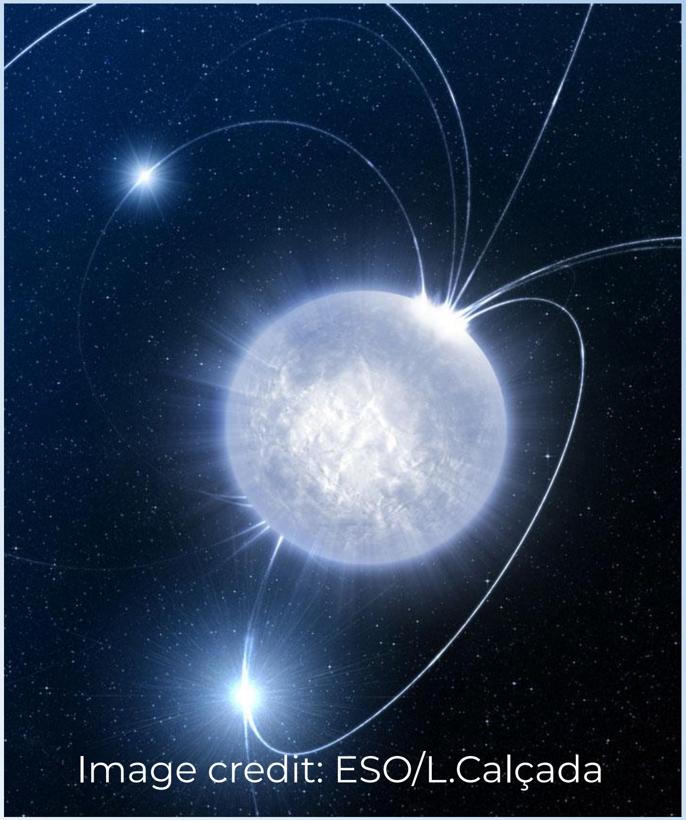
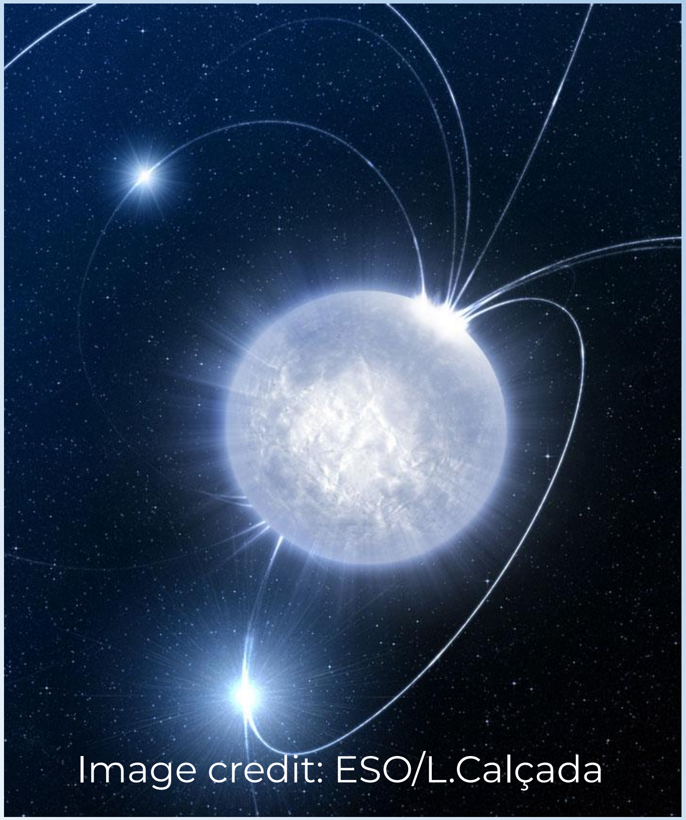


Stellar Death Part II -- Neutron Stars

CRAQ Summer School

June 14, 2019

Dr Vanessa Graber



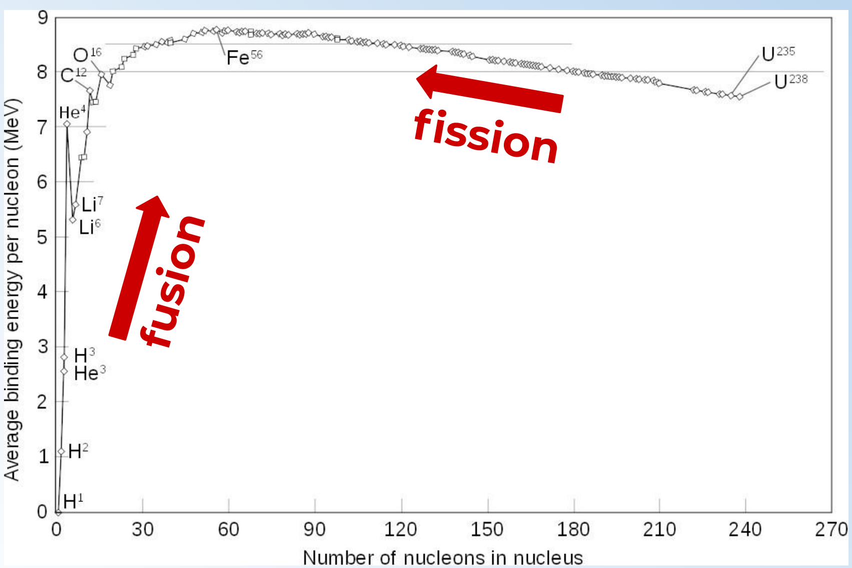
1. Formation

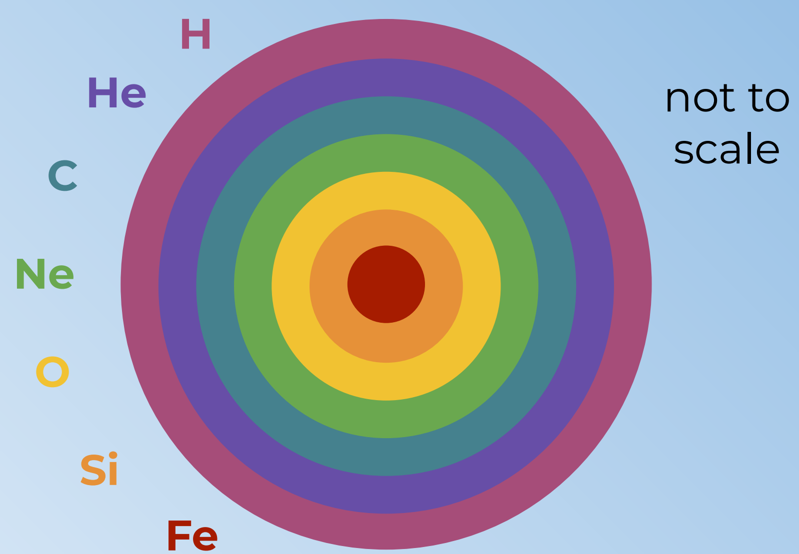
1. Formation - Progenitors

- Progenitors of NSs are **massive stars** with 8 - 20 $M_\odot$. As they move from the main sequence, **hydrogen** fuses into **helium**, which burns into **carbon**.

- For stars with $M < 8M_\odot$, the fusion process halts at this stage and stars cool down to form white dwarfs. Above this limit, temperatures and pressures are high enough to **ignite carbon**.

- Massive stars undergo subsequent burning stages and become **layered like onions** fusing increasingly higher mass elements. Chain halts at iron (no more net energy gain by fusion), leaving behind an **iron-nickel core**.





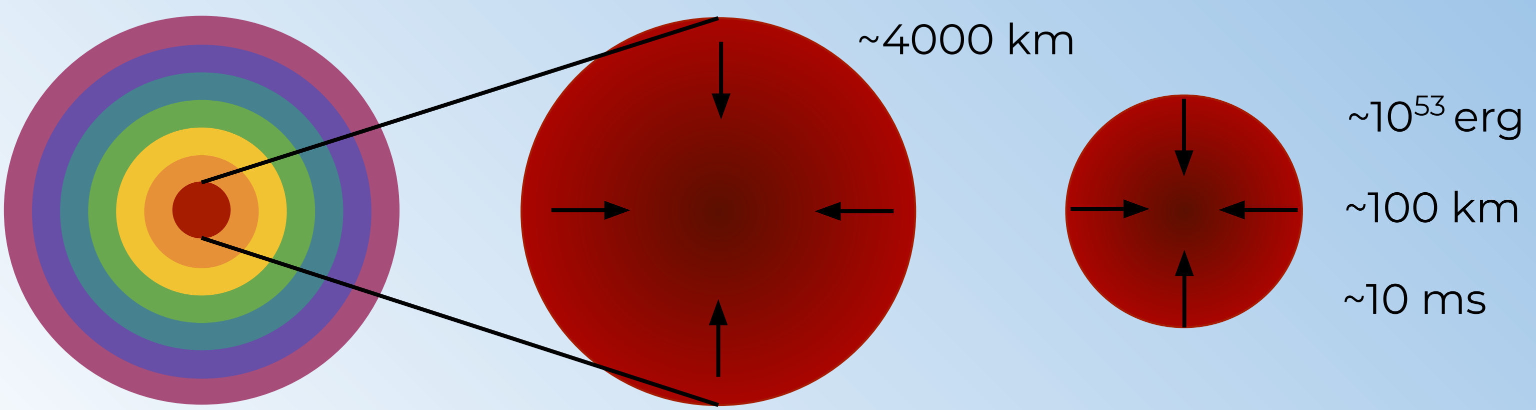
1. Formation - Core Collapse SN I

- The iron-nickel core experiences **extreme gravitational pressure** and is only supported by the **electron degeneracy pressure**.

- As outer layers continue to burn, the mass of the iron-nickel core grows. Once the **Chandrasekhar mass** of 1.4 $M_\odot$ is reached, electron degeneracy pressure is no longer sufficient and **gravitational collapses** is initiated.

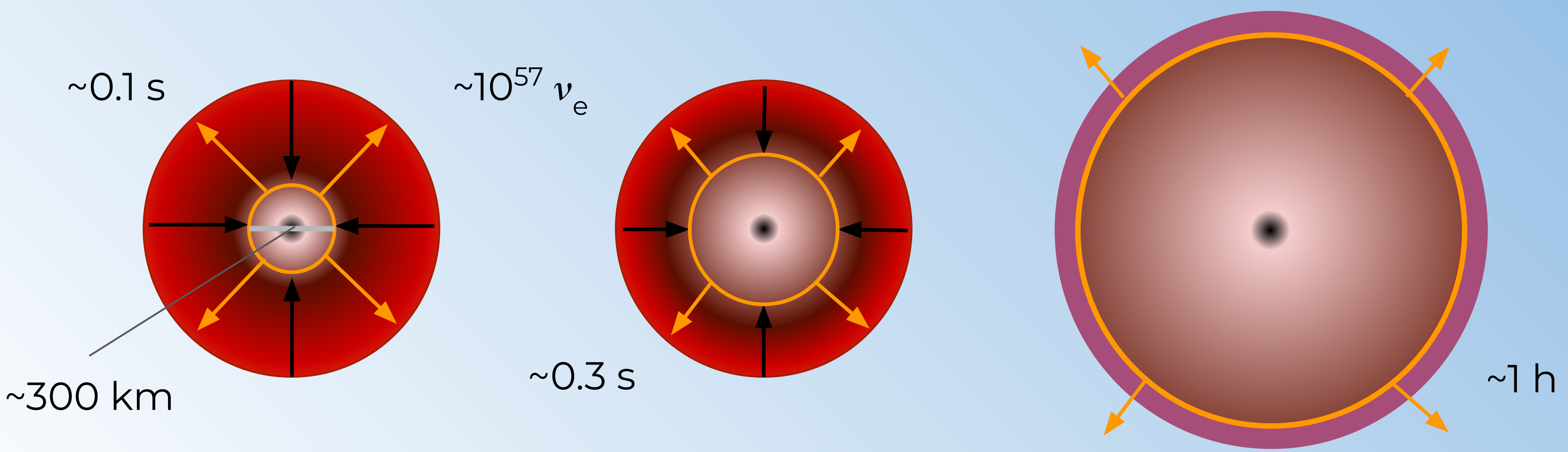
- Outer core layers fall inwards at ~25% the speed of light. This increases the temperature and generates gamma rays that split the iron nuclei into helium and free neutrons (**photodisintegration**).

- As the density in the inner core increases, **electron captures** take place: $p + e^- \longrightarrow n + \nu_e$. Neutrinos take away energy, accelerating the collapse.



1. Formation - Core Collapse SN II

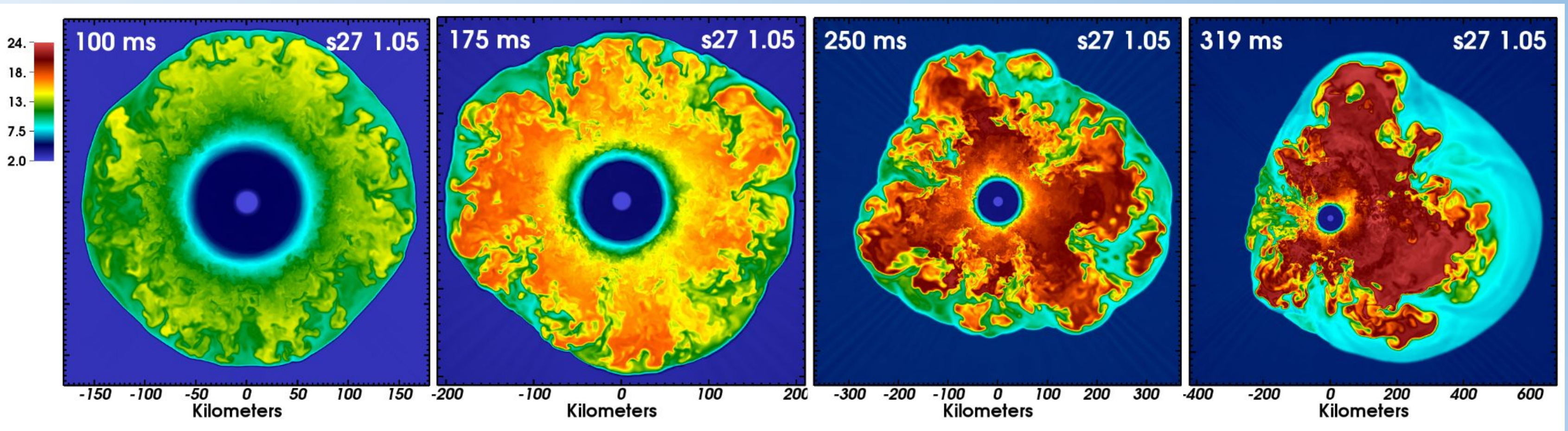
- At nuclear densities, collapse is eventually **halted** by the neutron-neutron repulsion and their degeneracy pressure. Infalling matter **bounces off** and forms an outward propagating **shock front**.
- This shock wave interacts with the heavy nuclei, causing it to lose energy and **stall**. The stalled shock is **revived** because of the **neutrinos** generated in the inner core (1% required). It is not clear how this exactly works (!).
- The revived shock front hits the outer layers and blast away material, which we observe as a **supernova**. Left behind is a **tiny compact object**.



1. Formation - Simulations

- In reality, the problem is much more **complex** and requires
  - 3D magnetohydrodynamics
    - rotation, magnetic fields, convection, instabilities
  - General relativity (GW emission)
  - Neutrino transport
  - Realistic microphysics
    - dense-matter equation of state, neutrino interactions
  - Main problem: reviving the shock

- Such simulations are very (!) **computationally expensive** and **complicated.**



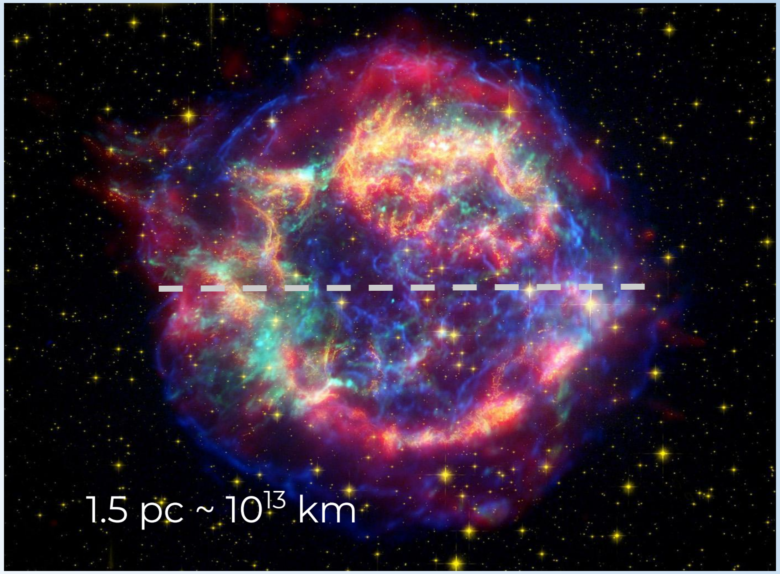
Couch and O'Connor (2014)

1. Formation - Observations

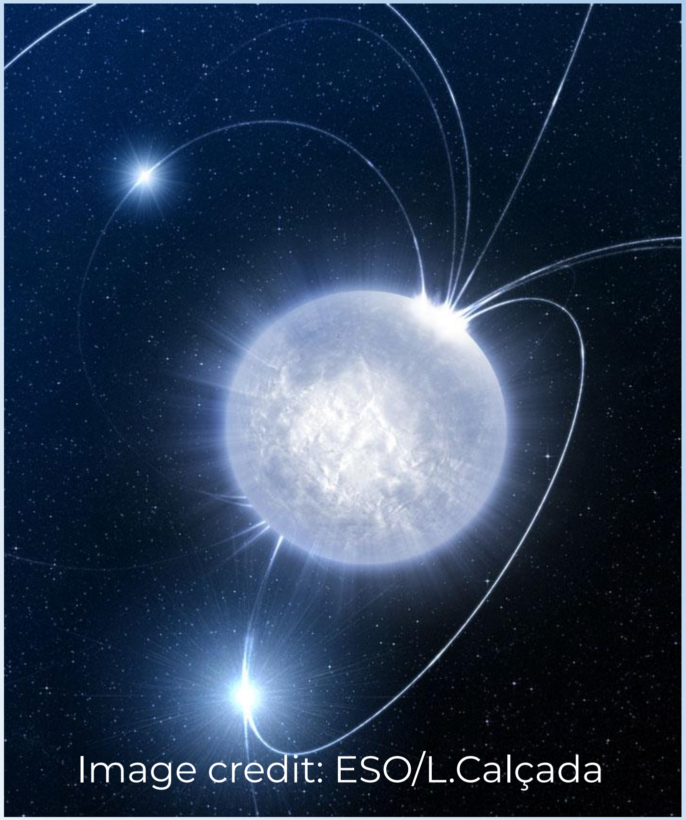
- Supernovae are the most energetic events in the Universe, releasing about **10^{51} erg**. For comparison, a hydrogen bomb releases about 10^{24} erg.
- Stars become about **8 orders of magnitude** brighter and are visible for months afterwards.
- We also observe **supernova remnants**, large-scale structures created by material ejected during the explosion and the interstellar medium accumulated by the shock.

Cas A
SN ~1670,

Image credit: NASA, JPL-Caltech, STScI, CXC, SAO



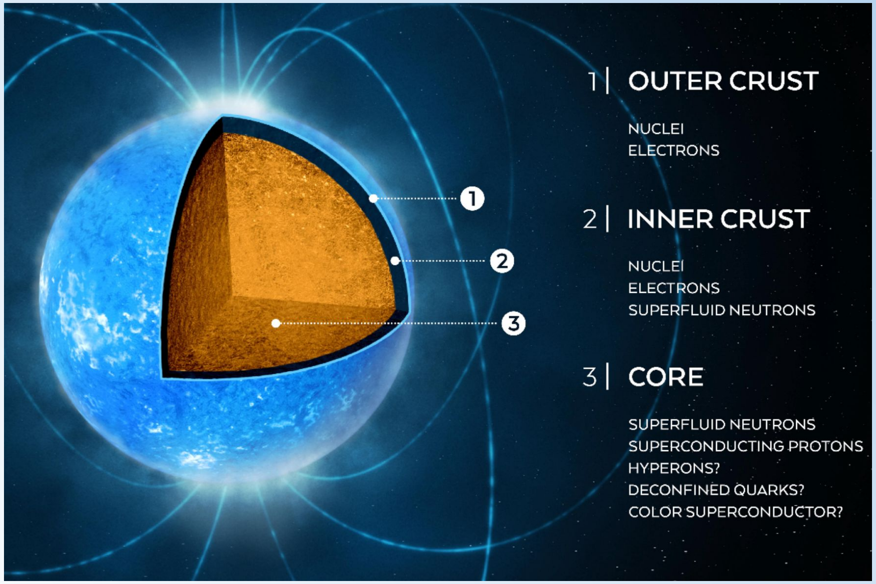
SN1987a, Image credit: ESO



2. Interiors

2. Interiors - Structure

- During the collapse, matter is compressed so much that repulsive forces between the protons and electrons are overcome and **neutrons** created. NSs contain about 95% neutrons, hence the name.



Watts et al. (2016)

- Compact remnants have **radii** of the order of **~10 km** and **masses** of **~ 1.4 - 2 $M_\odot$**. This gives **mass densities** of up to 10^{15} g/cm^3, exceeding those of atomic nuclei.
- We do not (!) know how matter behaves at these ultra-high densities. The **equation of state** of dense nuclear matter is **unknown**, but there is a **canonical under-standing** of the NS structure.

2. Interiors - TOV Equation

- A simple model of NSs can be obtained by assuming that the star is a spherically symmetric body of isotropic material, which is in **static gravitational equilibrium** and correctly described by General Relativity.

- Such an object can be described by the **metric** (line element)

$$ds^2 = e^{\nu} c^2\, dt^2 - \left(1 - \frac{2Gm}{rc^2}\right)^{-1} dr^2 - r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$$

where $\nu=\nu(r)$ and m=m(r) is the **gravitational mass** within a radius r.

- Solving Einstein's equation for this metric leads to the **Tolman-Oppenheimer-Volkoff** (TOV) equation

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho\left(1 + \frac{P}{\rho c^2}\right)\left(1 + \frac{4\pi r^3 P}{mc^2}\right)\left(1 - \frac{2Gm}{rc^2}\right)^{-1}$$

with density ρ and pressure P. The **continuity equation** provides

$$\frac{dm}{dr} = 4\pi r^2 \rho \qquad M = m(R) = \int_0^R 4\pi r^2 \rho\, dr$$

2. Interiors - Maximum Mass

- In the **Newtonian limit**, we would recover the standard equations that describe a spherical object in hydrostatic equilibrium.

- In general, to solve the TOV equation, we require an **equation of state**, a relation that connects **pressure** and **density**, $P=P(\rho)$, but an analytical solution is possible for an incompressible star with constant density $\rho=\rho_c$.

- In this case, the **mass function** is $m(r)=4\pi r^3\rho/3$ for $r\leq R$. **Integration** gives

$$P(r) = \rho_c c^2 \frac{\sqrt{1 - 2GM/c^2 R} - \sqrt{1 - 2GMr^2/c^2 R^3}}{\sqrt{1 - 2GMr^2/c^2 R^3} - 3\sqrt{1 - 2GM/c^2 R}}$$

- Physical solutions require a **finite pressure** P at the centre r=0

$$1 = 3\sqrt{1 - 2GM/c^2 R}, \qquad \rightarrow \qquad R > \frac{9GM}{4c^2}$$

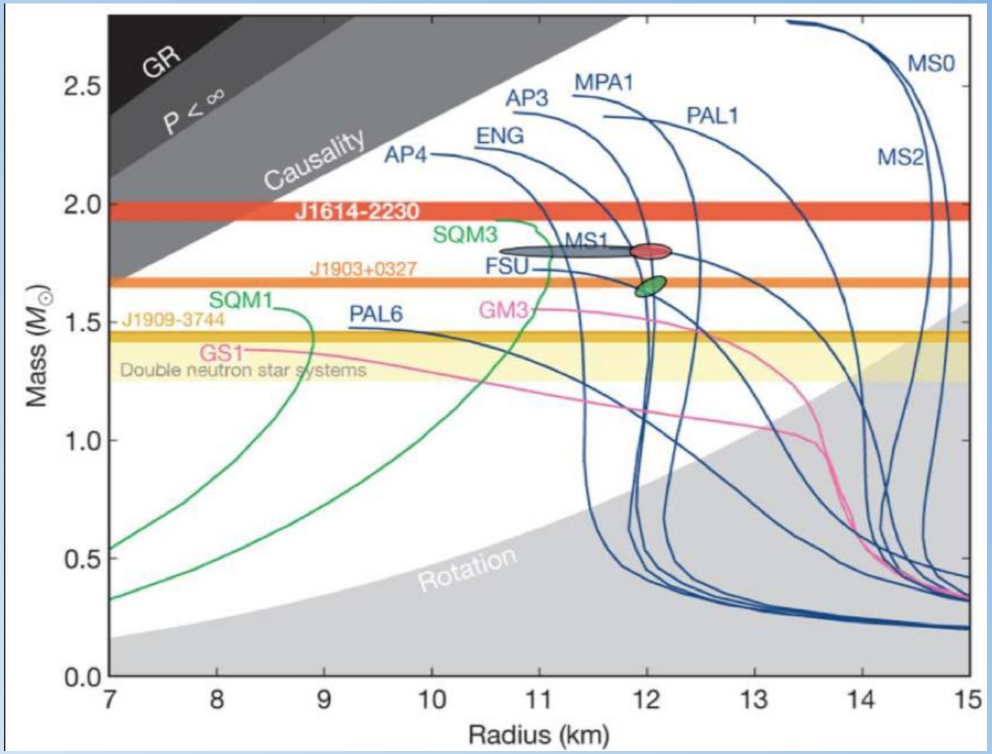
which results in a maximum mass (for $\rho_c=5\times10^{14}$ g/cm^3)

$$M < M_{max} \equiv \sqrt{\frac{1}{3\pi G\rho_c}} \frac{4c^3}{9G} \approx 5M_{\odot}$$

2. Interiors - M/R Relations

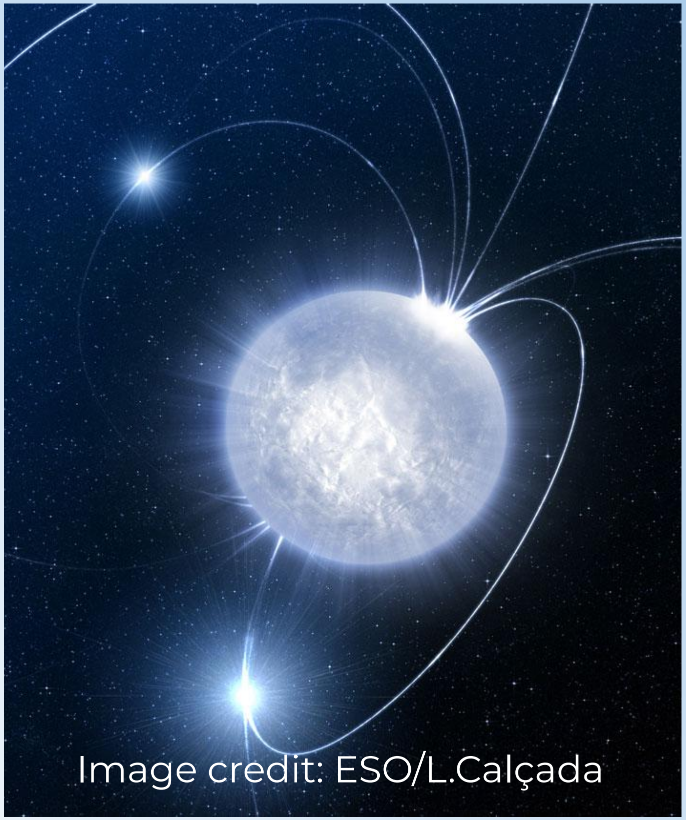
- The maximum mass above which NSs become unstable is **not unique**, but depends on the equation of state. This is often illustrated as

- Equations of state are typically classified as
  - **Soft:** matter is more compressible and allows for larger central densities and subsequently smaller radii and maximum masses
  - **Stiff:** smaller central densities with larger radii and maximum masses



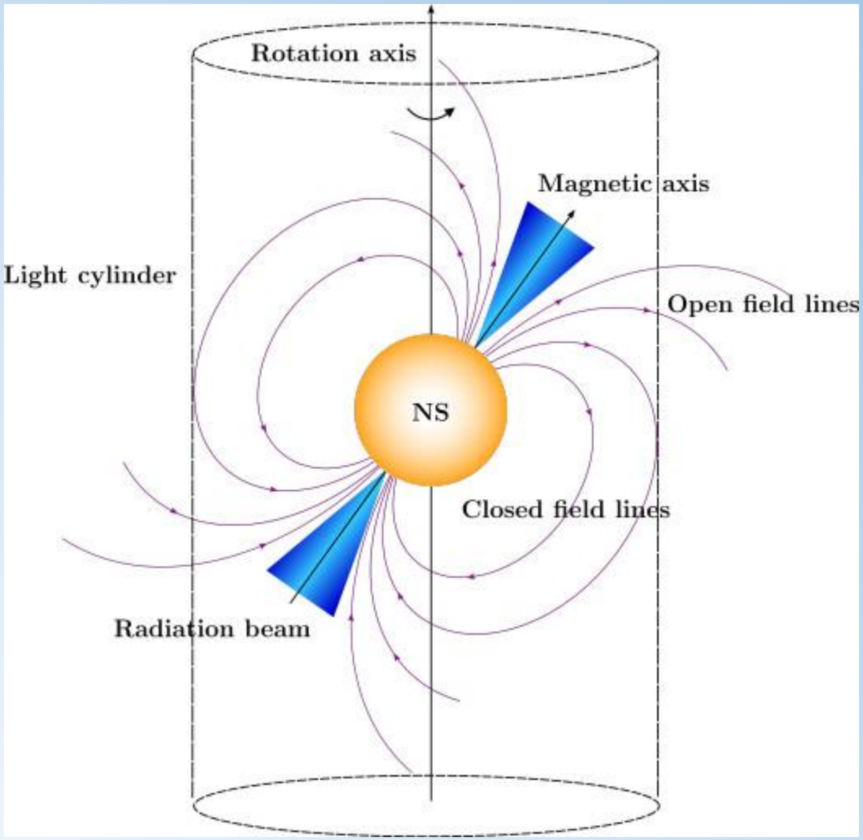
Demorest et al. (2010)

- **Observations** of neutron star masses can put **stringent limits** on theoretical equations of state calculations.



3. Pulsars

3. Pulsars - Rotation and Fields



- NSs also have incredibly **high magnetic fields** in the range of 10^8 - 10^{15} G. For comparison, the Earth's field is about 0.5 G.
- NSs are also very **fast** and stable **rotators** (up to ~700 times per second).
- As rotation and magnetic field axes are misaligned, NSs emit pulses similar to a **lighthouse**.

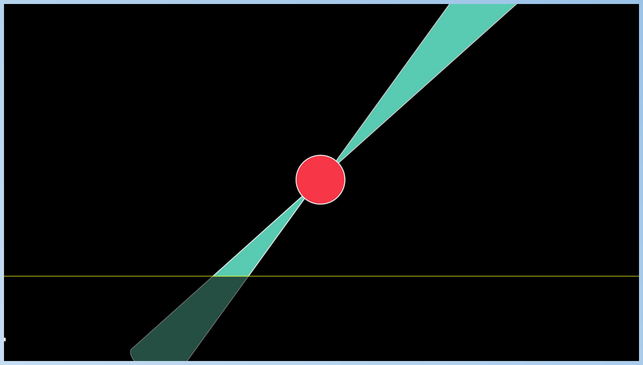
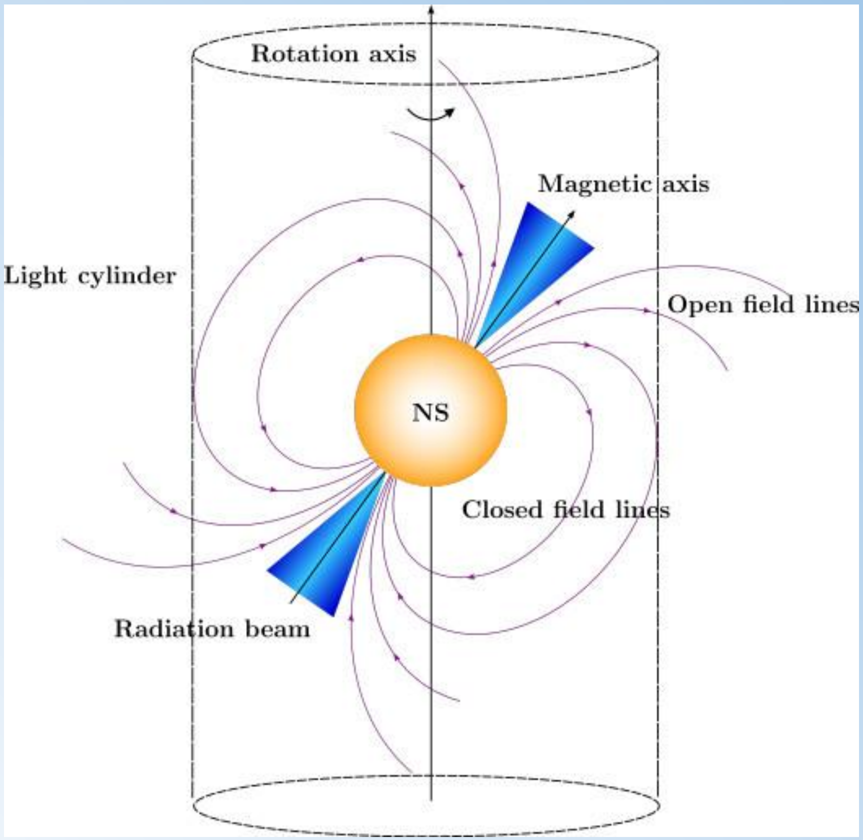


Image credit: J. Christiansen

3. Pulsars - Rotation and Fields



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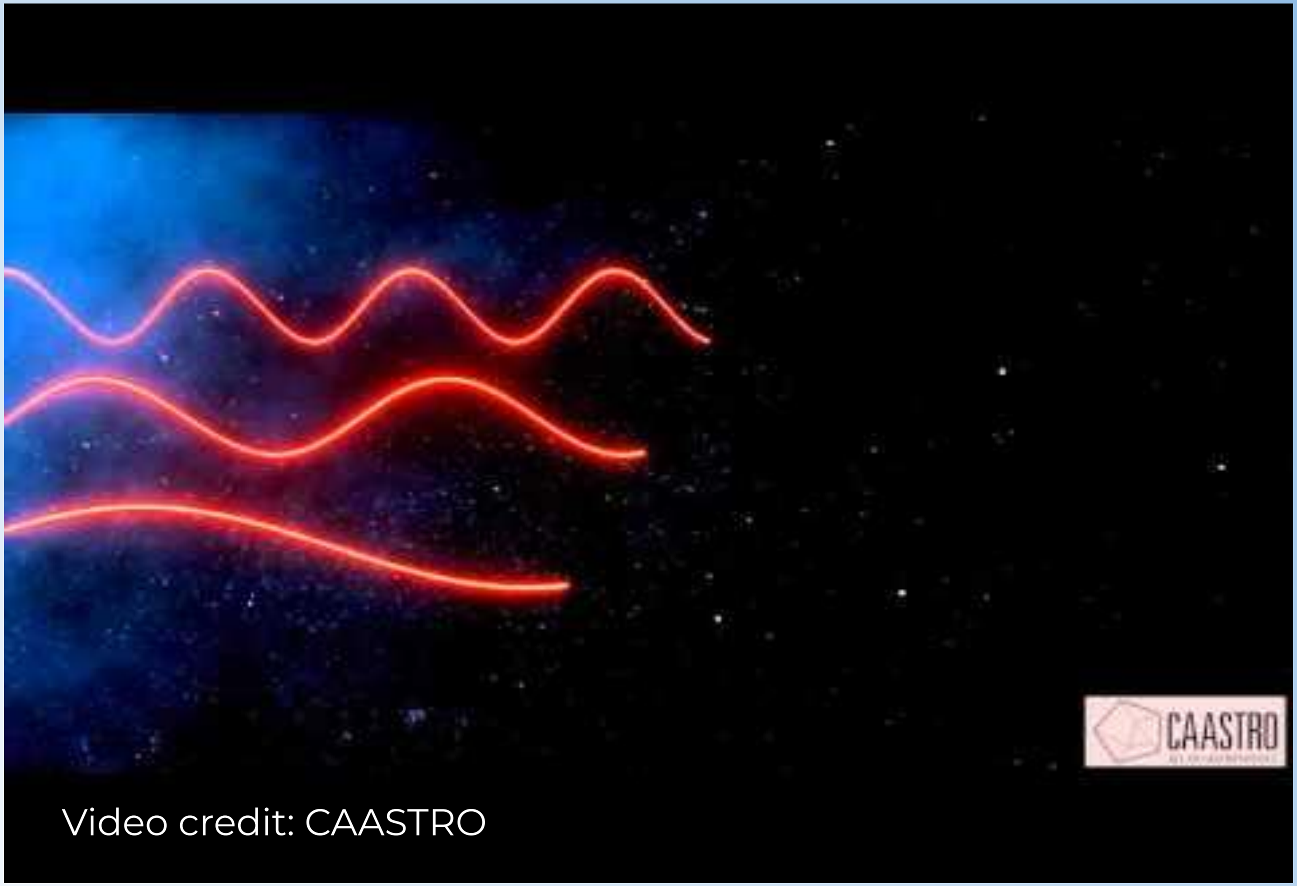
- Pulses are observable with **radio** telescopes on Earth. First detection of a **pulsar** by **Jocelyn Bell Burnell** in 1967, over 30 years after their existence was first predicted.

3. Pulsars - Dispersion

- As the electromagnetic radiation propagates from the pulsar towards the Earth, the waves interact with electrons in the interstellar medium. This causes **dispersion:** lower frequencies are delayed w.r.t. higher frequencies.



Video credit: CAASTRO

3. Pulsars - Dispersion Measure

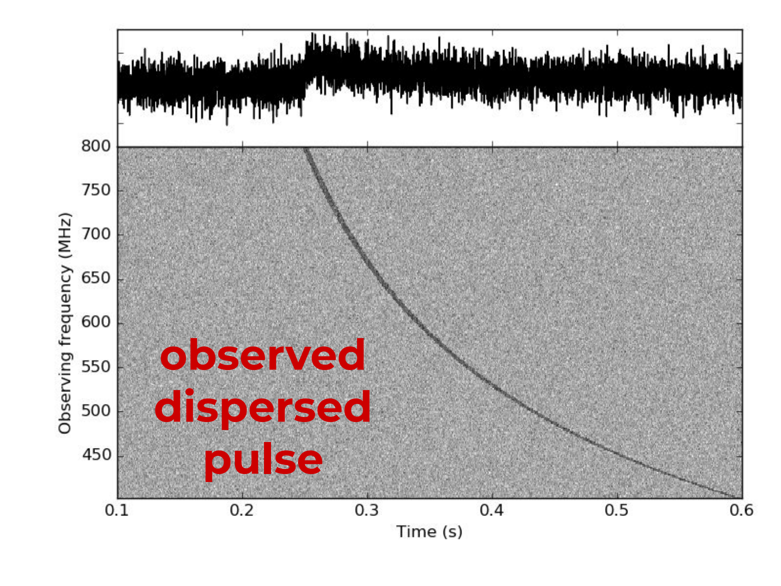
- Dispersion causes a characteristic **frequency dependence** and the **delay** between two frequencies is given by

$$\Delta t = k_{\mathrm{DM}} \cdot \mathrm{DM} \cdot \left(\frac{1}{\nu_{\mathrm{lo}}^2} - \frac{1}{\nu_{\mathrm{hi}}^2} \right)$$

$$k_{\mathrm{DM}} = \frac{e^2}{2\pi m_e c} \simeq 4.149\,\mathrm{GHz}^2\,\mathrm{pc}^{-1}\,\mathrm{cm}^3\,\mathrm{ms}$$

- DM is the **dispersion measure** (integrated e^- density), measured in pc per cm^3

$$\mathrm{DM} = \int_0^d n_e \, dl$$



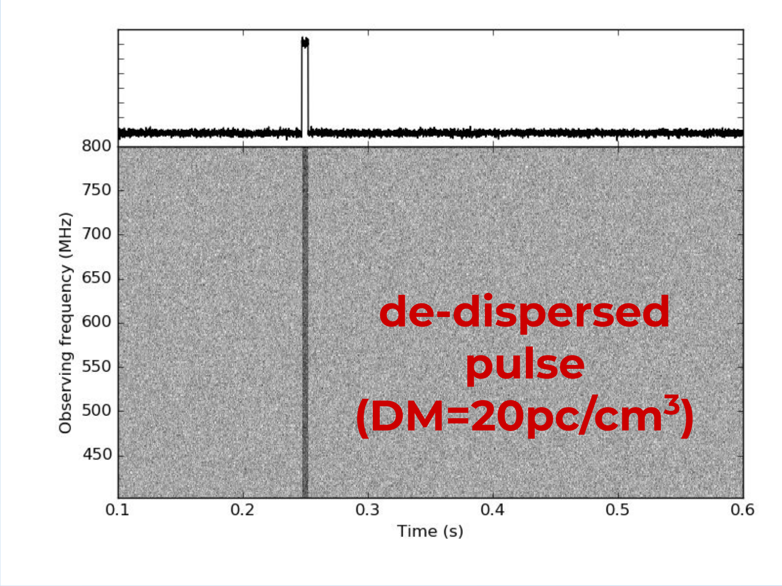
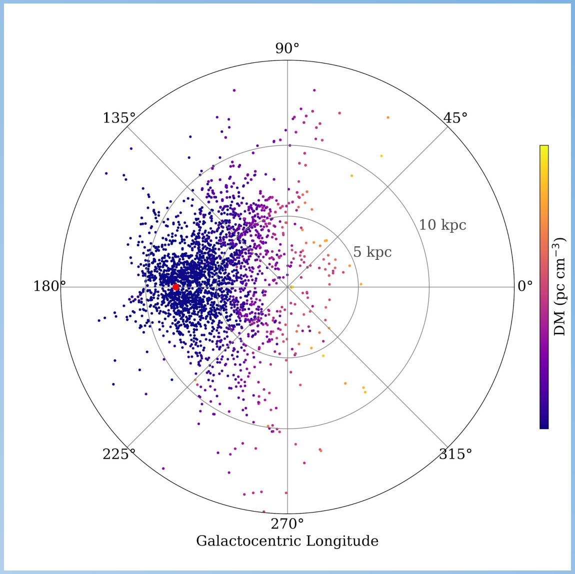
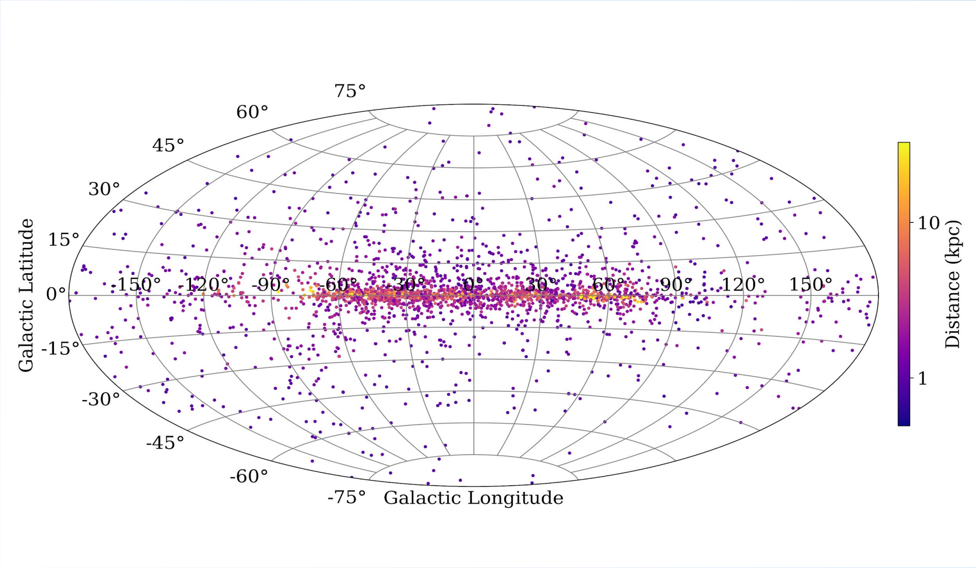


Image credit: E. Parent

3. Pulsars - Galactic distribution

- To date, we know of **~3,000 pulsars**.
- We can combine their measured DM values with theoretical **models** of the electron distribution in our galaxy to **estimate distances** to the pulsars.
- Important tool to test the distribution of the **interstellar medium**.





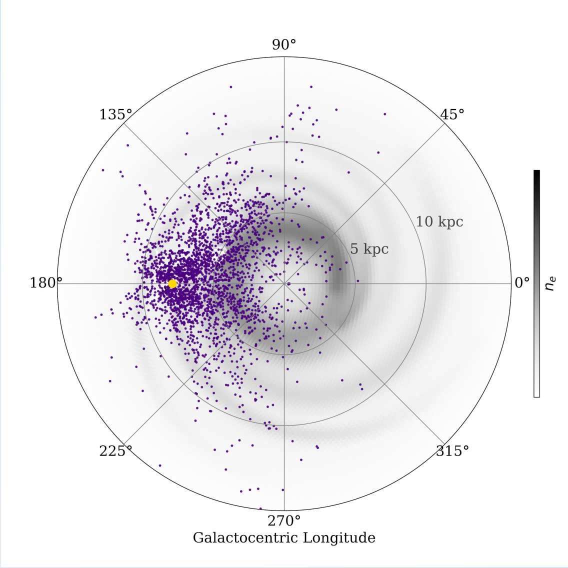


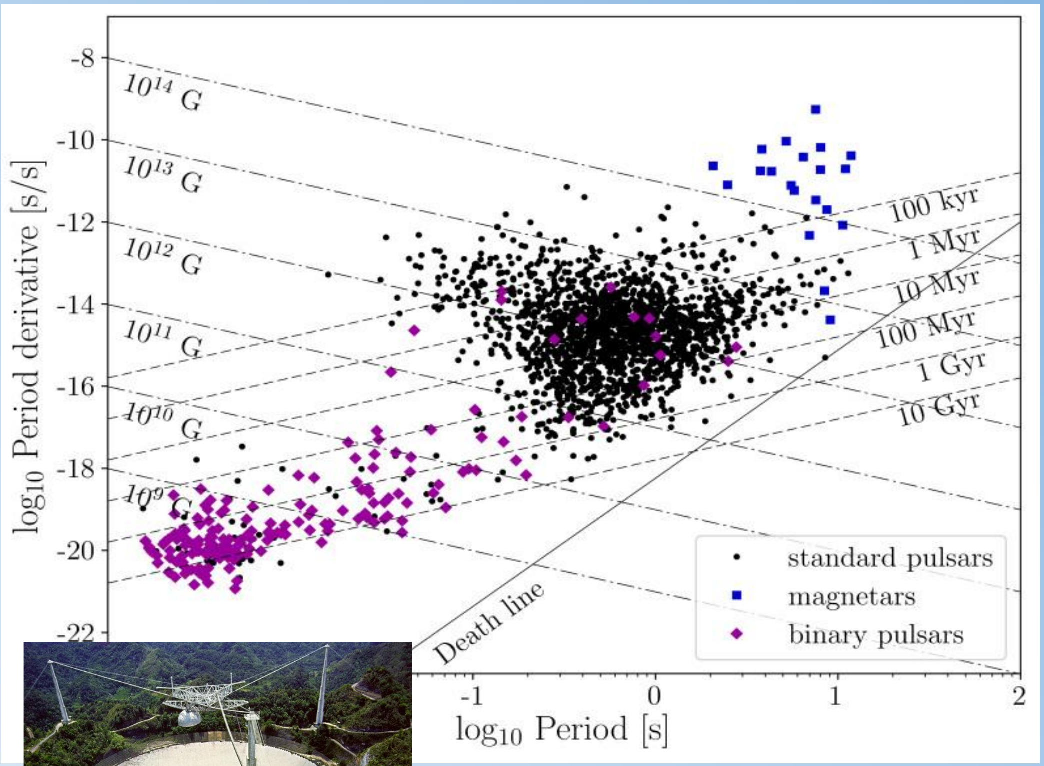
Image credit: E. Parent

3. Pulsars - P-Pdot Diagram

- Because pulsars are incredibly **stable rotators**, we can time them and not only measure **periods** but also **period derivatives** (for ~2,500 objects).
- Plot these in a P-Pdot diagram to study different **classes** of the pulsar population and their characteristics, e.g. ages and magnetic fields.
- We can estimate

$$\tau_c \sim 0.5\, P \dot{P}^{-1}$$

$$B \sim 3.2 \times 10^{19} (P\dot{P})^{1/2}\ \mathrm{G}$$

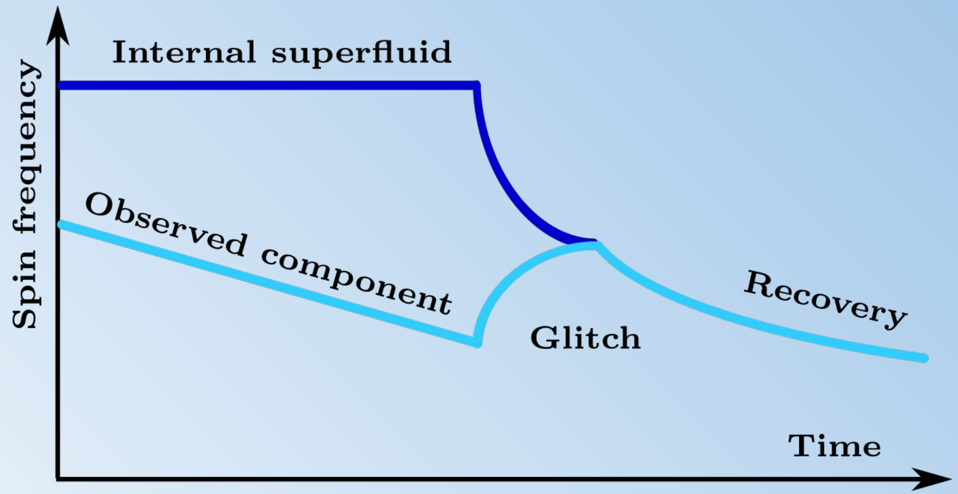


Data from the ATNF pulsar catalogue

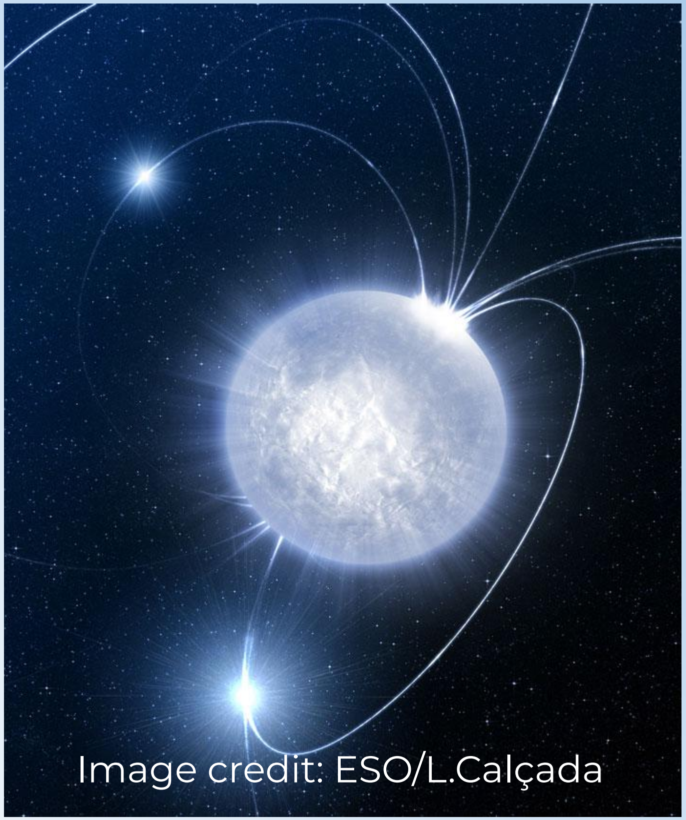
3. Pulsars - Glitches

- Because **pulsar timing** is very **precise**, we can detect very small changes in the stars' rotation. For ~200 pulsars, we have detected **glitches**, sudden spin ups that interrupt the regular neutron star spin down.

- These spin ups are typically attributed to **internal physics** and can be explained by a **superfluid component**. This superfluid is decoupled from the crust (which we observe via timing) until a critical lag is reached. **Angular momentum** is transferred and the crust spun up.



- By analysing the **morphology of glitches**, we can study **dense matter**.



4. Gravitational Waves

4. GWs - Interferometers

- Gravitational waves are **ripples in space-time**, generated by acceleration of masses close to the speed of light. They were predicted by Einstein in 1916 based on his theory of General Relativity.

- Even for the most extreme objects (NSs and BHs) these ripples are of very **small amplitude** and detection require highly **sensitive interferometers**.

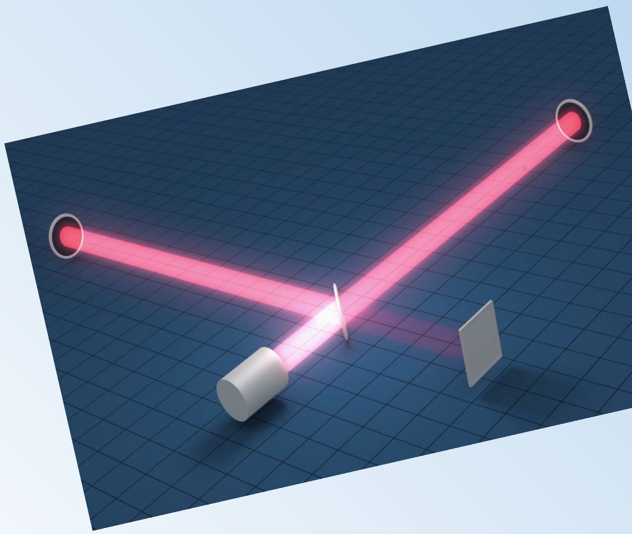
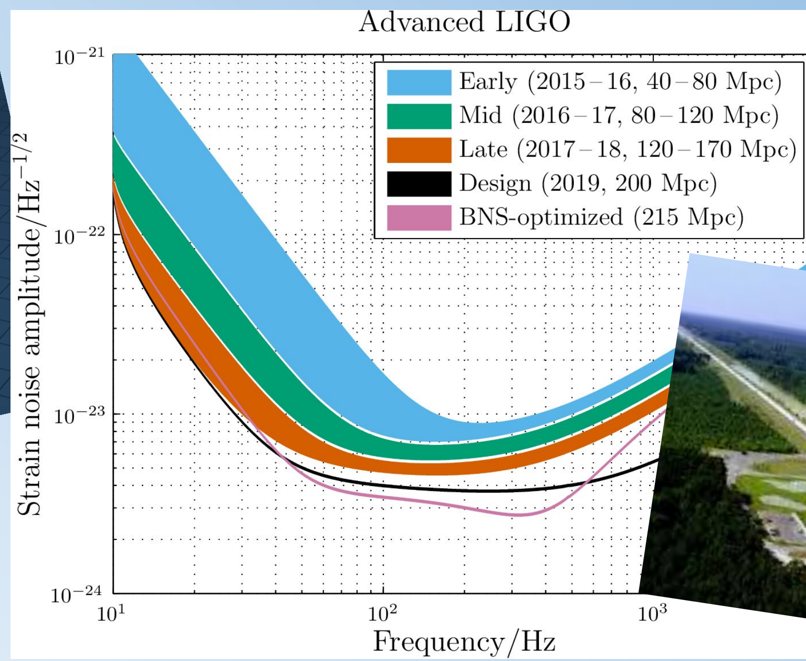


Image credit: LSC



- The **first detection** of GWs from a binary BH merger was made in 2015, almost 100 years after their first prediction.

4. GWs - Isolated NSs

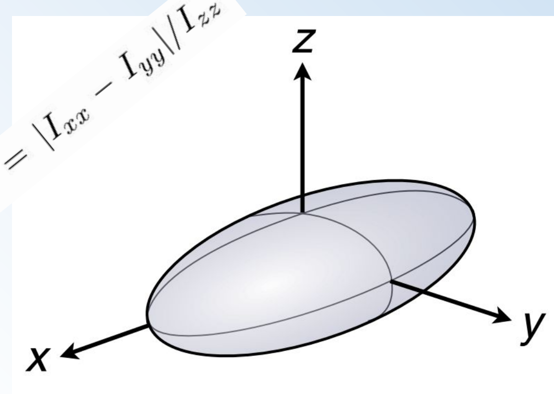
- Due to their compactness, NSs have **strong gravity** (~10^{11} x the Earth's gravitational acceleration). These compact objects interact strongly with **space-time** and are major sources of detectable **gravitational waves.**

- GWs are emitted by systems that have a non-vanishing **mass quadrupole** moment. **Isolated NSs** can thus emit gravitational waves because of '**mountains**' on their surfaces or **internal oscillations** of the fluids.

- Resulting GWs are of **small amplitude** resulting in GW strains $h_0 \lesssim 10^{-24}$. This is below the sensitivity of current detectors - continuous gravitational waves from isolated NSs have not been detected (yet!).

- **Non-detection** of GWs from pulsars set limits on their **ellipticities**

$$\epsilon = |I_{xx} - I_{yy}| / I_{zz}$$



$$\epsilon = 9.5 \times 10^{-5} \left(\frac{h_0}{1.2 \times 10^{-24}}\right) \left(\frac{D}{1\ \mathrm{kpc}}\right) \left(\frac{100\ \mathrm{Hz}}{f}\right)^2$$

LSC (2019)

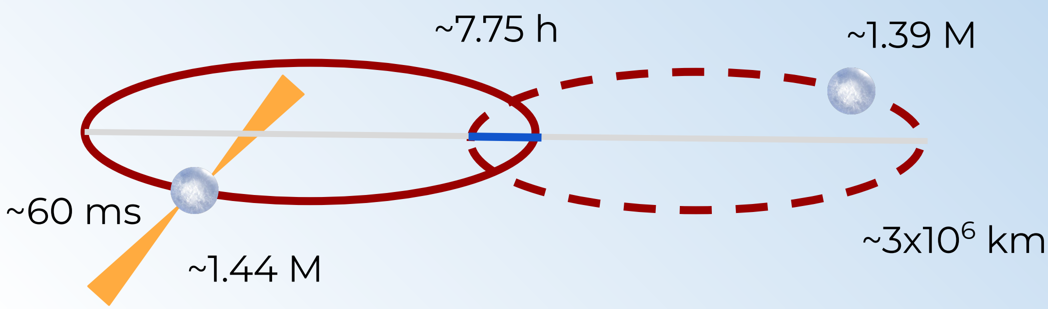
- For some NSs, this constraint limits the size of **mountains** on their surfaces to less than 1mm.

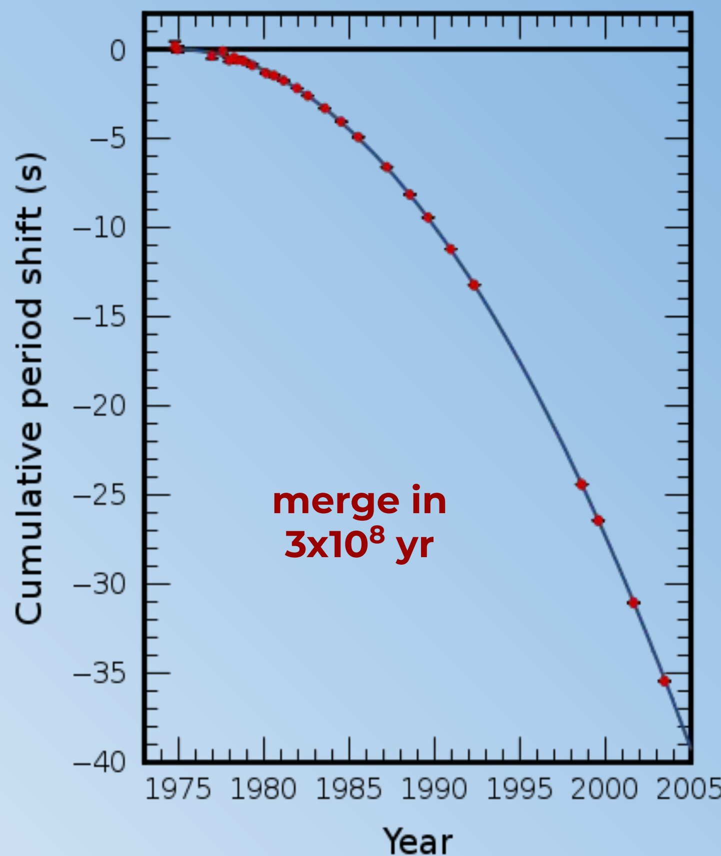
4. GWs - Binary NSs

- A **binary neutron star system** produces much stronger space-time disturbances and GW signals, because the large **orbital energy** of the binary is converted into gravitational waves.

- As the system emits gravitational radiation, the **orbital period** decreases. If one of the NSs is a pulsar, we can accurately measure the orbital decay.

- This was first achieved in the **Hulse-Taylor pulsar** (PSR B1913+16): first **indirect detection** of gravitational waves that showed that **GR** is correct to high precision in strong regime.

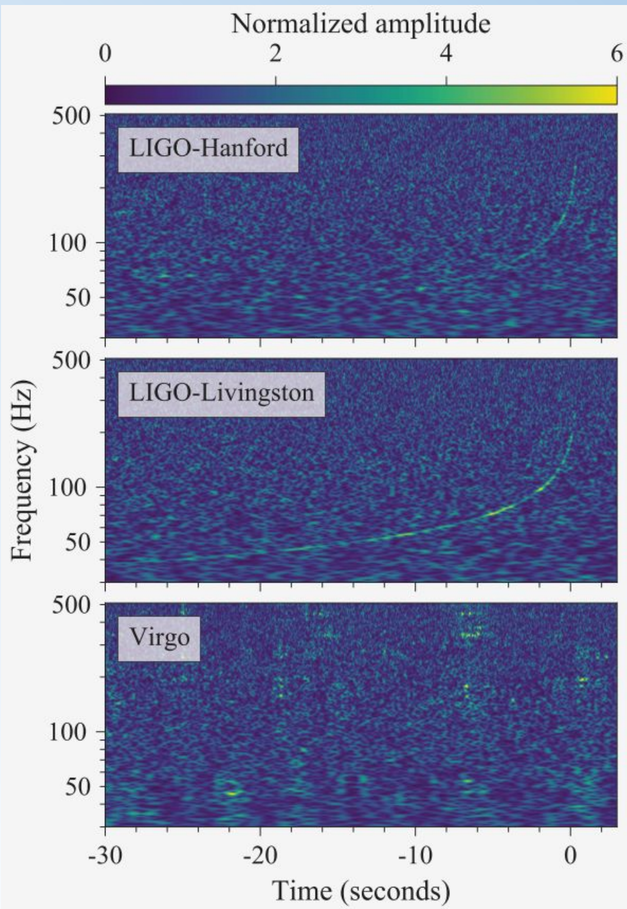




Weisberg and Taylor (2004)

4. GWs - GW170817

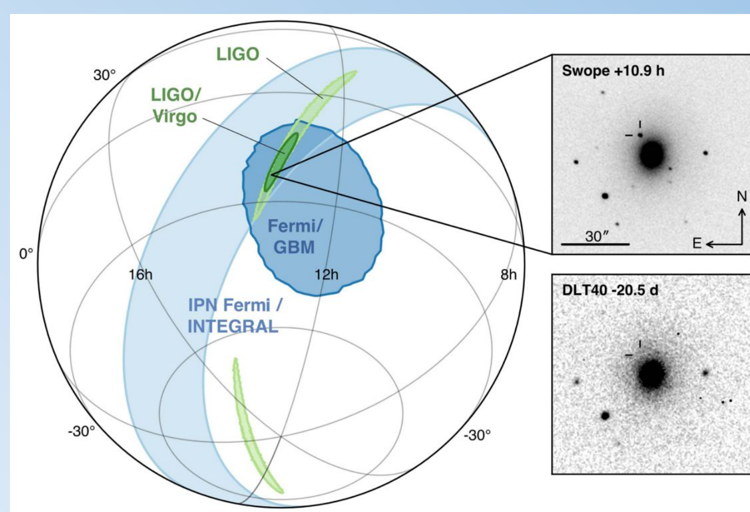
- Because NSs are so complex and we do not understand all the microphysics (they have **'hair'**), it is very difficult to accurately predict the **wave forms**.



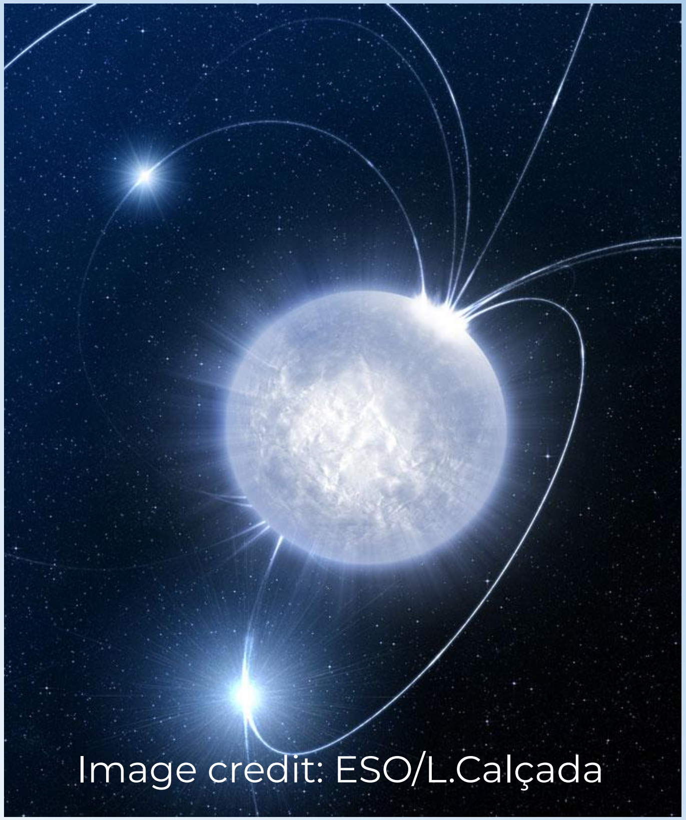
Abbott et al. (2017a)

- First **direct GW detection** from two merging NSs was made two years ago. Signal was very bright not only in GW but also had EM counter-parts in ɣ-rays (sGRB detected by Fermi ~2 s after GW signal), X-rays, optical, radio and IR.

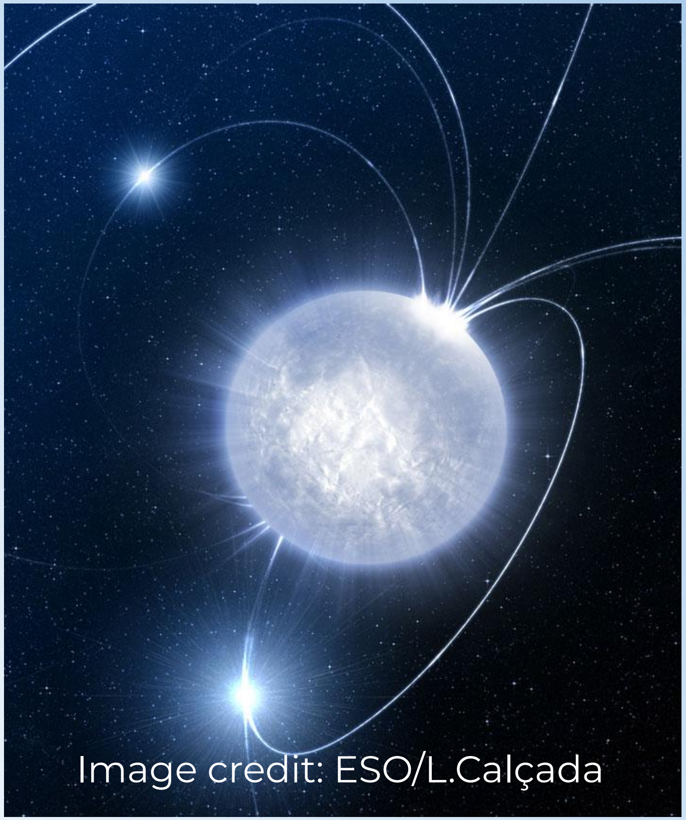
- This event initiated the era of **multi-messen-ger astronomy**: learn about astrophysics from many different angles.



Abbott et al. (2017b)



The End!



Reading

- *Black Holes, White Dwarfs, and Neutron Stars* - Shapiro and Teukolsky
- *Neutron Stars 1: Equation of State and Structure* - Haensel, Potekhin and Yakovlev
- *Handbook of Pulsar Astronomy* - Lorimer and Kramer
- *Neutron Stars and Pulsars* - Becker (Ed.)
- *Gravitation* - Misner, Thorne and Wheeler
- *General Relativity* - Wald