# Black holes

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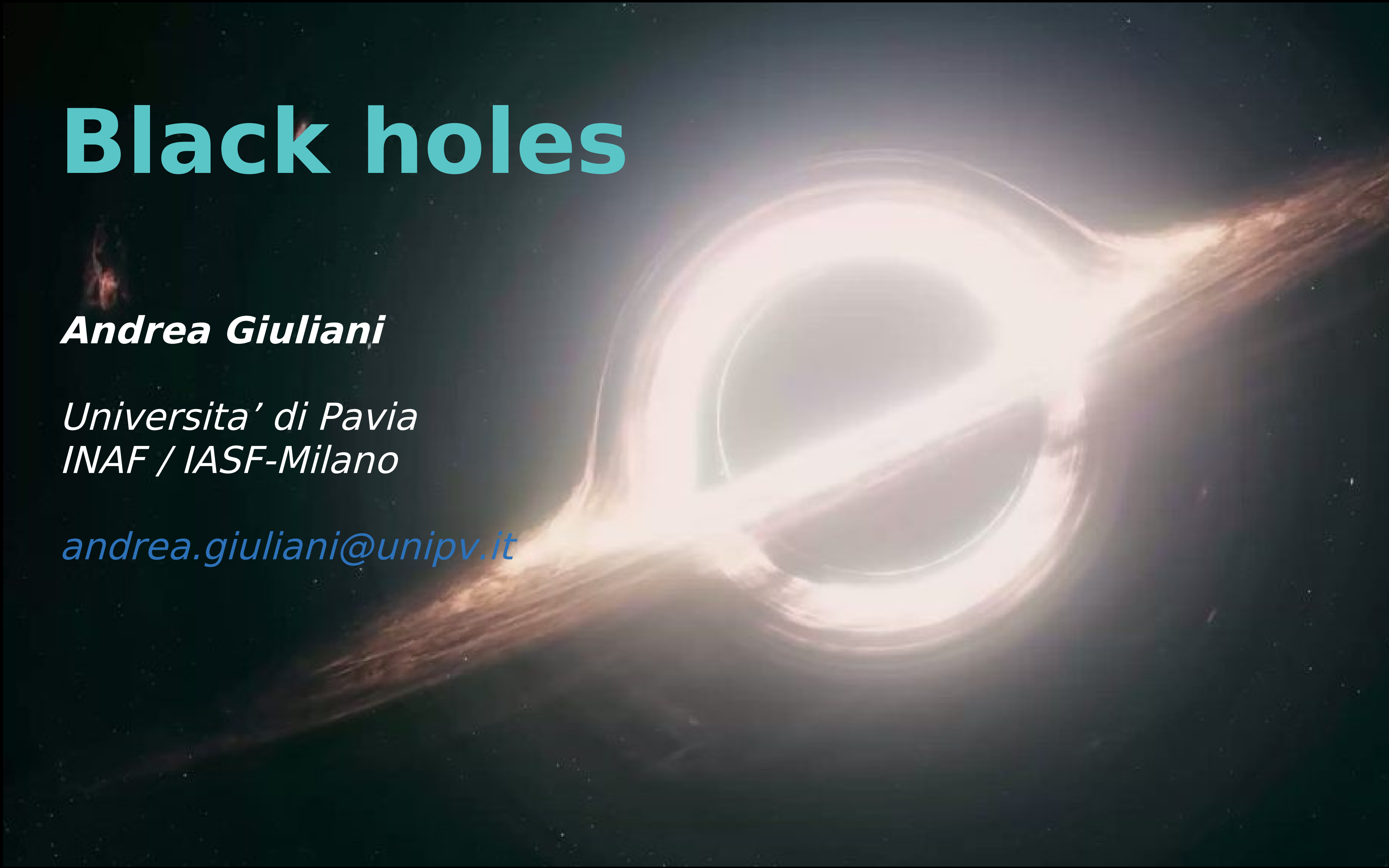


# BH : according to LaPlace

He gave a talk before Royal Astronomical Society in 1783 on the gravitation of stars. He used a thought experiment to explain that light would not leave the surface of a very massive star if the gravitation was sufficiently large.

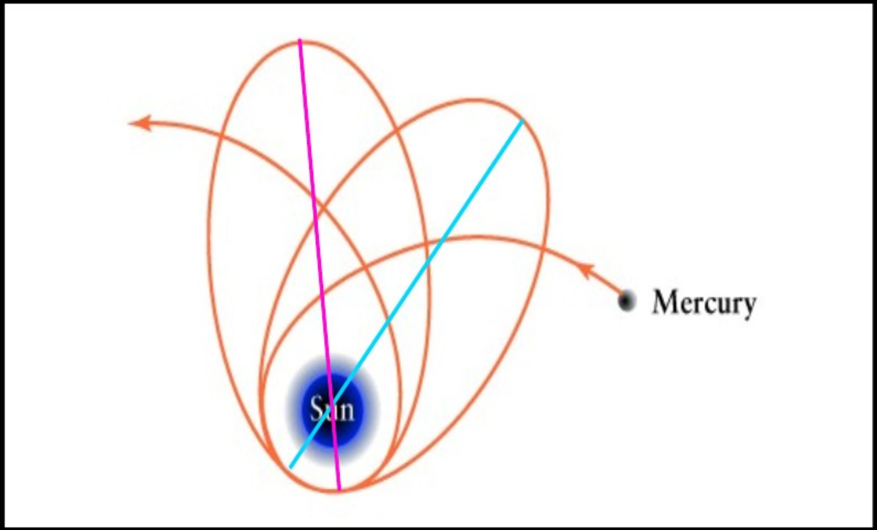
And he deduced: "**Should such an object really exist in nature, its light could never reach us**."

$$v_e = \sqrt{\frac{2GM}{r}},$$

B.H. radius → $r = \dfrac{2GM}{c^2}$

# General Relativity 1915

## Mercury orbit precession

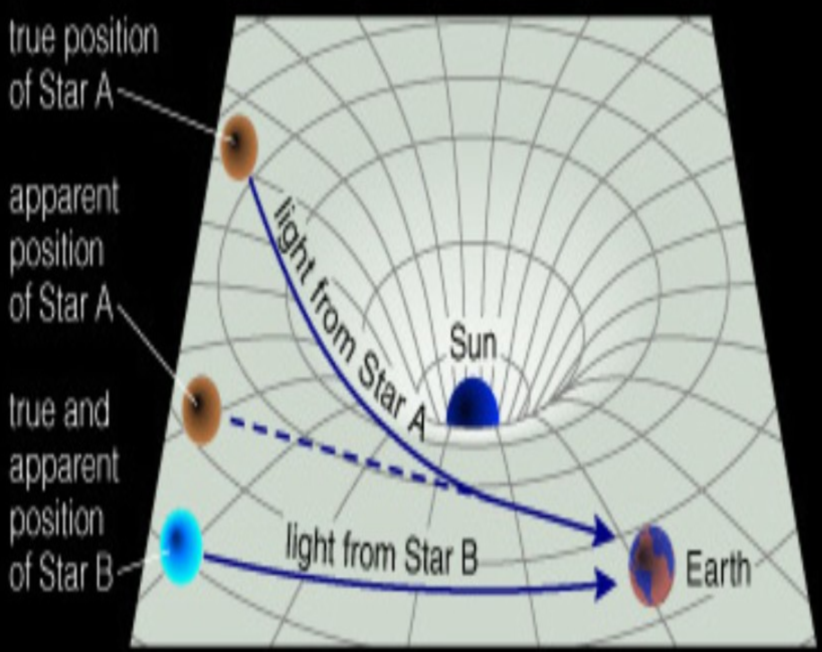



Newtonian Gravity Predicts: 5557.62 arcsec/century

Observed Value: 5600.73 arcsec/century

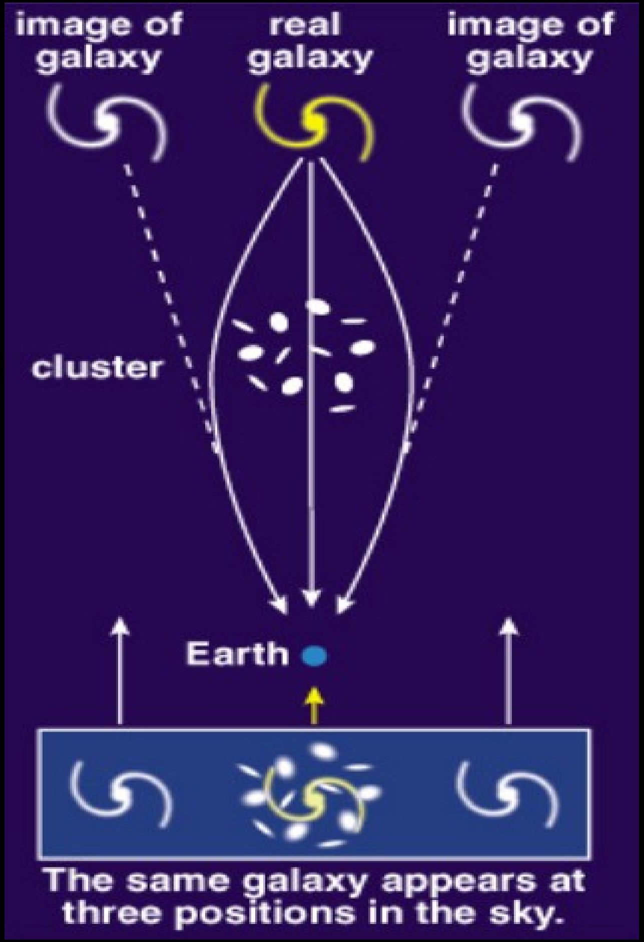
Difference: 43.11 ± 0.45 arcsec/century too fast!!

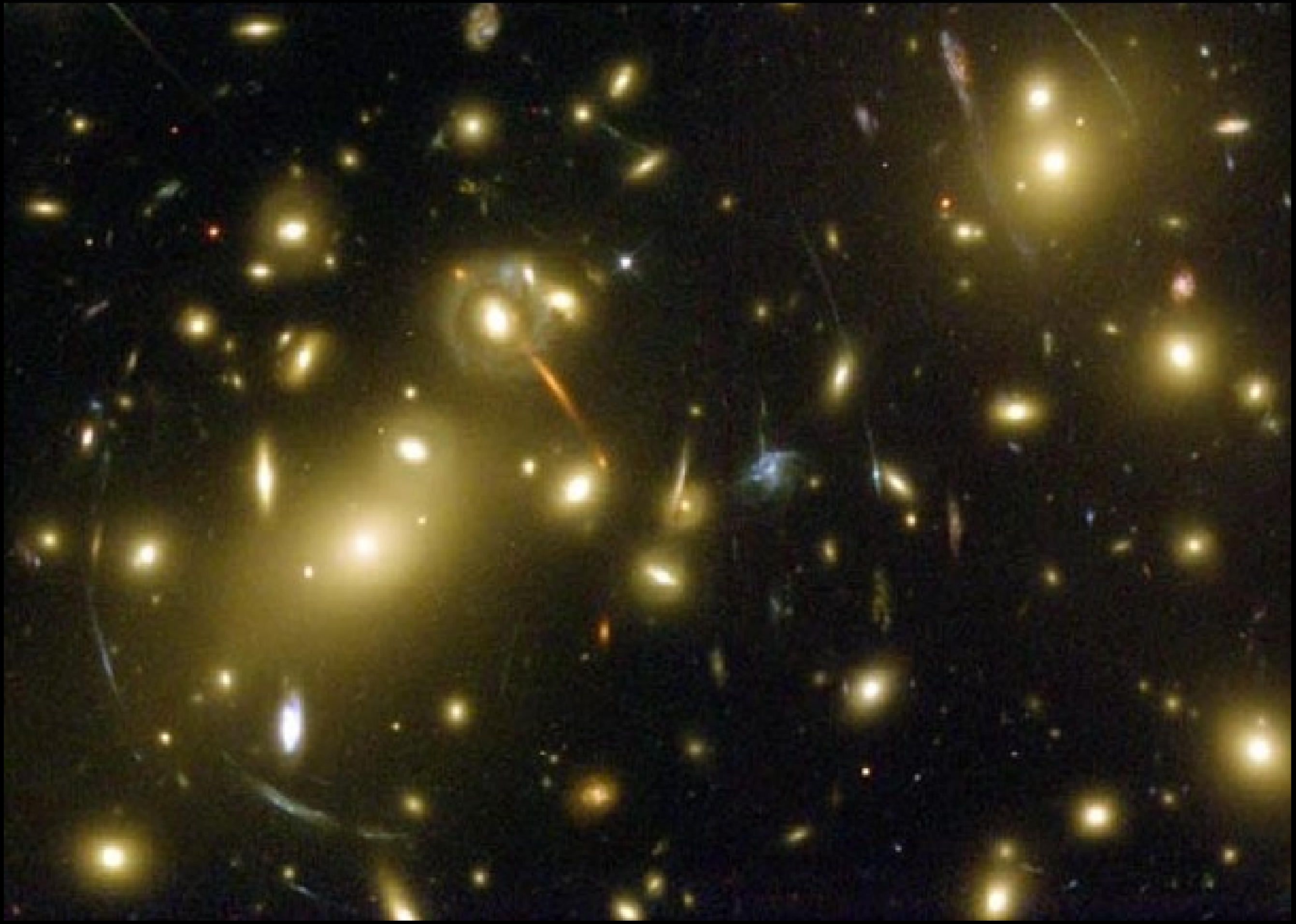
## Deflection of starlight



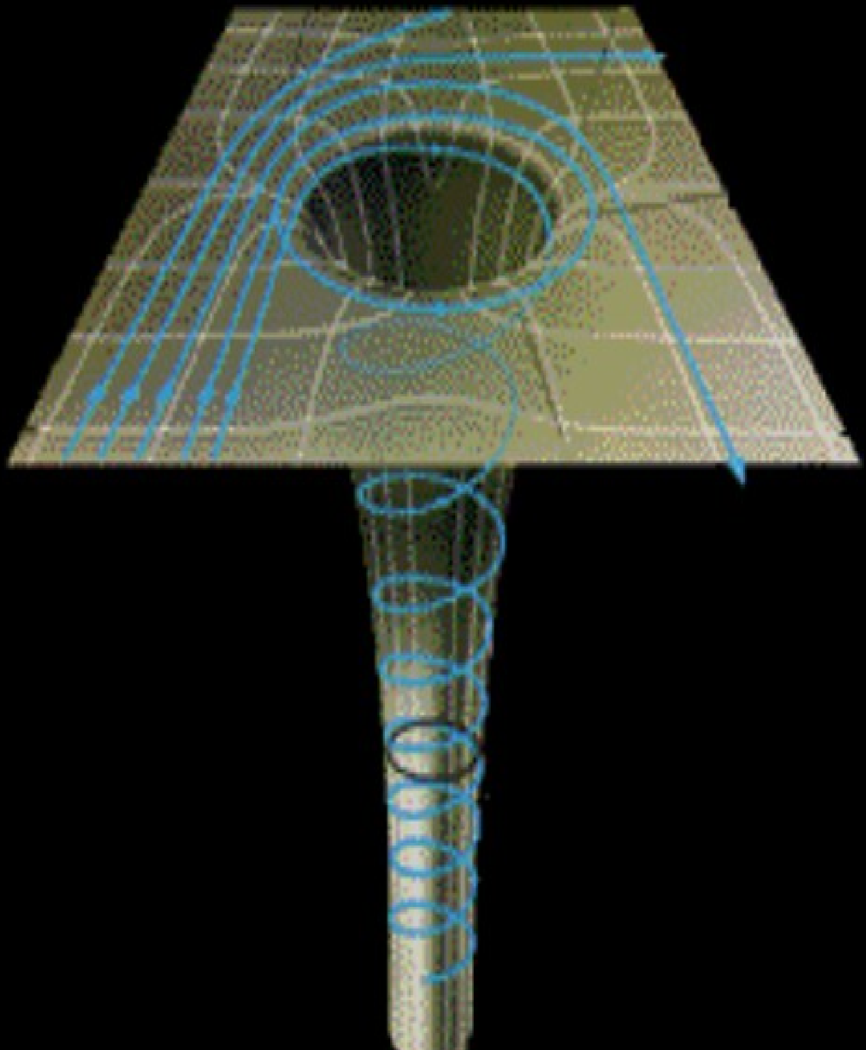
# Eddington observation (1919)

# Gravitational Lensing



# Black Holes



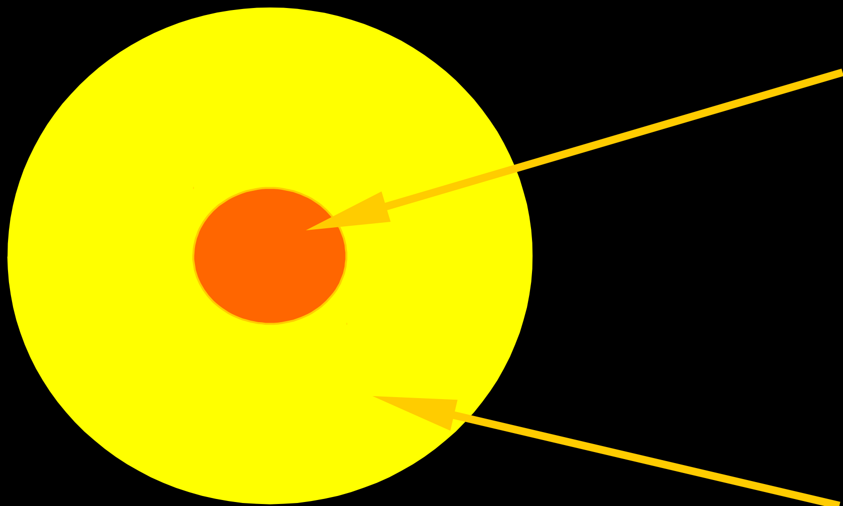
Black holes are a fundamental prediction of the theory of general relativity (Einstein 1915).

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:*

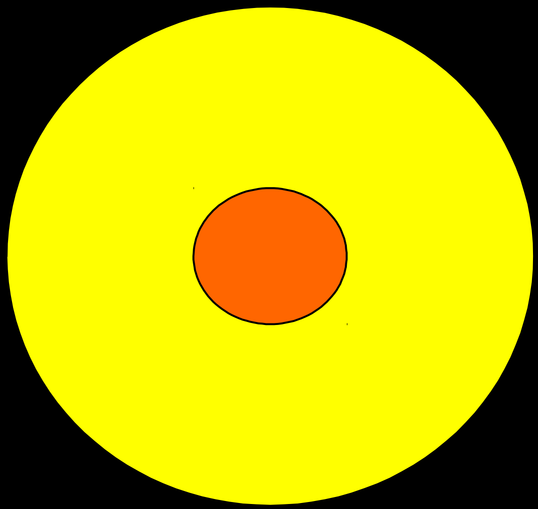
$$R_S = \frac{2GM}{c^2} \approx 3\frac{M}{M_{Sun}}\ km$$

# Sun’s Structure



- Core
  - Where nuclear fusion occurs
- Envelope
  - Supplies gravity to keep core hot and dense

# Main Sequence Evolution



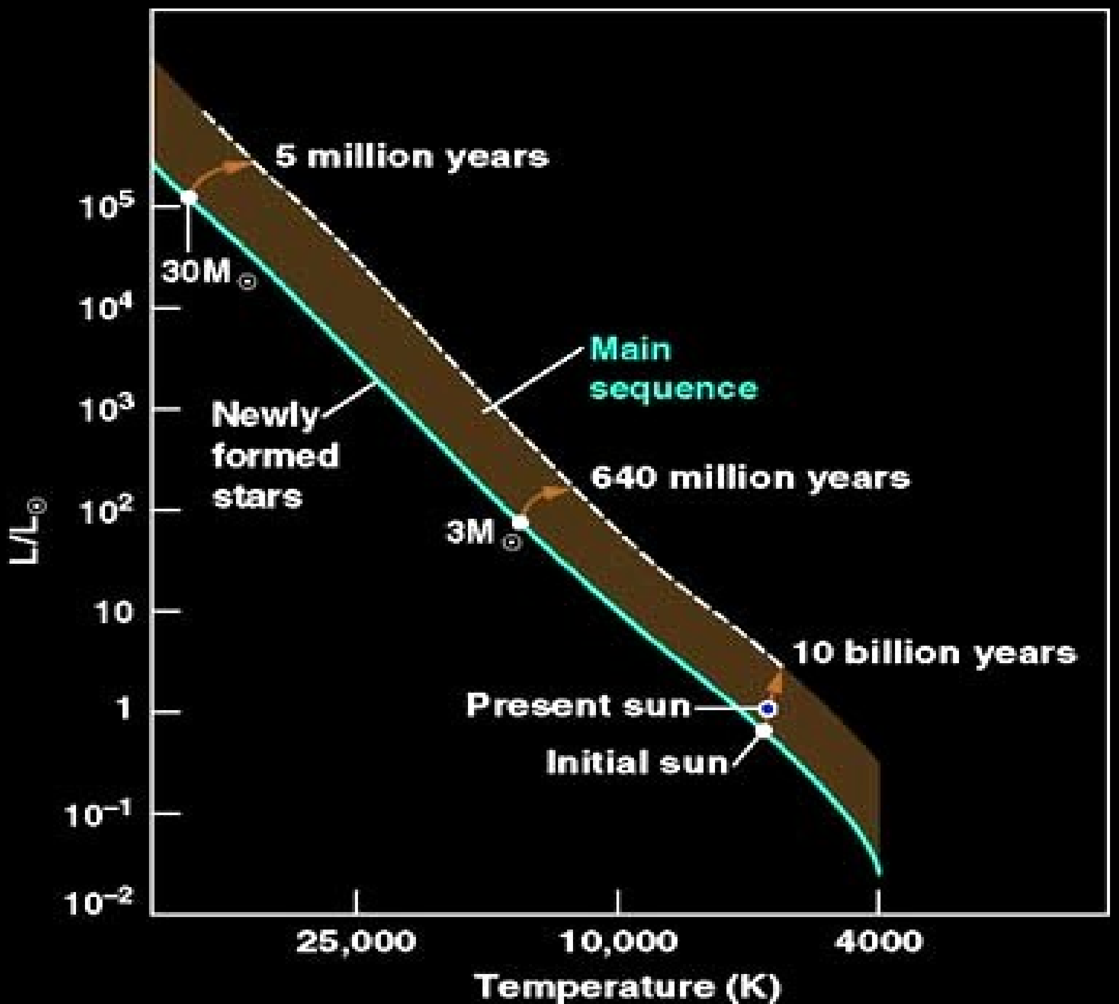
- Core starts with same fraction of hydrogen as whole star
- Fusion changes H → He
- Core gradually shrinks and Sun gets hotter and more luminous

# Main Sequence Evolution

When stars initiate H burning in their cores, they are located on the ***zero-age main sequence*** (ZAMS).

As they age, they evolve slowly away from the ZAMS.

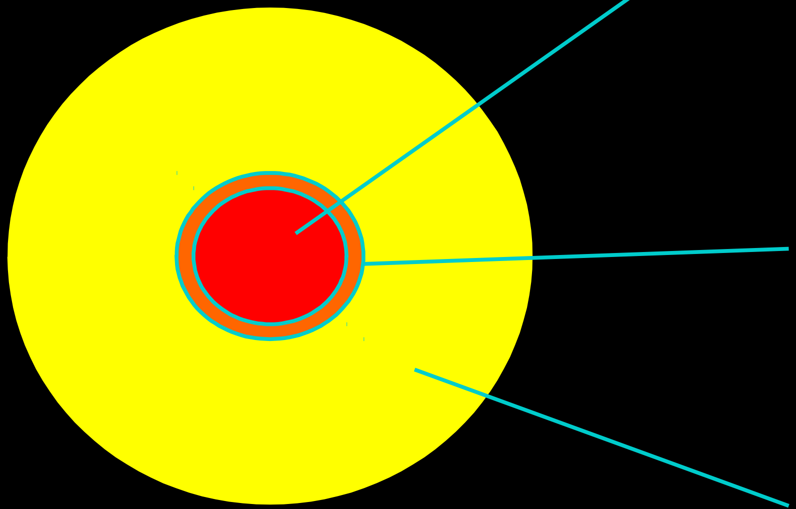
Most stars, regardless of their mass, spend roughly 90% of their total lifetimes as main sequence stars.



## Table 21-1 Main-Sequence Lifetimes

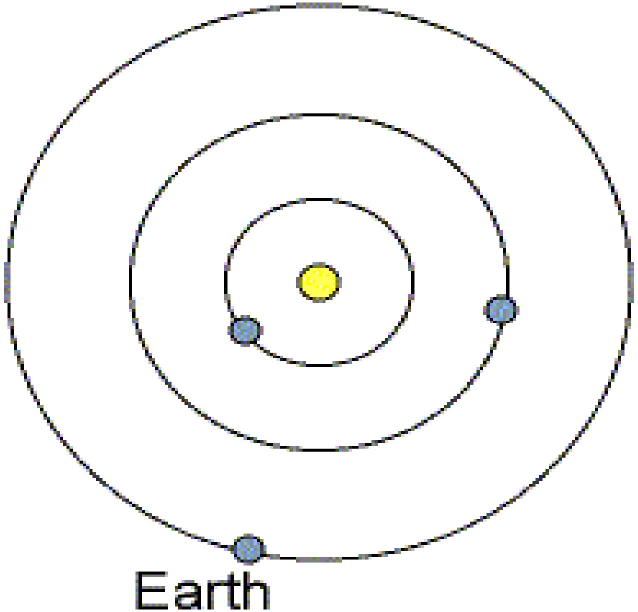
| Mass ($M_\odot$) | Surface temperature (K) | Spectral class | Luminosity ($L_\odot$) | Main-sequence lifetime ($10^6$ years) |
|---|---|---|---|---|
| 25 | 35,000 | O | 80,000 | 3 |
| 15 | 30,000 | B | 10,000 | 15 |
| 3 | 11,000 | A | 60 | 500 |
| 1.5 | 7000 | F | 5 | 3000 |
| 1.0 | 6000 | G | 1 | 10,000 |
| 0.75 | 5000 | K | 0.5 | 15,000 |
| 0.50 | 4000 | M | 0.03 | 200,000 |

# Red Giant Phase

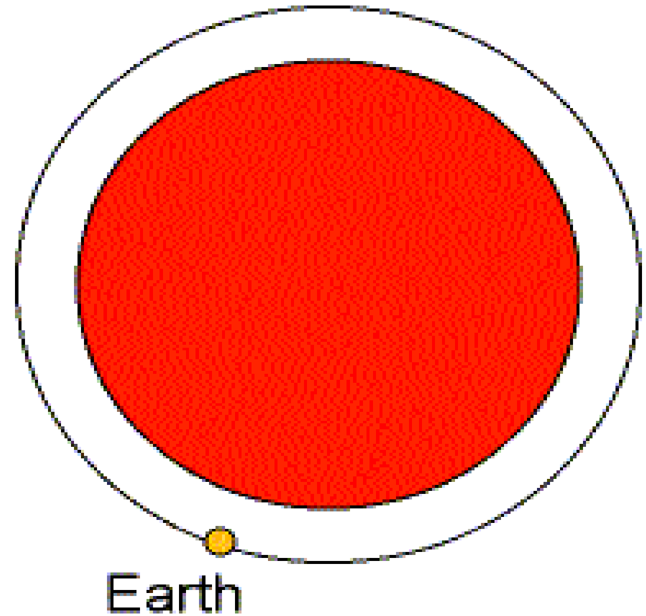


- He core
  - No nuclear fusion
  - Gravitational contraction produces energy
- H layer
  - Nuclear fusion
- Envelope
  - Expands because of increased energy production
  - Cools because of increased surface area

# Sun's Red Giant Phase

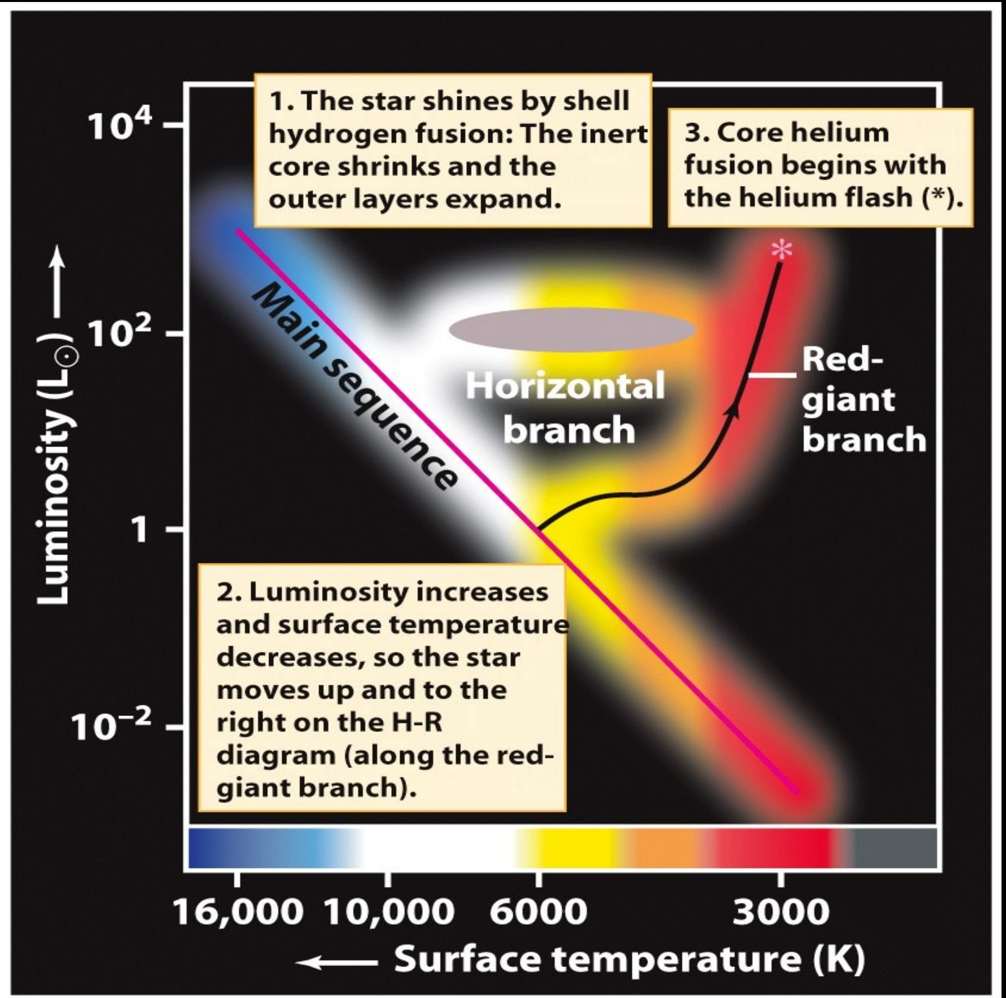



Now: hot core + warm surface; small size.



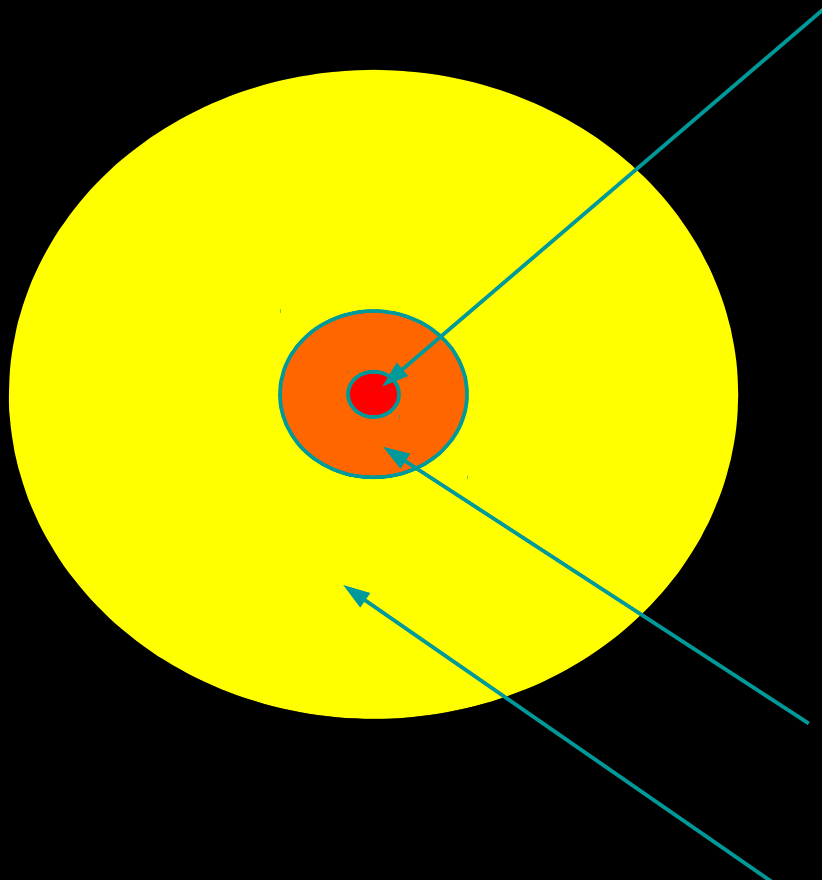

Future: very hot core + cool surface. Large size

# Movement on HR diagram



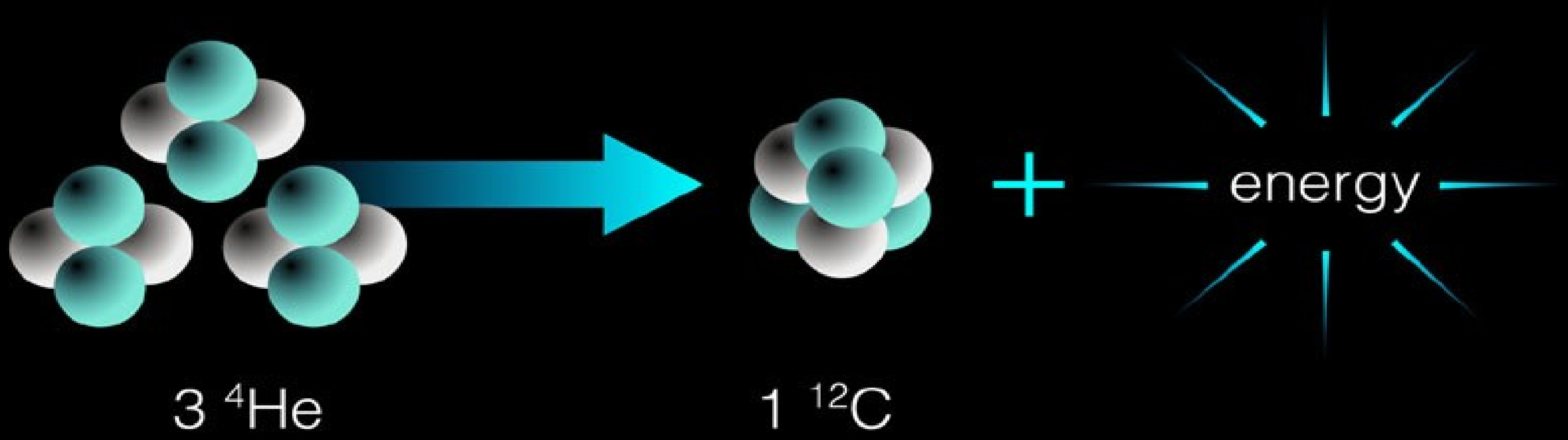

Before the helium flash: A red-giant star

# Helium Flash



- He core
  - Eventually the core gets hot enough to fuse Helium into Carbon.
  - This causes the temperature to increase rapidly to 300 million K and there’s a sudden flash when a large part of the Helium gets burned all at once.
  - We don’t see this flash because it’s buried inside the star.
- H layer
- Envelope

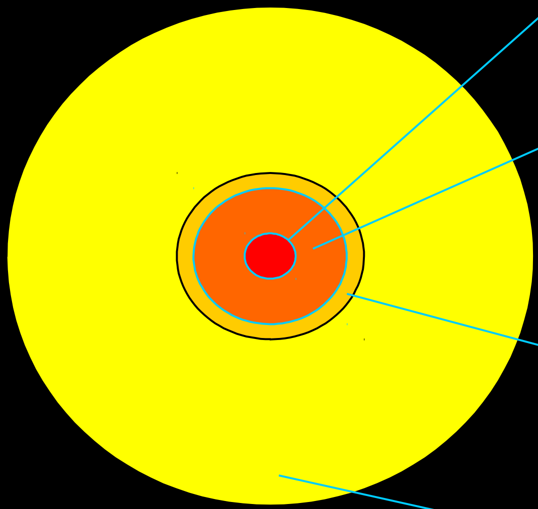
# Helium fusion




Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion—larger charge leads to greater repulsion

Fusion of two helium nuclei doesn't work, so helium fusion must combine three He nuclei to make carbon

