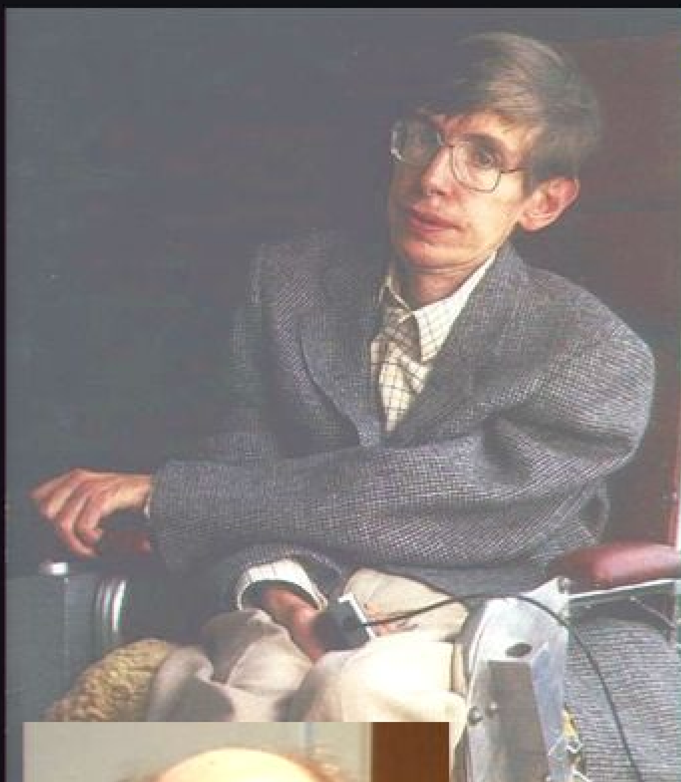
Title: General Relativity 2

Date: Aug 20, 2009 02:30 PM

URL: http://pirsa.org/09080060

Abstract: The complete story of how the scientistsâ€™ had predicted the final stages of stars of varying masses: from the application of General Relatively, to the latest astronomical observations. Our journey starts with White Dwarfs and ends with a journey to and into a Black Hole and all the implications such a trip would hold for our visitor.

The Blackhole Stars Today

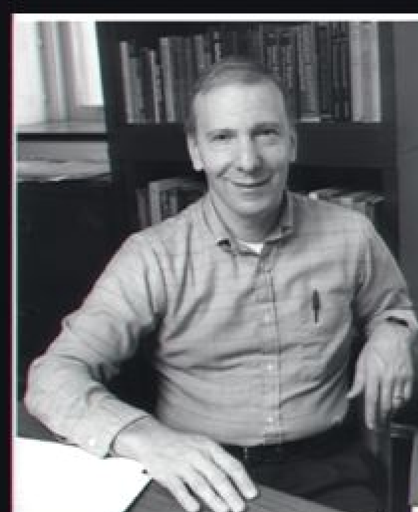


Hawking

Bekenstein

Thorne

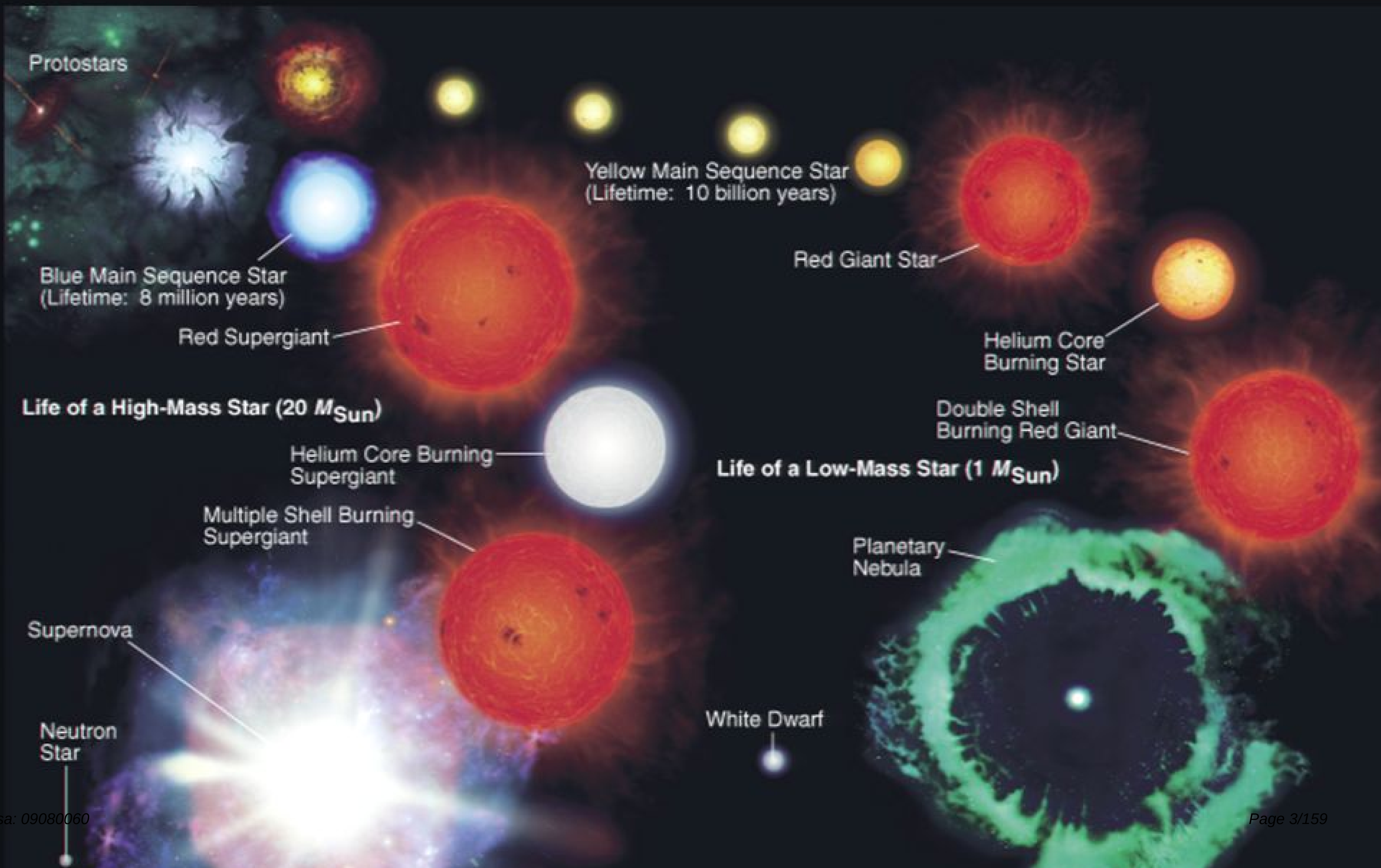
Susskind



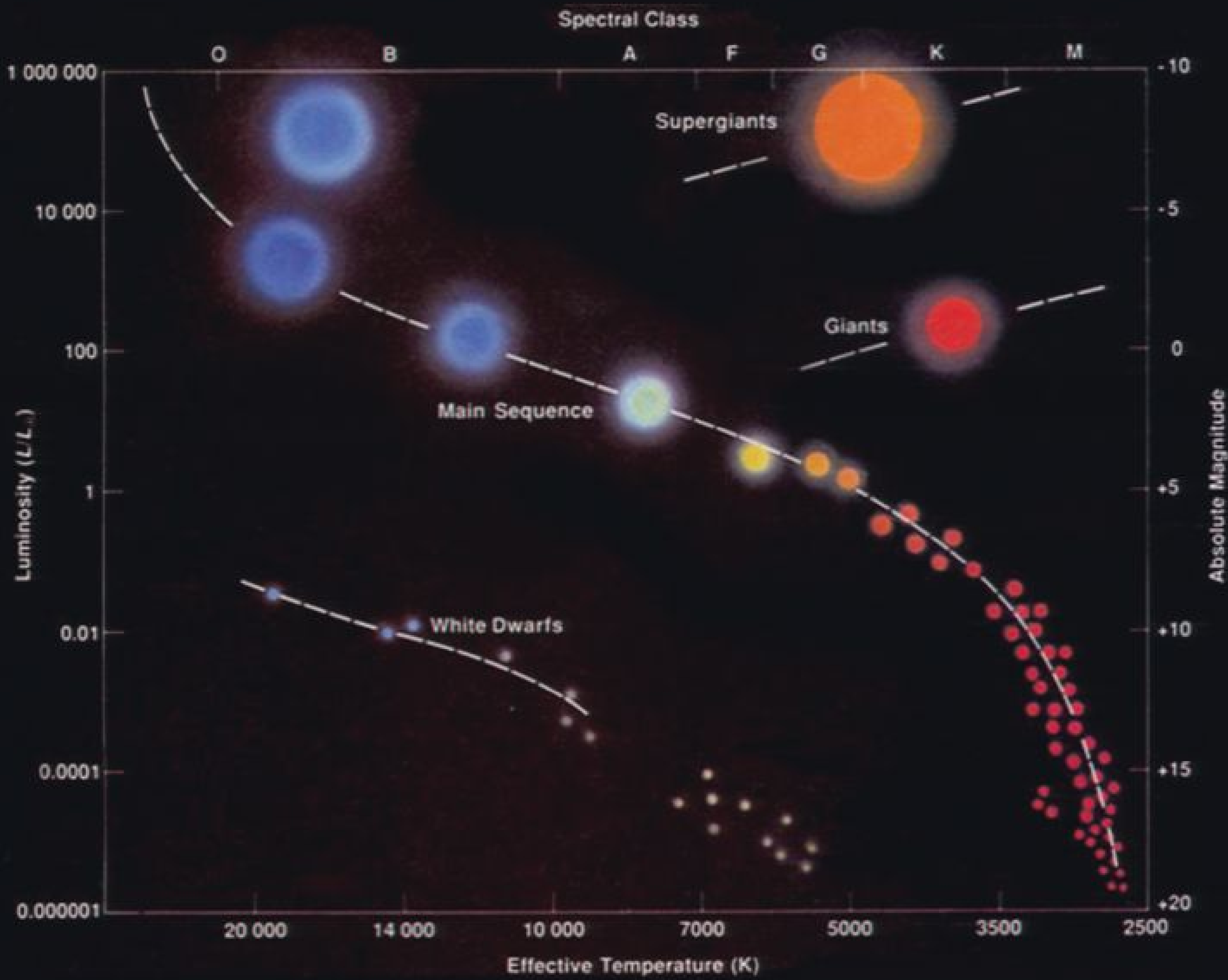
Werner Israel

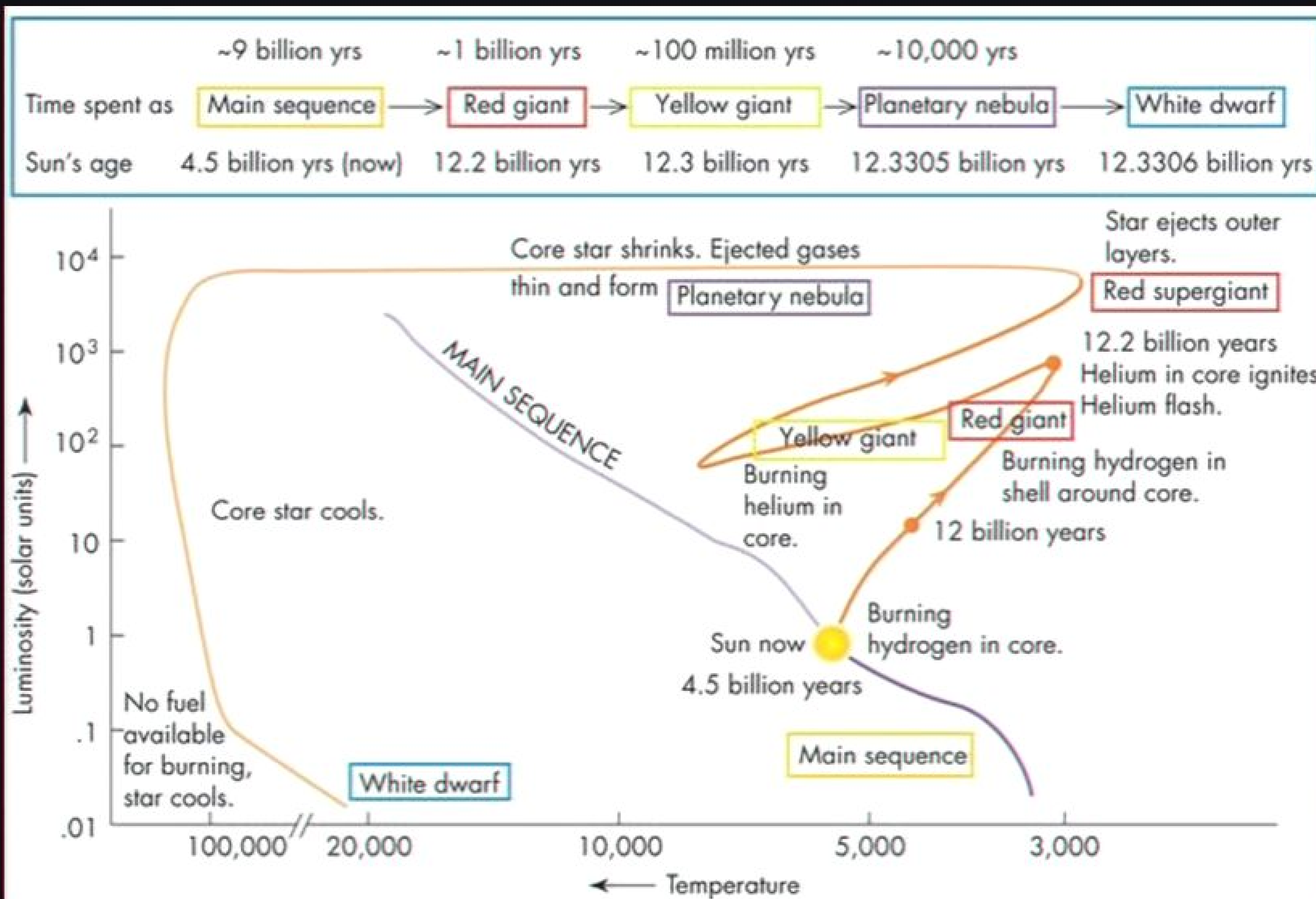
Robert Wald

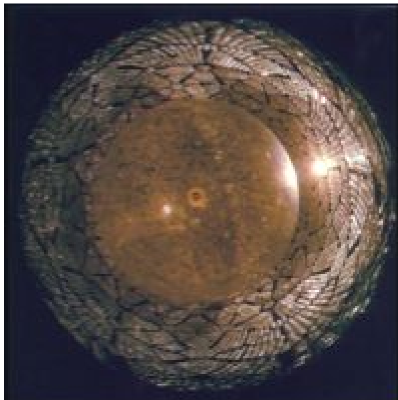
Life Cycle of Stars



Hertzsprung-Russel Diagram




~9 billion yrs
~1 billion yrs
~100 million yrs
~10,000 yrs
Time spent as
Main sequence
Red giant
Yellow giant
Planetary nebula
White dwarf
Sun's age
4.5 billion yrs (now)
12.2 billion yrs
12.3 billion yrs
12.3305 billion yrs
12.3306 billion yrs
Star ejects outer layers.
Red supergiant
Core star shrinks. Ejected gases thin and form
Planetary nebula
MAIN SEQUENCE
12.2 billion years
Helium in core ignites:
Helium flash.
Red giant
Yellow giant
Burning helium in core.
Burning hydrogen in shell around core.
12 billion years
Core star cools.
Burning hydrogen in core.
Sun now
4.5 billion years
No fuel available for burning, star cools.
White dwarf
Main sequence
Luminosity (solar units)
10^4
10^3
10^2
10
1
.1
.01
100,000
20,000
10,000
5,000
3,000
Temperature



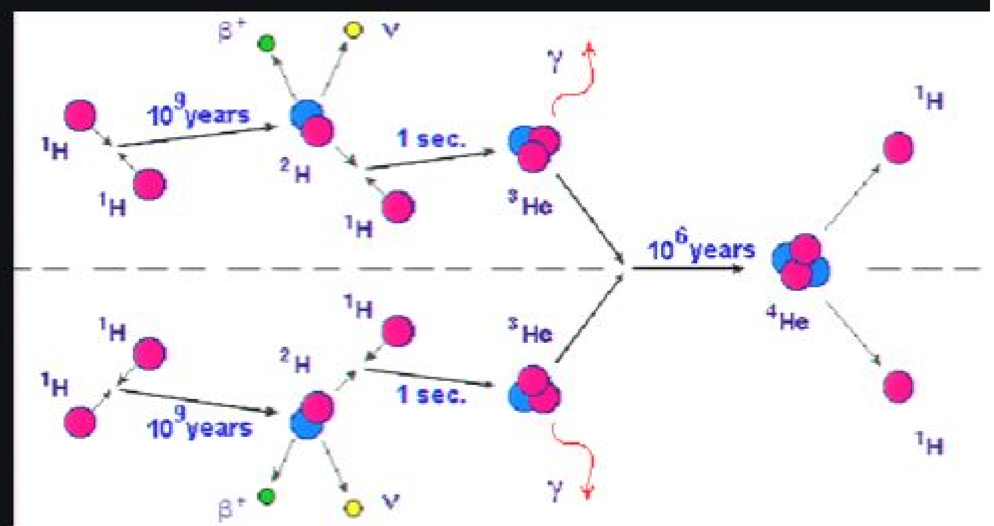
Stellar Energy

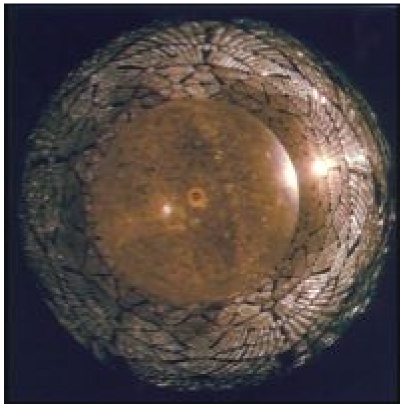
Proton-Proton Chain [4H→He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

Proton-Proton Reaction

- = Neutron
- = Proton



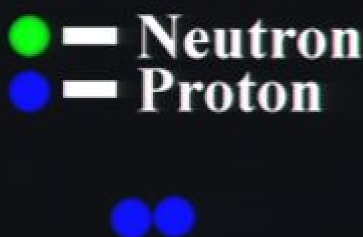


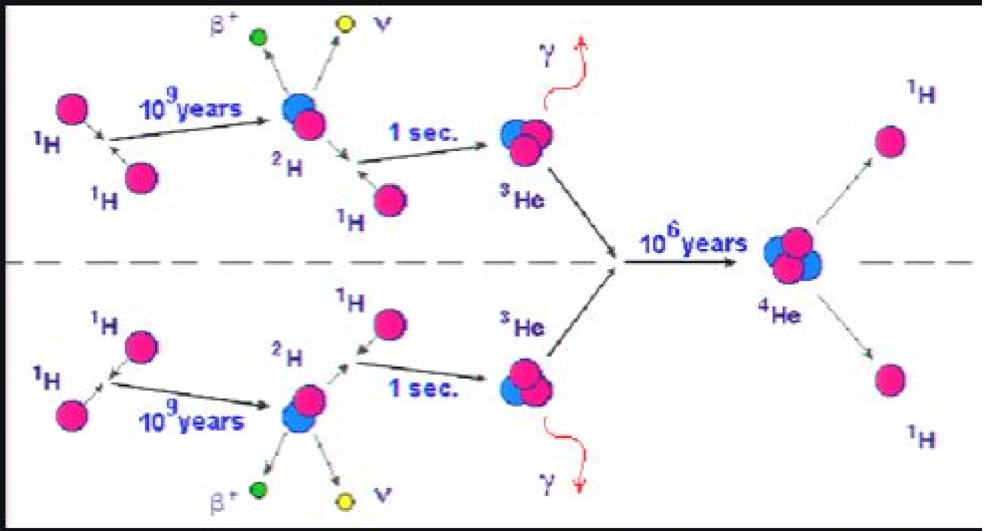
Stellar Energy

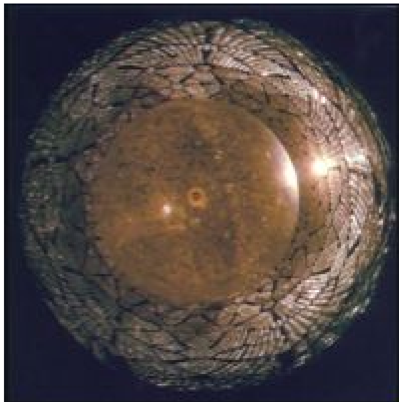
Proton-Proton Chain [4H → He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

Two 1H Atoms Combine







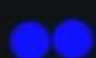
Stellar Energy

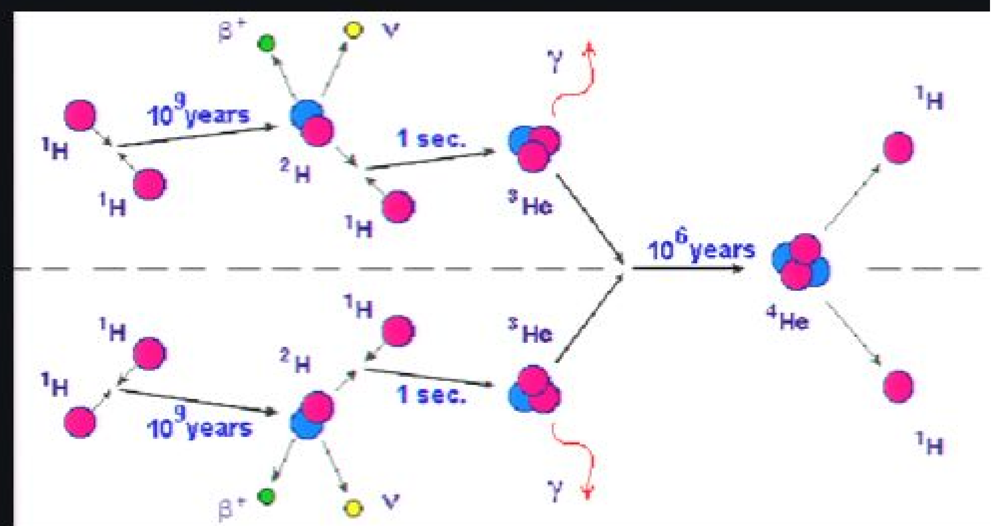
Proton-Proton Chain [4H → He + energy]

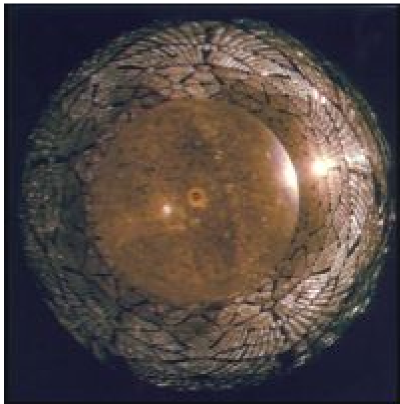
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

2He Is Formed

● = Neutron
● = Proton





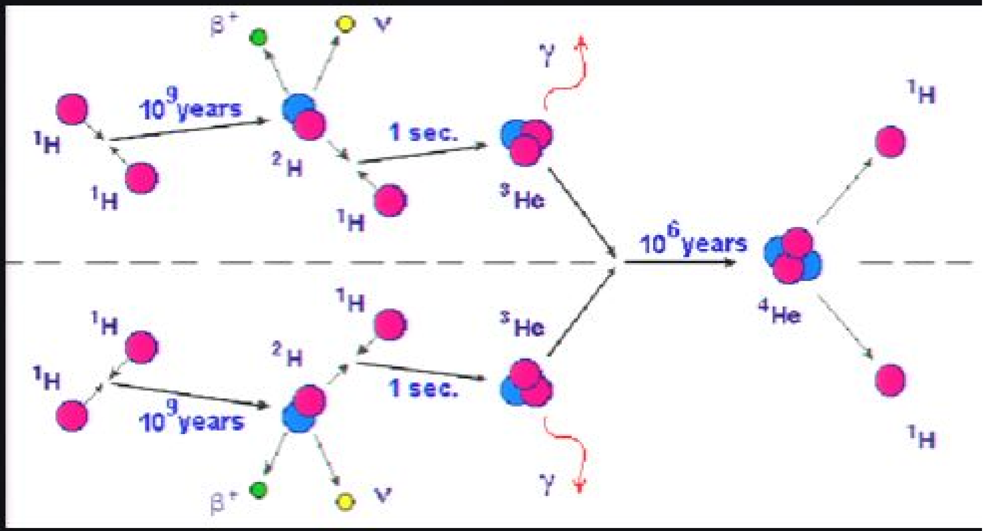


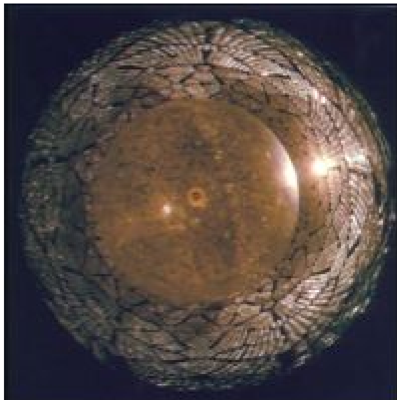
Stellar Energy

Proton-Proton Chain [4H → He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron, and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

Proton Decays Into A Neutron

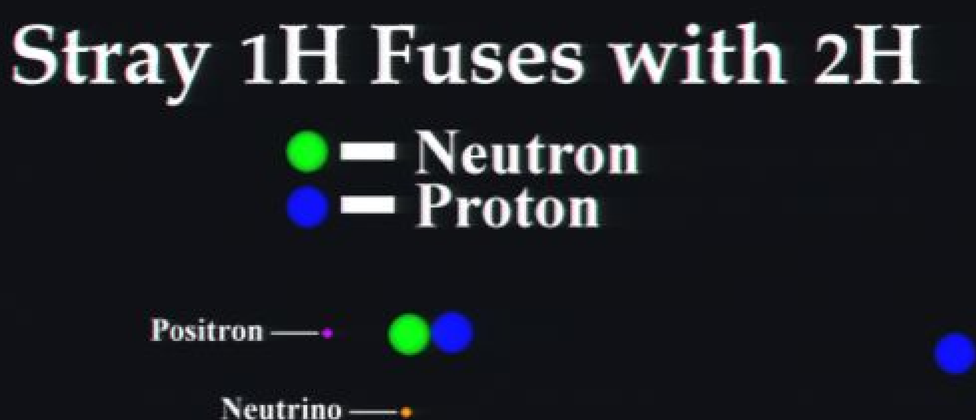


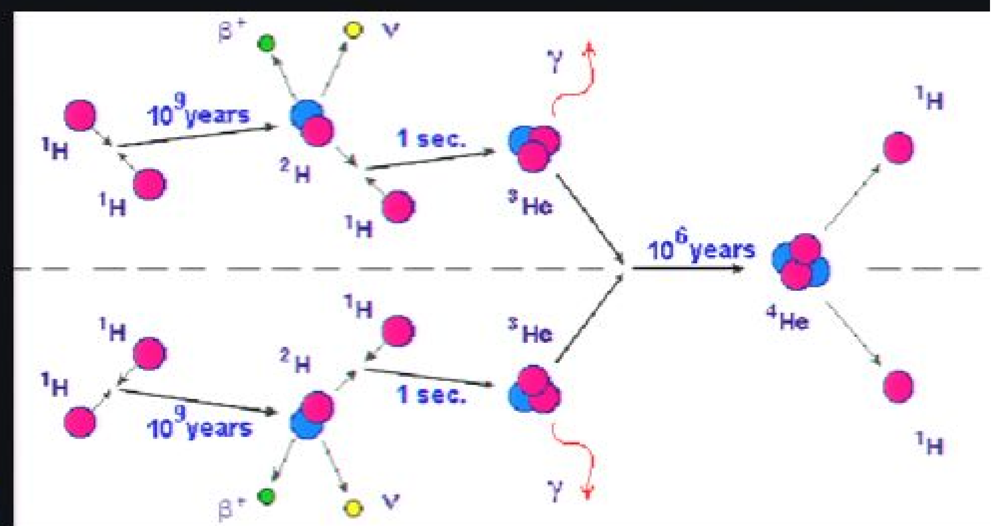


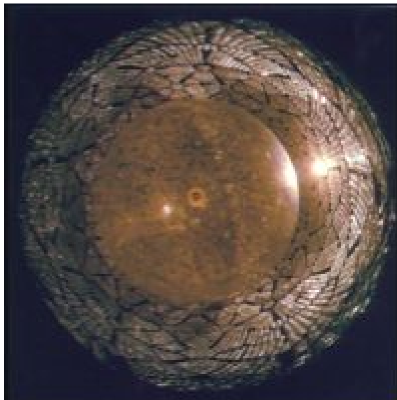
Stellar Energy

Proton-Proton Chain [4H→He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron, and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.



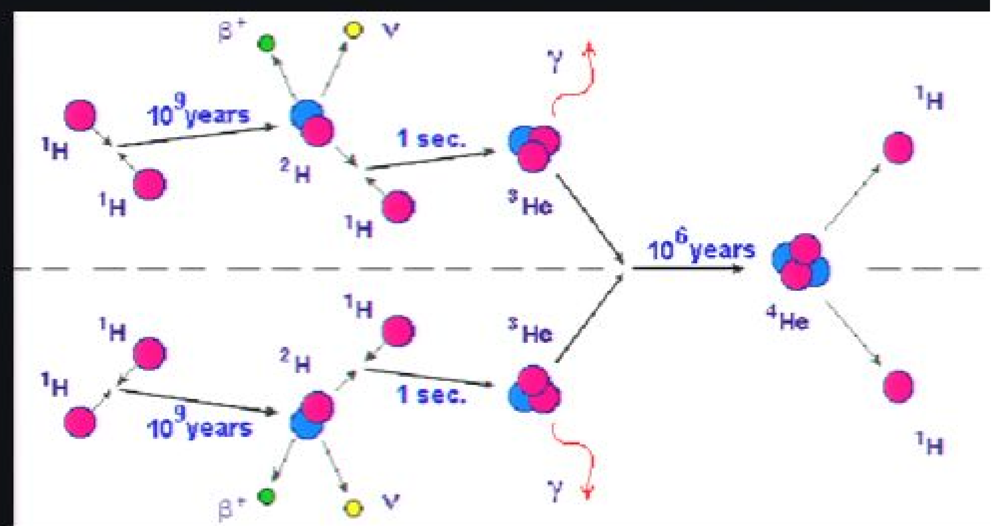




Stellar Energy

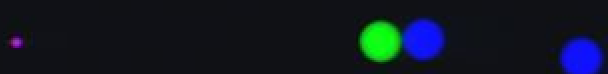
Proton-Proton Chain [4H→He + energy]

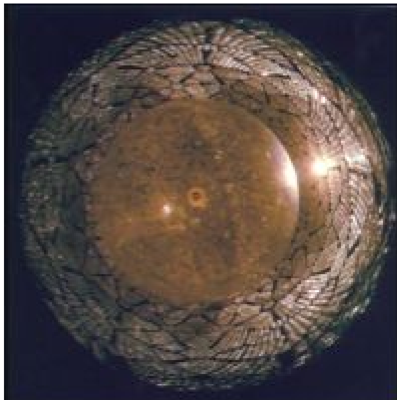
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.



Stray 1H Fuses with 2H

- ● = Neutron
- ● = Proton





Stellar Energy

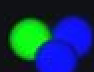
Proton-Proton Chain [4H→He + energy]

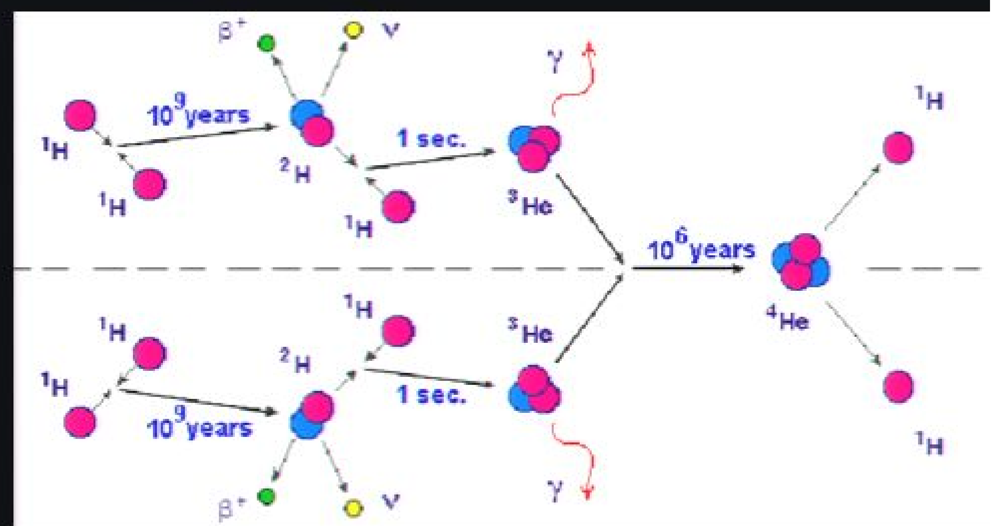
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

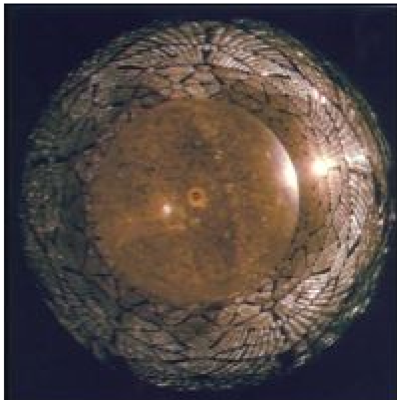
3He Is Created

● = Neutron

● = Proton



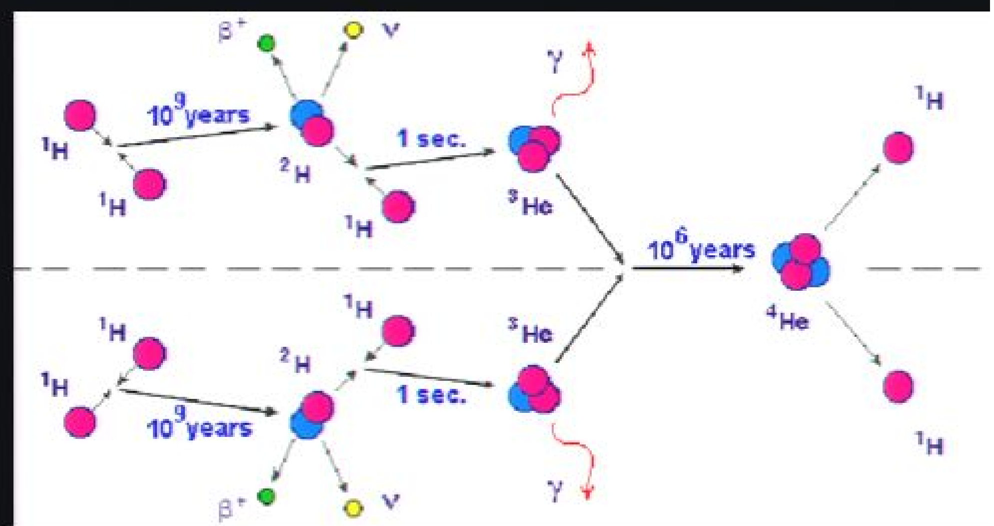




Stellar Energy

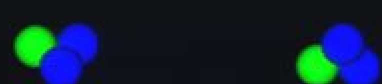
Proton-Proton Chain [4H→He + energy]

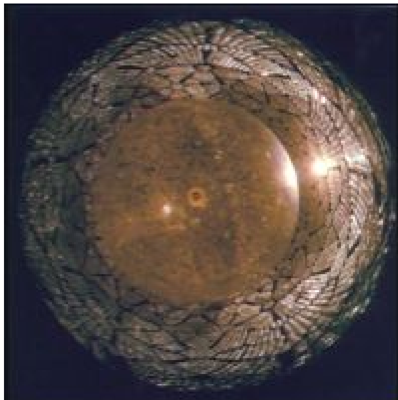
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.



Two 3He Fuse Together

- ● = Neutron
- ● = Proton

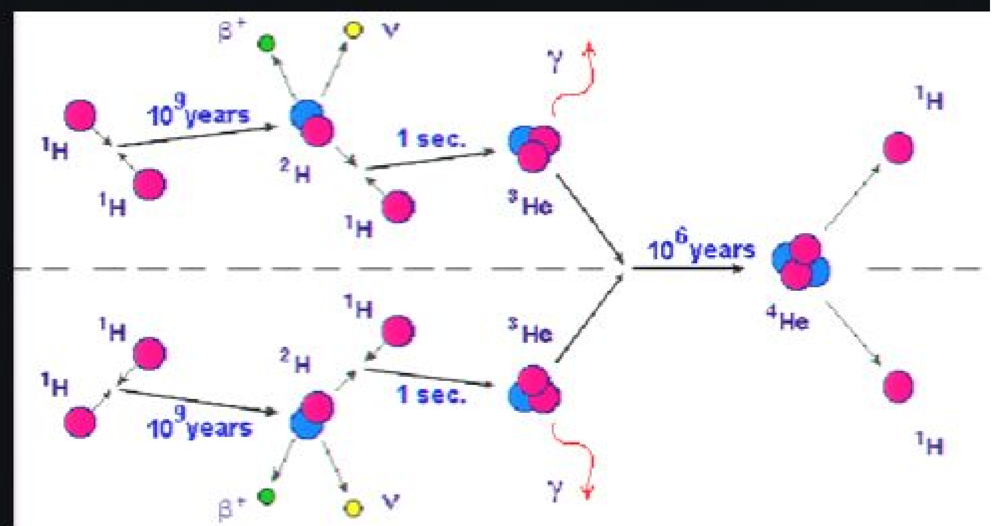




Stellar Energy

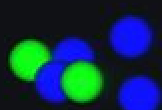
Proton-Proton Chain [4H→He + energy]

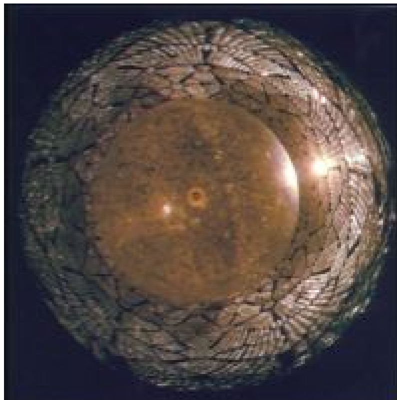
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.



