How well have we tested Einstein's Special Relativity?

There was a young lady named Bright,
Whose speed was far faster than light;
She started one day
In a relative way,
And returned on the previous night.

Tiny Neutrinos May Have Broken Cosmic Speed Limit

By DENNIS OVERBYE
Published: September 22, 2011

Roll over, Einstein?

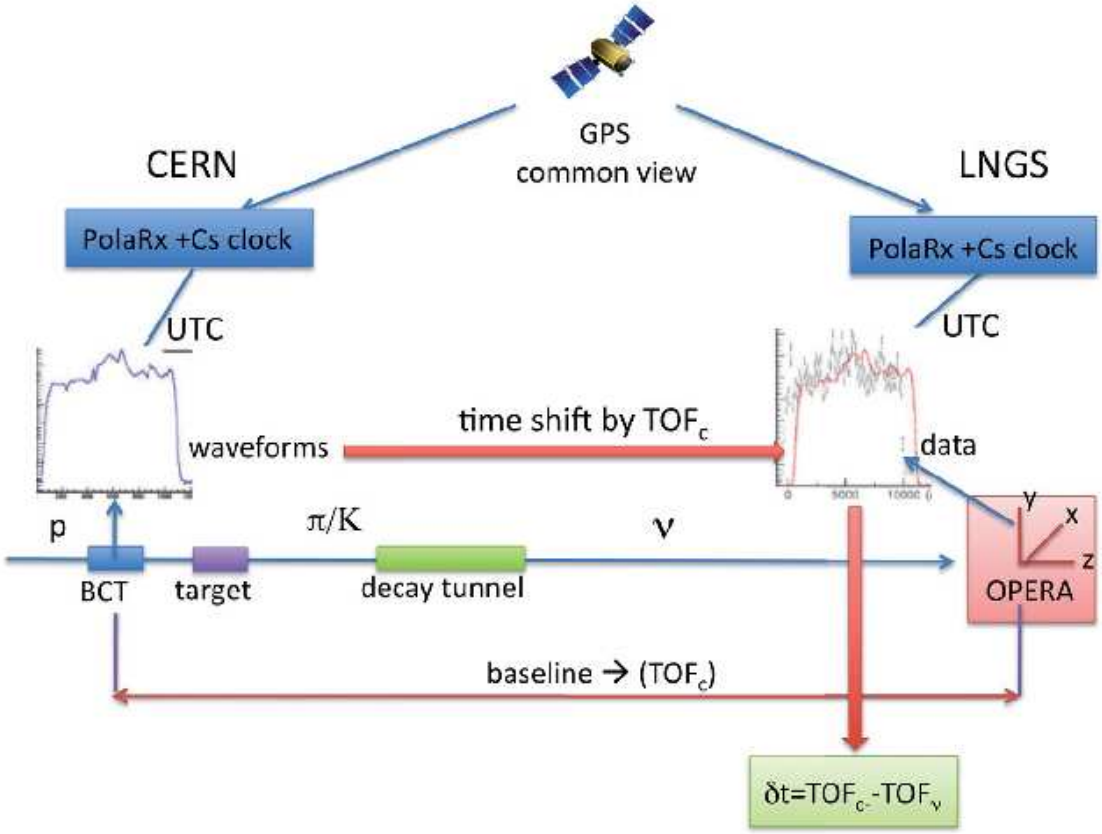
The physics world is abuzz with news that a group of European physicists plans to announce Friday that it has clocked a burst of subatomic particles known as neutrinos breaking the cosmic speed limit — the speed of light — that was set by Albert Einstein in 1905.

If true, it is a result that would change the world. But that "if" is

CERN accelerator complex fired neutrinos from Geneva to Gran Sasso (Italy). OPERA experiment detected them:

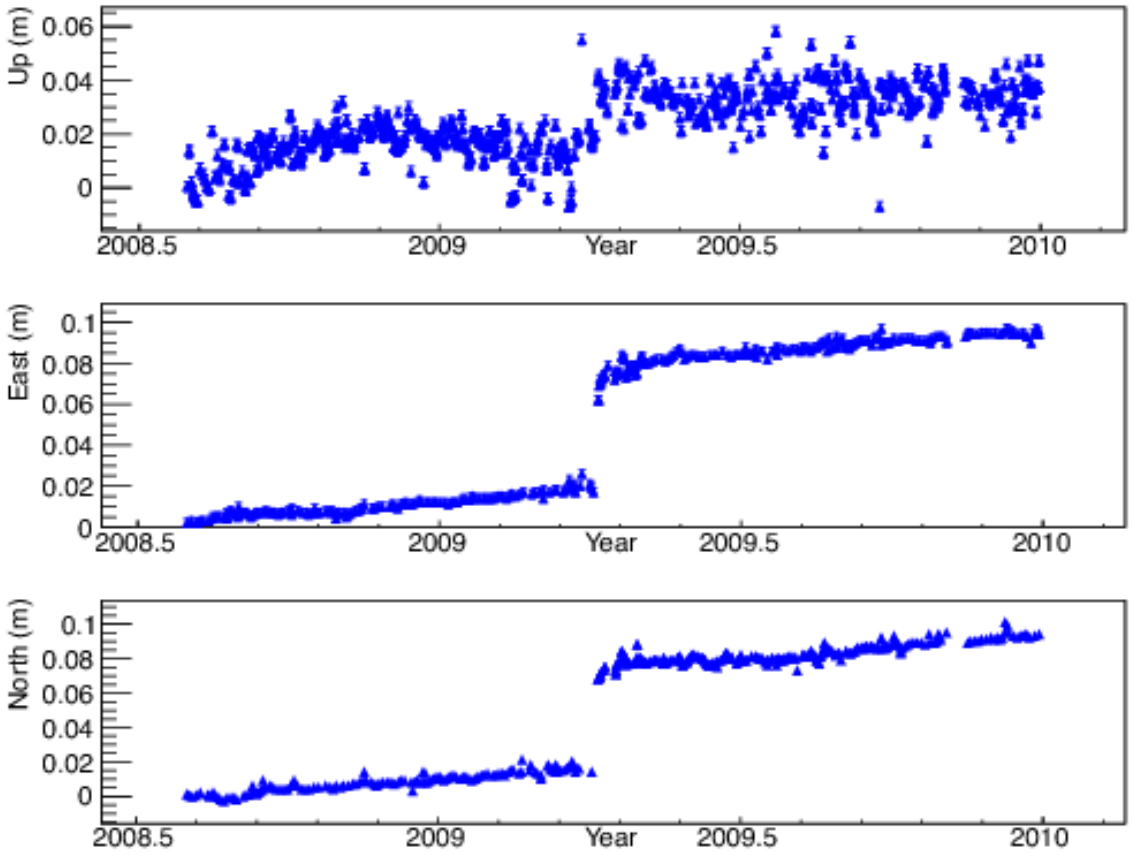
Neutrinos: very weakly interacting particles. Studying some properties requires send them 100–1000 km from source to detector. 1 in 10^{15} is detected...