# Red Giant after Helium Ignition



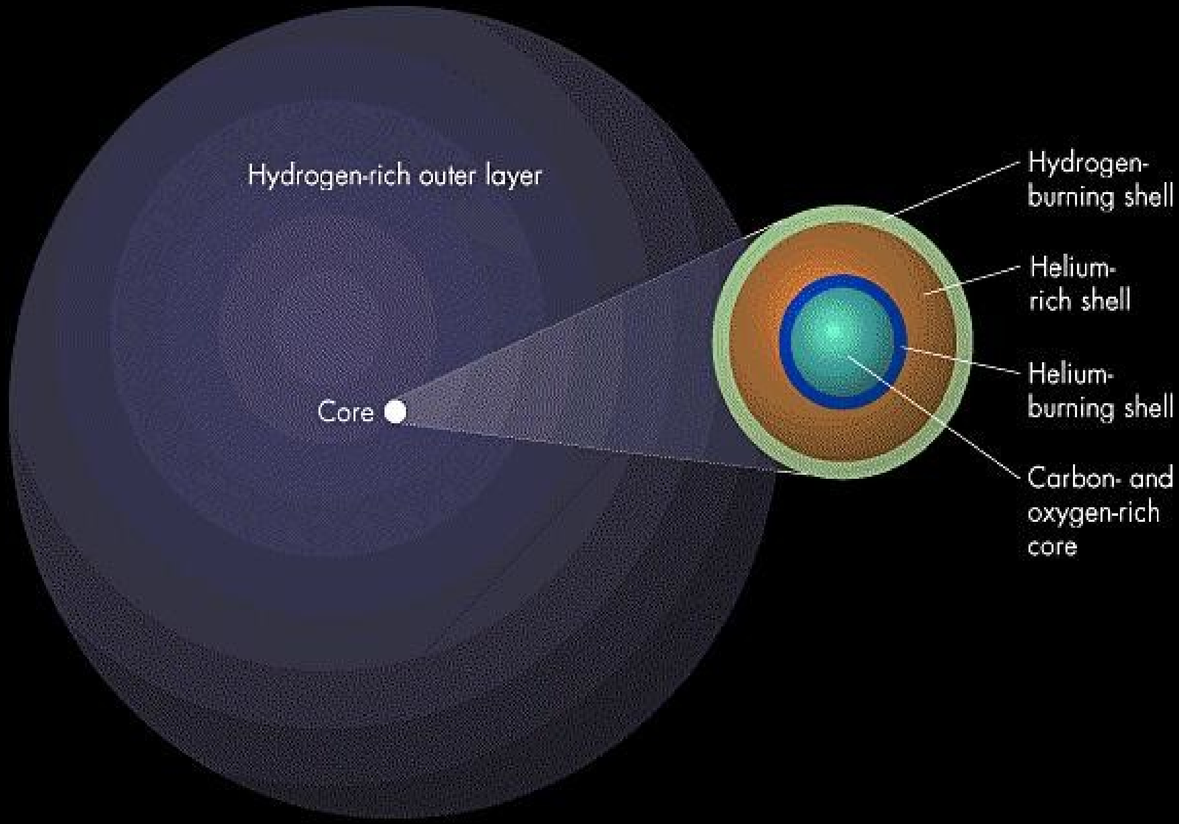
- He burning core
  - Fusion burns He into C, O
- He rich core
  - No fusion
- H burning shell
  - Fusion burns H into He
- Envelope

# Helium burning in the core stops

H burning is continuous

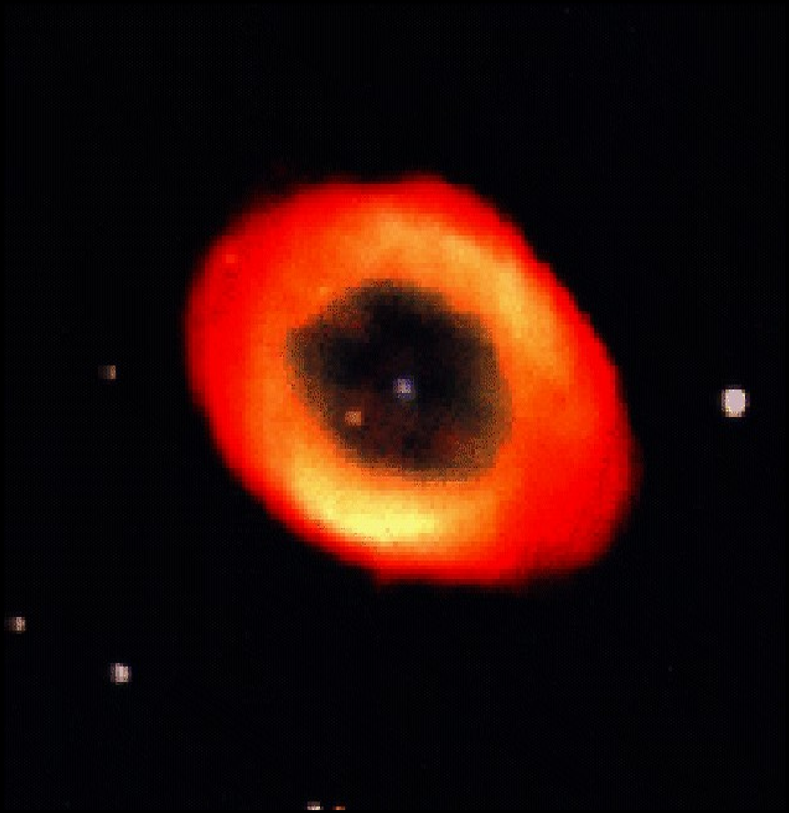
He burning happens in "thermal pulses"

Core is degenerate

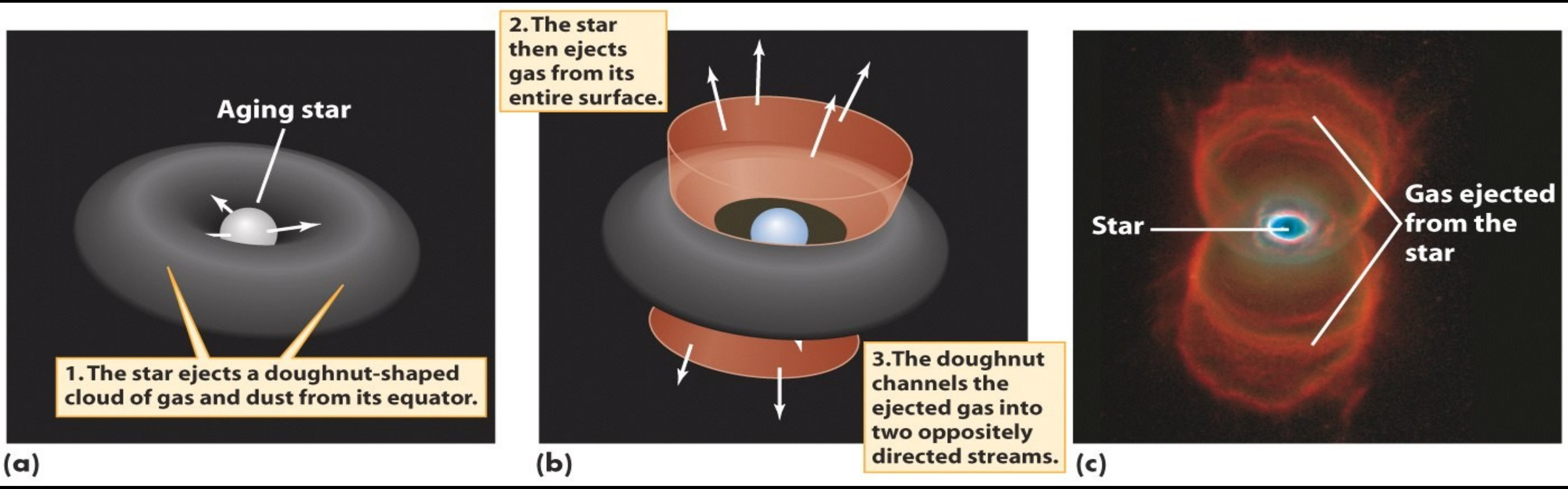


# Sun loses mass via winds

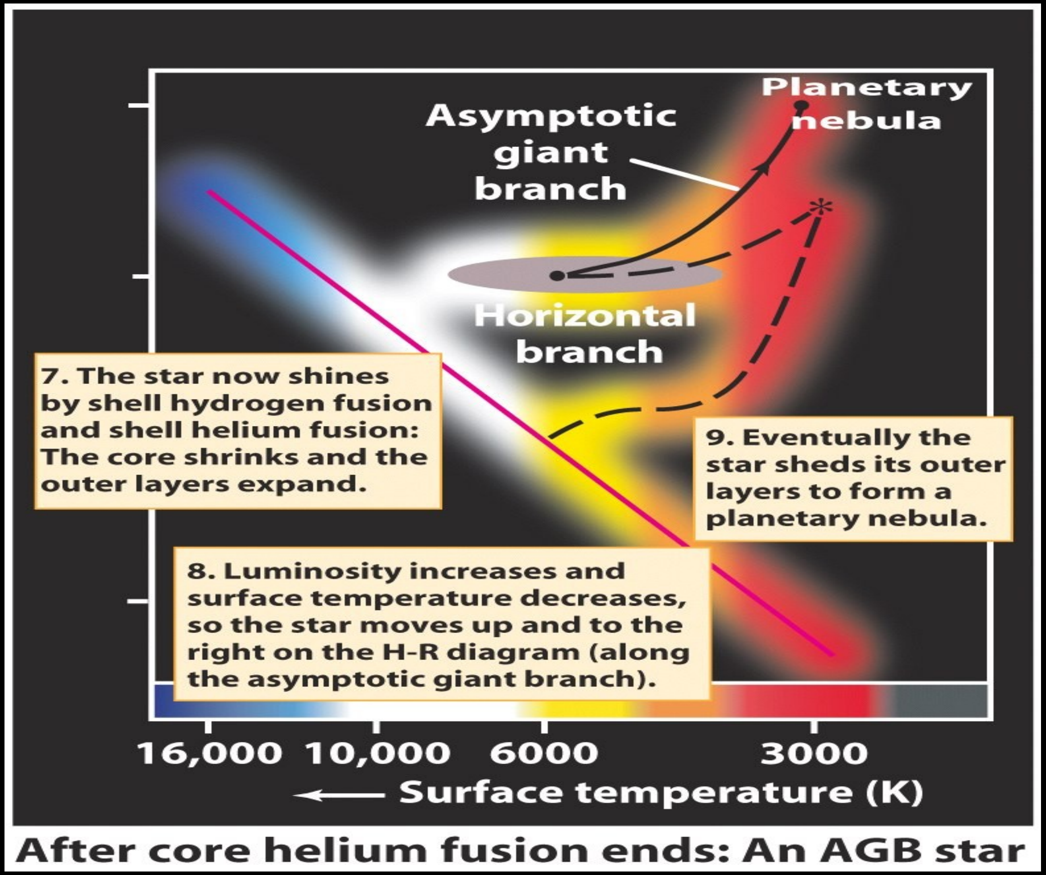
- Creates a “planetary nebula”
- Leaves behind core of carbon and oxygen surrounded by thin shell of hydrogen
- Hydrogen continues to burn



# Bipolar planetary nebulae



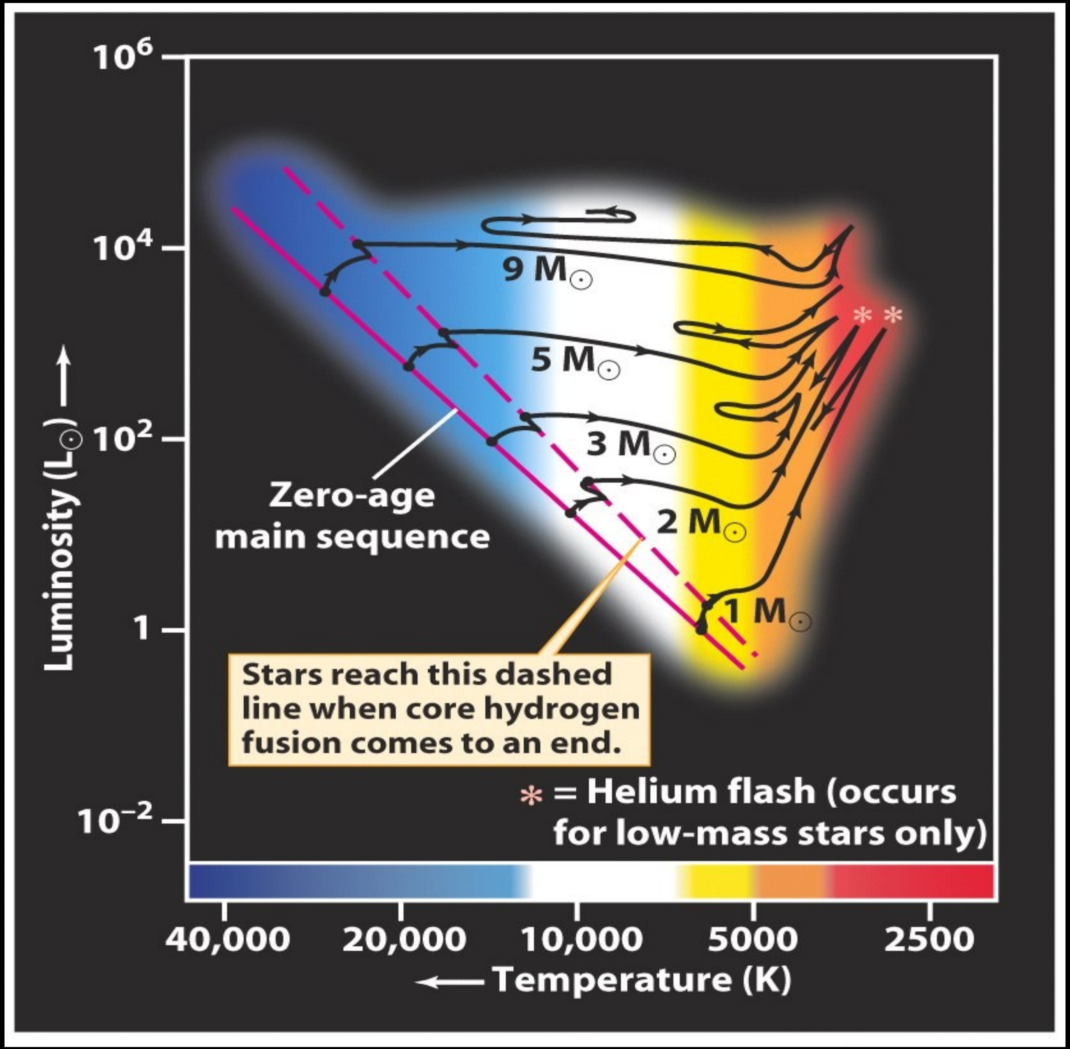
# Sun moves onto Asymptotic Giant Branch (AGB)



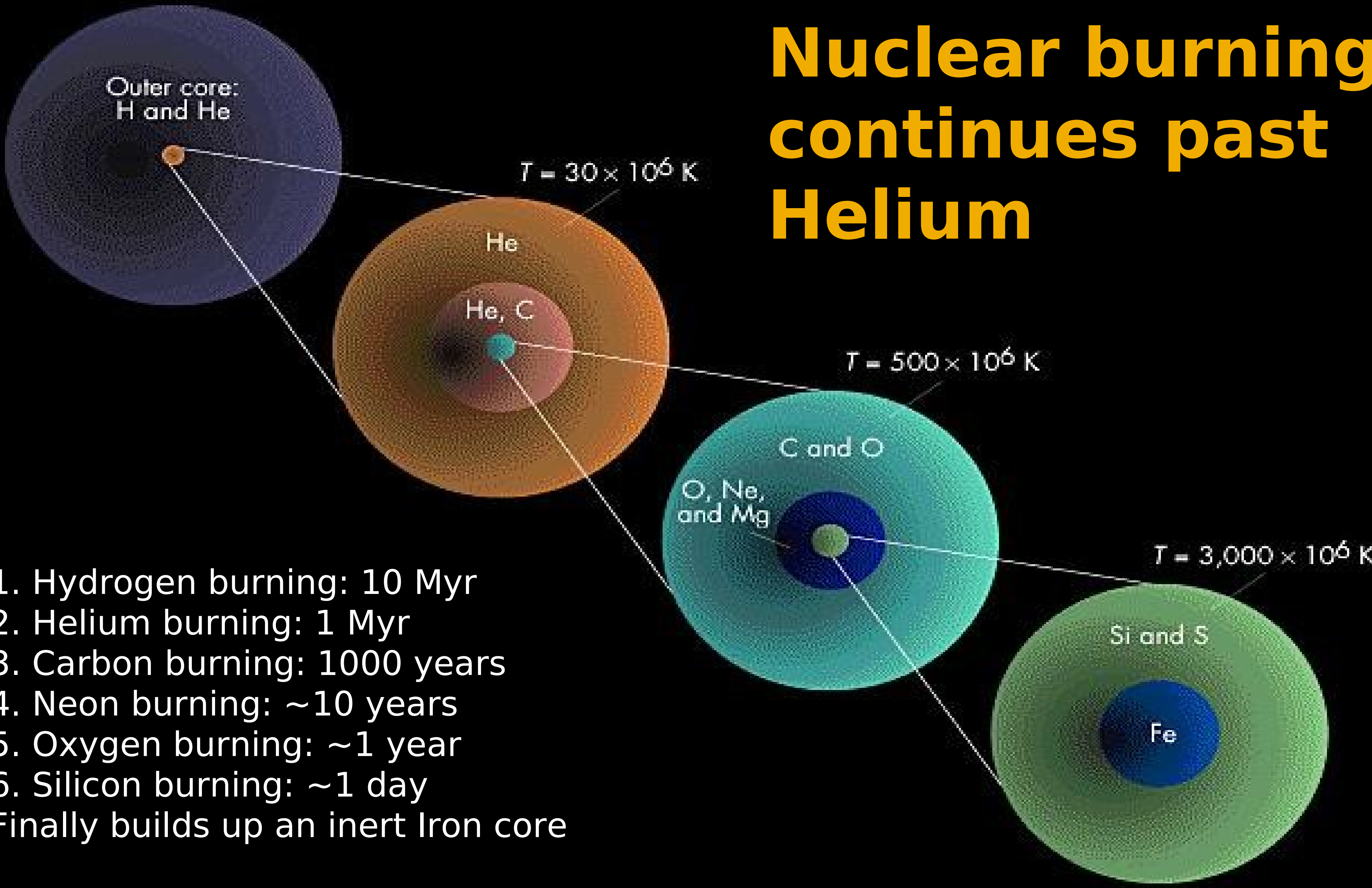
# White dwarf

- Star burns up rest of hydrogen
- Nothing remains but degenerate core of Oxygen and Carbon
- “White dwarf” cools but does not contract because core is degenerate
- No energy from fusion, no energy from gravitational contraction
- White dwarf slowly fades away…

# Higher mass stars do not have helium flash



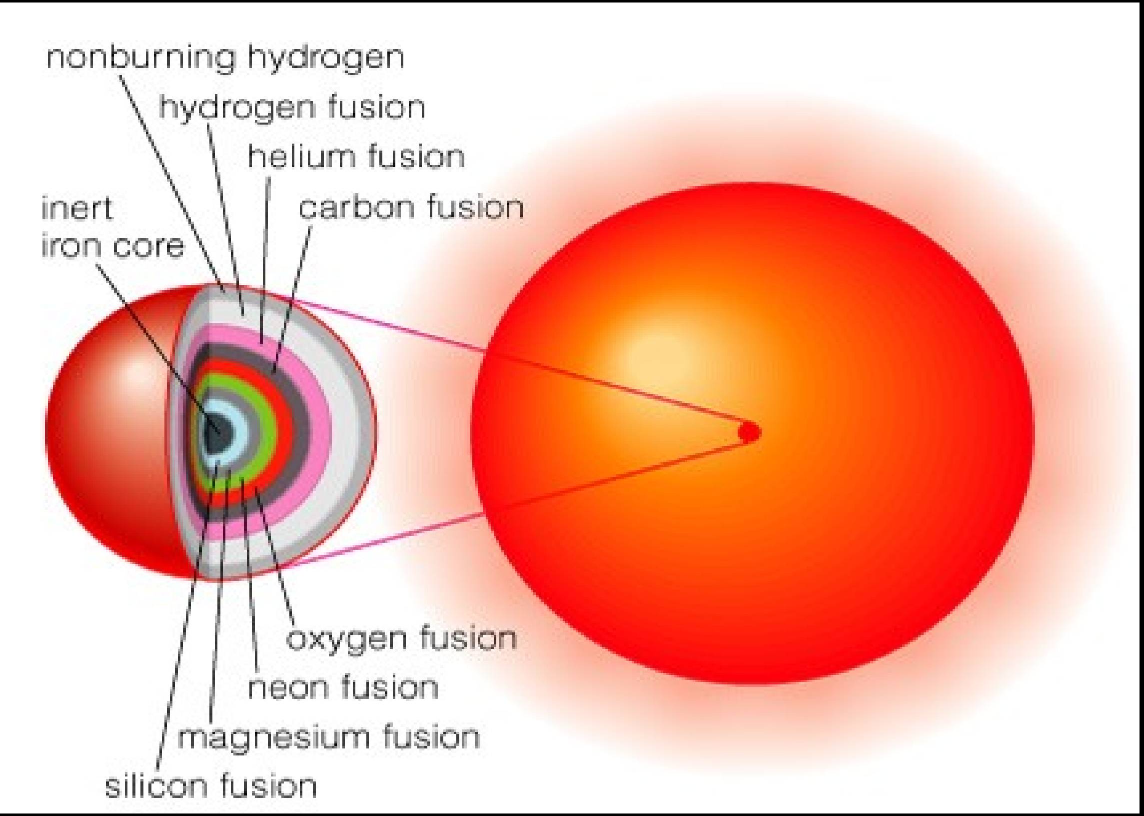
# Nuclear burning continues past Helium



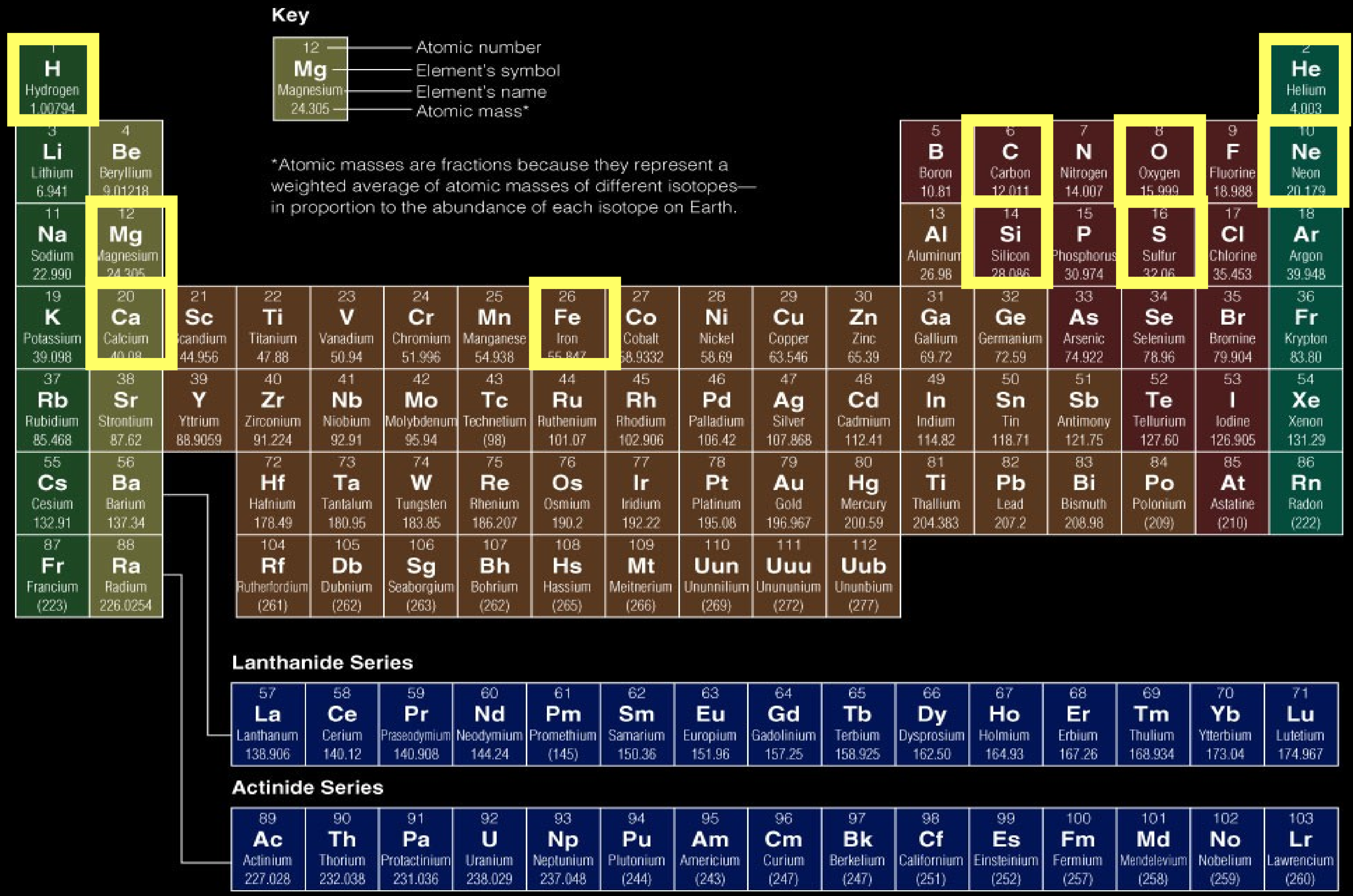

1. Hydrogen burning: 10 Myr
2. Helium burning: 1 Myr
3. Carbon burning: 1000 years
4. Neon burning: ~10 years
5. Oxygen burning: ~1 year
6. Silicon burning: ~1 day

Finally builds up an inert Iron core

# Multiple Shell Burning

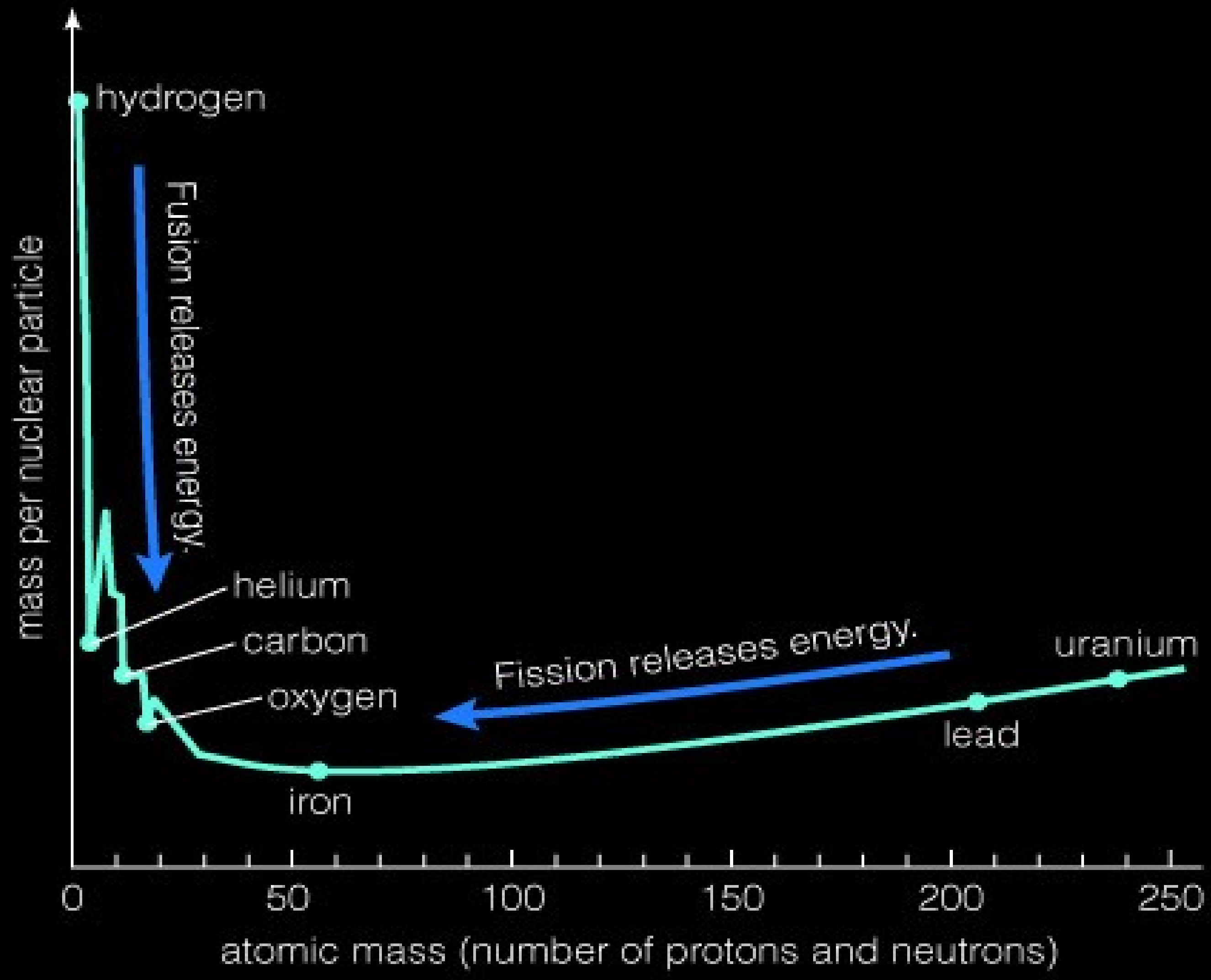



- Advanced nuclear burning proceeds in a series of nested shells



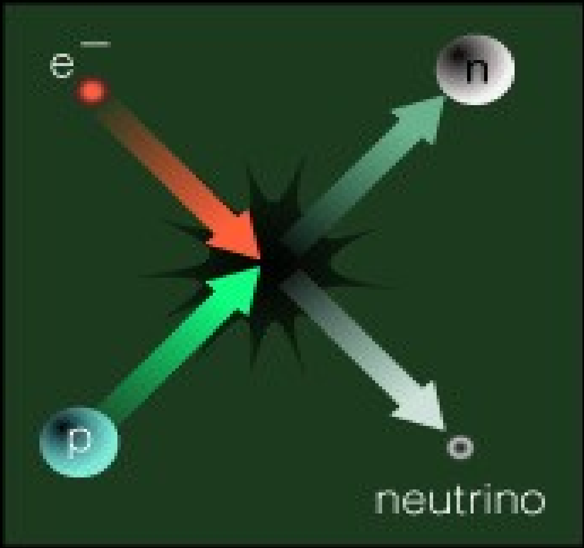

Advanced reactions in stars make elements like Si, S, Ca, Fe

# Why does fusion stop at Iron?

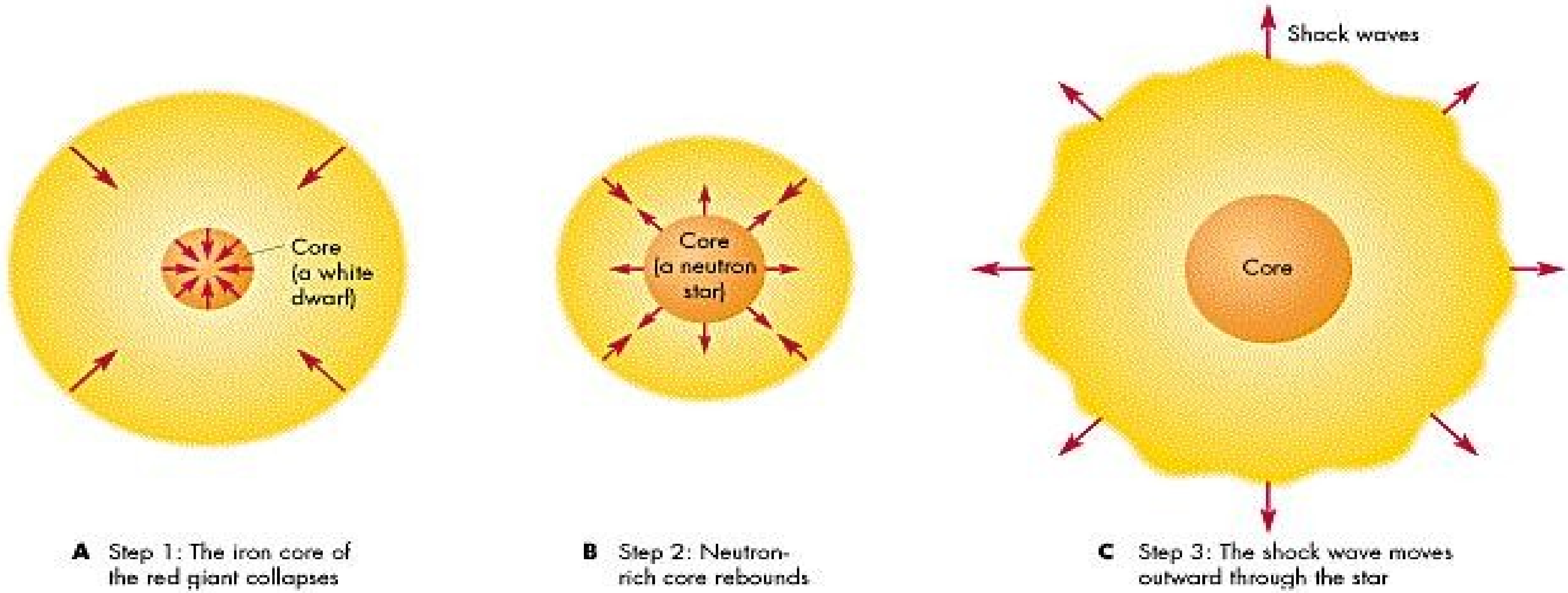


# Core collapse

- Iron core is degenerate and grows until it is too heavy to support itself
- Core collapses and iron nuclei are converted into neutrons with the emission of neutrinos
- Core collapse stops, neutron star is formed
- Rest of the star bounces off the new neutron star (also pushed outwards by the neutrinos)

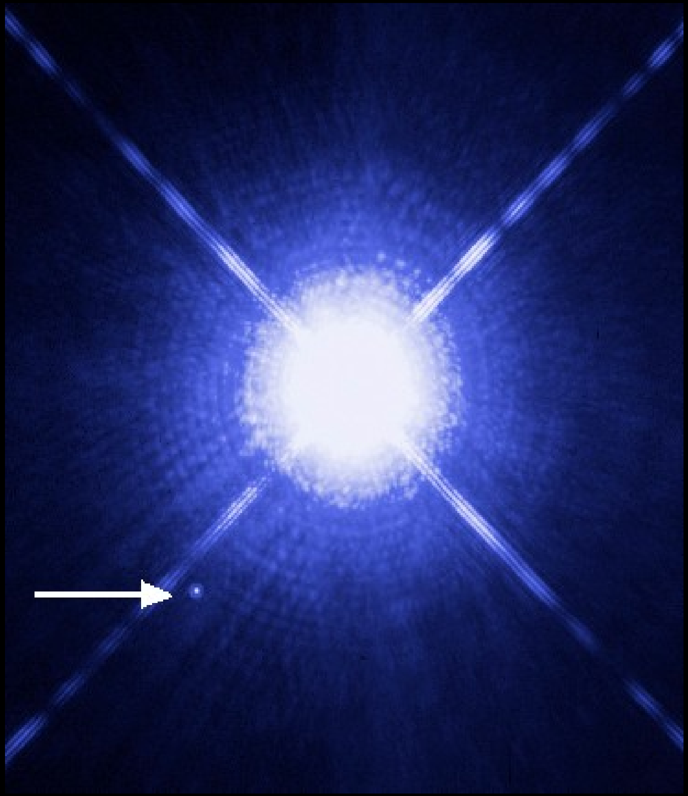


# Supernova explosion



# Compact objects

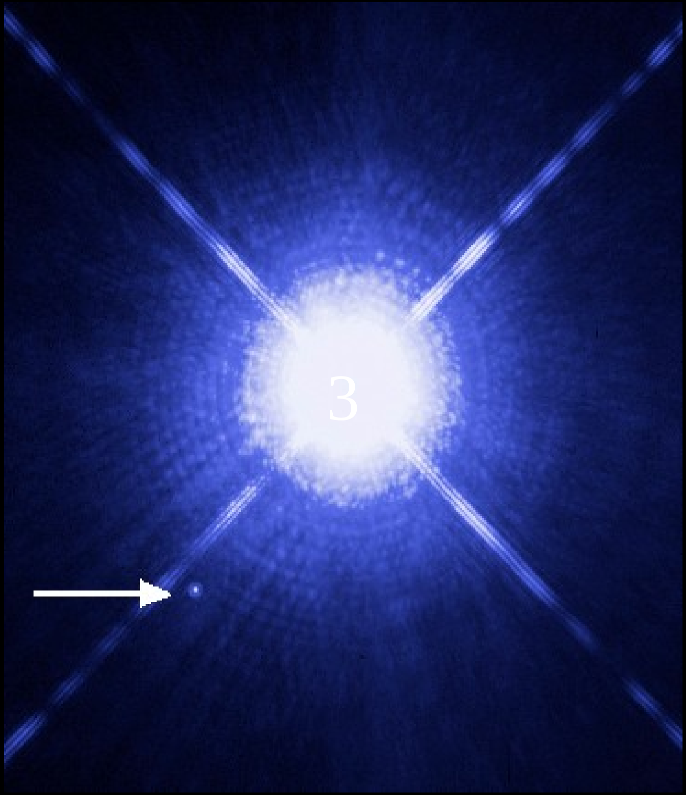
# Sirius B



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

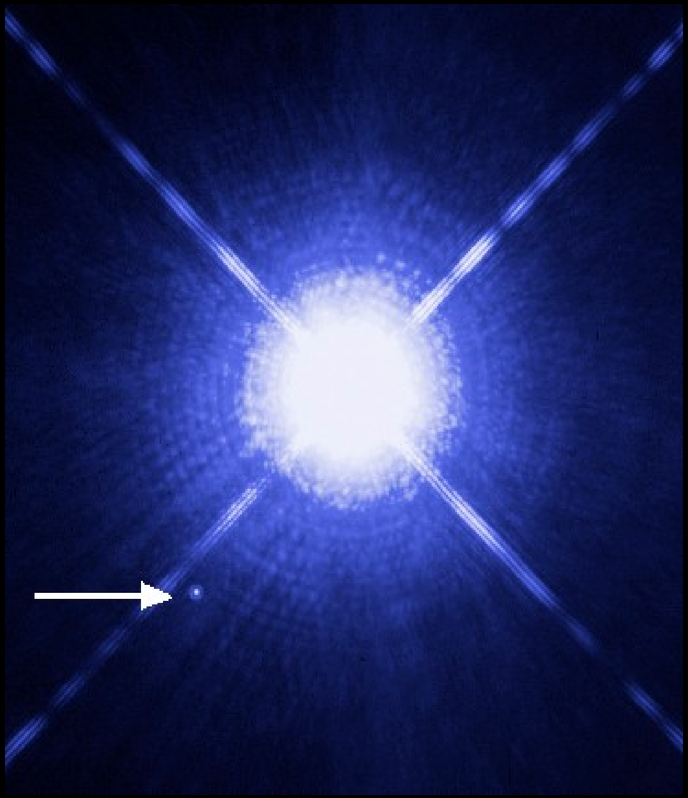
- Radius ?

