Introduction to Neutron Stars

A meeting point of all extreme physics

Leonel Morejon

Summer Student Program 2019

Origins / Detection : Death of stars

Are neutron stars and the Sun much different?
What can compress matter so much?
Where can we look for neutron stars?

Rotation & Magnet : Cosmic compasses

Is rotation important?
Ho do we measure the frequency?
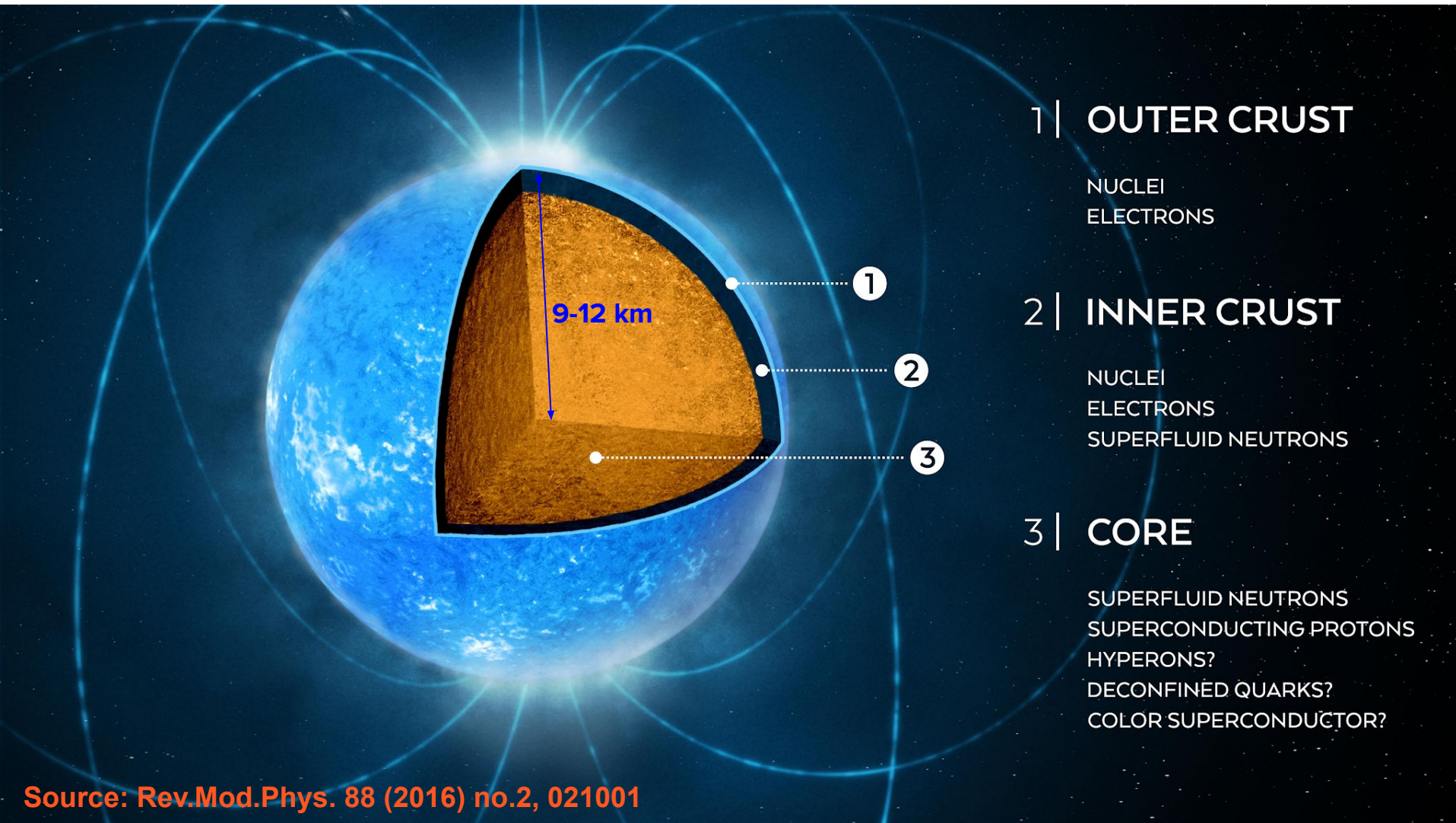**How strong are the magnetic fields**

!! CLOCK / COMPASS !!

ROTATION + MAGNETIZATION

Structure: Gravity vs Quantum forces

9-12 km

1 | **OUTER CRUST**

NUCLEI
ELECTRONS

2 | **INNER CRUST**

NUCLEI
ELECTRONS
SUPERFLUID NEUTRONS

3 | **CORE**

SUPERFLUID NEUTRONS
SUPERCONDUCTING PROTONS
HYPERONS?
DECONFINED QUARKS?
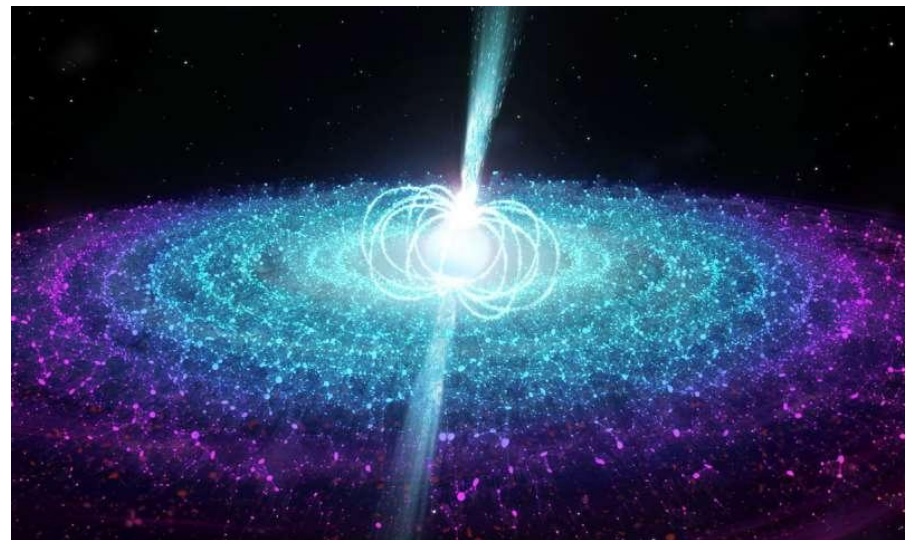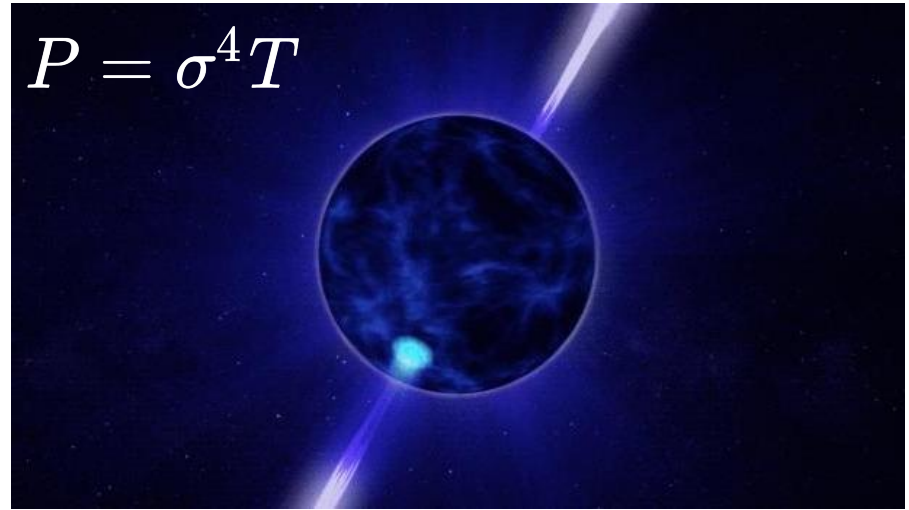COLOR SUPERCONDUCTOR?

Radiation / Temperature :

$$T \approx 100 - 1000 \times T_\odot$$

The peak emission is on X-rays! Visible light is much less ...

... additionally, the **strong magnetic field** powers the heating and **radiation of the surrounding matter** ejected in the SuperNova Explosion!

$$P = \sigma^4 T$$

1000 ways to die... by a neutron star

... a fun gedanken experiment for the end:

WHEN FALLING INTO A NEUTRON STAR, WHAT KILLS YOU FIRST?

SPAGHETTIFICATION?

CRUSHED BY OWN WEIGHT?

BURNED BY X-RAYS?

TORN BY CENTRIFUGAL FORCES?

CRUSHED BY OWN WEIGHT?

1000 WAYS TO DIE

Historical context

GiGantic nucleus...

