LHC from the Sidelines

or

Other Frontiers of Particle Physics

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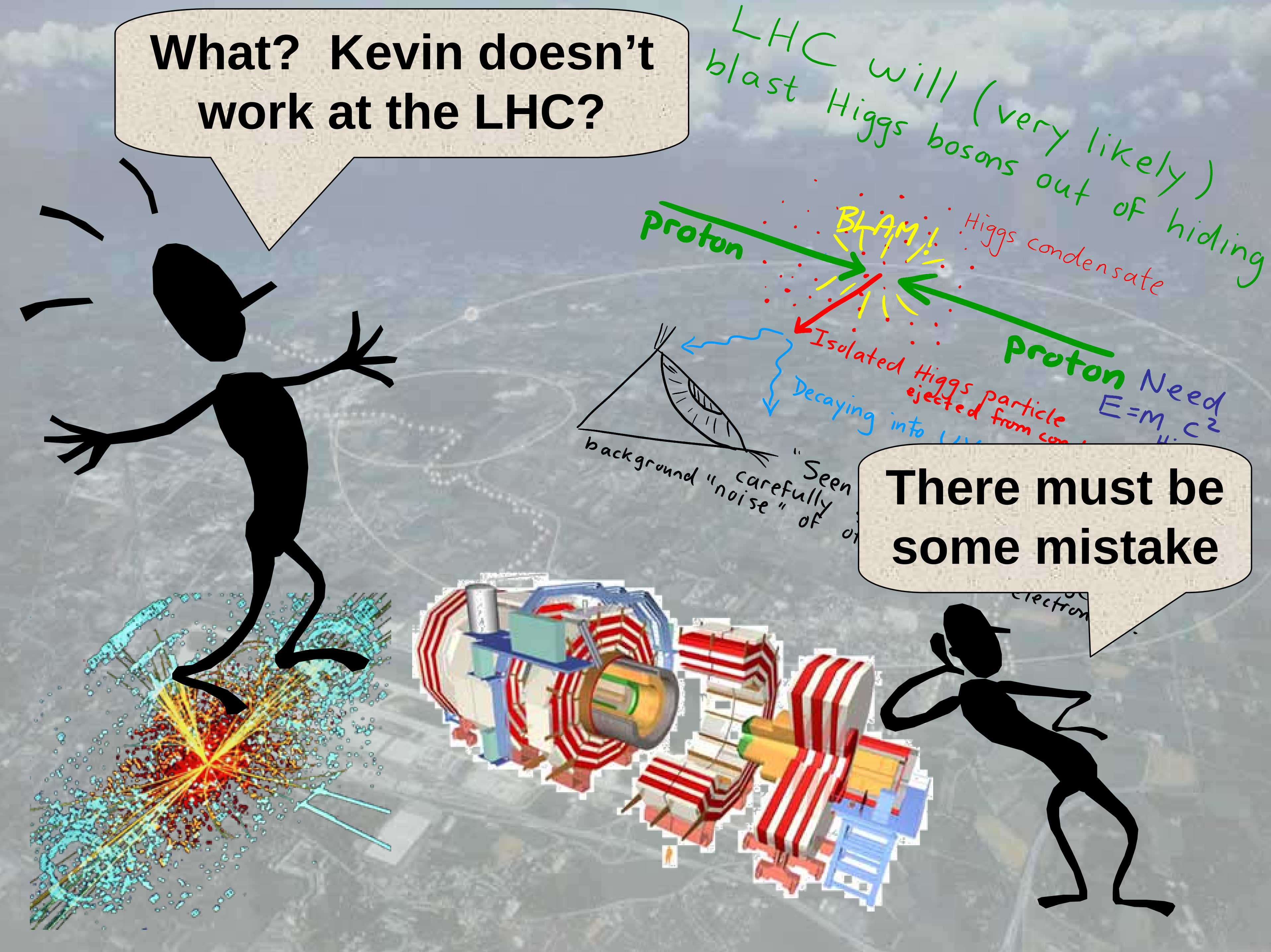
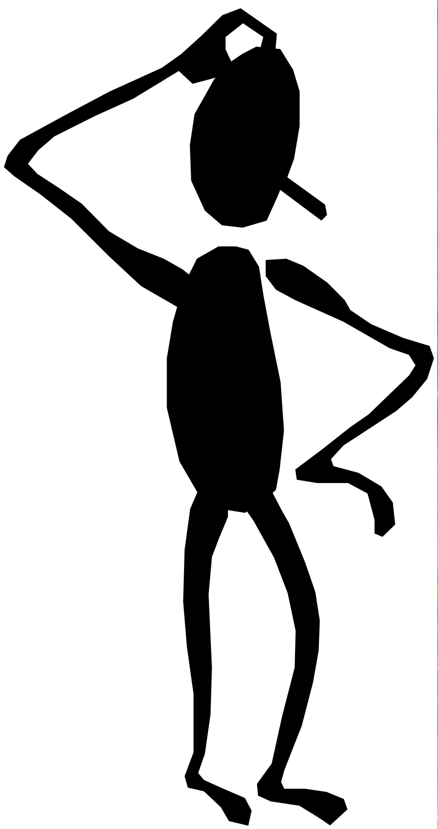


What? Kevin doesn't work at the LHC?
LHC will (very likely) blast Higgs bosons out of hiding
proton
BLAM!
Higgs condensate
proton
Need
$E=mc^2$
Isolated Higgs particle
ejected from
Decaying into
background "noise" of
carefully
"Seen
There must be some mistake

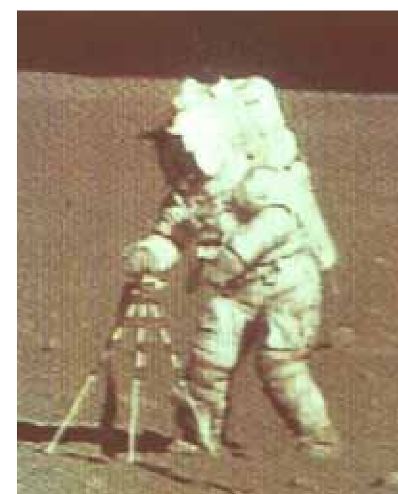
Perhaps he prefers the Japanese coffee to that in Switzerland?

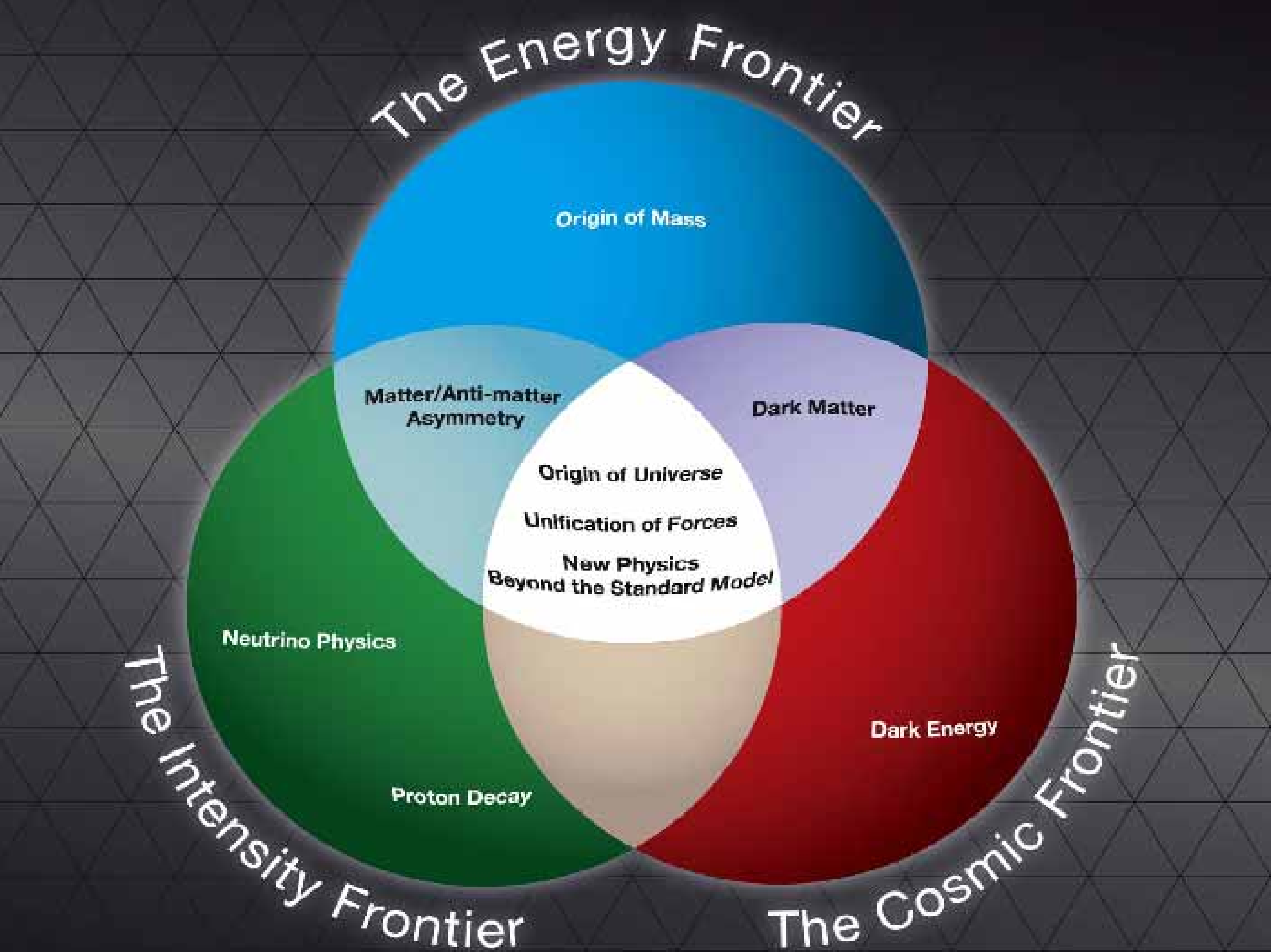


Frontiers

- Particle Physics is a science of exploration
  - We may have good ideas of what we might find, but we do not know until we look
- The frontier of energy (per particle) is our most important tool, *but it is only one tool*



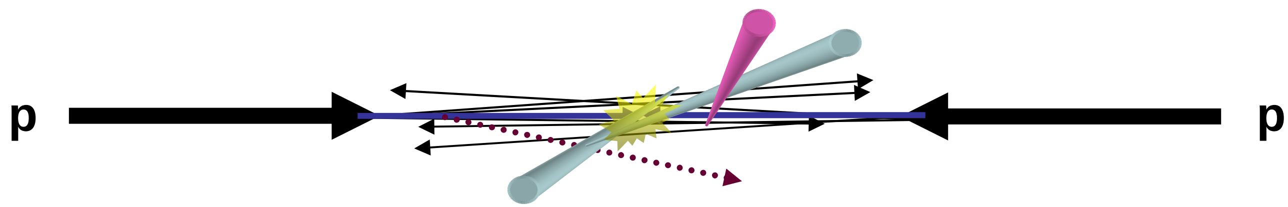




The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
The Intensity Frontier
The Cosmic Frontier

What is the *Intensity* Frontier?

