Astrophysical Black Holes

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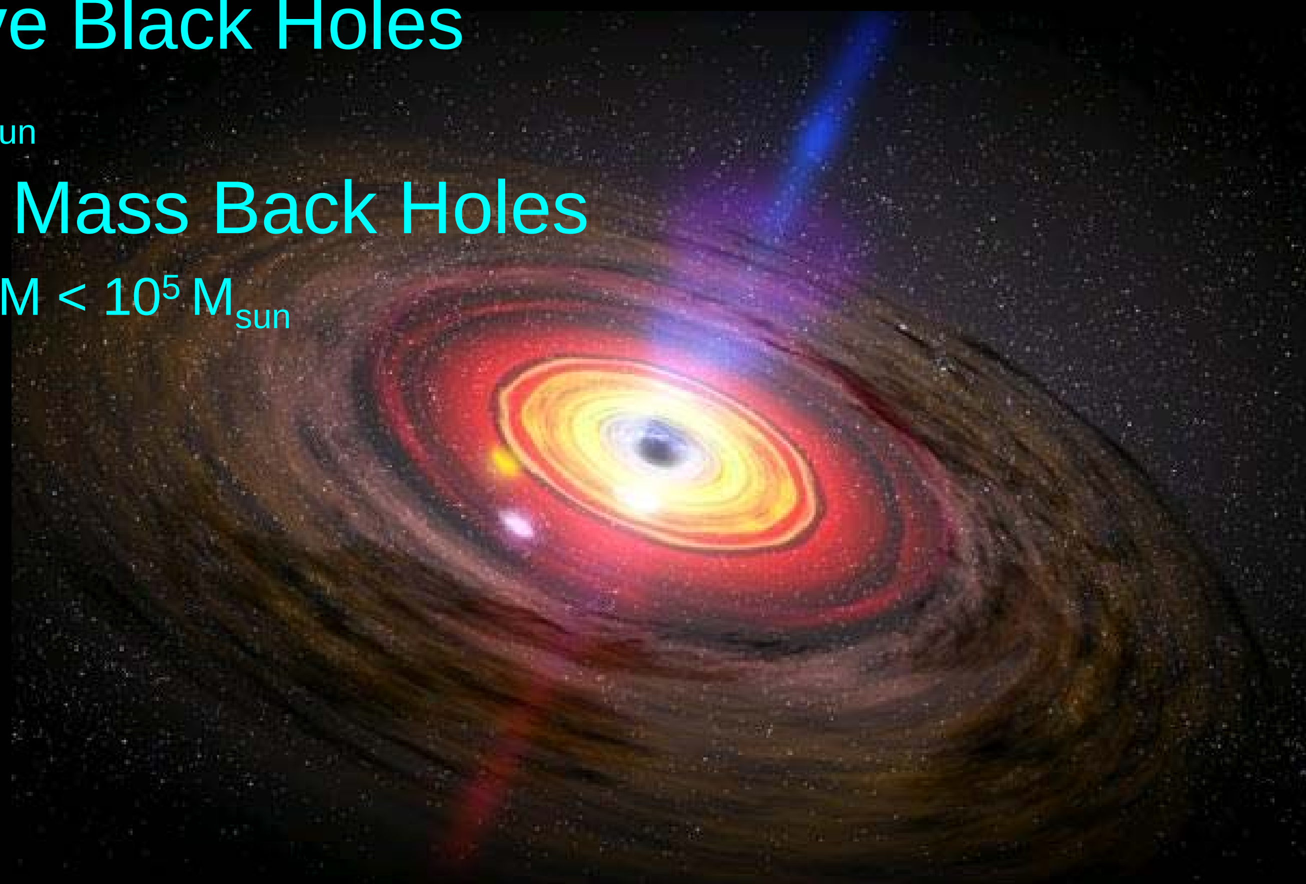
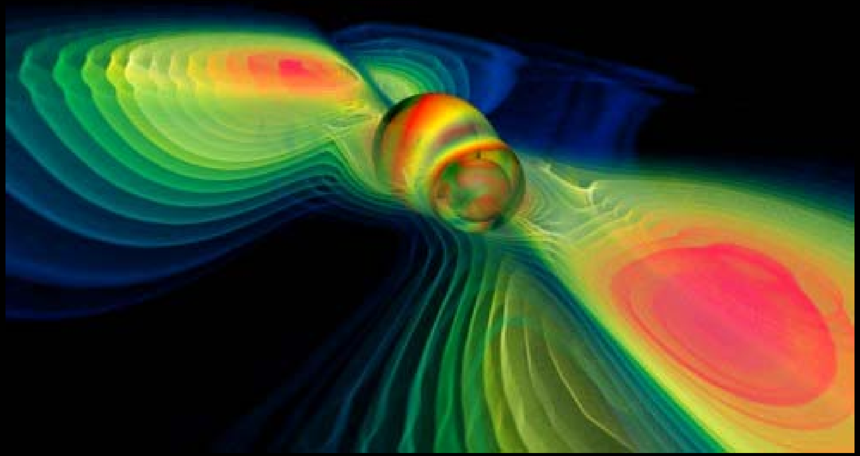
Contents

- Stellar Mass Black Holes
  - $3\ M_{sun} < M < 20\ M_{sun}$
- Supermassive Black Holes
  - $M > 10^6\ M_{sun}$
- Intermediate Mass Back Holes
  - $10^2\ M_{sun} < M < 10^5\ M_{sun}$

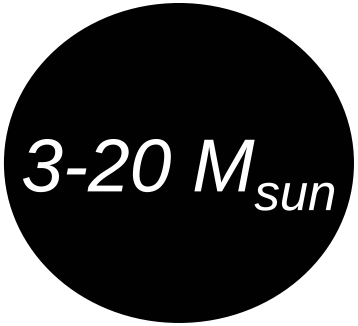


Gravitational Wave Searches for BHs

- Have looked for gravitational wave signature of perturbed black holes (e.g. from binary merger) in LIGO data since S2, no detection so far.
- GW detection would provide unambiguous evidence for BH.
- Important to understand astrophysics of BHs and evidence for them from electromagnetic observations.
- This talk is concerned with electromagnetic observations of BHs.



Stellar Mass Black Holes



Theoretical Foundations



- **Michell (1784)**
  - Described a star so dense that not even light could escape
- **Laplace (1792)**
  - Similar discussion without reference to Michell
- **Schwarzschild (1916)**
  - found exact solution to Einstein's equations
- **Chandrasekhar (1930)**
  - upper limit to mass of white dwarf, 1.4 M_{sun}
- **Oppenheimer & Volkoff (1939)**
  - upper limit to mass of neutron star, 0.7 M_{sun}
- **Oppenheimer & Snyder (1939)**
  - Used GR to demonstrate the implosion of a idealized massive star to form a black hole
- **Wheeler (1967)**
  - coined the term 'black hole'



Theoretical Black Holes

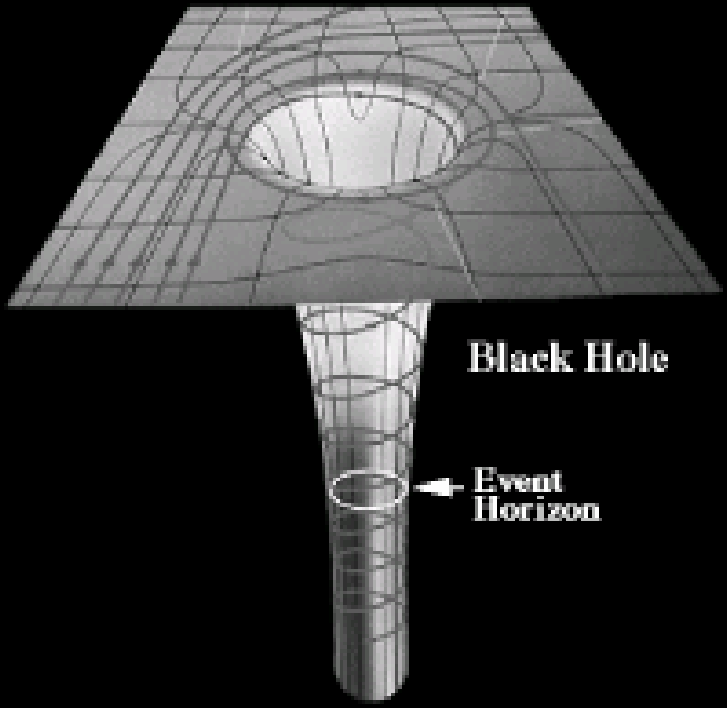
- According to General Relativity a black hole is a singularity in space-time curvature producing a gravitational field so strong that not even light can escape

- Schwarzschild radius is the radius within which a star of mass M will collapse to a form singularity, $R_S=2GM/c^2$.

- Event horizon marks the point of no return for photons.

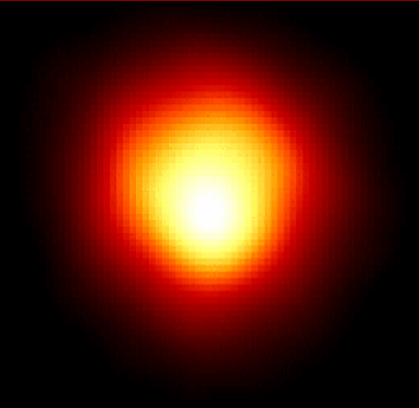
- The surface of a black hole is not made up of matter, so doesn't radiate EM

- We can observe the effects of the strong gravitational field of a BH by EM radiation from nearby particles.



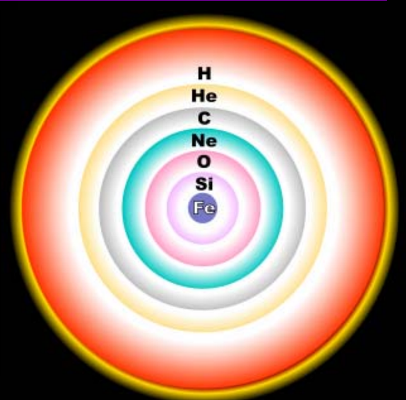
Stellar Mass Black Hole Formation

Massive star ($M>8M_{sun}$) burns hydrogen and helium & becomes red supergiant

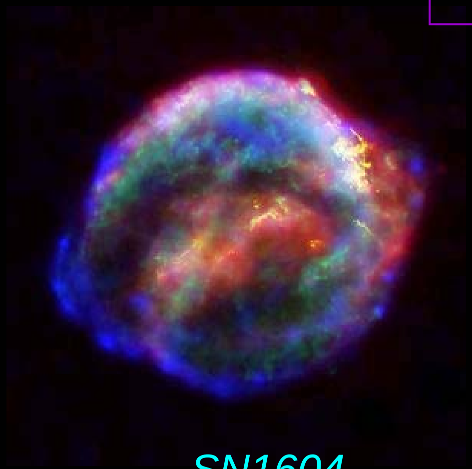


Betelgeuse
(Photo Credit: A. Dupree, R. Gilliland)

Carbon core starts chain of reactions, eventually forming an iron core

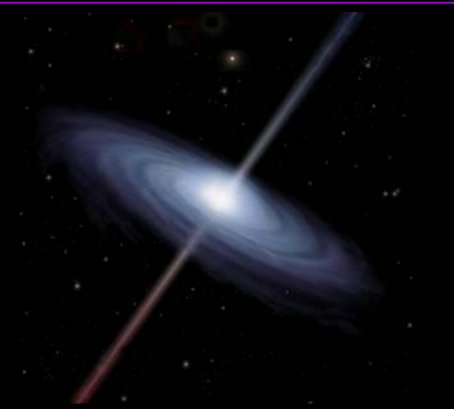


Collapsing core halted by strong force, causes shock wave



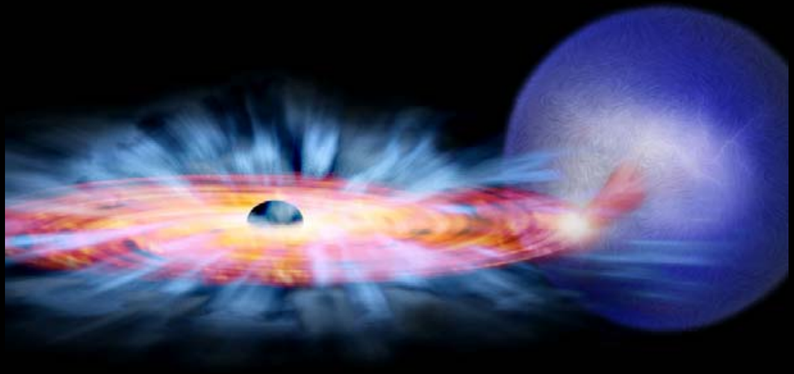
SN1604
(Photo Credit: NASA)

Neutron degeneracy pressure not sufficient to withstand pull of gravity, collapses to a black hole



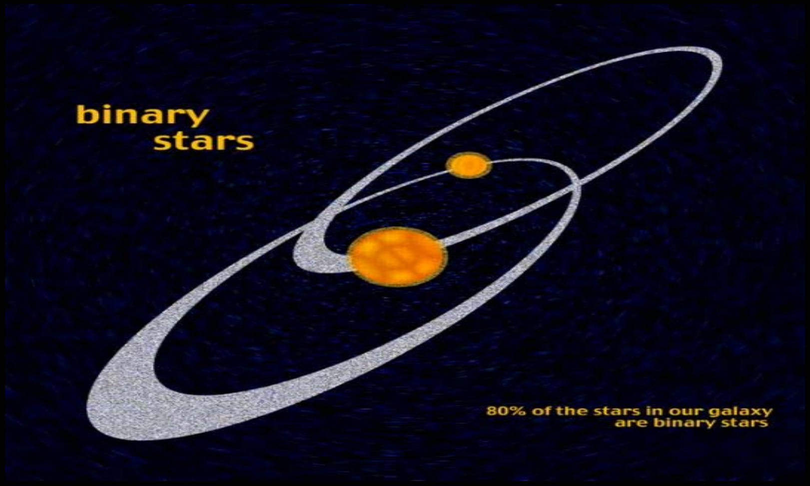
Theoretical Search

- In 1966 Zel'dovich & Novikoff and Salpeter (independently) realized that gas orbiting around a black hole would be heated to very high temperatures emitting X-rays.



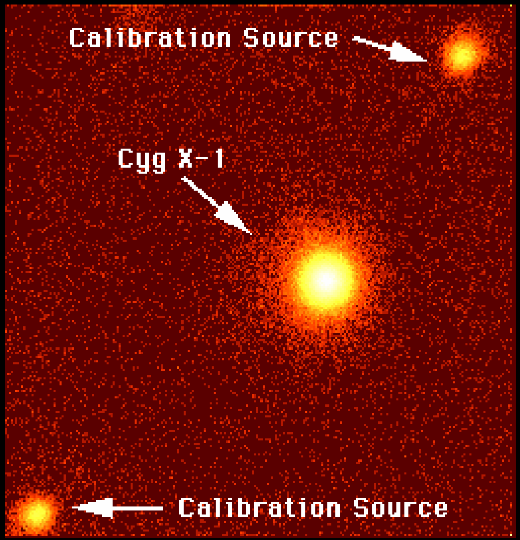
(Illustration: NASA/CXC/M.Weiss)

- If the black hole had an optical companion its spectrum would infer its velocity from which the mass of the black hole could be inferred.

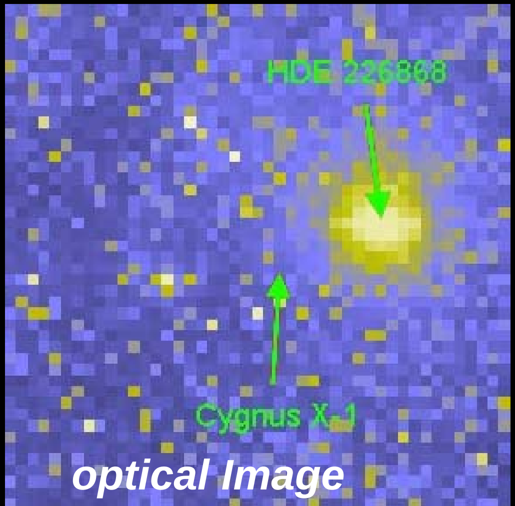


Cygnus X-1

- Discovered in 1964 in a rocket flight (Bowyer *et al.*)
- Position was narrowed down to a 2 arc-minute sized error box by Uhuru observation in 1971.
- Radio flare observed in 1971 Uhuru error box (Hjellming *et al.*).
- Binary companion identified in the optical, HDE 226868 (Bolton *et al.*) 1971.
- Need to measure the mass of the compact object to verify that it is not a neutron star, $M < 2.8M_{sun}$ (Kalogera & Baym '96)



X-ray Image:BeppoSAX/LECS Team at ESA/ESTEC



Dynamical Mass Estimate

Companion radial velocity ~64 km s^{-1}

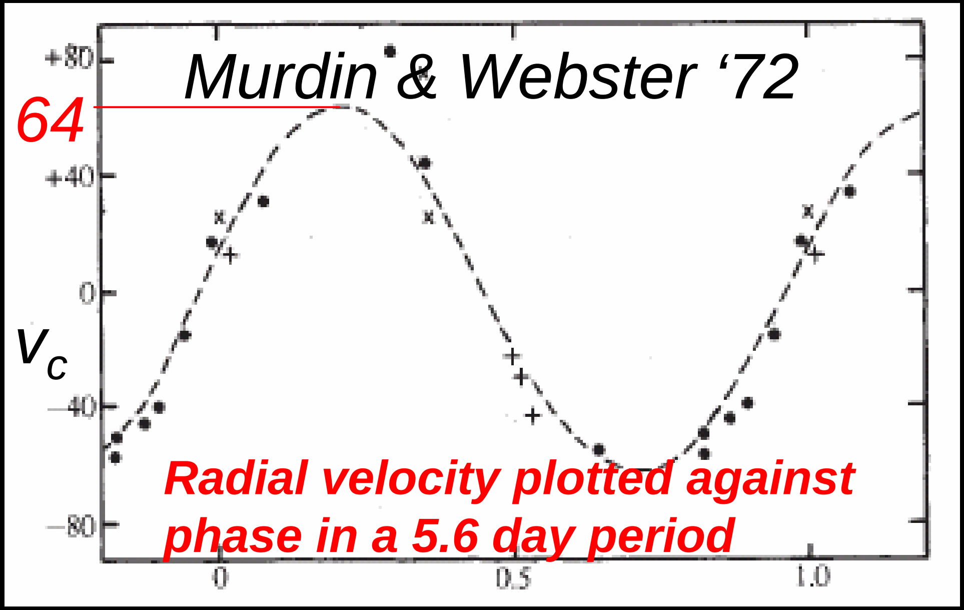
orbital period ~5.6 days

$$\frac{P}{2\pi G} v_c^3 = \frac{M_x^3 \sin^3 \iota}{(M_c + M_x)^2}$$

Inclination of orbit, ~ 60^o

Companion mass ~$10M_{sun}$

Mass of compact object

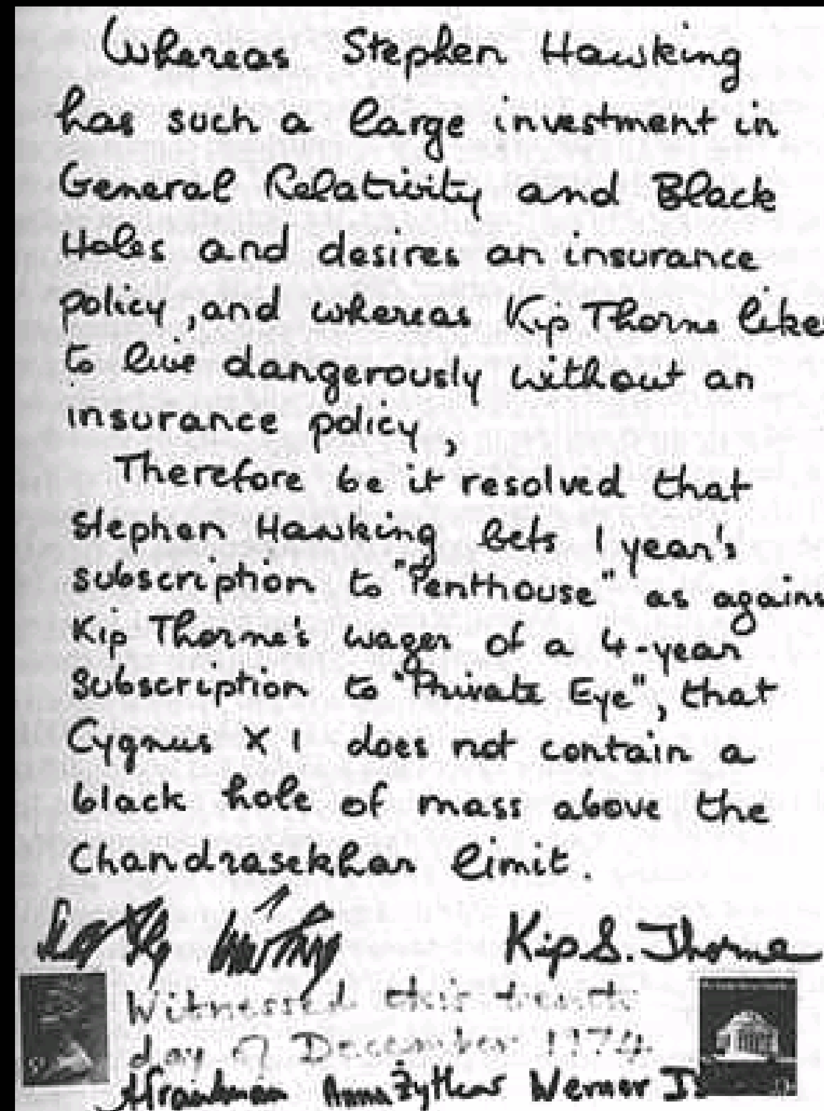


$M_x > 4M_{sun}$

➡ BLACK HOLE!

Cygnus X-1

- Cyg X-1 was the only BH candidate for 10 years.
- Now there is “no doubt about the presence of a black hole in the system”
- 6.85 $M_{sun} < M_x < 13.25\ M_{sun}$, *(Orosz ’02)*
- Cyg X-1 was the subject of a bet between Hawking and Thorne in 1974.
- Hawking conceded that it is a BH in 1990.


Whereas Stephen Hawking has such a large investment in General Relativity and Black Holes and desires an insurance policy, and whereas Kip Thorne likes to live dangerously without an insurance policy,

Therefore be it resolved that Stephen Hawking bets 1 year's subscription to "Penthouse" as against Kip Thorne's wager of a 4-year subscription to "Private Eye", that Cygnus X 1 does not contain a black hole of mass above the Chandrasekhar limit.

[illegible] Kip S. Thorne

Witnessed this [illegible] day [illegible] December 1974.

[illegible]

How many stellar mass BHs are there?

Confirmed black hole candidates in X-ray binaries: Casares '06

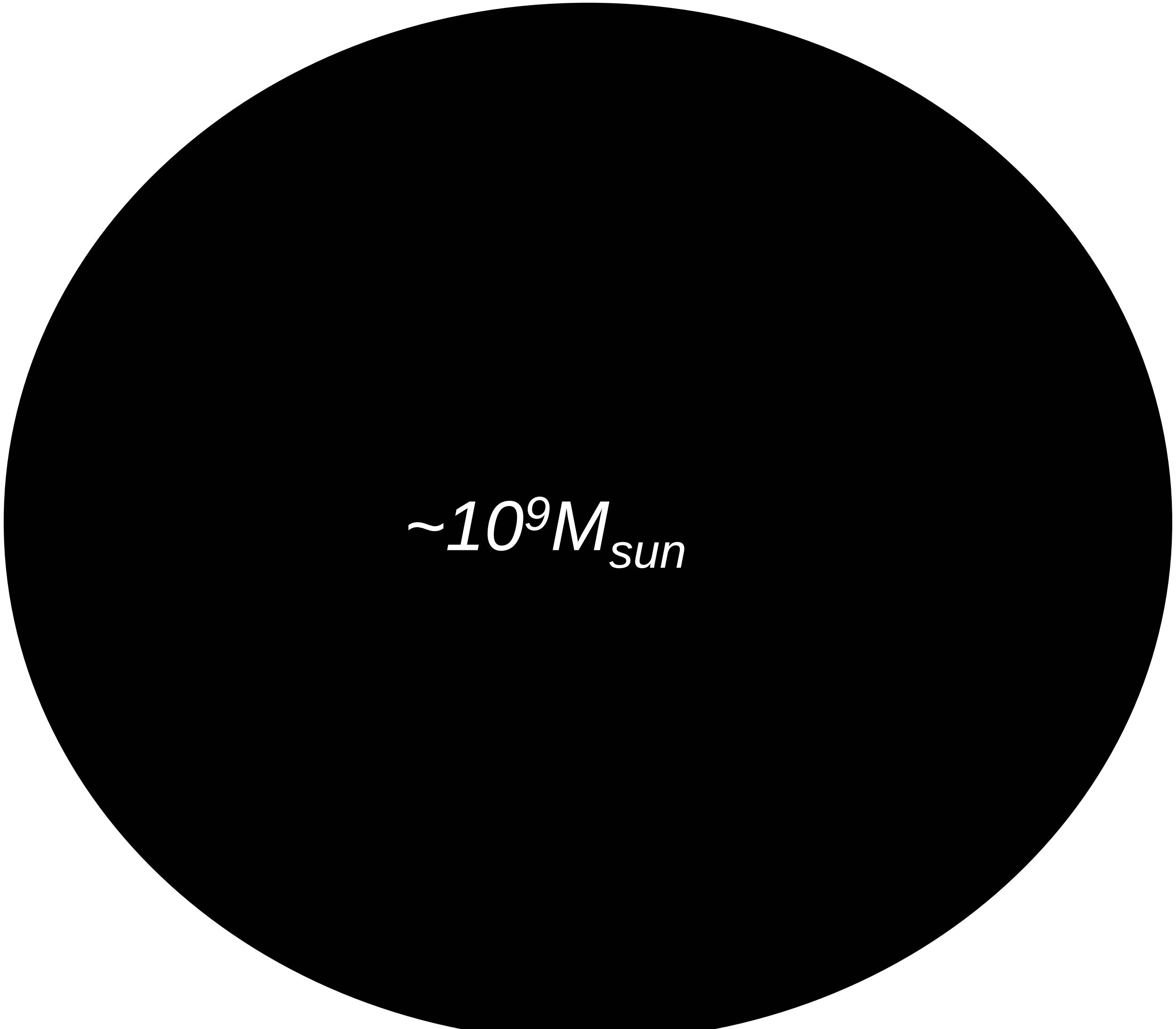
System	P_{orb} [days]	$f(M)$ [$M_{\odot}$]	Donor Spect. Type	Classification	M_x † [$M_{\odot}$]
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	,,	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	,,	> 4
XTE J1819-254	2.816	3.13 ± 0.13	B9 III	IMXB/Transient	7.1 ± 0.3
GRO J1655-40	2.620	2.73 ± 0.09	F3/5 IV	,,	6.3 ± 0.3
BW Cir[b]	2.545	5.74 ± 0.29	G5 IV	LMXB/Transient	> 7.8
GX 339-4	1.754	5.8 ± 0.5	–	,,	
LMC X-3	1.704	2.3 ± 0.3	B3 V	HMXB/Persistent	7.6 ± 1.3
XTE J1550-564	1.542	6.86 ± 0.71	G8/K8 IV	LMXB/Transient	9.6 ± 1.2
4U 1543-475	1.125	0.25 ± 0.01	A2 V	IMXB/Transient	9.4 ± 1.0
H1705-250	0.520	4.86 ± 0.13	K3/7 V	LMXB/Transient	6 ± 2
GS 1124-684	0.433	3.01 ± 0.15	K3/5 V	,,	7.0 ± 0.6
XTE J1859+226[c]	0.382	7.4 ± 1.1	–	,,	
GS2000+250	0.345	5.01 ± 0.12	K3/7 V	,,	7.5 ± 0.3
A0620-003	0.325	2.72 ± 0.06	K4 V	,,	11 ± 2
XTE J1650-500	0.321	2.73 ± 0.56	K4 V	,,	
GRS 1009-45	0.283	3.17 ± 0.12	K7/M0 V	,,	5.2 ± 0.6
GRO J0422+32	0.212	1.19 ± 0.02	M2 V	,,	4 ± 1
XTE J1118+480	0.171	6.3 ± 0.2	K5/M0 V	,,	6.8 ± 0.4

How many stellar mass BHs are there?

- In the last year new observations included:
  - Largest stellar mass black hole (15.65$\pm$1.45) M_{sun} in M33, (Orosz *et al.* Oct '07).
  - Smallest stellar mass black hole ~3.8 M_{sun} (Shaposhnikov & Titarchuk Apr '08).

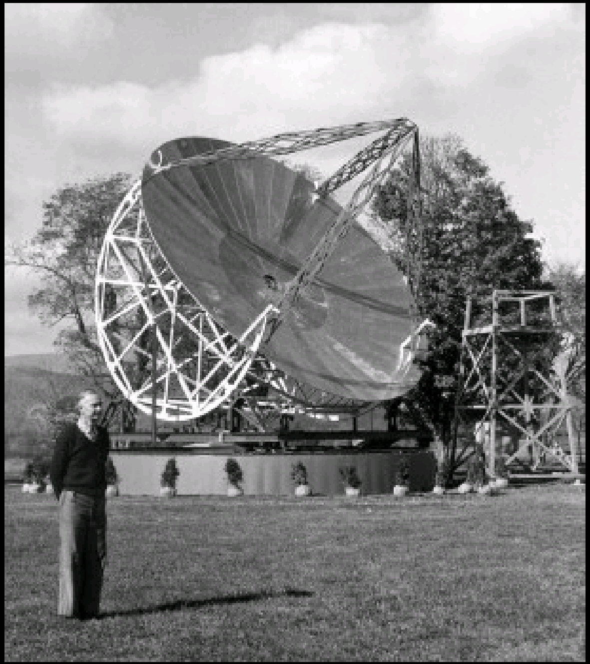
- *This is just the tip of the iceberg…*
  - Population synthesis models predict ~10^3 stellar mass black hole binaries in the galaxy (Yungelson *et al*.'06).
  - Evolutionary models predict a population of 10^9 stellar mass black holes in the galaxy (Bethe & Brown '94).

Supermassive Black Holes (SMBHs)



First Observational Evidence for SMBHs

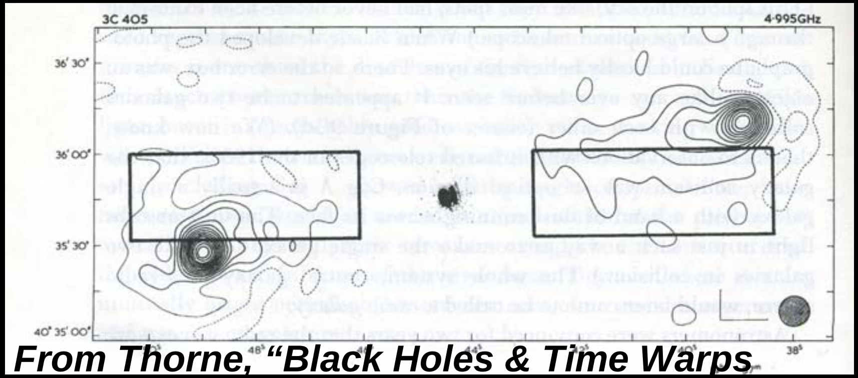
- The effects of supermassive black holes were observed long before they were identified
  - Inspired by Jansky's detection of cosmic radio waves, Reber designed and built a 30m radio telescope in 1939 and made radio maps of the sky. (radio galaxies)



  - In a 1943 paper Carl Seyfert identified 6 galaxies with highly unusual nuclei. He observed emission lines broadened by Doppler motion by amounts up to 8500 km s^{-1}.

Discovery of Radio Galaxies

- By the 1950s radio telescopes had achieved resolutions comparable to optical telescopes.
- Guided by a radio observation by a group in Cambridge in 1951 Baade and Minkowski took an optical image and identified the radio source with Cyg A.
- In 1953 further improvements in radio telescopes revealed that the radio emission was coming from giant lobes on either side of the 'colliding galaxies'.
- Later discovered it was a single galaxy with jets of gas emitted from the core in opposite directions ("*radio galaxy*").



From Thorne, "Black Holes & Time Warps

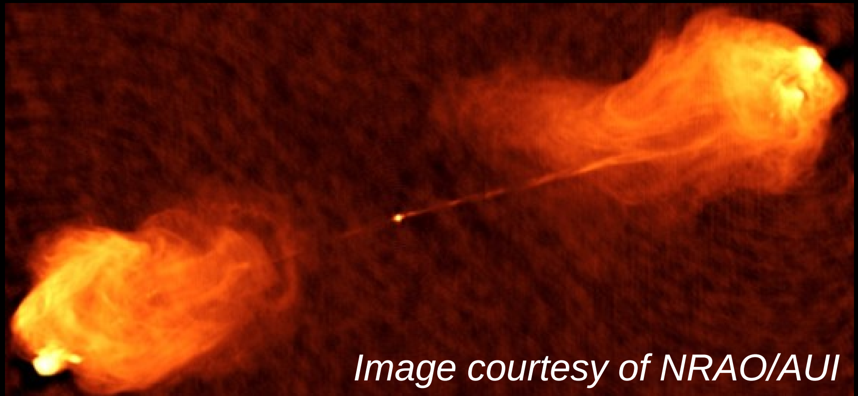


Image courtesy of NRAO/AUI

Discovery of Quasars

- 1960: QUASi-stellAR radio source, 3C48 was discovered.
- Optical observation *(Sandage)* confirmed that was a point of light however its spectrum was unlike that ever seen before.
- 1963: Schmidt; the four brightest lines in 3C273 were the Balmer lines of hydrogen shifted to the red by 16%.
- Most likely due to Hubble expansion producing a highly red-shifted spectrum of a very distant source

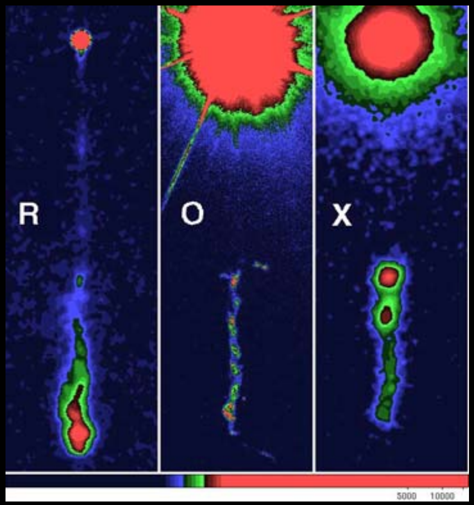
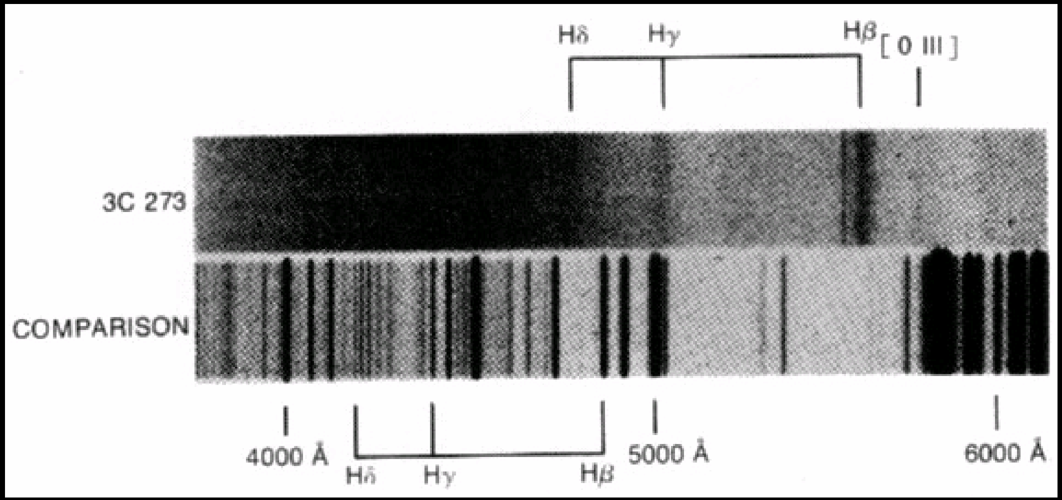


Image: VLA (R), HST (O), Chandra (X)



- Luminosities are 10 times larger than the brightest radio galaxy.
- Question: what is powering them?

Gravity as a Source of Energy

- In 1964 Zel'dovich and Salpeter extended their idea of radiation produced by a stream of gas to the observed radiation in quasars, suggesting that they were powered by black holes.
- Lynden-Bell in 1969 strengthened the argument for a gravitational source of energy by comparing it to a nuclear source.

Observed Energy: $E_q = 10^{61}$ erg $= 10^7 M_{sun}$ *radius:* $R=10^{13}m$

Mass required to produce this energy: $M = (a^{-1}-1)10^7 M_{sun}$

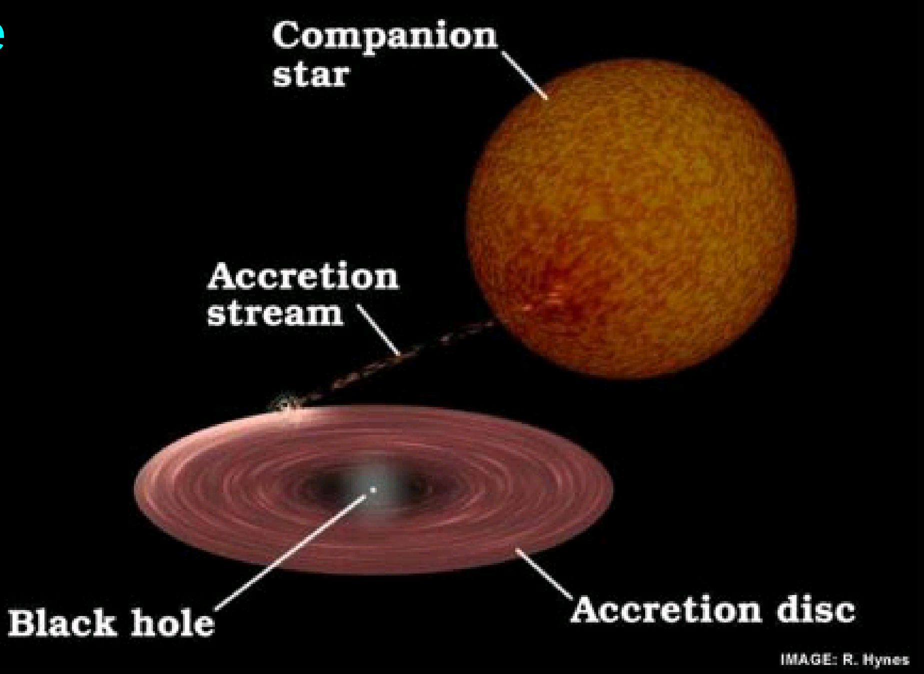
Efficiency of nuclear burning: $a = 1\%$ *implies* $M = 10^9 M_{sun}$

Gravitational potential energy: $E_{grav}=3/5\ GM/R = 10^{62}$ *erg*

"Evidently although our aim was to produce a model based on nuclear fuel, we have ended up with a model which has produced more than enough energy by gravitational contraction. The nuclear fuel has ended as an irrelevance." (Lynden-Bell `78).

SMBHs Responsible for Radio Emission

- In 1969 Lynden-Bell extended the idea of radiation producing by orbiting gas to active galactic nuclei (AGN).
- He suggested that the in-falling gas would form an accretion disk around the black hole.
- He speculated that the "*powerful emissions from the centers of nearby galaxies may represent dead quasars*".



- Rees, Lynden-Bell and Blandford showed that the swirling motion of the BH or the disk could strengthen any magnetic field present producing jets of high energy particles and magnetic fields (synchrotron radiation) such as were seen from radio galaxies.

Direct Detection of SMBHs

- Today, the presence of dark mass 10^6-10^9 M_{sun} is unambiguous but while the presence of a SMBH is the most plausible scenario this has not yet been *proven*.
- Strongest evidence to date for a central dark mass concentration comes from the dynamical observations of stars within its sphere of influence.
- Use this to derive the mass distribution *M(r)* and compare it to the light distribution *L(r)*. If *M(r)/L(r)* increases rapidly as *r* decreases, then there is a central compact dark object.
- By 2001, 37 SMBH candidates had been identified by dynamical methods in other galaxies
- Measurement of relativistic velocities near the Schwarzschild radius $R_s=2GM/c^2$ would provide stronger evidence for SMBHs.
- Definitive proof requires observation of gravitational waves.

Sagittarius A*

- Supermassive black hole at the center of the Milky Way galaxy, $M = (4.0 \underline{+} 0.3) \times 10^6\ M_{sun}$.
- Relatively inactive AGN, radio luminosity $L \sim 10^{34}$ erg s^{-1} ($L_{quasar} \sim 10^{46}$ erg s^{-1});
- Orbits of inner stars have been monitored for over 10 years. The closest star has an orbital period of 15 years and in 2002 came within 17 light-hours (3×10^{-5} pc) of the radio source, traveling at ~5000 km s^{-1}.
- *"The new measurements exclude with high confidence that the central dark mass consists of a cluster of unusual stars or elementary particles, and leave little doubt of the presence of a supermassive black hole at the centre of the galaxy in which we live" (ESO press release)*
- *Show movie of orbits around Sgr A*, from Max-Planck-Society:*
  - *http://www.eso.org/public/outreach/press-rel/pr-2002/video/vid-02-02.mpg*

Formation of SMBH

- Stellar mass black hole seeds from Population III stars grow by merging
- Direct formation from collapsing gas clouds in proto-galaxies
- Runaway collapse of dense stellar clusters
- Primordial black hole seeds grow by merging

(Djorgovski '08)

Rees, 1978

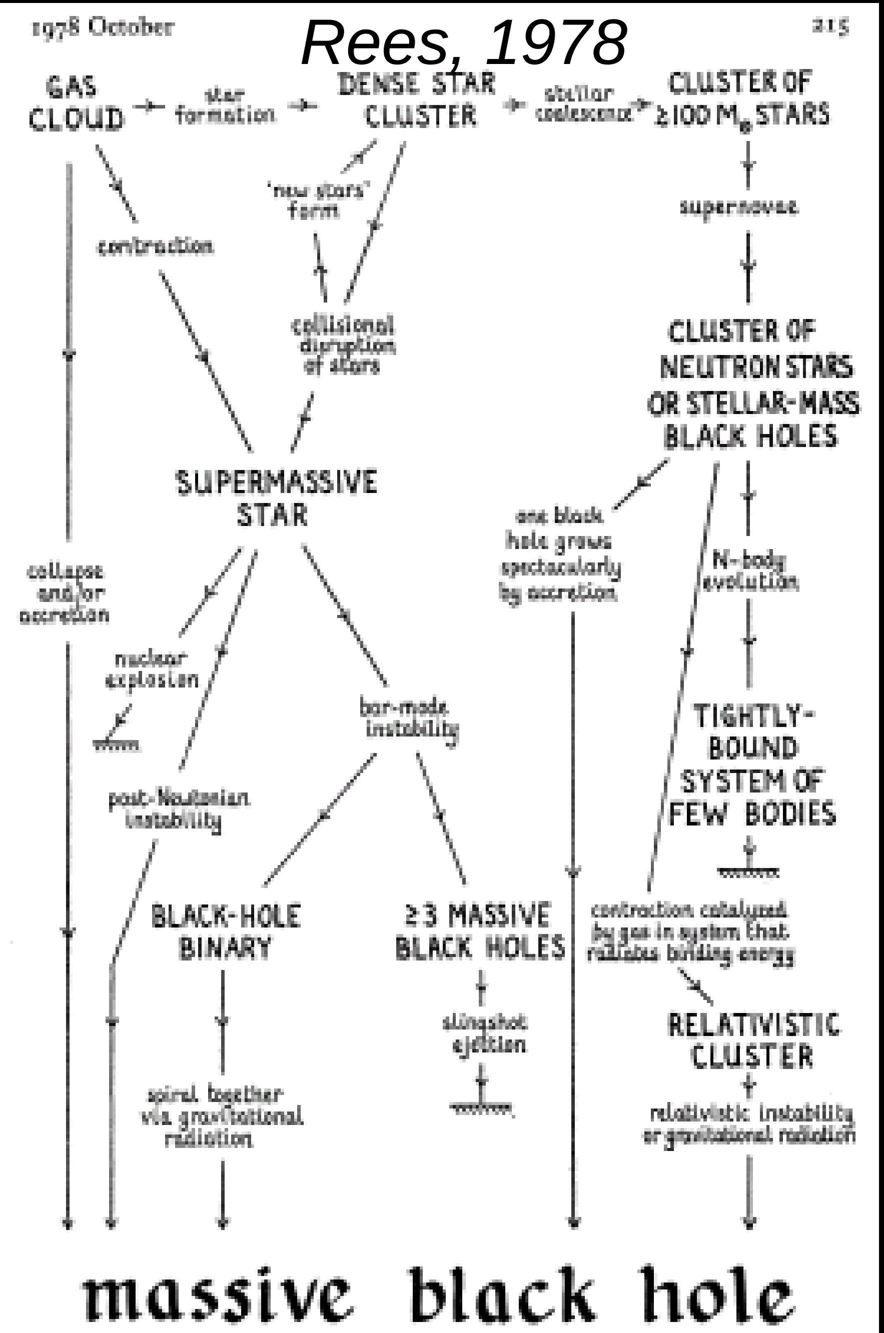


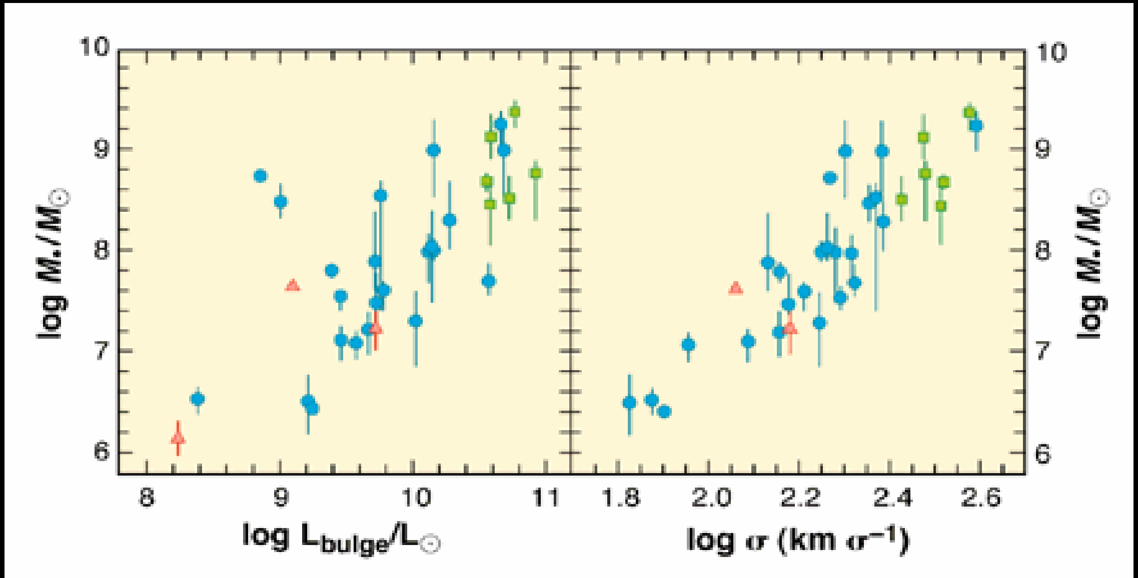
Fig. 2

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

Growth of SMBH, 2000

- HST surveys are finding SMBHs in every galaxy with a bulge component.
- Kormendy `93: $M_{SMBH}=10^{-3}M_{bulge}$.
- Ferrarese & Merritt '00: $M_{SMBH} \sim \sigma^4$, (σ = velocity dispersion)
- *"The observations show that the major events that form a bulge and the major growth phases of its BH were the same event".*

Kormendy 1993

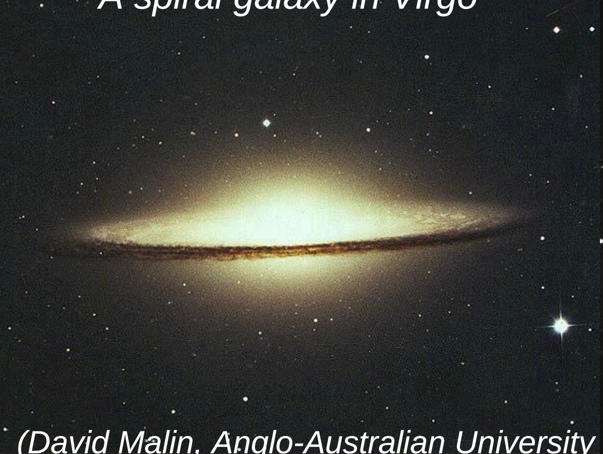


Ferrarese & Merritt 2000

Growth of SMBH, 2008

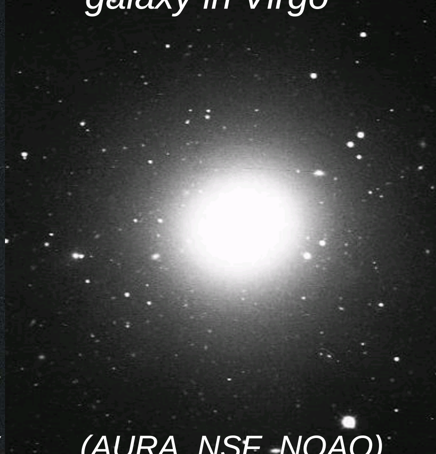
- Is a bulge necessary for a black hole to grow?
- Disk galaxy M33 shows no evidence of a SMBH. NGC 4395 and POX52 have no bulge but do contain an AGN.
- Recent Spitzer (IR) results show AGN in 7 out of 32 (bulgeless) disk galaxies which demonstrated no optical activity. This implies that bulges are not necessary for black hole growth.

The Sombrero Galaxy
A spiral galaxy in Virgo



(David Malin, Anglo-Australian University

M84, an elliptical galaxy in Virgo



(AURA, NSF, NOAO)

NGC 4395, a bulgeless spiral galaxy in Canes Venatici

(GALEX//NASA)

NGC 3621, a bulgeless spiral galaxy in Hydra

(2MASS)

Intermediate Mass Black Holes

?

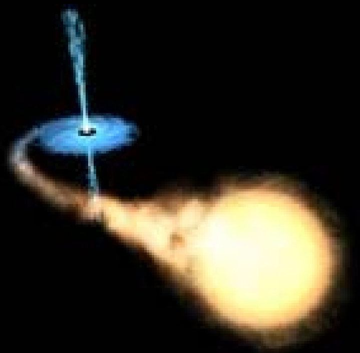
~10^2-10^5 M_{sun}

?

Eddington Luminosity

- L_E is the maximum luminosity achievable by a black hole powered by accretion from a companion star. If $L > L_E$ accretion is halted.

$$L_E = \frac{4\pi G M m_p}{\sigma_T} = 1.3 \times 10^{38} \frac{M}{M_{sun}} ergs^{-1}$$



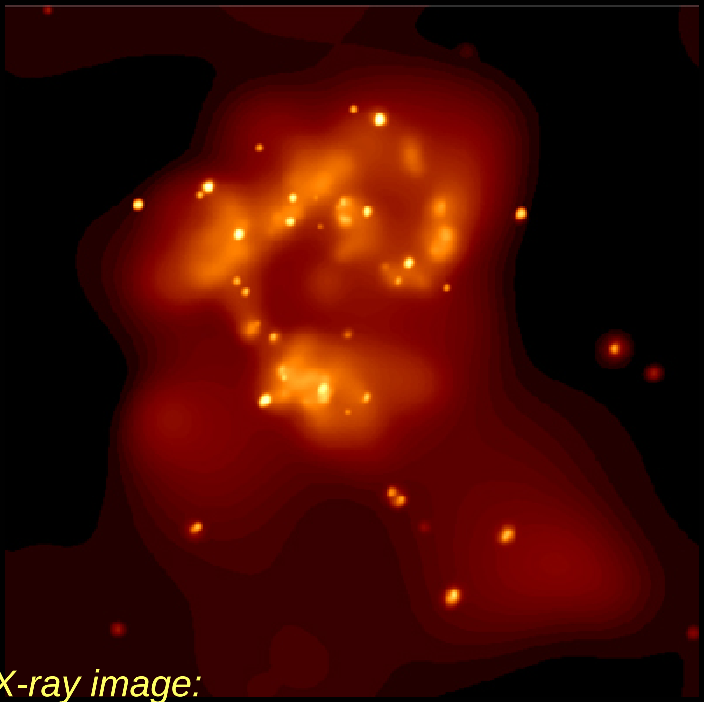
- For a 20 M_{sun} BH, $L_E \sim 3 \times 10^{39}$ erg s^{-1}
- Define an object radiating above 10^{39} erg s^{-1} but below L_E for a SMBH as an Ultra-luminous X-ray source, ULX,
- Assuming a source is radiating at its Eddington luminosity gives a lower bound on the mass of the accreting object.

If $L > L_E(20\ M_{sun})$ => *Intermediate Mass Black Hole* (IMBH) ?

Ultra-Luminous X-ray Sources

- Antennae Galaxies
  - continuing collision between galaxies NGC 4038 and NGC 4039
  - Ideal environment for merging stars

(Optical image: Brad Whitmore (STScI) and NASA)

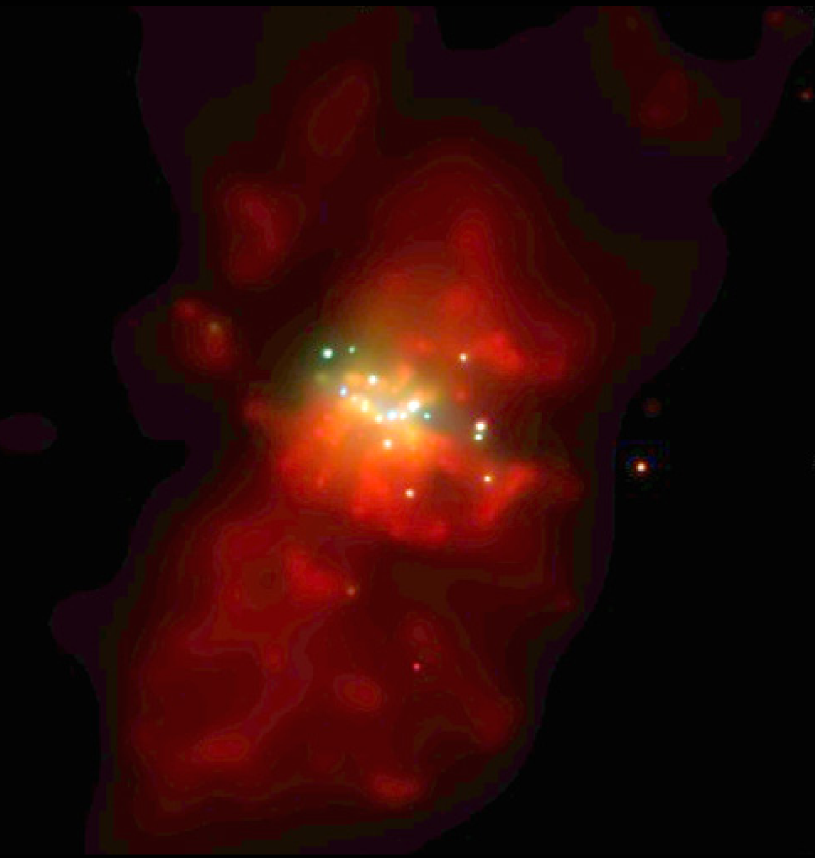


(X-ray image: NASA/SAO/CXC/G.Fabbiano et al.)

- Contains the largest population of ULXs
- 14 sources with $L_X > 10^{39}$ erg s^{-1}
- 10 of which show long term variability *(Zezas et al. 2006)*
- Flux could be beamed?
- Cannot rule out IMBH

Ultra-Luminous X-ray Sources

- M82
  - Brightest ULX is X41.4+60, associated with the star cluster MGG11
  - $L=10^{40}$-10^{41}erg s^{-1} implies $M > 500M_{sun}$
  - Luminosity too high to be beamed emission from stellar mass BH, high degree of variability, not coincident with core of galaxy implies $M < 10^5 M_{sun}$
  - QPO detected from core from which an upper limit on mass was placed $3x10^4 M_{sun}$ *(Feng & Kaaret 2007)*
  - Simulations of a star cluster like MGG11 demonstrate that run away collisions of stars could form IMBH *(Portegies Zwart et al 04)*

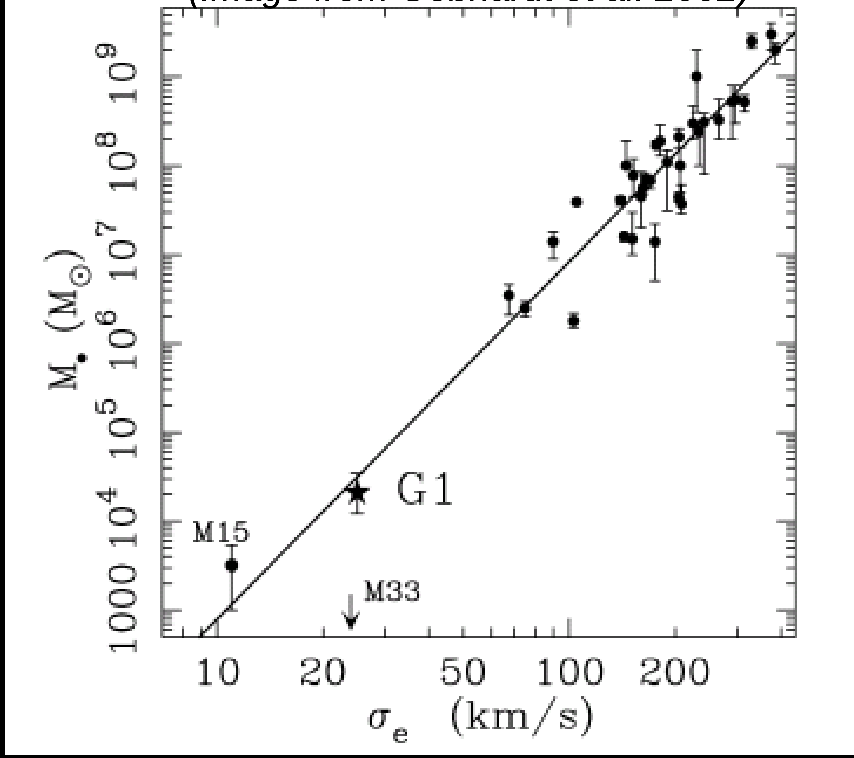


(Image: NASA/SAO/CXC/G. Fabbiano et al.)

Globular Clusters

- Dynamical mass measurements:
  - G1 in Andromeda,
    - **M= 2x10⁴** ***M*** $_{sun}$ *(Gebhardt et al. `02)*
  - M15 in Milky Way
    - **M ~3x10³** ***M*** $_{sun}$ *(Gerssen et al. `02, `03, van den Bosch et al. 06)*
  - *IMBH best fit, but not essential*
- Radio emission:
  - **G1:** Radio emission detected *(Ulvestad `07) consistent with accretion onto IMBH, but better sensitivity need to confirm this*
  - **M15:** No radio emission detected by VLA *(Bash et al. 08)*

(Image from Gebhardt et al. 2002)



- M15 and G1 fit to an extension of the M-σ relationship for nearby galaxies suggesting connection between galaxies and stellar clusters.

Summary

- Strong evidence for the existence of stellar mass and supermassive black holes
- In the case of stellar mass black holes theory directed observation, for supermassive black holes observation guided theory.
- Intermediate mass black holes still uncertain.
- GW detection will provide conclusive proof of existence and nature of astrophysical black holes.

Main references:

- Historical: Thorne, *Black holes and Time Warps*
- Stellar mass BH: *Casares '06*
- SMBH: Kormendy website,
- IMBH review: Miller & Colbert '04

The End