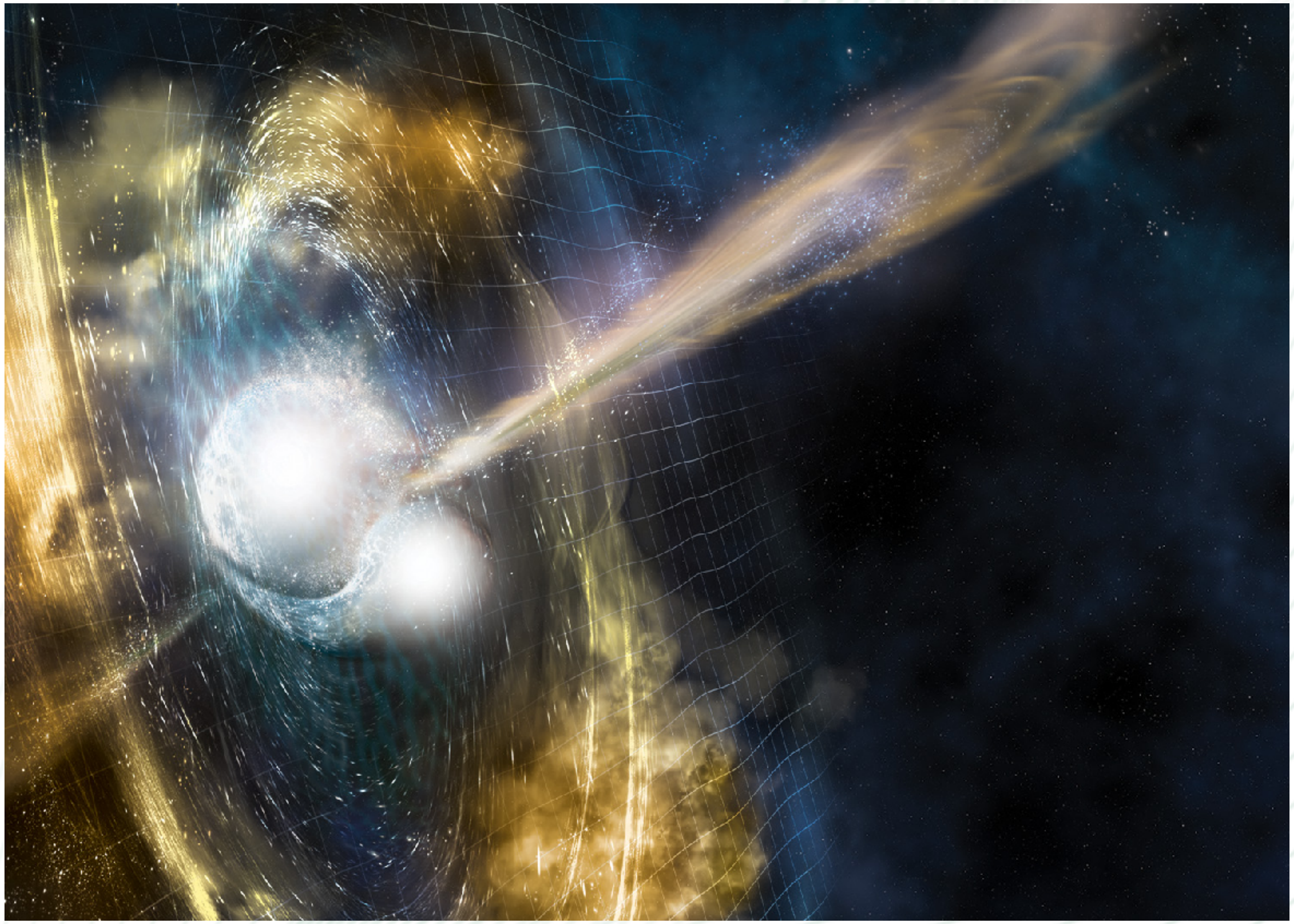
Neutron Stars and Gravitational Waves - Part 1



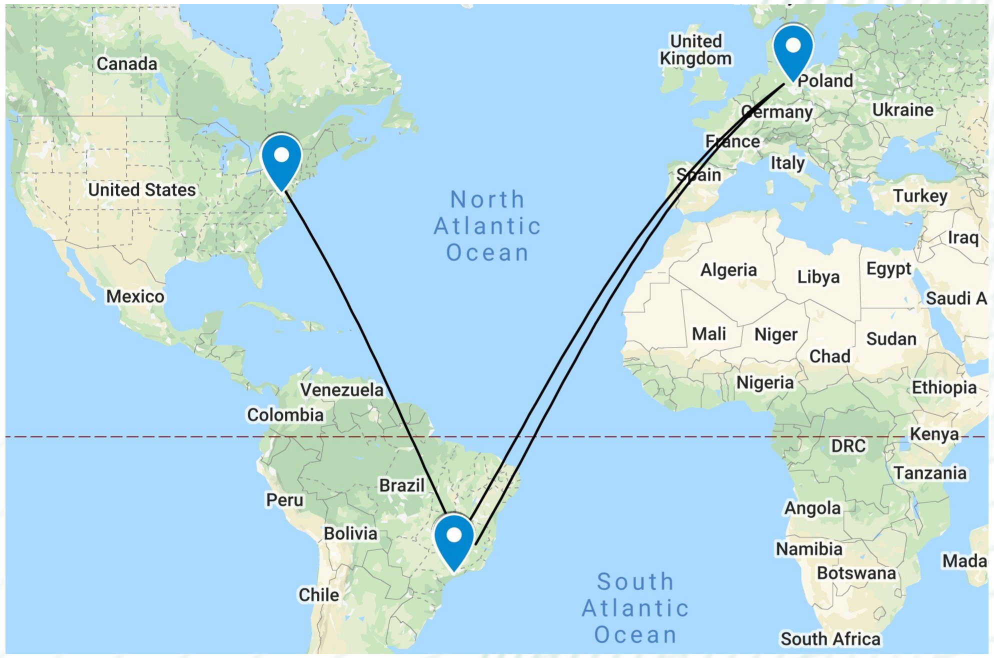
Partner

Cecilia Chirenti

Fermi Summer School - Lewes DE - June 2 2022

Introductions

4 (Visiting) Associate Research Scientist UMD/GSFC/CRESST



2 Postdoc at MPI for Gravitational Physics Albert Einstein Institute (AEI), Germany

3 Assistant (and then Associate) Professor of Applied Mathematics at UFABC, Brazil

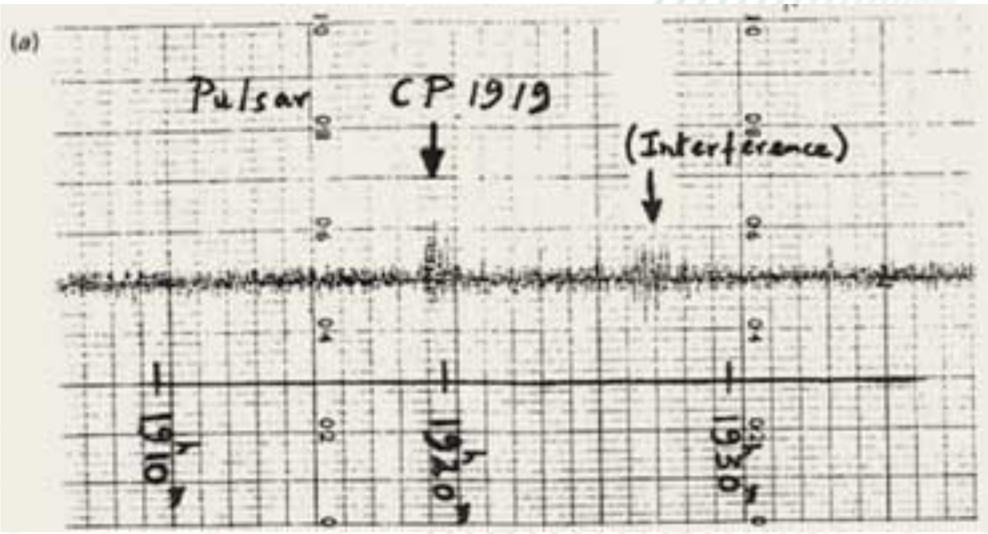
1 Physics BSc and PhD at University of São Paulo, Brazil