One month before the discovery of the neutron by **Chadwick**, a paper by **Landau** describes the extreme conditions of neutron stars "(...) *the density of matter becomes so great that atomic nuclei come in close contact, forming one **gigantic nucleus**.*" **Physikalische Zeitschrift der Sowjetunion, Jan. 1932**
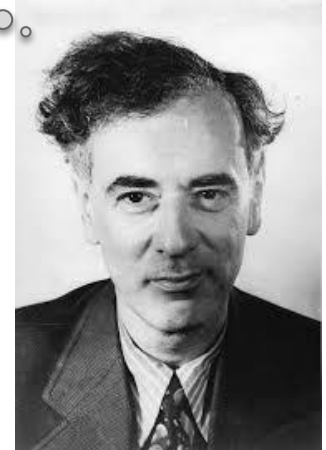
...TIGHTLY PACKED LIKE THIS!
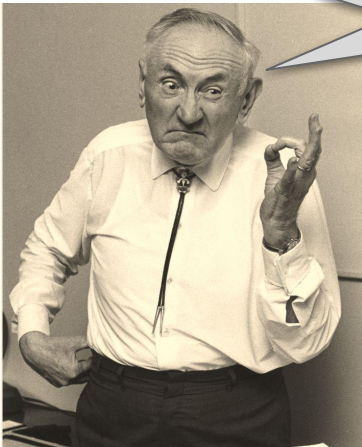
"...supernovae represent the transitions from ordinary stars into *neutron stars*, which (...) consist of extremely closely packed neutrons."   **1934, W. Baade & F. Zwicky**
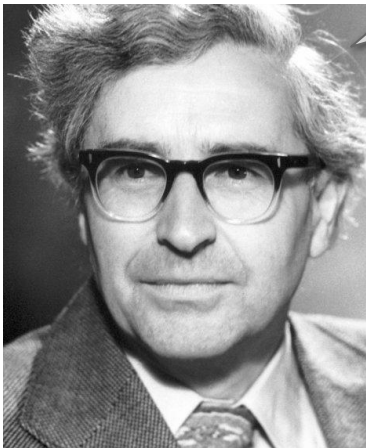
Historical context

Can't be aliens !?

Jocelyn Bell, a student under **Antony Hewish**, recorded a repeating pulse of radio waves. It was suspiciously regular and they named it **LGM1 (L**ittle **G**reen **M**en**) 1965**

Pulsating radio signal!?

Hewish's radio telescope was intended for solar wind effect on the signal from radio sources. The source however was outside of the solar system. Three years later it was published, suggesting a variable compact object consistent with neutron stars. **1968**
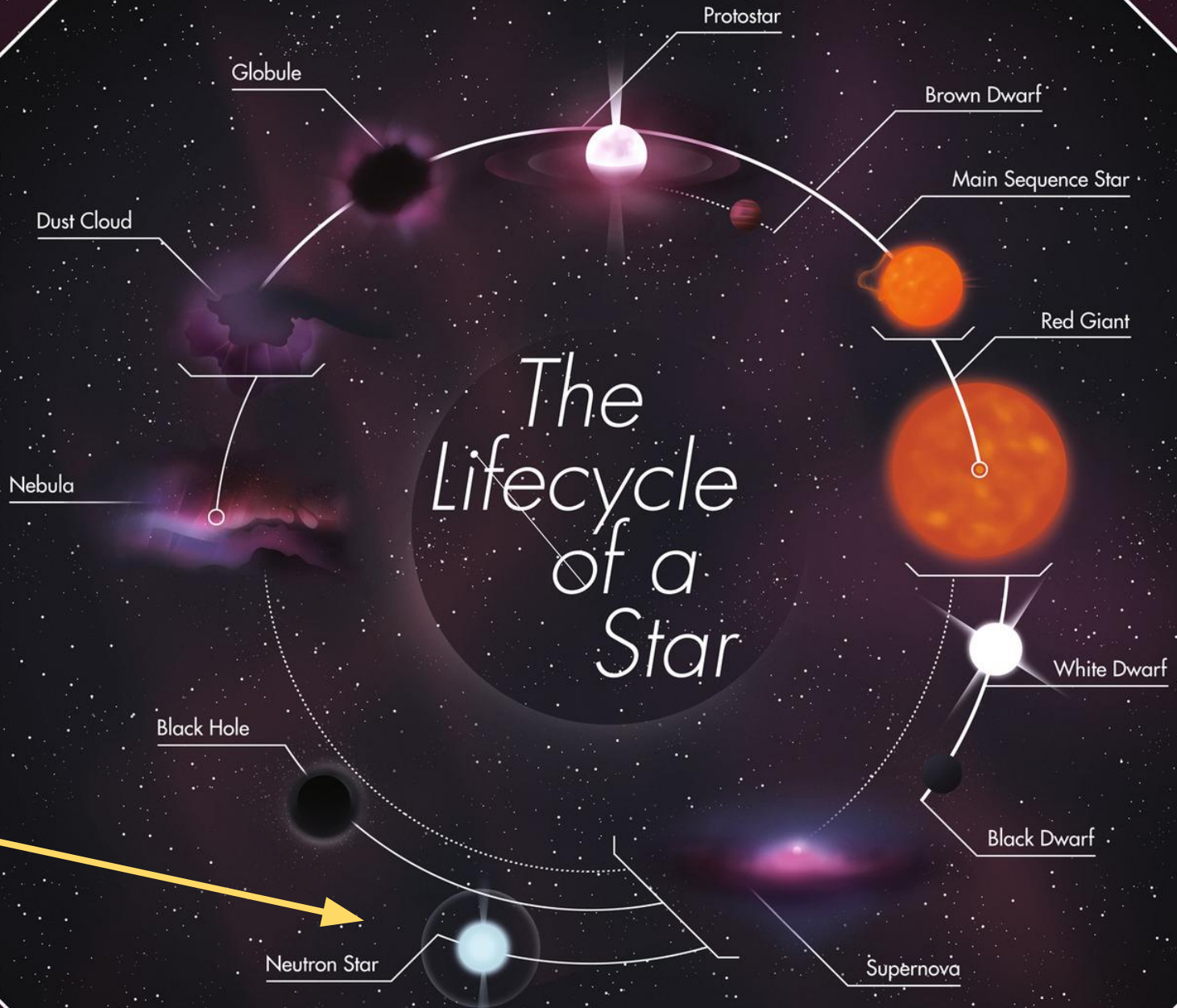
Origin:

Birthed in the Supernova explosion (SNE) of a massive star...

$$M_S \approx 8 - 10 M_\odot$$

We might find them in sites Supernova Remnants (SNR)

Protostar

Globule

Brown Dwarf

Dust Cloud

Main Sequence Star

Red Giant

Nebula

The Lifecycle of a Star

White Dwarf

Black Hole

Black Dwarf

Neutron Star

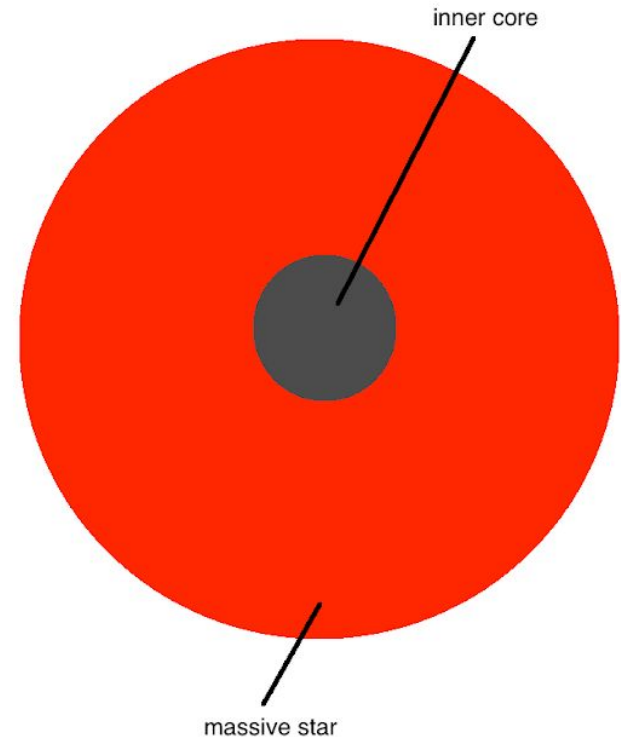Supernova

Imagining a Supernova explosion

Step 1: Burnout

Heavier nuclei produced during fusion concentrate in lower layers.

Near the end of the star, the core is very rich in iron, fuel is depleted.

The radiation pressure can no longer stop the graviational infall.

Source: https://en.wikipedia.org/wiki/Neutron_star

inner core

massive star

EQUATIONS FOR STELLAR EQUILIBRIUM (SPHERICAL SYMMETRY)

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{Gm\rho}{r^2} \qquad \frac{\mathrm{d}T}{\mathrm{d}r} = -\frac{1}{k}\frac{l}{4\pi r^2}$$

$$\frac{\mathrm{d}l}{\mathrm{d}r} = 4\pi r^2 \rho \left(\epsilon - \epsilon_\nu \right)$$

$$\frac{\mathrm{d}T}{\mathrm{d}r} = \left(1 - \frac{c_v}{c_p} \right) \frac{T}{P} \frac{\mathrm{d}P}{\mathrm{d}r}$$
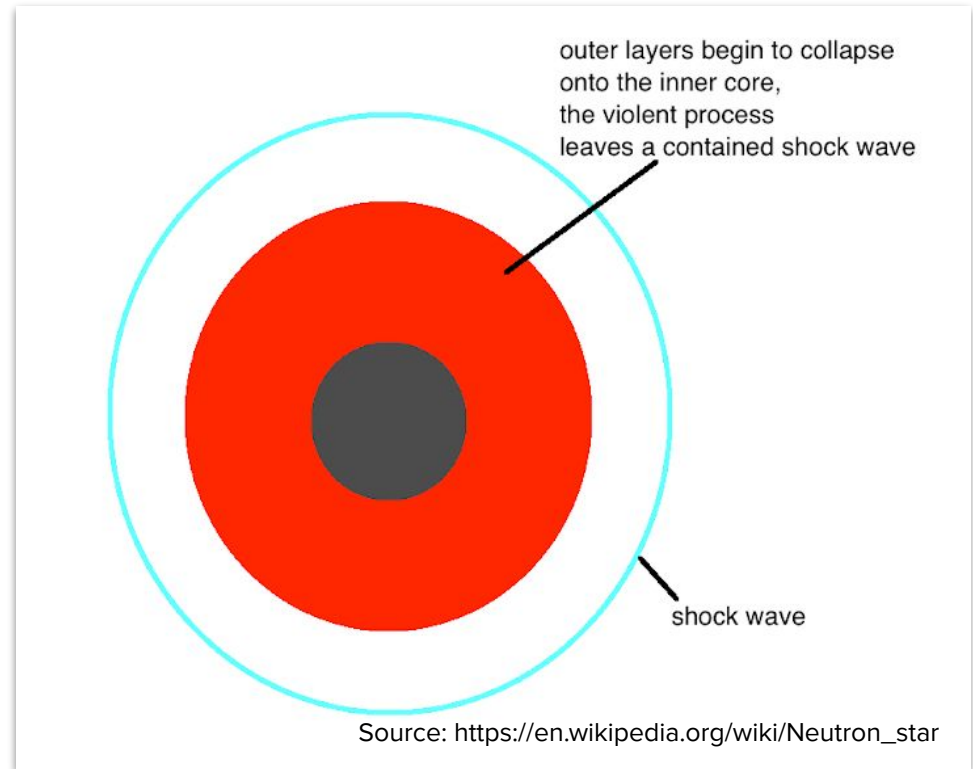
Imagining a Supernova explosion

Step 2: Collapse

The mass of the star rapidly collapses under its own weight.

