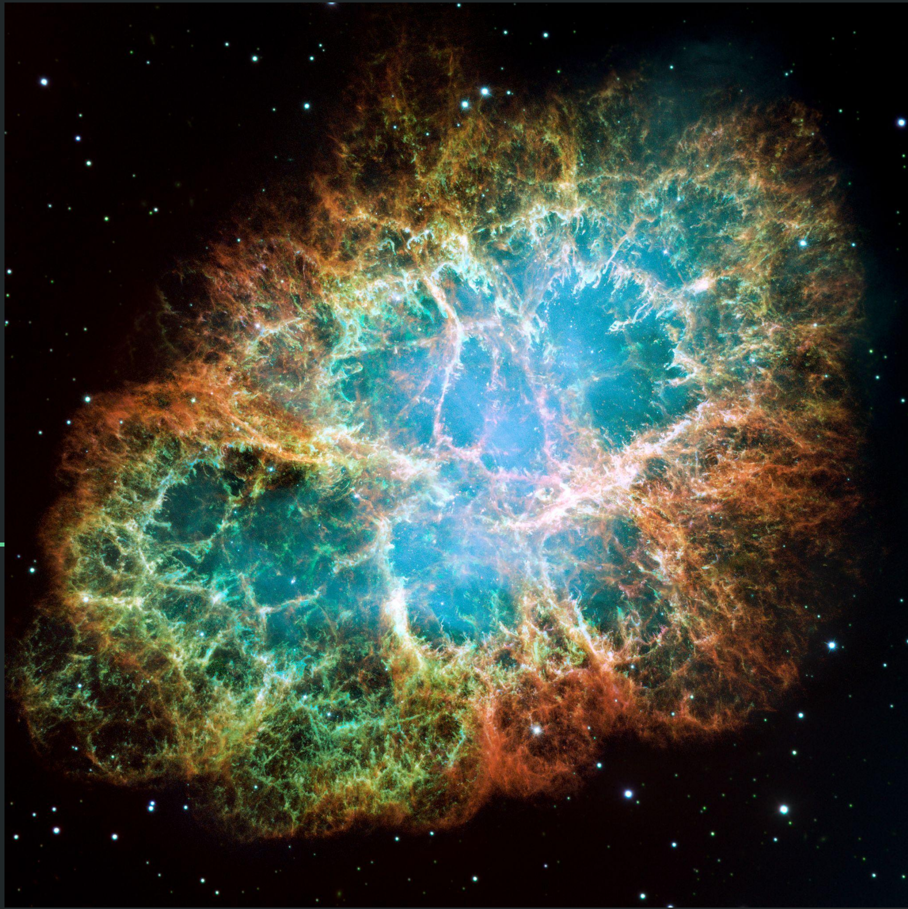
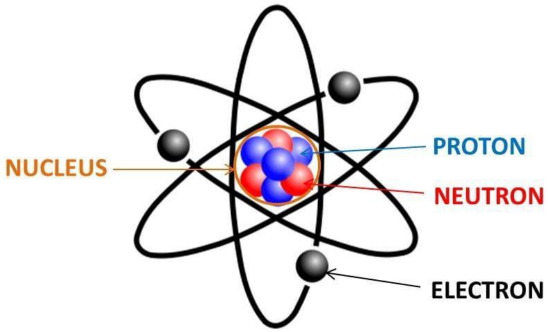
# Neutron Stars

An Overview



# History: The *Idea* of Neutron Stars




**1932:** James Chadwick confirms the existence of neutrons

**1934:** Bade & Zwicky coin the term “supernova” and hypothesize that supernova leave behind extremely high density, neutron-rich stars.

**1939:** Oppenheimer & Volkoff publish a theory of these “neutron stars” held up by neutron degeneracy pressure

# Theory: Physics of NS formation

How do the forces of pressure and gravity maintain equilibrium?

$P = F/A$ "$P_{grav}$" $= F_{grav}/4\pi R^2$ $P_{net} = -P_{grav} + P_{internal} = 0$

**Fusing Stars:** thermal + radiation pressure

**Post-Fusion:** non-rel. (electron) degeneracy pressure [White Dwarf (WD), $v_e \ll c$]

↓

relativistic (electron) degeneracy pressure [$v_e \rightarrow c$, WD limit: $M \lesssim M_{Chandrasekhar} =$ 1.4M_sun]

