Building and detection black holes

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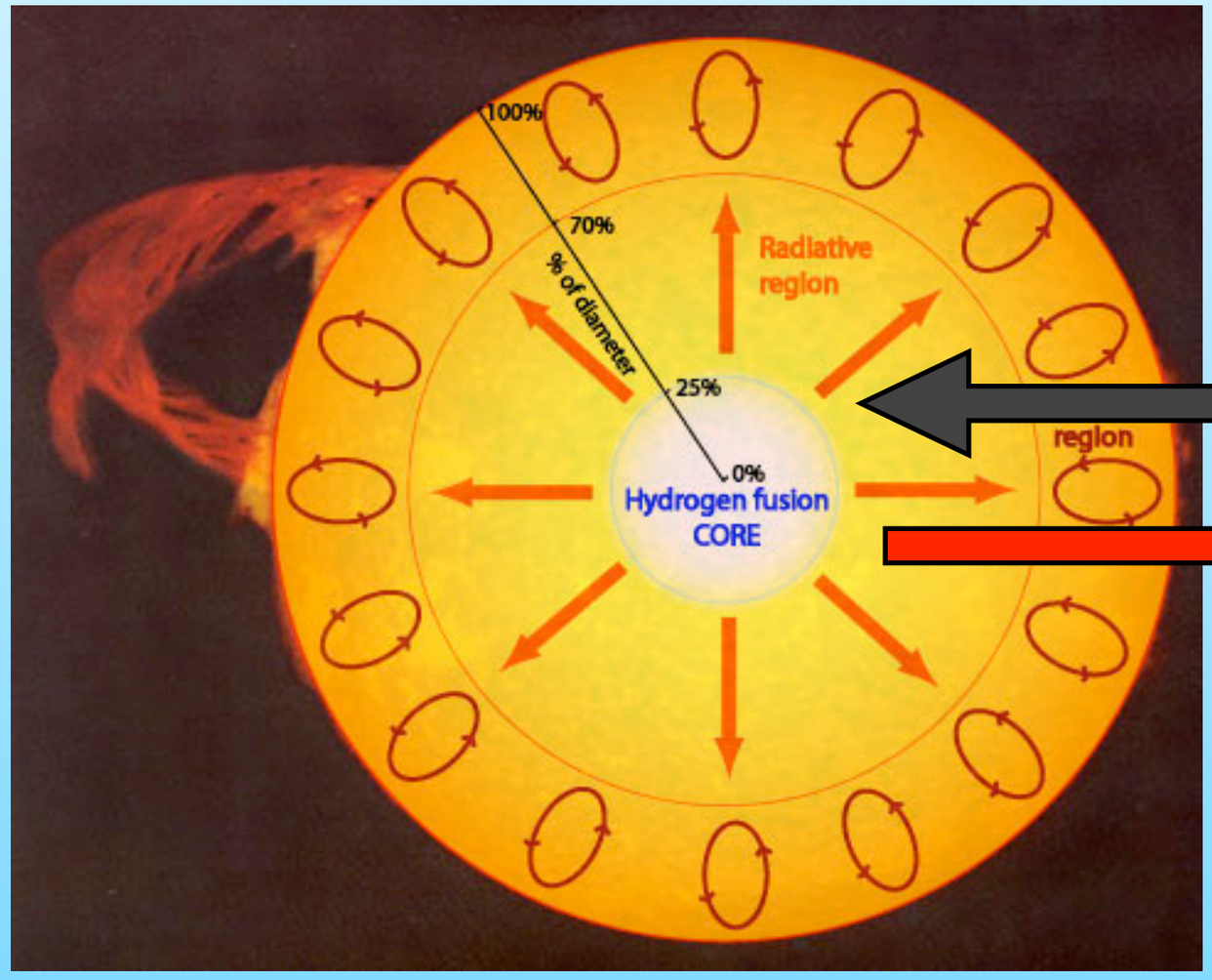
- Compact Objects
- black holes
- GRAVITATIONAL WAVES

Compact Objects

- Stellar Evolution
- Nuclear fusion
- End of stellar evolution
- Red Giants
- White Dwarves
- Supernovae
- Neutron Stars
- Black Holes

Nuclear Fusion

To counter gravitational collapse, the star exerts an outward radiation pressure due to nuclear fusion in the stellar interior



Gravity

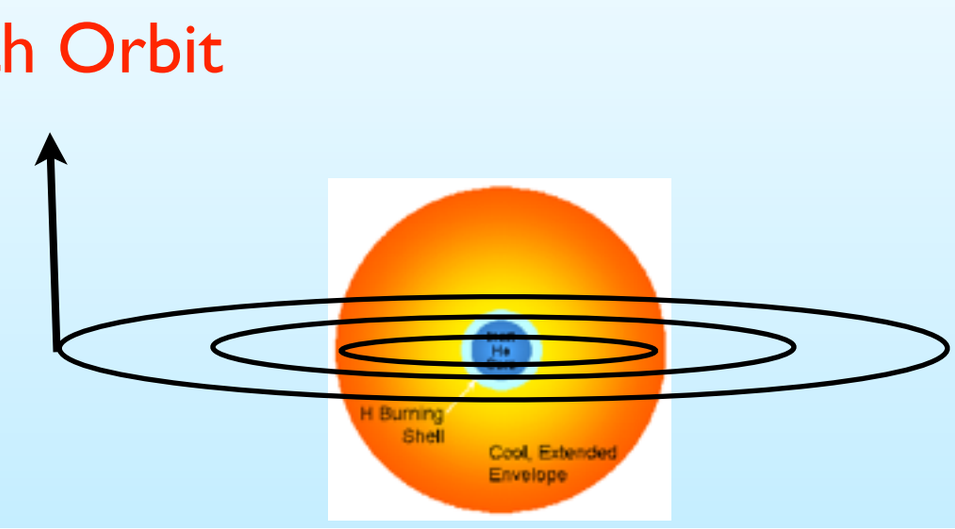
Radiation pressure

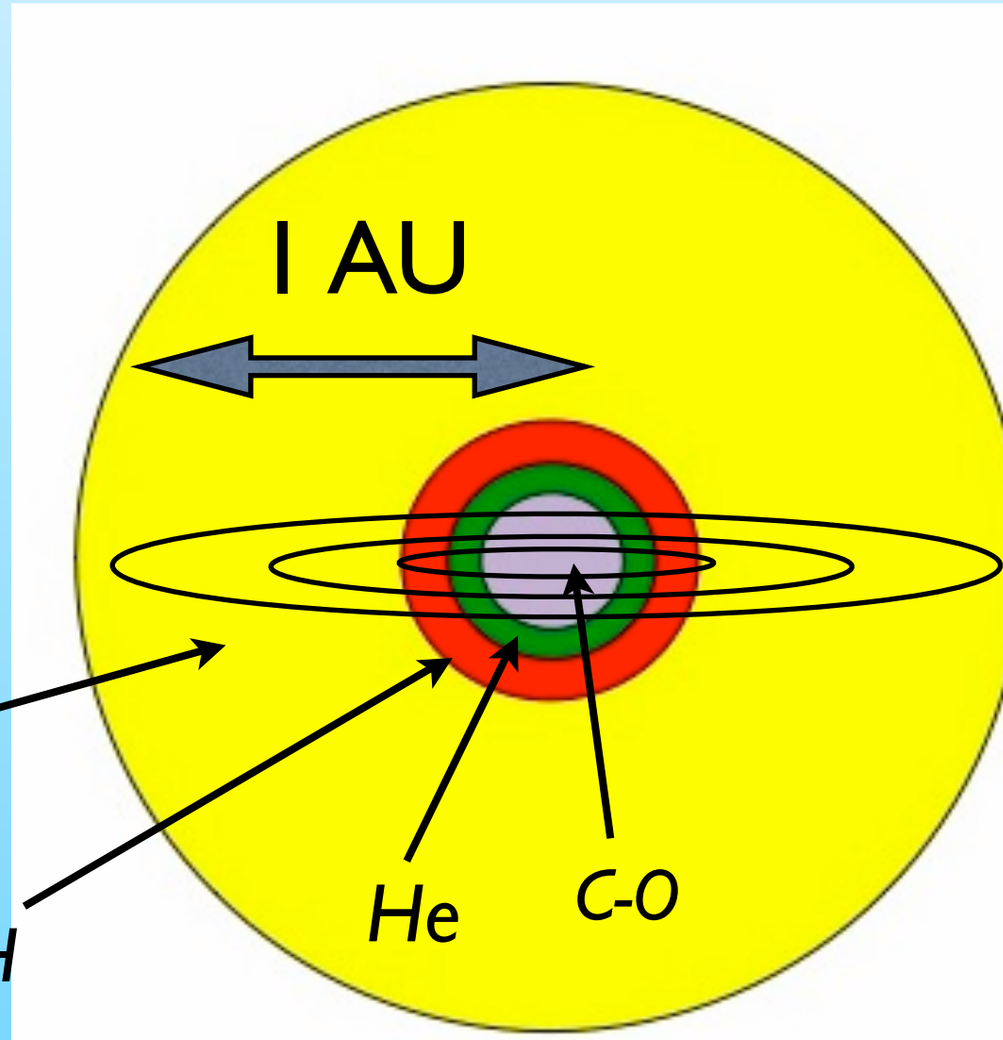
End of evolution 1

- Star like the Sun
- Formation of a He core either by p-p or CNO cycles
- Star is not massive enough to burn He
- Core contraction begins
- Collapse and re-heating of exterior layers.
- H fusion begins in a shell around the He core
- Outer layers expand to the orbit of Mercury

Red Giant

- $T_c \sim 10^8$ K, He fusion begins
- Formation of C,N,O
- Not massive enough to burn C
- Core collapses
- Outer layers expand to Earth's orbit.
- Star becomes instable

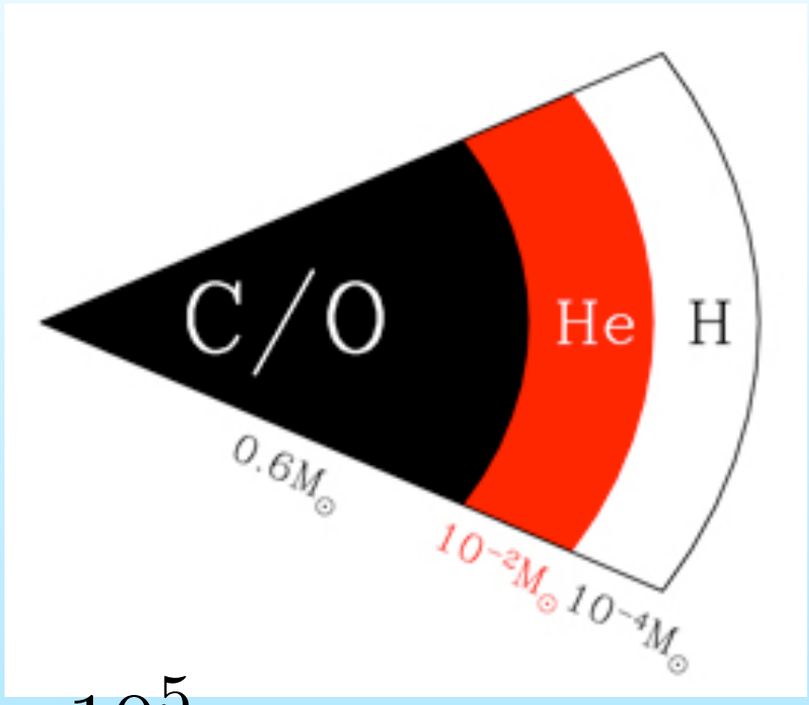




White Dwarf

Mass : $M_{WD} \sim 0.6 M_{\odot}$

Size : $R_{WD} \sim R_{\oplus} \sim 10^{-2} R_{\odot}$



Density : $\rho_{WD} \sim 10^{9} kg\, m^{-3} \sim 10^{4} \rho_{\odot} \sim 10^{5} \rho_{\oplus}$

Temperature : $T_{surf} \sim 10^{4} K \sim 10 T_{\odot}^{surf}$

$T_c \sim 10^{7} K \sim T_{\odot}^{c}$

And the battle against Gravity?

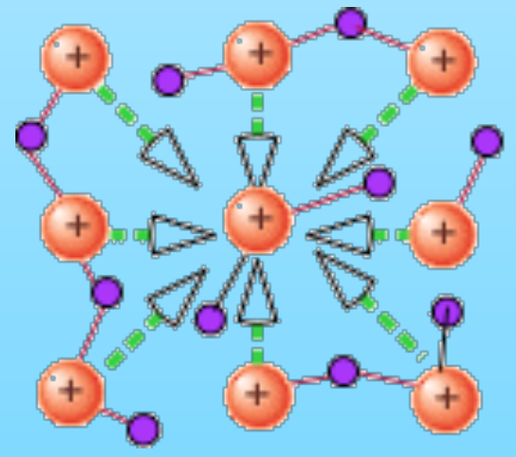
The white dwarf still needs to resist the force of gravity.

To understand how, we need to use quantum mechanics.

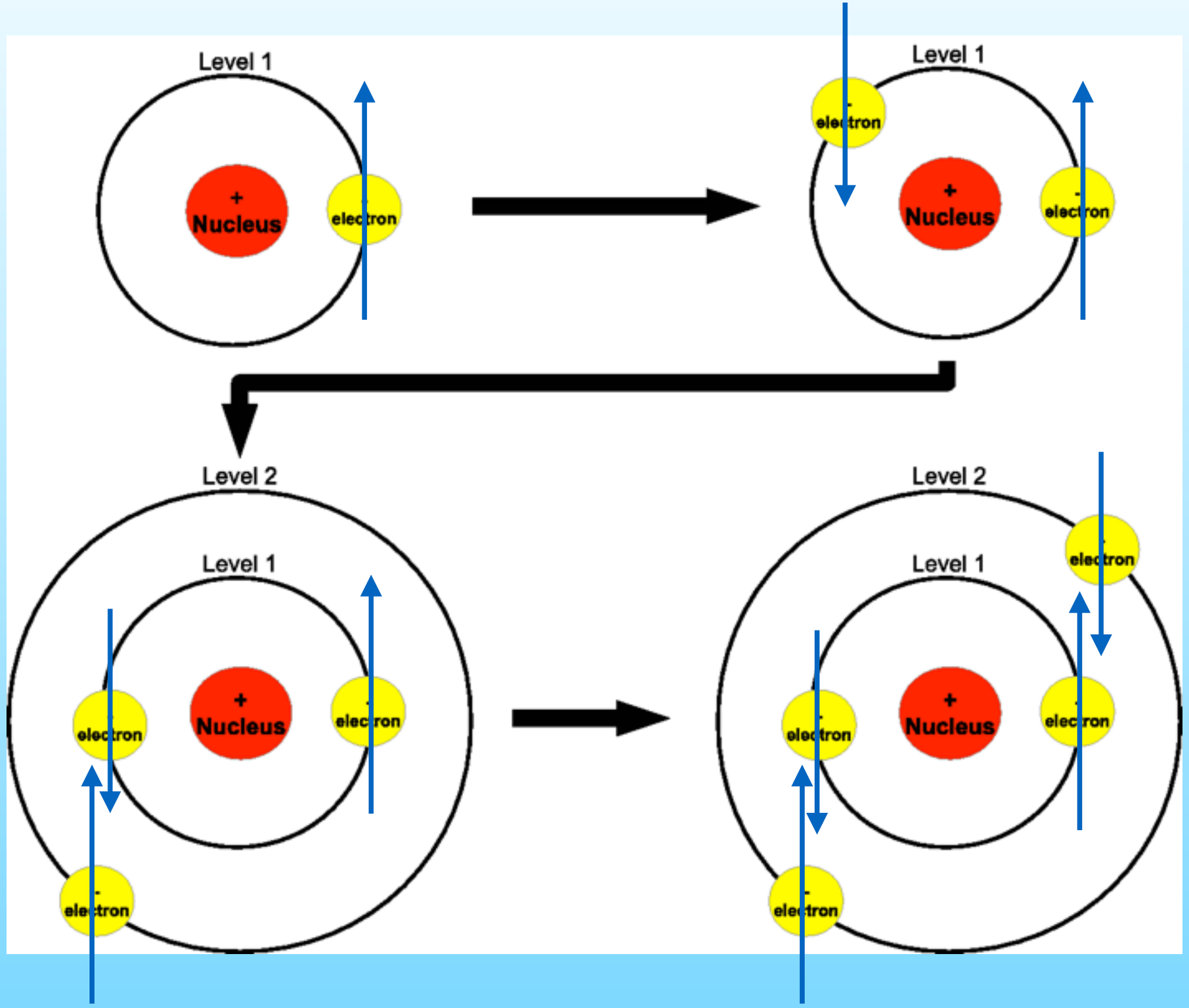
The particles inside a white dwarf exist in a plasma.

As usual, gravity tries to pull everything towards the center of the potential…

Gravity loses due to the Pauli Exclusion priciple.



Pauli Exclusion Principle



Degenerate Matter

For a normal gas : $P = nkT$

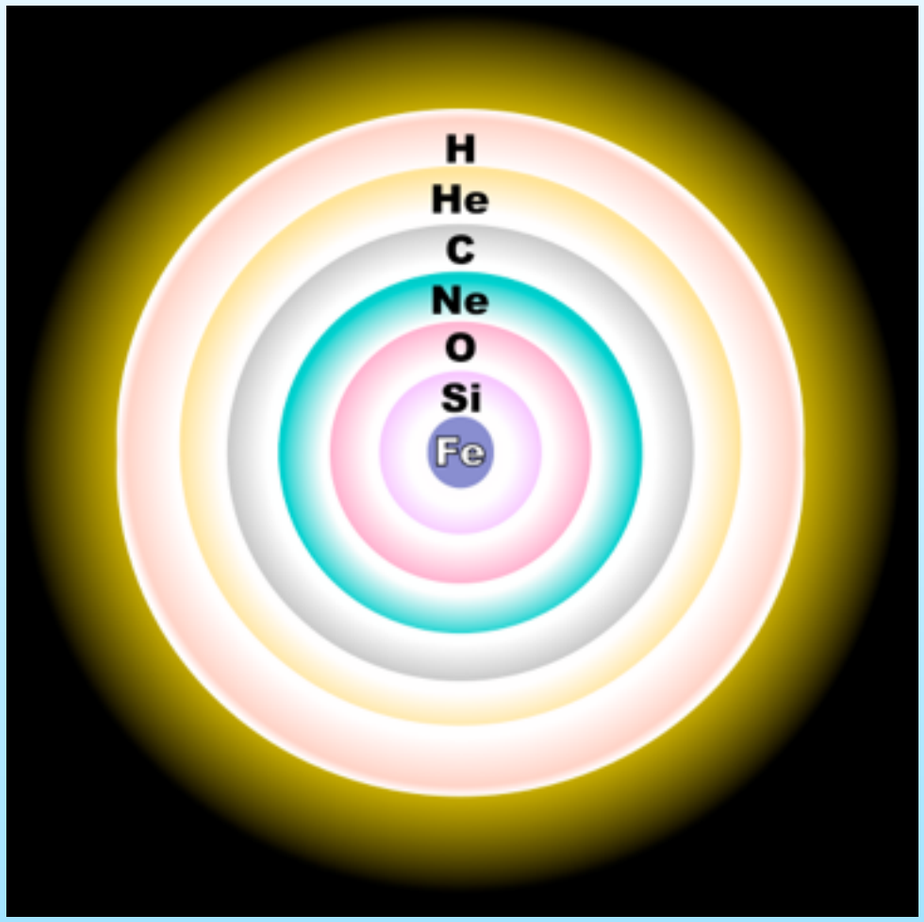
But for degenerate matter : $P \propto \hbar c \left(\frac{\rho}{m_e}\right)^{4/3}$

A relation exists between the size and mass of a white dwarf : $R \sim M^{-1/3}$

Chandrasekhar mass : $M_C \propto \left(\frac{\hbar c}{G}\right)^{3/2} \sim 1.4\, M_\odot$

End of Evolution 2

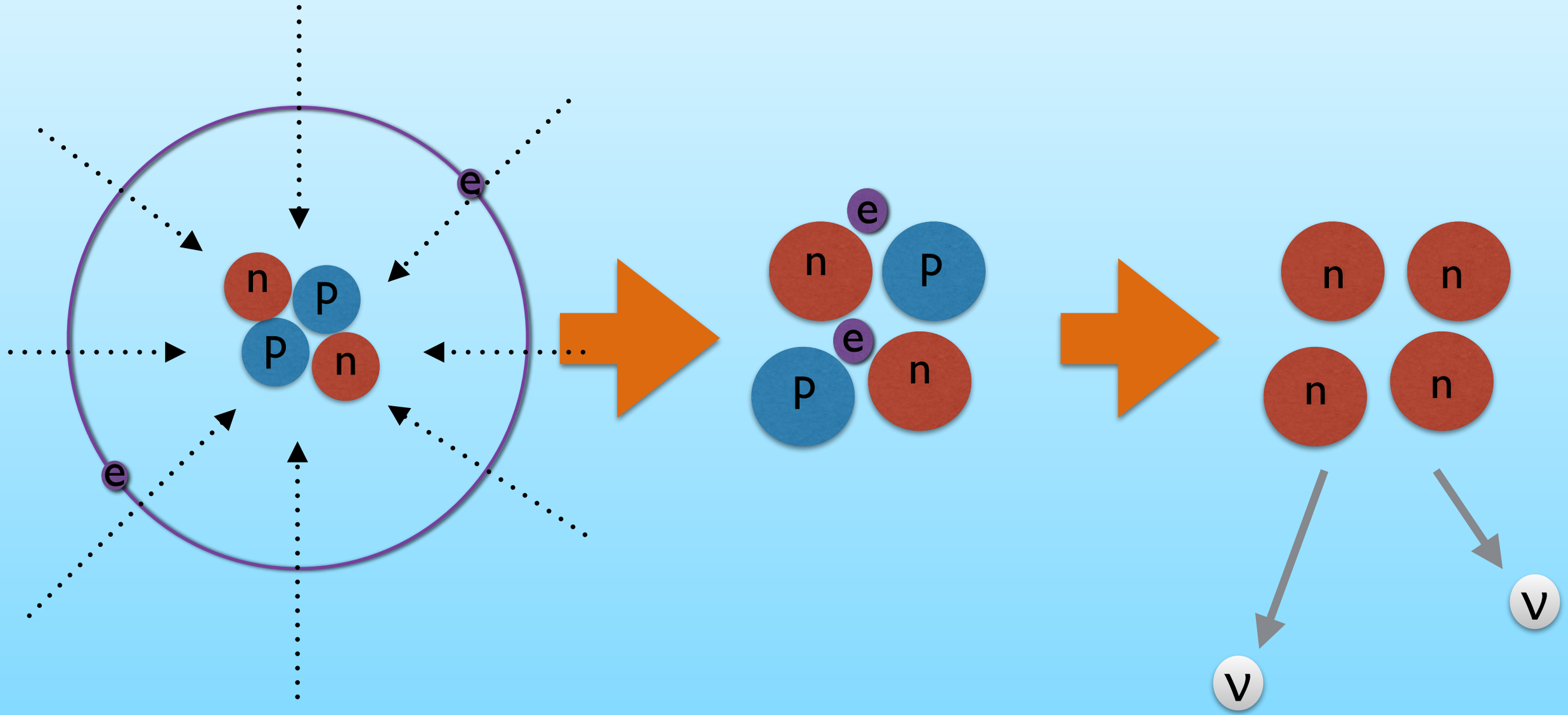
For stars with mass greater than $10\,M_\odot$ we can create elements all the way to ^{56}Fe



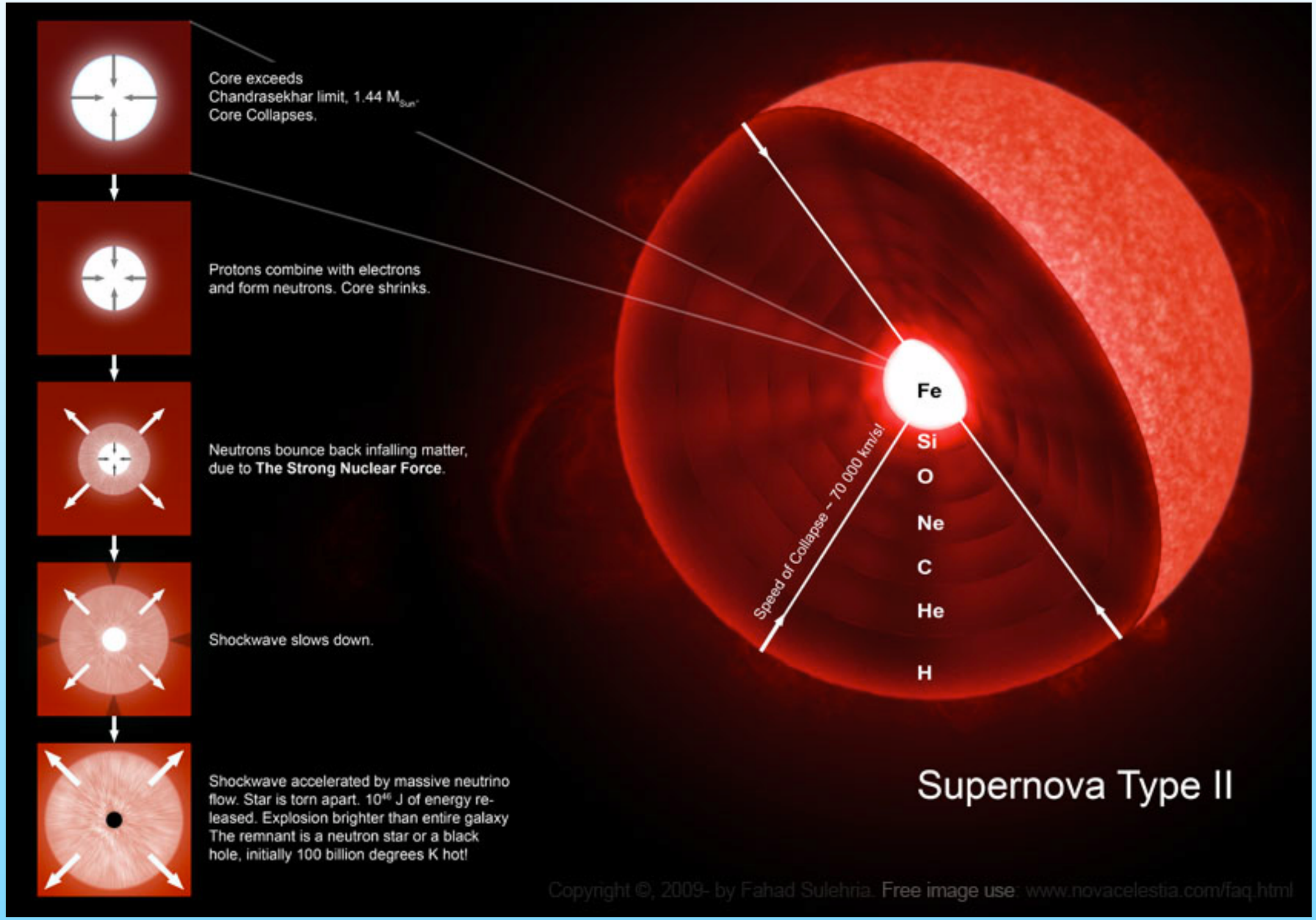
In this case, electron degeneracy is too weak to prevent gravitational core collapse

Neutron Degeneracy

Now, the pressure to counteract against gravity comes from degenerate neutron pressure



Supernovae


Core exceeds
Chandrasekhar limit, 1.44 M_{Sun}.
Core Collapses.
Protons combine with electrons
and form neutrons. Core shrinks.
Neutrons bounce back infalling matter,
due to **The Strong Nuclear Force**.
Shockwave slows down.
Shockwave accelerated by massive neutrino
flow. Star is torn apart. 10^{46} J of energy re-
leased. Explosion brighter than entire galaxy
The remnant is a neutron star or a black
hole, initially 100 billion degrees K hot!
Fe
Si
O
Ne
C
He
H
Speed of Collapse ~ 70 000 km/s!
Supernova Type II
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Neutron Stars

Mass : $M_{NS} \sim 1.35 - 2\, M_{\odot}$

Size : $R_{NS} \sim 12\, km \sim 10^{-4}\, R_{\odot}$

Density : $\rho_{NS} \sim 10^{17}\, kg\, m^{-3} \sim 10^{14} \rho_{\odot}$

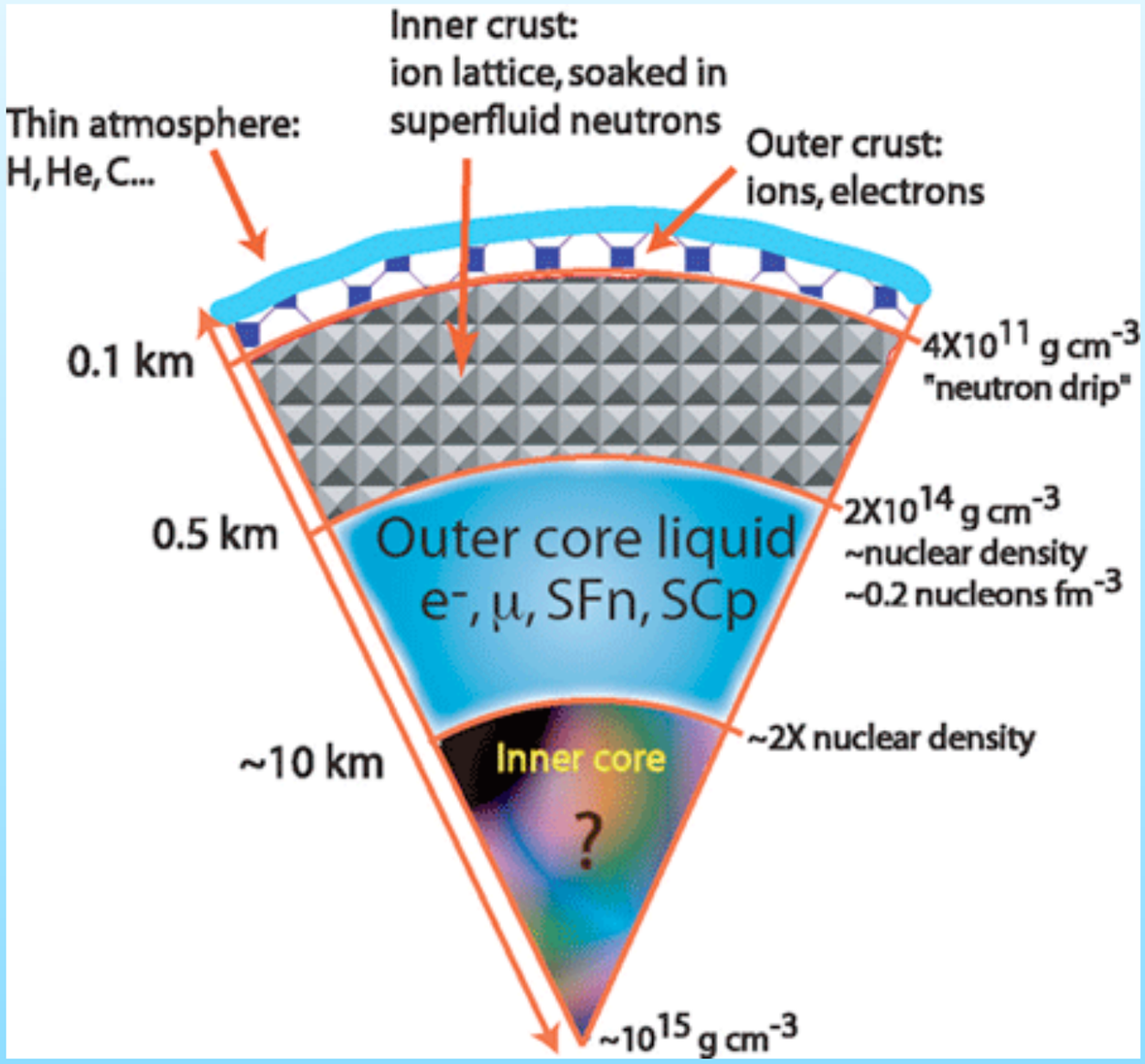
Temperature : $T_{NS} \sim 10^{11} K$

Rotation : $\omega \sim 1.4\, ms - 30\, secs$

Gravity : $g_{NS} \sim 10^{12}\, m\, s^{-2} \sim 10^{11} g$

Escape velocity : $v_{esc} \sim 10^{5} km\, s^{-1} \sim 0.3c$

Neutron Stars



Black Holes

If the core mass is greater than $3\,M_\odot$, neither e^- nor n degeneracy pressure can resist the pull of gravity.

With this amount of mass squashed into a sphere 18km across, the only option is the formation of a black hole.

Black holes are simultaneously, the simplest and most complex objects in the universe.

Black Holes

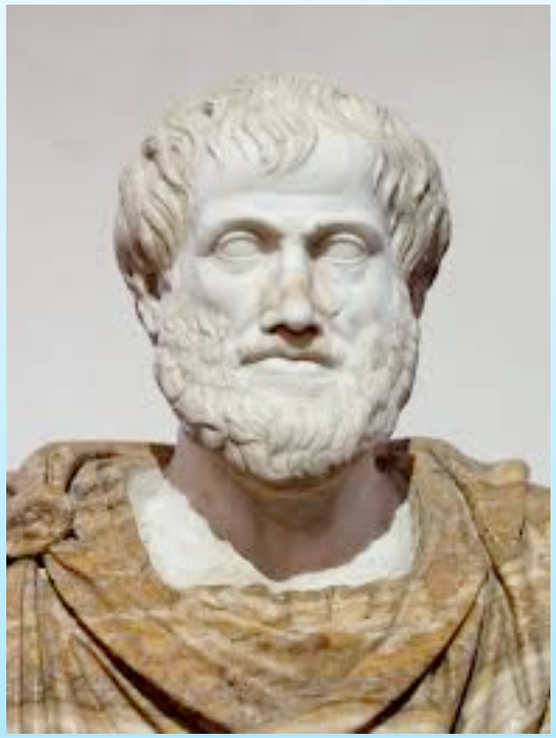
- General Relativity
- Spacetime
- Black Holes
- Event Horizon
- Singularity
- Binary Systems
- Supermassive Black Holes

But First...A Brief History of Gravity..

...followed by...

...A crash course In General Relativity.

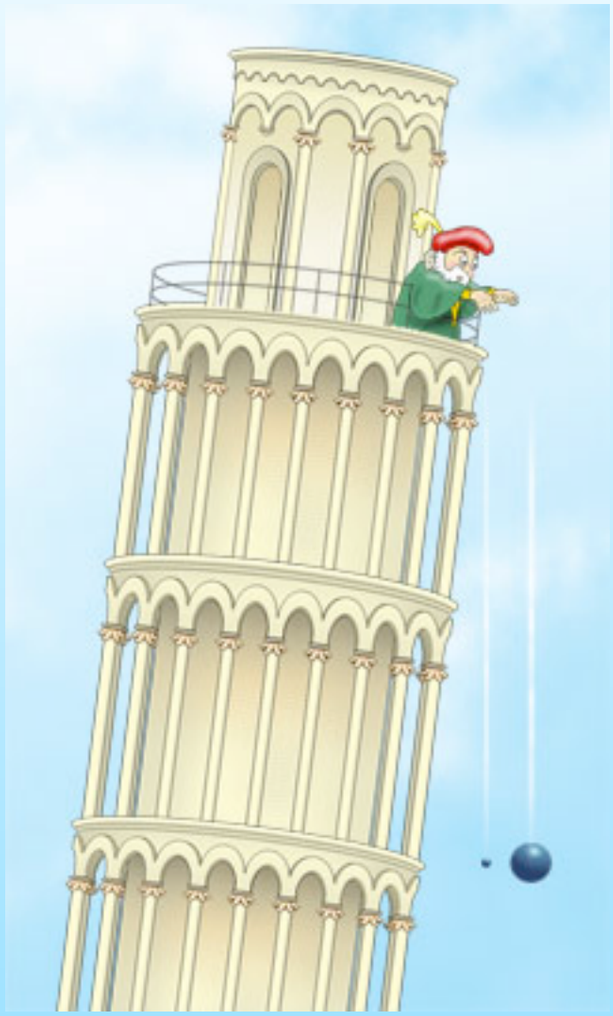
A Brief History of Gravity



Aristotle : Heavy elements, due to their nature, fall towards the center of the Universe…

The heavier an object is, the faster it falls!

A Brief History of Gravity



Gallileo : All objects accelerate equally when falling.

A Brief History of Gravity

Newton : law 0 - Never sit under an apple tree.

law 1 - Universal gravitation

$$F = G\frac{m_1 m_2}{r^2}$$

Introduced the concept of absolute space and time

A Brief History of Gravity

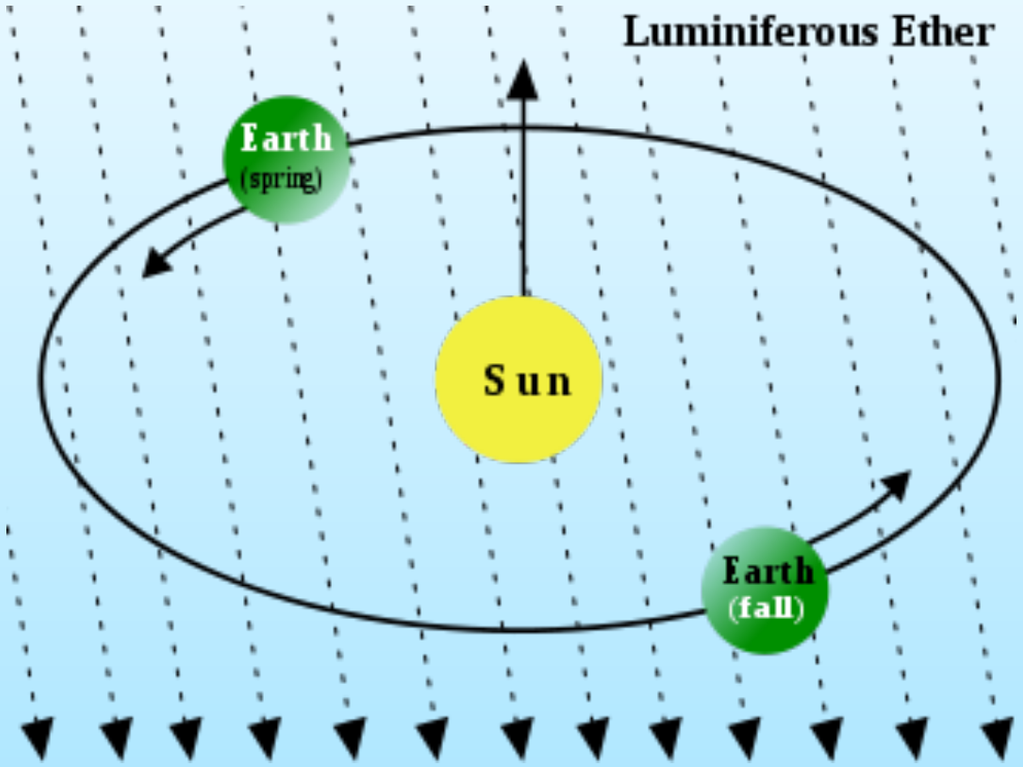
Time is universal

Space is also universal

There is exists a single universal frame of reference

Light travels as a wave through the aether

A Brief History of Gravity



As water waves have the medium of water…

…light had the medium of the aether

A Brief History of Gravity

Michelson-Morley :

Michelson had measured the speed of light in 1897

As the speed of sound is relative to the air, the speed of light must be relative to the aether.

Measured speed of light as Earth orbited the sun

Found no evidence of an aether!?!

Current measurements show a $\Delta c/c < 10^{-17}$

A Brief History of Gravity

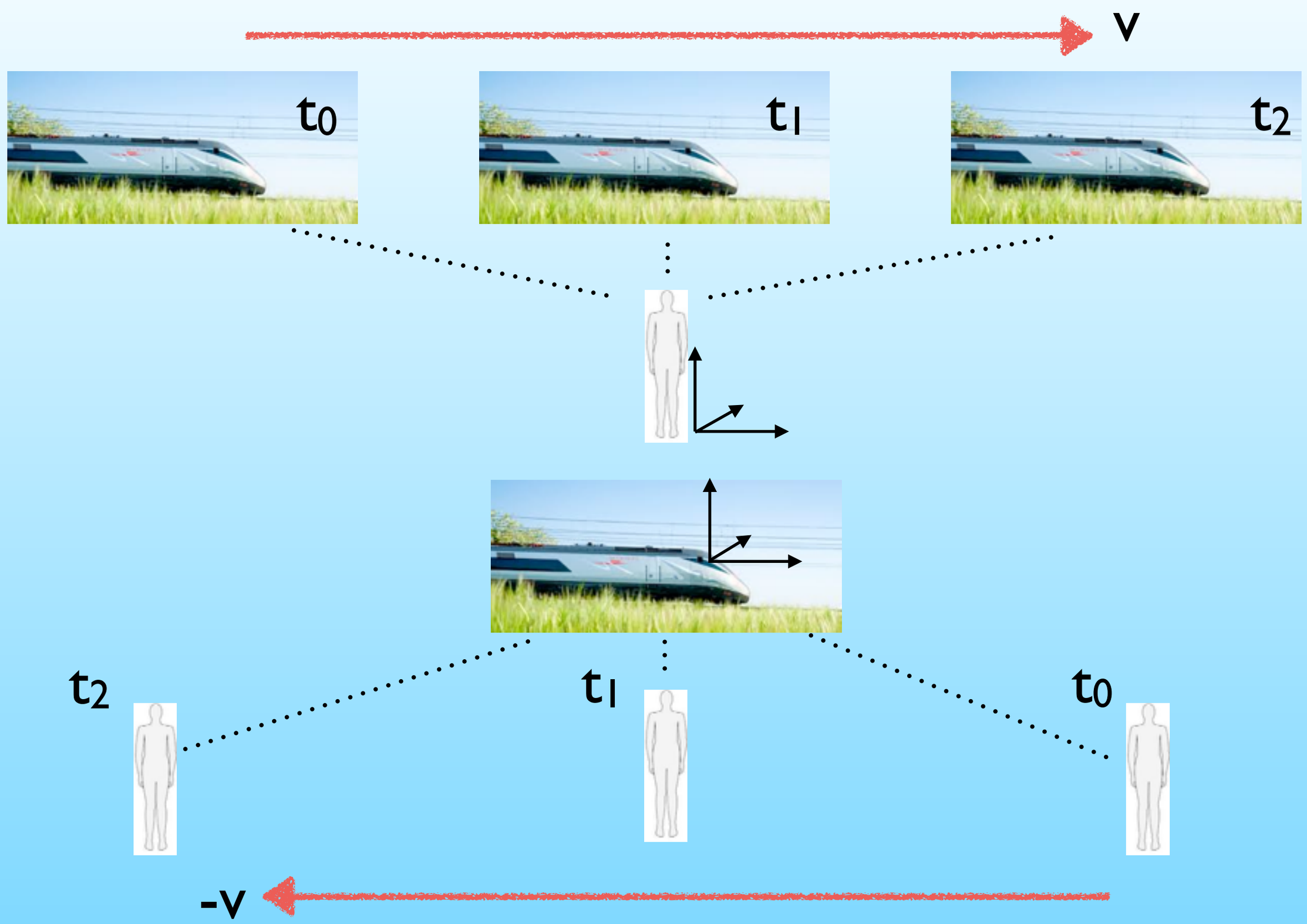
Albert Einstein : Special Theory of Relativity

As there was no aether, there was no absolute reference frame.

Special relativity is based on the "**principle of relativity**"

So, back we go to Galileo…

Galilean Relativity



A Brief History of Gravity

Albert Einstein : Special Theory of Relativity

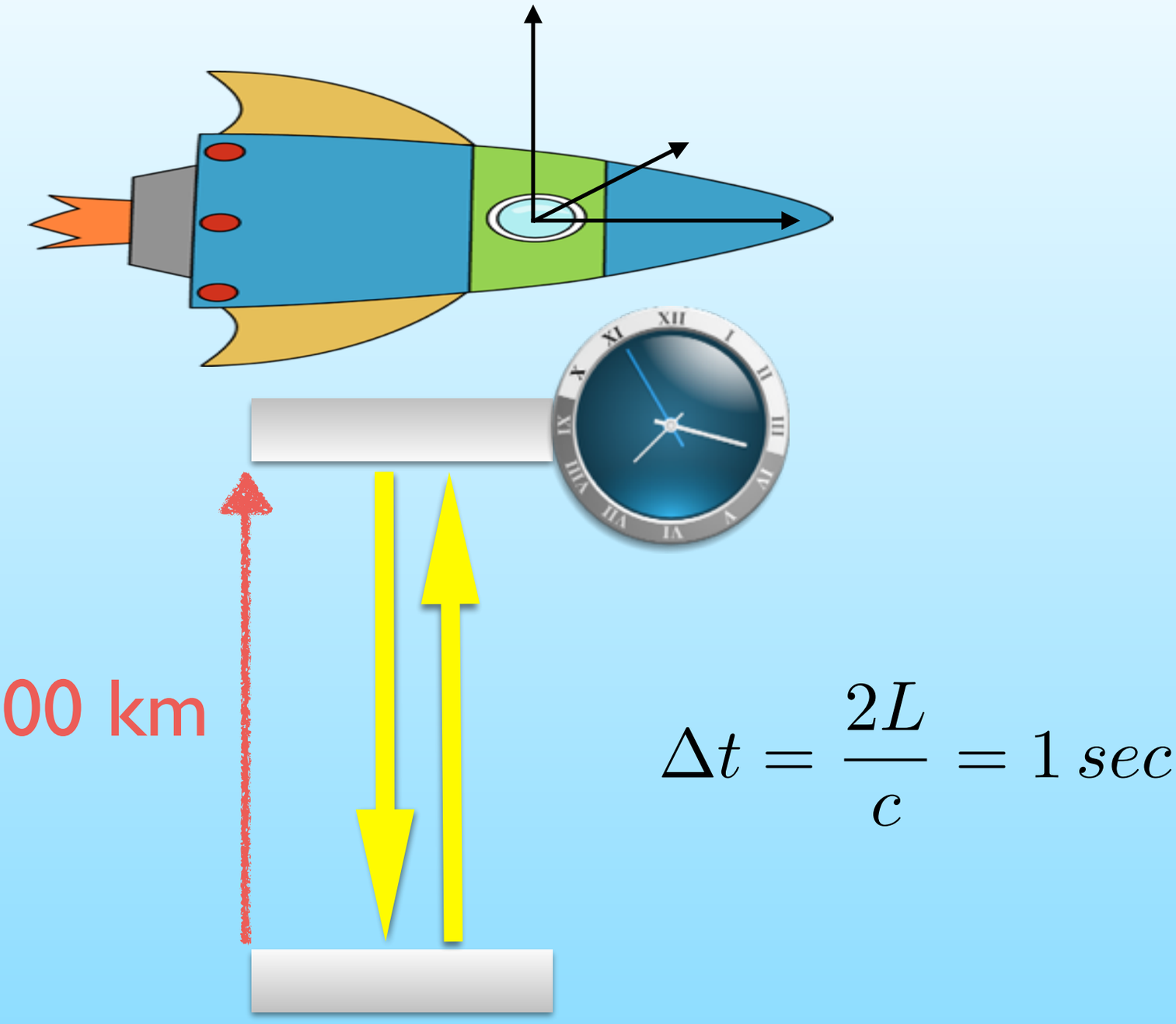
Postulates :

Any reference frame moving with uniform velocity will observe the same laws of physics

The speed of light in a vacuum is always constant

…which leads to "weirdness"…

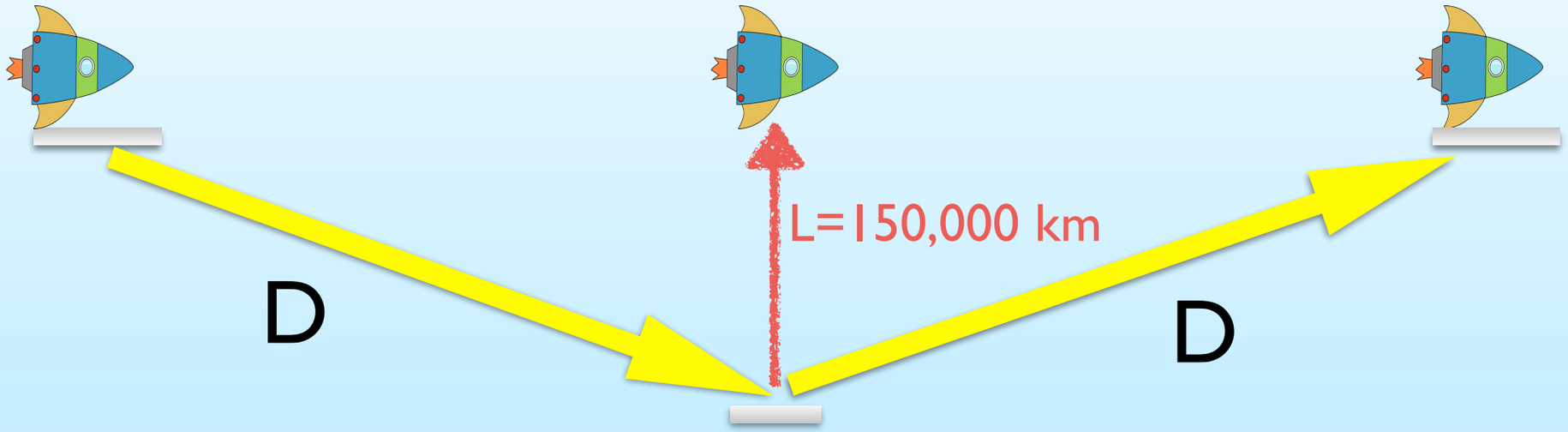
Time Dilation



L=150,000 km

$$\Delta t = \frac{2L}{c} = 1\,sec$$

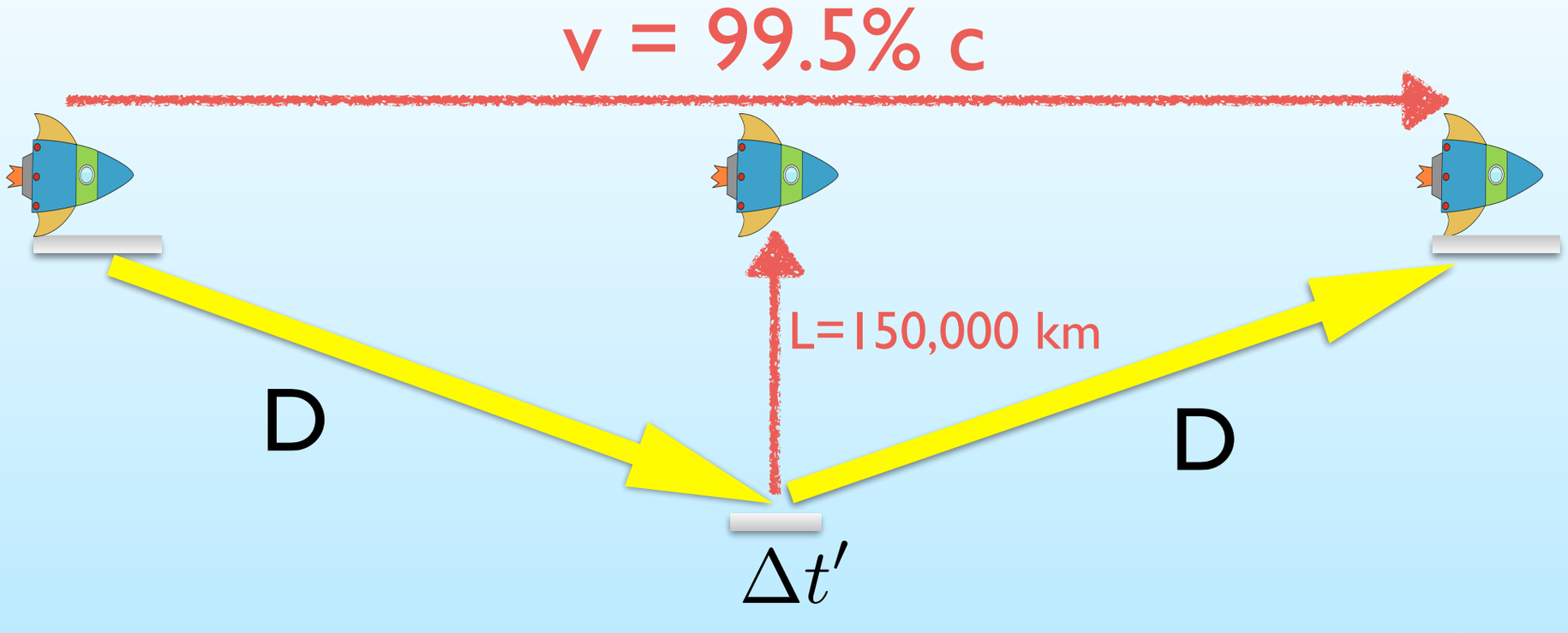
Time Dilation



$\Delta t'$

$$\Delta t' = \gamma \Delta t = \frac{\Delta t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Time Dilation



$$\frac{v^2}{c^2} = 0.995 \rightarrow \gamma = 14$$

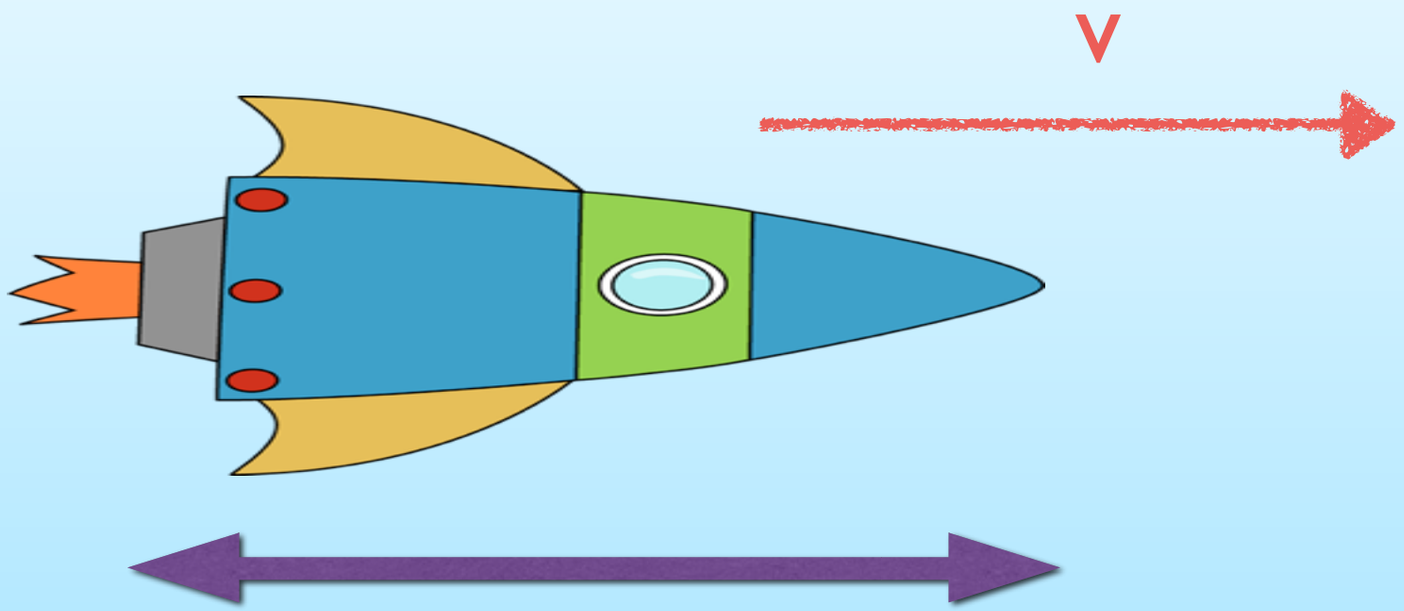
Our observer thinks that the clock on the ship is ticking at a rate 14 times slower than his clock

Observation

As I move faster, a stationary observer concludes that my time has slowed down.

However, from my point of view, nothing has changed!

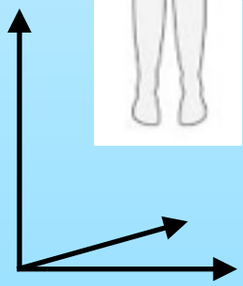
Length Contraction



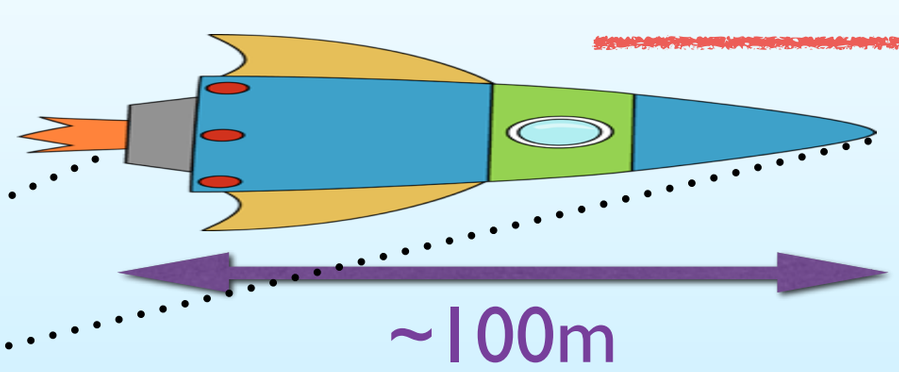
To me…my ship is 100m long and all is normal…

…But what does a stationary observer see?

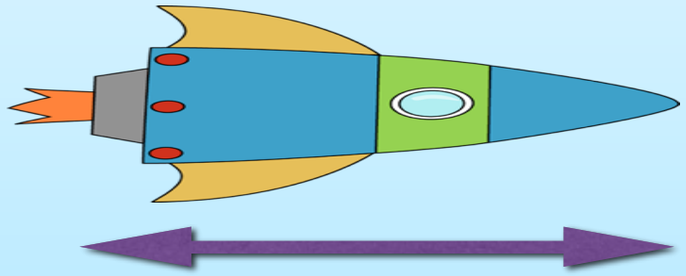
Length Contraction



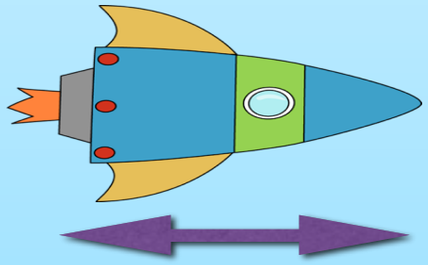
$$L = \gamma^{-1} L_0$$



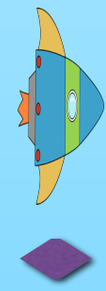
v = 0.01c



v = 0.5c

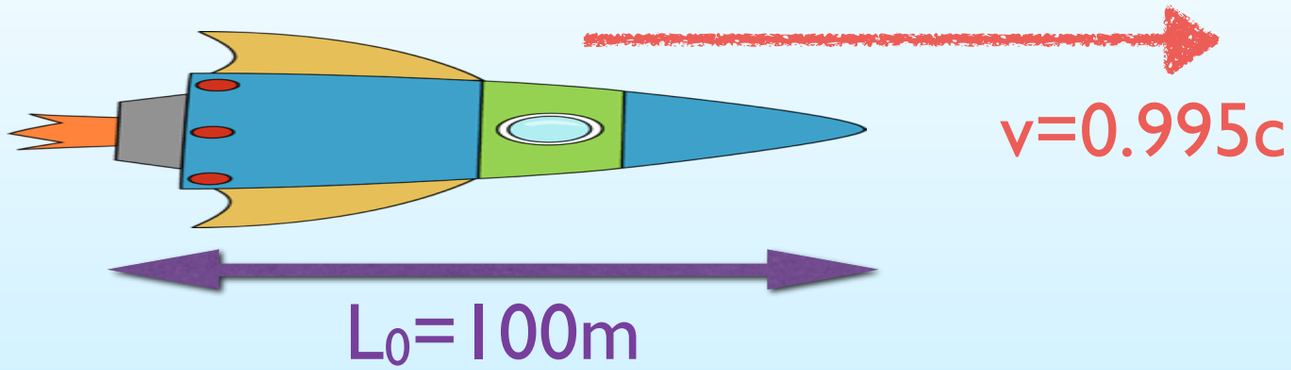


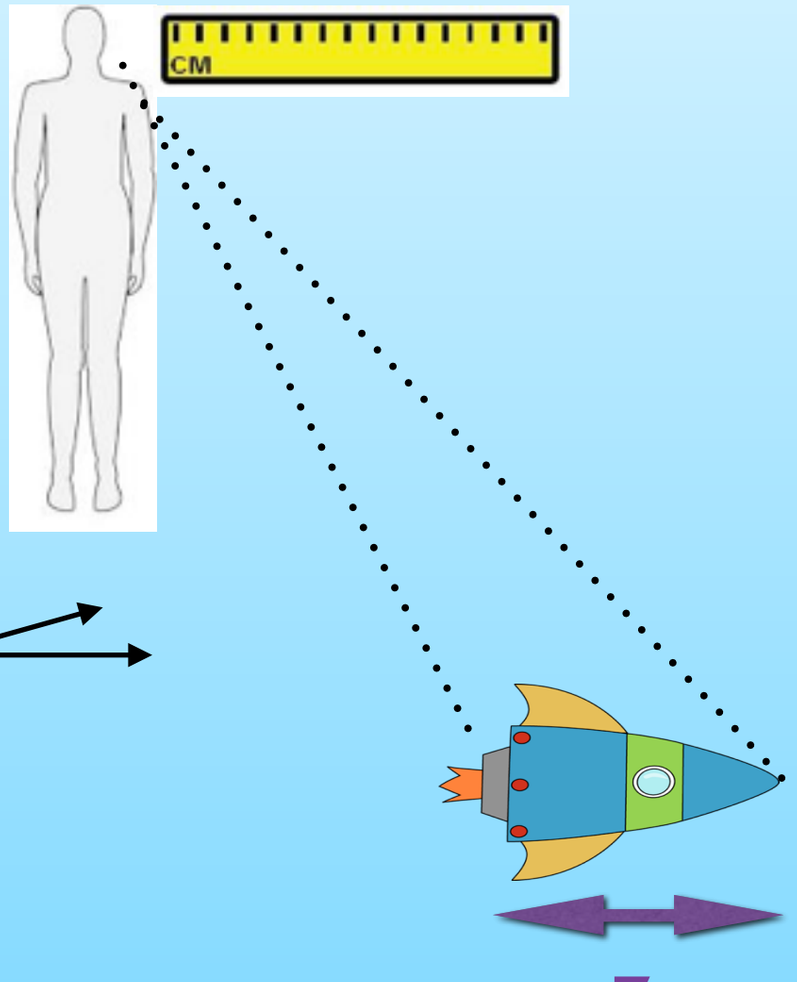
v = 0.9c



v = 0.9999c

Length Contraction



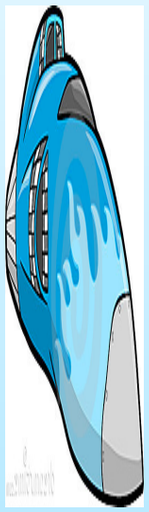


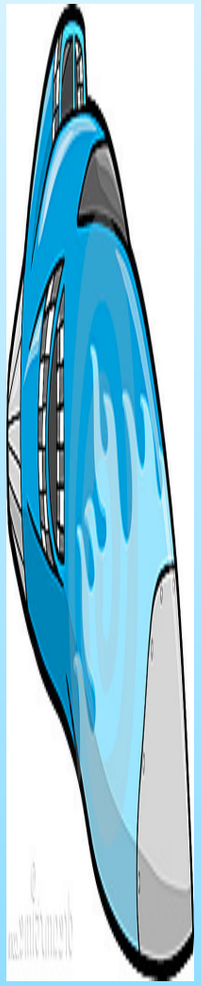
$$L = \gamma^{-1} L_0$$

$$\frac{v^2}{c^2} = 0.995 \rightarrow \gamma = 14$$

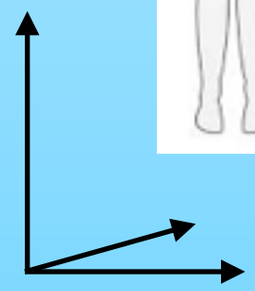
Our observer thinks my ship is
14 times smaller than it actually is!

Length Contraction



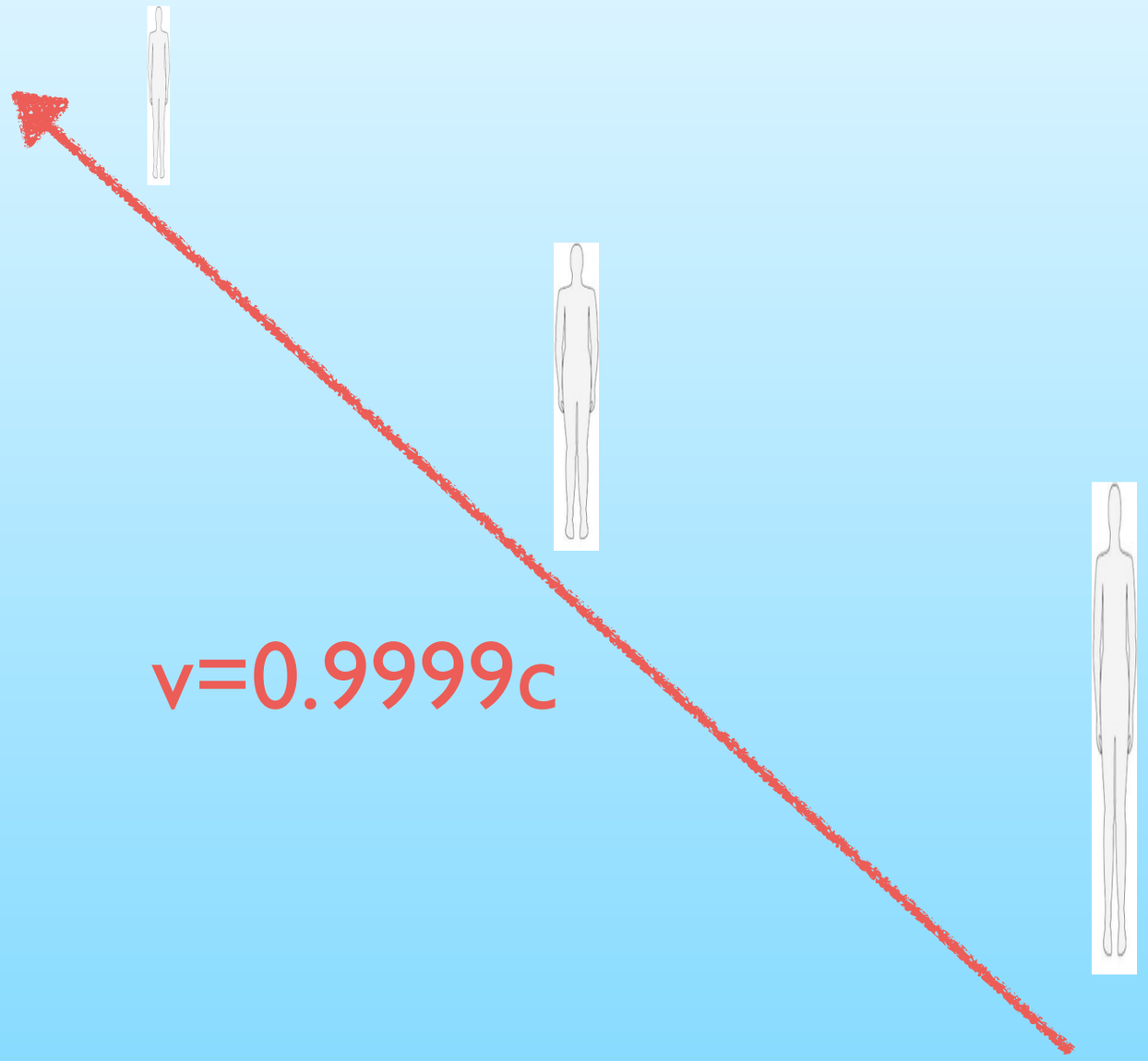


v=0.9999c

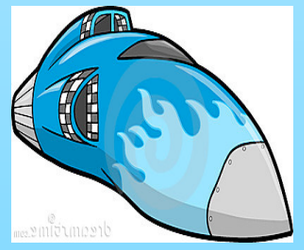


Observer viewpoint

Length Contraction



v=0.9999c



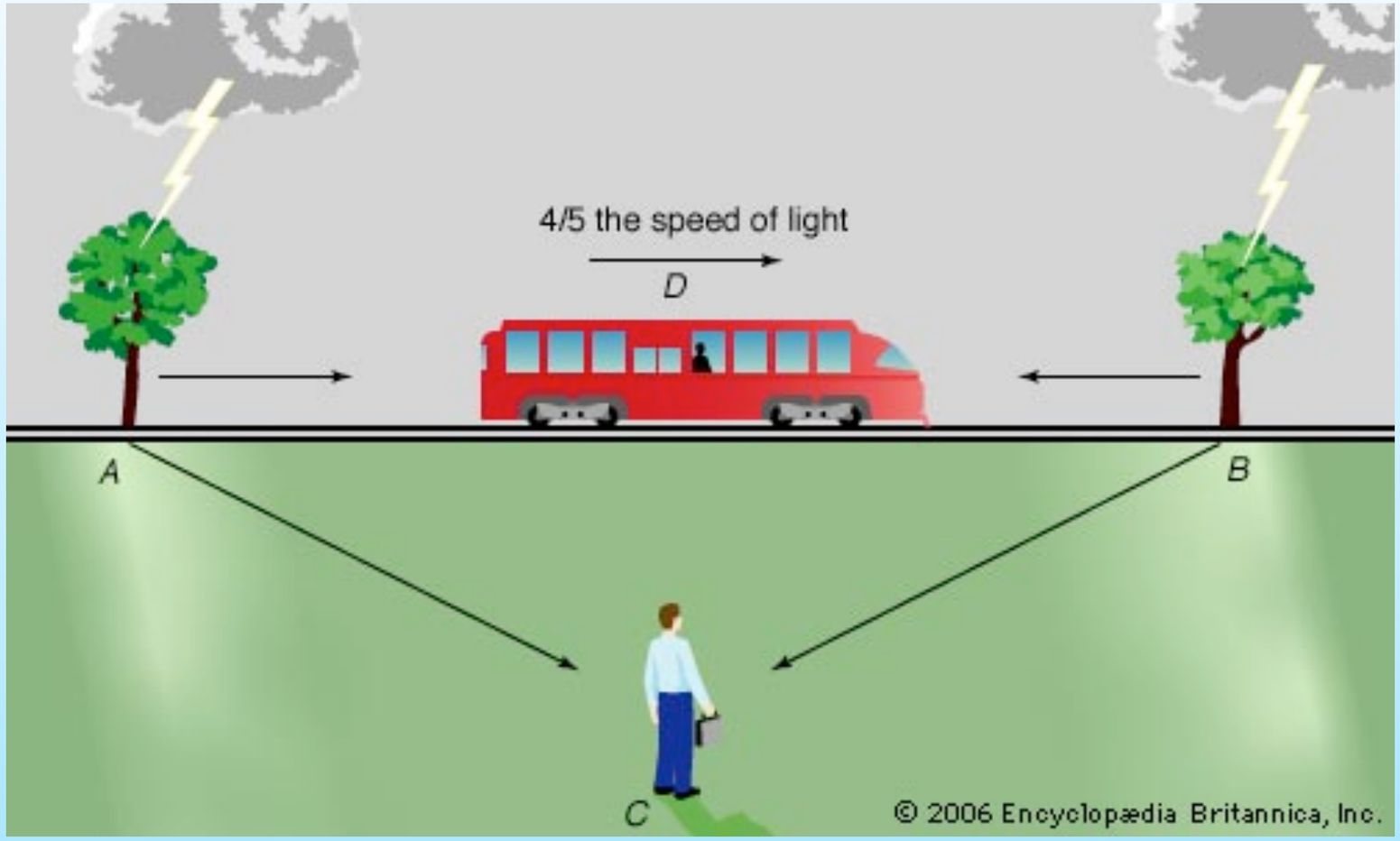
Pilot viewpoint

Observation

Things moving fast relative to me look compressed, I look compressed to them.

However, from my point of view, nothing has changed!

Relativity of Simultaneity



Person at C sees both lightning strikes simultaneously

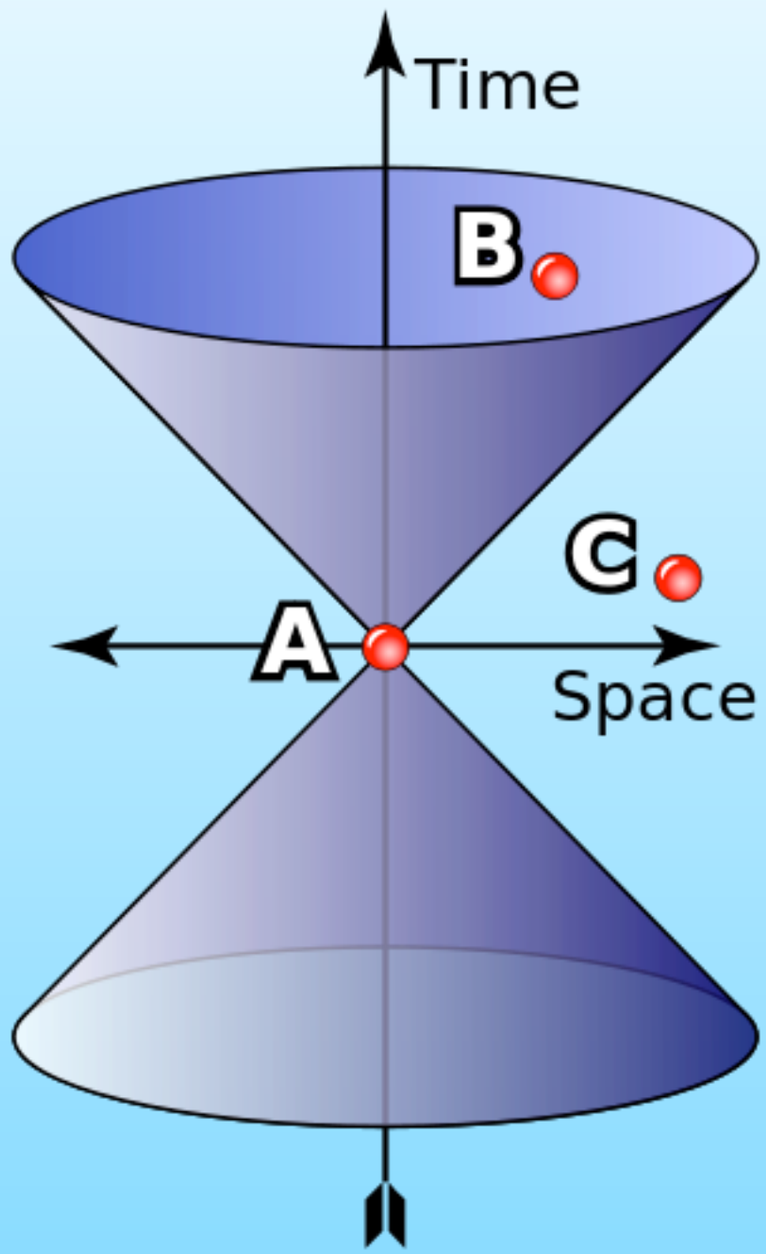
Person at D sees tree B get struck first!

Observation

Events appear to occur at different times depending on whether I am stationary or moving…

Spacetime

light moves
at 45° angles

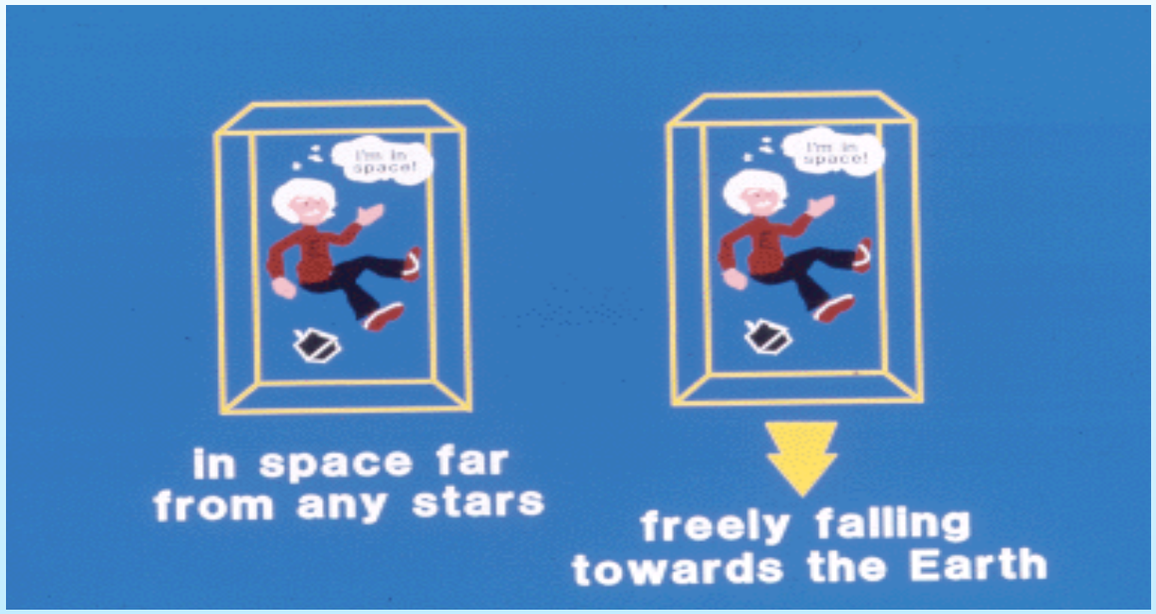


Special Relativity

Successfully reconciled Newtonian laws of motion and Maxwell's theory of electromagnetism.

Now needed something that would reconcile Newtonian gravity and special relativity…

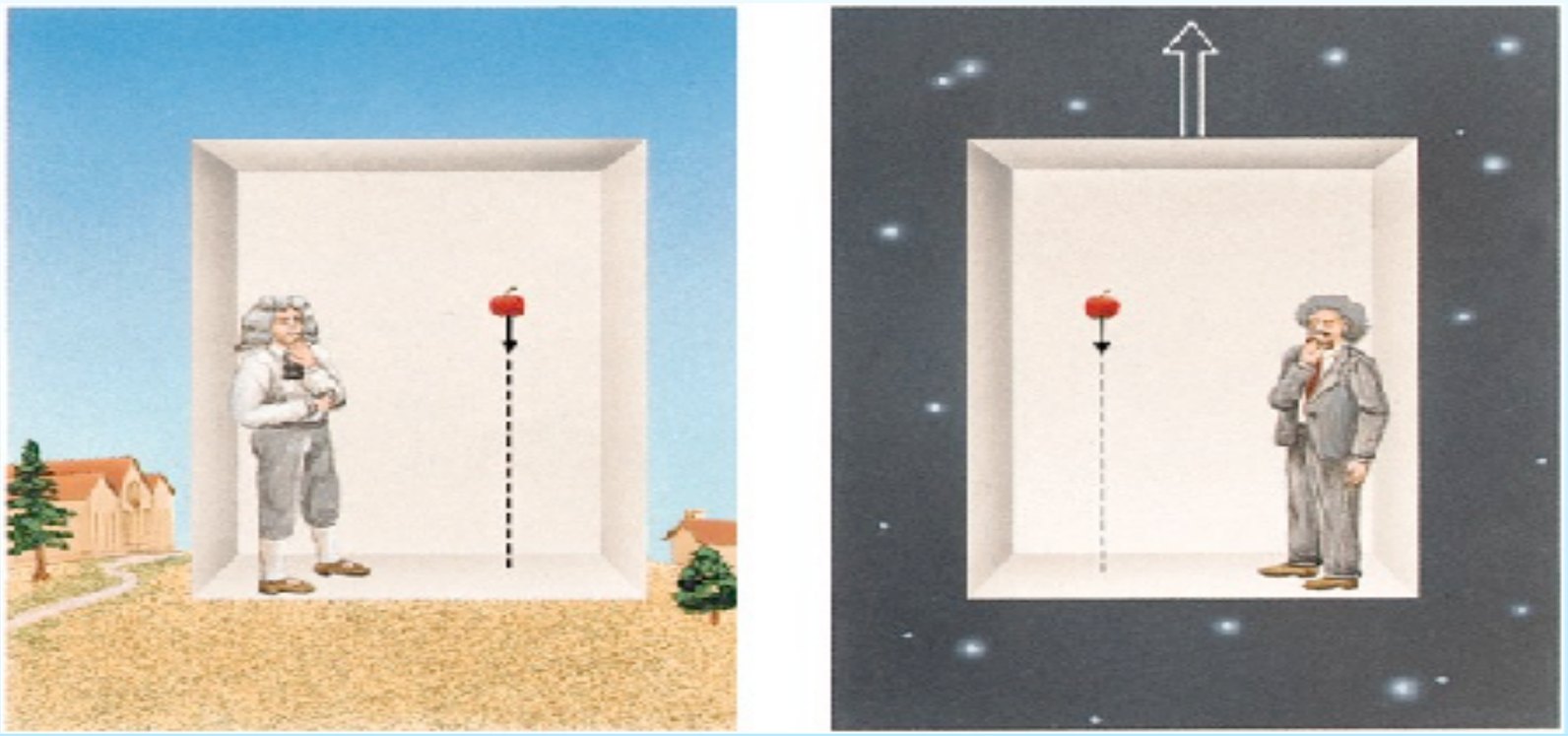
General Relativity



Principle of equivalence (step 1) :

A person in free fall experiences weightlessness,
A person in space far from a gravitational source experience weightlessness

General Relativity

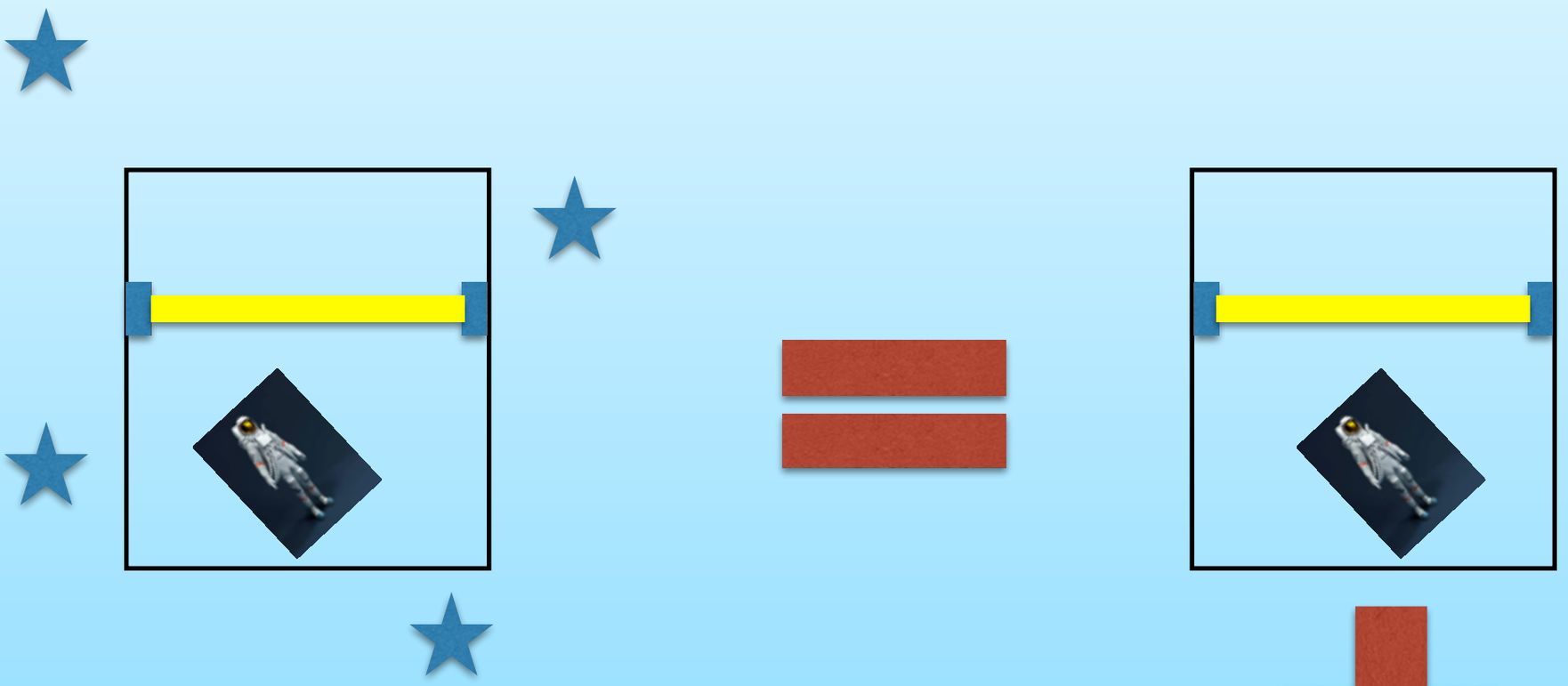


Principle of equivalence (step 2) :

It is impossible to tell if one is sitting in a gravitational field with strength g, or accelerating in space with acceleration g.

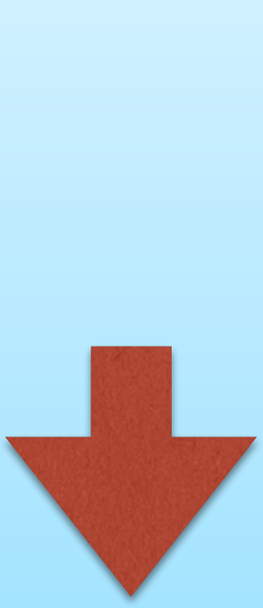
General Relativity

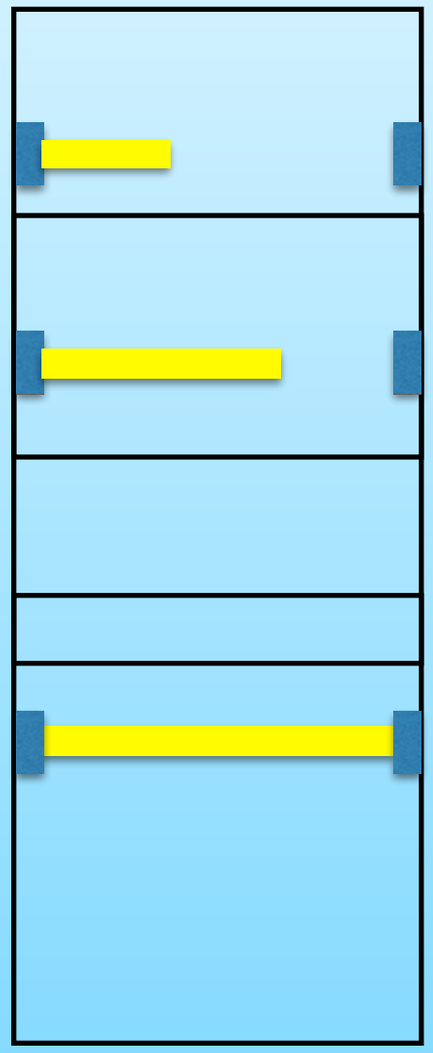
Gravity may not be a force, but related to free motion in spacetime!!

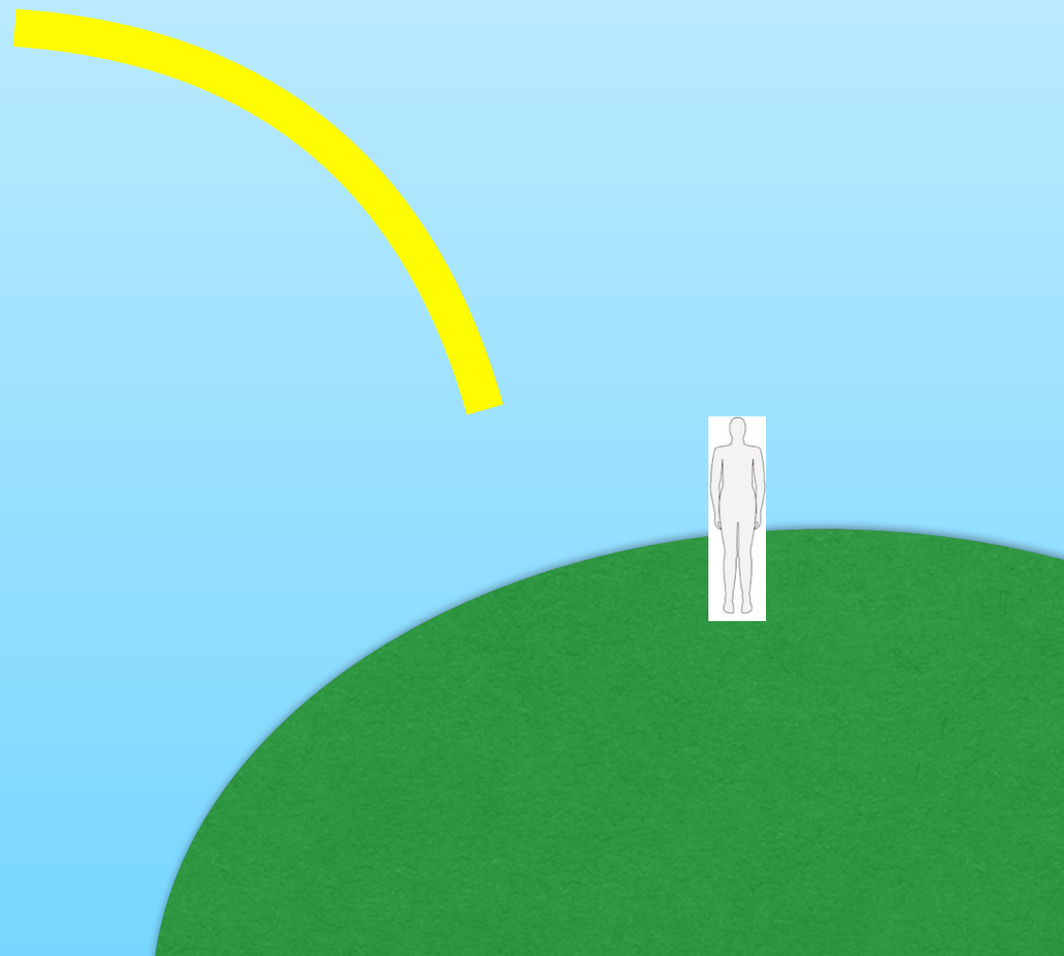


General Relativity

But what does an external observer see?

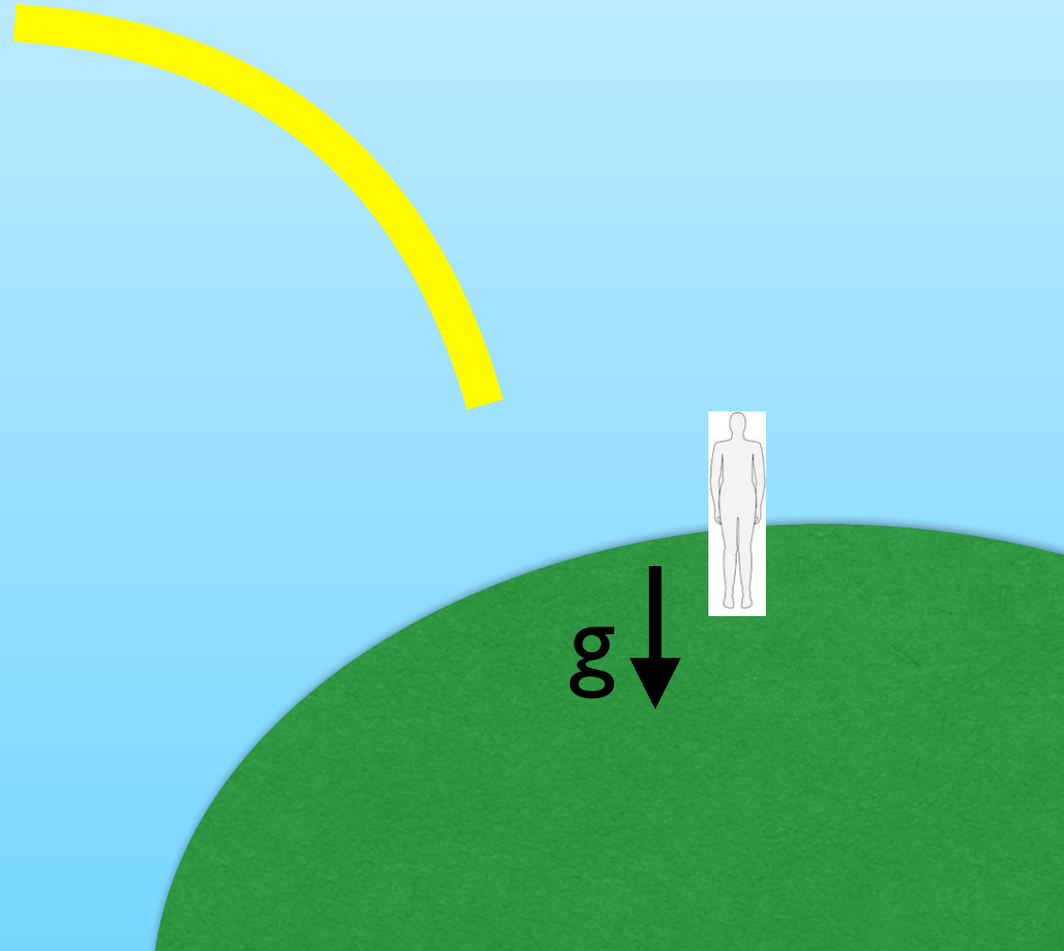






General Relativity

Observer concludes that gravity bends light…



General Relativity

Einstein concluded that :

An observer observes that gravity bends light…

Light tries to travel on the straightest line possible…

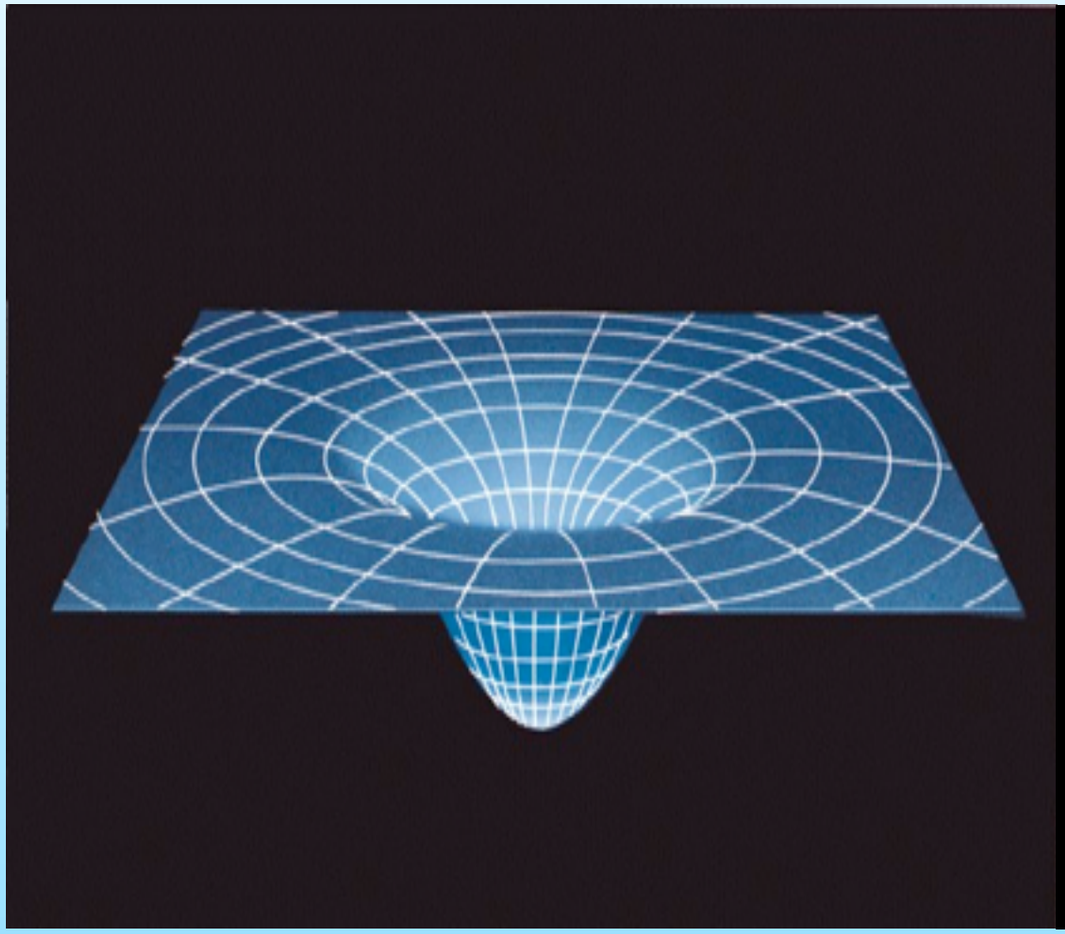
This can only be true if the spacetime the light traveled through is curved…

…Gravity is the manifestation of a curved spacetime

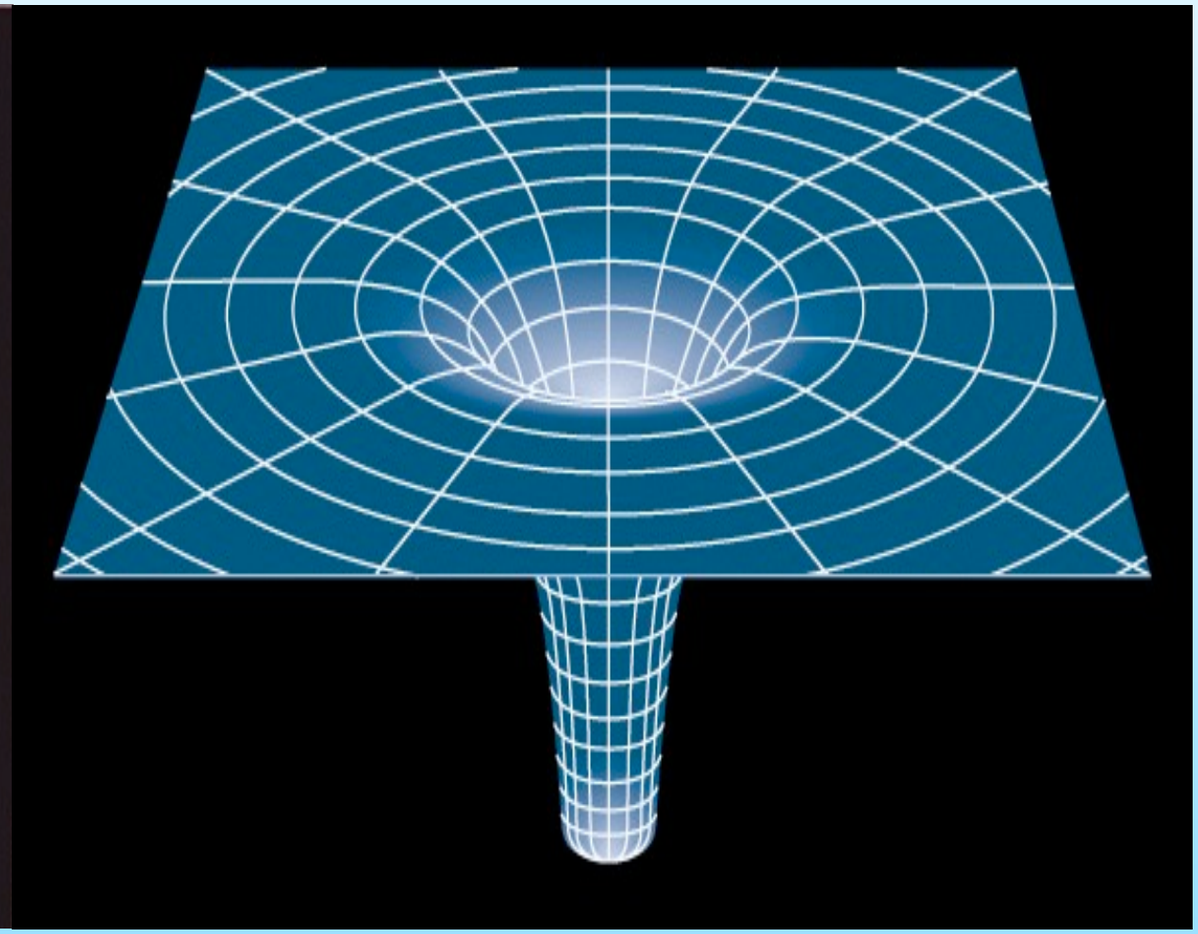
…light travels on a geodesic & clocks should run slower in a gravitational field

General Relativity

solar system

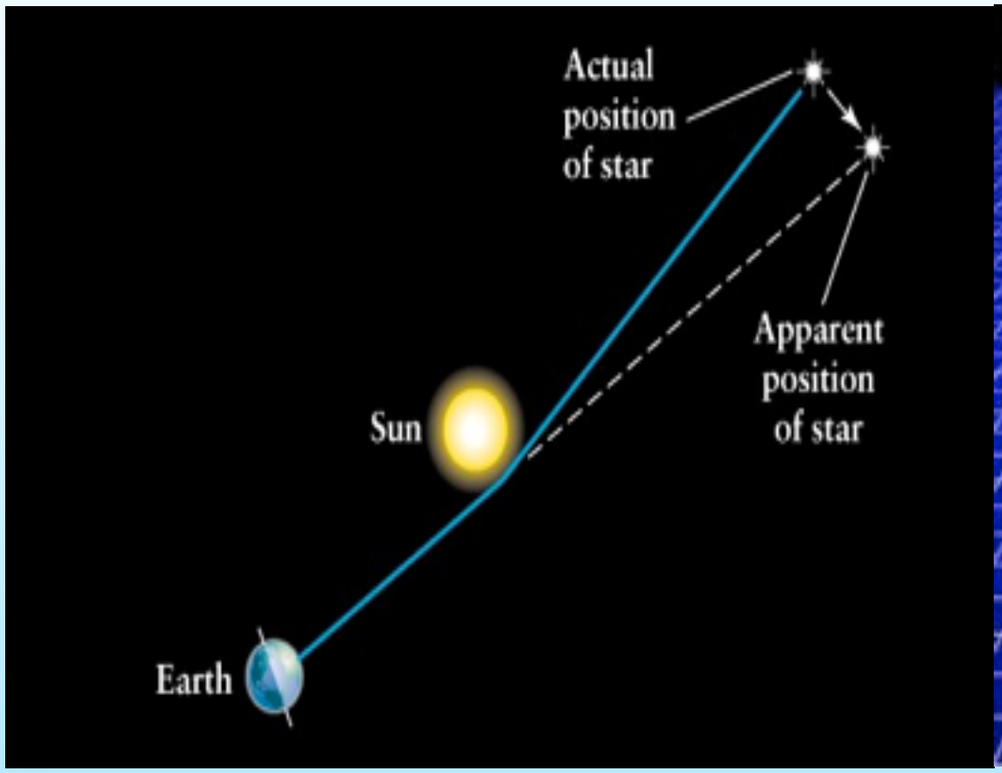


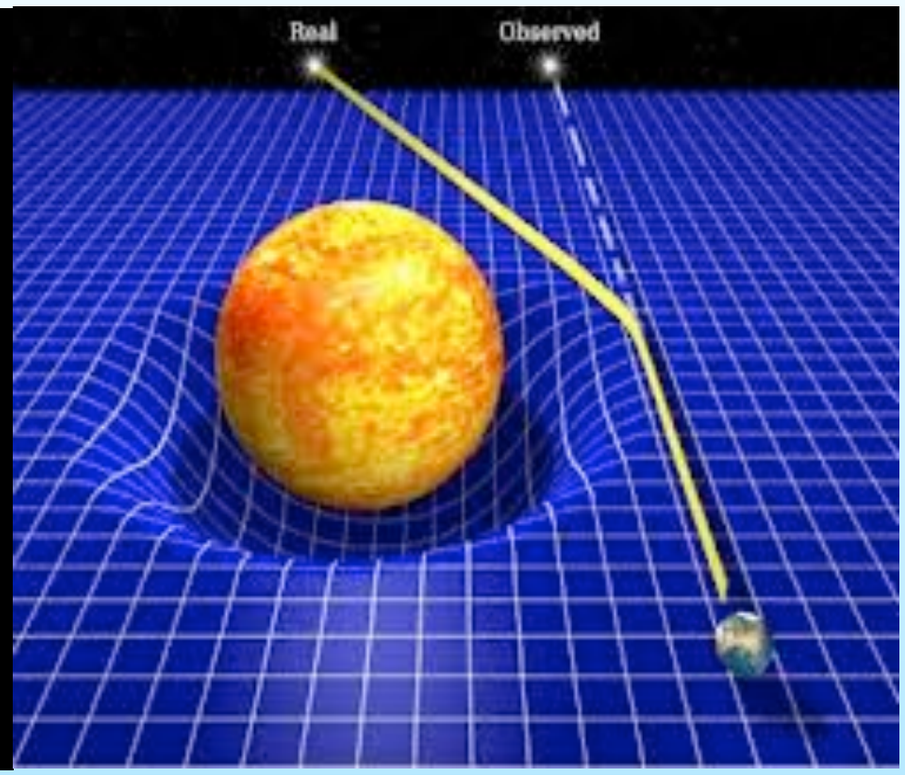
black hole

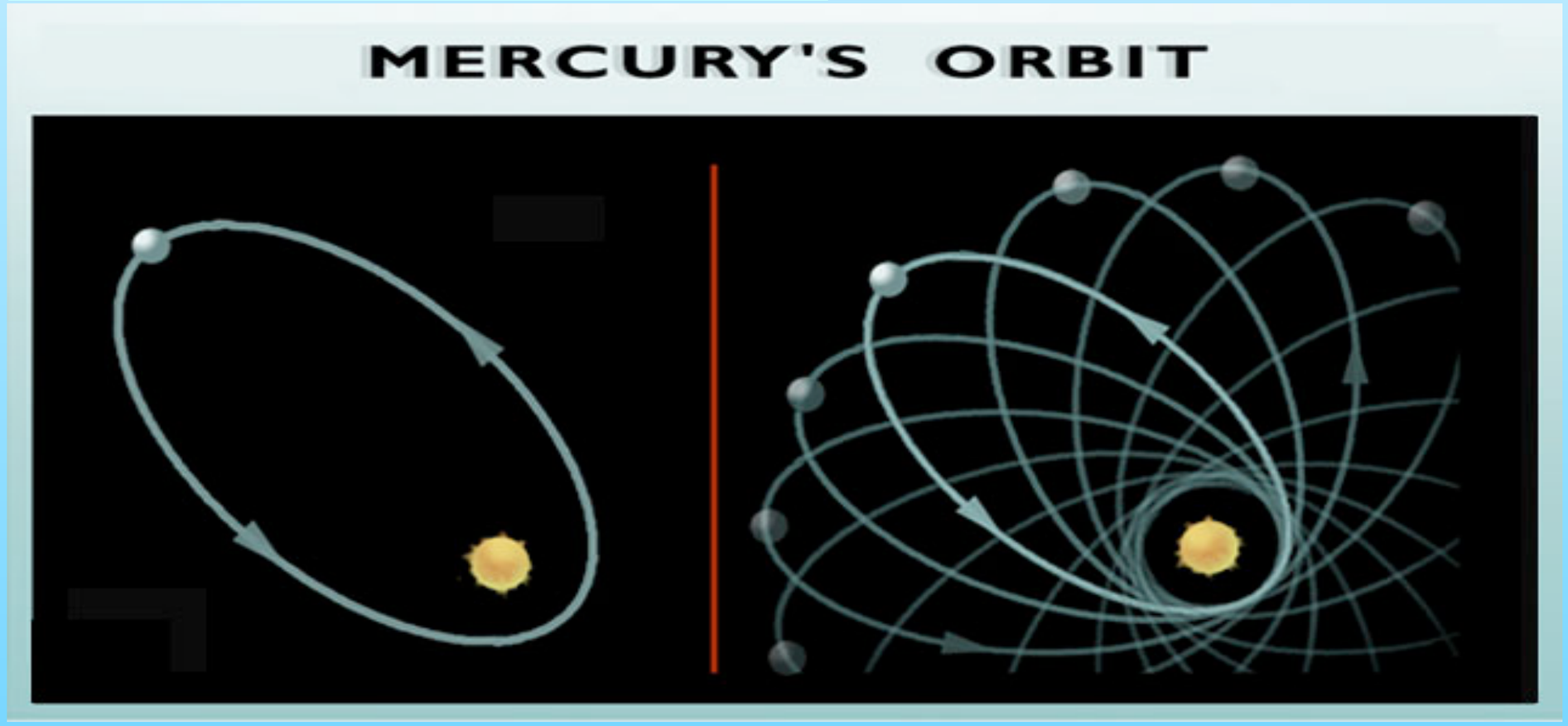


The higher the mass, the higher the curvature

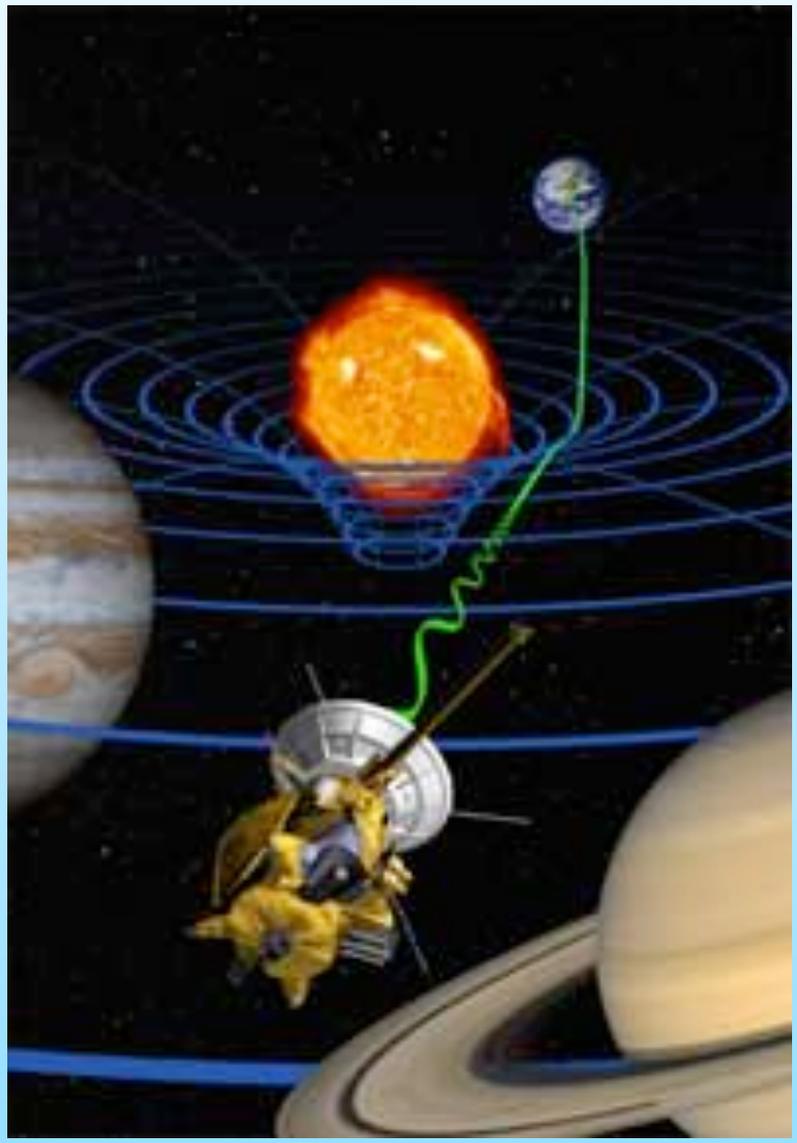
General Relativity







General Relativity

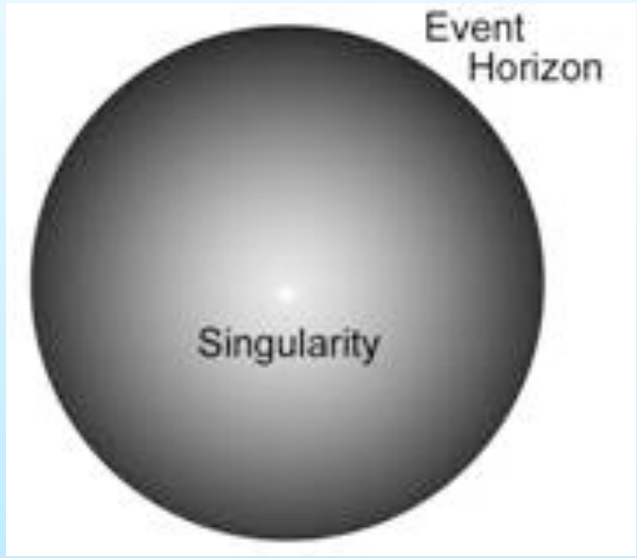


Cassini probe

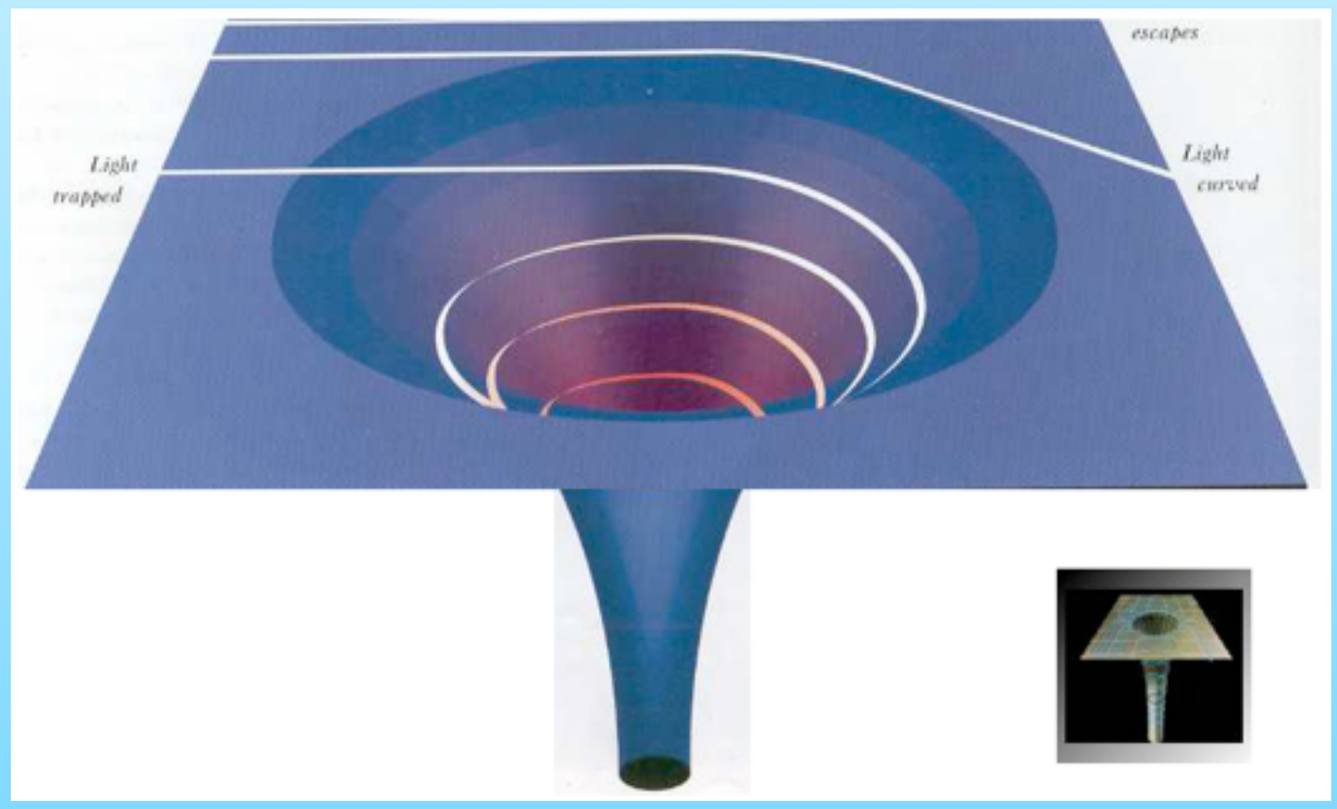
SO FINALLY...BLACK HOLES...

Black Holes

A black hole is composed of an Event Horizon & a Singularity.



Black holes deform spacetime



Schwarzschild Radius

The point in spacetime where the escape velocity equals the speed of light is called the **Event Horizon**.

It is also known as the **Schwarzschild radius**.

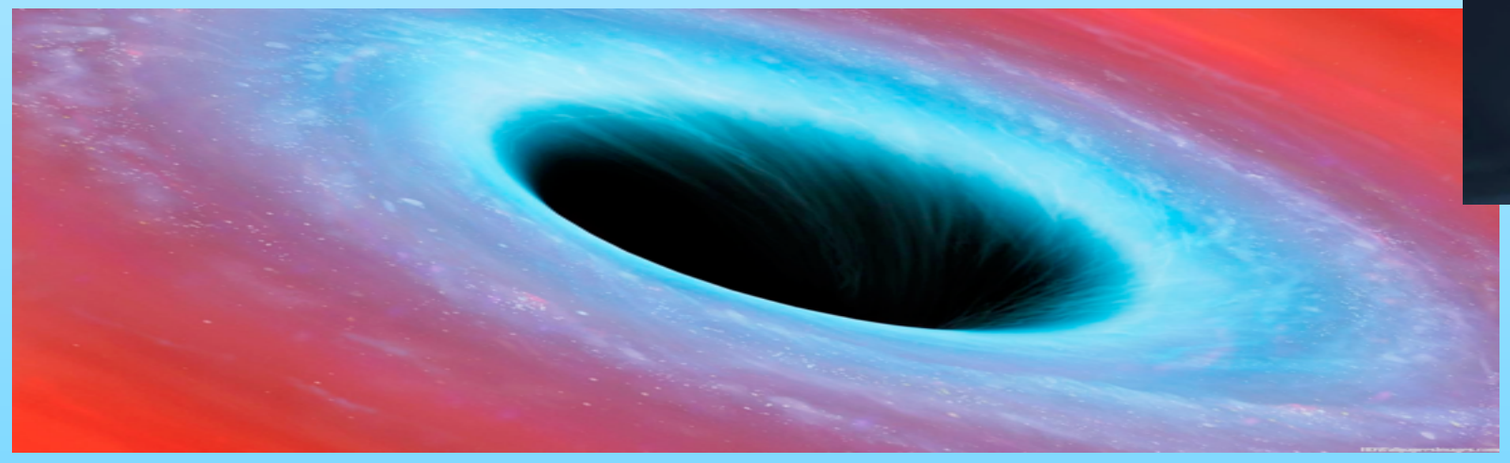
$$R_S = \frac{2GM}{c^2}$$

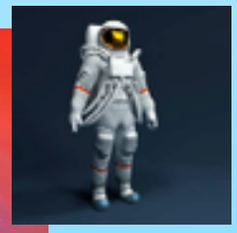
e.g. for the sun :

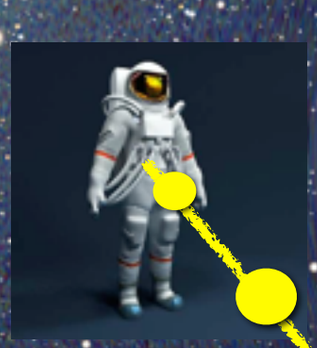
$$R_S = \frac{2 \times 6.67 \times 10^{-11} \times 2 \times 10^{30}}{9 \times 10^{16}} \sim 3 \times 10^3\, m = 3\, km$$

Black Holes

So, as a little experiment…we are going to visit a black hole, and one of the crew will investigate the inside of the black hole. Just so we know where he is, his suit gives off a flash of light every second.







1 sec

1 sec

1 sec

3.2sec

1.7sec

1sec

Infinity

1.7days

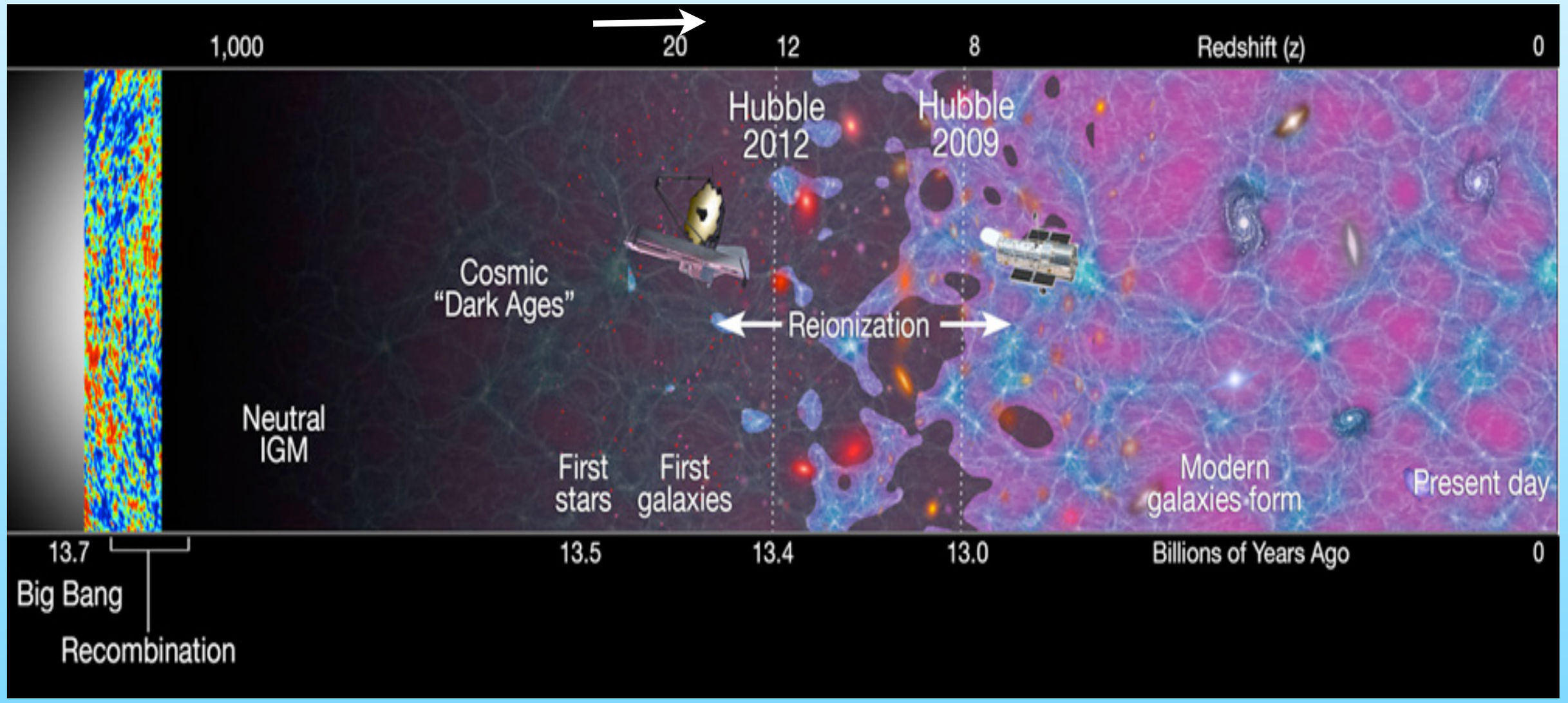
6h23sec

Formation of Supermassive Black Holes

- Redshift
- Black Hole “Seeds”
- Galactic Mergers
- Supermassive Black Hole Binaries

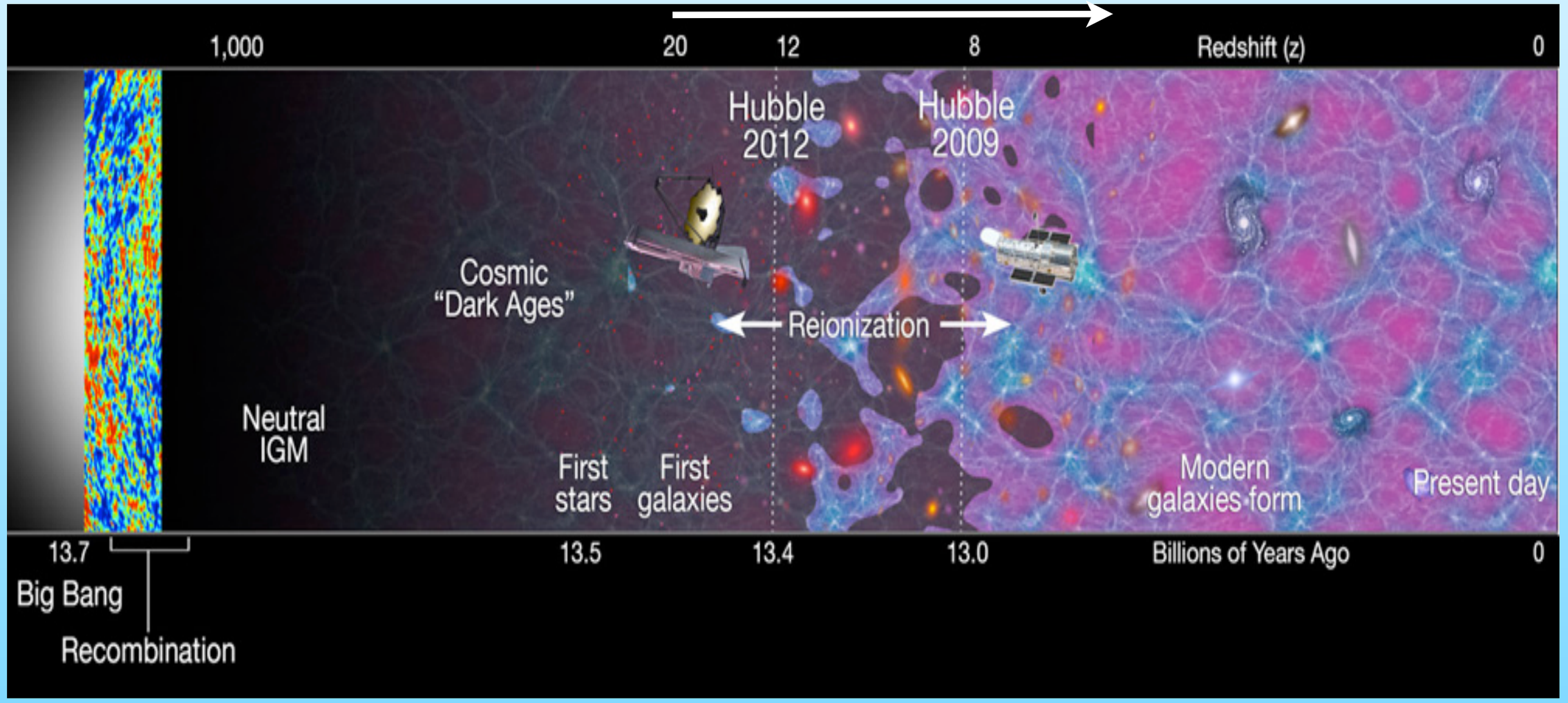
Cosmic Distance

Pop III Stars



Cosmic Distance

First Galaxies form



Black Hole "seeds"

There are currently two hyptheses :

1) Remnants of Pop III stars

- low mass BHs : 10s-100s solar masses
- form at z=18
- when the Universe was 0.2 Gyrs
- However, no proof for the existence of Pop III stars

Black Hole "seeds"

2) Direct collapse of proto-galaxies.

An artist's impression of a proto-galaxy in the very early Universe, ablaze with star formation and growing activity in the black hole at its heart. Image: ESA/Wolfram Freudling (ESO).

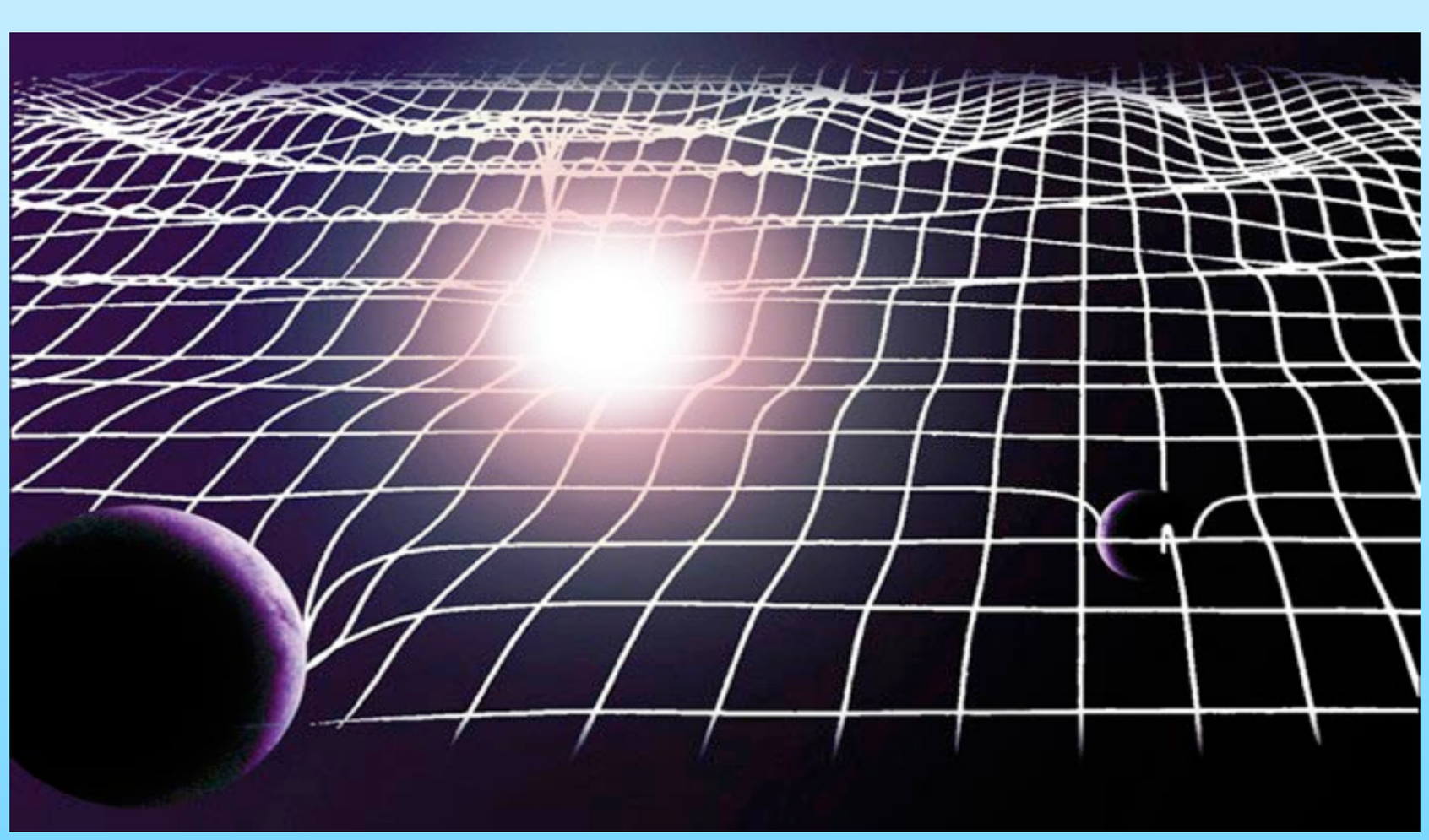
- high mass : > 1000 solar masses
- form at z=11
- when the Universe was 0.45 Gyrs old
- Again, no proof…

Gravitational Waves

- Definition
- Gravitational Wave Sources
- Importance of Binary Systems
- Gravitational Wave Detection
- Virgo/LIGO/KAGRA
- eLISA/LISA-Pathfinder

Gravitational Waves

- Last untested prediction of General Relativity
- Oscillations in the curvature of spacetime
- GWs are generated by large masses and large accelerations

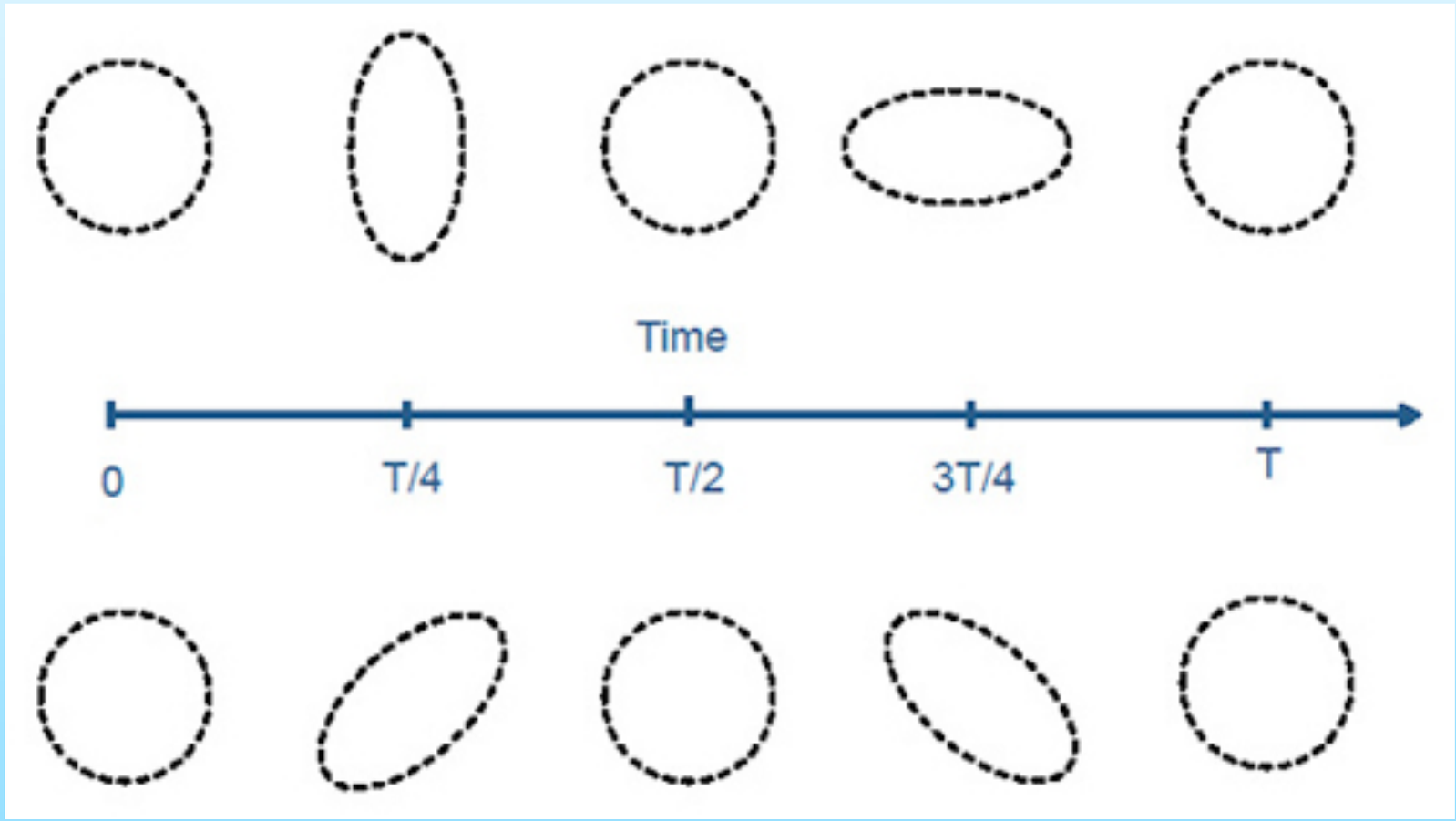


Comparison with EM waves

EM	GW
inverse square law	inverse square law
v	v
2 polarisations	2 polarisations
rotation of 90°	rotation of 45°
scattered & diffracted due to interaction with matter	virtually no interaction with matter
oscillation of the electromagnetic field	oscillation of spacetime

GW Polarisations

Plus



Cross

GW Sources

- Binaries of white dwarves, neutron stars and black holes of all sizes

- The beginning of the Universe

- Defects during the beginning of the Universe such as cosmic strings etc

- Mountainous pulsars

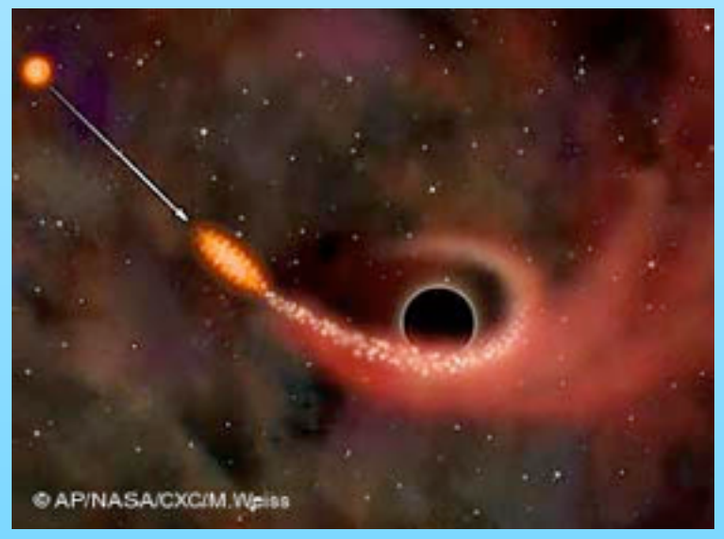
- Supernovae

Binary Systems

The majority of the stars in our galaxy are in binary systems

The evolution of stars in binary systems is very different to isolated stars

The interaction with a second body can destroy an object, change its mass, convert a white dwarf into a neutron star, or a neutron star into a black hole.

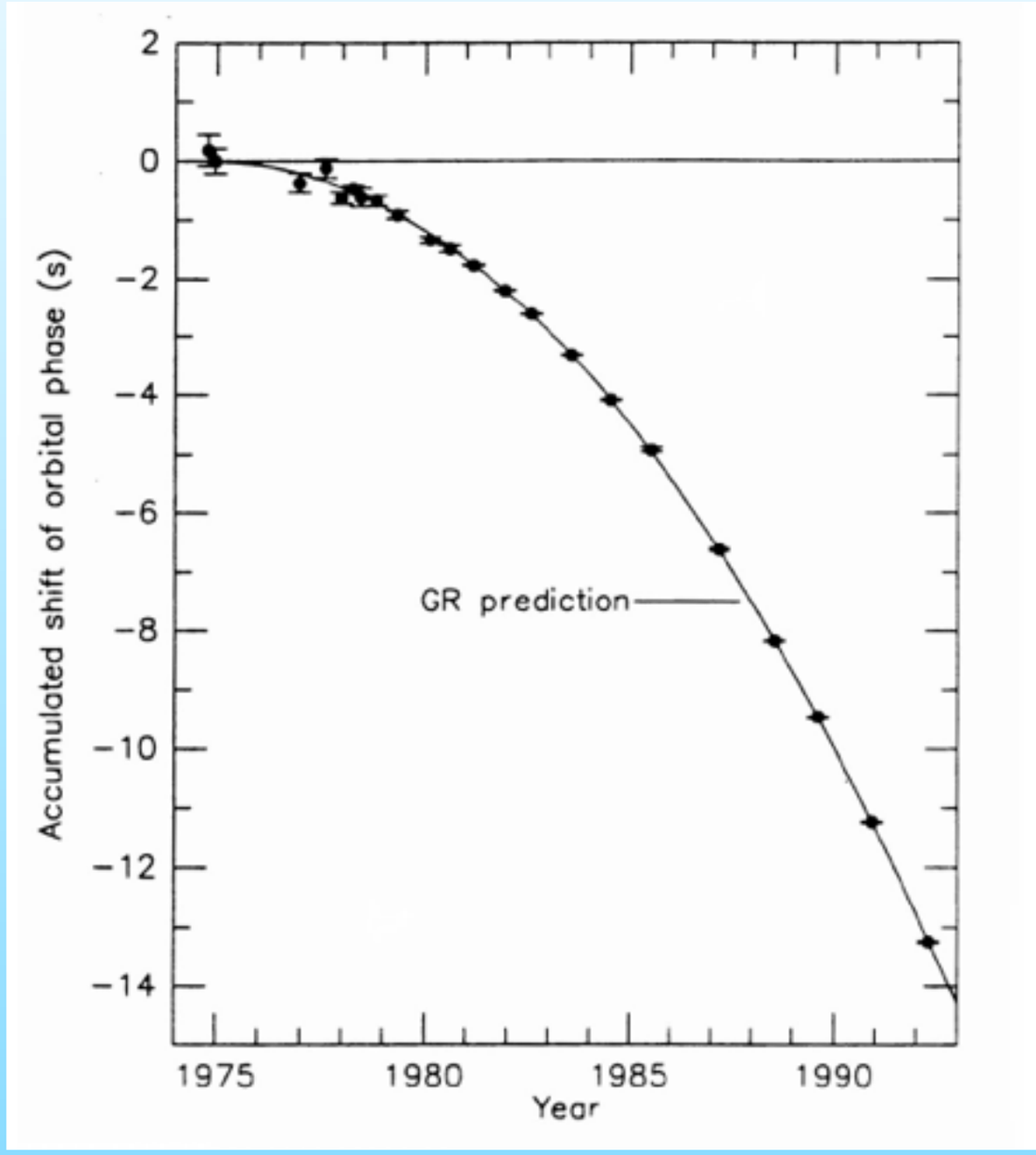


Indirect Proof of GWs

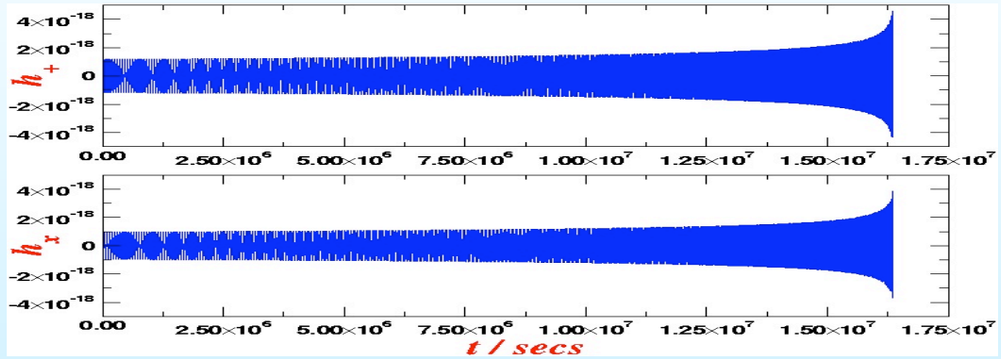
Hulse-Taylor Binary Pulsar

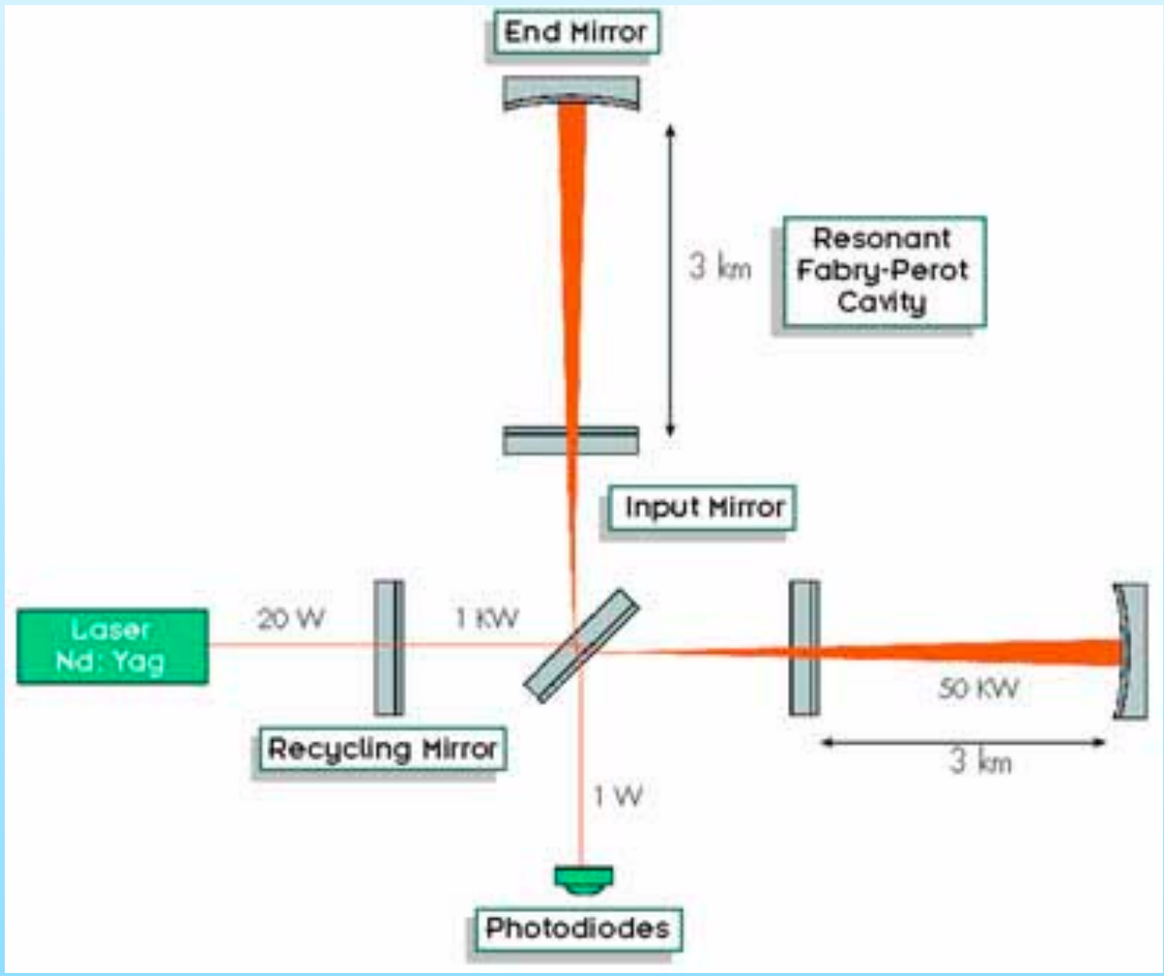
dP/dt ~ GR prediction

Other systems now known, including one who's orbit has decayed more in the last 2.5 years that the HT pulsar has in the last 30



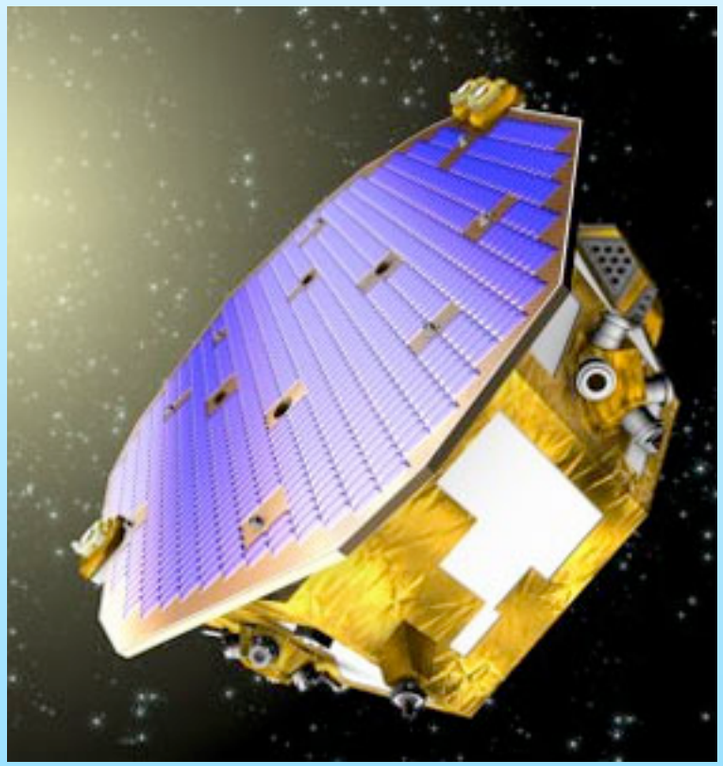
The Detection of GWs





LISA Pathfinder

- ESA Mission
- Technology verification mission
- Launch date : July 2015



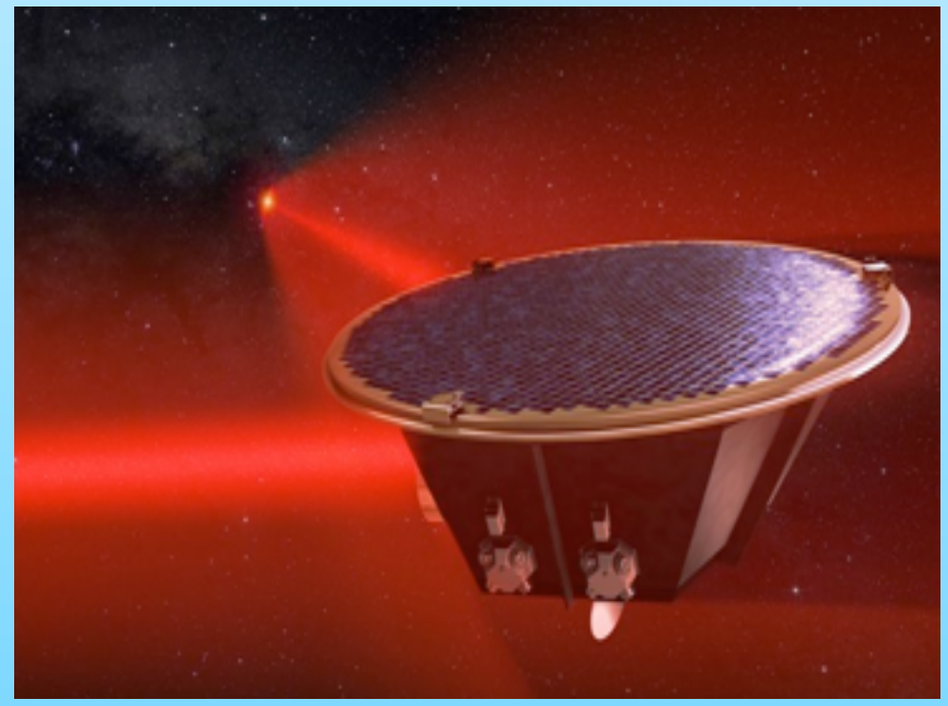
eLISA

- ESA Mission

- Will detect SMBHBs out to z=10, compact binaries in our own galaxy, bursts of GWs from cosmic (super)strings and maybe a cosmological background

- 4000 sources per year

- Launch date : 2034



Why are GWs Important

The error is distance estimates from a standard EM telescope is around 30-70%,while the error in mass estimates can be100%.

One is the best ways to estimate distance is to use supernovae.

In photons, a supernova can be as bright as

$$L_{SN} \sim 10^{40}\, W \sim 10^{14}\, L_{\odot}$$

In GWs, the coalescence of two supermassive black holes is as bright as

$$L_{gw} \sim 10^{52}\, W \sim 10^{26}\, L_{\odot}$$

As the polarisations are proportional to $h \propto \frac{1}{D_L}$

We hope to measure the distance to objects with an error < 10%, and masses to < 0.01%.

Thank You!