- The LHC is optimized for maximum energy in the collision of two protons
  - 14 TeV (or 0.0000002 Joules) per proton pair



  - occasionally a large fraction of that energy is available for production of new particles
  - therefore, LHC must store and collide many protons to be at the energy frontier

What is the *Intensity* Frontier?

- The LHC is optimized for maximum energy in the collision of two protons

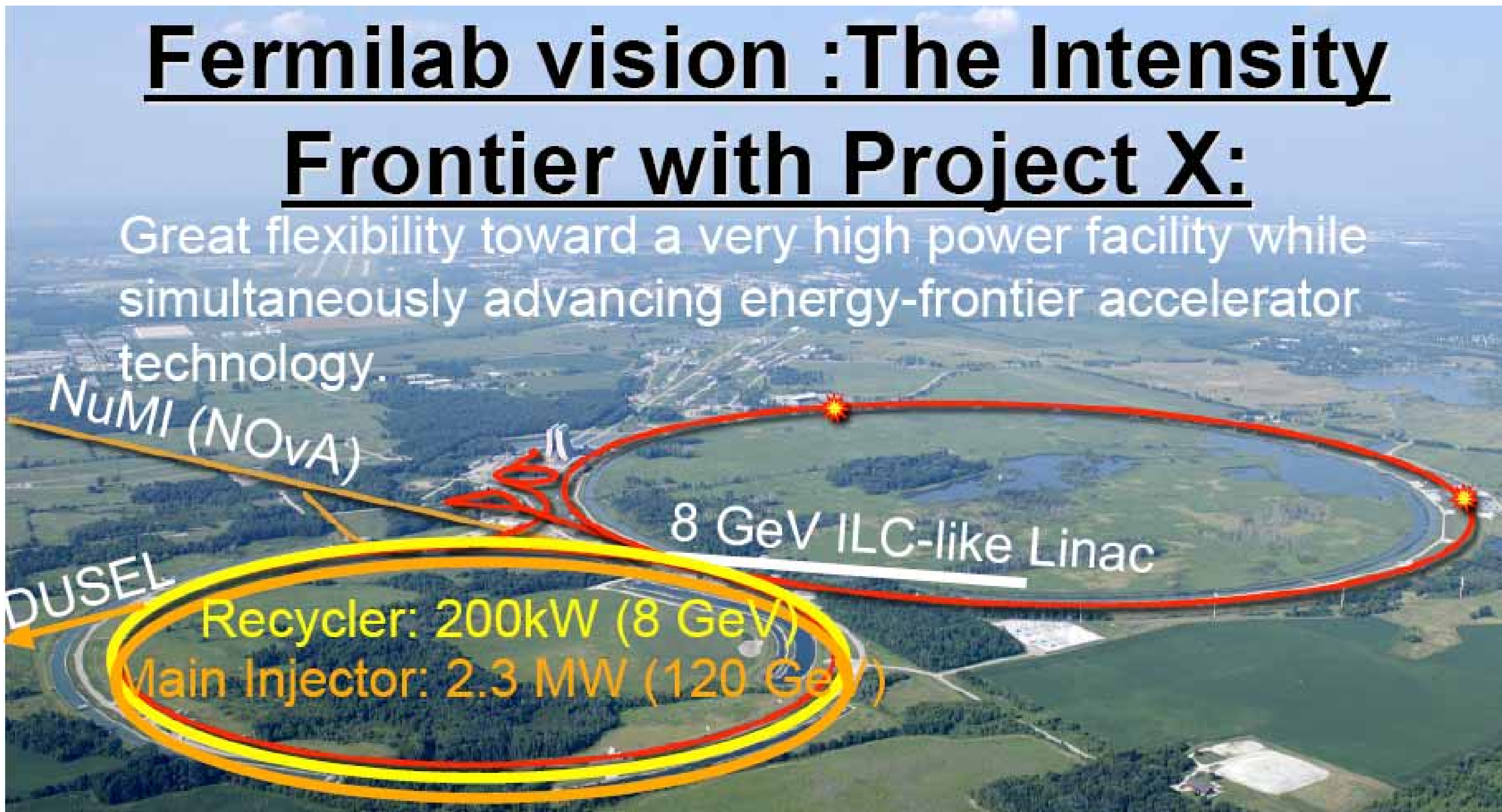
- Other accelerators aim to create very high numbers of lower energy particles in colliding beams or single extracted beam
  - useful for creating large numbers of other particles to study their properties
  - we sometimes call these machines “factories”

Where is the *I n t e n s i t y* Frontier?

- There are many intensity frontiers
  - Bottom quarks: Stanford (recently ended) and KEK in Japan; next facility in Italy?
  - Charm quarks and tau leptons: Cornell (recently ended), Beijing
  - Weak bosons: successful CERN and Stanford programs concluded in the late 1990s
  - Neutrons and Photons: many facilities, mostly aimed at biological and material sciences
- Active development in particle physics: *proton sources for neutrinos*

Where is the *I n t e n s i t y* Frontier?

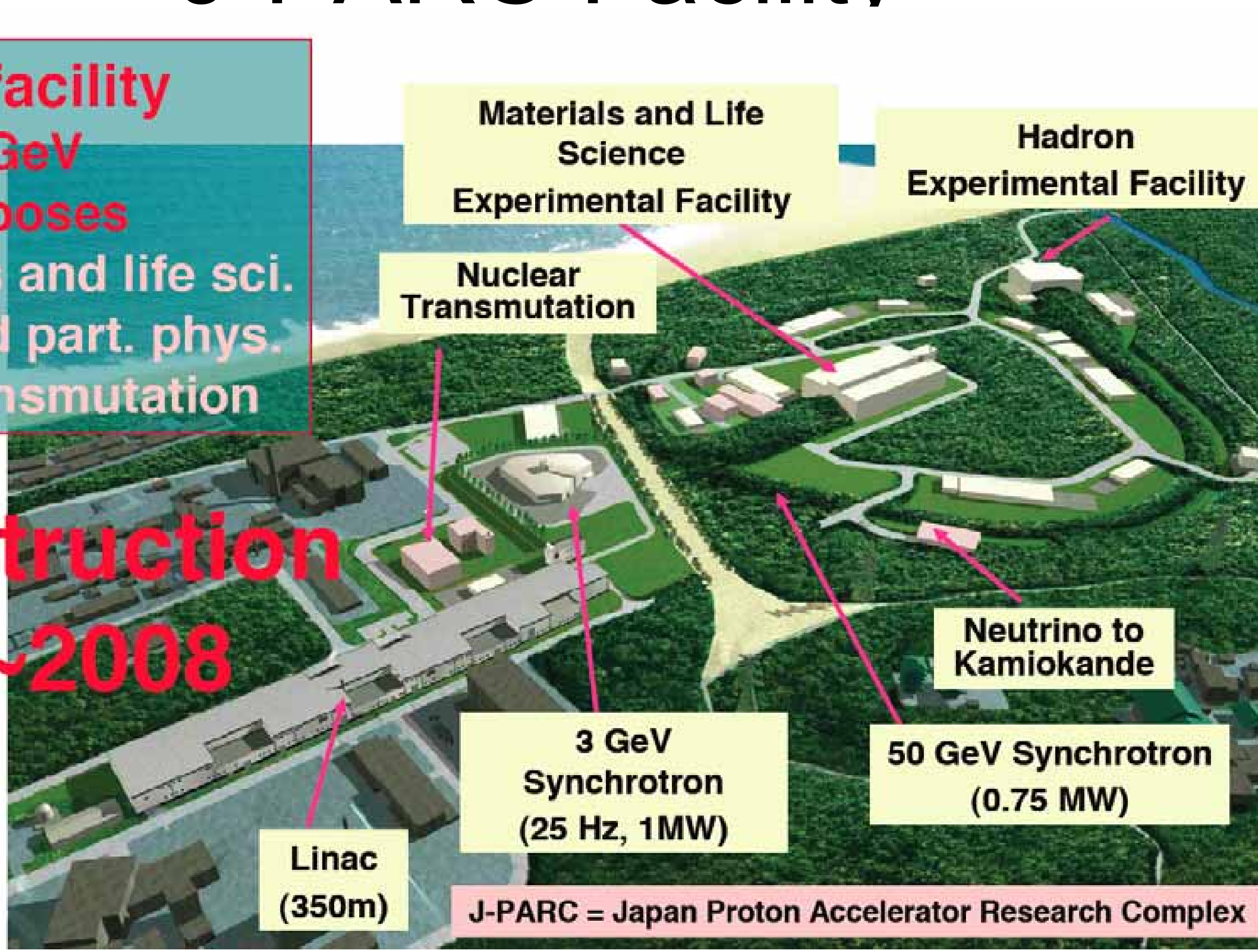
- Now at Fermilab… again in the future?



