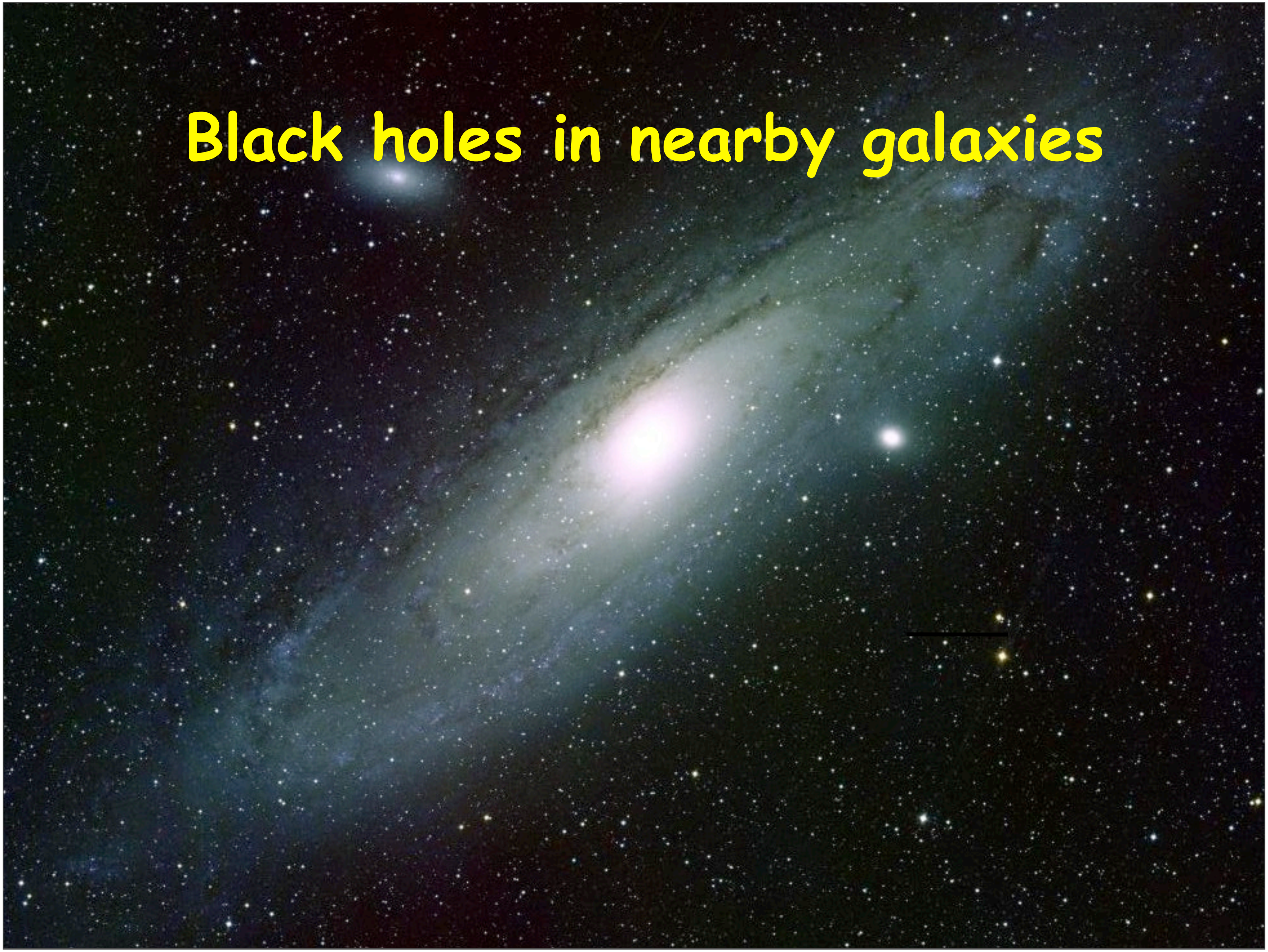
Black holes in nearby galaxies

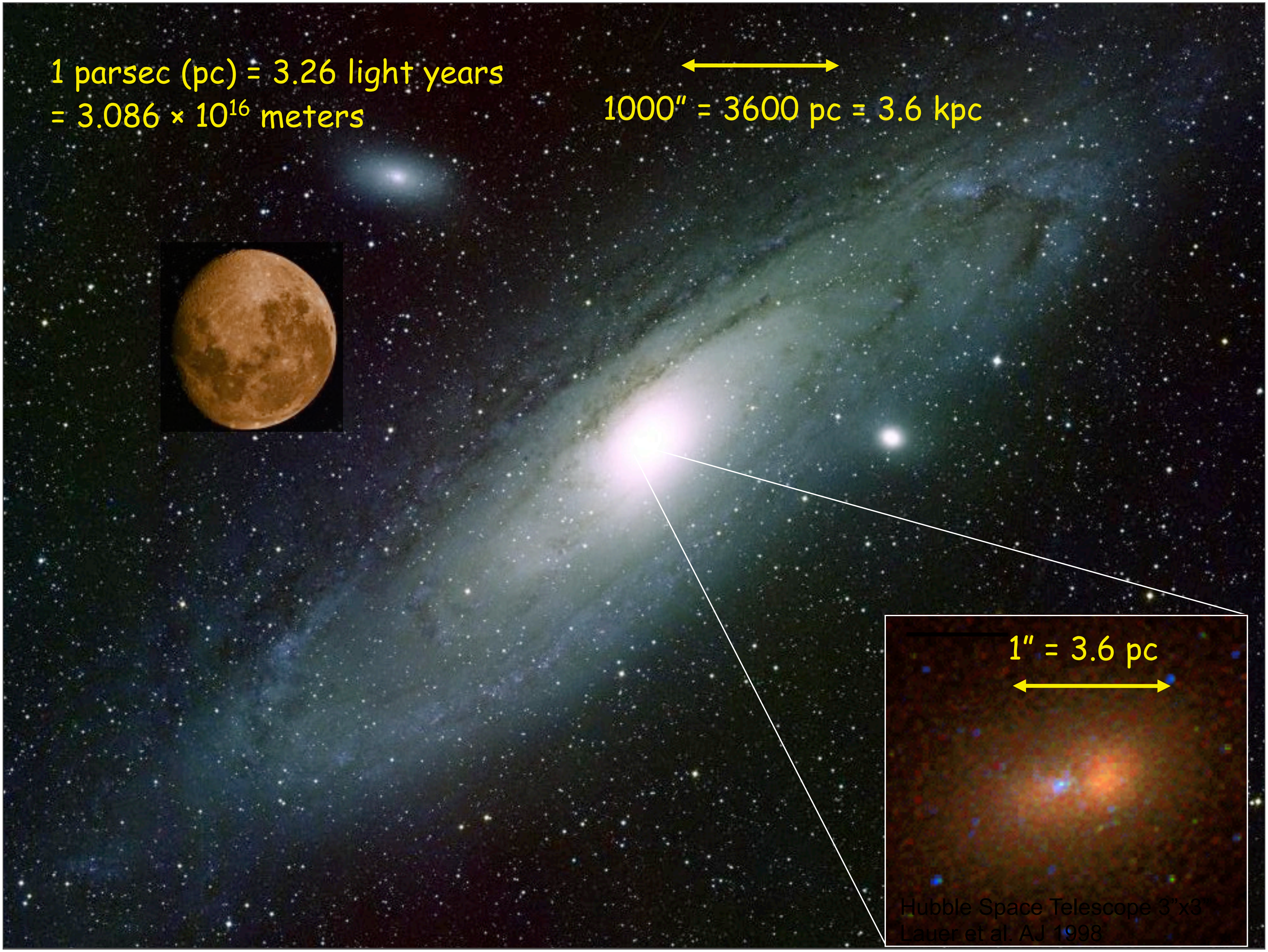


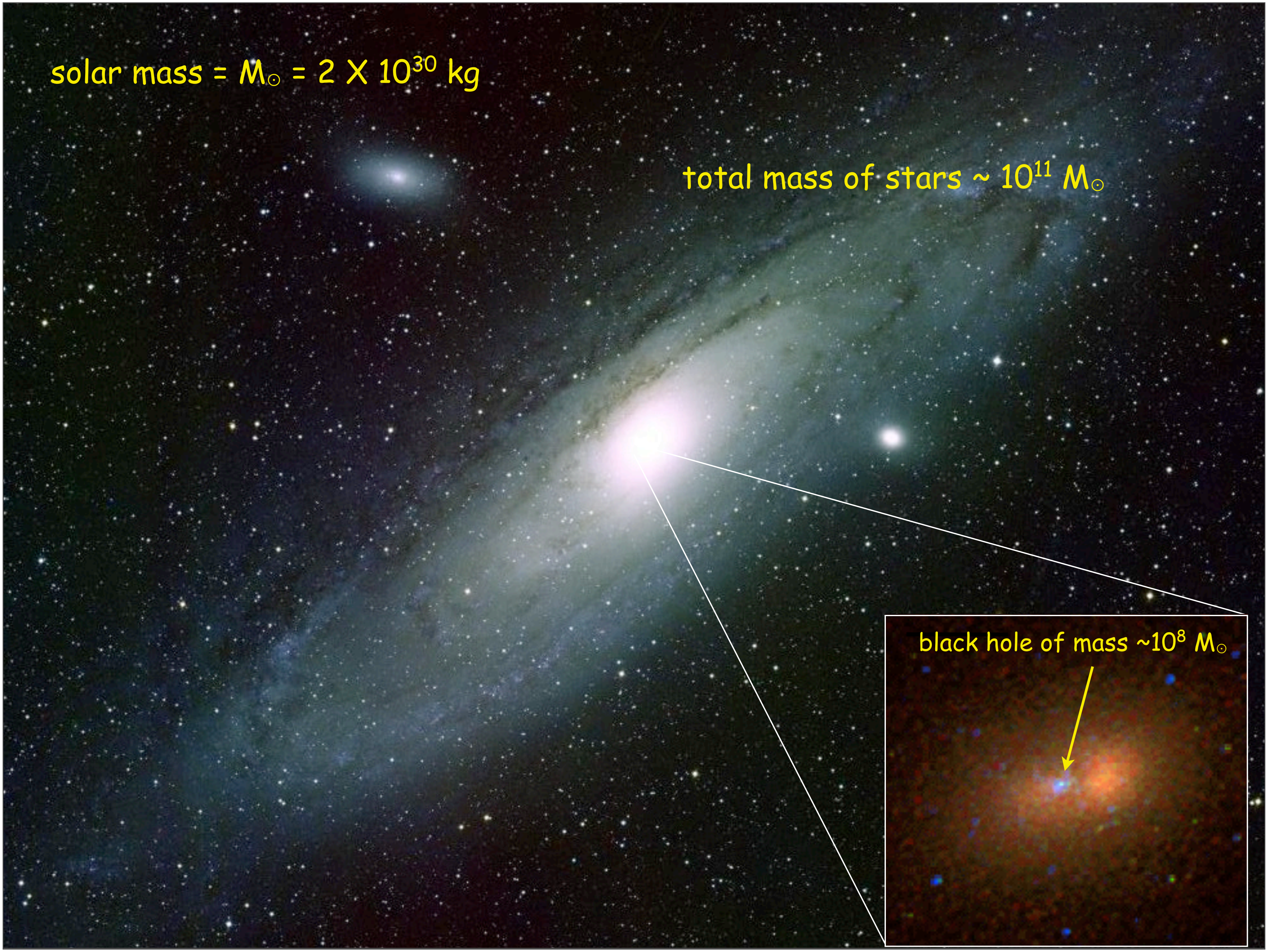
Black holes in nearby galaxies (today)

1. Prior evidence for black holes
2. Posterior evidence for black holes
3. The relations between black holes and their host galaxies
4. Binary black holes

Dynamics of galaxy centers (Friday)

1. Hypervelocity stars
2. The nucleus of M31
3. Statistical mechanics in galaxy centers


1 parsec (pc) = 3.26 light years
= 3.086 × 10¹⁶ meters
1000″ = 3600 pc = 3.6 kpc
1″ = 3.6 pc
Hubble Space Telescope 3″x3″
Lauer et al. AJ 1998


solar mass = $M_\odot$ = 2 X 10^{30} kg
total mass of stars ~ 10^{11} $M_\odot$
black hole of mass ~10^8 $M_\odot$

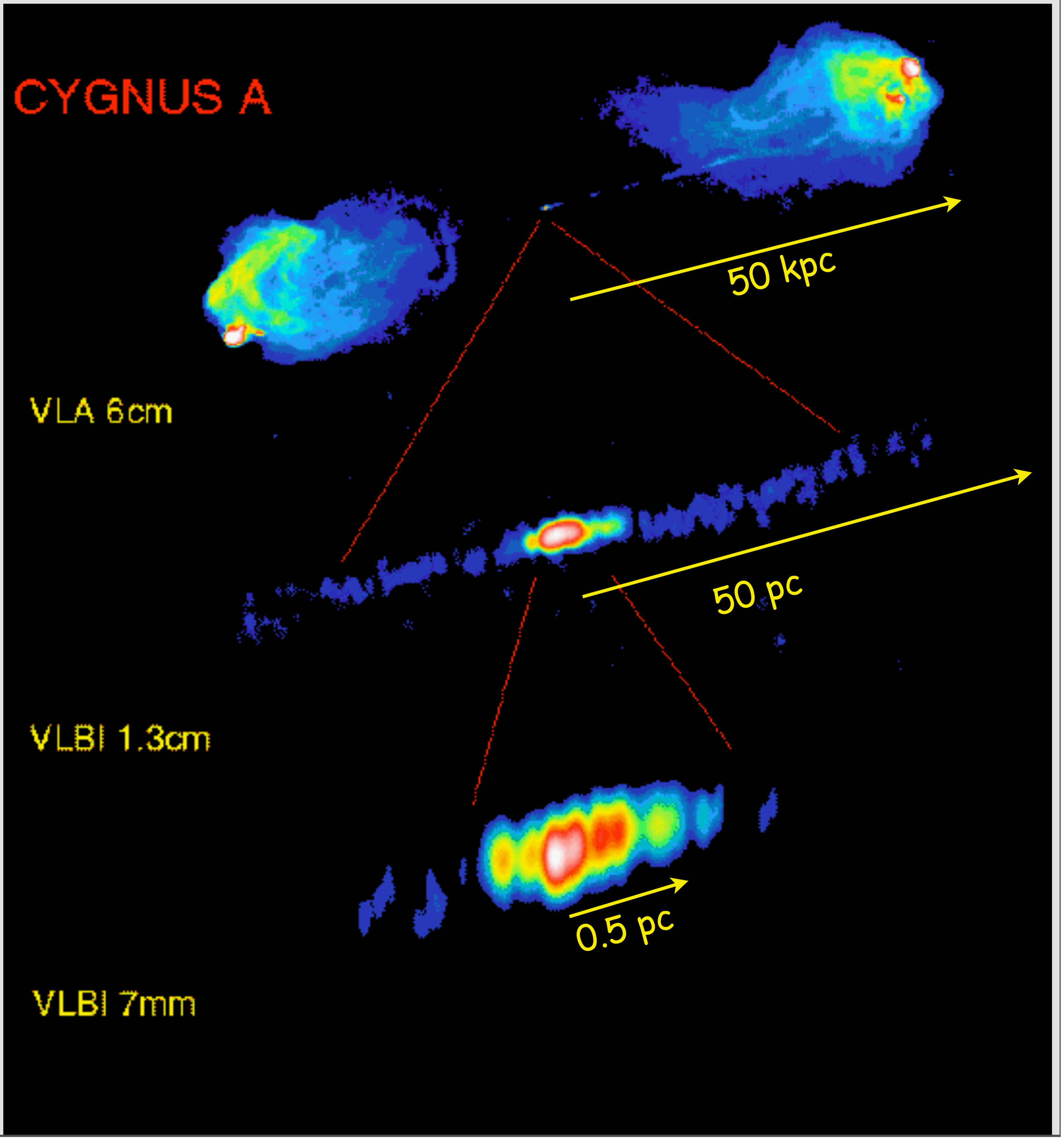
1. Prior evidence for black holes

- quasars are the most luminous active galactic nuclei (AGN)
- emit up to ~$10^{13}\,L_\odot$, or 100–1000 times a typical galaxy luminosity
- energy source for all AGN is believed to be accretion of material onto a black hole of mass up to $10^{10}M_\odot$
- corresponding Schwarzschild radius 1.6×10^{15} cm $(M/10^{10}M_\odot)$ = 5 mpc $(M/10^{10}M_\odot)$

milliparsecs

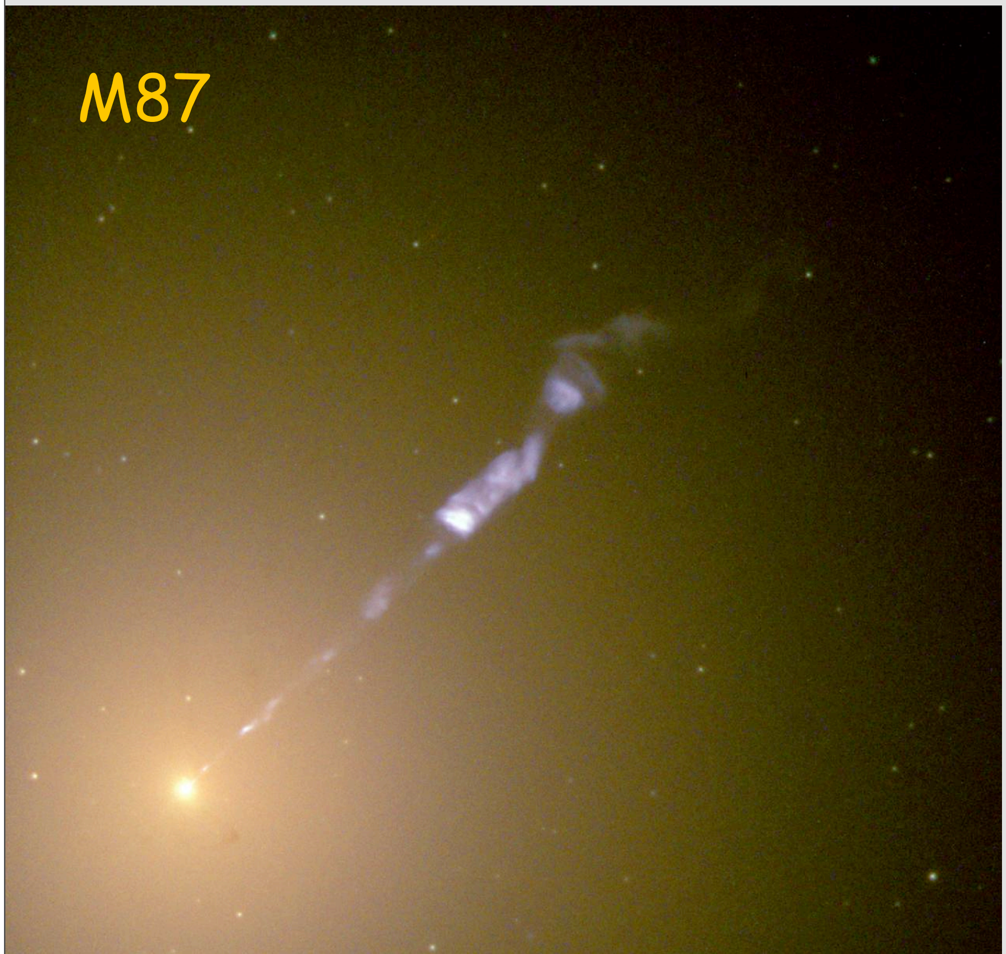
why quasars require black holes

directional stability of radio jets over timescales of ~10^5 yr requires a gyroscope that could be provided by a spinning black hole