As an extra, OPERA measured distance and time info.



Time: GPS, local atomic clocks, cabling.

Distance: GPS (surface only!), distance meters.



Observe Italy's drift, and L'Aquila earthquake

Precision measurements!

Time: $2,439,221 \pm 7$ nanosec (0.002439221 seconds)

Distance: $731,278.0 \pm 0.2$ meters

Expected time in transit:

$$\Delta t = \frac{\text{Distance}}{\text{Speed}} = \frac{731,278\ \text{m}}{299,792,458\ \text{m/s}} = 0.002439281\ \text{s}$$

Actual arrival time is .000000060 seconds *early*

Implies velocity 7400 m/s *faster* than light.

Neutrinos went faster than light?!

Most physicists were dismissive

"They must have done something wrong!"

"I wonder what they did wrong?"

Everyone I know

Is this narrow-mindedness?

Or were there good reasons for assuming a mistake?

When a result contradicts accepted theory, you should check it very carefully.

If it also contradicts prior, more precise *measurements*, it's probably in error!

I will now explain an indirect experimental test of Relativity, including

neutrino-light speed difference, with **far** higher precision than OPERA's test!

PHYSICAL REVIEW D, VOLUME 70, 065002

Limits on Lorentz violation from the highest energy cosmic rays

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(Received 30 April 2004; published 3 September 2004)

We place several new limits on Lorentz violating effects, which can modify particles' dispersion relations, by considering the highest energy cosmic rays observed. Since these are hadrons, this involves considering the partonic content of such cosmic rays. We get a number of bounds on differences in maximum propagation speeds, which are typically bounded at the 10^{-21} level, and on momentum dependent dispersion corrections of the form $v = 1 \pm p^2/\Lambda^2$, which typically bound $\Lambda > 10^{21}$ GeV, well above the Planck scale. For (*CPT* violating) dispersion correction of the form $v = 1 + p/\Lambda$, the bounds are up to 15 orders of magnitude beyond the Planck scale.

DOI: 10.1103/PhysRevD.70.065002 PACS numbers: 11.30.Cp, 11.10.Nx, 13.85.Tp

I. INTRODUCTION

It is generally believed that Lorentz invariance is an exact symmetry of nature. This belief is supported by extremely precise experimental tests, and by strong and well motivated theoretical prejudice. Indeed, exact Lorentz invariance is used as one of the cornerstones on which relativistic quantum field theory is built, leading to the extremely successful standard model of particle physics. Together with the equivalence principle, local Lorentz invariance is one of the assumptions underpinning general relativity. Alternatively, we could say that general relativity is the gauge theory of general coordinate invariance, and has exact local Lorentz invariance as a consequence. In either case, it is intimately related to both our best theories of particle physics and of gravity.

While most physicists believe that Lorentz symmetry is an exact symmetry of nature, one of our jobs as physicists is to put all of our assumptions to the most vigorous

corrections to their dispersion relations. This opens up the possibility of Cherenkov radiation; a particle with a larger limiting velocity is energetically allowed to radiate particles with lower limiting velocities, even though such radiation by a particle at rest is not kinematically allowed. For instance, suppose the limiting velocity of an electron is $c_e > c_\gamma$, where c_γ is the limiting velocity of a photon. Then the energy of an electron of momentum $p \gg mc_e$ is

$$E_{e,p} = \sqrt{p^2c_e^2 + m_e^2c_e^4} \simeq pc_e + \frac{m_e^2c_e^3}{2p}, \qquad (1.1)$$

while the energy of a photon of momentum k is kc_γ. The process $e \longrightarrow e\gamma$ is kinematically allowed if the final state energies sum to the initial state energy and the sum of the magnitudes of the final state momenta exceeds the magnitude of initial state momentum (so a nonvanishing opening angle is allowed). Denoting the final photon momentum as k, defining $\epsilon \equiv (c_e - c_\gamma)/c_\gamma$, and taking

Special Relativity

Special relativity arises from two **Postulates**:

1. All inertial reference frames observe the same laws of physics.

2. There is a fixed maximum speed c. No object or information can move faster.

In vacuum, light happens to move at the maximum speed.
All of Special Relativity follows logically from these.
So these are what we want to test!

What is an inertail frame?

Point of view of someone/thing which is not feeling forces.

