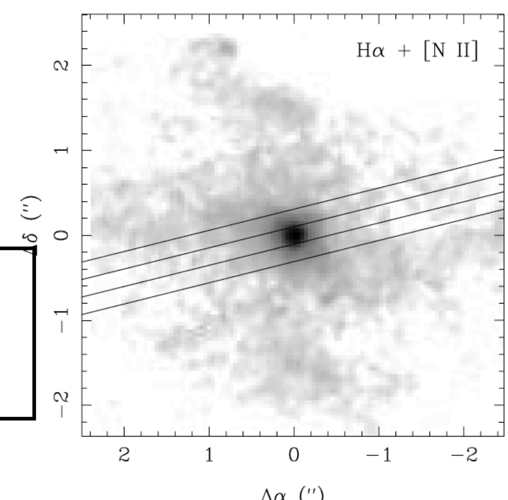


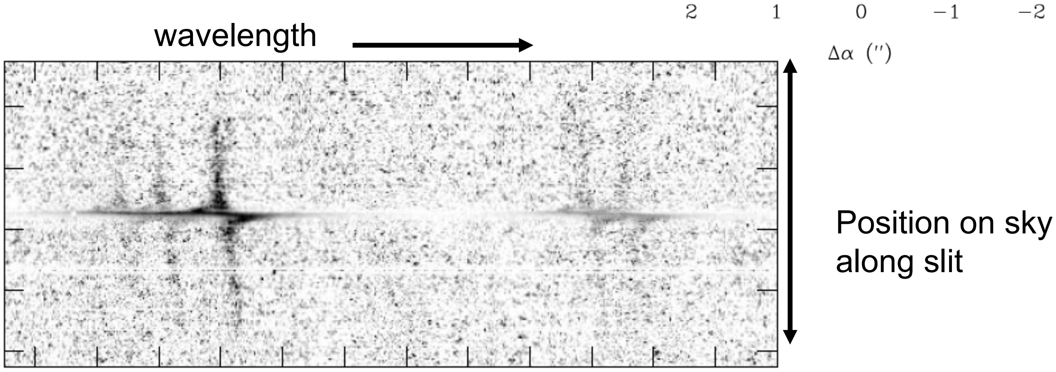
Figure 9
(*top*) Schematic views of the almost-edge-on, warped maser disk of NGC 4258 (from Moran 2008) with warp parameters from Herrnstein et al. (2005) and including the inner contours of the radio jet.

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.



