

Buracos Negros

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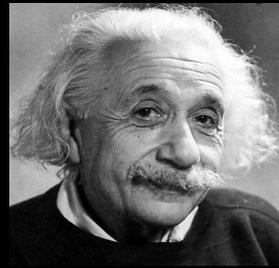


Escola Parque – Maio de 2018

O Que São Buracos Negros

- Objetos compactos
 - Soluções das Equações de Einstein
 - Remanescentes de Supernovas
-
- Pierre-Simon Laplace – *Exposition du Système du Monde* (1798)
ensaio sobre o teorema de que a força atrativa de um corpo celeste pode ser tão grande que a luz não consiga fluir para fora de si

O Que é a Teoria da Relatividade



A. Einstein
(1879-1955)

- Teoria da Relatividade Restrita
 - rompimento com a noção newtoniana de tempo
 - reconhecimento dos conceitos serem definidos apenas através de procedimentos de medida

- Teoria da Relatividade Geral
 - rompimento com a noção newtoniana de espaço
 - identificação do campo gravitacional com geometria do E-T

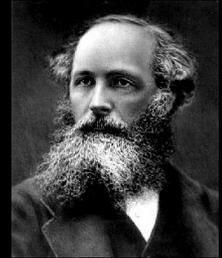
O Que é a Teoria da Relatividade

1685 - Newton "Philosophiæ naturalis principia mathematica"



Isaac Newton
(1643-1727)

1890 - Maxwell et al. desenvolvem a teoria eletromagnética



J. C. Maxwell
(1831-1879)

1905 - Einstein "zur Elektrodynamik bewegter Körper"

1911 - Einstein propõe a deflecção da luz pelo Sol

1912 – Einstein, Abraham e Nordström propõem uma teoria escalar da gravitação

1913 - Einstein se convence que gravitação deve ser descrita por geometria

1916 - Einstein "Die Grundlage der allgemeinen Relativitätstheorie"

Teoria da Relatividade Restrita

Mecânica

- Partículas pontuais
posição e velocidades
- 3 leis de Newton
- Observadores inerciais

\times

Eletrromagnetismo

- Campos físicos
campos elétricos e magnéticos
- leis de Maxwell
- Observadores inerciais

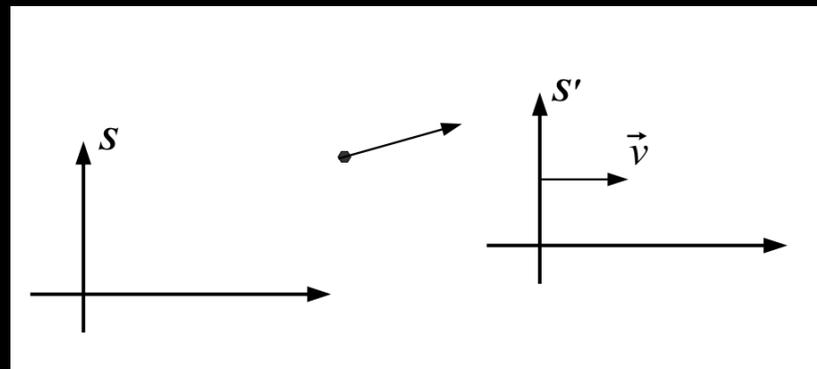
Transformações de Galileu

$$\vec{u}' = \vec{u} - \vec{v}$$

$$x' = x - v \cdot t$$

$$t' = t$$

Incompatível



$$c = \frac{1}{\sqrt{\mu\epsilon}}$$

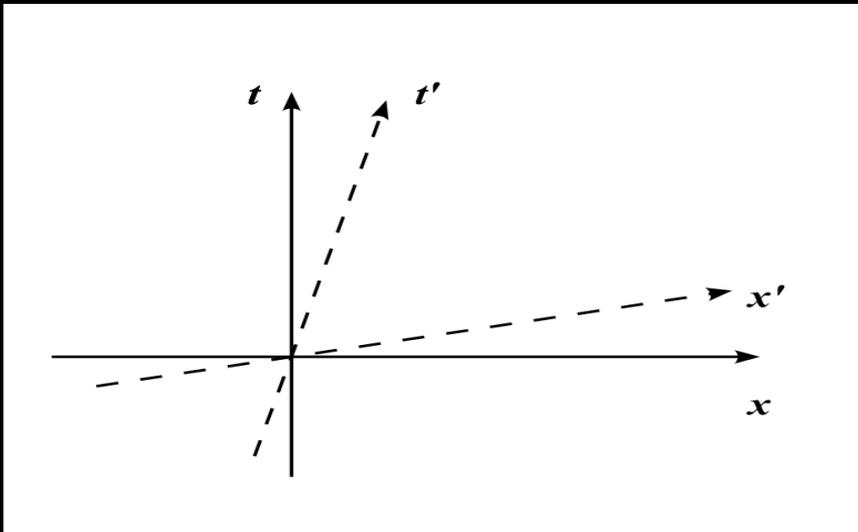
Teoria da Relatividade Restrita

- *Harmonização de Newton com Maxwell*

1- *Princípio da relatividade*
Observadores inerciais

2- *Princípio da constância da Luz*

Transformações de Lorentz



Velocidade da Luz

$$c = \frac{1}{\sqrt{\mu\varepsilon}}$$

Velocidade limite!

$$x' = \gamma(x - v \cdot t)$$

$$y' = y$$

$$z' = z$$

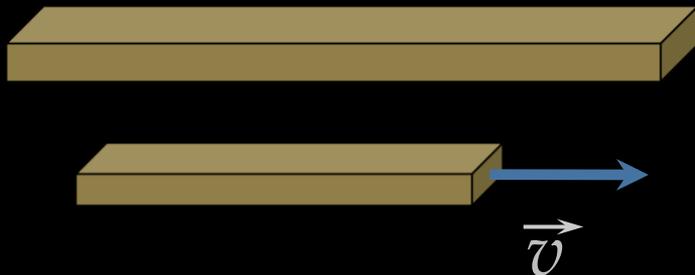
$$t' = \gamma \left(t - \frac{v \cdot x}{c^2} \right)$$

$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

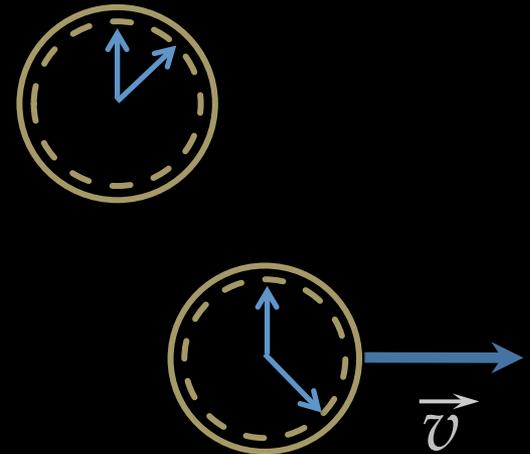
Teoria da Relatividade Restrita

Efeitos Cinemáticos

Contração de Lorentz



Dilatação Temporal



Mas... são realmente reais?

- *relógios atômicos*
- *GPS*

Pseudo-paradoxos....

- *paradoxo dos gêmeos*

Teoria da Relatividade Restrita

Mesma dinâmica

$$V^\mu = \frac{dx^\mu}{d\tau} = (\gamma c, \gamma \vec{v})$$

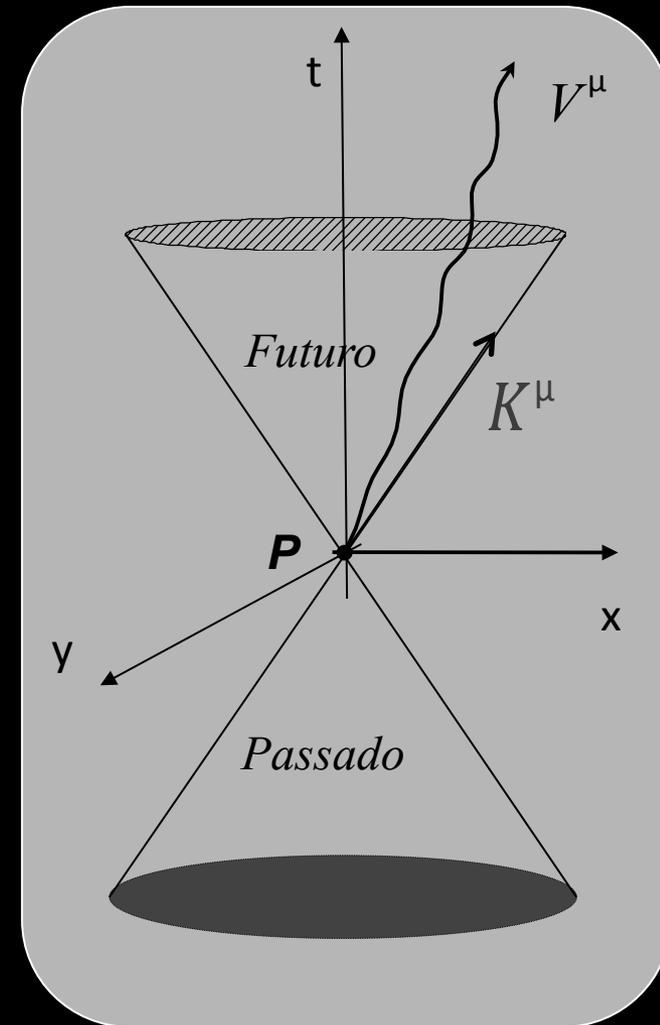
$$P^\mu = mV^\mu = \left(\frac{E}{c}, \vec{p} \right)$$

$$P^\mu P_\mu = \left(\frac{E}{c}, \vec{p} \right) \cdot \left(\frac{E}{c}, \vec{p} \right)$$

