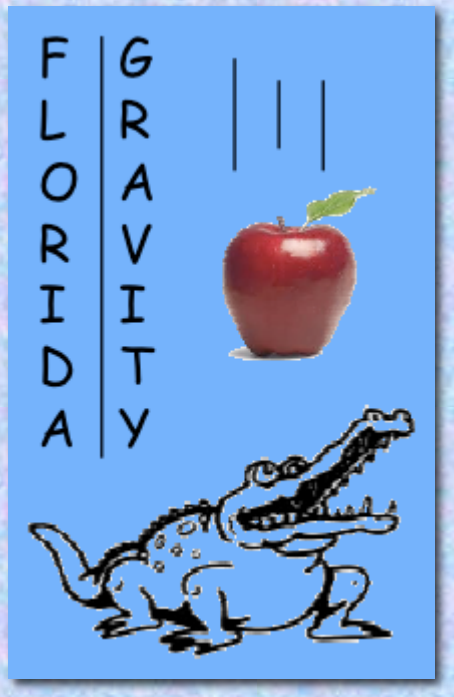
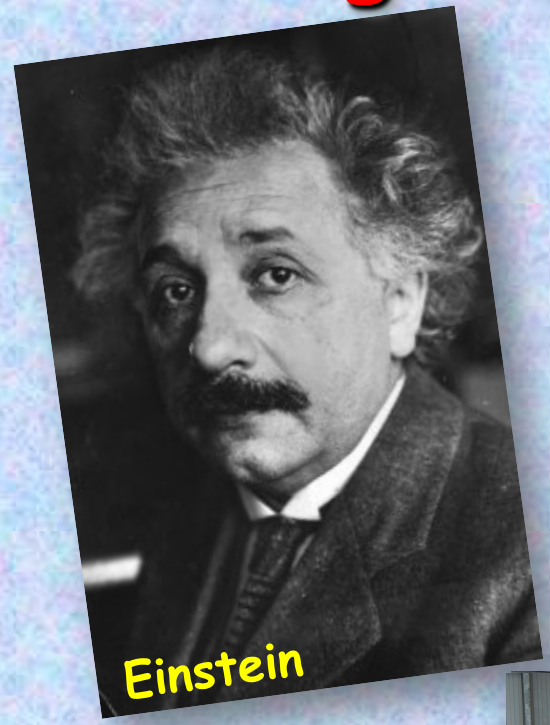
Is Einstein Still Right?

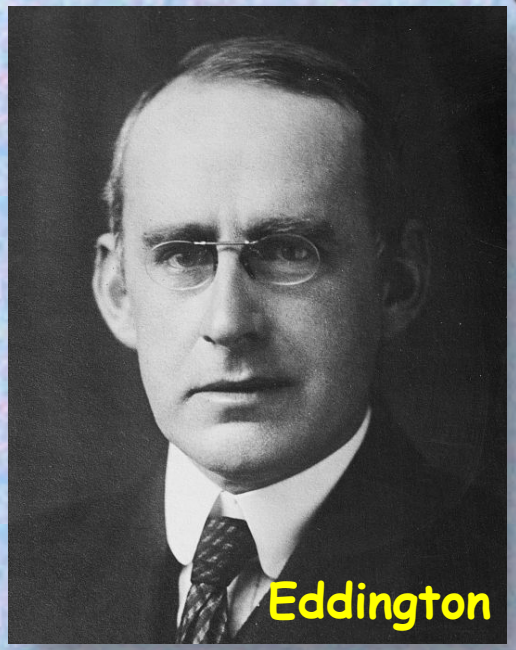


Clifford Will
University of Florida, Gainesville
Institut d'Astrophysique de Paris

Eddington at Sundy, Principe Island, 27 May 2019

The general relativity fairy tale





Principe 2019

FLORIDA GRAVITY

Is Einstein Still Right?

- The Einstein Equivalence Principle: Gravity = Geometry
- Geometry bends light
- Mercury's perihelion . . . keeps on giving
- The Strong Equivalence Principle
- Gravitational waves: a new tool for testing GR