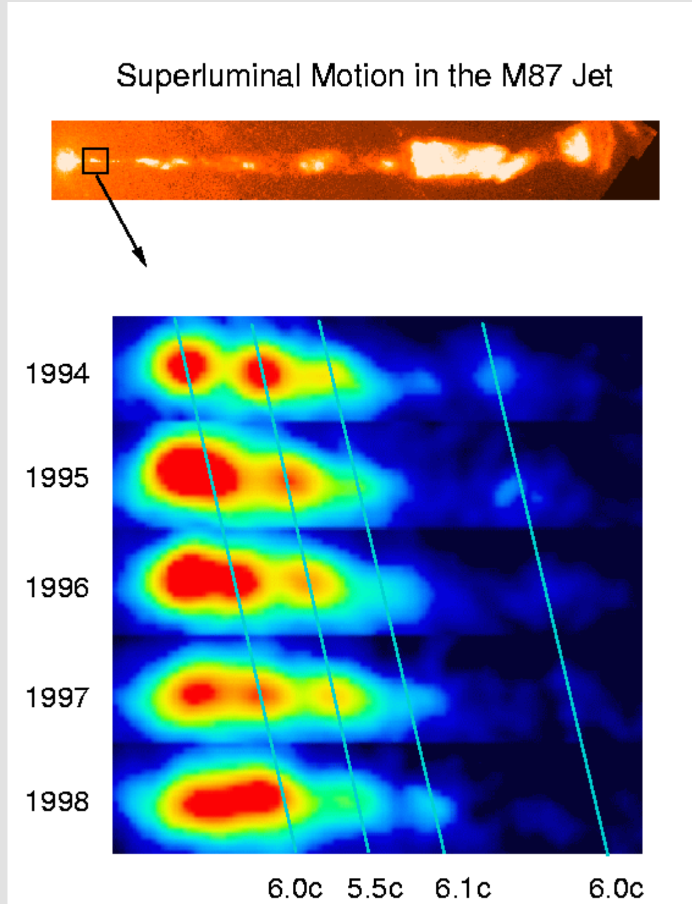
Krichbaum et al. (1998)

why quasars require black holes



Hubble Space Telescope images

- apparent superluminal motion of radio jets

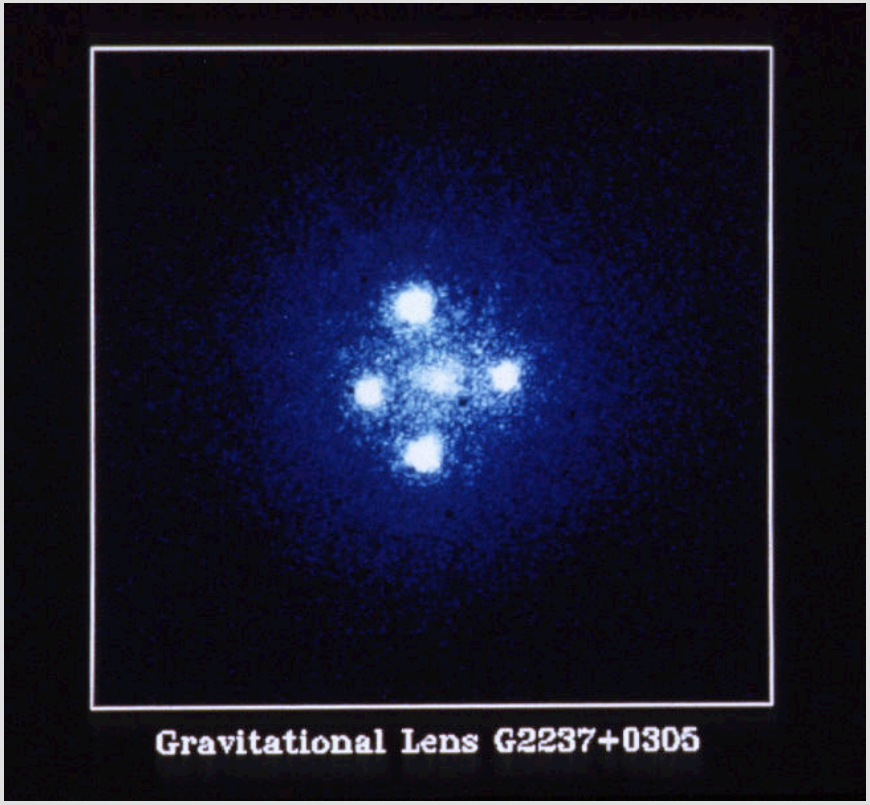


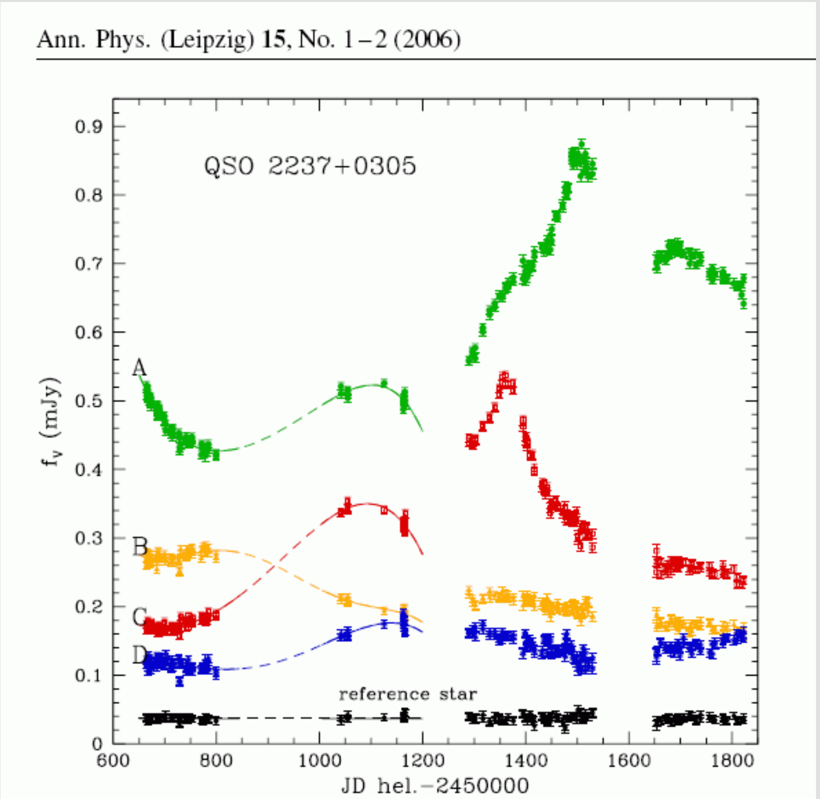
why quasars require black holes

- time variability on timescales of weeks

  size < ct ~ 2×10^{16} cm × (t/1 week) = 7 mpc × (t/1 week)

- gravitational lensing by individual stars implies emitting region smaller than Einstein radius of the star



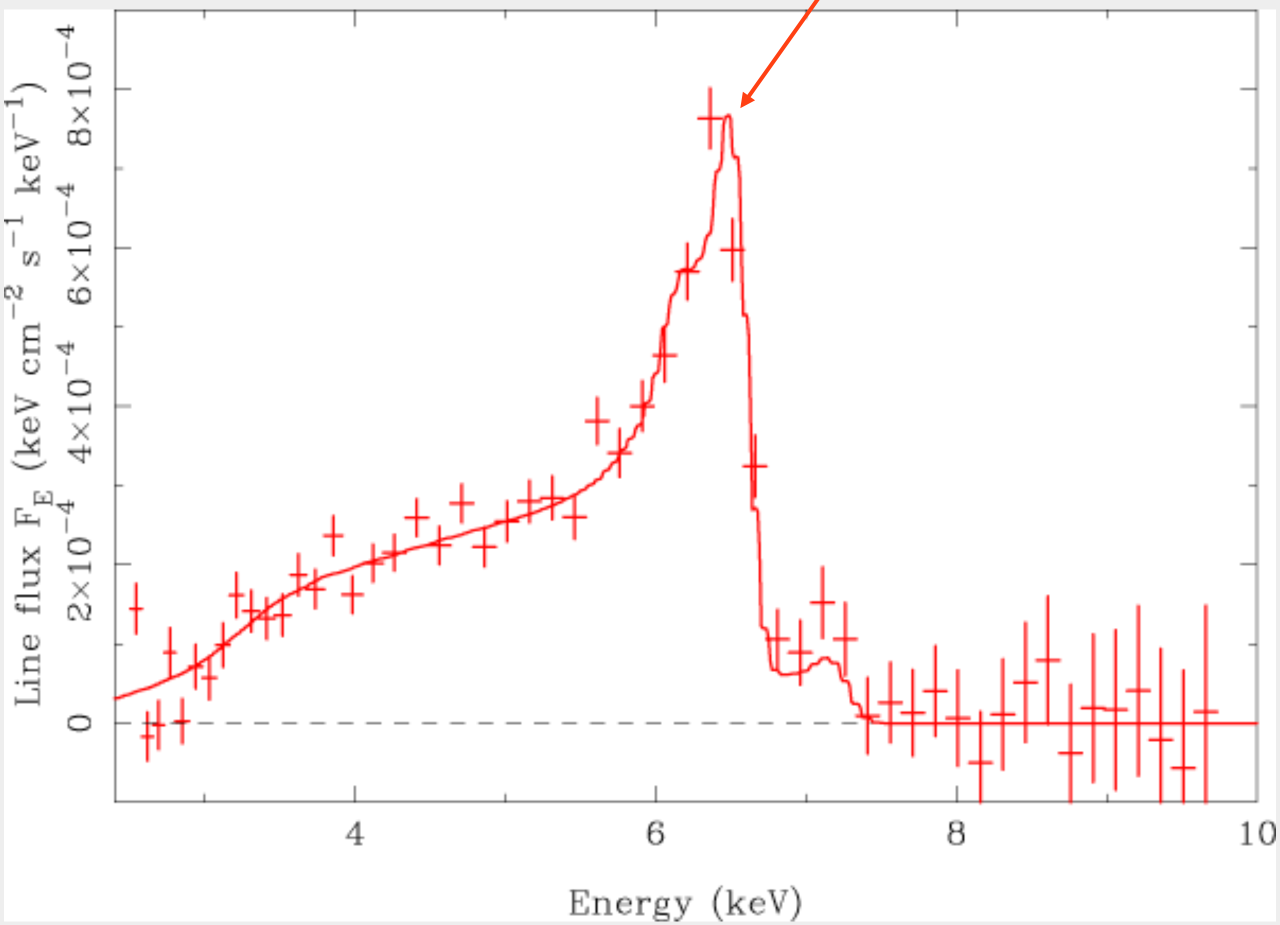


Wambsganss (2006)

why quasars require black holes

- relativistically broadened and redshifted X-ray emission lines

iron Kα rest wavelength



why quasars require black holes

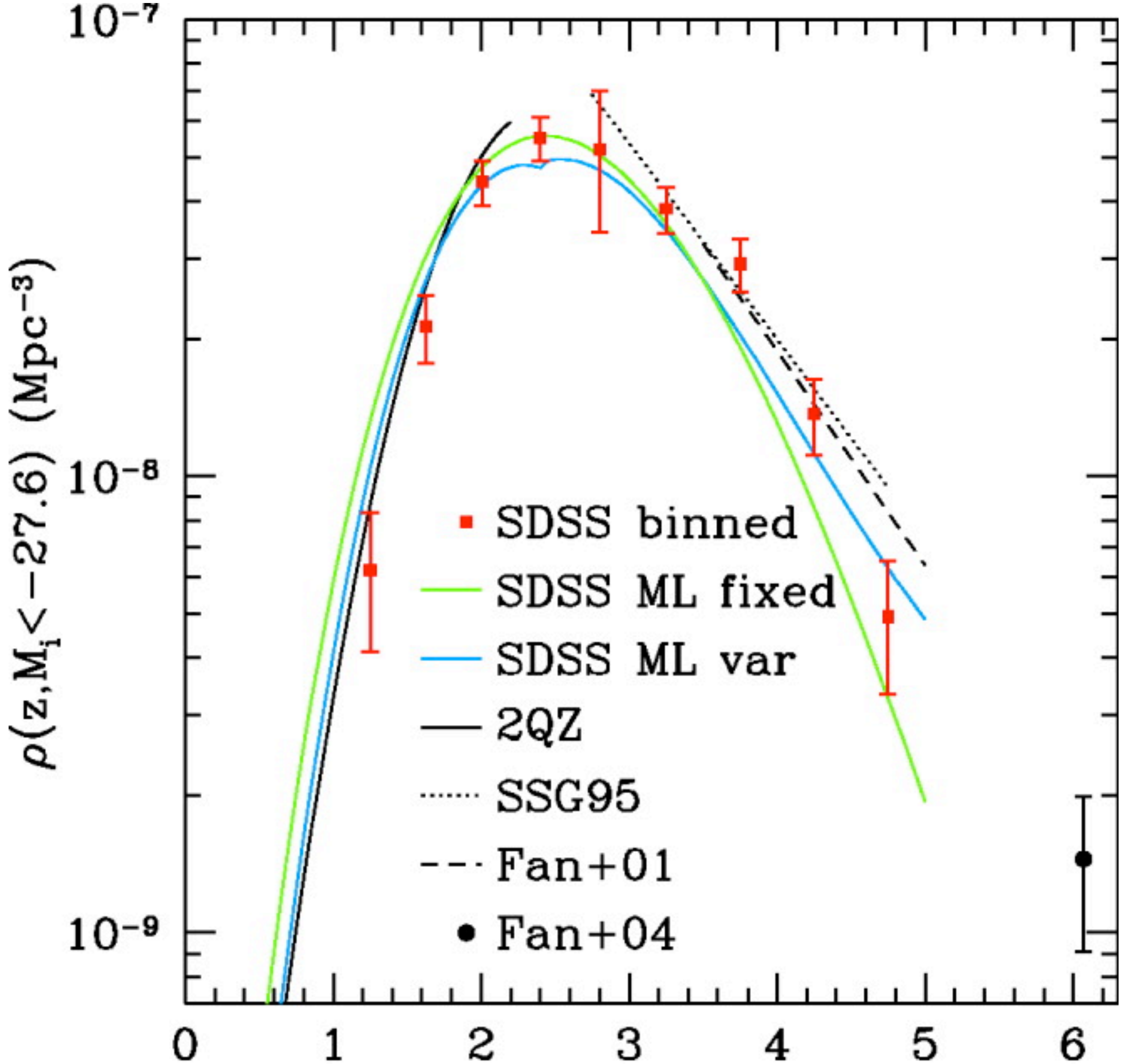
Burning a mass ΔM produces energy ΔE with efficiency

$$\epsilon = \frac{\Delta E}{\Delta M c^2}$$

$\epsilon < 0.008$ for nuclear reactions
$\epsilon = 0.057$ for accretion onto a non-rotating black hole
$\epsilon = 0.3$ for accretion onto a black hole in equilibrium spin state
$\epsilon = 0.423$ for accretion onto a maximally rotating black hole

Emission of energy Δ E produces "ash" of mass

$$\frac{1-\epsilon}{\epsilon}\frac{\Delta E}{c^2}$$



- comoving number density of quasars is strongly peaked at redshift ~2

SDSS = Sloan Digital Sky Survey

redshift

13.7	9.9	3.3	2.2	1.6	1.2	0.95	time since Big Bang (Gyr)

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 galaxies

then

many nearby galaxies must contain massive black holes or "dead quasars" (Lynden-Bell 1969)

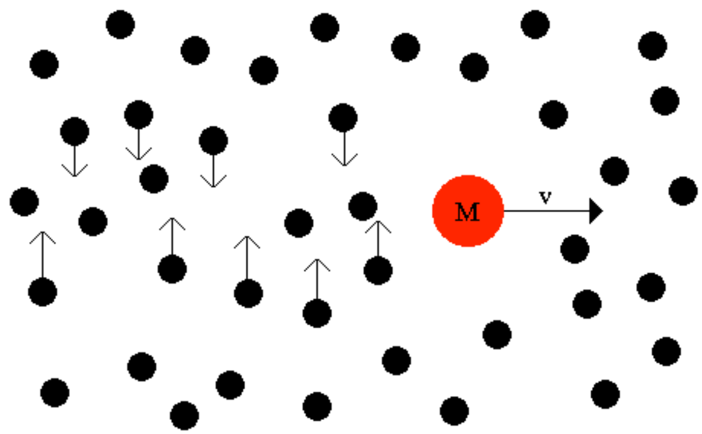
- expected density of quasar ash ~ $3\times10^5\,(\varepsilon/0.1)\,M_\odot/\mathrm{Mpc}^3$ (Sołtan 1982)

Black holes in the centers of galaxies

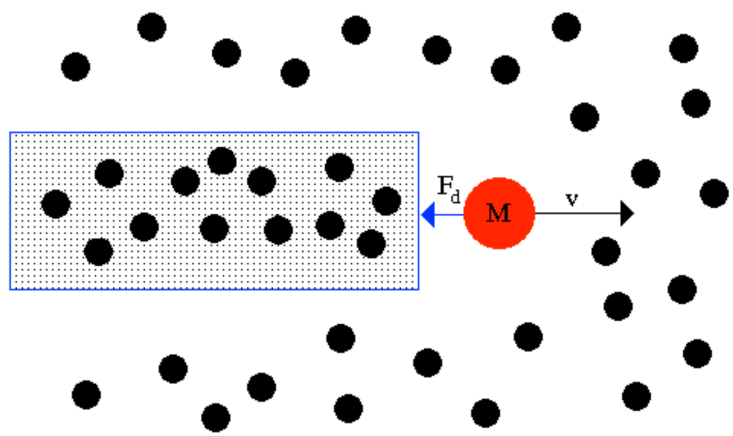
why are they at the center?

