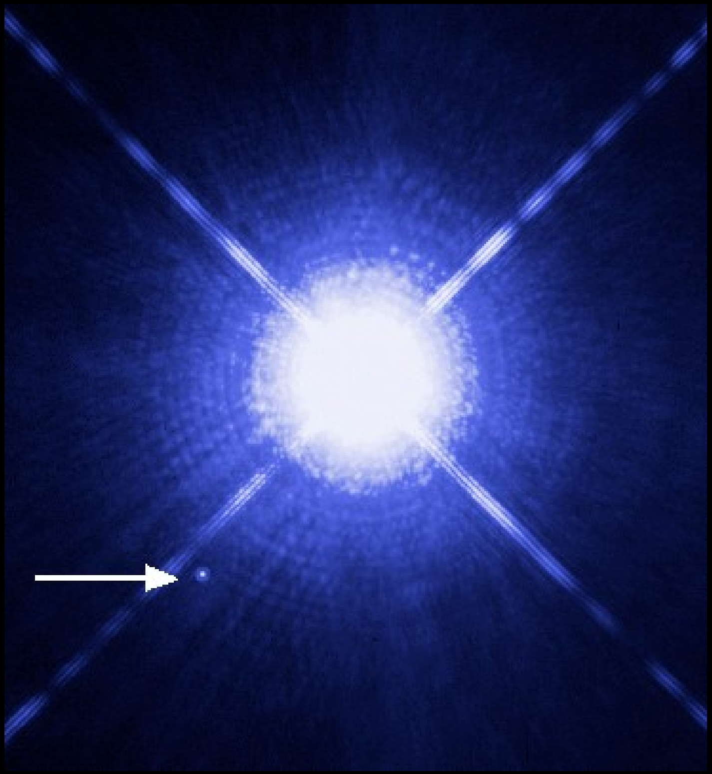
Compact objects

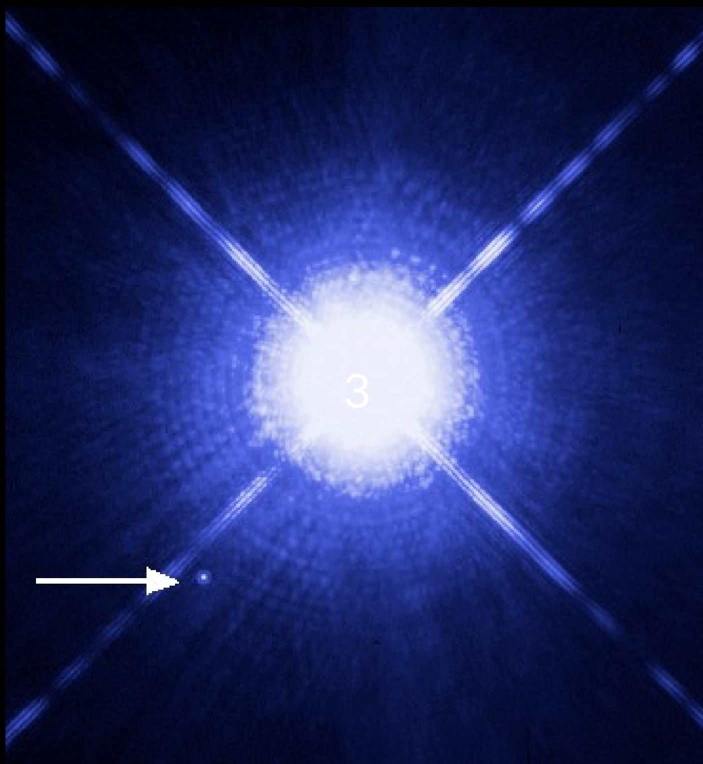
Sirius B



- Sirius B discovered in 1862
- Luminosity : 0.056 sol. Lum.
- Temp. : 25 000° K

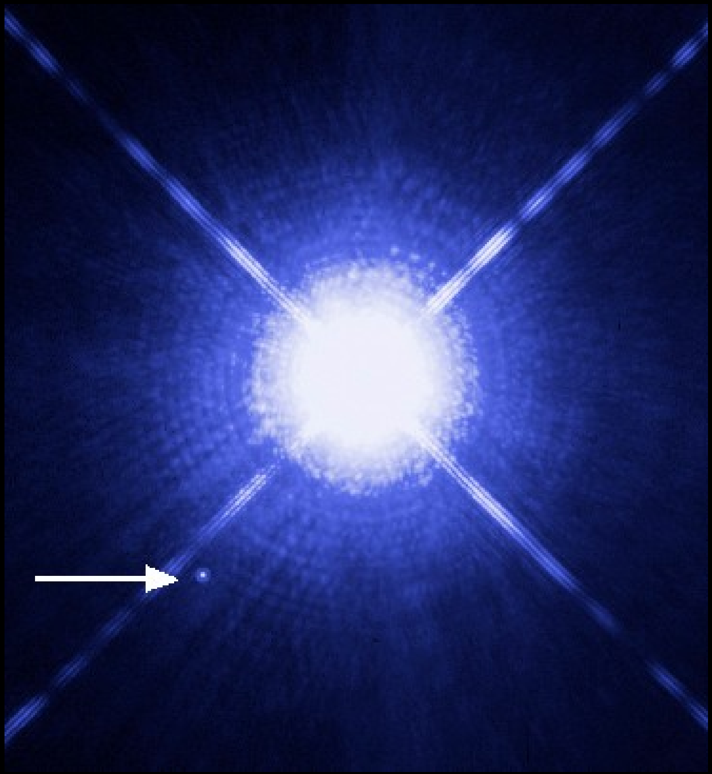
- Radius ?

White Dwarfs



- Sirius B discovered in 1862
- Luminosity : 0.056 sol. Lum.
- Temp. : 25 000° K
- $$R = \sqrt{\frac{L}{4\pi\sigma T^4}} \simeq 0.01 R_\odot$$
- Density ?

White Dwarfs



- Sirius B discovered in 1862
- Luminosity : 0.056 sol. Lum.
- Temp. : 25 000° K
- $$R = \sqrt{\frac{L}{4\pi\sigma T^4}} \simeq 0.01 R_\odot$$
- $$\rho = \frac{3M}{4\pi R^3} \simeq 10^6 \;\; g/cm^3$$

Degenerate gas

For a degenerate gas :

$$(\frac{4\pi}{3})^2 \frac{R^3 p_f^3}{\hbar^3} \simeq \frac{M}{m_p} \quad \rightarrow \quad p_f = (\frac{3\rho}{4\pi m_p})^{1/3}\ \hbar$$

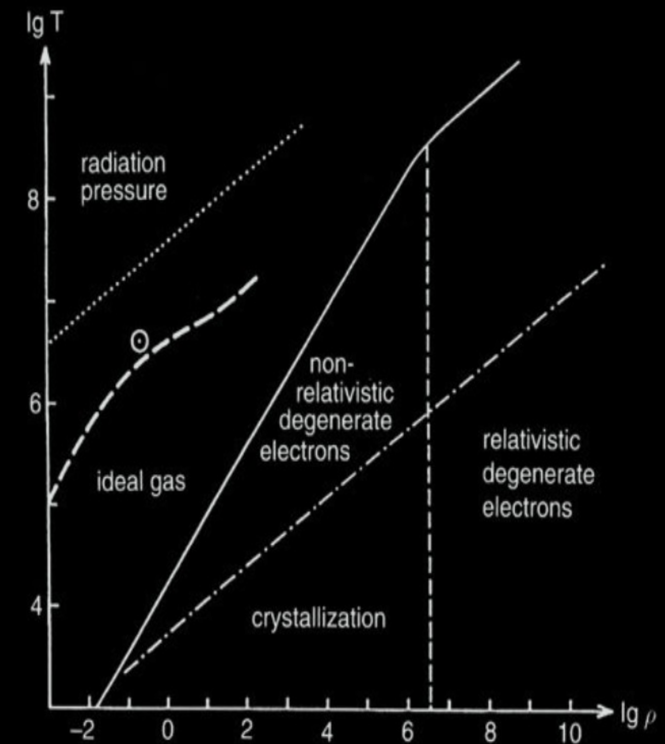
In a ideal gas :

$$E = \frac{3}{2}KT = \frac{p^2}{2m}$$

Therefore :

$$3mKT >> (\frac{3\rho}{4\pi m_p})^{\frac{2}{3}}\ \hbar^2$$

$$\rho << 4\sqrt{3}\pi \left(\frac{mKT}{\hbar}\right)^{\frac{3}{2}}\ m_p$$



A sketch of the density–temperature plane showing the regions in which different types of equation of state are applicable. In addition to the regions discussed in the text, the diagram also shows the regions in which radiation pressure exceeds the gas pressure and also the region in which the degenerate gas is expected to become a solid, that is, it represents the melting temperature of the stellar material. The heavy dashed line shows the location of the Sun from its core to envelope (Kippenhahn and Weigert, 1990).

The Chandrasekhar's limit

General argument by **Landau** (1932) on limiting mass for a degenerate gas of **electrons** (WDs) or **neutrons** (NSs)

N fermions in star of radius $R \Rightarrow n \sim N/R^3$

Volume per fermion $\sim 1/n$ (**Pauli exclusion principle**) and momentum $\sim \hbar n^{1/3}$ (**Heisenberg principle**)

Fermi energy of fermionic gas in relativistic regime:

$$E_F = p_F c \sim \hbar n^{1/3} c \sim \hbar c N^{1/3}/R$$

Gravitational energy per fermion:

$E_G \sim -GMm_B/R$ ($M = Nm_B$, most of the mass in baryons)

Equilibrium at a minimum of the total energy function:

$$E = E_F + E_G = \hbar c N^{1/3}/R - GNm_B{}^2/R$$

The Chandrasekhar's limit

$$E(N) = E_F + E_G = \hbar c N^{1/3}/R - GNm_B{}^2/R$$

For arbitrary large N, E is always negative ⇒ if R decreases, E continues to decrease ⇒ collapse continues indefinitely ⇒ M_{max}

For small N, first term dominates ($E > 0$) ⇒ minimum at $E(N)=0$

$$N_{max} \sim (\hbar c/Gm_B{}^2)^{3/2} \sim 2 \times 10^{57} \Rightarrow M_{max} \sim N_{max}\, m_B \sim 1.7\ M_\odot$$

From this simplified calculation, same M_{max} for WDs and NSs.

Equilibrium radius: $E_F \sim mc^2$ in the relativistic regime and m is the mass of electrons or neutrons, giving WD and NS radius, respectively

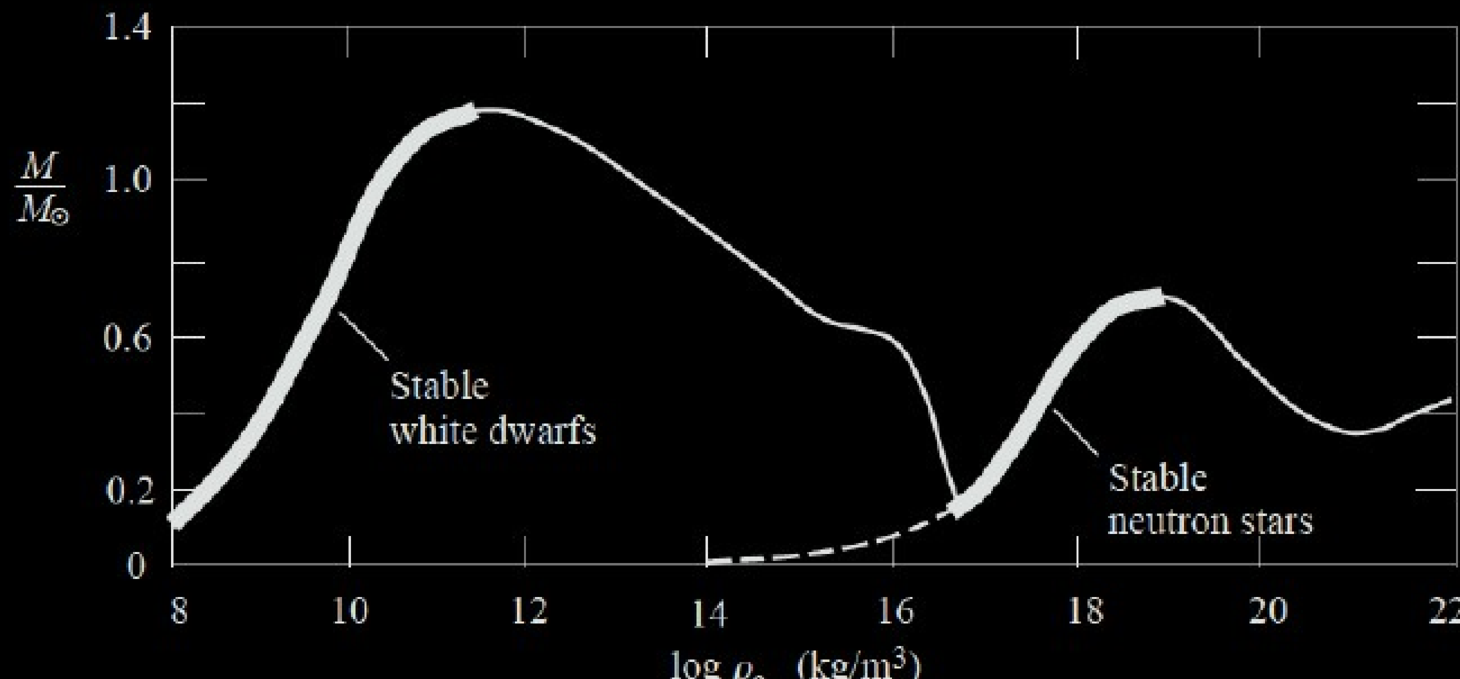
$$E_F \sim \hbar c N^{1/3}/R \sim mc^2 \quad R \sim \hbar/mc(N_{max})^{1/3} \sim \hbar/mc\ (\hbar c/Gm_B{}^2)^{1/2}$$

$R_{WD} \sim 5 \times 10^8$ cm for $m=m_e$; $R_{NS} \sim 3 \times 10^5$ cm for $m=m_n$

NS radii m_n/m_e times smaller than WD radii

Stability of Wds and NSs

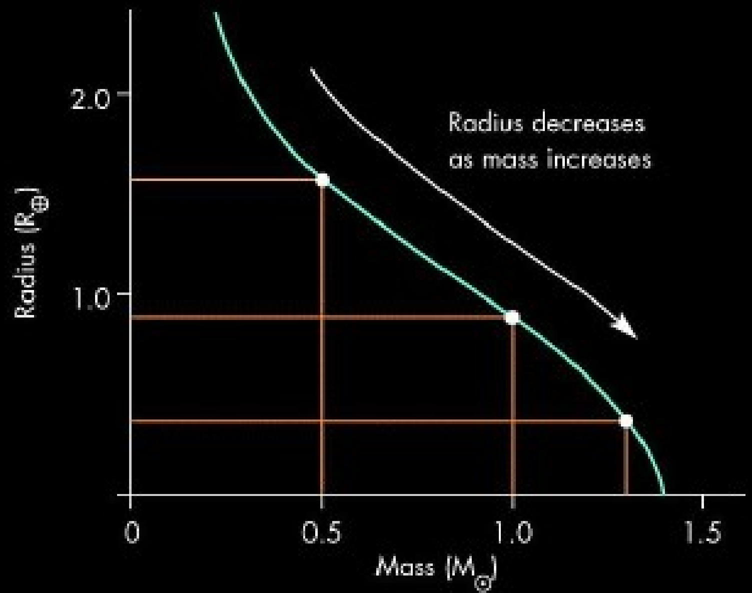
HW (1958) and OV (1939) equations of state, *ignoring nuclear forces*.

