Black holes in the nearby universe

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20 September 2014

Different “types” of black hole in astrophysics

Approx. 10 002 black holes around the Andromeda Galaxy.

Overview

(At least) two different "types" of astrophysical BHs.

	Stellar mass	**Supermassive**	
Mass [$M_\odot$]	10	10^6–10^9	$M_\odot = 2 \times 10^{30}$ kg
Horizon	30 km	$\sim$ AU	
Where	among stars	galaxy centres	
Origin	dead star	???	
$\theta_{\rm horizon}$ ["]	10^{-5}	10^{-5}	$3600'' = 1^\circ$

Optical/IR telescopes resolve $\Delta\theta \sim 0\farcs1 \gg \theta_{\rm horizon}$:

- BH looks like Newtonian point mass, $\Phi = -GM/r$;
- can hope to measure M, but not spin (at least not directly);

Find compact M, then argue that it *must* be a BH.

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1. Stellar-mass black holes
   - one example
2. “Supermassive” black holes
   - three examples
   - consequences

I. Stellar-mass BHs

(Remnants of dead stars)

Stars

Q: What stops stars from collapsing? **A:** Pressure.

- thermal pressure in normal stars;
- electron degeneracy pressure in white dwarfs;
- neutron degeneracy pressure in neutron stars.

There is a maxmimum mass for the latter.

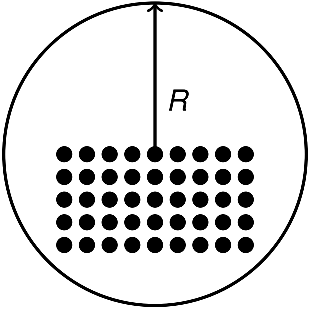
Identical fermions refuse to share states with one another. When $T \to 0$, states up to some maximum energy E_F, the Fermi energy, are fully occupied.

For n ultrarelativistic fermions/unit volume, $E_F \sim n^{1/3}\hbar c$.

Neutron stars

Landau's (1932) derivation of maximum mass

Assume: equilibrium = state of minimum total energy.



N neutrons, mass m, within radius R.

Fermi energy is

$\varepsilon_F \sim \hbar c \left(\frac{N}{R^3}\right)^{1/3}$.

(ultrarel. degenerate fermions)

Star's total energy

$$E(N,R) \sim N\varepsilon_F - \frac{GM^2}{R} = \frac{\hbar c N^{4/3} - G(mN)^2}{R}.$$

Numerator<0 $\Rightarrow E \downarrow$ if $R \downarrow$: collapse!

So, for stability we must have

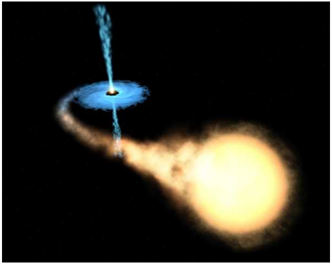
$$M = Nm \lesssim \left(\frac{\hbar c}{Gm^2}\right)^{3/2} m.$$

More complete models with GR and $P(\rho)$ give $M \simeq 3.1\,M_\odot$.

Observations of X-ray binaries

Circular binary with masses $M_\bullet$ and $M_\star$, separation r.

We observe $\star$, not $\bullet$.



Binary's orbital period

$$T = 2\pi\sqrt{\frac{r^3}{G(M_\bullet + M_\star)}}.$$

Peak line-of-sight velocity

$$v_\star = \frac{M_\bullet}{M_\bullet + M_\star} v \sin i,$$

where

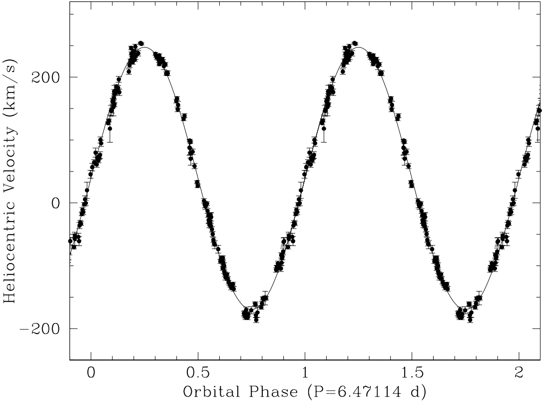
$$v = \sqrt{\frac{G(M_\bullet + M_\star)}{r}}.$$

Therefore the quantity

$$f(M_\bullet) \equiv \frac{Tv_\star^3}{2\pi G} = \frac{M_\bullet \sin^3 i}{(1 + M_\star/M_\bullet)^2} < M_\bullet.$$

Example: V404 Cygni
(Shahbaz et al. 1994)

