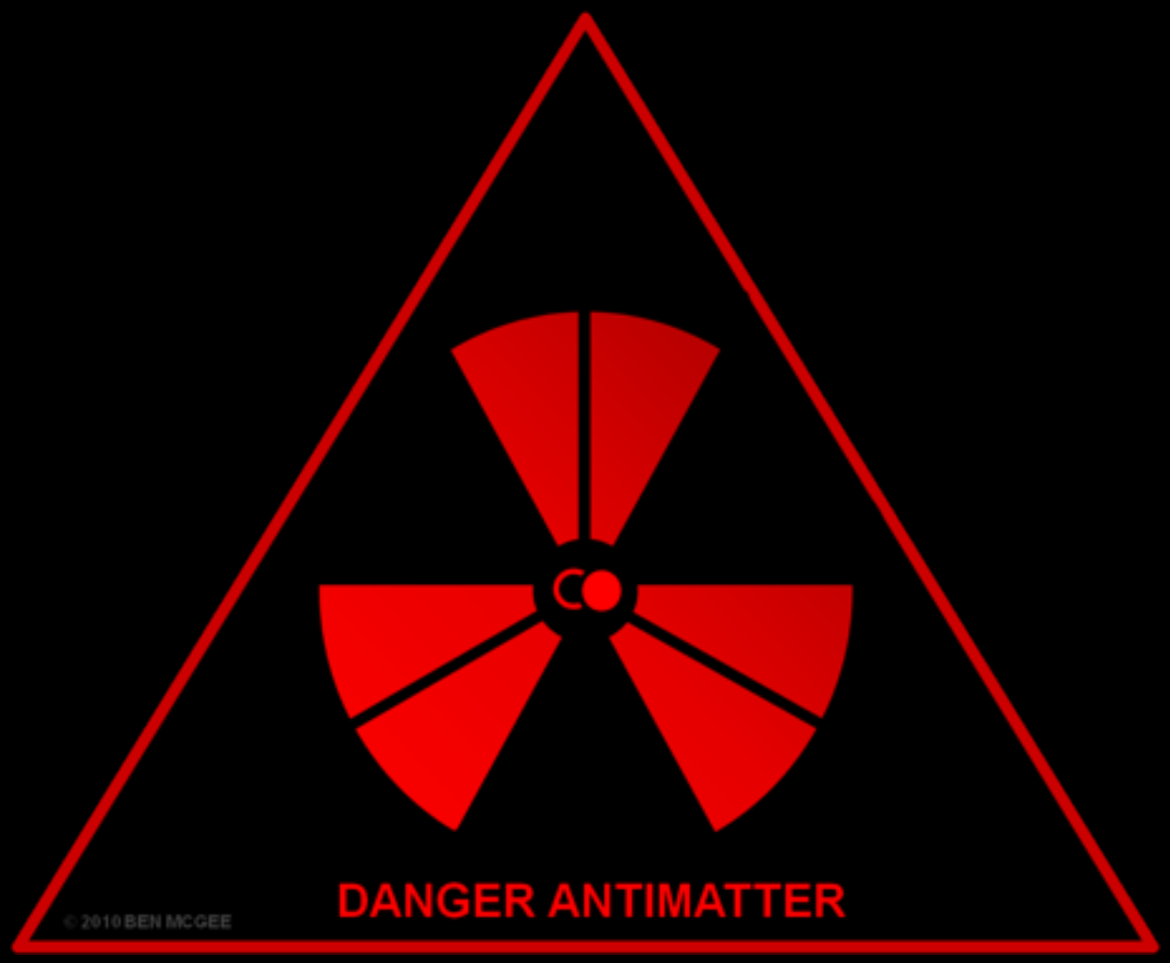
INSTITUTE OF PARTICLE PHYSICS

What's the matter with antimatter?

H.A. Tanaka (UBC/IPP)

TRIUMF Saturday Morning Lectures
23 November, 2013

On the web:


DANGER ANTIMATTER
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ANTIMATTER
10


Searching for
UNLIMITED
POWER

What's the big deal?

- Energy and (anti) matter
- What is antimatter?
- What's the big deal about it?
- Current research into antimatter
  - what distinguishes matter from antimatter?
  - why is there so little antimatter around us?
  - why do we exist?
  - what are we doing at TRIUMF to understand this better?

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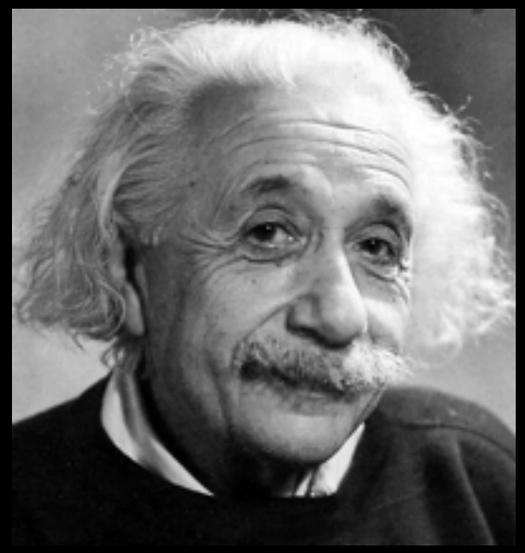

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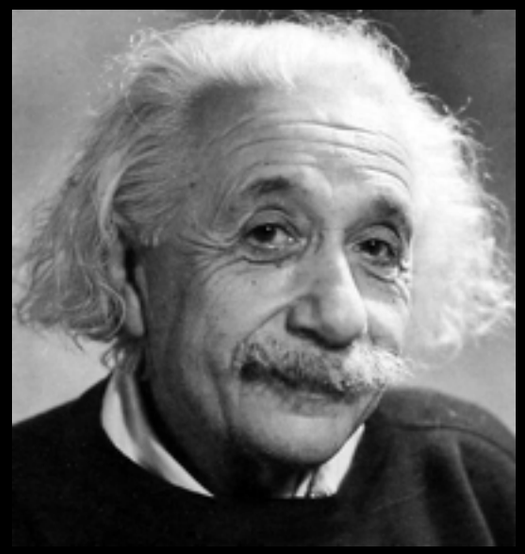

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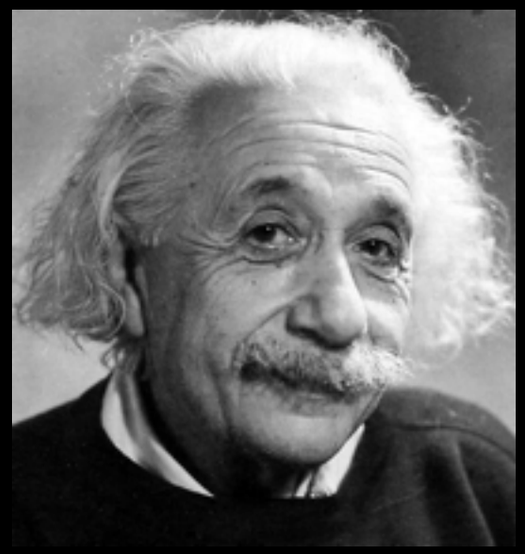

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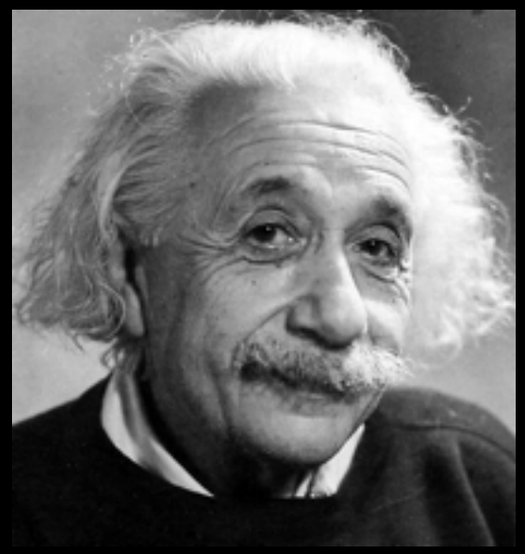

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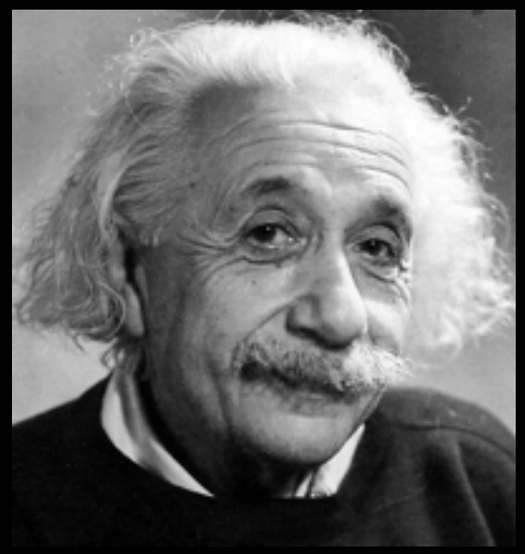

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  - some illustrations . . . . .

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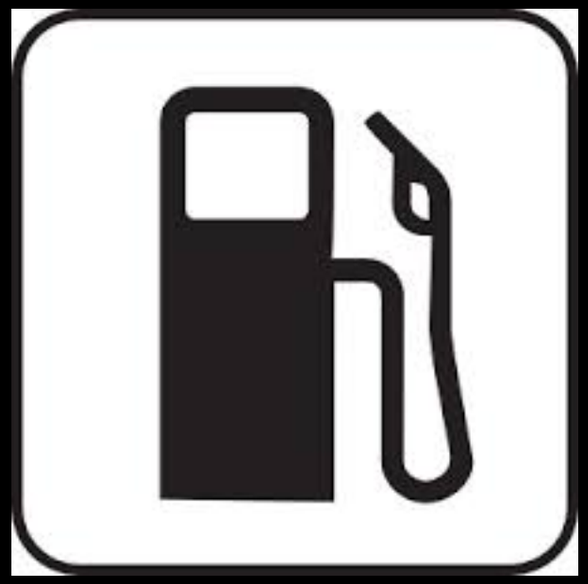

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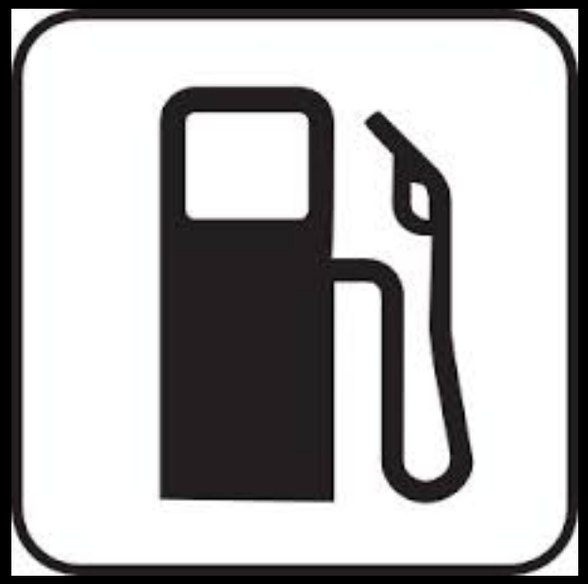

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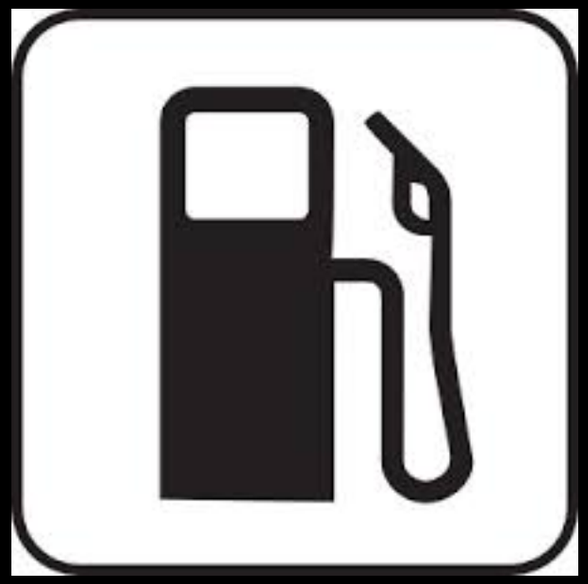

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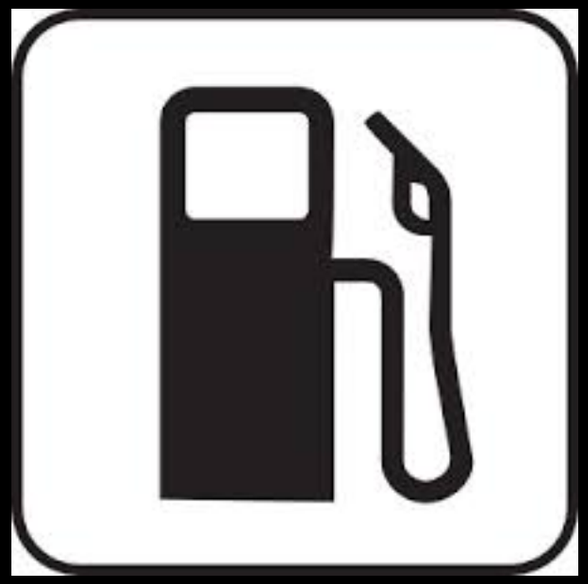

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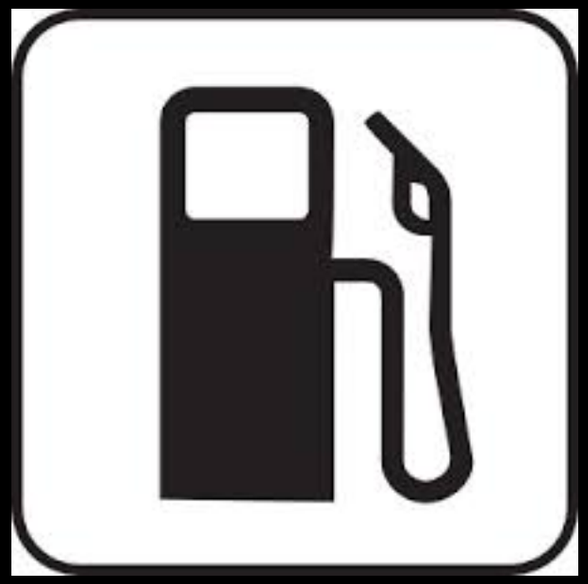

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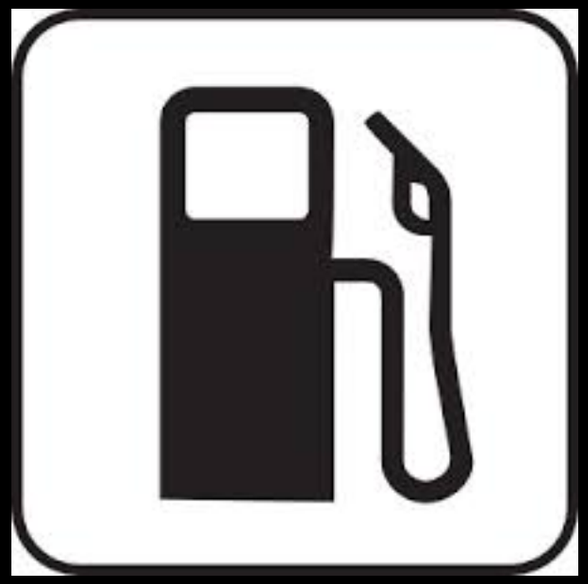

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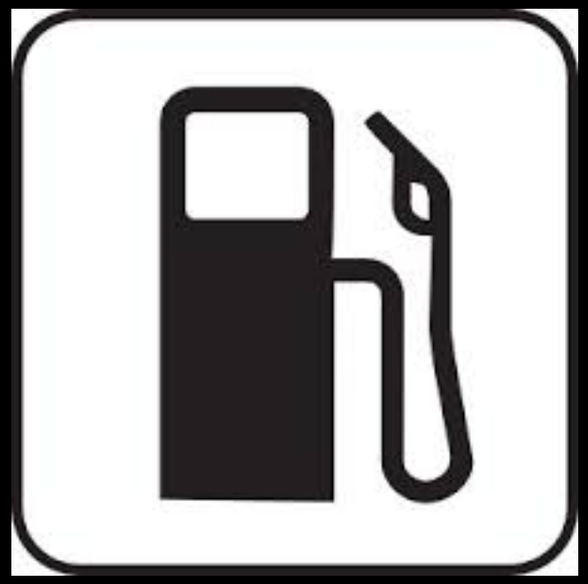

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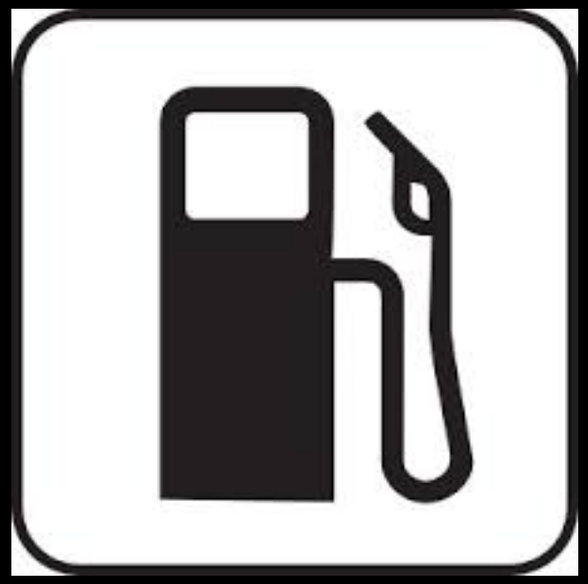

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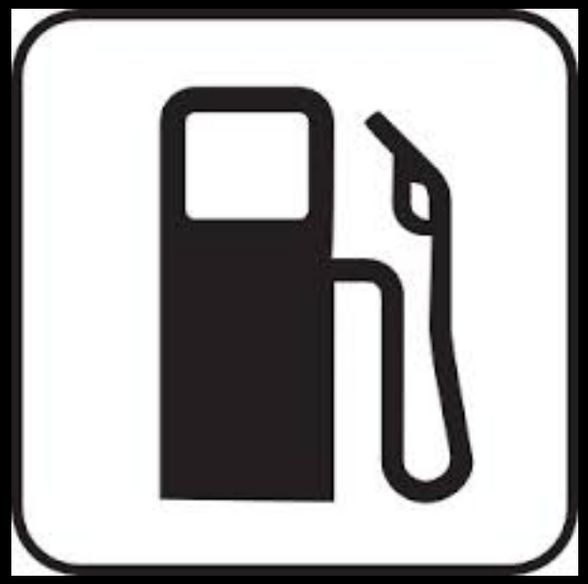

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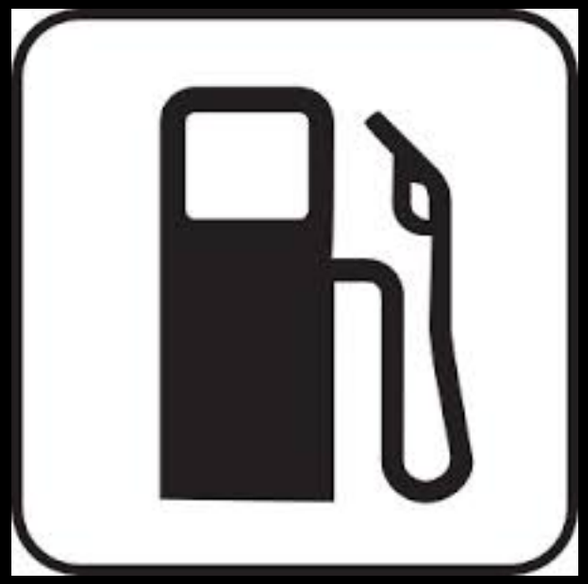

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T1-class "ultra large crude carrier" 6x larger than the largest aircraft carriers

Energy Production

- 1 kg of ^{235}U produces 83,140,000 MJ of energy
  - primary fuel of nuclear reactors
- Bruce Power Generating Station
  - (2nd largest in world)
  - 6,700 MW = MJ/sec
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1 kg of matter contains 10% of the annual output of Bruce Power Generating Station

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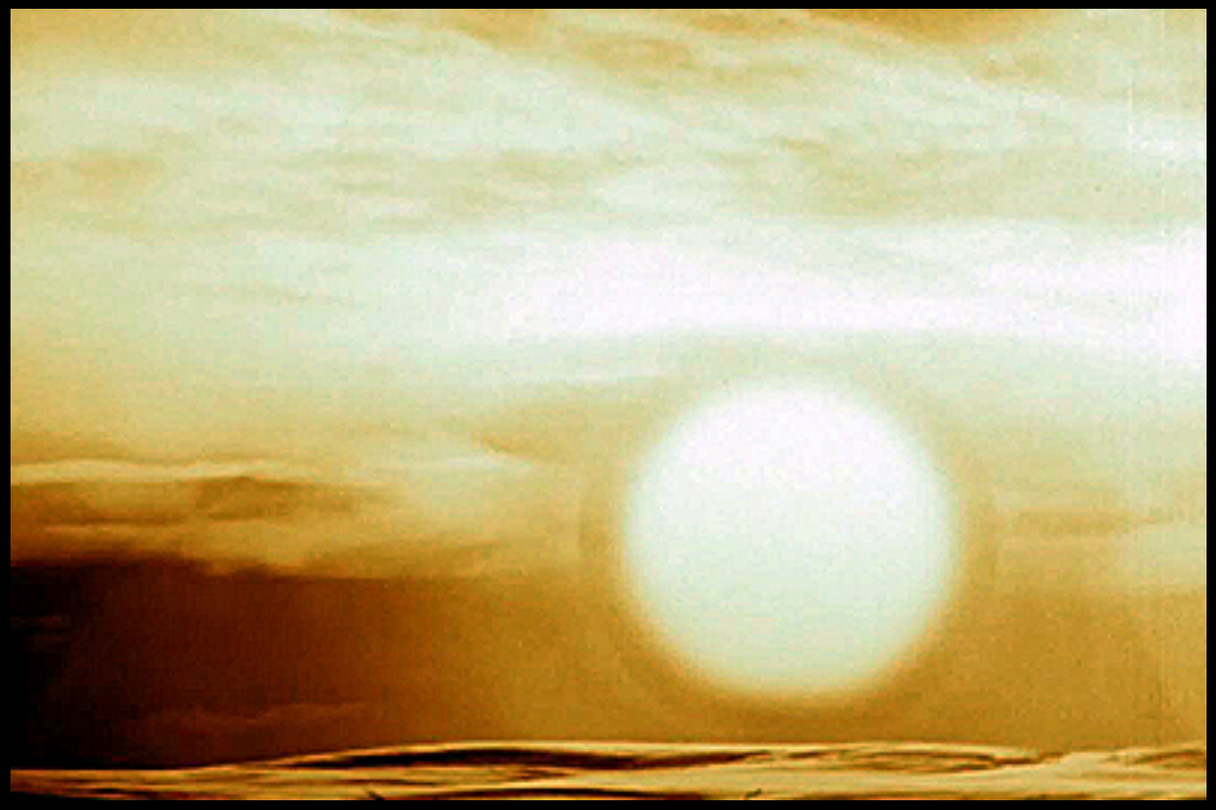

