General Relativity Traffic Jam

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Newtonian gravity, theoretically

- Based on action-reaction: The earth exerts a force on an apple, which makes it fall.
- The heavier the objects and the closer they are together, the larger the force. Newton gave a precise formula:

$$F = \frac{G m_1 m_2}{r^2}$$

- Newton (along with Leibnitz) invented the mathematical tools needed to translate this force law into the behavior of falling apples, orbiting planets, etc.

Newtonian gravity, experimentally

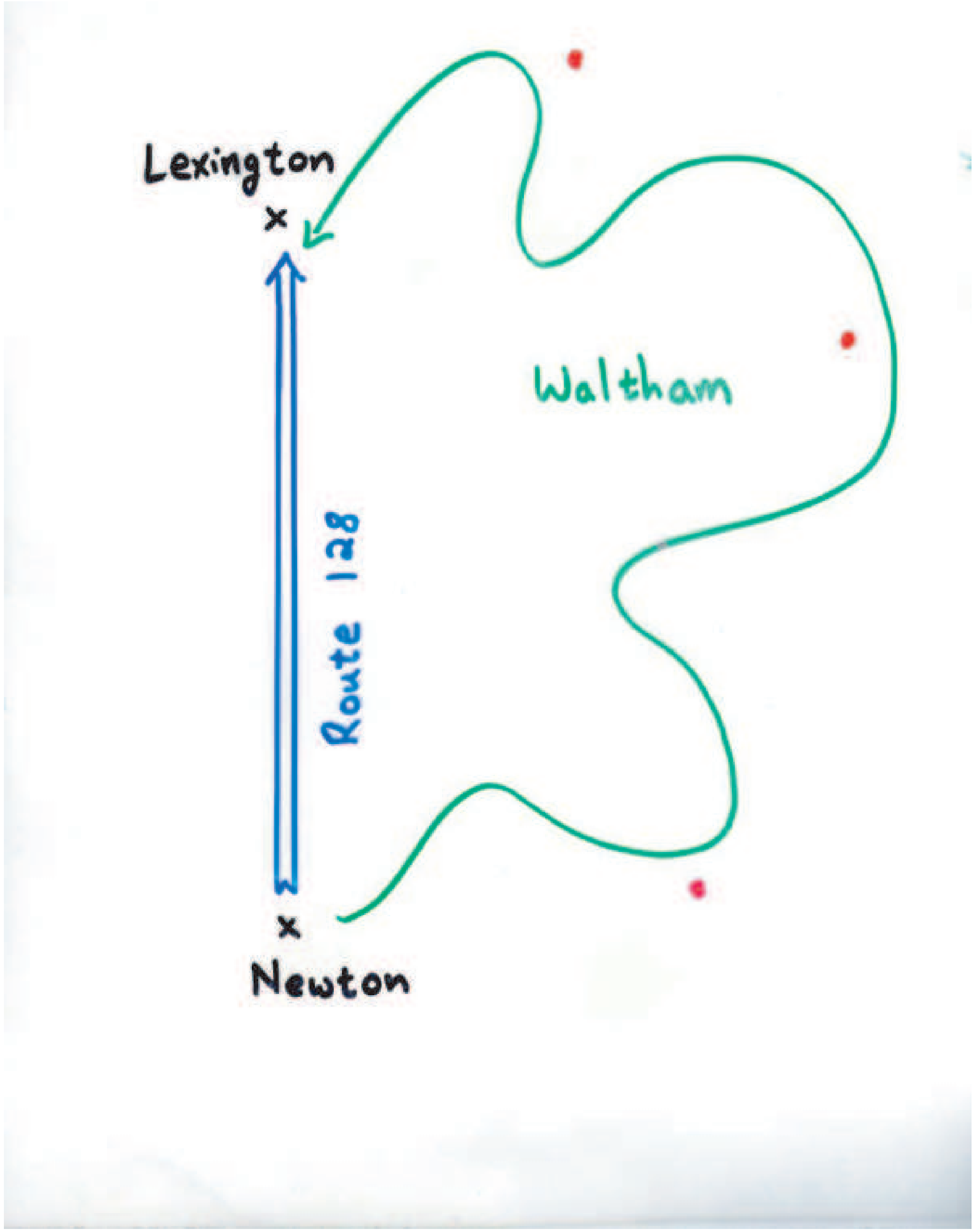
- Describes not only falling apples, but also orbits: The sun pulls on the earth, causing it to circle around rather than flying off into space.
- And it works! Tells us how to land a spacecraft on the moon, launch a weather satellite, design a roller coaster, etc.
- But there are some (small) discrepancies. . .

General relativity, theoretically

- Requires thinking about gravity geometrically: caused by curvature in space-time itself.
- The only major example of a theoretical discovery made in the absence of any direct experimental motivation.
- Mathematical structure is tantalizingly similar to theories of other forces, but unlike other forces it cannot be reconciled (so far) with quantum mechanics.

General relativity, experimentally

- Still the most complete description of gravity we have.
- Agrees with a variety of precision experiments.
- Includes Newtonian gravity as an approximation (differences only at high speeds/large masses)
- Predicts a variety of bizarre effects: black holes, bending of light by massive objects, and more.
- Needed for GPS to work!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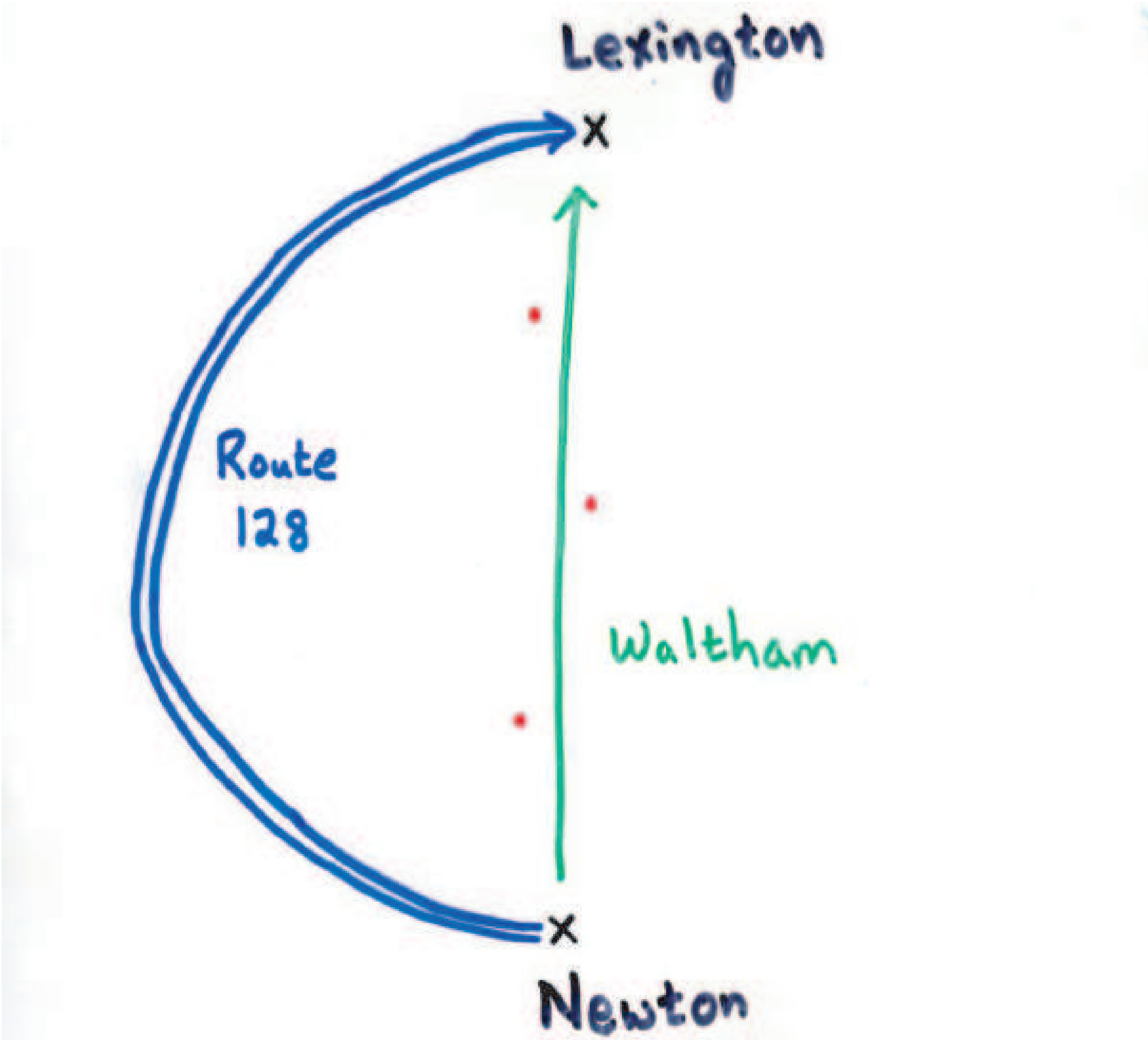
Newton


Lexington
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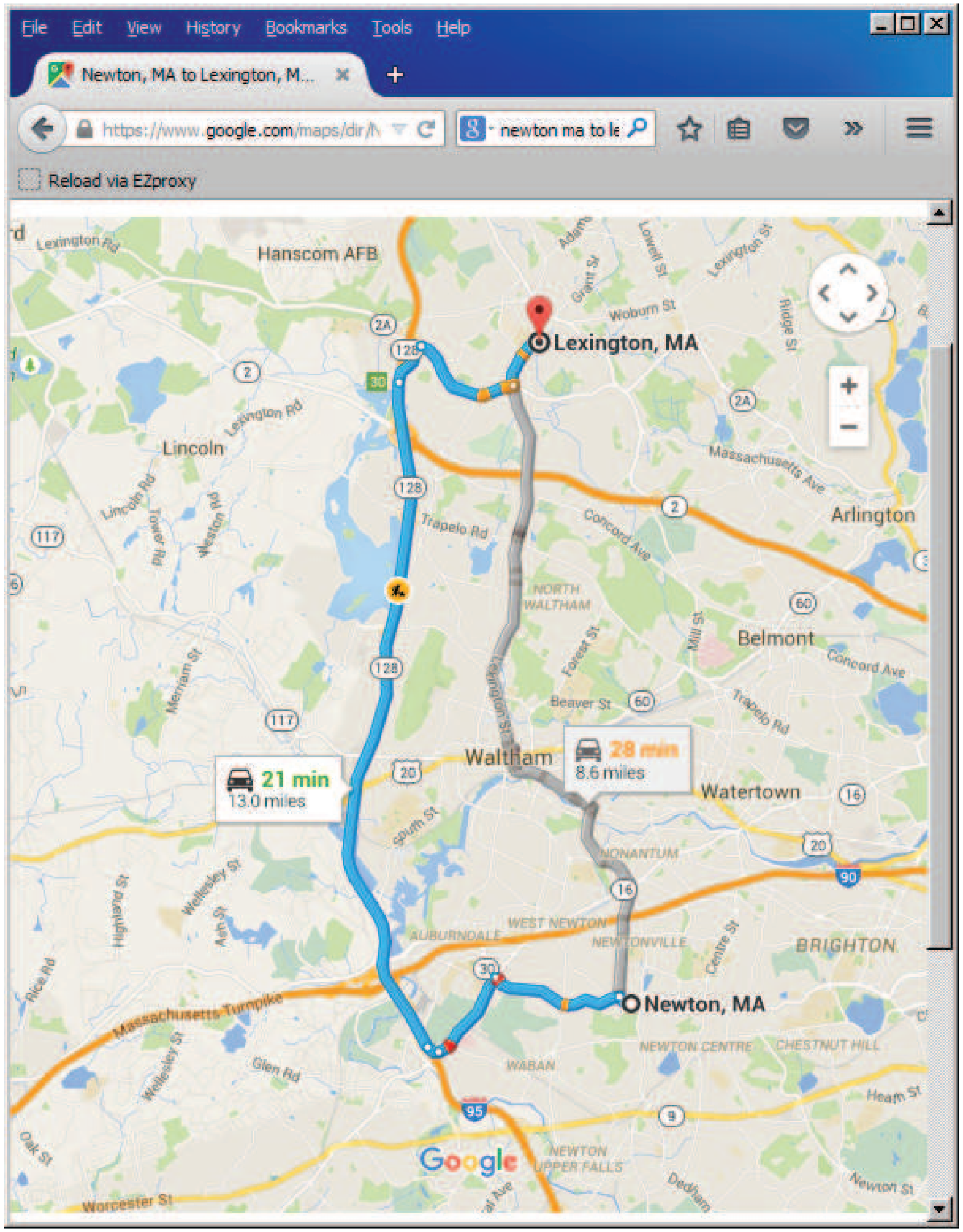
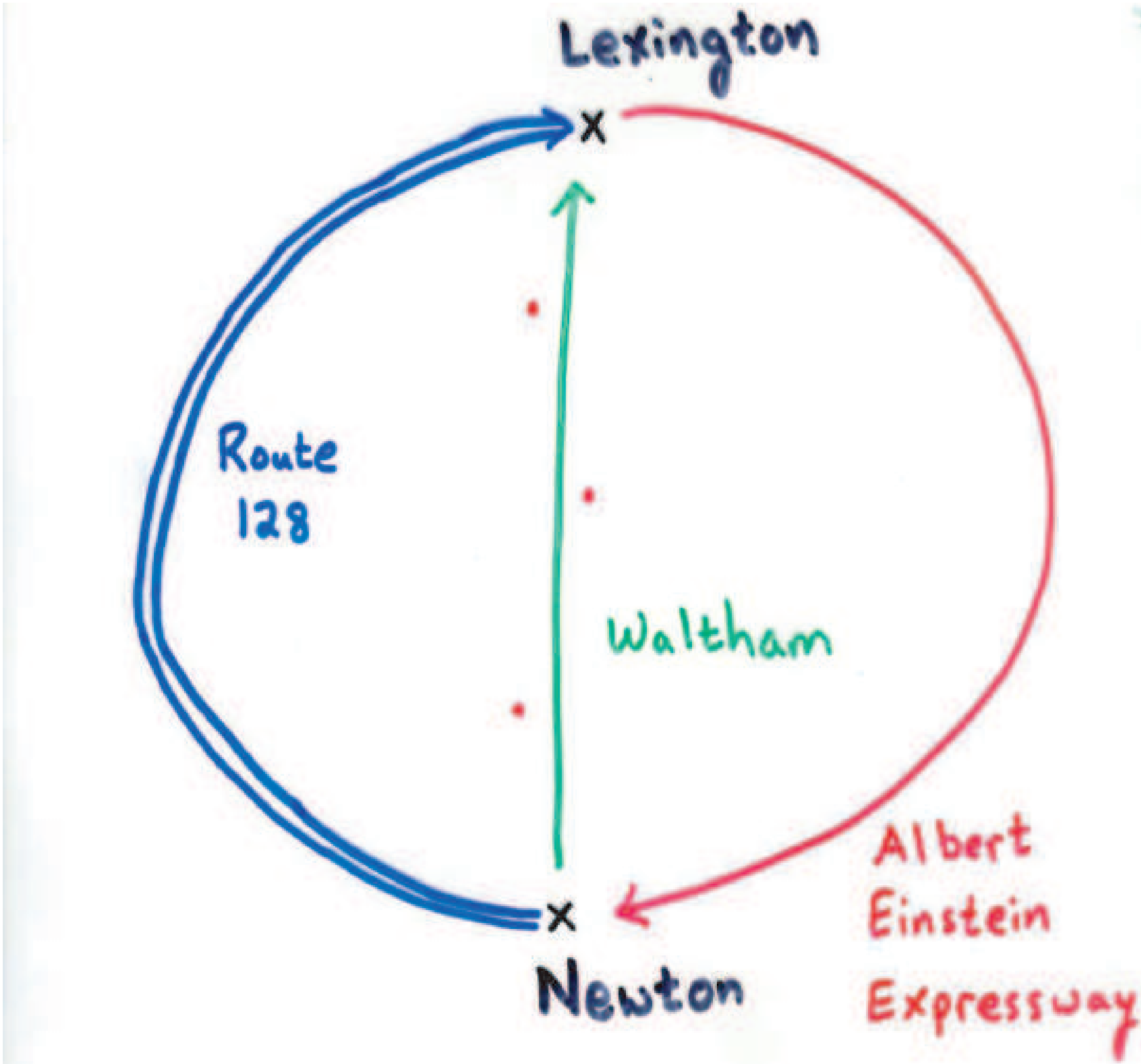
Newton

Shortest distance vs. shortest time:




Lexington
Route
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Waltham
Albert
Einstein
Expressway
Newton

Mapmaker, mapmaker, make me a map

Suppose we would like to construct a map where the distance between two points on the map corresponds to the time it takes to get from one place to the other. Then the fastest route will appear as a straight line on the map.

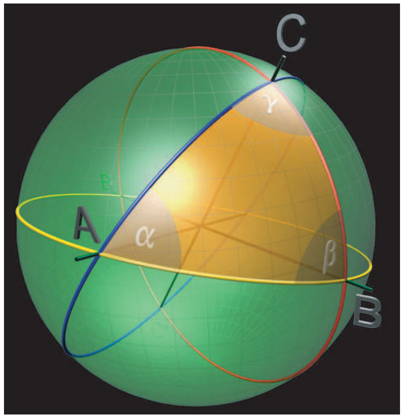
The problem: it's not going to fit on a piece of paper!

If our traffic patterns are complex, we will have to let our map "bubble out" into a curved surface in three (or more) dimensions.

Non-Cartesian Cartography

Even ordinary maps have this problem: You can't draw an accurate map of the spherical surface of the earth on a flat piece of paper.

The geometry of "straight lines" in a curved space can be very different — triangles can have three right angles!



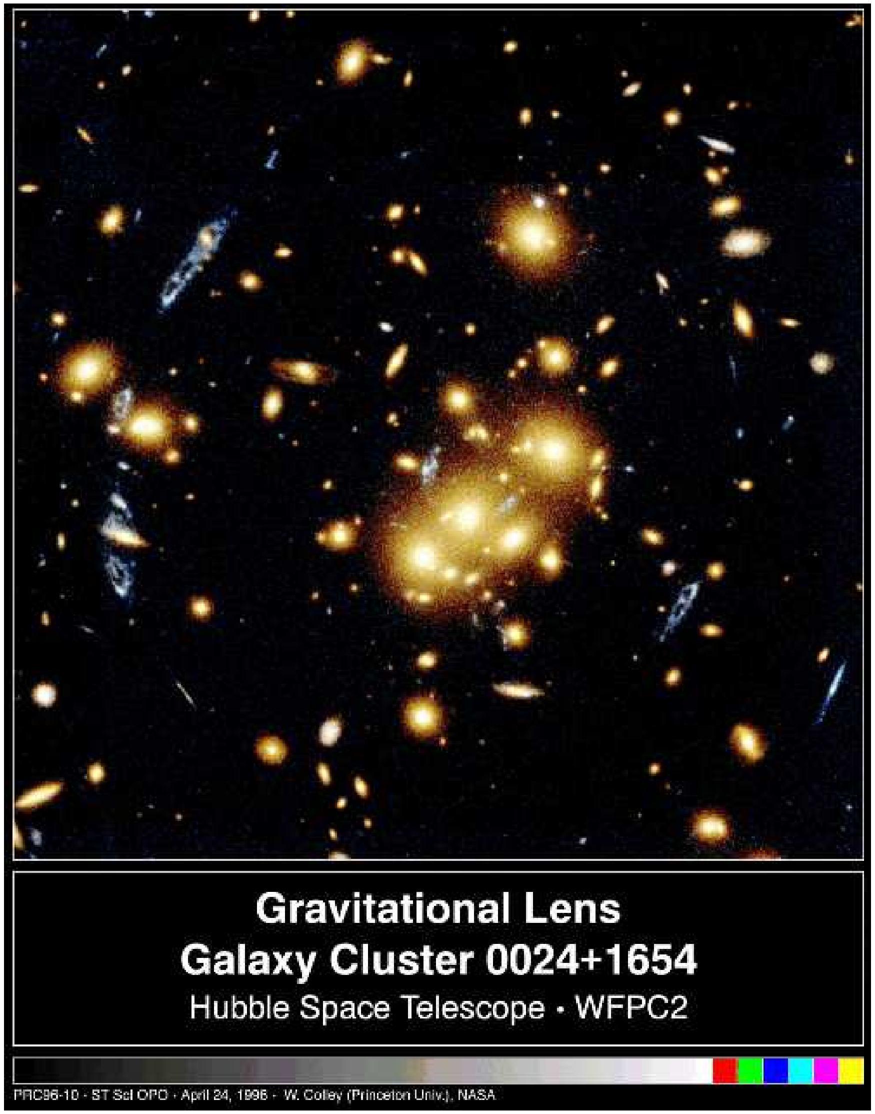
This is a good thing in general relativity, because we can discover how curved our universe is just from measurements made within it.

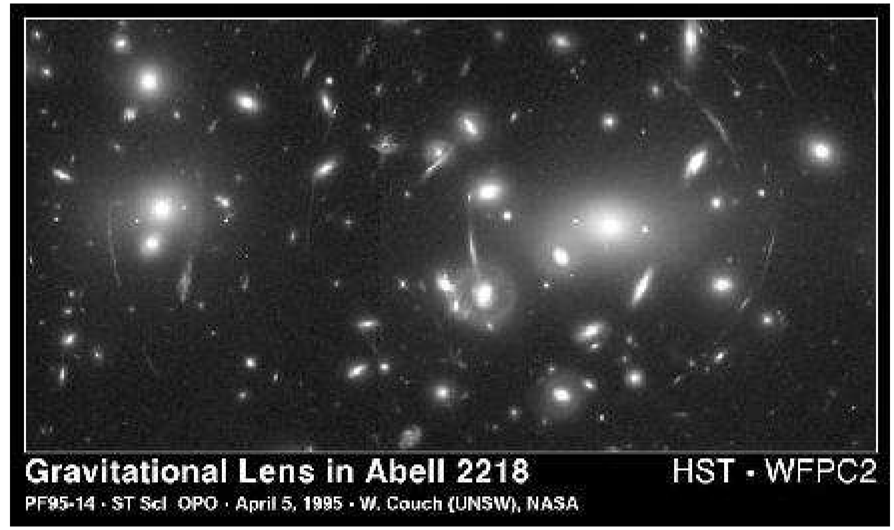
General relativity traffic jam

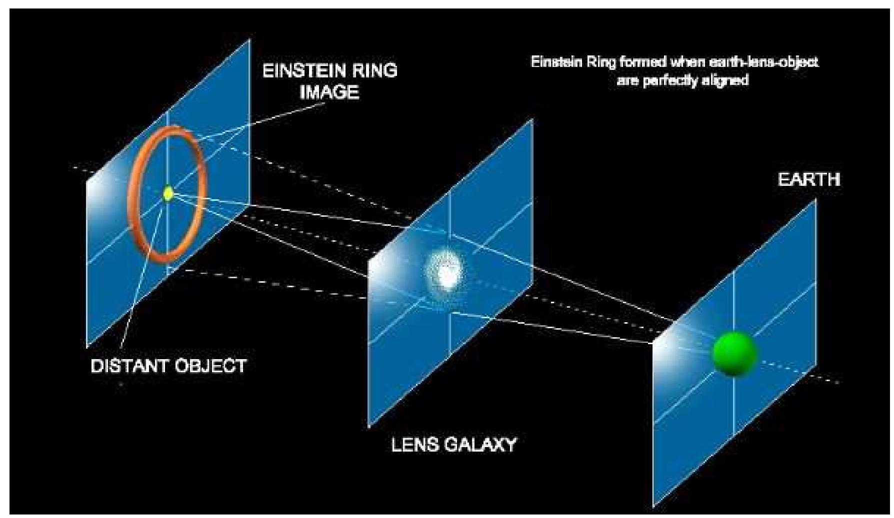
General relativity says: a big mass is like a traffic jam. So particles travel in “straight lines” that actually bend around massive objects.

Amazingly, motion obeying this rule is well approximated (as long as you don’t go too fast) by Newton’s Laws!

Even light gets bent by massive objects!







Black hole gridlock

If we add more and more mass to a given region of space, we make traffic worse and worse.

Eventually we get gridlock — nothing can get through.

This is a black hole: a gravitational field so strong that not even light can escape it.

One final twist

Although general relativity has been known for almost a century, a new result in the last decade has shaken theorists out of our complacency.

We we look out at other stars and galaxies we see that they are all moving away from us — the universe is expanding.

What we learned recently is that when we look at distant supernovae (remnants of cataclysmic explosions of giant stars), we find that this expansion is accelerating.

Universal urban sprawl

In our map analogy, the time it takes to drive from one place to another is constantly increasing.

Traffic is constantly getting worse, across all roads, at a faster and faster rate.

Since traffic corresponds to massive objects, it's as if there is mass associated with empty space.

Sometimes called "dark energy" (since $E = mc^2$).

Einstein's blunders

This idea was actually first introduced by Einstein, who called it the "cosmological constant."

He was trying to reconcile general relativity with the incorrect view at the time that the universe was static.

But since the universe isn't static, general relativity was right all along, and Einstein famously called the cosmological constant his "greatest blunder."

Einstein's blunders revisited

The supernova data are telling us that there is a cosmological constant, but it is very small compared to the one Einstein invented.

Quantum mechanics provides many potential sources for very large cosmological constants. One sign that we don't know how to reconcile quantum mechanics with general relativity is we don't know why the cosmological constant is neither huge nor zero.