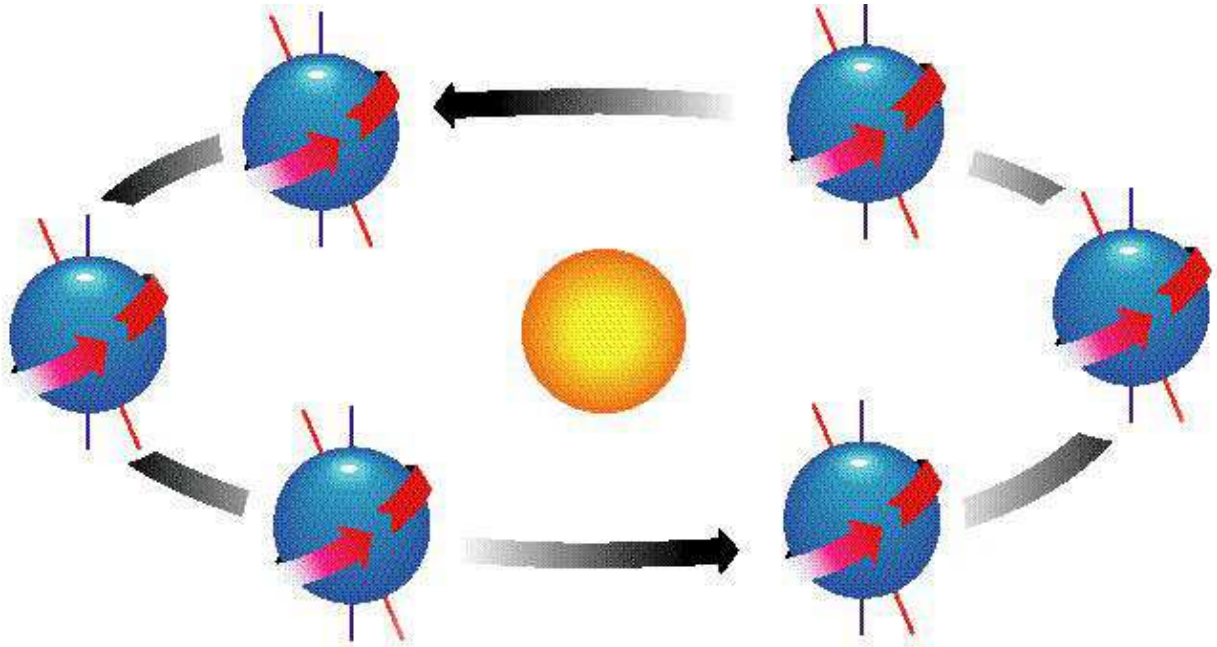
In a steady moving train you see the ground pass at a constant rate.

On the ground you see the train pass at a constant rate.

You both observe the same physics laws, inside and outside the train.

Is Inertial Frame thing well tested?

You bet! Earth rotates (460m/s) and orbits the Sun (30,000m/s)

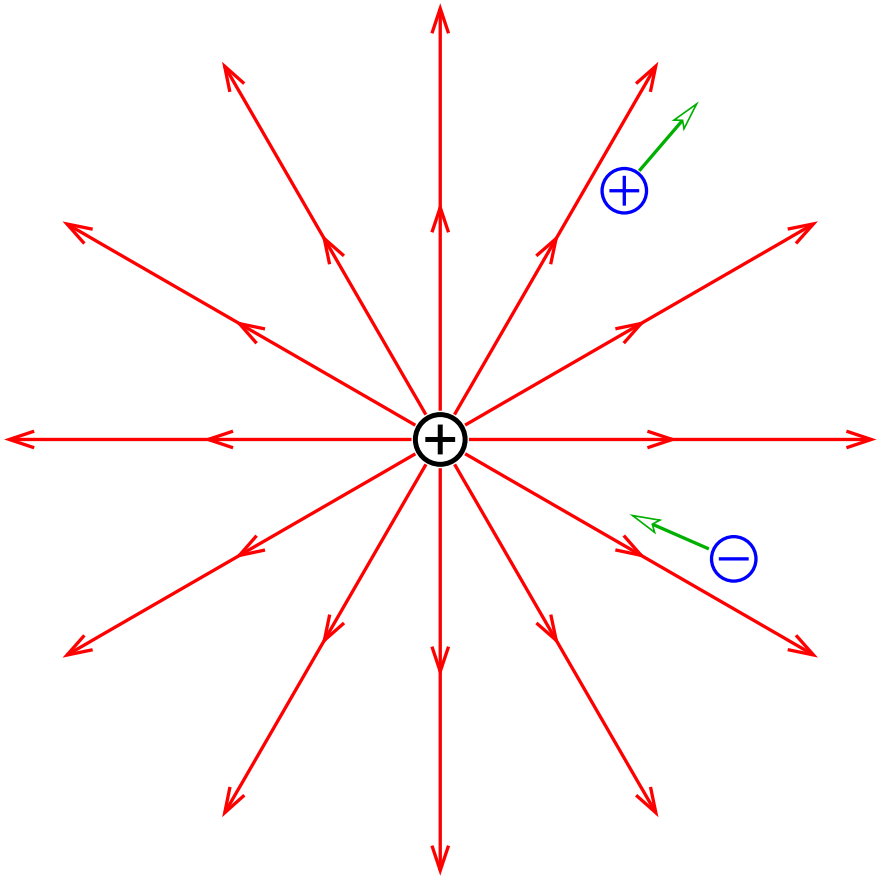


but physics on Earth is not seasonal!

How do we test if things can go faster than light?