Neutron stars: how it all began

Jocelyn Bell - 1967

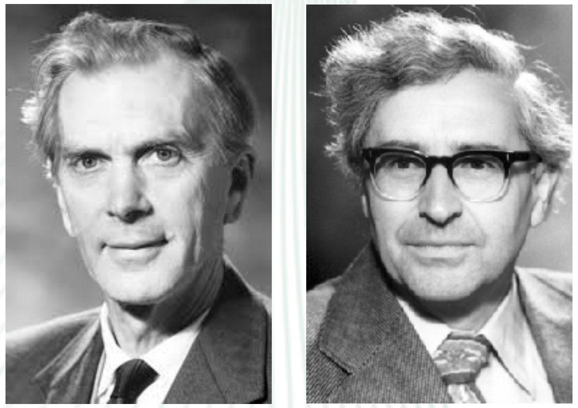
Little Green Men?
LGM1, LGM2, LGM3

The discovery of pulsars



dados

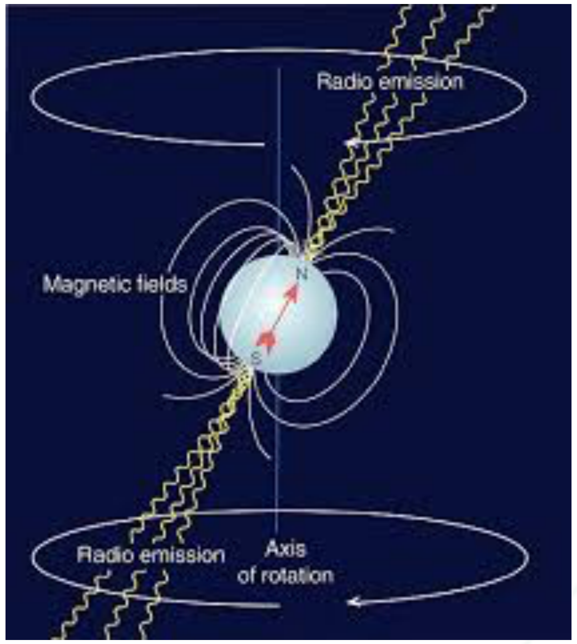
“telescope” in Cambridge



Physics Nobel Prize 1974

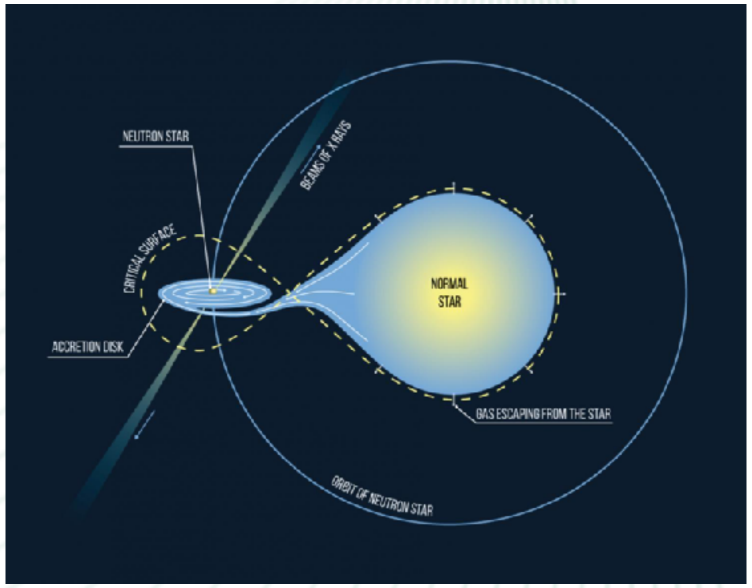
Breakthrough Prize 2018

How do we observe neutron stars?



Radio pulsars

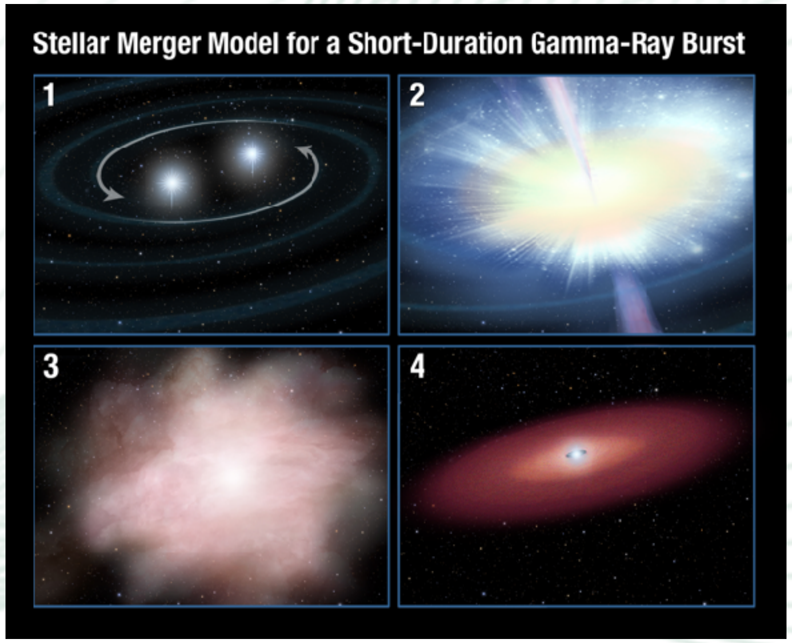
Crab Nebula



X-ray binaries

Gravitational waves

LIGO



Kilonova

Short gamma-ray burst

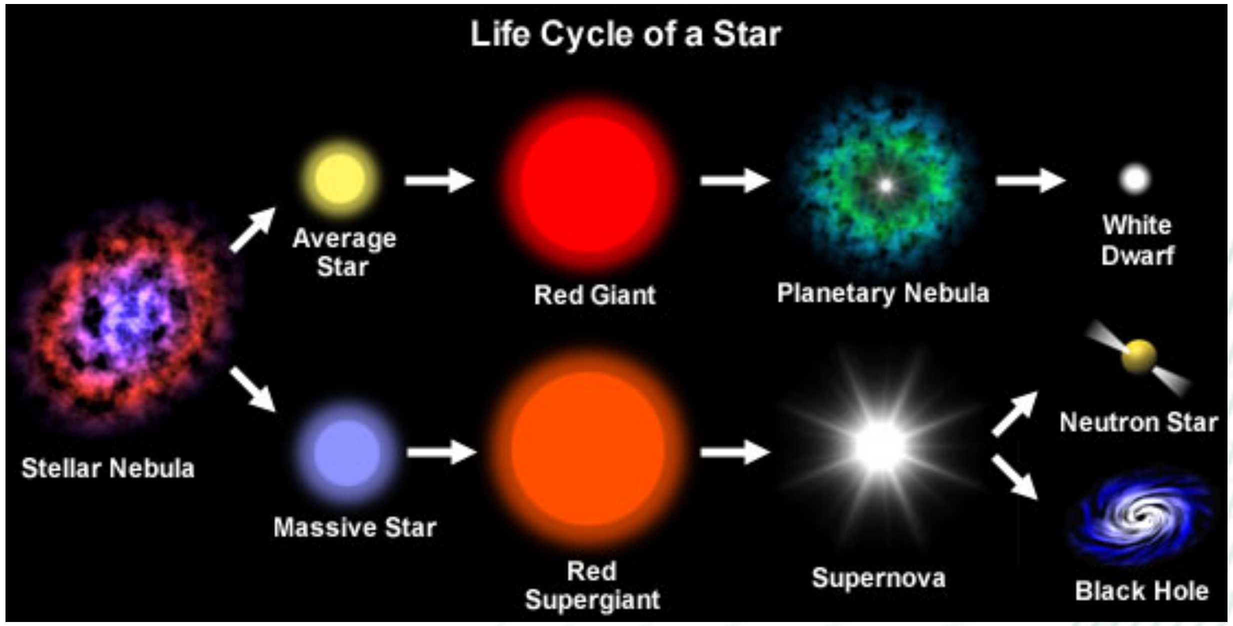
Fermi

How are neutron stars born?
Supernovae! (*not* type Ia)

Poll:

Are supernovae rare events?
Estimate:
One per galaxy per century!

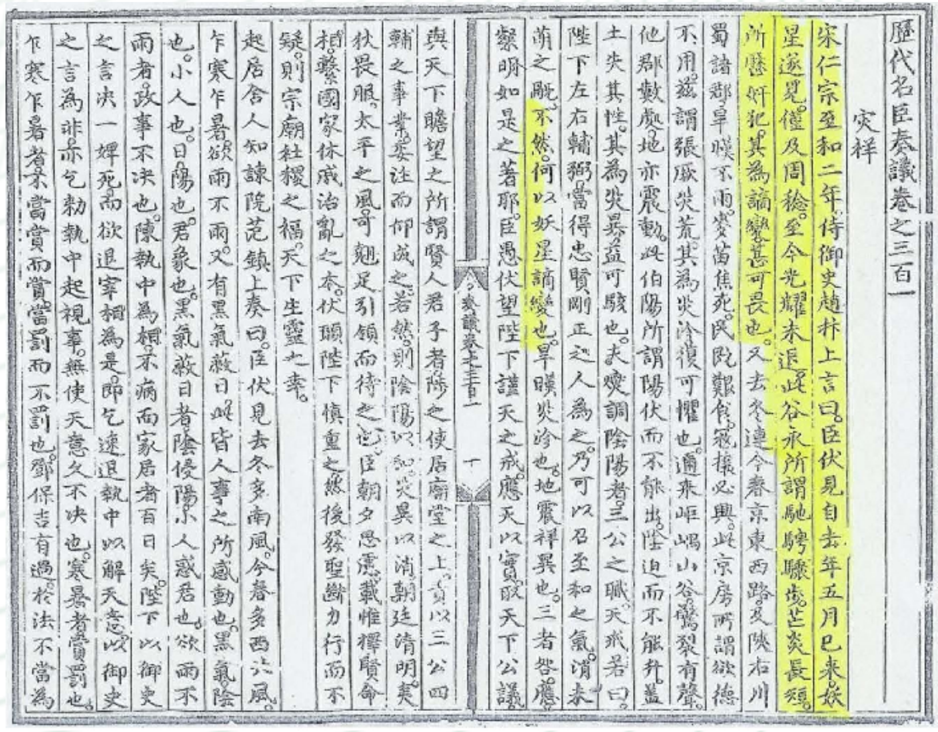
What is the total number of supernovae per second in the universe?
a) 30,000; b) 30; c) 0.03; d) 0.00003;
e) 0.00000003 /s



The initial mass determines the fate of the star

1st supernova observation in 184 AD!

“The heavens are not immutable?”



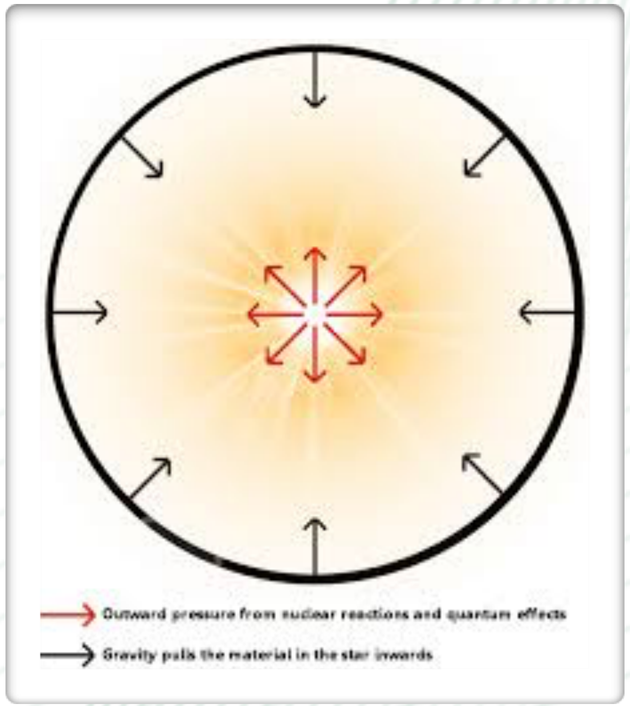
The crab supernova was observed by Chinese astronomers in 1054 AD: a guest star

Why neutrons?