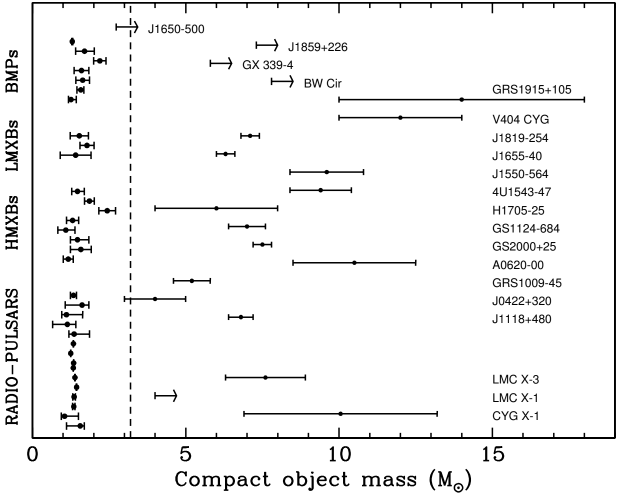
V404 Cygni: variable star/nova/X-ray transient, $\sim$ 2 kpc away.



$$v_\star \sin i \simeq 220\text{km/s}$$
$$T = 6.47\text{d}$$
$$\Rightarrow f(M) \simeq 7\, M_\odot$$

Detailed modelling constrains also i and $M_\star$.

Demographics of stellar remnants
(Casares 2006)



Upper bound $f(M_\bullet)$ shrunk by detailed modelling of binary system to constrain $(i, M_\star)$.

II. Supermassive black holes

(origin unknown)

Why expect supermassive BHs?

Observational: QSOs (Quasi-Stellar objects), 1960's

- Distant ($z \gtrsim 0.1$) point-like sources;
- power outputs $\sim 10^{12}\,L_\odot \sim 10^{39}$ W;
- (some) variable on $\sim$ day timescales
    - no more than light days across

Interpretation:

- Lynden-Bell (1969): QSOs caused by accretion by "Schwarzschild throats" located in the middle of galaxies;
- Rees (1978, 1984): supermassive BHs should be easy to form.

Rees 1978

1978Obs....98..210R

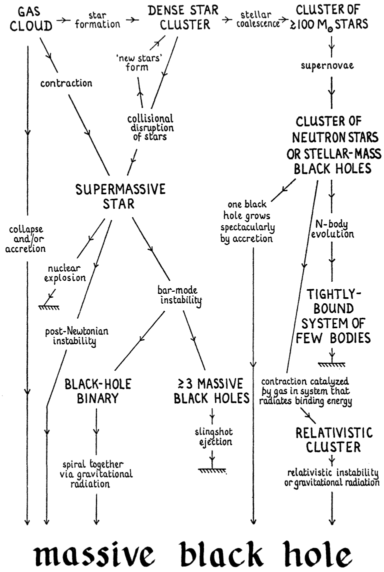
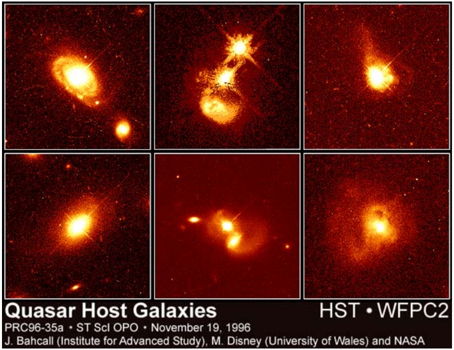


FIG. 2
Possible modes of formation of a massive black hole in a galactic nucleus.

Nowadays: less certain.

Why expect supermassive BHs?



1996
Hubble Space Telescope confirms that QSOs are located in galaxies.

Co-moving number density has decreased $\sim$ 100-fold between $z = 2$ and present.

Where are the dead QSOs now?

Use dynamical tracers (stars, gas) to probe central potentials of nearby, inactive galaxies.

Orbits of stars around BH
(A reminder)

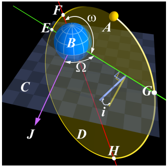
Stars move in gravitational potential

$$\Phi(\mathbf{r}) = -\frac{GM_\bullet}{r} + \Phi_\star(\mathbf{r}).$$

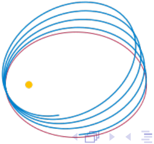
Close to BH, $\Phi_\star$ is small perturbation: akin to solar system!

To 0$^{\text{th}}$-order ($\Phi_\star \to 0$), orbits are closed ellipses with constant

- semimajor axis a,
- eccentricity e,
- argument of periapse ω,
- angles (i, Ω) giving orientation of orbit plane / **L** vector.