J-PARC Facility

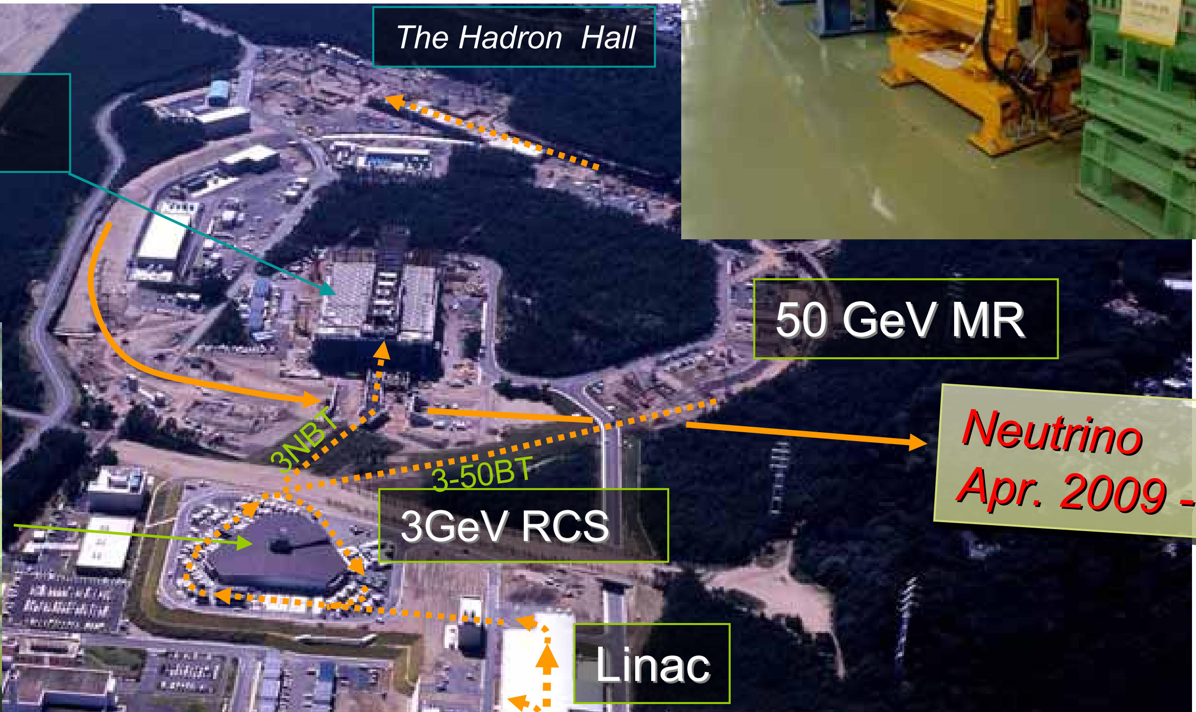
Unique facility
3GeV+50GeV
Multi-purposes
- Materials and life sci.
- Nucl. and part. phys.
- Nucl. transmutation

Construction 2001~2008



Status of J-PARC

MR commissioning May, Jun, Dec~ in 2008

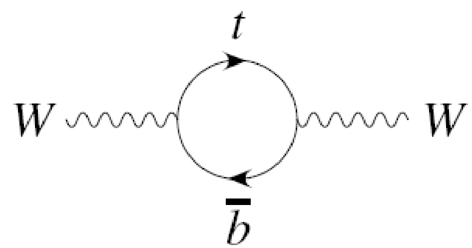


3 GeV RCS beam commissioning succeeded in Nov. 2007

Linac succeeded in 181 MeV acceleration in Jan. 2007

What science is done at the *Intensity* Frontier?

- We study the “shadows” of high energy phenomena with quantum fluctuations



- We explore the most difficult corner of the known building blocks of matter…
  the neutrino

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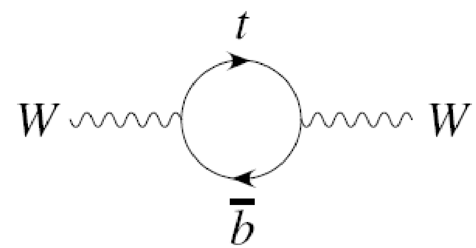
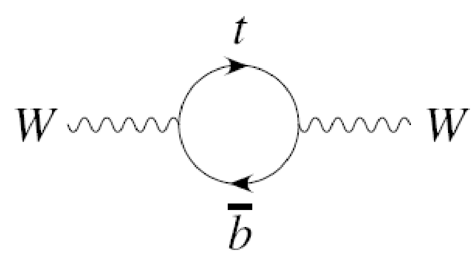


- We explore the most difficult corner of the known building blocks of matter… the neutrino

Quantum Fluctuations

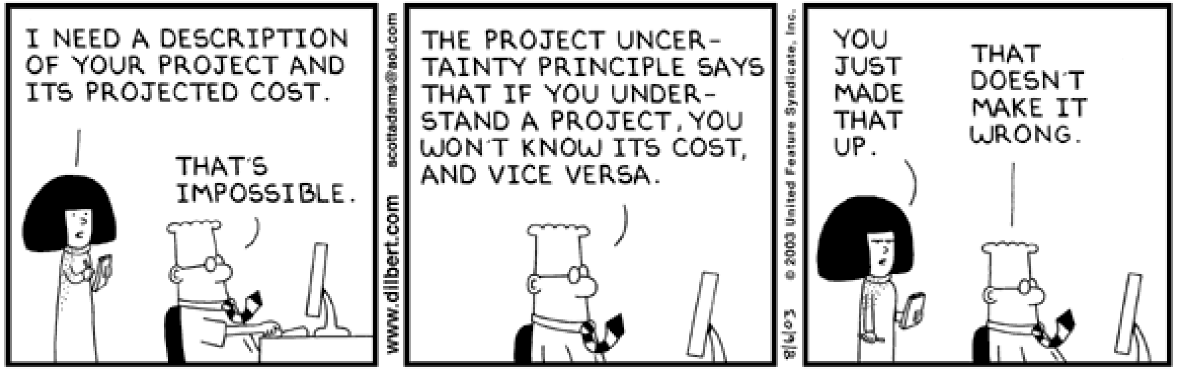
PRECISION LOW-ENERGY TESTS
$E < E_{KK}$ sensitive to quantum
"shadows" of KK excitations ⇒
$E_{KK} >$ few TeV (10^{12})
near limits of LHC reach.
Even lowest KK excitations will be challenging...

- Heisenberg's Uncertainty Principle allows us to study processes that are impossible for the amount of energy available
  - in the process at right,
    a W boson fluctuates into
    a top and bottom quark pair
  - however, the mass of the W boson is less than that of the top quark
  - *how can this happen? is it real?*



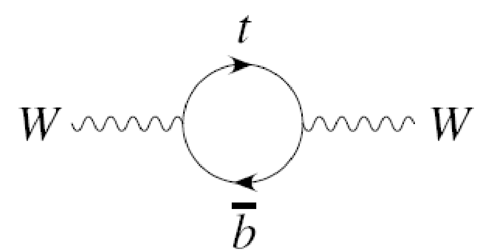
Quantum Fluctuations

- Heisenberg says $(\Delta E)(\Delta t) > \frac{\hbar}{2}$
  - this uncertainty allows us to "borrow" energy from the vacuum, but only for a short time
  - *One interpretation of this is that it takes time to measure the energy so violation of energy conservation never occurs.*



Quantum Fluctuations

- Heisenberg says $(\Delta E)(\Delta t) > \frac{\hbar}{2}$
  - this uncertainty allows us to “borrow” energy from the vacuum, but only for a short time
- The W boson may spend some of its time as a top and bottom quark pair…

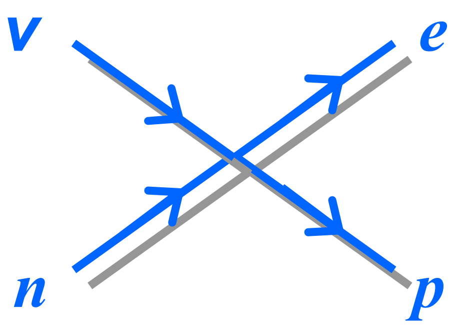


  - but it must return the original W boson
- *This fluctuation makes a measurable quantum correction to the mass of the W*

Let's Calculate a Quantum Fluctuation!

$$\nu n \rightarrow e^- p$$

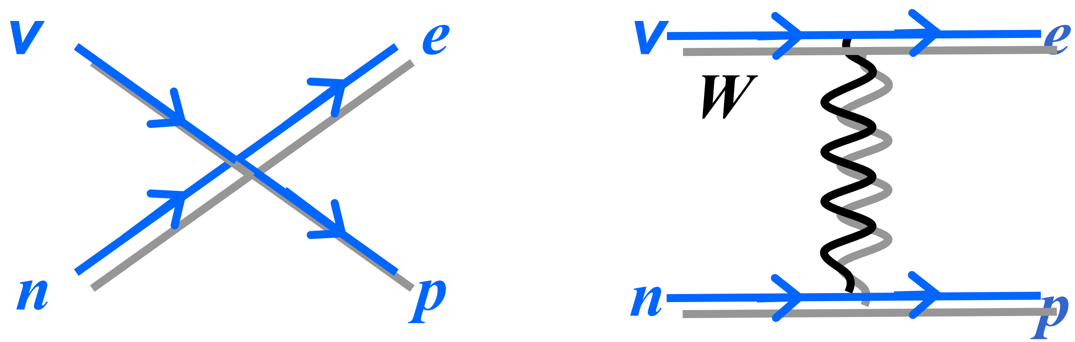
- In this process, an incoming neutrino hits a neutron and changes it to a proton.
- The neutrino becomes an electron.



Let's Calculate a Quantum Fluctuation!

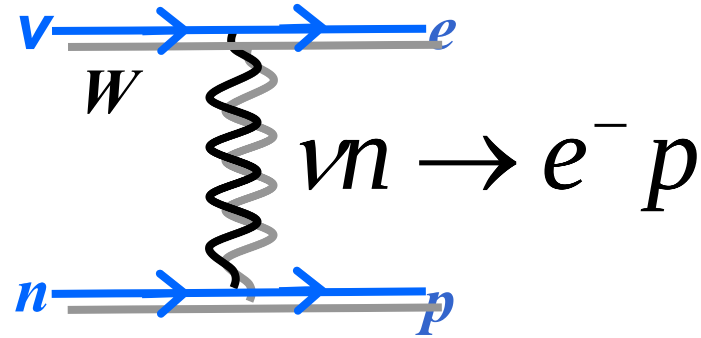
$$\nu n \rightarrow e^{-} p$$

- This reaction involves the exchange of a W boson with a mass of ~80 GeV/c^2



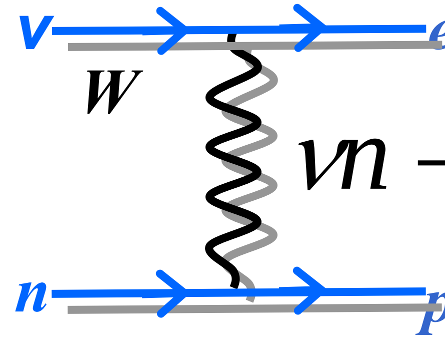
- *but this reaction typically will have only a few GeV of available energy to produce the W*

Let's Calculate a Quantum Fluctuation!