Two 1H Atoms Released

- Neutron
- Proton

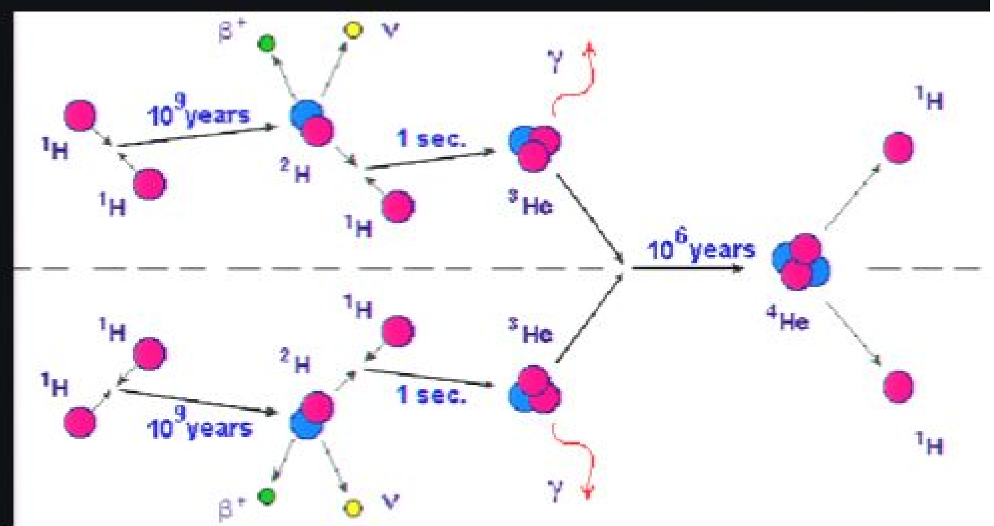




Stellar Energy

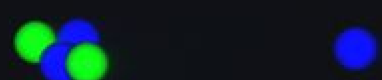
Proton-Proton Chain [4H→He + energy]

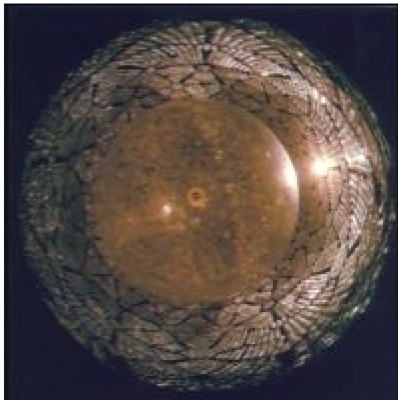
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.



4He Is Formed

- Neutron
- Proton

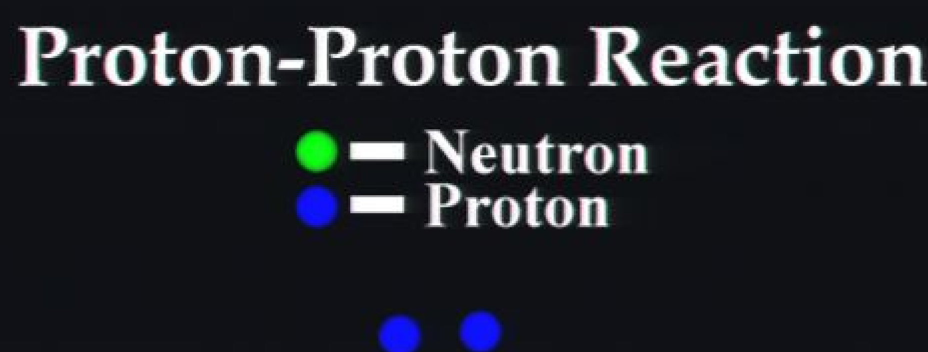


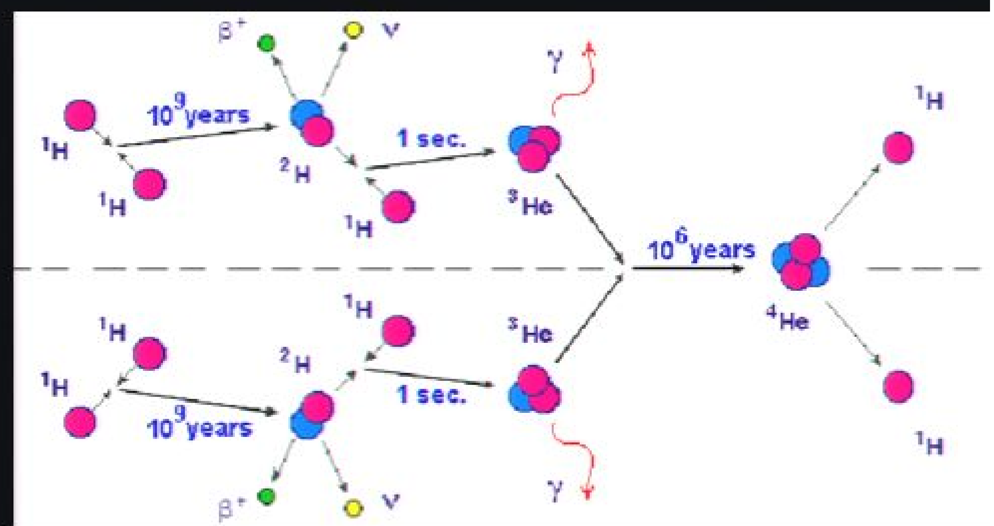


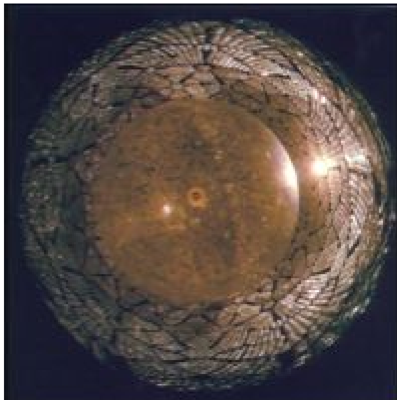
Stellar Energy

Proton-Proton Chain [4H → He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.



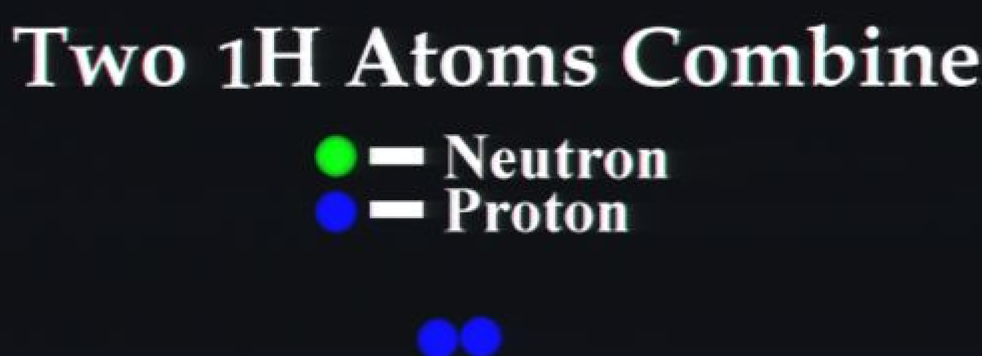


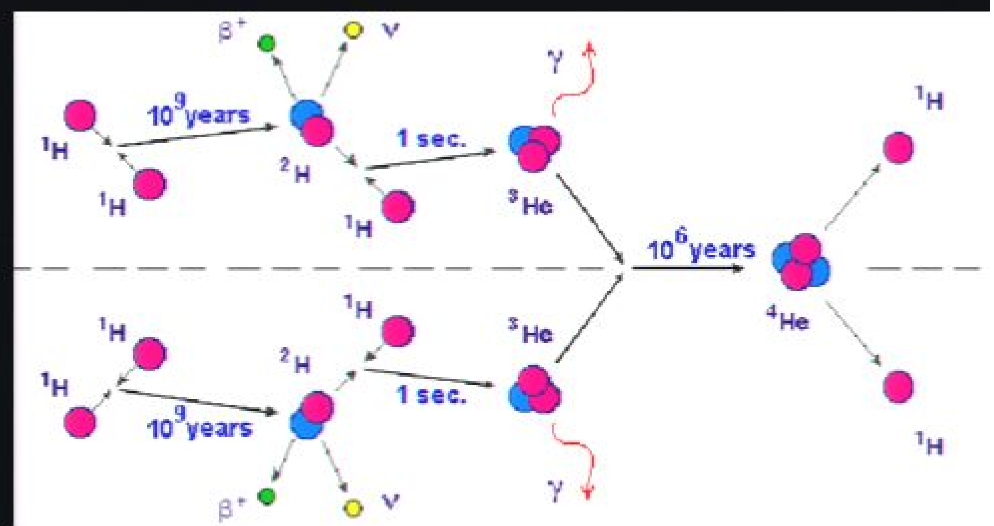


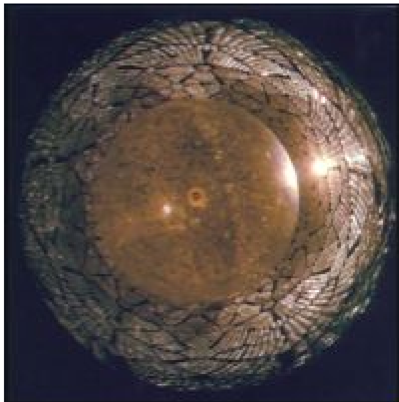
Stellar Energy

Proton-Proton Chain [4H→He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.







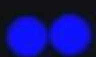
Stellar Energy

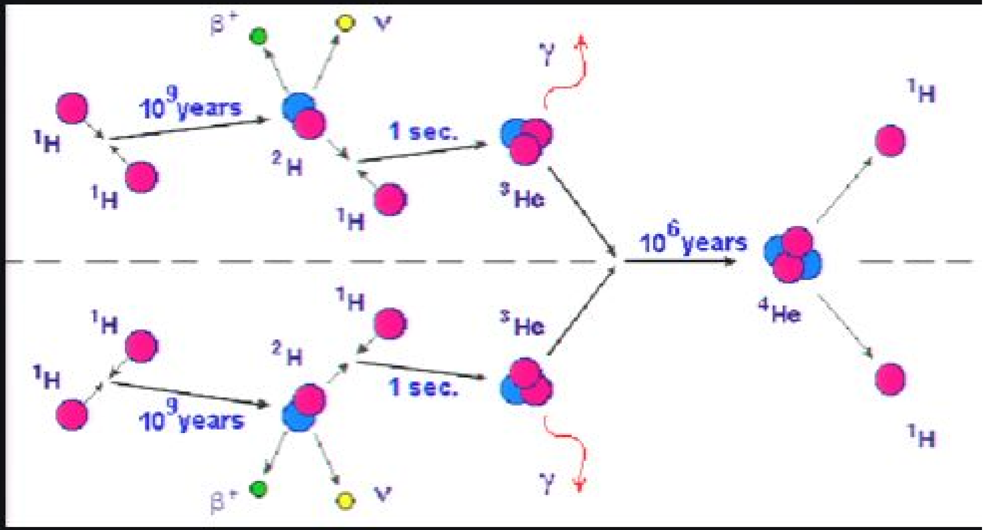
Proton-Proton Chain [4H → He + energy]

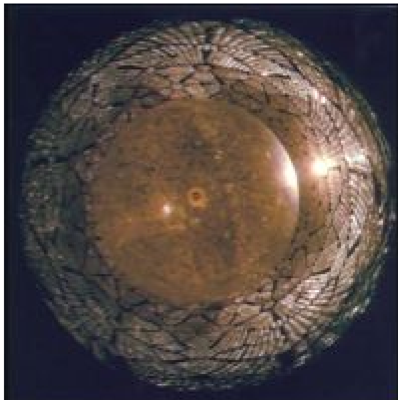
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

2He Is Formed

- ● = Neutron
- ● = Proton







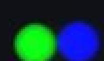
Stellar Energy

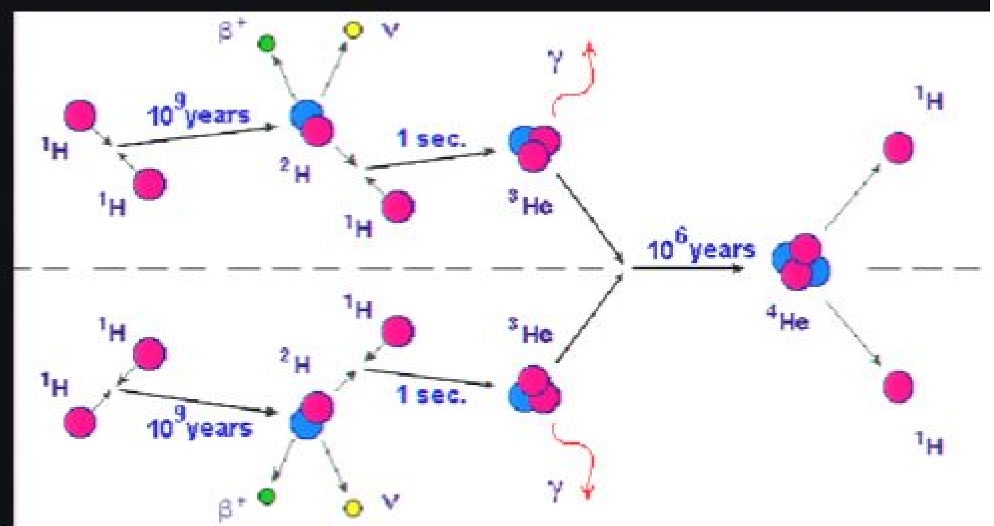
Proton-Proton Chain [4H→He + energy]

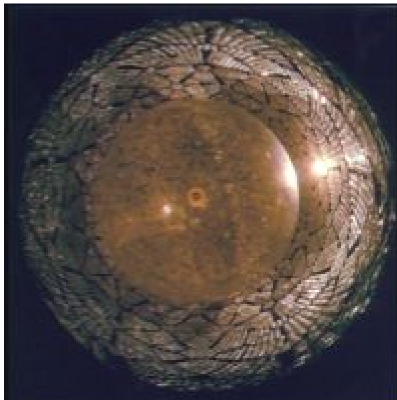
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

Proton Decays Into A Neutron

● = Neutron
● = Proton



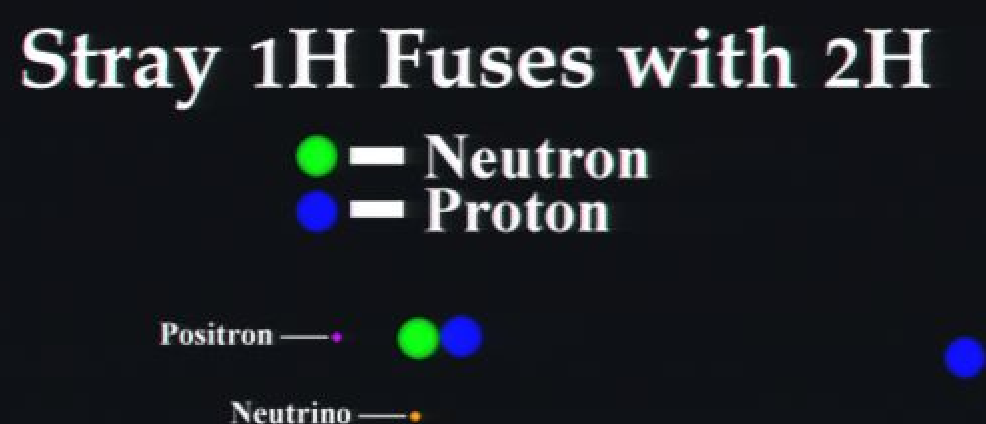


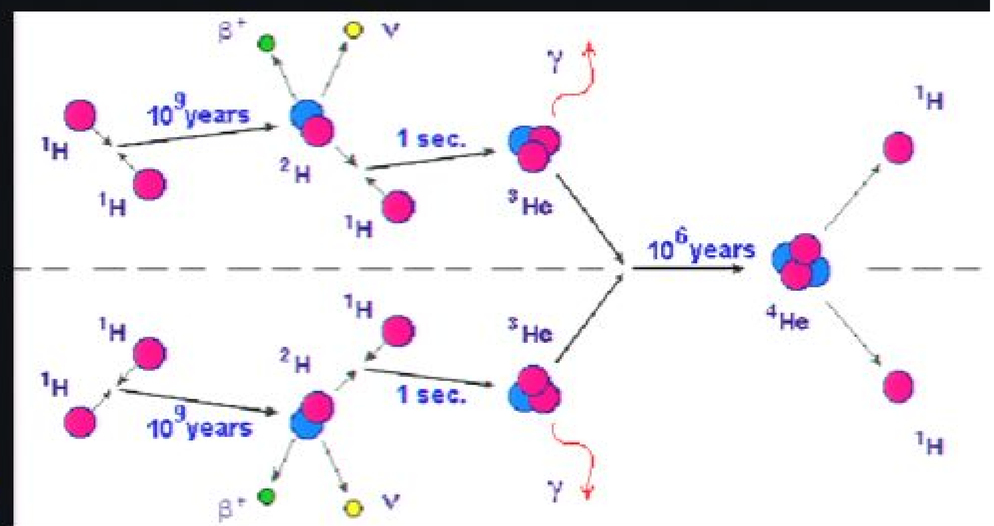


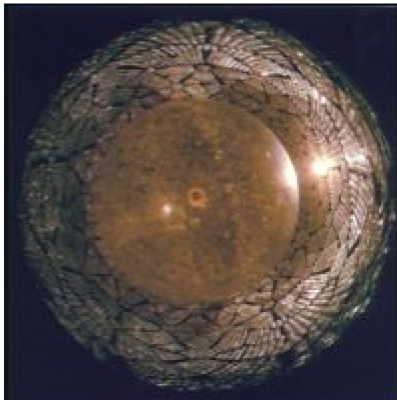
Stellar Energy

Proton-Proton Chain [4H → He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron, and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.







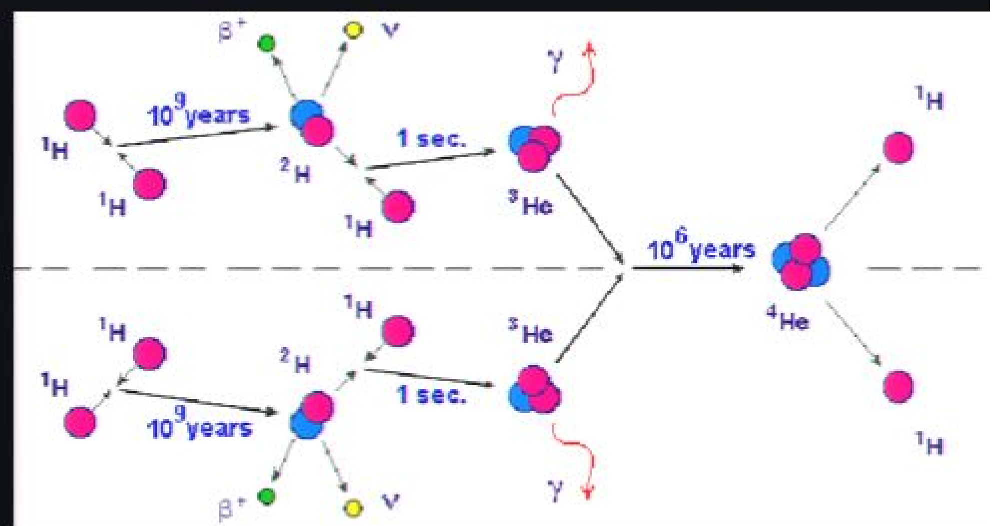
Stellar Energy

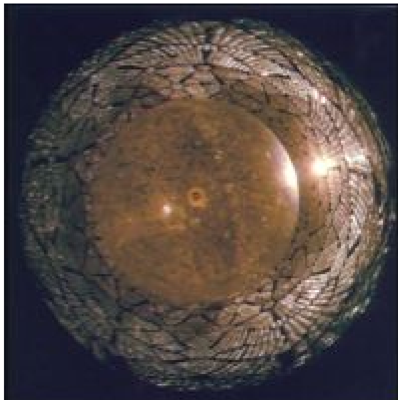
Proton-Proton Chain [4H→He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

Stray 1H Fuses with 2H

- Neutron
- Proton





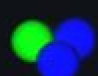
Stellar Energy

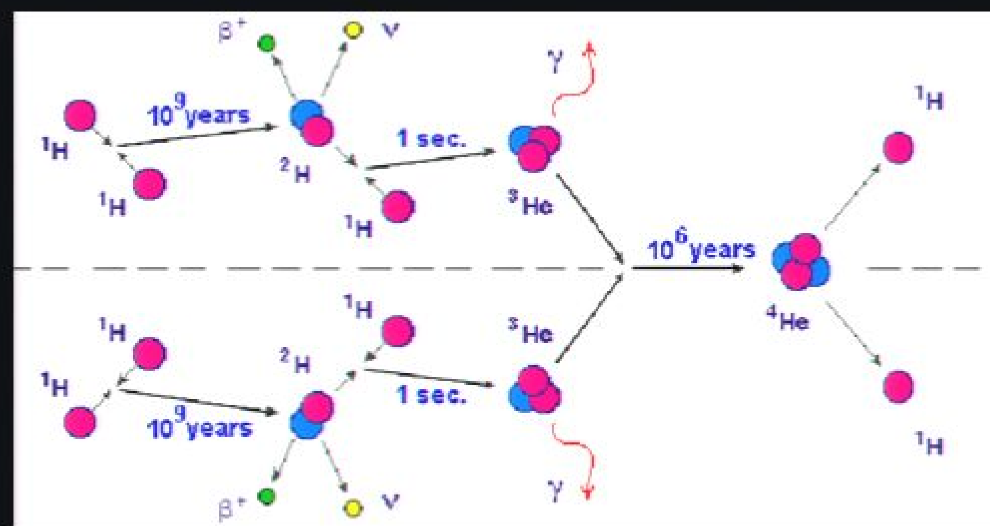
Proton-Proton Chain [4H → He + energy]

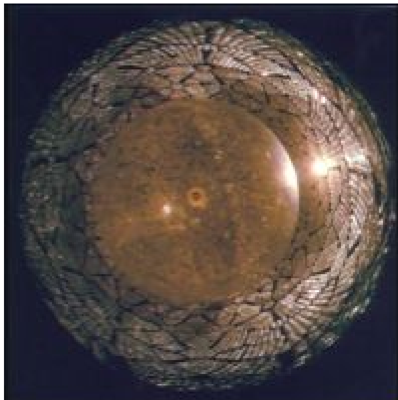
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

3He Is Created

● = Neutron
● = Proton







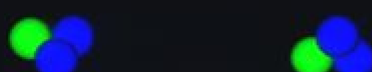
Stellar Energy

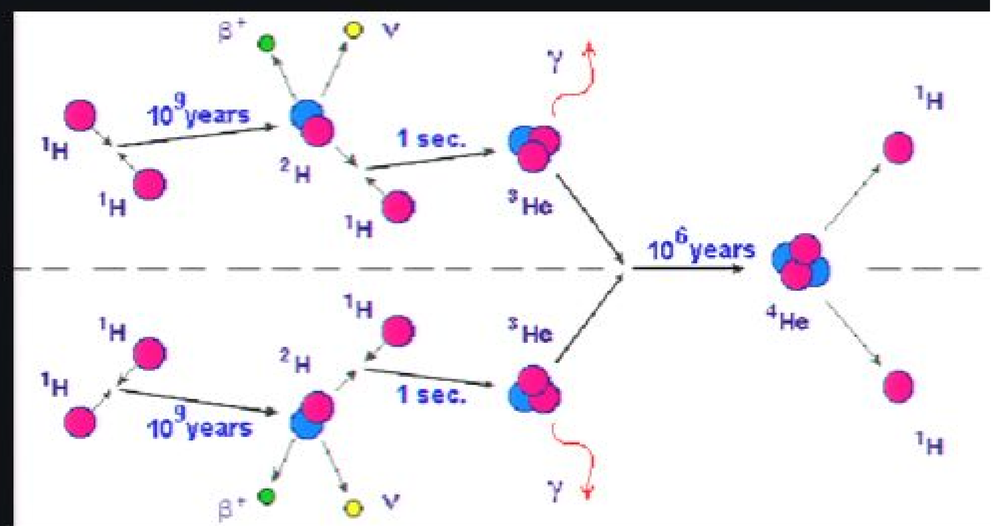
Proton-Proton Chain [4H → He + energy]

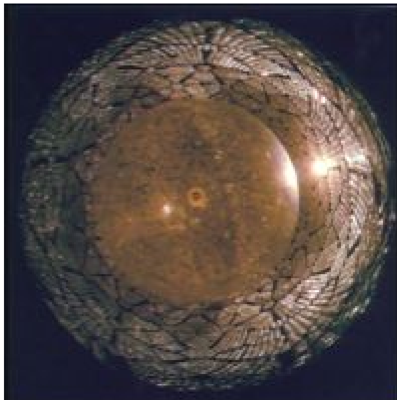
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

Two 3He Fuse Together

● = Neutron
● = Proton



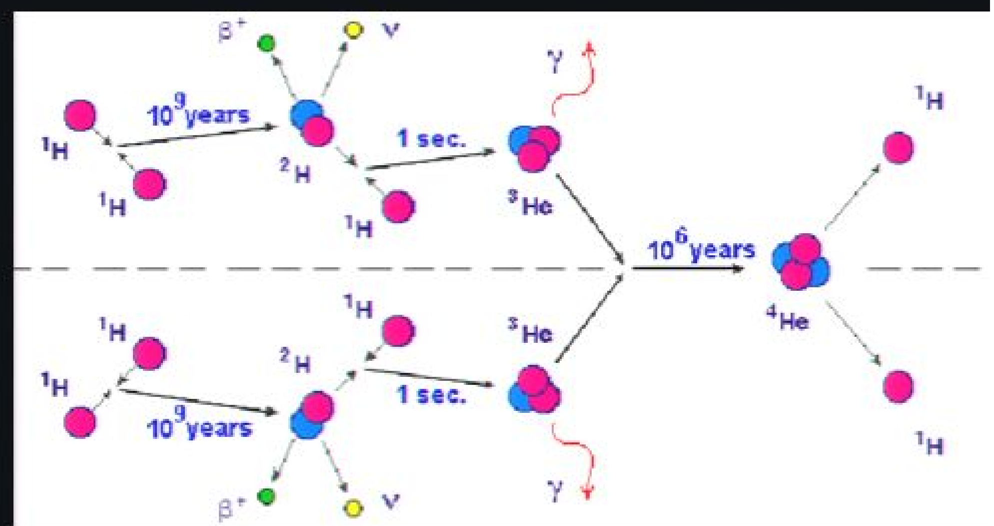




Stellar Energy

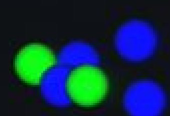
Proton-Proton Chain [4H→He + energy]

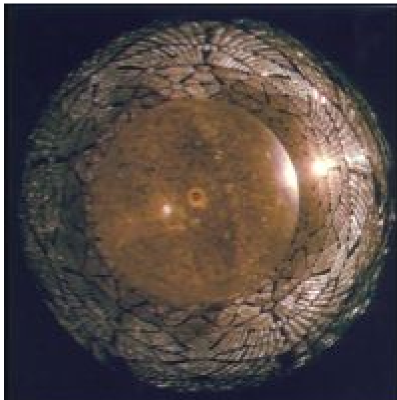
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.



Two 1H Atoms Released

● = Neutron
● = Proton

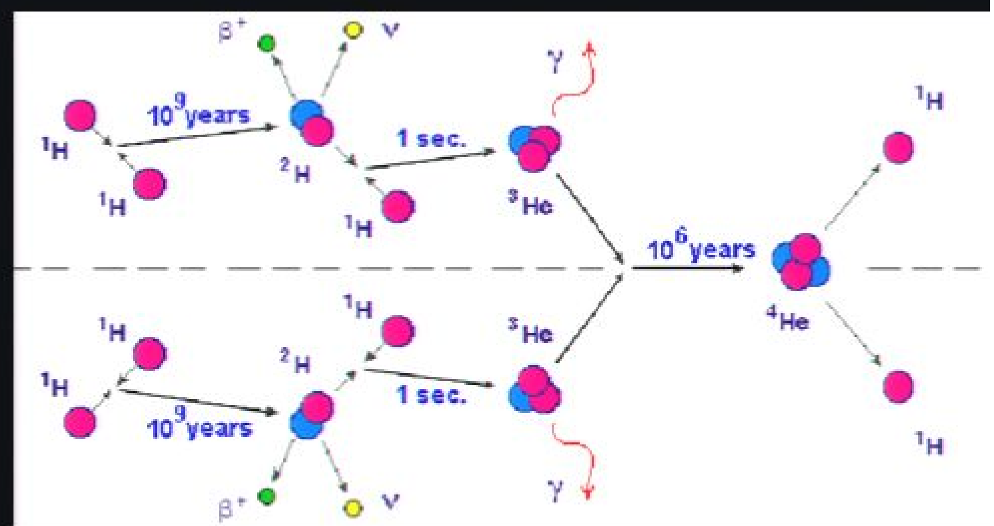




Stellar Energy

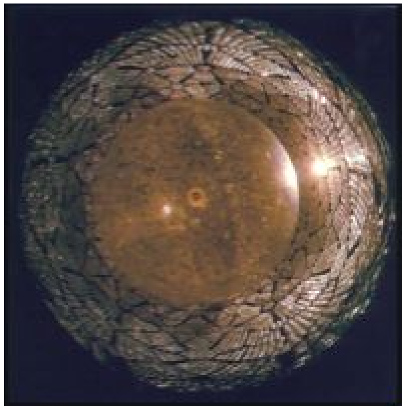
Proton-Proton Chain [4H→He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.



4He Is Formed

● = Neutron
● = Proton



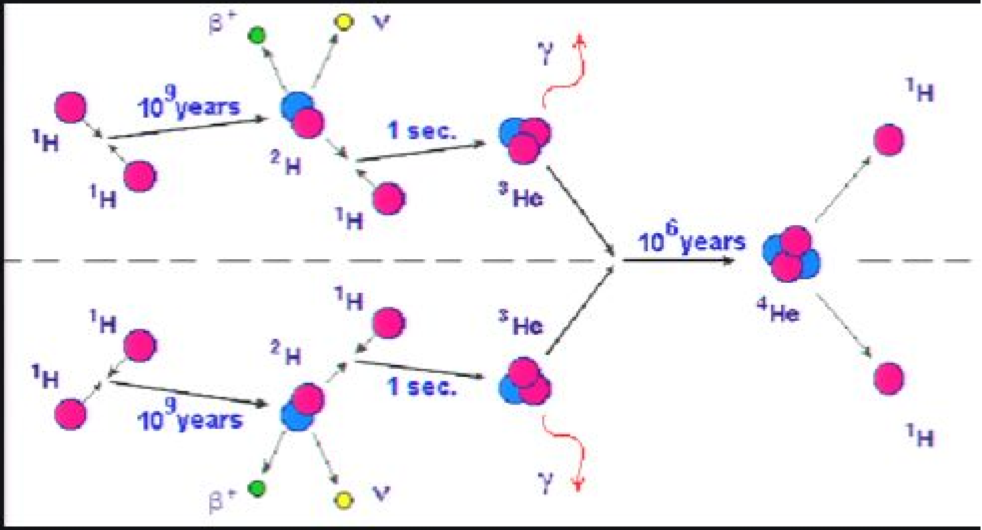
Stellar Energy

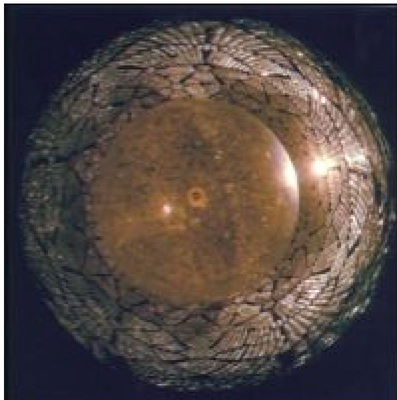
Proton-Proton Chain [4H → He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

Proton-Proton Reaction

● = Neutron
● = Proton

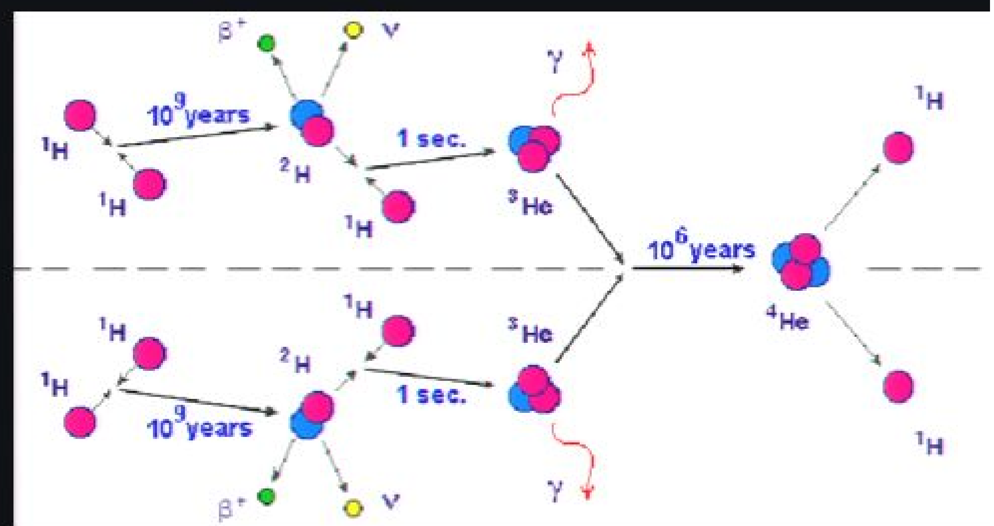




Stellar Energy

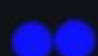
Proton-Proton Chain [4H → He + energy]

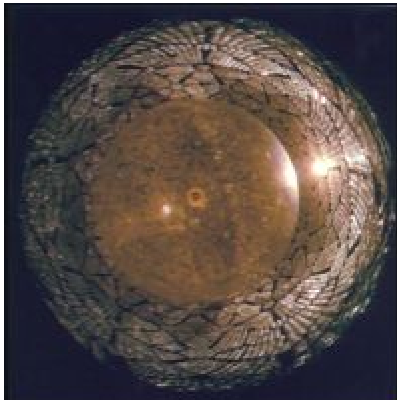
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.



Two 1H Atoms Combine

- = Neutron
- = Proton





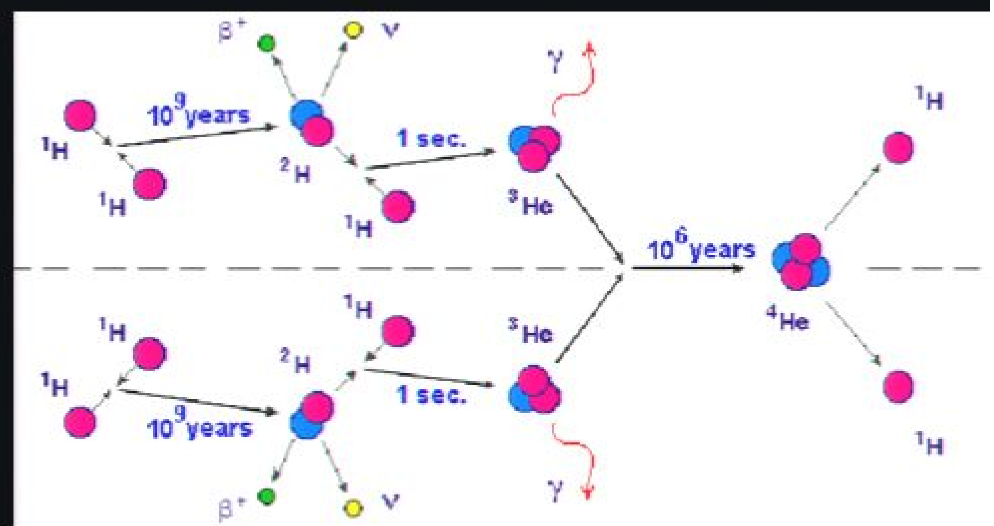
Stellar Energy

Proton-Proton Chain [4H→He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

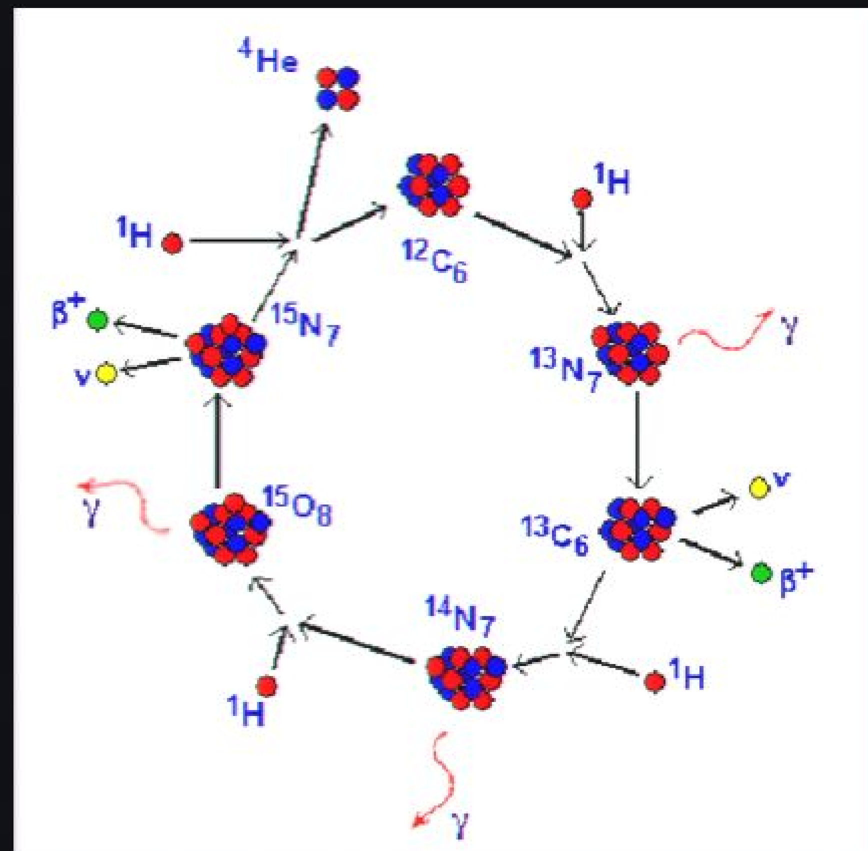
2He Is Formed

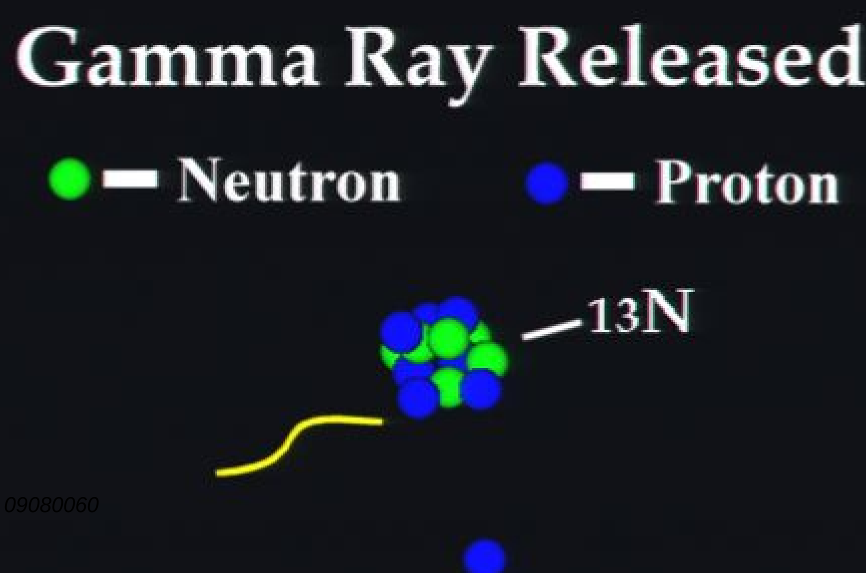
- Neutron
- Proton



CNO Cycle

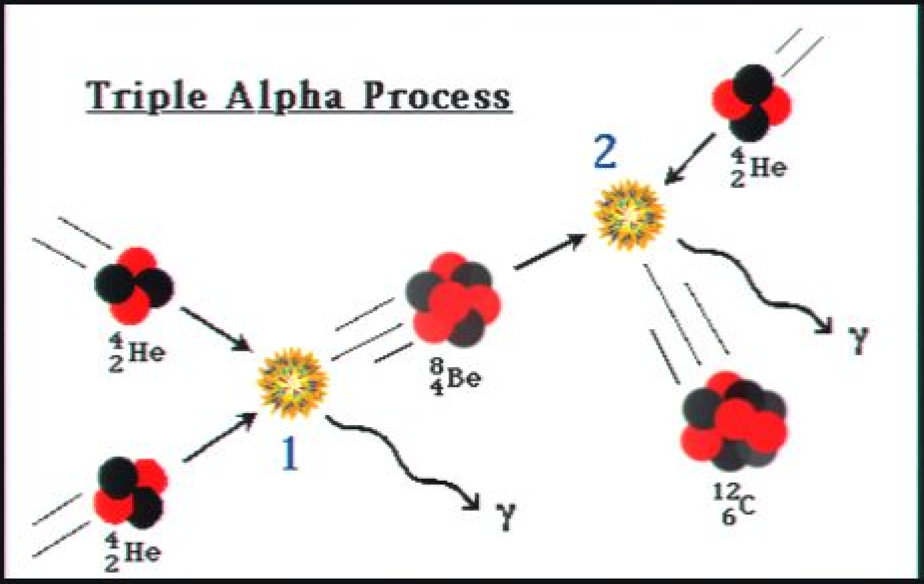
- *The higher the temperature, the more important the production of energy from the CNO.*
- *For stars less than 1 solar mass proton-proton cycle dominates.*





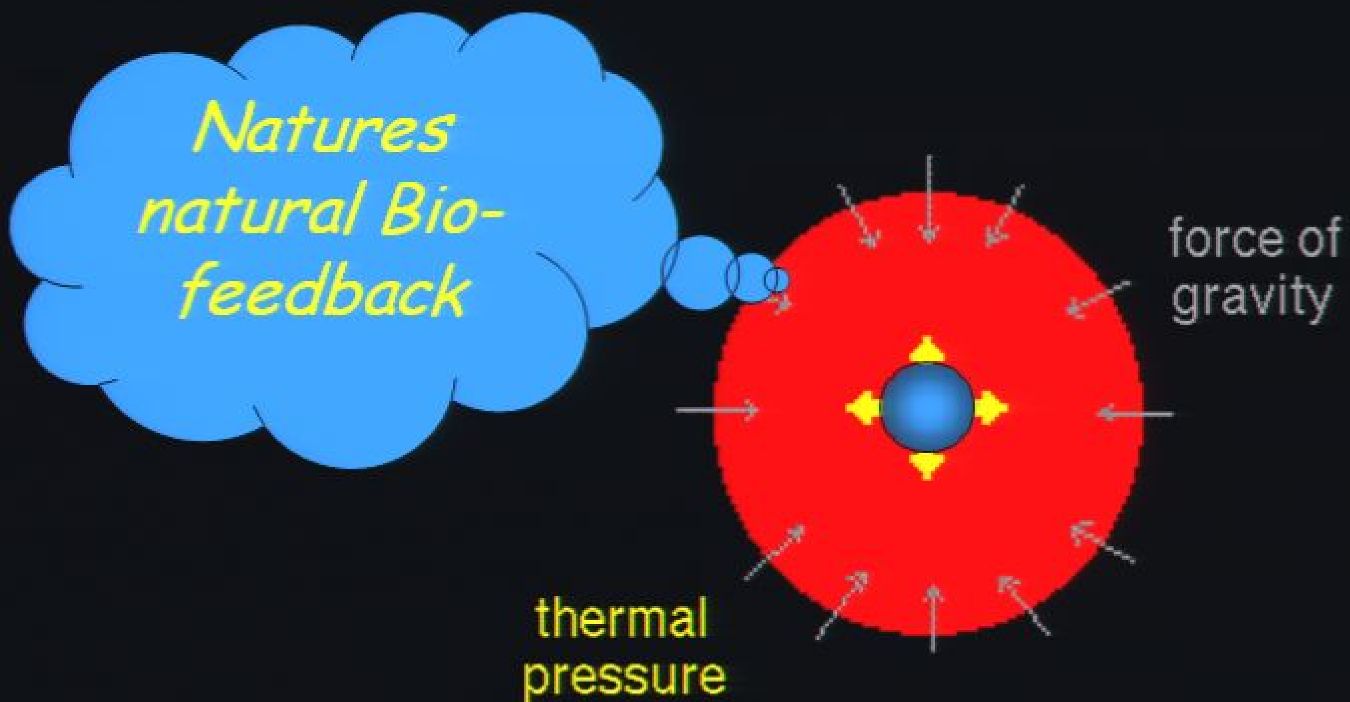
Beyond Helium

As Hydrogen is exhausted in the core of the star, Helium nuclei merge to create Beryllium with again fuses with another Helium nucleus to give Carbon and then to Oxygen then to Silicon until we finally end up with Iron.