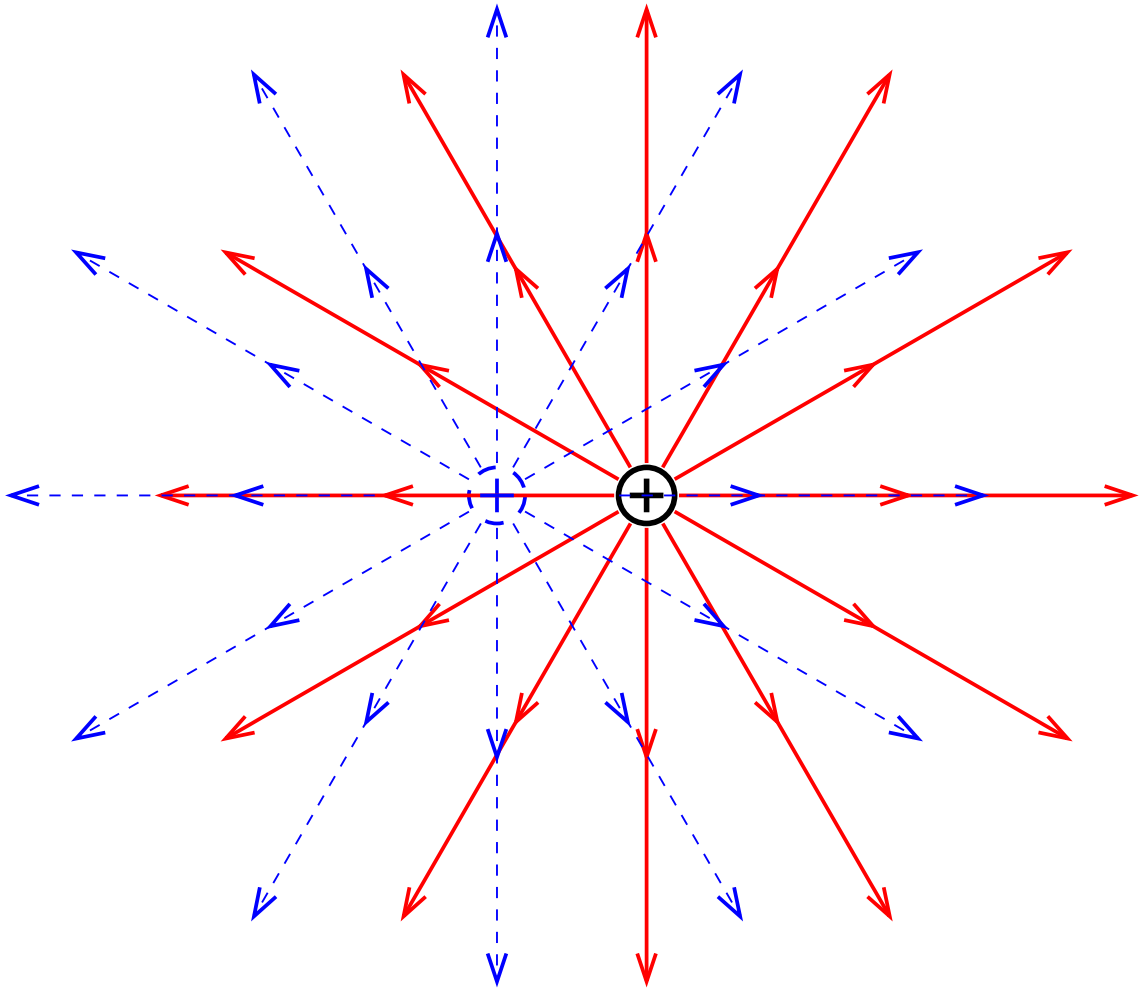
First, what is light anyway?

Story starts with the Electric Field around a charge:



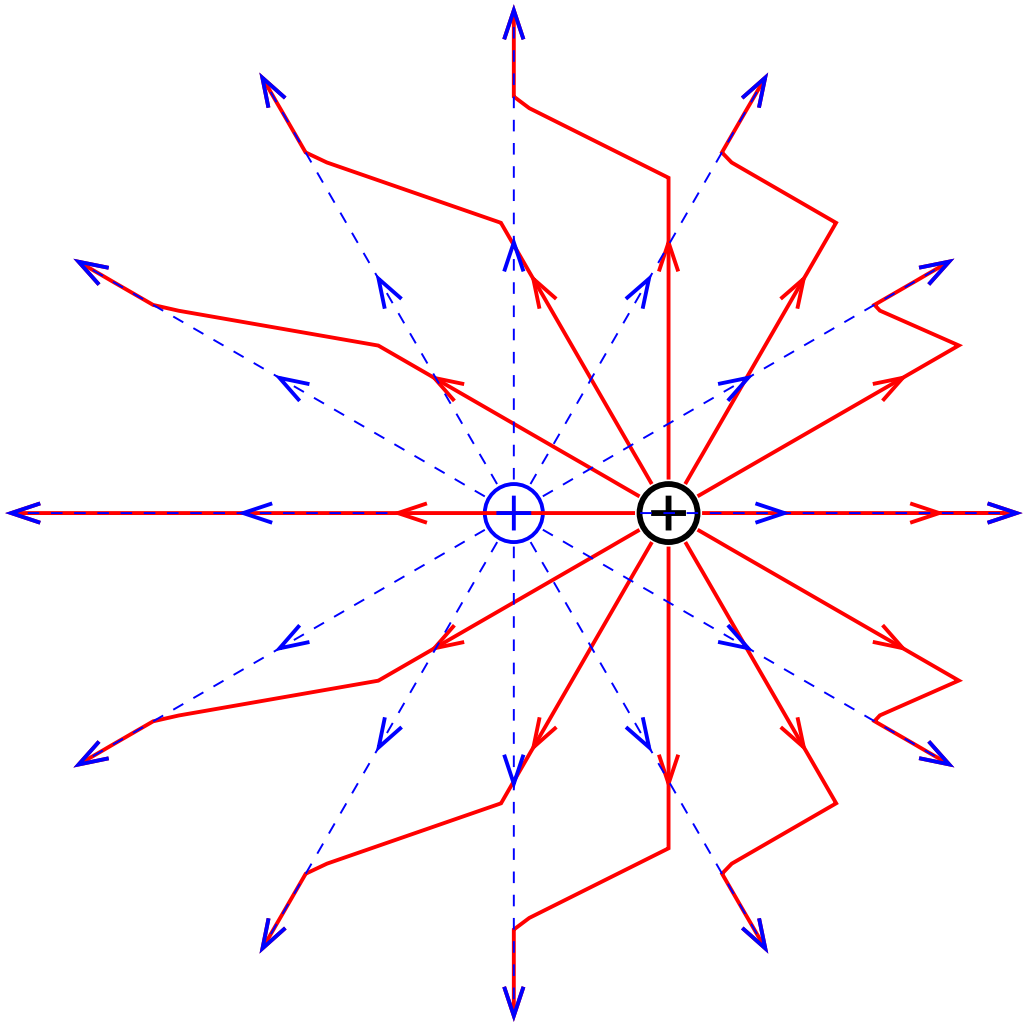
Field pushes away like charges and pulls in opposite charges. This+Quantum effects give all the forces you feel day-to-day except gravity.