# 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

- $R = \sqrt{\dfrac{L}{4\pi\sigma T^4}} \simeq 0.01 R_\odot$

- $\rho = \dfrac{3M}{4\pi R^3} \simeq \ 10^6 \ \ g/cm^3$

# Degenerate gas

For a degenerate gas :

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

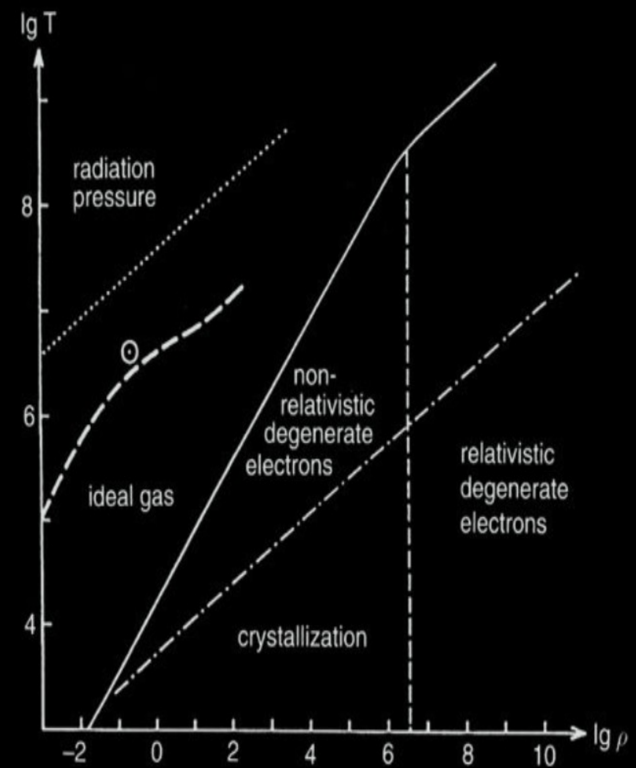
In a ideal gas :

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

Therefore :

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

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




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:

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

**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

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

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 $E(N)=0$

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

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

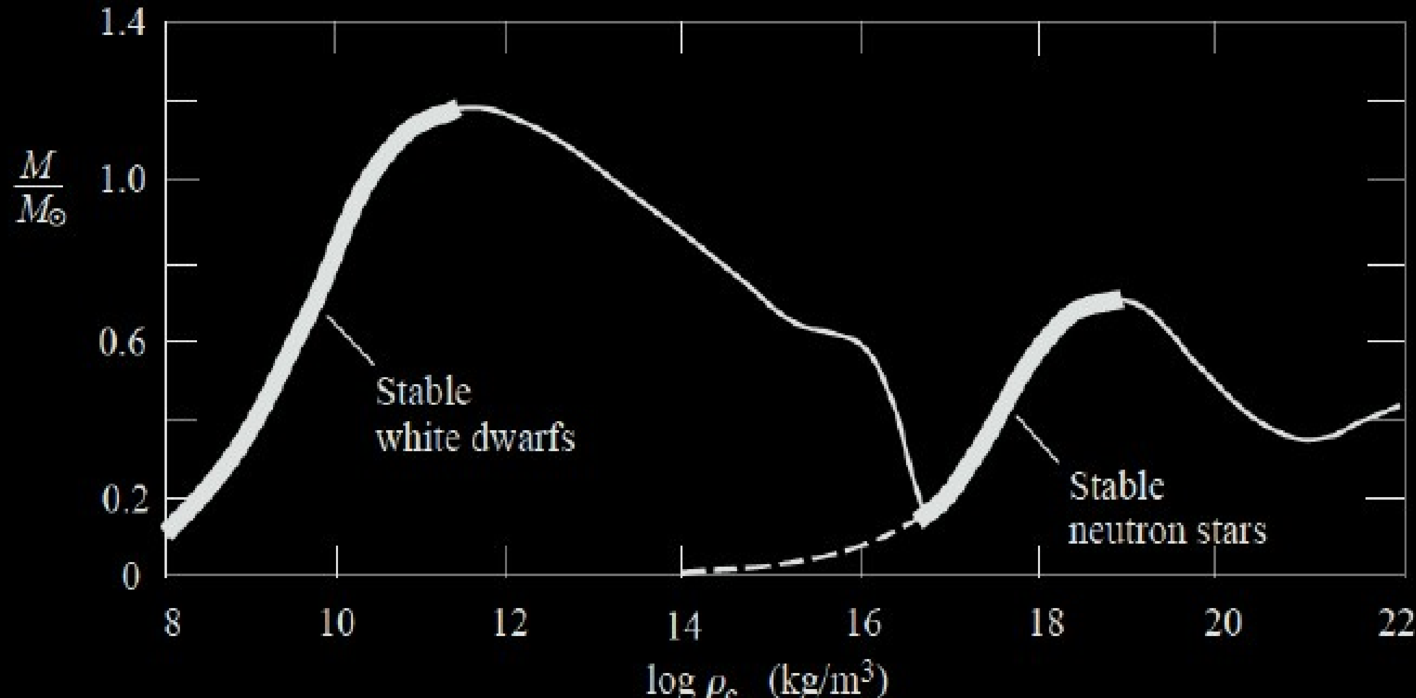
$$E_F \sim \hbar c N^{1/3}/R \sim mc^2 \quad R \sim \hbar/mc(N_{max})^{1/3} \sim \hbar/mc\ (\hbar c/G m_B{}^2)^{1/2}$$

$R_{WD} \sim 5 \times 10^8$ 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*.

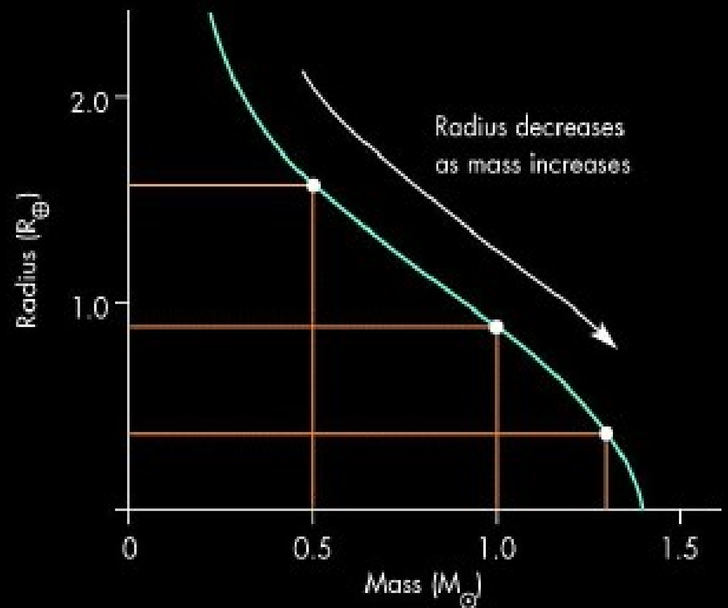


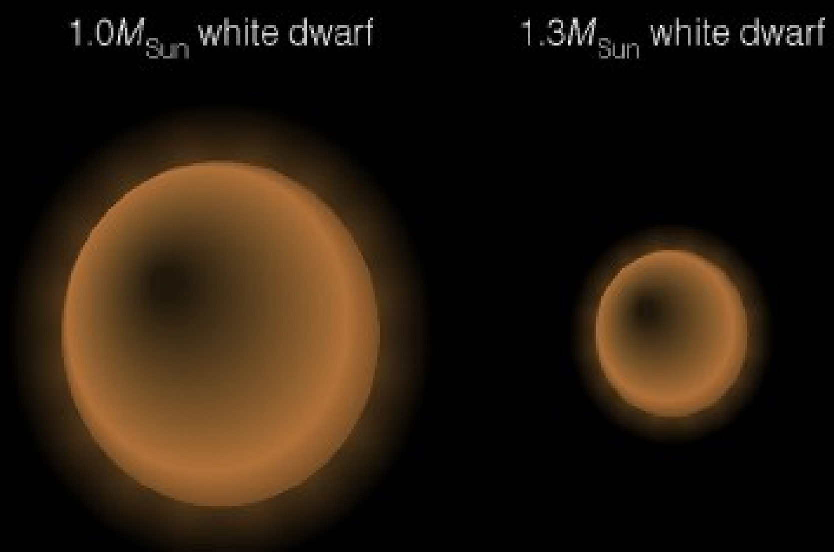

Stability only if mass increase implies larger density

⇒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



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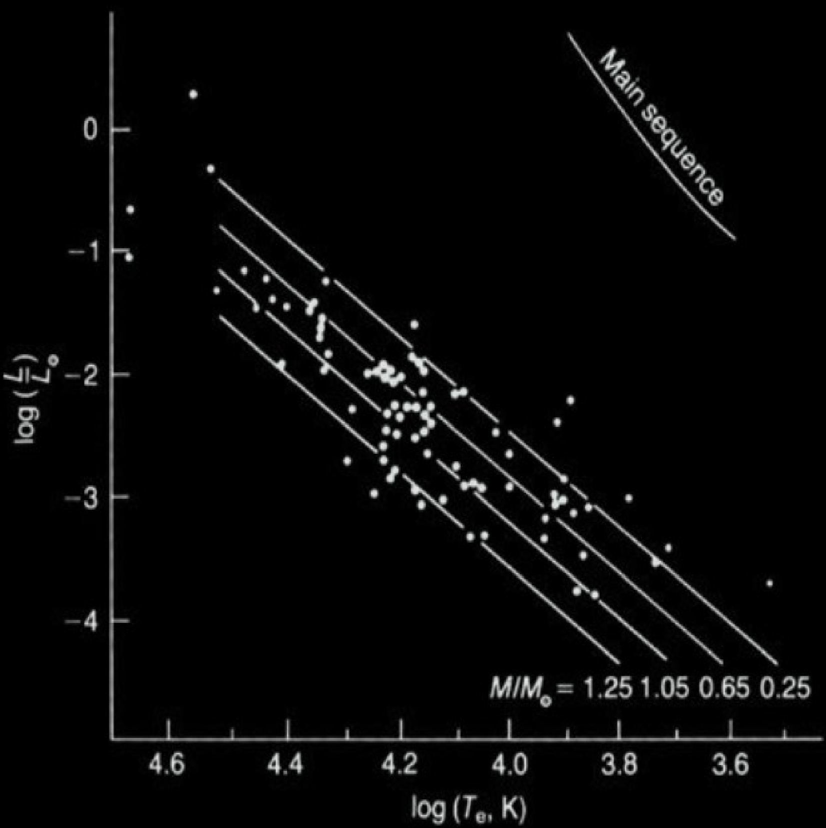
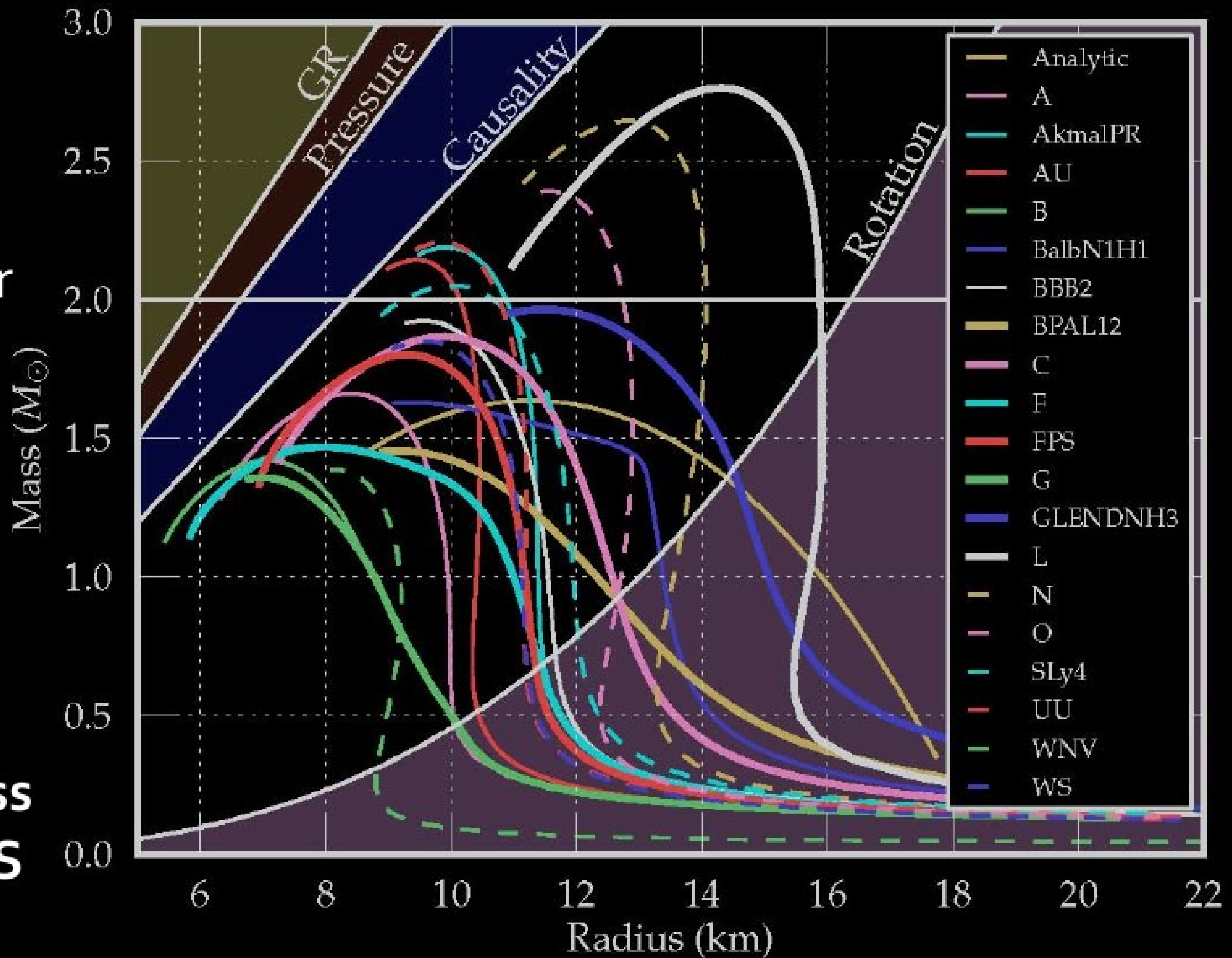


# Neutrons Stars

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*** $\rho \le 10^6$ 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*** $10^6 \le \rho \le 4.3\times10^{11}$ 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*** $4.3\times10^{11} \le \rho \le 2\times10^{14}$ g cm−3

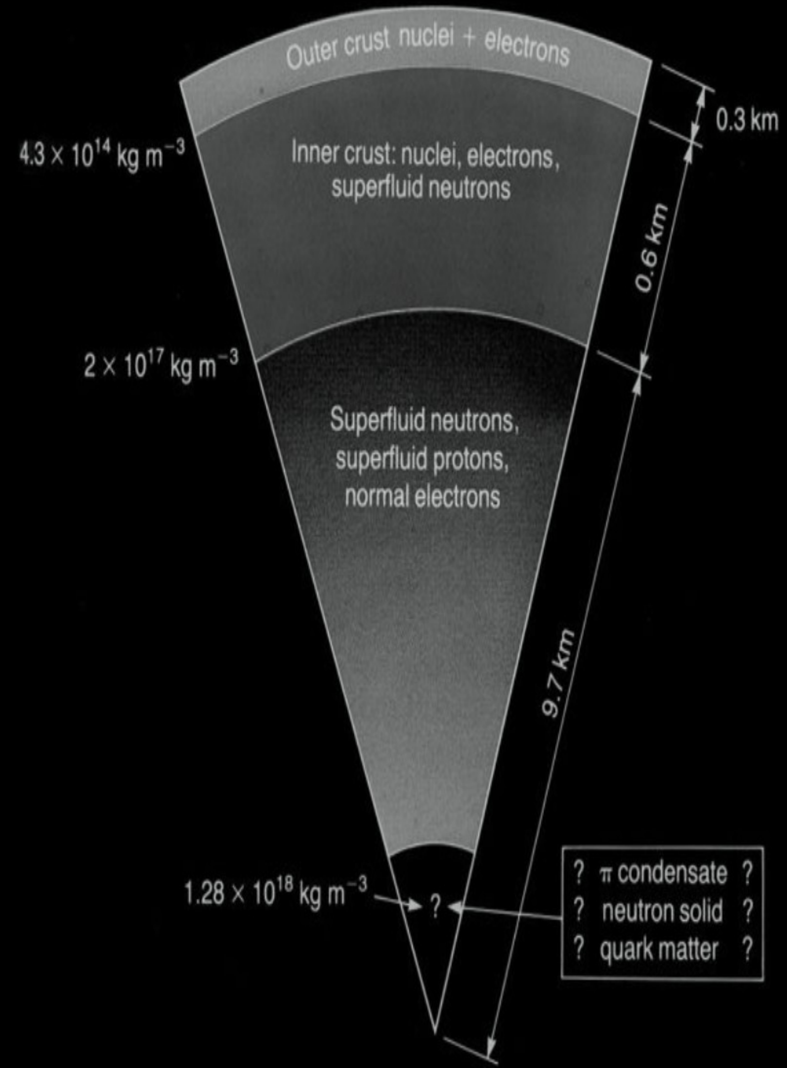
- Lattice of neutron-rich nuclei together with free degenerate neutrons and a degenerate relativistic electron gas.
- Nuclei begin to dissolve, the neutron fluid provides most of the pressure.

***Neutron liquid phase*** $\rho > 2\times10^{14}$ g cm−3

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

***Core*** $\rho \ge 3\times10^{15}$ 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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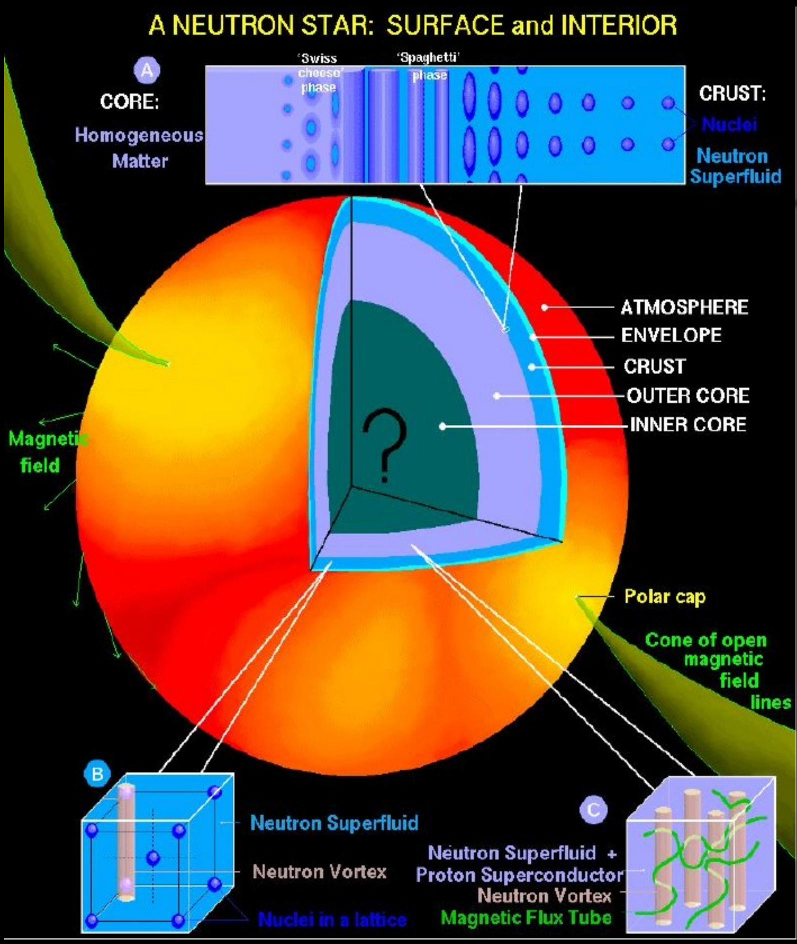
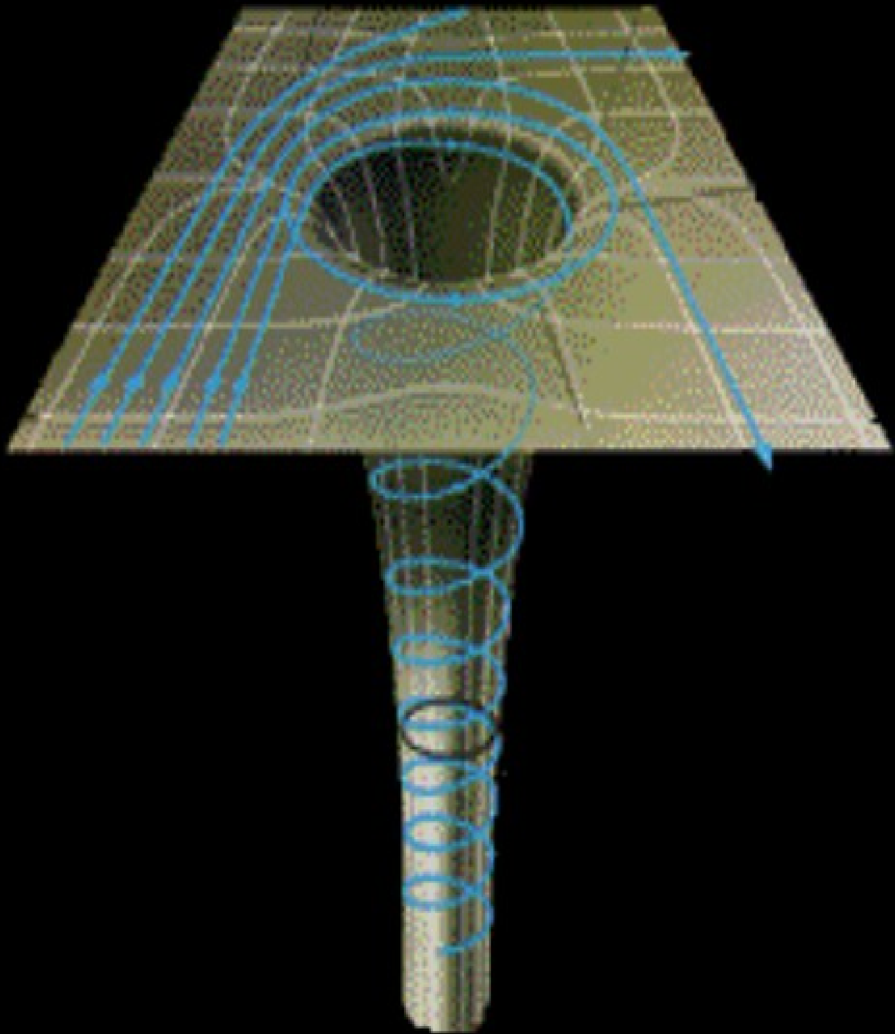


# BH: Einstein & Schwarzchild

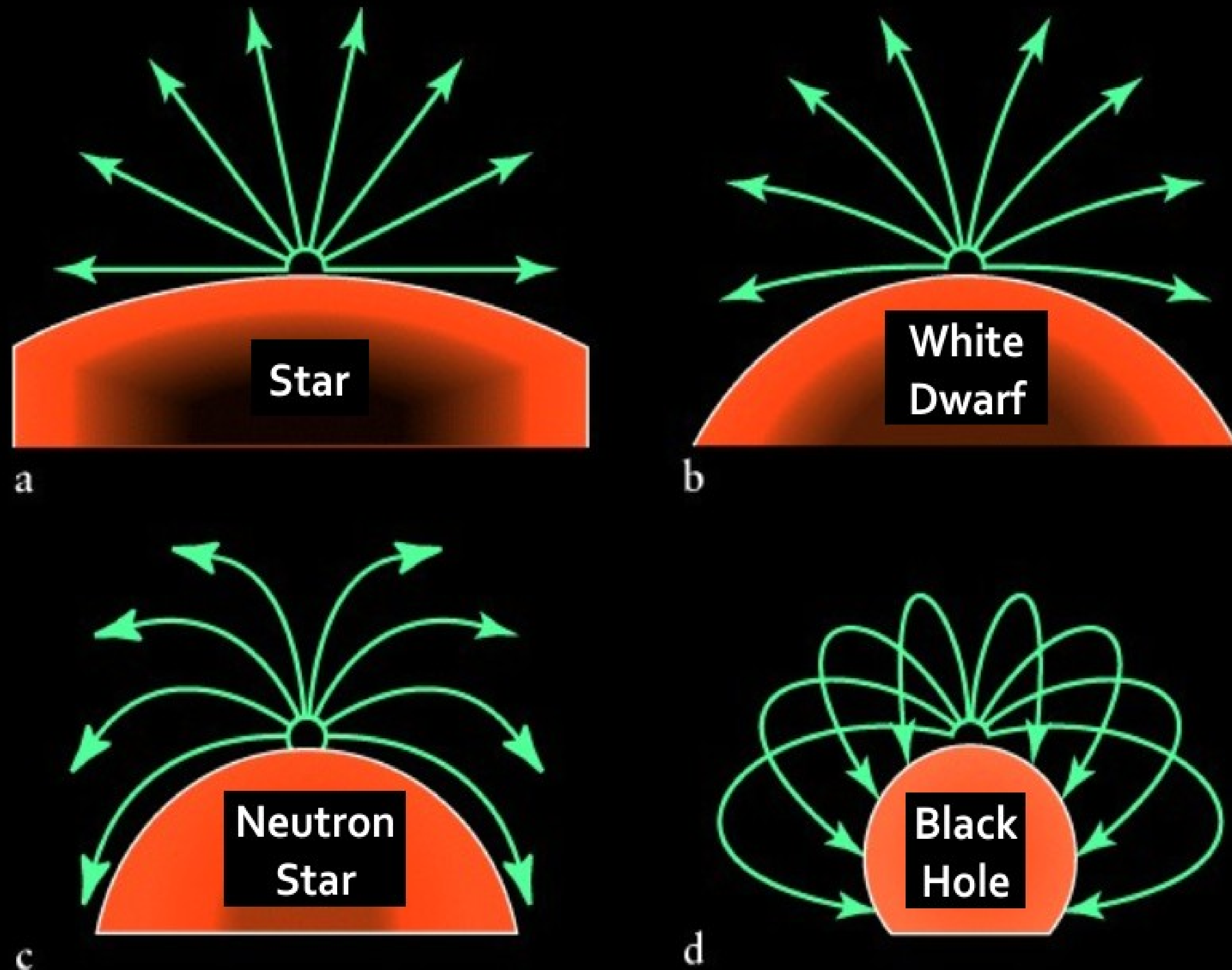


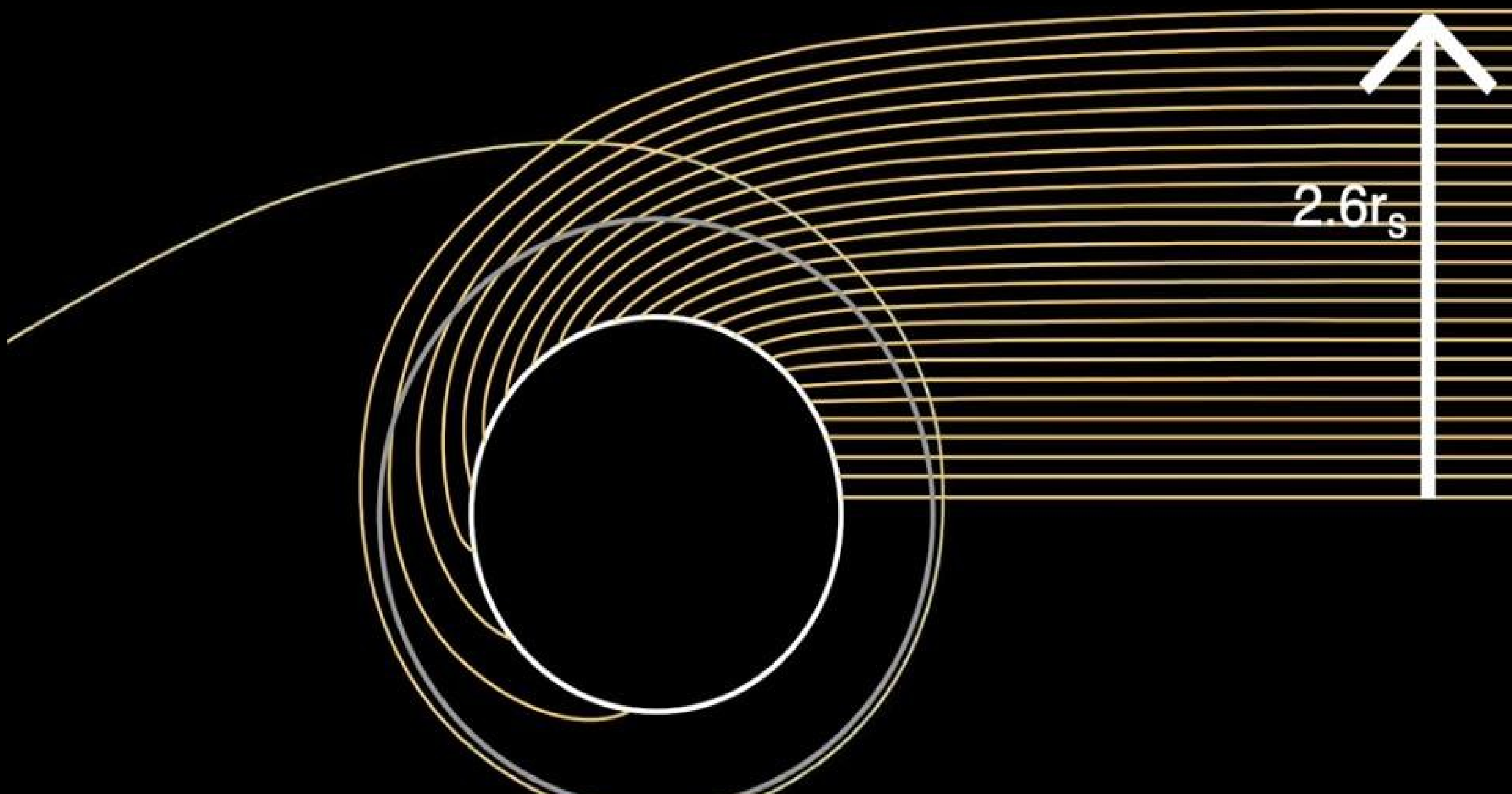
Black holes are a fundamental prediction of the theory of general relativity (GR; Einstein 1915).

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:***

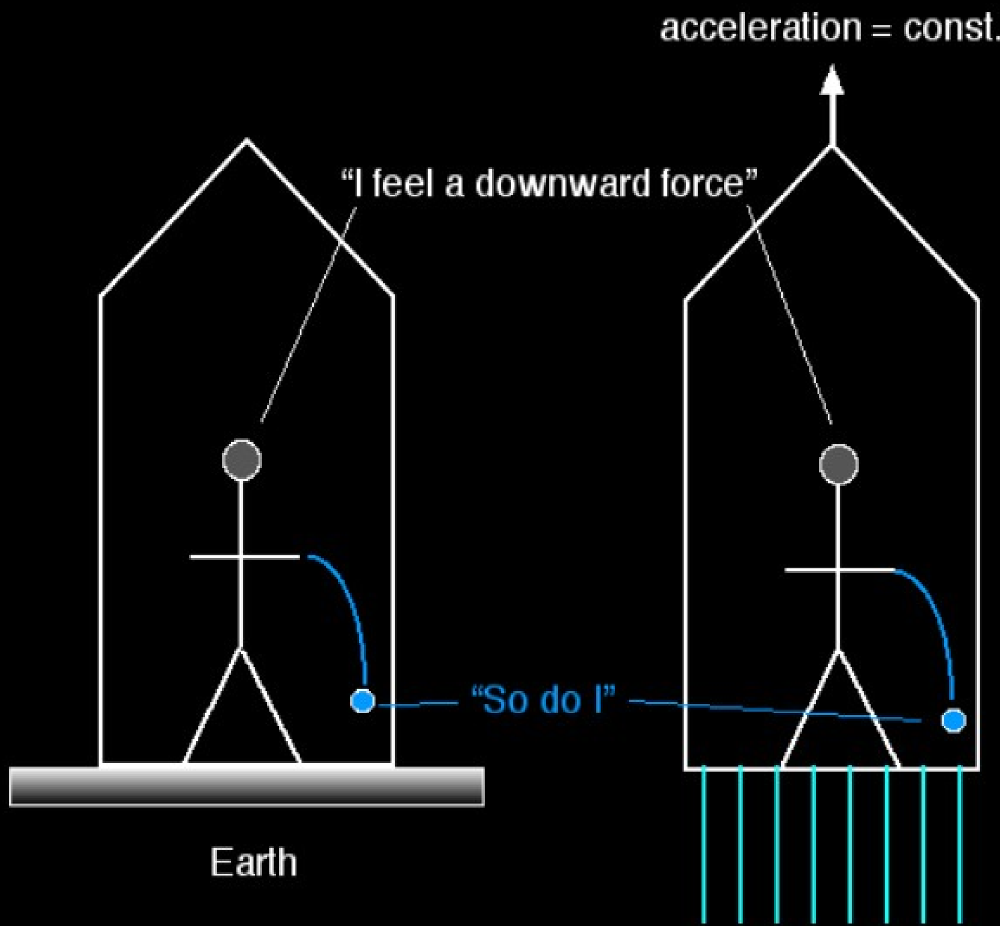
$$R_S = \frac{2GM}{c^2} \approx 3\frac{M}{M_{Sun}}\ km$$


Star
a
White
Dwarf
b
Neutron
Star
c
Black
Hole
d


$2.6r_s$

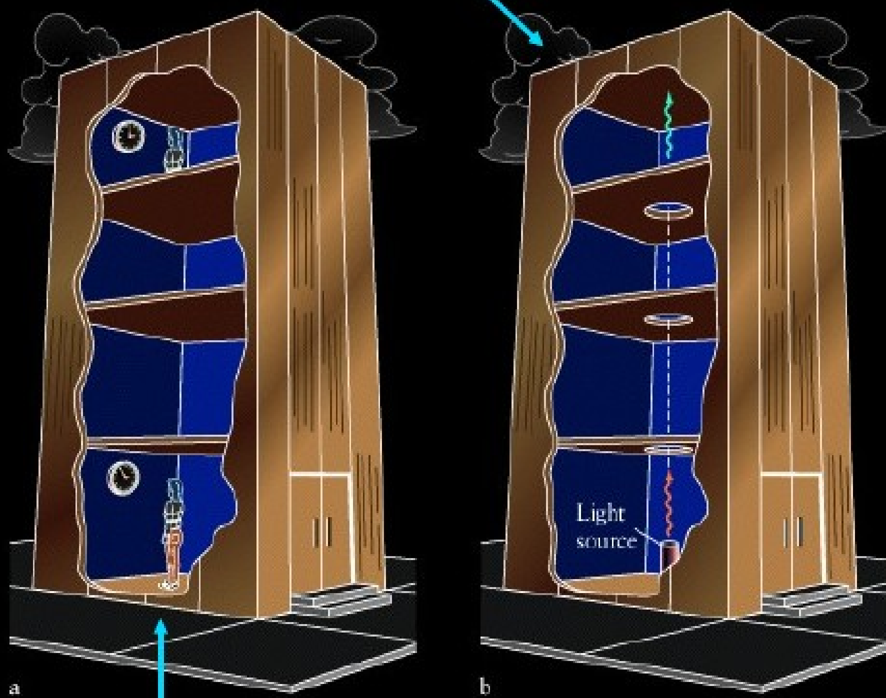
# Gereral Relativity

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



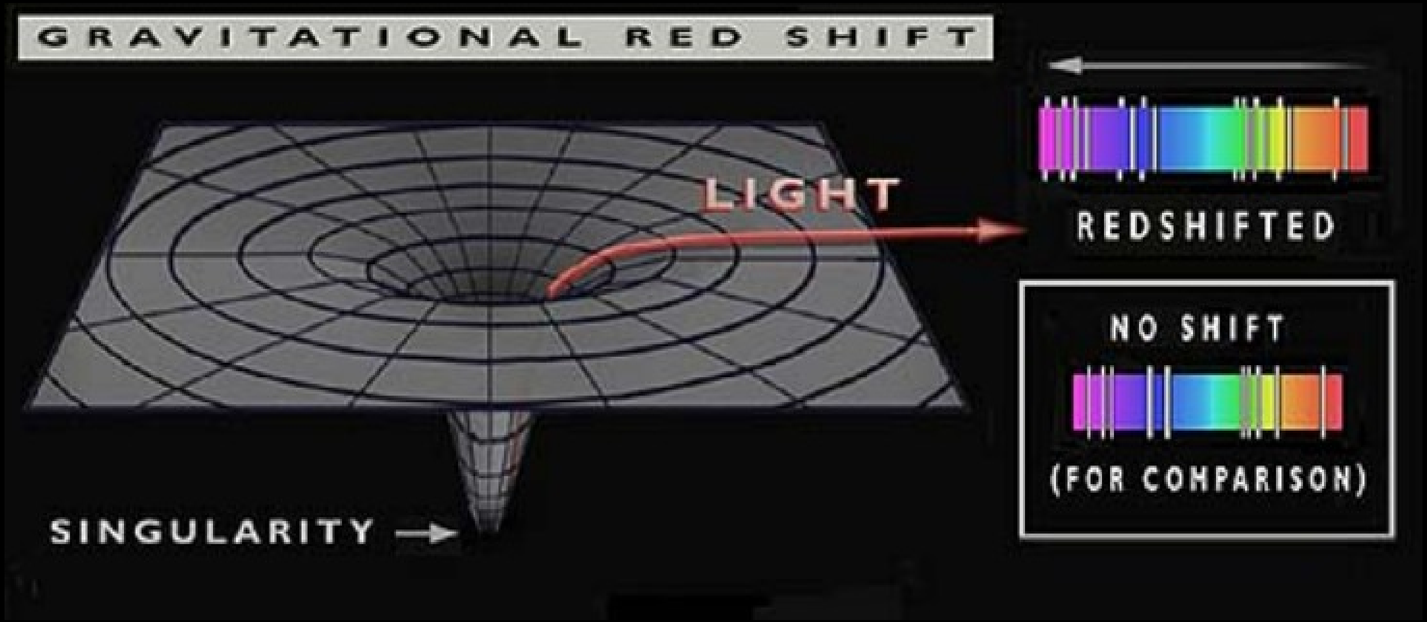
# Equivalence principle

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

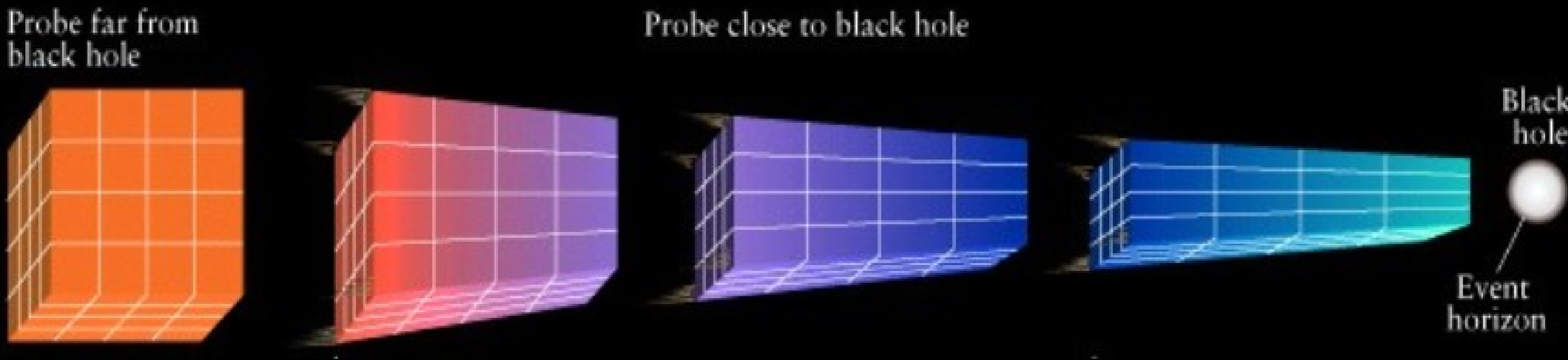



$$\frac{\nu}{\nu_{\rm r}} = \left(1 - \frac{2GM}{c^2 r}\right)^{1/2} \Rightarrow \nu \rightarrow 0 \text{ for } r \rightarrow R_S$$

# 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**.

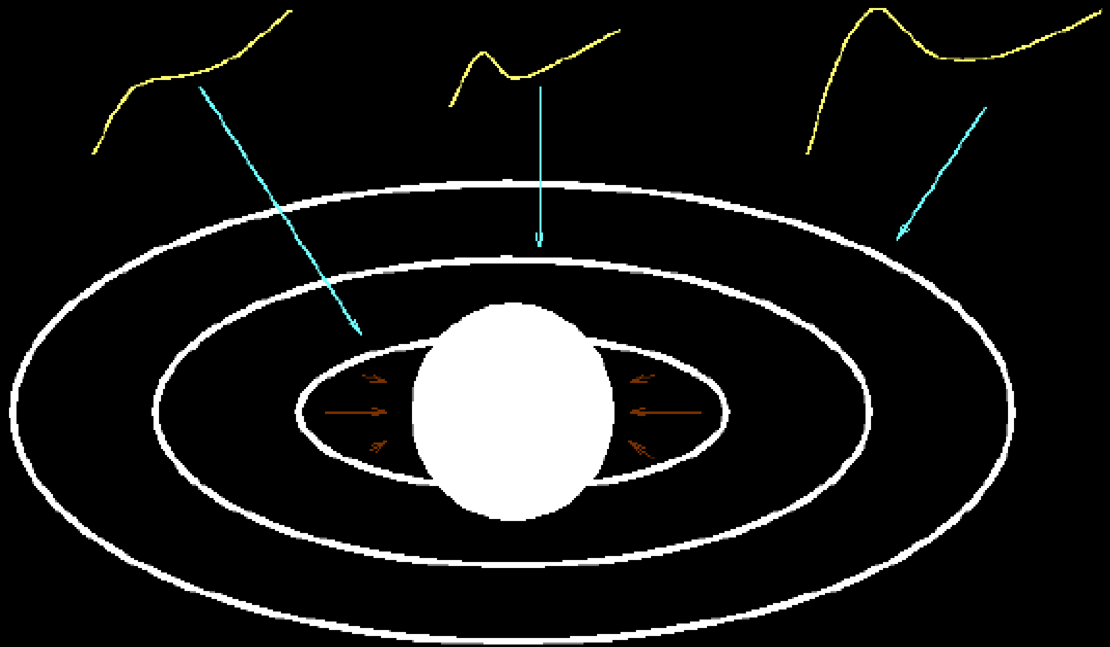
# Spaghettification



# 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**.

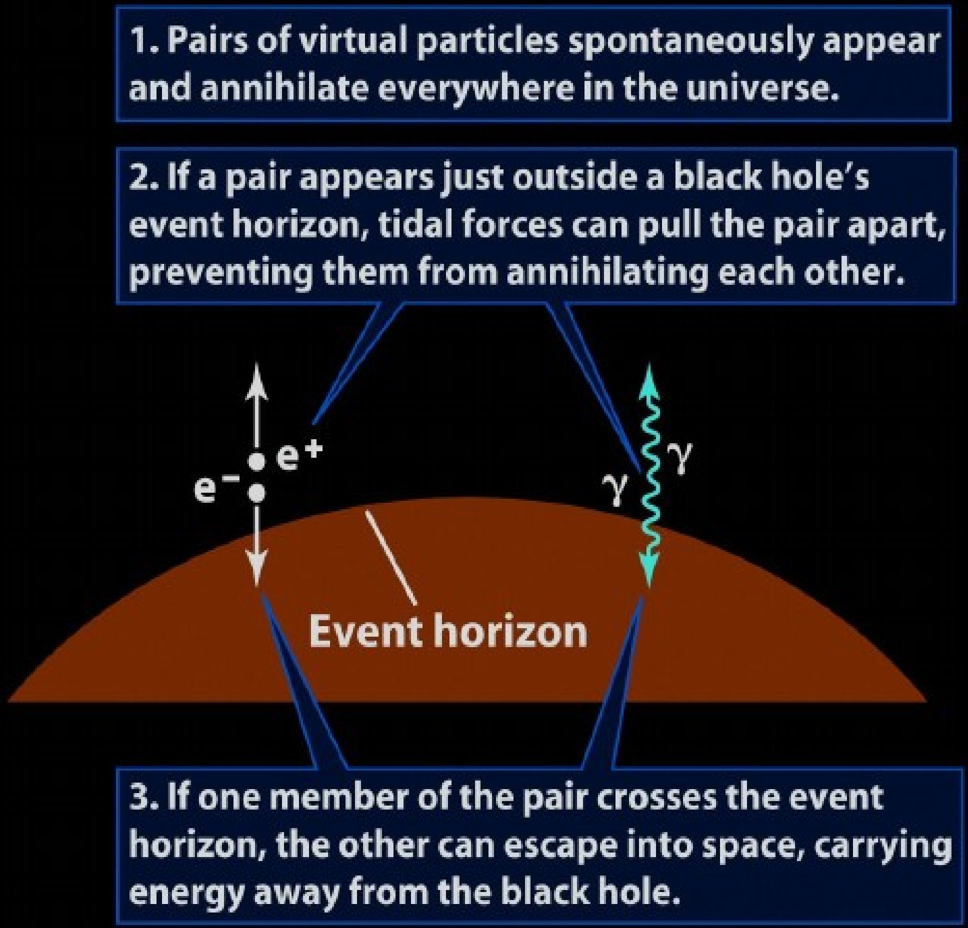
# Black holes



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***

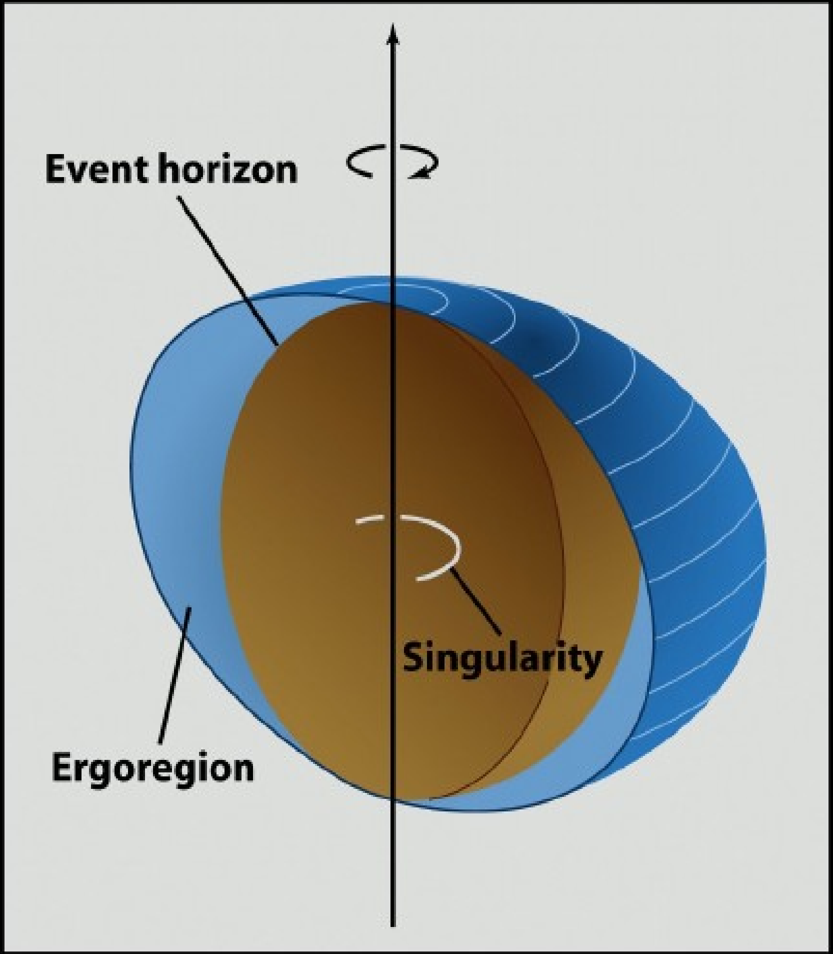
- Mass ($M$)
  - As measured by the black hole's effect on orbiting bodies, such as another star
- Total electric charge ($Q$)
  - As measured by the strength of the electric force (Q = 0)
- Spin = angular momentum ($a_*$)
  - How fast the black hole is spinning ($a_* < 1$)

# 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

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

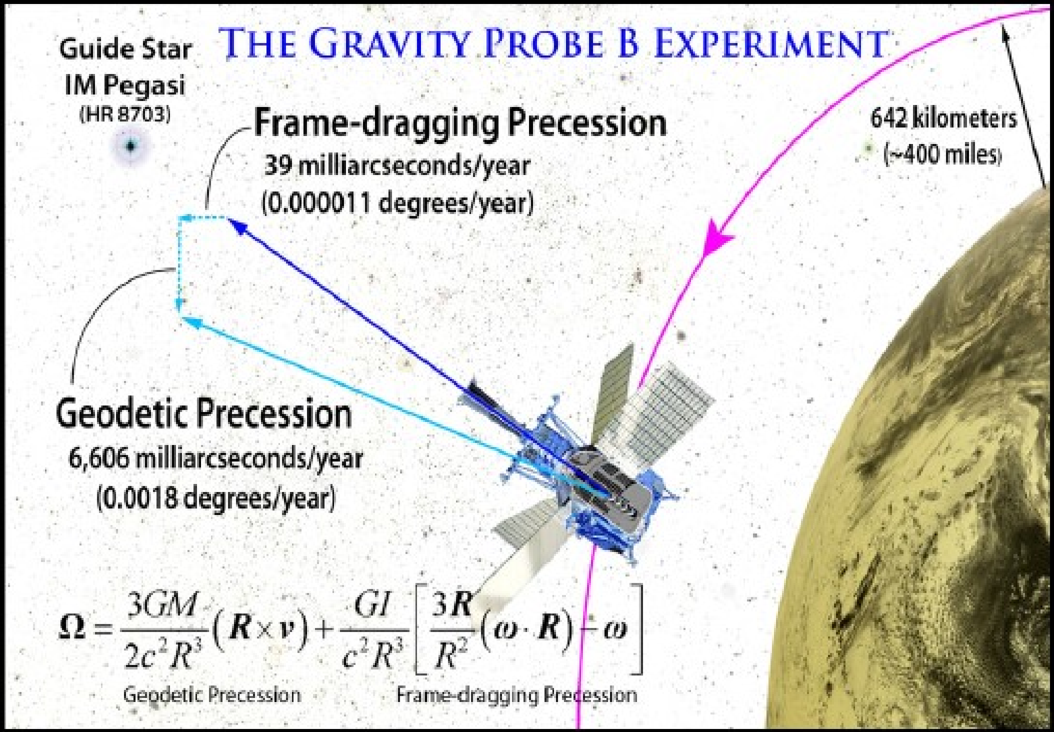
$$R_{ISCO}=GM/c^2=R$$

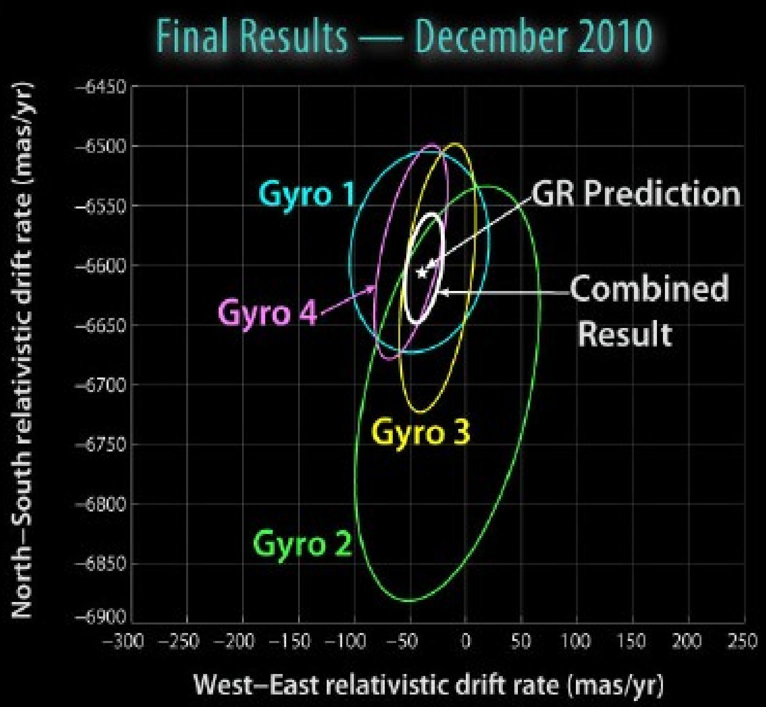



*A rotating mass has a tendency to pull space-time along with it*

# Gravity Probe B

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



# Binary systems

# Accretion in binary systems

Compact star M , normal star M with $M_2 < M_1$


Normal star expanded or binary separation decreased **=>** normal star feeds compact star

# The mass function

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

Kepler's 3rd law becomes:

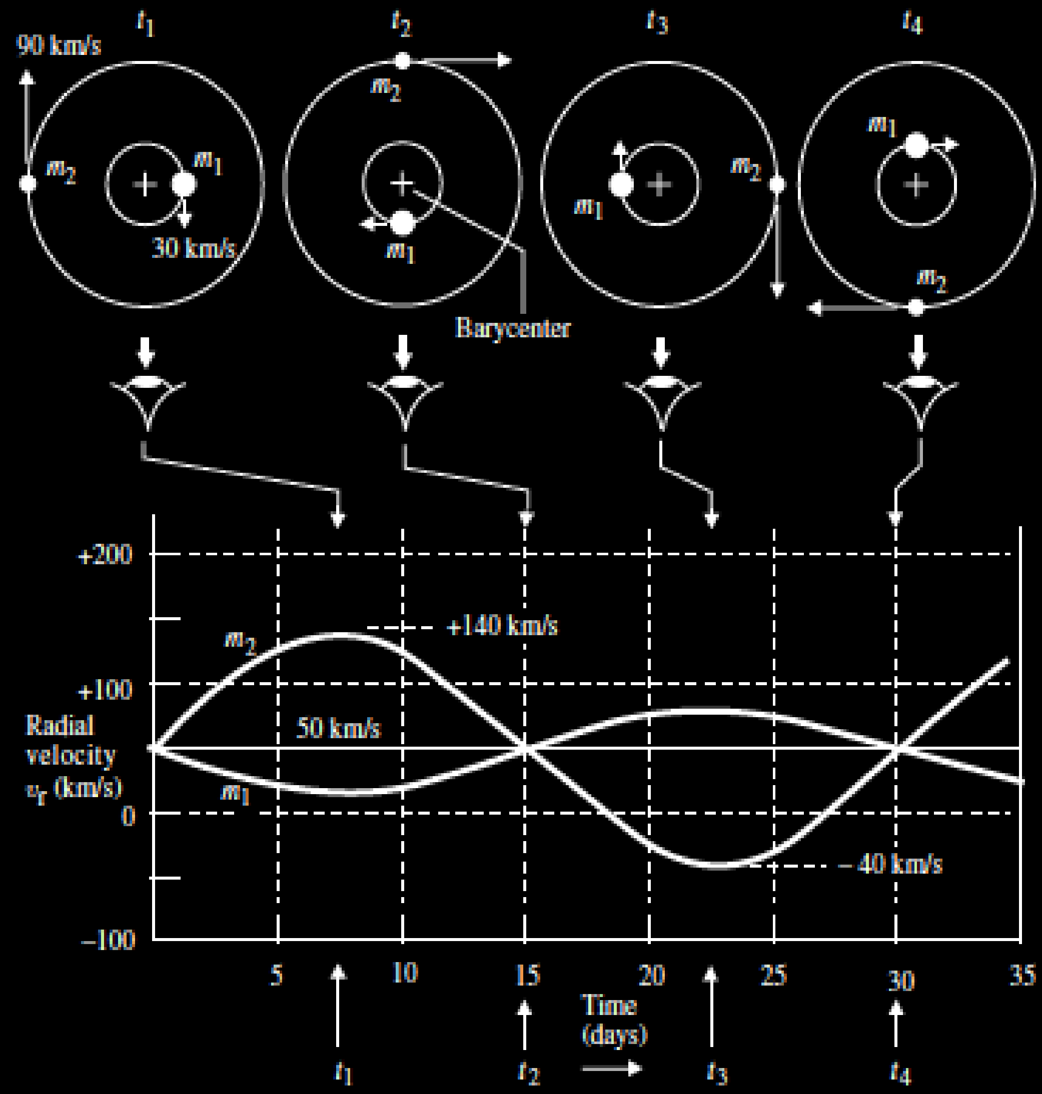
$$\omega^2 = G\frac{M_* + M_o}{a^3}$$

We can also measure :

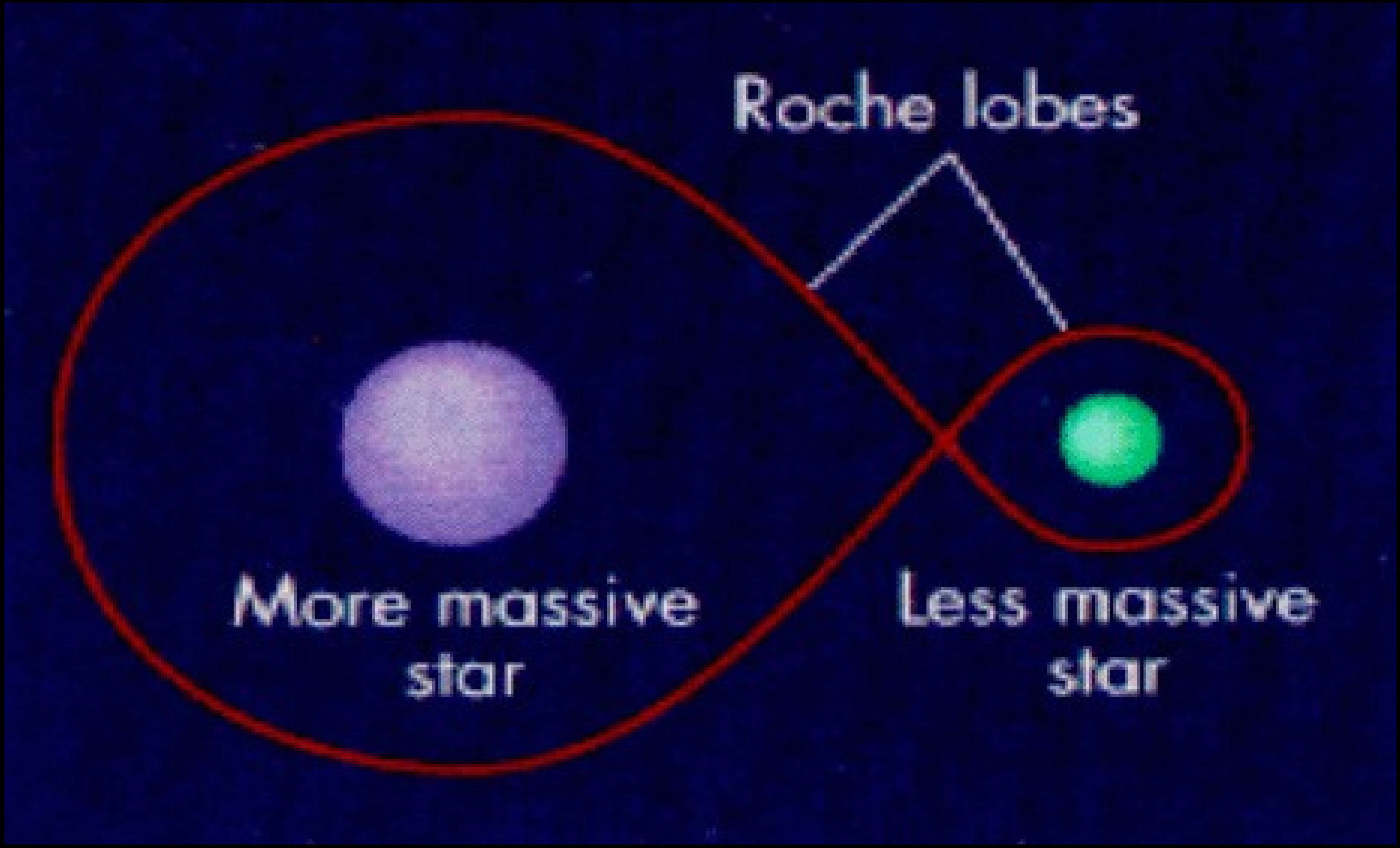
$$v_{max} = \omega a_* sin(i)$$

We define ***mass function*** :

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

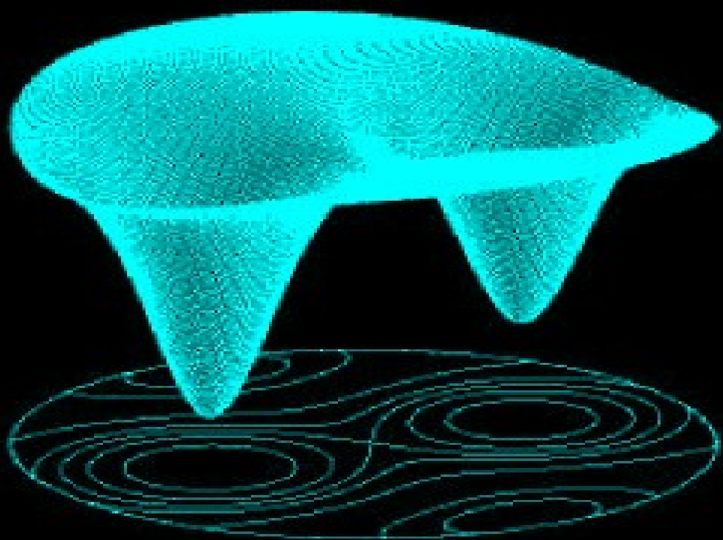


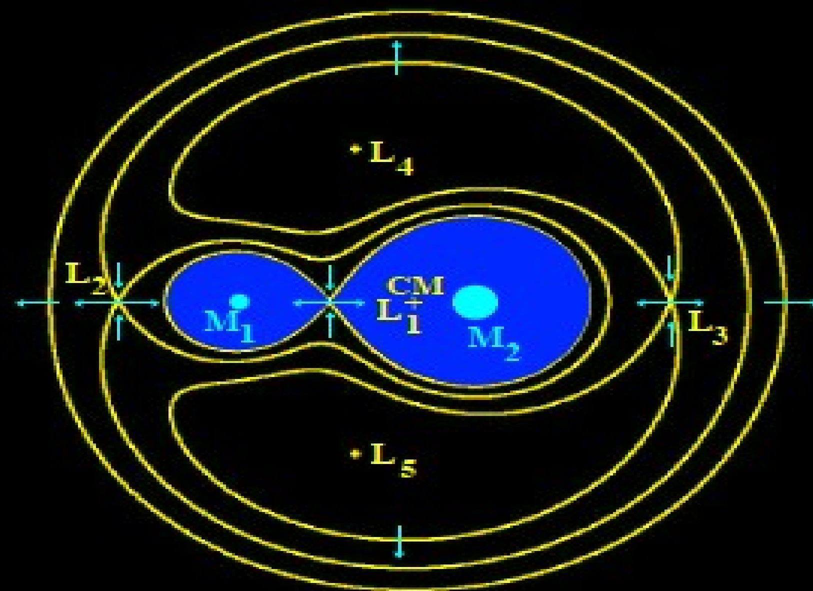
# Roche Lobes



# Roche lobes and Lagrangian points

Test particle in binary system: equipotential surface

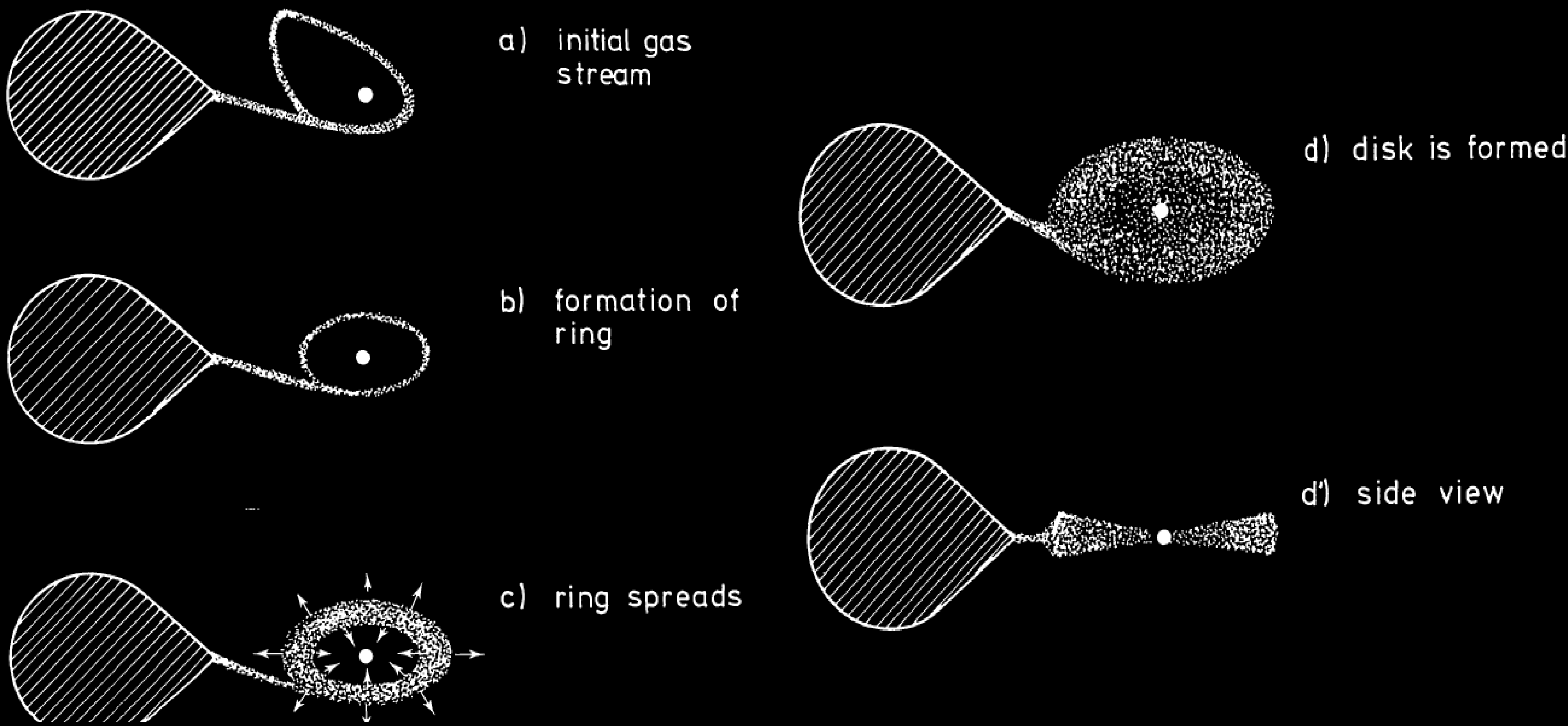





5 equilibrium points: Lagrangian points

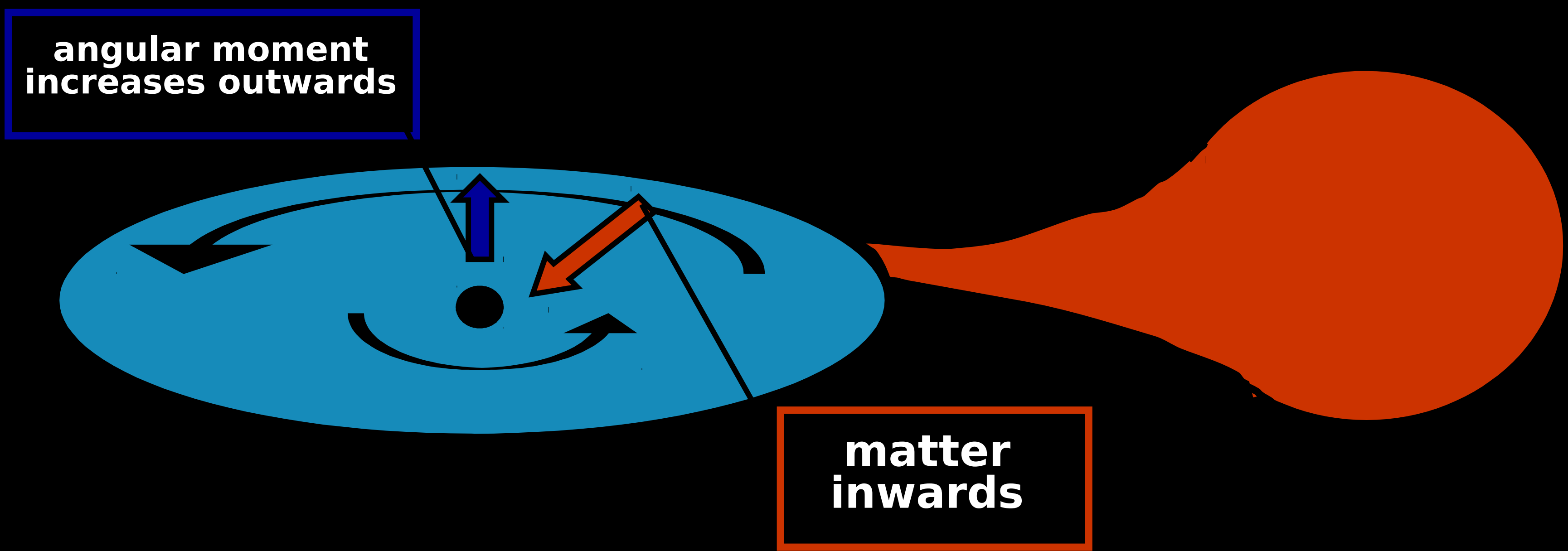
If a star fills its Roche lobe ⇒ mass transfer ⇒ accretion

# Formation of an accretion disk



# Accretion disk formation

Matter circulates around the compact object:



# Accretion disk

- Material transferred has high **angular momentum** so must lose it before accreting => disk forms
- Gas loses angular momentum through collisions, shocks, **viscosity** and magnetic fields: kinetic energy converted into **heat** and radiated.
- Matter sinks deeper into **gravity** of compact object

# *Viscosity*

**Accretion Disc ⬅ Disc+ viscosity**

- **Converts shear to heat**
- **Heat radiated away**
- **Energy being lost**

⇨ **Gas sinks deeper in the potential well**

**Gravitational potential energy**

**Viscosity**

**Radiation**

# Gravitational Energy


surface gravity: $g = \frac{GM}{r^2}$

grav. force: $F = mg$

work: $dE = Fdr$

total work / potential energy:

$$E = m \int_R^\infty g dr = m \int_R^\infty \frac{GM}{r^2} dr$$

$$E = m \left[ \frac{GM}{r} \right]_R^\infty$$

$$\boxed{E = \frac{GMm}{R}}$$

# Accretion: gravitational power plant

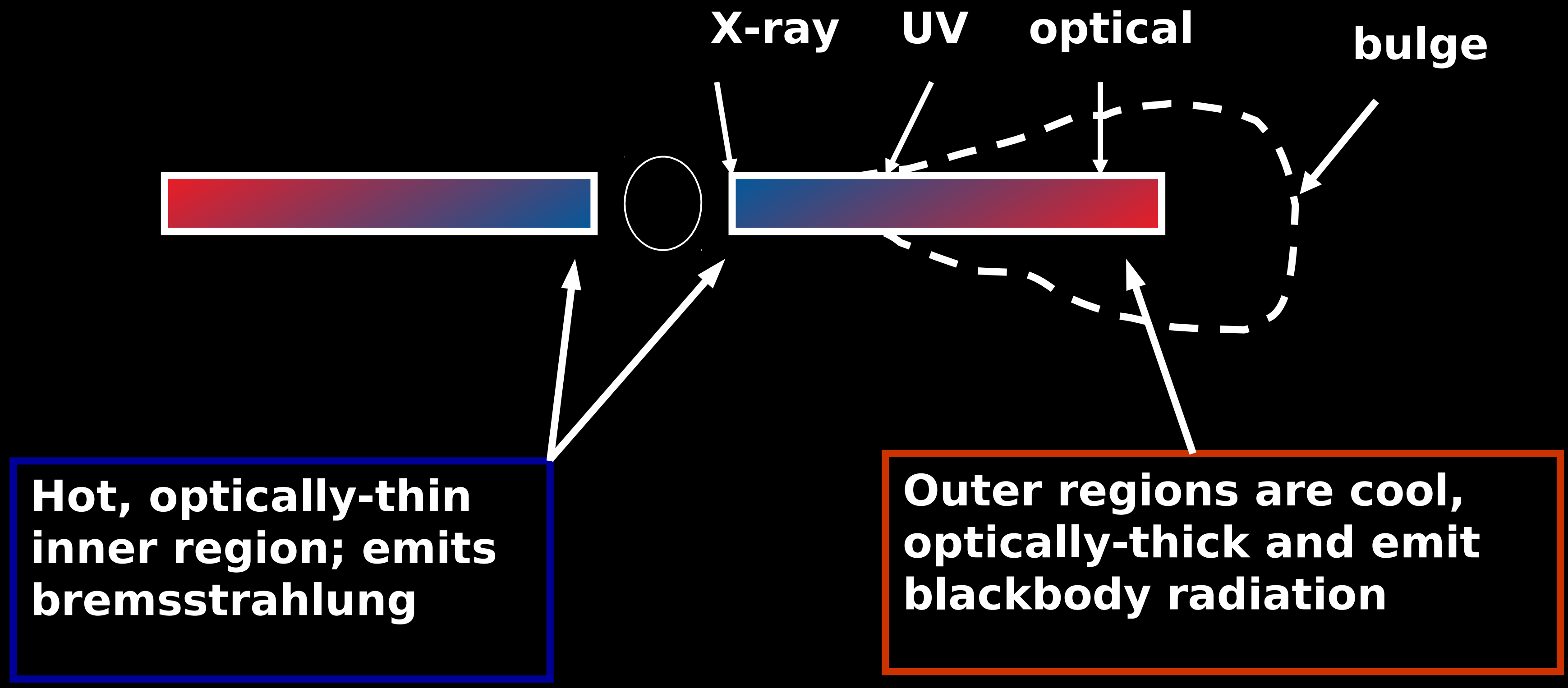
potential energy: $\dfrac{GM_c m}{R_c}$

$\longrightarrow$ kinetic energy: $\dfrac{1}{2}mv^2$

$\longrightarrow$ thermal energy: $\dfrac{3}{2}kT$

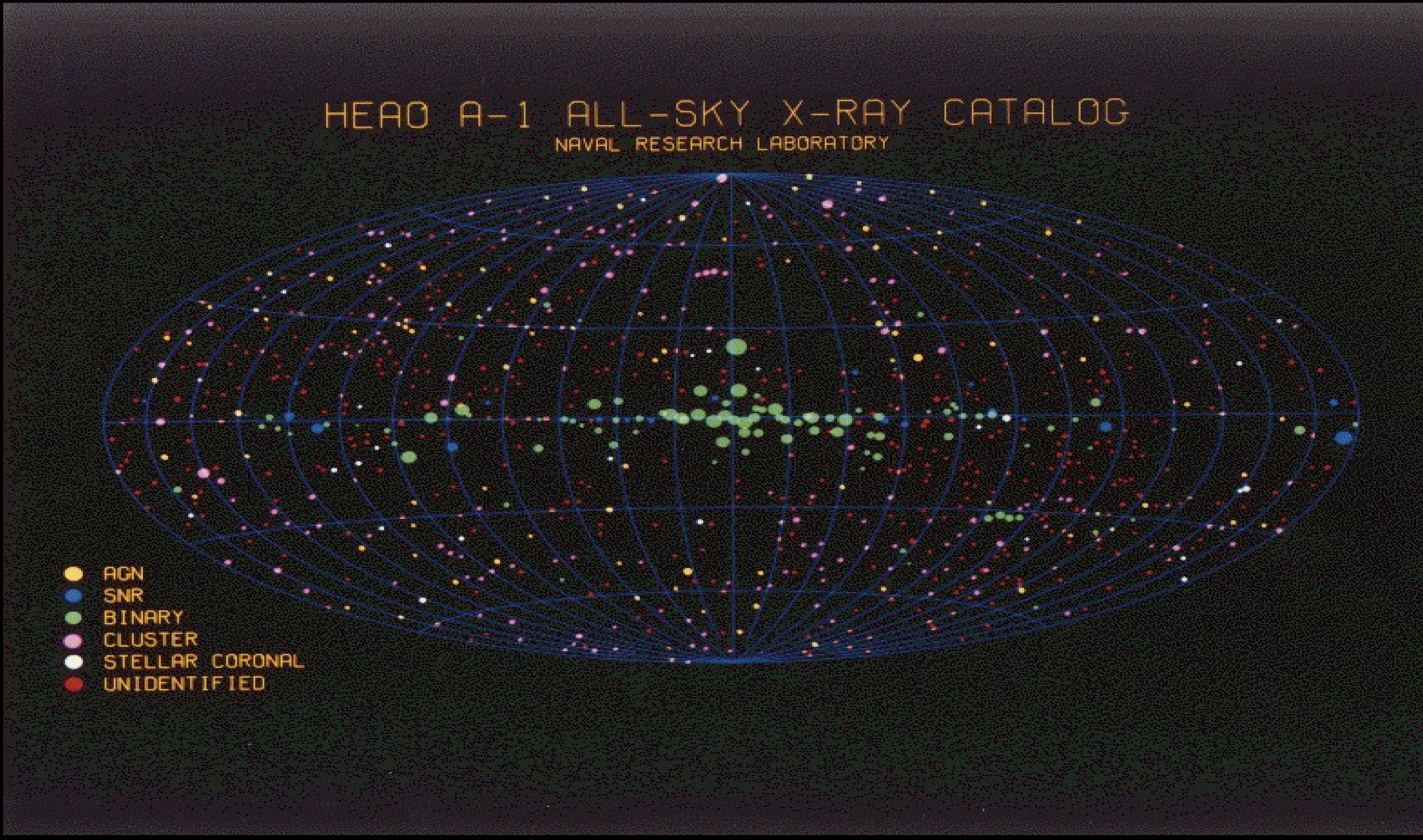
$\longrightarrow$ radiation: $h\nu$

# Disk structure




The other half of the accretion luminosity is released very close to the star.

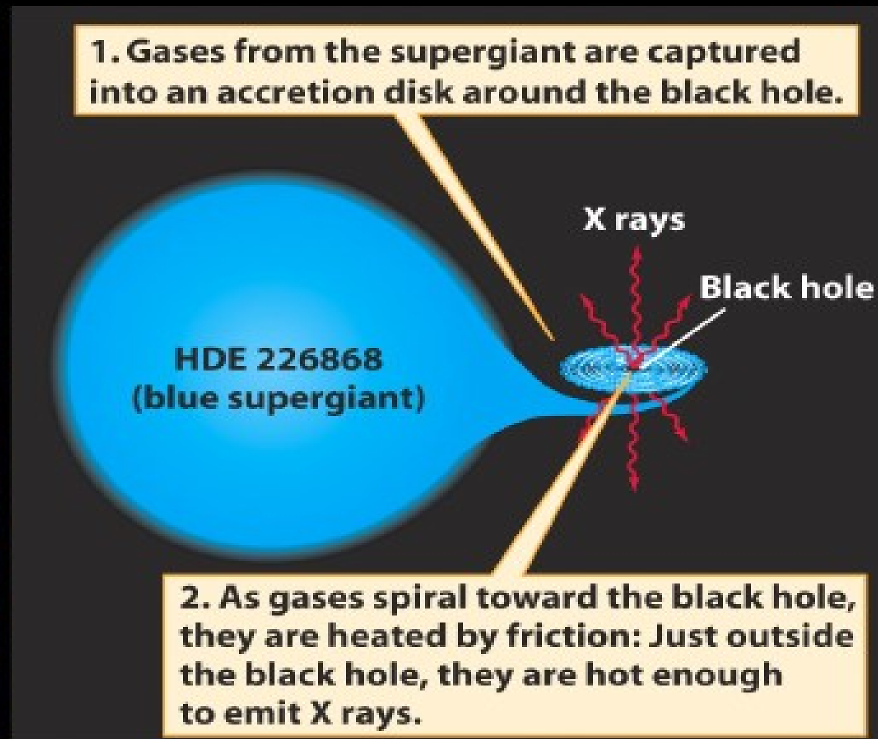
# X-ray sky



HEAO A-1 ALL-SKY X-RAY CATALOG
NAVAL RESEARCH LABORATORY
AGN
SNR
BINARY
CLUSTER
STELLAR CORONAL
UNIDENTIFIED

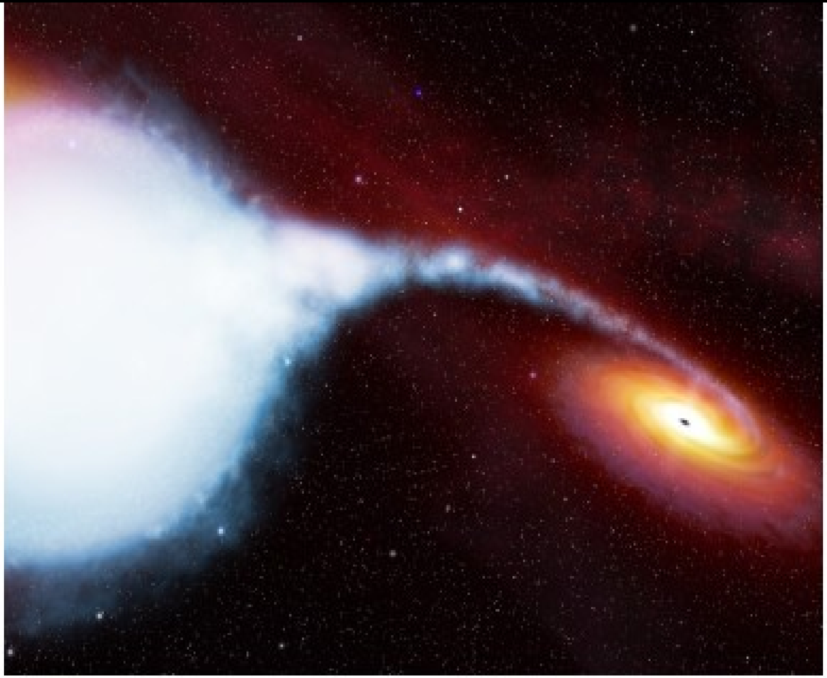
# Cyg X-1

Bright X-ray sources when in accreting binary systems


**Cyg X-1**: X-ray variability on <1 s timescale; $M \sim 15\ M_\odot$

# Efficiency



Gravitational energy at ISCO ($R_{ISCO} = 3R_S \sim 100$ *km for a* $10\ M_\odot$ *BH*):

$$E_G \sim GmM/3R_s = GmMc^2/6GM = mc^2/6$$

**Efficiency**: $E_G/mc^2 \sim 1/6$ **~ 20%** » 0.7% (nuclear fusion)

# Examples: White dwarf


$M = 0.6\ M_{\odot}$

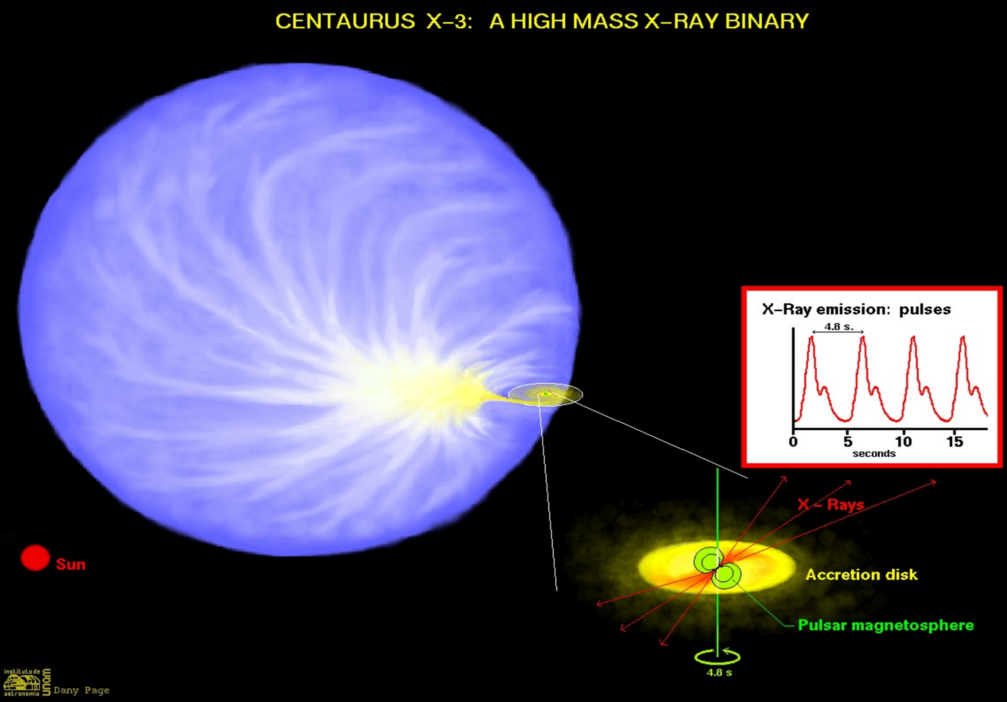
$R = 10\ 000$ km

$E = GMm/R$

$m = 1$ g $\Rightarrow$

$E \approx 8 \times 10^{16}$ erg

# Example: Neutron star




$M = 1.4\ M_{\odot}$

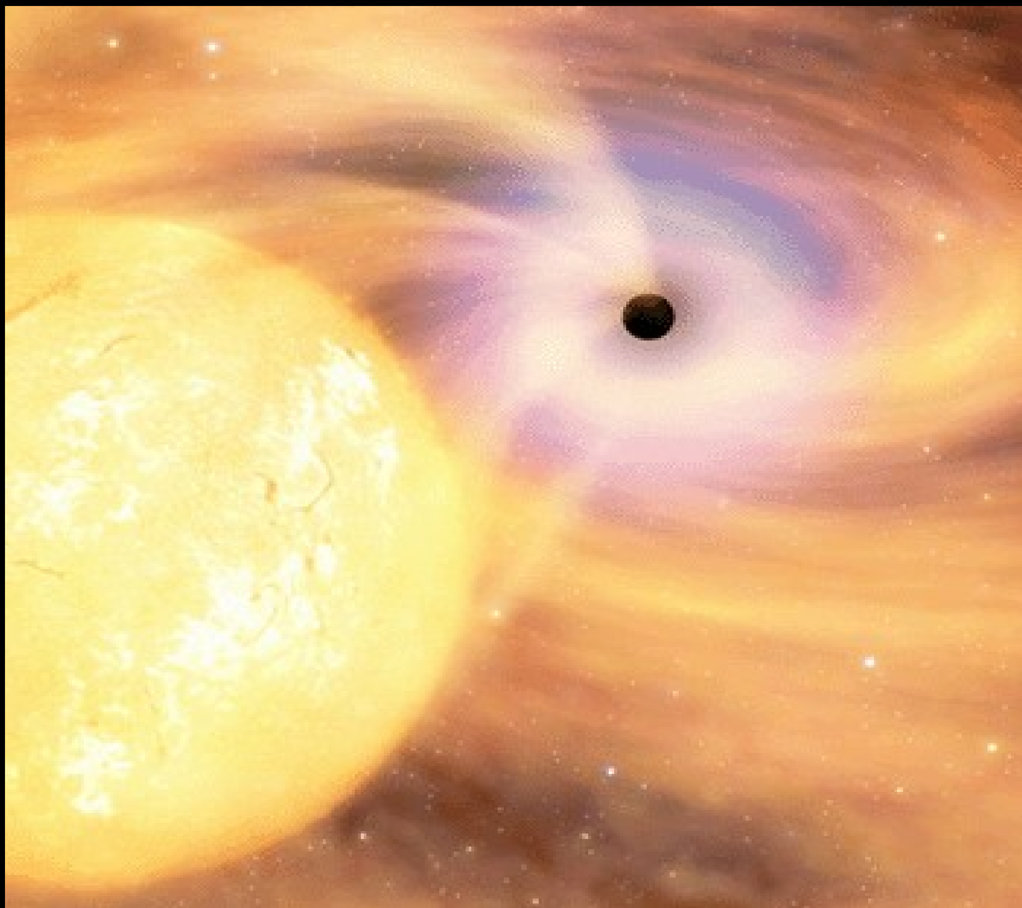
$R = 10$ km

$E = GMm/R$

$m = 1\ g \Rightarrow$

$E \approx 2 \times 10^{20}$ erg

# Example: Stellar black hole



$M = 6\ M_\odot$

$R \approx 2GM/c^2 \approx 18$ km

$E = GMm/R \approx 0.5\ mc^2$

$m = 1$ g $\Rightarrow$

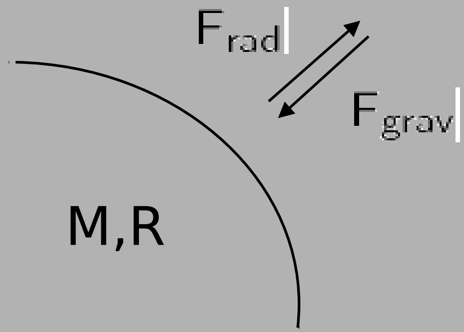
$E \approx 4 \times 10^{20}$ erg

$m = 1\ M_\odot \Rightarrow$

$E \approx 8 \times 10^{53}$ erg

$\Rightarrow$ If energy released in seconds/minutes: **GRB** luminosity (collapsar model)

# The Eddington luminosity




$$L = 4\pi R^2 F \implies F_{rad} = \frac{\sigma_T L}{4\pi R^2 c}$$

$$m_p = 1830 m_e \implies F_{grav} = \frac{GMm_p}{R^2}$$

$$F_{rad} = F_{grav} \implies \boxed{L_E = \frac{4\pi GMm_p c}{\sigma_T}}$$

Accretion rate: $\dot{M}$ (measured in [g/s] or [$M_{\odot}$/yr])

Accretion luminosity: $L_{acc} = \dfrac{GM\dot{M}}{R}$ **[erg/s]**

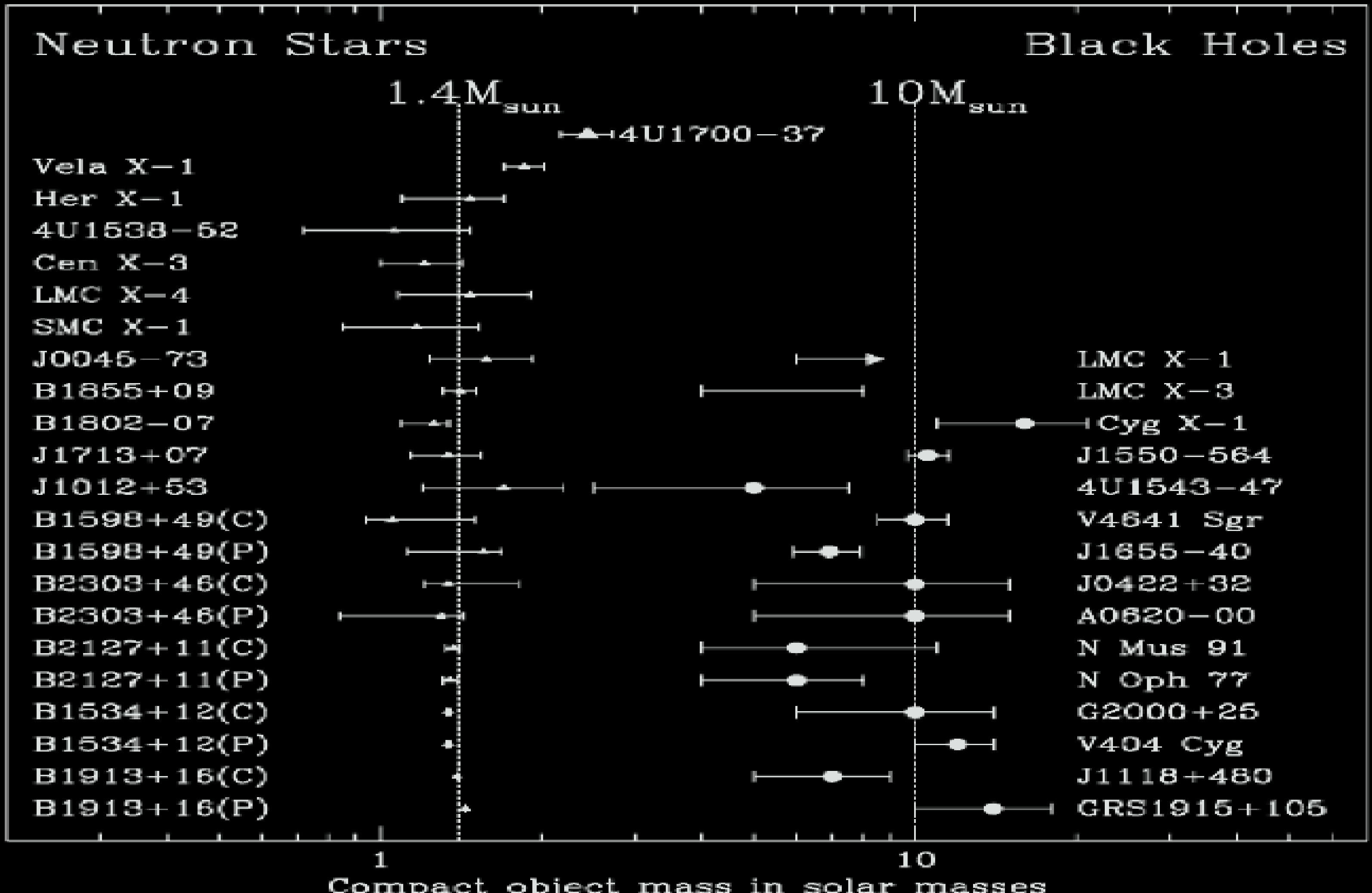
Maximum accretion rate onto a **neutron star**:

$$L_{E,NS} \approx 1.8 \times 10^{38} \text{ erg/s} \Rightarrow \dot{M}_{E,NS} = \frac{L_{E,NS}R}{GM} \approx 1.5 \times 10^{-8} \quad \mathbf{M_{0/yr}}$$

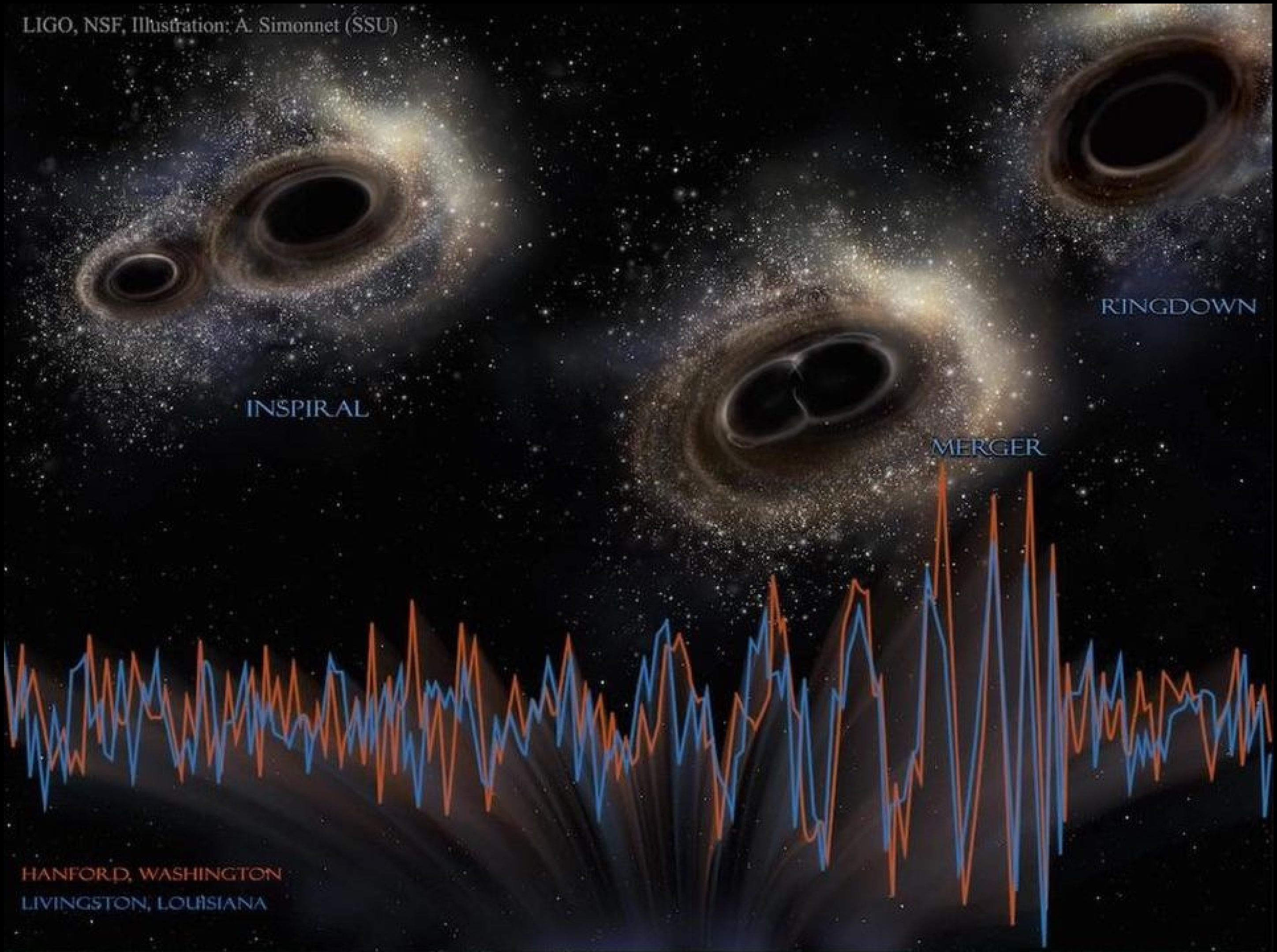
Maximum accretion onto a **supermassive** ($10^8$) **black hole**:

$$L_{E,AGN} \approx 10^{46} \text{ erg/s} \Rightarrow \dot{M}_{E,AGN} \approx 0.5 \quad \mathbf{M_{o/yr}}$$

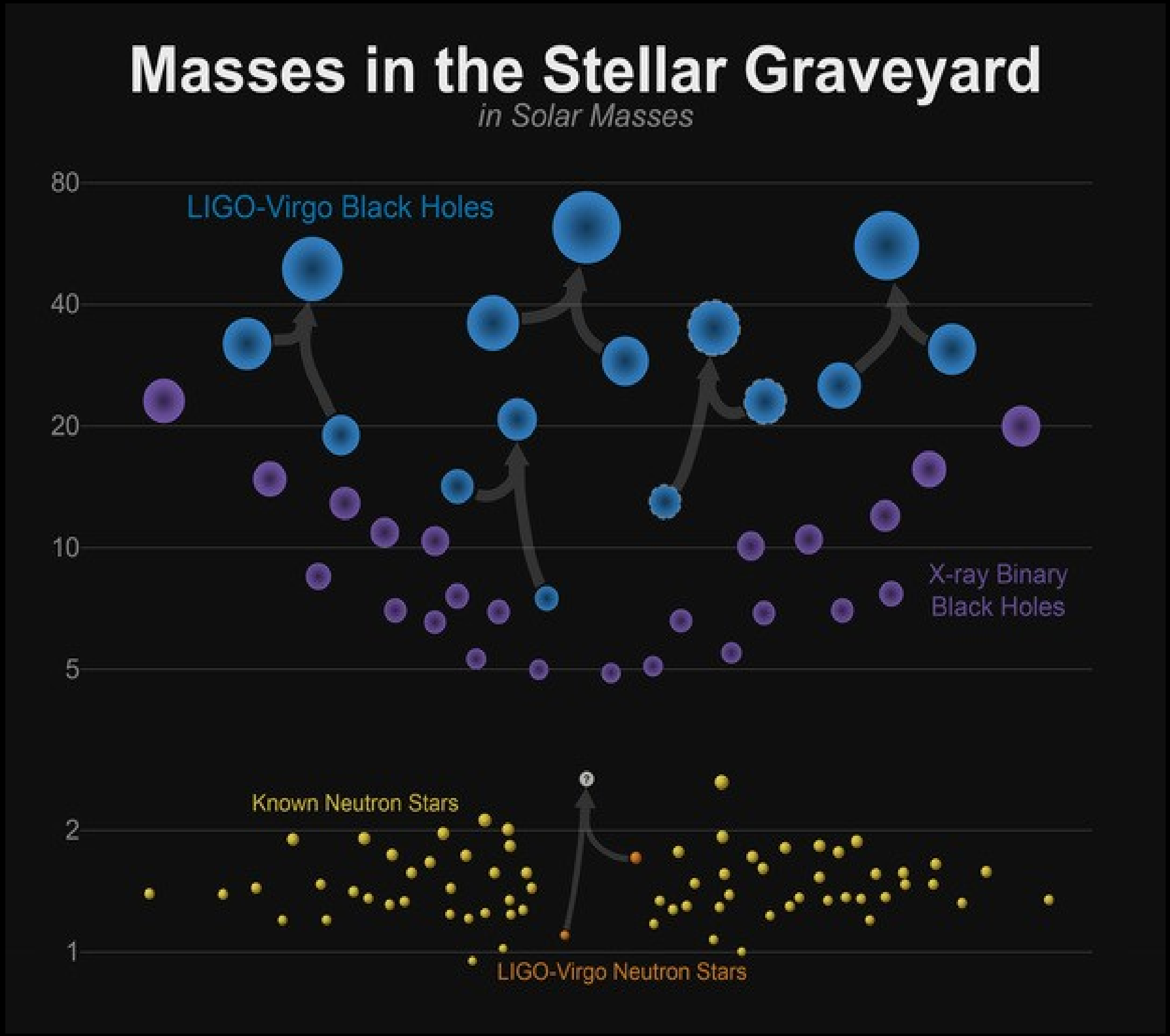
# Compact objects on binary systems



# GWs detection



# 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

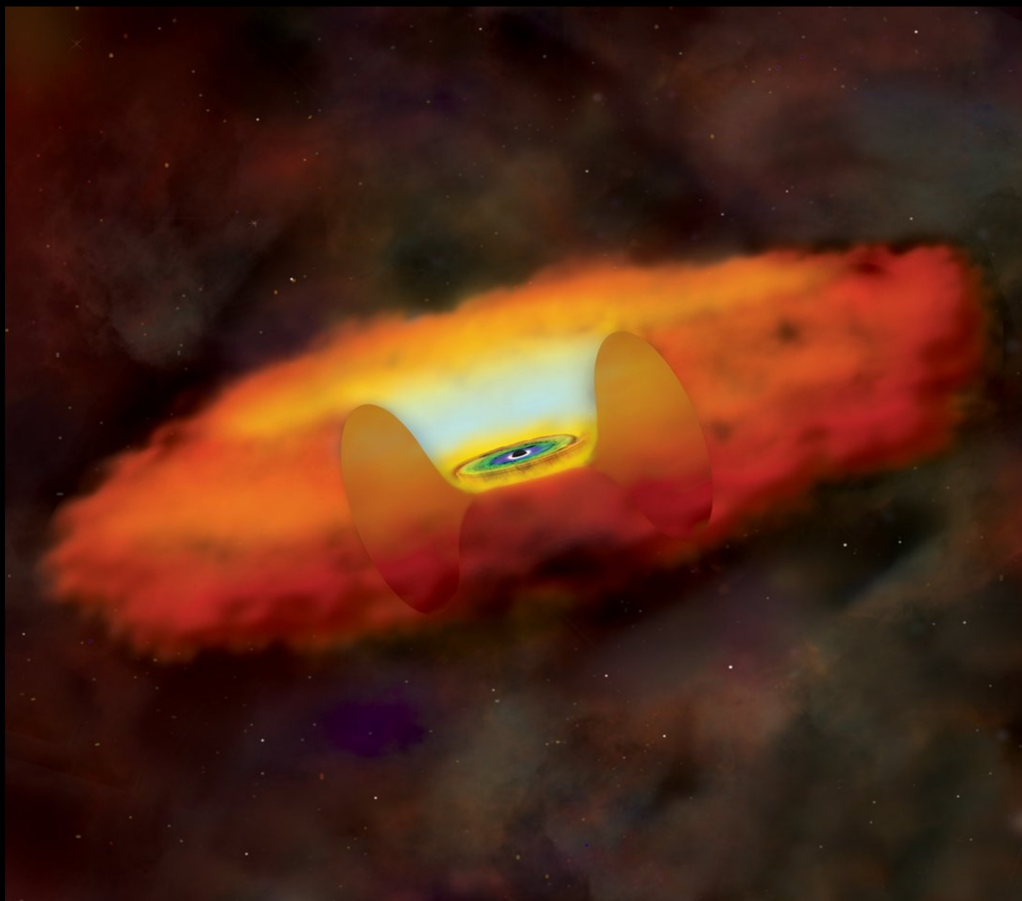
# Quasars

***Quasar*** is short for “quasi-stellar radio source,” as the first quasars visually looked like stars but were extremely far away and were emitting tremendous amount of energy.

Quasars are now recognized as active galactic nuclei, which are particularly bright galactic centers that are emitting more light, upwards of 1000 Milky Way galaxies.

The energy source of a quasar is theorized to be from a large accretion disk emitting intense radiation as matter from the disk spirals into a supermassive black hole.