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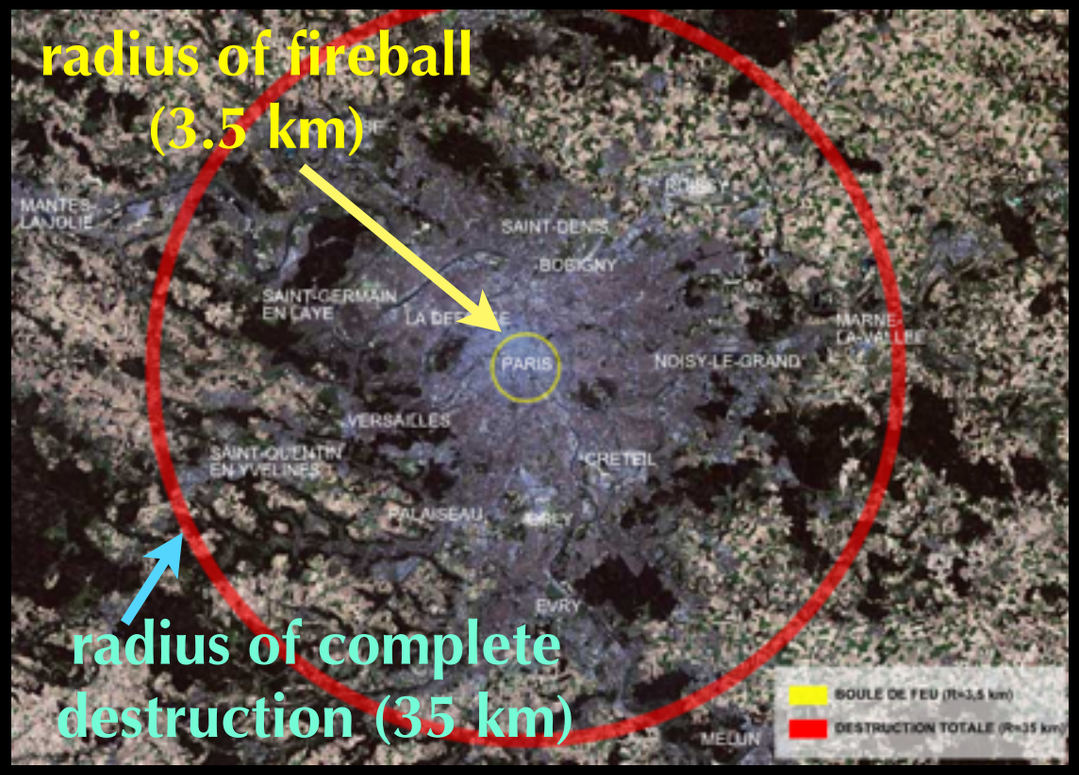

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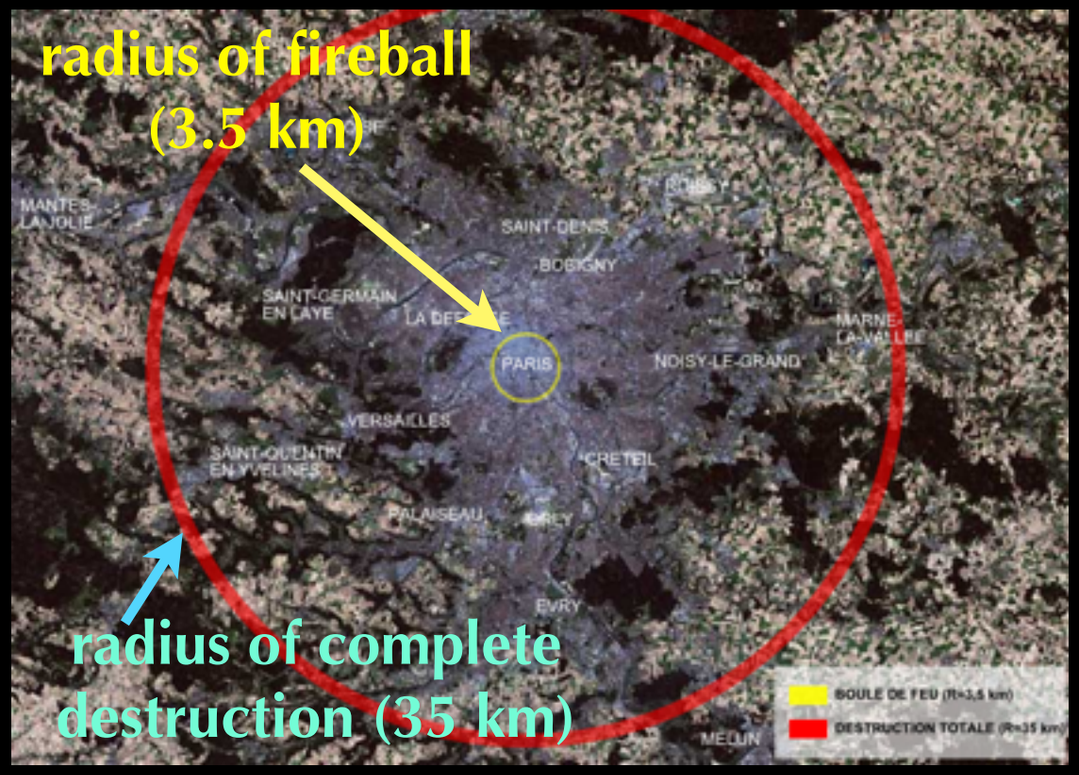
8.1 on the Richter scale



So what?

- Can we tap into this energy?
- In principle yes, but there are some fundamental issues that make it less than straightforward . . .

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- Energy conservation allows transformations between all forms of energy so long as the total is the same

Aside . . .

- There is a profound connection between "symmetries" and conservation laws
  - symmetry: transformation that leaves laws of physics unchanged
- Symmetries of space and time:
  - time ↔ energy conservation
  - space ↔ momentum conservation
  - rotation ↔ angular momentum conservation
- Other "quantum" symmetries give rise electric charge conservation
  - there are other forms of "charge" conservation

- Noether's symmetry
  - symmetries in law of physics ↔ conserved quantity

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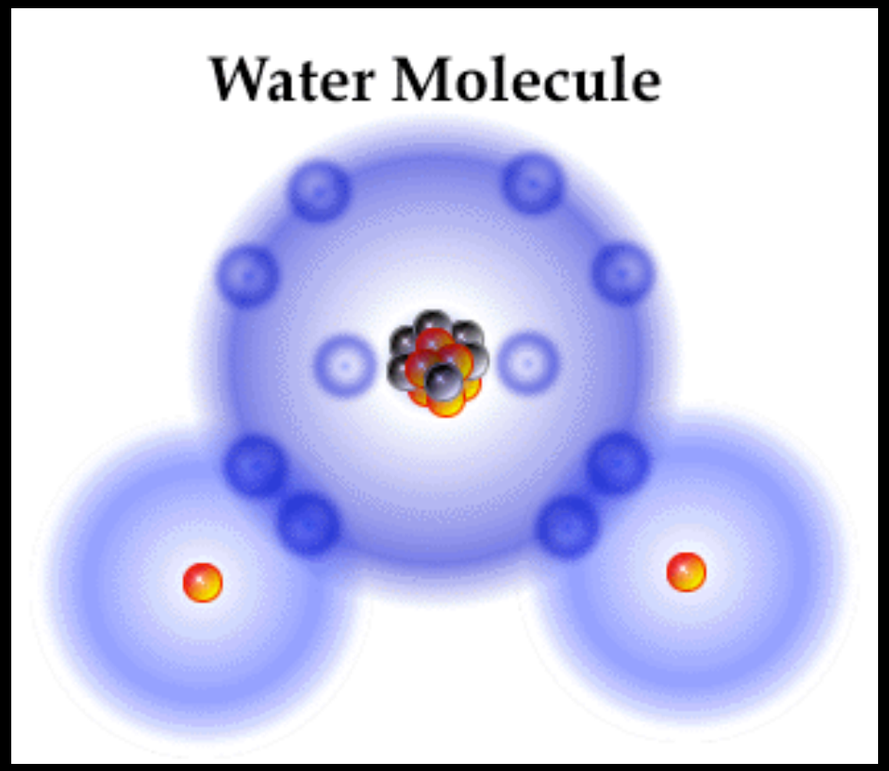

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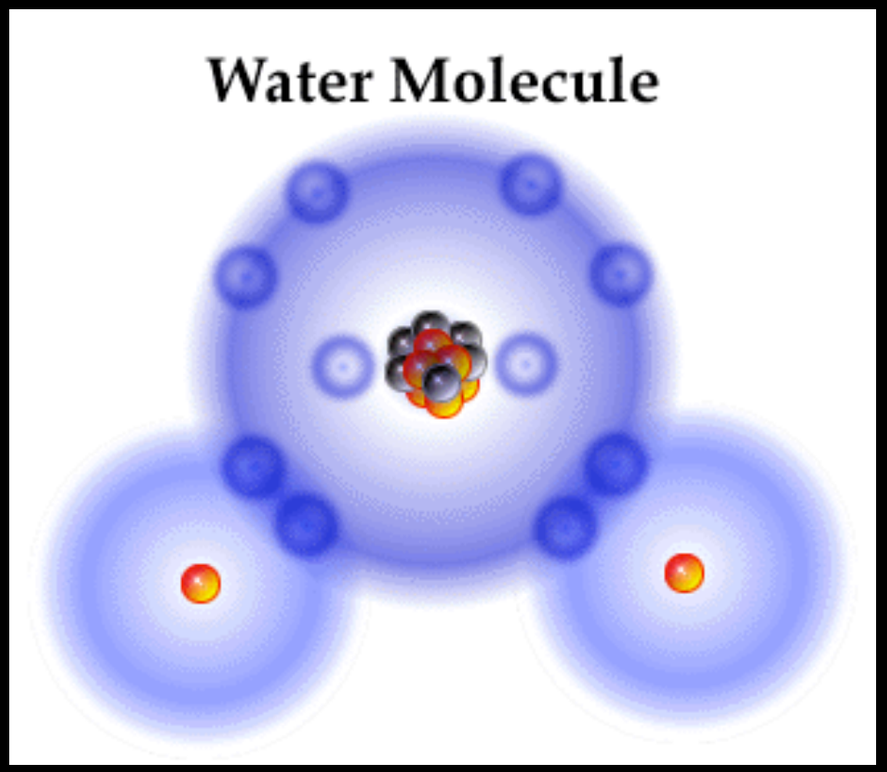

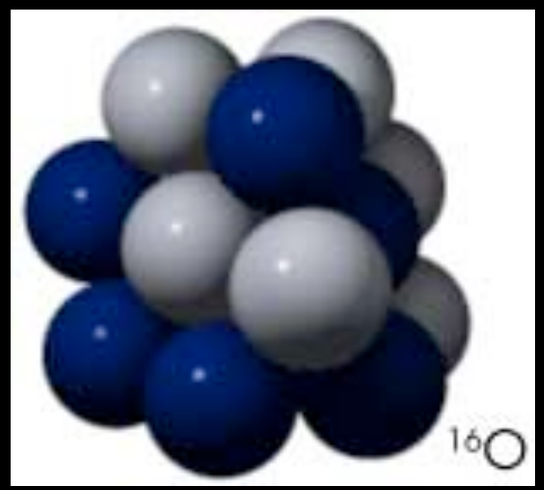

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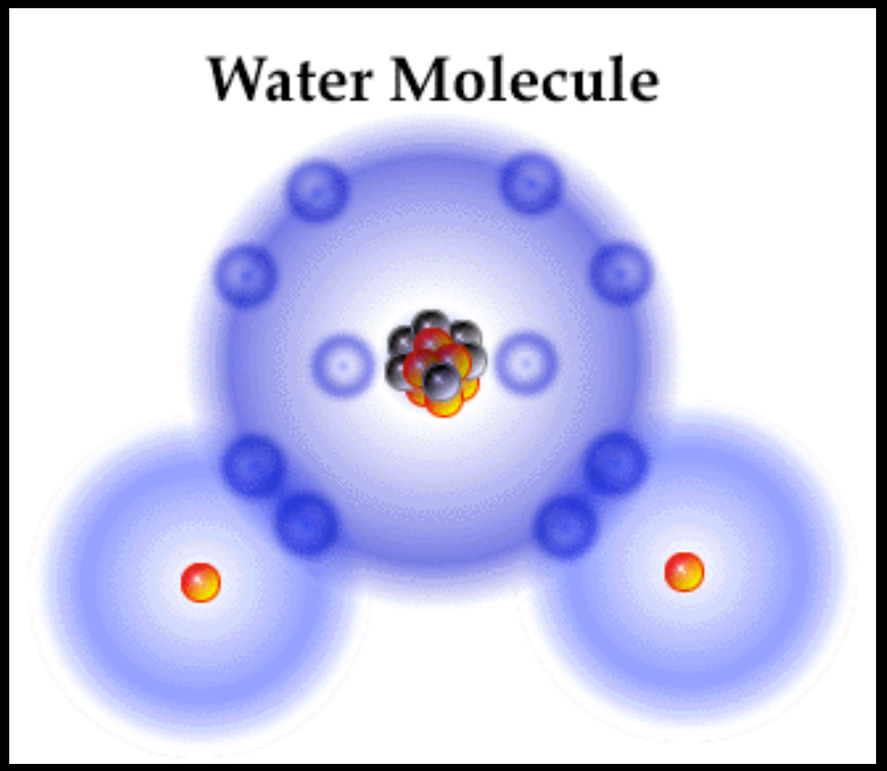

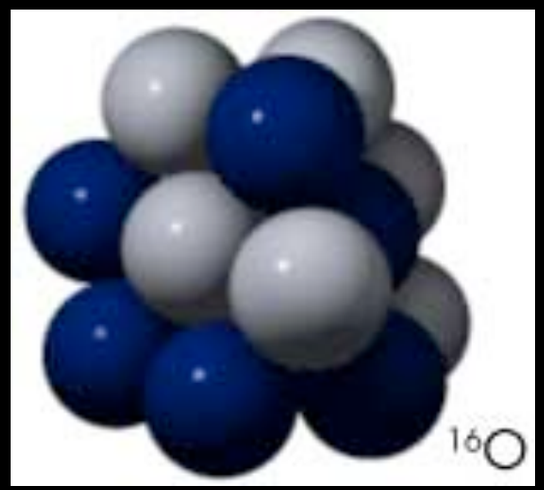

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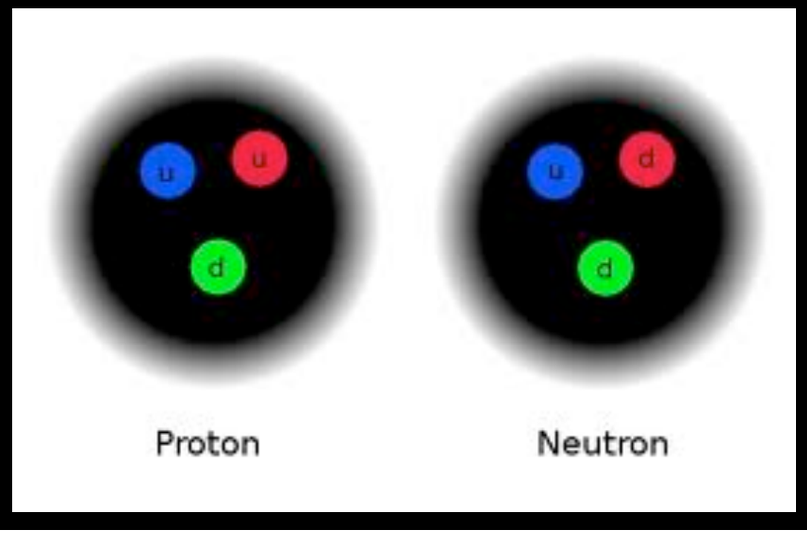

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- Protons/neutrons are ~2000 times more massive then an electron
  - hence "baryon" and "lepton"
  - fundamental distinction:
    - baryons consist of three quarks, leptons are fundamental particles which do not interact via the strong interaction

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TNT

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    - +1 charge (rather than -1)
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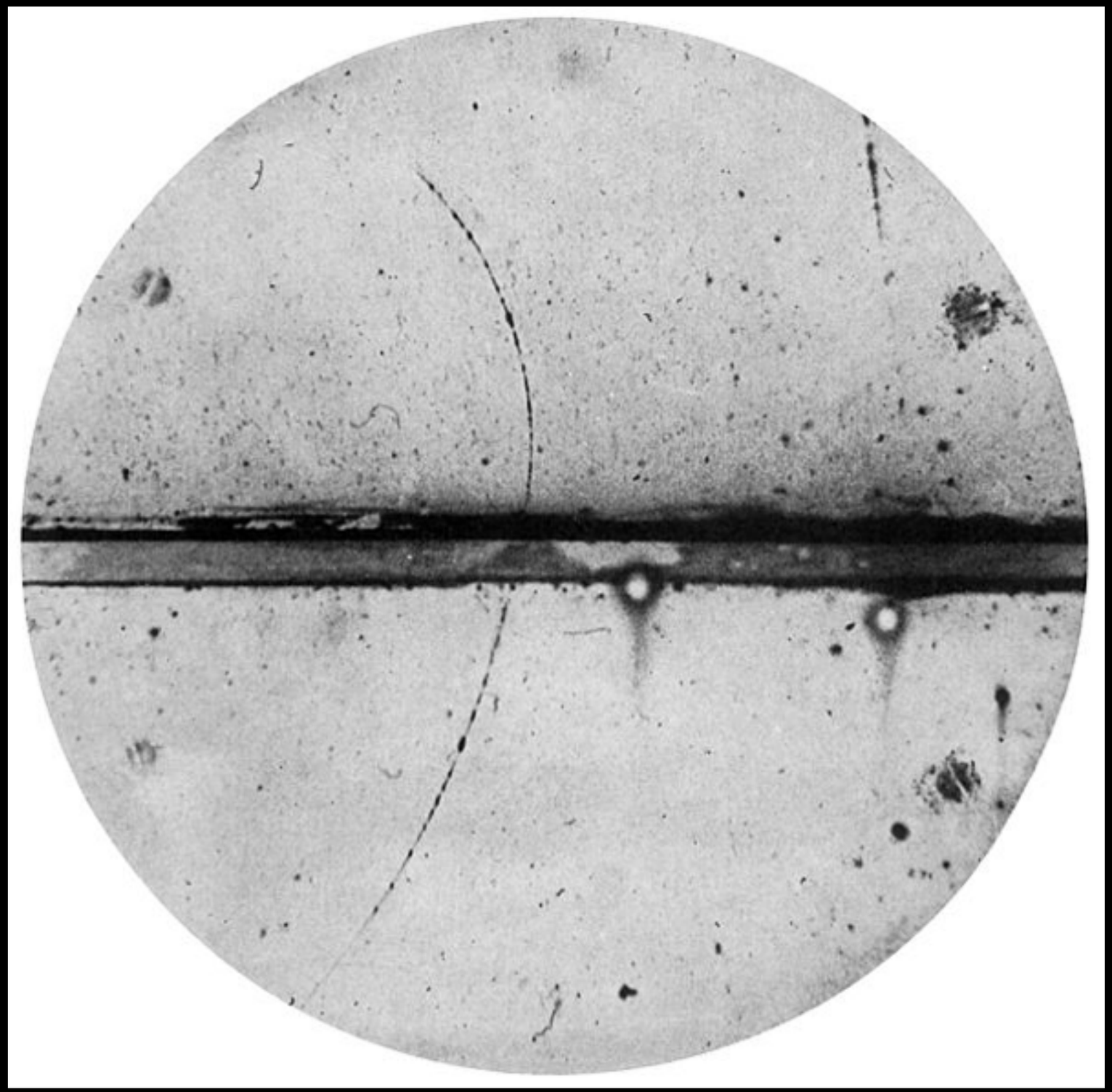
- Antimatter is "stuff" comprised of antiparticles

Do such things exist?



- First evidence for the existence of antimatter (1932)
- particle that looks just like an electron, but has opposite charge

A Loophole

- The fact that antiparticles have opposite charge and baryon/lepton number allow the following reactions:
- $e^+ + e^- \rightarrow$ energy
  - lepton number zero before/after reaction
- $p + \bar{p} \rightarrow$ energy
  - baryon number zero before/after reaction

- "Reverse" reactions also possible: e.g.
  - light (energy) $\rightarrow e^+ + e^-$

Examples:

- Top:
  - energy (light) coming in and producing $e^+ + e^-$ pair
- Right:
  - "shower" induced by alternating release of energy (light) and subsequent conversion to $e^+ + e^-$ pairs

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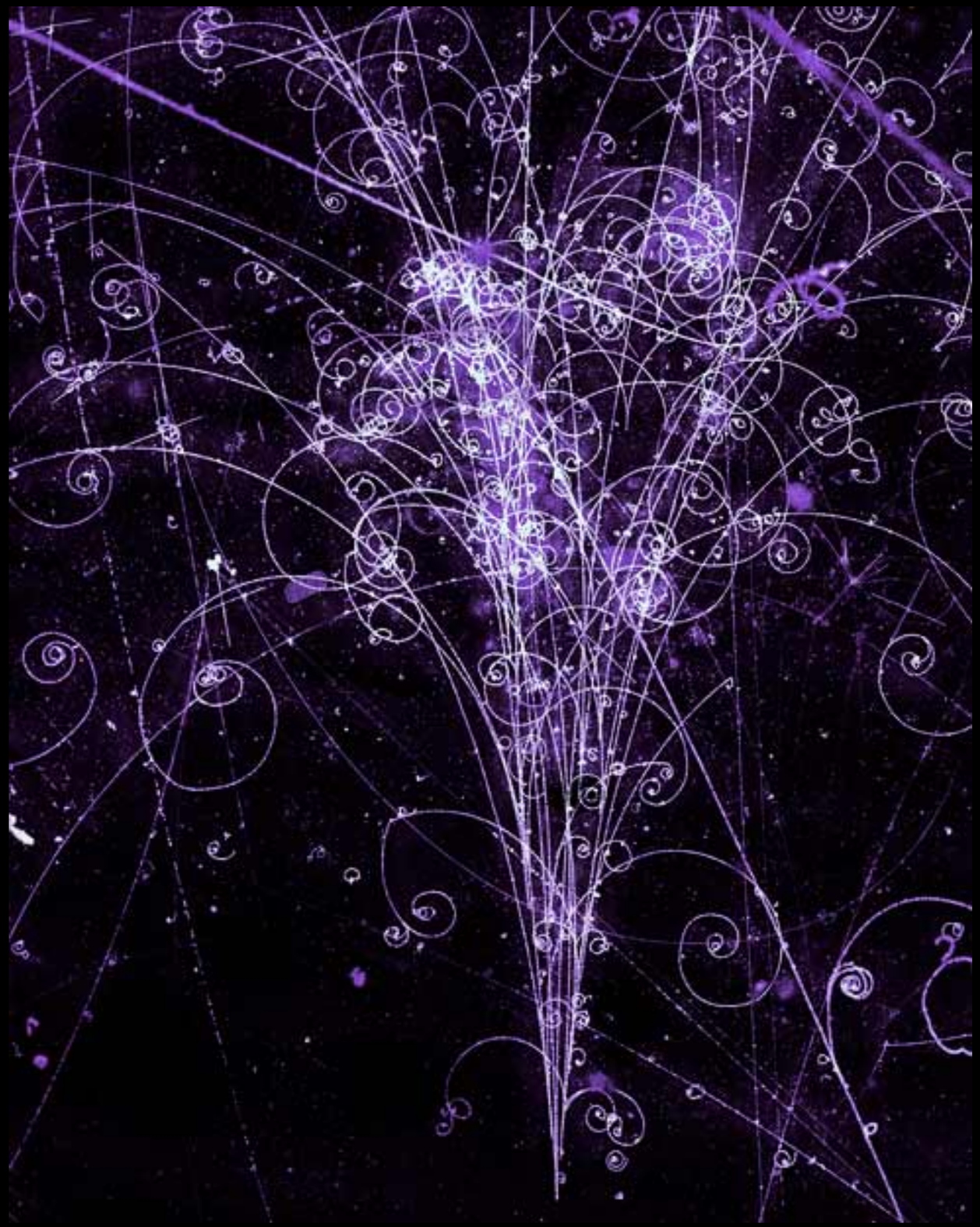

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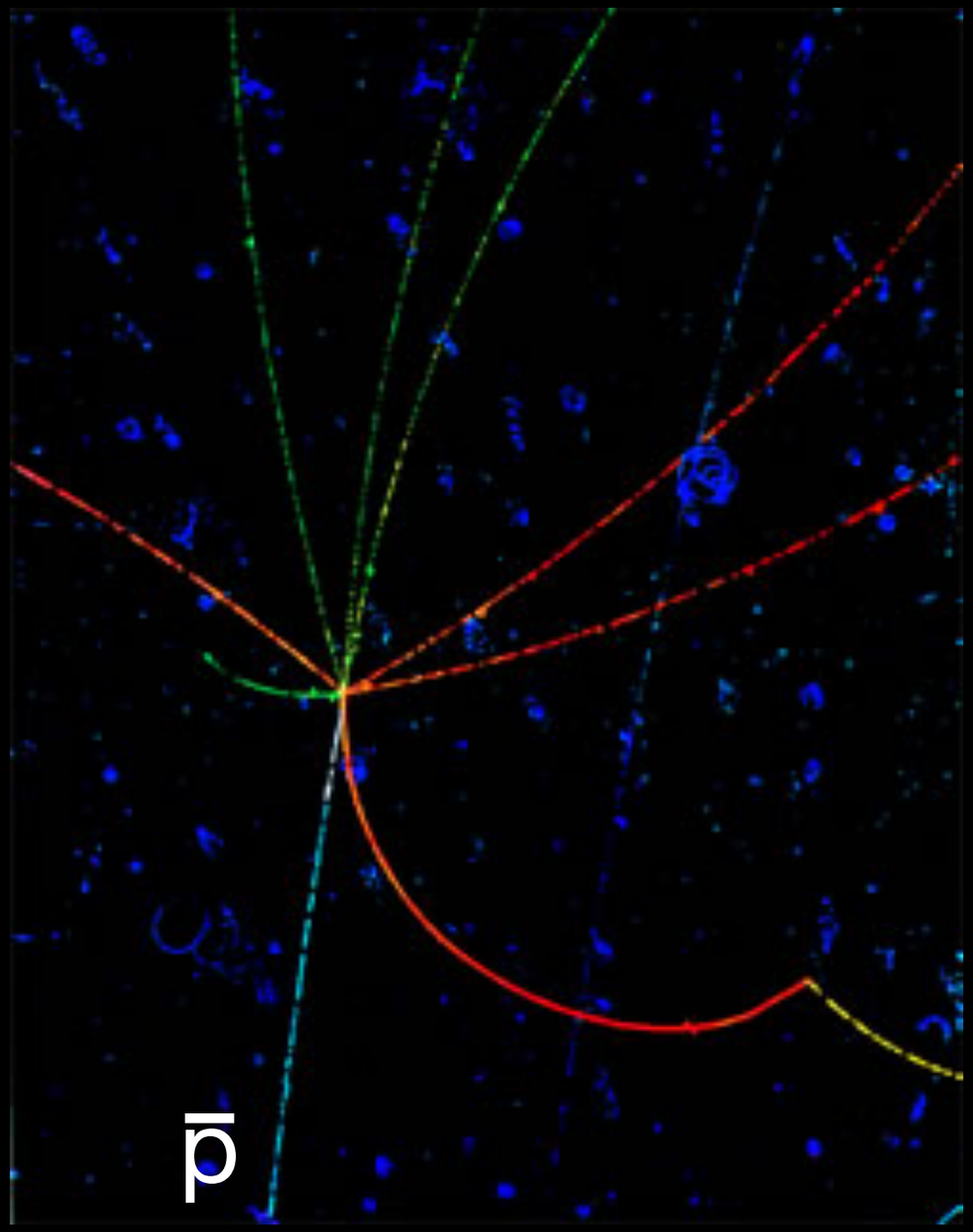
Examples: antiproton



- antiprotons produced by accelerator annihilating with proton in hydrogen to produce “star” of light particles

"Applications"

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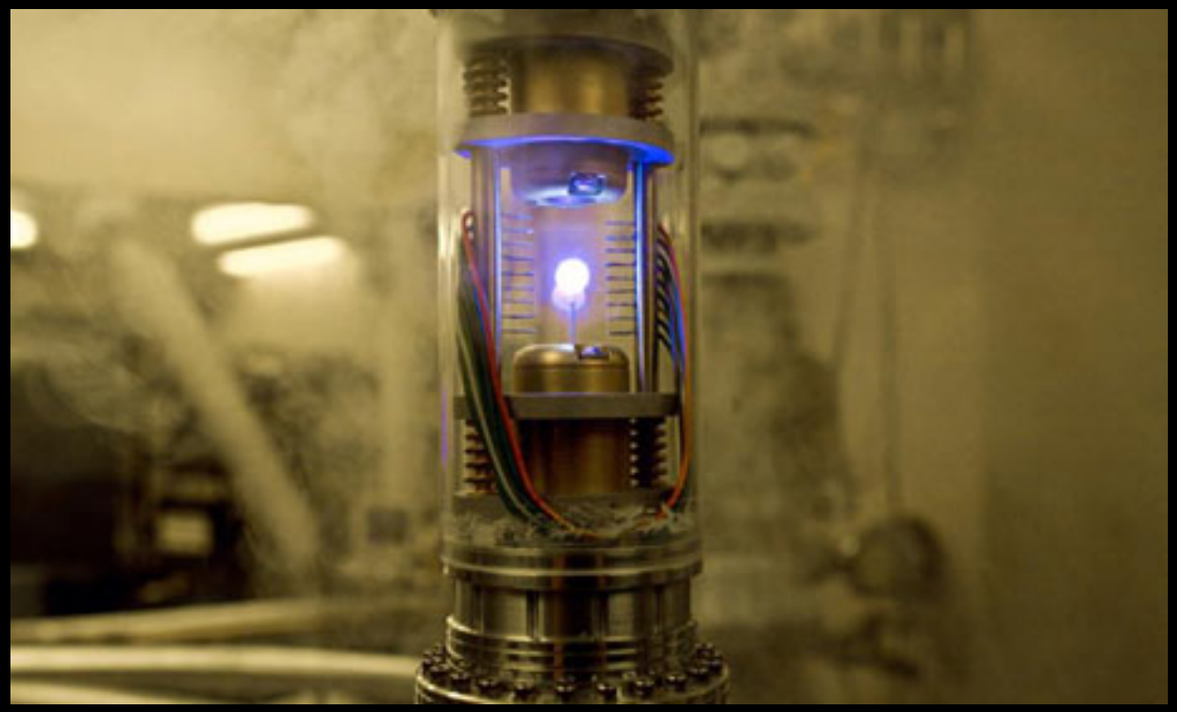

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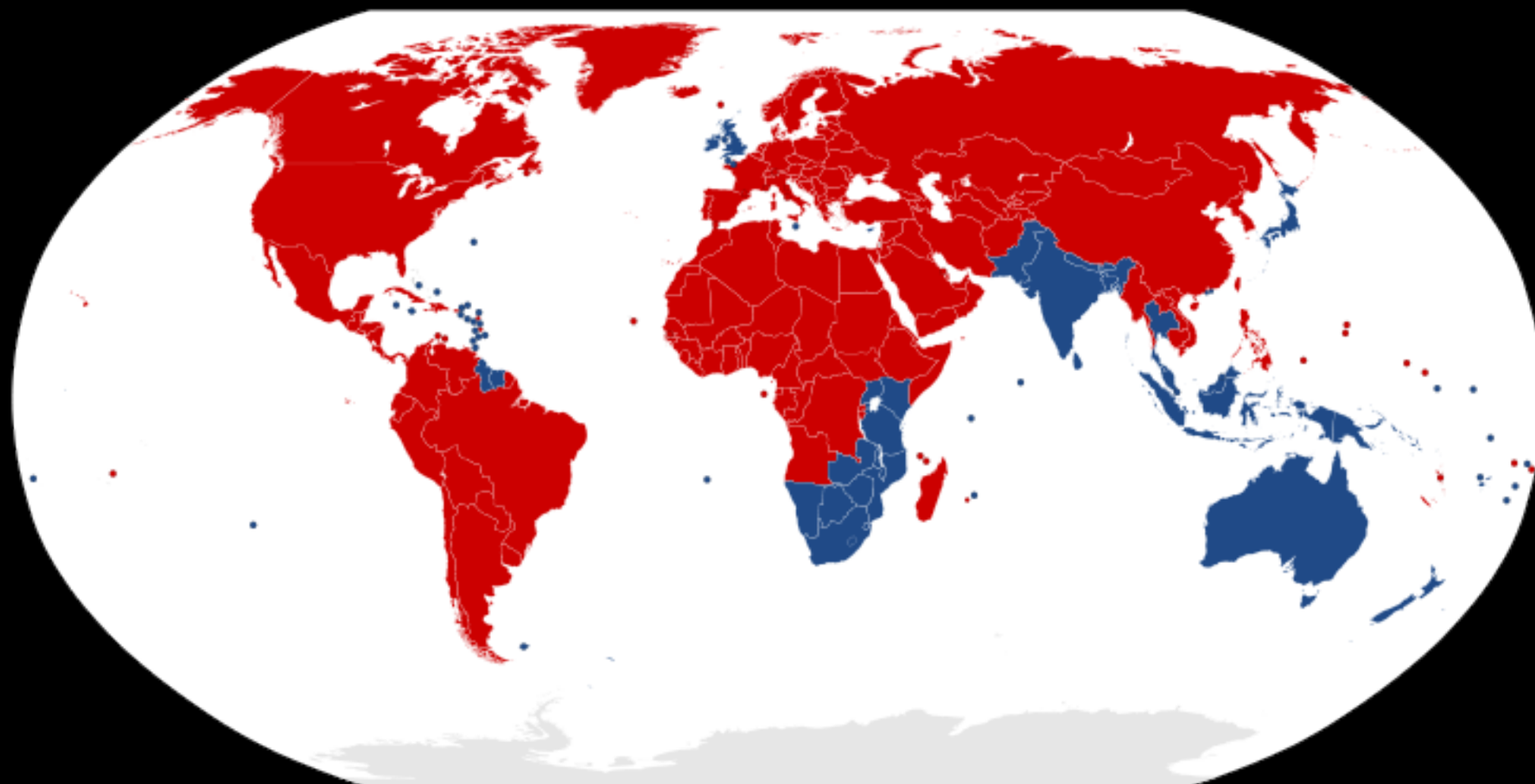
- We have talked about matter having positive baryon/lepton number, antimatter having negative but:
  - the essential point is that they are “opposite”
  - “opposite” is a relative
  - it would be exactly the same if it were the other way around.

Left vs. Right



- In some countries (red), one drives on the right side of the road
- In others (blue), on drives on the left side of the road
- All is fine as long as one stays within one colour
  - but if a left-side driver drives on the left in right-side country (or vice versa) there will be some problems

“Symmetry Breaking”

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Likewise, a bit of antimatter is very much out of place in a world full of matter.

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  - genetics?
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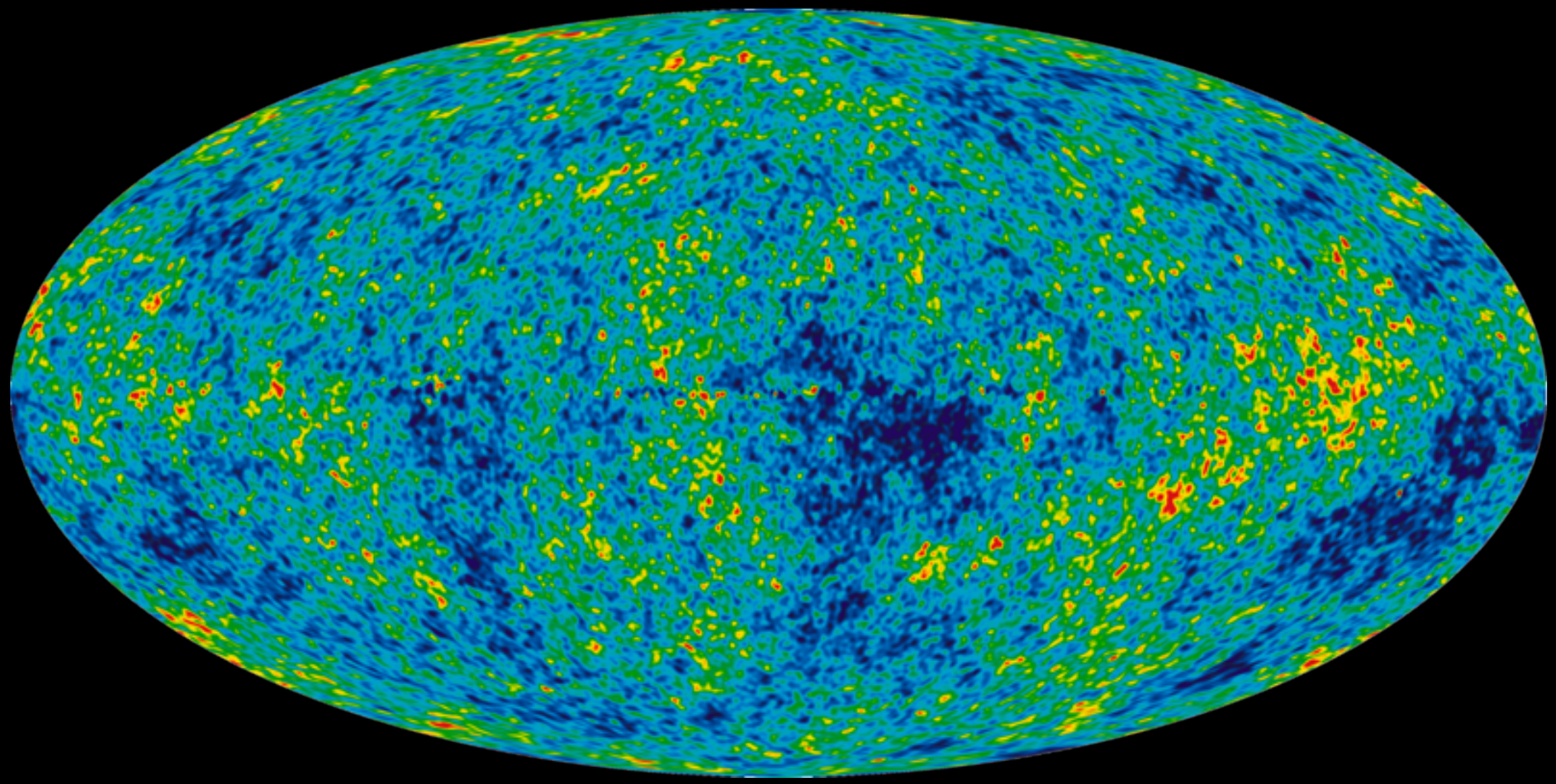
- Likewise, we have a very poor understanding of why our universe is dominated by matter
  - Big Bang: conversion of energy → matter + antimatter
  - what happened to all the antimatter?
    - why would the fate of matter be different any different then antimatter?
    - if we created matter/antimatter equally, why does anything exist?

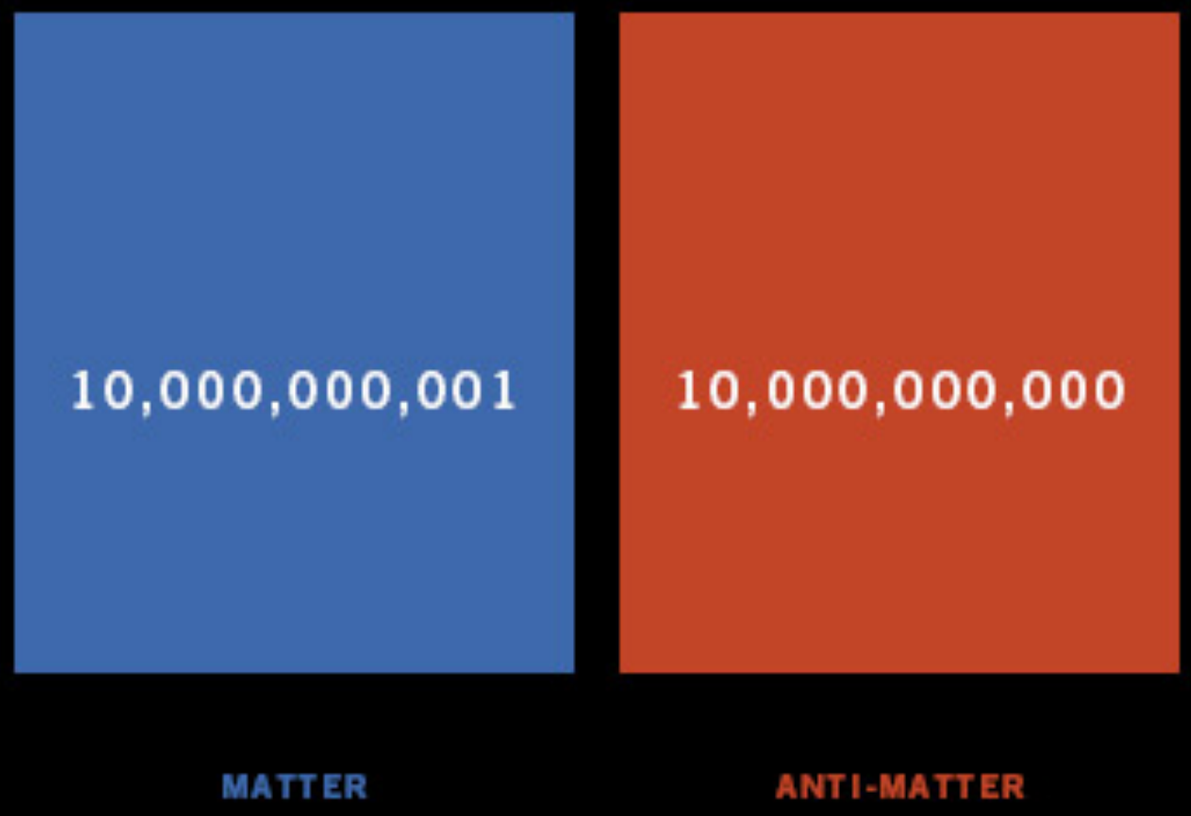

LOST PROPERTY
"Sorry Doc, we had a load of Anti-Matter around 13 billion years ago, but it got lost when we moved"

The imbalance



- The Cosmic Microwave Background:
  - light left over from the primordial processes following the big bang including matter/antimatter annihilations

A cosmic



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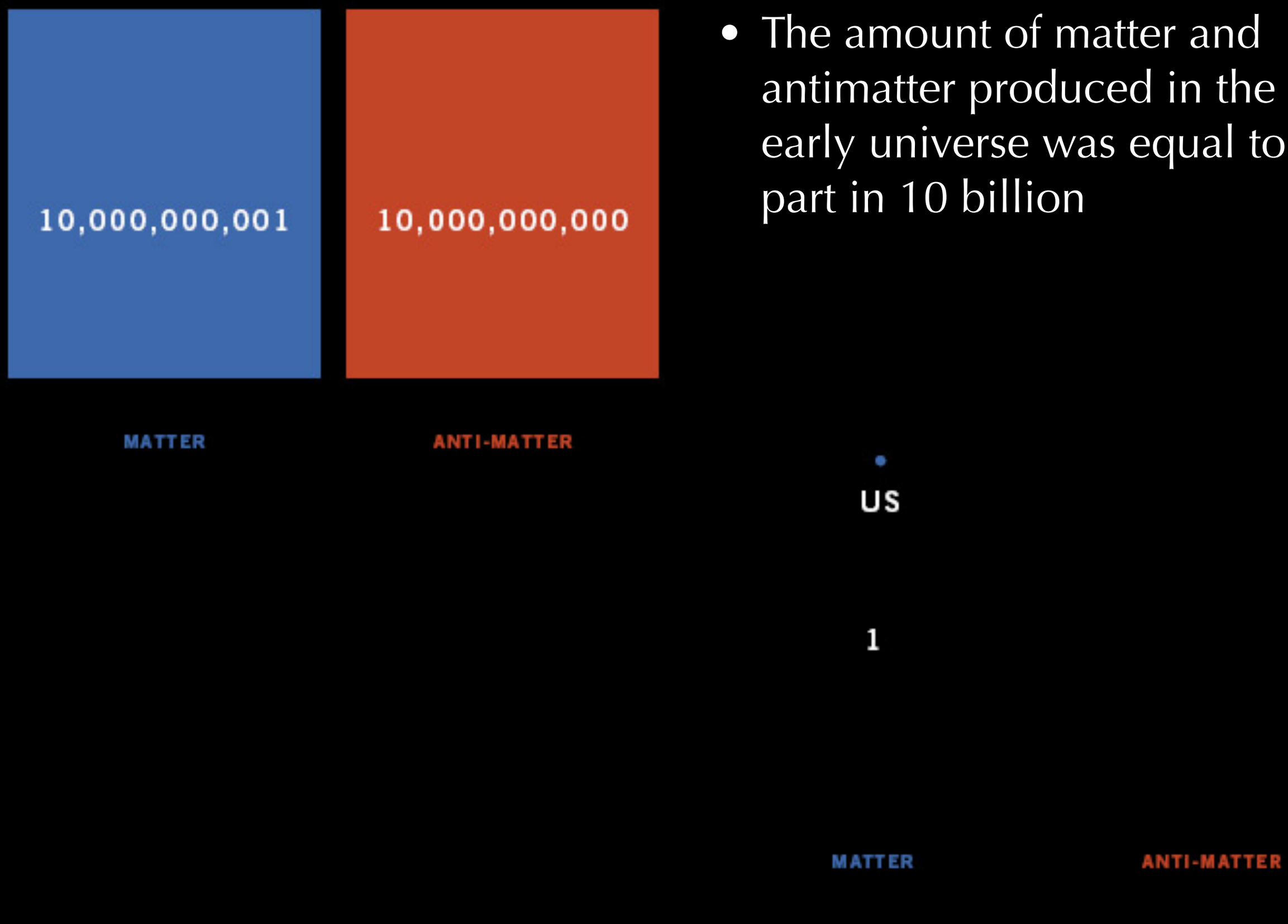

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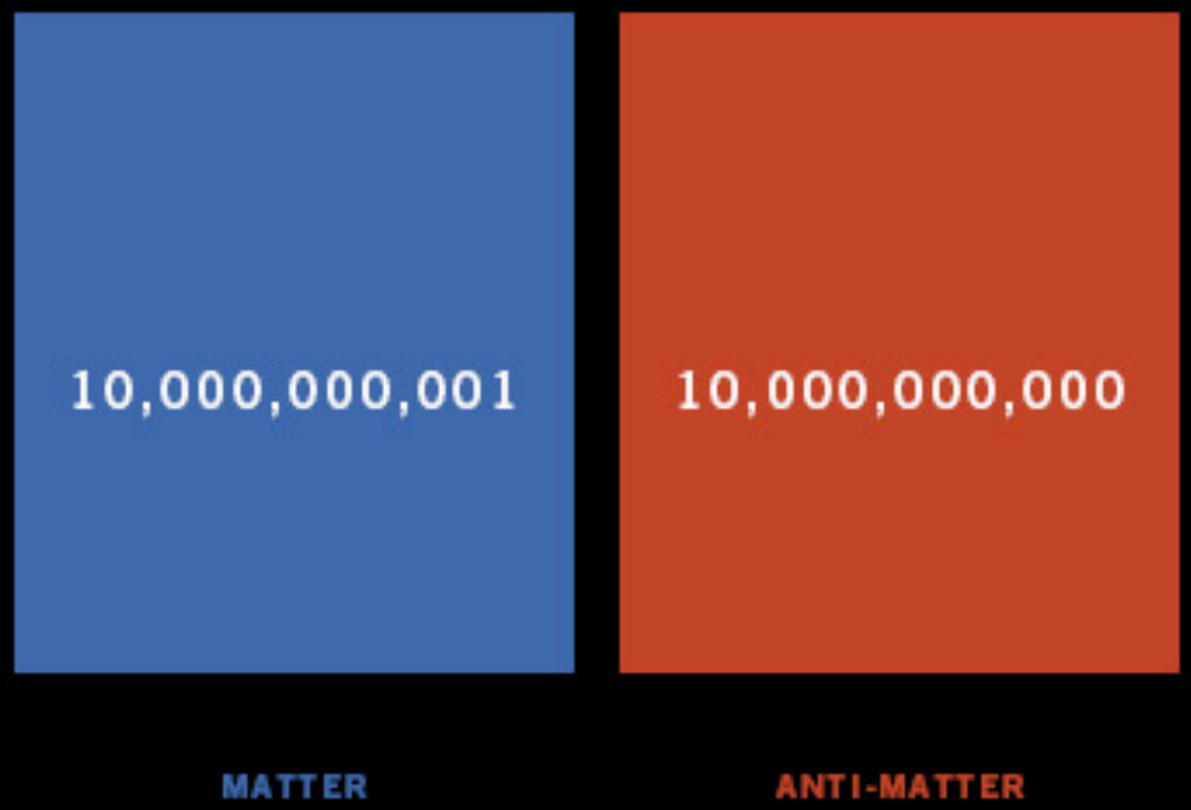

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- The extremely tiny imbalance left behind a bit of matter
- This is all the matter we see in the Universe
- How did this happen?

matter vs. antimatter revisited

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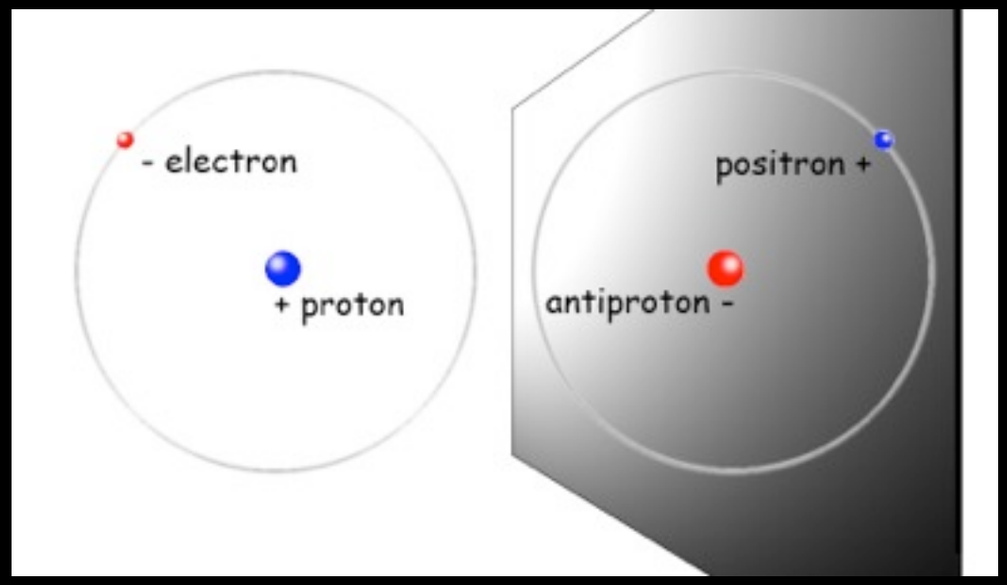
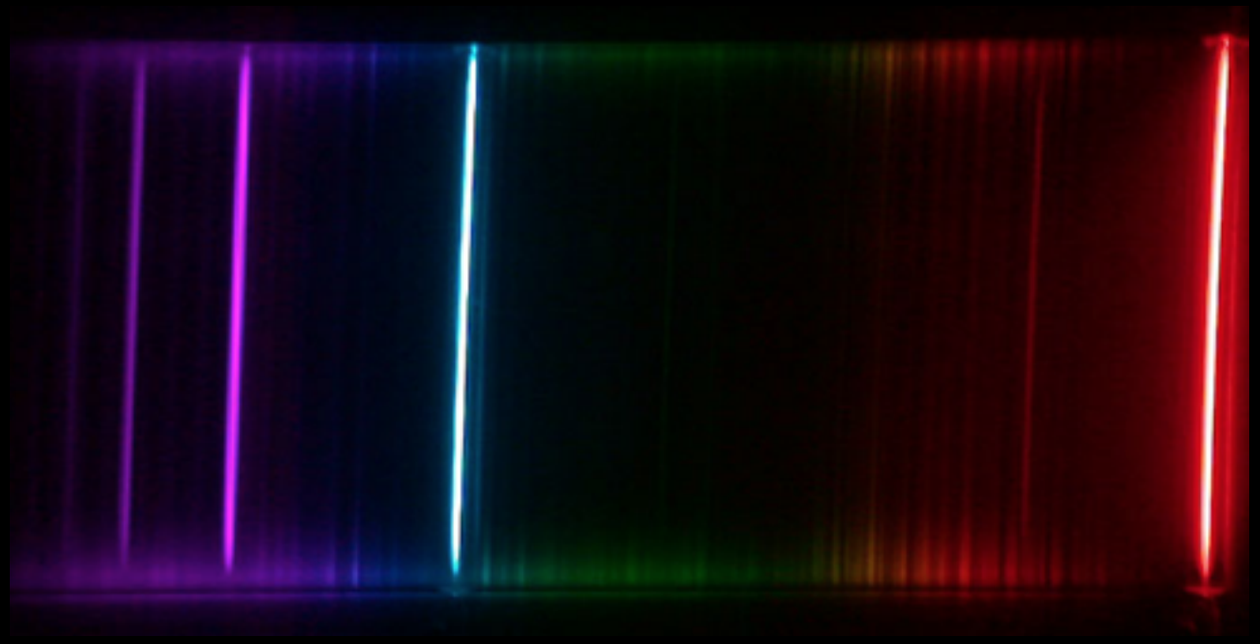
- The search for matter/antimatter differences is a very active effort in physics.
  - Fundamentally understand the (anti)particles and interactions
  - Explain why there was ever so slightly more matter than antimatter in the early universe

Antihydrogen



- When excited, hydrogen emits light at particular wavelengths (colours)
  - determined by how the electron is attacted to the proton in quantum mechanics
  - one of the most precisely studied and understood systems in physics



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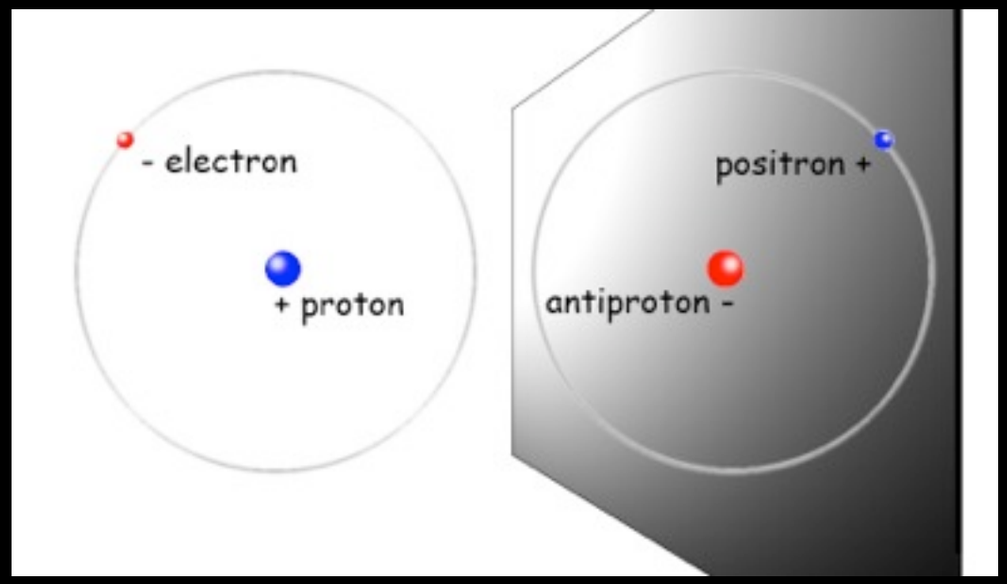

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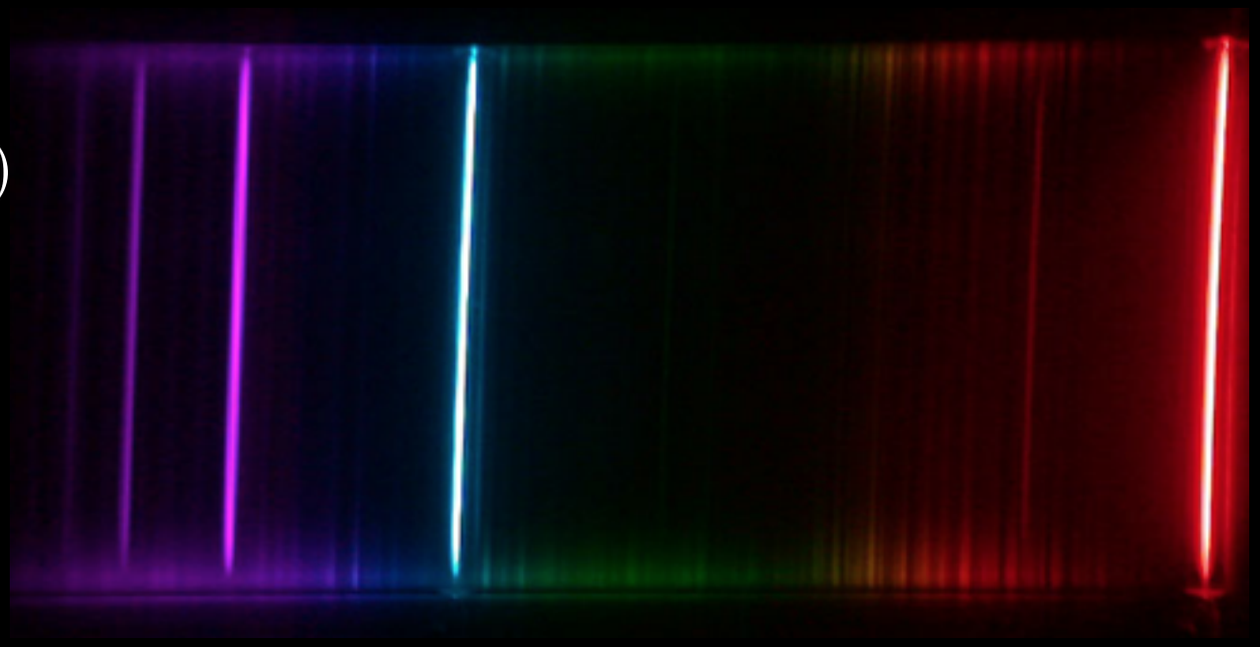

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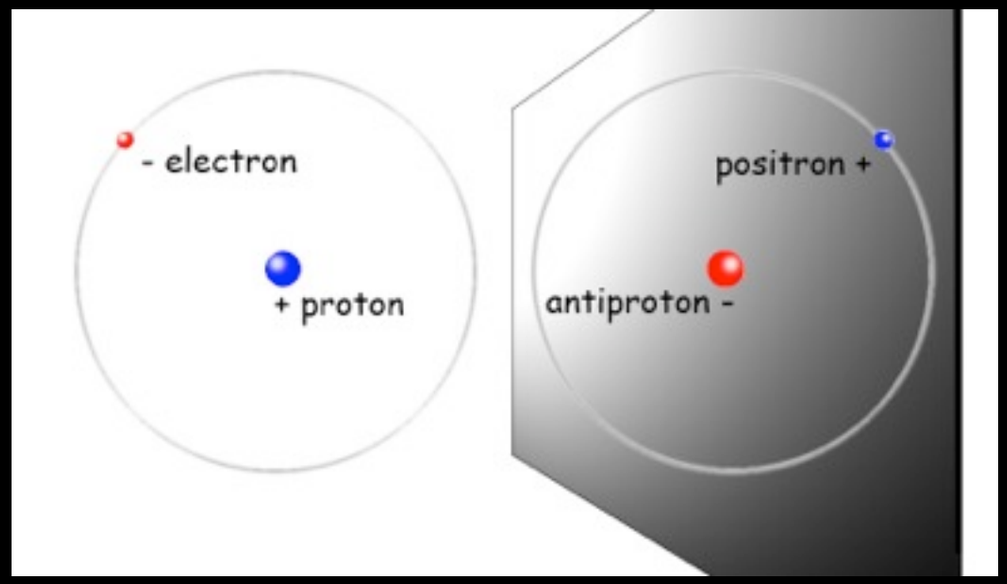

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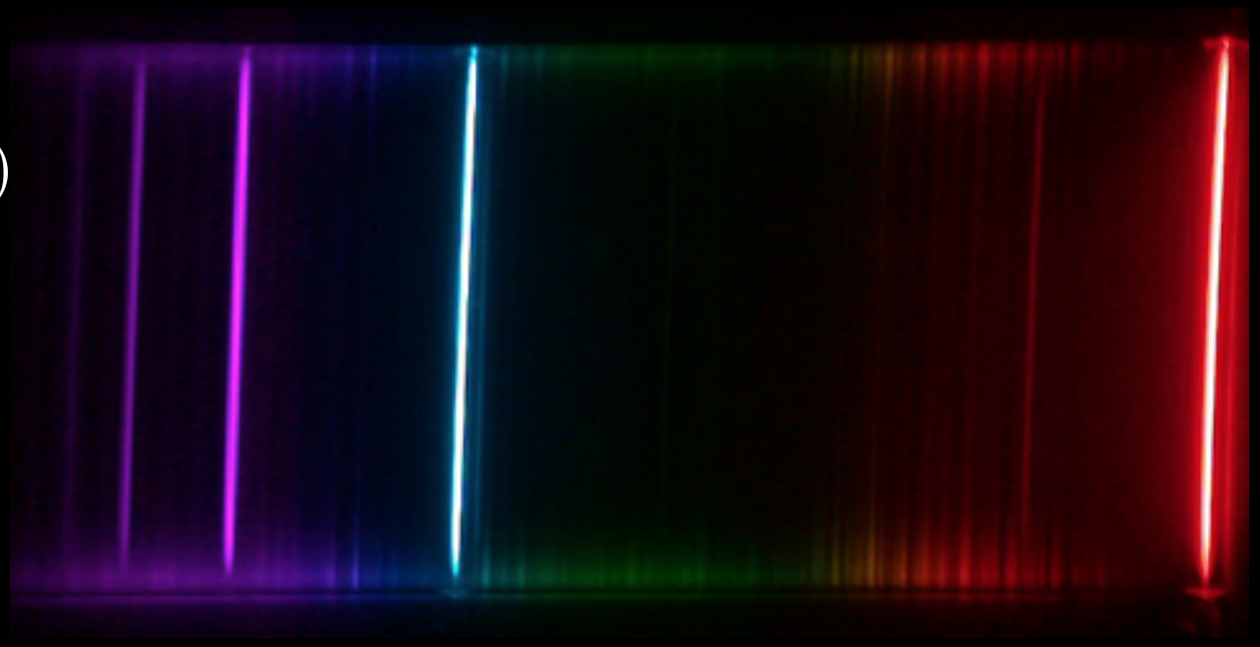


  - Challenge:
    - produce antihydrogen by combining antiprotons and positrons
    - trap it long enough to study its emission spectrum

Making antihydrogen

10^{-12}

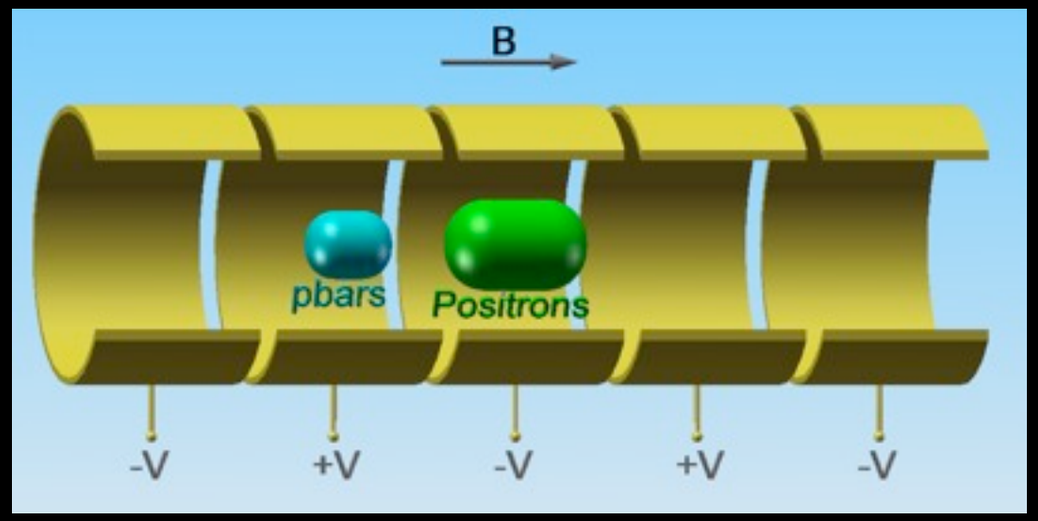
AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (~ meV)



10^{-9}

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)

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Making antihydrogen

10^{-12}

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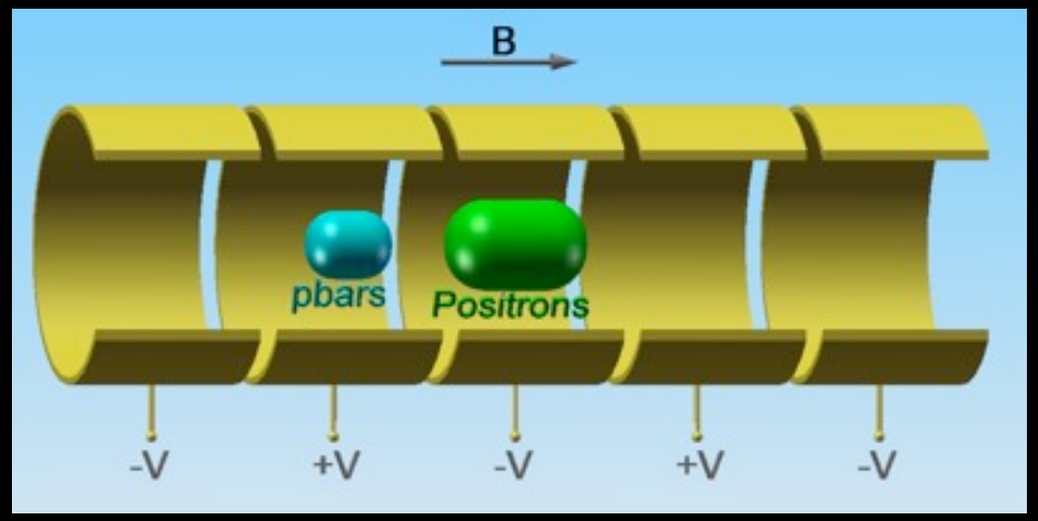

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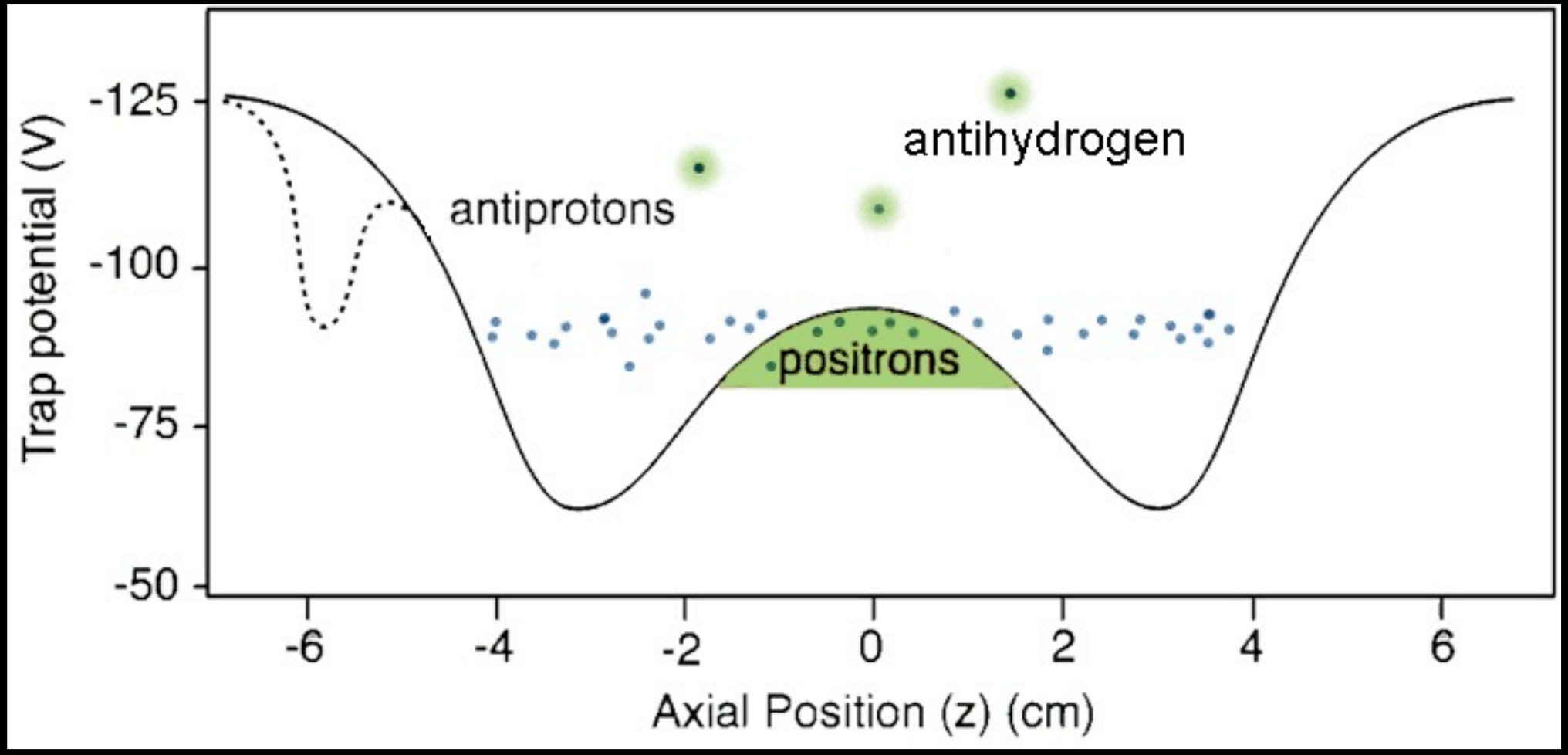
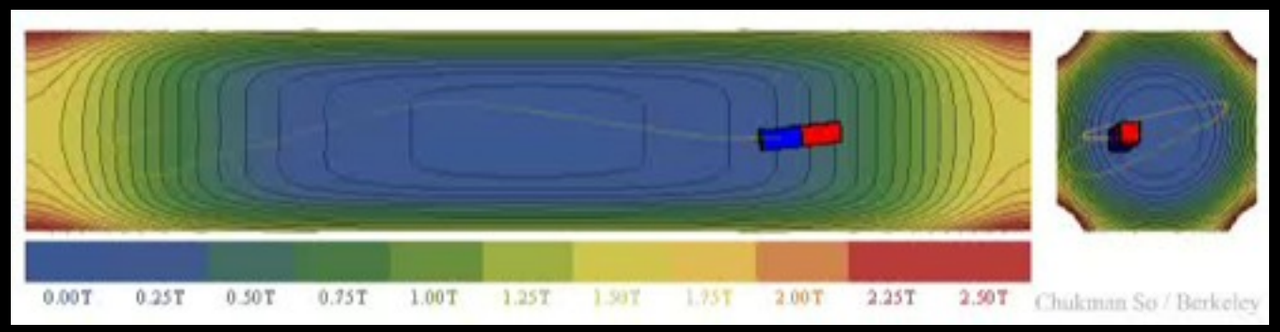


Trapping and Detection



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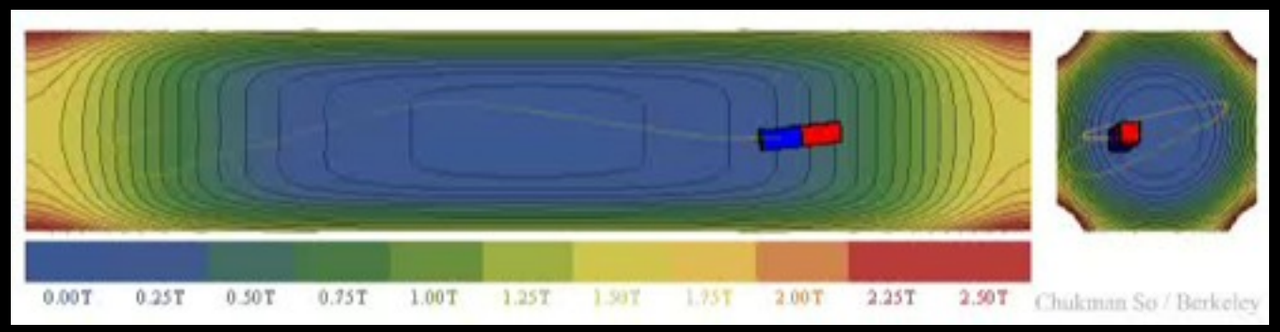

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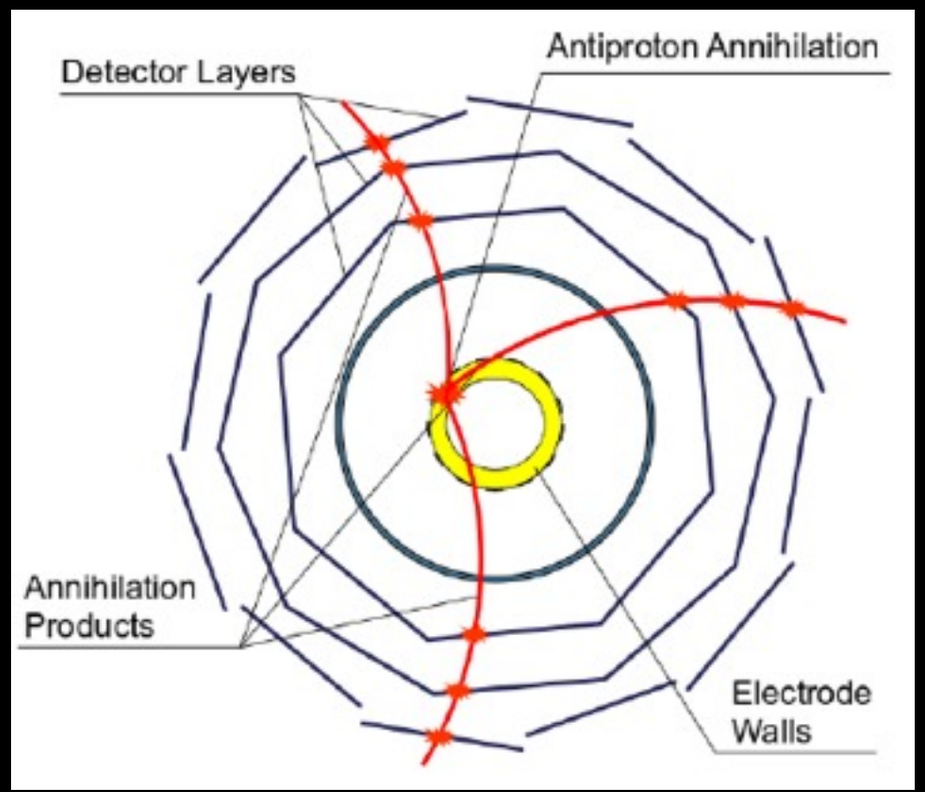
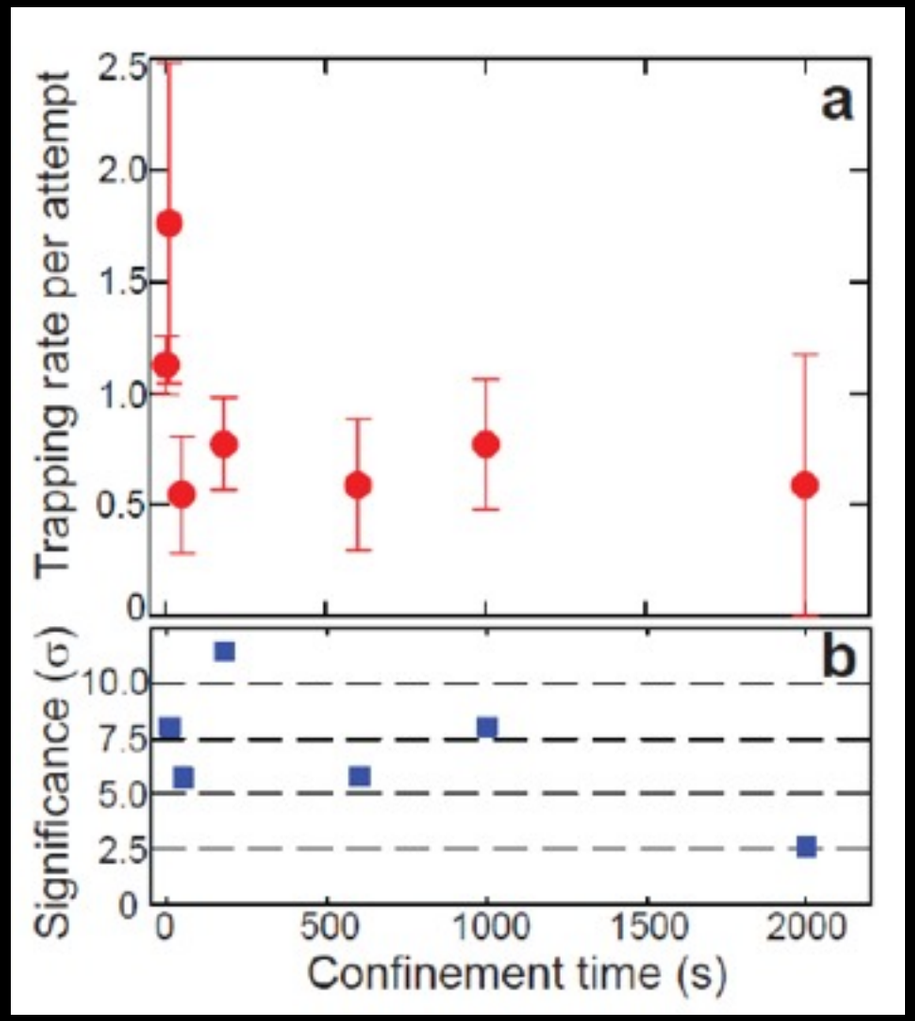
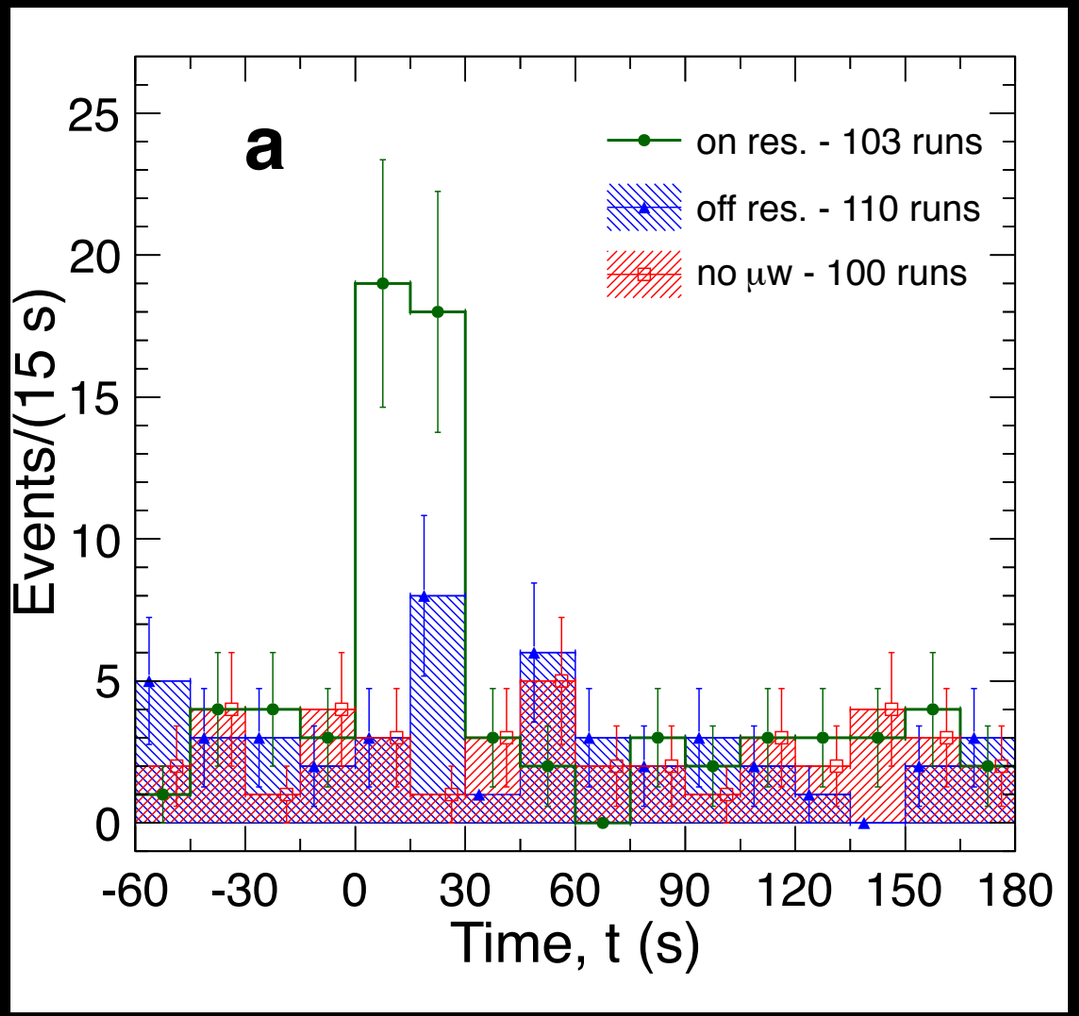


- The trapped antihydrogen "wanders" around the volume
  - eventually, it will run into the wall of the electrodes and annhilate
  - annhilation products detected by silicon strip detectors that precisely measure the position of charged particles passing through them

Trapping and Flipping



- How long can we trap antihydrogen?
  - recently demonstrated >1000 sec (16 min) confinement time



- Microwaves can be used to flip the magnetic moment of the antihydrogen
  - successful flip results in it being ejected from the trap

The New York Times — Science

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More Sci- Than Fi, Physicists Create Antimatter

By DENNIS OVERBYE

Physicists working in Europe announced yesterday that they had passed through nature's looking glass and had created atoms made of antimatter, or antiatoms, opening up the possibility of experiments in a realm once reserved for science fiction writers. Such experiments, theorists say, could test some of the basic tenets of modern physics and light the way to a deeper understanding of nature.

CNN.com/SCIENCE & SPACE

Physicists brew antimatter to test Big Bang theory

Thursday, September 19, 2002 Posted: 10:08 AM EDT (1408 GMT)

LONDON (Reuters) — European scientists have developed enough antimatter to try to answer one of the great questions of Big Bang theory, researchers said.

Scientists think the Big Bang that created the cosmos about 15 billion years ago produced equal amounts of matter and antimatter. But the antimatter, in which subatomic particles have the opposite electrical charge to matter, disappeared just after the Big Bang.

Now researchers at the European Organization for Nuclear Research (CERN) in Geneva have created large amounts of antihydrogen -- the partner to hydrogen in antimatter terms -- to test the standard models of physics and help discover where the antimatter went.

Previously, scientists had produced a few molecules of hydrogen antimatter, but not enough to test the theories.

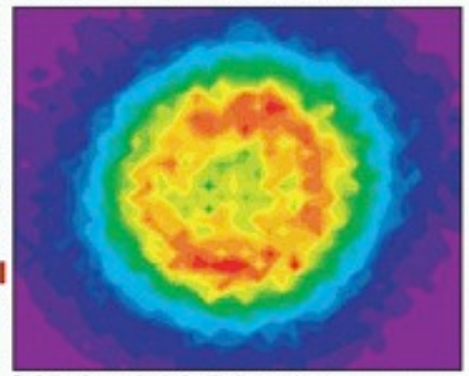
"This is a milestone that has opened up new horizons to enable scientists to study

BBC NEWS WORLD EDITION

You are in: Science/Nature

Wednesday, 18 September, 2002, 19:51 GMT 20:51 UK

Antimatter is mass-produced



Radiation from a cloud of antihydrogen atoms

By Dr David Whitehouse
BBC News Online science editor

Physicists say they have mass produced antimatter, a crucial first step towards precision studies of its properties that may help solve one of the greatest mysteries of the Universe.

Antihydrogen has been made before, but only a few atoms at a time.

"This one is a big step

2011 John Dawson Award for Excellence in Plasma Physics Research Recipient

Makoto Fujiwara (TRIUMF)

Citation:

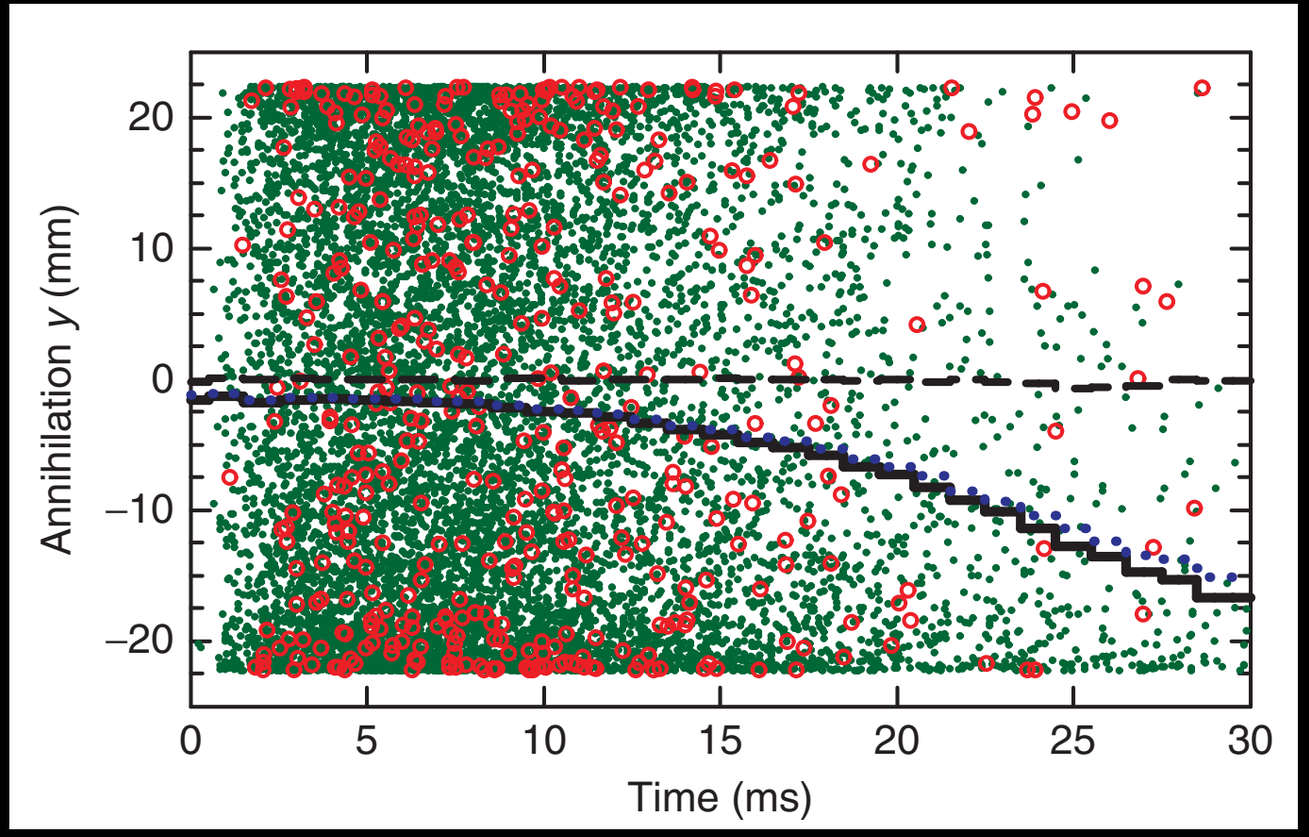
"*For the introduction and use of innovative plasma techniques which produced the first demonstration of the trapping of antihydrogen.*"

ALPHA

antigravity?

- Does antimatter "fall" upwards or downwards?
  - indirect tests indicate that antimatter behaves just like matter in this regard
  - however, there have been no direct tests of this phenomenon

- Analysis of antihydrogen produced in ALPHA
  - if antimatter "falls" like normal matter, it will tend annhilate at the bottom of the detector
  - if it "antifalls" then it will annihilate at the top



Conservation Laws revisted:

- We discussed how “baryon/lepton number conservation” lies at the inability to easily convert matter directly into matter
  - this also ensures the stability of matter
  - otherwise it would turn into other forms of energy

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[9] It is conceivable, for instance, that a conservation law for the number of heavy particles (protons and neutrons) is responsible for the stability of the protons in the same way as the conservation law for charges is responsible for the stability of the electron. Without the conservation law in question, the proton could disintegrate, under emission of a light quantum, into a positron, just as the electron could disintegrate, were it not for the conservation law for the electric charge, into a light quantum and a neutrino.

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adapted from E. Kearns (IF lecture, FNAL)

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- However, unlike energy, momentum, electric charge conservation, the basis for baryon/lepton conservation is not so fundamental

Why believe it?

Why believe it?

adapted from E. Kearns
(IF lecture, FNAL)

"Why did these three learned gentlemen, Weyl, Stückelberg, and Wigner, feel so sure that baryons are conserved? Well, you might say that it's very simple: **they felt it in their bones**. Had their bones been irradiated by the decays of nucleons, they would have noticed effects considerably exceeding "permissible radiological limits" if the nucleon lifetime were $<10^{16}$ years and if at least 10% of the nucleon rest mass were to appear as radiation absorbable in the body. That is a fairly sensitive measurement, but one can do much better by a deliberate experiment."

M. Goldhaber

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- To put in context:
  - Age of the universe: 13.7 billion years
  - other considerations: proton lifetime is $>10^{23}$ years
- We can:
  - watch one proton and wait $>10^{23}$ years for it to decay.
  - "lifetime" = "average lifetime": watch many protons
    - each has ~1/lifetime probability of decaying in a year.

M. Goldhaber

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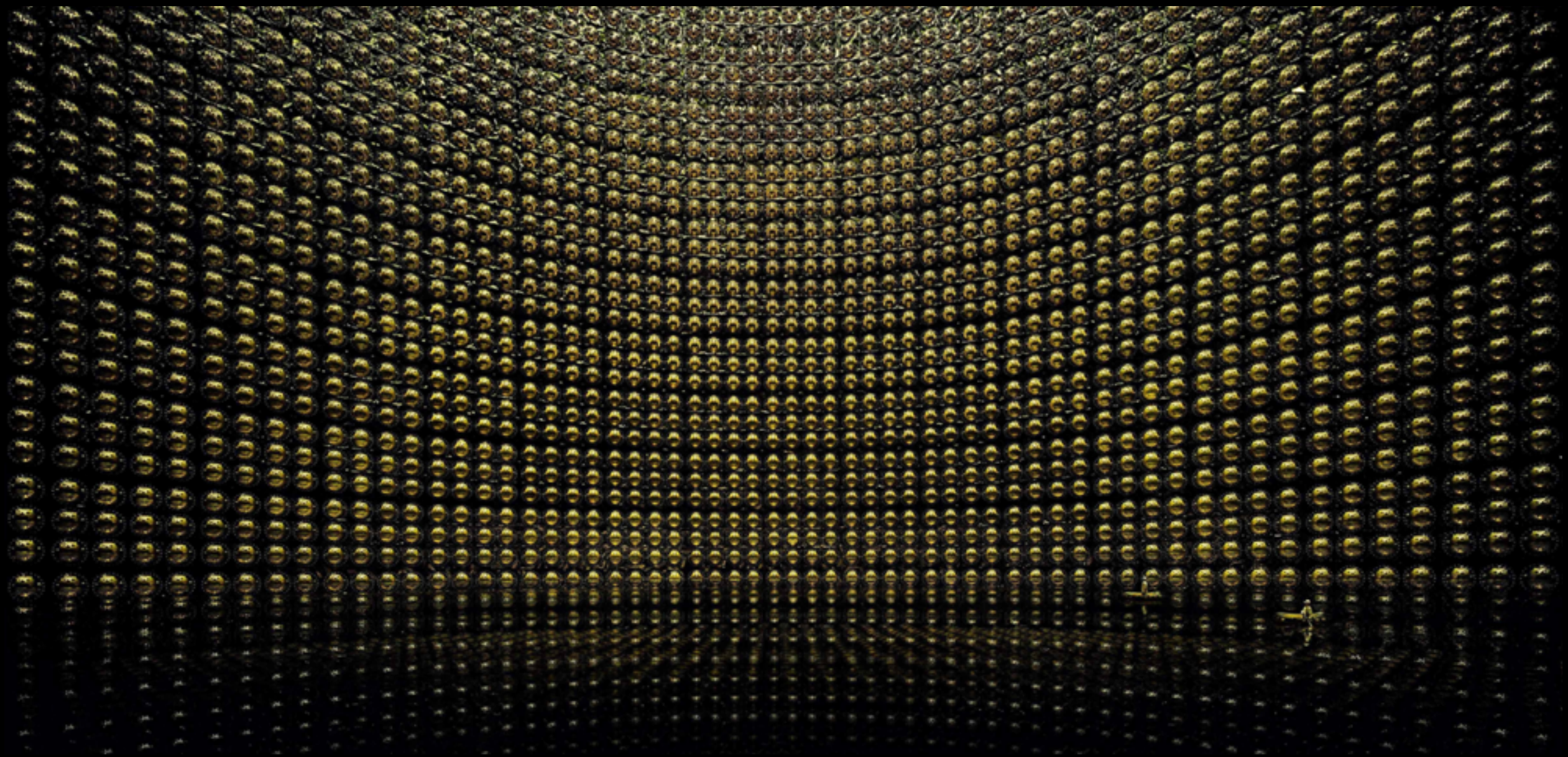
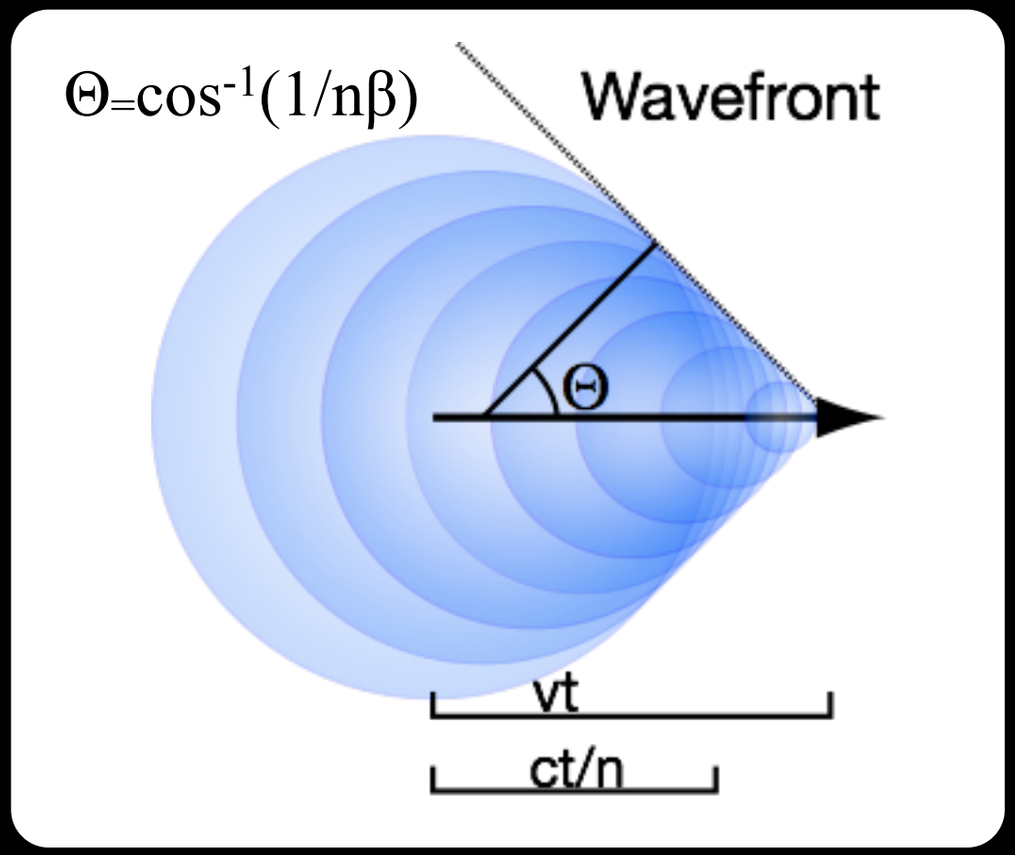
  - expect ~6 to decay in a year
- The more protons we can observe, the more probability we have of observing one of them decay.
- How would they decay?
  - Many possibilities (depending on underlying mechanism)
  - $p \rightarrow e^+ + \pi^0$ is one possibility
  - π^0 is a short-lived particle that decays to two photons (particles of light)
    - $\pi^0 \rightarrow \gamma + \gamma$

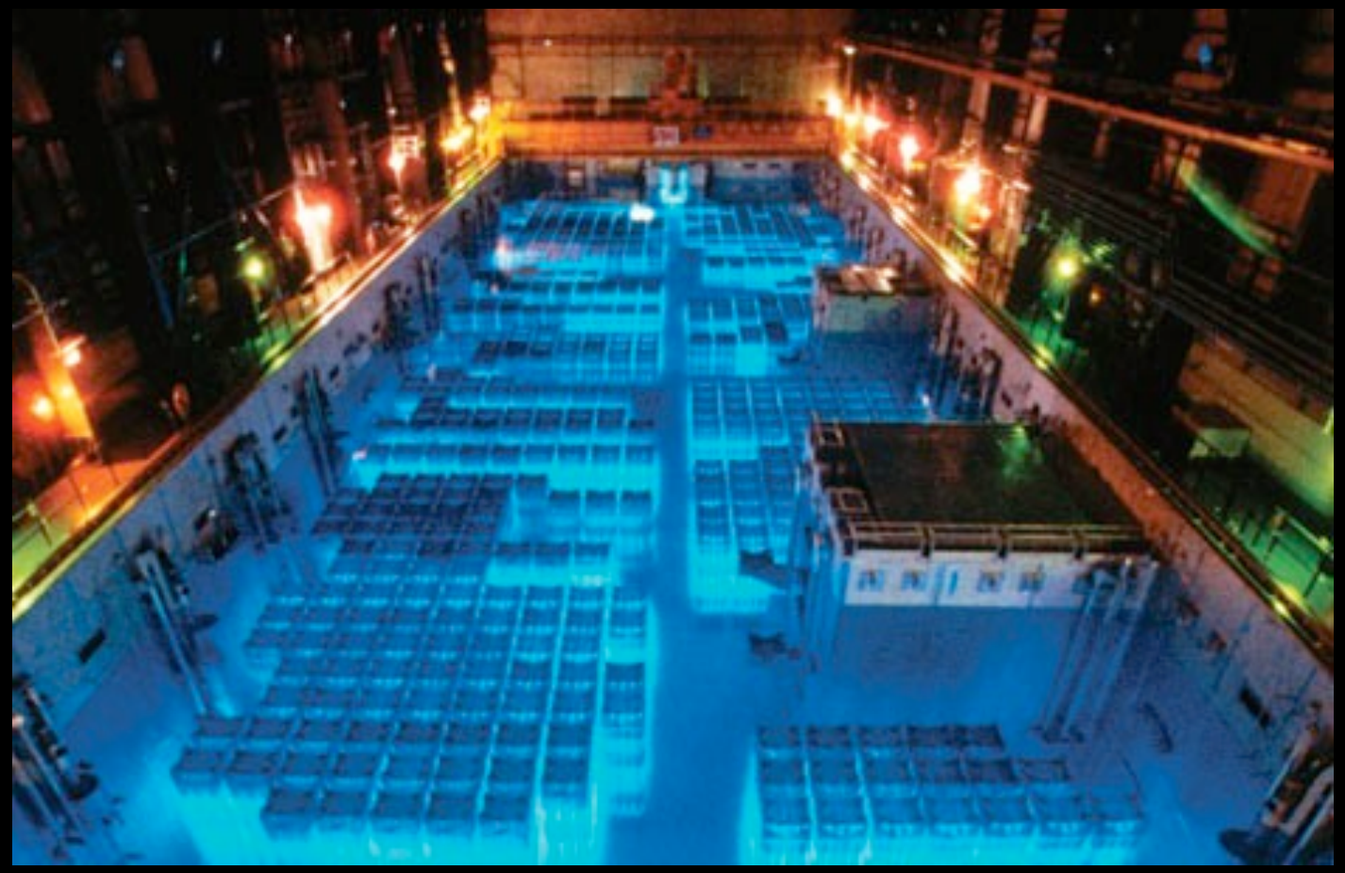
Extreme Science:



- Super-Kamiokande:
  - Observe 22.5 kton of water for the decay of proton
  - ~7.5×10^{33} protons → 1 decay/year if the average lifetime is 10^{33} years

Cherenkov Radiation

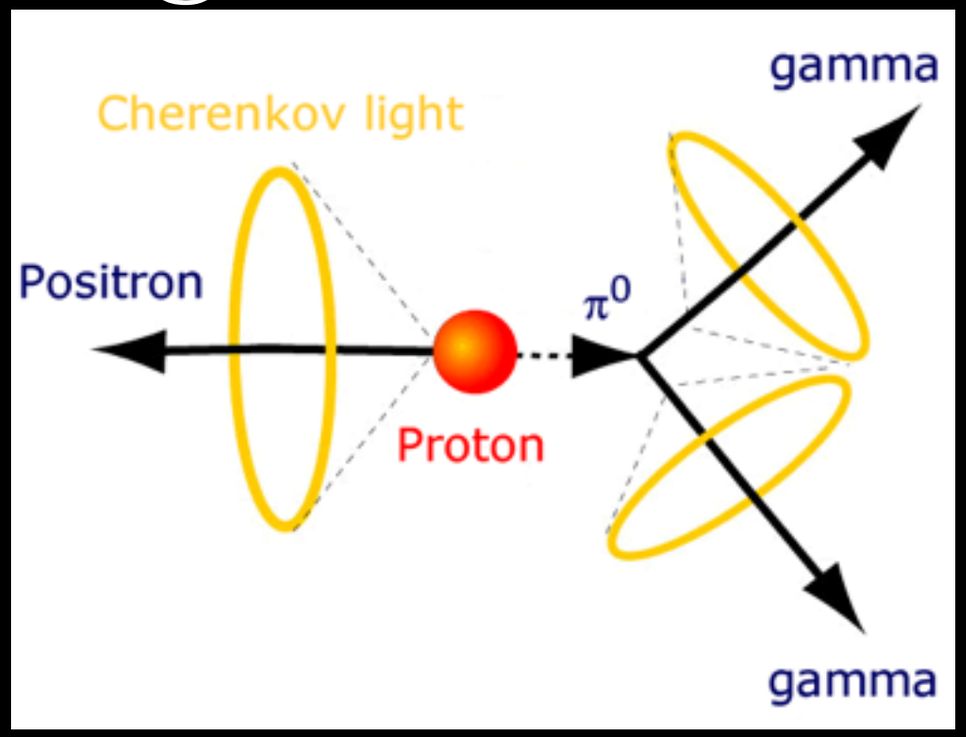


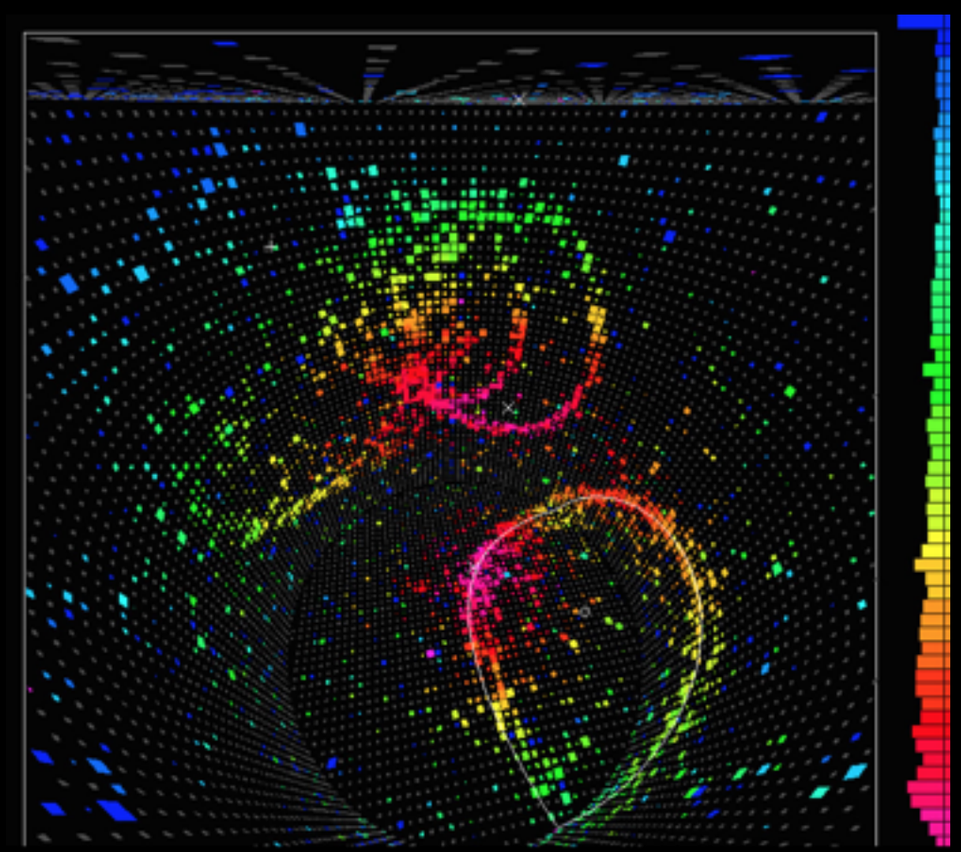


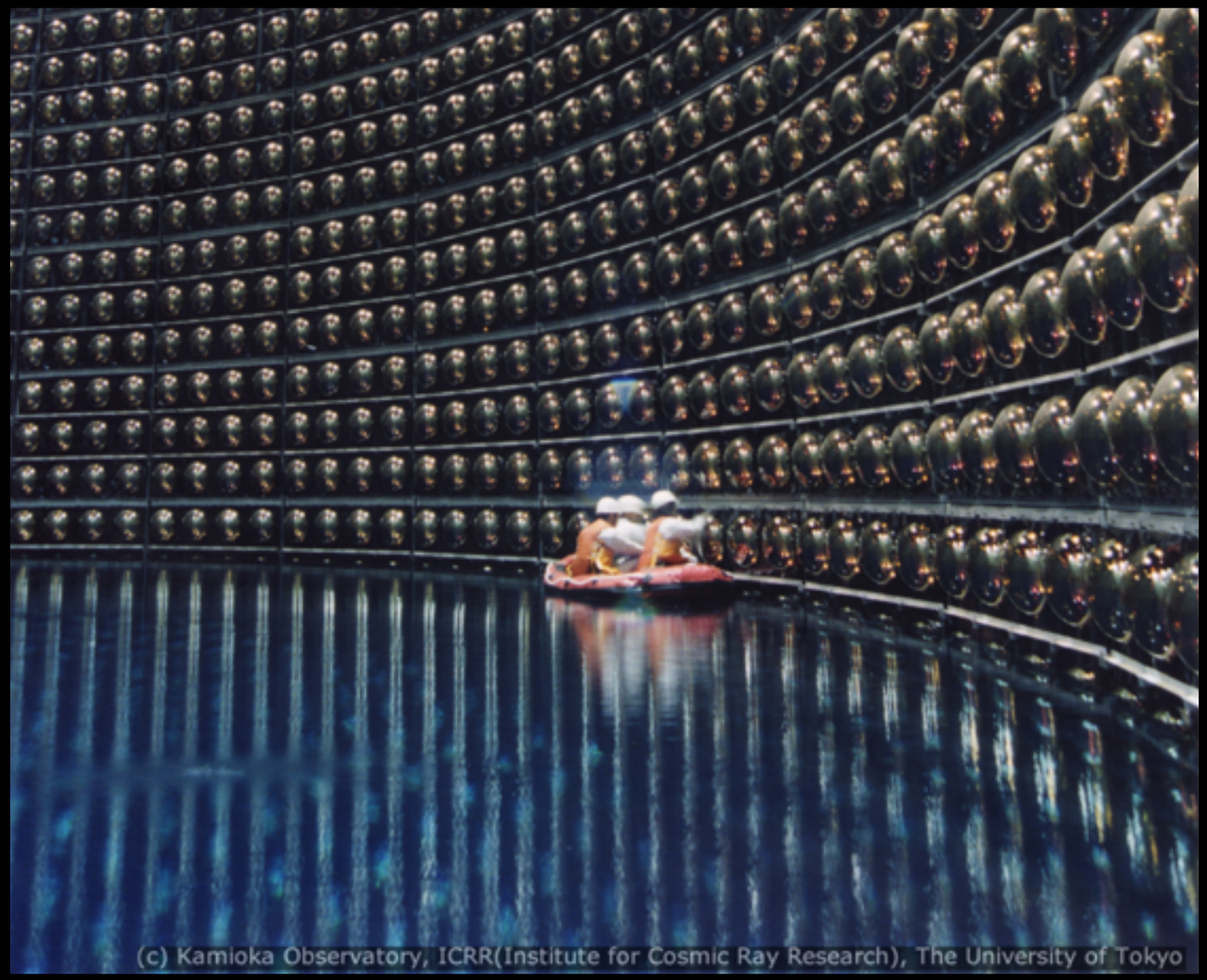
light emitted in when a charged particle exceeds velocity of light in a dielectric medium

- optical analog of "sonic boom"
- For water, n ~ 1.33
  - "threshold" for Č radiation is 0.75 x c
    - 225,000 km/sec
  - Θ ~ 42° for v ~ c

Signature







- Each particle produces a cone of Cherenkov radiation that is imaged by an array of light sensors (photomultipliers)

Results:

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- As it turns out, there is another reason why we might consider building such an enormous detector.
    - Searching for proton decay then comes "for free"

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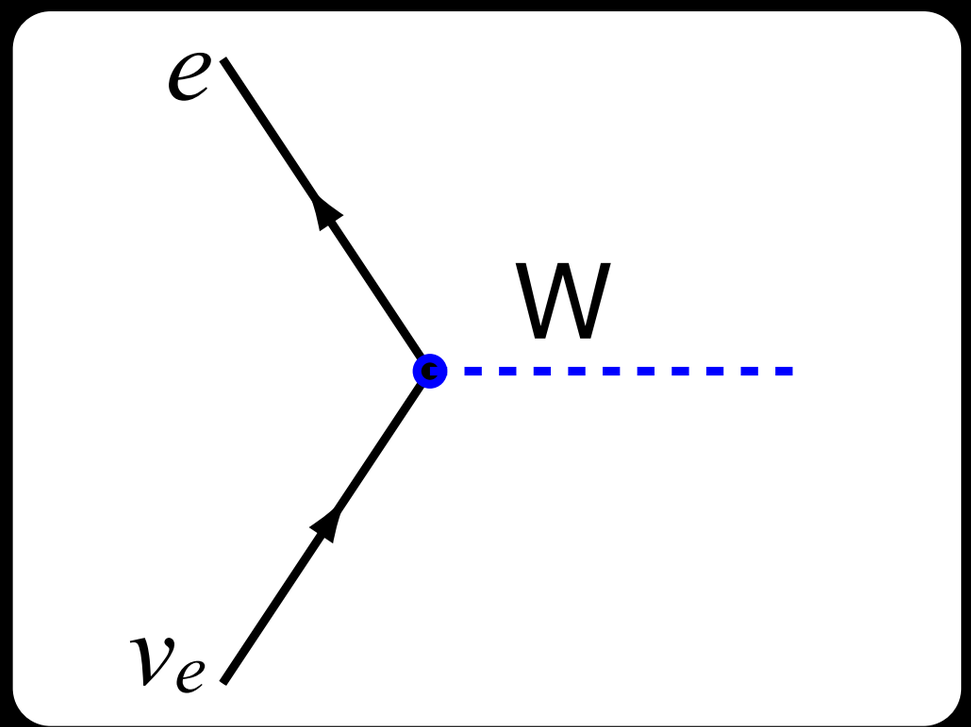

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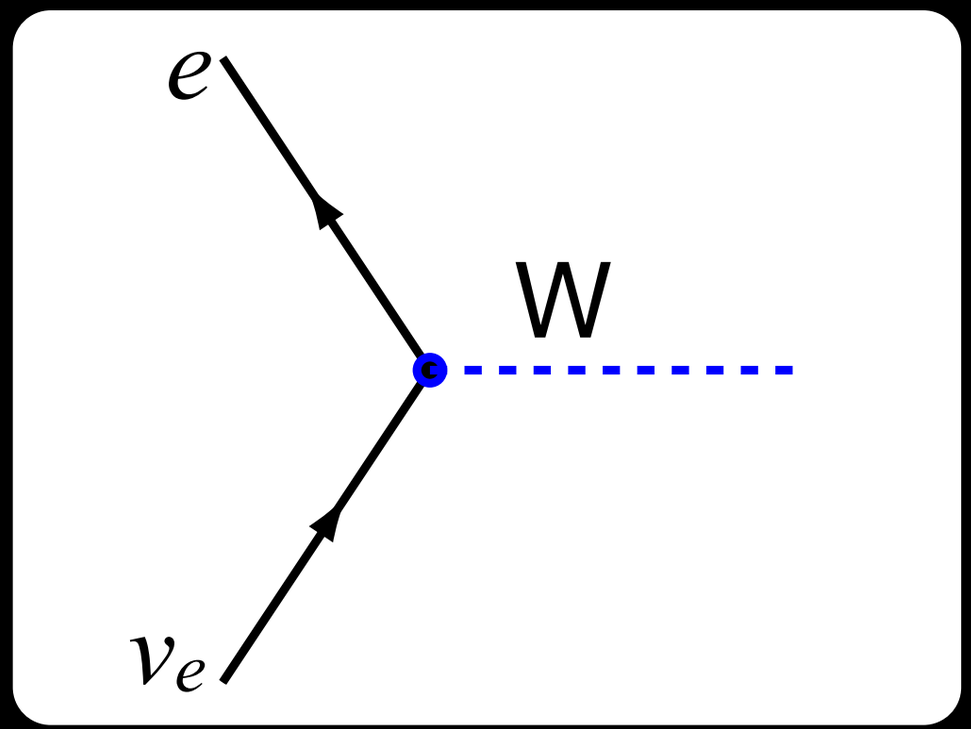

ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-

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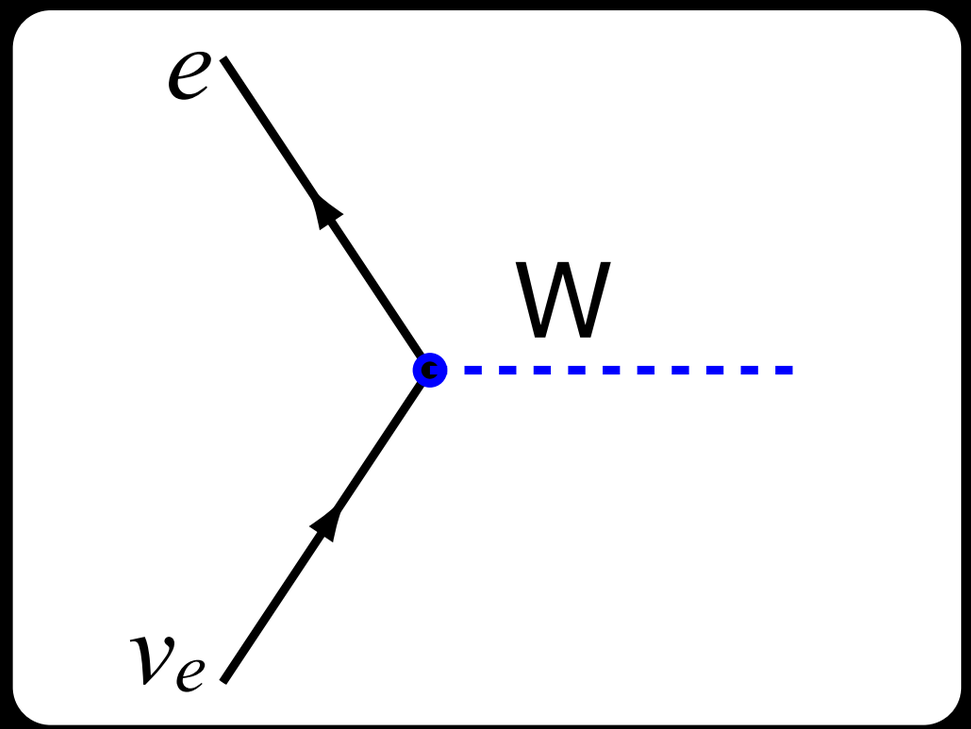

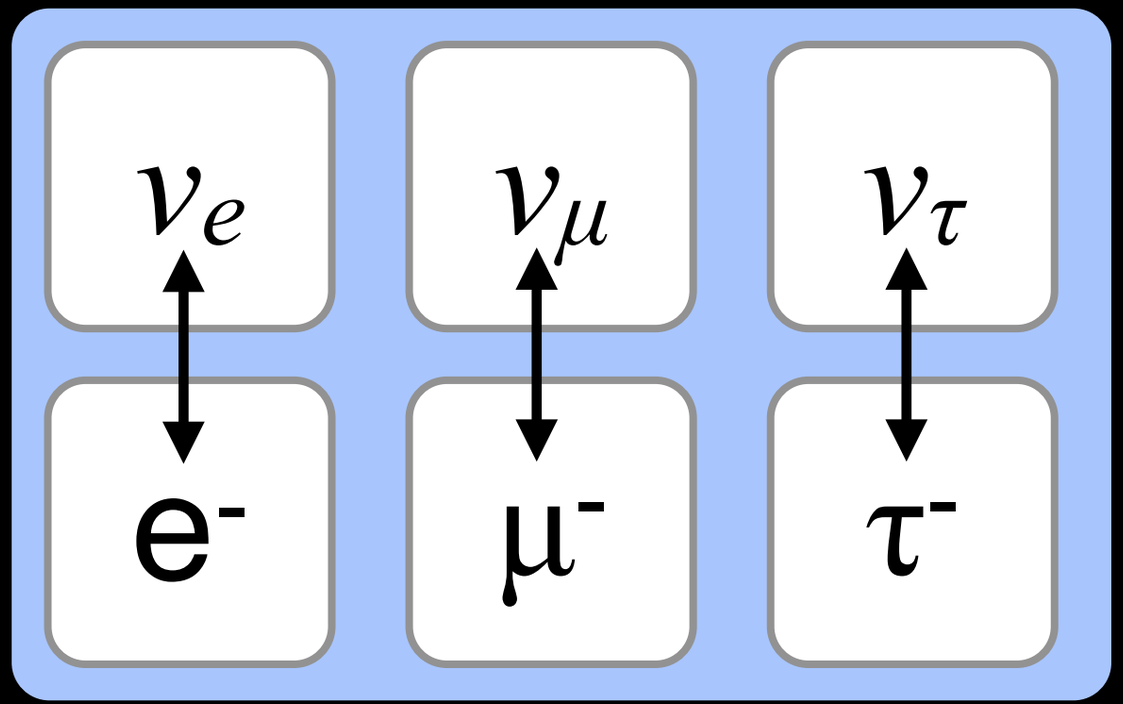

Observing neutrinos

- Neutrinos the most elusive of the known elementary particles
  - depending on its energy, a neutrino can traverse (on average) 1 light-year (10 trillion km) of lead without interacting
- we can improve the chances we observe a neutrino by:
  - making as many neutrinos as possible
    - = intense source
  - the number of interactions is proportional to “targets”
    - = enormous detector

Neutrinos oscillations:

- Neutrinos exhibit a phenomenon where they "age"
  - a neutrino born in one flavor (ν_e, ν_μ, ν_τ) can appear as a different type some time later.
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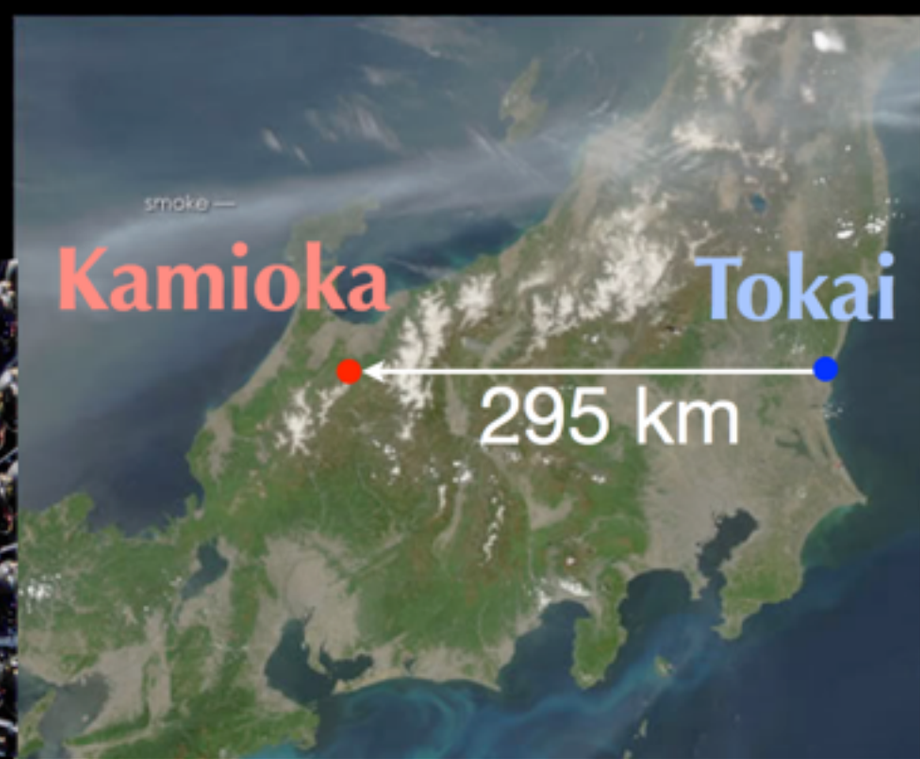
ND280

"near" detector

J-PARC

Super Kamiokande
"far" detector



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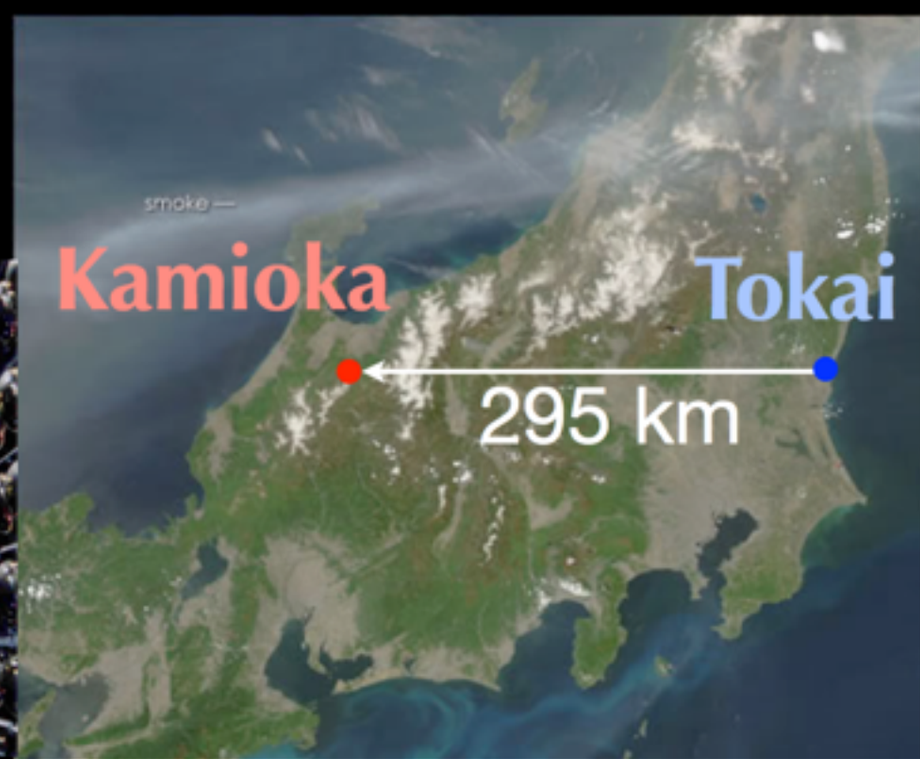

produce a
pure ν_μ beam

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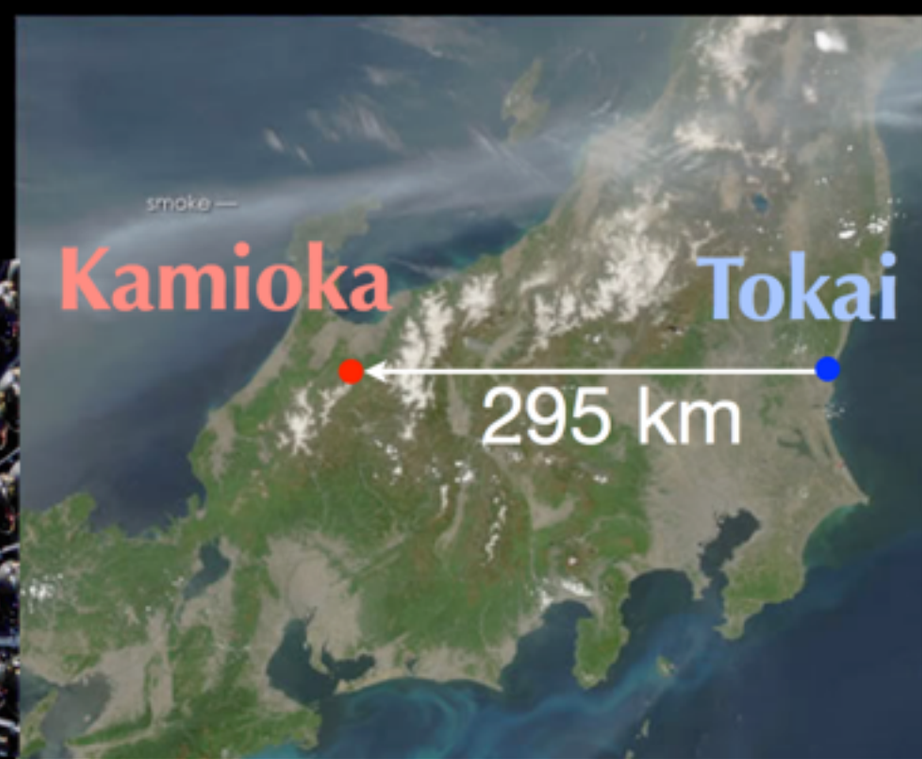
observe other neutrino flavor

Super Kamiokande "far" detector



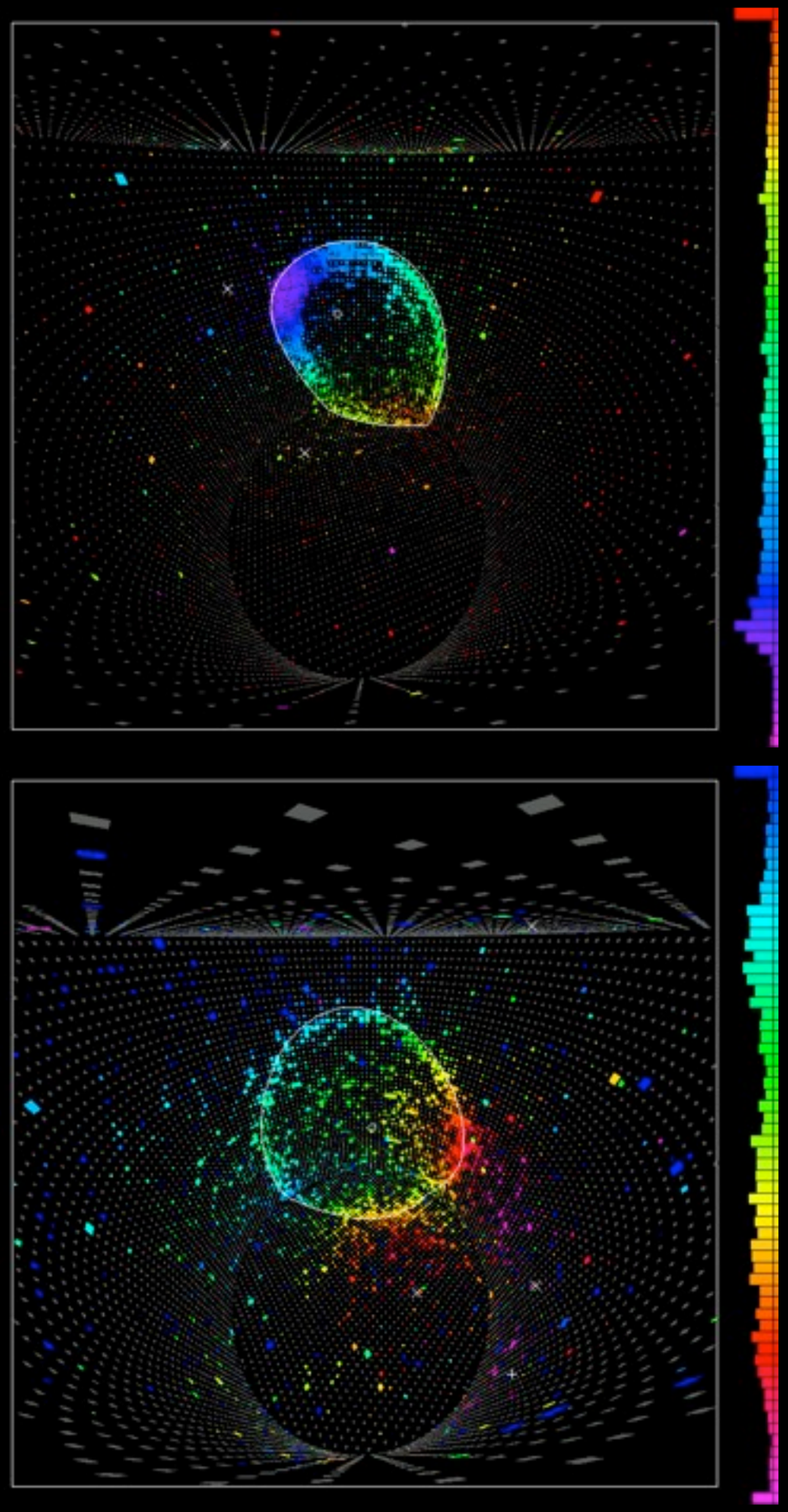
ND280

"near" detector

J-PARC

produce a pure ν_μ beam

Recent developments



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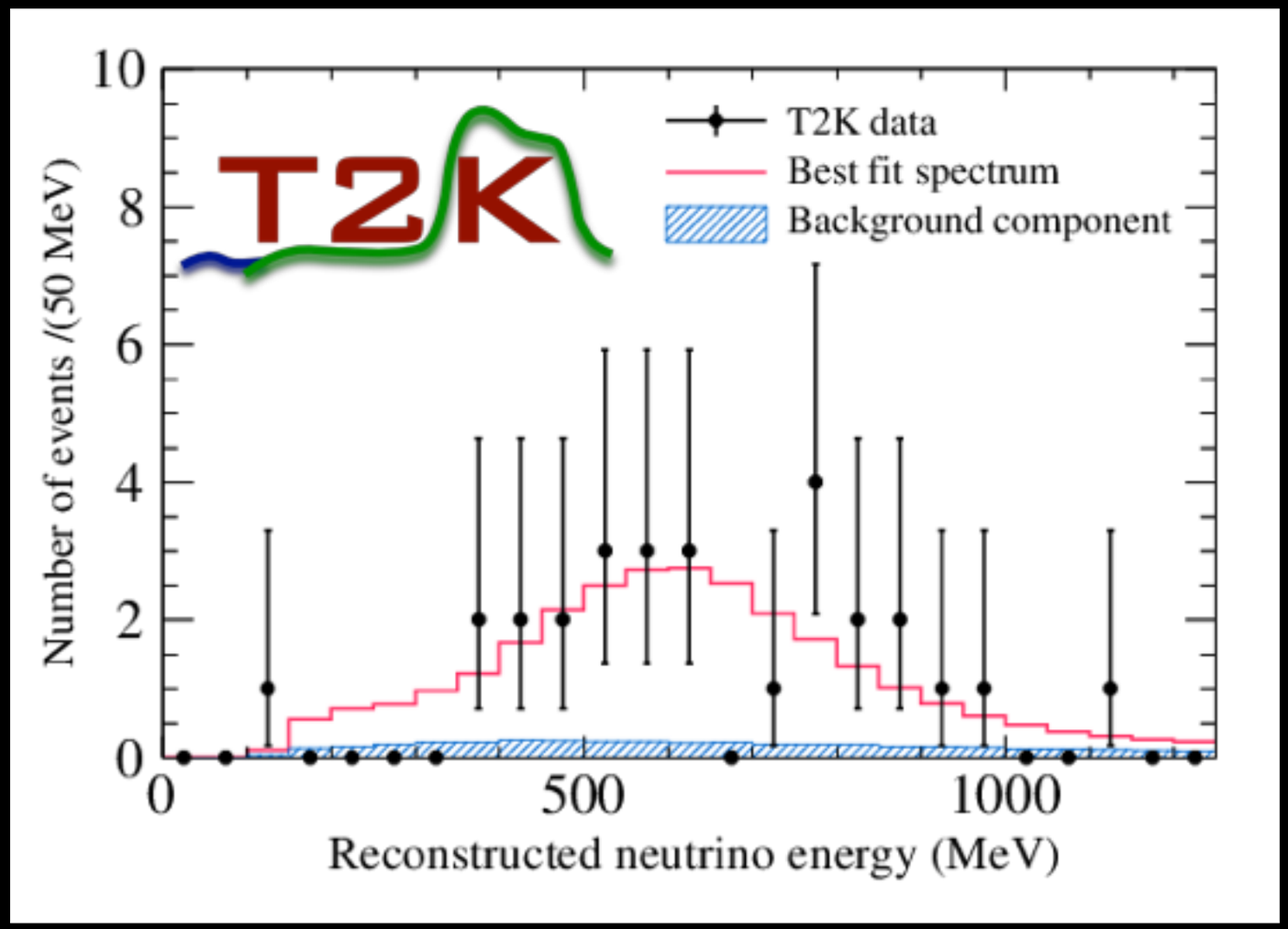

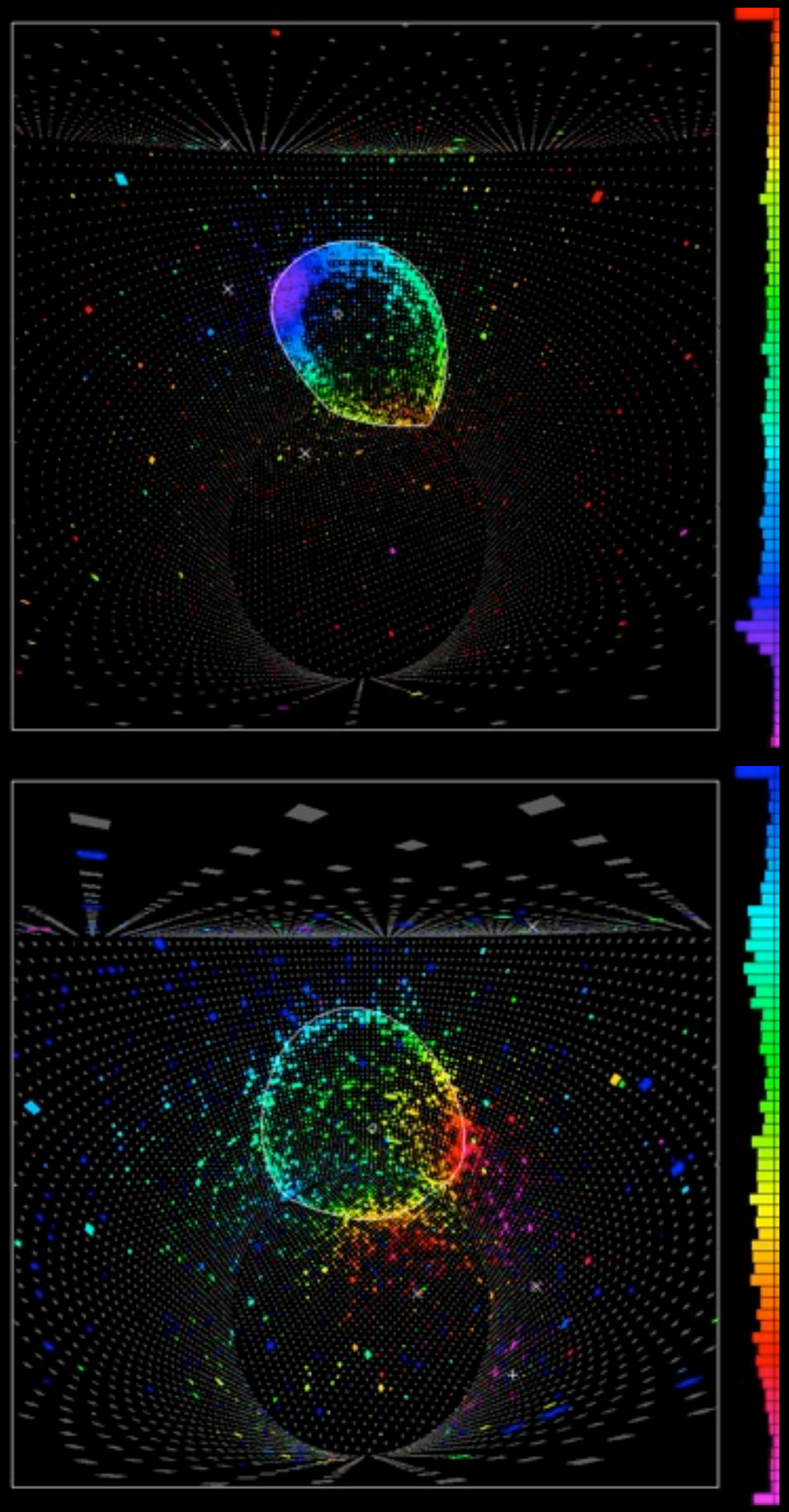

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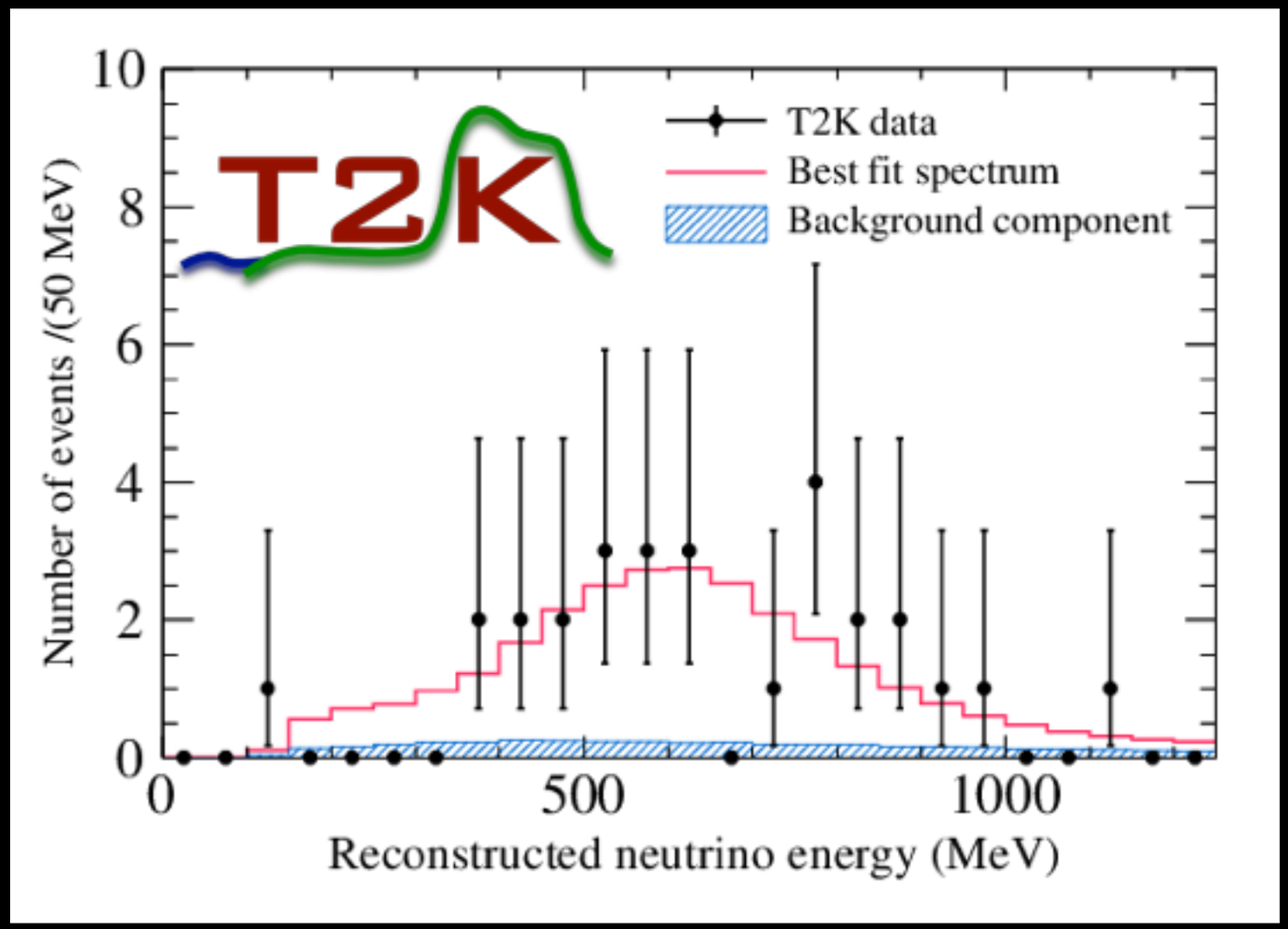

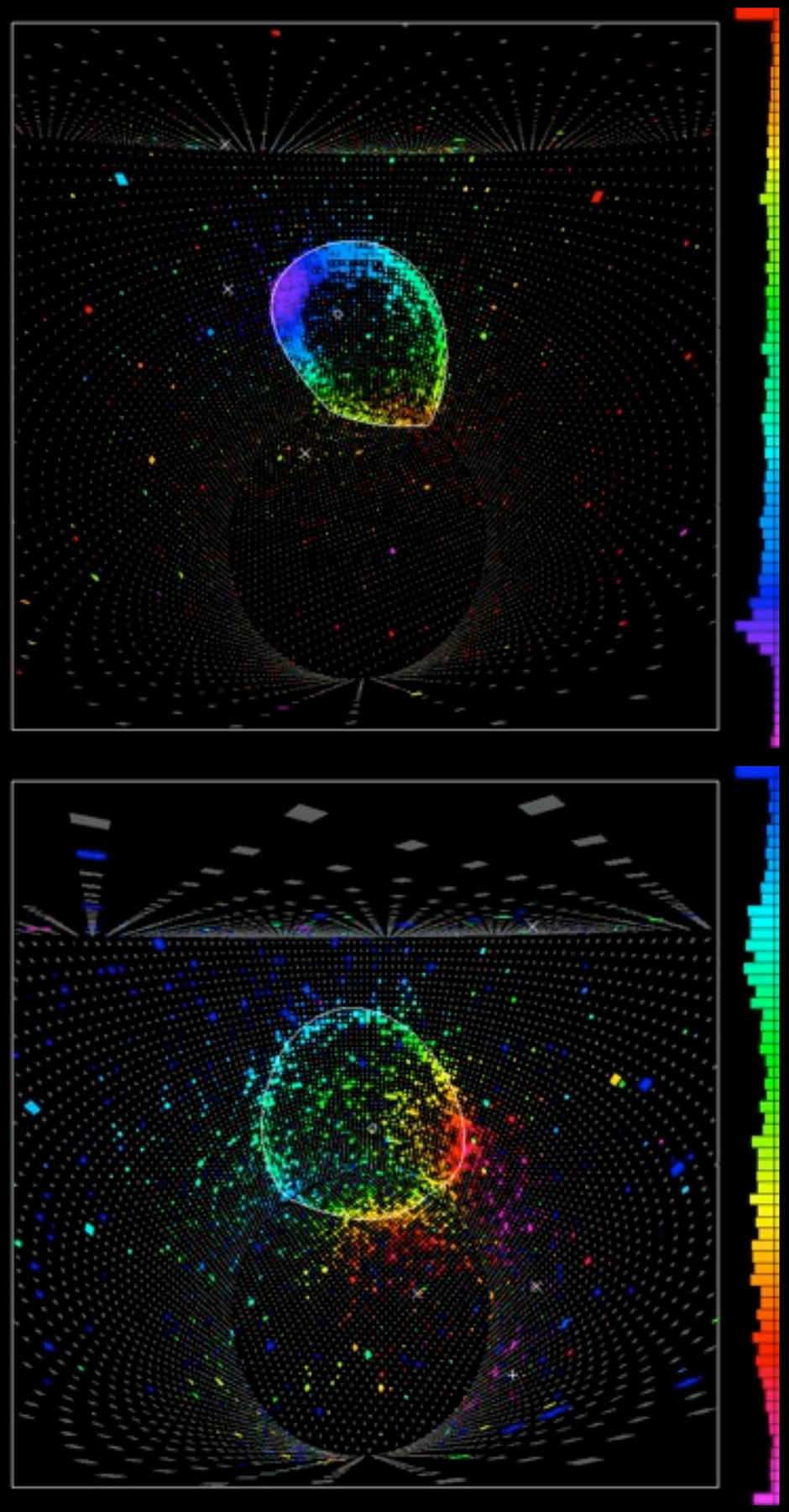

- 28 ν_e observed in initially pure ν_μ beam
  - first observation of a new neutrino flavour appearing in a beam of neutrinos of initially of a different flavour.

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  - we would need an upgrade to the detector
    - 20x bigger to get ~1000 events/year

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T2K

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The Economist

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Neutrinos

Delta force

A study of neutrinos may explain why things are made of matter, not antimatter

Jun 23rd 2011 | from the print edition

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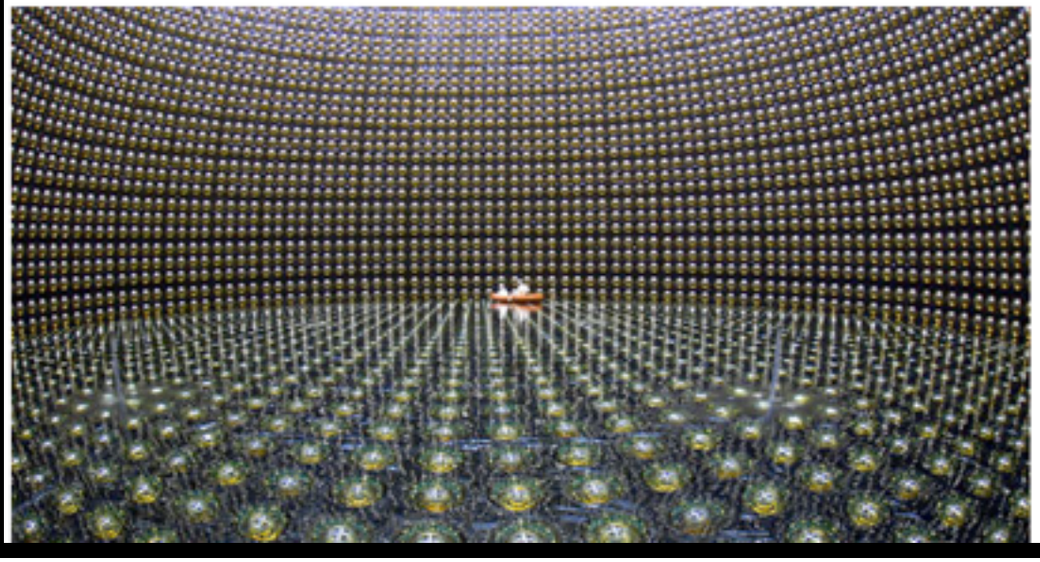

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Canadians helping to unravel secret of universe's existence

VIVIAN LUK

VANCOUVER — The Globe and Mail

Published Friday, Jul. 19 2013, 9:08 PM EDT

Last updated Saturday, Jul. 20 2013, 7:47 AM EDT

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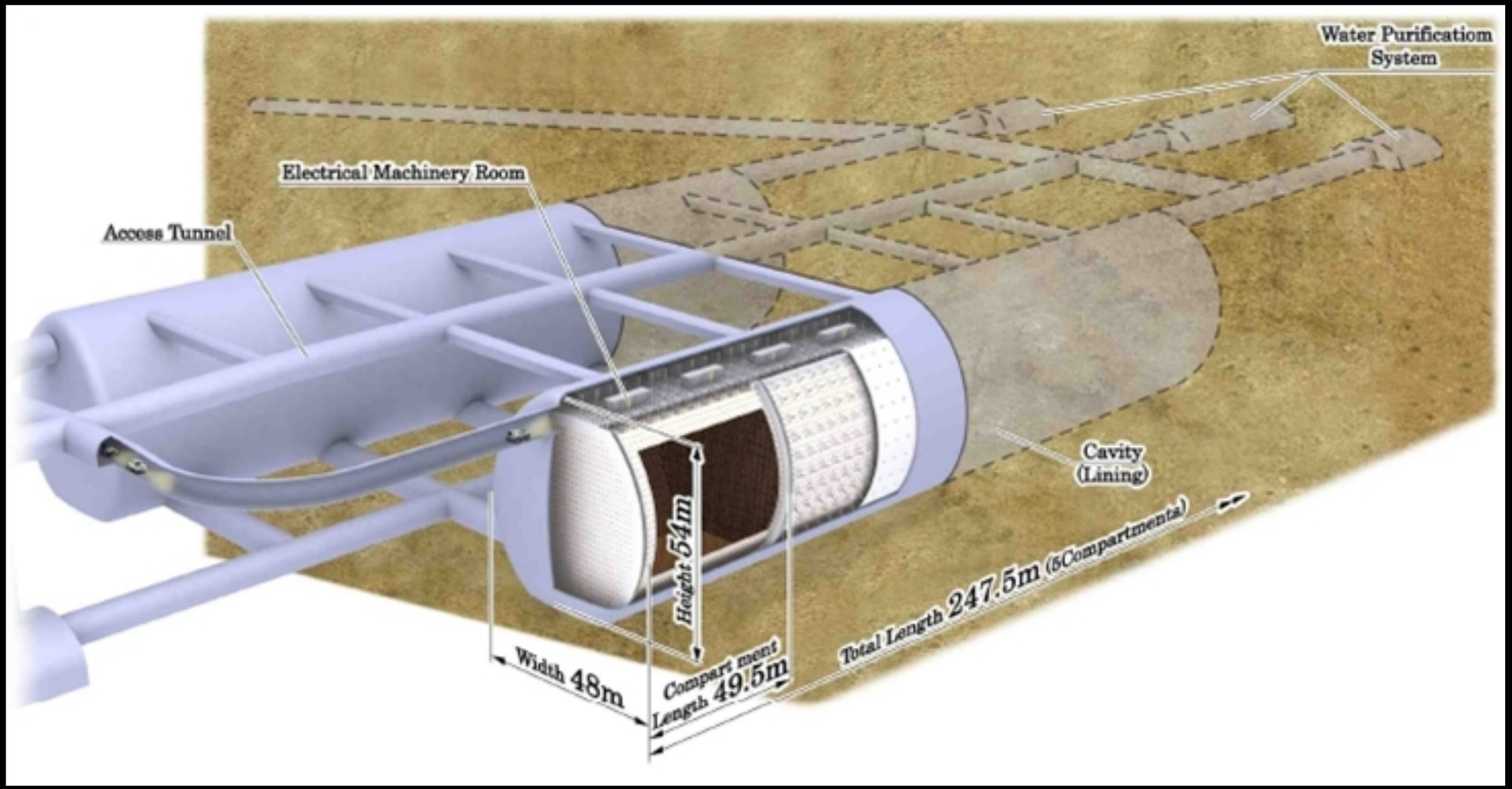
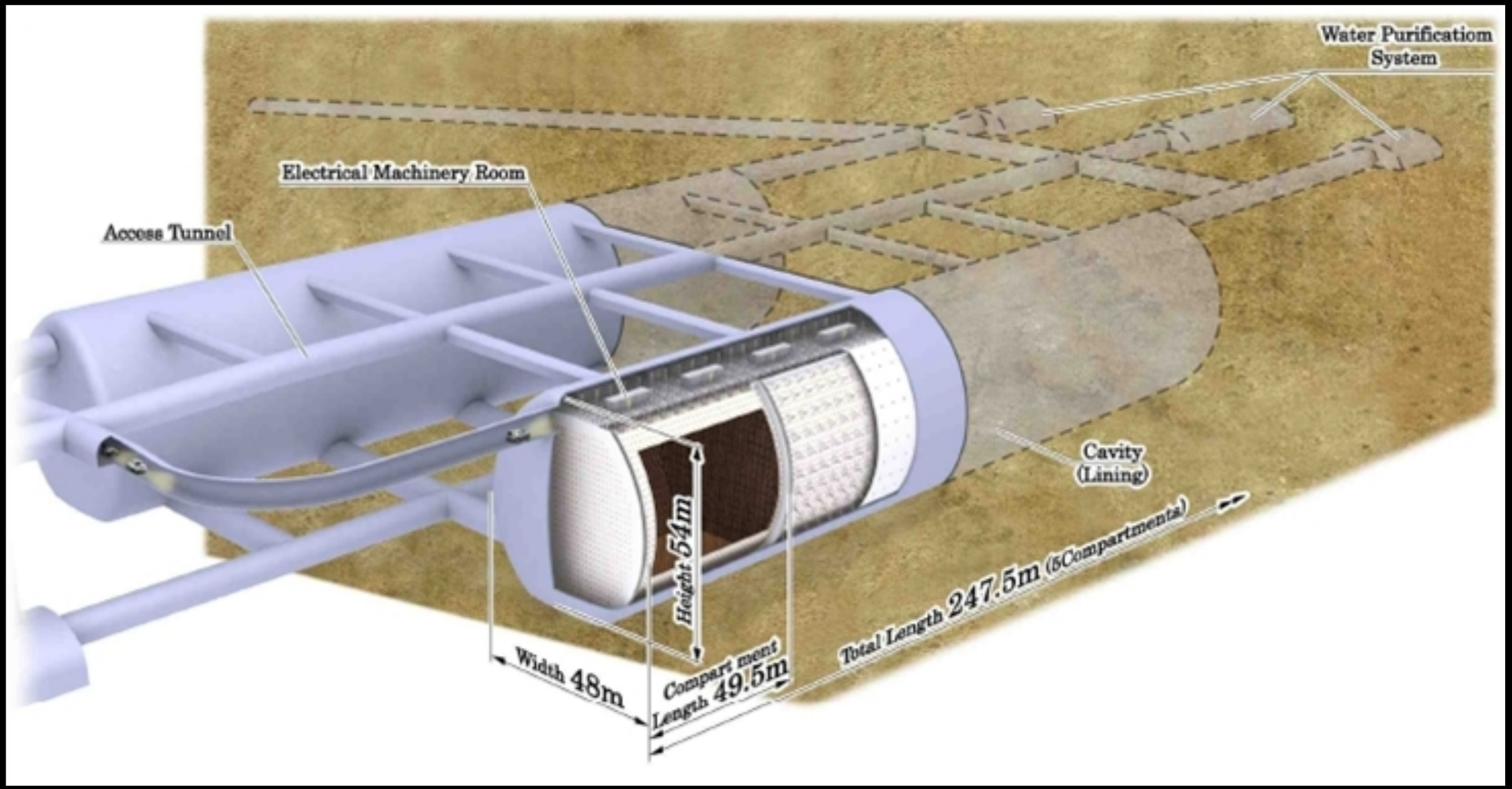
Science is one step closer to solving one of the most profound mysteries in the cosmos due to what an international team of physicists say is an unprecedented observation about a fundamental particle in the universe.

"Hyper-Kamiokande"



"Hyper-Kamiokande"



- x20 upgrade of Super-Kamiokande to 1 megatonne of detector.
- Canadian physicists are playing a major role in the R&D for HK

What is science, what is fiction?

- Antimatter definitely exists
  - it is naturally produced by cosmic rays
  - we can produce it and study it
  - it is part of “everyday life” in the form of PET machines
- It is not:
  - an untapped source of energy
    - (you have to make the antimatter)
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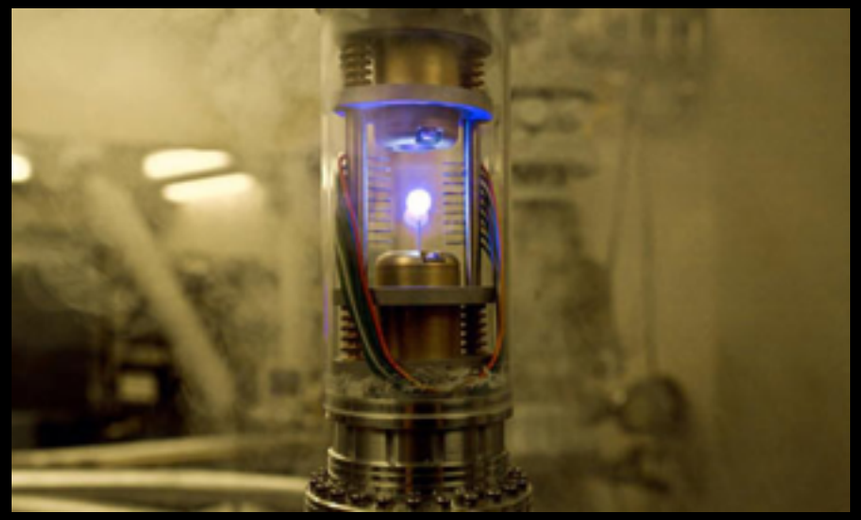

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- Behind this incredible potential is a profound mystery
  - what distinguishes matter from antimatter?
  - why is there so little antimatter in the universe?

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- Scientists at TRIUMF and associated universities are actively trying to find clues and answers
  - are the conservation laws that “protect” matter valid?
    - does the proton decay?
    - can electron pairs without neutrinos be spontaneously produced by radioactive decay?
  - does antimatter behave differently from matter?
    - Trapped antihydrogen will allow us to answer whether
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- Recent breakthroughs in setting the stage for the answers
  - please stay tuned for further progress . . . .
  - or join the fun!