When a charge moves, the field must re-arrange.



Old/new locations have different E-fields.

Field far away cannot "know" instantly that charge moved.

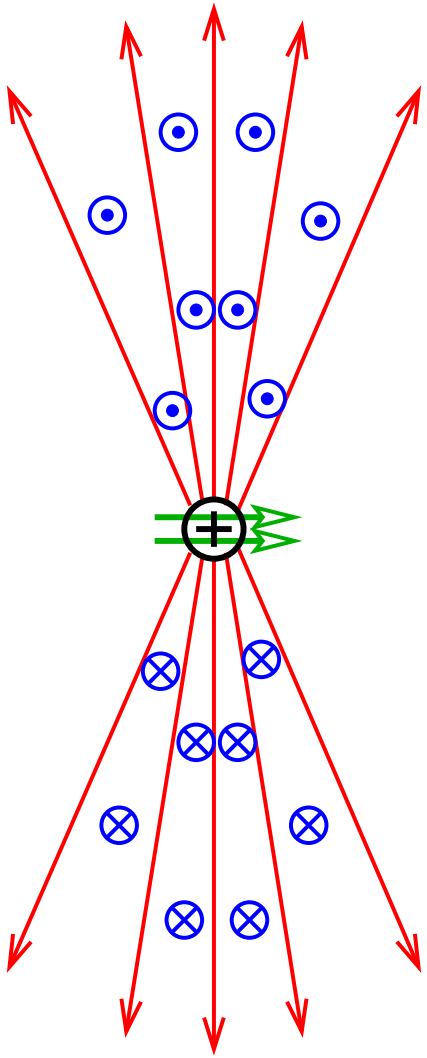


New field in close, old field far away. Distance to "bend" in field = distance information can travel since charge moved.

This "bend" in the field *is* light!

How does the E-field know how to change?

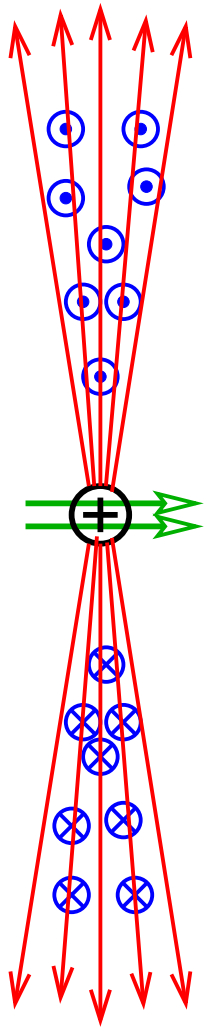
That is the role of the magnetic field $\vec{B}$.



B-field tells E-field how to move. And vice versa. A moving charge always carries both. The faster it moves, the more B field there is. And the more the E and B field lines come out to the sides, not front-and-back.

B-field in blue: out of the board above, into the board below.

As a charge approaches the speed of light, E, B focus into a "pancake" around the charge



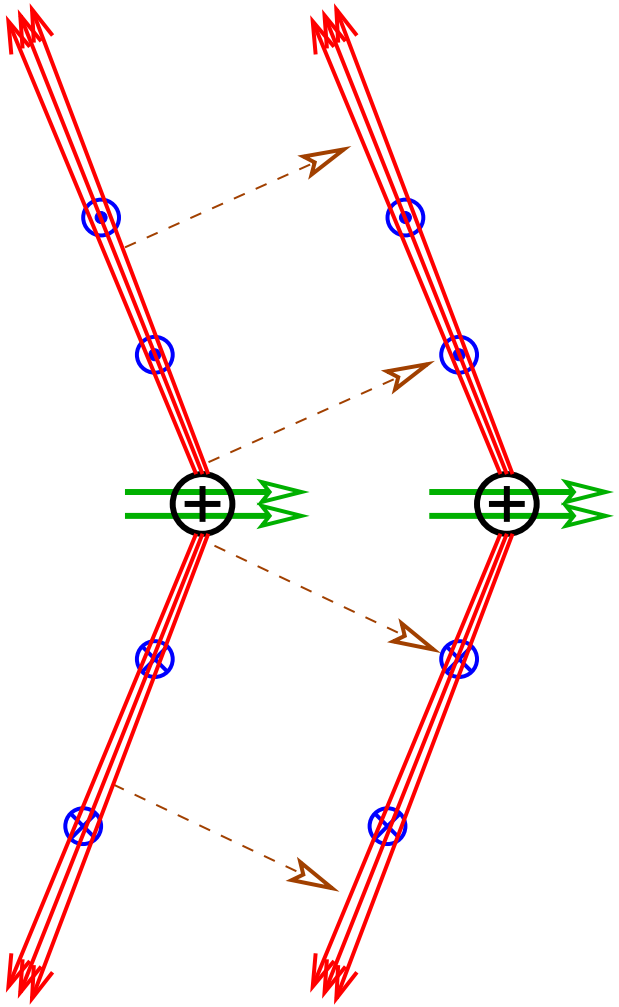
And $B \simeq E$. As $v \to c$, the pancake gets perfectly thin, and it is all E, B can do to keep up. The E, B at a spot are the ones which arose from the same spot a moment ago...

What if a charge goes faster than the speed of light?

We actually know the answer! Light goes slower than c (the maximum speed) when impeded by a material like glass or water.

So look at the behavior of fast charges in water.