To next order ($\Phi_\star \neq 0$), ω precesses with frequency $\propto M_\star$

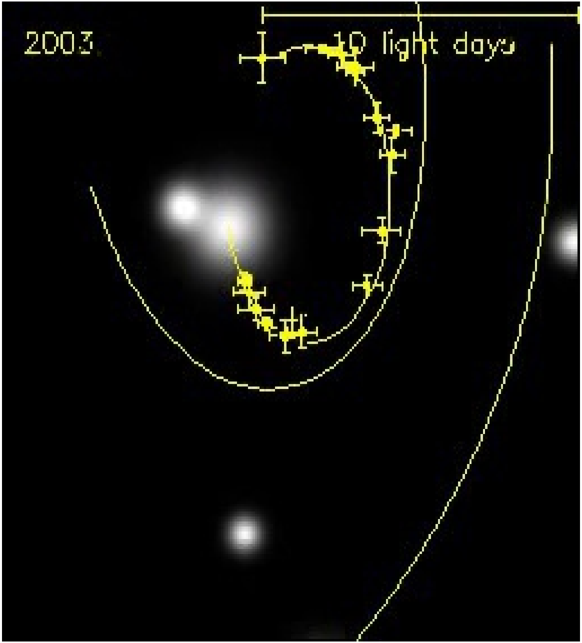


The Milky Way
(Genzel et al.; Ghez et al.)

We're $\sim$ 8 kpc from Galactic centre.
Undetectable in optical: dust attenuates by factor $\sim 10^{-10}$.

Radio:
Compact source Sgr A* (1974).
Size 37 microarcsec (VLBI observations, 2008): $\sim$ 1 AU.

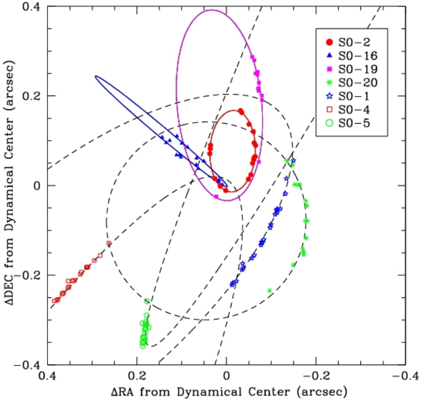
Infrared: (1992–present)
2 groups start long-term monitoring.
See stars at GC move!

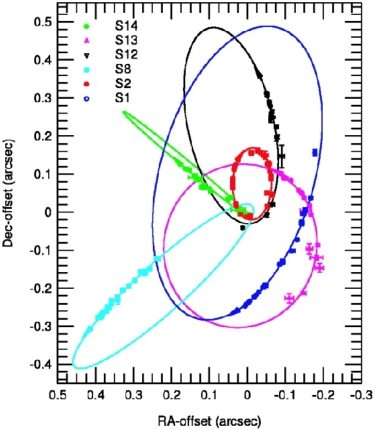


Movie credit: MPE

The massive dark object at the Galactic Centre
(Genzel+MPE, Ghez+UCLA)

Orbits of *S stars* around Sgr A*:





All fit by Kepler ellipses around $M_\bullet = 4.4 \times 10^6\, M_\odot$ at Sgr A*.
NB: star S2 has period 15.2 yr, pericenter 17 light hours.

Is this massive dark object a BH?

Lack of detectable deviations from Keplerian ellipse for S2 $\Rightarrow$ extent of dark object $\lesssim 10^{-3}$ pc.

Suppose object is cluster of things of mass $m_\star$ spread over radius $r_{1/2}$.
Cluster "evaporates" on timescale (Maoz 1998)

$$t_{\rm evap} = 10^8 \left(\frac{M_\bullet}{4\times 10^6\,M_\odot}\right)^{1/2} \left(\frac{M_\odot}{m_*}\right) \left(\frac{r_{1/2}}{0.01\,\rm pc}\right)^{3/2} \,\rm yr.$$

This rules out any plausible, known cluster constituents.

Maybe it's something more exotic than BH?

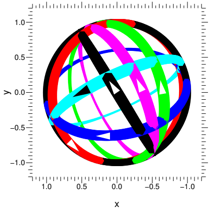
Puzzles among the tracers

Naive expectation:

- only old stars
- completely relaxed, Maxwell-Boltzmann $f(\mathbf{p})$

Reality:

1. Dominant old, relaxed population
   - Observations sample only the very brightest stars
2. S stars:
   - B stars with masses $3.5 - 20\, M_\odot$
   - found at radii $r \lesssim 0.02$ pc
   - randomized orbits



(Paumard+2006: Black, blue, red)

3. Population of ~ 100 massive young stars in innermost pc.
   - O/WR stars, born with $30 - 100\, M_\odot$.
   - Arranged in two eccentric, warped discs.
   - Discs are misaligned with each other,
   - but have identical 6 ± 2 Myr ages.

Warped discs around a BH
(Rauch & Tremaine 1997; Tremaine 2005)

When $\Phi_\star$ is small, $t_{\rm orb} \ll t_{\rm precess} \sim t_{\rm orb}(M_\bullet/M_\star)$.

On timescales $\lesssim t_{\rm precess}$, replace stars by orbit-averaged elliptical rings.
Each ring labelled by $(a, e, i, \omega, \Omega)$.