- that's the bottom of the potential well
- that's the only place we can find them
- dynamical friction causes orbits of massive bodies to spiral to the center

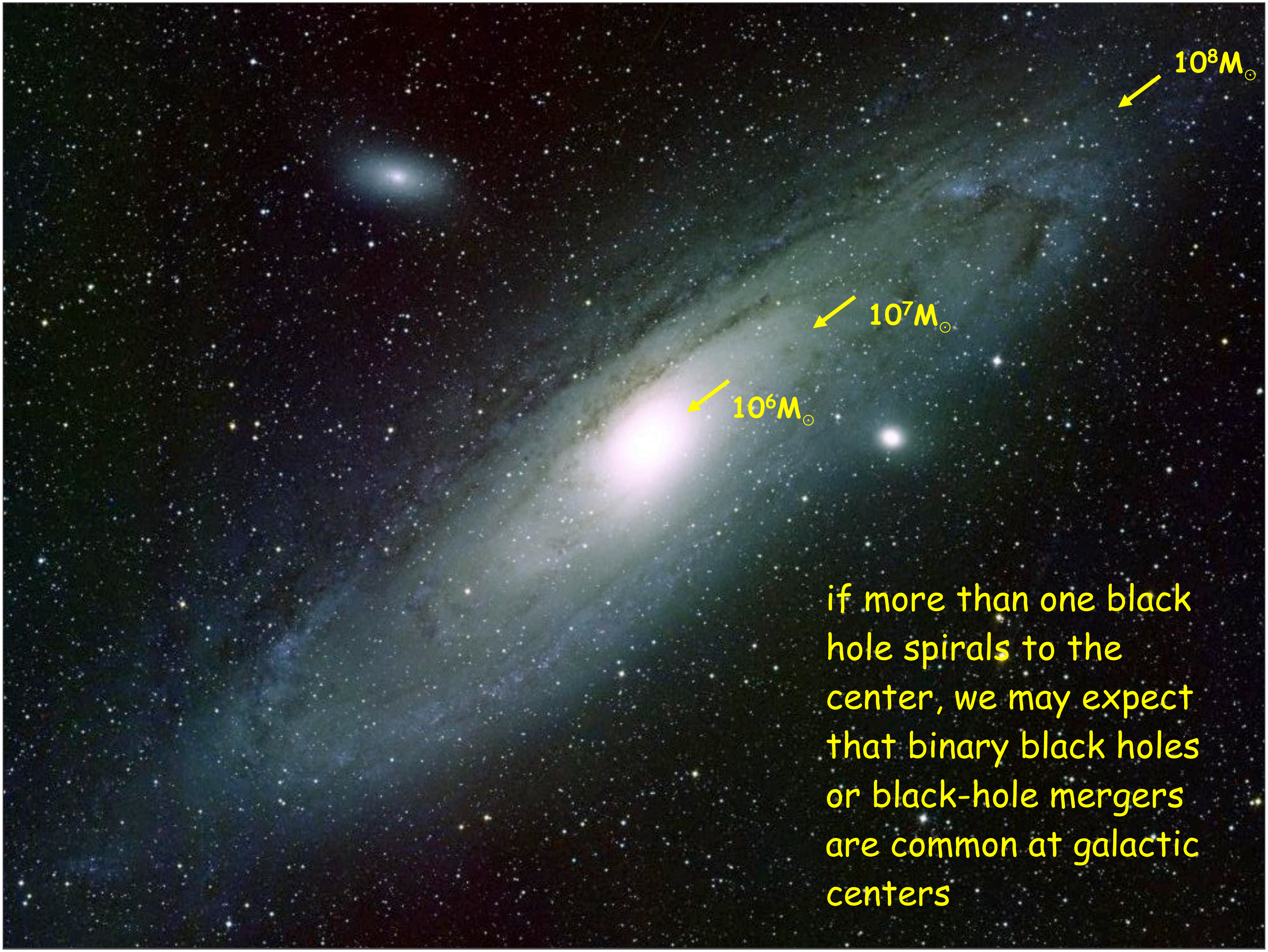
consider a mass, M, moving through a uniform sea of stars. Stars in the wake are displaced inward.



this results in an enhanced region of density behind the mass, with a drag force, F_d known as dynamical friction

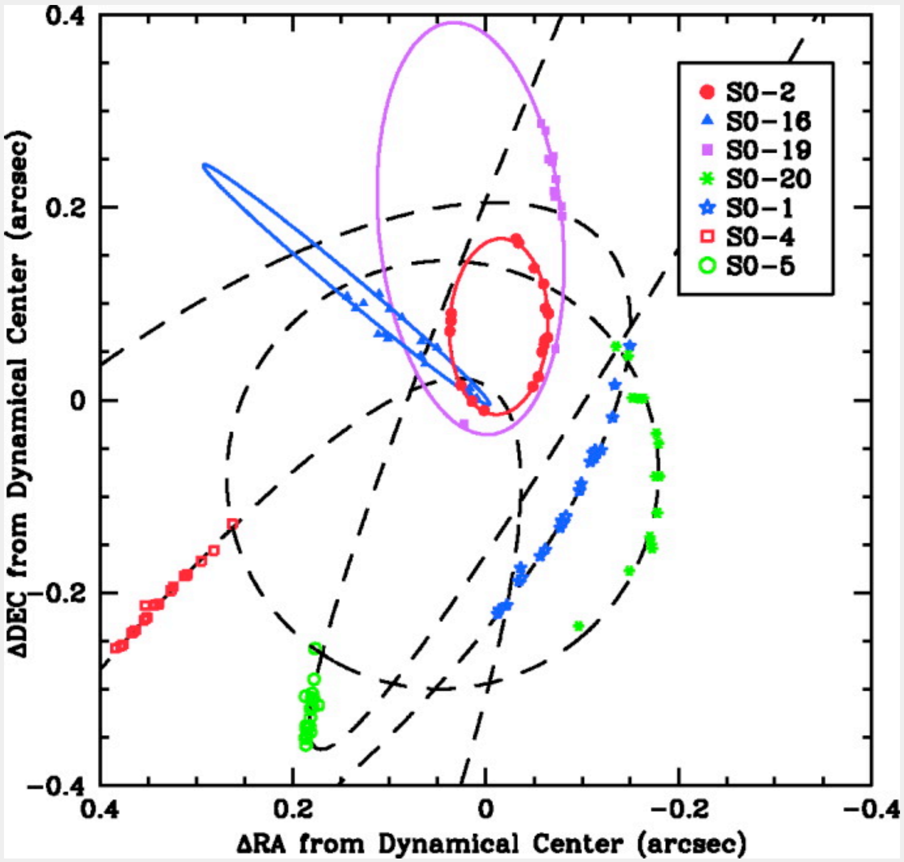


J. Schombert,
University of Oregon


$10^8 M_\odot$
$10^7 M_\odot$
$10^6 M_\odot$
if more than one black hole spirals to the center, we may expect that binary black holes or black-hole mergers are common at galactic centers

2. Posterior evidence for black holes

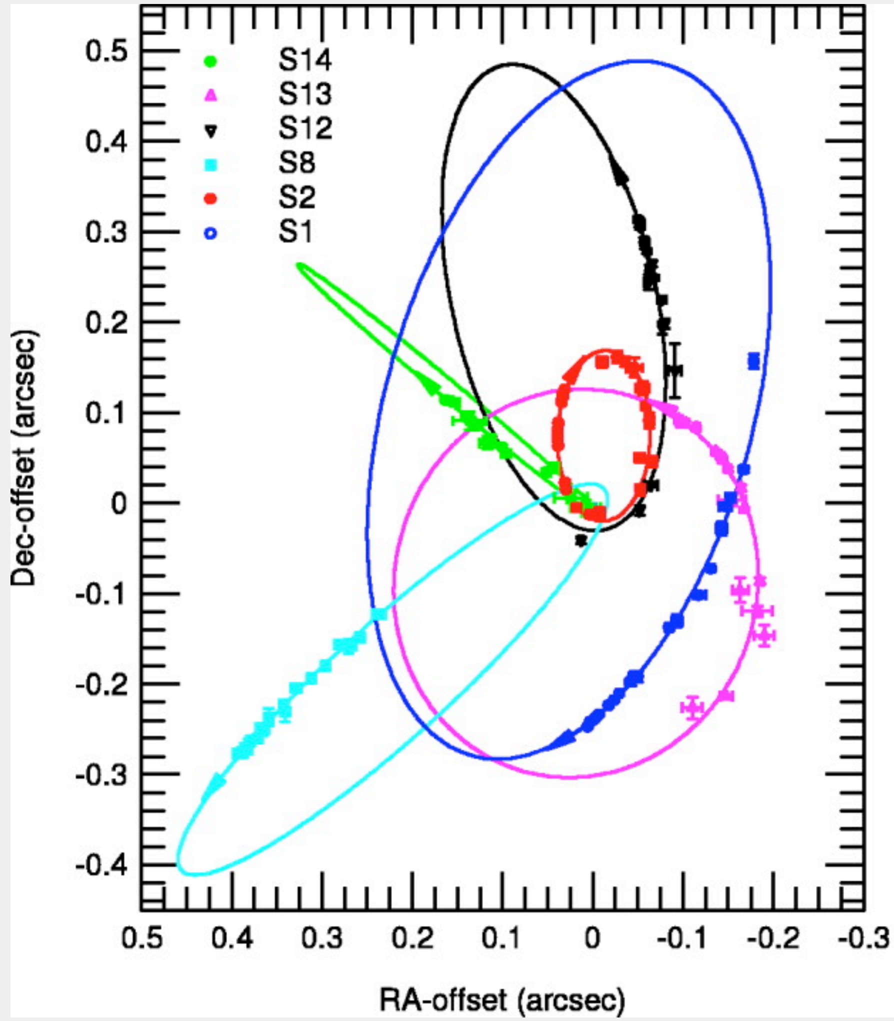
The black hole in the Galactic center



10 X Sun-Pluto distance

10 mpc

Ghez et al. (2005)



Eisenhauer et al. (2005)

The black hole in the Galactic center

• center of attraction is located at the radio source Sagittarius A* which is presumably the black hole

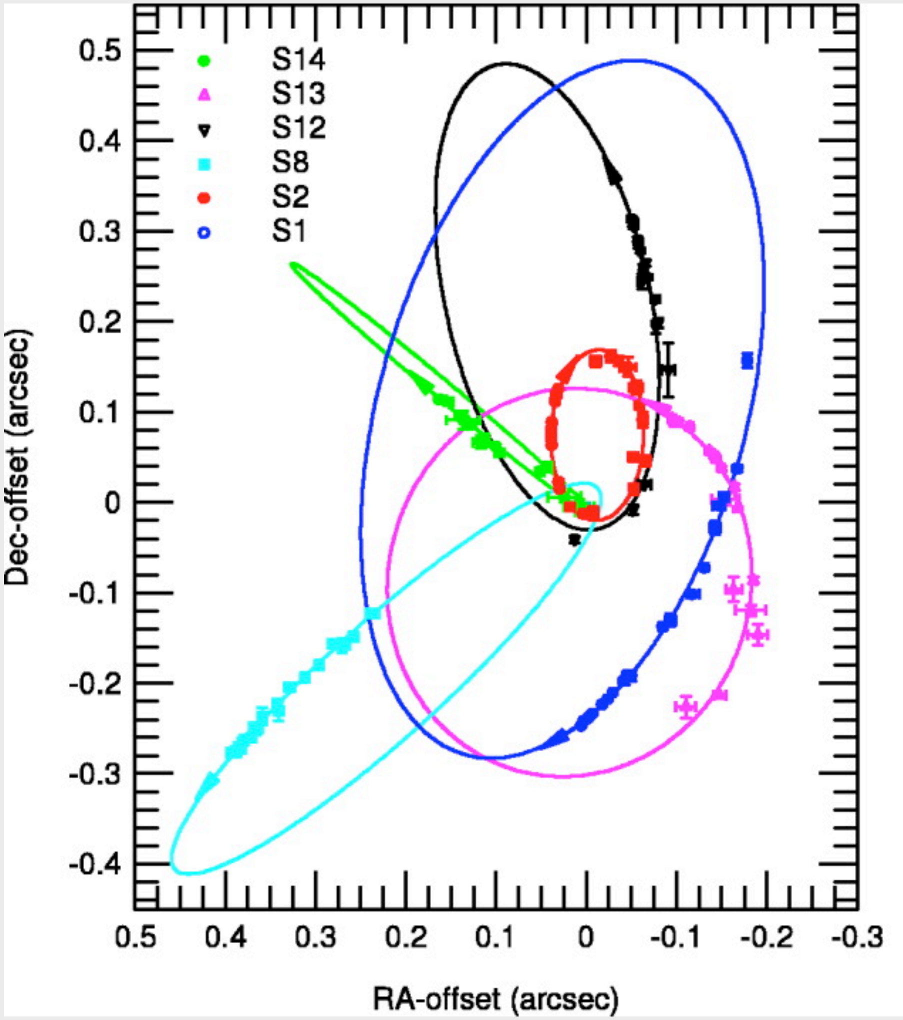
• smallest pericenter is only ~ 0.5 mpc ~ 3X distance to Neptune; and smallest orbital period is only 16 yr

• orbits are **closed** ellipses so central mass must be not bigger than 0.5 mpc

• $M = (3.95 \pm 0.06) \times 10^6\ M_\odot$ if distance $R_0 = 8000$ pc = 8 kpc

• $R_0 = 8.33 \pm 0.35$ kpc

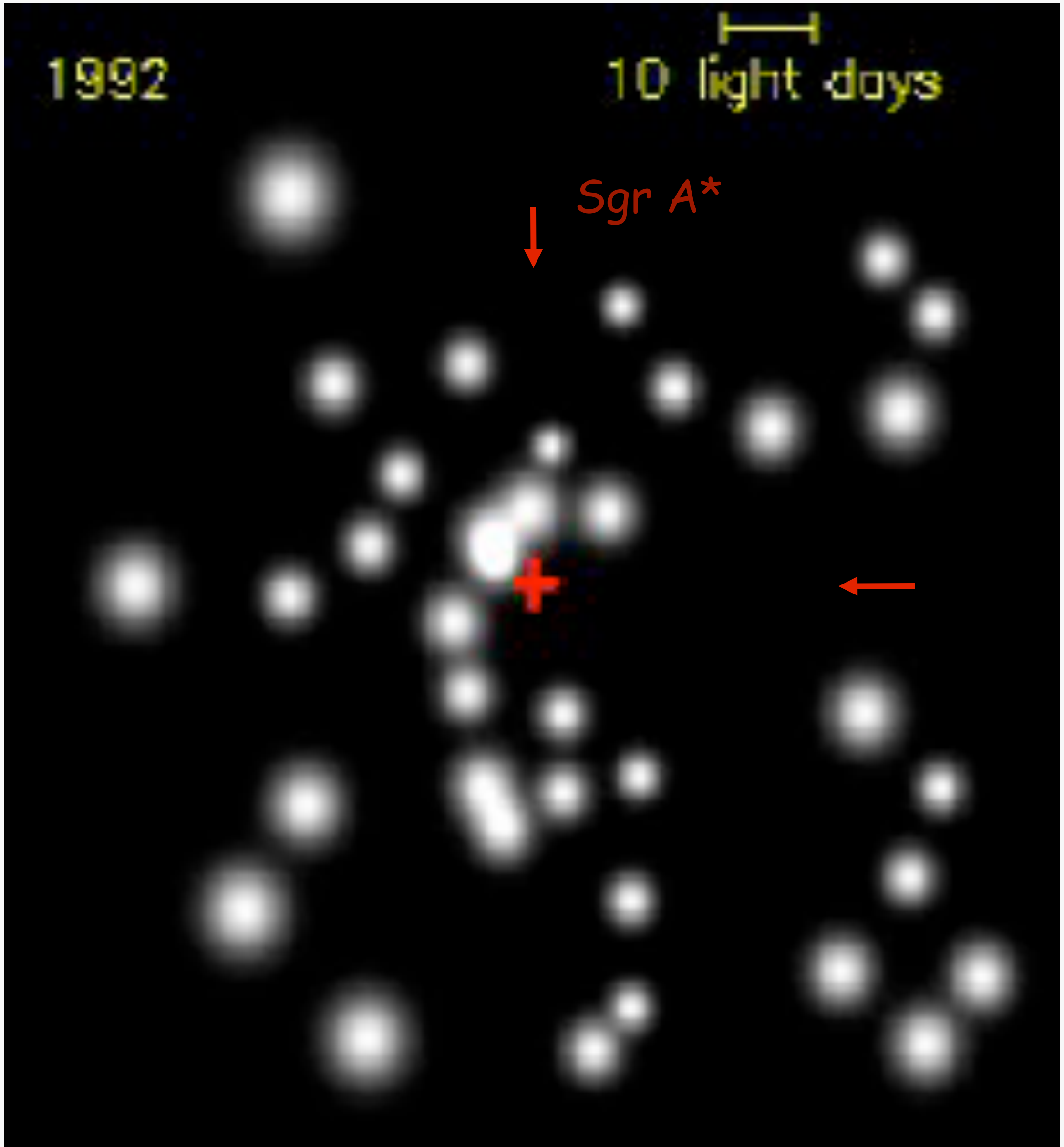
(Gillessen et al. 2009)



Sgr A*

1000 AU

- Galactic center contains $4{\times}10^6$ $M_\odot$ in < 0.5 mpc (3X distance to Neptune)
- event horizon for this mass is only 0.2 μpc (20% of Mercury's orbit)
- all plausible alternatives to a black hole have very short lifetimes (e.g., cluster of neutron stars)
- some implausible alternatives can survive:
    - cluster of 10^{10} Saturn-mass black holes
    - Bose-Einstein condensate of some unknown elementary particle