Electric, magnetic field lines cannot keep up



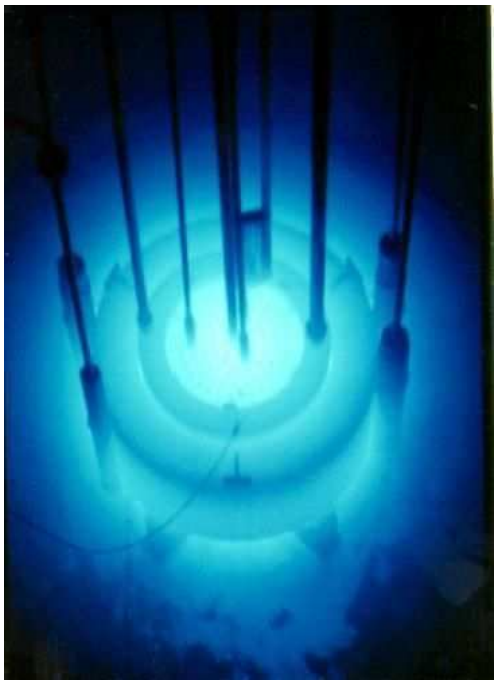
Lines bend backwards.

Propagation as shown.

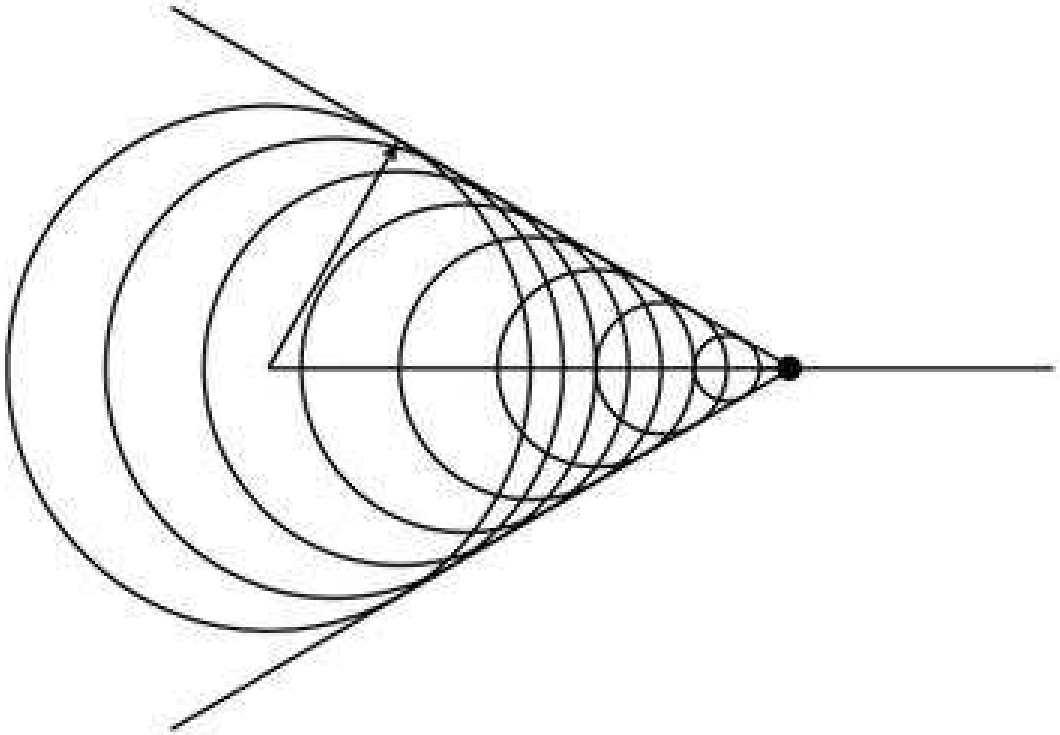
E, B near charge must constantly get "generated" by the charge

Represents *Cherenkov* radiation

Visualizing Cherenkov Radiation



Reactor Core



Light propagation and Cherenkov Cone

Intensity, angle, spectrum all correctly predicted....

Coleman Glashow, Phys. Rev. D 1998

If the maximum speed for electrons is faster than light, then super-high energy electrons will move with $v > c$.
They will then Cherenkov radiate and lose energy (very fast).

They also showed an effect similar to the Cherenkov effect: if the maximum speed for electrons is *slower* than c, then sufficiently high-energy photons will break up into an electron and its anti-particle, the positron. If not all particles have the same maximum velocity, nature prefers to make the slower-moving ones.

Arguments *assume validity of Quantum Mechanics*: almost no other assumptions (do NOT assume Relativity).

Strongest limits from the highest-energy particles.

Accelerators have made electrons with 10^{11} eV energy.
LHC has made photons with a few times more energy.

Nature does better. 1.6×10^{13} eV photon in cosmic rays.
Electrons of 5×10^{13} eV inferred indirectly around pulsars.

10^{12} eV is the energy needed for a fly to do a pushup.

At 5×10^{13} eV, Relativity says electron should go at the speed of light, minus 0.5 meters/year.
If max speed of electrons is 0.5 meter/year faster than light, those electrons should have Cherenkov radiated and stopped.

Speed of light and maximum speed of electrons must be the same to within a few meters/year.

Can we do better?

What's the highest energy charged particle we've seen?

Cosmic rays – protons – have energies up to 10^{20} eV.
One seen in 1991 had energy 3×10^{20} eV.

Roughly, energy of a baseball pitch. But in a Single Particle!!

How fast was that proton moving?

Relativity says it would be moving at the speed of light,

minus 50 microns/millenium One hair's width per millenium

Suppose the max. speed of protons $> c$ by $>$ 50 micron/millenium.

Then the proton could Cherenkov radiate away energy.

Distance to lose 1/2 energy: 1 meter.

Distance to travel to Earth: size of galaxy$=10^{20}$ meters.

If the proton top-speed is $> c$ plus 50 micron/millenium,
proton would never make it to Earth with so much energy.

Protons have a maximum speed which is slower than, equal to, or at most 50micron/millenium faster than that of light.

What about neutrinos, though?

If neutrinos are *slower* than the proton, then the proton will emit *pairs* of neutrinos by a process analogous to (but more complex than) Cherenkov radiation.

Happens as soon as actual proton speed exceeds limiting neutrino speed. Therefore we place the limit:

The maximum speed of neutrinos is *at least* the speed of light, minus 50 microns/millenium.

Limiting faster-than light neutrinos is harder.