S. Chandrasekhar and wife - 1939

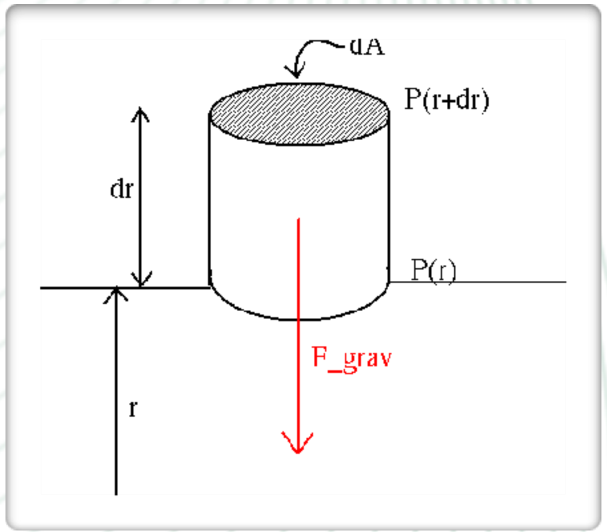
Pauli's exclusion principle
(fermions)

Stellar equilibrium



Gas pressure balances the gravitational attraction

$$F_{\text{gas}} = F_{\text{gravitational}}$$



$$F_{\text{gas}} = \frac{P}{A}, \quad m = \rho V$$

$$F_{gravitational} = -\frac{GMm}{r^2}$$

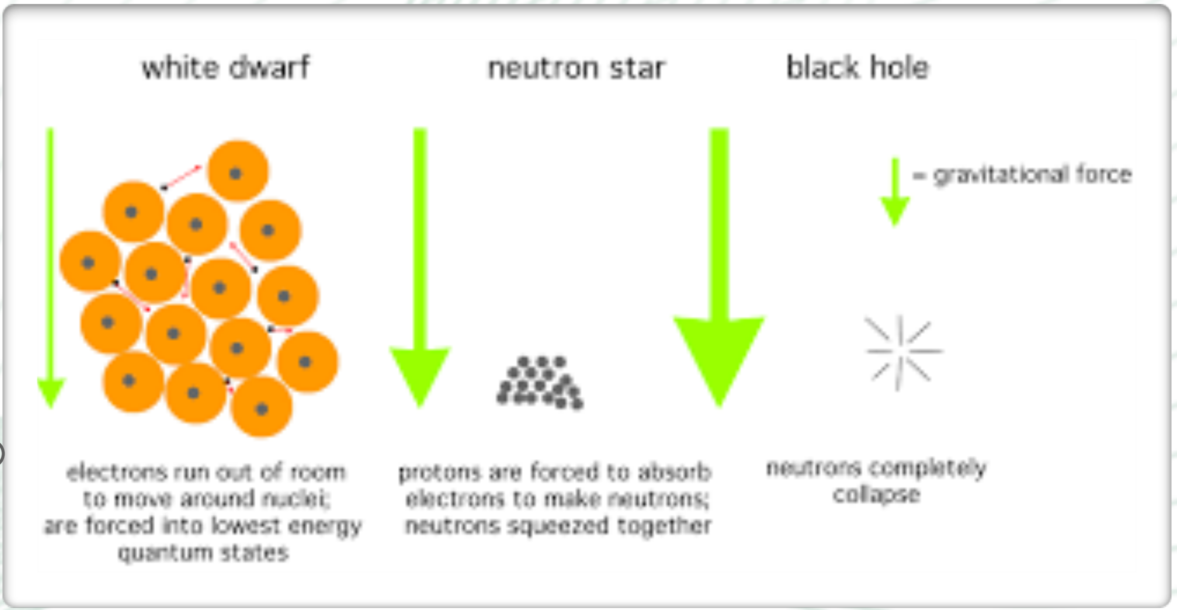
$$\boxed{\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2}}$$

Hydrostatic equilibium

Maximum mass:

white dwarfs $\sim 1.4 M_\odot$
(Chandrasekhar limit)

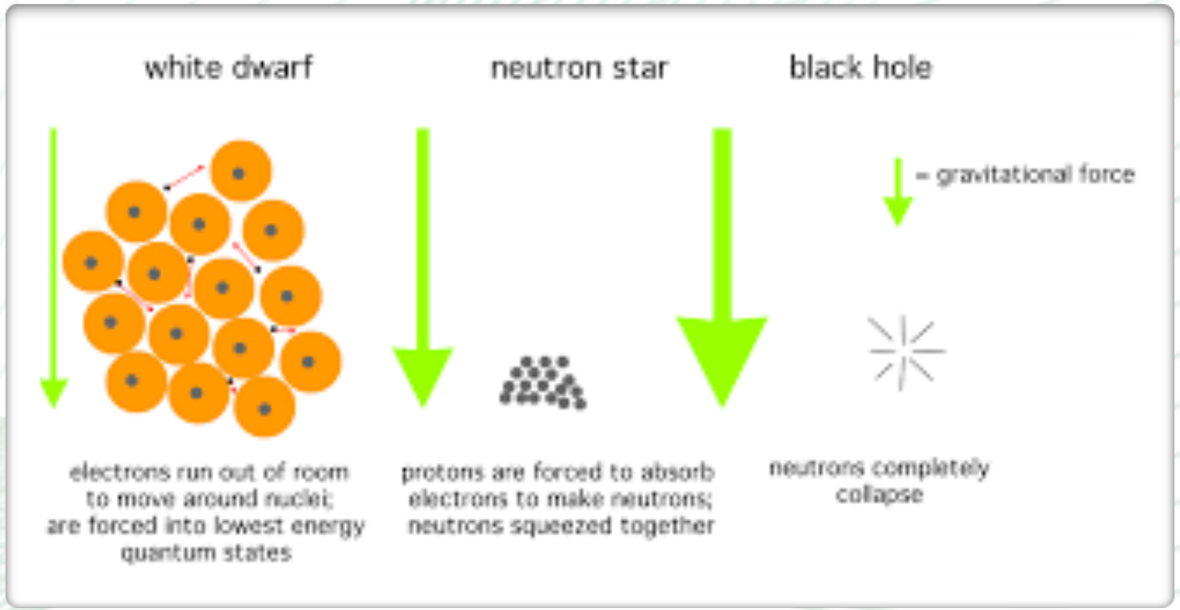
neutron stars $\sim 2.2 - 3 M_\odot$



Group discussion question

Can there be stars more compact than neutron stars?

What would they look like?

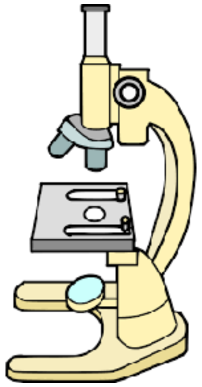


electrons run out of room to move around nuclei; are forced into lowest energy quantum states

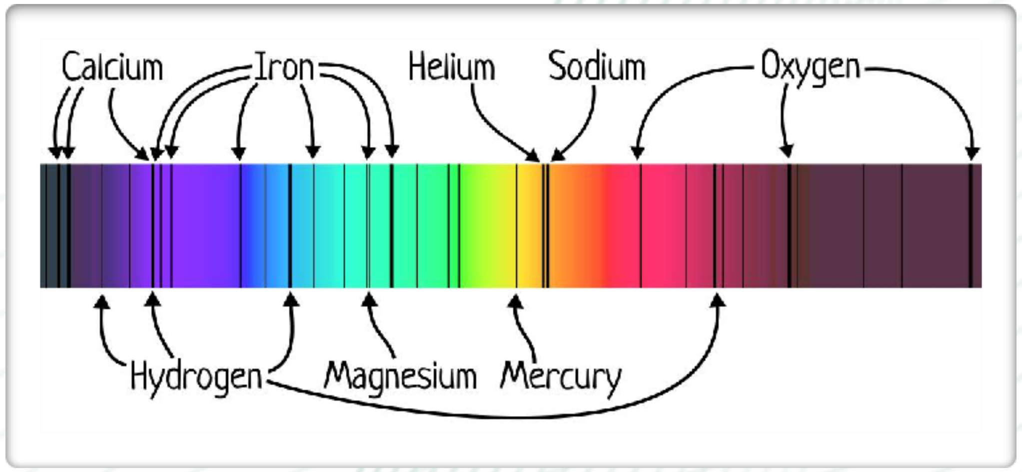
protons are forced to absorb electrons to make neutrons; neutrons squeezed together

neutrons completely collapse

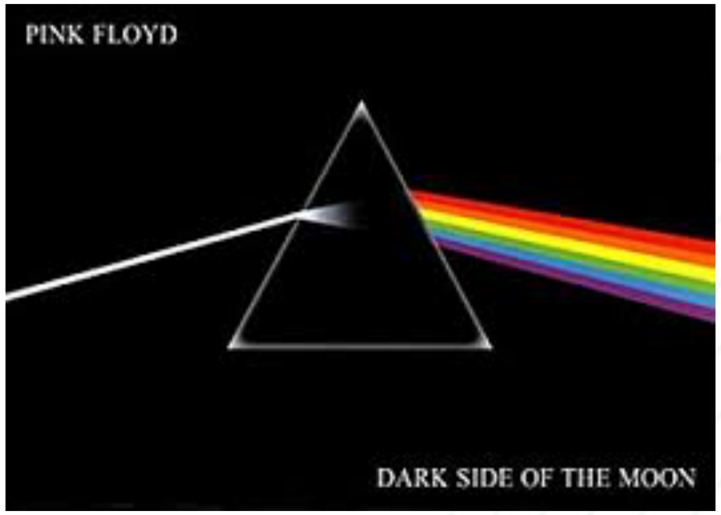
What are stars made of?



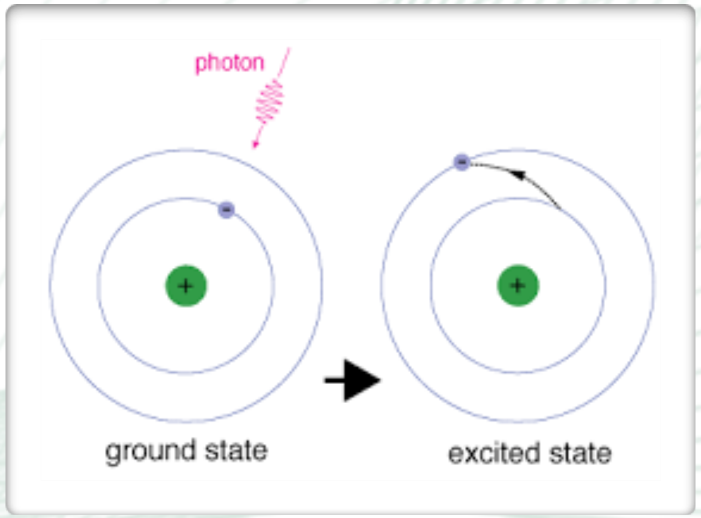
Spectral lines of the sun



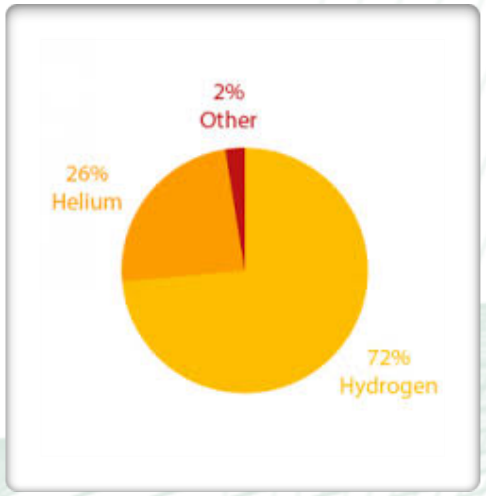
Cecilia Payne - 1925

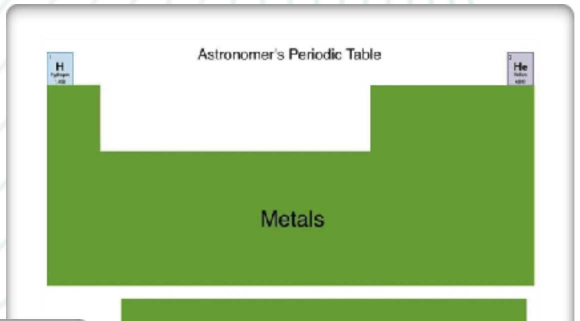


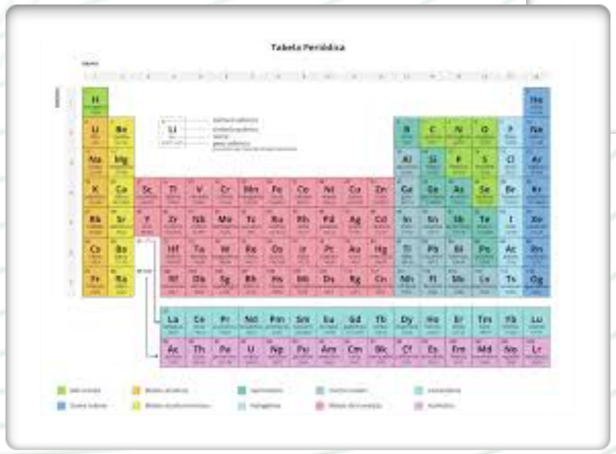
ionized atom



Composition of the sun







“astronomer periodic table”

Periodic table

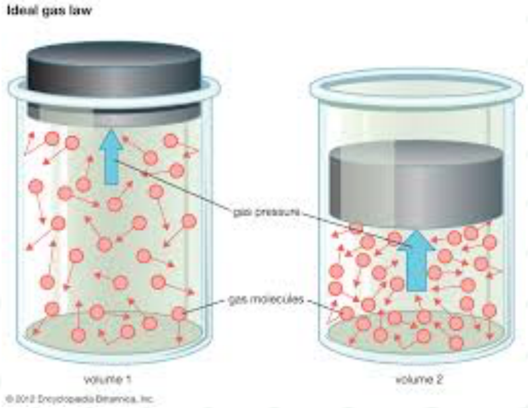
Equation of State (EOS)

Unfortunately, spectroscopy doesn't work for neutron stars: the spectrum has no lines! (*Why?*)

For an ideal gas:

$$PV = nRT$$

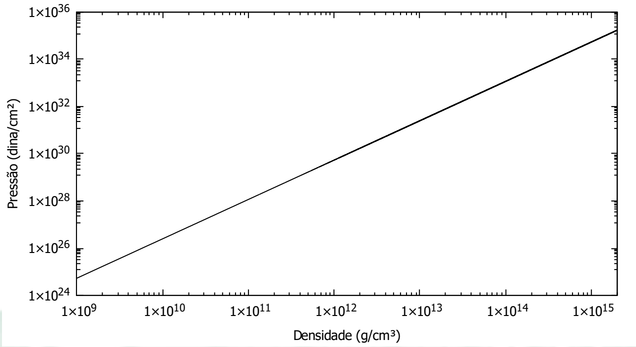
$$P = P(\rho, T)$$

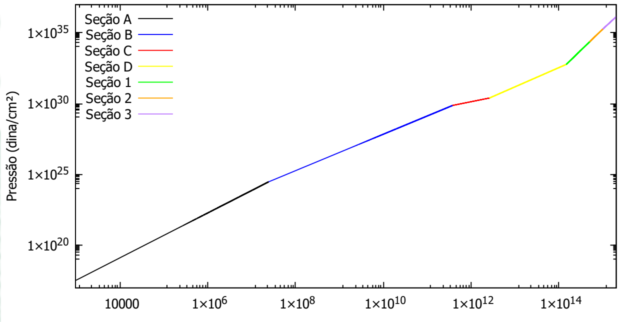


Simplifying (a lot) more:

$$\boxed{P = P(\rho) = \kappa\rho^{\Gamma}}$$

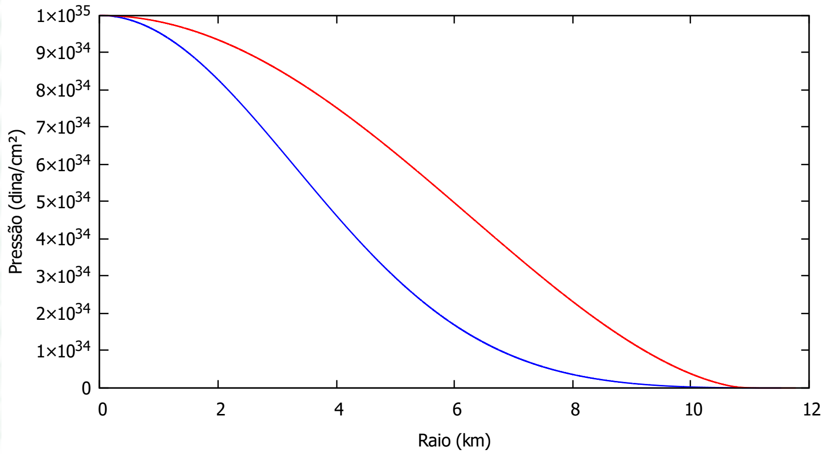
Polytropic EOS



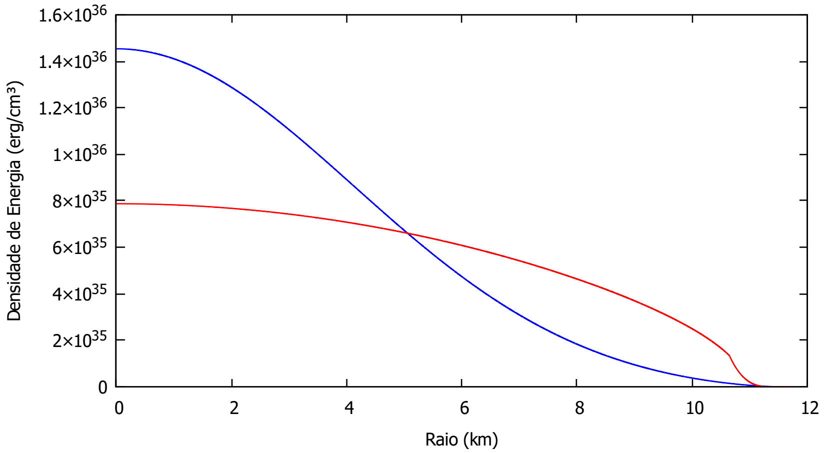


Realistic EOS

pressure

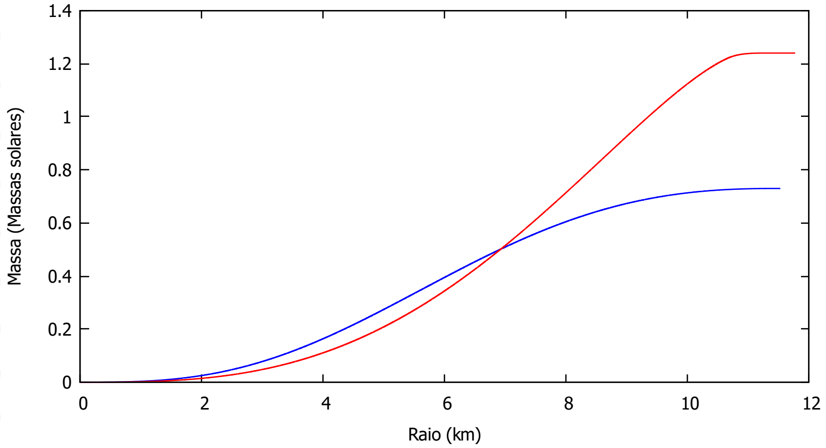


density



nuclear density:
$2 \times 10^{35} \mathrm{erg/cm}^3$

mass

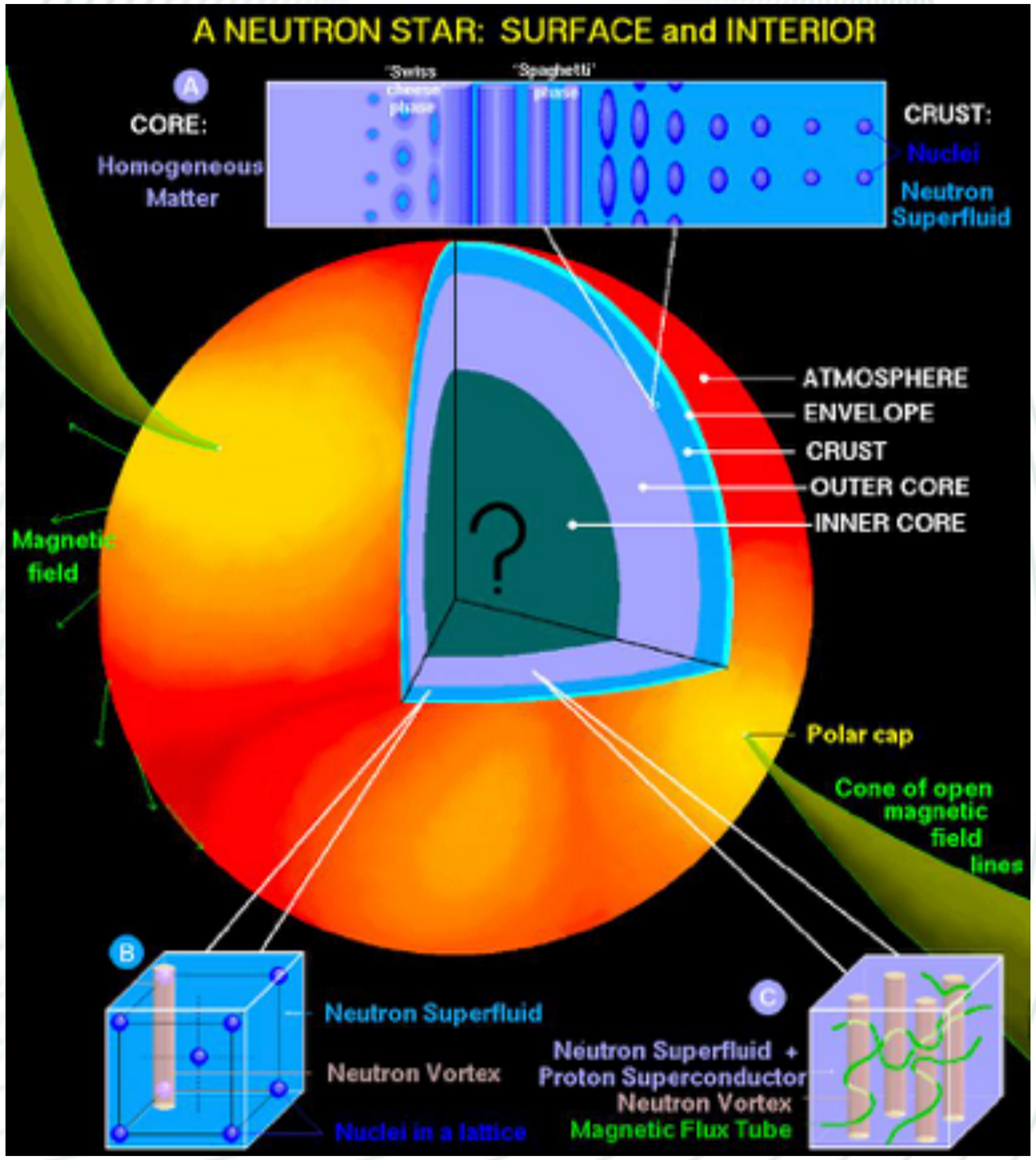


radial profiles of $p(r), \rho(r), M(r)$ inside the star

Inside a neutron star

- The core of a neutron star is at several times the nuclear density

- The composition is unknown:
  - Nucleons?
  - Strange matter?
  - Quark matter?
  - Condensates?



http://www.astroscu.unam.mx/neutrones/NS-picture/NStar/NStar-I.gif

A particle physics problem?

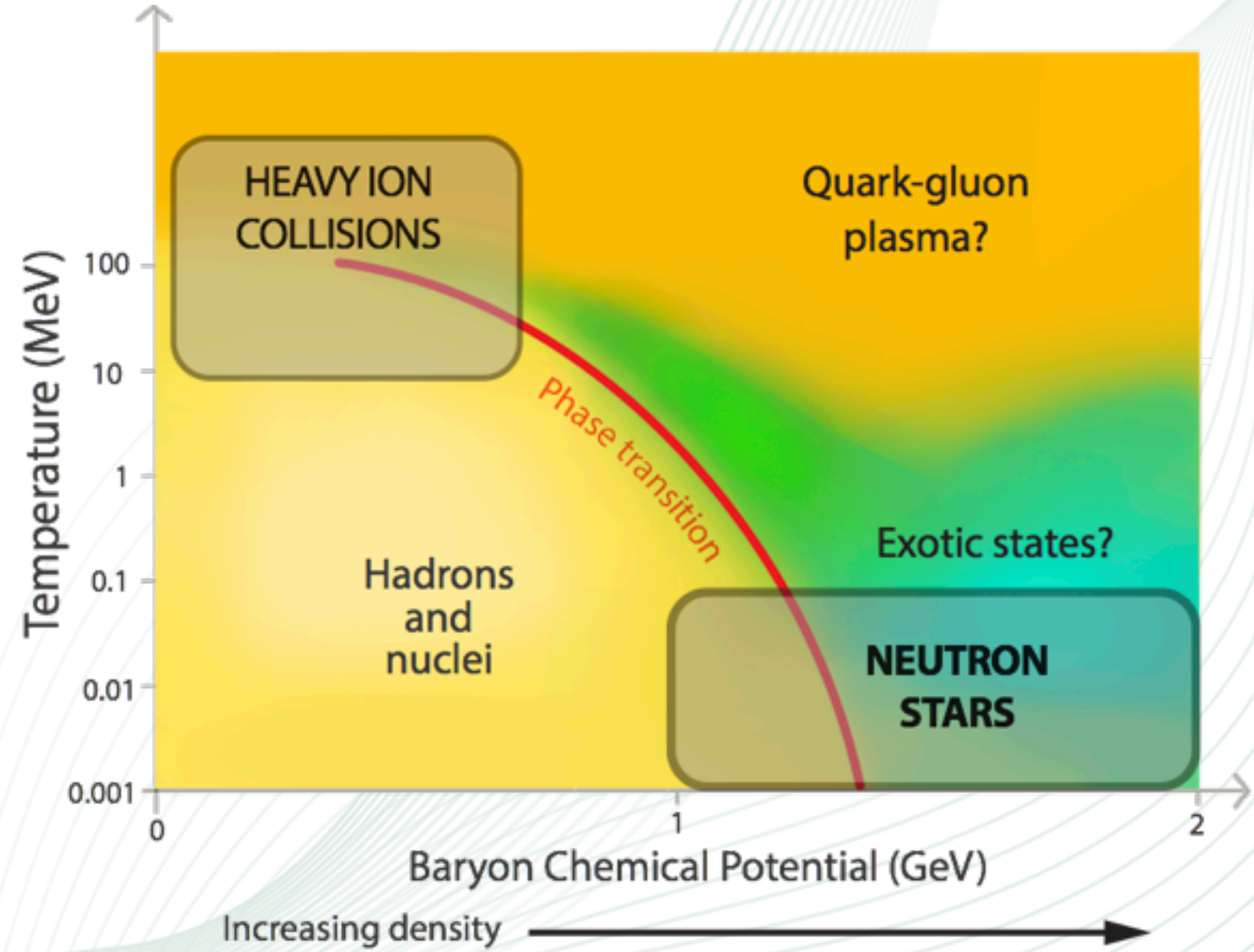
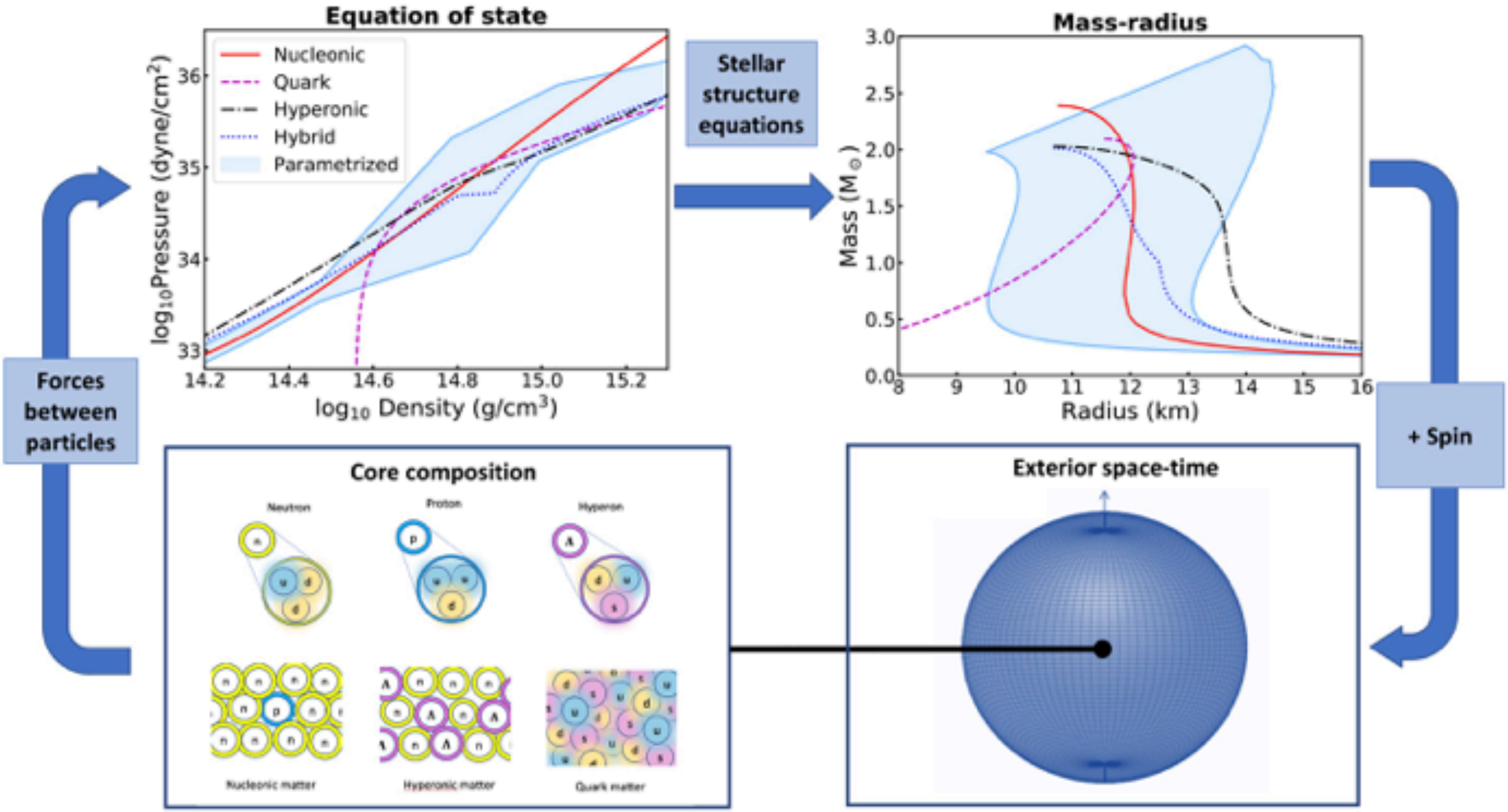


Figure: Watts et al. 2016

Particle physics vs. Curved spacetime



Stellar structure equations

Forces between particles

+ Spin

Figure: Adapted from Ray et al. 2019

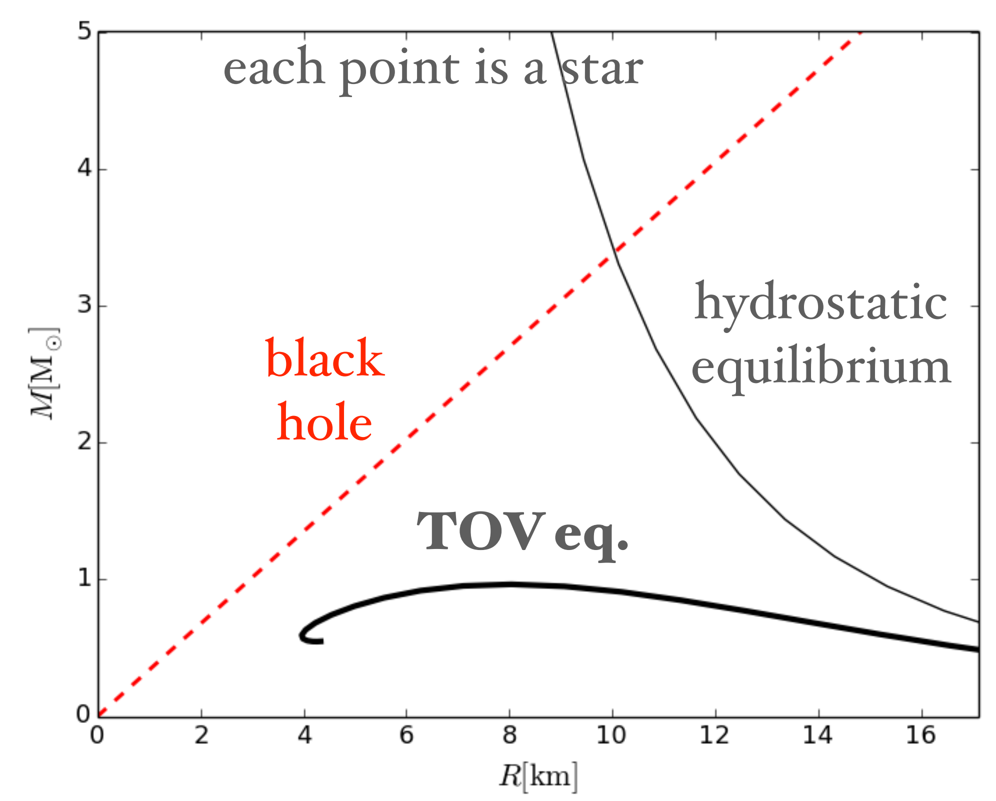
Maximum Mass

If the central density increases,
then the total mass must
increase, right? *Wrong!*

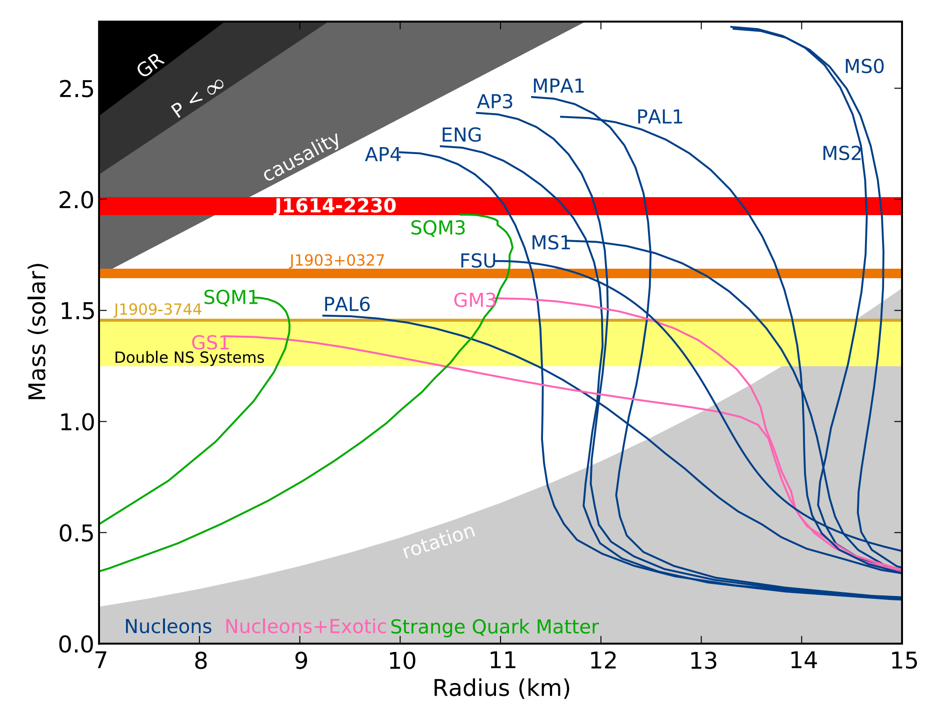
Tolman-Oppenheimer-Volkoff (TOV) eq.

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

(this is the **relativistic** version of the Newtonian hydrostatic equilibrium: take c → ∞)

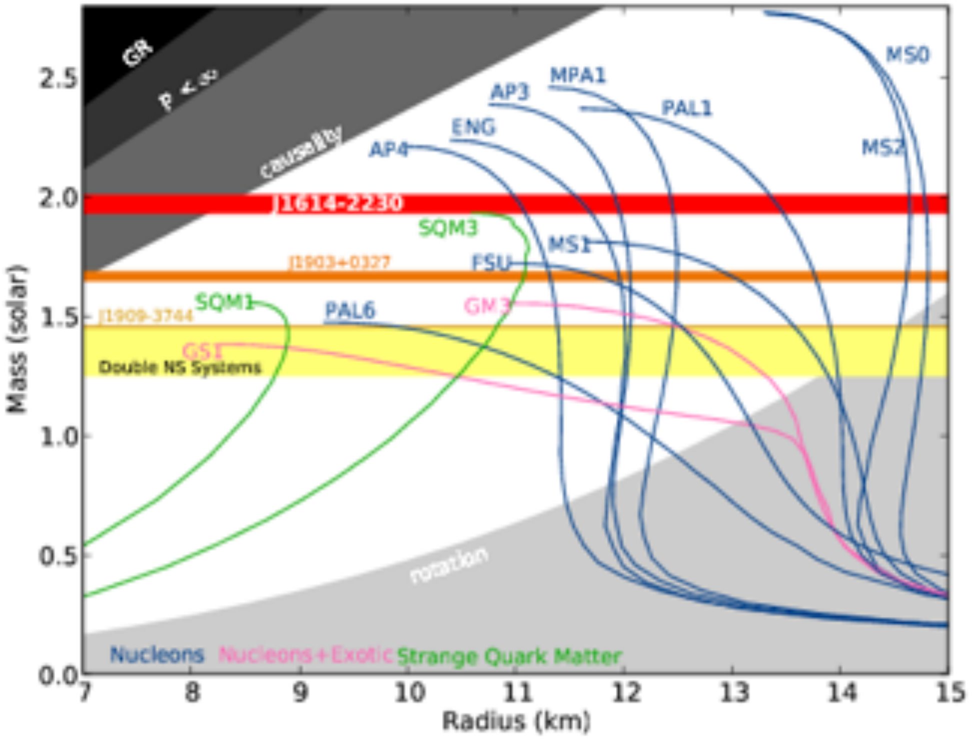


Each proposed
EOS *model*
produces a
different curve.
Which are the
viable models?