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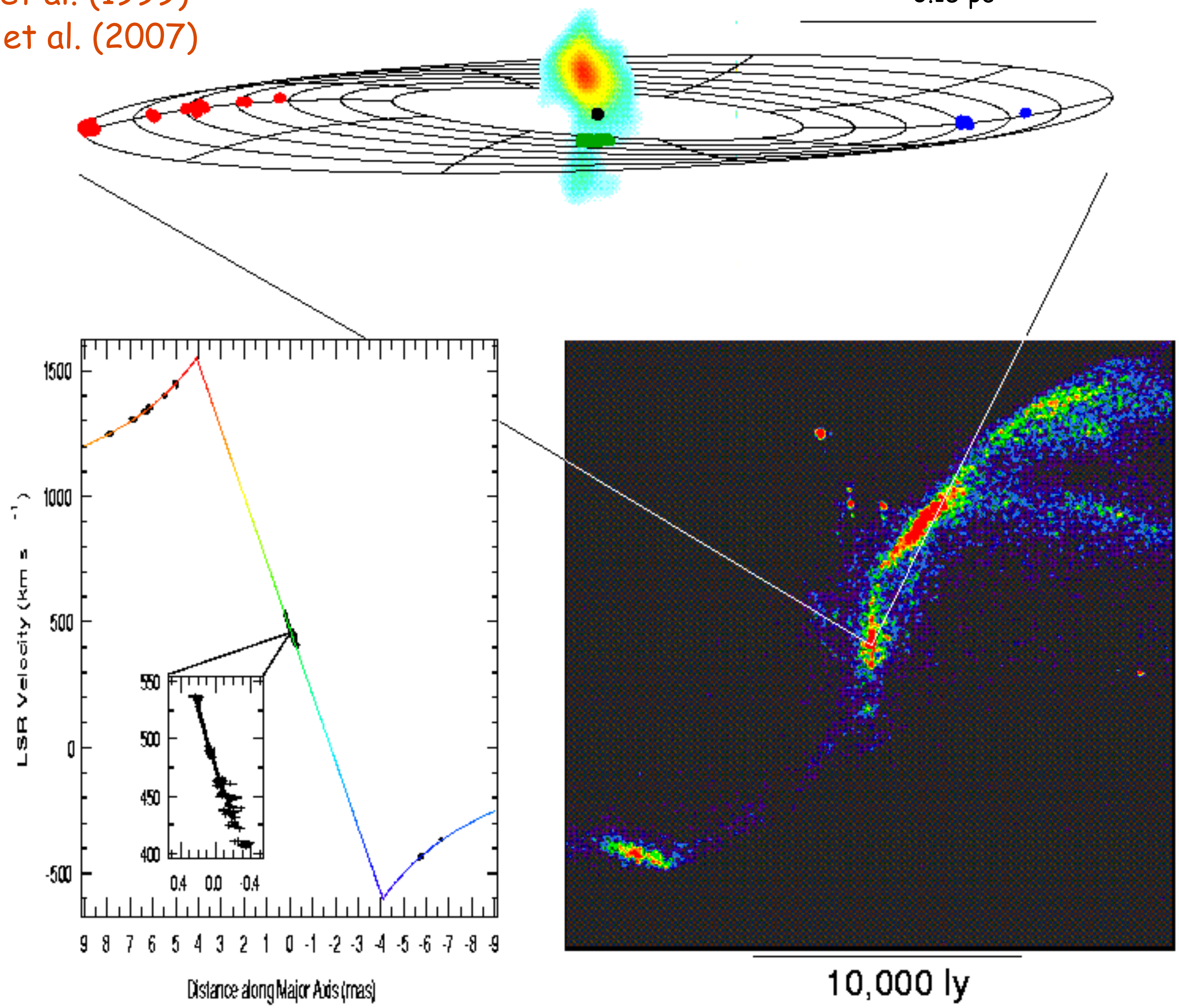
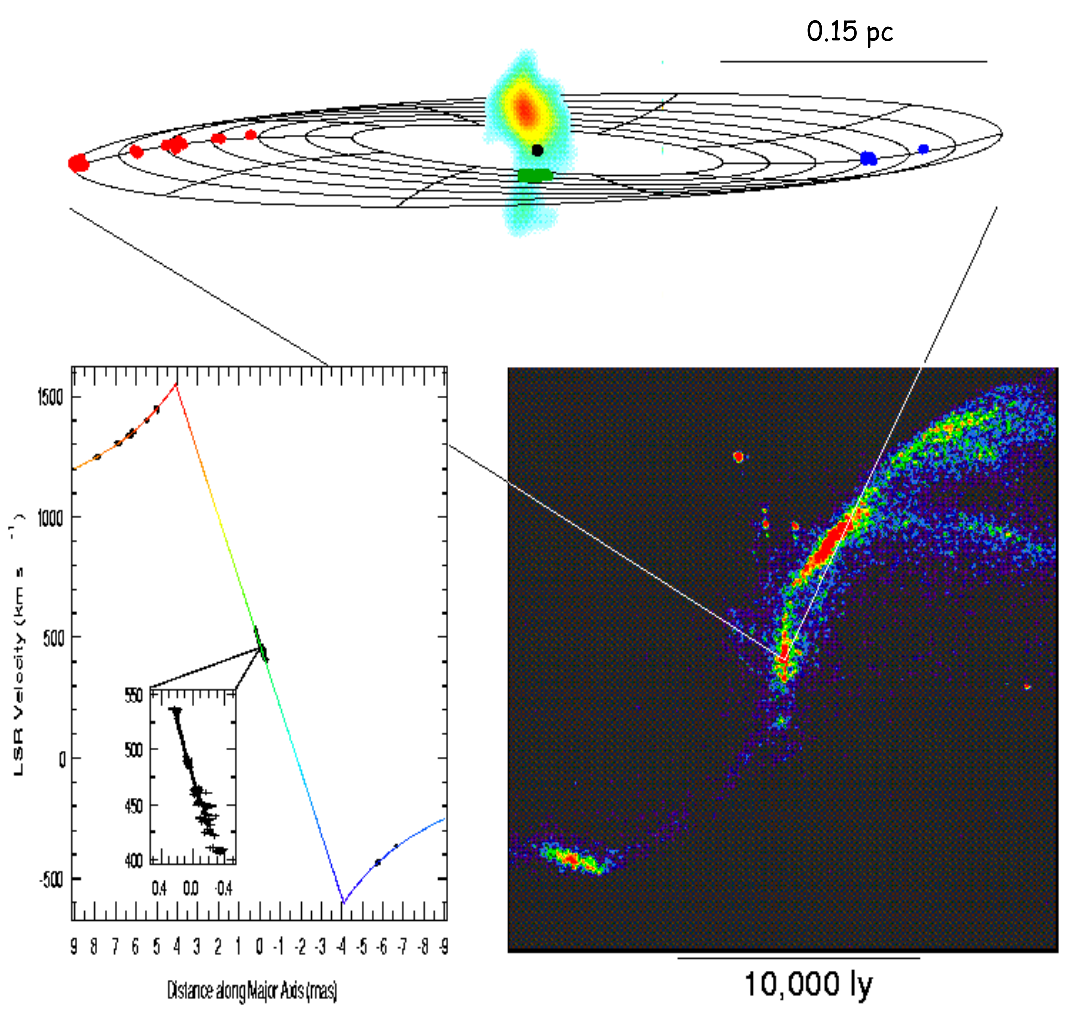
NGC 4258

Miyoshi et al. (1995)
Herrnstein et al. (1999)
Humphreys et al. (2007)

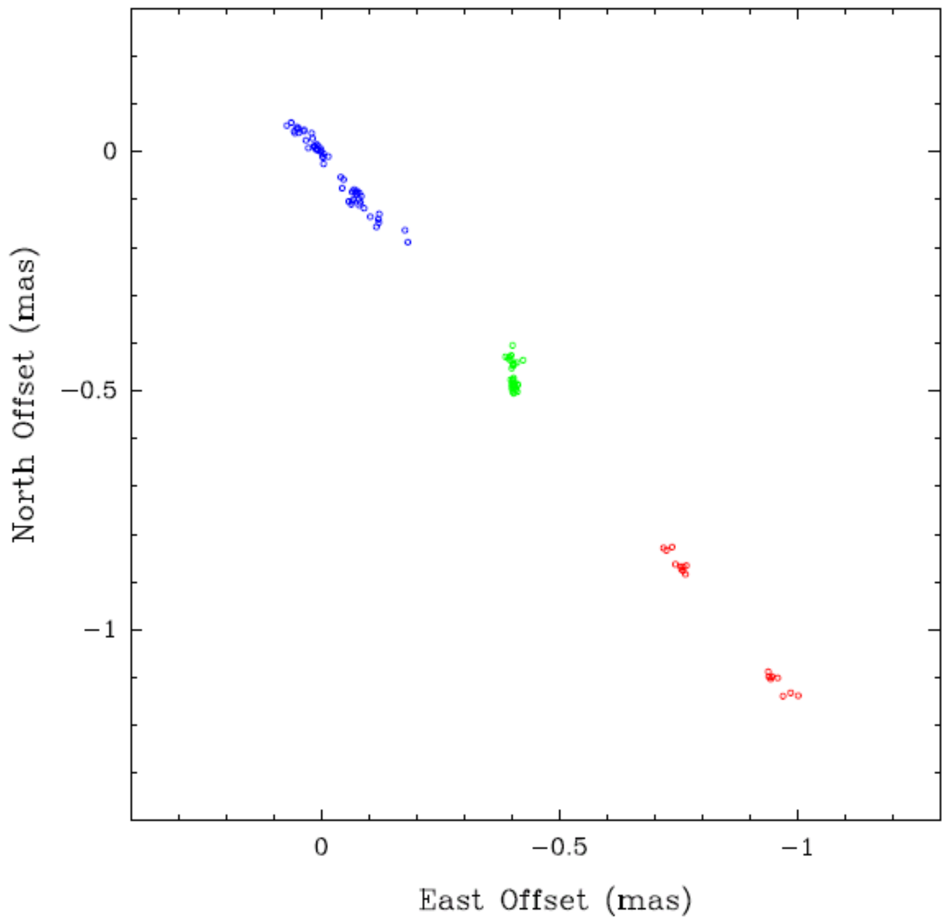


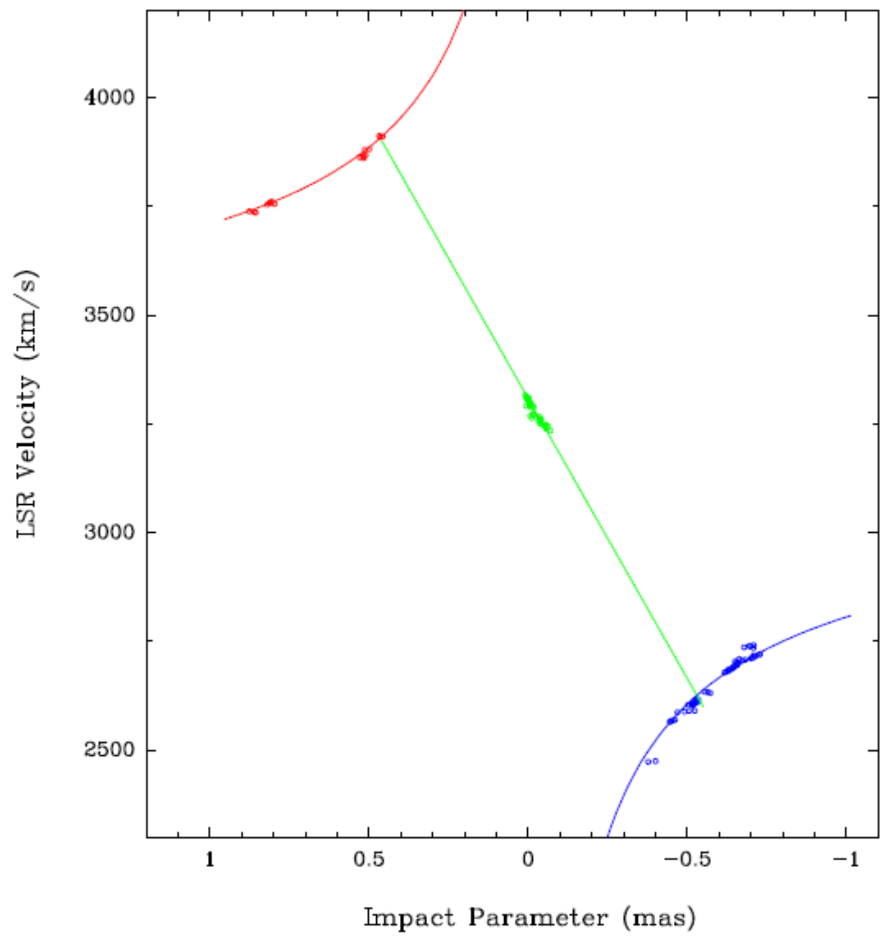
NGC 4258



- four observational data:
  - amplitude of Keplerian rotation curve
  - proper motion of systemic masers, 31.5±1 milliarcseconds/yr
  - acceleration of systemic masers, 9.3±0.3 km/s/yr
  - velocity versus distance for systemic masers
- three unknown parameters:
  - radius of systemic masers
  - distance of galaxy d
  - black-hole mass M
- $M=(3.9\pm0.1)\times10^7\ M_\odot$
- d=7.1±0.2 and 7.2±0.2 Mpc

UGC 3789


North Offset (mas)
East Offset (mas)
0
−0.5
−1
0
−0.5
−1


LSR Velocity (km/s)
Impact Parameter (mas)
4000
3500
3000
2500
1
0.5
0
−0.5
−1

finding black holes in "normal" nearby galaxies

• measure optical spectrum of light from the galaxy at a given position
• if typical star as a spectrum $F^*(\lambda)$ and the number of stars as a function of line-of-sight velocity is $n(v)dv$, the actual spectrum will be

$$F(\lambda) = \int F^*(\lambda - v/c)n(v)dv$$

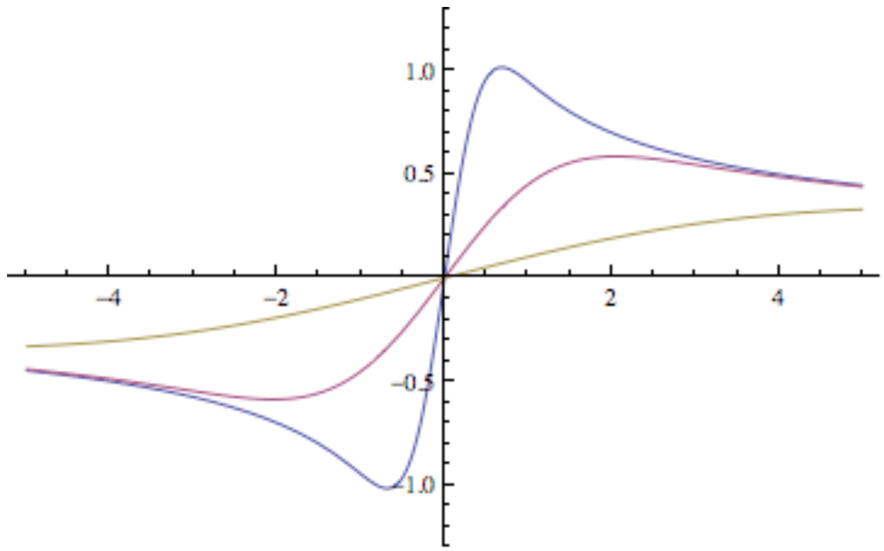
• knowing F and F* gives n(v) -- parametrize by mean velocity $\langle v \rangle$ and dispersion σ
• central black hole of mass M influences kinematics only inside a radius r such that

$$GM/r > \max[\sigma^2, \langle v \rangle^2] \quad \text{"sphere of influence"}$$

• crucial problem is to resolve the sphere of influence -- number of galaxies in which a black hole can be detected varies as FWHM^3 where FWHM is full-width half-maximum of telescope point-spread function
    • typical ground-based telescope at excellent site FWHM = 0.5-1″
    • Hubble Space Telescope FWHM = 0.08″
    • 8-meter ground-based telescope with adaptive optics FWHM = 0.1″

finding black holes in “normal” nearby galaxies

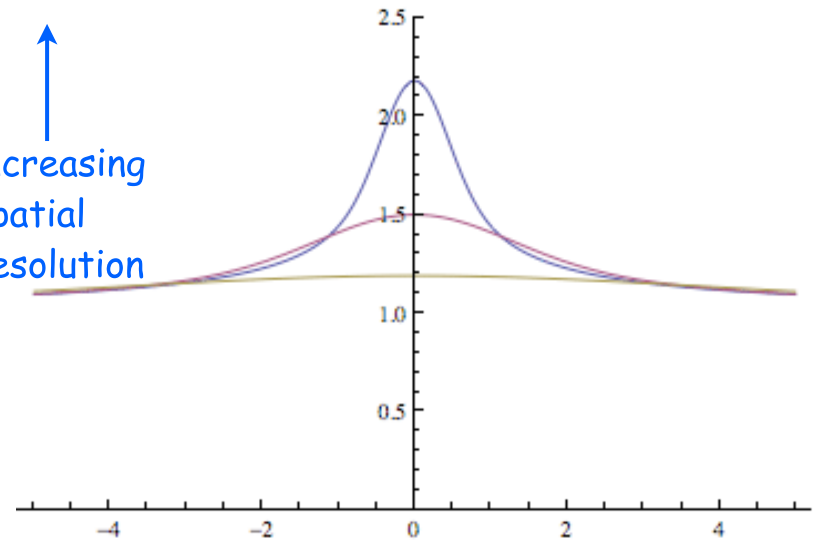
rotation profile



sphere of influence

increasing spatial resolution

velocity dispersion profile

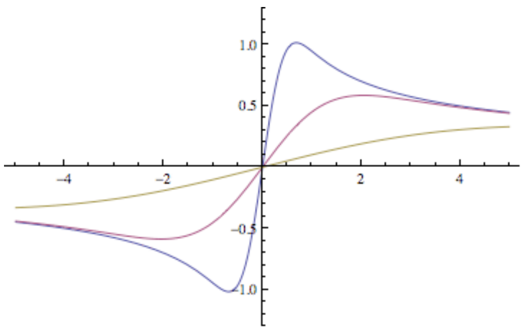


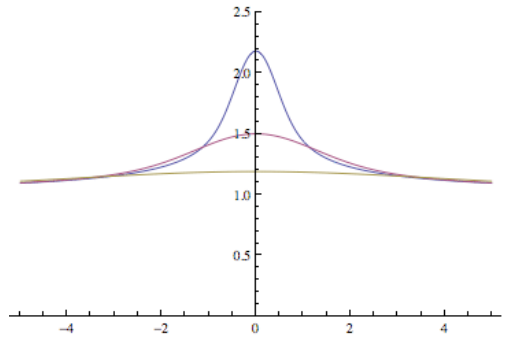
sphere of influence

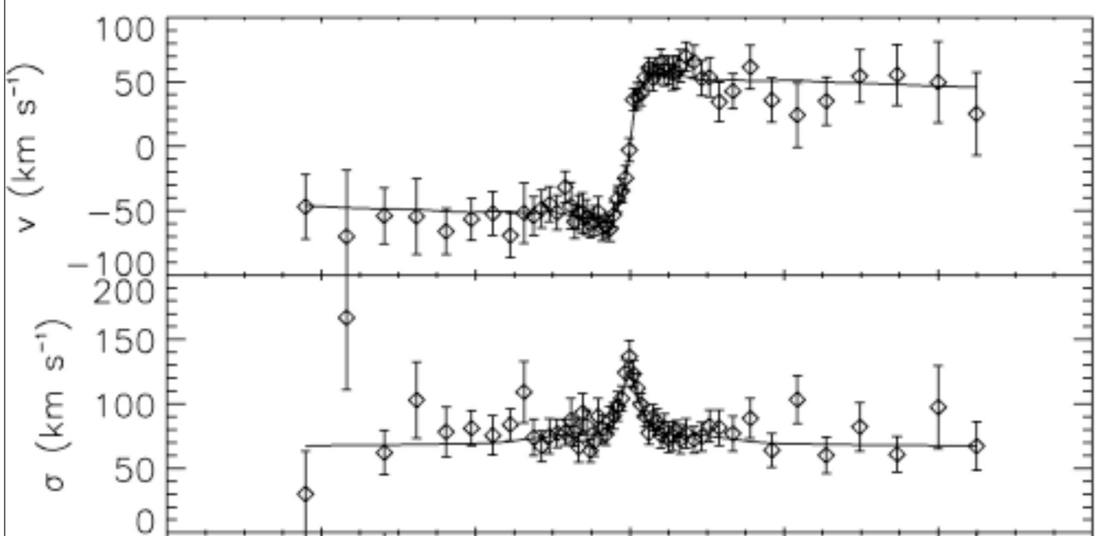
G=M=1, asymptotic velocity dispersion = 1

