INAF ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

INAF - Arcetri

Observational evidences and demography of Black Holes

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VIII CICLO (2005 -2006): III CORSO

Dinamica delle galassie – Nuclei galattici attivi

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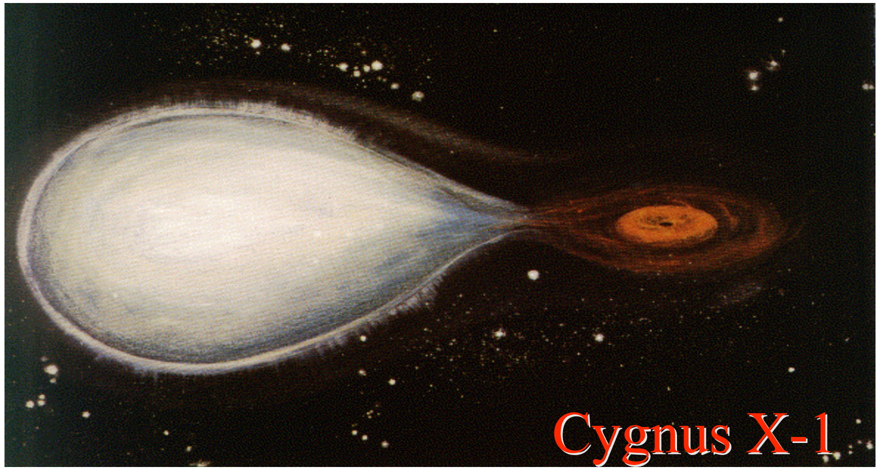
Outline of Lectures

- Lecture 1
  - Observational evidences for supermassive black holes and mass measurements.
- Lecture 2
  - Relations with the host galaxy and demography of local black holes.
- Lecture 3
  - Local supermassive black holes and Active Galactic Nuclei.
  - Future developments: VLT interferometry (?)

What types of BHs?

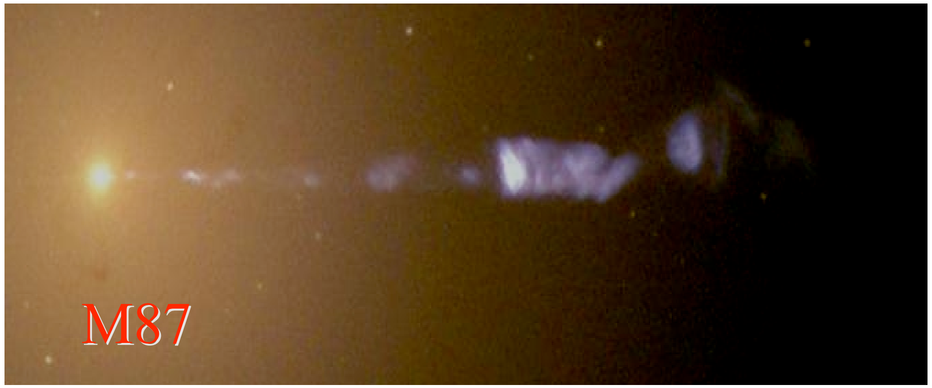


Stellar mass Black Holes

(~1-10 $M_{\odot}$)

- endpoints of the life of massive stars

Intermediate Mass Black Holes (~10^2-10^5 $M_{\odot}$) ???



Supermassive Black Holes

(~10^6-10^9 $M_{\odot}$)

- in galactic nuclei

Historical Overview

- 1783 - 1796: John Michell and Pierre-Simon Laplace hypothesized the existence of "dark stars"

  - Objects as dense as the Sun but with a diameter 500 times larger would have an escape speed larger than c

    $$M_{\text{Dark Star}} = 1.1 \times 10^{8}\ M_{\odot}$$

  - Dark stars can be detected from their gravitational effects on nearby stars.

- WRONG assumptions (corpuscolary theory of light; Newtonian mechanics) but CORRECT formula for the "Schwarzschild" radius.

1783: John Michell

From the letter by John Michell read by Henry Cavendish before the Royal Society on 27 November 1783:

> *If there should really exist in nature any bodies whose density is not less than that of the Sun, and whose diameters are more than 500 times the diameter of the Sun, since their light could not arrive at us; or if there should exist any other bodies of a somewhat smaller size which are not naturally luminous; of the existence of bodies under either of these circumstances, we could have no information from sight; yet, if any luminous bodies infer their existence of the central ones with some degree of probability, as this might afford a clue to some of the apparent irregularities of the revolving bodies, which would not be easily explicable on any other hypothesis; but as the consequences of such a supposition are very obvious, I shall not prosecute them any further.*

1795: Pierre-Simon Laplace

Laplace in his book “Exposition du Systeme du Monde” called these hypothetical objects *les corps obscures*, or "invisible bodies.”

> *invisible bodies as large, and perhaps in as great number, as the stars. A luminous star of the same density as the Earth, and whose diameter was two hundred and fifty times greater than that of the sun, would not, because of its [gravitational] attraction, allow any of its [light] rays to arrive at us; it is therefore possible that the largest luminous bodies of the universe may, through this cause, be invisible.*

Historical Overview

- 1915: Albert Einstein publishes the theory of General Relativity
- 1916: Karl Schwarzschild solves Einstein equations and finds the “black hole” solution
- 1963: Maarten Schmidt and, independently, Jesse Greenstein & Thomas Matthews discover Quasars
- 1964: Edwin Salpeter and Yakov Zel’dovich independently hypothesize that the powering mechanism of quasars is mass accretion onto a supermassive BH (10^6-10^{10} $M_{\odot}$).
- 1968: John Wheeler coins the term “Black Hole”
- Beginning of 1970s: X-ray source Cygnus X-1 is the first BH candidate with $M_{BH} \sim 12$ $M_{\odot}$
- 1978: Sargent et al. showed that images and spectra of the central region of M87 could be explained only with the presence of a BH with $M_{BH} \sim 3 \times 10^9$ $M_{\odot}$

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By Dr. M. SCHMIDT

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

THE only objects seen on a 200-in. plate near the positions of the components of the radio source 3C 273 reported by Hazard, Mackey and Shimmins in the preceding article are a star of about thirteenth magnitude and a faint wisp or jet. The jet has a width of 1″–2″ and extends away from the star in position angle 43°. It is not visible within 11″ from the star and ends abruptly at 20″ from the star. The position of the star, kindly furnished by Dr. T. A. Matthews, is R.A. 12h 26m 33·35s ±0·04s, Decl. +2° 19′ 42·0″ ±0·5″ (1950), or 1″ east of component *B* of the radio source. The end of the jet is 1″ east of component *A*. The close correla-

Table 1. Wave-lengths and Identifications

λ	$\lambda/1{\cdot}158$	λ_0	
3239	2797	2798	Mg II
4595	3968	3970	Hε
4753	4104	4102	Hδ
5032	4345	4340	Hγ
5200–5415	4490–4675		
5632	4864	4861	Hβ
5792	5002	5007	[O III]
6005–6190	5186–5345		
6400–6510	5527–5622		

Oke in a following article, and by the spectrum of another star-like object associated with the radio source 3C 48 discussed by Greenstein and Matthews in another com-

Schmidt 1963, Nature, 197, 1040

RED-SHIFT OF THE UNUSUAL RADIO SOURCE: 3C 48

By Dr. JESSE L. GREENSTEIN

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology

AND

Dr. THOMAS A. MATTHEWS

Owens Valley Radio Observatory, California Institute of Technology

THE radio source 3C 48 was announced to be a star[1] in our Galaxy on the basis of its extremely small radio diameter[2], stellar appearance on direct photographs and unusual spectrum. Detailed spectroscopic study at Palomar by Greenstein during the past year gave only partially successful identifications of its weak, broad emission lines; the possibility that they might be per-

cosmological speculation. A very interesting alternative, that the source is a nearby ultra-dense star of radius near 10 km containing neutrons, hyperons, etc., has been explored and seems to meet insuperable objections from the spectroscopic point of view. The small volume for the shell required by the observed small gradient of the gravitational potential is incompatible with the

Greenstein & Matthews 1963, Nature, 197, 1041

NOTES

ACCRETION OF INTERSTELLAR MATTER BY MASSIVE OBJECTS

Observations of quasi-stellar radio sources have indicated the existence in the Universe of extremely massive objects of relatively small size. The present note discusses the possible further growth in mass of a relatively massive object, by means of accretion of interstellar gas onto it, and the accompanying energy release. Although there is no evidence for (and possibly some evidence *against*) quasi-stellar radio sources occurring inside ordinary galaxies, for the sake of concreteness we consider the fate of an object of mass $M > 10^6$ (masses in solar units throughout) in an ordinary spiral galaxy somewhat like ours.

We first re-examine the hypothetical problem of an object of mass M moving with velocity U (in km/sec) relative to a completely uniform gas medium of density n (expressed as H-atoms per cm³) and thermal speed U_{th}. We define (Hoyle and Lyttleton 1939) a characteristic length s_0 and express the rate of accretion in terms of a dimensionless parameter a to be determined,

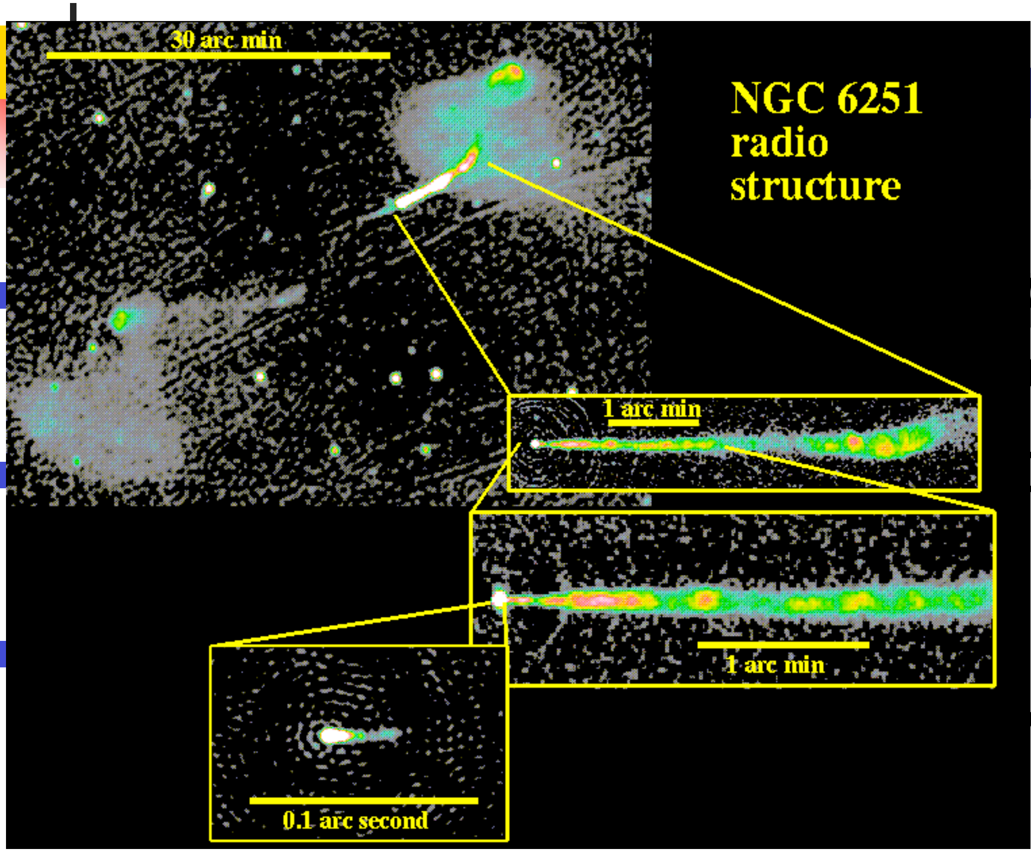
$$s_0 = GM/U^2 = (M/U^2) \times 4.3 \times 10^{-3}\ \text{pc}\,,$$

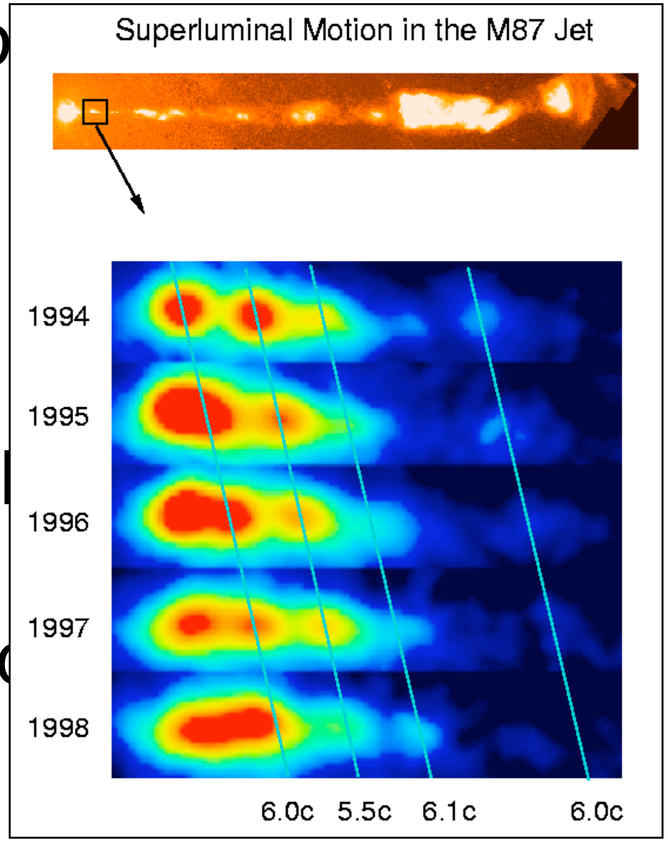
$$dM/dt = 2\pi a s_0^2\, nU \equiv aM/t_0\,, \quad (1)$$

Salpeter 1964, ApJ, 140, 796

...oles in AGNs?

- ...pectra of AGNs
...f energy production.
- ...o hours - days
- ...sio





- Jet stability and collimation over kiloparsecs in some objects impl... source (good gyroscope).
- Direct dynamical evidences (als... galaxies).

The Nuclear Engine

- If variability on hours time scales is due to global variations of emitting source its size is
  $d \approx \Delta t\, c = 8 \times 10^{-4}\, (\Delta t / 1\ \mathrm{day})\ \mathrm{pc}$
- Energy production inside d with efficiency ε is $E = \varepsilon\, m_H\, c^2$
- $\varepsilon = 0.7\ \%$ if E from nuclear fusion in stars
- Very conservative case: fusion of 10% of $M_\star$ in 10^7 yr: $L = \varepsilon\, 0.1\, M_\star c^2 / 10^7\ \mathrm{yr}$
- To obtain $L \sim 10^{45}$ erg/s requires $M_\star \sim 10^8\, M_{\odot}$ inside 10^{-3} pc, $\rho \sim 10^{17}\, M_{\odot}\, \mathrm{pc}^{-3}$

NO STARS!

Accreting BH scenario

- Accretion onto a compact object is much more efficient than nuclear fusion in stars (ε=0.007).

- In a BH ($R_{BH} = 2\ G\ M_{BH}/c^2$):

Non rotating BH (Schwarzschild)	$R_{LSO} = 3R_{BH}$	$\varepsilon = 0.057$
Rotating BH (Kerr)	R_{LSO}=0.5-4.5 R_{BH}	$\varepsilon = 0.3$-0.42

Accreting BH scenario

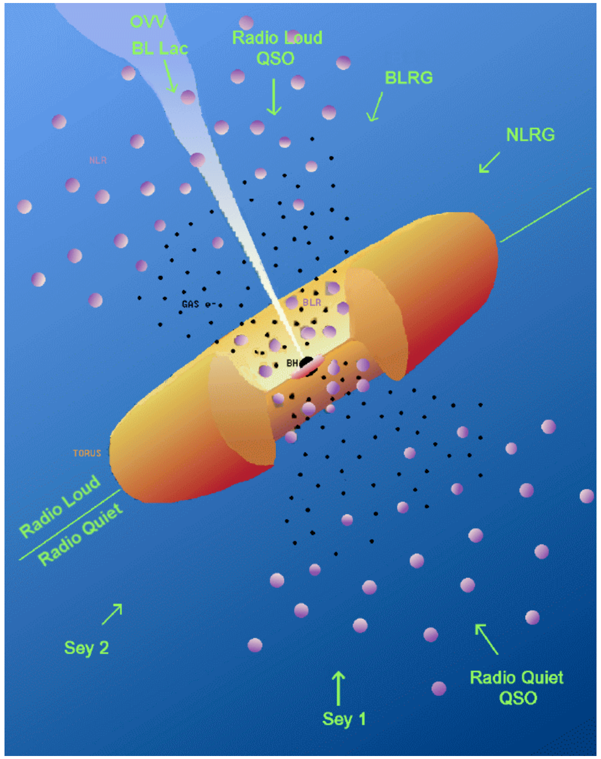
- Eddington limit: gravitational attraction = radiation pressure (Thomson scattering)

$$L < L_{Edd} = \frac{4\pi G m_H M_{BH}}{\sigma_T} = 1.3 \times 10^{38} \left(\frac{M_{BH}}{M_{sun}} \right) \text{erg/s}$$

$$L = 10^{45} \text{ erg/s} \Rightarrow M_{BH} > 10^{7} \; M_{sun}$$

Why BHs in Galactic Nuclei?

Powering mechanism of AGNs is accretion onto a massive BH
(e.g. Salpeter 1964, Zel’dovich 1964)



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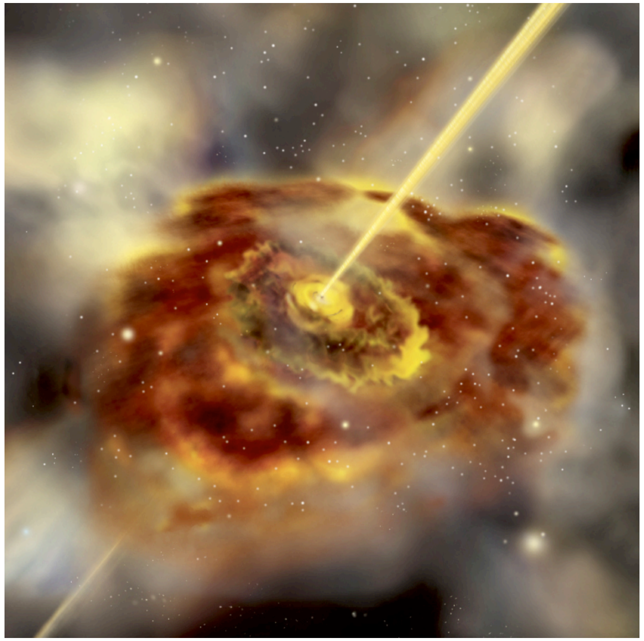
Observed evolution of AGNs



Most/all quiescent luminous galaxies should host a BH, relic of AGN activity (e.g. So_tan 1982).

AGN remnants

- Consider an Active Galactic Nucleus emitting with luminosity
  - $L_{AGN} = 10^{12} L_{\square}$ for _$t_{AGN} = 10^{7}$ yr ($\ll t_{H}$)
  - L_{AGN} = _ (_M_{acc}/_t) c^{2}
  - _M_{BH}= (1-_) _M_{acc}
  - _M_{BH} = L_{AGN}(1-_)/(_c^{2}) _t_{AGN}
  - _M_{BH} = 6.1 _10^{6} $M_{\square}$

Dynamical evidences for BHs

Use Gas/Stars as tracers to get kinematics V,σ around the BH

↓

Determine gravitational potential _ which gives rise to observed V,σ

_ = _ $_{Stars}$ + _ $_{BH}$

→

Get _ $_{Stars}$ from observed light distribution in galaxy nucleus (L ≈ M)

↑

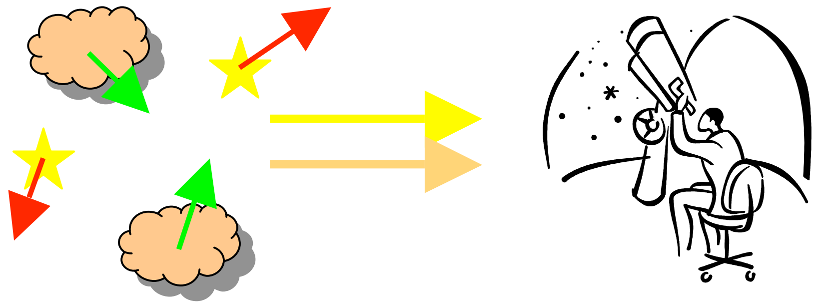
_ $_{BH}$ = G M_{BH} R^{-1}

(R > $R_{Schwarzschild}$)

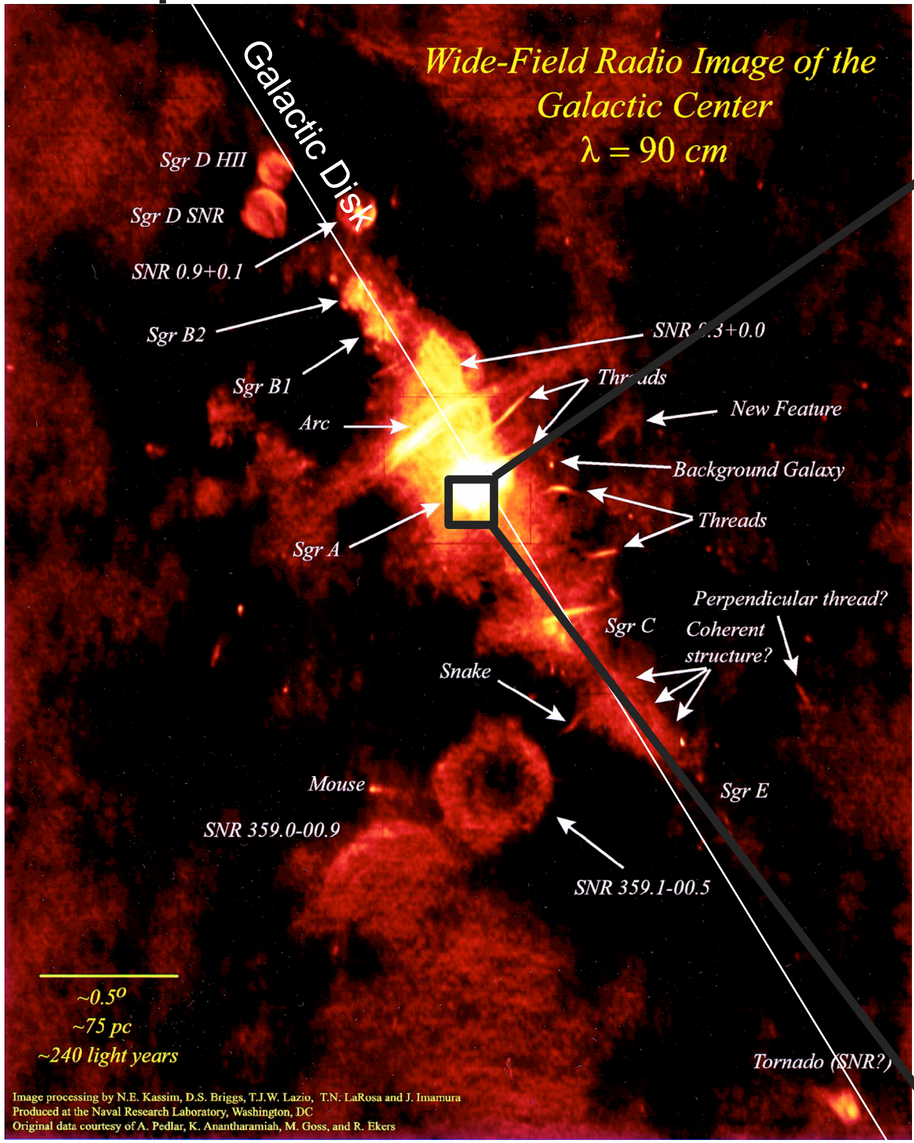
Direct Methods to measure M_{BH}

Motions of *test particles*

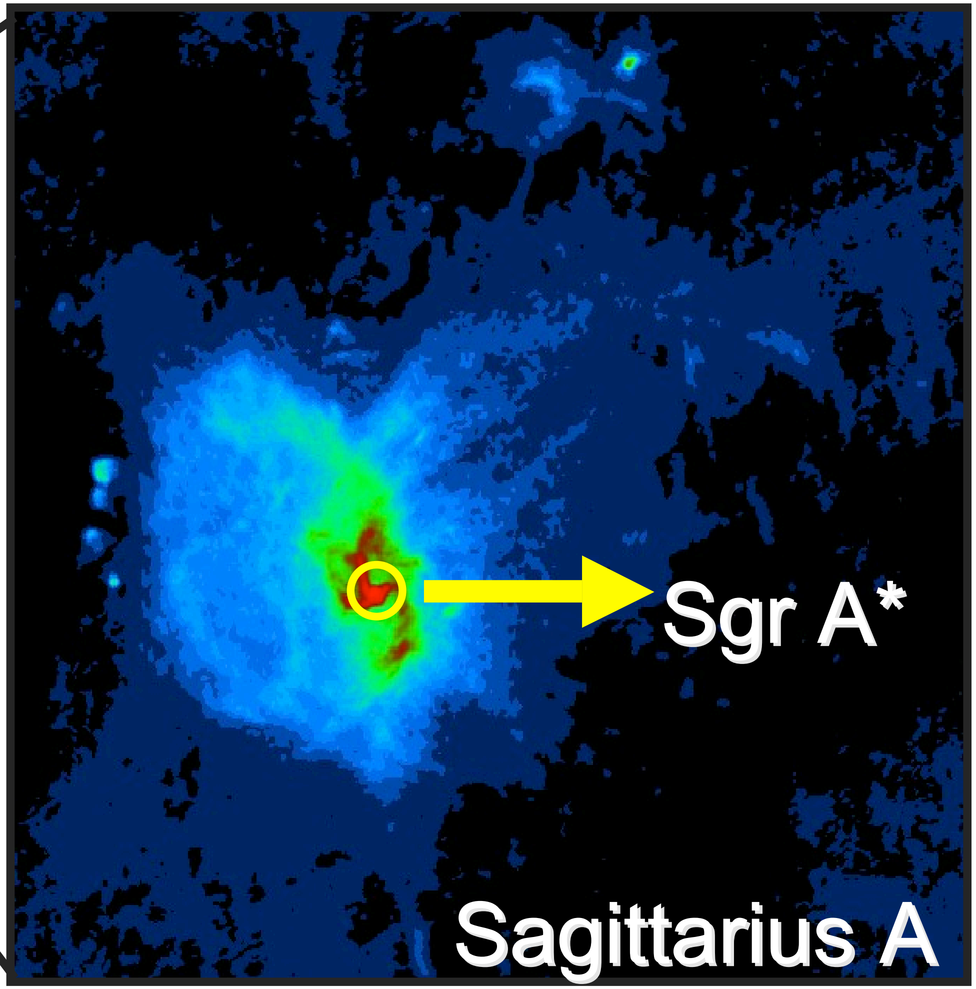
- Star proper motions and radial velocities ↳Milky Way
- Radial velocities of single gas clouds (masers) ↳NGC 4258



The center of the Milky Way



Radio (_ = 90 cm)

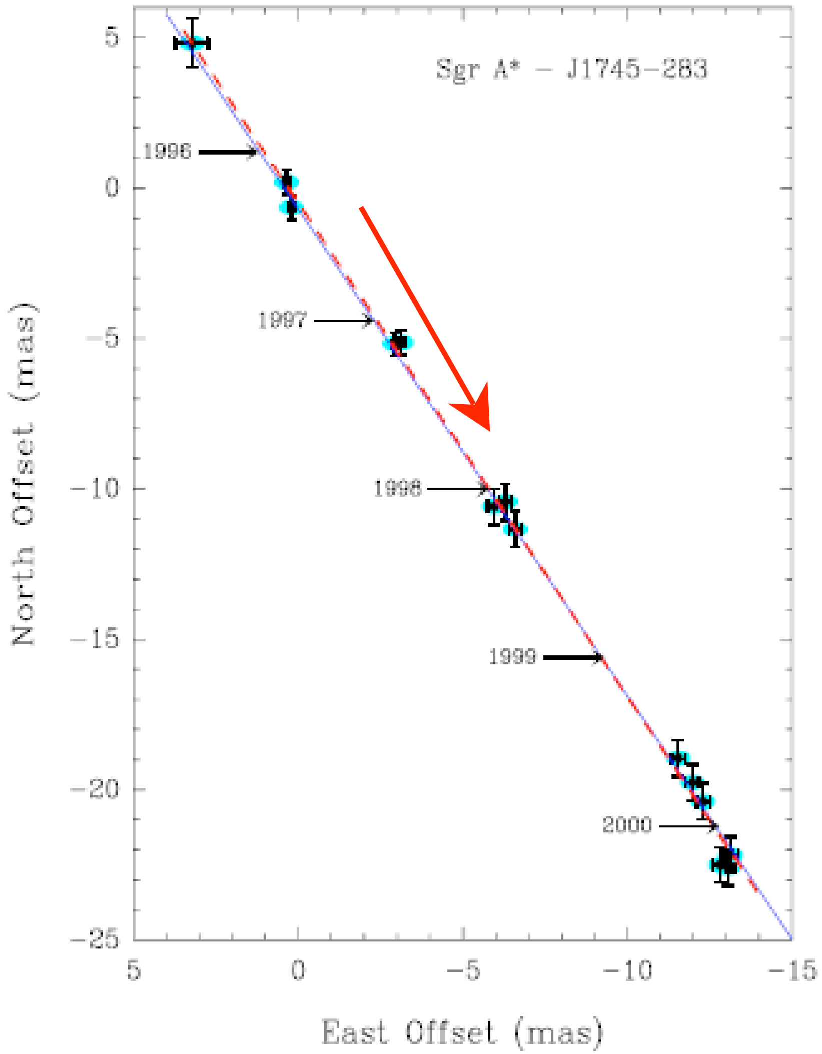


Proper motion of Sgr A*

- Sgr A* shows a secular parallax (Sun rotation around galactic center)
- Sgr A* proper motion is $V_{SgrA*} < 8$ km/s.
- Stars close to SgrA* have tipically $M \sim 10\ M_{\odot}$ and $V \sim 1000$ km/s
- If SgrA* has the same kinetical energy as a typical star $M_{SgrA*} > 2 \times 10^5\ M_{\odot}$
- Very massive “dark” object!
- Residual proper motion perpendicular to plane

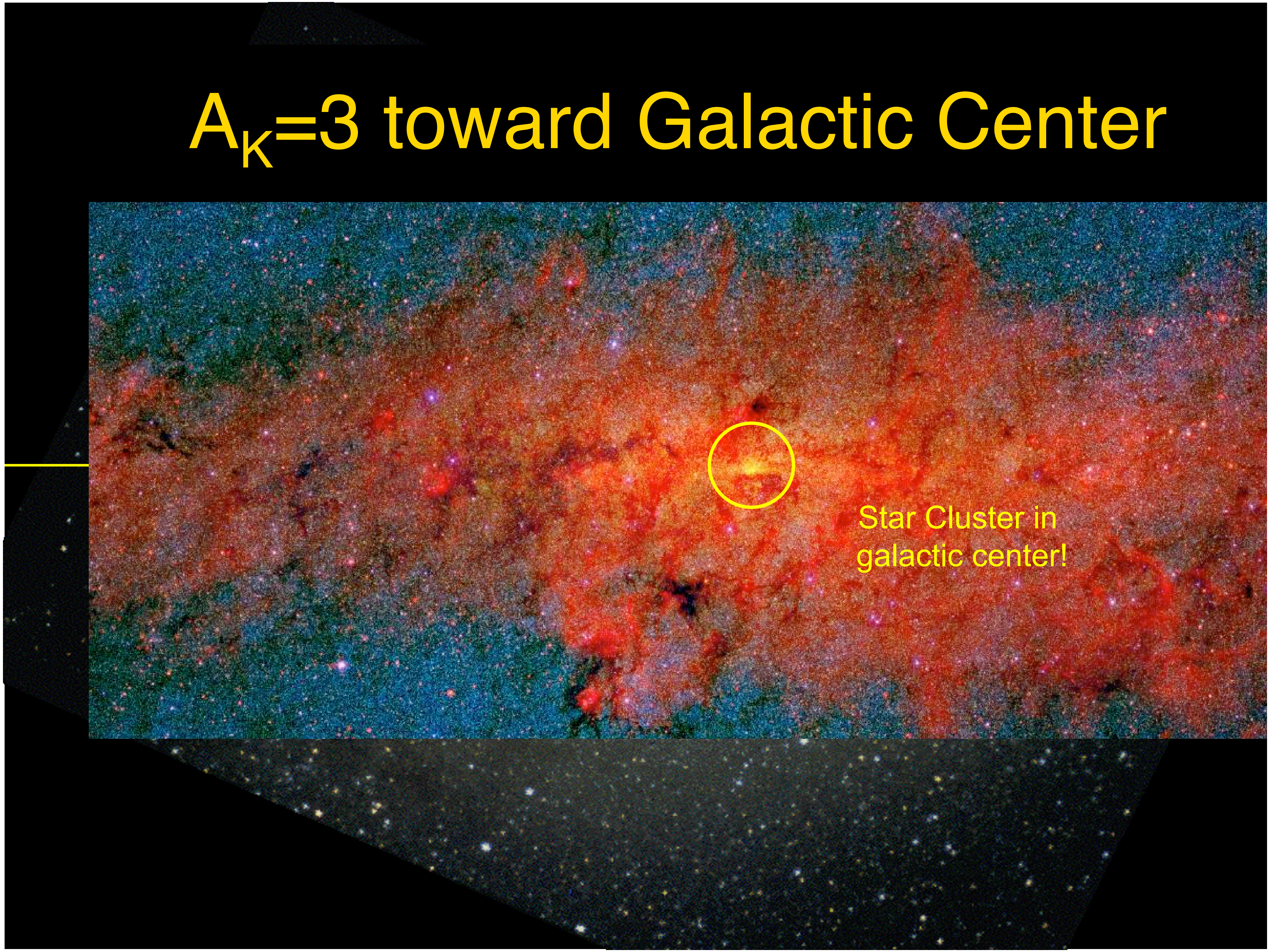
  -0.4 ± 0.9 km/s

  (Reid & Brunthaler 2004)

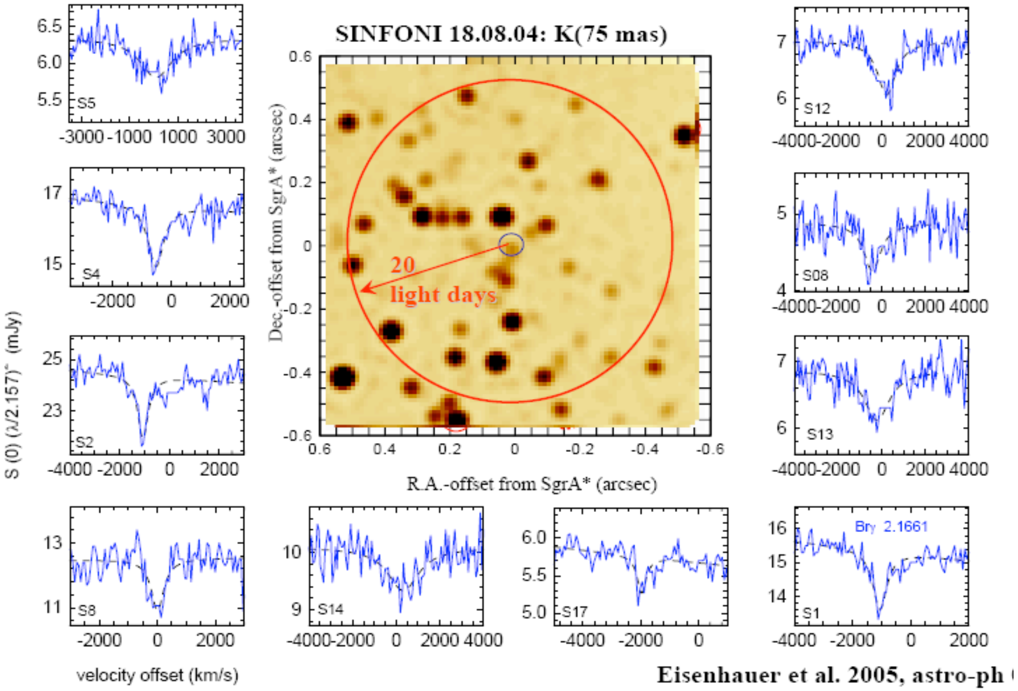


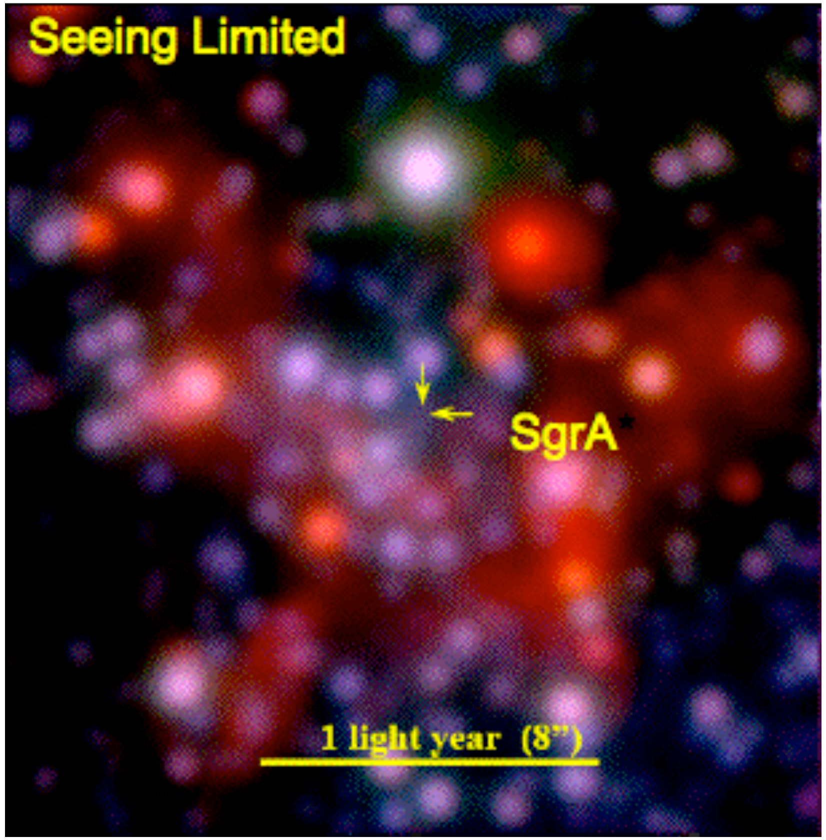
Backer & Sramek 1999

A_K=3 toward Galactic Center



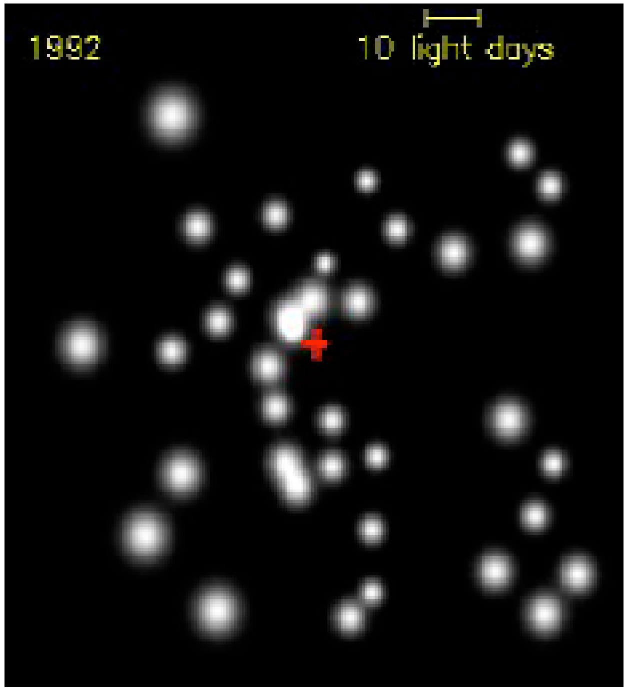
Multi Epoch NIR Imaging+Spectroscopy

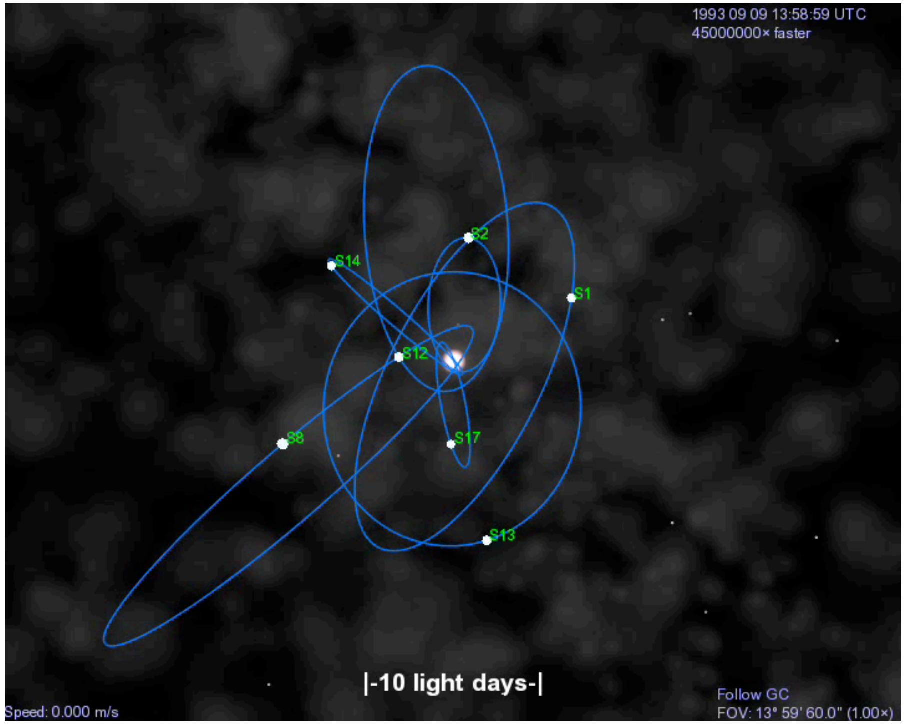




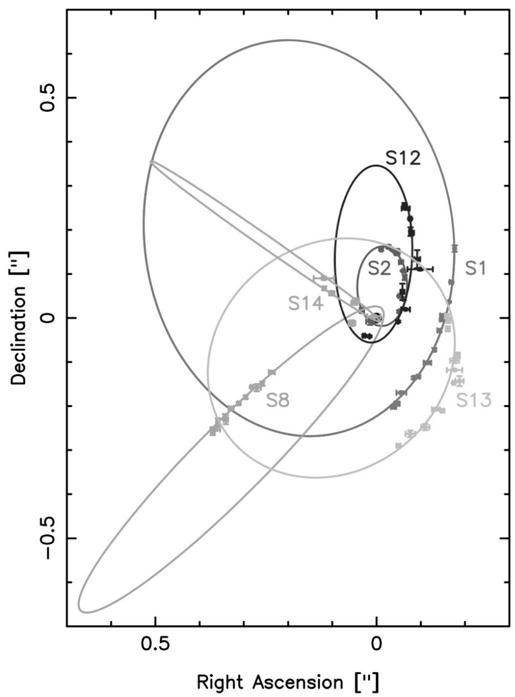
- Proper motions combined with radial velocities provide the full velocity vector for many “test particles” around SgrA*.

Show time!

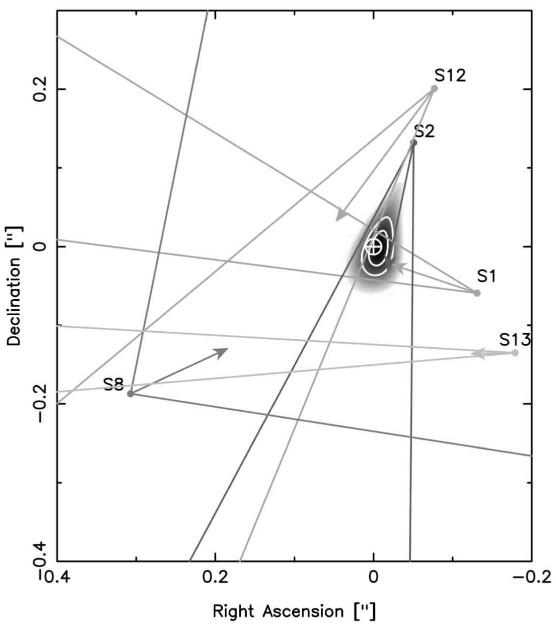

1992
10 light days

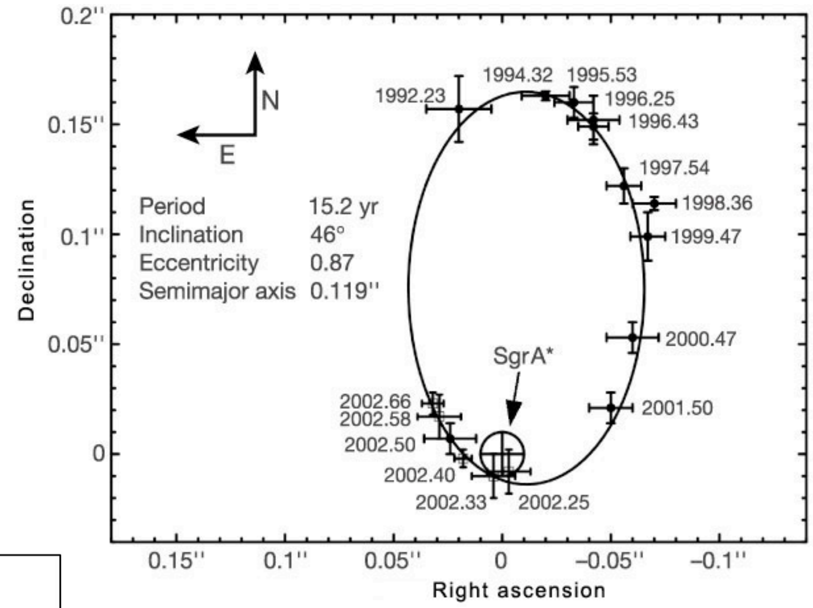

1993 09 09 13:58:59 UTC
45000000× faster
S2
S14
S1
S12
S8
S17
S13
|-10 light days-|
Speed: 0.000 m/s
Follow GC
FOV: 13° 59' 60.0" (1.00×)

Star Orbits and Accelerations



Schodel et al. 2003,
Ghez et al. 2002



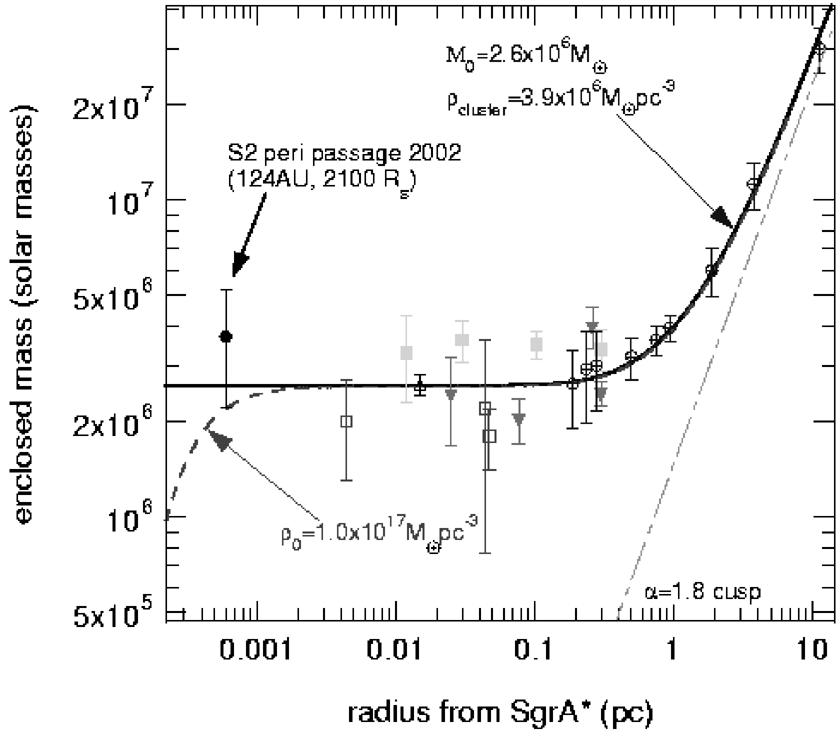


All acceleration vectors point toward the same point which is coincident withSgrA* position

Periastron passage of S2. From just this orbit it is possible to measure M_{BH} (de-project and apply Kepler law's)

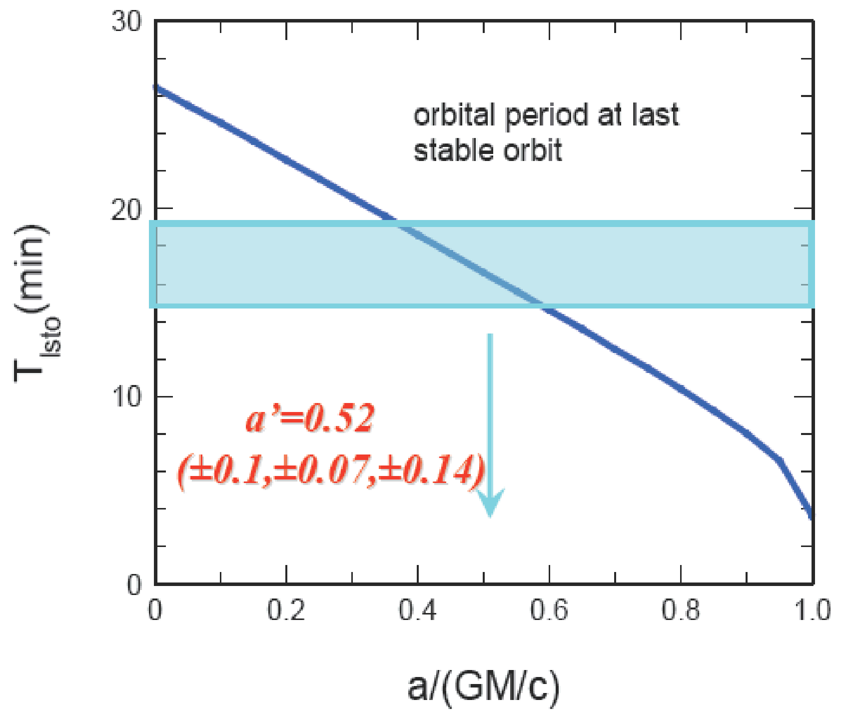
The BH mass

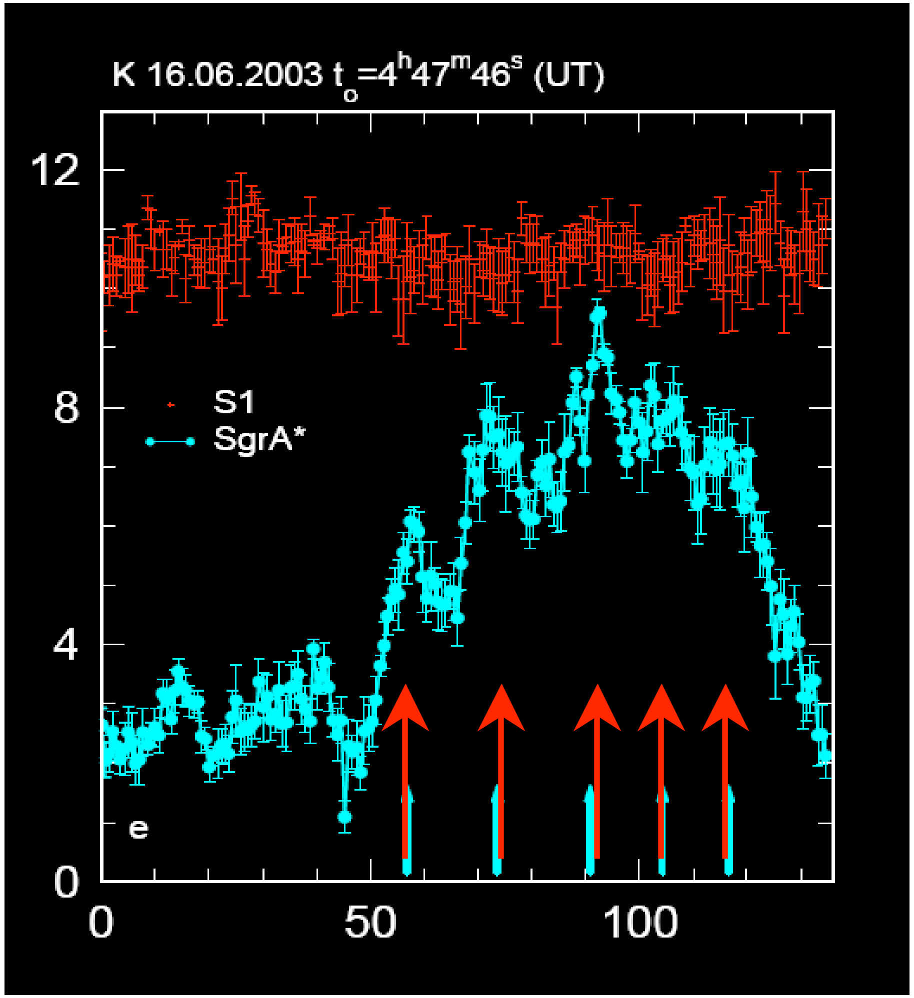
- From star velocities (proper motions and radial velocities) it is possible to estimate the enclosed mass at given radius M(r).
- There is a point mass of $M_{BH} \sim 3$ _ 10^6 M□ (Genzel et al 2000; Ghez et al. 2003; Schodel et al. 2003)



- Galactic center distance (proper motions ⇒ velocities): 7.9±0.42 kpc (Eisenhauer et al. 2003)
- The point mass is confined within 0.001 pc ⇒ $\rho_{\bullet} > 10^{17}$ M□ pc^{-3}
  It's a Black Hole!
- Star cluster surrouding the BH has $\rho = 7$_10^8 M□ pc^{-3} at r= 0.1" and $\rho(r) \sim r^{-1.8}$

Infrared Flares in Sgr A*





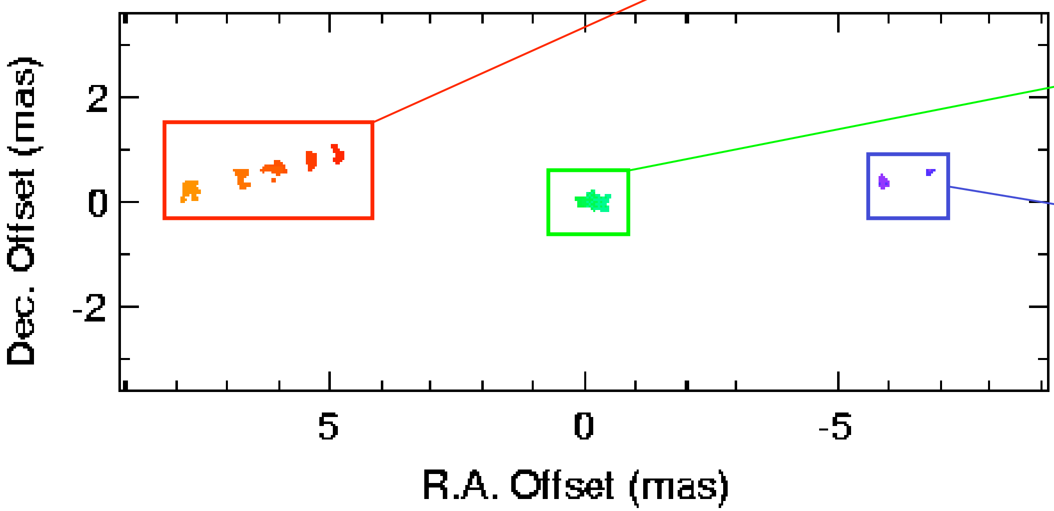
Periodic flares with period 17±2 minutes in H, K and L band (Genzel et al. 2003, Ghez et al. 2003)

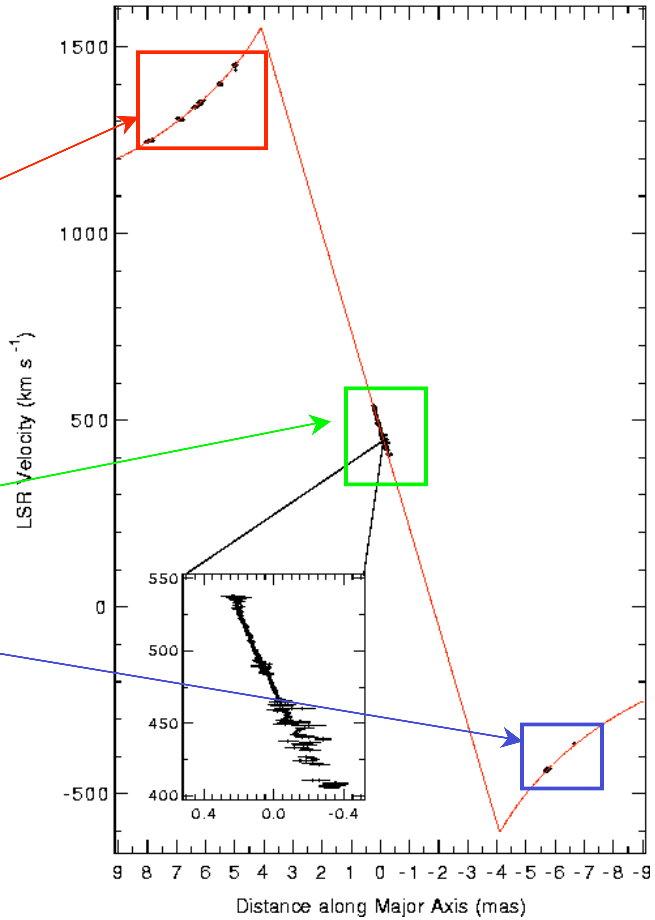
Orbital motion at the last stable orbit thus spinning BH?

Is it really a periodic signal?

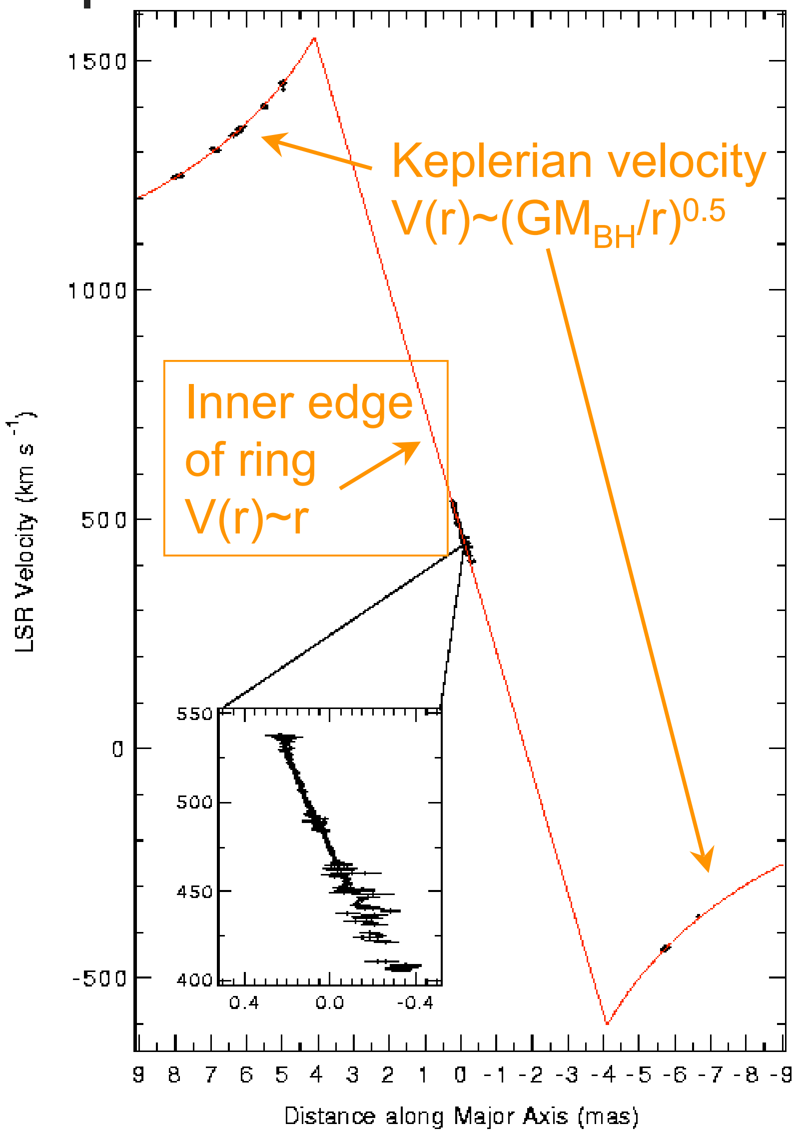
M_{BH} from H_2O masers: NGC 4258

- H_2O maser observations (λ=1.35 cm) with VLBI can reach exceptional spatial and velocity resolution :
  - $\Delta\theta$=0.6 mas $\times$ 0. 3 mas
  - ΔV= 0.2 km/s
- Observations of NGC 4258 (Miyoshi et al. 1995)

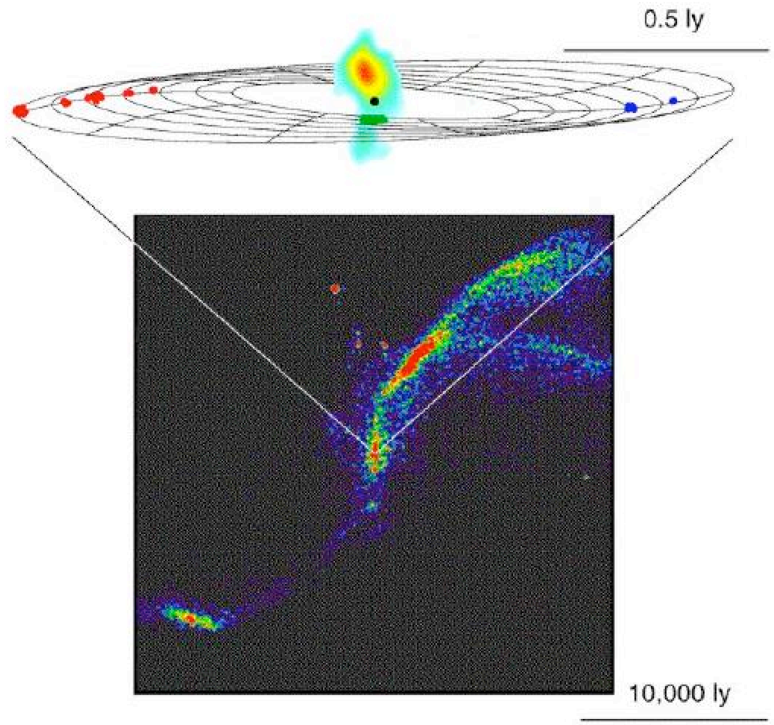




M_{BH} from H_2O masers: NGC 4258

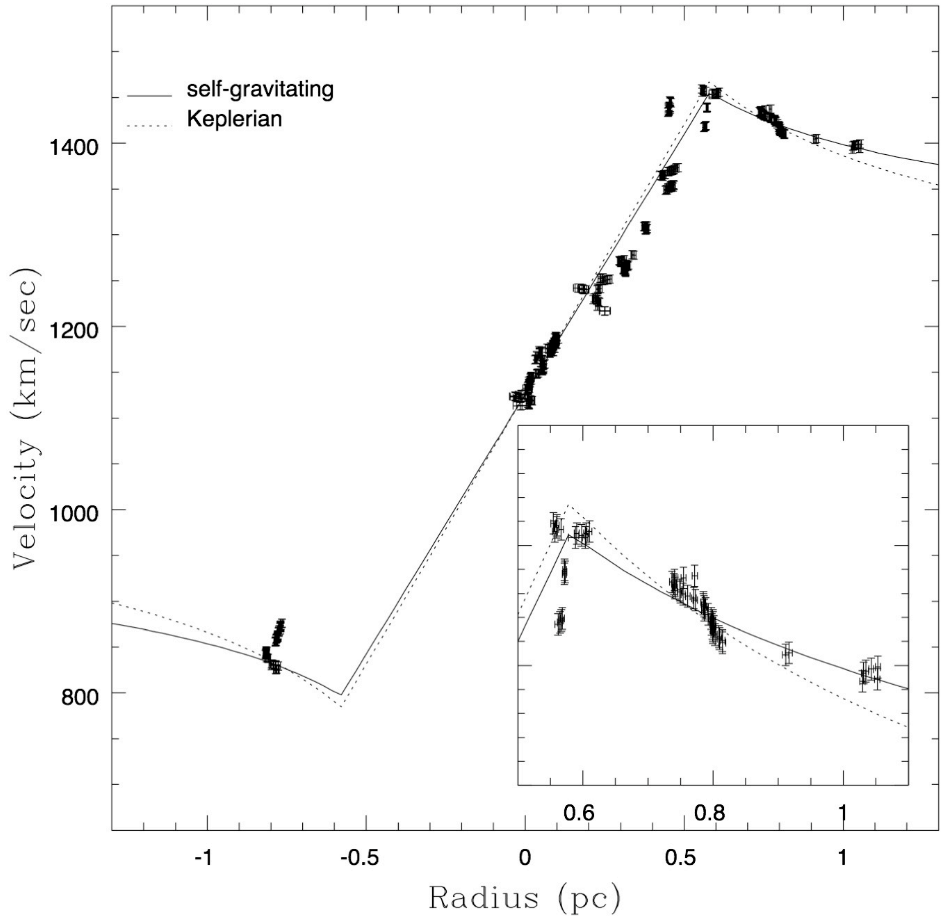


- $M_{BH} = 4$ _ $10^7\ M_{\odot}$ (Miyoshi et al. 1995)
- Possible to measure centripetal acceleration of maser spots and derive galaxy distance - similar to MW center (Herrnstein et al. 1999)



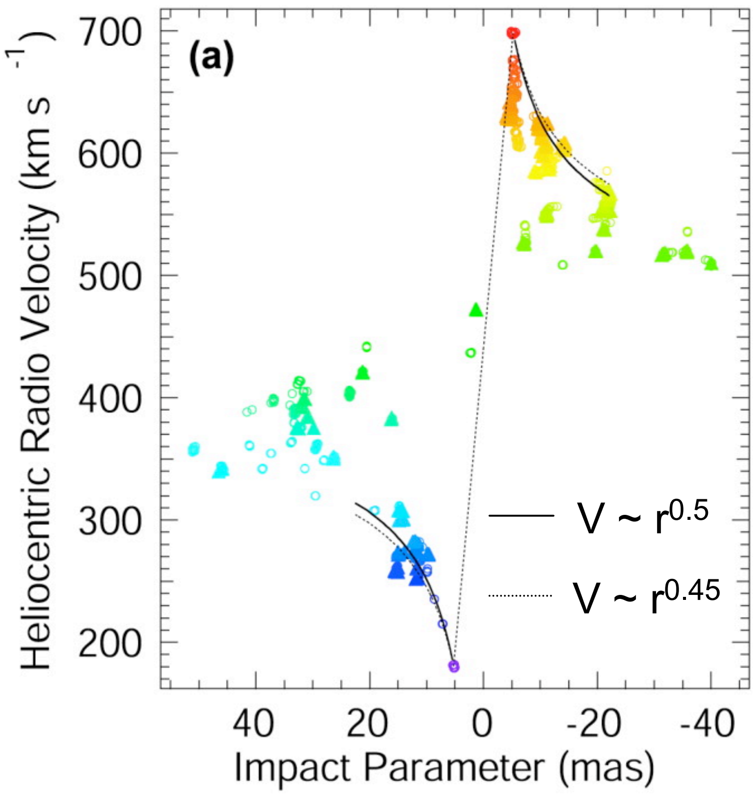
M_{BH} from H_2O masers: NGC 1068

- $M_{BH} \sim 10^7\ M_{\odot}$ (Greenhill et al. 1996)
  - but rotation flatter than Keplerian ...
  - Self-gravitating disk model by Lodato & Bertin (2003) gives $M_{BH} = (8.0 \pm 0.3) \times 10^6\ M_{\odot}$



M_{BH} from H_2O masers: Circinus

- $M_{BH}=(1.7\pm0.3)\times10^6\ M_{\odot}$ (Greenhill et al. 2001)
- Edge-on disk extends from 0.1 to 0.4 pc.
- The rotation curve is nearly Keplerian (massive disk is probably massive and self-gravity is not negligible).
- A second population of masers traces a wide angle outflow up to 1pc from the central engine.



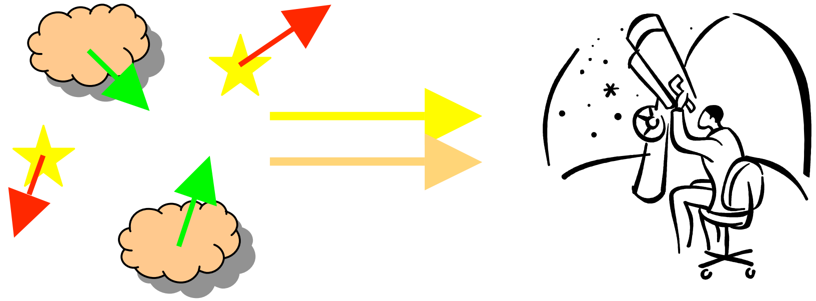
“Real life” is much harder …

- The galactic center and NGC 4258 are exceptional, "textbook" cases.
- Proper motions can be NOW measured only in our GC.
- 22 H_2O masers detected (out of ~700 galaxies obs.); 6 with "disk" structure (⇒ MBH) and NGC 4258 is still the best case by far (Moran et al. 2000)!
- 131 AGNs observed at the Parkes Observatory. 1 detection with disk emission (Greenhill et al. 2002)
- 1% efficiency of maser searches to find disk emission!!!
- We can use ONLY information from gas and stars integrated over large volumes (⇒ spatial resolution), and projected on the plane of the sky

Direct Methods to measure M_{BH}

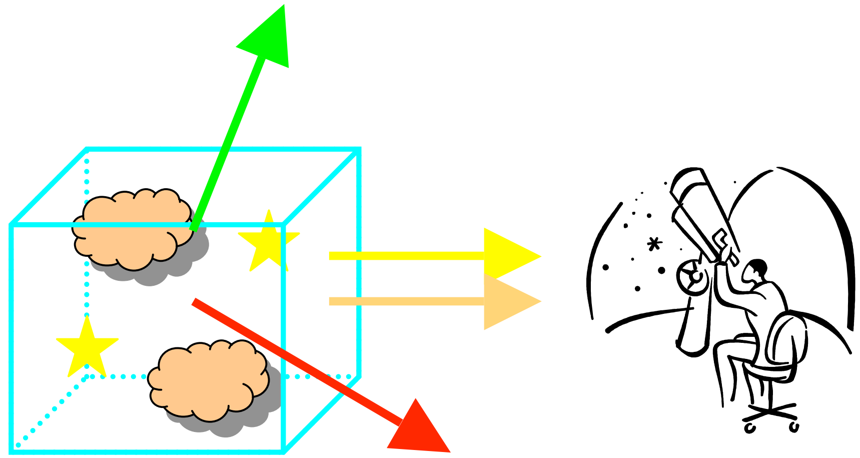
Motions of *test particles*

- Star proper motions and radial velocities ↳Milky Way
- Radial velocities of single gas clouds (masers) ↳NGC 4258



Volume averaged motions

- Stellar Dynamics
  V from Stellar Absorption Lines
- Gas Kinematics
  V from Gas Emission Lines



Black Hole Sphere of Influence

- Gravitational field of BH = Galactic gravitational field

$$r_{\mathrm{BH}} = \frac{GM_{\mathrm{BH}}}{\sigma_*^{\ 2}} = 10.7\,\mathrm{pc}\left(\frac{M_{\mathrm{BH}}}{10^8\mathrm{M}_{sun}}\right)\left(\frac{\sigma_*}{200\,\mathrm{km/s}}\right)^{-2}$$

- For a galaxy at distance D, r_{BH} corresponds to an angular size:

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

- Need high spatial resolution to probe within the BH sphere of influence and detect its effects.
- This is why the Hubble Space Telescope has produced such a major impact in the field.

Stellar dynamics

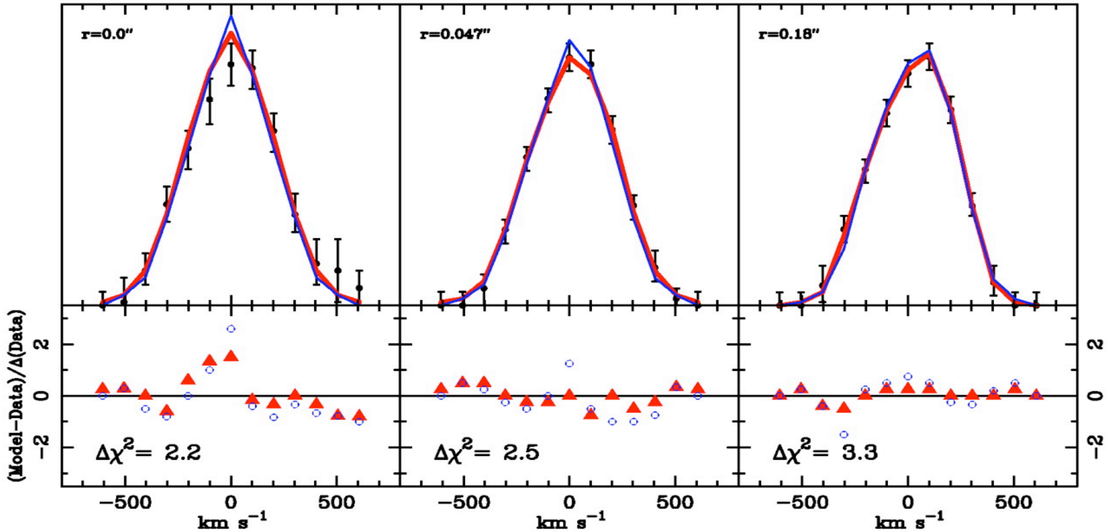
- The distribution function of stars $f(\vec{x},\vec{v};t)\,d^3\vec{x}\;d^3\vec{v}$
- follows the collisionless Boltzmann equation

$$\frac{\partial f}{\partial t} + \vec{\nabla}\cdot(f\vec{x}) + \vec{\nabla}\cdot(f\vec{v}) = \frac{\partial f}{\partial t} + \vec{v}\cdot\vec{\nabla}f - \vec{\nabla}\Phi(\vec{x})\cdot\frac{\partial f}{\partial \vec{v}} = 0$$

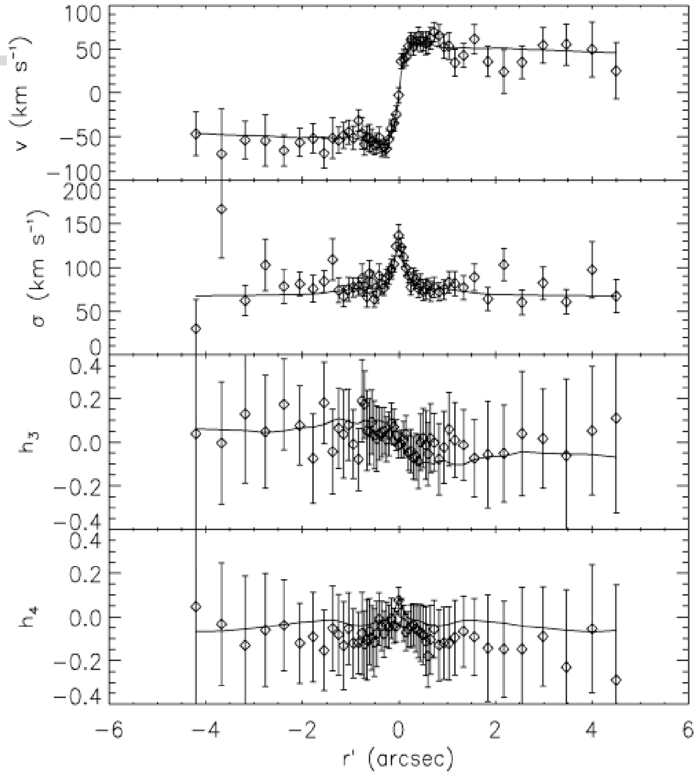
- ϕ is the galaxy gravitational potential (from images)
- Schwarzschild orbit superposition method
  - Complex technique to solve the stationary Boltzmann equation.
  - Assume axysimmetric system (can extend to triaxial systems).
  - Invert galaxy images to derive galaxy mass distribution (i.e. gravitational potential).
  - Assume that f depends on 2 or 3 integral of motions, e.g. $f=f(E,L_z)$.
  - Build library of stellar orbits.
  - Add up orbits to build galaxy (take into account instrumental effects).
  - Can now compute the Line of Sight Velocity Distribution (LOSVD) and compare with observed.

SEE LECTURES ON STELLAR DYNAMICS!

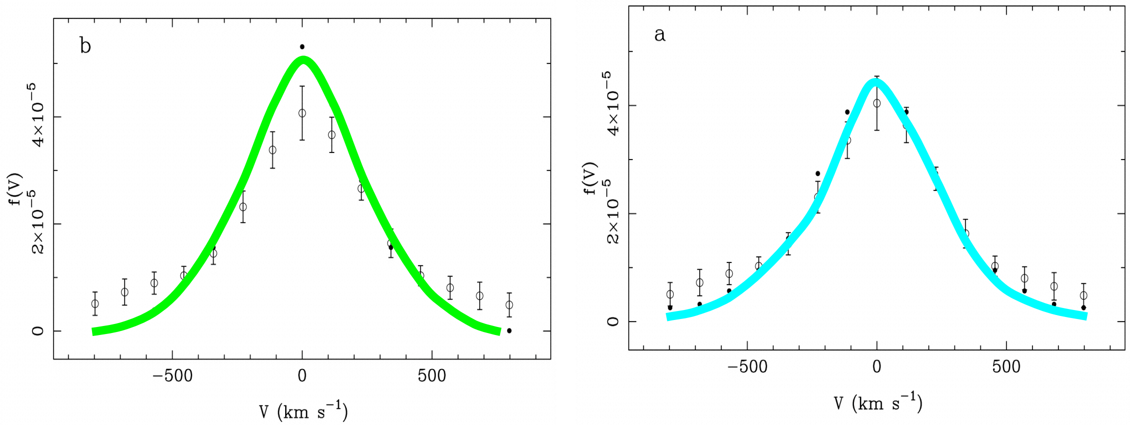
Stellar Dynamics



NGC 4560: Gebhardt et al. 2003



M32: Verolme et al. 200



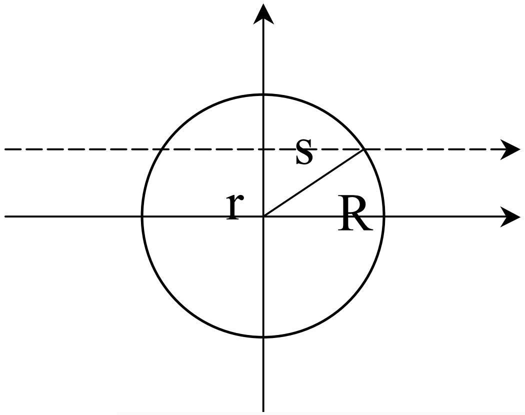
NGC 1023: Bower et al. 2001

Line of Sight
Velocity Distributions

stars only

stars + BH

Stellar mass density (Binney & Tremaine)

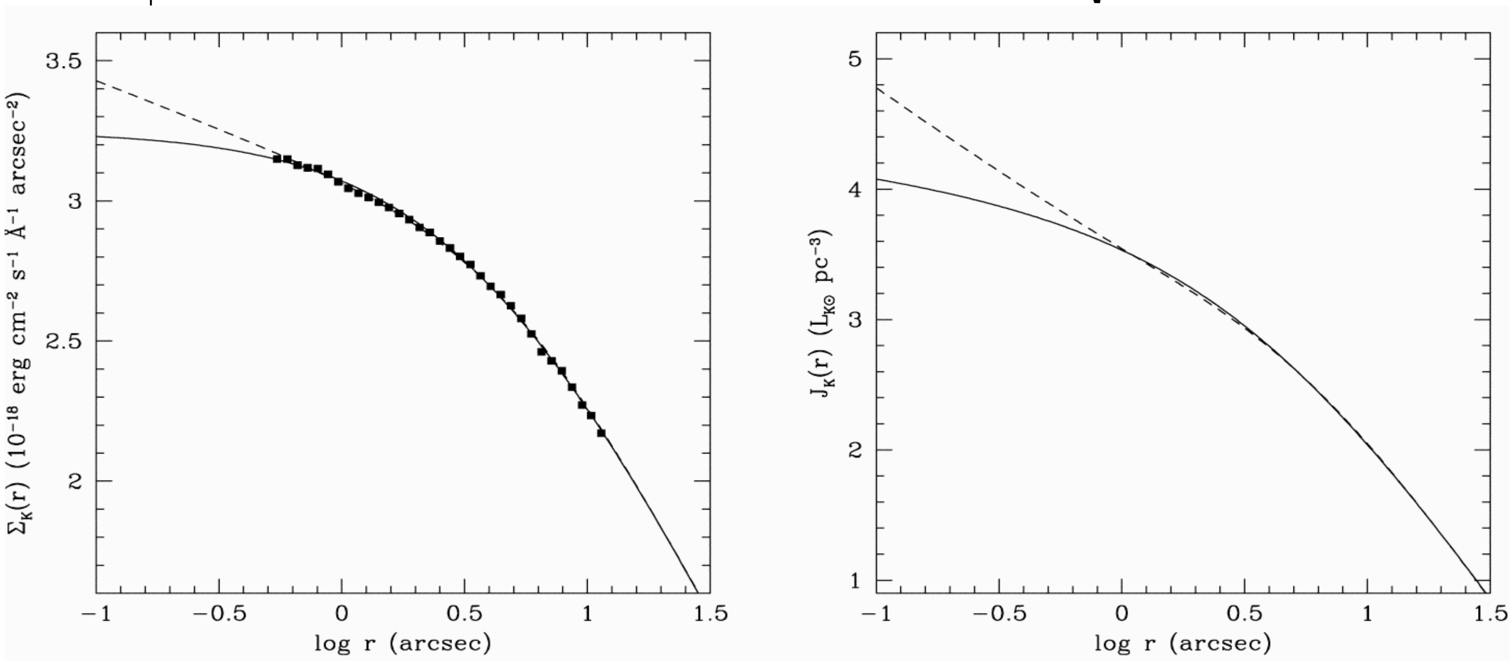


Assumption of spherical symmetry:

$$\Sigma(r) = \int_{-\infty}^{+\infty} J(s)ds = 2\int_{r}^{+\infty} \frac{J(R)R}{\sqrt{R^2 - r^2}} dR$$

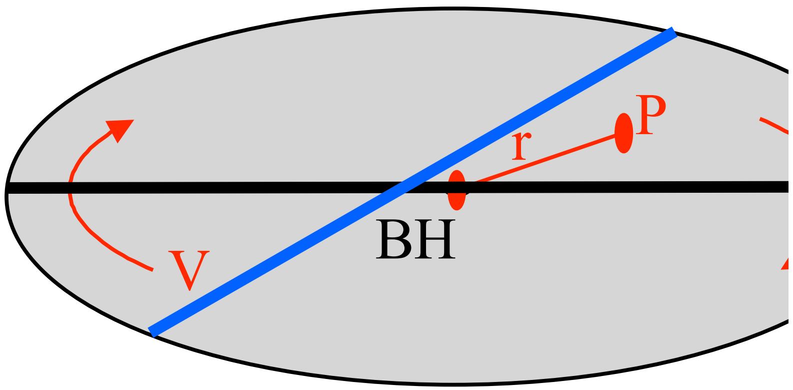
Abel's Equation with solution:

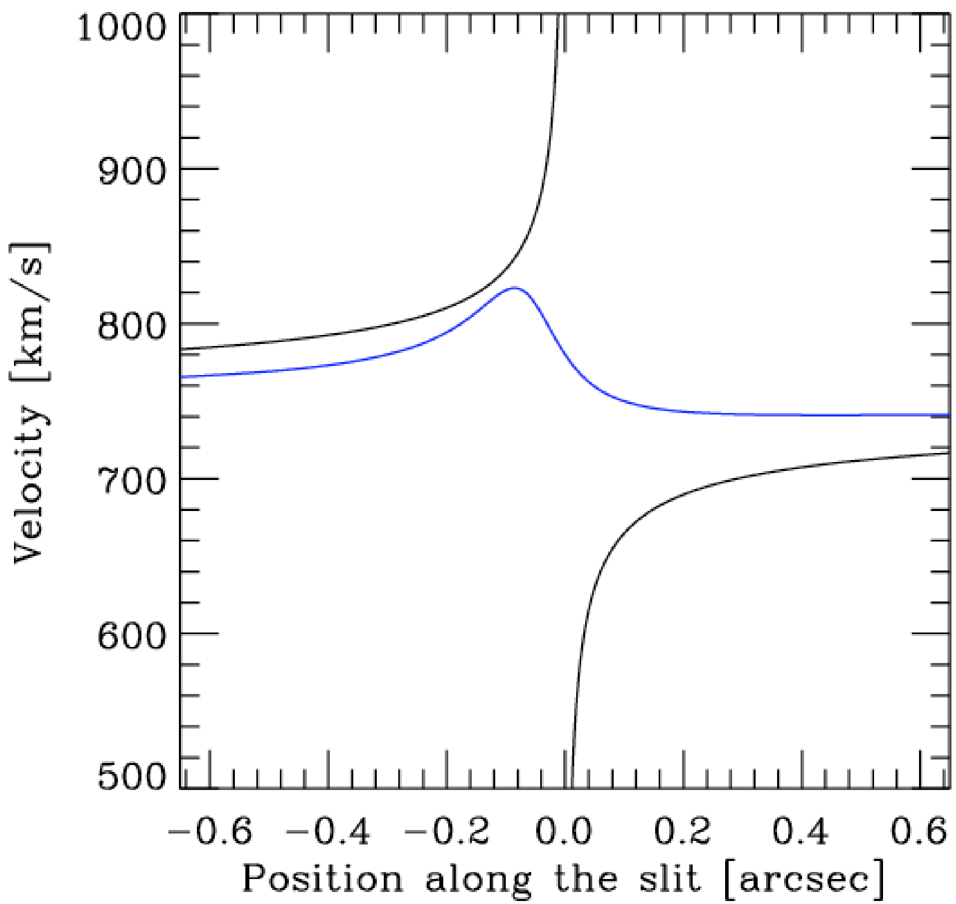
$$J(R) = -\frac{1}{\pi} \int_{R}^{+\infty} \frac{d\Sigma(r)}{dr} \frac{dr}{\sqrt{r^2 - R^2}}$$



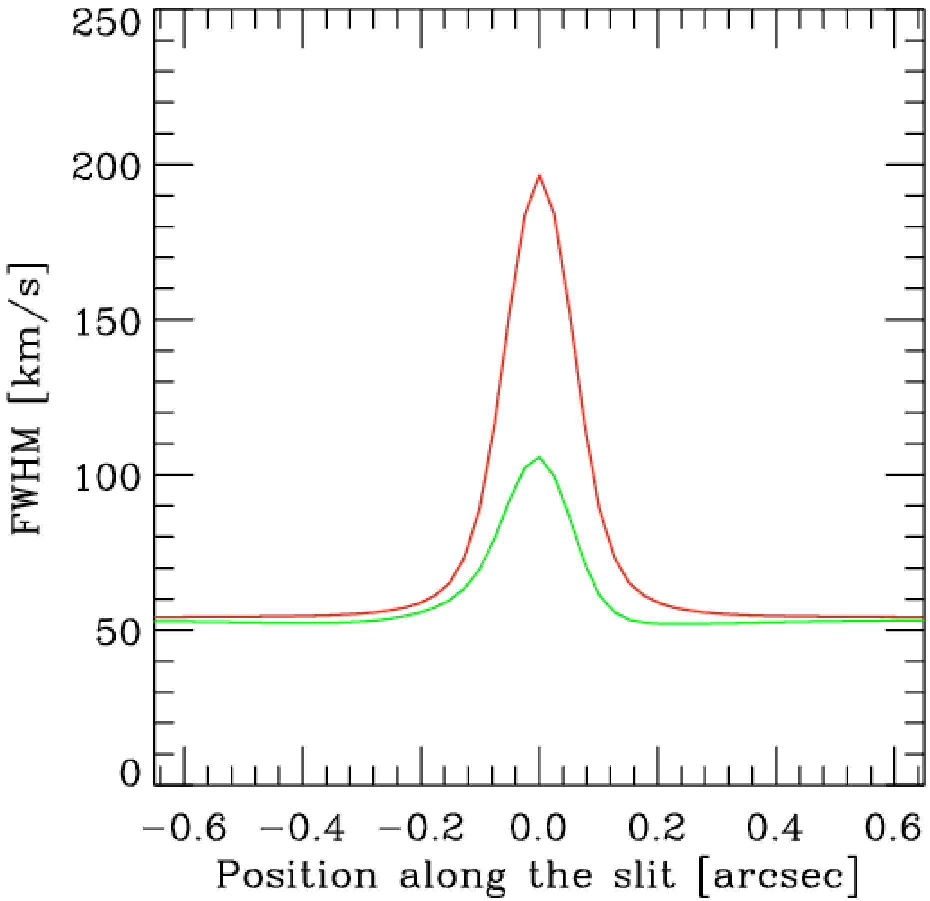
Gas Kinematics

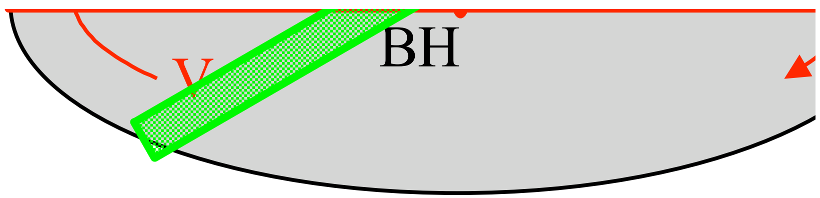
- BASIC ASSUMPTIONS:
  - no hydrodynamical effects (
    no pressure support);
  - disk composed of clouds ro
    in circular orbits;
  - motion is entirely determine
    gravity (Stars + BH).

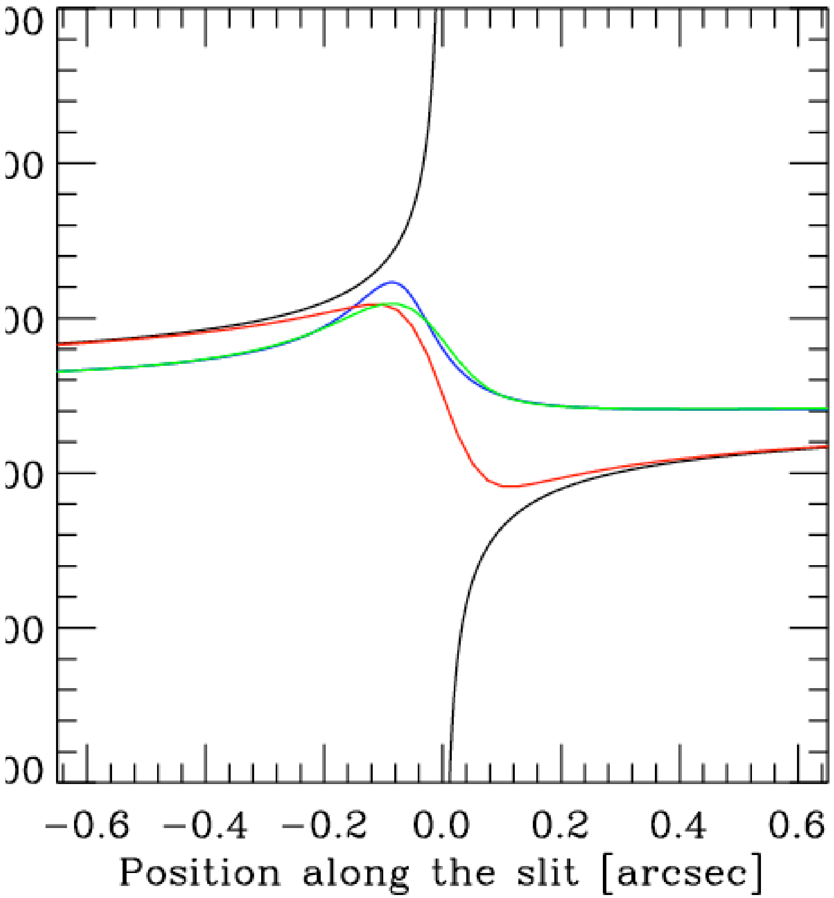




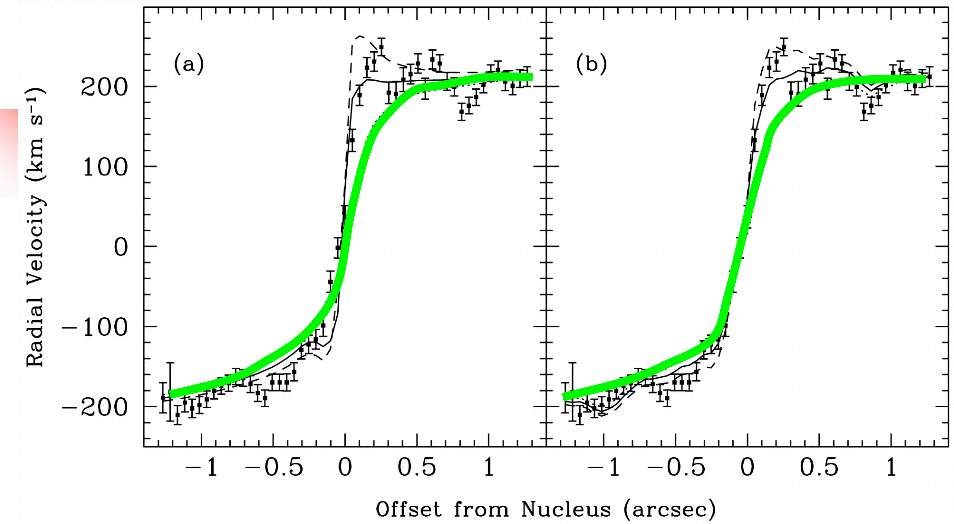
Gas Kinematics



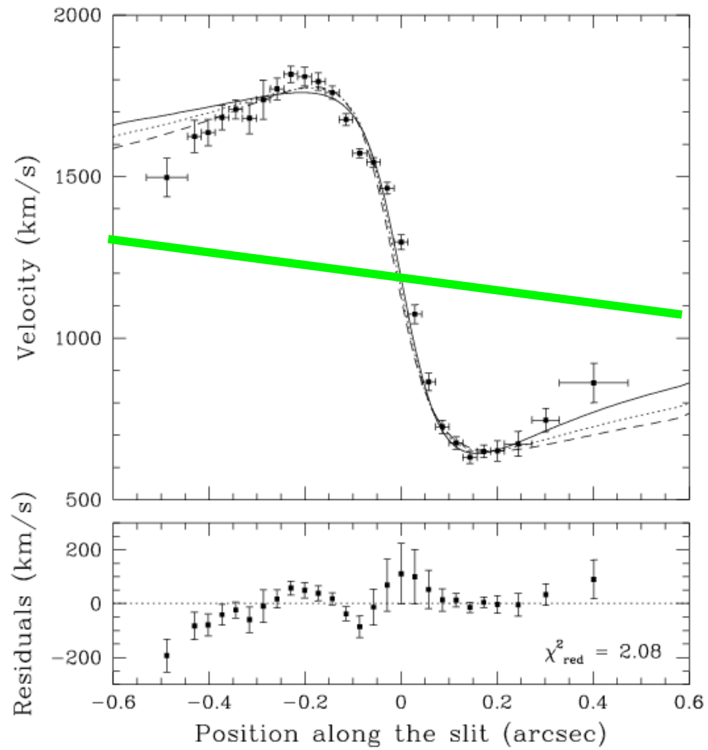




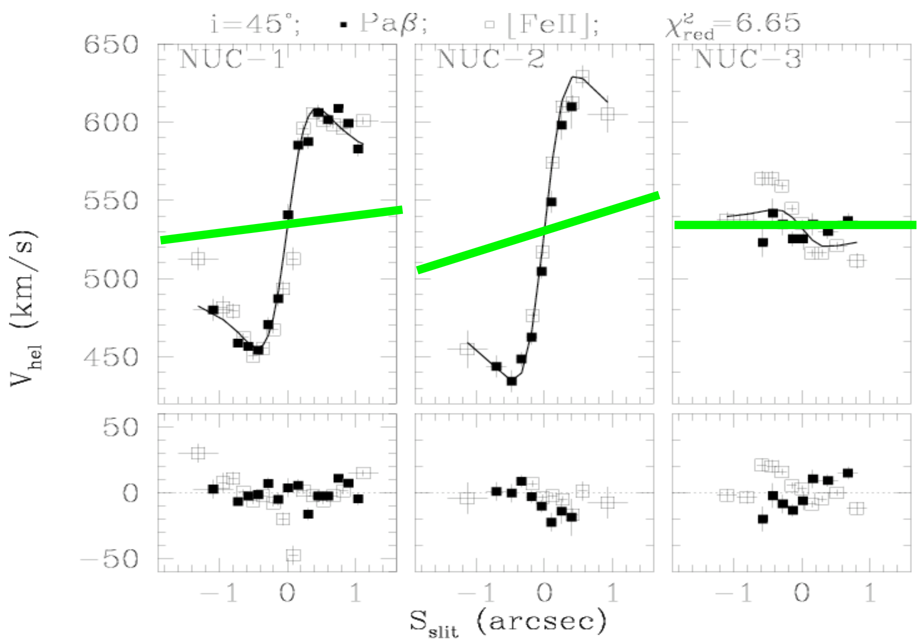
Gas Kinematics



NGC 3250: Barth et al. 2001



M87: Macchetto et al. 2001

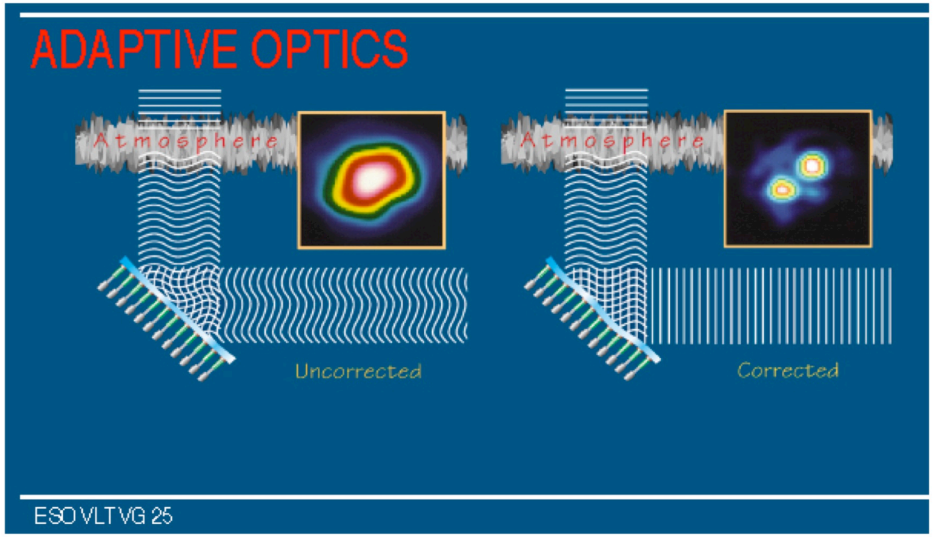


Centaurus A: Marconi et al. 2001

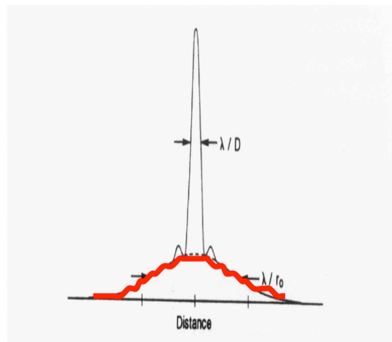
Rotation curves with stars only and no BH!

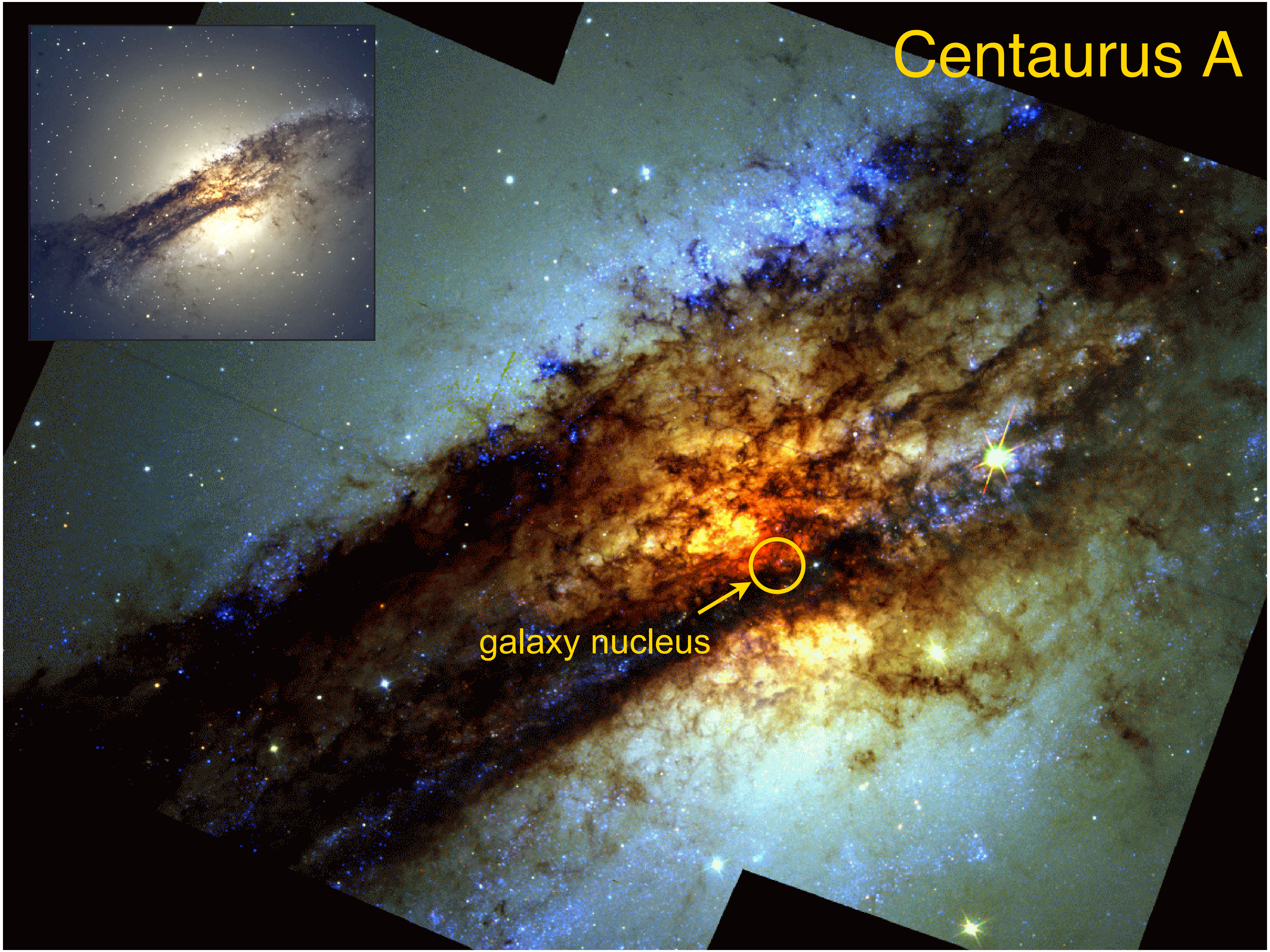
Infrared observations of BHs

- The case of the galactic center has clearly shown the need for near-IR (J, H or K) observations in order to:
  - reduce effects of dust reddening ($A_K/A_V\sim0.1$)
  - have good AO correction (Strehl ratio ~ $\lambda^{2.4}$)



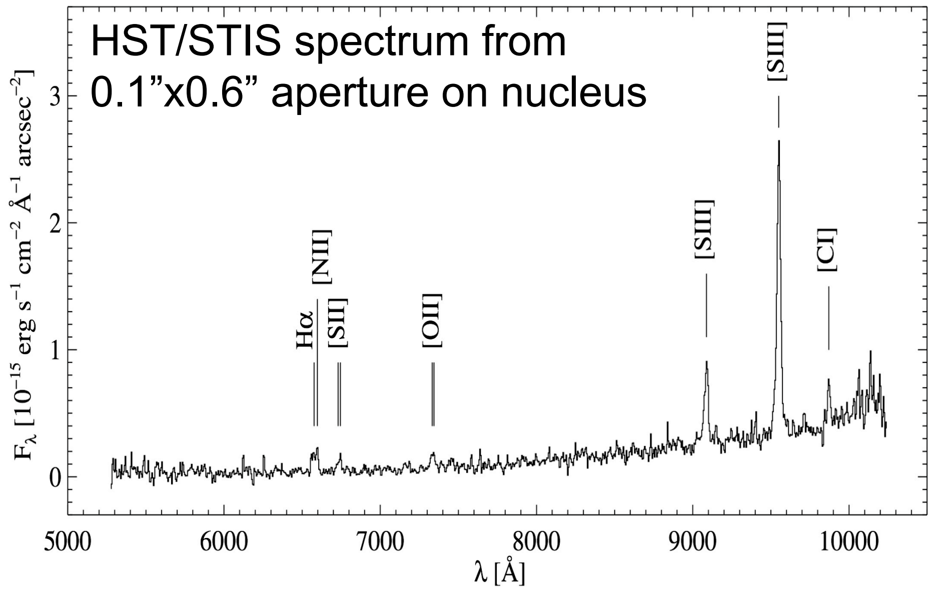
‘Strehl ratio’ = fraction of energy in central diffraction limited spike: $SR=1-\Sigma_j(\Delta_j\,(rad))$

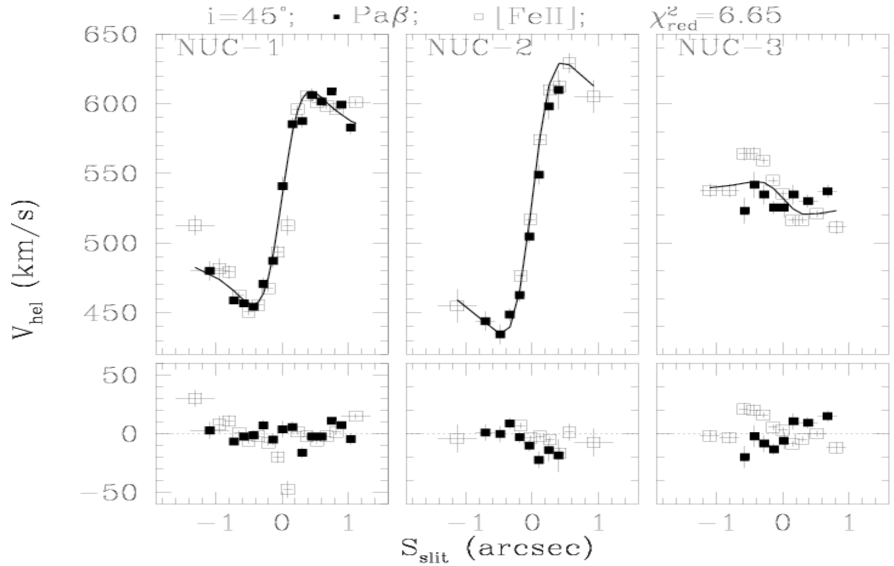



Centaurus A
galaxy nucleus

The case of Centaurus A

- A_V~7 toward the nucleus (Schreier et al. 1997)
  - [SIII] 9532/Ha ~ 0.3 in Seyferts and ~1 in LINERs (Osterbrock et al. 1992)
- Marconi et al. (2001) measure the BH mass using kinematics of Paβ and [FeII] lines at ~1.25 μm. Seeing limited observations (0.6" resolution).





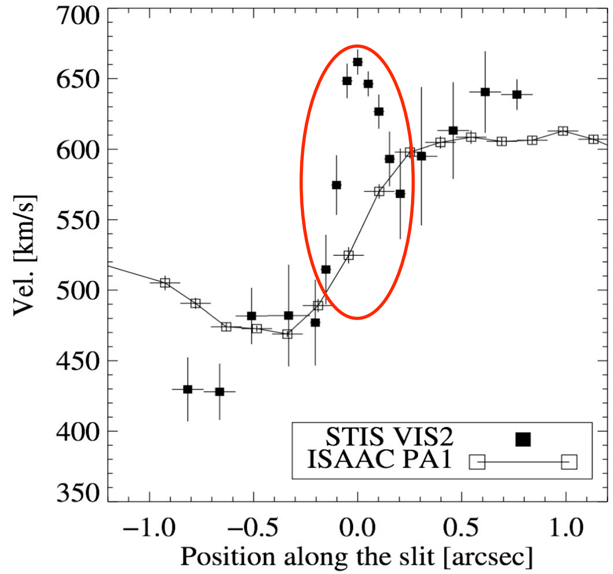
The case of Centaurus A

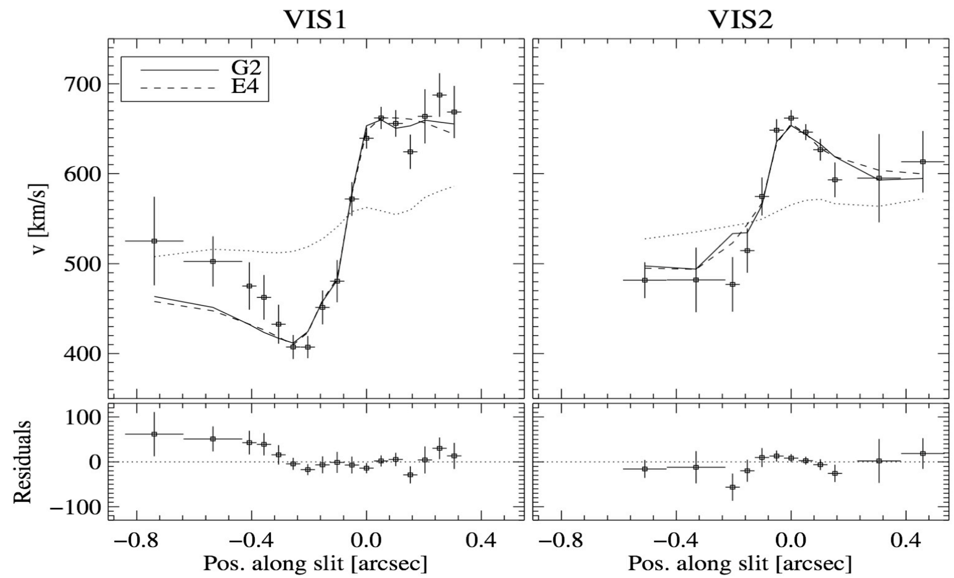
- HST/STIS observations of the [SIII] 9530Å line with 0.1” resolution (Marconi, Pastorini et al. 2006).

- High resolution STIS data (0.1”) provide same BH mass as “low” resolution ground based ISAAC data (0.6”): $M_{BH} \sim 2\times10^{8}\ M_{\odot}$

Curves from slits along the same direction

High velocities showing up with high spatial resolution



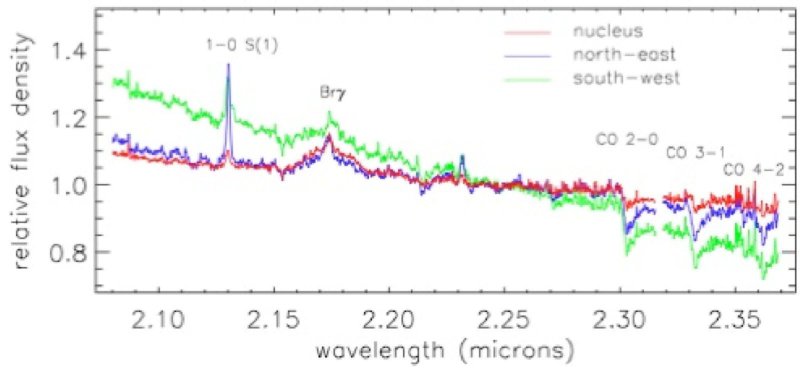


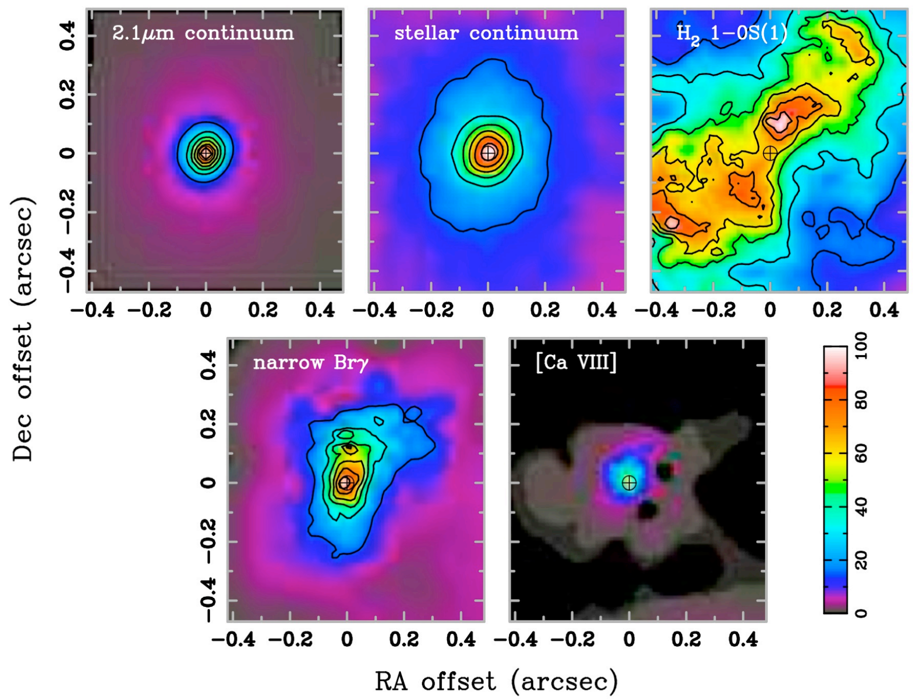
Adaptive Optics observations

- NAOS/CONICA (VLT) spectroscopic observations of NGC 1399 of the CO bandheads (2.4 μm) reach a spatial resolution of 0.15” = 14 pc (Houghton et al. 2006). Stellar dynamical models provide $M_{BH}=1.2\pm0.5 \times10^9$ M
- NAOS/CONICA spectroscopic observations of Centaurus A reach 0.06” in K and 0.11” in H band (Haering-Neumayer et al. 2006)
- Spatial resolution of HST is 0.07” at 6500 Å and 0.22” in K (but HST has no NIR spectrograph!)
- Drawback of AO is that you need a “bright” reference source(eg V<15) close (eg <20”) from your source (and good seeing, e.g. ~0.6”)

AO and integral field spectroscopy

- SINFONI (VLT) observations of Seyfert 1 galaxy NGC 3227 (Davies et al. 2006).
- Spatial resolution of 0.09” (K band)
- BH mass from stellar dynamics (CO bandheads at 2.3 μm):
  - $M_{BH}=7\times10^{6}-2\times10^{7}\ M_{\odot}$
  - Consistent with reverberation mapping estimate!
- See Guia Pastorini’s talk for more details on 3D spectroscopy and BHs





Gas vs Stellar Kinematics

Gas:

- high surface brightness, short integration times
- Easy interpretation

- but not in all galaxies
- only if system is a circularly rotating disk

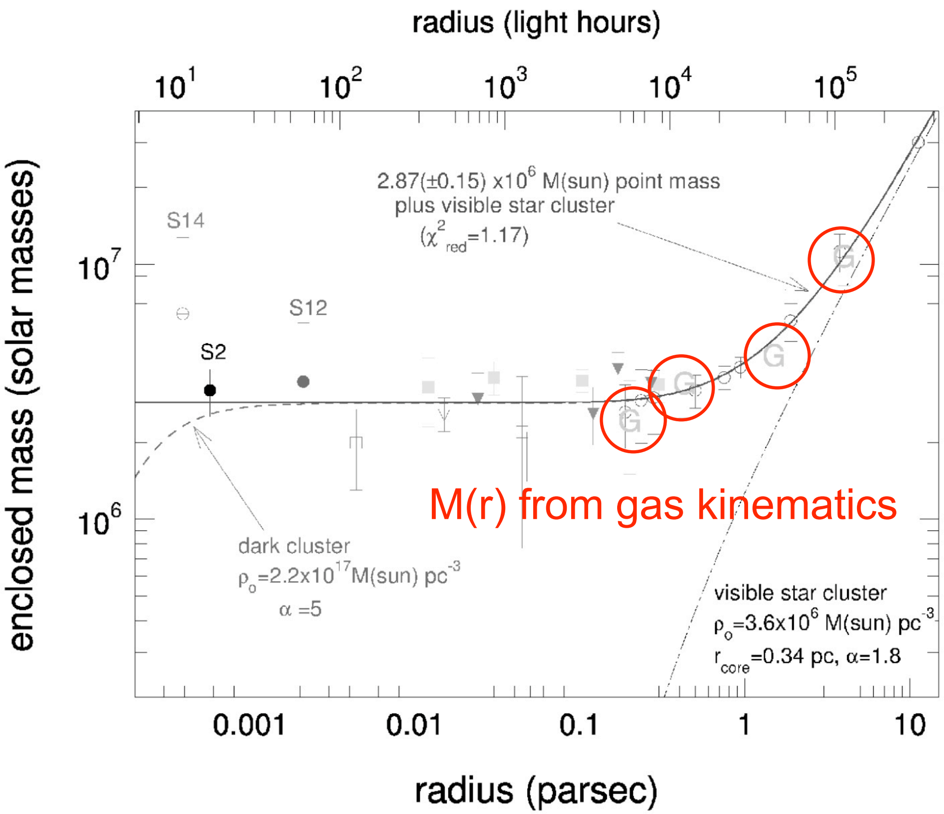
Stars:

- completely gravitational motions
- available in all galaxies

- but interpretation difficult (3D star orbits)
- but observations require long integration times

Gas vs Stellar Kinematics

- Are gas and stellar kinematical BH mass measurements consistent?
- Comparison have been done only for a two cases and the derived MBH are consistent!
  - Galactic Center (Schodel et al. 2003, Genzel & Townes 1987)
  - Centaurus A (Marconi et al. 2006, Silge et al. 2005)
- Need more tests!

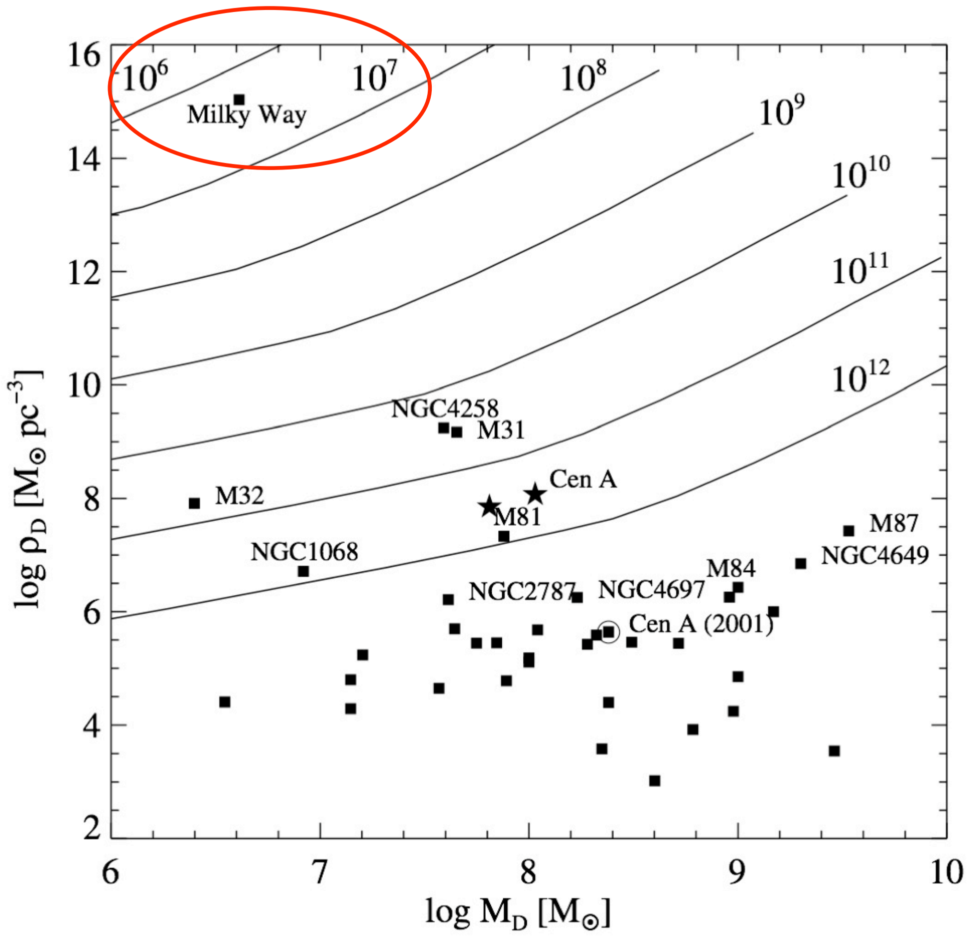


Are they really Black Holes?

- BHs are in reality Massive Dark Objects, i.e. dark matter objects unresolved at the spatial resolution of observations.
- Maoz (1997) use simple physical considerations to derive the maximum possible lifetime of a dark cluster (brown dwarfs, Jupiters, white dwarfs, neutron stars, stellar black holes, etc.)
- He computes the lifetime of the cluster against collapse to a supermassive BH. Main physical processes which lead to collapse are:
  - Evaporation (objects in the tail of Maxwellian distribution can escape gravitational attraction of cluster; cluster readjusts itself and contracts)
  - Collisions

Are they really Black Holes?

- M_D from observations
- Cluster size from spatial resolution of observations (FWHM~2 R_D)
- Estimate average density of star cluster ρ_D
- Only in the case of the Milky Way the cluster lifetime << age of the universe
- Boson star is the only possible alternative to a BH!
- Definitive Proof for existence of a BH is detection of relativistic velocities in orbits at a few Schwarzschild radii (Broad red wings of Fe Kα lines?)



Updated from Maoz (1998)

Status of BH searches

TABLE I

Probing the centers of galaxies.

Method & Telescope	Scale (R_S)	No. of SBH Detections	$M_\bullet$ Range ($M_\odot$)	Typical Densities ($M_\odot$ pc^{-3})
Fe Kα line (XEUS, ConX)	3–10	0	N/A	N/A
Reverberation mapping (Ground based optical)	600	36	$10^6 - 4 \times 10^8$	$\gtrsim 10^{10}$
Stellar proper motion (Keck, NTT, VLT)	1000	1	4×10^6	4×10^{16}
H_2O megamasers (VLBI)	10^4	1	4×10^7	4×10^9
Gas dynamics (optical) (Mostly *HST*)	10^6	11	$7 \times 10^7 - 4 \times 10^9$	$\sim 10^5$
Stellar dynamics (Mostly *HST*)	10^6	17	$10^7 - 3 \times 10^9$	$\sim 10^5$

Ferrarese & Ford 2005