Astro 358/Spring 2012

Galaxies and the Universe

Figures + Tables for Lectures on Apr 17, 19

Black Holes in Galaxies

Supermassive Black hole at Center of Milky Way

Radio image of the central region of the Milky Way

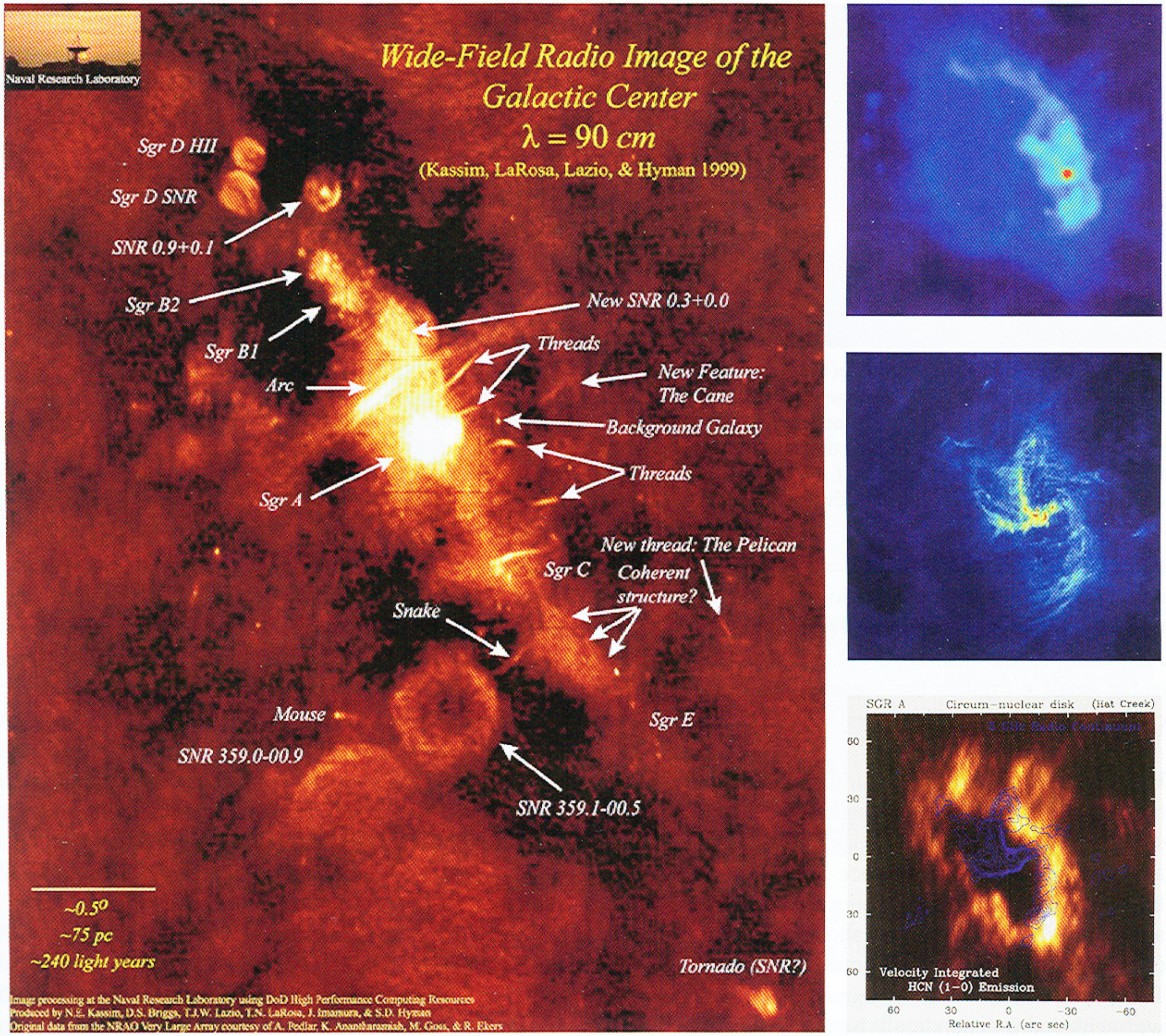


Fig. 2.34. Left: A VLA wide-field image of the region around the Galactic center, with a large number of sources identified. Upper right: a 20 cm continuum VLA image of Sgr A East, where the red dot marks Sgr A*. Center right: Sgr A West, as seen in a 6-cm continuum VLA image. Lower right: the circumnuclear ring in HCN line emission

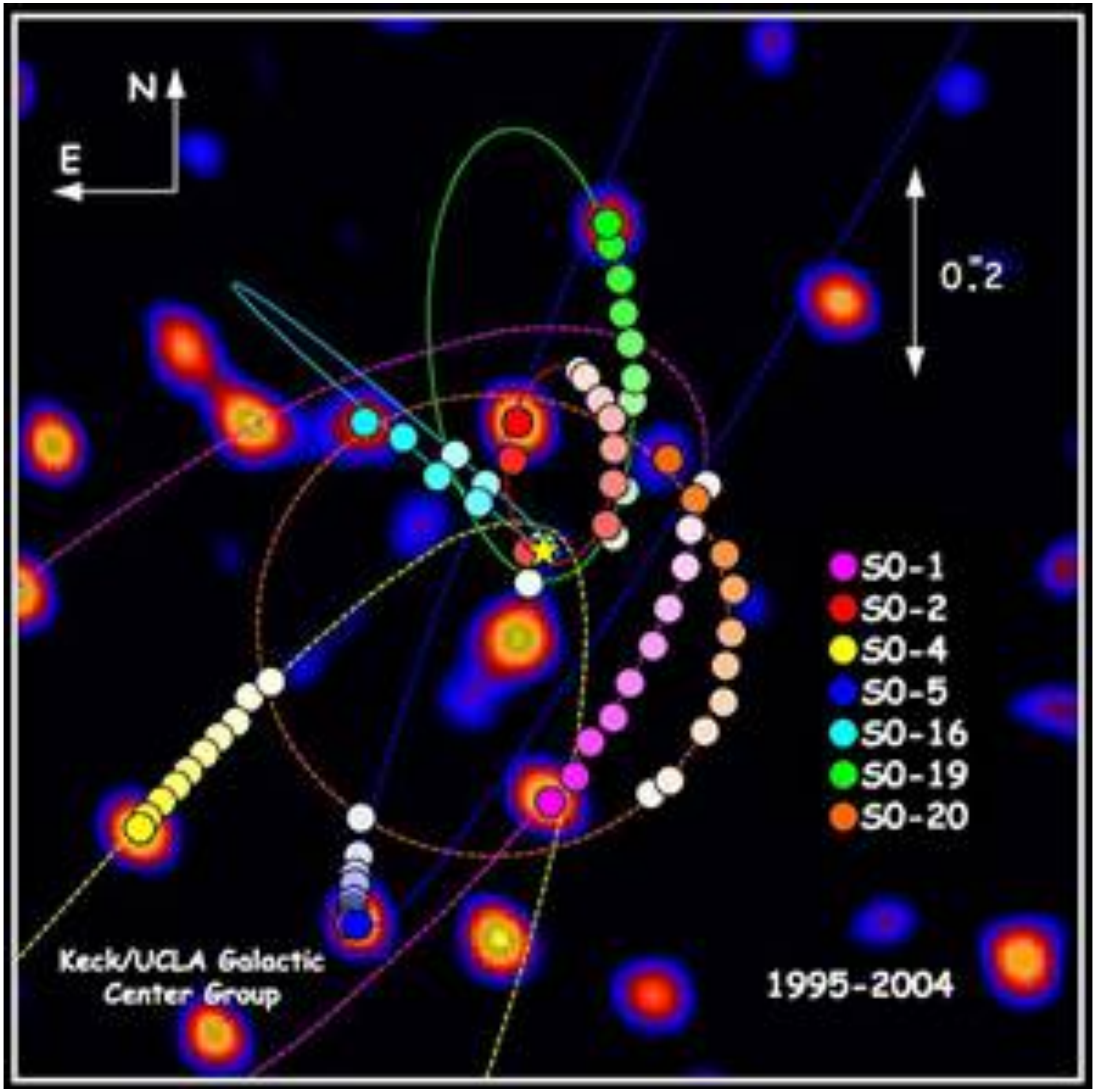
Top = Sgr A East, a non thermal radio continuum source. The red dot is Sgr A*, a compact radio source, coinciding with SMBH in center of Mliky Way

Center = Thermal radio continuum image of Sgr A West, an HII region.

Bottom= ring of dense molecular gas between radii of 2-8 pc

(Credit: EAC)