Gaussian point-spread function with dispersions = 0.3,1,3

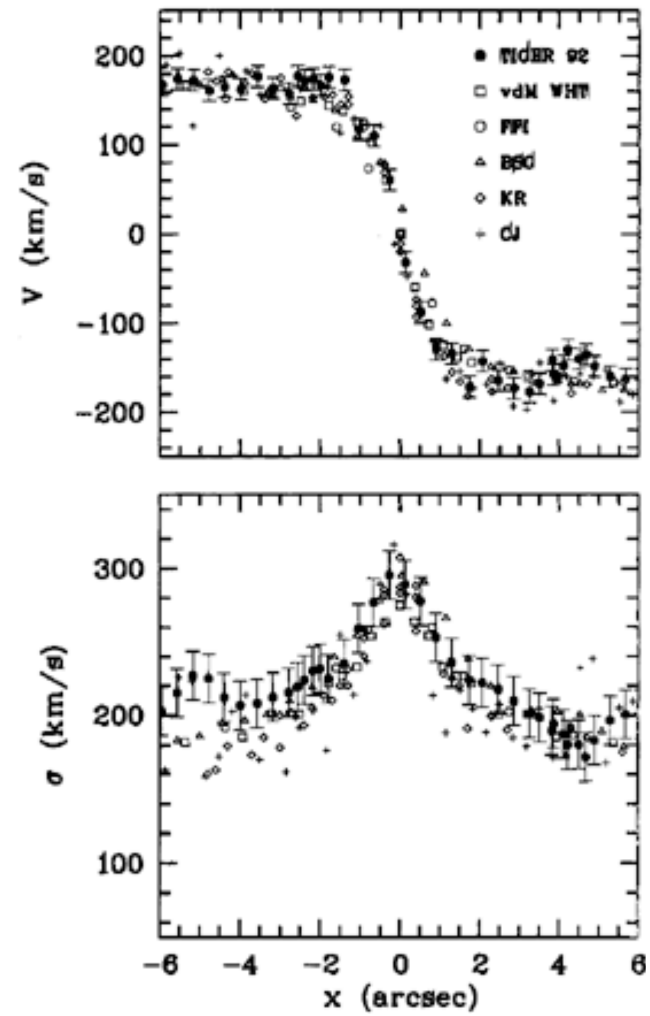
finding black holes in “normal” nearby galaxies



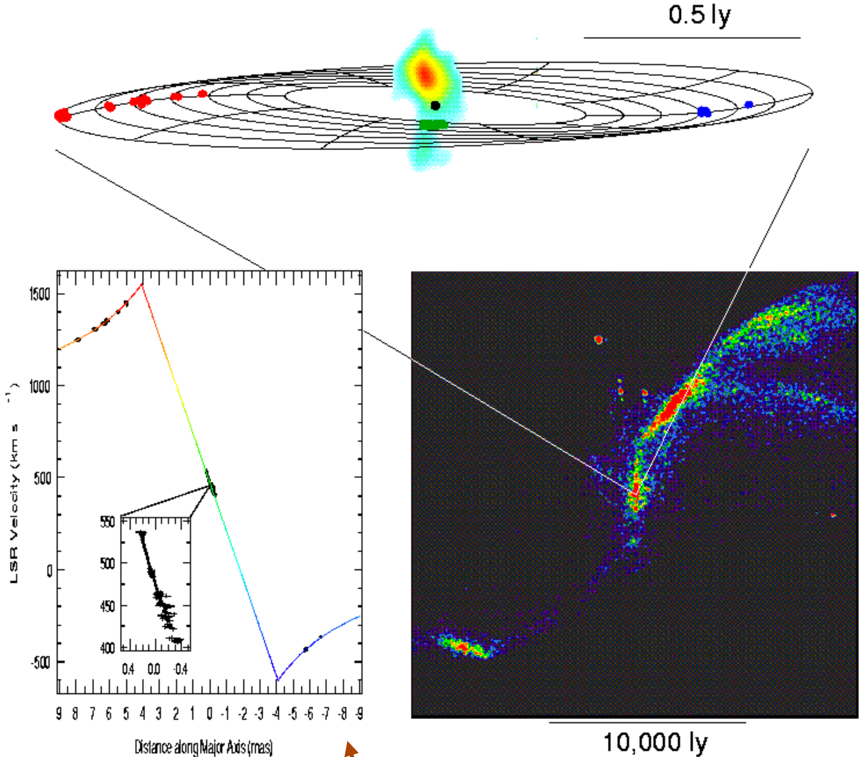


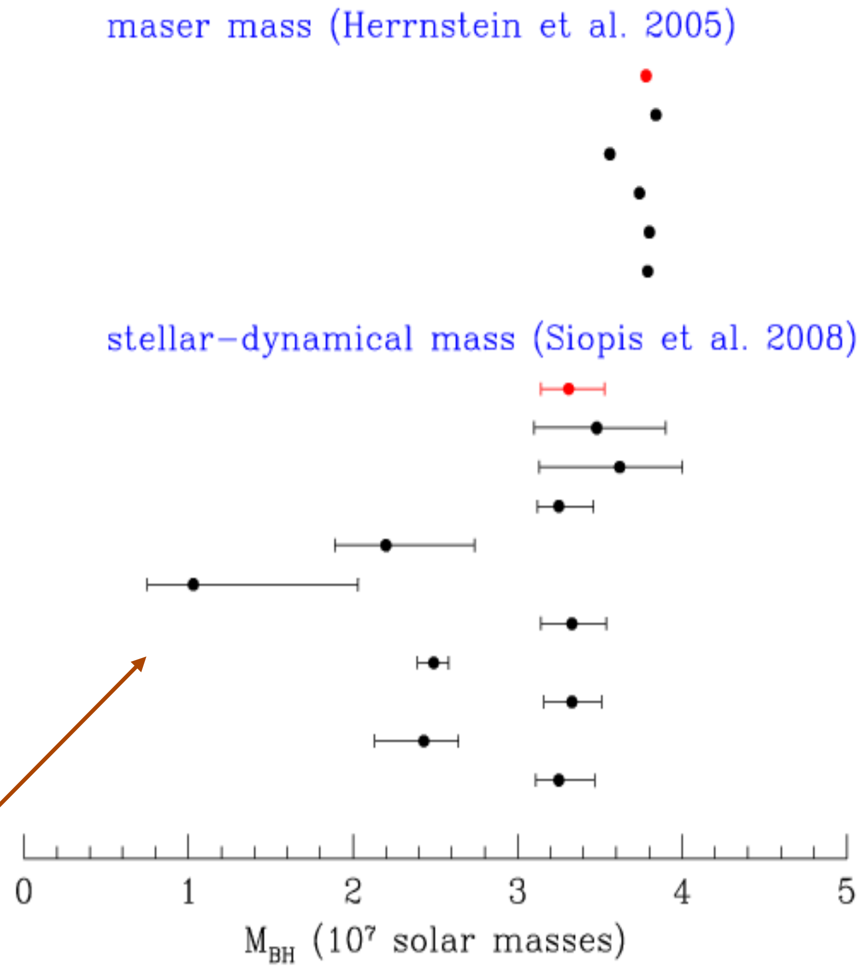


M32 (Verolme et al. 2002)



NGC 3115 (Emsellem et al. 1999)



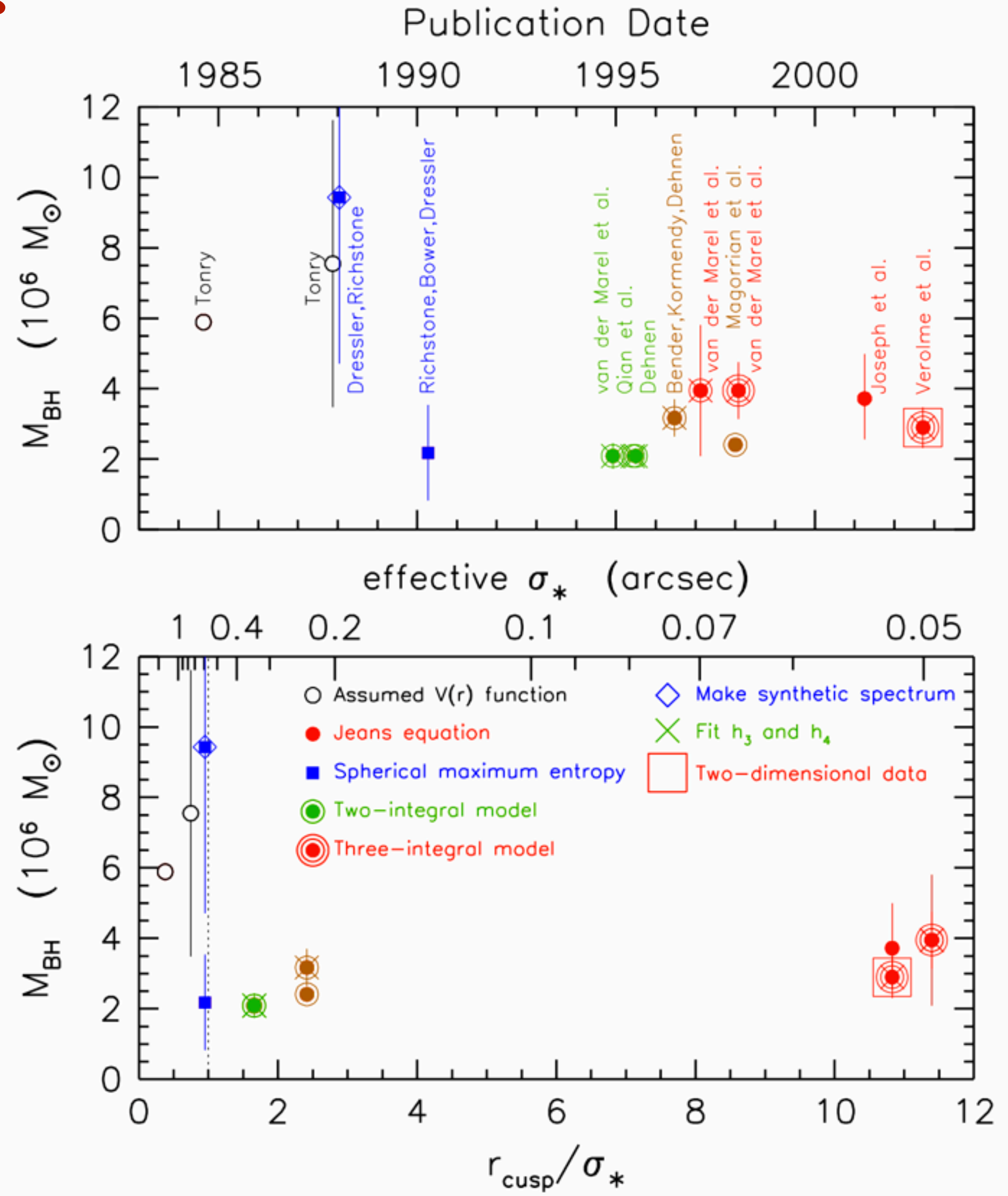


maser mass: $(3.82 \pm 0.01) \times 10^7\ M_\odot$

mass from stellar dynamics: $(3.2 \pm 0.2) \times 10^7\ M_\odot$

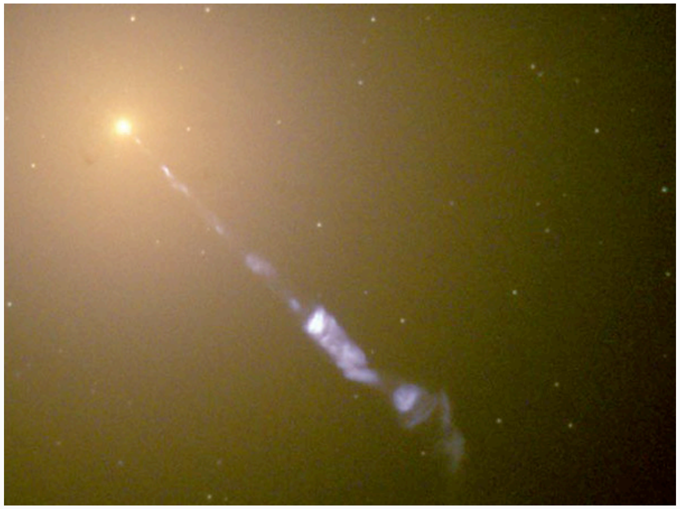
(Siopis et al 2009)

the history of BH mass determinations in M32

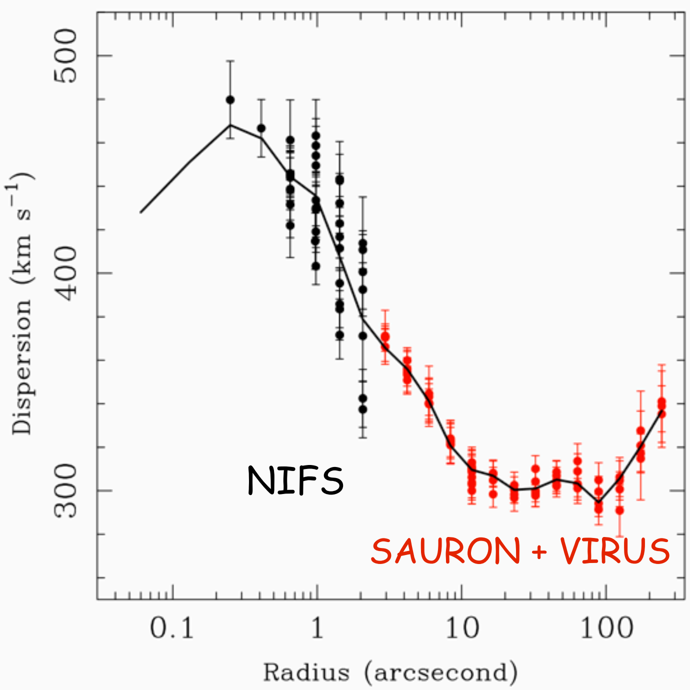


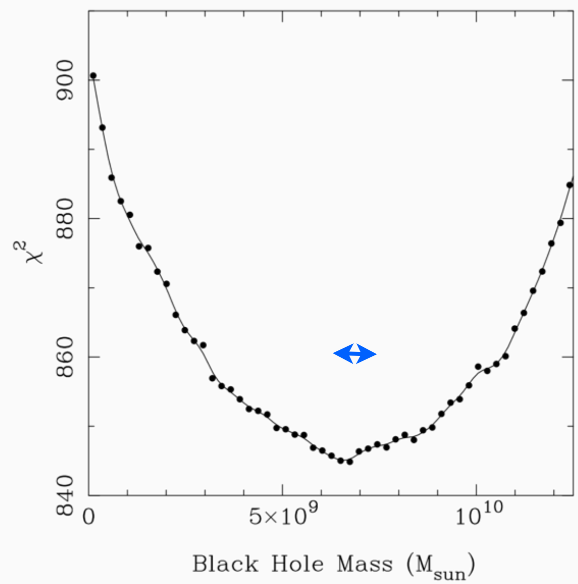
Kormendy (2004)

The history of the black hole in M87



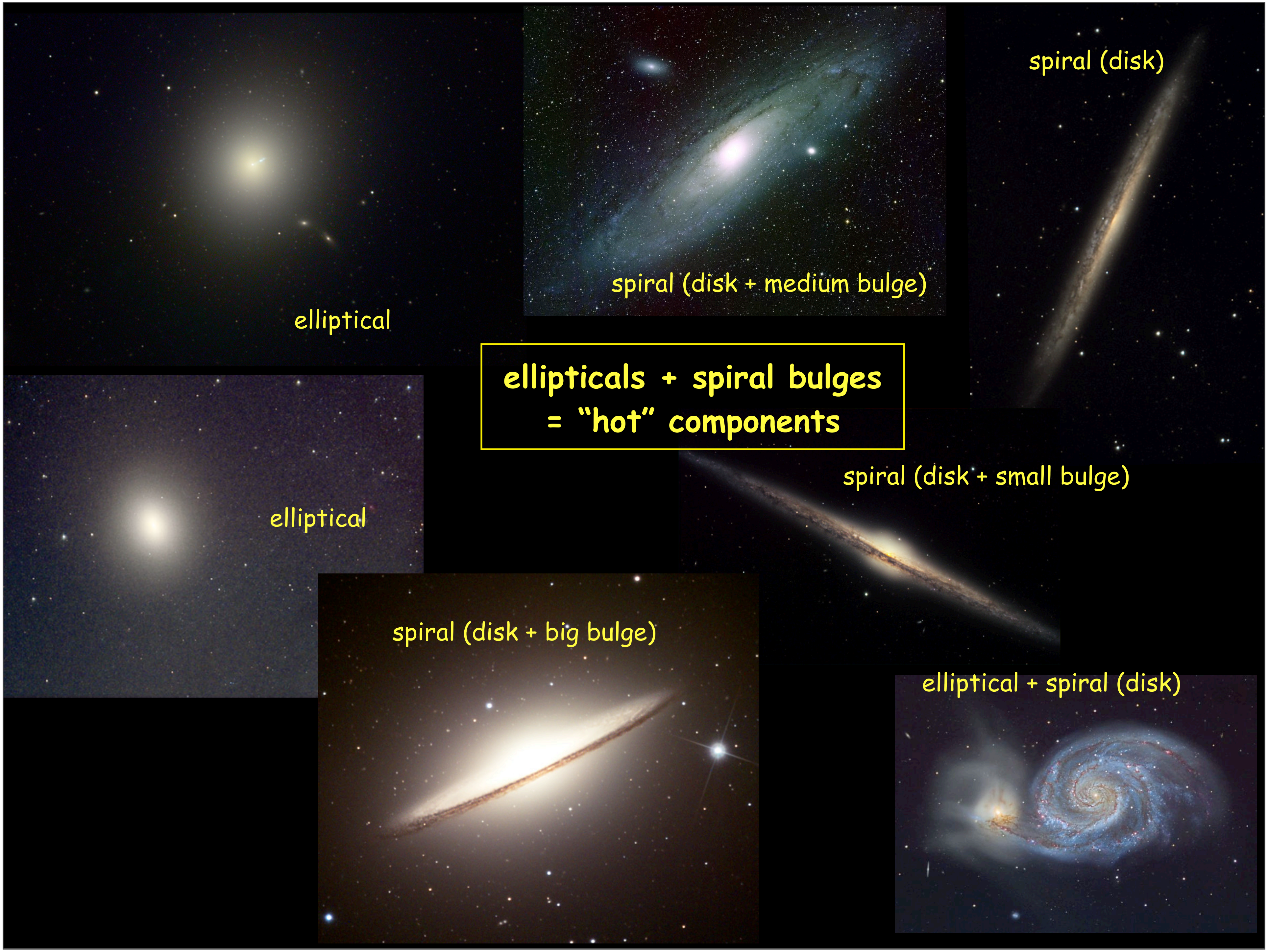
- Sargent et al. (1978): **~ 5 × 10^9 $M_\odot$** (ground-based, stars)
- Harms et al. (1994): **(2.4±0.7) × 10^9 $M_\odot$** (HST, gas)
- Macchetto et al. (1997) **(3.2±0.9)×10^9 $M_\odot$** (HST, gas)
- Gebhardt & Thomas (2009), Gebhardt et al. (2010): **(5.5±0.4) × 10^9 $M_\odot$** (ground-based adaptive optics, stars)
  - near IR integral-field spectrograph (NIFS) on Gemini + SAURON to 10"+ VIRUS to 250"
  - FWHM for kinematics is 0.16"

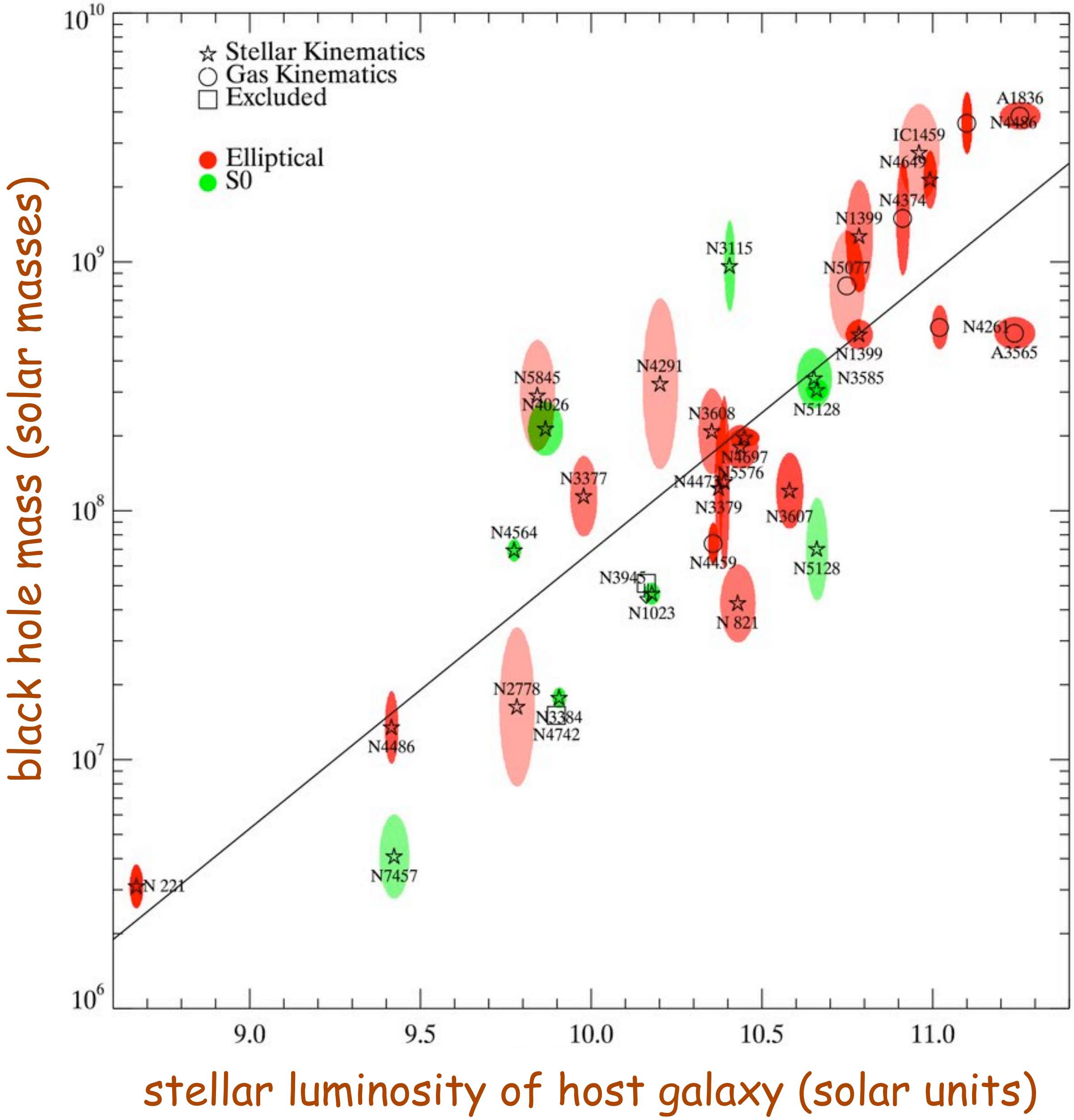




3. The relation between black holes and their host galaxies


elliptical
spiral (disk + medium bulge)
spiral (disk)
elliptical
spiral (disk + small bulge)
spiral (disk + big bulge)
elliptical + spiral (disk)


elliptical
spiral (disk + medium bulge)
spiral (disk)
ellipticals + spiral bulges
= "hot" components
elliptical
spiral (disk + small bulge)
spiral (disk + big bulge)
elliptical + spiral (disk)

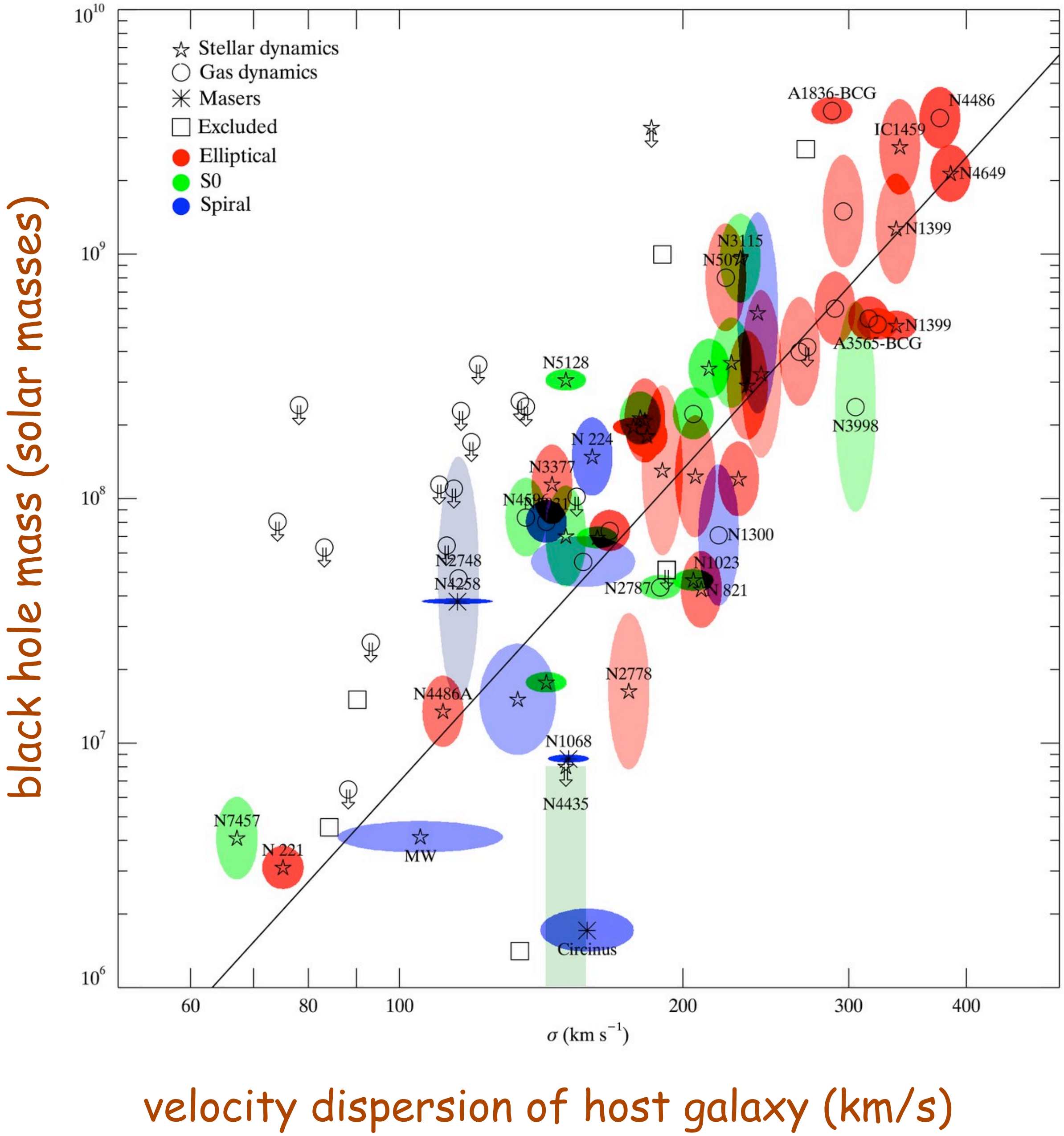


- by now there are ~40-50 detections of a massive dark object in nearby galaxies, 10^6-10^9 $M_\odot$
- mass determinations from
  - stellar dynamics
  - gas dynamics
  - maser disks
- black-hole mass correlates with luminosity of hot component; roughly

$$M \propto L$$

- in terms of stellar mass $M \approx 0.002\, M_{stars}$

Gültekin et al (2009)



- tighter correlation is with velocity dispersion σ of hot component of host galaxy; roughly

$$M \propto \sigma^4$$

with scatter of 0.3 in $\log_{10} M$ for elliptical galaxies

- almost all hot components contain black holes

Gültekin et al. (2009,2011)

Are the black holes in nearby galaxies dead quasars?

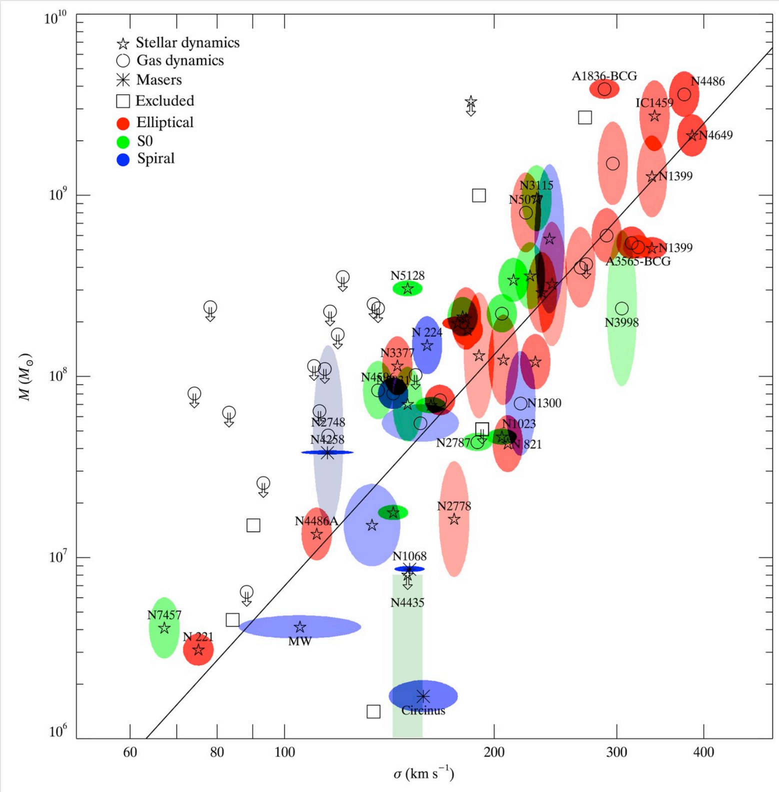
- masses of central black holes in nearby galaxies are about 0.2% of the stellar mass in hot component
- knowing the average density of galaxies we can estimate the average density in black holes,

$$\rho_{BH} = 3 \times 10^5\ M_\odot\ \mathrm{Mpc}^{-3}$$

- we know the local energy density in quasar photons. Expected density of quasar ash is

$$\rho_{QSO} = 3 \times 10^5\ M_\odot\ (\varepsilon/0.1)\ \mathrm{Mpc}^{-3}$$

(Soltan 1982)

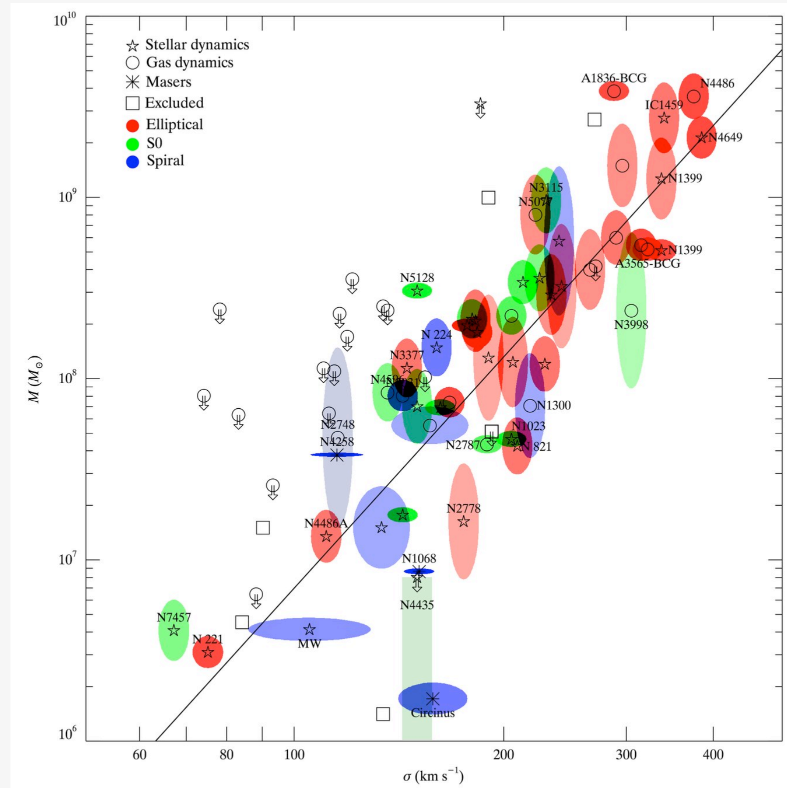


Origin of the M-σ relation

- masses of central black holes in nearby galaxies are only about 0.2% of the stellar mass in hot component
- however, energy released in forming the black hole is much larger than energy released in forming the galaxy

$$\frac{M_{\rm BH}c^2}{M_{\rm galaxy}\sigma^2} \approx 5000 \left(\frac{200\,{\rm km\ s^{-1}}}{\sigma} \right)^2$$

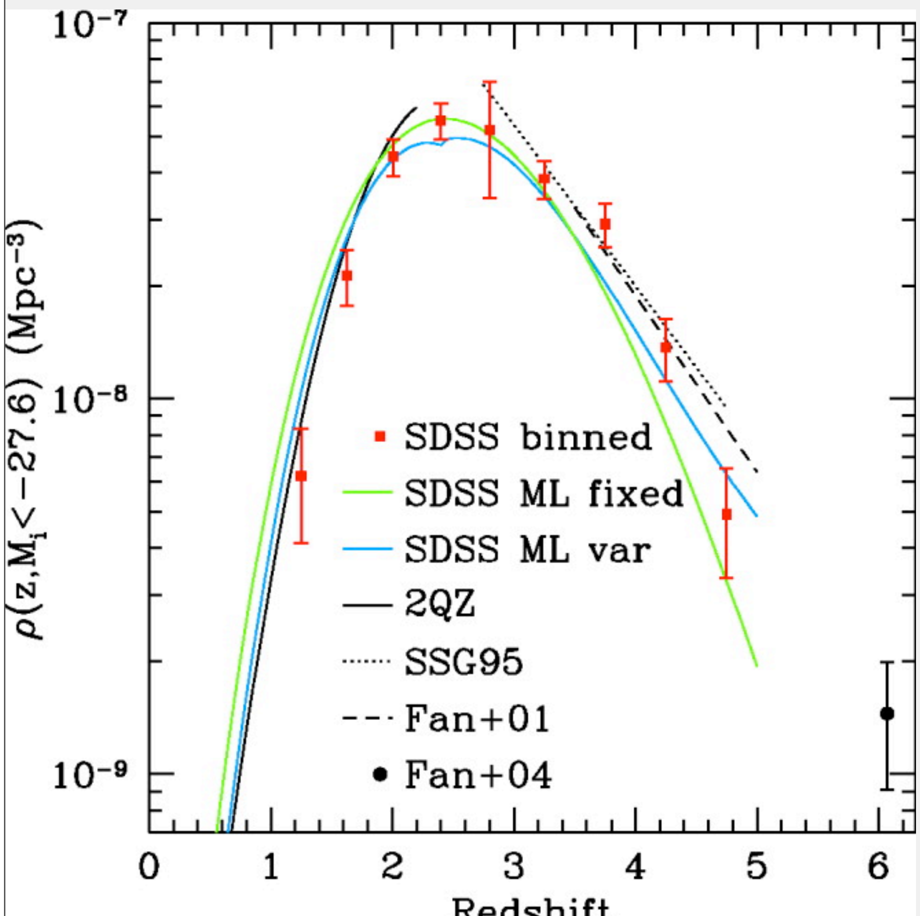
- black hole dominates the energy budget of the galaxy if even 0.1% of energy release is absorbed by the galaxy (“feedback”)