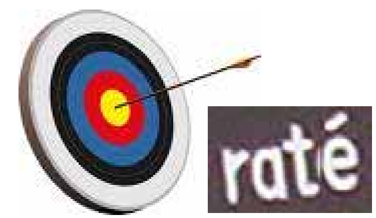
- How much energy do we have to borrow?
  - the whole W mass, more or less, 80 GeV/c^2
- $(\Delta E)(\Delta t) > \hbar/2 = 3\times 10^{-25}\,\text{GeV}\bullet\text{sec}$
  - so the time required to measure the violation is $\Delta t > 4\text{x}10^{-27}$ sec
- How far can the W travel in this time?
  - speed of light c~3x10^8 m/s, so 10^{-18} m
  - *this is distance to the bulls-eye (a quark) that the neutrino "arrow" can miss*

Let's (Try to) Calculate a Quantum Fluctuation!



$$\nu n \to e^- p$$

- 10^{-18} m is 1/1000 of the proton's radius
  - the interaction of a neutrino should be a millionth as likely as a proton-neutron process (relative target area)
- *Is that right?*
  - Umm… no. It's closer to a trillionth



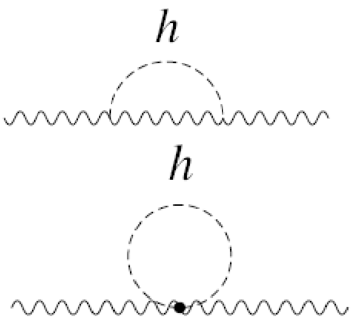
    - The simple "optical" bulls-eye model isn't correct
    - However, it does capture key qualitative features
- *Quantum fluctuations are rare, and more rare if you must borrow more energy!*
- *Quantum fluctuations make "weak" weak*

Quantum Fluctuations of Weak Bosons

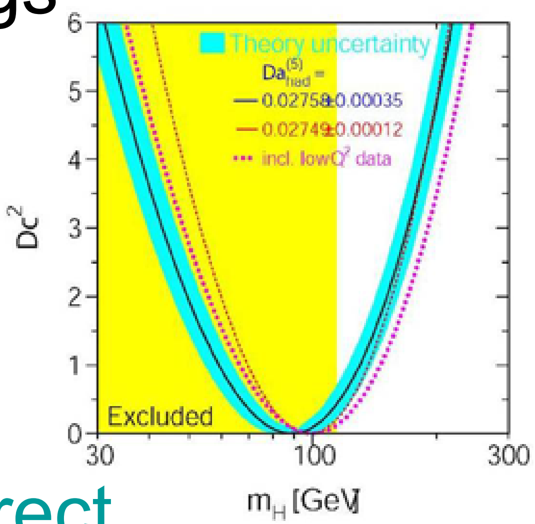
- Main intensity frontier program of 1990s produced few 10^7 Z and 10^5 W bosons
- A literal catalog of precision measurements of quantum fluctuations involving these bosons
  - it was literally impossible to go to a particle physics conference for twelve years and not see a form of the tabulated measurements to the right

Quantum Fluctuations of Weak Bosons

- Main intensity frontier program of 1990s produced few 10^7 Z and 10^5 W bosons
  - What did we learn?
- Studies of quantum fluctuations of bosons and in their interactions measured corrections from the Higgs



- The size of those corrections depended on how much borrowed energy was needed
  - we know (roughly) the Higgs mass, at least if the theory is correct…



What science is done at the *I n t e n s i t y* Frontier?

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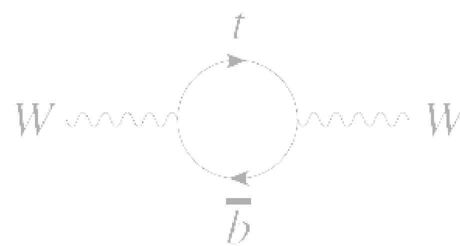
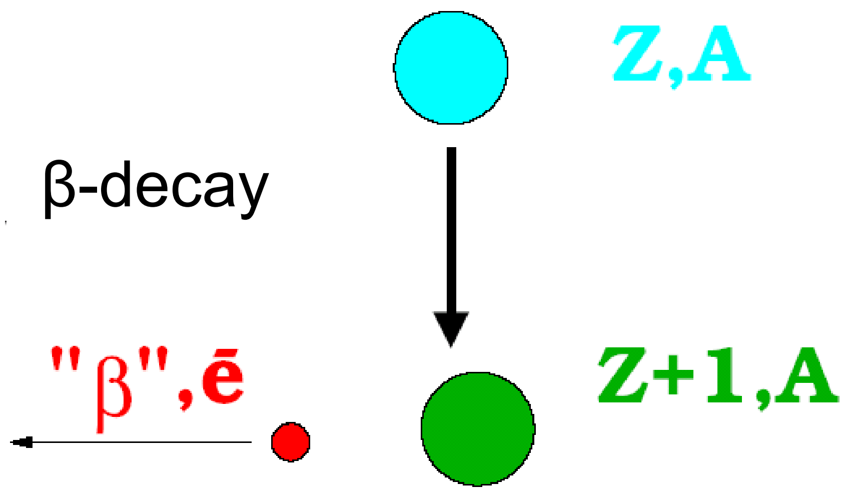
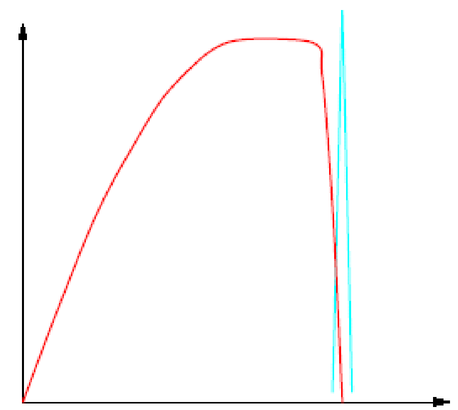


- We explore the most difficult corner of the known building blocks of matter… the neutrino

Beta Decay and Neutrinos





The Energy of the "β"

- If the above picture is complete, conservation of energy says β has one energy
  - but we observe this instead
- Pauli suggests in 1930 a light particle he calls a "neutron" takes away energy!
  - Chadwick steals the name; Fermi suggests "neutrino"

Is it just About Nuclear β-Decay?

- I hope not! Otherwise… *yawn*

- Let's put β-decay in the contact of the four fundamental forces
  - Gravity
  - Electromagnetism
  - Strong Nuclear Force
  - Weak Nuclear Force

The Other Fundamental Forces

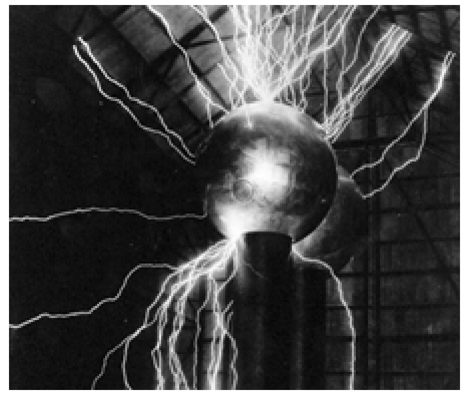
- Three of the four fundamental forces are important for the structure of matter around us

Gravity

- holds planets, galaxies, etc. together

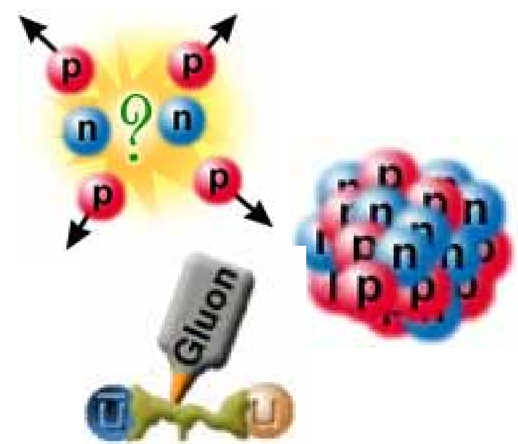
Electromagnetism

- holds atoms together
- keeps matter from collapsing under the force of gravity



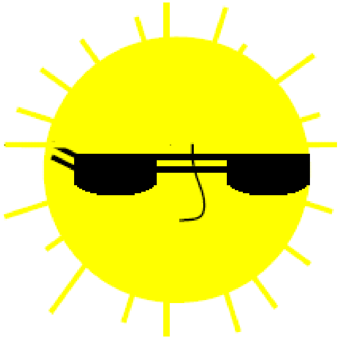
Strong force

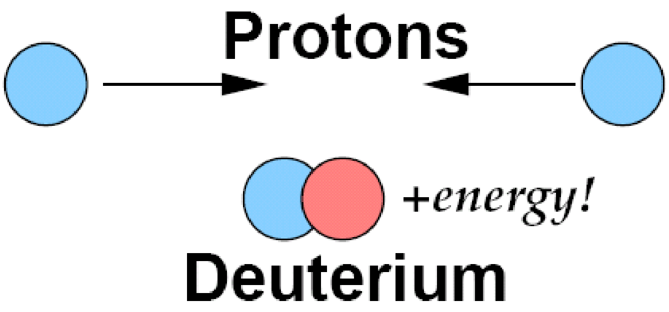
- holds nucleus together
- so strong that quarks are confined



β-Decay?

- Weak Nuclear Force
  - its role is to, well, make β-decays
  - that sounds awfully anticlimactic… who cares?
    - actually, you do. A lot.

