Black Hole Hunting

How we find them and measure them!

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Dark stars

- John Michell (1783)
  "If there really should exist in nature any bodies whose density is not less than that of the sun, and whose diameters are more than 500 times the diameter of the sun… their light could not arrive at us."

John Michell
(1724-1793)

- Pierre Simon Laplace (1796)
  "There exist in the heavens therefore dark bodies, as large as and perhaps as numerous as the stars themselves."

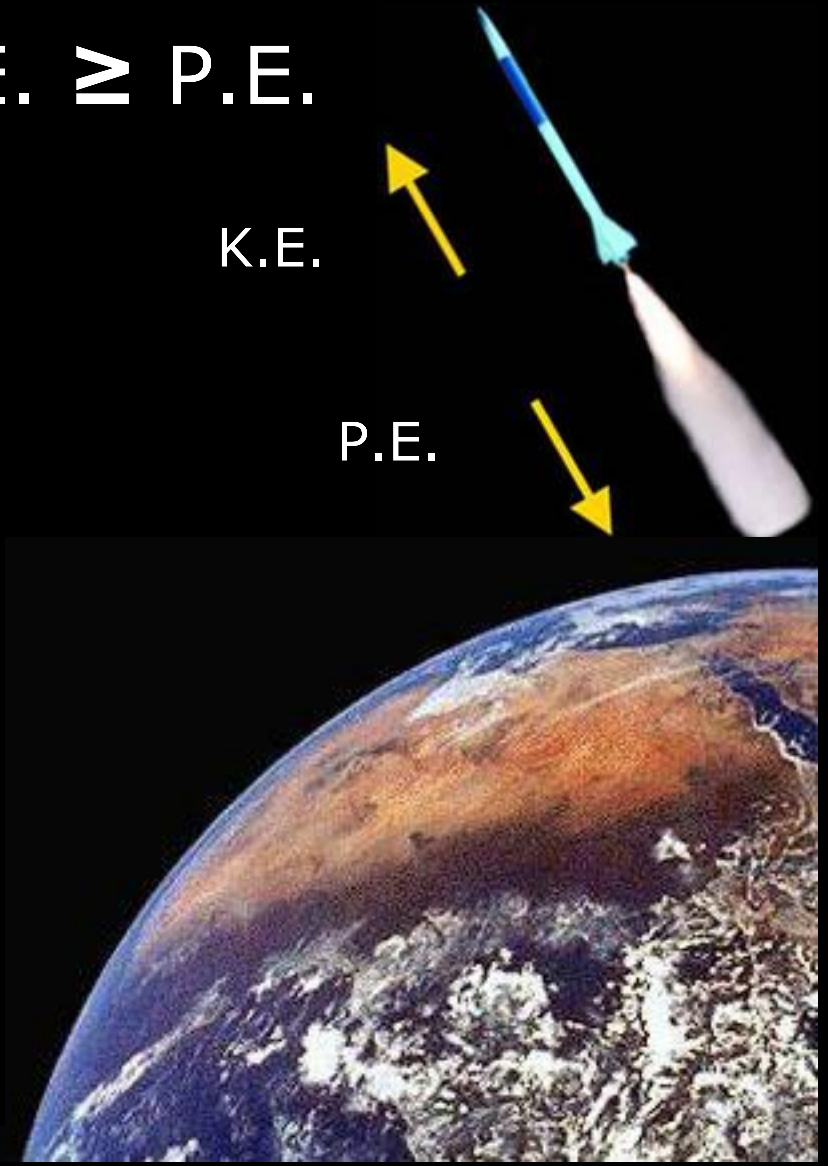
Pierre Laplace
(1749-1827)

Escape Velocity

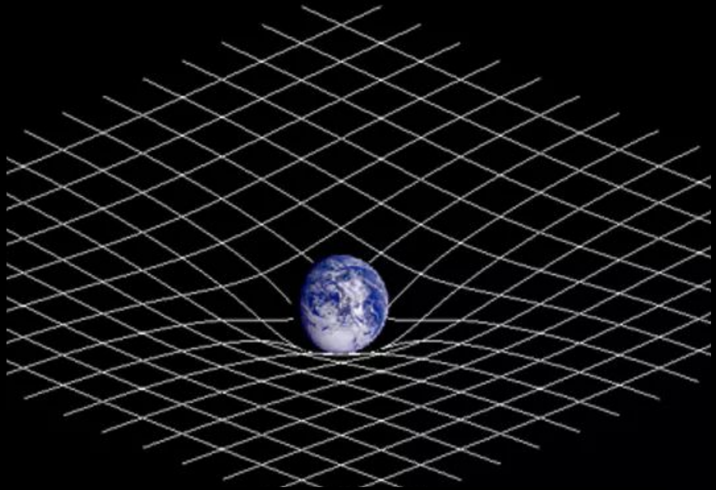
Rocket escapes when K.E. ≥ P.E.

$$\frac{1}{2}mu^2 = \frac{GMm}{R} \Rightarrow$$

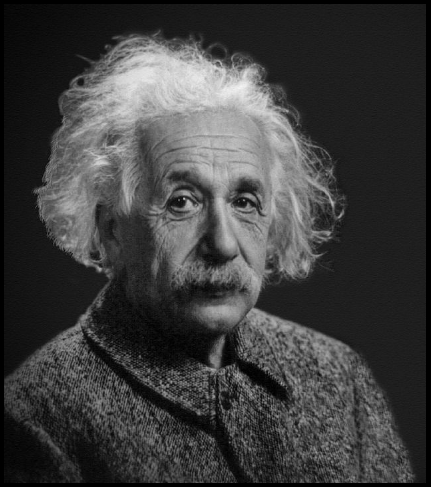
$$\Rightarrow u = \sqrt{\frac{2GM}{R}}$$



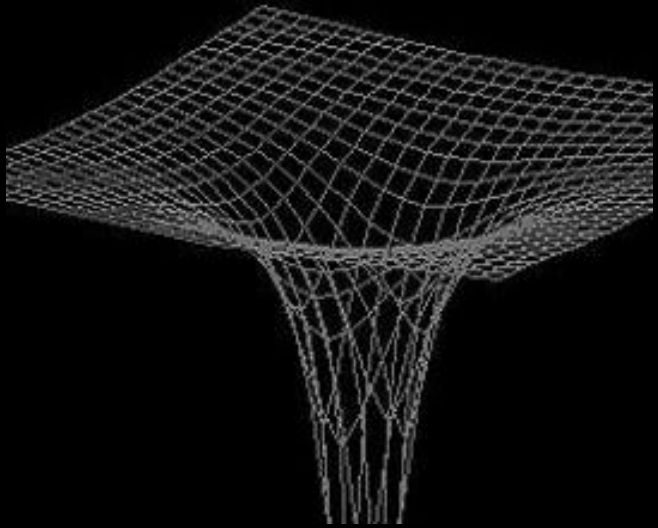
Black Hole Properties



General Theory of Relativity

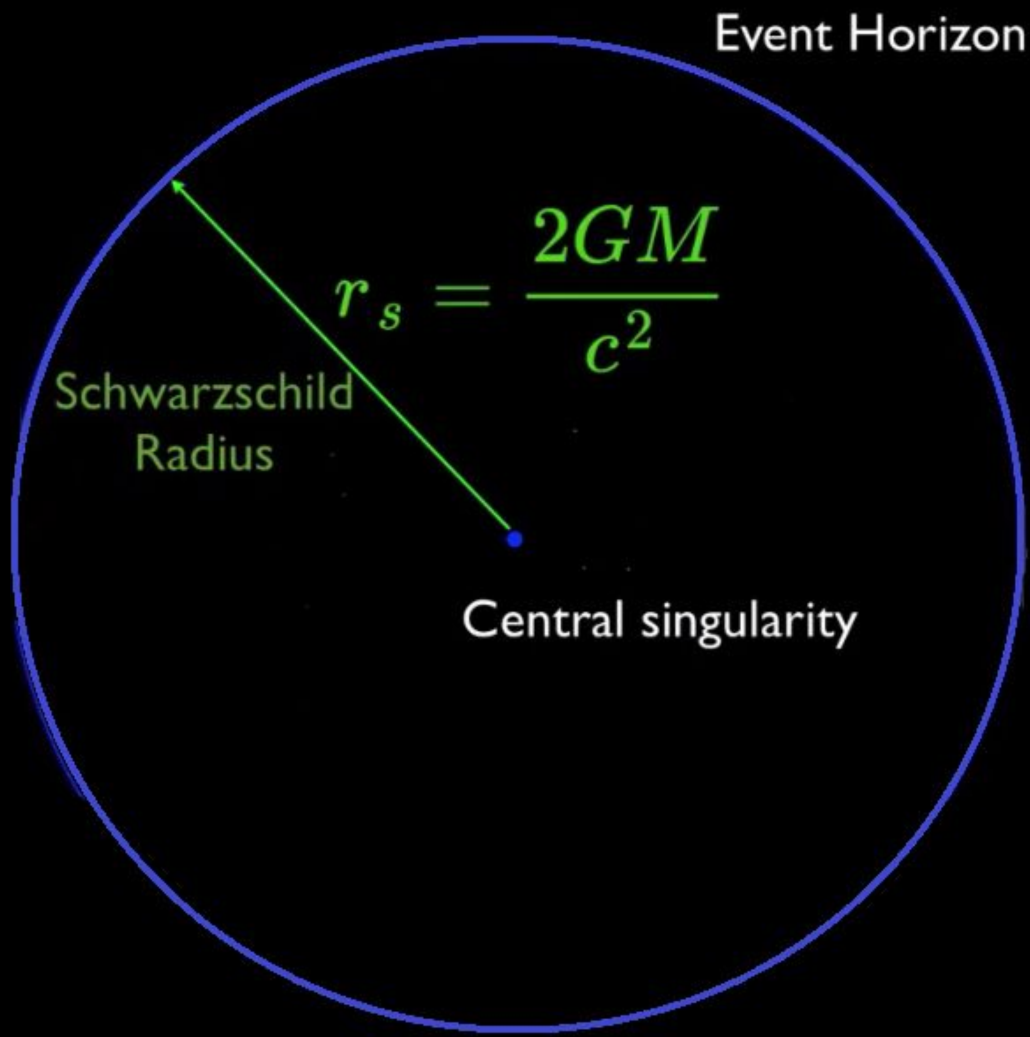


Albert Einstein
(1879-1955)



