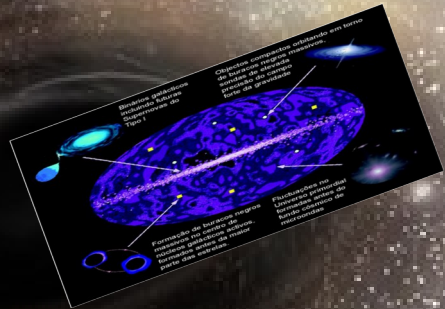




Sobre ondas gravitacionais e seus impactos na astronomia observacional



Profº Drº César Vásquez Flores



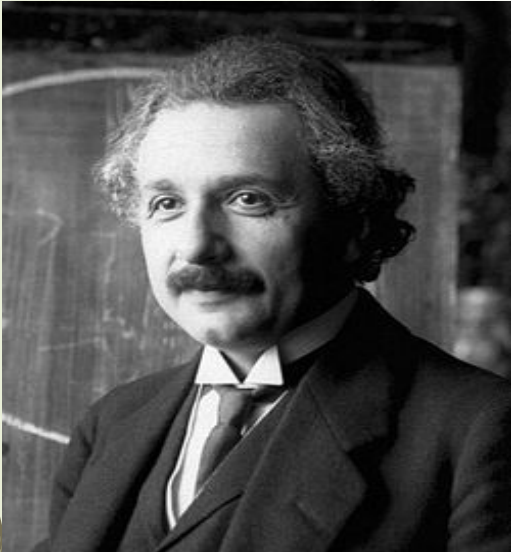
Sumário

O que são ondas gravitacionais?

Como detectá-las?

Ondas gravitacionais e a micro estrutura de estrelas de compactas

O que são ondas gravitacionais?



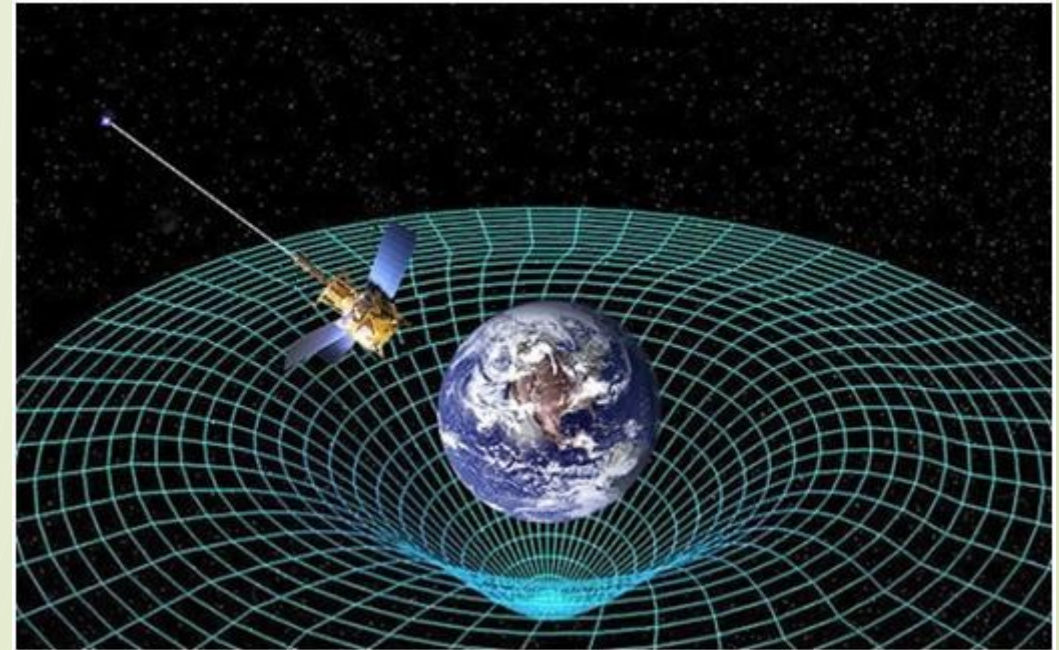
Nascido em 1879 no dia 18 de Março

Um Físico de grandes feitos em diversas áreas da Física

- Efeito Foto - Elétrico: Laureado com o Prêmio Nobel de 1922
- Relatividade Restrita

Relatividade Geral

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8 \pi G}{4} T_{\mu\nu}$$



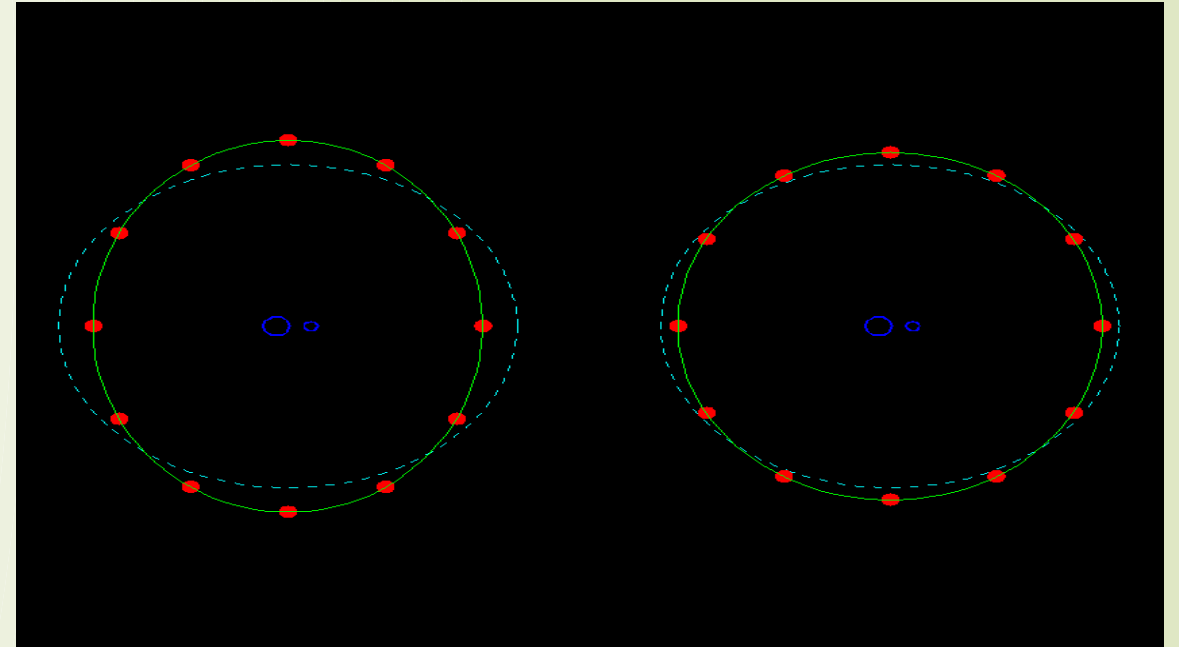
O que são ondas gravitacionais?

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8 \pi G}{4} T_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\nabla^2 h_{\mu\nu} - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} h_{\mu\nu} = \frac{8 \pi G}{c^4} T_{\mu\nu}$$

$$\nabla^2 h_{\mu\nu} - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} h_{\mu\nu} = 0$$



$$h_{\mu\nu} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Artigo publicado por Einstein no ano de 1916

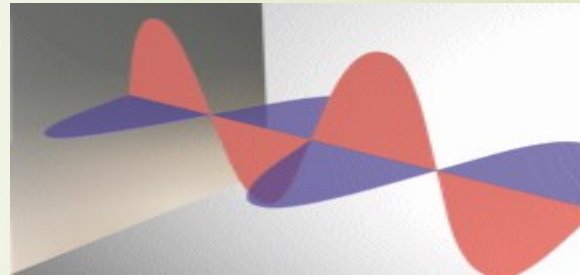
O que são ondas gravitacionais?

Façamos uma analogia:

Variações em um campo
eletromagnético



Onda Eletromagnética

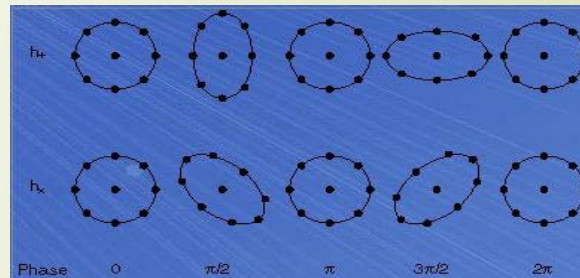


Fóton

Variações em um campo
Gravitacional



Onda Gravitacional



Gráviton

O que são ondas gravitacionais?

Massas aceleradas emitem
Ondas Gravitacionais



A amplitude da onda em tais eventos é muito baixa!

Porque a interação gravitacional tem natureza fraca

$$G = 6,67 \cdot 10^{-11} \text{ m}^3 \cdot \text{kg}^{-1} \cdot \text{s}^{-2}$$

Mas por quê?





https://www.nasa.gov/mission_pages/hubble/main/index.html



What powered the big bang?