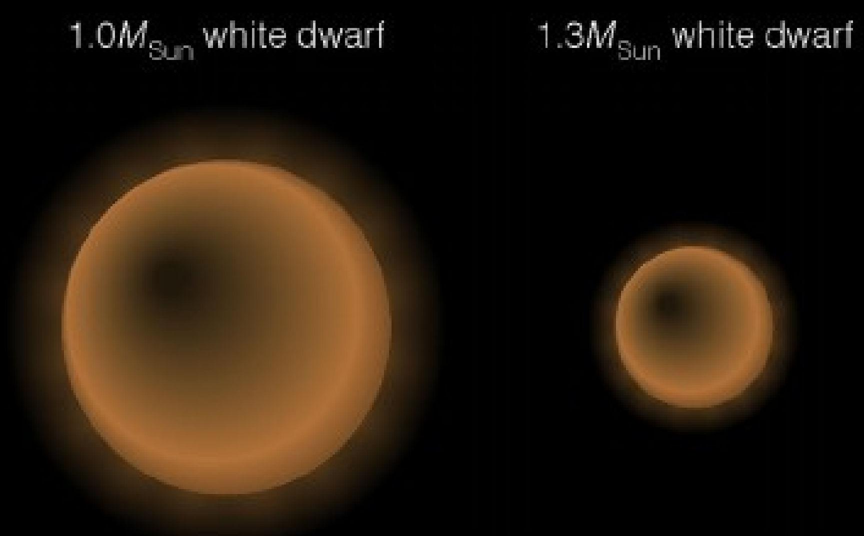


Stability only if mass increase implies larger density
$\Rightarrow$ larger pressure to contrast gravity ($P \propto \rho^\gamma$)

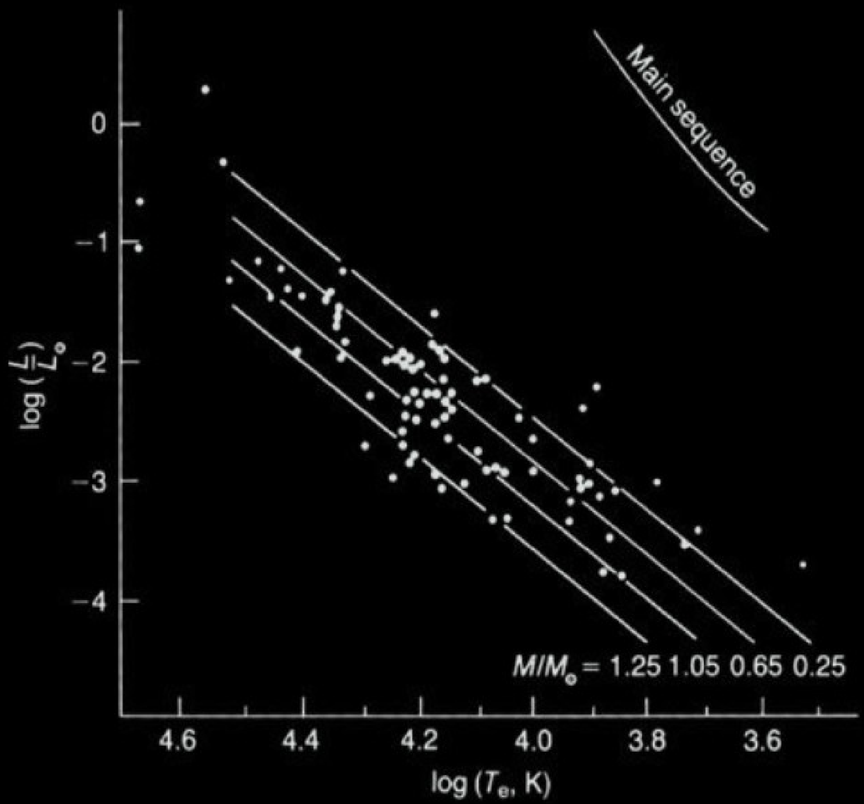
White Dwarfs

- The more mass the star has, the *smaller* the star becomes!
  - increased gravity makes the star denser
  - greater density increases degeneracy pressure to balance gravity





White Dwarfs

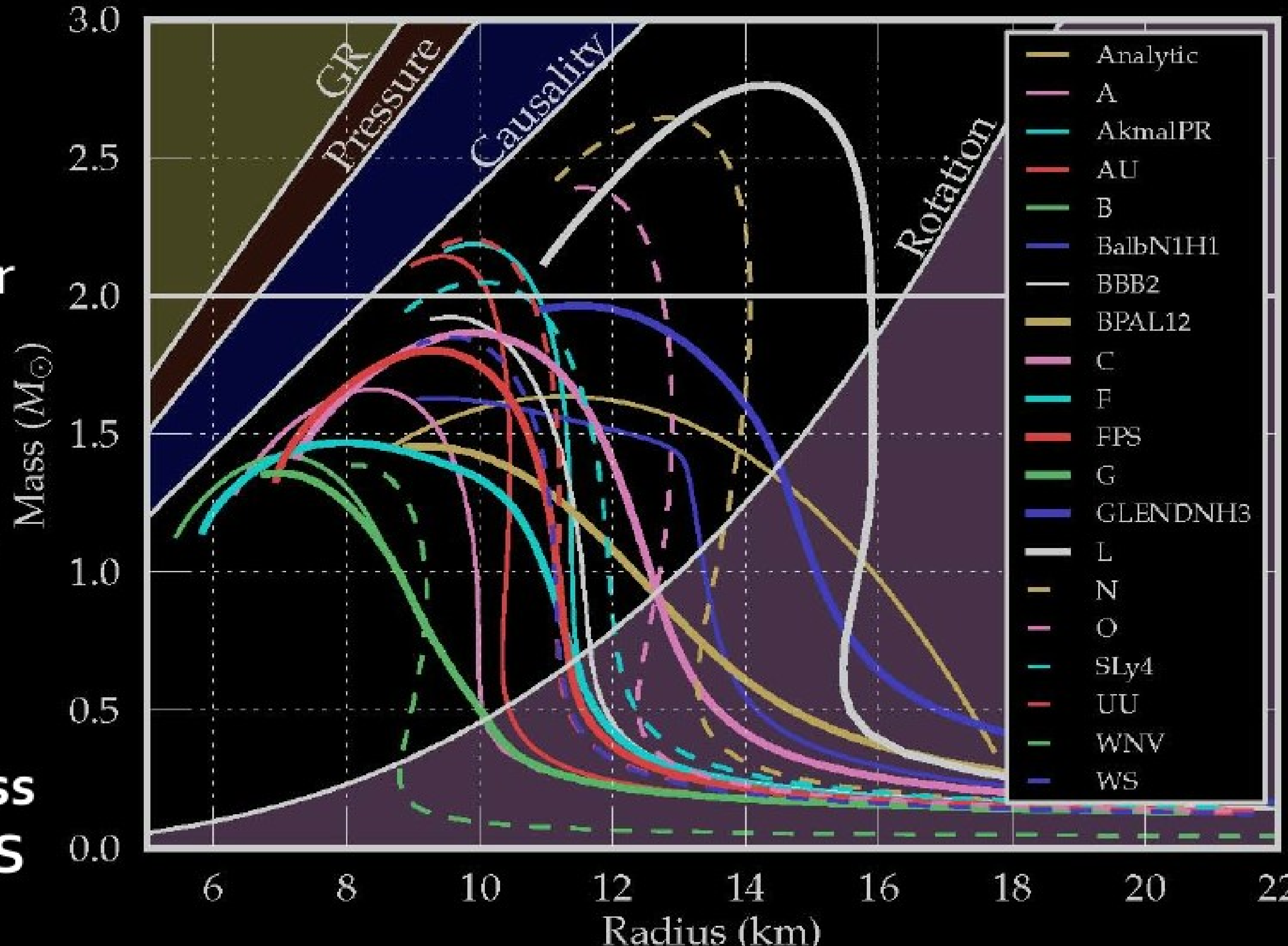


Neutrons Stars

To determine NS Equation of State (**EoS**) we need to know the behavior of matter at supranuclear density and use General Relativity

$$\left(\frac{GM_{NS}}{R_{NS}c^2} \approx 0.1 \right)$$

Maximum NS mass <3 $M_\odot$ for any EoS



Neutrons Stars

Surface layers ρ ≤ 10^6 g cm−3

- Atomic polymers of ^{56}Fe in the form of a close packed solid.
- Strong surface magnetic fields → the atoms become cylindrical, the matter behaves like a one-dimensional solid
- High conductivity parallel to the magnetic field and zero conductivity across it.

Outer Crust 10^6 ≤ ρ ≤ 4.3×10^11 g cm−3

- Solid region of matter similar to that found in white dwarfs, heavy nuclei forming a Coulomb lattice embedded in a relativistic degenerate gas of electrons.
- Inverse β decay increases the numbers of neutron-rich nuclei which would be unstable on Earth.

Inner Crust 4.3×10^11 ≤ ρ ≤ 2×10^14 g cm−3

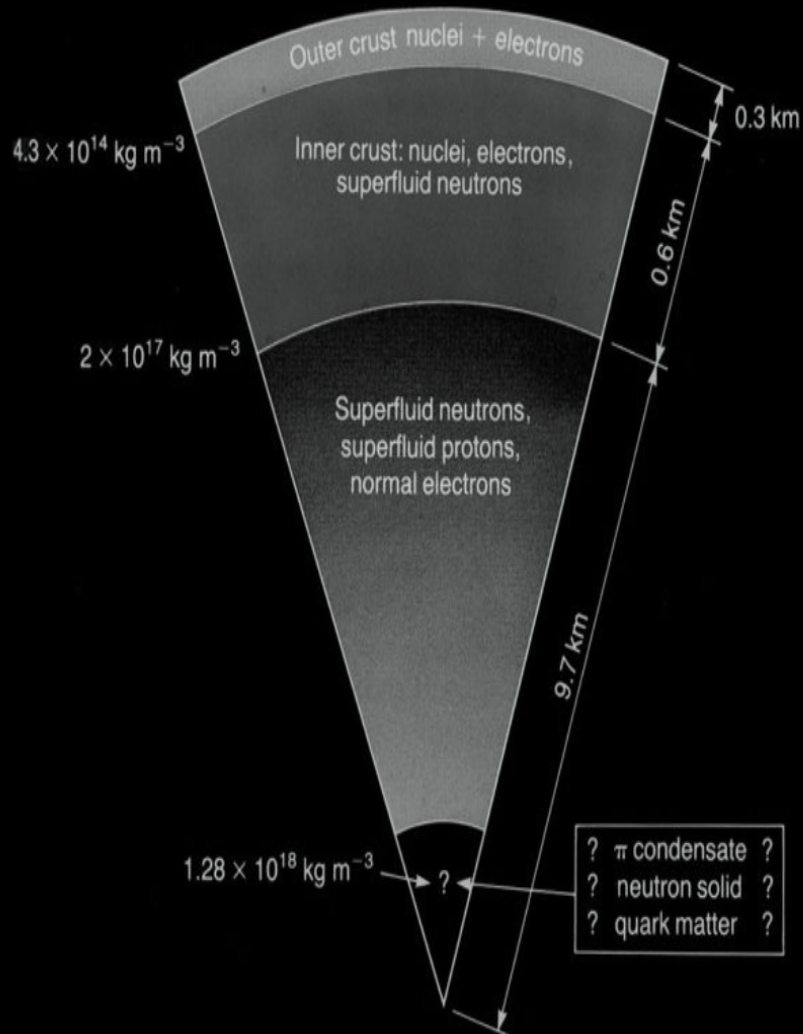
- Lattice of neutron-rich nuclei together with free degenerate neutrons and a degenerate relativistic electron gas.
- Nuclei begin to dissolve, the neutron fluid provides most of the pressure.

Neutron liquid phase ρ > 2×10^14 g cm−3

- Mainly of neutrons with a small concentration of protons and electrons.

Core ρ ≥ 3×10^15 g cm−3

- May or may not exist,it depends upon the behaviour of matter in bulk at very high energies and densities.
- Neutron solid ? quark matter ? (Camenzind 2007).



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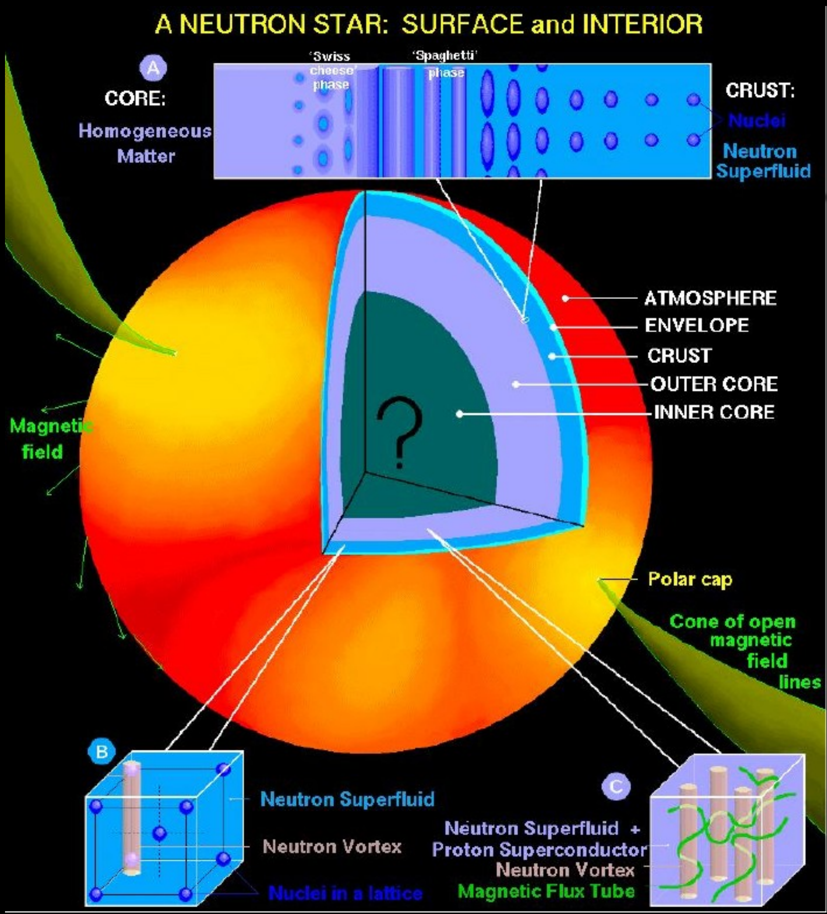
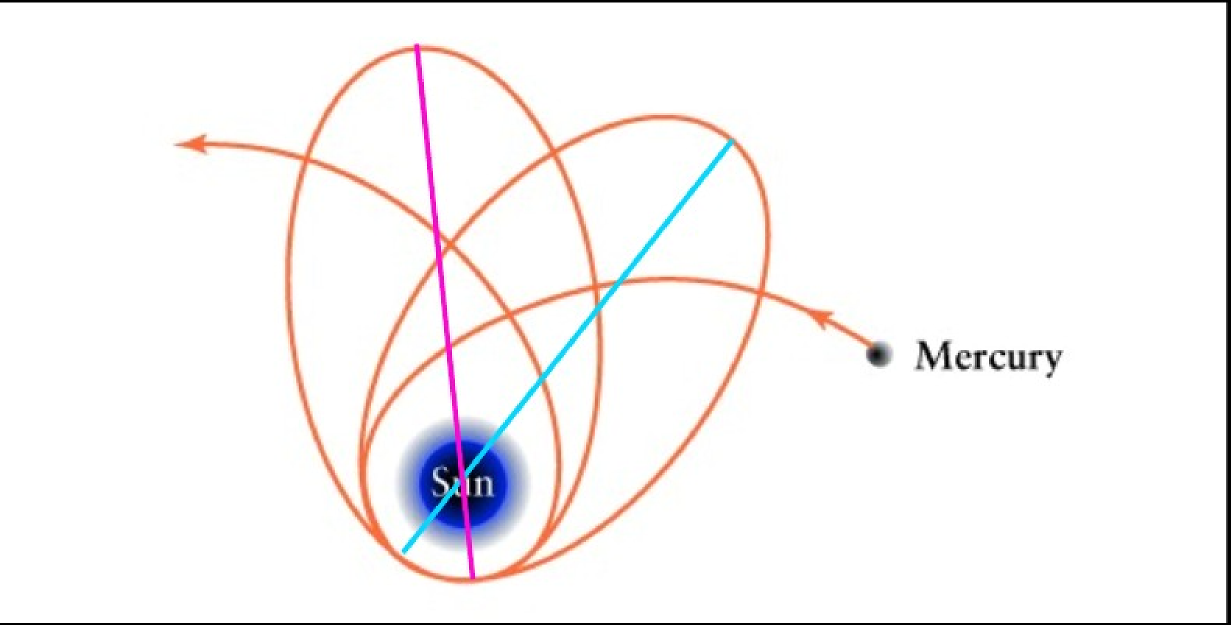


Mercury orbit precession

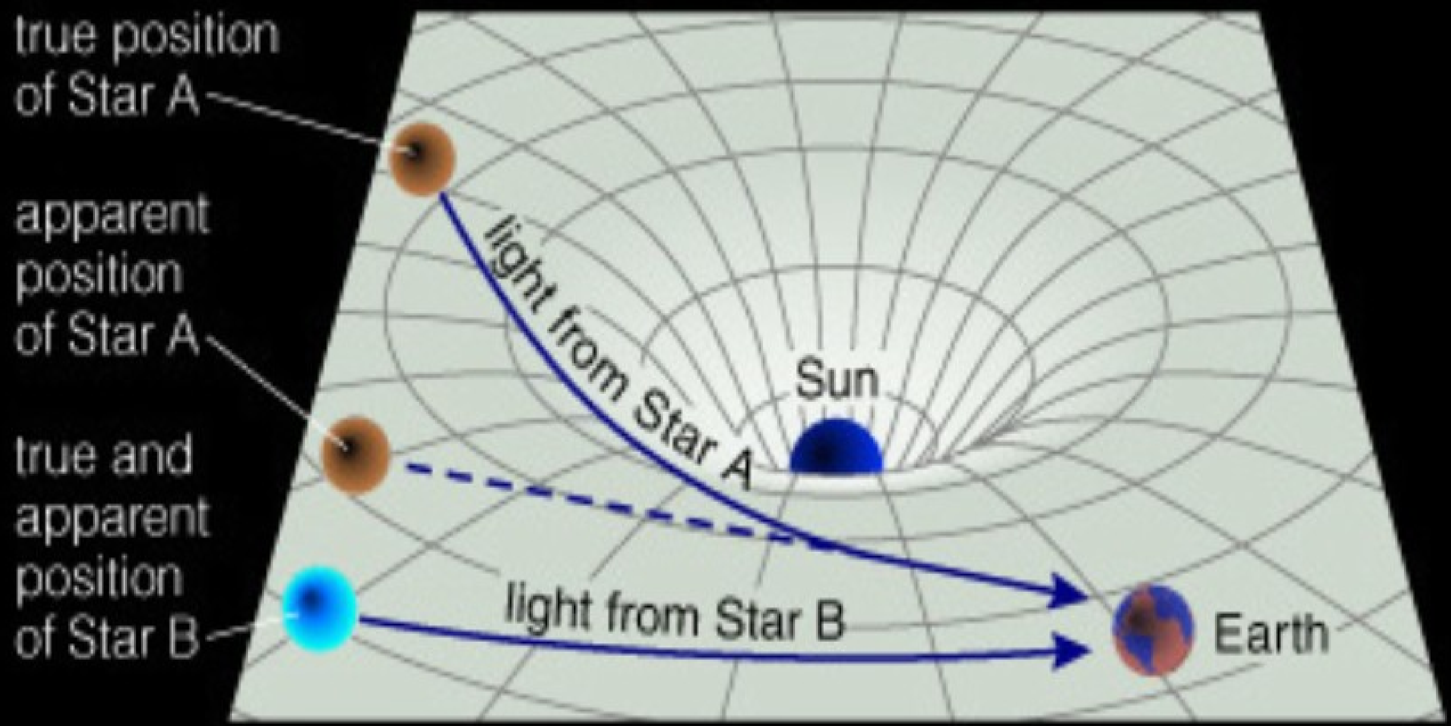


Newtonian Gravity Predicts: 5557.62 arcsec/century

Observed Value: 5600.73 arcsec/century

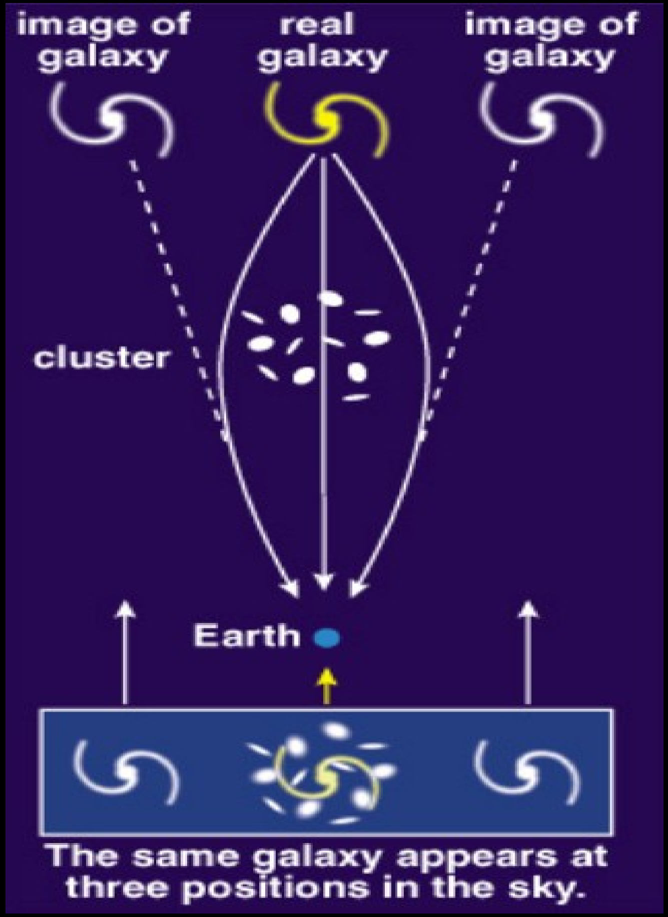
Difference: 43.11 ± 0.45 arcsec/century too fast!!

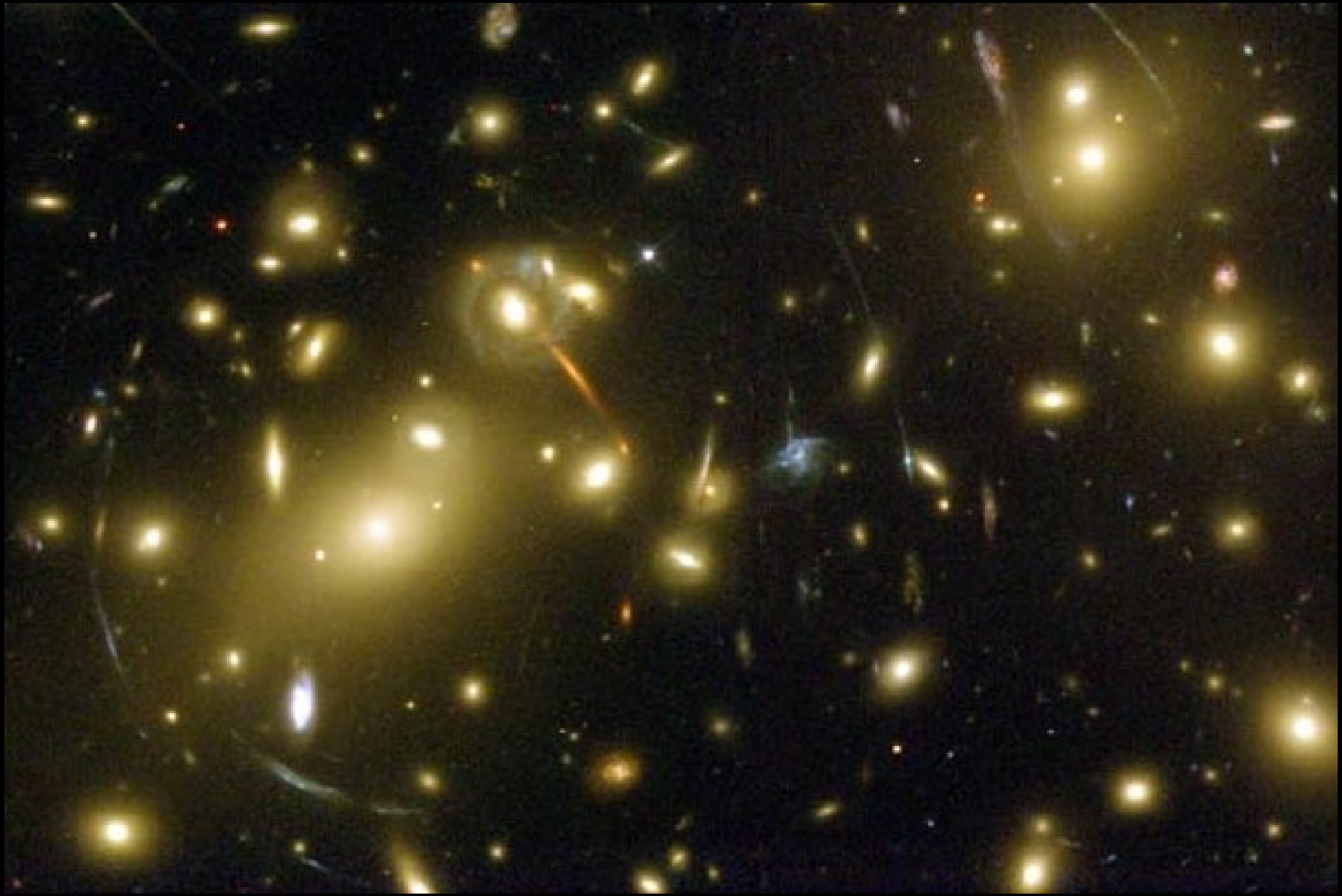
Deflection of starlight

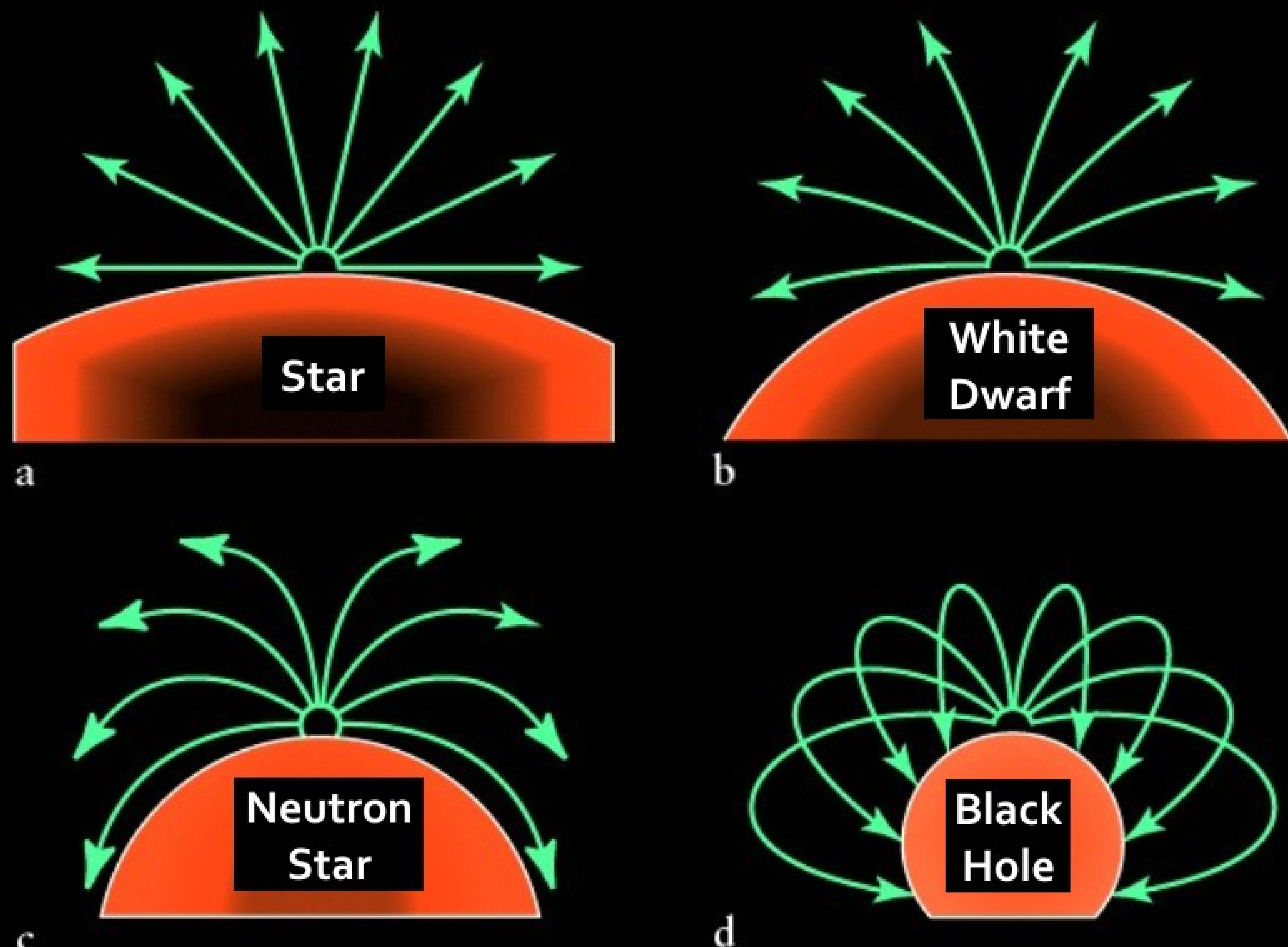


Eddington observation (1919)

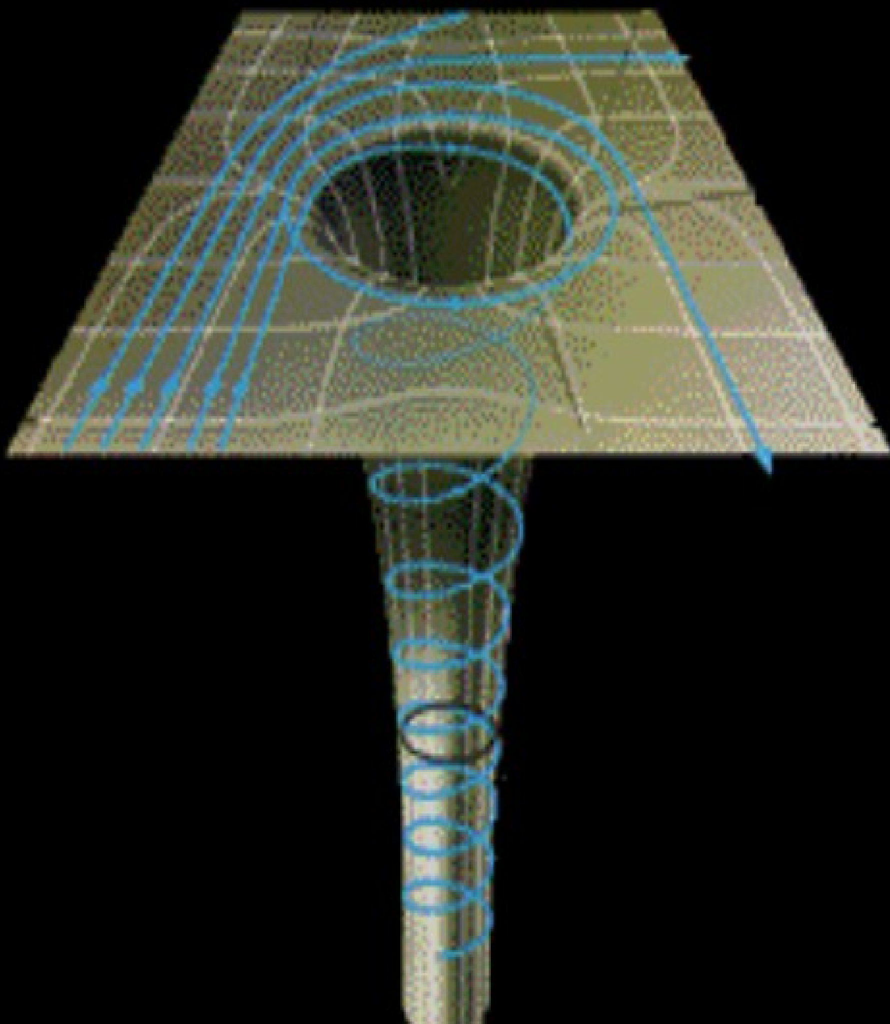
Gravitational Lensing






Star
a
White Dwarf
b
Neutron Star
c
Black Hole
d

Black Holes

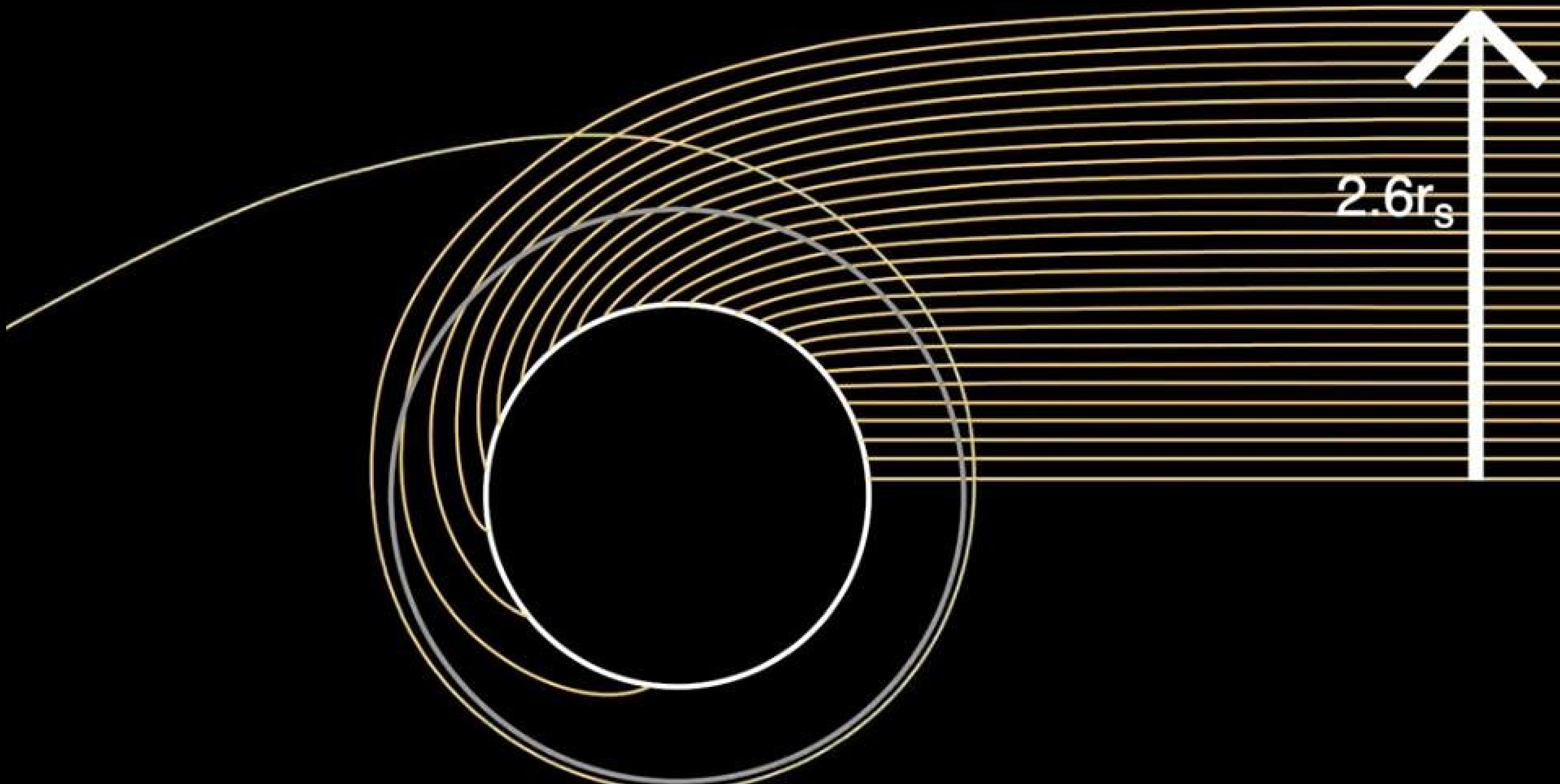


Black holes are a fundamental prediction of the theory of general relativity (GR; Einstein 1915).

A defining feature of black holes is their event horizon, a one-way causal boundary in spacetime from which not even light can escape (Schwarzschild 1916).

Schwarzschild radius:

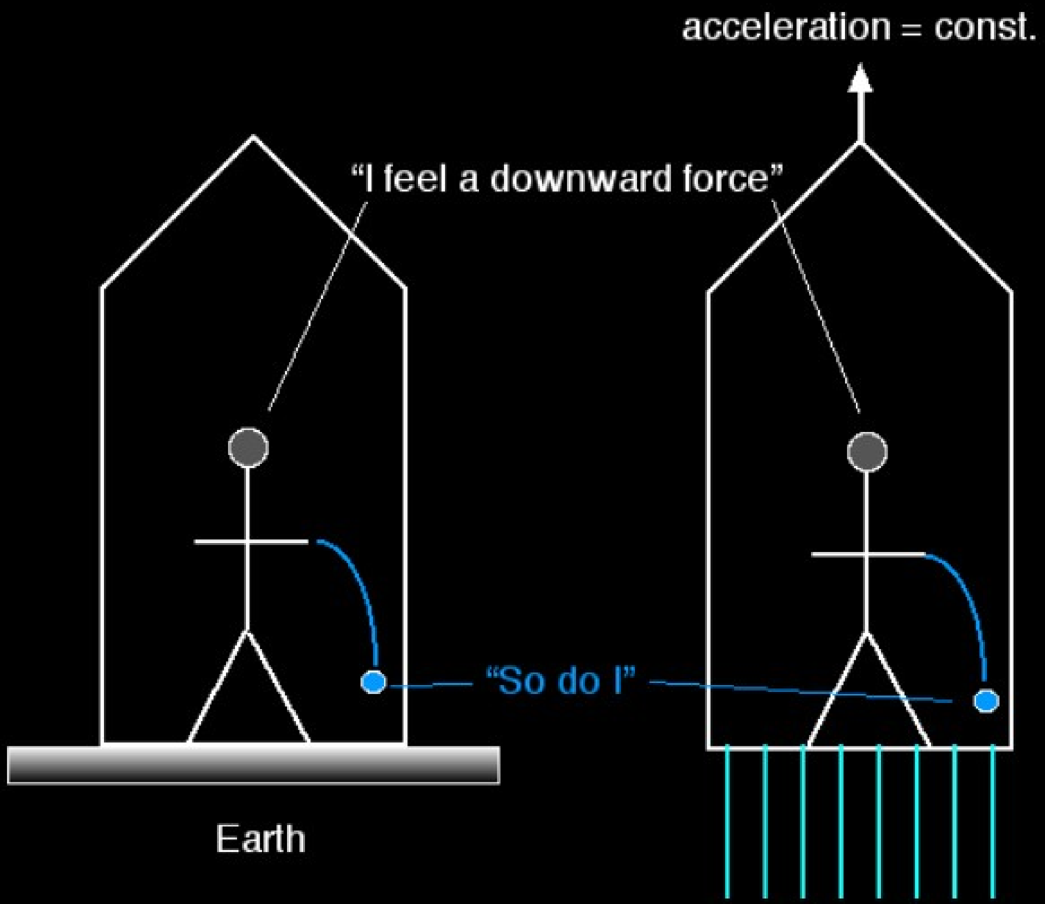
$$R_S = \frac{2GM}{c^2} \approx 3 \frac{M}{M_{Sun}} \; km$$



$2.6r_s$

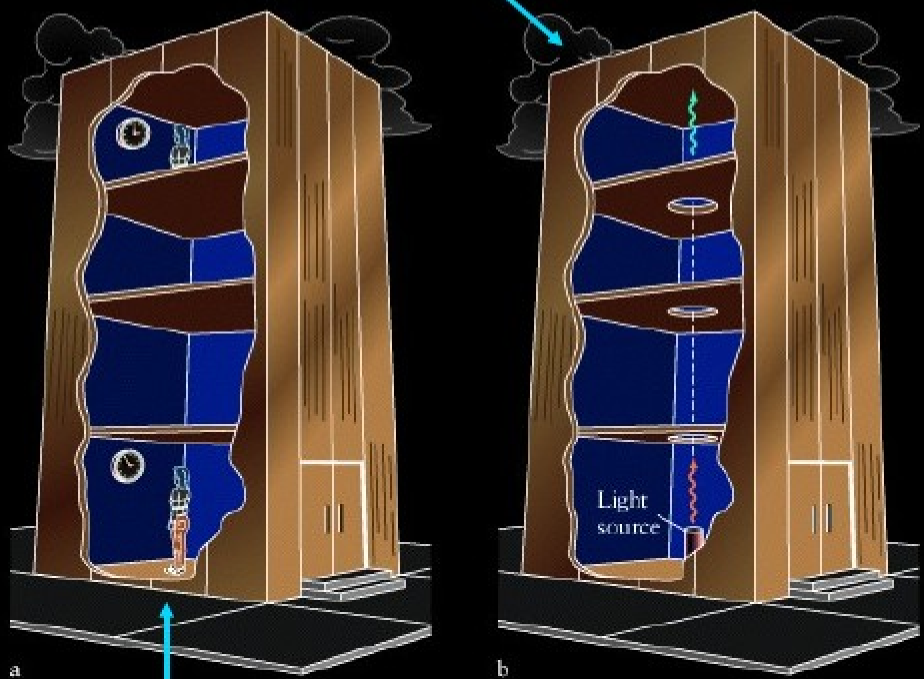
Gereral Relativity

The force of gravity is indistinguishable from the force due to accelerated motion.



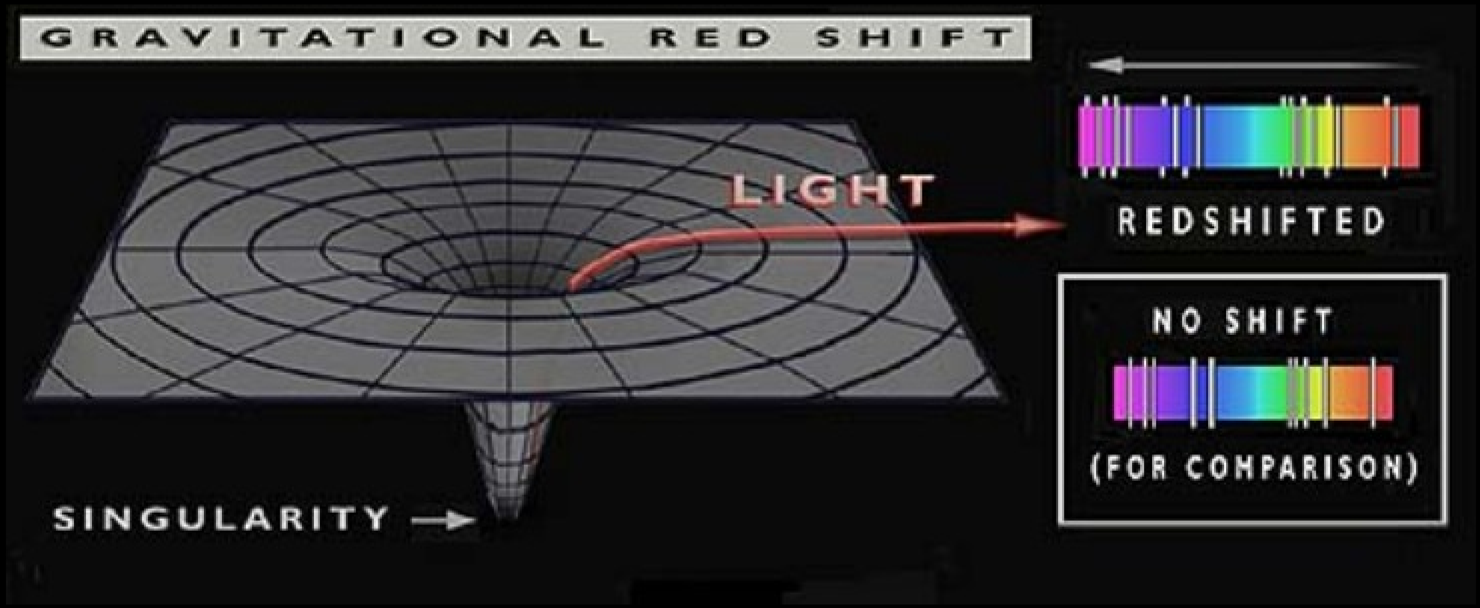
Equivalence principle

Light loses energy as it travels away from a source of gravity



Equivalent viewpoint: time runs more slowly the closer you are to a source of gravity!

Gravitational redshift

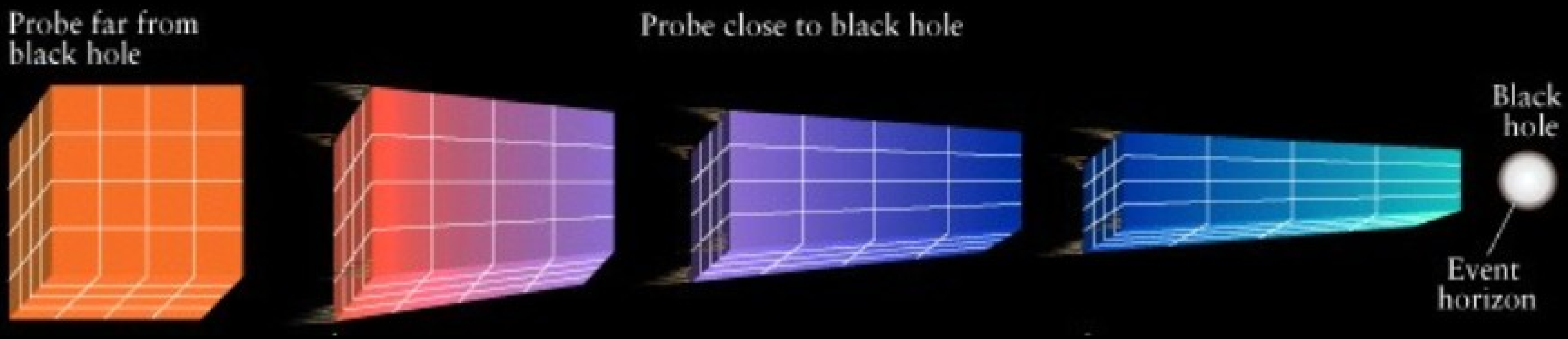


$$\frac{\nu}{\nu_r} = \left(1 - \frac{2GM}{c^2 r}\right)^{1/2} \Rightarrow \nu \rightarrow 0 \text{ for } r \rightarrow R_S$$

Black holes

- With a sufficiently ***large*** black hole, a **freely falling observer** would pass right through the event horizon in a finite time, **would not feel the event horizon**.
- A **distant observer** watching the freely falling observer would never see him/her fall through the event horizon (takes an **infinite time**).
- Signals sent from the freely falling observer would be **time dilated** and **redshifted**.

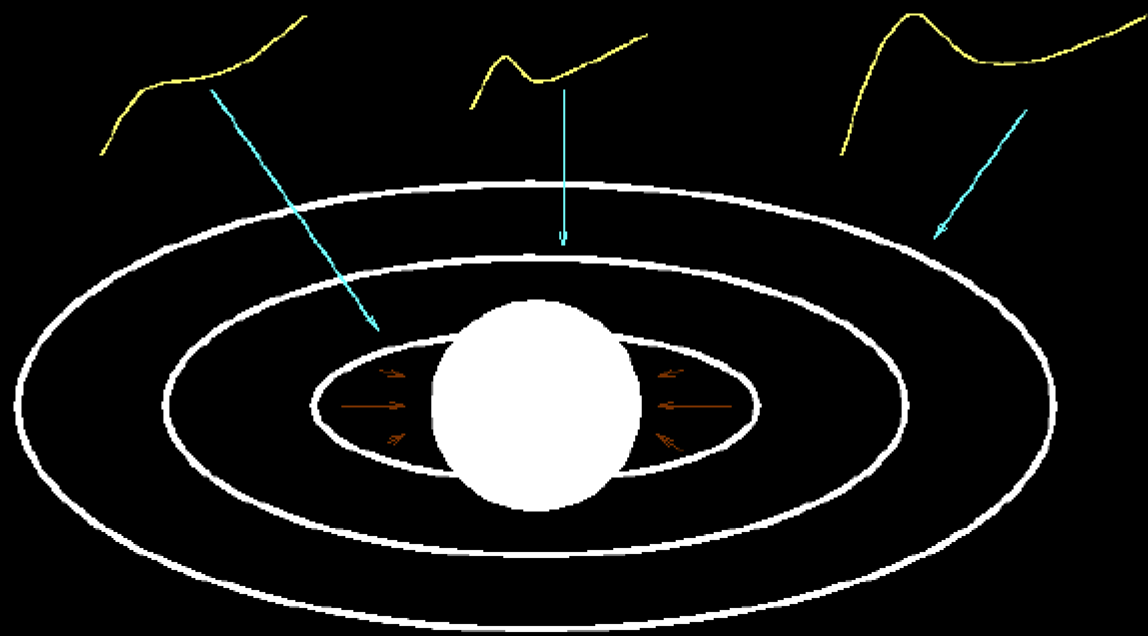
Spaghettification



Black holes

- Once **inside the event horizon, no communication** with the universe outside the event horizon is possible.
- But **incoming** signals from external world can enter.
- A black hole of mass M has exactly the same gravitational field as an ordinary mass M **at large distances**.

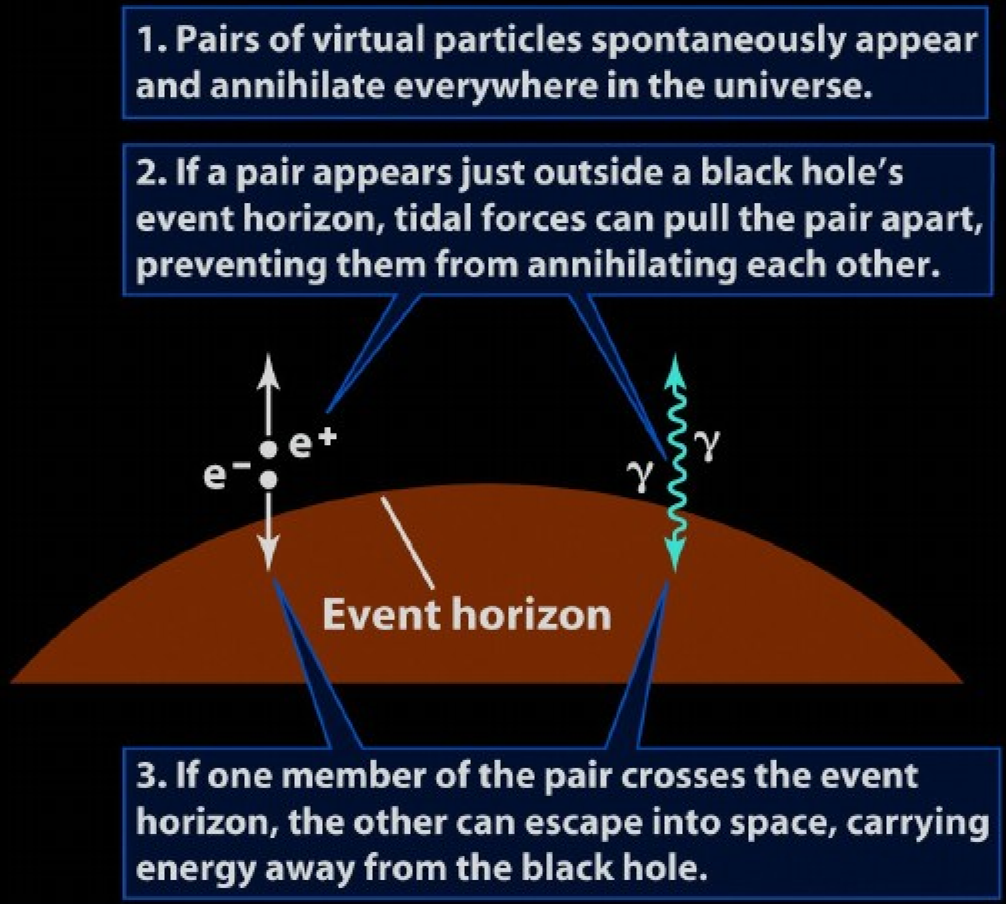
Black holes



By altering angular momentum, we get **stable orbits** at different radii: stable circular orbit at a minimum of potential.

At $R = 6GM/c^2 = 3R_S$ the minimum becomes a point of inflection $\Rightarrow$ **Innermost Stable Circular Orbit (ISCO)**

Hawking radiation



Extremely low luminosity (undetectable), but may cause evaporation of micro-BH (formed at Big Bang?)

Black holes

Three parameters completely describe the structure of a BH

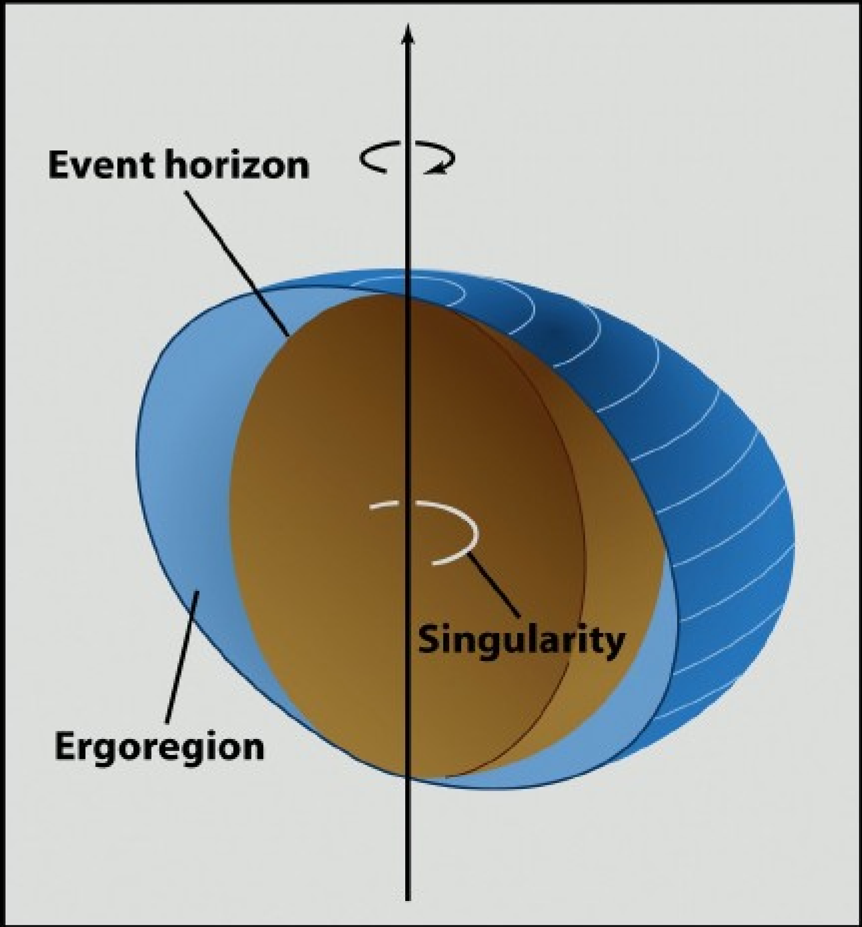
- Mass (M)
  - As measured by the black hole's effect on orbiting bodies, such as another star
- Total electric charge (Q)
  - As measured by the strength of the electric force (Q = 0)
- Spin = angular momentum (a_*)
  - How fast the black hole is spinning ($a_* < 1$)

Kerr black holes

- A rotating black hole has an **ergosphere** around the outside of the event horizon
- In the ergosphere, space and time themselves are dragged along with the rotation of the black hole
- If maximum spin (a_*=1): event horizon at

$$R=GM/c^2=1/2\ R_S\ ;$$

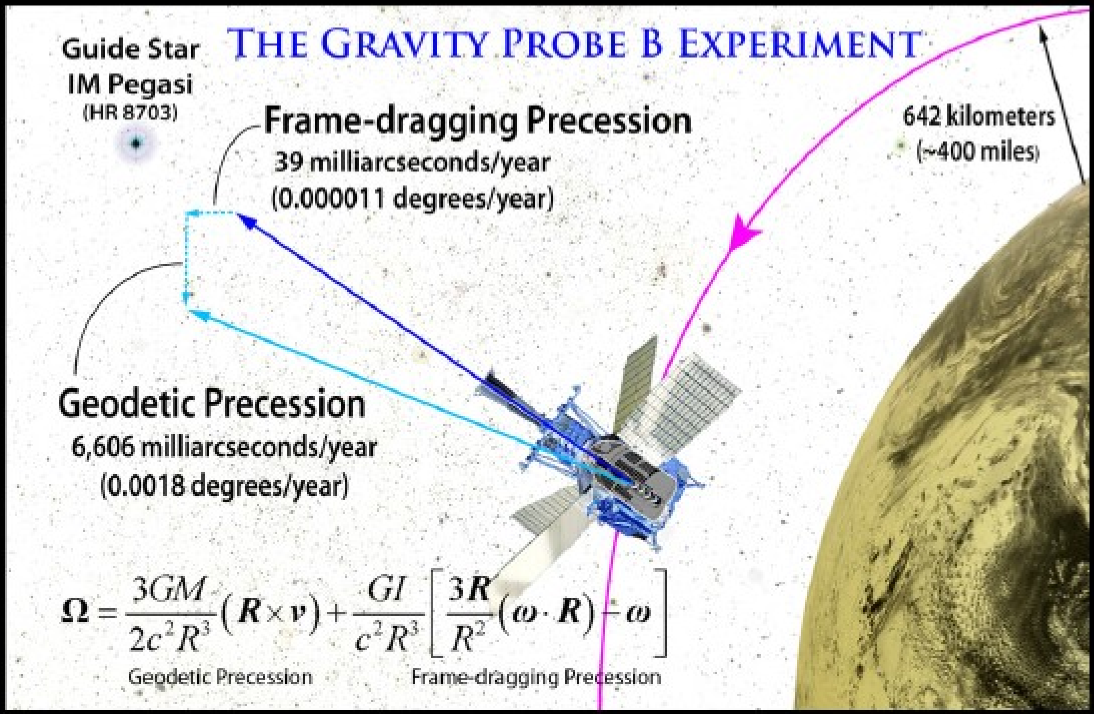
$$R_{ISCO}=GM/c^2=R$$

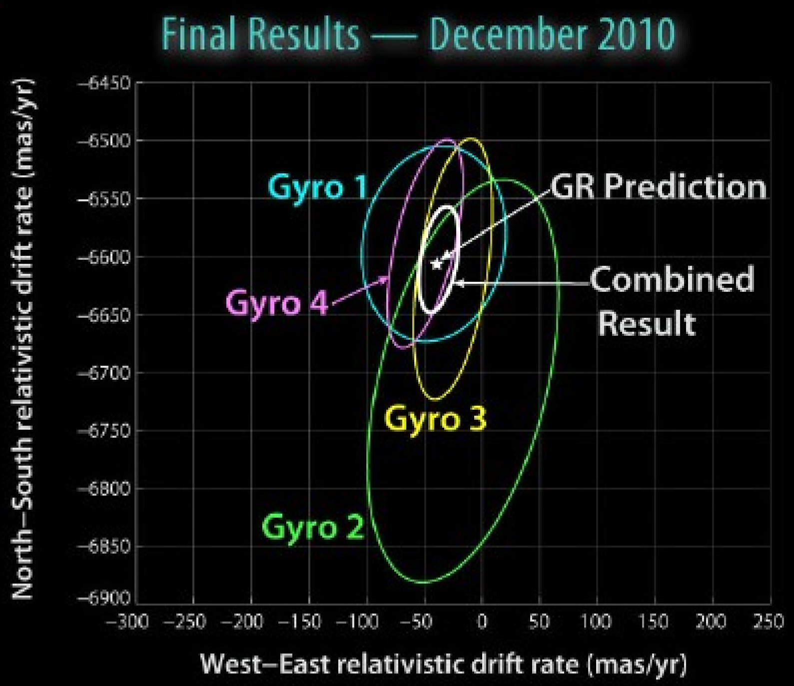


A rotating mass has a tendency to pull space-time along with it

Gravity Probe B

Launched 20 April 2004 to test geodetic and frame-dragging GR effects, by means of cryogenic gyroscopes in Earth orbit





The mass function

$$a_* = a\frac{M_o}{M_* + M_o}$$

Kepler's 3rd law becomes:

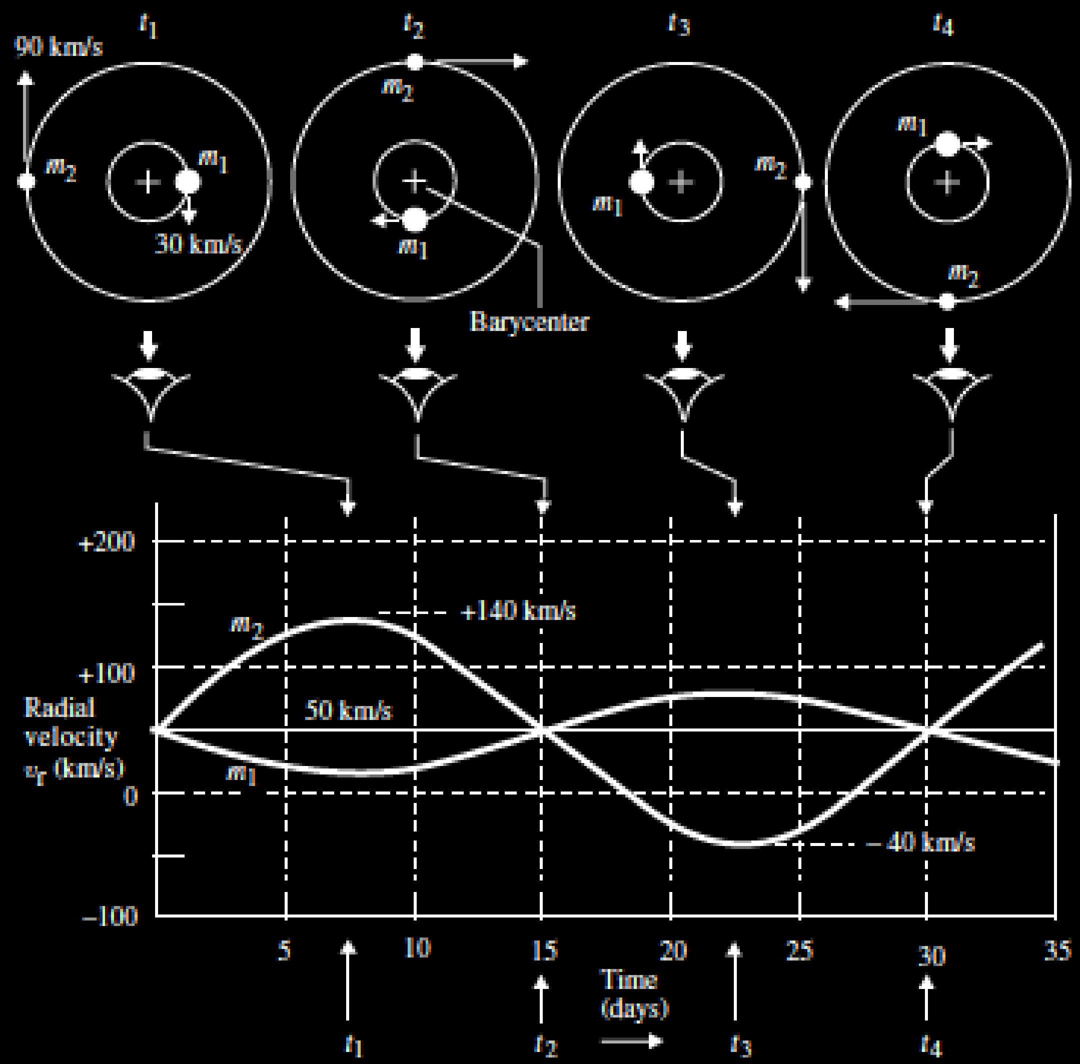
$$\omega^2 = G\frac{M_* + M_o}{a^3}$$

We can also measure :

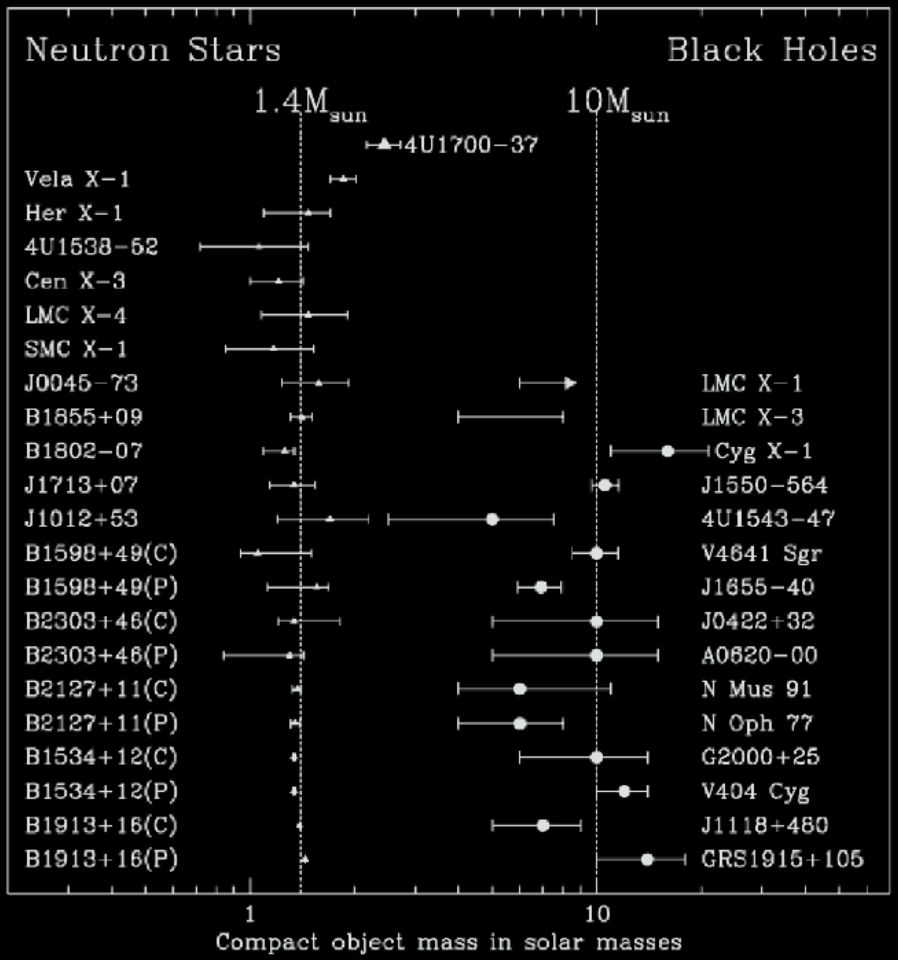
$$v_{max} = \omega a_* sin(i)$$

We define ***mass function*** :

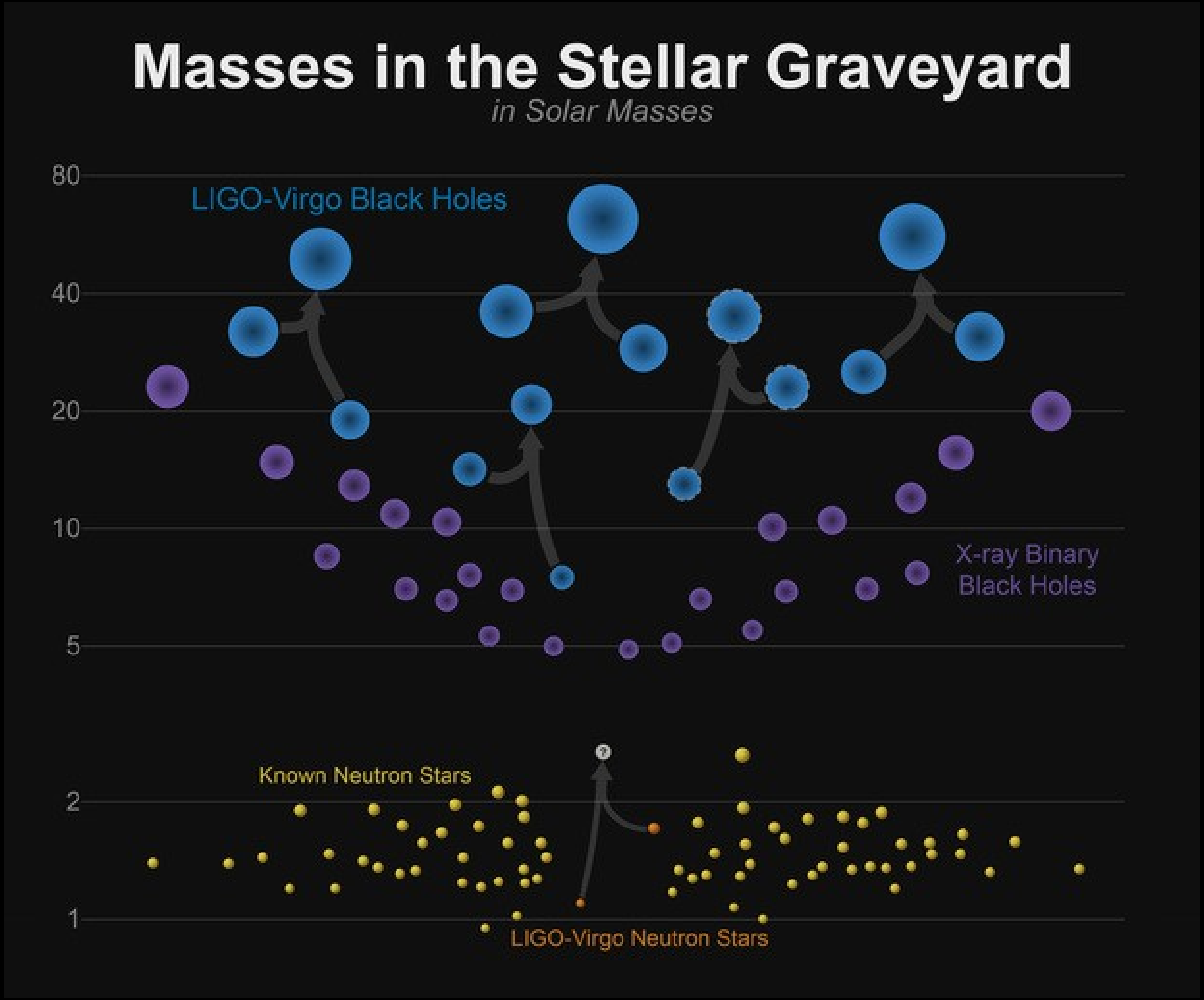
$$f = \frac{v_m^3}{\omega G} = \frac{M_o^3 sin^3 i}{(M_* + M_o)^2}$$



Compact objects on binary systems

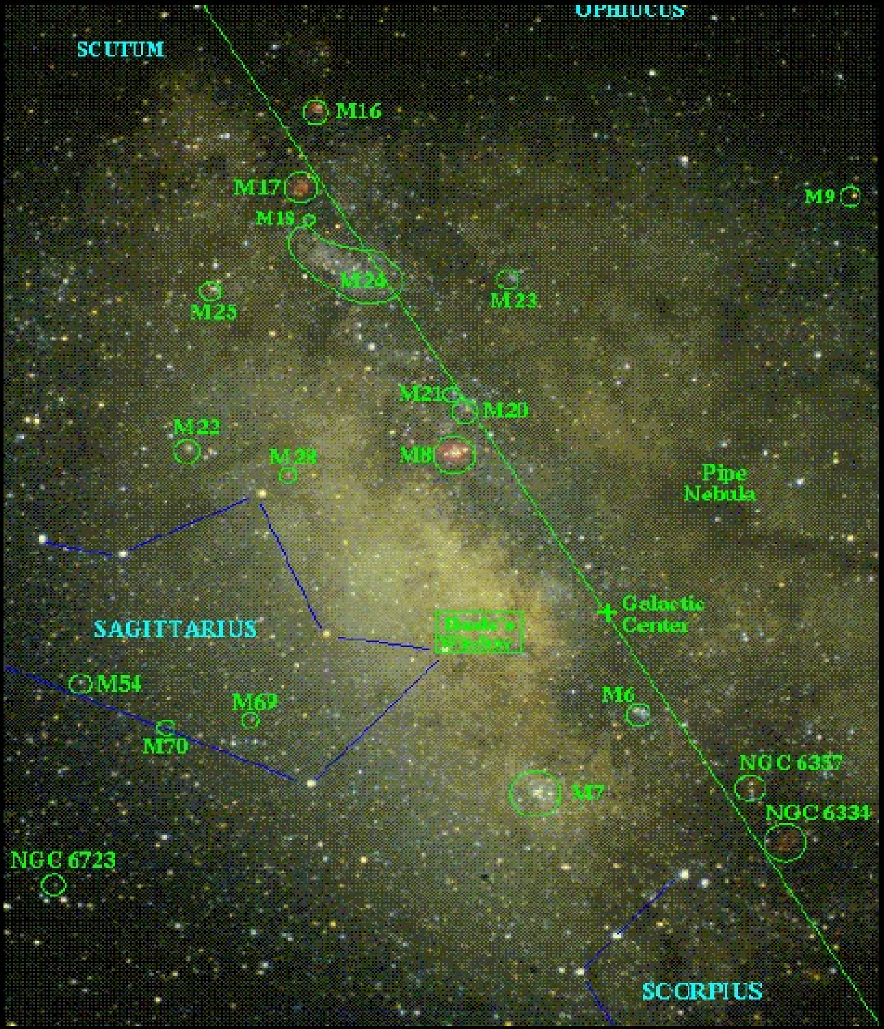


BHs masses



Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary
Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars

Sgr A*



Center of our galaxy: radio source Sgr A*

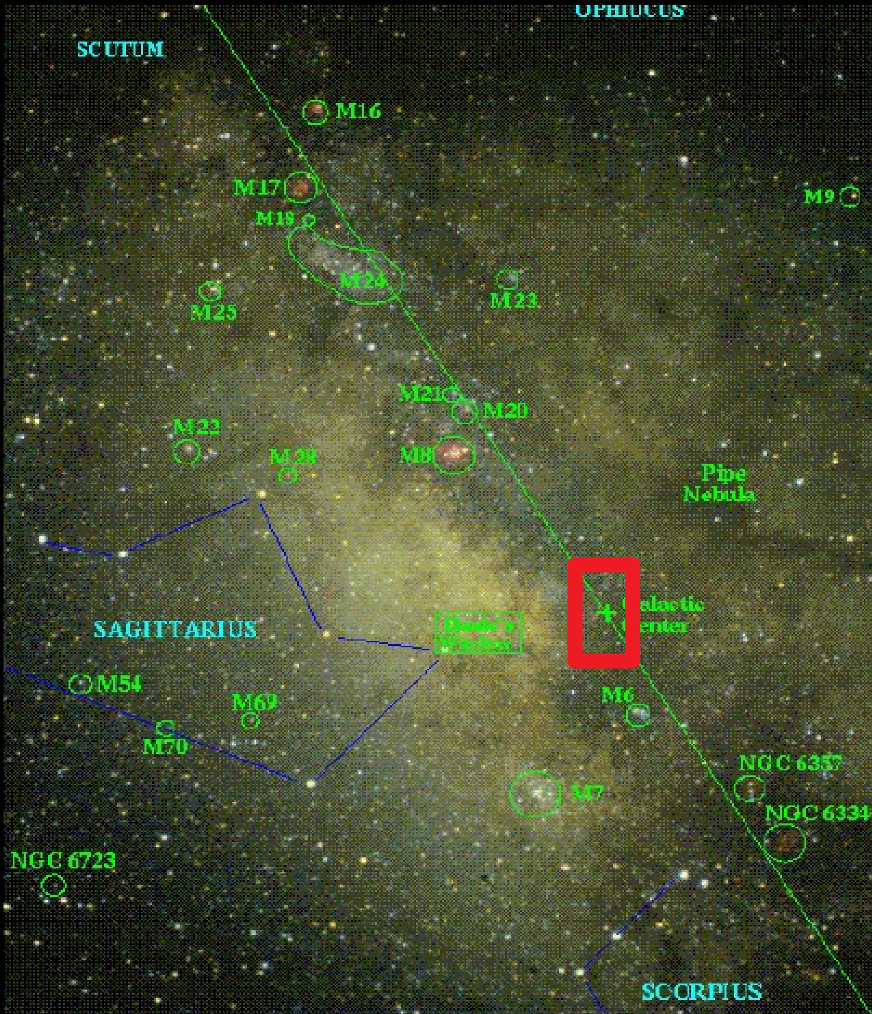
Distance: 8 kpc

Highly obscured in optical

Dense central star cluster visible in infrared

Photo/illustration from A. Tanner, UCLA

Sgr A*



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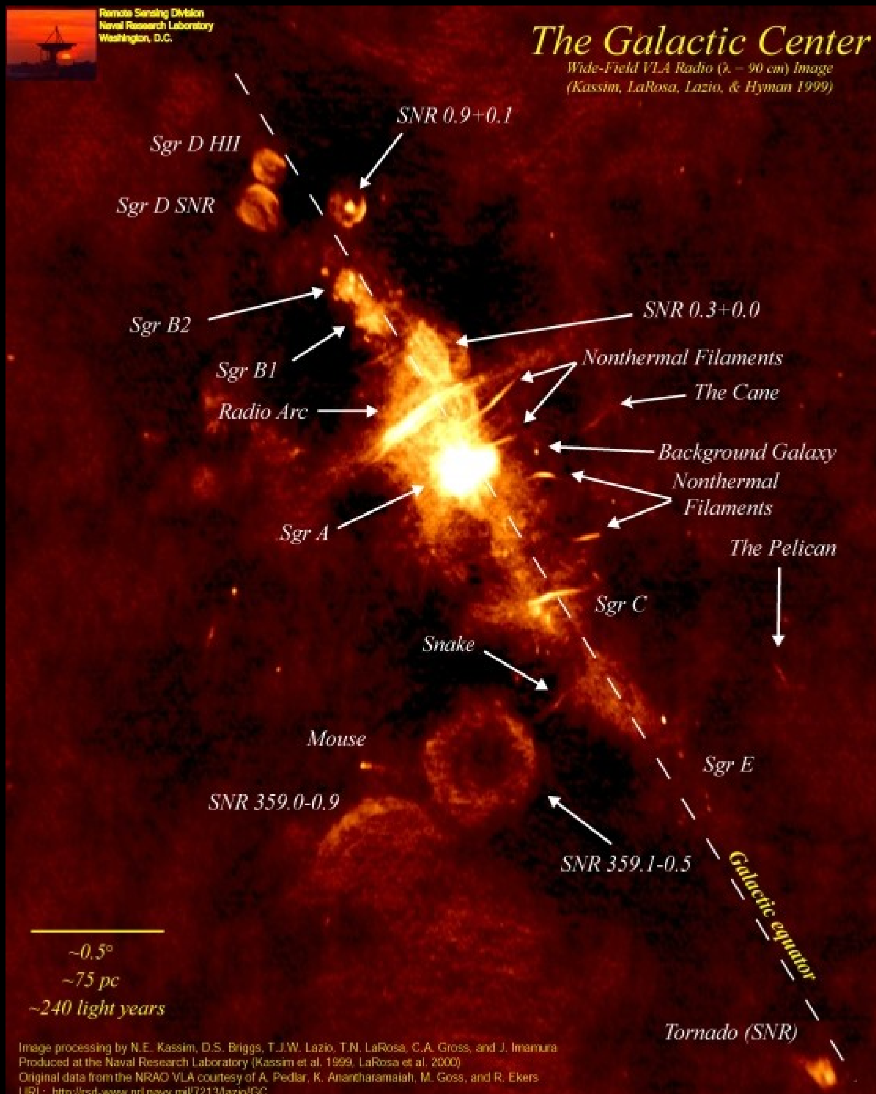

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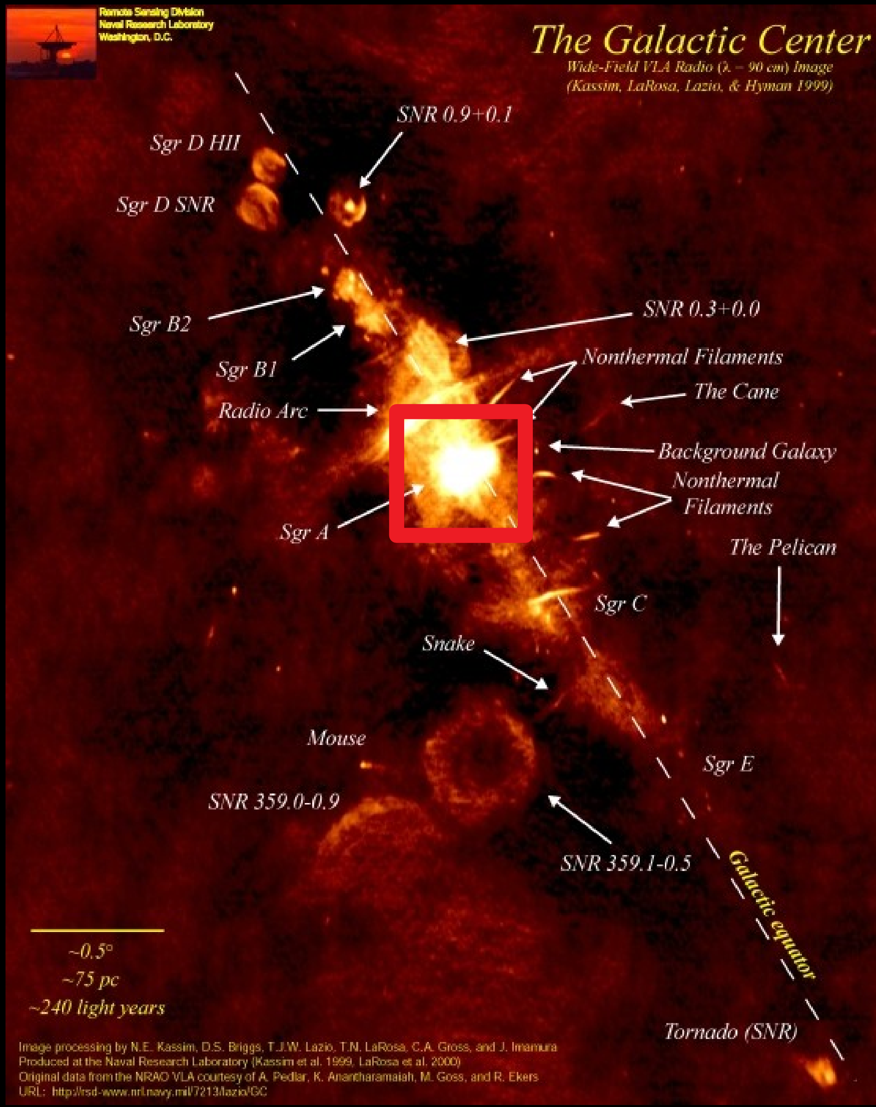

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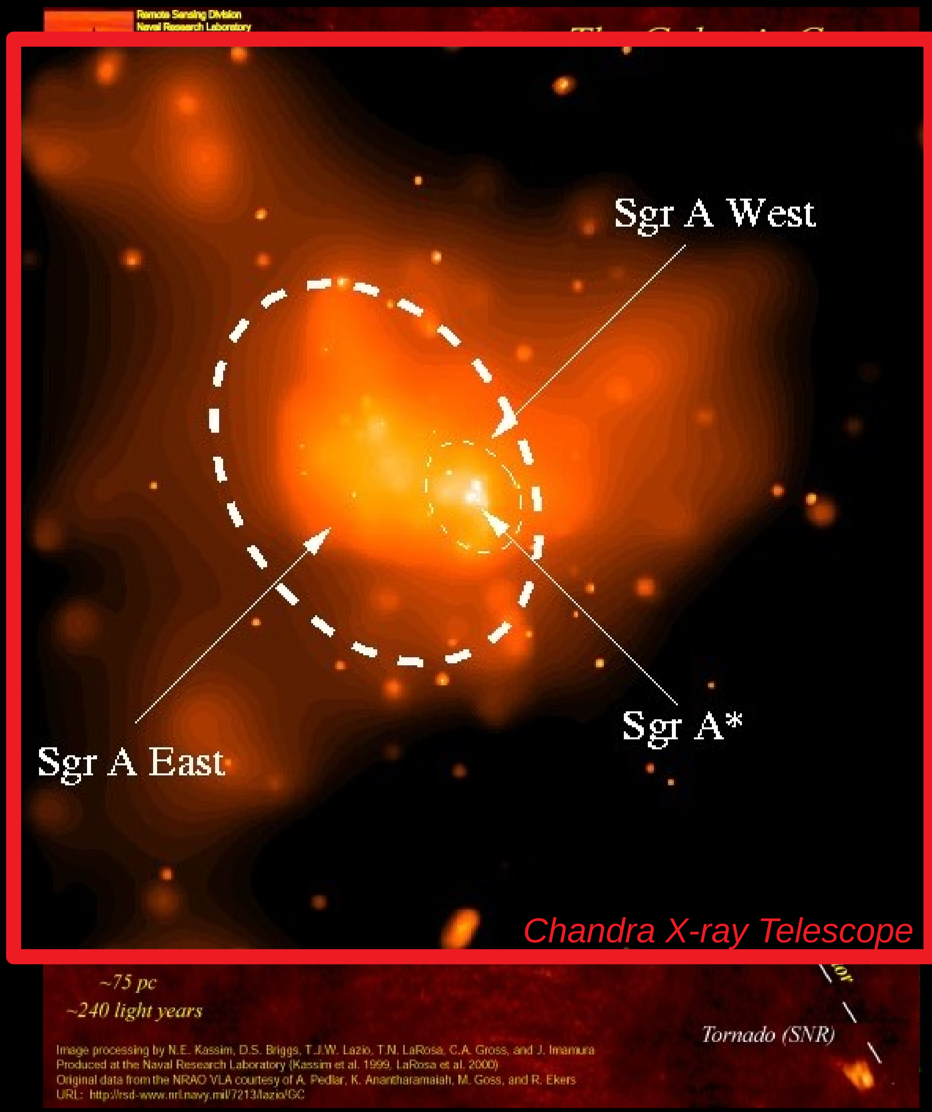

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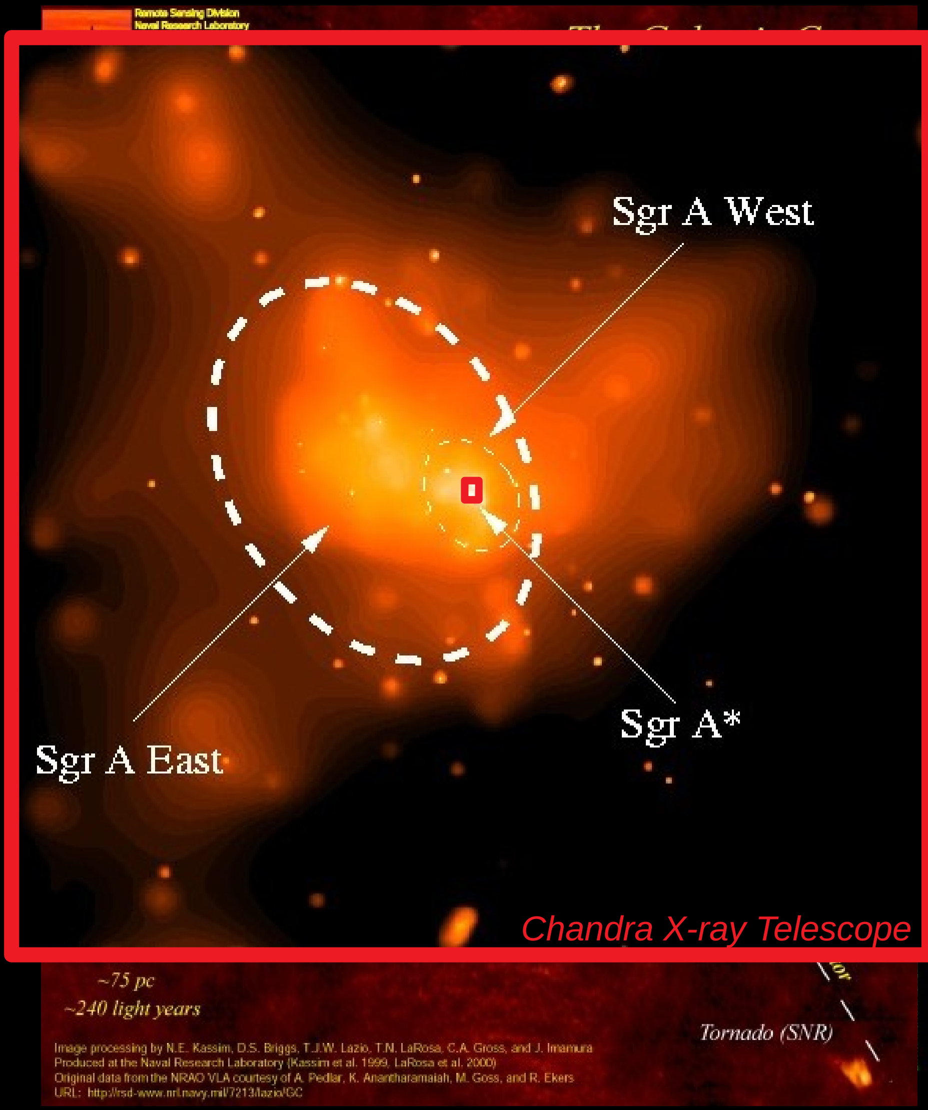

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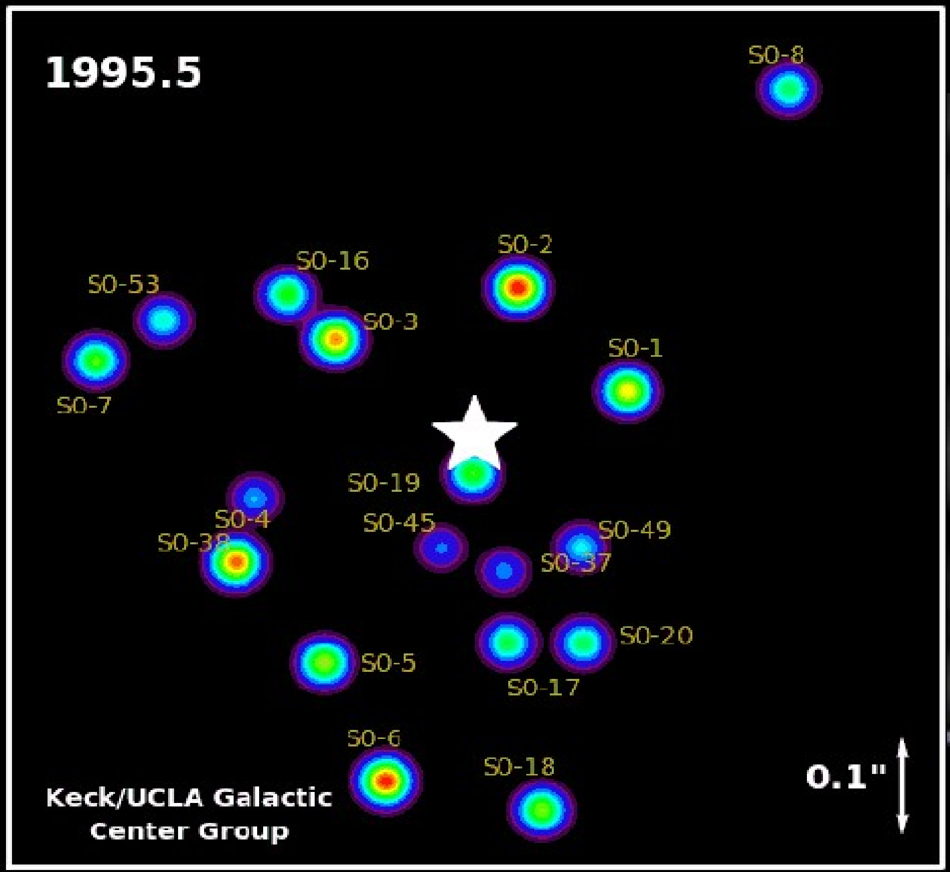
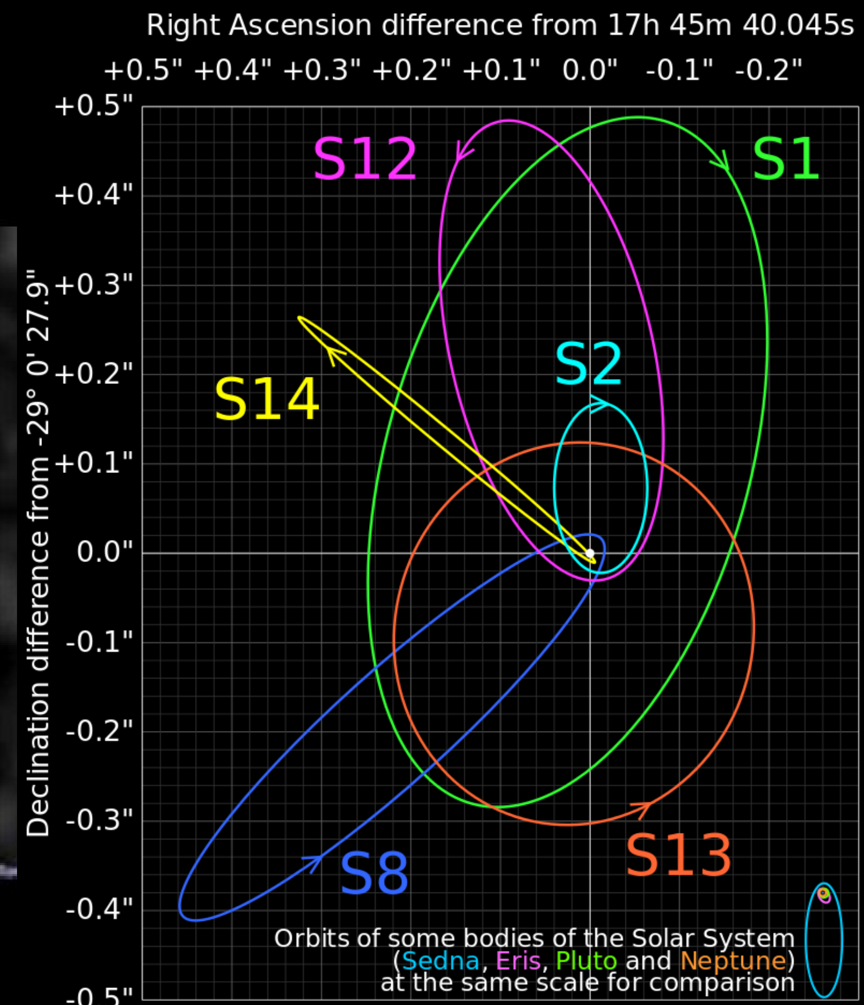
Sag A*





Mass = $4 \times 10^6 M_\odot$; $R_S \sim 10^7$ km $\sim 10 R_\odot \sim 1/15$ AU

Cloud G2

LETTER

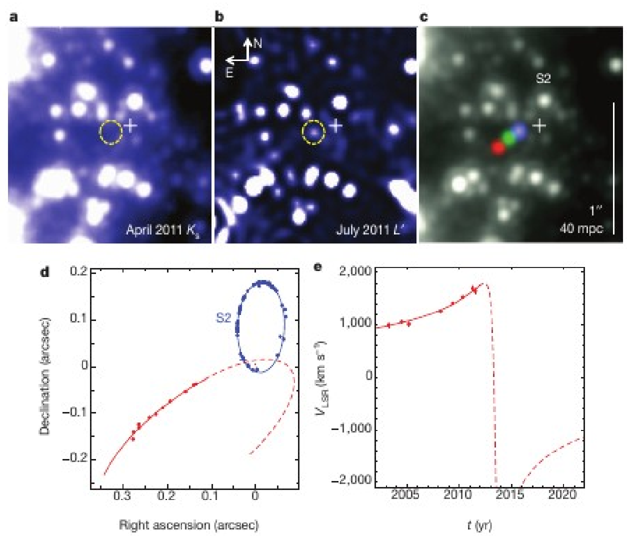
Nature 481, 51–54 (05 January 2012)
Received 25 August 2011 Accepted 17 October 2011
Published online 14 December 2011

doi:10.1038/nature10652

A gas cloud on its way towards the supermassive black hole at the Galactic Centre

S. Gillessen[1], R. Genzel[1,2], T. K. Fritz[1], E. Quataert[3], C. Alig[4], A. Burkert[4,1], J. Cuadra[5], F. Eisenhauer[1], O. Pfuhl[1], K. Dodds-Eden[1], C. F. Gammie[6] & T. Ott[1]

Measurements of stellar orbits[1–3] provide compelling evidence[4,5] that the compact radio source Sagittarius A* at the Galactic Centre is a black hole four million times the mass of the Sun. With the exception of modest X-ray and infrared flares[6,7], Sgr A* is surprisingly faint, suggesting that the accretion rate and radiation efficiency near the event horizon are currently very low[3,8]. Here we report the presence of a dense gas cloud approximately three times the mass of Earth that is falling into the accretion zone of Sgr A*. Our observations tightly constrain the cloud's orbit to be highly eccentric, with an innermost radius of approach of only ~3,100 times the event horizon that will be reached in 2013. Over the past three years the cloud has begun to disrupt, probably mainly through tidal shearing arising from the black hole's gravitational force. The cloud's dynamic evolution and radiation in the next few years will probe the properties of the accretion flow and the feeding processes of the supermassive black hole. The kilo-electronvolt X-ray emission of Sgr A* may brighten significantly when the cloud reaches pericentre. There may also be a giant radiation flare several years from now if the cloud breaks up and its fragments feed gas into the central accretion zone.



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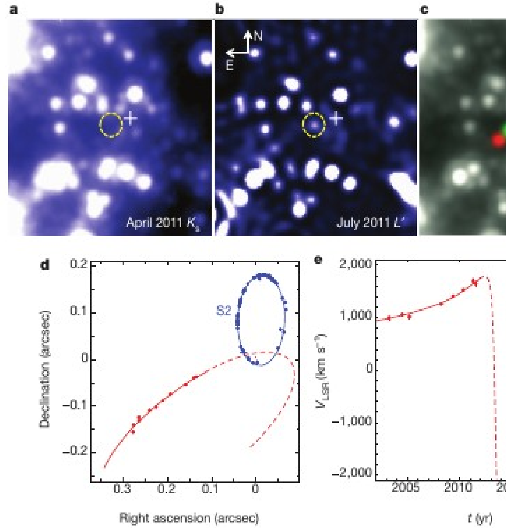
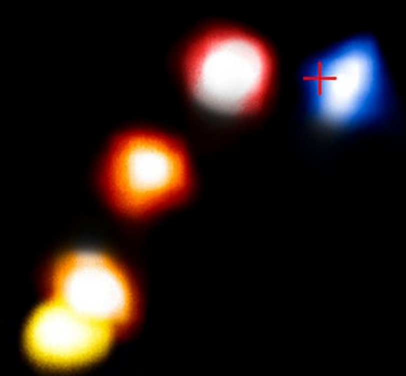
A gas cloud on its way towards the supermassive black hole at the Galactic Centre

S. Gillessen[1], R. Genzel[1,2], T. K. Fritz[1], E. Quataert[3], C. Alig[4], A. Burkert[4,1], J. Cuadra[5], F. Eisenhauer[1], O. Pfuhl[1], K. Dodds-Eden[1], C. F. Gammie[6] & T. Ott[1]

Measurements of stellar orbits[1–3] provide compelling evidence[4,5] that the compact radio source Sagittarius A* at the Galactic Centre is a black hole four million times the mass of the Sun. With the exception of modest X-ray and infrared flares[6,7], Sgr A* is surprisingly faint, suggesting that the accretion rate and radiation efficiency near the event horizon are currently very low[3,8]. Here we report the presence of a dense gas cloud approximately three times the mass of Earth that is falling into the accretion zone of Sgr A*. Our observations tightly constrain the cloud's orbit to be highly eccentric, with an innermost radius of approach of only ~3,100 times the event horizon that will be reached in 2013. Over the past three years the cloud has begun to disrupt, probably mainly through tidal shearing arising from the black hole's gravitational force. The cloud's dynamic evolution and radiation in the next few years will probe the properties of the accretion flow and the feeding processes of the supermassive black hole. The kilo-electronvolt X-ray emission of Sgr A* may brighten significantly when the cloud reaches pericentre. There may also be a giant radiation flare several years from now if the cloud breaks up and its fragments feed gas into the central accretion zone.

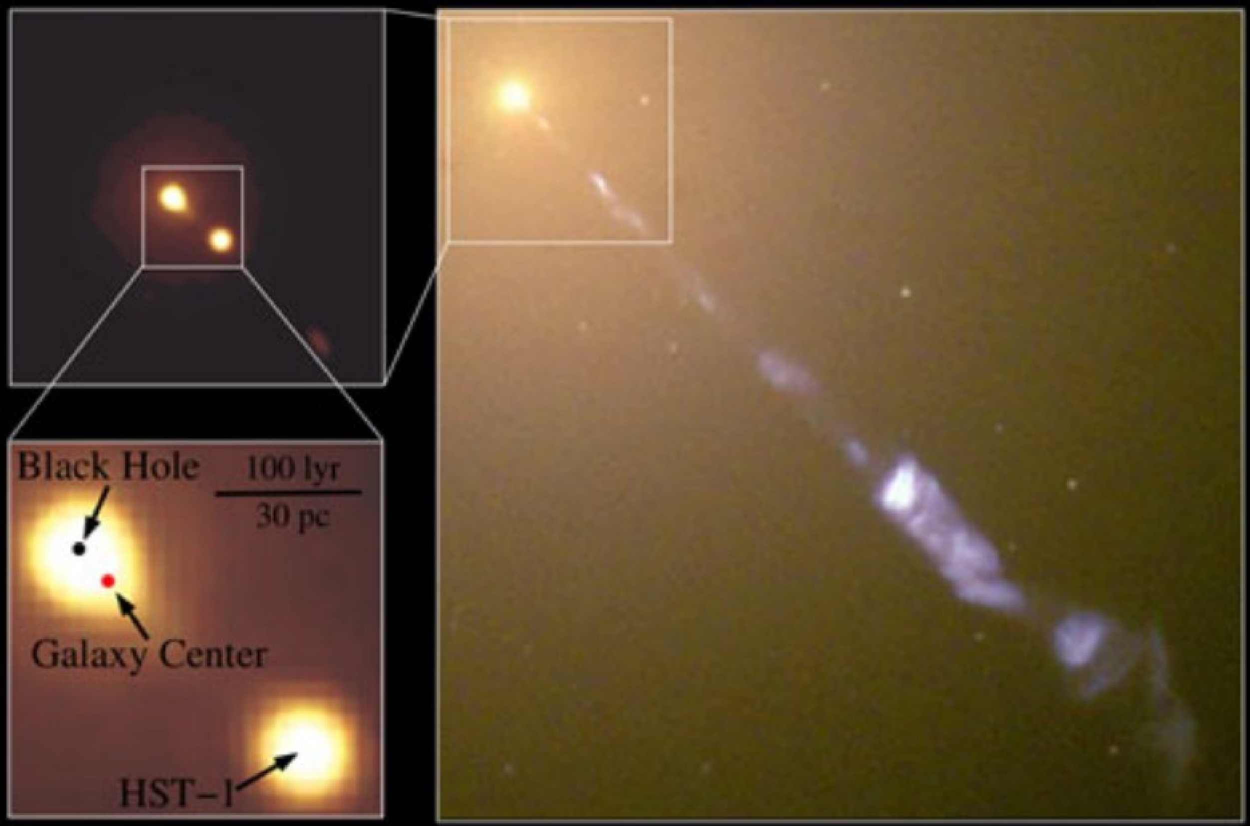




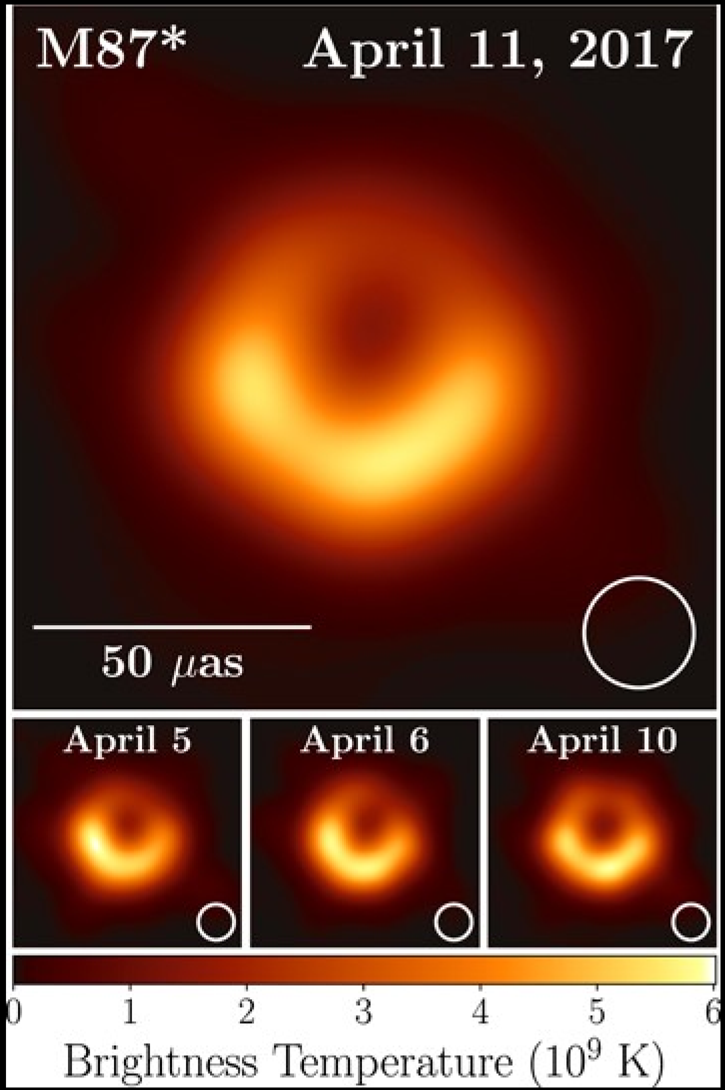
...and in 2015

SuperMassive BHs

Accreting supermassive BHs (up to billions of Solar masses) at the center of galaxies



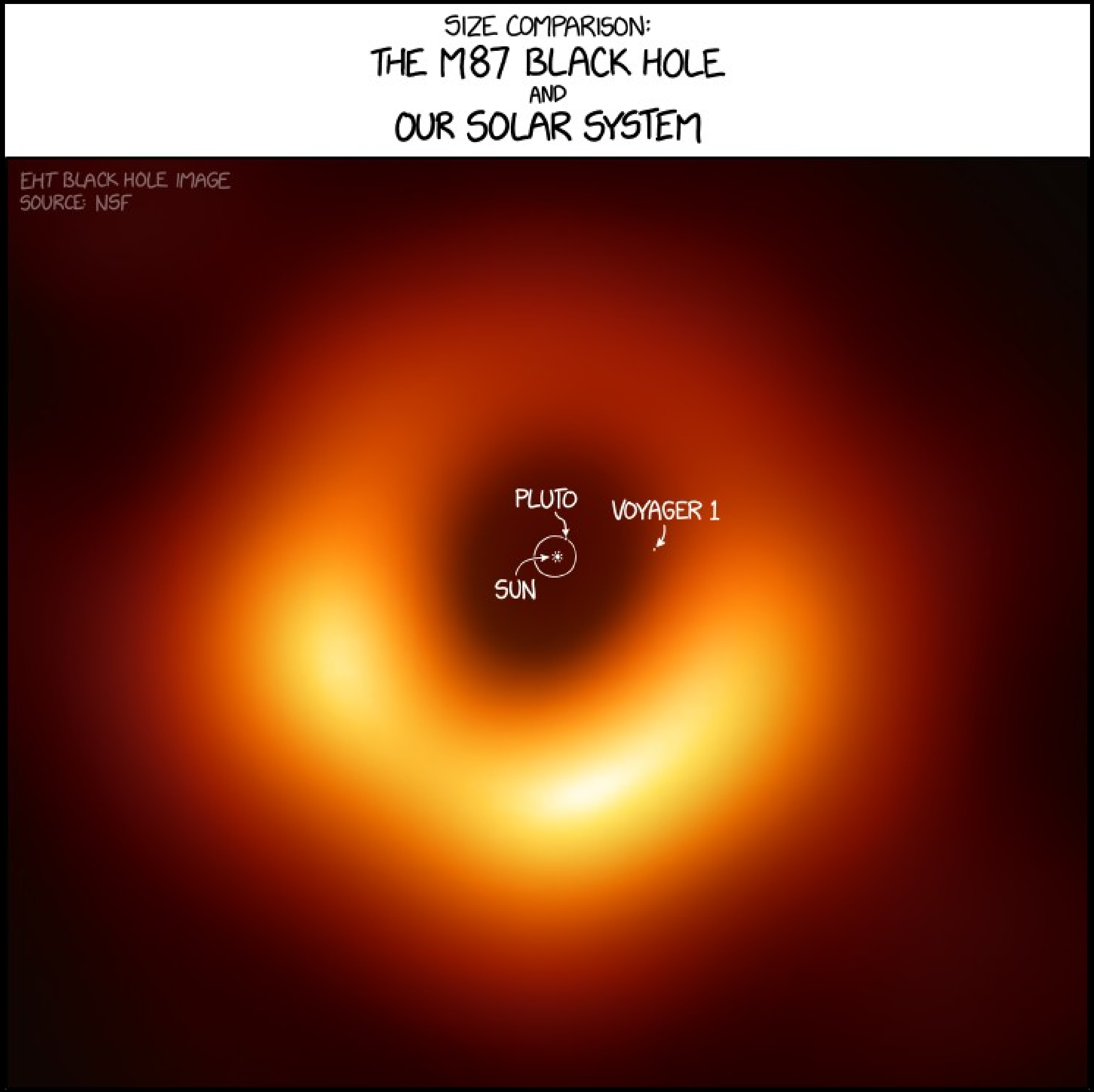
M87*



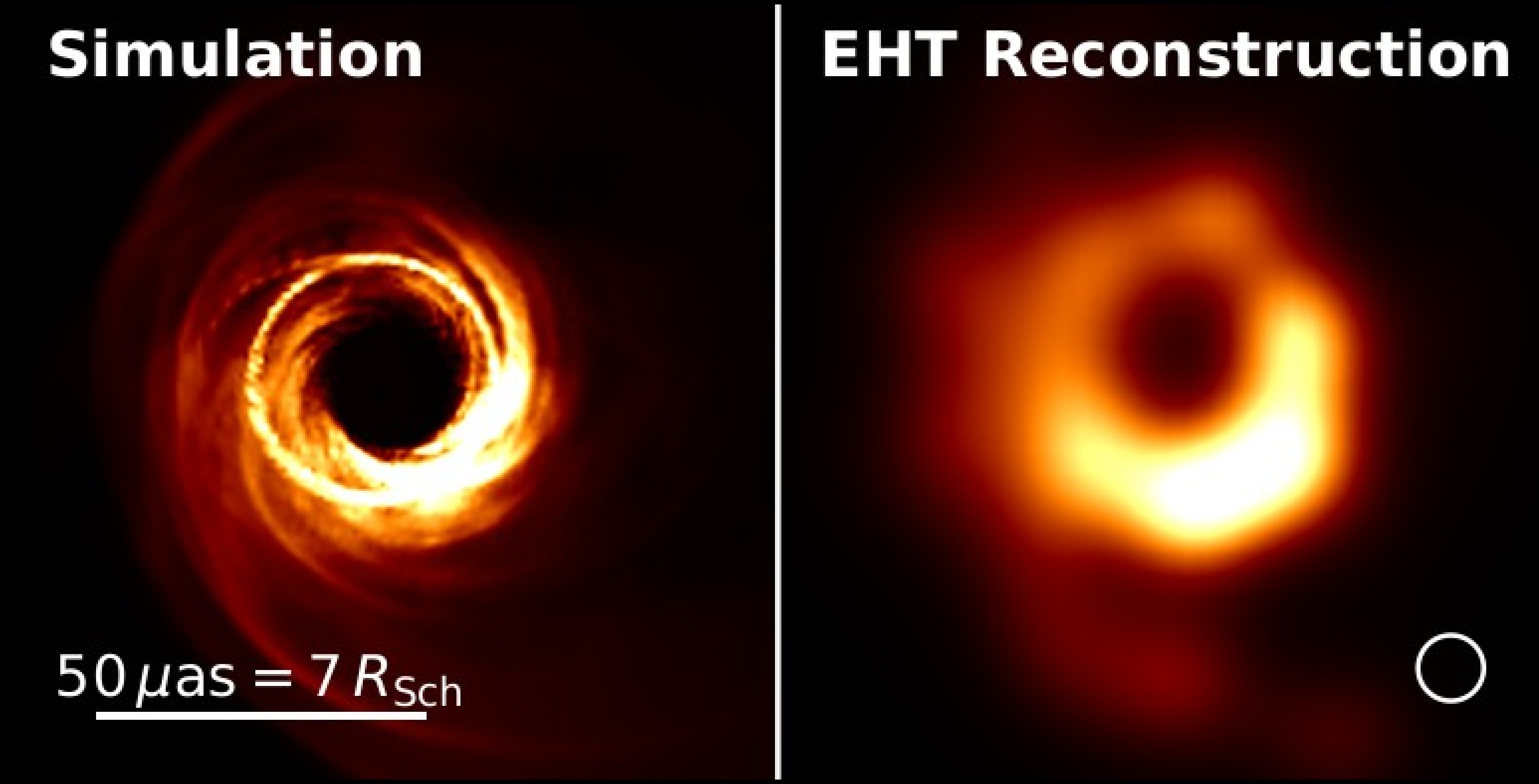
Parameter	Estimate
Ring diameter [a] d	42 ± 3 μas
Ring width [a]	<20 μas
Crescent contrast [b]	>10:1
Axial ratio [a]	<4:3
Orientation PA	150°–200° east of north
$\theta_g = GM/Dc^2$ [c]	3.8 ± 0.4 μas
$\alpha = d/\theta_g$ [d]	$11^{+0.5}_{-0.3}$
M[c]	$(6.5 \pm 0.7) \times 10^9\ M_\odot$

Parameter	Prior Estimate
D [e]	(16.8 ± 0.8) Mpc
M(stars) [e]	$6.2^{+1.1}_{-0.6} \times 10^9\ M_\odot$
M(gas) [e]	$3.5^{+0.9}_{-0.3} \times 10^9\ M_\odot$

M87*


SIZE COMPARISON:
THE M87 BLACK HOLE
AND
OUR SOLAR SYSTEM
EHT BLACK HOLE IMAGE
SOURCE: NSF
PLUTO
VOYAGER 1
SUN

Simulated M87*



Black holes masses