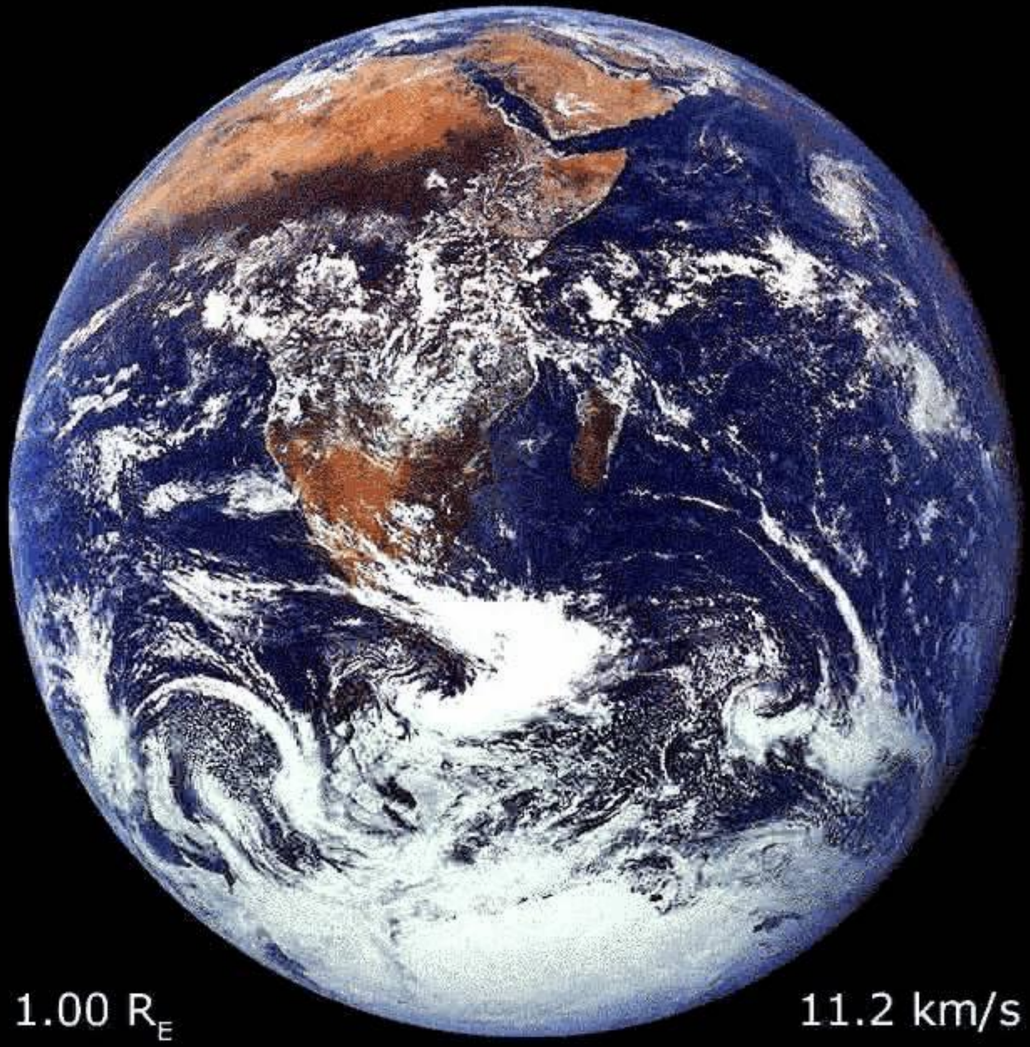
$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

Schwarzschild Radius



Karl Schwarzschild
(1876-1916)

Schwarzschild Radius



Schwarzschild Radius

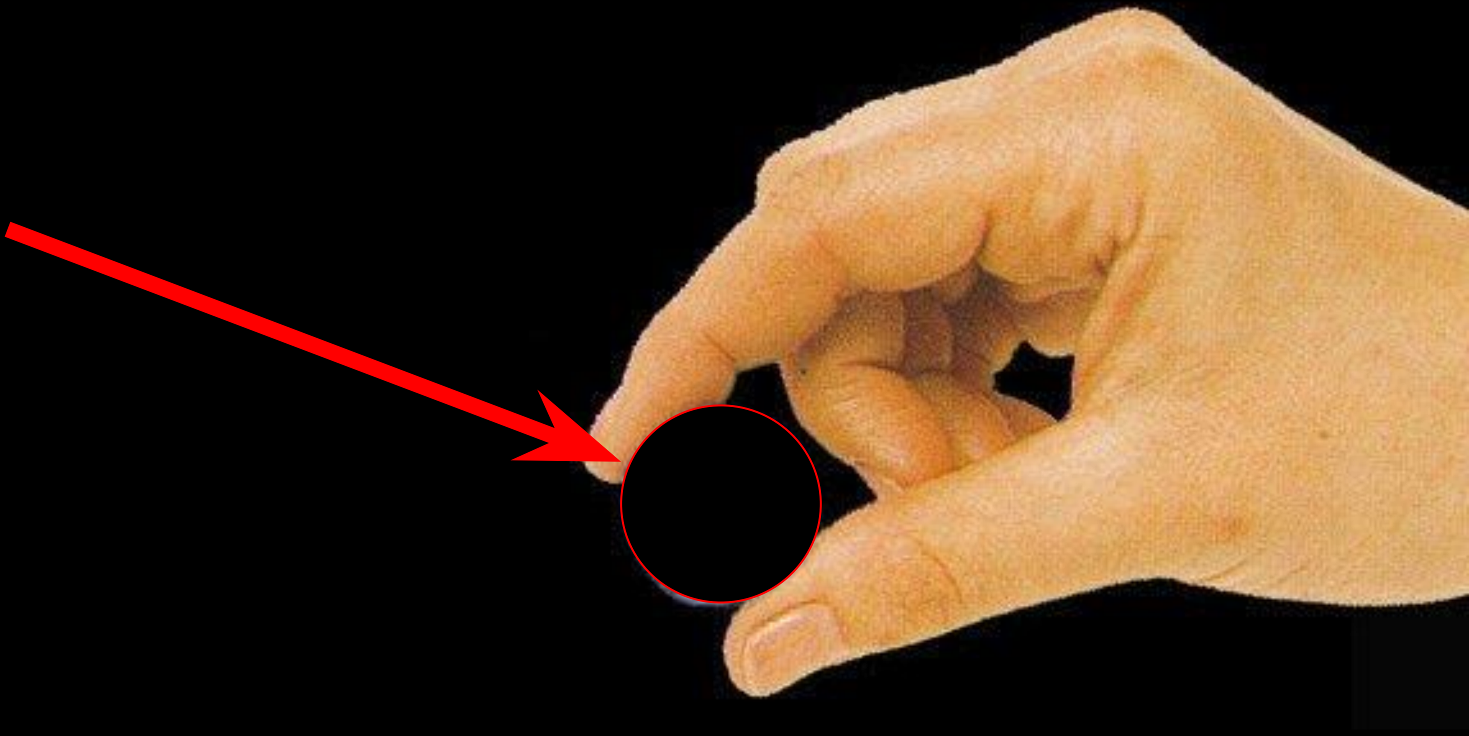
$0.50\ R_E$ 15.8 km/s

Schwarzschild Radius

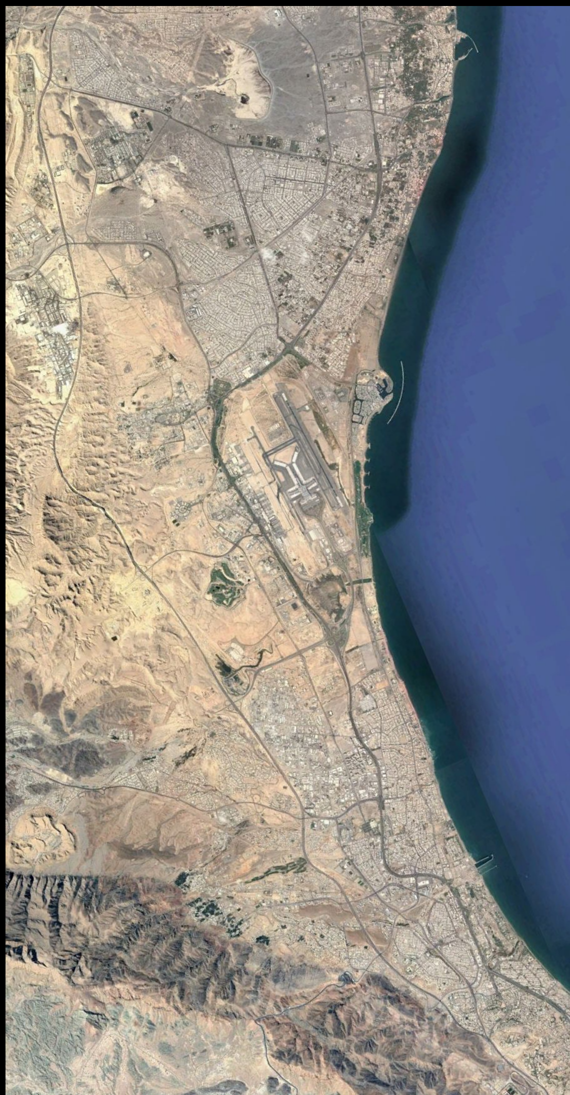
Black Hole

R_s~1 cm

$M = M_{Earth}$



Schwarzschild Radius



30 km

Black Hole

R_s=15 km

M = 5x M_{Sun}

Schwarzschild Radius

Object	Mass	R_S
Atom	10^{-26} kg	10^{-51} cm
Human Being	70 kg	10^{-23} cm
Earth	6.0×10^{24} kg	0.89 cm
Sun	2.0×10^{30} kg	3.0 km
Galaxy	10^{11} M_S	10^{-2} l.y.
Universe (if closed)	10^{23} M_S	10^{10} l.y.

Black Hole Properties

- Schwarzschild (1916)
  - mass
- Reissner-Nordström (1916, 1918)
  - mass, electric charge
- Kerr (1963)
  - mass, angular momentum
- Kerr-Newman (1965)
  - mass, angular momentum, electric charge

Black Hole Properties

Hawking Radiation

- In quantum theory, there is an intrinsic uncertainty in energy and time: $\Delta E \, \Delta t \geq h/4\pi$
- This implies the existence of 'virtual particles' even in a vacuum
- Virtual particles appear in pairs, consisting of a particle and its corres-ponding antiparticle

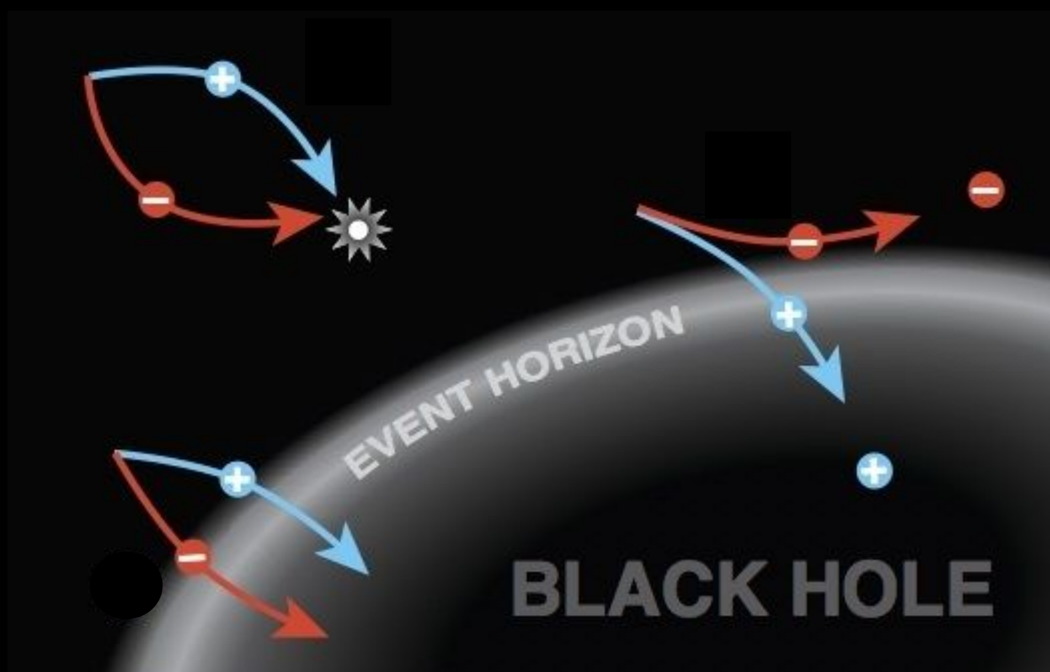
Stephen Hawking
(1942-2018)

Black Hole Properties

Hawking Radiation

One partner of a virtual-particle pair falls into a black hole, carrying negative energy with it, effectively, the black hole appears to be emitting particles and losing mass!