Infrared image of Galactic Center

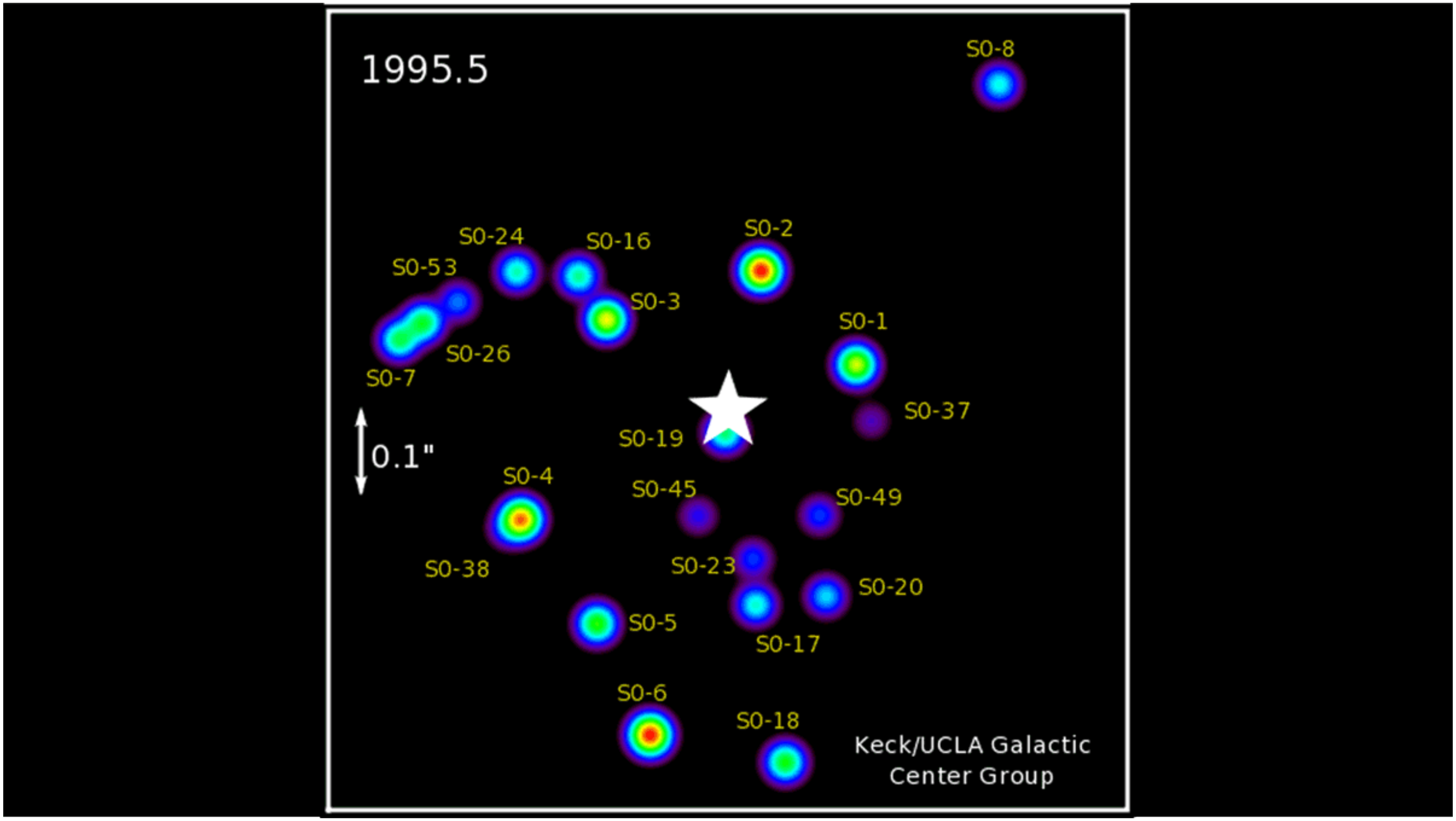


NIR image shows a compact stellar cluster, centered on Sgr A* radio source

Keck observations with adaptive optics were taken over 15 years to map out complete orbits of individual stars in the cluster.

Note stars S02 and S0-16

Supermassive Black Hole at center of Milky way



→ Star S0-2 = orbit comes close to BH, has short period <16 yrs, fully traced
Star S0-16 = comes within 90 AU of BH

→ Estimated mass of BH: ~ 3.6 million solar masses!

Map Proper Motion and Orbits of Stars around Sgr A*

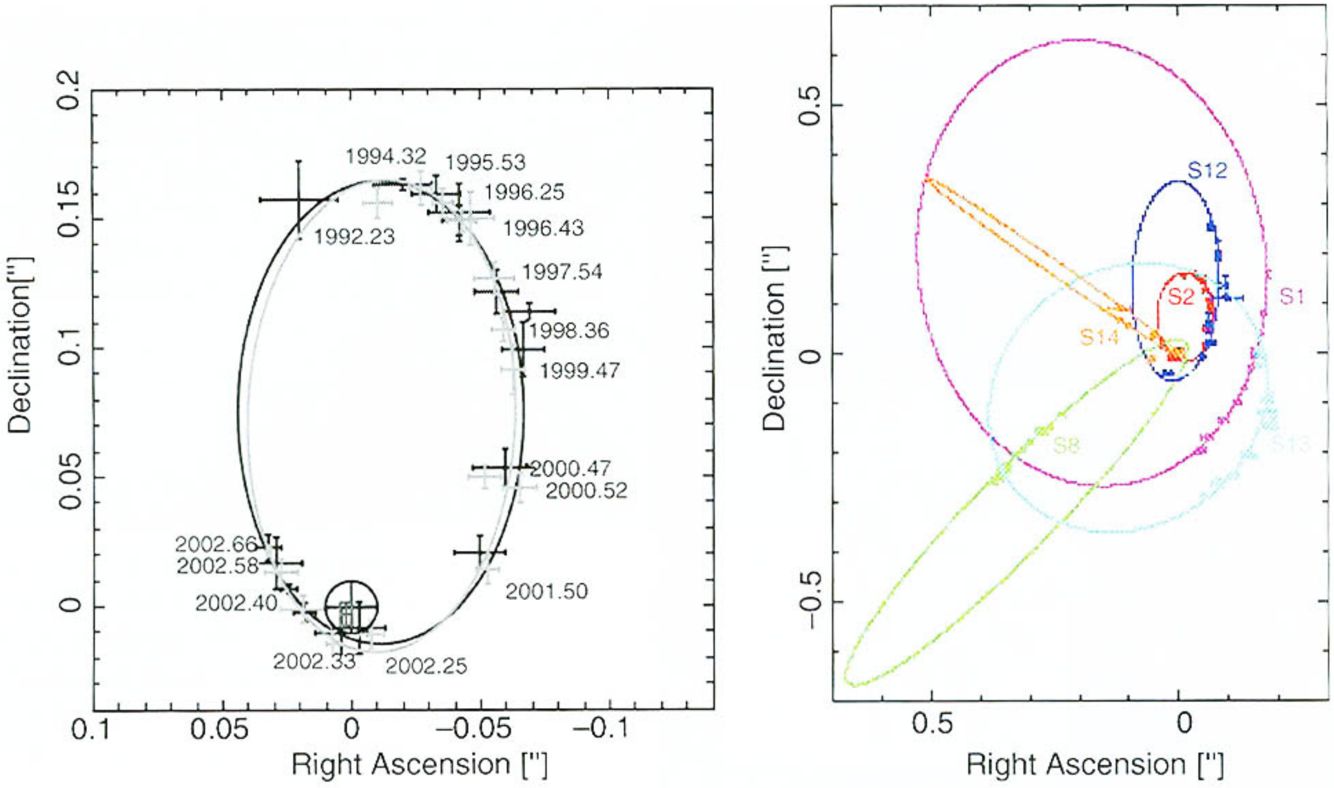
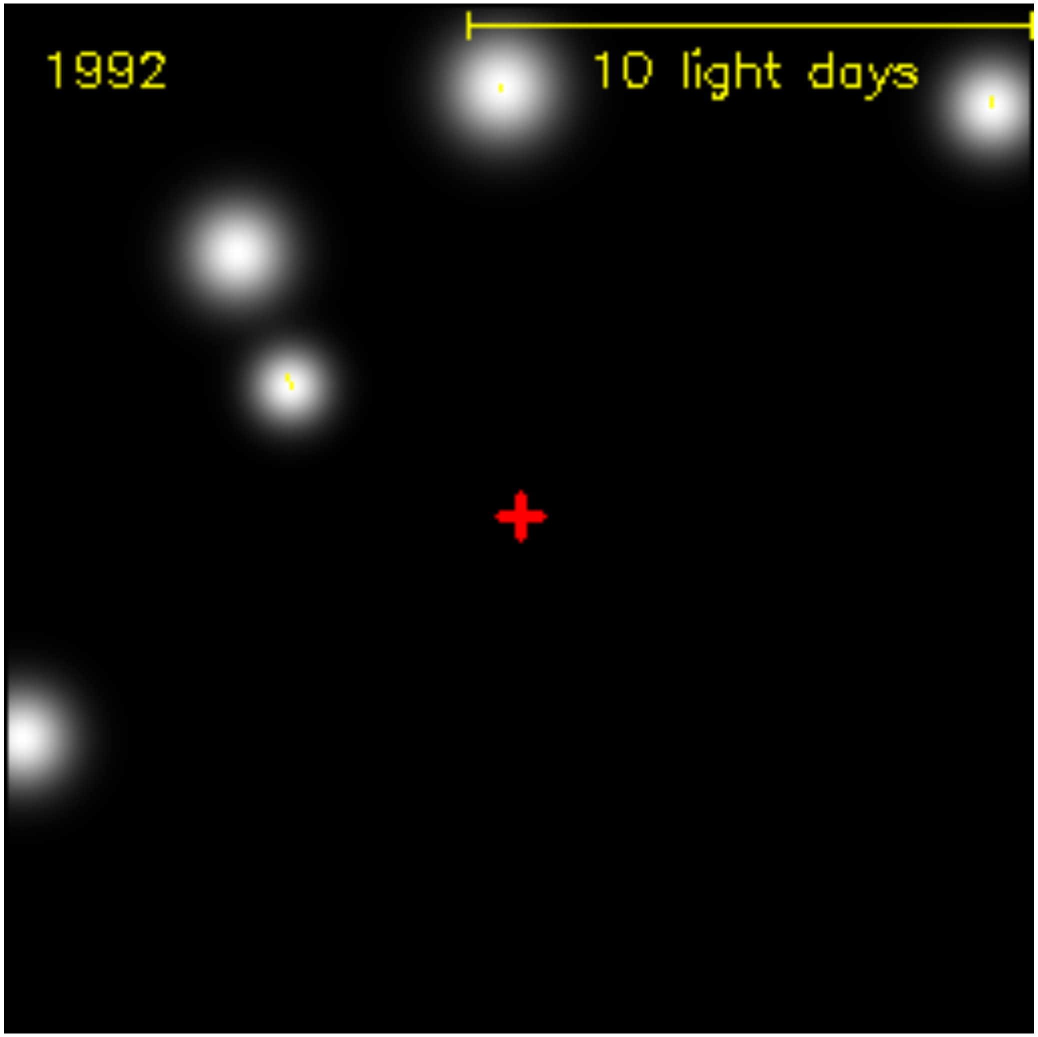


Fig. 2.37. At left, the orbit of the star S2 around Sgr A* is shown as determined by two different observing campaigns. The position of Sgr A* is indicated by the black circled cross. The individual points along the orbit are identified by the epoch of the observation. The right-hand image shows the orbits of some other stars for which accelerations have already been measured

L in cm^2 s^{-1}

(Credit: EAC)

Supermassive Black Hole at center of Milky way



Estimated mass: ~ 3.6 million solar masses!

