Relativity:
what is it, & what is it good for?

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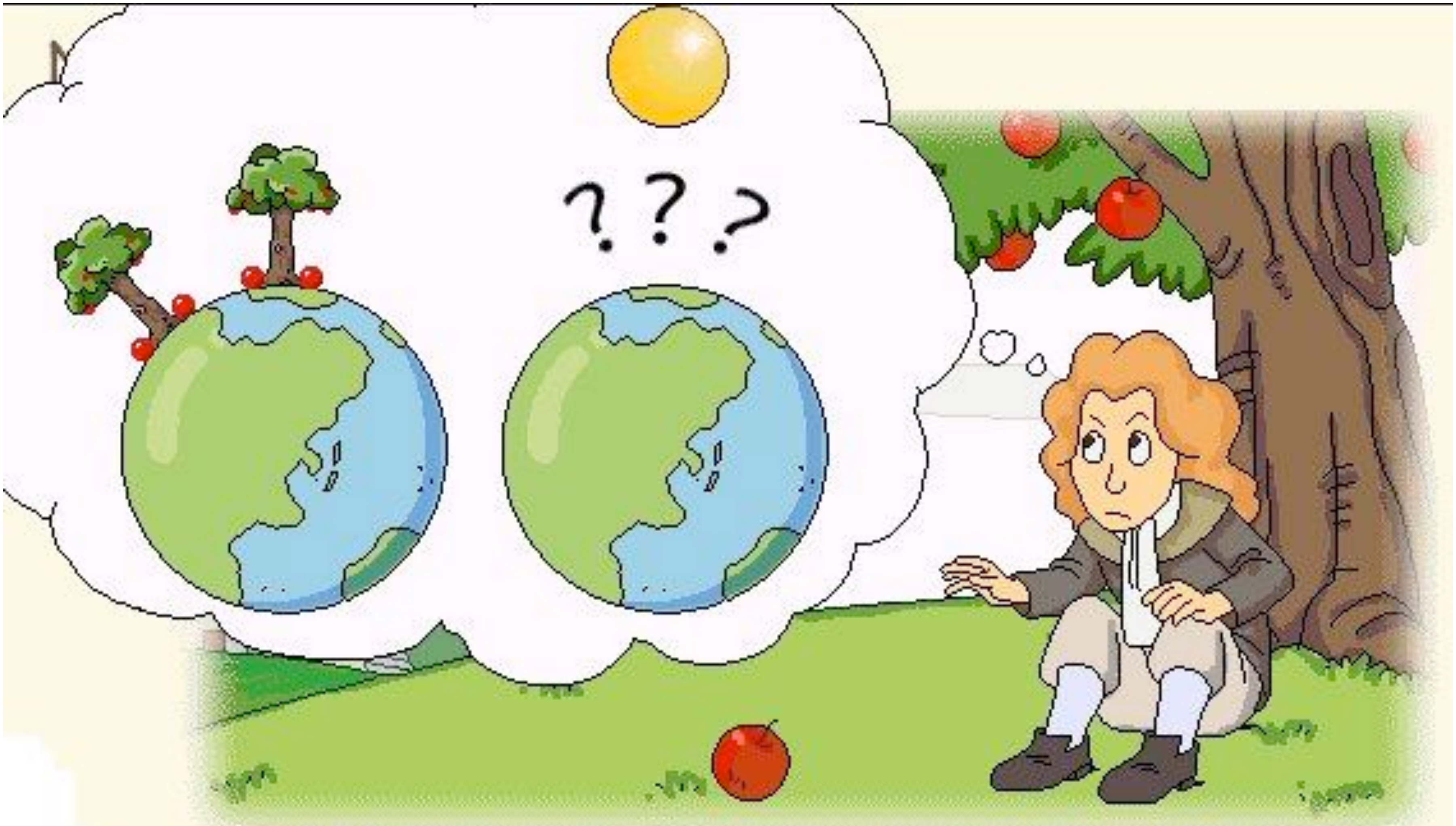
Outline

- **Before Einstein** (30%)
  - Newton's theory of gravity.
  - How strong and how fast is gravity?
  - Old-fashioned relativity: adding speeds.
  - Problems with Newton's theory!
- **Einstein** (60%)
  - Einstein's improved version: special relativity.
  - Relativity of speed. Time dilation.
  - "Twin Paradox".
  - GPS gizmos and general relativity.
- **Beyond Einstein** (10%?)
  - Black holes: theory and experiment.
  - Hawking radiation. String Theory.

Part I:
Before Einstein

An apple drops on Newton



Newton's theory of gravity

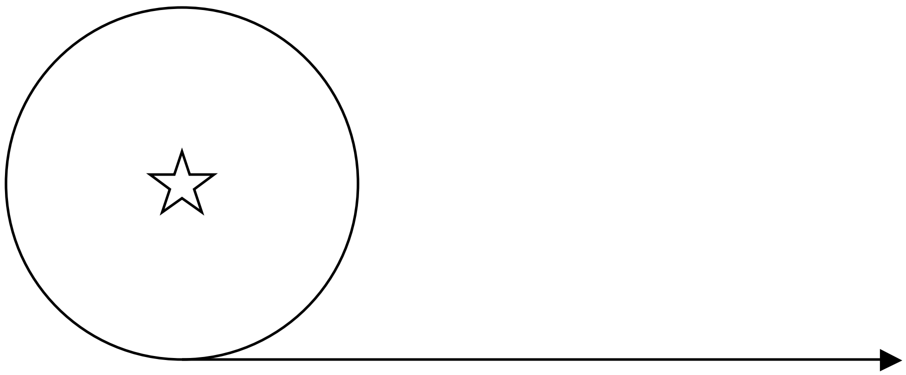
- Everything in the universe attracts everything else.
  All stuff in the Universe is one big happy huggy family.
  (Or... you can't get away from gravity!)

- How *strong* is gravity?
- Let's look at two things that have "mass":
  they're made of regular stuff like mud or carbon.
- Gravitational force between two things depends on:
  - mass of first thing (proportional),
  - mass of second thing (proportional),
  - distance between them ("inverse-square").

  Gravity is *four* times weaker if you *double* the distance.

A major problem with Newton's gravity

- Newton's force law doesn't seem to say anything about how fast gravity is.
- In fact, Newton's theory says gravity is *infinitely* fast !
- So, if a wizard made our sun magically disappear (poof!), earth would *instantly* stop orbiting in a circle and fling off into outer space.



- Note: even sunlight takes 500 seconds to get to earth.
- Hey - isn't the speed of light the fastest that's allowed?

What’s relativity?

- If any influence of gravity happens instantly, it’s very hard to make any sense of cause & effect: which is which?
- Causality problem with Newton’s theory of gravity is closely related to another idea: “relativity”.

- Let’s concentrate on something interesting that moves around as time ticks by.

  e.g. butterfly →

- What does its movement look like in a different frame of reference? Useful idea: *relative motion*.
- Suppose you go by on rollerblades; what differs for you?

Old-fashioned relativity

- Back in the Stone Age , figuring out what happened in another frame of reference was pretty easy:
  - speeds were just added and subtracted normally;
  - time was exactly the same for everybody.

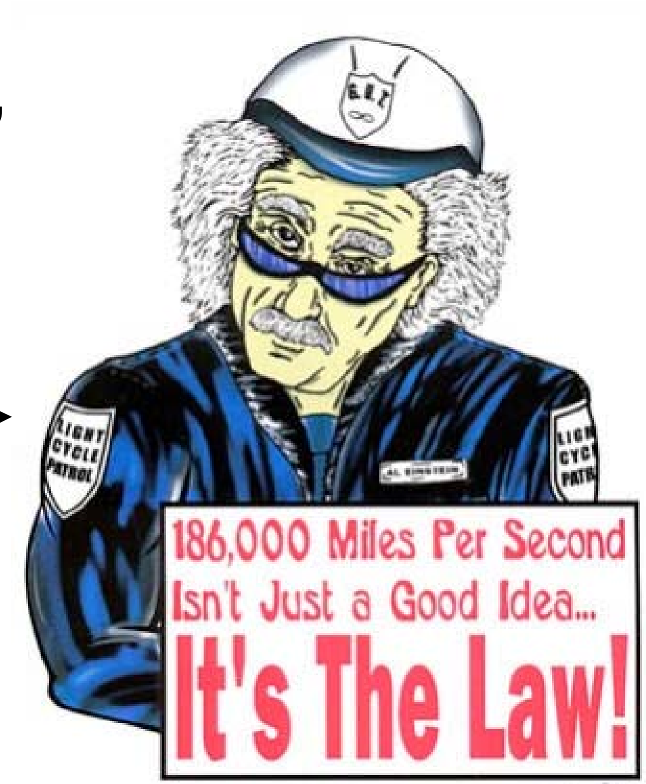
- <u>Example</u> of relative speed: suppose that
  - Honda Civic goes 50km/h south down Yonge St,
  - TTC subway moves south 60 km/h *faster* than Honda.

  - So subway goes 110km/h down Yonge St. ... right?

Part II: Einstein's new ideas

Einstein's new relativity

- More than 2 centuries after Newton, Einstein figured out a better - more accurate - version of relativity.
- Einstein: the speed of light "c" is the *fastest possible* speed. →



- *Nothing* goes faster. Not even subatomic particles. Gravity is no exception.

- Why is this important?
- Example: suppose Honda goes at 50% of "c", and TTC car goes 60% of "c" *faster*. Adding simply says: TTC goes at 110% of lightspeed down Yonge! ... Einstein says: *84.6%.*

How is Einstein's relativity different?

- Speed of light "c" is approximately
  - 300,000 kilometres per second (30 billion furlongs per fortnight)
- You can fly to Los Angeles and back four times in under 1 second, at that rate!

- Einstein's newfangled relativity, "Special Relativity", differs noticeably from old-fashioned relativity only when the speeds involved are a decent fraction of lightspeed.

- Human intuition is built for much lower speeds than that.
- Einstein's relativity often seems *really weird* to humans: we're just not familiar with ultra-high-speed territory.

What finite lightspeed means

- Light is faster than sound.
  This is why we see a firework go off before we hear it go bang.
- Now let's turn the volume off. How long does it take from when an explosion happens until we *see* that explosion?

- It is a finite time-lag, because the speed of *light* is finite.
  - Light from our sun takes about 8 min & 20 sec to travel 150 million km all the way to earth.
- Light taking 1 year to reach earth started out about 9,418 billion km far (scaling this to earth width, I'm as tall as O_2).
- Modern astrophysicists can look far *back* in time: they just study very old light coming from faraway galaxies. (From *past only*; no Star Trek style "time travel"!)

The “Twin Paradox” setup

- Einstein is famous for quite a few things. Possibly his most useful invention for physicists was his idea of the *thought experiment*.   (= cheaper than a real one...)

- Let’s imagine Bart, a homebody who stays on earth, and his astronaut twin who rockets off into outer space for awhile.

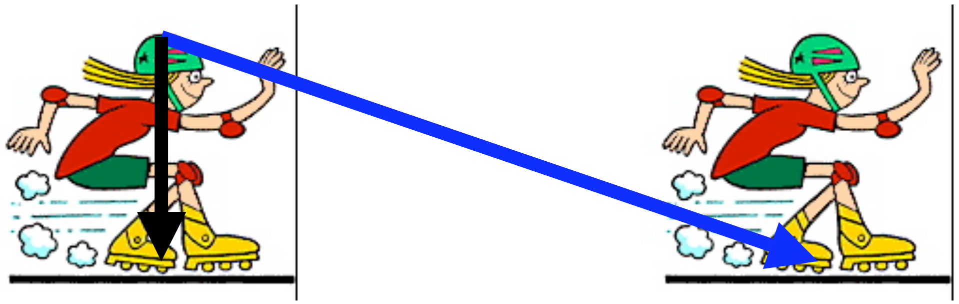
∗ Question: do they age the same?

- Old relativity would say yes - everyone keeps same time.
- Einstein said: actually, moving clocks run *slow*! And if one gets older quicker - who is it?

Time dilation

- *Why* did Einstein claim that moving clocks run slow?
- He figured it out by realizing that sending light-pulses between different places in space is the only sensible way to compare (and hence synchronize) different clocks.

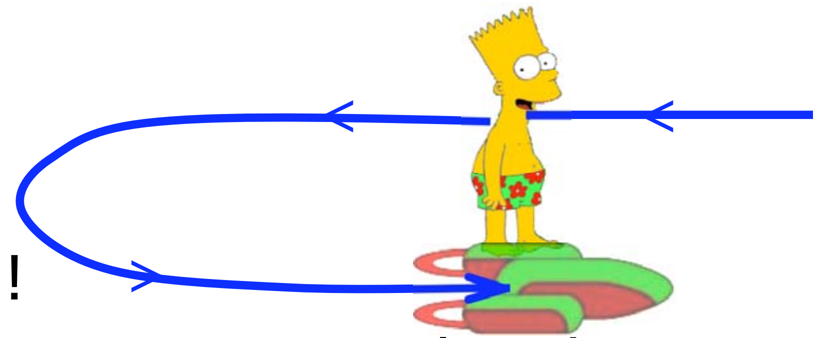
- Suppose you flash light from your head to your left toe, while you go by me on rollerblades. Then what do I see?



- Longer lightpath, same “c” ⇒ I see your clock run slower!
- (Symmetrical: you also see mine run slower.)

Role of acceleration

- According to Einstein's special relativity, *each* Bart sees the other twin's clock running slower than theirs.



- Now, astronaut-Bart actually has to *accelerate,* to turn around!
- We can figure out time dilation for constant acceleration (by using calculus).

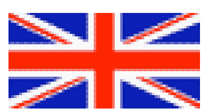
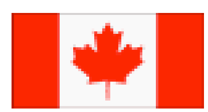
  Intuitively, *acceleration adds to the trip's time dilation*. The slower the acceleration, the smaller the extra effect.

- The acceleration of astronaut-Bart also breaks the symmetry between the twins. It gives us a reason to trust Einstein's theory, which says that homebody-Bart always does age faster than astronaut-Bart. $\Rightarrow$ No paradox!

Testing special relativity

- Time dilation (and length contraction) can be measured with exquisite precision in particle accelerators. Einstein's theory works *perfectly*, e.g. short-lived subatomic particles live much longer whizzing by at nearly lightspeed.

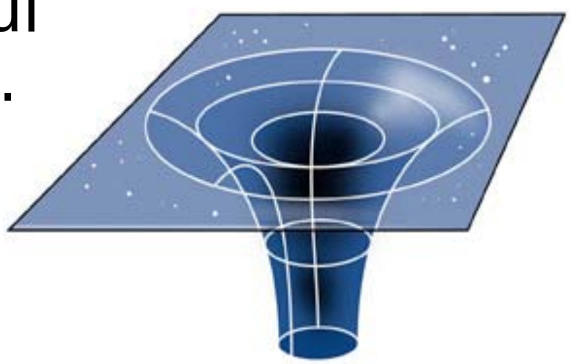
- Large Hadron Collider (LHC) → being built in Geneva, Switzerland. Multi-country effort; *HUGE*.

- (My countries:   )

Pillar of 20th C. physics: General Relativity

- Up near speed of light: Special Relativity says:-
  - moving clocks look to be running slow;
  - objects look shrunken in direction of motion;
  - pumping in more energy gives ever-diminishing returns when trying to accelerate a massive object.
- Is it possible to incorporate Einstein's new relativity with Newton's old theory of gravity? ... No. Need a new theory.

- Einstein's GR: gravity becomes beautiful unified geometrical concept: spacetime.
- *Matter tells spacetime how to curve, spacetime tells matter how to move.*
- GR experimentally tested robustly;
  ... amusingly, Einstein didn't care!



GPS gizmos

- GR in your everyday life: GPS! →

- 24 satellites orbiting Earth, each has precise atomic clock. Need 3 or more satellite radio signals to get latitude, longitude & altitude, within few metres.
- Used in air navigation, wilderness recreation, sailing, cars, trucks, etc. (Even can land planes on auto-pilot!)
- Satellites are in *high-speed* orbits, and *further from Earth* where space-time is a bit less curved. Overall clocks tick at slightly different rates than ground clocks.
- Not using SR and GR would cause navigational errors adding up to lots of *kilometres* per day!
- GPS units use SR+GR every day to electronically adjust clocks, and build Eintein’s theory into receiver chips that find your location based on satellite radio signals.

Part III:
Beyond Einstein

Black holes

- When really big stars run out of gas, gravity forces them to collapse to Black Holes. Other forces powerless to resist!
- Need star with mass more than about ten times sun-mass (otherwise make neutron star or white dwarf star).
- Gravity pull of BH weak far away, stronger closer in.

- Event horizon: place of no return. If fall in, can't escape, no matter how strong your rockets. Distance from centre: few km for sun-mass BH, ~1 cm for earth-mass BH.
- Inside BH, everything crushed/torn to pieces. Very nasty singularity at centre. (worse... GR breaks down there!!)

Black hole evidence

- BH are rather like vacuum cleaners; run on gravity power.
- Suck in stuff like gas & stars, which don't want to go in; they spit out radiation madly as spiral inward.

- Astronomers detect radiation in telescopes; can tell how fast stuff is going (redshift) versus distance from centre.
- Very specific relationship of speed versus distance for BH, as compared to other objects like stars.

- Evidence for BH shows
  - e.g. Milky Way has BH around ten-sun mass;
  - million/billion-sun mass BH @ centre of most galaxies.

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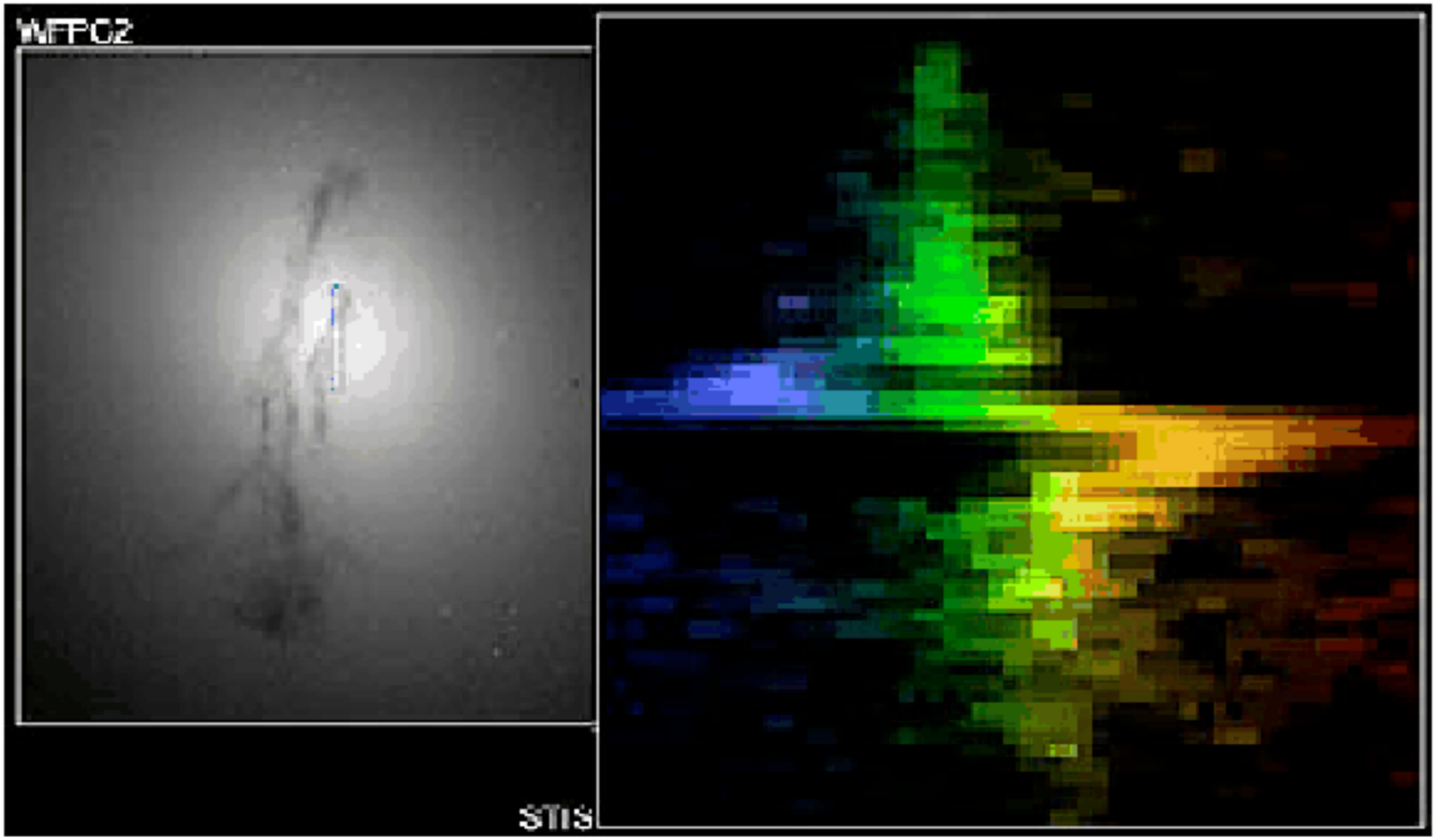
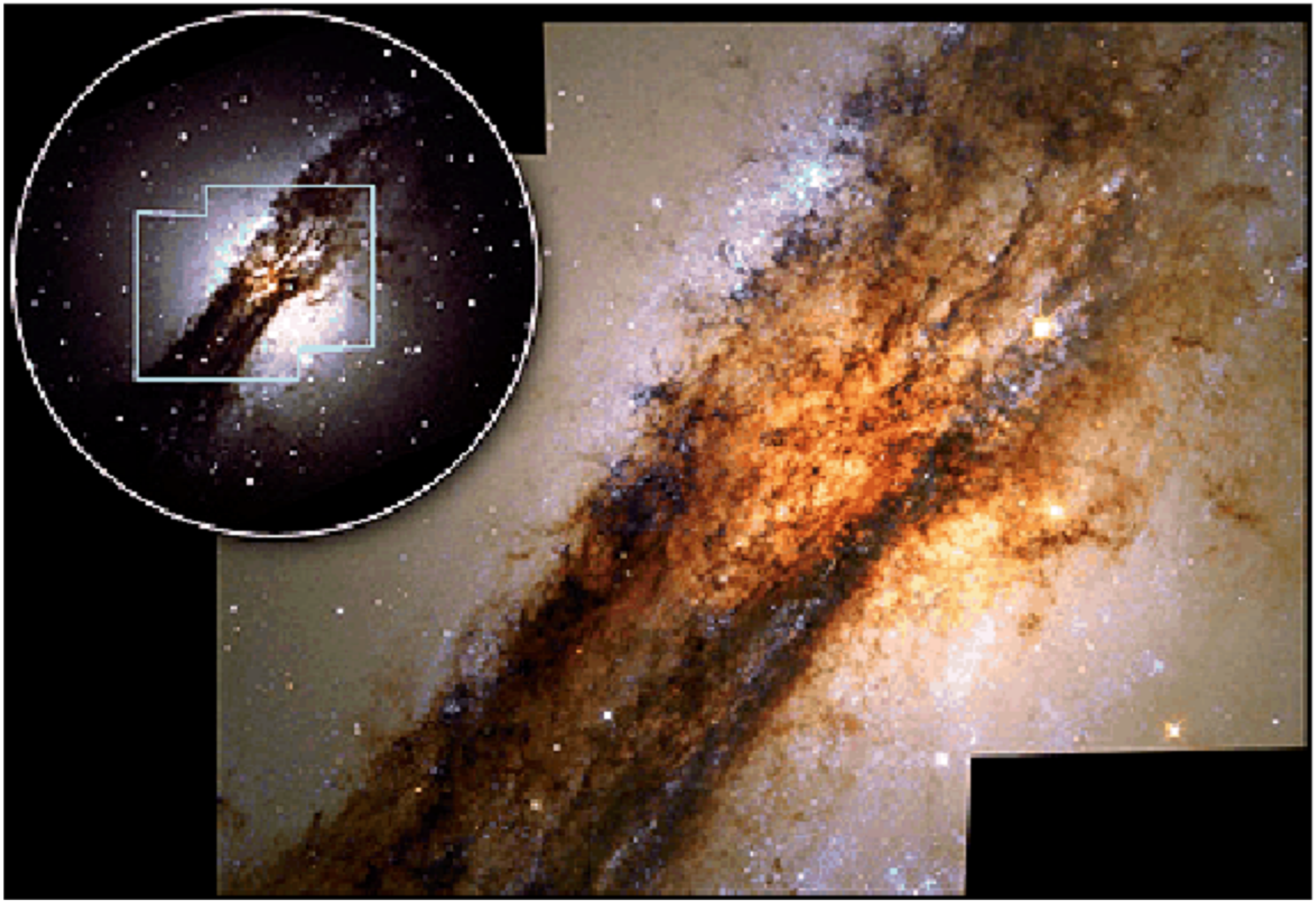


Centaurus A



Hawking radiation

- In mid-1970s, Hawking discovered something does get out of black holes: radiation.
- Not same as radiation spit out by stuff in accretion disk. Hawking radiation happens even if BH alone in universe.

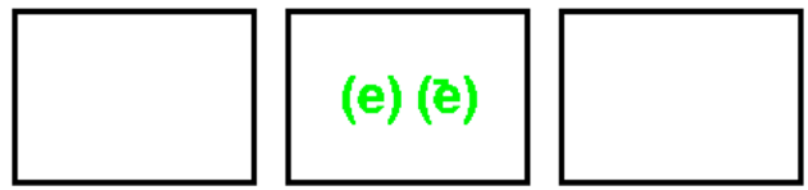
- Hawking temperature very cold for astrophysical BH. Much colder than CMB.

- Quantum weirdness allows antiparticles!
- Antiparticle has same mass & spin, but opposite charge.
- Particle and antiparticle annihilate to make pure energy

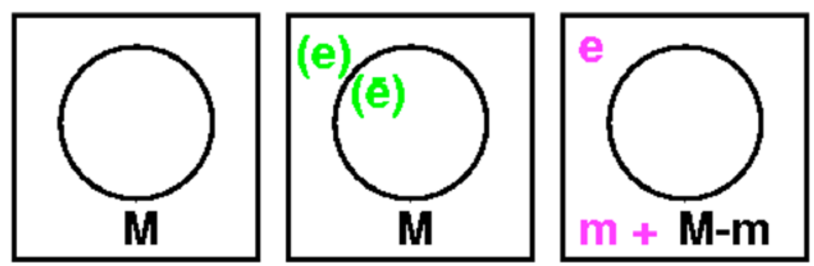
$$E = 2(mc^2)$$

Pairs popping in and out of existence

- Quantum weirdness, via Heisenberg uncertainty principle, allows pair to
  - pop out of vacuum,
  - exist as virtual particles (for *very* short time),
  - pop back out of existence!

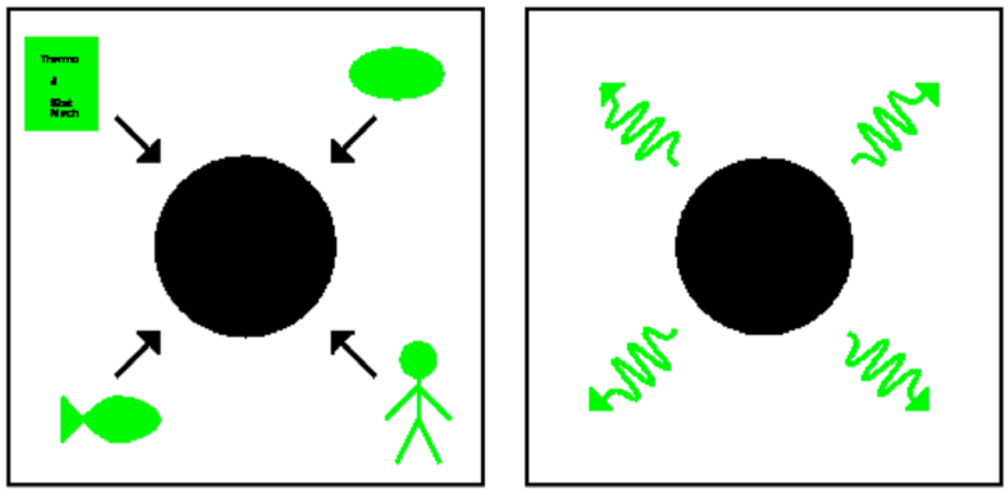


- Pair-popping happens everywhere all the time.
- Relatively boring, usually.
- Unless pair straddles horizon of BH... then one lost inside and other escapes as radiation.



Black hole information puzzle

- Big Problem: Hawking's calculations said: all that ever comes out of a black hole is radiation, depending *only* on mass and angular momentum of infalling stuff.



- So we lose information about what went in? Gone?!?
- Perhaps if we know more about quantum theory of gravity we can explain where black hole information went. (Don't want unified theory to gobble information!)

String theory to the rescue!

- Idea: *strings* are basic Legos of everything in universe.

- Different vibrations of string are different *'particles'*. Includes matter and force-carriers. Nature's symphony!
- **Includes gravity naturally, neatly and beautifully.**
- In just last decade: use quantum physics of superstrings and D-branes to compute black hole thermal properties. Get same answer as relativity guys 25 years ago. Success! Also string theory gives ideas about information problem.
- Our most powerful observatories can't see strings - yet.

The End ...

Where to learn more