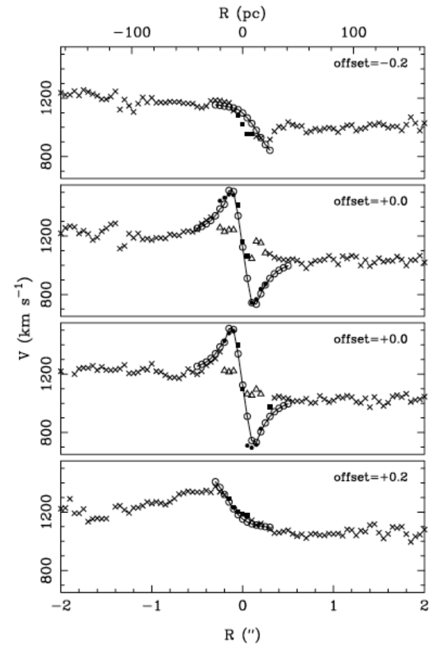
Analysis of Spectral Data for M84

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

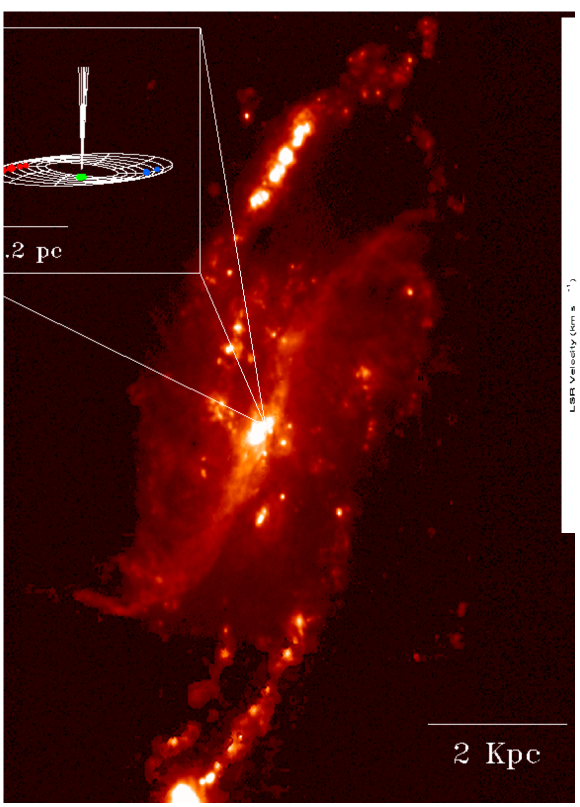
TABLE 1
KEPLERIAN DISK MODEL PARAMETERS

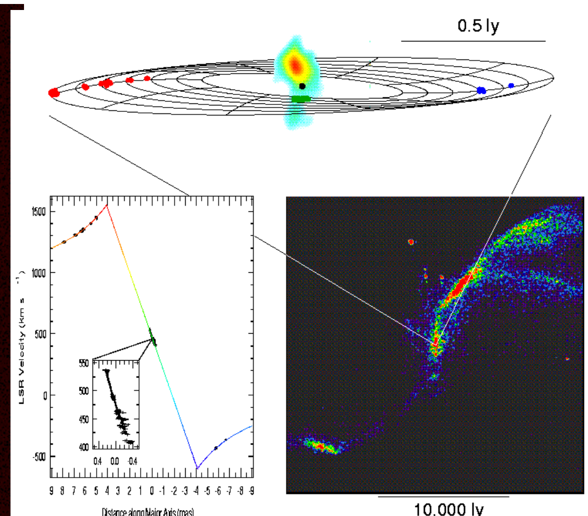
Parameter	Best Fit	Uncertainty Range
Black hole mass ($M_\odot$)	1.5×10^9	$(0.9\text{–}2.6) \times 10^9$
Disk inclination (deg)	80	75–85[a]
Disk P.A. (deg)	83	80–85
Gas systemic velocity (km s^{-1})	1125	1100–1150
Intensity law	$I(r) \propto r^{-1}$	...
$I(r)$ inner radius (pc)	1	0.3–3
$V(r)$ inner radius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

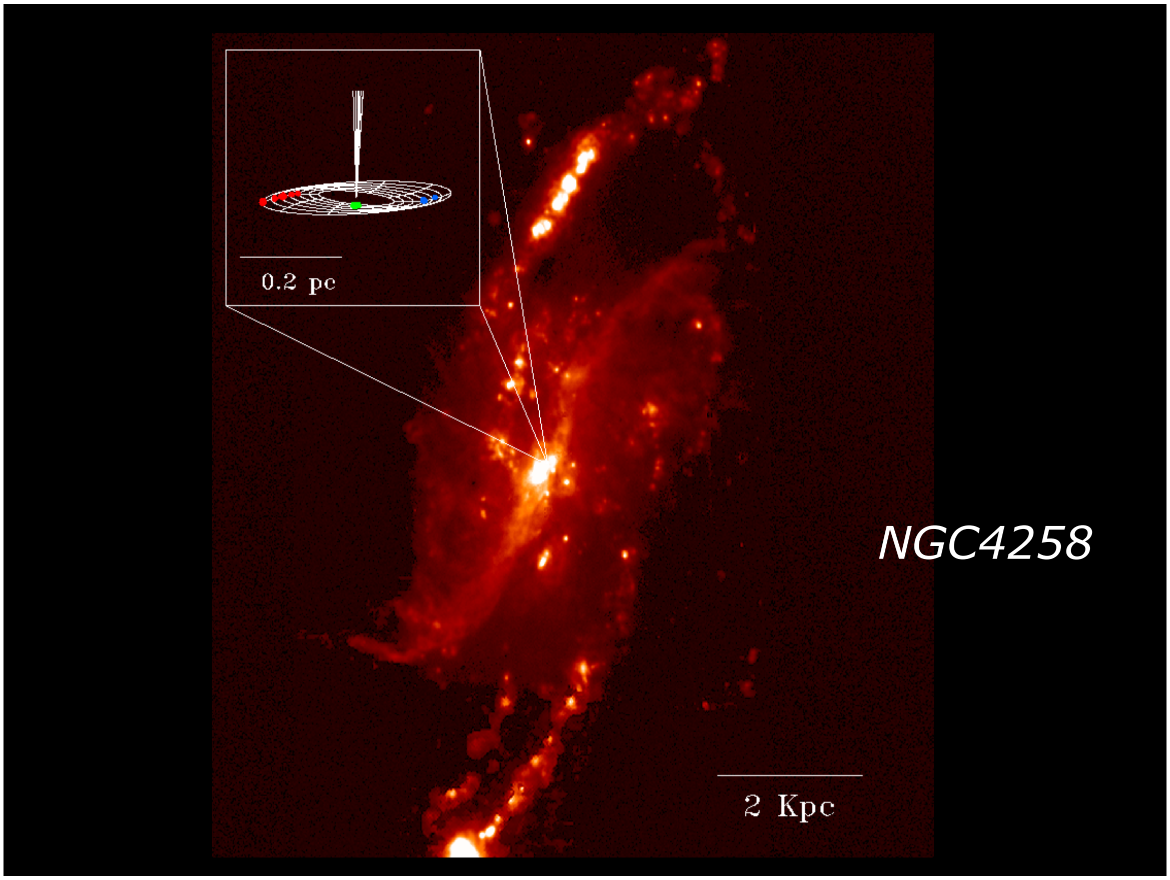
[a] Lower mass requires lower inclination.



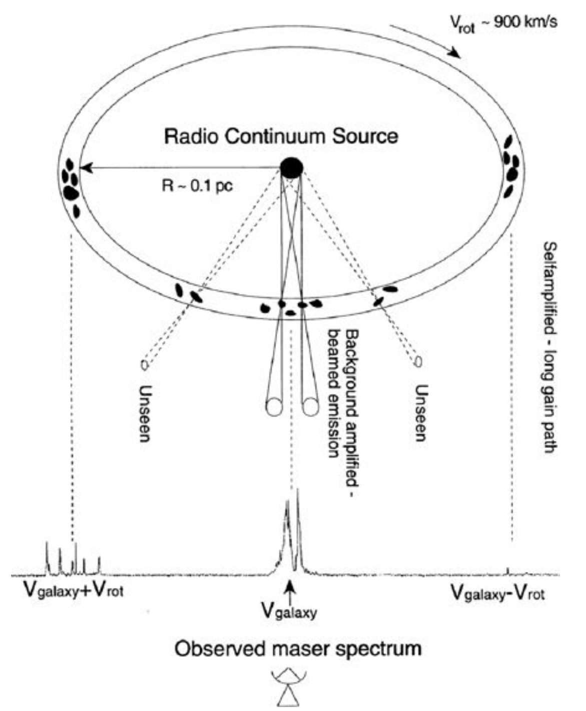
Velocity of gas vs distance from center of emission along 3 parallel lines





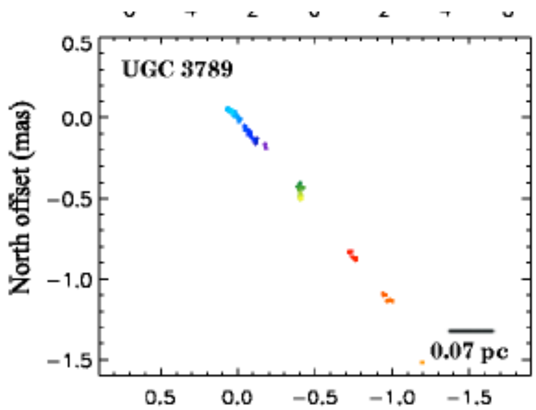


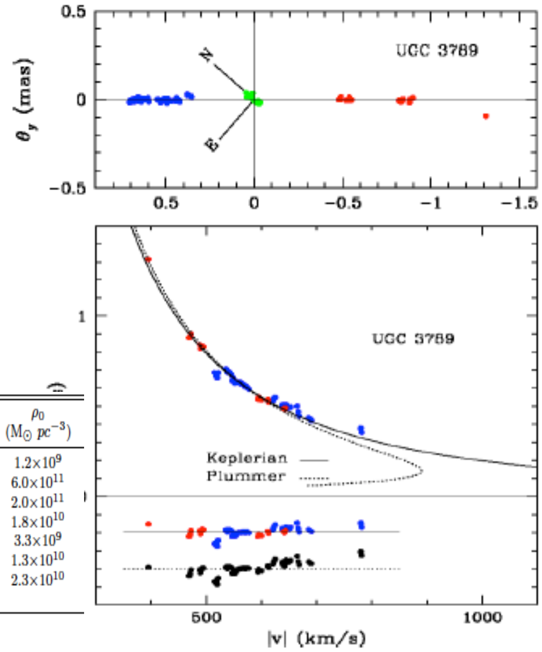
Maser Geometry Longair pg 619



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

Other Masers

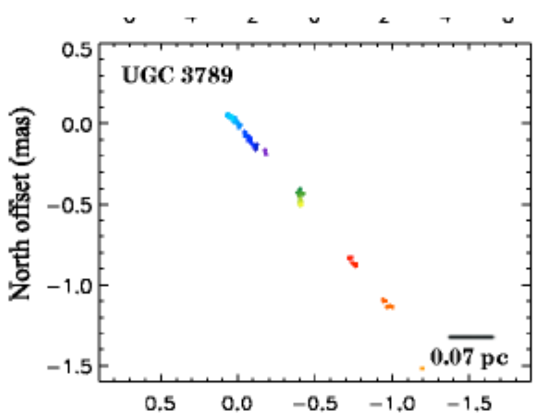


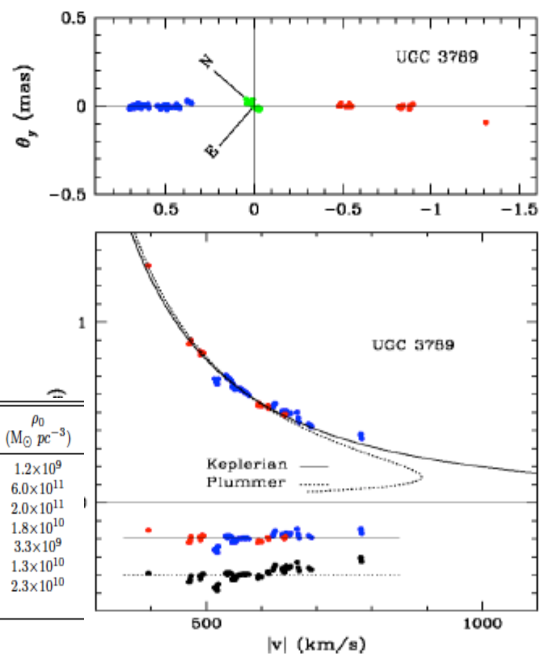


Name	Dist. (Mpc)	BH mass (10^7 $M_\odot$)	Disk Size (pc)	P.A. (°)	Incl. (°)	r_c (pc)	ρ_0 ($M_\odot$ pc^{-3})
NGC 1194	52	6.4±0.3	0.53-1.30	157	85	0.250	1.2×10^9
NGC 2273	26	0.76±0.04	0.028-0.085	153	84	0.015	6.0×10^{11}
UGC 3789	50	1.12±0.05	0.09-0.32	41	> 88	0.024	2.0×10^{11}
NGC 2960	71	1.14±0.05	0.13-0.36	−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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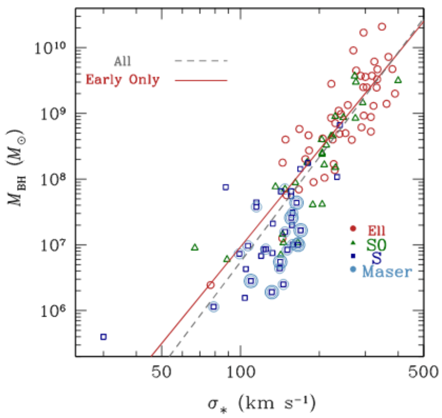
Kuo et al 2010

Updated Mega Maser Sample

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

Greene et al 2016 arxiv 1606.00018

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

Centaurus-A The Nearest AGN