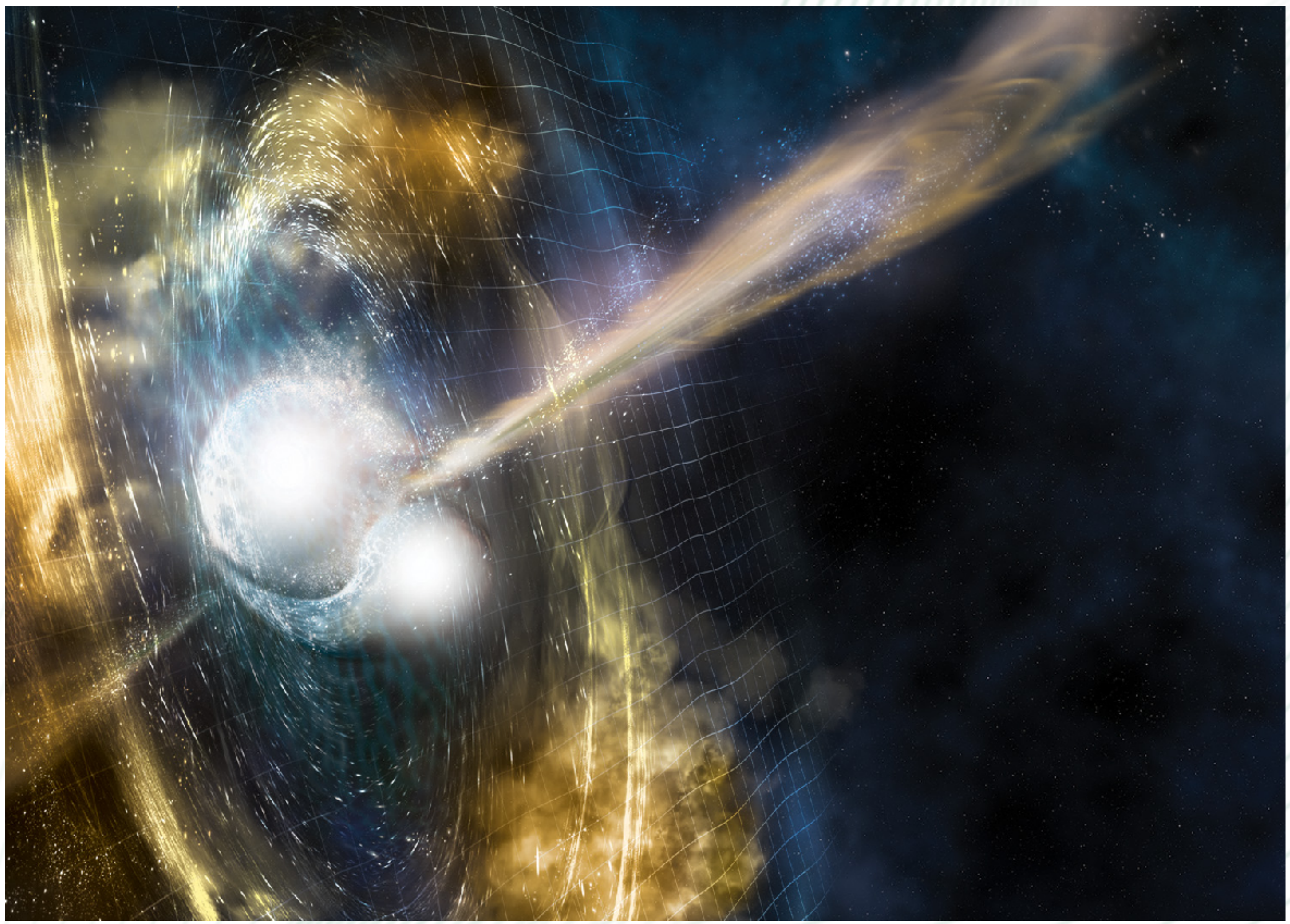
# Neutron Stars - Part 1



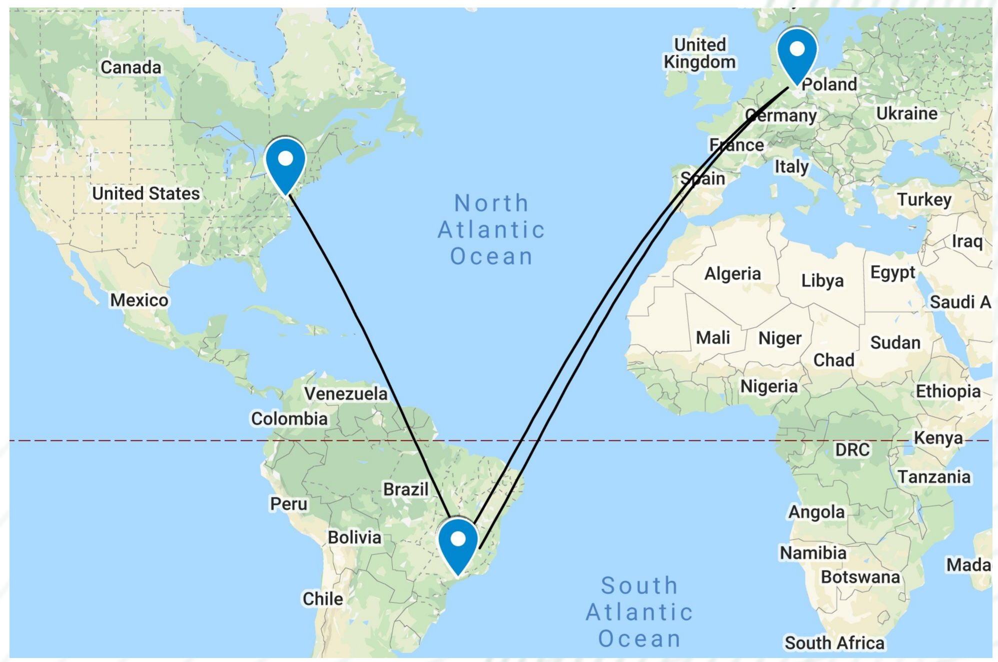
Cecilia Chirenti

Fermi Summer School - Lewes DE - May 29 2024

# 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

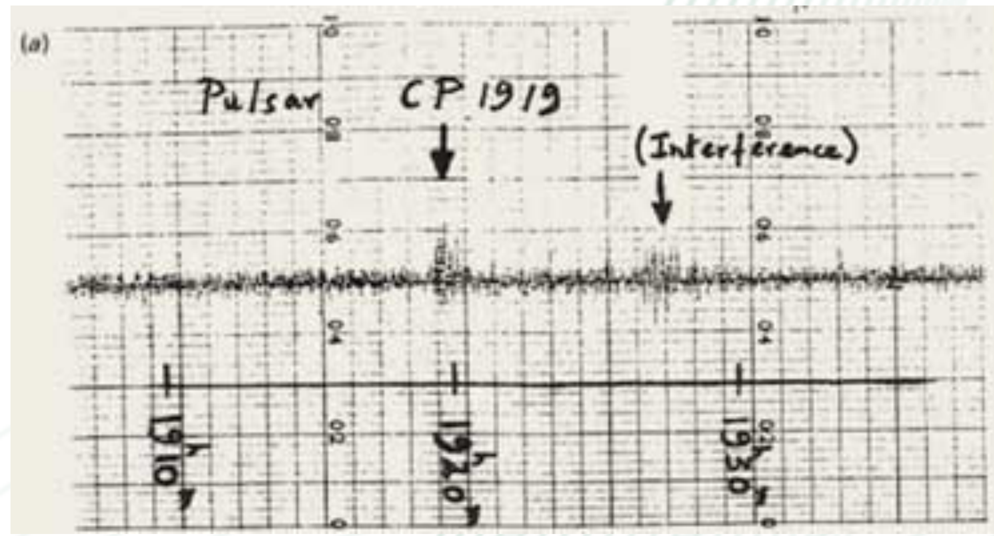
1 Physics BSc and PhD at University of São Paulo, Brazil


# Neutron stars: how it all began

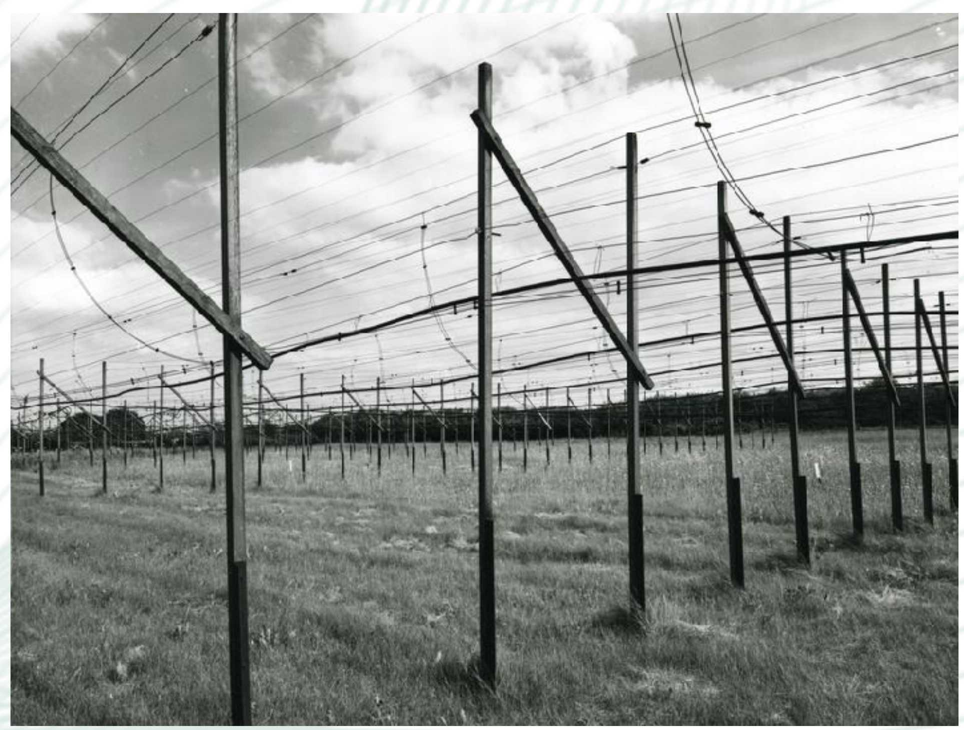
## The discovery of pulsars

Jocelyn Bell - 1967

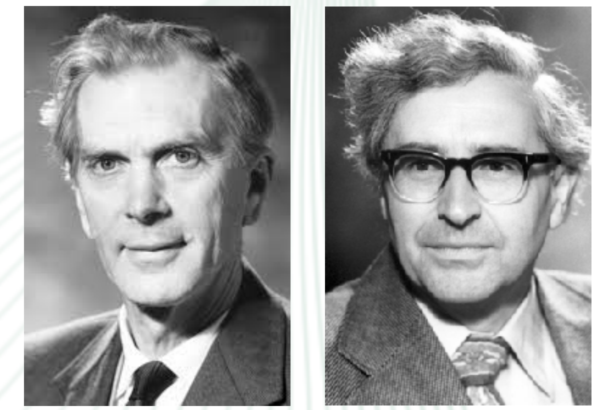
Little Green Men?
LGM1, LGM2, LGM3




dados



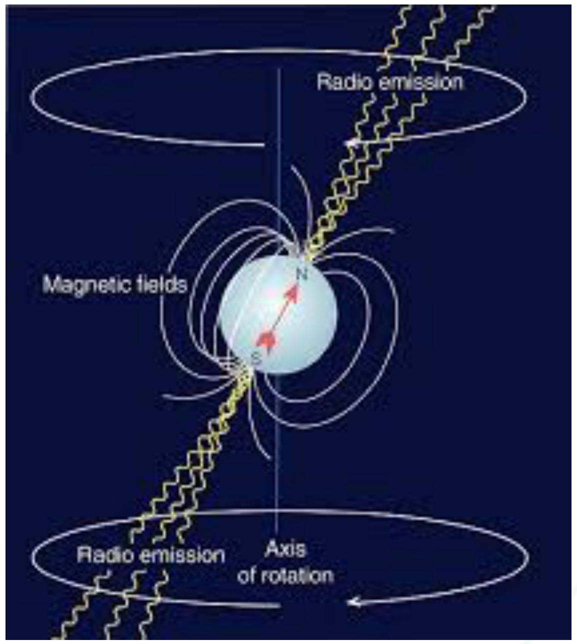
“telescope” in Cambridge



Physics Nobel Prize 1974

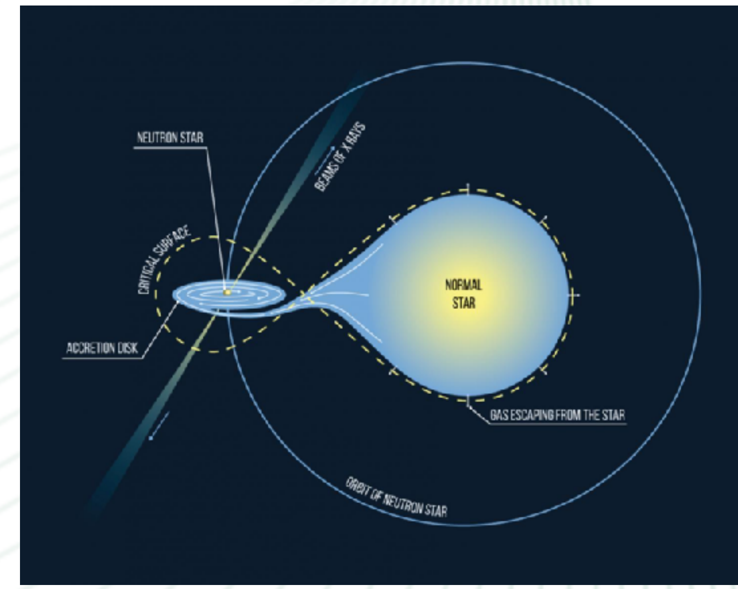
Breakthrough Prize 2018

# How do we observe neutron stars?




Radio pulsars

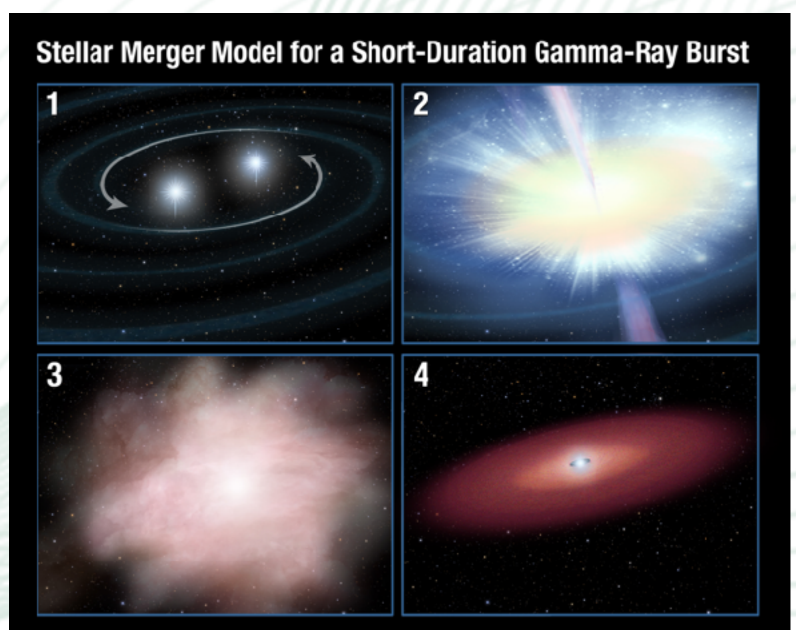
Crab Nebula




X-ray binaries

Gravitational waves

LIGO

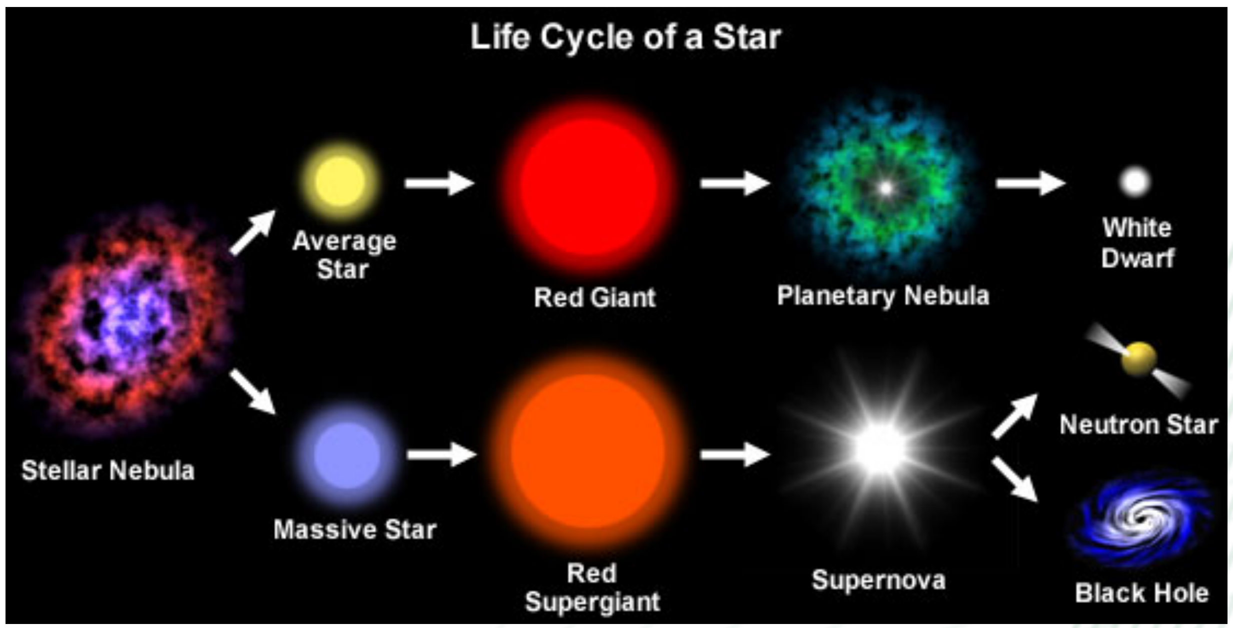



Kilonova

Short gamma-ray burst

Fermi

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



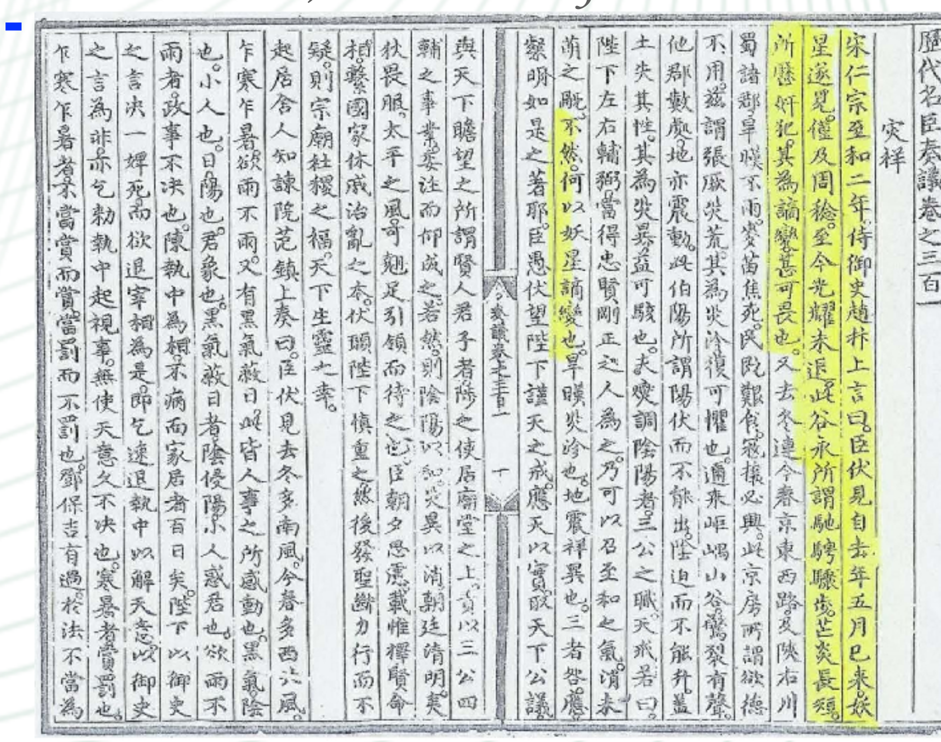

The initial mass determines the fate of the star

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



歷代名臣奏議卷之三百一

災祥

宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖星遂見僅及周稔至今光耀未退此谷永所謂馳騁驟步芒炎長類所營奸犯其為譴變甚可畏也又去冬連今春京東西路及陝右川蜀諸郡旱暵不雨麥苗焦死民既艱食寇攘必興此京房所謂欲德不用茲謂張厥災荒其為災沴復可懼也邇來㟁嵎山谷騭裂有聲他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋土失其性其為災異益可駭也夫燮調陰陽者三公之職天戒若曰陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消未萌之眺不然何以妖星譴變也旱暵災沴也地震祥異也三者咎應

奏議卷之三百一 十

纍明如是之著耶臣愚伏望陛下謹天之戒應天以實啟天下公議與天下瞻望之所謂賢人君子者陽之使居廟堂之上貢以三公四輔之事業委注而仰成之若然則陰陽以和災異以消朝廷清明矣狀畏服太平之風可翹足引領而待之也臣朝夕思慮載惟擇賢命相繫國家休戚治亂之本伏願陛下慎重之無後發聖斷力行而不疑則宗廟社稷之福天下生靈之幸

起居舍人知諫院范鎮上奏曰臣伏見去冬多南風今春多西北風乍寒乍暑欲雨不雨又有黑氣蔽日此皆人事之所感動也黑氣陰也小人也日陽也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不雨者政事不決也陳執中為相不病而家居者百日矣陛下以御史之言決一婢死而欲退宰相為是耶乞速退執中以解天意以御史之言為非耶乞勅執中起視事無使天意久不決也寒暑者賞罰也乍寒乍暑者不當賞而賞當罰而不罰也鄧保吉有過於法不當為

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

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# Why neutrons?

S. Chandrasekhar and wife - 1939

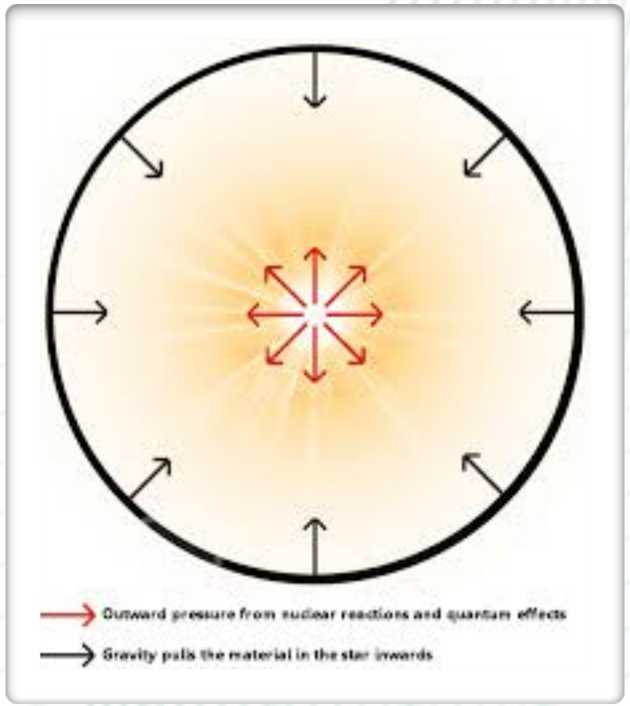
Pauli's exclusion principle
(fermions)

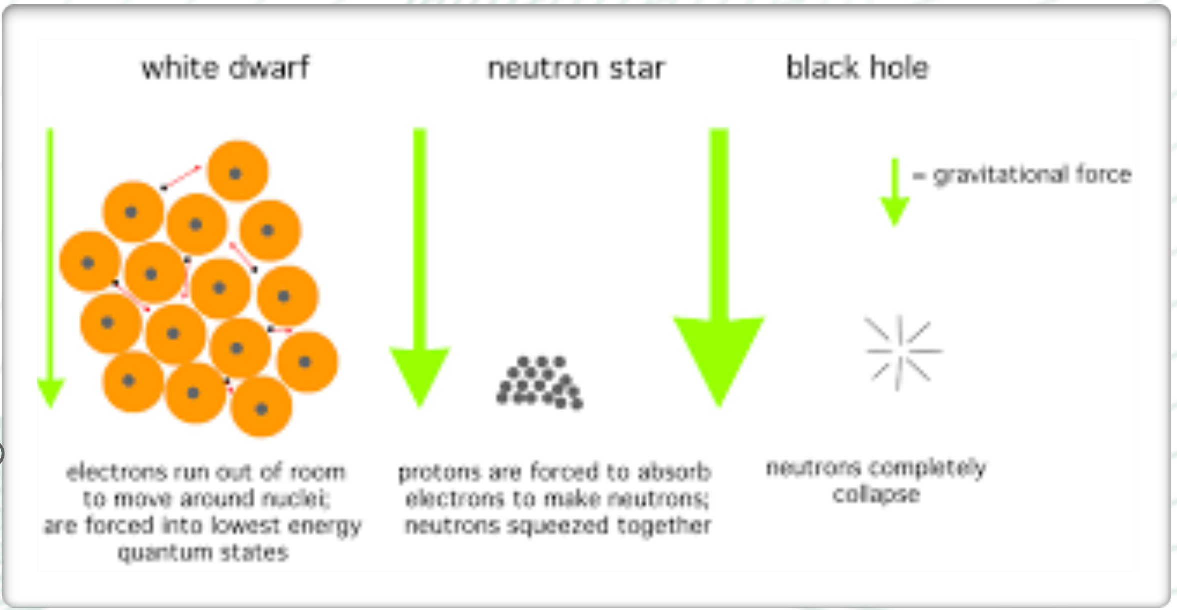
Maximum mass:

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

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

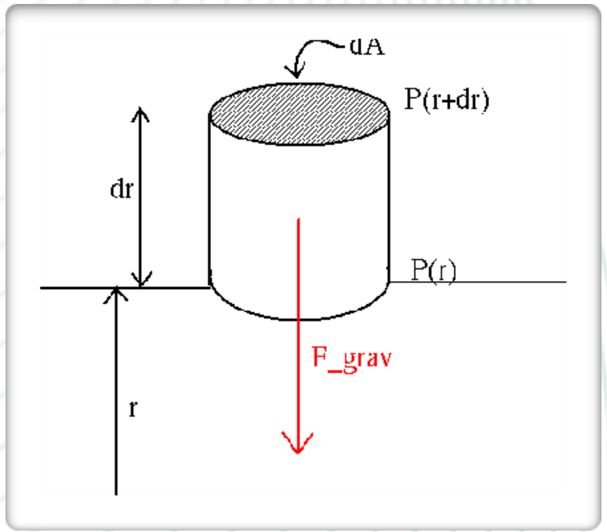
Stellar equilibrium




Gas pressure balances the gravitational attraction

$$F_{gas} = F_{gravitational}$$




$$F_{gas} = PA\,, \quad m = \rho V$$

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

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

**Hydrostatic equilibibum**

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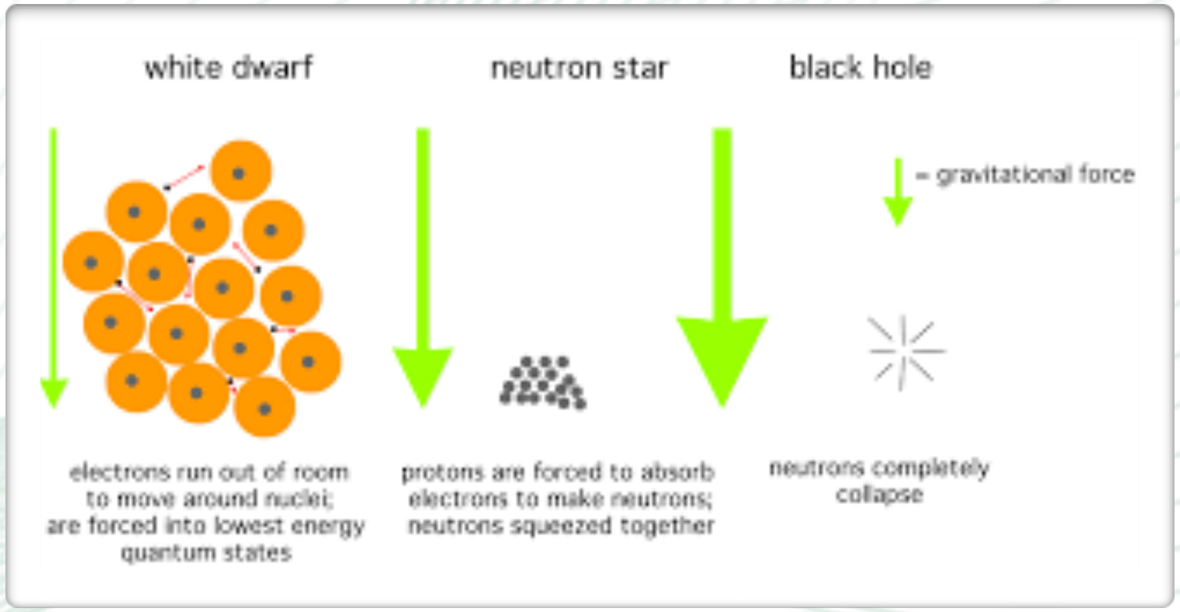
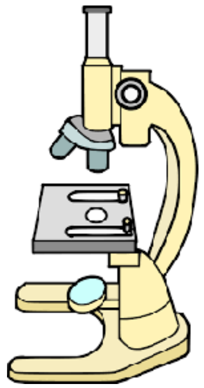
# Group discussion question

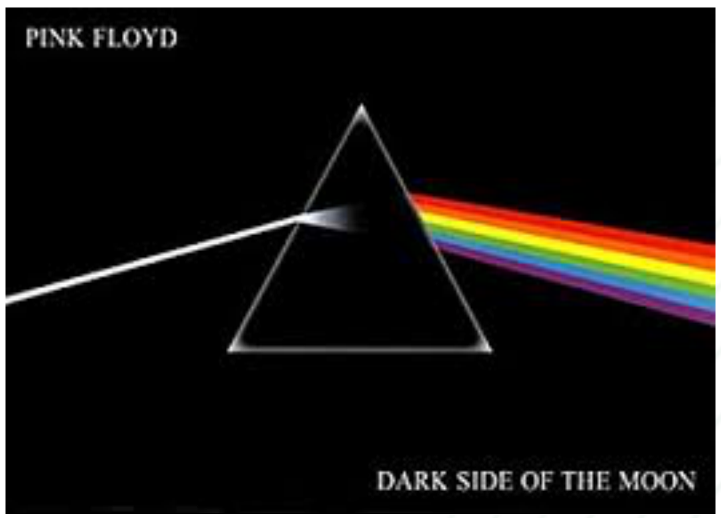
*Can there be stars more compact than neutron stars?*

*What would they look like?*

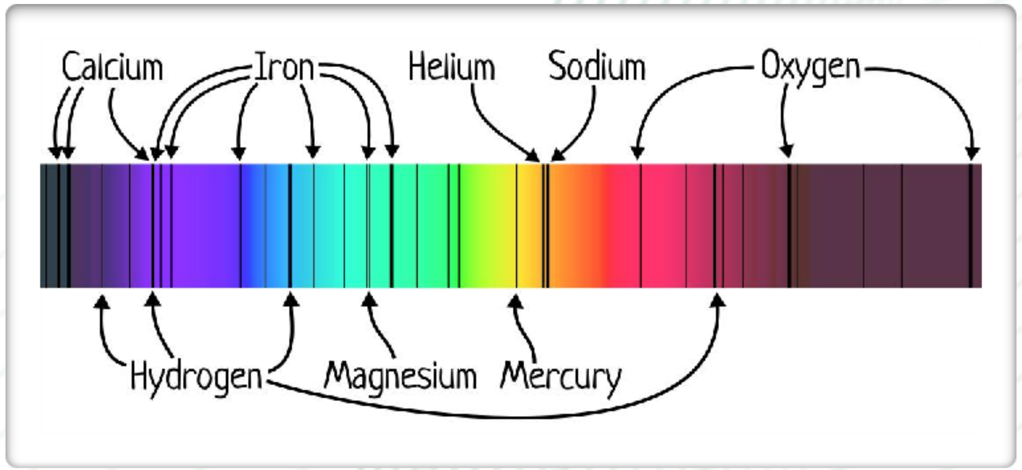


# What are stars made of?

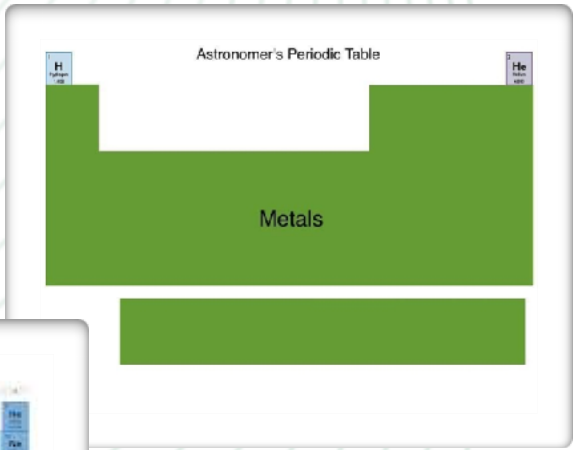





Spectral lines of the sun

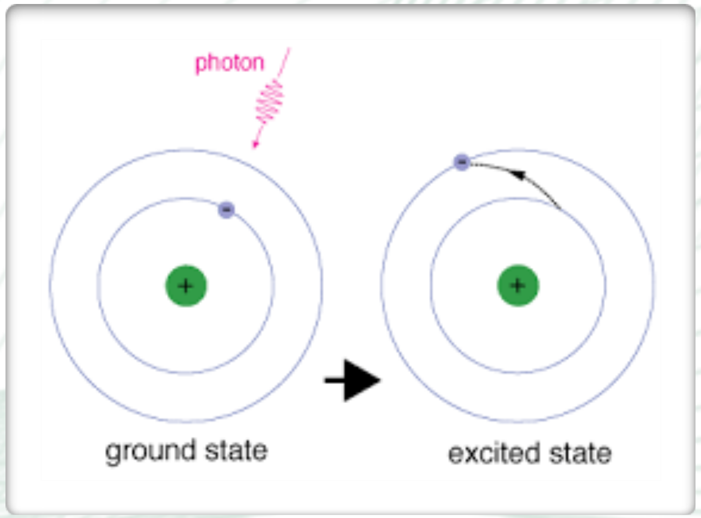



Cecilia Payne - 1925

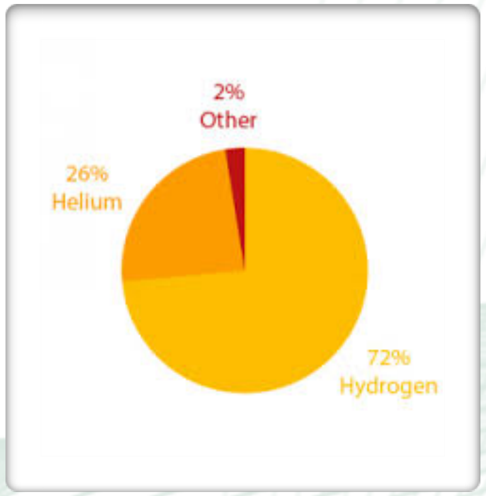


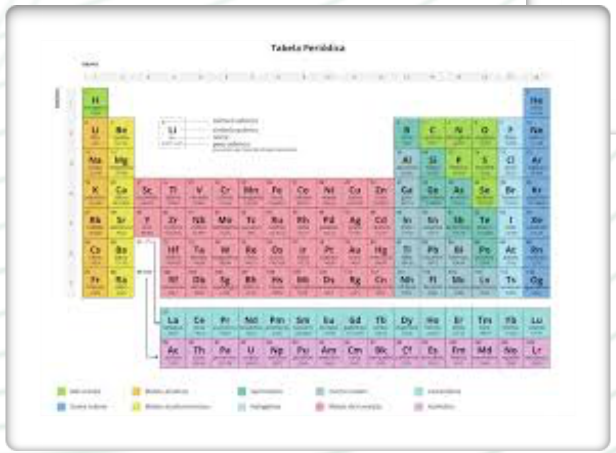

“astronomer periodic table”

ionized atom




Composition of the sun



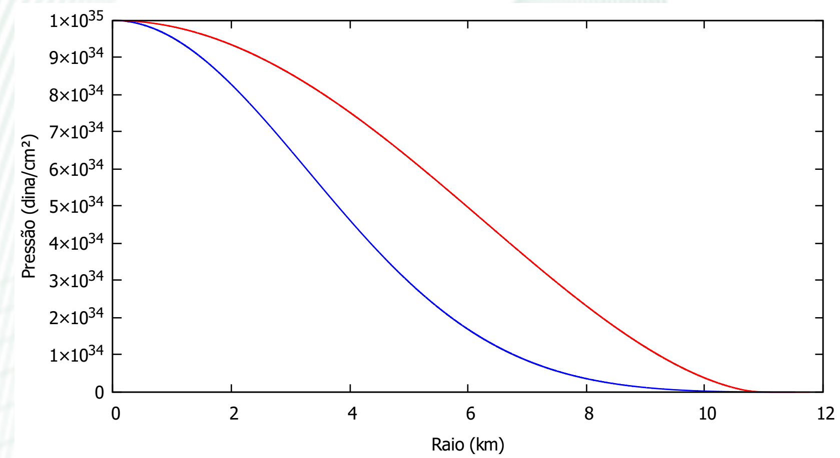



Periodic table

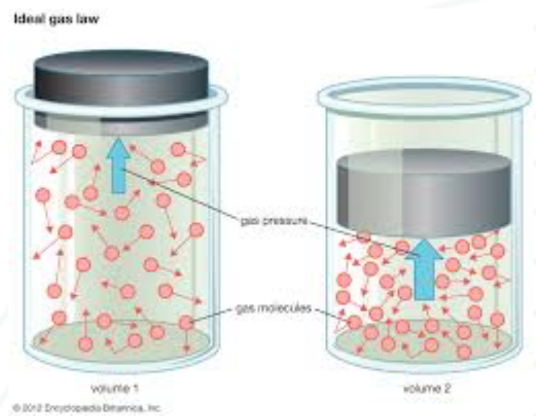
# Equation of State (EOS)

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

pressure



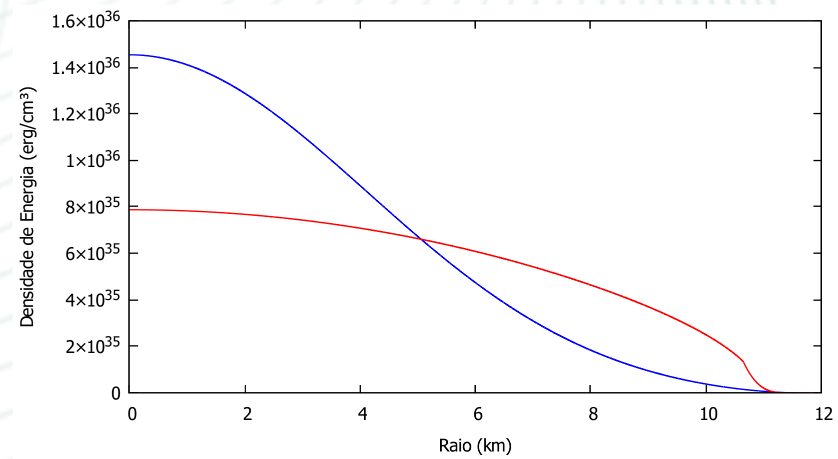

For an ideal gas:




$$PV = nRT$$

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

density



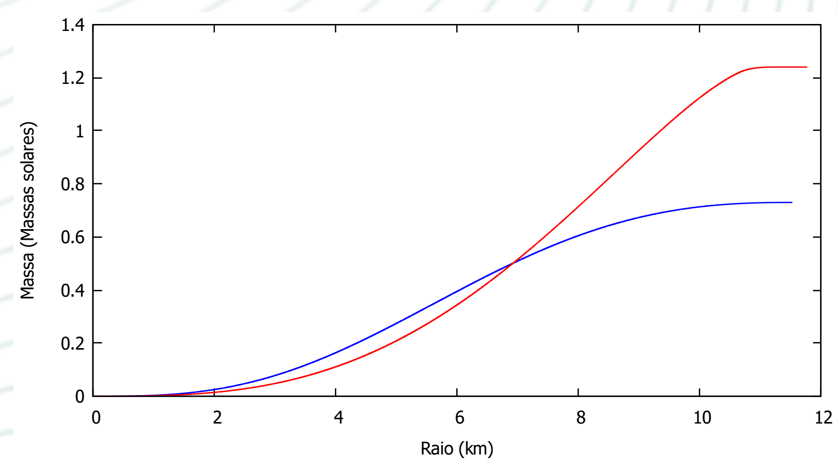

nuclear saturation density: $2 \times 10^{14} \mathrm{g/cm}^3$

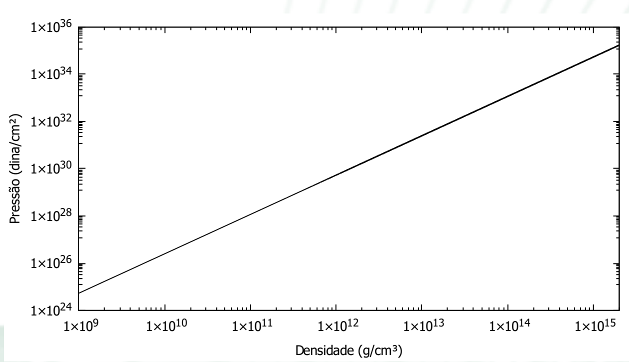
Simplifying (a lot) more:

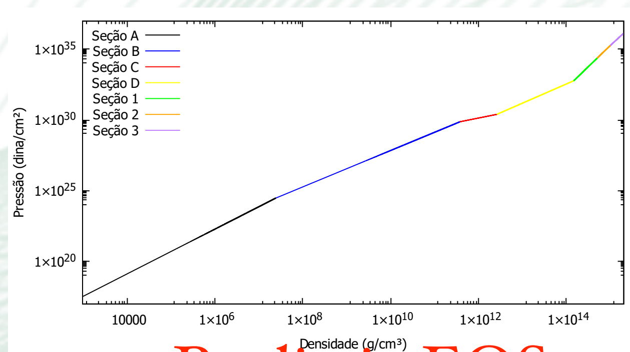
$$P = P(\rho) = \kappa\rho^{\Gamma}$$

Polytropic EOS

mass




Realistic EOS

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

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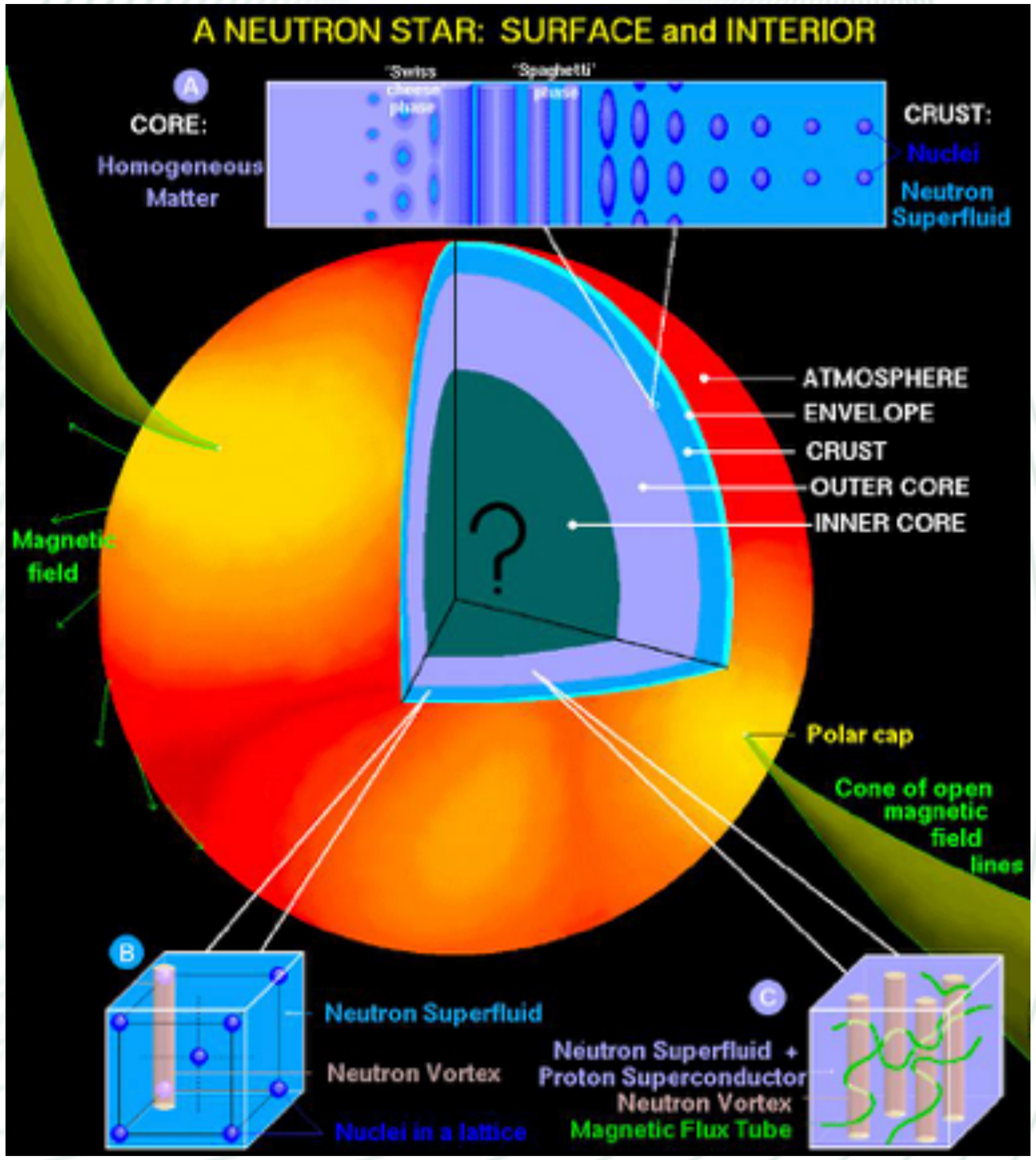
# Inside a neutron star

* 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

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# A particle physics problem?

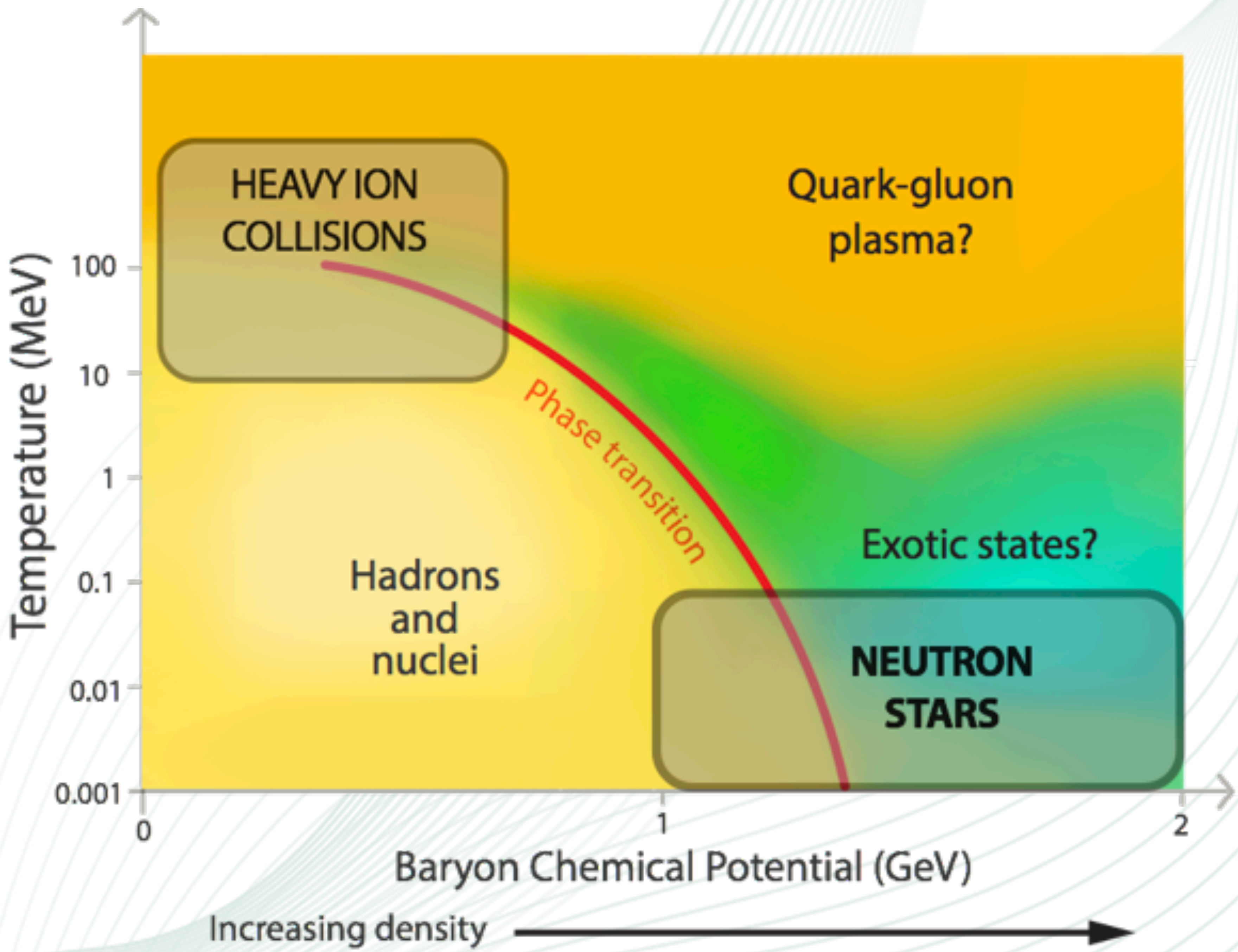


Figure: Watts et al. 2016

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# Particle physics vs. Curved spacetime

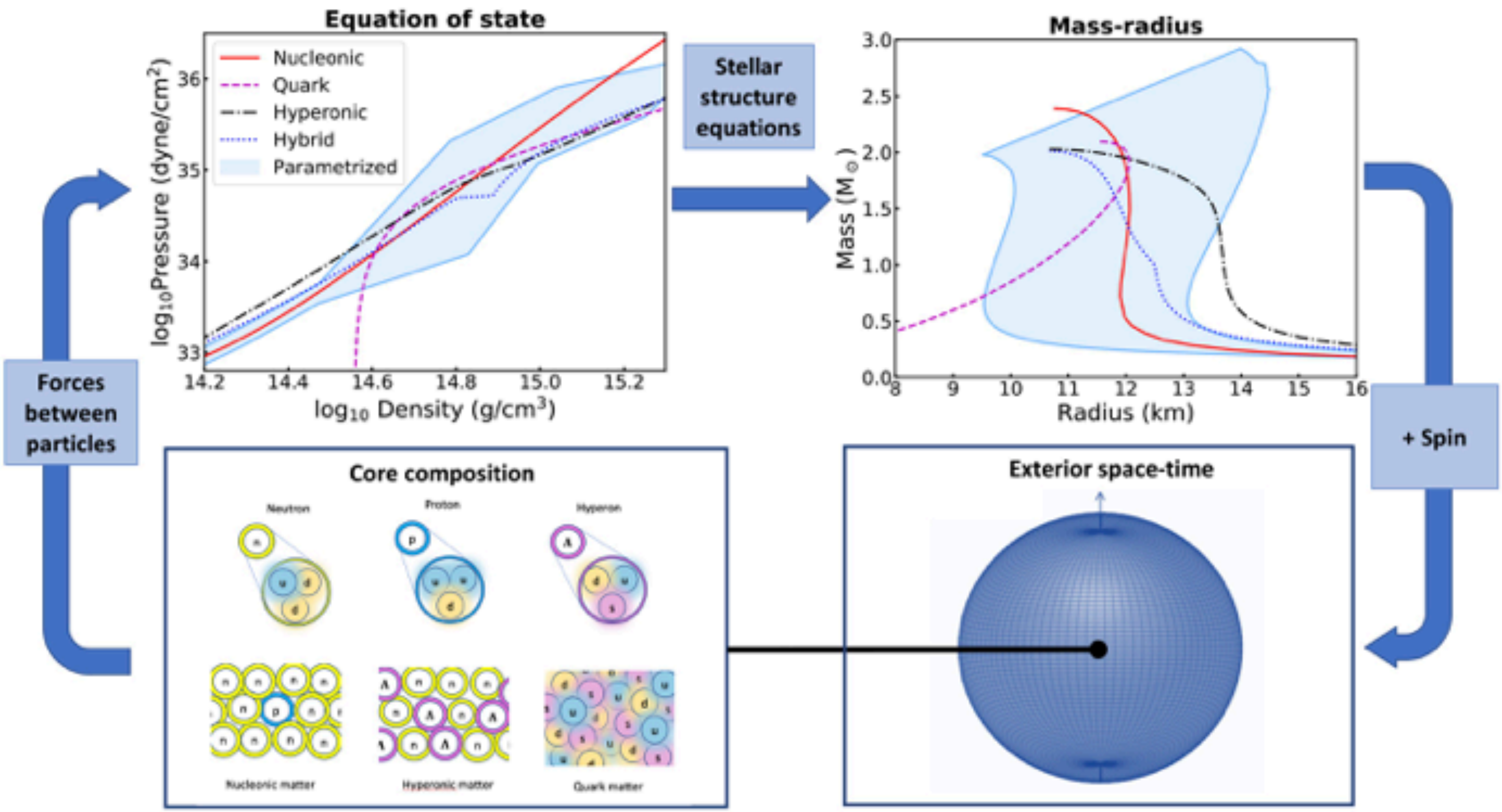



Figure: Adapted from Ray et al. 2019

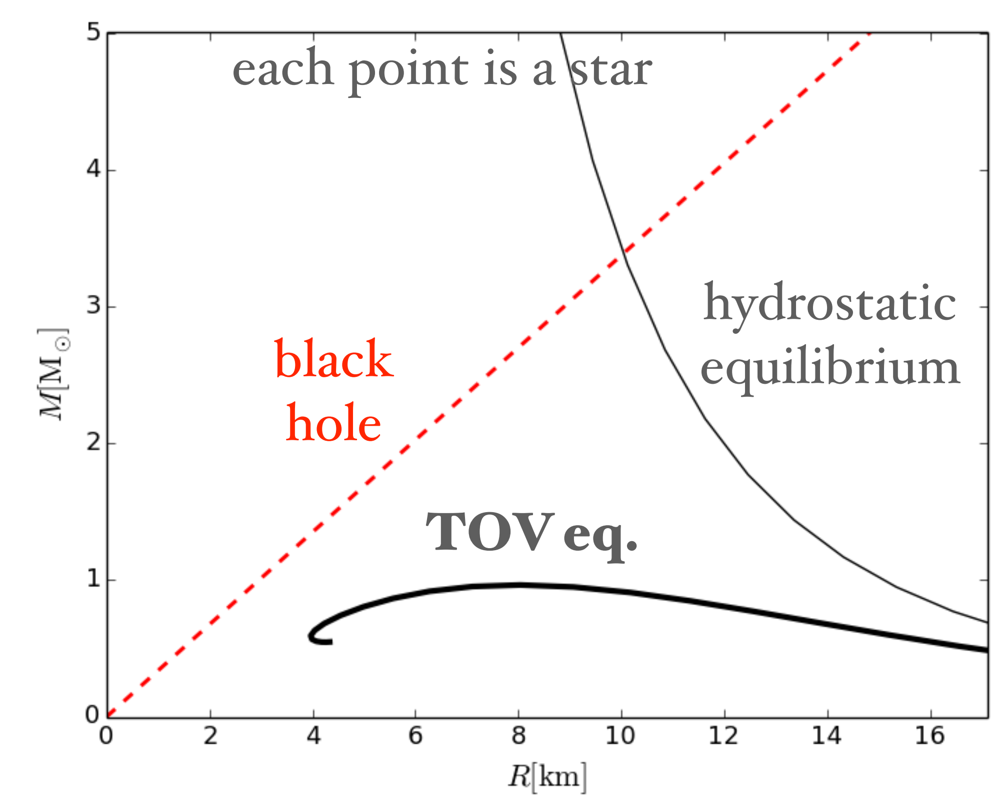
# Maximum Mass

If the central density increases, then the total mass must increase, right…?

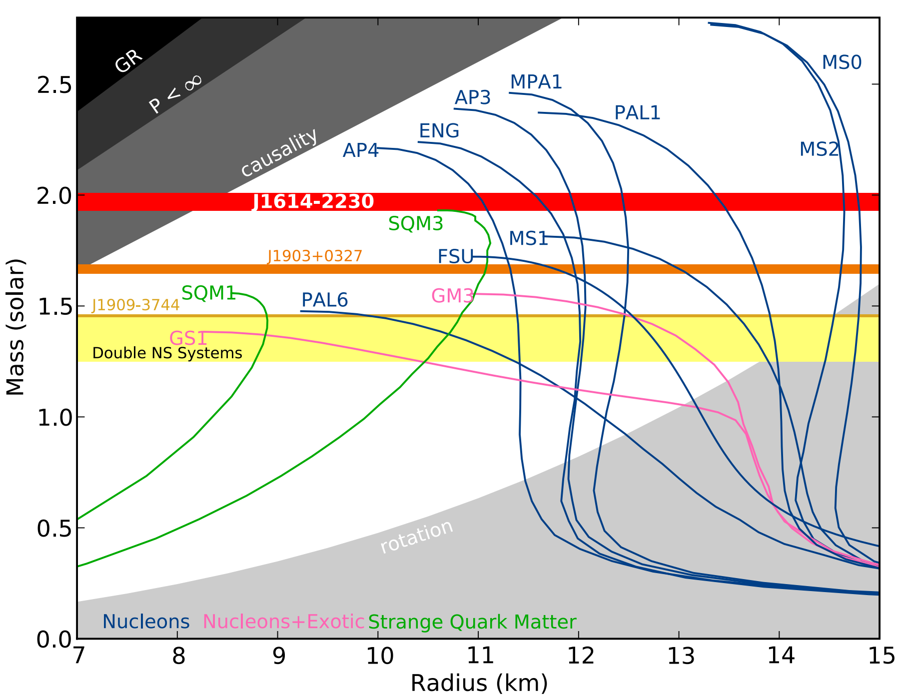
Tolman-Oppenheimer-Volkoff (TOV) eq.

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

(this is the **relativistic** version of the Newtonian hydrostatic equilibrium: take $c \to \infty$)

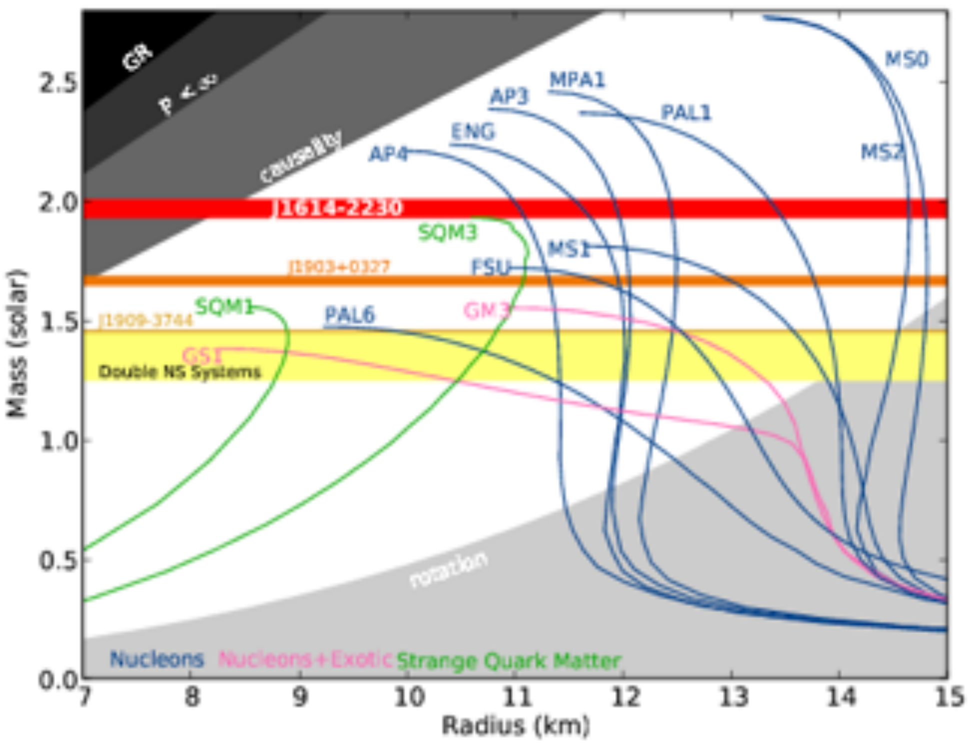



Each proposed EOS *model* produces a different curve. Which are the *viable* models?




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

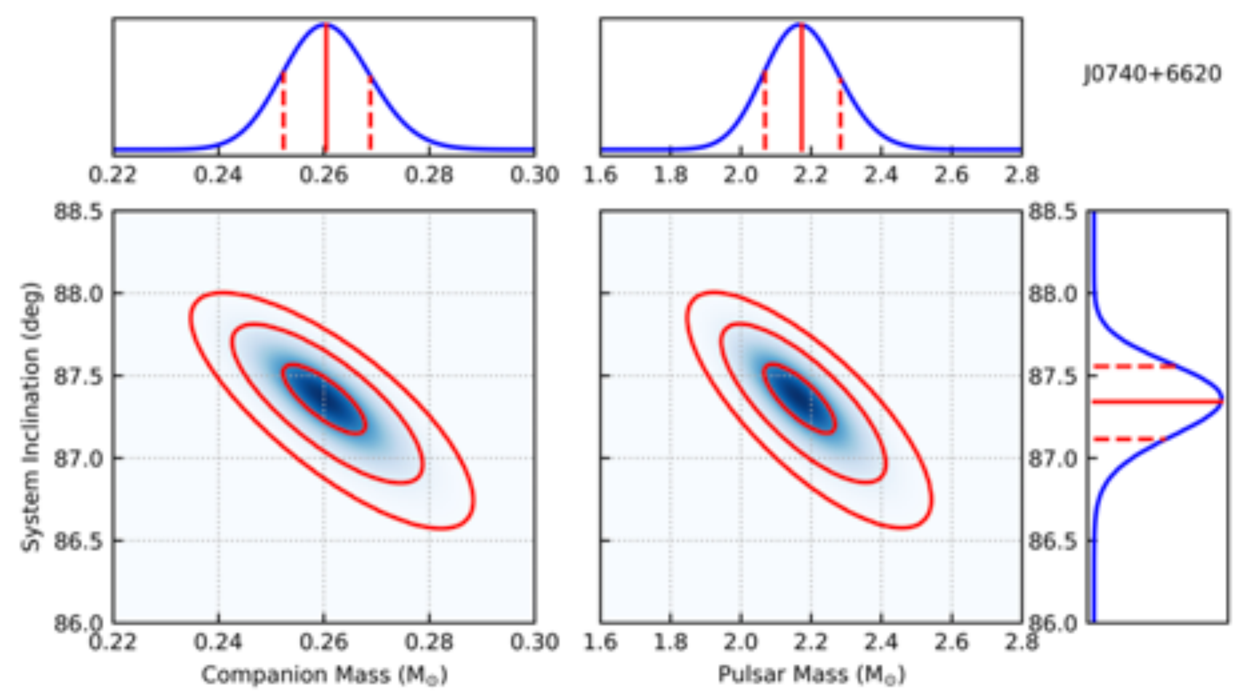
# Observed high masses




Demorest et al. 2010

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

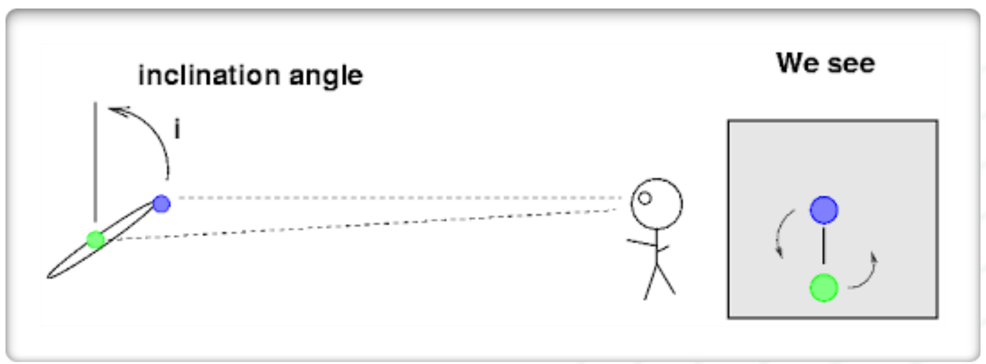
*softer* EOSs predict a lower maximum mass and more compact stars

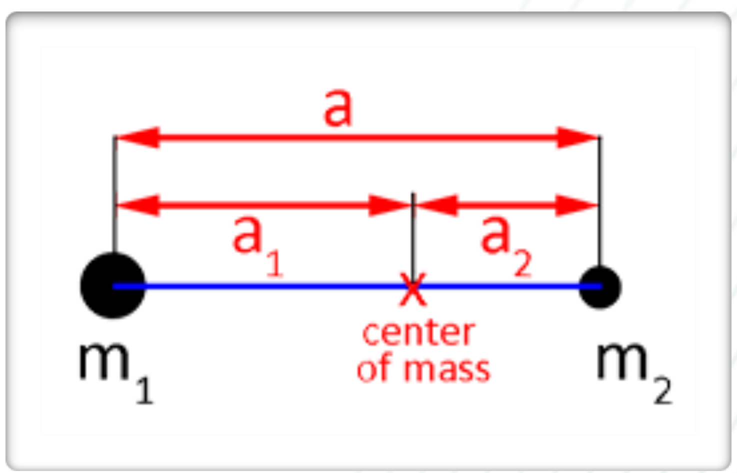



Cromartie+ 2019

# 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

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

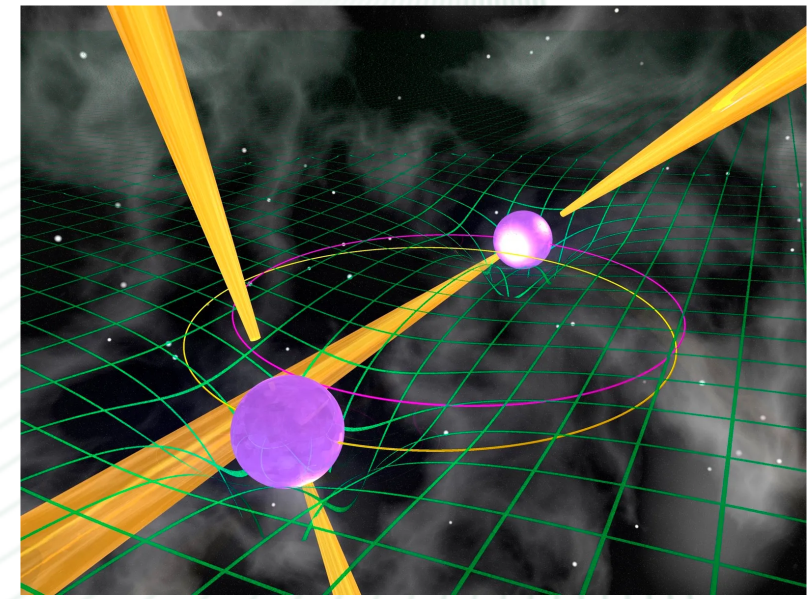
we can write

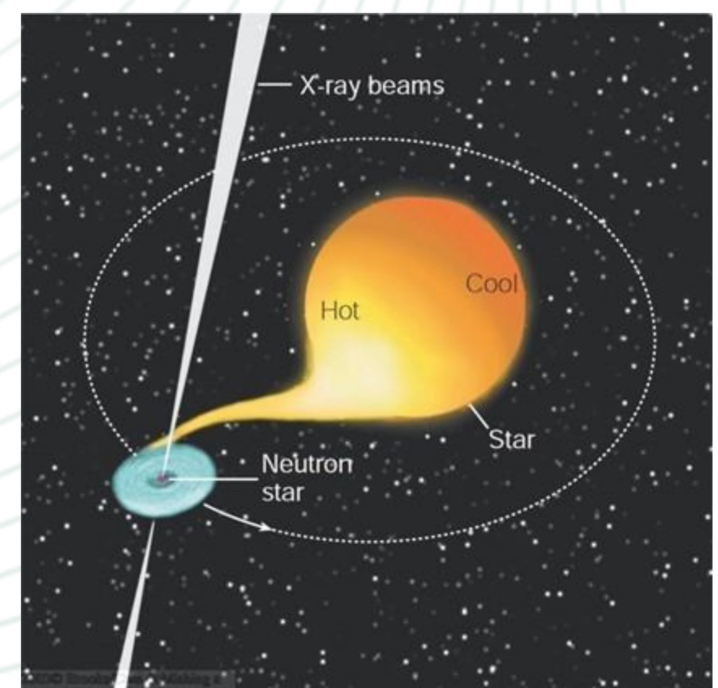
$$f_1(m_1, m_2, i) \equiv \frac{m_2^3 \sin^3 i}{(m_1 + m_2)^2} = \frac{P v_1^3}{2\pi G}$$

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

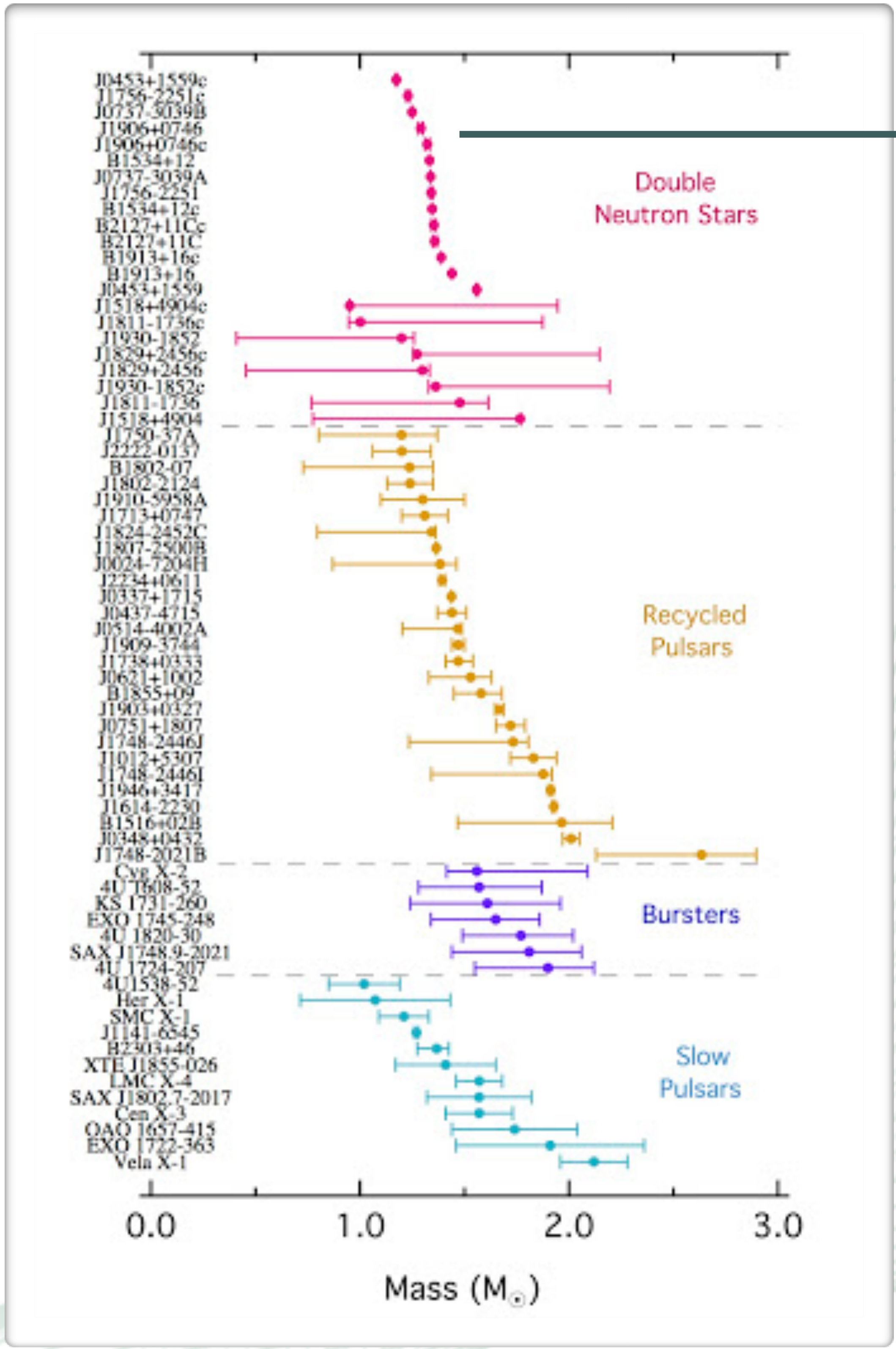
$$m_1 = \frac{f_1 q (1+q)^2}{\sin^3 i}$$

and from $f_2/f_1$ we have $q$.

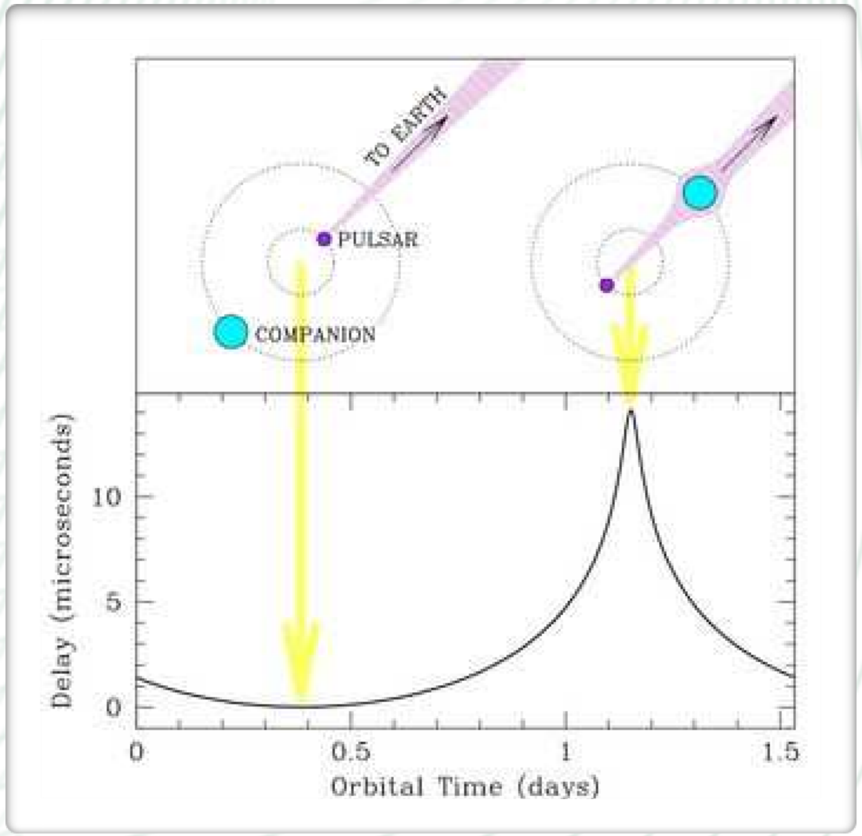




# Observed Neutron Star masses



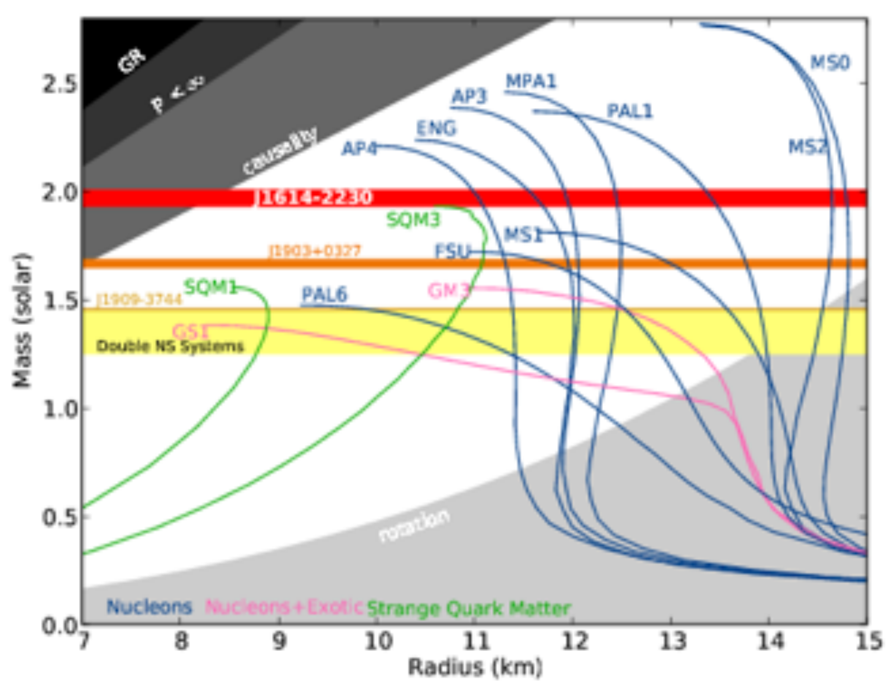

Shapiro Delay:



# Group discussion question

*How can we measure the radius of a neutron star?*

*What accuracy should we have?*

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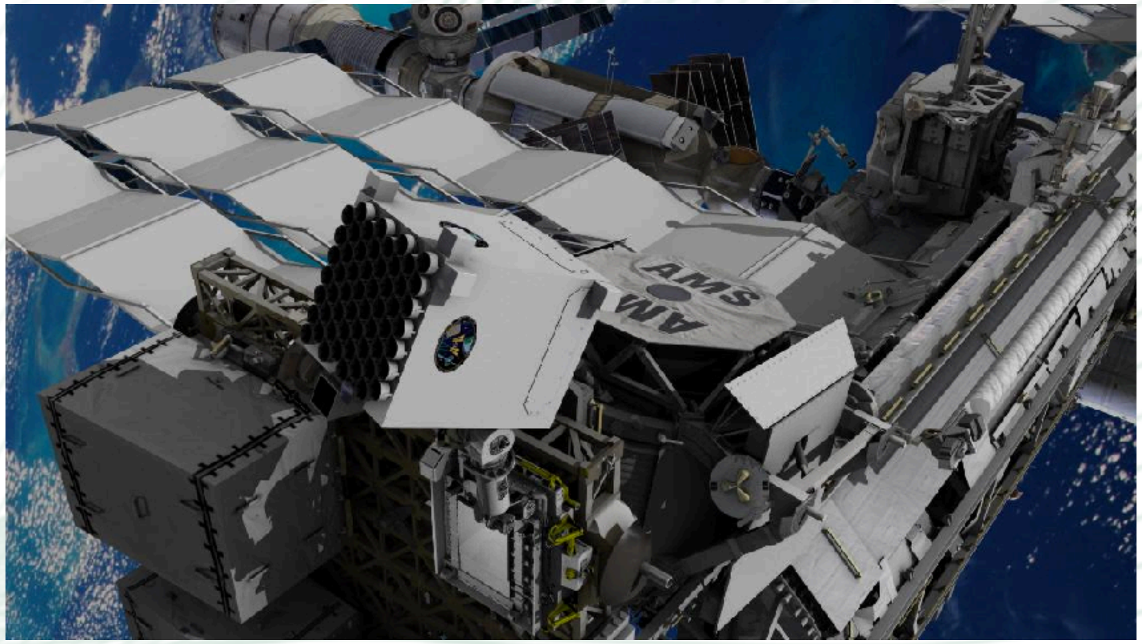
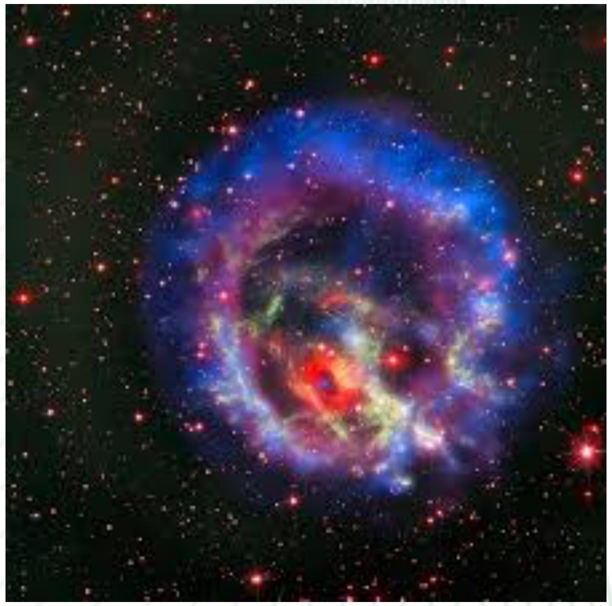
# NICER

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.



# Lunch Break





We'll be back on Friday for:
Neutron Stars - Part II