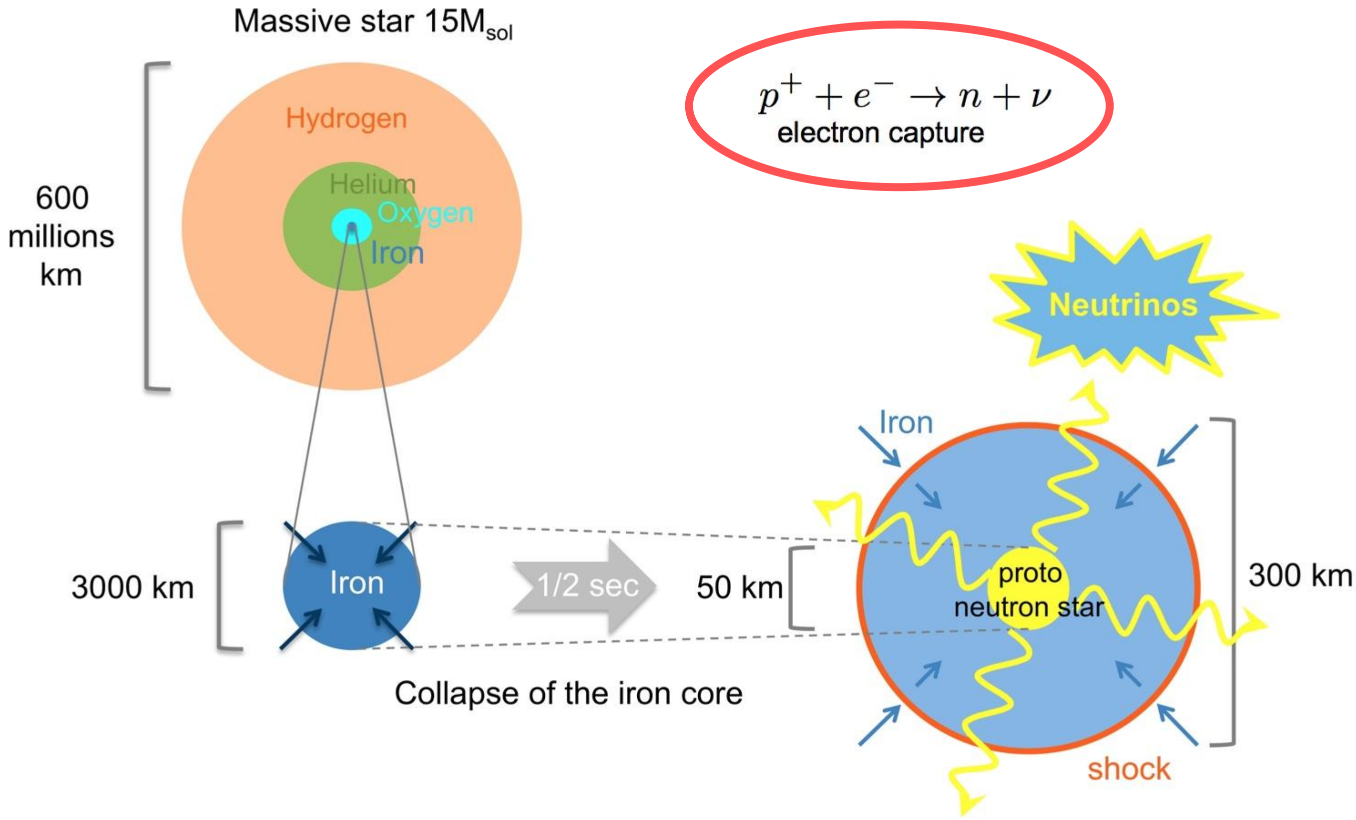
↓

neutron degeneracy pressure [Neutron Star (NS), $v_n$ still $\ll c$]

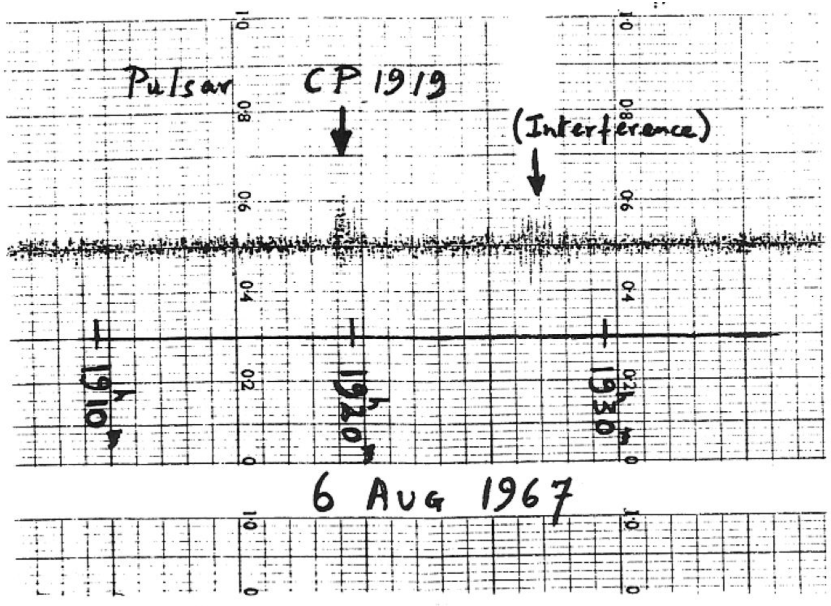
↓

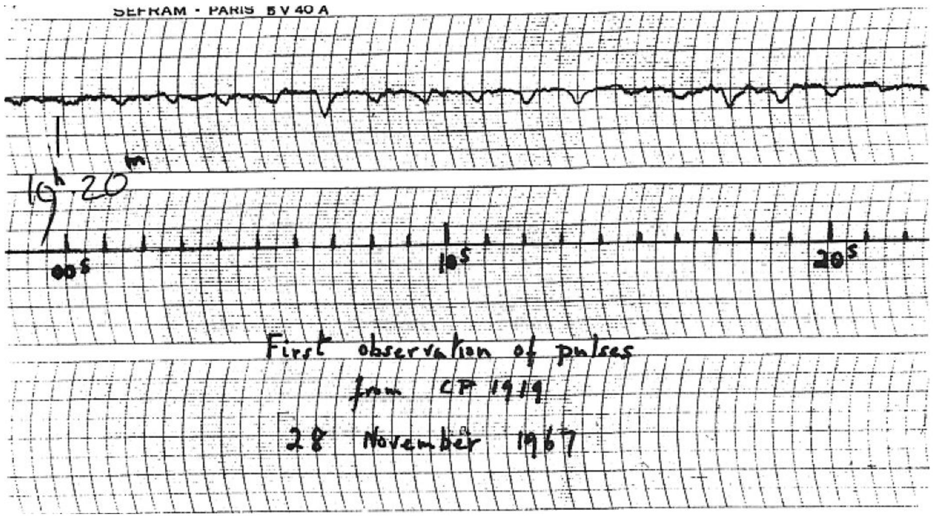
no pressure can support the mass! [ Black Hole (BH), criteria: $R < 2GM/c^2$]