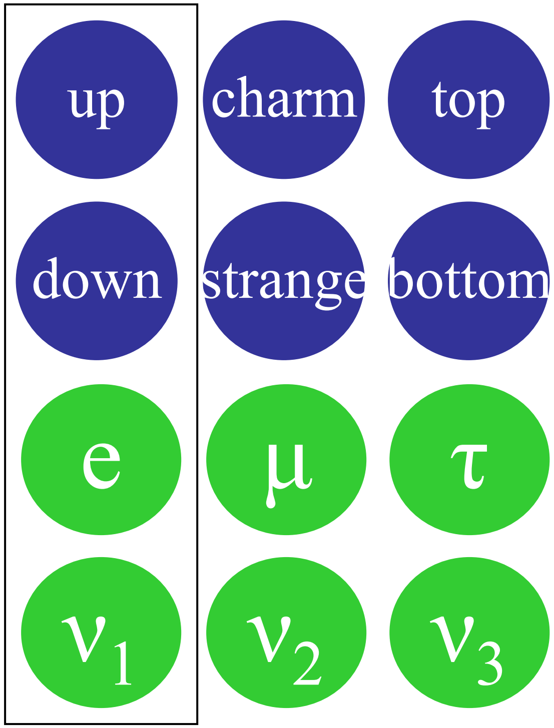


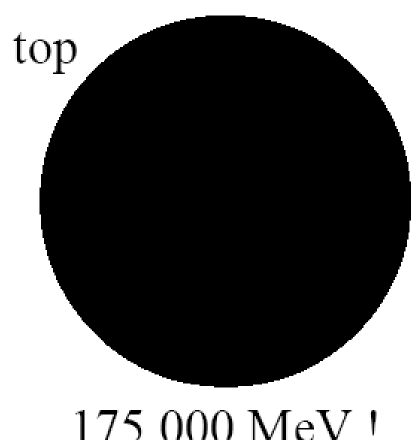


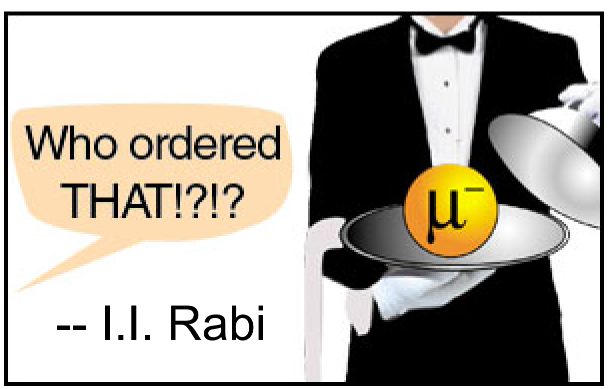
  - Fusion in the sun requires that a proton turn into a neutron. Inverse of β-decay!

Generations of Matter

- the particle "periodic table" has up and down quarks which make protons and neutrons
- which bind with electrons → atoms
  - *a neutrino is there, for beta decay!*
- so what's all the stuff to the right?
  - there just appear to be three copies ordinary matter
  - distinguished only by mass



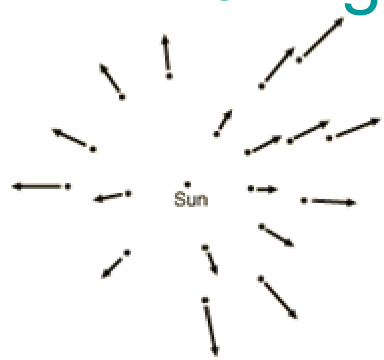


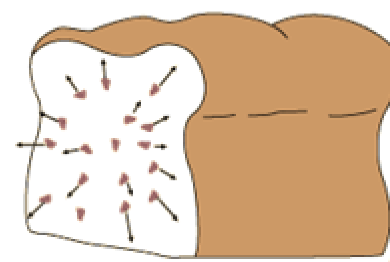


(Abridged) History of the Universe

(Student Tested! Easy demonstrations!)

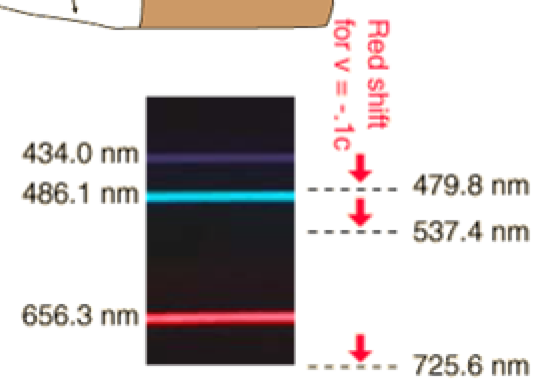
- In the beginning, the Universe was very small and very hot
  - Why small? Well, if we look at other galaxies, we see they are ALL moving away from us?





  - It is something we said? No.

  - How do we know? Doppler shift of light.



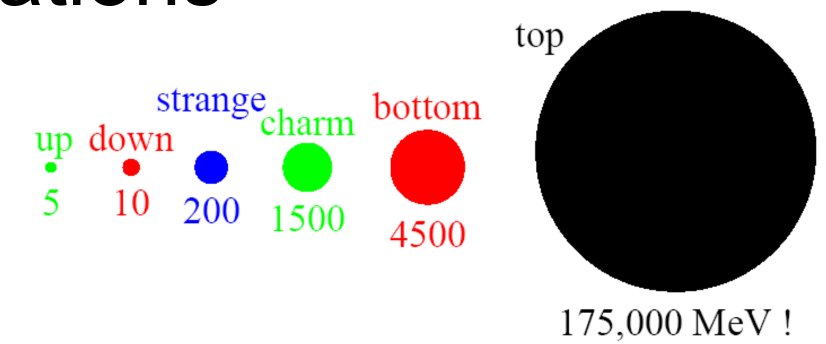
(Abridged) History of the Universe…

(Student Tested! Easy demonstrations!)

- In the beginning, very small and very hot
  - Why hot?
  - When you let a gas expand, it cools…
- Now remember mass is energy ($E=mc^2$)
- And heat is energy too.
  - Very early in the Universe, it was so hot that the masses of the different generations didn't matter to the particles
  - Then as the universe cools, suddenly generational mass differences were a big deal, and the massive generations needed to shed their extra mass (energy)

β-Decay and the Universe

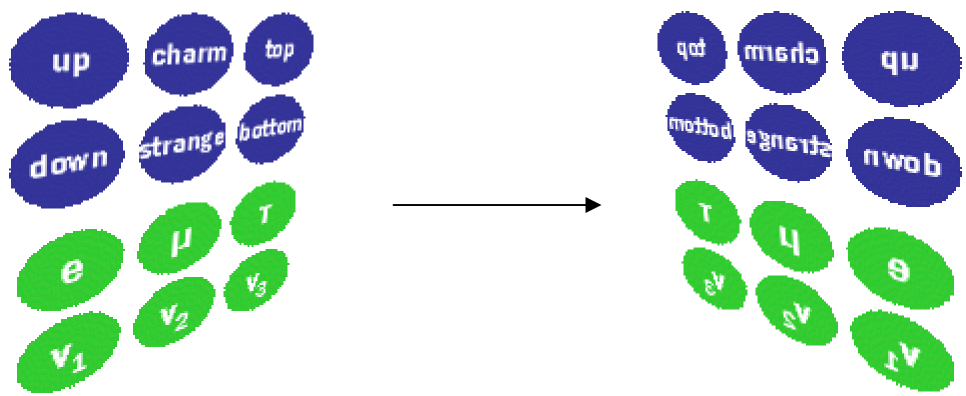
- Extra generations must have shed mass by decaying to light generations
  - Why? Well, we don't see the heavy ones today in the Universe!



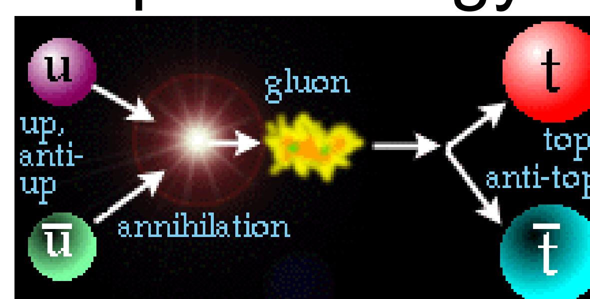
- And the only way for that to happen is…
  - β-Decay!!
  - Just as neutrons could decay to protons by β-decay, so heavy generations decay to light.

Matter and Anti-matter in the Universe

- Every fundamental particle has an anti-matter partner



- When the meet, they annihilate into pure energy. Alternatively, energy can become matter plus anti-matter

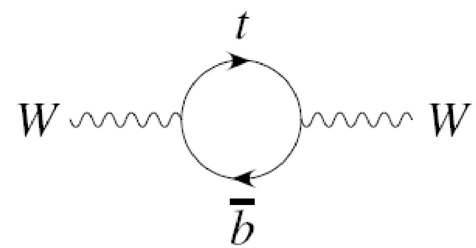


So you might ask…

- The early Universe had a lot of energy. Where is the anti-matter in the Universe?
- It isn't visible in the Universe today
  - We look for annihilations.
  - As far away as we can tell, today there aren't big matter and anti-matter collisions
- Why not? Oh, and why is there left over matter after annihilations?
  - *How did we get left behind?*

What science is done at the *Intensity* Frontier?

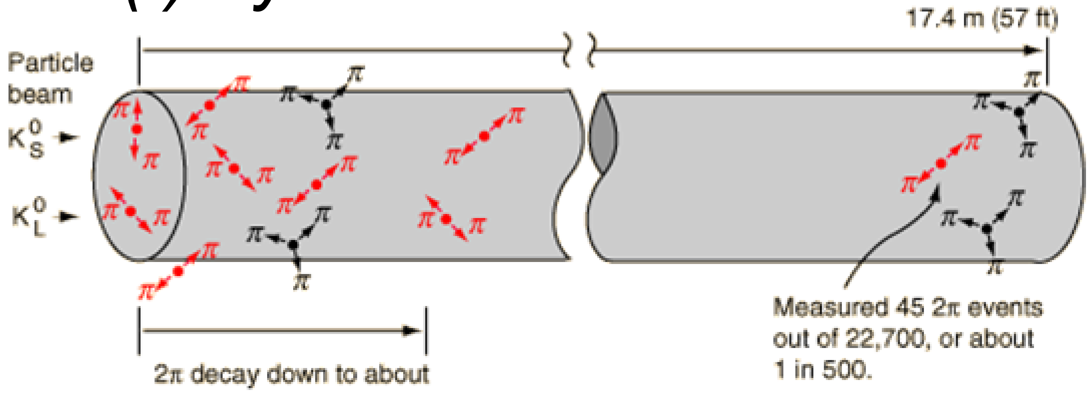
- We study the “shadows” of high energy phenomena with quantum fluctuations



- We explore the most difficult corner of the known building blocks of matter… the neutrino