We have to delve into proton's structure!

A proton is not really "a" particle!

It's more like a bag of marbles!

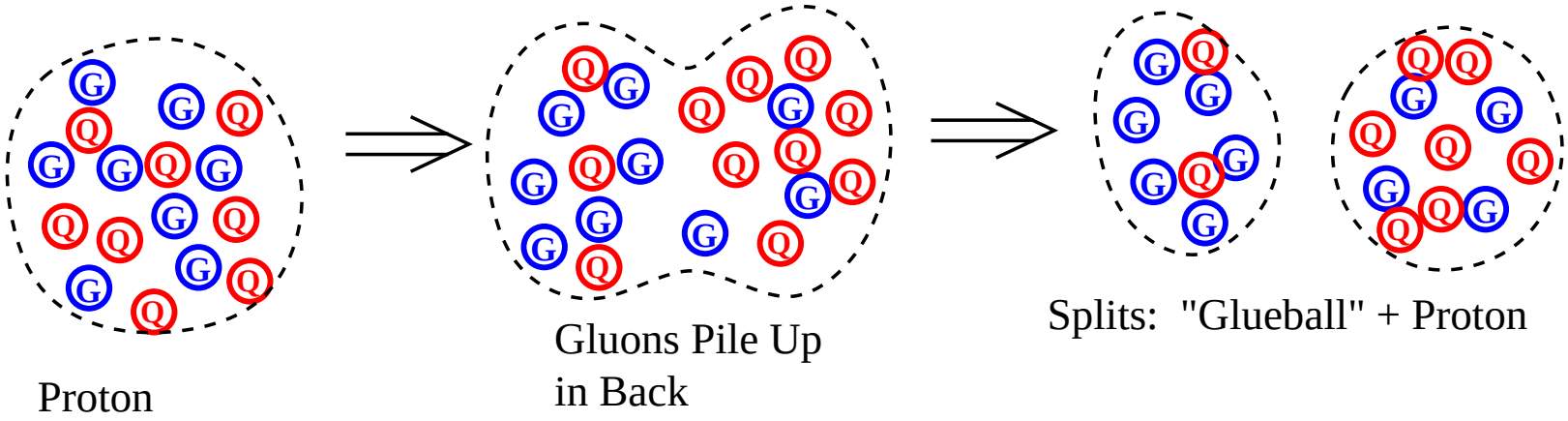
Size of bag: 10^{-15} meters. Types of "marbles": Quarks, Anti-Quarks, Gluons. 3 more Quarks than Anti-Quarks.

High-energy collisions open the bag, spilling marbles.

At Large Hadron Collider, average 30 fragments/collision.

Do Quarks, Gluons have same max. velocities?

If gluons are slower, they will "pile up" at the back of the proton. If enough slower – "bag" splits in two



Detailed calculation: how hard is it to pull proton in half?
Result: Proton split, therefore arrive with reduced energy, unless Quark, gluon velocities agree to ± 2 mm/century.

And Neutrinos?

Not quite all the "marbles" are Quarks and Gluons!!
The proton is:

- 49.2% Quarks, 45.4% Gluons
- 4% W,Z bosons, 1% photons
- 0.3% Higgs bosons (!!)
- 0.1% Neutrinos!

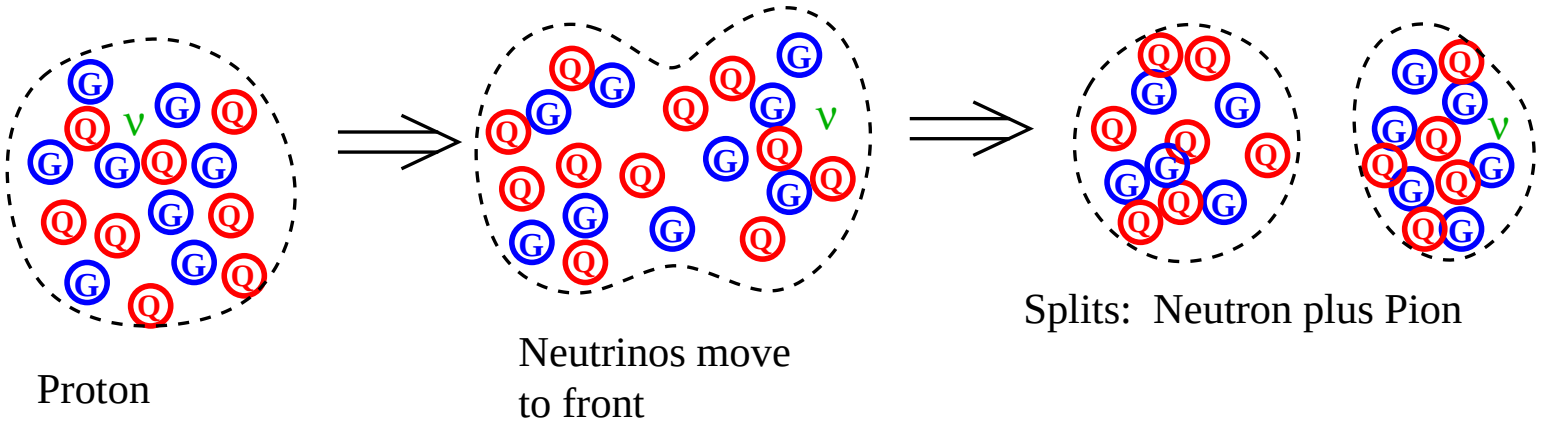
Other "bag of marbles" particles have different neutrino mixtures. Neutrons have slightly less (0.08%).

If neutrinos are faster than light, then protons are faster than neutrons.

Cherenkov Radiating a Neutron

Any time particle A has a higher maximum speed than particle B, then particle A can Cherenkov radiate particle B.

A proton can radiate away a neutron!



Very small neutrino content – velocity difference must be bigger to make this happen.

Detailed calculation

To pull a proton apart, neutrino velocity must be "significantly" larger than speed of light.