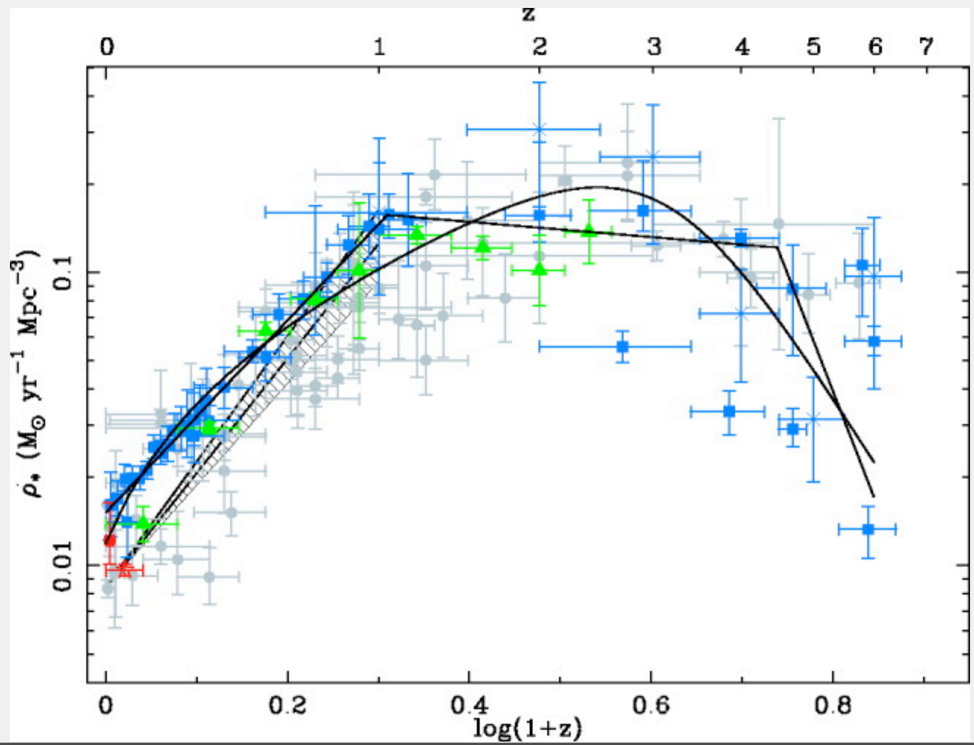
Circumstantial evidence for feedback

- AGNs were most active at about the time galaxies were forming

AGN luminosity density



star formation rate
(Hopkins & Beacom 2006)



Circumstantial evidence for feedback

- AGNs were most active at about the time galaxies were forming
- blue-shifted X-ray absorption lines seen in some quasars suggest strong winds (e.g., Reeves et al. 2003)
- bimodal color distribution of galaxies seems to require expulsion of cold gas after mergers (Springel et al. 2005)
- central cooling times in some clusters of galaxies are short but there is no evidence of cool gas, suggesting that AGN heating balances radiative cooling
  - AGNs found in most clusters with short cooling times
  - bubbles of hot gas

Circumstantial evidence for feedback

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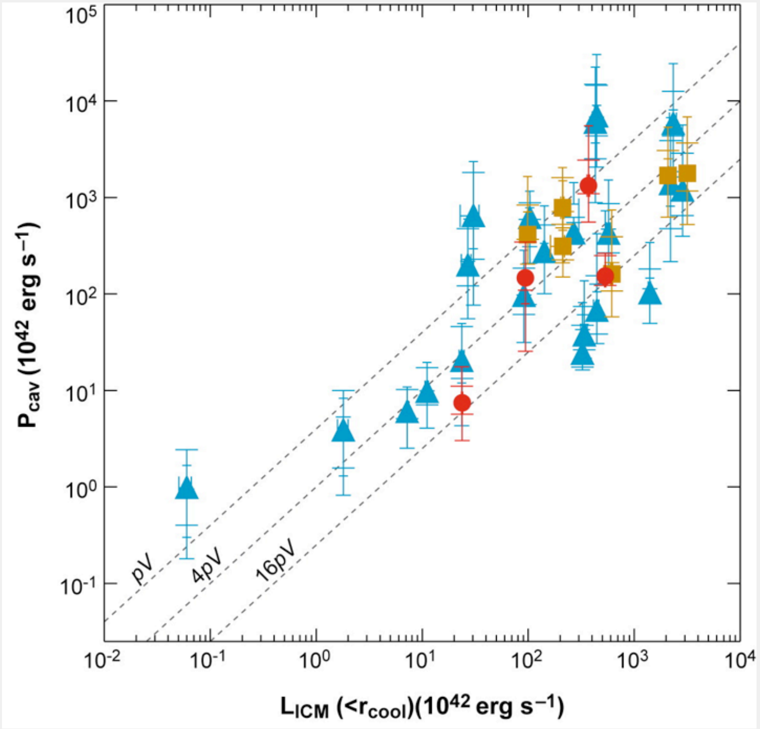
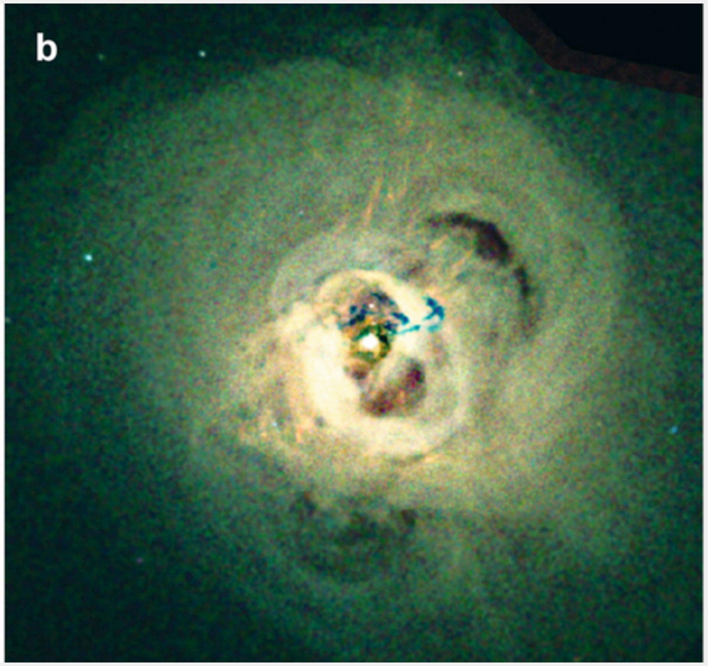
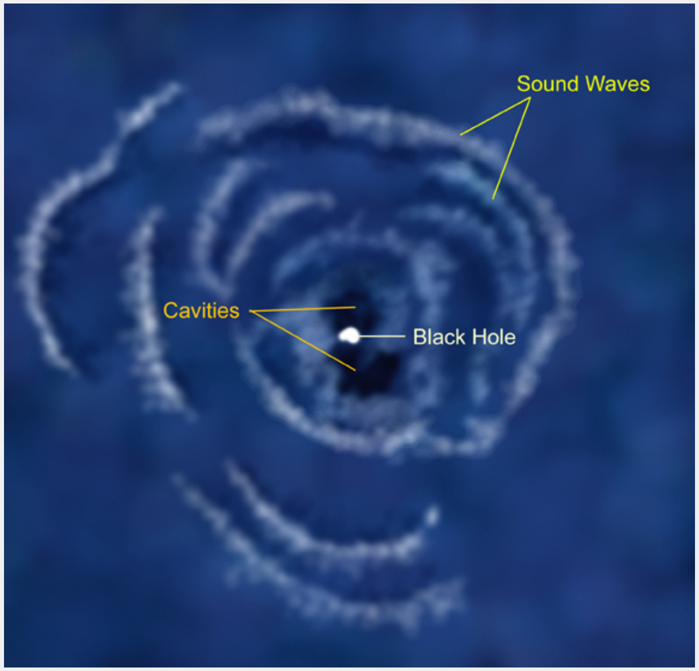






McNamara & Nulsen (2007)

A toy model for feedback

Natural upper limit to black-hole luminosity is the Eddington luminosity

$$L_{\rm Edd} = \frac{4\pi G M_{\rm BH} c}{\kappa_T}$$

where κ_T is the Thomson scattering opacity.

If galaxy is optically thick to dust, the dust and gas absorb momentum at a rate L_{Edd}/c

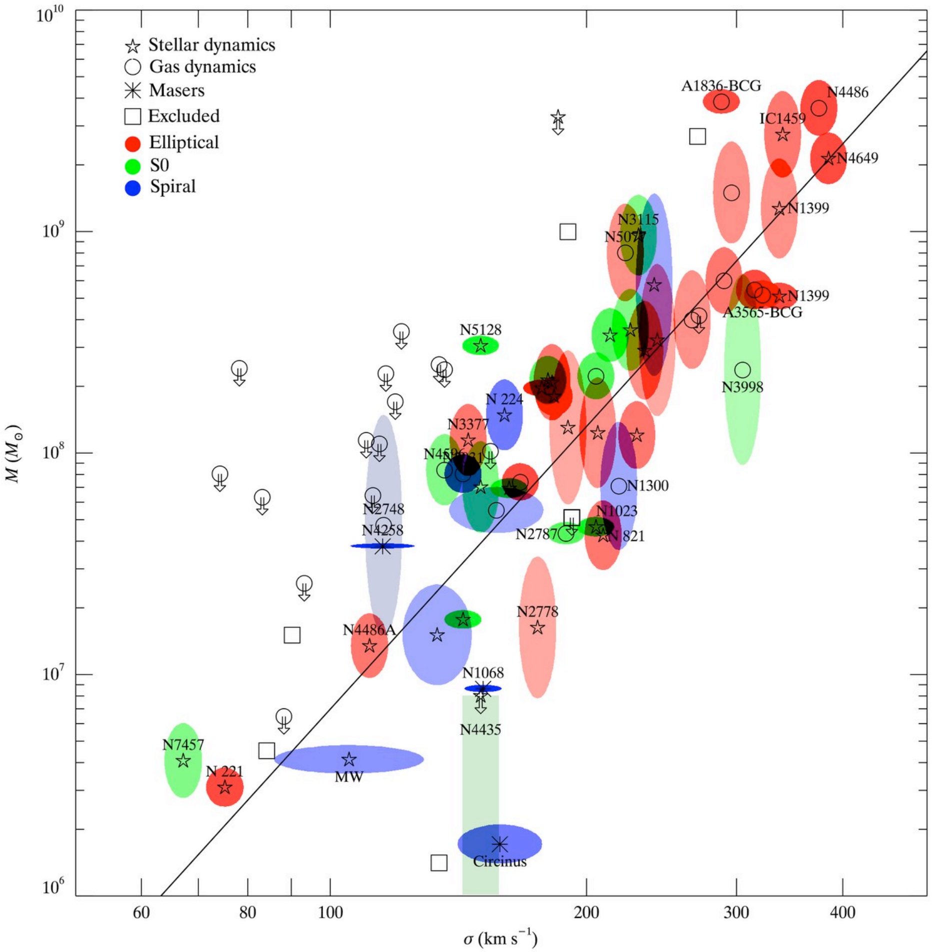
Gravitational force from stars on gas is $GM^* M_{gas}/R^2$

where M_{gas} = f M* with f~0.1 and galaxy mass M^* and radius R are related to dispersion by $\sigma^2 \sim 0.2GM^*/R$. Then gas is blown out if

$$M_{\rm BH} > \frac{f\kappa}{4\pi(0.2)^2 G^2}\sigma^4 \simeq 1\times10^9 M_\odot \frac{f}{0.1}\left(\frac{\sigma}{200\,{\rm km\ s^{-1}}}\right)^4$$

(Silk & Rees 1998, Fabian 1999, King 2003, Murray et al. 2005)

A toy model for feedback



Natural up ... dington luminosity

where κ_T is ...

If galaxy i... absorb momentum at a rate L_{Edd}/c...

Gravitation...

where M_{gas} ... radius R are related to dispersion

$$\ldots \left(\frac{\sigma}{\mathrm{km\ s^{-1}}}\right)^4$$

(Silk & Rees 1998, Fabian 1999, King 2003, Murray et al. 2005)

A toy model for feedback

Natural up … dington luminosity

where κ_T is

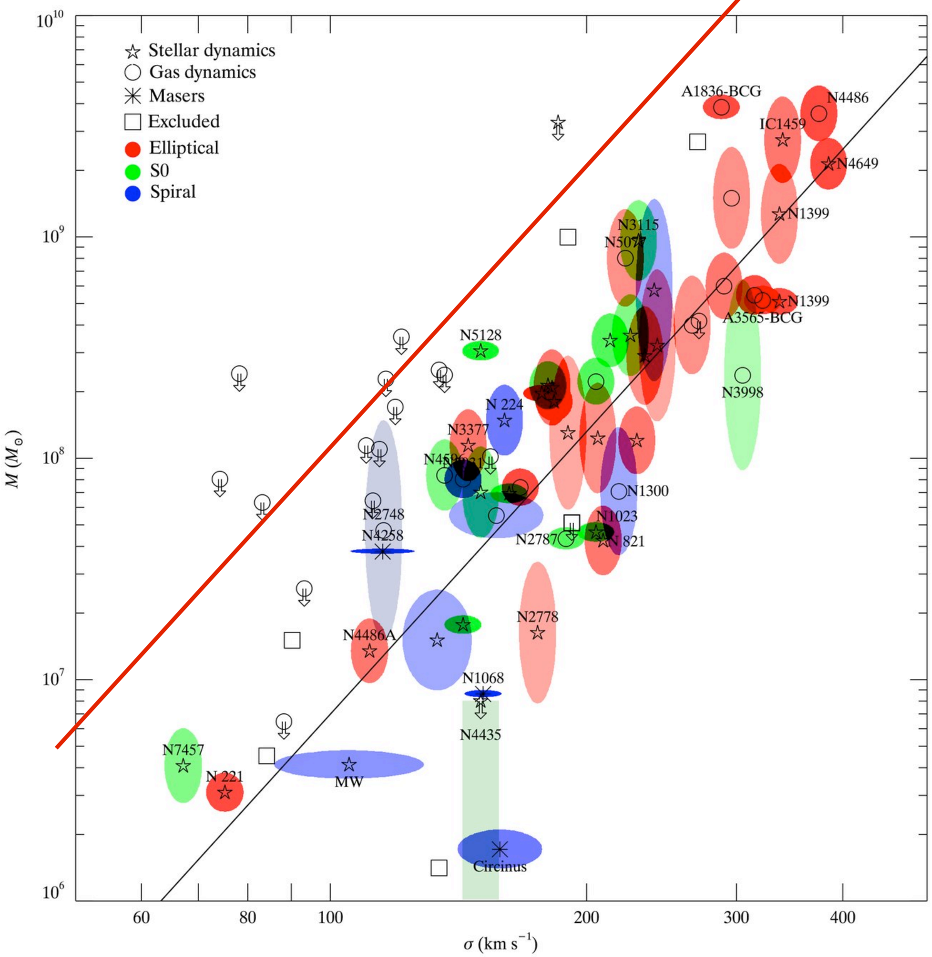
If galaxy i… absorb momentum at a

rate L_{Edd}/c

Gravitation

where M_{gas} … radius R are related to

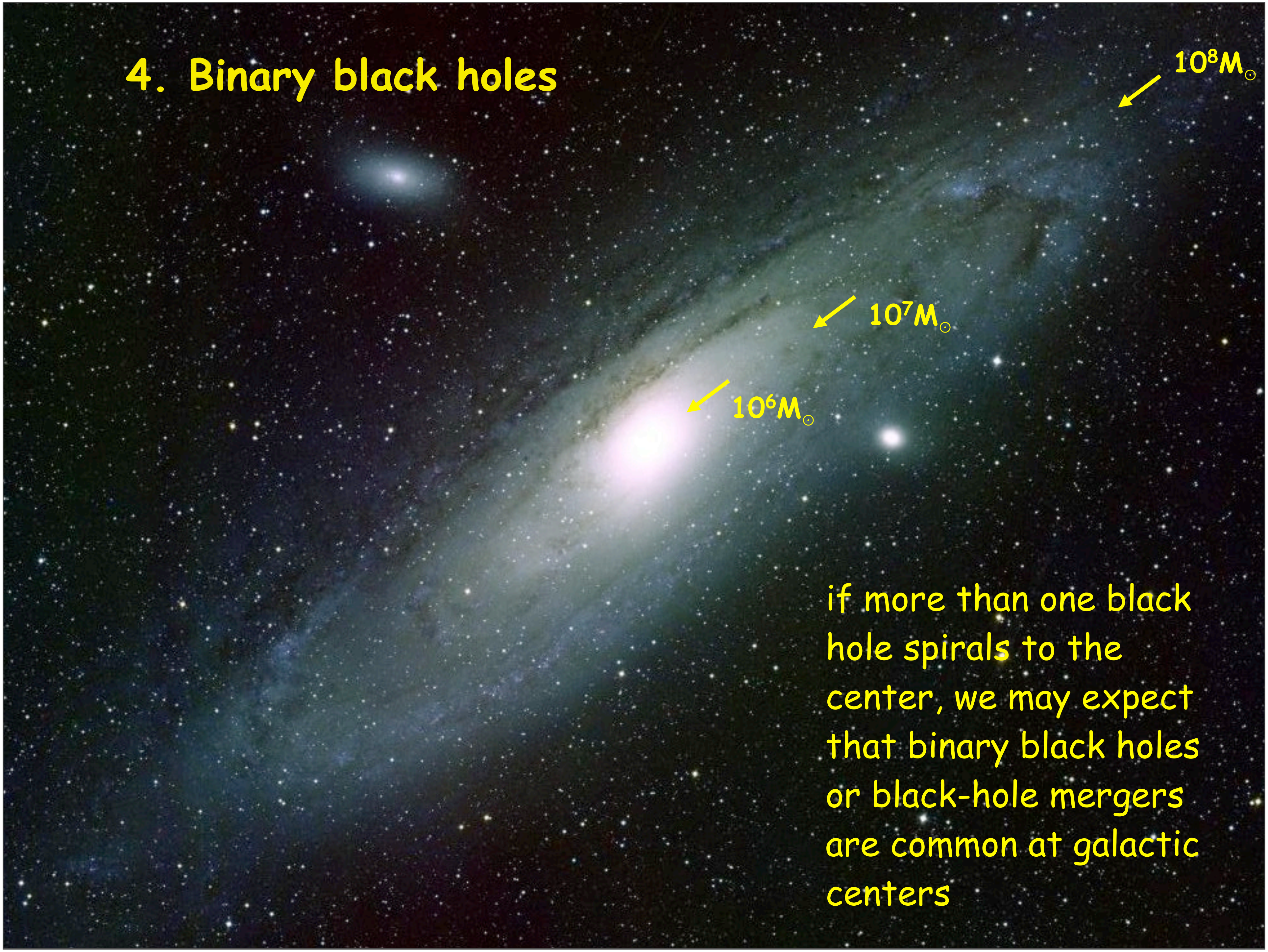
dispersion



$$\ldots \left(\frac{\sigma}{\mathrm{km\ s^{-1}}}\right)^4$$

(Silk & Rees 1998, Fabian 1999, King 2003, Murray et al. 2005)

4. Binary black holes



if more than one black hole spirals to the center, we may expect that binary black holes or black-hole mergers are common at galactic centers

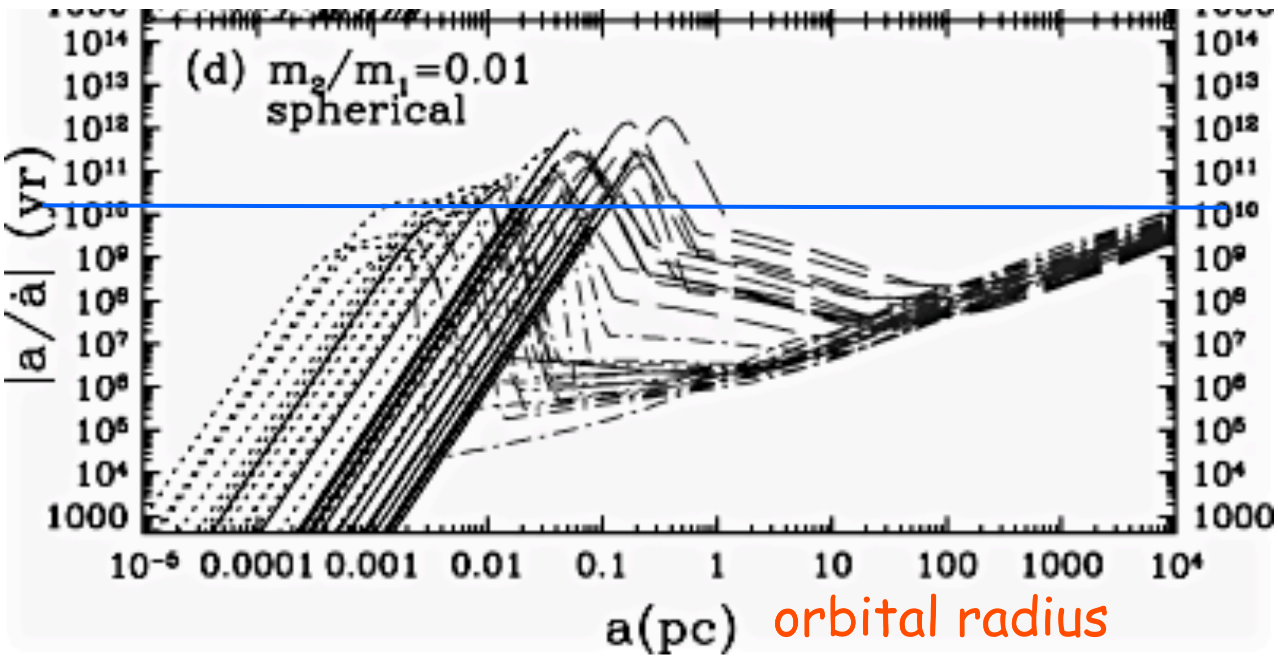
The bottleneck radius

- dynamical friction becomes more and more effective as the secondary black hole spirals from ~ 30 kpc to ~ 10 pc
- dynamical friction becomes less and less effective as the secondary black hole spirals from ~ 10 pc inwards
  - once the black holes form a bound binary, the orbital velocity grows as $v \sim r^{-\frac{1}{2}}$, and friction timescale grows as v^3
  - mass of black hole can exceed the mass of all the stars that can interact with it
- gravitational radiation becomes more and more effective at even smaller radii
- leads to a bottleneck at 10 pc - 1 mpc
- decay times at the bottleneck are generally larger than the Hubble time (Begelman, Blandford & Rees 1980)

gravitational radiation ⟷ dynamical friction

bottleneck radius

binary ⟷ unbound



Hubble time

orbital radius

estimates of decay timescales for ~30 nearby galaxies using BH masses from the M-σ relation (Yu 2002)

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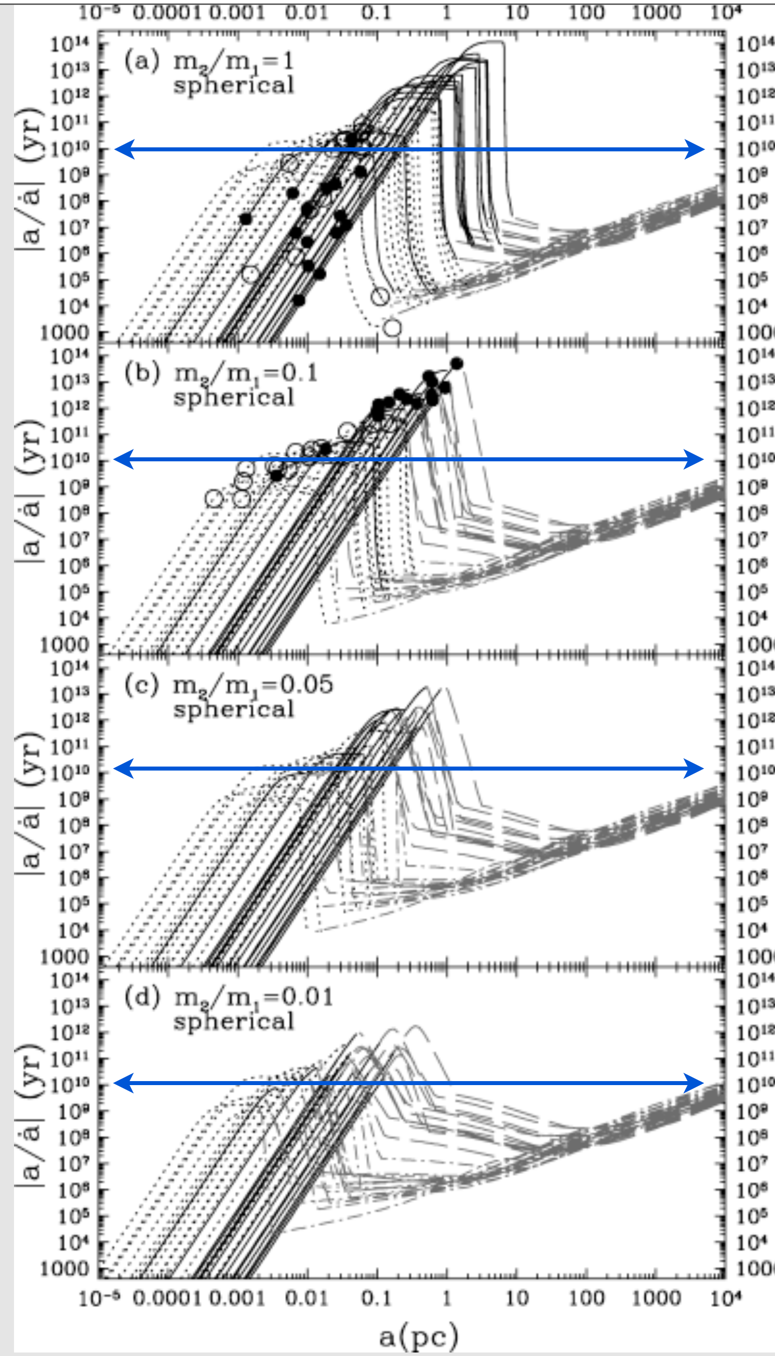
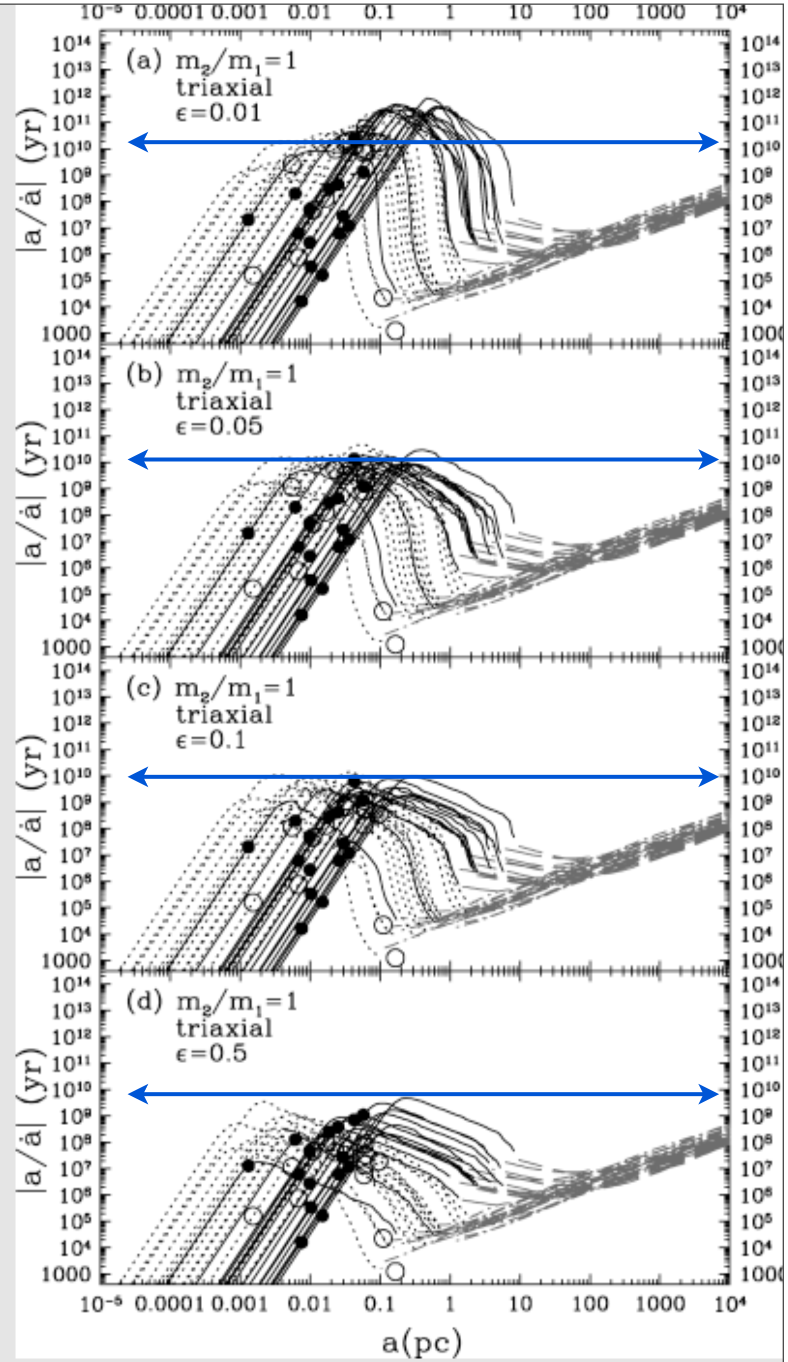


spherical galaxies, varying mass ratios (Yu 2002)

The final parsec problem: decay times at the bottleneck are generally larger than the Hubble time (Begelman, Blandford & Rees 1980)

Ways around the problem:

- oblate or triaxial galaxies produce torques that can bring in fresh stars to interact with the black-hole binary
- gas drag or migration due to interactions with a massive disk
- gravitational interactions with additional merging black holes



triaxial galaxies, equal masses (Yu 2002)

The final parsec problem:

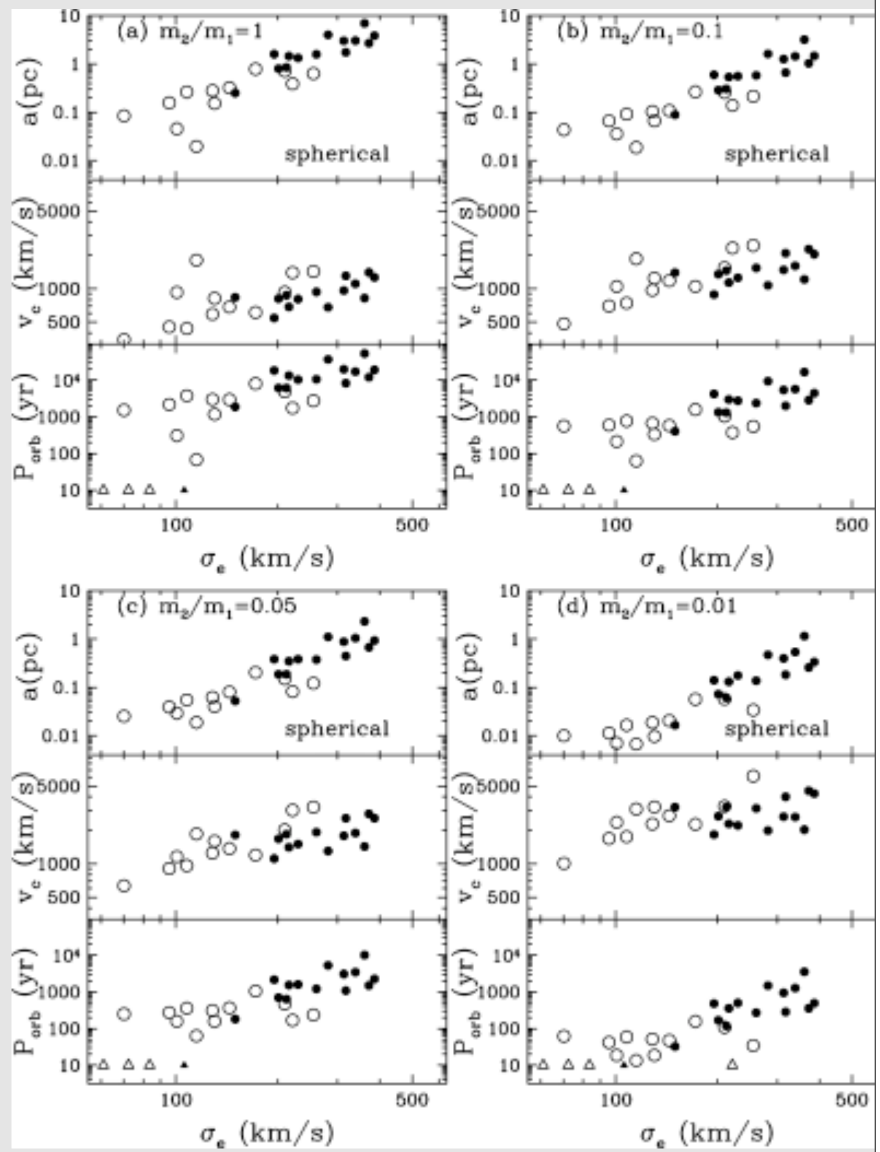
- this is not a “problem” unless you want to detect gravitational waves from merging black holes

- most or all binary black holes may survive for the age of the universe

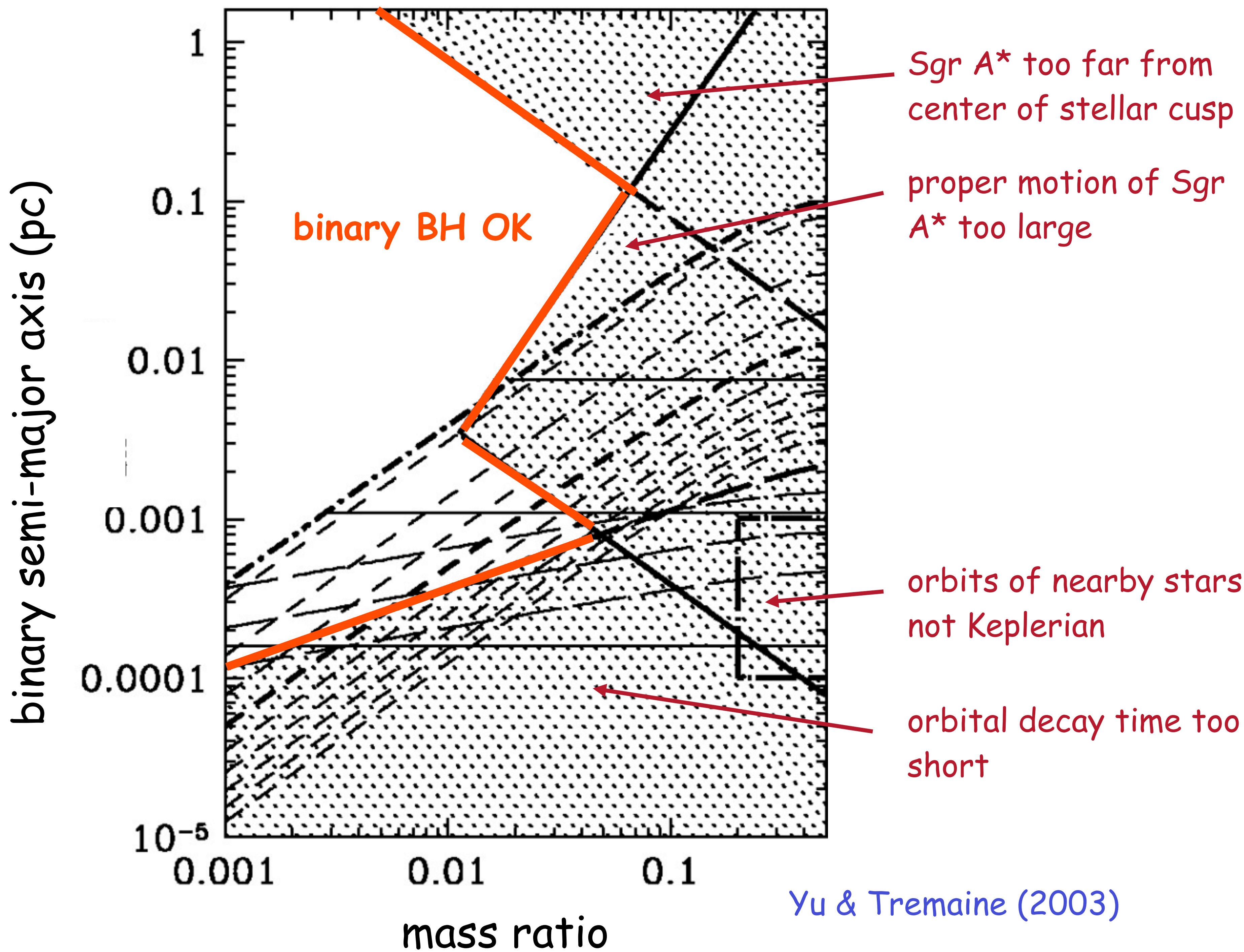
- typical radii 0.01-0.1 pc; orbital periods 10-10^4 yr; orbital velocities 10^2-10^4 km/s

- could be detected as double nuclei, double radio sources, double-peaked or displaced AGN emission lines, periodicity in AGN emission, precession of radio jets

- only a handful of plausible cases so far but it’s hard to know what to expect (e.g., can two black holes in a close binary be AGN at the same time?)



Yu (2002)


binary semi-major axis (pc)
1
0.1
0.01
0.001
0.0001
10^{-5}
0.001
0.01
0.1
mass ratio
binary BH OK
Sgr A* too far from center of stellar cusp
proper motion of Sgr A* too large
orbits of nearby stars not Keplerian
orbital decay time too short
Yu & Tremaine (2003)

Summary

• dark, compact objects of 10^6-10^{10} solar masses are present at the centers of galaxies containing hot components (ellipticals and spiral bulges)

• their properties are inconsistent with any plausible, long-lived astrophysical system except black holes

• arguments based on energy budgets strongly suggest that these are dead quasars

• black-hole masses are correlated with properties of the host galaxy, in particular velocity dispersion

• the correlation may arise from feedback, i.e., energy input from the black hole plays a central role in galaxy formation

• formation of black-hole binaries of ~ parsec separation is a common process, but the lifetime of these binaries is not known

• rate of black-hole mergers is unknown