# Theory: Physics of NS formation



# 1967: Jocelyn Bell sees “a little bit of scruff”




(pulsing every 1.377s)

# 1967: What Did We Know About The “Pulsar”?

- Relatively small, as constrained by light-crossing time:

  R ≤ pulse duration * c ~ 5000km

<u>In this range:</u>

- Planets
- White Dwarves
- Neutron Stars
- Black Holes
- Spaceships?

- Parallax angle very small

Non-local (outside our solar system)

- The period was incredibly precise (pulse separation consistent to 1 part in $10^8$!)

<u>Mechanisms for precise periodicity:</u>

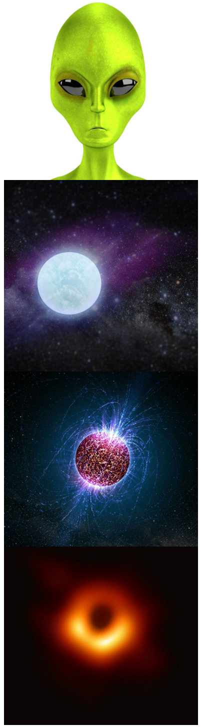
- Pulsation/vibration
- Rotation
- Binary orbit
- Intelligence?

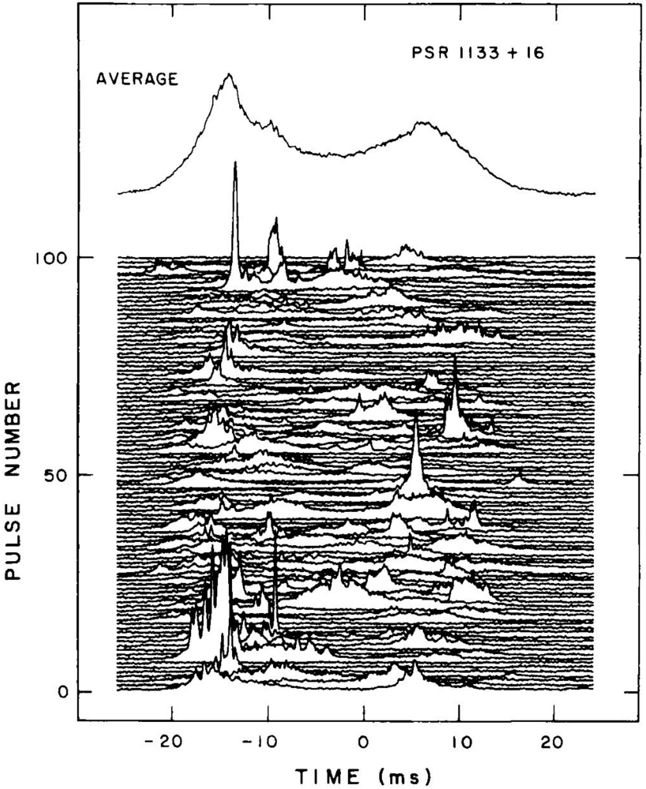
# How Did We Know It Was a Neutron Star?

We didn't!

Contenders:

- Aliens! (LGM-1)
- White Dwarves
- Neutron Stars
- Black Hole





# What We Learned in the Following Year:

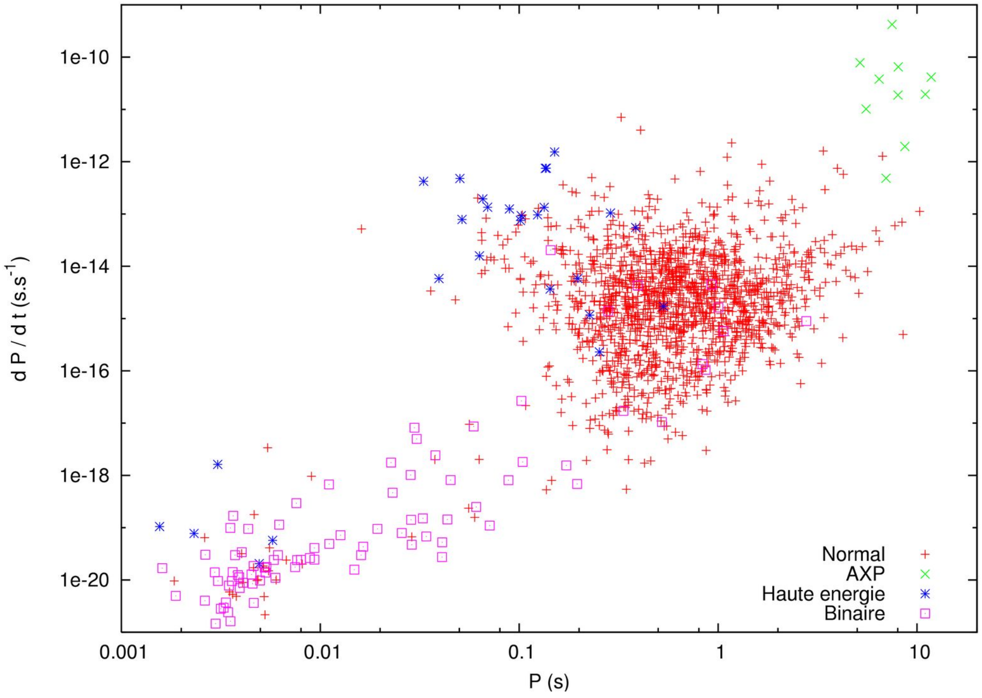
Found at least a dozen more with:

- Pulse durations of 10 - 35ms
- Pulse periods of 33ms - 1.4s

They don't seem to exhibit doppler-shifts

The pulses slow down over time:

The pulse period tends to increase at a rate of P/(dP/dt) ~ $10^7$ yrs on average



# How Did We Know It Was a Neutron Star?

We didn’t!

Contenders:

- Aliens! (LGM-1)
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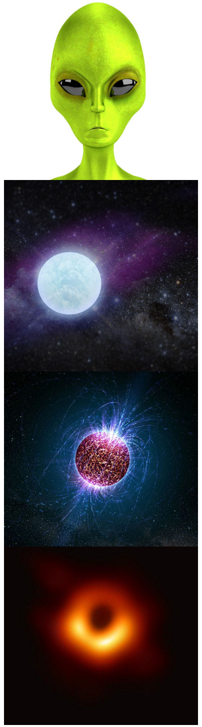
- Black Hole



<u>Found at least a dozen more with:</u>

- Pulse durations of 10 - 35ms
- Pulse periods of 33ms - 1.4s

<u>They don’t seem to exhibit doppler-shifts</u>

<u>The pulses slow down over time:</u>

The pulse period tends to increase at a rate of $P/(dP/dt) \sim 10^7$ yrs on average

# How Did We Know It Was a Neutron Star?

We didn't!

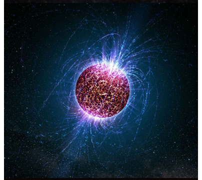
Contenders:

- Aliens! (LGM-1)

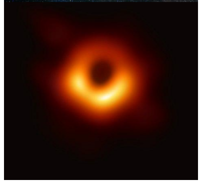
Too many sources in too many places, no doppler shift!

- White Dwarves

- Neutron Stars

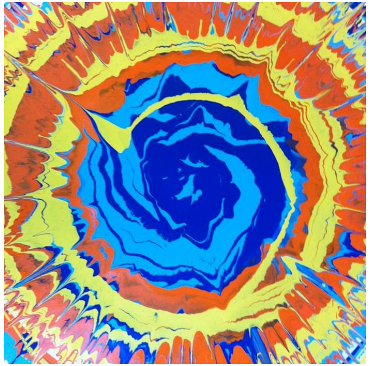


- Black Hole



Orbits stay usually *speed up* & accretion is *messy*

# How Did We Know It Was a Neutron Star?: NS vs WD



Rotating: limited by the “mass-shedding”/“splatter” limit

$F_c < F_g \;\rightarrow\; \Omega^2 R < GM/R^2$

$\rightarrow\; (2\pi/P)^2 < GM/R^3$

...

$P_{\text{splatter, WD}} \sim 2\pi^*(GM_{WD}/R_{WD}{}^3)^{-½} \sim 1\text{s}$

$P_{\text{splatter, NS}} \sim 2\pi^*(GM_{NS}/R_{NS}{}^3)^{-½} \sim 1\text{ms}$

Pulsing: should include the fundamental frequency

$P_{\text{fund, WD}} \sim (G\rho_{WD})^{-½} \sim 2\text{s}$

$P_{\text{fund, NS}} \sim (G\rho_{NS})^{-½} \sim 1\text{ms}$

# History: Timeline & Credit

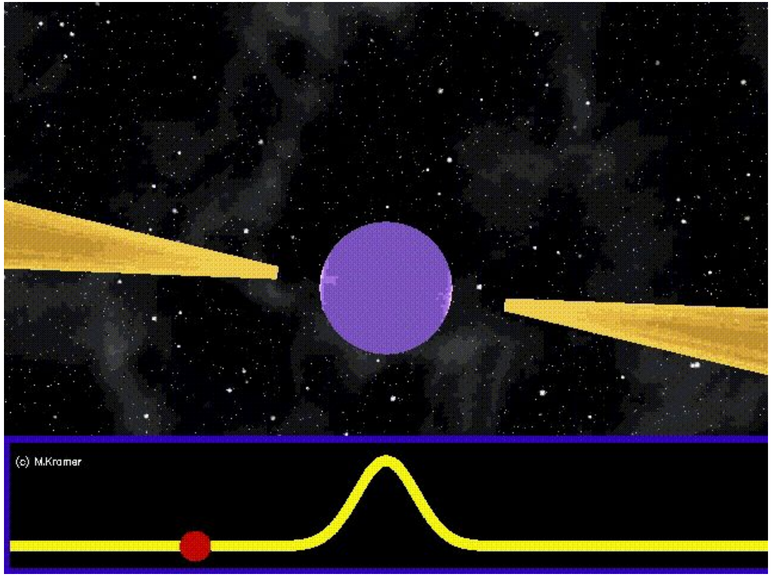
**1967:** A radio source at 81.5MHz repeating every 1.377s is discovered by grad student Jocelyn Bell under supervision of advisor Antony Hewish

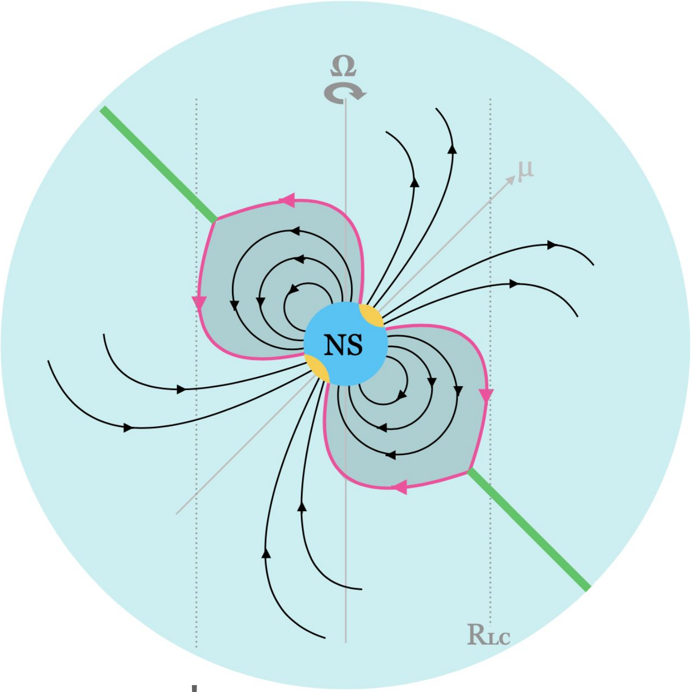
**May 1968:** Thomas Gold publishes paper summarizing arguments in favor of pulsars being neutron stars

**1974:** Bell's advisor and his colleague receive Nobel Prize for the discovery of pulsars

**2018:** Bell receives special breakthrough prize in fundamental physics for the discovery of pulsars and uses prize to create fund for underrepresented graduate students in physics

# Wait, How is the Light Generated?



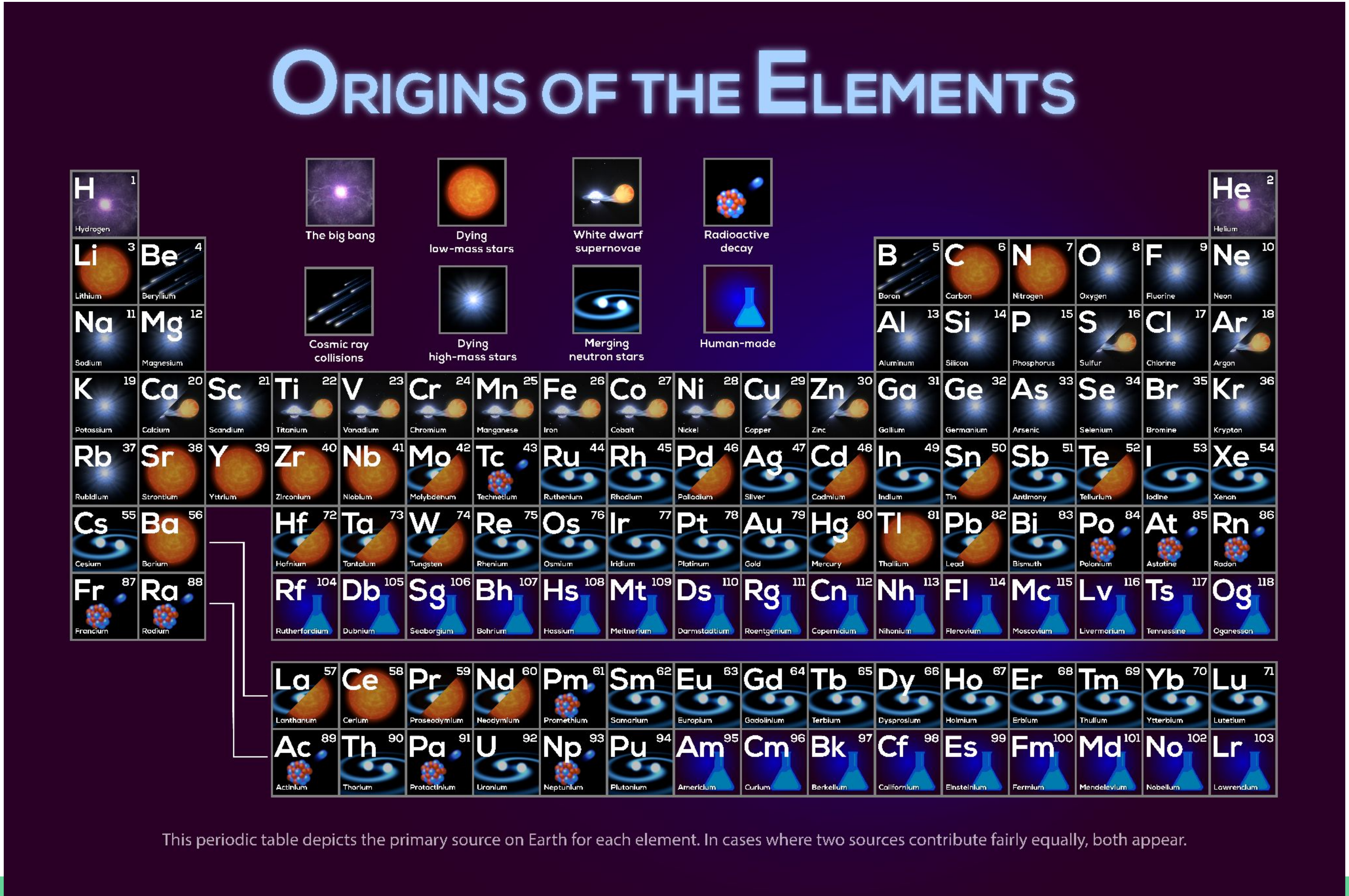

Complicated Magnetic Field-Related Phenomena!