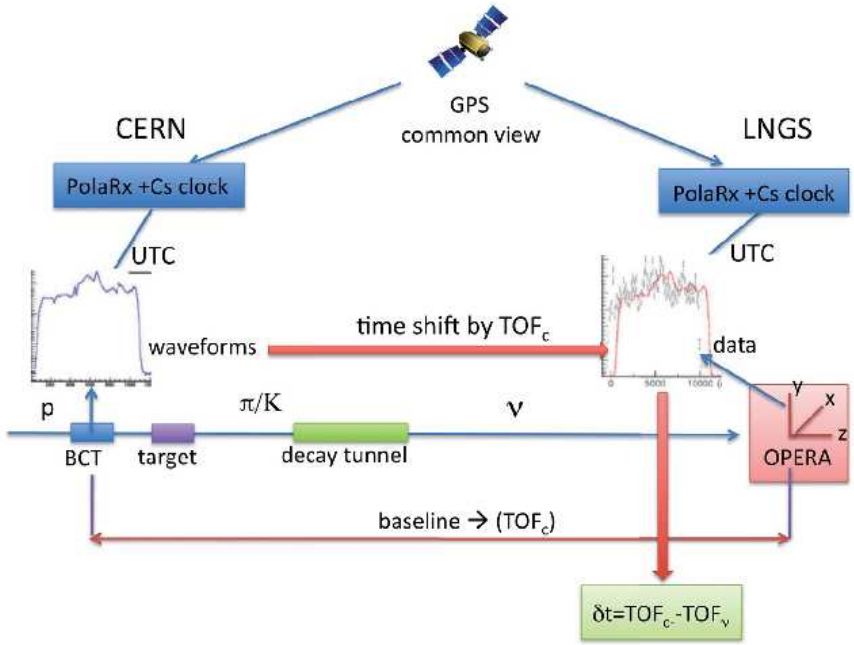
Significant compared to what?
To the speed difference of the proton and light.

Speed difference between proton and light was tiny, 50 microns/millenium. So limit on neutrino velocity is still pretty good:

Neutrinos can be faster than light by at most 4×10^{-20} times c, or 4 cm/century.

One step since the birth of Jesus

What about the OPERA result??



OPERA used GPS to synchronize clocks on the surface. Cables carried the clock signals underground where the experiments occurred.

first they measured the time delays caused by each cable.
then someone bumped something, knocking loose a cable
then they did the experiment.
The loose cable had a 60 nanosecond propagation delay.

NATURE | NEWS

Neutrinos not faster than light

ICARUS experiment contradicts controversial claim.

Geoff Brumfiel

16 March 2012 Corrected: 19 March 2012

Neutrinos obey nature's speed limit, according to new results from an Italian experiment. The finding, posted to the preprint server arXiv.org, contradicts a rival claim that neutrinos could travel faster than the speed of light.

The ICARUS detector in Gran Sasso, Italy, has confirmed that neutrinos travel no faster than the speed of light.
INFN GRAN SASSO NATIONAL LABORATORY

Neutrinos are tiny, electrically neutral particles produced in nuclear reactions. Last September, an experiment called OPERA turned up evidence that neutrinos travel faster than the speed of light (see 'Particles break light speed limit'). Located beneath the Gran Sasso mountain in central Italy, OPERA detected neutrinos sent from CERN, Europe's premier particle-physics laboratory near Geneva, Switzerland. According to the group's findings, neutrinos made the 731-kilometre journey 60 nanoseconds faster than predicted if they had travelled at light speed.

The announcement made international headlines, but physicists were deeply sceptical. The axiom that nothing travels faster than light was first formulated by Albert Einstein and is a cornerstone of modern physics. OPERA defended its announcement, saying that it could find no flaw in its measurement.

Now another experiment located just a few metres from OPERA has clocked neutrinos travelling at roughly the speed of light, and no faster. Known as ICARUS, the rival monitored a beam of neutrinos sent from CERN in late October and early November of last year. The neutrinos were packed into pulses just 3 nanoseconds long. That meant that the timing could be measured far more accurately than the original OPERA measurement, which used 10-microsecond pulses.

NATURE NEWS BLOG

Leaders of faster-than-light neutrino team resign

30 Mar 2012 | 15:54 GMT | Posted by Eugenie Samuel Reich | Category: Physics & Mathematics, Policy

A month after revealing errors in their high-profile claim that subatomic neutrinos had been clocked traveling faster than the speed of light, two leaders of the Italian OPERA collaboration have resigned. Both spokesman Antonio Ereditato of the University of Bern in Switzerland and physics coordinator Dario Autiero of Lyon's Institute of Nuclear Physics in France, who presented the stunning result in September 2011 to a packed auditorium at CERN (pictured), sent out resignations today.

Autiero says that both men have been concerned about the existence of a large split within OPERA's 170-strong collaboration, and want to make way for an alternative leadership that can provide more unity. Ereditato, reached by phone, says firmly, "my comment is no comment."

OPERA had clocked neutrinos traveling 730 kilometres from CERN near Geneva, Switzerland, to Gran Sasso National Laboratory near L'Aquila, Italy, finding that they arrived 60 nanoseconds faster than a light beam would do. This seemed to conflict with Einstein's Special Theory of Relativity, which bans faster-than-light travel. But a subsequent investigation of the experiment's systematics revealed a troublesome cable and timing device that cast doubt on the certainty of the result. OPERA still plans to repeat its measurement in May with the goal of quantifying the effect of its errors.

Autiero denied that he was stepping down because of mistakes in the measurement, saying that the discovery of an unknown systematic error is an inevitable hazard for any scientist doing a precision measurement. "In science you cannot pretend to be the owner of any absolute truth," he says. Instead, he says that he and Ereditato felt that tensions that had always existed within OPERA were becoming impossible to bridge. He acknowledges that these were exacerbated by the publication of the provocative result, with some complaining from the beginning that the findings were likely to be wrong. He also agrees that the spectacular degree of media attention has brought

Speeds, Compared using a Logarithmic Scale: