Gravitational Radiation

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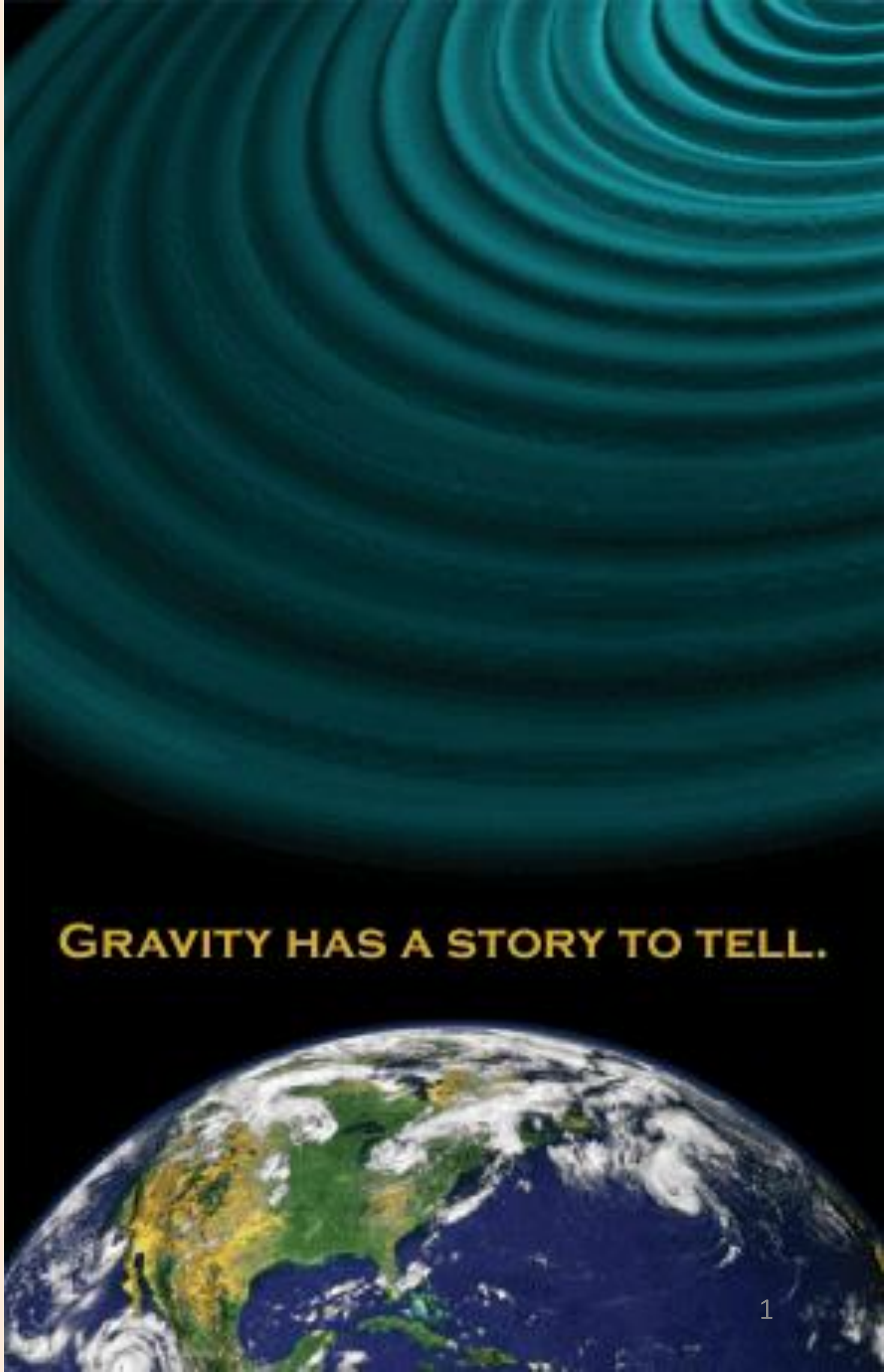
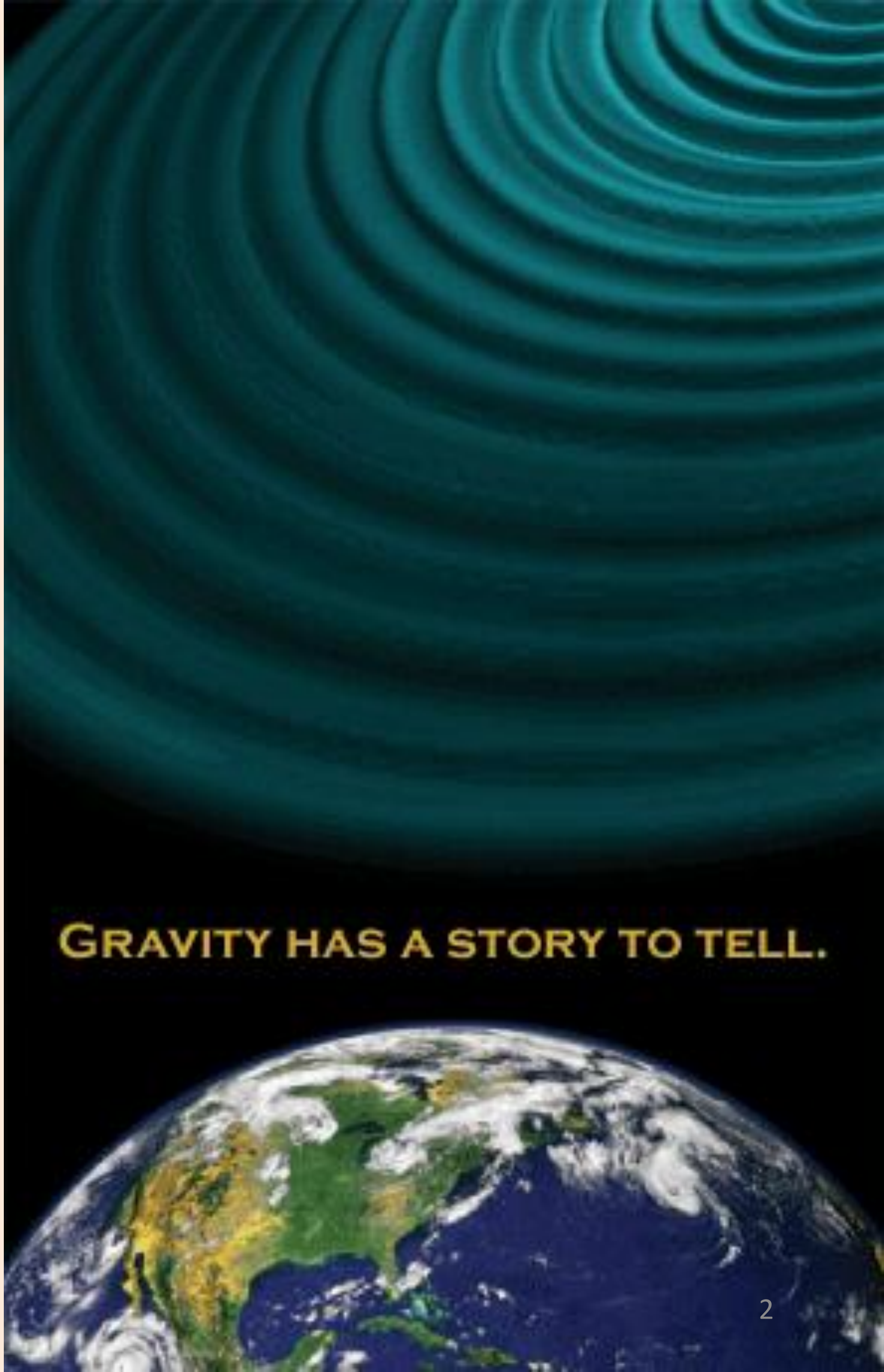


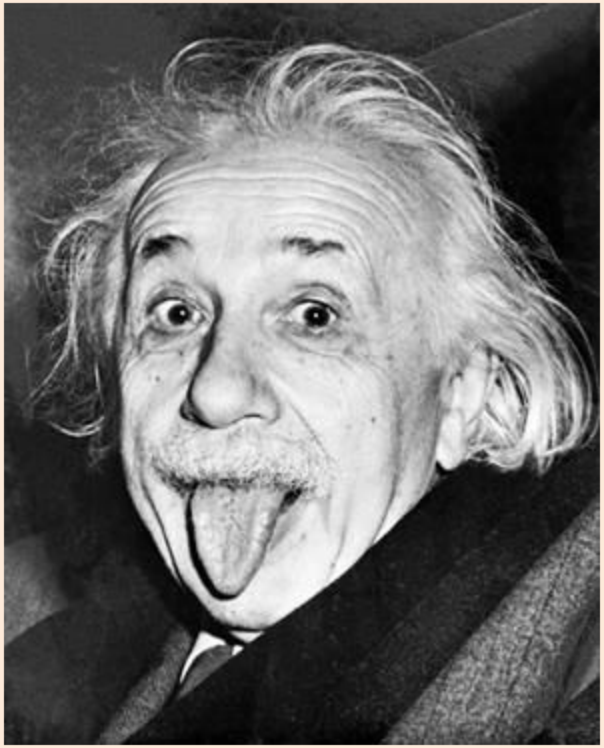
Outline

- General Relativity and linearized Einstein Field Equations
- Generation of Gravitational Waves
- Detection of Gravitational Waves



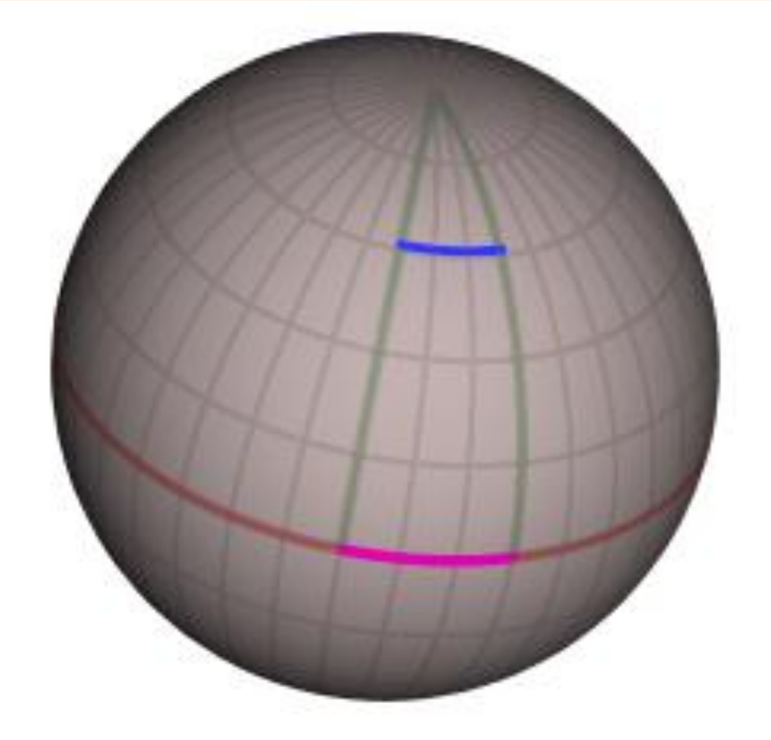
General Relativity

- Geometric theory of gravitation (Einstein 1915)
- Confirmed by many observations such as
  - Perihelion precession of Mercury’s orbit
  - Deflection of light by the Sun
  - **Loss of energy through gravitational radiation**



General Relativity

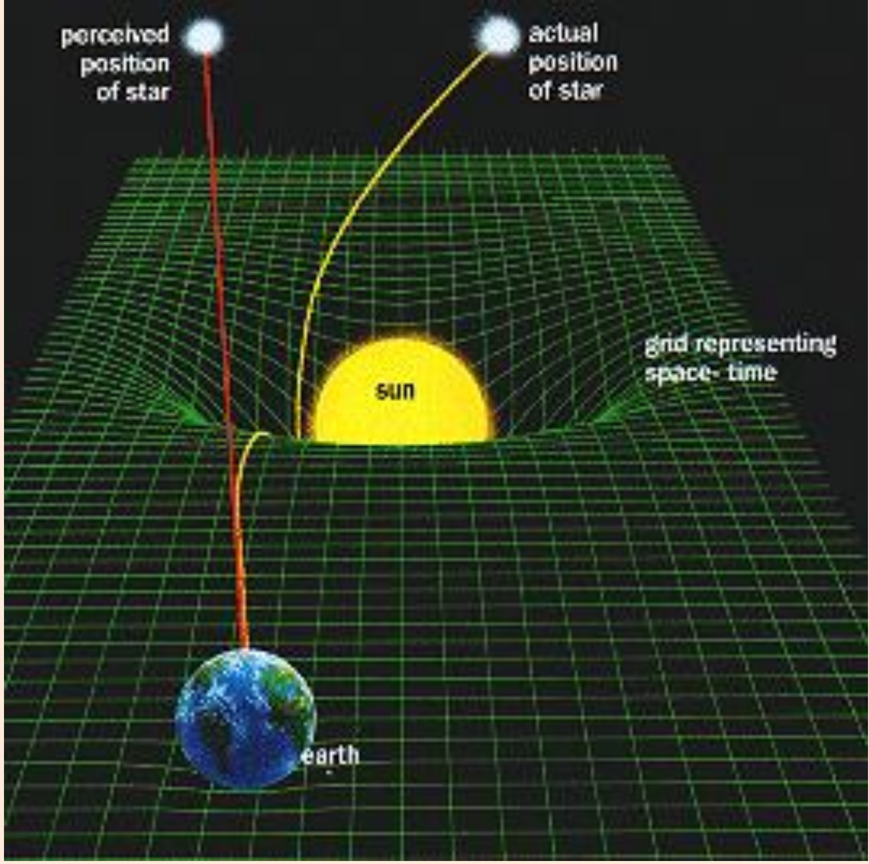
- Spacetime is a 4-dimensional Lorentzian manifold
- Distances and angles can be measured with the metric g, a 4x4 matrix, for Minkowski spacetime:



$$\eta_{\mu\nu} = diag(-1,1,1,1)$$

Einstein Field Equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} \cdot T_{\mu\nu}$$



Einstein tensor

Stress-energy tensor

Linearized Einstein Equations

- Assume a weak gravitational field:

  $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with $|h_{\mu\nu}| << 1$

- Calculate the Einstein Tensor

- Introduce the trace reversed pertubation

$$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h$$

- Use Lorentz gauge

$$\partial_\mu \bar{h}^\mu{}_\nu = 0$$

Linearized Einstein Equations

$$\Rightarrow \Box \overline{h_{\mu\nu}} = -16\pi G \cdot T_{\mu\nu}$$

with $\Box = -\frac{\partial^2}{\partial t^2} + \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$

Or in vacuum: $\Box \; \overline{h_{\mu\nu}} = 0$

Solution: $\overline{h}_{\mu\nu} = C_{\mu\nu} e^{ik_\sigma x^\sigma}$

Generation of Gravitational Waves

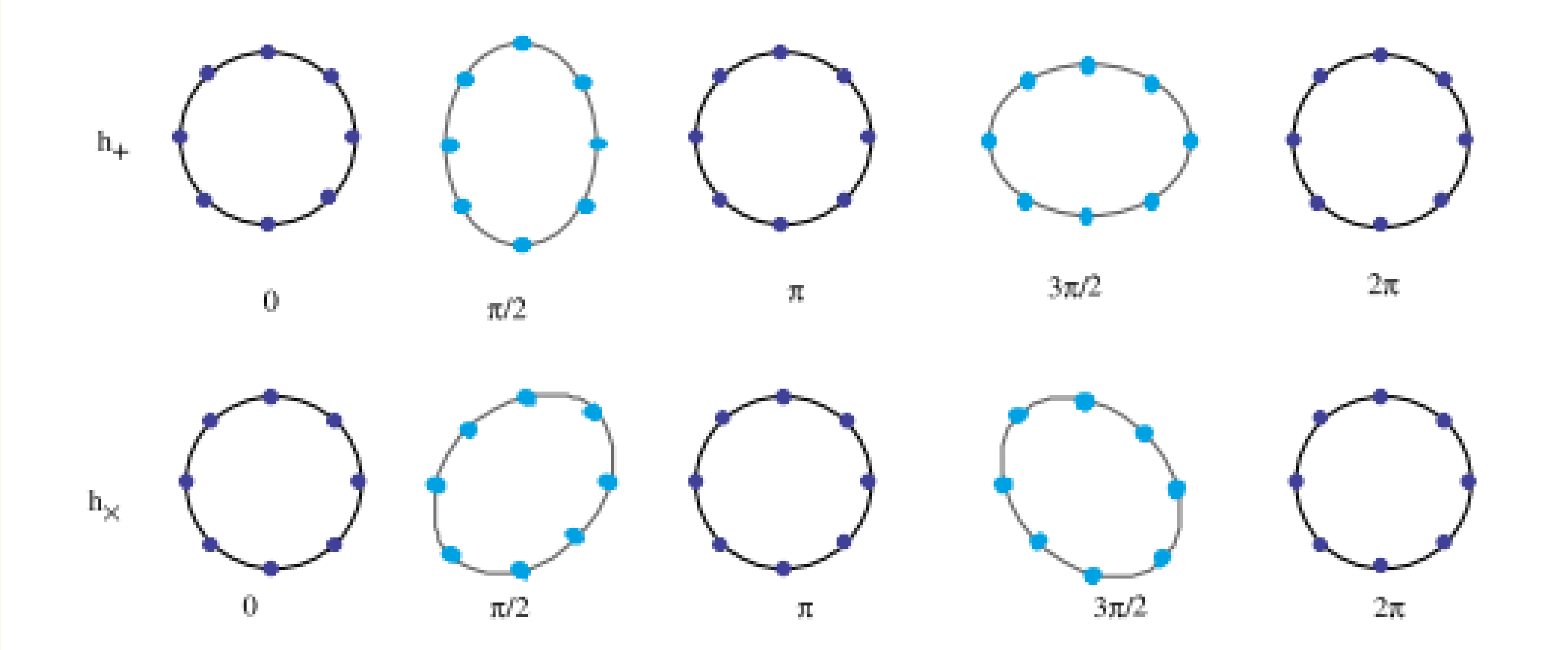
- Gravity has only one charge: no negative mass!

- Action equals reaction, momentum is conserved.

- The spacing of two equal masses cannot change.

Generation of Gravitational Waves

⇨ There is a time-varying quadrupole moment.
No variation in monopole or dipole moment!



Generation of Gravitational Waves

Three types of sources:

- Burst sources (formation of neutron stars or black holes in supernova events)

- Narrow-band sources (rotation of pulsars, binary star systems)

- Stochastic backgrounds (integrated effects of many weak sources, cosmological processes in the early universe)

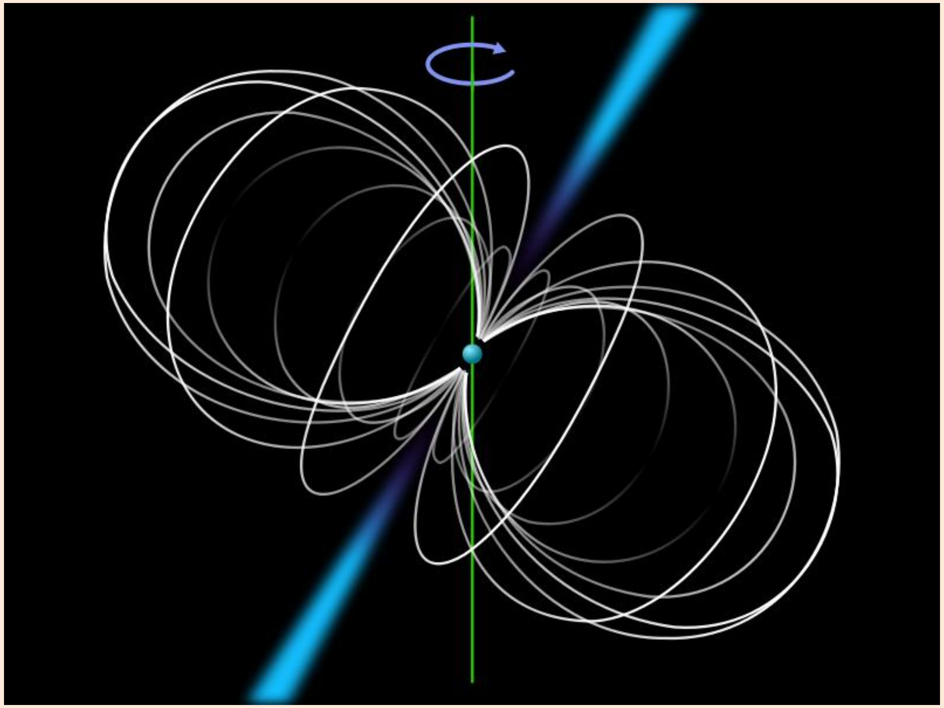
Detection of Gravitational Waves

• Indirectly: Loss of energy through gravitational radiation (PSR B1913 + 16, disovered in 1974 by Hulse and Taylor, Nobel Prize in Physics 1993)

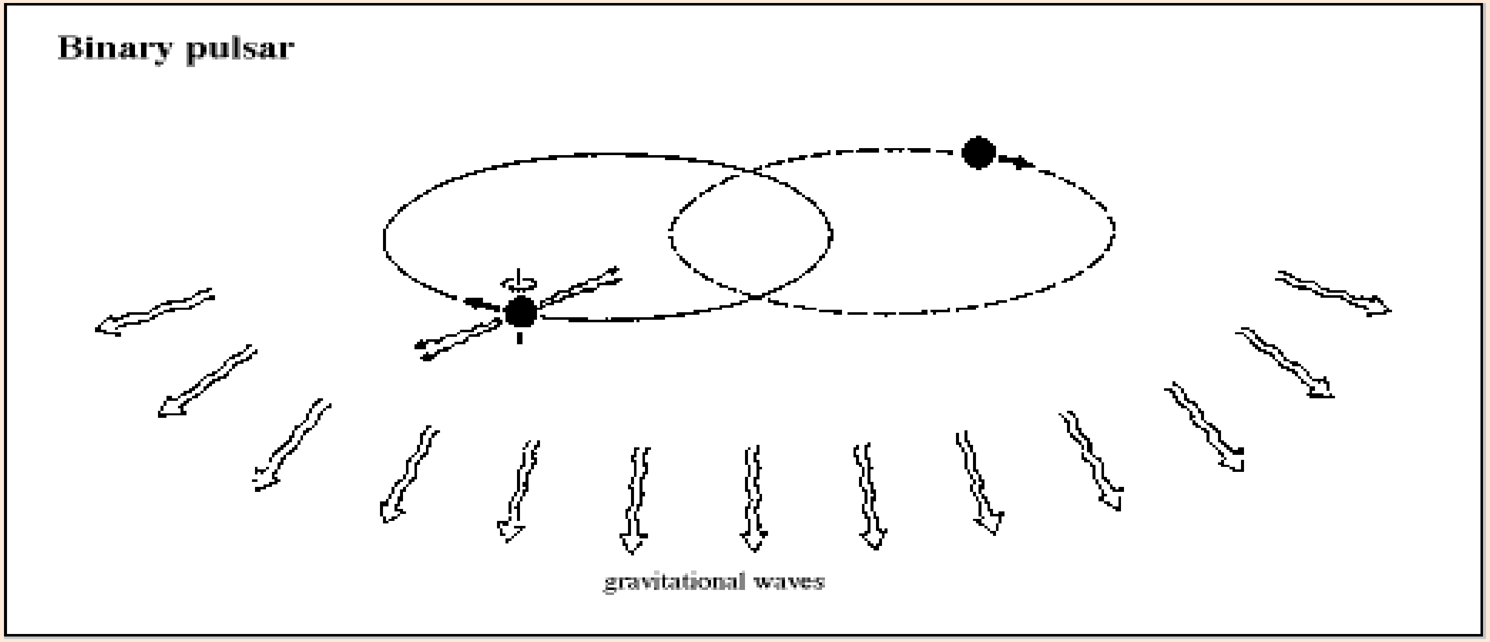
•Directly (no success yet): Gravitational waves will cause a (very small) displacement in test masses.

Pulsars

- Highly magnetized, rotating neutron stars
- Emit a beam of electromagnetic radiation



Indirect detection of Gravitational Waves

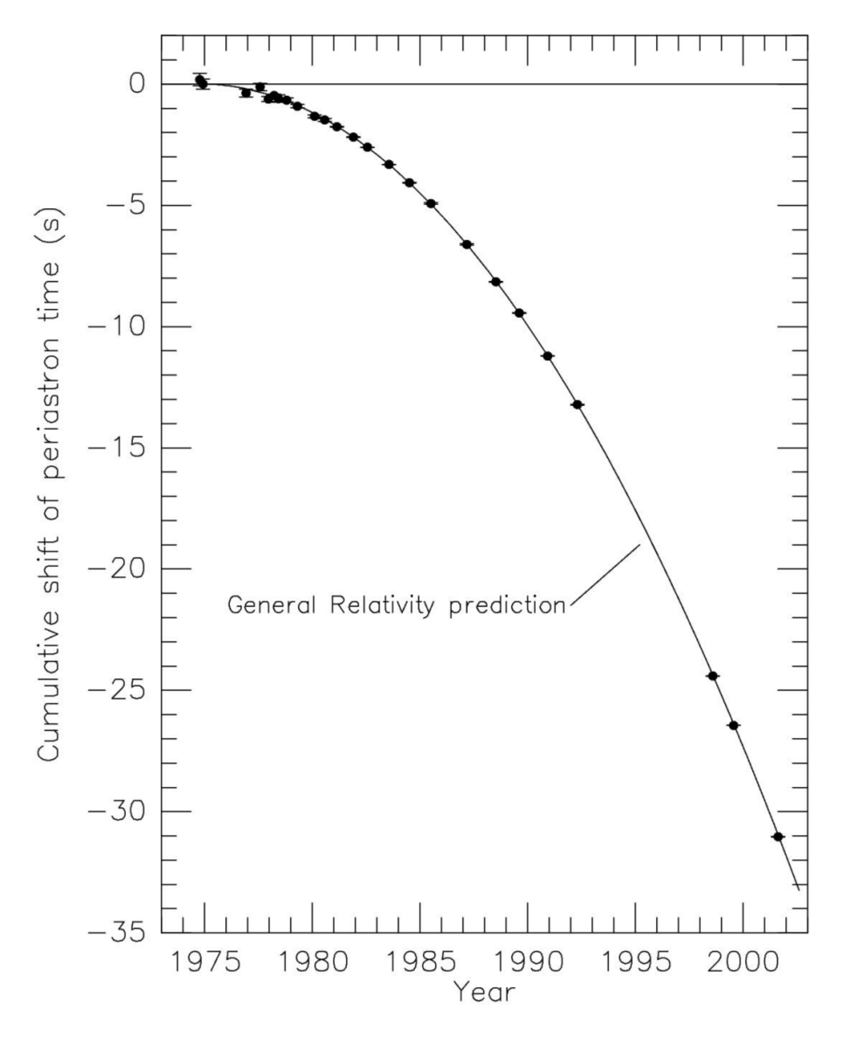


Binary pulsar: Pulsar in a binary star system (two stars orbiting around their common center of mass).

PSR B1916+13: A natural testing laboratory for general relativistic effects.

Indirect detection of Gravitational Waves

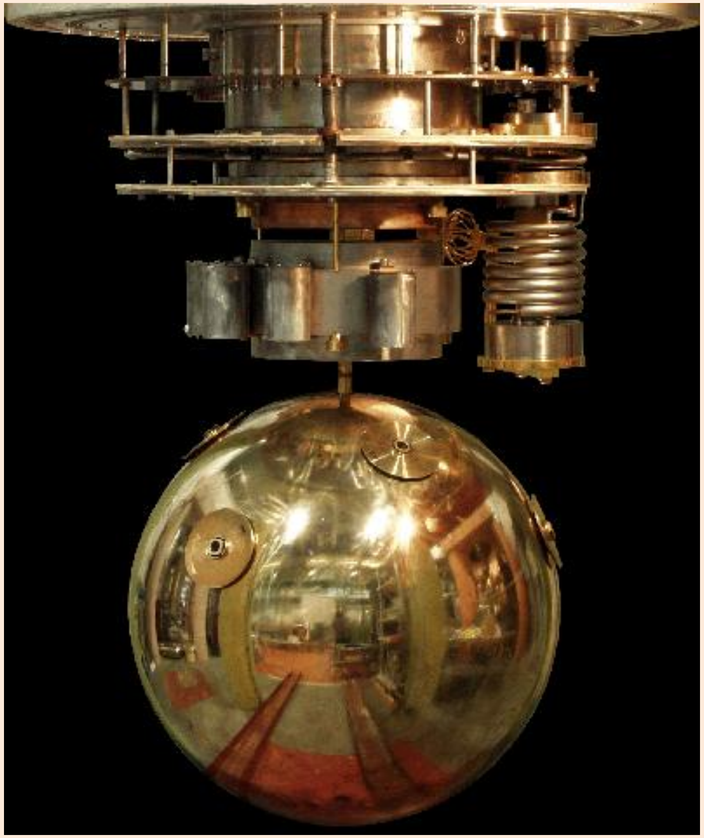
The system loses energy through gravitational radiation, the orbital period shrinks (by 76.5 microseconds per year).

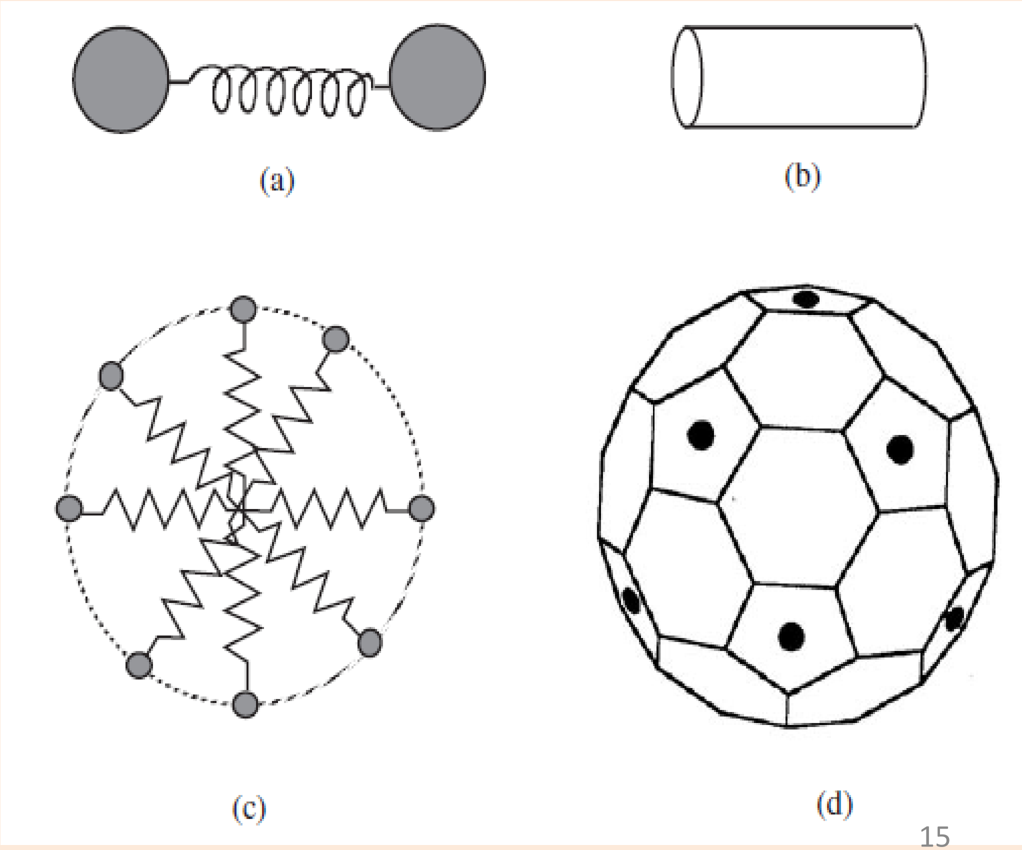


Data from Weisberg and Taylor (2004)

Direct detection of Gravitational Waves

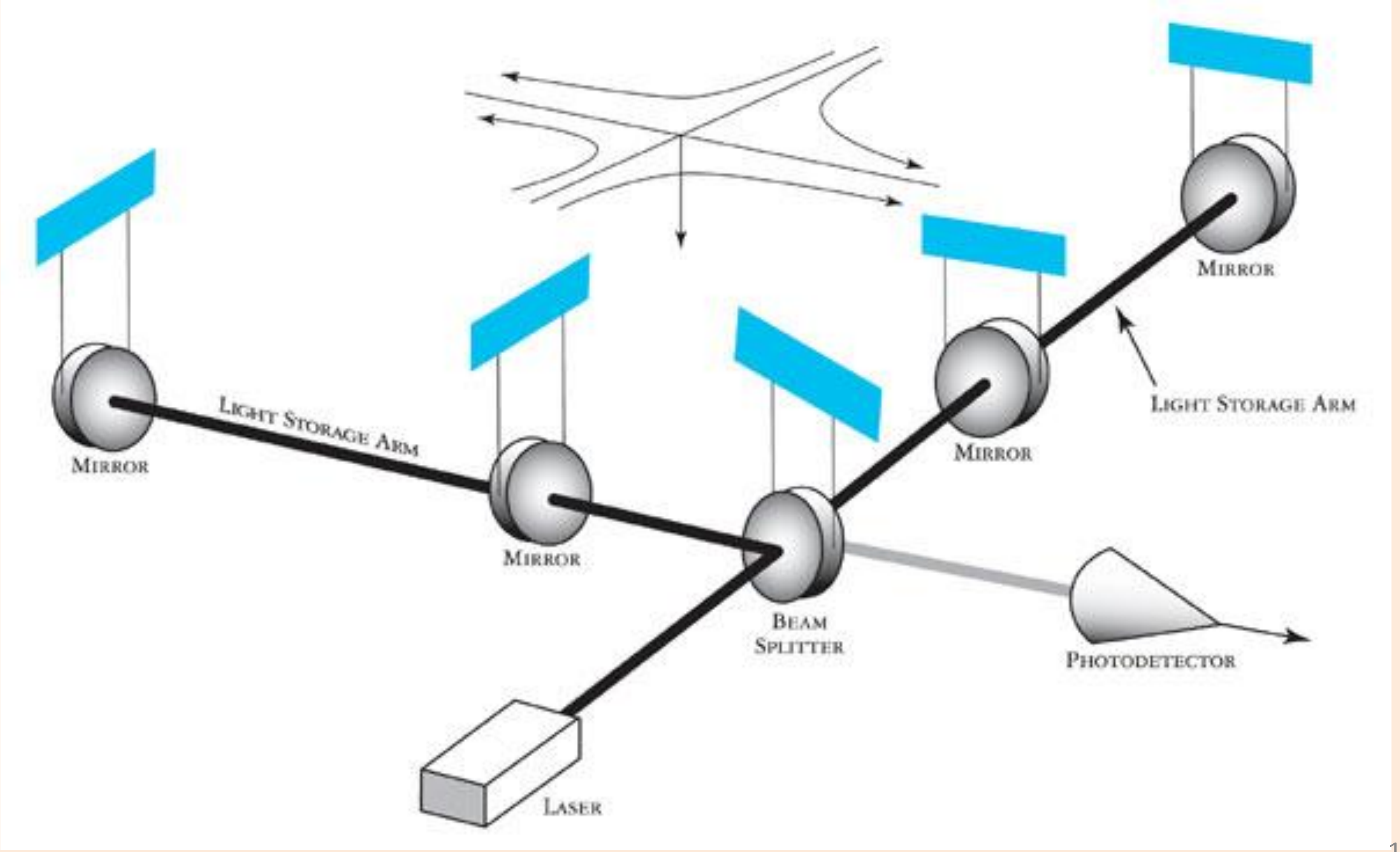
- Weber bars
- MiniGRAIL





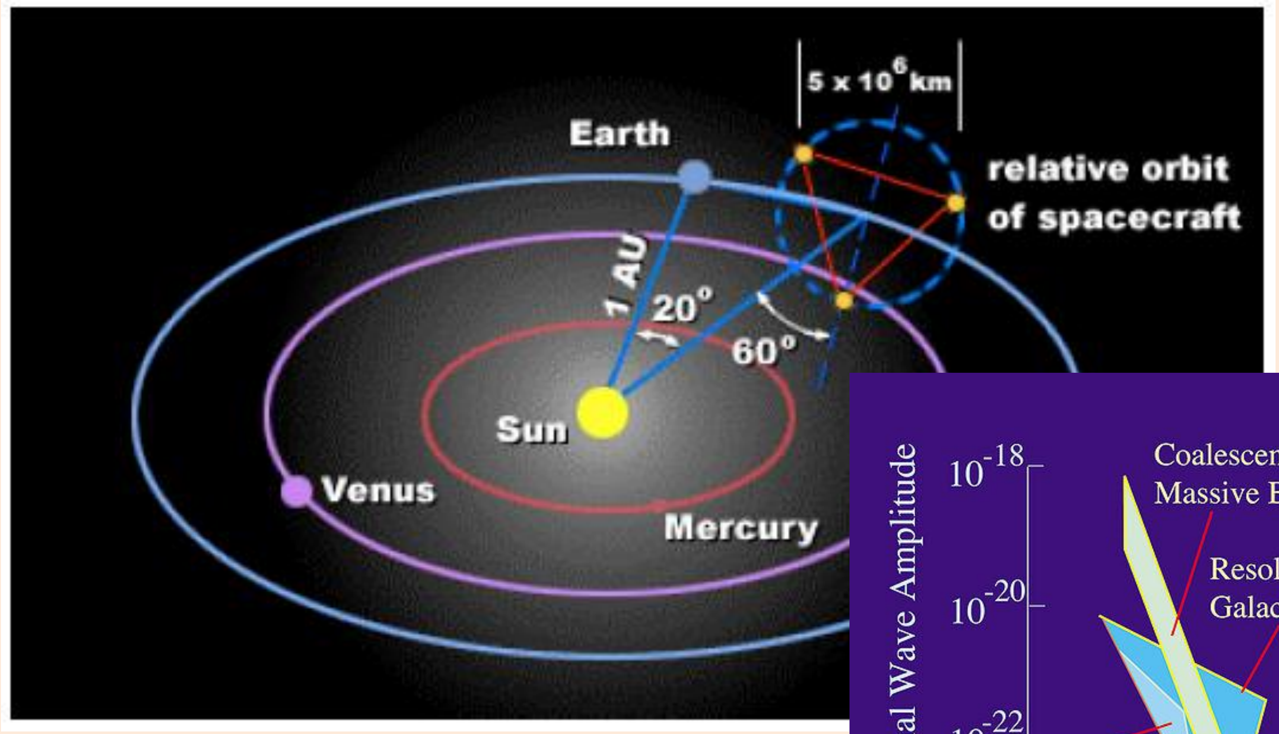
Direct detection of Gravitational Waves

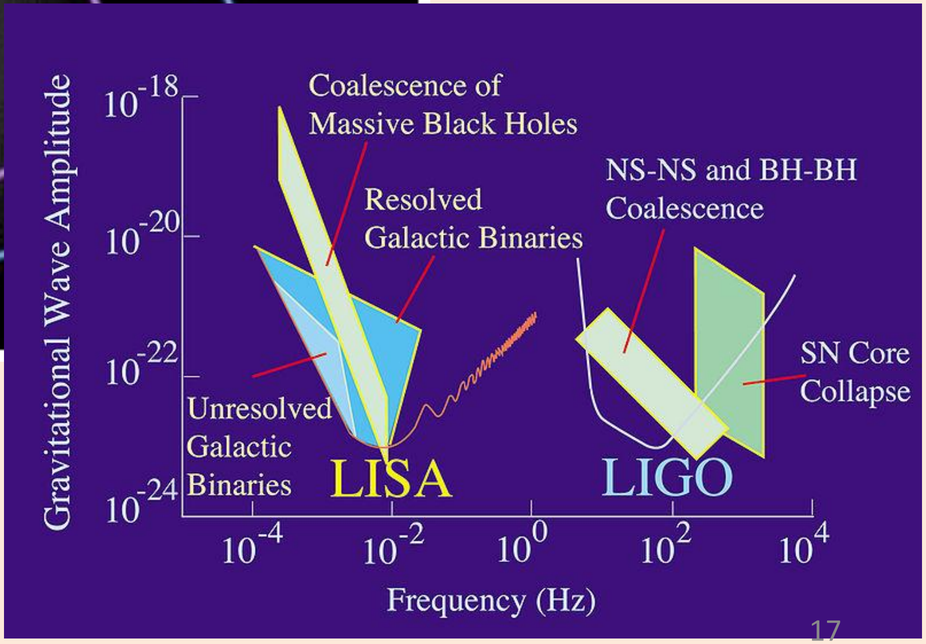
- Interferometers



Direct detection of Gravitational Waves

- LISA (laser interferometer space antenna)





Conclusions

If we could detect gravitational waves …

- … this would be a wonderful fulfillment of Einstein's classic theory.
- … we would be able to light up some of the darkest places in the Universe.

v · d · e	Gravitational wave detectors
Ground-based (operational)	CLIO · LIGO · GEO 600 · Virgo · TAMA 300 · MiniGrail
Ground-based (proposed)	AIGO · LCGT · Einstein Telescope · INDIGO
Space-based (planned and proposed)	LISA · BBO
Astronomical	EPTA · NANOGrav · PPTA
Data analysis	Einstein@Home

References

- Sean M. Carroll: “Lecture Notes on General Relativity”, URL: http://xxx.lanl.gov/abs/gr-qc/9712019
- L Ju, D G Blair and C Zhao: “Detection of gravitational waves”, URL: http://iopscience.iop.org/0034-4885/63/9/201
- J. M. Weisberg, J. H. Taylor: “Relativistic Binary Pulsar B1913+16: Thirty Years of Observations and Analysis”, URL: http://arxiv.org/abs/astro-ph/0407149

- The experiments:
  - MiniGRAIL: http://www.minigrail.nl/
  - LIGO: http://www.ligo.caltech.edu/
  - LISA: http://lisa.nasa.gov/