Pulsars

Robert Clemenson

(Sussex U & Royal Holloway UoL)

Southend Planetarium, Spring Space Day – 16.04.2025

Lecture Overview

- Discovery and History
- Neutron Stars & Pulsars
- Life Cycle of a Star
- Pulsar Properties
- Pulsars as tools for new discoveries
- Q&A (**Questions welcome throughout the talk!**)

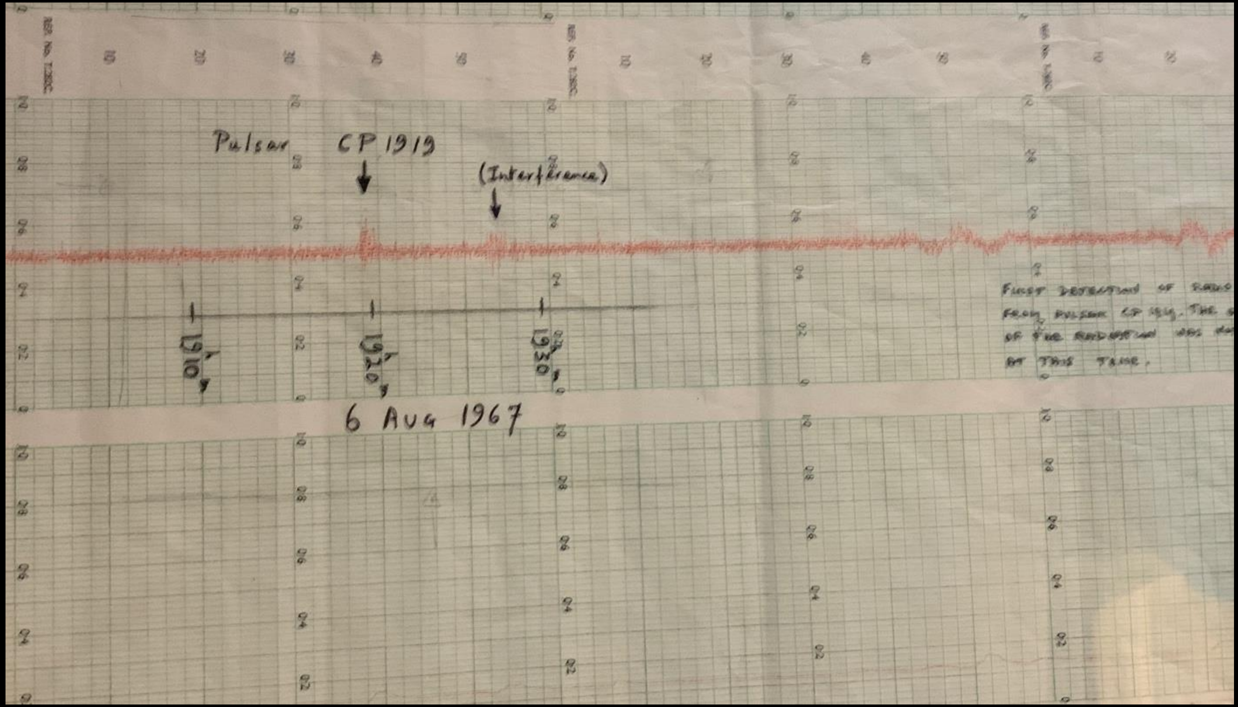
Jocelyn Bell-Burnell

Nearly 60 years ago, in a field a few miles southwest of Cambridge; a 24-year-old PhD student notices a string of radio wave pulses exactly one-and-a-third seconds apart…

Jocelyn Bell-Burnell in 1967

“Little Green Men”

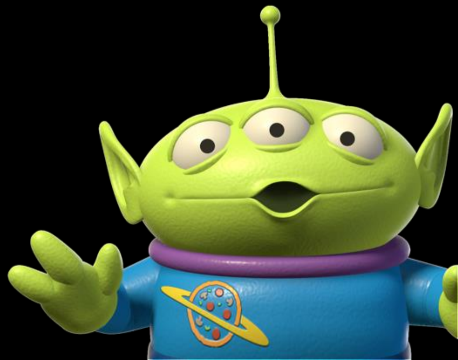
These pulsing radio sources were jokingly nicknamed ‘LGM’ or ‘Little Green Men’ by Bell & her PhD advisor Anthony Hewish – as there was initially such uncertainty regarding their true nature.



Remaining sections of the Interplanetary Scintillation Array at the Mullard Radio Astronomy Observatory

Jocelyn Bell-Burnell in 2011

Antony Hewish in 2009



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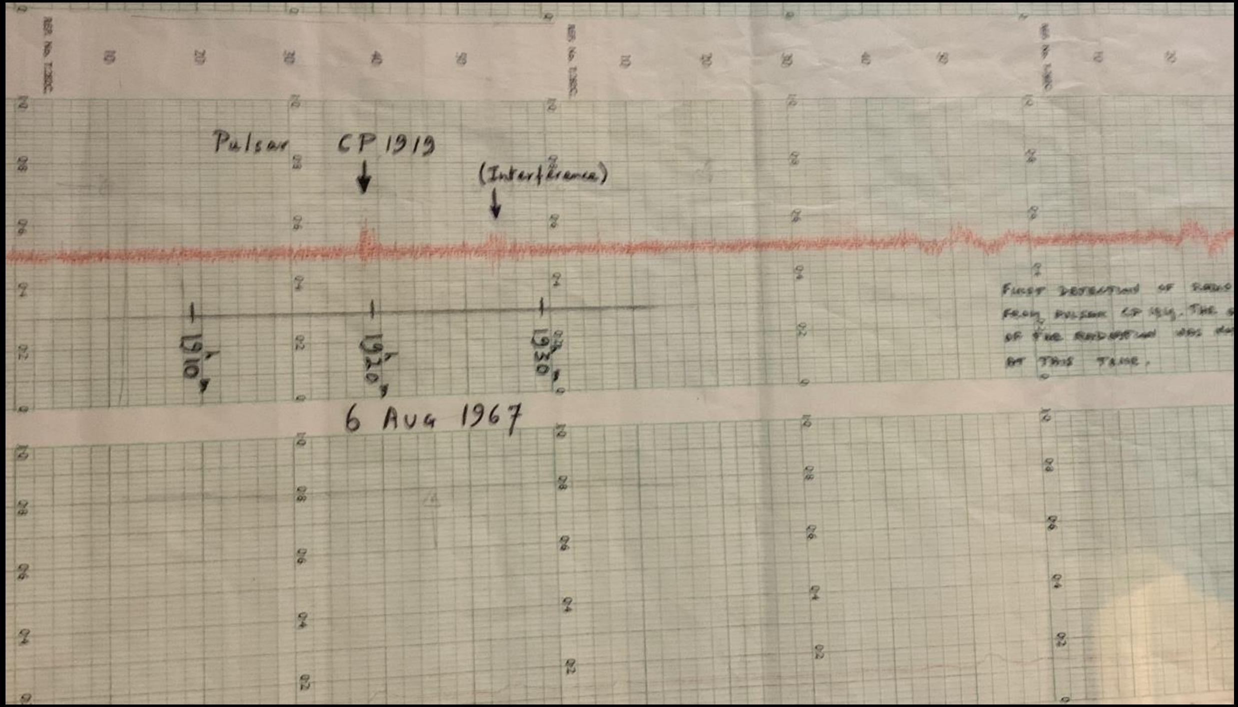

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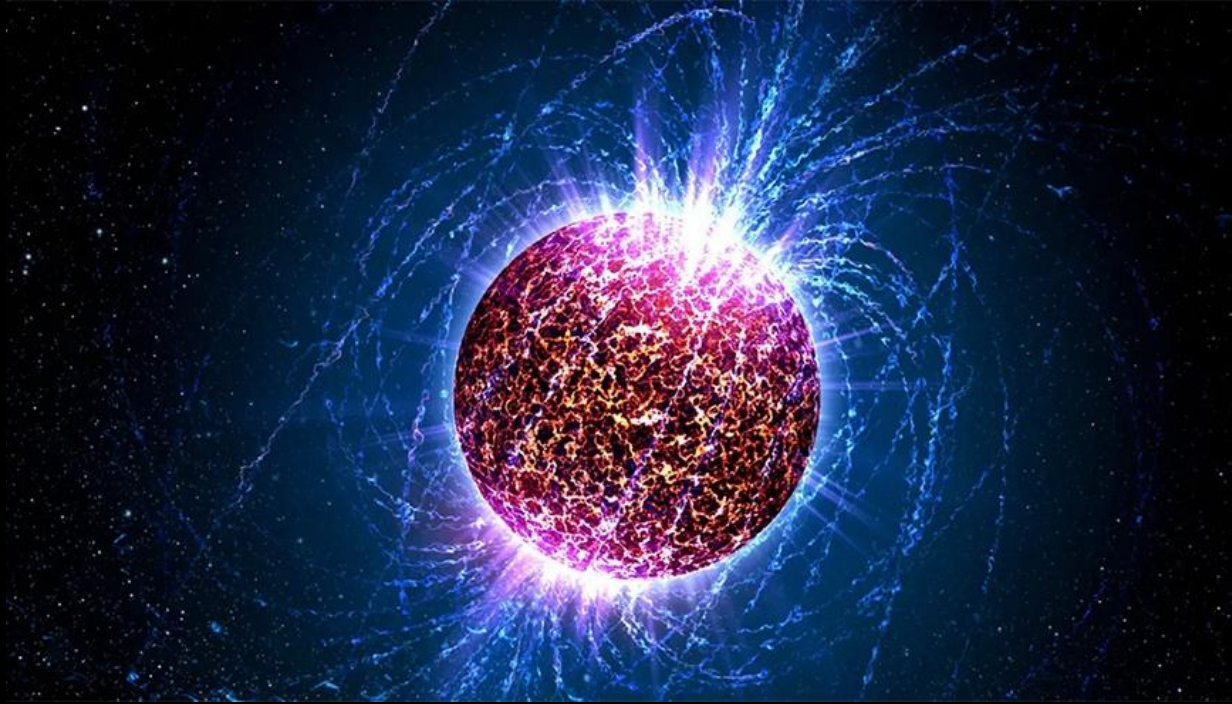
But what actually were they?

Could Pulsars be Neutron Stars?

In 1934 Walter Baade and Fritz Zwicky theorized that the supernova of a significantly large star could leave behind a dead super-dense core.

They called this hypothetical object a *Neutron Star*.



An artists depiction of a Neutron Star, with an ultra-strong magnetic field shown.

Walter Baade in the 1950's

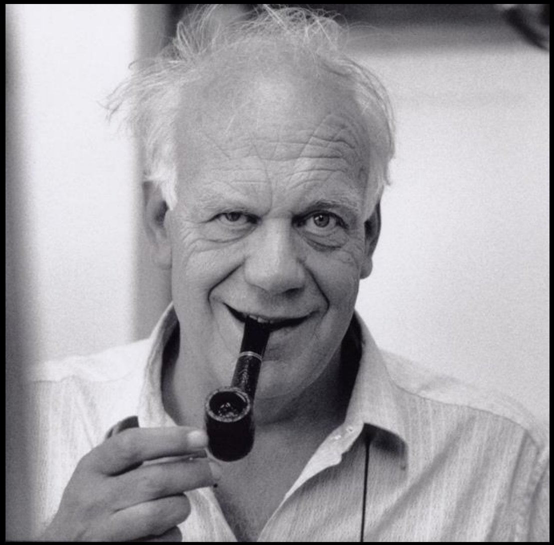
Fritz Zwicky in 1947

Could Pulsars be Neutron Stars?

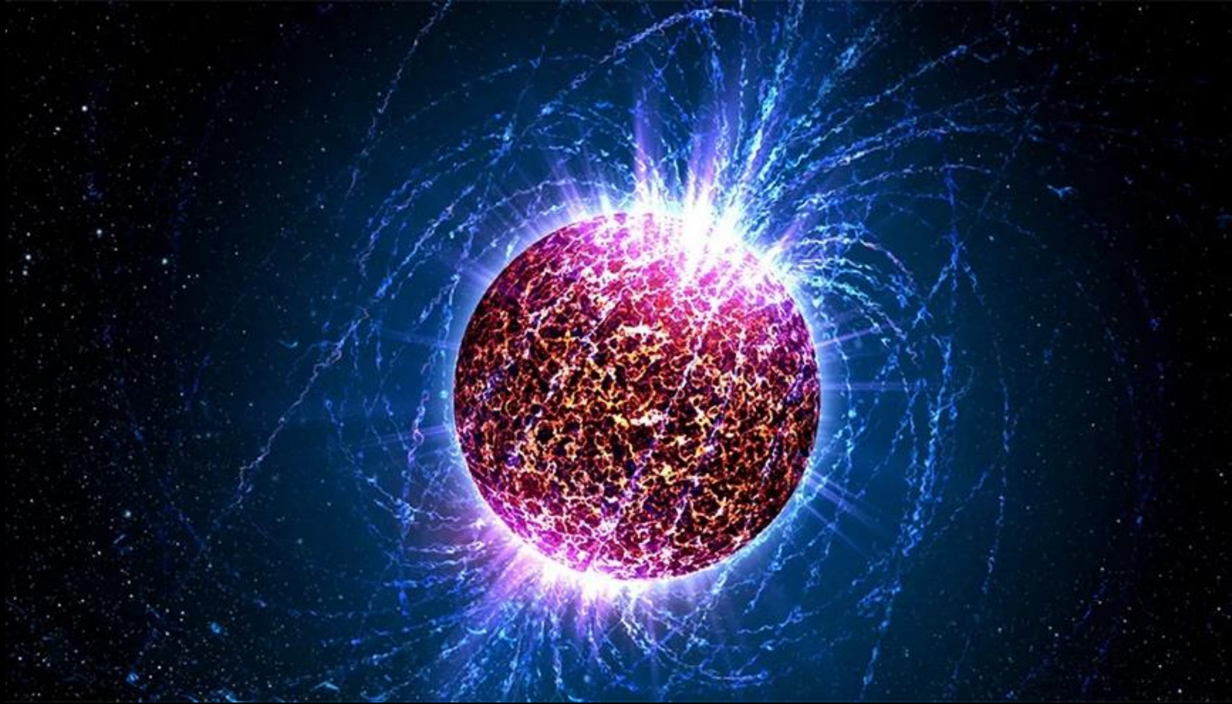
In 1964 Lodewijk Woltjer proposed that these Neutron Stars (if they even exist!) would create ultra-strong magnetic fields.

More work is still needed…

Lodewijk Woltjer in the 1981



Franco Pacino in 2012



An artists depiction of a Neutron Star, with an ultra-strong magnetic field shown.

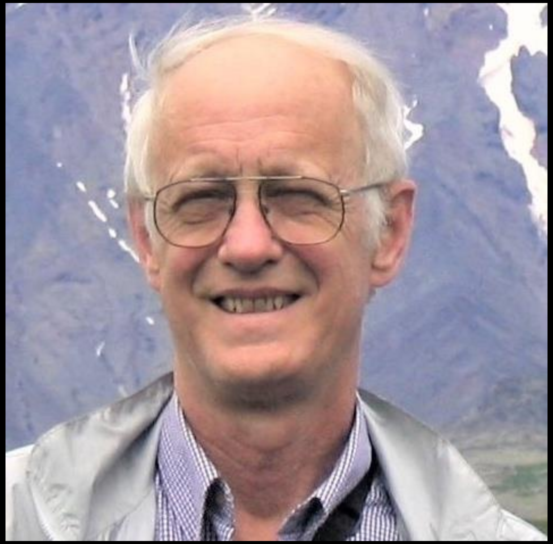
Then.. in the same year that Jocelyn Bell detected radio pulses (1967):

Franco Pacini wrote a paper suggesting that a fast-spinning Neutron Star with an ultra-strong magnetic field would be able to emit radiation (such as radio waves!).

Could Pulsars be Neutron Stars?

Finally, in 1968 Richard Lovelace and his collaborators discovered the Pulsar at the center of the Crab Nebula.

This Pulsar makes 30 full rotations every second. Much faster than any of the non-neutron star theories would permit.



Richard Lovelace in 2004

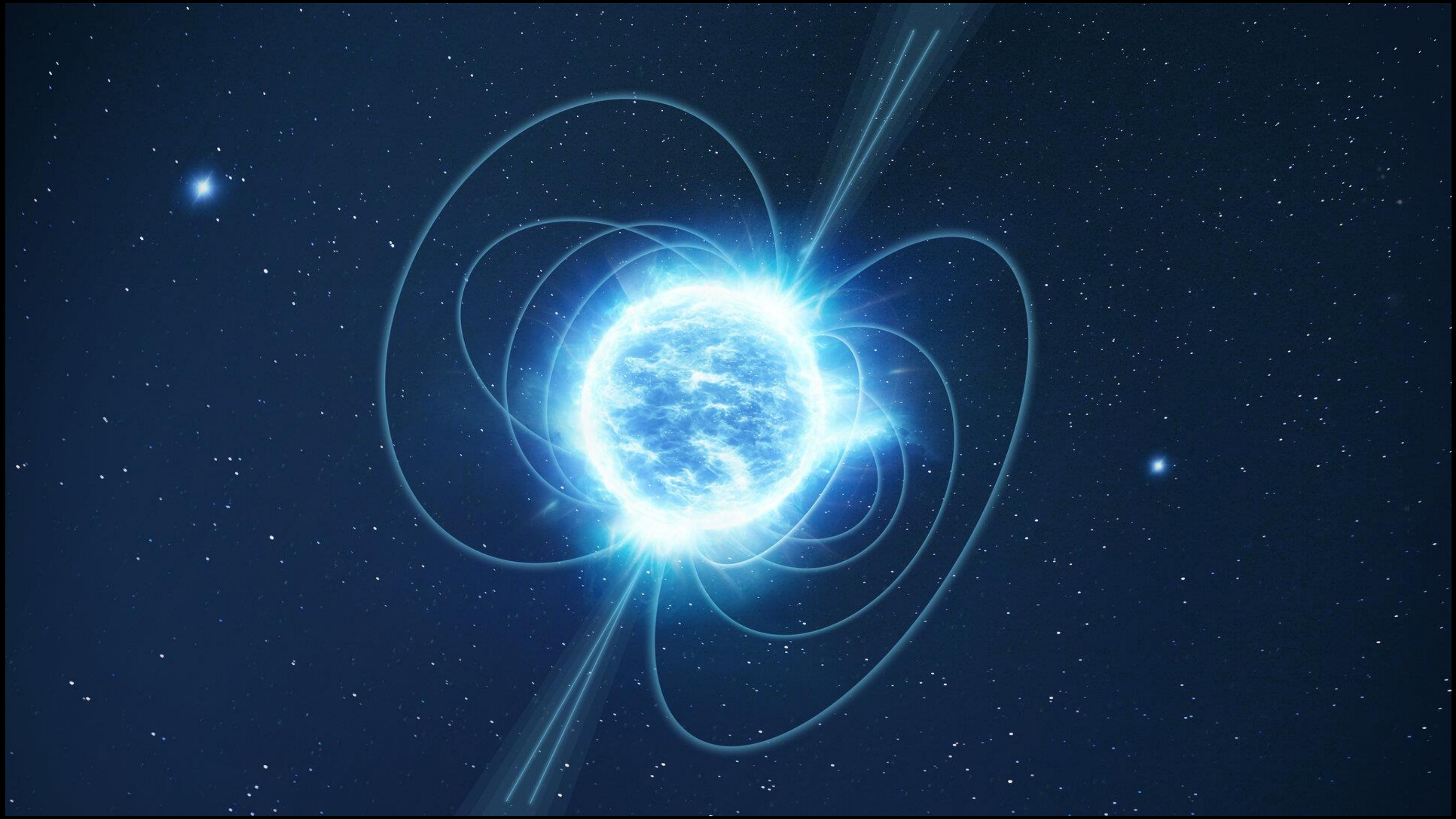
Full view of the Crab Nebula

The Crab Nebula Pulsar, within the Crab Nebula.

Pulsars ***ARE*** Neutron Stars

So, Pulsars ***are*** neutron stars.

Let’s dive a little deeper into the theory of the life-cycles of stars, to learn more about these strange and exotic objects.



An artists depiction of a Pulsar. Note the curved lines that represent the ultra-strong magnetic field, and the beams of radio waves emitted from each pole.

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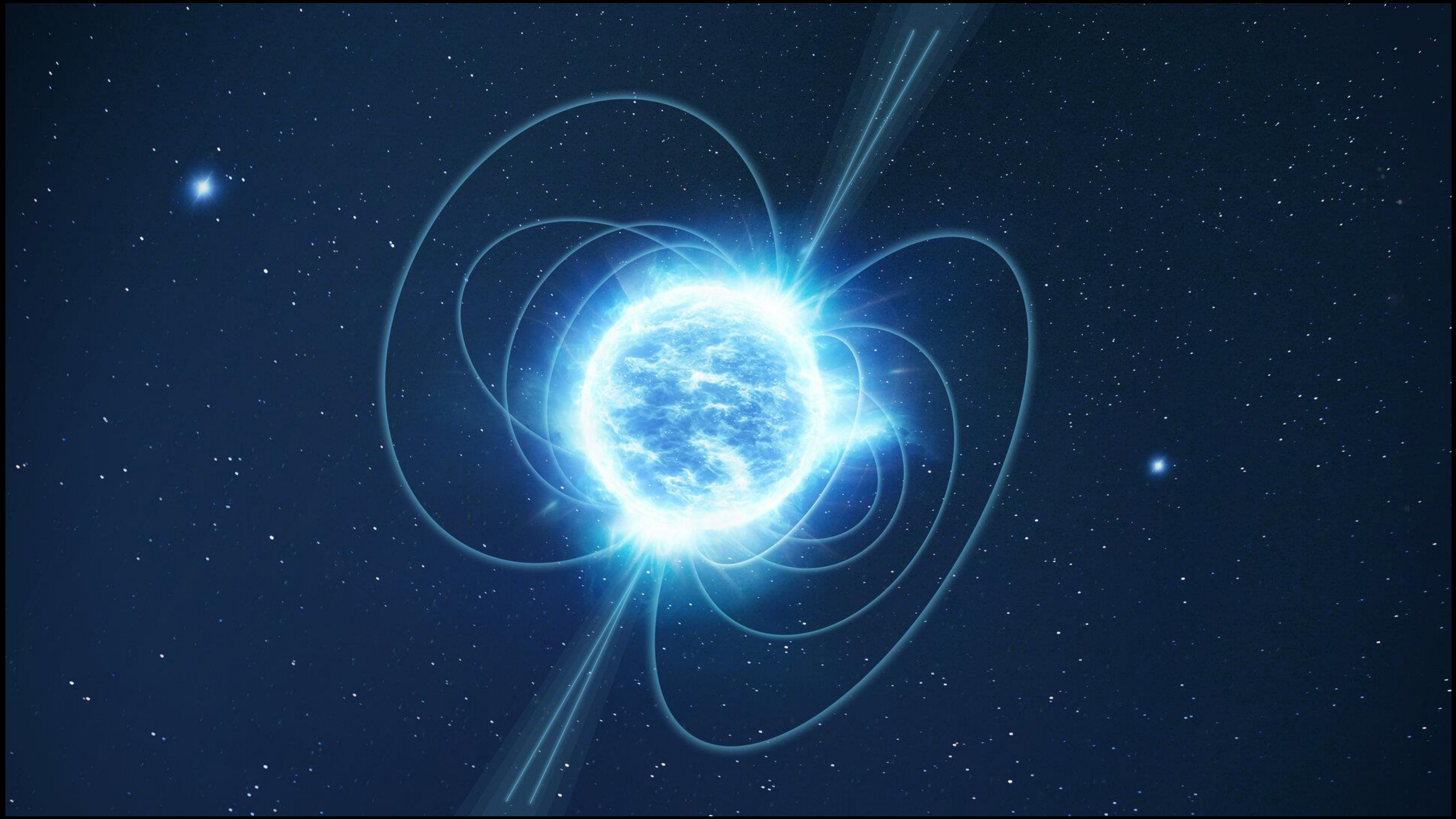


An artists depiction of a Pulsar. Note the curved lines that represent the ultra-strong magnetic field, and the beams of radio waves emitted from each pole.

Theory leads discovery!

(at least.. in this instance)

Like a Phoenix, from the ashes…

Stars are born from the clouds of gas and dust left behind from the explosive deaths of earlier stars.

We call these stellar graveyards / nurseries, ***Nebulae***.

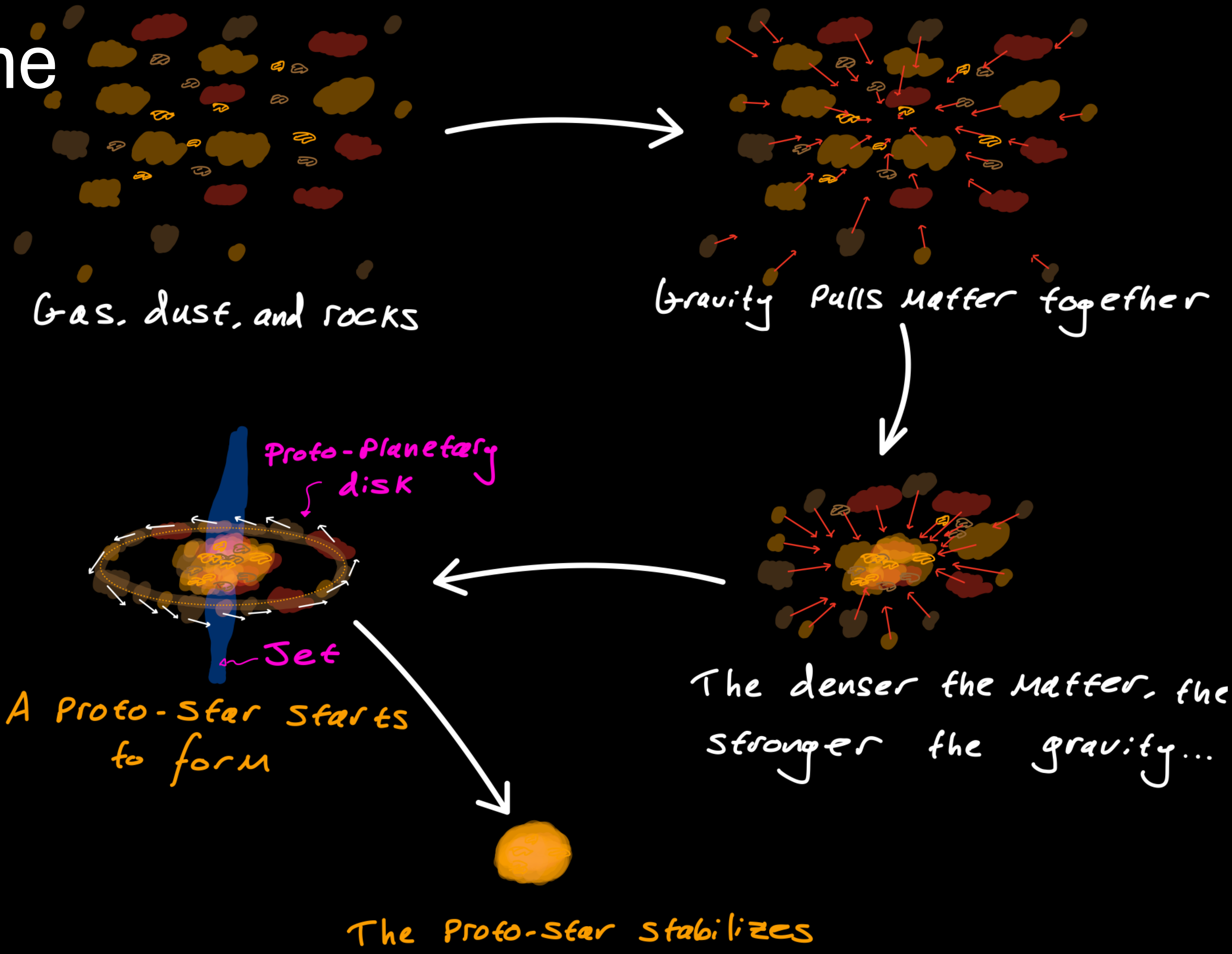
Pictured in the backdrop is the Carina Nebula. A vast and varied amalgam of stellar nurseries, supergiant stars, and globular structures. 230 lightyears across and nearly 8500 lightyears from the Earth

The Gravity of the Situation…

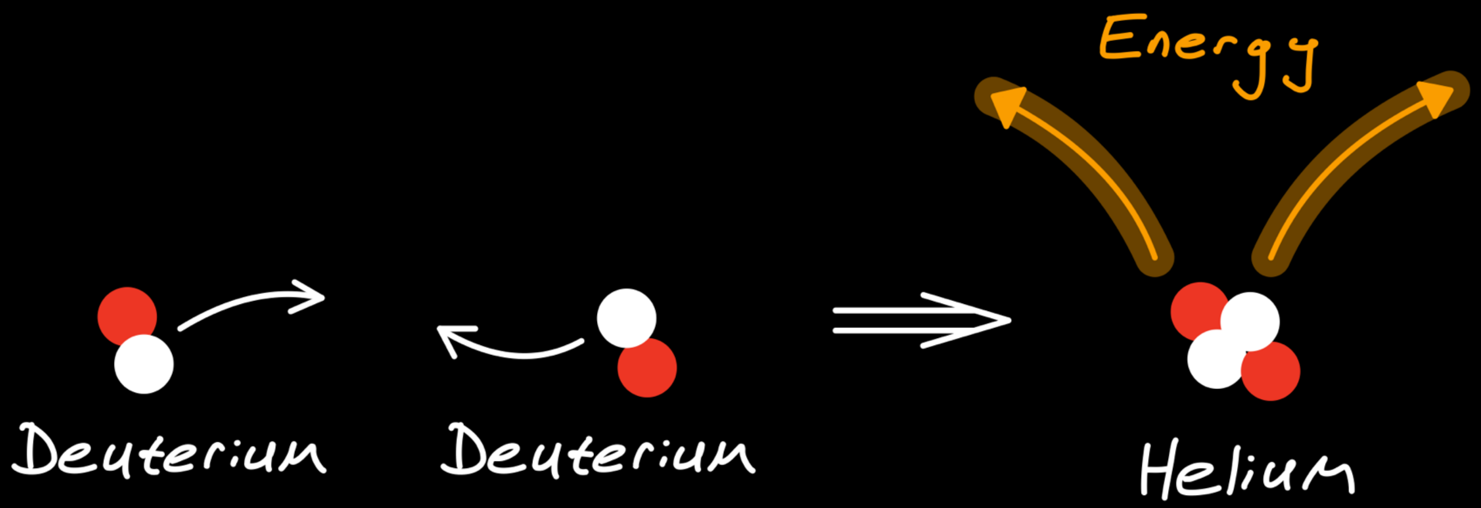
Gravity is the driver of so much in astrophysics.

All matter (stuff with weight) mutually attracts and given the opportunity; will collapse inwards to a common center.

This collapse initiates a self-sustaining Nuclear Fusion reaction, in what can now (almost) be called a Star.



Nuclear Fusion



Nuclear Fusion is the process of combining (or fusing) smaller atomic nuclei into a larger nucleus.

This process releases large quantities of energy; which is responsible for the suns heat and light we feel on Earth.

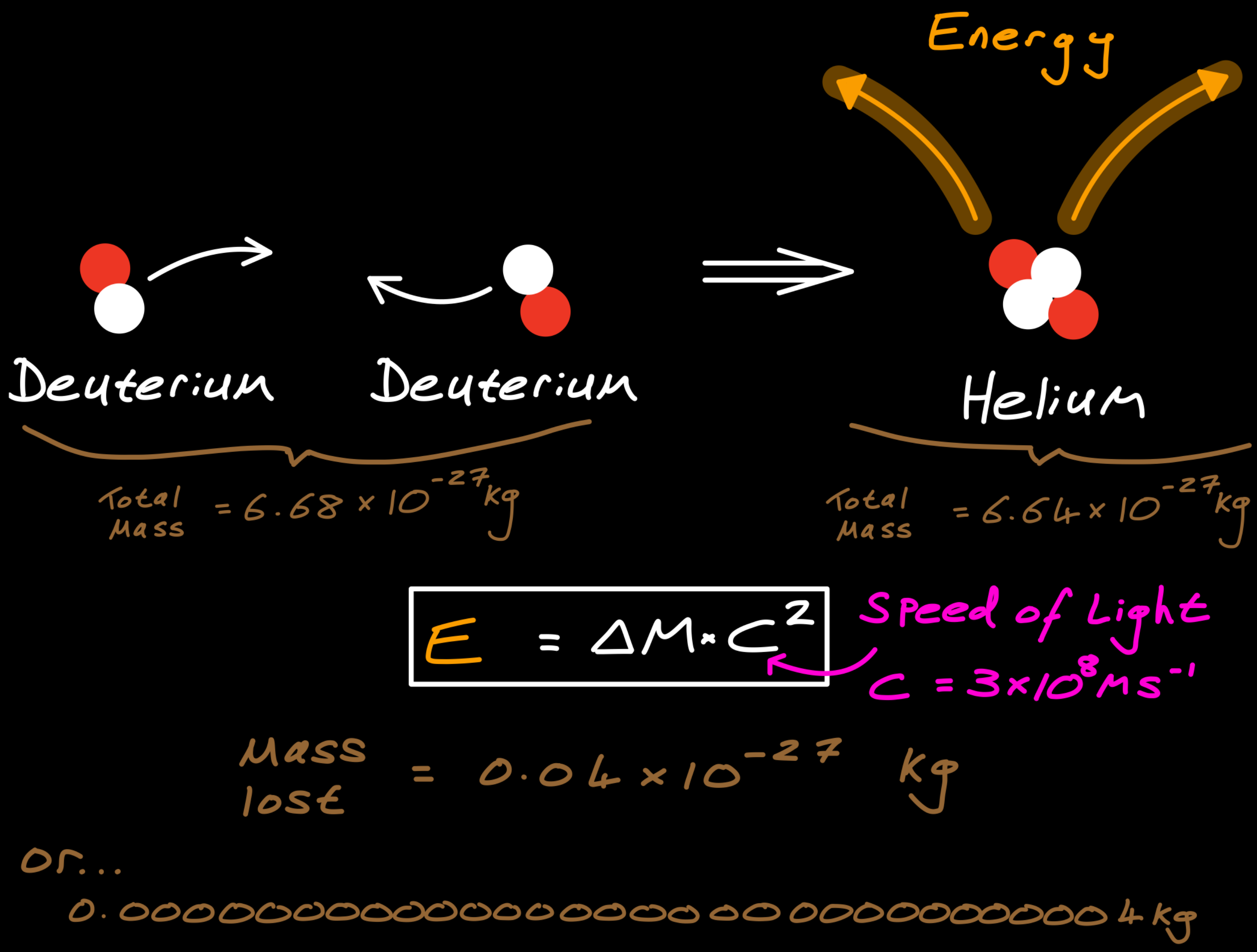
But why does Fusion release energy?

In our own sun, the principal reaction that occurs is the fusion of Deuterium (an *isotope* of Hydrogen) into Helium.

Nuclear Fusion

The mass of the Helium nucleus formed is slightly less than the combined mass of the two Deuterium nuclei.

This lost mass (mass deficit) is converted into energy, according to Einstein's famous formula.



Nuclear Fusion

Compare the energy from the fusion of a single gram of Deuterium, with the equivalent mass of coal we would need to burn...

$$E = (0.4 \times 10^{-29}) \times (3 \times 10^{8})^2$$

$$= 3.6 \times 10^{-12}\ J$$

1 gram of Deuterium → 540 Billion Joules of Energy

Equivalent to burning 18,500 kg of coal

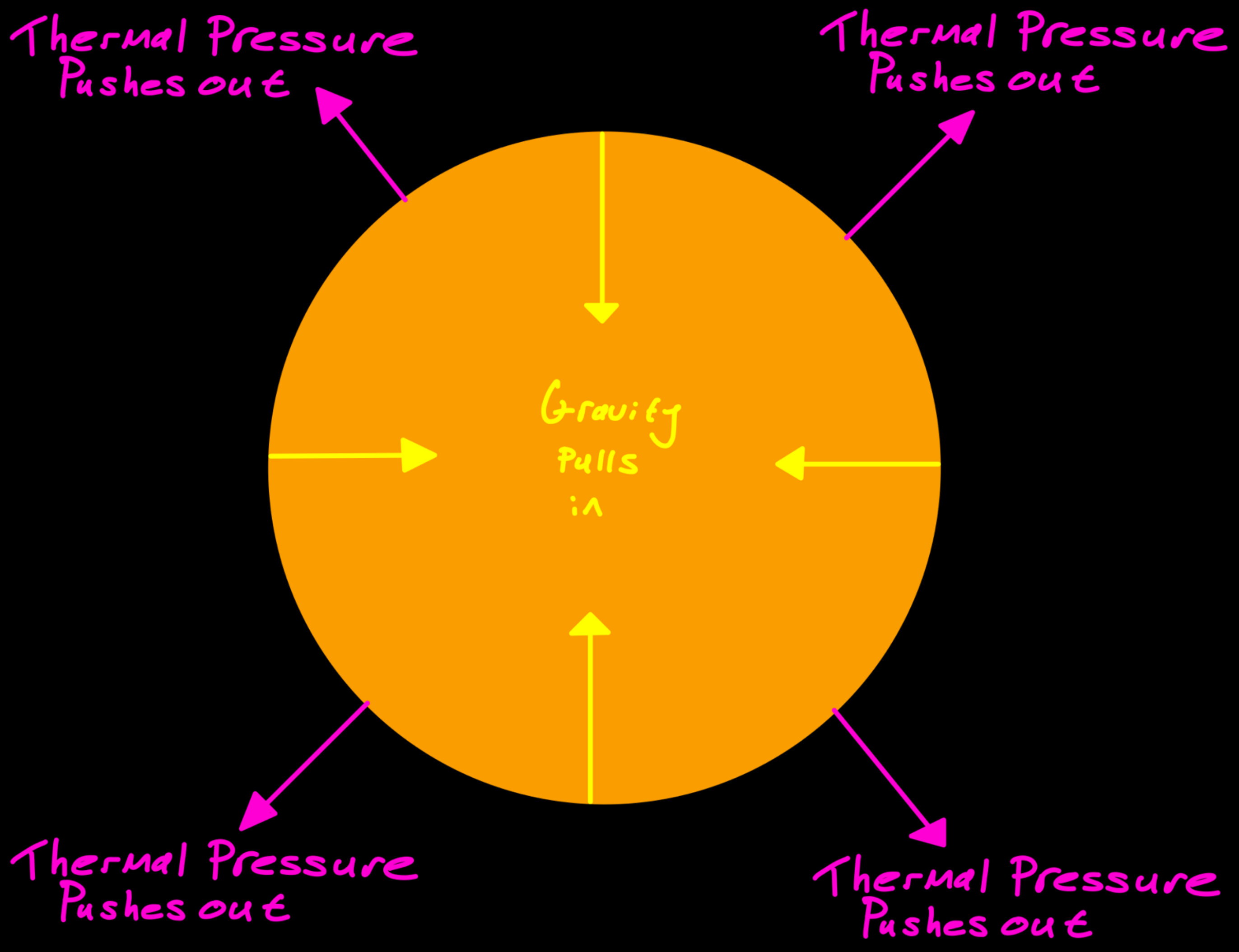
Balanced Forces

There are two major forces acting within a star:

Gravity – acts to collapse the star inwards.

Thermal Pressure – acts to explode the star outwards.

For most of a stars life these forces are in near perfect balance, and the star is stable.

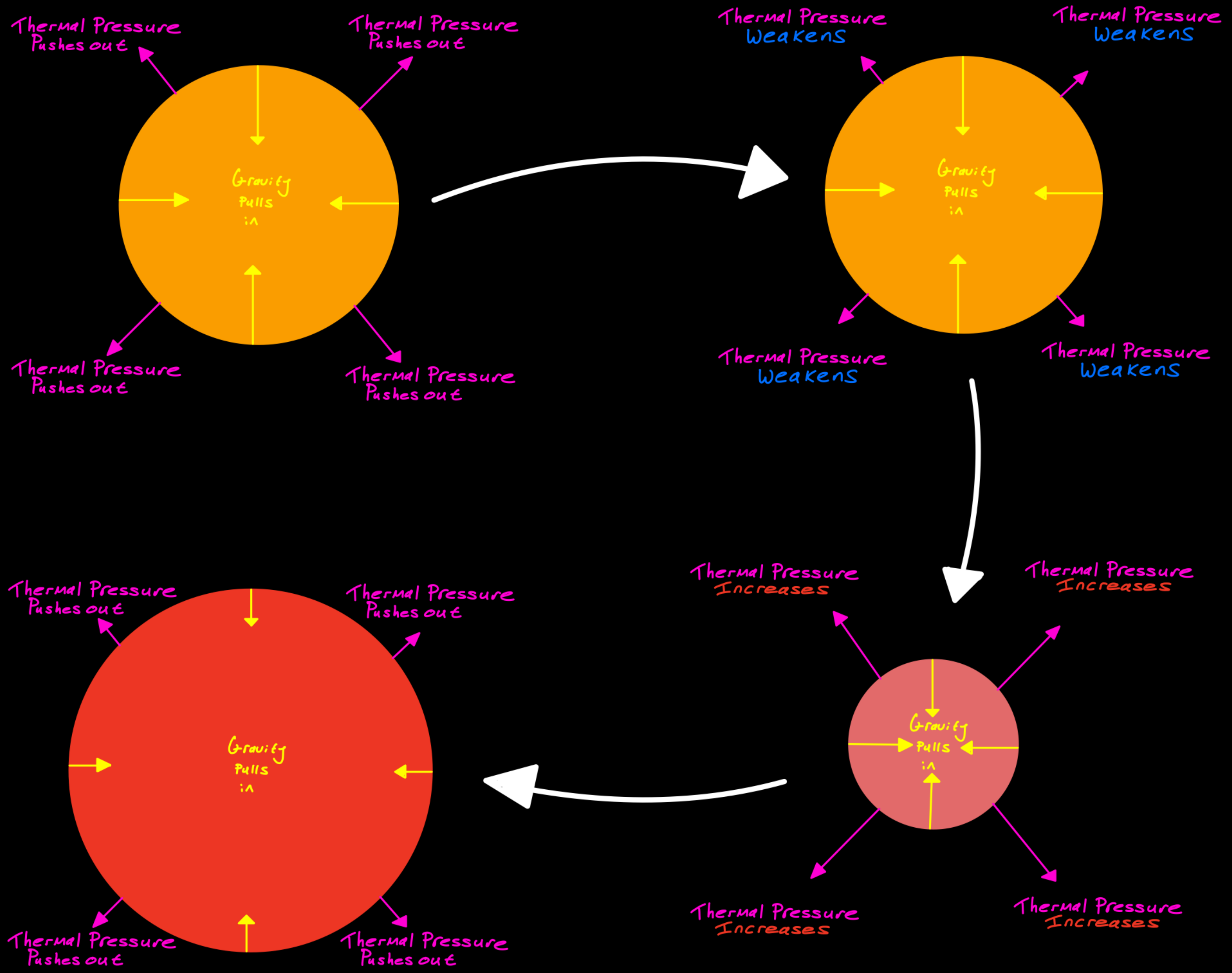


Middle-aged stars, like our own sun, are in the Main Sequence phase

Un-Balanced Forces…

When one force gets the upper hand, changes occur within the star.

1. Deuterium runs out within the stars core.
2. Fusion slows down.
3. The core cools, and gravity takes advantage.
4. The core contracts
5. Pressure rises.
6. Fusion of Helium begins.
7. Thermal pressure increases.
8. The star expands into a Red Giant.

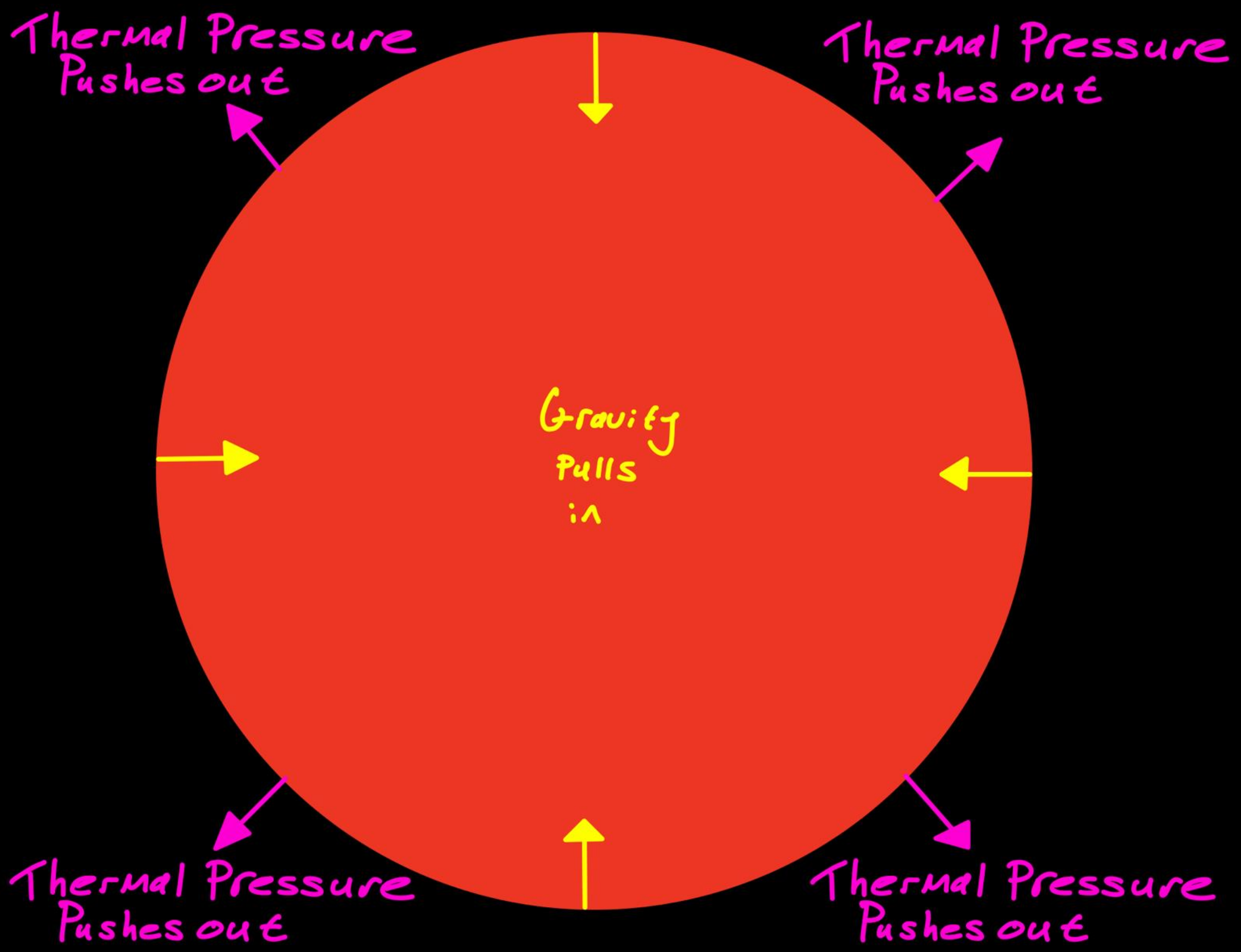


Red Giants

Red Giant Stars are far larger, and far cooler than Main Sequence Stars.

They are able to fuse Helium, and heavier elements all the way up to Iron in their core.

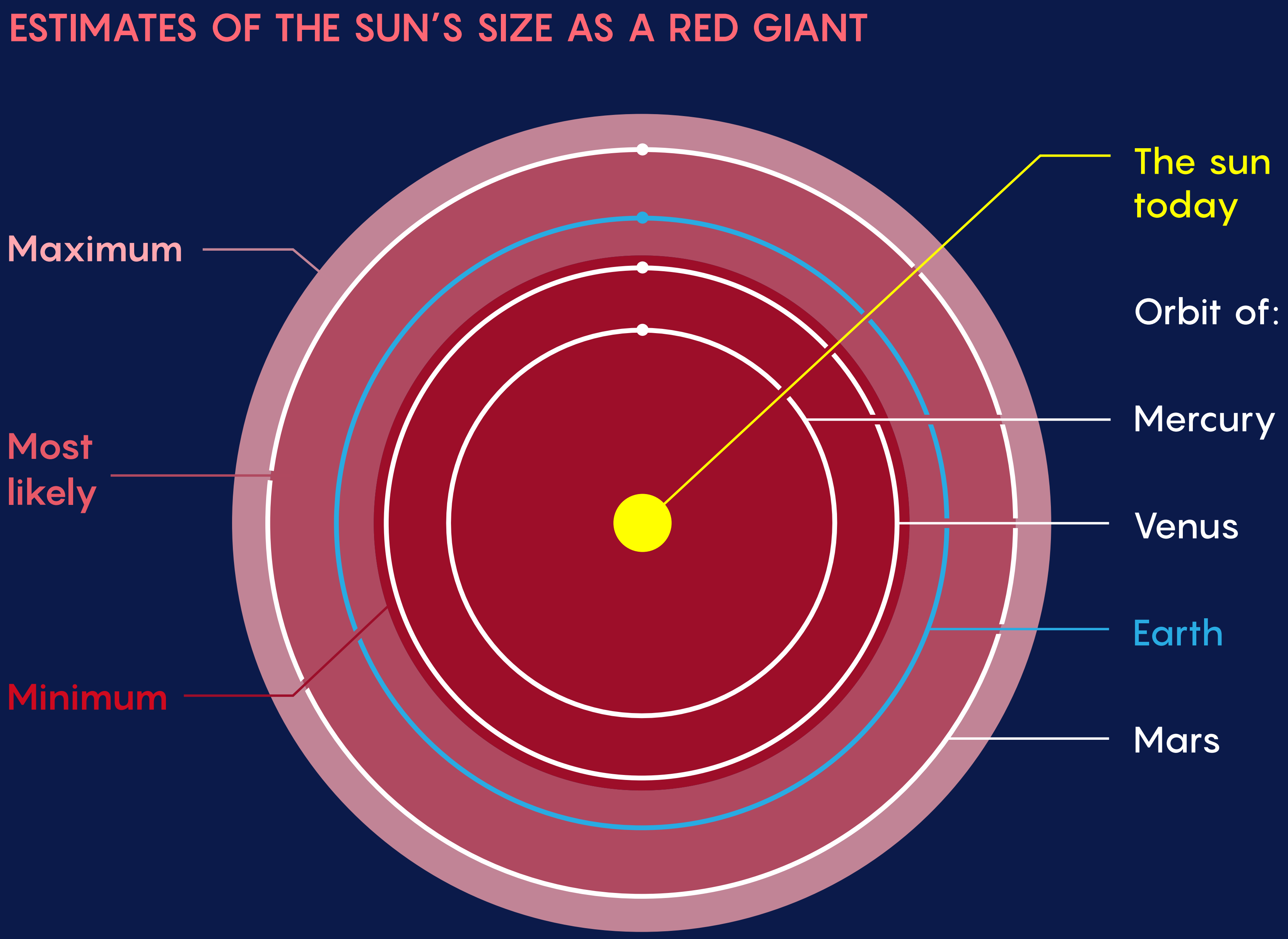
Eventually.. Even they will run out of nuclear fuel.



The Sun as a Red Giant

Our own sun will expand into Red Giant in about 5 billion years.

When it does, it's radius will extend to roughly where the Earth is now (around 200 times its current size).



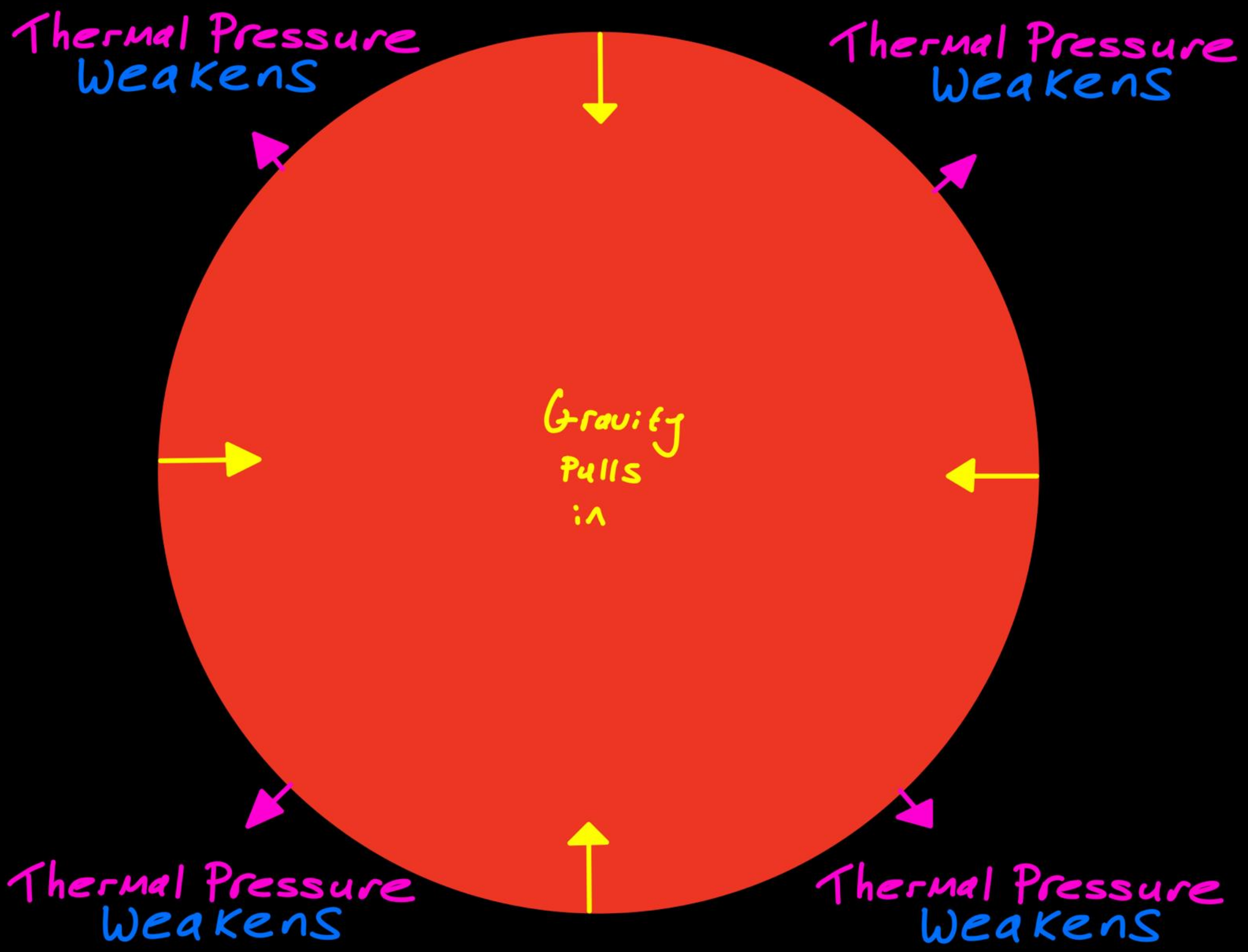
Merrill Sherman / Quanta Magazine

Supernovae

When the core of a Red Giant Star turns to Iron, nuclear fusion can no longer proceed.

Thermal Pressure drops, and gravity takes the upper hand.

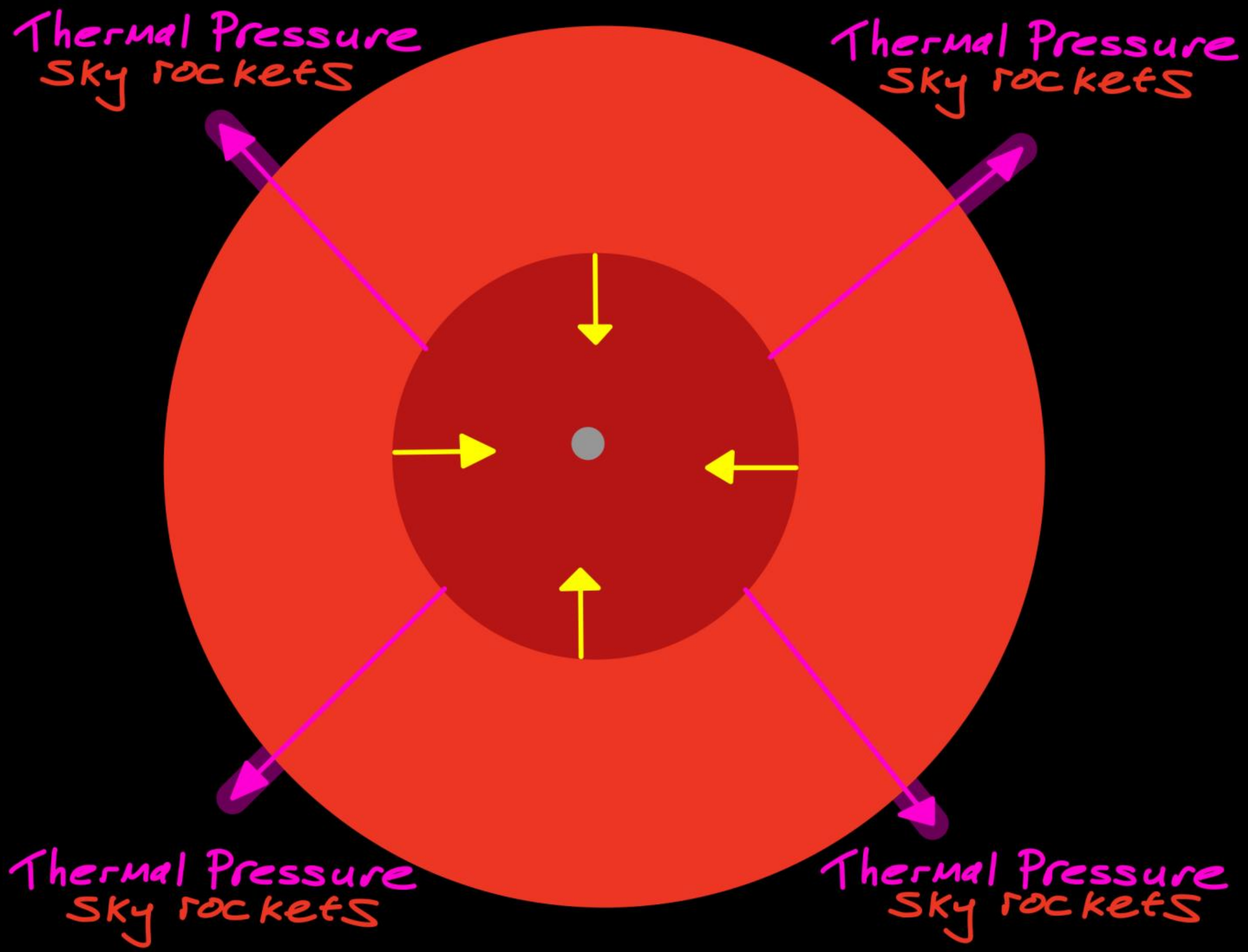
The core of the star collapses under the immense gravitational pull.



Supernovae

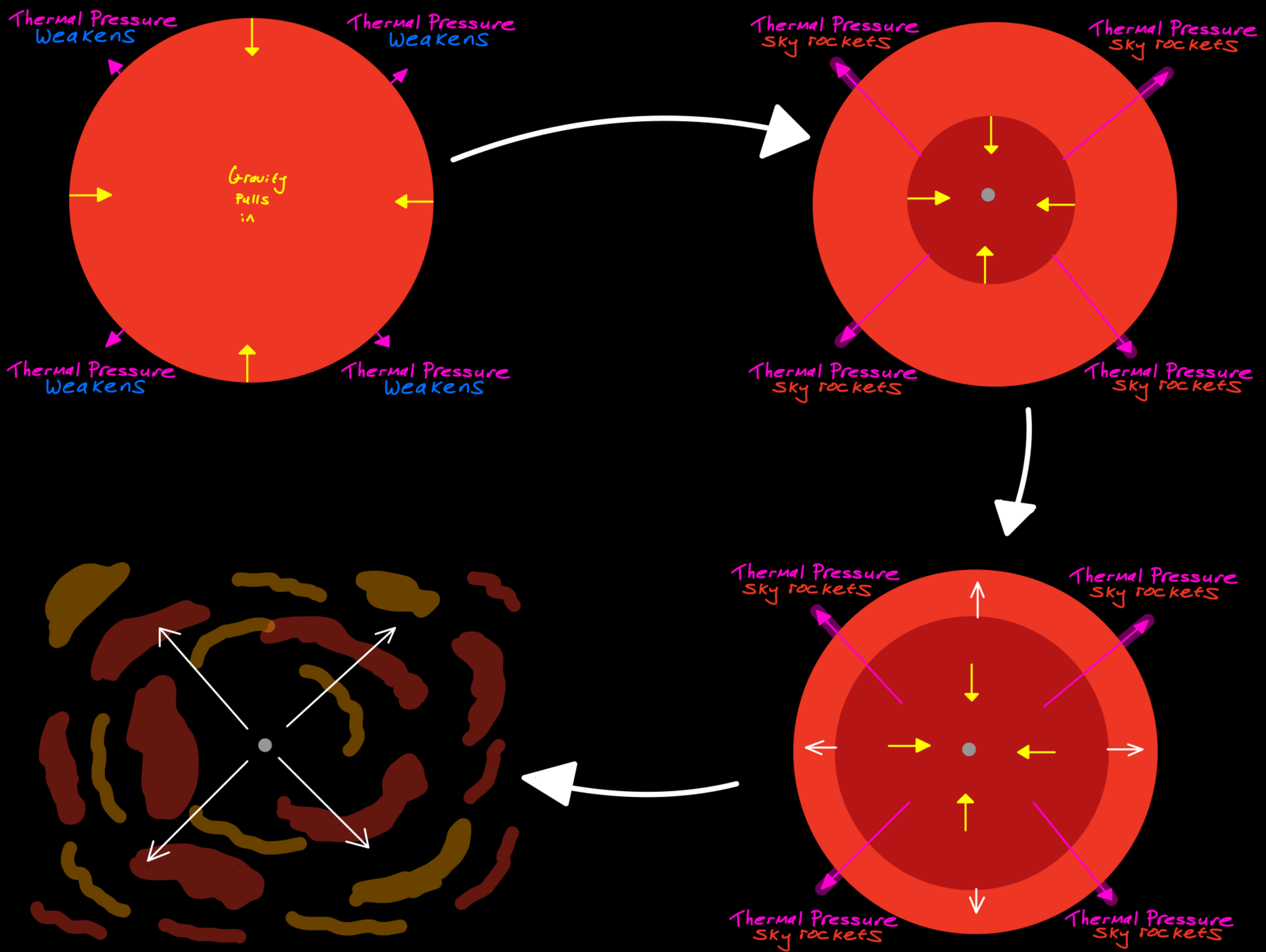
During the collapse, the core releases a huge number of neutrinos.

The neutrinos deposit catastrophic levels of energy into the outer layers of the star, triggering an explosions (or type II Supernova).



Supernovae

The outer layers of the star explode out into space, forming a nebula and leaving behind a dead degenerate core (either a white dwarf star, a neutron star / pulsar, or a black hole).



Pulsar Formation

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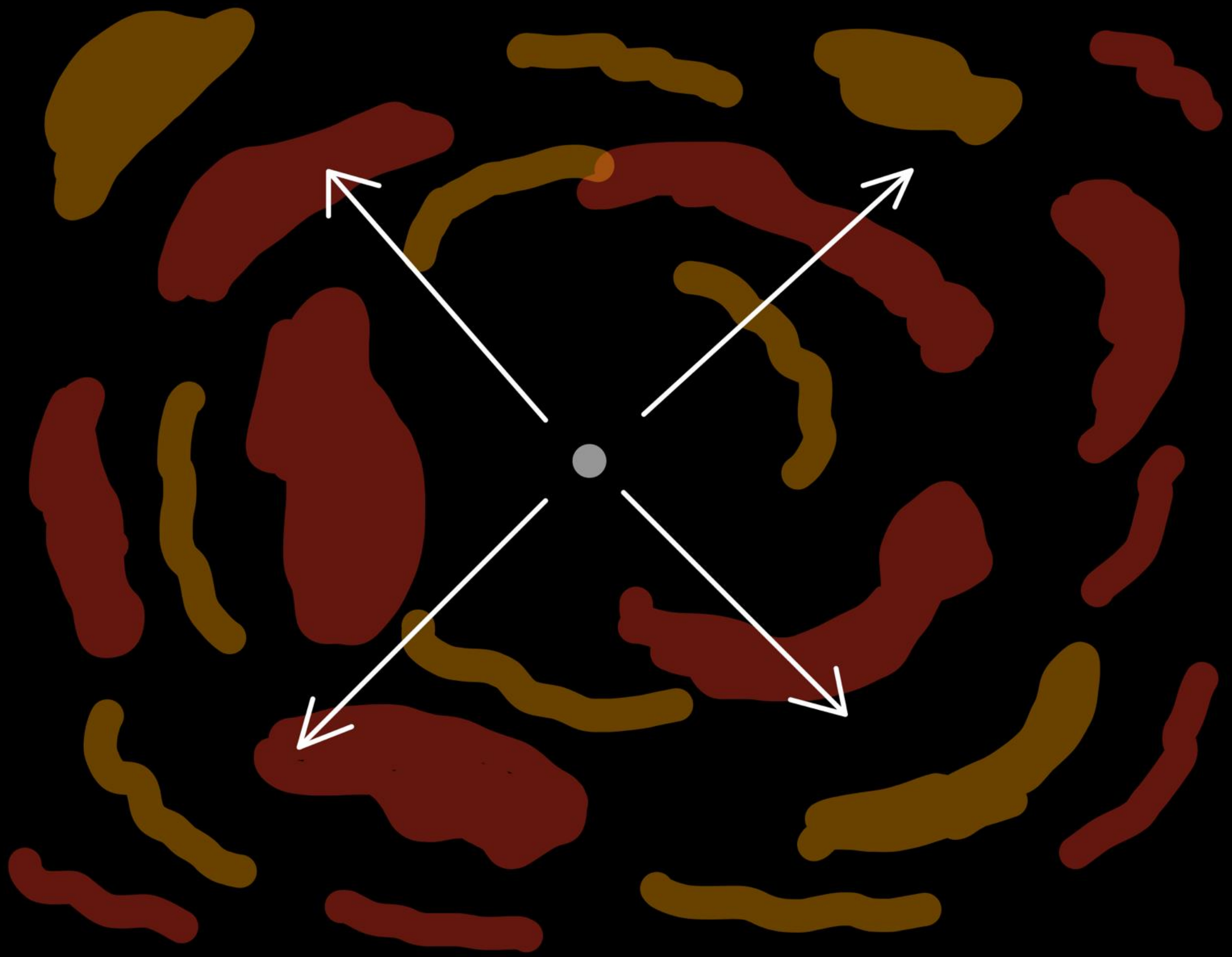


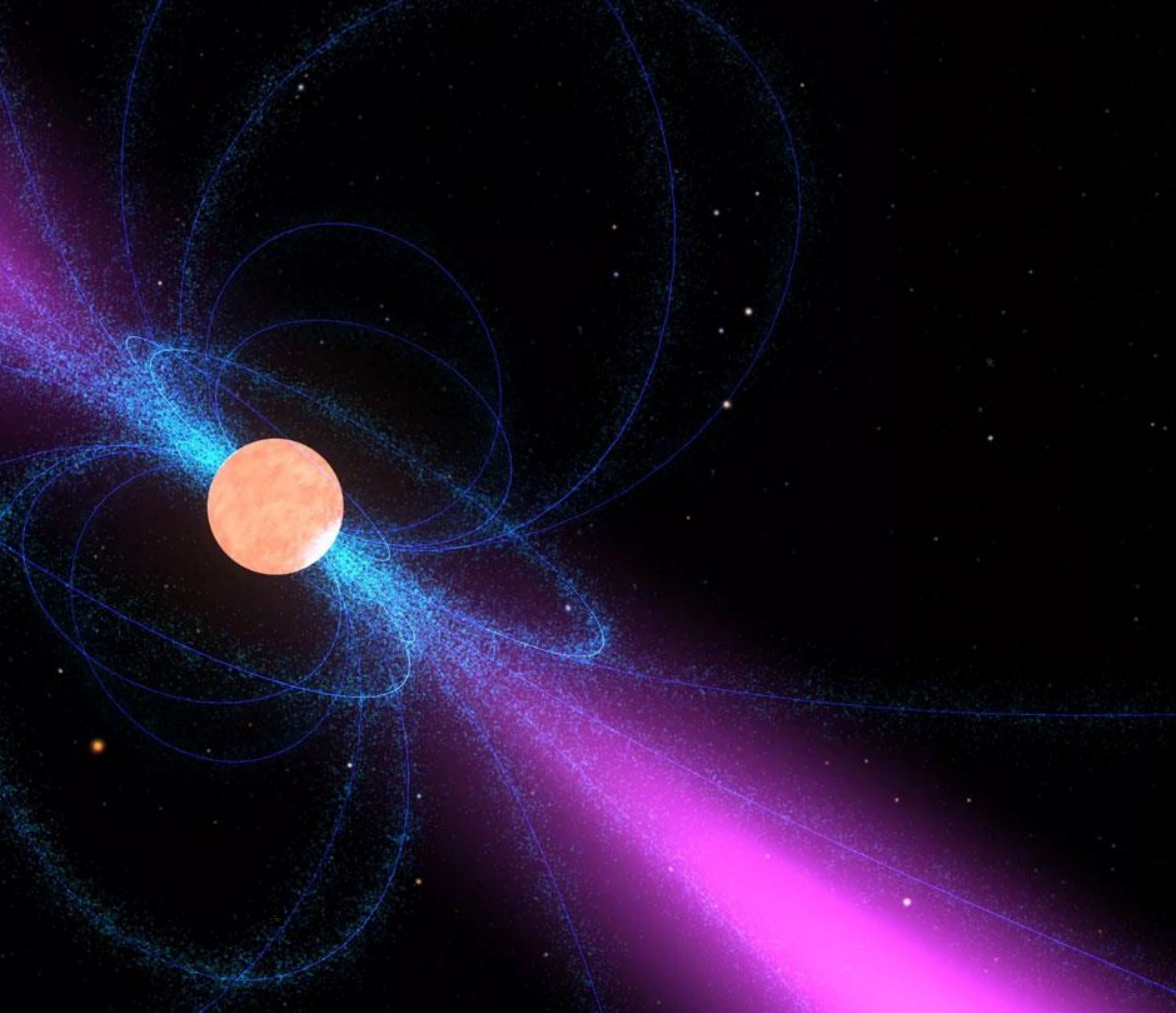
Pulsar Formation

The 'Veil Nebula' is part of the Cygnus Loop Nebula, thought to contain a Neutron Star.

Pulsar Properties

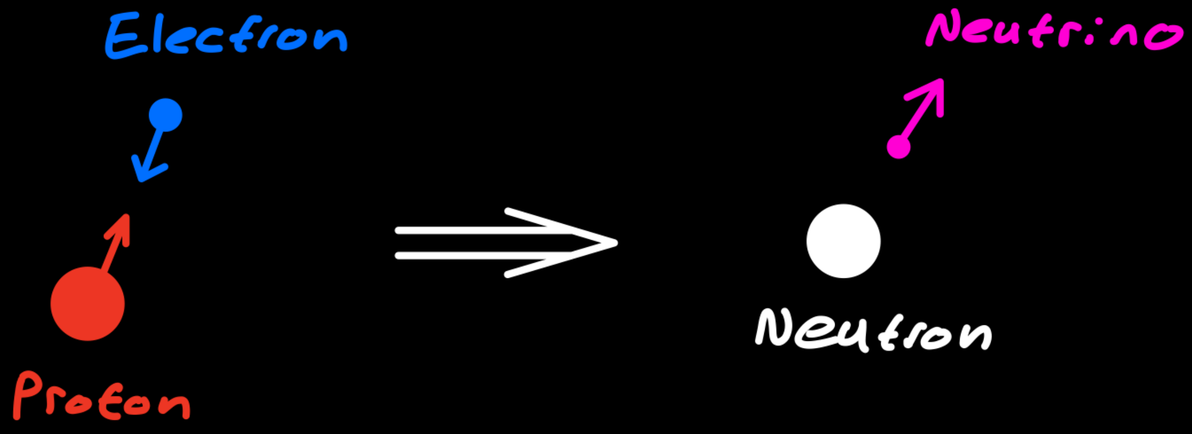
Let’s dig into the properties than make pulsars o interesting:

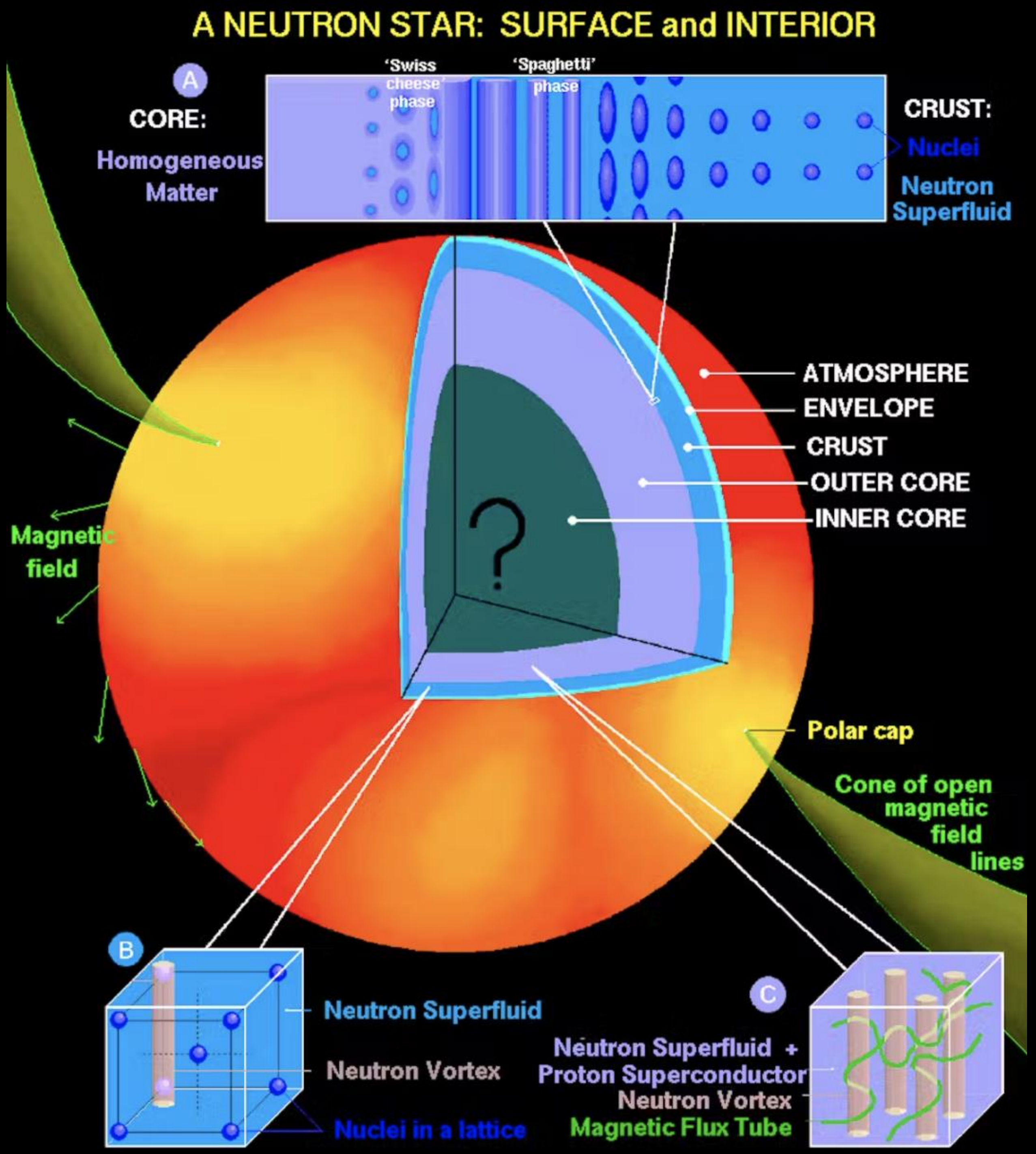
1. Structure
2. Density
3. Spinning
4. Magnetic Field
5. X-ray Beams



1. Structure

Neutron Stars are composed almost entirely of Neutrons, formed when Protons and Electrons within the collapsing stars core are forced to combine.





2. Density

Neutron Stars are extremely small.

A typical Neutron Star has a mass of around 20km.

That's about the distance from the Beecroft Gallery to Basildon.

But… Neutron Stars typically weight between 10 and 25 times the weight of the Sun!

2. Density

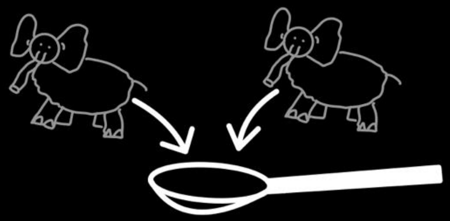
A huge amount of mass, compressed into a tiny volume leads to a very high density.

My preferred unit for neutron star density is EpT (Elephants per Teaspoon).

Neutron star Density $\simeq 5 \times 10^{17}$ kg/m^3

or...

15 Million Elephants Per Teaspoon



2. Density

Density calculations...

$1\ \text{tsp} \simeq 5\ \text{ml} = 5\ \text{cm}^3$

$\text{Neutron star Density} \simeq 5 \times 10^{11}\ \text{kg/cm}^3 = 1 \times 10^{11}\ \text{kg/tsp}$

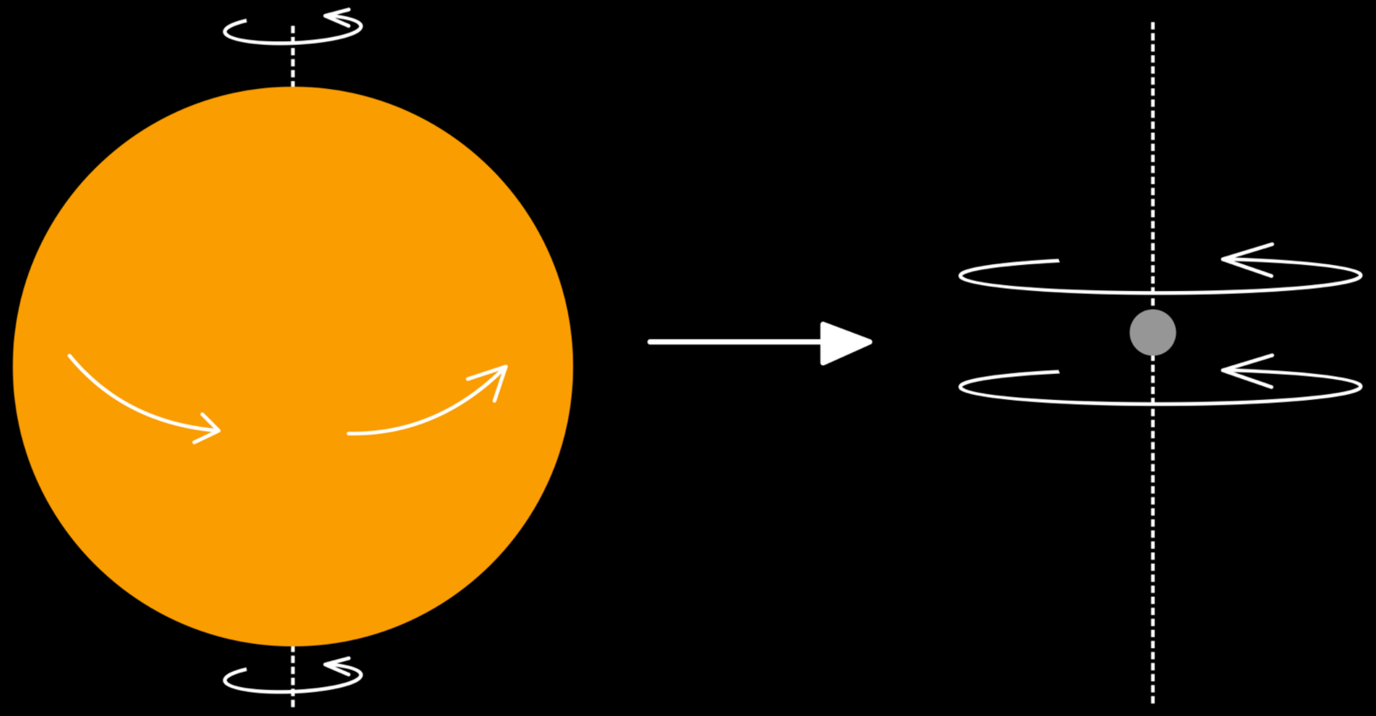
$1\ \text{African Bull Elephant} \simeq 6800\ \text{kg}$

$\Rightarrow \text{Neutron star Density} \simeq$ 15 Million Elephants Per Teaspoon

3. Spinning

Neutron stars spin extremely quickly.

To understand this, we will first learn a little more about *angular momentum*, and the *moment of inertia*.

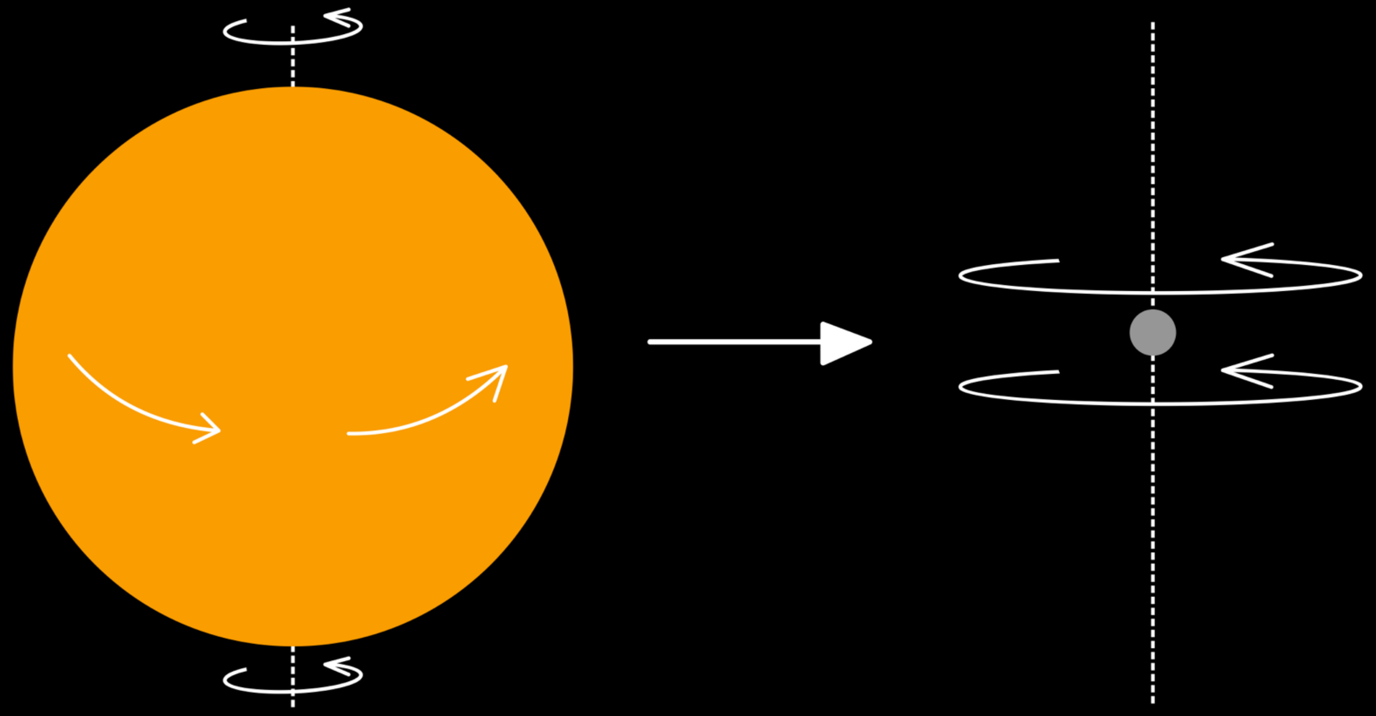


Aside:
Angular Momentum

Angular Momentum is a quantity that describes 'how hard' something is spinning.

It is a property of spinning objects that is conserved. Meaning, the total is always unchanged.

That is not to say that a spinning object will always spin.. But in-order to slow down, it must transfer its angular momentum elsewhere, and impart a spin to another object.



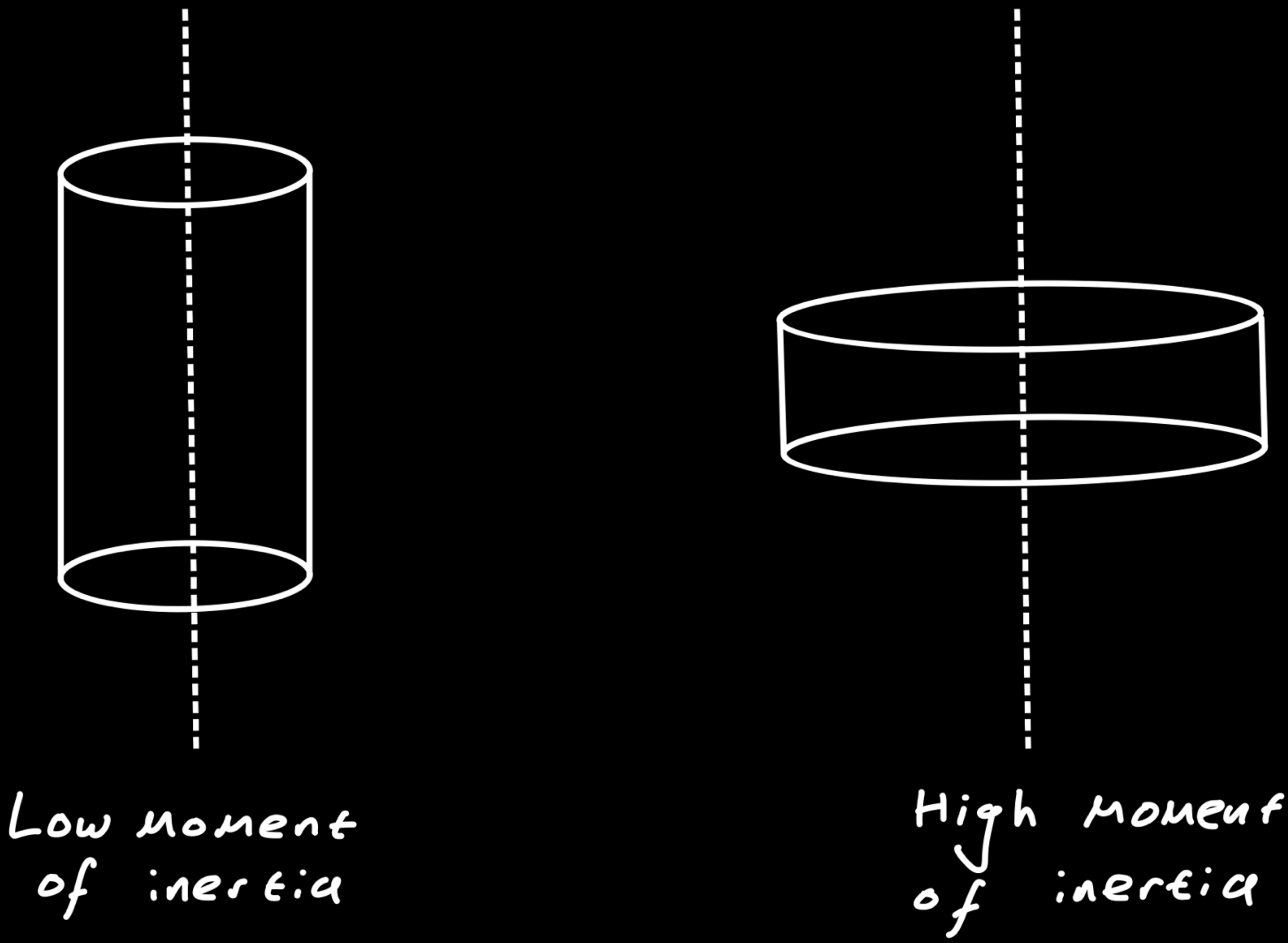
The angular momentum of the stars core before collapse, is the same as the angular momentum of the neutron star after collapse.

Aside:
Moment of Inertia

The Moment of Inertia is a measure of how distributed matter is away from the axis of rotation.

A high moment of inertia indicates matter spread far away from the rotation axis.

The higher the moment of inertia, the harder it is to get a stationary object to start spinning, or to stop a spinning object from spinning.



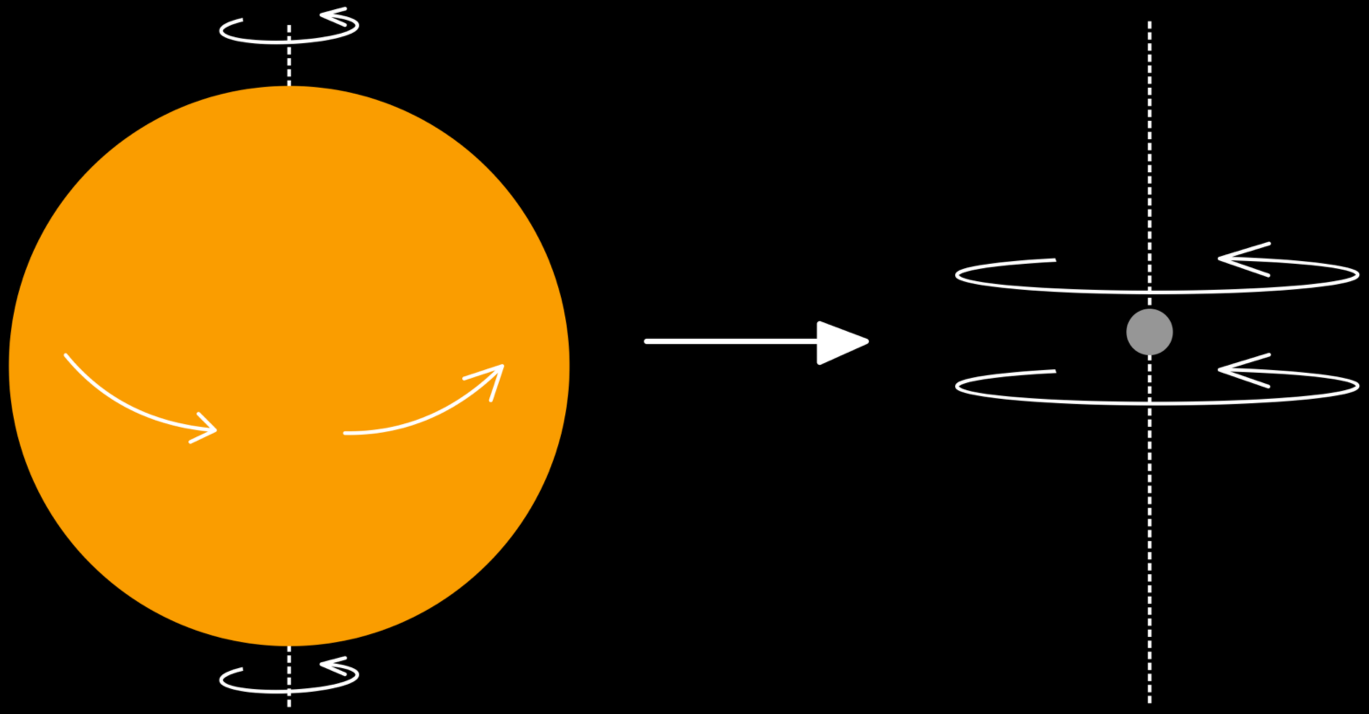
Aside:
Moment of Inertia

Mathematically, angular momentum is the product of the moment of inertia and the rotation speed.

$$\text{Angular Momentum} = \text{Moment of Inertia} \times \text{Rotation Speed}$$

Let's see what this means in practice…

Aside:
Moment of Inertia



When the stars core collapses, the moment of inertia decreases.

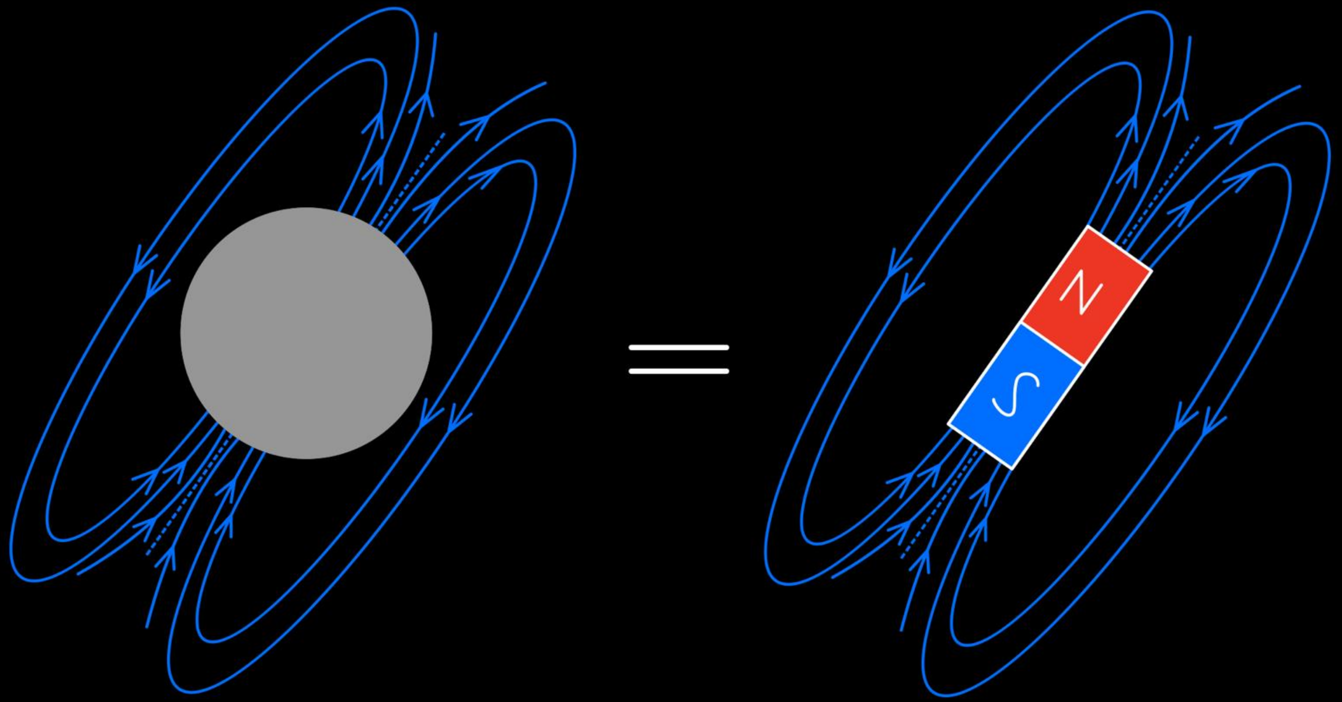
However, because angular momentum is conserved the rotation speed must increase accordingly.

Angular Momentum = Moment of Inertia × Rotation speed

4. Magnetic Field

Neutron stars have extremely powerful magnetic fields (about one trillion times the Earths magnetic field strength).

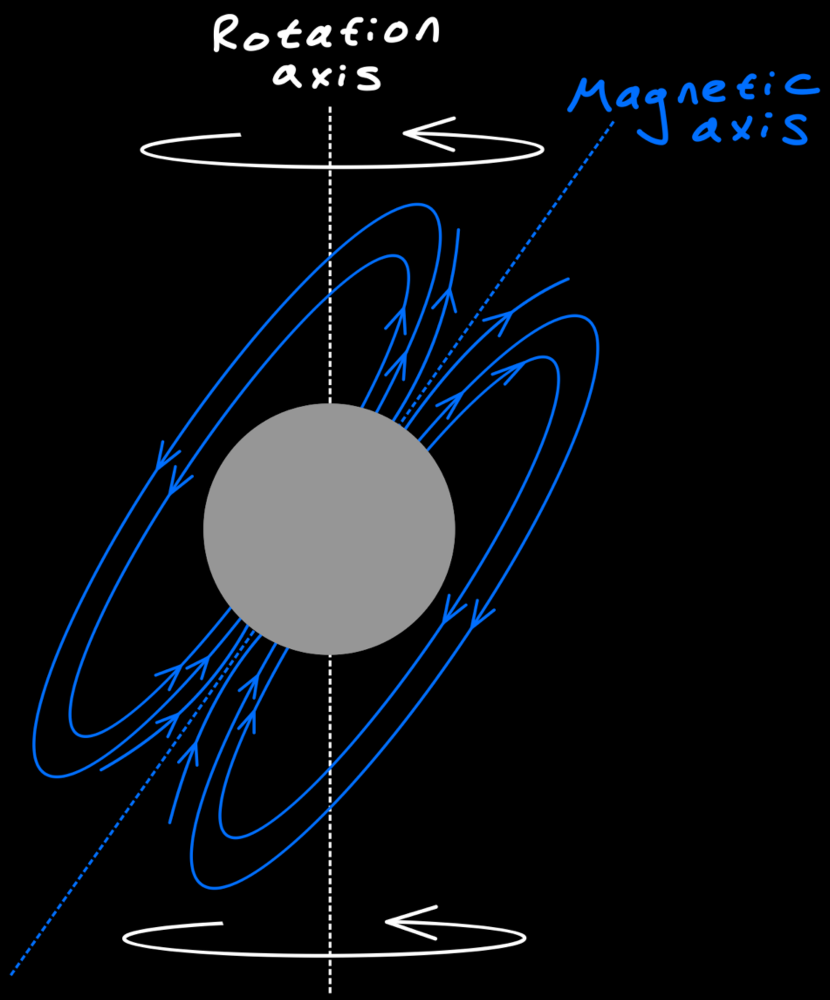
The exact origin of the super strong magnetic field is not completely understood.



Aside:
Moving Magnets

The axis of rotation and the axis of the magnetic field are often misaligned.

Let's study the effect of this rapidly rotating magnetic field.

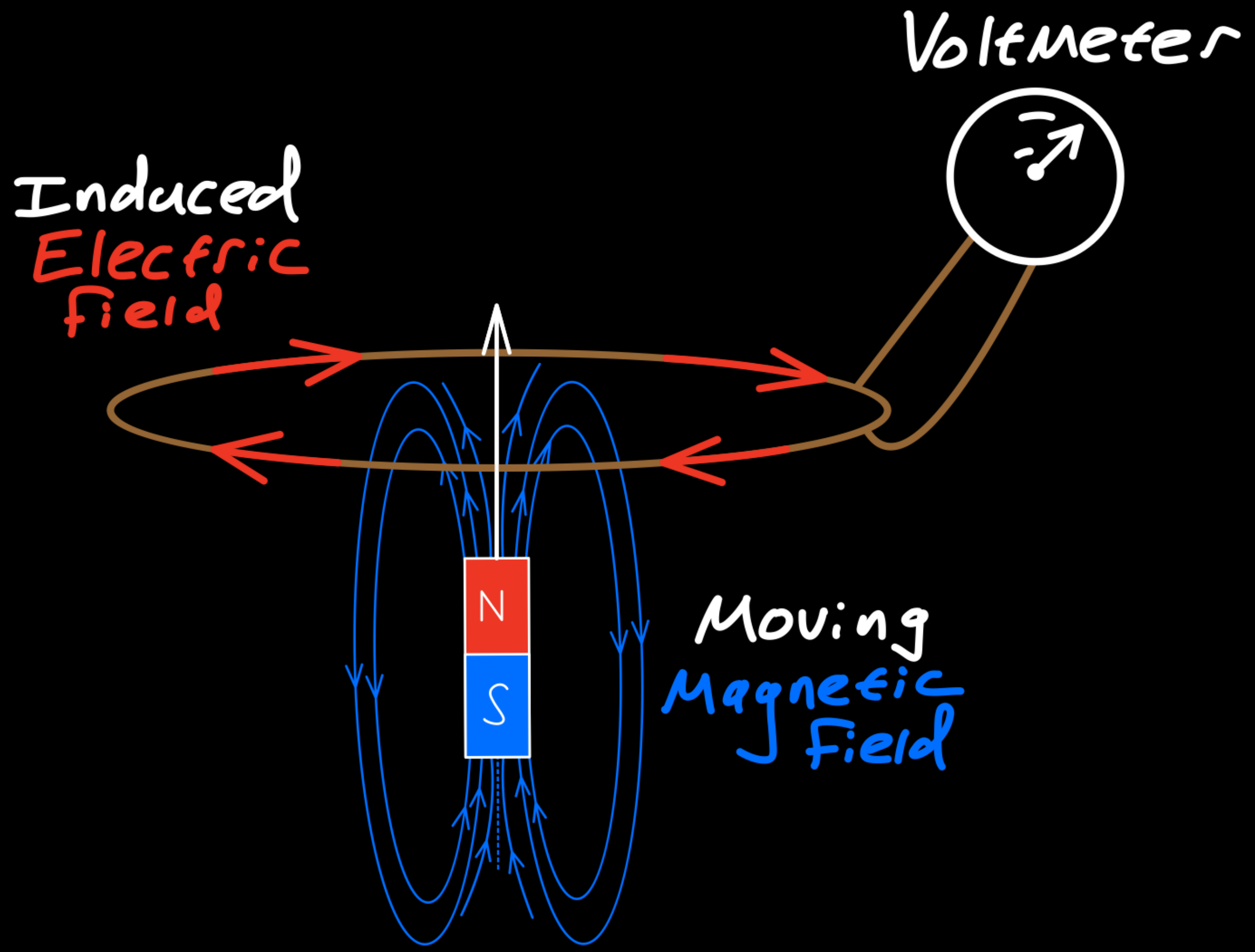


Aside:
Moving Magnets

Moving magnetic fields generate and electrical field.

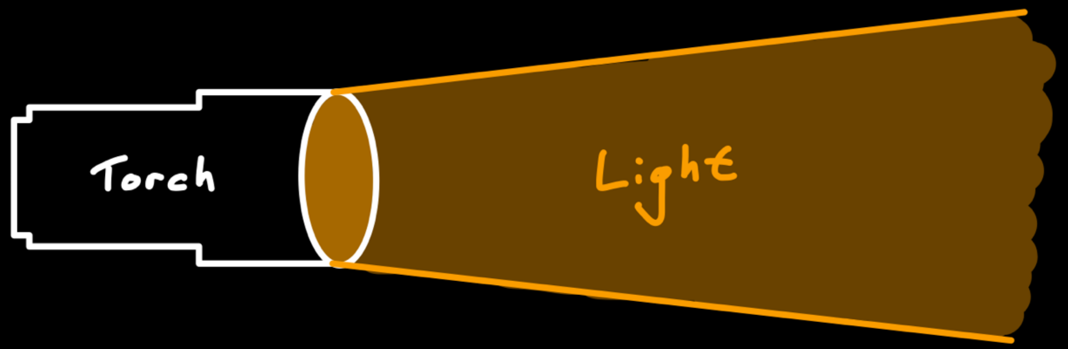
We can see this as a voltage created in a loop of wire by a moving magnet.

This is called Electro-Magnetic Induction. This is the cornerstone of almost all electrical power generation.



Aside:
What is Light?

Q: What is light?



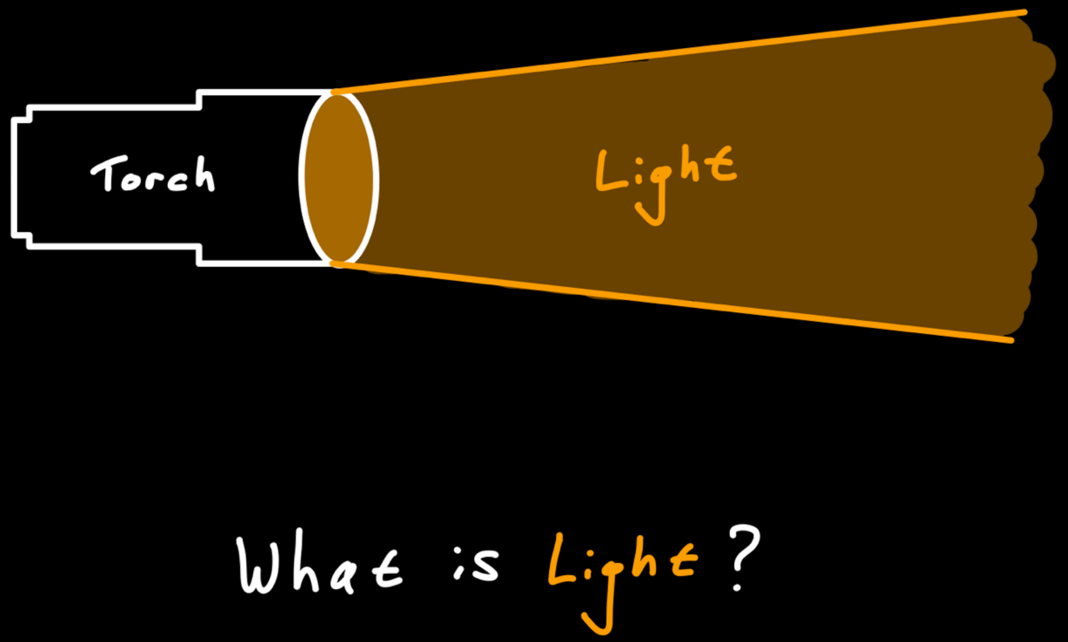
What is Light?

Aside:
What is Light?

Q: What is light?

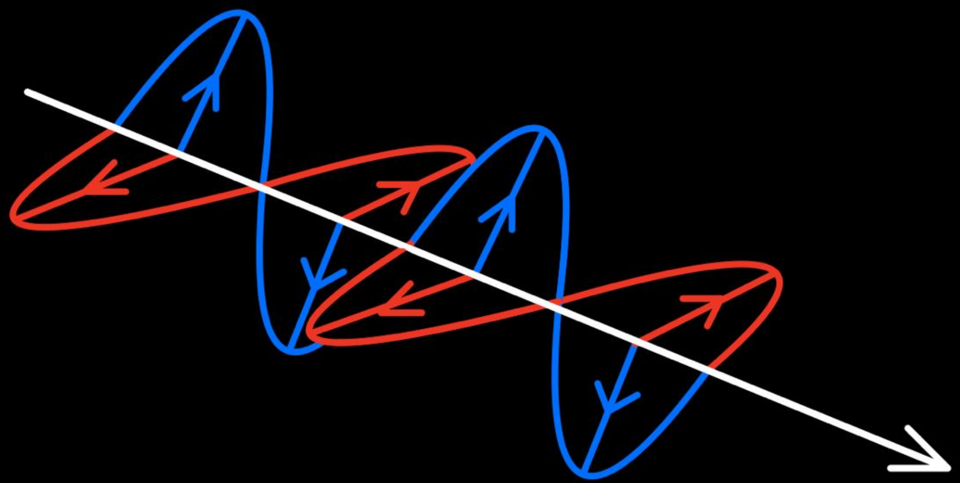
A: Light is a Wave

But what is waving?



Aside:
What is Light?

The Electro-Magnetic Field



Q: What is light?

A: Light is a Wave

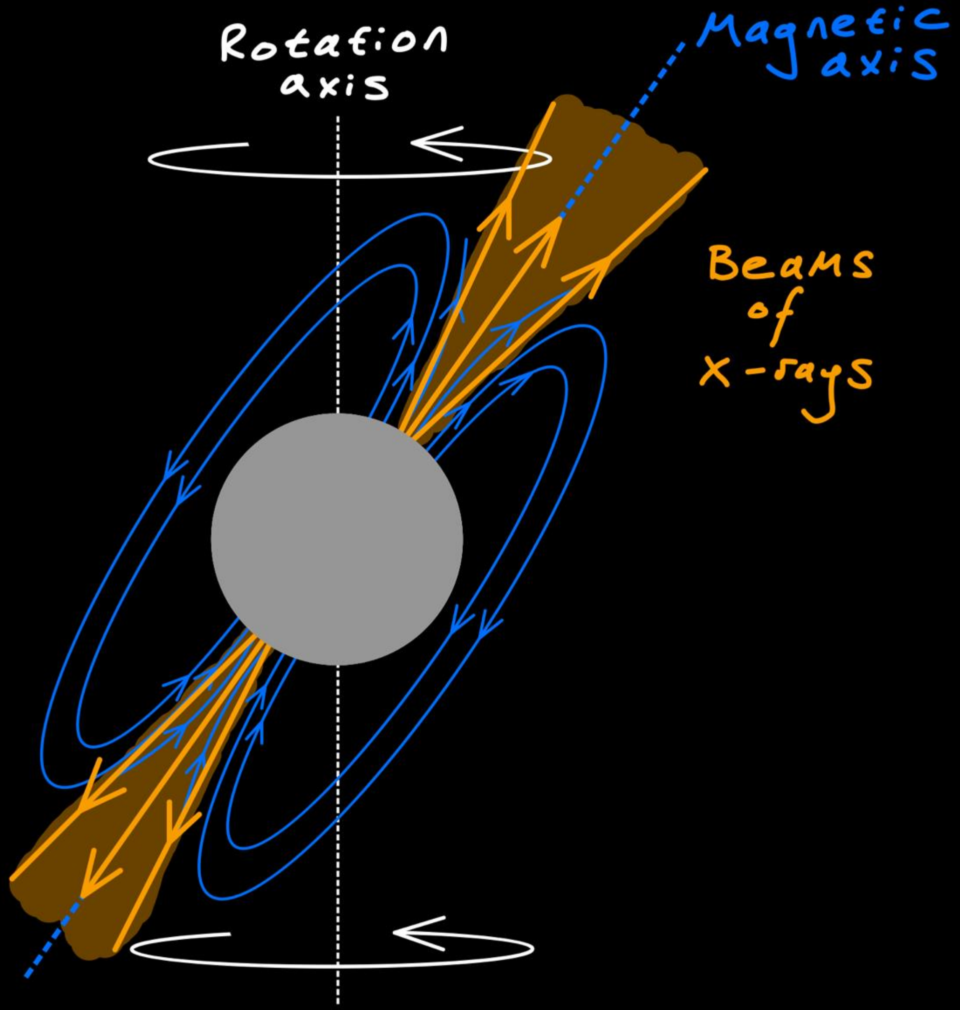
But what is waving?

Light is an "Electro-Magnetic wave".

5. X-ray beams

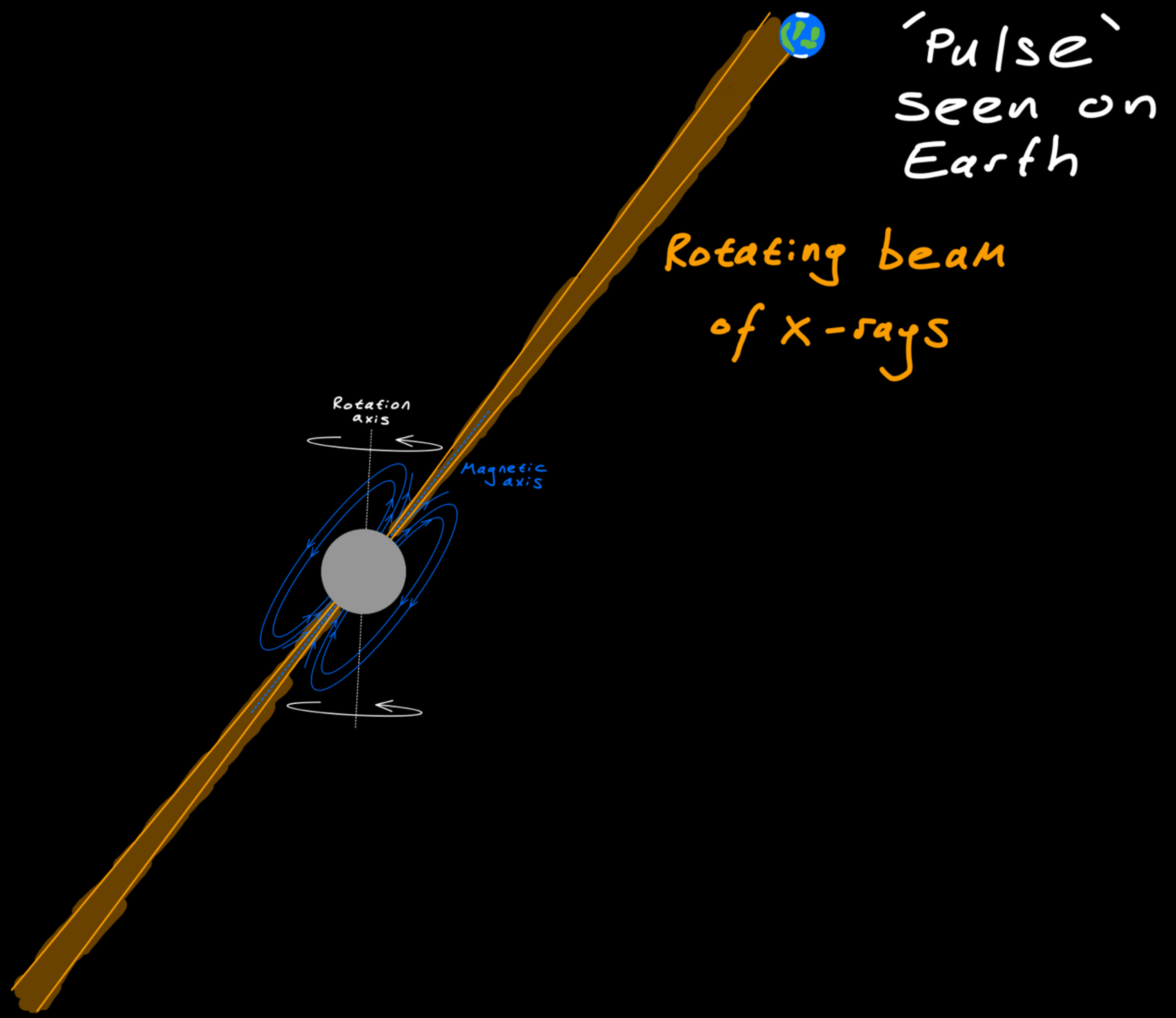
Given that light is an Electro-Magnetic wave, and that moving magnetic fields will generate electric fields…

We can start to understand how pulsars generate powerful jets of x-rays (a kind of high frequency Electro-Magnetic wave).

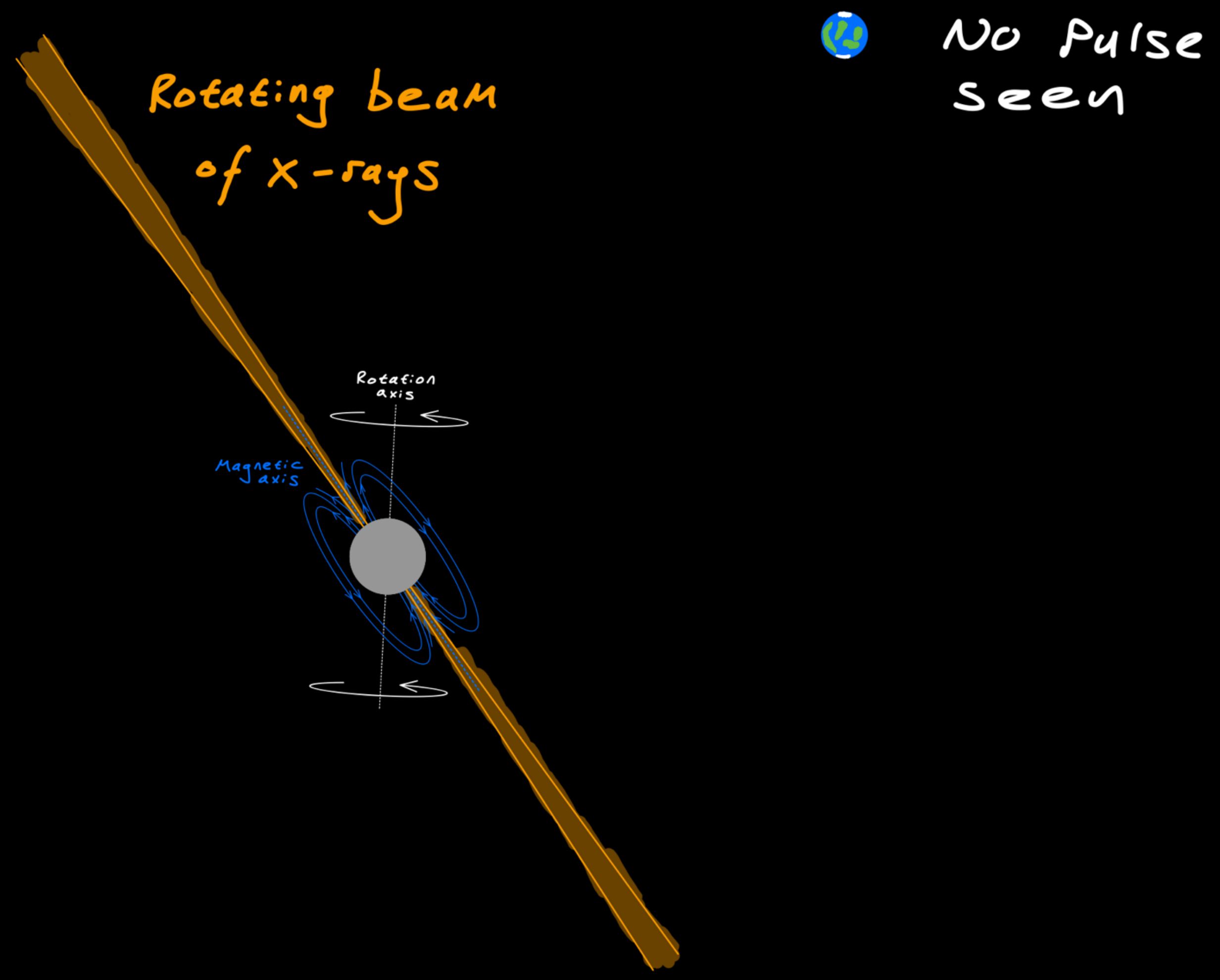


5. X-ray beams

If this beam of x-rays happens to be directed towards the Earth, it can be detected by astronomers.



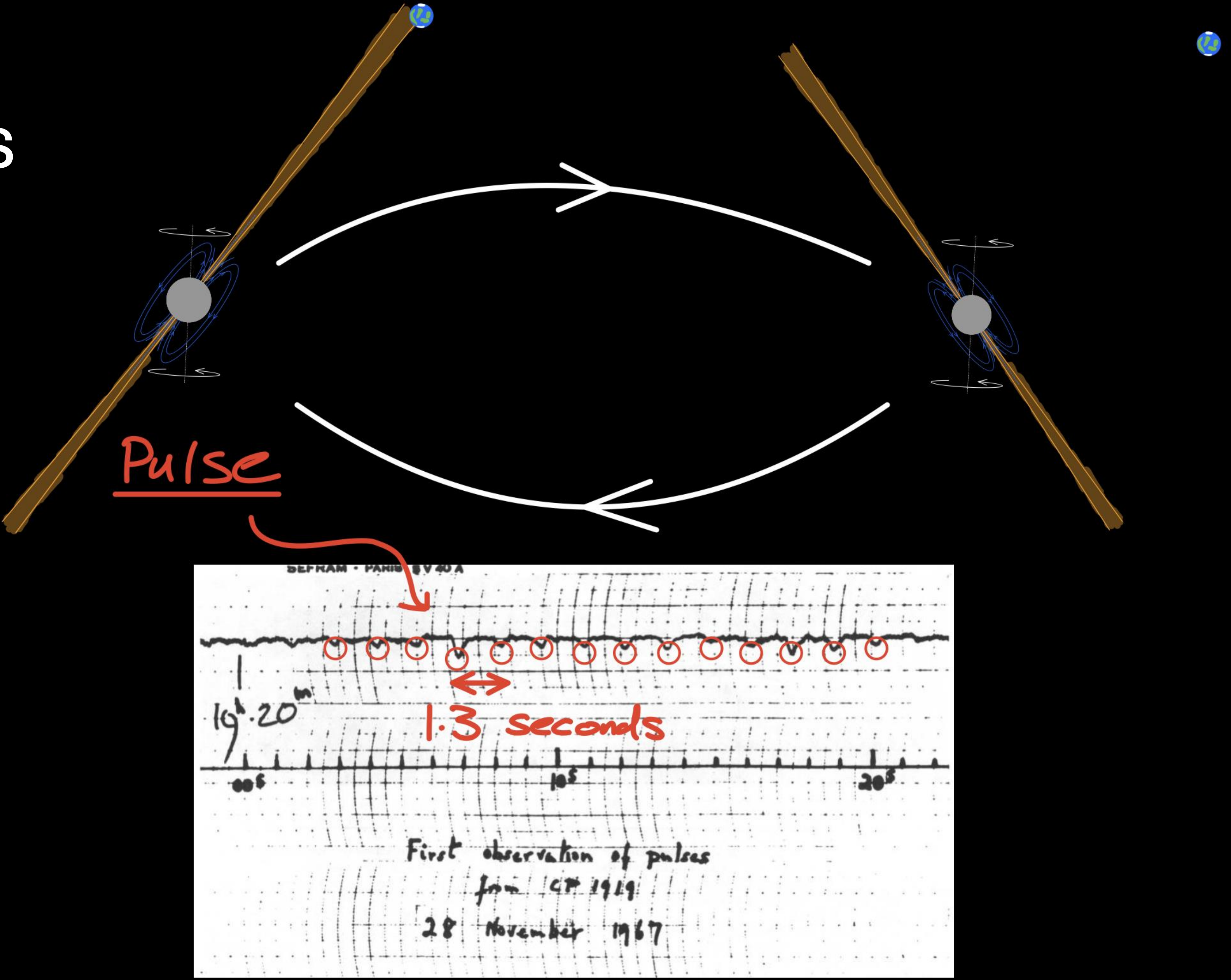
5. X-ray beams



As the beam rotates, the jet of radiation periodically points towards us and away from us.

5. X-ray beams

The beam of x-rays from the pulsar spins around, illuminating the Earth periodically, giving the impression of a ‘Pulse’.



Questions!

Coming Up…

The Science of Space: A Physicists Guide to the Galaxy

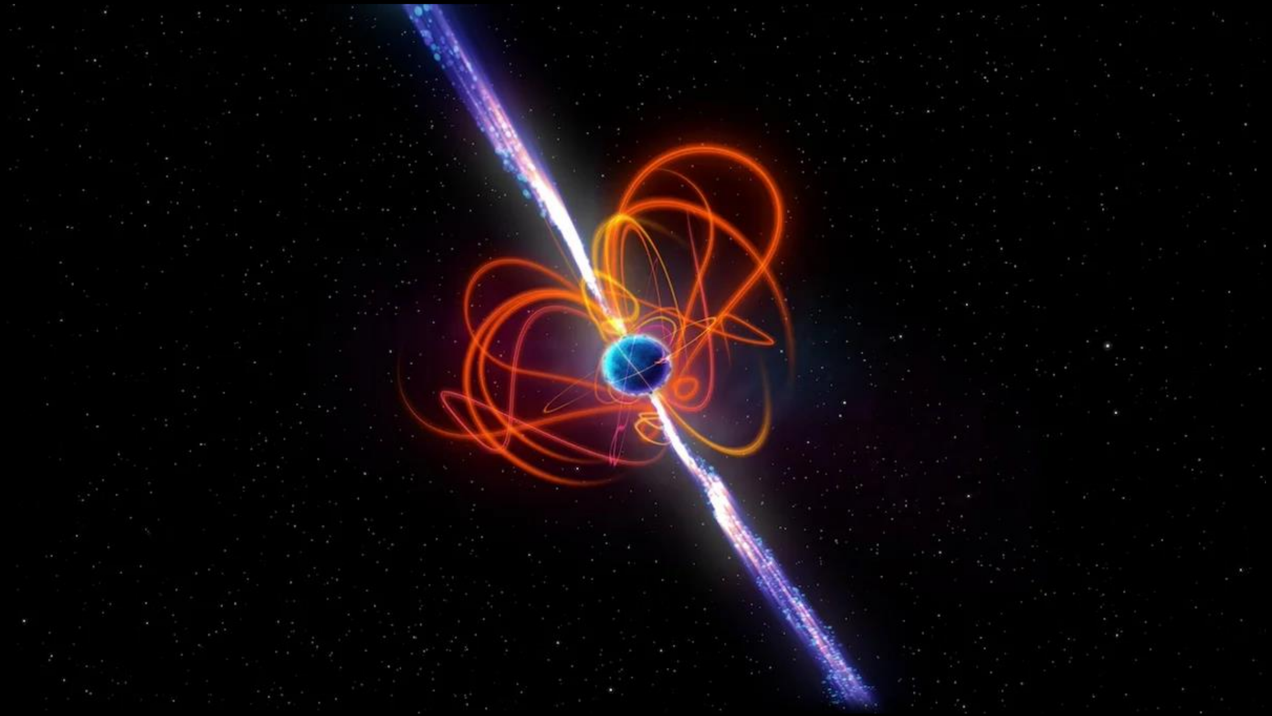
Every Sunday 11:30am in May @ The Beecroft Gallery Lecture Theatre

‘Our Place in the Cosmos’ (04/05)

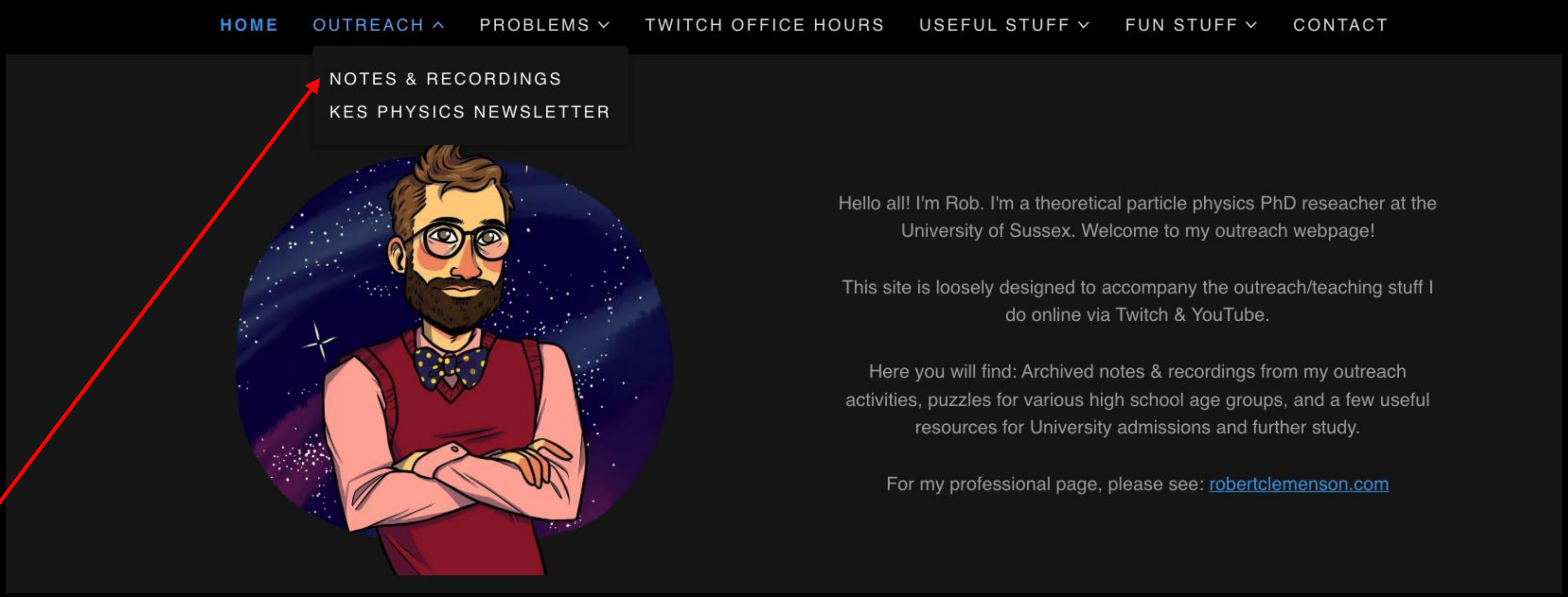
‘Schrodinger’s Cat in the Particle Zoo’ (11/05)

‘Time Travel 101’ (18/05)

‘Black Holes and Beyond’ (25/05)



Lecture Slides



These lecture slides are available on my outreach website:

CosmicConundra.com