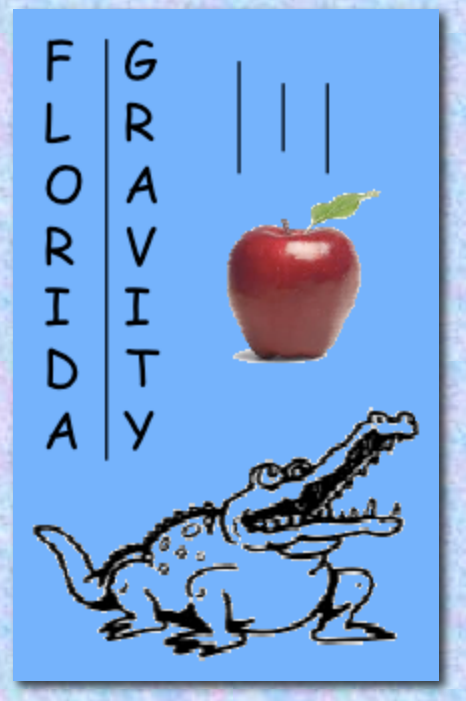
Was Einstein Right?
A Centennial Assessment



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

Einstein Symposium, ETH Zurich, 13 November, 2015

Was Einstein Right?
A Centennial Assessment

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

- Strong-field tests
- Gravitational-wave tests
- Extreme-range tests

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- Early struggles
- Highlights from the first century
- Prospects for the second century
  - Geometry bends light
  - Geometry warps time
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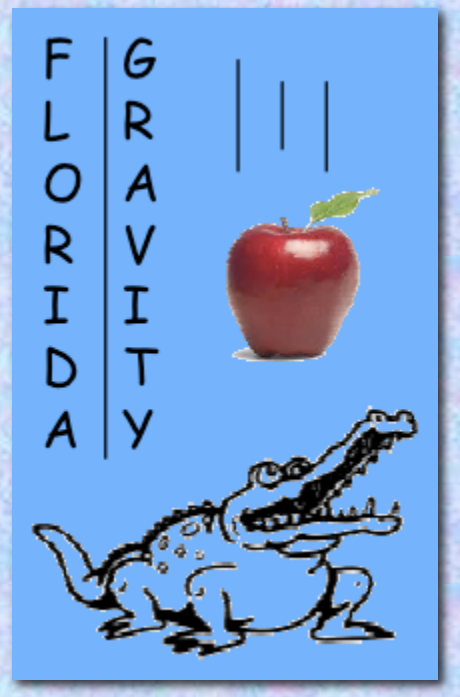

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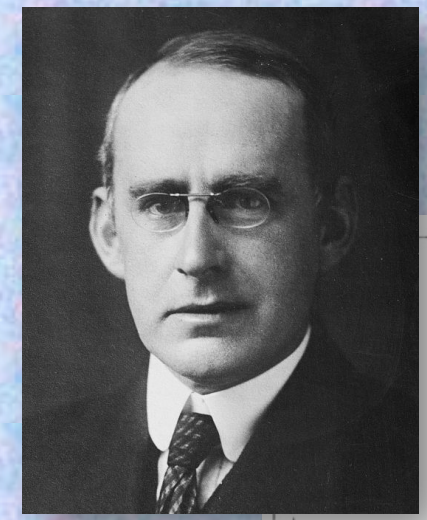
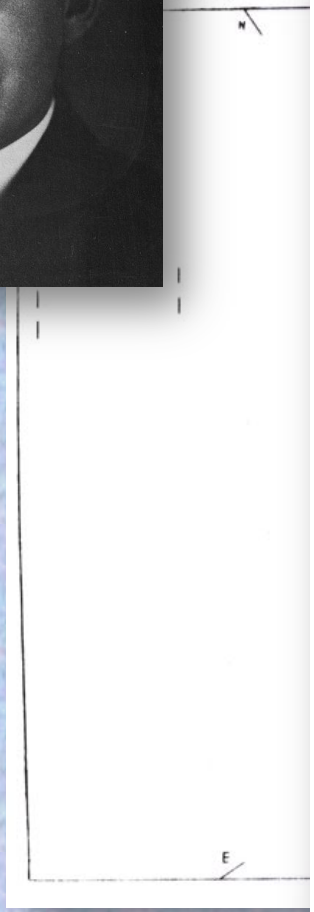
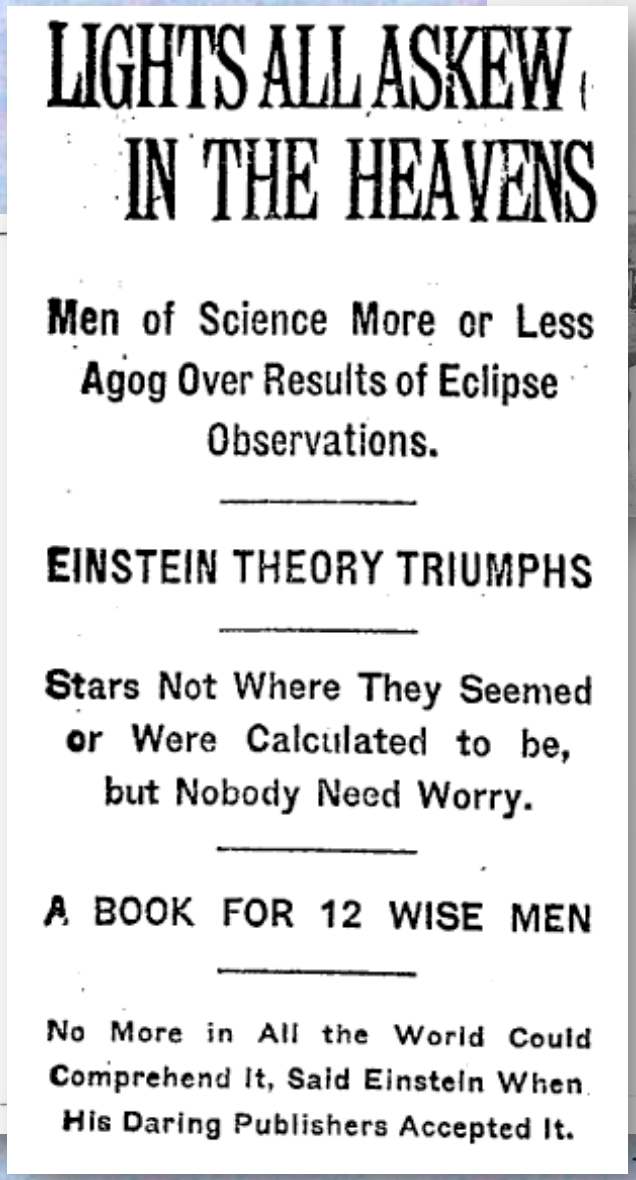
Geometry bends light: The 1919 Eclipse



A. S. Eddington





LIGHTS ALL ASKEW IN THE HEAVENS

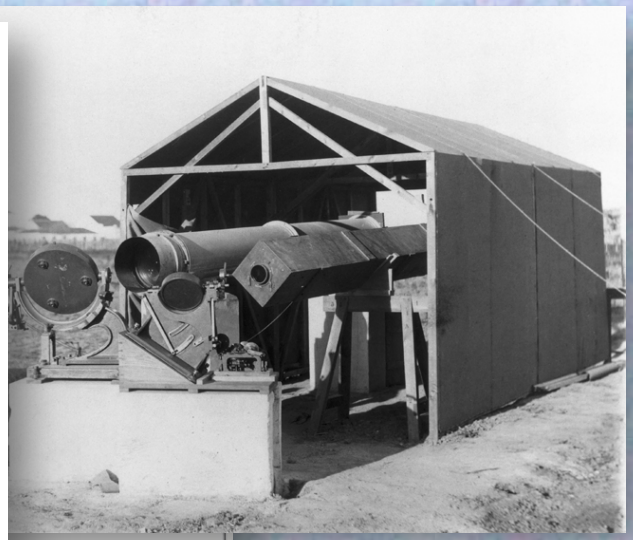
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

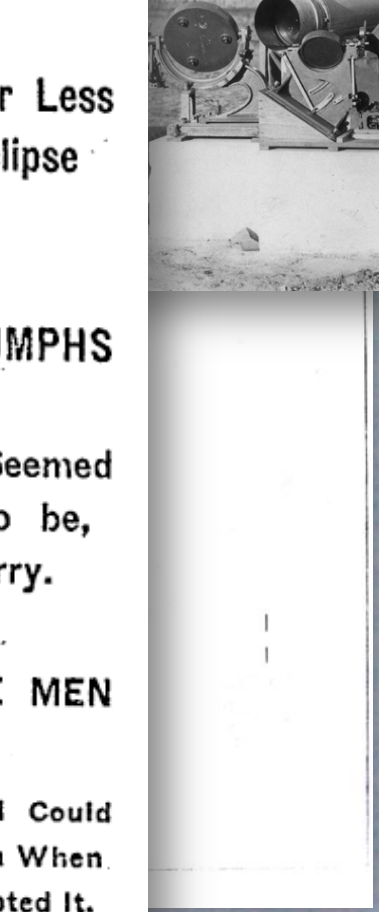
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

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

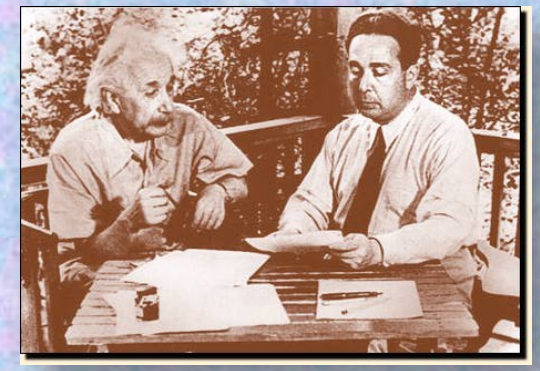


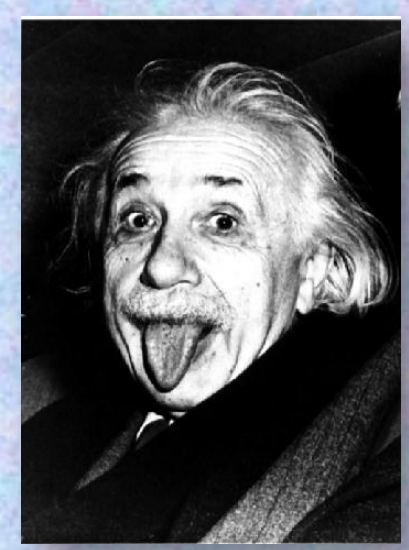
Sobral site

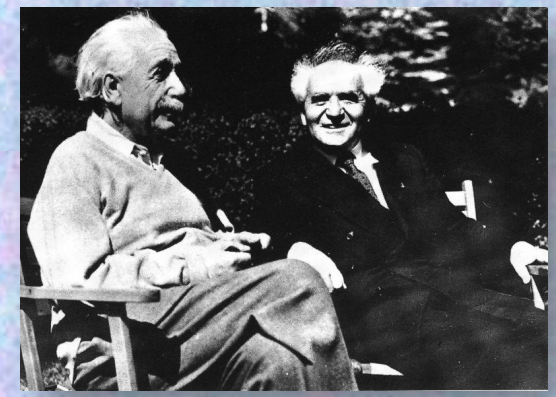


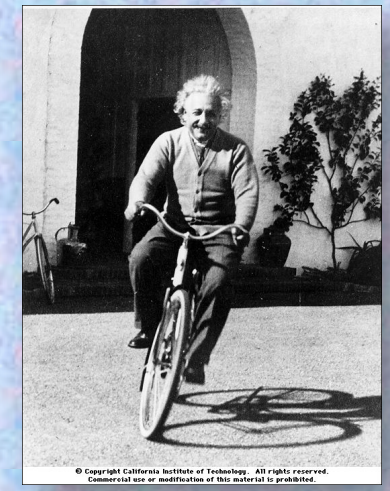
from Principe

The public Einstein









SOMALIA: THE MESSY FUTURE OF WAR

Newsweek

June 28, 1993 : $2.95

THE PUZZLE OF GENIUS

New Insights Into Great Minds

DECEMBER 31, 1999 $4.95

www.time.com

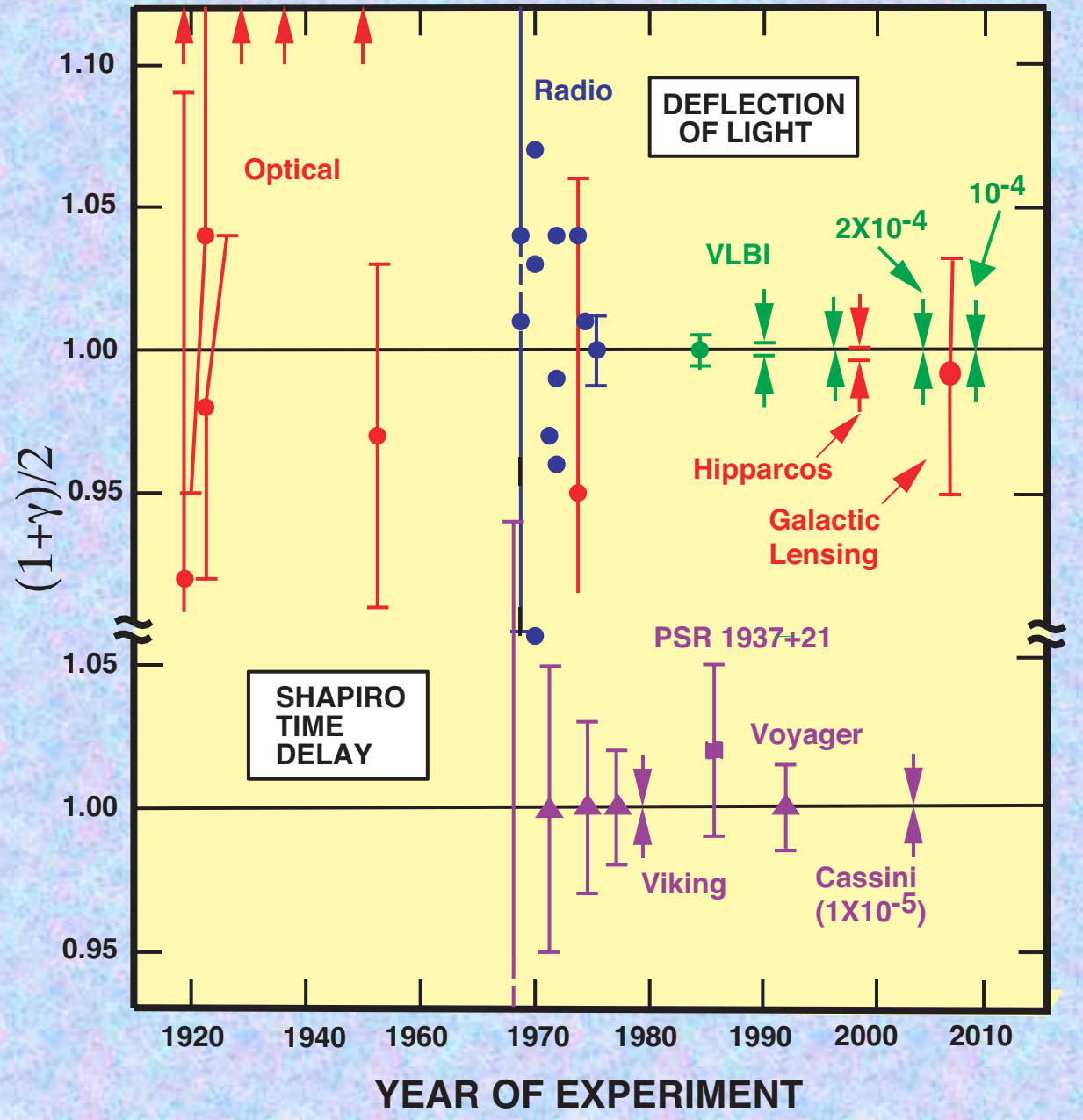
PERSON OF THE CENTURY

TIME

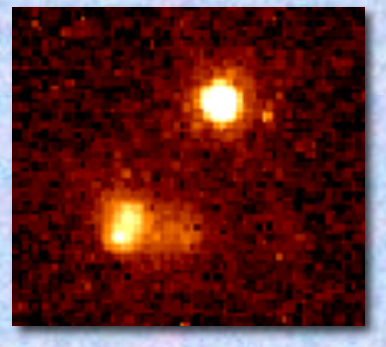
ALBERT EINSTEIN

splay Until 1/10/00

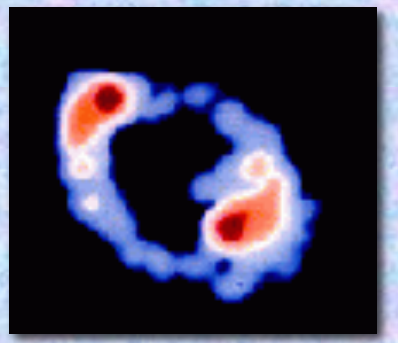
Geometry bends light: The PPN parameter γ



Geometry bends light: Gravitational lenses





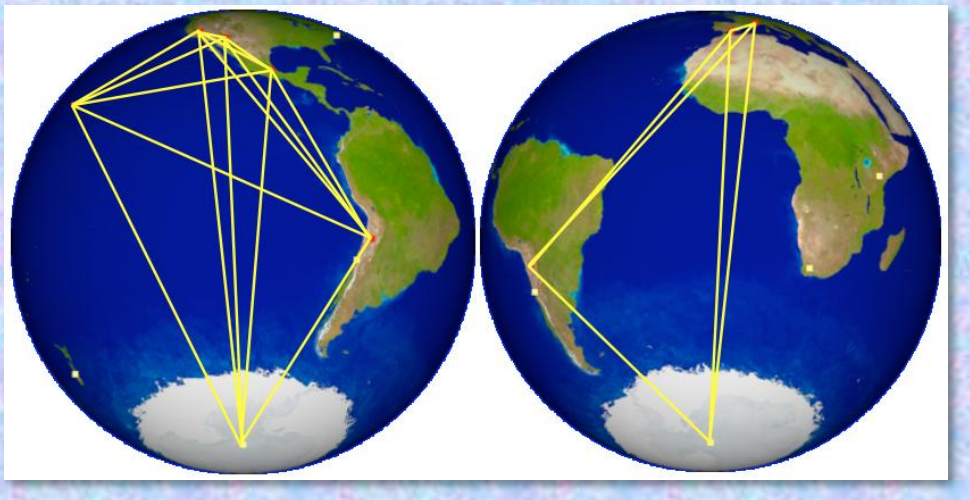



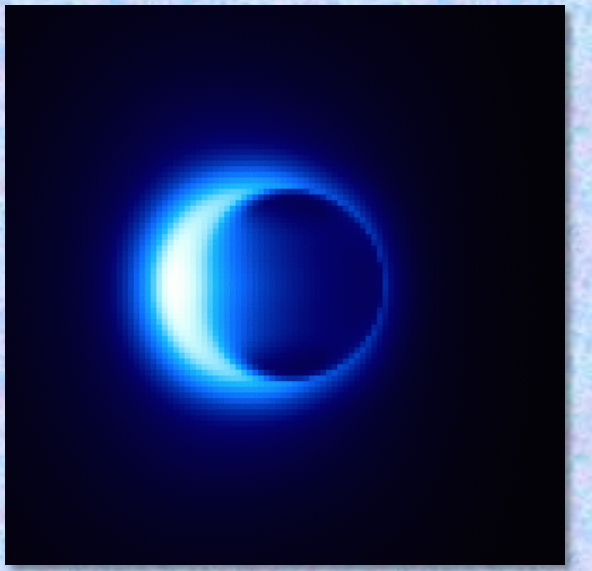
Einstein's gift to astronomy

Geometry bends light: and wins an Oscar!

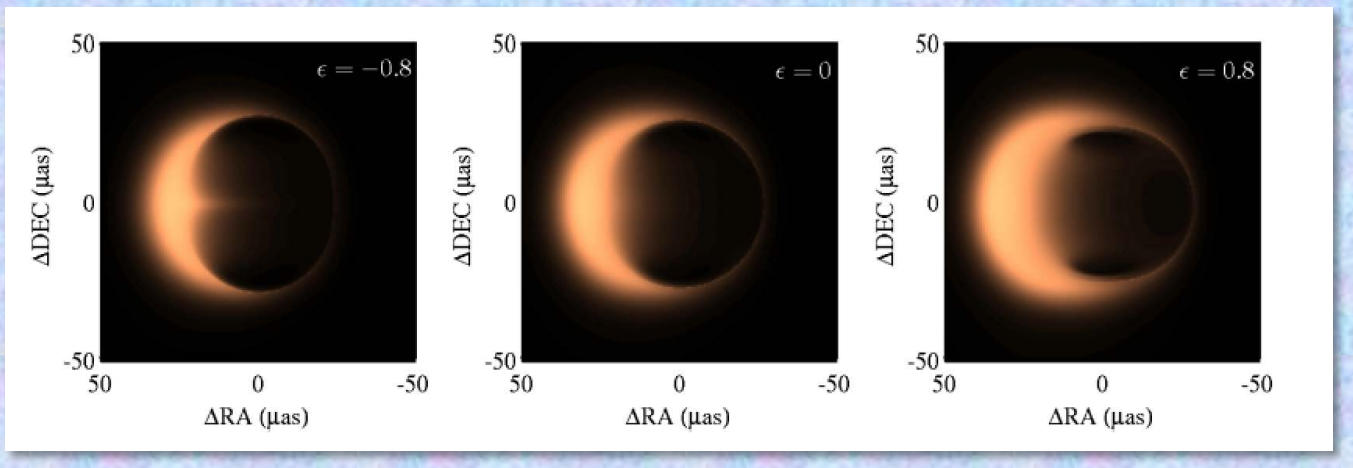
Interstellar, Paramount Pictures, Directed by Christopher Nolan
Starring: Matthew McConaughey, Anne Hathaway, Jessica Chastain, Michael Caine, …
Image based on calculations by Kip Thorne and Double Negative Co.

Geometry bends light: Black hole shadows





Event Horizon Telescope (EHT)
- mm wavelength
- horizon scale angular resolution at SgrA* and M87



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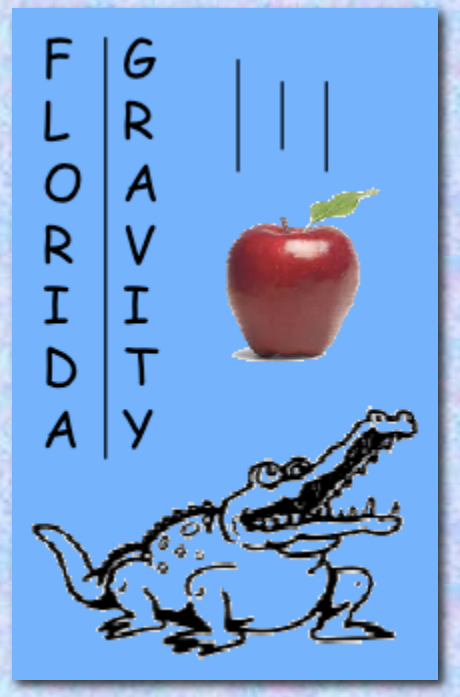
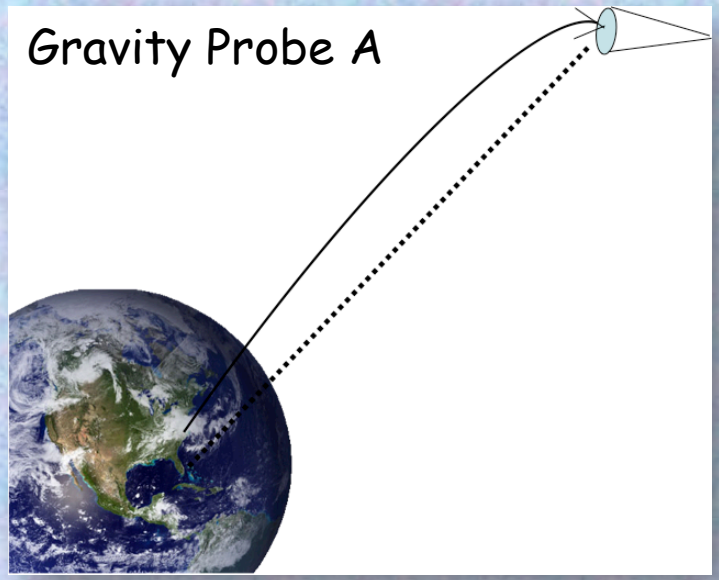
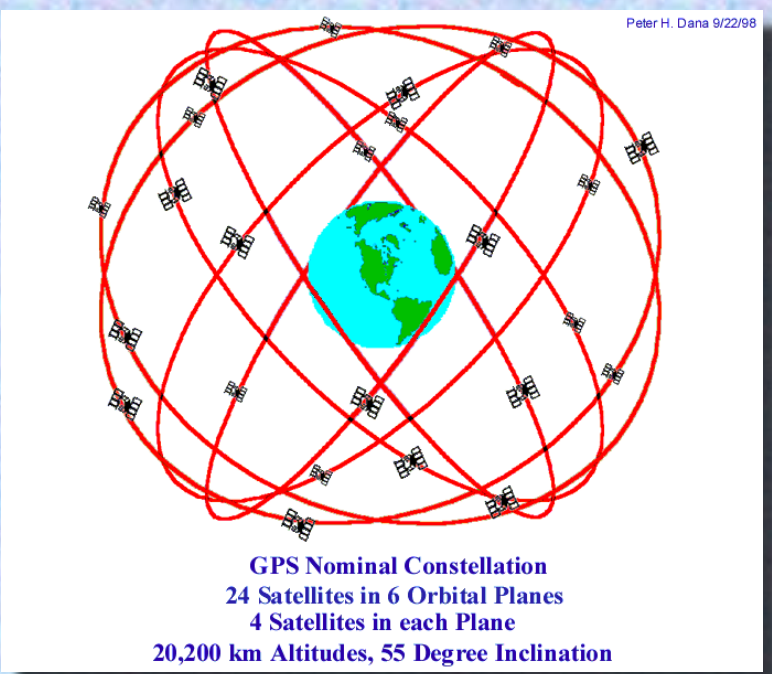


Einstein Symposium, ETH Zurich, 13 November, 2015

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
- 2017: ACES/PHARAO on the ISS





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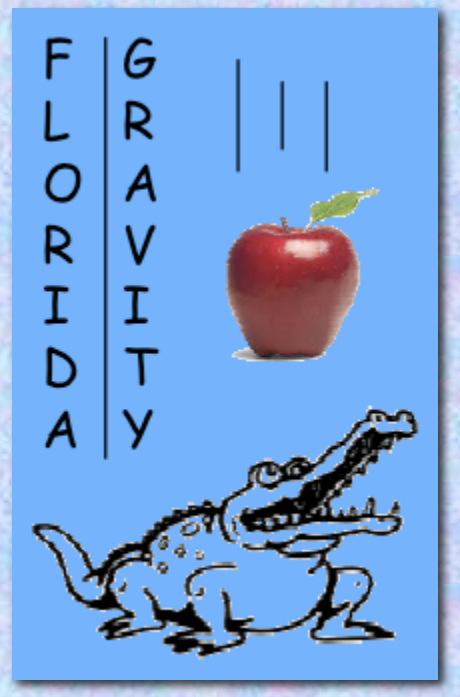

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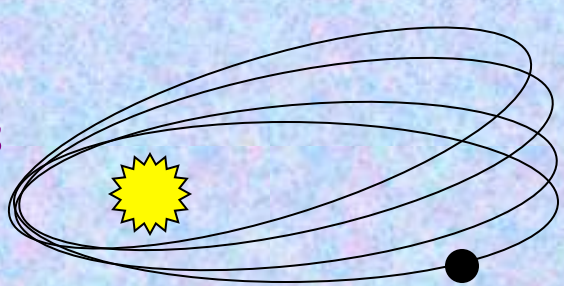
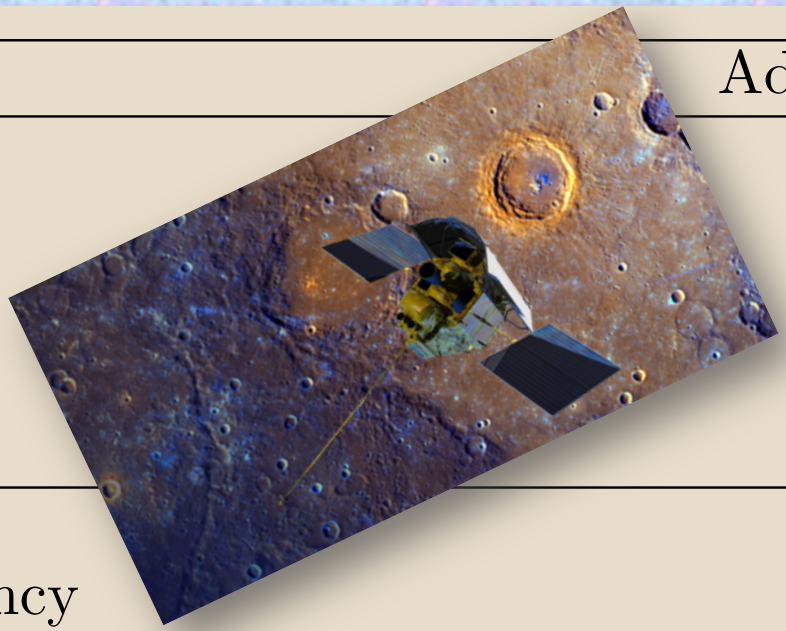
Geometry moves mass: Mercury's perihelion

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



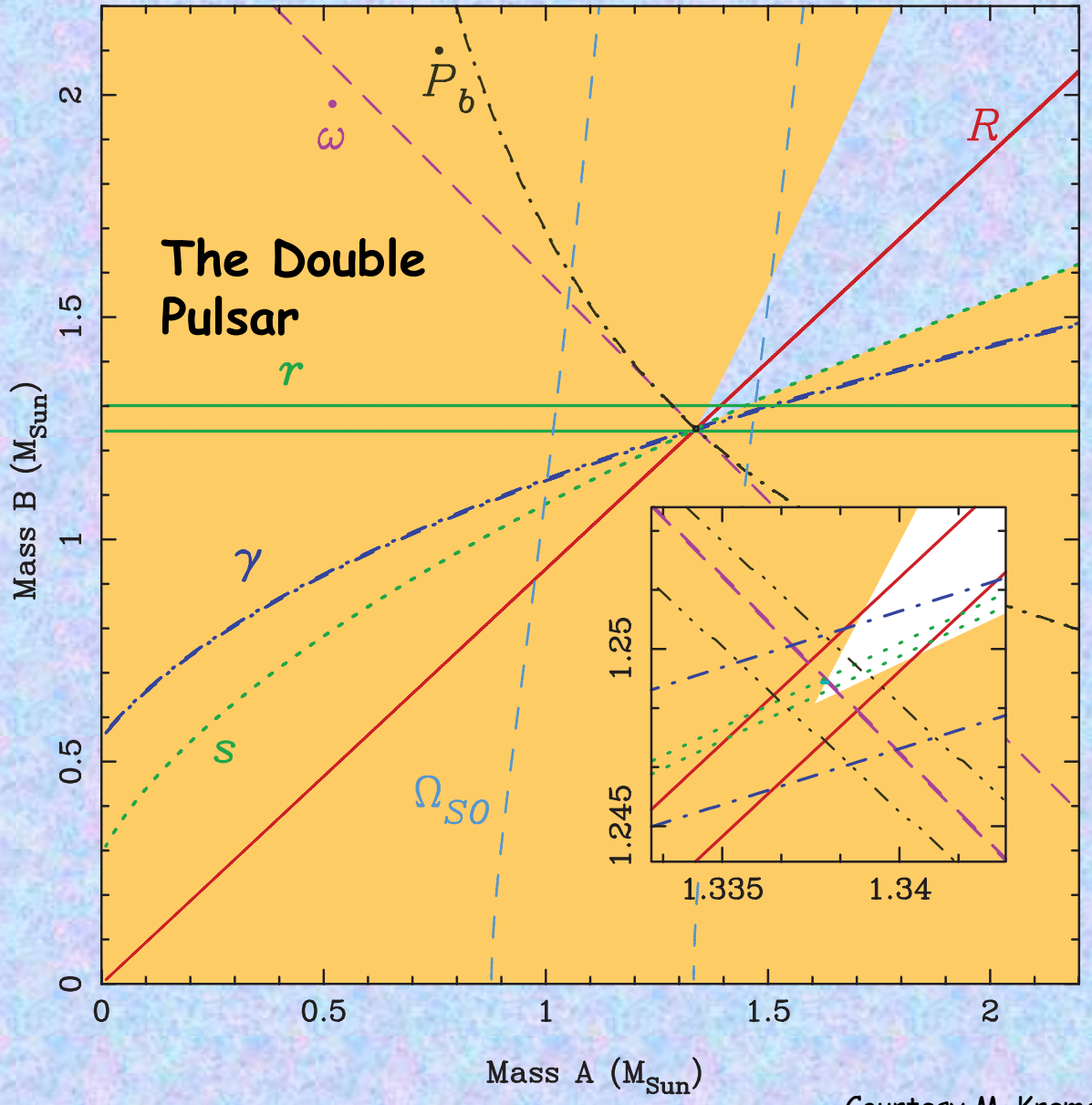
575 " per century

Planet	Advance
Venus	277.8
Earth	90.0
Mars	2.5
Jupiter	153.6
Saturn	7.3
Total	531.2
Discrepancy	42.9



$J_2=2.2\times10^{-7}$

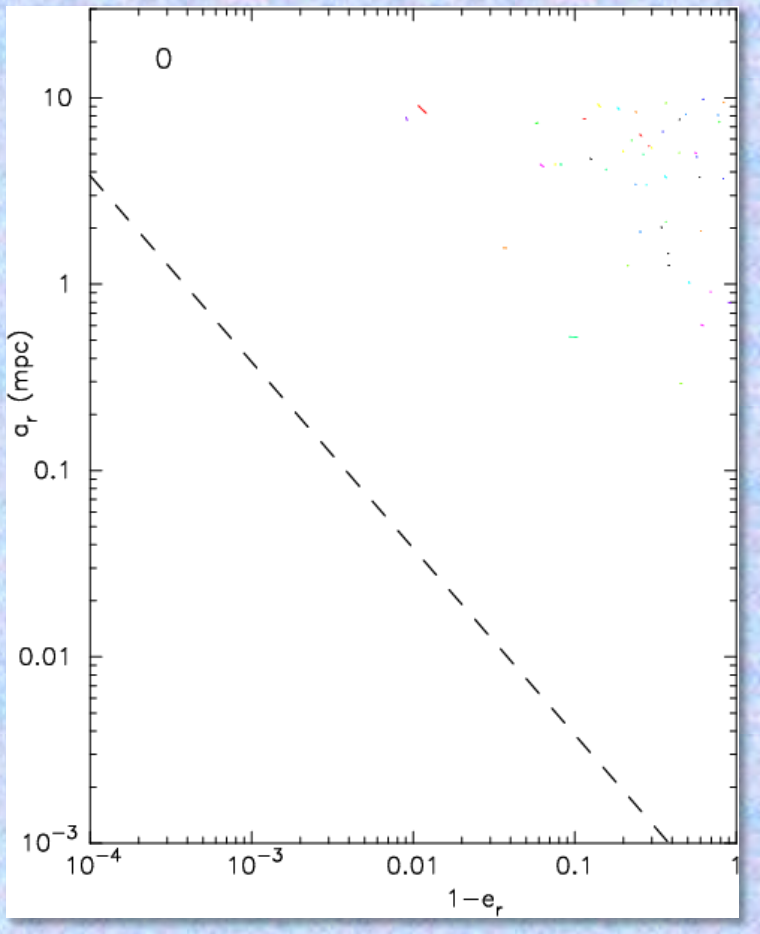
Pericenter advance and strong-field GR

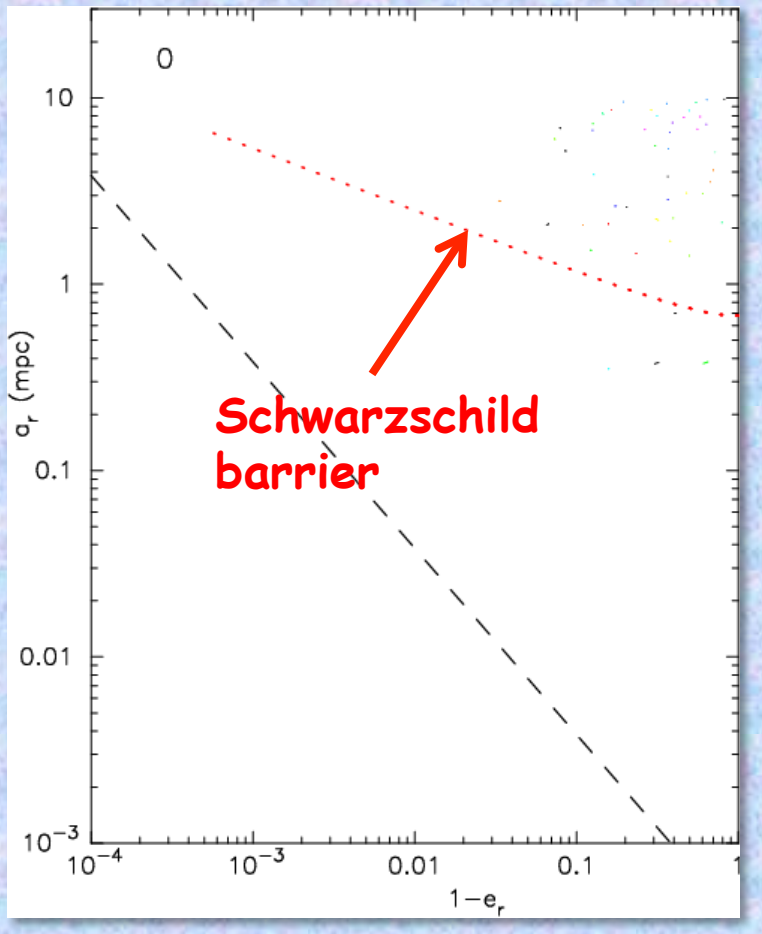


Courtesy M. Kramer

Pericenter advance and strong-field GR

Stellar clusters around SMBH





Hopman & Alexander 2007
Merritt, Alexander, Mikkola & CMW 2011

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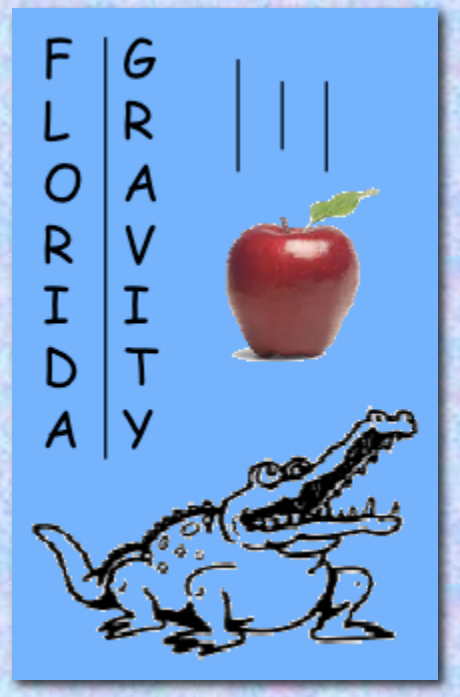

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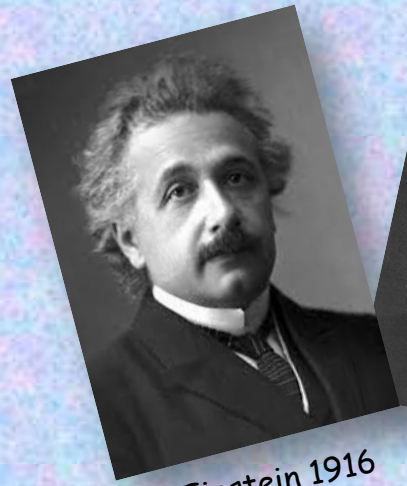
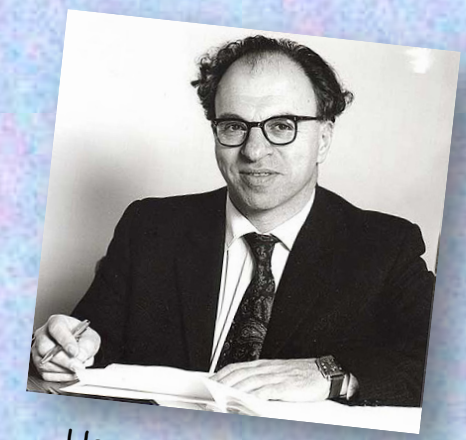
Geometry makes waves



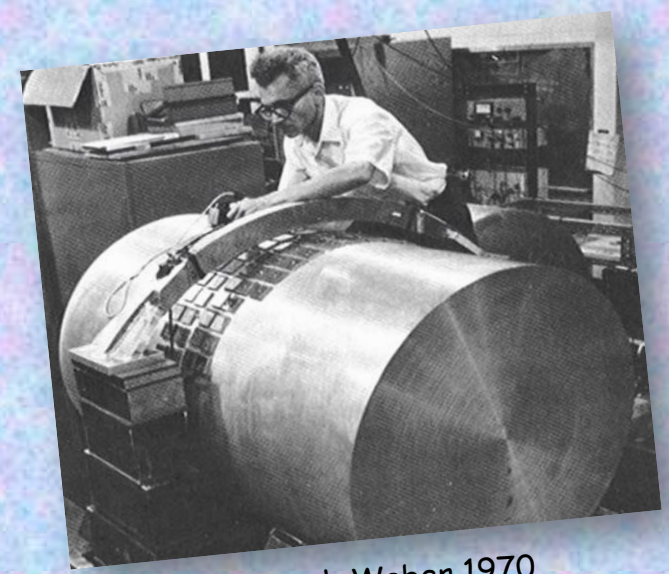
Einstein 1916

Eddington 1922

Einstein, Rosen & Robertson 1938



Hermann Bondi 1950s



Joseph Weber 1970

Bob Forward

Ron Drever

Rai Weiss

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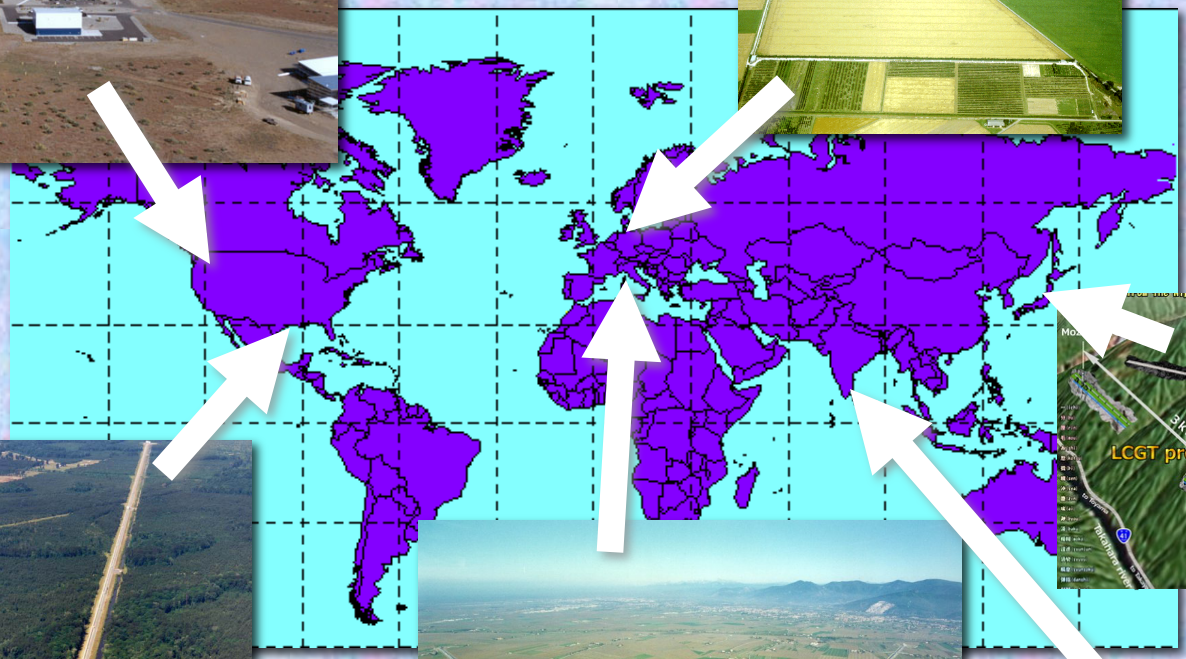
A Global Network of Interferometers

LIGO Hanford 4 km (2015)

GEO Hannover 600 m



Kagra Japan
3 km (2018)

LIGO Livingston 4 km (2015)

Virgo 3 km (2016)

LIGO India
(2022)

Pulsar Timing Arrays

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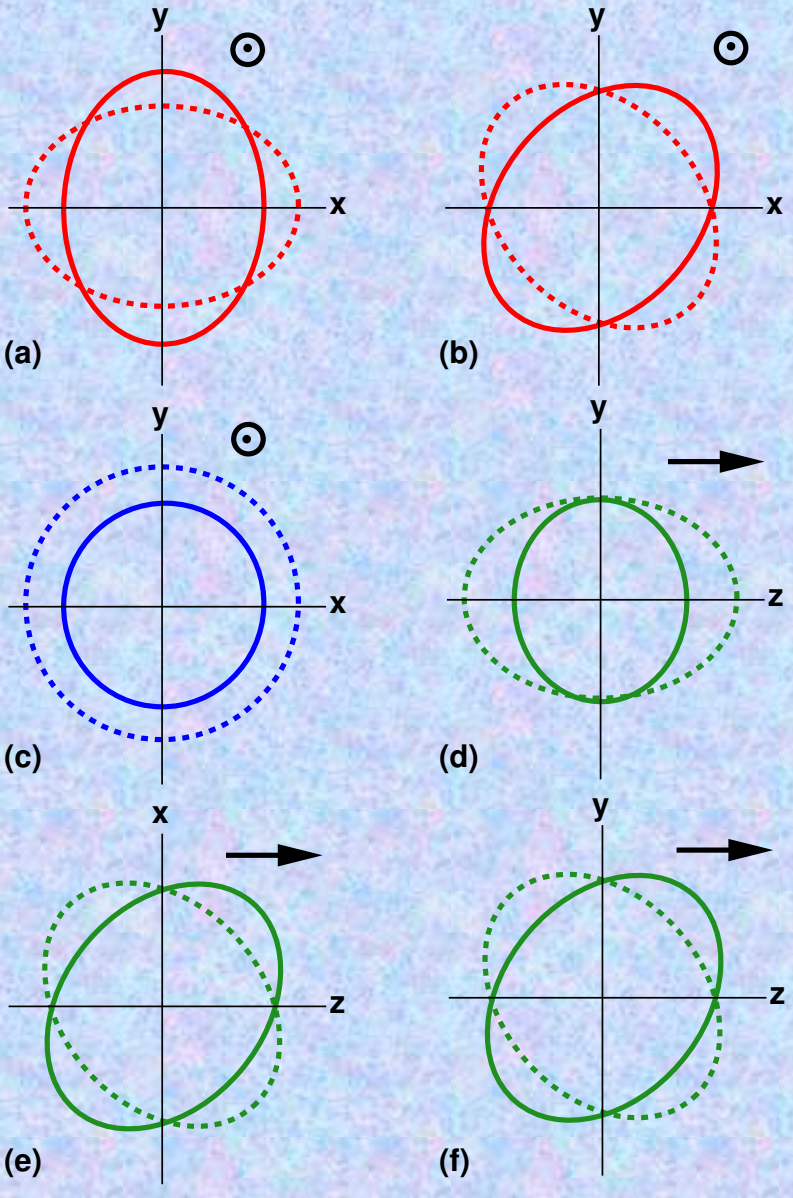
eLIS
inte

with NASA participation

Gravitational-wave tests of GR: Polarizations



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

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

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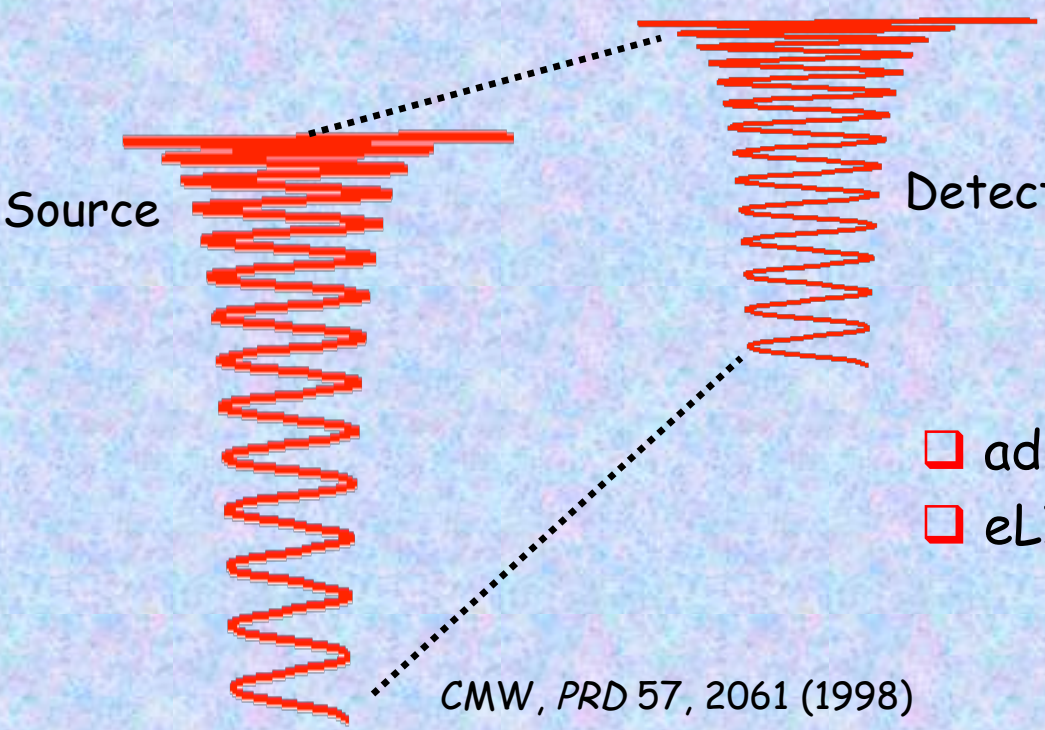
Gravitational-wave tests of GR: Speed

$$1 - \frac{v_g}{c} = 5 \times 10^{-12} \left(\frac{200\,\mathrm{Mpc}}{D} \right) \left(\frac{\Delta t}{1\,\mathrm{day}} \right)$$

- The first GR test following GW detection?

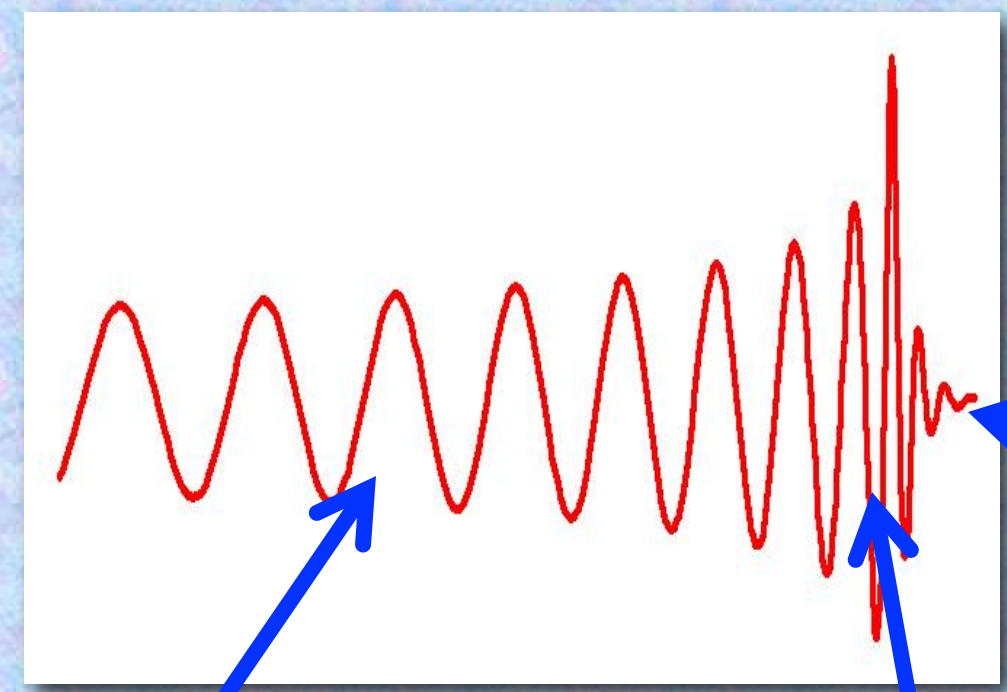
Gravitational-wave tests of GR: Graviton mass



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

CMW, *PRD* 57, 2061 (1998)

Inspiralling Compact Binaries: Strong Gravity GR Tests?



Ringdown phase: Test the no-hair theorems

Inspiral phase: test alternative theories using precise phase evolution (PPE, PN)

Merger phase: dynamical scalarization?

Strong-Field tests of general relativity

- neutron star masses and radii
- existence of event horizons with ADAFs
- measurement of maximum BH spins
- short gamma-ray bursts
- tidal disruption events

Extreme-range tests of general relativity

- gravity at sub-mm and micron scales
- dark matter vs. MOND at galactic scales
- evolution of structure - dark energy vs modified gravity
- CMB fluctuations – tests of modified gravity

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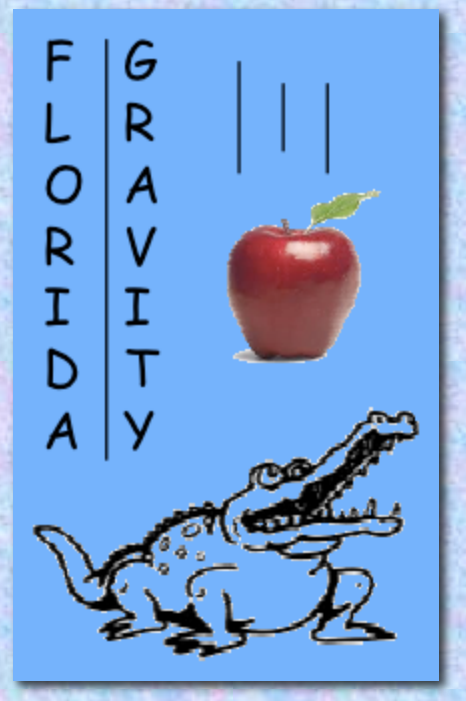

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