Elliptical rings exert torques on each other (Laplace–Lagrange).
Orientation of each ring undergoes a random walk.

Warps, misalignments develop on timescales $Nt_{\rm precess}$, where $N = M_\star/m_\star$ is the number of rings.

At $r \simeq 0.5$ pc from GC BH, $t_{\rm precess} \sim 10^6\, M_\odot$:
consistent with 6 Myr stellar ages.

How long before the BH consumes us?

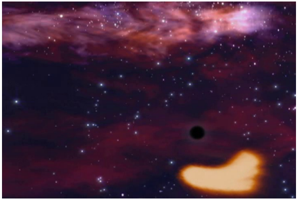
Stars of mass $m_\star$, radius $r_\star$ that come within radius

$$r_{\rm t} \approx \left(\frac{M_\bullet}{m_\star}\right)^{1/3} r_\star$$

of the BH are *tidally disrupted*.

$\sim \frac{1}{2}$ debris swallowed by BH.

$r_t \sim 10 r_S$ for sun at GC.



Animation: ESA

Only stars with angular momenta $L^2 \lesssim 2GMr_t$ have $r_{\rm peri} < r_t$.
Total mass of such stars in MW: $\sim 10\,M_\odot$!
Composed of plunging radial orbits, unbound to BH.

Fluctuations in $\Phi_\star$ give stars small kicks in L^2.
Steady-state delivery rate $\dot{M}_\bullet \sim 10^{-4}\,M_\odot/\mathrm{yr}$.

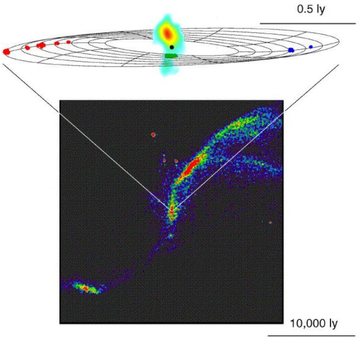
$\Rightarrow$ **BHs don't grow by eating stars!**

NGC 4258
(aka Messier 106, $\sim$ 10 Mpc distant)

Optical image:

NGC 4258
(Miyoshi et al. 1995)

Radio interferometry reveals a central disc of molecular gas, with water maser emission.



Beautifully Keplerian. $M_\bullet = 4 \times 10^7\,M_\odot$.

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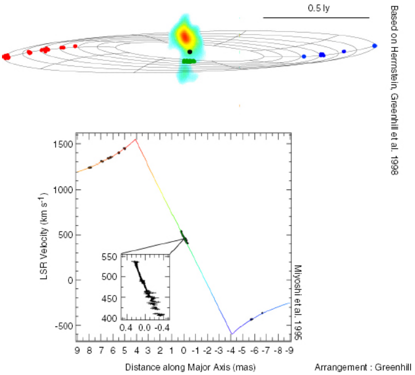
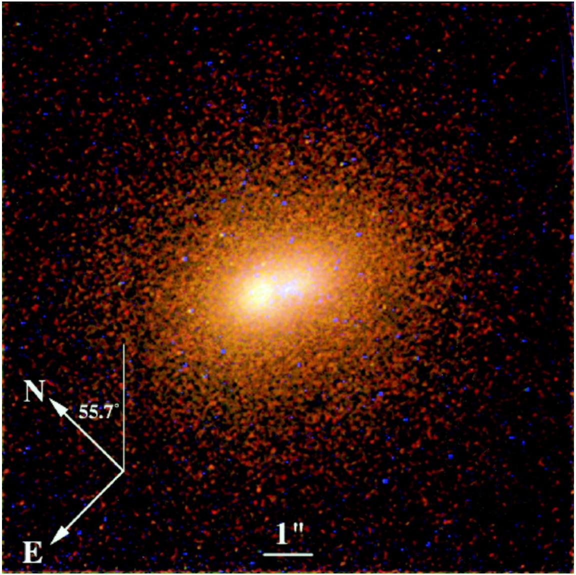


Beautifully Keplerian. $M_\bullet = 4 \times 10^7\, M_\odot$.

The black hole at the centre of Andromeda (M31)

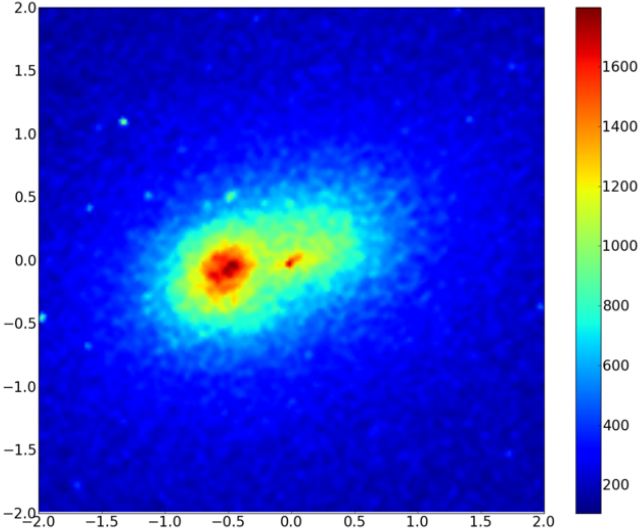
Data

True-colour HST photometry (Lauer et al 98):