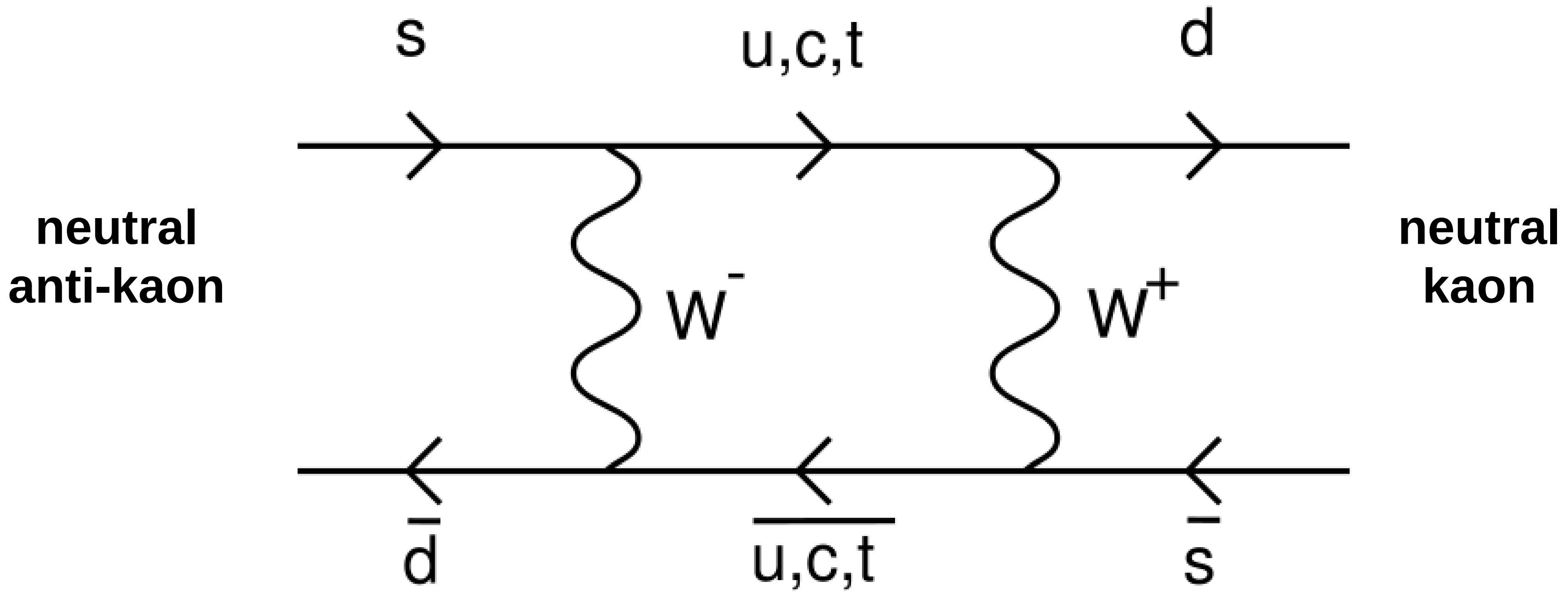
Quantum Fluctuations and Rare Violations of Symmetries

- "CP" symmetry predicts particles and their anti-particles have identical decay rates
  - but in studies at the intensity frontier, we know that CP is violated!
- *First observed in 1964(!) by Cronin and Fitch*
  - decay of a long-lived "kaon" forbidden by CP



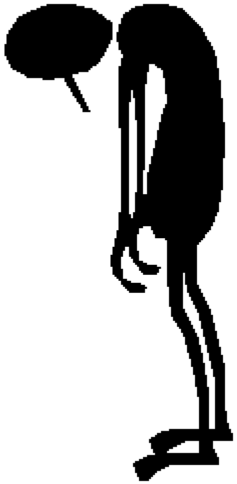
Quantum Fluctuations and Rare Violations of Symmetries

- How was CP violated?
  - Quatum fluctuations involving particles of the third generations. At least three generations are required for this phenomenon!



Quantum Fluctuations and Rare Violations of Symmetries

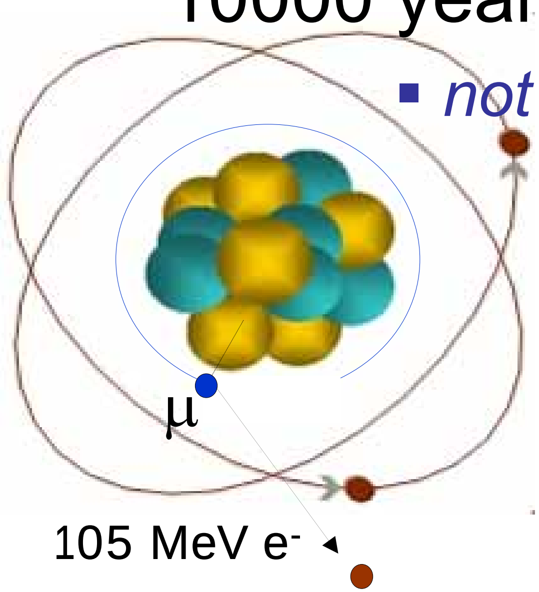
- *To recap…*
  - The universe has more matter than anti-matter, which requires matter and anti-matter to behave differently
  - CP violation has been discovered, which allows different decay rates of unstable matter and anti-matter
  - *This has led to a broad program of CP violation physics at the intensity frontier!*

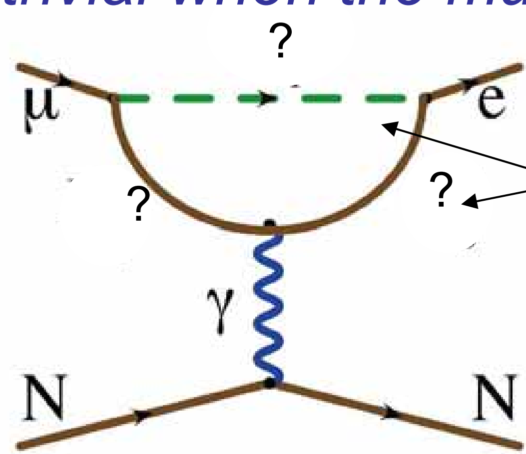


- The conclusion of which is that…
  - This CP violation in quarks is not sufficient to explain the amount of left-behind matter we see today

Quantum Fluctuations and Rare Violations of Symmetries

- What is the heir to these sorts of studies?
  - A promising one is looking for conversion of generations *without neutrinos* in μ→e
  - We think we can "wait" the equivalent of 10000 years for this rare thing to happen
    - *not so trivial when the muon lives 2 μs !*

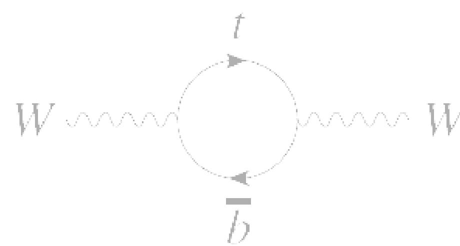




we don't know what these might be, but they might help us understand generations if we find them!

What science is done at the *Intensity* Frontier?

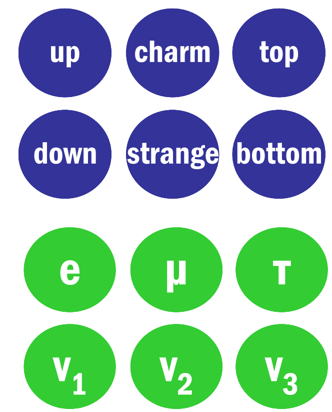
- We study the “shadows” of high energy phenomena with quantum fluctuations



- We explore the most difficult corner of the known building blocks of matter…
  the neutrino

Where are Neutrinos Found?

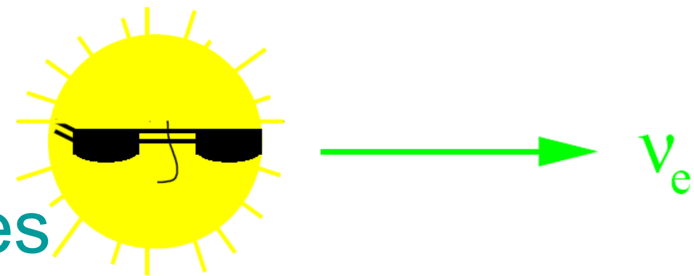
- We should find neutrinos anywhere there are weak interactions!



- The early Universe
  - Decays of heavy generations left a waste trail of 100/cm^3 of each neutrino species
  - They are (now) very cold and ***slow*** and hard to detect
  - But if they have even a very small mass, they are a significant part of the mass of the universe
    - as much as atoms, according to the latest results

Where are Neutrinos Found?

- In the sun

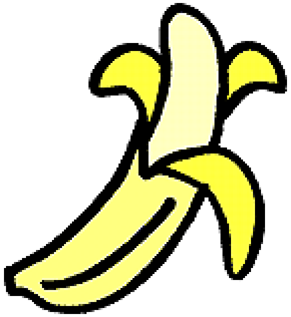


  - If the sun shines by fusion, energy reaching earth in light and in neutrinos is similar
  - 100 billion neutrinos per cm^2 per second rain on us

- Supernova 1987A (150000 light years away) exploded, releasing 100 times the neutrinos the sun will emit in its whole lifetime
  - we observed 11 neutrinos in detectors on earth!

Where are Neutrinos Found?

- Bananas?

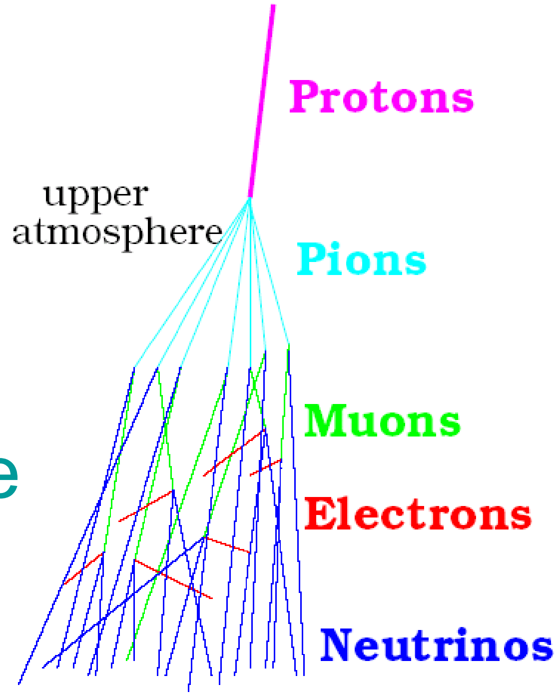


  - We each contain about 20mg of ^{40}K which is unstable and undergoes β decay
  - So each of us emits 7500 neutrinos/sec

- For the same reason, the radioactivity of the earth results in 10 million neutrinos per cm^2 per second here

Where are Neutrinos Found?