The core is compressed producing heat. A fast "neutronization" occurs, with intense neutrino emission.
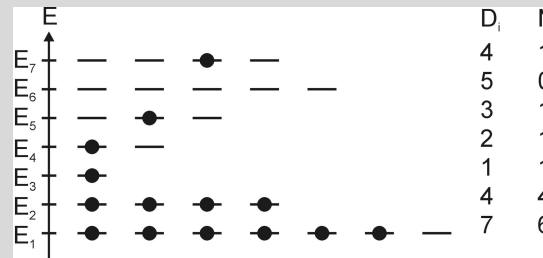
Degeneracy pressure builds up until the core can no longer compress, and outer layers are "bounced" away.

outer layers begin to collapse onto the inner core, the violent process leaves a contained shock wave

shock wave

Source: https://en.wikipedia.org/wiki/Neutron_star
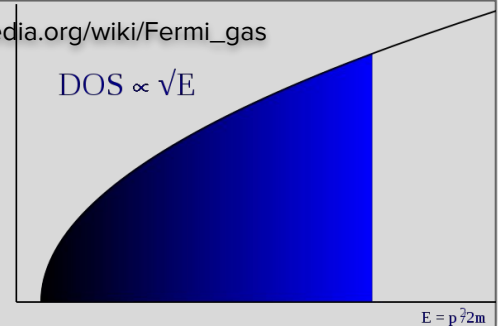
Degeneracy Pressure (Fermi Gas Model)

Pressure due to energy density of a fermion system with degeneracy of energy levels.

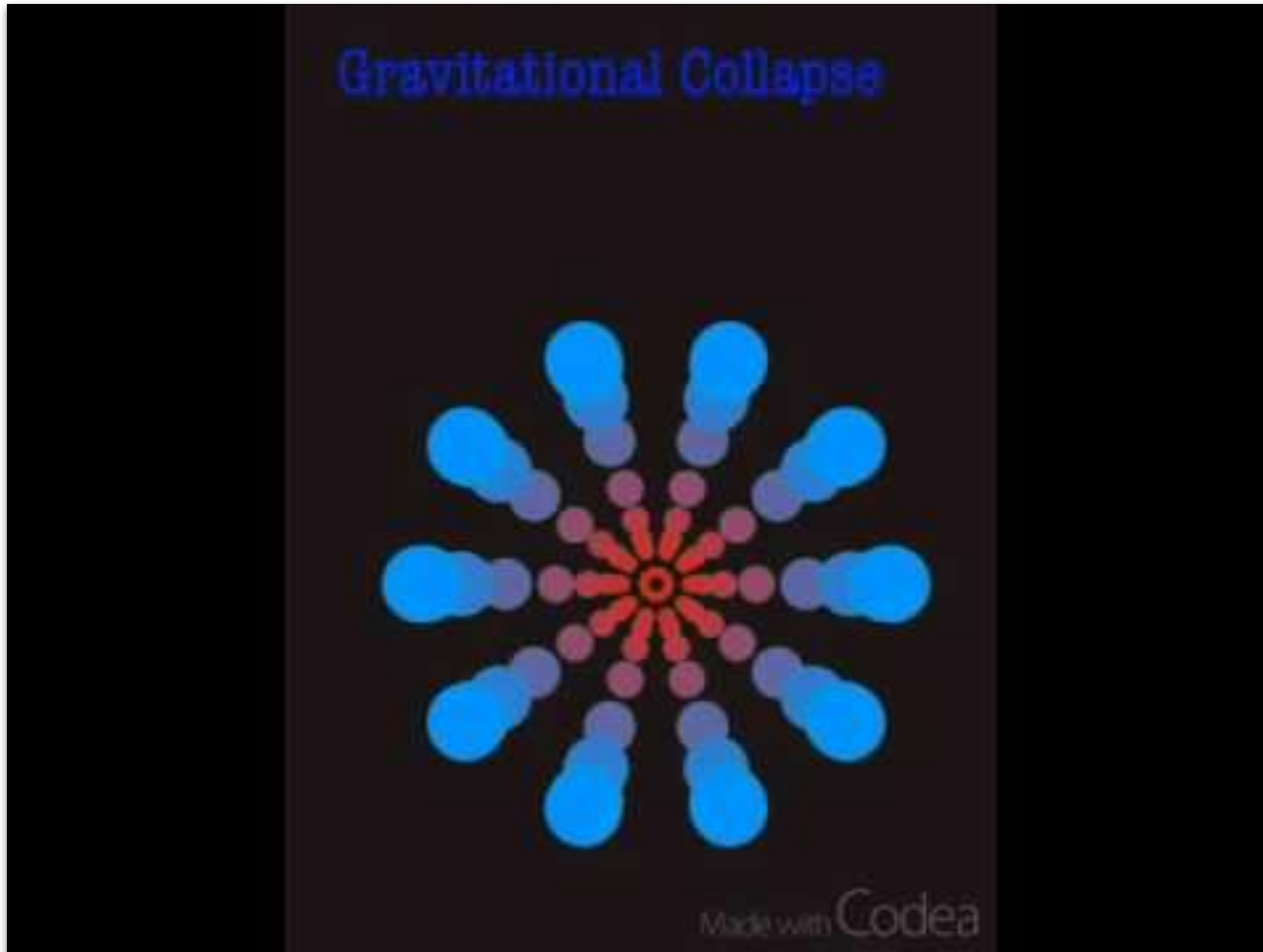$$P = \frac{2}{3}\frac{E}{V} = \frac{2}{3}\frac{\hbar p_F^5}{10\pi^2 m}$$

Source: https://en.wikipedia.org/wiki/Fermi_gas

E					D_i	N_i
E_7	—	—	●	—	4	1
E_6	—	—	—	—	5	0
E_5	—	●	—		3	1
E_4	●	—			2	1
E_3	●				1	1
E_2	●	●	●	●	4	4
E_1	●	●	●	●	●	7	6

DOS $\propto \sqrt{E}$

$E = p^2/2m$

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Imagining a Supernova explosion

Video illustrating gravitational collapse

https://www.youtube.com/watch?v=vz90_X3TuJM

Imagining a Supernova explosion

Step 3: Supernova Explosion, naked core

Heavier nuclei produced during fusion concentrate in lower layers.

Near the end of the star, the core is very rich in iron, fuel is depleted.

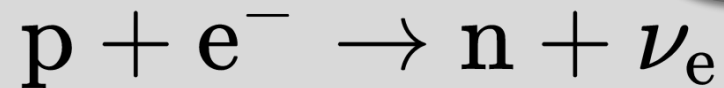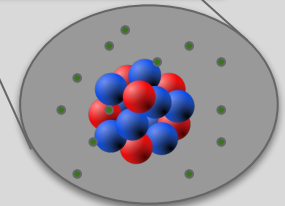The radiation pressure can no longer stop the graviational infall.

the shockwave is released, carrying the matter away in the blast

Neutronization

Compression of nuclear matter is easier when the electric charge is reduced.

The nuclei in the heated core rapidly absorb the electrons turning protons into neutrons.

$$p + e^- \rightarrow n + \nu_e$$

The scales of a neutron star

Typical values for neutron stars

Broadly speaking a neutron star can be viewed as a giant nucleus with a mean density of the order of ~1E14 − 1E15 gcm−3. A neutron star contains ~1E57 nucleons, 90% being neutrons.

Neutronization density

$$\rho_{ND} \approx 7 \times 10^{-4} \rho_0$$

Nuclear matter density

$$\rho_0 = 2.8 \times 10^{14} \, \text{g cm}^{-3}$$

Compared to the Sun

$$M \approx 1 - 2 M_\odot$$
$$R \approx 10^{-5} R_\odot$$
$$T \approx 10^2 - 10^3 T_\odot$$

Canonical Neutron Star Model (spherical non rotating)

$$M = 1.4 \, M_\odot \quad R = 10 \text{km}$$

Detection

**Neutron stars' radiation says it all**

Neutron stars are multi-wavelength emitters: radio, infrared, optical, UV, X-rays, gamma rays. Possibly neutrinos and gravitational waves.

Supernova remnants are good places to look for neutron stars, also binaries with optical companions, or pulsars.
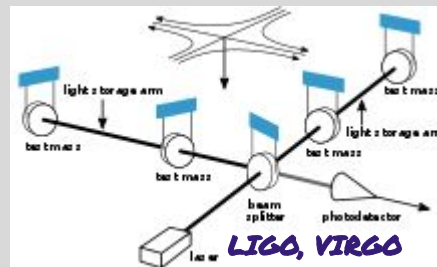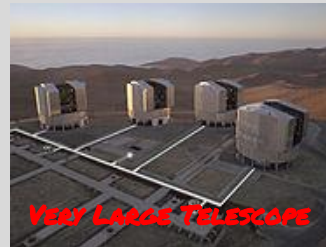
Models relate the structure and global quantities (**M**, **R**, **T**, **B**) to radiation properties like **spectrum**, **time dependence**.

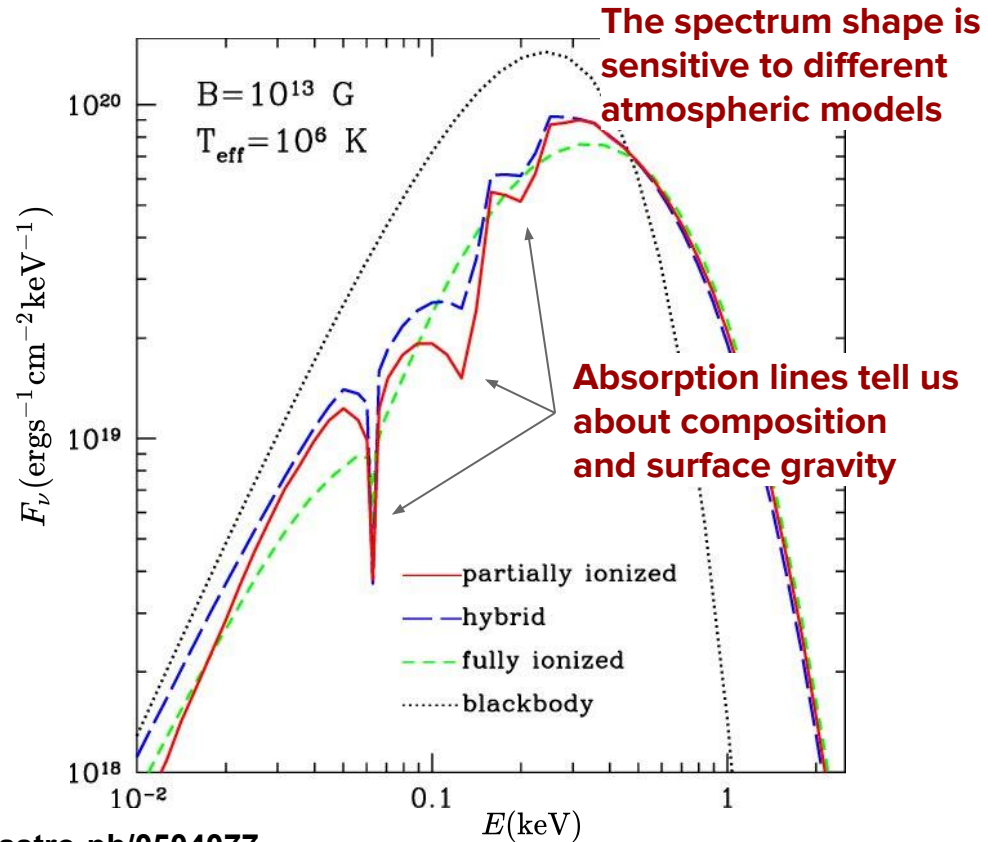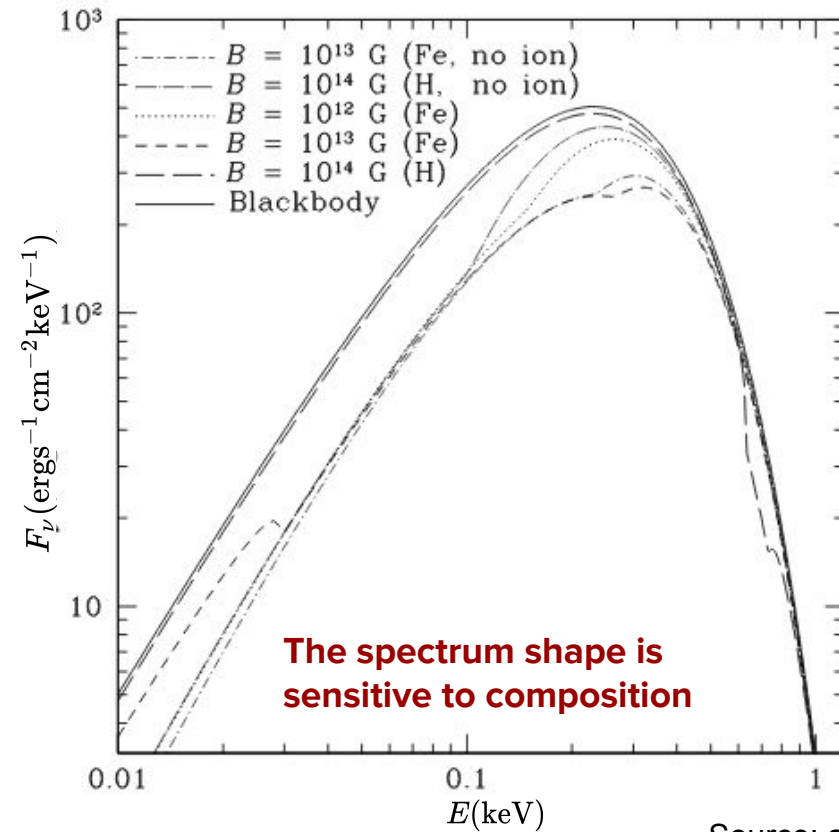Measuring instruments

UV, Xrays and gamma from orbit...
INTEGRAL
Hubble
XMM-Newton
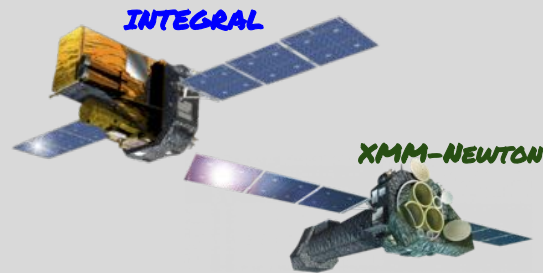
Infrared, radio, optical and G-waves from ground...
Very Large Telescope
Arecibo radio telescope

LIGO, VIRGO

Detection

Models of radiation depend on the star properties, and so measuring the radiation can help constraint these properties (M, R, T, etc.)

Modeled X-ray spectra from Magnetars

The spectrum shape is sensitive to composition

The spectrum shape is sensitive to different atmospheric models

Absorption lines tell us about composition and surface gravity
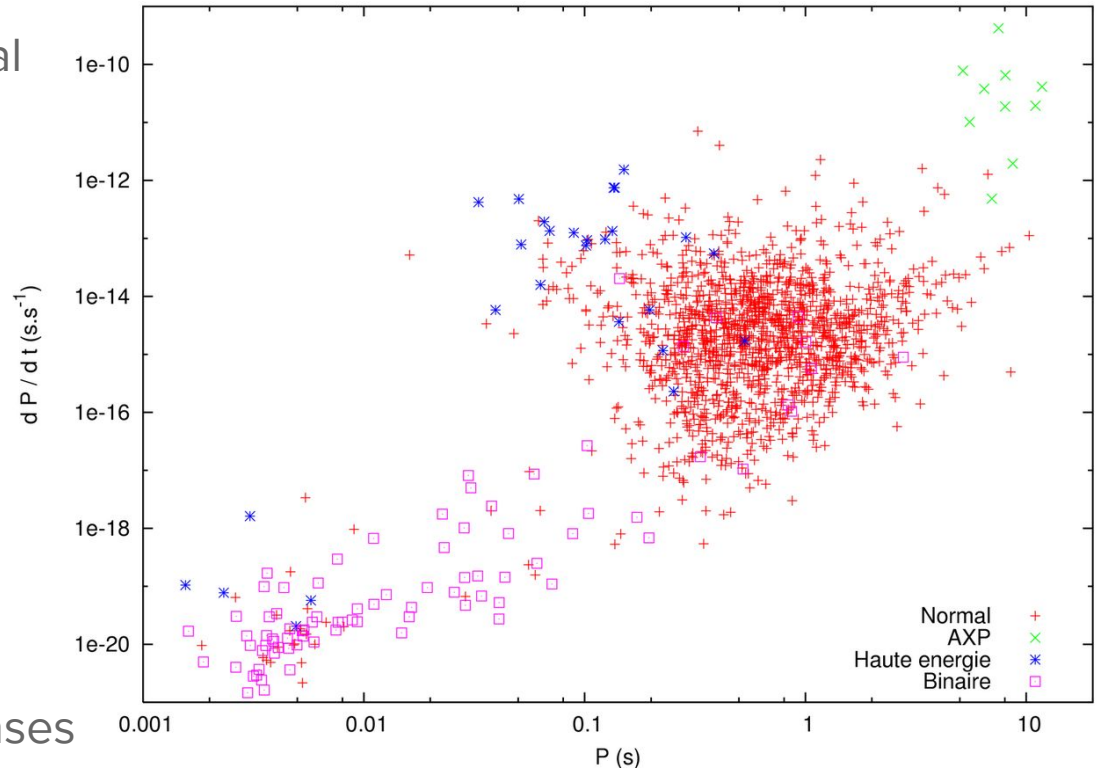
Source: **arxiv:astro-ph/0504077**

Rotation

The rotation of neutron stars is residual from its original angular momentum

The compression of the original core leads to a faster rotation.

$$L = I\Omega \quad I \propto MR^2$$

$$P = \frac{2\pi}{\Omega} \quad \dot{P} = \frac{dP}{dt}$$

The spin period usually decreases although very slowly. Neutron stars can be used as very precise clocks!

Rotation and Measurements

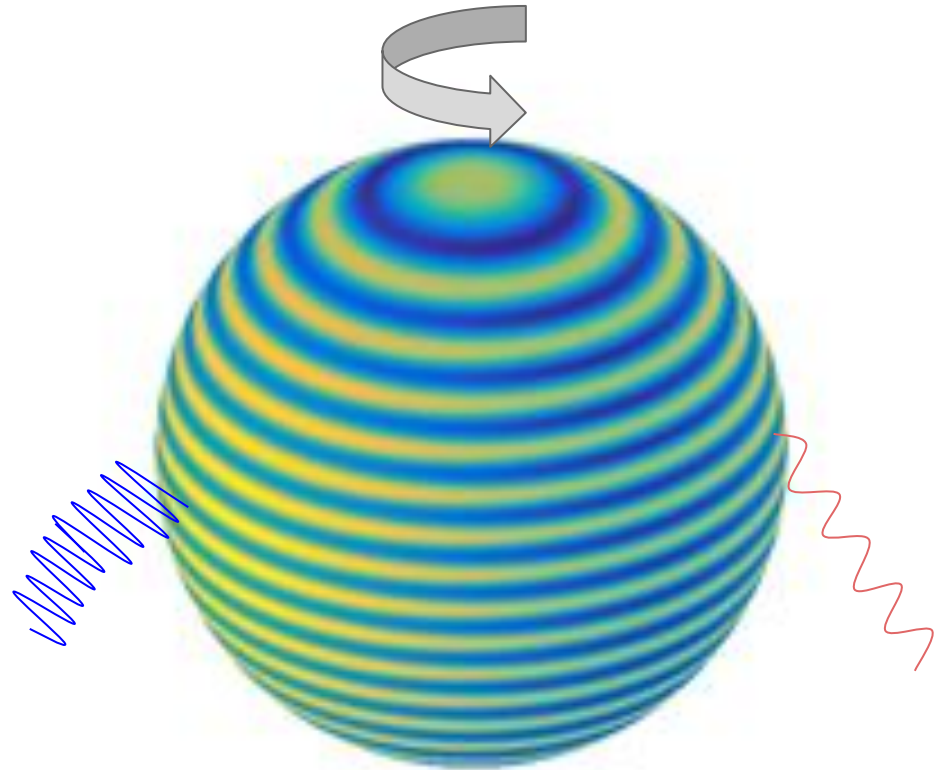**Spectral line emission from the star is affected by rotation**

The rotation has effects on the
observed atomic lines from the x-ray
emission of nuclei in its atmosphere
and crust.

Rotation and Measurements

Spectral line emission from the star is affected by rotation

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- **Relativistic Doppler Boost** affects emission of equator
- **Gravitational lensing** alters the poles / equator relative emission

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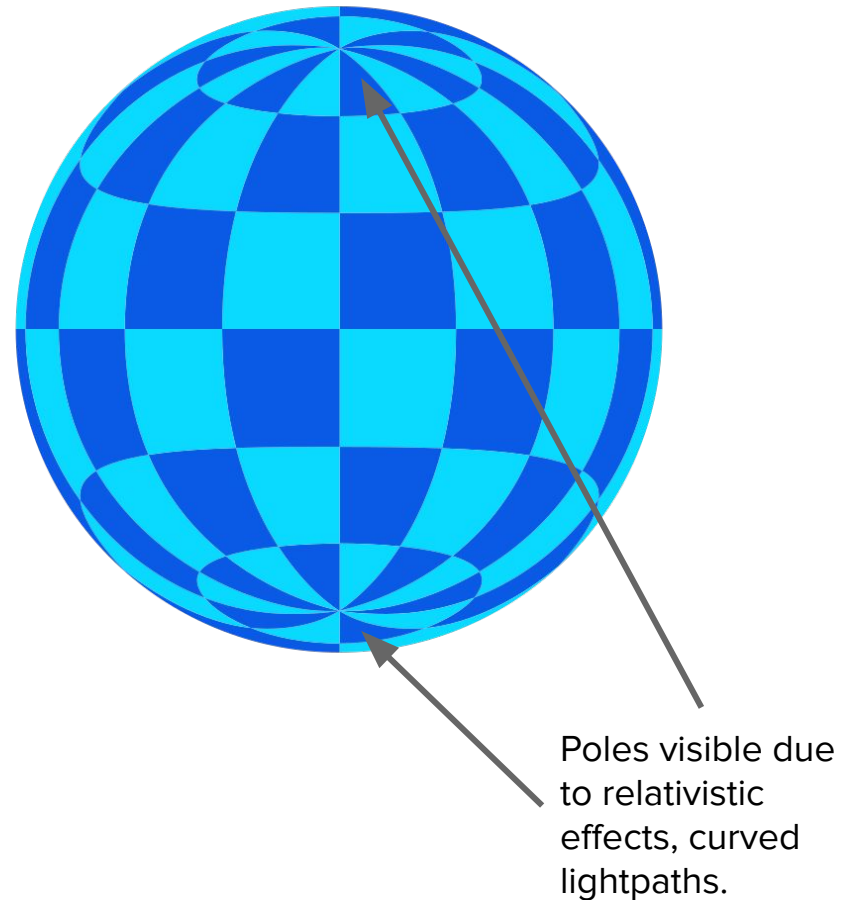- **Gravitational lensing** alters the poles / equator relative emission

Poles visible due to relativistic effects, curved lightpaths.

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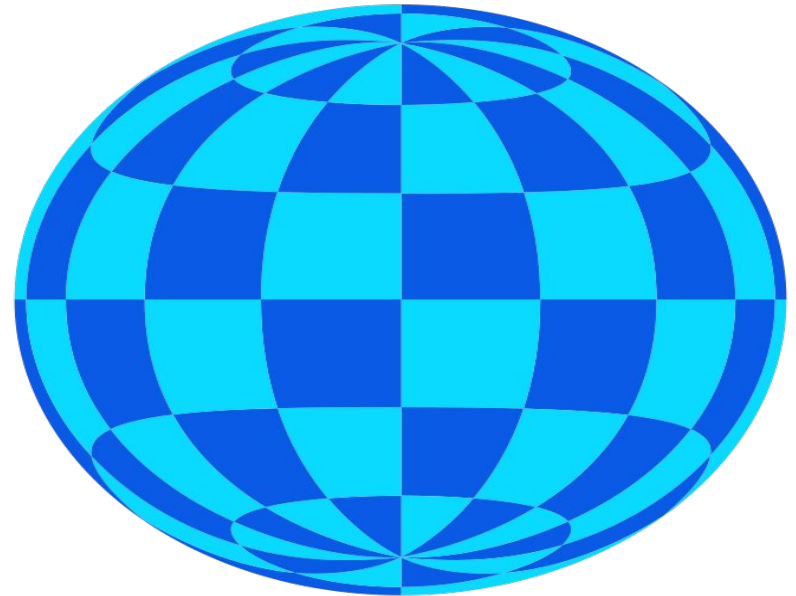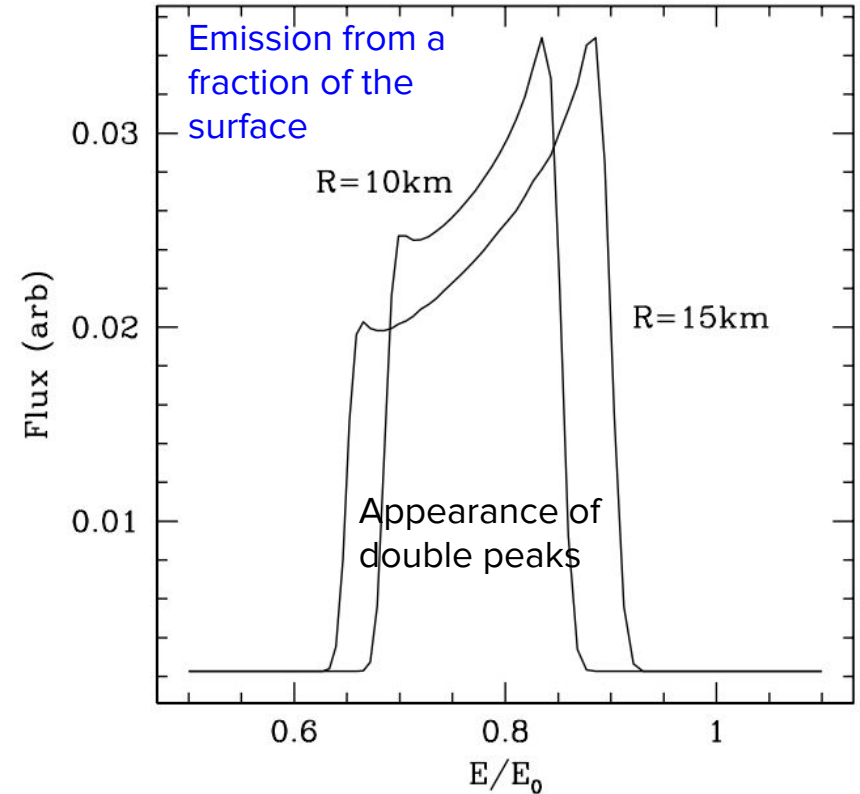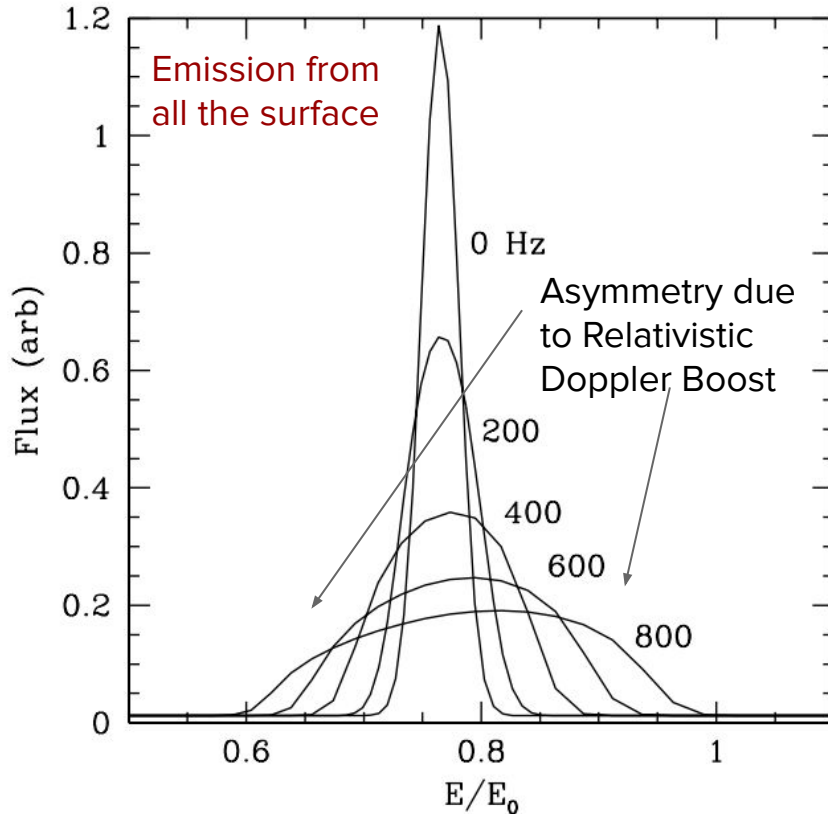- **Gravitational lensing** alters the poles / equator relative emission
- **Centrifugal force** produces oblateness and deepens poles / equator emission differences

Rotation and Measurements

Spectral line emission from the star is affected by rotation

Emission line affected by rotation $M = 1.4 M_\odot, R = 10\,\mathrm{km}$

Emission from all the surface

0 Hz

Asymmetry due to Relativistic Doppler Boost

200

400

600

800

Emission from a fraction of the surface

R=10km

R=15km

Appearance of double peaks

Source: **arxiv:astro-ph/0209225**
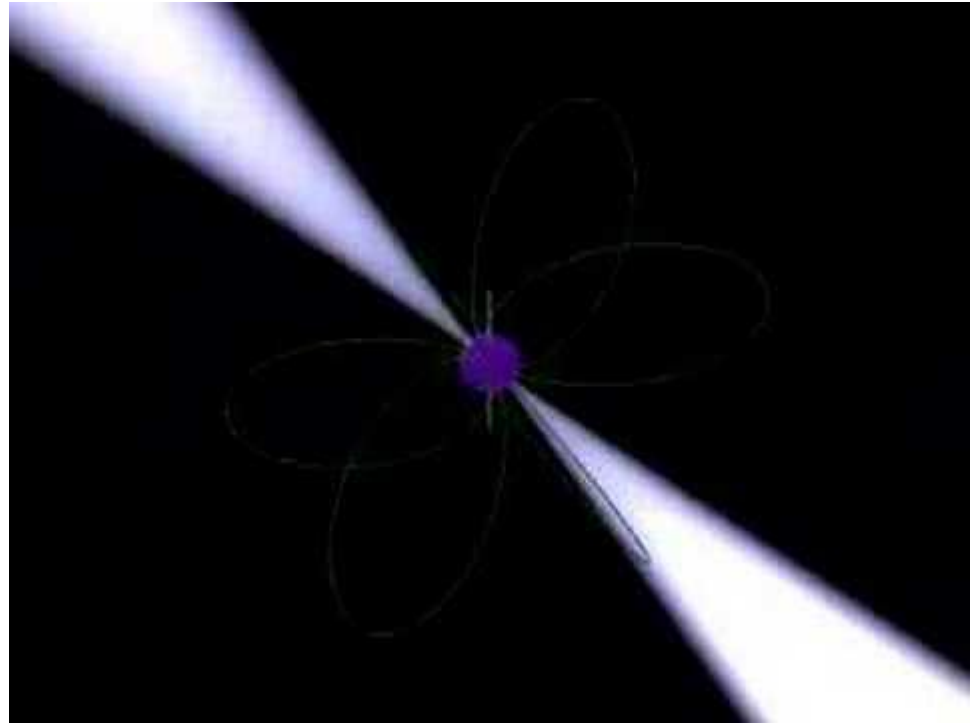
Pulsars

Magnetized neutron that rotate

The emission of pulsars is modulated by the rotation.

The magnetic field can be estimated assuming that the neutron star is an isolated rotating dipole losing power by radiation:

$$I\dot{\Omega} = \tau \qquad P = \frac{2\pi}{\Omega}$$

$$\tau = -\frac{2}{3} B_{\text{eff}} \left(\frac{\Omega R}{c} \right)^3$$

$$B_{\text{eff}} = \left(\frac{3Ic^3}{8\pi^2 R^6} P\dot{P} \right)^{1/2}$$

Age of a pulsar is estimated as:

$$t = P/2\dot{P}$$
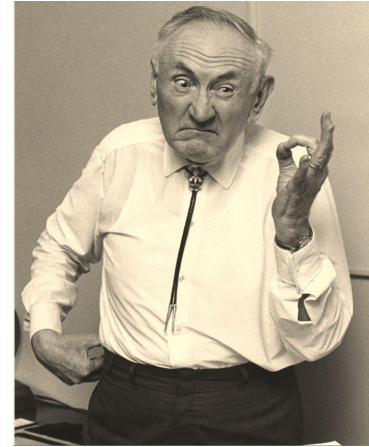
Gravitational mass

The mass equivalent to the binding energy

The extreme gravitation field leads to a considerable binding energy.

$$BE = \frac{0.6\beta}{1 - \frac{\beta}{2}} \qquad \beta = \frac{GM}{Rc^2}$$

For a standard neutron star…

$$BE \approx .14Mc^2$$

Fritz Zwicky was the first to notice that the term "neutron star mass" is ambiguous.

He determined the maximum binding energy to be 42% of the matter content of the star!!
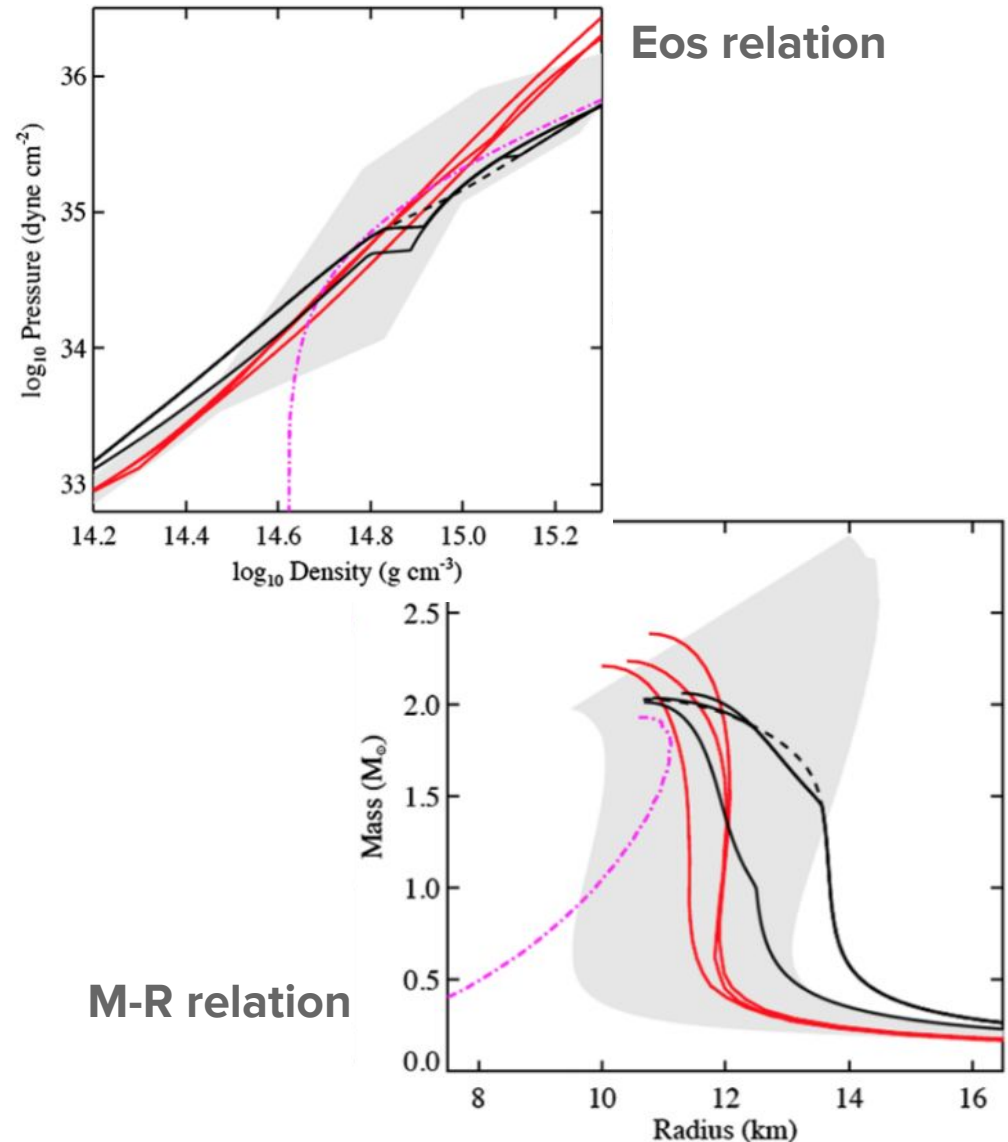
Relation between Mass and Radius

Integrating the TOV equations

Tolman-Oppenheimer-Volkoff equations relate radial pressure to mass distribution:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = \frac{G}{c^2} \frac{(P+\epsilon)(m+4\pi r^3 P/c^2)}{r(r-2Gm/c^2)}$$

$$\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi r^2 \epsilon/c^2$$

Having an Equation of State (EoS) that relates pressure and density, the mass radius relation can be obtained.
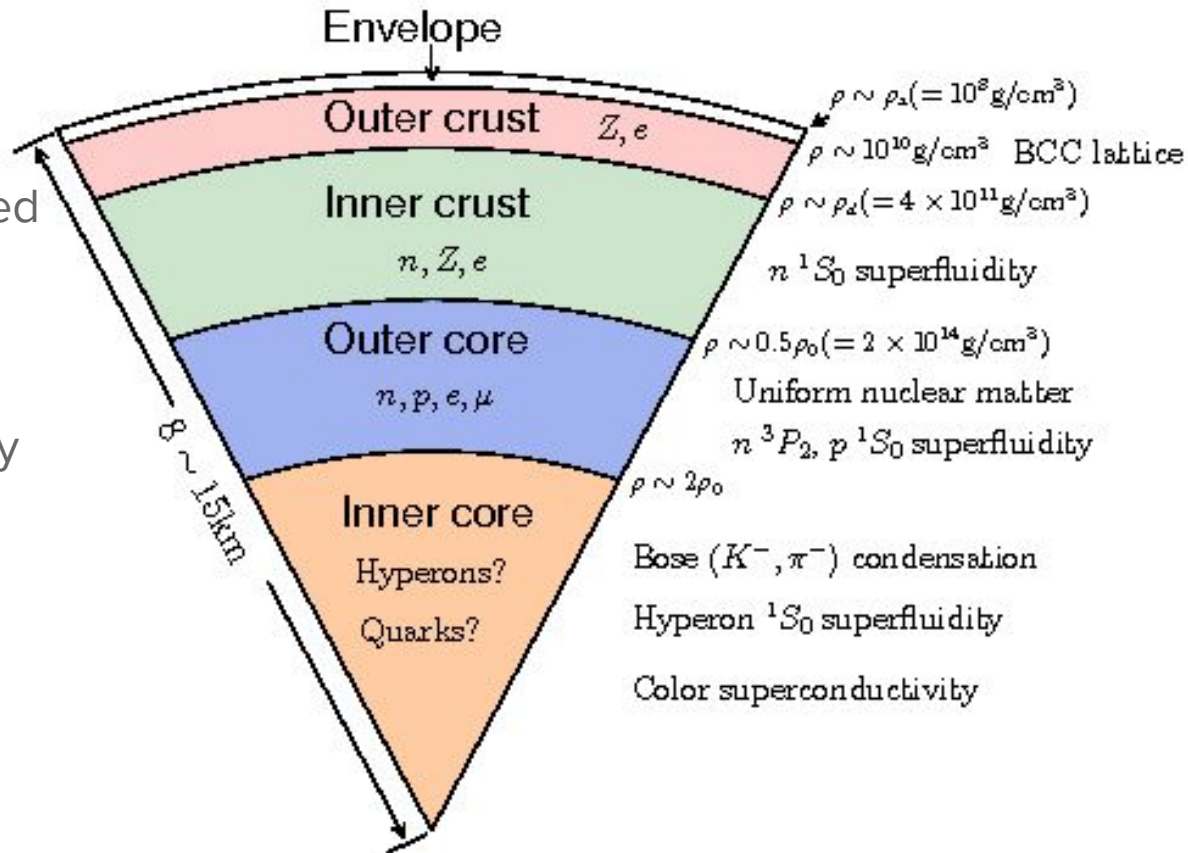
Eos relation

M-R relation

Composition

Relating neutron star structure to density

Stellar equilibrium is established by balancing gravitational pressure and quantum forces.

Different models are necessary to describe the different densities inside a neutron star.

The matter composition of the interior is not fully understood and models do not agree.

Envelope

Outer crust Z, e
$\rho \sim \rho_1 (= 10^8 \text{g/cm}^3)$
$\rho \sim 10^{10} \text{g/cm}^3$ BCC lattice

Inner crust n, Z, e
$\rho \sim \rho_d (= 4 \times 10^{11} \text{g/cm}^3)$
$n\, {}^1S_0$ superfluidity

Outer core n, p, e, μ
$\rho \sim 0.5 \rho_0 (= 2 \times 10^{14} \text{g/cm}^3)$
Uniform nuclear matter
$n\, {}^3P_2,\ p\, {}^1S_0$ superfluidity
$\rho \sim 2\rho_0$

Inner core
Hyperons?
Quarks?
Bose (K^-, π^-) condensation
Hyperon ${}^1S_0$ superfluidity
Color superconductivity

$8 \sim 15\text{km}$

Source: Int.J.Mod.Phys. E26 (2017) no.4, 1750015

Equation of State (EoS) and Rotation

Rotation can constrain some nuclear models

Rotation can constrain EoS by placing a limit on the radius, for a given mass.

The frequency at which the mass in the equator is shed by centrifugal forces has been estimated

$$f_{\max} \approx C \left[\frac{M}{M_{\odot}} \right]^{1/2} \left[\frac{R}{10\text{km}} \right]^{-3/2} kHz$$

Models to the right of the frequency curve are excluded. Current fastest rotator does not exclude any EoS model.
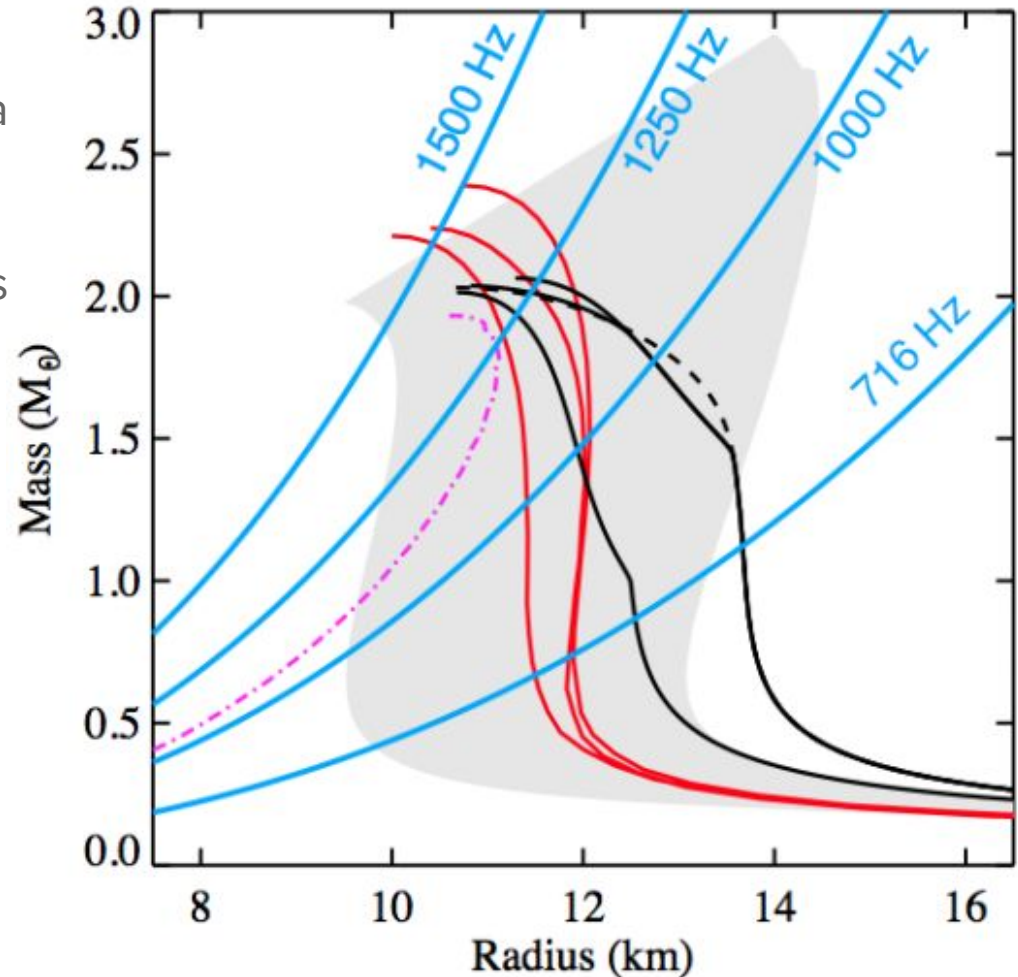
Source: arxiv:1602.01081

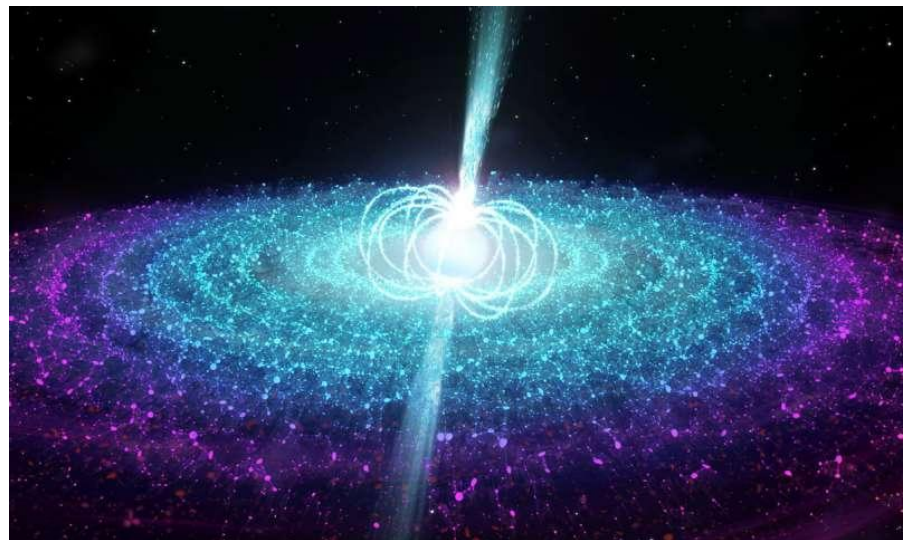# Radiation from a neutron star

Multiple emissions from different mechanisms

The temperature is 1000 times that in the Sun, and comparable luminosity:

$$L = 4\pi R^2 \sigma T^4 \approx L_\odot$$

with the peak emission in X-rays.

The strong magnetic field powers the heating and radiation of the surrounding matter ejected in the SuperNova Explosion.

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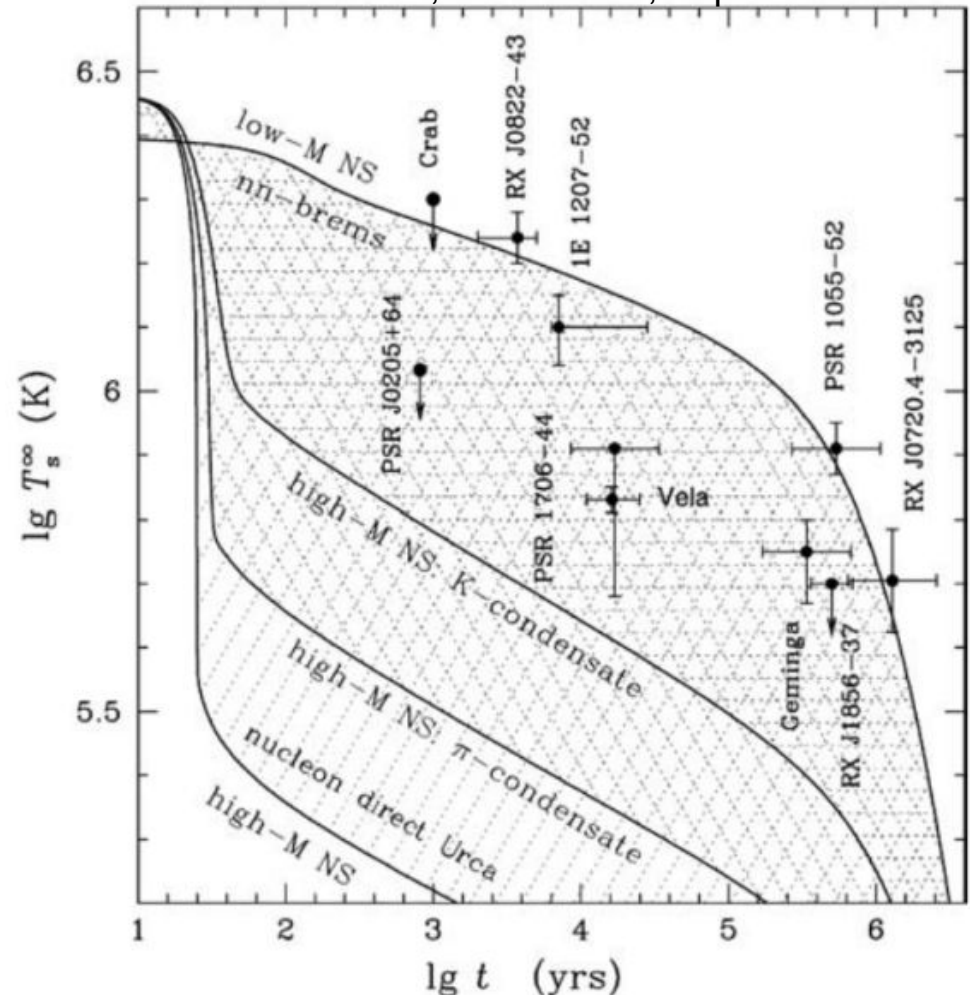
Cooling processes

A neutron stars cools by emitting neutrinos initially

The initial temperature is a trillion degrees and cooling happens quickly through neutrino emission.

- **URCA process** neutron decays to proton which recaptures an electron with neutrino emission
- **Black body radiation** photon from the surface

Neutron stars can also heat up by accretion of matter from a companion star!

Source: ARA&A, 42:169–210, September 2004.

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Cooling processes

A neutron stars cools by emitting neutrinos initially

Cooling process can be used to understand the composition of the envelope of the neutron star.

The figure shows the cooling evolution with time for an envelope composed of light elements and the difference for heavy elements.
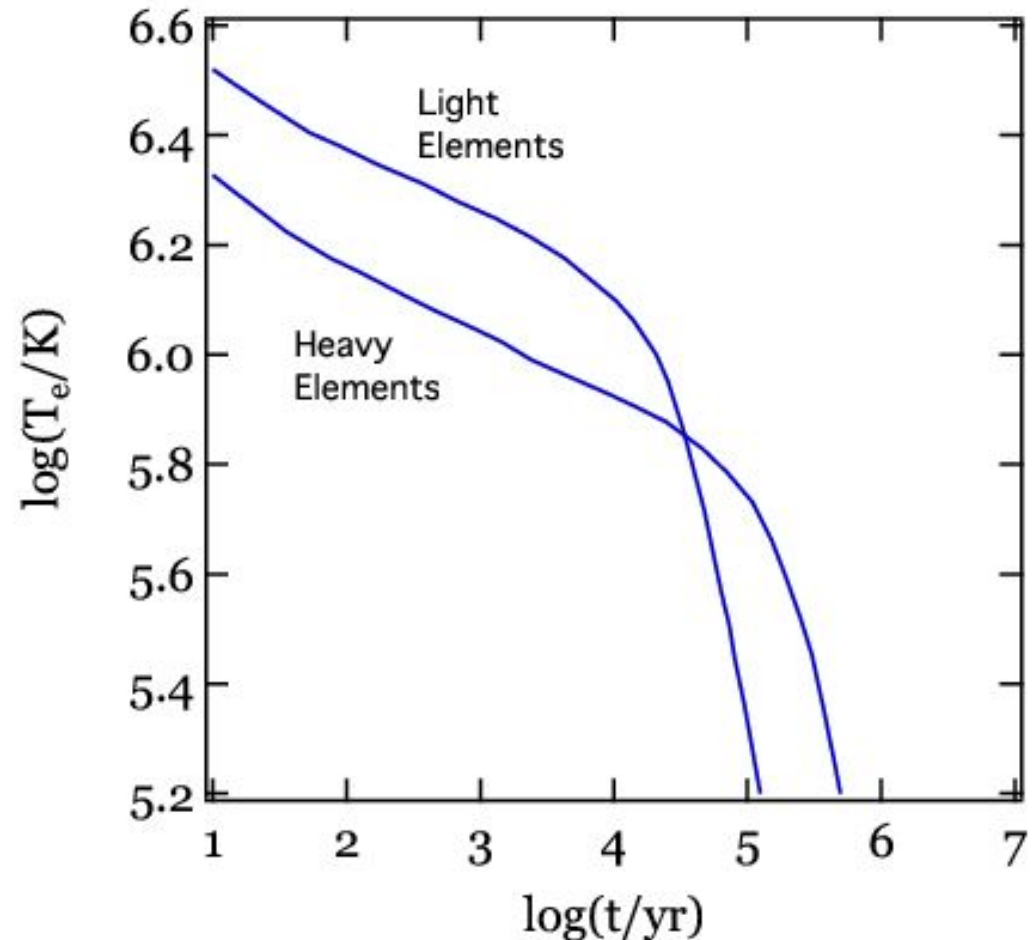
Recap / Takeaways

Too much information in too little time...

- Neutron stars are extreme objects which allow studying matter conditions beyond our lab possibilities.

- We can study them and measure their properties due to the strong connection between them.

- The measured radiation properties are connected to other quantities using models of EoS, gravitational equilibrium, rotation etc.

- We have not yet arrived to conclusions about their interiors, but we have the means and methods

What we had no time for

Other aspects of neutron stars...

Magnetars: Extremely powerful magnetic fields 1E13-1E15 Gauss, about 1E15 times that of Earth. They might be a stage in the life of pulsars.
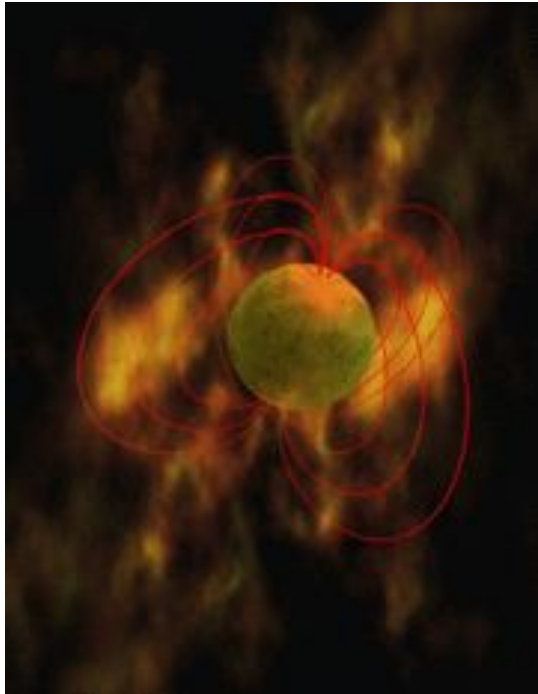
Neutron star mergers: Source of gravitational waves detected last year. Considered now the main origin of heavy elements in the periodic table.

Further reads

- "Neutron stars 1, Equation of State and Structure" by P. Haensel, A. Y. Potekhin, D. G. Yakolev, Springer 2006

- "Neutron stars and pulsars" by Freeman Dyson, Springer 2009

- "High- Energy Emission from Pulsars and their systems", SpringerLink 2011