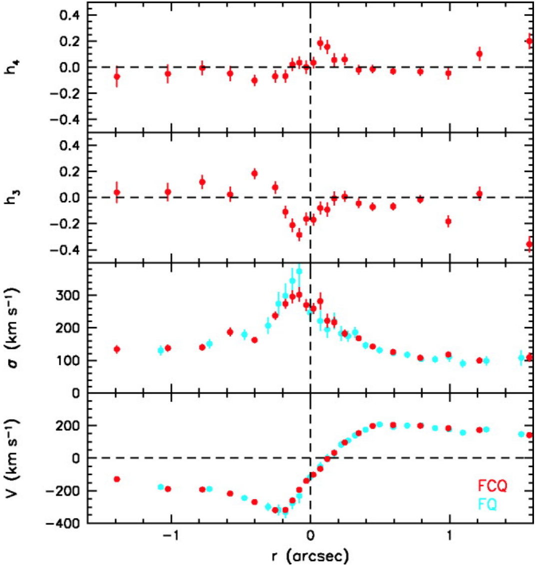
Data

Single-band false colour image (Lauer et al 98):



Data

STIS CaT long-slit kinematics (Bender et al 2005):



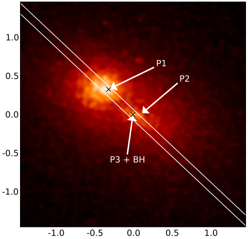
Characteristic numbers for M31 double nucleus

Distinct nucleus $L_V \simeq 6 \times 10^6 L_\odot$ with two peaks, P1 and P2.

P1 and P2 have identical colours: **old, red**.

P2 is photometric centre of galaxy (to $\sim 0.1''$).

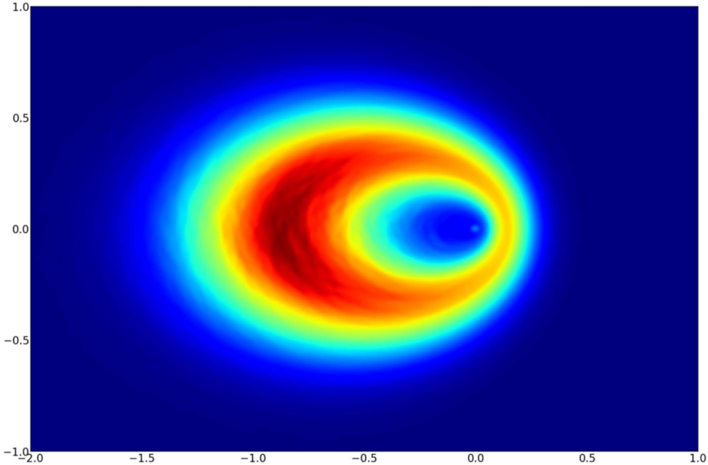
- P1-P2 separation $r = 0.5$ arcsec = 2 parsec
- $\Delta v \sim 200$ km/s
- Dynamical time $2\pi r/v \sim 10^5$ yr.



Two distinct clusters?
Dynamical friction timescale only $\sim 10^8$ yr.

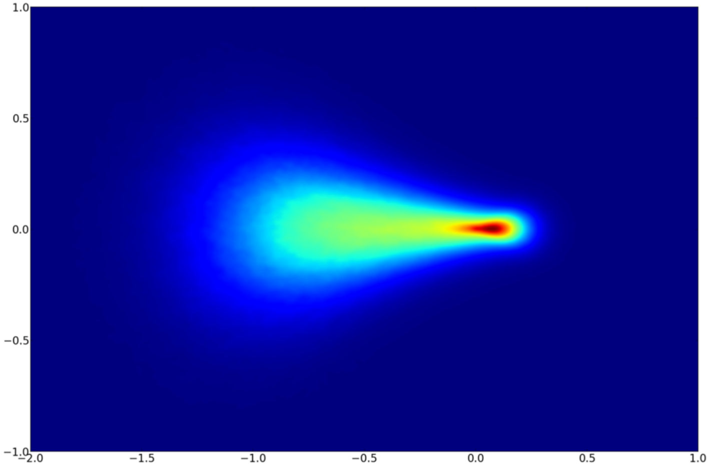
An eccentric disc around a BH?
Tremaine 1995

Clump of orbits around $a = 1$, $e = 0.7$ viewed top down:



An eccentric disc around a BH?
Tremaine 1995

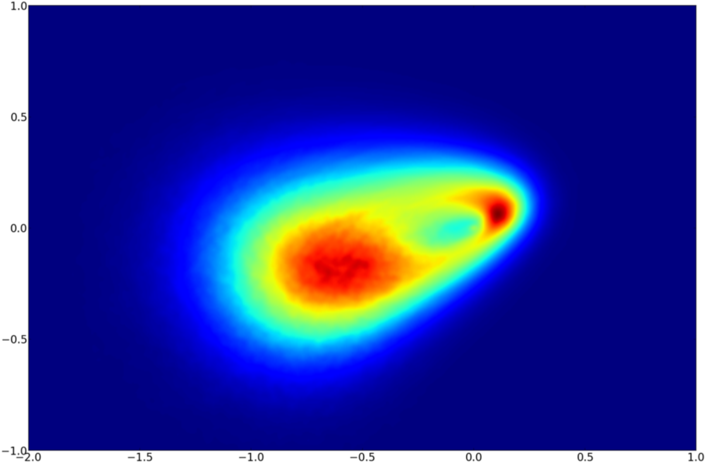
Clump of orbits around $a = 1$, $e = 0.7$ viewed edge on:



An eccentric disc around a BH?

Tremaine 1995

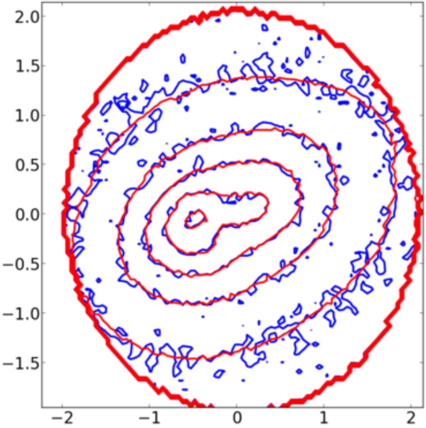
Clump of orbits around $a = 1$, $e = 0.7$ viewed just right:



Naive models of M31 nucleus
(Brown & JM, 2013, 2015)

Assume biaxial symmetry in y and z planes (no warp!).
Find distribution $f(a, e, i, \omega, \Omega)$ that reproduces observations.

Results: Fit to photometry



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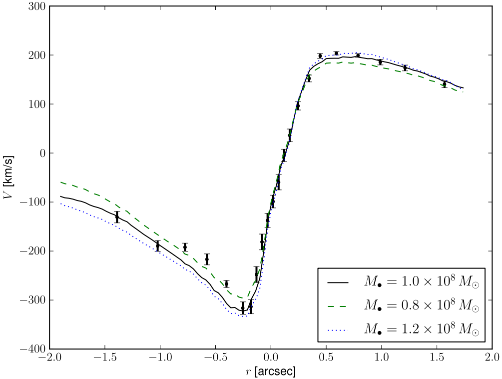
Results: Fit to HST V for various assumed $M_\bullet$



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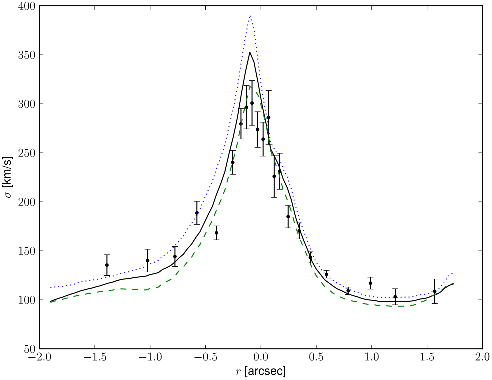
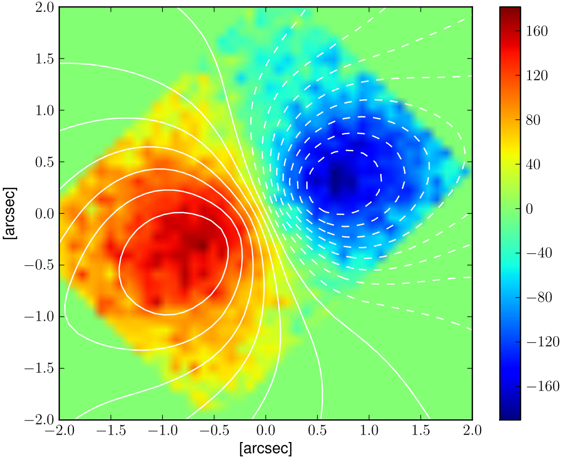
Results: Fit to HST σ for various assumed $M_\bullet$



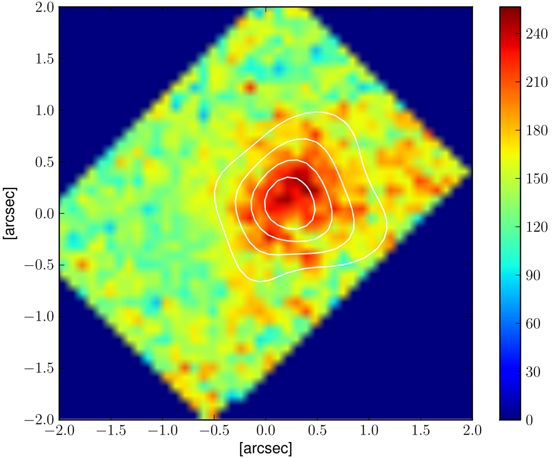
Naive models of M31 nucleus

Model *predictions* for $M_\bullet \simeq 10^8 M_\odot$ vs 2d kinematic maps: V



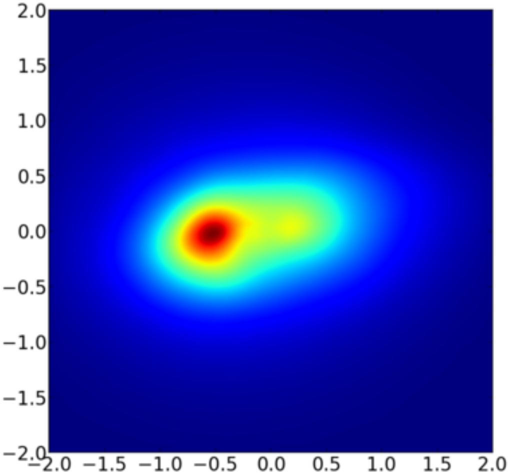
Naive models of M31 nucleus

Model *predictions* for $M_\bullet \simeq 10^8 M_\odot$ vs 2d kinematic maps: σ



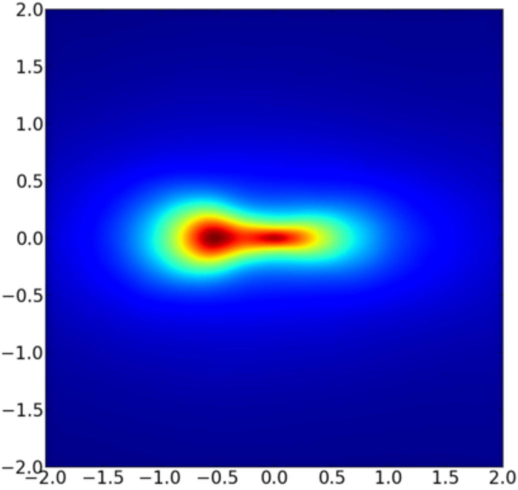
Naive models models of M31 nucleus

What does the disc look like? LOS projection:



Naive models of M31 nucleus

What does the disc look like? Edge-on:



Naive models: a puzzle

When we examine our best-fit $f(a, e, i, \omega, \Omega)$, we find

$$\frac{\langle i^2 \rangle}{\langle e^2 \rangle} \simeq 2.$$

But standard dynamical models of two-body relaxation in *circular* discs predict

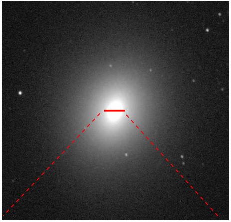
$$\frac{\langle i^2 \rangle}{\langle e^2 \rangle} = \frac{1}{2}.$$

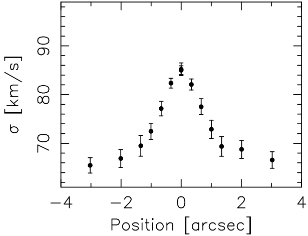
Our result seems robust, subject to biaxial assumption.

III. Supermassive BHs are standard equipment in galaxy bulges

Other galaxies

Q:What stops galaxy from collapsing? **A:** pressure!
Example: kinematics at very centre of M32





Must resolve radii where BH dominates Φ: nearby galaxies only.

Other galaxies

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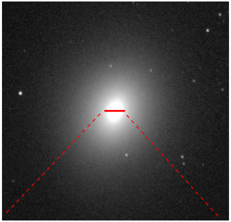

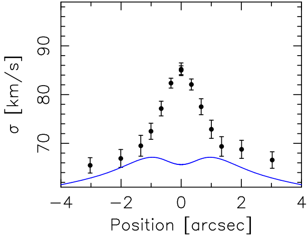

Model with no BH

Must resolve radii where BH dominates Φ: nearby galaxies only.

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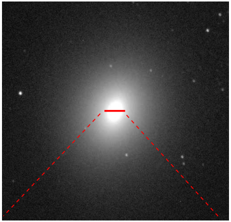

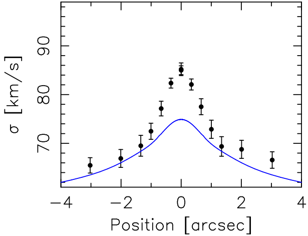

$$M_\bullet = 1 \times 10^6\, M_\odot$$

Must resolve radii where BH dominates Φ: nearby galaxies only.

Other galaxies

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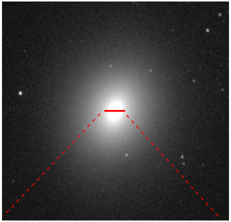

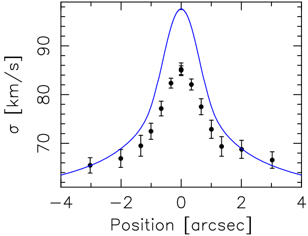

$$M_\bullet = 4 \times 10^6\, M_\odot$$

Must resolve radii where BH dominates Φ: nearby galaxies only.

Other galaxies

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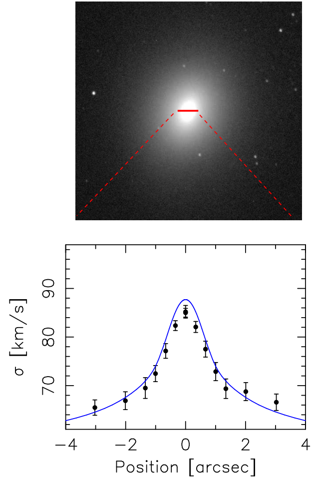
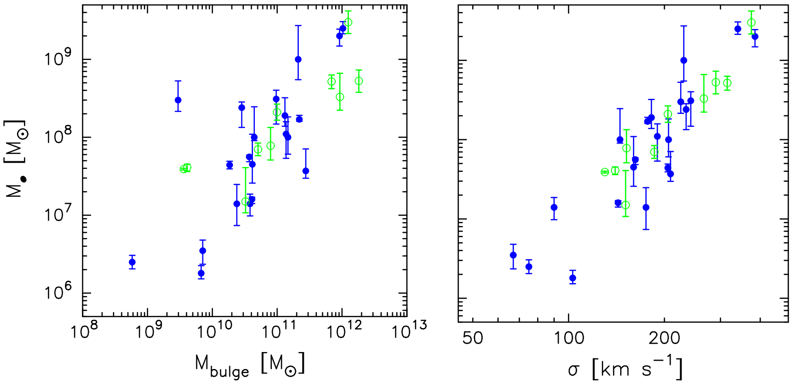


$$M_\bullet = 2.6 \times 10^6\, M_\odot$$

Must resolve radii where BH dominates Φ: nearby galaxies only.

The most remarkable fact about BHs
(Gebhardt et al; Ferrarese & Merritt; Tremaine et al.)

BHs know about their host bulges:



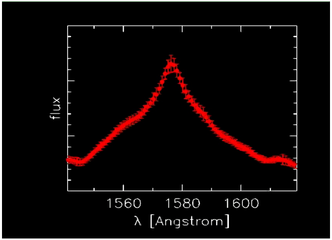
Upper left ~~definitely~~ empty(ish); bottom right almost certainly so.

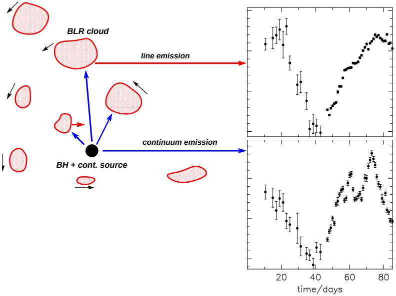
$M_\bullet \approx 10^{-3} M_{\rm bulge}$; $M_\bullet \sim \sigma^4$.

Reverberation mapping

We can measure $M_\bullet$ directly only in nearby, inactive galaxies. What about distant, active ones? Broad Line Regions.

Time variation of CIV line in NGC 5548:





$M_\bullet = frv^2/G$, where v is line width, r is lag between line and continuum, and fudge factor f depends on geometry of BLR.

Works at very high redshift.

Reverberation mapping

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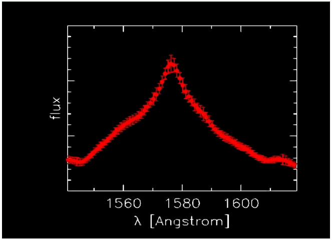

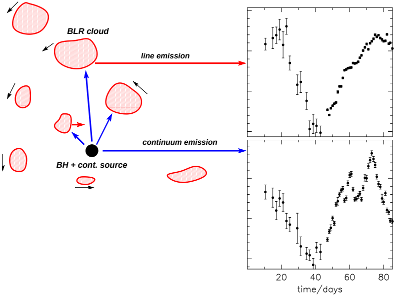

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Summary

1. Astrophysical evidence for BHs is compelling, but indirect:
   - limited by spatial resolution
   - No clear signature of event horizon (therefore spin)
   - but we can still measure masses.
   - At least two different ways of forming BHs.
   - In the future, gravitational-wave detectors should detect mergers of stellar-mass BHs.
2. Interesting dynamics in almost Keplerian potentials.
3. Most nearby galaxy bulges harbour a supermassive black hole
   - we don't understand how either form
   - but galaxy growth somehow linked to BH growth.