- Cosmic Rays
  - Cosmic rays from galaxy
  - Each particle (mostly protons) has many GeV of energy
  - Collisions in upper atmosphere create particles which decay (weakly) to neutrinos

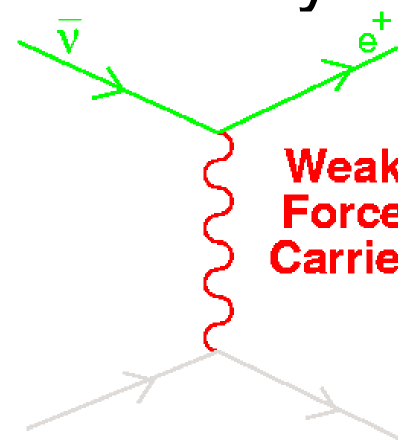


- *We use the same technique to produce neutrinos at intensity frontier accelerators*

Neutrino Generations

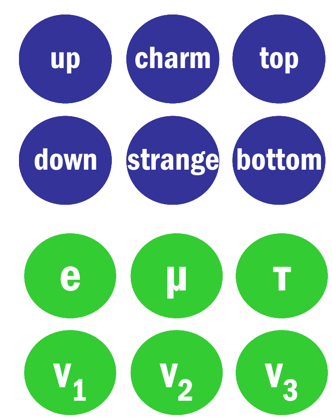
- Remember that neutrinos were discovered by

$$\bar{\nu}\, p \rightarrow e^{+} n$$



  - the appearance of the positron is not without information
  - we can observe *three* types of neutrinos, each associated with a generation (or "flavor")

$$\nu_e \leftrightarrow e$$
$$\nu_\mu \leftrightarrow \mu$$
$$\nu_\tau \leftrightarrow \tau$$



- There are also three different masses of neutrinos, but…

Would the real neutrino please stand up?

- Are these neutrinos "of definite flavor" the "real neutrinos" (definite mass)

$$\nu_e \leftrightarrow e$$
$$\nu_\mu \leftrightarrow \mu$$
$$\nu_\tau \leftrightarrow \tau$$

- Or are we looking at neutrino puree?

- *And of course, is the puree just a "good mixture" or does it have implications*

couldn't resist this phrase… my wife's grandfather used to use it to describe anything with enough ketchup on it

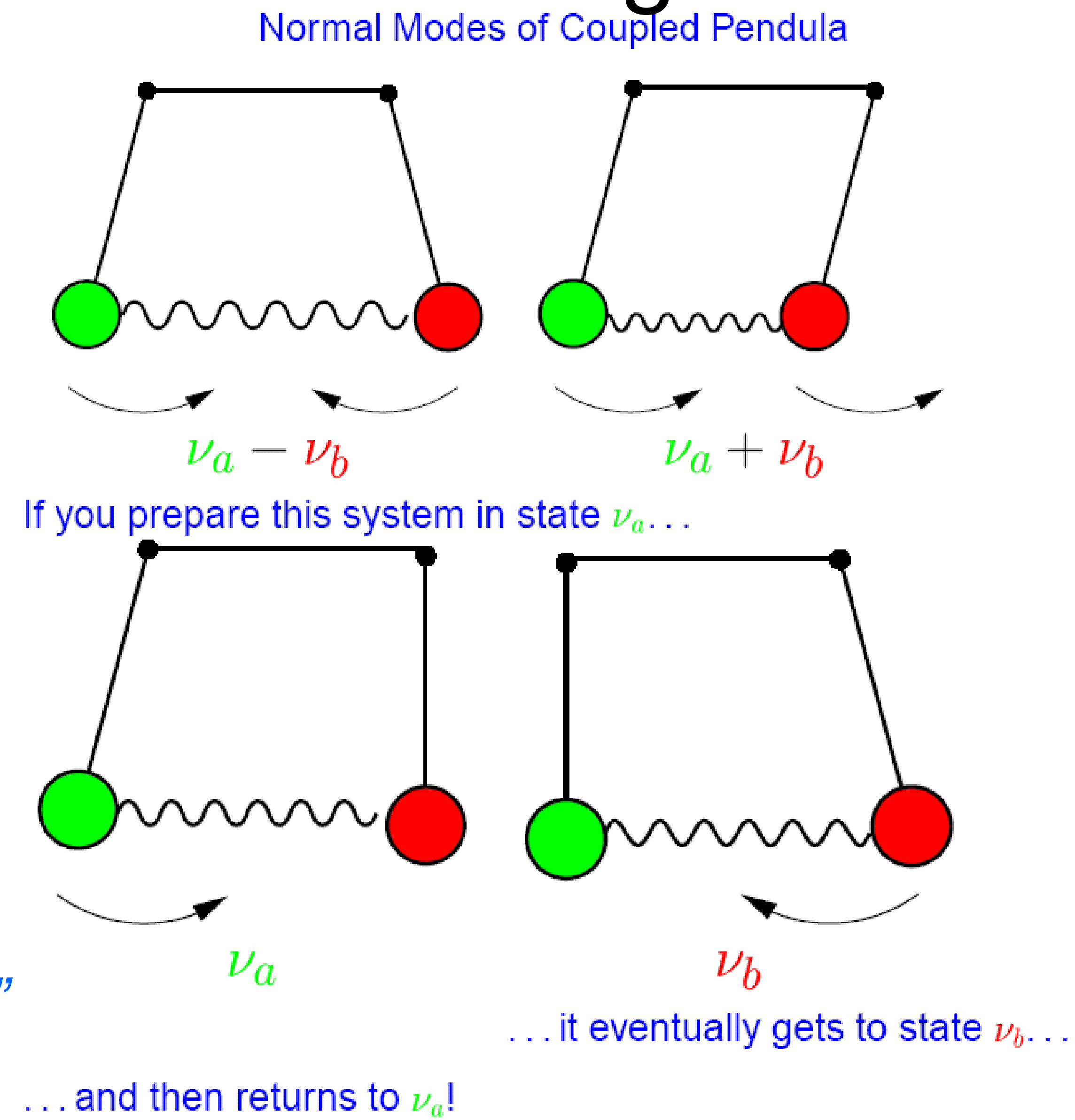
Neutrino Flavor Mixing

- What if neutrinos are a puree?
  - "normal modes" not ***a*** or ***b*** but a mix

- *What happens to the pendulum?*

This is called "neutrino flavor oscillation"

a*→*b*→*a



Our Goals for Neutrino Oscillations

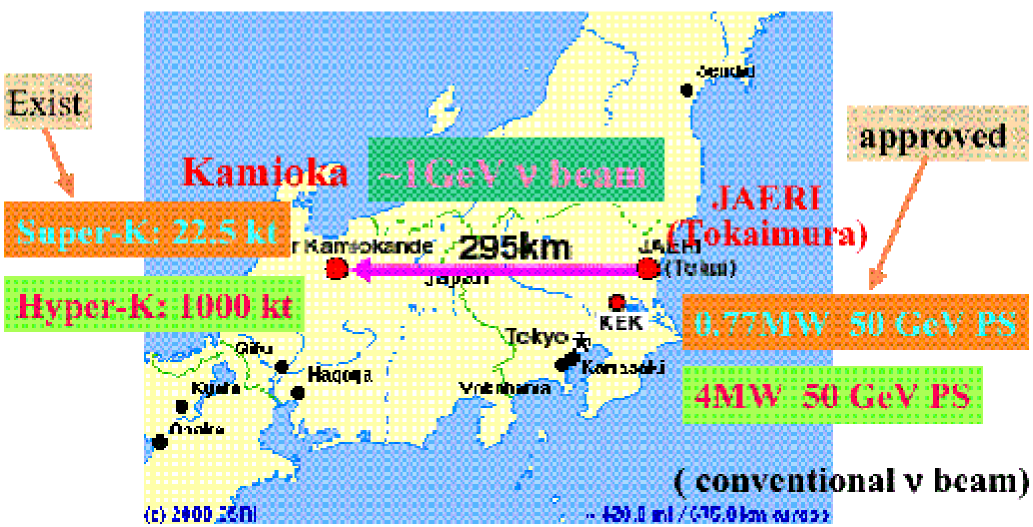
- Can we show that…

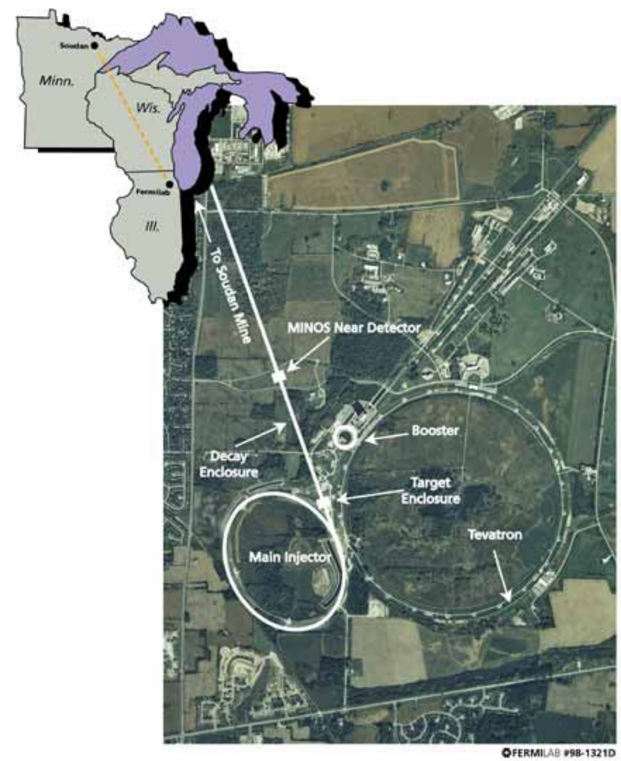
  …neutrinos cause a large matter vs. anti-matter asymmetry in the Universe!

  - *Because of three neutrinos, it may be so!*
- We are using intensity frontier accelerators to make neutrinos to study whether or not neutrino anti-neutrino differences seeded this as the Universe cooled…

Future Neutrino Hunting

- New Ideas afoot
- Produce neutrinos at accelerators, send them long distances to massive detectors

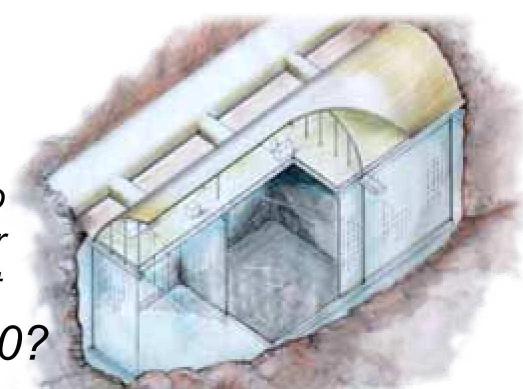




What does it take?

- Megawatts of accelerated protons to produce neutrinos
  - e.g., J-PARC beam: 0.8-4.0 MW

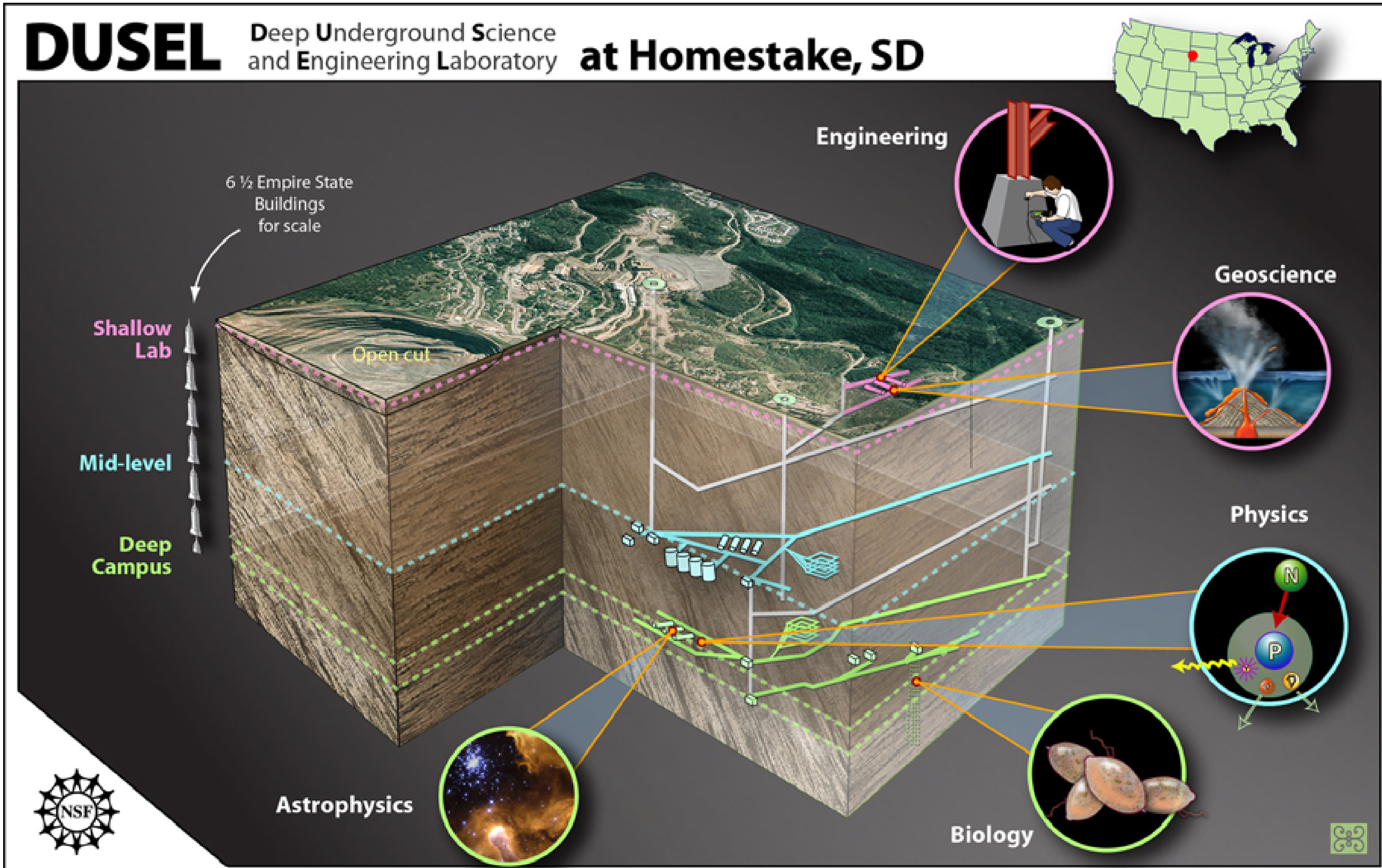
- 100-1000kTon detectors, hundreds of km from source
  - 1MTon is a cube of water, 100 meters on a side



UNO neutrino detector concept

~2020?

A Facility for the Intensity and Cosmic Frontiers…

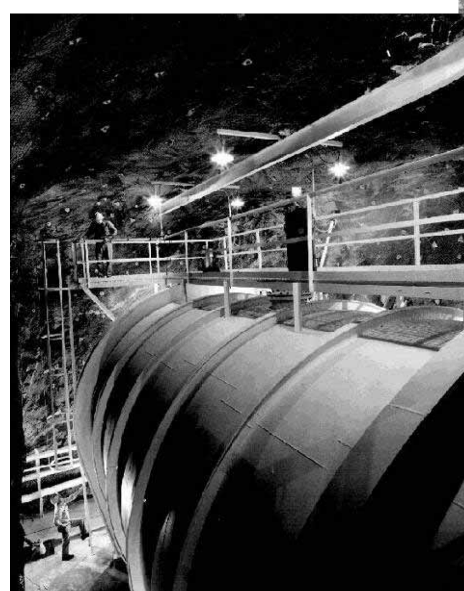


History of DUSEL

- Active gold mining area from 1830s

- Very deep mine

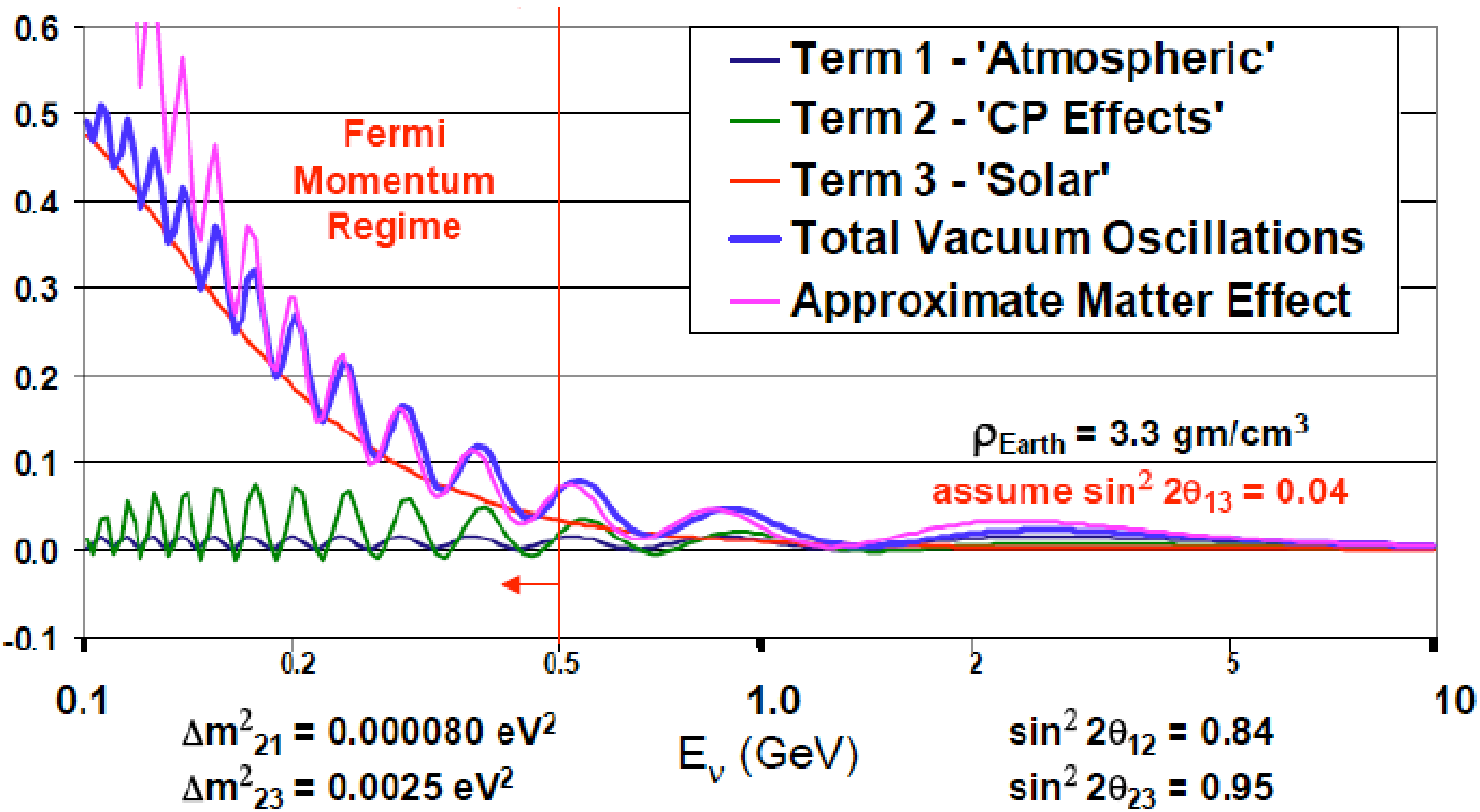
- Neutrinos were mined here!
  - neutrino emission from the sun found in 635 tons of dry-cleaning fluid
  - *now we want to send a neutrino beam there!*



- *The same facility can host detectors for dark matter*
- **Gold, indeed**

Measuring CP Violation in Neutrino Oscillations at DUSEL

$P(\nu_\mu \rightarrow \nu_e)$



← increasing oscillation time

increasing neutrino energy →

Conclusions

- While the LHC is our flagship…

  … particle physics has many frontiers under active exploration

  - These other frontiers inform and motivate our current and future plans for the energy frontier
  - These frontiers also access phenemona the LHC will not address and broaden our reach
    - riskier in the LHC… only a part of our portfolio!
- *What do I expect to see at the LHC from my view on the sidelines?*


GOAL!

Force Carriers and Particles