5. Massive black holes in galactic nuclei

Frontiers of Astronomy Workshop/School
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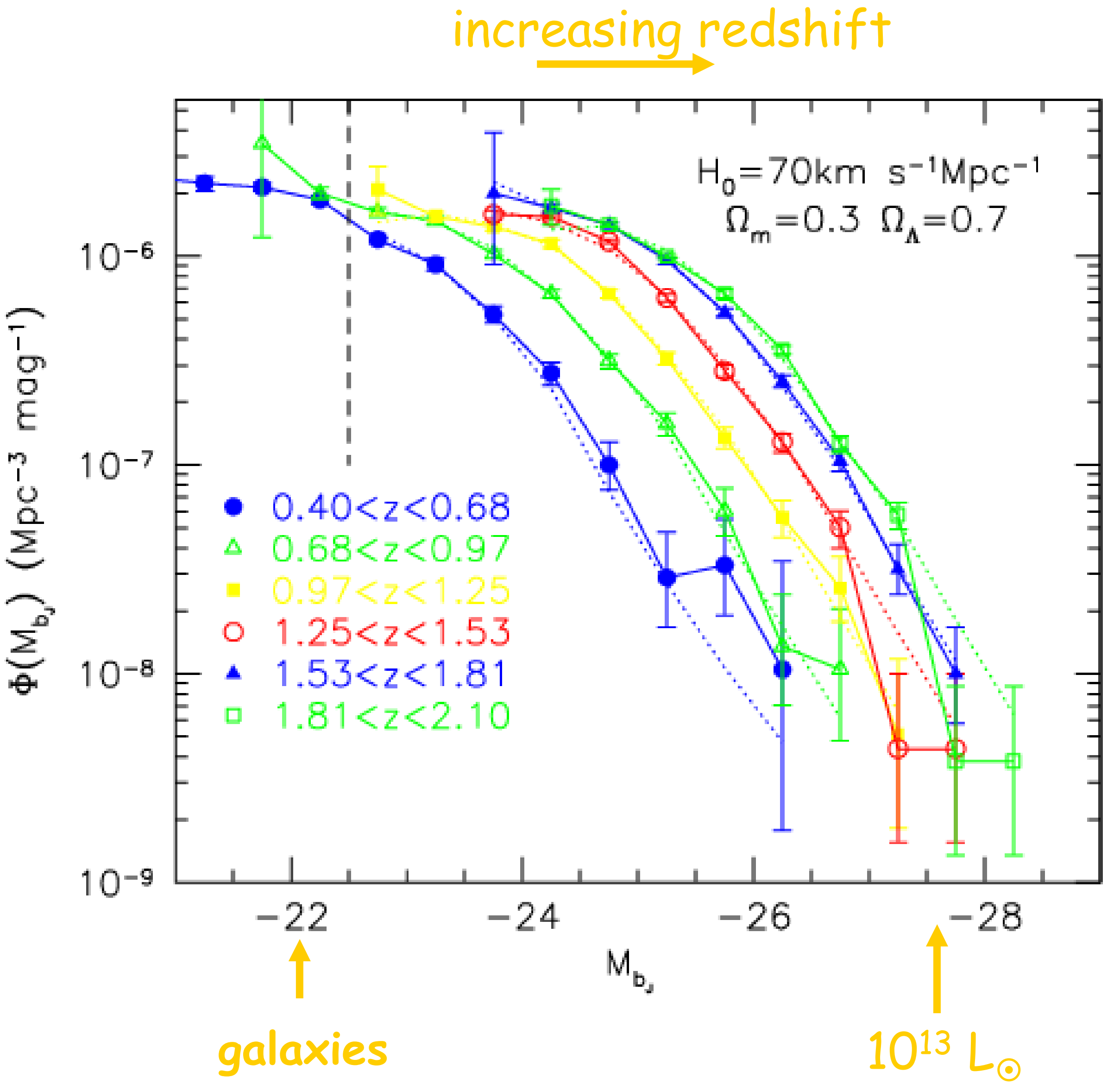
Active galactic nuclei

- ~ 1% of galaxies contain a bright, unresolved, central nucleus that emits non-stellar radiation
- there is a large zoo of AGNs: radio galaxies, Seyfert galaxies (type 1, type 2), BL Lacs, emission-line galaxies, quasars (QSOs), optically violent variables, blazars, etc.
- quasars or QSOs are the most luminous AGNs, $\sim 10^{46}$ erg/sec or $10^{13}\,L_\odot$, or 100–1000 times typical galaxy luminosity



2dF quasar redshift survey

Croom et al. (2004)

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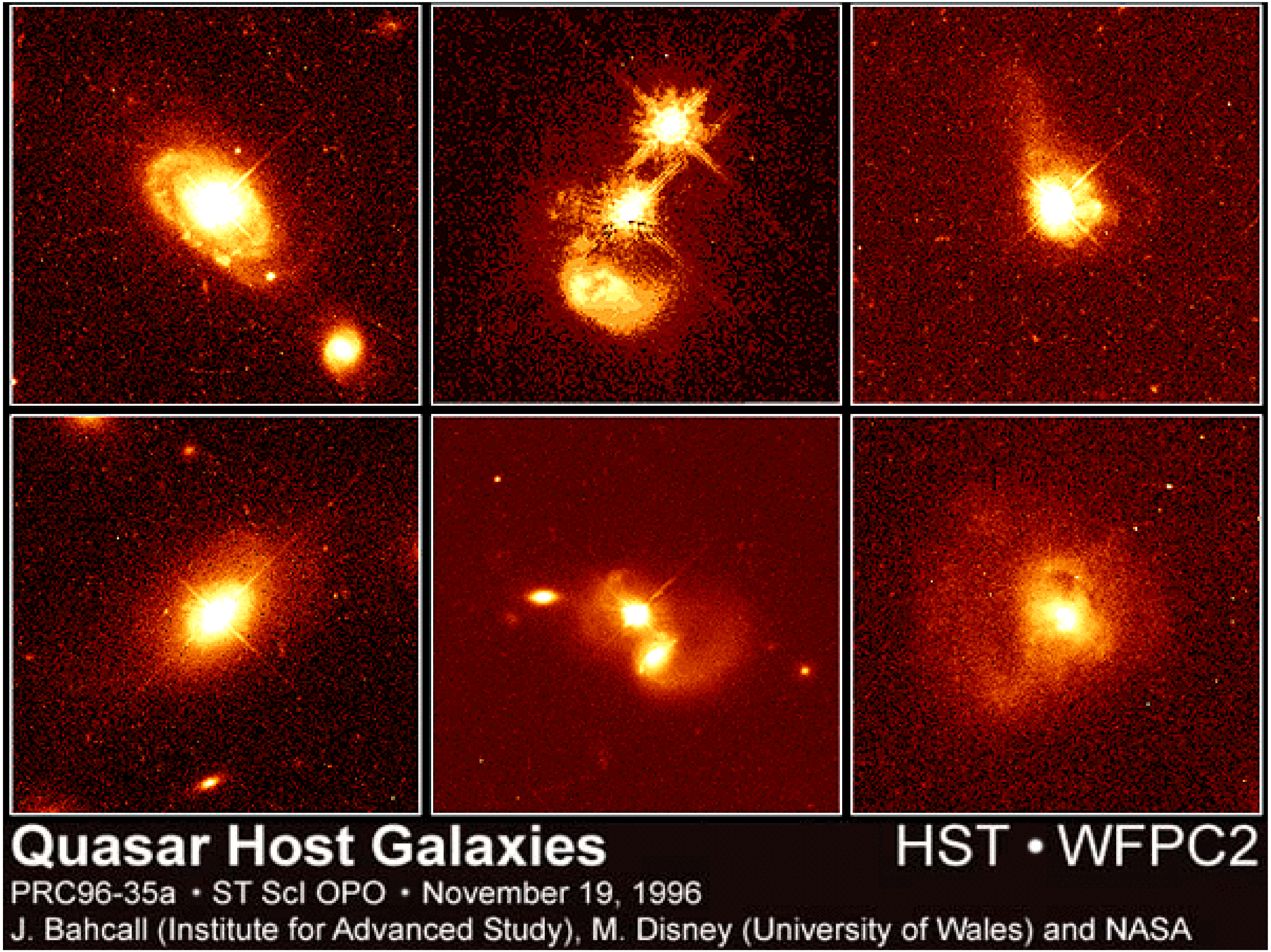
Quasar Host Galaxies
HST • WFPC2
PRC96-35a • ST ScI OPO • November 19, 1996
J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA

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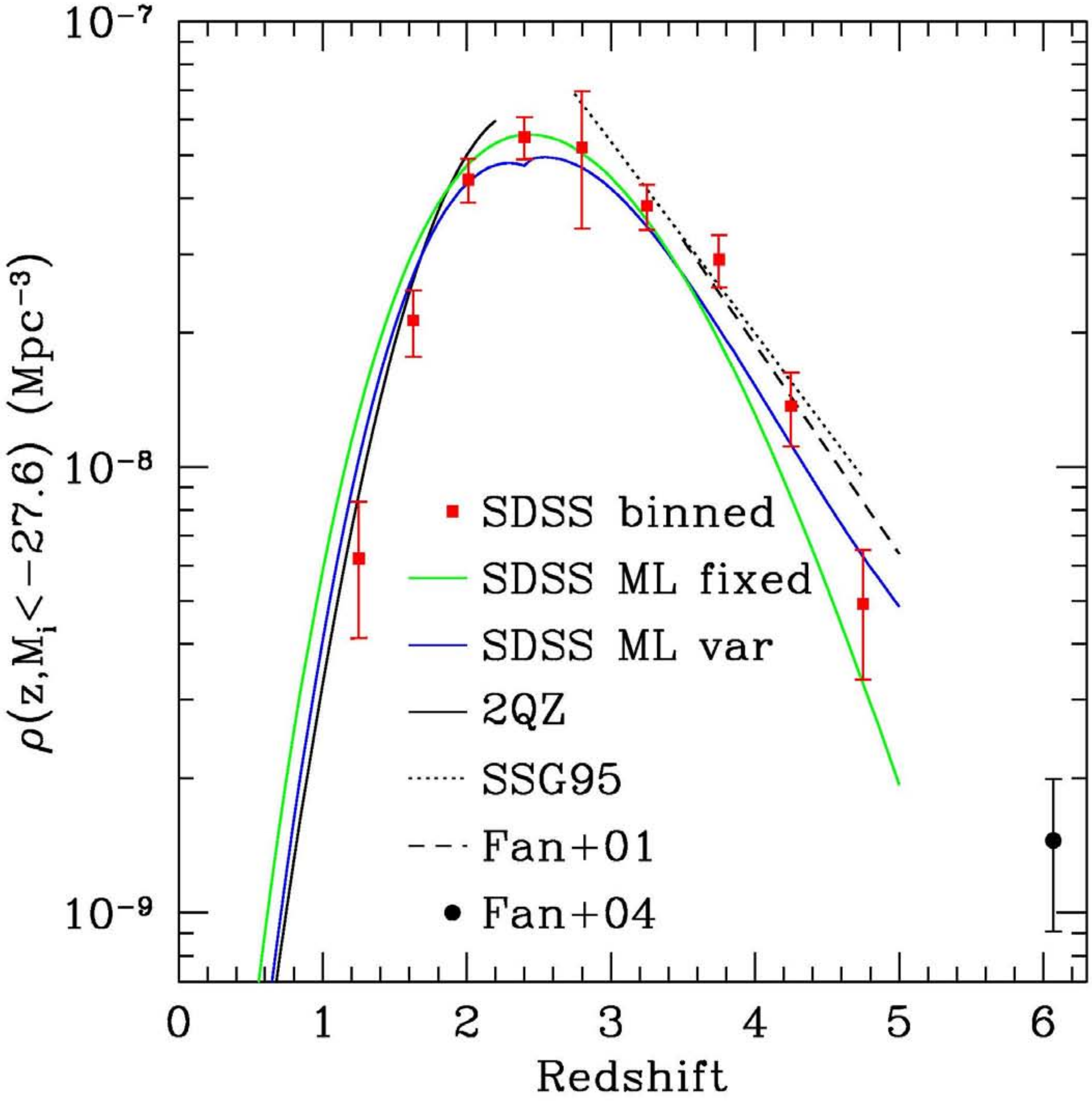
- bright QSOs are concentrated at redshifts 2–3



Sloan Digital Sky Survey

Richards et al. (2006)

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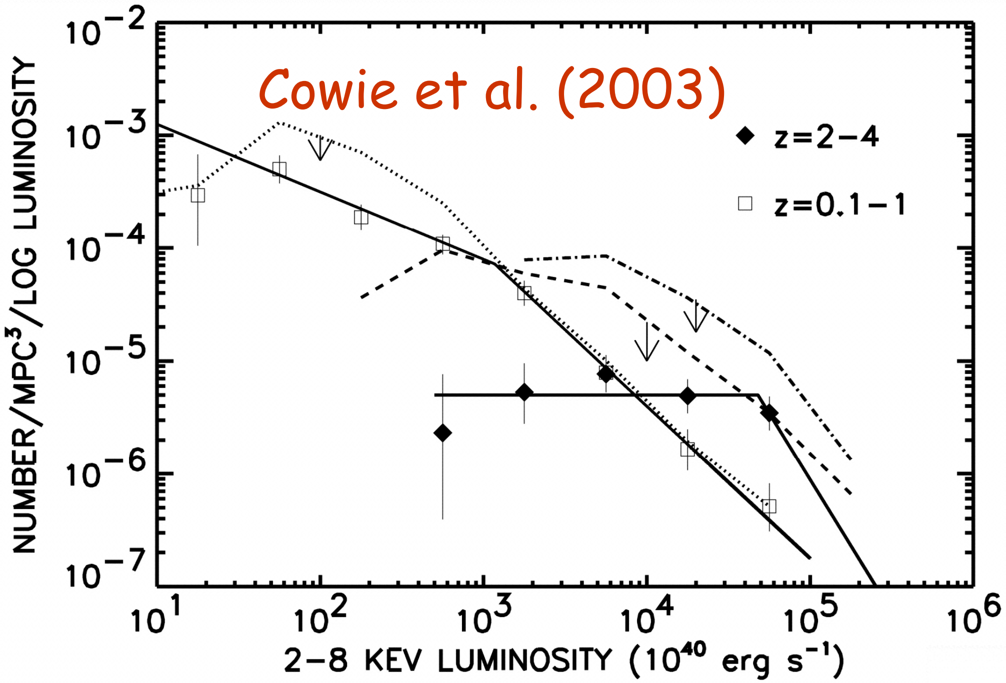
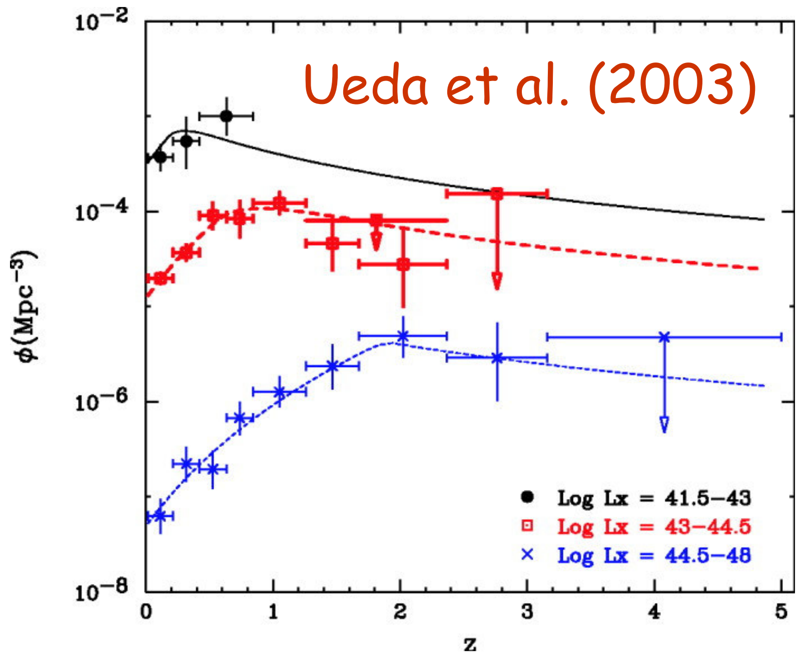
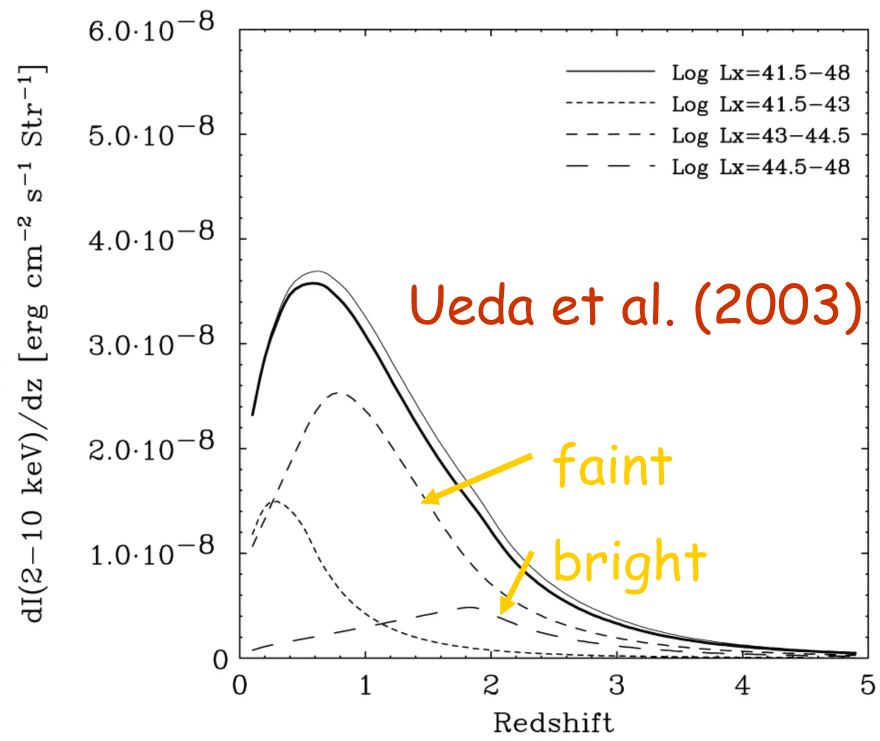
- QSOs are usually bright enough to hide host galaxy at ground-based resolution
- QSOs are concentrated at redshifts 2–3
- most of the X-ray background is due to obscured AGN at smaller redshift ($z \approx 0.7$) and lower luminosity


Cowie et al. (2003)
z=2−4
z=0.1−1
NUMBER/MPC^3/LOG LUMINOSITY
2−8 KEV LUMINOSITY (10^{40} erg s^{-1})


Ueda et al. (2003)
ϕ(Mpc^{-3})
z
Log Lx = 41.5−43
Log Lx = 43−44.5
Log Lx = 44.5−48


Ueda et al. (2003)
Log Lx=41.5−48
Log Lx=41.5−43
Log Lx=43−44.5
Log Lx=44.5−48
dI(2−10 keV)/dz [erg cm^{-2} s^{-1} Str^{-1}]
Redshift
faint
bright

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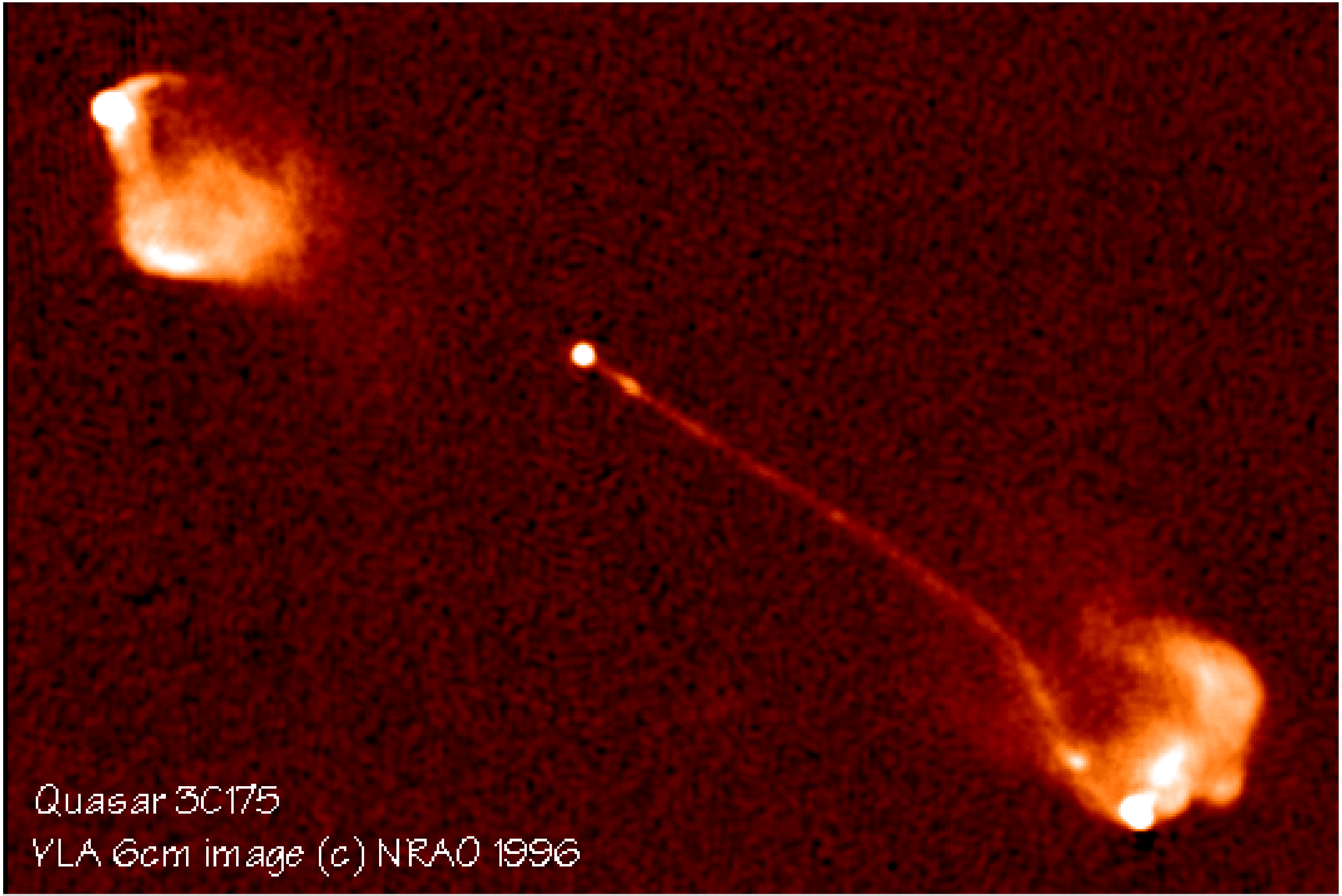
- QSOs are usually bright enough to hide host galaxy at ground-based resolution
- QSOs are concentrated at redshifts 2–3
- most of the X-ray background is due to obscured AGN at smaller redshift and lower luminosity
- the power source for AGNs is accretion onto a black hole (Salpeter 1964; Lynden-Bell 1969)

Black holes as the power source for AGN

- directional stability of radio jets maintained for 1 Myr or more



Bridle et al. (1994)

Black holes as the power source for AGN

- directional stability of radio jets maintained for 1 Myr or more
- relativistic velocities in radio jets

Black holes as the power source for AGN

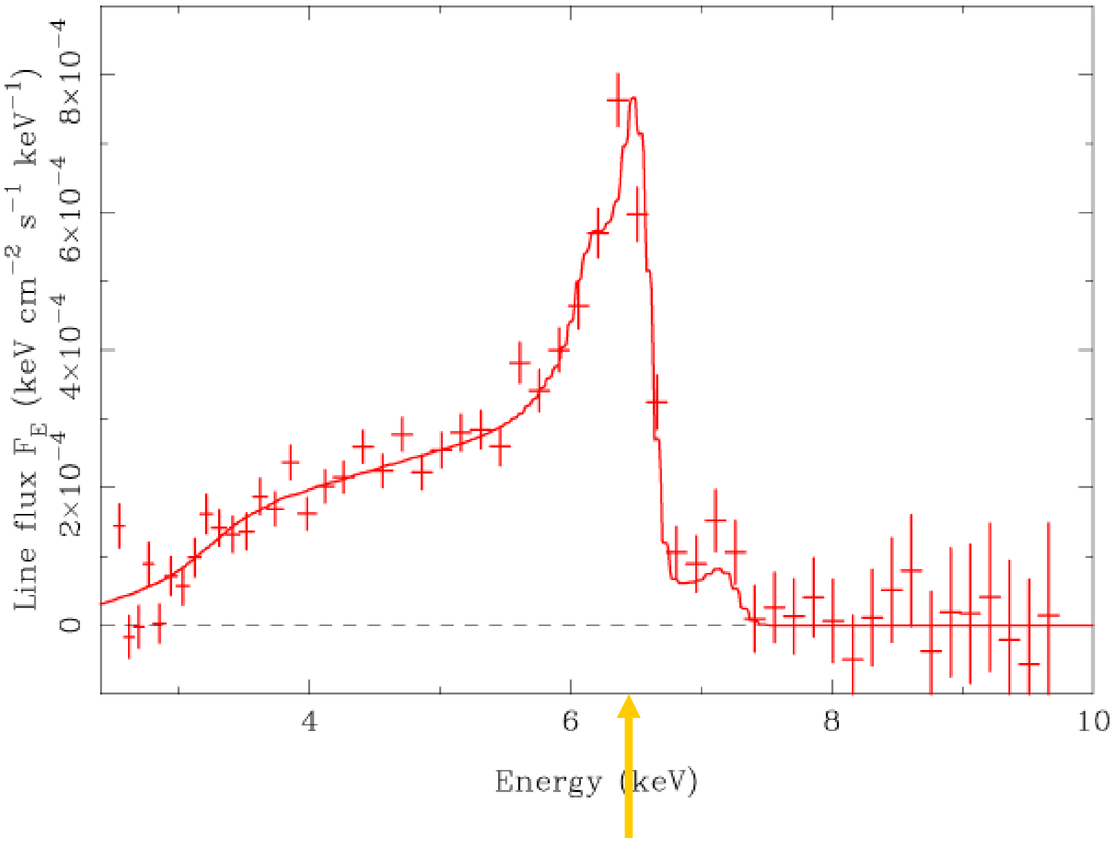
- directional stability of radio jets maintained for 1 Myr or more
- relativistic velocities in radio jets
- rapid time variability:
  - flickering in BL Lac objects on timescales down to 30 s
  - X-ray flare in PKS 0558-504 on timescale 200 s
  - X-ray flares common in Seyfert galaxies on timescale of hours

For comparison,

- Schwarzschild radius $R_{Sch}= 2.9 \times 10^{13} M_8$ cm, $M_8=M/10^8 M_\odot$
- minimum variability timescale is $R_{Sch}/c=1000 M_8$ s

Black holes as the power source for AGN

- directional stability of radio jets maintained for 1 Myr or more
- relativistic velocities in radio jets
- rapid time variability
- iron emission line



- Seyfert galaxy MCG-6-30-15
- relativistically broadened and redshifted iron K a line
- model fit to inner and outer accretion disk radii, disk inclination, total line flux, power-law radial emissivity distribution
- required radius range is ~1-10 r_{Sch}

Shih, Iwasawa & Fabian (2002)

Black holes as the power source for AGN

- directional stability of radio jets maintained for 1 Myr or more
- relativistic velocities in radio jets
- rapid time variability
- efficiency

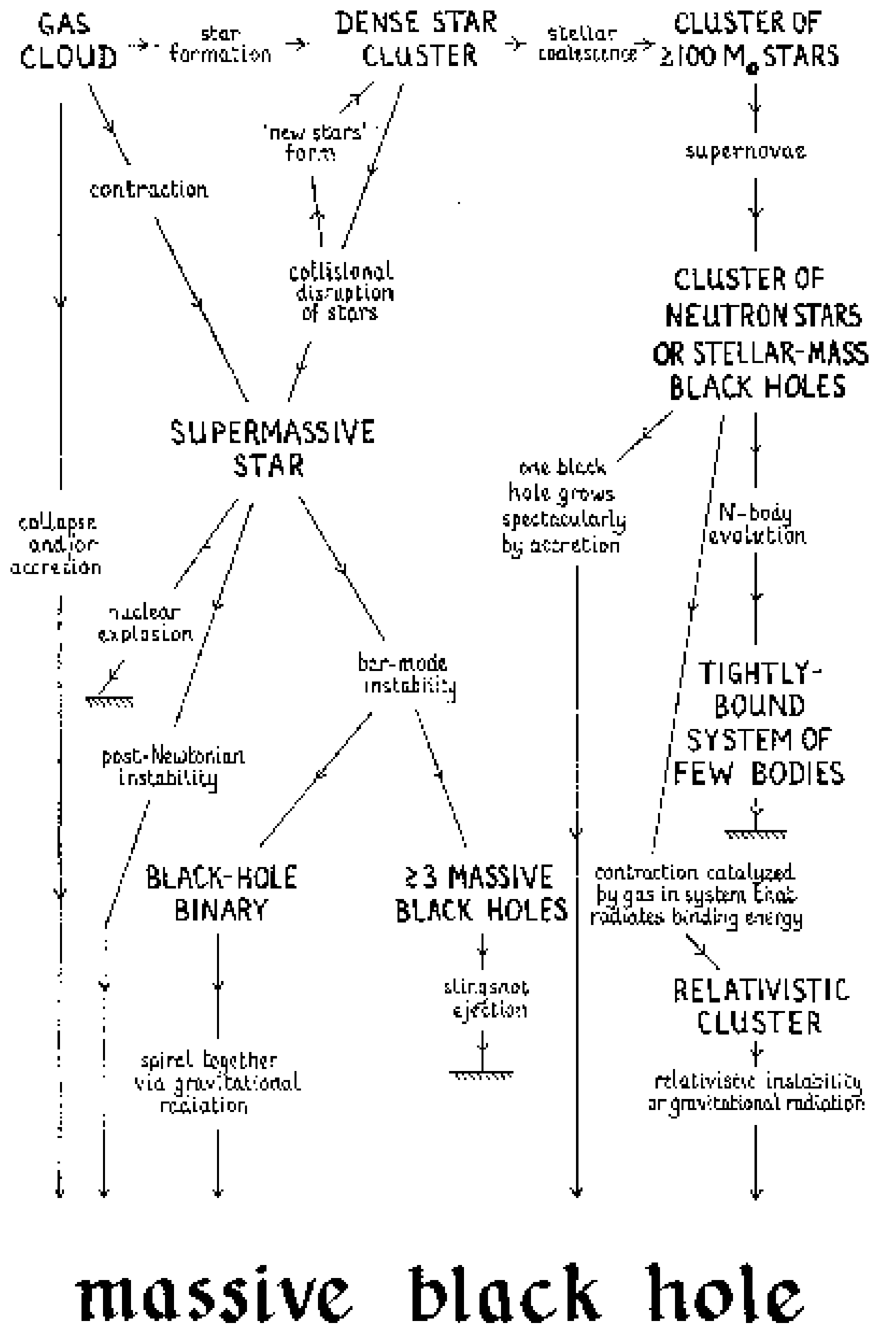
Burning a mass ΔM produces energy ΔE with efficiency

$$\varepsilon \equiv \frac{\Delta E}{\Delta M c^2}$$

$\varepsilon < 0.008$ for nuclear reactions
$\varepsilon < 10^{-4}$ for supernovae (excluding neutrinos)
$\varepsilon = 0.057$ for accretion onto a non-rotating (Schwarzschild) black hole
$\varepsilon = 0.3$ for accretion onto a Kerr black hole in equilibrium spin state
$\varepsilon = 0.423$ for accretion onto a maximally rotating black hole

Black holes as the power source for AGN

- directional stability of radio jets maintained for 1 Myr or more
- relativistic velocities in radio jets
- rapid time variability
- efficiency
- most other plausible sources eventually turn into black holes anyway, and the black holes provide more efficient engines than their precursors


GAS CLOUD
star formation
DENSE STAR CLUSTER
stellar coalescence
CLUSTER OF ≥100 M☉ STARS
supernovae
'new stars' form
contraction
collisional disruption of stars
CLUSTER OF NEUTRON STARS OR STELLAR-MASS BLACK HOLES
SUPERMASSIVE STAR
one black hole grows spectacularly by accretion
N-body evolution
collapse and/or accretion
nuclear explosion
bar-mode instability
TIGHTLY-BOUND SYSTEM OF FEW BODIES
post-Newtonian instability
BLACK-HOLE BINARY
≥3 MASSIVE BLACK HOLES
contraction catalyzed by gas in system that radiates binding energy
slingshot ejection
RELATIVISTIC CLUSTER
spiral together via gravitational radiation
relativistic instability or gravitational radiation
massive black hole

Rees (1984)

Black holes as the power source for AGN

if

- black holes are the power source for quasars
- the present comoving number density of quasars is much less than the density at earlier epochs
- quasars are found in the centers of galaxies

then

many nearby galaxies must contain black holes at their centers

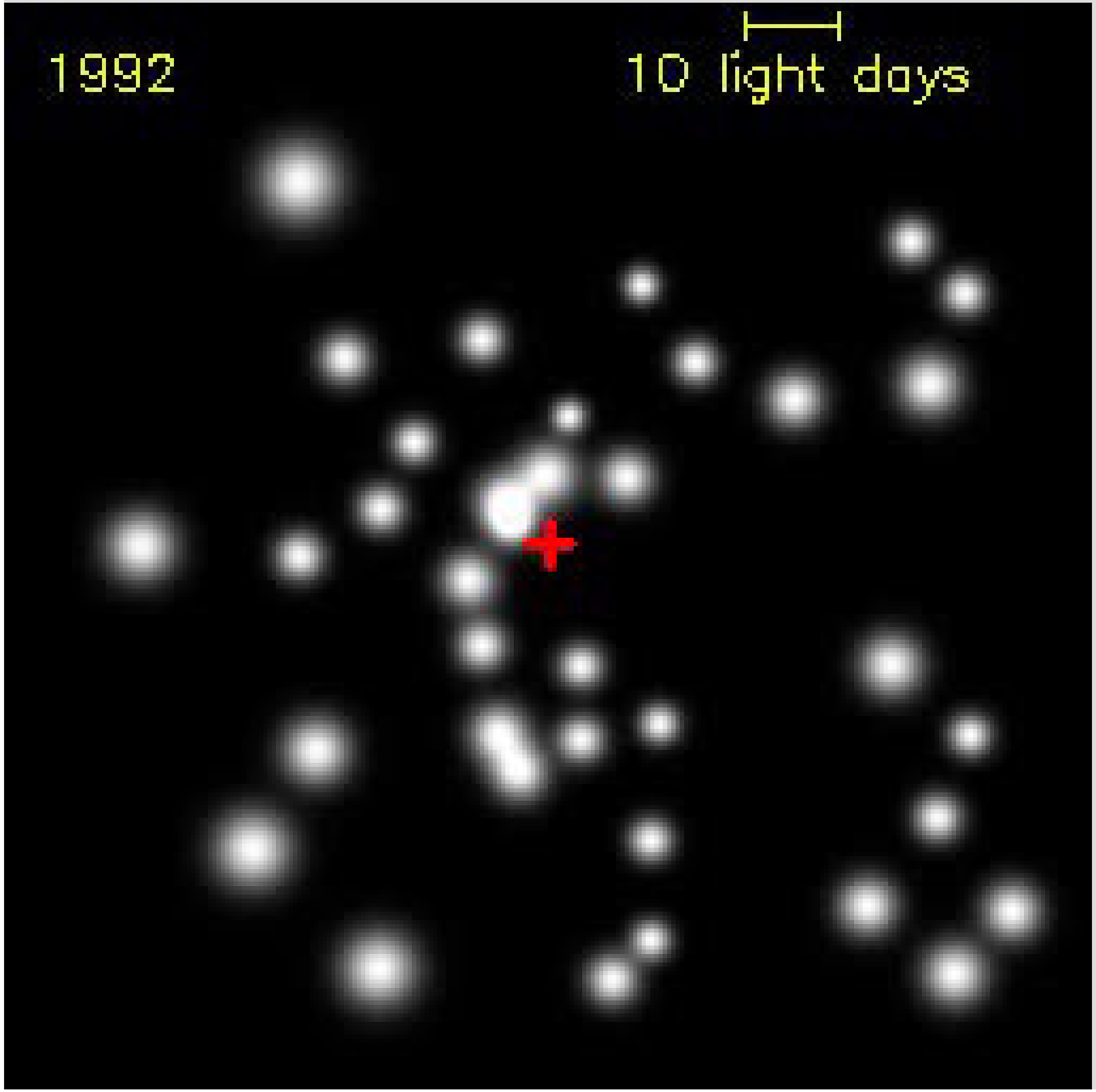
Lynden-Bell (1969) "*Galactic nuclei as collapsed old quasars*"

"…it seems probable that a dead quasar-like object inhabits the Local Group of galaxies and we must expect many nearer than the Virgo cluster"

Massive black holes in nearby galaxies

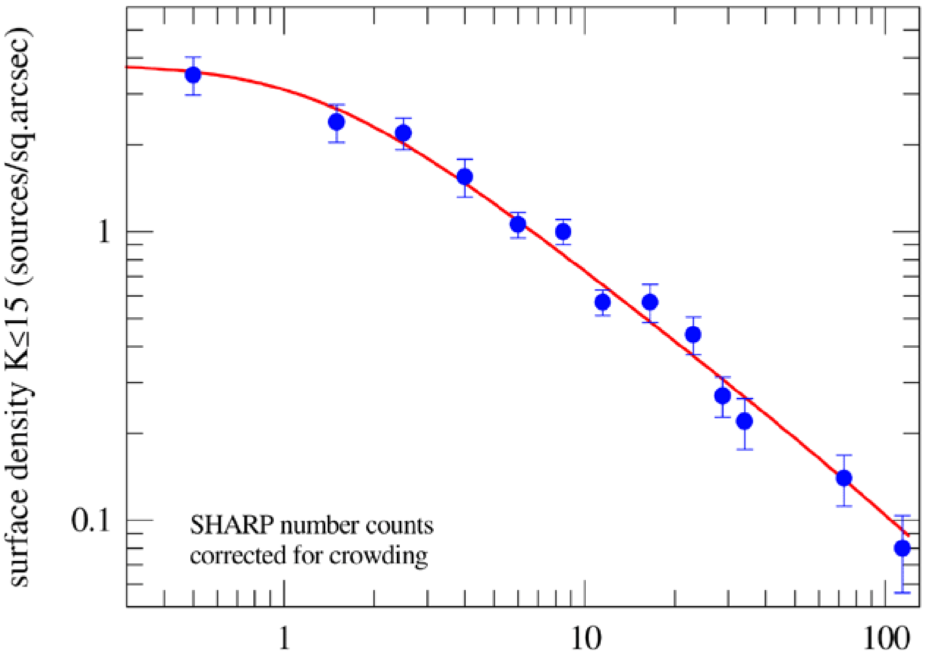
- the detections are of massive dark objects (10^5 - 10^6 r_{Sch}) but
  - There are no plausible candidates other than black holes
  - Black holes are needed anyway to power AGN
- 40 nearby galaxies have measured black-hole masses in the literature:
  - 26 from stellar kinematics
  - 10 from gas kinematics
  - 3 from maser kinematics
  - Milky Way
- data and models have varying quality

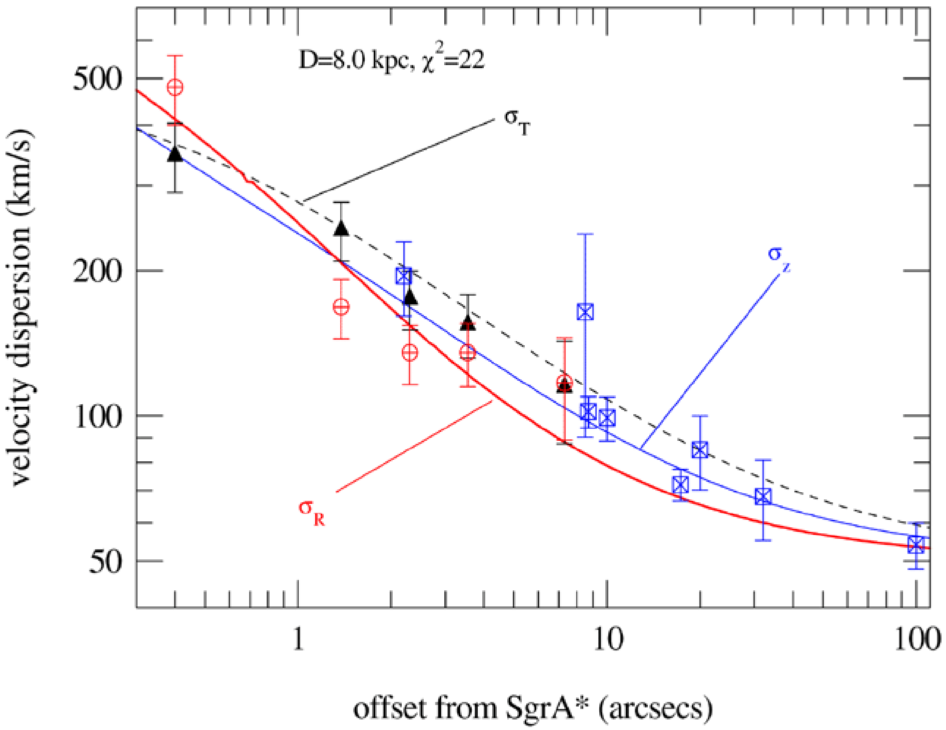
The Milky Way Galaxy



- center is believed to be marked by radio source Sgr A* (+)
- probes distances as small as 0.01 pc ~10 light days ~3×10^{16} cm ~5×10^{4} Schwarzschild radii
- highest spatial resolution of any galactic center ⇒ strongest constraints on alternatives to black holes
- orbits ⇒ gravitational potential

Genzel et al. (2003)





The Milky Way Galaxy

$$\frac{dP}{dr} = -\rho\frac{d\Phi}{dr} = -\frac{GM\rho}{r^2}$$

P = pressure
ρ = density

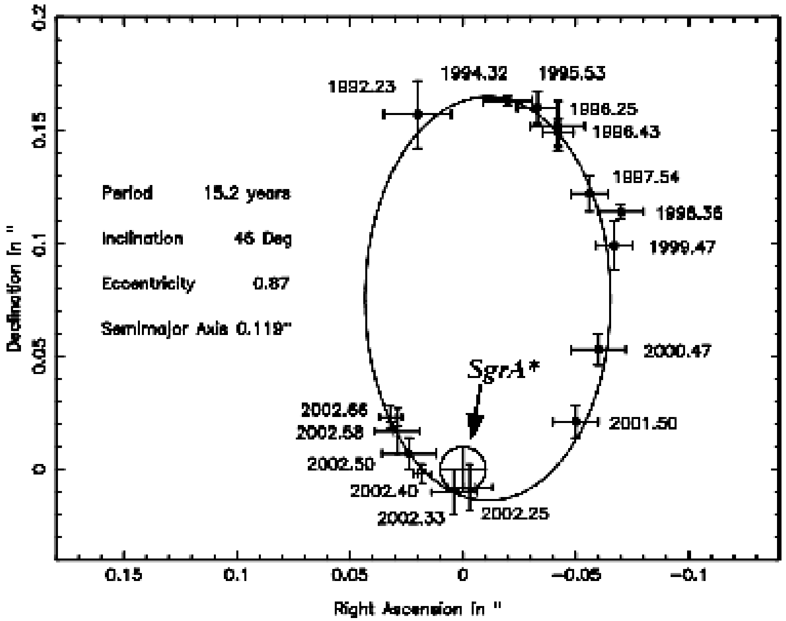
$$\left.\begin{array}{l} P = \text{pressure} \\ \rho = \text{density} \end{array}\right\} \text{gas}$$

$P \Rightarrow \nu\sigma^2 \quad \rho \Rightarrow \nu$
ν = number density
σ = velocity dispersion

$$\left.\begin{array}{l} P \Rightarrow \nu\sigma^2 \quad \rho \Rightarrow \nu \\ \nu = \text{number density} \\ \sigma = \text{velocity dispersion} \end{array}\right\} \text{stars}$$

Genzel et al. (2000)

The Milky Way Galaxy



Schodel et al. (2002)

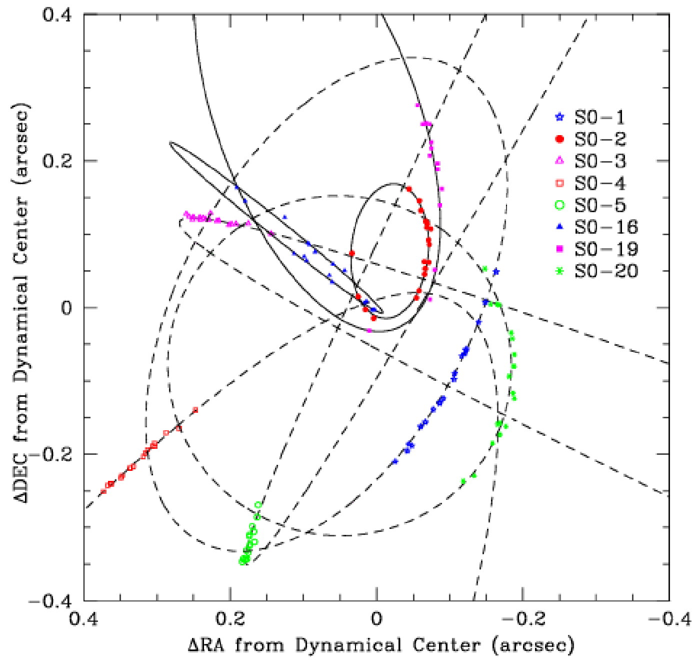
$P = 15.8 \pm 0.8$ yr

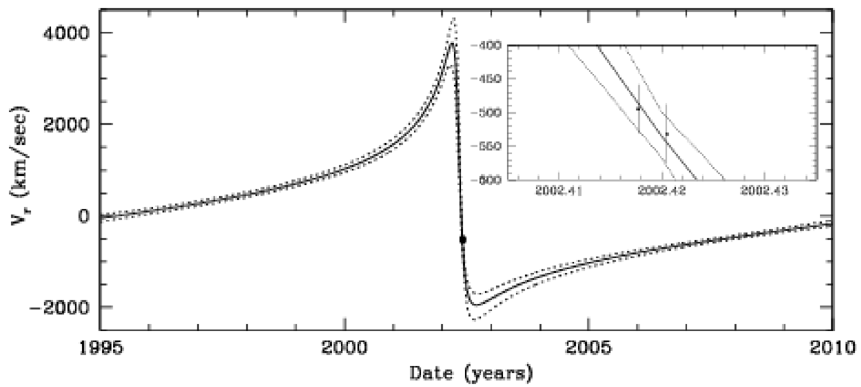
$e = 0.874 \pm 0.008$

$a = 125.6 \pm 5.5$ milliarcsec

$= 1000 \pm 40$ AU

$q = a(1-e) = 125$ AU

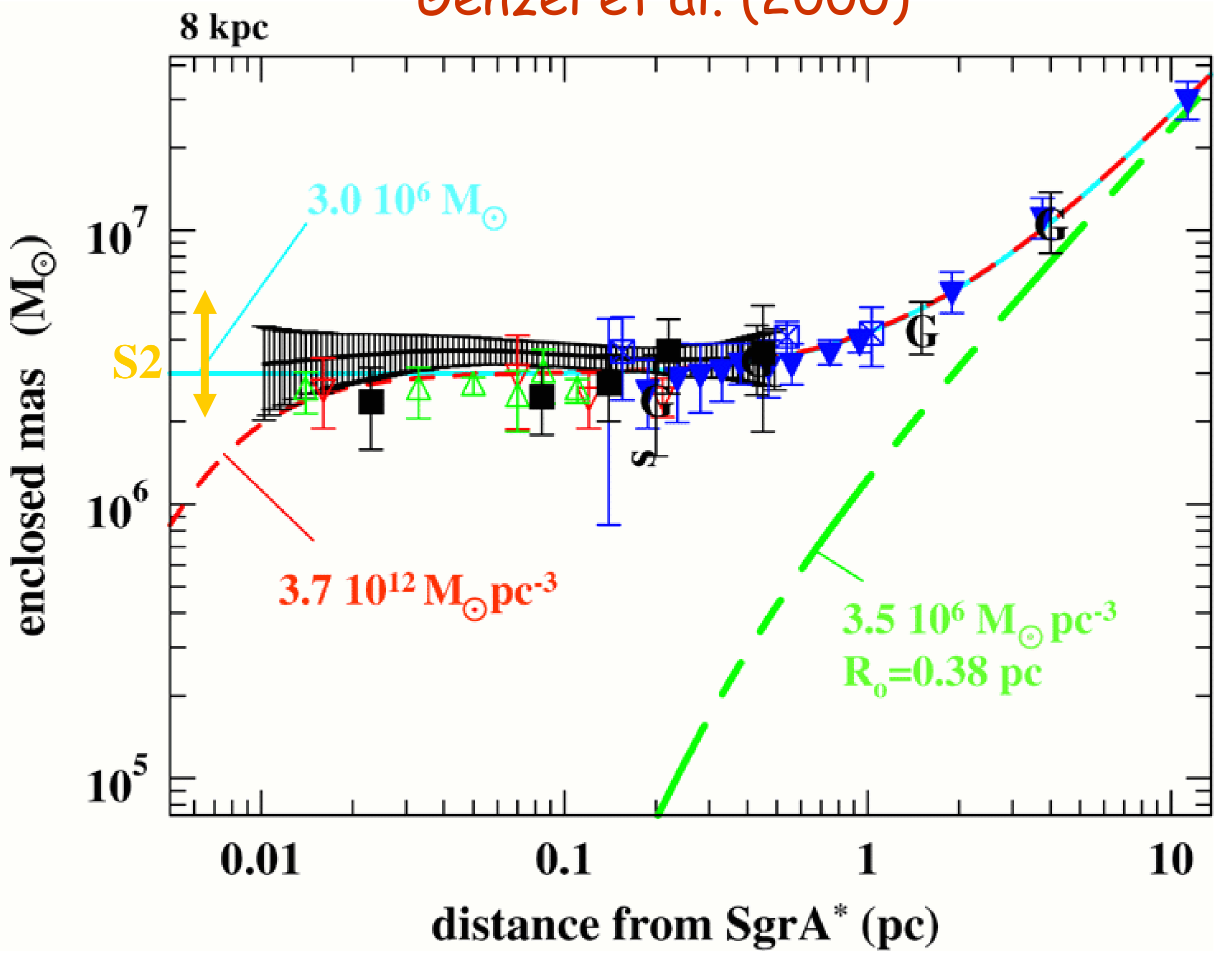




Ghez et al. (2003)

The Milky Way Galaxy

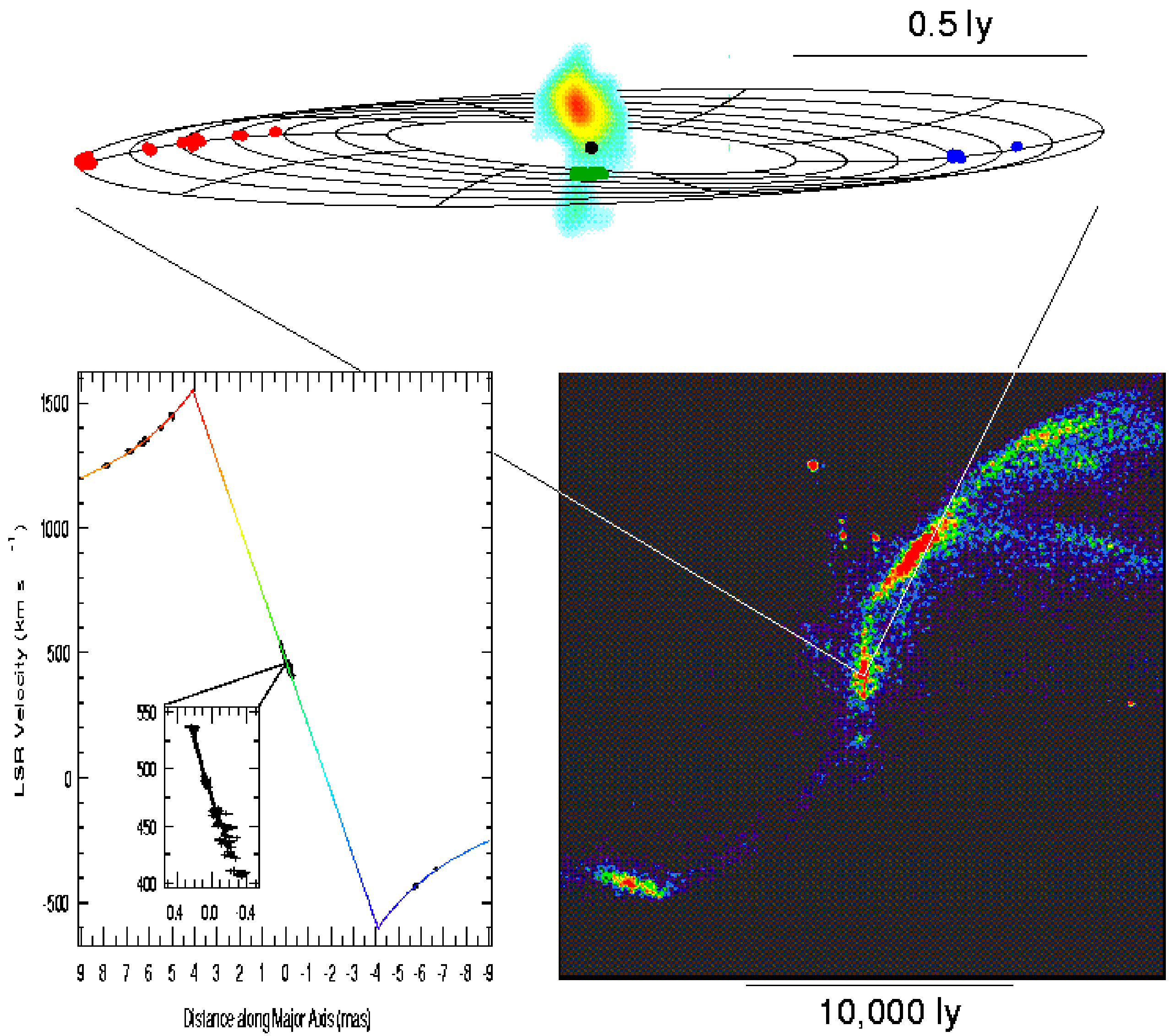
Genzel et al. (2000)



- central dark mass $M=(1.8\pm0.4)\times10^{6}\ M_{\odot}$ from proper motions and velocities (Chakrabarty & Saha 2001)
- $M=(4.1\pm0.6)\times10^{6}\ M_{\odot}$ from orbit of S2 (Ghez et al. 2003) or $M=(3.3\pm0.7)\times10^{6}\ M_{\odot}$ (Schoedel et al. 2003)
- no sign of extended mass distribution to 100 AU
- $R_0=7.9\pm0.4$ kpc (Eisenhauer et al. 2003)

NGC 4258

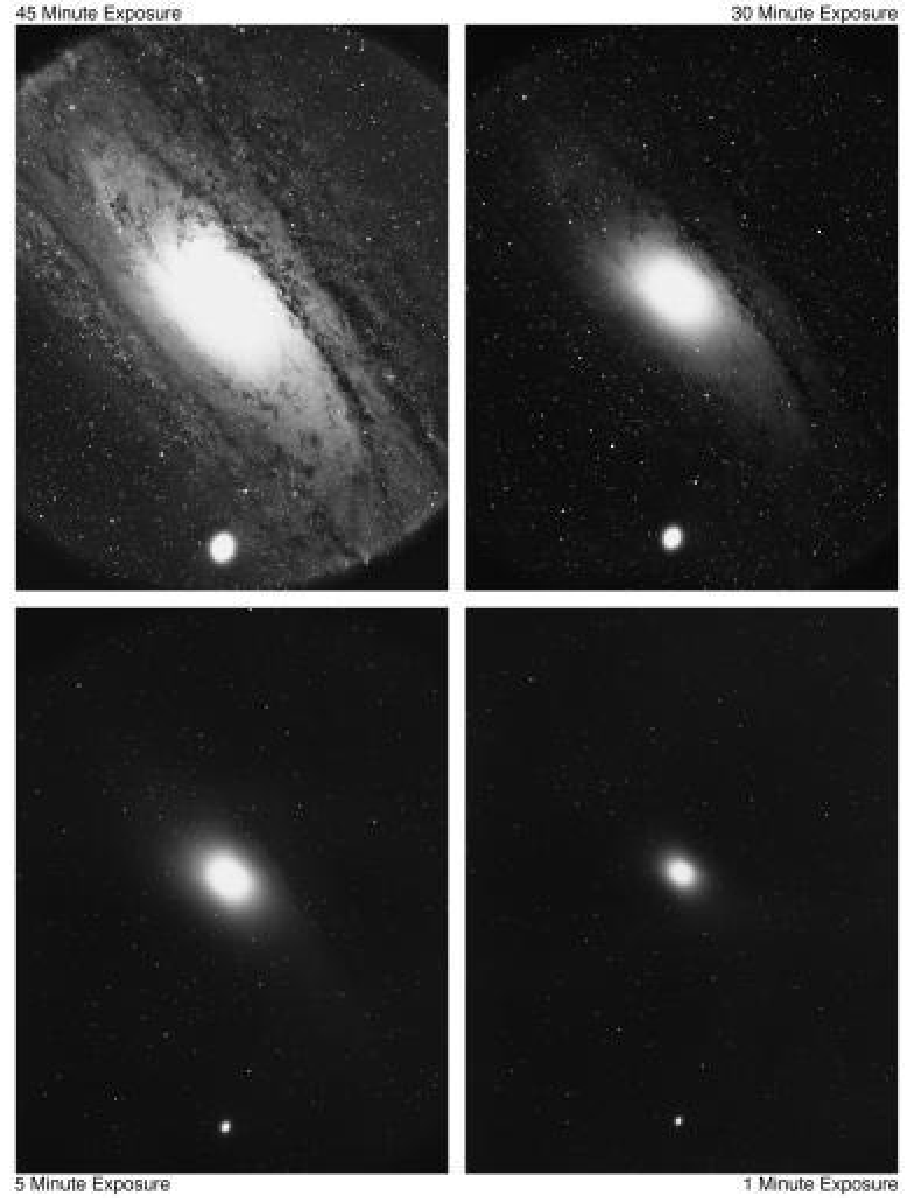
Miyoshi et al. (1995), Herrnstein et al. (1999)



- high-velocity maser emission from disk shows Keplerian rotation at r~0.2 pc
- $M=(3.9\pm0.1)\times10^7\ M_\odot$
- disk mass < 10% of black-hole mass
- masers at systemic velocity show proper motion 31.5±1 mas/yr and acceleration 9.3±0.3 km/s/yr
- proper motion and acceleration yield independent distance estimates of 7.1±0.2 Mpc and 7.2±0.2 Mpc

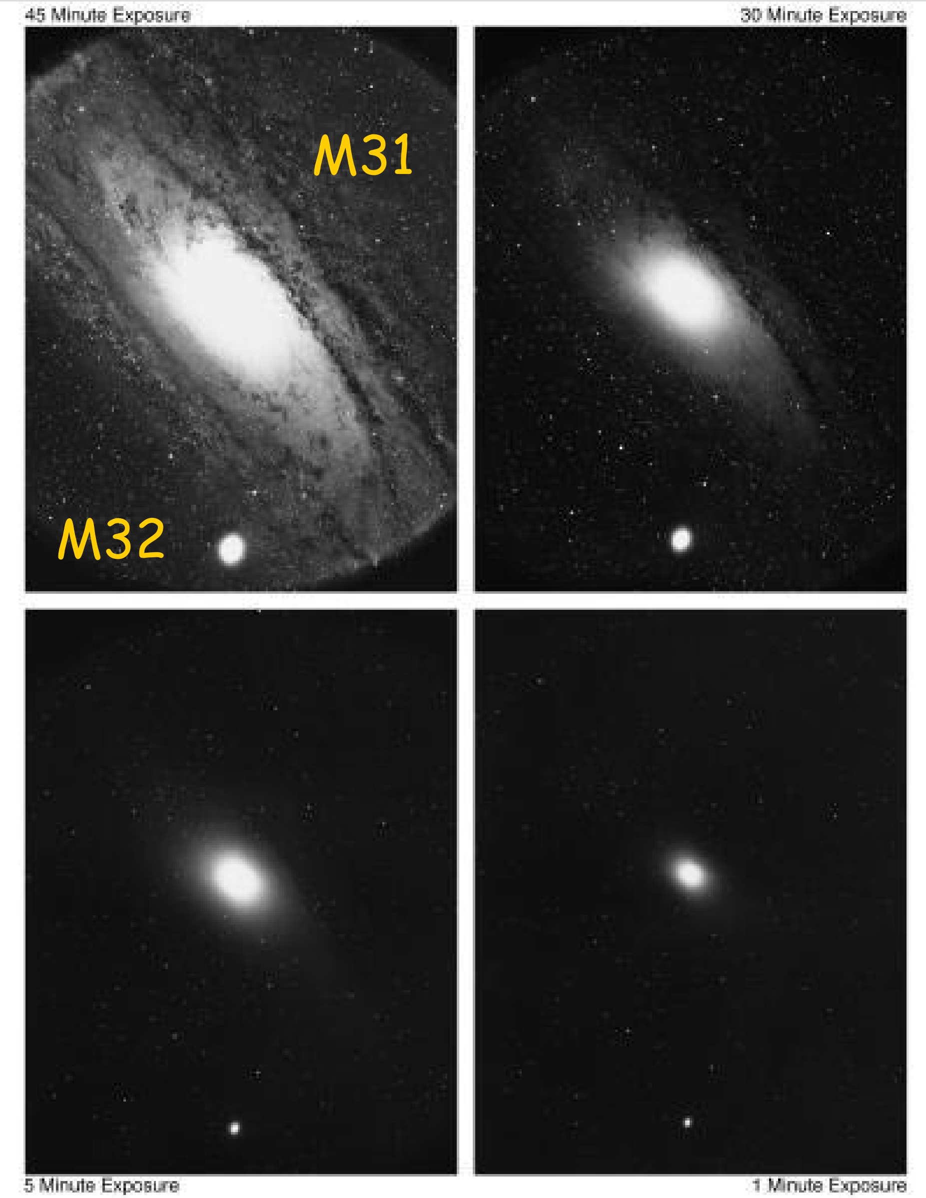
Black hole detection by stellar kinematics

- black hole is guaranteed to be at the center of the galaxy (orbits decay by dynamical friction)
- photometry gives surface-brightness distribution of stars on the sky $I(x,y)$
- spectroscopy gives mean velocity $\langle v \rangle$ (Doppler shift of spectral lines) rms velocity dispersion along the line of sight σ (smoothing of spectral lines)
- characteristic sphere of influence radius GM_{BH}/σ^2 is small
- combine Hubble observations (high resolution, expensive, small field of view) with ground-based observations



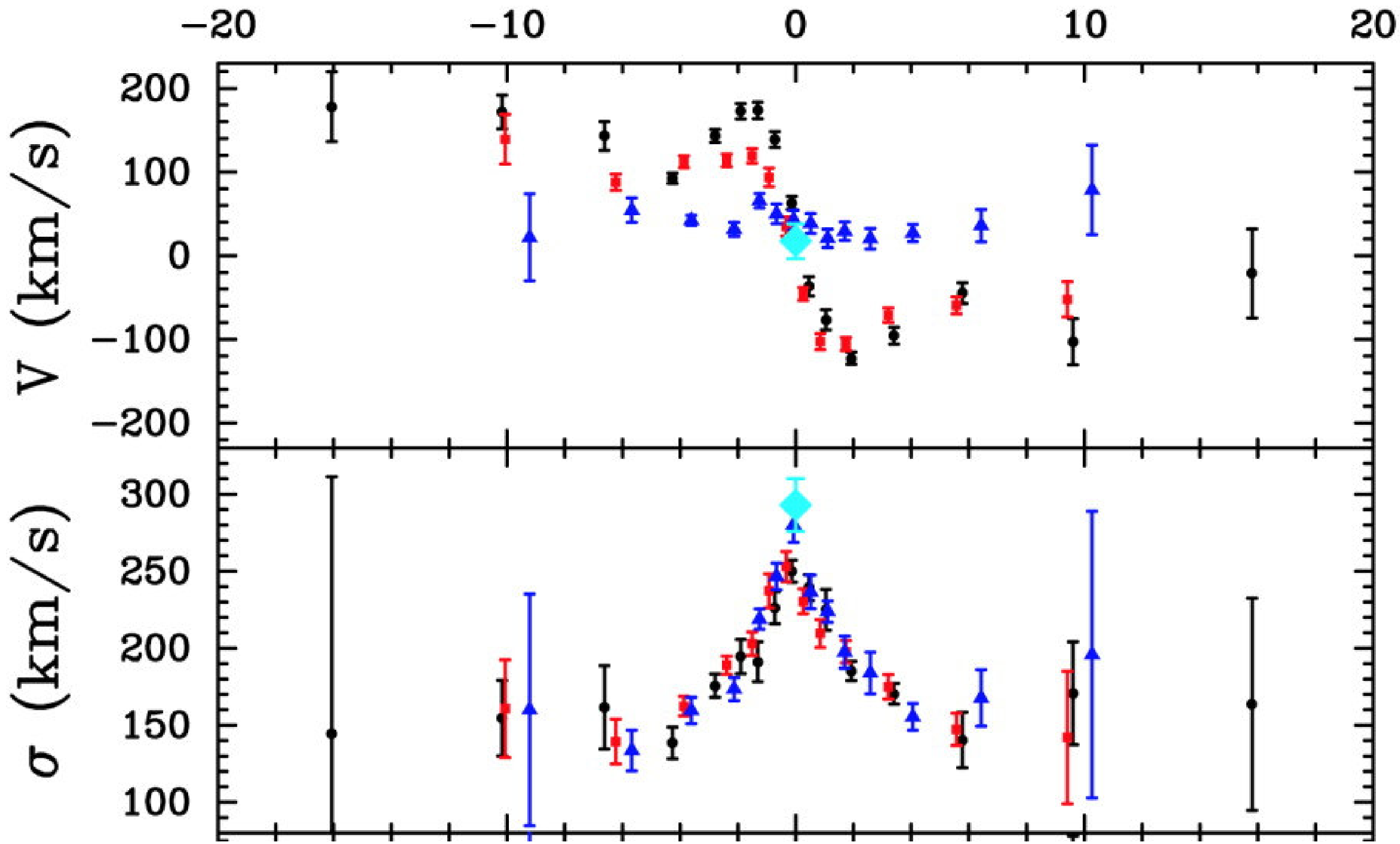
Black hole detection by stellar kinematics

- advantages:
  - no non-gravitational forces on stars
  - can be applied to systems with no gas, dust, young star formation, M/L gradients
- disadvantages:
  - no guarantee that velocity distribution is isotropic
  - doesn't work well for high-luminosity galaxies
  - complicated dynamical modeling



NGC 5845

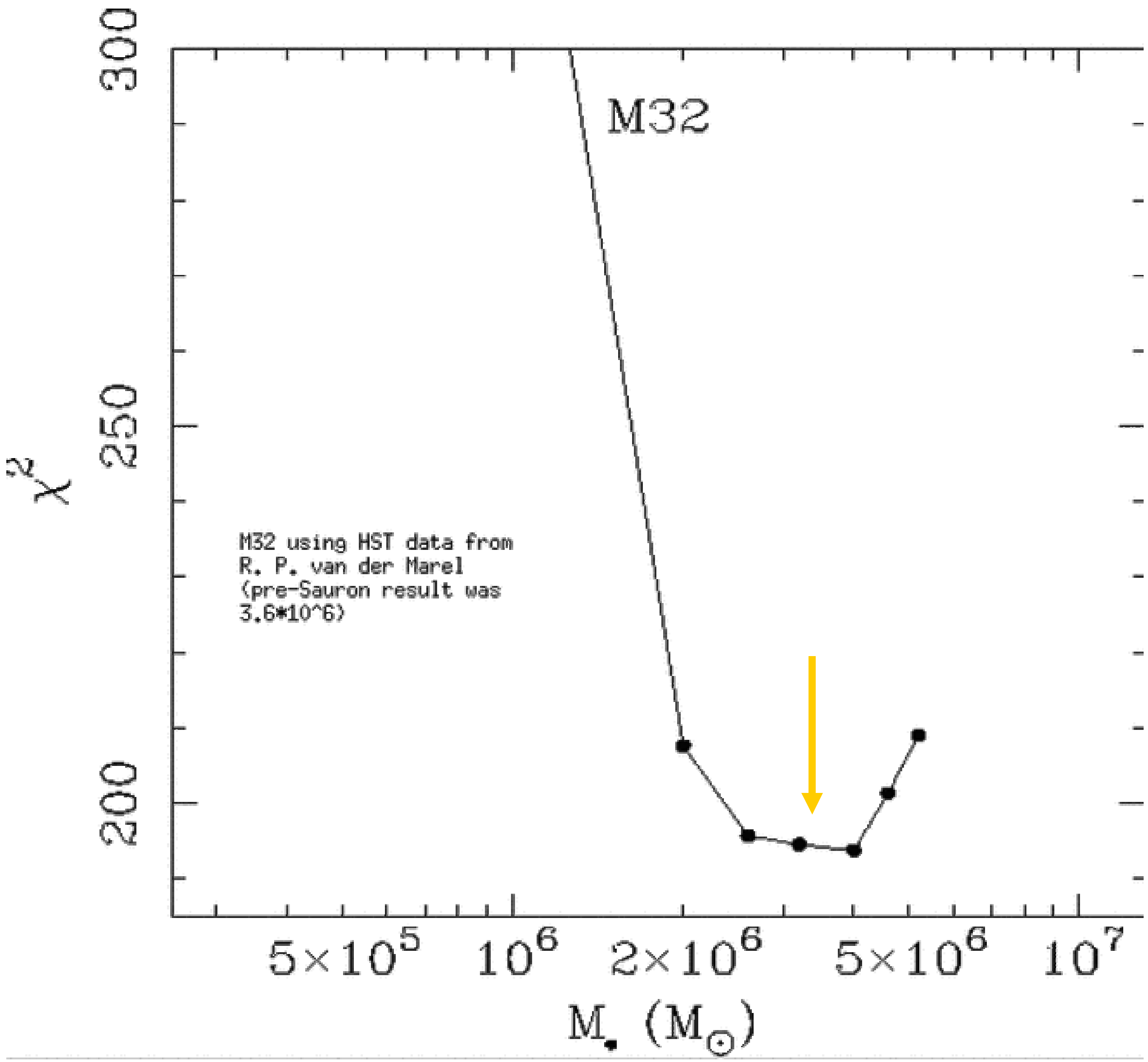
Gebhardt et al. (2003) "nukers"
black = major axis
blue = minor axis
red = intermediate axis
radius in arcsec



Orbit-based axisymmetric dynamical models

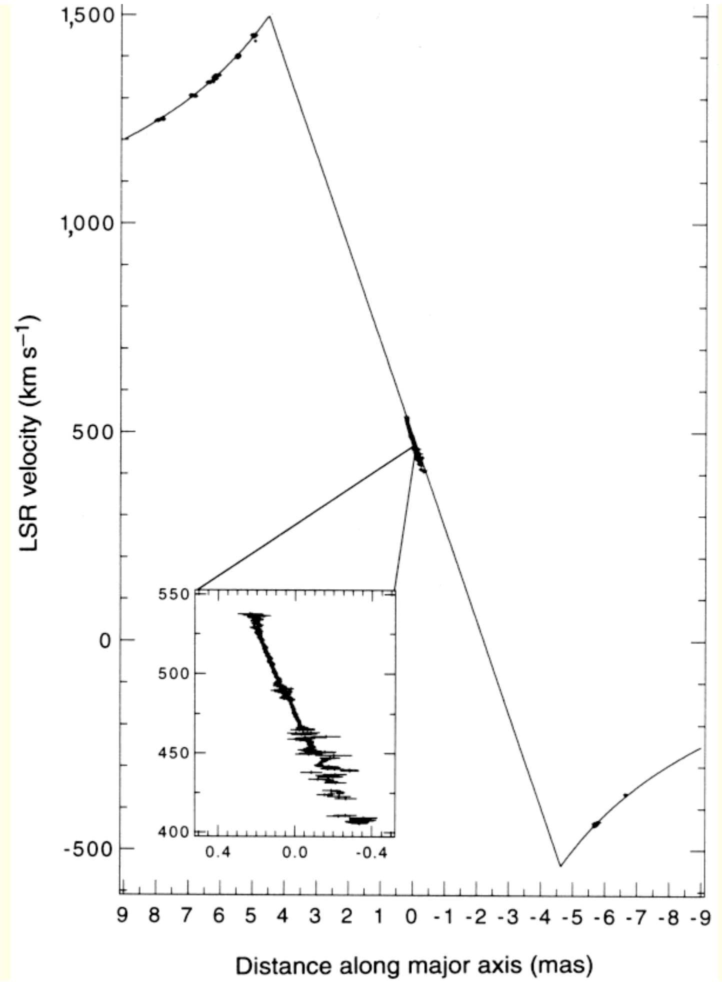
- photometry $\rightarrow$ surface brightness $I(x,y)$
- assume inclination, assume emissivity constant on spheroids $\rightarrow$ emissivity $j(R,z)$
- assume mass-to-light ratio independent of position $\rightarrow$ density $\rho(R,z)=(M/L)j(R,z)$
- solve Poisson's equation $\nabla^2\Phi^*=4\pi G\rho$
- add potential due to black hole, $\Phi=\Phi^*-GM/r$
- divide phase space into a grid of cells, $j=1,\ldots,N$
- numerically integrate orbits in the potential Φ from $i=1,\ldots,M$ different initial conditions and compute f_{ij}, the fraction of time orbit i spends in cell j
- find weights w_i for each orbit i such that we reproduce surface brightness $I(x,y)$, $\langle v \rangle$, and σ at each position
- choose M, M/L, inclination to minimize χ^2
- problem is underconstrained so find maximum-entropy solution

M32

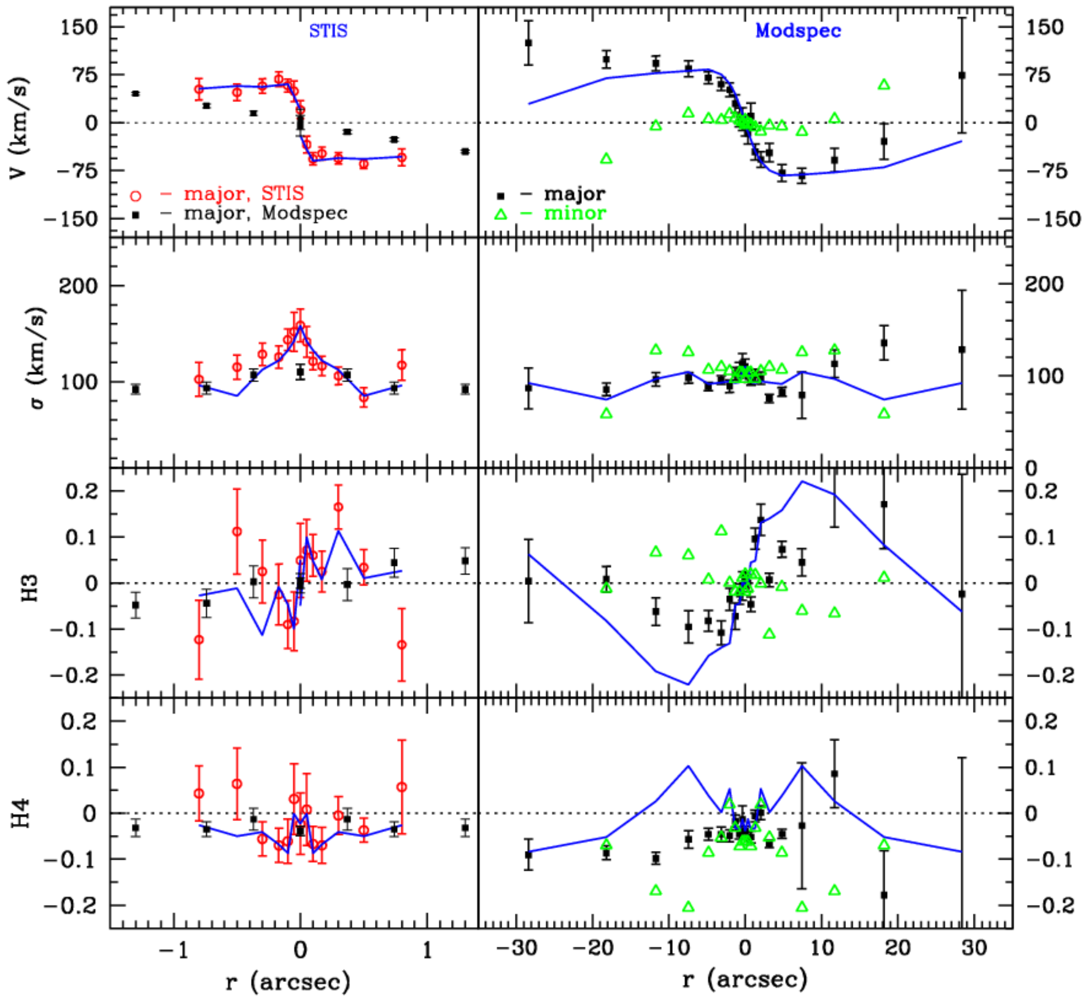


- data from van der Marel et al. (1998)
- their black-hole mass is $(3.4\pm0.7)\times10^6\ M_\odot$
- Nuker analysis of their data with our programs yields very similar result

NGC 4258



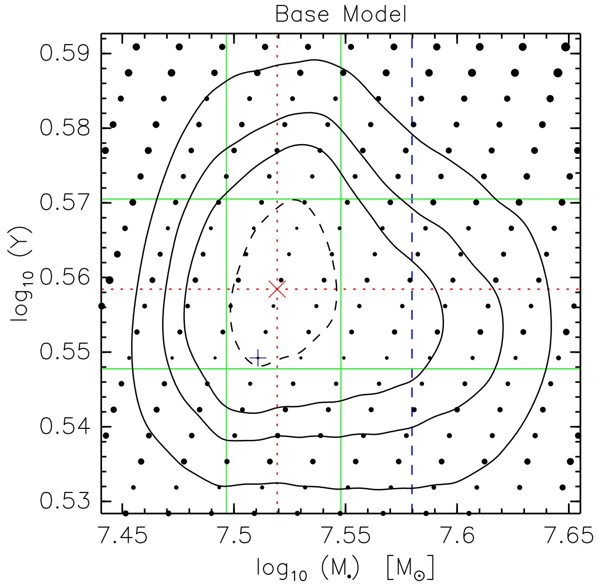
HST ground

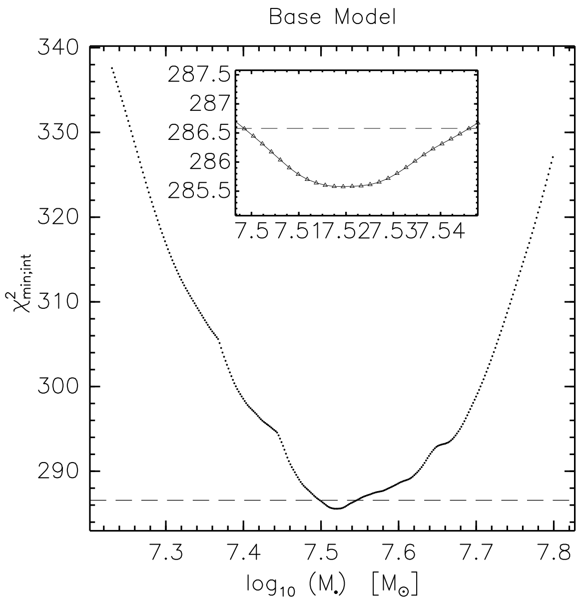


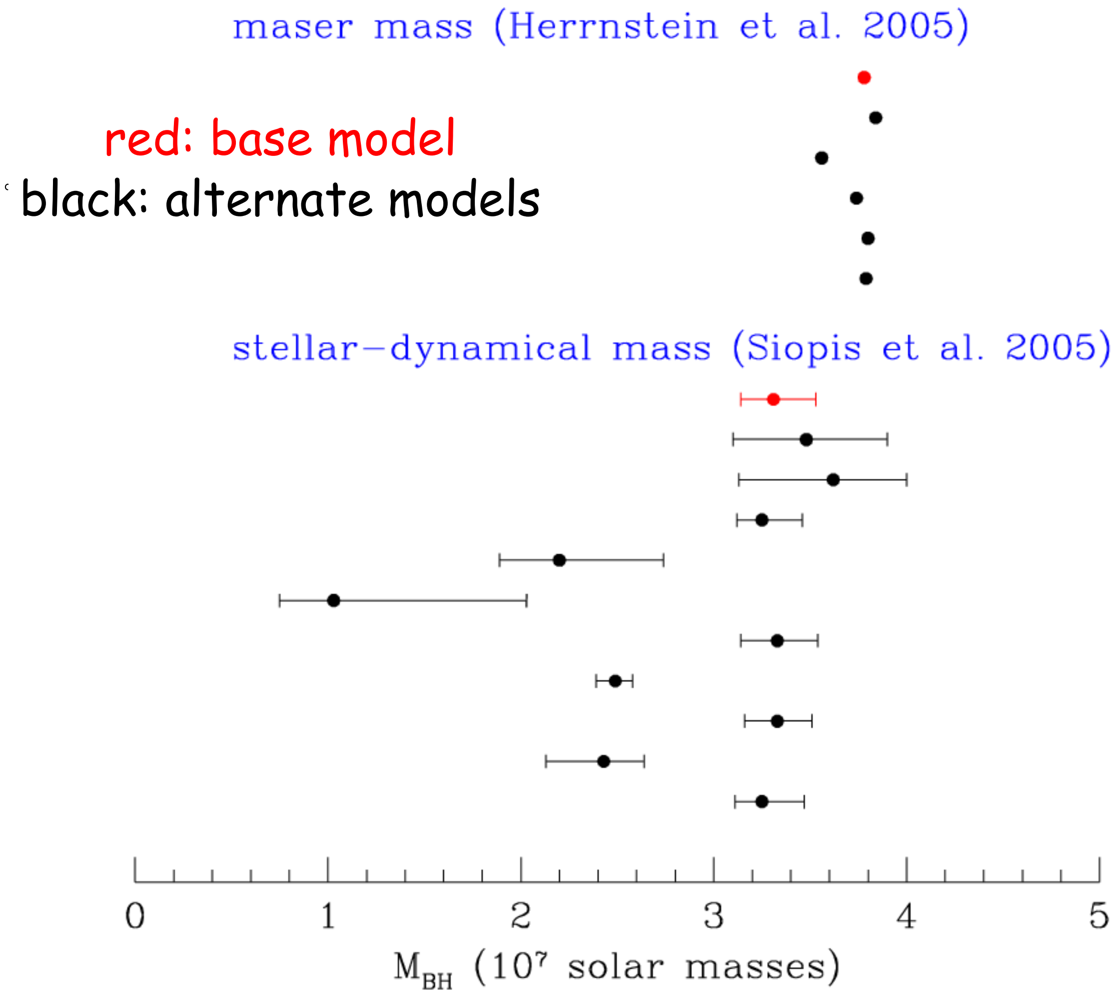
Miyoshi et al. (1995)

Siopis et al. (2005)

Siopis et al. (2005)

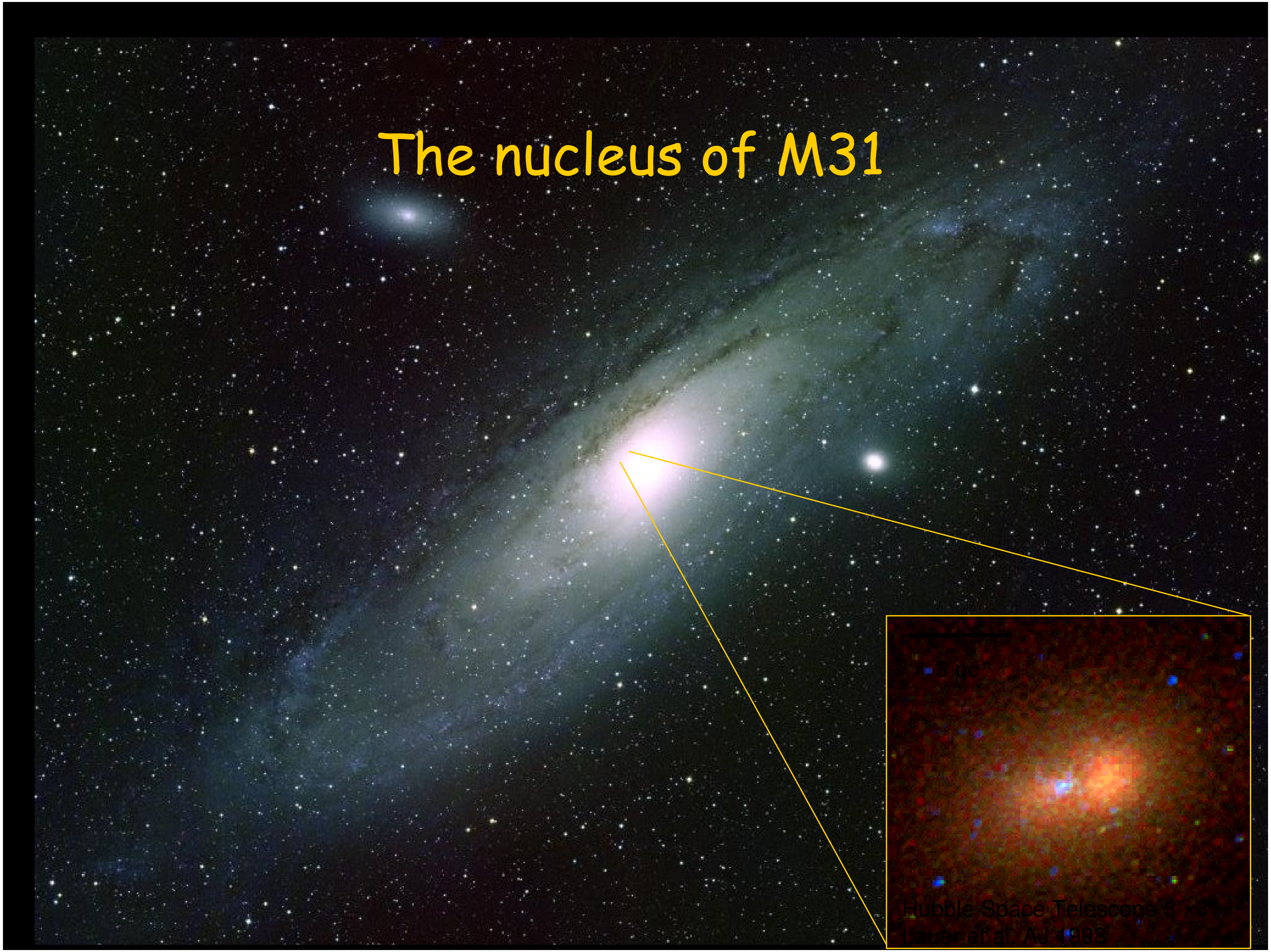






base models agree within 15%; stellar-dynamical mass is lower than maser mass

The nucleus of M31

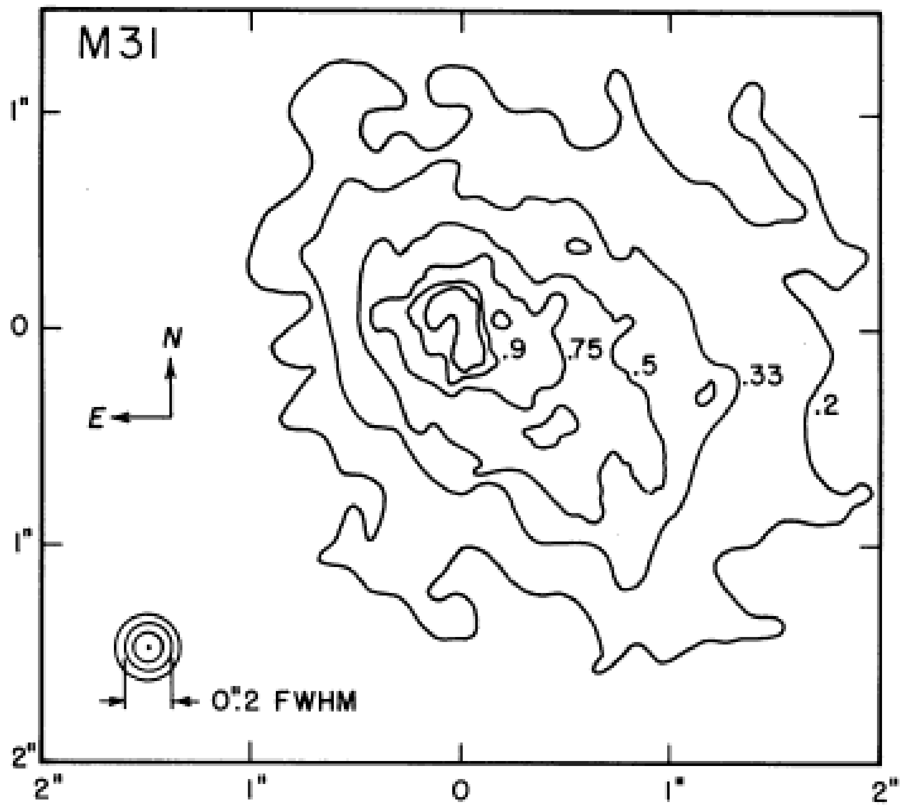


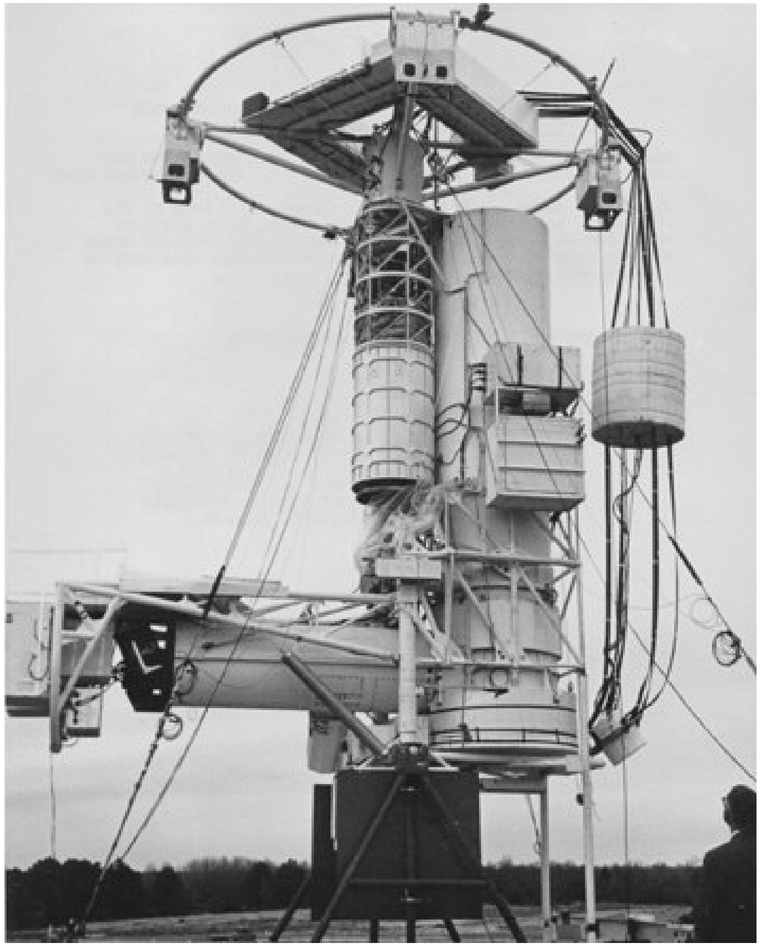
Why M31 is important

- large angular size of sphere of influence GM_{BH}/σ^2:

galaxy	GM_{BH}/σ^2 (arcsec)
Milky Way	39
M31	3.2
NGC 3115	2.8
NGC 5128	2.3
NGC 4594	1.7
M87	1.4

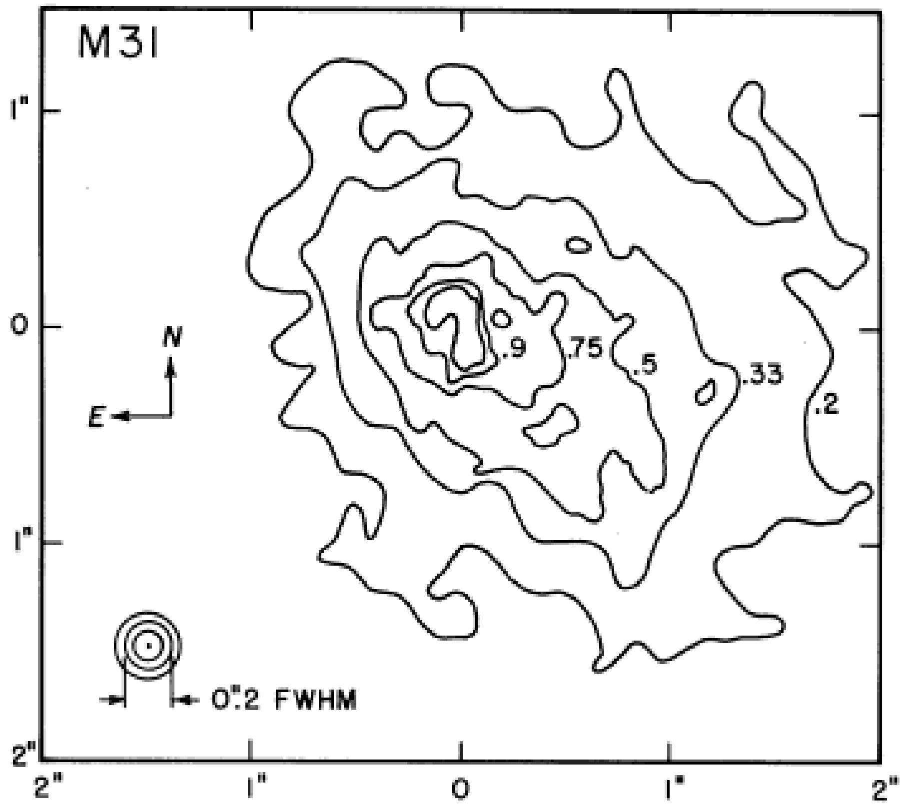
- 30-40 times as massive as Milky Way black hole, large enough to produce a luminous AGN
- little or no gas, dust, recent star formation
- short dynamical time $L/v \sim 1$ pc/100 km/s $\sim 10^4$ yr so well-mixed



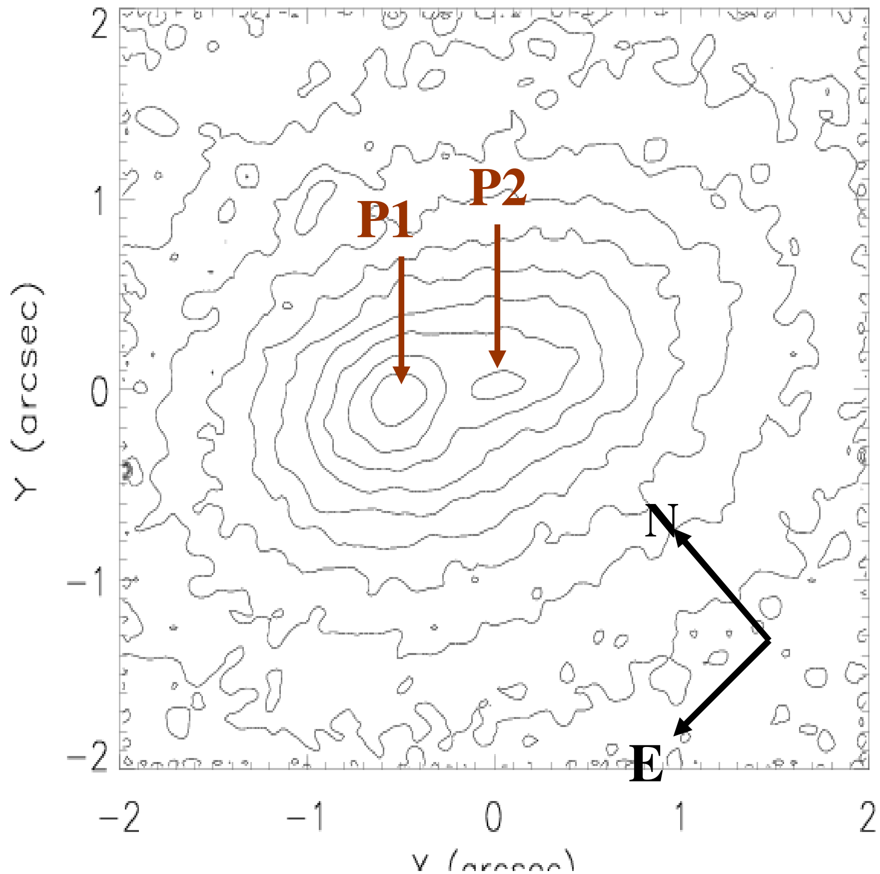


Light, Danielson & Schwarzschild (1974)

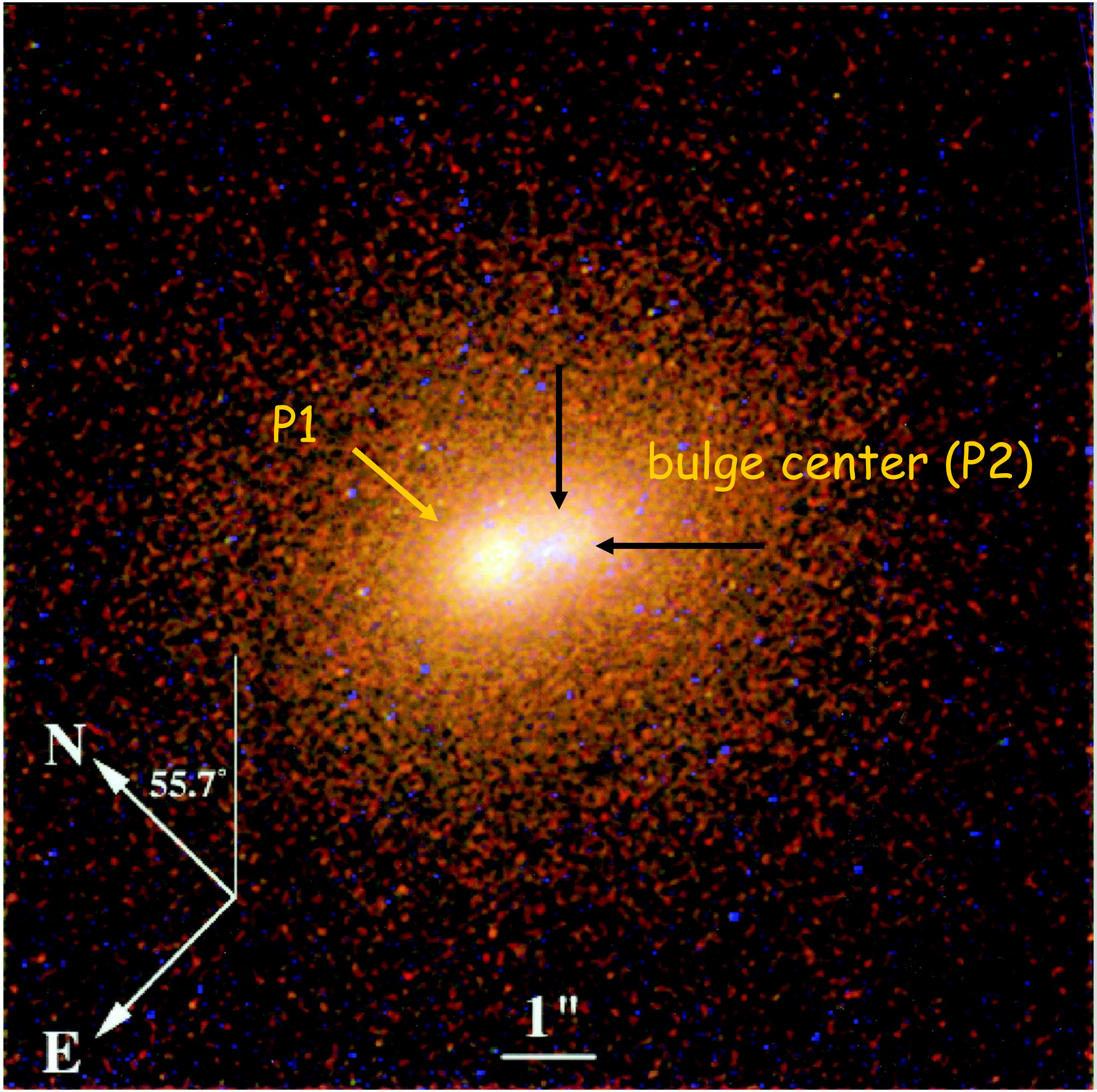
"A puzzling aspect of the high-resolution images is the offset of the peak brightness with respect to the outer portions of the nucleus...if no significant dust is present, the observed asymmetry is an intrinsic property of the nucleus which will probably require a dynamical explanation."



Stratoscope



Hubble Space Telescope



- faint component (P2) is at the bulge center
- P2 is cuspy
- P2 has a compact blue component at its center (P3)
- bright component P1 is smooth
- total luminosity $6\times10^6\ L_\odot$ (r~0.5 pc) and is cuspy

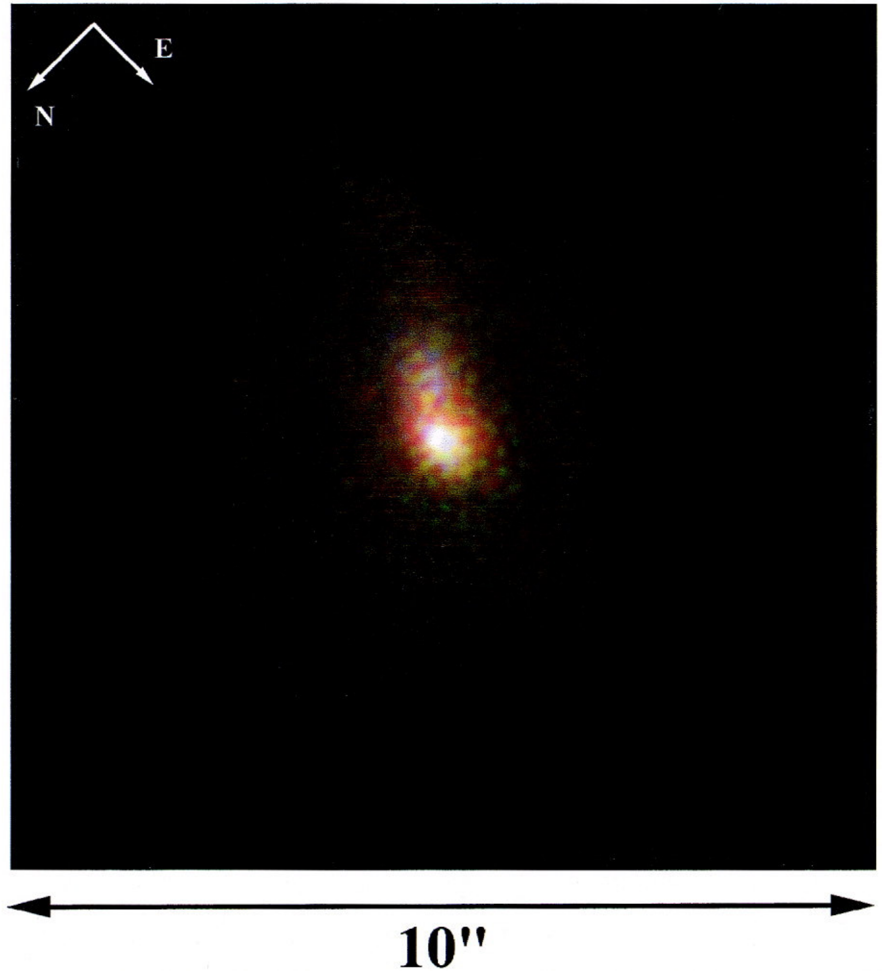
Lauer et al. (1998)

A binary stellar system?

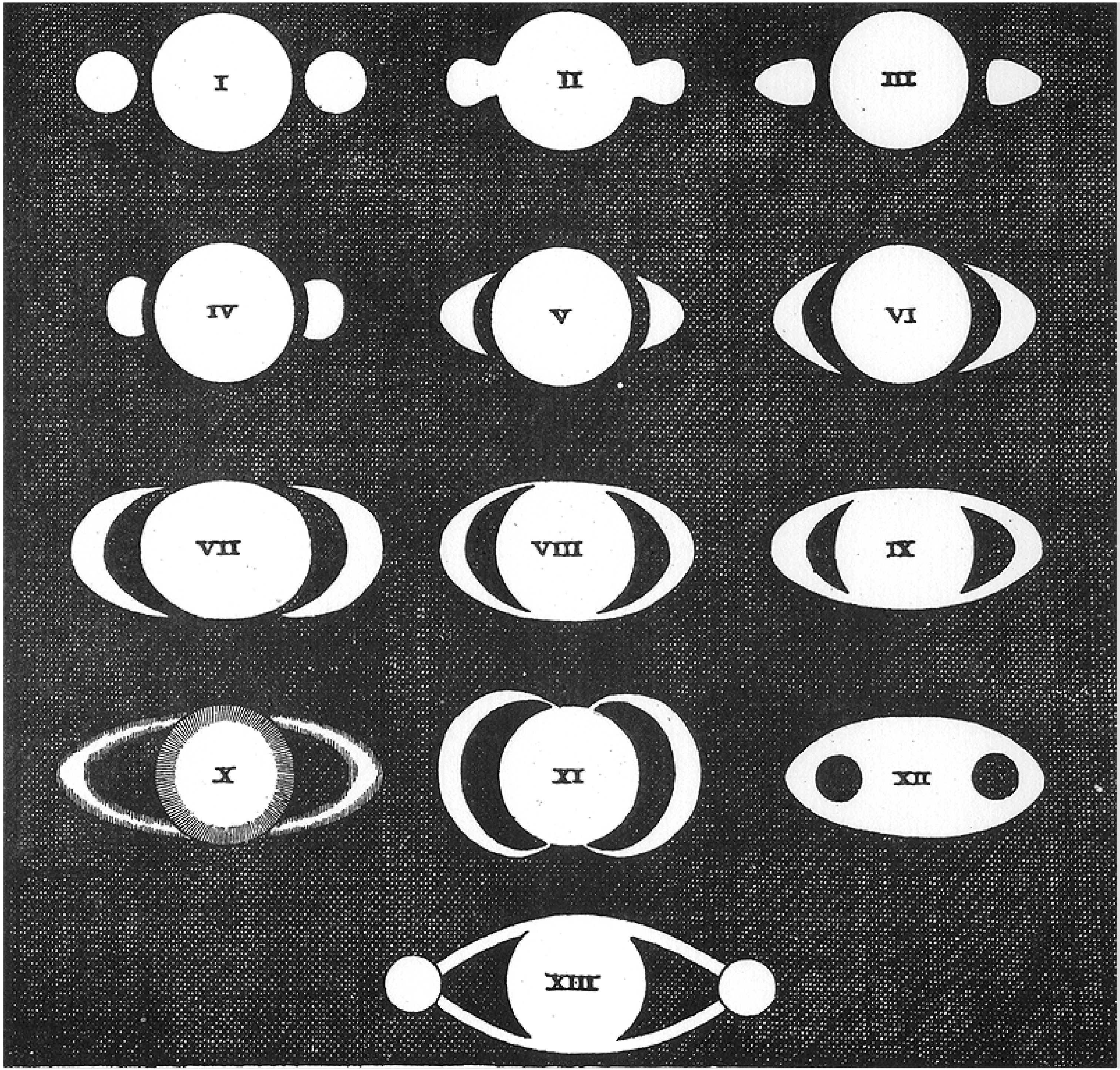
- P1 and P2 have the same colours, except for the compact source P3
- isophotes cannot be decomposed into superposition of two elliptical stellar systems $\Rightarrow$ P1 and P2 must be in close proximity and are not simply projected onto the same position
- orbital period only 50,000 yr and inspiral time due to dynamical friction from the bulge is ~ $10^8 \times (10^6\ M_\odot/M)$ yr << age

Dust?

- colours of P1 and P2 are the same
- double structure is still present in near-infrared; no evidence of colour gradient

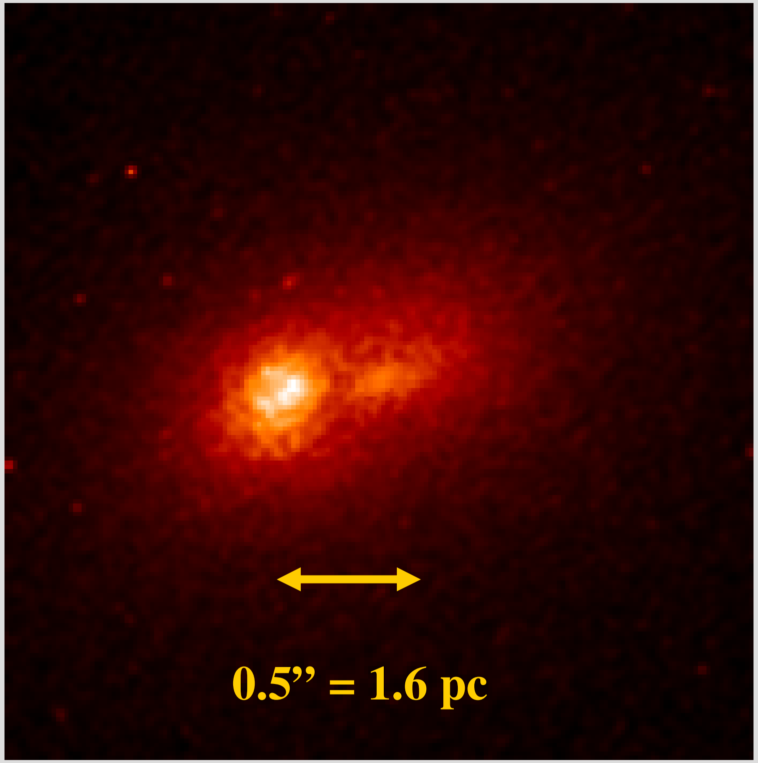


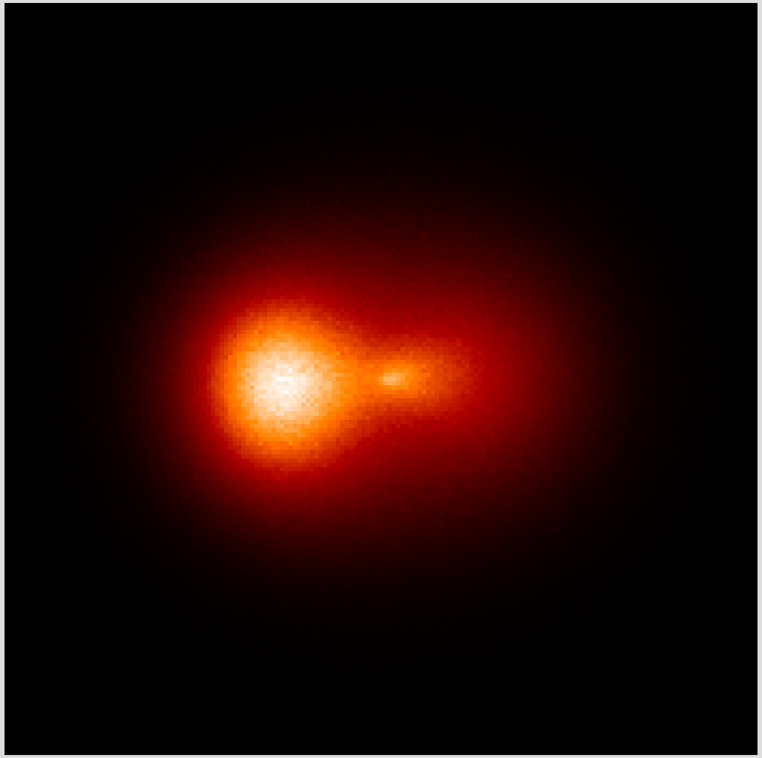
Corbin et al. (2001)



Huygens
(1659)

M31





- the double nucleus is probably a thick eccentric disk of stars orbiting a black hole (Tremaine 1995)
- black hole is at P2; P1 is apocenter region of disk

Peiris & Tremaine (2003)

The eccentric-disk model

• nucleus consists of a single massive black hole at P2, surrounded by a disk of stars

• stars in disk are on eccentric, nearly Keplerian orbits which are aligned so that apocenters point in the same direction

• P1 is the portion of the disk close to apocenter; stars move slowly near apocenter so most of them are found in this region at any given time

• black hole dominates gravitational potential so orbits are approximately closed

• best-fit black-hole mass $1 \times 10^{8} M_{\odot}$

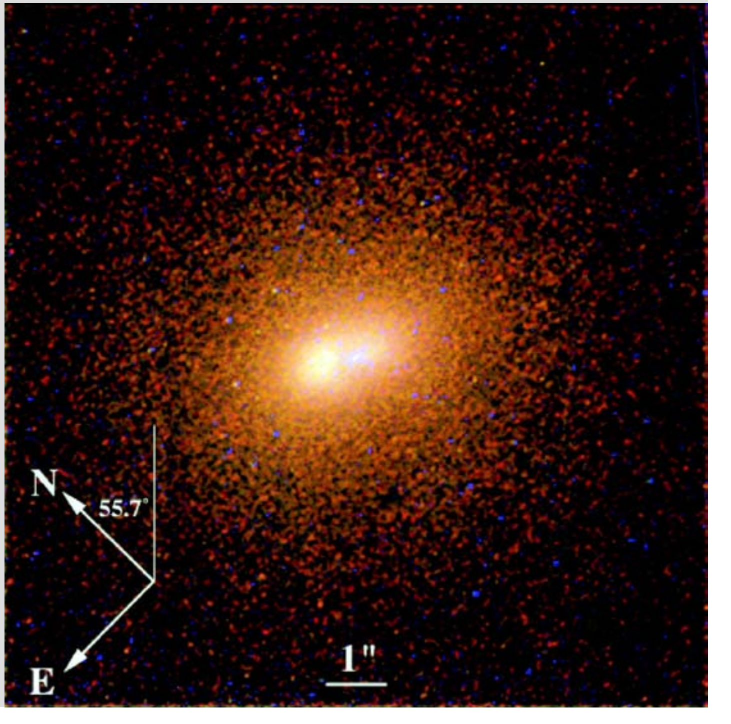
Correctly explains:

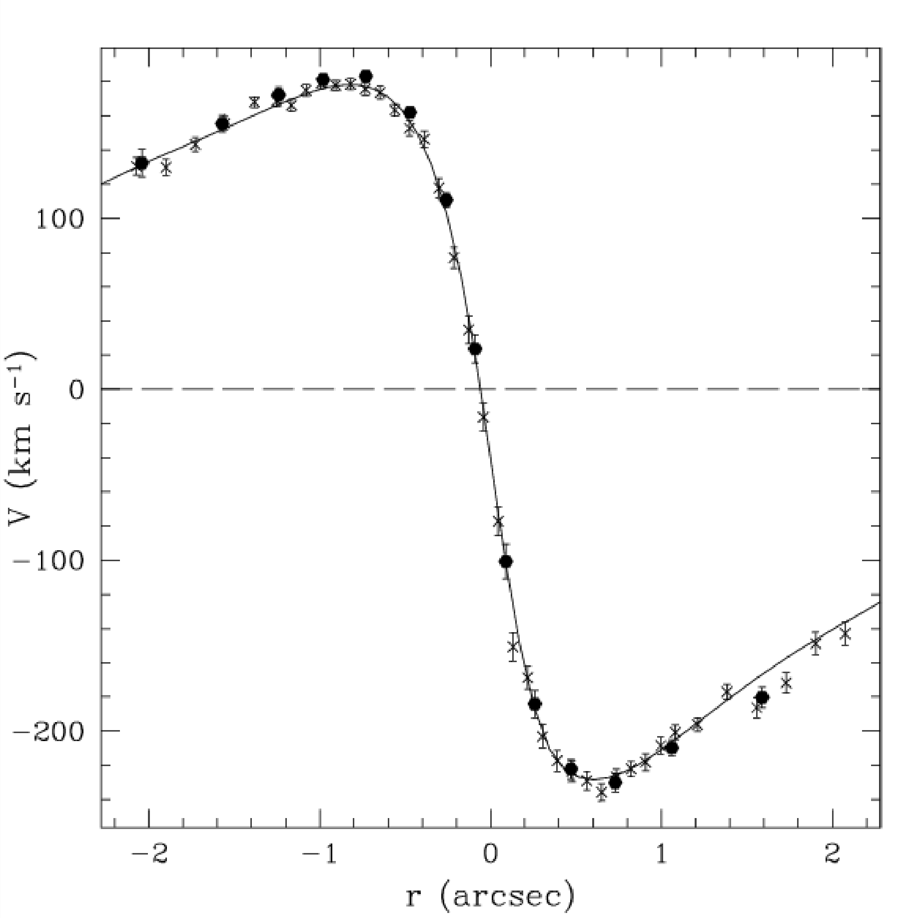
• rotation curve and dispersion profile

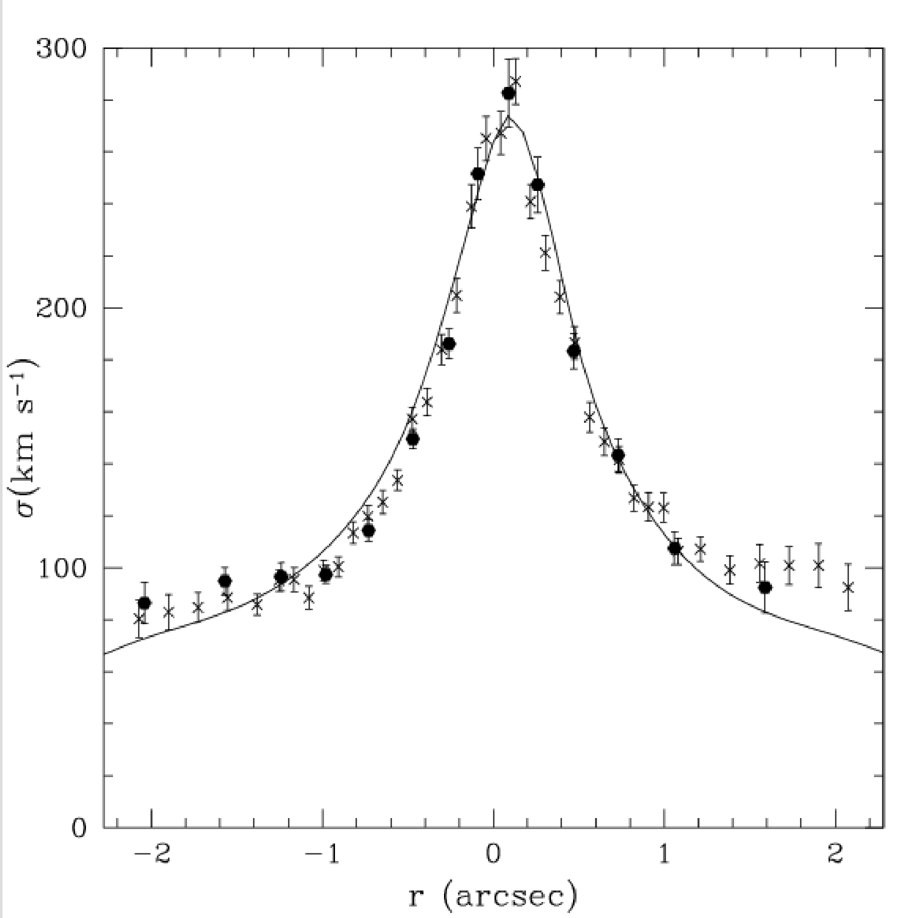
• why P2 is at the center of the bulge *(the black hole has most of the mass)*

• why colours of P1 and P2 are the same, and different from the bulge *(they're the same stars)*

• why P2 is cuspy but P1 is smooth *(stars are bound to P2 but not to P1)*

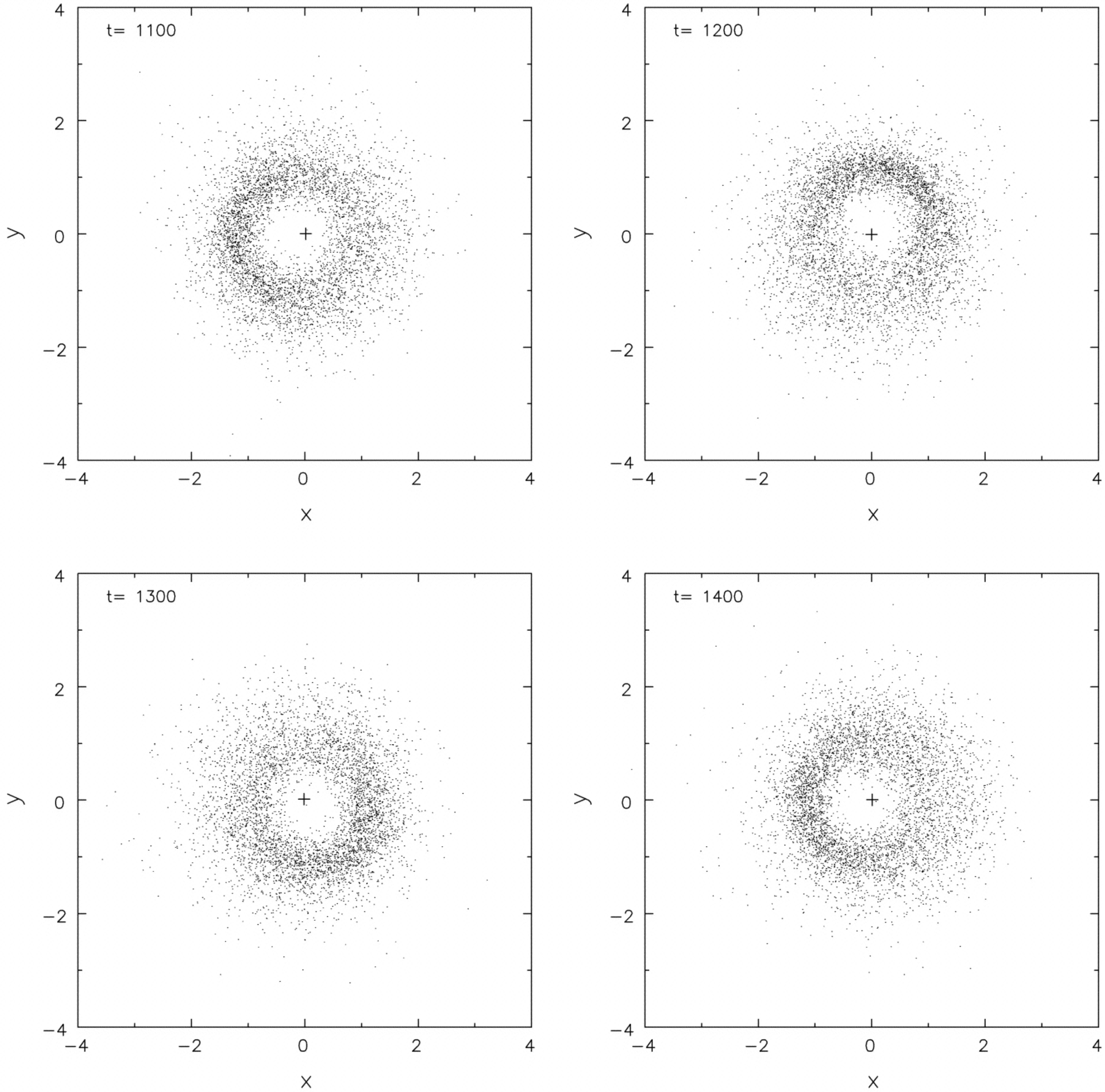




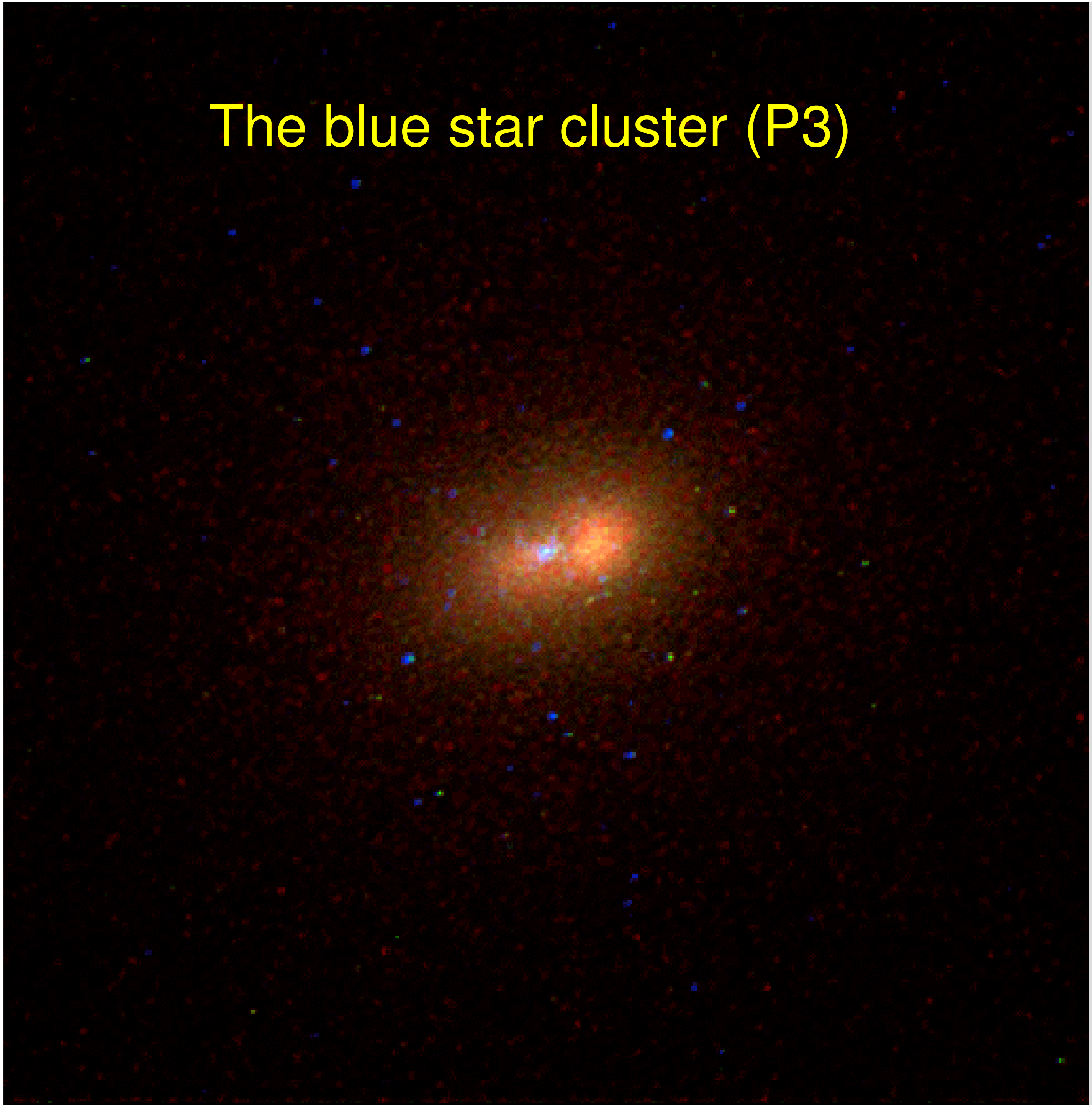


rotation curve

velocity dispersion

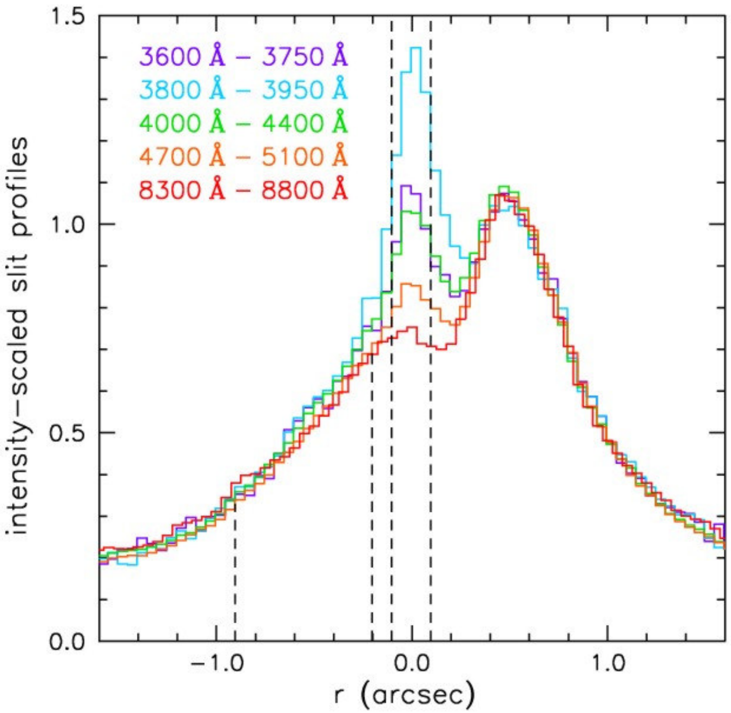


Jacobs &
Sellwood (2001)



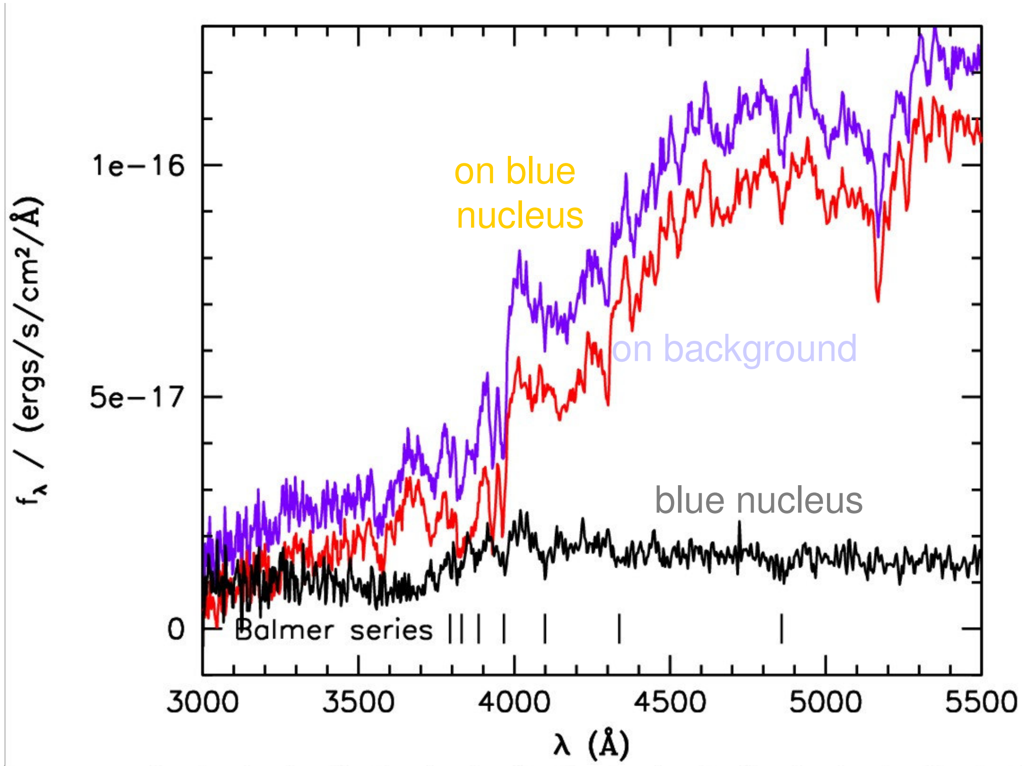
STIS spectroscopy by Bender, Kormendy, Bower, Green, Thomas and STIS Instrument Team (2005)

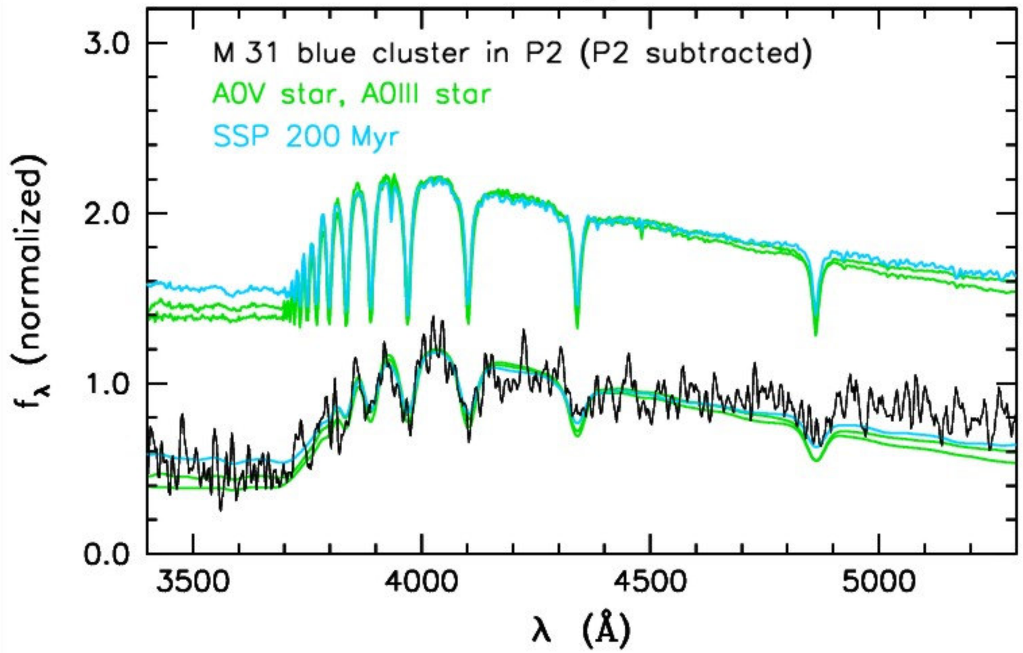
Bender et al. (2005)



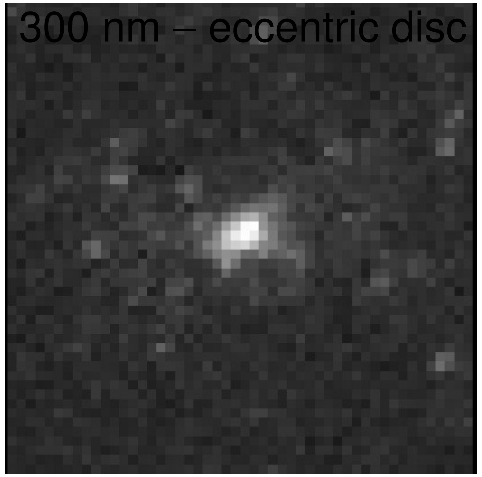
The blue source P3 at the center of P2 is a cluster of A-stars with age ~ 200 Myr, mass about 5000 M_{sun}, and velocity dispersion

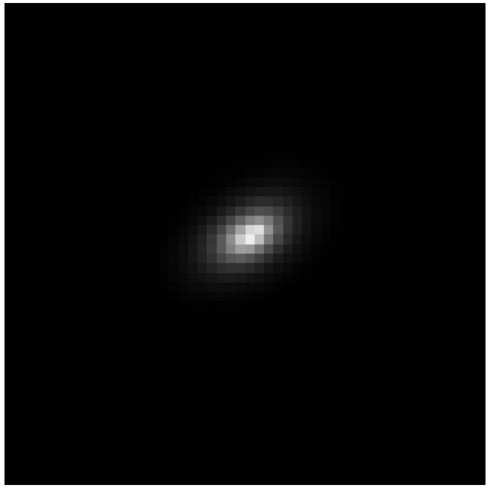
$\sigma = 960 \pm 106$ km/s

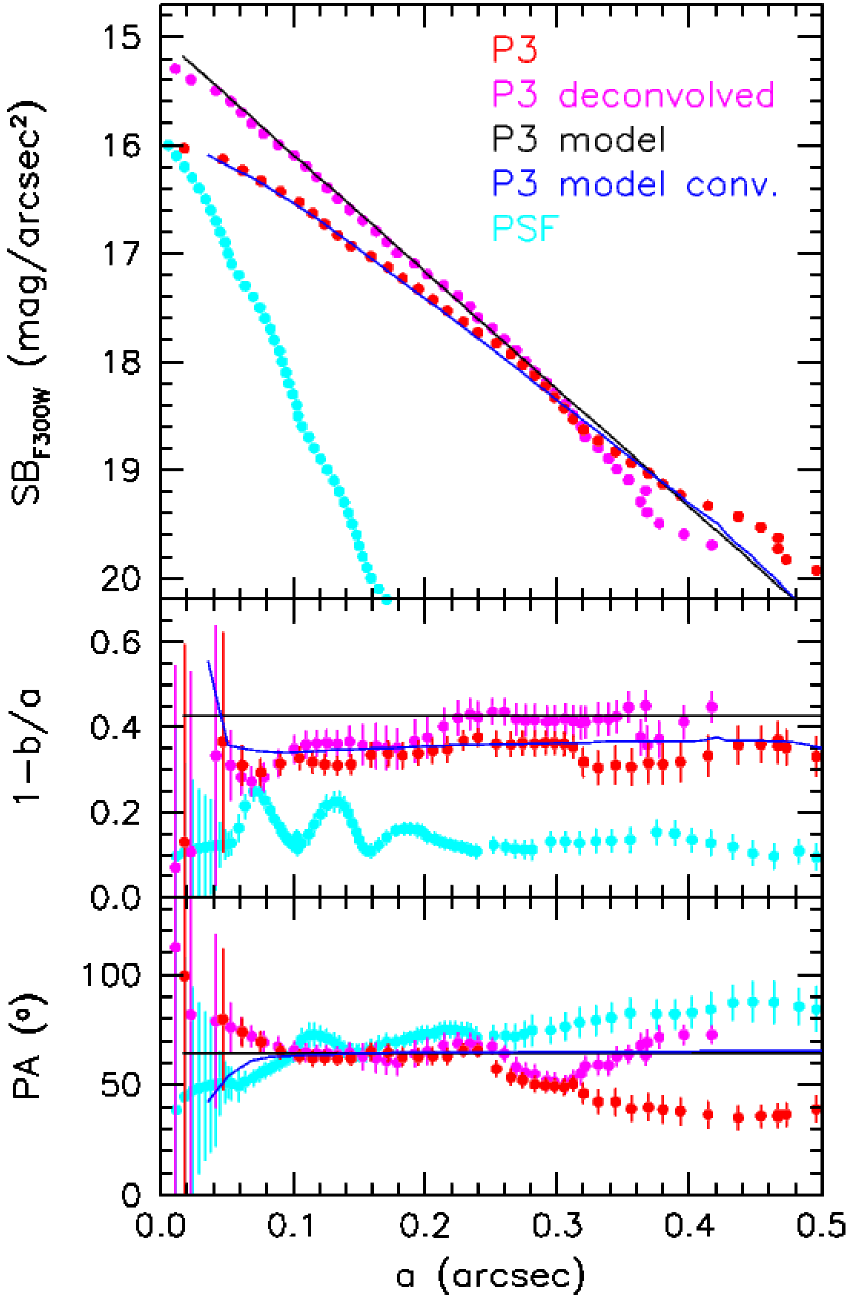




Modeling photometry and kinematics of P3, continued…



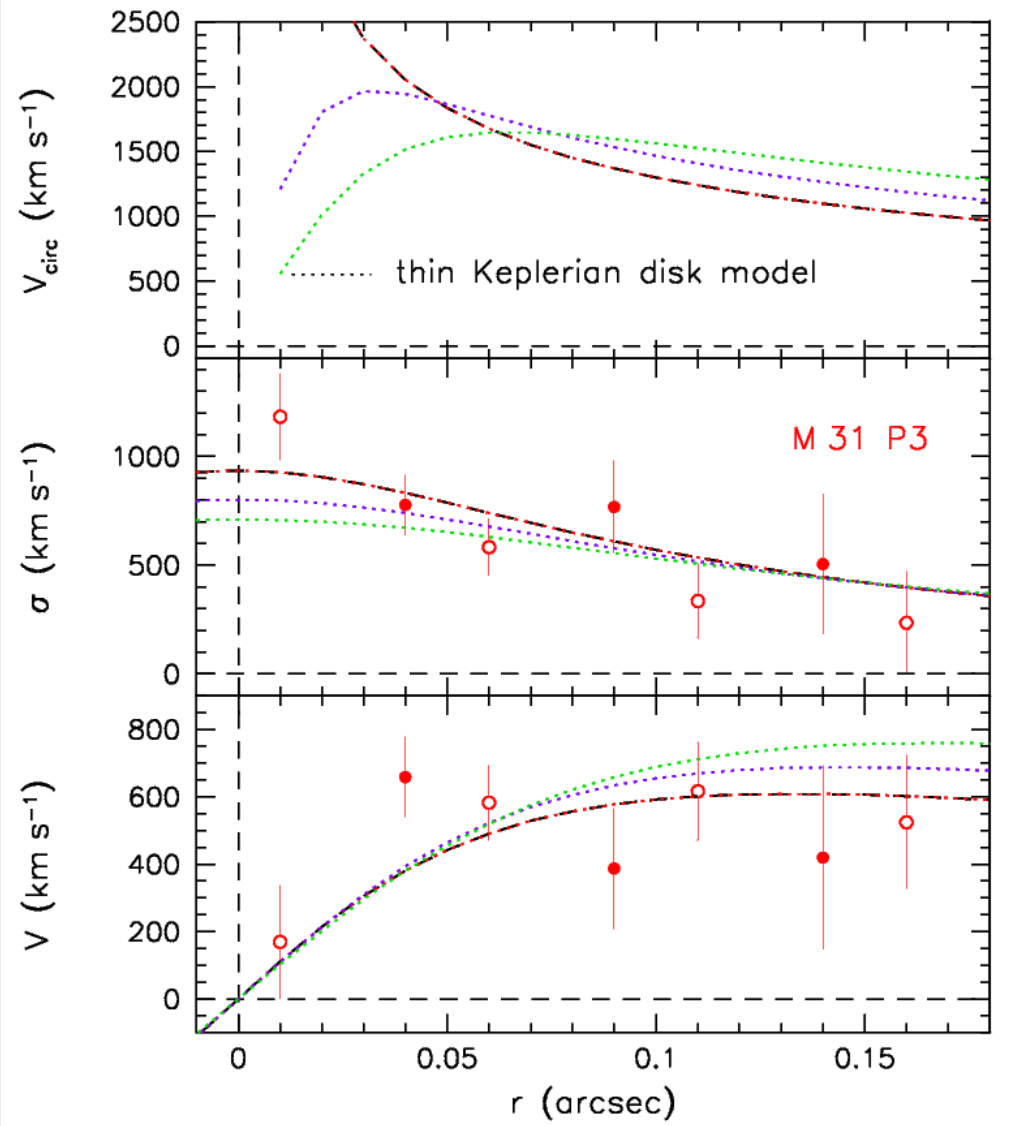




P3's flattening is high and consistent with <u>a disk seen at the same inclination as the larger P1+P2 eccentric disk</u>: inclination ~ 55°

Bender et al. (2005)

P3: observed kinematics vs thin disc model



Bender et al. (2005)

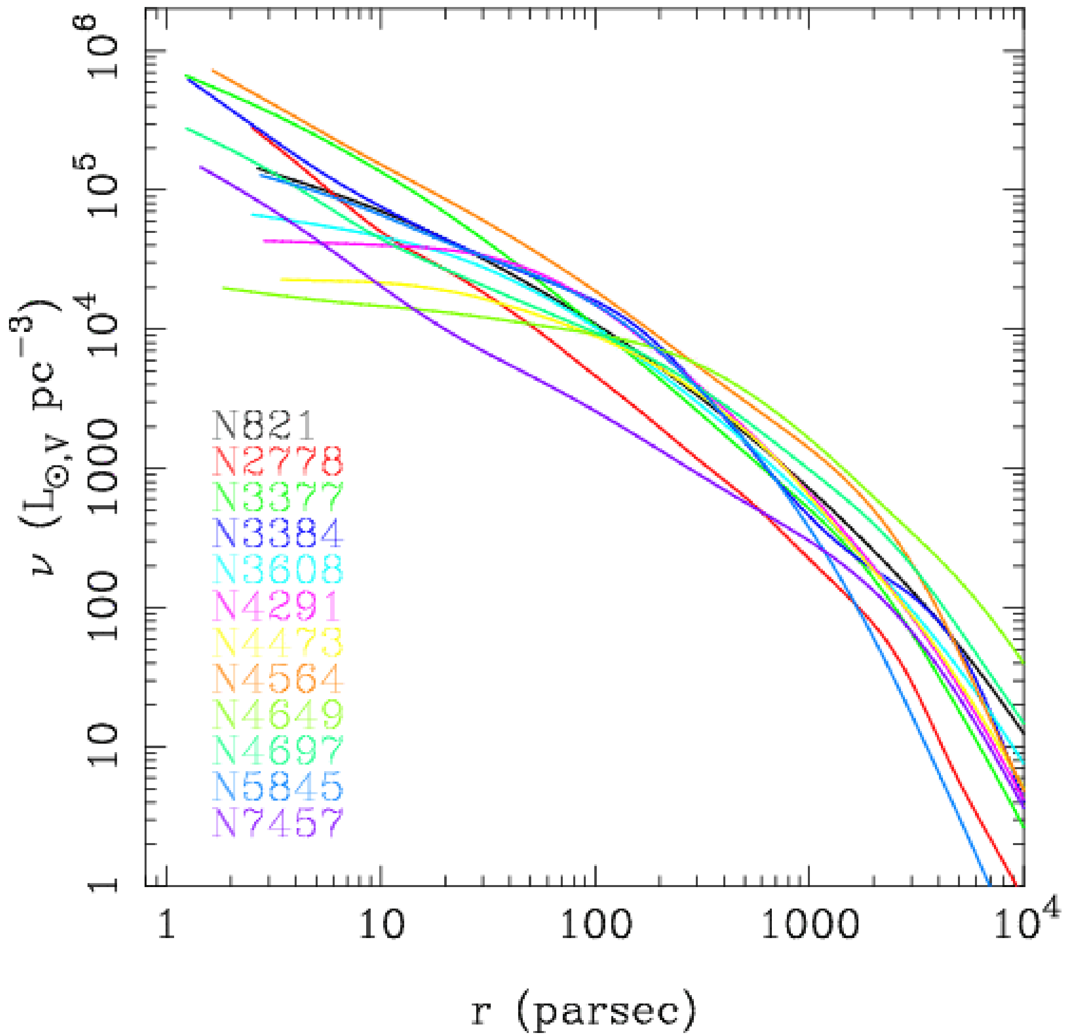
- blue nucleus P3 in M31 is a stellar disc in Keplerian rotation around a black hole
- The best fit is obtained for a point mass, i.e. a black hole of mass:

$$M_{BH} \sim (1.1 - 2.5) \times 10^8 \, M_\odot$$

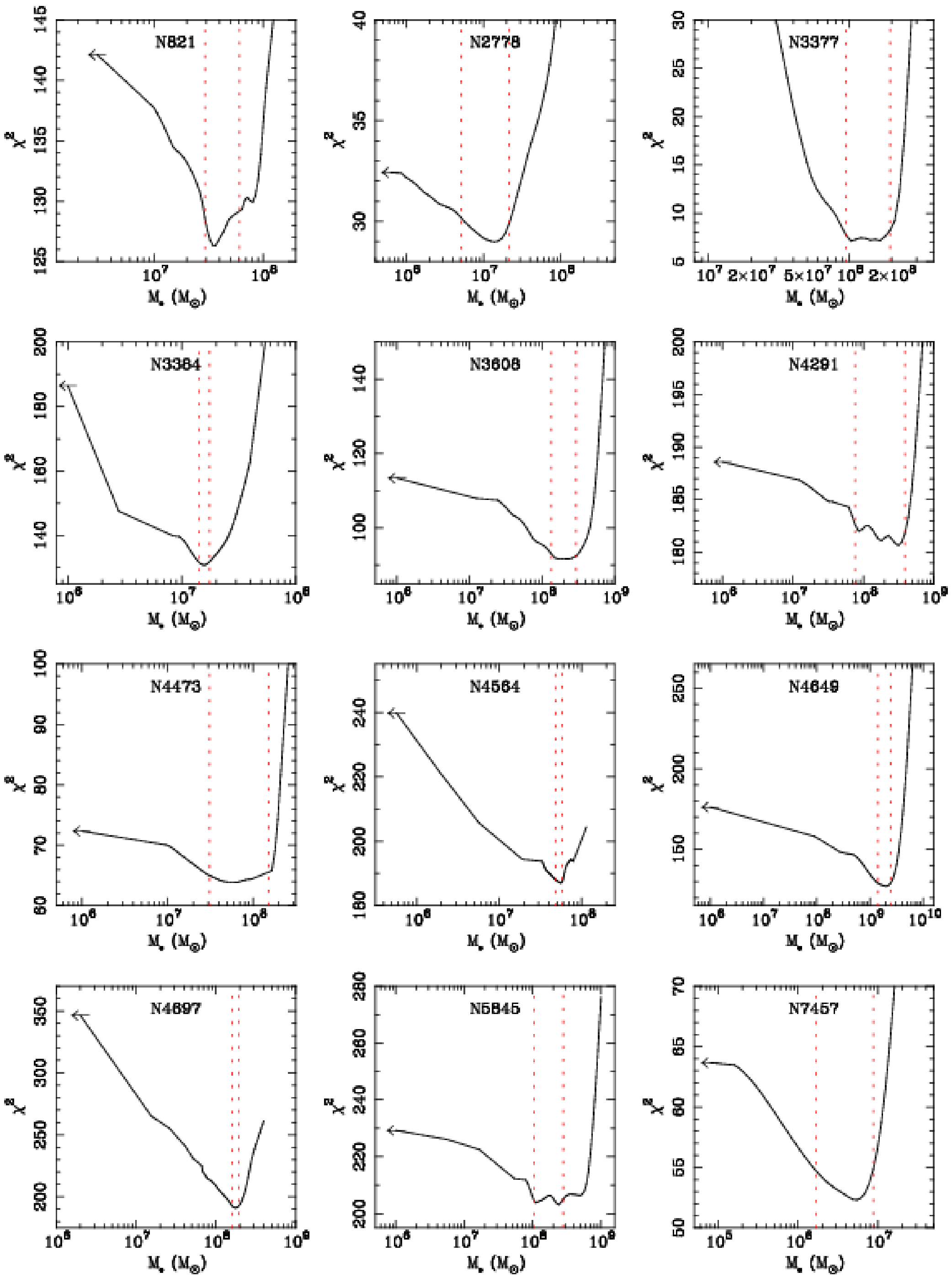
- A mass sphere of radius 0.03"=0.1 pc is 1-sigma off from the point-mass solution
- the P3 stellar population is dominated by *A*-type stars (why so young?)
- mass in P3 is so compact that alternatives to a black hole are ruled out
- mass obtained from P3 is consistent with mass obtained from modeling P1 and P2, $1\times10^8 \, M_\odot$

The Nuker sample

- 12 galaxies (10 ellipticals, 2 S0's)
- all have:
  - HST spectroscopy using STIS (10) or FOS (2)
  - HST photometry
  - ground-based photometry and spectroscopy at larger radii
  - orbit-based axisymmetric dynamical models that fit the line-of-sight velocity distribution
  - parameters are inclination, M/L of stars, black-hole mass

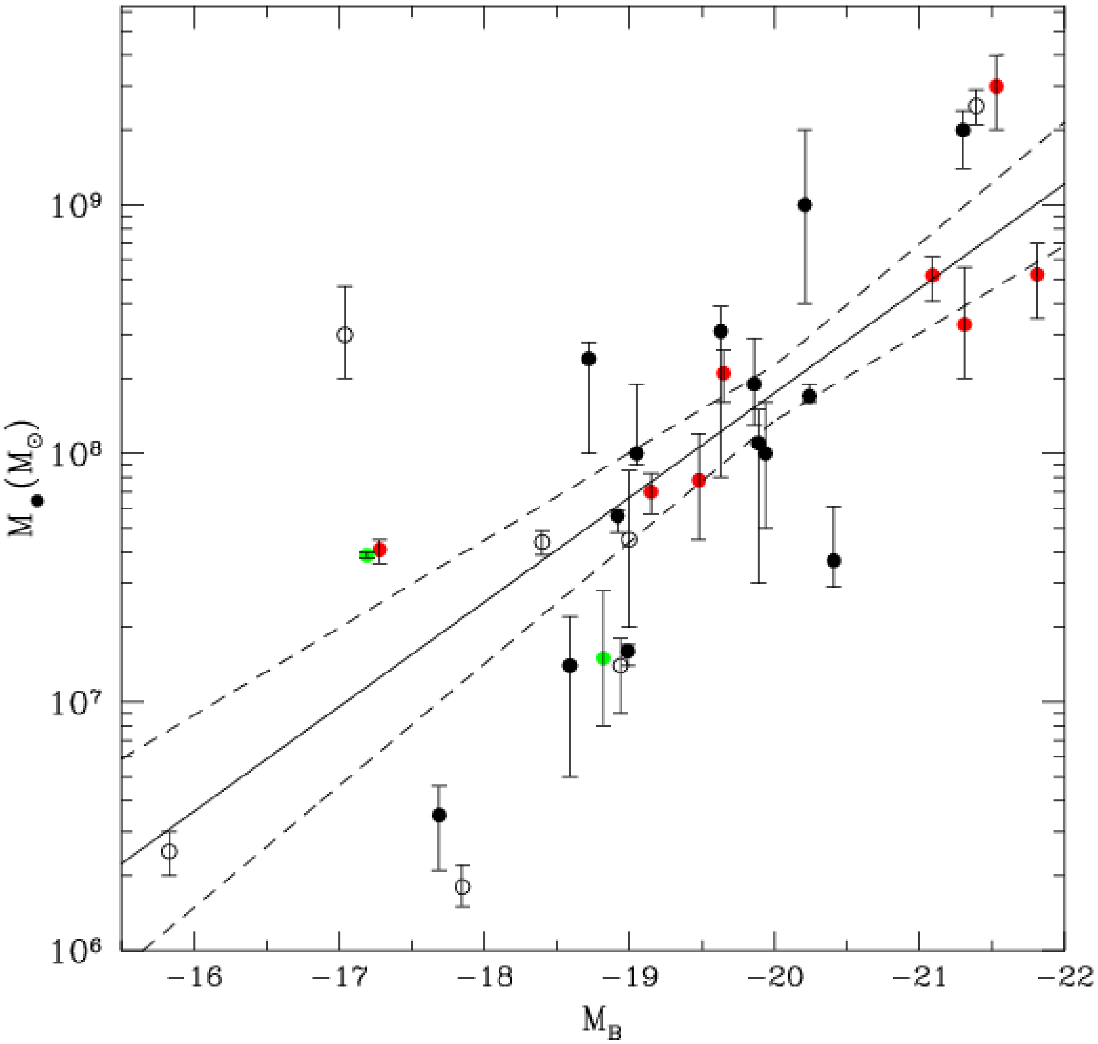


Gebhardt et al. (2002)



Gebhardt et al. (2002)

The mass-luminosity relation

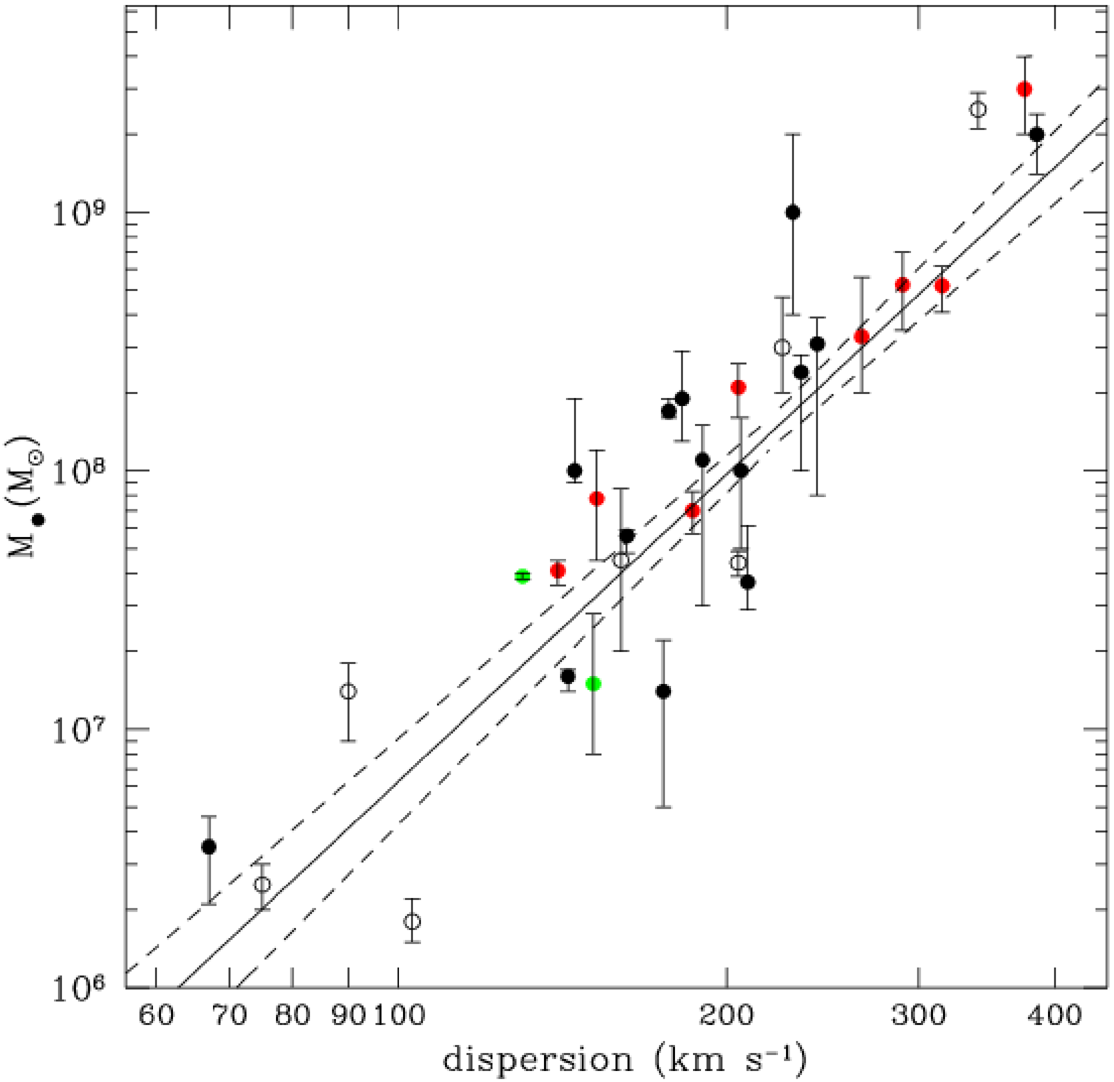


Tremaine et al. (2002)

- maser kinematics
- gas kinematics
- stellar kinematics (Nukers)
- stellar kinematics (others)

- 31 galaxies with most reliable masses
- $M \sim L^a$, $a = 1.05 \pm 0.17$
- intrinsic dispersion in M of 0.5 dex or smaller
- correlation is with luminosity of hot component (ellipticals, spiral bulges)
- Kormendy (1993)

The mass-velocity dispersion relation

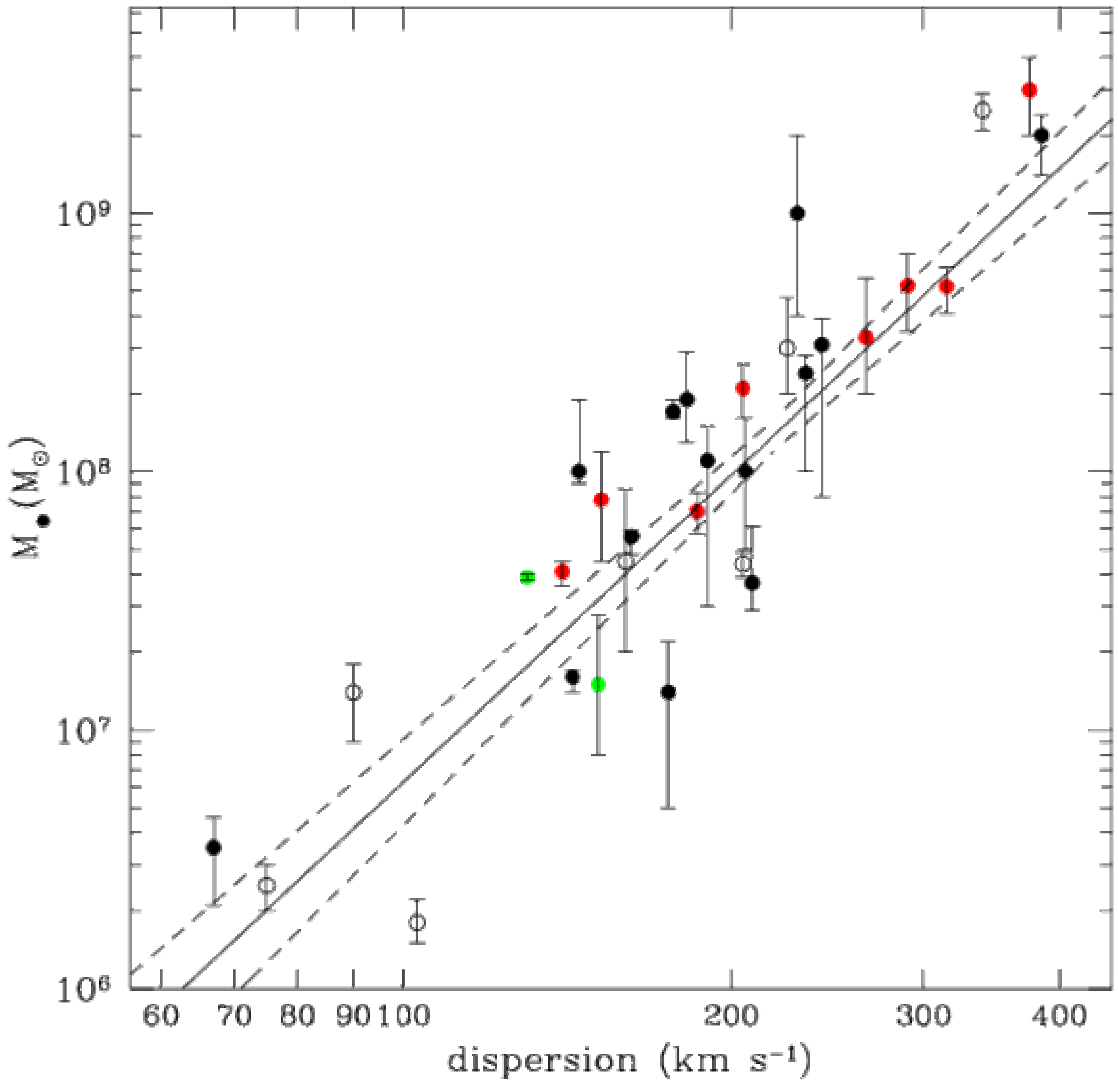


Tremaine et al. (2002)

- maser kinematics
- gas kinematics
- stellar kinematics (Nukers)
- stellar kinematics (others)

- $M \sim \sigma^b$, $b=4.0\pm0.3$
- intrinsic dispersion in log M of < 0.3
- Gebhardt et al. (2000), Ferrarese & Merritt (2000)

The mass-velocity dispersion relation



Tremaine et al. (2002)

- no evidence of systematic differences between different methods
- no evidence of differences between ellipticals and spiral bulges
- consistent with masses of Seyfert nuclei determined by reverberation mapping (Gebhardt et al. 2000)
- only well-determined between 130 and 300 km/s but this includes L* galaxies

The Kormendy number

This is the density $\rho_\bullet(\text{local})$ of black holes at $z = 0$, assuming all black holes are found in galaxy centers. Using the black-hole mass vs. galaxy luminosity relation and the galaxy luminosity function

$$\rho_\bullet(\text{local}) = \mathrm{M}_\odot\,\mathrm{Mpc}^{-3} \begin{cases} 3.5 \times 10^5 & \text{Salucci (1999)} \\ (4 \pm 2) \times 10^5 & \text{Marconi \& Salvati (2001)} \\ 5.8 \times 10^5 & \text{Yu \& Tremaine (2002)} \\ (4.5 \pm 2) \times 10^4 & \text{Marconi et al. (2003)} \end{cases}$$

A better procedure is to use the mass vs. dispersion relation and the velocity dispersion distribution (Bernardi et al. 2003, Sheth et al. 2003); this yields

$$\rho_\bullet(\text{local}) = \mathrm{M}_\odot\,\mathrm{Mpc}^{-3} \begin{cases} (2.5 \pm 0.4) \times 10^5 & \text{Yu \& Tremaine (2002)} \\ (4.8 \pm 1.6) \times 10^5 & \text{Aller \& Richstone (2002)} \\ (4.6 \pm 1.7) \times 10^5 & \text{Marconi et al. (2003)} \end{cases}$$

The Sołtan number

Assume quasar luminosity is produced by accretion onto black holes with efficiency ϵ,

$$\Delta E = \epsilon \Delta M c^2.$$

Total black hole mass ("ash") left after producing energy E is

$$M_\bullet = \frac{1-\epsilon}{\epsilon}\frac{E}{c^2}.$$

If $\Psi(L,z)dL$ is the comoving number density of QSOs with luminosity $(L, L+dL)$ at redshift z, then local density of black-hole ash is (Sołtan 1982, Chokshi & Turner 1992, Small & Blandford 1992)

$$\rho_\bullet(\mathrm{AGN}) = \frac{1-\epsilon}{\epsilon}\int_{z=0}^{\infty} dz \frac{dt}{dz}\int_0^\infty dL\,\Psi(L,z)\frac{L_{\mathrm{bol}}}{c^2}.$$

bolometric luminosity

The Soltan number

Assuming ε=0.1 and using X-ray/optical surveys of AGN,

$\rho(AGN) \approx 2 \times 10^5\ M_\odot/Mpc^3$ (Cowie et al. 2003)

$\rho(AGN) \approx (4 - 5) \times 10^5\ M_\odot/Mpc^3$ (Fabian 2003)

$\rho(AGN) \approx (5 - 10) \times 10^5\ M_\odot/Mpc^3$ (Marconi et al. 2003)

Current estimates of the Kormendy number are

$\rho(local) \approx (2 - 5) \times 10^5\ M_\odot/Mpc^3$

which are roughly consistent if $\varepsilon \approx 0.1 - 0.3$ (range for thin-disk accretion onto Schwarzschild and Kerr black holes)

Summary – what we know

- there is now strong evidence for massive dark objects in 20-30 nearby galaxies. Mass range 10^6-10^9 $M_\odot$
- there is strong circumstantial evidence that the massive dark objects are black holes
- $M \propto \sigma^4$ with scatter of 0.2-0.3 in log
- local black hole mass density is consistent with expected density of ash from QSOs if $\varepsilon \approx 0.1 - 0.3$ (!)
- obscured or dark accretion cannot be important for luminous QSOs

Summary – what we don't know

- what is the high-mass and low-mass end of the black hole mass function?
- do black holes merge efficiently when galaxies merge or are there binary black holes or wandering black holes in galaxy halos?
- why is black-hole mass so tightly correlated with the galaxy properties?
- what is the event rate of gravitational-wave bursts that will be detected by LISA (estimates range from 0.1/yr to 100/yr)?
- where are the former hosts of the brightest QSOs?