

**O que as ondas gravitacionais
podem nos ensinar sobre
os pulsares?**



**Débora Peres Menezes (UFSC)
dezembro - 2021**

Diagrama HR (Hertzsprung - Russel)

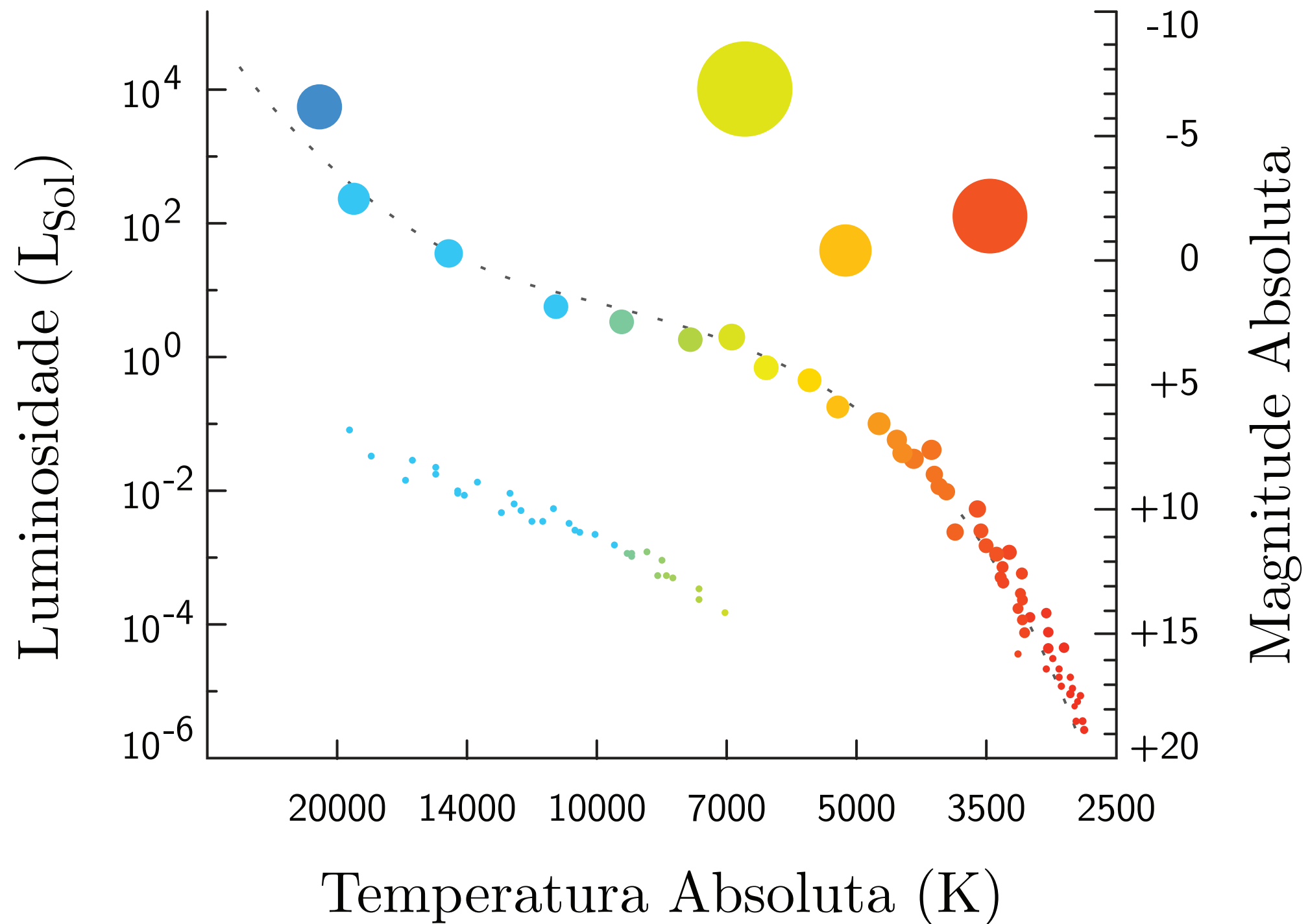
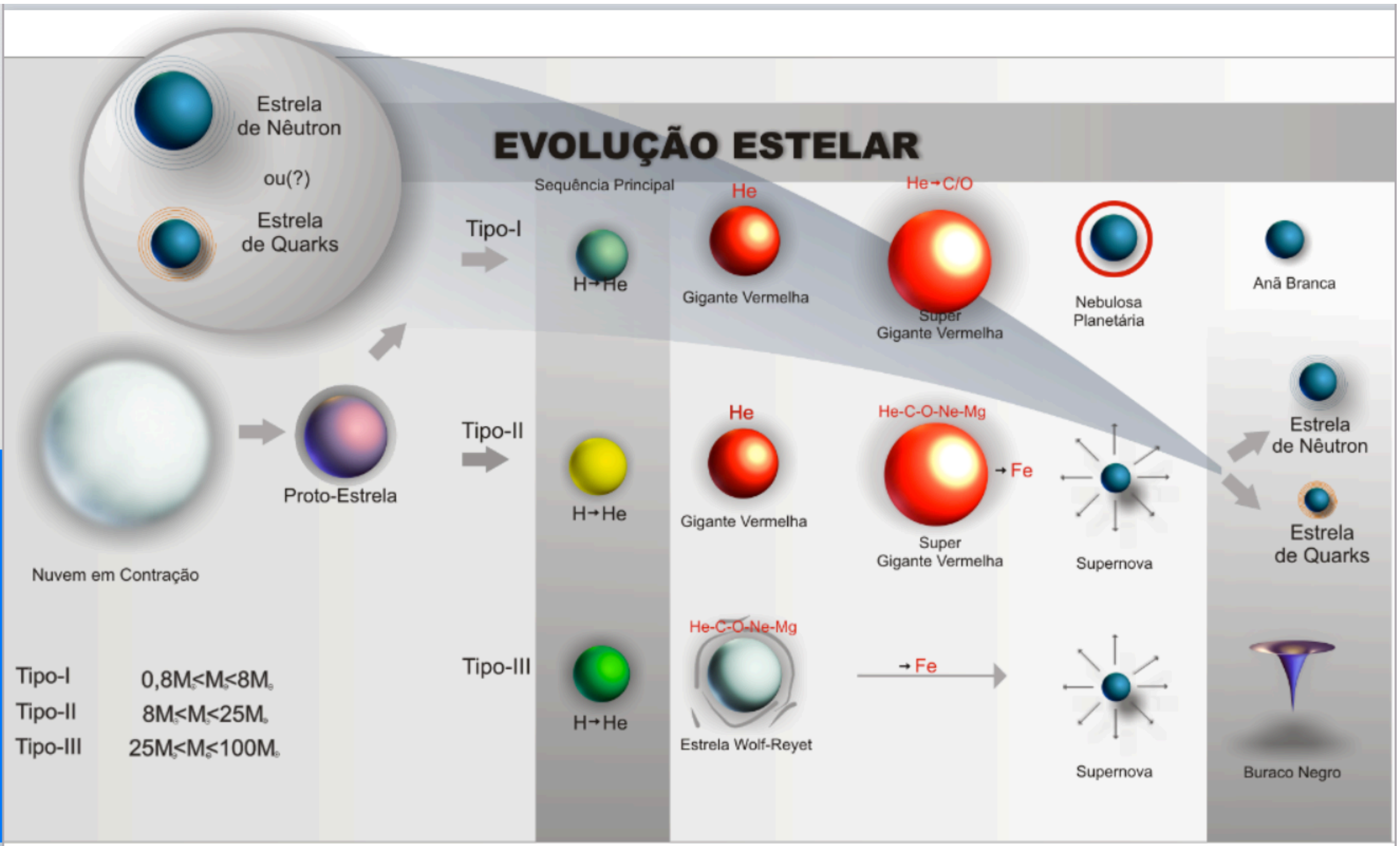


Figura de Kevin Schroeder

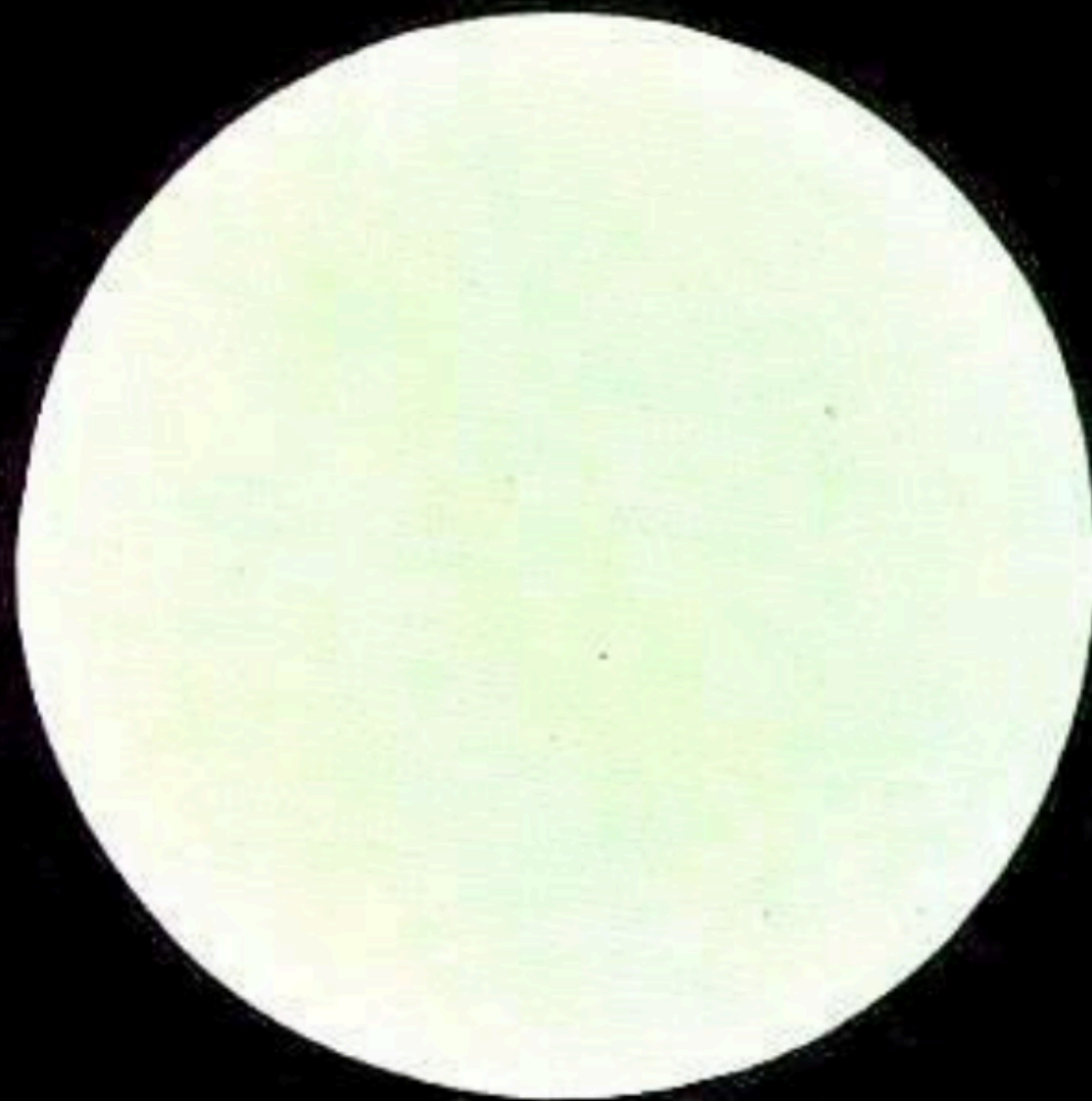


Msc. Thesis - James Rudinei Torres

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)

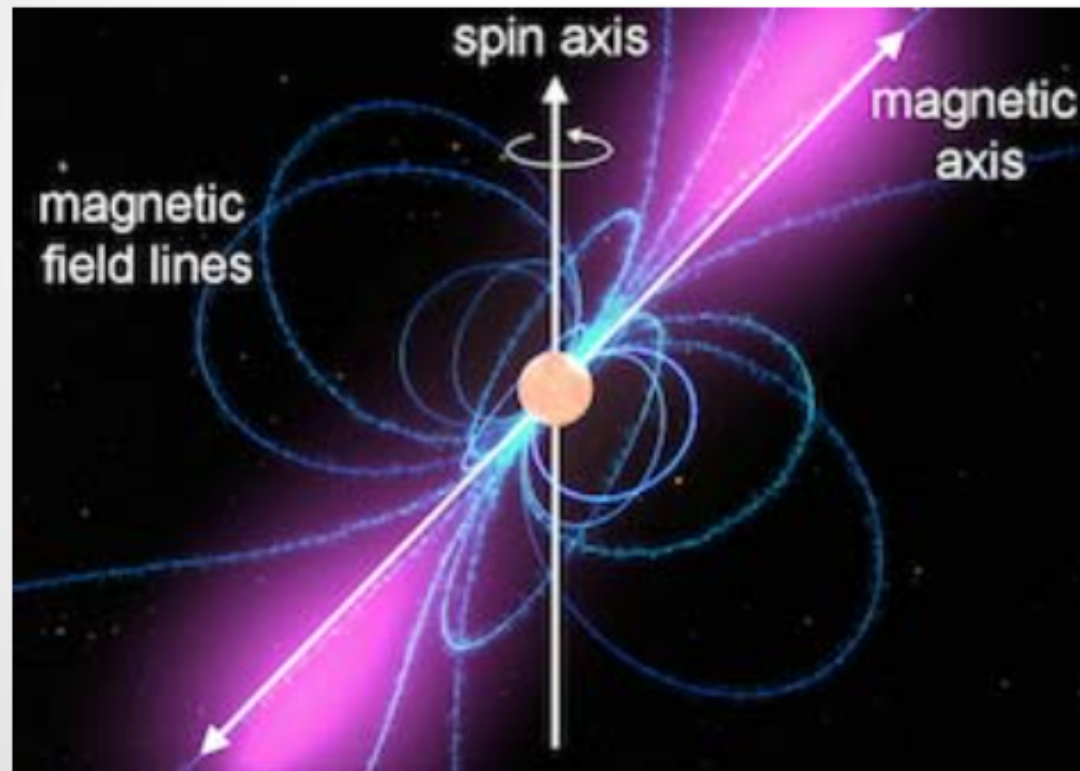
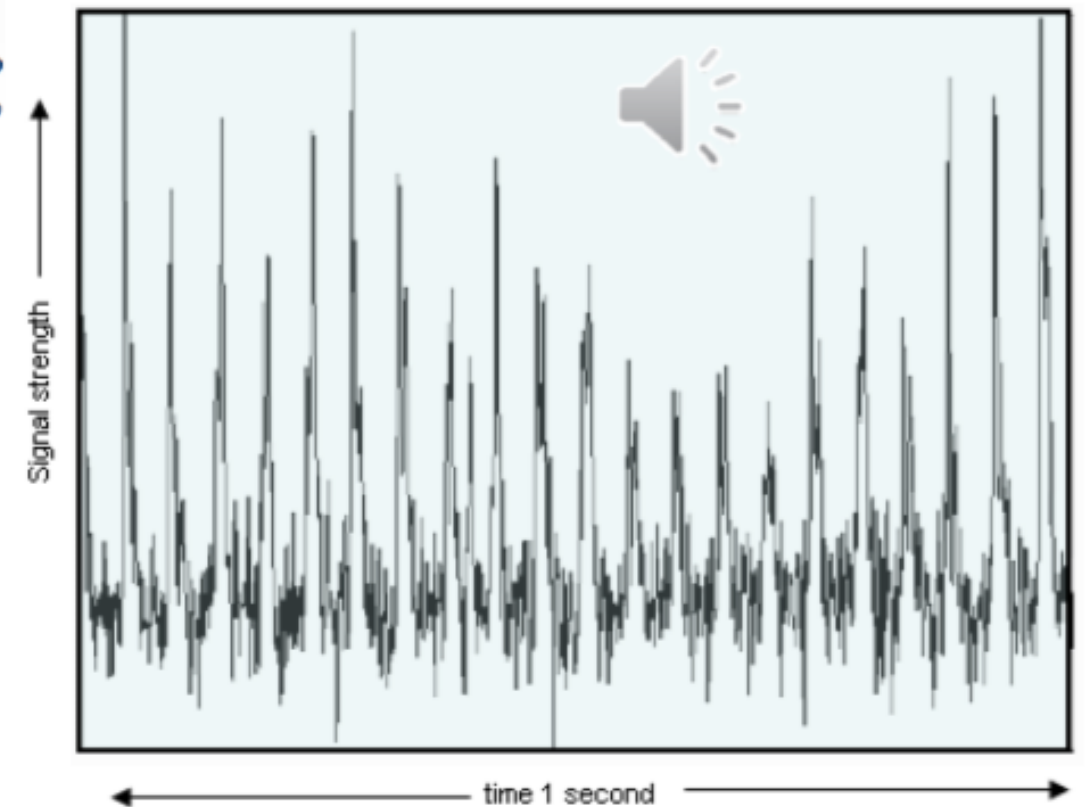
1964 - Quarks (Gell-Mann e Zweig)

**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



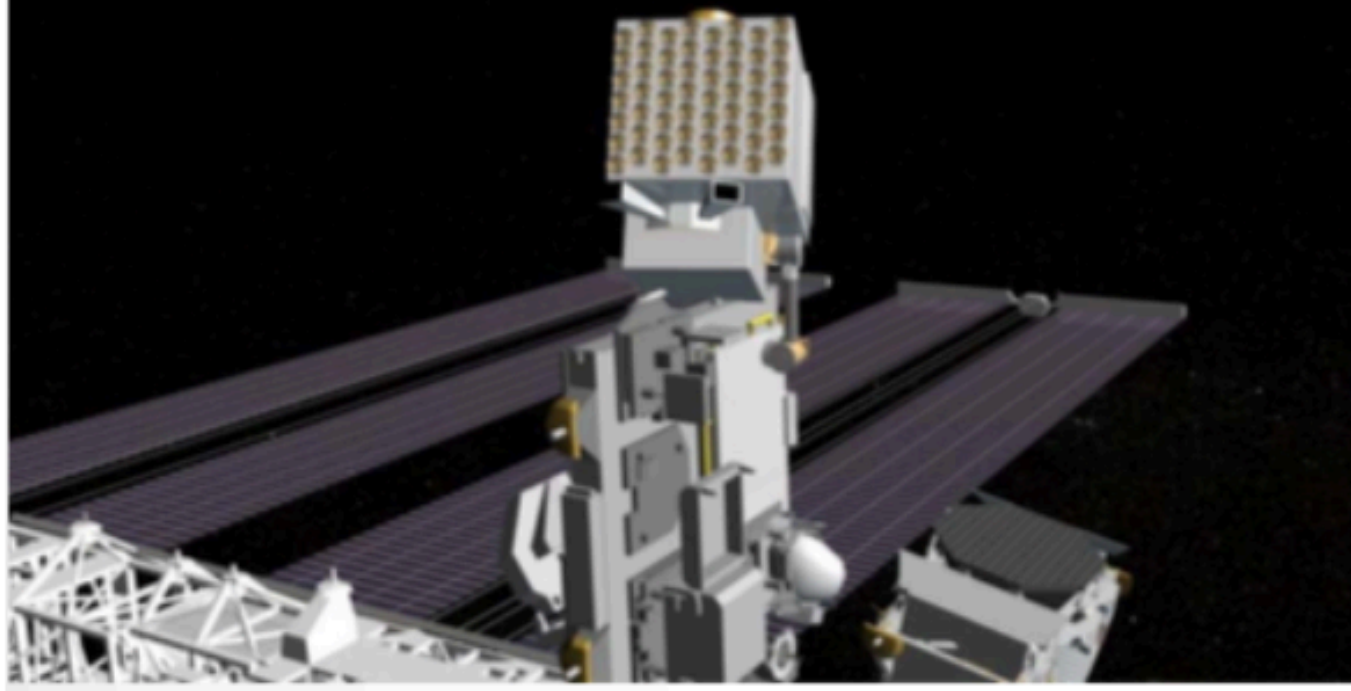
Mulheres na Ciência

OLHOS DIFERENTES

com

DÉBORA PERES MENEZES

Nicer



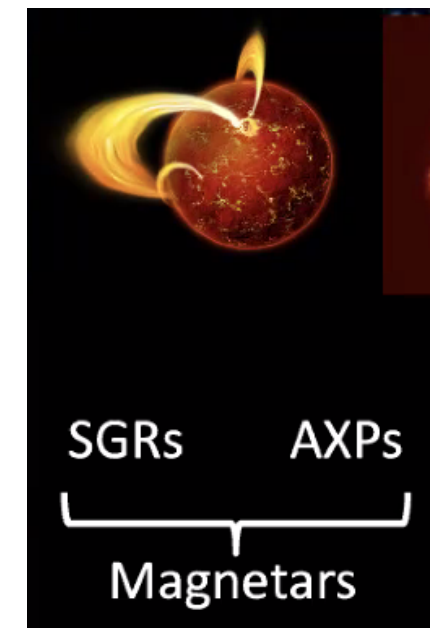
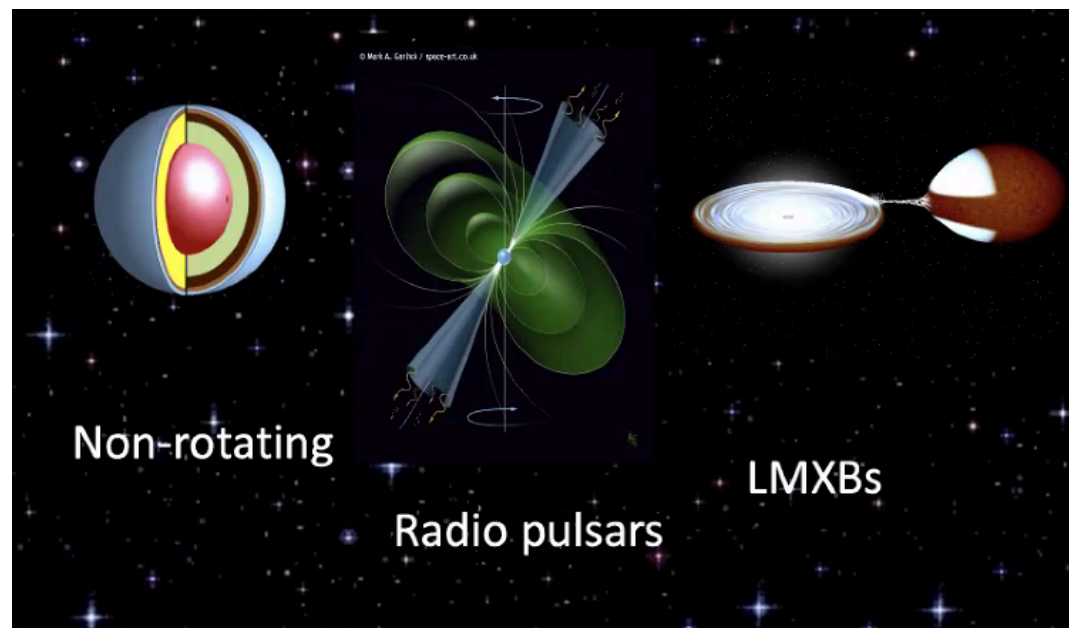
Main NS manifestations:

- **Pulsars** - powered by rotation energy (1900 observed in radio-frequency)
- **Accreting X-Ray Binaries** powered by gravitational energy
rotation periods 0.0015-1000 s)

$$M = M_{\odot} \simeq 10^{30} \text{ Kg}$$

$$\rho = M/R^3 \simeq 10^{18} \text{ Kg/l}$$

$$R \simeq 10 \text{ Km}$$



NS interior composition explorer - 06/2017

1974 - Hulse and Taylor (Nobel 1993)

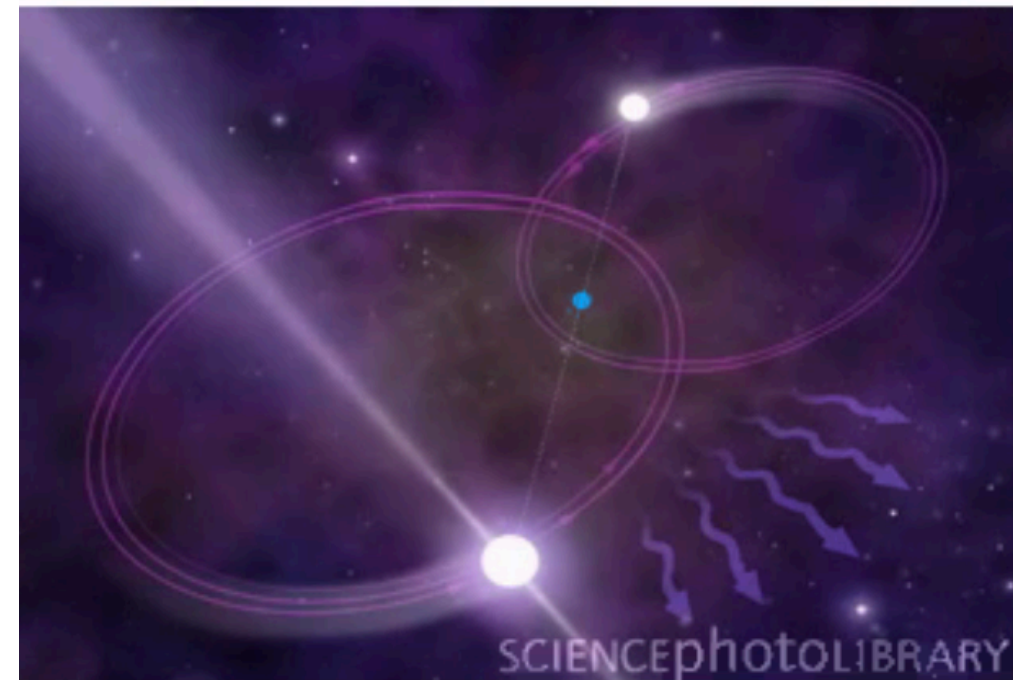


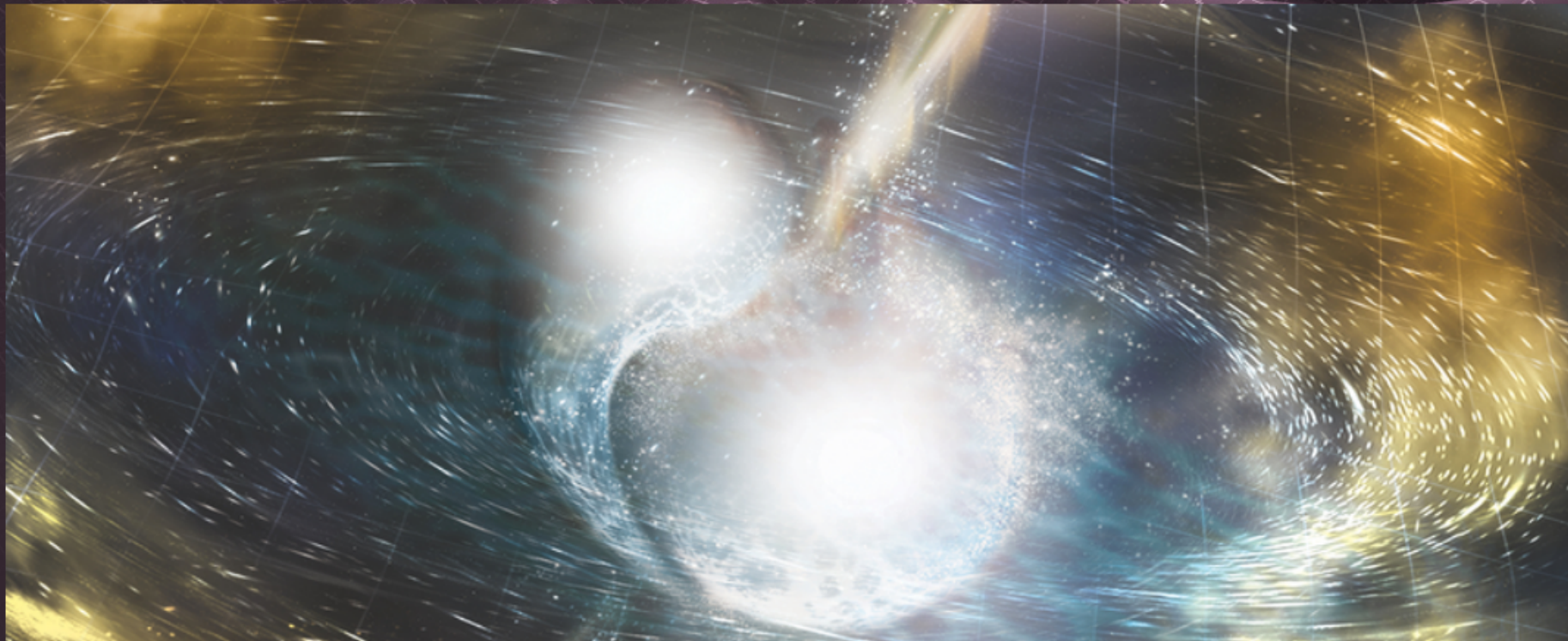
**first binary pulsar PSR1913+16
(radiotelescope Arecibo)
very precise pulse period**

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)**





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 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 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.



LIGO-Hanford



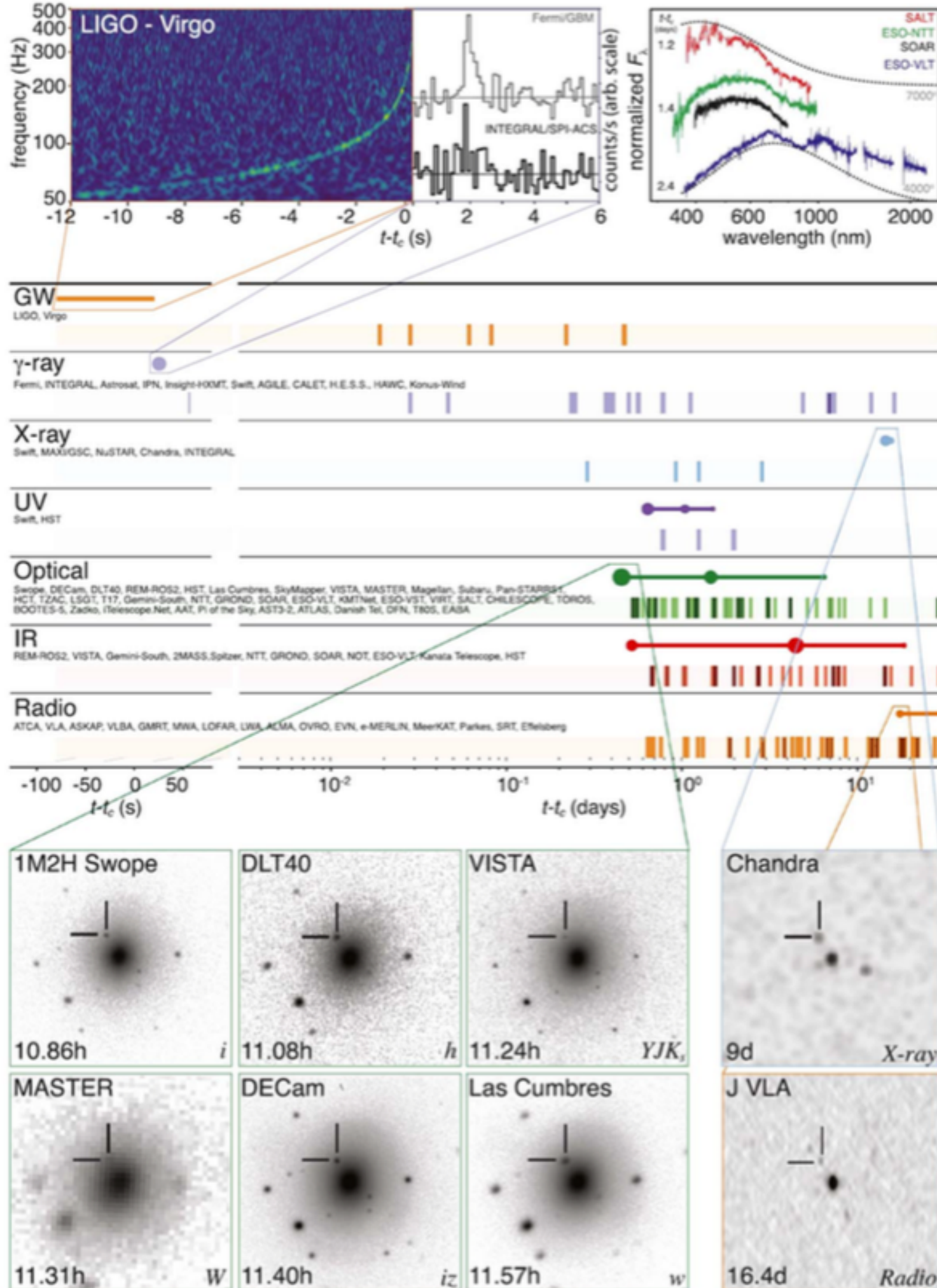
LIGO-Livingston

LIGO - Hanford (Washington) + Livingston (Louisiana)
VIRGO - Santo Stefano a Macerata (near Pisa)



VIRGO

multi-messenger event

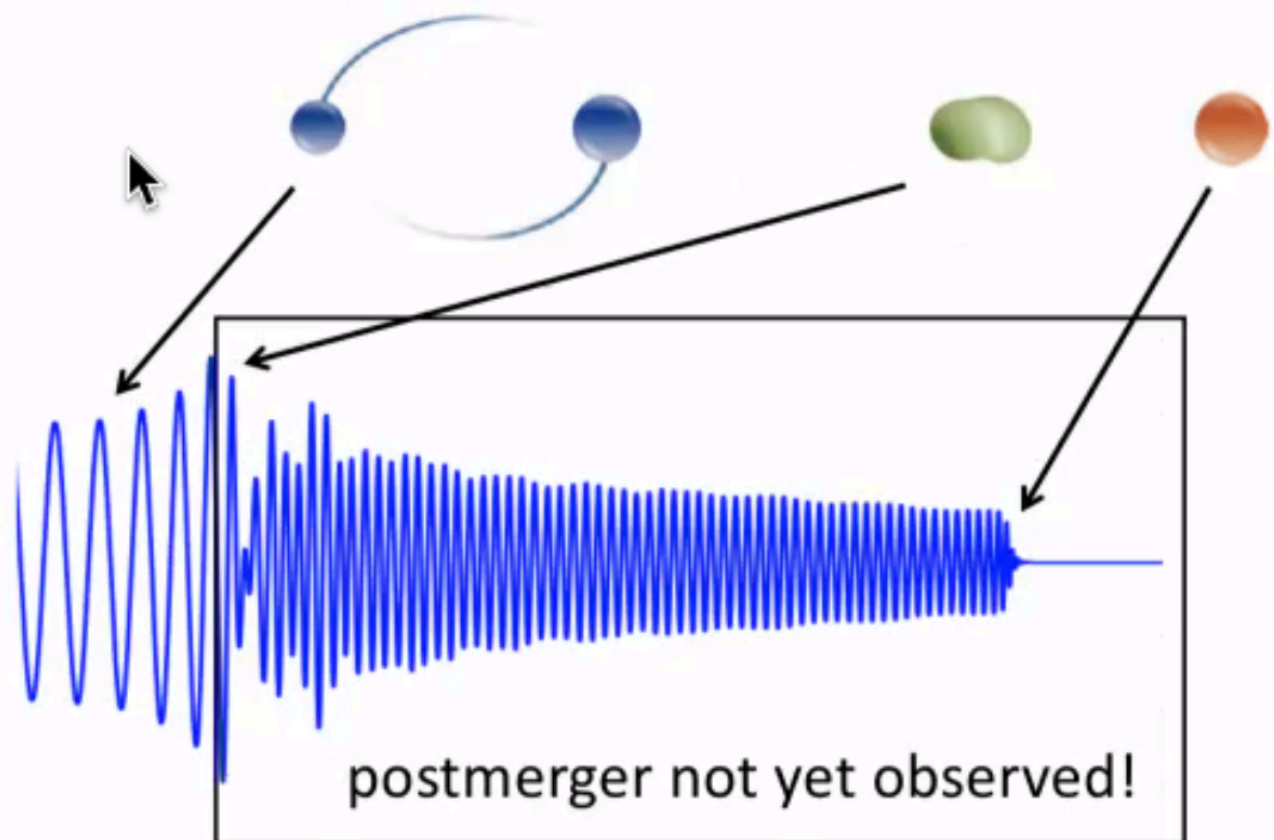


Neutron Star Merger GW170817

**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

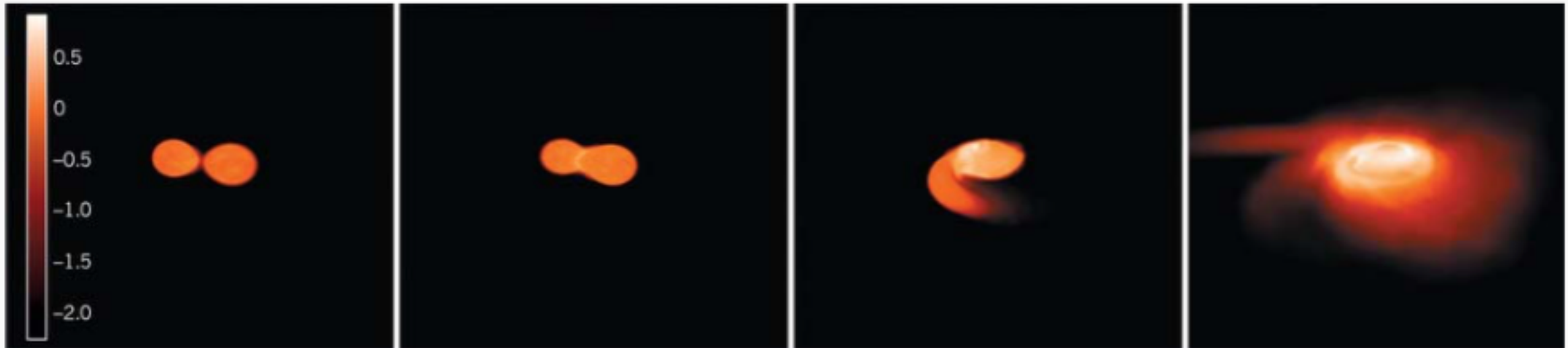
Números de Love - caracterizam a deformabilidade de um objeto (compacto) devido às forças de maré externas.

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

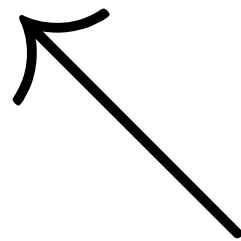
tidal polarizability $\Lambda = \frac{2}{3} k_2 \left(\frac{c^2 R}{G M} \right)^5$

Slide by Francesca Gulminelli

To calculate it, we need an EOS

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

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



stellar properties

Structure of a NS

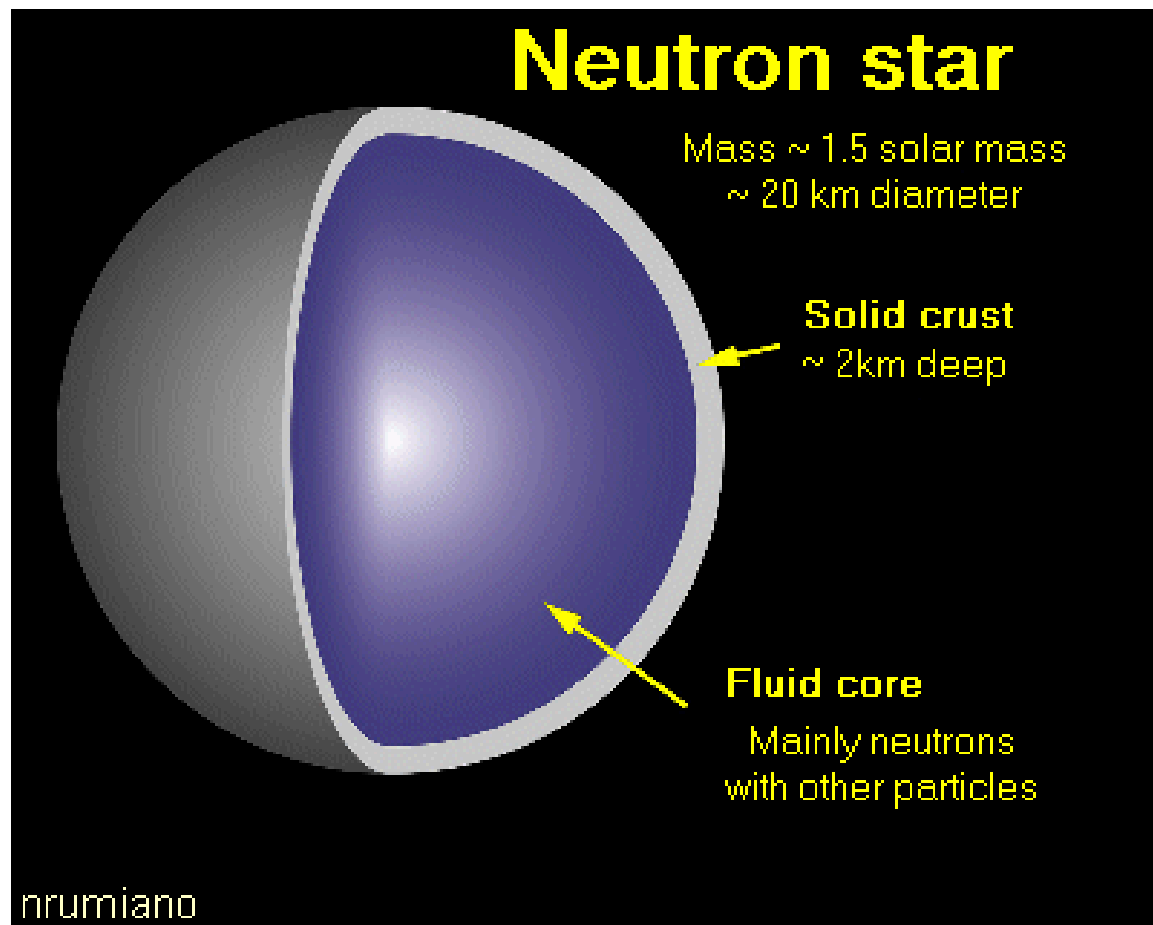
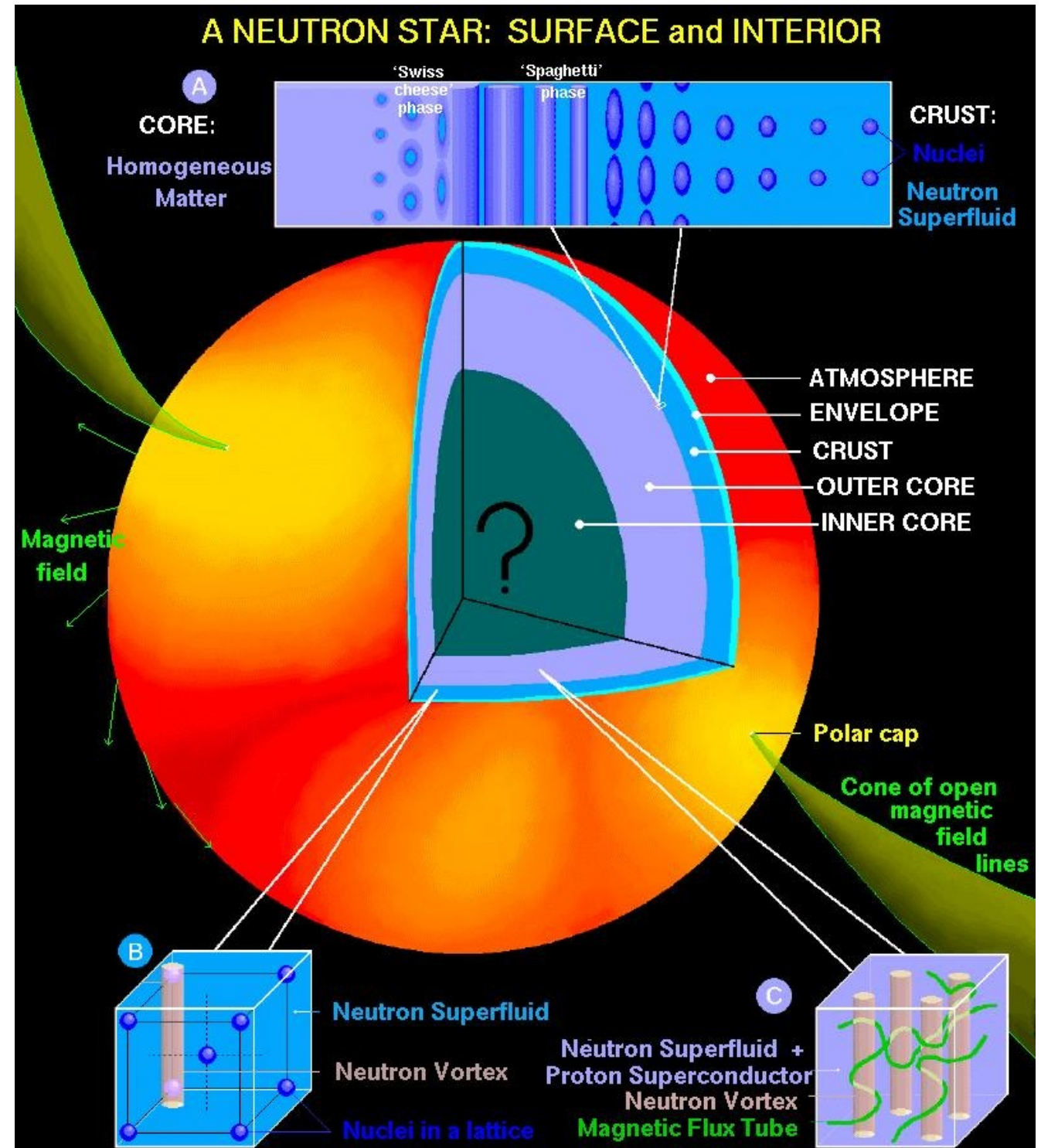


Figure by Danny Page



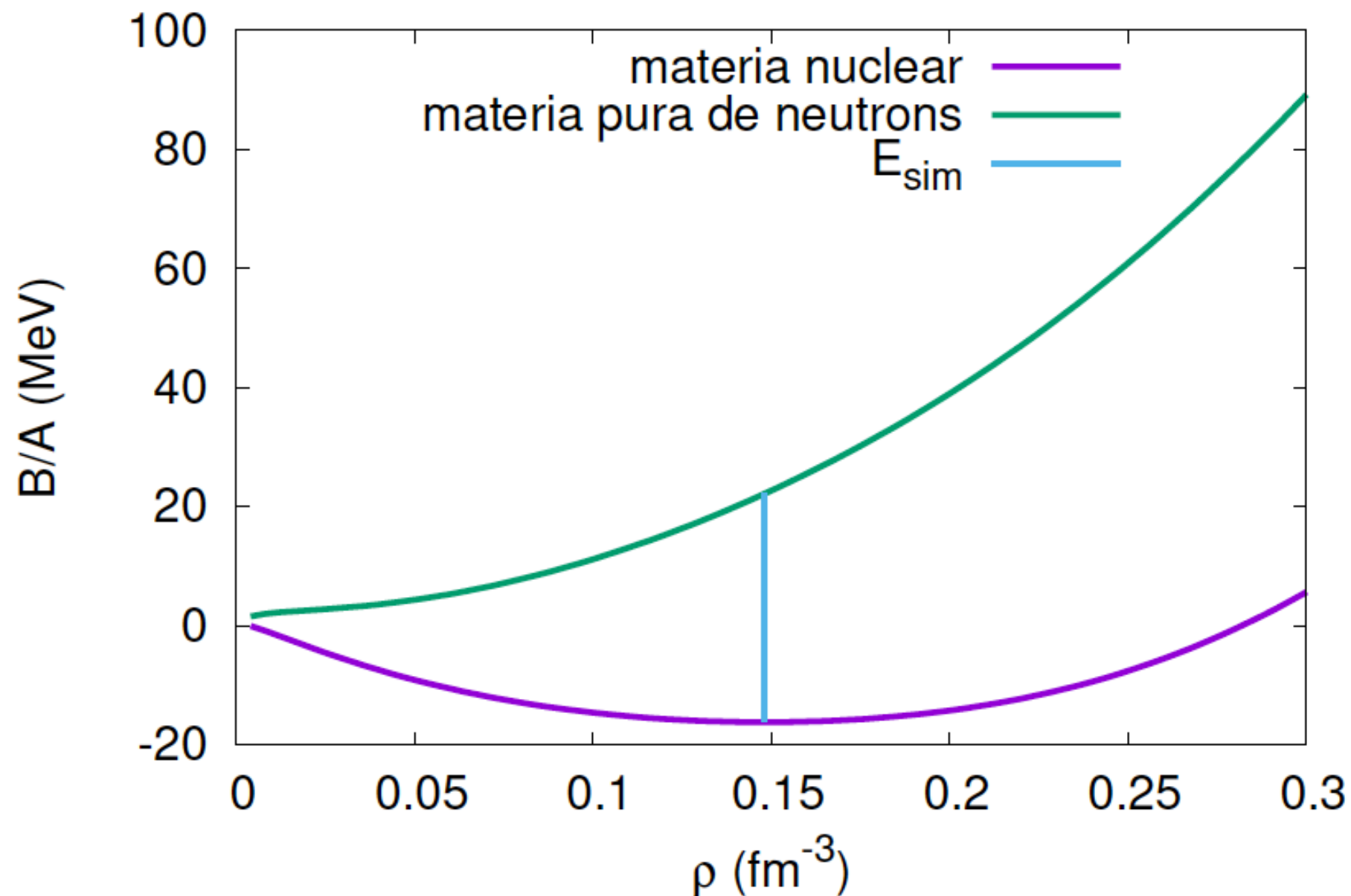
Existing models

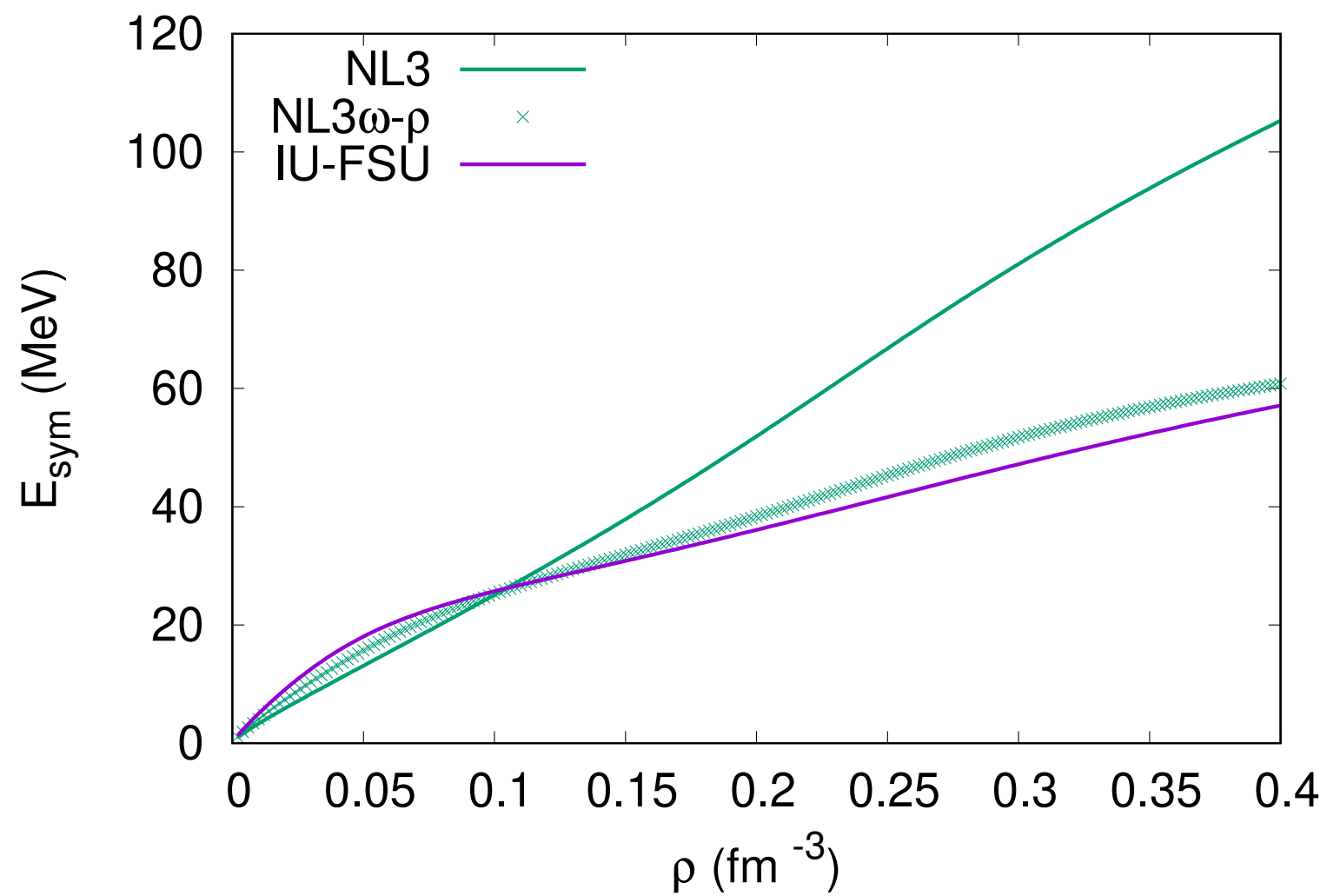
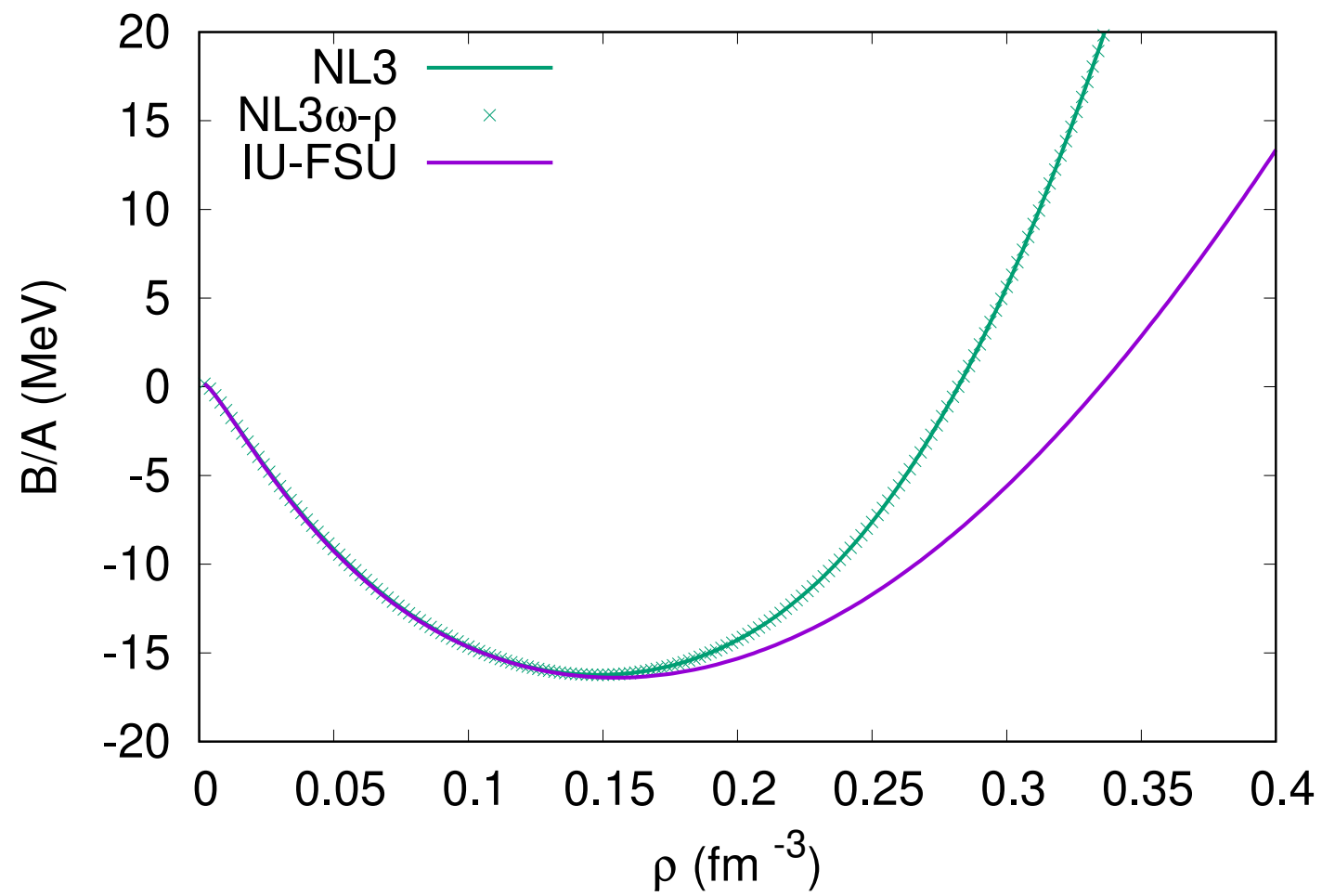
- Parameter dependent nuclear models should satisfy some **nuclear bulk properties**:
- Saturation density, binding energy , symmetry energy (and its derivatives), (in)compressibility
- Many parameters lead to many different models that satisfy them, both **non-relativistic** (Skyrme-type) and **relativistic** ones.
- How to choose?

$$E(\rho_B, \delta) \simeq E(Y_p = 0.5, \rho_B) + E_{sym}(\rho_b)\delta^2$$

$$E_{sym}(\rho_b) = \frac{1}{2} \frac{\partial^2 E}{\partial \delta^2} \Big|_{\delta=0} = 0$$

$$\delta = \frac{\rho_n - \rho_p}{\rho_B}, \quad \delta = 0 \rightarrow Y_p = 0.5$$





$$E_{sym} = J + L\left(\frac{\rho - \rho_0}{3\rho_0}\right) + \frac{K_{sym}}{2}\left(\frac{\rho - \rho_0}{3\rho_0}\right)^2 + \mathcal{O}(3)$$

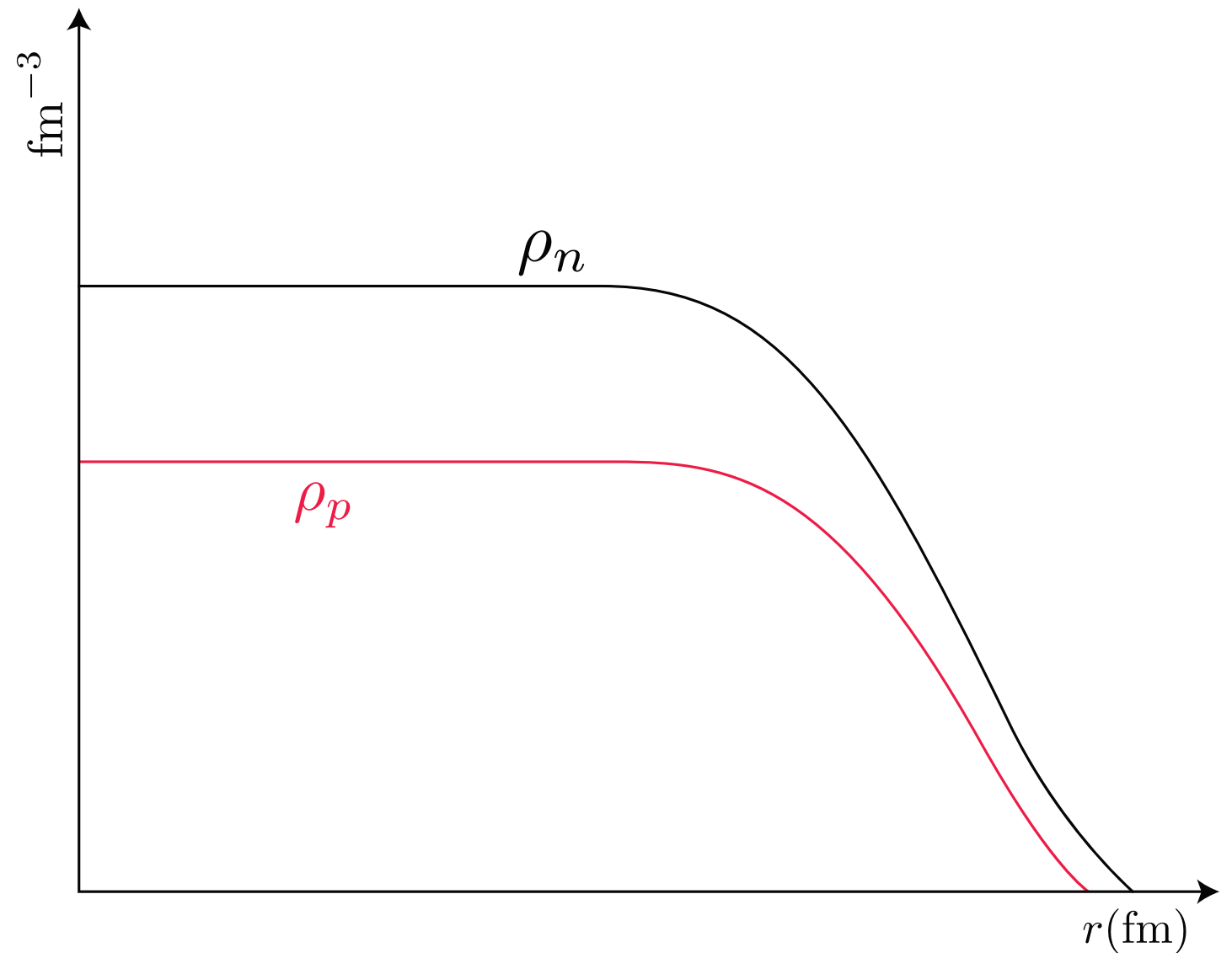
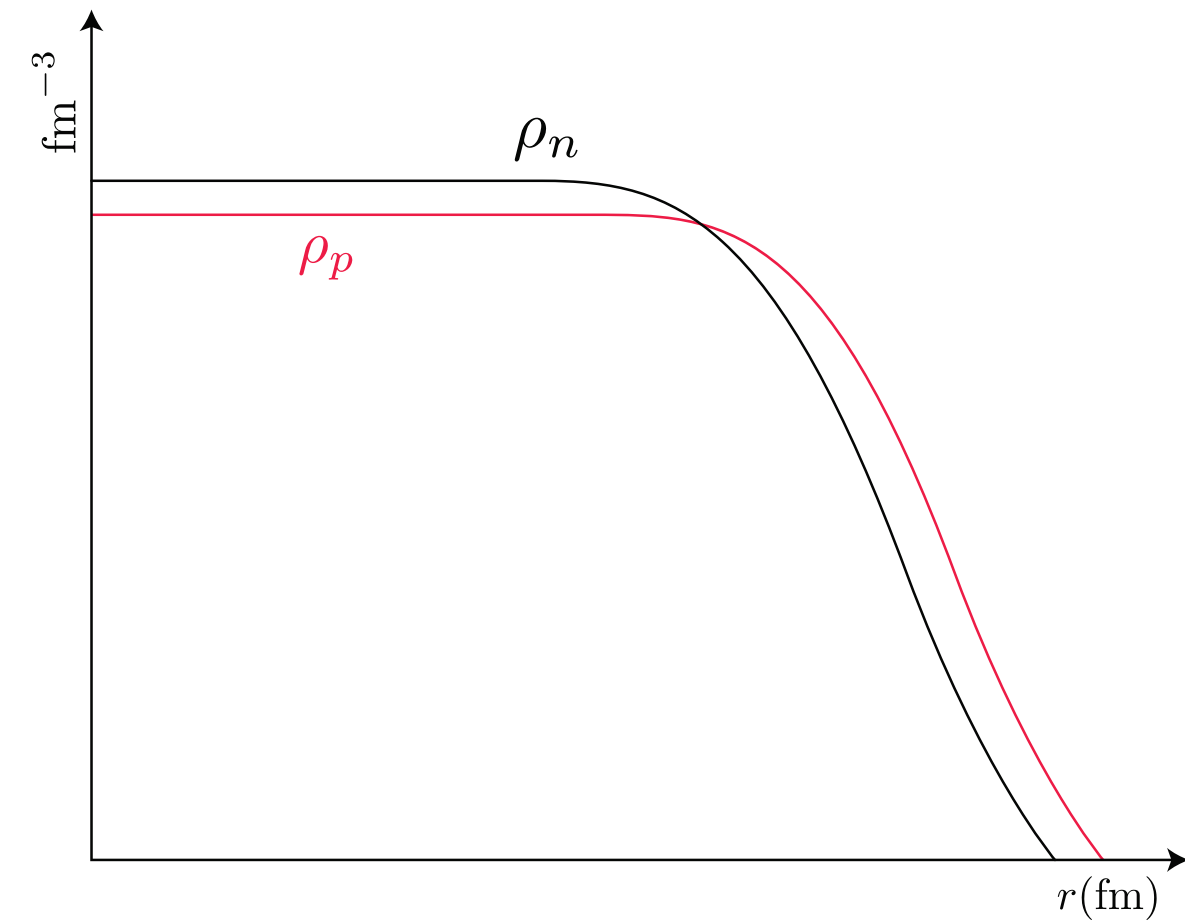
$$L = 3\rho_0 \left(\frac{\partial E_{sym}(\rho)}{\partial \rho} \right)_{\rho=\rho_0}$$

Phys. Lett. B 727, 276 (2013) $25 < L_0 < 115 \text{ MeV}$

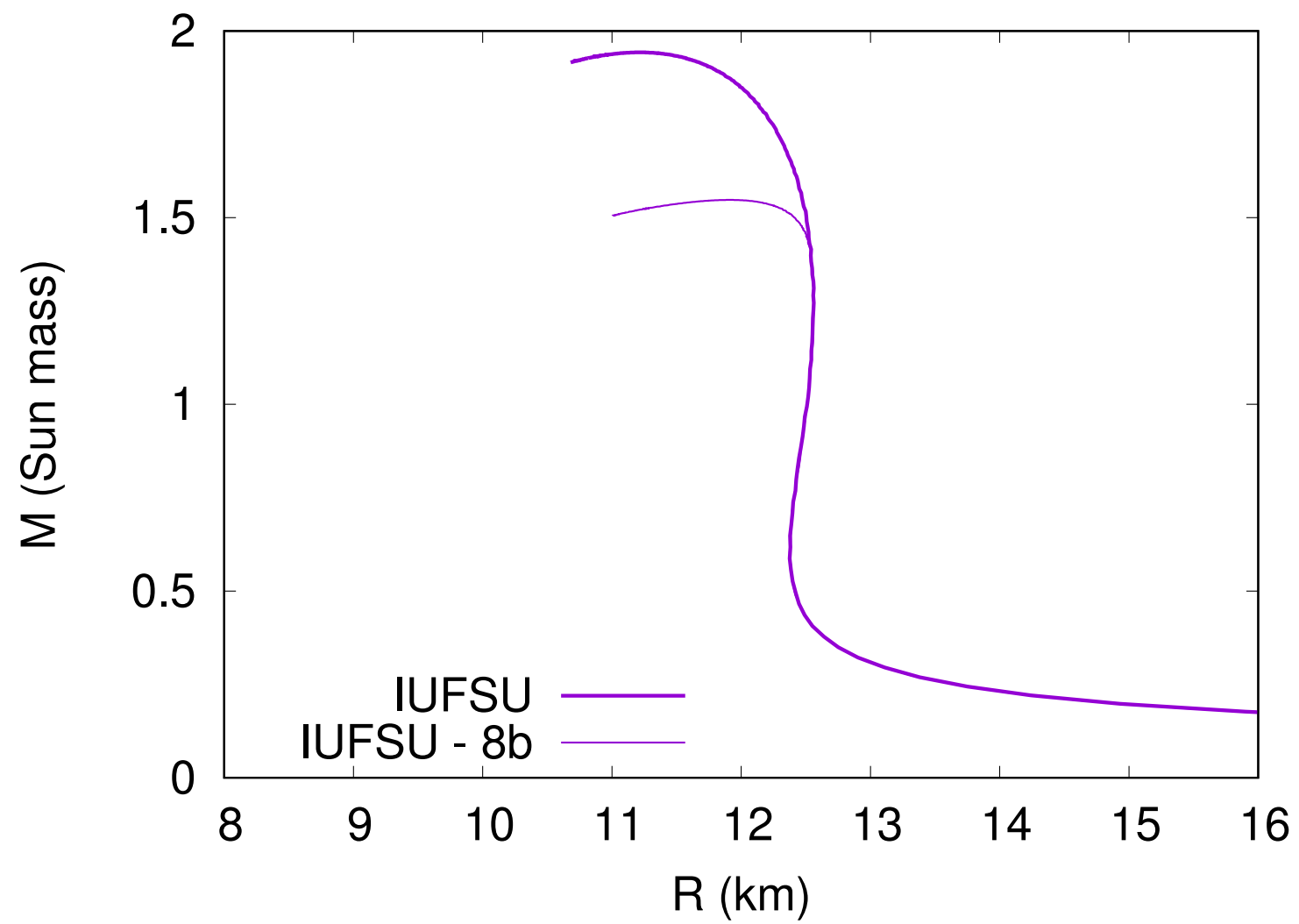
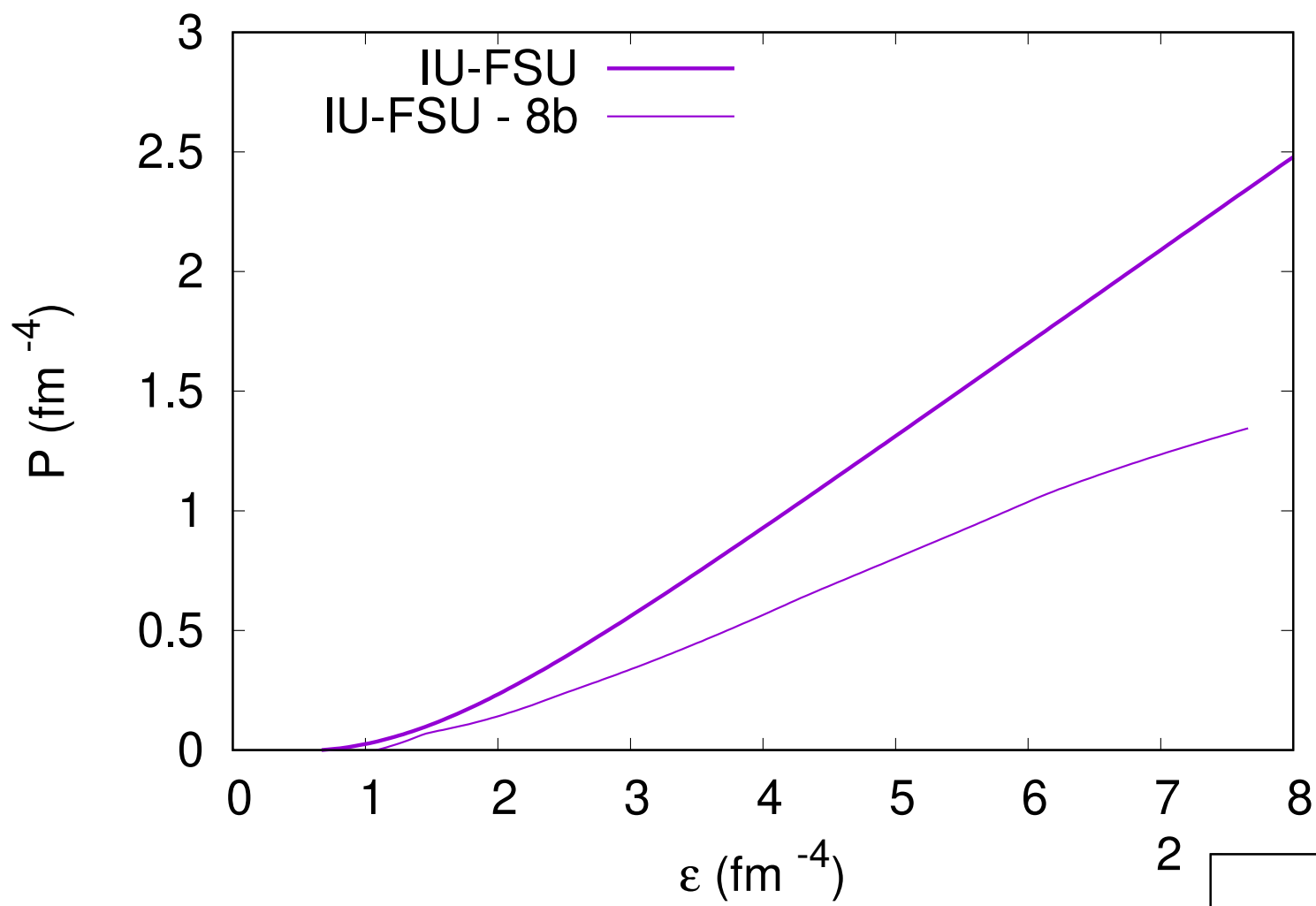
PRC 90, 055203 (2014) $30.6 < L_0 < 80.6 \text{ MeV}$

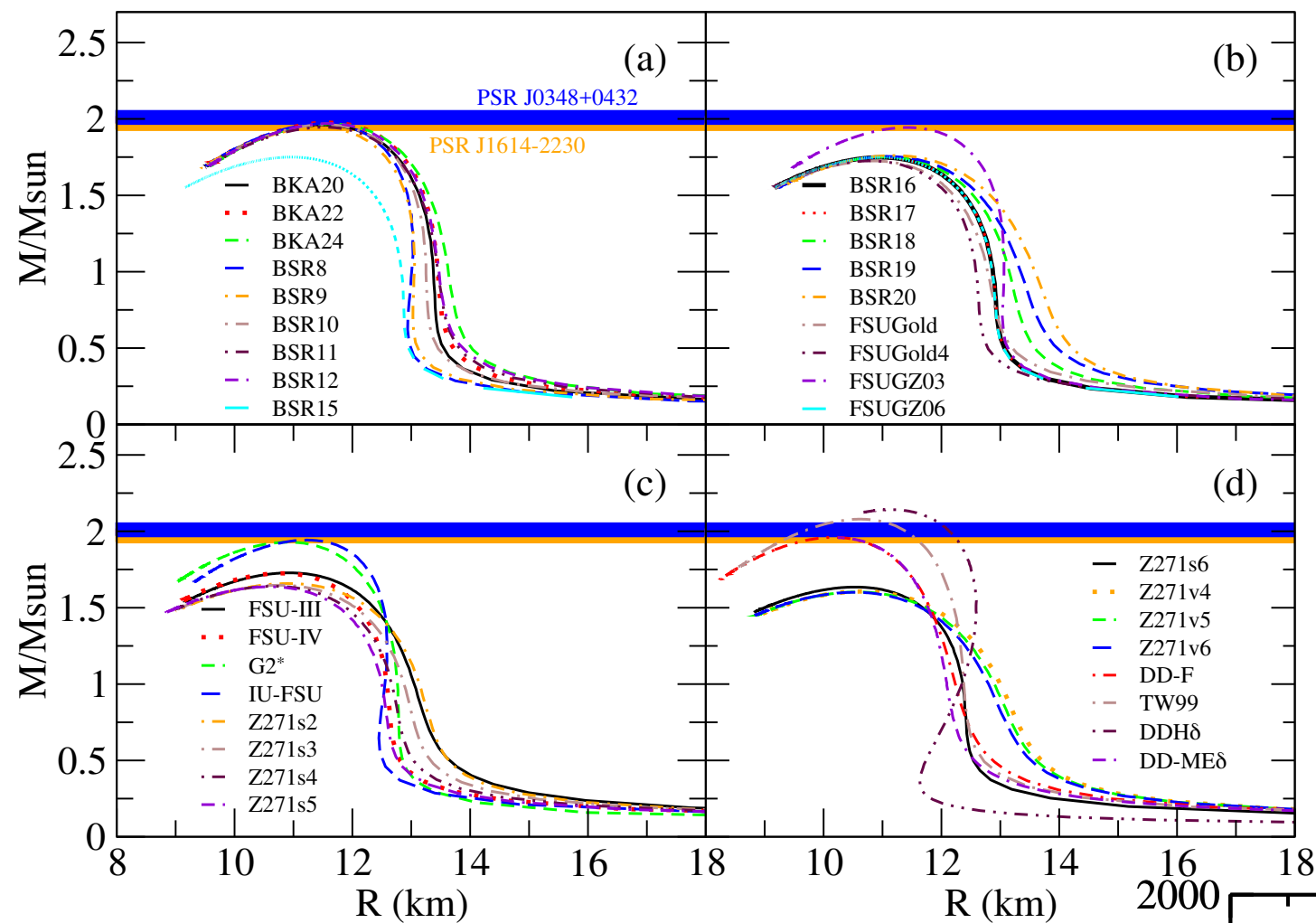
**Slope está correlacionado com
a pele de nêutrons e raio da estrela de nêutrons**

Pele de nêutrons



$$R_{\text{skin}} = R_n - R_p$$





But now...

PSR J0740+6620

$$2.07 \pm 0.08 M_{\odot}$$

H.~Cromartie et al: Nat. Astr. (2020)

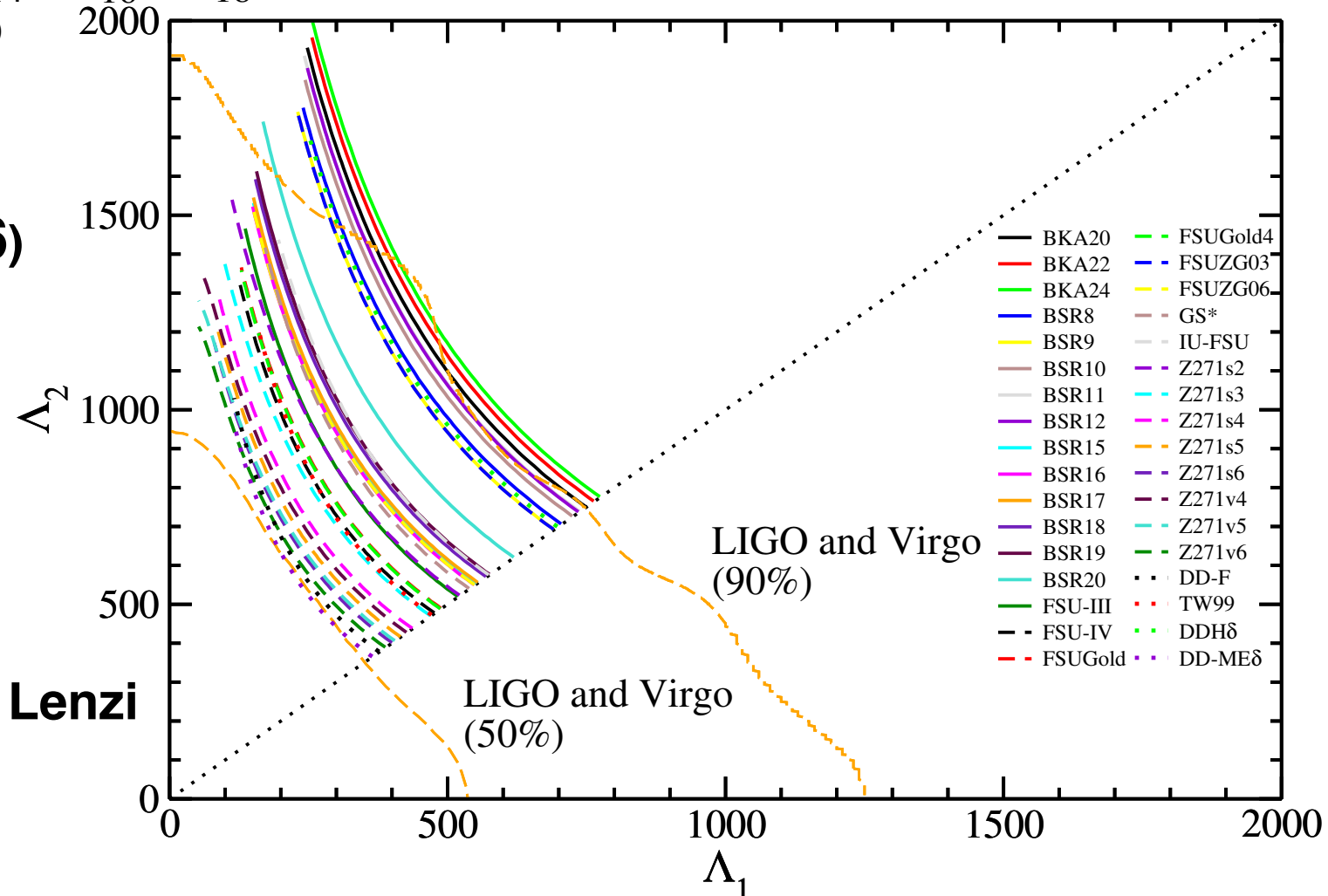
M.C.Miller et al, arXiv: 2105.06979

**Not mentioning the
hyperon puzzle**

**Mariana Dutra, Odilon Lourenço,
DPM, Phys. Rev. C 93, 025806 (2016)**

**5 modelos satisfazem
ambos**

**Odilon Lourenço, Mariana Dutra, César H. Lenzi
Cesar V. Flores and DPM,
Phys. Rev. C 99, 045202 (2019).**

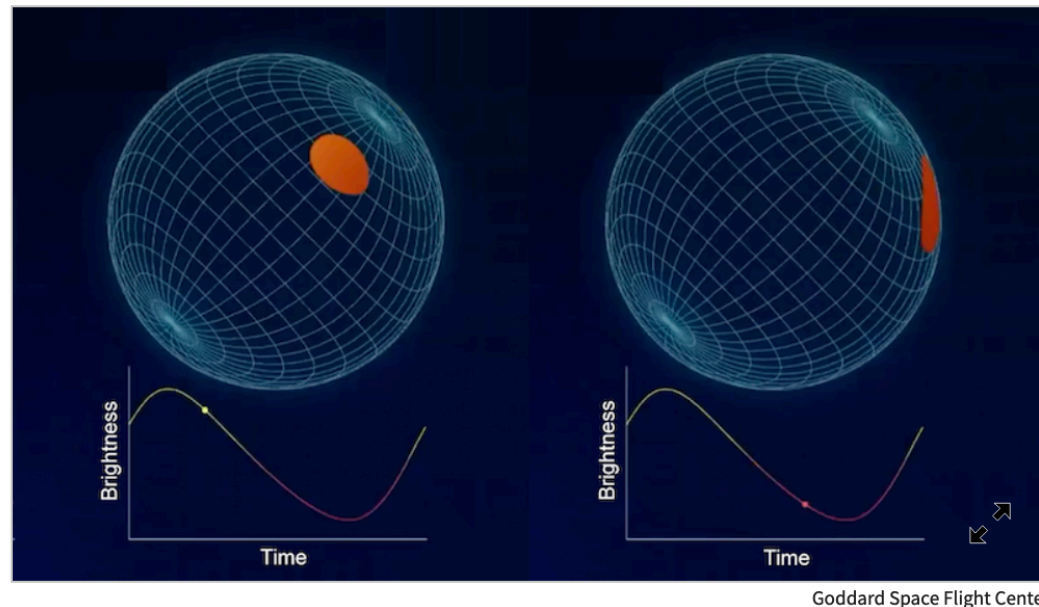


RESEARCH NEWS

Sizing Up the Most Massive Neutron Star

April 29, 2021 • *Physics* 14, 64

A satellite experiment has revealed that the heaviest known neutron star is unexpectedly large, which suggests that the matter in the star's inner core is less “squeezable” than some models predict.



NICER measures the size of a neutron star by tracking the x-ray emission from “hot spots” on the surface as the star rotates. These spots occur at the magnetic poles of the star, where the field slams particles onto the star surface.

Neutron stars are “**cosmic zombies**”—corpses of massive stars that collapsed in violent explosions after running out of fuel. By studying these ultradense objects, researchers hope to understand the behavior of matter under extreme conditions, which might help in cracking some of the biggest mysteries in physics. As announced at a press conference during the 2021 **APS April meeting**, NASA’s **Neutron star Interior Composition Explorer** (NICER), an x-ray telescope on the International Space Station, has measured the size of the heaviest known neutron star. The surprisingly large radius measured for this star implies a stiffer-than-expected state of matter in the core, disfavoring models that predict a “squishy” center.

E os raios? Quais os vínculos?

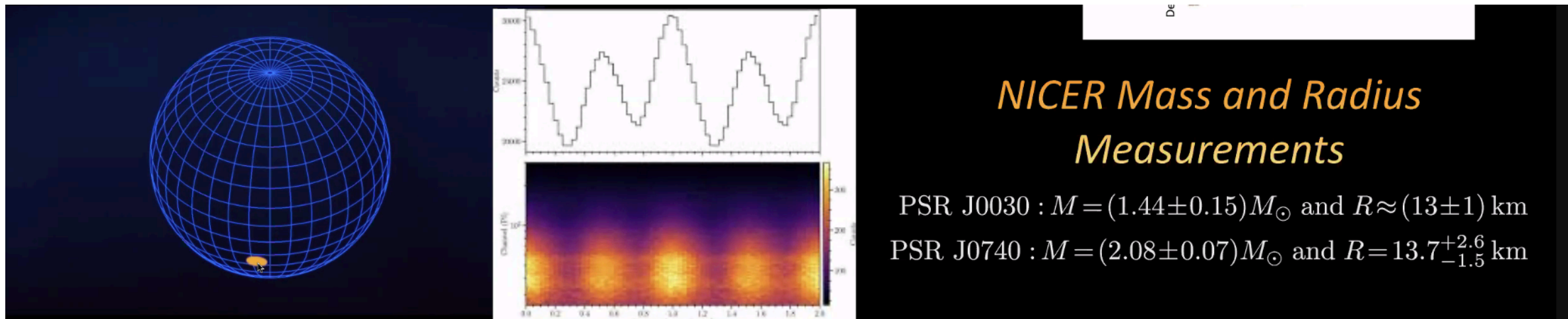
GW170817

$$70 < \Lambda_{1.4} < 580$$

$$10.5 \text{ km} \leq R_{1.4} M_{\odot} \leq 13.4 \text{ km}$$

Capano et al, Nat. Astr. (2020)

$$R_{1.4} M_{\odot} \leq 11.9 \text{ km}$$



NICER

Miller et al, arXiv 2105.06979

$$2.07 \pm 0.08 M_{\odot}$$

PSR J0740+6620

$$11.6 \text{ km} < R < 13.1 \text{ km}$$

PSR J0030+0451

$$11.8 \text{ km} < R_{1.4} M_{\odot} < 13.1 \text{ km}$$

Accurate Determination of the Neutron Skin Thickness of ^{208}Pb through Parity-Violation in Electron Scattering

D. Adhikari,¹ H. Albataineh,² D. Androic,³ K. Aniol,⁴ D. S. Armstrong,⁵ T. Averett,⁵ C. Ayerbe Gayoso,⁵ S. Barcus,⁶ V. Bellini,⁷ R. S. Beminiwattha,⁸ J. F. Benesch,⁶ H. Bhatt,⁹ D. Bhatta Pathak,⁸ D. Bhetuwal,⁹ B. Blaikie,¹⁰ Q. Campagna,⁵ A. Camsonne,⁶ G. D. Cates,¹¹ Y. Chen,⁸ C. Clarke,¹² J. C. Cornejo,¹³ S. Covrig Dusa,⁶ P. Datta,¹⁴ A. Deshpande,^{12,15} D. Dutta,⁹ C. Feldman,¹² E. Fuchey,¹⁴ C. Gal,^{12,11,15} D. Gaskell,⁶ T. Gautam,¹⁶ M. Gericke,¹⁰ C. Ghosh,^{17,12} I. Halilovic,¹⁰ J.-O. Hansen,⁶ F. Hauenstein,¹⁸ W. Henry,¹⁹ C. J. Horowitz,²⁰ C. Jantzi,¹¹ S. Jian,¹¹ S. Johnston,¹⁷ D. C. Jones,¹⁹ B. Karki,²¹ S. Katugampola,¹¹ C. Keppel,⁶ P. M. King,²¹ D. E. King,²² M. Knauss,²³ K. S. Kumar,¹⁷ T. Kutz,¹² N. Lashley-Colthirst,¹⁶ G. Leverick,¹⁰ H. Liu,¹⁷ N. Liyange,¹¹ S. Malace,⁶ R. Mammei,²⁴ J. Mammei,¹⁰ M. McCaughan,⁶ D. McNulty,¹ D. Meekins,⁶ C. Metts,⁵ R. Michaels,⁶ M. M. Mondal,^{12,15} J. Napolitano,¹⁹ A. Narayan,²⁵ D. Nikolaev,¹⁹ M. N. H. Rashad,¹⁸ V. Owen,⁵ C. Palatchi,^{11,15} J. Pan,¹⁰ B. Pandey,¹⁶ S. Park,¹² K. D. Paschke^{11,*}, M. Petrusky,¹² M. L. Pitt,²⁶ S. Premathilake,¹¹ A. J. R. Puckett,¹⁴ B. Quinn,¹³ R. Radloff,²¹ S. Rahman,¹⁰ A. Rathnayake,¹¹ B. T. Reed,²⁰ P. E. Reimer,²⁷ R. Richards,¹² S. Riordan,²⁷ Y. Roblin,⁶ S. Seeds,¹⁴ A. Shahinyan,²⁸ P. Souder,²² L. Tang,^{6,16} M. Thiel,²⁹ Y. Tian,²² G. M. Urciuoli,³⁰ E. W. Wertz,⁵ B. Wojtsekhowski,⁶ B. Yale,⁵ T. Ye,¹² A. Yoon,³¹ A. Zec,¹¹ W. Zhang,¹² J. Zhang,^{12,15,32} and X. Zheng¹¹

(PREX Collaboration)

$$R_{\text{skin}} = 0.283 \pm 0.071 \text{ fm}$$

Implications of PREX-2 on the Equation of State of Neutron-Rich Matter

Brendan T. Reed^{1,2,*} F. J. Fattoyev^{3,†} C. J. Horowitz^{2,‡} and J. Piekarewicz^{4,§}

¹*Department of Astronomy, Indiana University, Bloomington, Indiana 47405, USA*

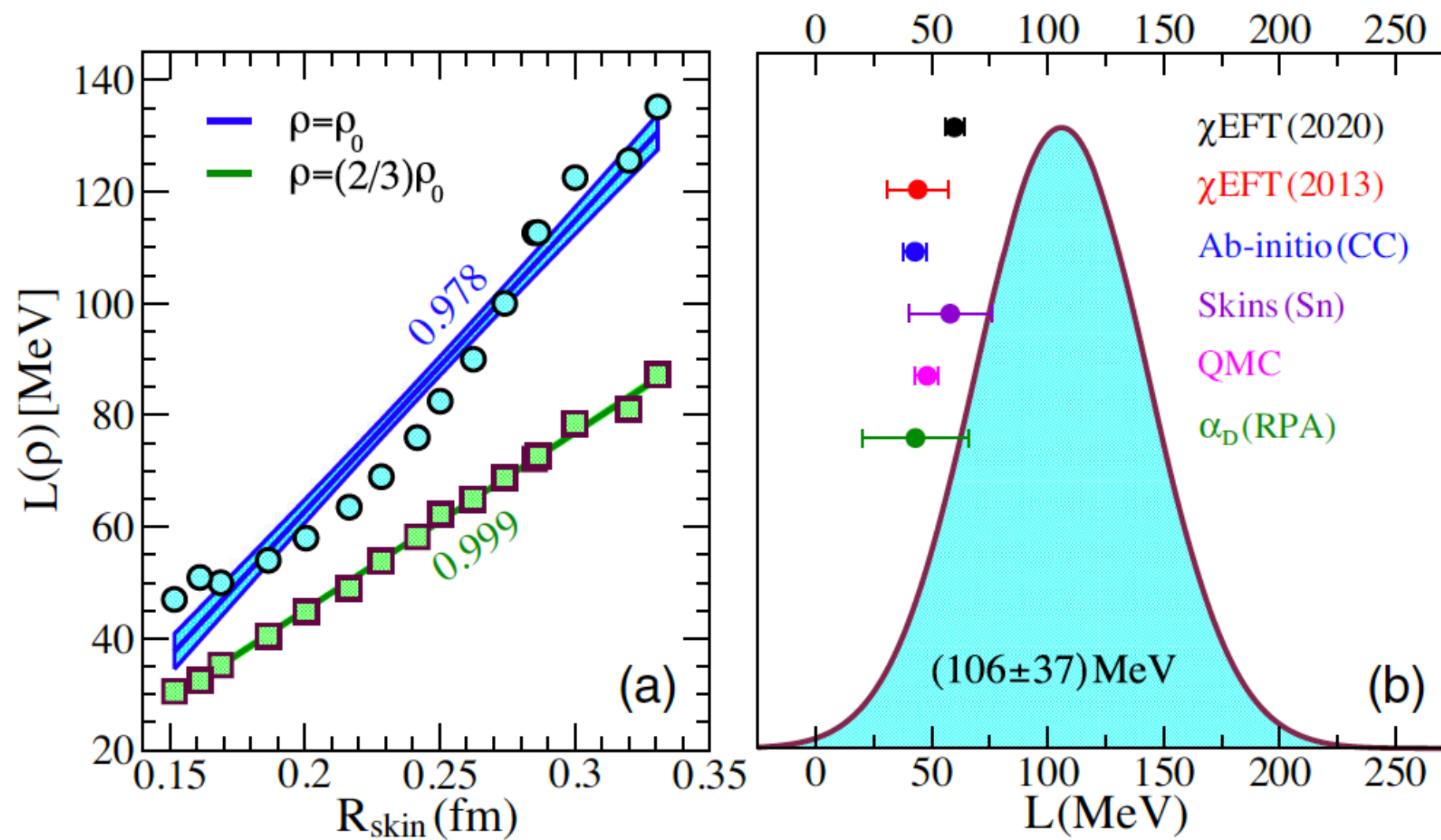
²*Center for Exploration of Energy and Matter and Department of Physics, Indiana University, Bloomington, Indiana 47405, USA*

³*Department of Physics, Manhattan College, Riverdale, New York 10471, USA*

⁴*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*



(Received 24 February 2021; accepted 31 March 2021; published 27 April 2021)

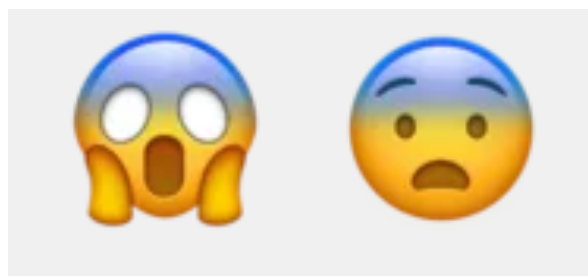


$$E_{sym} = J + L\left(\frac{\rho - \rho_0}{3\rho_0}\right) + \frac{K_{sym}}{2}\left(\frac{\rho - \rho_0}{3\rho_0}\right)^2 + \mathcal{O}(3)$$

$$L = 3\rho_0 \left(\frac{\partial E_{sym}(\rho)}{\partial \rho} \right)_{\rho=\rho_0}$$

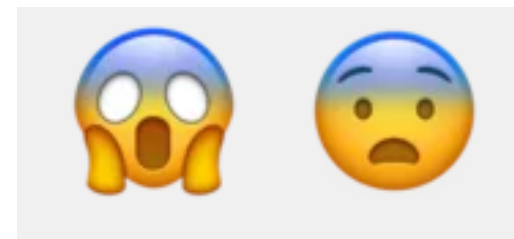
Phys. Lett. B 727, 276 (2013) $25 < L_0 < 115 \text{ MeV}$

PRC 90, 055203 (2014) $30.6 < L_0 < 80.6 \text{ MeV}$



PRL 126, 172503 (2021) $69 < L_0 < 143 \text{ MeV}$

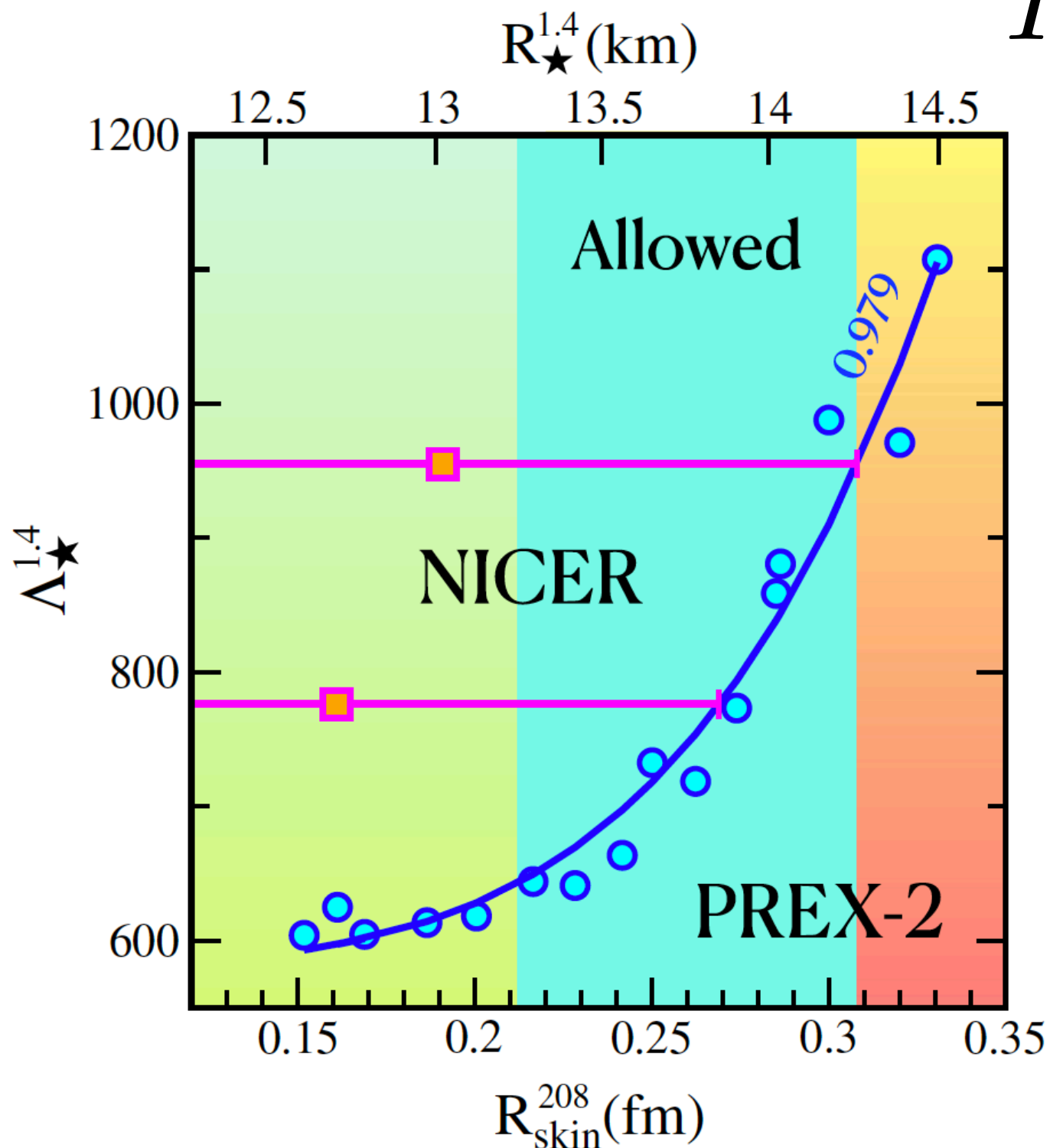
$$R_{1.4} \text{ M}_{\odot} \geq 13.25 \text{ km}$$



$$0.21 \lesssim R_{\text{skin}} (\text{fm}) \lesssim 0.31,$$

$$13.25 \lesssim R_{\star}^{1.4} (\text{km}) \lesssim 14.26,$$

$$642 \lesssim \Lambda_{\star}^{1.4} \lesssim 955.$$



Moreover, a precise knowledge of the EOS of the crust is needed to minimize possible systematic uncertainties

Scientists Measure Calcium's Thin Skin

A precision measurement of the neutron skin in a calcium nucleus surprisingly reveals a thinner skin than expected from a similar measurement in lead

12-Oct-2021 3:00 PM EDT, by [Thomas Jefferson National Accelerator Facility](#)

- *PREX-II*: Neutron-skin thickness of ^{208}Pb
(Contrary to expectations, skin is thick!)
- *CREX*: Neutron-skin thickness of ^{48}Ca
(Contrary to expectations, skin is thin!)



“Our new, extremely precise CREX measurement on calcium-48 indicates a thin neutron skin around its nucleus. In contrast, our PREX measurement on lead-208 revealed a somewhat thick skin around that nucleus,” said Caryn Palatchi, a research associate at the University of Virginia who presented the results on behalf of the CREX collaboration.

This discrepancy is exciting for nuclear physics. It presents the opportunity for further exploration to determine why there’s such a big difference between the medium-density calcium nucleus and the high-density lead nucleus.

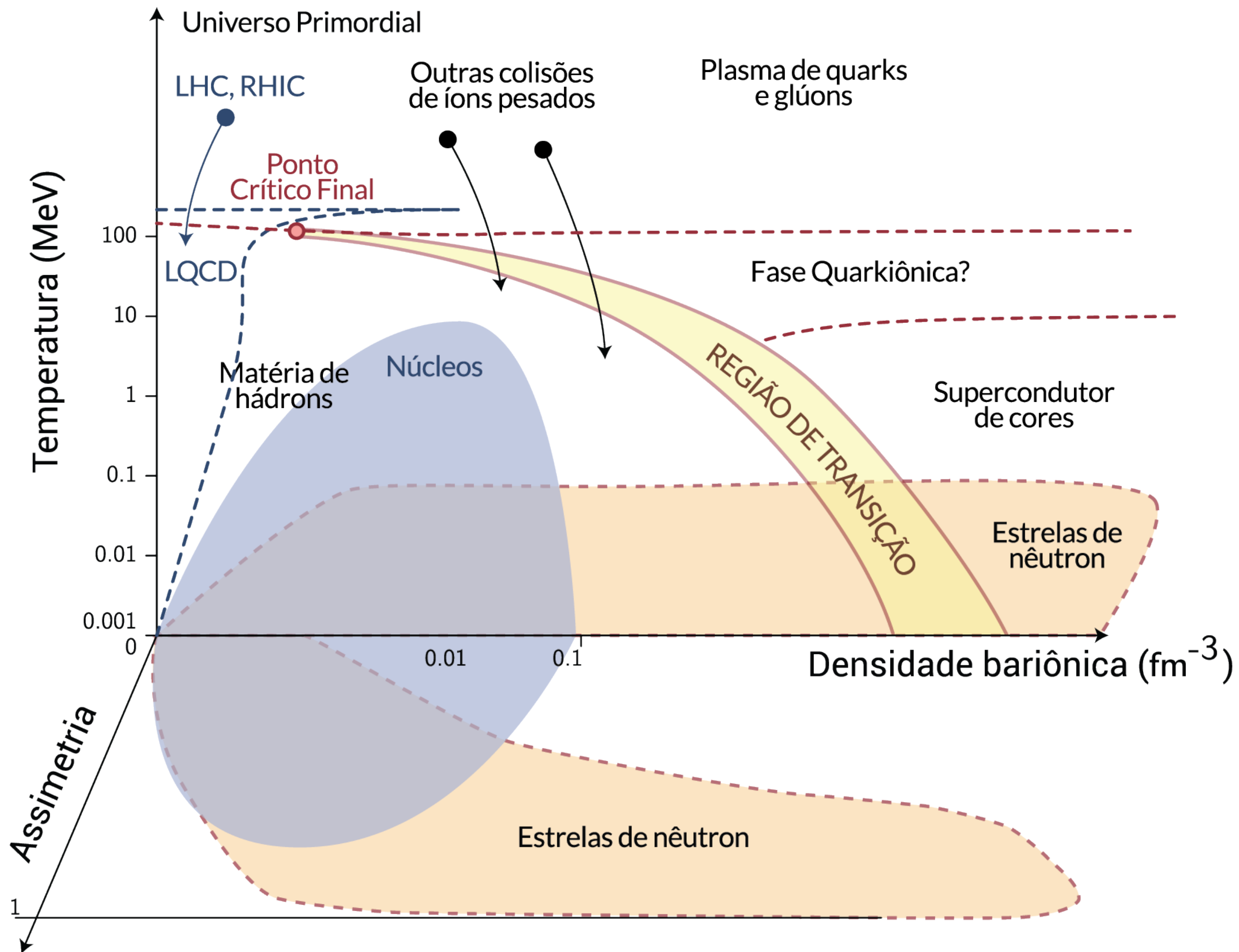
nature > nature physics > letters > articleLetter | [Open Access](#) | [Published: 01 June 2020](#)

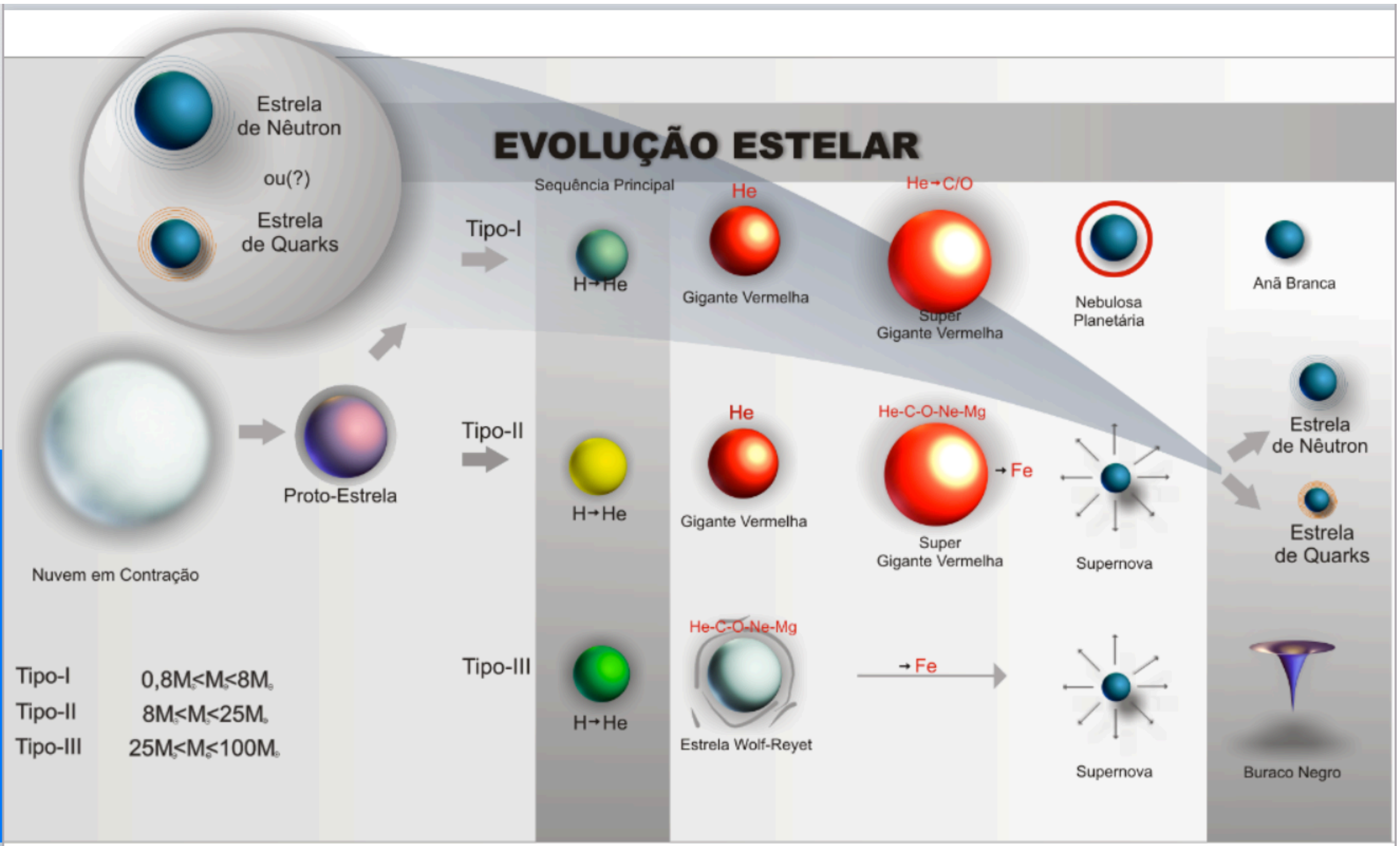
Evidence for quark-matter cores in massive neutron stars

[Eemeli Annala](#), [Tyler Gorda](#) , [Aleksi Kurkela](#) , [Joonas Nättilä](#) & [Aleksi Vuorinen](#) [Nature Physics](#) **16**, 907–910(2020) | [Cite this article](#)**20k** Accesses | **62** Citations | **425** Altmetric | [Metrics](#)

Abstract

The theory governing the strong nuclear force—quantum chromodynamics—predicts that at sufficiently high energy densities, hadronic nuclear matter undergoes a deconfinement transition to a new phase of quarks and gluons¹. Although this has been observed in ultrarelativistic heavy-ion collisions^{2,3}, it is currently an open question whether quark matter exists inside neutron stars⁴. By combining astrophysical observations and theoretical ab initio calculations in a model-independent way, we find that the inferred properties of matter in the cores of neutron stars with mass corresponding to 1.4 solar masses ($M_{\odot}$) are compatible with nuclear model calculations. However, the matter in the interior of maximally massive stable neutron stars exhibits characteristics of the deconfined phase, which we interpret as evidence for the presence of quark-matter cores. For the heaviest reliably observed neutron stars^{5,6} with mass $M \approx 2M_{\odot}$, the presence of quark matter is found to be linked to the behaviour of the speed of sound c_s in strongly interacting matter. If the conformal bound $c_s^2 \leq 1/3$ (ref. ⁷) is not strongly violated, massive neutron stars are predicted to have sizable quark-matter cores. This finding has important implications for the phenomenology of neutron stars and affects the dynamics of neutron star mergers with at least one sufficiently massive participant.





Estrelas hadrônicas, híbridas, de quarks

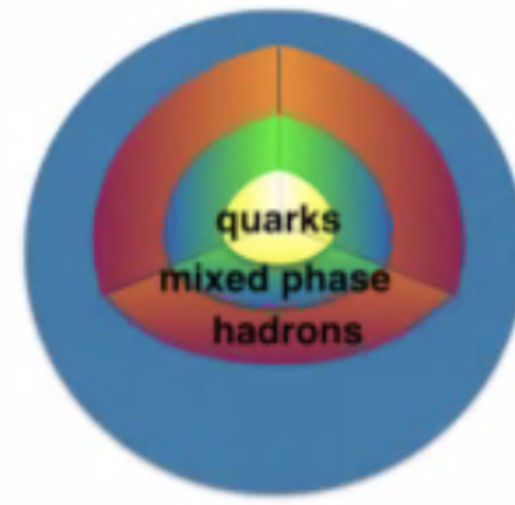
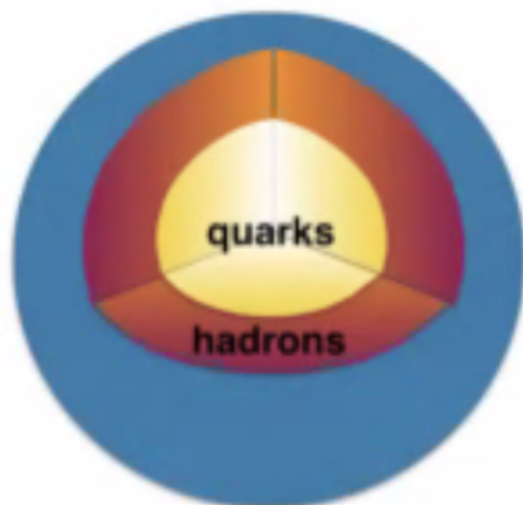
**1969 - estrelas híbridas (possibilidade de um
caroço supercondutor)**

Ivanenko + Kurdgelaidze

1970 - estrelas de quarks - Itoh

**conjectura de Bodmer (1971) - Witten (1984)
estrelas estranhas**

estrelas híbridas - com ou sem fase mista





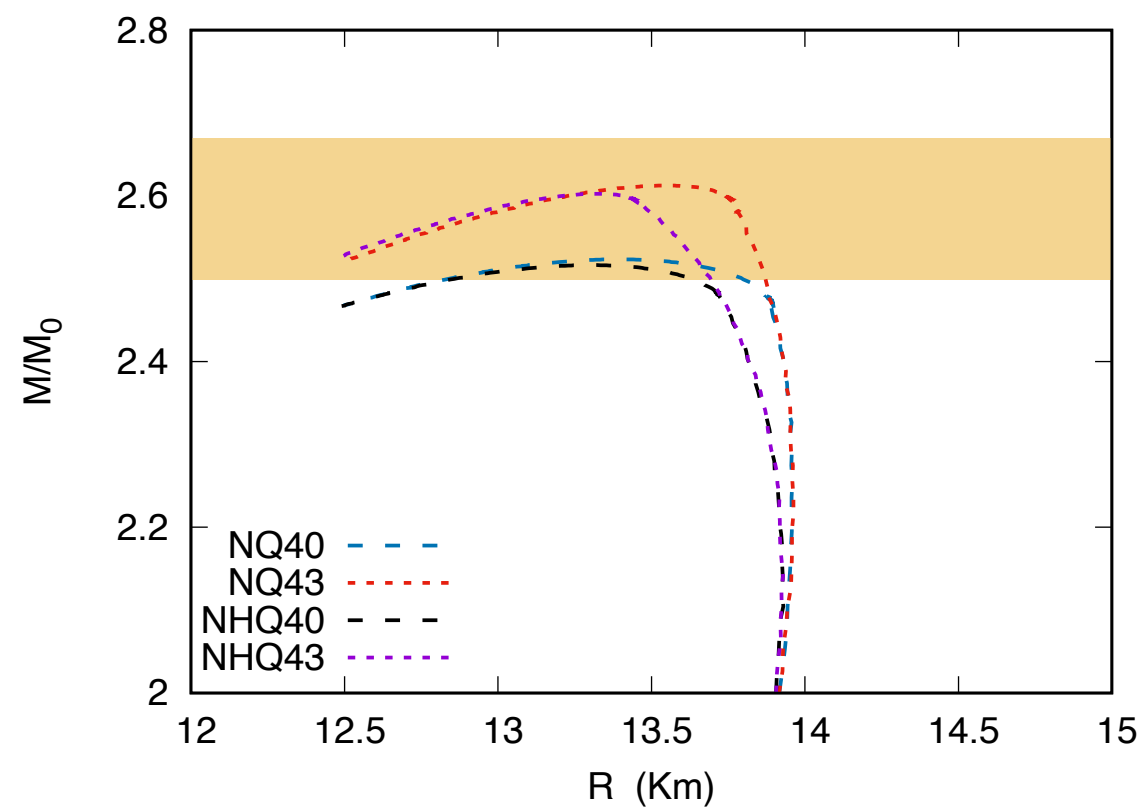
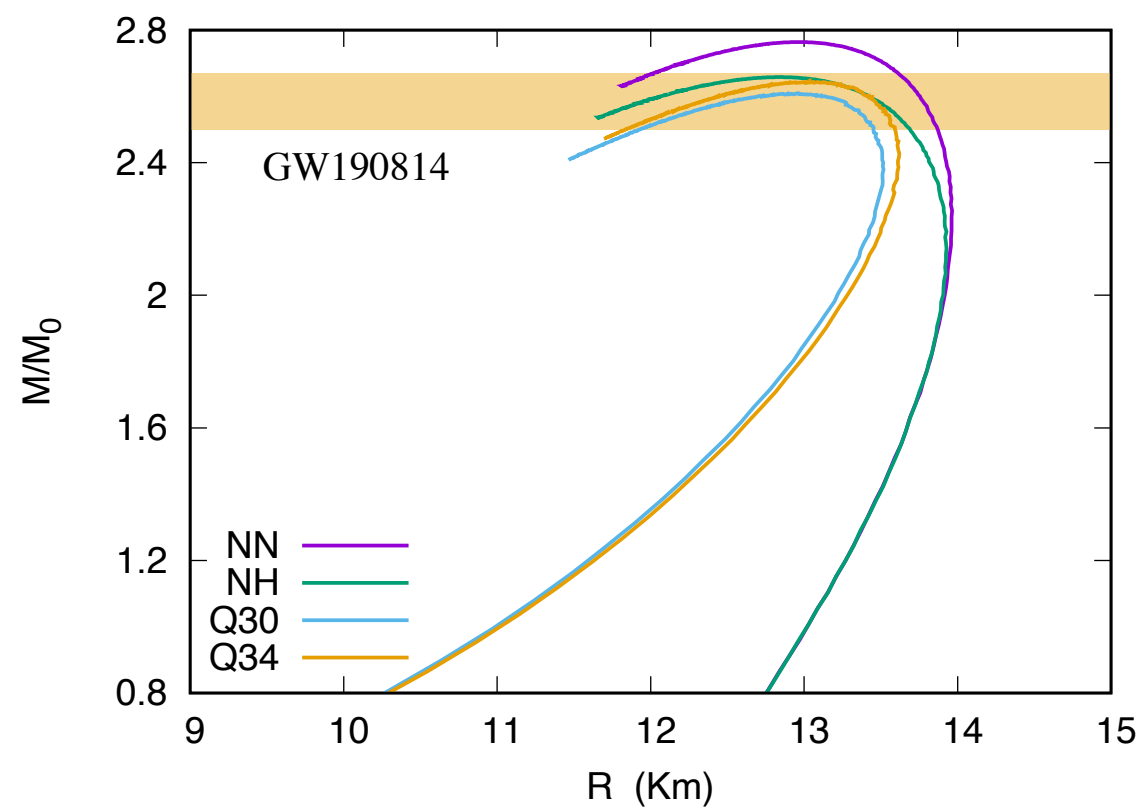
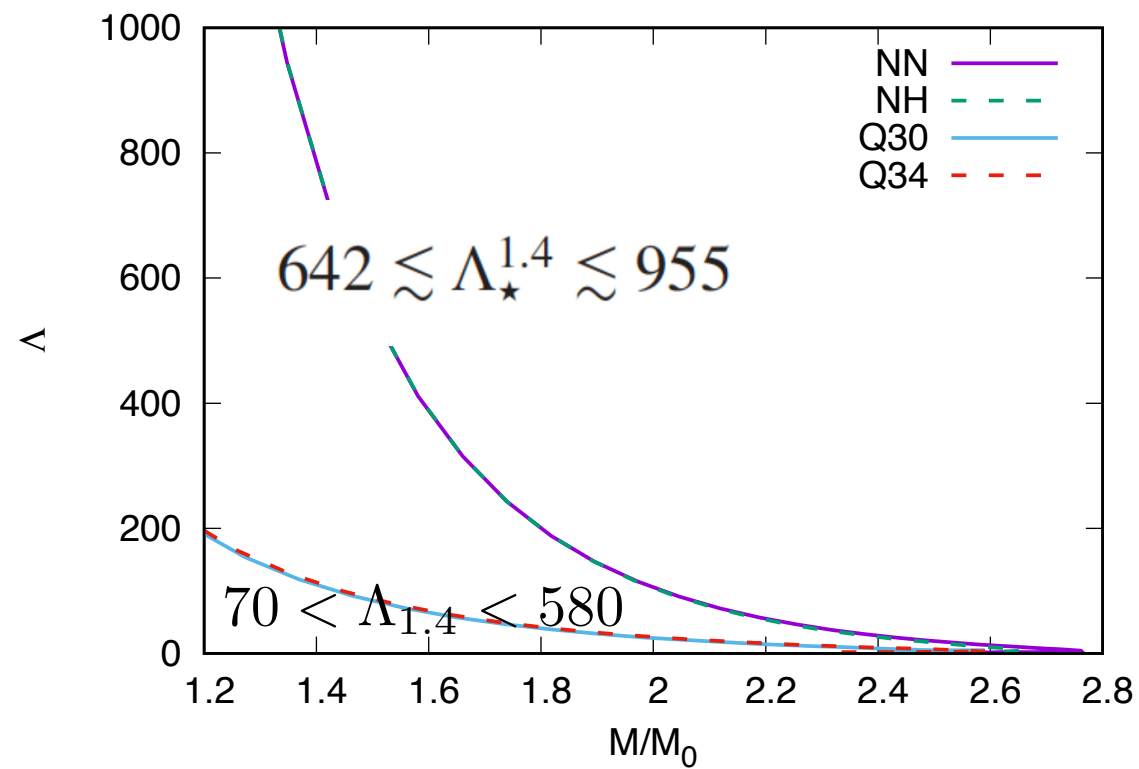
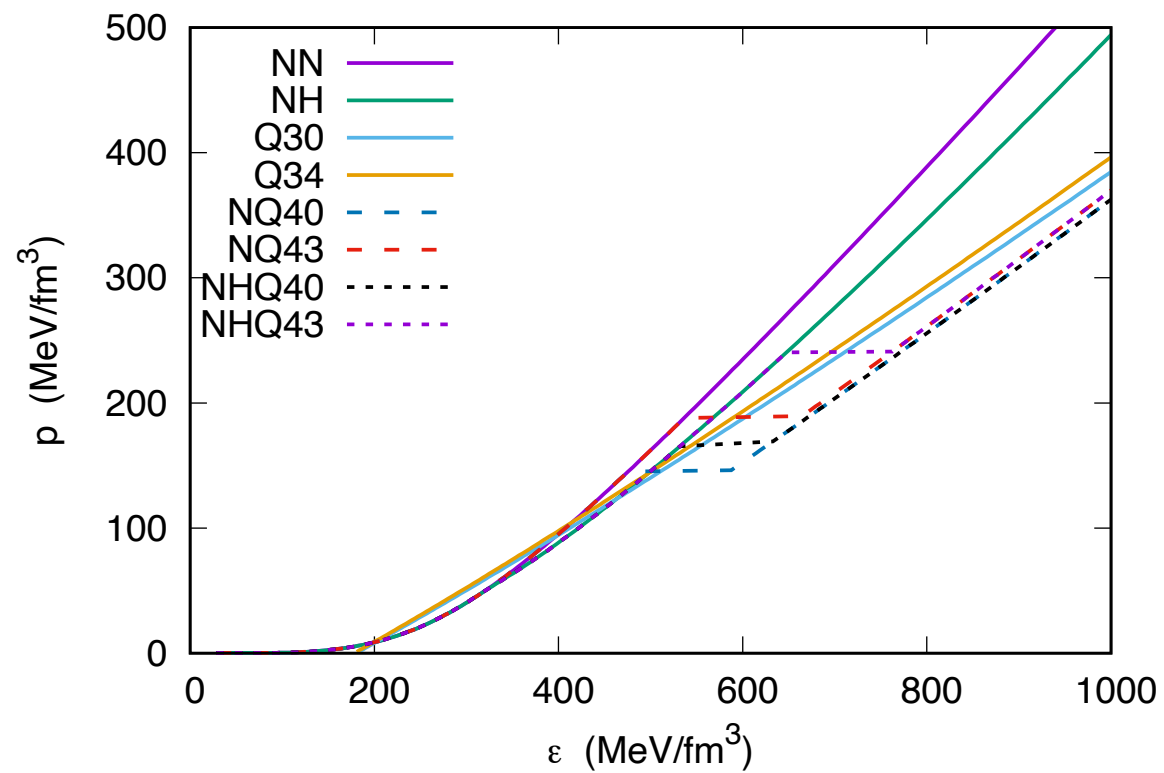
Most massive $\text{NS} < 2.5 M_{\odot}$

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

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

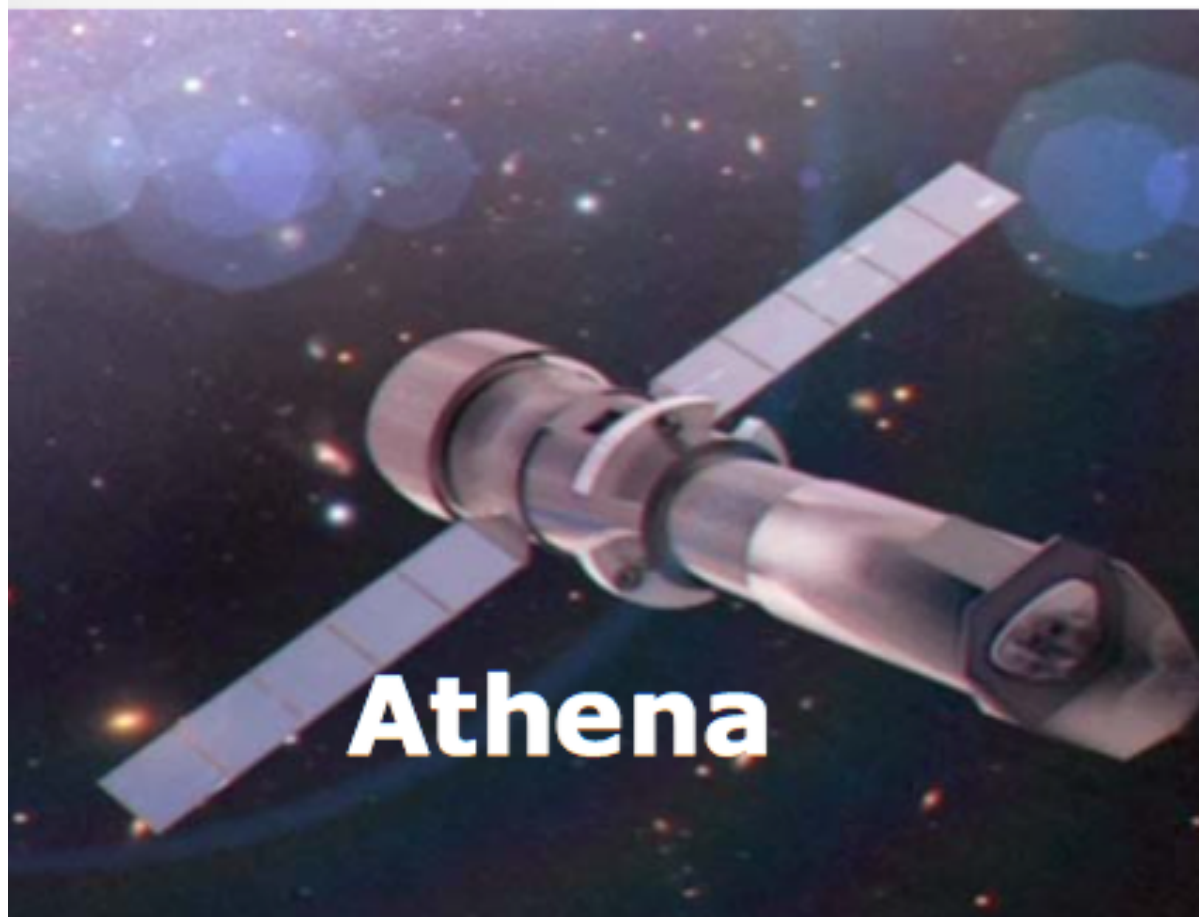
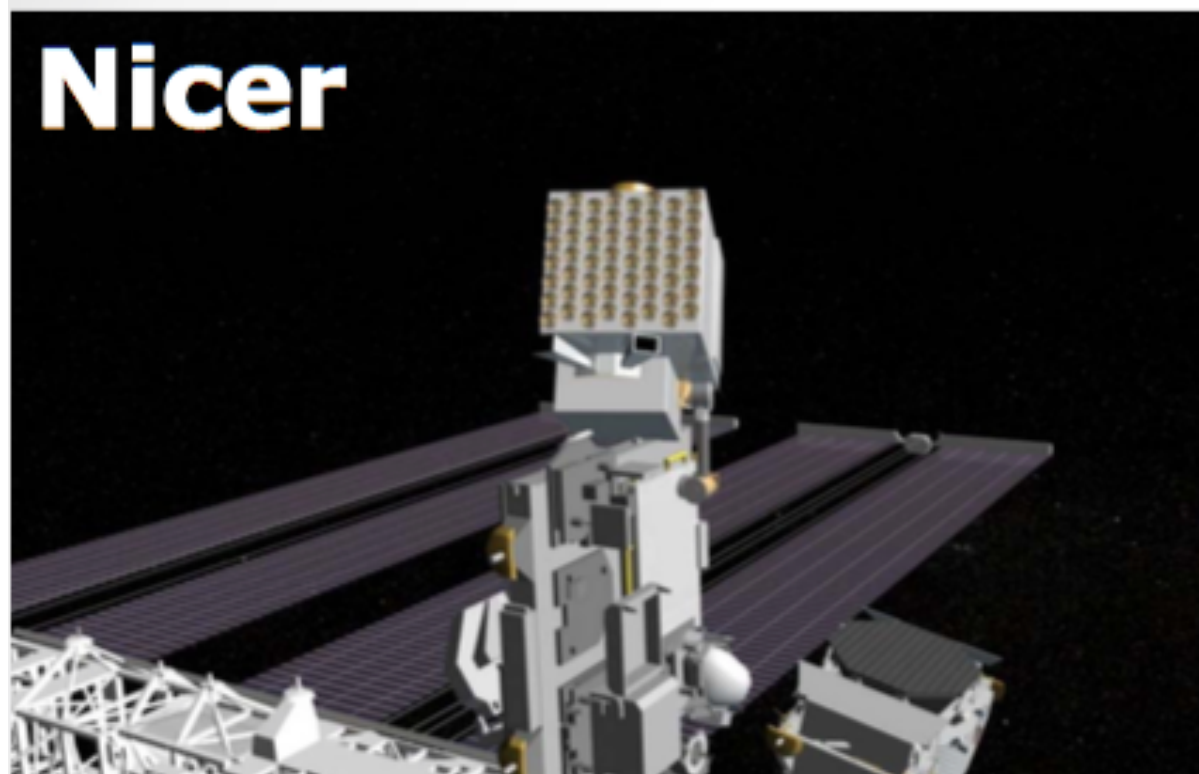
$2.59 M_{\odot} (???) + 25.6 M_{\odot}$

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



The Future ???

2017



2030



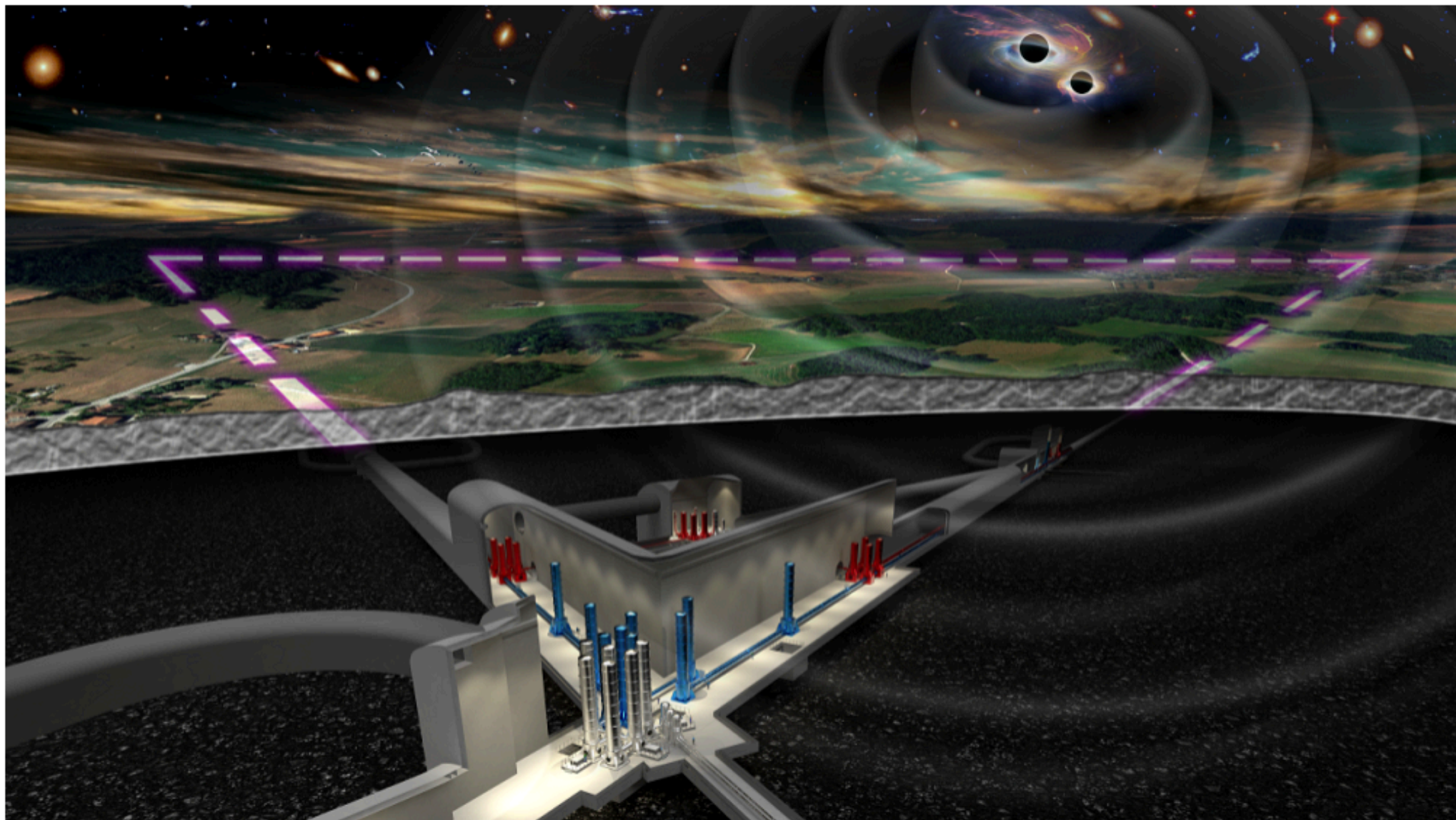
Evolved Laser Interferometer Space Antenna

2034

A Evolved Laser Interferometer Space Antenna ou Antena Espacial de Interferômetro a Laser, ou ainda como é conhecida pela abreviação de cada uma de suas primeiras letras, eLISA, é um sistema de três satélites da Agência Espacial Europeia com previsão de lançamento em 2034. [Wikipédia](#)



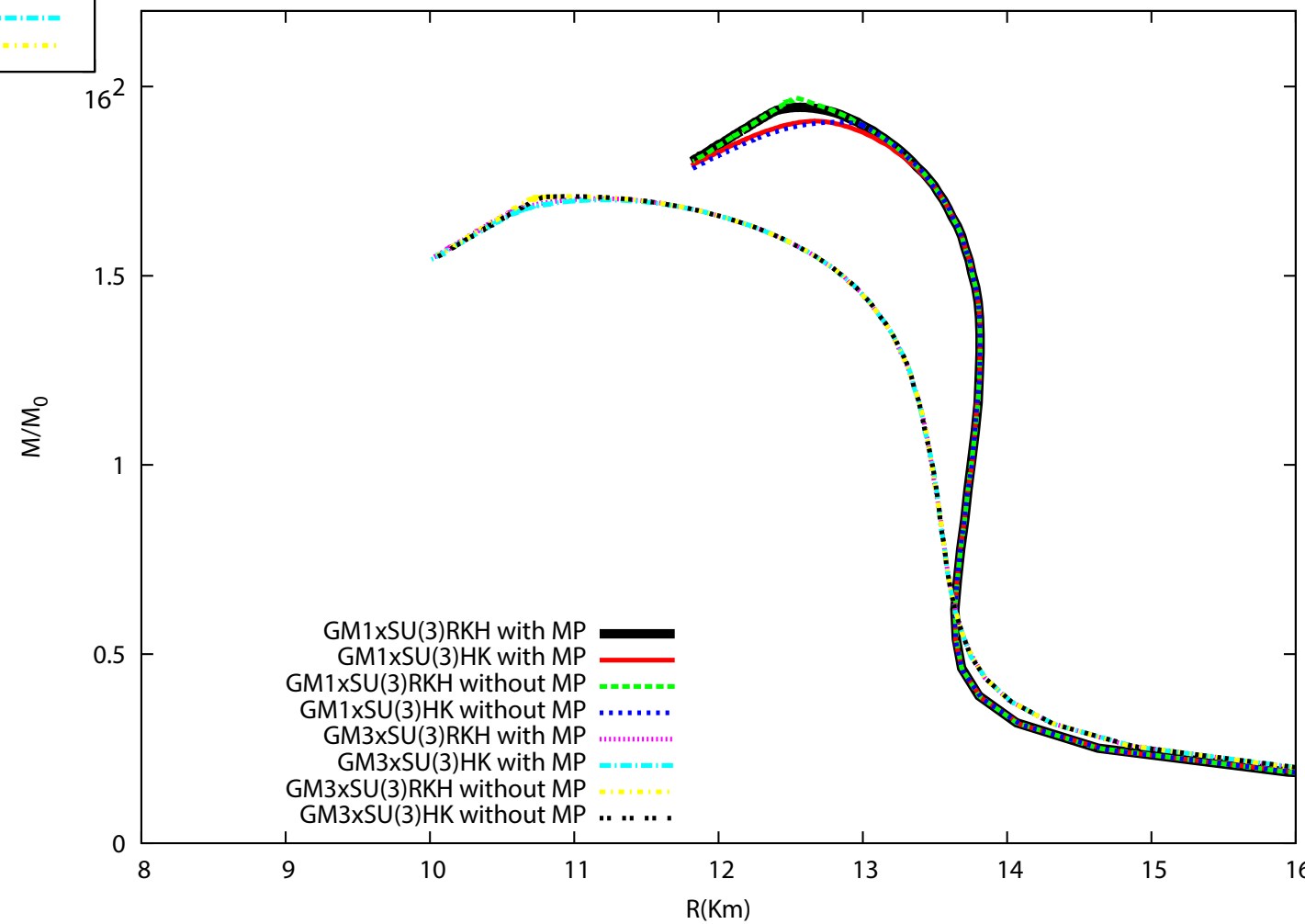
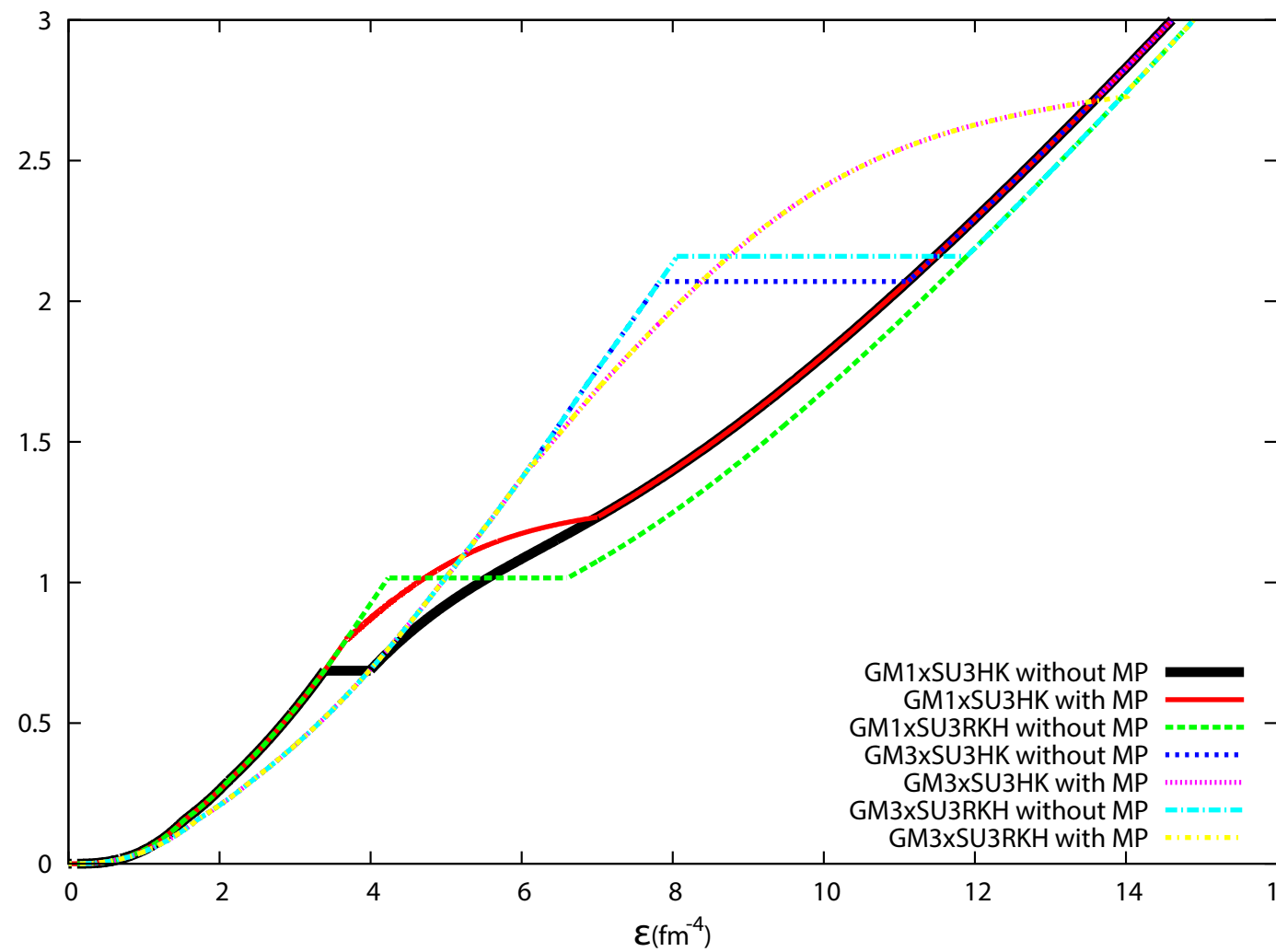
ET - underground infrastructure - 3rd generation gravitational wave observatory - 2030 ?



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

Bill Gelletly





Quark Stars ???

J.R. Torres and DPM, Europhysics Letters, 101 (2013) 42003

Betânia C. Backes, E. Hafemann, I. Marzola and DPM, J.Phys.G48, 055104 (2021)