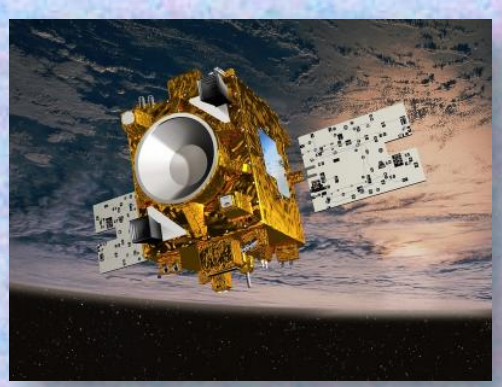
The Einstein Equivalence Principle

- Test bodies fall with the same acceleration
  Weak Equivalence Principle (WEP)
- In a local freely falling frame, physics (nongravitational) is independent of frame's velocity
  Local Lorentz Invariance (LLI)
- In a local freely falling frame, physics (non-gravitational) is independent of frame's location
  Local Position Invariance (LPI)

EEP => Metric theory of gravity

- $\eta_{\mu\nu}$ locally -> symmetric $g_{\mu\nu}$
- "comma" -> "semicolon"

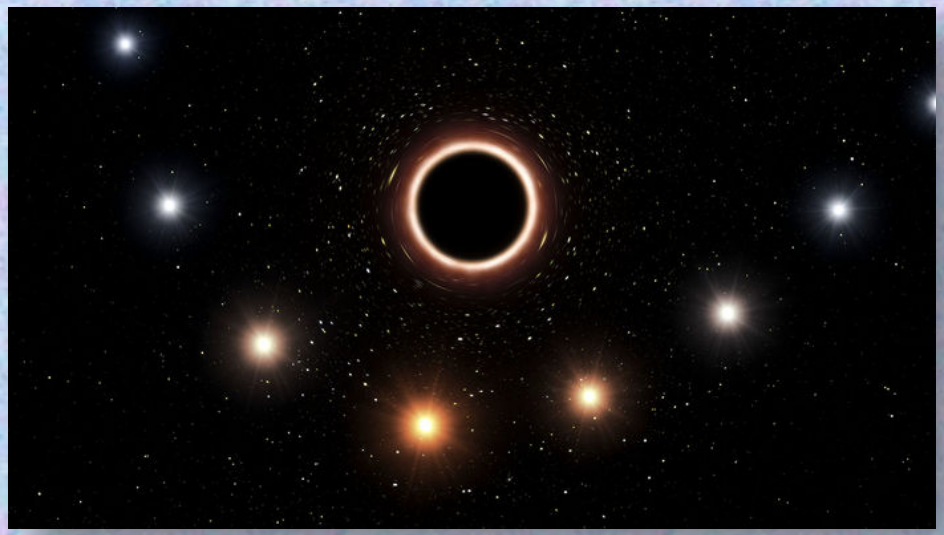
Gravity = Geometry

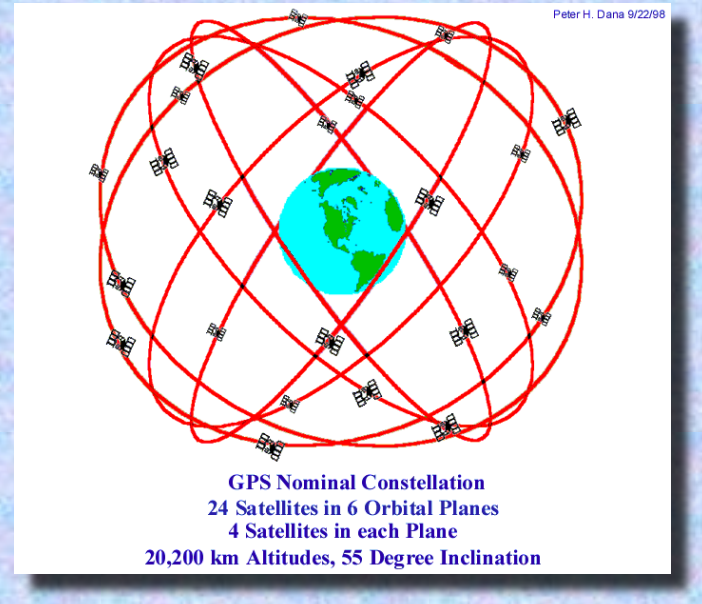


Microscope

Local Position Invariance: the redshift

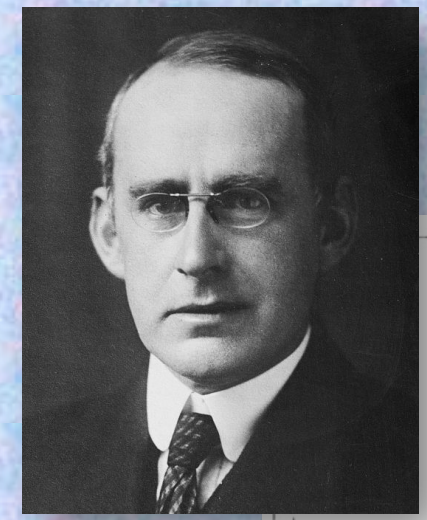
- 1907: Einstein's "happiest thought"
- 1917: C. E. St. John and others: no Solar redshift effect
- 1925: Adams, Eddington & Sirius B
- 1960: Pound-Rebka: gamma rays from ^{57}Fe over 23 m
- 1976: Gravity Probe A
- 1980s – now: GPS
- 2010: ^{27}Aluminum ion clocks over 1/3 m
- 2018: S2 passage 130 a.u from SgrA*
- 2020: ACES/PHARAO on the ISS