Stephen Hawking
(1942-2018)

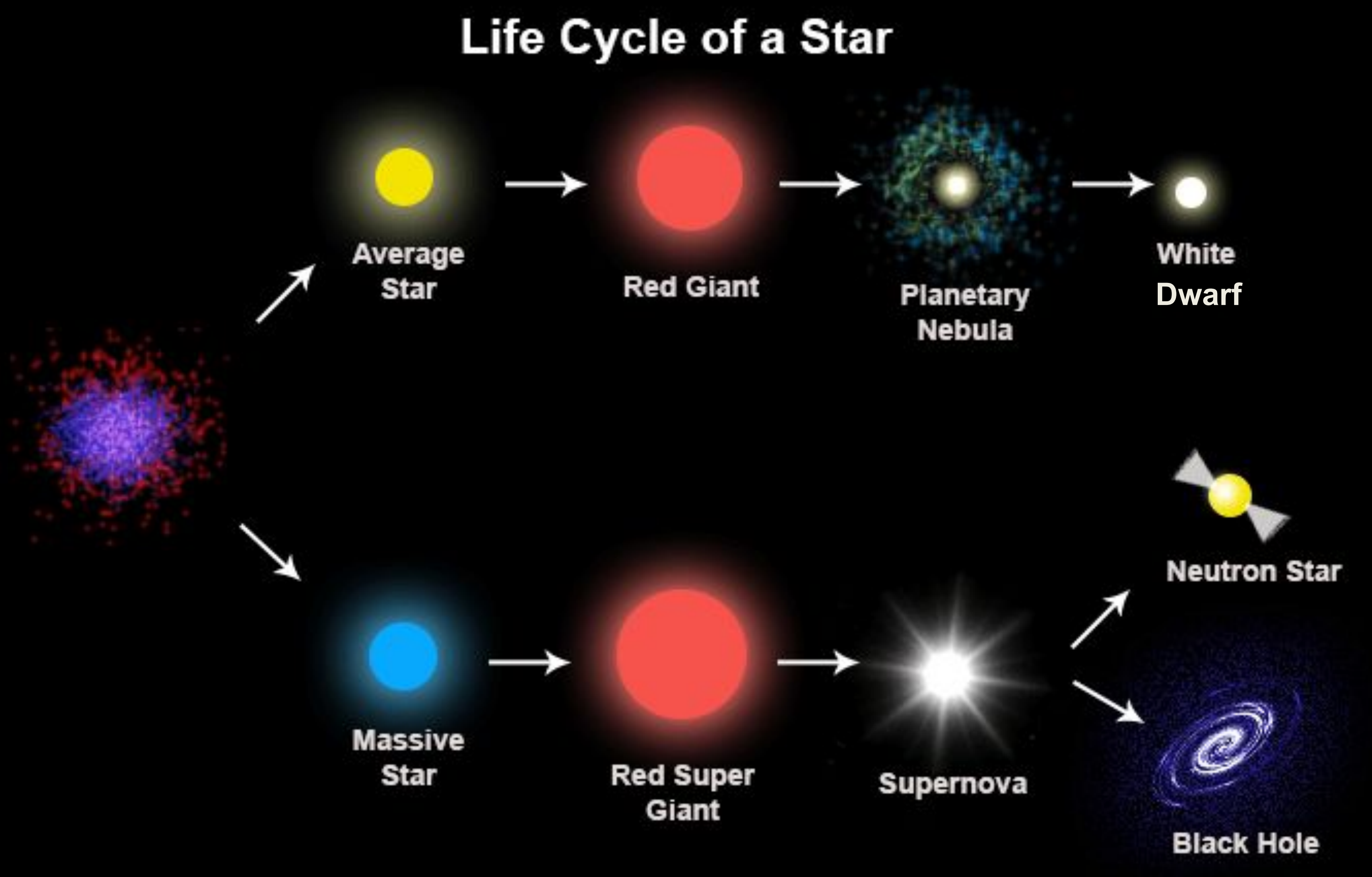


Black Hole Properties

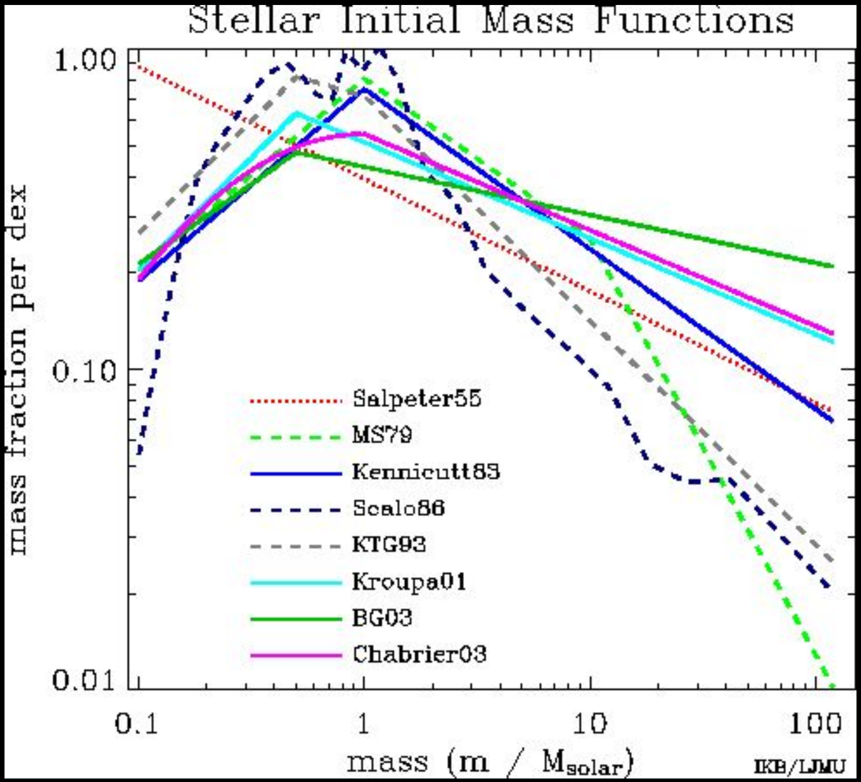
- At a distance, a black hole exerts gravitational force according to Newton's Law.
  - just like any other star with the same mass
  - if our Sun was replaced by a 1-M_{Sun} black hole, the planet's orbits would not change
- Only at a distance of 3 R_s from the black hole will the gravity increase from what Newton's Law predicts.
  - then one could eventually fall into the black hole

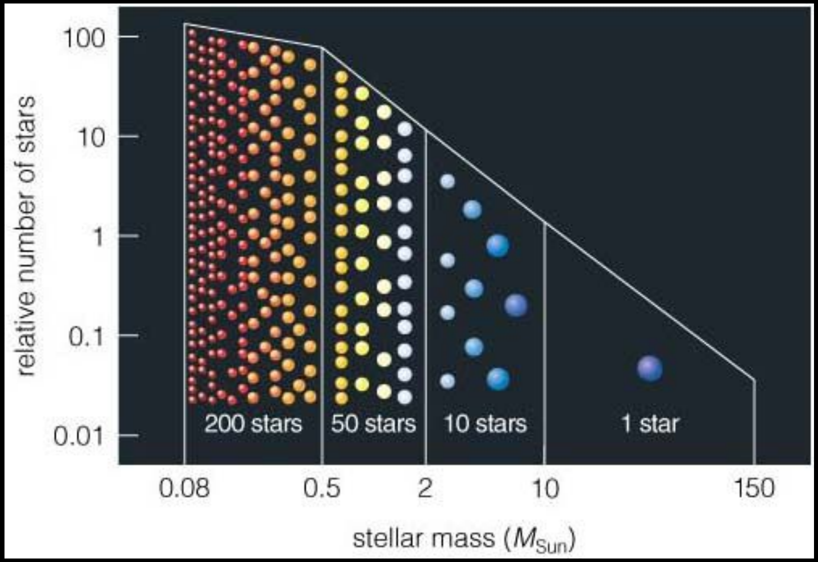
A black hole does not suck in everything around it!

Black Hole Creation



Black Hole Creation





at least a few x10^6 Black Holes in the Milky Way Galaxy

Black Hole Hunting

Stellar Mass Black Holes

A060-00
4U 1543-475
Cyg X-1
Cyg X-3
GRO J0422+32
GRO J1655-40
GRS 1124-683
GRS 1915+105
GS 2000+25
GX 339-4
IGR J17091-3624
M33 X-7
SS 433
V404 Cyg
XTE J1118+48
XTE J1550-564
XTE J1650-500
XTE J1819-254
MACHO-96 to 99
GW 151226
GW 170104
GW 170608
GW 170814

Supermassive Black Holes

Sag A*	NGC 821
3C 371	NGC 1023
3C 75	NGC 1097
Cen A	NGC 1365
Fornax A	NGC 1566
M31	NGC 2778
M32	NGC 2787
M51	NGC 3079
M60	NGC 3115
M77	NGC 3245
M81	NGC 3377
M84	NGC 3384
M87	NGC 3608
M104	NGC 3894
M105	NGC 3608
M106	NGC 3894
Mrk 180	NGC 4151
Mrk 421	NGC 4473
Mrk 501	NGC 4697
IC 1459	NGC 4949
Arp 220	NGC 5033
AP Lib	NGC 5845
OJ 287	NGC 7052

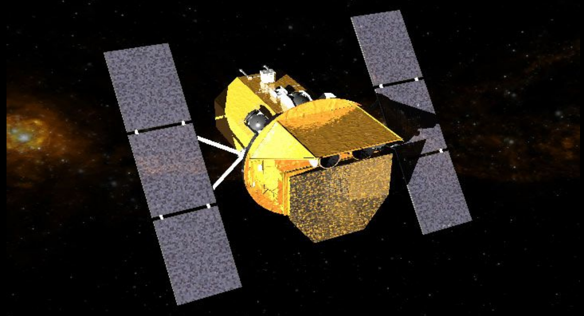
Intermediate Black Holes

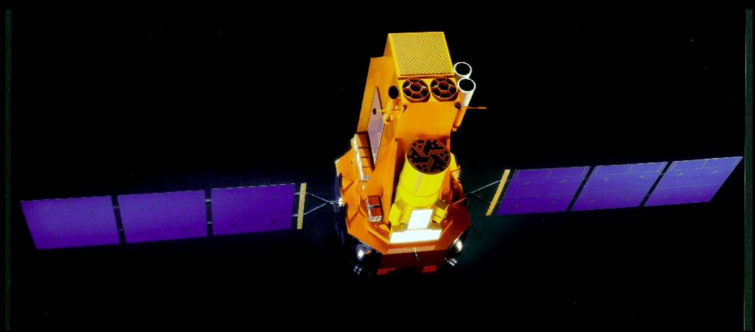
HLX01
M82 X-1
M15
M110
NGC 1313 X-1
NGC 1313 X-2
NGC 253
M33
GW150914

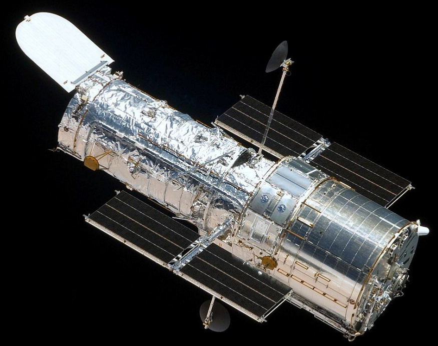
Miniature Black Holes

?

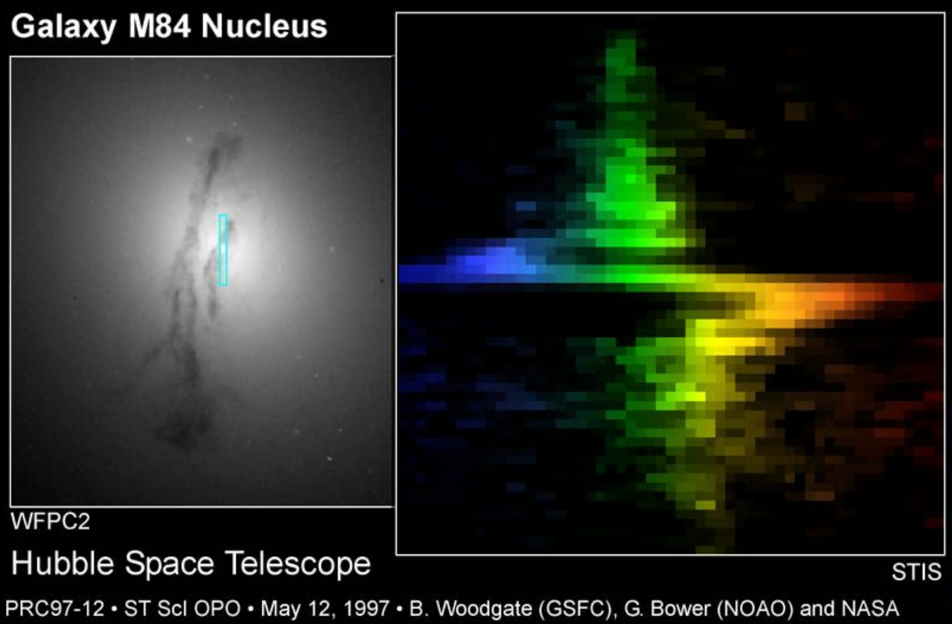
Black Hole Hunting Tools





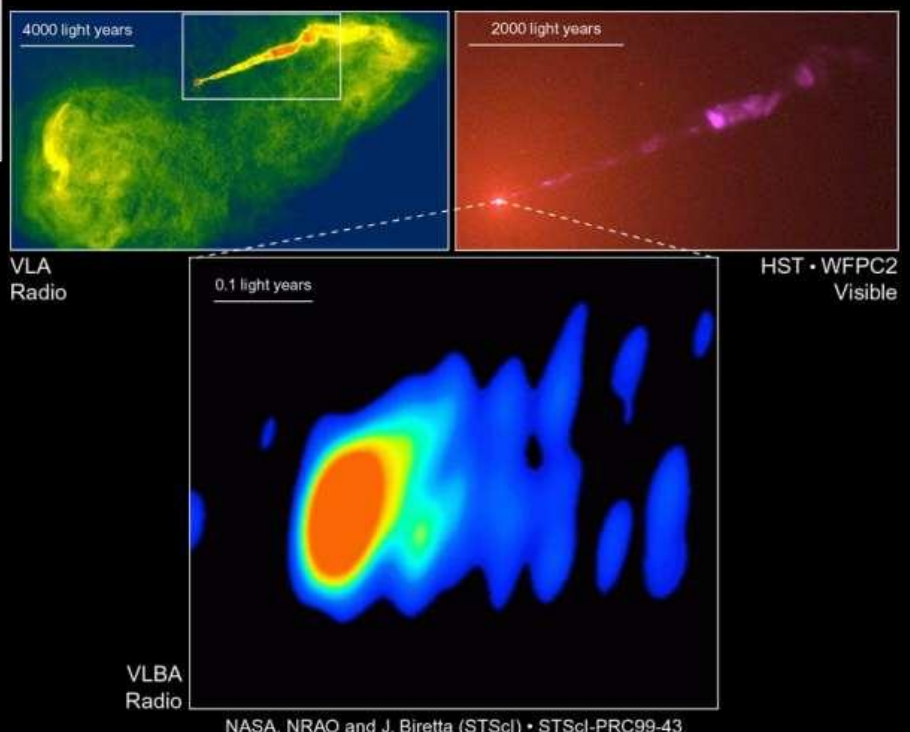


Black Hole Hunting

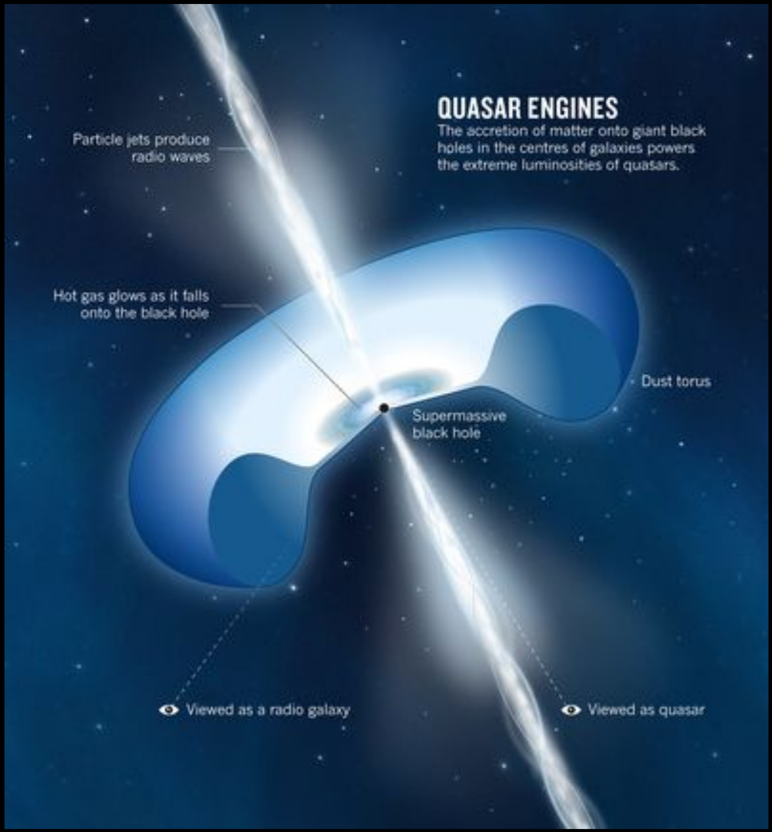


Gas rotating around a galaxy nucleus

Quasar Jets



Black Hole Hunting

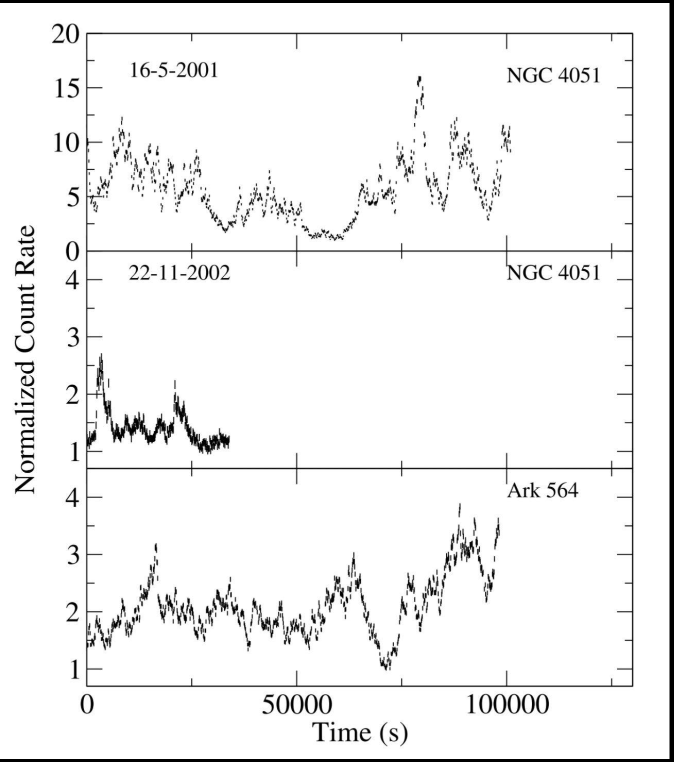


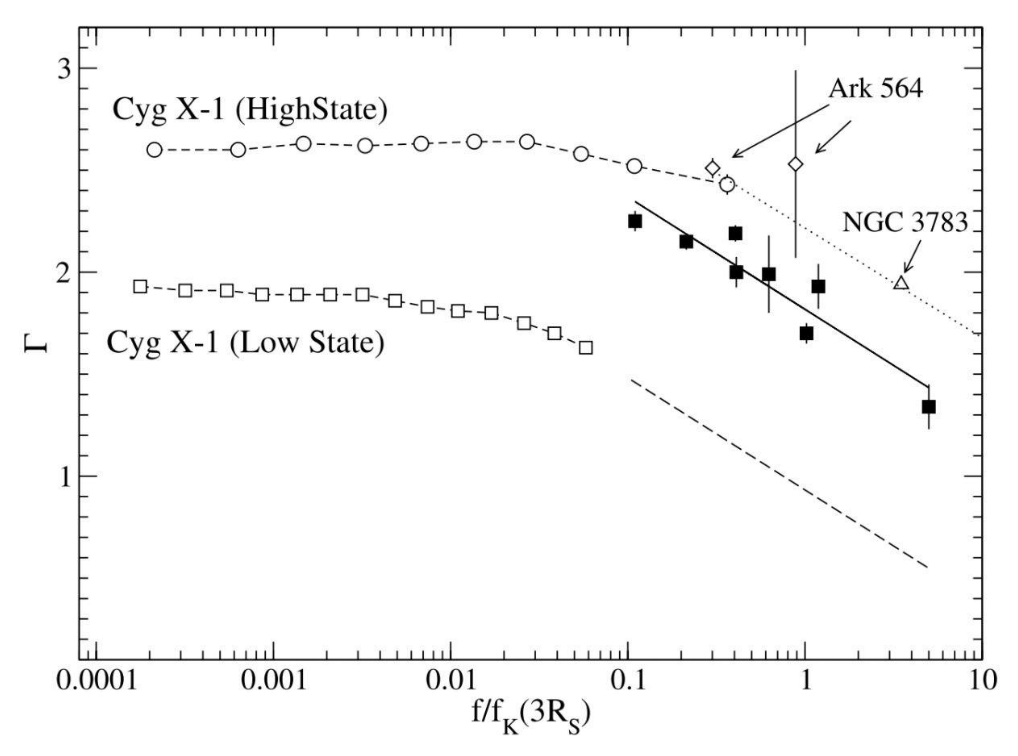
Optical Jet of M87 galaxy

Black Hole Hunting

Active Galactic Nuclei show variability in ALL timescales!

Indicating energy production region is small ~ a few light hours or less!





From: Papadakis, Ioannou & Kazanas (2007)

Black Hole Hunting

Direct mass measurements of Sag A* supermassive black hole

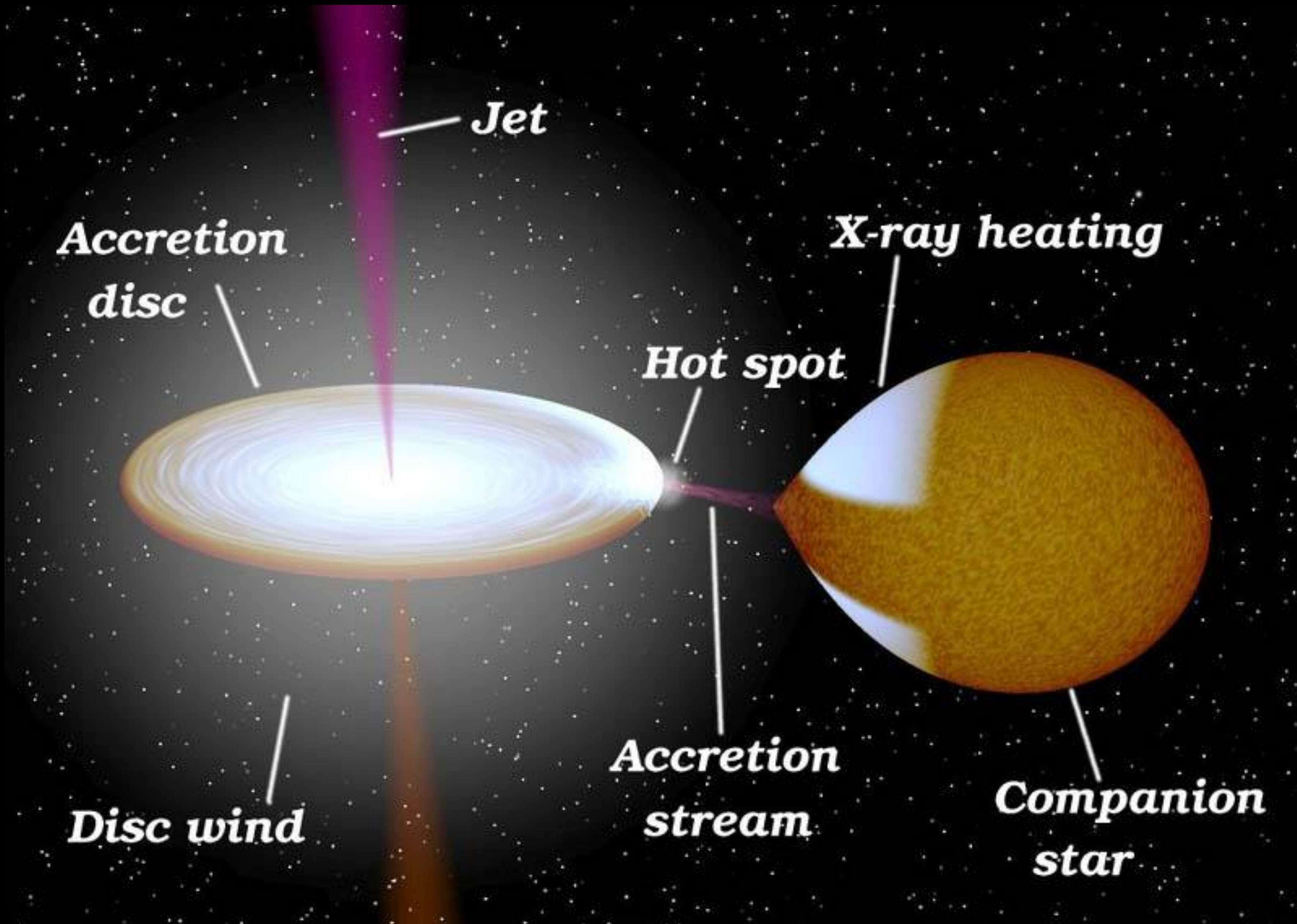
Newton's version of Kepler's 3rd Law

$$p^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3$$

Mass of Sgr A* ~ 2×10^6 M_{Sun}

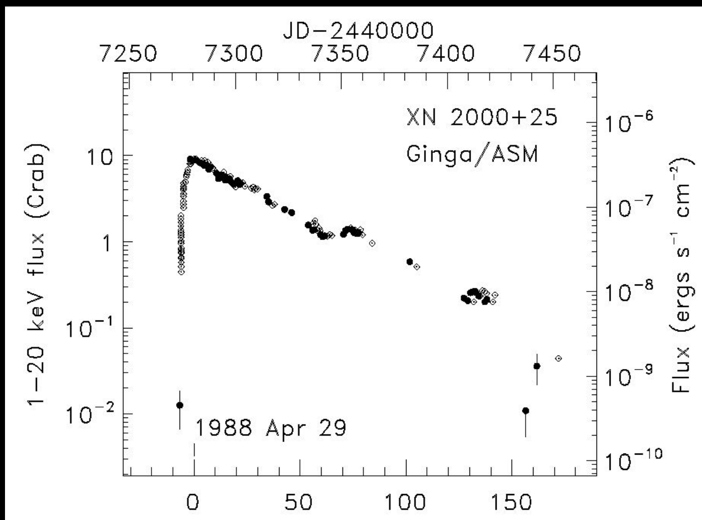
From: European Southern Observatory (ESO)

Black Hole Hunting

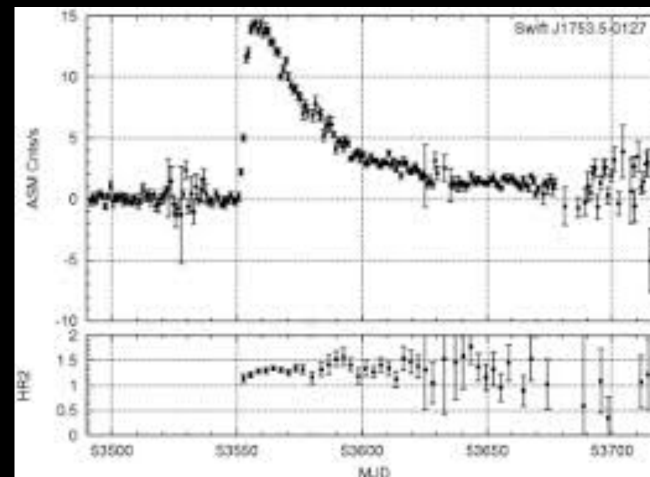


Black Hole Hunting

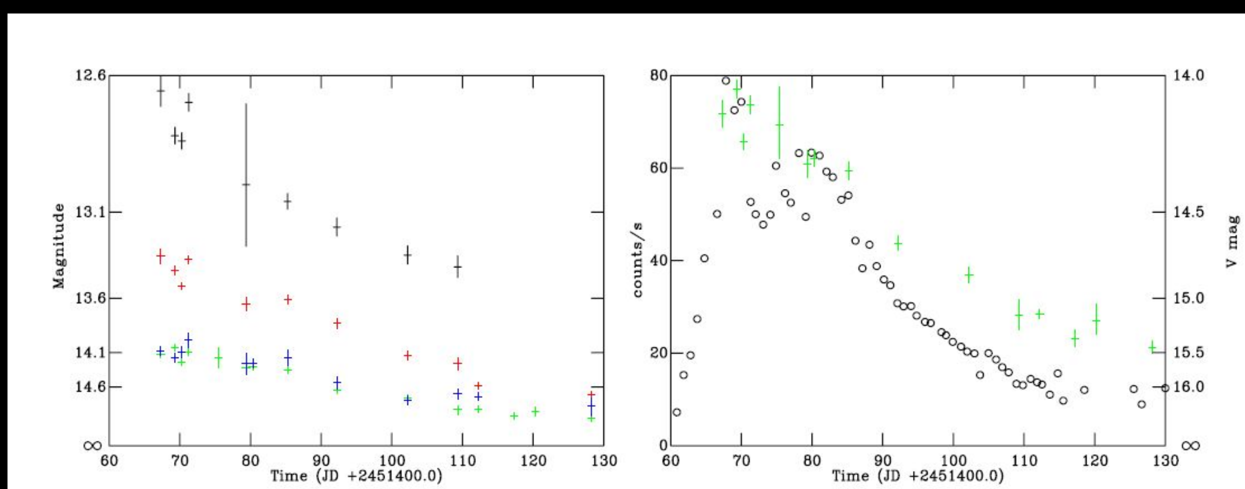
GS 2000+25



Swift J1753-226



XTE J1859+226



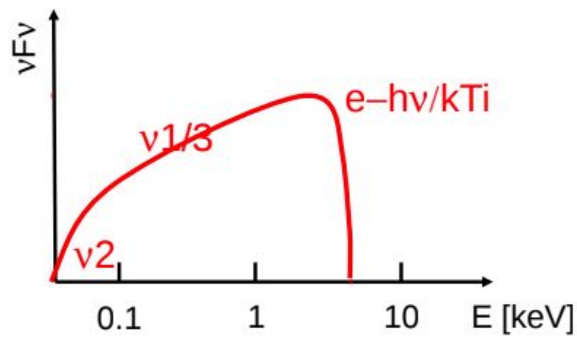
Black Hole Hunting

- **Total Luminosity:**

$$L_{rad} = \int_{r_*}^{\infty} F(r) 2\pi r \, dr \approx \frac{GM\dot{m}}{2 r_*}$$

Radiation Spectrum:

$$T(r) \approx \left(\frac{3\, GM\dot{m}}{8\,\pi\,\sigma\, r^3}\right)^{1/4} \propto r^{-3/4} \qquad I_\nu(r) = 2\pi r\, B_\nu\left(T(r)\right)$$

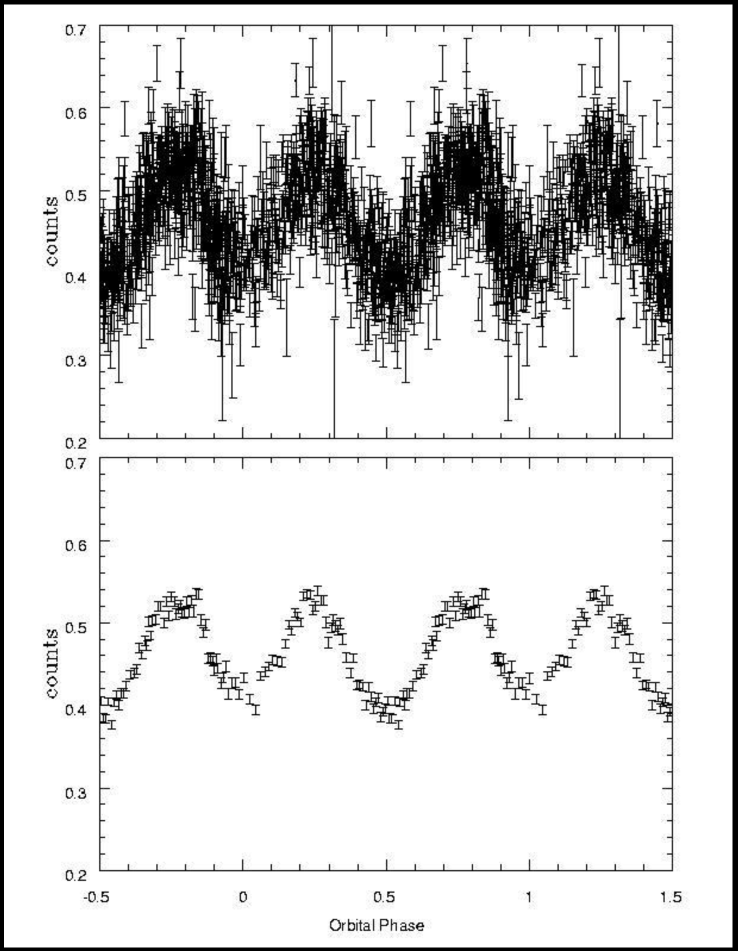


$$T_i \sim 2 \times 10^7 \left(\frac{M}{M_{sun}}\right)^{-1/4} K$$

For accretion at the Eddington Limit

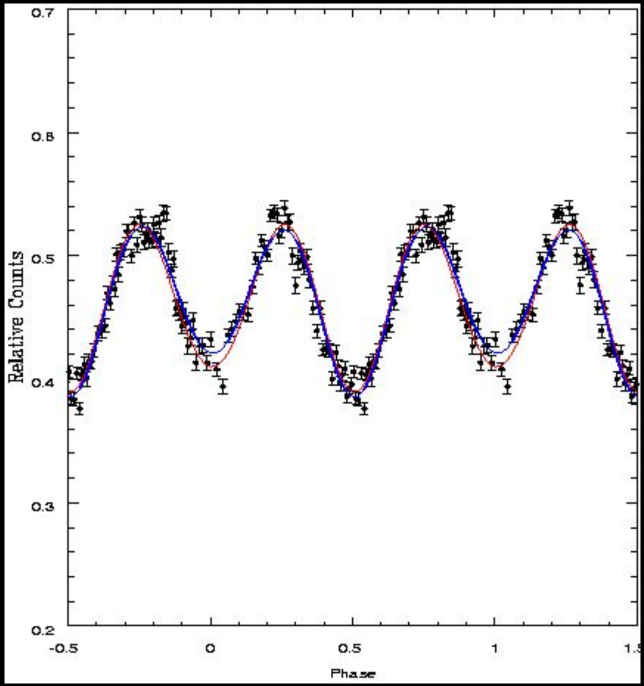
Black Hole Hunting

GS 2000+25



Black Hole Hunting

GS 2000+25



Mass Function:

$$f(M_x) = M_1 sin^3 i \left(1 + \frac{1}{q}\right)^2 = \frac{P_{orb} K_2^3}{2\pi G}$$

Unknowns

Mass Ratio

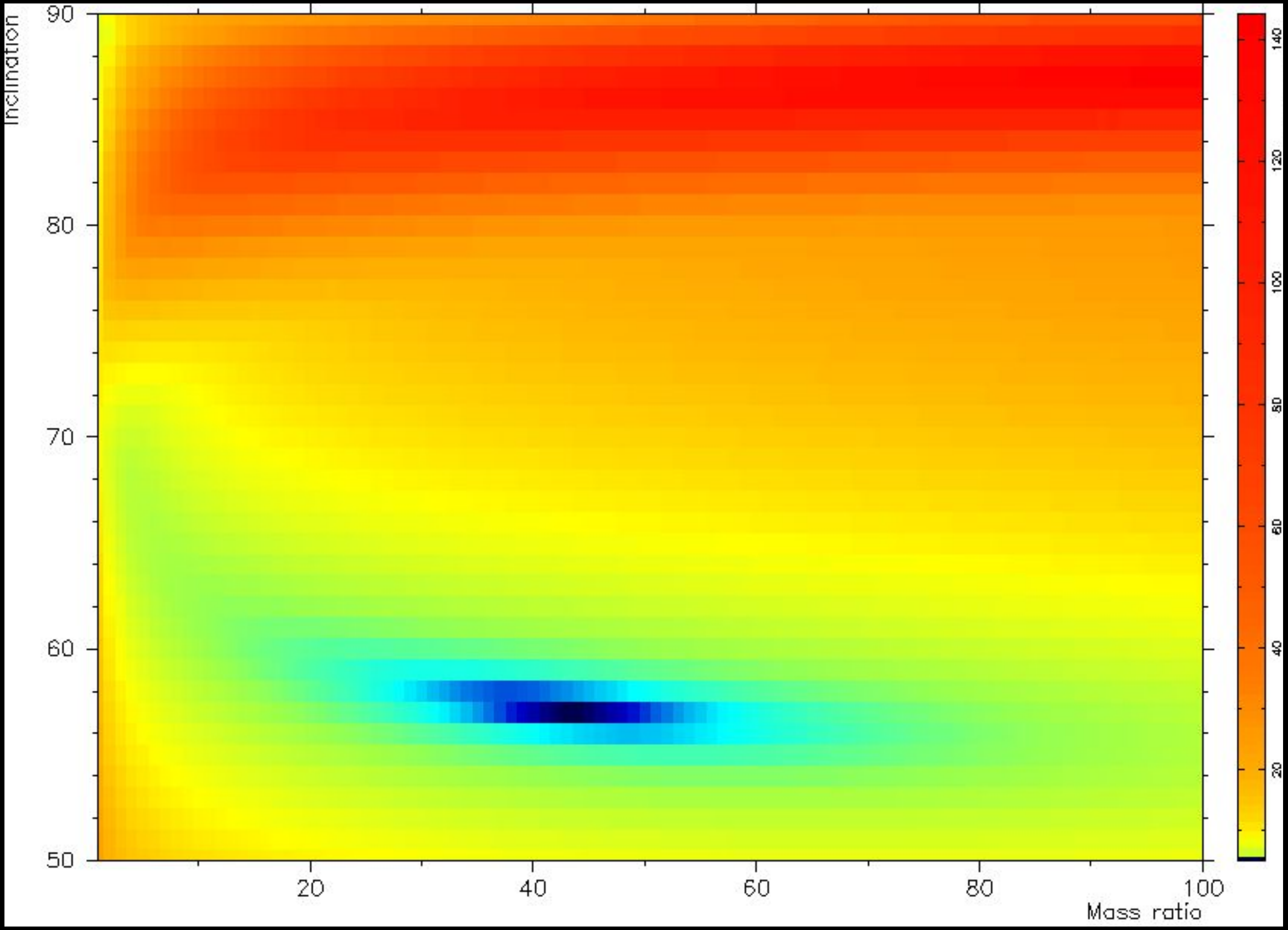
$$q = \frac{M_1}{M_2}$$

Inclination

$$i$$

Black Hole Hunting

Inclination v Mass Ratio models for GS 2000+25



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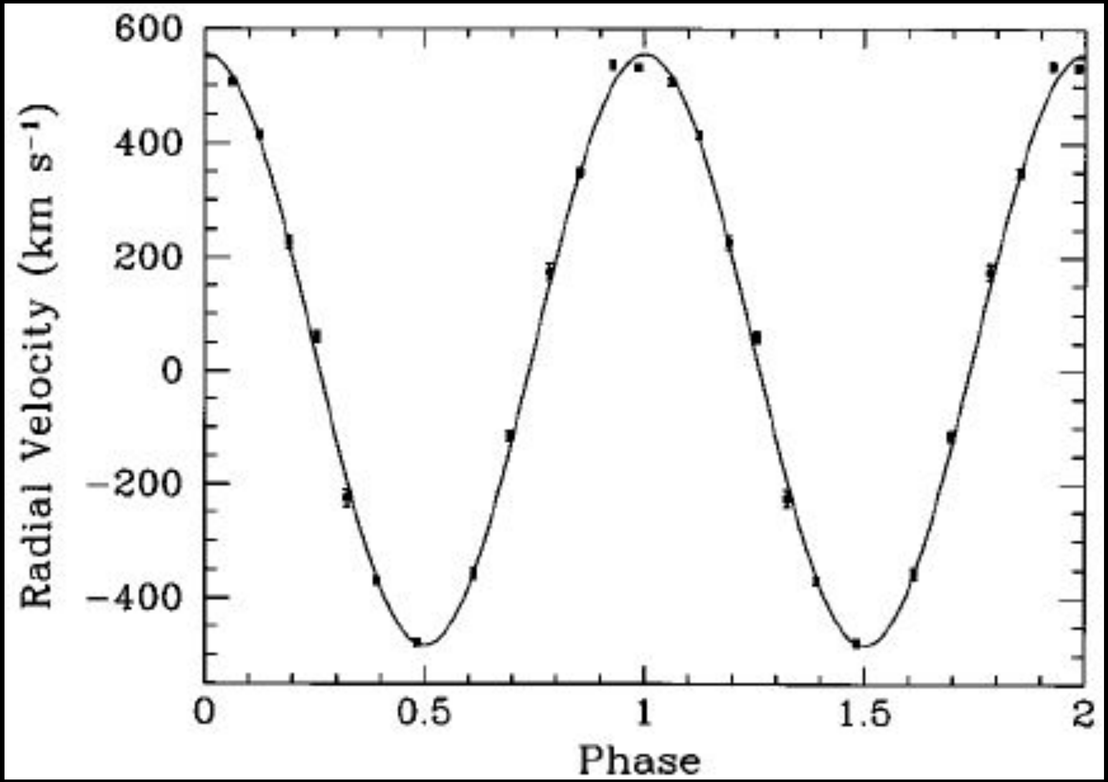
Radial Velocity curve of GS 2000 + 25

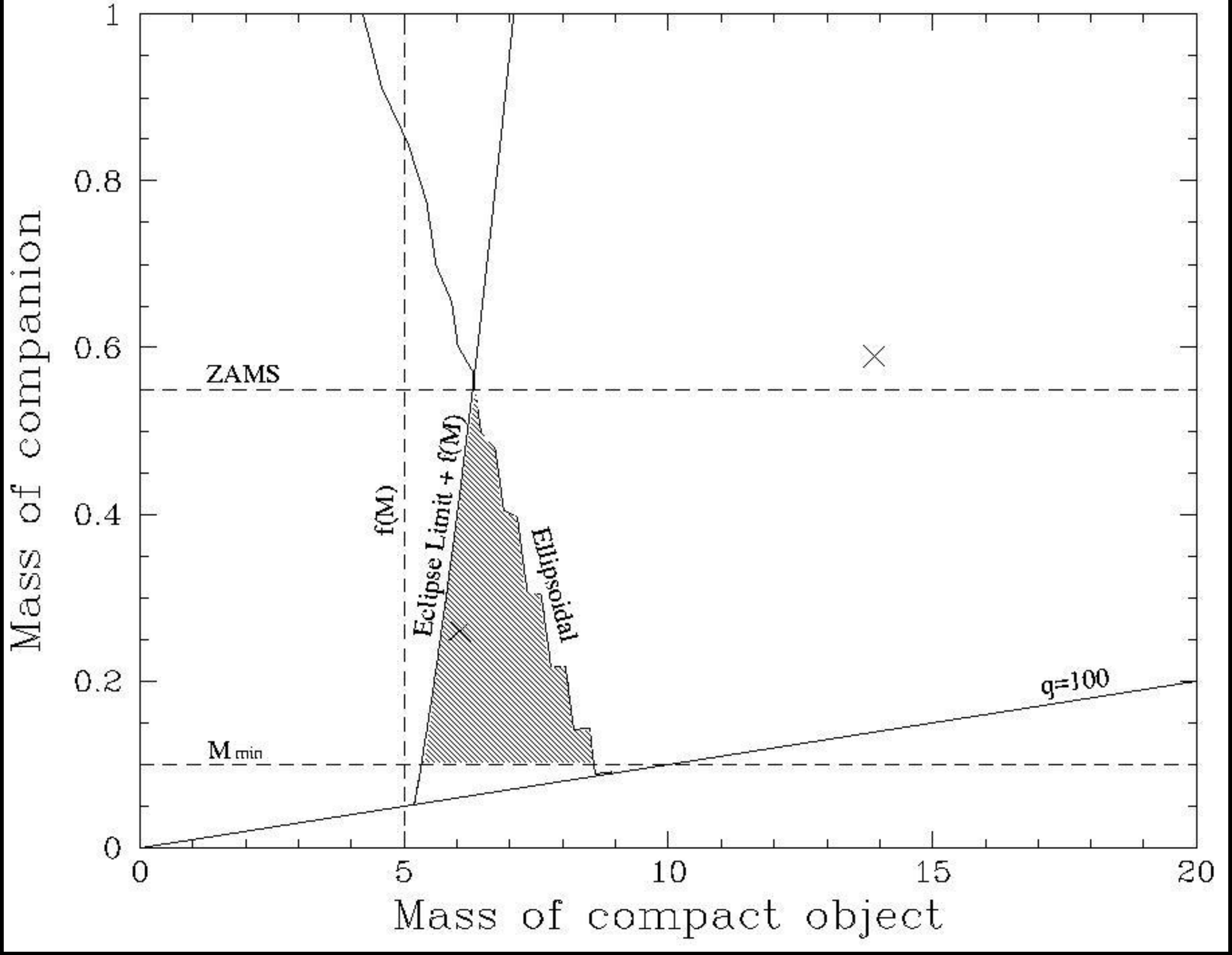


$$v\sin(i) = 519.9 \pm 5.1\ km\ s^{-1}$$

$$f(M_x) = 5.01 \pm 0.12\ M_{Sun}$$

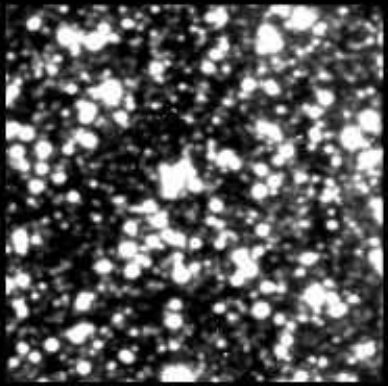
Black Hole Hunting

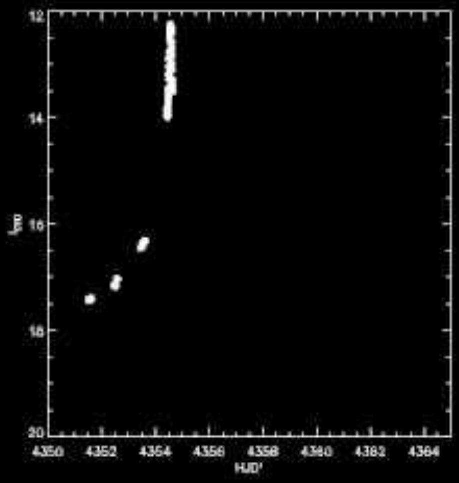
Component Masses for GS 2000+25

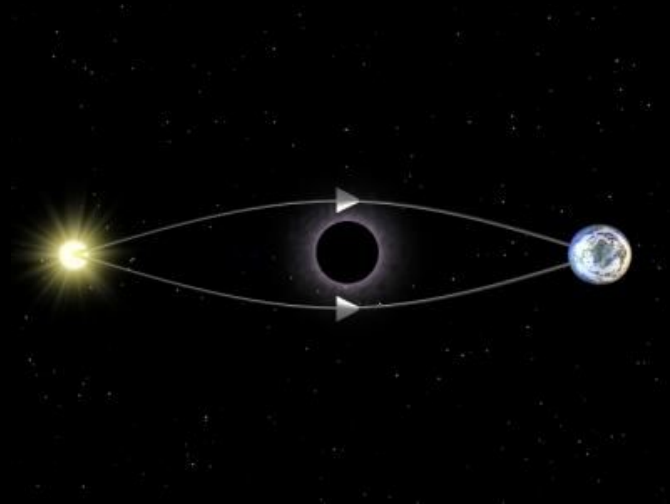


Black Hole Hunting

Gravitational Lensing

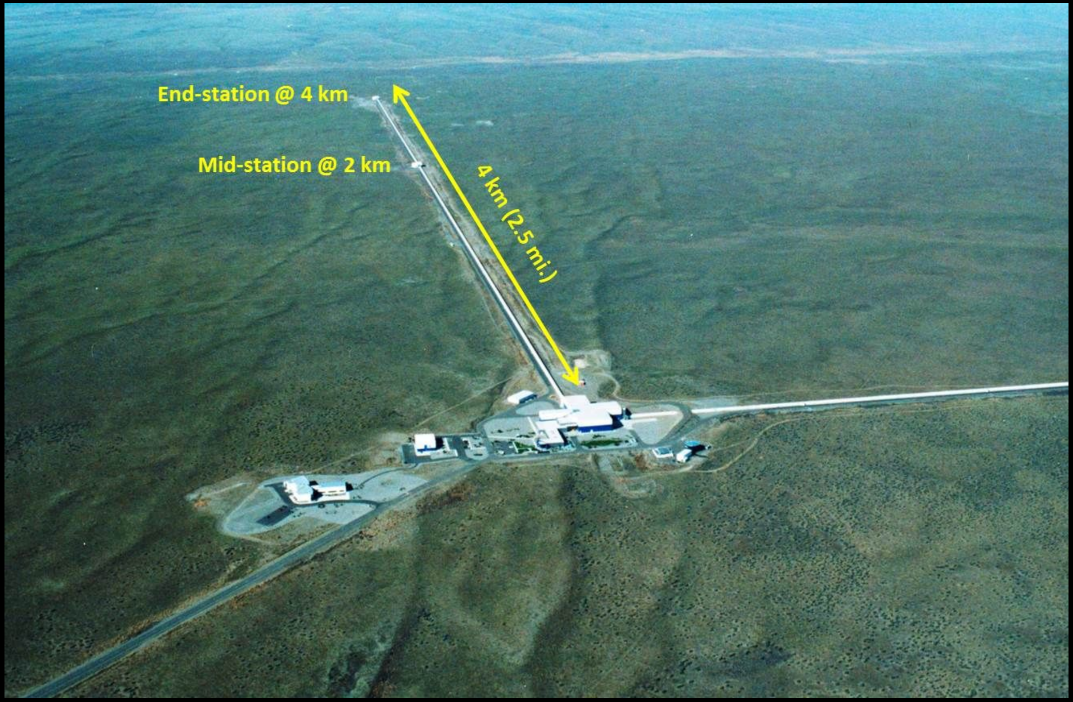


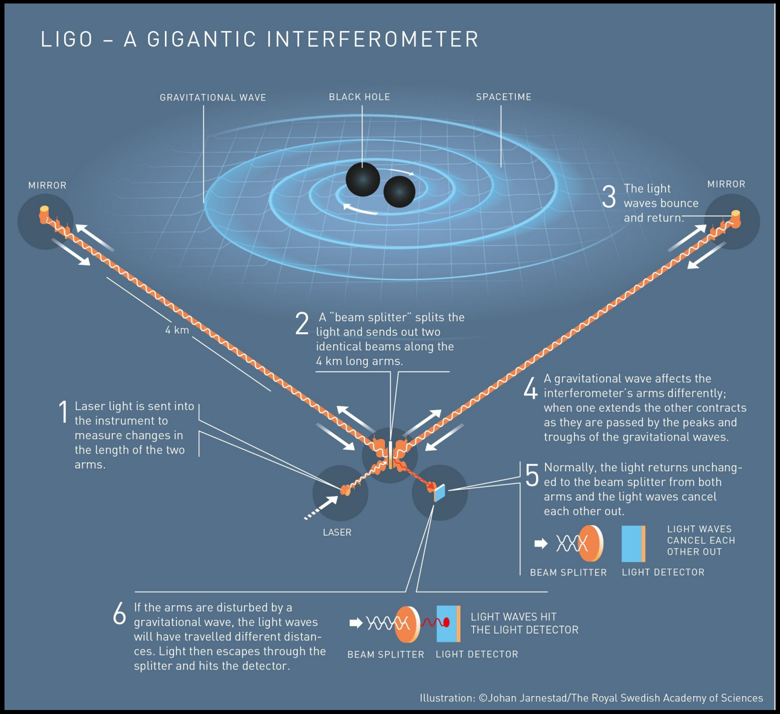




Black Hole Hunting

Direct detection of gravitational waves





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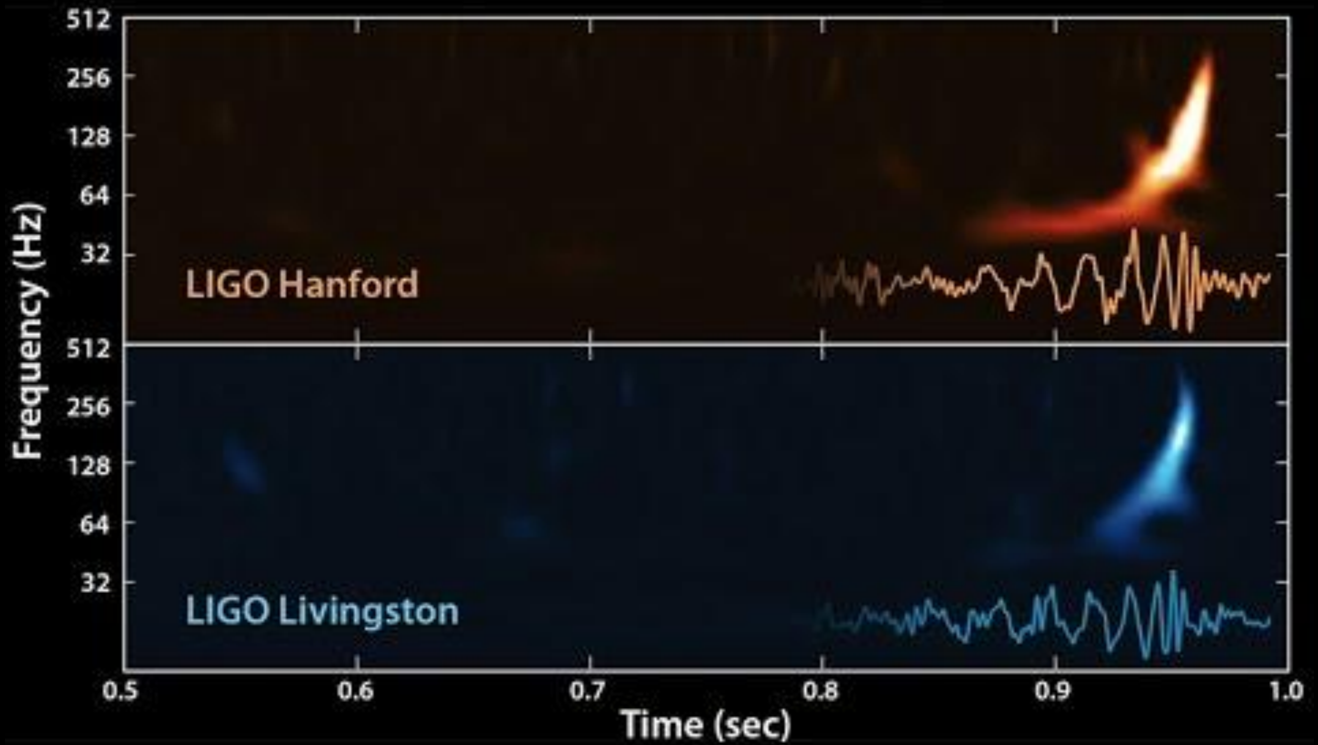
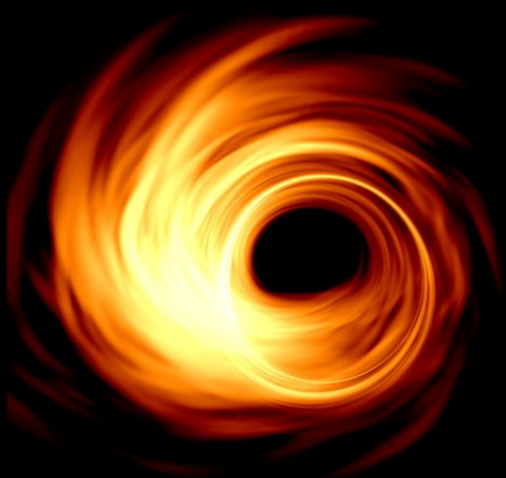


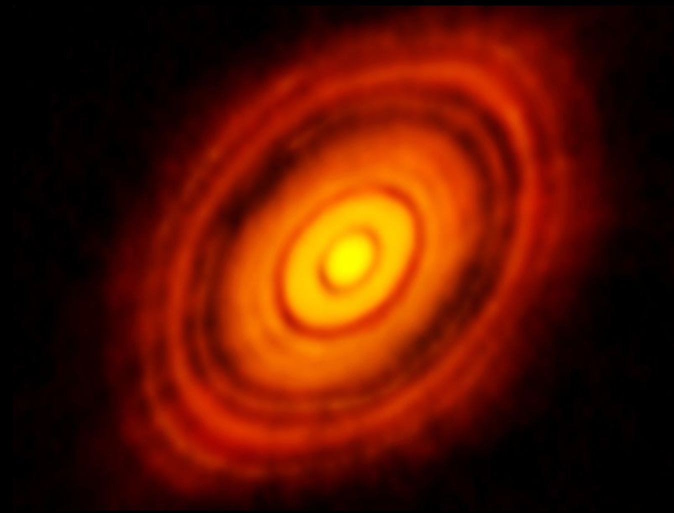
The Future of Black Hole Hunting

Event Horizon Telescope will attempt to directly image the black hole at Sgr A* - The center of our Milky Way galaxy!

Event Horizon Telescope



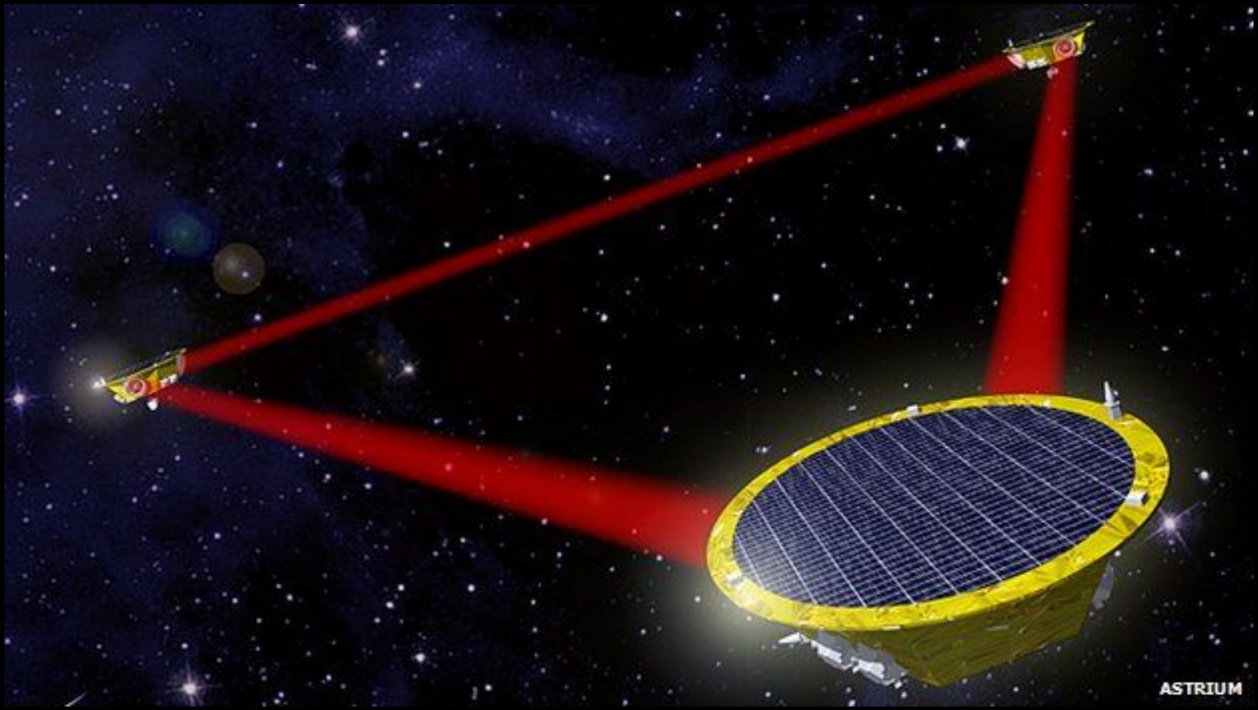
Simulated EHT image

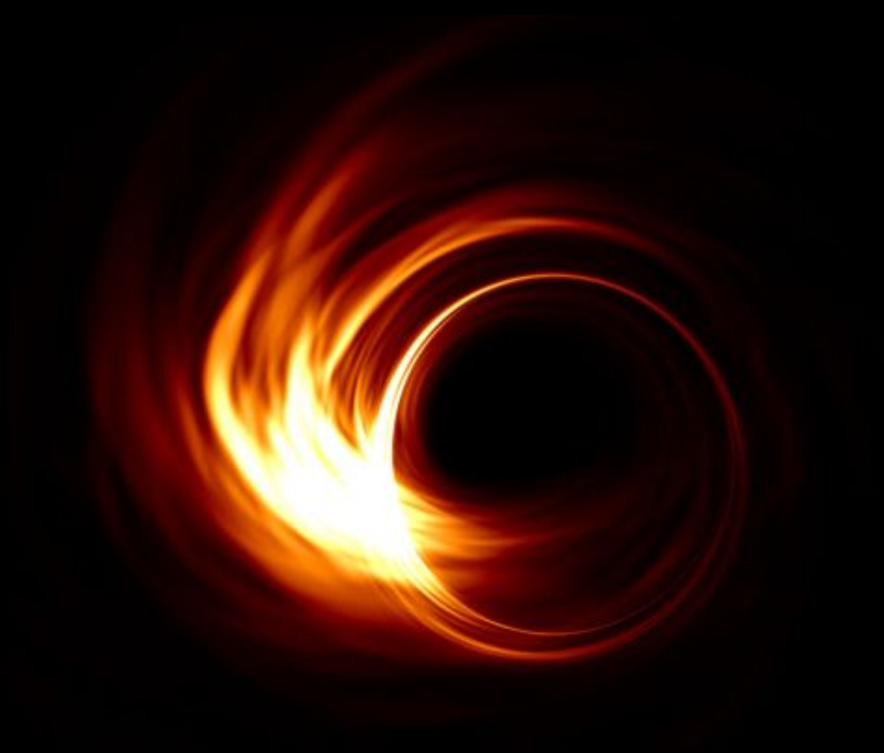


Real image of a stellar disk from ALMA

The Future of Black Hole Hunting

LISA - **L**aser **I**nterferometer **S**pace **A**ntenna





...to be continued