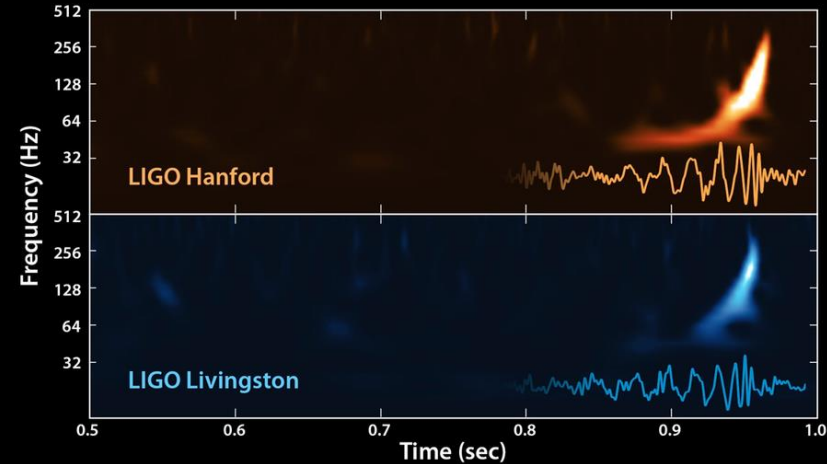
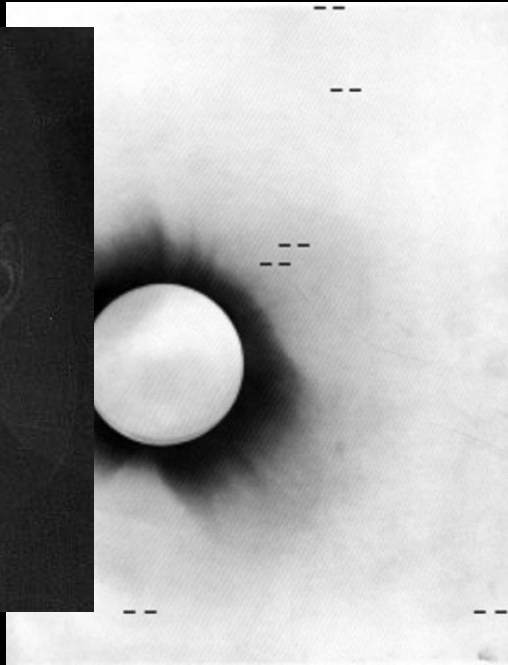




De Eddington ao LIGO: 100 anos de testes da Relatividade Geral

Raissa F. P. Mendes

Universidade Federal Fluminense

A Relatividade Geral

- A busca pela Relatividade Geral: 1905 - 1915



Fonte: Gutfreund & Renn, *The Road to Relativity*

A Relatividade Geral

- Em 25 de novembro de 1915:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

1916.

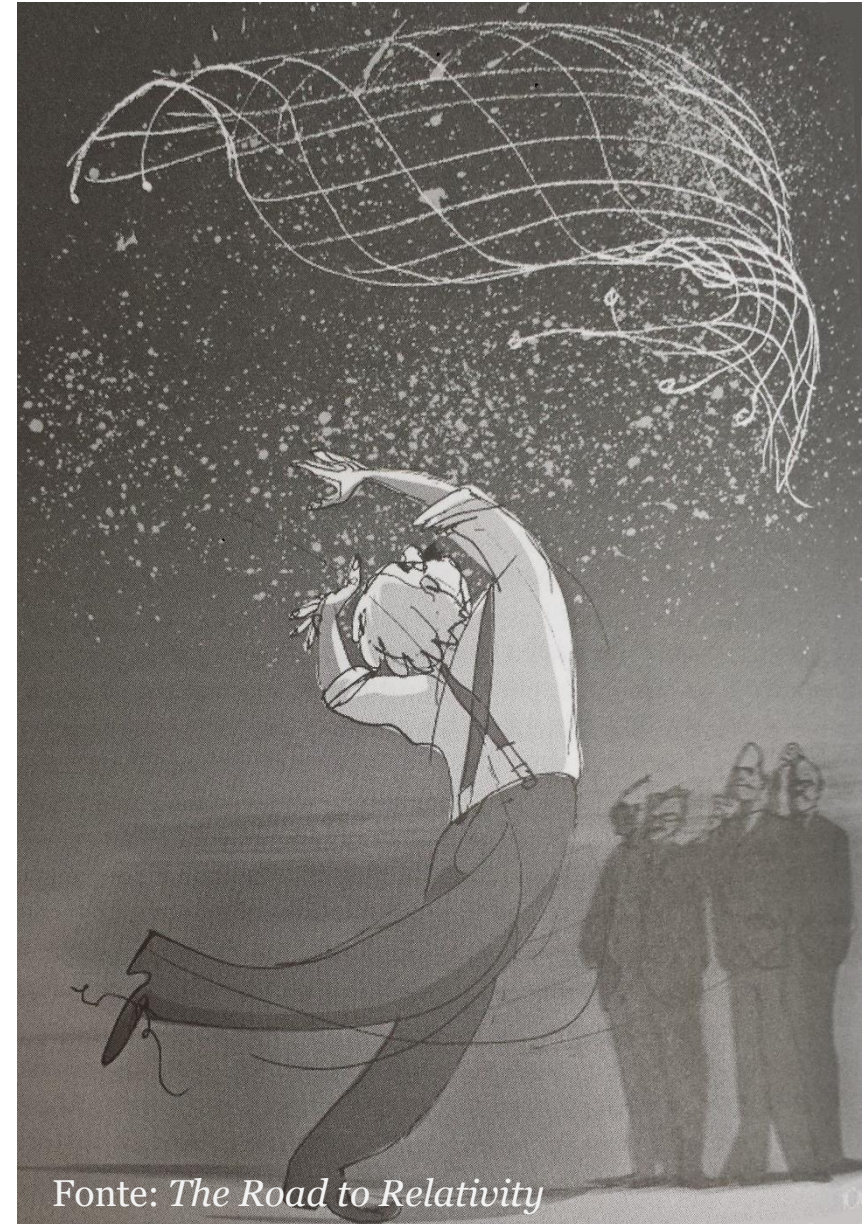
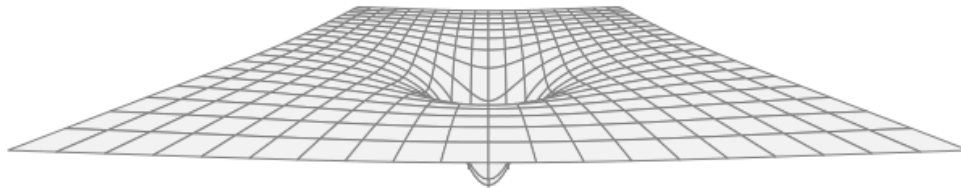
Nº 7.

ANNALEN DER PHYSIK.

VIERTE FÖLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie;* von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie“ bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie“ und setze sie als bekannt voraus. Die



Fonte: *The Road to Relativity*

A Relatividade Geral

- Em 25 de novembro de 1915:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

1916.

Nº 7.

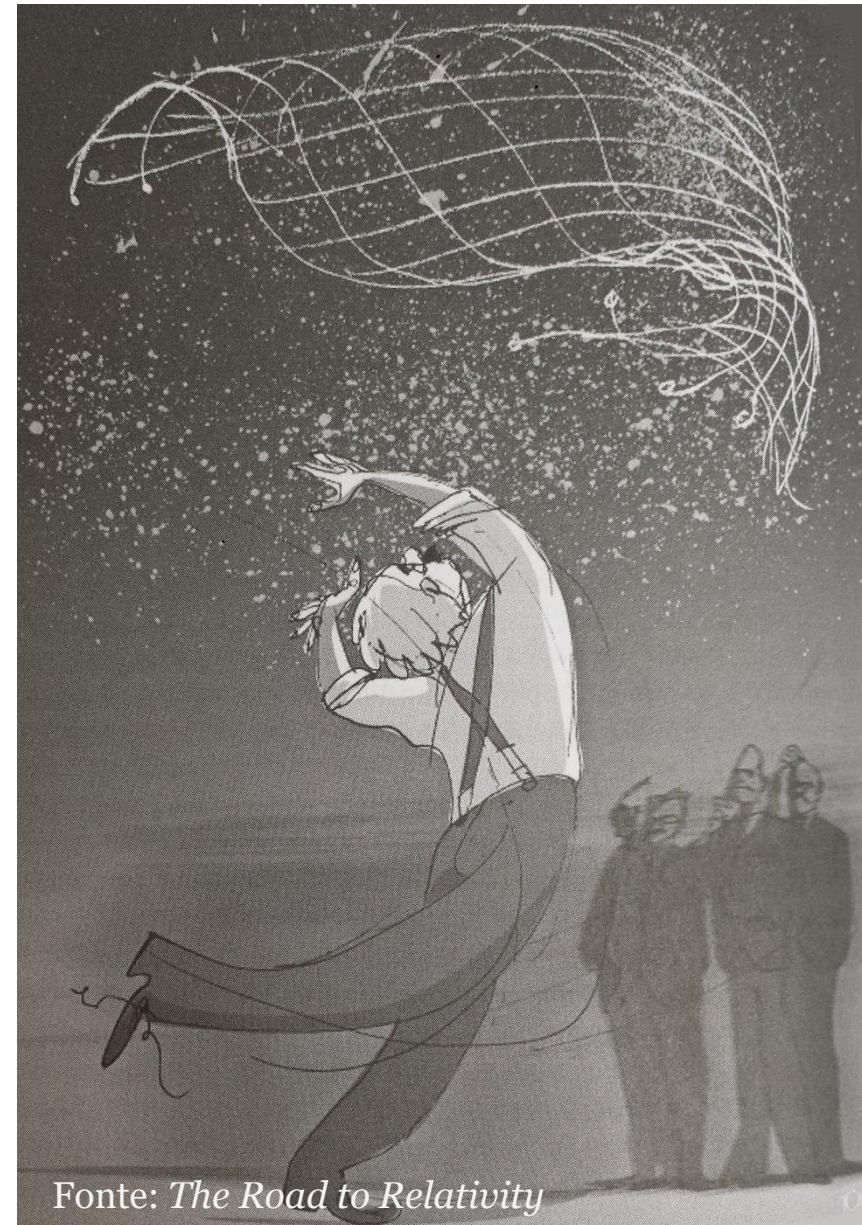
ANNALEN DER PHYSIK.

VIERTE FÖLGE. BAND 49.

1. Die Grundlage der allgemeinen Relativitätstheorie; von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie“ bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie“ und setze sie als bekannt voraus. Die

*“uma espécie de teatro ultramoderno,
em que o próprio palco se transforma
em um dos atores”*



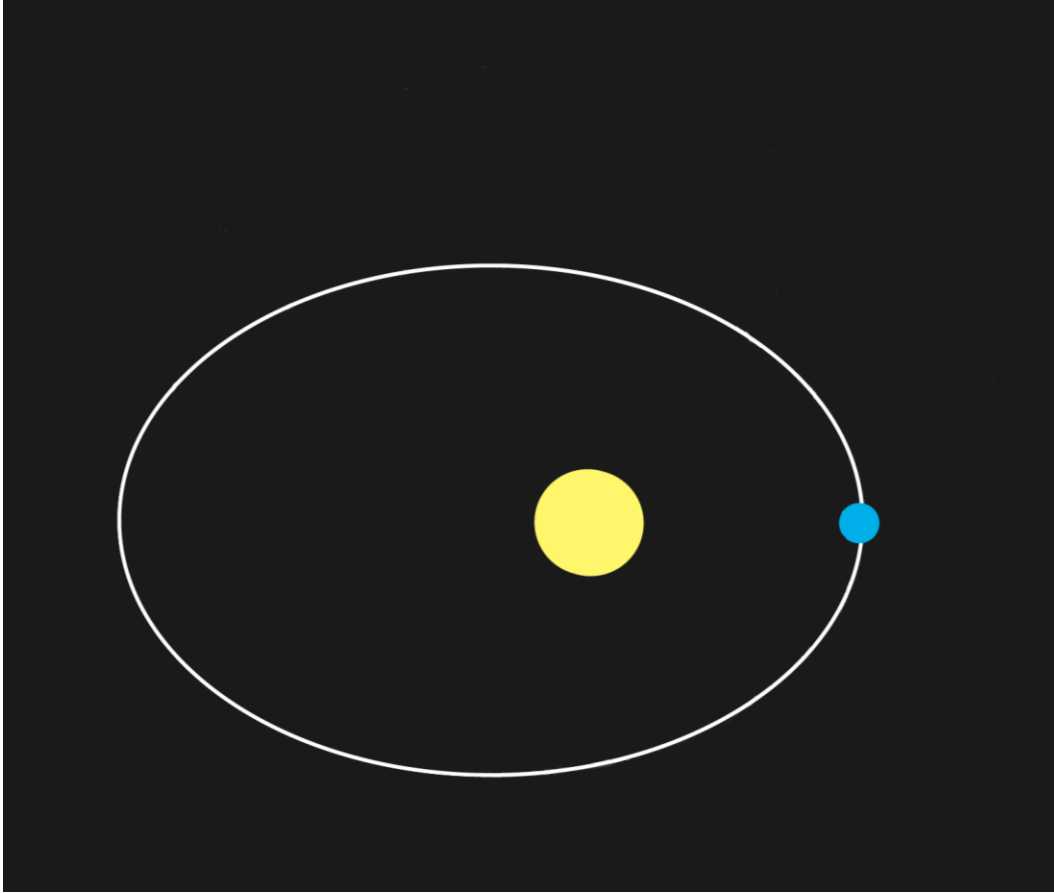
Fonte: *The Road to Relativity*

O que define o valor de uma teoria física?

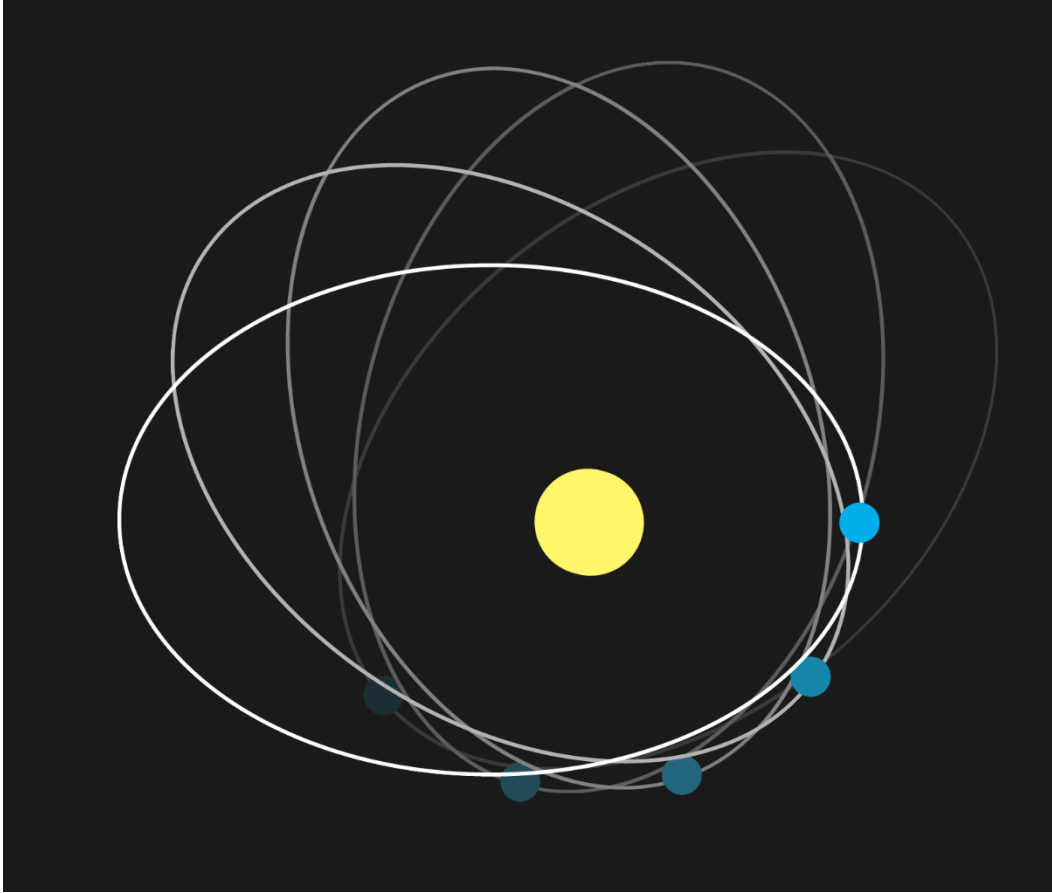


Crédito: Meshari Aldulaimi

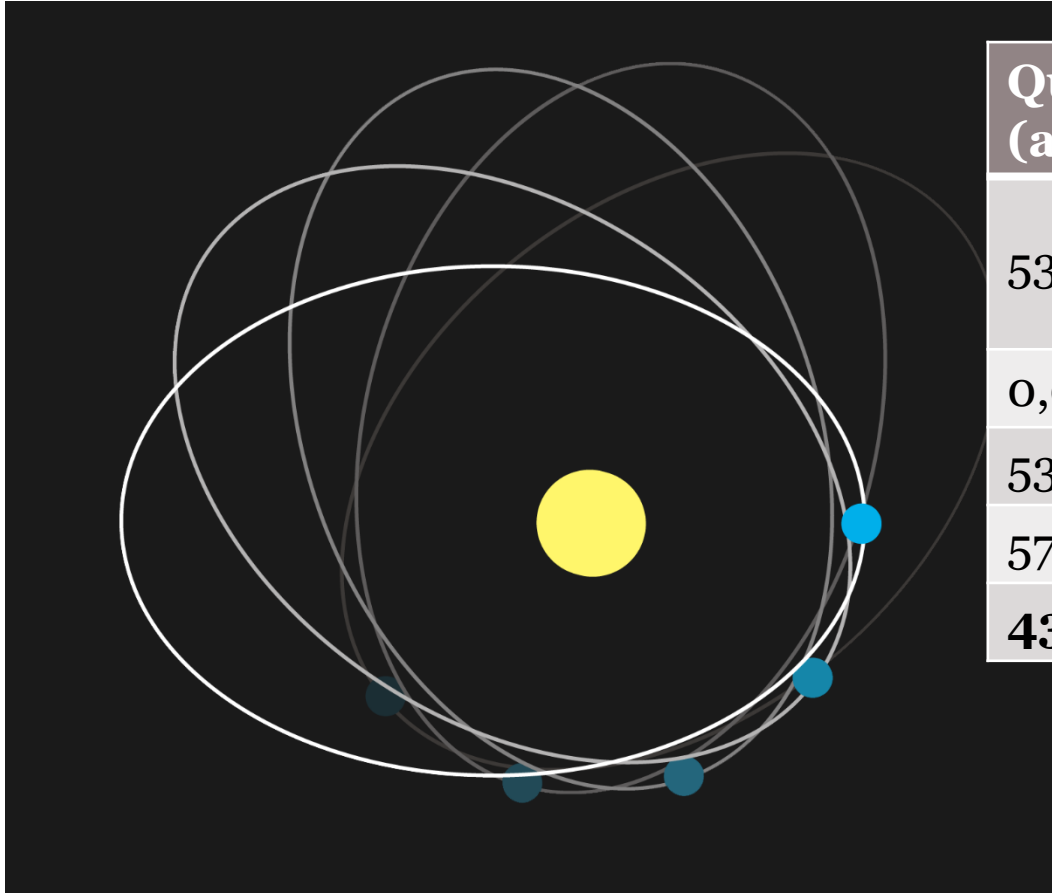
A precessão do periélio de Mercúrio



A precessão do periélio de Mercúrio



A precessão do periélio de Mercúrio



Quantia (arcseg/sec)	Causa
532,30	Atração gravitacional dos outros corpos no sistema solar
0,03	O sol é oblato
532,33	Total previsto
575,31	Total observado*
43	Diferença

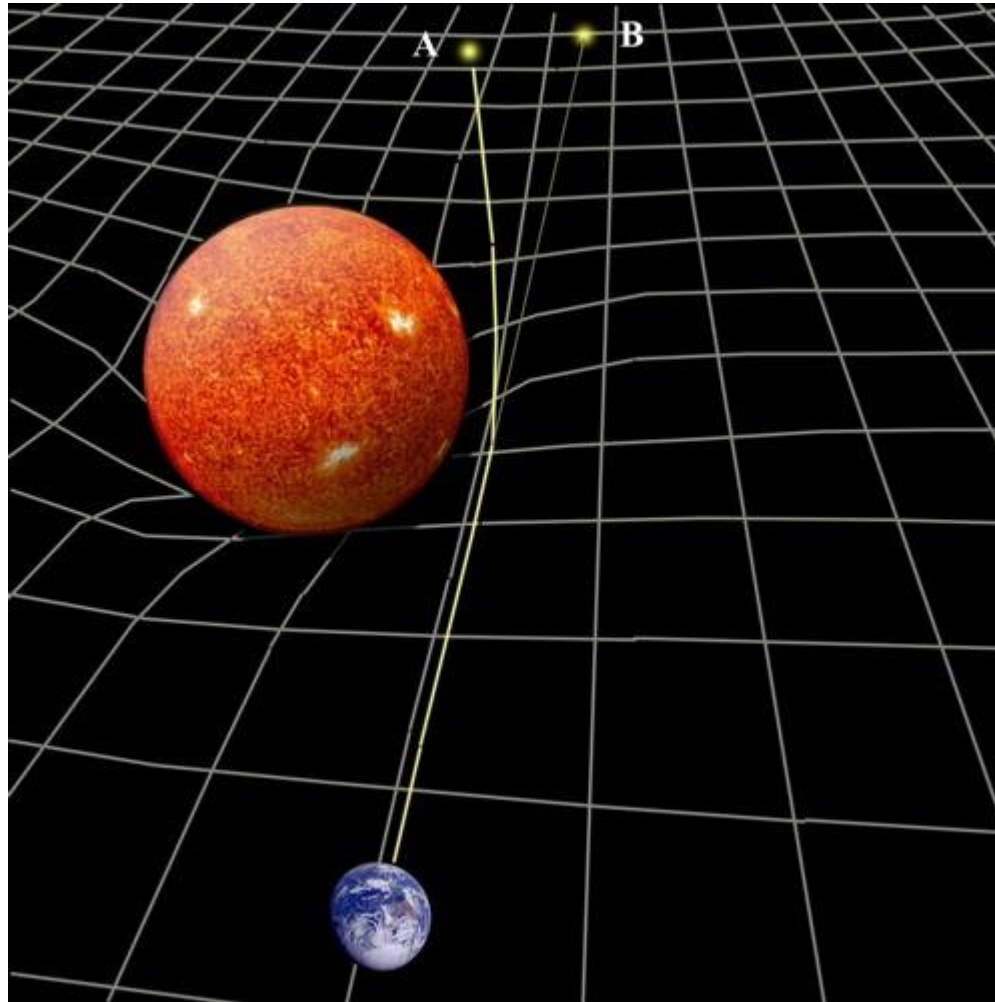


* The Astron. J. 153:121 (2017)

Le Verrier, 1859

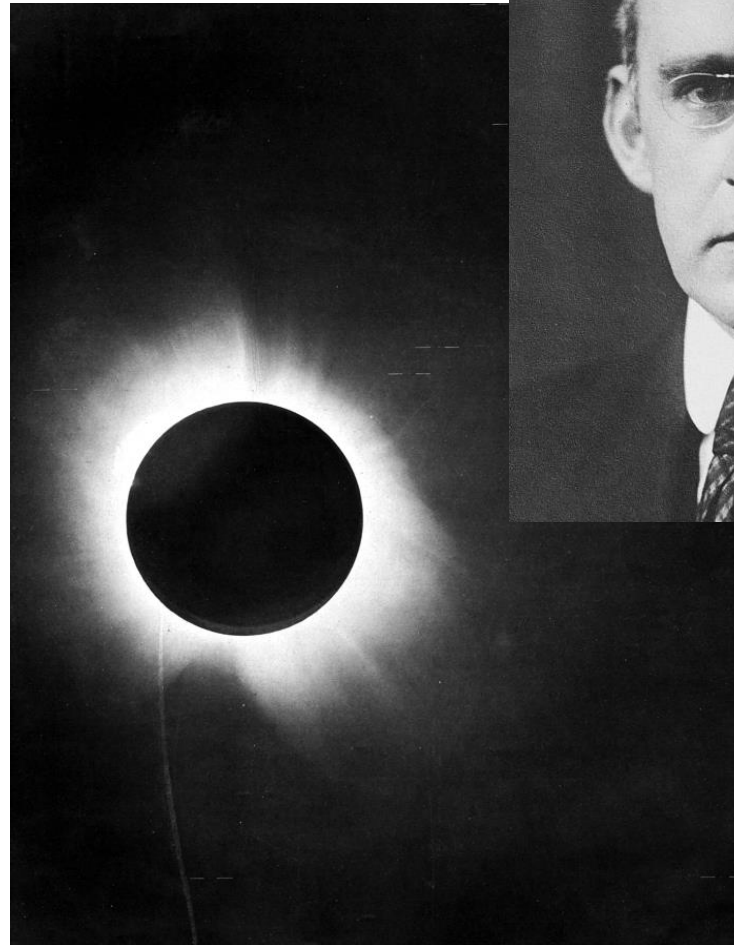
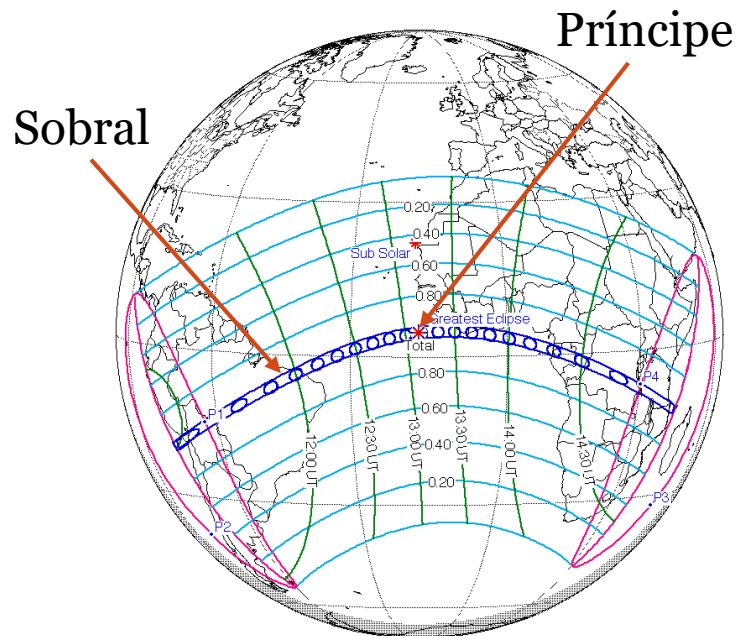
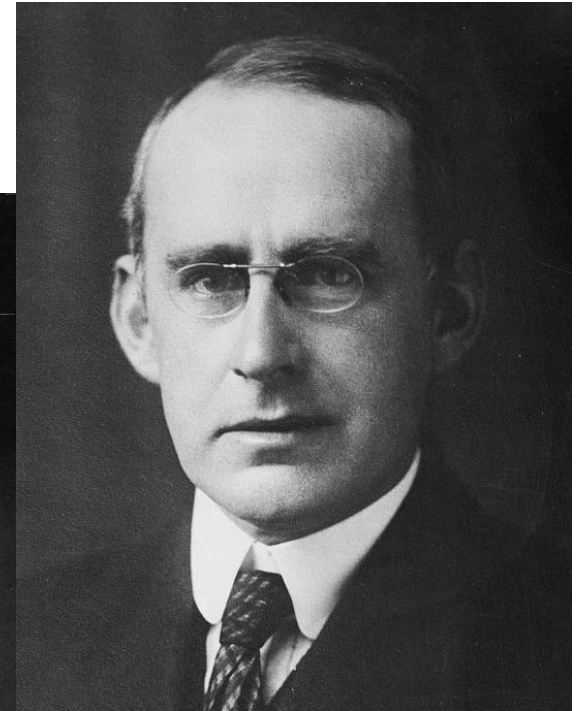
Eddington, 1919

- O desvio da luz pelo sol



Eddington, 1919

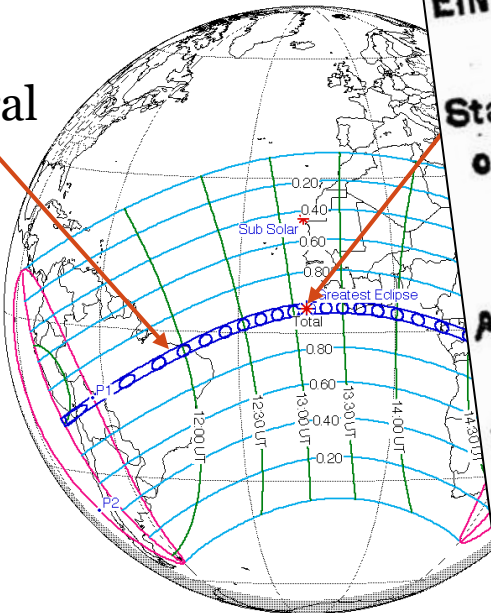
- O eclipse total de 29 de maio de 1919



Eddington, 1919

- O eclipse total

Sobral



LIGHTS ALL ASKEW IN THE HEAVENS
Special Cable to THE NEW YORK TIMES.
New York Times 1857; Nov 10, 1919; ProQuest Historical Newspapers The New York Times (1851 - 2004)
p. 17

LIGHTS ALL ASKEW IN THE HEAVENS

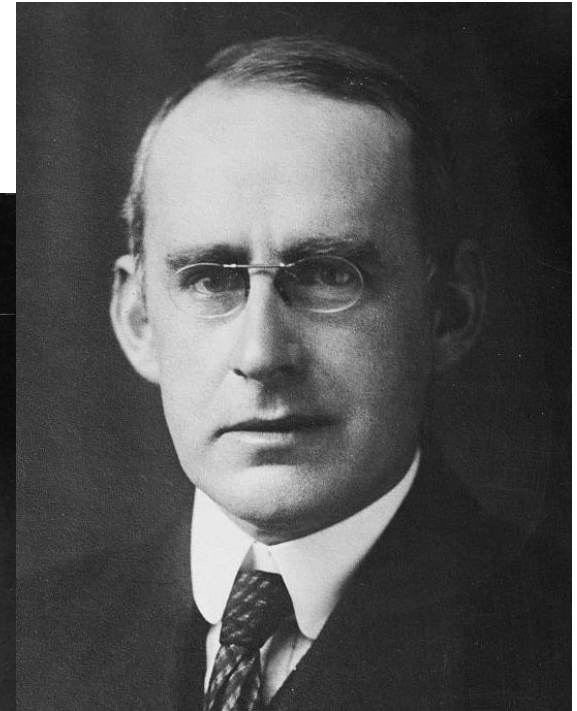
Men of Science More or Less
Agog Over Results of Eclipse
Observations.

EINSTEIN THEORY TRIUMPHS

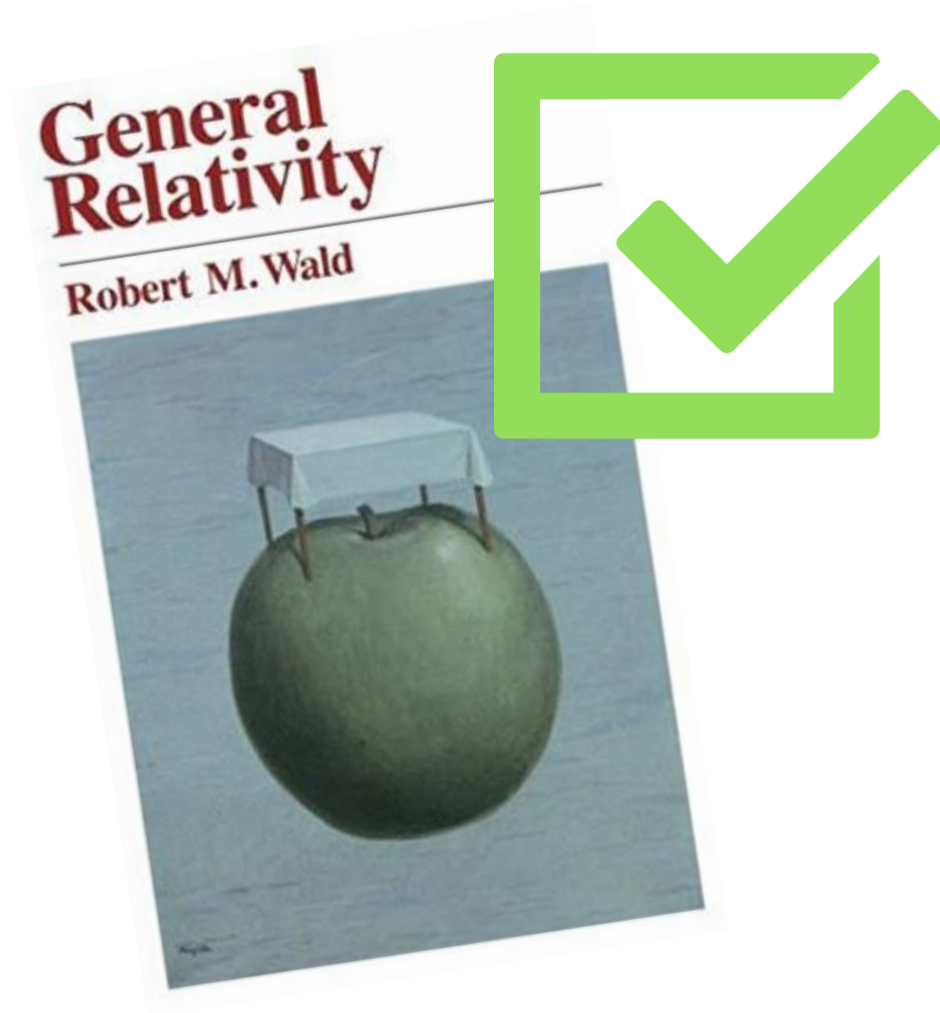
Stars Not Where They Seemed
or Were Calculated to be,
but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

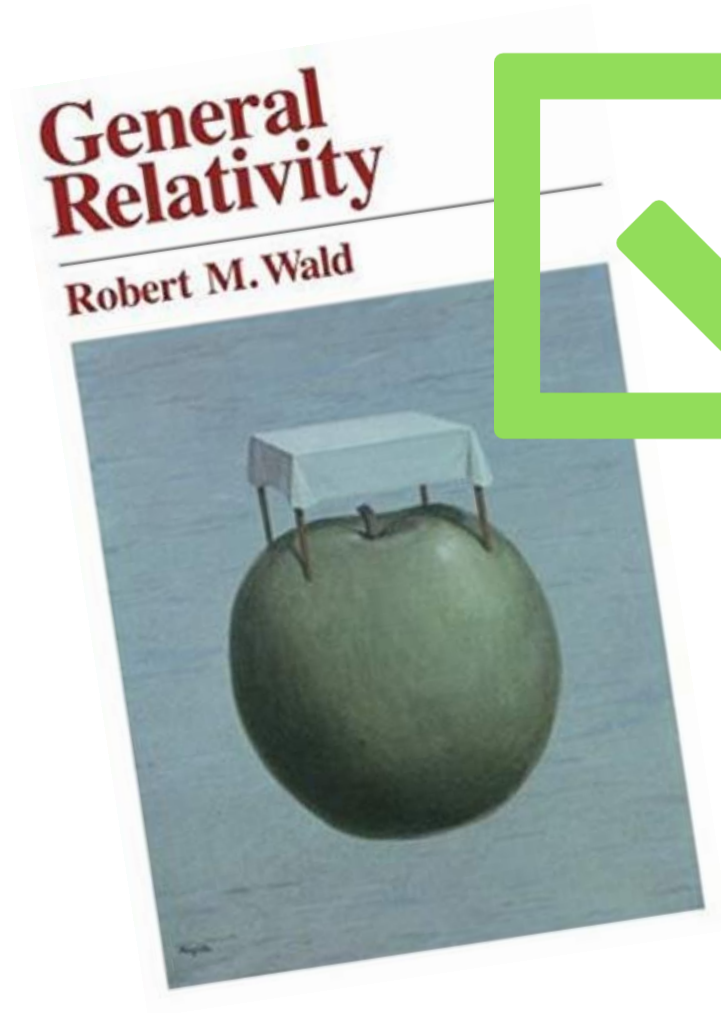
No More in All the World Could
Comprehend It, Said Einstein When
His Daring Publishers Accepted It.



O que basta para ‘validar’ uma teoria física?



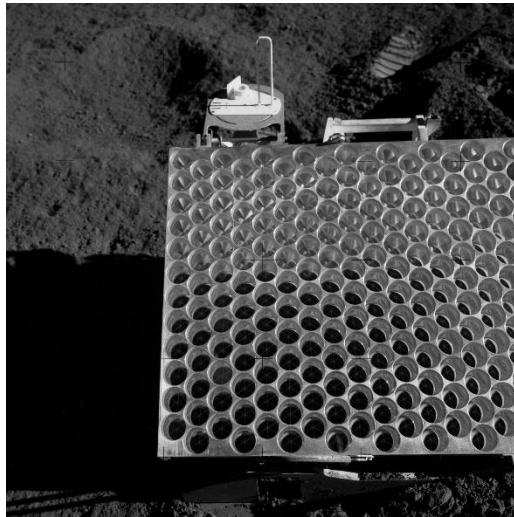
O que basta para ‘validar’ uma teoria física?



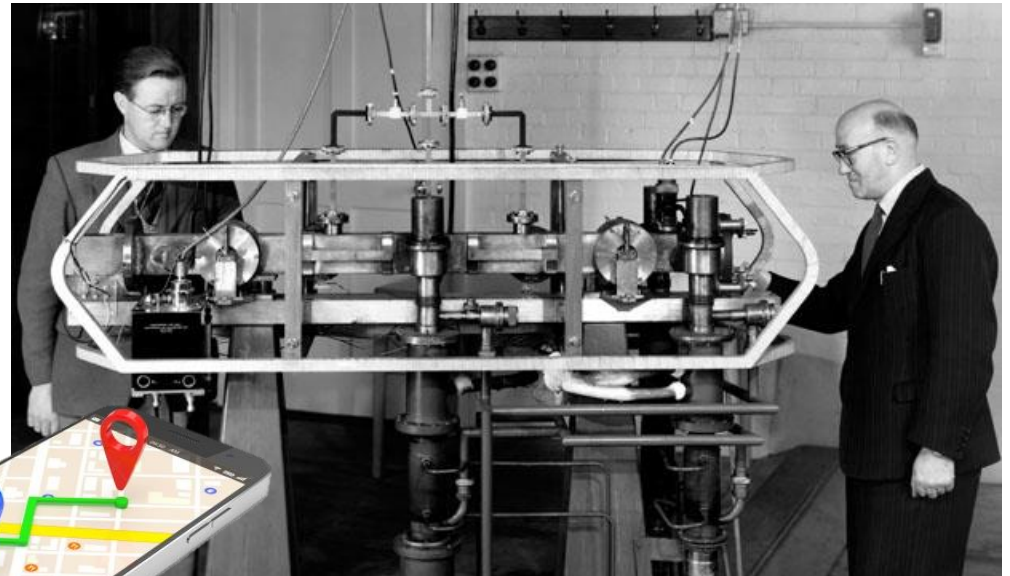
- Medições precisas; testes severos
- Sondar o cosmos em busca de “condições apropriadas”
 - Buracos negros
 - Ondas gravitacionais

* K. Popper, “The Logic of Scientific Discovery”

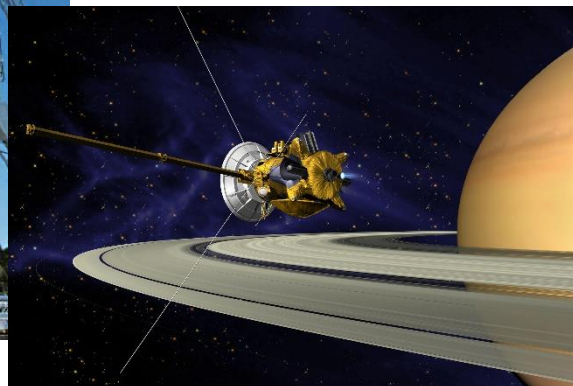
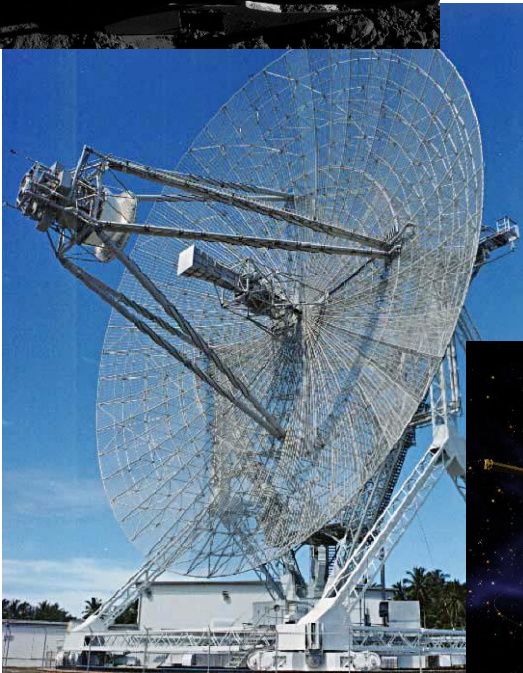
Medidas precisas, testes severos



Refletor
instalado
na Lua pela
Apollo 11.



Primeiro relógio atômico de césio-133.



Cassini



BepiColombo

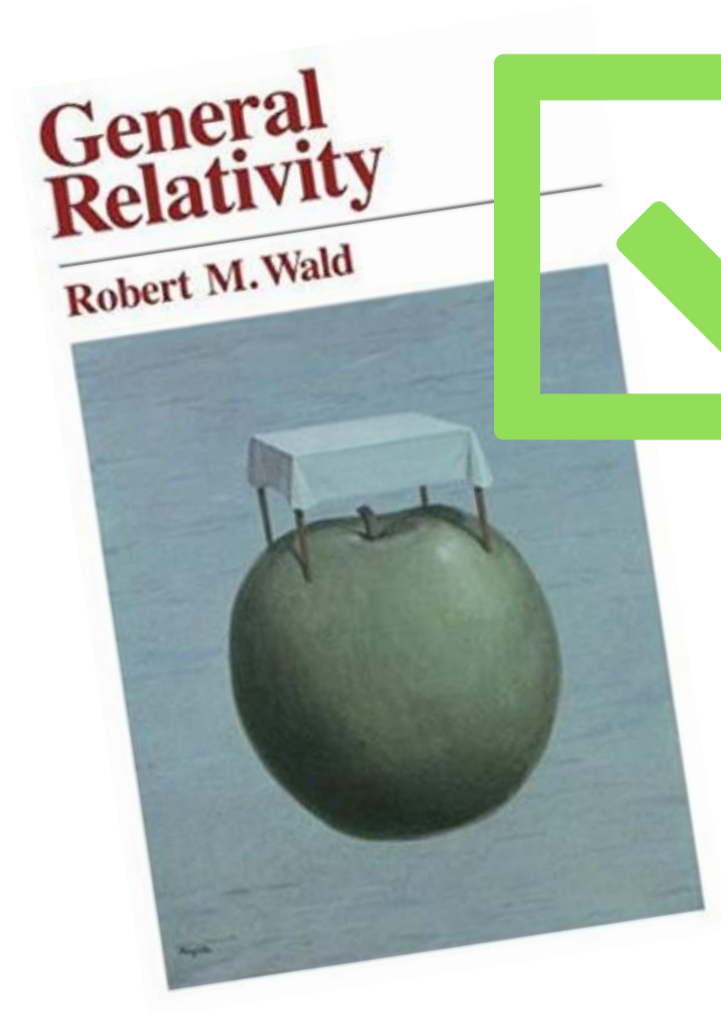
Medidas precisas, testes severos

■ Vínculos em parâmetros pós-Newtonianos

Parameter	Effect	Limit	Remarks
$\gamma - 1$	time delay	2.3×10^{-5}	Cassini tracking
	light deflection	4×10^{-4}	VLBI
$\beta - 1$	perihelion shift	3×10^{-3}	$J_2 = 10^{-7}$ from helioseismology
	Nordtvedt effect	2.3×10^{-4}	$\eta_N = 4\beta - \gamma - 3$ assumed
ξ	Earth tides	10^{-3}	gravimeter data
α_1	orbital polarization	10^{-4}	Lunar laser ranging
		2×10^{-4}	PSR J2317+1439
α_2	spin precession	4×10^{-7}	solar alignment with ecliptic
α_3	pulsar acceleration	4×10^{-20}	pulsar $\dot{P}$ statistics
η_N	Nordtvedt effect	9×10^{-4}	lunar laser ranging
ζ_1	—	2×10^{-2}	combined PPN bounds
ζ_2	binary acceleration	4×10^{-5}	$\ddot{P}_p$ for PSR 1913+16
ζ_3	Newton's 3rd law	10^{-8}	lunar acceleration
ζ_4	—	—	not independent (see Equation (58))

Table 4: *Current limits on the PPN parameters. Here η_N is a combination of other parameters given by $\eta_N = 4\beta - \gamma - 3 - 10\xi/3 - \alpha_1 + 2\alpha_2/3 - 2\zeta_1/3 - \zeta_2/3$.*

O que basta para ‘validar’ uma teoria física?



- Medições precisas; testes severos
- Sondar o cosmos em busca de “condições apropriadas”
 - Buracos negros
 - Ondas gravitacionais

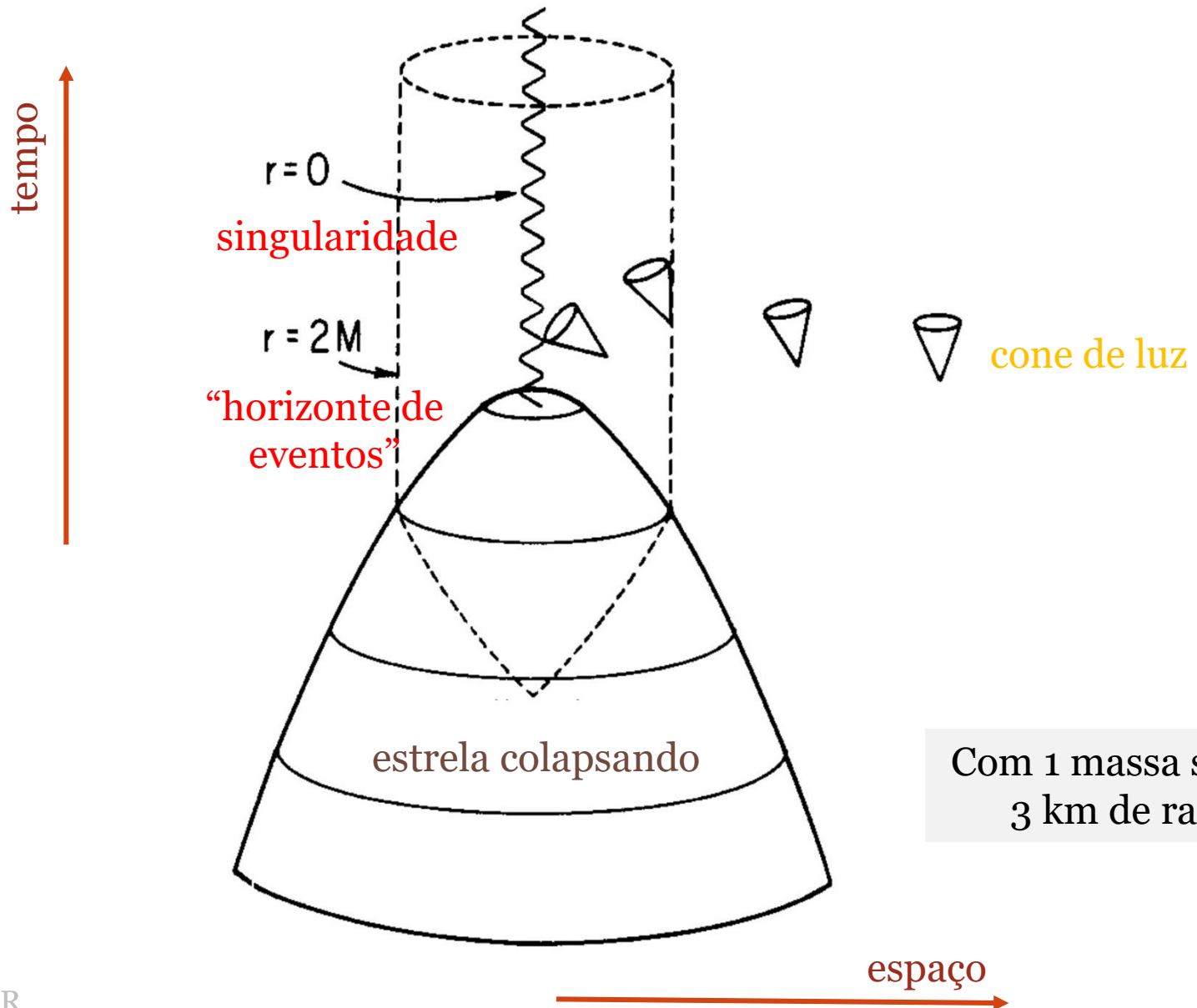
Buracos negros



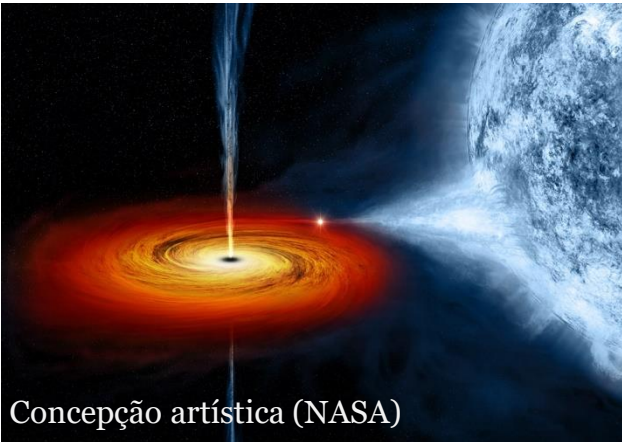
Buracos negros



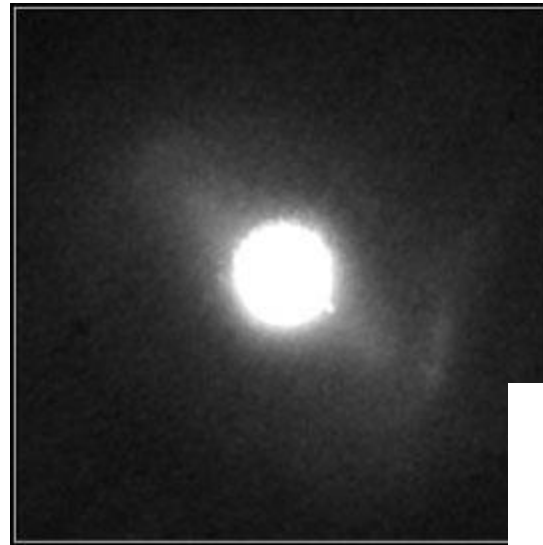
Buracos negros



Buracos negros



Concepção artística (NASA)



Quasar 1229+204
(Hubble)

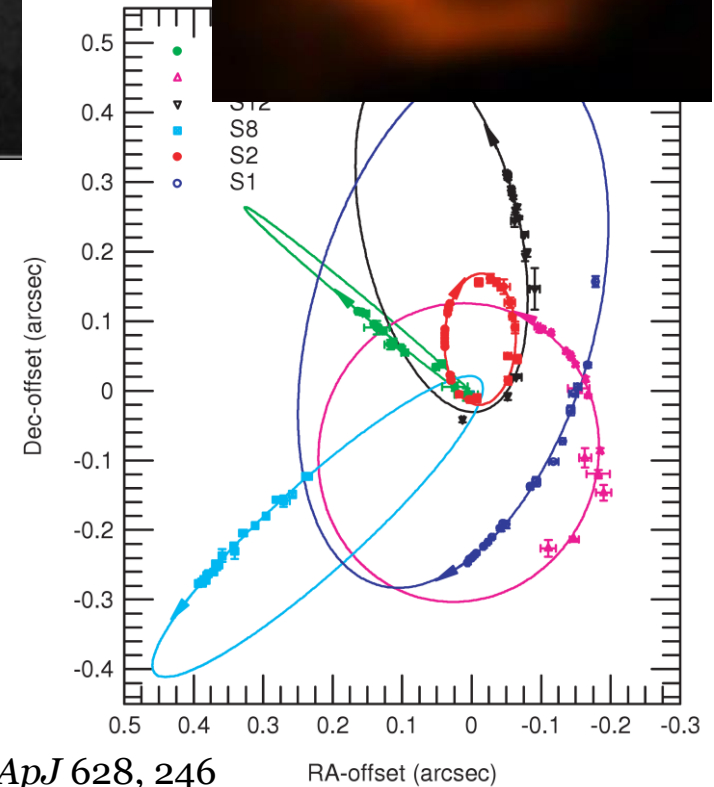
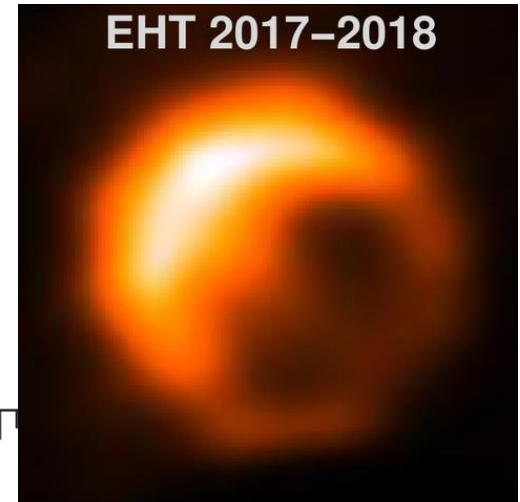
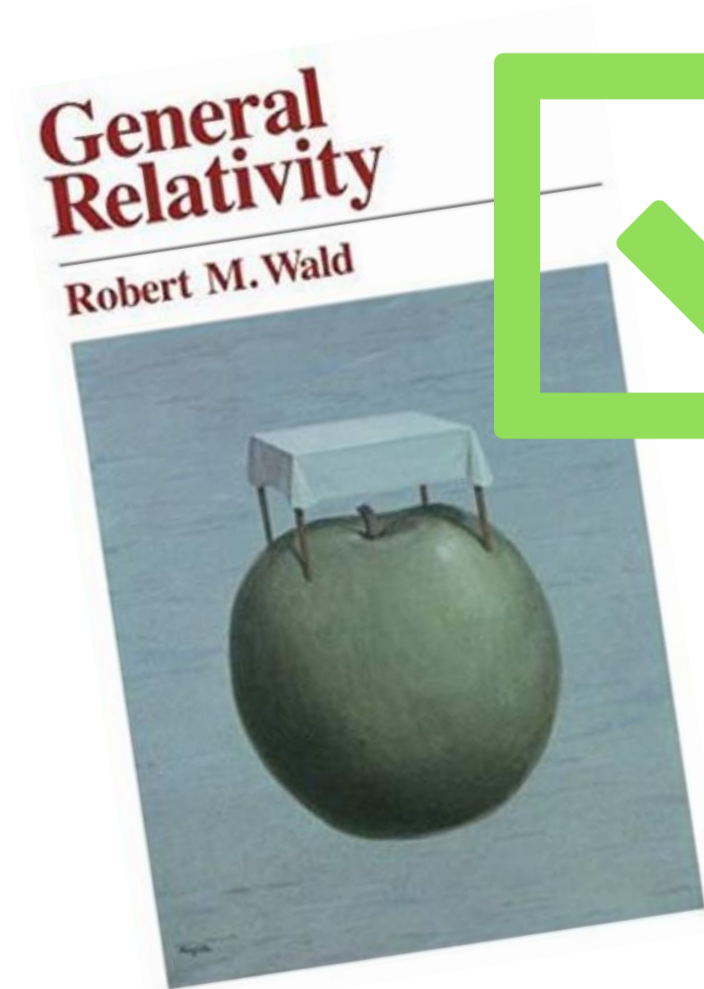


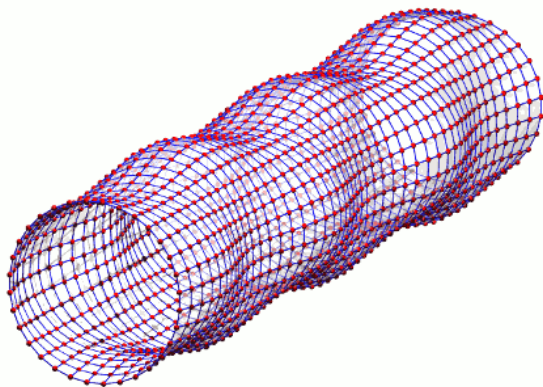
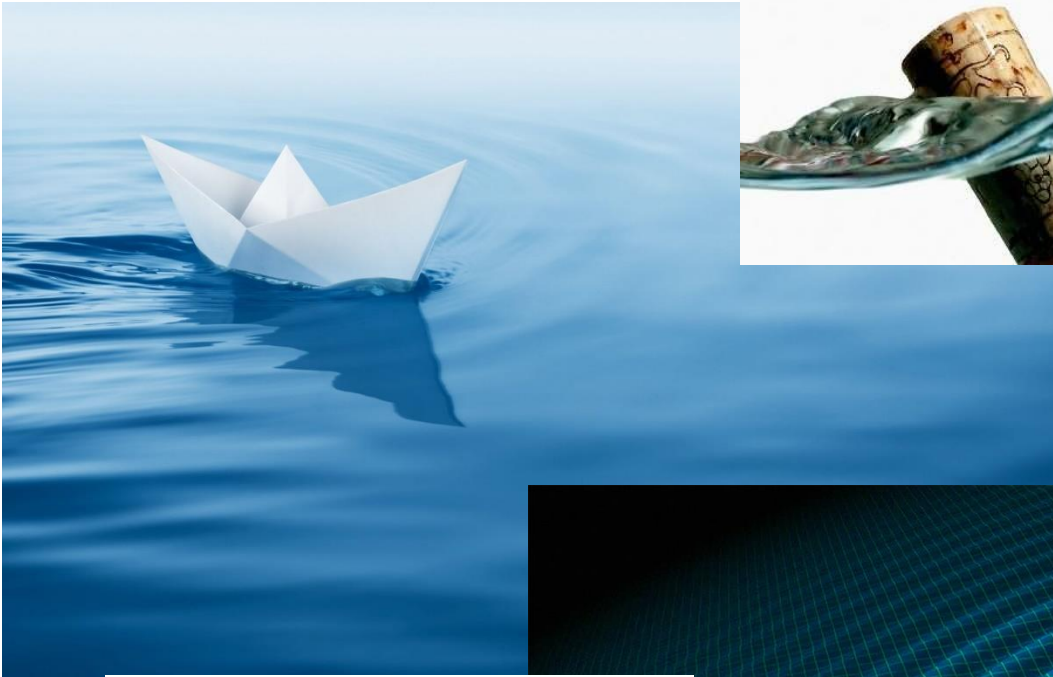
Imagem em raio-X de
Cygnus X-1 (Chandra)

O que basta para ‘validar’ uma teoria física?



- Medições precisas; testes severos
- Sondar o cosmos em busca de “condições apropriadas”
 - Buracos negros
 - Ondas gravitacionais

Ondas gravitacionais



www.einstein-online.info

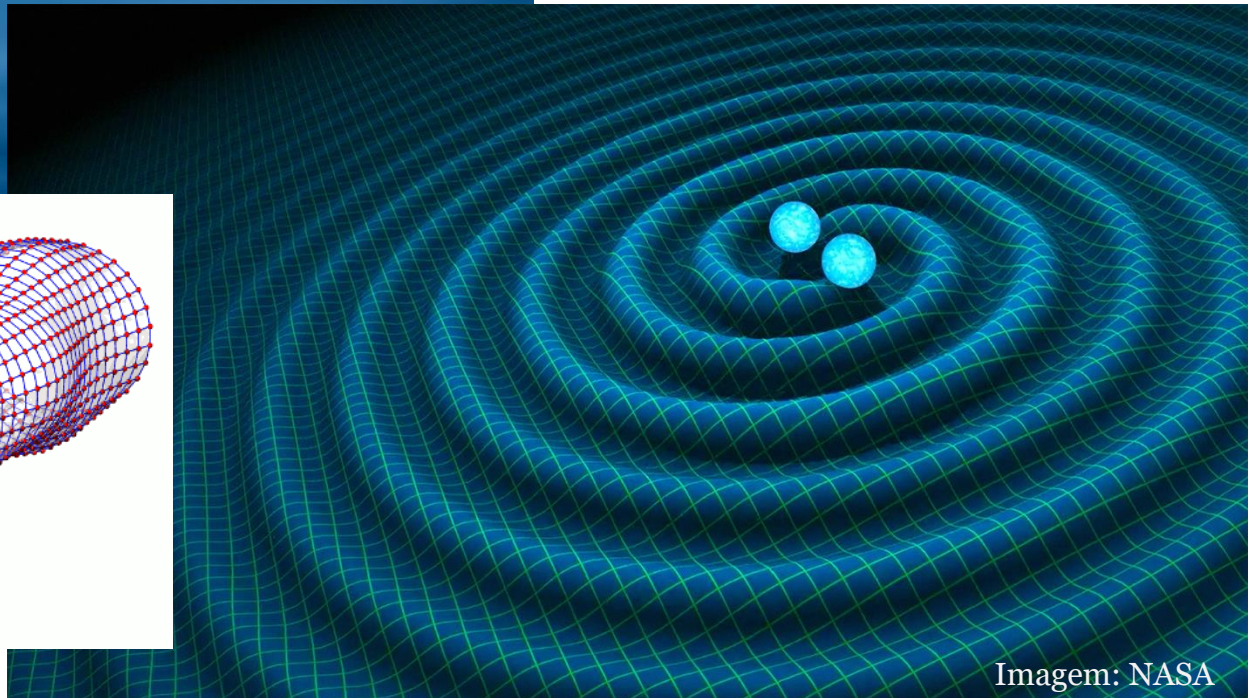
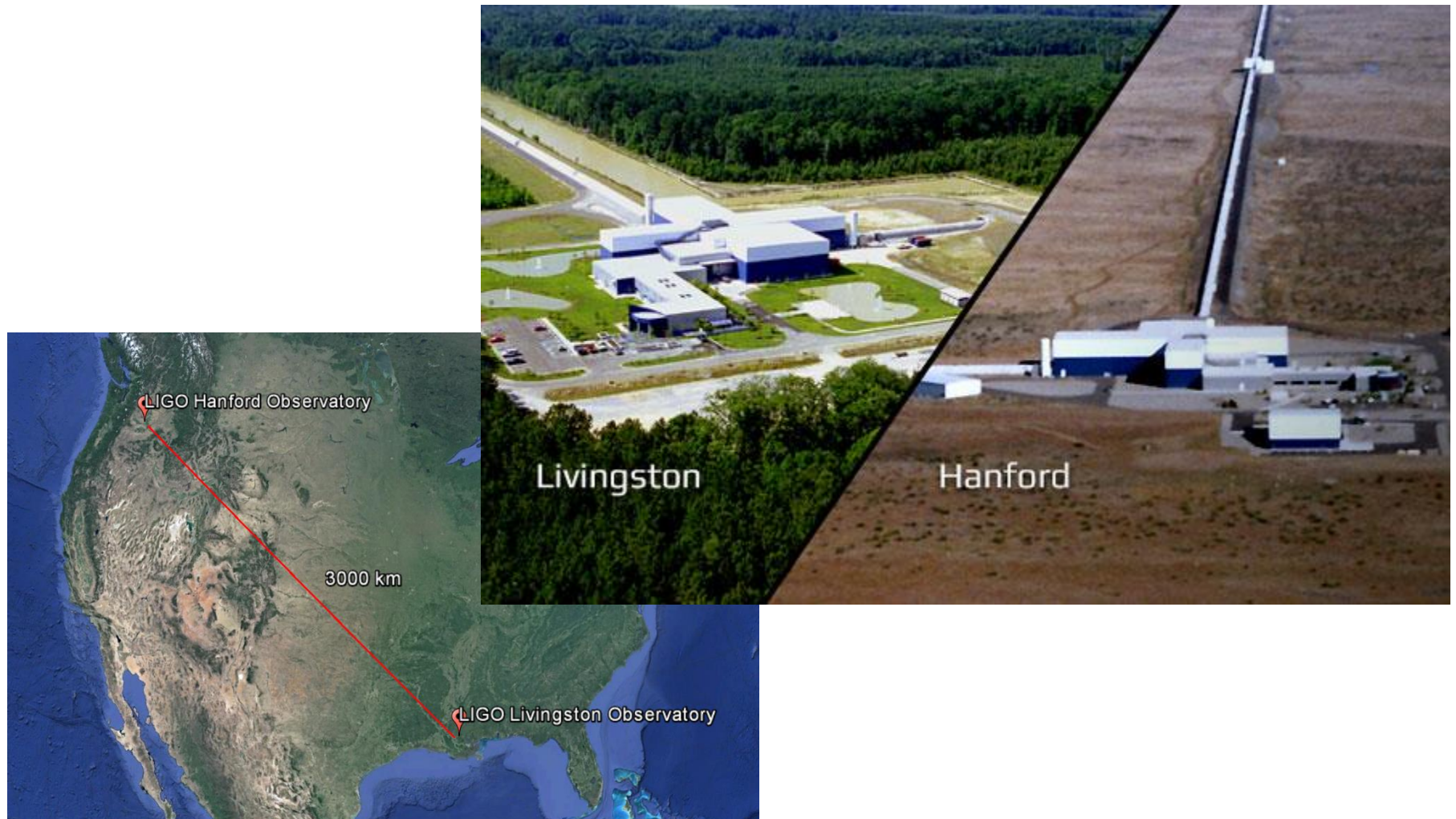


Imagem: NASA

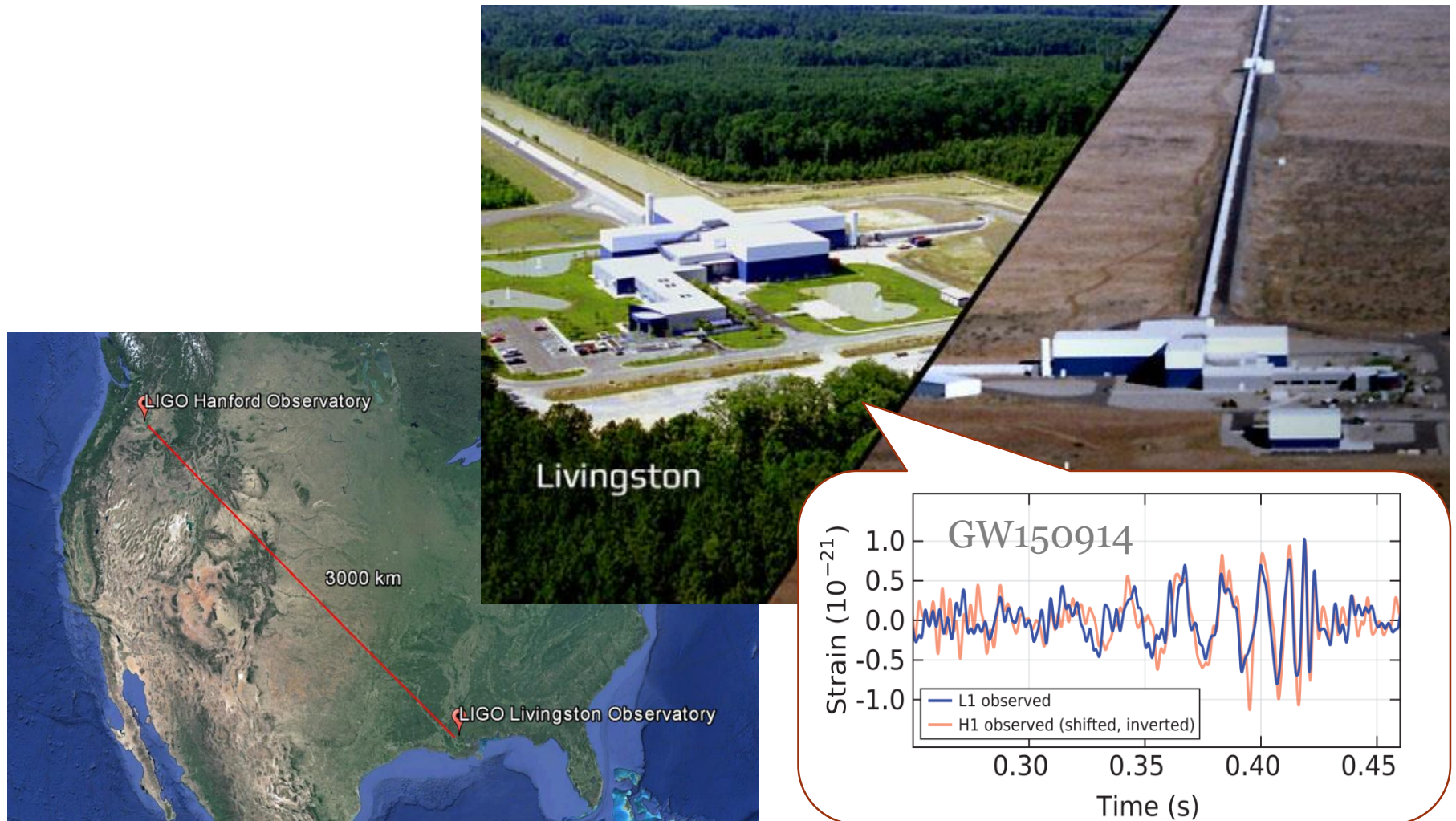
Ondas gravitacionais

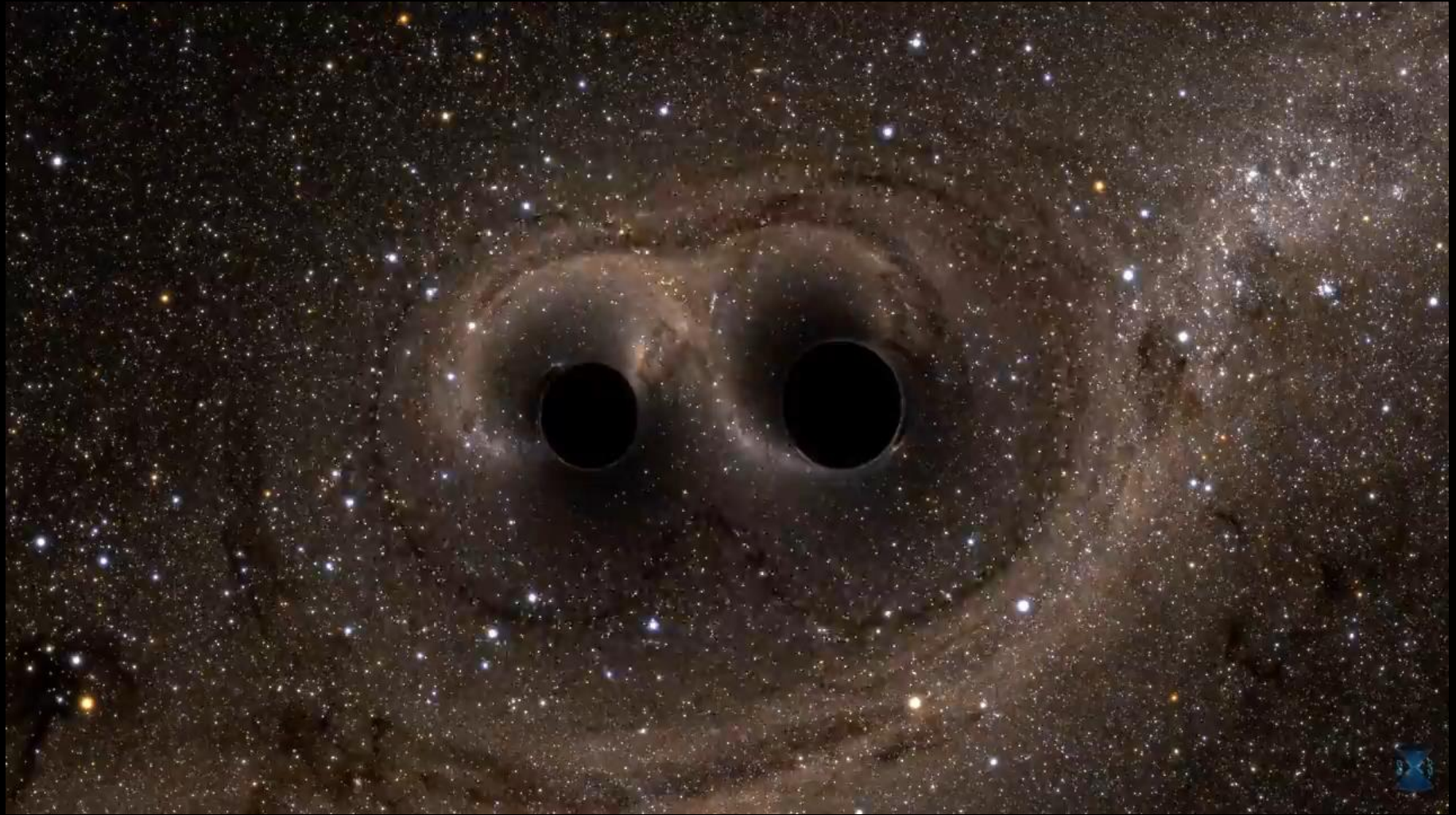
- LIGO (Observatório de Interferometria Gravitacional a Laser)



Ondas gravitacionais

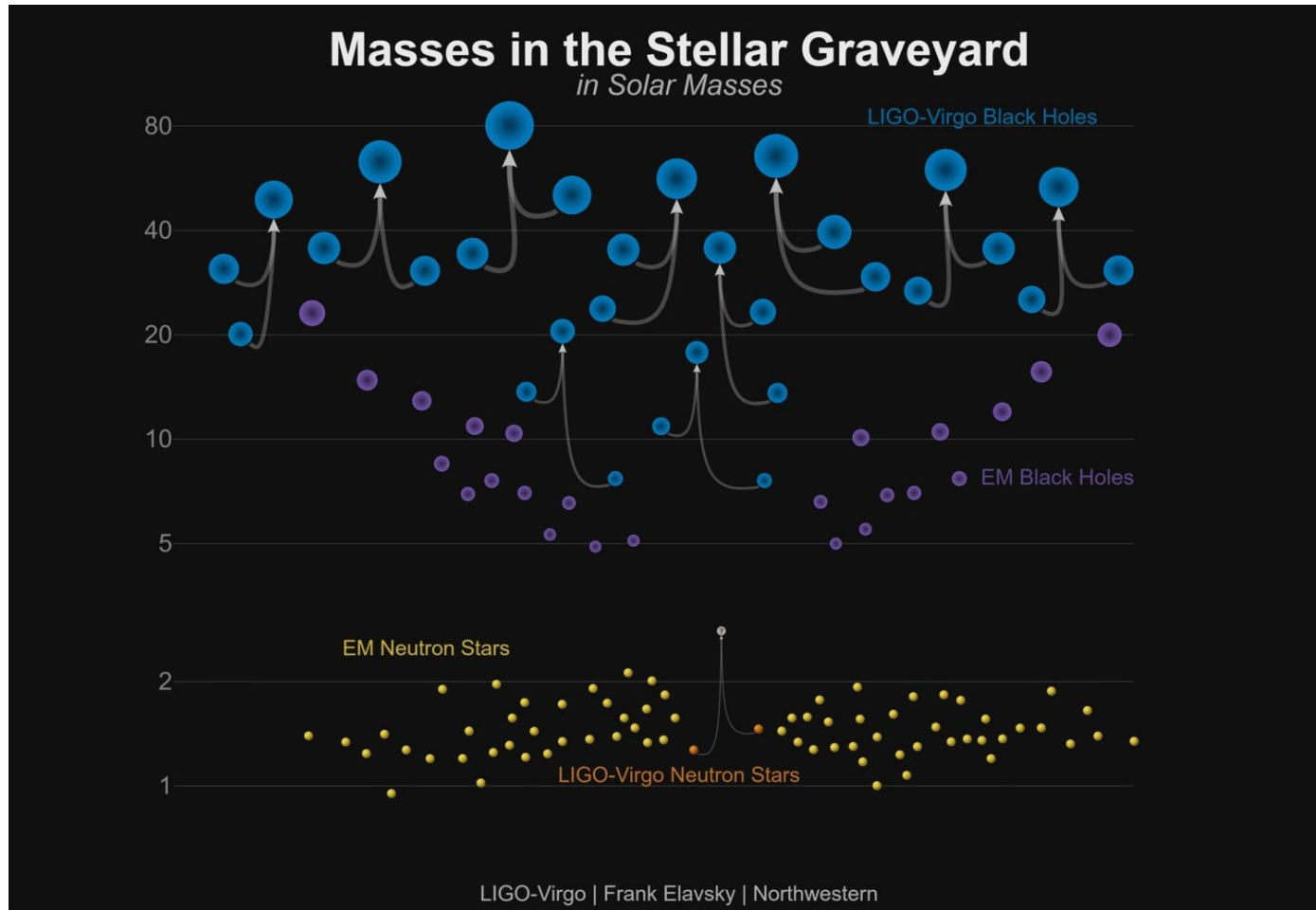
- LIGO (Observatório de Interferometria Gravitacional a Laser)





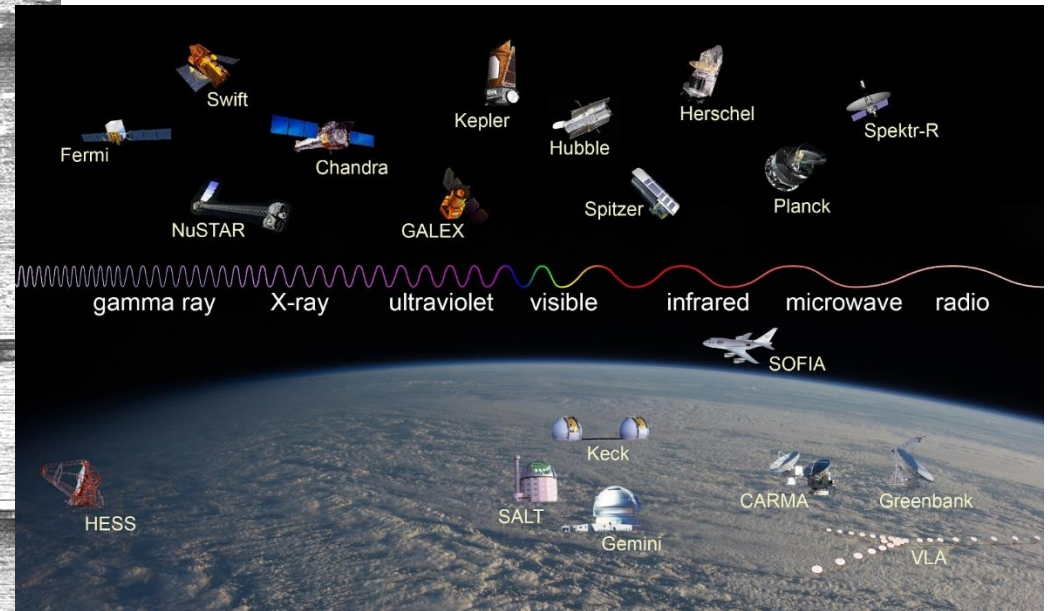
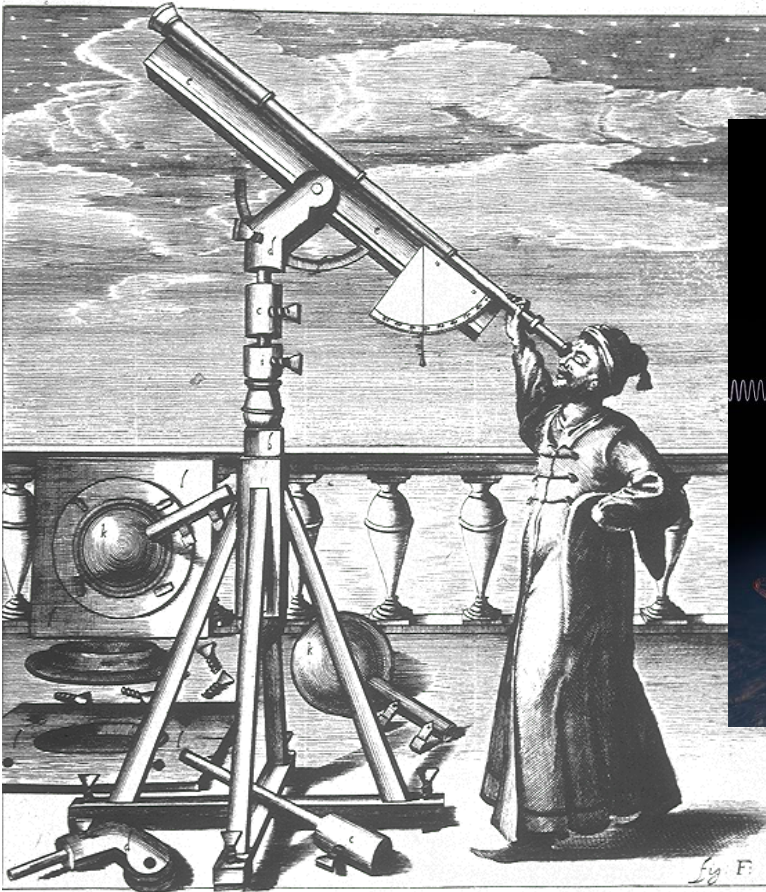
Ondas gravitacionais

- Eventos detectados até agora



Ondas gravitacionais

- Uma nova era para a astronomia!



■ Quais as implicações para a Relatividade Geral?

PRL **116**, 221101 (2016)

 Selected for a **Viewpoint** in *Physics*
PHYSICAL REVIEW LETTERS

week ending
3 JUNE 2016



Tests of General Relativity with GW150914

B. P. Abbott *et al.**

(LIGO Scientific and Virgo Collaborations)

(Received 26 March 2016; revised manuscript received 9 May 2016; published 31 May 2016)

Dark Energy after GW170817

Jose María Ezquiaga^{1,2,*} and Miguel Zumalacárregui^{2,3,†}

¹*Instituto de Física Teórica UAM/CSIC, Universidad Autónoma de Madrid,
C/ Nicolás Cabrera 13-15, Cantoblanco, Madrid 28049, Spain*

²*Berkeley Center for Cosmological Physics, LBNL and University of California at Berkeley,
Berkeley, California 94720, USA*

³*Nordita, KTH Royal Institute of Technology and Stockholm University,
Roslagstullsbacken 23, SE-106 91 Stockholm, Sweden*

(Dated: October 17, 2017)

Dark Energy after GW170817

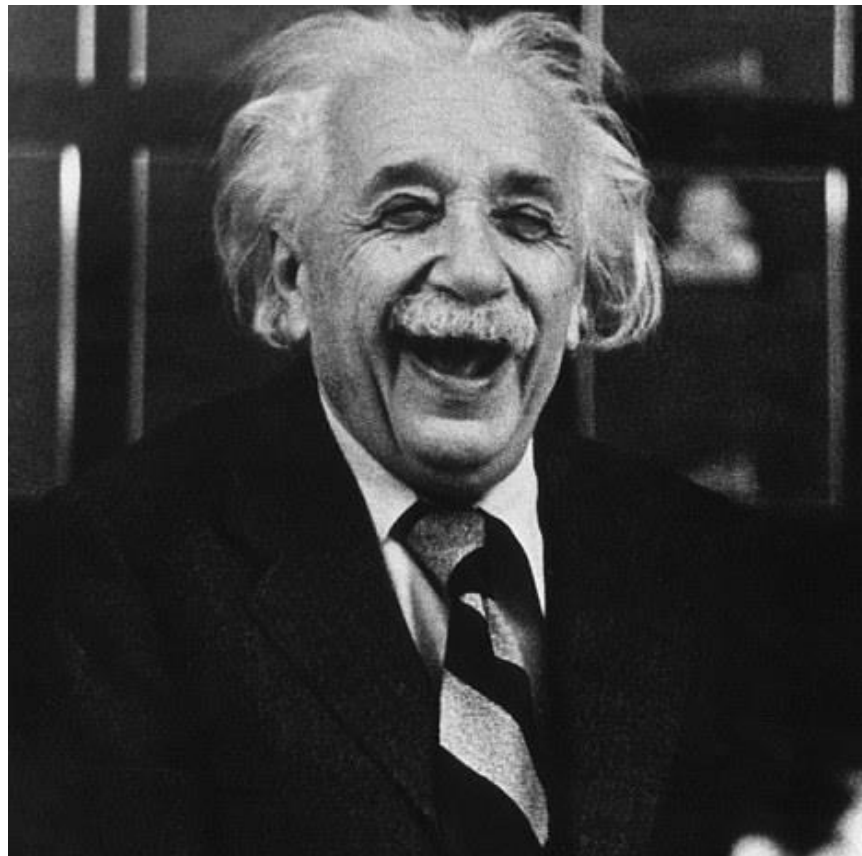
Paolo Creminelli¹ and Filippo Vernizzi²

¹*Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, 34151, Trieste, Italy*

²*Institut de physique théorique, Université Paris Saclay CEA, CNRS, 91191 Gif-sur-Yvette, France*

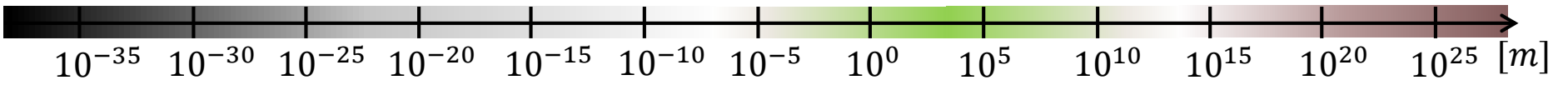
(Dated: October 17, 2017)

Podemos (enfim!) dizer que Einstein estava certo?



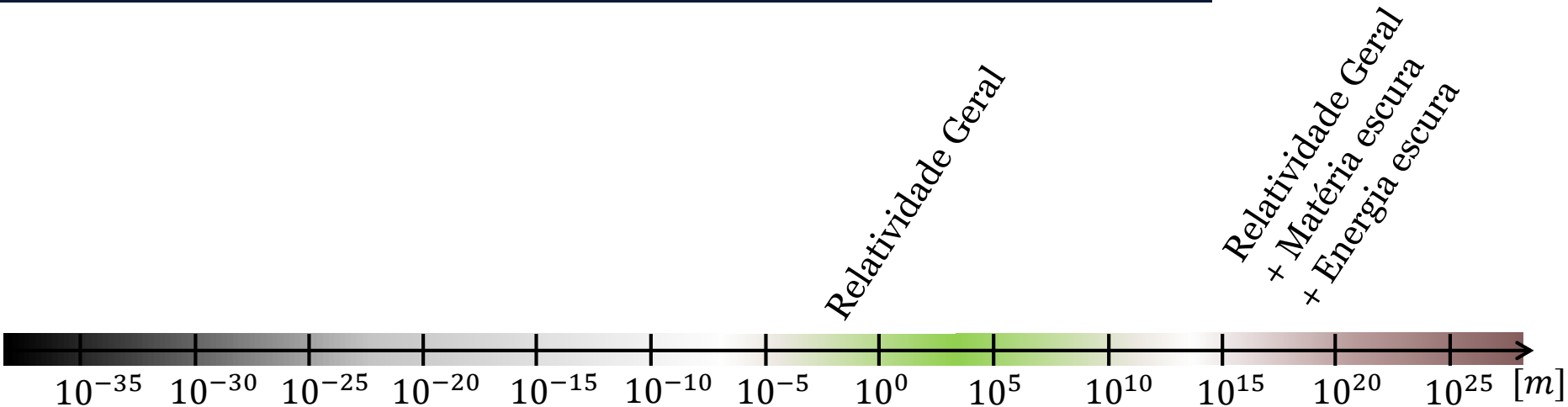
Ainda é cedo!

Relatividade Geral

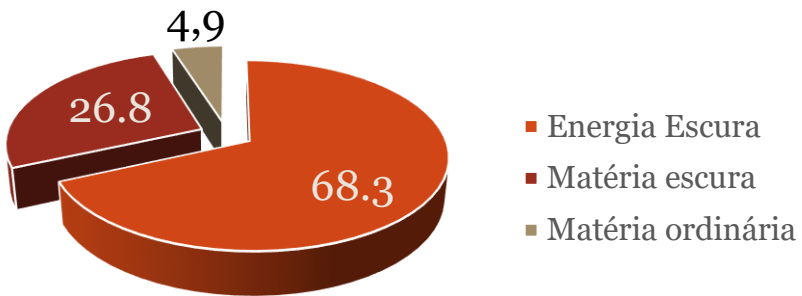


10^{-35} 10^{-30} 10^{-25} 10^{-20} 10^{-15} 10^{-10} 10^{-5} 10^0 10^5 10^{10} 10^{15} 10^{20} 10^{25} [m]

Ainda é cedo!



■ O modelo padrão de cosmologia



Ainda é cedo!

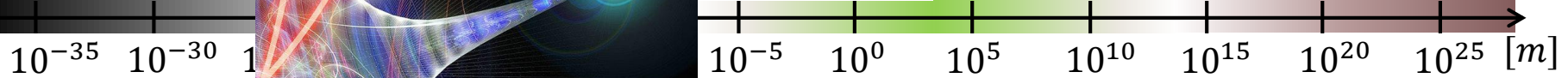
- Singularidades

Gravitação
quântica?

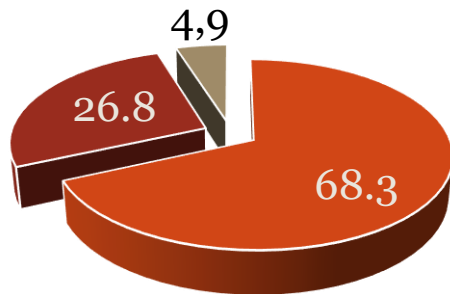


Relatividade Geral

Relatividade Geral
+ Matéria escura
+ Energia escura



- O modelo padrão de cosmologia



- Energia Escura
- Matéria escura
- Matéria ordinária



E o futuro?