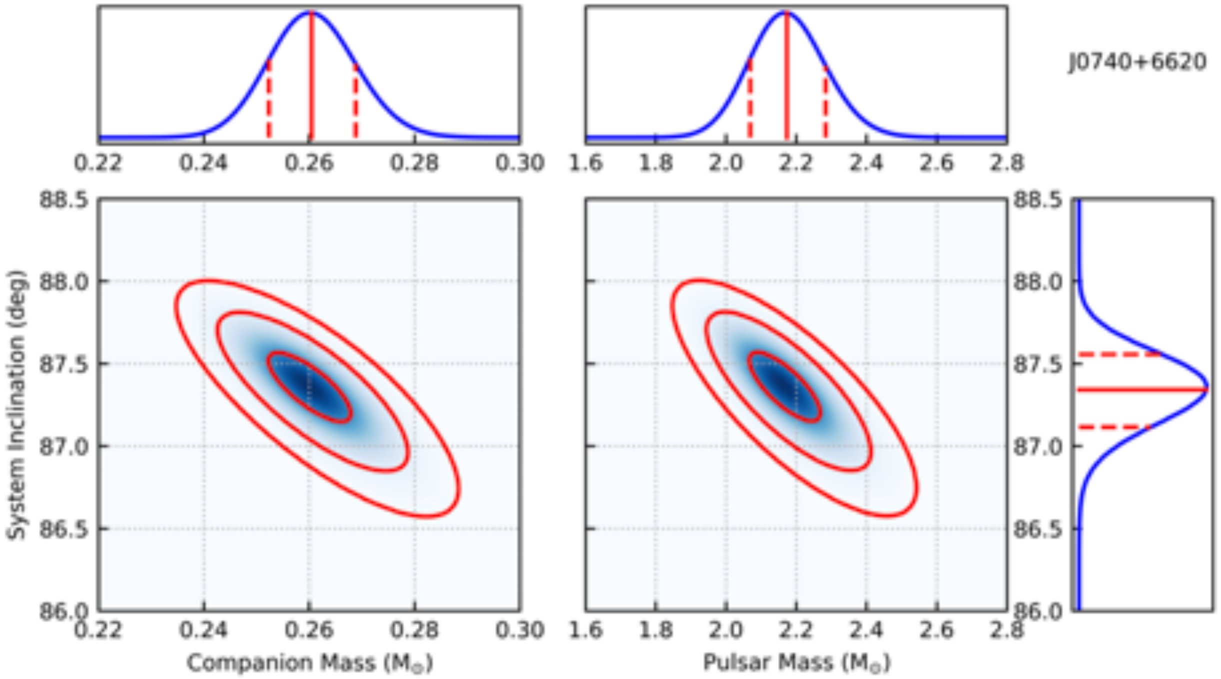
The mass radius curves as
parametrized by the central
density of the star

Observed high masses



Demorest et al. 2010

A viable EOS must have a maximum mass larger than the highest observed masses

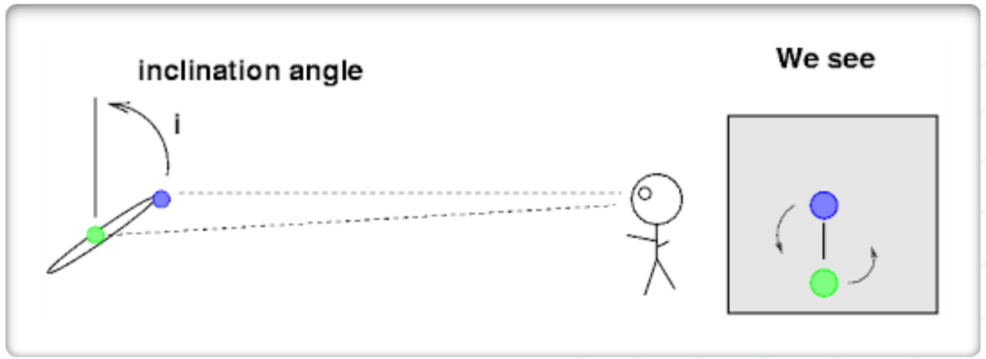


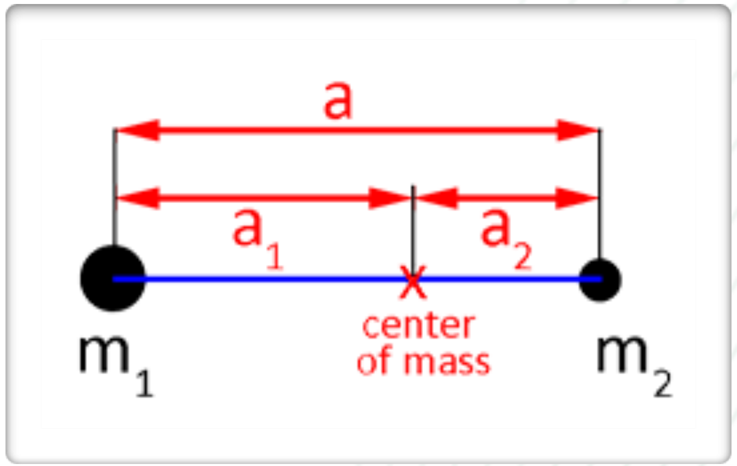
Cromartie+ 2019

softer EOSs predict a lower maximum mass and more compact stars

How to measure the mass of a neutron star (in a binary system)

Doppler effect





$$a = a_1 + a_2$$

$$m_1 a_1 - m_2 a_2 = 0$$

$$q = m_1/m_2$$

If we can measure

P - period of the binary

$$v_1 = \frac{2\pi}{P} a_1 \sin i \text{ (Doppler)}$$

Using Kepler's 3rd law

$$\frac{P^2}{a^3} = \frac{4\pi^2}{G(m_1 + m_2)}$$

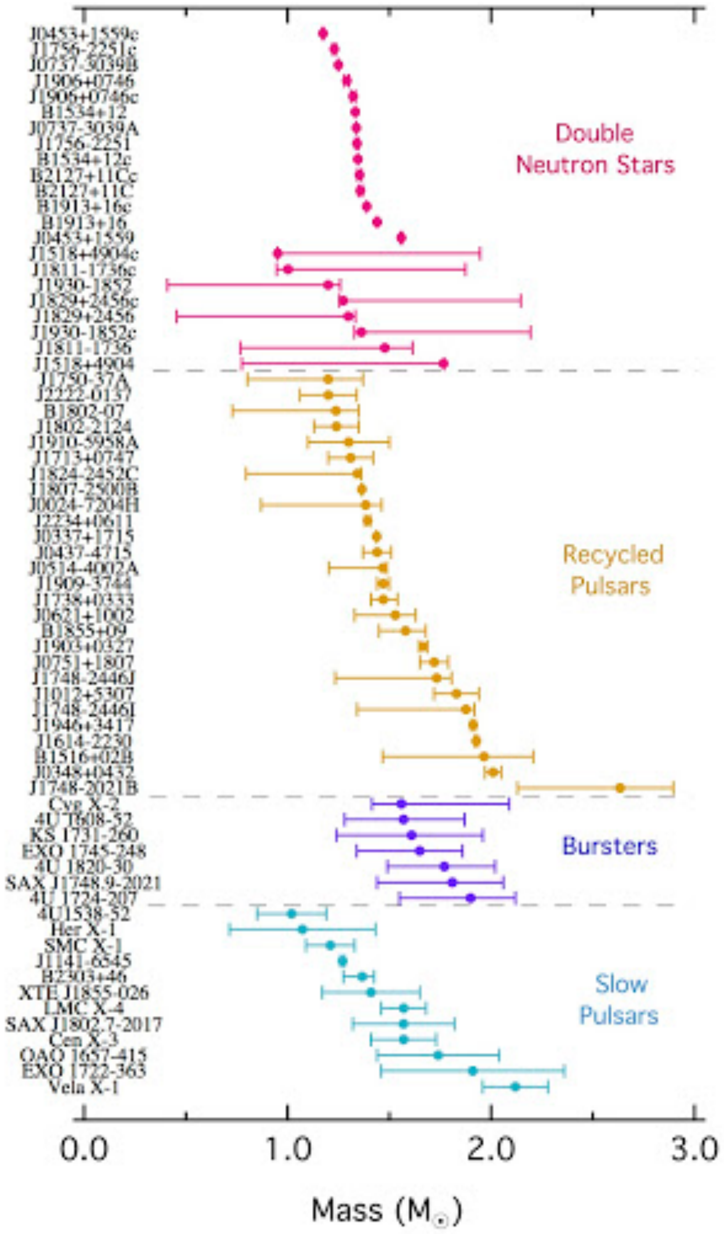
we can write

$$f_1(m_1, m_2, i) \equiv \frac{m_2^3 \sin^3 i}{(m_1 + m_2)^2} = \frac{P v_1^3}{2\pi G}$$

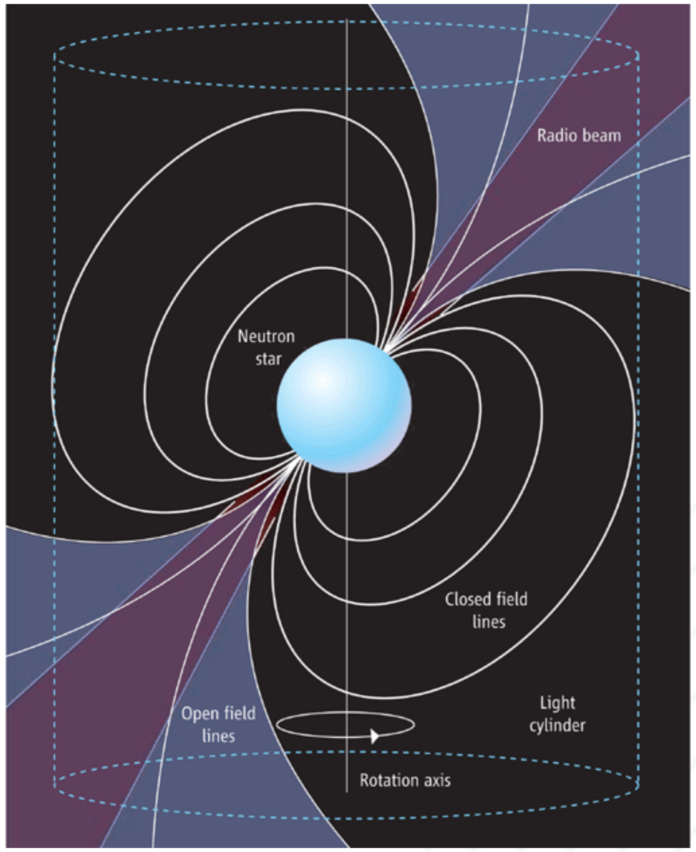
If we are also able to measure f_2 (*how?*) we can find

$$m_2 = \frac{f_2 q (1 + q)^2}{\sin^3 i}$$

and from f_2/f_1 we have q.



What is the age of a pulsar?



The magnetic field brakes the rotation of pulsars $\frac{dE}{dt} \propto -B^2$

We can measure: P - period

$\dot{P} = \frac{dP}{dt}$ - rate of change of the period

So we can calculate $t = \frac{1}{2}\frac{P}{\dot{P}}$,

the characteristic age

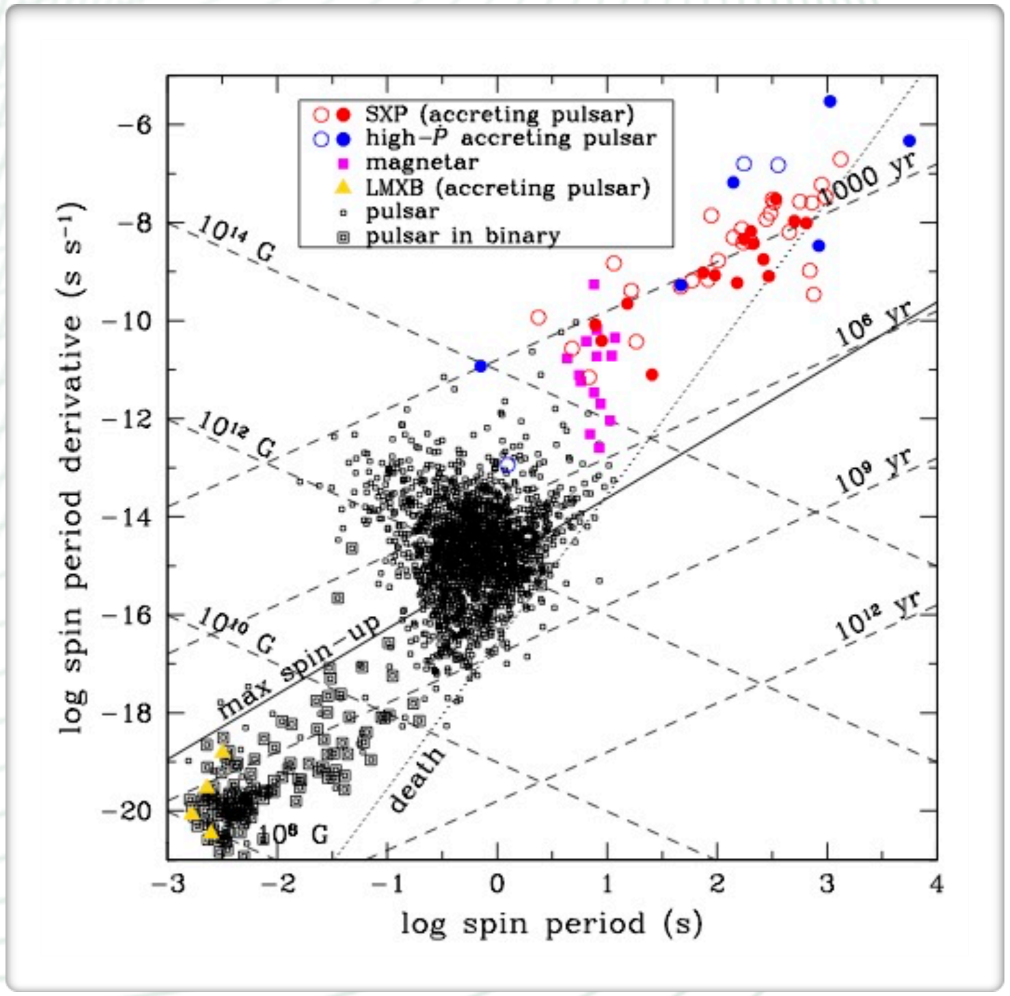
For the Crab pulsar:

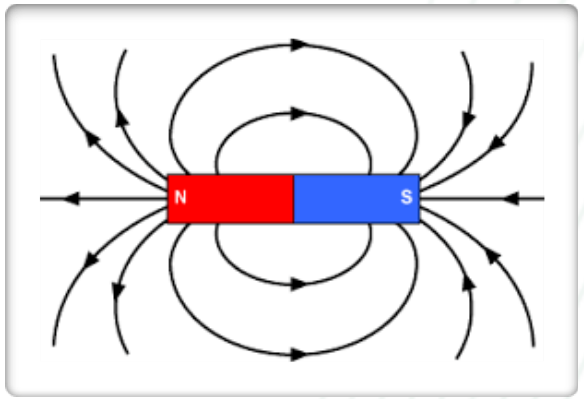
$P = 0.0331$ s or $f = 30$ Hz

$\dot{P} = 4.22 \times 10^{-13}$ s/s

$t = \frac{1}{2}\frac{P}{\dot{P}} \approx 1240$ years

(30 % overestimate)





Earth's magnetic field ~ 0.5 G

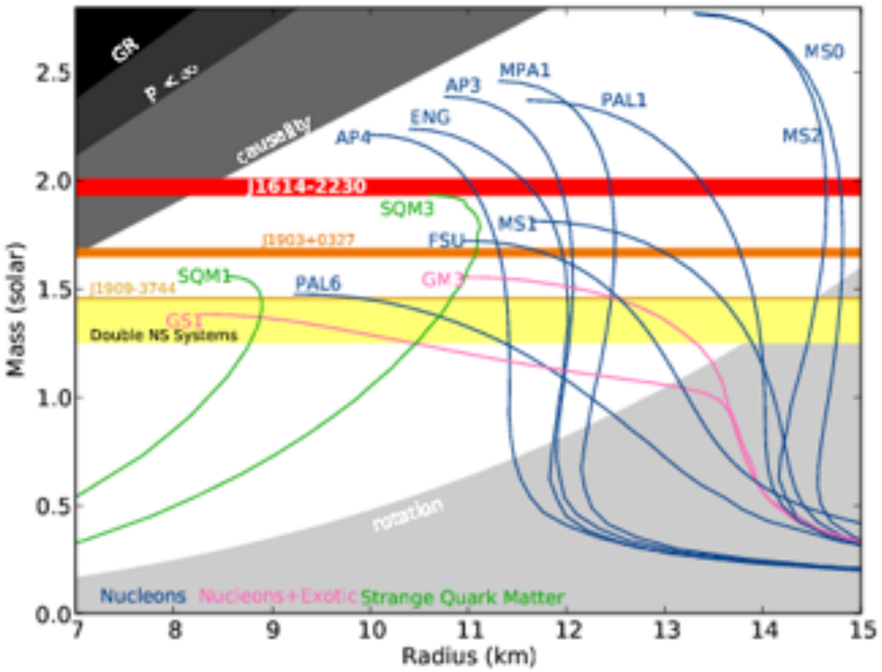
solar magnetic field ~ 10 G

magnetars can have $B \sim 10^{15}$ G

Group discussion question

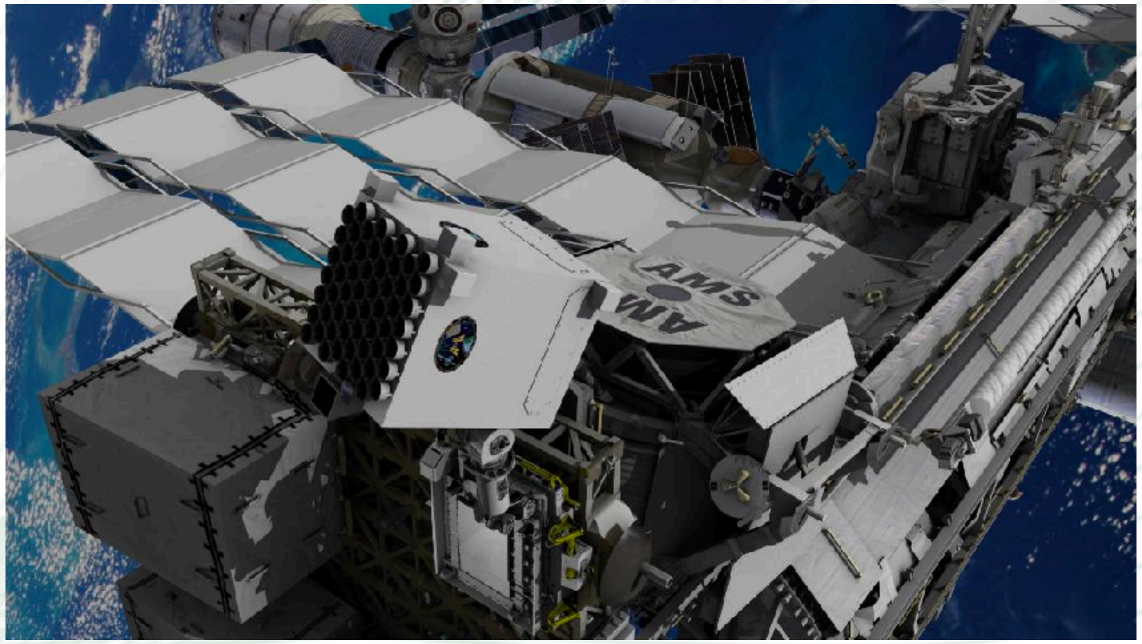
How can we measure the radius of a neutron star?

What accuracy should we have?



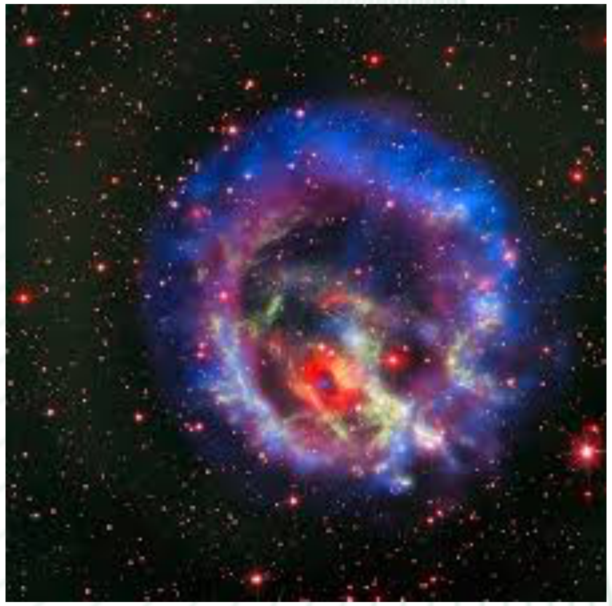
NICER

The best current estimate for the radius of a $M = 1.4M_\odot$ is $R = (12 \pm 1)\,\mathrm{km}$, obtained by NICER (Neutron star Interior Composition ExploreR), onboard the International Space Station. NICER uses X-ray observations and waveform modeling for the emission from hotspots in isolated neutron stars.



Coffee Break





We'll be back in 30 minutes