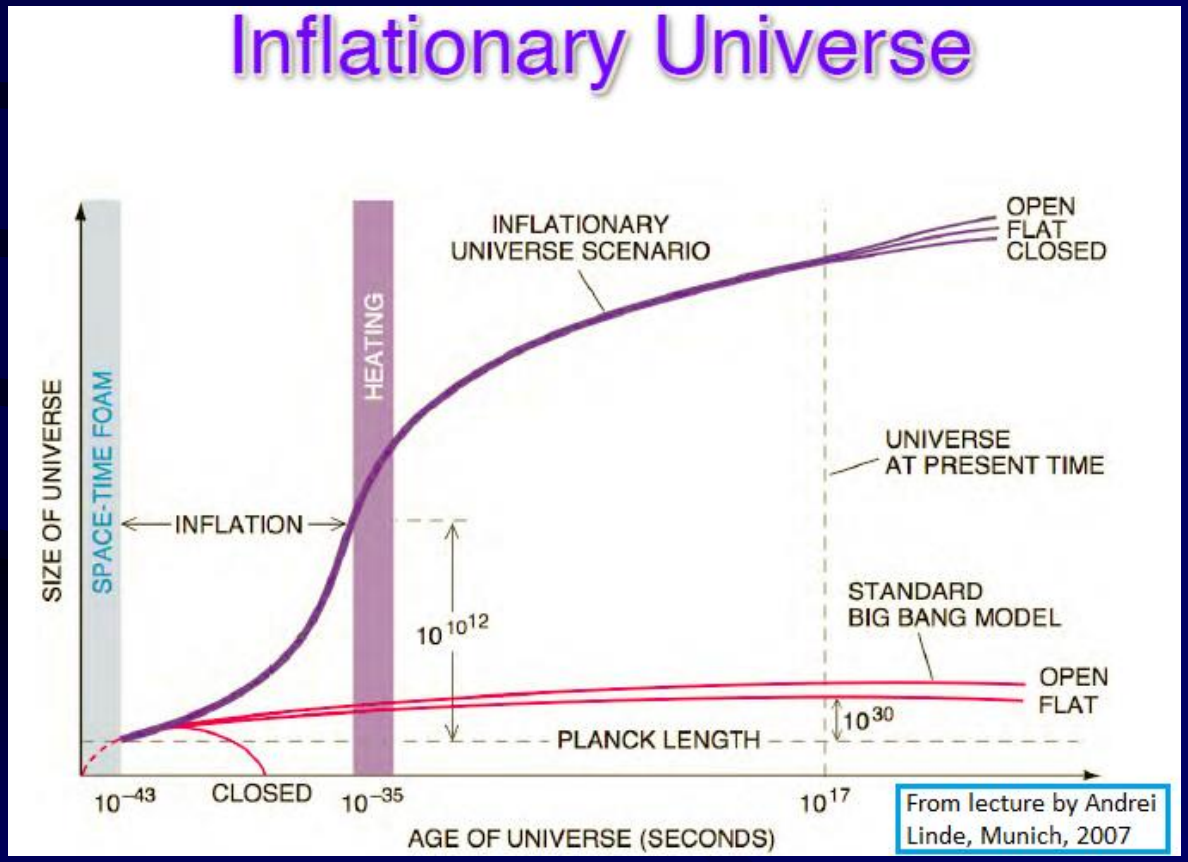
The Expanding Universe - Conclusion

Inflation solves the Horizon & Flatness Problems



- Youtube Video

This just in: Gravitational Waves are a new Window to the Universe!

- For the longest time: visible light only
- Then: radio waves
- Microwaves, infrared
- Particles: neutrinos, cosmic rays (protons)
- Now: gravitational waves from places very remote and hidden

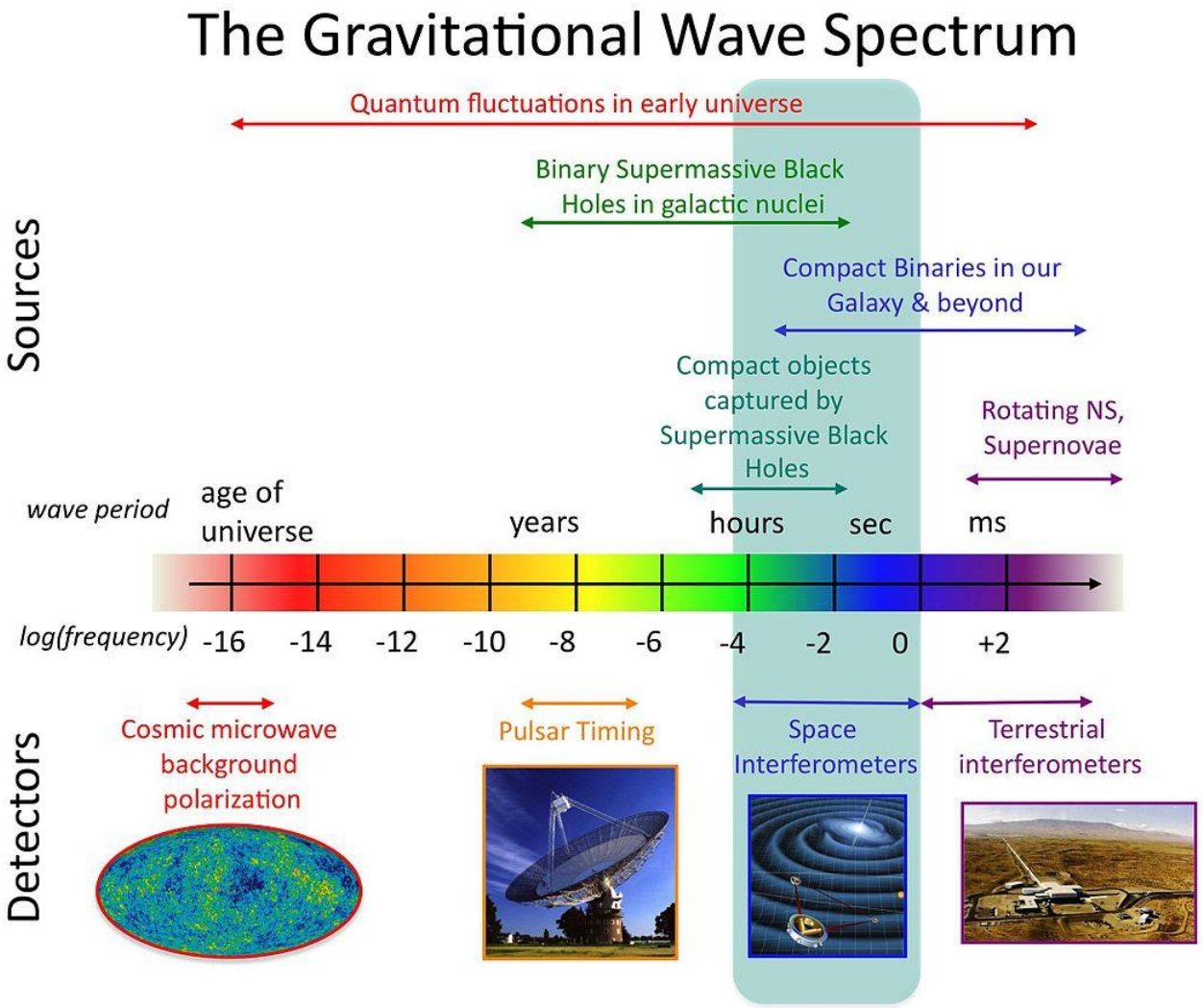
Gravitational Waves

- Masses interact via the gravitational force
- The theory describing gravity is general Relativity (GR, Einstein 1915)
- The equations of GR allow wave solutions
  - Cf. EM waves, aka light: wave solution of Maxwell's eqns of electrodynamics
- Simulation: Neutron Star binary emitting gravitational waves

What are gravitational waves?

- The solution of GR equations is the “shape” of space-time
- So GR is a theory that describes how space and time evolve given a mass distribution
  - Cf: ED describes how electric and magnetic fields evolve given a charge distribution
- Gravitational waves warp space & time
  - Basically they put ripples in spacetime

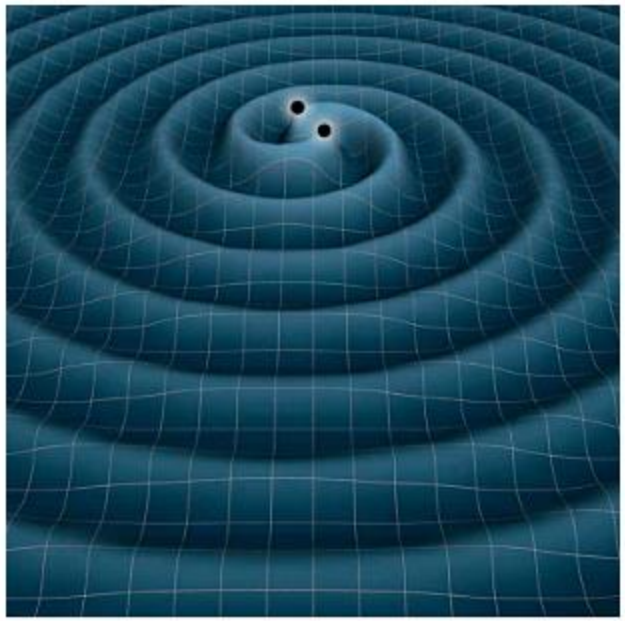
Sources of Gravitational Waves

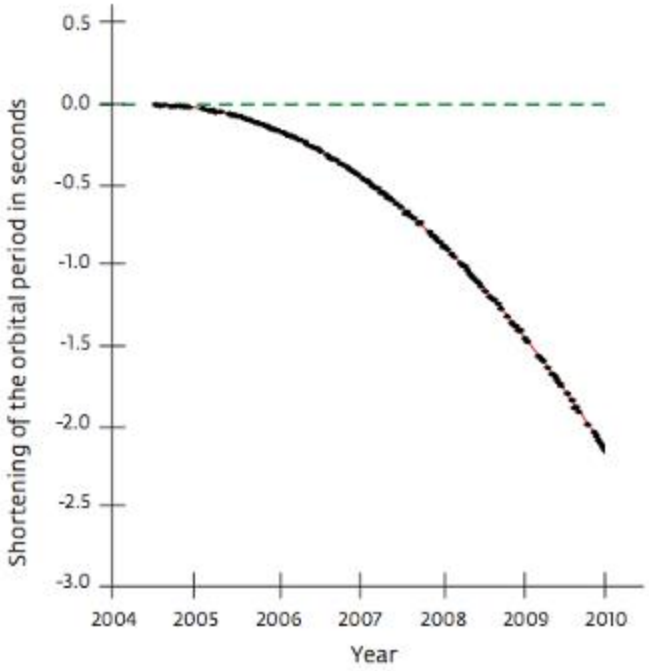


What happens as objects radiate gravitational waves?

- Waves transport energy, so objects that radiate waves LOSE energy
- This energy comes from the “configuration” of the binary system: closer means less energy

General Relativity predicts how fast the binary orbit should shrink (and therefore its rotation speed up)





Pas de deux in space: When two neutron stars dance about a common center of gravity, they emit gravitational waves (left). Because this causes both objects to continuously lose a portion of their orbital energy, they slowly approach each other on a spiral-shaped orbit, and their orbital periods grow shorter. The diagram at right shows these conditions for the double pulsar PSR J0737-3039.

Indirect Evidence: **PSR B1913+16**

- This double pulsar (2 orbiting neutron stars radiating radio waves) was observed by Taylor & Hulse (Nobel 1993) in 1974
- They measured the orbital period to decrease exactly as predicted by GR
  - Assumption: gravitational waves carry away energy

Direct Measurement

- Gravitational waves warp space & time
  - Basically they put ripples in spacetime
- This means that, for a short time as the wave runs through the detector, its shape is going to change
- If you can measure the size of your detector very, very precisely, you can detect gravitational waves

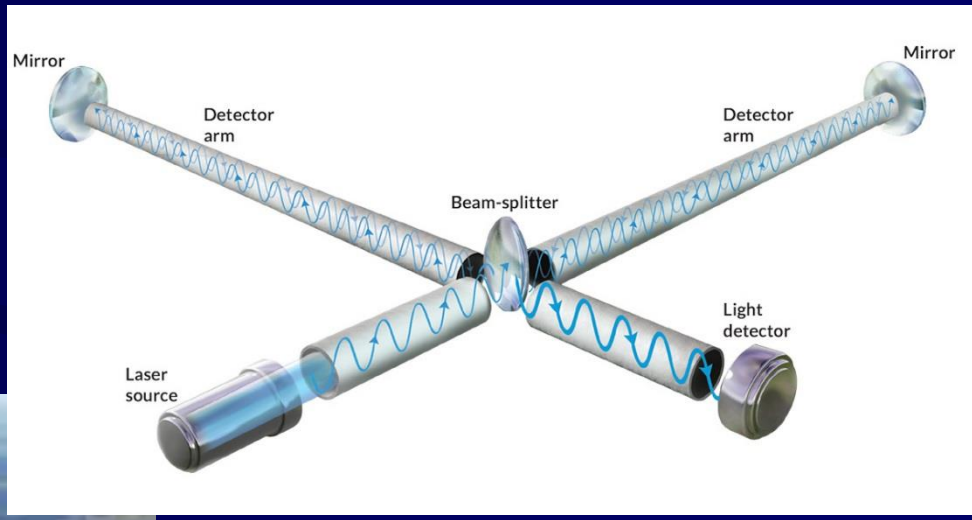
Extraordinary claims require extraordinary evidence

- Construct 2 independent detectors!
- Check expected time delay
- Calibrate very well, suppress background
  - These guys have been running since decades (without ever detecting anything)

LIGO: Laser Interferometer Gravitational-Wave Observatory

- LIGO is designed to open the field of gravitational-wave astrophysics through the direct detection of gravitational waves predicted by Einstein's General Theory of Relativity. LIGO's multi-kilometer-scale gravitational wave detectors use laser interferometry to measure the minute ripples in space-time caused by passing gravitational waves from cataclysmic cosmic sources such as the mergers of pairs of neutron stars or black holes, or by supernovae. LIGO consists of two widely separated interferometers within the United States—one in Hanford, Washington and the other in Livingston, Louisiana—operated in unison to detect gravitational waves.

Light interferes and makes a pattern. Even the slightest change in arm length results in a pattern change



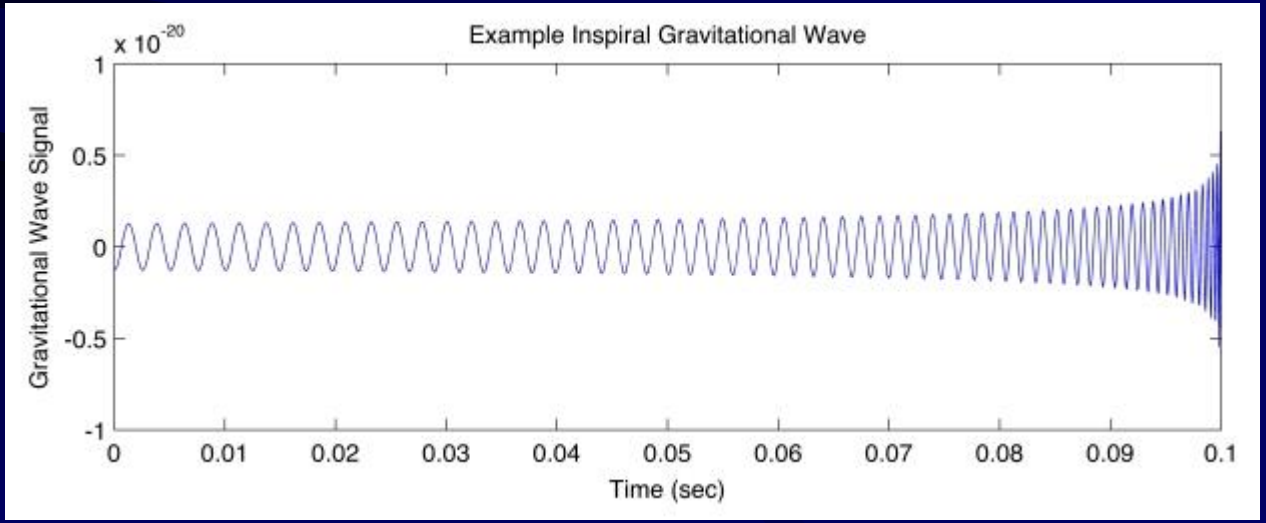
The LIGO Detector: Sensitivity requirements

- Typical gravitational waves are expected to distort the 4 kilometer mirror spacing by about 10^{-18} m
  - This is less than one-thousandth the diameter of a proton!
- Equivalently, this is a relative change in distance of approximately one part in 10^{21}

➔ Need to suppress any vibration from other sources extremely well

Inspiral Gravitational Waves

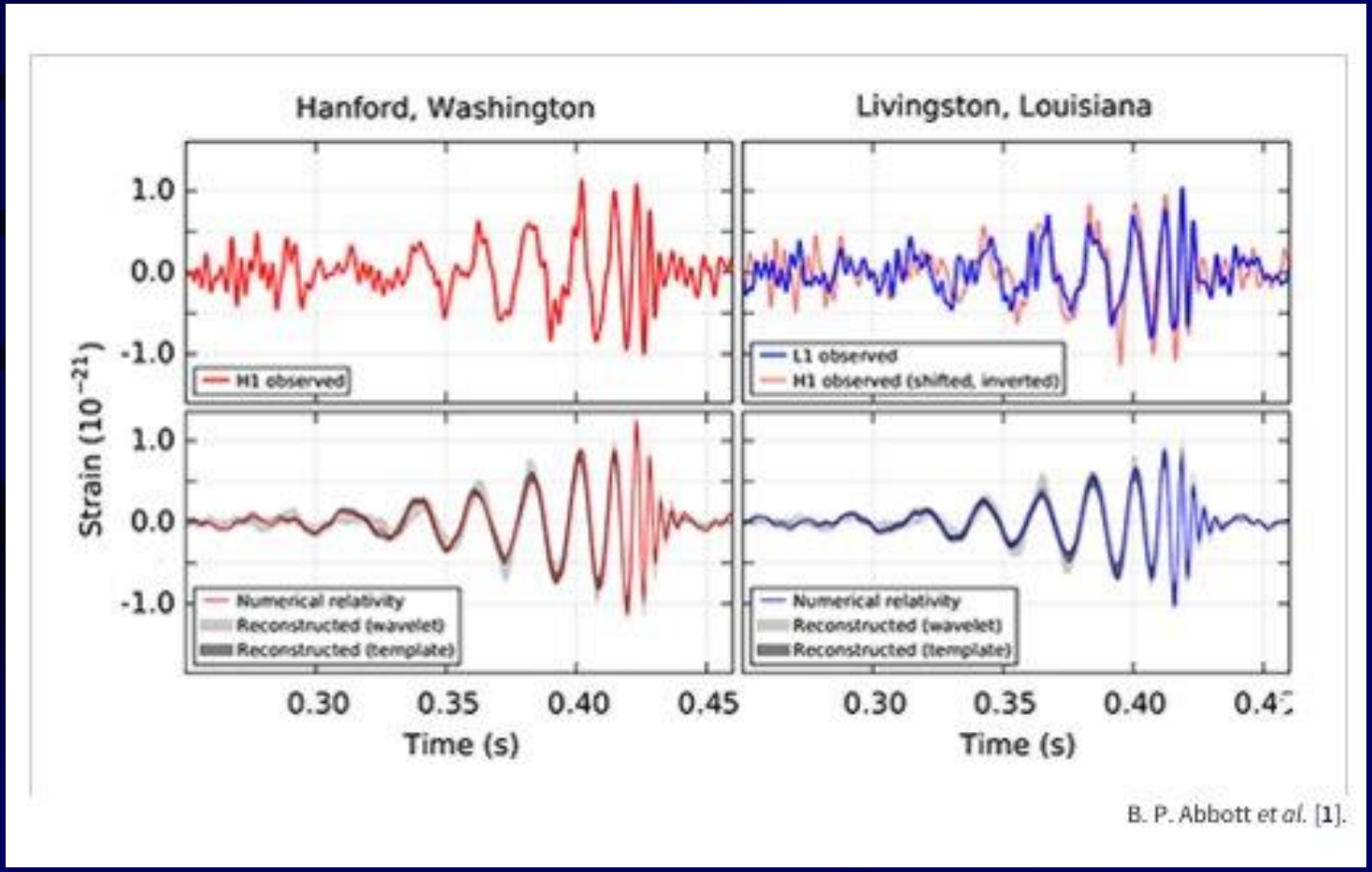
- The gigantic merger produces a gravitational "chirp", a hiccup in the fabric of spacetime



The Event: Merger of two massive Black Holes (each more than 25 solar masses!)

- They were rotating faster and getting closer (b/c radiating grav. waves) until they merged
- In the 1 second of collision they radiate 50x more energy than the rest of the universe combined!
- And this gigantic cataclysm produces a gravitational "chirp", a hiccup in the fabric of spacetime

The Signal



B. P. Abbott *et al.* [1].

Thus ends the story of the doubly expanding universe for now…

- Thanks for your attention, patience, persistence, and interest
- Please evaluate!