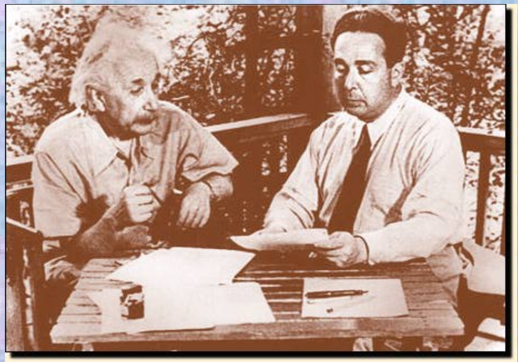
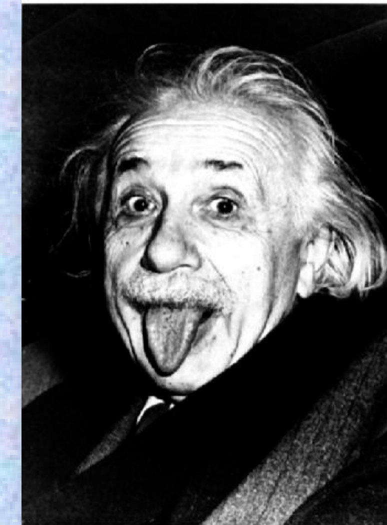
Was Einstein Right?
A Centennial Assessment

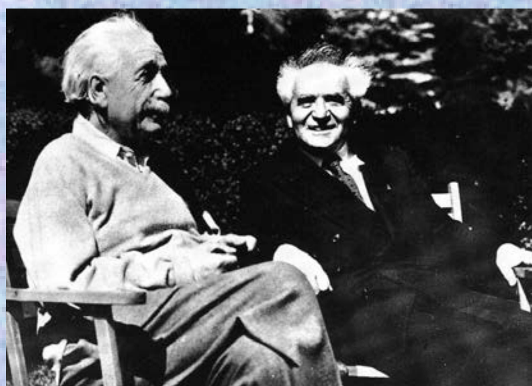
Clifford Will
University of Florida, Gainesville
Institut d'Astrophysique de Paris

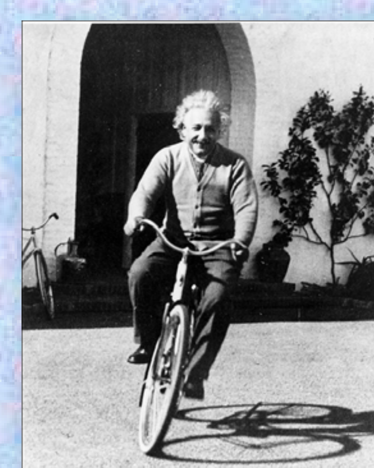
University of British Columbia, 5 February, 2015

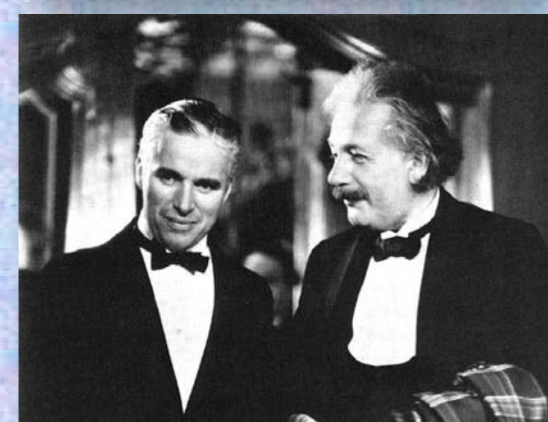
The public Einstein

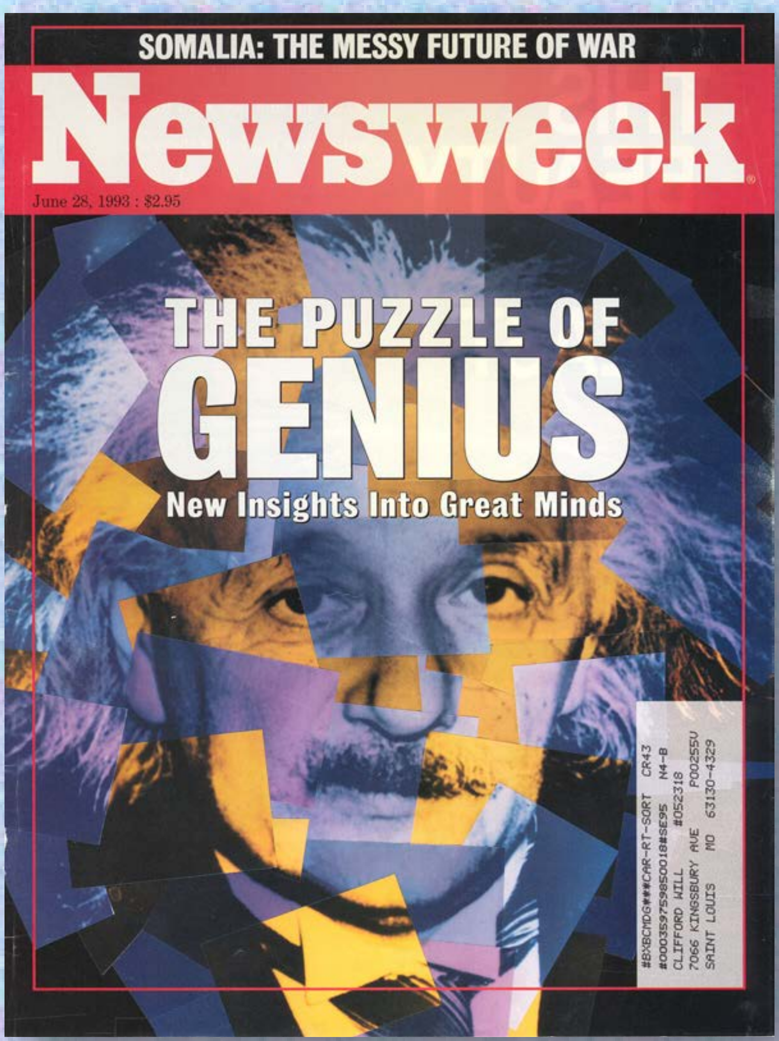











SOMALIA: THE MESSY FUTURE OF WAR
Newsweek
June 28, 1993 : $2.95
THE PUZZLE OF
GENIUS
New Insights Into Great Minds
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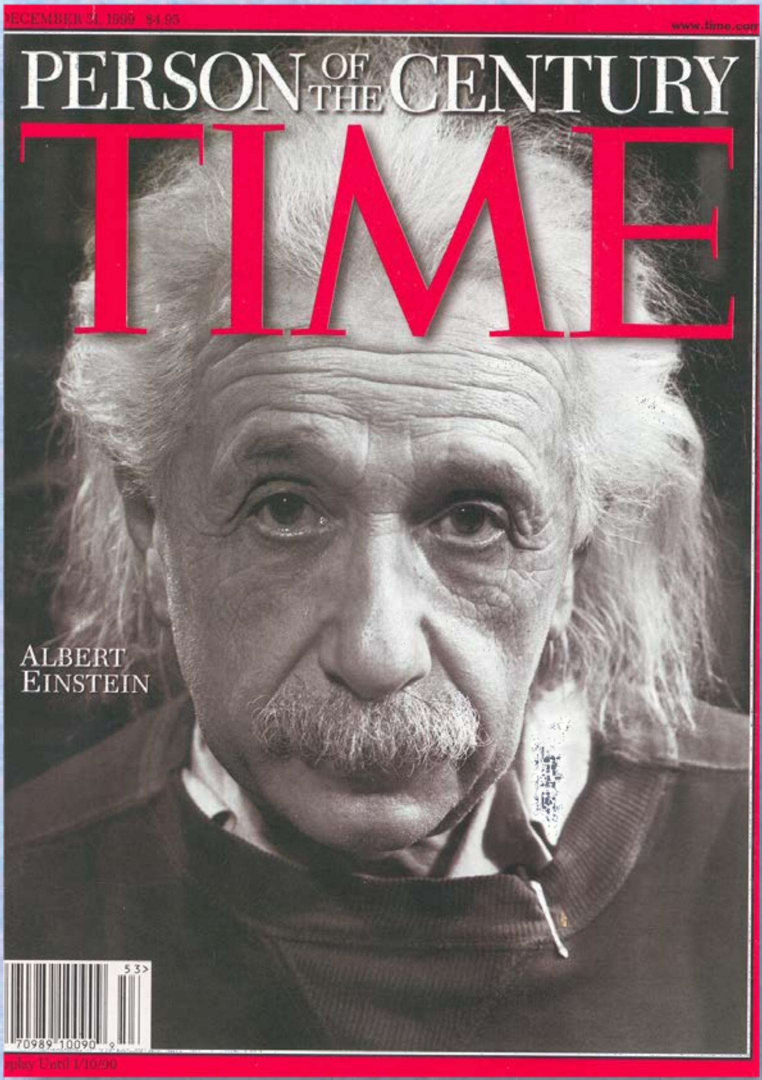
www.time.com
PERSON OF THE CENTURY
TIME
ALBERT
EINSTEIN

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Einstein triumphant, or was he?

- Early struggles and uncertainties

1st century themes

- High precision technology (clocks, space)
- Frameworks for comparing and testing theories
- Theory-experiment synergy

2nd century themes

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- Gravitational-wave tests
- Extreme-range tests

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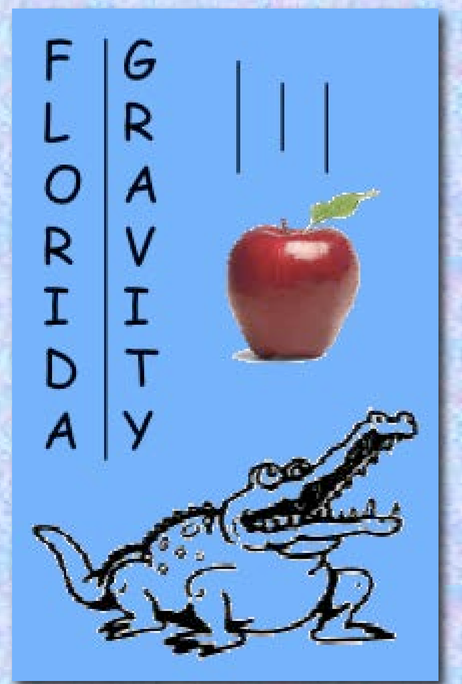
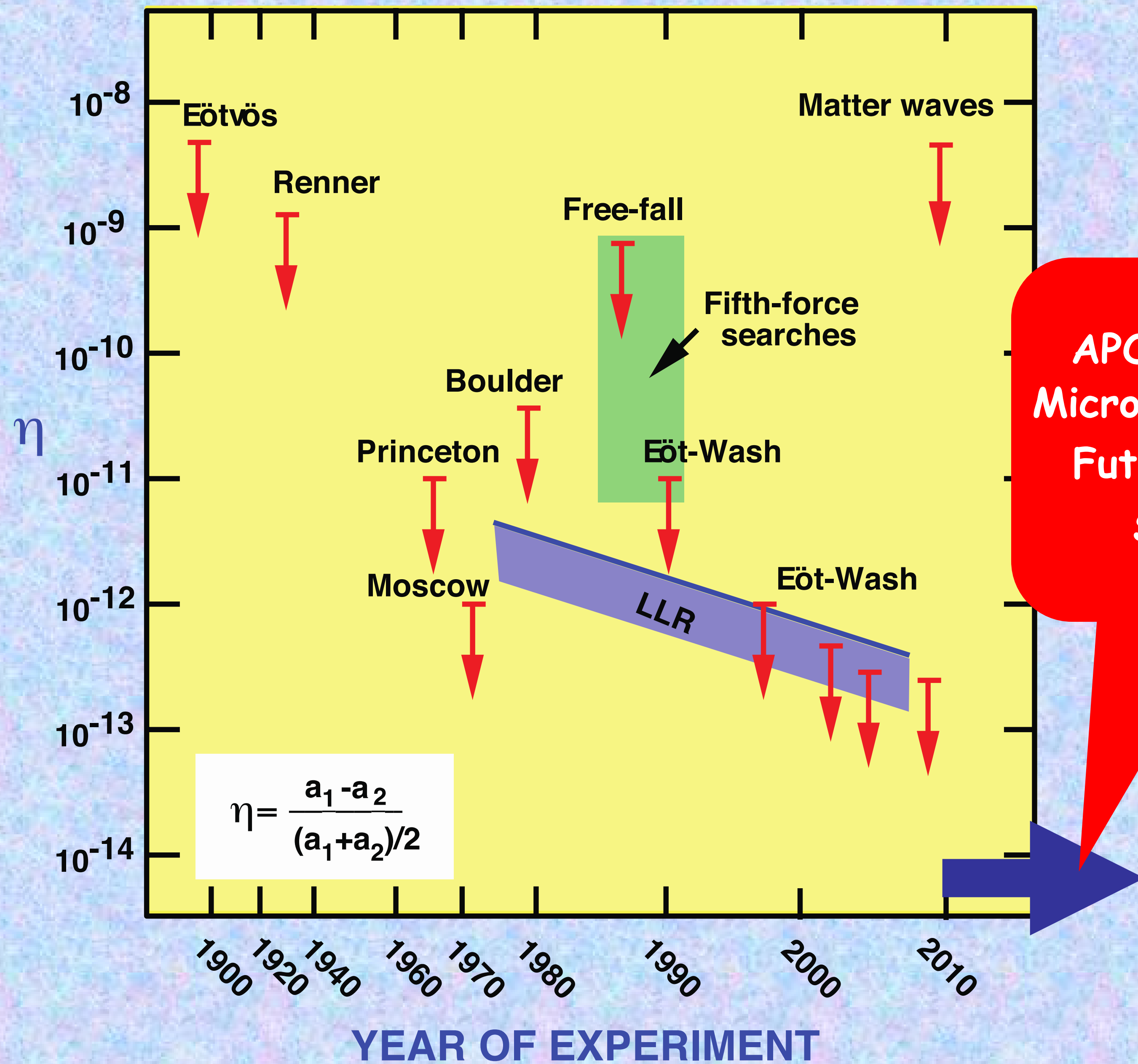
- Prospects for the second century

  - Gravity is geometry
  - Geometry bends light
  - Geometry warps time
  - Geometry moves mass
  - Geometry has waves
  - Geometry makes black holes



Gravity is geometry: the equivalence principle



APOLLO (LLR) 10^{-13}

Microscope 10^{-15} (2015)

Future: STEP, GG, STE-QUEST

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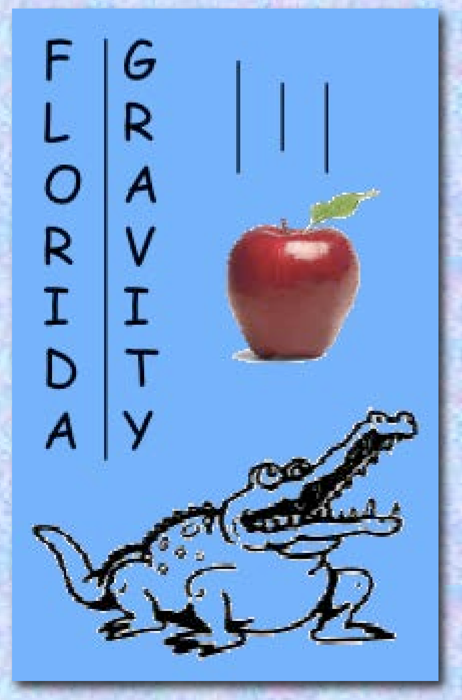
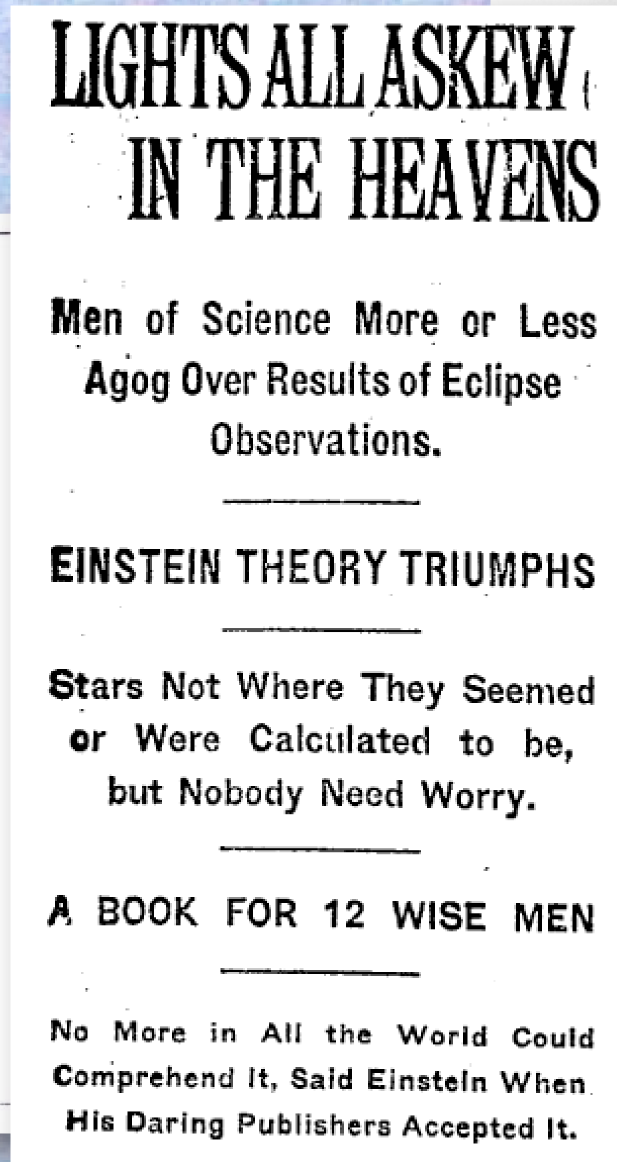


University of British Columbia, 5 February, 2015

Geometry bends light: The 1919 Eclipse

A. S. Eddington



LIGHTS ALL ASKEW IN THE HEAVENS

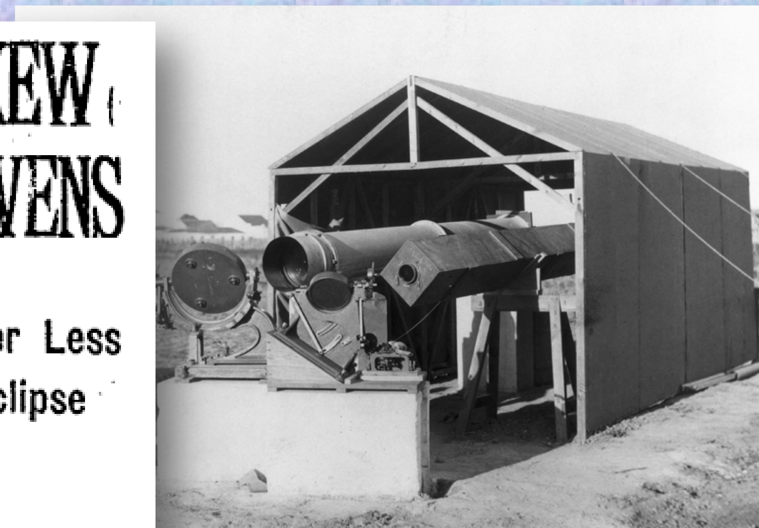
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

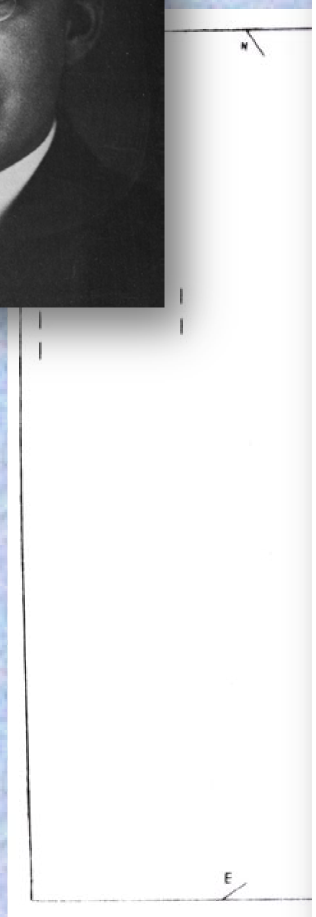
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

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

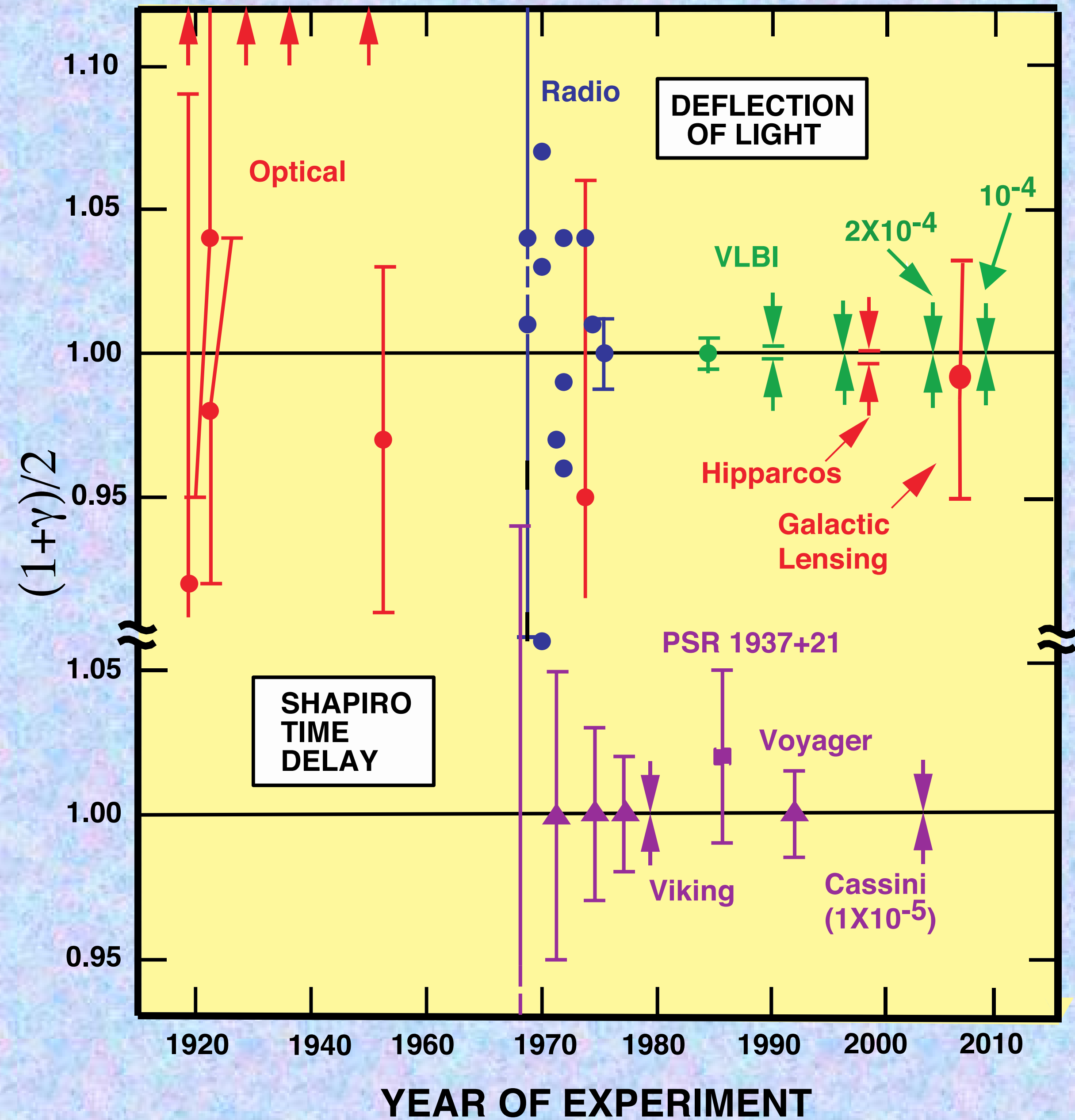


Sobral site

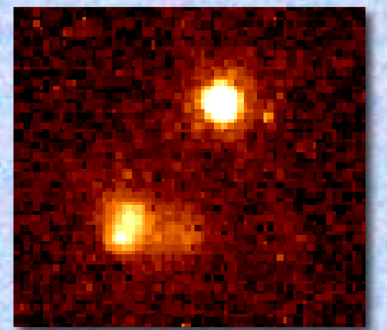
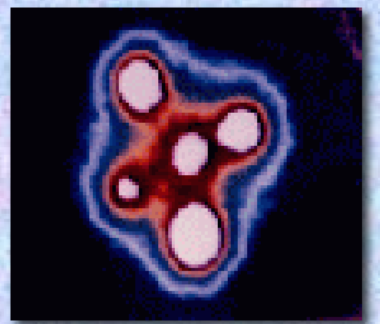
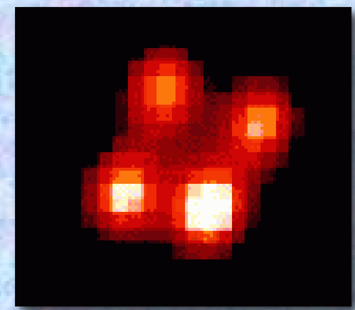
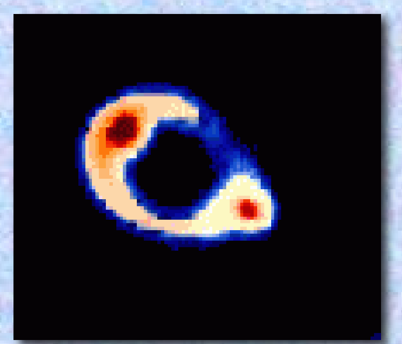


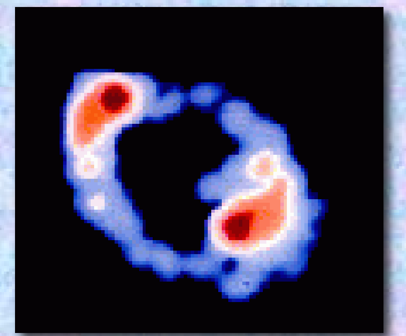
from Principe

Geometry bends light: The PPN parameter γ



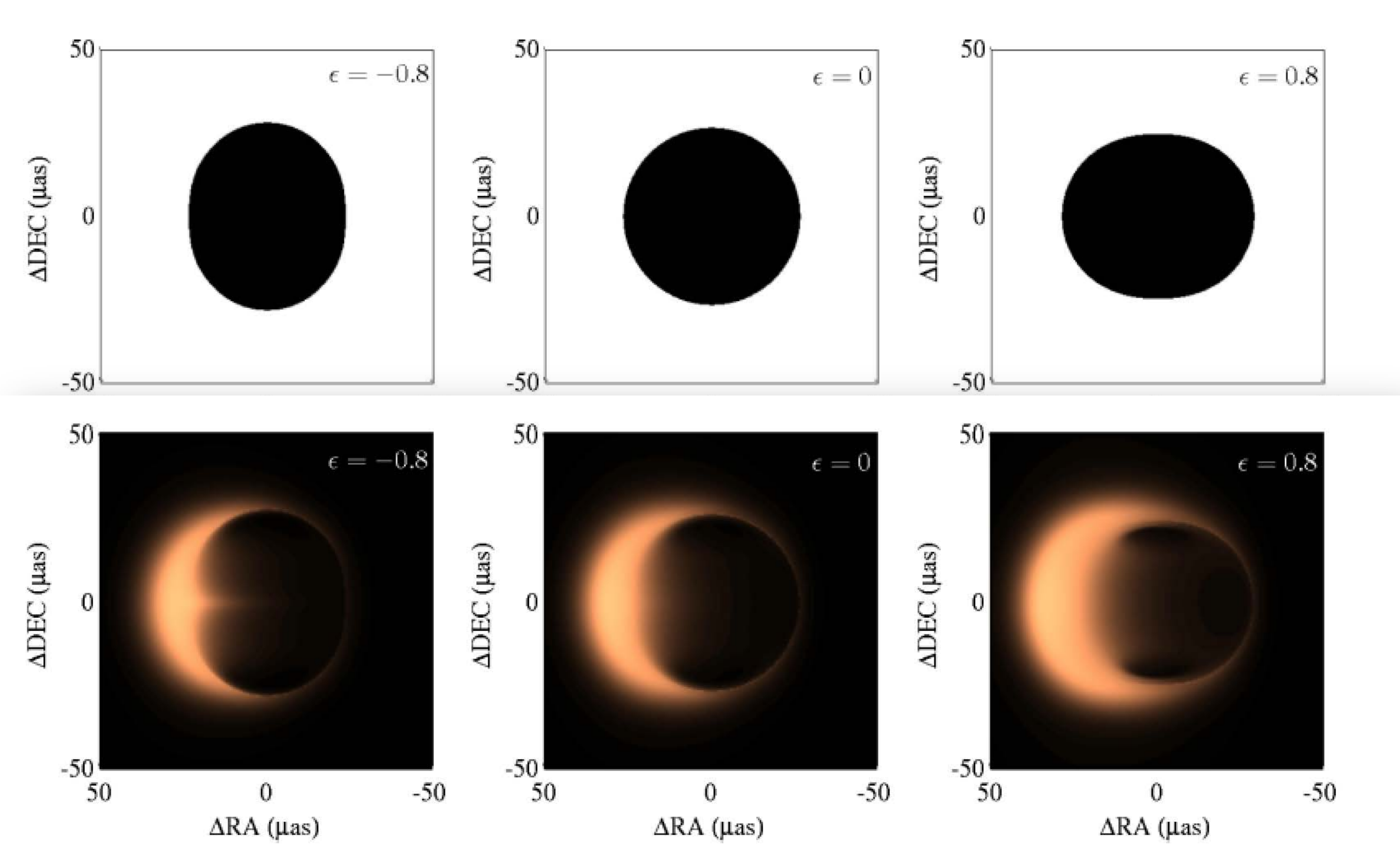
Geometry bends light: Gravitational lenses




Geometry bends light: Black hole shadows

$$\epsilon = \frac{Q_2 + Ma^2}{M^3}$$



mm-wavelength VLBI using Event Horizon Telescope

Broderick et al, *Ap J.* 784, 7 (2014)

Geometry bends light: Black hole shadows

Interstellar, Paramount Pictures
Directed by Christopher Nolan
Image based on calculations by Kip Thorne and Double Negative Co.

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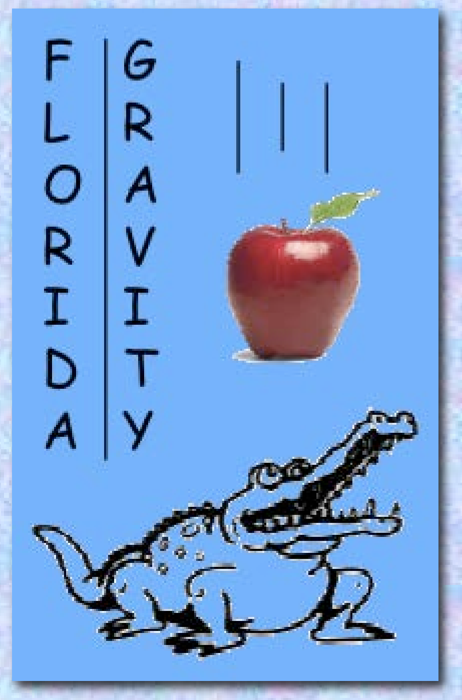
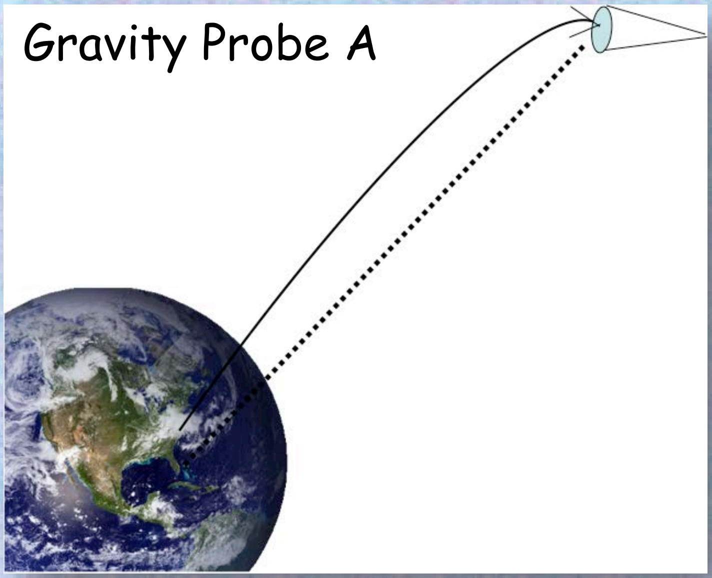
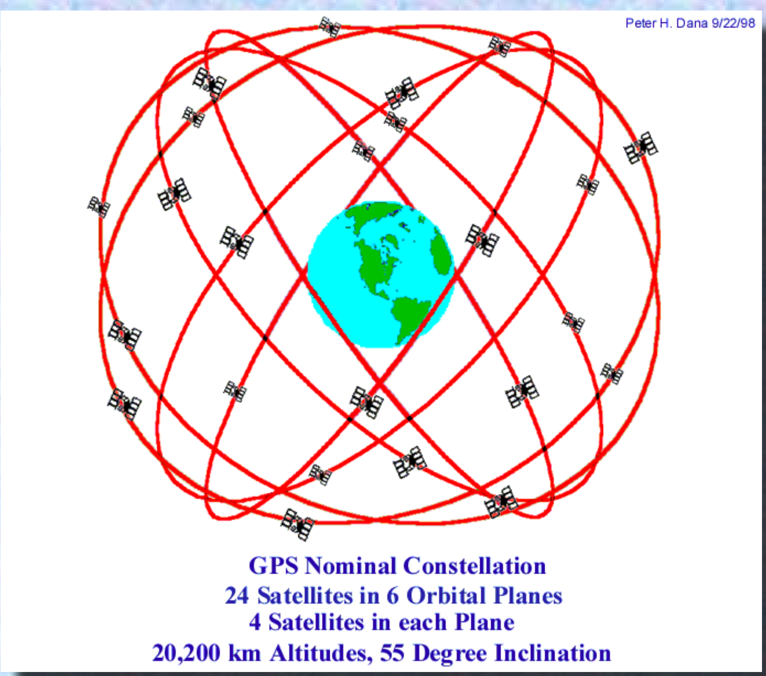


Geometry warps time: The redshift

- 1907: Einstein's "happiest thought"
- 1917: C. E. St. John and others: no Solar redshift effect
- 1960: Pound-Rebka: gamma rays from ^{57}Fe over 23 m
- 1962, 1972, 1991: finally, the Solar redshift measured
- 1976: Gravity Probe A
- 1980s – now: GPS
- 2010: ^{27}Aluminum ion clocks
  over 1/3 m
- 2016: ACES/PHARAO on the ISS





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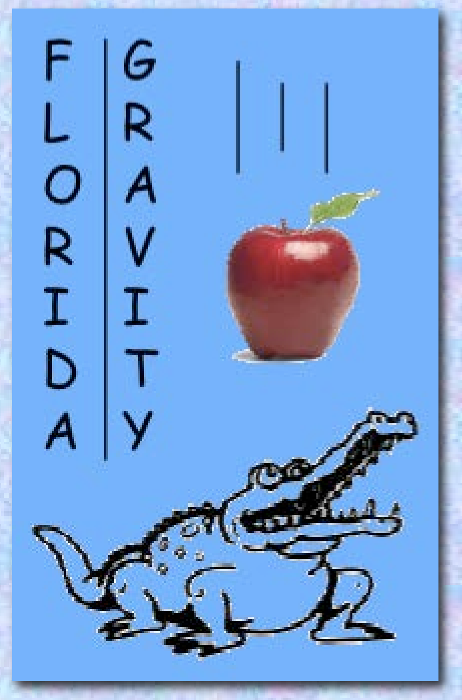
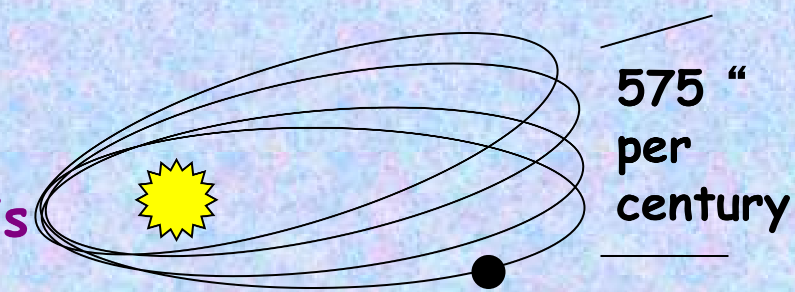
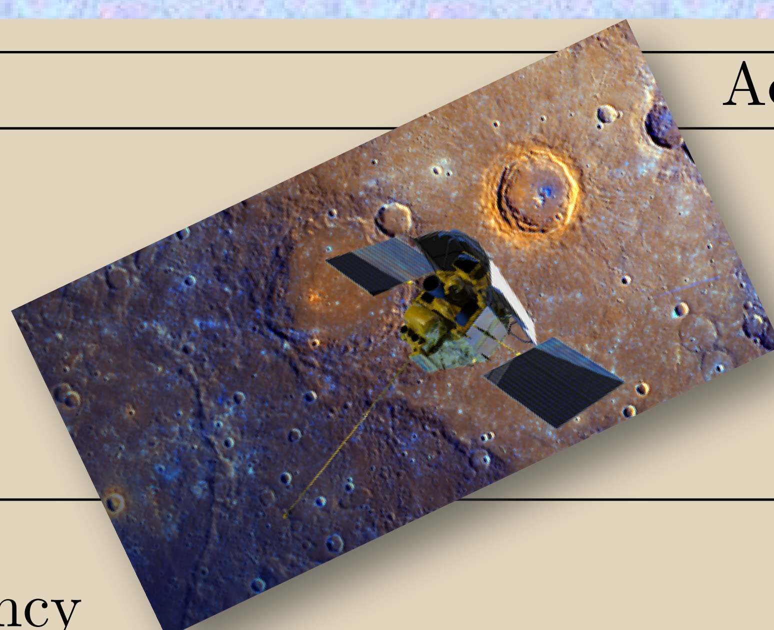


University of British Columbia, 5 February, 2015

Geometry moves mass: Mercury's perihelion

- 1687 Newtonian triumph
- 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

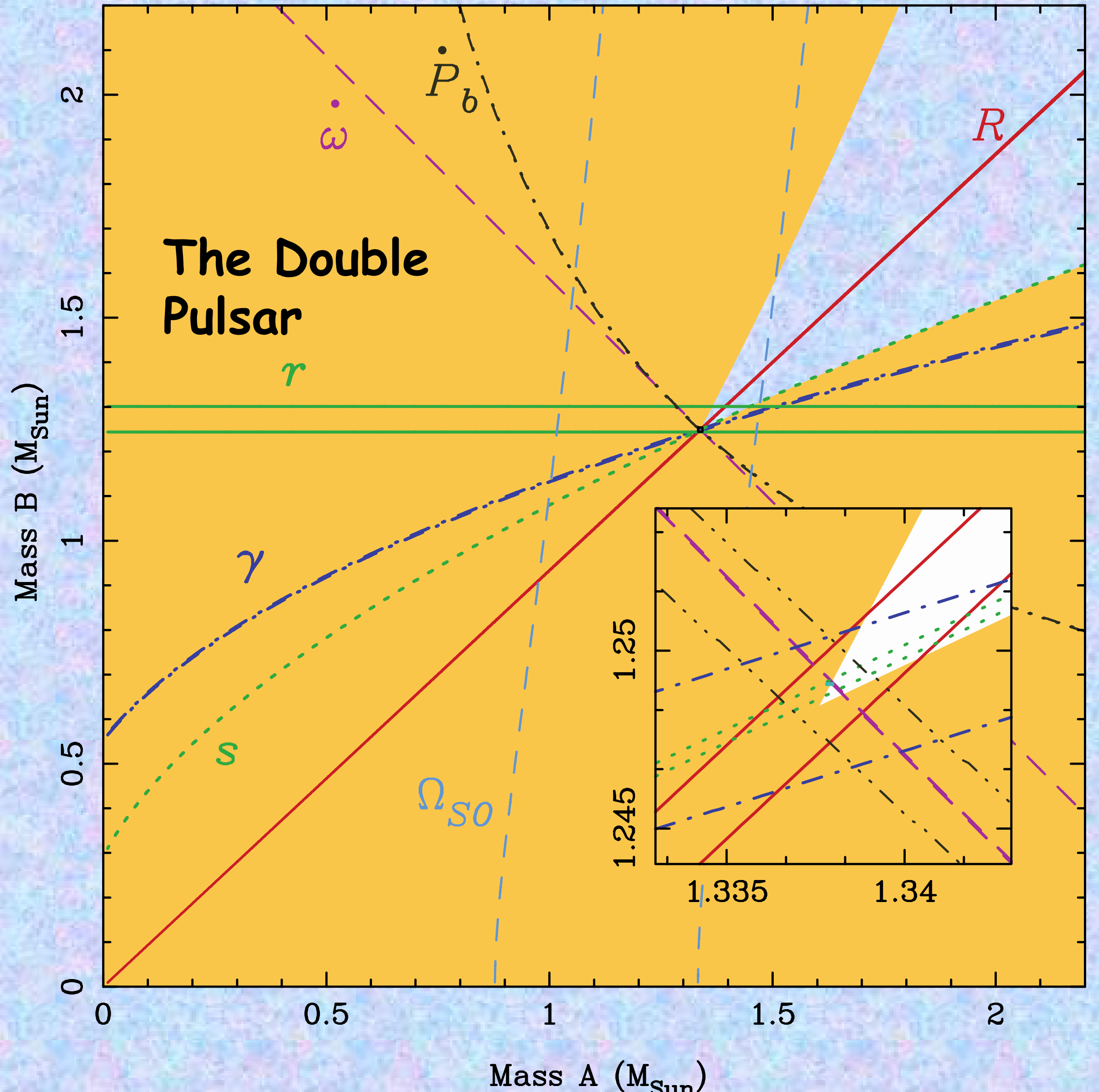
$J_2 = 2.2 \times 10^{-7}$

Bounds on the PPN Parameters

Parameter	Effect or Experiment	Bound	Remarks
$\gamma - 1$	Time delay	2.3×10^{-5}	Cassini tracking
	Light deflection	2×10^{-4}	VLBI
$\beta - 1$	Perihelion shift	3×10^{-5}	$J_2 = 2.2 \times 10^{-7}$
	Nordtvedt effect	2.3×10^{-4}	Lunar laser ranging
ξ	Spin Precession	4×10^{-9}	Millisecond pulsars
α_1	Orbit polarization	10^{-4}	Lunar laser ranging
		4×10^{-5}	Pulsar J 1738+0333
α_2	Spin precession	2×10^{-9}	Millisecond pulsars
α_3	Self-acceleration	4×10^{-20}	Pulsar spindown
ζ_1	--	2×10^{-2}	Combined bounds
ζ_2	Binary acceleration	4×10^{-5}	PSR 1913+16
ζ_3	Newton's 3rd law	10^{-8}	Lunar acceleration
ζ_4	--		Not independent

Bound on scalar-tensor gravity: $\omega > 40{,}000$

Geometry moves mass: GR test-beds



Courtesy M. Kramer

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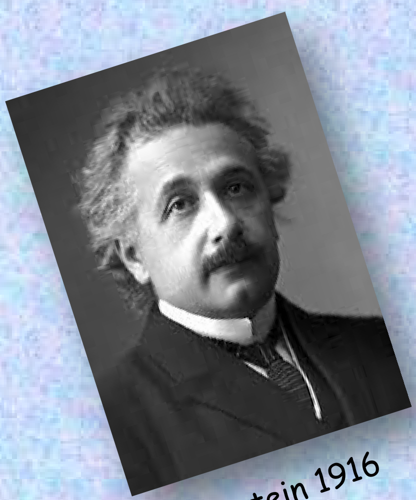
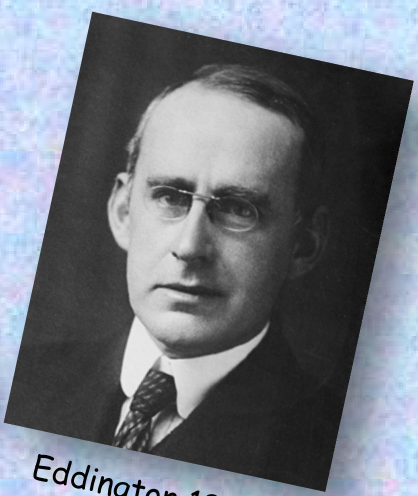
Geometry has waves

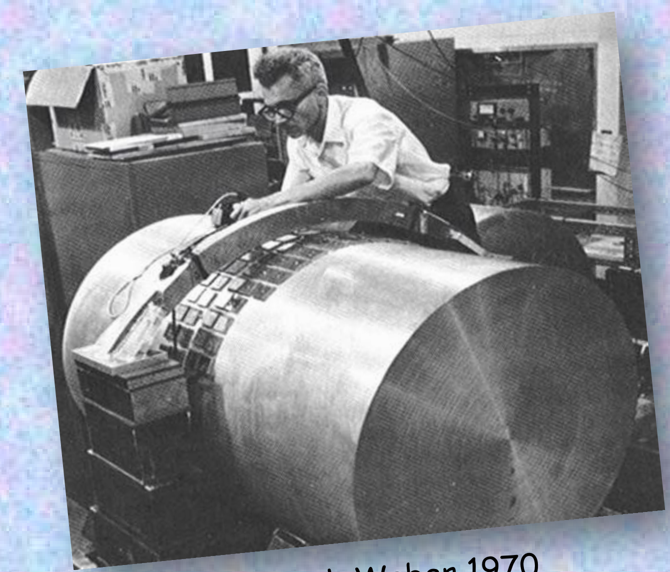


Einstein 1916



Eddington 1922

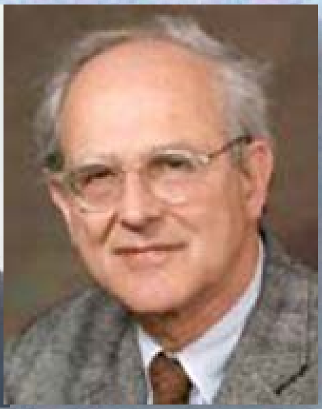
Hermann Bondi 1950s



Joseph Weber 1970

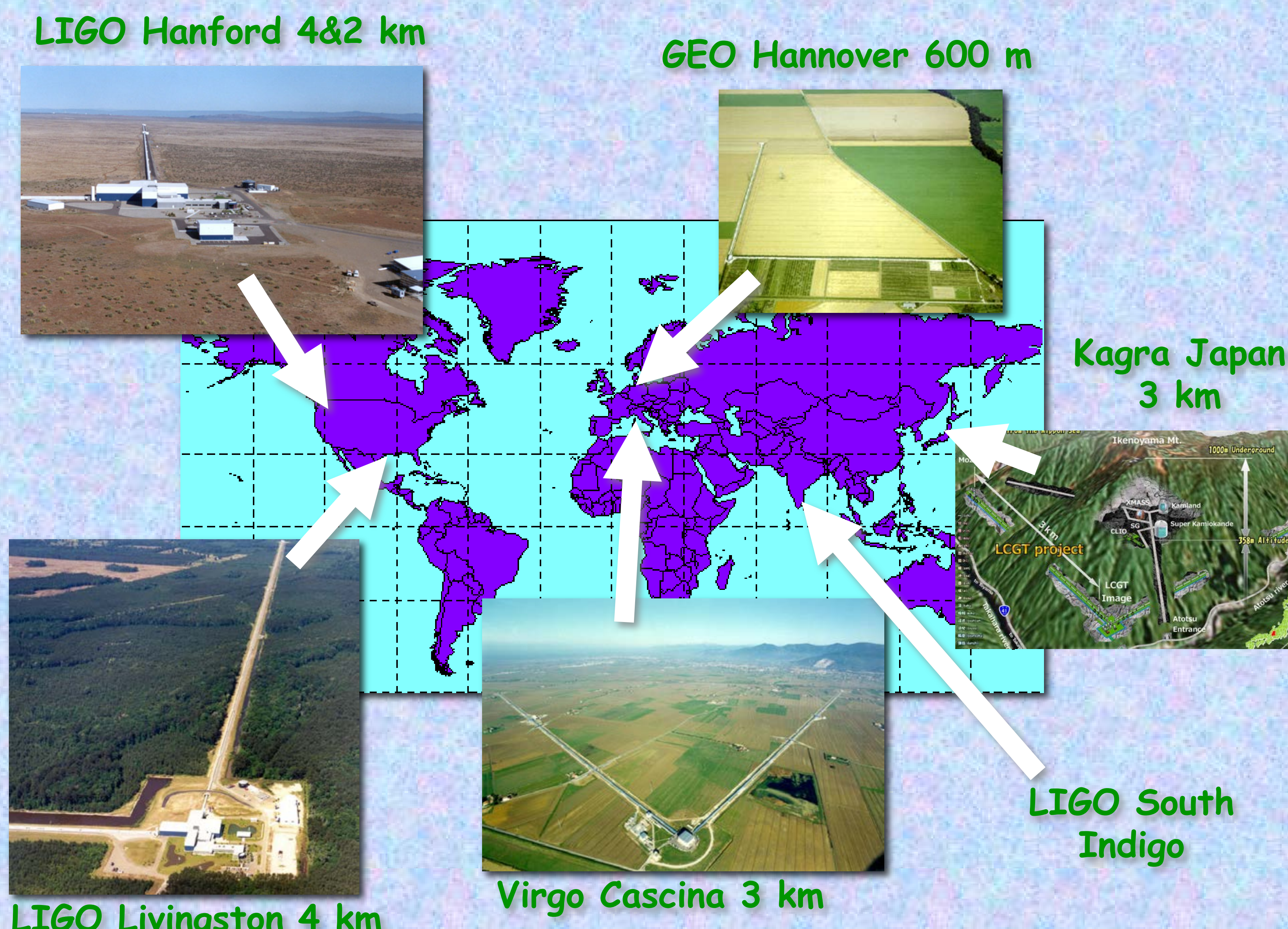
Bob Forward

Ron Drever



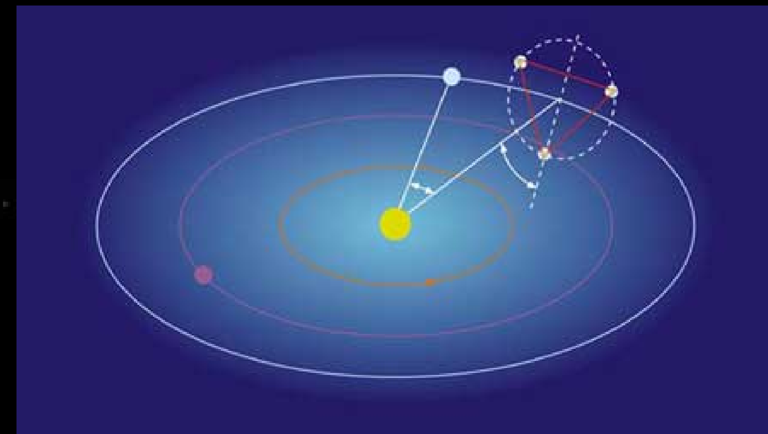
Rai Weiss

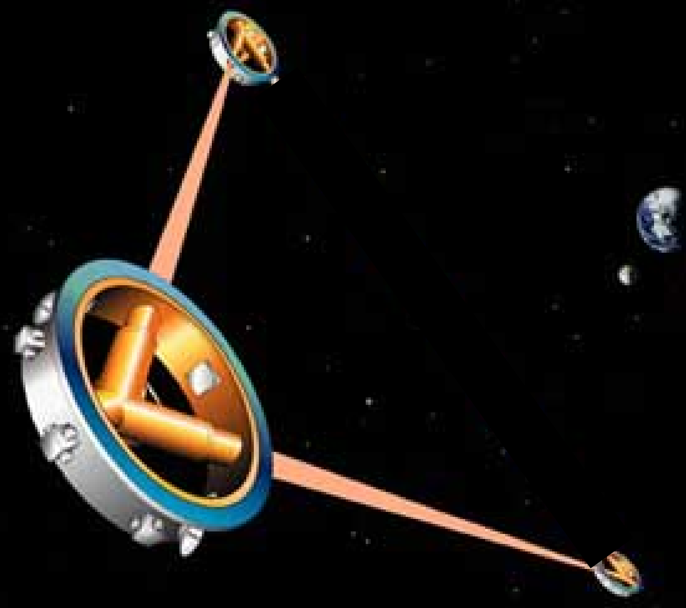
A Global Network of Interferometers

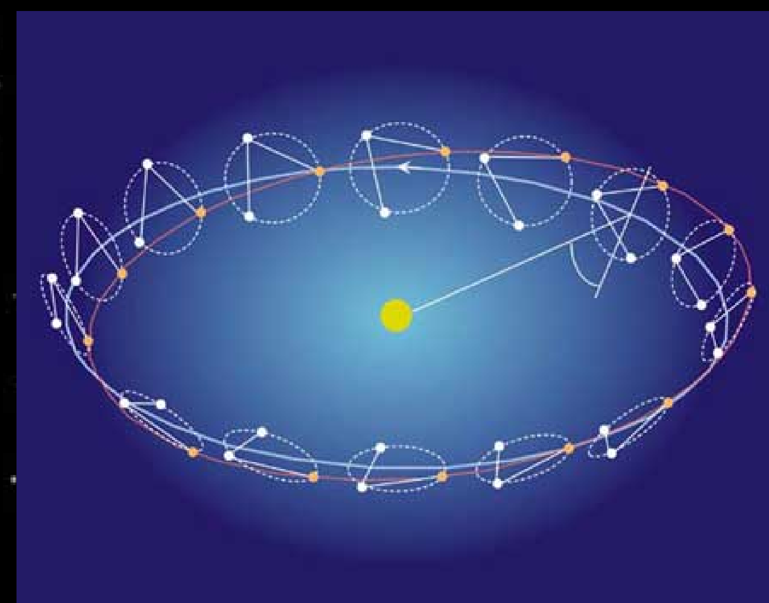


Pulsar Timing Arrays

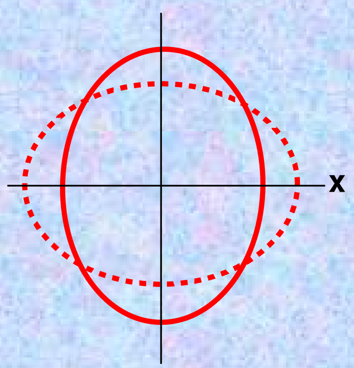
eLISA: a European space interferometer







Gravitational-wave tests of GR: Polarizations



- Array of ground based detectors
- Modulation due to eLISA's orbit
- Correlation of pulsar timing residuals as a function of angular separation

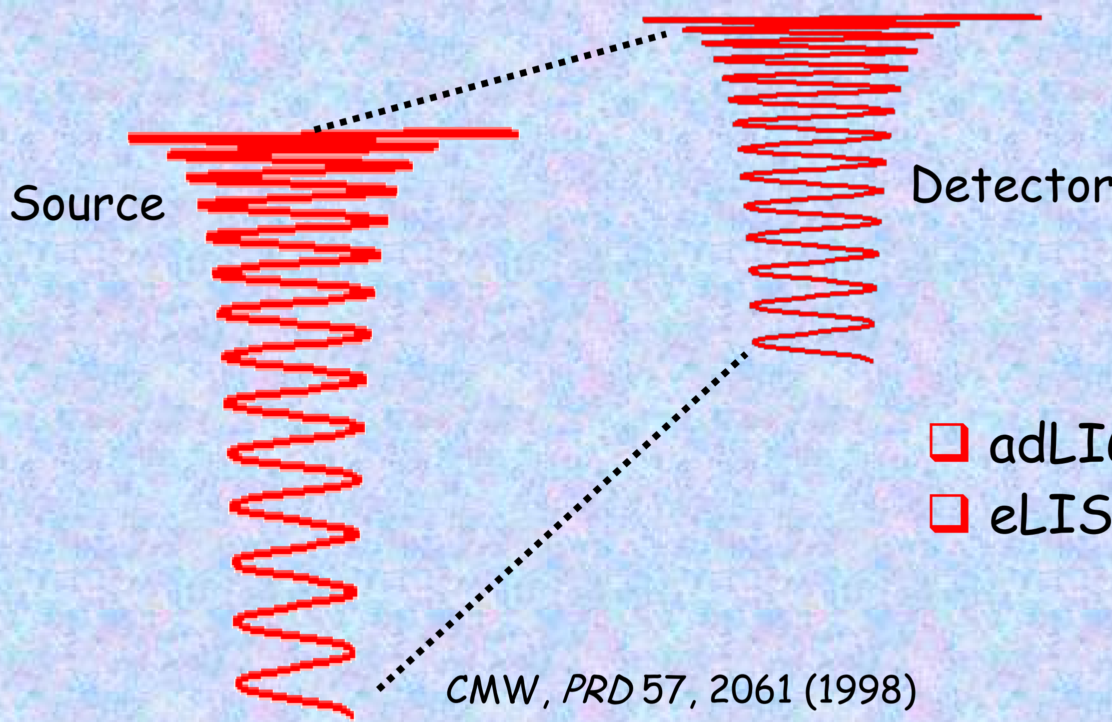
CMW, *Living Reviews in Relativity* 17, 4 (2014)

Gravitational-wave tests of GR: Speed

$$1 - \frac{v_g}{c} = 2 \times 10^{-11} \left(\frac{50\,\mathrm{Mpc}}{D} \right) \left(\frac{\Delta t}{1\,\mathrm{day}} \right)$$

- The first GR test following GW detection?

Gravitational-wave tests of GR: Graviton mass



- adLIGO/VIRGO: 10^{12} km
- eLISA: 10^{16} km

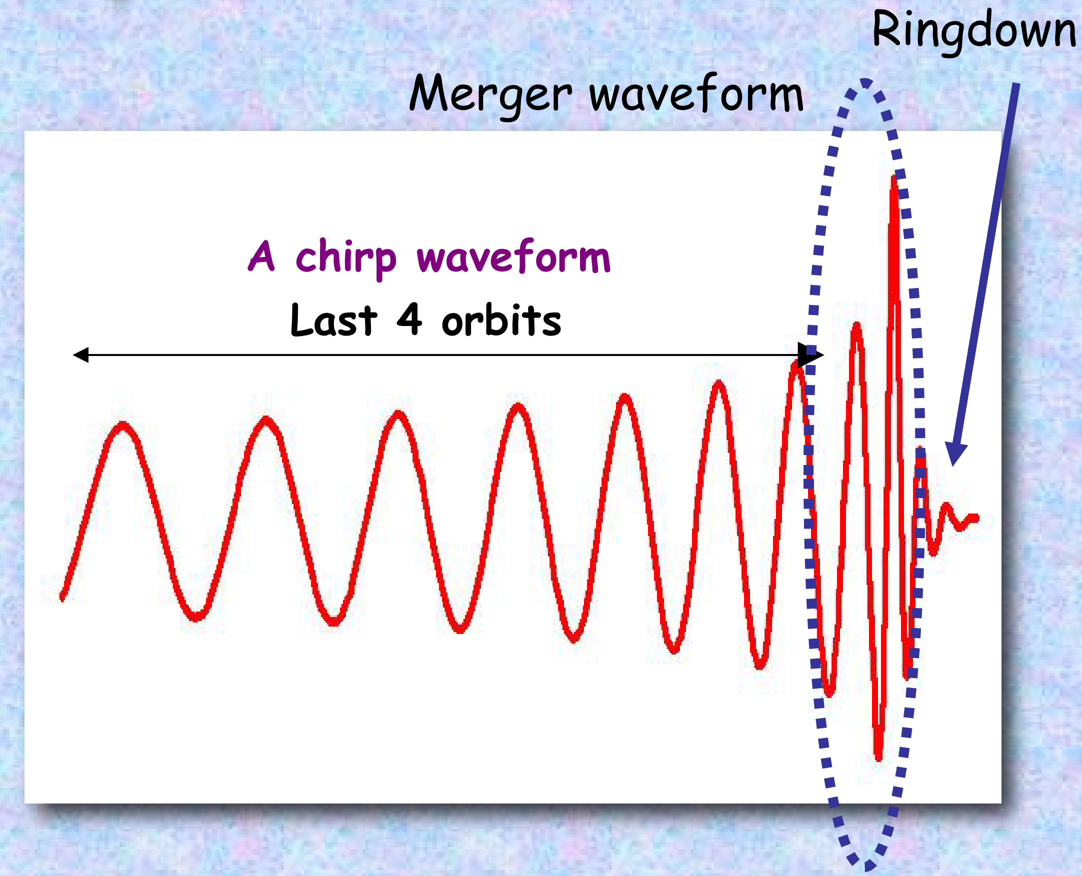
CMW, *PRD* 57, 2061 (1998)

Inspiralling Compact Binaries: Strong Gravity GR Tests?

Ground-Based (hectahertz)
- Last few minutes (10K cycles) for NS-NS
- 40 - 700 per year by 2018
- BH inspirals could be more numerous

Space-Based (millihertz)
- MBH pairs (10^5 - 10^7 M_s) in galaxies to large Z
- EMRIs

Pulsar Timing Arrays (nanohertz)
- MBH pairs



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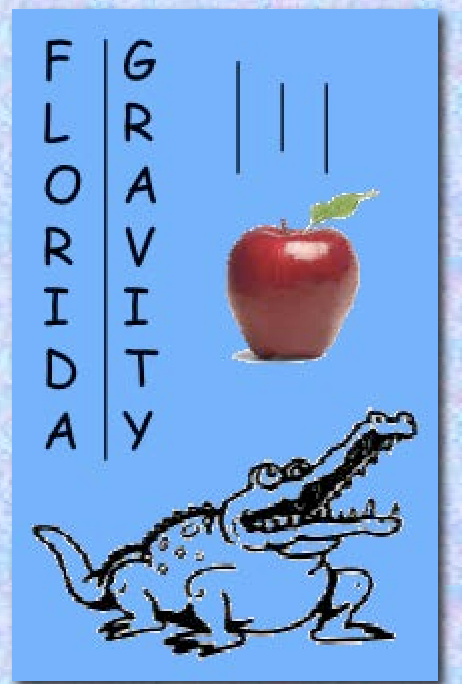
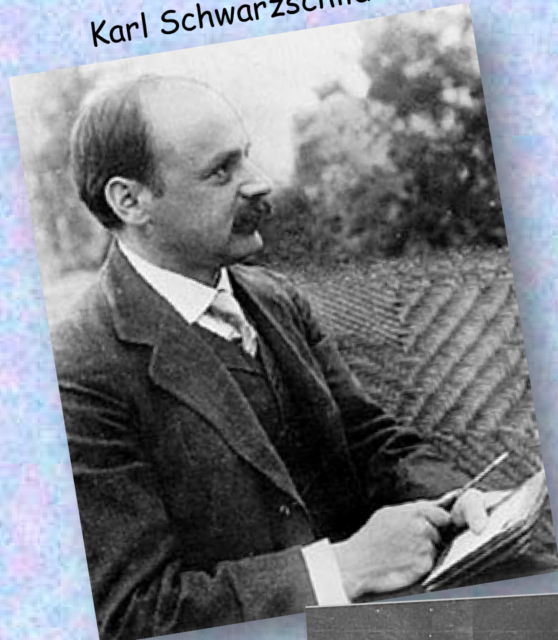
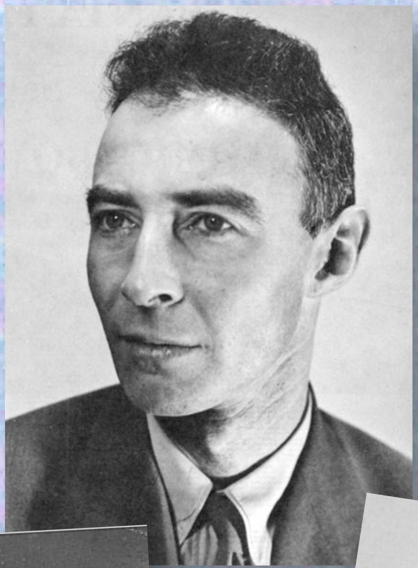


Geometry makes black holes

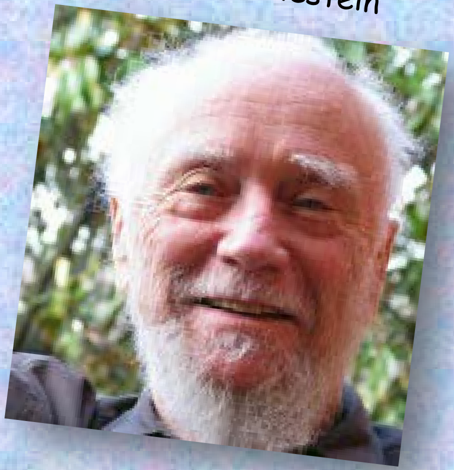
Karl Schwarzschild

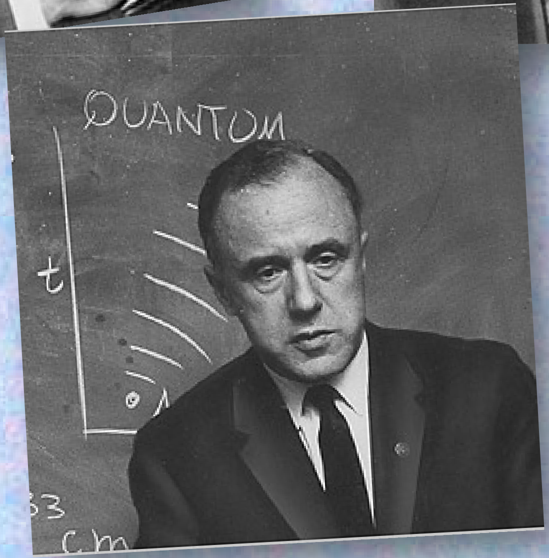


J. R. Oppenheimer



David Finklestein





John Wheeler

Roy Kerr

Geometry makes black holes

$1.6 \times 10^8 M_{sun}$

J. Michell (1784):

If there should really exist in nature any bodies whose density is not less than that of the sun, and whose diameters are more than 500 times the diameter of the sun, since their light could not arrive at us... we could have no information from sight; yet if any other luminous bodies should happen to revolve about them we might still [infer] the existence of the central ones....

P. S. Laplace (1796):

... the attractive force of a heavenly body could be so large that light could not flow out of it.

FLORIDA GRAVITY

Are black holes really bald?

The 3 Stooges: Moe, Curly & Larry (1934 -46)

Black holes have no hair

Exterior geometry of Kerr

$$g_{00}: \frac{M}{r} + \frac{Q_2 P_2(\cos\theta)}{r^3} + \frac{Q_4 P_4(\cos\theta)}{r^5} + \cdots$$

$$g_{0\varphi}: \frac{J}{r^2} + \frac{J_3 \tilde{P}_3(\cos\theta)}{r^4} + \frac{J_5 \tilde{P}_5(\cos\theta)}{r^6} + \cdots$$

No hair theorem

$$Q_\ell + iJ_\ell = M(ia)^\ell$$

$$Q_0 = M$$

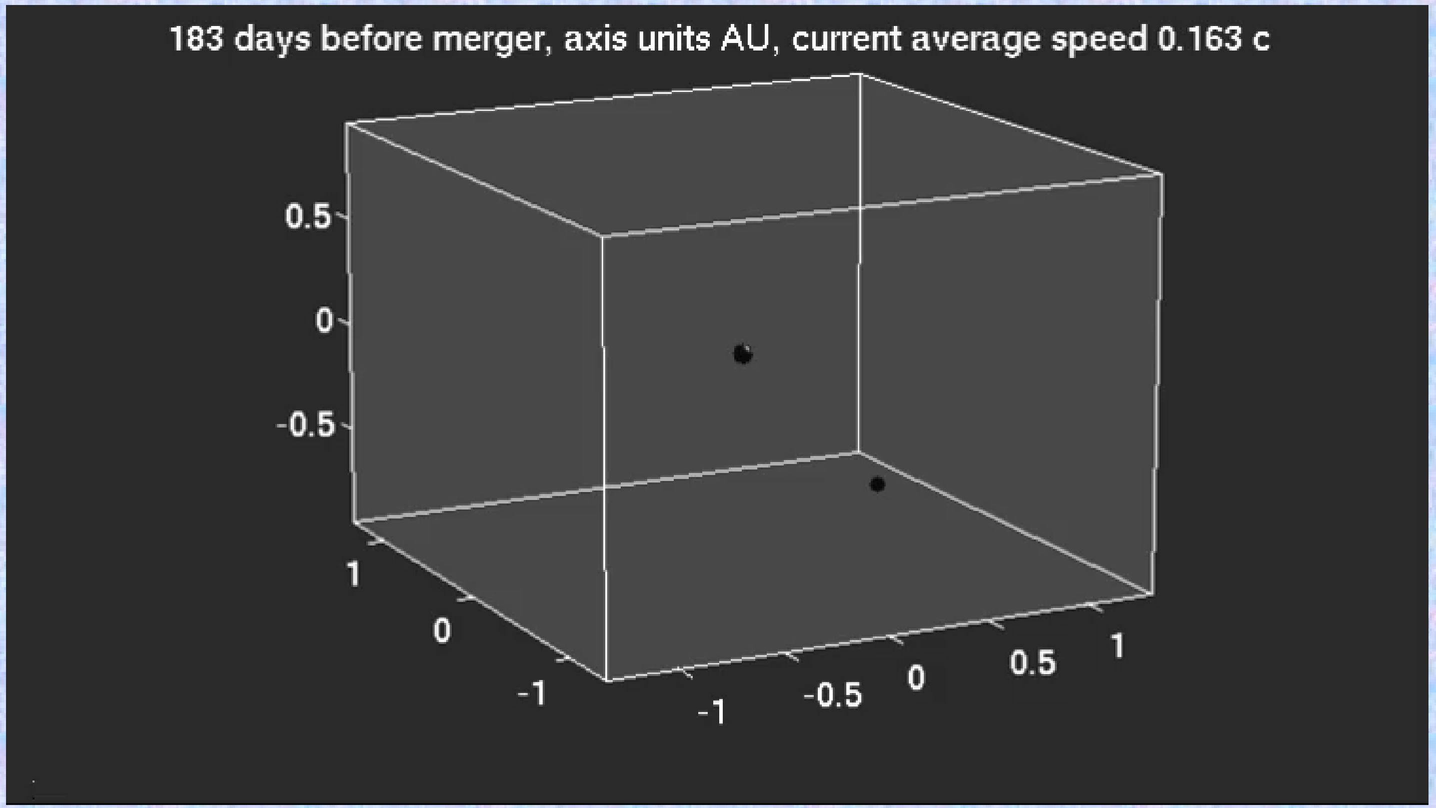
$$J_1 = J$$

$$a = J / M$$

Hansen 1974

$$Q_2 = -Ma^2 = -J^2 / M$$

Hair counting using GW from EMRIs



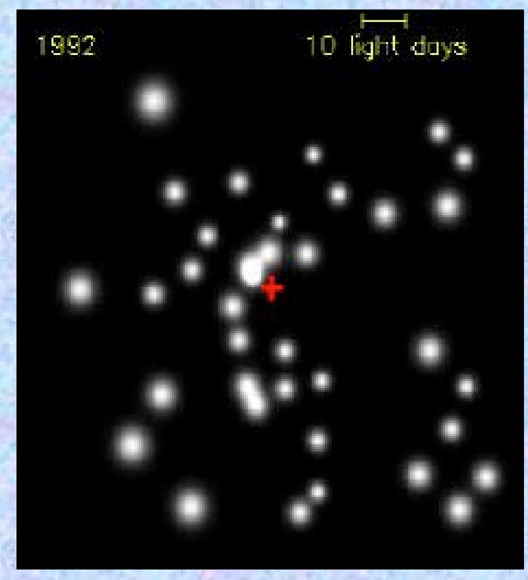
Animation by Steve Drasco, JPL

Counting hair on the galactic center black hole SgrA*

- No hair theorems:

$$M_L + iJ_L = M(ia)^L$$

- $J = Ma$; $Q_2 = -Ma^2$
- relativistic effects: pericenter advance, redshift Doppler shifts, Shapiro delays
- Frame dragging (J) and quadrupole moment (Q_2) produce precessions of planes



SgrA* - a $4.3 \times 10^6\ M_{sun}$ rotating black hole

Counting hair on the galactic center black hole SgrA*

$J/M^2 > 0.5$, $e \sim 0.9$

$P \sim 0.1$ yr, $a < 10^{-3}$ pc,

$\Rightarrow \Delta\theta \sim 10\ \mu$as/yr

CMW, Ap J Lett. **647**, L25 (2008)

Gravity

Keck

…..pulsars would also work!

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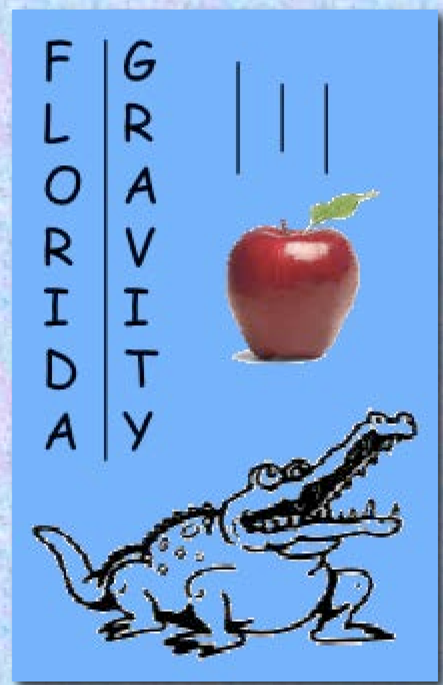

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