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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- Early struggles
- Highlights from the first century
- Prospects for the second century

- Geometry bends light
- Geometry warps time
- Geometry moves mass
- Geometry does the twist
- Geometry makes waves
Geometry bends light: The 1919 Eclipse

A. S. Eddington

Sobral site

Photo from Principe
Geometry bends light: The 1919 Eclipse

A. S. Eddington

Sobral site

Photo from Principe
The public Einstein
Geometry bends light: The PPN parameter $\gamma$
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”

<table>
<thead>
<tr>
<th>Planet</th>
<th>Advance</th>
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<tbody>
<tr>
<td>Venus</td>
<td>277.8</td>
</tr>
<tr>
<td>Earth</td>
<td>90.0</td>
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<tr>
<td>Mars</td>
<td>2.5</td>
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<tr>
<td>Jupiter</td>
<td>153.6</td>
</tr>
<tr>
<td>Saturn</td>
<td>7.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>531.2</strong></td>
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<tr>
<td><strong>Discrepancy</strong></td>
<td><strong>42.9</strong></td>
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<tr>
<td><strong>Modern measured value</strong></td>
<td><strong>42.98 ± 0.001</strong></td>
</tr>
<tr>
<td><strong>General relativity prediction</strong></td>
<td><strong>42.98</strong></td>
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</tbody>
</table>
Pericenter advance and strong-field GR

The Double Pulsar

Diagram showing the relationship between Mass A and Mass B, with various lines and labels indicating different physical parameters such as $\gamma$, $\Omega_{SO}$, and $\dot{P}_b$.
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

Gravity Probe B: The final science result

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geodetic Precession (mas)</strong></td>
<td>6602 ± 18</td>
<td>6606</td>
</tr>
<tr>
<td><strong>Frame-Dragging (mas)</strong></td>
<td>37.2 ± 7.2</td>
<td>39.2</td>
</tr>
</tbody>
</table>

Classical & Quantum Gravity Focus Issue, Nov 2015
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

\[ Q_2 = -Ma^2 = -\frac{J^2}{M} \]

\( J/M^2 > 0.5, \quad e \sim 0.9 \)
\( P \sim 0.1 \text{ yr}, \quad a < 10^{-3} \text{ pc}, \)
\( \Rightarrow \Delta \theta \sim 10 \mu\text{as/yr} \)


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?

Source  Detector

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

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

CMW, PRD 57, 2061 (1998)
Berti, Buonanno, CMW (2005)
Arun, CMW (2009)
Stavridis, CMW (2009)
Mirshekari, Yunes, CMW (2012)
Gravitational-wave tests of GR: Strong gravity

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

Merger phase: Numerical relativity Neutron-star disruption

Ringdown phase: Test the no-hair theorems

From GW150914: Bounds on deviations of PN terms from GR
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)
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