Was Einstein Right?
A Centennial Assessment

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GR @ 100, 6th Biennial Bacon Conference, Caltech, 11 March 2016

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

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    - Geometry warps time
    - Geometry moves mass
    - Geometry does the twist
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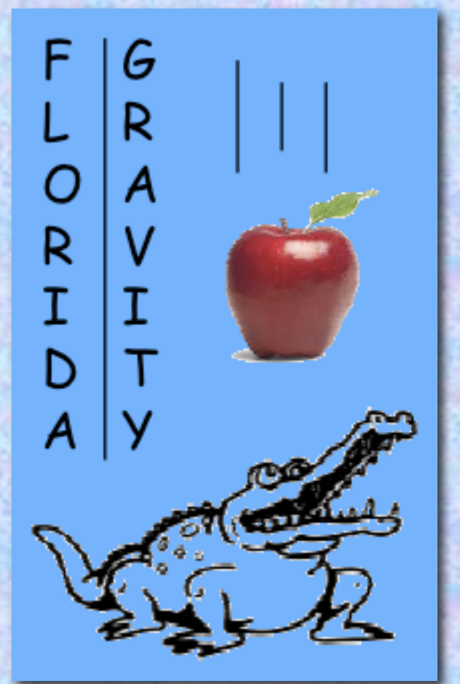
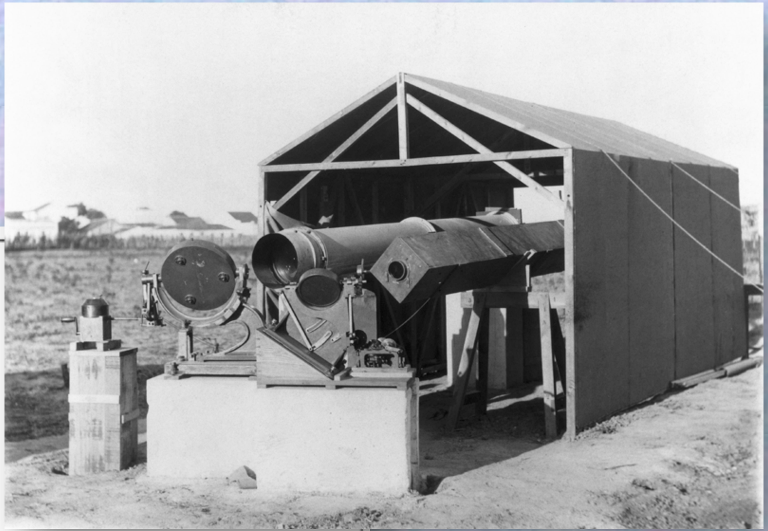


Geometry bends light: The 1919 Eclipse

A. S. Eddington



Sobral site

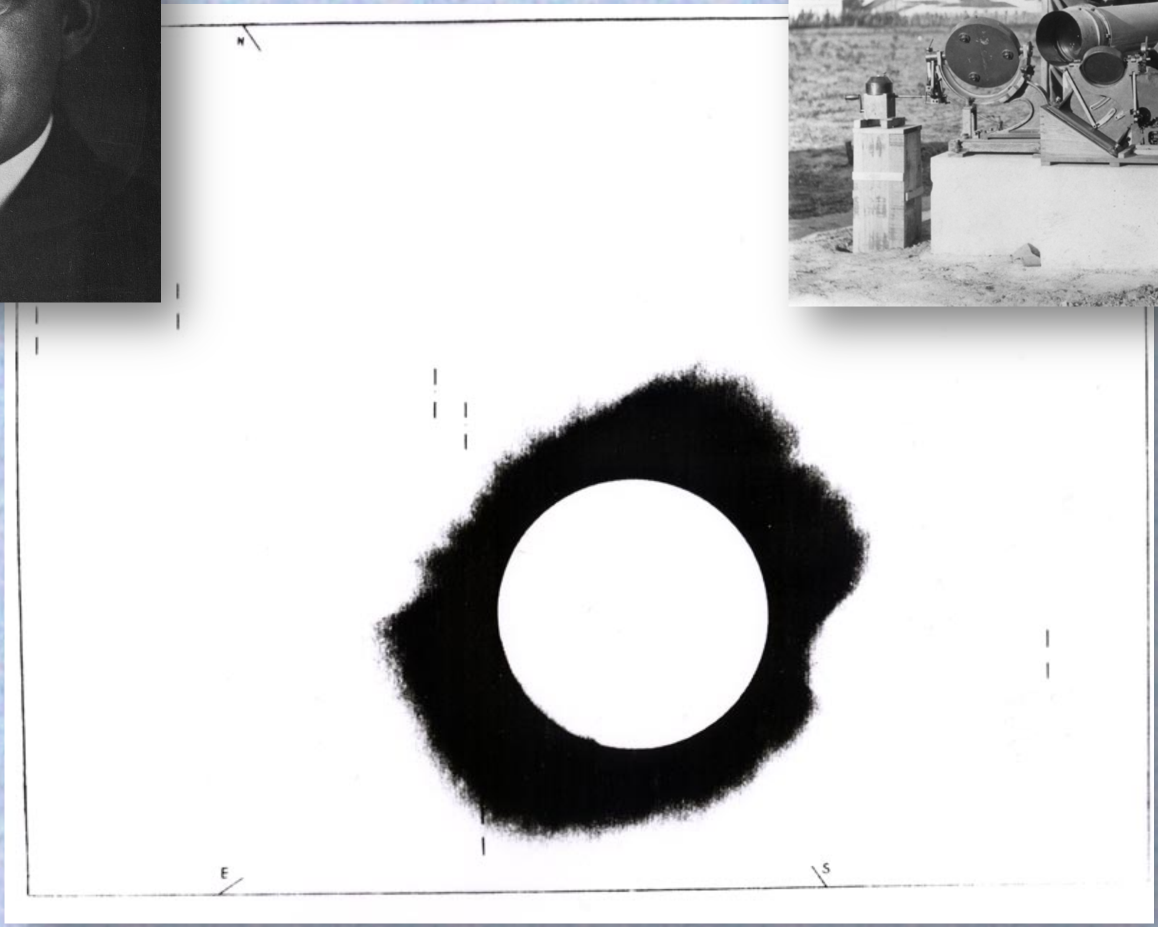


Photo from Principe

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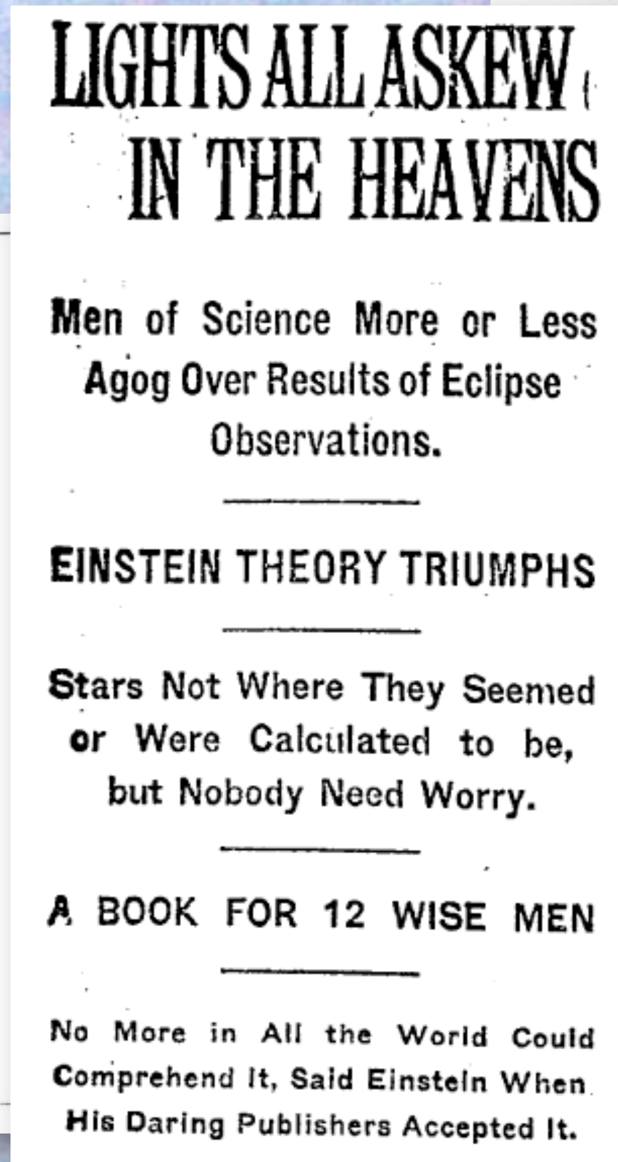


LIGHTS ALL ASKEW IN THE HEAVENS

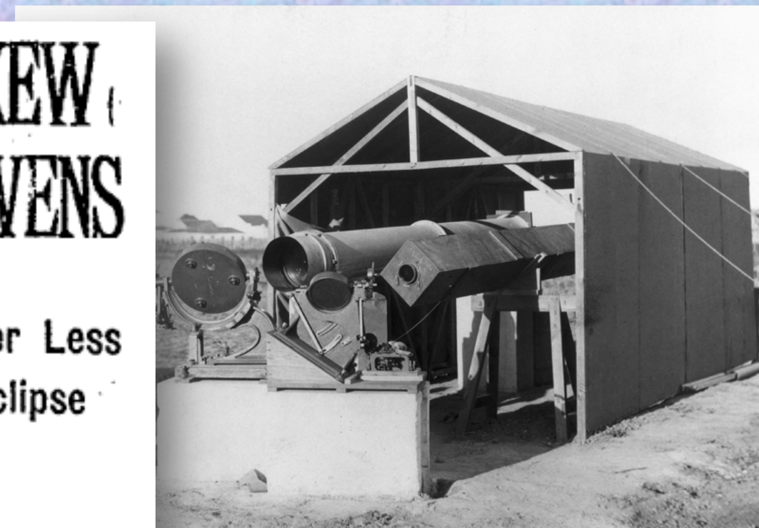
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

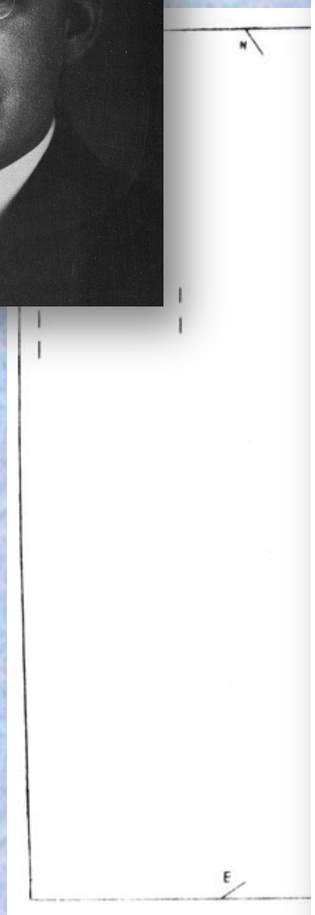
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

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

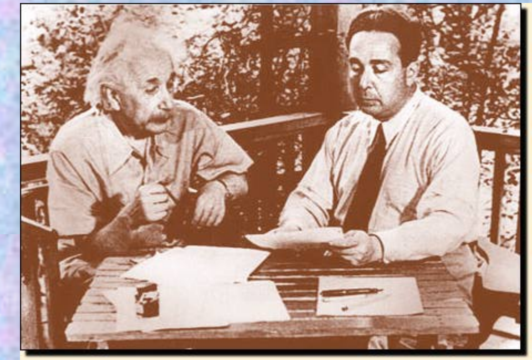


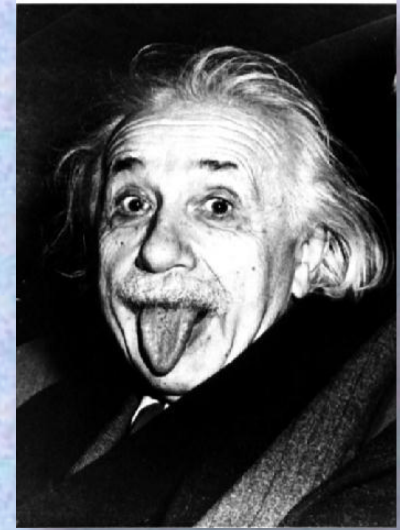
Sobral site

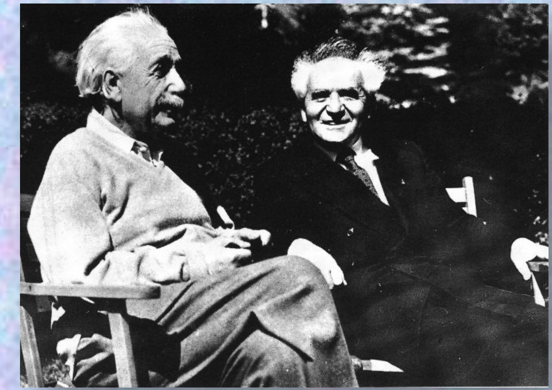


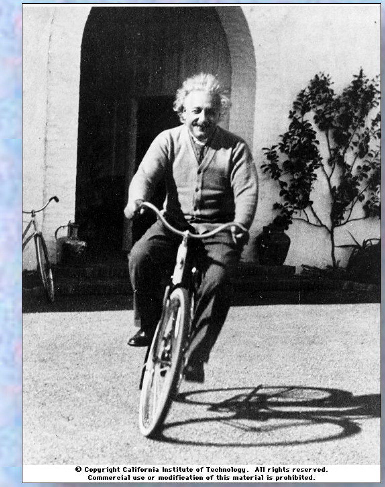
from Principe

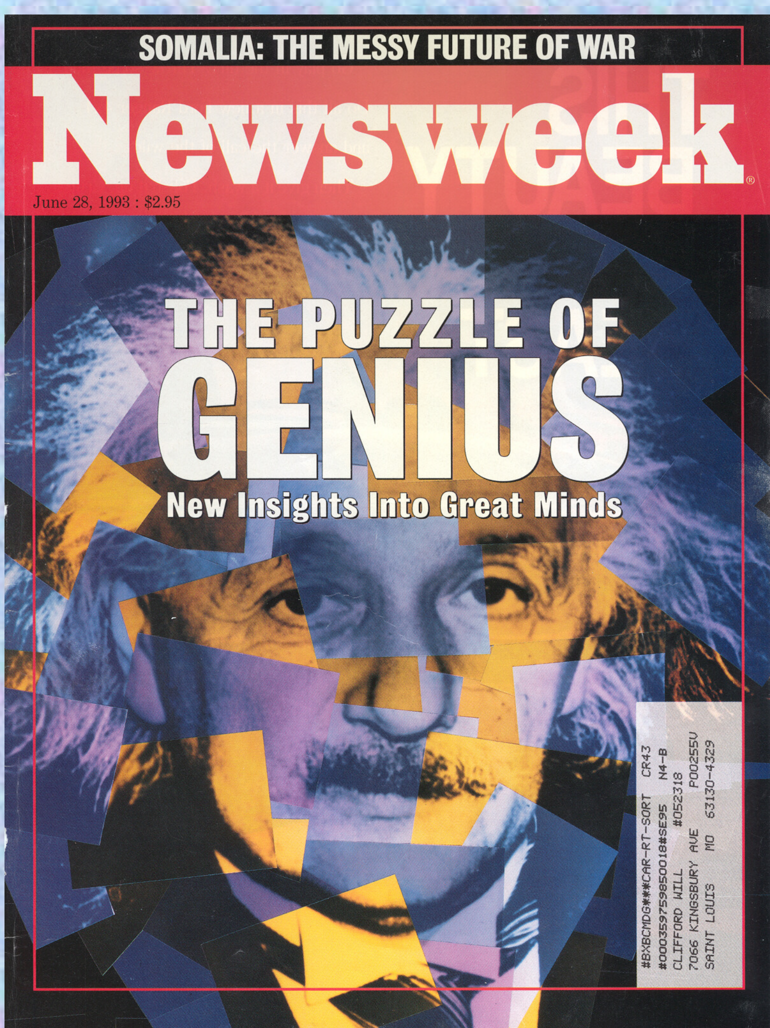
The public Einstein










SOMALIA: THE MESSY FUTURE OF WAR
Newsweek
June 28, 1993 : $2.95
THE PUZZLE OF
GENIUS
New Insights Into Great Minds
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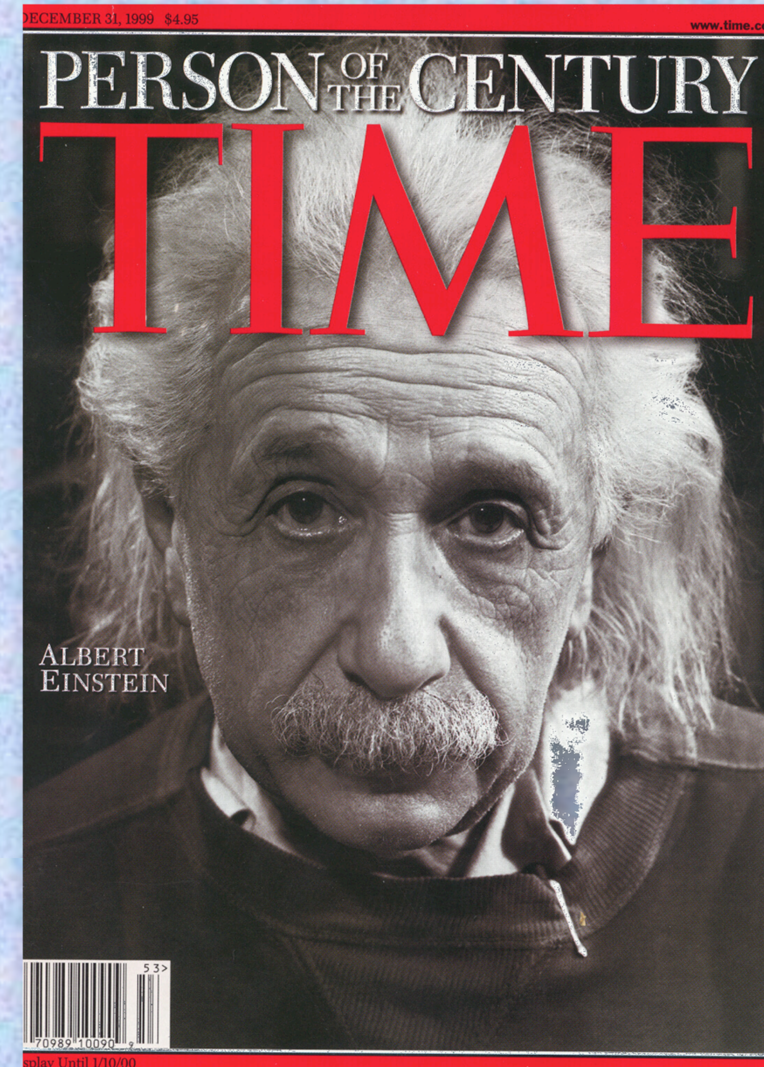
SAINT LOUIS MO 63130-4329


DECEMBER 31, 1999 $4.95
www.time.com
PERSON OF THE CENTURY
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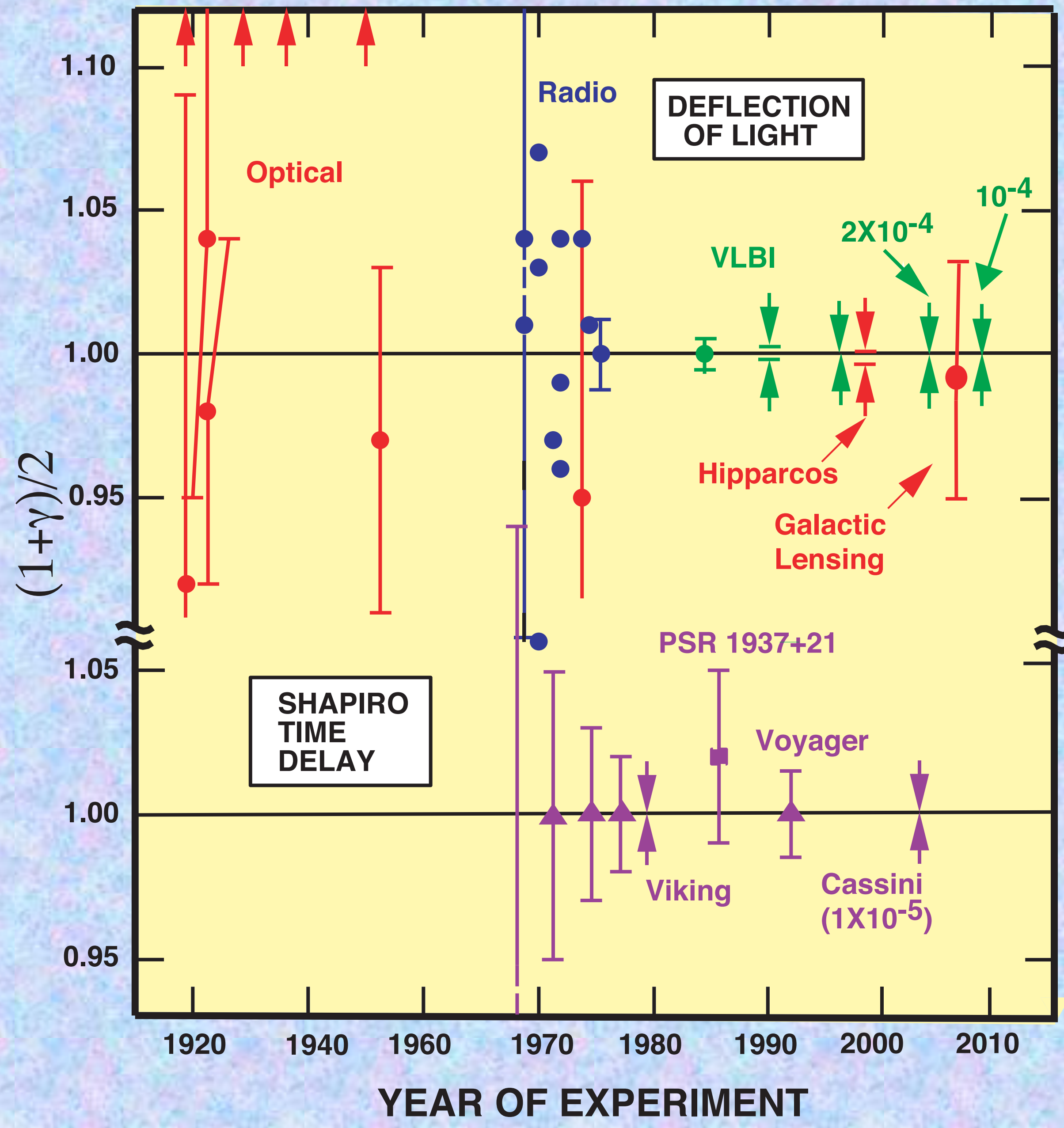
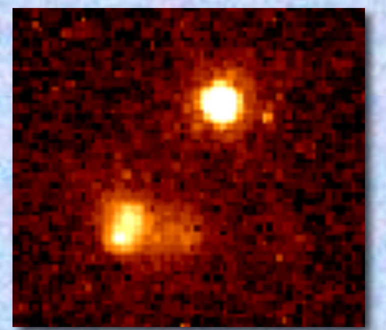
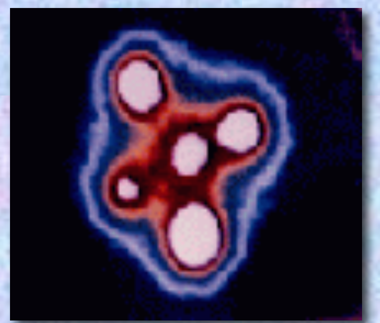
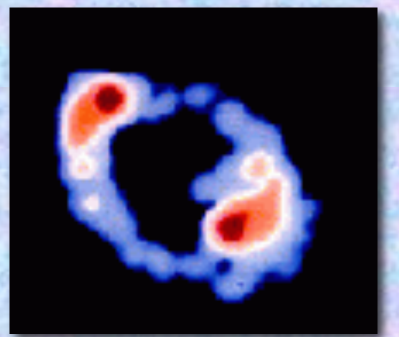
Geometry bends light: The PPN parameter γ



Geometry bends light: Gravitational lenses





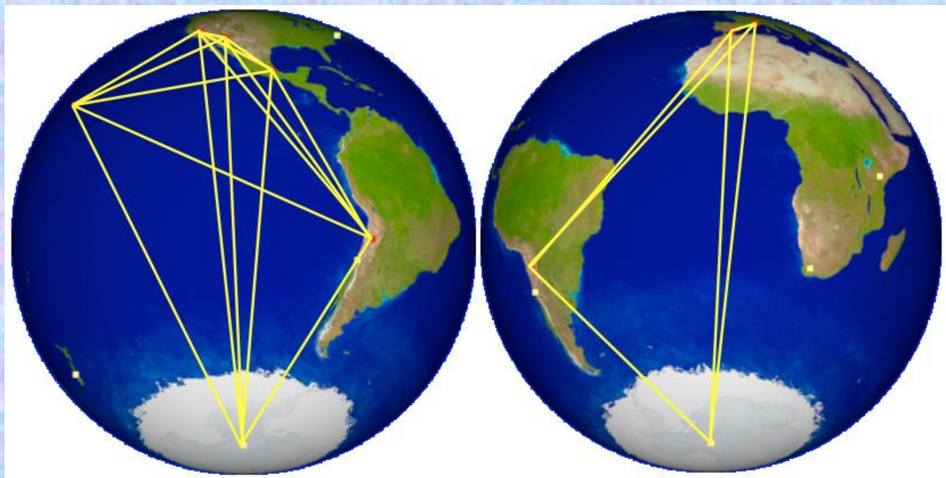


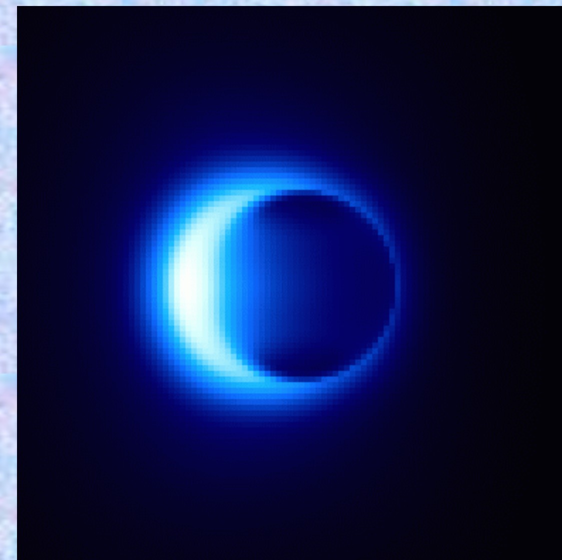
Einstein's gift
to astronomy

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.

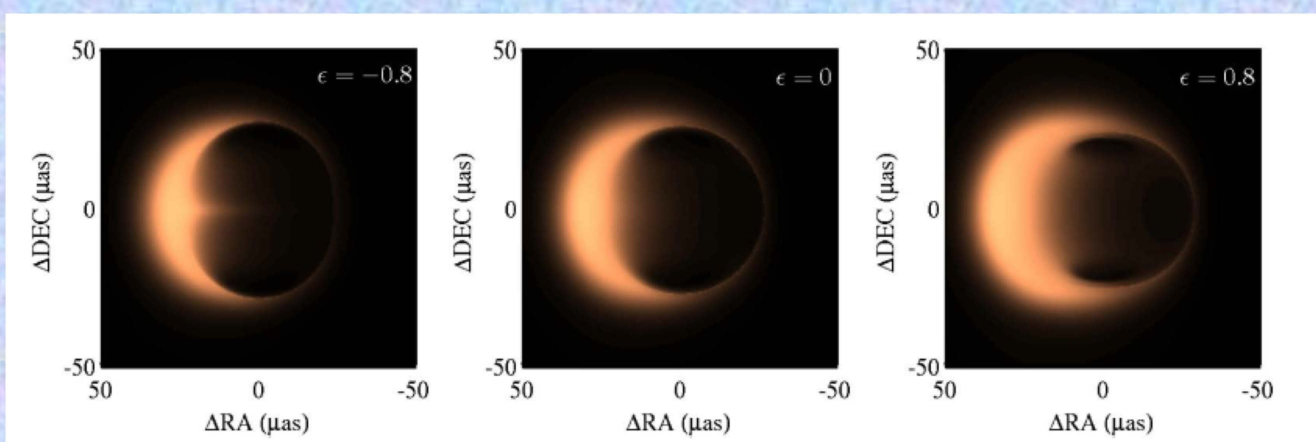
Geometry bends light: Black hole shadows





Event Horizon Telescope (EHT)

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



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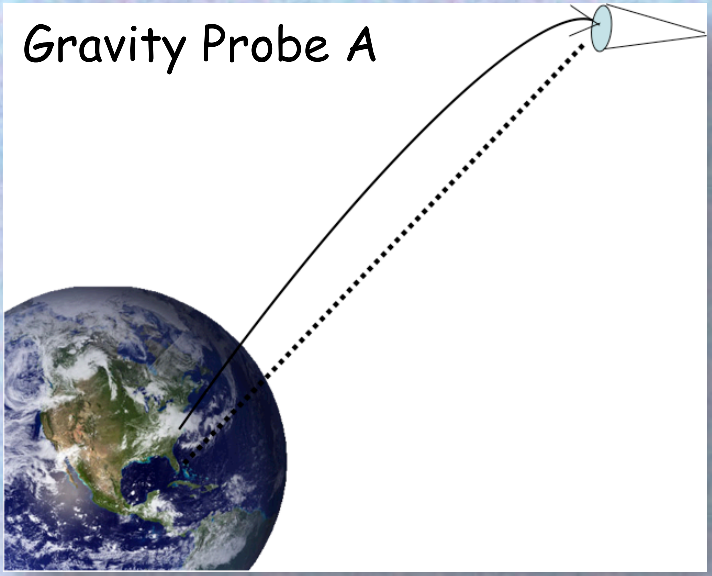
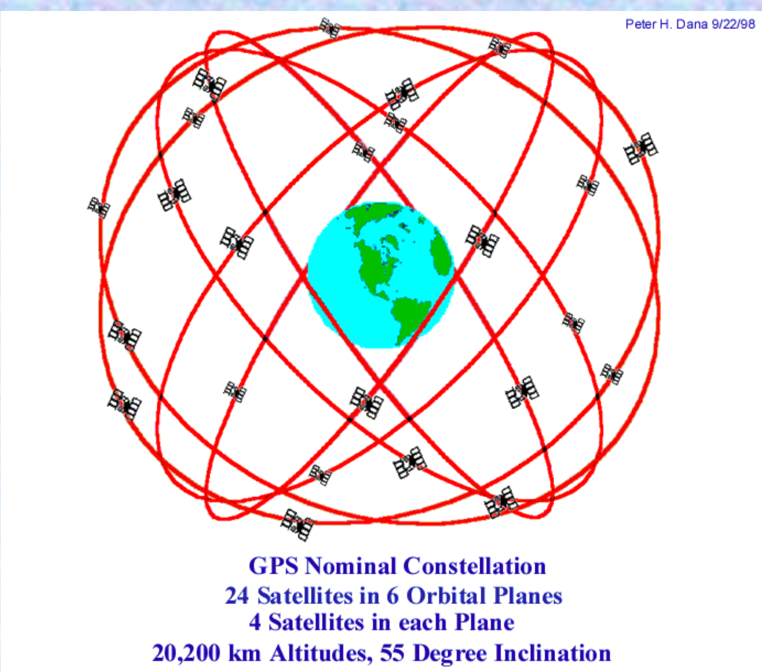
Geometry warps time: The redshift

- 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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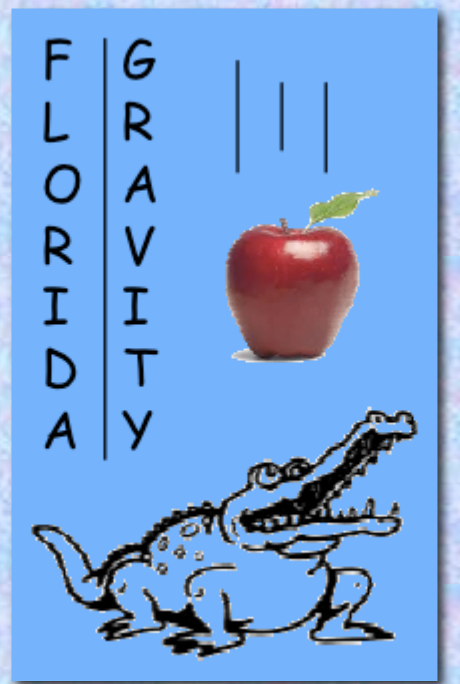
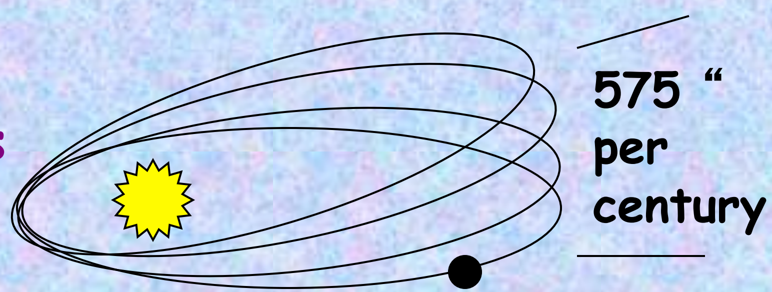


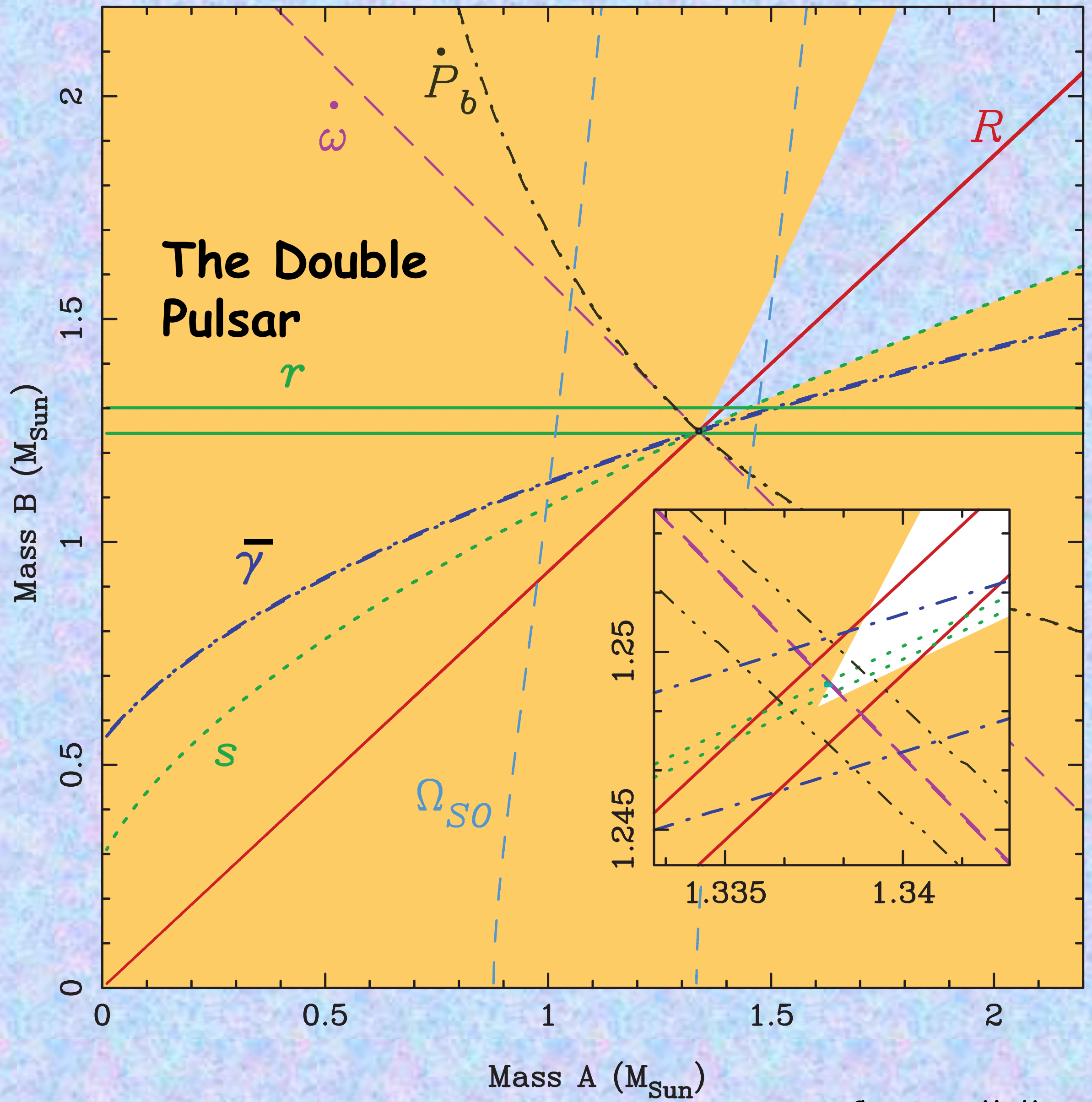
Geometry moves mass: Mercury's perihelion

- 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	42.98 ± 0.001
General relativity prediction	42.98

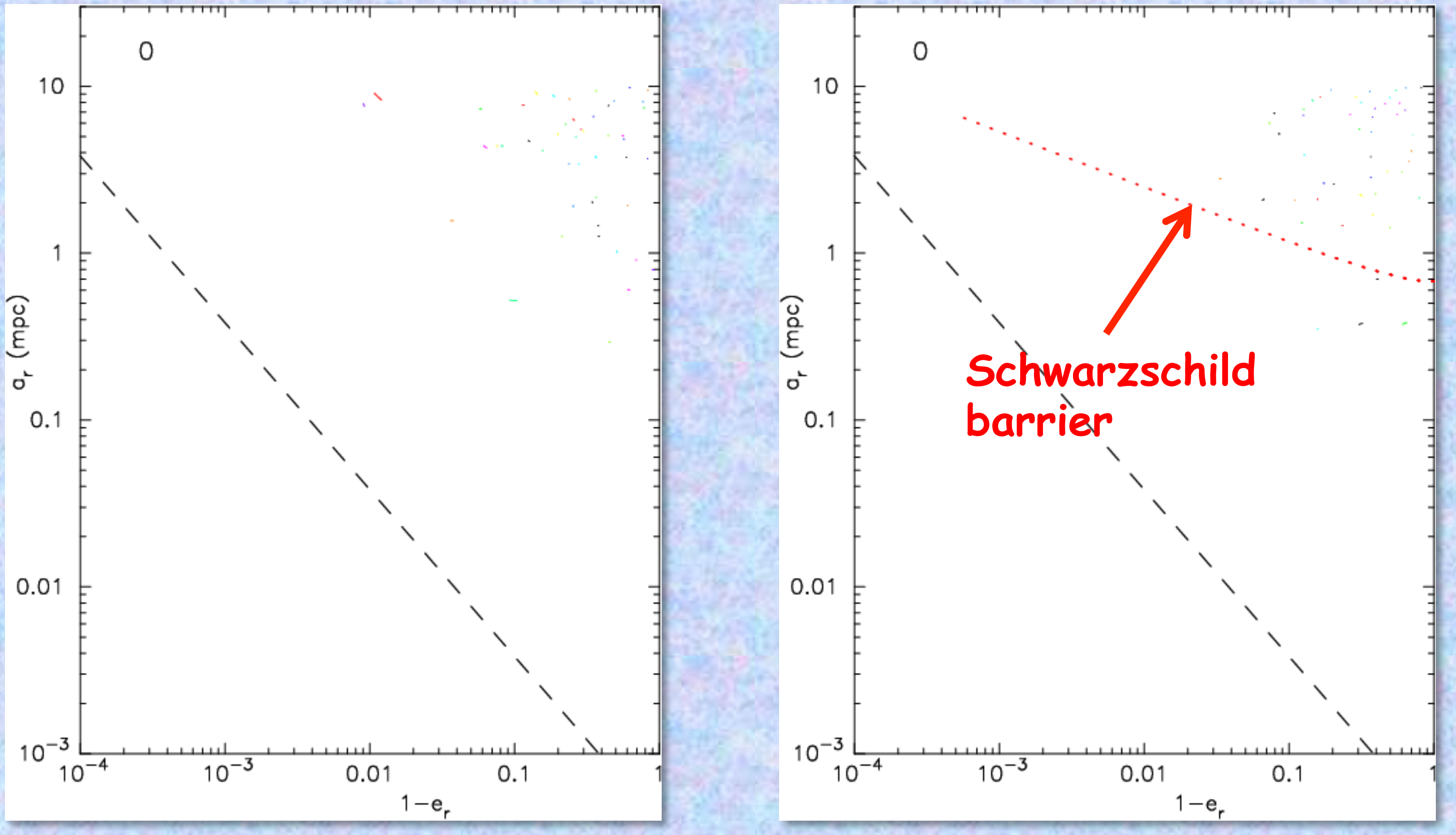
Pericenter advance and strong-field GR



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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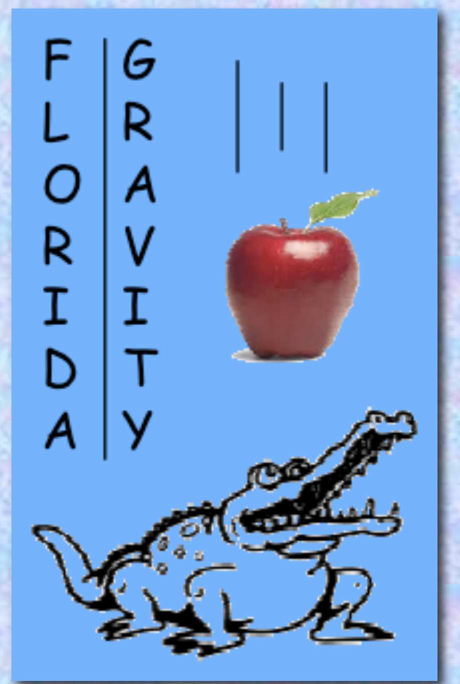
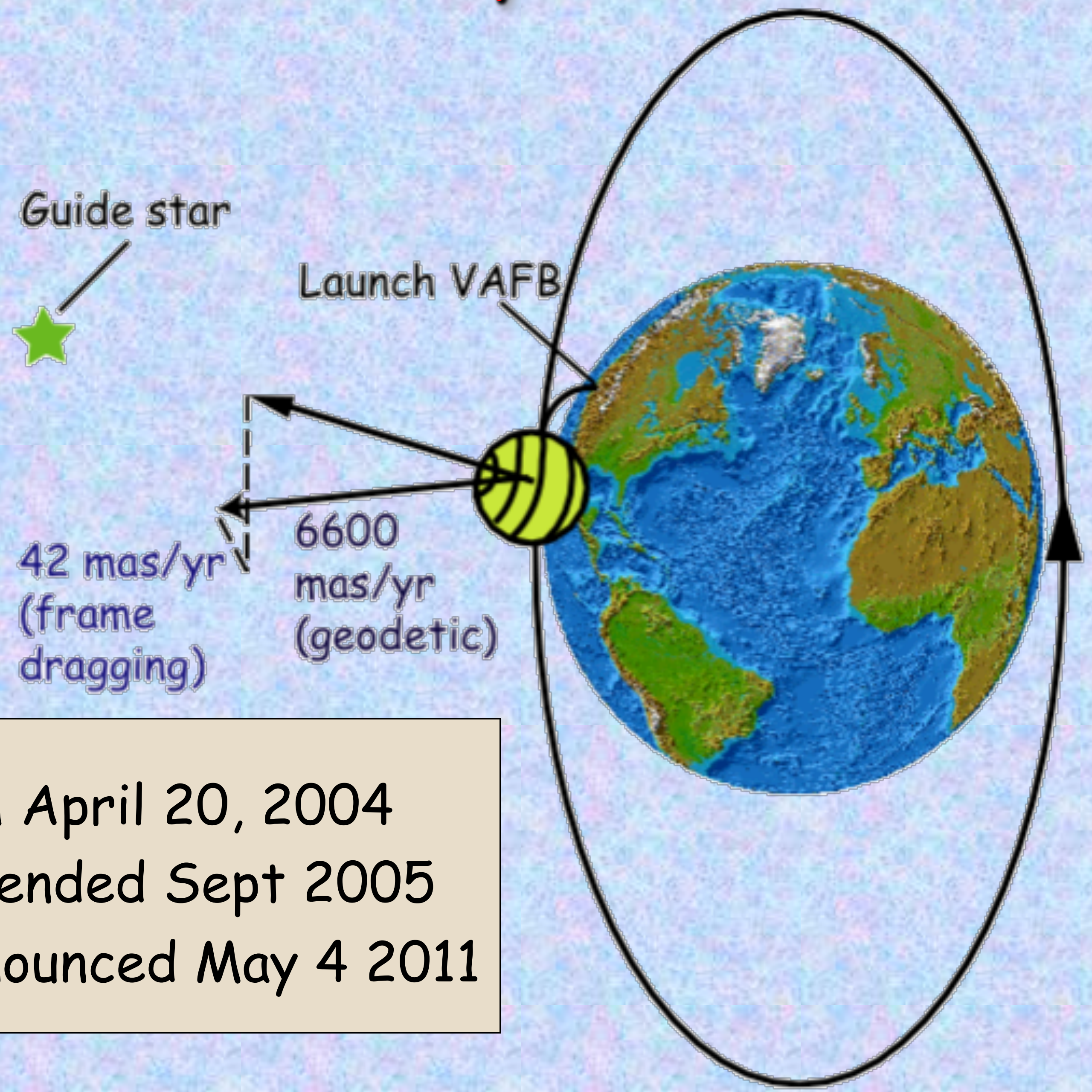


Gravity Probe B

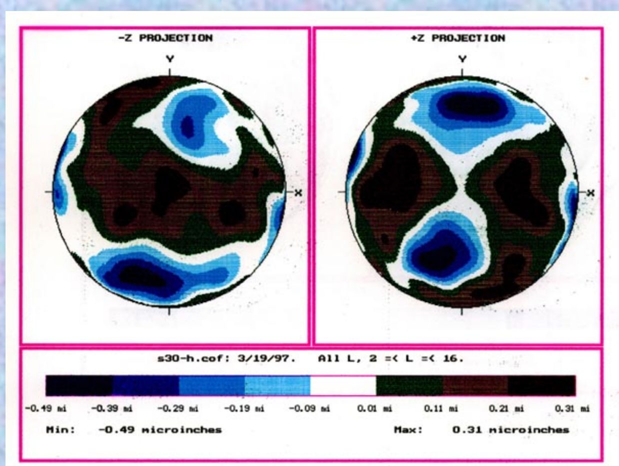


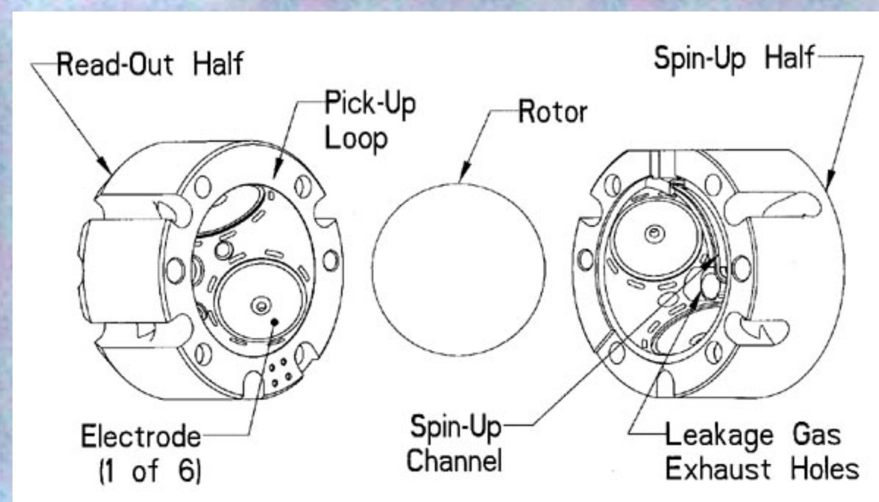
Launch April 20, 2004

Mission ended Sept 2005

Result announced May 4 2011

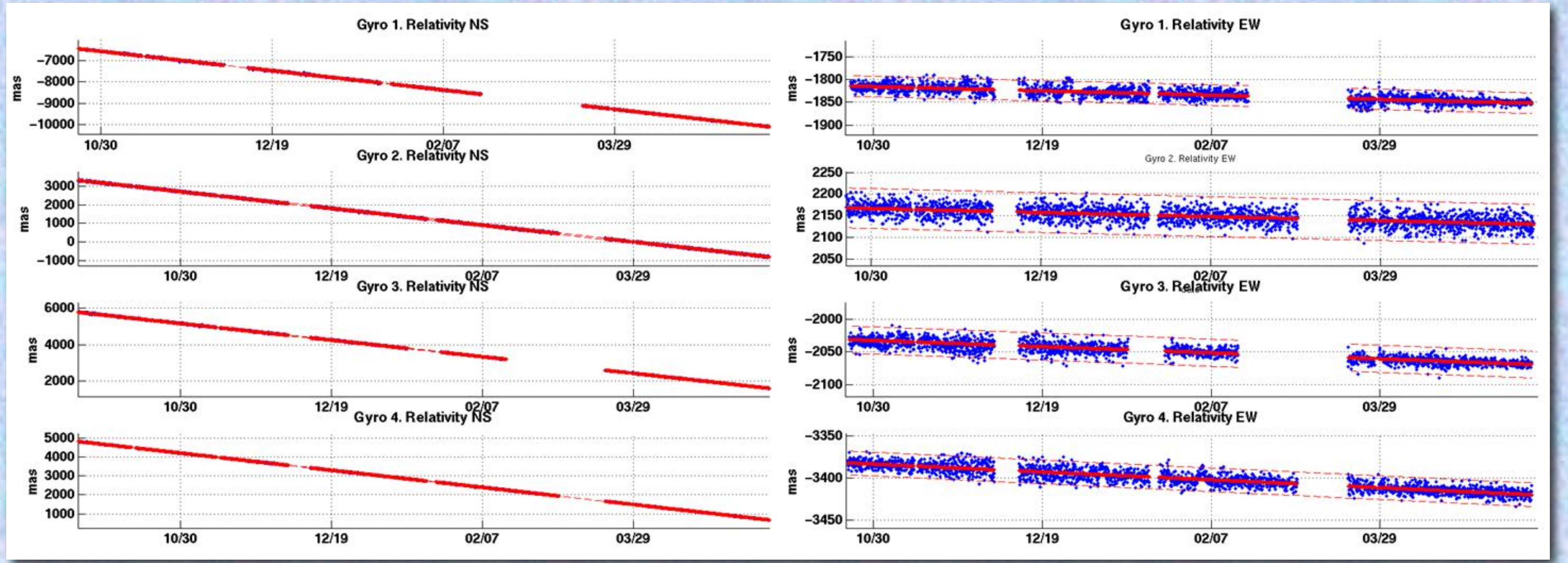
Gravity Probe B: The Gyroscopes





Disclosure: CMW chaired NASA's Science Advisory Committee for GPB (1998-2011)

Gravity Probe B: The final science result

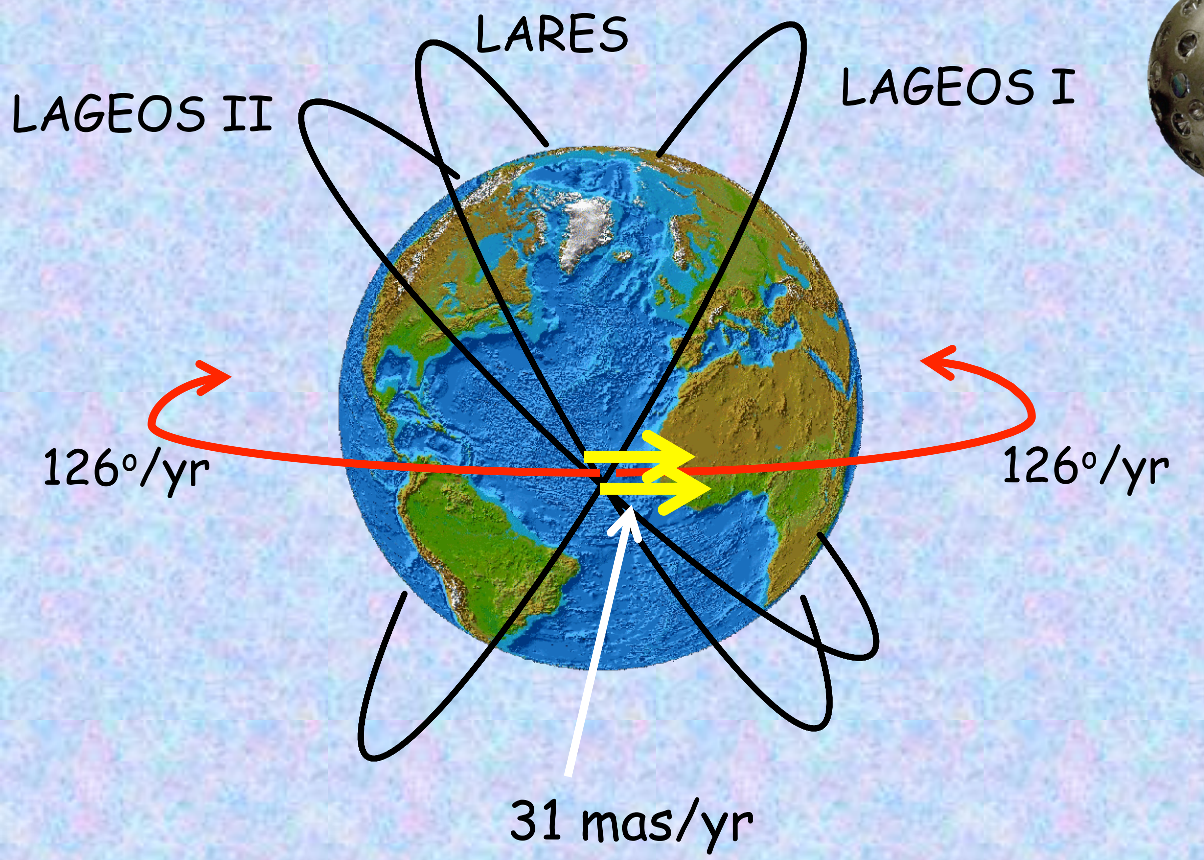


	Measured	Predicted
Geodetic Precession (mas)	6602 ± 18	6606
Frame-Dragging (mas)	37.2 ± 7.2	39.2

Classical & Quantum Gravity Focus Issue, Nov 2015

FLORIDA GRAVITY

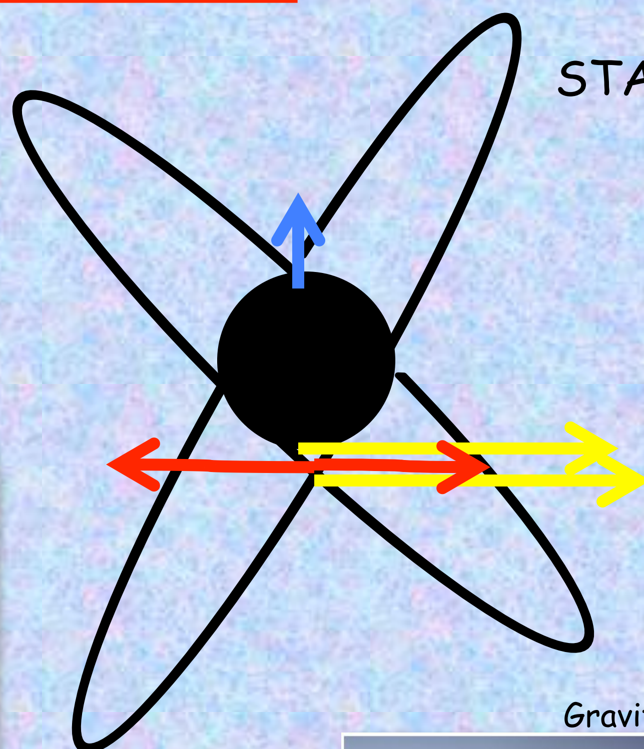
LAGEOS/LARES: Measuring Earth's J

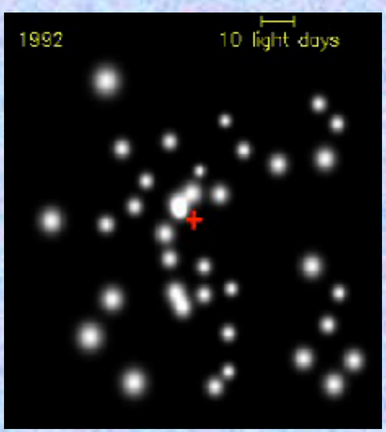


- LAGEOS I & II plus GRACE data: 10% test (Ciufolini et al 2011)
- LARES (launched 2012) plus GRACE: goal = 1%

SgrA*: Testing the BH no-hair theorem

$$\boxed{Q_2 = -Ma^2 = -J^2/M}$$





$J/M^2 > 0.5$,

$e \sim 0.9$

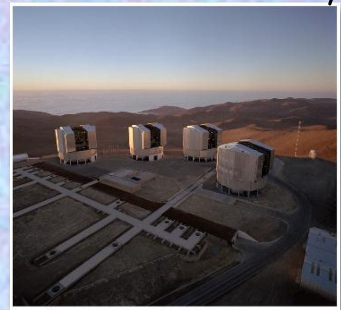
$P \sim 0.1$ yr,

$a < 10^{-3}$ pc,

=> $\Delta\theta \sim 10$ μas/yr

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

Gravity



Keck

.....pulsars would also work!

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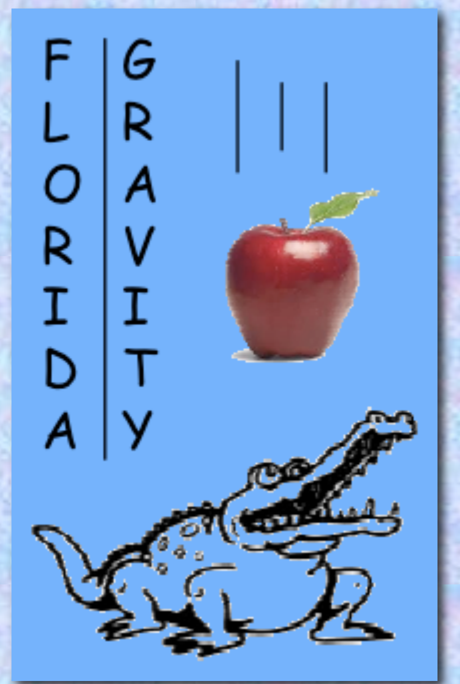
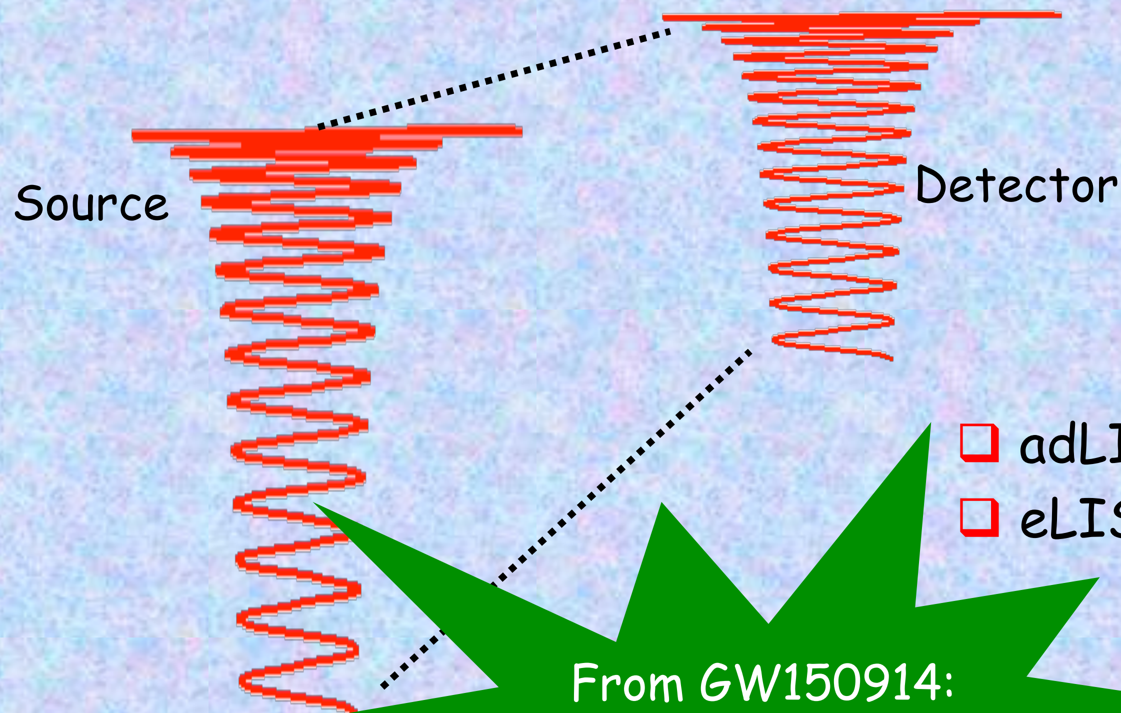


Gravitational-wave tests of GR: Speed

Does the speed depend on wavelength?
Is gravity massive?



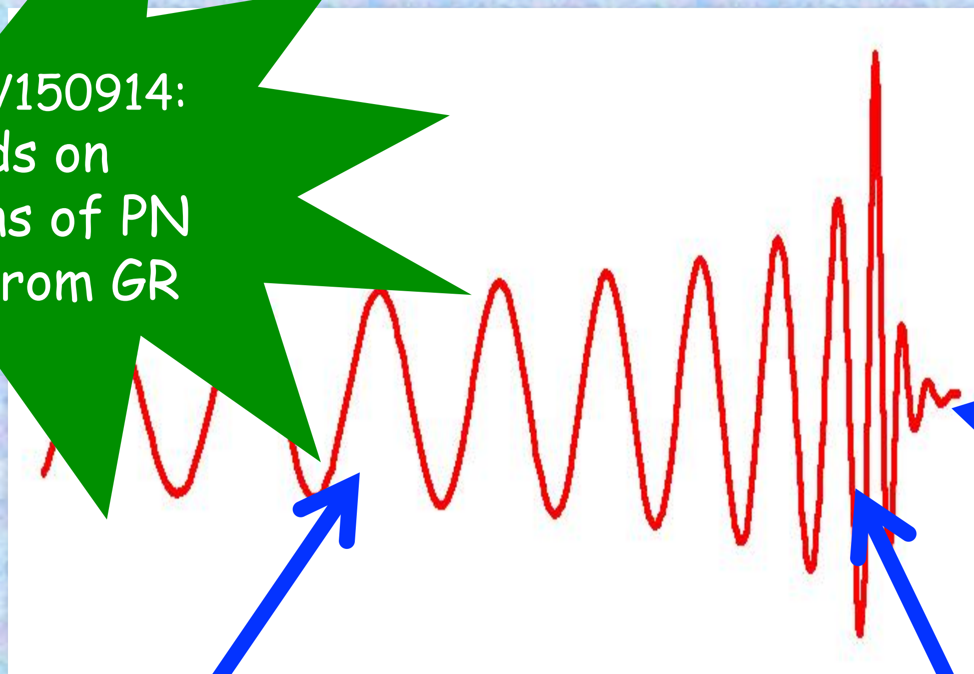
CMW, *PRD* 57, 2061 (1998)
Berti, Buonanno, CMW (2005)
Arun, CMW (2009)
Stavridis, CMW (2009)
Mirshekari, Yunes, CMW (2012)

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

From GW150914:
$\lambda_g > 10^{13}$ km
$m_g < 10^{-22}$ eV

Gravitational-wave tests of GR: Strong gravity

From GW150914: Bounds on deviations of PN terms from GR

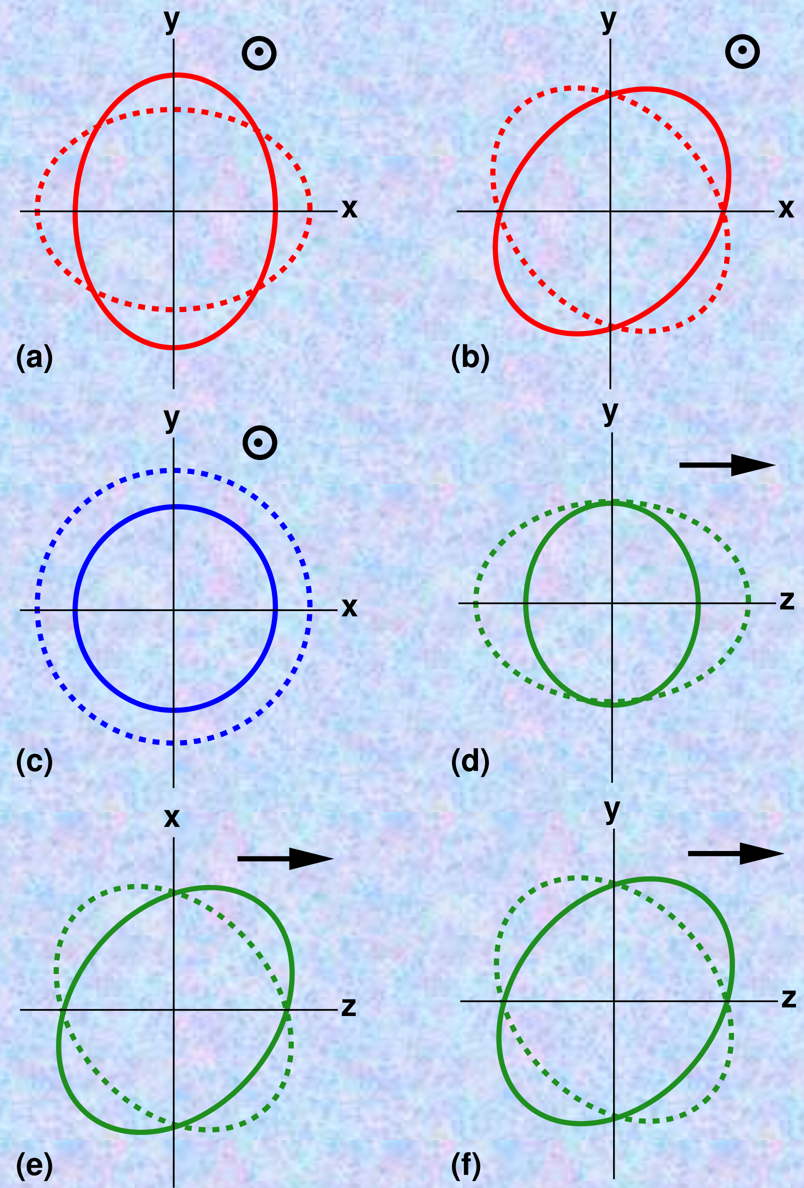


Ringdown phase: Test the no-hair theorems

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

Merger phase:
Numerical relativity
Neutron-star disruption

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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GR @ 100, 6th Biennial Bacon Conference, Caltech, 11 March 2016