

Neutron Stars : composition and observation



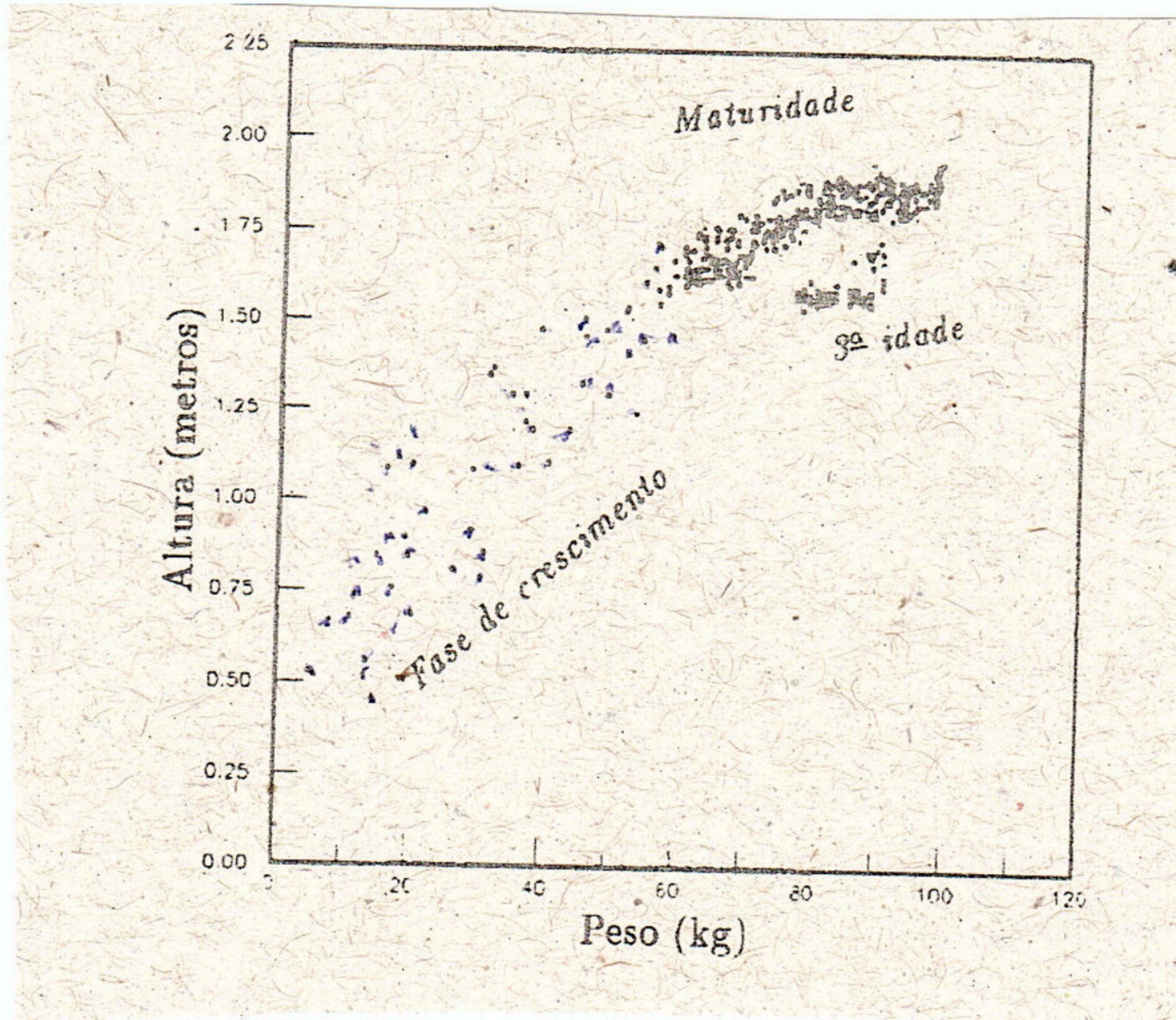
Débora Peres Menezes (UFSC)
30/09/2021



V José Plínio Baptista School of Cosmology

COMPACT OBJECTS

Stars - life and death



Chung - Vida e morte das estrelas

Diagrama HR (Hertzsprung - Russel)

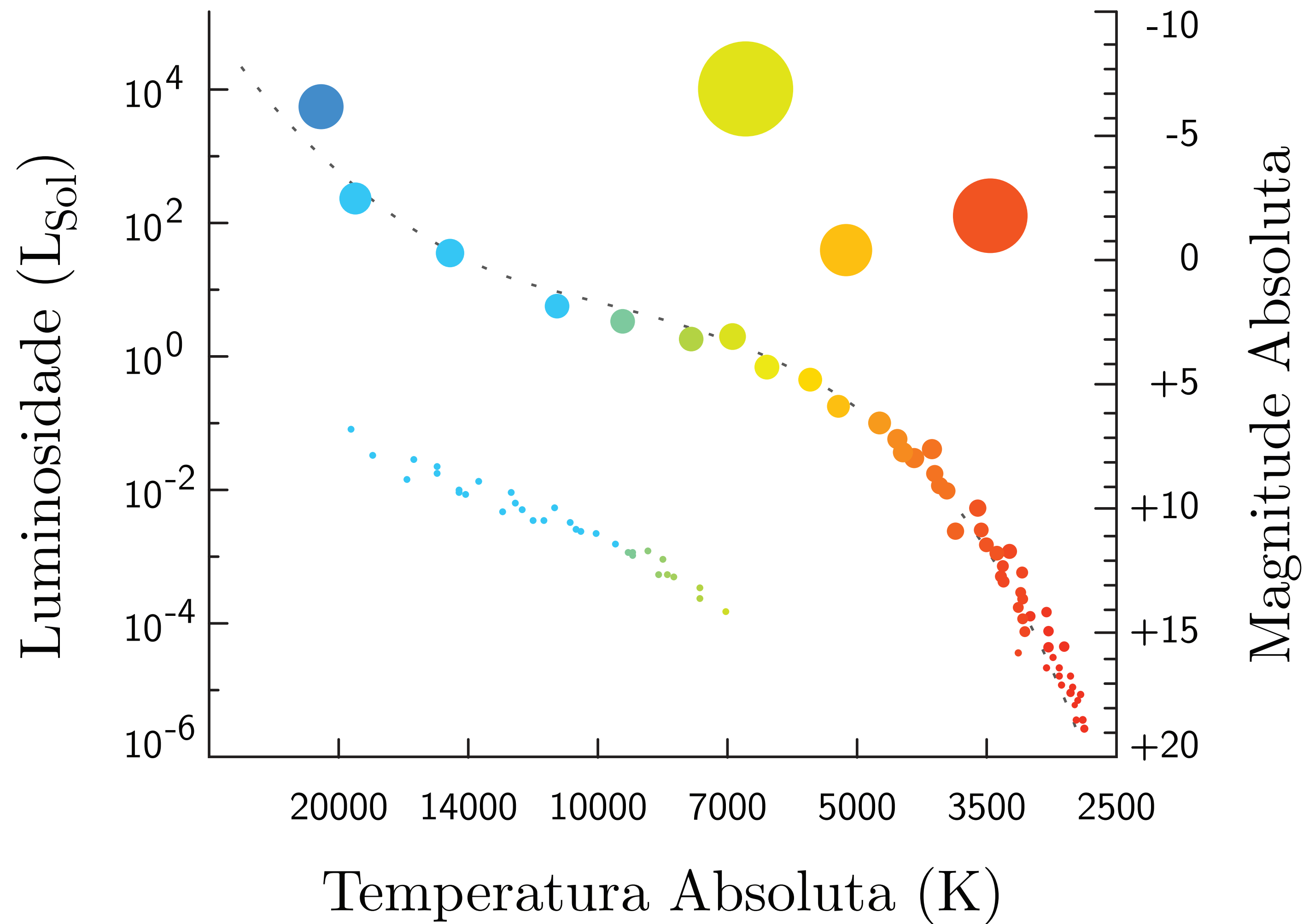
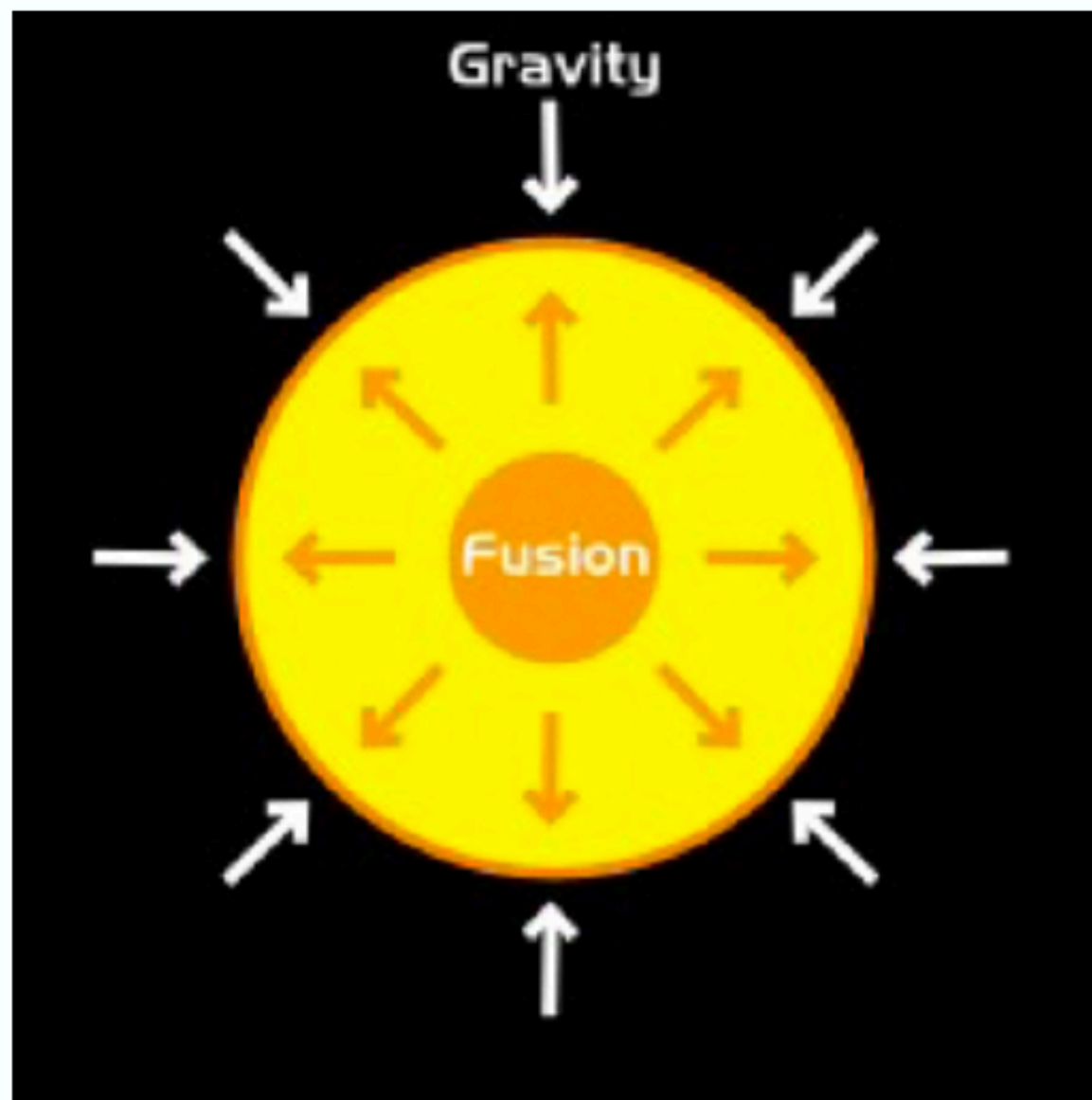


Figura de Kevin Schroeder

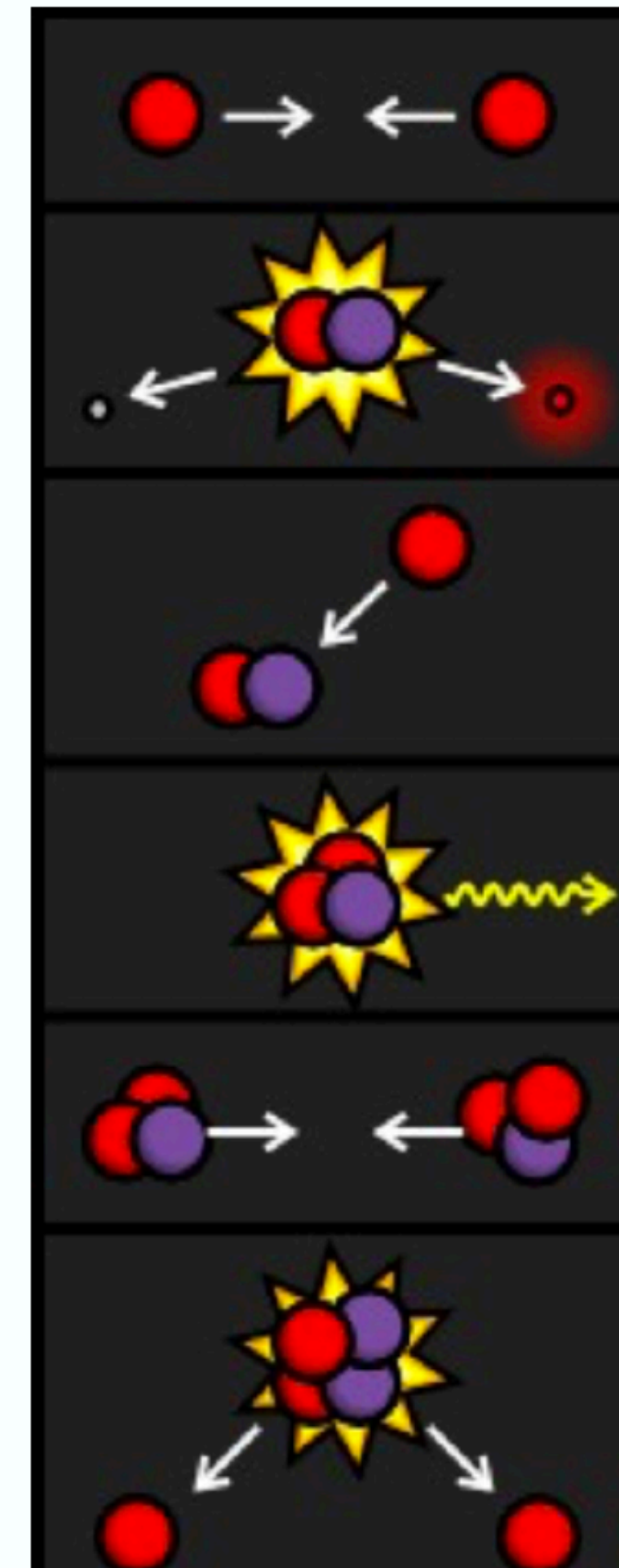
**90% of the stars are in the main sequence
(the longest period in a star life);**

**low mass stars are colder and less luminous
massive stars are hotter and more luminous**

**fusion is the reaction that keeps
the star alive**



**At the end,
gravity wins and
the star dies**



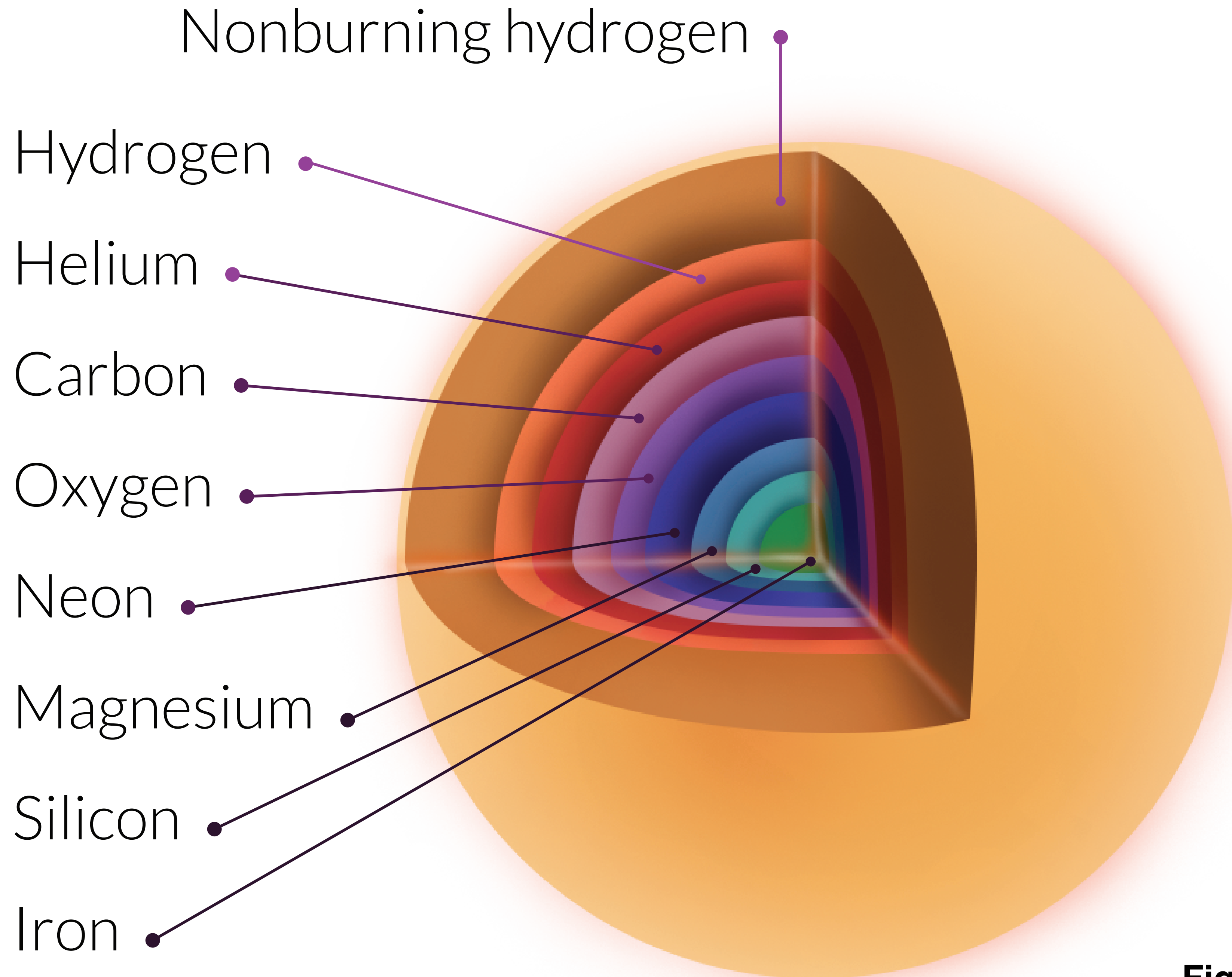
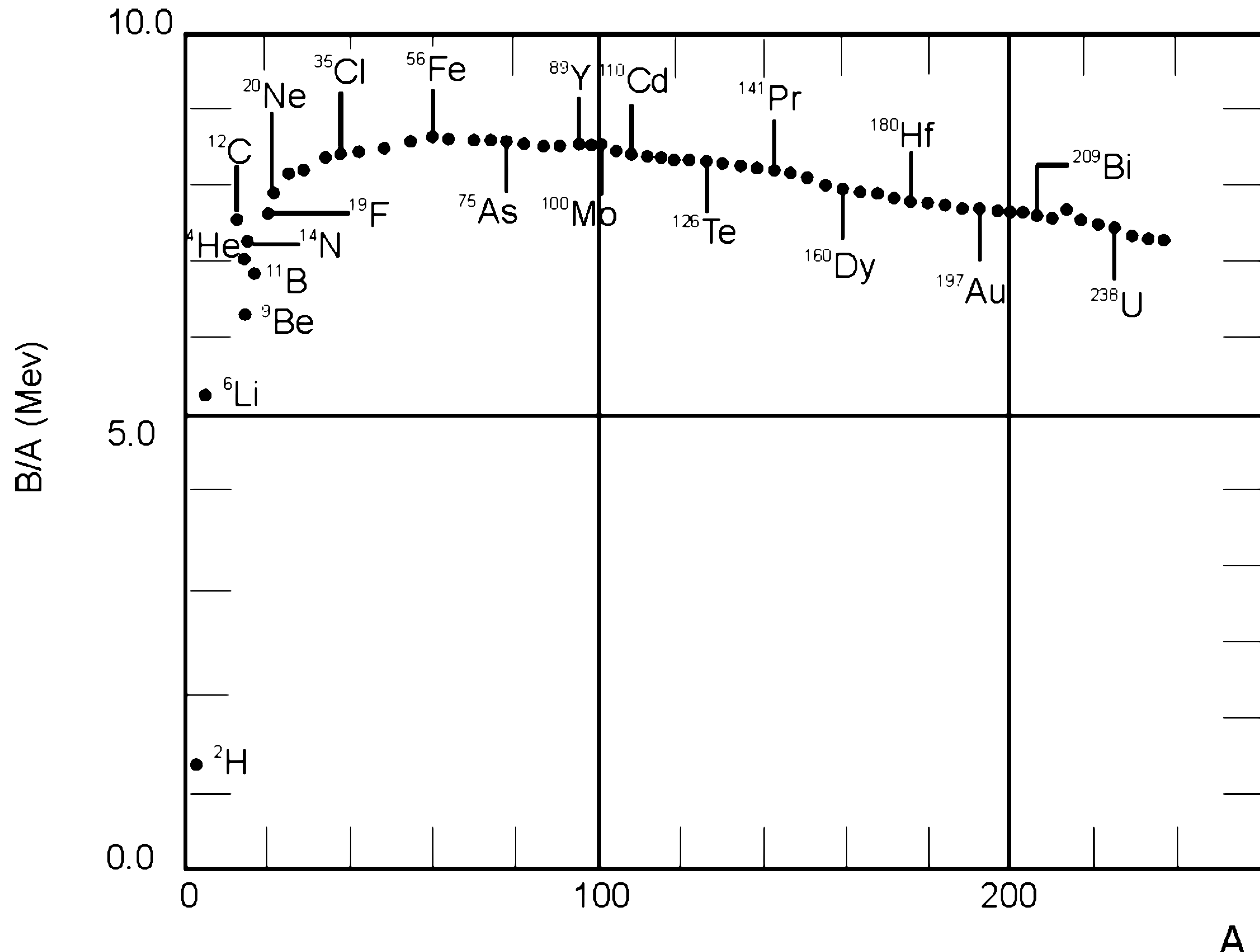
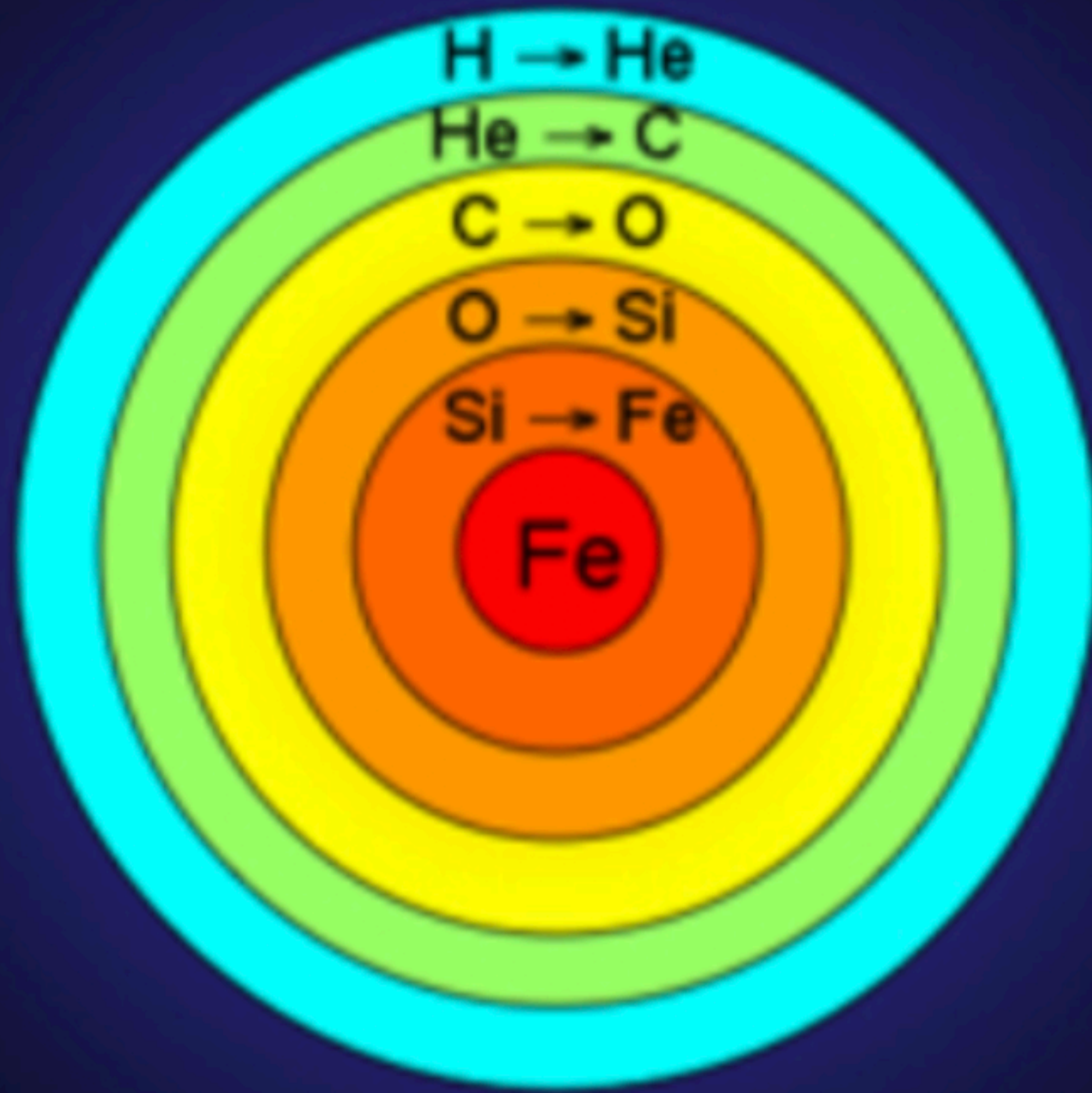


Figura de Kevin Schroeder



For a 25 solar mass star:



Stage	Duration
$H \rightarrow He$	7×10^6 years
$He \rightarrow C$	7×10^5 years
$C \rightarrow O$	600 years
$O \rightarrow Si$	6 months
$Si \rightarrow Fe$	1 day
Core Collapse	1/4 second

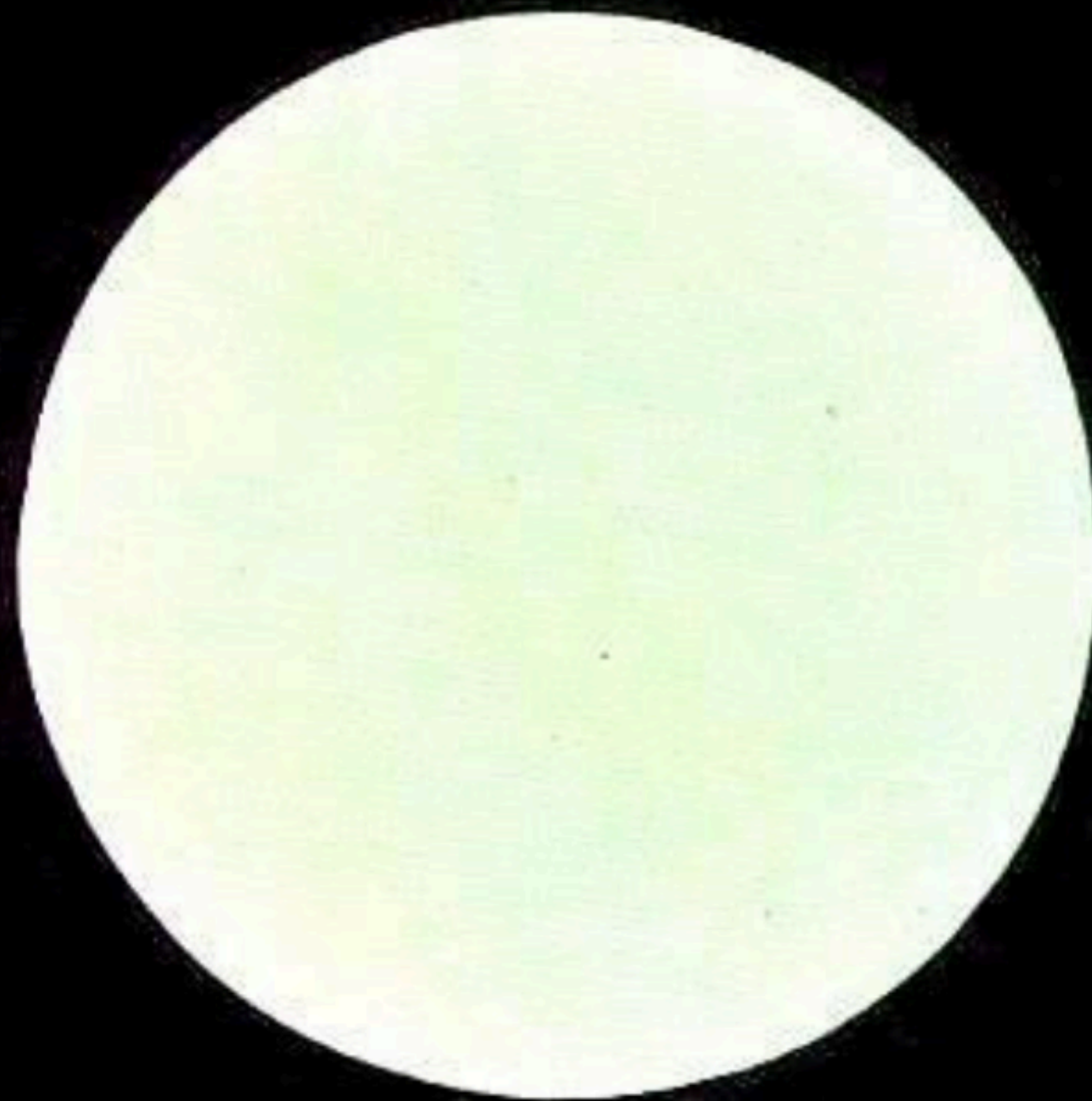


Msc. Thesis - James Rudinei Torres

EARTH



WHITE DWARF



NEUTRON STAR



Compact Stars - Brief history

1844 - Sirius (B) is predicted as part of a binary system (Frederick Bessel)

1862 - observed (Alvan Clark Jr)

1914-1915 - Both stars had the same T at the surface.

but Sirius B was much denser than Sirius A -

spectroscopy (Walter Adams)

1926 - Fowler - White dwarf described as a gas of

degenerate electrons whose pressure would

compensate the gravitational force

1930 - Maximum mass of a white dwarf

(Chandrasekar)

What if a massive star is **even denser
than a white dwarf ?**

**1931 - In this case, the atomic nuclei would
overlap and the star will be a huge nucleus.
(Lev Landau)**

(prediction of the neutron star)

1932 - Neutron is detected (Chadwick)

**1934 - Compact objects seen as possible
supernova explosion remnants
(Baade e Zwicky)**

1939 - Tolman, Oppenheimer and Volkoff

1940 - Urca process (Gamow and Schenberg)

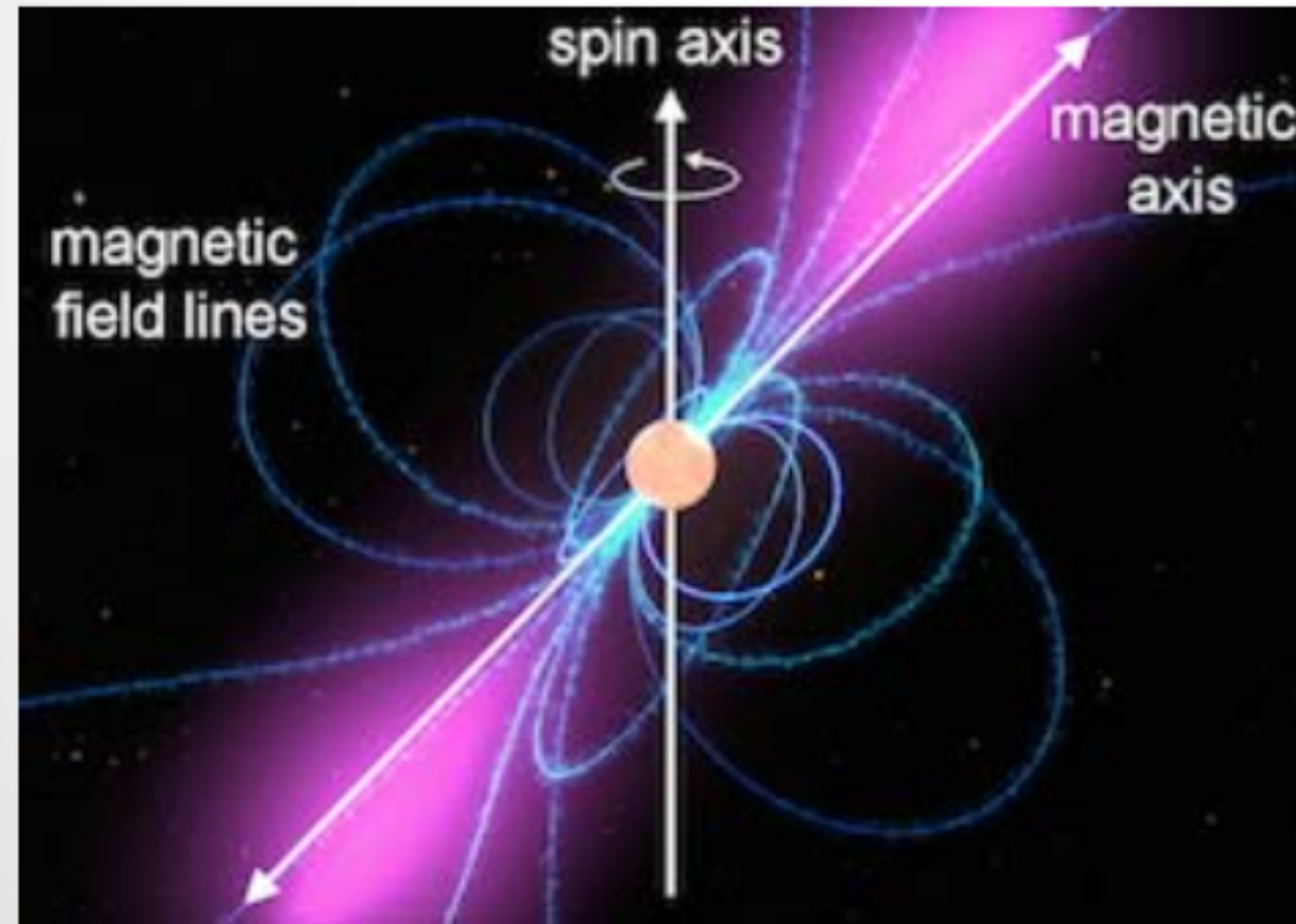
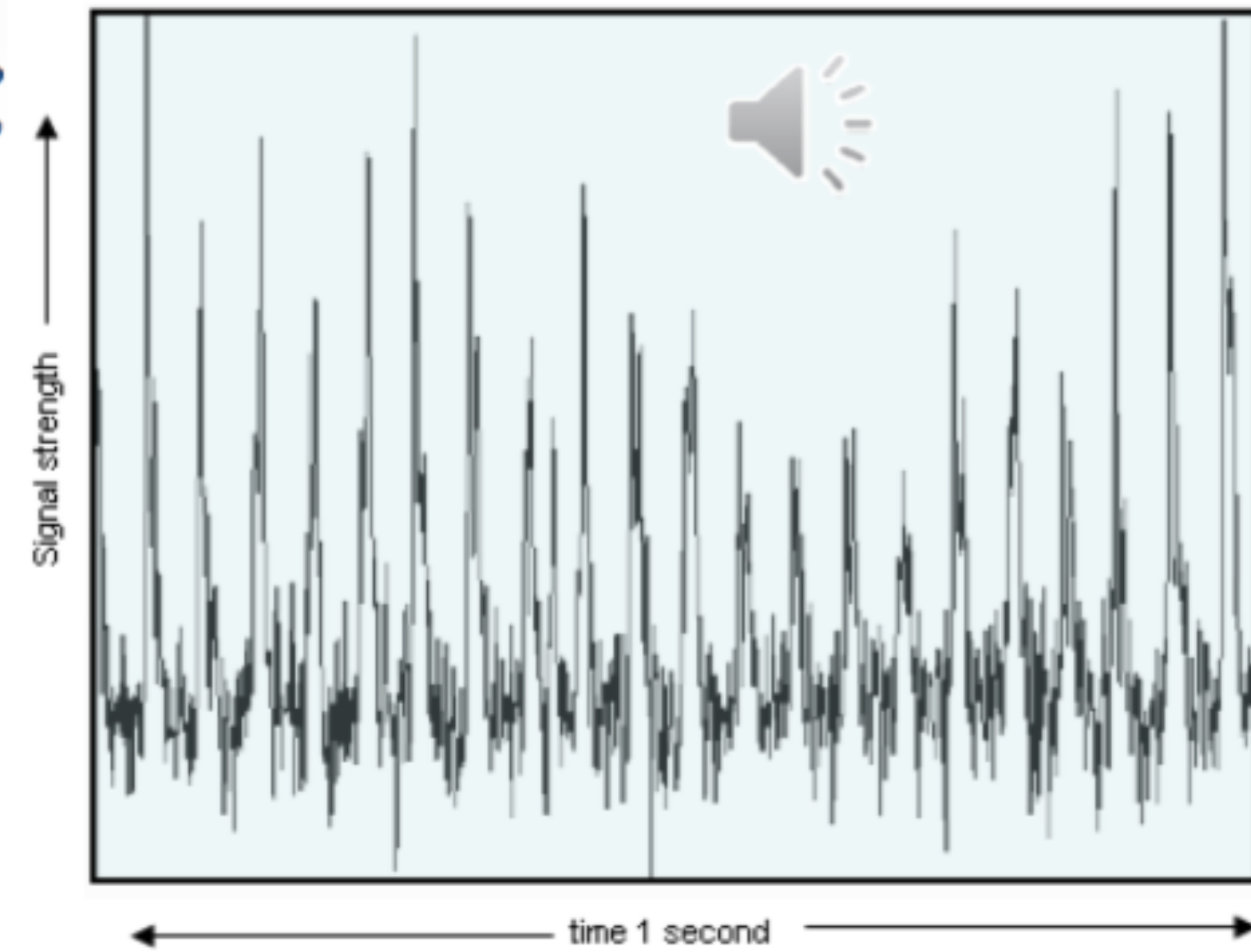
1964 - Quarks (Gell-Mann e Zweig)

**1967 - Neutron stars detected
(Jocelyn Bell and Antony Hewish)**



NS discovery: LGM-1

Jocelyn Bell
& Antony Hewish
(Nobel 1974)



Credit: NASA/Goddard Space
Flight Center Conceptual Image
Lab



Mulheres na ciência

OLHOS DIFERENTES

com
DÉBORA PERES MENEZES

1974 - Hulse and Taylor (Nobel 1993)

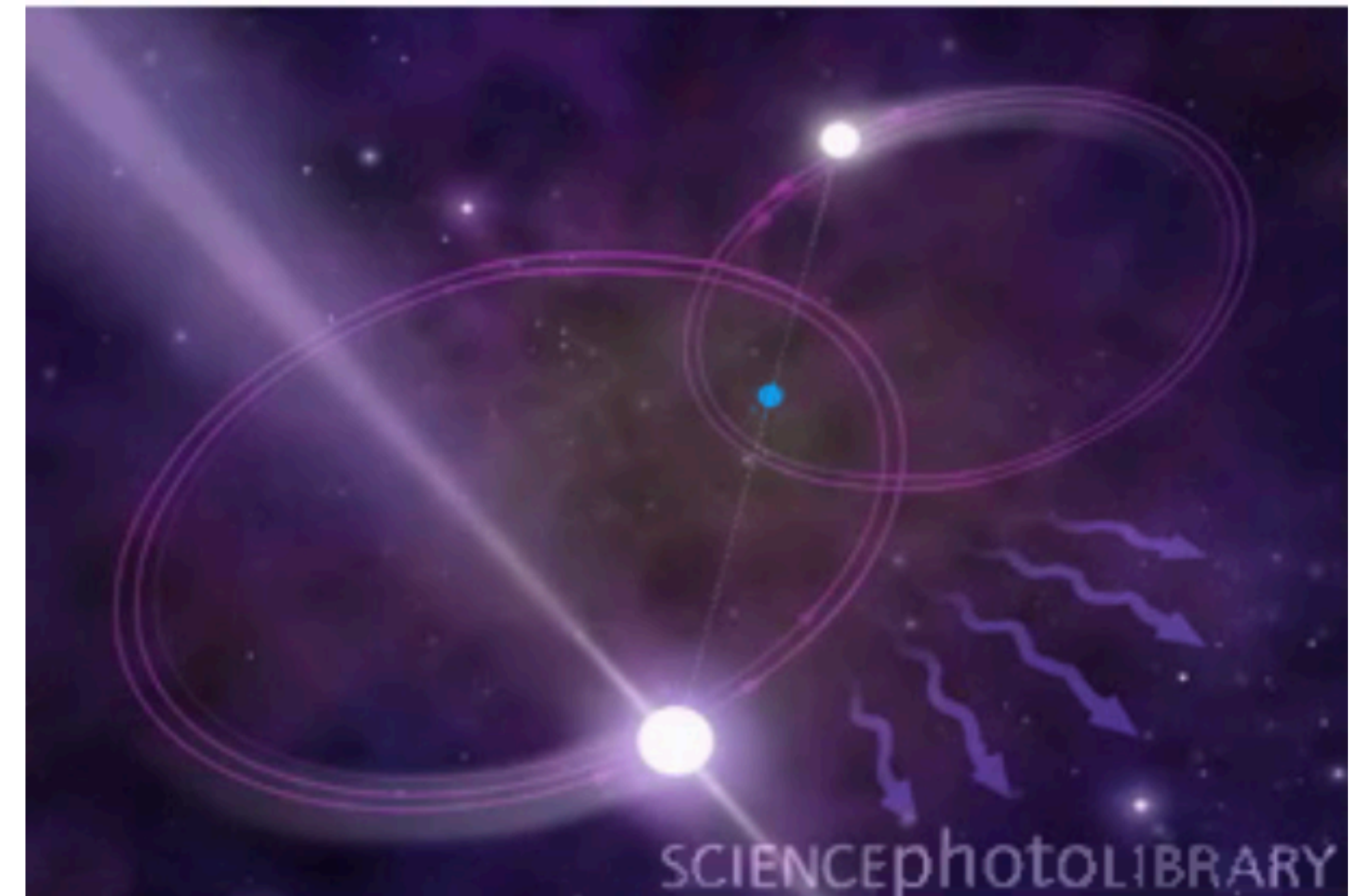


first binary pulsar PSR1913+16
(radiotelescope Arecibo)
very precise pulse period

NS mass can be measured **directly**
only in binary systems
(**5 - 10%** of known pulsars are in binaries)

explanation: loss of energy in the form of GW

2015 - GW150914 (two colliding black holes)

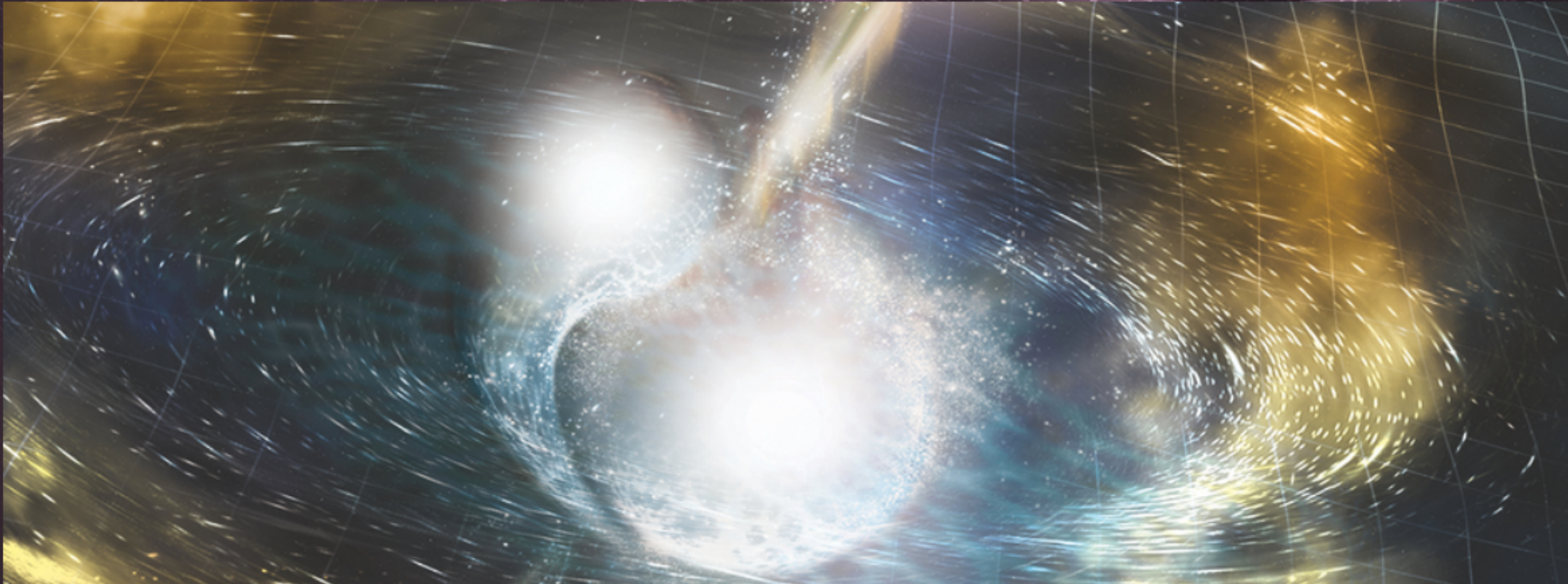




LIGO

Laser Interferometer
Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT

[About](#) [Learn More](#) [News](#) [Gallery](#) [Educational Resources](#) [For Scientists](#) [Study & Work](#)



Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

GW170817 Press Release

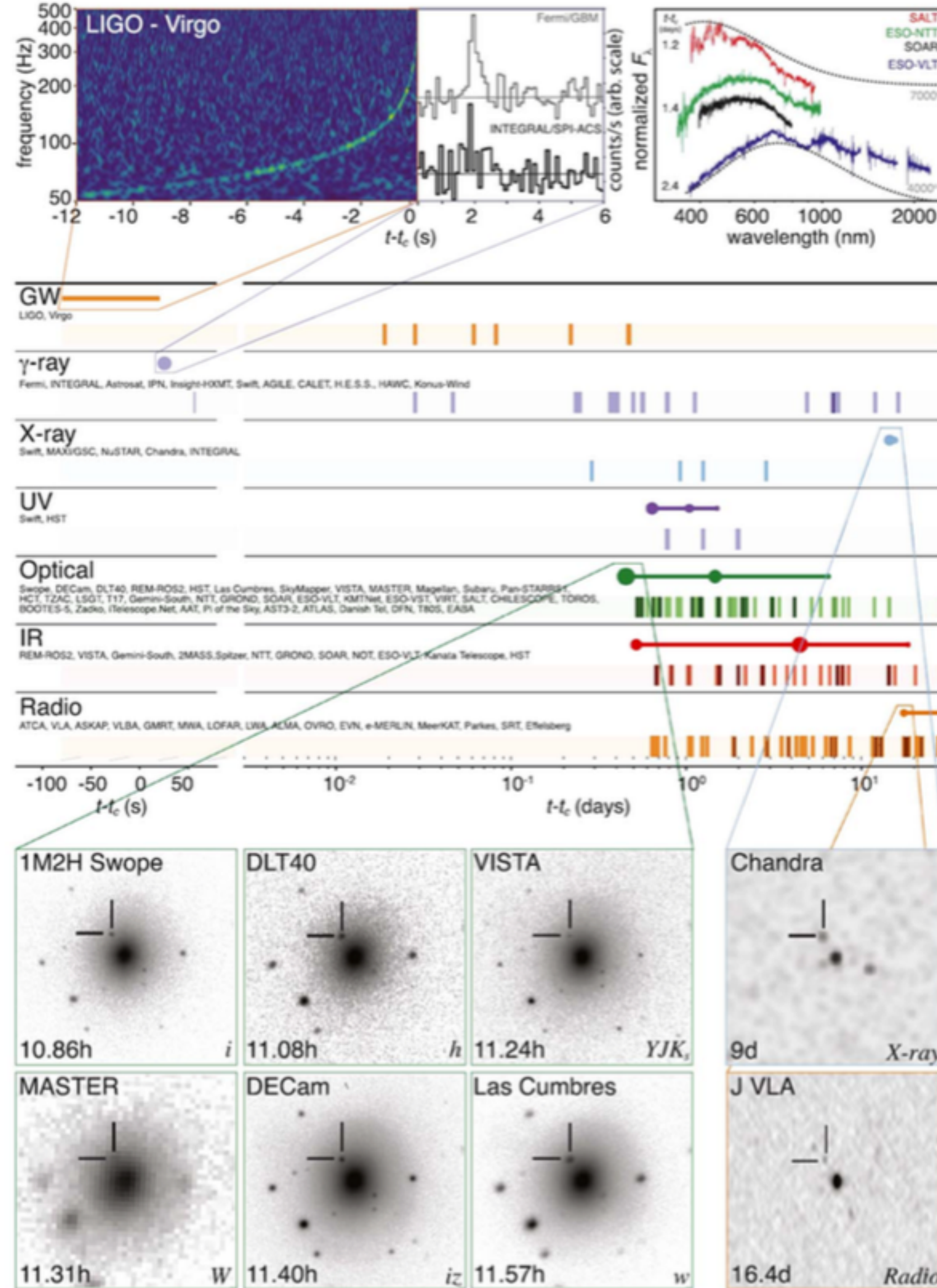
LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

Discovery marks first cosmic event observed in both gravitational waves and light.

Watch the recording of a press conference announcing the discovery, at the National Press Club in Washington, DC:

17/08/2017

multi-messenger event



**From microscopic physics
(quantum and nuclear phys.)
to macroscopic properties
(astronomical observations)**

Equation of state $\longrightarrow$ **hydrostatic equilibrium**



stellar properties

Free Fermi Gas - $T=0$

$$\epsilon = \frac{1}{\pi^2} \int_0^{k_F} \sqrt{m^2 + k^2} k^2 dk$$

$$P = \frac{1}{3\pi^2} \int_0^{k_F} \frac{k^4}{\sqrt{m^2 + k^2}} dk$$

(degeneracy pressure)

$$P = \frac{k_F^3}{3\pi^2}$$

$$\frac{dP}{dr} = - \frac{G M(r)}{r^2}$$

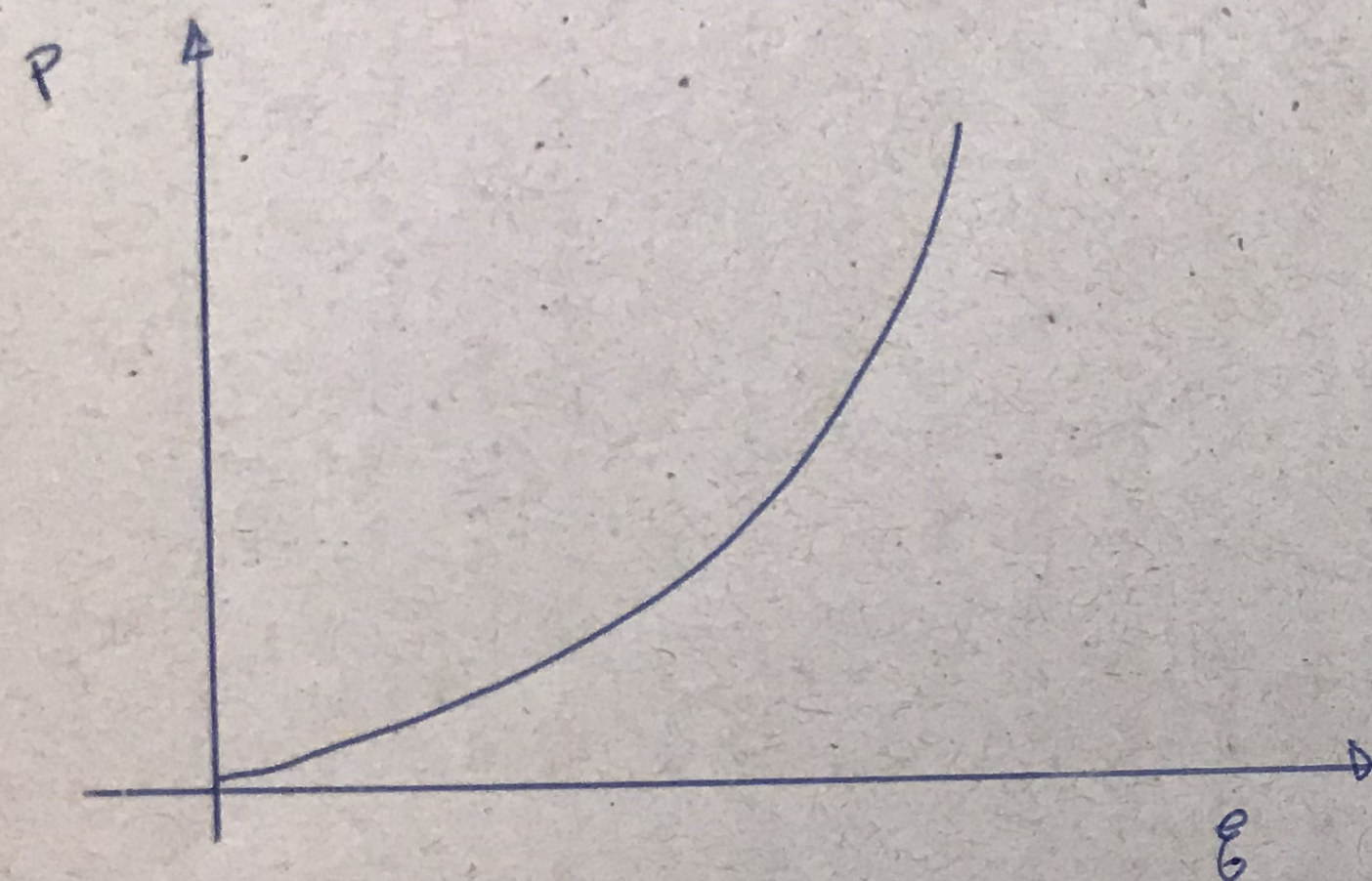
$$\frac{dM}{dr} = 4\pi r^2 \epsilon$$

Newtonian eqs.

Natural units - $\hbar = c = 1$

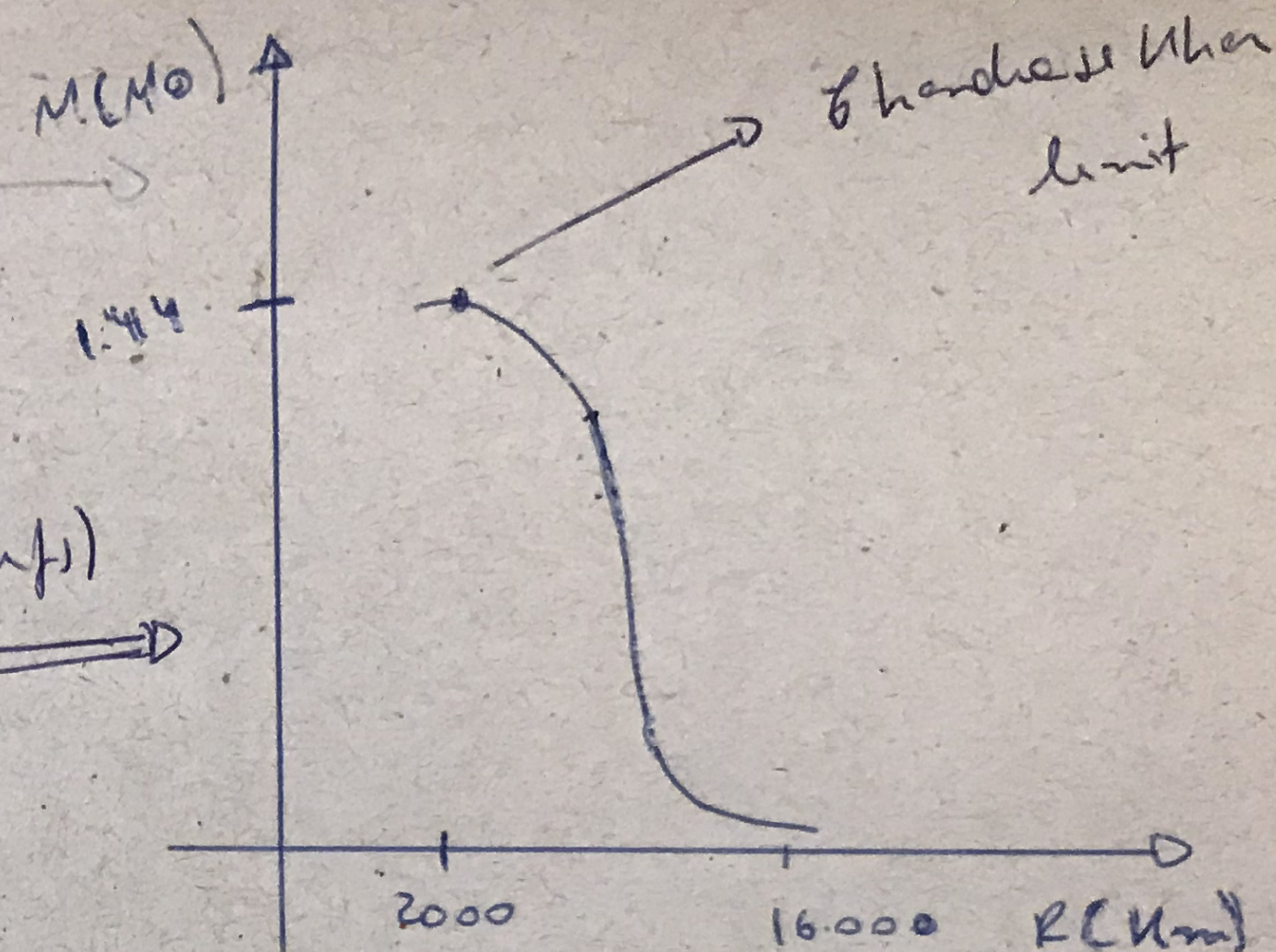
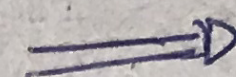
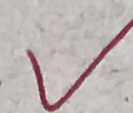
$$m = m_e \text{ (electron gas)}$$

$$m = m_n \text{ (neutron gas)}$$

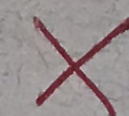


(different scalar)

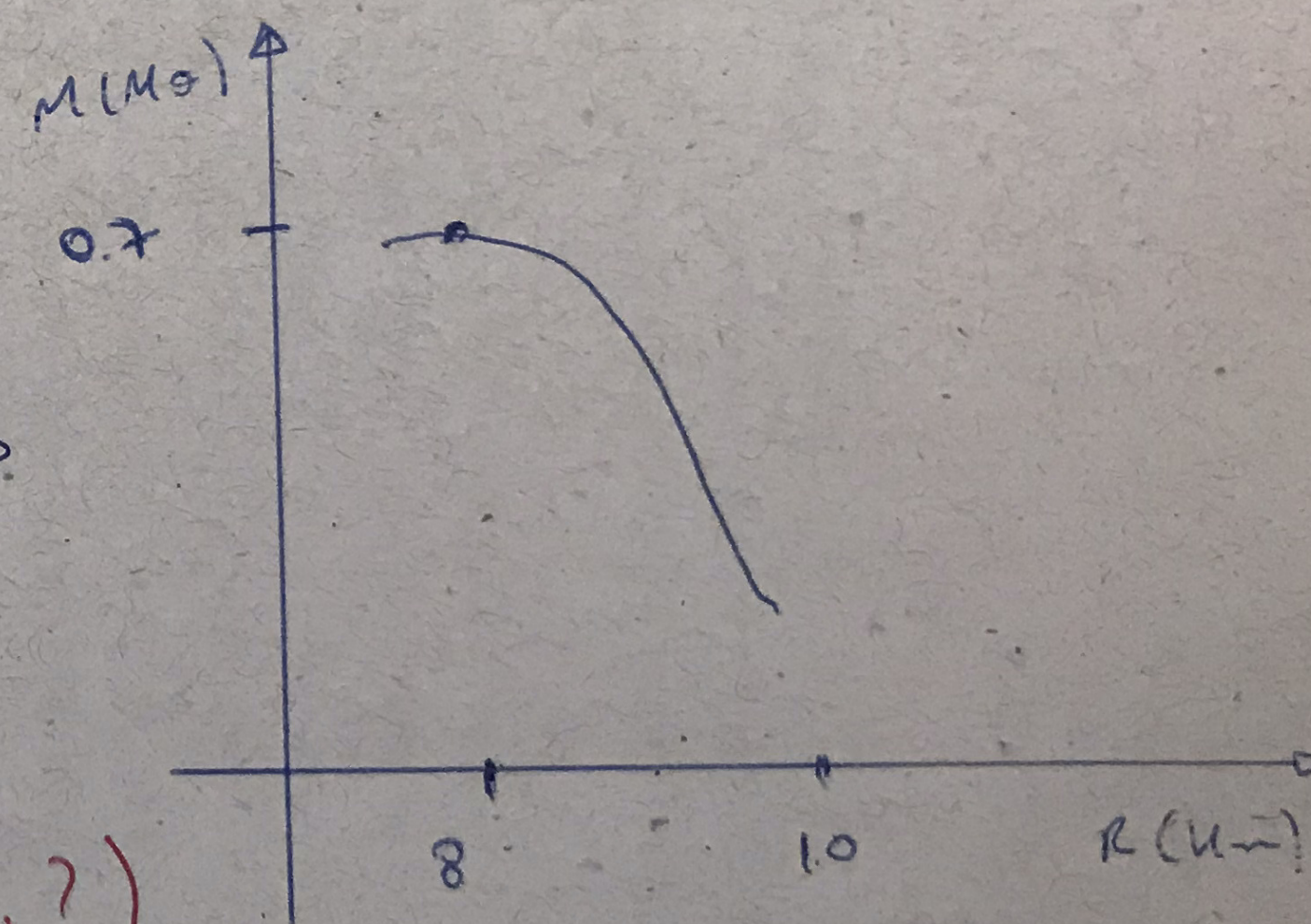
(white dwarf)



NS $\Rightarrow$



(what's missing?)



Missing bits

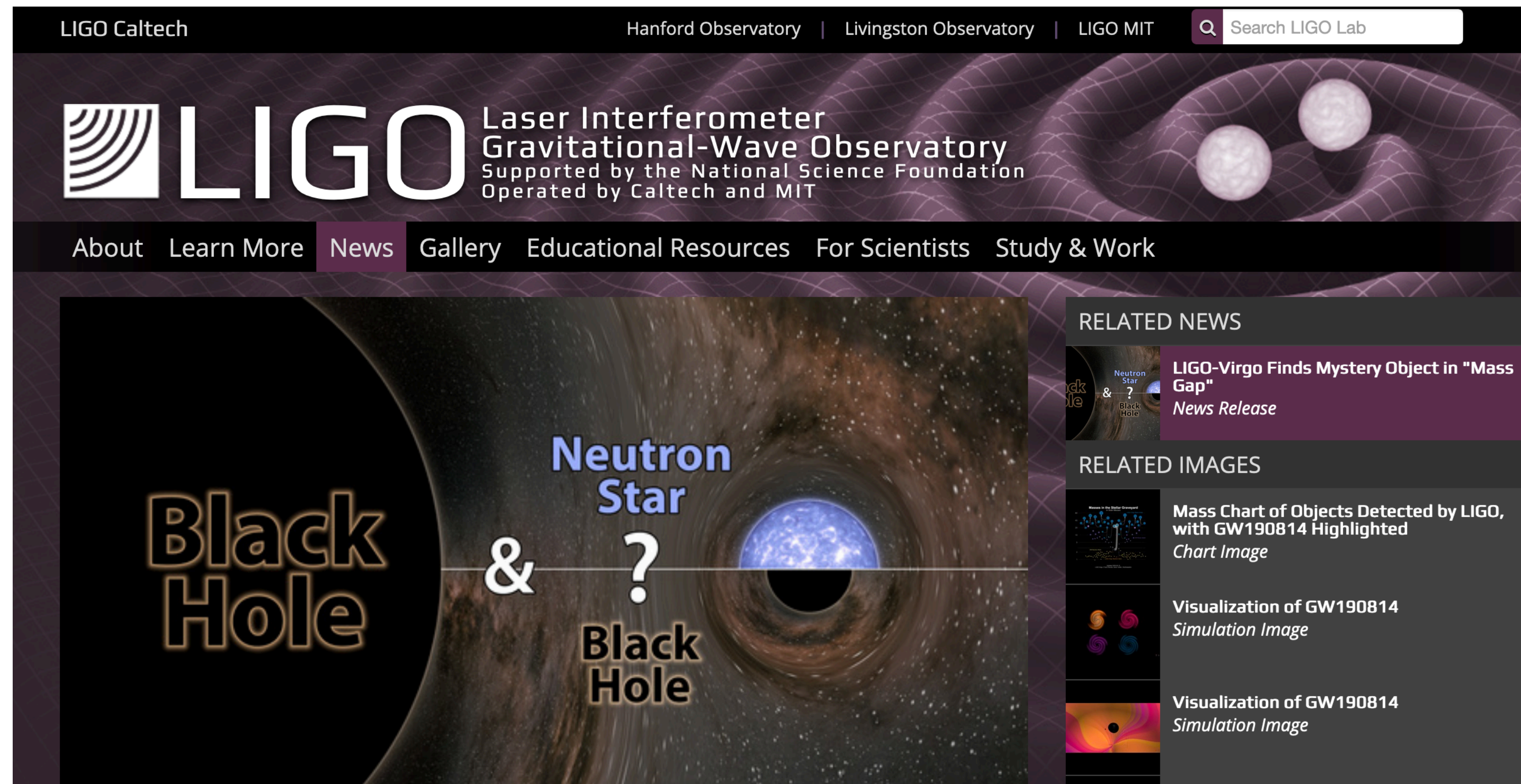
EOS $\rightarrow$ **nuclear interaction**

Hydro $\rightarrow$ **special and general relativity**

Tolman-Oppenheimer-Volkoff eqs

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

$$\frac{dM}{dr} = 4\pi r^2 \epsilon$$



Most massive $\text{NS} < 2.5 M_{\odot}$

Least massive $\text{BH} \simeq 5 M_{\odot}$

$2.5 < \text{mass gap} < 5$

$2.59 M_{\odot} (???) + 25.6 M_{\odot}$

**Signal-to-noise ratio
not large enough to
obtain the tidal deformability**

A unicorn in monoceros: the $3 M_{\odot}$ dark companion to the bright, nearby red giant V723 Mon is a non-interacting, mass-gap black hole candidate FREE

T Jayasinghe ✉, K Z Stanek, Todd A Thompson, C S Kochanek, D M Rowan, P J Vallely, K G Strassmeier, M Weber, J T Hinkle, F-J Hambsch, D V Martin, J L Prieto, T Pessi, D Huber, K Auchettl, L A Lopez, I Ilyin, C Badenes, A W Howard, H Isaacson, S J Murphy

[Author Notes](#)

Monthly Notices of the Royal Astronomical Society, Volume 504, Issue 2, June 2021, Pages 2577–2602, <https://doi.org/10.1093/mnras/stab907>

Published: 01 May 2021 **Article history** ▼

V723 Mon companion (mass gap):

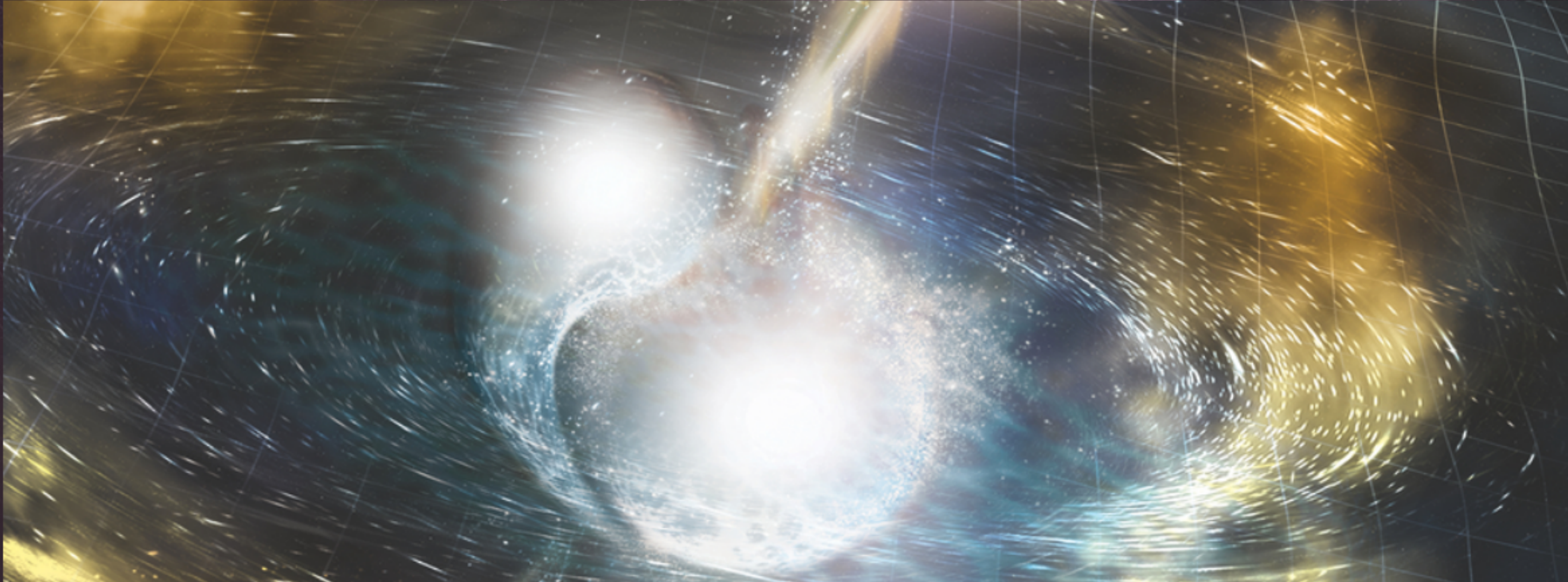
$$M \geq 2.91 \pm 0.08 M_{\odot}$$



LIGO

Laser Interferometer
Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT

[About](#) [Learn More](#) [News](#) [Gallery](#) [Educational Resources](#) [For Scientists](#) [Study & Work](#)



Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

GW170817 Press Release

LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

Discovery marks first cosmic event observed in both gravitational waves and light.

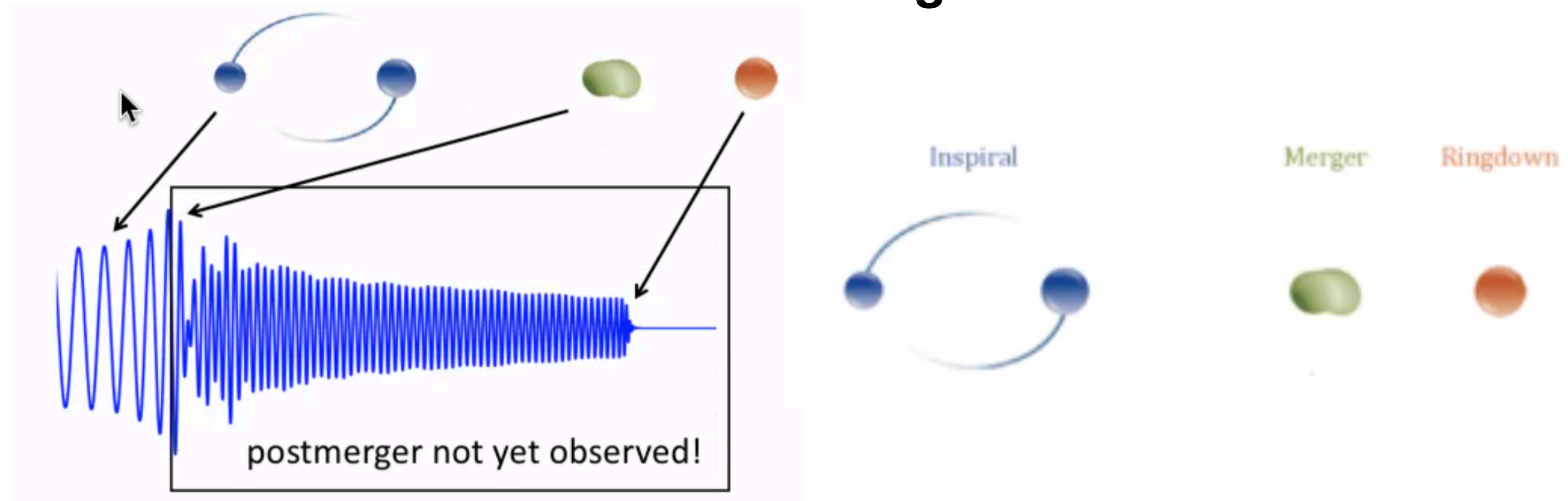
Watch the recording of a press conference announcing the discovery, at the National Press Club in Washington, DC:

Neutron Star Merger GW170817

GW vieram da galáxia NGC 4993
140 milhões de anos-luz

Observado (eletromagneticamente) por
70 observatórios nos 6 continentes e no espaço
além da colaboração LIGO-Virgo

Formas da GW baseadas em simulações
de relatividade geral:



Marés na Terra e nas Estrelas de Nêutrons

Modelagem do fenômeno das marés - gravitação Newtoniana - Augustus Love - 1909

Números de Love - caracterizam a deformabilidade de um objeto (compacto) devido às forças de maré externas.

**Damour, Nagar, Binnington and Poisson (2009)
estenderam o cálculo - efeitos da relatividade geral**

(Second order) Love numbers - Terra $\rightarrow 0,3$

NS (no sistema binário GW170817) $\rightarrow 0,1$

Tidal polarizability



- The tidal field of the companion induces a mass quadrupole moment which accelerates the coalescence
- Coalescence time is determined by the

$$\text{tidal polarizability } \Lambda = \frac{2}{3} k_2 \left(\frac{c^2 R}{G M} \right)^5$$

Slide by Francesca Gulminelli

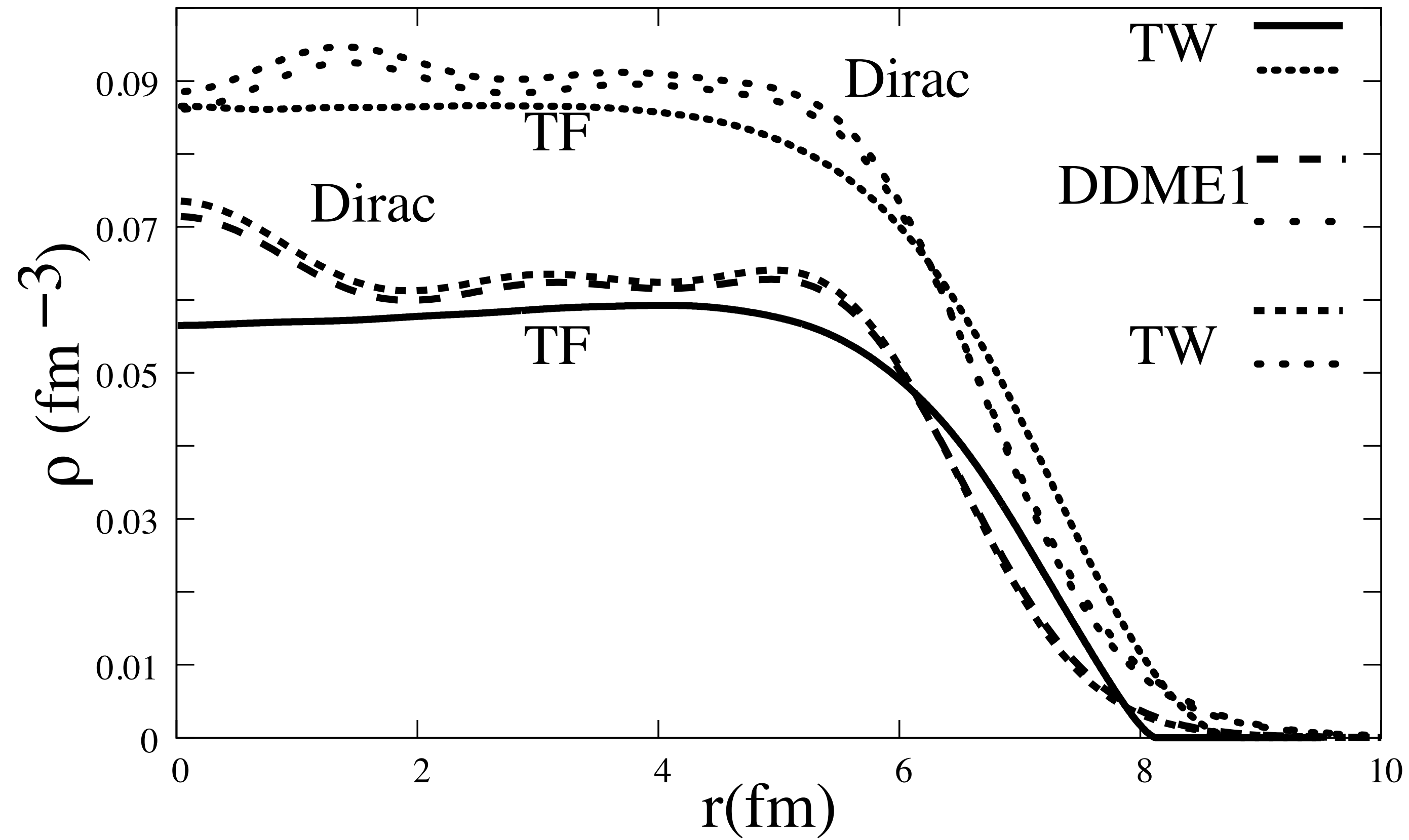
To calculate it, we need an EOS

A bit of history

Liquid drop model (1929)

- The liquid is **incompressible** - the nucleus has low compressibility due to its almost cte internal density
- Nuclei present **well defined surface**
- Radius vary with the number of nucleons such as
$$R = R_0 A^{1/3}$$
- The nuclear force **saturates** and it is **isospin independent**

nuclear density profiles



A bit of history

Semi-empirical mass formula - Bethe and Weizsäcker - 1935

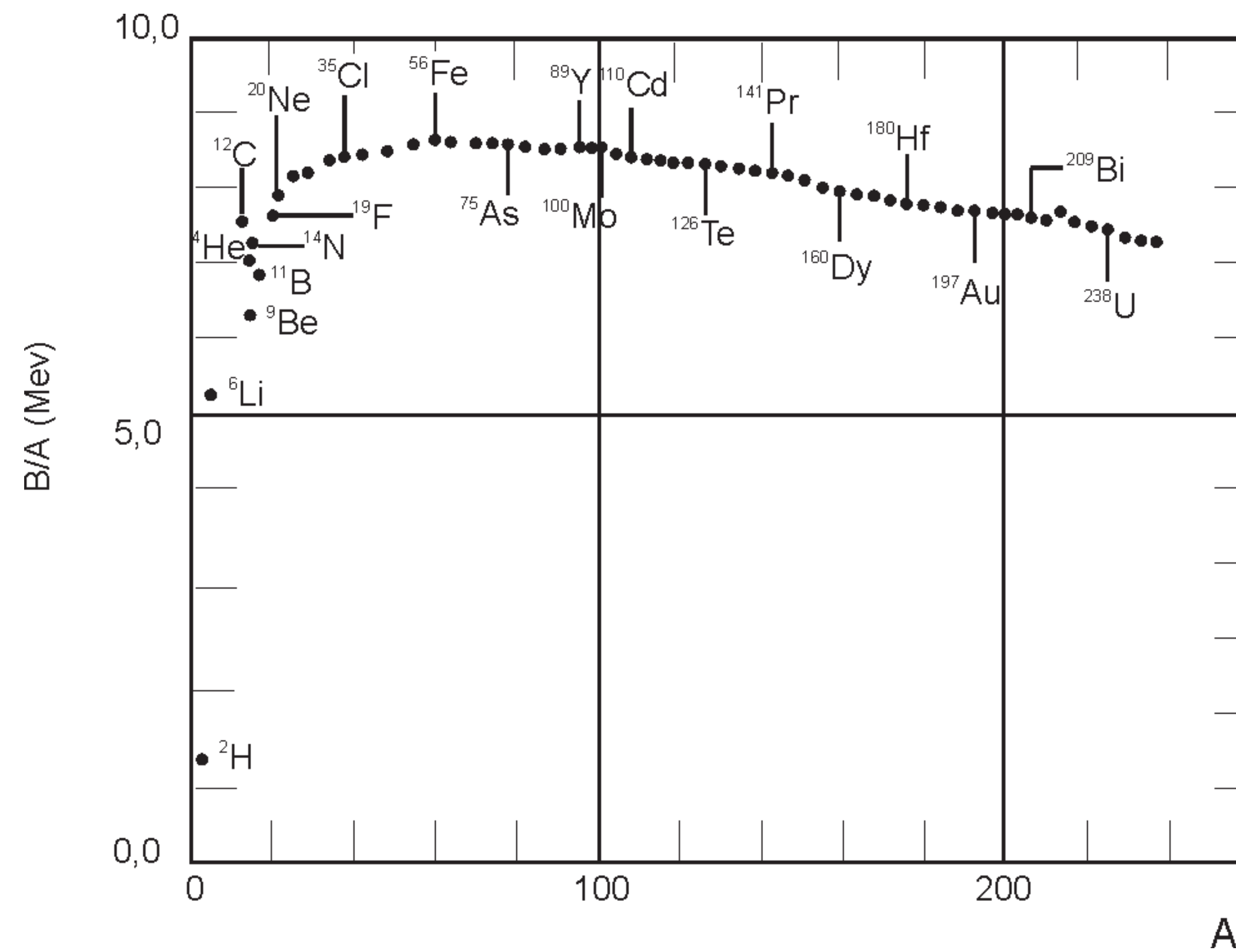
$$m(Z, A) = Zm({}^1H) + Nm_n - B(Z, A)/c^2$$

$$B(Z, A) = a_v A - a_s A^{\frac{2}{3}} - a_c e^2 \frac{Z(Z-1)}{A^{\frac{1}{3}}} - a_i \frac{(N-Z)^2}{A} + \delta(A)$$

$$a_v = 15,68 \text{ MeV}, a_s = 18,56 \text{ MeV}, a_c \times e^2 = 0,72 \text{ MeV}, a_i = 18,1 \text{ MeV}$$

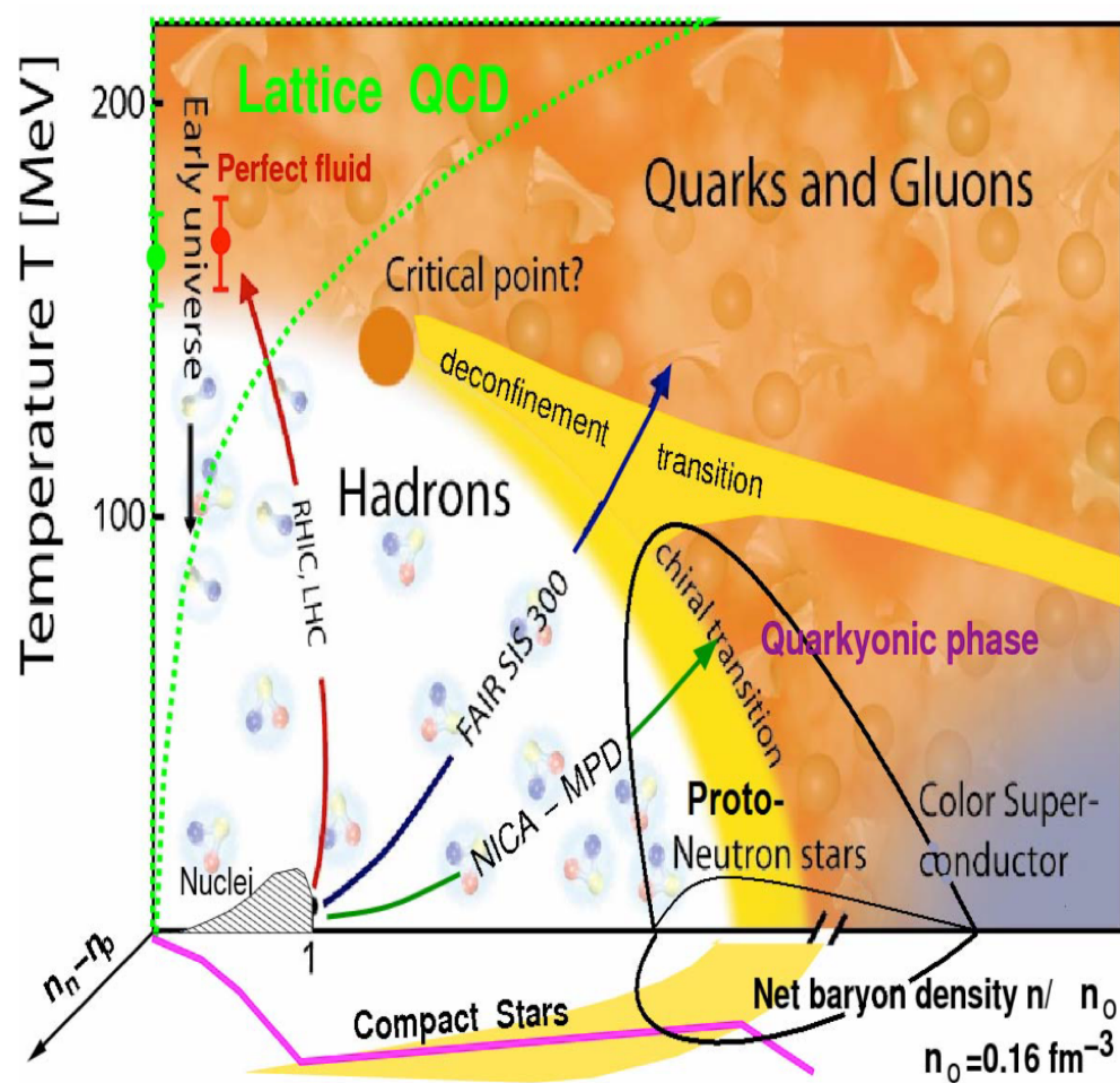
$$\delta = \pm 34 A^{-3/4}, 0 \text{ MeV} - \text{even} - \text{even}, \text{odd} - \text{odd}, \text{even} - \text{odd} \text{ nuclei}$$

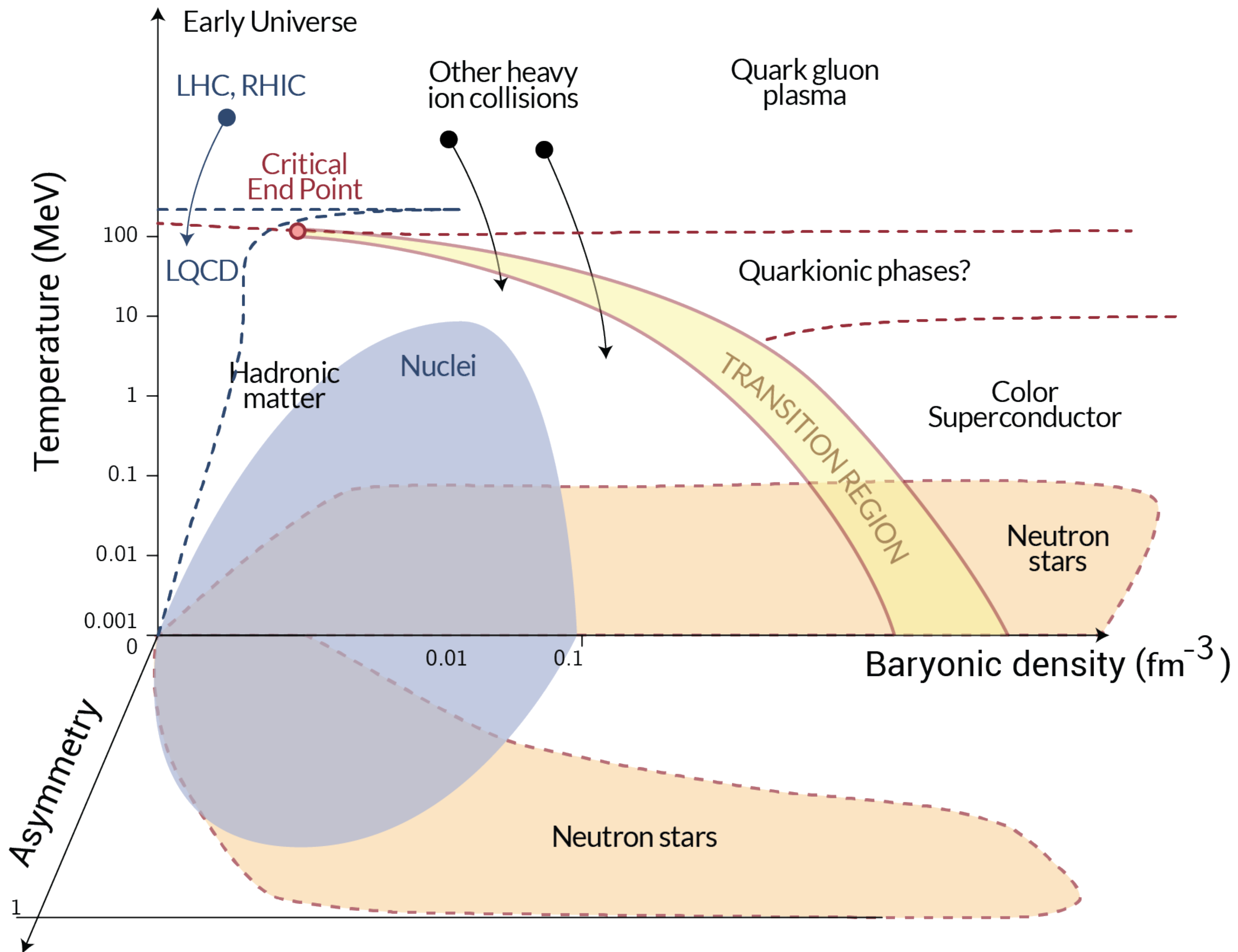
Many other possible parameter sets are possible



Although very naive, it works well even to explain fission - Coulomb X surface terms

QCD Phase Diagram - what parts can we explain?





When you look up at the night sky, remember that almost everything you see is the result of a nuclear reaction.

Bill Gelletly

