Plan of Lecture

General Relativity

Principles of general relativity.

Tests of general relativity.

Accreting neutron stars.

Binary pulsars.

Principles of General Relativity

After developing special relativity, Einstein turned to gravity (final version 1915).

Newton's laws suggested instantaneous action, but speed of light is finite.

Radical idea: spacetime could be altered by presence of mass!

For Newton, "natural" motion was straight line.

For Einstein, free fall was natural.

What does this mean? Freely falling object feels no force!

Matter tells spacetime how to curve.

Spacetime tells matter how to move.

Principles, Part 2

In a more mathematical sense, Einstein's theory says:

Mass changes distances, times.

Far away from any mass, things fall freely in straight lines.

Think of spacetime as a rubber sheet:

Bent by masses.

Flat far from masses.

Flat in small enough region.

The last is the *equivalence principle*: in small enough distance, time, everything acts like no gravity!

Only tidal forces can be felt!

Test: Gravitational Redshift

The first theoretical prediction came in 1908, prior to full theory.

Do a thought experiment.

- **e^-, e^+ annihilate.**
- **Photons sent upwards.**
- **Reconverted to e^-, e^+ higher up.**
- **Allowed to fall, annihilate.**

If we believe energy is conserved, then the photons must lose energy when traveling up.

- **e^-, e^+ gain energy in fall!**

Therefore, photons must be redshifted by gravity.

- **Measured in 1960s.**
- **Also implies time is slowed.**

Test: Deflection of Light

This is what made Einstein a popular icon.

Light follows curved spacetime, so it bends.

Prediction: twice Newtonian bend.

Observed in 1919, during solar eclipse.

Expedition leader: Eddington.

Englishman confirms German!

In more extreme circumstances (black hole!), light can bend more than 360°!

Test: Precession of Pericenter

In Newtonian theory, two-body orbits are perfect ellipses.

Trace over themselves.

In GR, slight extra strength of gravity leads to spirograph pattern.

Angle of pericenter changes.

Angle will also change by effect of other planets.

Prior to Einstein, noticed that Mercury precesses 43" per century more than expected.

GR explains perfectly!

In extreme circumstances: zoom-whirl orbits!

Test: Delay of Propagation

Imagine the rubber sheet again.

Takes longer to go from A to B if there is a dip between!

Prediction: delay of signal past a massive body.

Observed in signals from planetary probes.

GR passes all these tests. However, this is all in weak gravity. Can we do better?

Binary Pulsars

1974: Graduate student Russell Hulse at Aricebo.

Discovers pulsar (yawn).

Timing solution is strange.

In binary with another NS!

A double NS binary is an incredible laboratory for tests of GR!

Extremely accurate timing.

Point masses; no complications.

Hulse's advisor Joseph Taylor has observed this object for 30 years.

What effects can be discovered?

Tests With Binary Pulsars

Only one of the two NS is a pulsar.

Still, can see many effects.

Pericenter precession: 4°/yr!

Time delay.

Normal Newtonian motions.

Since pulsars are so precise, very small motions can be seen.

Predictions are confirmed to $\sim 10^{-4}$ precision.

But is there something else that can be measured??

Gravitational Radiation

Consider two bowling balls on a rubber sheet.

- **Start them orbiting.**
- **Produces ripples in sheet.**
- **Carries away energy.**
- **Spiral together.**

In same way, orbiting object generate ripples in spacetime.

Change distances and time as they pass.

Prediction: orbits decay.

- **Mostly negligible.**
- **Measureable for double NS binary!**
- **Won Hulse, Taylor a Nobel prize.**

A Double Pulsar

Two months ago, an even more exciting discovery was announced.

Double *pulsar* system!

Shortest period double NS orbit.

Orbit nearly edge-on.

Why important? Many extra constraints!

Get perfect mass ratio.

Might measure precession of spin.

Over next few years, will test GR better than ever possible before.

Summary

In general relativity, gravity warps spacetime, matter follows warps.

In small region, during small time, you can pretend that there is no gravity at all!

Equivalence principle.

Relatively few classical tests, but GR passes them all.

Double neutron star systems allow very precise tests.

Challenge: What is the redshift from the surface of a neutron star?