$$\Rightarrow E^2 = p^2 c^2 + m^2 c^4$$



Estrutura Causal



Se estiver parado

$$E = mc^2$$

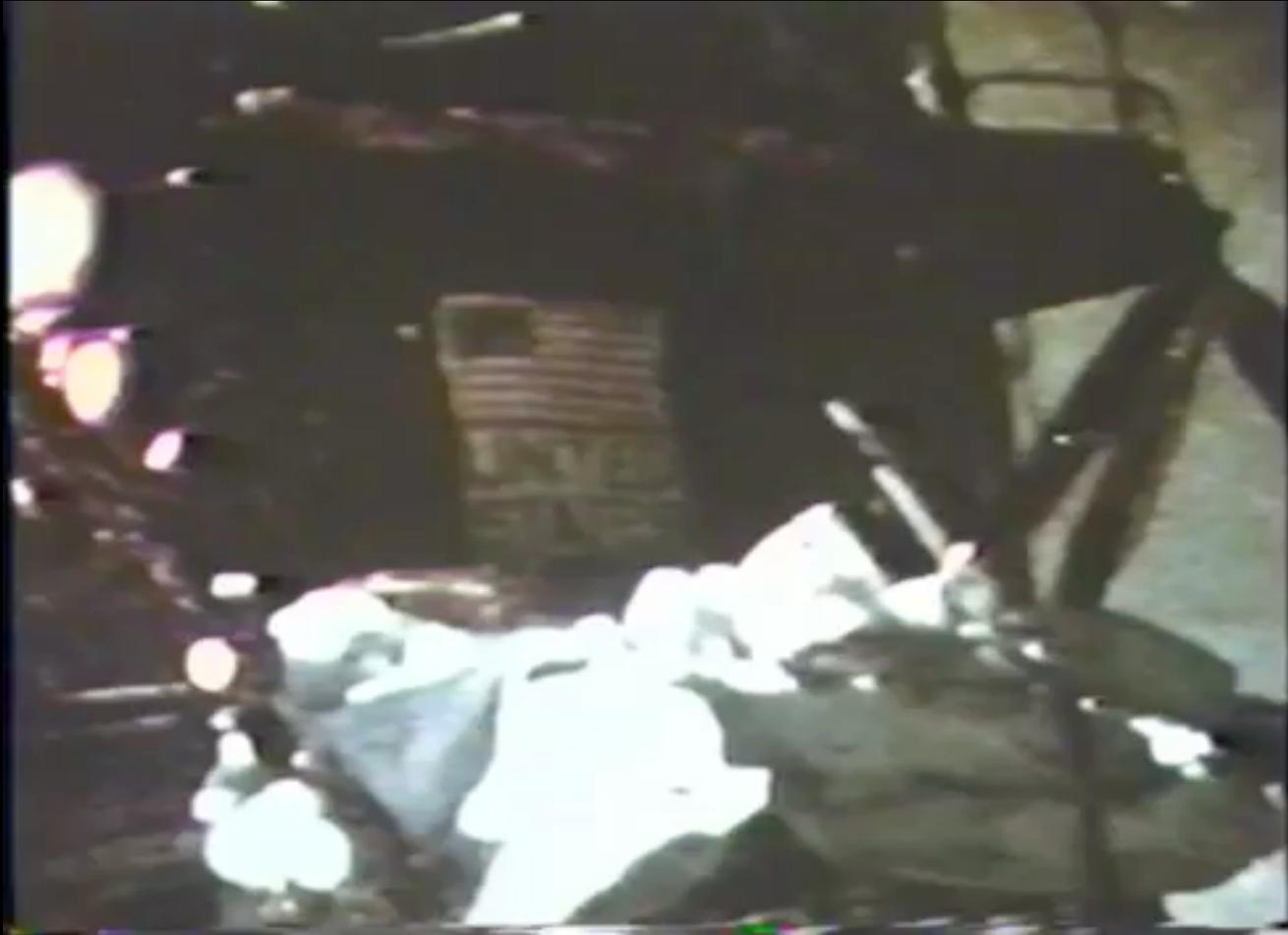
Além da Relatividade Restrita

Bases conceituais da Relatividade Geral

- *Princípio de Mach...*
e o balde de Newton
- *Princípio de equivalência...*
e o movimento dos corpos
- *Princípio de Covariância...*
a estrutura das teorias físicas (objetos absolutos?)

Além da Relatividade Restrita

Martelo e a Pena - Apollo 15 (1971)



Além da Relatividade Restrita

Gravidade não se encaixa...

- ação-a-distância

Observadores inerciais são especiais....

- não vale aceleração

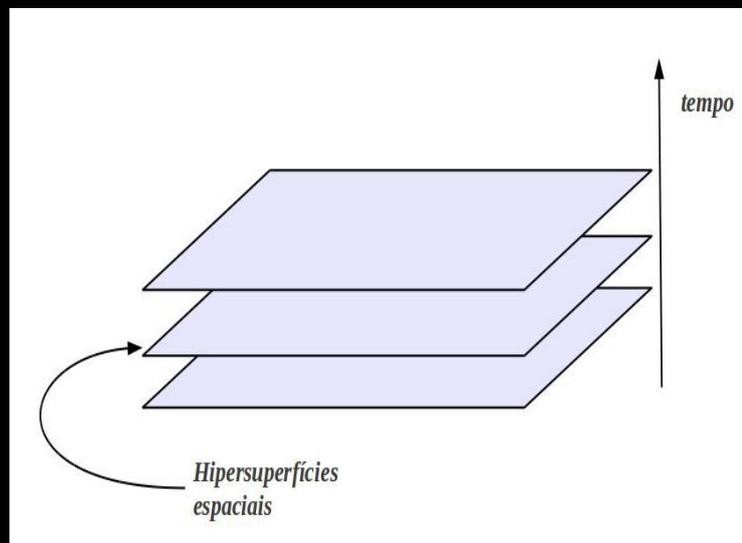
mas...

$$m_i \approx m_g$$

Gravitação é universal !



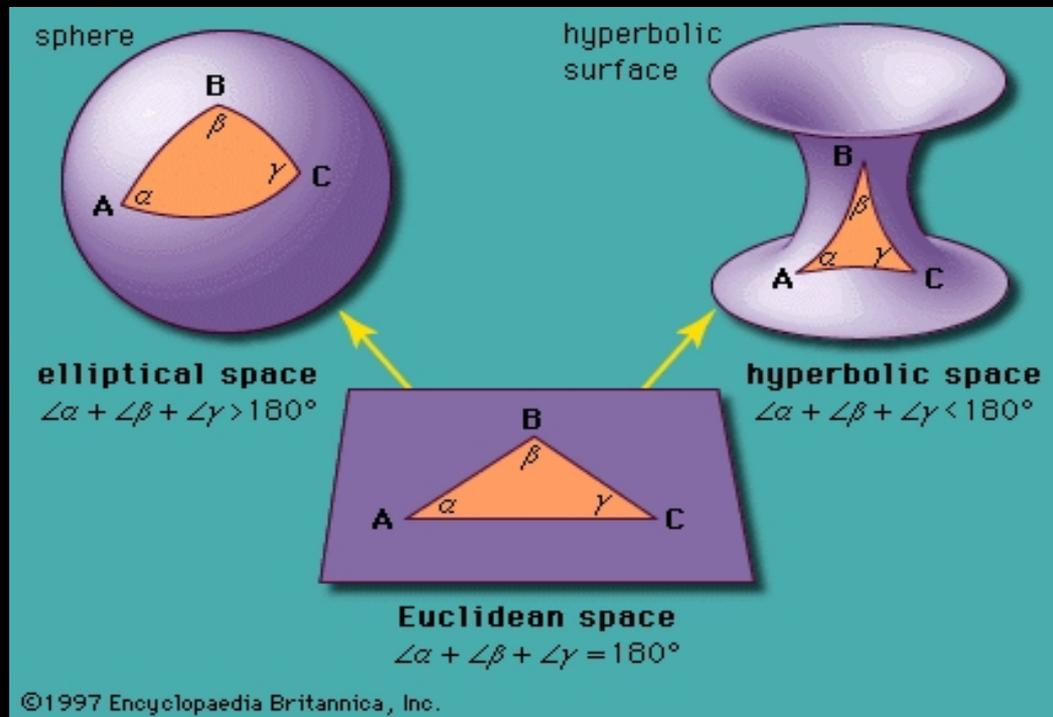
Geometria Não-euclidiana



Espaço plano

geometria convencional

menor distância são retas

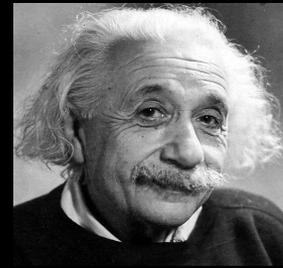


Espaços curvos

novas relações

curvas geodésicas

O Que é a Teoria da Relatividade Geral



A. Einstein
(1879-1955)

TRG é uma teoria relativística de gravitação....

não há força gravitacional ...

... a estrutura do espaço-tempo é curva

Obs: não há....

- tempo global
- conceito unívoco de distância

métrica { propriedades do E-T
determina distância e tempo
trajetórias das partículas testes

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

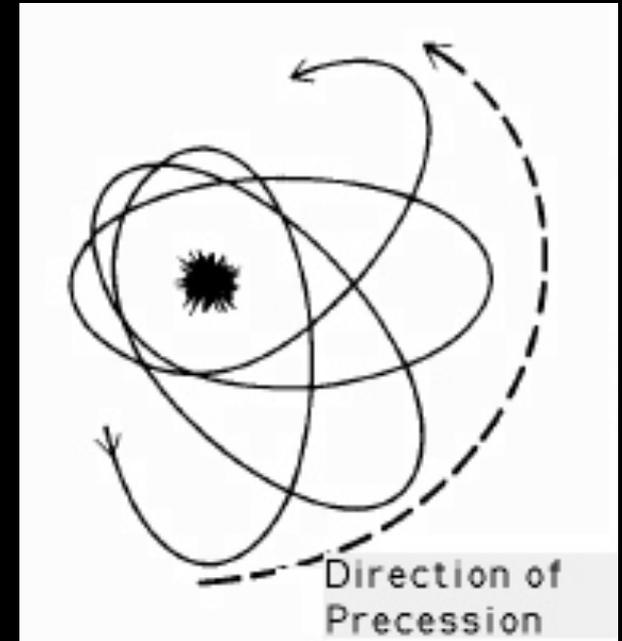
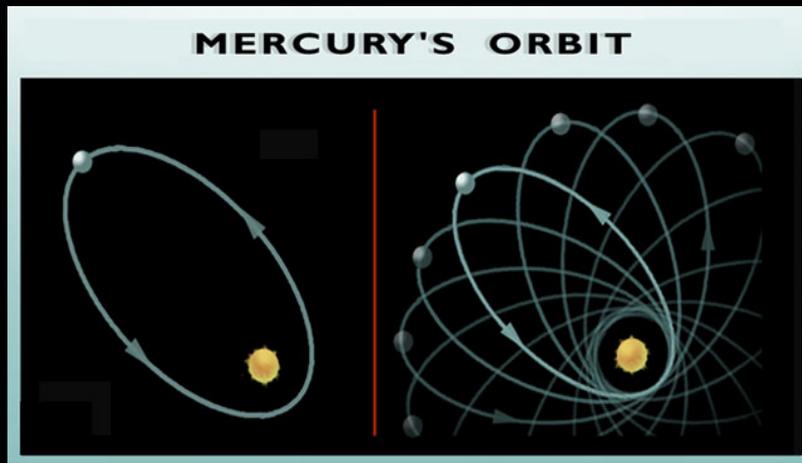
propriedades geométricas = distribuição de matéria

Comprovação RG (Avanço do Periélio)

Comprovação da Teoria

- *Precessão do perihélio de Mercúrio*

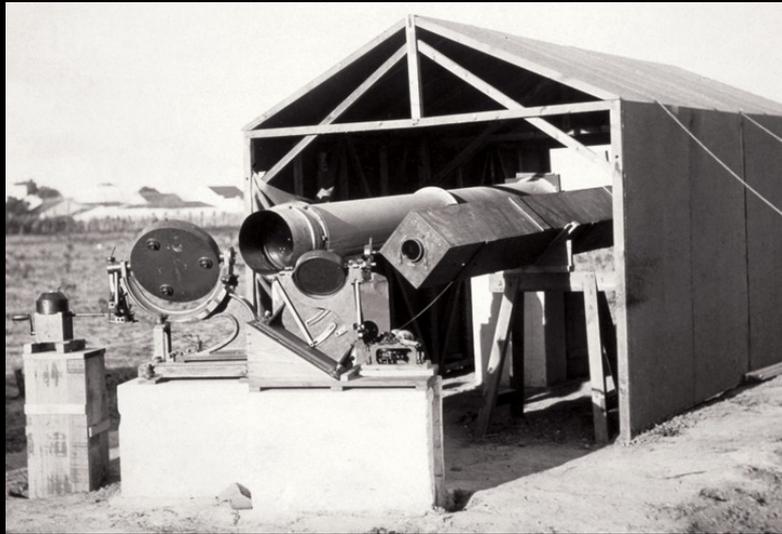
avanço do perihélio



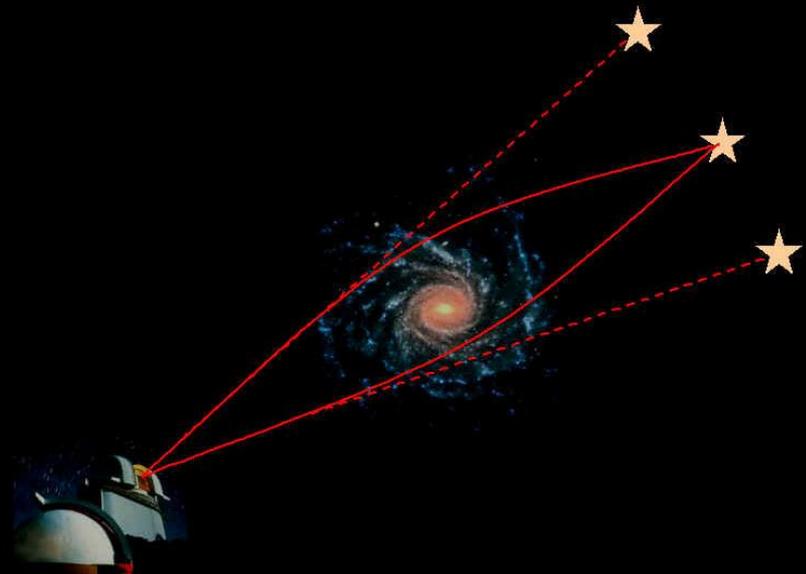
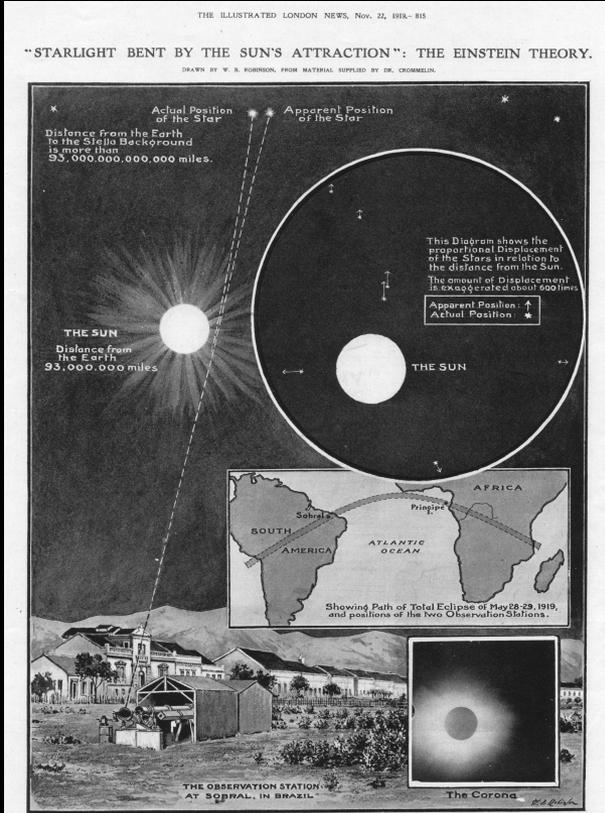
Comprovação RG (Desvio da Luz)

Comprovação da Teoria

- *Desvio da Luz ao passar pelo Sol*



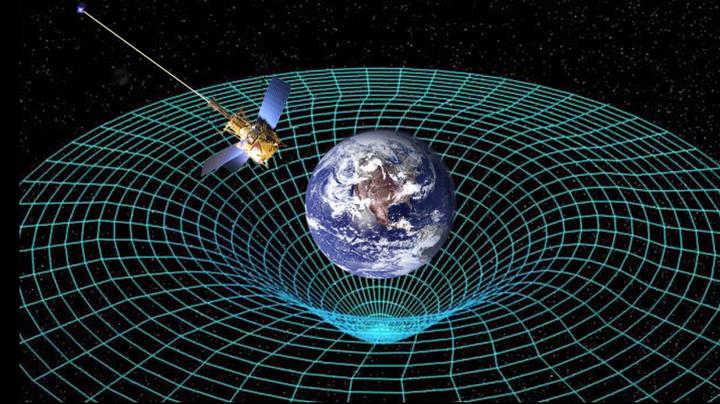
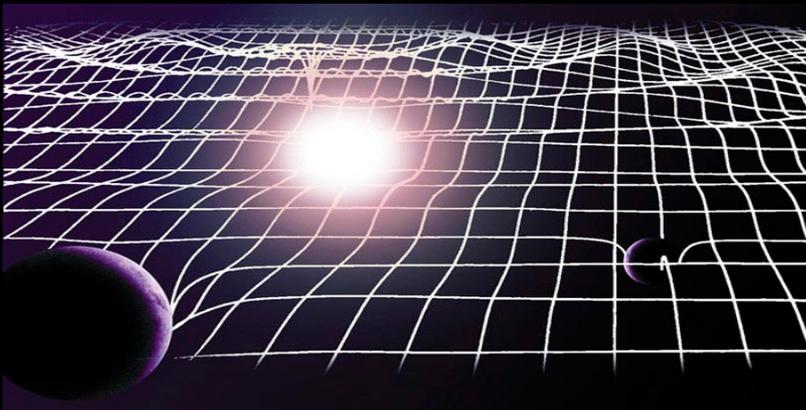
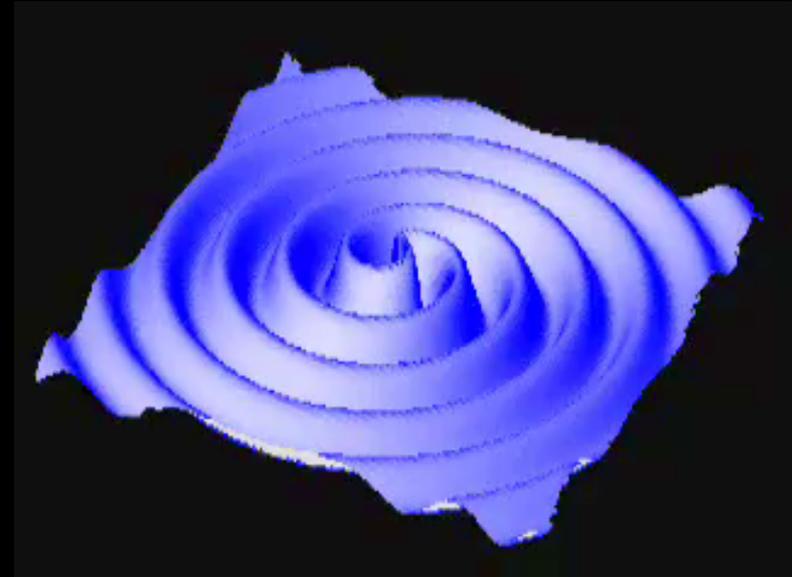
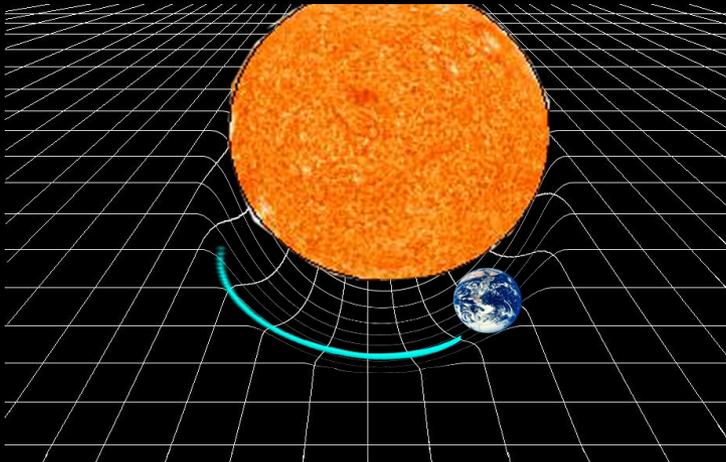
Telescópio refrator astrográfico
Eclipse Sobral 1919



Comprovação RG (Ondas Gravitacionais)

Comprovação da Teoria

- *Ondas gravitacionais...
e o pulsar binário*



Pulsar Binário

Comprovação da Teoria

- Ondas gravitacionais...
e o pulsar binário

Pulsares...

estrelas de neutrons

extremamente magnetizadas

períodos de 10^{-3} a 8.51 segundos

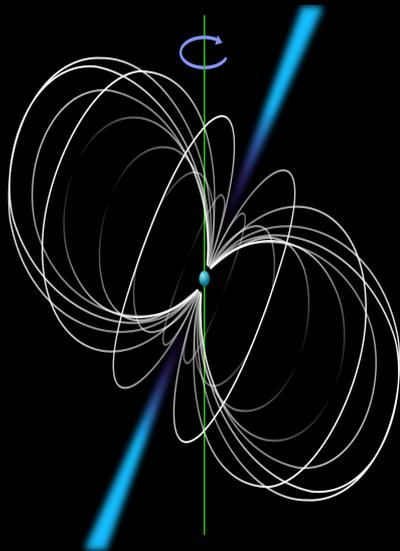
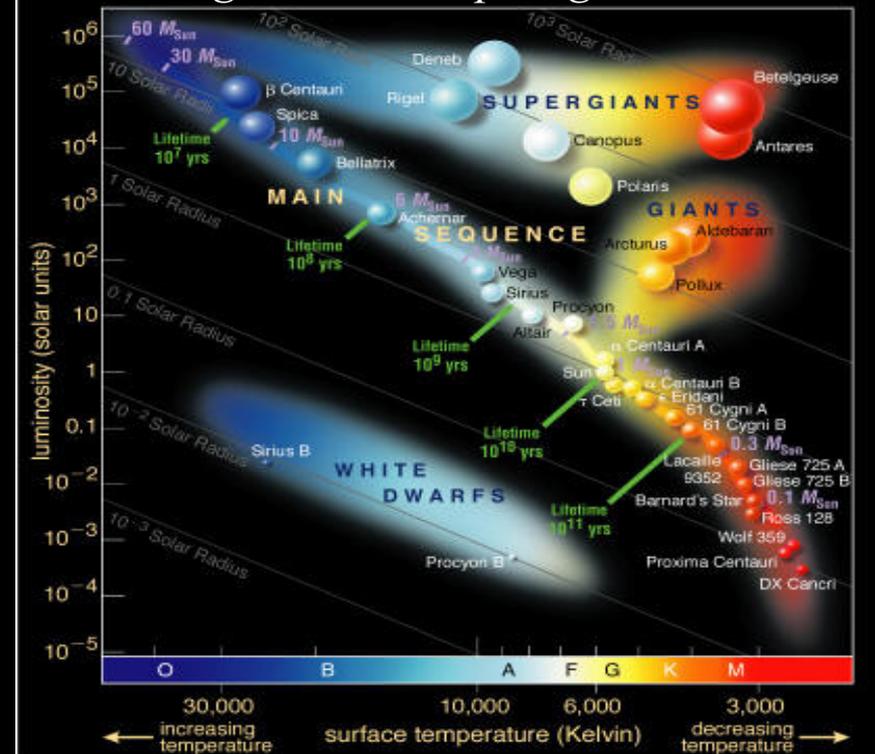


diagrama Hertzsprung-Russell



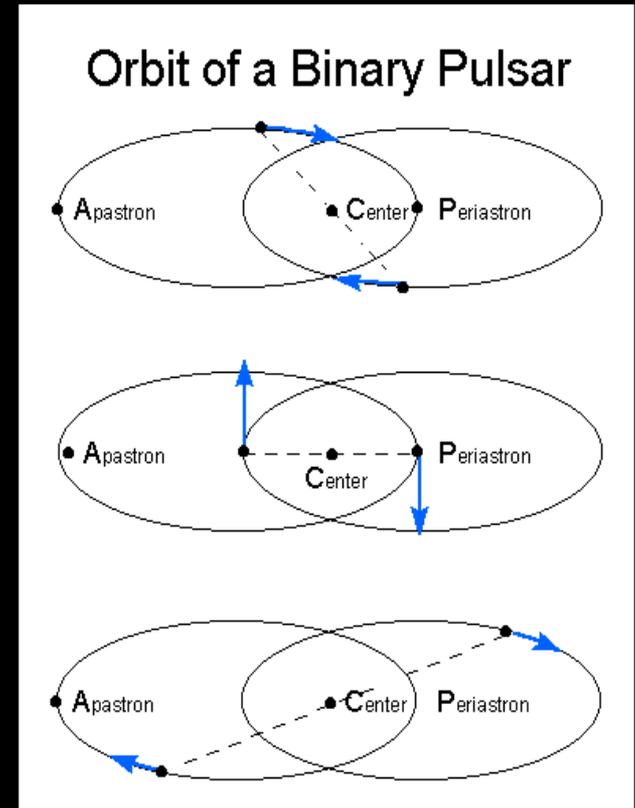
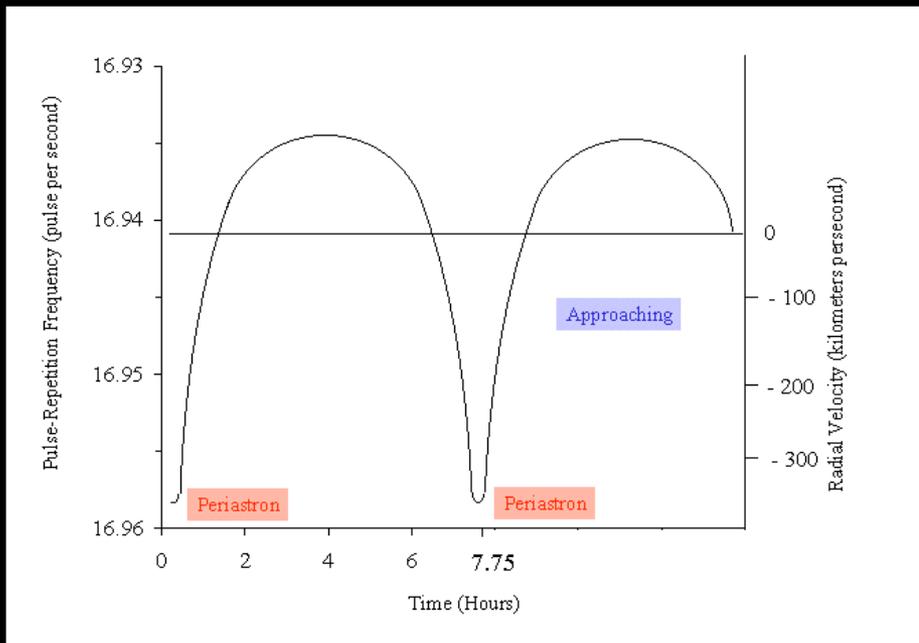
formação...

remanescentes de supernovas tipo II, Ib ou Ic

Pulsar Binário (Ondas Gravitacionais)

Pulsar Binário B1913+16
(Hulse & Taylor 1975)

1993 - prêmio Nobel em Física

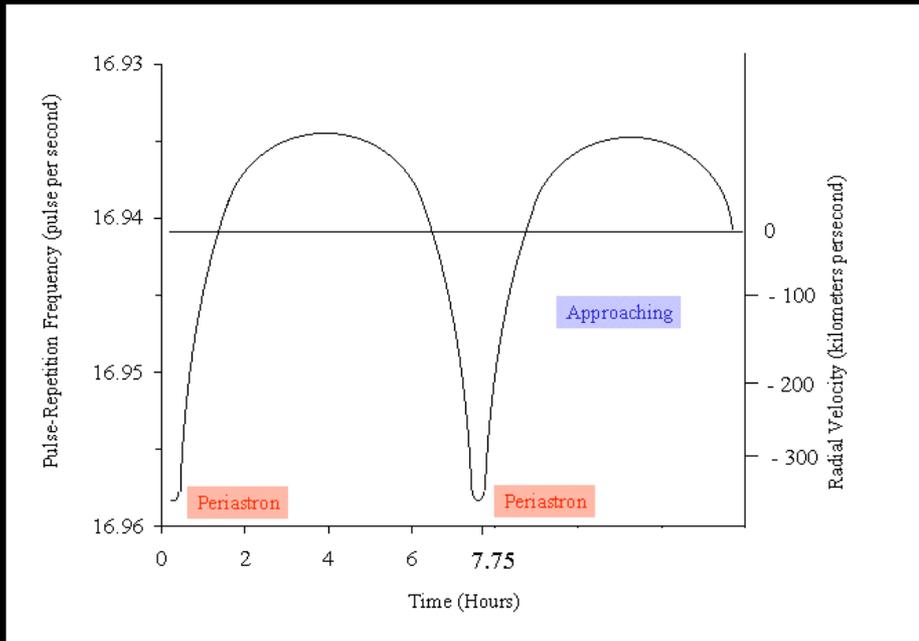


variação frequência → sistema binário

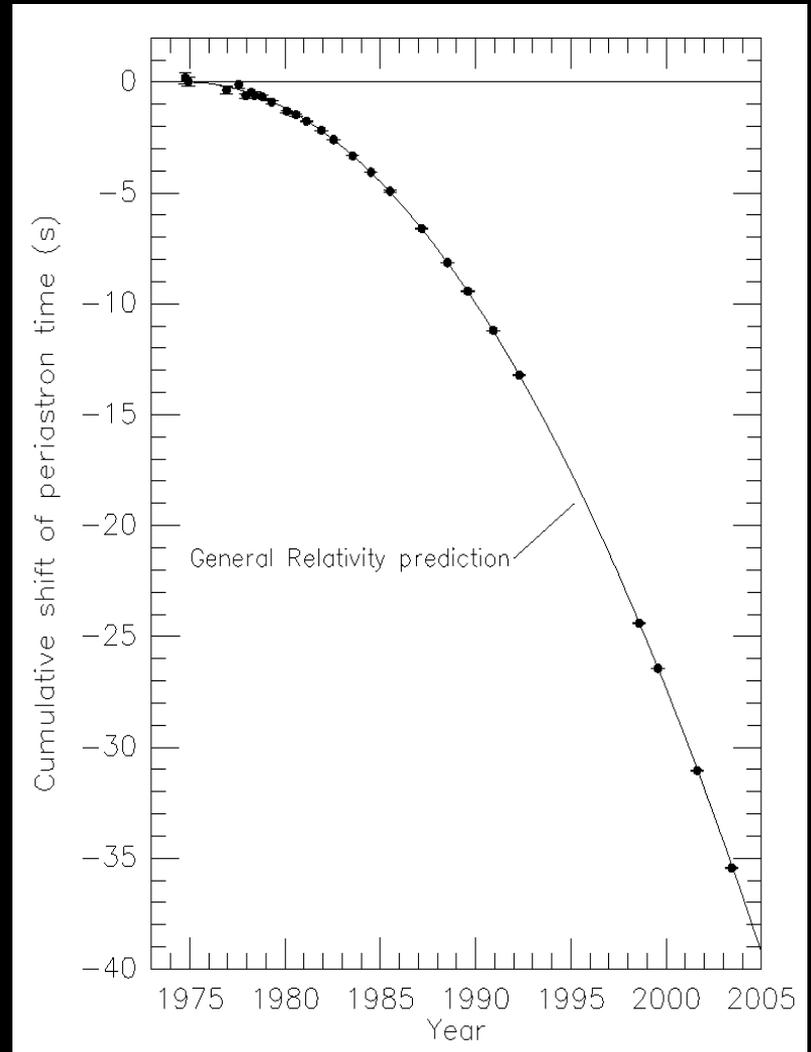
Pulsar Binário (Ondas Gravitacionais)

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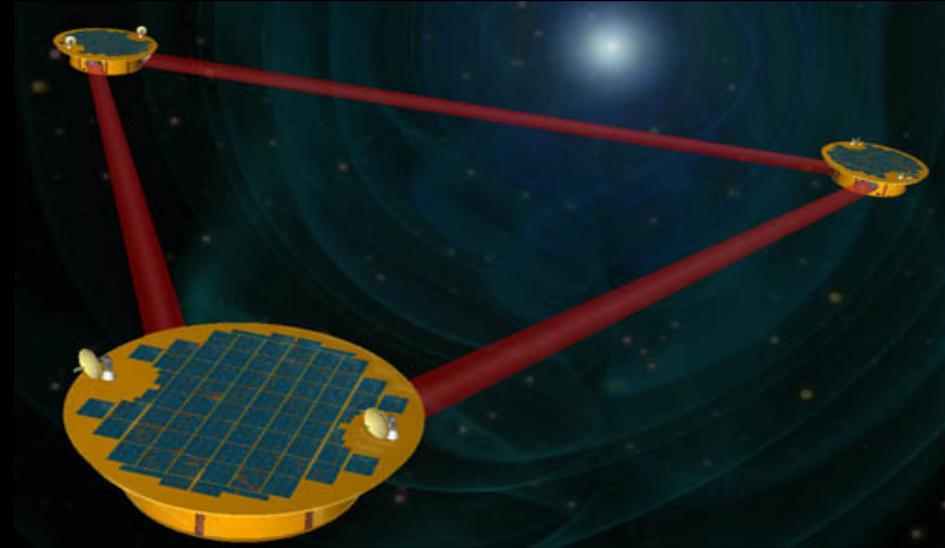
Ondas Gravitacionais

LISA

Comprovação da Teoria

- *Detectores de ondas gravitacionais....*

LIGO em Lousiana, USA



Mário Schenberg - INPE

Buracos Negros

↪ *Estágio final de uma estrela*

↪ *Possui um horizonte de eventos*

↪ *É realizado na Natureza?*

Sustentação de uma estrela...

Anã branca:

- *tamanho similar ao da Terra; massa Solar*
- *luminosidade ~ energia termal;*
- *pressão da degenerescência dos elétrons;*

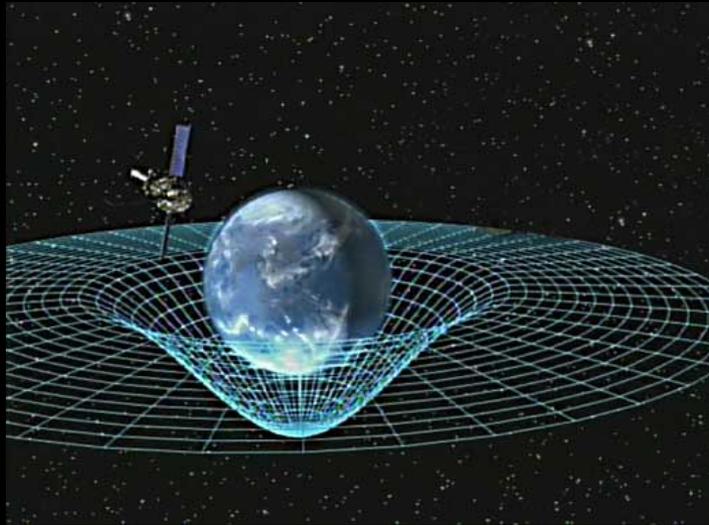
Estrela de Neutrons:

- *raios da ordem de 10 Km; massa Solar ~ 1.4 a 3*
- *emissão em raios-X*

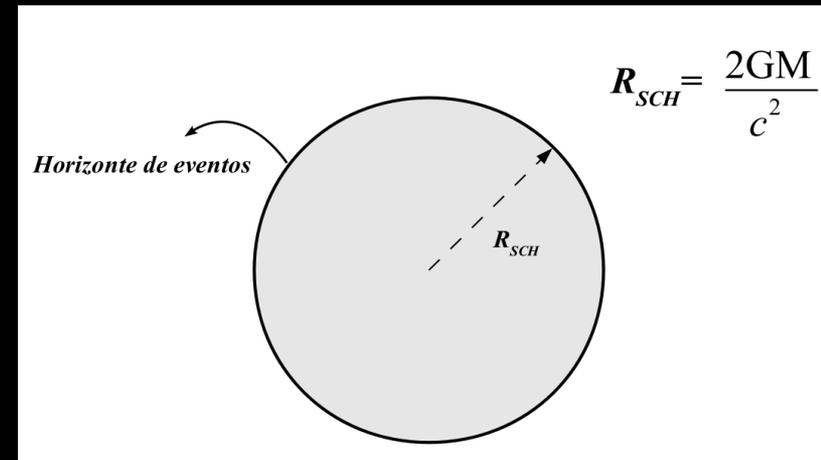
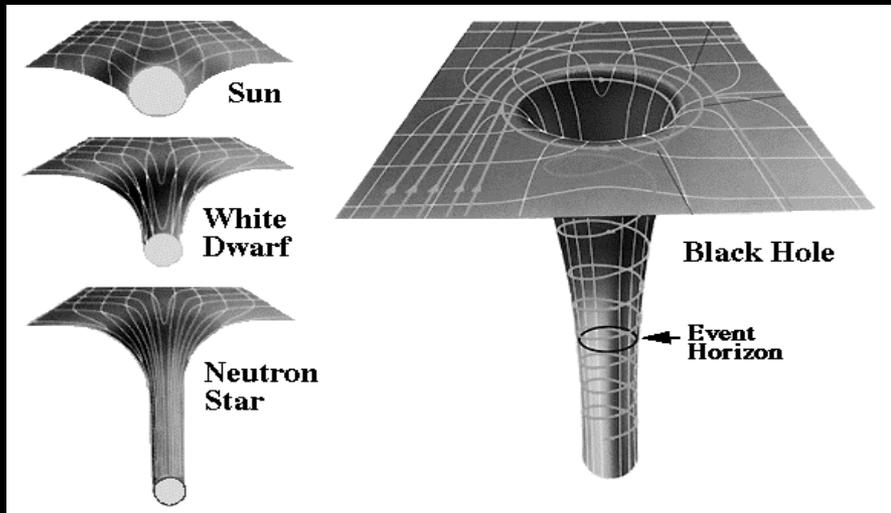
pressão da degenerescência dos neutrons;

Estrela de quarks (?)

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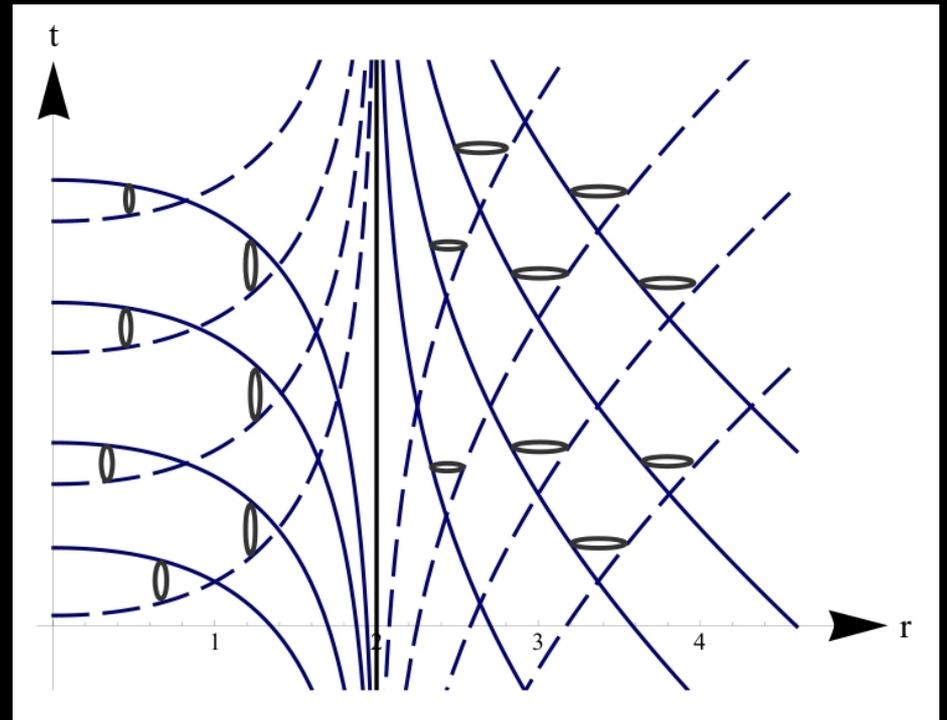
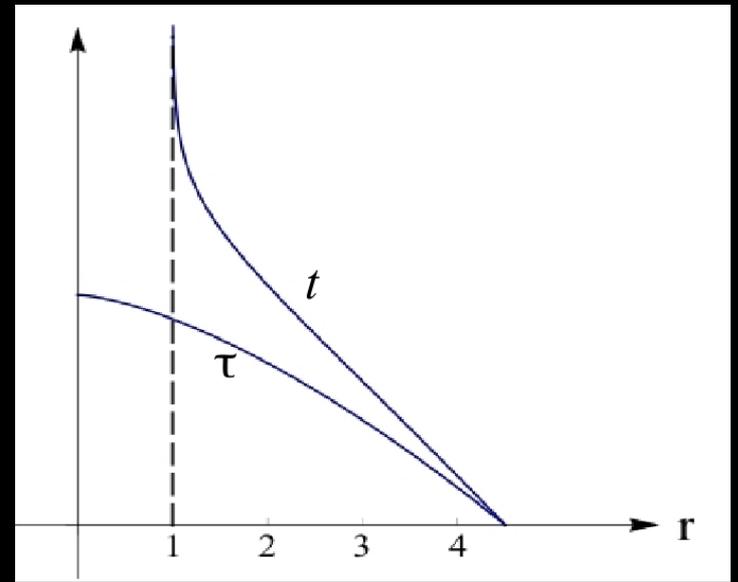
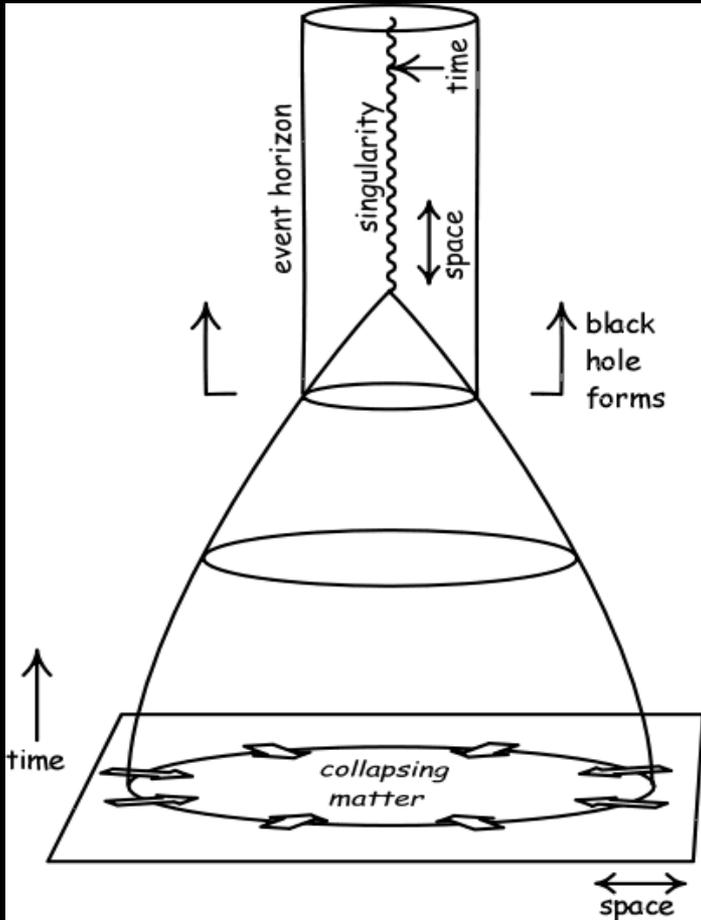


	<i>Raio de Schwarzschild</i>	<i>Raio Físico</i>
<i>Est. Neutrons</i>	<i>6 Km</i>	<i>10 Km</i>
<i>Sol</i>	<i>3 Km</i>	<i>7x10⁵ Km</i>
<i>Terra</i>	<i>9x10⁻⁶ Km</i>	<i>6x10³ Km</i>



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Horizonte de eventos



Buracos Negros (Ondas Gravitacionais)

Detecção do Ligo – GW150914

Phys. Rev. Lett. 116 (2016)

PRL 116, 061102 (2016)

PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

properties of space-time in the strong-field, high-velocity regime and confirm predictions of general relativity for the nonlinear dynamics of highly disturbed black holes.

II. OBSERVATION

On September 14, 2015 at 09:50:45 UTC, the LIGO Hanford, WA, and Livingston, LA, observatories detected

the coincident signal GW150914 shown in Fig. 1. The initial detection was made by low-latency searches for generic gravitational-wave transients [41] and was reported within three minutes of data acquisition [43]. Subsequently, matched-filter analyses that use relativistic models of compact binary waveforms [44] recovered GW150914 as the most significant event from each detector for the observations reported here. Occurring within the 10-ms intersite

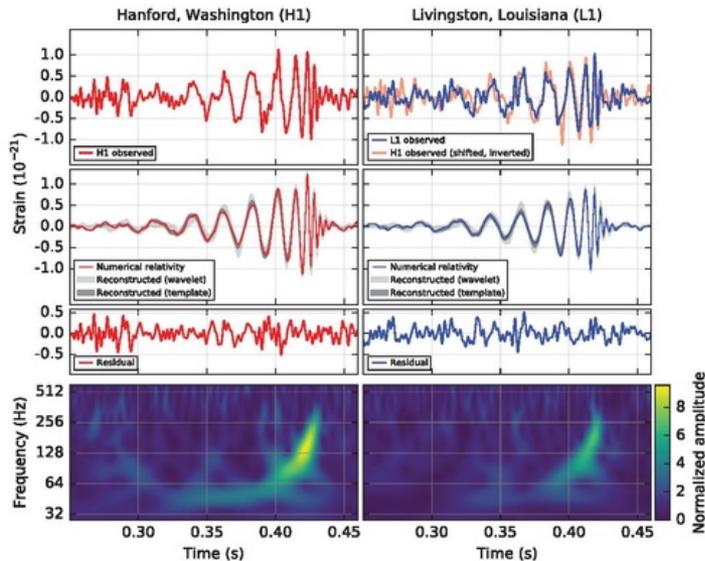


FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors’ most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines seen in the Fig. 3 spectra. *Top row, left:* H1 strain. *Top row, right:* L1 strain. GW150914 arrived first at L1 and 6.9 $^{+0.5}_{-0.2}$ ms later at H1; for a visual comparison, the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors’ relative orientations). *Second row:* Gravitational-wave strain projected onto each detector in the 35–350 Hz band. Solid lines show a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914 [37,38] confirmed to 99.9% by an independent calculation based on [15]. Shaded areas show 90% credible regions for two independent waveform reconstructions. One (dark gray) models the signal using binary black hole template waveforms [39]. The other (light gray) does not use an astrophysical model, but instead calculates the strain signal as a linear combination of sine-Gaussian wavelets [40,41]. These reconstructions have a 94% overlap, as shown in [39]. *Third row:* Residuals after subtracting the filtered numerical relativity waveform from the filtered detector time series. *Bottom row:* A time-frequency representation [42] of the strain data, showing the signal frequency increasing over time.

PRL 116, 061102 (2016)

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propagation time, the events have a combined signal-to-noise ratio (SNR) of 24 [45].

Only the LIGO detectors were observing at the time of GW150914. The Virgo detector was being upgraded, and GEO 600, though not sufficiently sensitive to detect this event, was operating but not in observational mode. With only two detectors the source position is primarily determined by the relative arrival time and localized to an area of approximately 600 deg² (90% credible region) [39,46].

The basic features of GW150914 point to it being produced by the coalescence of two black holes—i.e., their orbital inspiral and merger, and subsequent final black hole ringdown. Over 0.2 s, the signal increases in frequency and amplitude in about 8 cycles from 35 to 150 Hz, where the amplitude reaches a maximum. The most plausible explanation for this evolution is the inspiral of two orbiting masses, m_1 and m_2 , due to gravitational-wave emission. At the lower frequencies, such evolution is characterized by the chirp mass [11]

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G} \left[\frac{5}{96} \pi^{-8/3} f^{-11/3} \dot{f} \right]^{3/5},$$

where f and \dot{f} are the observed frequency and its time derivative and G and c are the gravitational constant and speed of light. Estimating f and \dot{f} from the data in Fig. 1, we obtain a chirp mass of $\mathcal{M} = 30M_\odot$, implying that the total mass $M = m_1 + m_2$ is $\geq 70M_\odot$ in the detector frame. This bounds the sum of the Schwarzschild radii of the binary components to $2GM/c^2 \geq 210$ km. To reach an orbital frequency of 75 Hz (half the gravitational-wave frequency) the objects must have been very close and very compact; equal Newtonian point masses orbiting at this frequency would be only ≈ 350 km apart. A pair of neutron stars, while compact, would not have the required mass, while a black hole neutron star binary with the deduced chirp mass would have a very large total mass, and would thus merge at much lower frequency. This leaves black holes as the only known objects compact enough to reach an orbital frequency of 75 Hz without contact. Furthermore, the decay of the waveform after it peaks is consistent with the damped oscillations of a black hole relaxing to a final stationary Kerr configuration. Below, we present a general-relativistic analysis of GW150914; Fig. 2 shows the calculated waveform using the resulting source parameters.

III. DETECTORS

Gravitational-wave astronomy exploits multiple, widely separated detectors to distinguish gravitational waves from local instrumental and environmental noise, to provide source sky localization, and to measure wave polarizations. The LIGO sites each operate a single Advanced LIGO

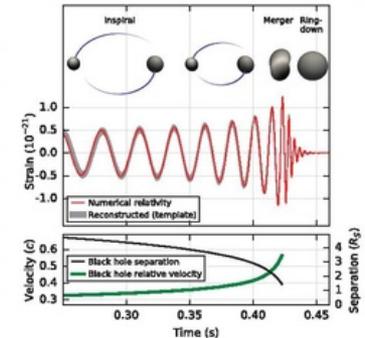


FIG. 2. *Top:* Estimated gravitational-wave strain amplitude from GW150914 projected onto H1. This shows the full bandwidth of the waveforms, without the filtering used for Fig. 1. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce. *Bottom:* The Keplerian effective black hole separation in units of Schwarzschild radii ($R_s = 2GM/c^2$) and the effective relative velocity given by the post-Newtonian parameter $v/c = (GM\pi f/c^3)^{1/3}$, where f is the gravitational-wave frequency calculated with numerical relativity and M is the total mass (value from Table I).

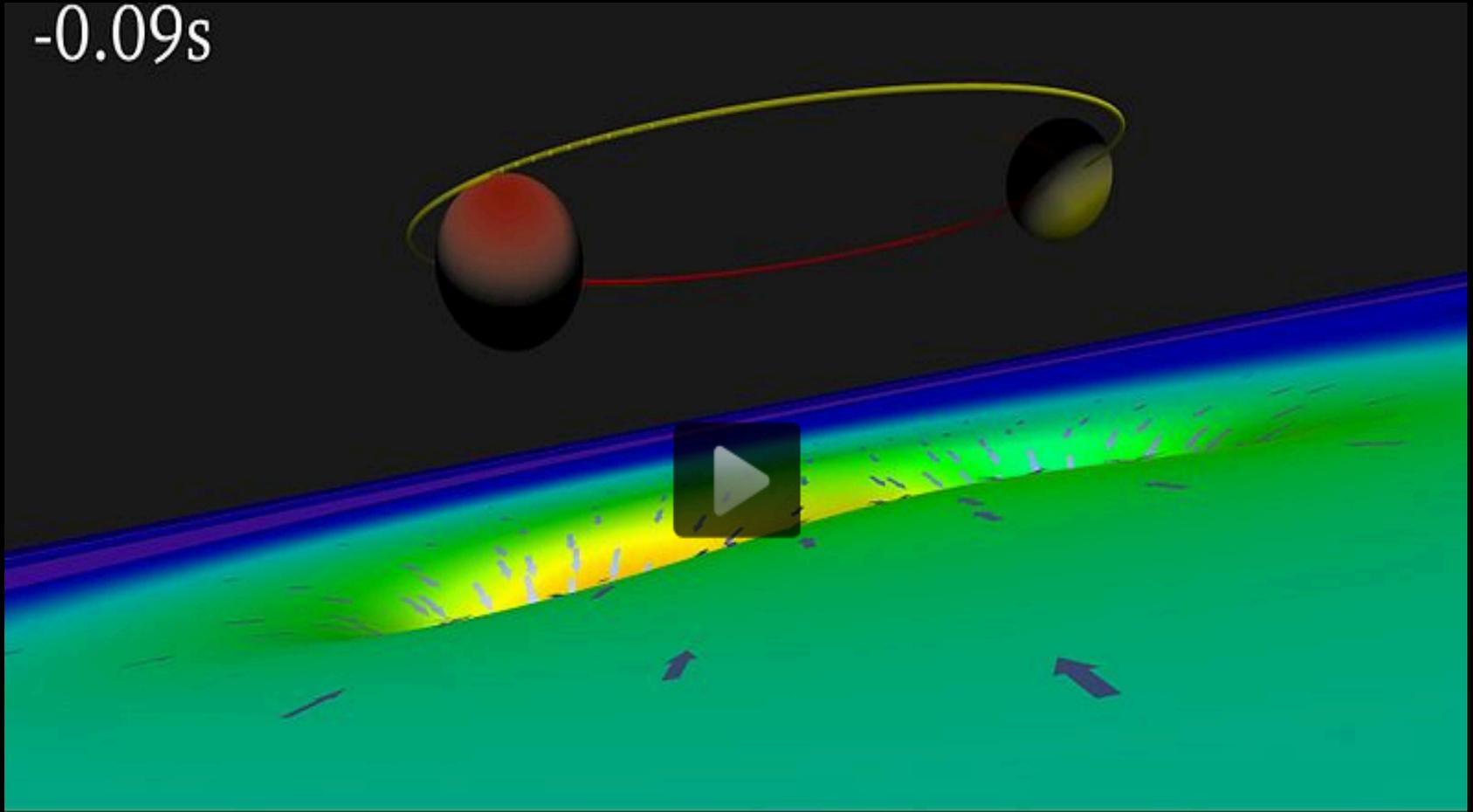
detector [33], a modified Michelson interferometer (see Fig. 3) that measures gravitational-wave strain as a difference in length of its orthogonal arms. Each arm is formed by two mirrors, acting as test masses, separated by $L_x = L_y = L = 4$ km. A passing gravitational wave effectively alters the arm lengths such that the measured difference is $\Delta L(t) = \delta L_x - \delta L_y = h(t)L$, where h is the gravitational-wave strain amplitude projected onto the detector. This differential length variation alters the phase difference between the two light fields returning to the beam splitter, transmitting an optical signal proportional to the gravitational-wave strain to the output photodetector.

To achieve sufficient sensitivity to measure gravitational waves, the detectors include several enhancements to the basic Michelson interferometer. First, each arm contains a resonant optical cavity, formed by its two test mass mirrors, that multiplies the effect of a gravitational wave on the light phase by a factor of 300 [48]. Second, a partially transmissive power-recycling mirror at the input provides additional resonant buildup of the laser light in the interferometer as a whole [49,50]: 20 W of laser input is increased to 700 W incident on the beam splitter, which is further increased to 100 kW circulating in each arm cavity. Third, a partially transmissive signal-recycling mirror at the output optimizes

Buracos Negros (Ondas Gravitacionais)

Detecção do Ligo

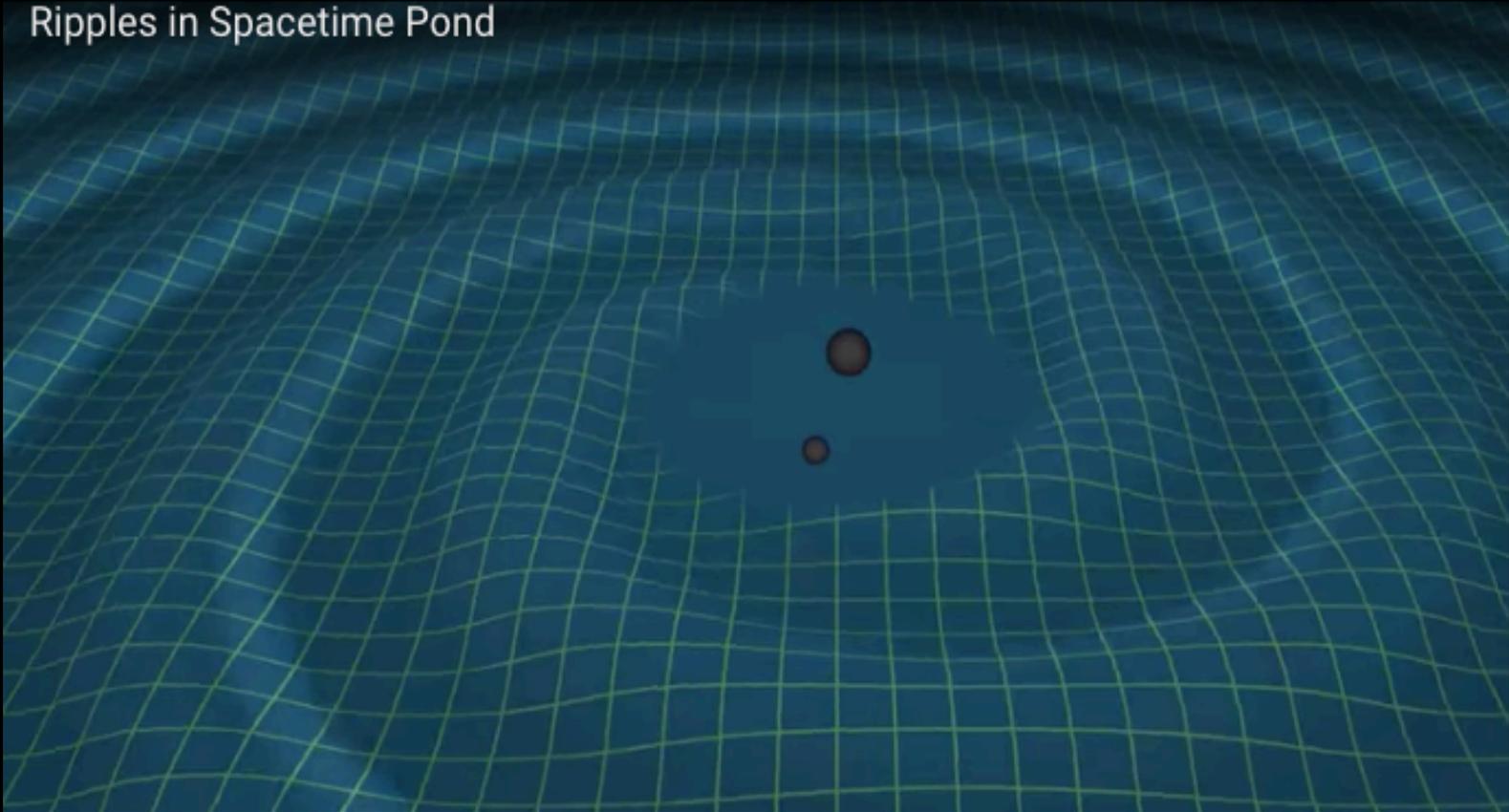
-0.09s



Buracos Negros (Ondas Gravitacionais)

Detecção do Ligo

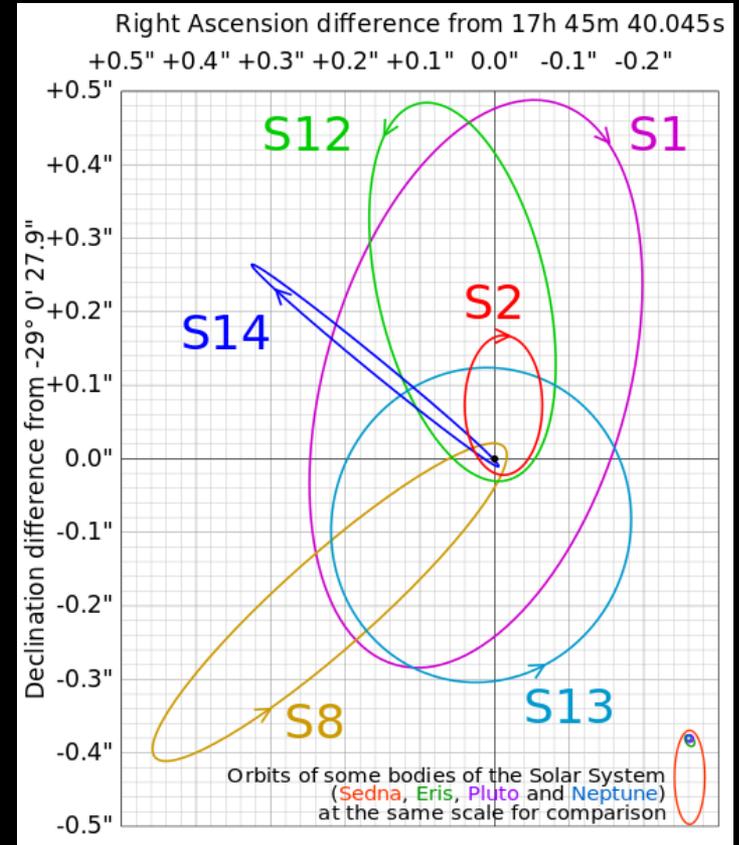
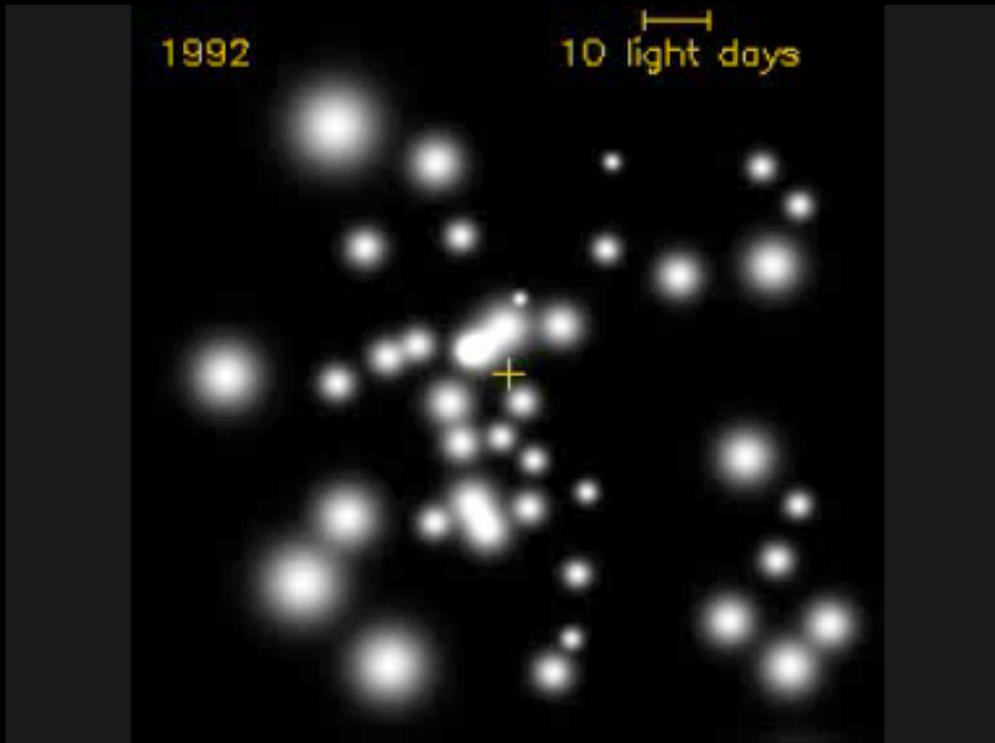
Ripples in Spacetime Pond



Buracos Negros

Centro da Via Láctea

BN supermassivo a 26.000 anos-luz
na região Sagittarius A*

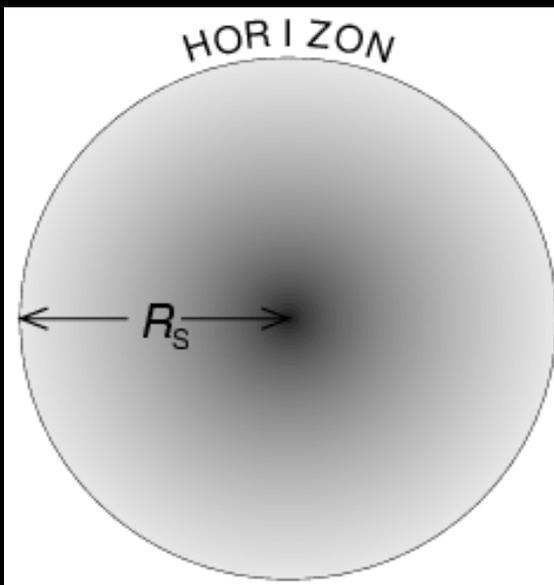


Órbita inferida de 6 estrelas
em torno do centro da Via Láctea

Buracos Negros

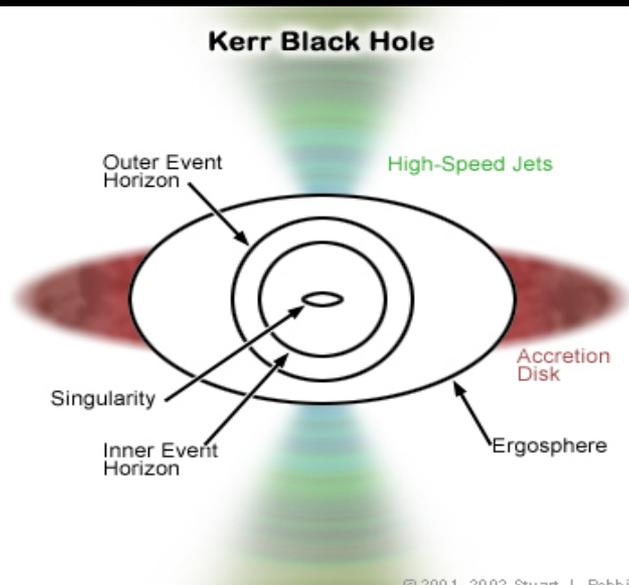
Tipos de Buracos negros

Schwarzschild



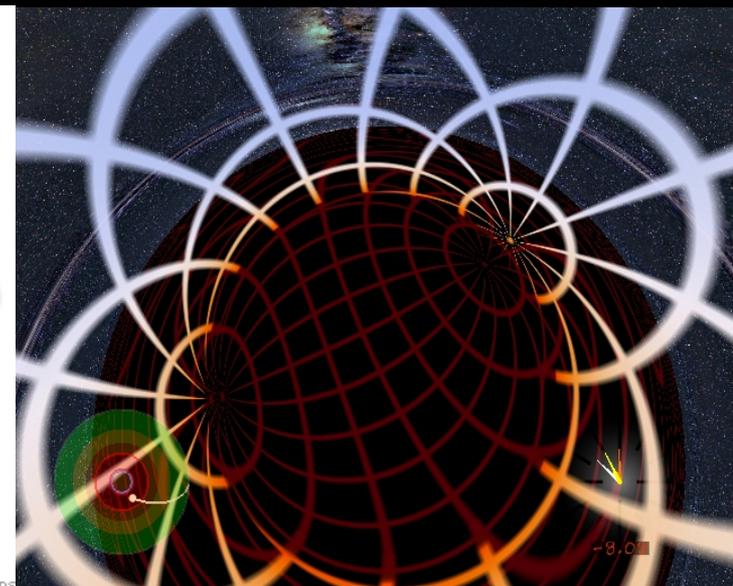
\mathcal{M}

Kerr



\mathcal{M}, \mathcal{J}

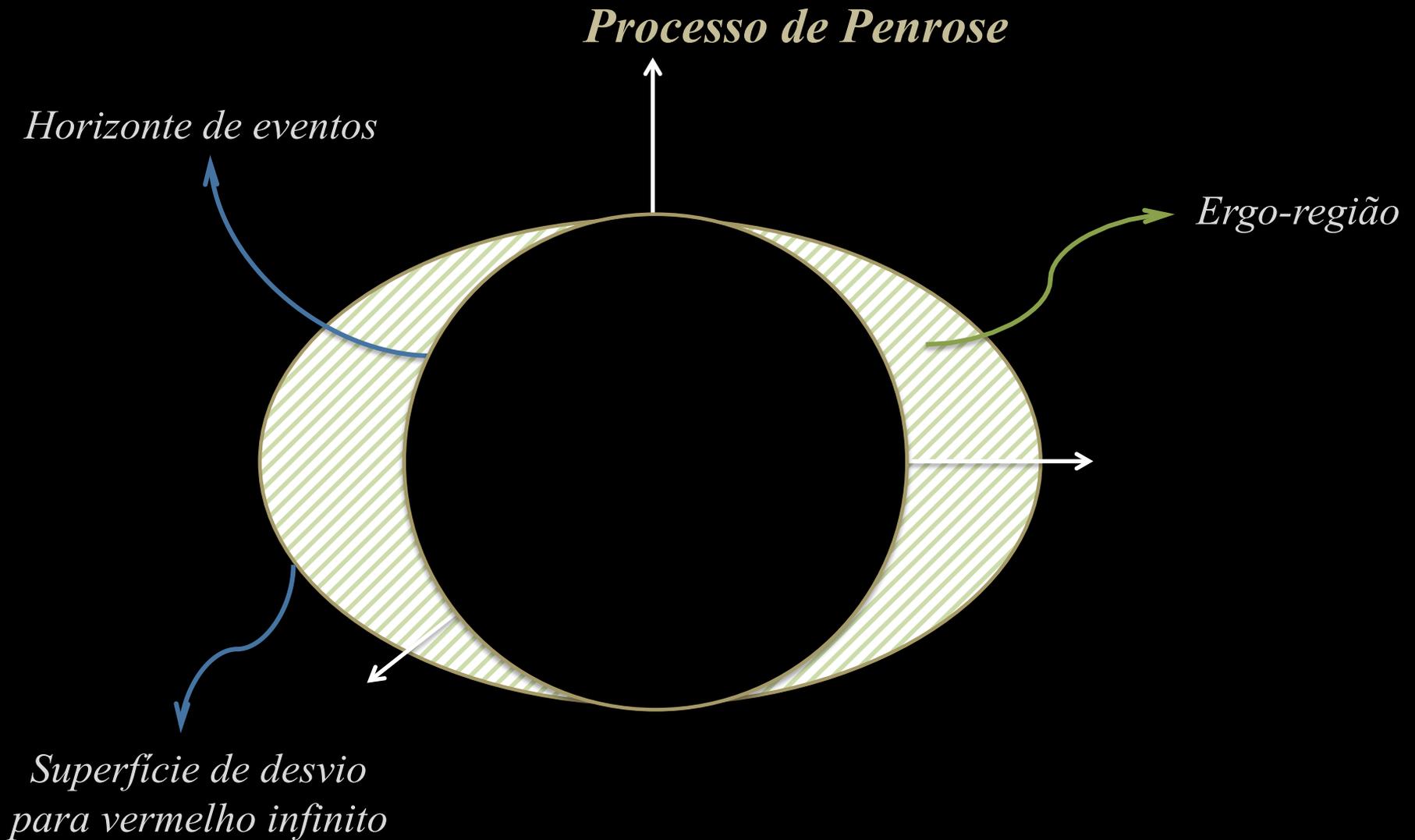
Reissner-Nordström



\mathcal{M}, \mathcal{Q}

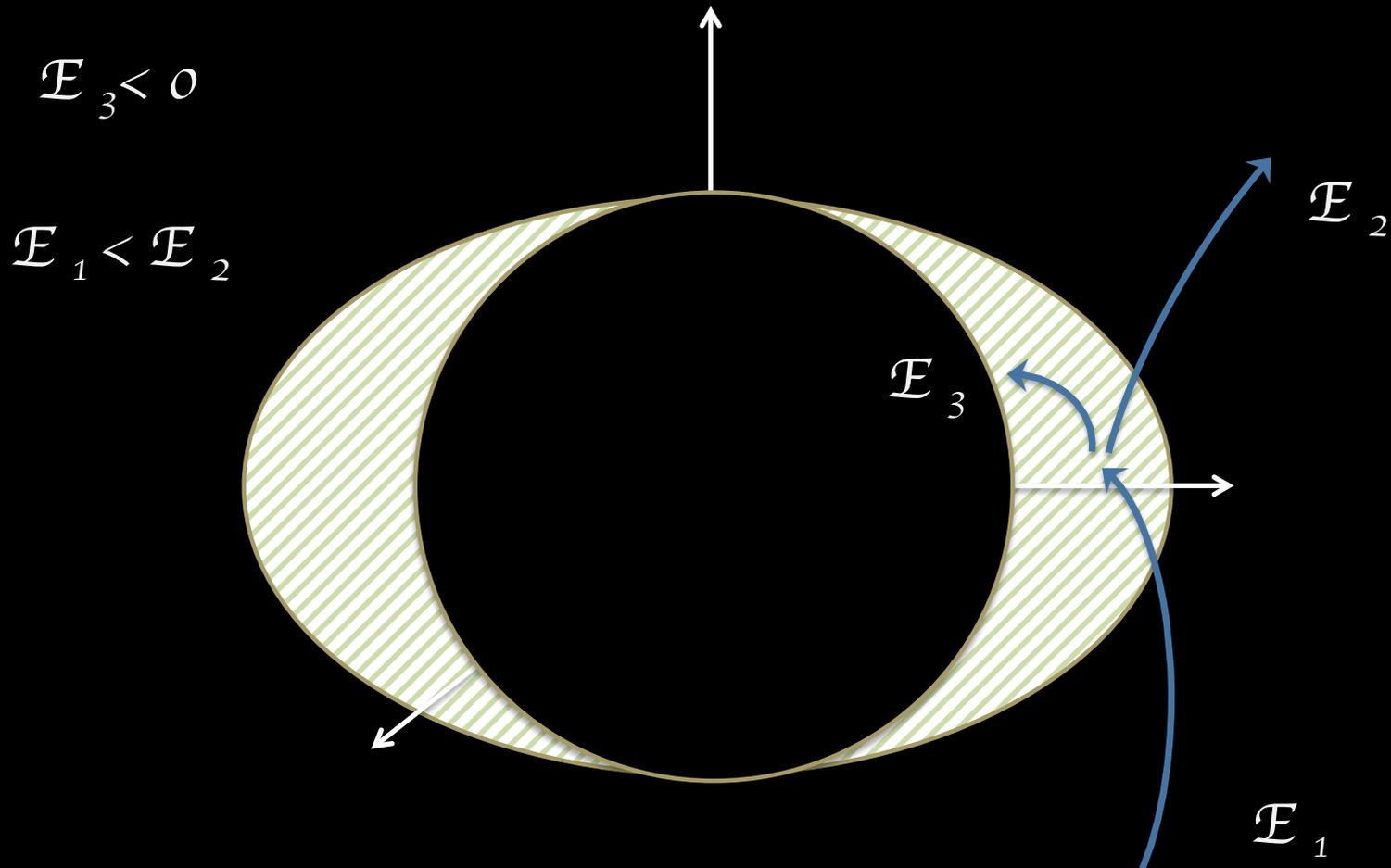
Buraco negro mais geral possível - Kerr-Newman ($\mathcal{M}, \mathcal{J}, \mathcal{Q}$)

Buracos Negros



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Processo de Penrose

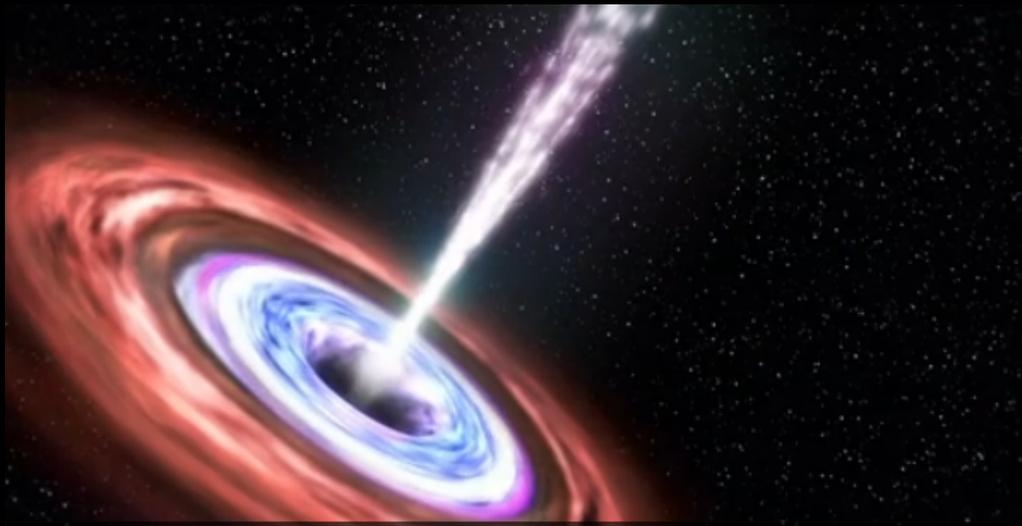
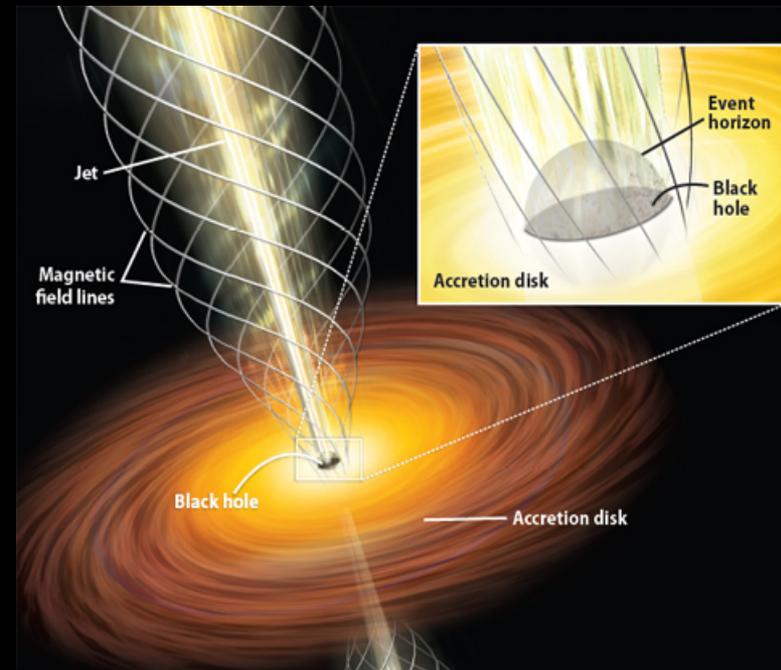
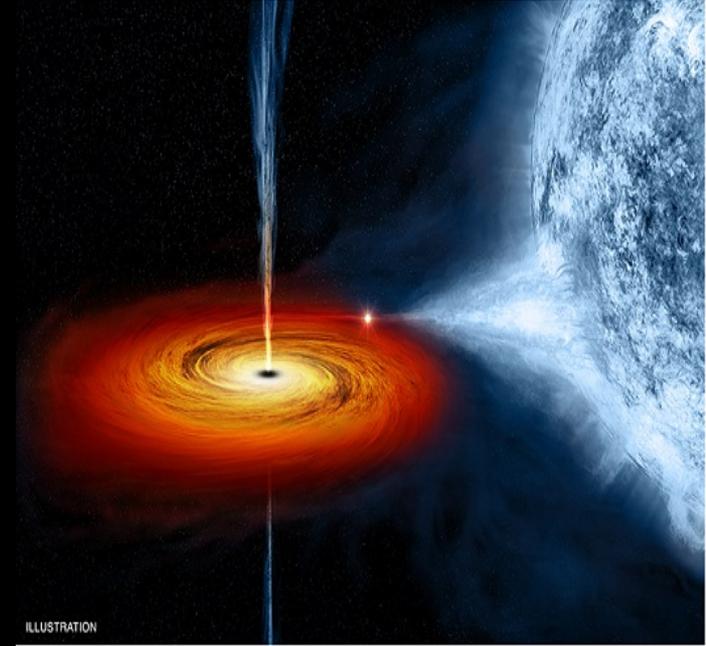


Termodinâmica de Buracos Negros

	Termodinâmica	Buracos Negros
Lei zero	T é constante em equilíbrio	κ é constante em equilíbrio
1º Lei	$\Delta E = \delta Q - P \Delta V$	$\Delta M = (1/\kappa) \cdot \Delta A + \Omega \cdot \Delta J$
2º Lei	$\Delta S \geq 0$	$\Delta A \geq 0$

Buracos Negros

Mas....



Buracos Negros

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