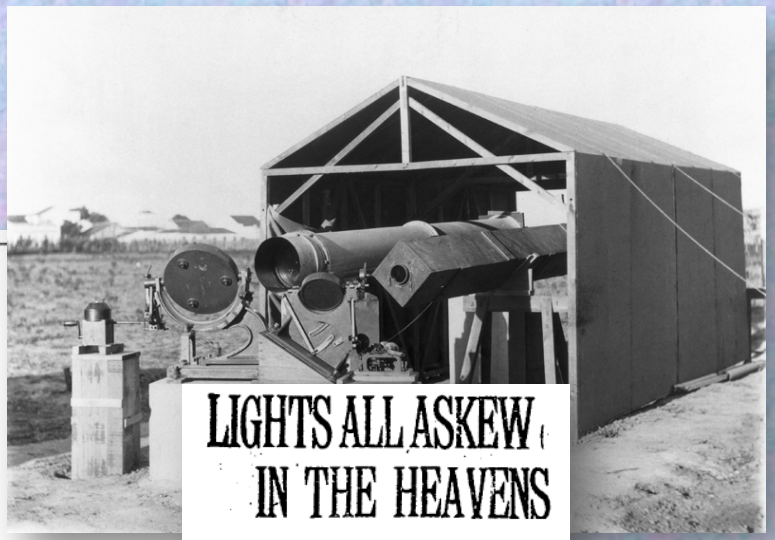


FLORIDA GRAVITY

Geometry bends light: the 1919 expedition



A. S. Eddington



Sobral site

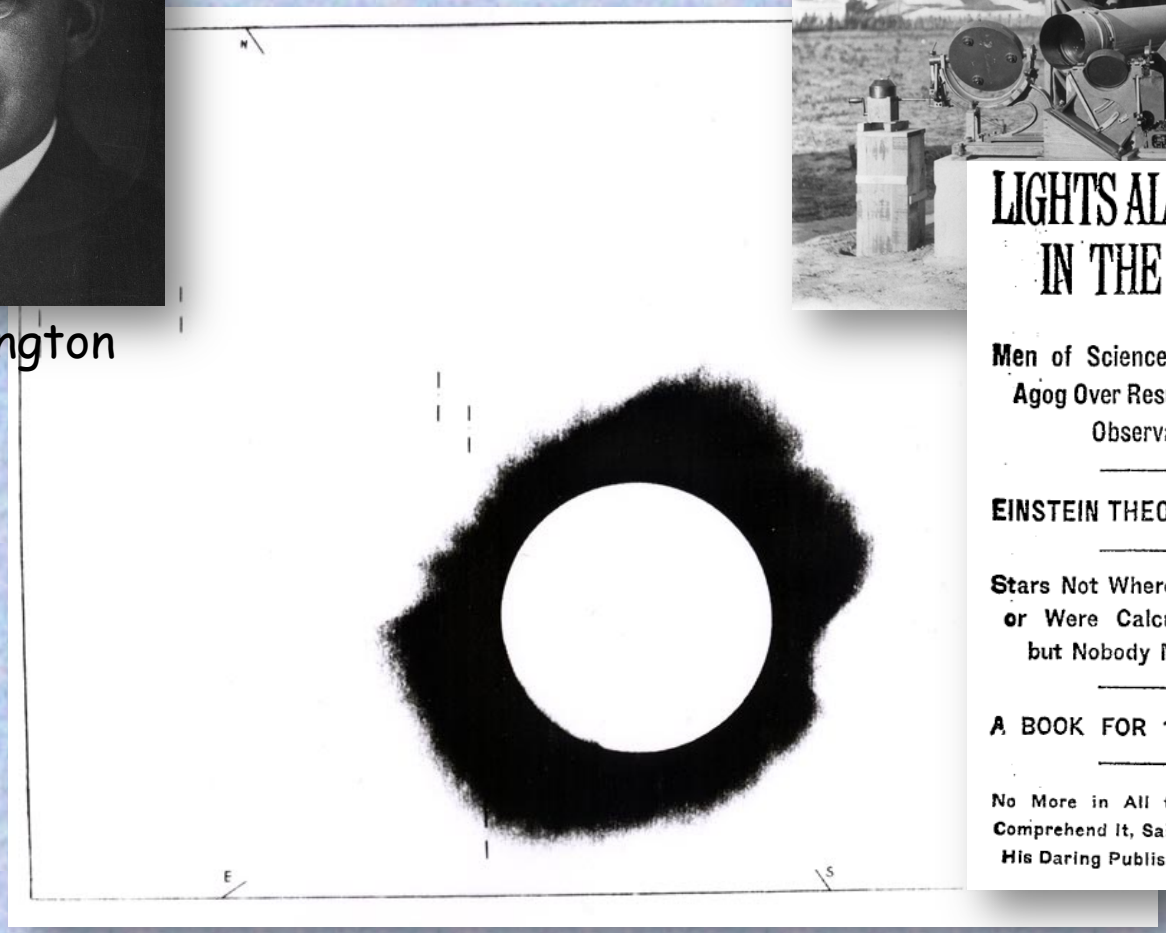


Photo from Principe

LIGHTS ALL ASKEW IN THE HEAVENS

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

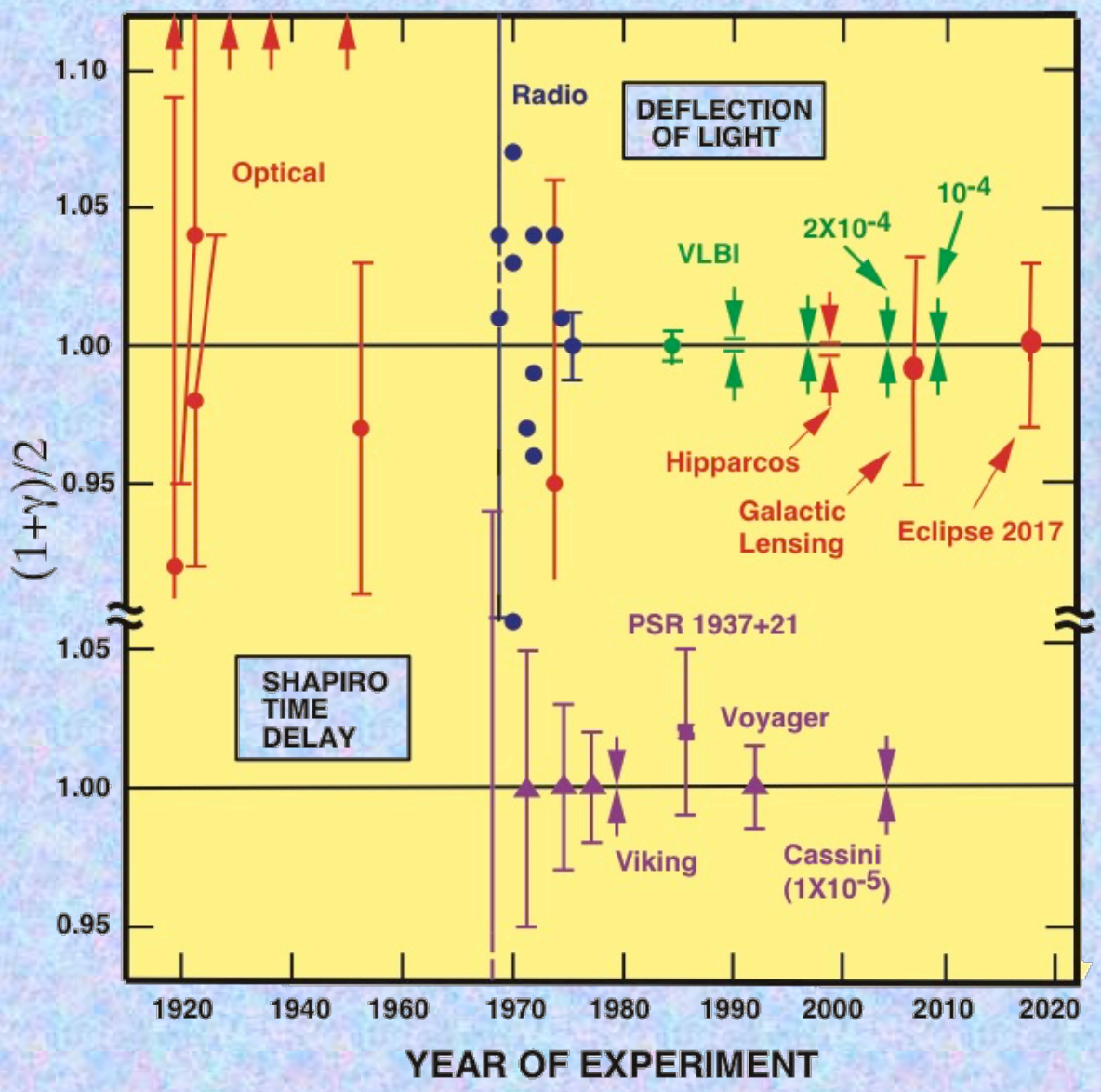
EINSTEIN THEORY TRIUMPHS

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

A BOOK FOR 12 WISE MEN

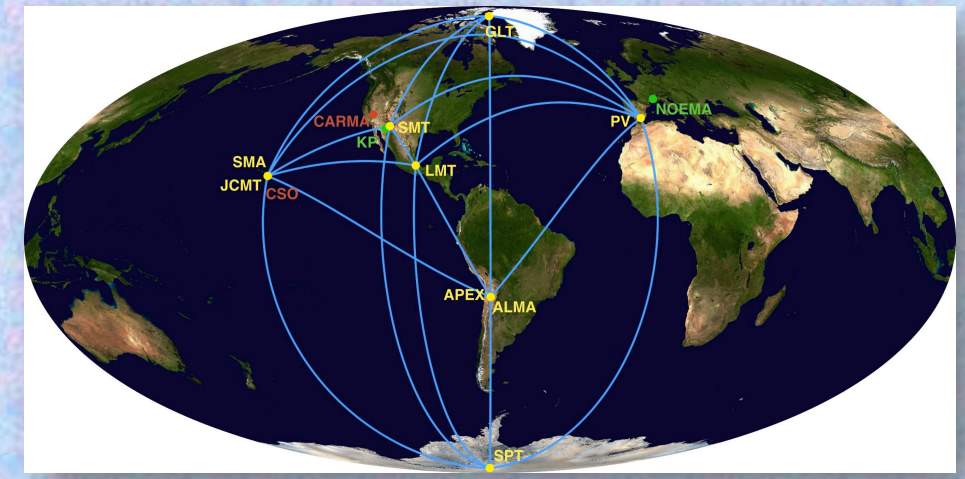
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Measuring the PPN parameter γ



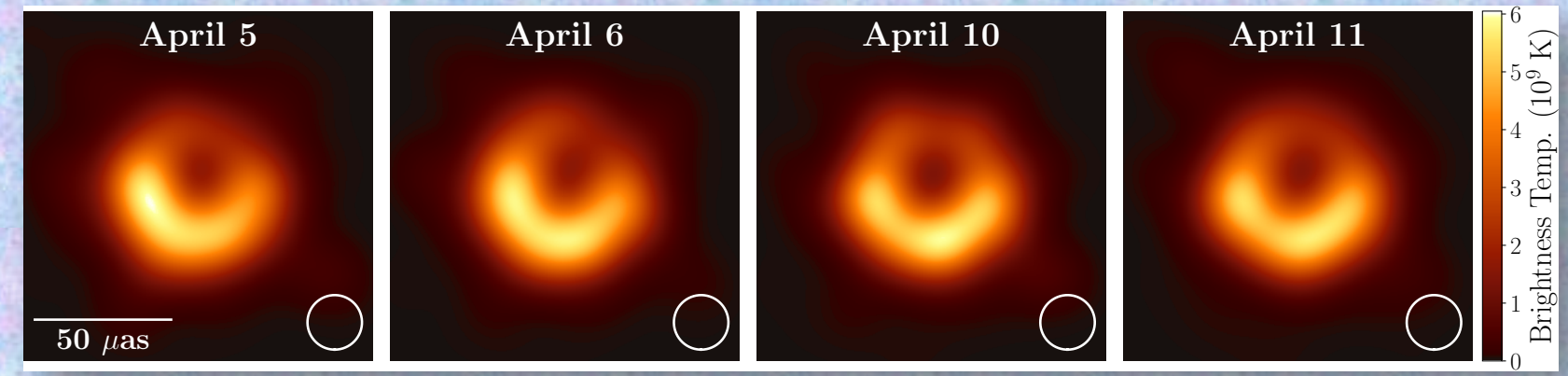
Donald Bruns in Wyoming

Geometry bends light: Black hole shadows



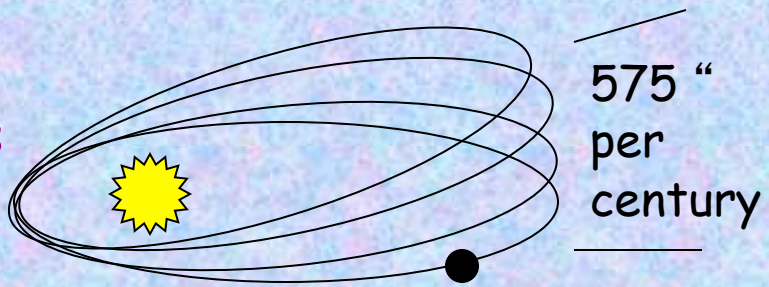
Event Horizon Telescope (EHT)

- mm wavelength
- horizon scale angular resolution at SgrA* and M87



Mercury's perihelion advance

- 1859 Leverrier's conundrum
- 1900 A turn-of-the century crisis
- 1915 "Palpitations of the heart"



Planet	Advance
Venus	277.8
Earth	90.0
Mars	2.5
Jupiter	153.6
Saturn	7.3
Total	531.2
Discrepancy	42.9
Modern measured value	42.982 ± 0.002
General relativity prediction	42.98

Mercury's perihelion advance

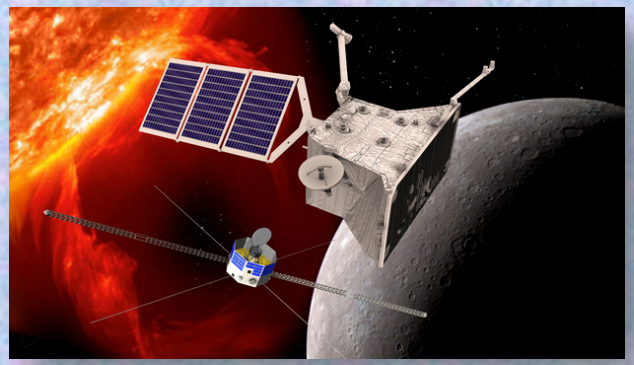
$$\Delta\omega = \left(\frac{2+2\gamma-\beta}{3}\right)\frac{6\pi GM}{c^2 a(1-e^2)} + \frac{3\pi}{2}\frac{m_3}{m}\left(\frac{a}{R}\right)^3 (1-e^2)^{1/2}$$

PPN

Other bodies

Effect	Formula (rad/orbit)	Value relative to GR
Solar oblateness	$3\pi J_2 (R/p)^3$	6.5×10^{-4}
Frame dragging	$-8\pi GJ/c^2(Gmp^3)^{1/2}$	4.7×10^{-5}
PN cross term	$(3\pi Gm_3a^2/4c^2R^3)(28+47e^2)(1-e^2)^{-3/2}$	3.7×10^{-6}
GM/de Sitter	$(4\pi Gm_3/c^2a)\,(a/R)^{5/2}$	1.5×10^{-6}
2PN	$-6\pi(Gm/2c^2p)^2(10-e^2)$	6.6×10^{-8}

CMW, PRL **120**, 191101 (2018)



BepiColombo
Launched 20/10/2018
2 Mercury orbiters

Tests of the Strong Equivalence Principle

- ~~Test~~ All bodies fall with the same acceleration

- In a local freely falling frame, physics ~~(nongravitational)~~ is independent of frame's velocity

- In a local freely falling frame, physics ~~(non-gravitational)~~ is independent of frame's location

The Strong Equivalence Principle, satisfied by GR, but not by most alternative theories. The motions of **all** bodies, including NS and BH, are independent of their internal structure – in GR!

Tests of the Strong Equivalence Principle

$$\Delta a \sim \Delta\left(\frac{E_g}{mc^2}\right) \times g$$

Body	E_g/mc^2
Earth	-4.8×10^{-10}
Moon	-0.2×10^{-10}
Sun	$\sim 10^{-6}$
White dwarf	$\sim 10^{-4}$
Neutron star	~ 0.2

Lunar Laser Ranging

$$\Delta a/g < 2 \times 10^{-13}$$

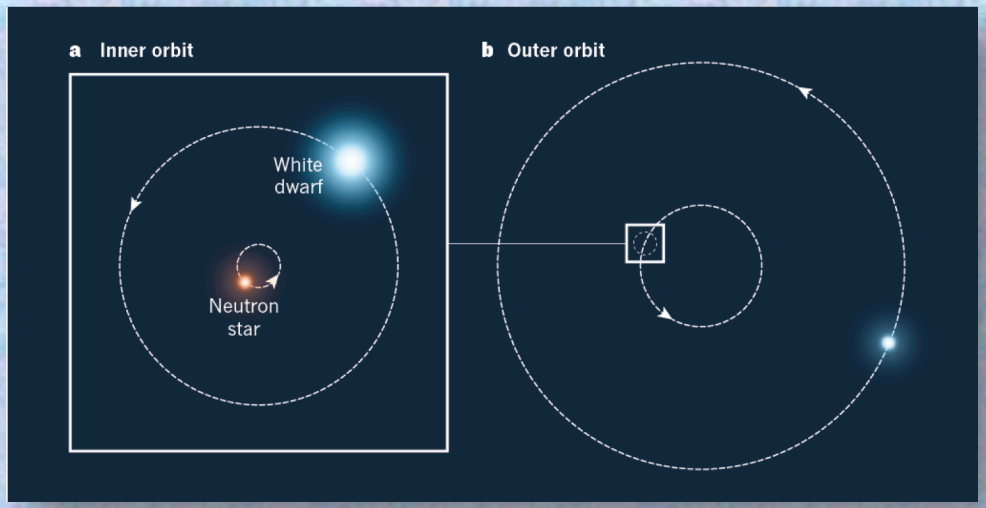
$$\Delta(E_g/mc^2) = 4.6 \times 10^{-10}$$

$$\text{constraint} < 4.4 \times 10^{-4}$$

A Strong-field test of SEP

A pulsar in a triple system J0337+1715 (2014)

	Inner binary	Outer binary
$M_1(M_\odot)$	1.4378	1.6353
$M_2(M_\odot)$	0.1975	0.4103
$P_b(\text{days})$	1.629	327.26
$e(10^{-2})$	0.0692	3.5356



$$\Delta a/g < 2 \times 10^{-6}$$

$$\Delta(E_g/mc^2) \sim 0.2$$

$$\text{constraint} < 10^{-5}$$

Archibald et al *Nature* **559**, 73 (2018)
CMW, Commentary, *Nature* **559**, 40 (2018)

GW Events during O1 and O2

Name	Nature	Detectors	Masses ($M_\odot$)	Distance (Mpc)
GW150914	BH-BH	LIGO	29 & 36	430
GW151012	BH-BH	LIGO	14 & 23	1000
GW151226	BH-BH	LIGO	8 & 14	440
GW170104	BH-BH	LIGO	20 & 31	960
GW170608	BH-BH	LIGO	8 & 11	320
GW170729	BH-BH	LIGO	34 & 51	2750
GW170809	BH-BH	LIGO	24 & 35	990
GW170814	BH-BH	LIGO-Virgo	25 & 31	580
GW170817	NS-NS	LIGO-Virgo EM detectors	1.3 & 1.5	40
GW170818	BH-BH	LIGO-Virgo	27 & 36	1000
GW170823	BH-BH	LIGO	29 & 40	1850

O3 began April 1, 2019 with LIGO & Virgo for 12 months

FLORIDA GRAVITY

Propagation of Gravitational Waves: Speed

Why Speed could differ from "1"

- massive graviton: $v_g^2 = 1 - (m_g/E_g)^2 = 1 - (\lambda/\lambda_g)^2$
- $g_{\mu\nu}$ coupling to background fields: $v_g = F(\phi, K^\alpha, H^{\alpha\beta})$
- gravity waves propagate off the brane

Examples

- General relativity. For $\lambda \ll R$, GW follow geodesics of background spacetime, as do photons ($v_g = 1$)
- Scalar-tensor gravity. Tensor waves can have $v_g \neq 1$, if scalar is massive
- Horndeski-type theories: $g_{\mu\nu}$ coupling to ϕ and its derivatives
- Massive gravity theories with background metric.

Possible Limits

$$v_g - 1 = 5 \times 10^{-17} \left(\frac{200\,\mathrm{Mpc}}{D} \right) \left(\frac{\Delta t - (1+Z)\Delta t_e}{1\,\mathrm{s}} \right)$$

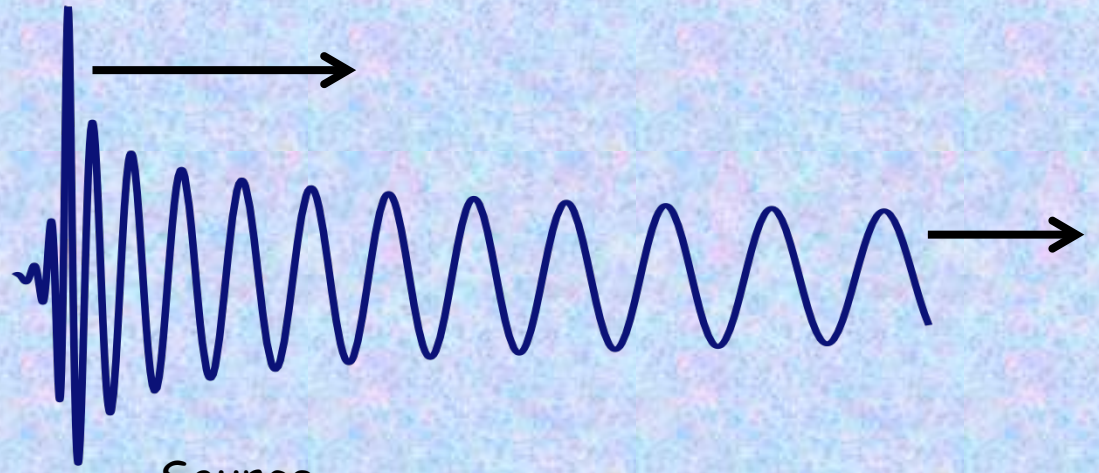
GW170817 & GRB170817: $v_g = 1$

$$D = 43\,\mathrm{Mpc}\,, \quad \Delta t = 1.74\,\mathrm{s}\,, \quad \Delta t_e \sim (0, 10)\,\mathrm{s}$$

$$-2 \times 10^{-15} < v_g - 1 < 4 \times 10^{-16}$$

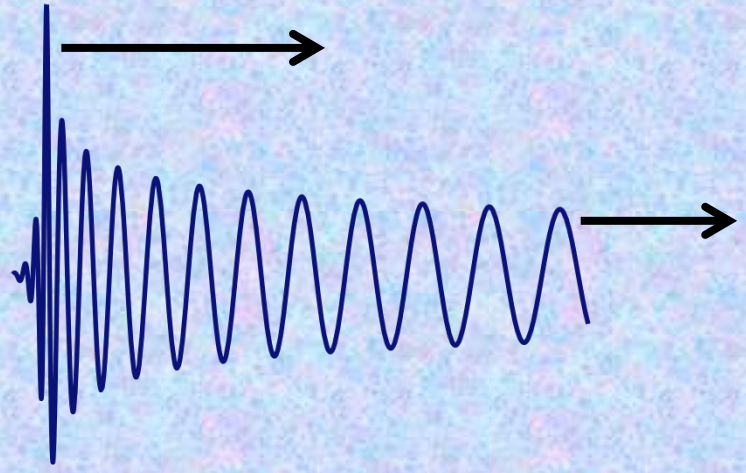
Phys. Rev. Lett. **119**
22 Dec 2017:
Baker et al. 251301
Creminelli et al. 251302
Sakstein et al. 251303
Ezquiaga et al. 251304

Bounding the graviton mass



Source

Detector



CMW, PRD 57, 2061 (1998)

Bounding the graviton mass

m_1	m_2	Distance(Mpc)	Bound on λ_g (km)
Ground-Based (LIGO/VIRGO)			
1.4	1.4	300	4.6×10^{12}
10	10	1500	6.0×10^{12}
Space-Based (LISA)			
10^7	10^7	3000	6.9×10^{16}
10^5	10^5	3000	2.3×10^{16}

Berti, Buonanno, Yunes, Arun, Stavridis, CW

Other methods	Comments	Bound on λ_g (km)
Solar system $1/r^2$ law	Assumes direct link between static λ_g and wave λ_g	3×10^{12} (Talmadge et al 1988)
Galaxies & clusters	Model dependent	6×10^{19}

Bounding the graviton mass

GW150914, GW151226 & GW170104:
$\lambda_g > 1.6 \times 10^{13}$ km

O1 & O2 BBH
$\lambda_g > 2.4 \times 10^{13}$ km
(arXiv:1903.04467}

Mars perihelion advance:
$\lambda_g > (1.2 - 2.2) \times 10^{14}$ km
(CMW, *CQG Lett.* 2018)

Full ephemeris analysis
$\lambda_g > 1.8 \times 10^{13}$ km
(Bernus et al 1901.04307)

		ance(Mpc)	Bound n λ_g)
		PGO)	
		0	6
10^5	10^5	000	2.3 X 6

Berti, Buonanno, Yunes, run, Stavridi W

		tic λ_g	
Ge		pendent	X

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