# What’s New (& Exciting)?

# 60 years later:

- There are at least 3000 pulsars, 30 “magnetars”, and 6 magnetar-pulsars!
    - with average masses of roughly 1.4-1.5 M_sun
    - with most massive to date at 2.35 $\mp$ 0.17 M_sun
- They emit over the entire EM spectrum!
- They can spin-*up* (speed up) too, due to:
    - Accretion
    - Mergers
    - “Glitches” (?)
- Their mergers create gravitational waves! (see: GW170817)

# Neutron Star Mergers are Necessary to Life! (& nice things)



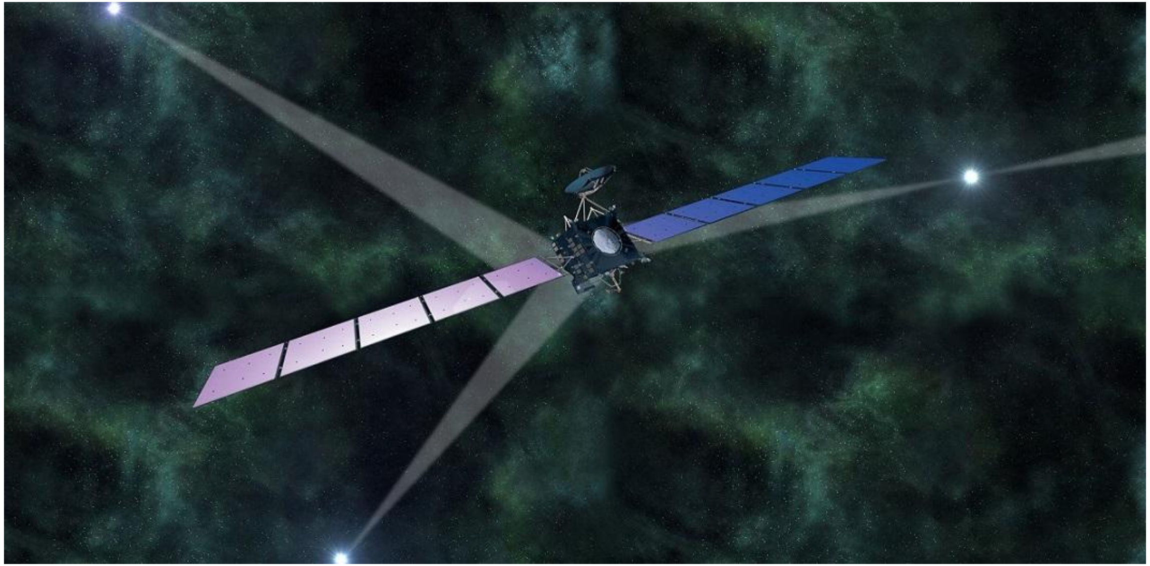
# Neutron Stars are the Future of Space Technology!

Remember when I said the pulses were incredibly precise?

NS are some of the best clocks in the universe—and they only get more precise as we get better at predicting them.

# Neutron Stars are the Future of Space Technology!

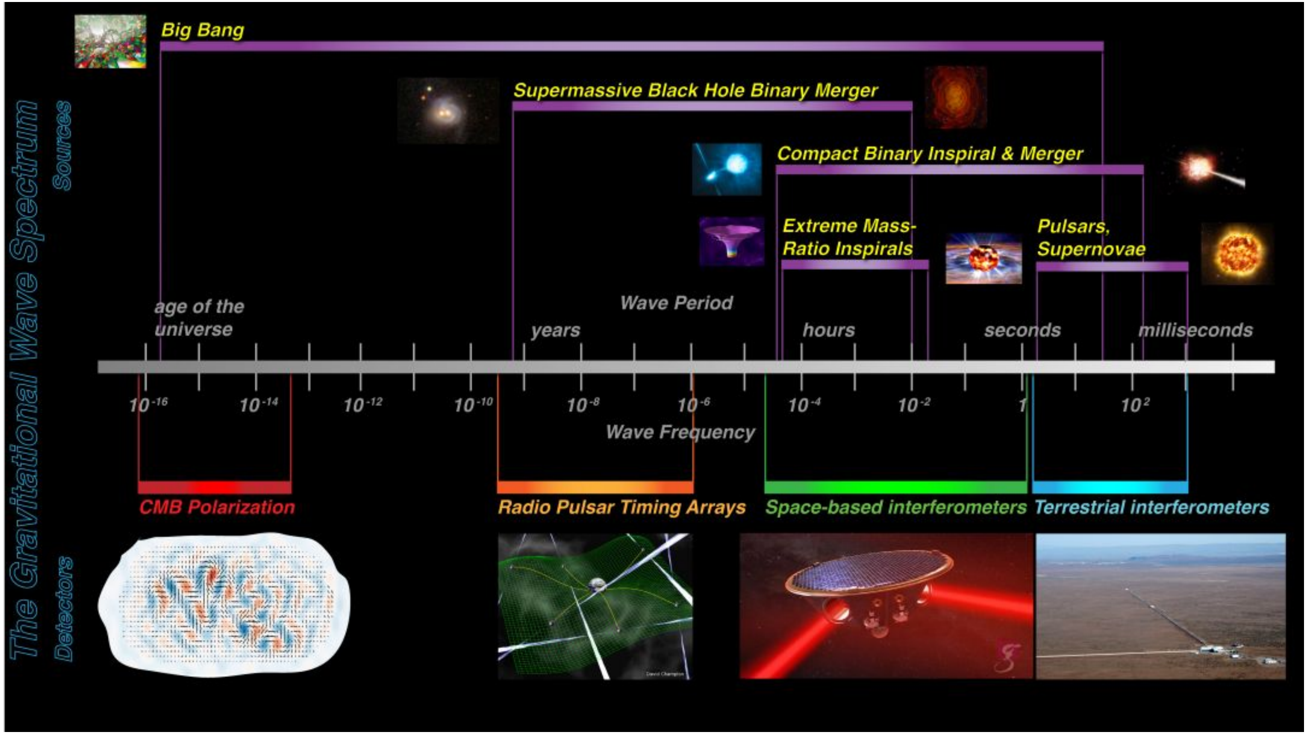
NASA is developing technology to utilize X-ray millisecond pulsar signals for deep-space clock calibration and navigation beyond the reach of earth-bound satellites and radio communications.



