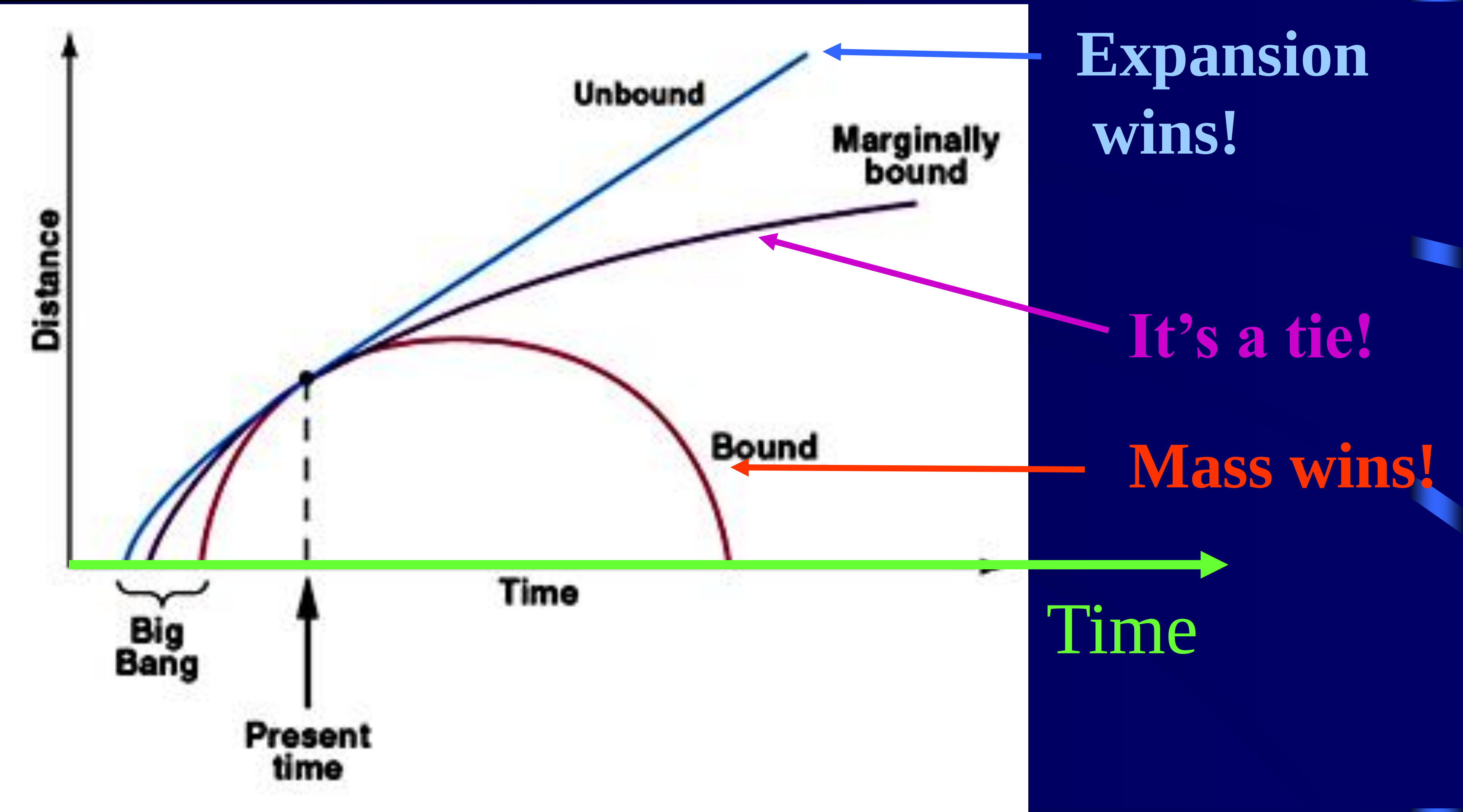
Failure of Standard Cosmology

Recall the three Scenarios in Standard Cosmology



Expansion of the Universe

- Either it grows forever
- Or it comes to a standstill
- Or it falls back and collapses (“Big crunch”)
- In any case: Expansion slows down!

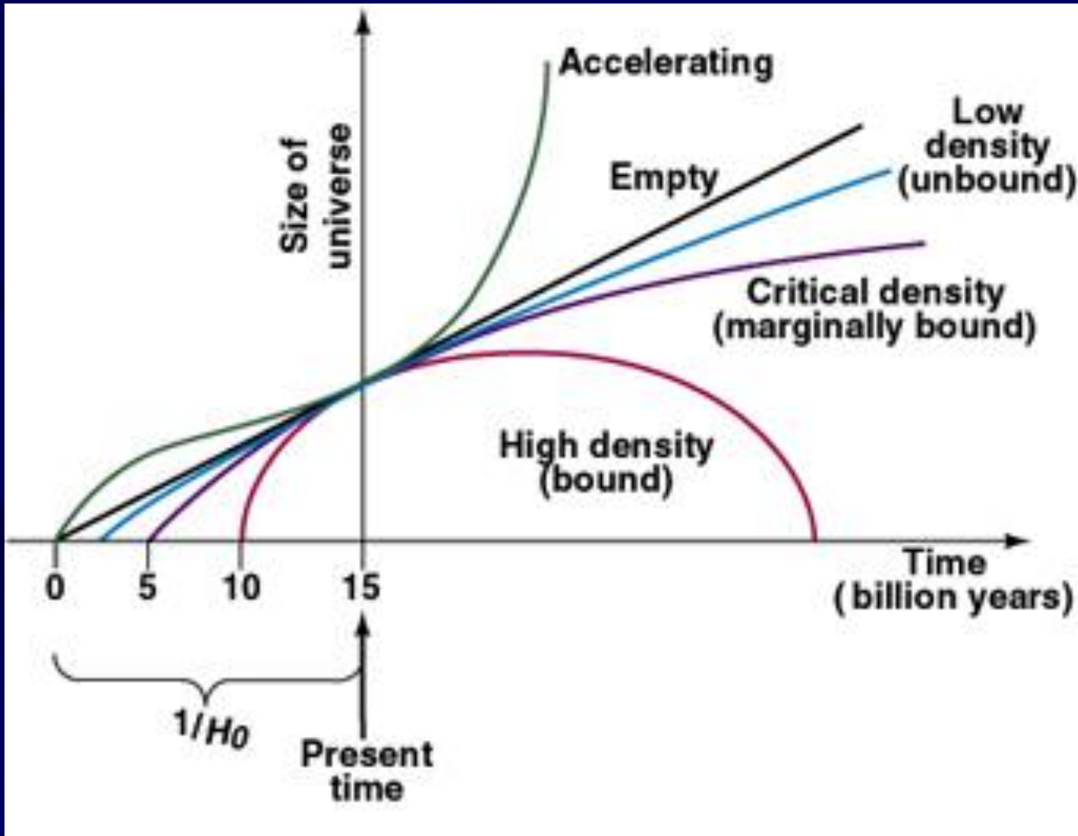
Surprise of the year 1998
(Birthday of Dark Energy):

All wrong! It accelerates!

Enter: The Cosmological Constant

- Usually denoted Λ_0, it represents a uniform pressure which either helps or slows down the expansion (depending on its sign)

- Physical origin of Λ_0 is unclear
- Einstein's biggest blunder – or not !
- Appears to be small but not quite zero!
- Particle Physics' biggest failure



Triple evidence for Dark Energy

- Supernova data
- Large scale structure of the cosmos
- Microwave background

Microwave Background: Signal from the Big Bang

- Heat from the Big Bang should still be around, although red-shifted by the subsequent expansion

- Predicted to be a blackbody spectrum with a characteristic temperature of 2.725 Kelvin by George Gamow (1948)

➔ **Cosmic Microwave Background Radiation (CMB)**

Discovery of Cosmic Microwave Background Radiation (CMB)

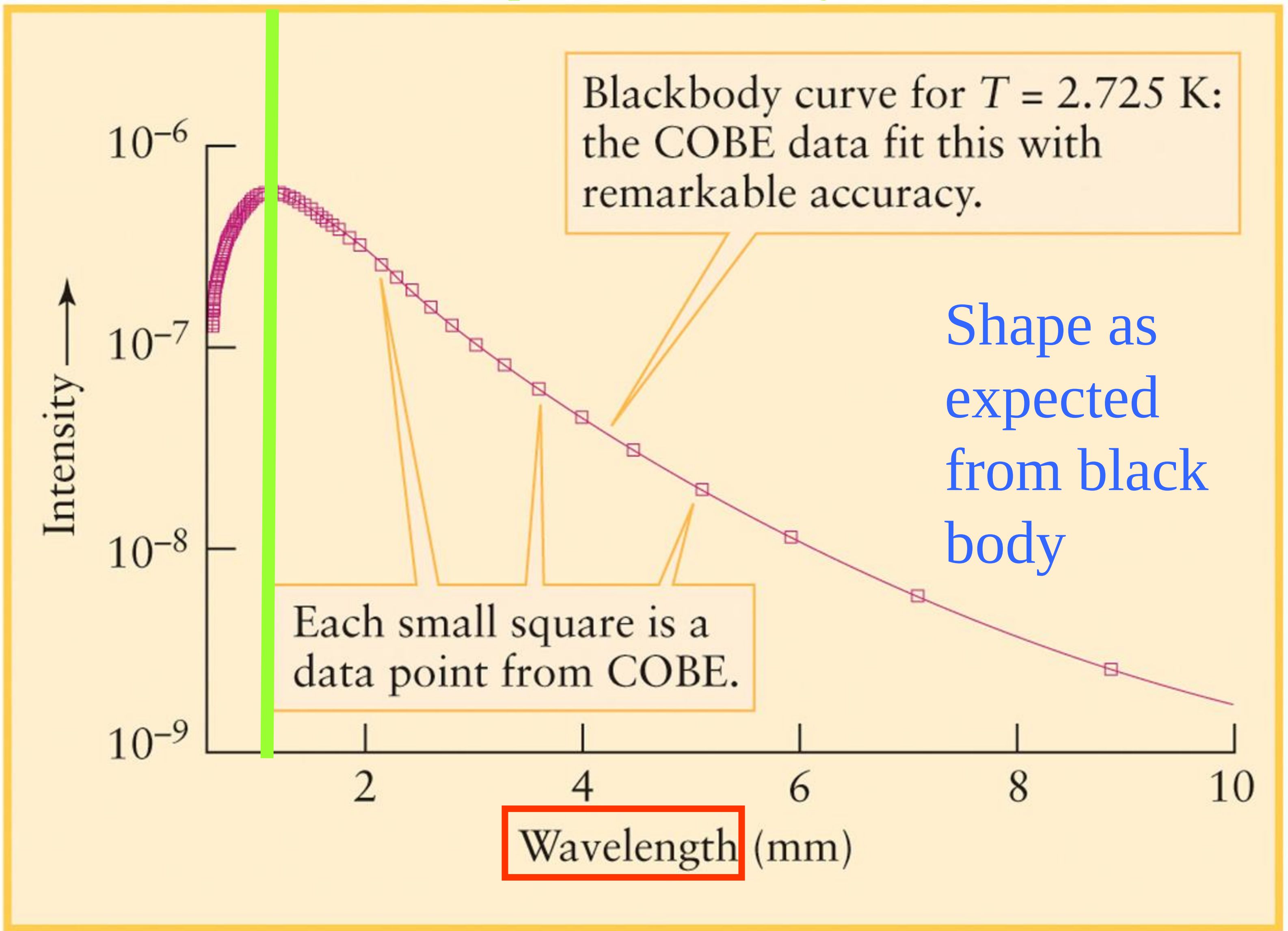
- Penzias and Wilson (1964)
- Tried to "debug" their horn antenna
- Couldn't get rid of "background noise"

➔ Signal from **Big Bang**

- Very, very isotropic (1 part in 100,000)

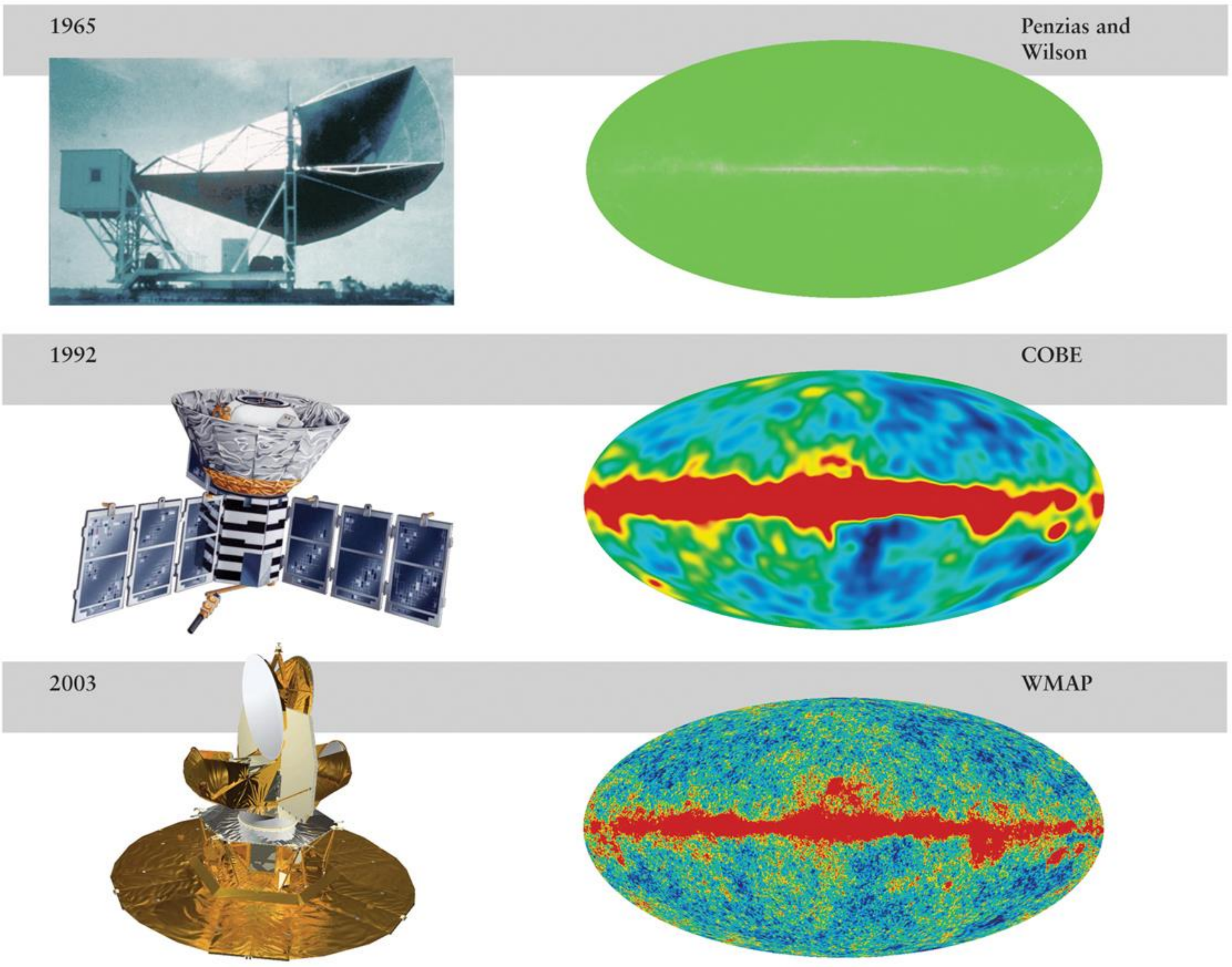
CMB: Here's how it looks like!

Peak as expected from object at 2.725 Kelvin



Shape as expected from black body

CMB measurements improve

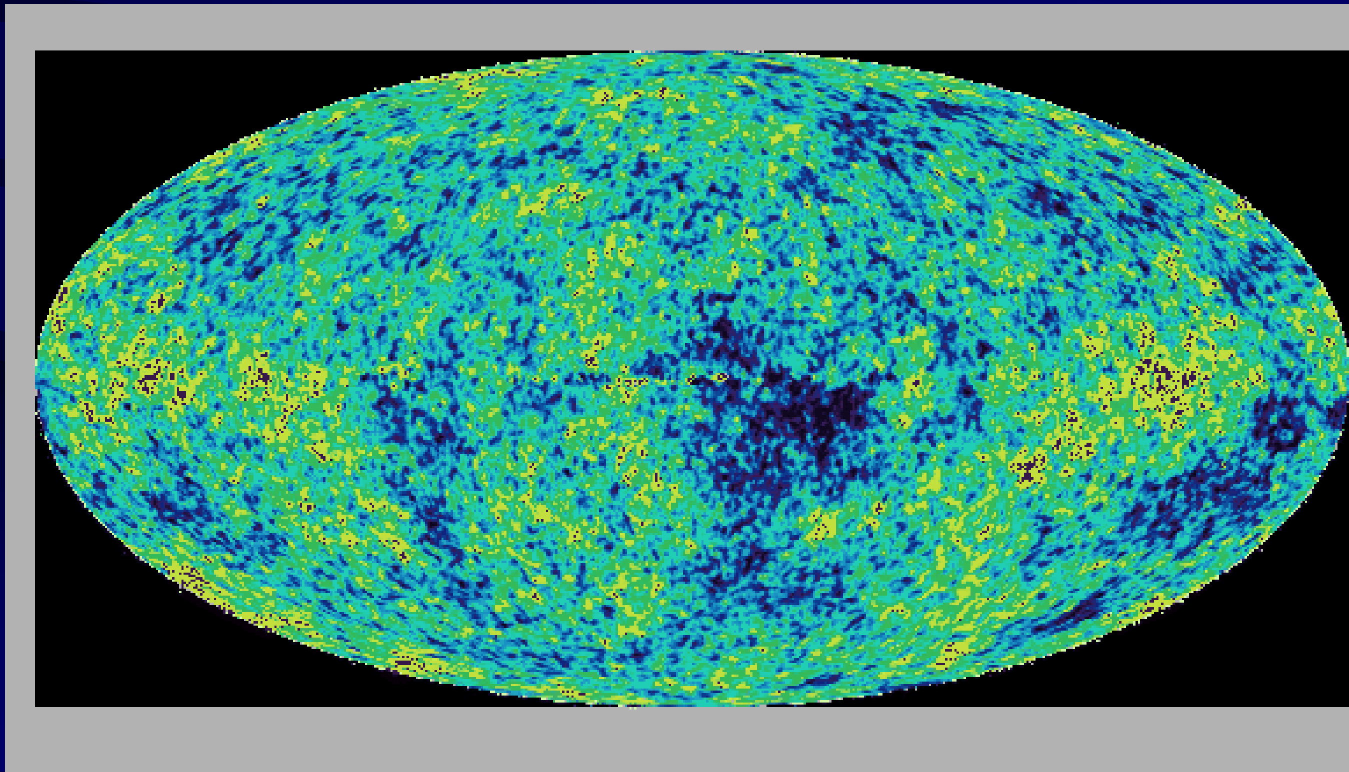


NASA/WMAP Science Team

Latest Results: PLANCK

- Measure fluctuations in microwave background
- Expect typical size of fluctuation of ½ degree if universe is flat
- Result:

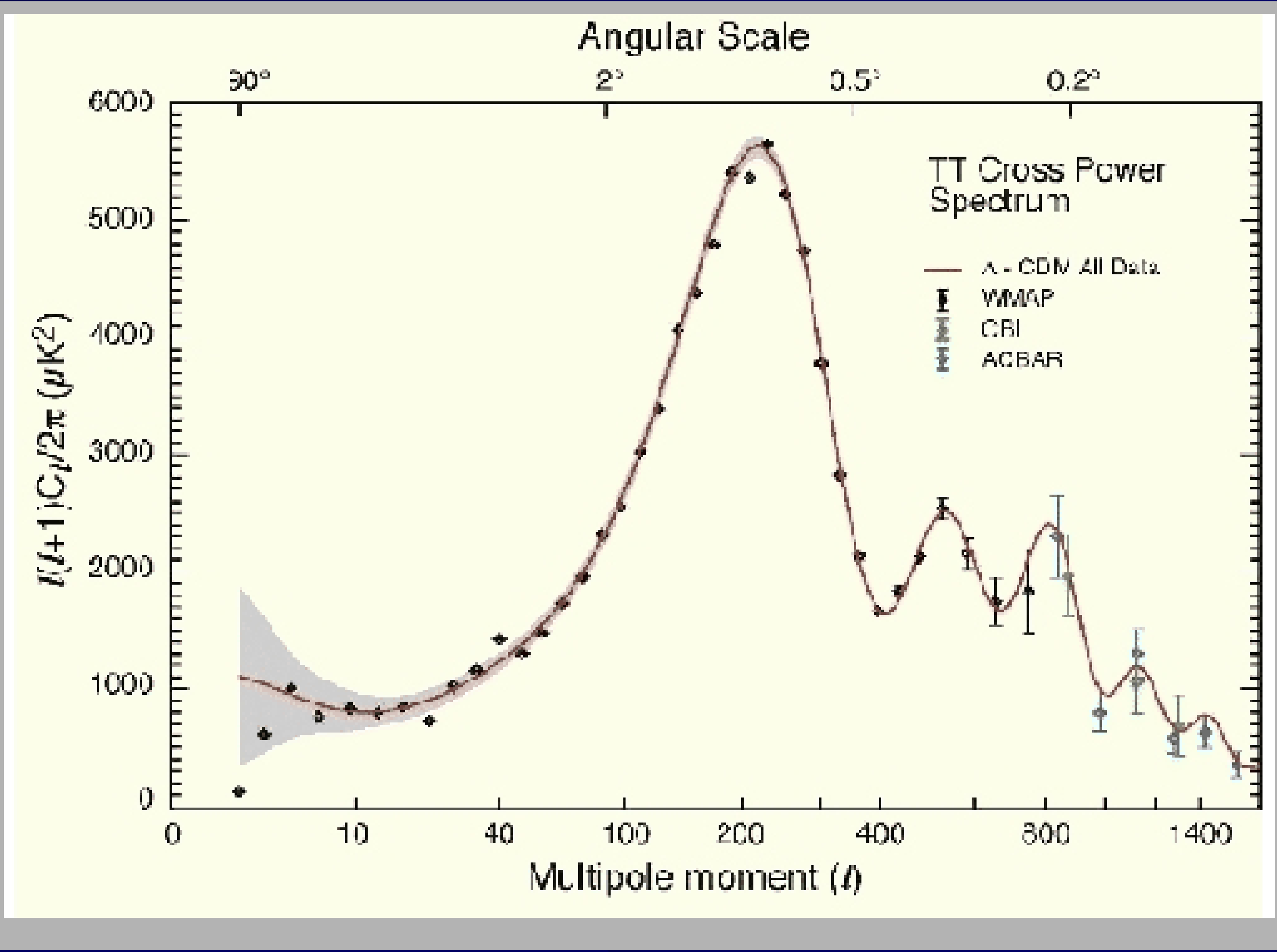
Universe is flat !



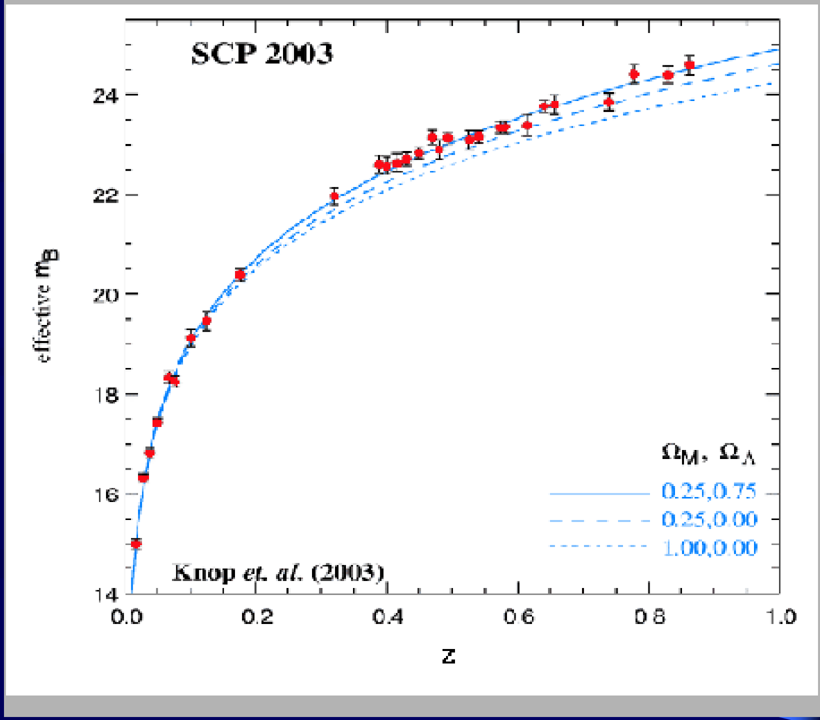
Experiment and Theory

Expect "accoustic peak" at l=200

➔ There it is!

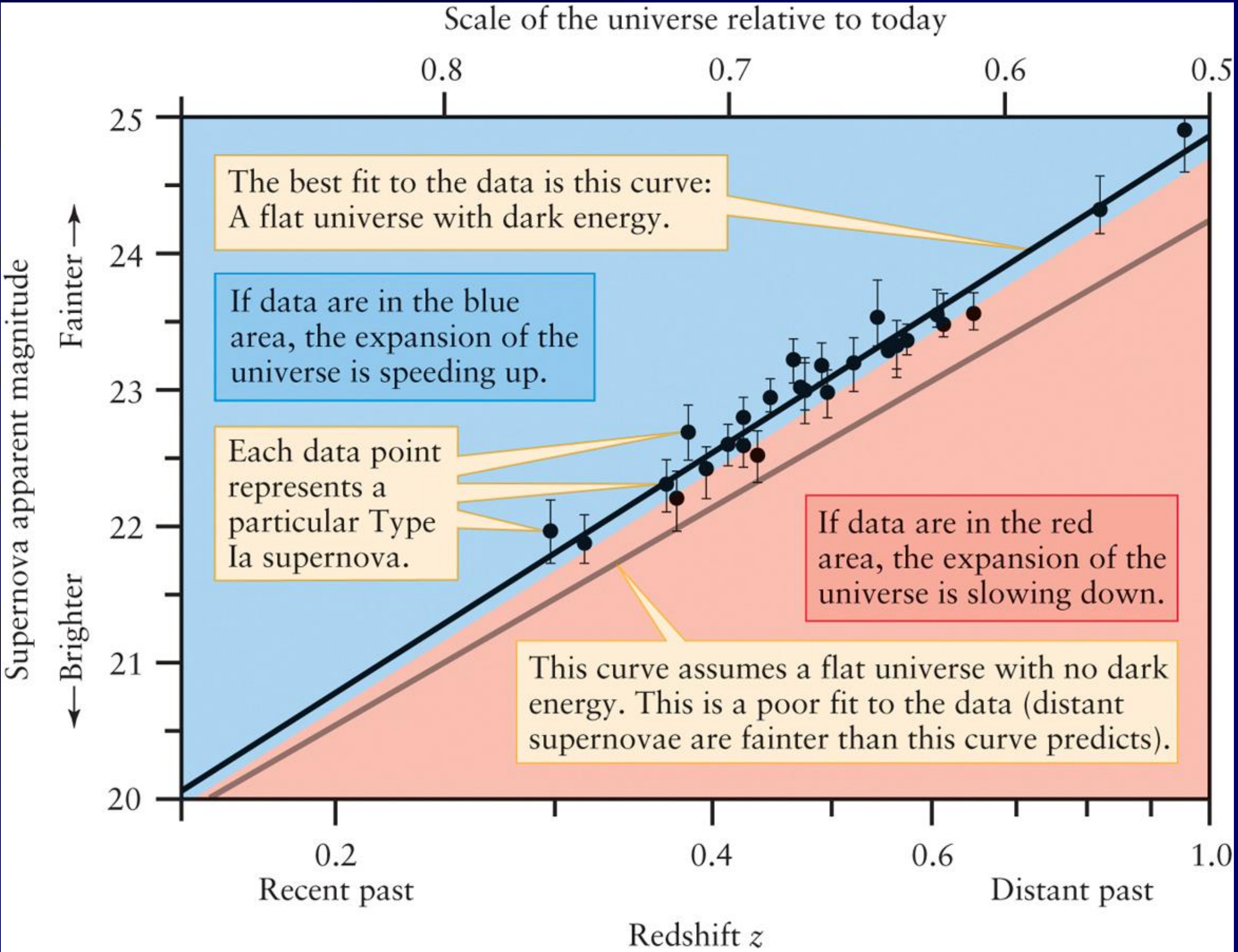


Supernova Data



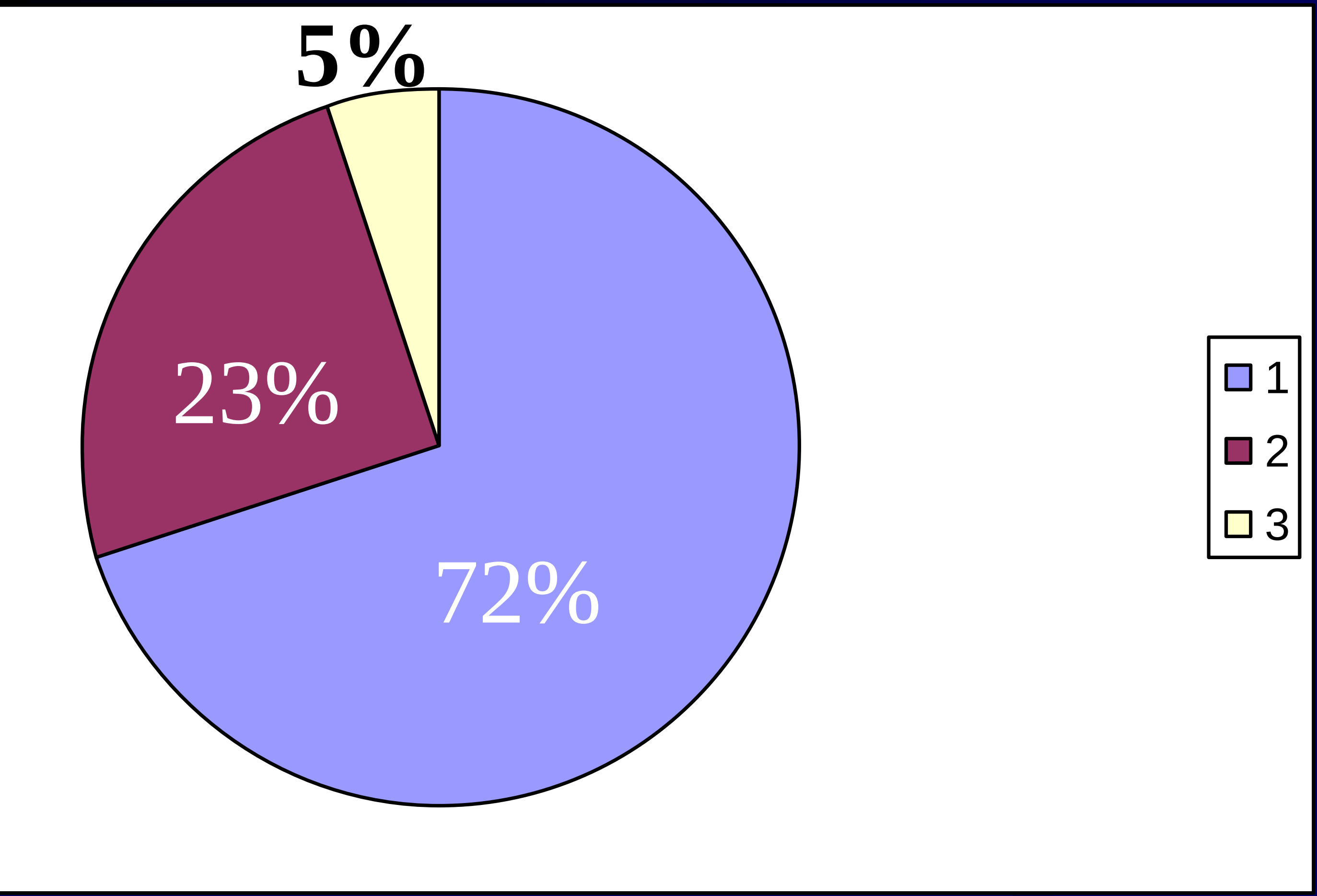
- Type Ia Supernovae are standard candles
- Can calculate distance from brightness
- Can measure redshift
- General relativity gives us distance as a function of redshift for a given universe

➔ Supernovae are further away than expected for any decelerating (“standard”) universe



Data from The Supernova Cosmology Project/R. A. Knop et al.

Pie in the Sky: Content of the Universe



Dark Energy
Dark Matter
SM Matter

→We know almost everything about almost nothing!

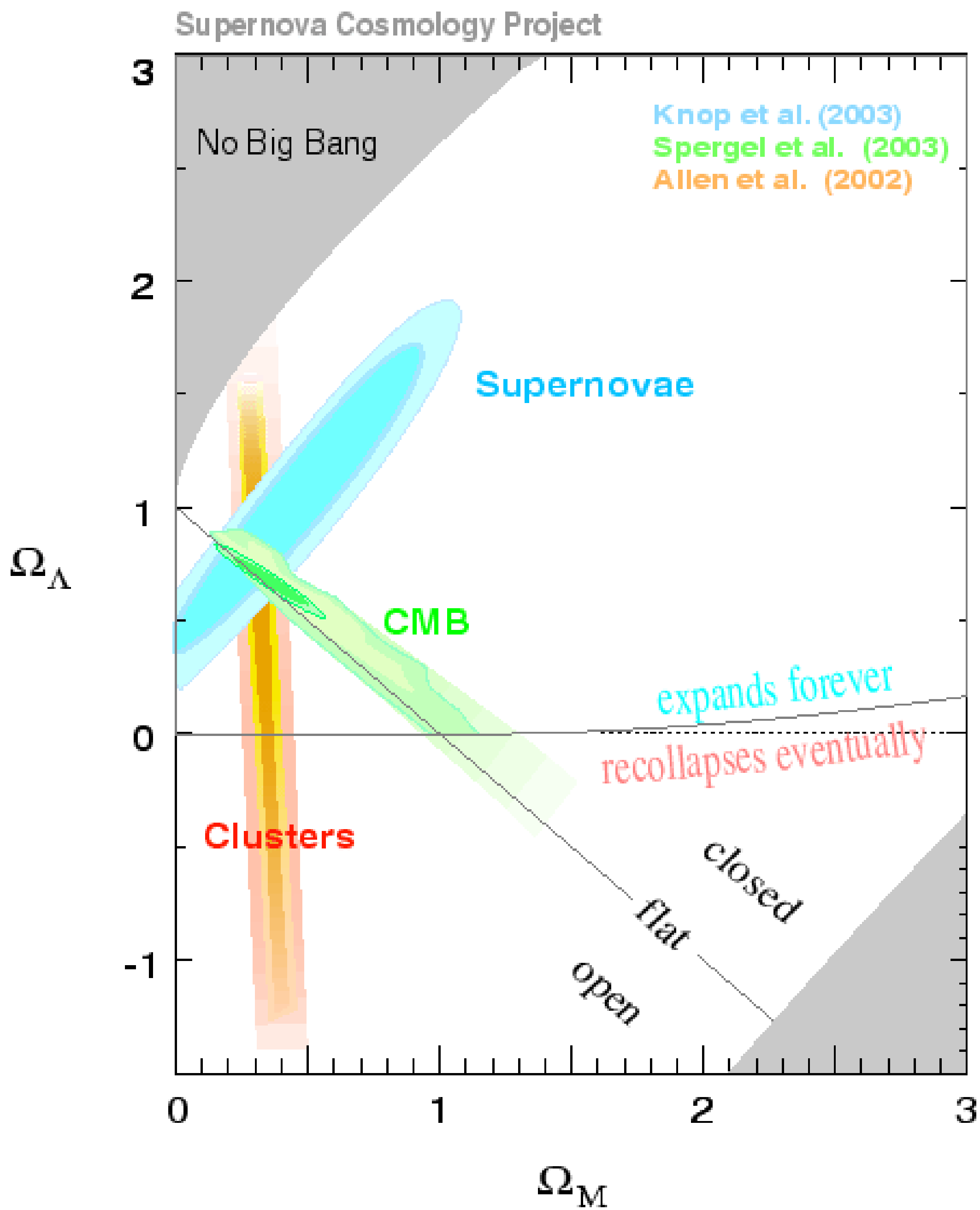
Properties of Dark Energy

- Should be able to explain acceleration of cosmic expansion ➔ acts like a negative pressure
- Must not mess up structure formation or nucleosynthesis
- Does not dilute as the universe expands ➔ will be different % of content of universe as time goes by

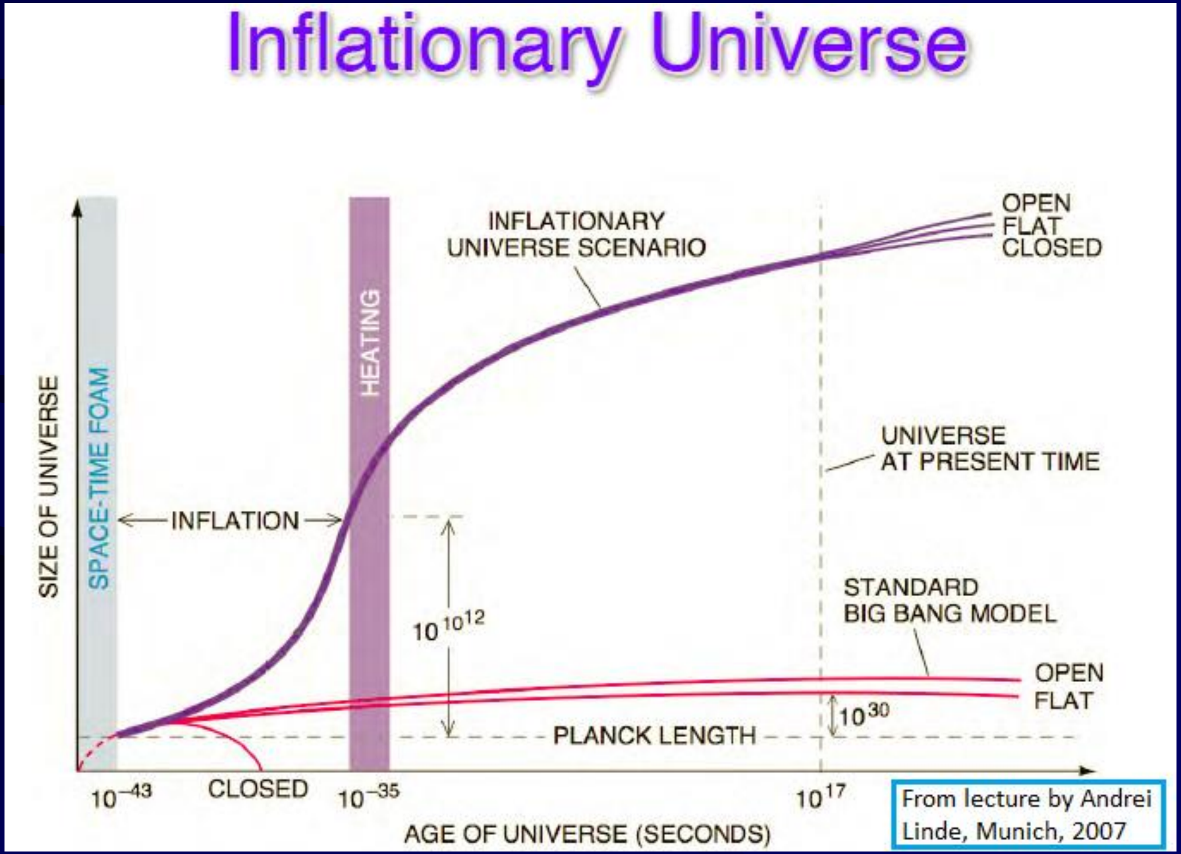
Threefold Evidence

Three independent measurements agree:

- Universe is flat
- 28 % Matter
- 72 % dark energy



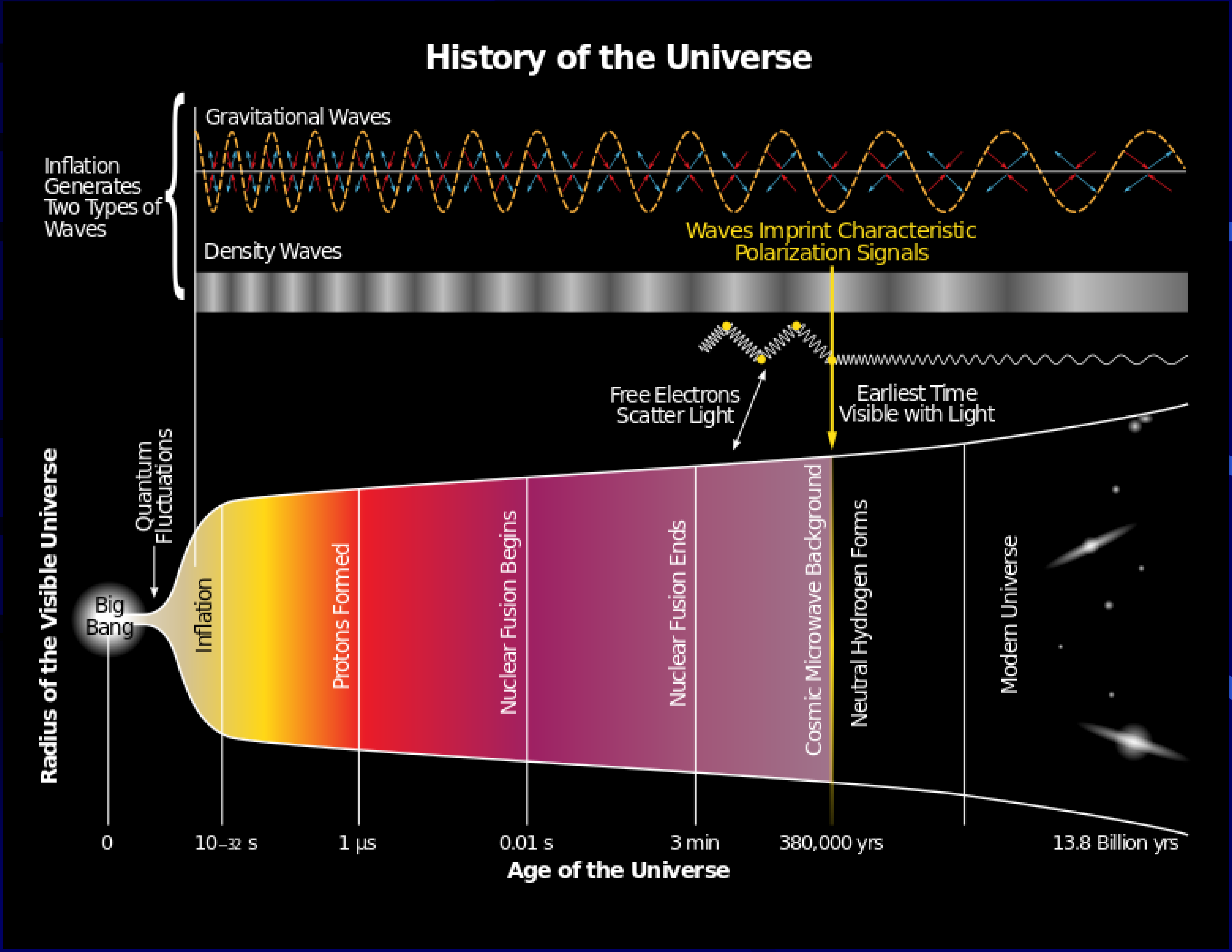
Inflation solves the Horizon & Flatness Problems



- Youtube Video (Intense Brit explain it all...)

History of the Universe: Hot & small → cold & big

before 10^{-43} s		?????? ("Planck Era")
10^{-43} s	$T=10^{32}$ K	gravity splits from other forces
10^{-43} to 10^{-35} s		Grand Unification era
10^{-35} s	$T=10^{28}$ K	Strong force splits from others. Epoch of inflation?
10^{-35} s to 10^{-10} s		"Electroweak era"
10^{-10} s	$T=10^{15}$ K	Electromagnetic force splits from others
10^{-10} to 10^{-4} s		"Quark era"
10^{-4} s	$T=10^{13}$ K	Quarks combine to form protons and neutrons
10^{-4} to 500,000 years		Radiation era
180 s (3 minutes)	$T=10^{9}$ K	Protons and neutrons combine to form nuclei (mainly Helium, deuterium)
500,000 years	T=3,000 K	Nuclei and electrons combine to form atoms – Decoupling
500,000 years to present		Matter era


History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10–32 s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

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

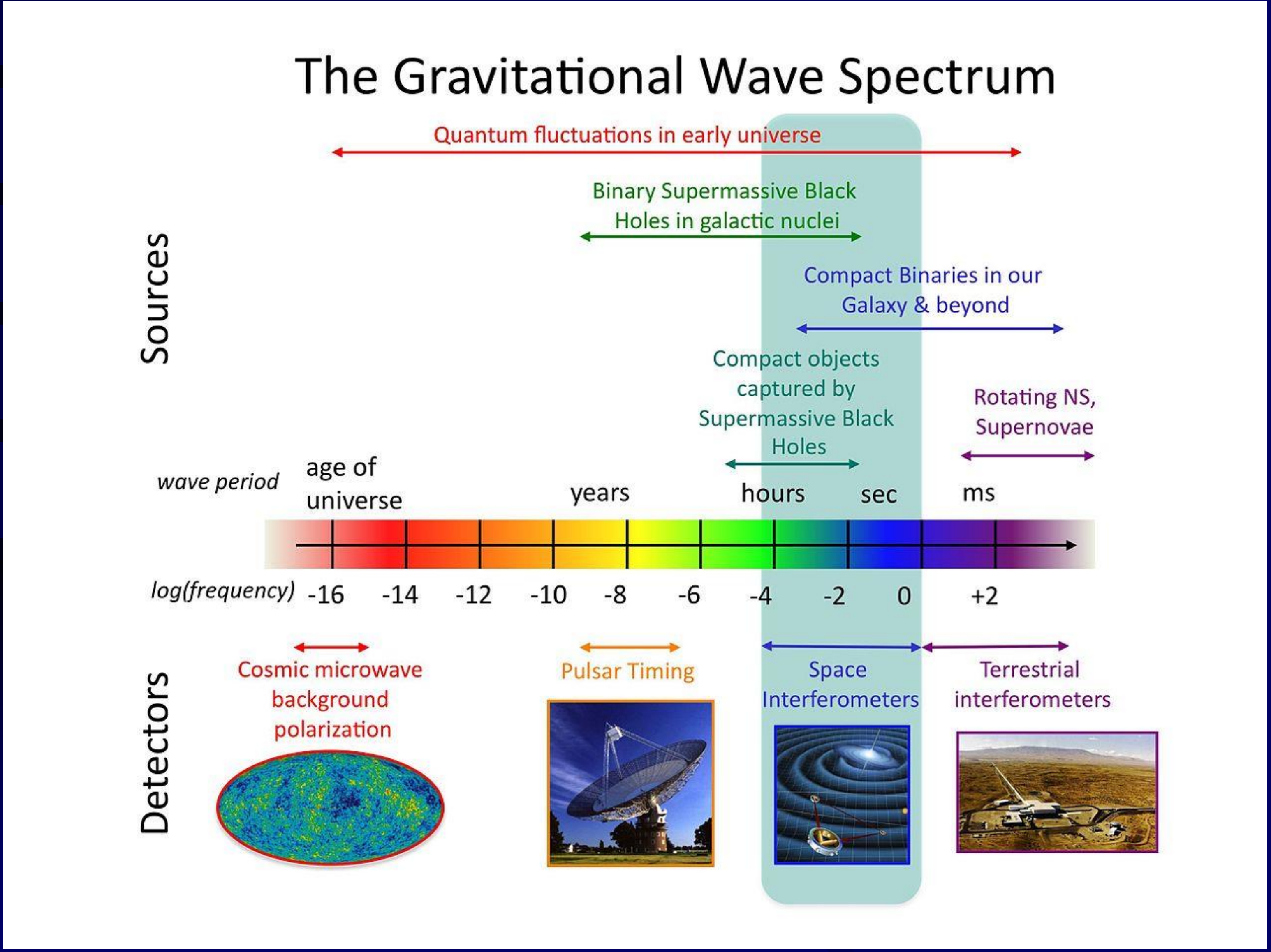
Gravitational Waves

- 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

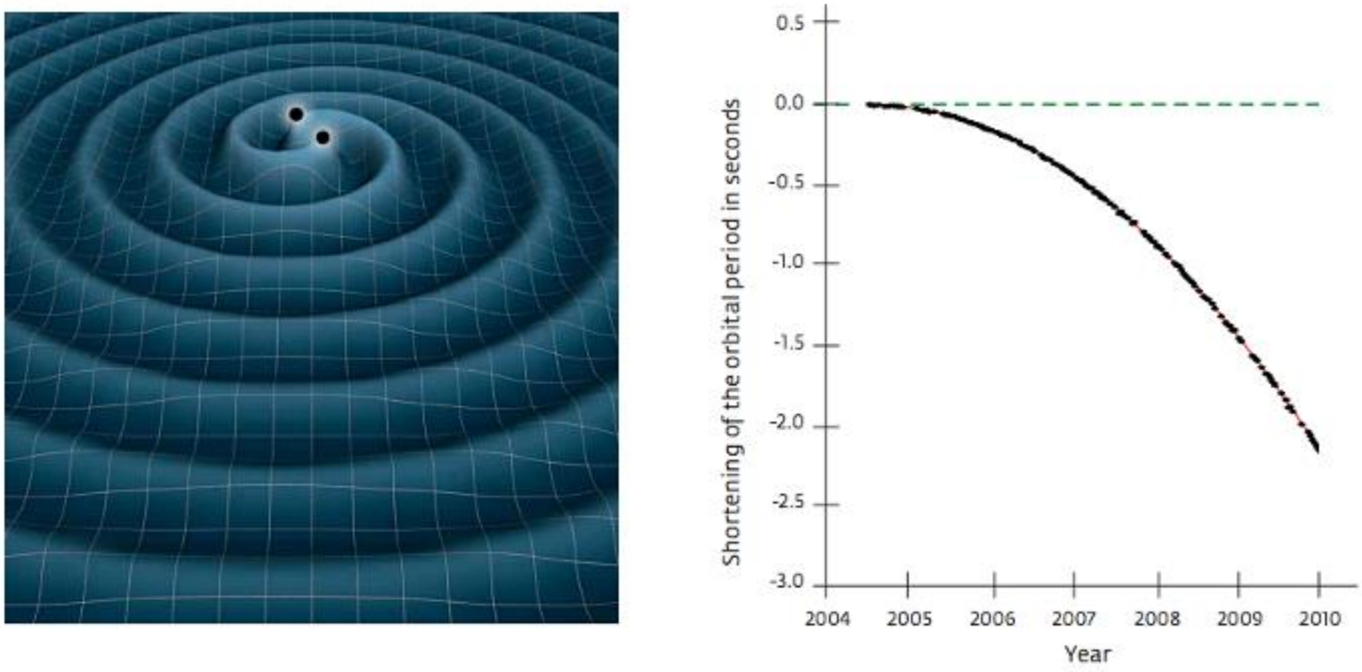
Sources of Gravitational Waves



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

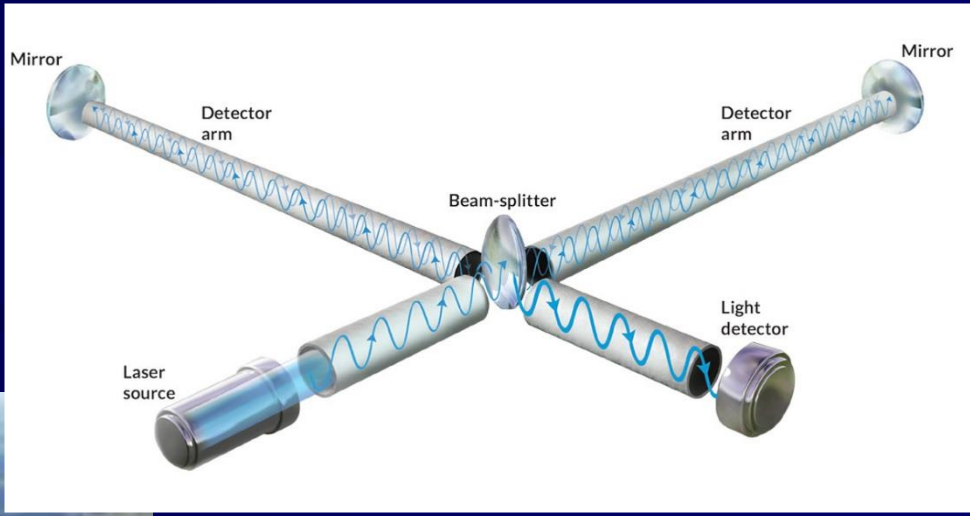
Extraordinary claims require extraordinary evidence

- 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



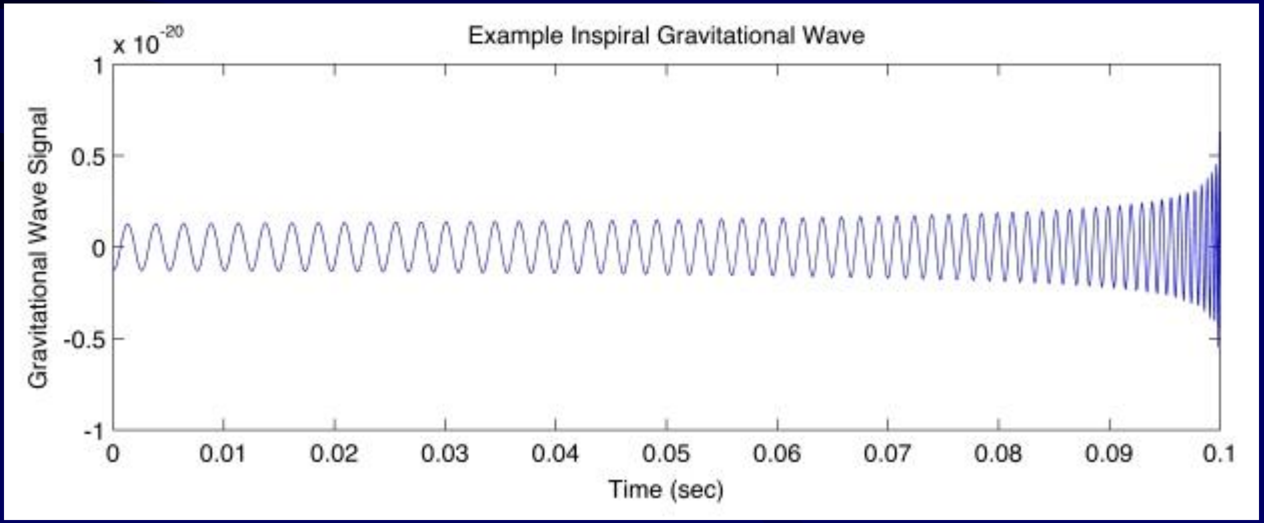
The LIGO Detector: Sensitivity requirements

- 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

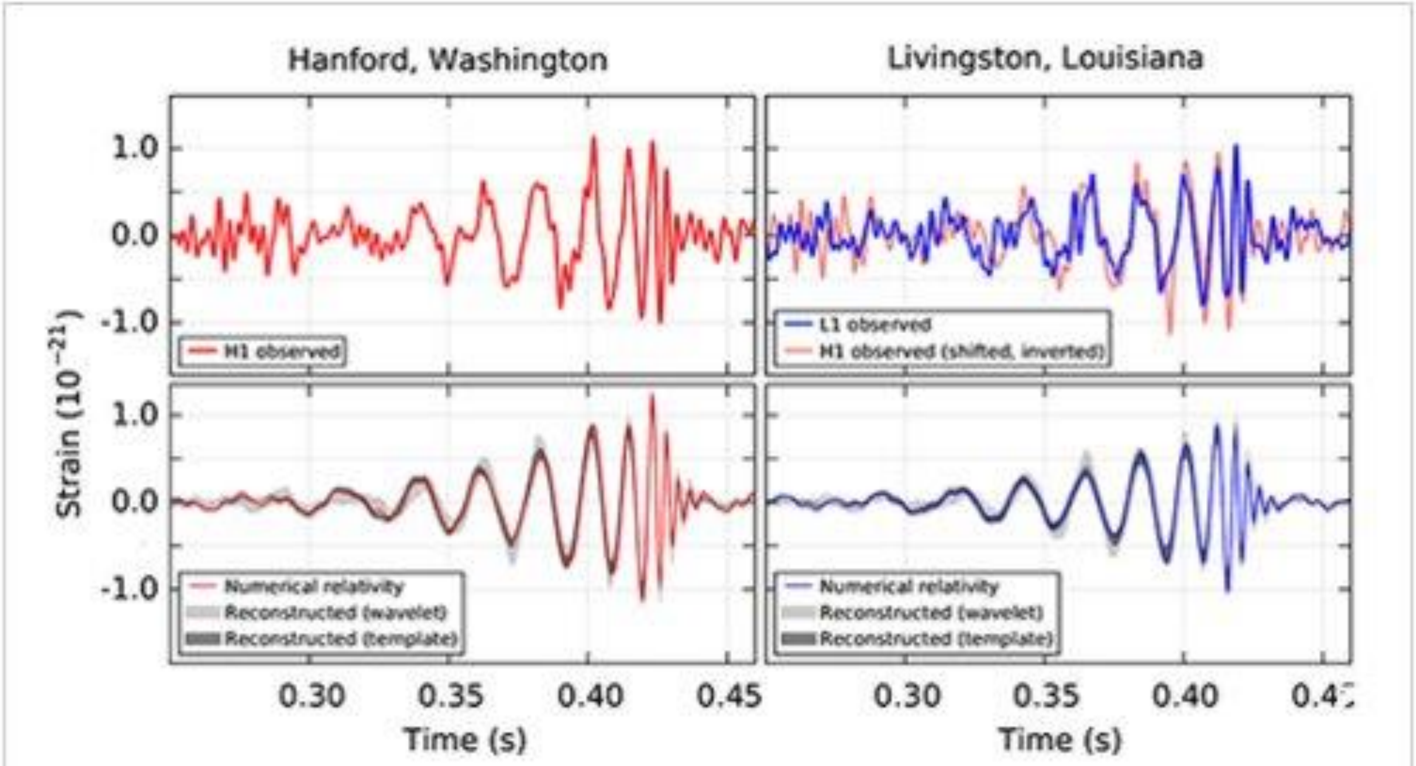
- The gigantic merger produces a gravitational "chirp", a hiccup in the fabric of spacetime



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].