Supermassive Black Hole at center of Milky way

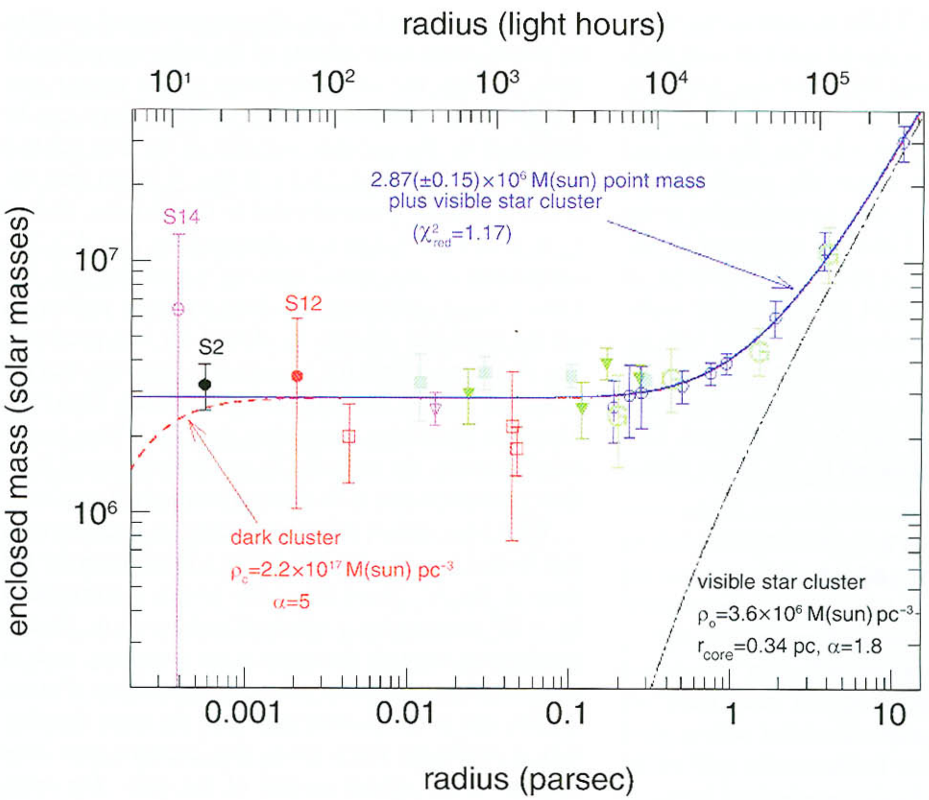


Fig. 2.38. Determination of the mass $M(r)$ within a radius r from Sgr A*, as measured by the radial velocities and proper motions of stars in the central cluster. Mass estimates obtained from individual stars (S14, S2, S12) are given by the points with error bars for small r. The other data points were derived from the kinematic analysis of the observed proper motions of the stars, where different methods have been applied. As can be seen, these methods produce results that are mutually compatible, so that the mass profile plotted here can be regarded to be robust. The solid curve is the best-fit model, representing a point mass of $2.9 \times 10^6 M_\odot$ plus a star cluster with a central density of $3.6 \times 10^6 M_\odot/\mathrm{pc}^3$ (the mass profile of this star cluster is indicated by the dash-dotted curve). The dashed curve shows the mass profile of a hypothetical cluster with a very steep profile, $n \propto r^{-5}$, and a central density of $2.2 \times 10^{17} M_\odot\,\mathrm{pc}^{-3}$

L in cm^2 s^{-1}

(Credit: EAC)

X-ray image of central region of Milky Way

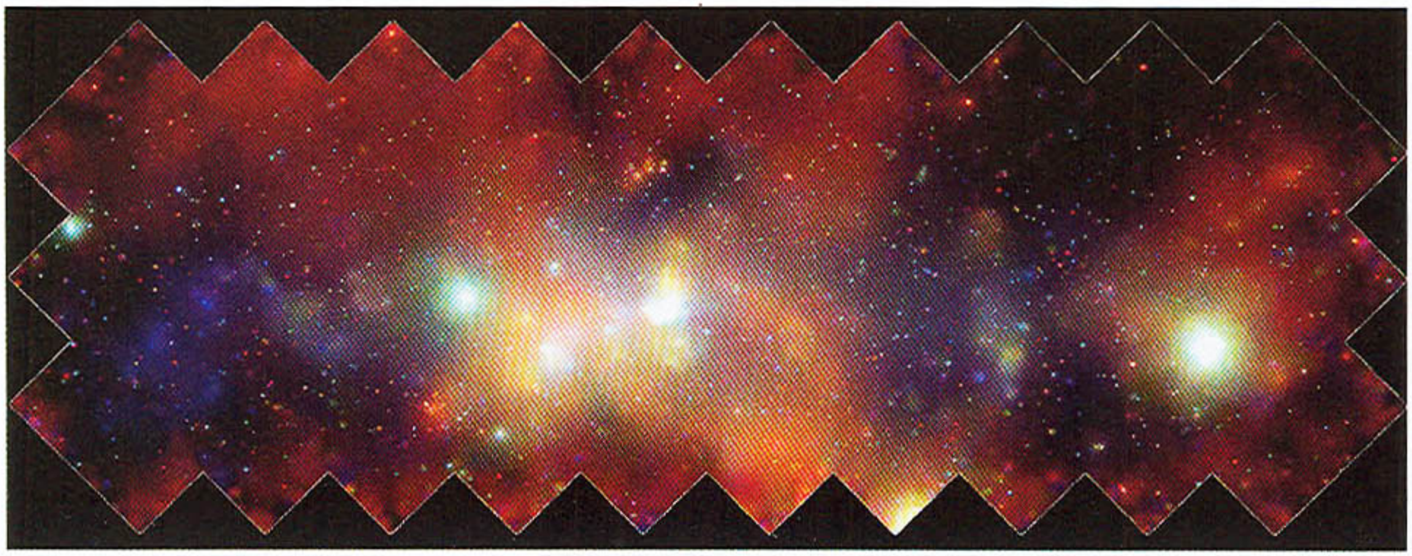


Fig. 2.35. Mosaic of X-ray images of the Galactic center, taken by the Chandra satellite. The image covers an area of about 130 pc × 300 pc ($48' \times 120'$). The actual GC, in which a supermassive black hole is suspected to reside, is located in the white region near the center of the image. Furthermore, on this image hundreds of white dwarfs, neutron stars, and black holes are visible that radiate in the X-ray regime due to accretion phenomena (accreting X-ray binaries). Colors code the photon energy, from low energy (red) to high energy (blue). The diffuse emission, predominantly red in this image, originates in diffuse hot gas with a temperature of about $T \sim 10^7$ K

L in $cm^2 s^{-1}$

(Credit: EAC)

Supermassive Black Holes in External Galaxies

L in cm^2 s^{-1}

Supermassive Black Holes in External Galaxies

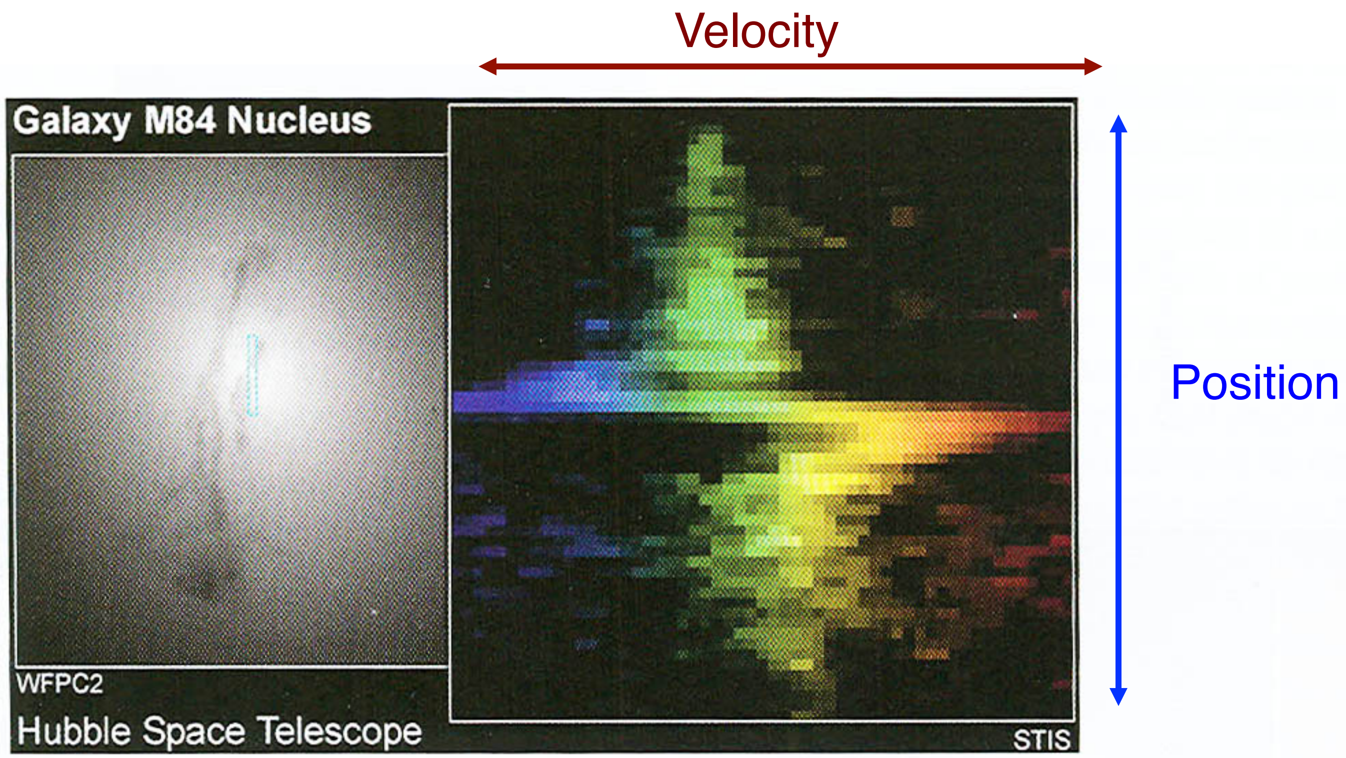


Fig. 3.24. An HST image of the nucleus of the galaxy M84 is shown in the left-hand panel. M84 is a member of the Virgo Cluster, about 15 Mpc away from us. The small rectangle depicts the position of the slit used by the STIS (Space Telescope Imaging Spectrograph) instrument on-board the HST to obtain a spectrum of the central region. This long-slit spectrum is shown in the right-hand panel; the position along the slit is plotted vertically, the wavelength of the light horizontally, also illustrated by colors. Near the center of the galaxy the wavelength suddenly changes because the rotational velocity steeply increases inwards and then changes sign on the other side of the center. This shows the Kepler rotation in the central gravitational field of a SMBH, whose mass can be estimated as $M_\bullet \sim 3 \times 10^8 M_\odot$

(Credit: EAC)

Supermassive Black Holes in External Galaxies

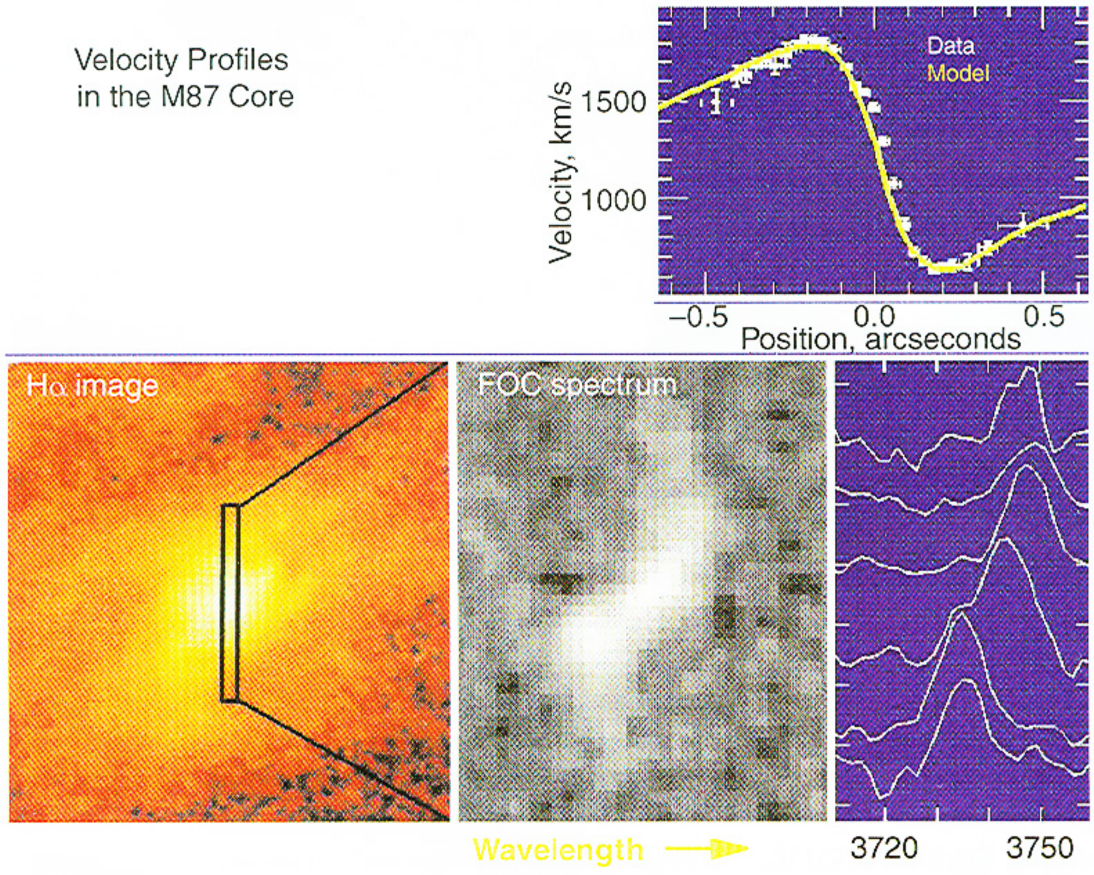


Fig. 3.26. M87 has long been one of the most promising candidates for harboring an SMBH in its center. In this figure, the position of the slit is shown superimposed on an Hα image of the galaxy (lower left) together with the spectrum of the [OII] line along this slit (bottom, center), and six spectra corresponding to six different positions along the slit, separated by 0.″14 each (lower right). In the upper right panel the rotation curve extracted from the data using a kinematical model is displayed. These results show that a central mass concentration with $\sim 3 \times 10^9 M_\odot$ must be present, confined to a region less than 3 pc across – indeed leaving basically no alternative but a SMBH

L in cm^2 s^{-1}

(Credit: EAC)

Supermassive Black Holes in External Galaxies

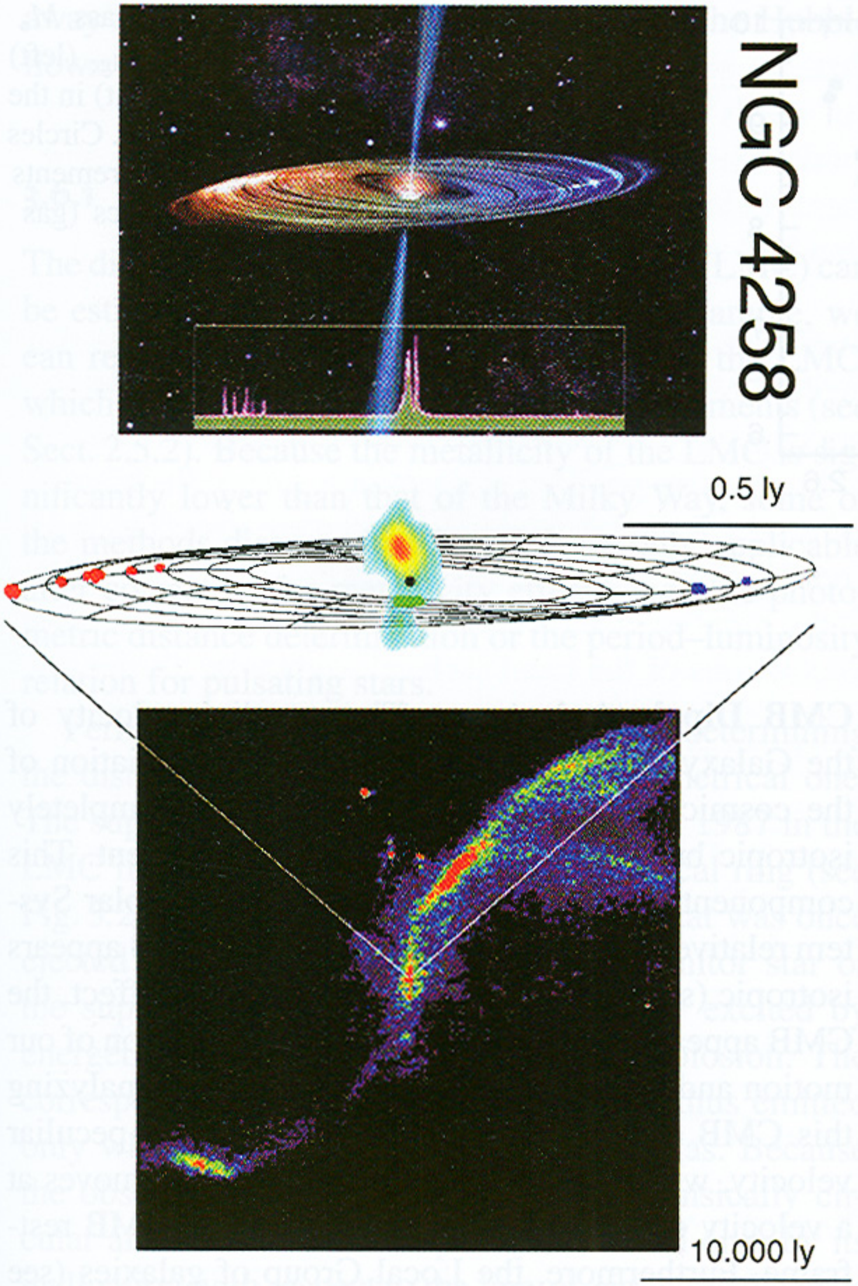


Fig. 3.27. The Seyfert galaxy NGC 4258 contains an accretion disk in its center in which several water masers are embedded. In the top image, an artist's impression of the hidden disk and the jet is displayed, together with the line spectrum of the maser sources. Their positions (center image) and velocities have been mapped by VLBI observations. From these measurements, the Kepler law for rotation in the gravitational field of a point mass of $M_\bullet = 25 \times 10^6 M_\odot$ in the center of this galaxy was verified. The best-fitting model of the central disk is also plotted. The bottom image is a 20-cm map showing the large-scale radio structure of the Seyfert galaxy

(Credit: EAC)

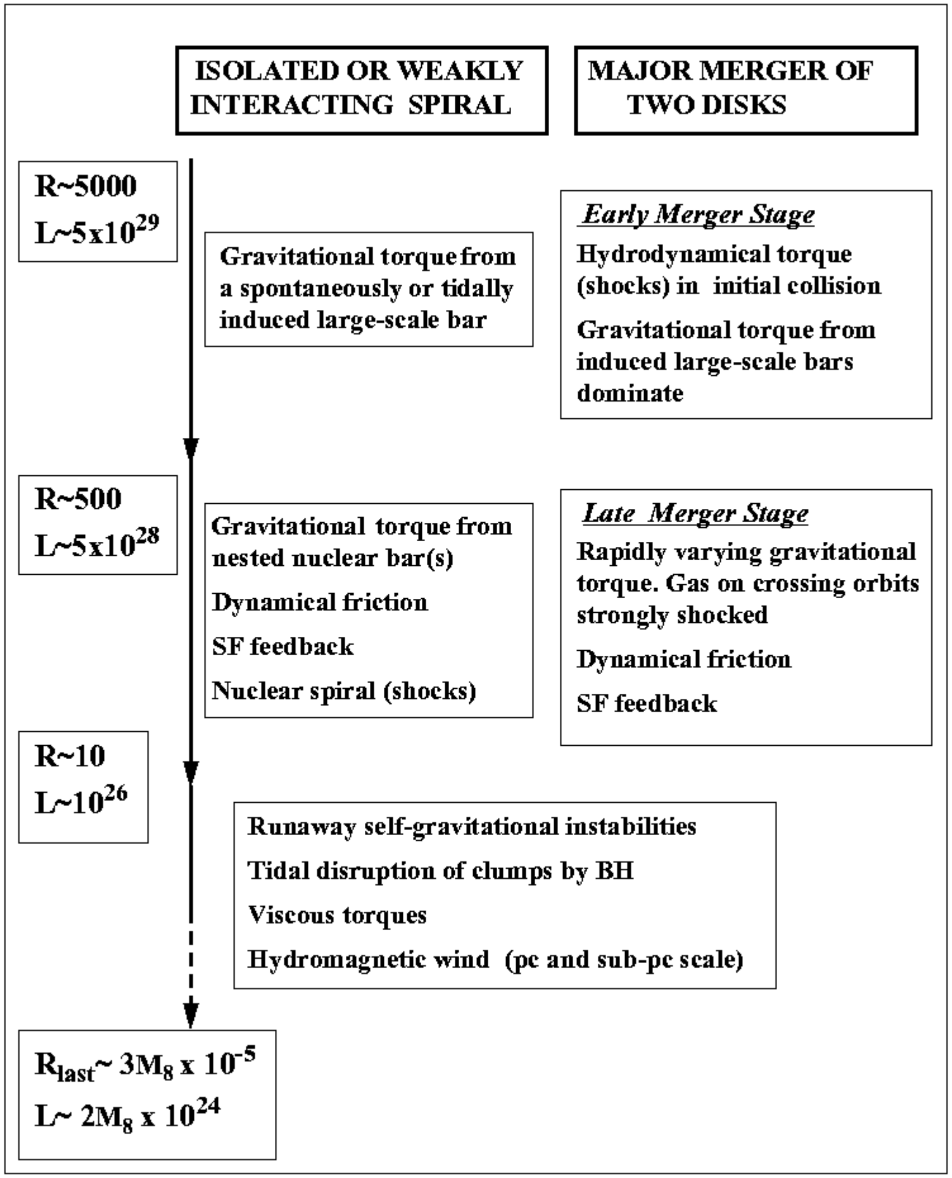
L in cm^2 s^{-1}

Fueling the Central BH :The Angular Momentum Problem

Before gas in the outer disk at a radius R of ~5 kpc can can feed a black hole , its specific angular momentum L must be lowered by a factor of 10^5.

Interactions or mergers can help at least partly

See section 3.2 and 7 in the review by Jogee 2006,posted on the class website



ISOLATED OR WEAKLY INTERACTING SPIRAL

MAJOR MERGER OF TWO DISKS

$R \sim 5000$, $L \sim 5 \times 10^{29}$

Gravitational torque from a spontaneously or tidally induced large-scale bar

Early Merger Stage
Hydrodynamical torque (shocks) in initial collision
Gravitational torque from induced large-scale bars dominate

$R \sim 500$, $L \sim 5 \times 10^{28}$

Gravitational torque from nested nuclear bar(s)
Dynamical friction
SF feedback
Nuclear spiral (shocks)

Late Merger Stage
Rapidly varying gravitational torque. Gas on crossing orbits strongly shocked
Dynamical friction
SF feedback

$R \sim 10$, $L \sim 10^{26}$

Runaway self-gravitational instabilities
Tidal disruption of clumps by BH
Viscous torques
Hydromagnetic wind (pc and sub-pc scale)

$R_{last} \sim 3M_8 \times 10^{-5}$, $L \sim 2M_8 \times 10^{24}$

cm^2 s^{-1}

(Jogee 2006, Ch6, AGN Physics on All Scales; astro-ph/0408383)

Mass accretion rate to power high and low luminosity AGN

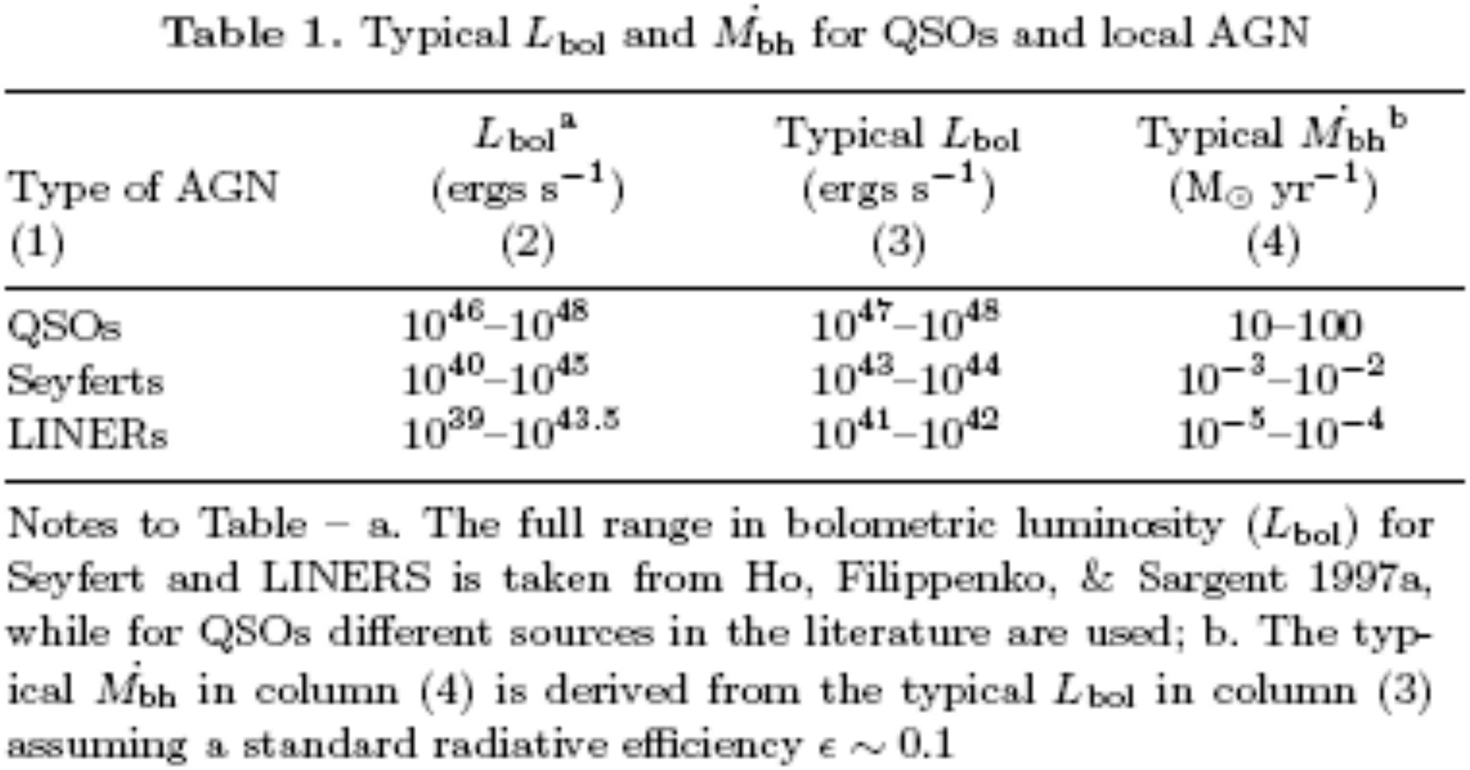


Table 1. Typical $L_{\rm bol}$ and $\dot{M}_{\rm bh}$ for QSOs and local AGN

Type of AGN (1)	$L_{\rm bol}$ [a] (ergs s^{-1}) (2)	Typical $L_{\rm bol}$ (ergs s^{-1}) (3)	Typical $\dot{M}_{\rm bh}$ [b] ($M_\odot$ yr^{-1}) (4)
QSOs	10^{46}–10^{48}	10^{47}–10^{48}	10–100
Seyferts	10^{40}–10^{45}	10^{43}–10^{44}	10^{-3}–10^{-2}
LINERs	10^{39}–$10^{43.5}$	10^{41}–10^{42}	10^{-5}–10^{-4}

Notes to Table – a. The full range in bolometric luminosity ($L_{\rm bol}$) for Seyfert and LINERS is taken from Ho, Filippenko, & Sargent 1997a, while for QSOs different sources in the literature are used; b. The typical $\dot{M}_{\rm bh}$ in column (4) is derived from the typical $L_{\rm bol}$ in column (3) assuming a standard radiative efficiency $\epsilon \sim 0.1$

(Jogee 2006, Ch6, AGN Physics on All Scales; astro-ph/0408383)

Correlation between BH mass and Bulge velocity dispersion

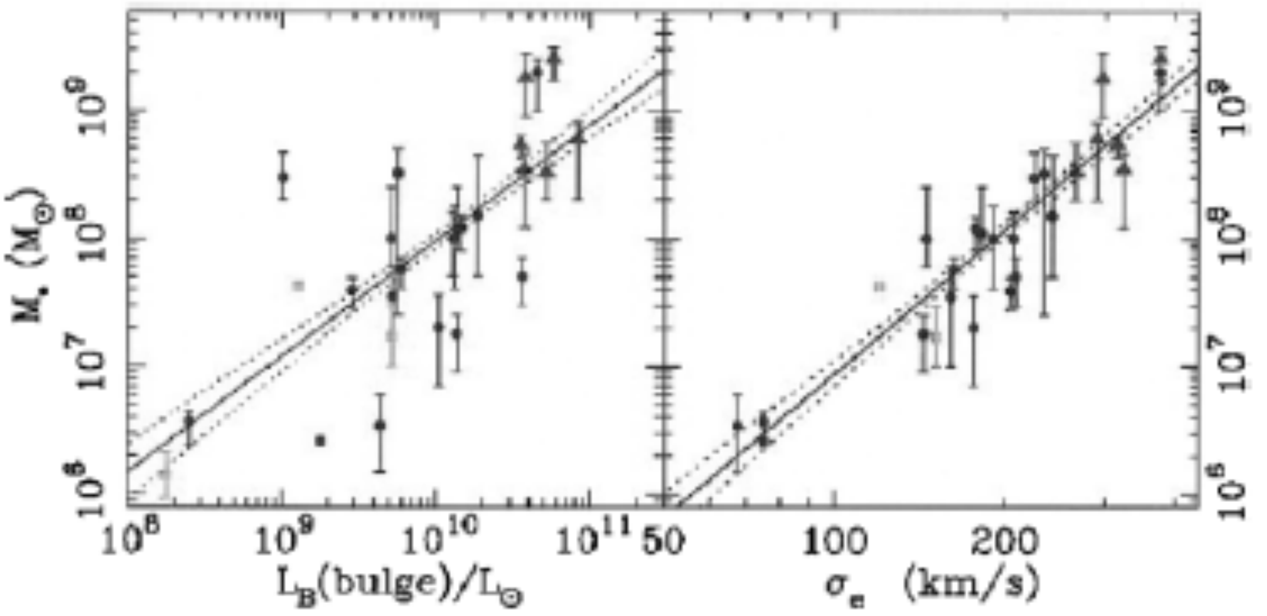


Fig. 1. Correlation between central BH mass and circumnuclear velocity dispersion – Black hole mass versus bulge luminosity (*left*) and the luminosity-weighted aperture dispersion within the effective radius (*right*). Green squares denote galaxies with maser detections, red triangles are from gas kinematics, and blue circles are from stellar kinematics. Solid and dotted lines are the best-fit correlations and their 68% confidence bands. (From Gebhardt et al. 2000)

(Fig from Gehbardt et al 2000)

Why do galaxies obey the BH Mass-Bulge σ relation?

1. Gravity of BH does not affect bulge : R_g >> R_bulge

2. But BH does impact bulge in terms of energy !

Energy E_{BH} generated by mass accretion onto BH >> Binding energy of bulge
(See in class calculations)

→ even if a few % of E_{BH} is injected into bulge it can cause bulge to dissolve!
→ a bulge of given velocity dispersion can only survive if mass of BH < some limit

3. Major mergers may cause concurrent growth of BH and some types of bulges called classical bulges … see next slides

Growth of some bulges and of central BH via major merger

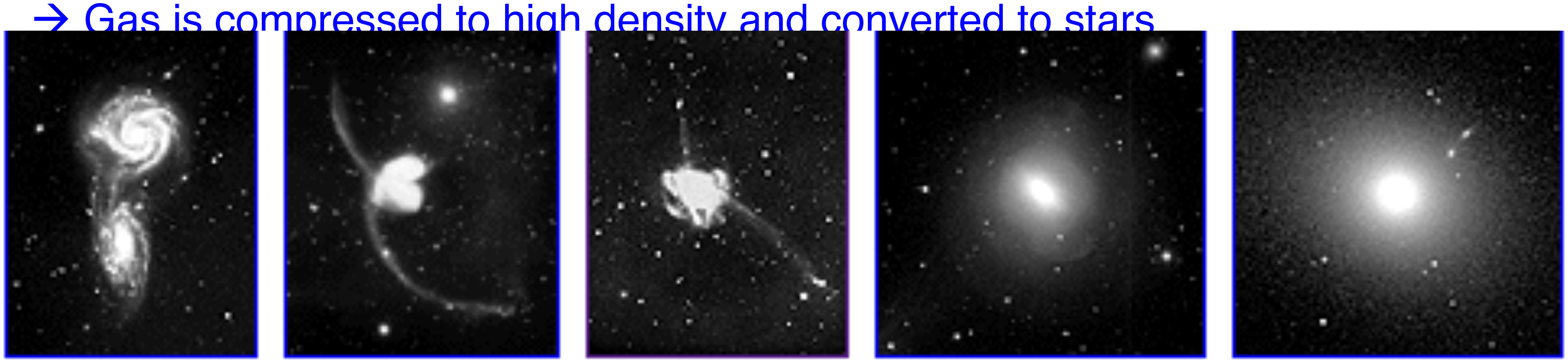
* Major mergers of 2 small disk galaxies made of gas and stars can form

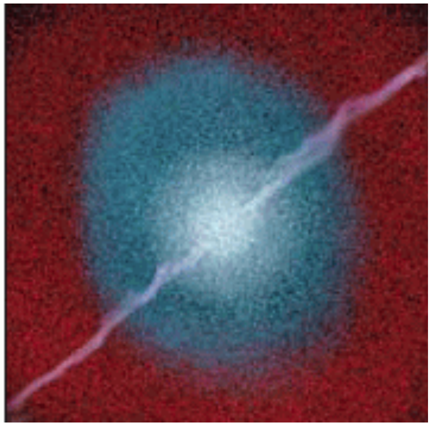
→ a bulge with a centrally concentrated surface brightness profile (characterized by a high Sersic index n>2.5) and with a low v/σ

◊ Such bulges often called ‘classical bulges’.

* During the merger

→ Gas is compressed to high density and converted to stars

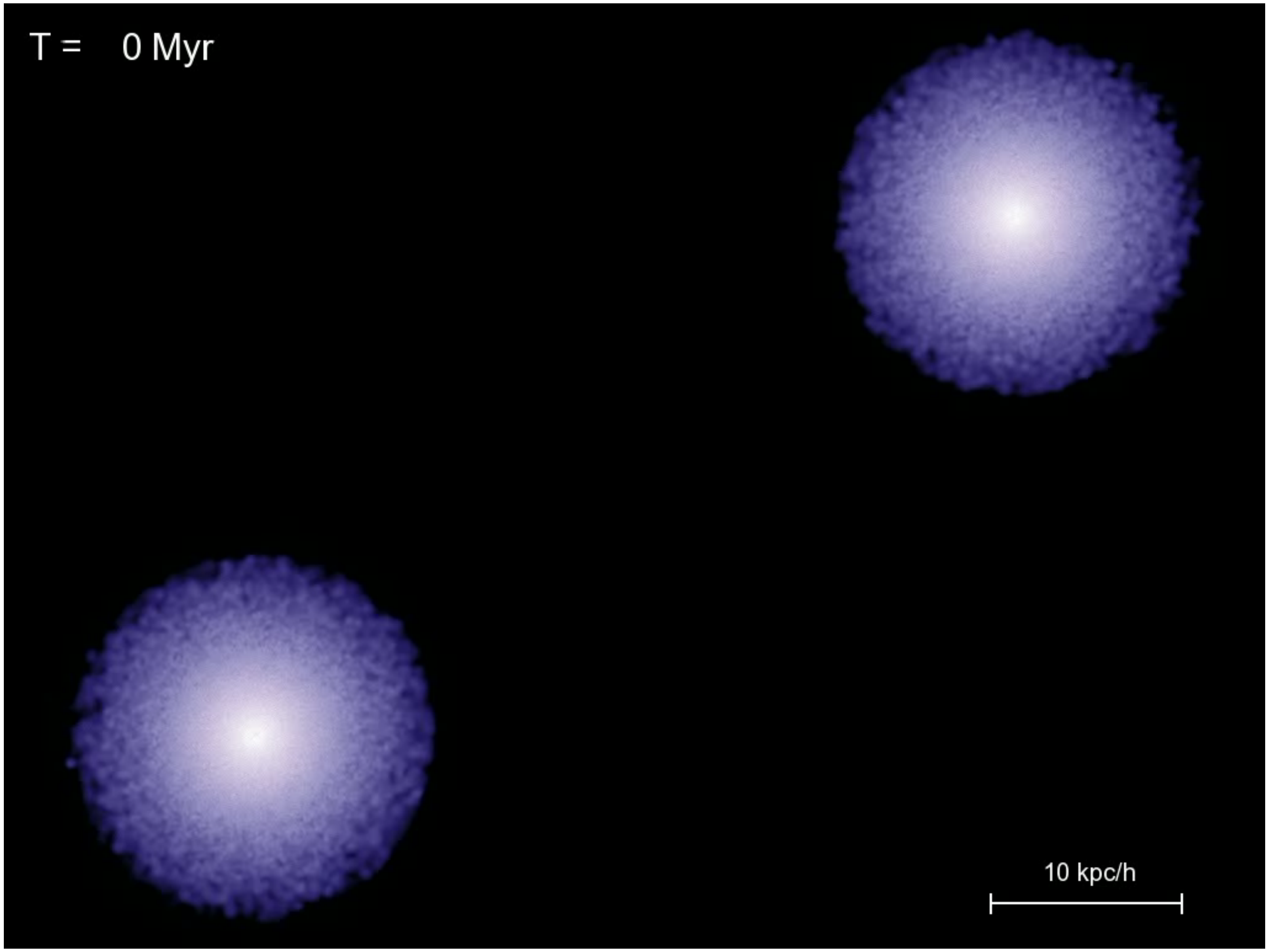




→ Gravitational Torques drive gas to low radii, causing BH to grow. Thus BH and bulges grow synchronously

→ Feedback: AGN jet heat/expel gas preventing further growth

Feedback from Black Holes quench SF and BH growth

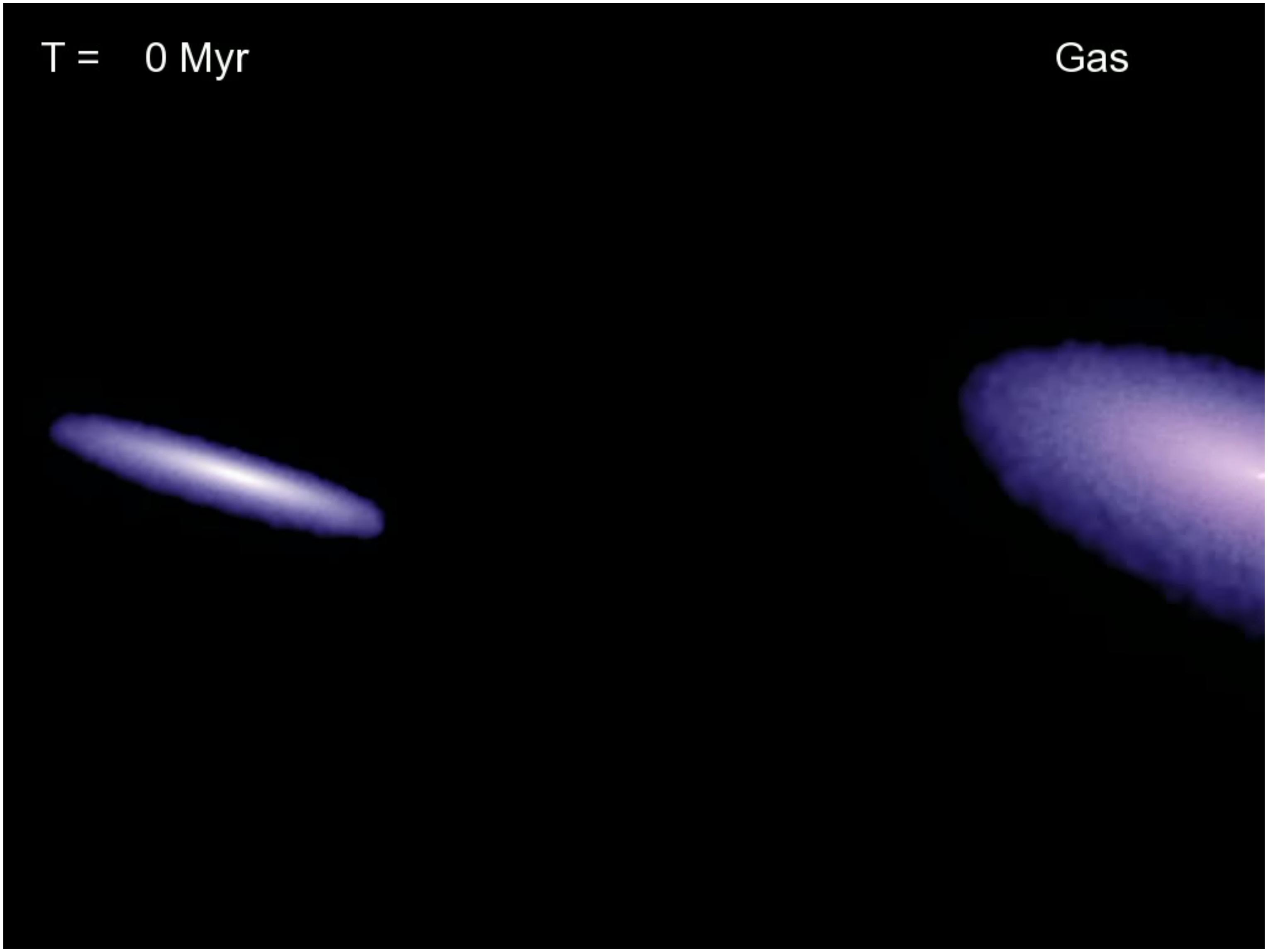


Di Matteo et al 2005

Show merger of two spiral galaxies that host central supermassive black holes. Only the gas distribution is shown. Brightness represents gas density. Color hue shows gas temperature.

→ Gas inflows feed central SF and BH until energy generated by mass accretion onto BH heat/expel gas, quenching both SF and BH growth

Simulation of major mergers with black holes

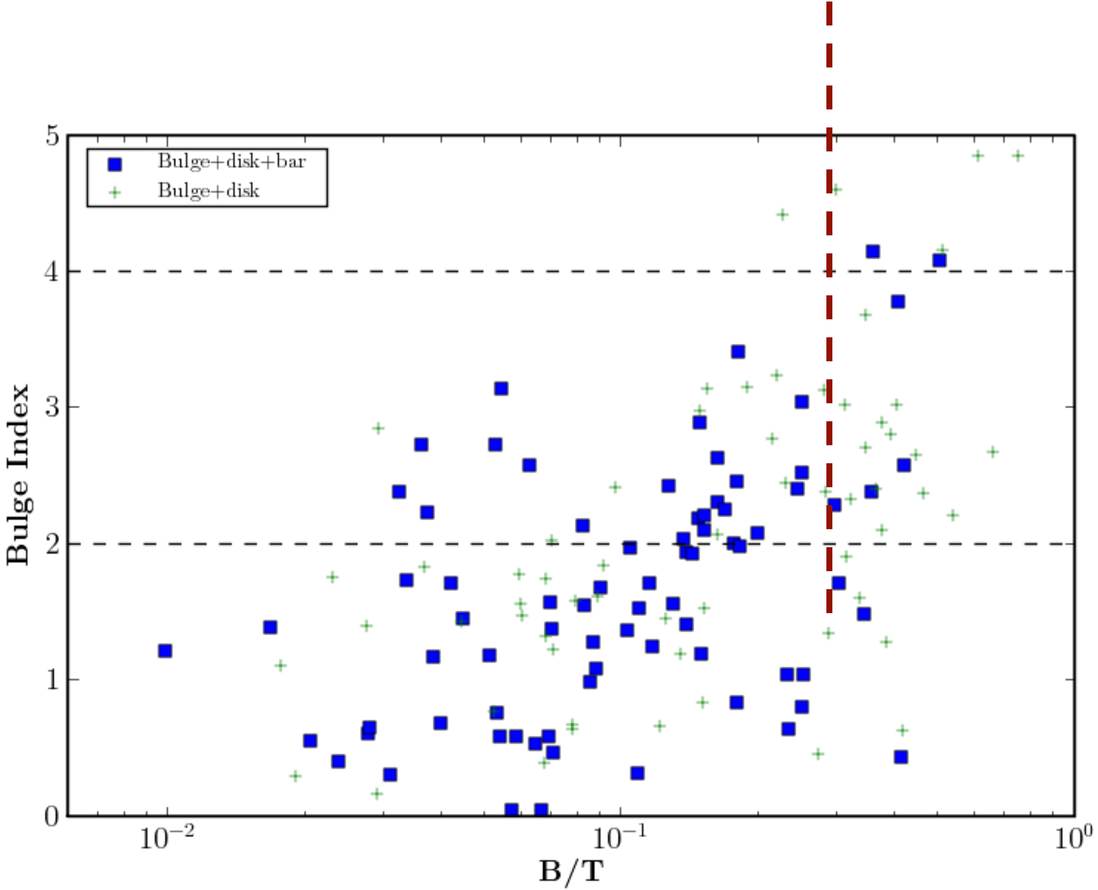


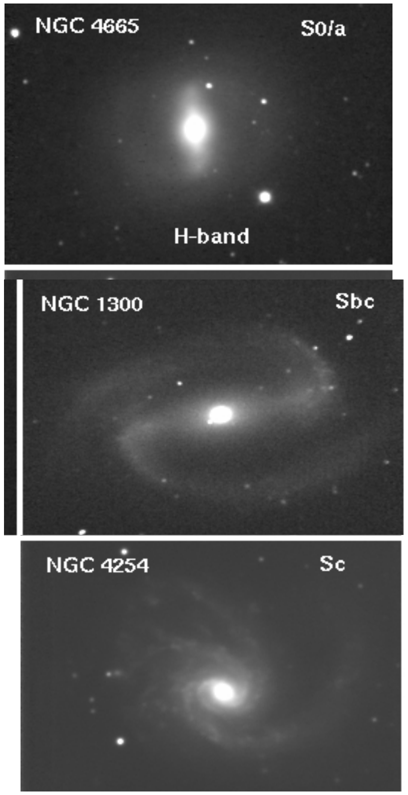
(Credit = V. Springel)

But… the synchronous growth of BH and bulges via major merger cannot fully explain the BH Mass—Bulge σ relation . Several challenges:

1) Non-classical bulges or pseudo-bulges

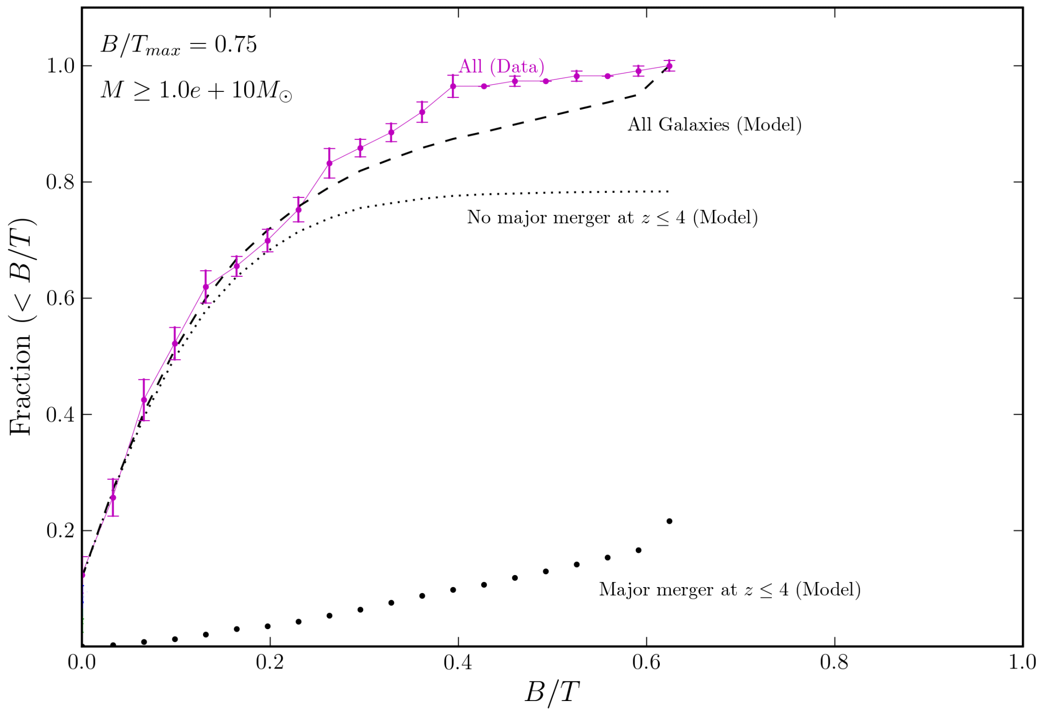
A large fraction (66%) of bulges in massive spirals are not classical (high Sersic n) bulges, but are instead “non-classical” bulges, having a low Sersic n and low bulge-to-total B/T ratio (Weinzirl et al 2009; Graham et al. 2008).





Weinzirl, Jogee, Khochfar, Burkert & Kormendy 2009, ApJ, in press (arXiv:0807.0040)

Present-day B/T	Data	Model galaxies w/ major merger since z<=4	Model galaxies w/o major merger since z <=4	Model galaxies All
B/T <=0.2	66%	~1.6%	~66%	~68%
0.2 <B/T<= 0.4	26%	~5%	~13%	~18%
B/T > 0.4	8%	~13%	~1 %	~14%



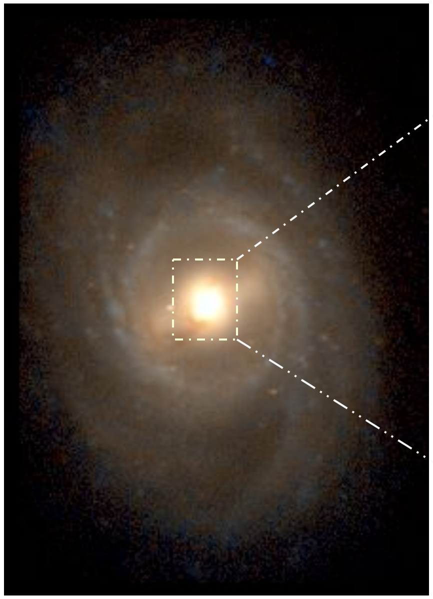
(Weinzirl, Jogee, Khochfar, Burkert & Kormendy 2009)

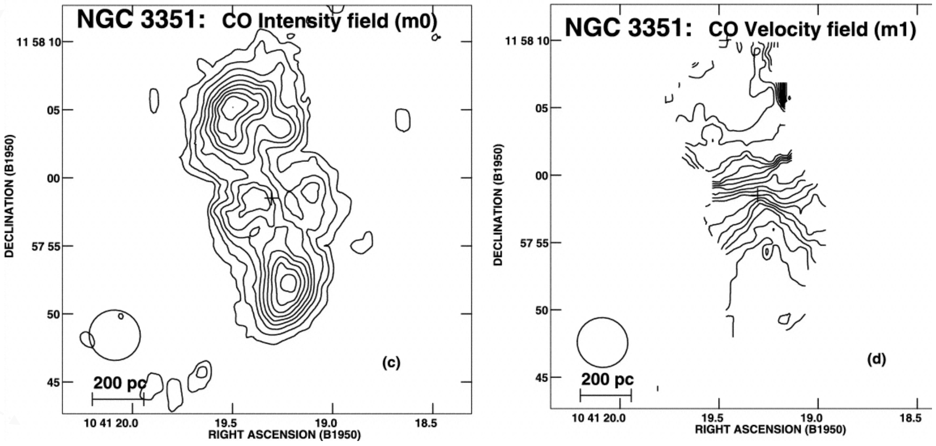
Such bulges are formed over the last 10 Gyr primarily via minor mergers and via secular evolution (bar-driven gas inflow) in isolated galaxies, rather than by major mergers. In fact, major mergers over the last 10 Gyr fail by a factor of over 30 to account for such bulges (Weinzirl et al. 2009)

Disky bulges (pseudobulges)

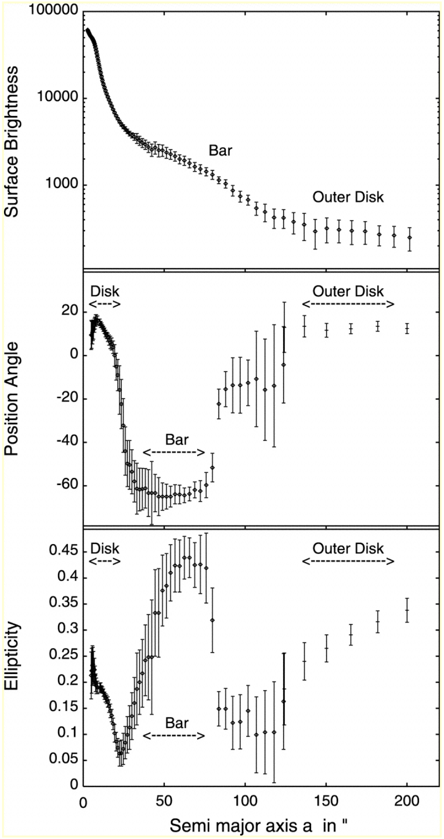
Disky bulges are stellar components that lie in the inner kpc of galaxies, have a **high v/σ**, and a surface brightness profile that is often exponential,

Believed to form when bars or minor mergers drive gas into inner kpc
→ gas settled into a disk and forms stars
→ get central stellar disks of **high v/σ** in central kpc, called "disky" bulge





NGC 3351 (Jogee, Scoville, & Kenney 2005)

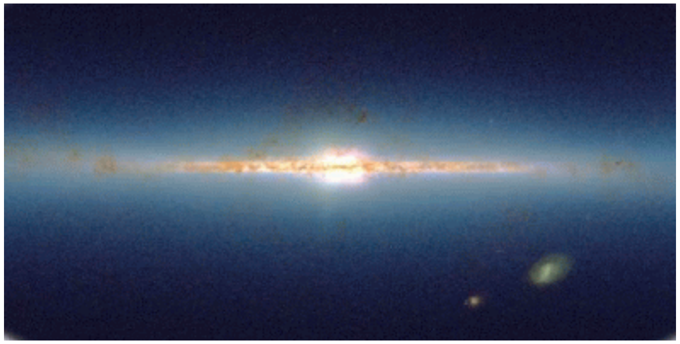


Boxy “bulges” are thickened bars viewed edge-on

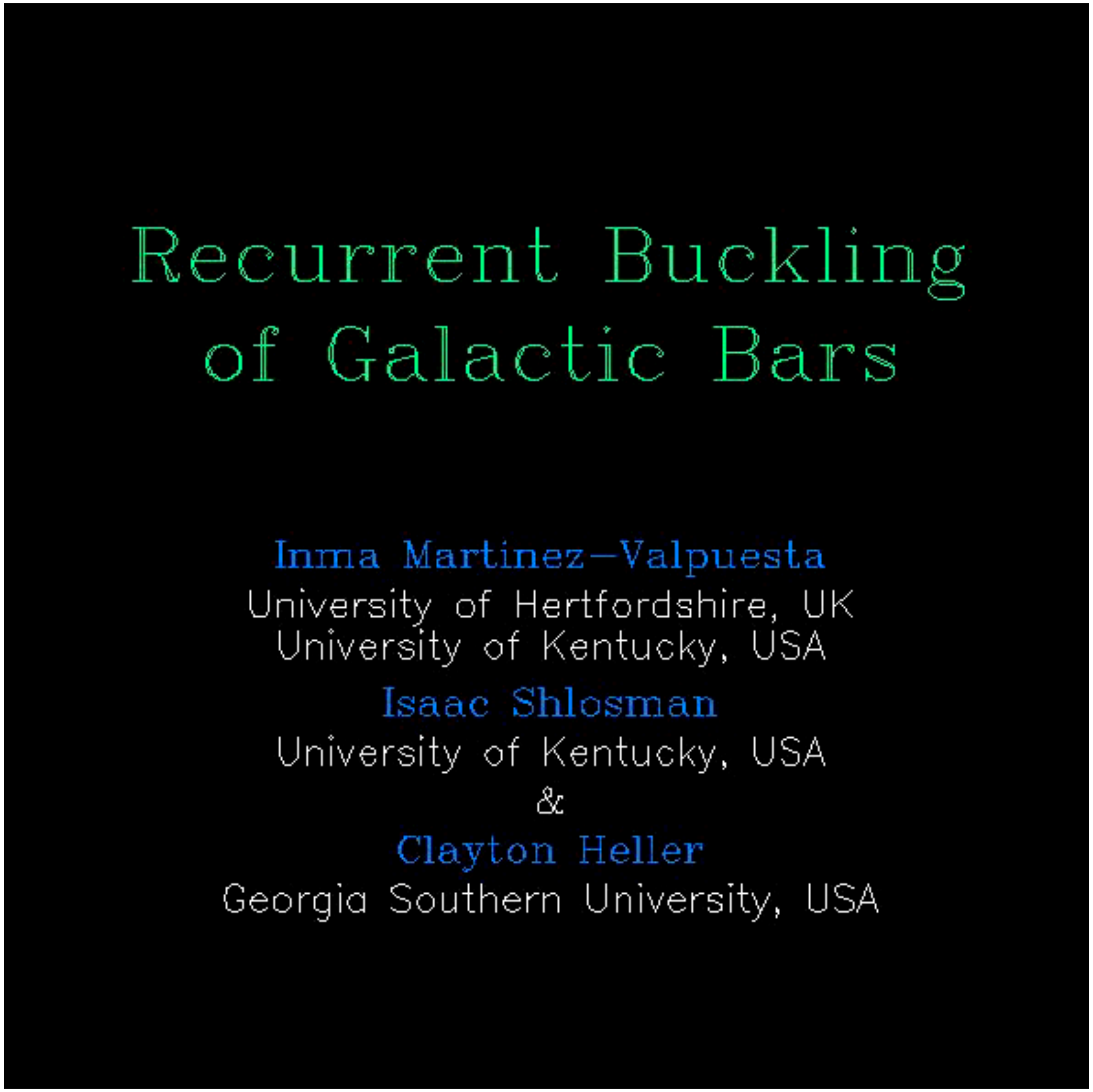
- Buckling instability and vertical resonances (ILRs) in a bar cause it to thicken.

- If this bar is viewed in an edge-on galaxy, it appears as a peanut or boxy bulge.

- Milky Way has boxy bulge



Bulge of Milky Way



Recurrent Buckling of Galactic Bars

Inma Martinez–Valpuesta
University of Hertfordshire, UK
University of Kentucky, USA
Isaac Shlosman
University of Kentucky, USA
&
Clayton Heller
Georgia Southern University, USA

Martinez-Valpuesta, Shlosman, & Heller 2005