BIG BANG

Only gravitational waves can escape from the earliest moments of the Big Bang

Big Bang plus 10^{-43} seconds

Big Bang plus 300,000 Years

Gravitational waves

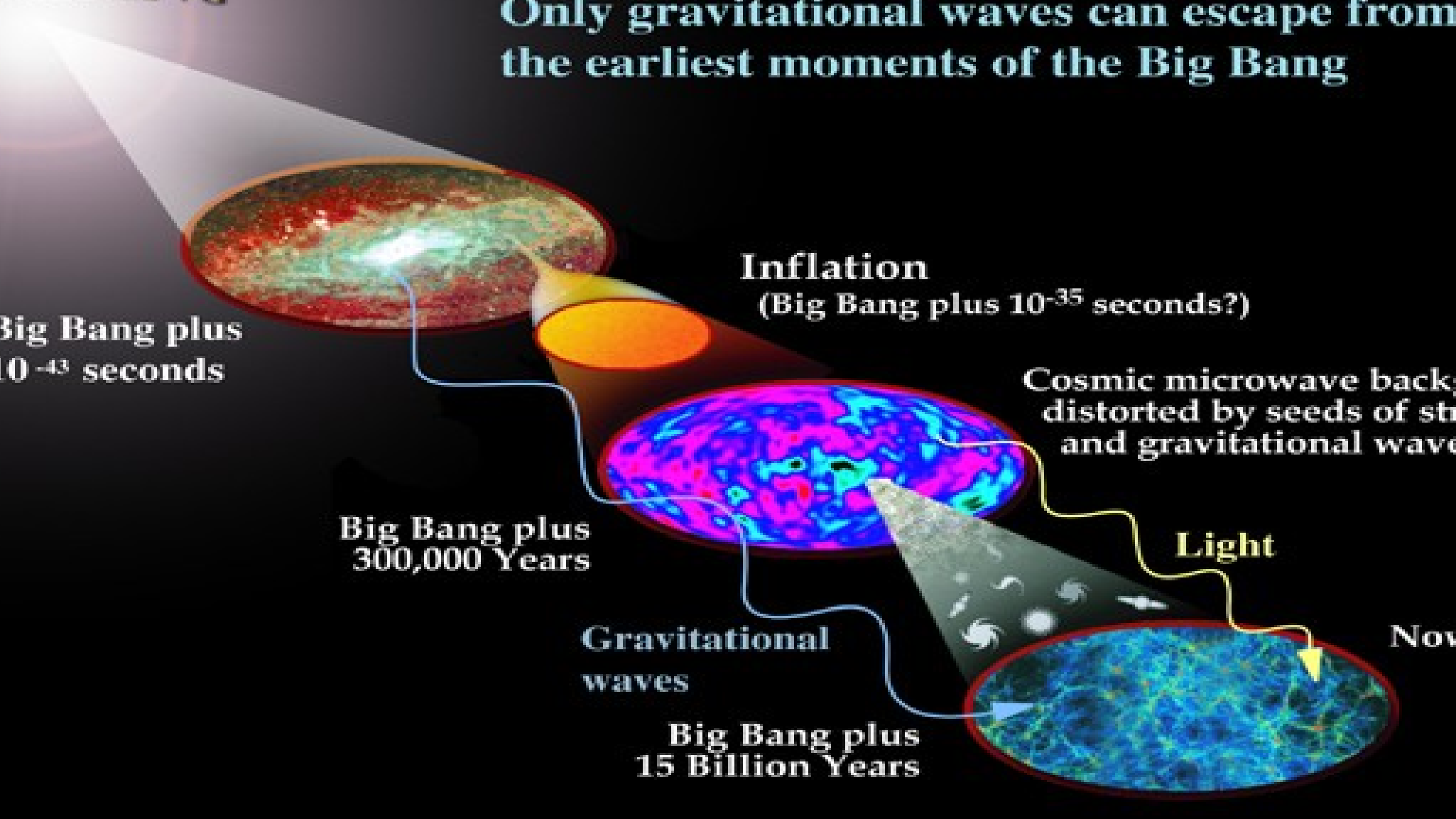
Big Bang plus 15 Billion Years

Inflation
(Big Bang plus 10^{-35} seconds?)

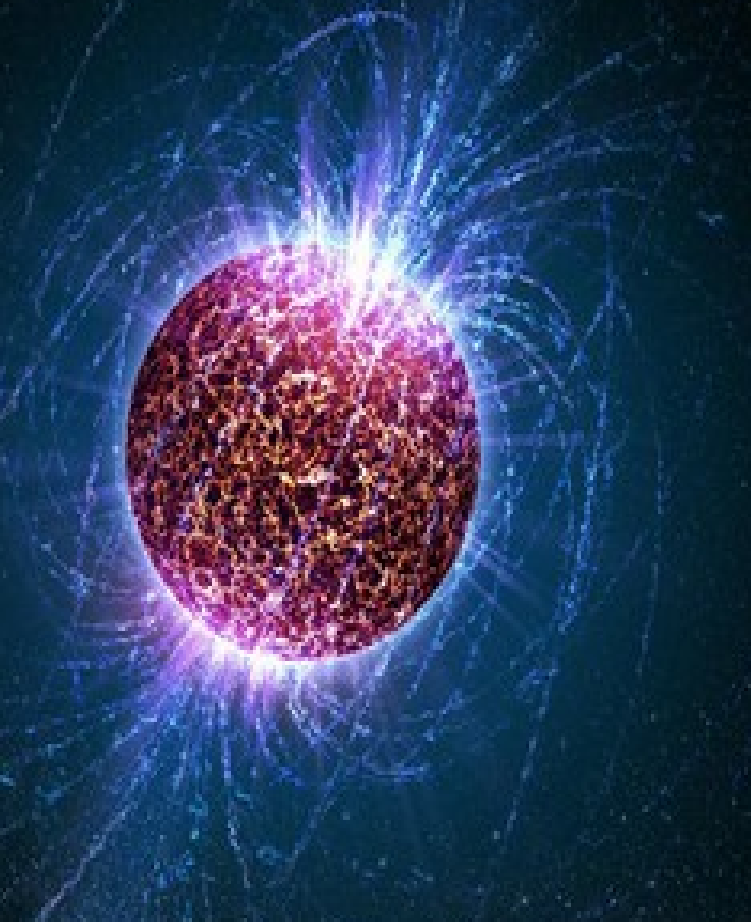
Cosmic microwave background, distorted by seeds of structure and gravitational waves

Light

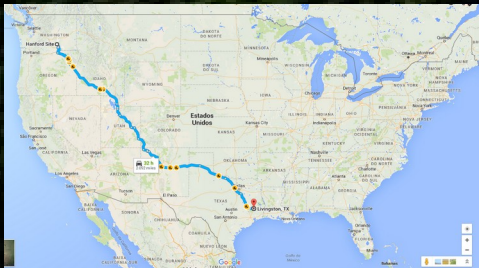
Now

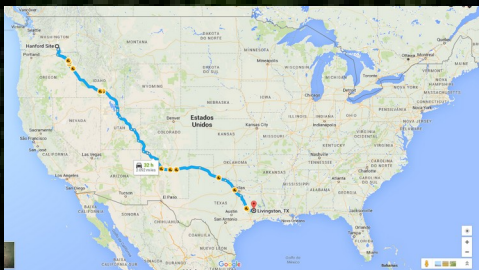
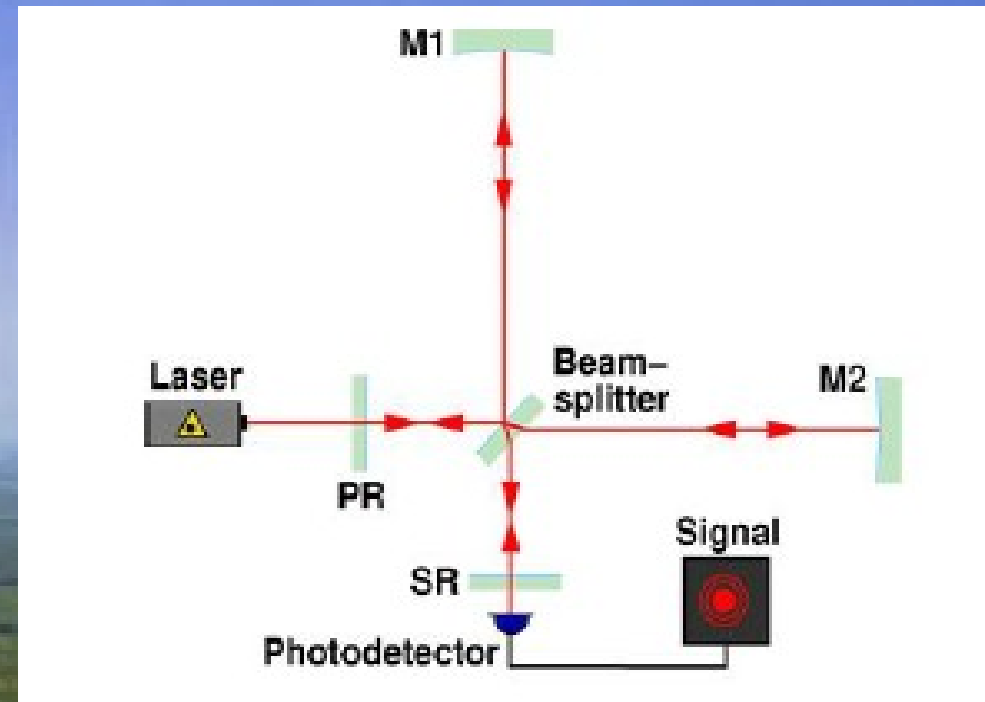


Uma importante fonte de ondas gravitacionais, são objetos astrofísicos compactos, tais quais os buracos negros e estrelas compactas. Estes objetos representam o estágio final de uma estrela muito massiva.



Estrelas de nêutrons são objetos astrofísicos extremamente misteriosos. Acredita-se que a estrutura interna desta classe de estrelas seja constituída por matéria exótica, do tipo que só conseguimos observar em aceleradores de partículas. Ou seja, estas estrelas são verdadeiros laboratórios para física de altas energias.

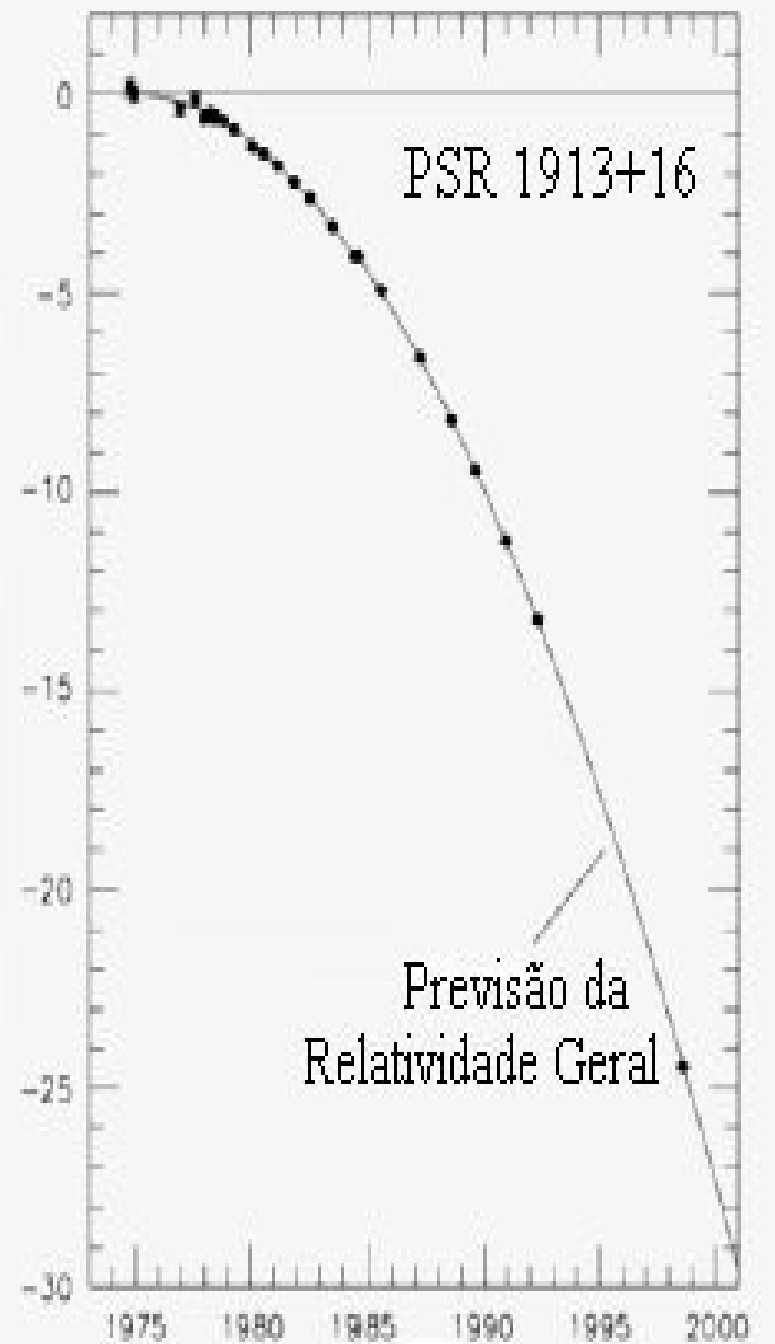




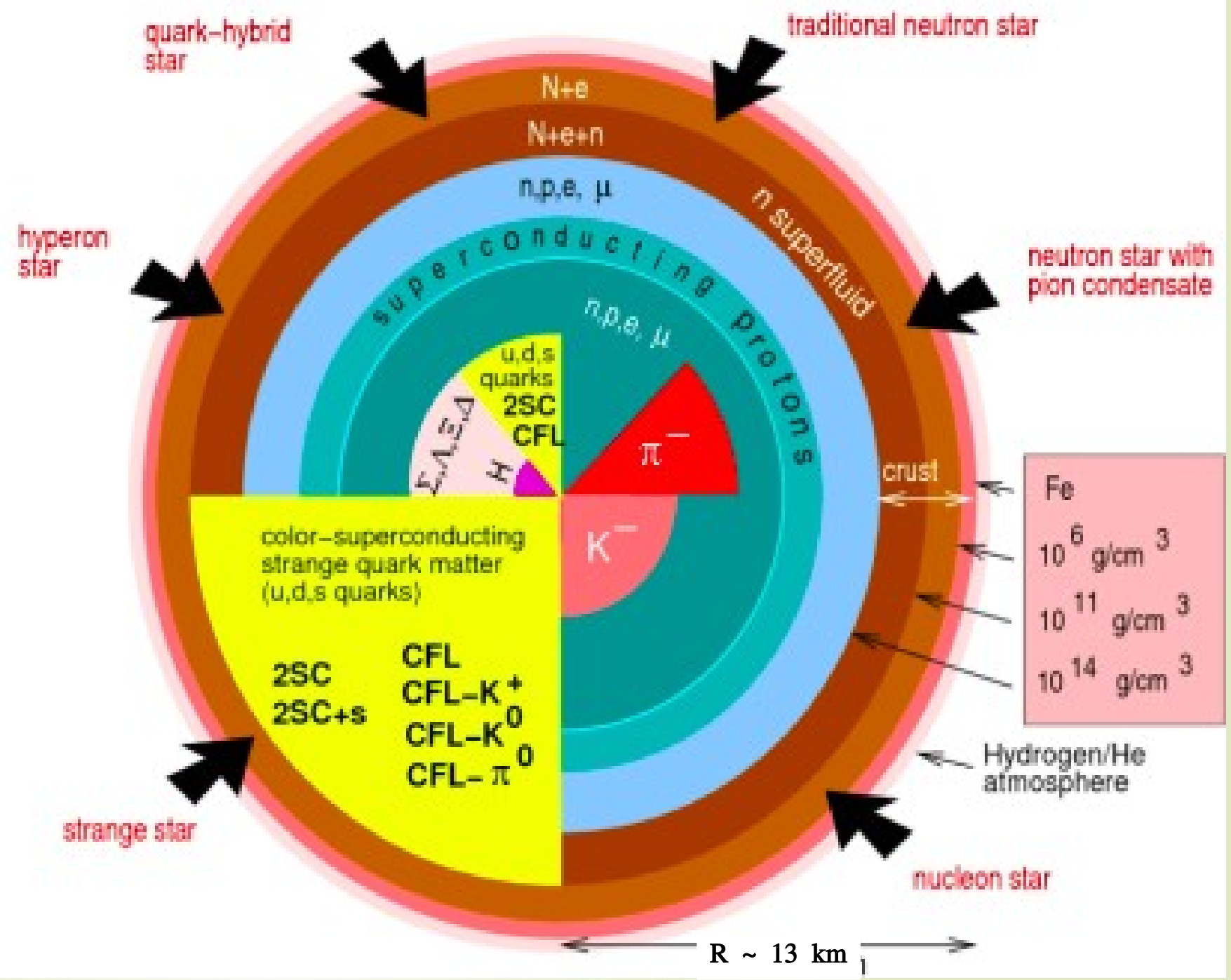




Desvio cumulativo
do tempo de passagem por periélio (s)



Ano

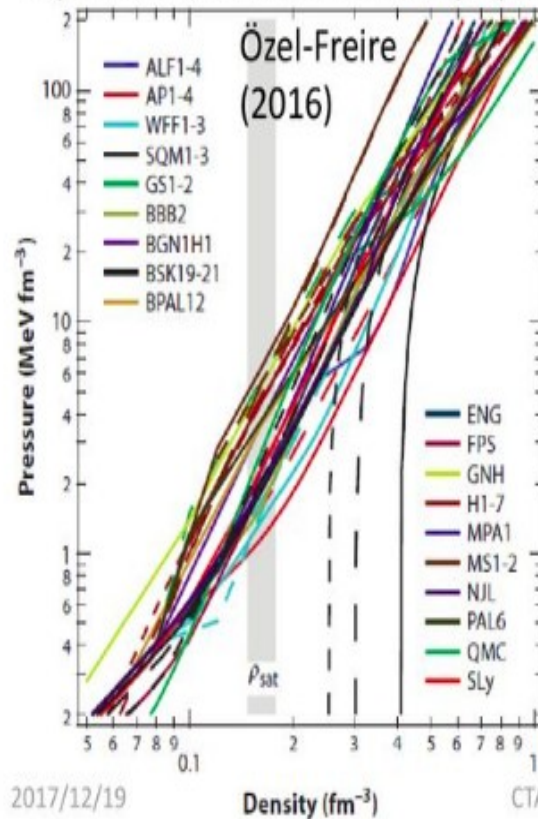


Equações de Tolman-Oppenheimer-Volkof

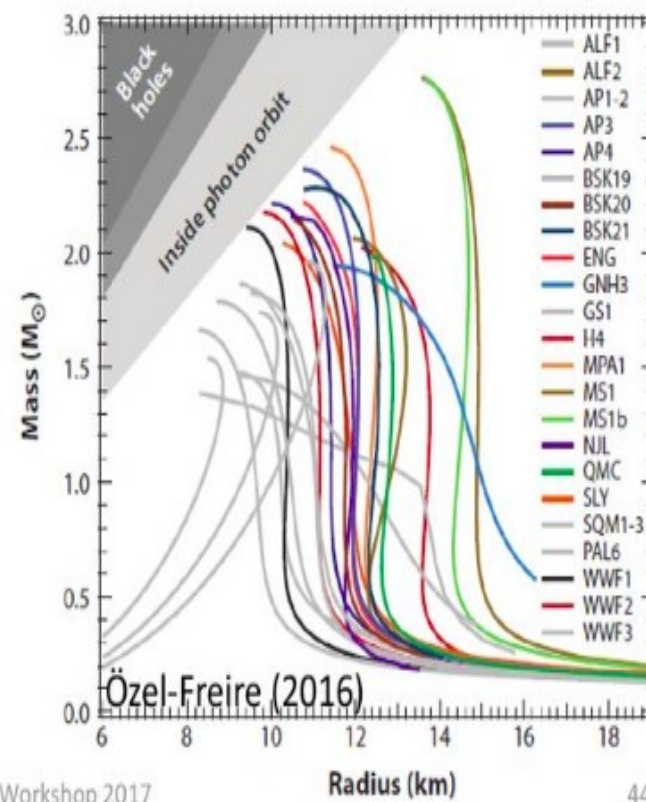
$$\frac{dP}{dr} = -\frac{Gm}{r^2} \left(1 + \frac{P}{\rho c^2}\right) \left(1 + \frac{4\pi r^3 P}{mc^2}\right) \left(1 - \frac{GM}{rc^2}\right)^{-1}$$

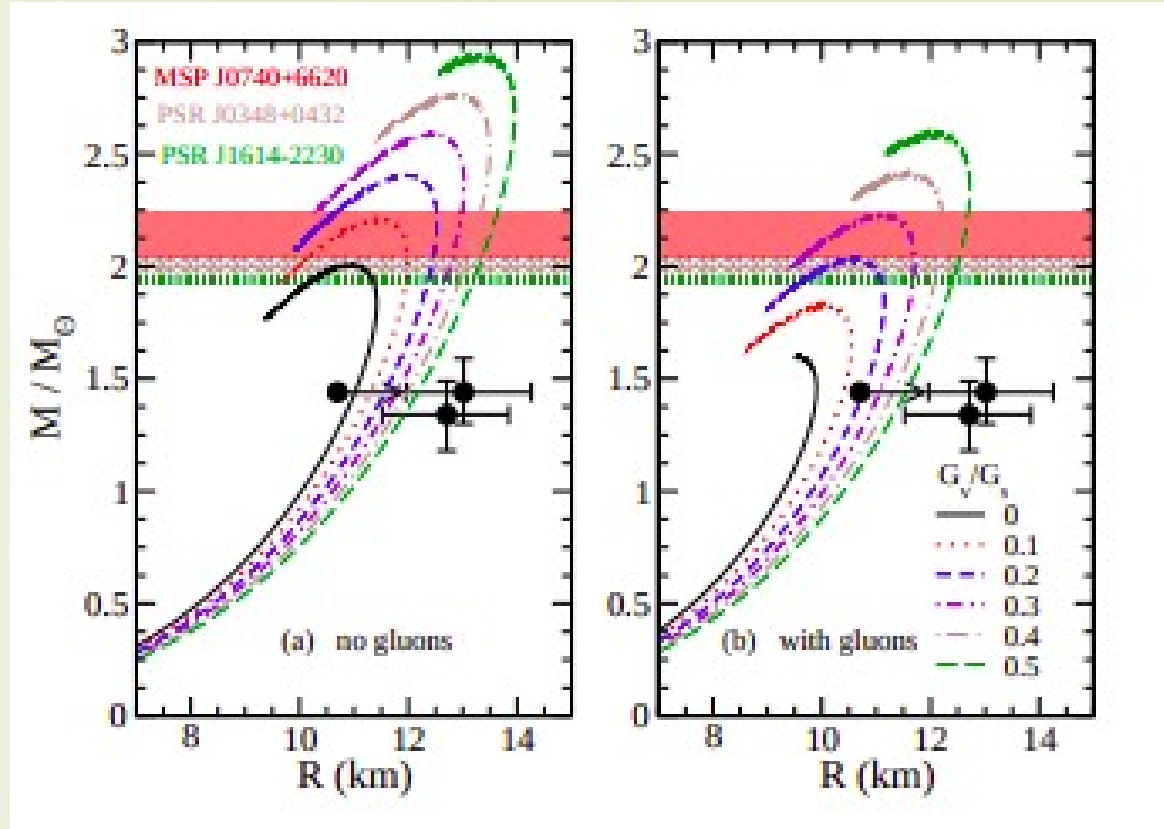
$$\frac{dM}{dr} = 4\pi r^2 \rho$$

Equation of state: Nuclear physics



Mass-Radius relation: Astrophysics





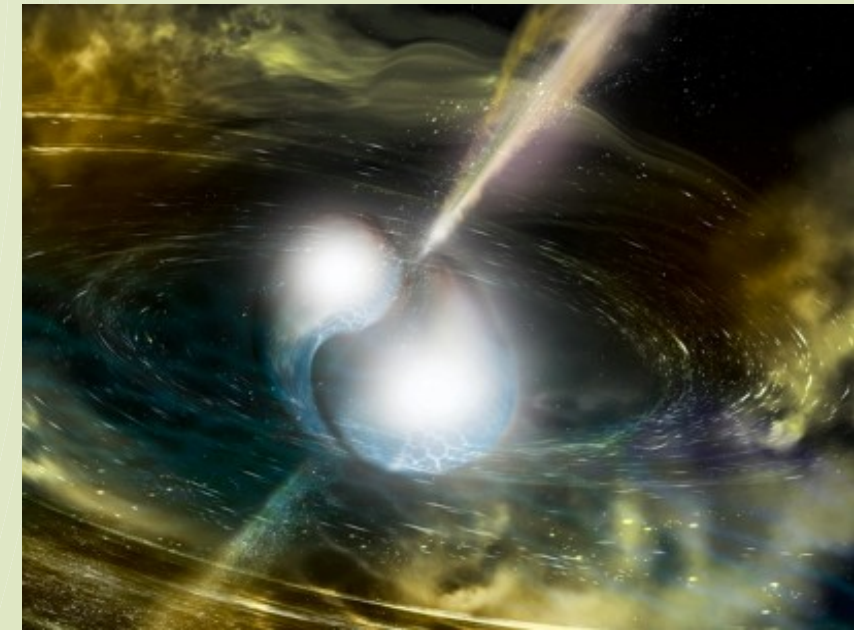
Neutron Star Interior Composition Explorer - ISS

$$\text{PSR J0030+0451} : M = 1.44^{+0.15}_{-0.14} M_{\odot} \longrightarrow R = 13.02^{+1.24}_{-1.02} \text{km}$$

$$\text{PSR J0740+6620} : M = 2.08^{+0.15}_{-0.14} M_{\odot} \longrightarrow R = (14 \pm 2 // 12.35 \pm 1.10) \text{km}$$



Em 2017, a colaboração LIGO-VIRGO, detectou um sinal gravitacional oriundo da colisão de um sistema binário de estrelas de nêutrons, a qual verificou-se contrapartida eletromagnética, inaugurando a era da astronomia observacional multimessageira. Este evento ficou conhecido como GW170817



GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and $2.26 M_{\odot}$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17 – $1.60 M_{\odot}$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_{\odot}$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ -ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ -ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.



Barry C. Barish (Caltech) Kip S. Thorne (Caltech) Rainer Weiss (MIT)



2017 Nobel Prize in Physics

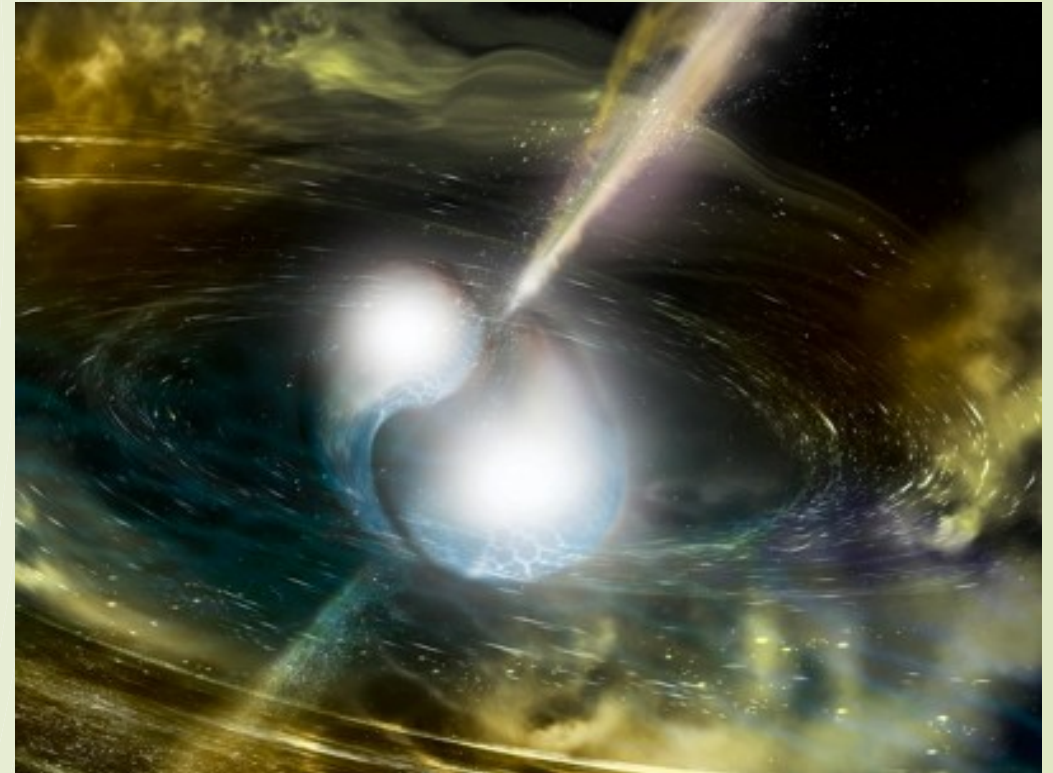
→ Nesta detecção, pôde ser verificada a assinatura de um forte efeito de maré, devido a aproximação das estrelas.

→ Este efeito pode ser quantificado em termos de um parâmetro conhecido como **deformabilidade de maré**

→ Este parâmetro quantifica a deformidade da estrutura multipolar da estrela, devido a presença de um campo externo não-uniforme e não-estático

$$\Lambda = \frac{3}{2} k_2 \frac{R^5}{M^5}$$

Love Number de segunda ordem



Trata-se de um parâmetro diretamente relacionado à microestrutura da estrela

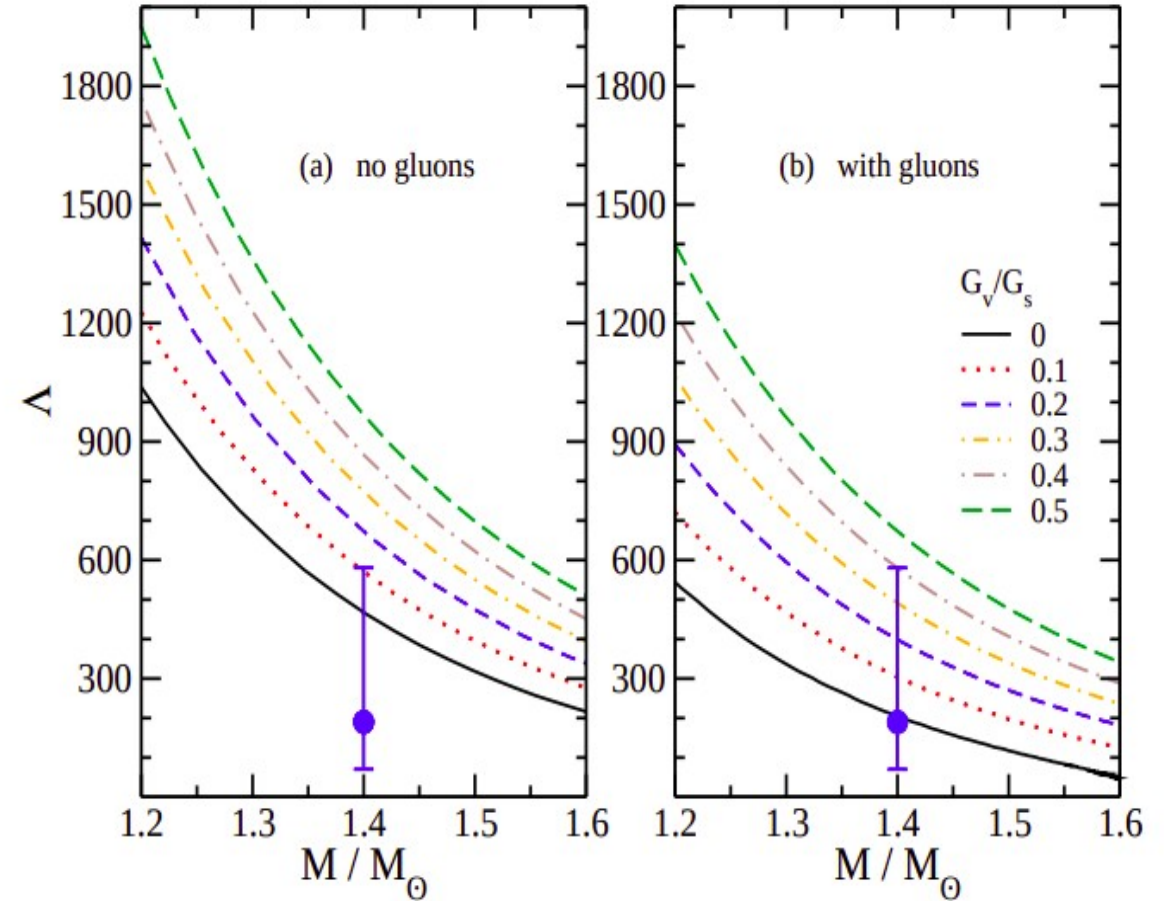
$$r \frac{dy}{dr} + y^2 + yF(r) + r^2 Q(r) = 0$$

$$F(r) = \frac{r - 4\pi r^3 [\epsilon(r) - p(r)]}{r - 2M(r)}$$

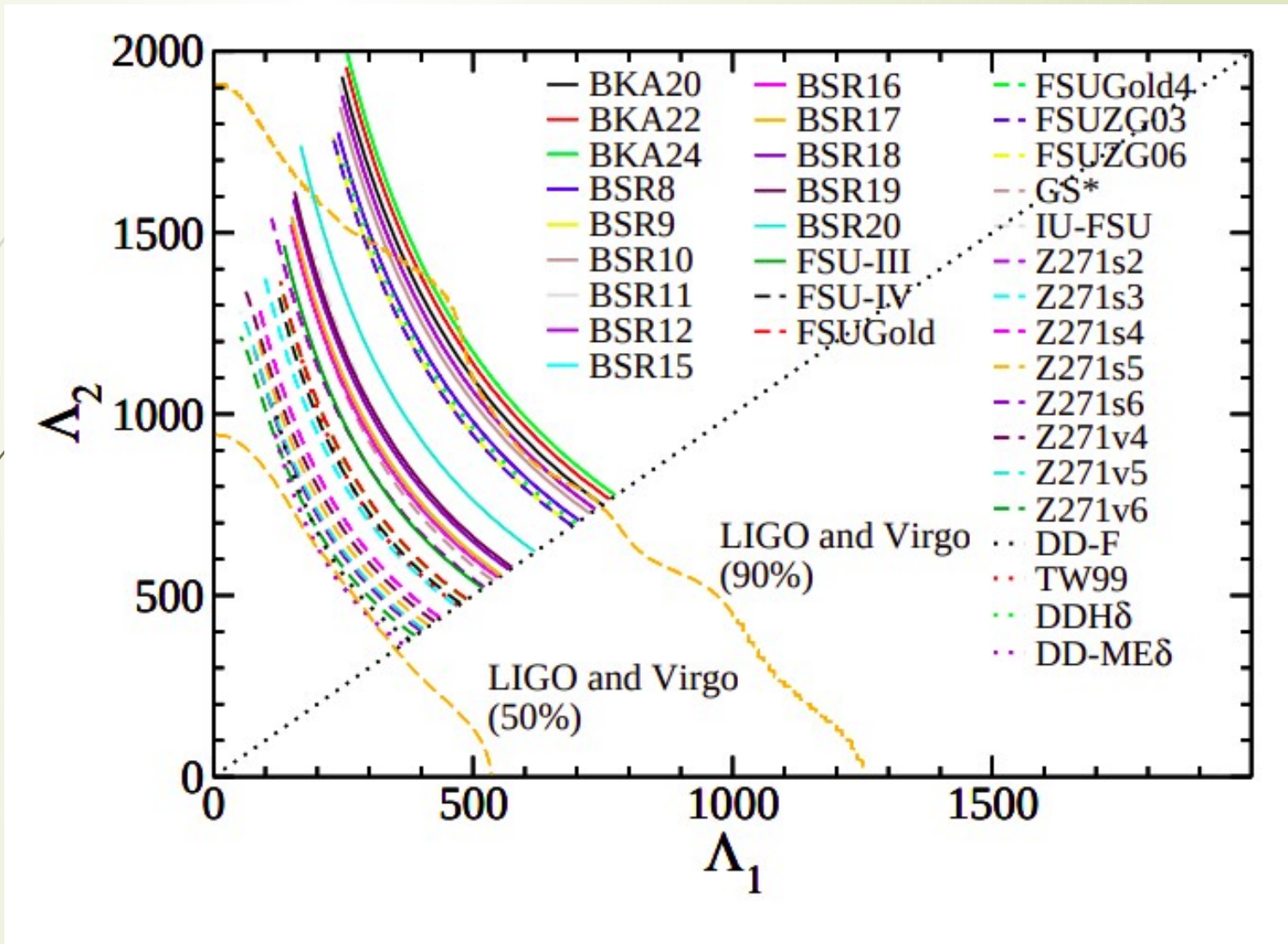
$$Q(r) = \frac{4\pi r \left[5\epsilon(r) + 9p(r) + \frac{\epsilon(r)+p(r)}{\partial p(r)/\partial \epsilon(r)} - \frac{6}{4\pi r^2} \right]}{r - 2M(r)} - 4 \left[\frac{M(r) + 4\pi r^3 p(r)}{r^2(1 - 2M(r)/r)} \right]^2$$

$$k_2 = \frac{8C^5}{5} (1 - 2C)^2 [2 + 2C(y_R - 1) - y_R] \times \left\{ 2C[6 - 3y_R + 3C(5y_R - 8)] + 4C^3[13 - 11y_R + C(3y_R - 2) + 2C^2(1 + y_R)] + 3(1 - 2C)^2 [2 - y_R + 2C(y_R - 1)] \ln(1 - 2C) \right\}^{-1}$$

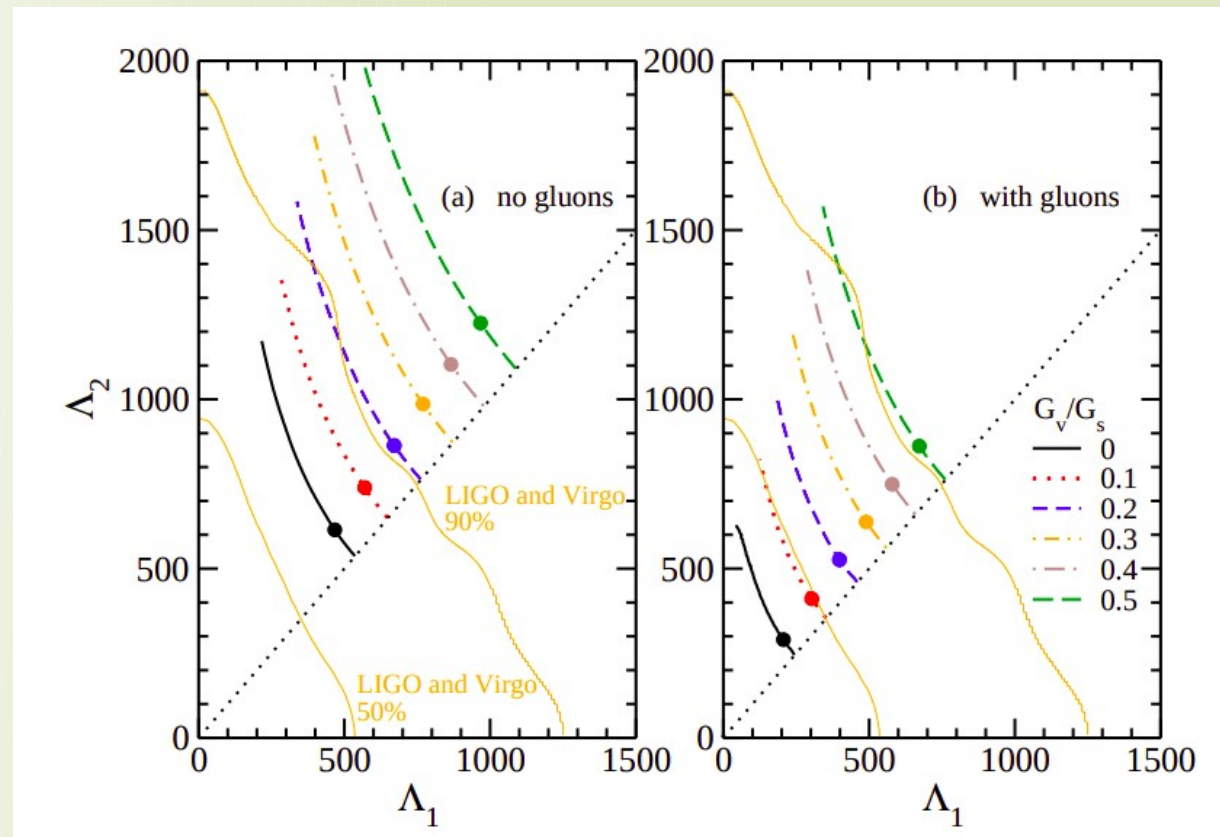
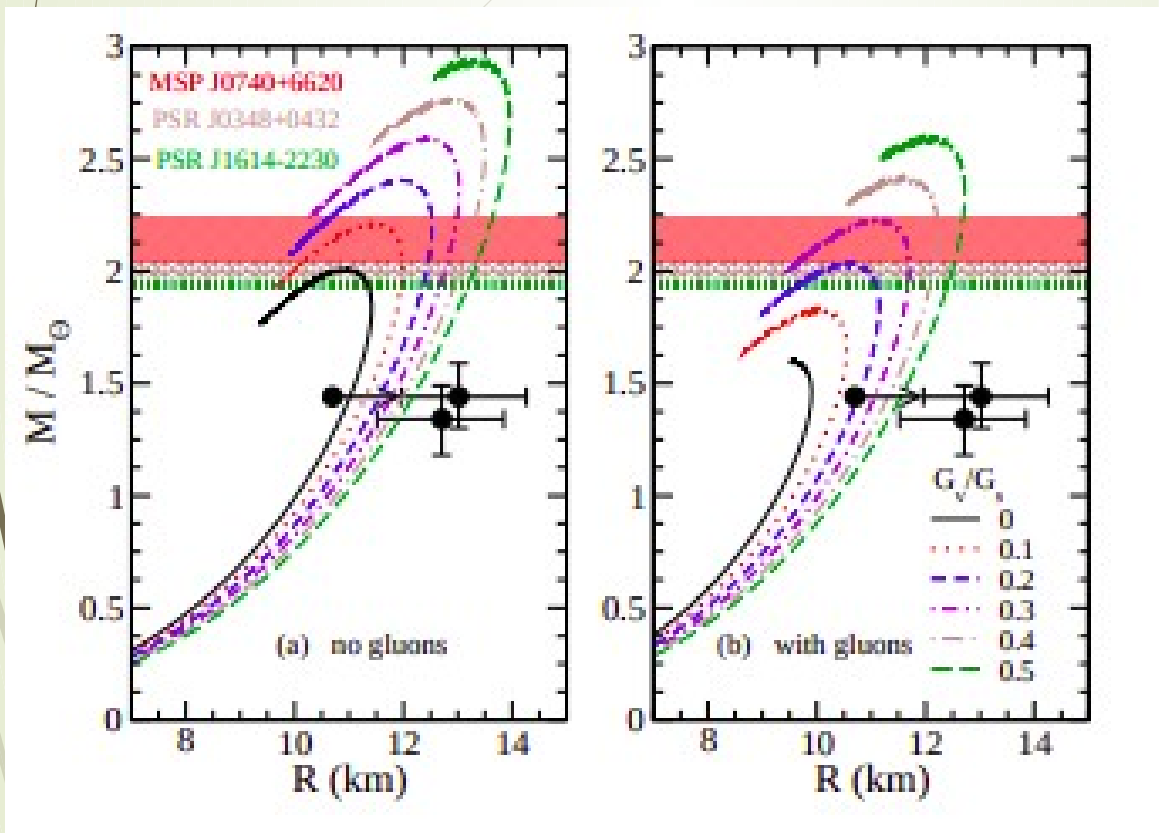
$$\mathcal{M}_{chirp} = \frac{(m_1 m_2)^{\frac{3}{5}}}{(m_1 + m_2)^{\frac{1}{5}}} = 1.188^{+0.004}_{-0.002} M_{\odot}$$



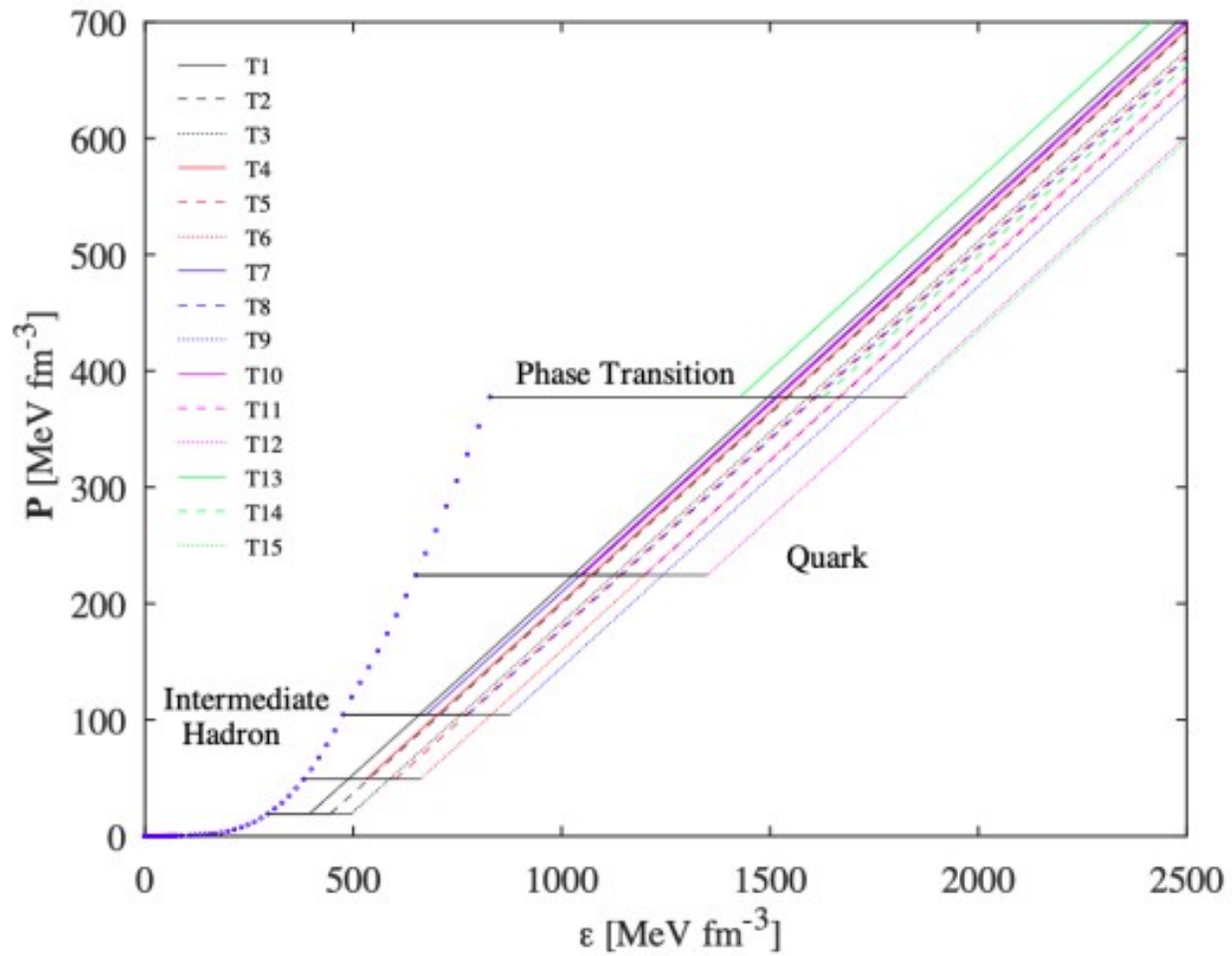
Testes com estrelas de nêutrons hadrônicas



Testes com estrelas de quarks puras

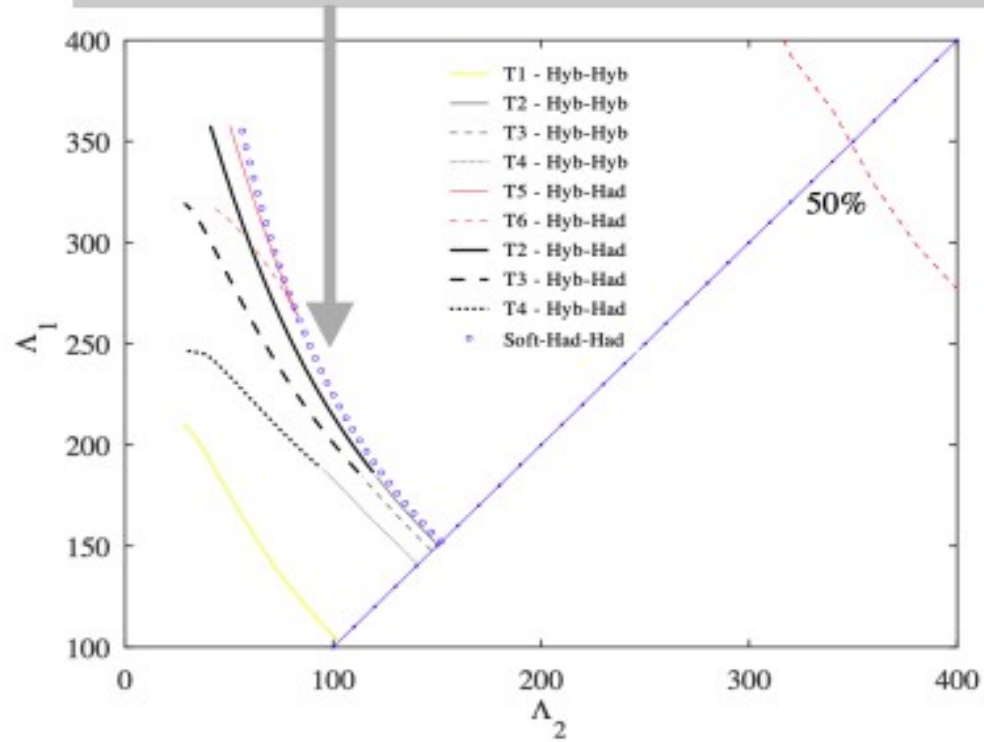


Testes com estrelas híbridas

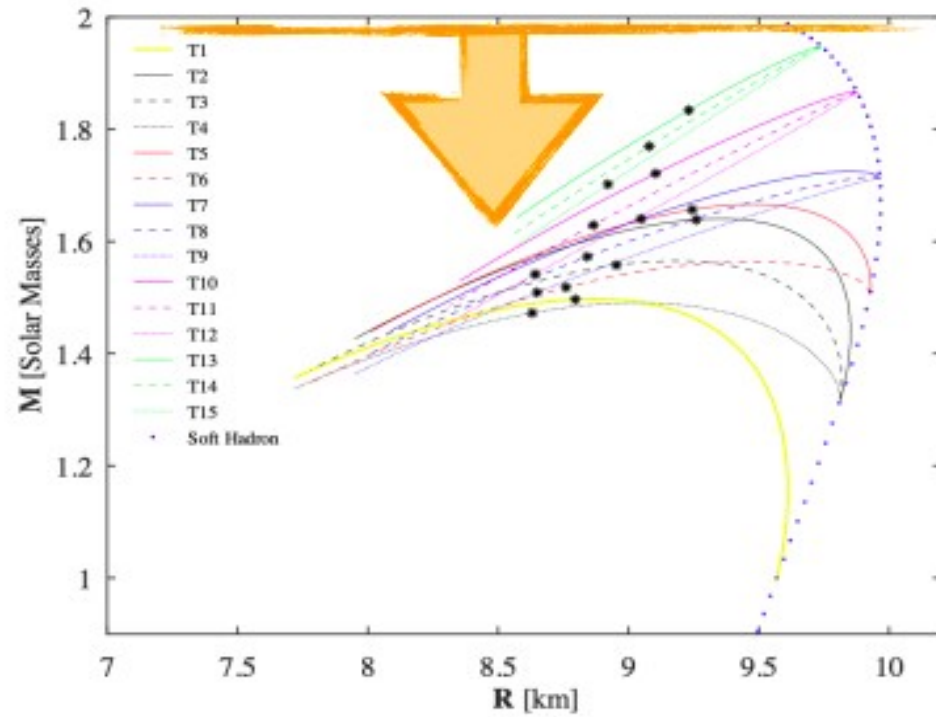


Testes com estrelas híbridas

👍 models with low enough transition pressure fall inside the 90% credible region for $\Lambda_1 - \Lambda_2$ of LIGO/Virgo.

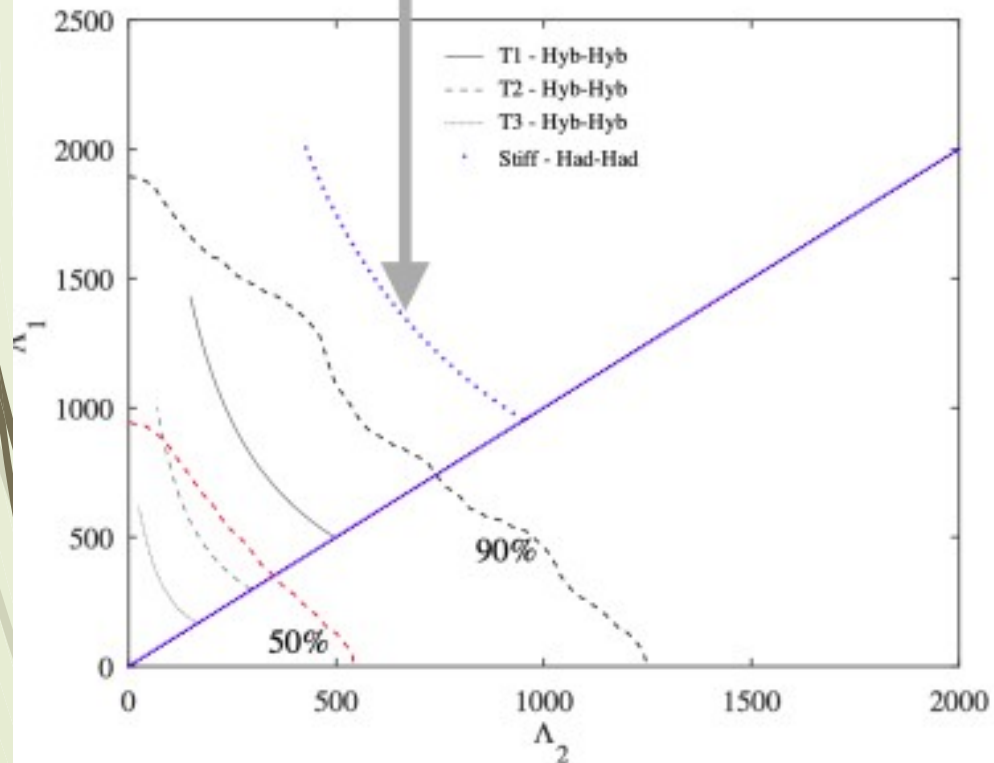


👎 $M_{max} < 2M_{\odot}$ for all models, in **disagreement** with the observation of PSR J0348+0432, PSR J0740+6620 and PSR J2215-5135.

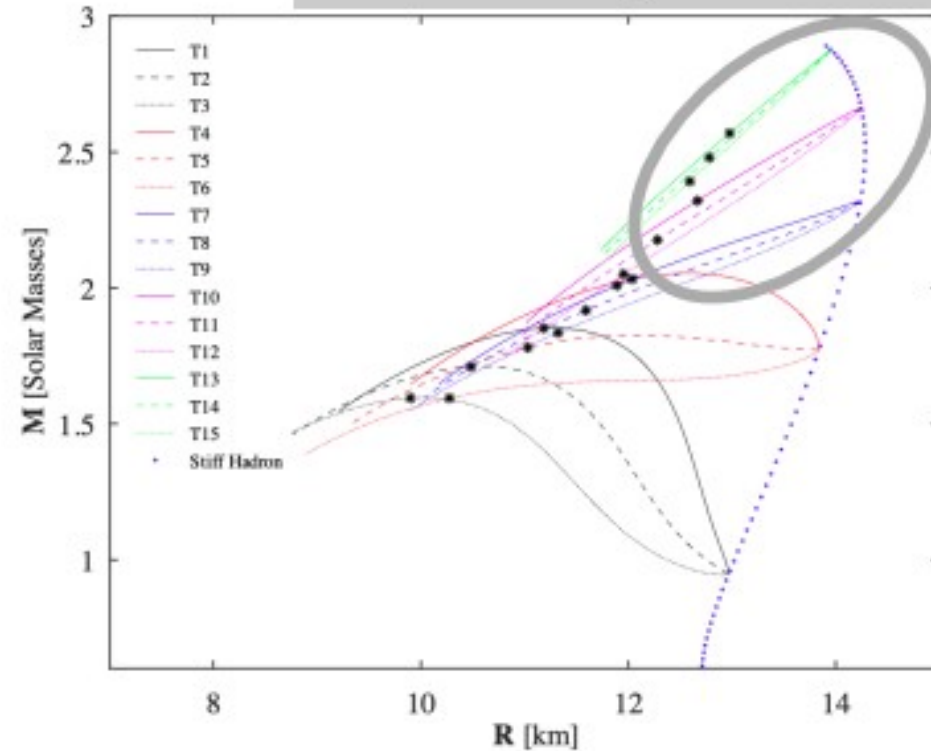


Testes com estrelas híbridas

👎 Pure hadronic model also **outside** the 90% credible region of LIGO/Virgo.

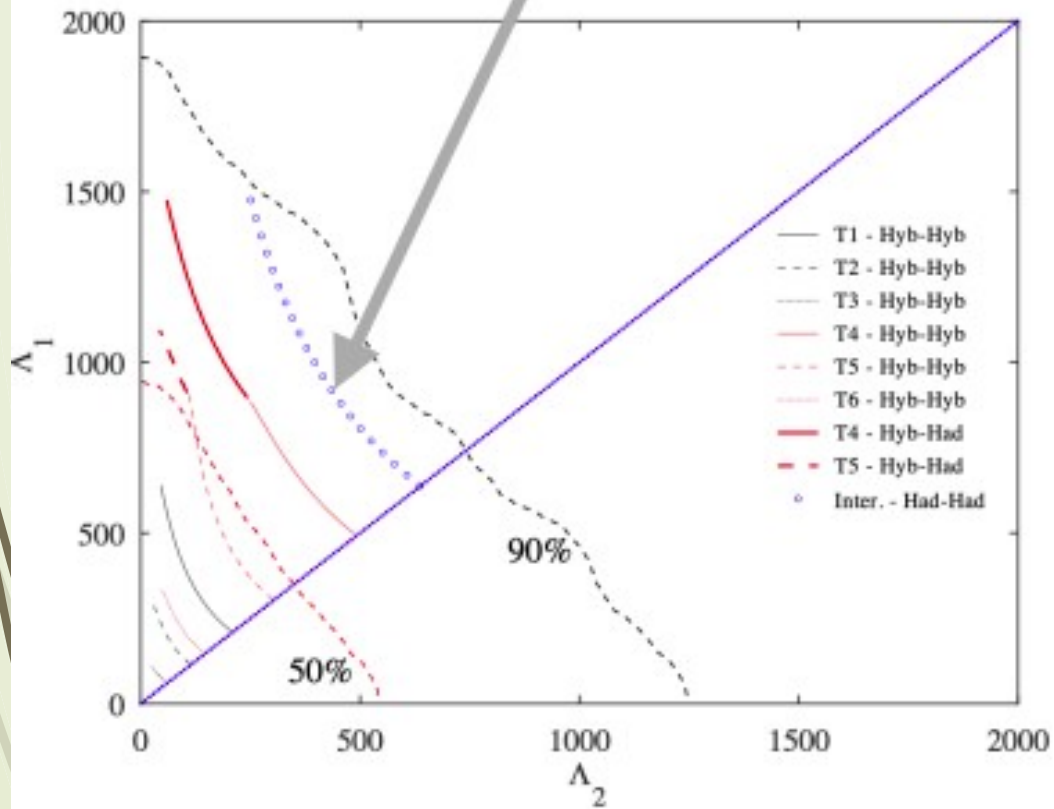


👎 Hybrid models with $M_{max} > 2M_{\odot}$ fall outside the 90% credible region of LIGO/Virgo.

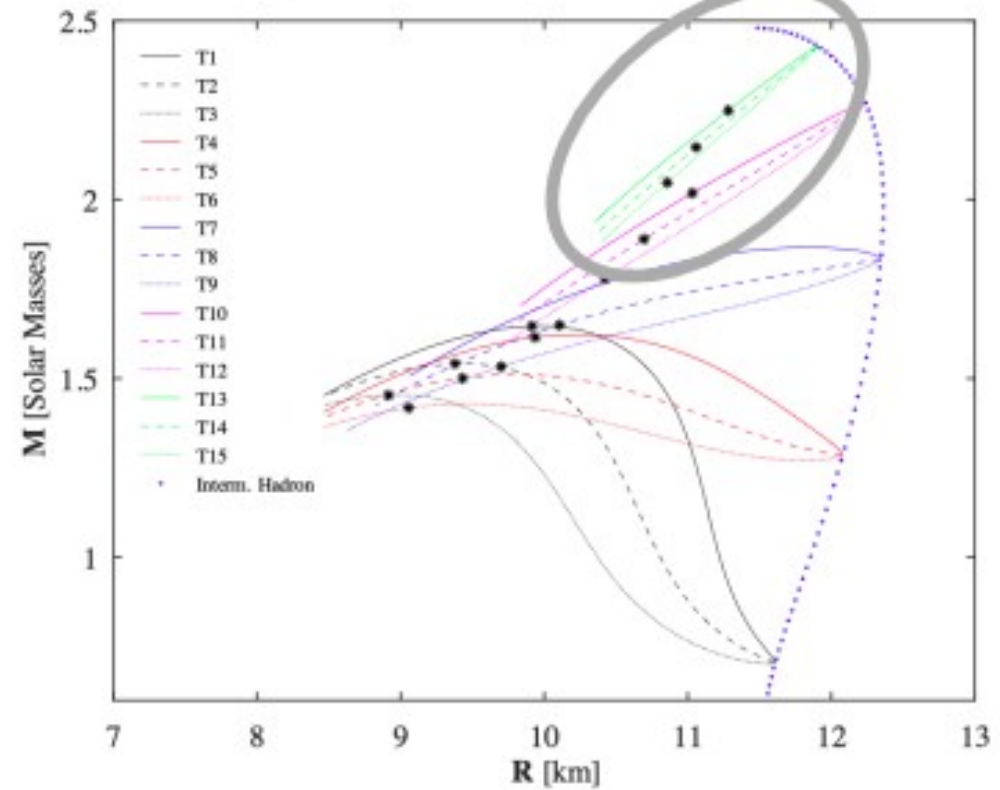


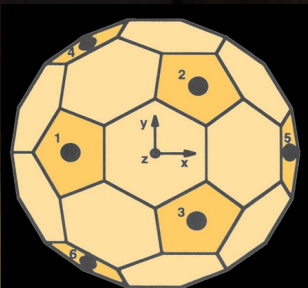
Testes com estrelas híbridas

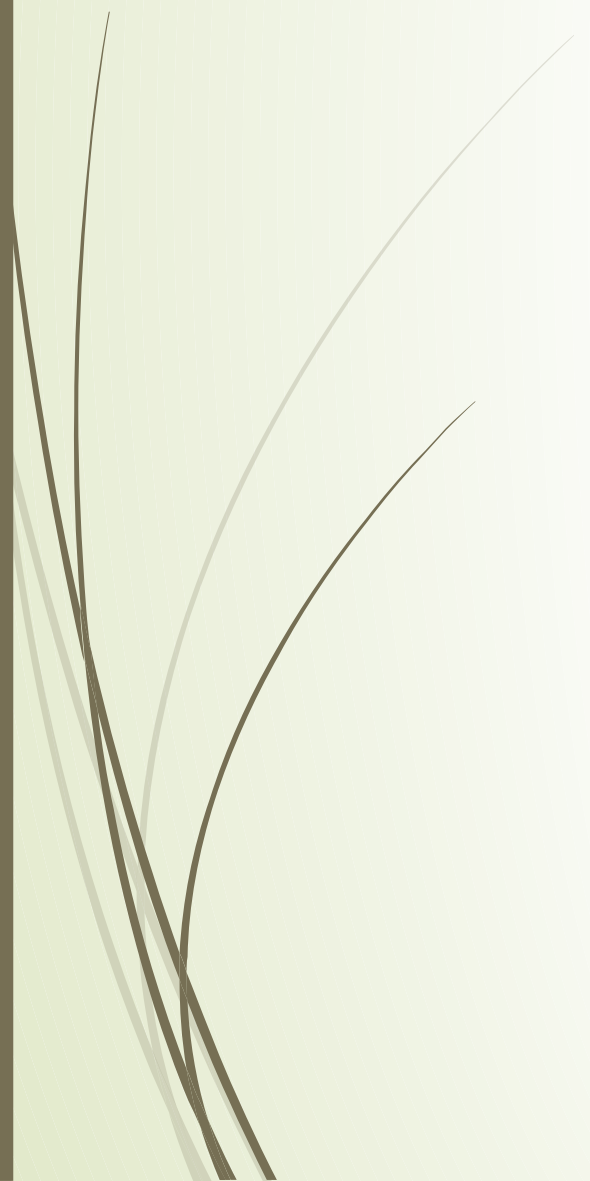
👍 Pure hadronic model **inside** the 90% credible region of LIGO/Virgo.



👍 hybrid models with $M_{max} > 2M_{\odot}$.







MUCHAS GRACIAS !

Como detectar esta classe de ondas?

$$R(t) = \frac{1}{2} h^{ij}(t) D_{ij}$$



$$D_{ij} = (\mathbf{n} \otimes \mathbf{n})_{ij} - \frac{1}{3} \delta_{ij}$$

$$\mathbf{D}^L = \begin{bmatrix} \sin^2 \theta_L \cos^2 \phi_L & \frac{1}{2} \sin^2 \theta_L \sin 2\phi_L & \frac{1}{2} \sin 2\theta_L \cos \phi_L \\ \frac{1}{2} \sin^2 \theta_L \sin 2\phi_L & \sin^2 \theta_L \sin^2 \phi_L & \frac{1}{2} \sin 2\theta_L \sin \phi_L \\ \frac{1}{2} \sin 2\theta_L \cos \phi_L & \frac{1}{2} \sin 2\theta_L \sin \phi_L & \cos^2 \theta_L \end{bmatrix}$$

Como detectar esta classe de ondas?

$$\frac{1}{2} [D_{11}^L h_{11} + 2D_{12}^L h_{12} + 2D_{13}^L h_{13} + D_{22}^L h_{22} + 2D_{23}^L h_{23} + D_{33}^L h_{33}] = R^L$$

$$\begin{bmatrix} D_{11}^1 & 2D_{12}^1 & 2D_{13}^1 & D_{22}^1 & 2D_{23}^1 & D_{33}^1 \\ D_{11}^2 & 2D_{12}^2 & 2D_{13}^2 & D_{22}^2 & 2D_{23}^2 & D_{33}^2 \\ D_{11}^3 & 2D_{12}^3 & 2D_{13}^3 & D_{22}^3 & 2D_{23}^3 & D_{33}^3 \\ D_{11}^4 & 2D_{12}^4 & 2D_{13}^4 & D_{22}^4 & 2D_{23}^4 & D_{33}^4 \\ D_{11}^5 & 2D_{12}^5 & 2D_{13}^5 & D_{22}^5 & 2D_{23}^5 & D_{33}^5 \\ D_{11}^6 & 2D_{12}^6 & 2D_{13}^6 & D_{22}^6 & 2D_{23}^6 & D_{33}^6 \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{22} \\ h_{23} \\ h_{33} \end{bmatrix} = 2 \begin{bmatrix} R^1 \\ R^2 \\ R^3 \\ R^4 \\ R^5 \\ R^6 \end{bmatrix}$$

Na falta de um transdutor

$$\begin{bmatrix} D_{11}^1 & 2D_{12}^1 & 2D_{13}^1 & D_{22}^1 & 2D_{23}^1 & D_{33}^1 \\ D_{11}^2 & 2D_{12}^2 & 2D_{13}^2 & D_{22}^2 & 2D_{23}^2 & D_{33}^2 \\ D_{11}^3 & 2D_{12}^3 & 2D_{13}^3 & D_{22}^3 & 2D_{23}^3 & D_{33}^3 \\ D_{11}^4 & 2D_{12}^4 & 2D_{13}^4 & D_{22}^4 & 2D_{23}^4 & D_{33}^4 \\ D_{11}^5 & 2D_{12}^5 & 2D_{13}^5 & D_{22}^5 & 2D_{23}^5 & D_{33}^5 \\ 1 & 0 & 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{22} \\ h_{23} \\ h_{33} \end{bmatrix} = 2 \begin{bmatrix} R^1 \\ R^2 \\ R^3 \\ R^4 \\ R^5 \\ 0 \end{bmatrix}$$

Como detectar esta classe de ondas?

$$\mathbf{h} \cdot \mathbf{e}_z = 0.$$

$$\mathbf{e}_z = \sin\beta \cos\gamma \mathbf{e}_x + \sin\beta \sin\gamma \mathbf{e}_y + \cos\beta \mathbf{e}_z$$

$$h_{11} \sin\beta \cos\gamma + h_{12} \sin\beta \sin\gamma + h_{13} \cos\gamma = 0,$$

$$h_{12} \sin\beta \cos\gamma + h_{22} \sin\beta \sin\gamma + h_{23} \cos\gamma = 0,$$

$$h_{13} \sin\beta \cos\gamma + h_{23} \sin\beta \sin\gamma + h_{33} \cos\gamma = 0.$$

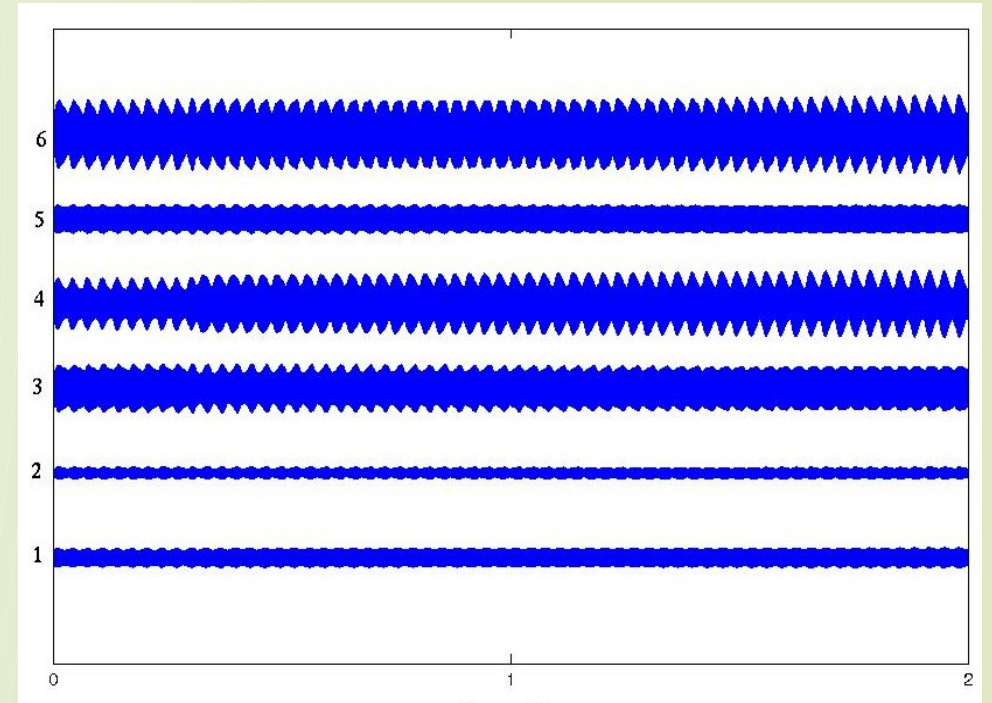
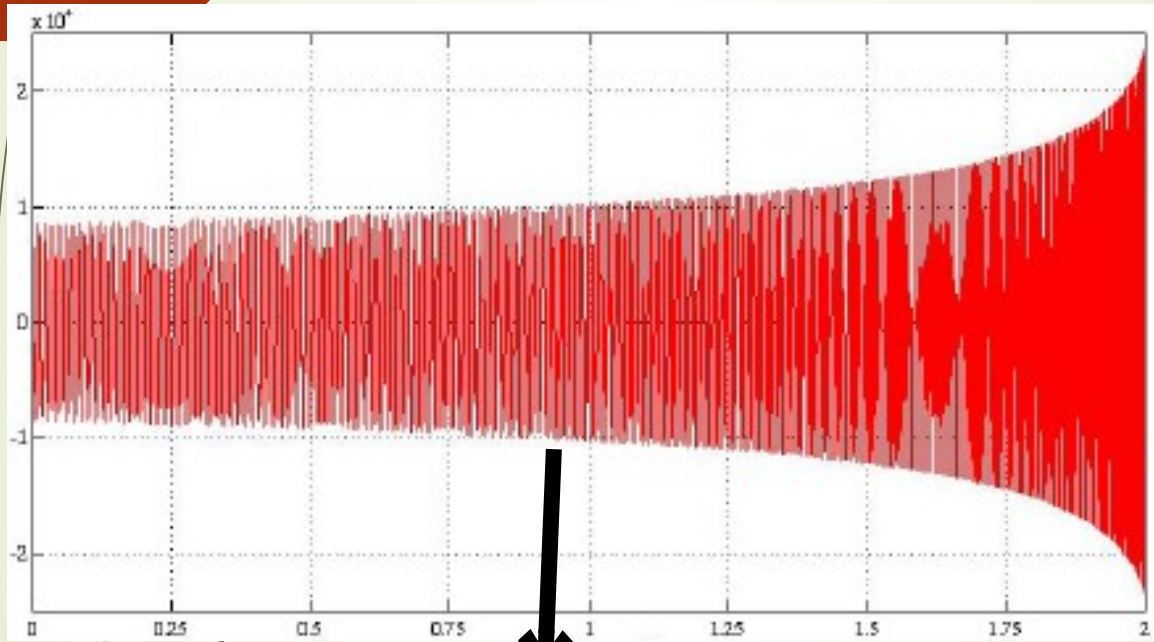
Como detectar esta classe de ondas?

$$\gamma = \frac{h_{12}h_{13} - h_{23}h_{11}}{h_{12}h_{23} - h_{13}h_{22}},$$

$$\tan \beta = \pm \frac{h_{12}h_{23} - h_{13}h_{22}}{h_{11}h_{22} - h_{12}^2} \sqrt{1 + \tan^2 \gamma}.$$

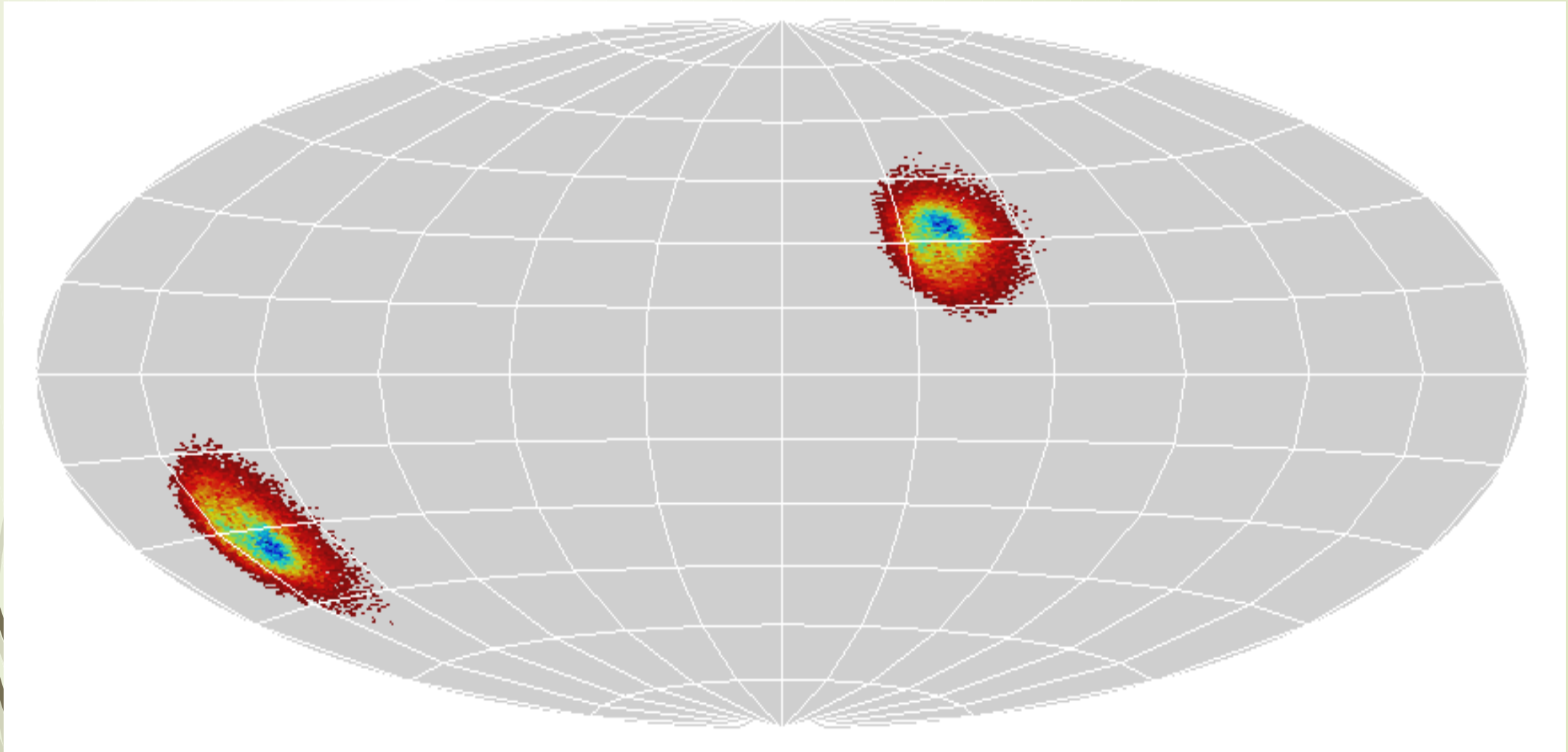
$$\begin{aligned} h_+ &= (\cos^2 \beta \cos^2 \gamma - \sin^2 \gamma)h_{11} + \sin 2\gamma(1 + \cos^2 \beta)h_{12} - \sin 2\beta \cos \gamma h_{13} + \\ &\quad (\cos^2 \beta \sin^2 \gamma - \cos^2 \gamma)h_{22} - \sin 2\beta \sin \gamma h_{23} + \sin^2 \beta h_{33}, \\ h_\times &= -\cos \beta \sin 2\gamma h_{11} + 2 \cos \beta \cos 2\gamma h_{12} + 2 \sin \beta \sin \gamma h_{13} \\ &\quad + \cos \beta \sin 2\gamma h_{22} - 2 \sin \beta \cos \gamma h_{23}. \end{aligned}$$

Como detectar esta classe de ondas?



Simulador

Como detectar esta classe de ondas?



Àqueles que consideram seus trabalhos inviáveis ou desmotivante!!!

“Pretendemos detectar uma onda que nunca foi detectada, que tenha como fonte um objeto que ninguém sabe se existe, utilizando um detector que ainda não funciona!!!”