# Example: Active galactic nucleus (AGN)



$M = 10^{8}\,M_{\odot}$

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

$E = GMm/R \approx 0.5\,mc^{2}$

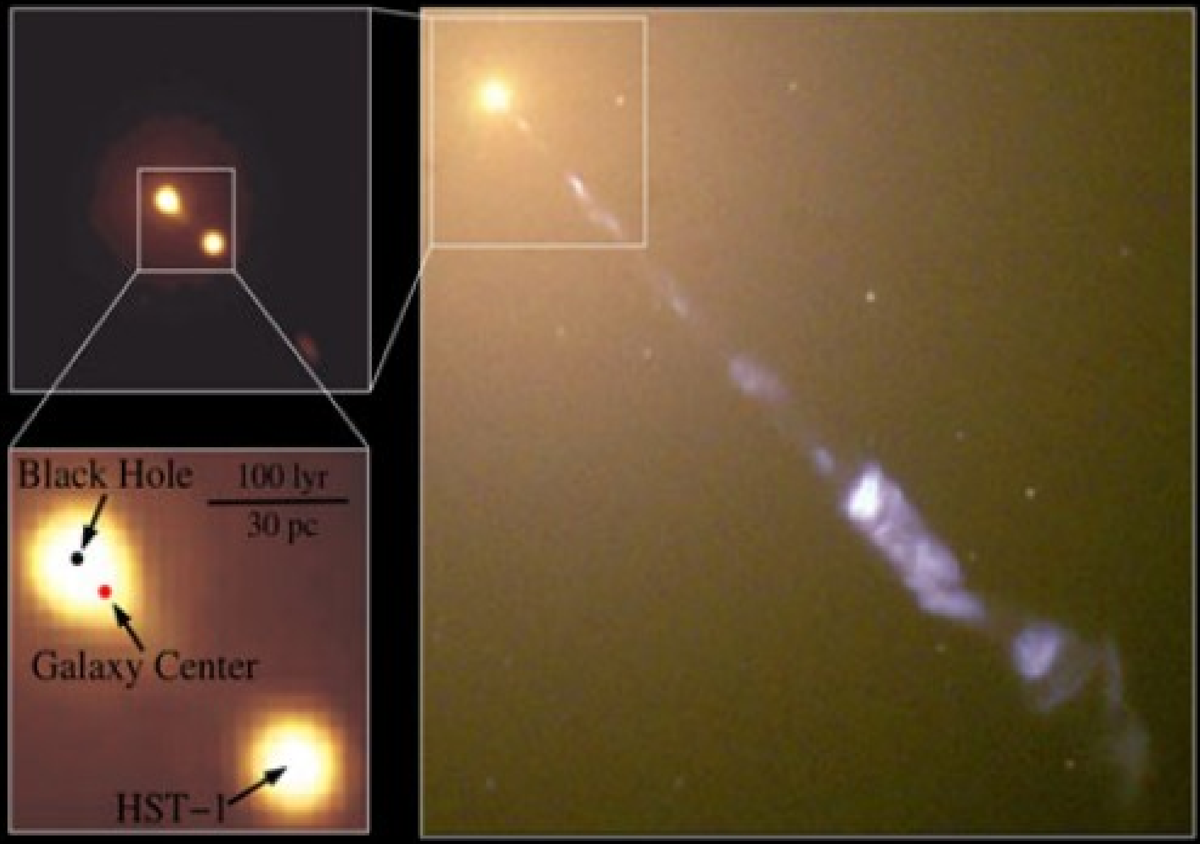
$m = 1\text{ g} \Rightarrow$

$E \approx 4 \times 10^{20}\text{ erg}$

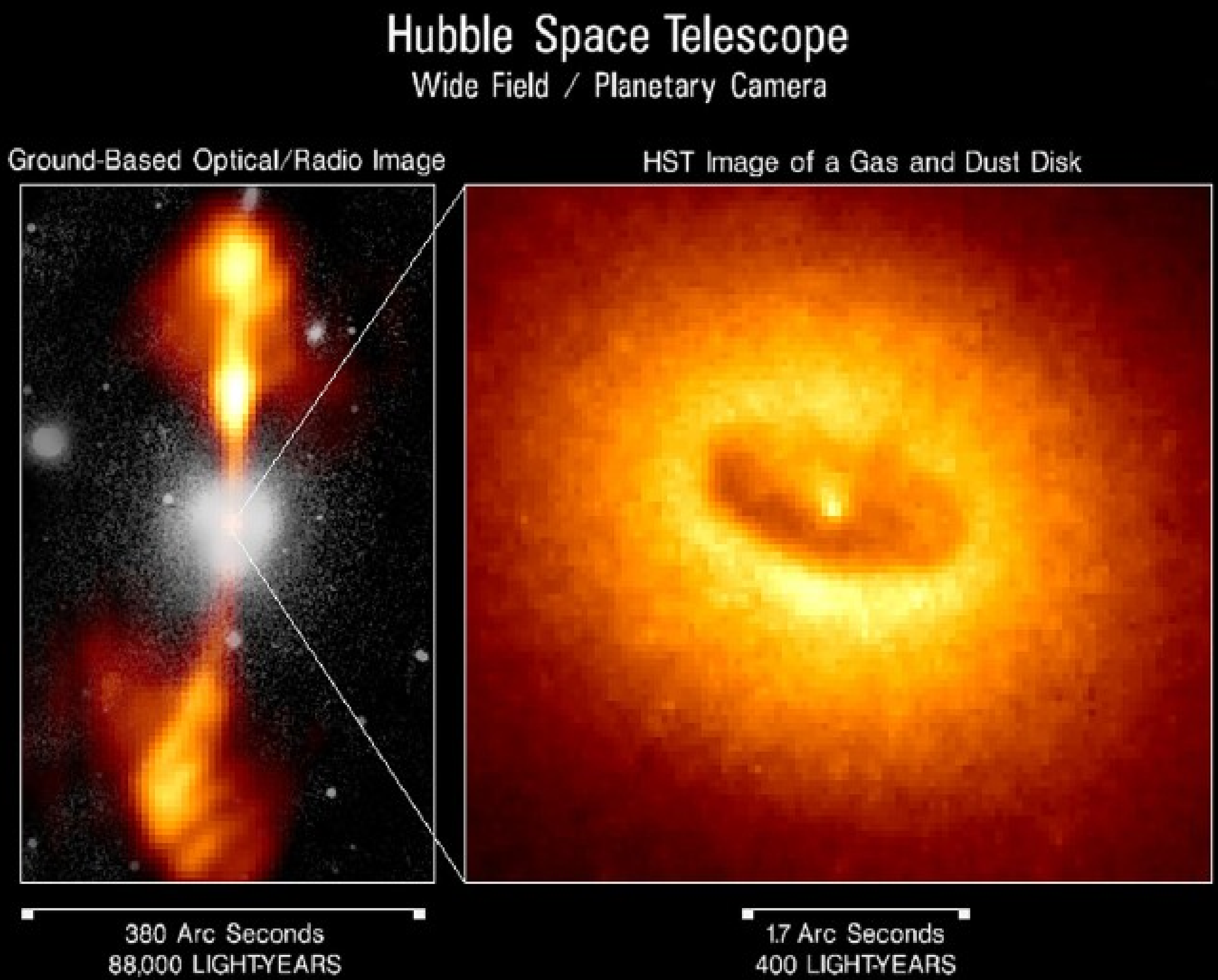
$\Rightarrow$ Are stellar BH as bright as AGN?!

# M 87

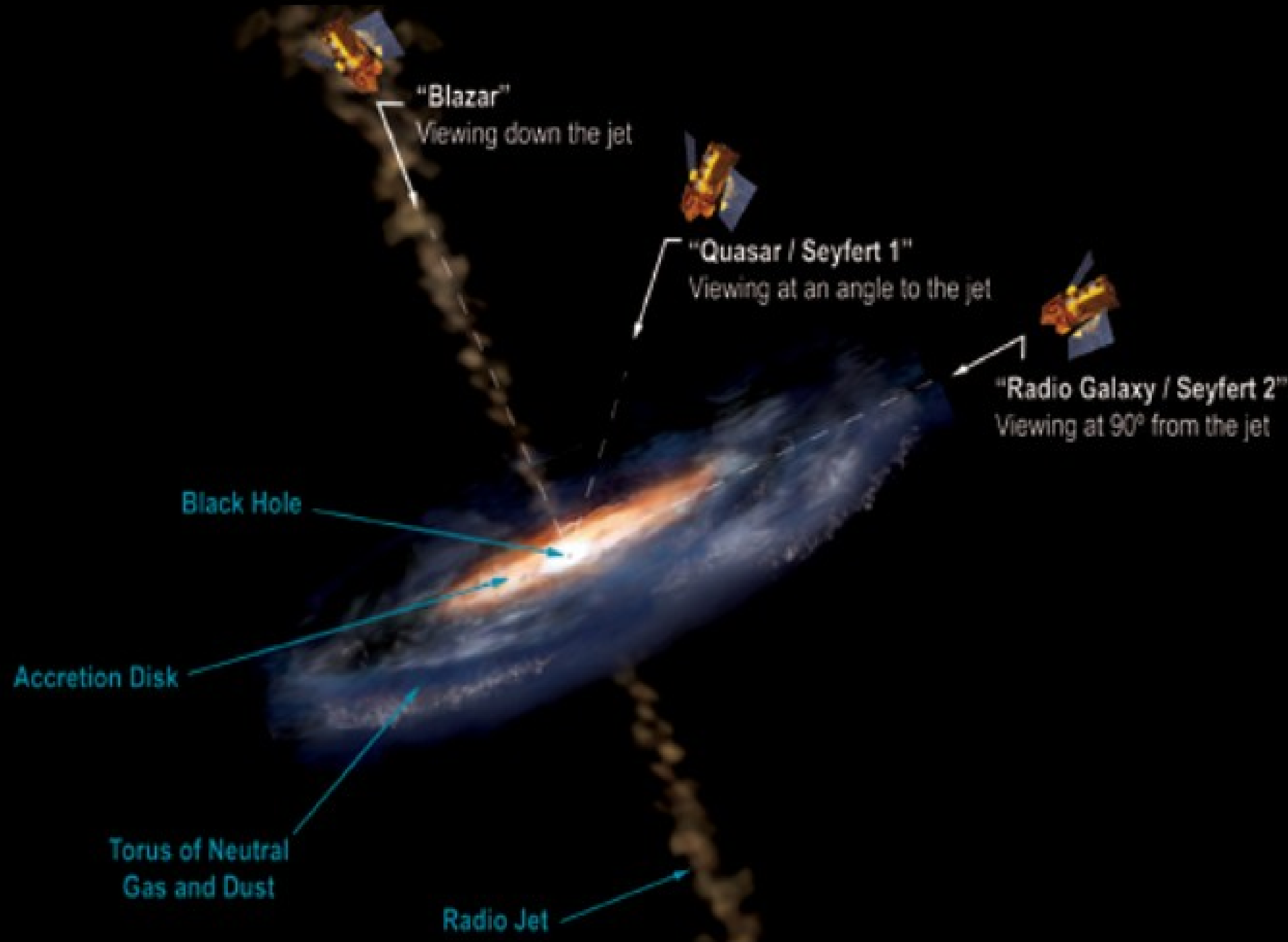
Accreting supermassive BHs (up to billions of Solar masses) at the center of galaxies

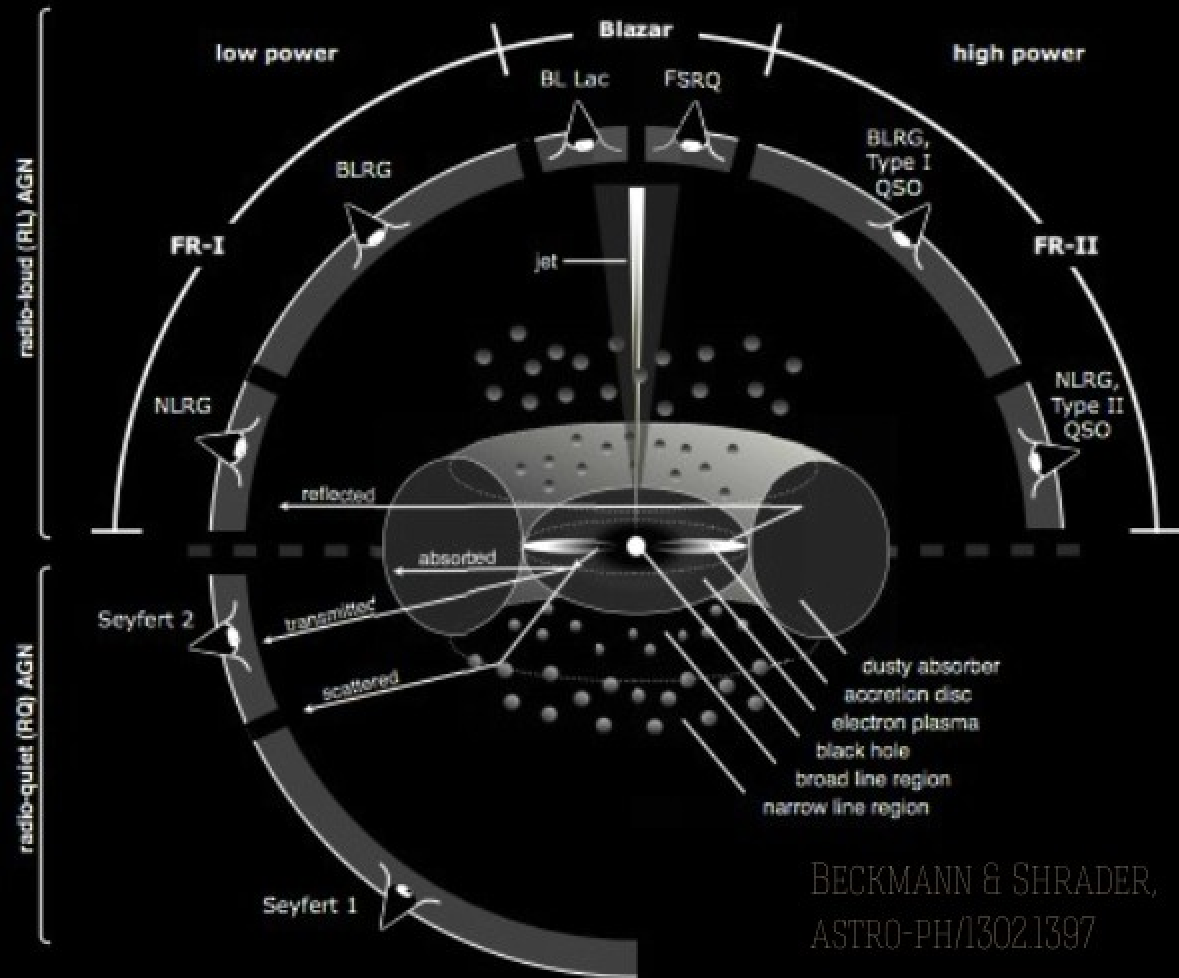


# NGC 4261



Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
380 Arc Seconds
88,000 LIGHT-YEARS
1.7 Arc Seconds
400 LIGHT-YEARS

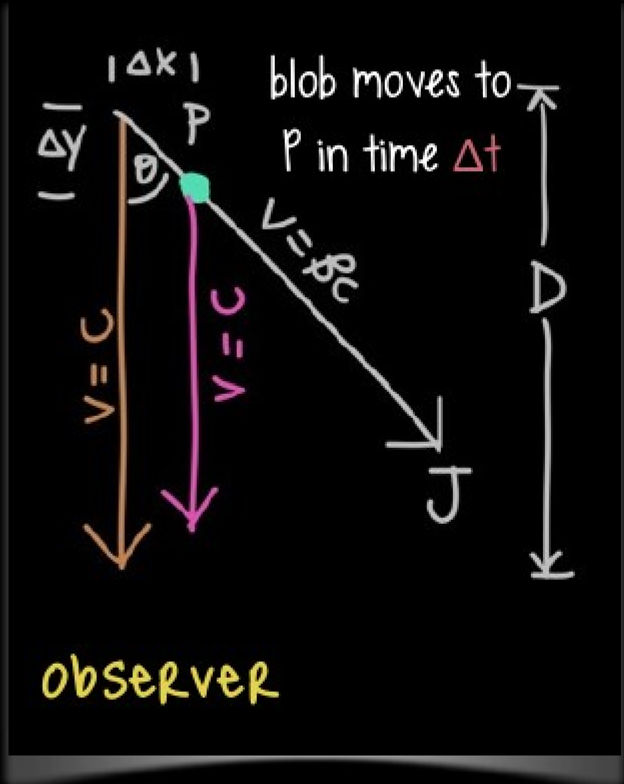

"Blazar"
Viewing down the jet
"Quasar / Seyfert 1"
Viewing at an angle to the jet
"Radio Galaxy / Seyfert 2"
Viewing at 90° from the jet
Black Hole
Accretion Disk
Torus of Neutral
Gas and Dust
Radio Jet




Beckmann & Shrader,
astro-ph/1302.1397

# Superluminal motion

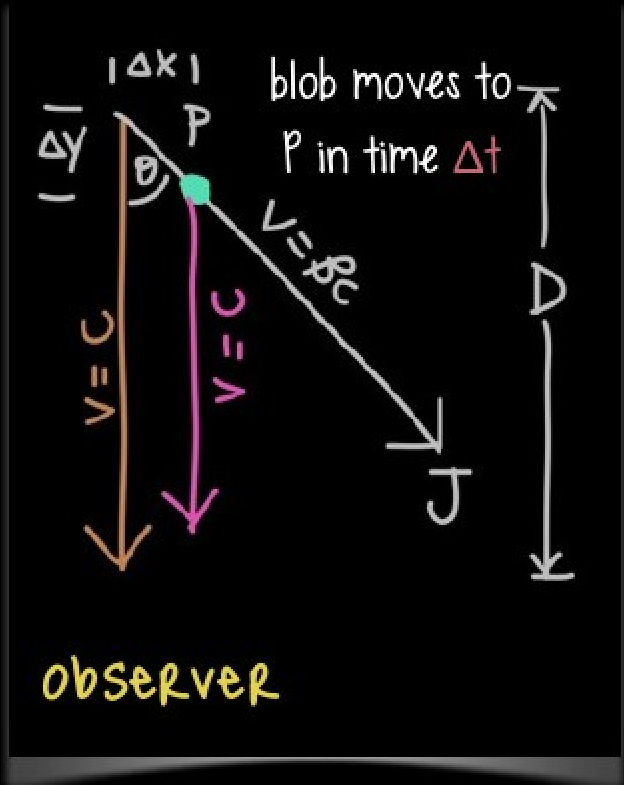
FIRST PROPOSED BY REES IN 1966 (NATURE, 211, 468) YEARS BEFORE IT WAS FIRST OBSERVED WHEN VLBI TECHNIQUES WERE DEVELOPED




first pulse travels to observer in time $D/c$; the second, emitted time $\Delta t$ later, has a shorter distance to travel: $D-\Delta y$. Difference in arrival time is:

$$\Delta t_{obs} = \left[\Delta t + \frac{(D-\Delta y)}{c}\right] - \left[\frac{D}{c}\right]$$

# Superluminal motion




Difference in arrival time is:

$$\Delta t_{obs} = \left[\Delta t + \frac{(D - \Delta y)}{c}\right] - \left[\frac{D}{c}\right]$$

substitute for $\Delta y$ & rearrange:

$$\Delta t_{obs} = \Delta t\,(1 - \beta\cos\theta)$$

measured transverse velocity, $v_{obs}$

$$v_{obs} = \frac{\Delta x}{\Delta t_{obs}} = \frac{\beta c \sin\theta}{(1 - \beta\cos\theta)}$$

therefore:

$$\beta_{obs} = \frac{\beta \sin\theta}{(1 - \beta\cos\theta)}$$

## Superluminal motion

So, if the plasma velocity was 0.95c and the angle to the observer was 5deg, the apparent velocity would be 1.5c. The effect is maximised when $\cos\theta = \beta$

$$\beta_{obs} = \frac{\beta \sin\theta}{(1 - \beta\cos\theta)}$$

## Relativistic beaming

- Another relativistic effect occurs because the knots of plasma are moving at velocities close to that of light
- When an emitting plasma has a bulk relativistic motion relative to a fixed observer, its emission is beamed in the forward direction in the fixed frame
- The flux density is thus changed by relativistic time dilation so an observer sees much more intense emission than if the plasma were at rest
- The observed emission, $S_{obs}$ is boosted in energy over that emitted in the rest frame, $S$

**Definitions:**

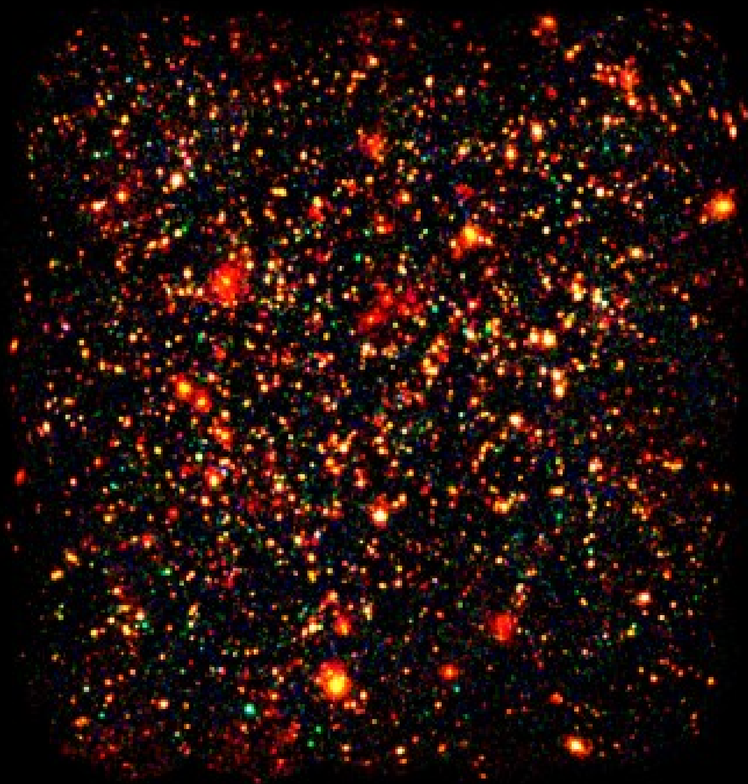
The Doppler factor is a measure of the strength of the beaming: $\delta = [\Gamma(1-\beta\cos\theta)]^{-1}$

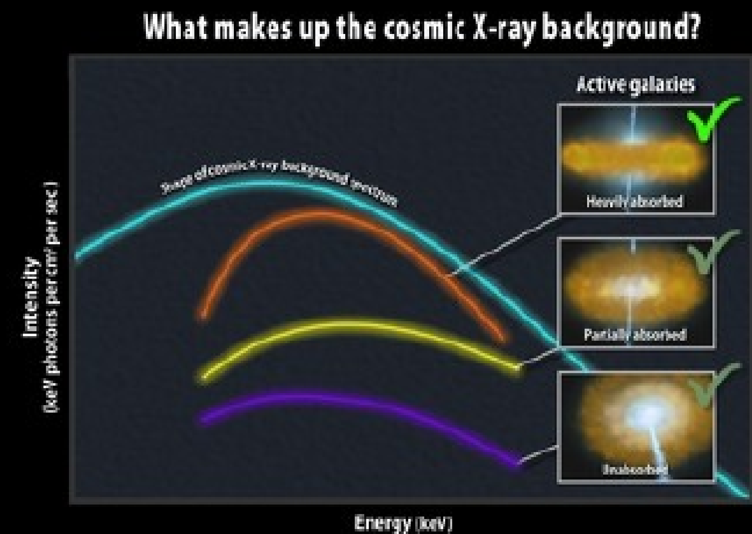
The Lorenz factor: $\Gamma = \frac{1}{\sqrt{1-\beta^2}}$ where $\beta = \frac{v}{c}$

$$S_{obs} = S[\Gamma(1-\beta\cos\theta)]^{-3}$$

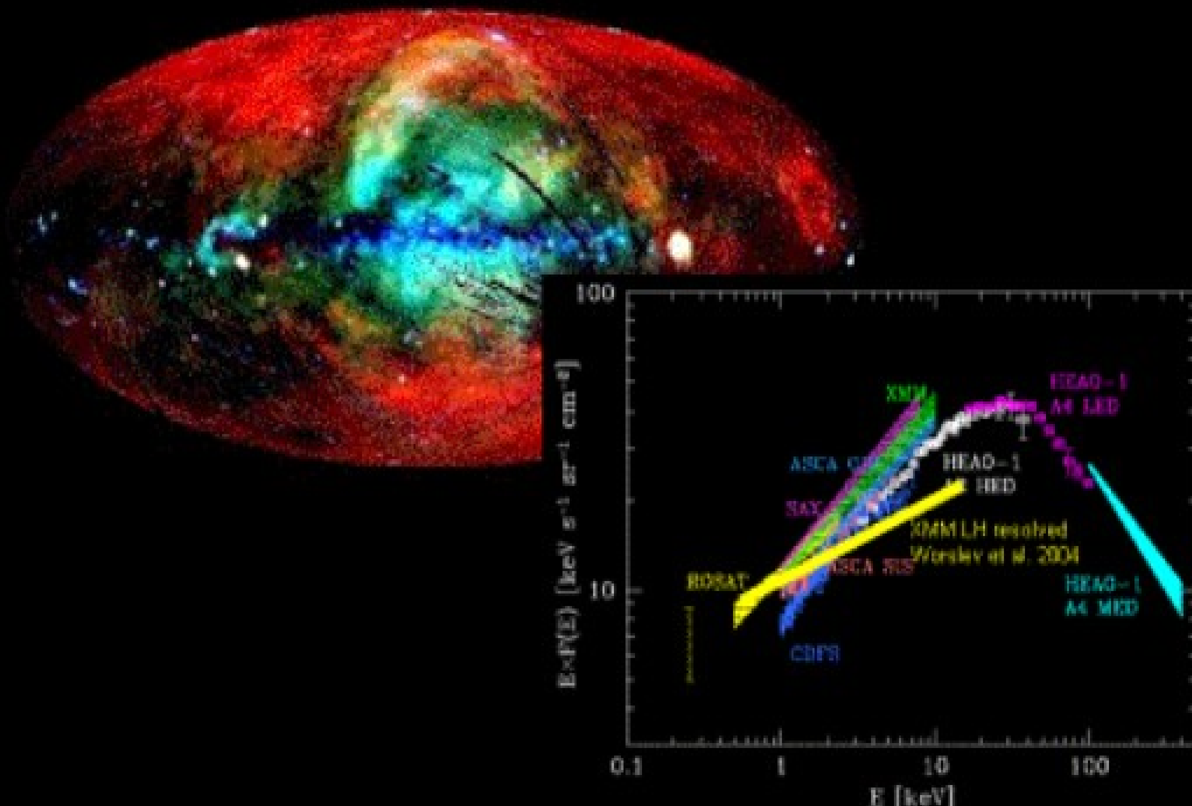
If plasma velocity is 0.95c and θ is 5deg, the boosting factor will be ~198

# CBX



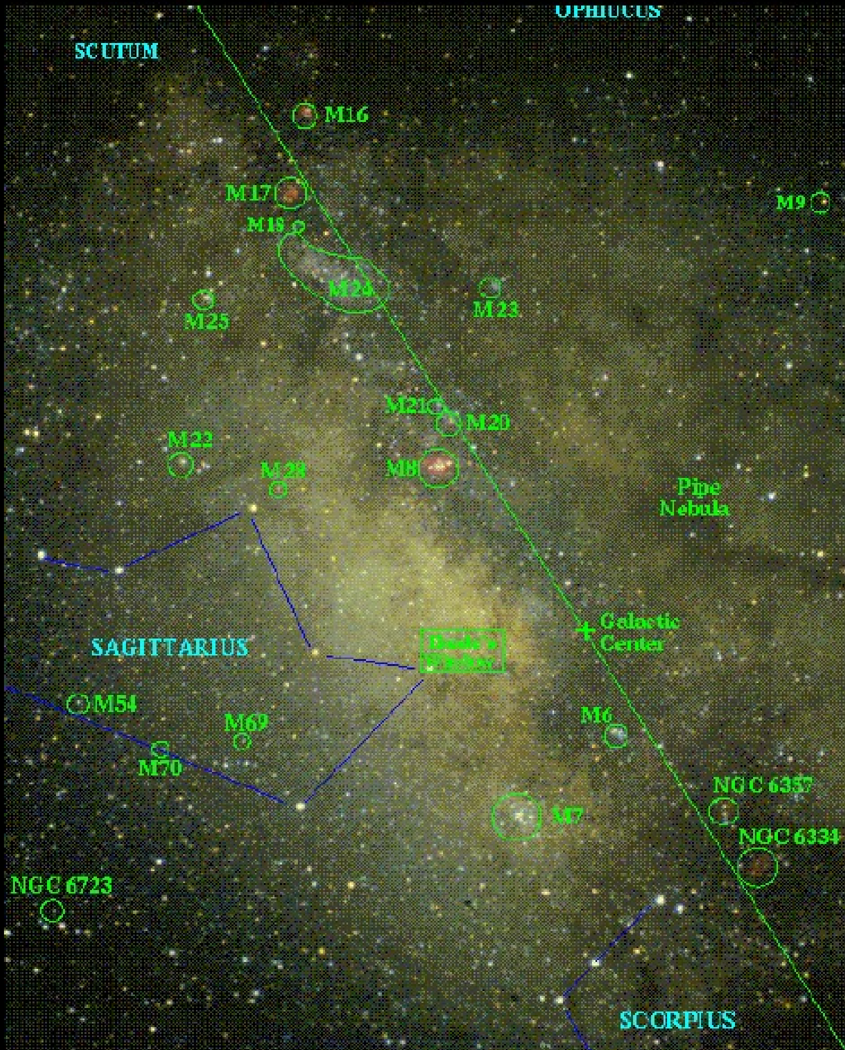



CXB is due to unresolved X-ray emission from distant AGNs




Removing discrete X-ray sources, residual diffuse emisssion

# Sgr A*




Center of our galaxy:
radio source Sgr A*

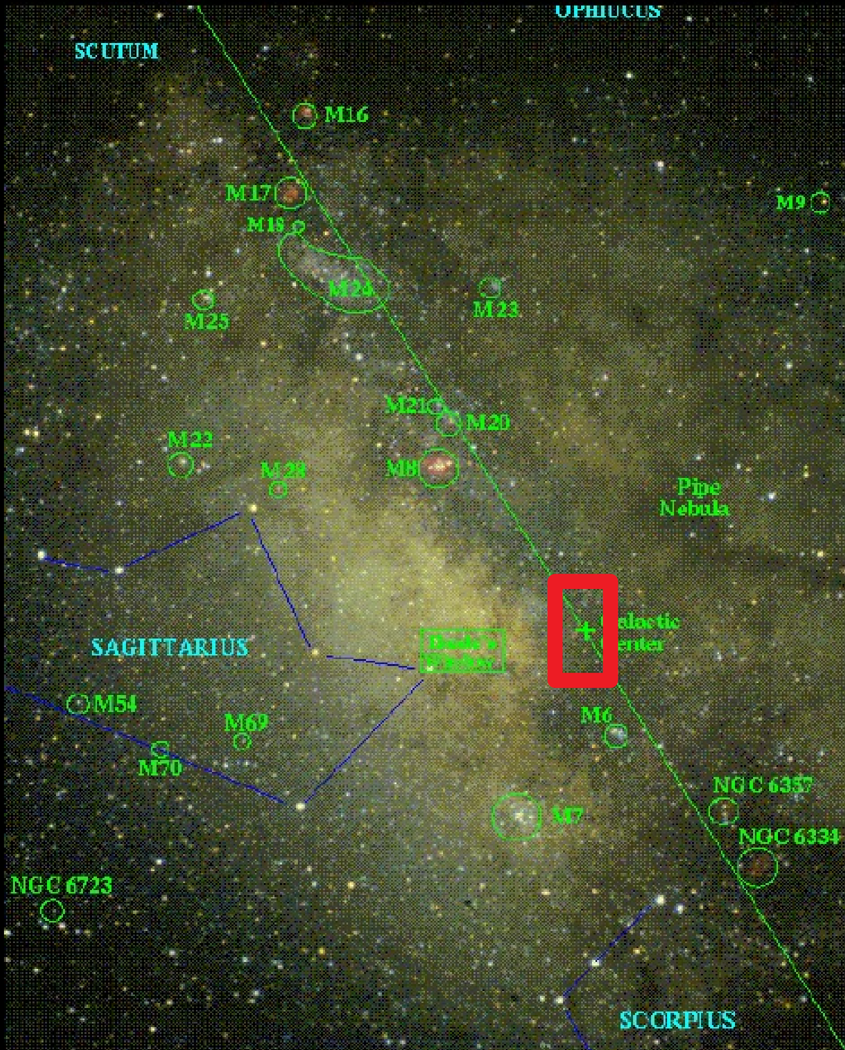
Distance: 8 kpc

Highly obscured in
optical

Dense central star
cluster visible in infrared

Photo/illustration from A. Tanner, UCLA

# Sgr A*

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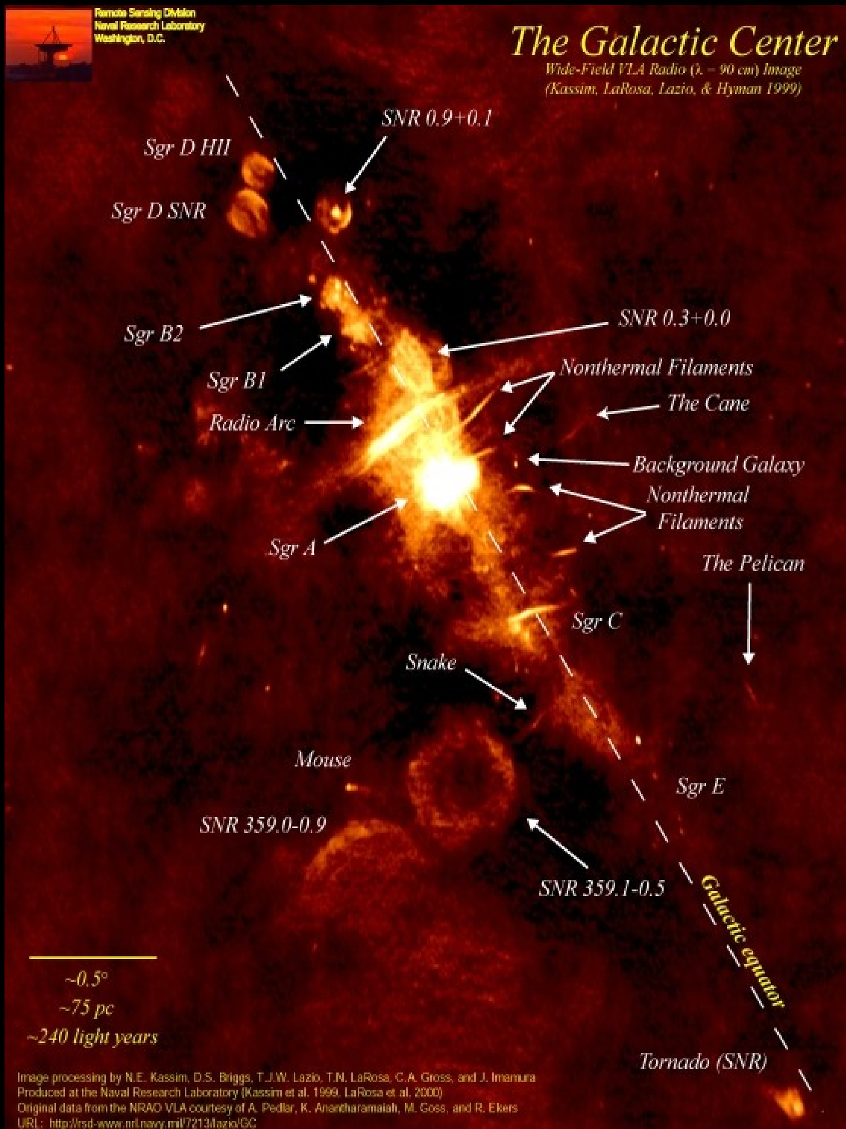


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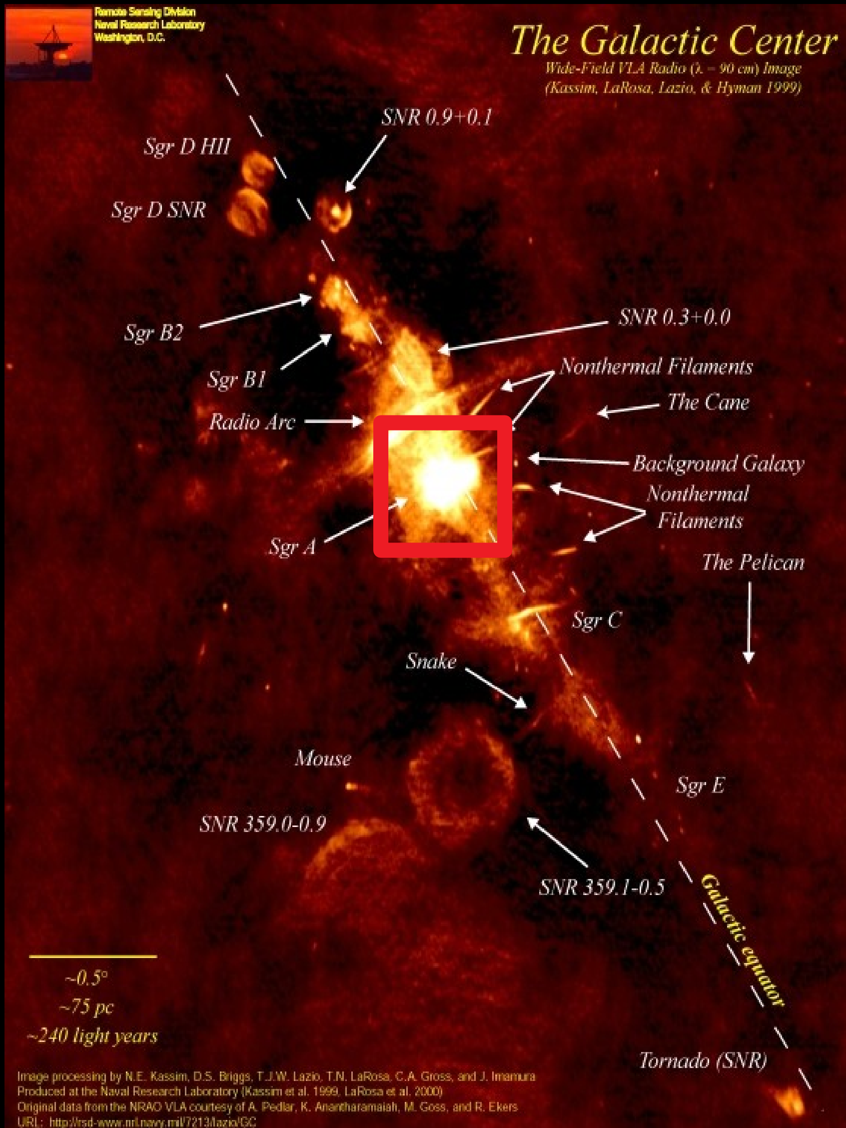


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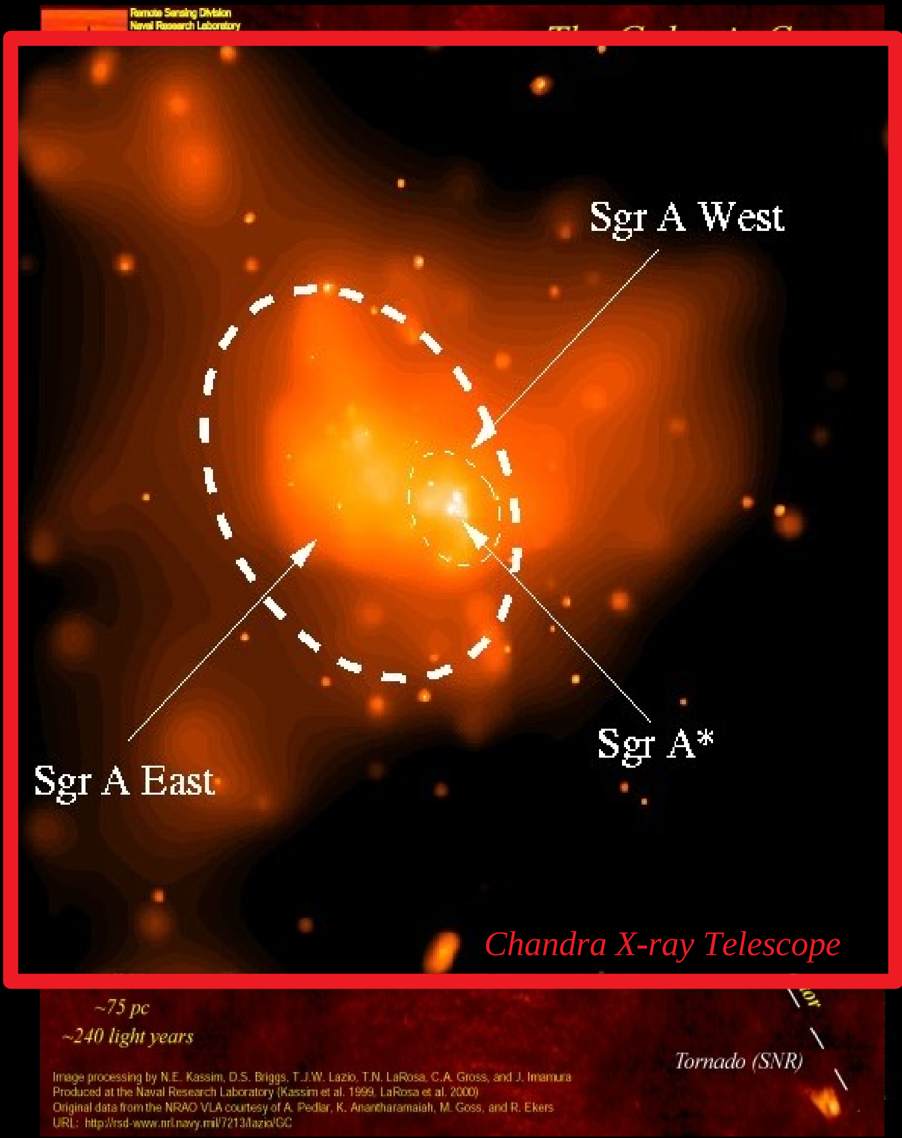


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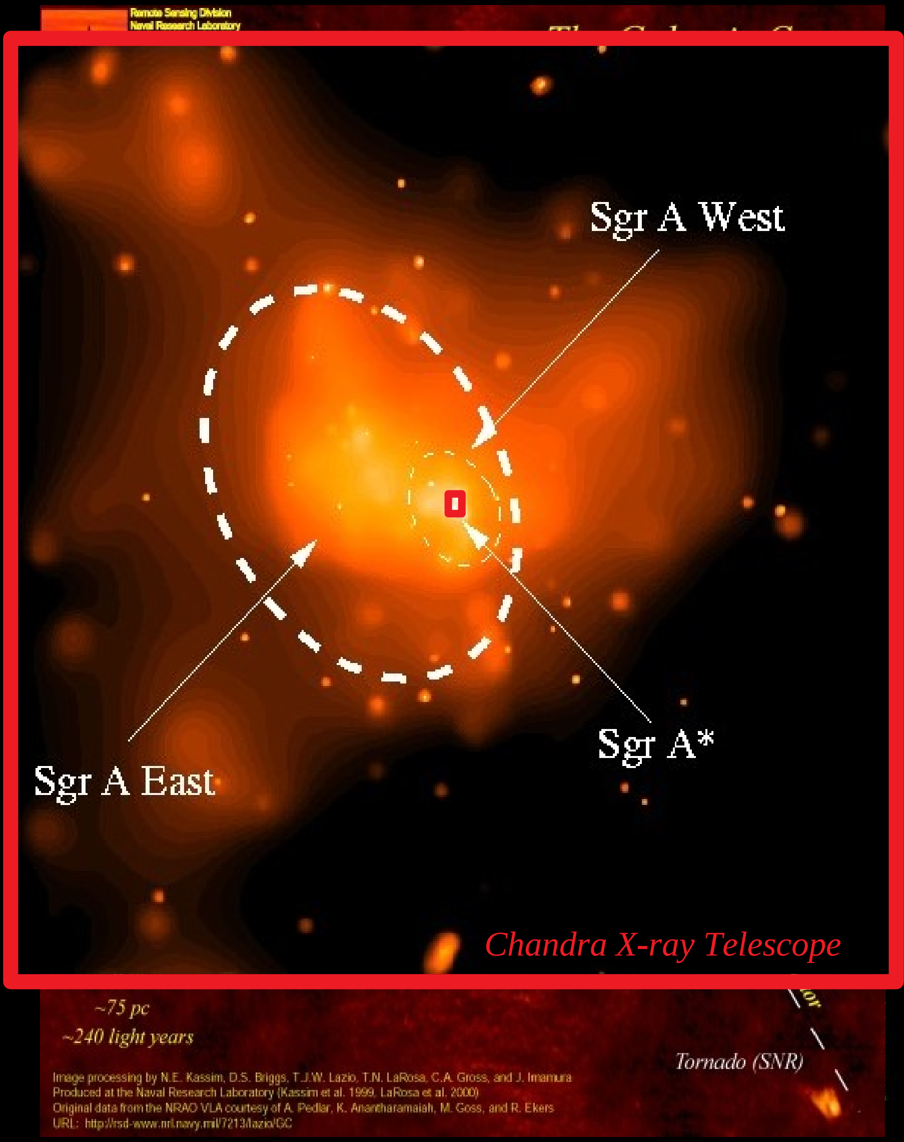



Center of our galaxy: radio source Sgr A*

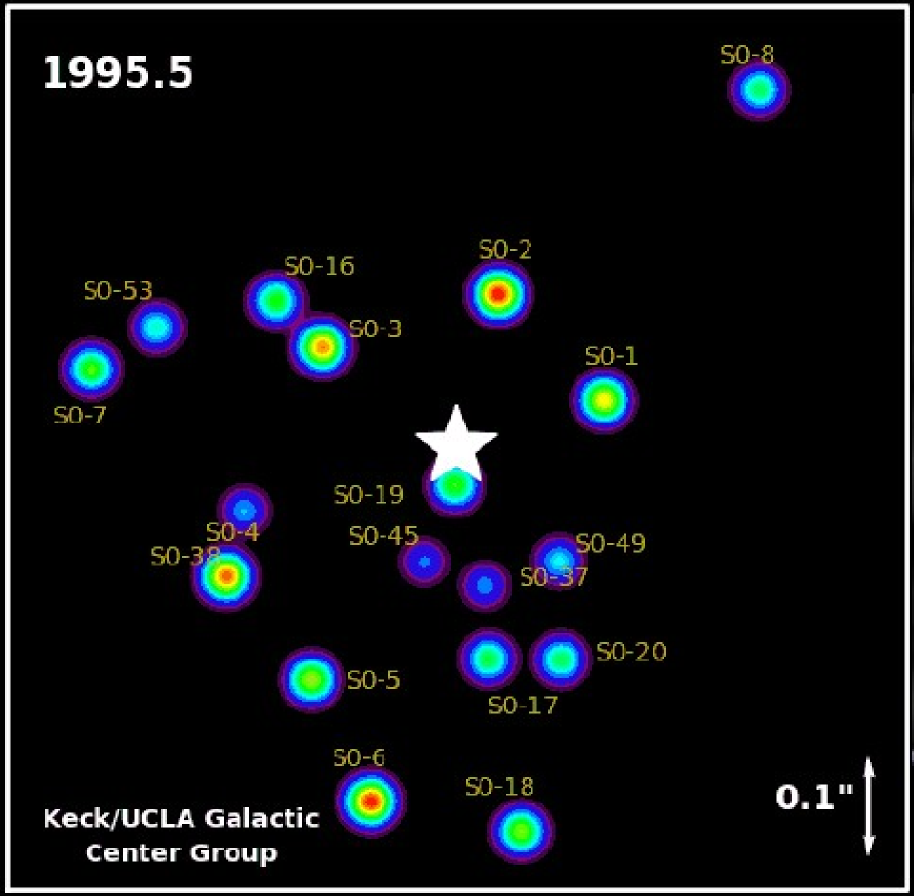
Distance: 8 kpc

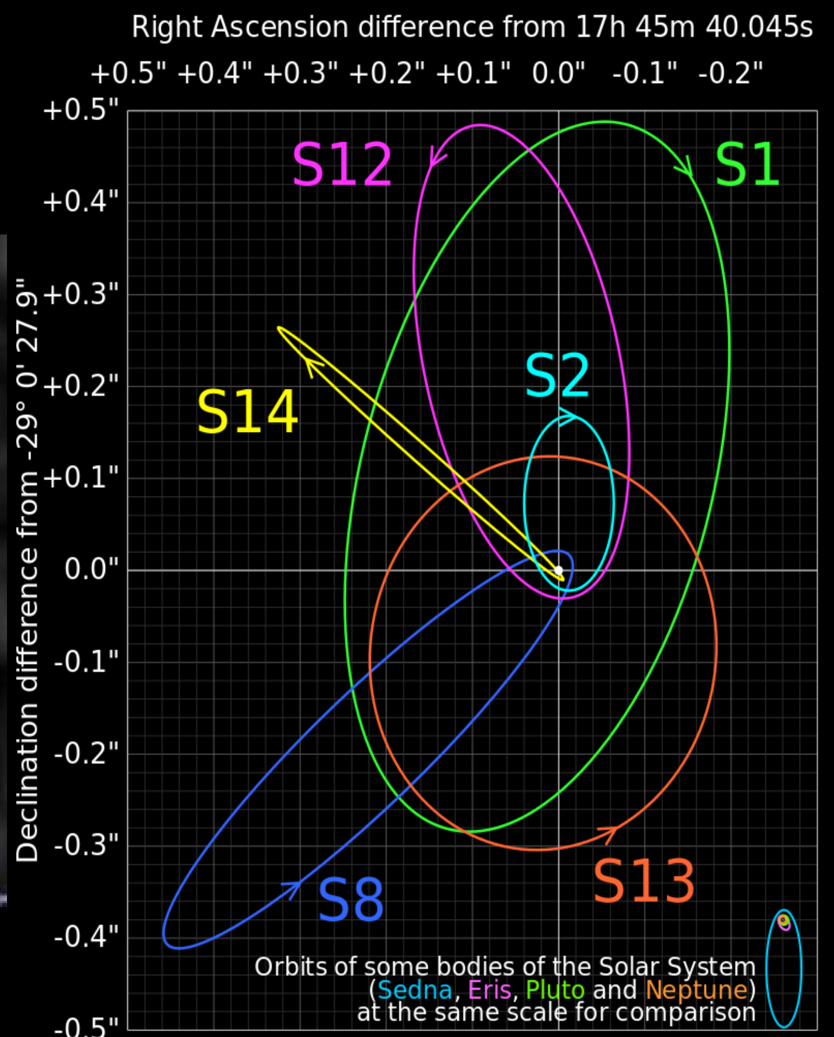
Highly obscured in optical

Dense central star cluster visible in infrared

Photo/illustration from A. Tanner, UCLA

# 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

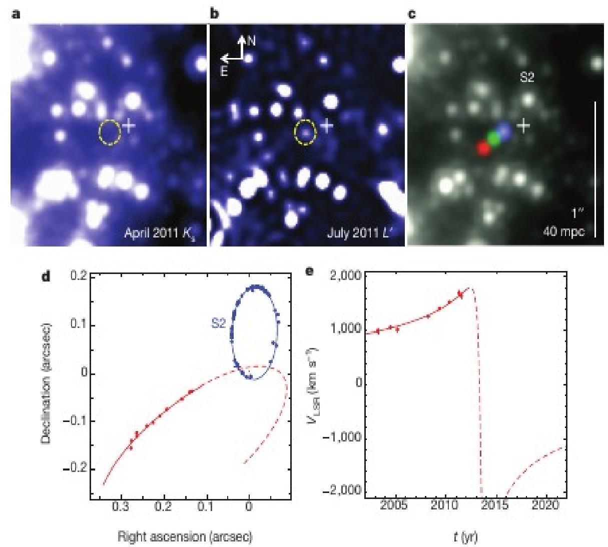
# LETTER

*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.**



# 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

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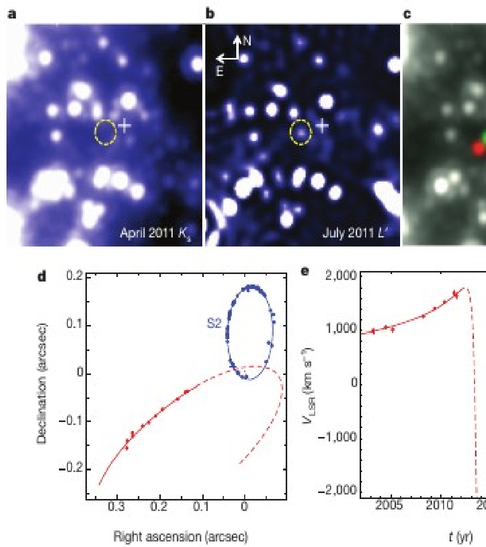
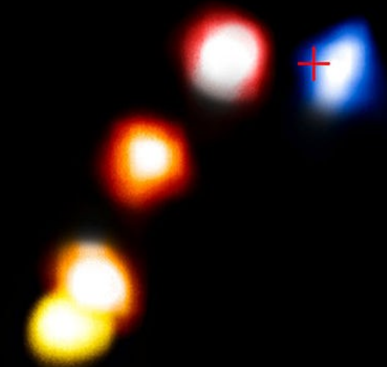
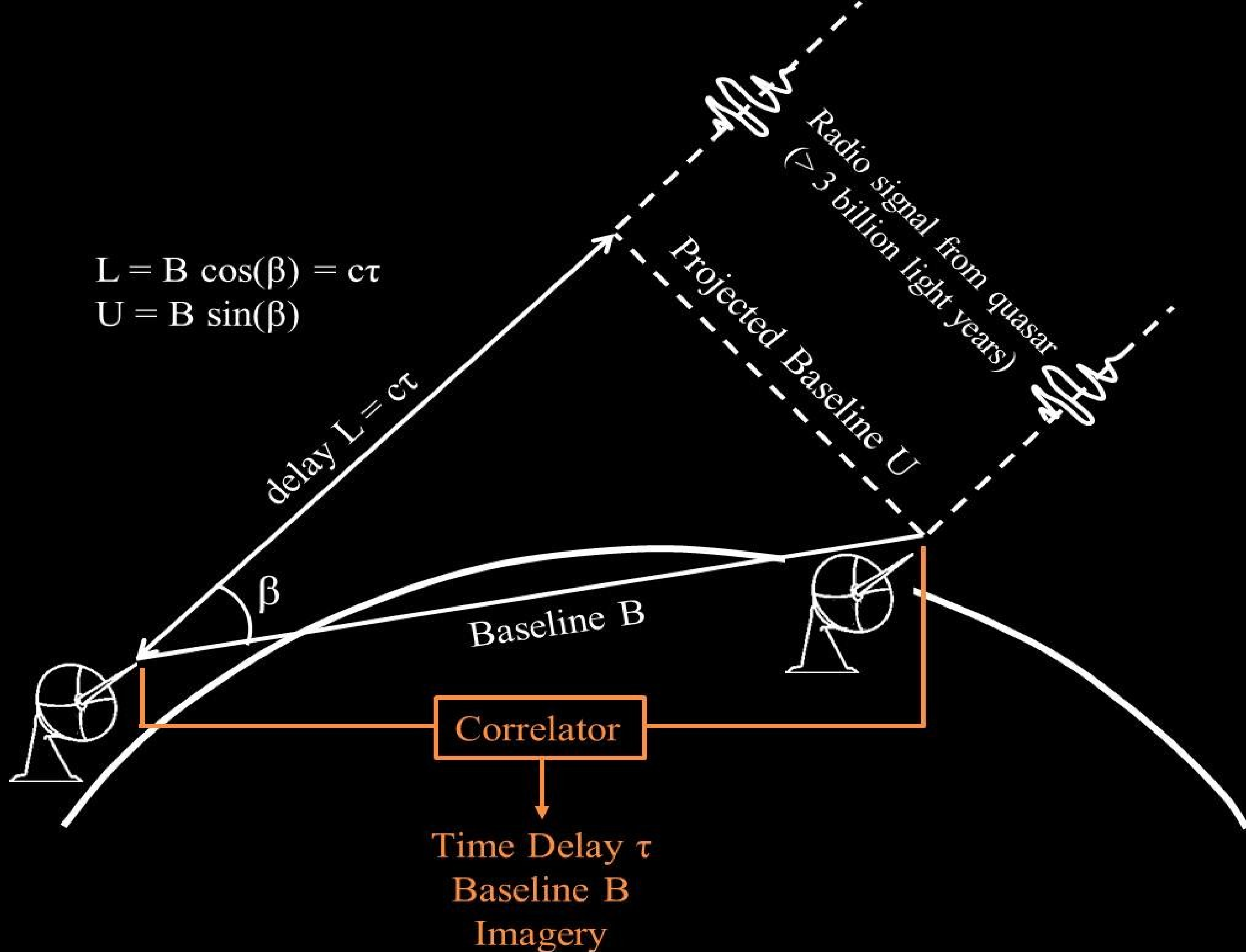
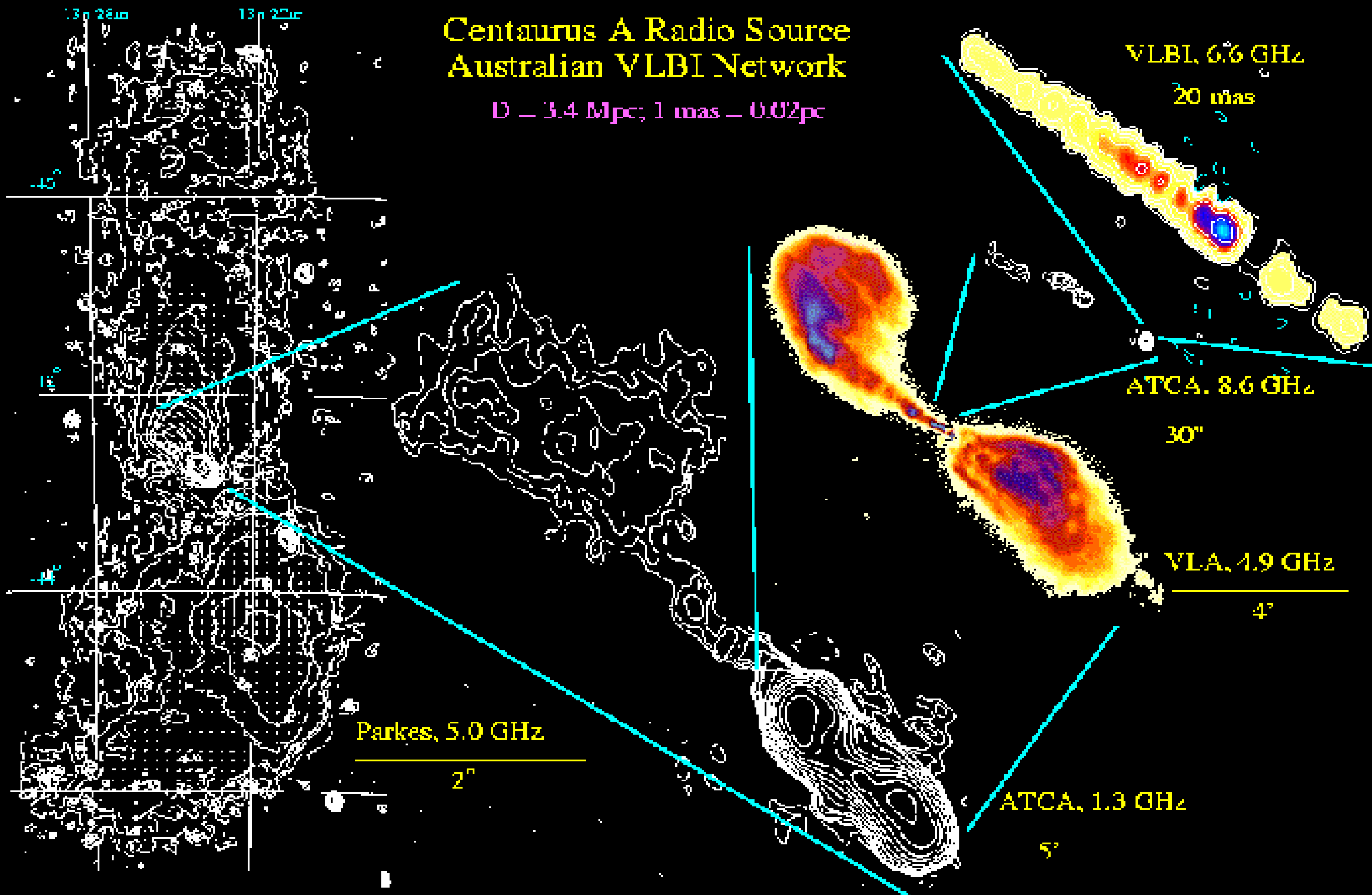


...and in 2015



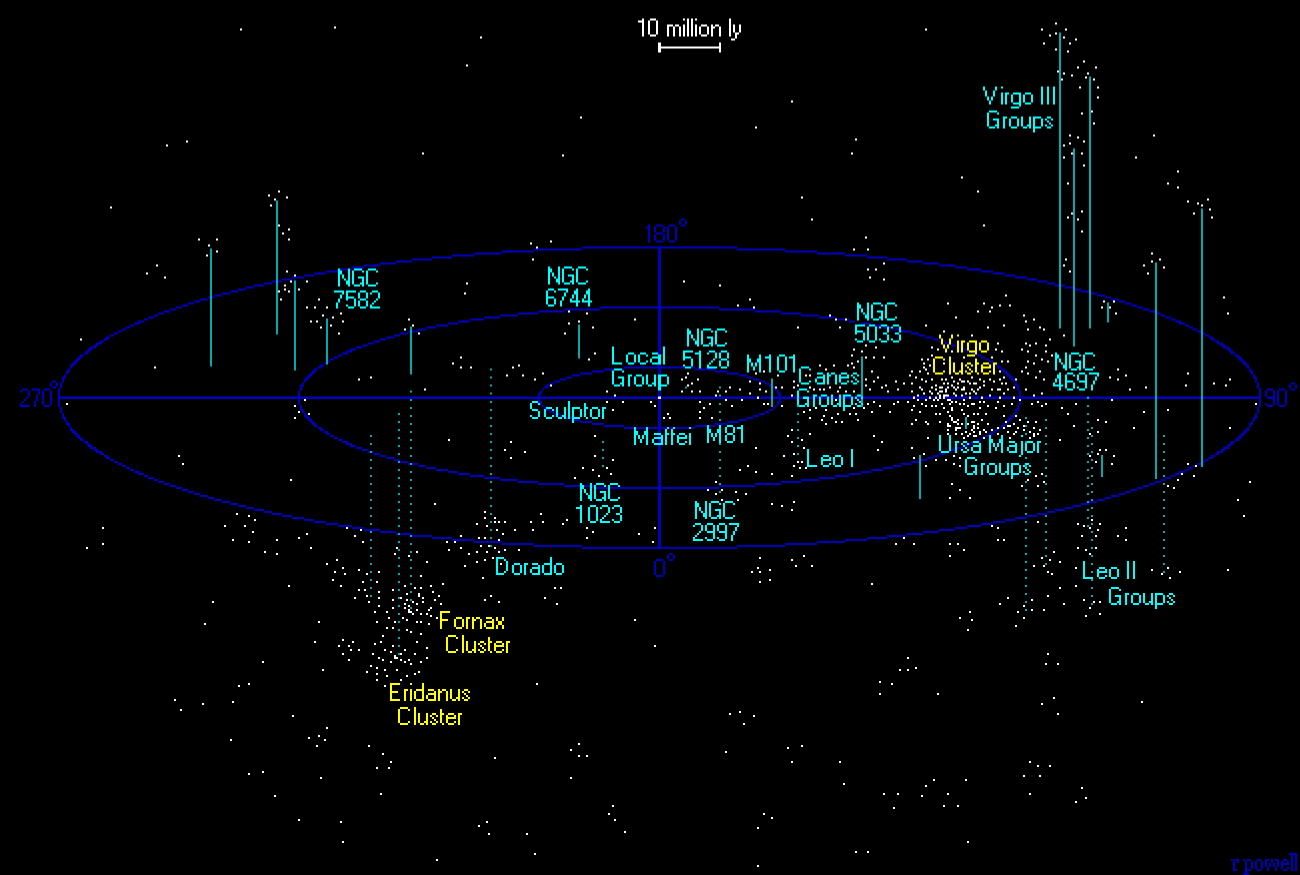
$L = B\cos(\beta) = c\tau$
$U = B\sin(\beta)$
delay $L = c\tau$
Radio signal from quasar
(> 3 billion light years)
Projected Baseline U
$\beta$
Baseline B
Correlator
Time Delay $\tau$
Baseline B
Imagery

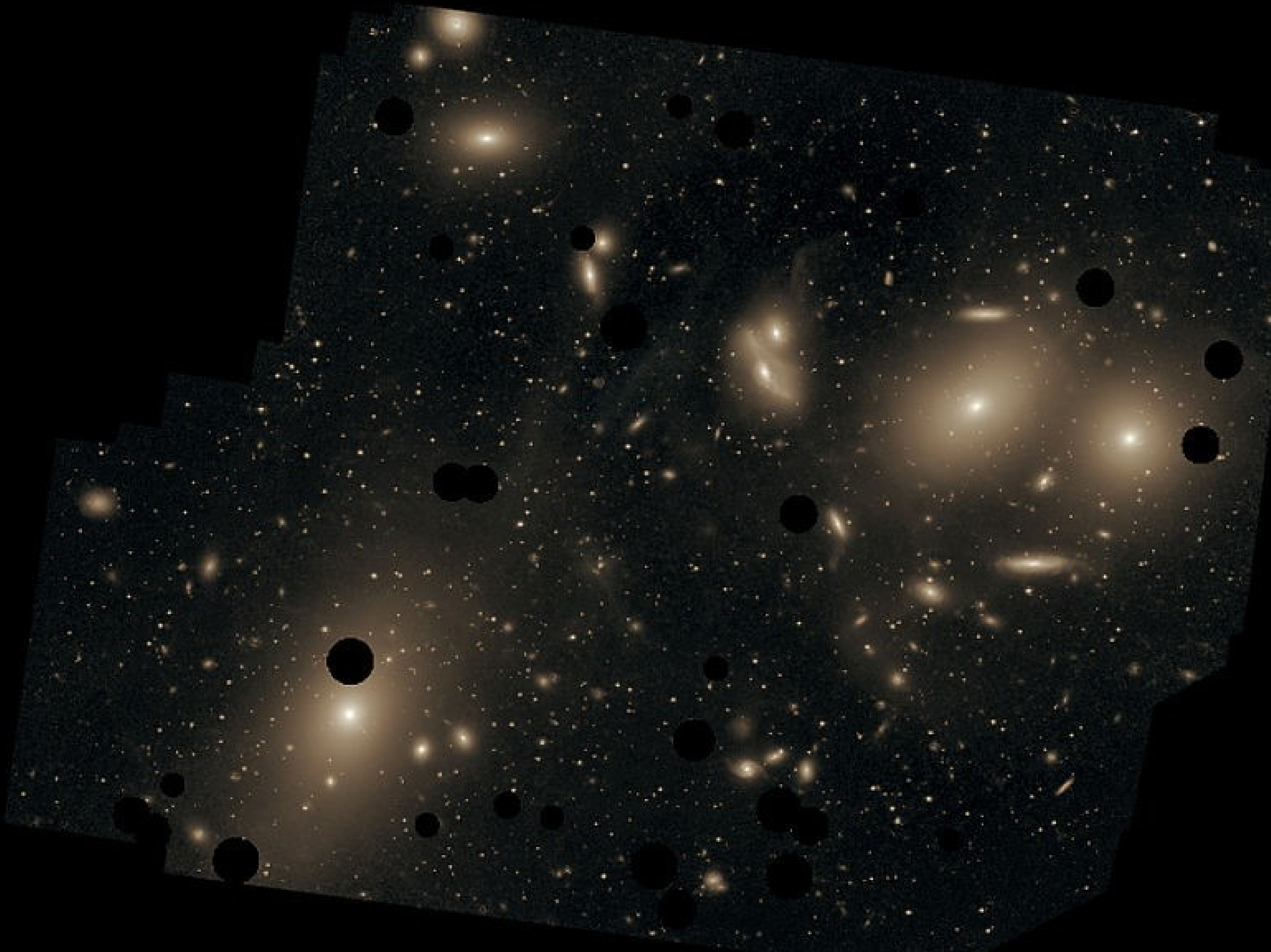


Centaurus A Radio Source
Australian VLBI Network
D = 3.4 Mpc; 1 mas = 0.02pc
VLBI, 6.6 GHz
20 mas
ATCA, 8.6 GHz
30"
VLA, 4.9 GHz
4'
ATCA, 1.3 GHz
5'
Parkes, 5.0 GHz
2°

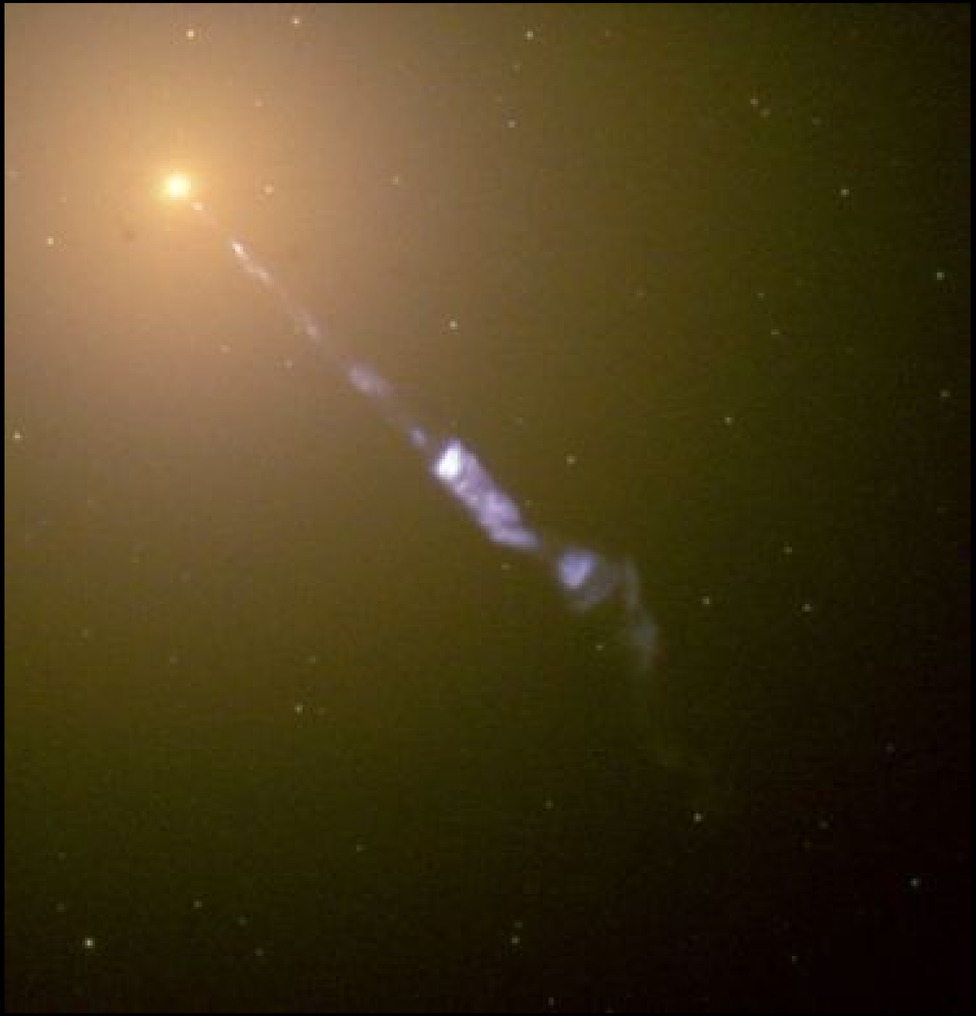
# Galaxy center

# Virgo Supercluster

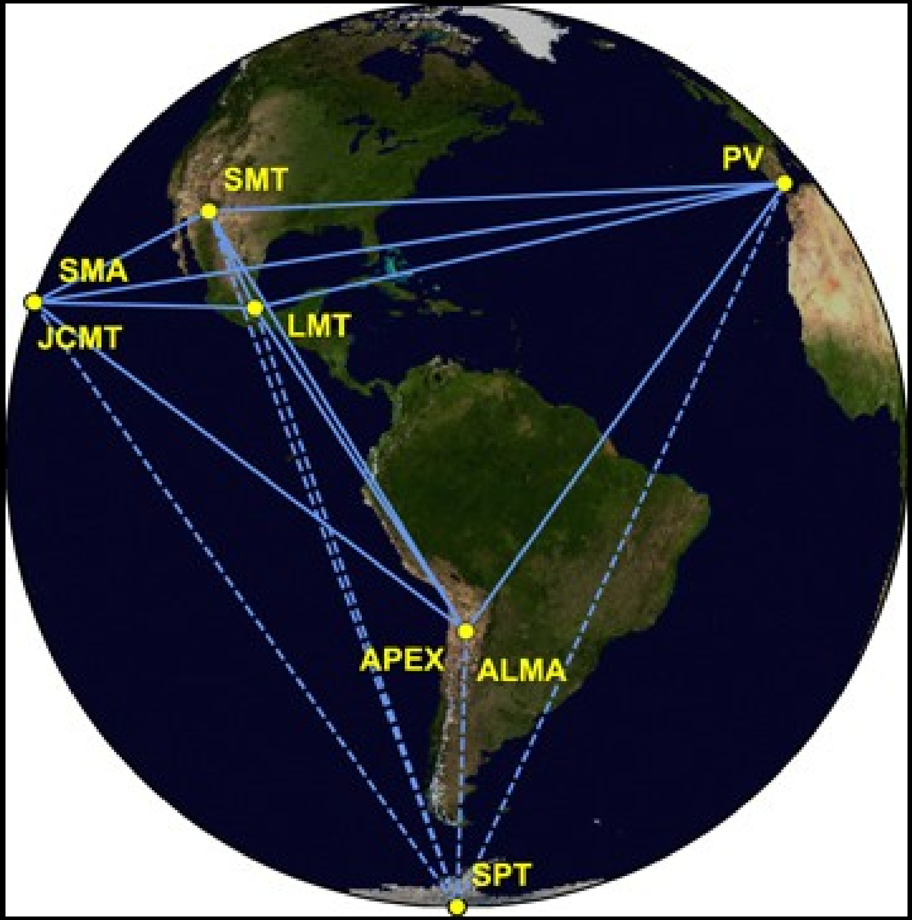


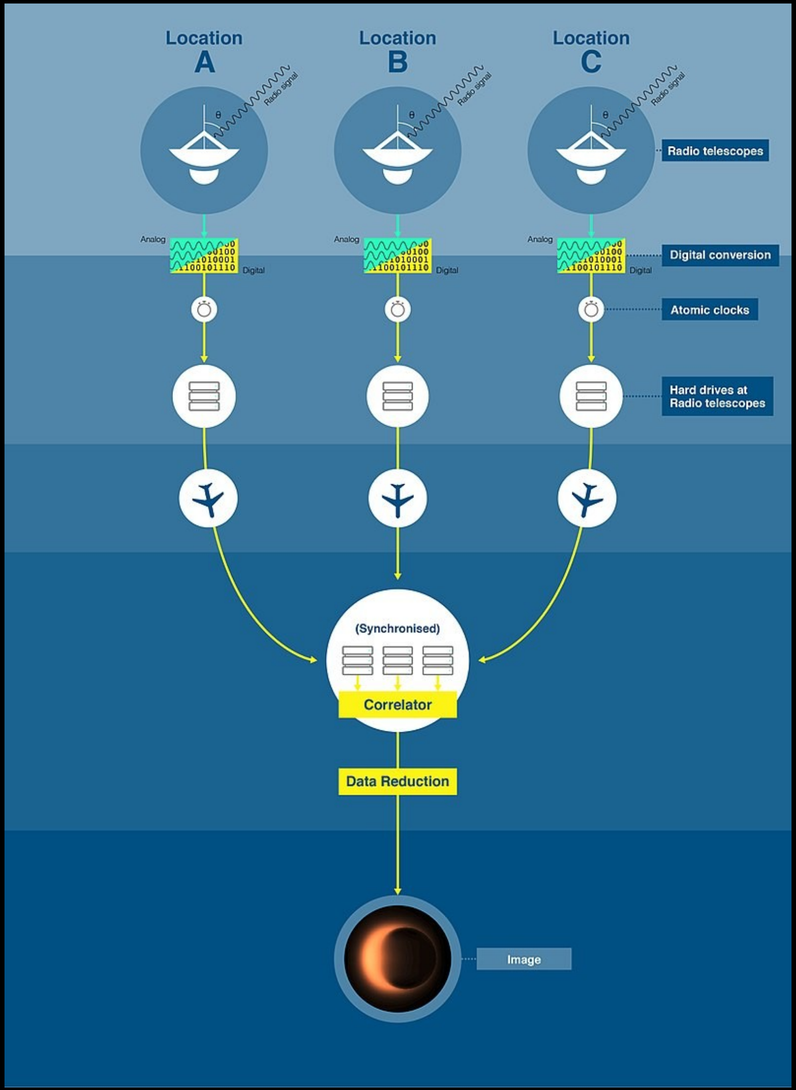


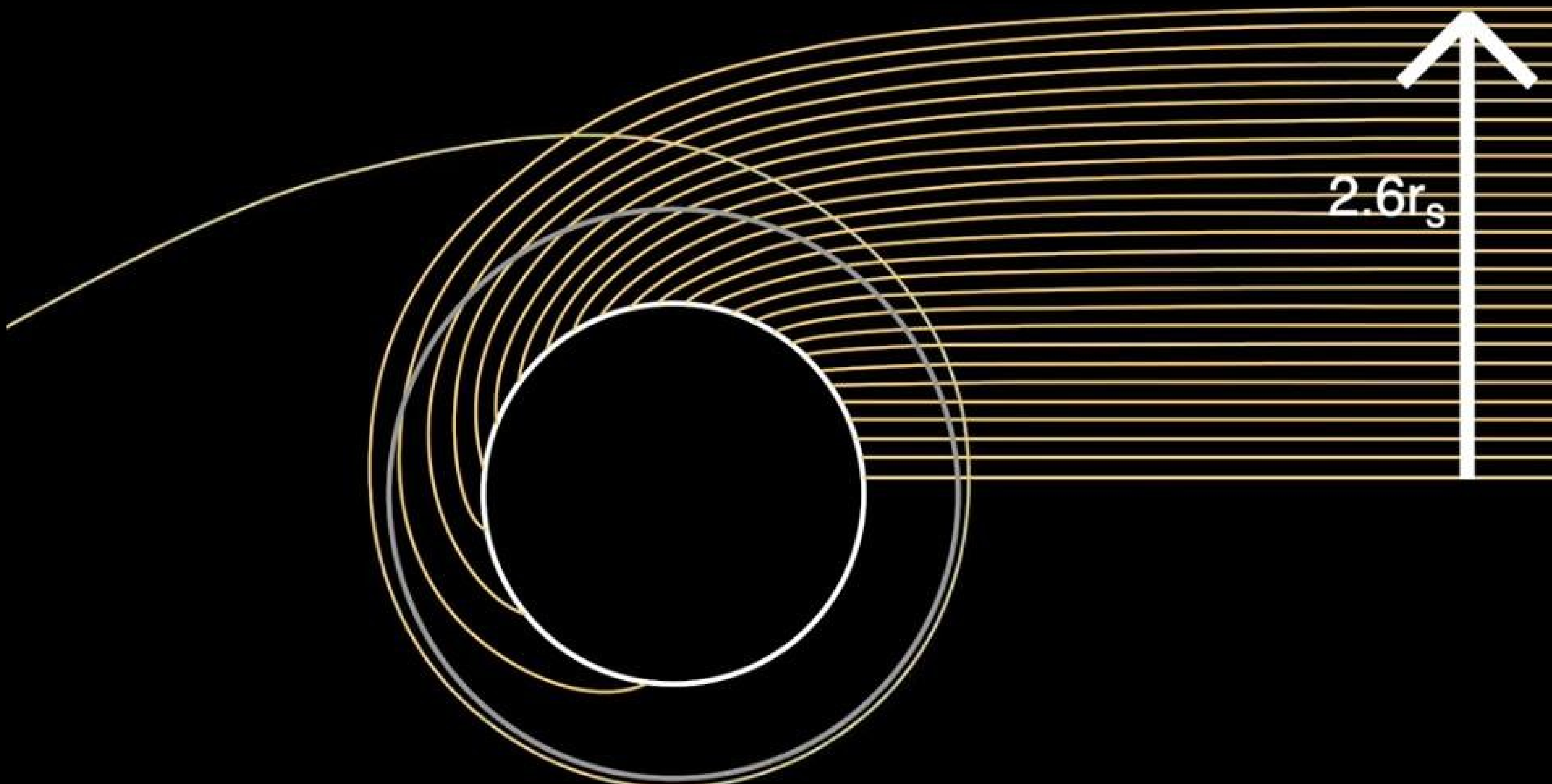
# M 87

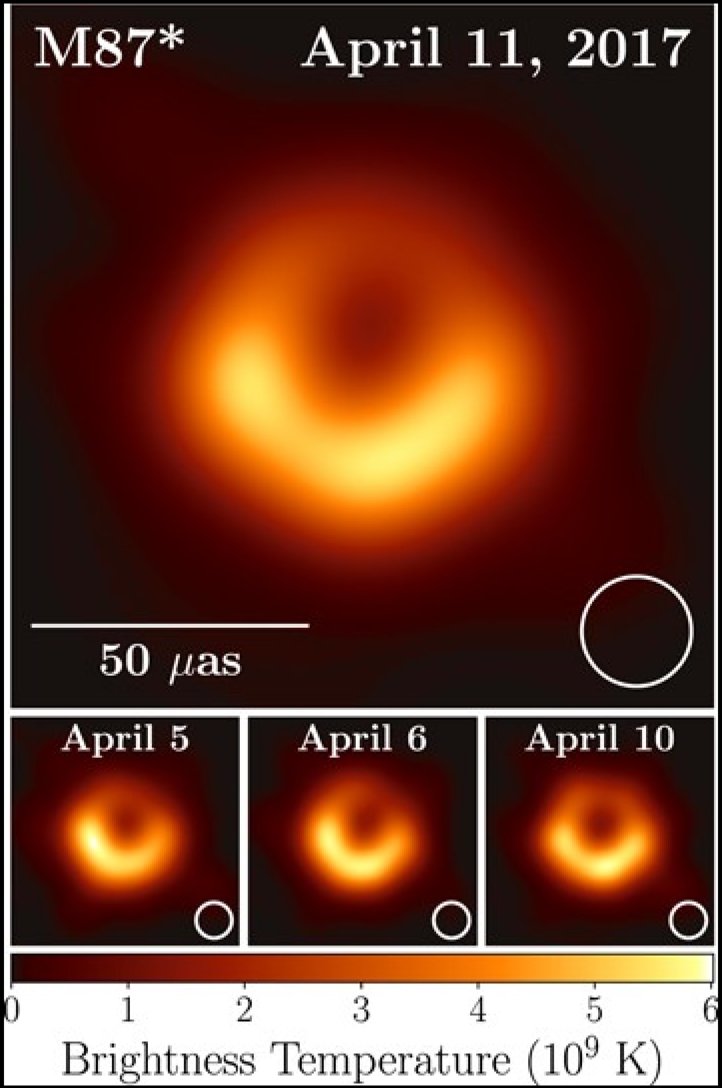


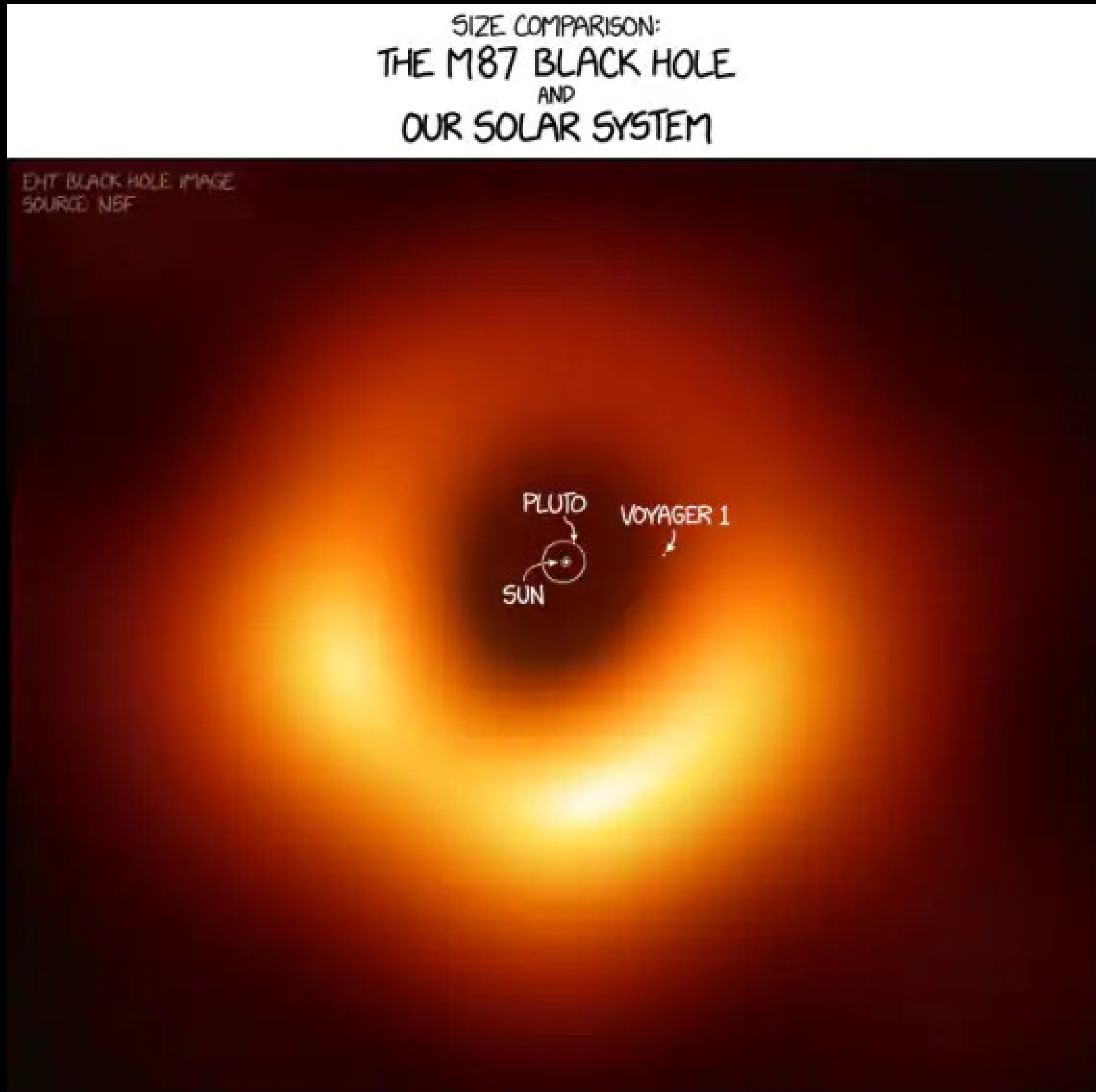
# Event Horizon Telescope

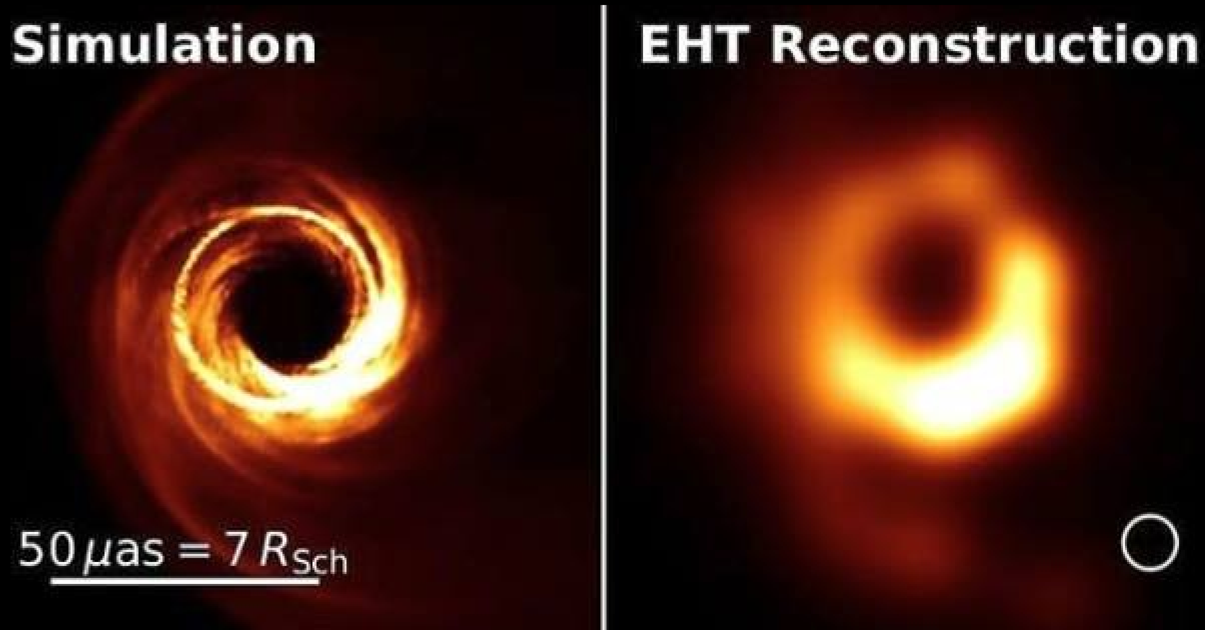


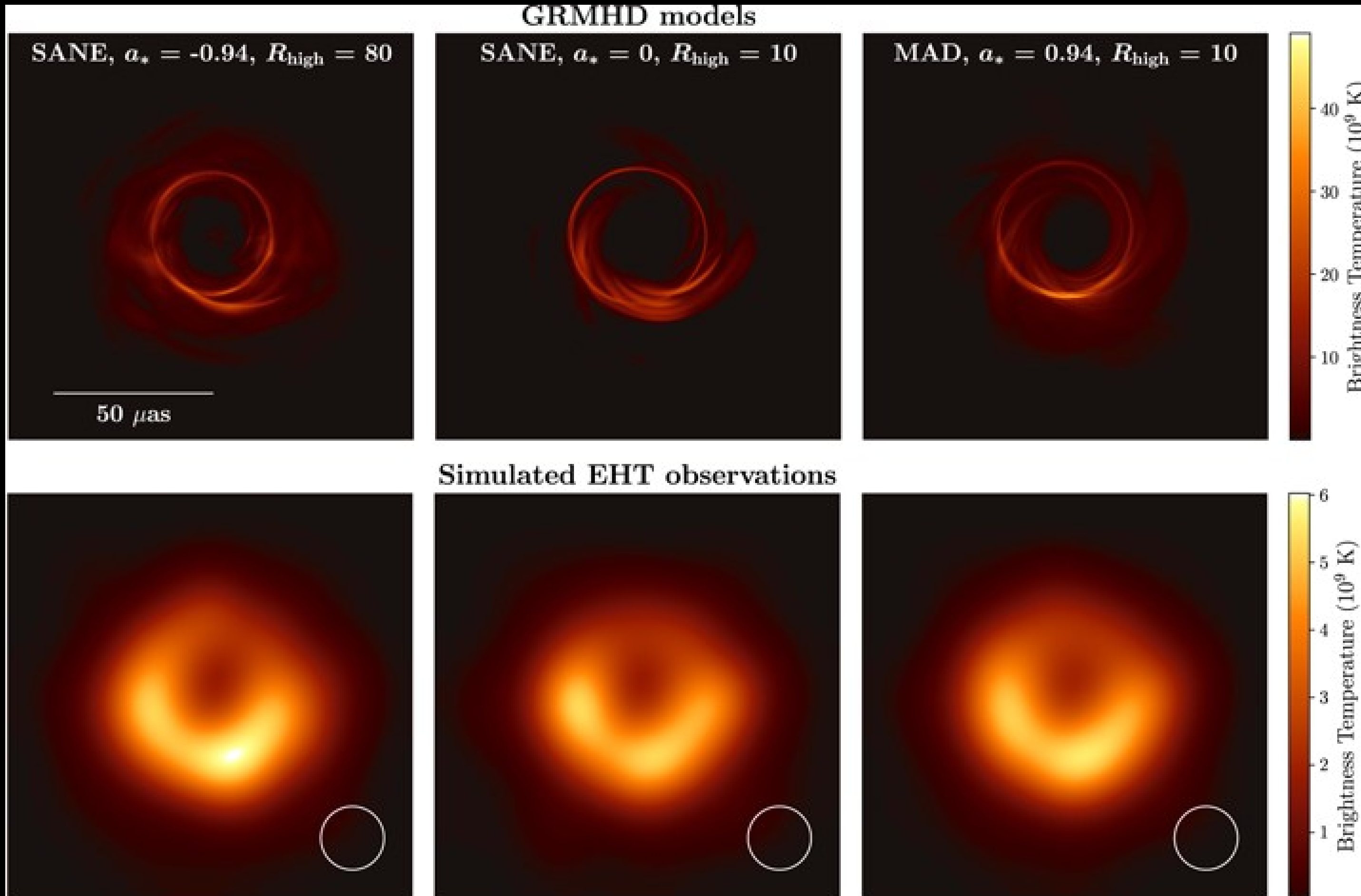

Location
A
Location
B
Location
C
Radio signal
Radio signal
Radio signal
Radio telescopes
Analog
Digital
Analog
Digital
Analog
Digital
Digital conversion
Atomic clocks
Hard drives at
Radio telescopes
(Synchronised)
Correlator
Data Reduction
Image


$2.6r_s$


M87*
April 11, 2017
50 μas
April 5
April 6
April 10
0
1
2
3
4
5
6
Brightness Temperature (10^9 K)


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

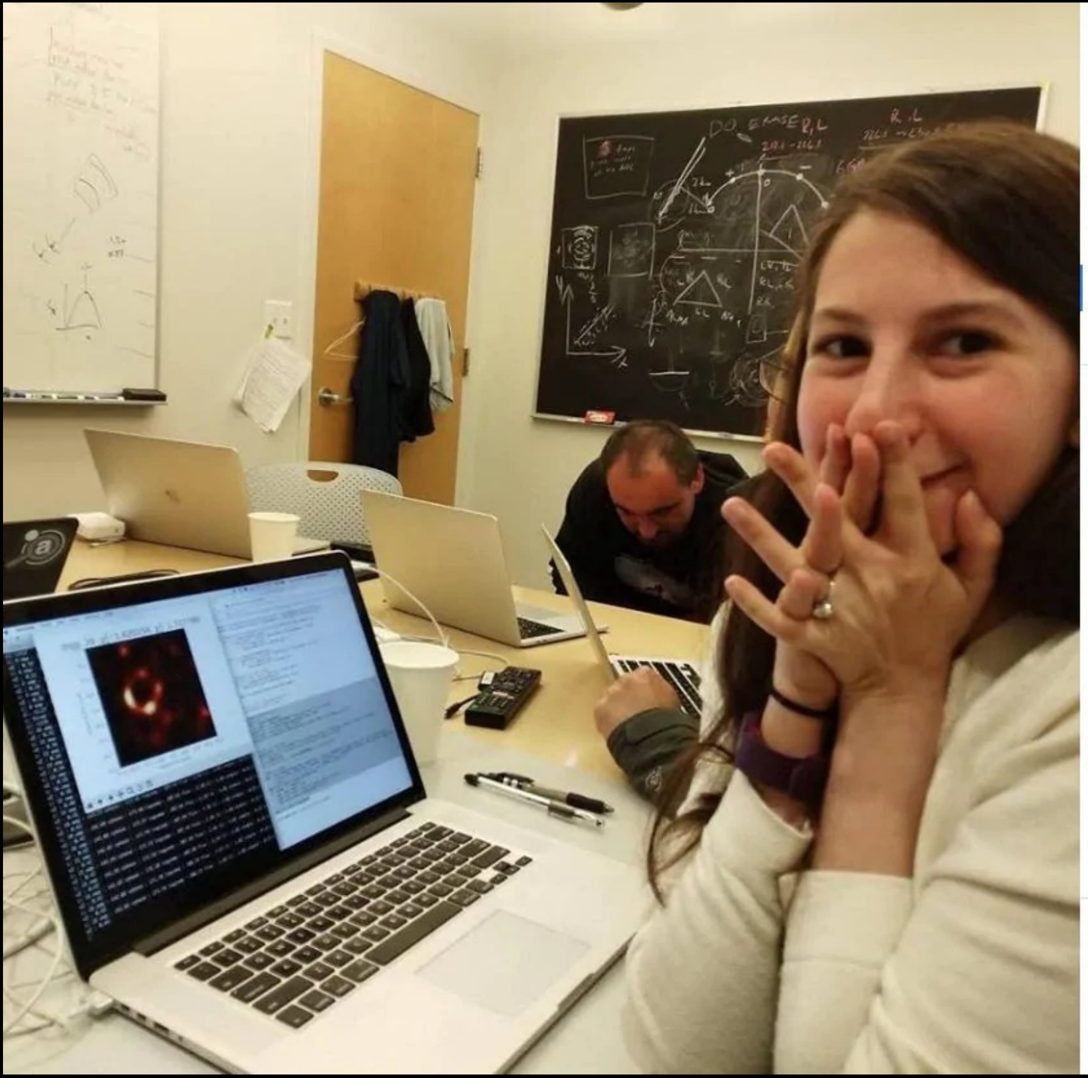

Simulation
EHT Reconstruction
$50\,\mu as = 7\,R_{Sch}$



GRMHD models
SANE, $a_* = -0.94$, $R_{\mathrm{high}} = 80$
SANE, $a_* = 0$, $R_{\mathrm{high}} = 10$
MAD, $a_* = 0.94$, $R_{\mathrm{high}} = 10$
50 $\mu$as
Brightness Temperature ($10^9$ K)
10
20
30
40
Simulated EHT observations
Brightness Temperature ($10^9$ K)
1
2
3
4
5
6

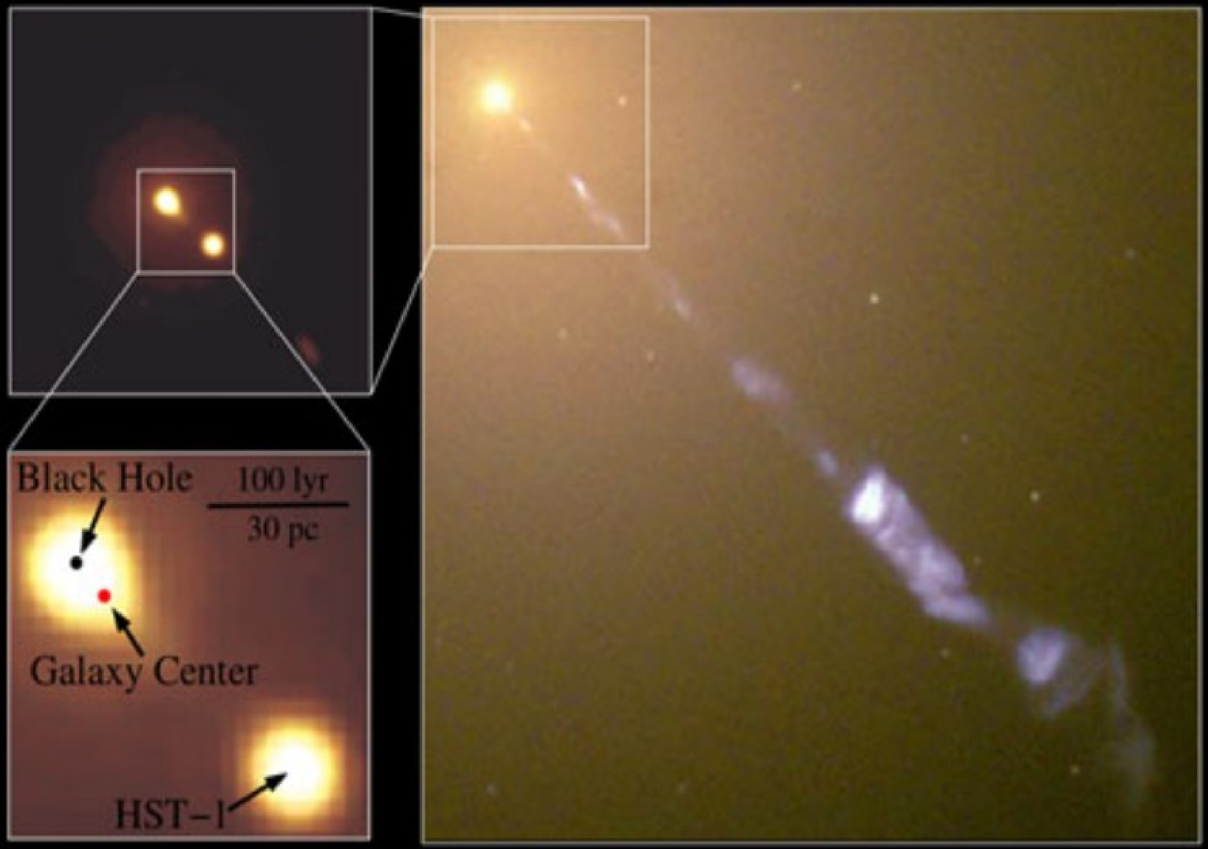
| Parameter | Estimate |
|---|---|
| Ring diameter [a] $d$ | $42 \pm 3\ \mu$as |
| Ring width [a] | $<20\ \mu$as |
| Crescent contrast [b] | >10:1 |
| Axial ratio [a] | <4:3 |
| Orientation PA | 150°–200° east of north |
| $\theta_g = GM/Dc^2$ [c] | $3.8 \pm 0.4\ \mu$as |
| $\alpha = d/\theta_g$ [d]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

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

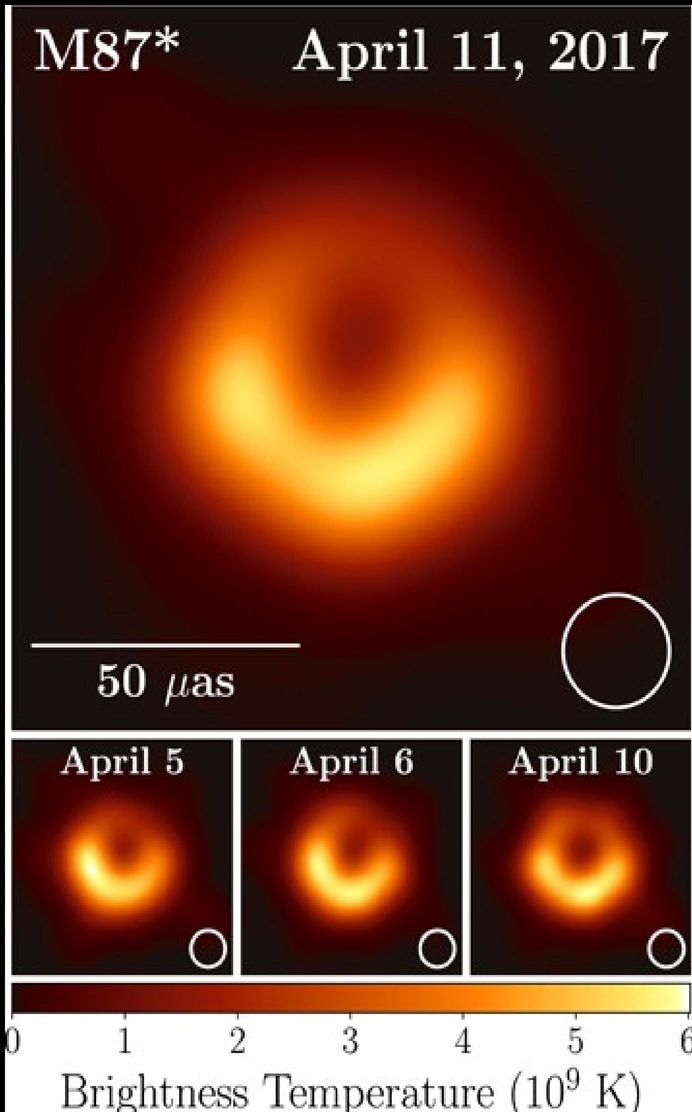


# SuperMassive BHs

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

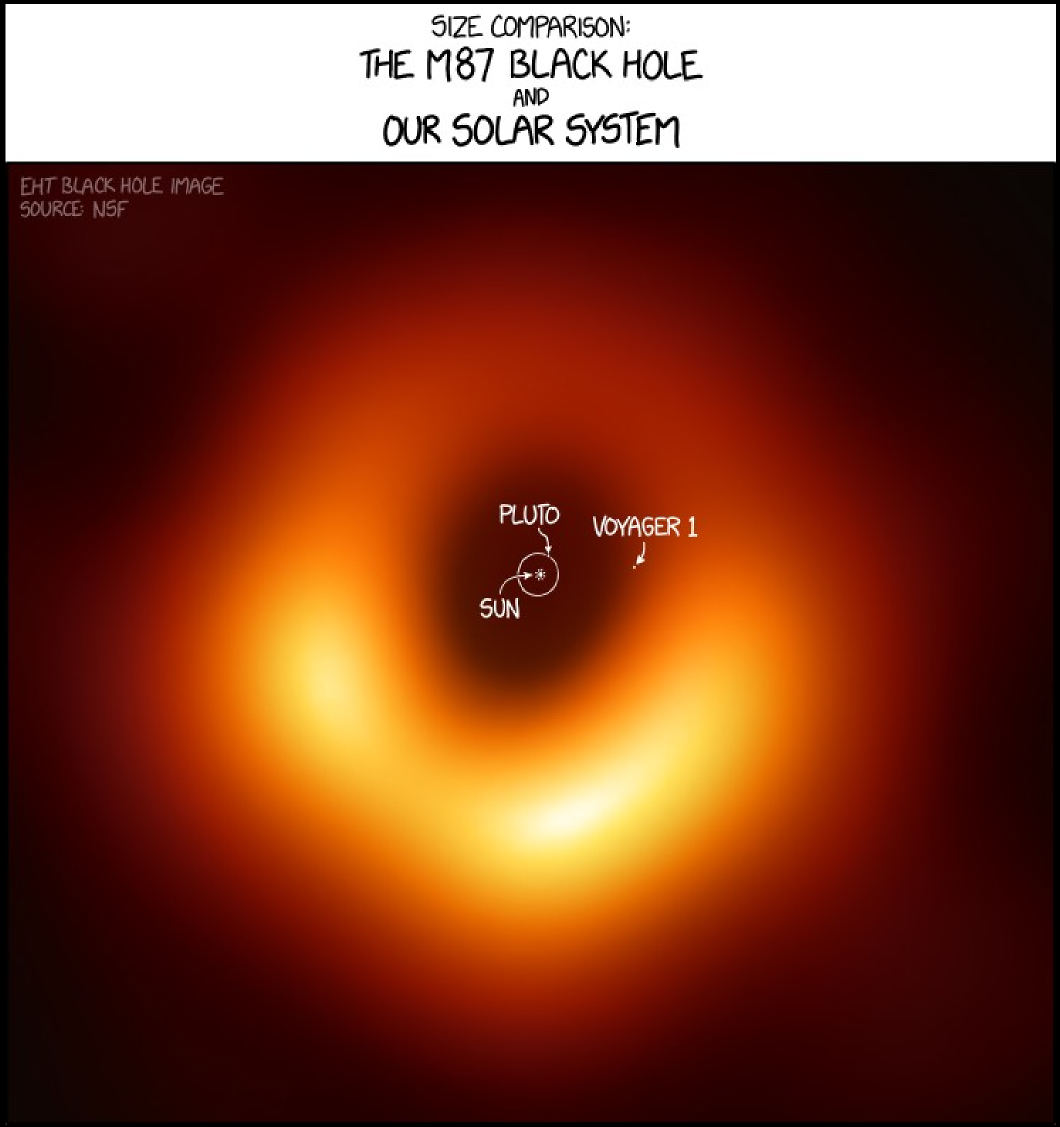


# M87*

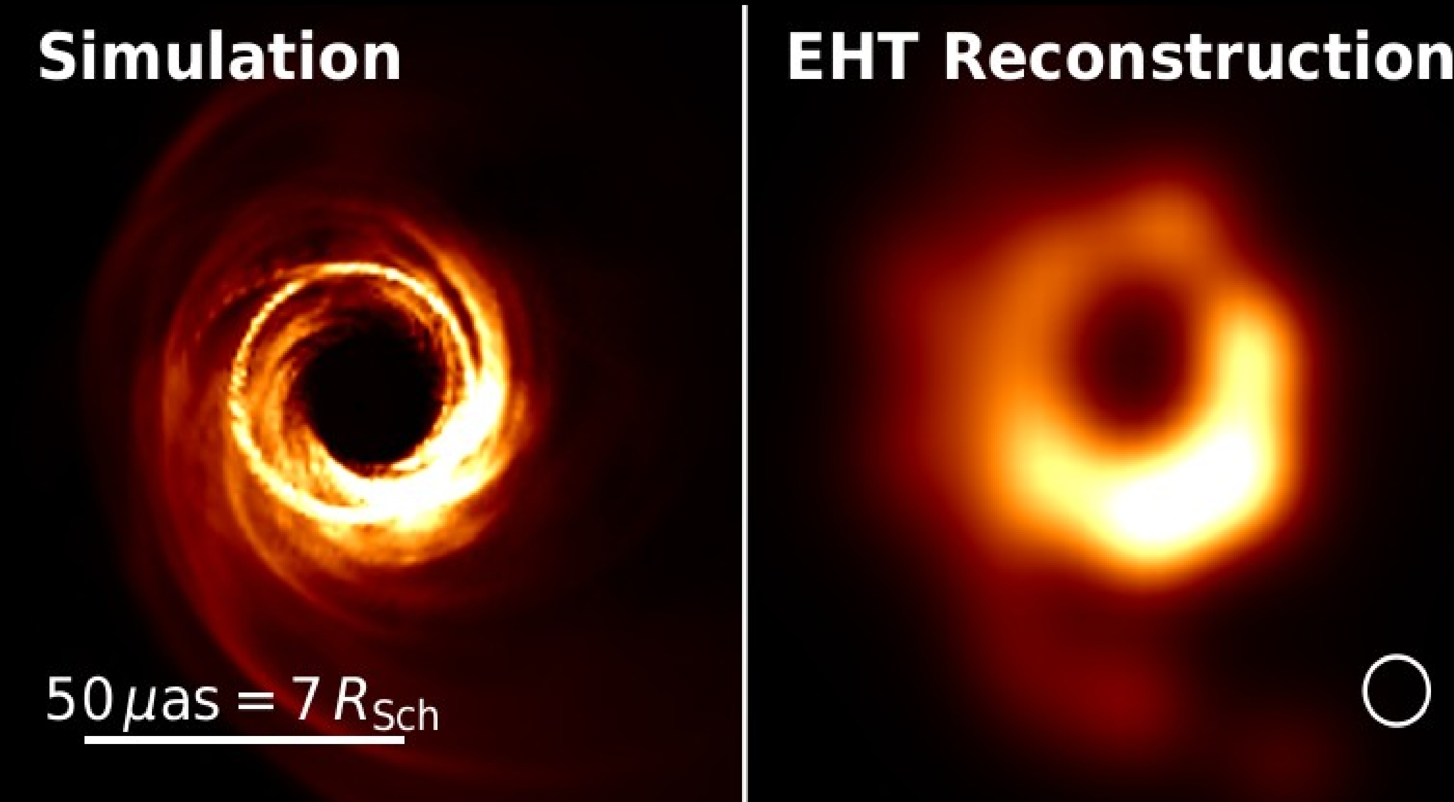



| Parameter | Estimate |
|---|---|
| Ring diameter [a] $d$ | $42 \pm 3$ μas |
| Ring width [a] | <20 μas |
| Crescent contrast [b] | >10:1 |
| Axial ratio [a] | <4:3 |
| Orientation PA | 150°–200° east of north |
| $\theta_g = GM/Dc^2$ [c] | $3.8 \pm 0.4$ μas |
| $\alpha = d/\theta_g$ [d] | $11^{+0.5}_{-0.3}$ |
| $M$[c] | $(6.5 \pm 0.7) \times 10^9\ M_\odot$ |
| **Parameter** | **Prior Estimate** |
| $D$ [e] | $(16.8 \pm 0.8)$ 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