The Death of Stars

Pressure Balance in a Star



Thermal Pressure = Force of Gravity

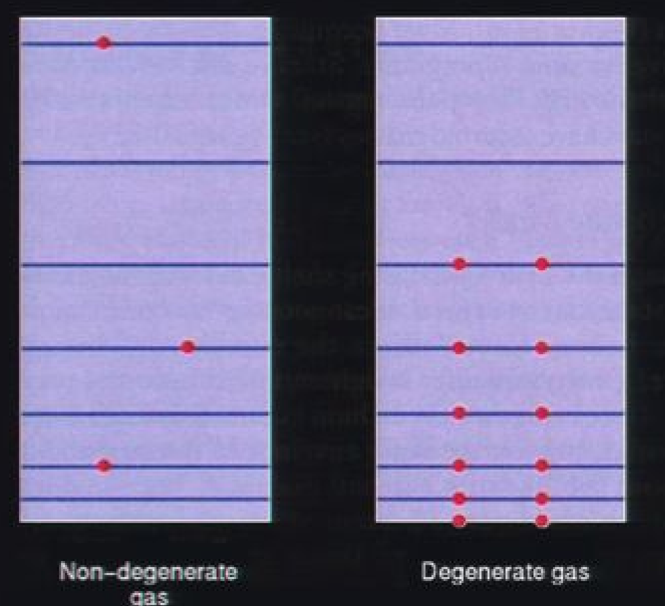
Model of an Atom

... an atom consists of mostly empty space ...

Electron Degeneracy Pressure

$$Radius = N_e^{\frac{2}{3}} \frac{h^2}{8Gm_e m_p M}$$

- Pauli Exclusion Principle:
  No two electrons (fermions) can occupy the same position in space at the same time doing the same thing.
- Electrons are packed side by side in a white dwarf
- This prevents it from collapsing any further



Calculate Magnitude of Radius

Electron Degeneracy Pressure

$$Radius = N_e^{\frac{2}{3}} \frac{h^2}{8Gm_em_pM}$$

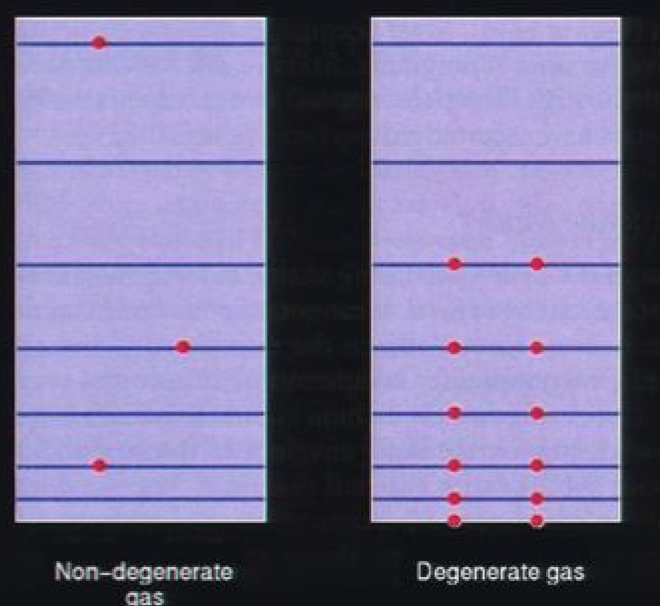
$$h = 6.6261 \times 10^{-34}$$

$$G = 6.6726 \times 10^{-11}$$

$$m_e = 9.1094 \times 10^{-31}$$

$$m_p = 1.6726 \times 10^{-27}$$

$$M = 1.989 \times 10^{30}$$



Calculate Magnitude of Radius

Electron Degeneracy Pressure

$$Radius = N_e^{\frac{2}{3}} \frac{h^2}{8Gm_e m_p M}$$

$$2.7\times10^{-31}m$$

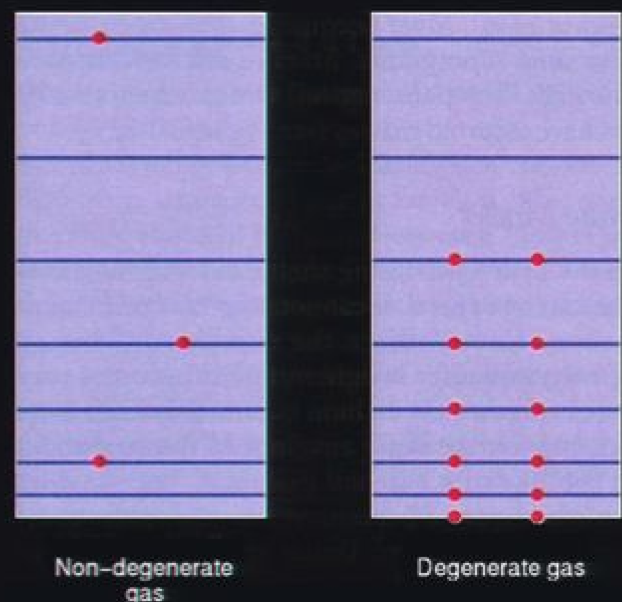
$$h = 6.6261\times10^{-34}$$

$$G = 6.6726\times10^{-11}$$

$$m_e = 9.1094\times10^{-31}$$

$$m_p = 1.6726\times10^{-27}$$

$$M = 1.989\times10^{30}$$



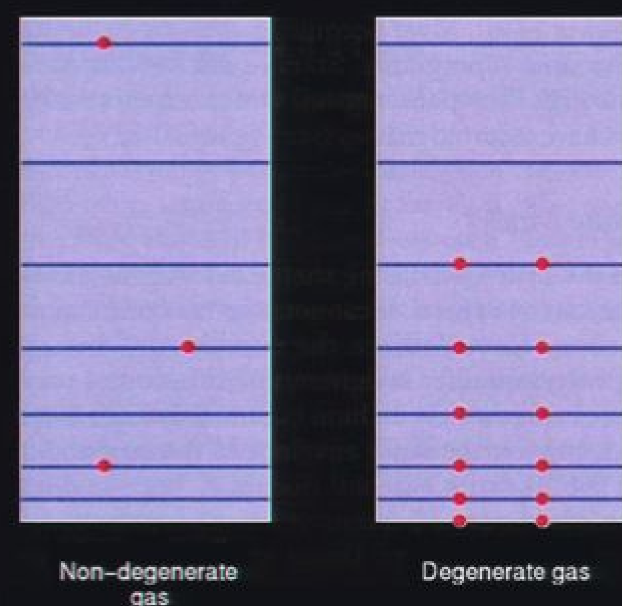
Electron Degeneracy Pressure

$$Radius = N_e^{\frac{2}{3}} \frac{h^2}{8Gm_e m_p M}$$

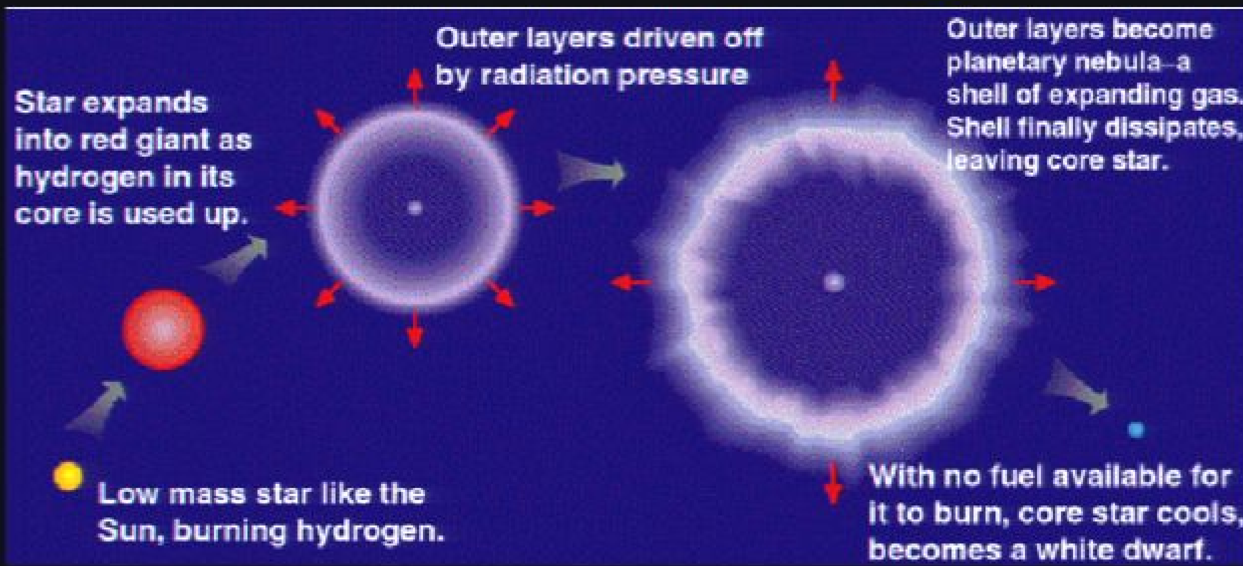
$$\left(5.95\times10^{56}\right)^{\frac{2}{3}}$$

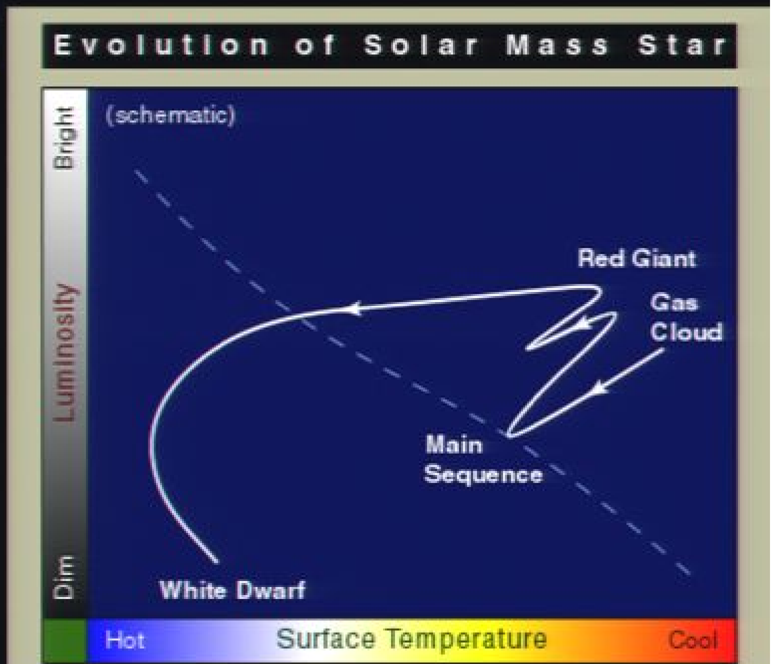
$$2.7\times10^{-31}\,m$$

$$\approx 10^7\,m$$



Path to being a White Dwarf





7 solar mass star now reduced to about 20% of its original mass

Properties of White Dwarfs

- Helium exhausted, core collapses until density forces electrons to leave their orbits around the atomic nuclei.

Properties of White Dwarfs

- Helium exhausted, core collapses until density forces electrons to leave their orbits around the atomic nuclei.
- ...are found in the centers of planetary nebula.

Properties of White Dwarfs

- Helium exhausted, core collapses until density forces electrons to leave their orbits around the atomic nuclei.
- ...are found in the centers of planetary nebula.
- ...have masses less than the Chandrasekhar mass (1.4 Solar Masses).

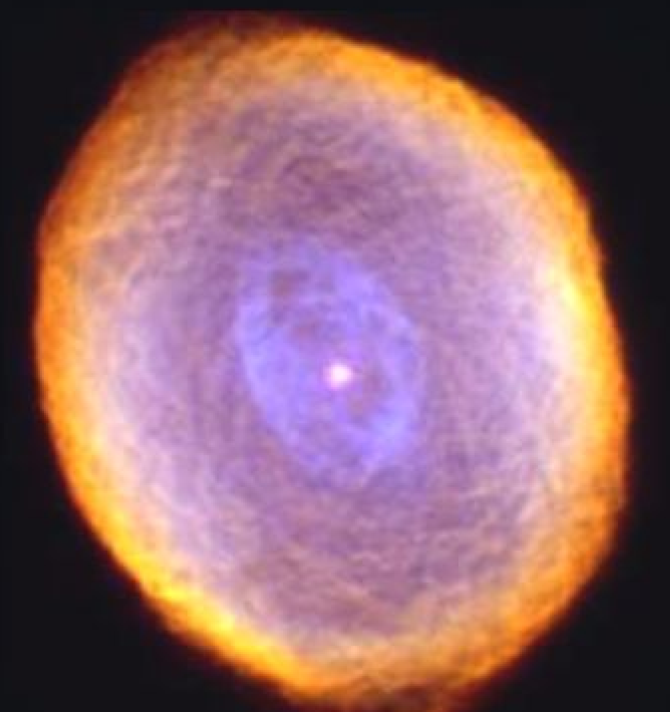
White Dwarf Properties

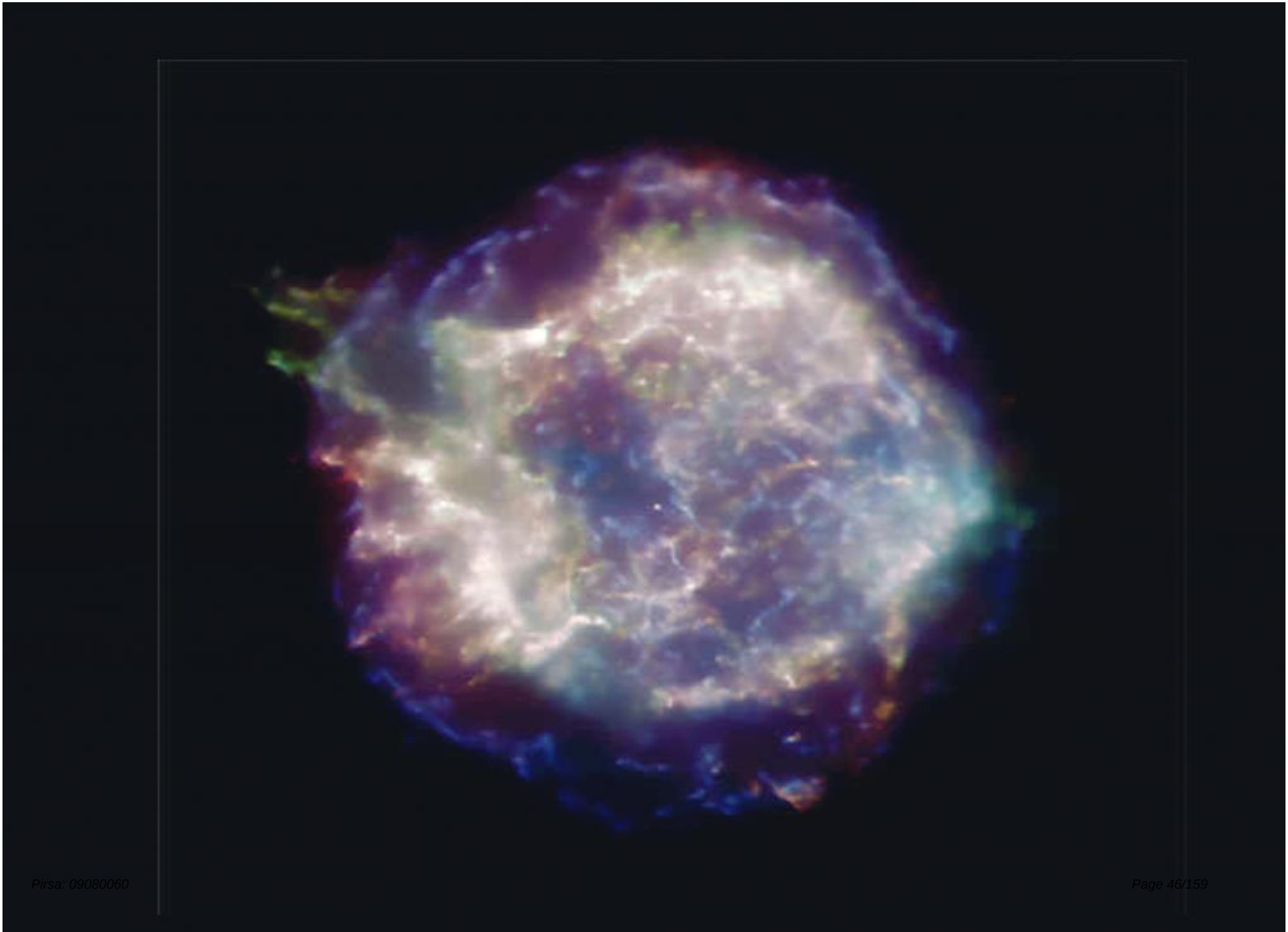
...have diameters about the same as the Earth's.

Look in the Middle

Cat's eye nebula

Spirograph Nebula





Eskimo Nebula

Above the Chandrasekhar Limit

- The maximum mass of a white dwarf is 1.4 solar masses

Above the Chandrasekhar Limit

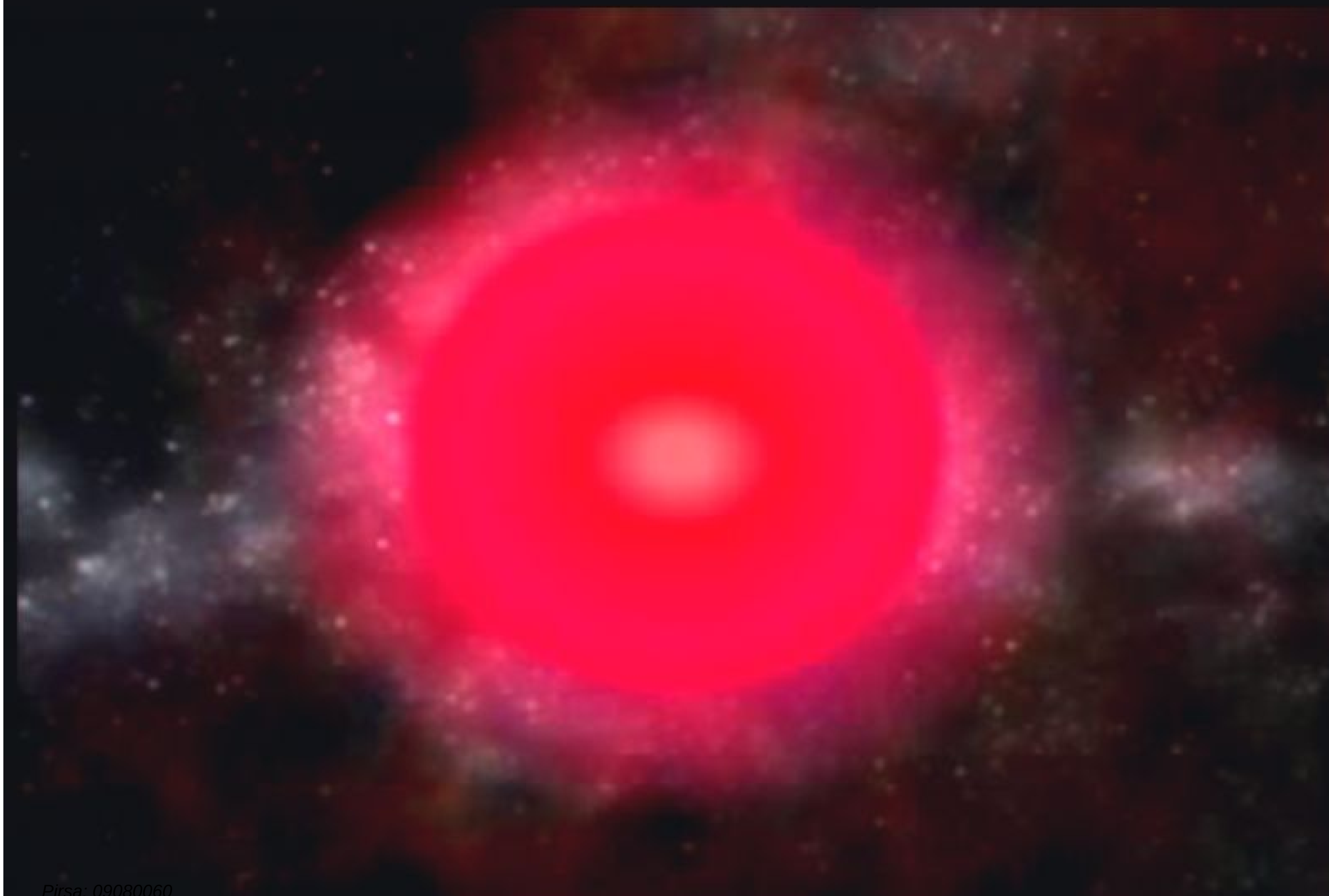
- The maximum mass of a white dwarf is 1.4 solar masses
- Above this, even electron degeneracy pressure cannot counterbalance gravity
- What is the fate of a star more massive than this?

Above the Chandrasekhar Limit

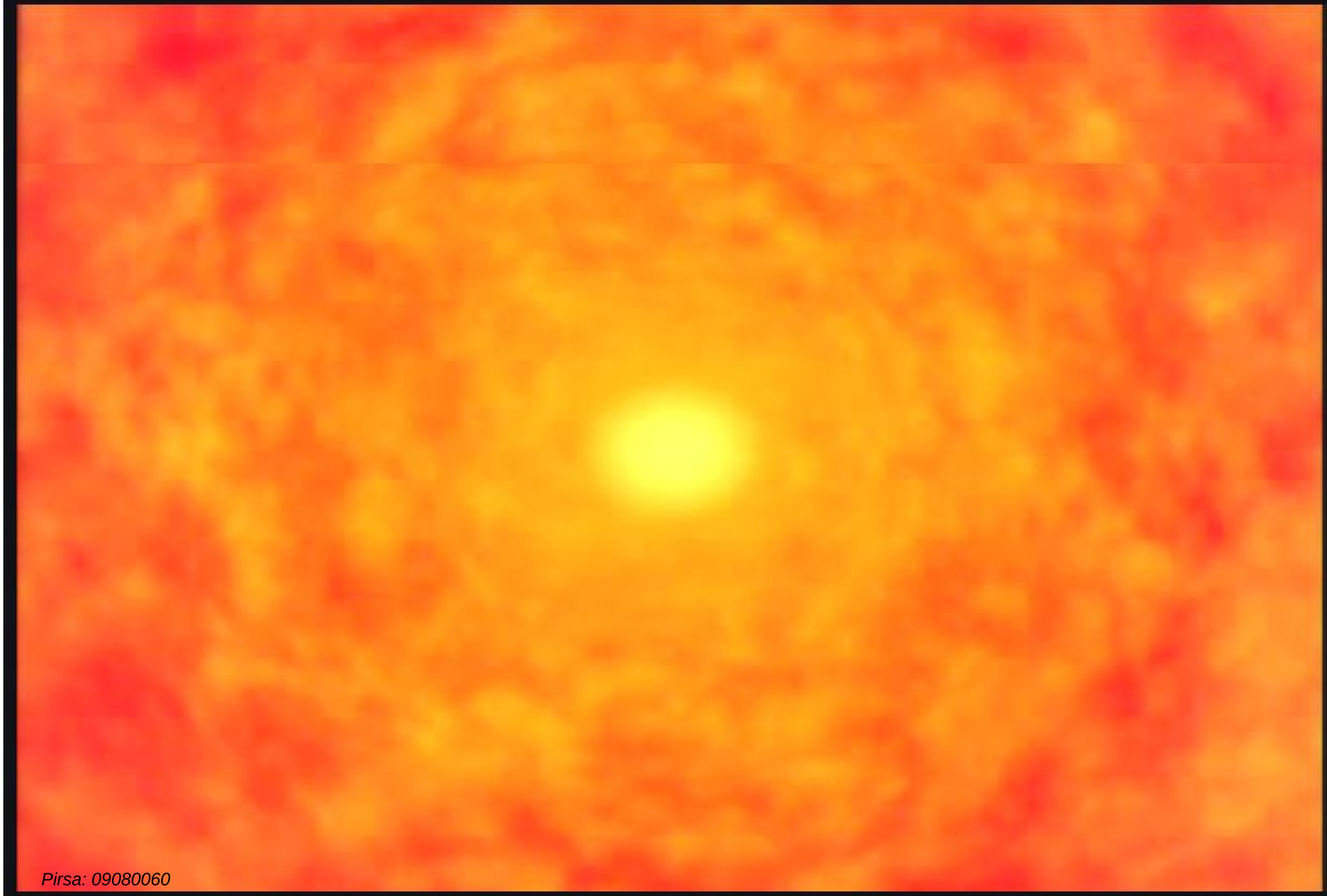
- The maximum mass of a white dwarf is 1.4 solar masses
- Above this, even electron degeneracy pressure cannot counterbalance gravity
- What is the fate of a star more massive than this?

Can you feel the suspense?

A Super Nova



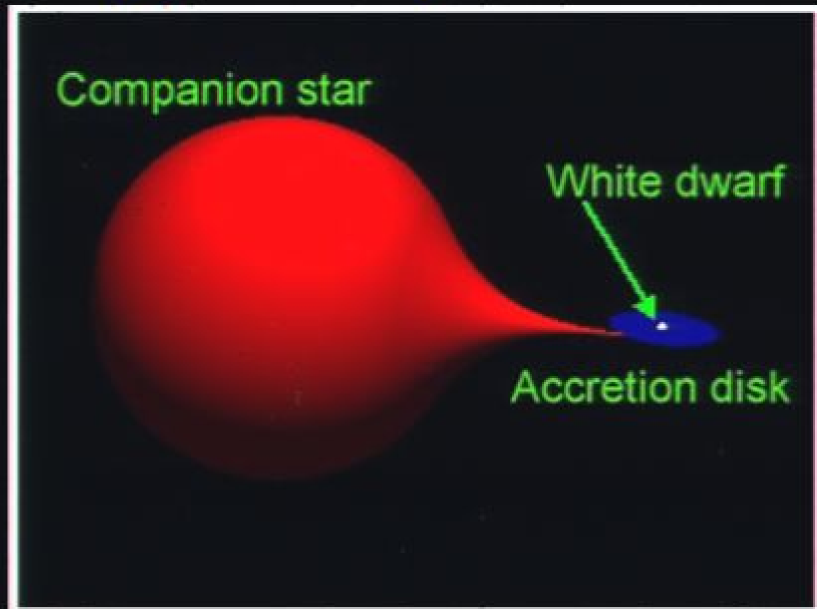
A Super Nova



A Super Nova

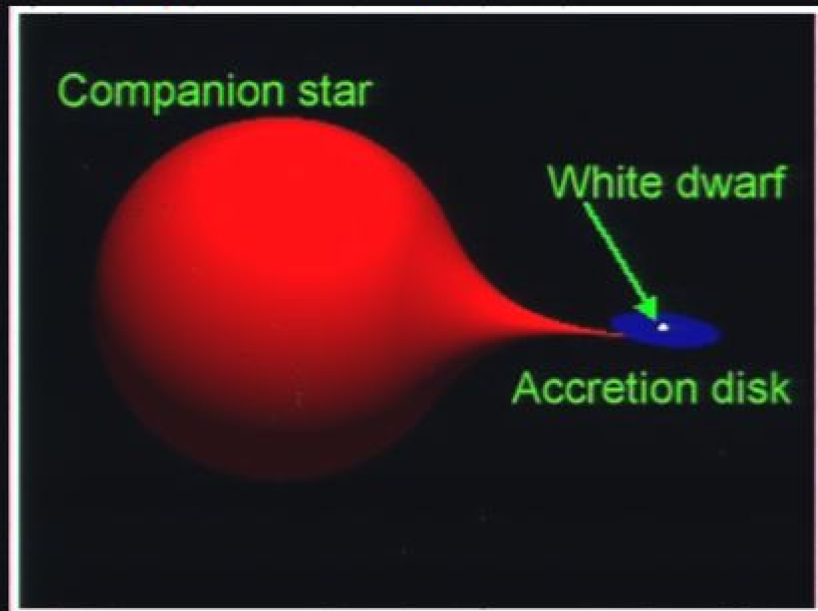
Type 1a Super Nova

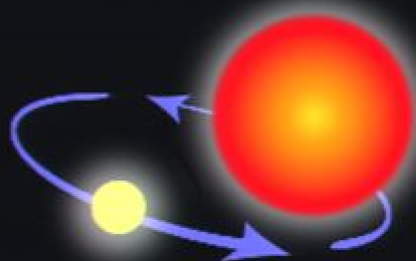
Two normal stars
are in a binary pair.



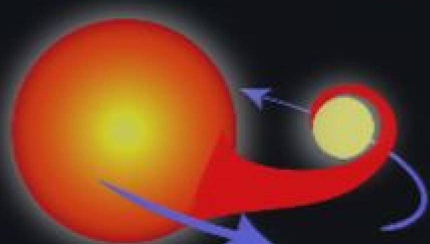
Type 1a Super Nova

Two normal stars
are in a binary pair.

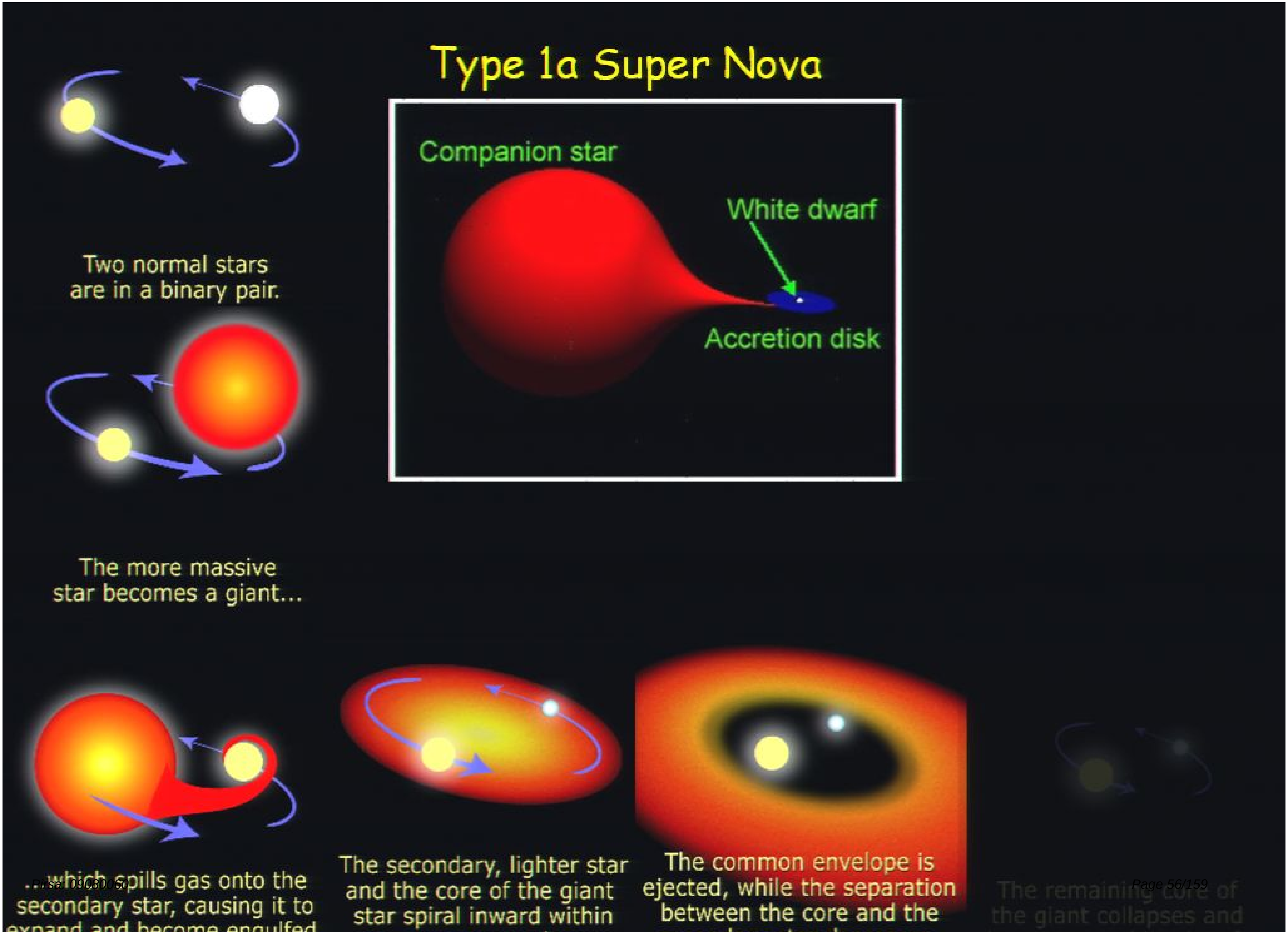




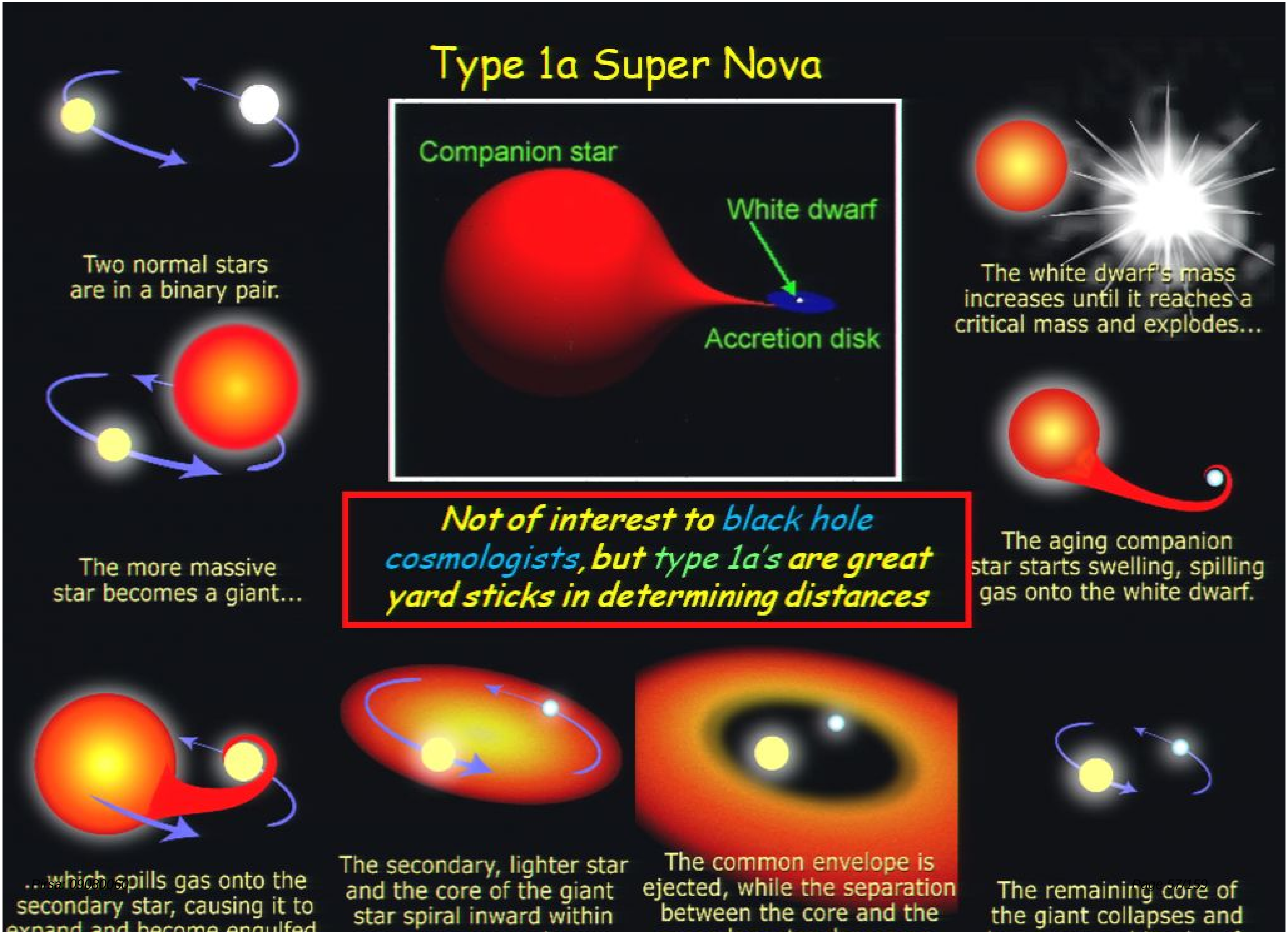
The more massive
star becomes a giant...



...which spills gas onto the
secondary star, causing it to
expand and become engulfed



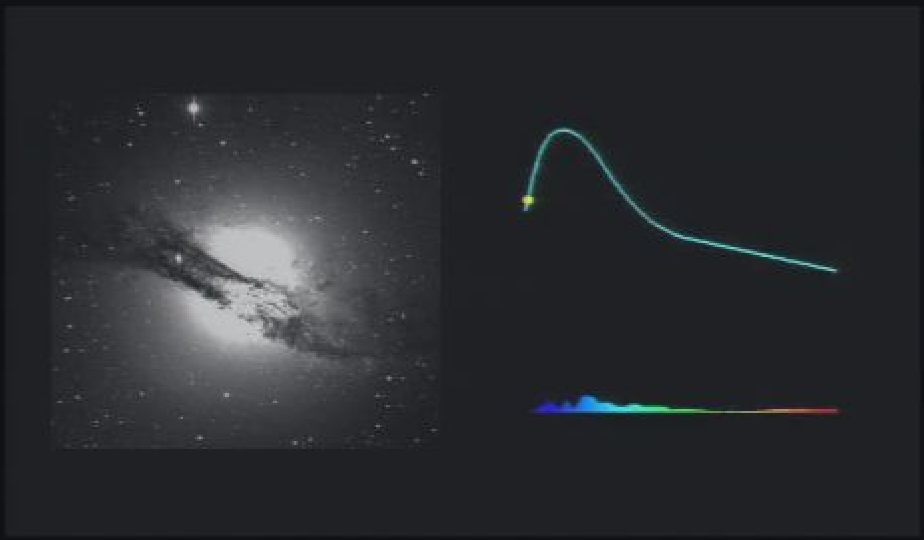
Type 1a Super Nova
Companion star
White dwarf
Accretion disk
Two normal stars are in a binary pair.
The more massive star becomes a giant...
...which spills gas onto the secondary star, causing it to
The secondary, lighter star and the core of the giant star spiral inward within
The common envelope is ejected, while the separation between the core and the
The remaining core of the giant collapses and

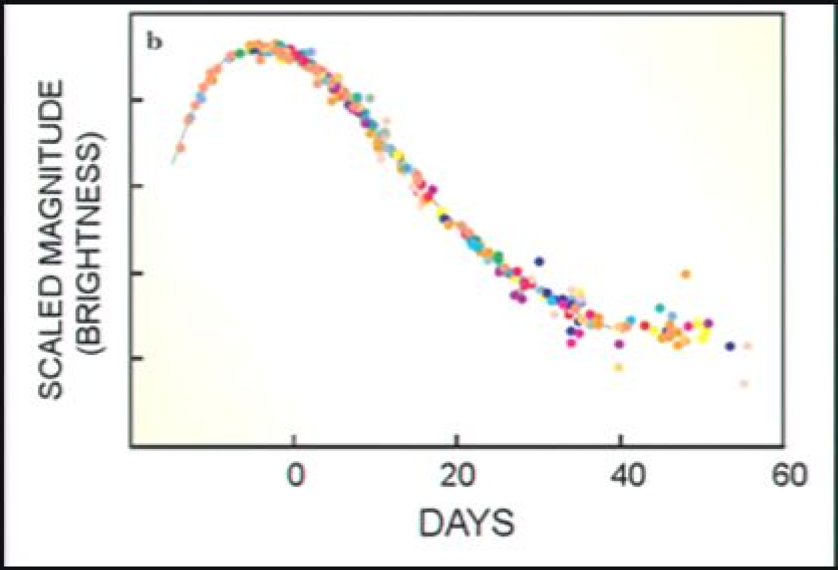

Type 1a Super Nova
Companion star
White dwarf
Accretion disk
Two normal stars are in a binary pair.
The more massive star becomes a giant...
Not of interest to black hole cosmologists, but type 1a's are great yard sticks in determining distances
The white dwarf's mass increases until it reaches a critical mass and explodes...
The aging companion star starts swelling, spilling gas onto the white dwarf.
...which spills gas onto the secondary star, causing it to
The secondary, lighter star and the core of the giant star spiral inward within
The common envelope is ejected, while the separation between the core and the
The remaining core of the giant collapses and

Standard Candle

Mark Phillips discovered that type 1a Supernova had a period/luminocity relationship. The time it takes for the SN to decline in brightness determined what the maximum brightness was. The decline took weeks so it became easy for astronomers to use these SN as a standard candle.

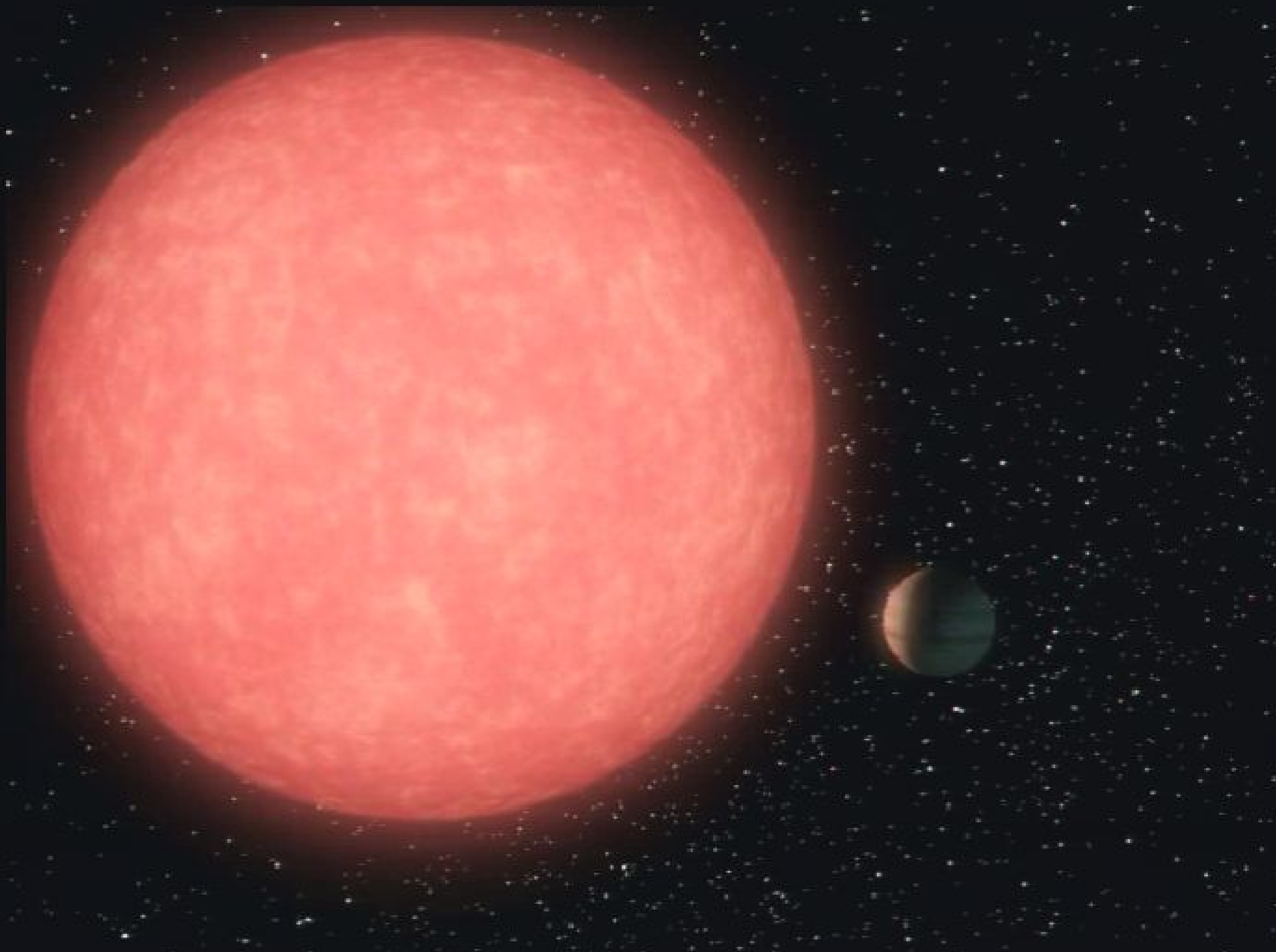
Standard Candle





Mark Phillips discovered that type 1a Supernova had a period/luminocity relationship. The time it takes for the SN to decline in brightness determined what the maximum brightness was. The decline took weeks so it became easy for astronomers to use these SN as a standard candle.

Type II Supernovae: Birth of a Neutron Star



- *The core survives and is prevented from collapsing any further by neutron degeneracy pressure*

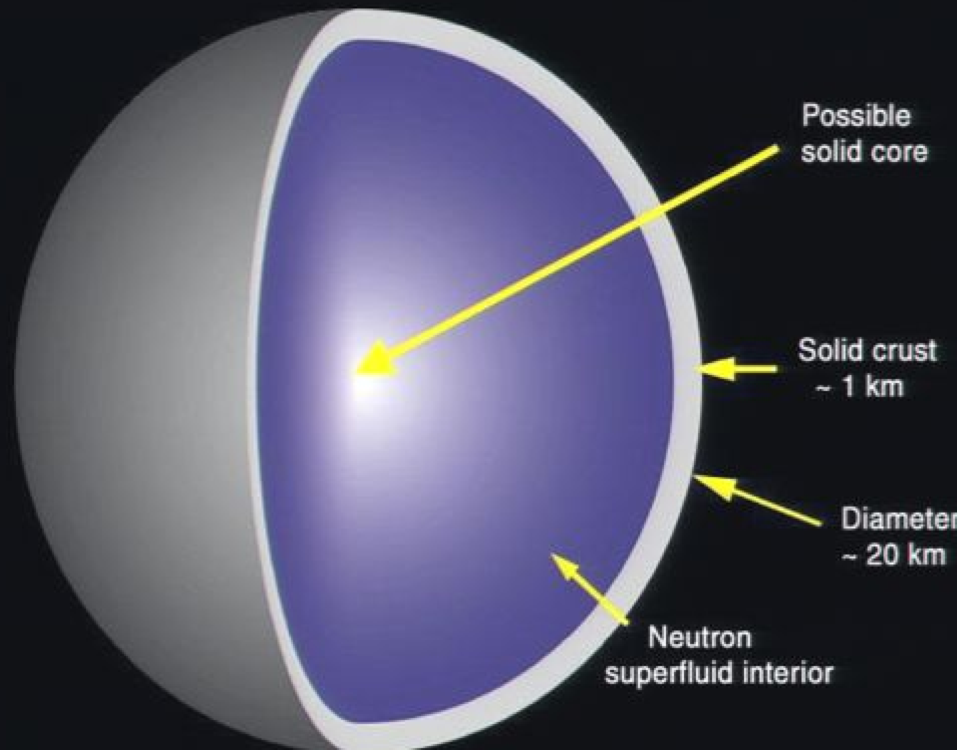
- *These are the type of supernovae we are interested in.*

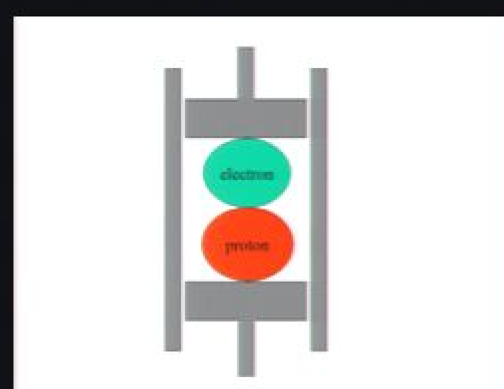
Supernova Remnant

- In the death of a high-mass star (<40 solar mass), the core is converted to neutrons and collapses catastrophically.
- The collapse and rebound creates a supernova.
- The electrons are 'merged' with the protons which produce neutrons.
- The central core is left behind as a small, dense, sphere of neutrons → a neutron star.
- Collapsing stops now because of Neutron Degeneracy Pressure.

Neutron Star Facts

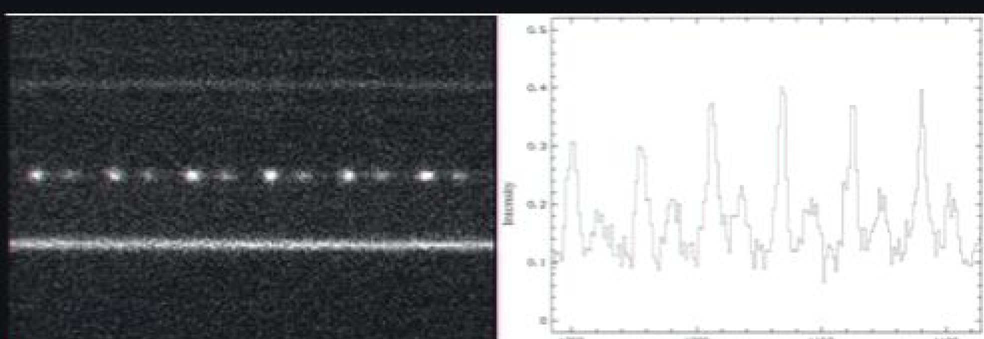
- A giant ball of neutrons.
- Mass : at least 1.4 x mass of the Sun to maximum of about 3 solar masses.
- Temperature 1 million degrees and cooling.
- Diameter: 20 km!
- Density: 10^{18} kg/m^3
  - A sugar cube of this matter weighs 400 billion tons
- Day: 1 – 0.001 seconds!
- Magnetic fields as strong as the Sun, but in the space of a city.
- But just a theory until 1968





Pulsars

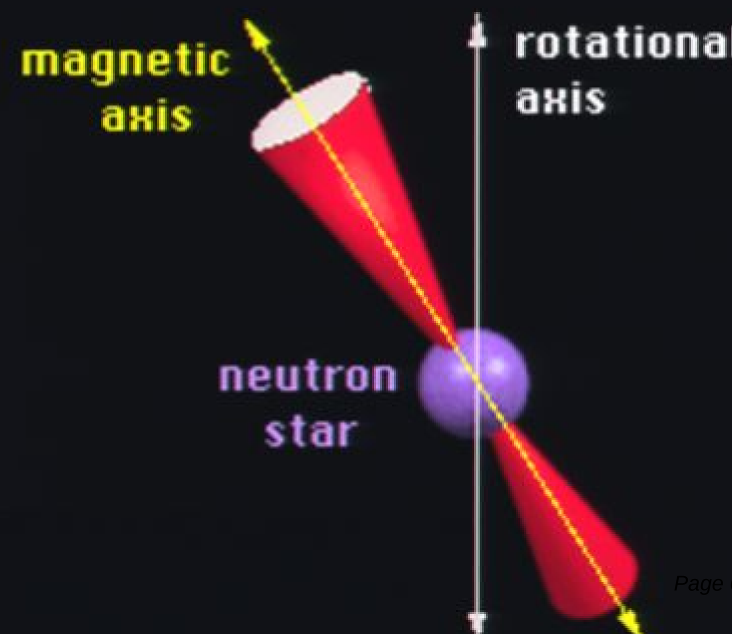
- Discovered by Bell and Hewish in 1968
- Stands for pulsating stars, since they emit regular pulses
- Now known to be spinning neutron stars



Time Sequence of Crab Pulsar

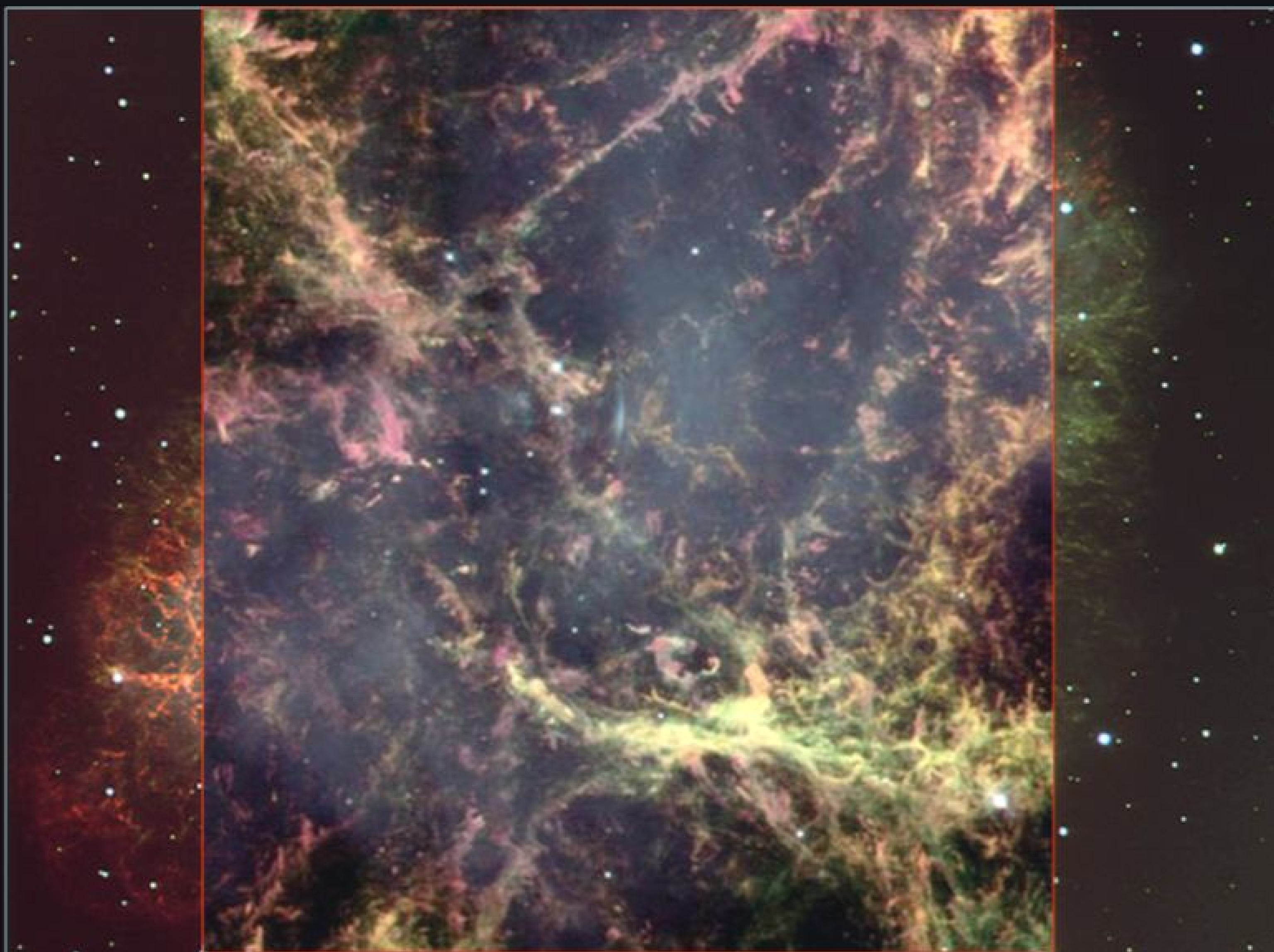
Light Curve of Crab Pulsar

(VLT KUEYEN + FORS2 + FIERA) © ESO

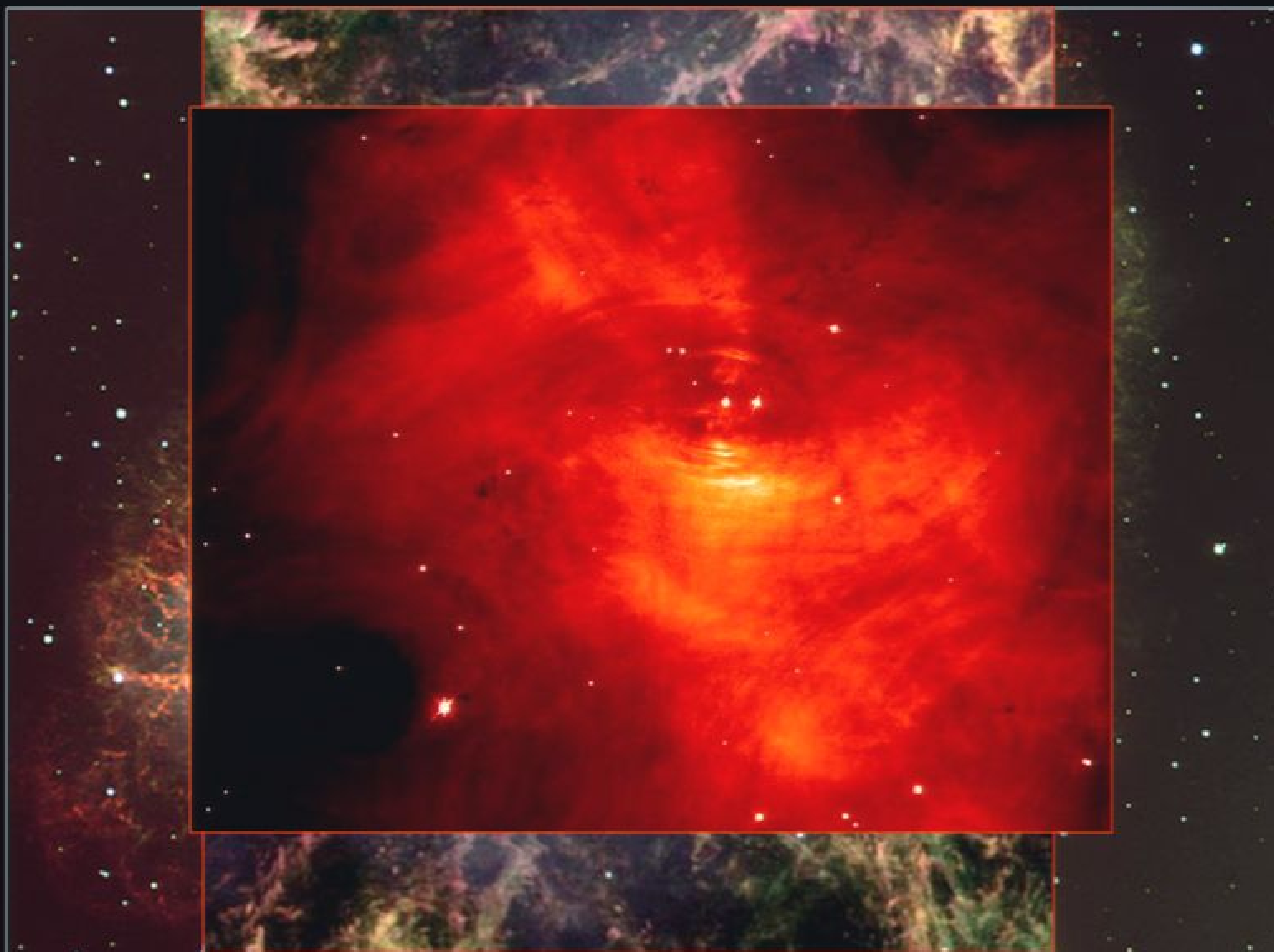


Crab Nebula Pulsar

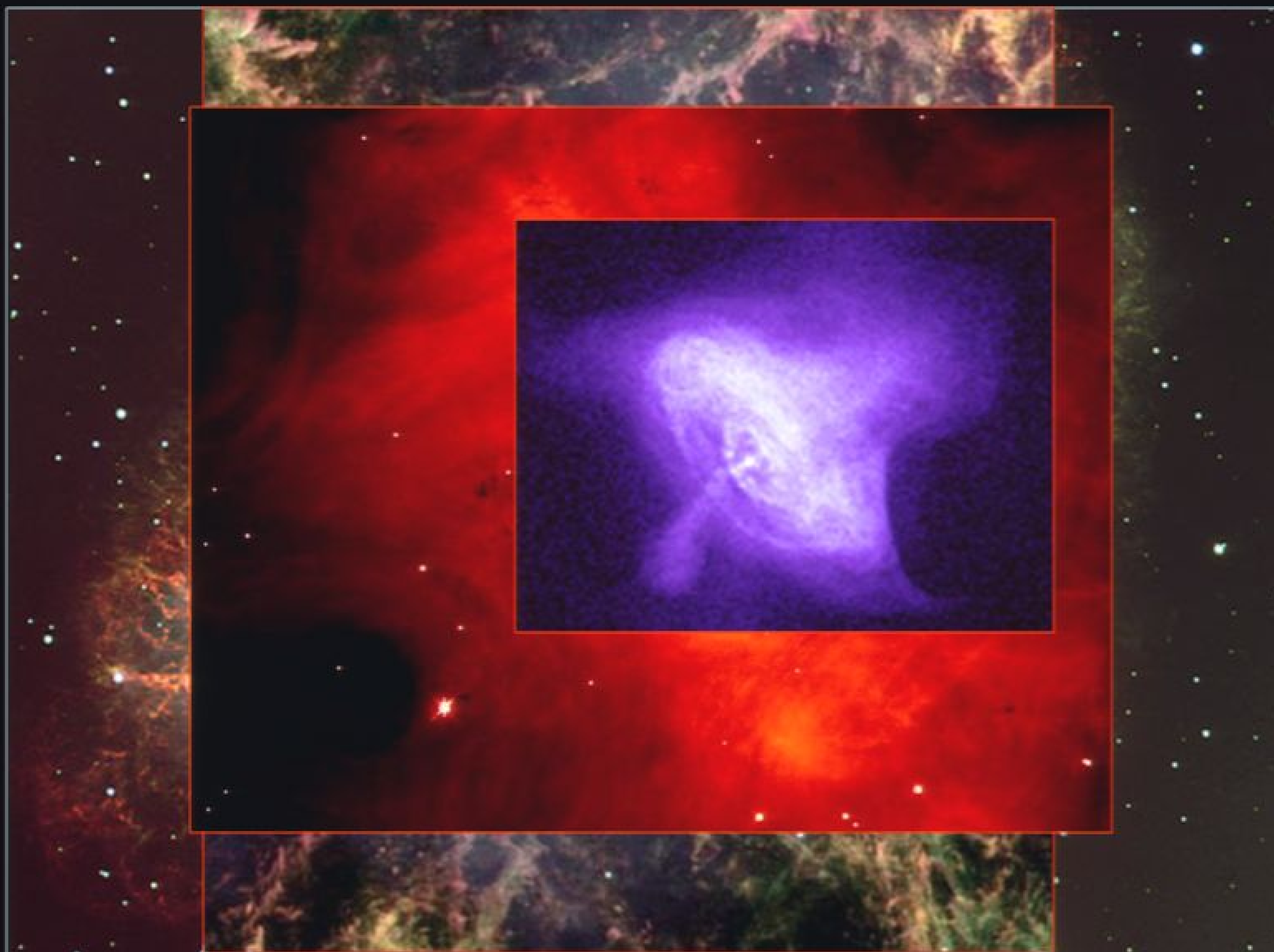
Crab Nebula Pulsar



Crab Nebula Pulsar



Crab Nebula Pulsar



Crab Nebula Pulsar

What Next

What Next

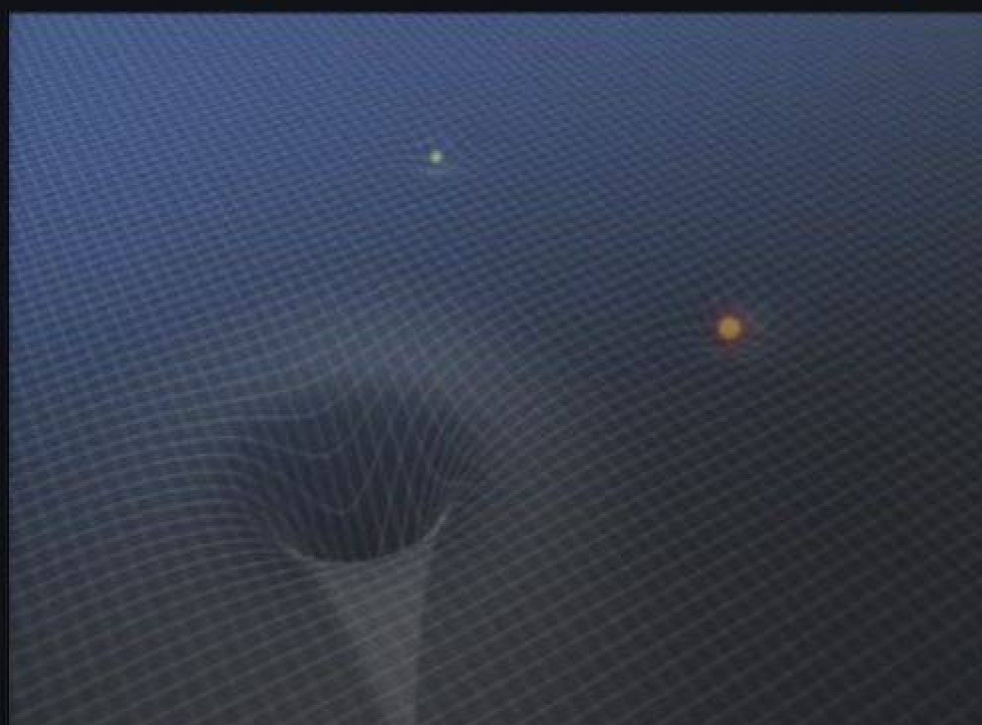
- Neutron stars are held up by neutron degeneracy pressure.
  - Recall electron degeneracy pressure for white dwarfs.
  - For white dwarfs, maximum mass of 1.4 M_{sun}
- For neutron stars, maximum mass ~3M_{sun}
- What happens if a high-mass star is SO big that its central core is bigger than this?
- What happens when gravity is stronger than even neutron degeneracy pressure?
- How dense can something get?
- How strong can the force of gravity be?
- What if the escape velocity is <u>faster than light</u>?

If we could eliminate the radiation and light, what would it be like to watch the collapsing of a star into a Black Hole? What would it be light to fall into a Black Hole?

Watching a Star Collapse from a Safe Distance

If you watched a star collapsing into a Black Hole, the light emitted from the star would be red-shifted and as a result would get dimmer by a factor of 2 every 20 micro-seconds per solar mass. At the same time the surface would appear to slow down and become frozen

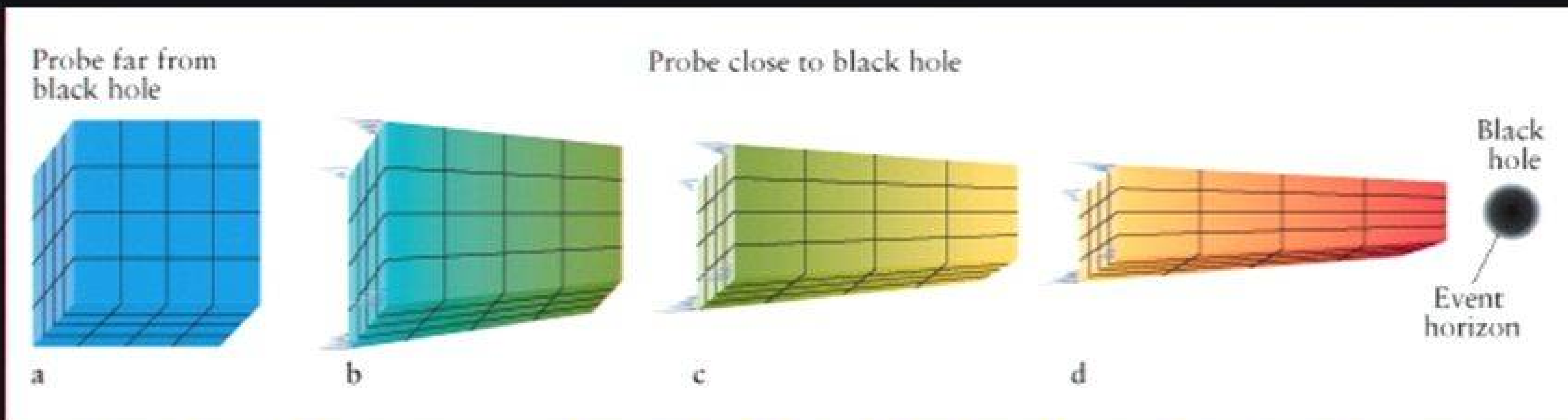
This is not too Exciting... what about visiting the Black Hole?



$$L \propto e^{-\frac{t}{3\sqrt{3}M}}$$

$$t = 10^{-3}\left(\frac{M_{star}}{M_{\odot}}\right)$$

Traveling into a Black Hole

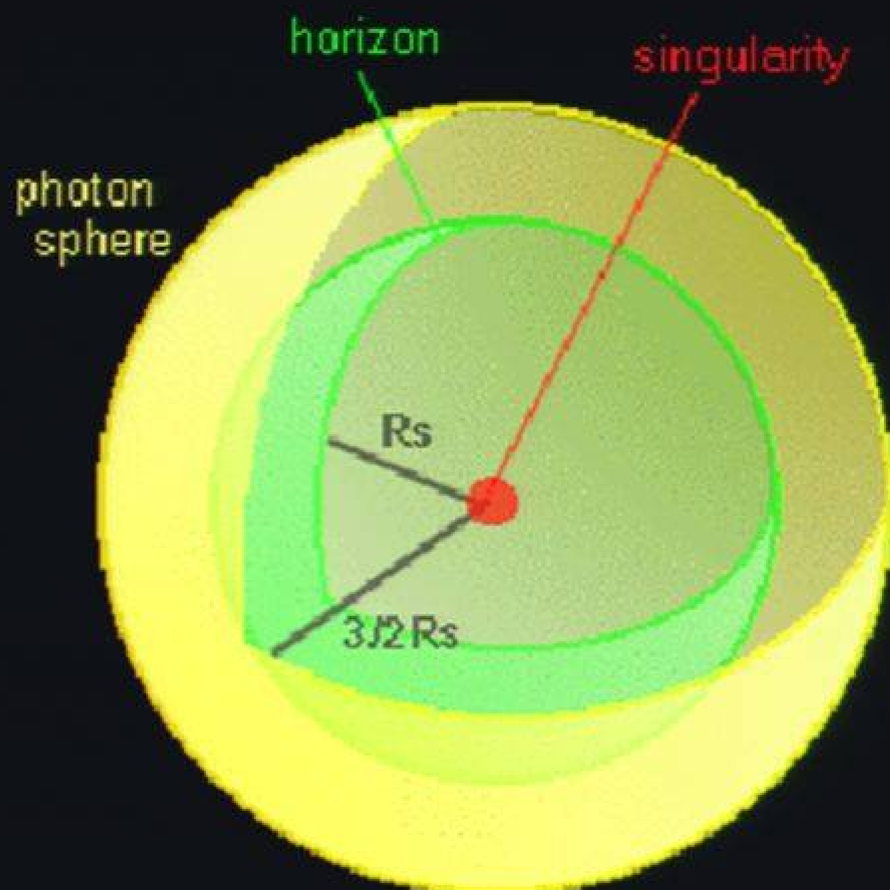


- As the ship approaches the black hole, the ship is elongated by the variation in gravity
- The ship is also gravitationally red shifted at the end closer to the black hole
- From the outside, the ship will appear to hover forever at the edge of the hole to us - an effect of the time dilation, yet in the ship, the occupant do enter into the black hole. Never to be heard from again.

Watching a clock fall into a black hole

To get a better understanding of what is happening, and more specifically where it is happening. Let's look at the anatomy of a Black Hole

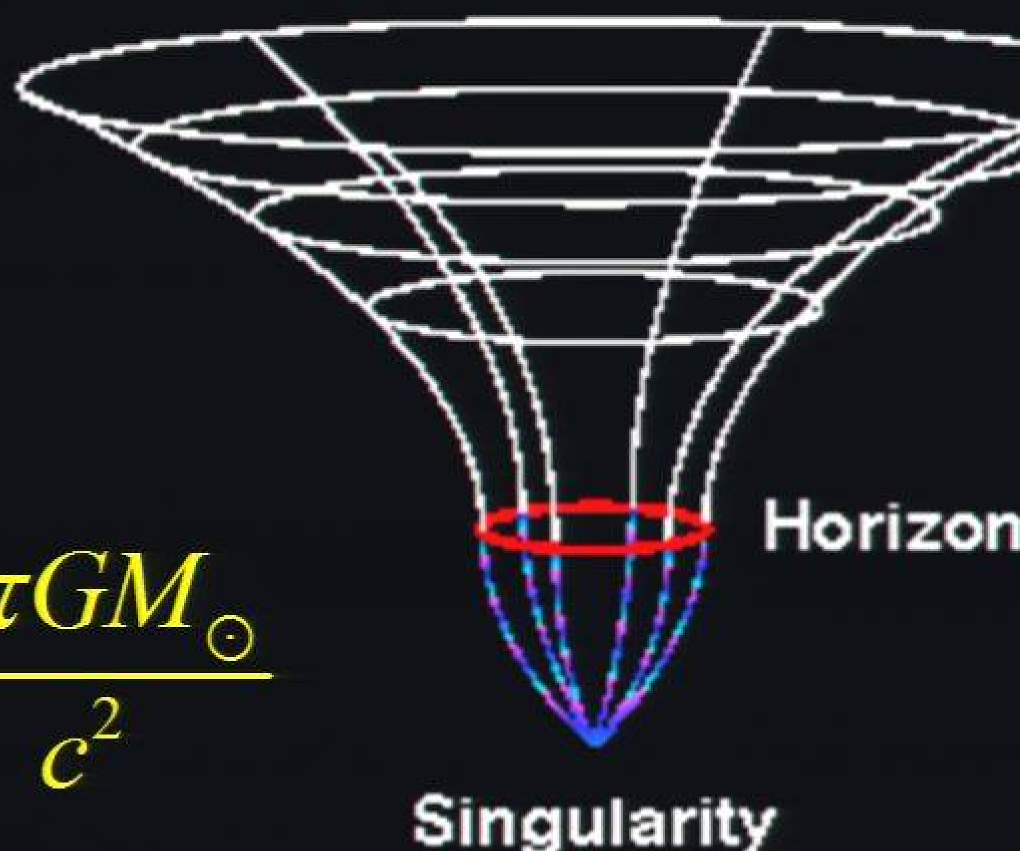
Structure of a Schwarzschild Black Hole



Singularity

- Within the singularity, matter is infinitely compressed into a region of infinite density. At the singularity, gravity is infinite. Space-time has become infinitely curved. At the present time, science has no tools to describe conditions within the singularity. All laws of physics lose meaning in such a region.
- At a singularity, space and time cease to exist as we know them. The laws of physics as we know them break down at a singularity, so it's not really possible to envision something with infinite density and zero volume.

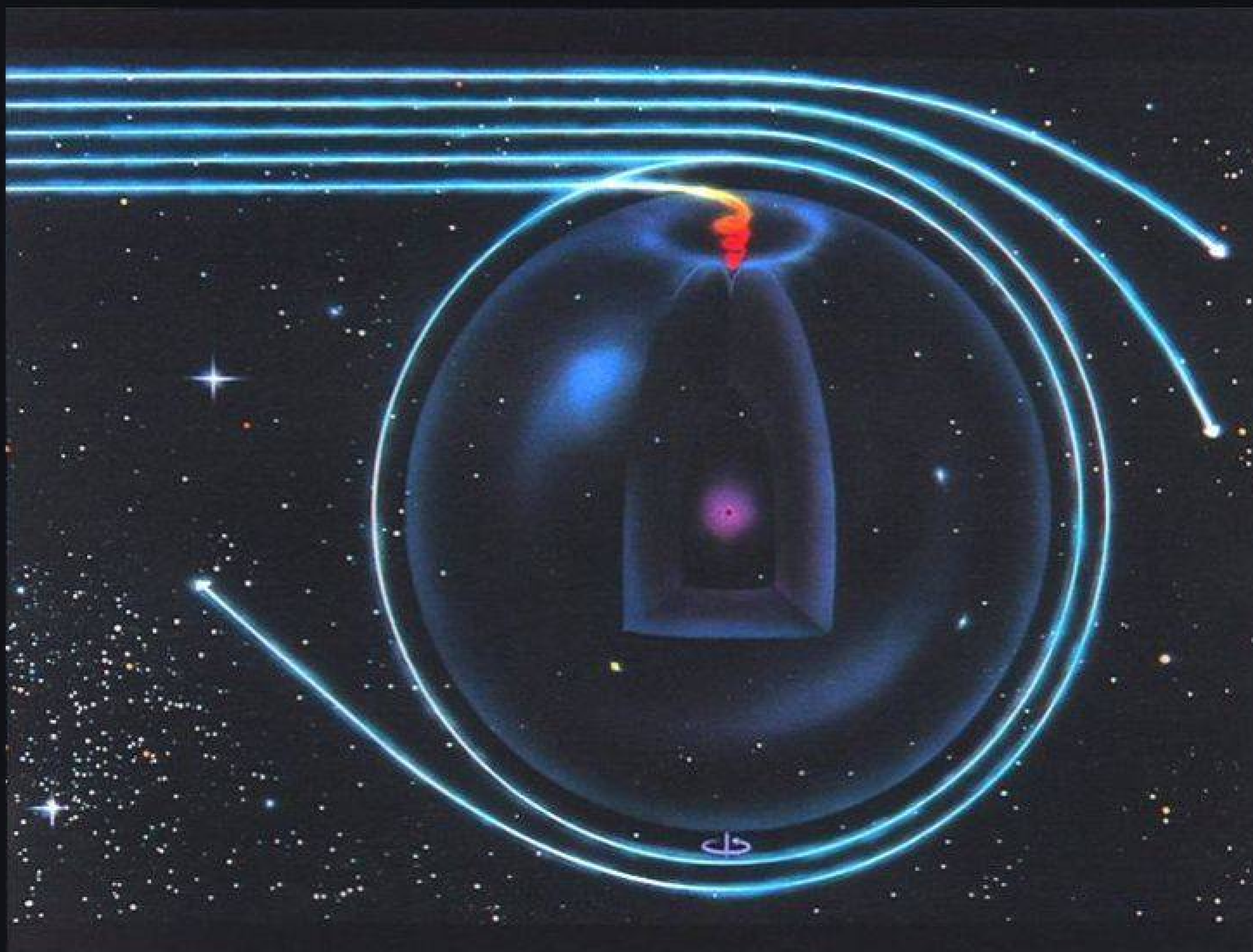
Embedding Structure



$$C_b = \frac{4\pi G M_\odot}{c^2}$$

$$r_s = \frac{2GM_\odot}{c^2}$$

Photon orbits around a black hole



Time Dilation and Blueshift

$$t_2 = \frac{t_1}{\sqrt{1 - \frac{C_b}{C}}}$$

If you hovered at 1.00 000 1 times the event horizon circumference, then one day for you would mean ...

Time Dilation and Blueshift

$$t_2 = \frac{t_1}{\sqrt{1 - \frac{C_b}{C}}}$$

If you hovered at 1.00 000 1 times the event horizon circumference, then one day for you would mean ...

1024 days for the rest of the universe.

$$\lambda_r = \lambda_e \sqrt{1 - \frac{C_b}{C}}$$

If you hovered at 1.00 000 8 times the event horizon circumference, visible light (5.8 x 10^{-7} m) from the stars would appear at wavelength ...

The Effects

No matter how powerful your starship, once you enter the Event Horizon, you might as well enjoy the trip, because you are going in.

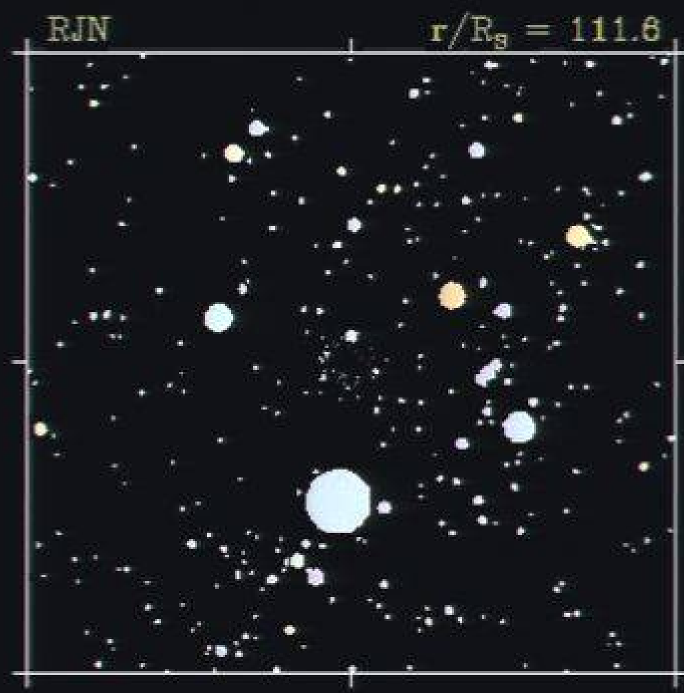
Visiting a Black Hole

Spaghettification!

$$\Delta a = \frac{16\pi^3 GLM_b}{C^3}$$

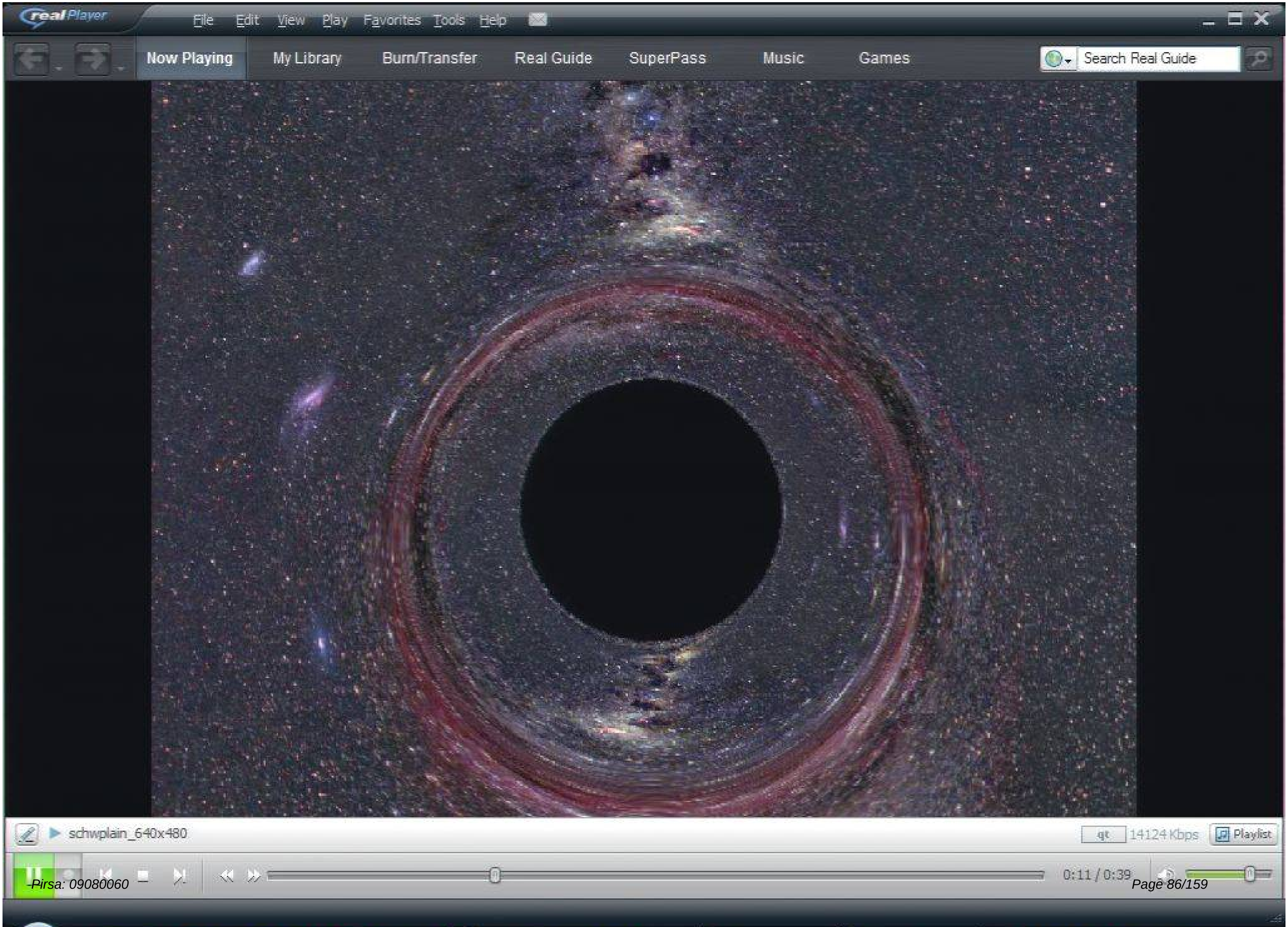
$$\Delta a \propto \frac{1}{{M_b}^2}$$

Approaching

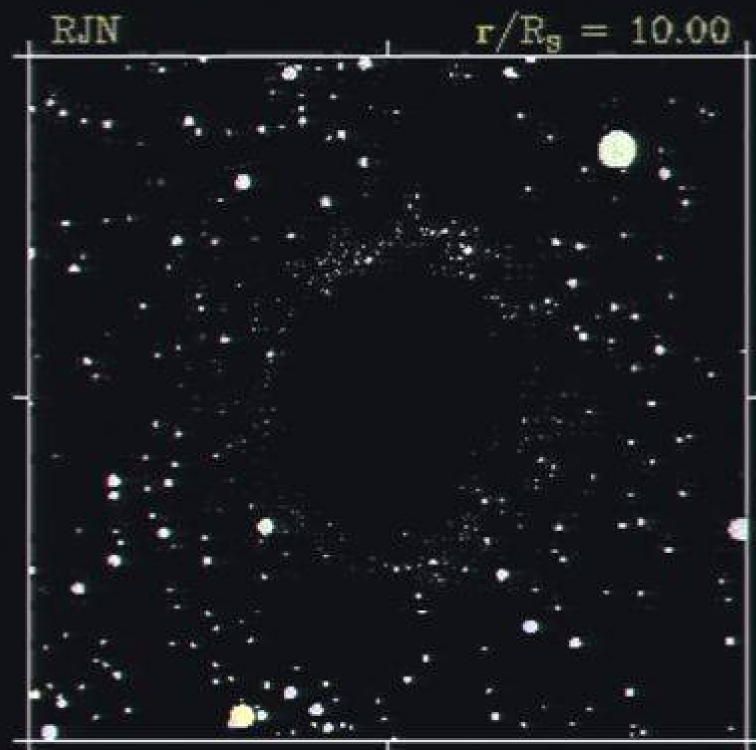


Modern

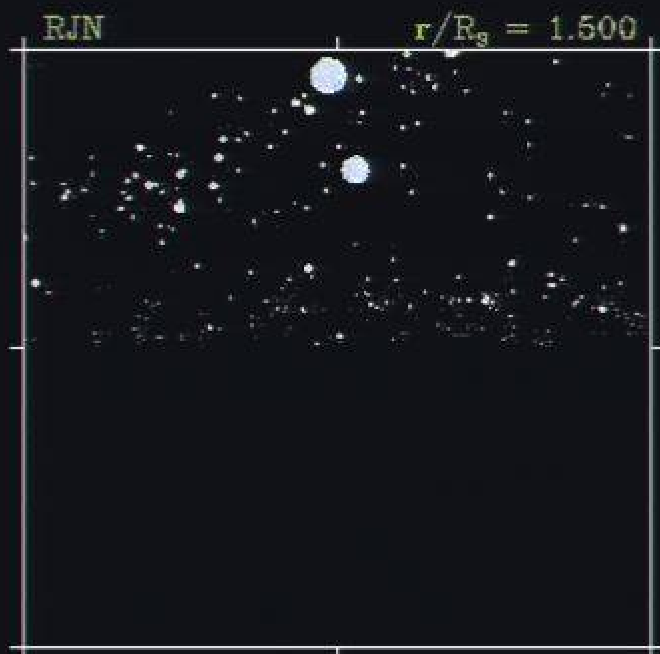
http://jilawww.colorado.edu/~ajsh/insidebh/schw.html


real Player
File
Edit
View
Play
Favorites
Tools
Help
Now Playing
My Library
Burn/Transfer
Real Guide
SuperPass
Music
Games
Search Real Guide
schwplain_640x480
qt
14124 Kbps
Playlist
0:11 / 0:39

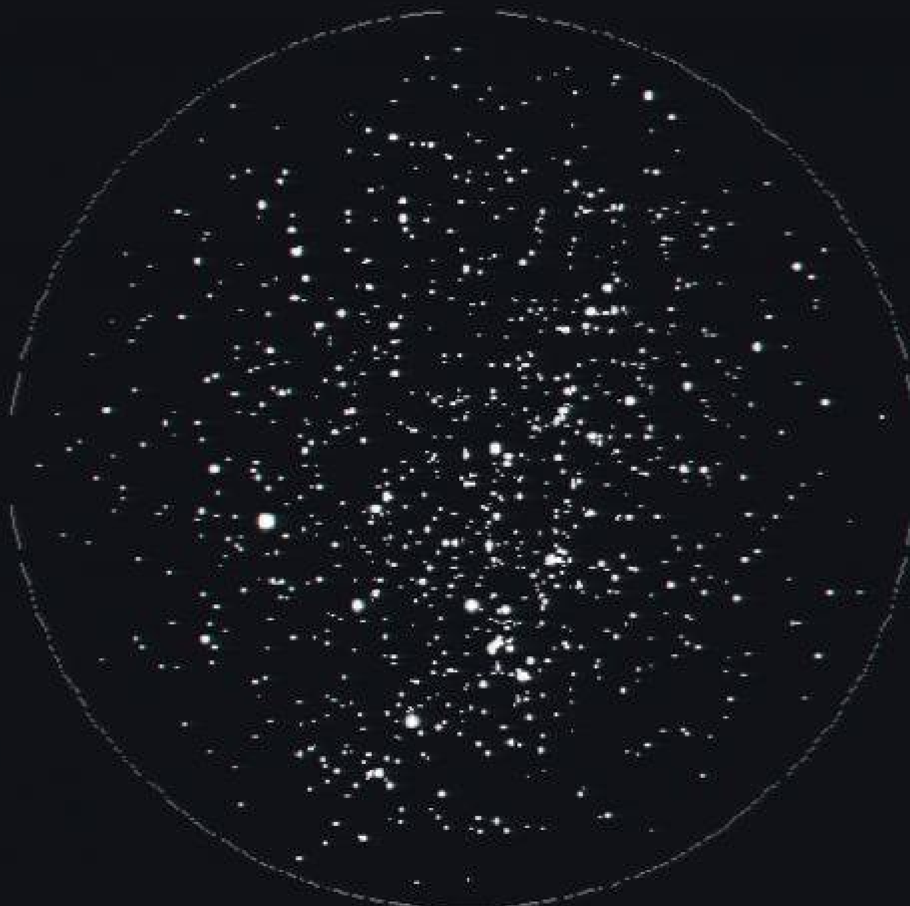
Orbiting Black Hole Looking Down



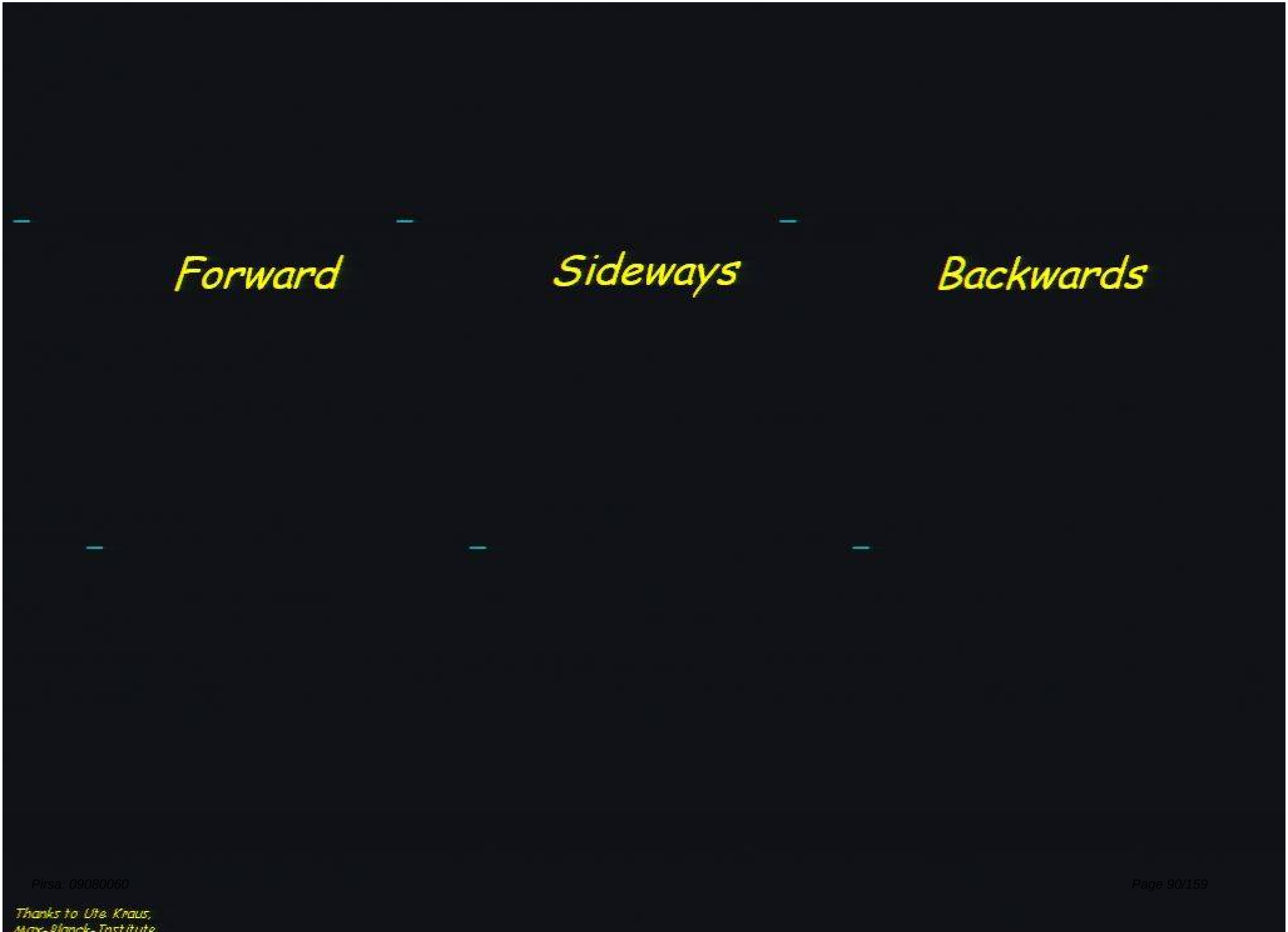
Orbiting Looking Horizontally at Photon Sphere



Looking Up



$$r = 12\tan\left(\frac{5\pi}{6}\sqrt{1-\frac{C_b}{C}}\right)$$


Forward
Sideways
Backwards
Thanks to Ute Kraus,
Max-Planck-Institute

Forward

Sideways

Backwards

r = 100 rs

Thanks to Ute Kraus,
Max-Planck-Institute

Forward

Sideways

Backwards

$r = 20\, r_s$

Thanks to Ute Kraus,
Max-Planck-Institute

Forward

Sideways

Backwards

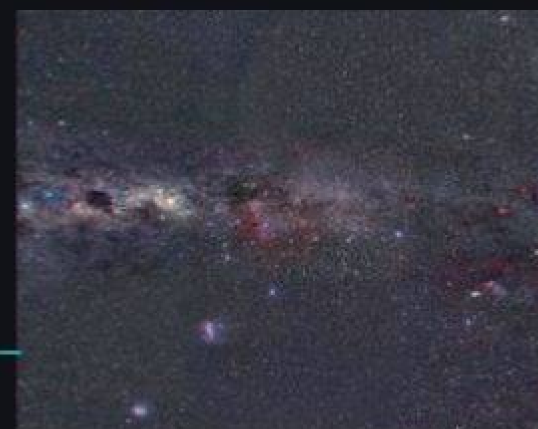
$r = 4.5\ rs$

Thanks to Ute Kraus,
Max-Planck-Institute

Forward

Sideways

Backwards

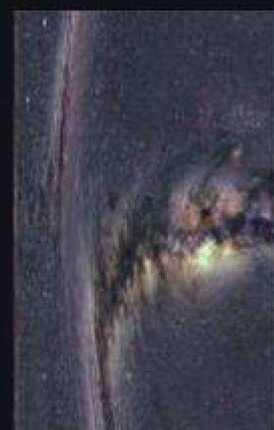


$r = 2.5\, rs$

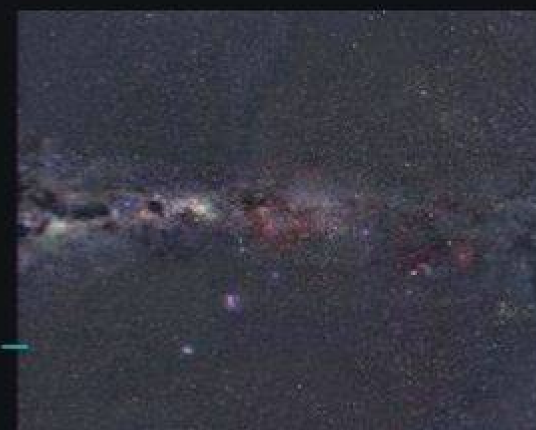
Thanks to Ute Kraus,
Max-Planck-Institute

Forward

Sideways



Backwards



$r = 1.5\ r_s$

Thanks to Ute Kraus,
Max-Planck-Institute

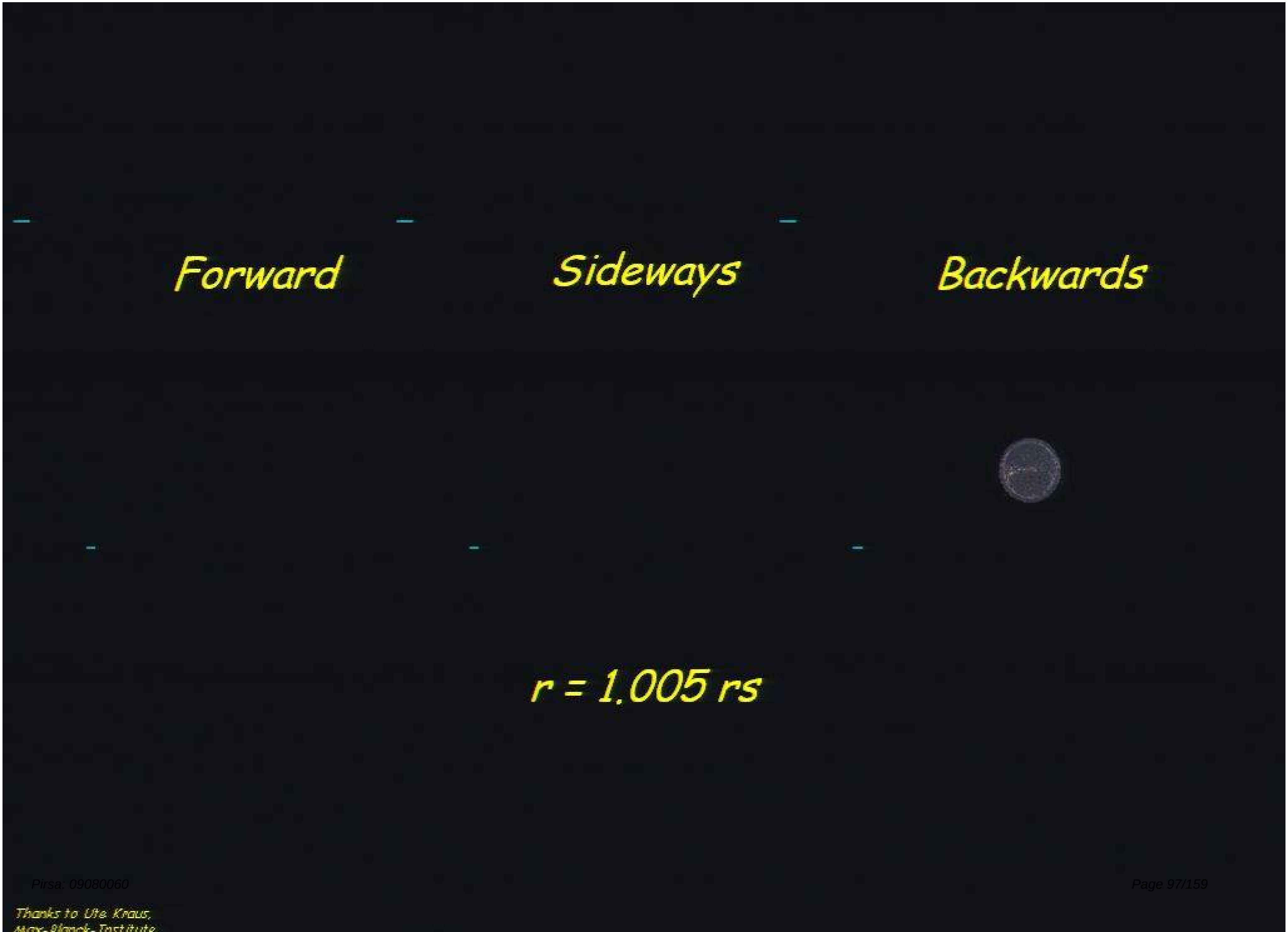
Forward

Sideways

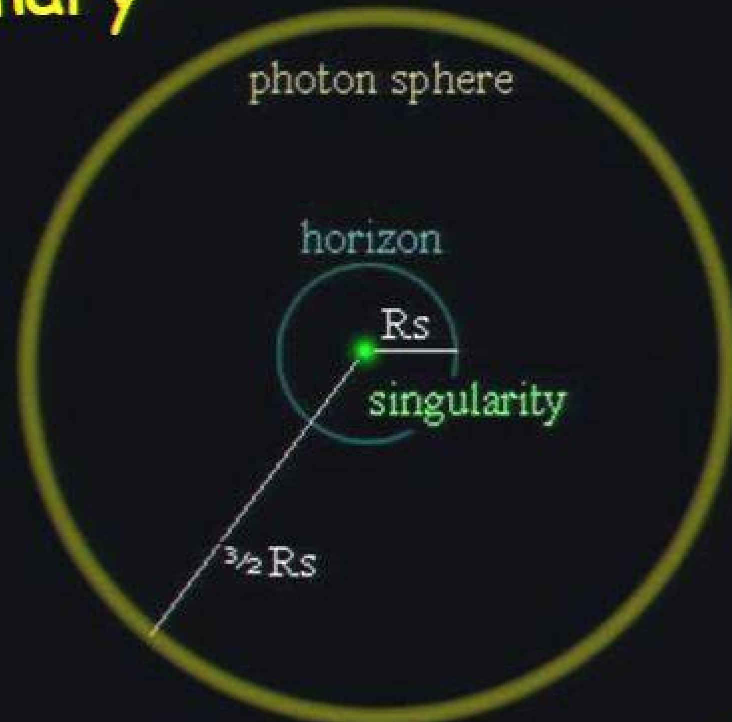
Backwards

r = 1.2 rs

Thanks to Ute Kraus,
Max-Planck-Institute


Forward
Sideways
Backwards
r = 1,005 rs
Thanks to Ute Kraus,
Max-Planck-Institute

The Anatomy Summary



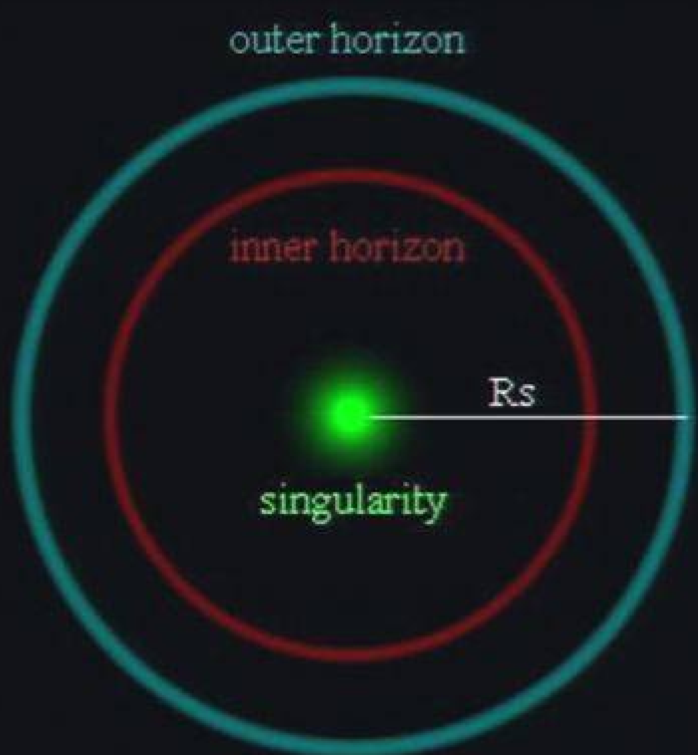
If you calculate the size of an object whose escape velocity is the speed of light, you get the "Schwarzschild radius", which defines the "event horizon". This is the formal size of a black hole (even though there is nothing at that location). It is given by R_s=3km(M_*/M_{sun}). It is the horizon over which you can see no more events. Outside that at 1.5 R_s photons would orbit the hole (the photon sphere).

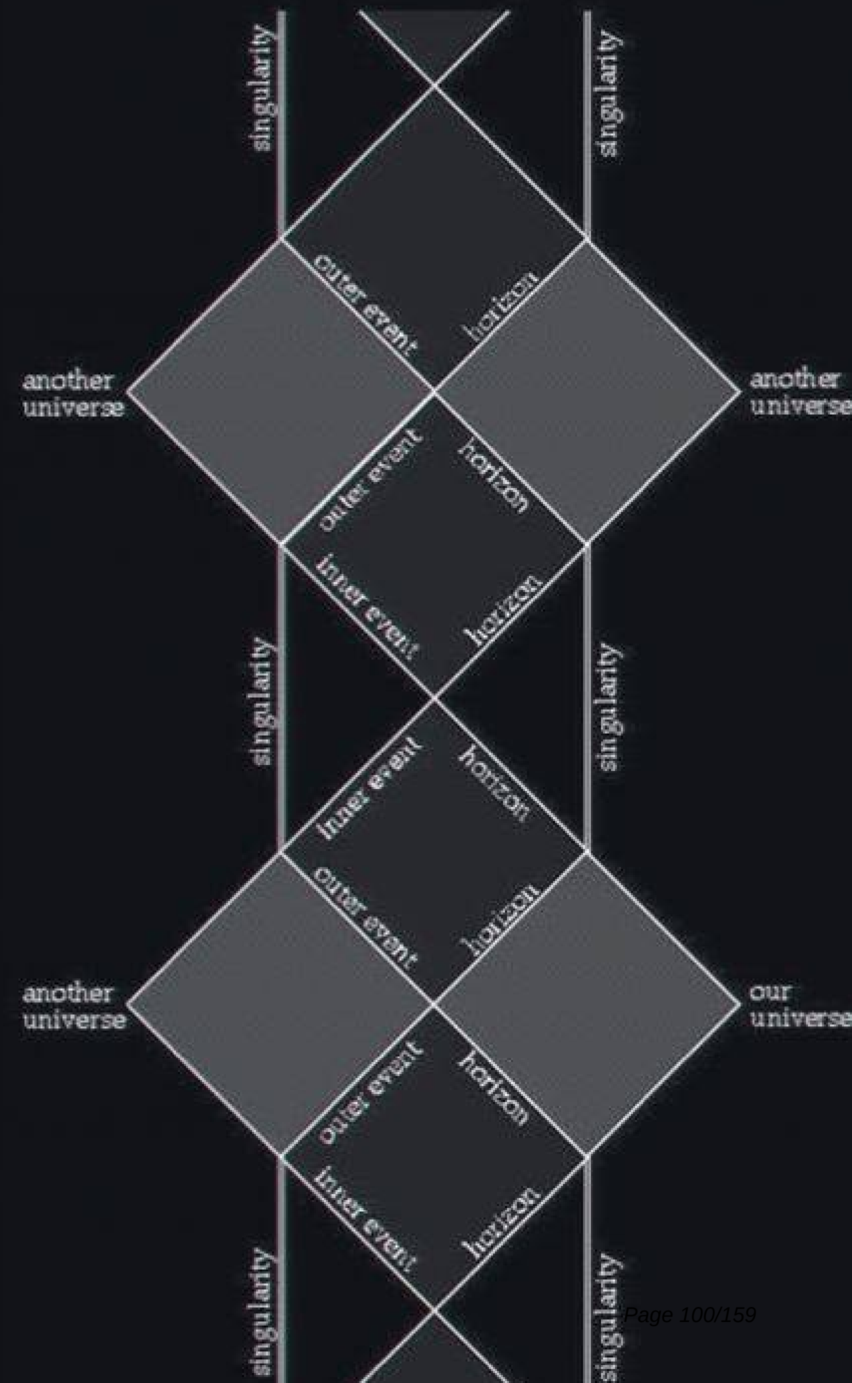
Far from the hole, the gravity is the same as it would be if the star were still there (so no "vacuum cleaner" effect). If the Sun collapsed to a BH, the Earth's orbit would be unaffected.

Types of Black Holes

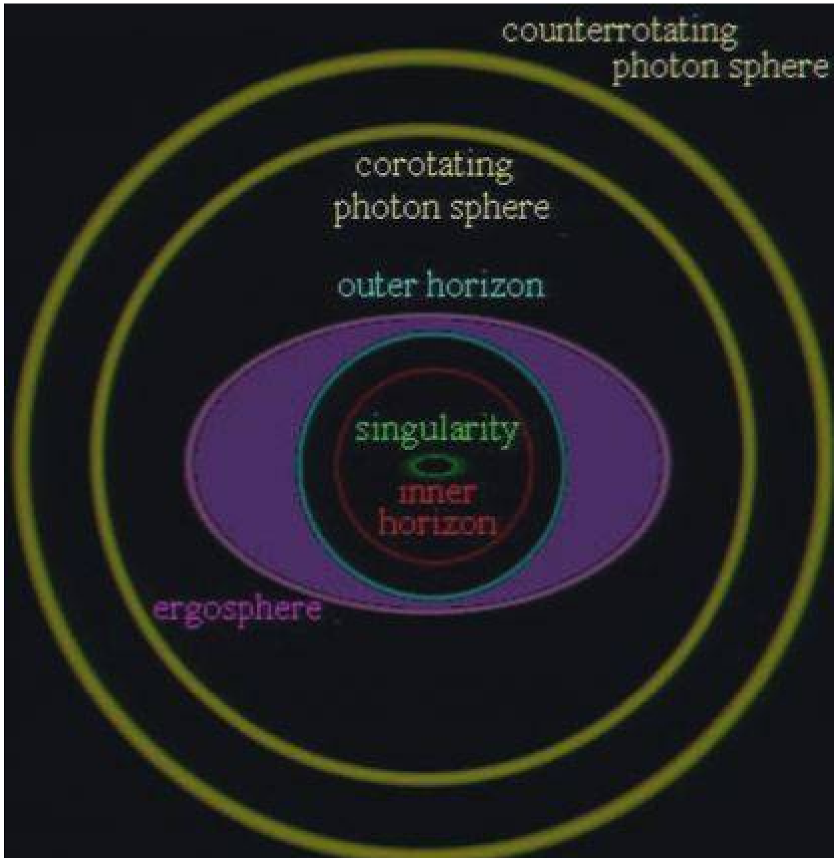
Reissner-Nordström Black Hole

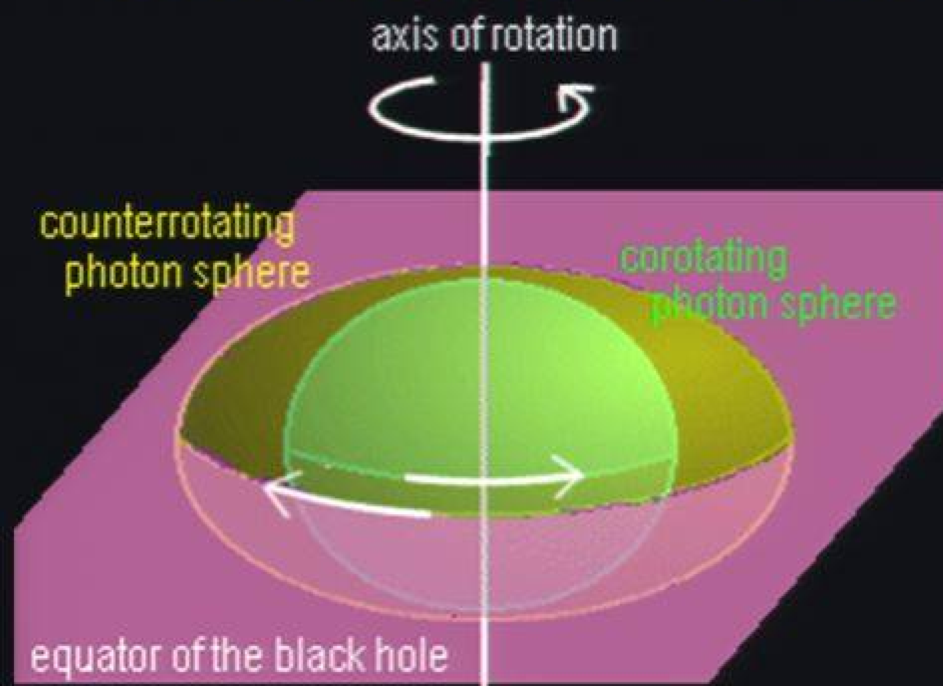
An electrically Charged Black Hole





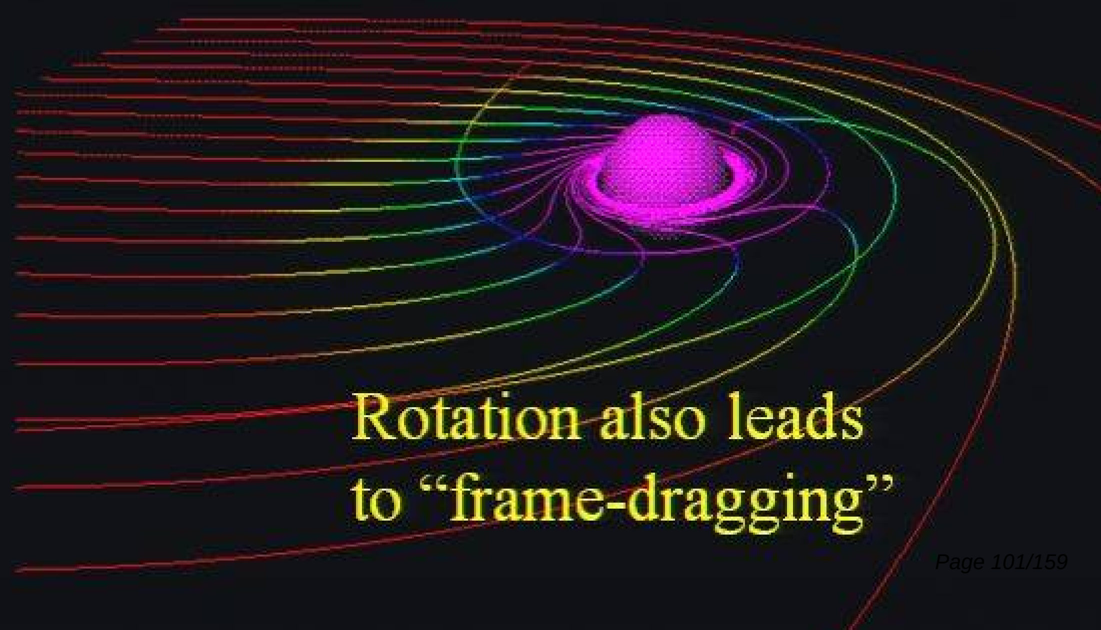
Rotating Black Holes





$$r_{inner} = \frac{r_s + \sqrt{r_s^2 + 4\frac{J}{Mc}}}{2}$$

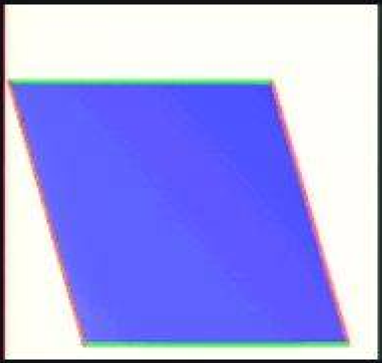
$$r_{outer} = \frac{r_s + \sqrt{r_s^2 + 4\left(\frac{J}{Mc}\cos(\theta)\right)^2}}{2}$$

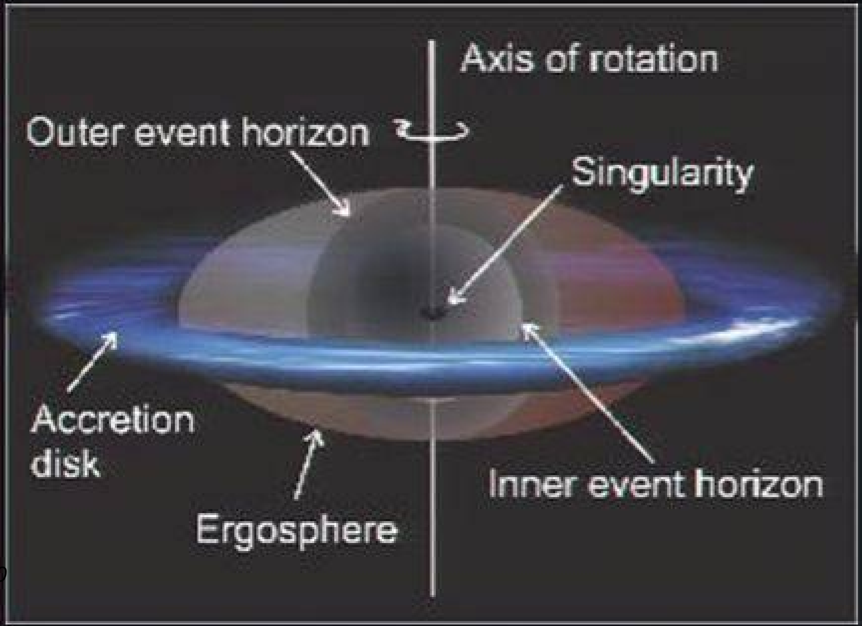


Rotation also leads
to "frame-dragging"

A Rotating Black Hole
(The Kerr Black Holes)

Why is it called a rotating black hole? The event horizon doesn't rotate---it's just a boundary-line, Though anything inside the ergosphere must co-rotate, that nothing can remain stationary

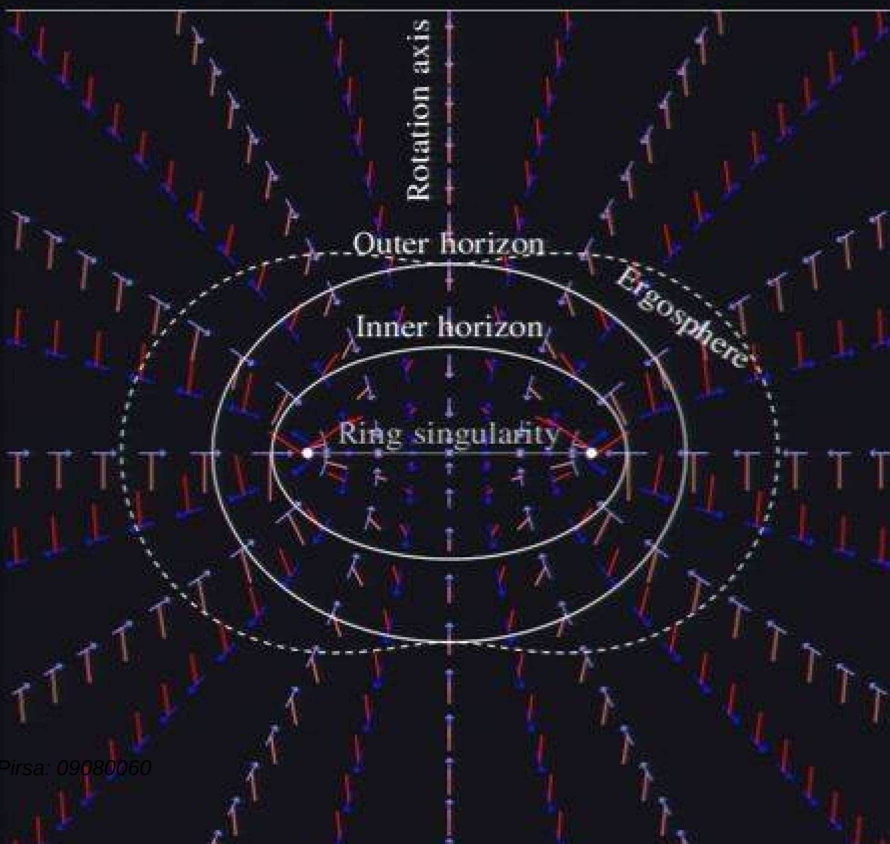


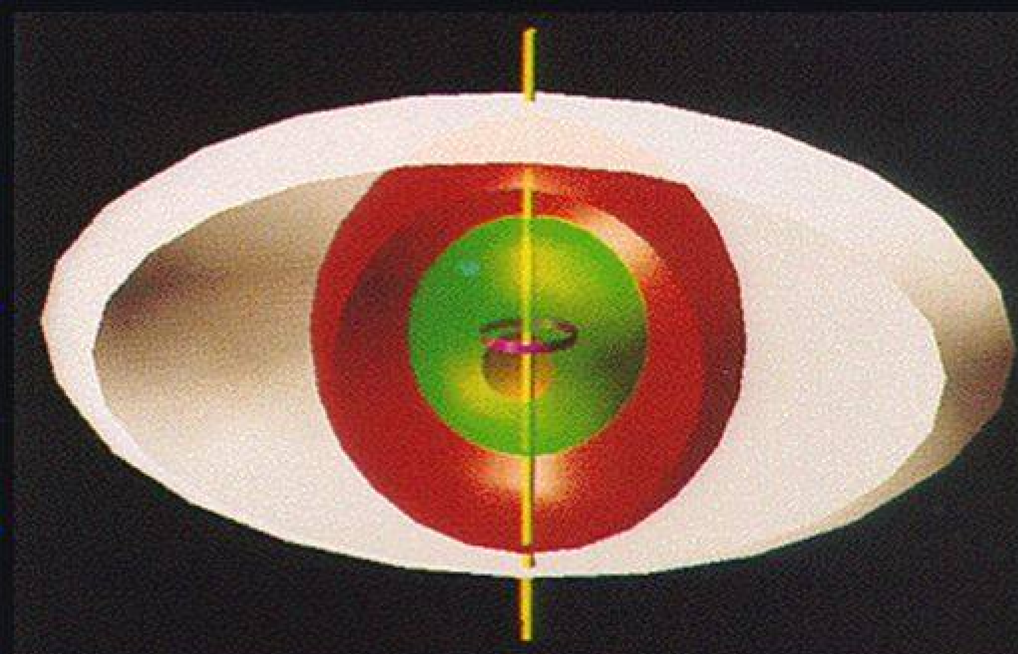


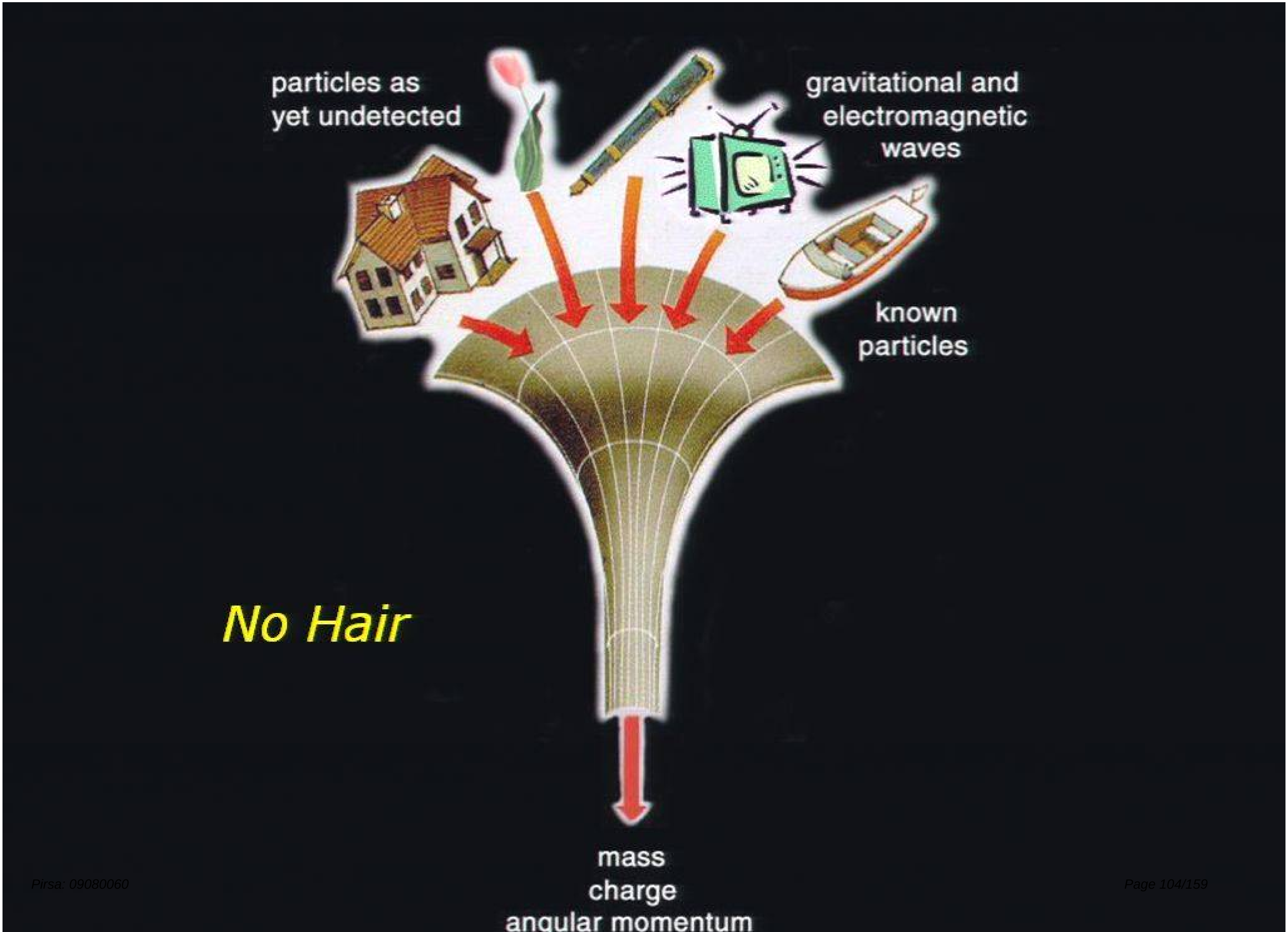
The Penrose effect allows for the black hole to lose energy from ergosphere and thus will slow down and eventually stop

Kerr-Newman Black Hole

Same Structure as Kerr Black Hole. But now it has a charge as well as a rotation. This type of Black hole is not a stable configuarion.






particles as
yet undetected
gravitational and
electromagnetic
waves
known
particles
No Hair
mass
charge
angular momentum

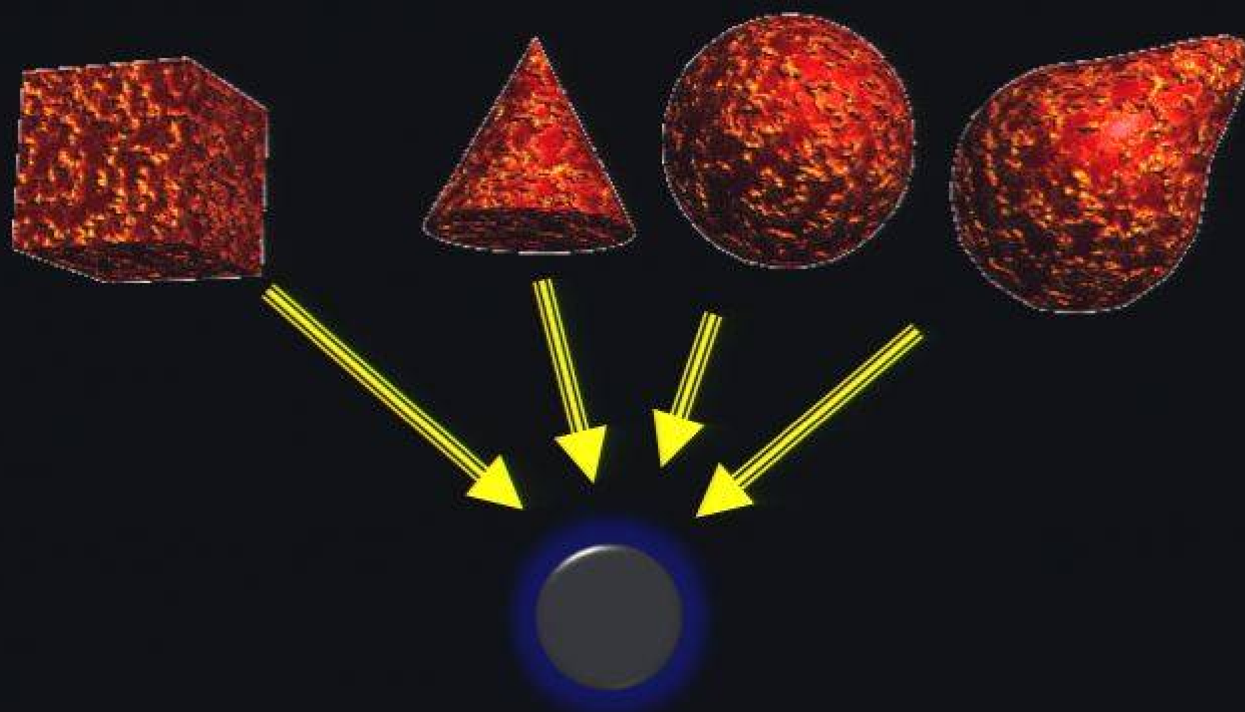
No-hair theorem (well maybe 3 hairs)

- A black hole has no hair;
  its only 'hair' are its

1. Mass
2. Angular momentum
3. Electric charge

John A. Wheeler (*b*1911)

Stars of all Shapes and Sizes



All end up looking the same

Types of black holes

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

Latest Mathematical Model of falling into a Black Hole

Entropy of Black Hole

- Black hole presents us with a problem: What happens to the information when a particle falls inside a Black Hole?
- Remember only 3 parameters are required to describe a Black Hole (charge, mass, and angular momentum).
- In order to describe a physical system, we need entropy (a measure of disorder).
- Hawking had no problem with this "entropy eater"
- Hawking (after changing mind) and Bekenstein produced laws of Black Hole mechanics that bore an amazing resemblance to laws of thermodynamics.
- The 2nd law of thermodynamics "Entropy (randomness) increases
- You replace "Horizon Area" with "Entropy"

$$S(entropy) = \frac{kAc^3}{4hG}$$

Entropy of Black Hole

New problem: if the Black Hole has an entropy, it must have a temperature too.

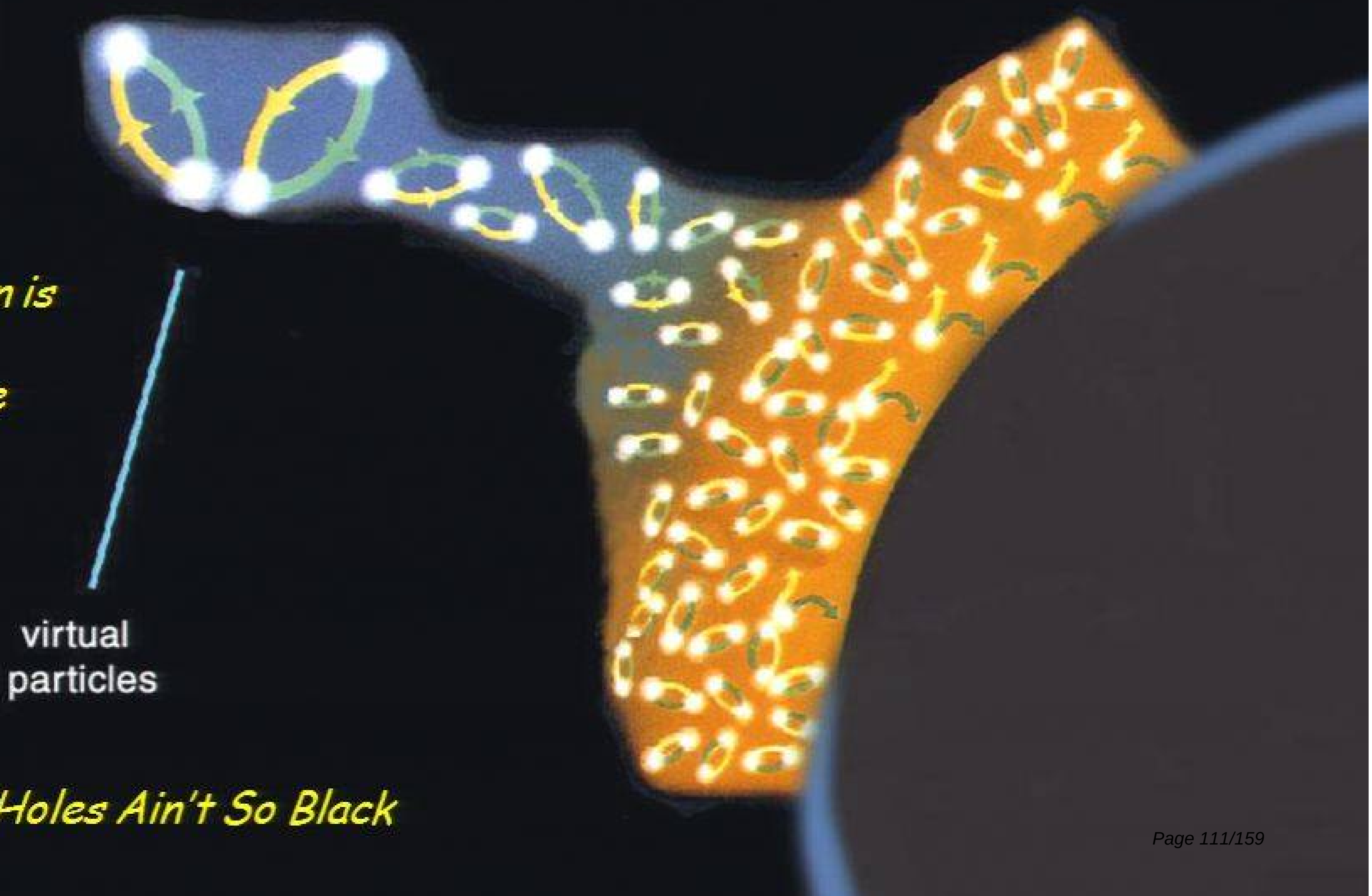
Worse Problem: If is has a temperature it must radiate, but in classical definition, nothing can escape a Black Hole.

Crisis:

- *Several ways to picture how a black Hole evaporates*
  - *Some ways correspond to different ways of formulating laws of quantum fields.*
  - *Some ways correspond to String Theory*
  - *Some ways correspond to Quantum Gravity*
  - *Some ways make no sense at all.*
  - *Next Talk will discuss this.*

Stephen W. Hawking (*b*1942)

Hawking radiation



Virtual photon is its own antiparticle

Black Holes Ain't So Black

Hawking Radiation

- The Hawking Radiation theory states that virtual particle-antiparticle pairs are sometimes created outside the event horizon of a black hole. Three things can happen to a pair of particles just outside the event horizon:
    - Both particles are pulled into the black hole.
    - Both particles escape from the black hole.
    - One particle escapes while the other is pulled into the black hole.
- For the third possibility, the particle that has escaped becomes real and can therefore be observed from Earth. The energy to separate the two virtual particles (thus making them real particles) is taken from the horizon, thus reducing the energy of the Black Hole.
- The wavelength of the particle/wave that enters the a hole will be of 25% of the hole's circumference.
- For Example: A black hole of 2 Solar Masses with a circumference of about 35Km will emit a wavelength of:

$$\frac{35}{4} \approx 9 \ km$$

Hawking Radiation

- The Hawking Radiation theory states that virtual particle-antiparticle pairs are sometimes created outside the event horizon of a black hole. Three things can happen to a pair of particles just outside the event horizon:
    - Both particles are pulled into the black hole.
    - Both particles escape from the black hole.
    - One particle escapes while the other is pulled into the black hole.
- For the third possibility, the particle that has escaped becomes real and can therefore be observed from Earth. The energy to separate the two virtual particles (thus making them real particles) is taken from the horizon, thus reducing the energy of the Black Hole.
- The wavelength of the particle/wave that enters the a hole will be of 25% of the hole's circumference.
- For Example: A black hole of 2 Solar Masses with a circumference of about 35Km will emit a wavelength of:

$$\frac{35}{4} \approx 9 \ km$$

Hawking Radiation

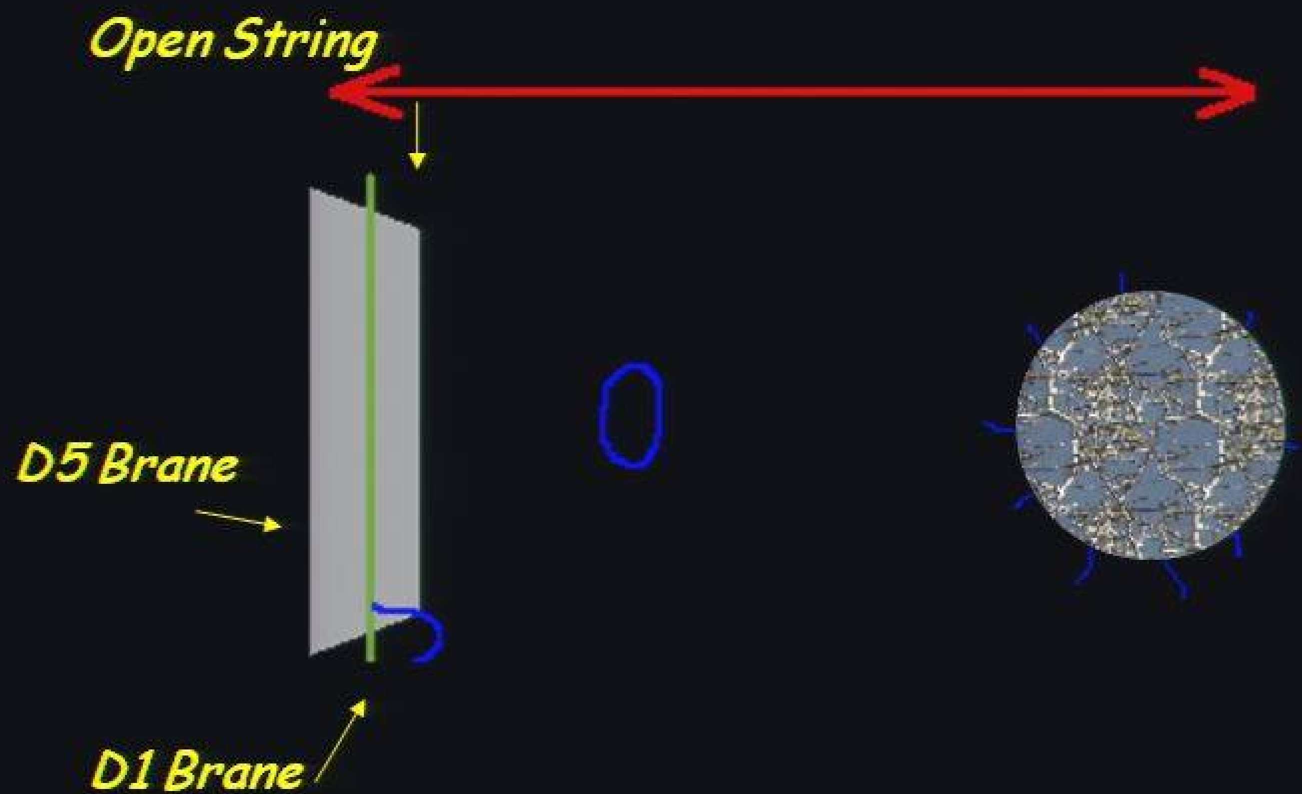
- The larger (more massive) the Black Hole the lower the temperature and the longer it takes to evaporate.

$$Temp_K \approx \frac{6\times 10^{-8}}{M_{\oplus}}$$

$$\tau ime \approx 10^{66}\cdot\left[M_{\oplus}\right]^3$$

- Remember the age of the Universe is 10^{10} years give or take 3 days.

Superstring Method



One of the most dramatic recent results in string theory is the derivation of the Bekenstein-Hawking entropy

Are Black Holes Real

What are we going to look for if Black Holes are Real

"It's black, and it looks like a hole.
I'd say it's a black hole."

Sidney Harris

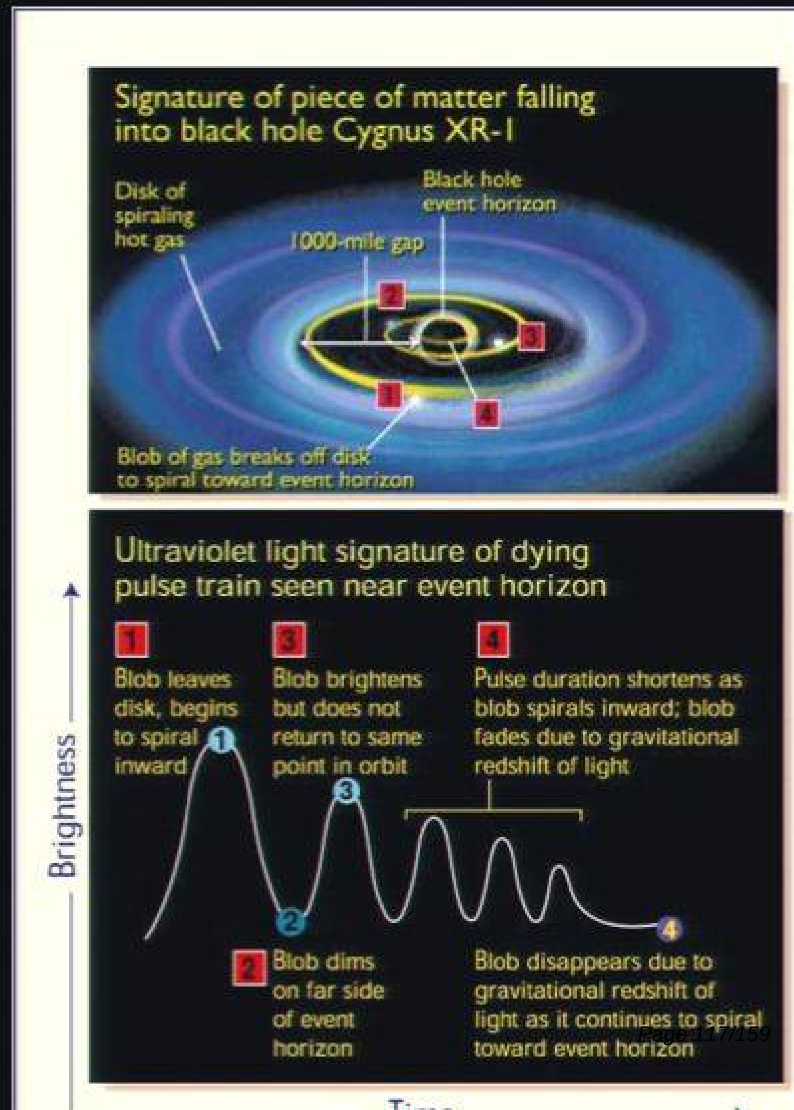
Finding Black Holes
Ultraviolet and X-rays

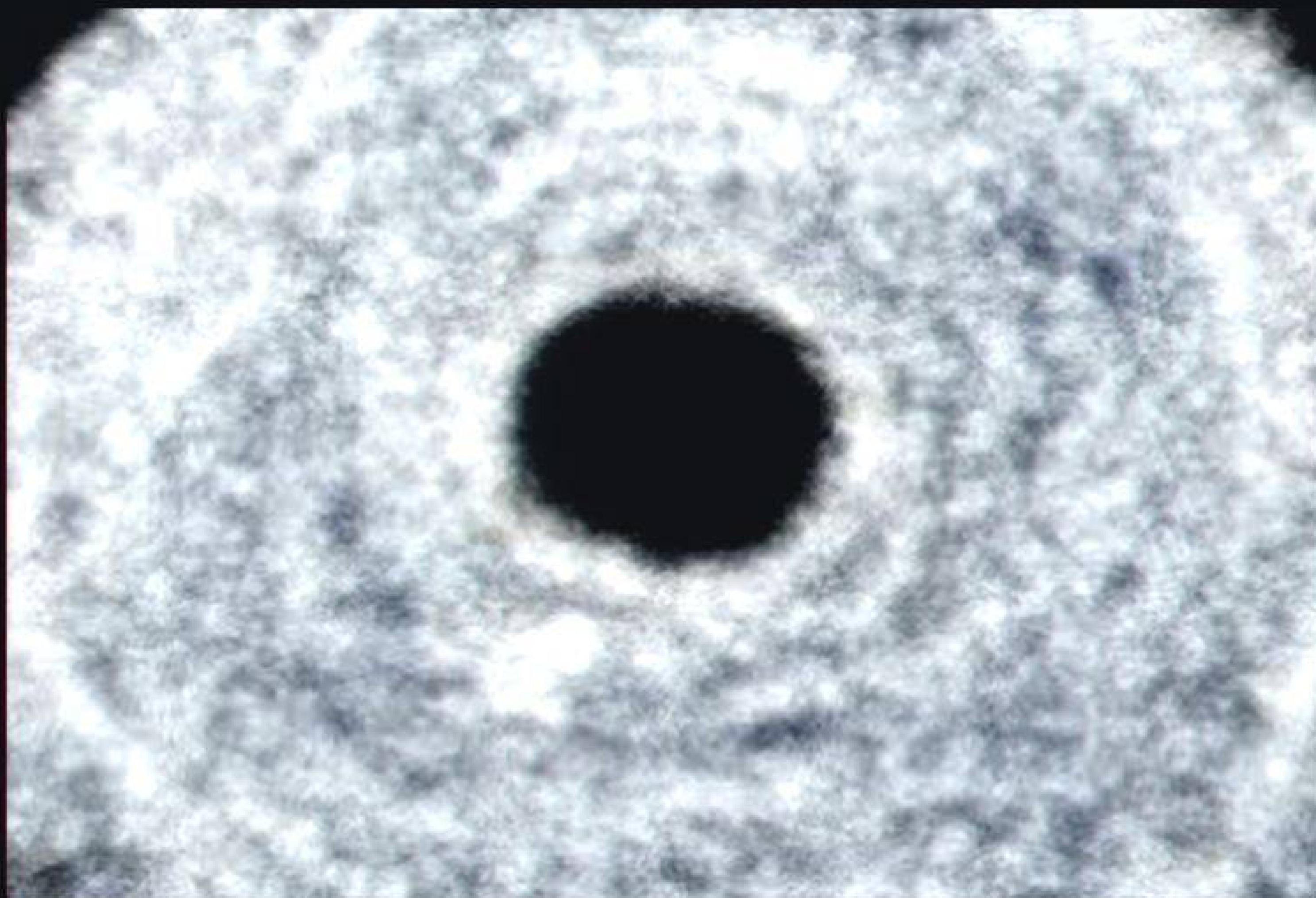
Seeing Matter Disappear

Hubble observed pulses of UV light emitted by material as it fell into a black hole.

• Pulses arise from material orbiting around intense gravity of the black hole.

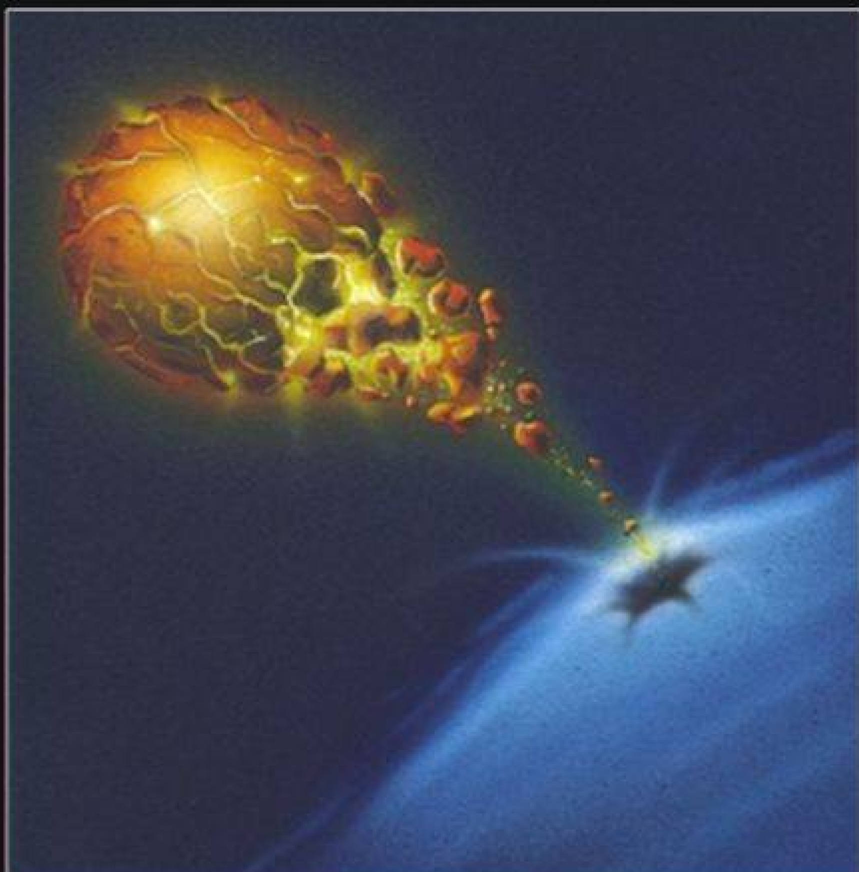
• Light pulses, lasting 0.2 s, are red-shifted from X-ray to UV, as they fall into gravity of the black hole.



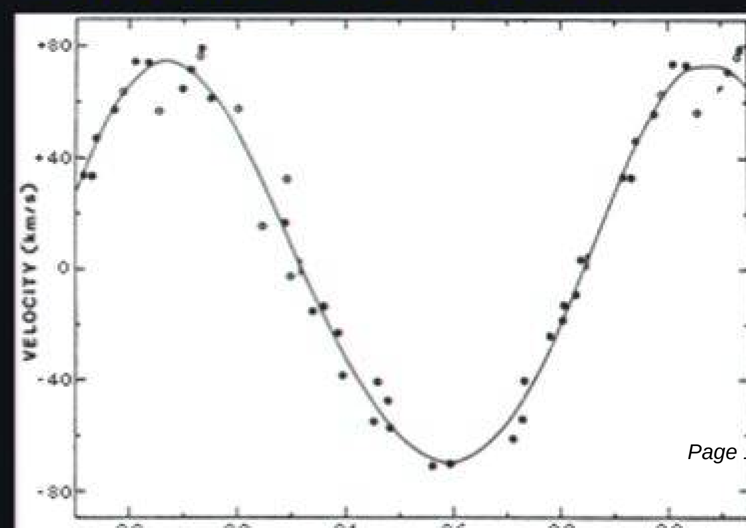


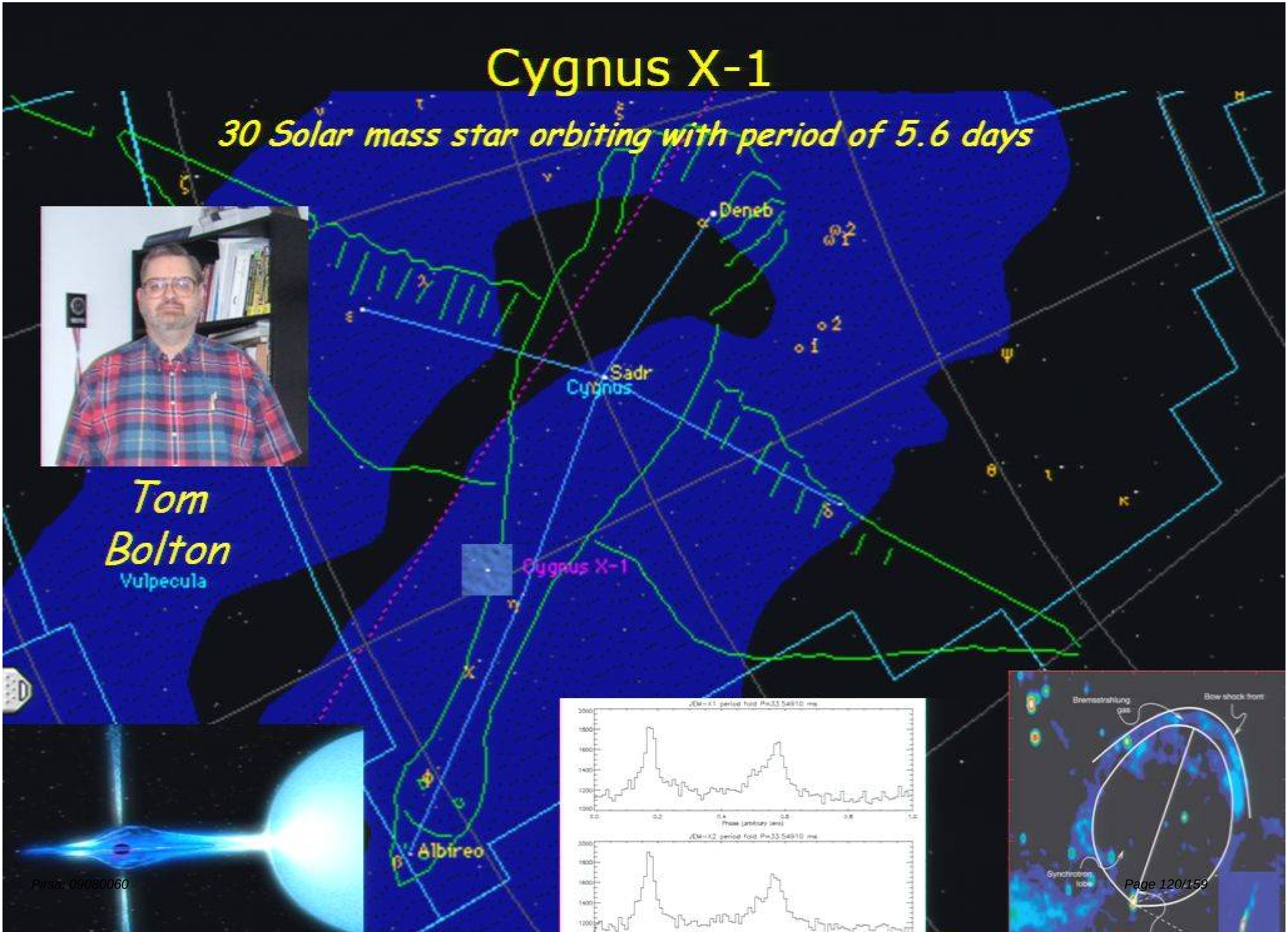
- Zel'dovich speculated that if a black hole was surround by gas and this gas was orbiting the black hole in an accretion disk, it Would give off x-rays
- The U.S. then used WW2 V-2 rockets with a simple x-ray machine in the

Seeing Holes



- Can't see black hole itself, but can see matter falling into a hole.
- Gravitational forces stretch and rip matter: heats up.
- Very hot objects emit in X-rays (interior of Sun)

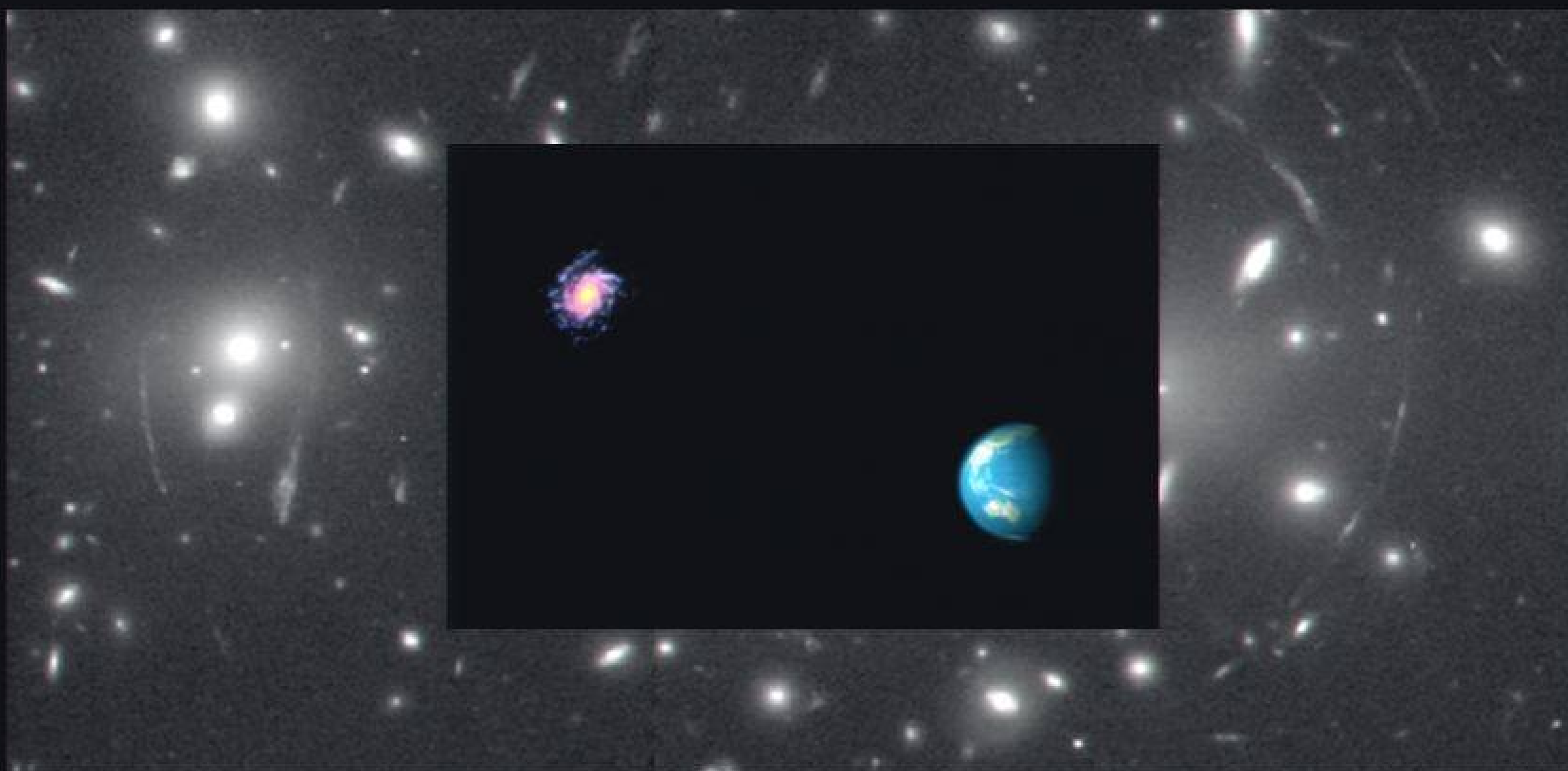



Cygnus X-1
30 Solar mass star orbiting with period of 5.6 days
Tom
Bolton
Vulpecula
Deneb
Sadr
Cygnus
Cygnus X-1
Albireo
Bremsstrahlung gas
Bow shock front
Synchrotron lobe

Even More Binary Black Holes

Name of Binary System	Companion Star Spectral Type	Orbital Period (days)	Black Hole Mass (Solar Units)
Cygnus X-1	B supergiant	5.6	6-15
LMC X-3	B main sequence	1.7	4-11
A0620-00 (V616 Mon)	K main sequence	7.8	4-9
GS2023+338 (V404 Cyg)	K main sequence	6.5	> 6
GS2000+25 (QZ Vul)	K main sequence	0.35	5-14
GS1124-683 (Nova Mus 1991)	K main sequence	0.43	4-6
GRO J1655-40 (Nova Sco 1994)	F main sequence	2.4	4-5
H1705-250 (Nova Oph 1977)	K main sequence	0.52	> 4

Lens



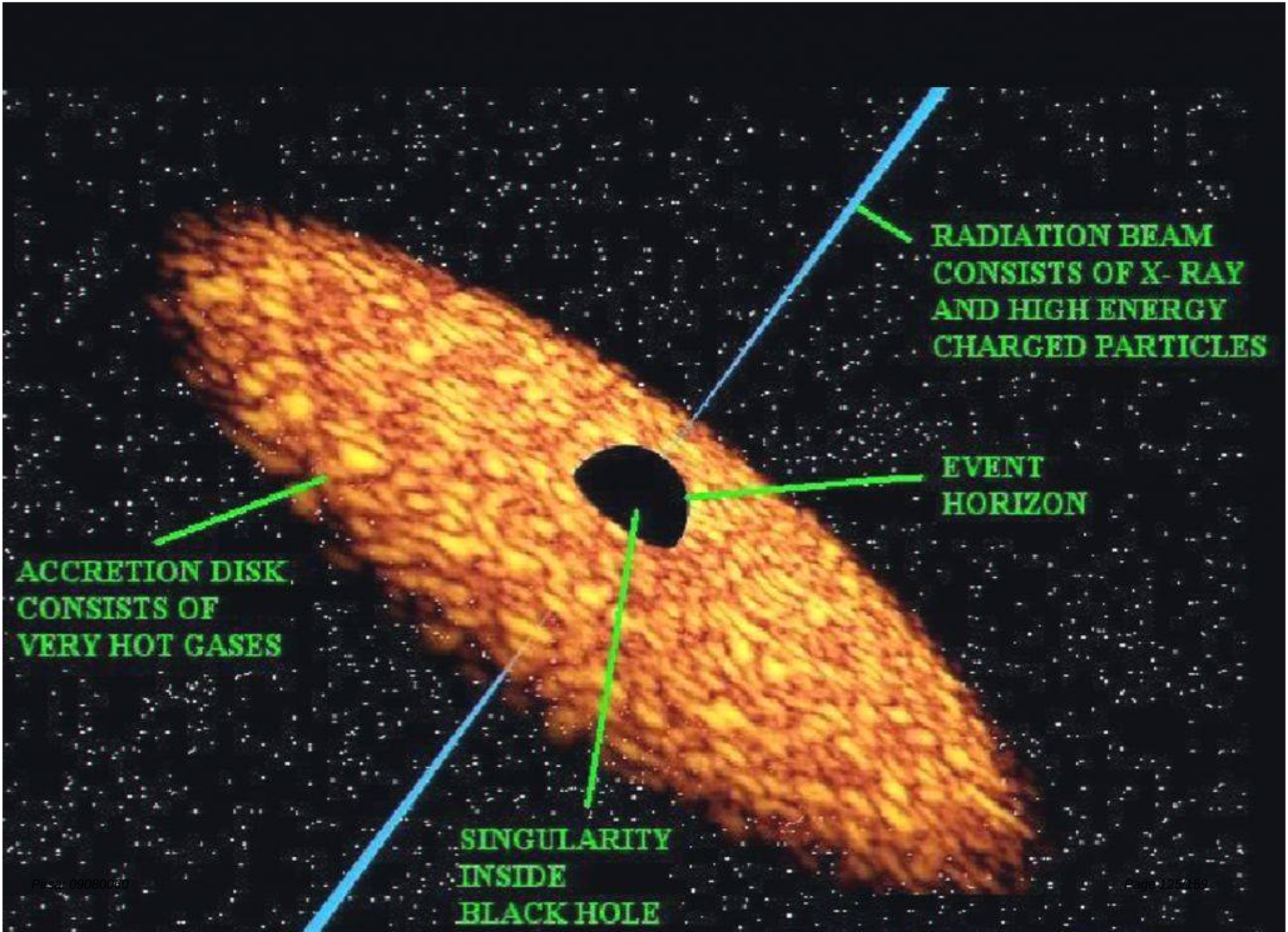
Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

Lens

Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

What else should we look for?

Jets


RADIATION BEAM
CONSISTS OF X- RAY
AND HIGH ENERGY
CHARGED PARTICLES
EVENT
HORIZON
ACCRETION DISK
CONSISTS OF
VERY HOT GASES
SINGULARITY
INSIDE
BLACK HOLE

Radio Jets from Black Holes

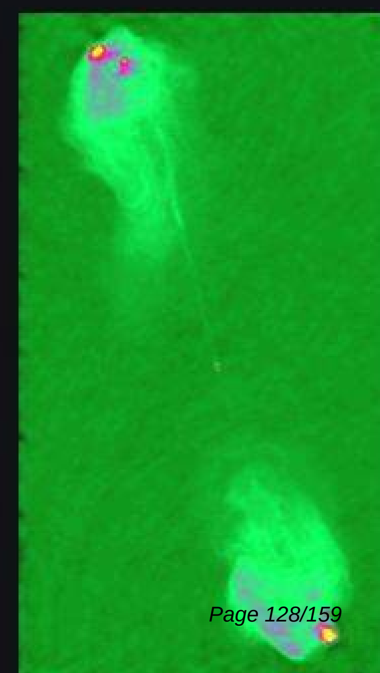
- Many black holes emit jets.
  - Material in jet moving at 0.9c.
  - Jet likely composed of electrons and positrons.
- Magnetic fields surrounding black hole expel material and form the jet.
  - Interaction of jet material with magnetic field gives rise to Radio emission.

Radio Jets from Black Holes

- Many black holes emit jets.
  - Material in jet moving at 0.9c.
  - Jet likely composed of electrons and positrons.

- Magnetic fields surrounding black hole expel material and form the jet.
  - Interaction of jet material with magnetic field gives rise to Radio emission.

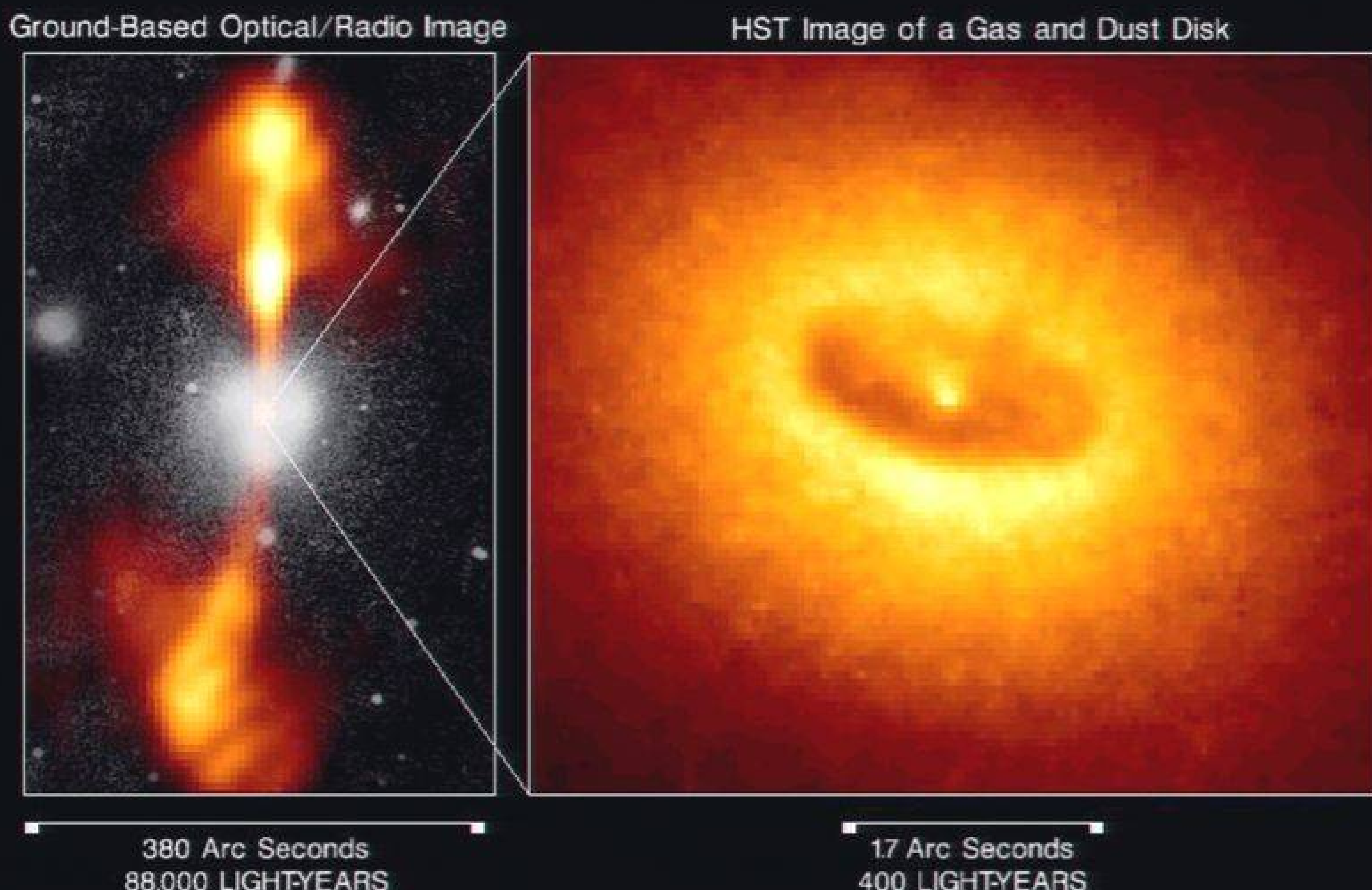
Jets



Core of Galaxy NGC 4261

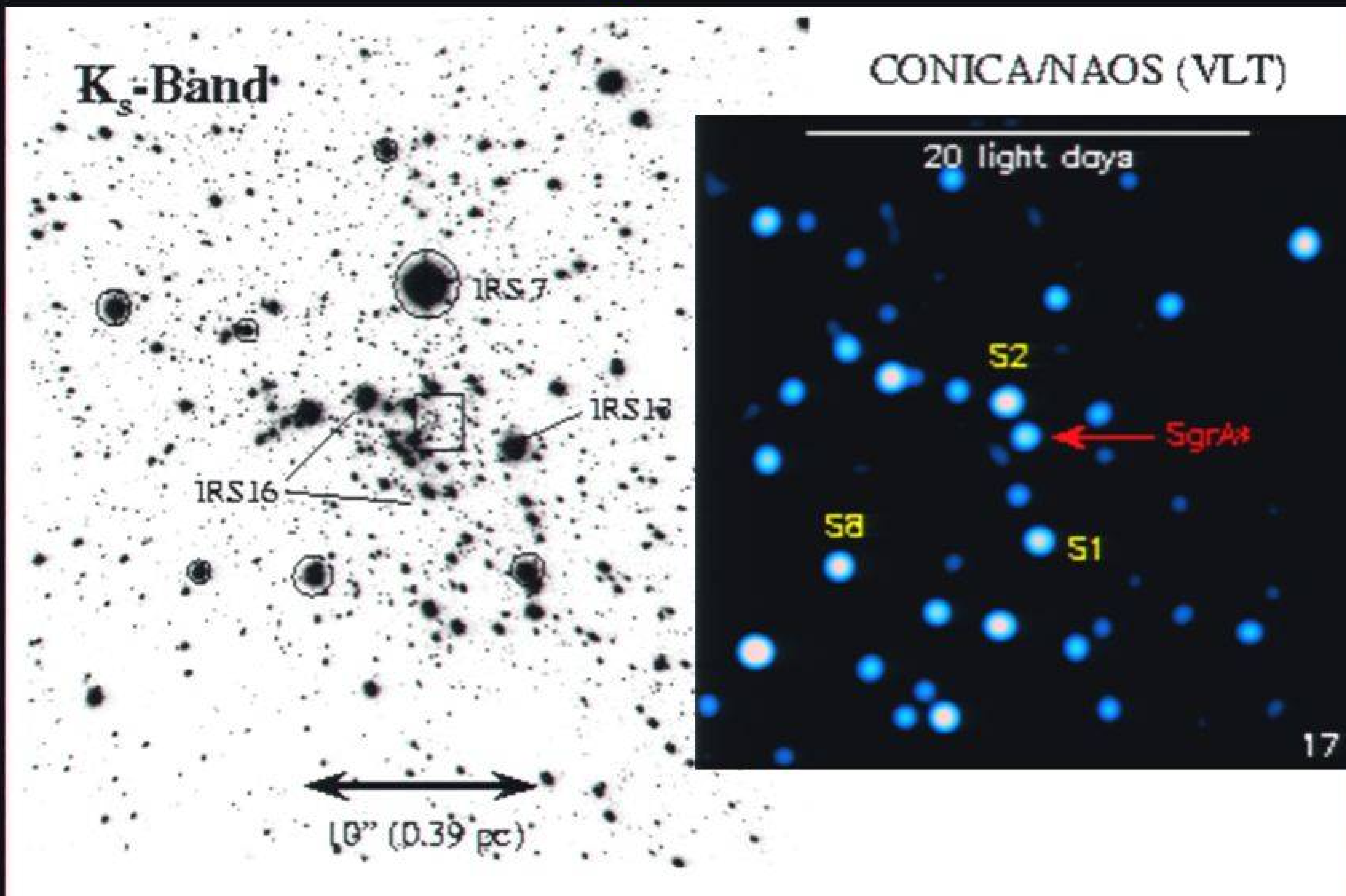
Hubble Space Telescope

Wide Field / Planetary Camera



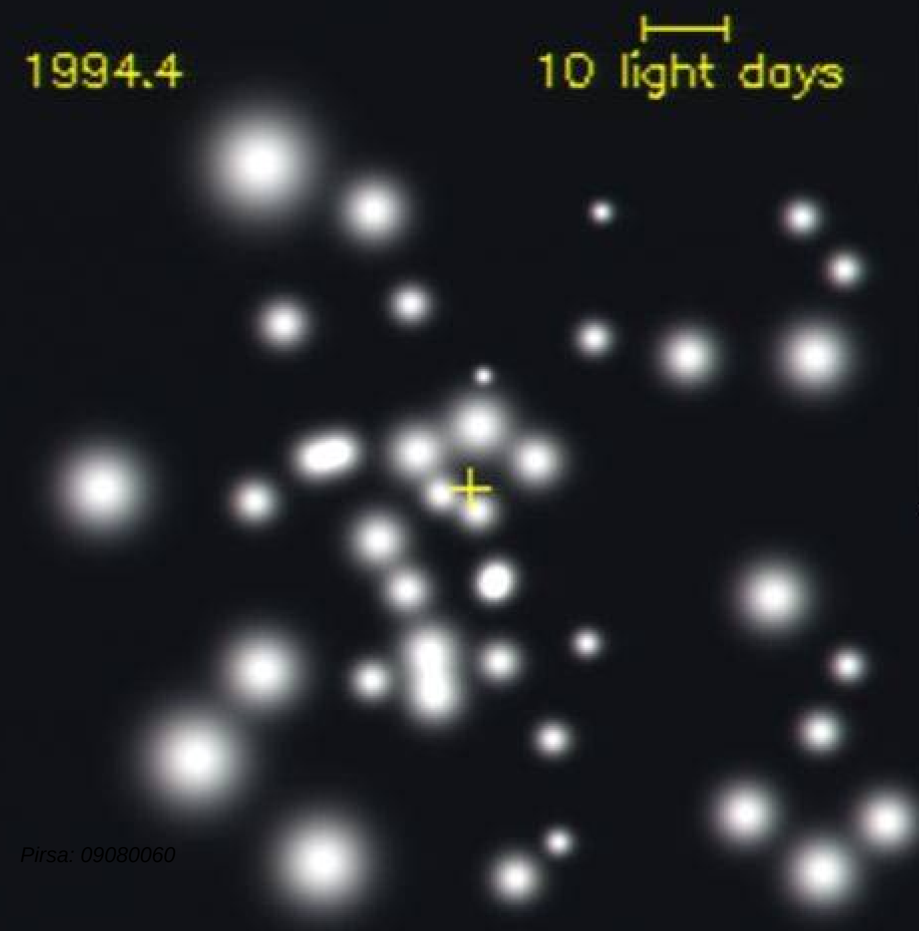
More Evidence

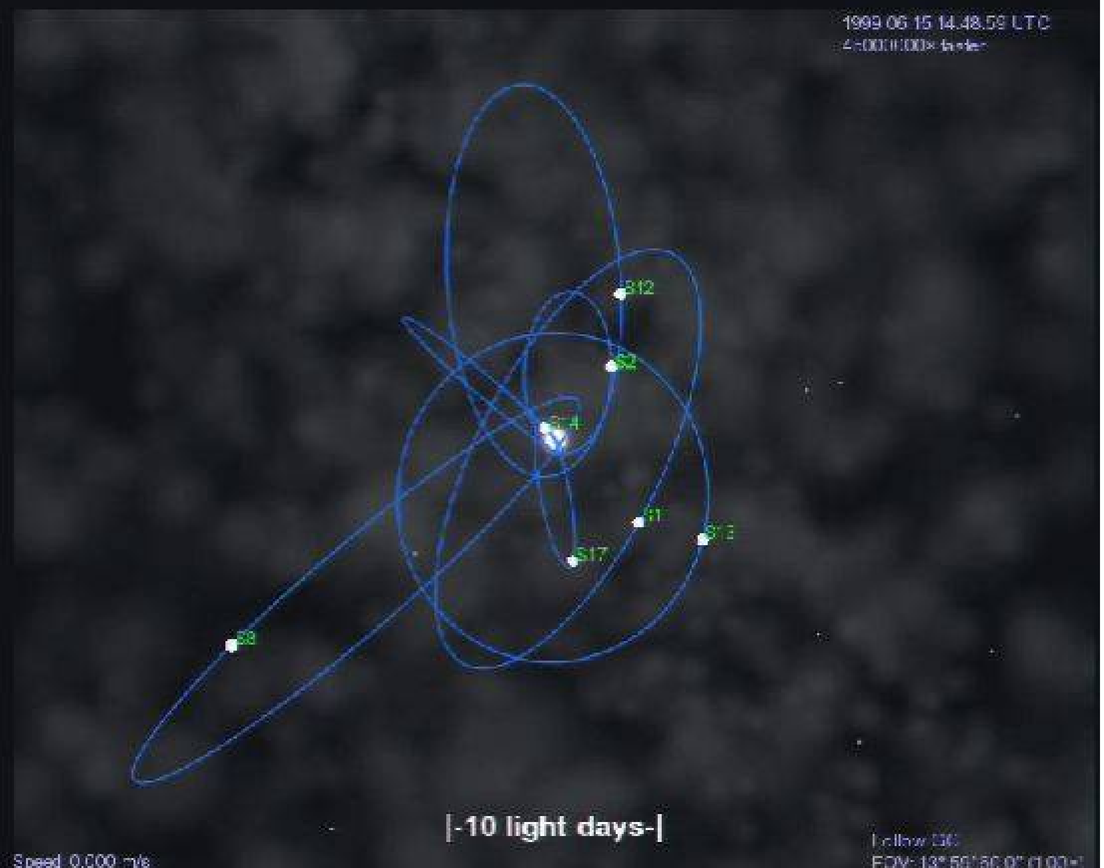
SgrA*



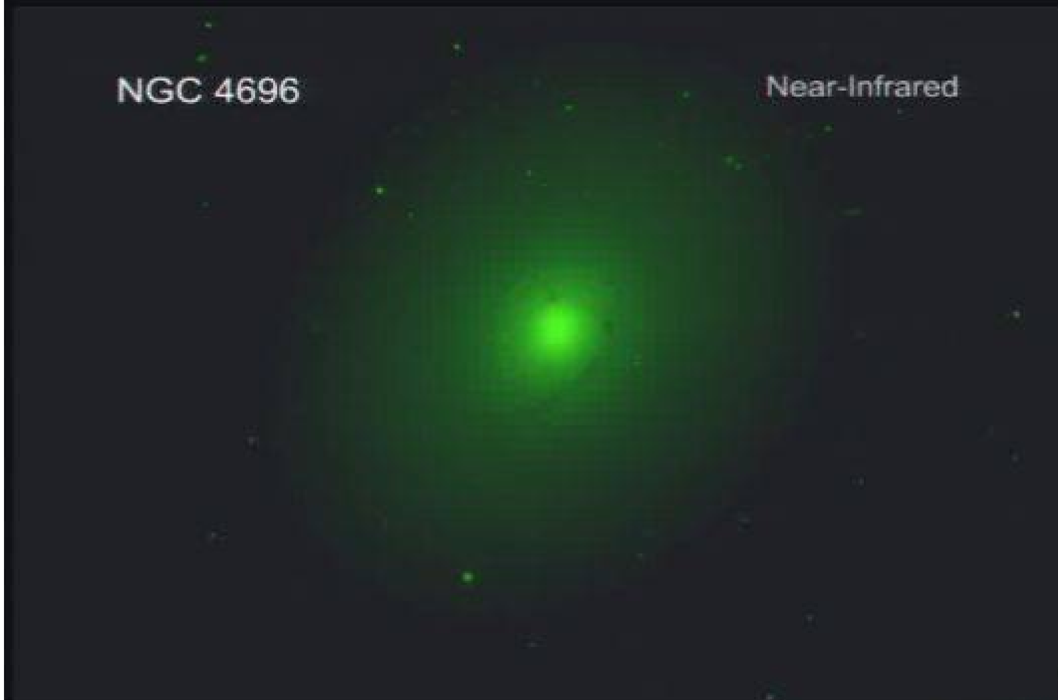
3,700,000 solar masses

SgrA*

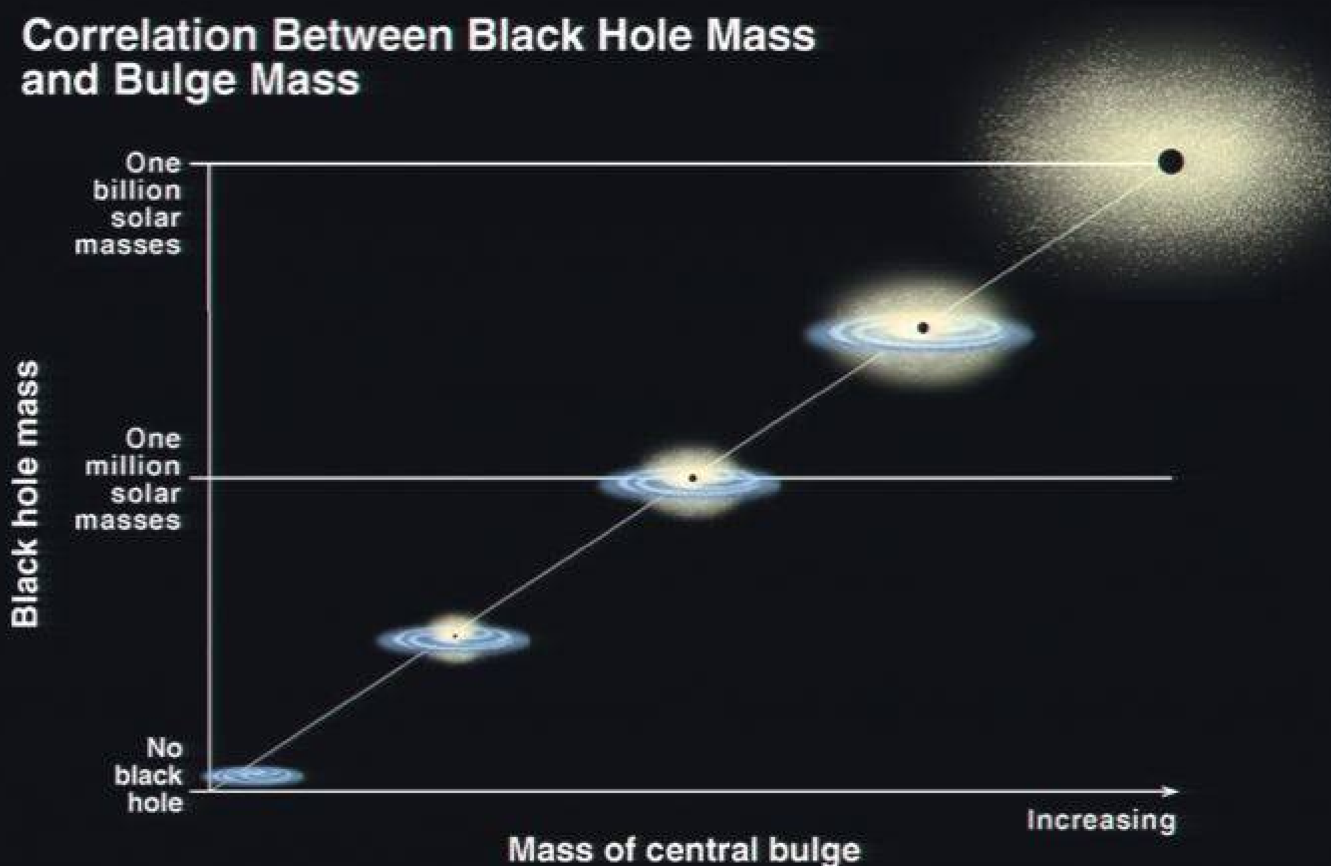

1994.4
10 light days


1999 06 15 14:48:59 UTC
S12
S2
S14
S1
S13
S17
S8
|-10 light days-|
Speed 0.000 m/s

Black Hole Evidence

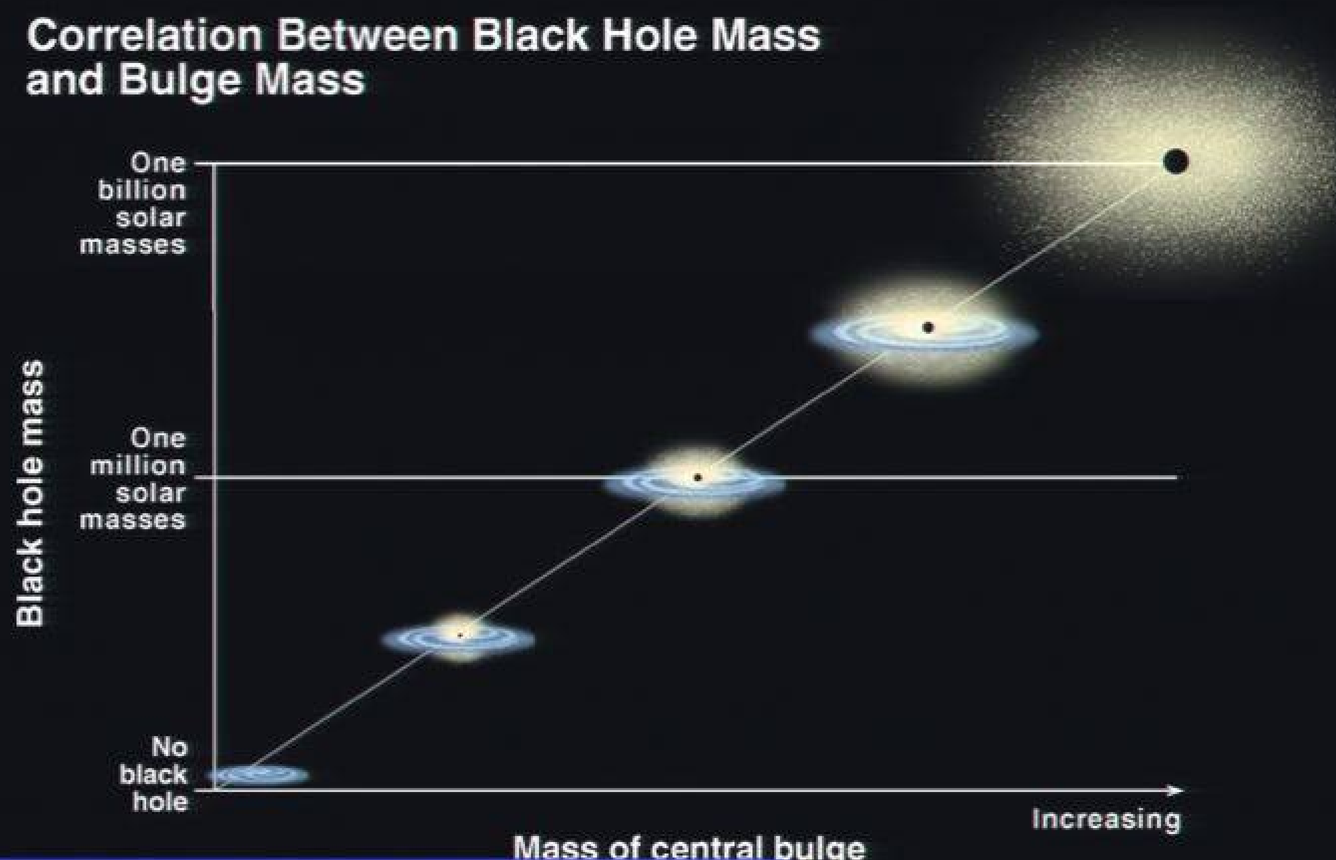


Speed of Gas and Black Holes



- It discovered a correlation between a Black Hole's mass and the average speed of the stars in the galaxy's central bulge.
- The faster the stars are moving, the larger the black hole.
- The central Black Hole comprises 0.5% of mass of stars in the spheroid of the galaxy. (Magorrian Relation)
- Previously, black holes were seen as the endpoints of evolution, the final resting state of most or all of the matter in the universe. Now we believe black holes also play a critical role

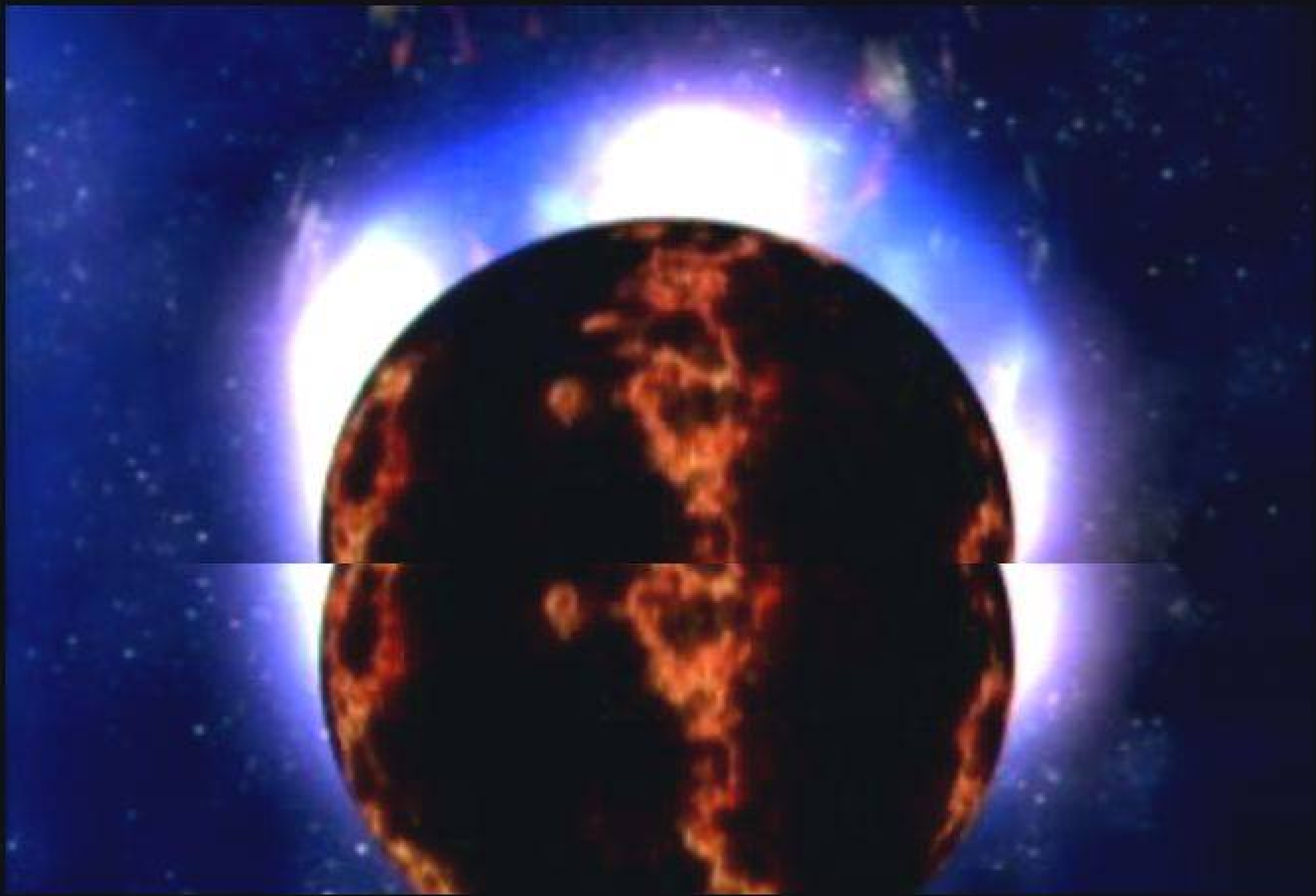
Speed of Gas and Black Holes



In Jan 2009, at the American Astronomical Society meeting, evidence from the Very Large Array Radio telescope, demonstrated (based on Black hole mass to Galactic Bulge) that Black Holes came First

- ...ss and the average speed of the
- ...ole.
- ...rs in the spheroid of the galaxy.
- ...tion, the final resting state of ... black holes also play a critical role

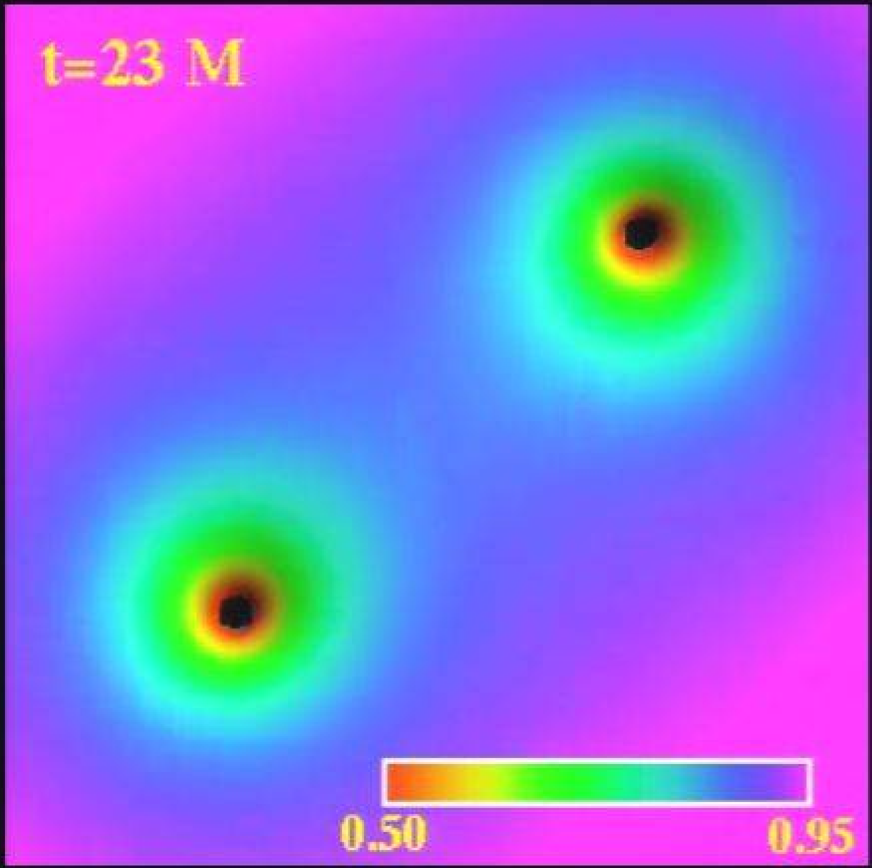
When Black Holes Collide



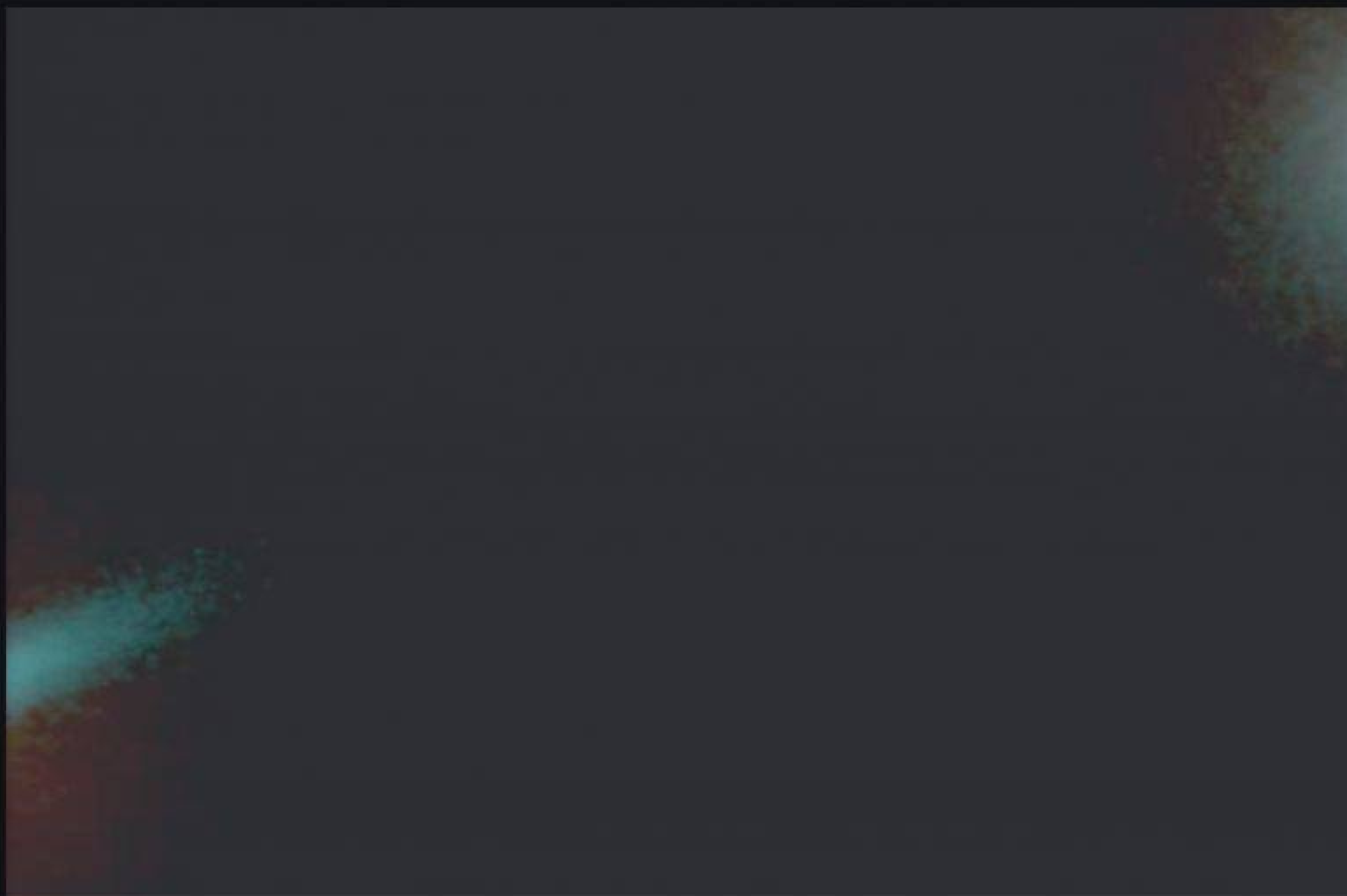
The Best Simulation

For over 20 years cosmologist have being trying to simulate colliding black holes.

In 2005 at Banff, Frans Pretorius was able to provide an accurate simulation of only 5 orbits of two colliding black holes

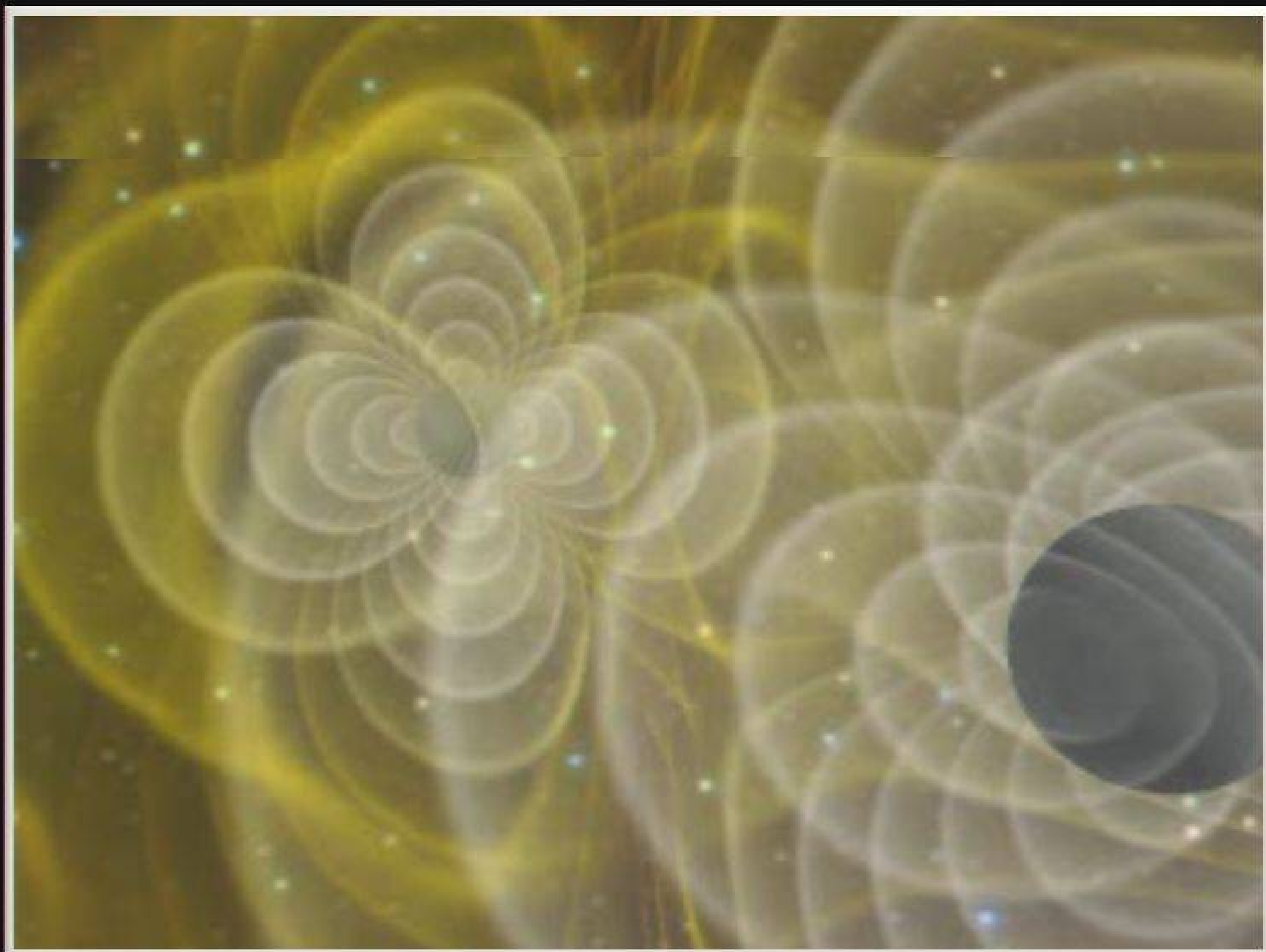


Frame Dragging and Gravitational Waves

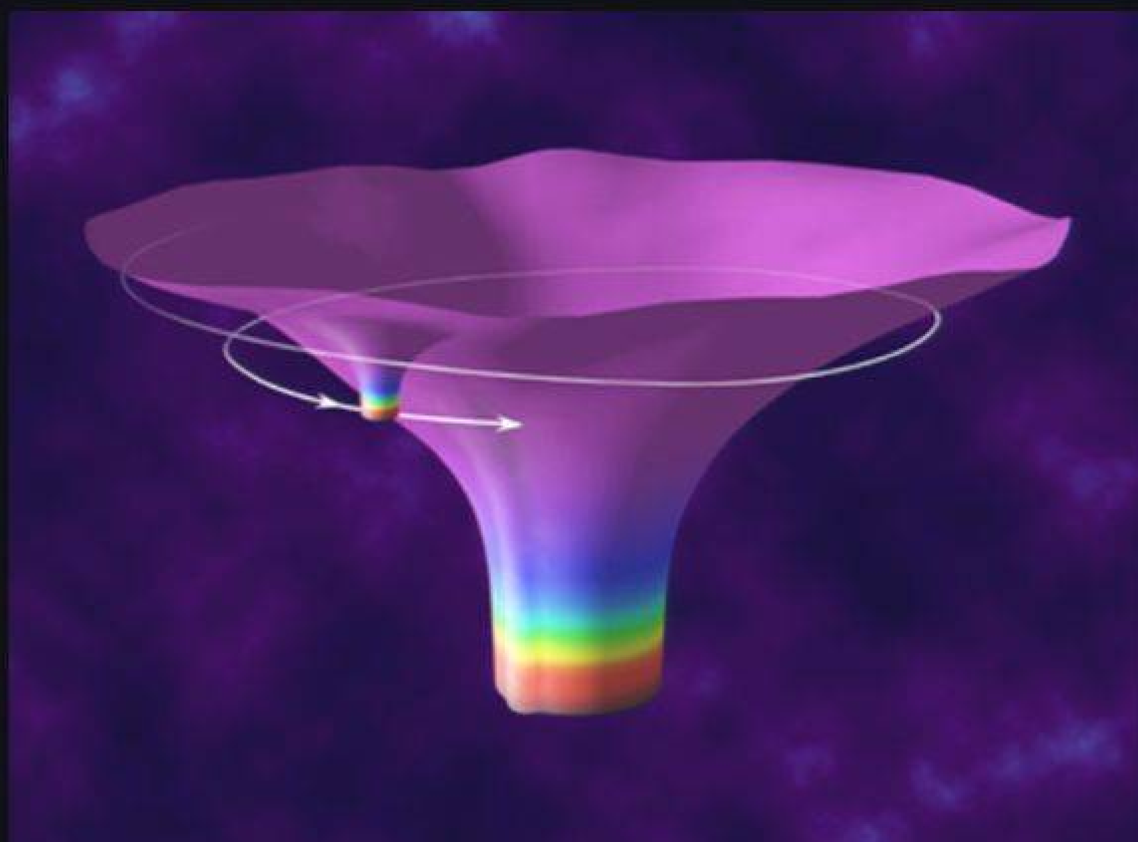


Frame Dragging and Gravitational Waves

Nasa's Latest Animation



This is the final piece of the puzzle that needs to be verified



Wave Detection

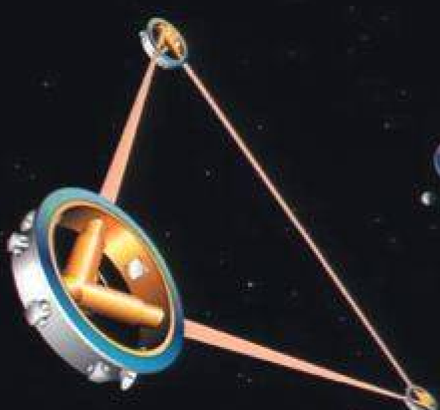
The race is on and the detectors are in place or being readied for orbit:

LIGO
VIRGO
GEO600
TAMA
AURIGA

Wave Detection

The GEO600 detector, located in a field outside Hannover in Germany

Auriga

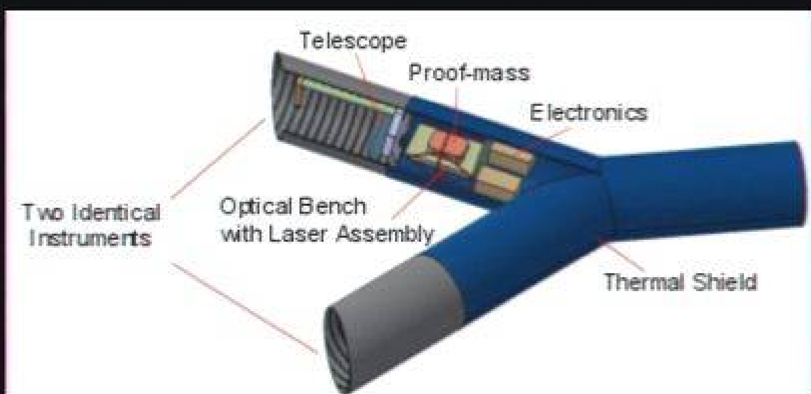


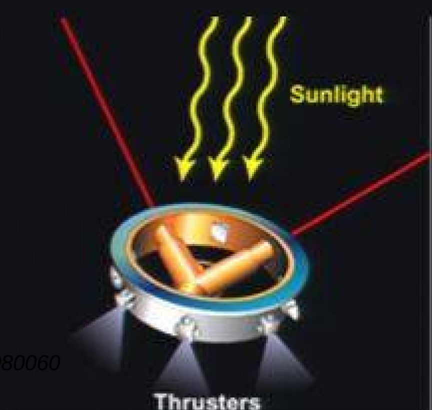
Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO) Richland

Lisa

- Distance between each craft is 5,000,000 km
- Will follow Earth's orbit by 20 degrees
- Will be able to detect $\Delta L/L$ less then 10^{-21} (that ΔL of 10^{-10} cm)
- Launch date set for 2015 (5 year duration)

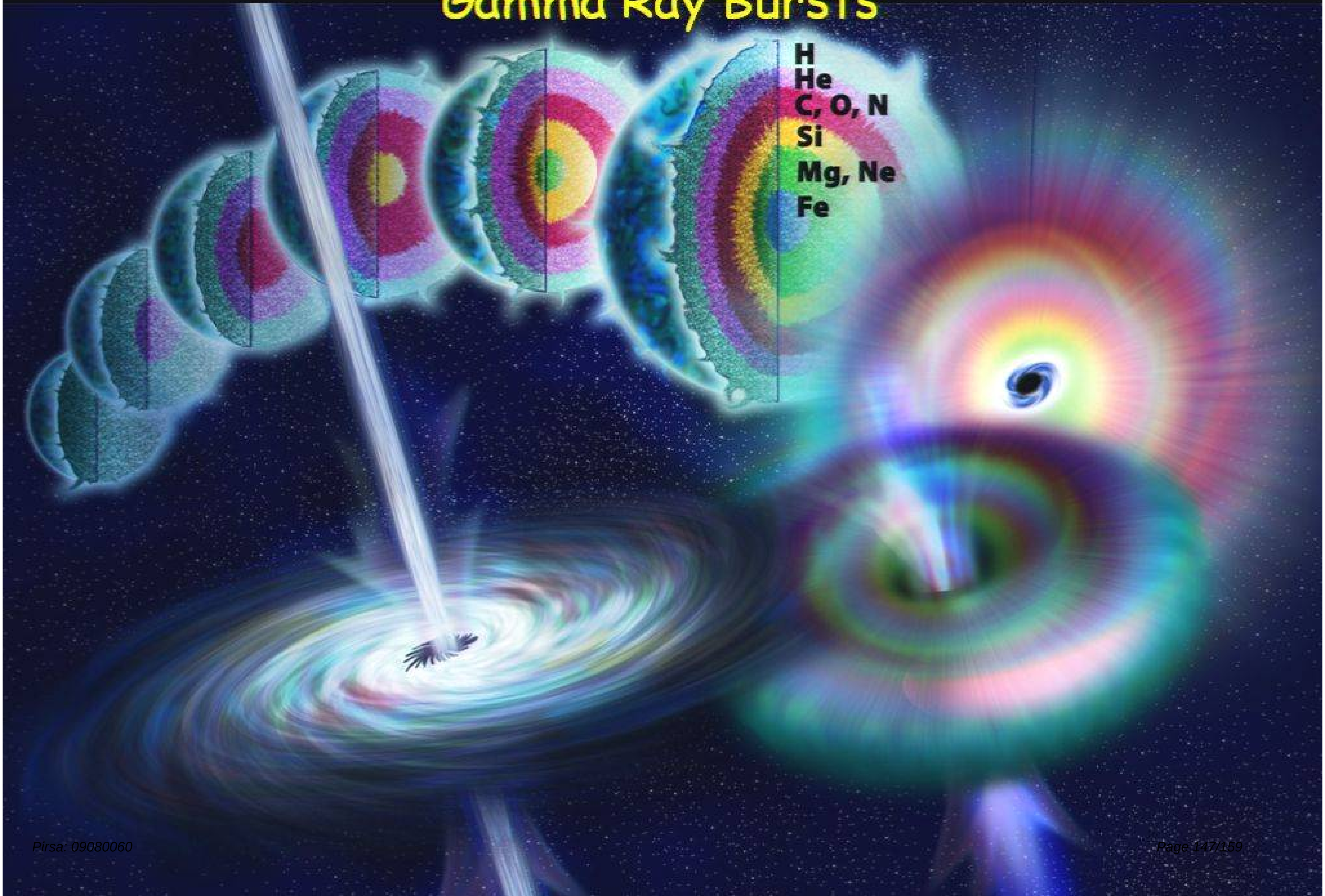




The Sound of collapse

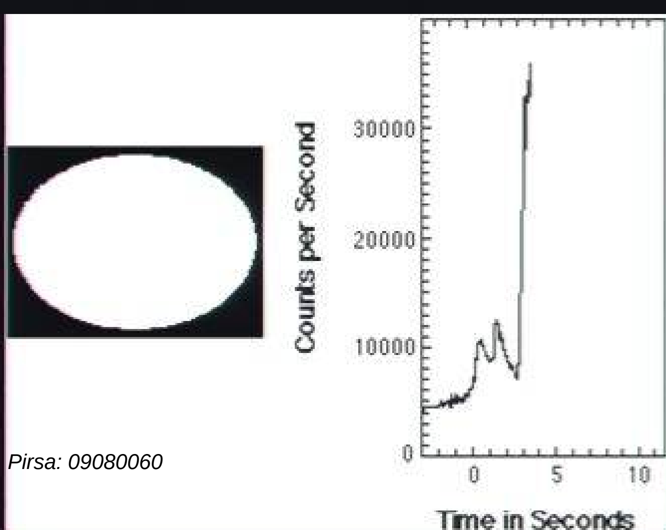
Strange Predictions

Gamma Ray Bursts

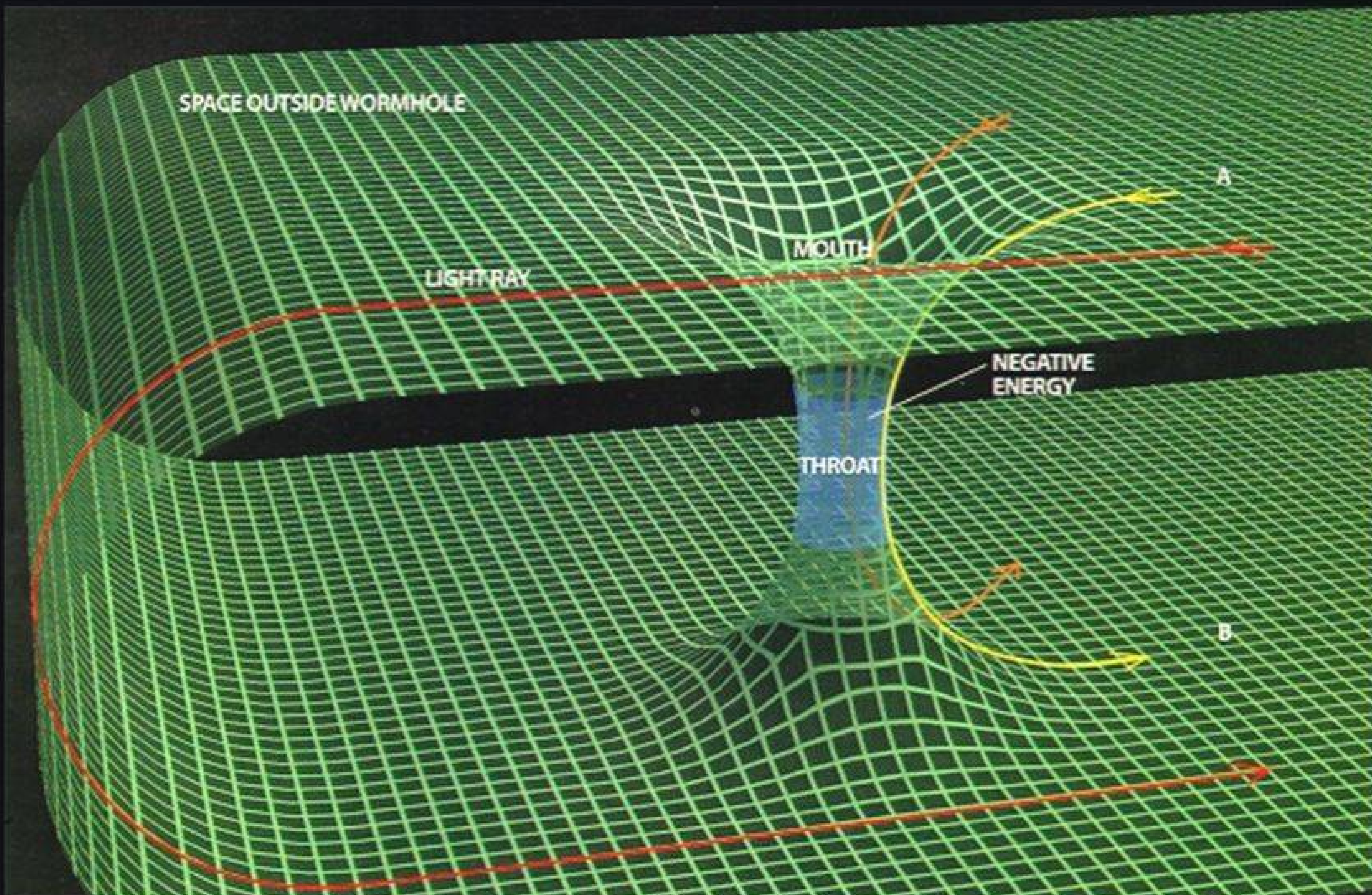


GRB

Record-breaking Gamma Ray Burst (GRB) in the act on Wednesday (March 19th, 2008), the worlds telescopes swung toward the constellation of Boötes to watch the afterglow of this massive explosion. One instrument in a Chile observatory was observing in Swift's field of view at the time of the blast and has put together a short frame-by-frame video of the event. So if you missed this historic burst from 7.5 billion years ago (which you probably did!) you can watch it now…

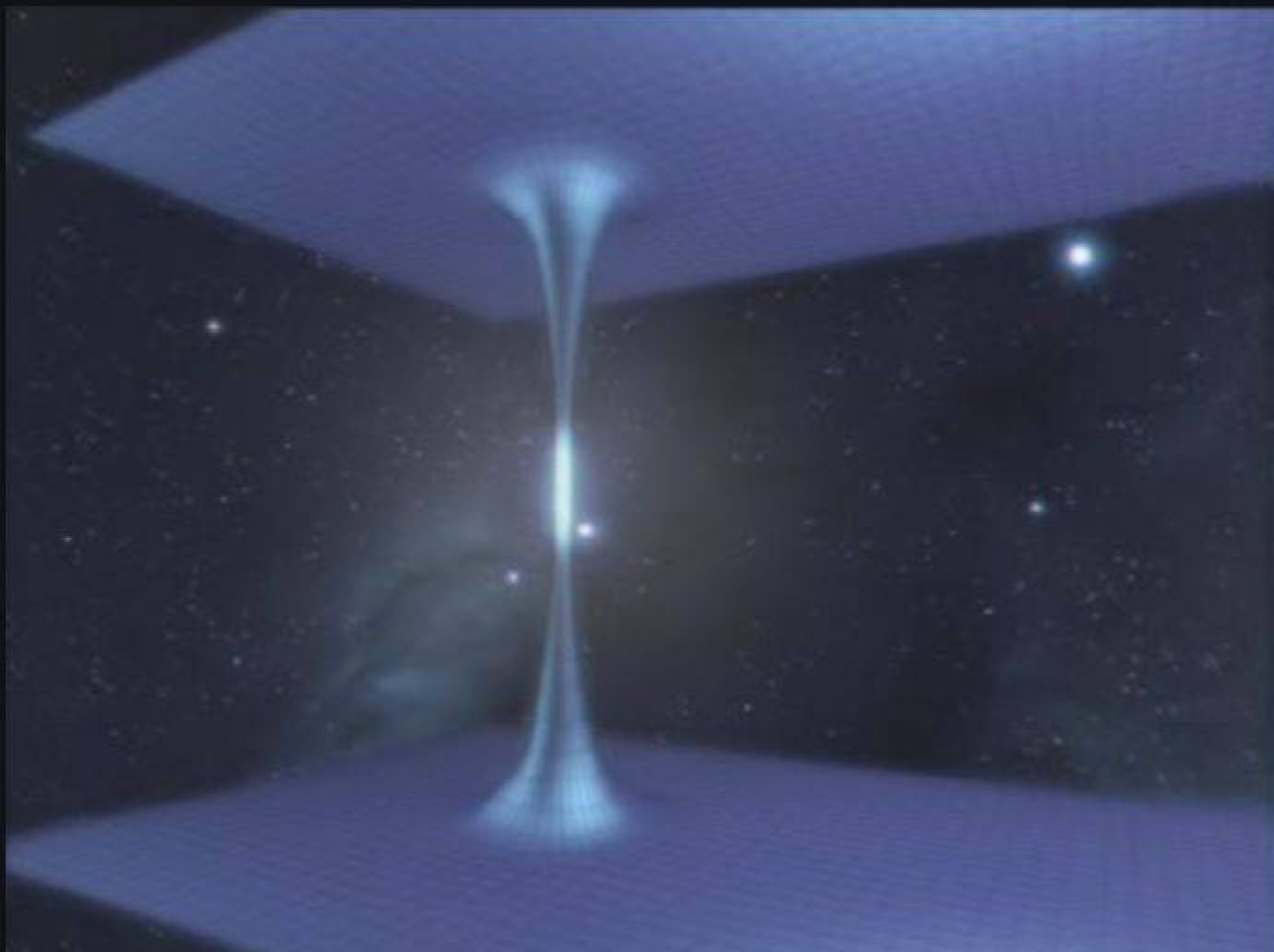


Wormholes

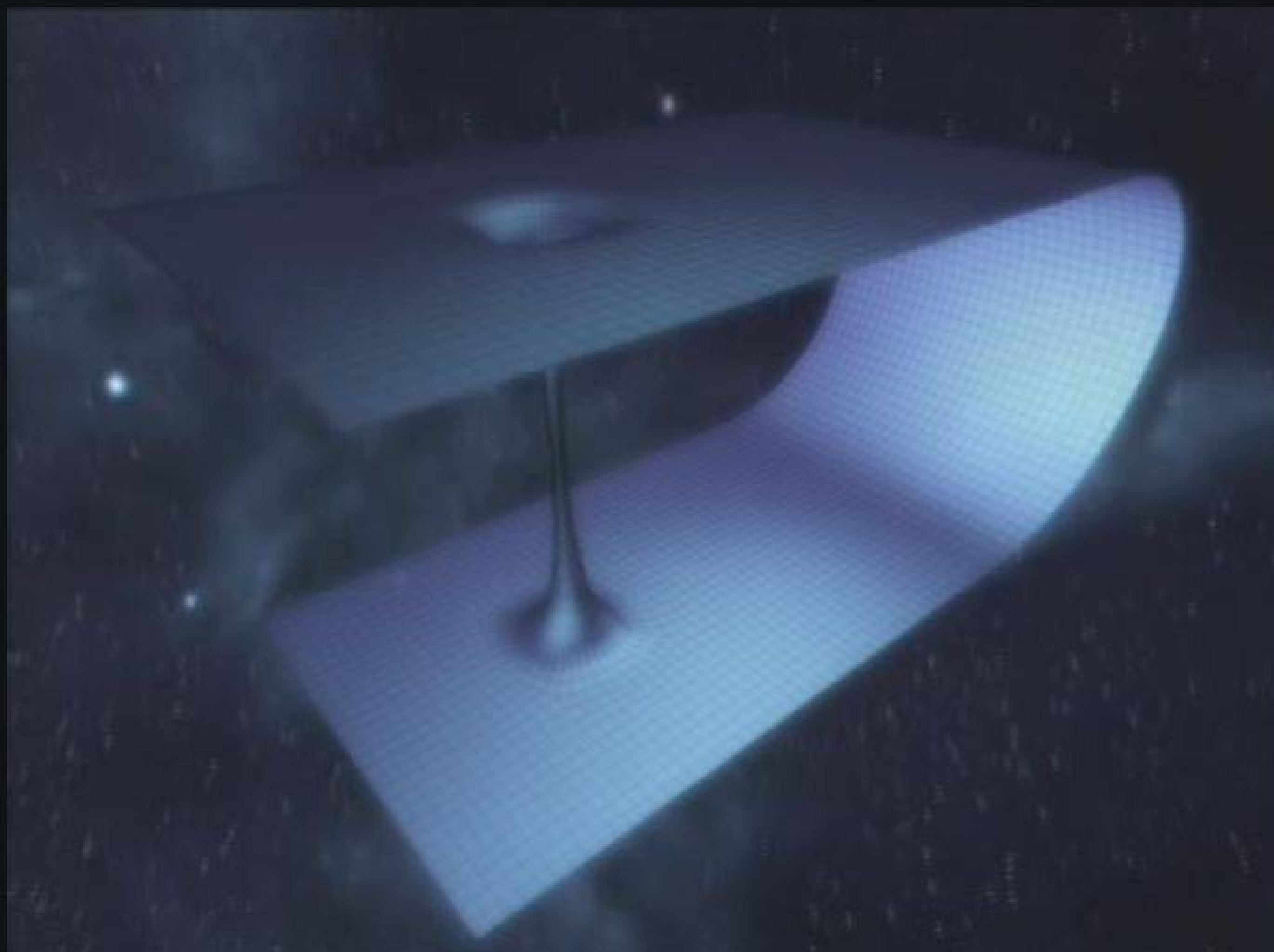

SPACE OUTSIDE WORMHOLE
A
MOUTH
LIGHT RAY
NEGATIVE
ENERGY
THROAT
B

Wormholes (the traveler's view)

Wormholes (the traveler's view)



Wormholes (the traveler's view)



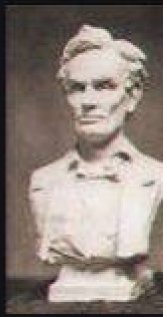
Naked Singularity

Such a naked singularity would be a breakdown in the laws of physics. After that, you could no longer guess what would come out of the black hole--it could be anything (to quote William H. Press) "from television sets to busts of Abraham Lincoln."

A singularity that is not inside a black hole (not surrounded by an event horizon), and therefore can be seen by someone outside it.

Naked Singularity

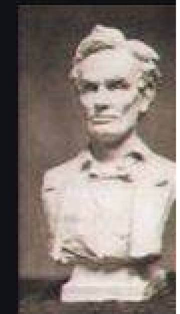
Such a naked singularity would be a breakdown in the laws of physics. After that, you could no longer guess what would come out of the black hole--it could be anything (to quote William H. Press) "from television sets to busts of Abraham Lincoln."



A singularity that is not inside a black hole (not surrounded by an event horizon), and therefore can be seen by someone outside it.

Naked Singularity

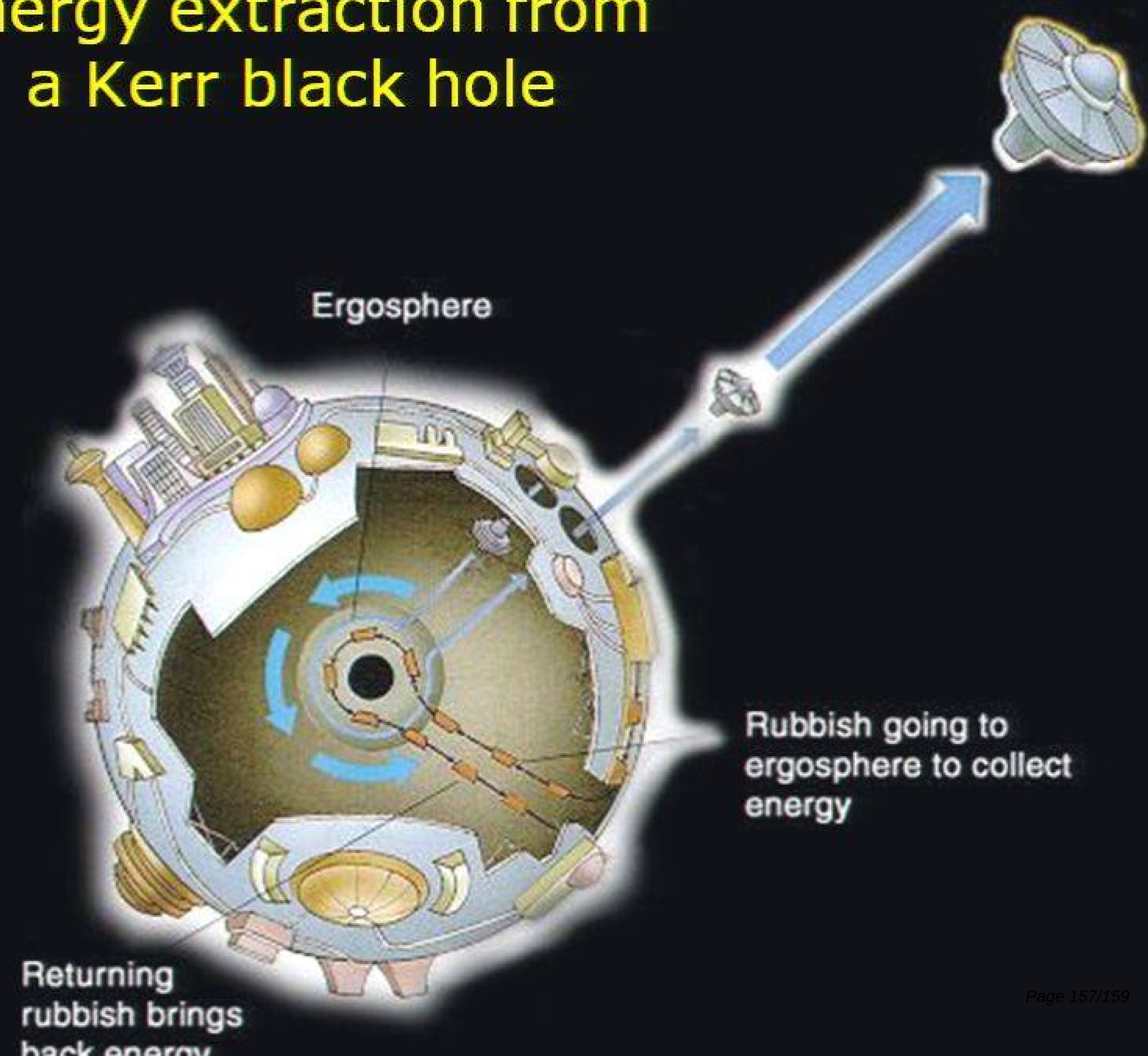
Such a naked singularity would be a breakdown in the laws of physics. After that, you could no longer guess what would come out of the black hole--it could be anything (to quote William H. Press) "from television sets to busts of Abraham Lincoln."



A singularity that is not inside a black hole (not surrounded by an event horizon), and therefore can be seen by someone outside it.

Time Travel

Energy extraction from a Kerr black hole




WOW! THAT'S MY BEST TEE SHOT TODAY! STRAIGHT AND LONG!
NOW I UNDERSTAND WHY THIS HOLE IS A PAR ONE!
CAUTION! BLACK HOLE
THAVES


The End