PHY 7097 | Modern Astrophysics

Lecture VIII.

Neutron stars

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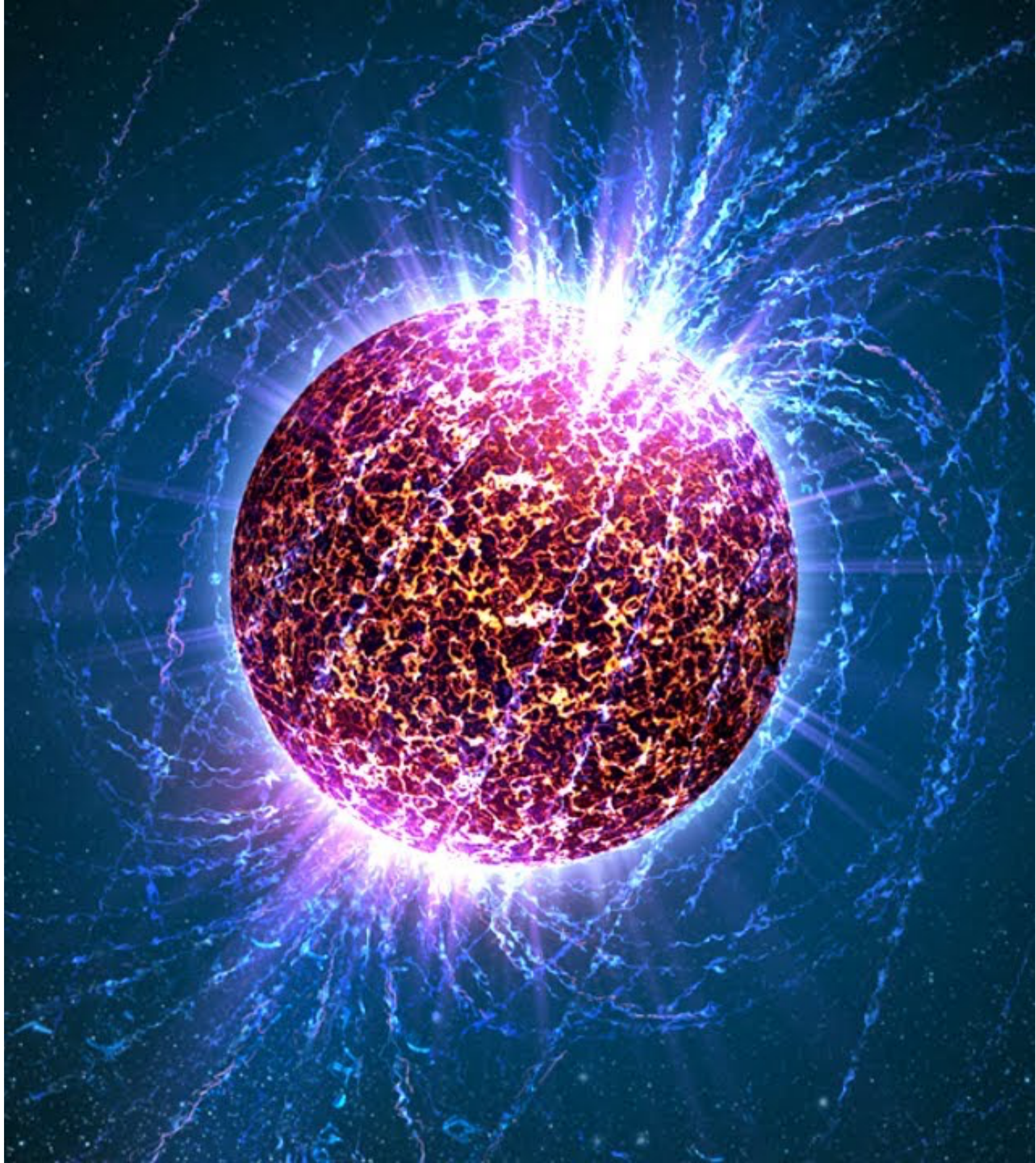


Homework

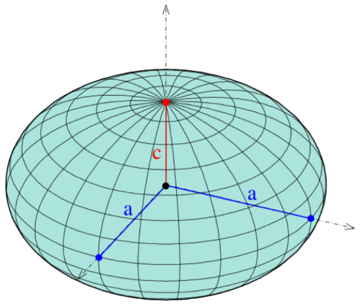
$$E_{\mathrm{GW}} \approx 10^{-2} M_\odot c^2 \left(\frac{\epsilon}{0.2}\right)^2 \left(\frac{f}{2\,\mathrm{kHz}}\right)^6 \left(\frac{M}{1.4\,M_\odot}\right) \left(\frac{R}{12\,\mathrm{km}}\right)^2 \left(\frac{\tau}{0.1\,\mathrm{s}}\right)$$

Assume realistic dependence of epsilon on f.

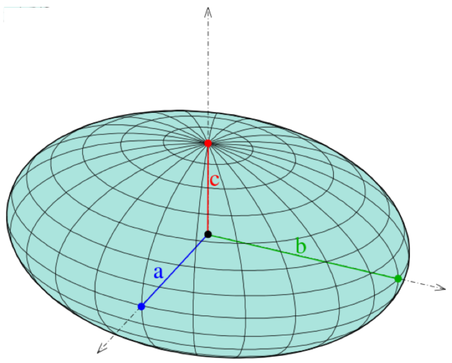
What will be the gravitational waveform?

Rotating Spheroids

MacLaurin spheroids

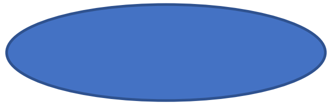


Jacobi spheroids
(or Dedekind spheroids)



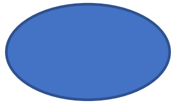
Dynamically unstable:

- $T/|W| > 2.7$
- $e > 0.95$ (1:3:3)



Secular instability:

- $T/|W| > 1.4$
- $e > 0.81$ (1:1.7)



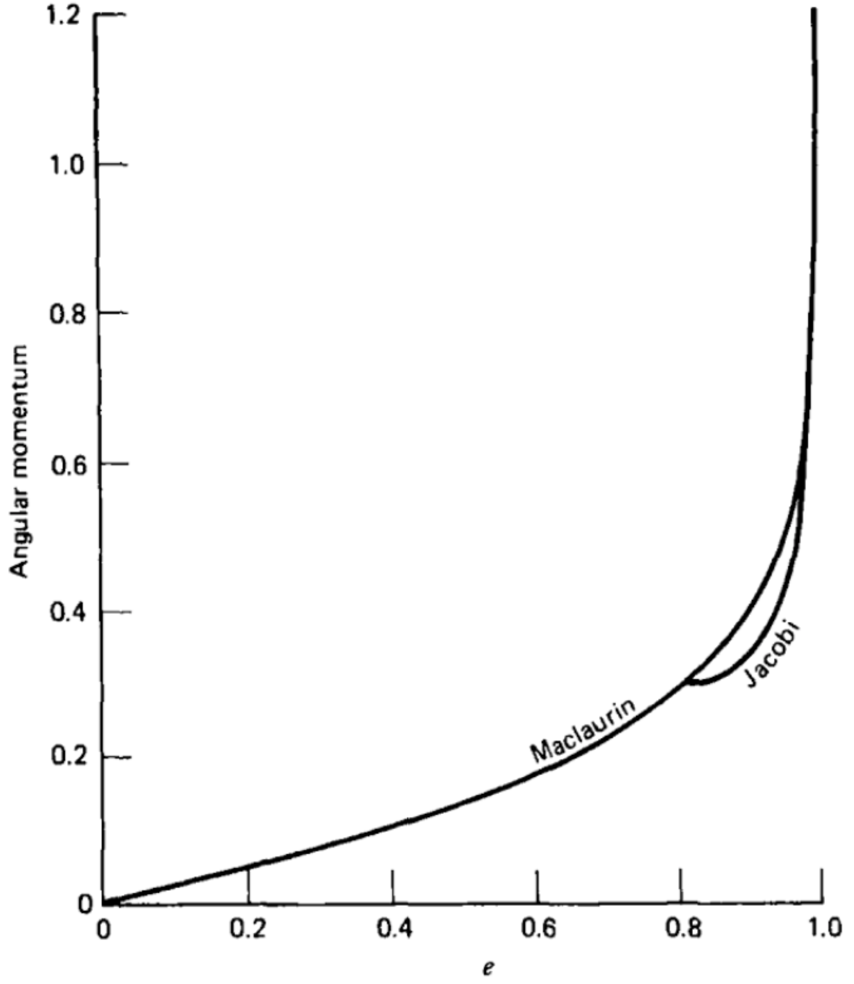
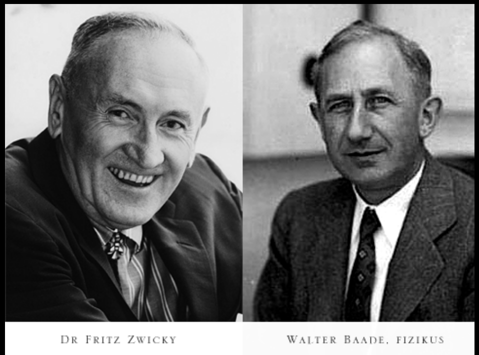
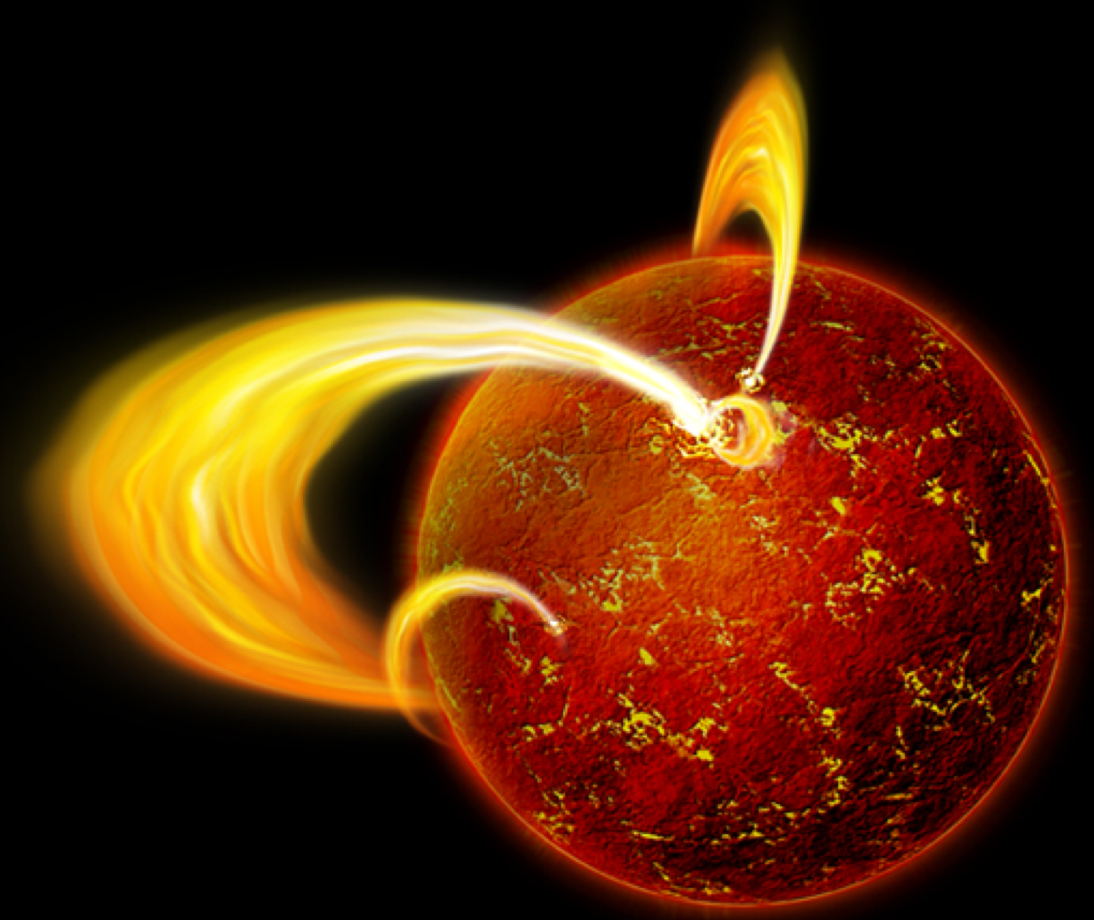


Figure 7.3 The angular momentum [in the unit $(GM^3\bar{a})^{1/2}$] along the Maclaurin and the Jacobian sequences. Here $\bar{a}$ is related to the three semimajor axes by $\bar{a} \equiv (abc)^{1/3}$; for a Maclaurin spheroid $a = b$. The abscissa in both cases is the eccentricity defined by Eq. (7.3.9). [Reproduced, with permission, from *Ellipsoidal Figures of Equilibrium* by S. Chandrasekhar, published by Yale University Press. © 1969 by Yale University.]

neutron stars





proposed in 1934, ~1 year after the
discovery of the neutron by James Chadwick!

neutron

Letters to the Editor

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Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about $0 \cdot 3$ (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3 \cdot 2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52×10^6 electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about $1 \cdot 3$ mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about 3×10^9 cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting α-particle appear to have a much smaller range than those ejected by the forward radiation. This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

The Oldoway Human Skeleton

A LETTER appeared in NATURE of Oct. 24, 1931, signed by Messrs. Leakey, Hopwood, and Reck, in which, among other conclusions, it is stated that "there is no possible doubt that the human skeleton came from Bed No. 2 and not from Bed No. 4". This must be taken to mean that the skeleton is to be considered as a natural deposit in Bed No. 2, which is overlaid by the later beds Nos. 3 and 4, and that all consideration of human interment is ruled out.

If this be true, it is a most unusual occurrence. The skeleton, which is of modern type, with filed teeth, was found completely articulated down even to the phalanges, and in a position of extraordinary contraction. Complete mammalian skeletons of any age are, as field palæontologists know, of great rarity. When they occur, their perfection can usually be explained as the result of sudden death and immediate covering by volcanic dust. Many of the more or less perfect skeletons which may be seen in museums have been rearticulated from bones found somewhat scattered as the result of death from floods, or in the neighbourhood of drying water-holes. We know of no case of a perfect articulated skeleton being found in company with such broken and scattered remains as appear to be abundant at Oldoway. Either the skeletons are all complete, as in the *Stenomylus* quarry at Sioux City, Nebraska, or are all scattered and broken in various degrees, as in ordinary bone beds. The probability, therefore, that the Oldoway skeleton represents an artificial burial is thus one that will occur to palæontologists.

The skeleton was exhumed in 1913, and published photographs show that the excavation made for its disinterment was extensive. It is, therefore, very difficult to believe that in 1931 there can be reliable evidence left at the site as to the conditions under which it was deposited. If naturally deposited in Bed No. 2, the skeleton is of the highest possible importance, because it would be of pre-Mousterian age, and would be in the company of *Pithecanthropus* and the Piltdown, Heidelberg, and Peking men, all of whose remains are fragmentary to the last degree. Of the few other human remains for which such antiquity is claimed, the Galley Hill skeleton and the Ipswich skeleton are, or apparently were, complete. The first of these was never seen *in situ* by any trained observer, and the latter has, we believe, been withdrawn by its discoverer. The other fragments, found long ago, are entirely without satisfactory evidence as to their mode of occurrence.

½ page
1 Nobel prize

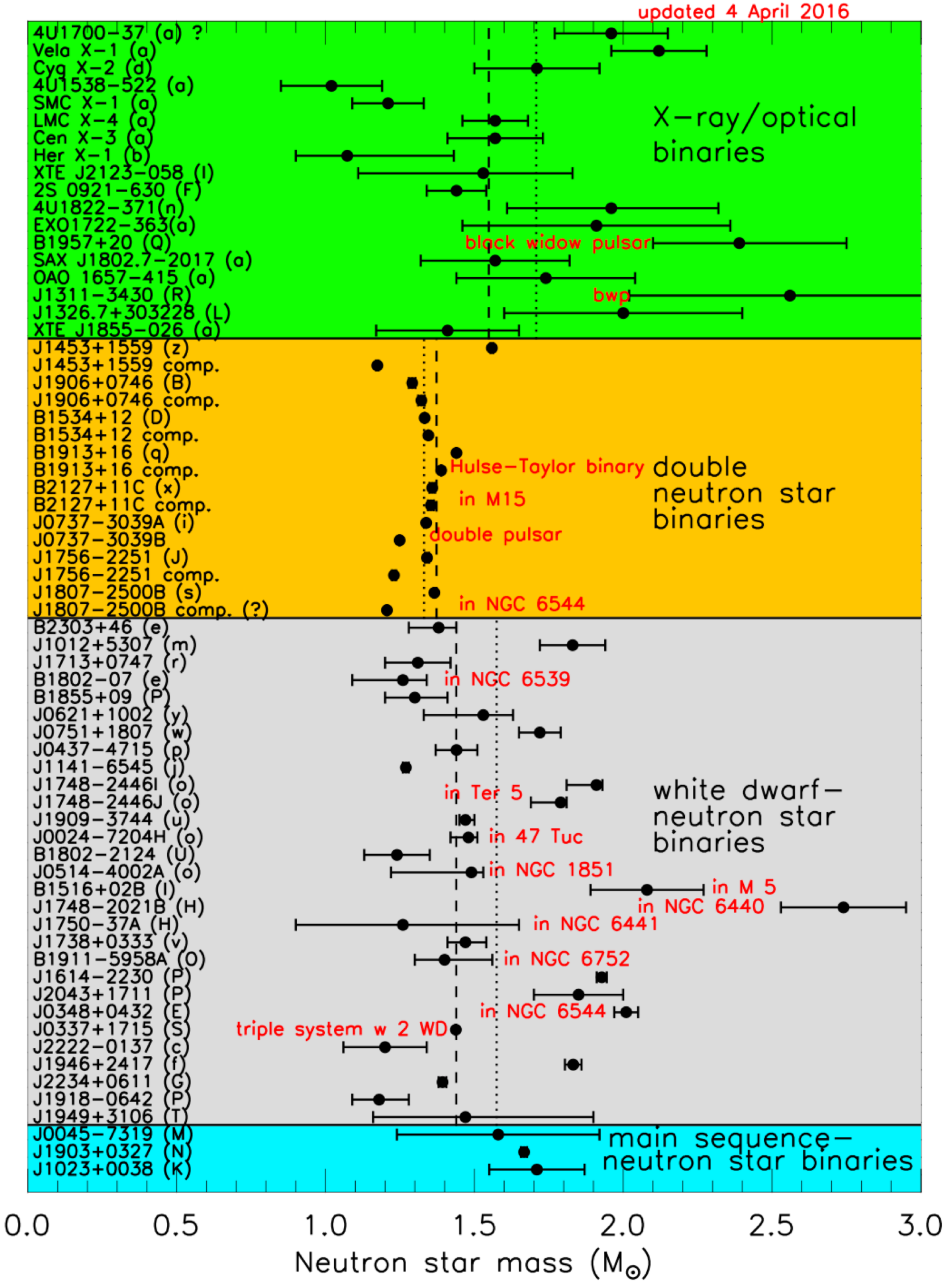
Properties - Mass

There should be a lower limit just from formation. --- 1.1 Msun

Maximum observed mass --- ~2 Msun

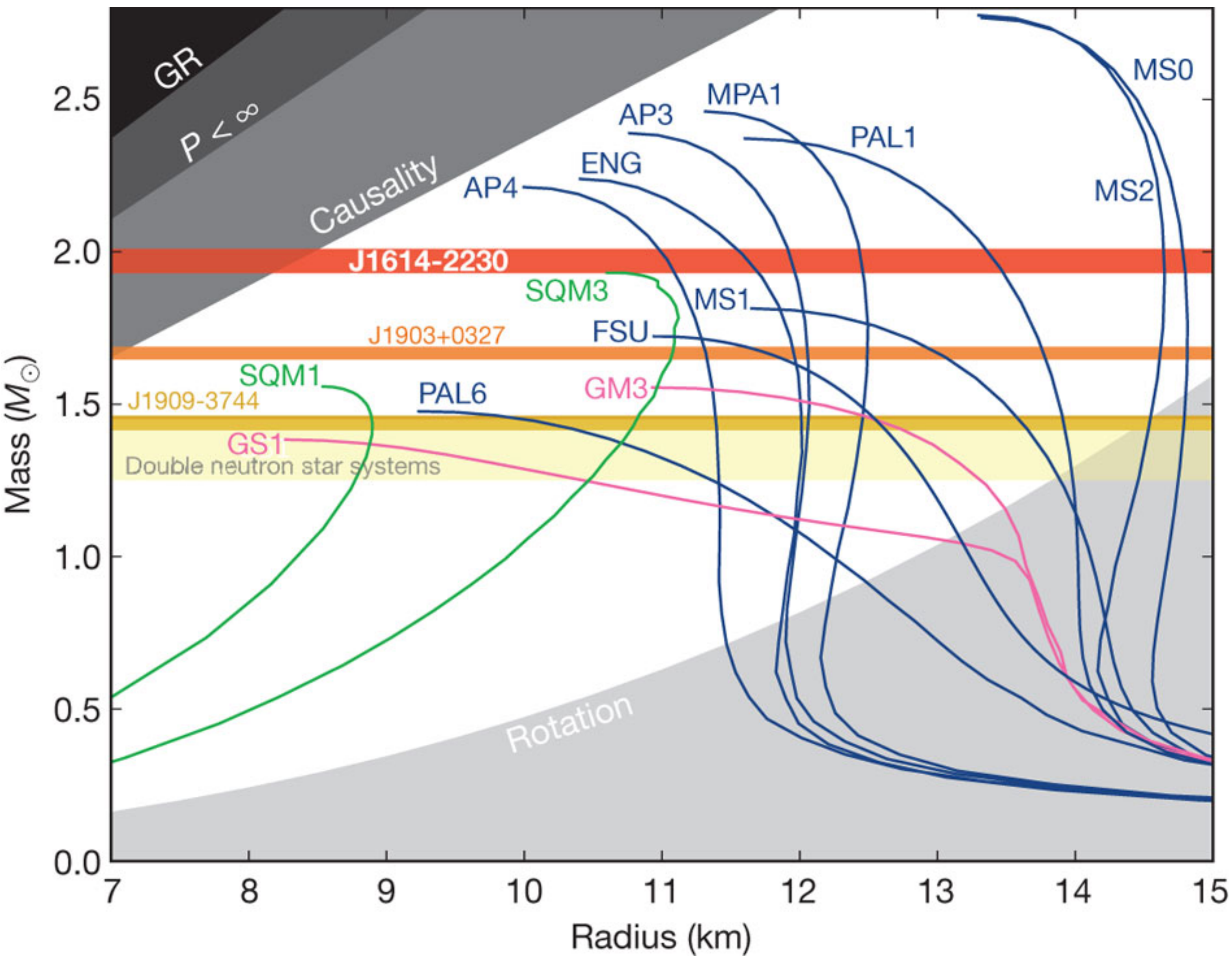
Maximum mass from GW170817 --- 2.17 Msun

Mass distribution depends on NS companion



https://stellarcollapse.org/nsmasses

Properties – Equation of state



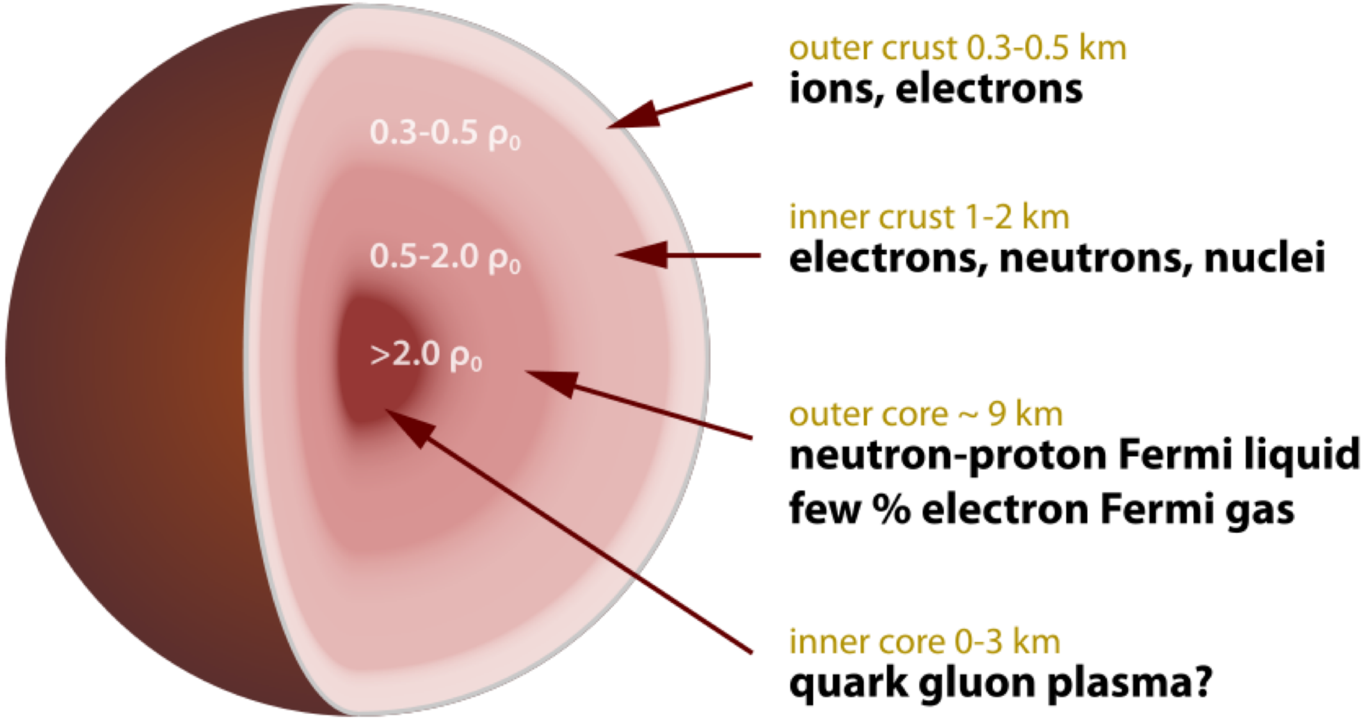
Structure

Mostly unknown

There is likely a NS “crust”

There is likely a NS “crust” and core

Quark-gluon plasma in core?



Robert Schulze

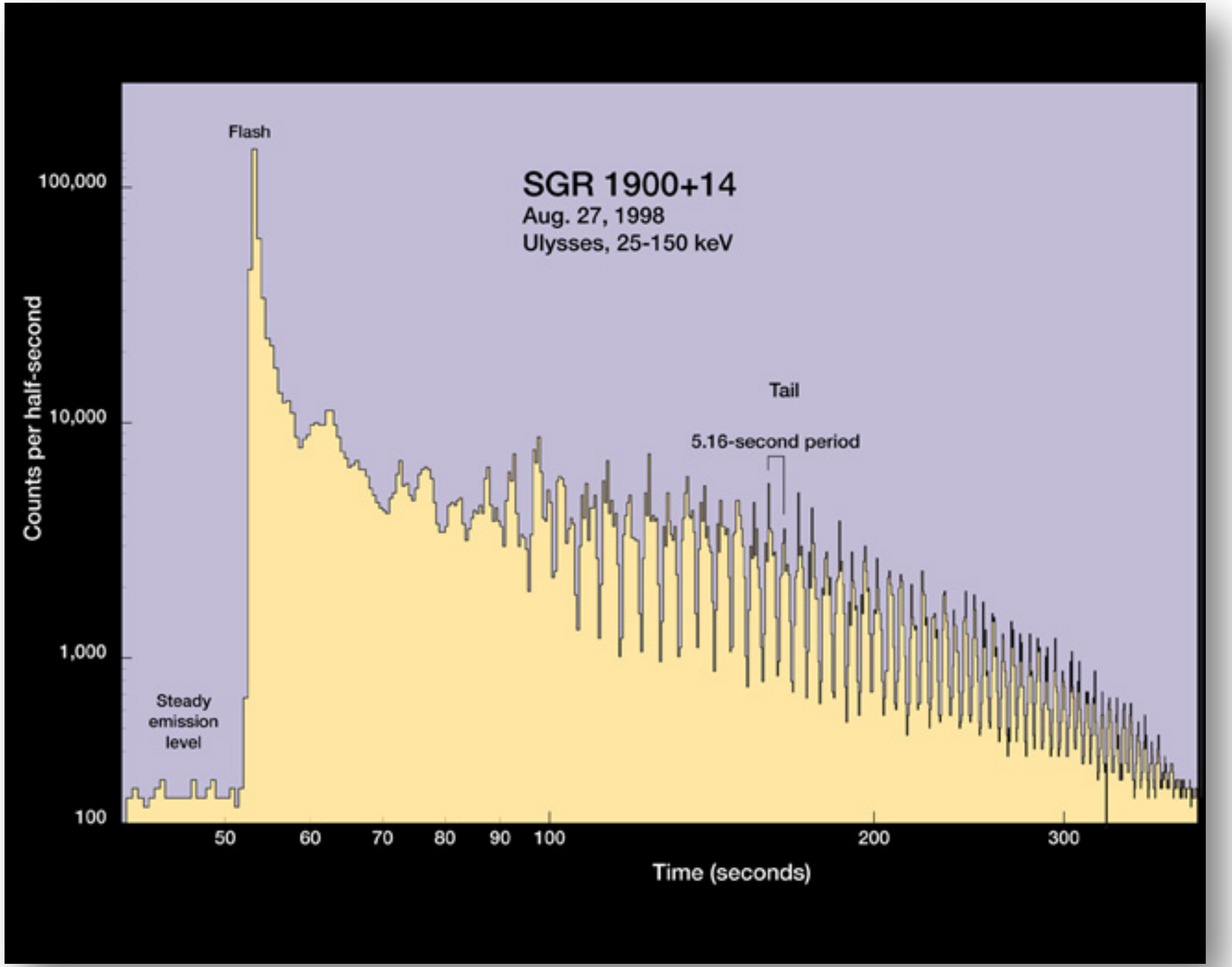
Soft gamma repeaters

Occasional outbursts of gamma rays

Quasi-periodic oscillations

Starquakes??

Magnetic field reorganization?



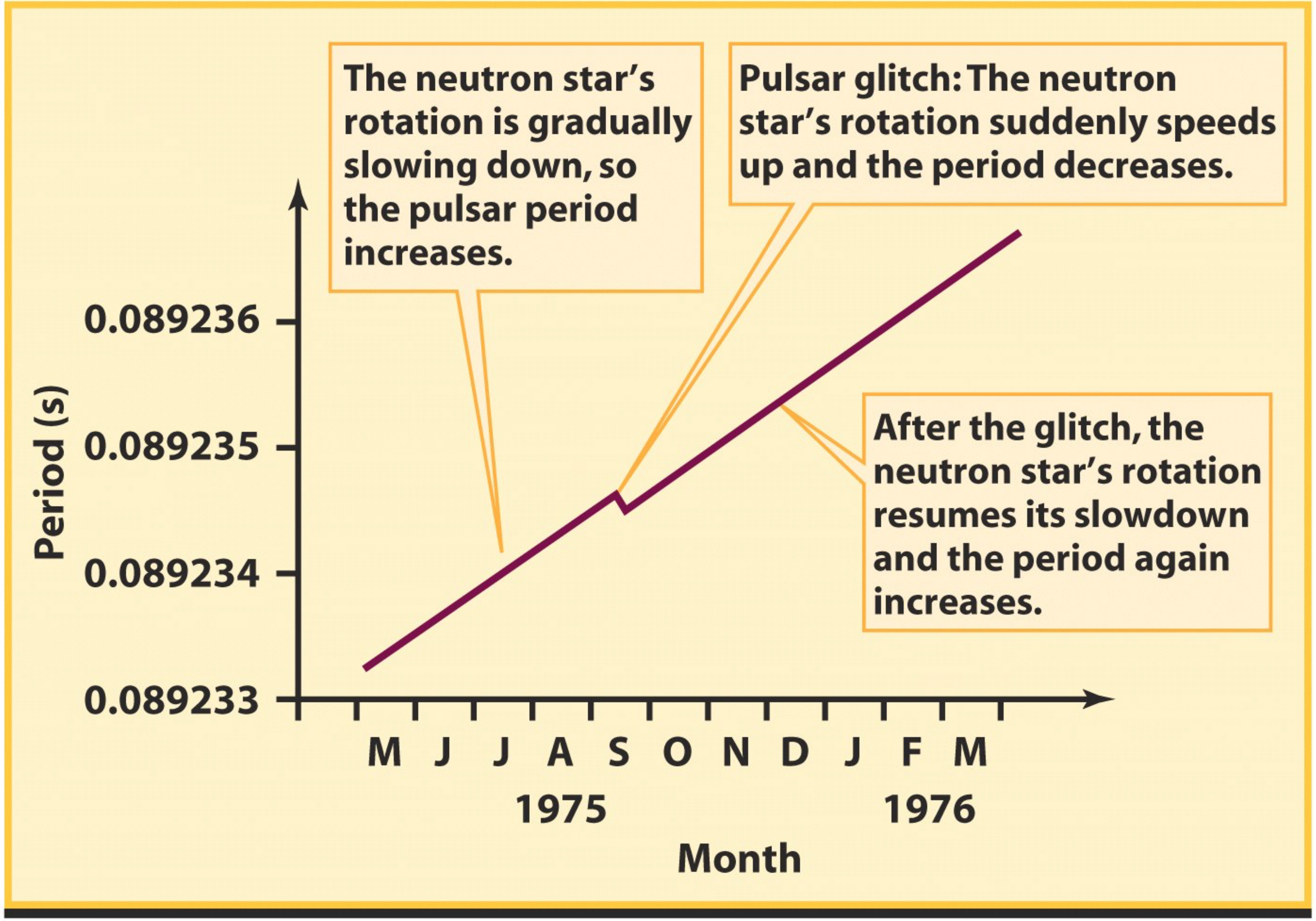
Glitches

<u>Starquakes?</u>
NS crust ruptures
→ radius decreases
→ faster rotation

Core reorganization that releases energy?

<u>Anti-glitches</u>
Unclear??

Bad for pulsar timing



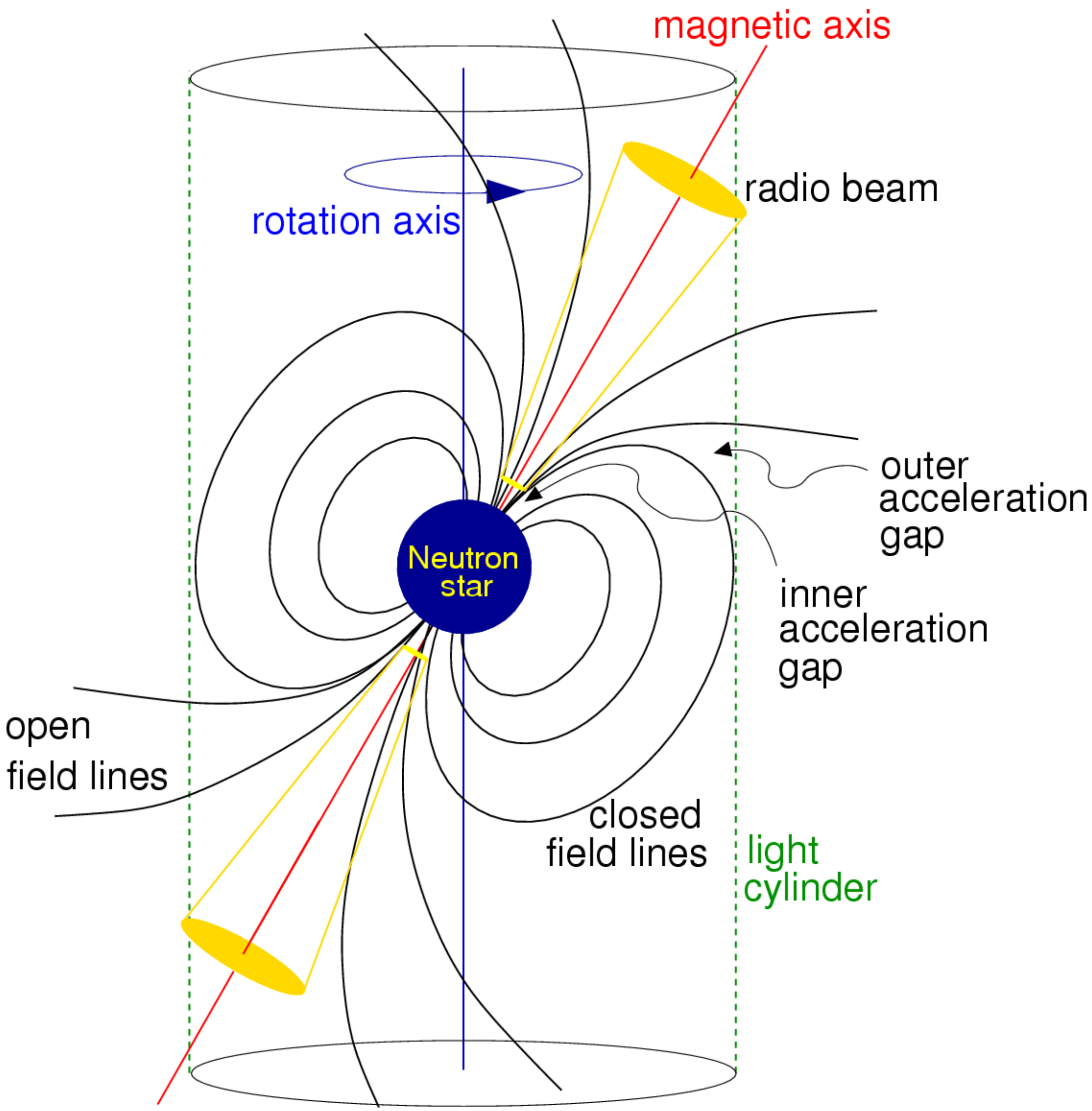
Pulsars

Very regular period

Formed in a supernova

After sufficient slowdown the radio pulsar mechanism is turned off.

Energy source:
- Rotation
- Accretion
- Magnetic fields



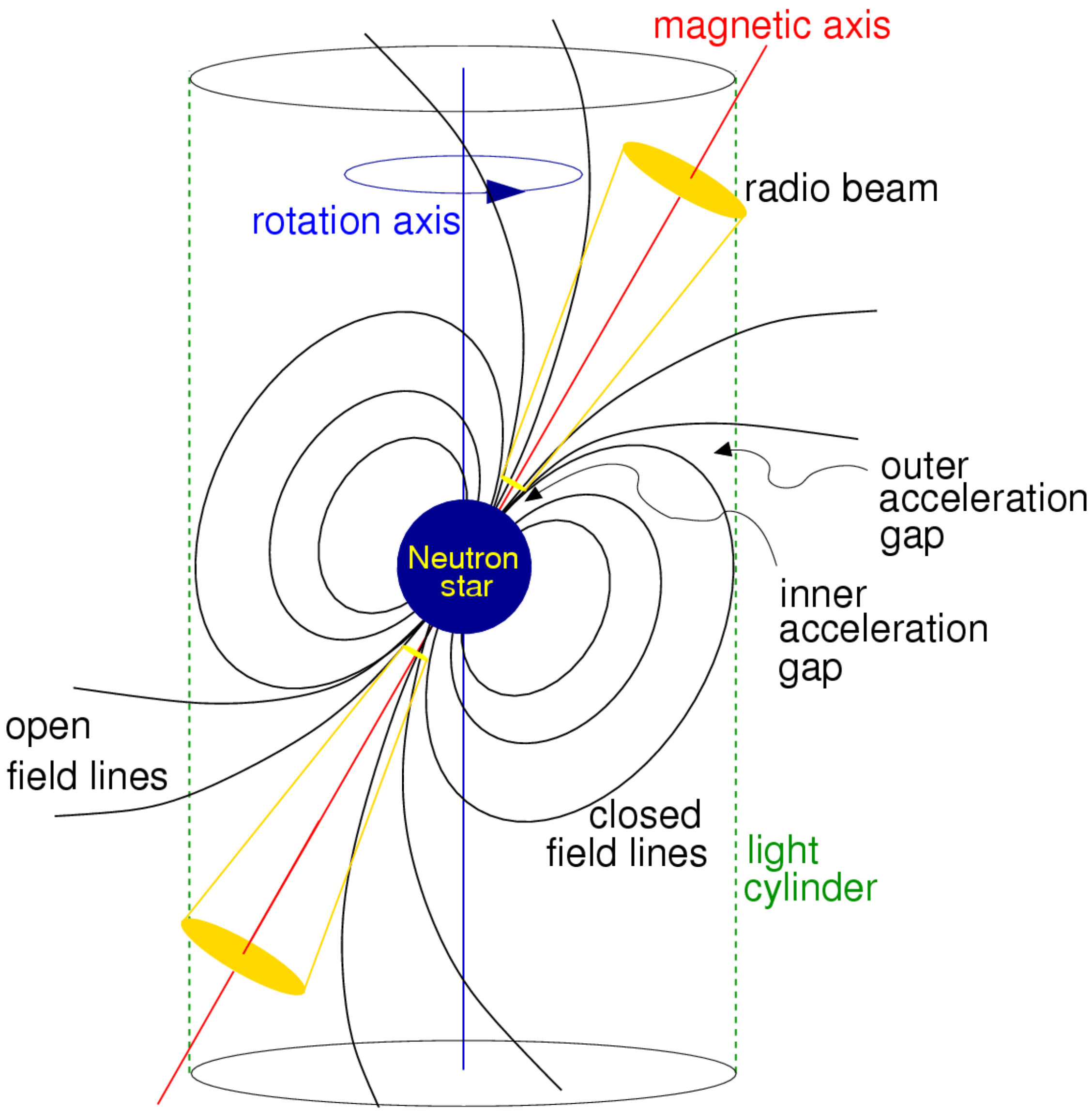
http://www.cv.nrao.edu

Pulsars

If the magnetic dipole is inclined from the rotation axis
→ Magnetic dipole radiation

We can find the magnetic field strength of the NS from the spindown rate.

$$\left(\frac{B}{\mathrm{Gauss}}\right) > 3.2 \times 10^{19} \left(\frac{P\dot{P}}{\mathrm{s}}\right)^{1/2}$$



http://www.cv.nrao.edu/course/astr534/Pulsars.html

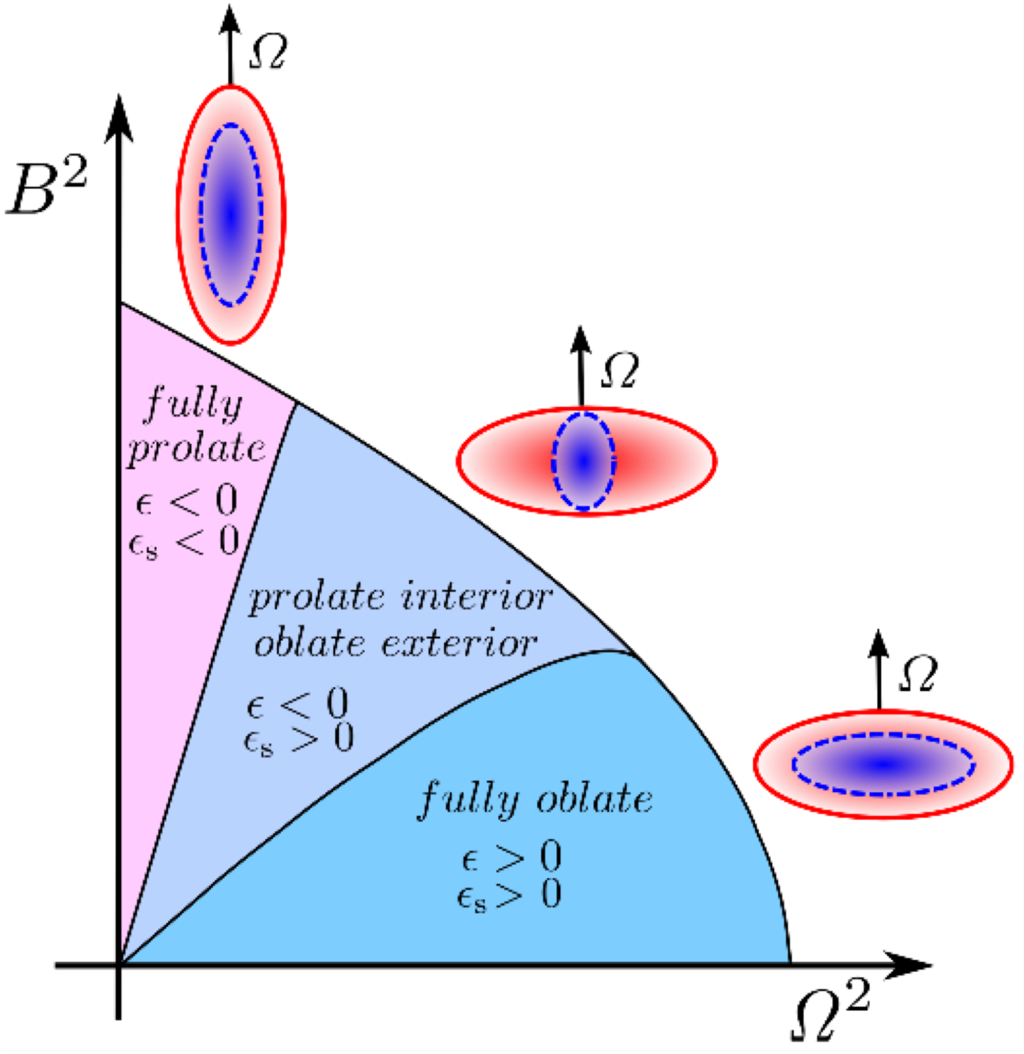
Magnetic deformation

If the magnetic dipole is inclined from the rotation axis
→ Magnetic dipole radiation

We can find the magnetic field strength of the NS from the spindown rate.

$$\epsilon = -\frac{3}{2}\varepsilon = \frac{1}{18}\frac{B^2 R^4}{GM^2}$$
$$\approx 10^{-12}\left(\frac{R}{10\,\mathrm{km}}\right)^4\left(\frac{M}{1.4\,\mathrm{M}_\odot}\right)^{-2}\left(\frac{\bar{B}}{10^{12}G}\right)^2$$

Haskell+ 2002



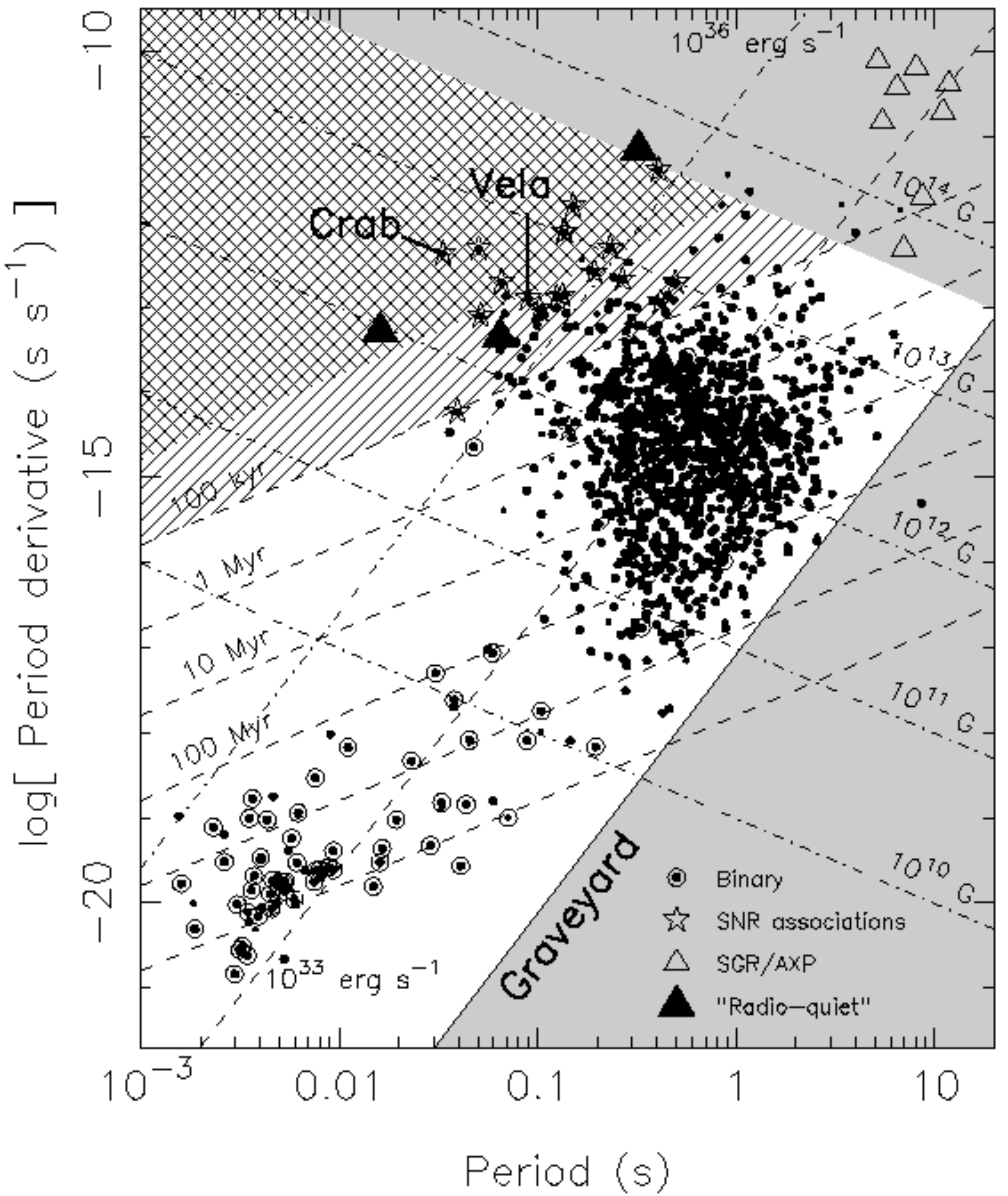
Fieben & Rezzolla 2014

Spin Down

Longer period typically means higher spindown rate.

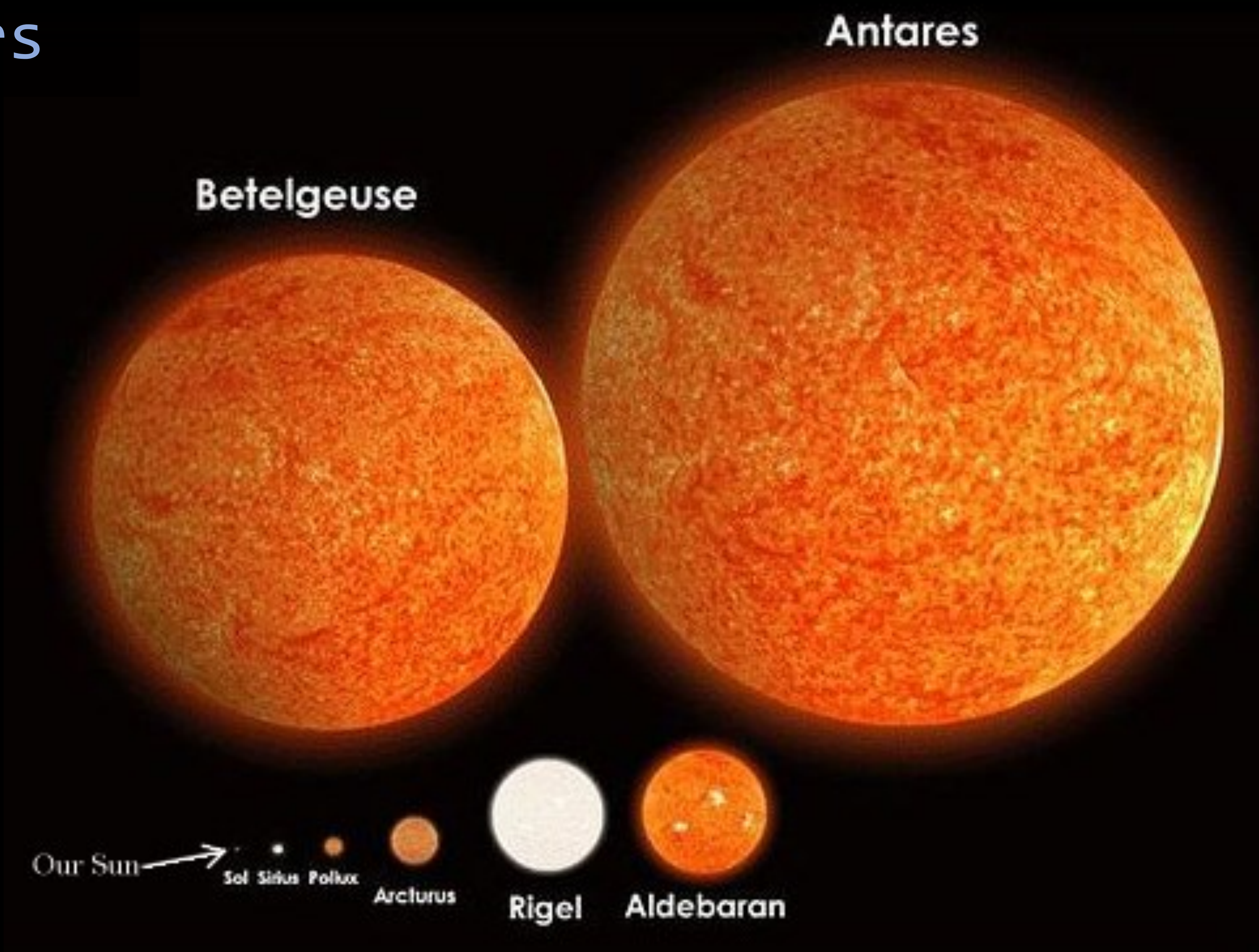
If luminosity ~ spin down power
→ <u>rotation powered</u>

Spindown rate and period gives us an estimate on the <u>characteristic age</u> of the pulsar.



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

dark stars



John Michell (1783)

Mitchell: Escape velocity for sufficiently massive+small stars would escape the speed of light.

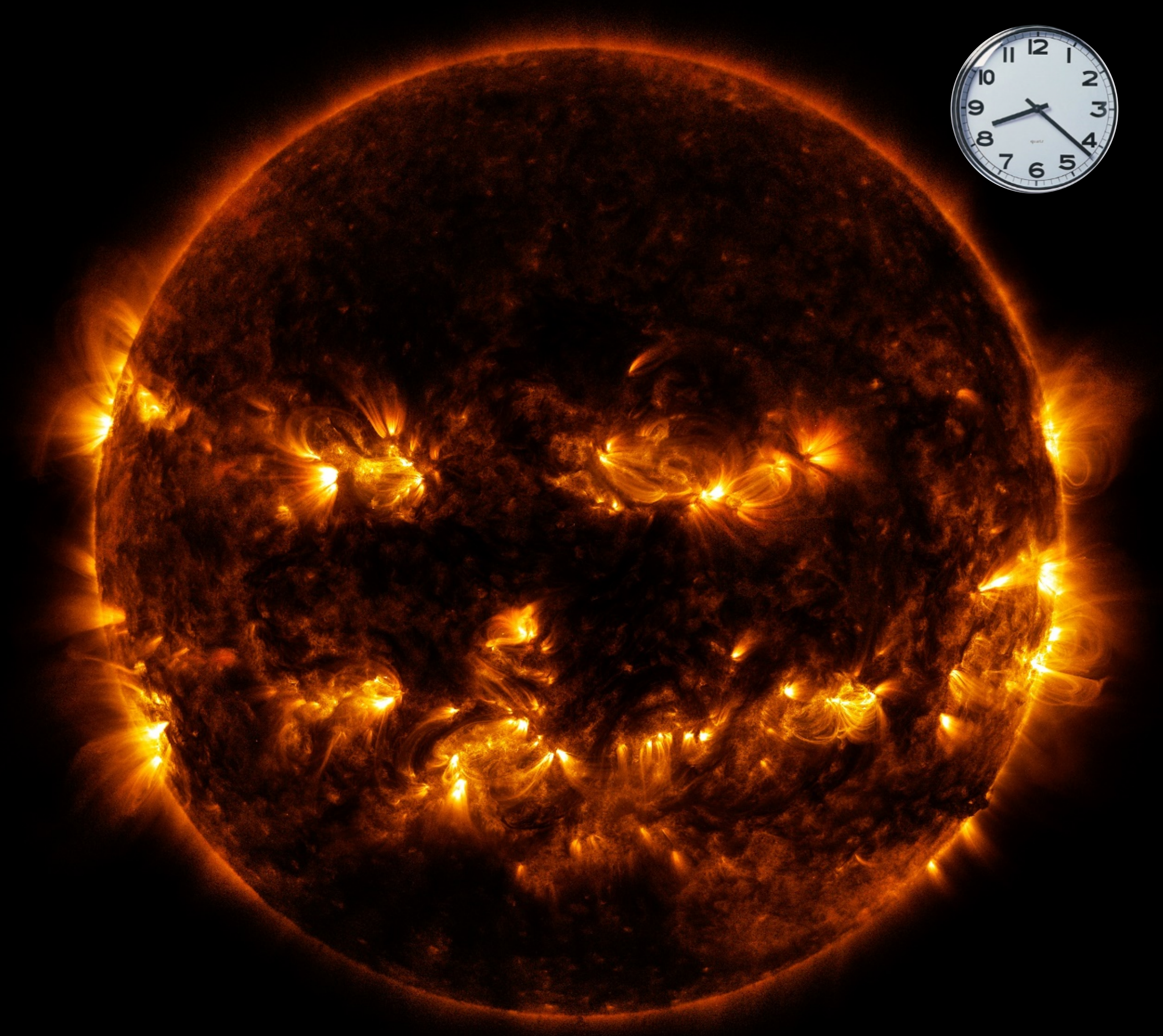
Eddington: showed that very large stars like Betelgeuse cannot possibly have the density of the Sun.

Escape velocity

At what radius would an object with the mass of the Sun become “dark?”
(assuming Newtonian gravity)

$$v_e = \sqrt{\frac{2GM}{r}}$$

“frozen stars”



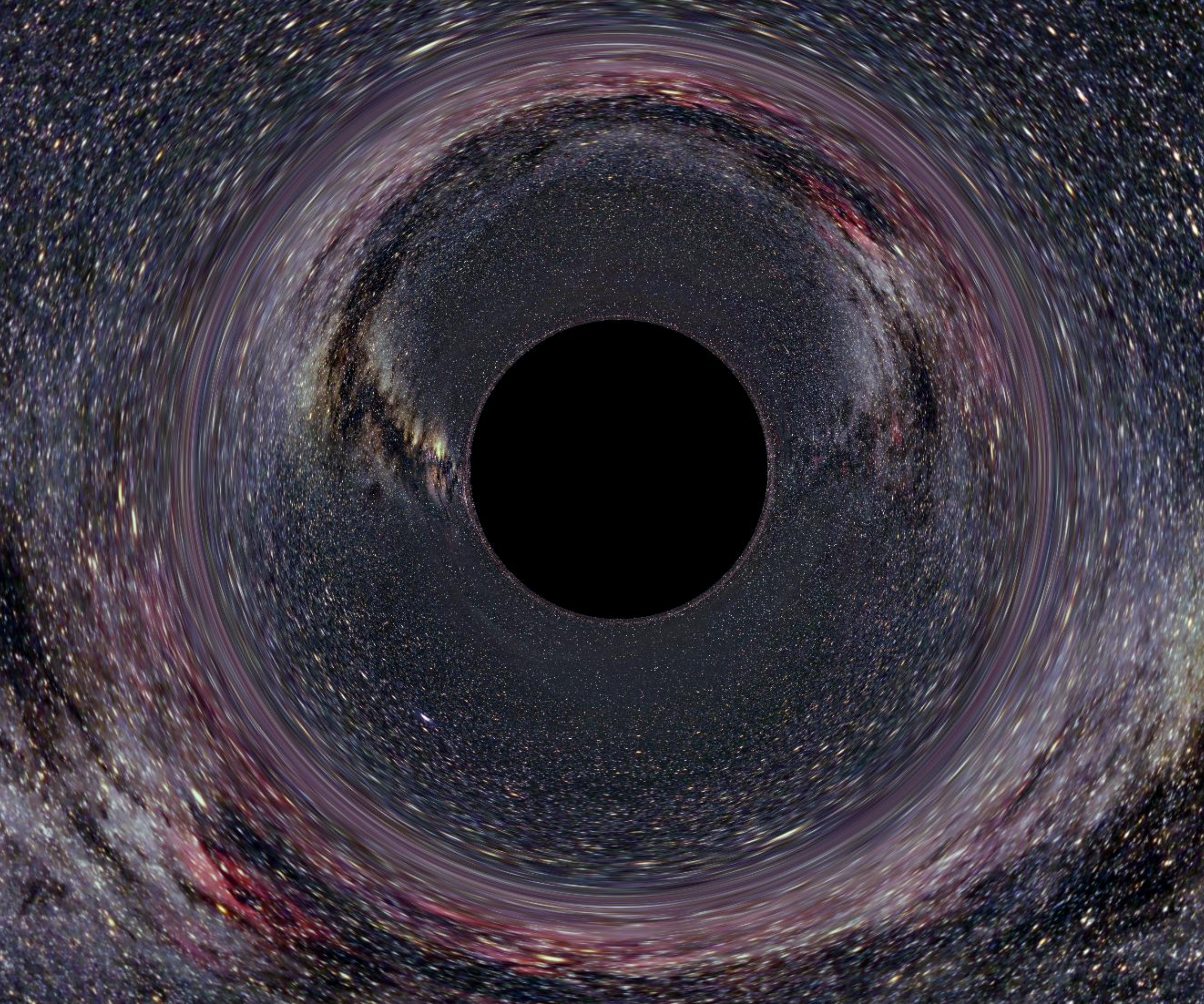
There is a mass limit above which gravitational collapse is inevitable. (Chandrasekhar 1931 for white dwarfs)

I think that there should be a law of Nature to prevent the star from behaving in this absurd way. (Eddington 1935)

…all stars heavier than 1SM, certainly possess regions in which the laws of quantum mechanics (and therefore quantum statistics) are violated.

There is a mass limit above which gravitational collapse is inevitable. (Tolman–Oppenheimer-Volkoff in 1939 for neutron stars)

→ Time would stop for the collapse at the Schwarzschild radius → frozen stars



1962 – discovery of compact X-ray sources.

1963 – discovery of quasars.

1963 - Kerr solution.

1965 - Newman solution.

1968 – discovery of pulsars.

1968 - Wheeler coins the name “black hole.”

1970’s – observation of X-ray binary Cygnus X-1.