Fun fact: the rubidium clocks aboard GPS satellites need to be recalibrated by signals from Earth TWICE A DAY

# Neutron Stars are the Future of Space Technology!

Pulsar Timing Arrays use radio pulsar-to-Earth signals as arms in a giant, low-frequency gravitational wave detector.



# Neutron Stars Contain the Mysteries of Ultra-Dense Matter!

**Post-Fusion:** non-rel. (electron) degeneracy pressure [White Dwarf (WD), $v_e$ << c]

relativistic (electron) degeneracy pressure [$v_e$ ~ c, WD limit: $M \lesssim M_{Chandrasekhar}$ = 1.4M_sun]

neutron degeneracy pressure [Neutron Star (NS), $v_n$ still << c]

[????????]

no pressure can support the mass! [ Black Hole (BH), criteria: $R < 2GM/c^2$]

# Neutron Stars Contain the Mysteries of Ultra-Dense Matter!

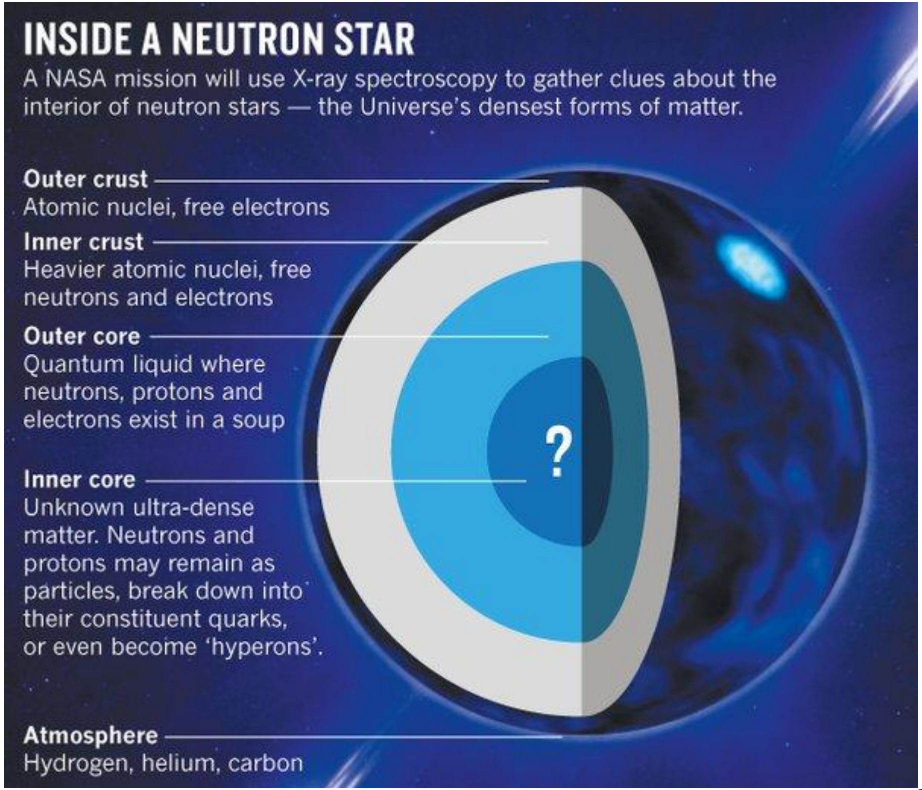
Yet-to-be determined equation(s) of state govern the dense cores of NS.

Labs on Earth can’t recreate matter at this density and temperature.

The theoretical predictions from quantum chromodynamics (QCD) are too difficult to calculate it from first principles.

-BUT-

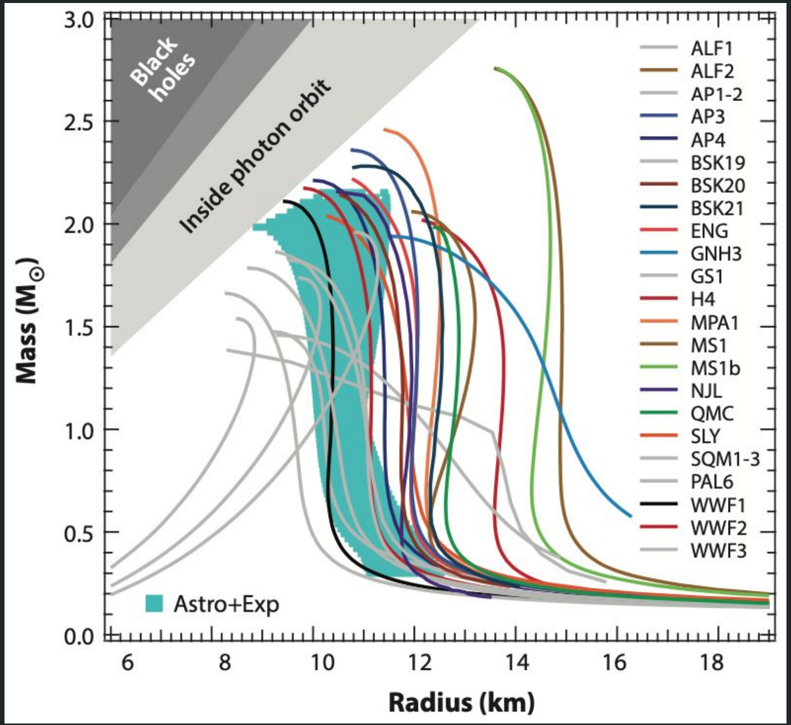
We can learn about the equation of state in NS cores by measuring the relationship between their mass and radius…



# ICA 20: The NS Equation of State

# M vs R

In more detail

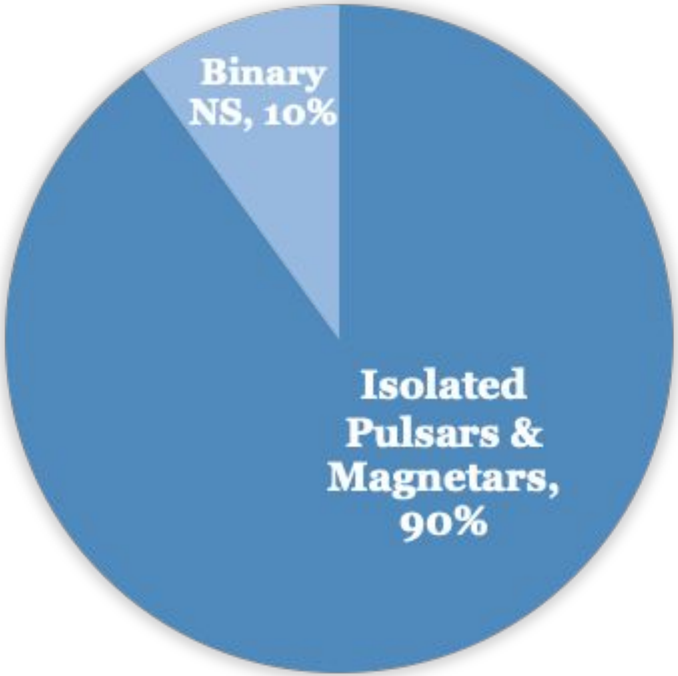



Özel & Freire, 2016 (Annual Reviews)

# Why It's Not Easy to Measure M/R

Ways to observe Neutron Stars:

- Electromagnetic emissions
- Binary companion behavior
- Gravitational Wave events

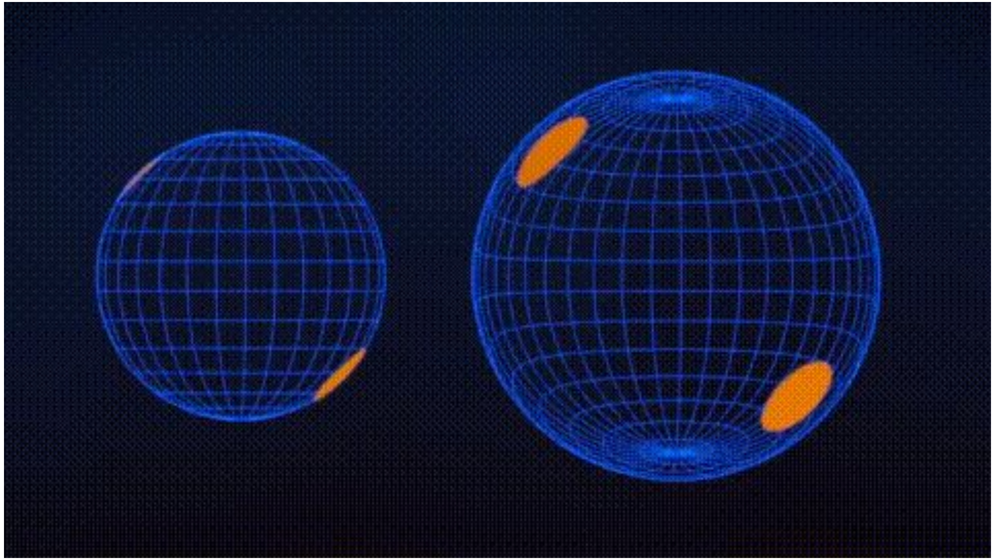


# Why It’s Not Easy to Measure M/R

X-ray emission regions for a dipole magnetic field:

Without GR lensing

Shape due solely to magnetic field



NICER

With GR lensing

Shaped by magnetic field + GR distortion

We need to know likely magnetic field structures to disentangle effects of magnetic topology vs. neutron star spacetime & measure M/R!

# Why It's Not Easy to Measure M/R

Two attempts at reconstructing the X-ray emission regions of PSR J0030-0451: