# *The Fermi National Accelerator Laboratory:*
## *How Frontier Physics meets Medical Sciences*

*Young-Kee Kim*
*Fermilab and the University of Chicago*

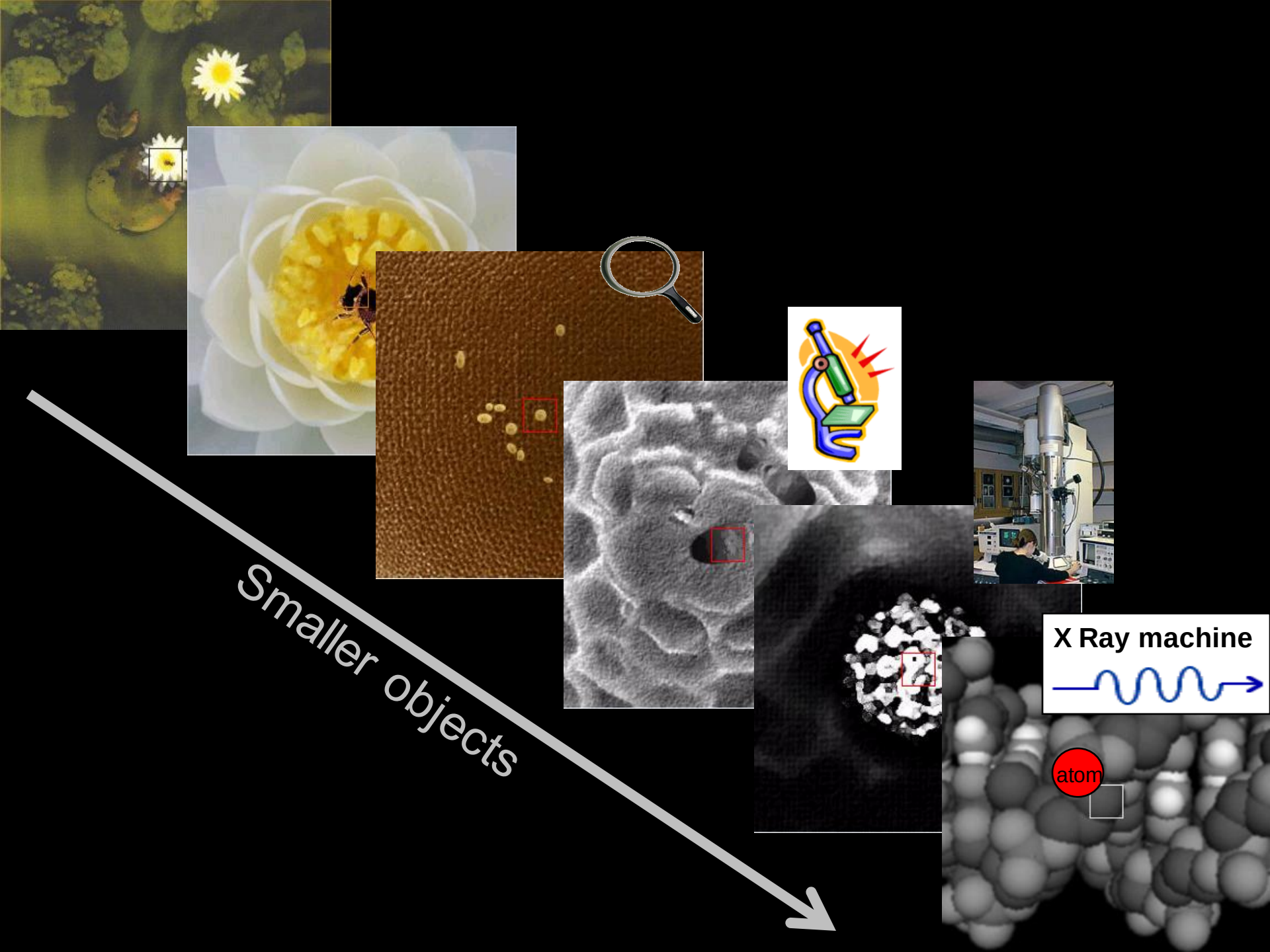
*Erice International School of Scientific Journalism and Communication*
*May 9 – 13, 2010, Erice, Sicily, Italy*

What is the world made of?
What holds the world together?
Where did we come from?

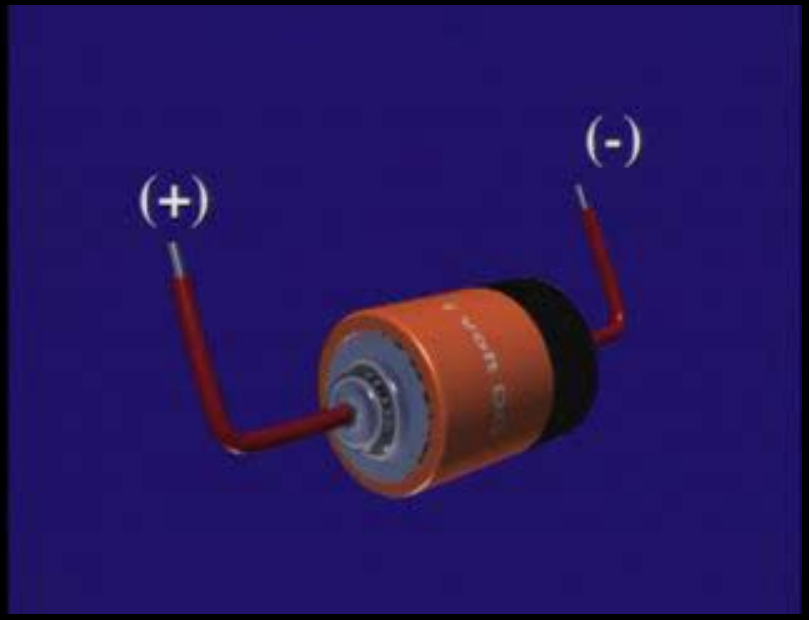
Tools ?

the smallest things in the world
interactions (forces) between them
the Universe's past, present, and future

Particle Physics: physics where
small and big things meet,
inner and outer space meet


Smaller objects
X Ray machine
atom

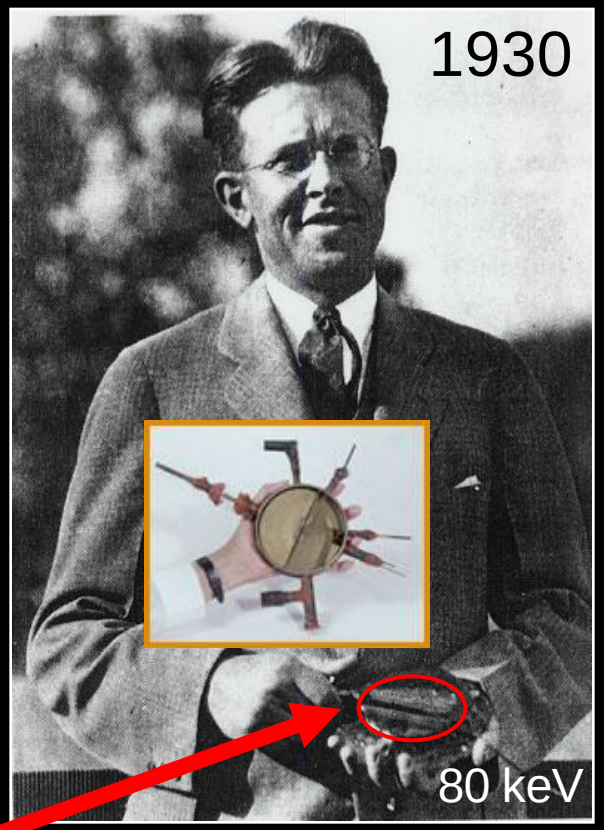
# Accelerators



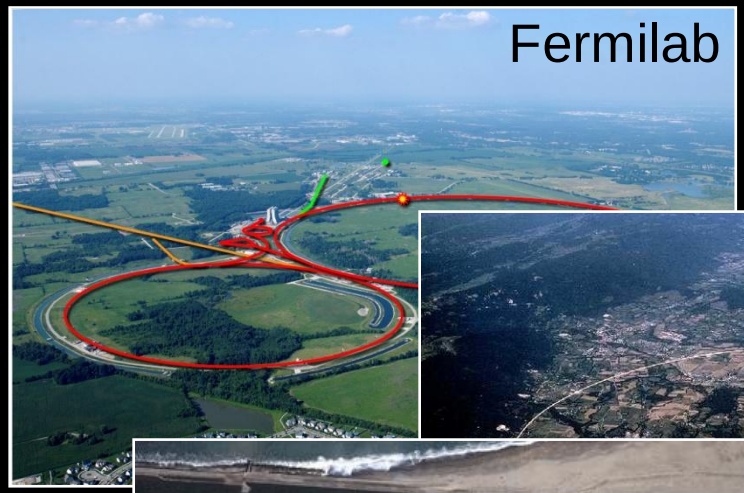

1 eV (electron Volt)
1 electron in 1 Volt battery

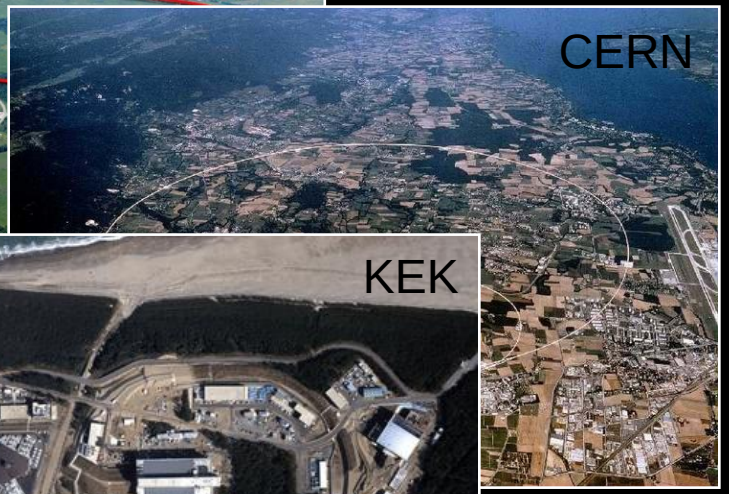
GeV (billion eV)
TeV (trillion eV)

Many generations of particle accelerators:
each generation built on the accomplishments of the previous ones
raising the level of technology ever higher




Ernest Lawrence
(1901 - 1958)

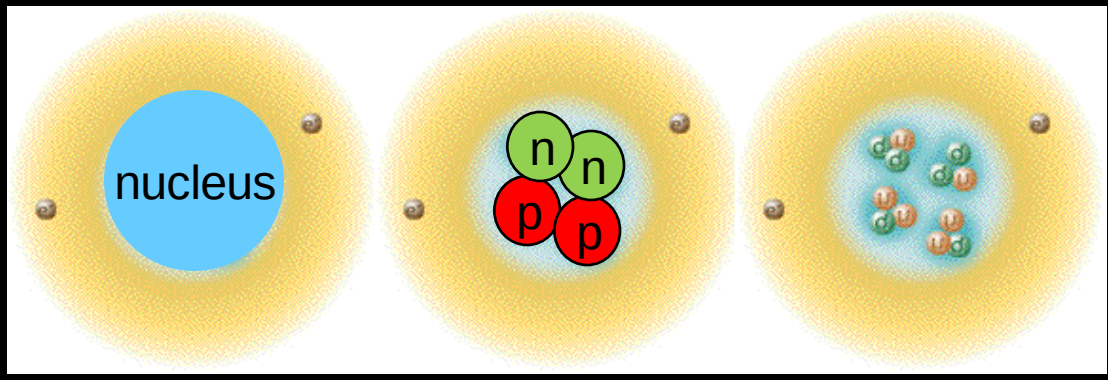



# Accelerators are Ultimate Microscopes.

(higher energy beam particle = better resolution / small objects)

*What is the world made of?*




up quark, down quark, electron

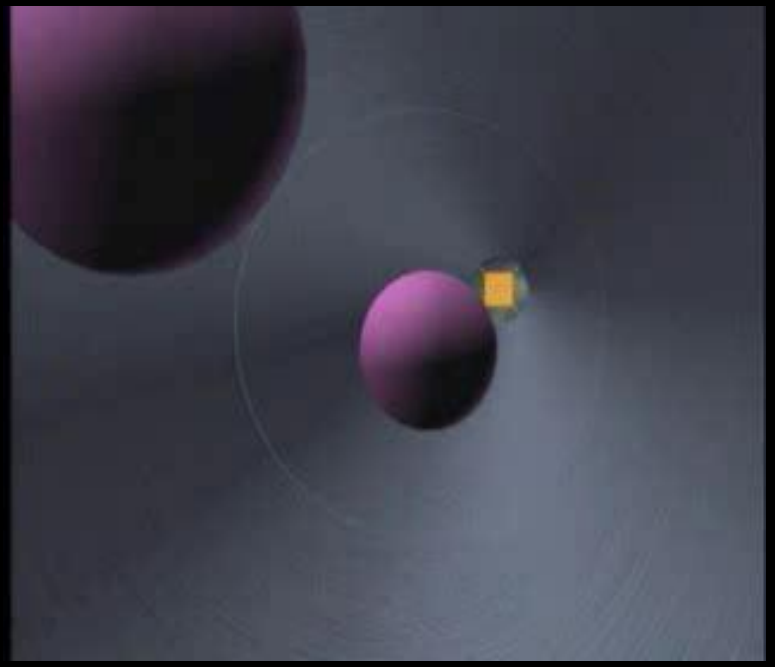
$10^{-18}$ m

nana nano meter

*What holds the world together?*

# Accelerators are like Time Machines.

because they make particles last seen in the earliest moments of the universe.



neutrinos
muons
kaons
….

anti particles

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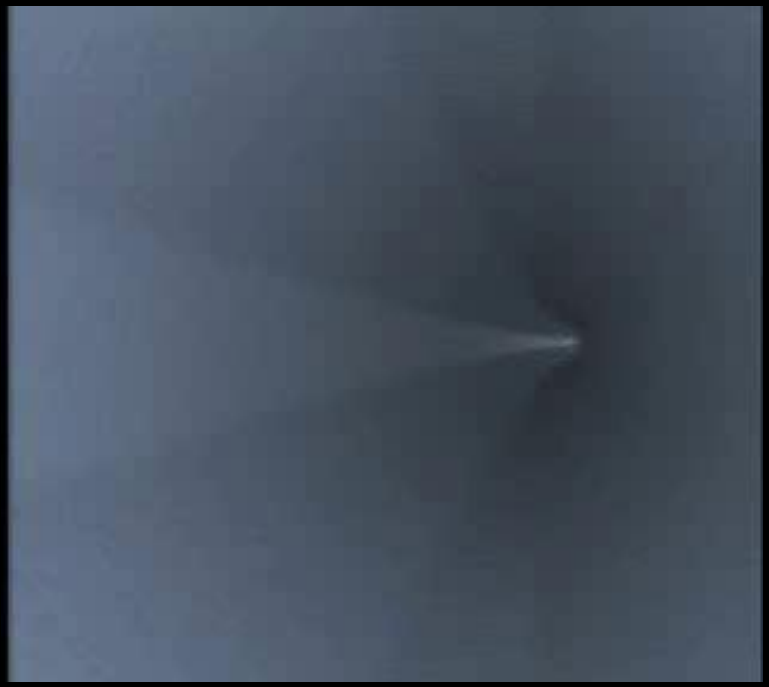

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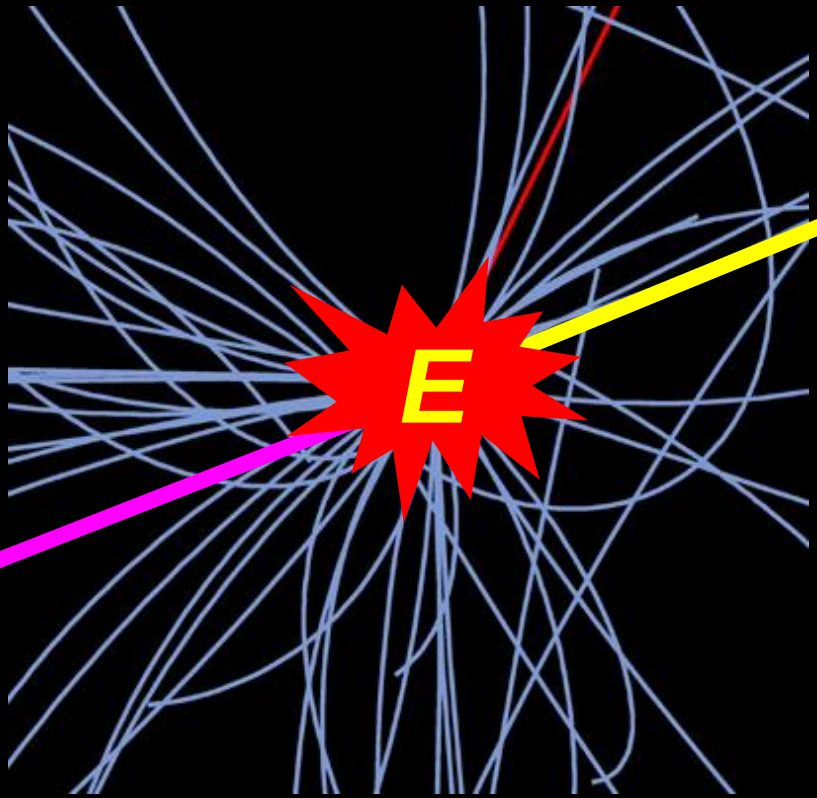
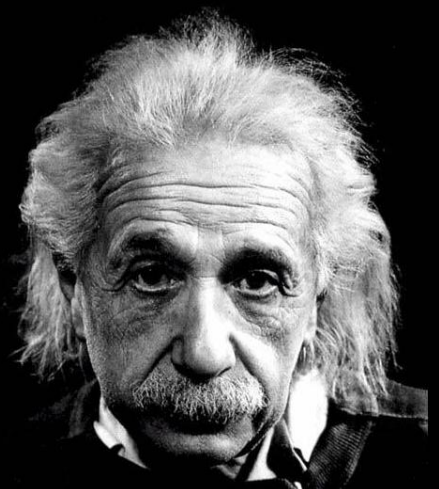



anti particle

particle



$E = Mc^2$

# Accelerators are like Time Machines.

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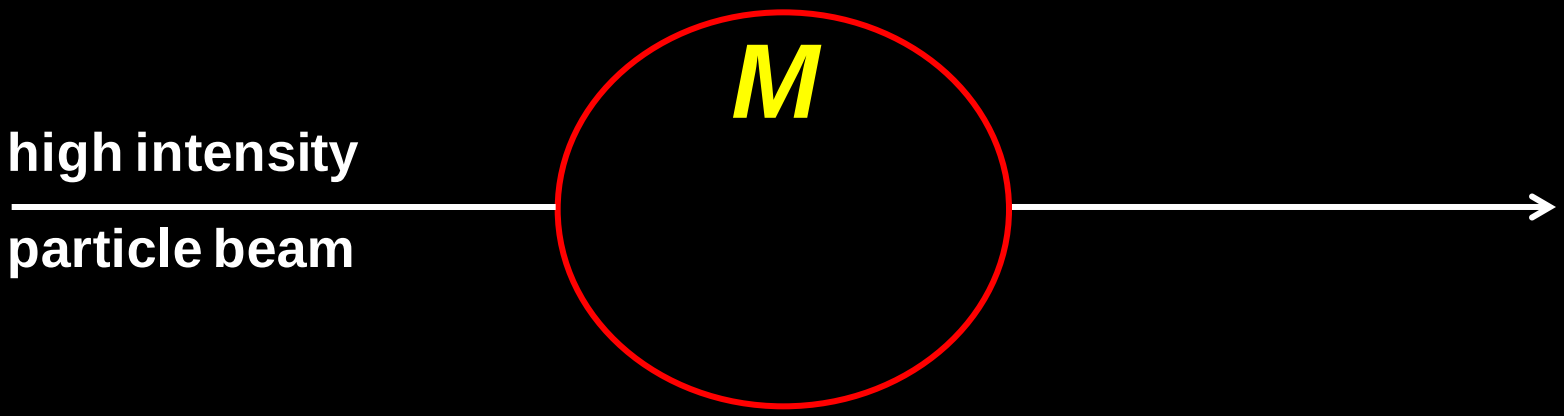
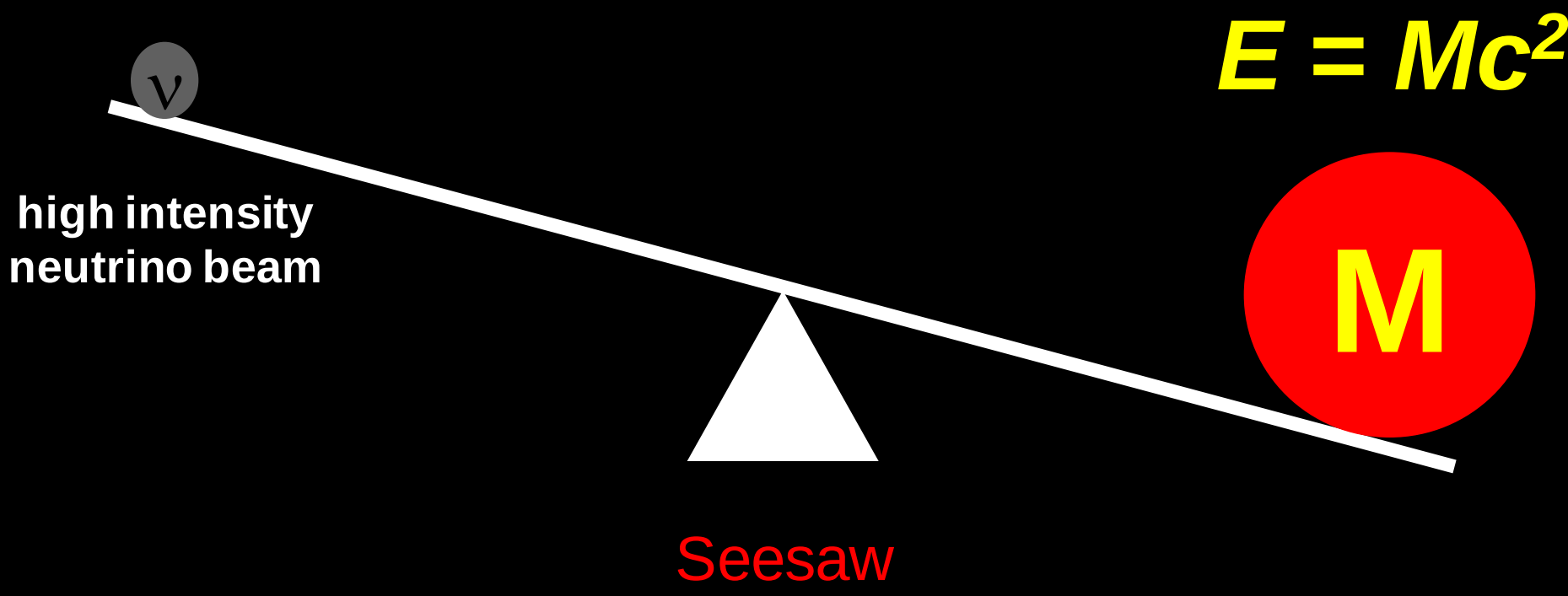
$$E = Mc^2$$



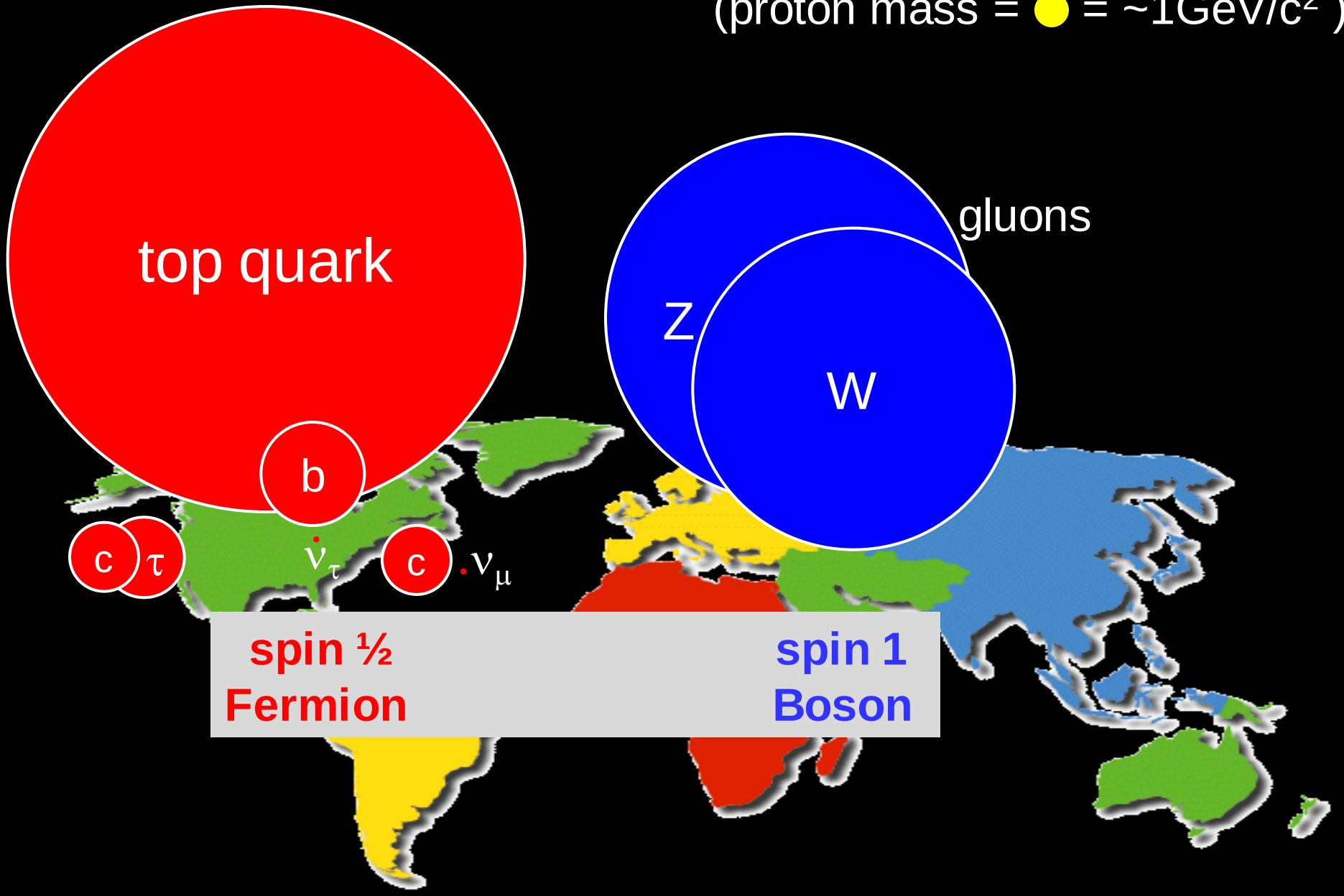

Quantum Fluctuation

# Accelerators are like Time Machines.

because they make particles last seen
in the earliest moments of the universe.

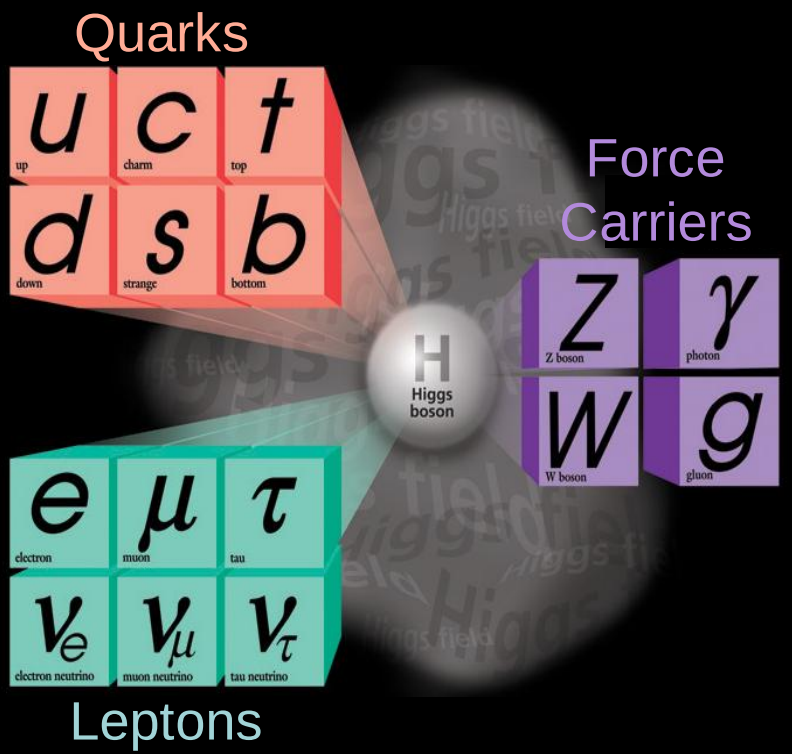


(proton mass = ● = ~1GeV/$c^2$ )



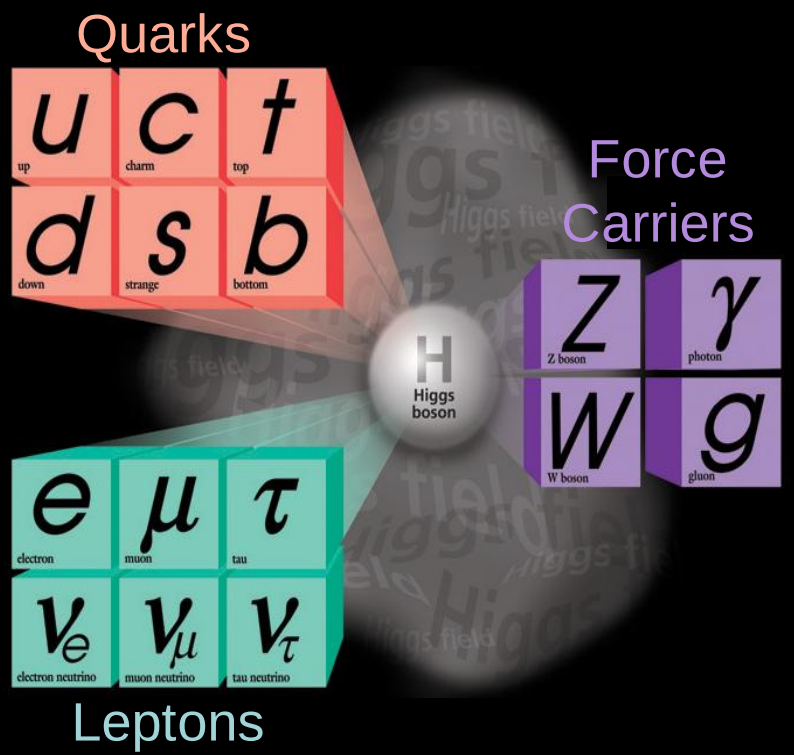
# The triumphs……

- The present theory is a remarkable intellectual construction
- Particle experiments done at the laboratory beautifully fits in this framework



# ……. and the mysteries

- Why?
- Why?
- Why?
- …



# …… and the mysteries

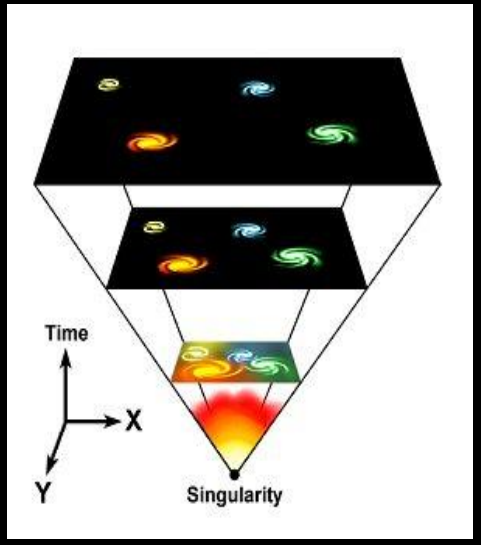
- Where did all antimatter go?

# …… and the mysteries

- What is dark matter?

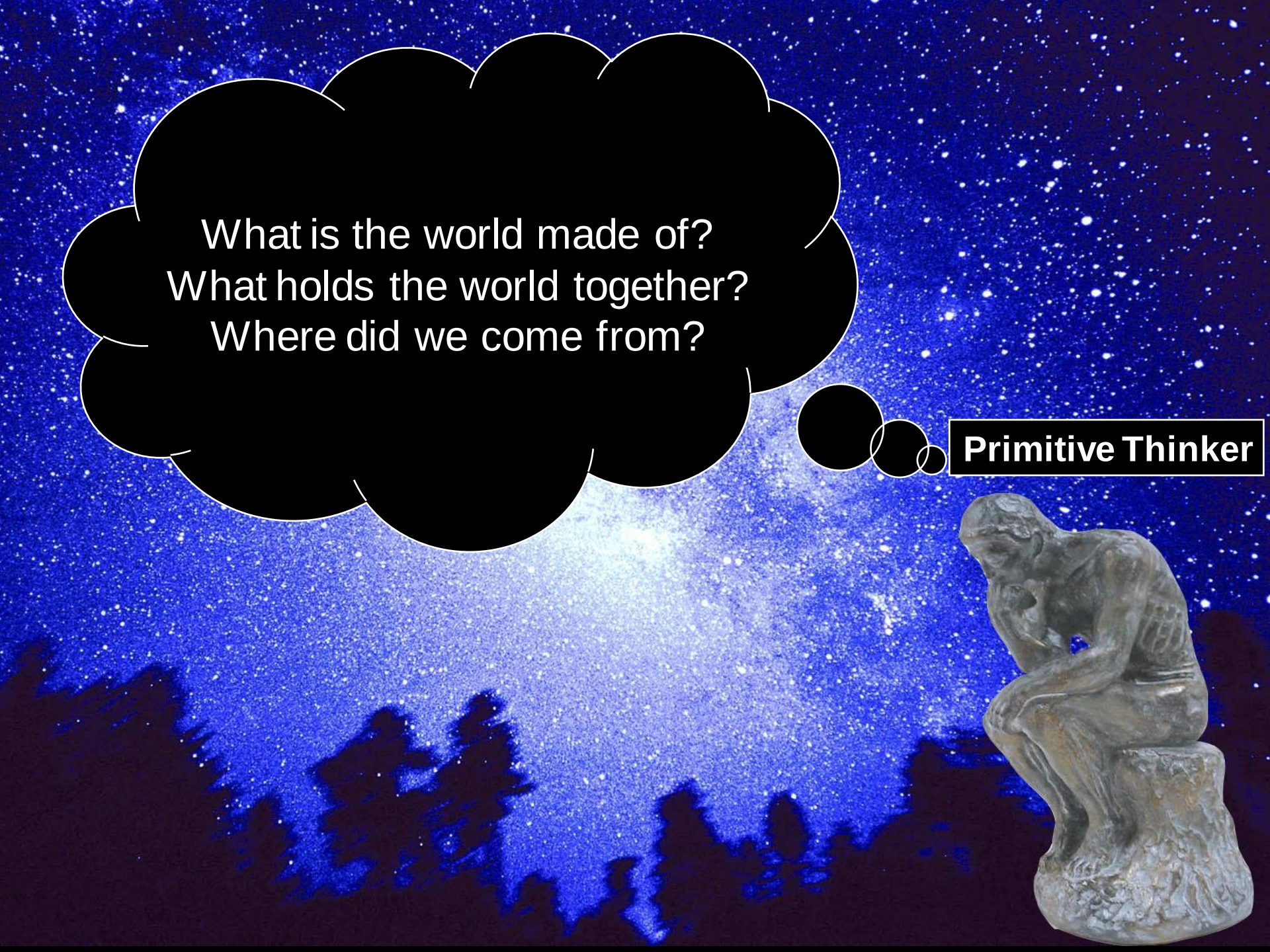
# ……. and the mysteries

- Expanding the universe





- Accelerating the universe
- What is dark energy?

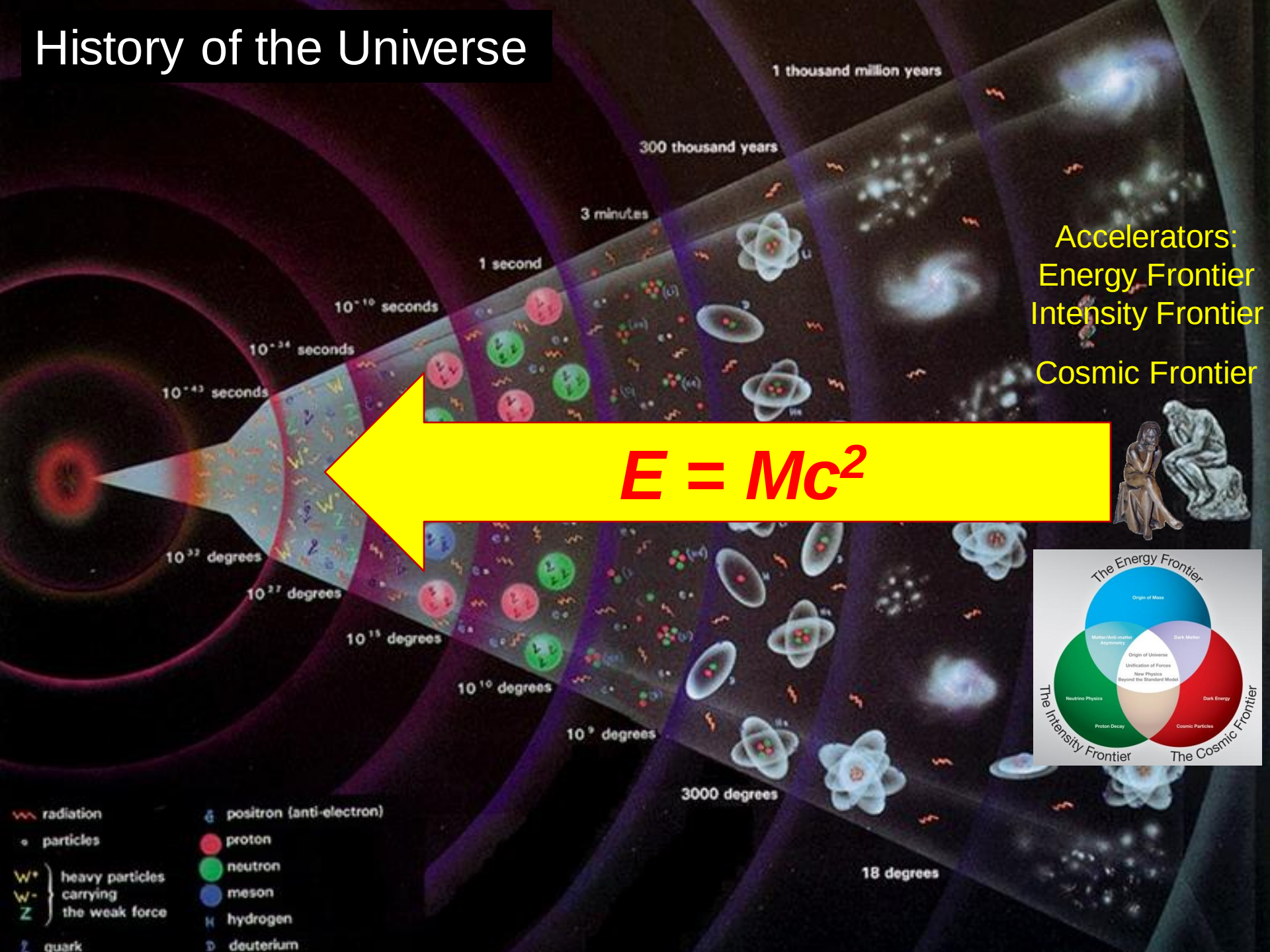

What is the world made of?
What holds the world together?
Where did we come from?
Primitive Thinker

# 21st Century Questions in Particle Physics

- What is the origin of mass for fundamental particles?
- Why are there so many kinds of particles?
- Do all the forces become one?
- Are there extra dimensions of space?
- What are neutrinos telling us?
- Do charged leptons change from one kind to another?
- Do protons decay?
- Are there undiscovered principles of nature:
  new symmetries, new physical laws?
- What happened to the antimatter?
- What is dark matter?
- How can we solve the mystery of dark energy?
- How did the universe come to be?

**Evolved Thinker**

# History of the Universe

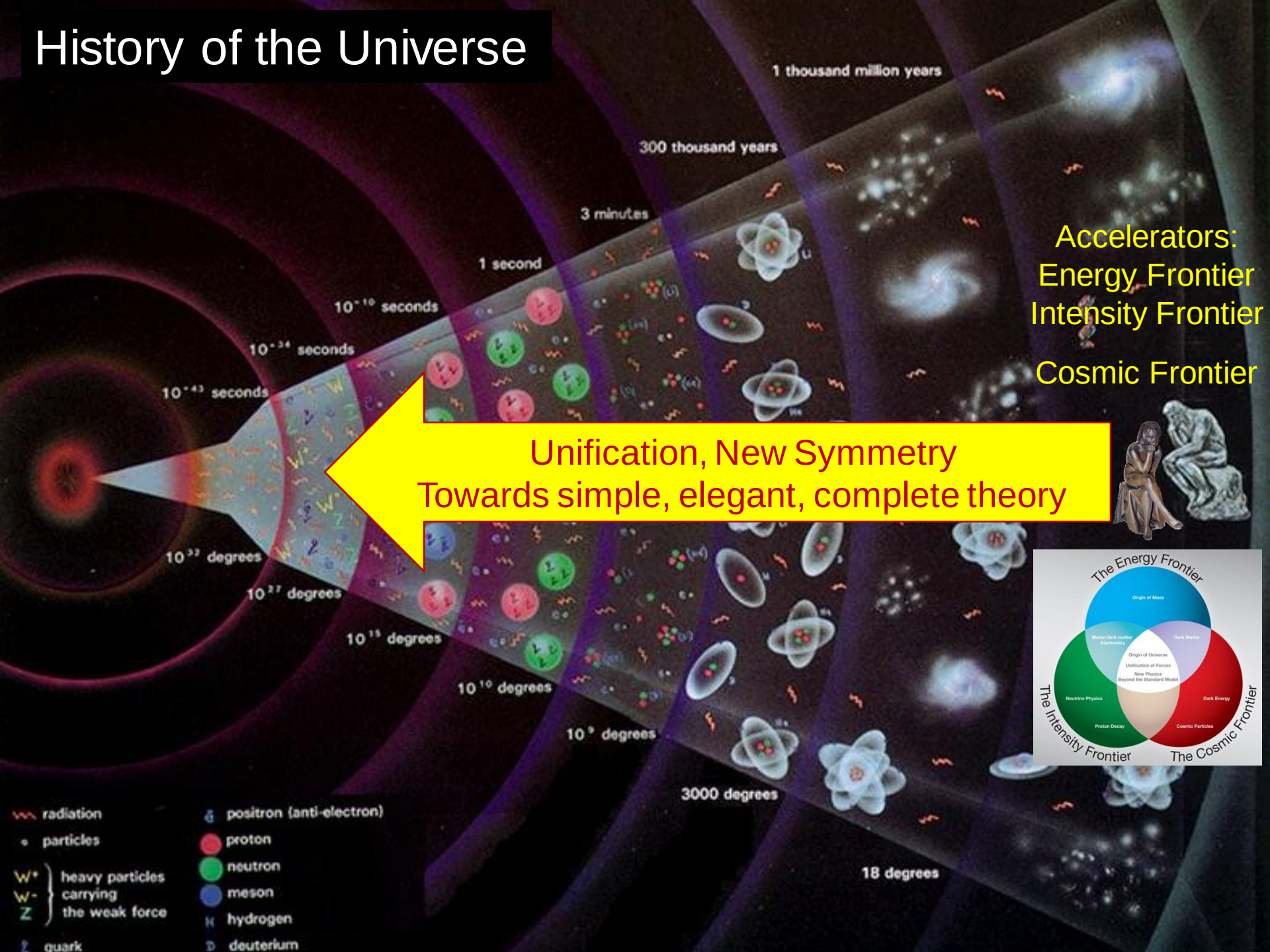



Accelerators:
Energy Frontier
Intensity Frontier

Cosmic Frontier

$E = Mc^2$

# History of the Universe

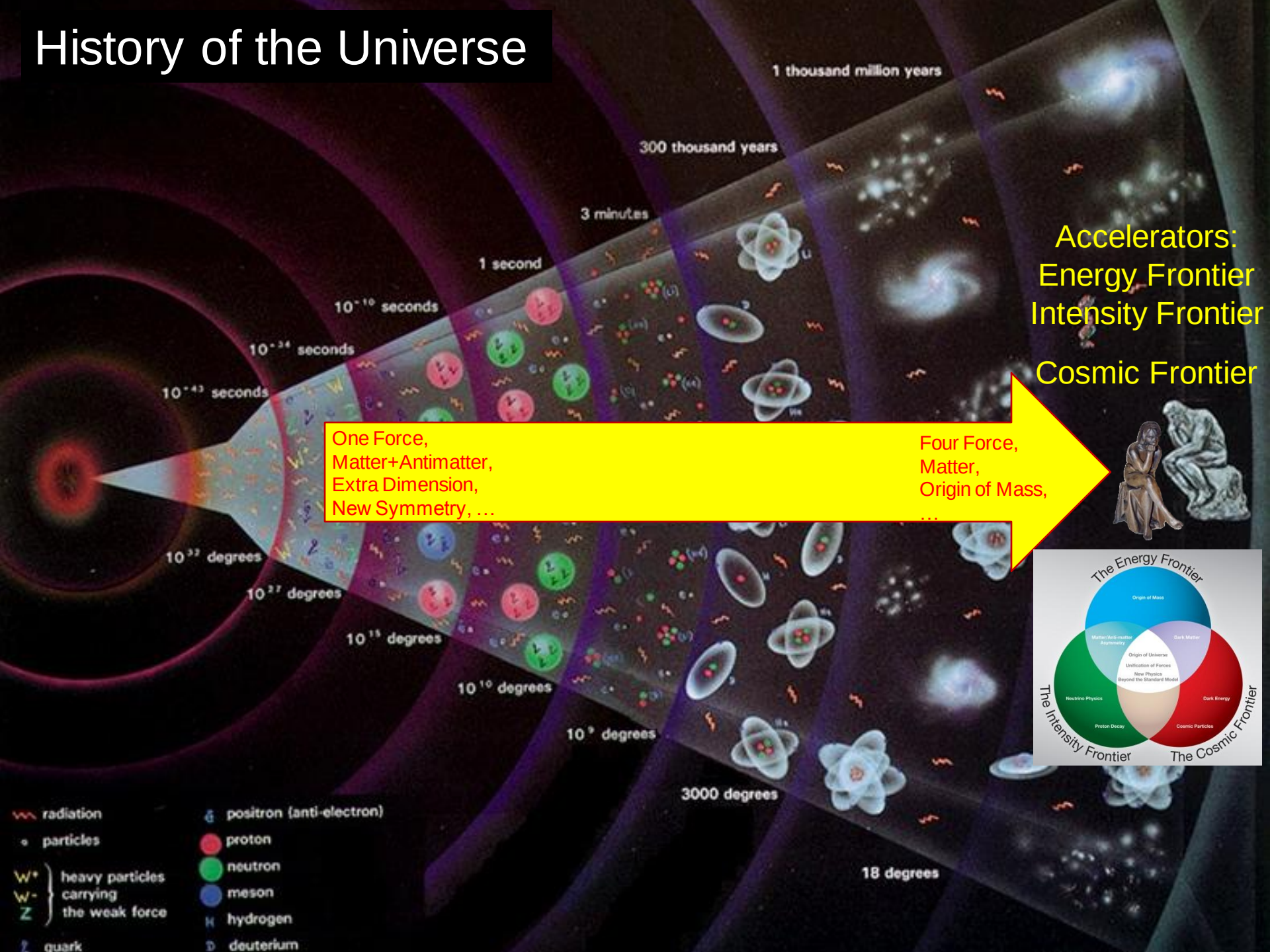



Accelerators:
Energy Frontier
Intensity Frontier

Cosmic Frontier

Unification, New Symmetry
Towards simple, elegant, complete theory

# History of the Universe




One Force,
Matter+Antimatter,
Extra Dimension,
New Symmetry, …

Four Force,
Matter,
Origin of Mass,
…

Accelerators:
Energy Frontier
Intensity Frontier

Cosmic Frontier

# Fermilab today

- 1900 employees
- 2300 users (~1/2 from abroad)
- 6800 acres, park-like site

A herd of American bison, symbolizing Fermillab's presence on the frontiers of particle physics and the connection to its prairie origins

Now at Fermilab

Now at Fermilab

Now at Fermilab

Now at Fermilab

Now at Fermilab

# Tour of Accelerator Complex at Fermilab

# Cockroft-Walton

# Linac

# Booster

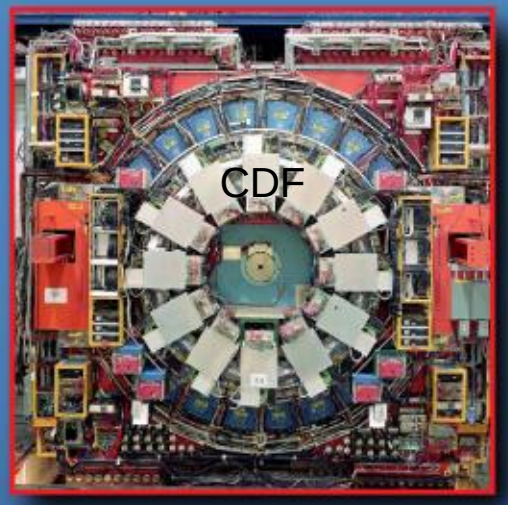
# Main Injector

# Tevatron

Antiproton


# Tevatron

CDF and DZero



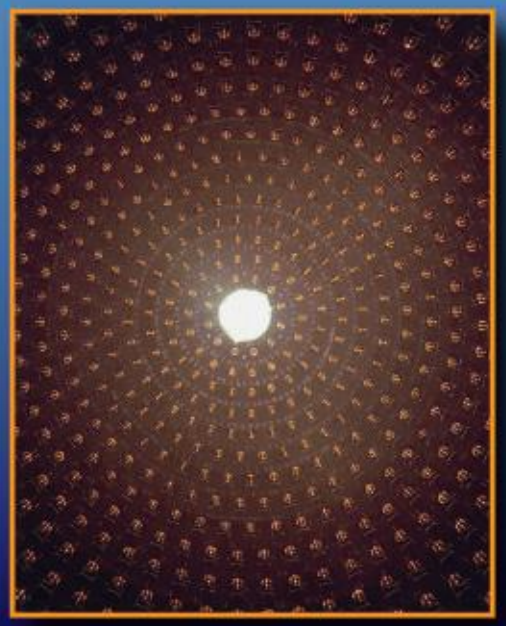


# ν's from Main Injector

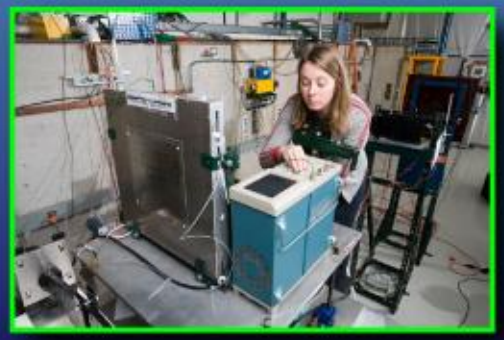
MINOS
MINERvA


# $\nu$'s from Booster

MiniBooNE



# Beam for Detector Development



Test Facility for Accelerator Development

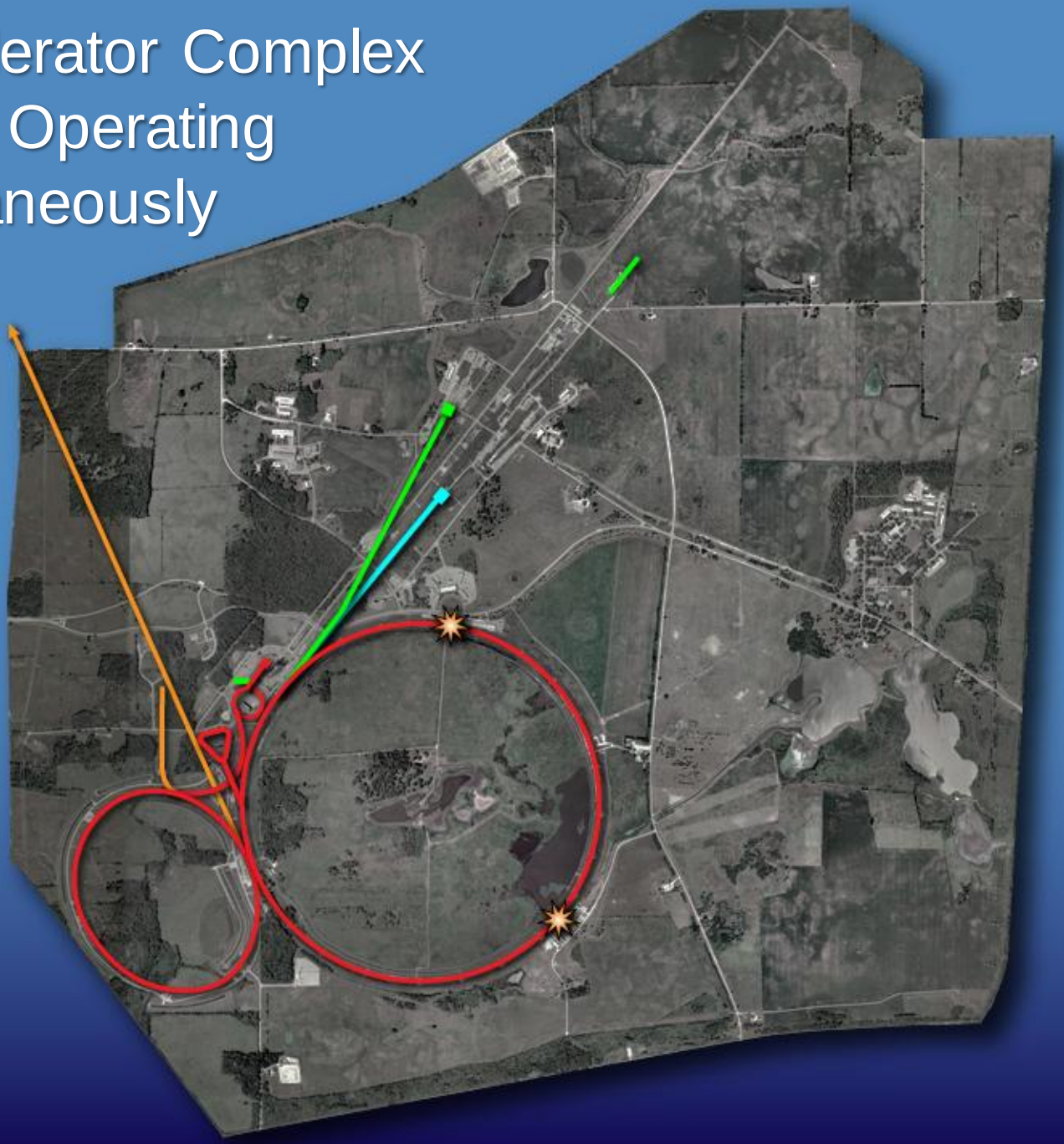
Super Conducting RF Technology

# Test Facility for Muon Cooling

Proton

SeaQuest

# Fermilab Accelerator Complex Currently Operating Simultaneously



# Energy Frontier Accelerators






Tevatron

LHC

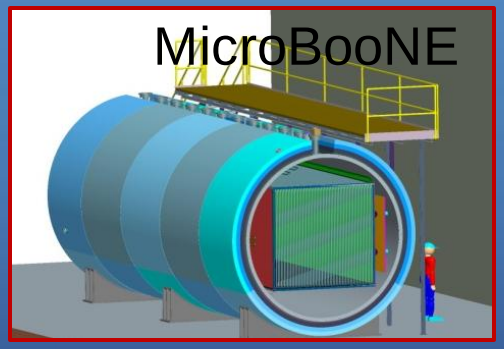
Lepton Collider

(energy to be determined)

(technology, site to bedetermined)

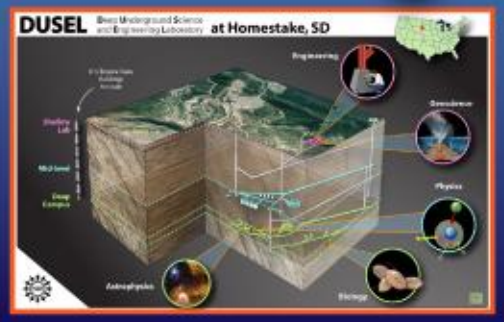
2013

Neutrinos
NOvA
MINERvA
MicroBooNE


Neutrinos
neutrinos to DUSEL
(proton decay)

Muons
muon → electron


# DUSEL Deep Underground Science and Engineering Laboratory at Homestake, SD








Ray Davis's Experiment

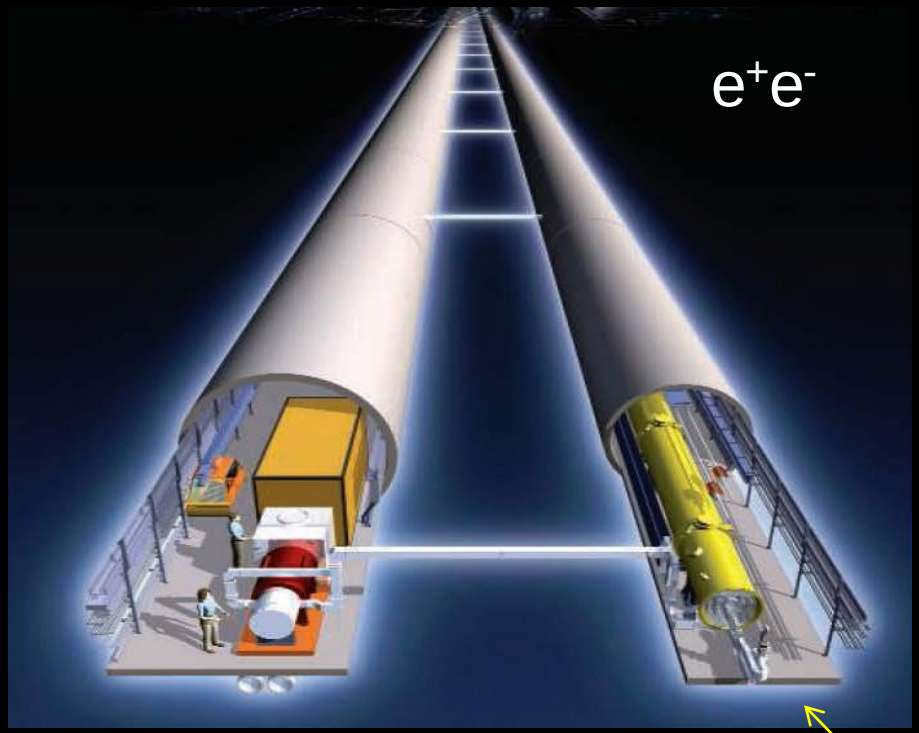
# Project X

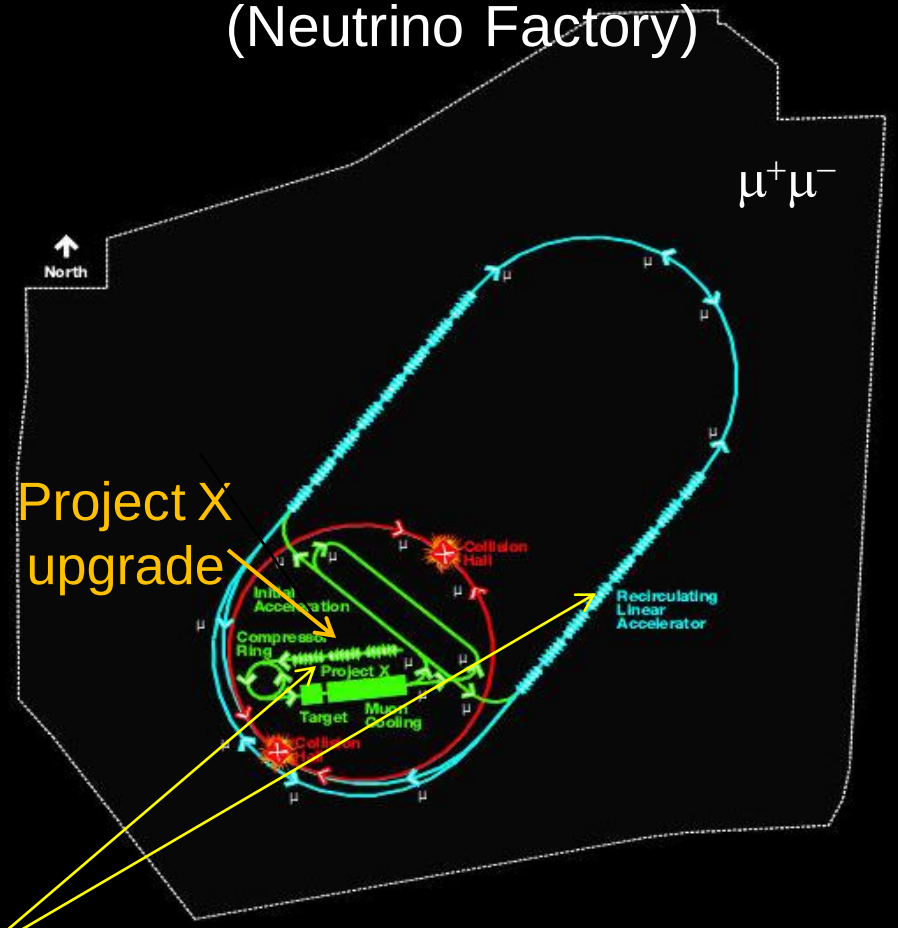
Neutrino physics
Muon physics
Kaon physics
Nuclear physics
“simultaneously”

# from Project X to Lepton Collider / Neutrino Factory

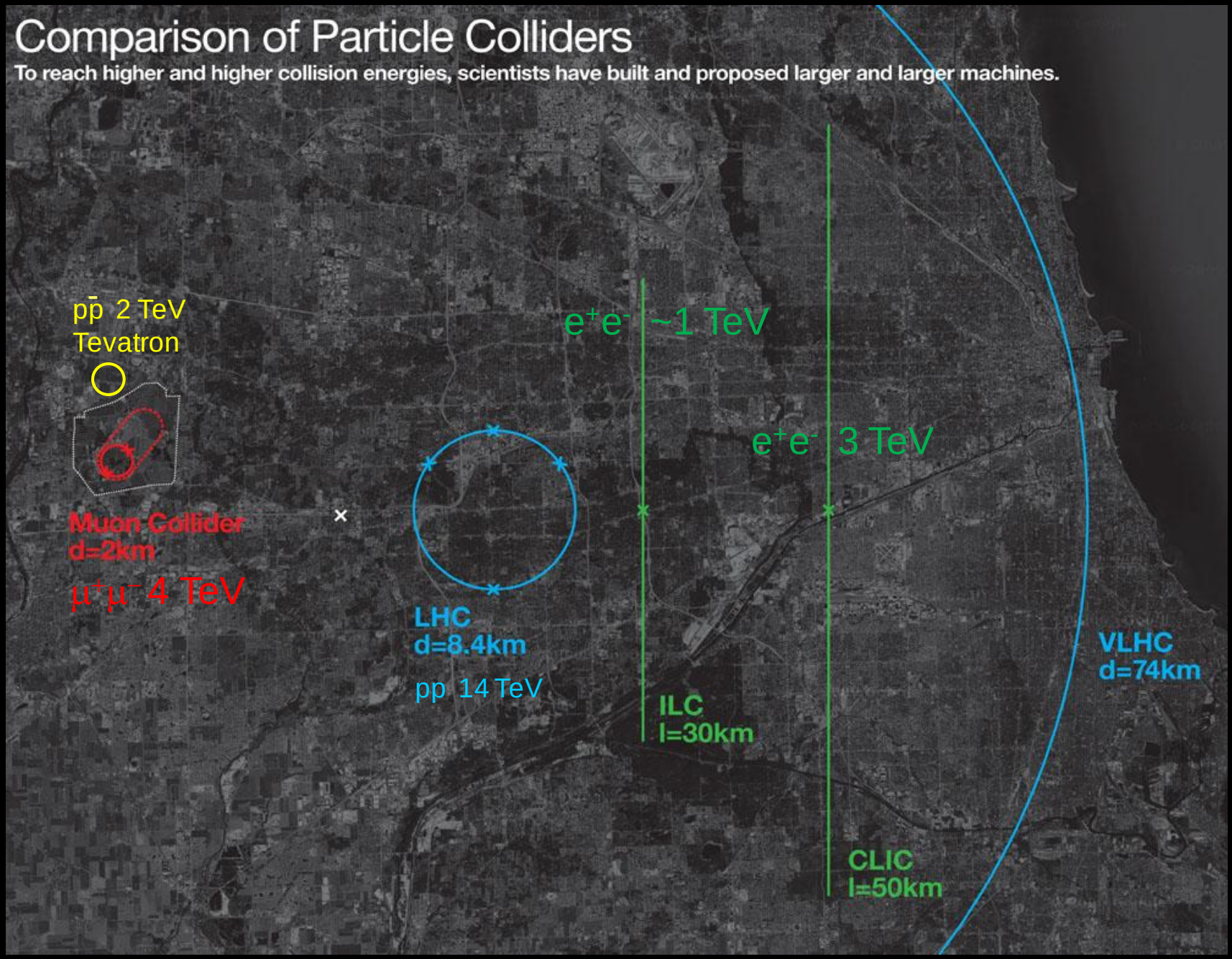
0.5 – 1 TeV Linear Collider

4 TeV Muon Collider
(Neutrino Factory)




Superconducting RF Technology for
Project X, ILC, Muon Collider, Neutrino Factory


Comparison of Particle Colliders
To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.
p$\bar{p}$ 2 TeV
Tevatron
Muon Collider
d=2km
$\mu^+\mu^-$ 4 TeV
LHC
d=8.4km
pp 14 TeV
$e^+e^-$ ~1 TeV
$e^+e^-$ 3 TeV
ILC
l=30km
CLIC
l=50km
VLHC
d=74km

# What are accelerators used for?

Today, > 17,000 accelerators are in operation around world

- Discovery science

- Materials research / manufacturing

- National security

- Energy and the environment
- Medical sciences

# Particle Accelerators and Medical Science

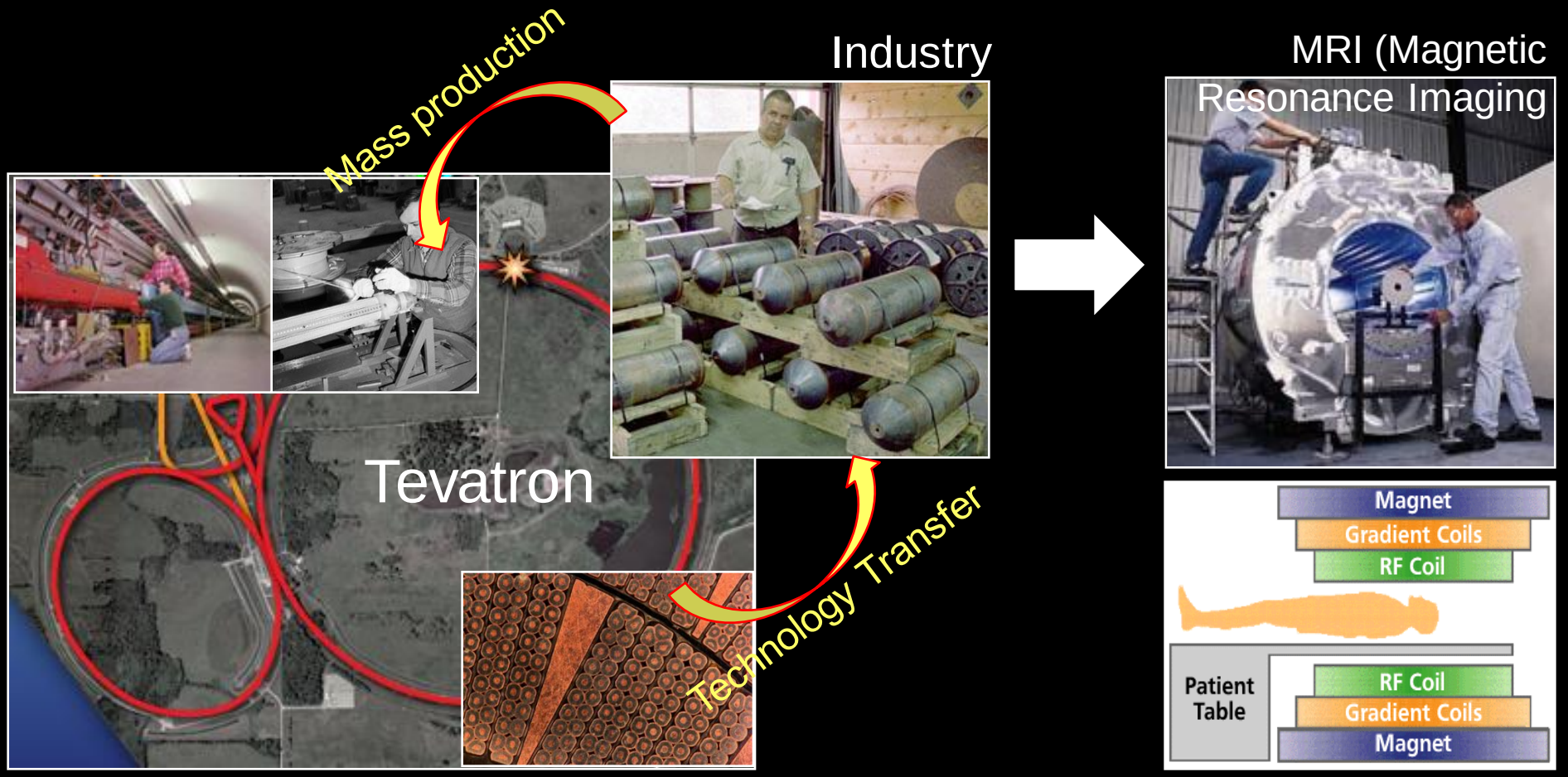
- From the earliest days of high-energy physics in the 1930s to the latest 21st-century initiatives, the bold and innovative technologies of particle accelerators have created powerful new tools for medicine.

- The technology breakthroughs that allow physicists to unlock the deepest secrets of the universe also inspire advances in the understanding, diagnosis and healing of disease.

# Particle Accelerators and Medical Science

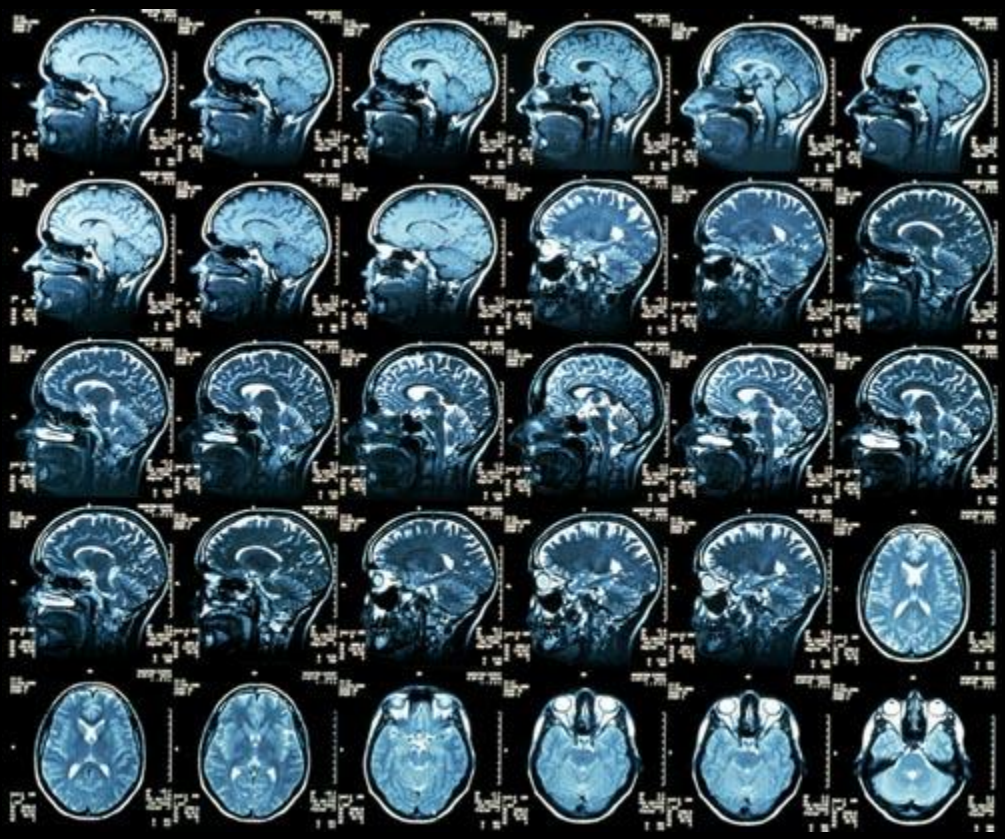
- Tools for Diagnosis
- Tools for Healing
- Tools for Biomedical Research
- Tools for the Future

# Tevaton superconducting wire → MRI




"Every program in superconductivity that there is today owes itself in some measure to the fact that Fermilab built the Tevatron and it worked."
Robert Marsh, of ATI Wah Chang, world's largest supplier of superconducting alloys.

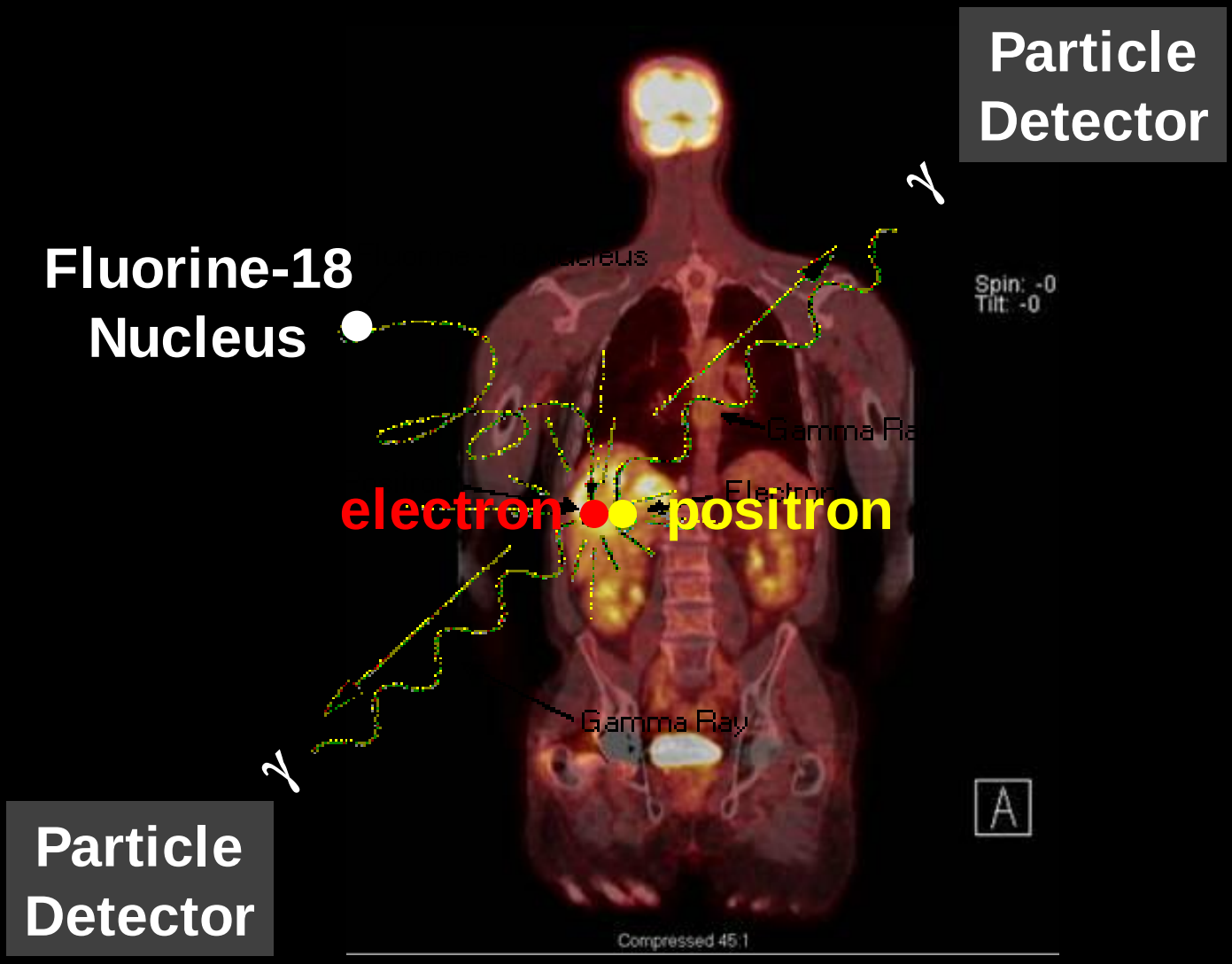
MRI is a technique used to produce high quality images of the inside of the human body



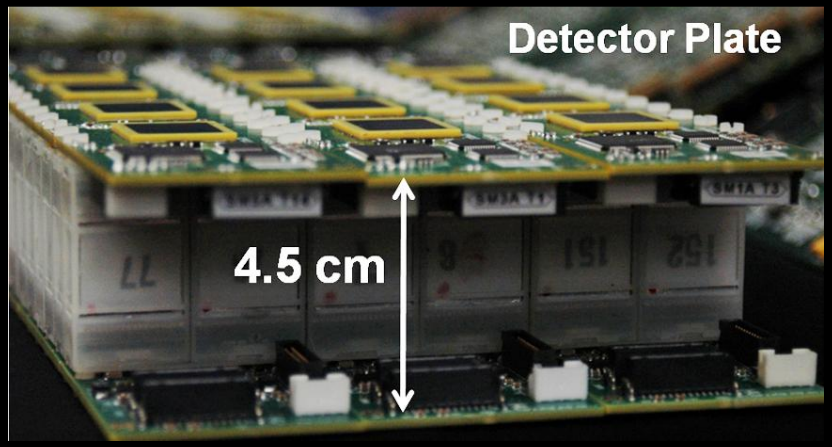
MRI scans through a human head showing a healthy brain.

Whole body MRI – product of a number of MRI scans made along the length of the body and combined

# PET (Positron Emission Tomography) Scan



# Particle Detector → PET and PEM




Positron-Emission Mammogram
compact module developed by
CMS collaboration
(crystals & electronics)


Technology
Demonstration → Industry

Application
to medicine

# Particle Accelerators and Medical Science

- Tools for Diagnosis
- Tools for Healing
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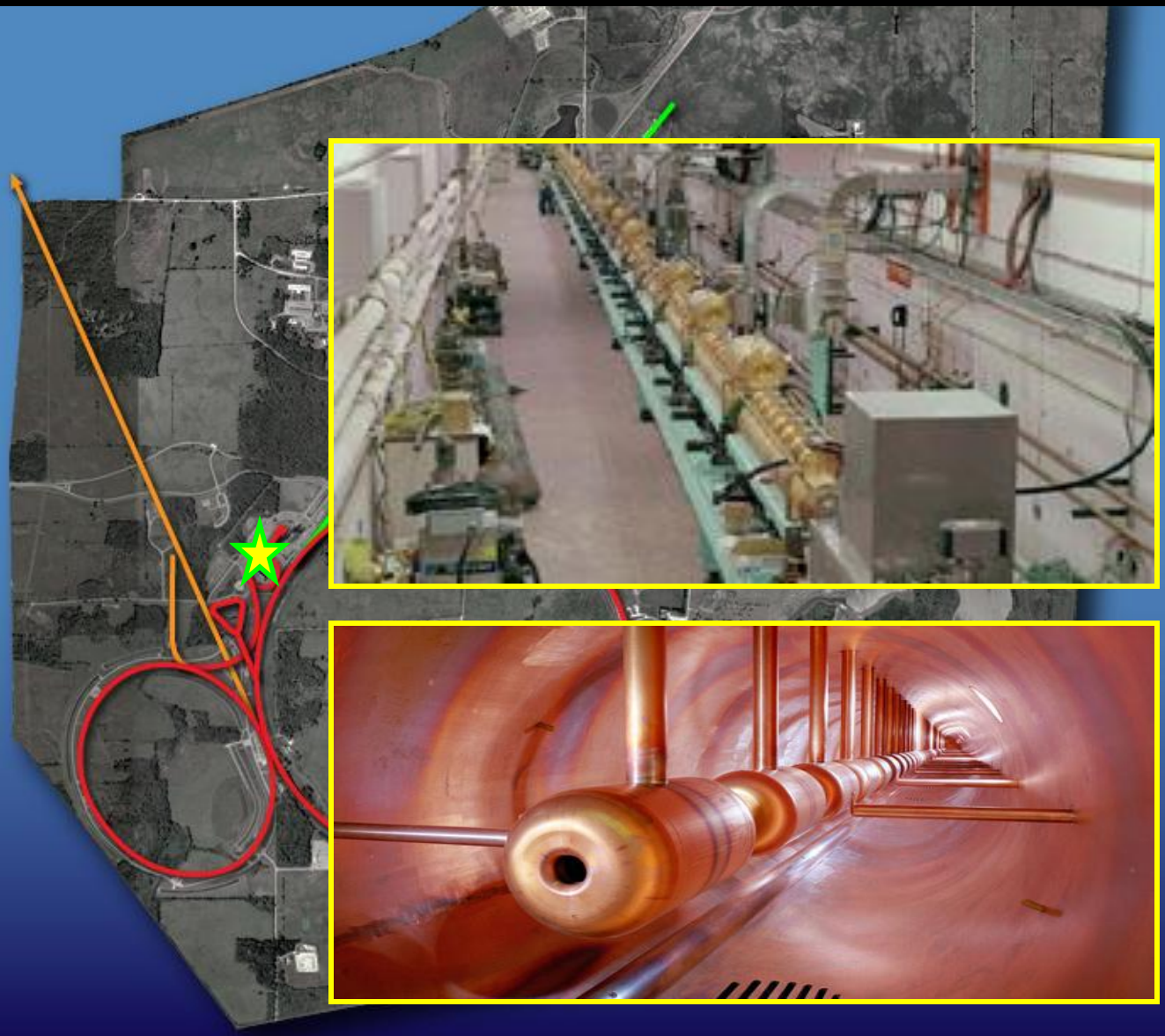
# Neutron Cancer Therapy at Fermilab

Patient treatments since 1976



# 1st Neutron Cancer Therapy

Lawrence's 27 inch cyclotron

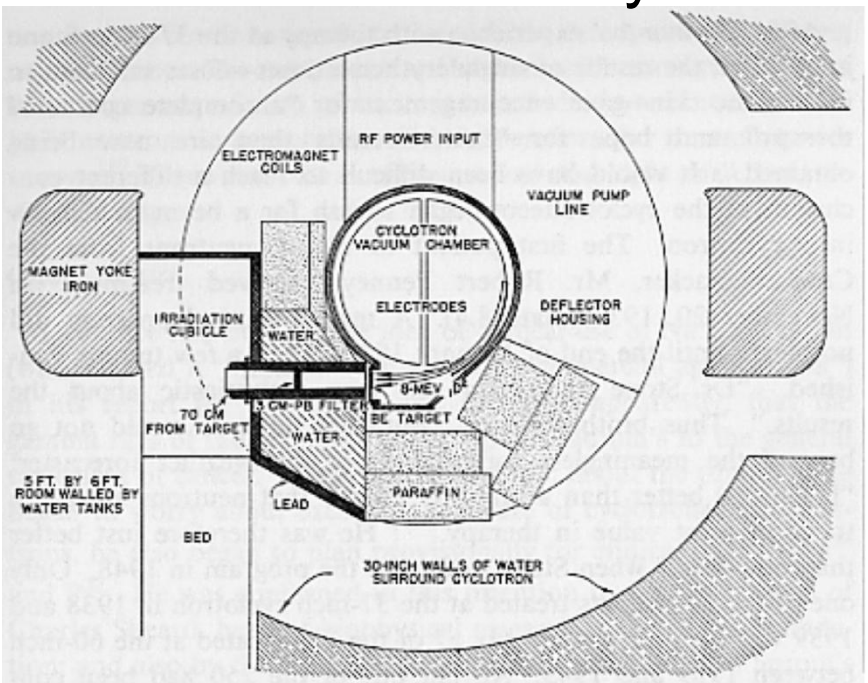
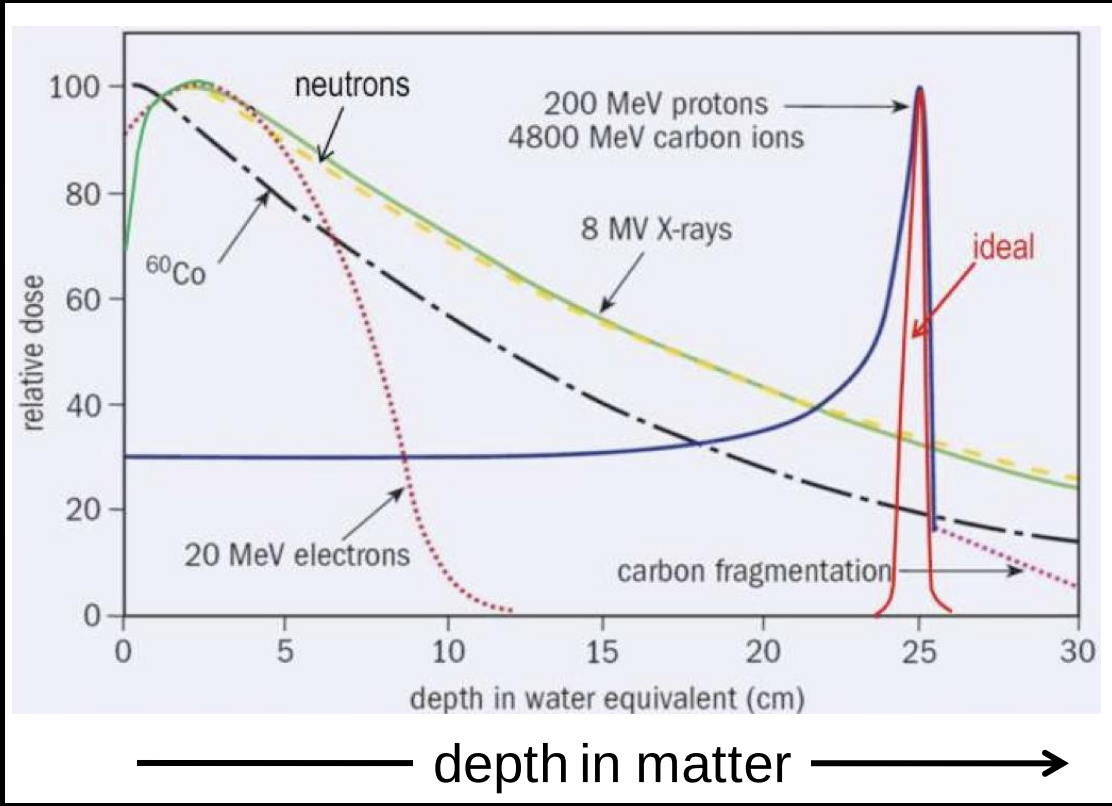



FIG. 8.5 Aebersold's arrangement for neutron therapy. The treatment room is at the left, within the magnet yoke. Not all the water tanks surrounding the cyclotron are shown. Aebersold, *PR, 56* (1939), 717.

Medical isotopes for research and treatment: Lawrence's mother Gunda became the 1st patient to be treated (1937).
Neutrons for therapy in patients, starting in late 1938

# Proton Cancer Therapy

First proposed by Robert Wilson, founding Director of Fermilab




Protons deliver most of their energy at their destination thanks to a characteristic of the beam, called the Bragg Peak

# Proton Cancer Therapy

World's 1st proton accelerator built specifically for proton therapy

Loma Linda Proton Therapy and Treatment Center

Designed and built at Fermilab
Has treated > 8,000 patients

Technology Demonstration → Industry

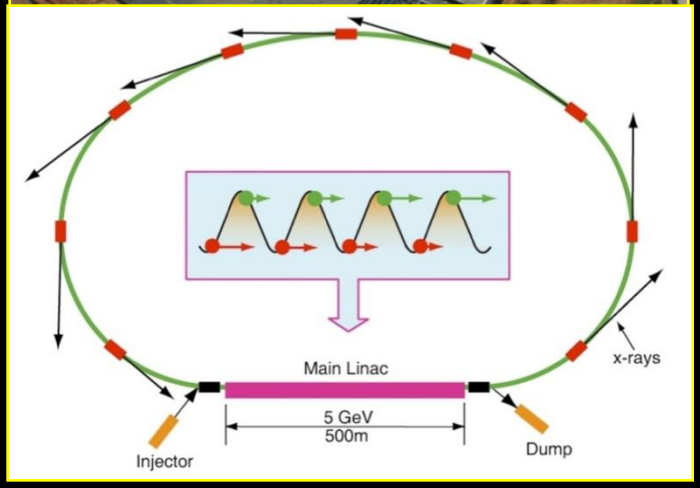
Today there are ~25 proton therapy centers in operating or under construction worldwide

Loma Linda is working with NASA in testing space suits to protect astronauts from radiation in outer space

# Particle Accelerators and Medical Science

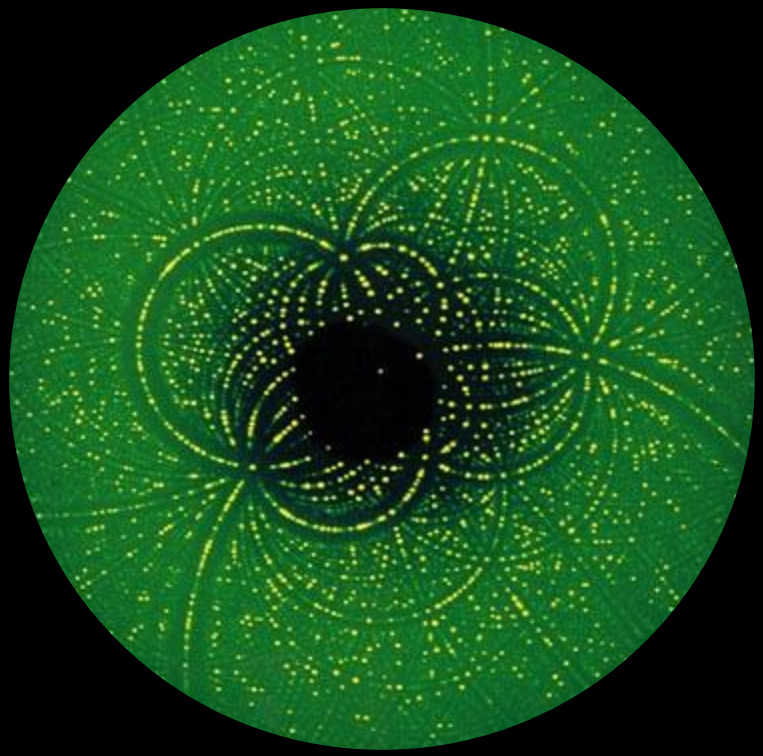
- Tools for Diagnosis
- Tools for Healing
- Tools for Biomedical Research
- Tools for the Future

Synchrotron Accelerators



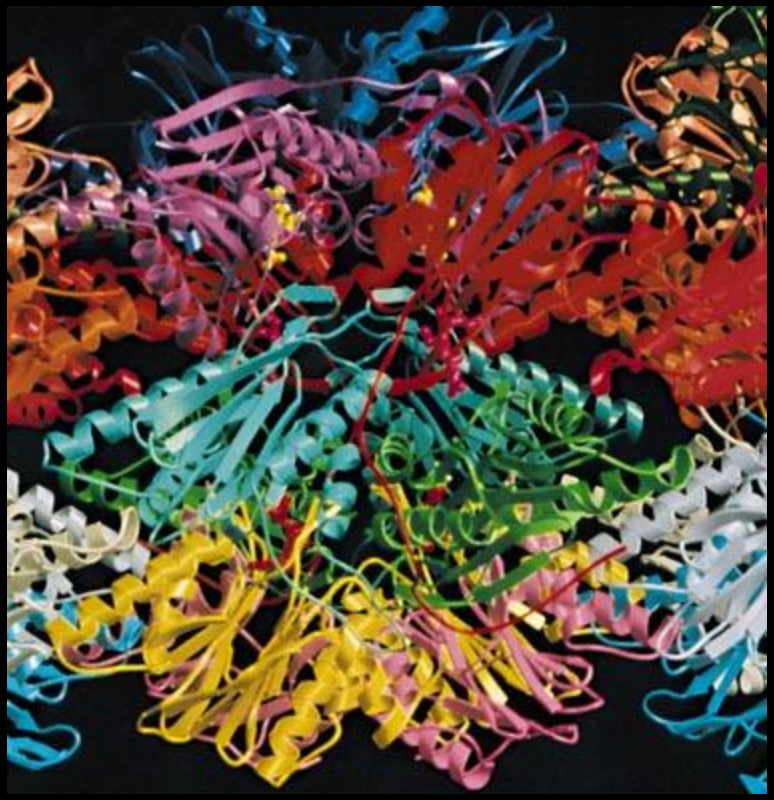

When forced into a circular path, electrons emit light, and this light goes through a protein crystal. The crystal scatters the light onto a detector. From the scattering pattern, we can create a 3D image of the molecule.

Human Heat Shock Protein 70 (hsp70)
is important in cell folding and binding
is created in large quantities when the body is under stress
(photo courtesy of Argonne National Laboratory)



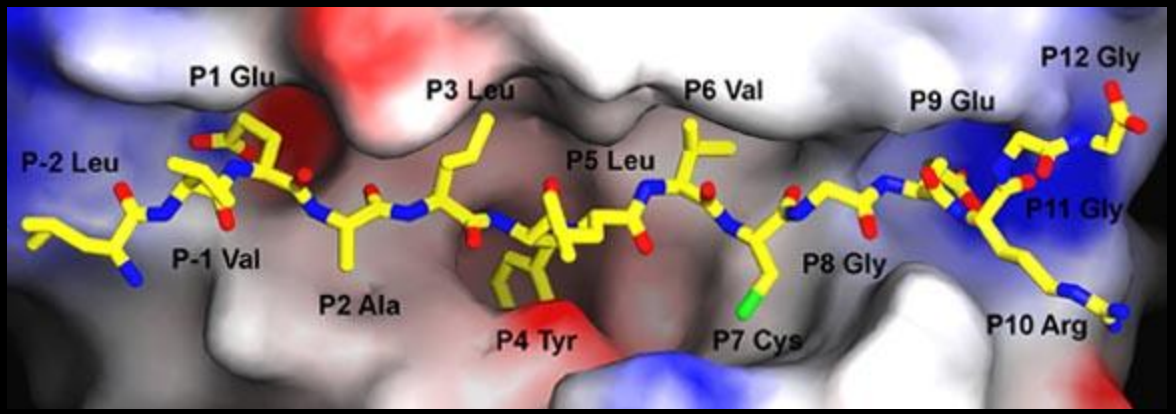
Diffraction Image of a Biomolecule

Using this diffraction technique, we can decode the internal structure of complex protein molecules such as enzymes (photo courtesy of DESY)



## Protein Structure

We can determine the nuclear structure of proteasome, which functions as a kind of “garbage disposal” in living cells (photo courtesy of DESY)




An insulin molecule binds to a human glycoprotein found at the cell surface → discovering clues that promise a better understanding of the prevention of juvenile diabetes. (photo courtesy of Argonne National Laboratory)

# Particle Accelerators and Medical Science

- Tools for Diagnosis
- Tools for Healing
- Tools for Biomedical Research
- Tools for the Future

# Future Accelerators

- R&D on future accelerators is about making them smaller
- Higher accelerating gradients mean smaller sizes and more “bang for the buck”
- Thus the same R&D that will make future accelerators in particle physics affordable will also enable medical accelerators that are smaller, cheaper, more portable, and more reliable

# Superconducting Linacs

- Provide large accelerating gradients with better reliability and lower wall-plug power. We are preparing to build Project X at Fermilab. (European XFEL at DESY)

Fermilab Test Facility

Fabrication

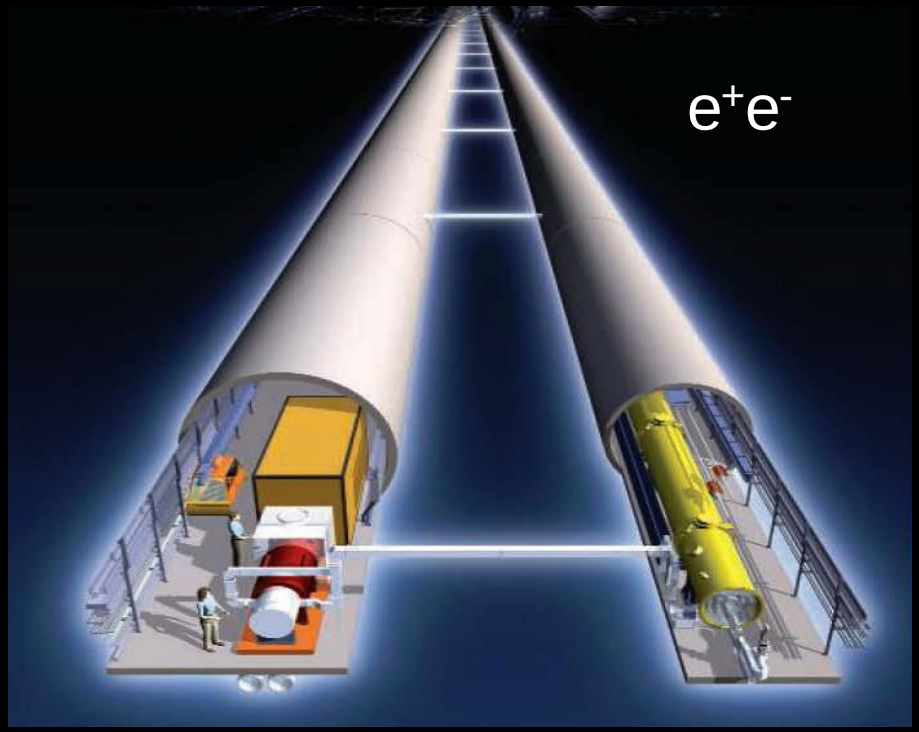
Industry (AES)

Technology Transfer

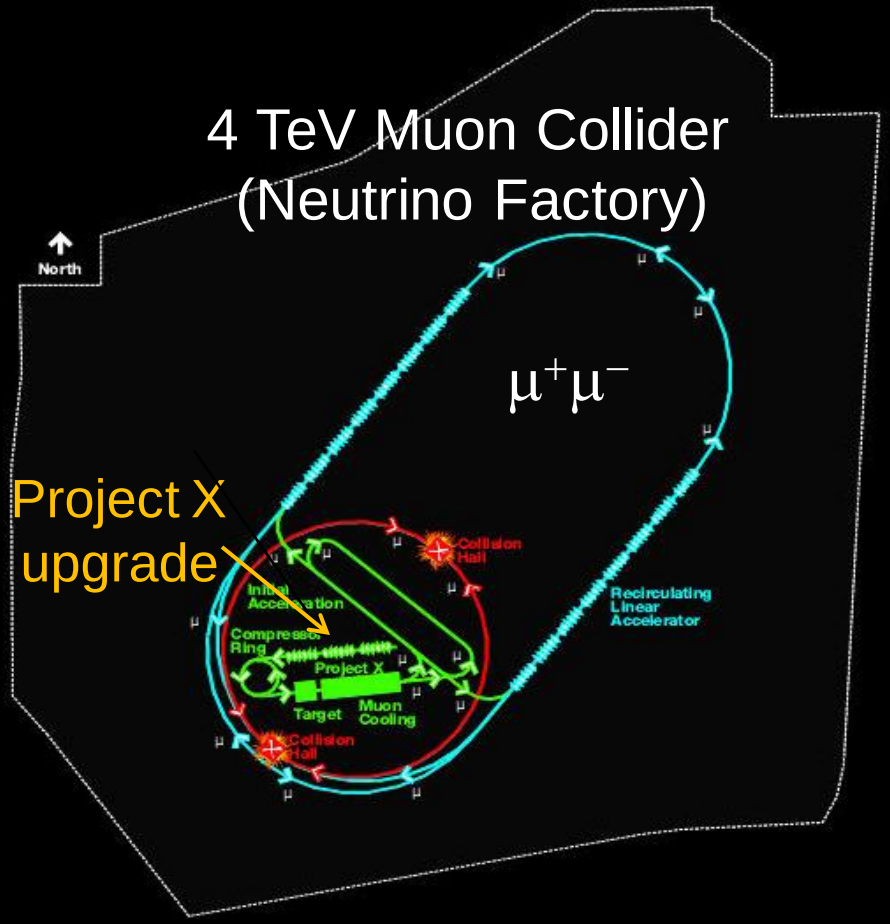
# Superconducting Linacs

- In the future, this technology could be used to build the successor to the LHC, or the successor to Project X

0.5 – 1 TeV Linear Collider



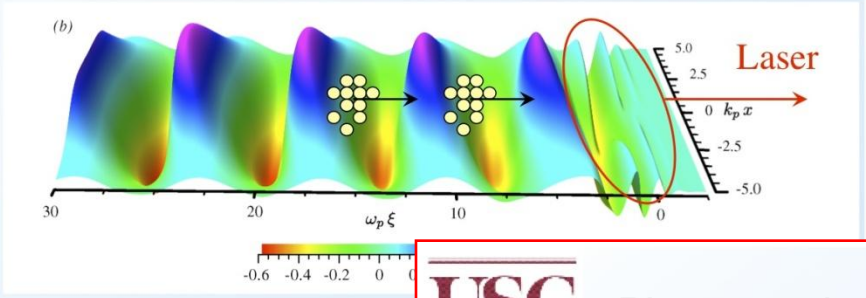

4 TeV Muon Collider
(Neutrino Factory)



# Laser Wakefield Accelerators

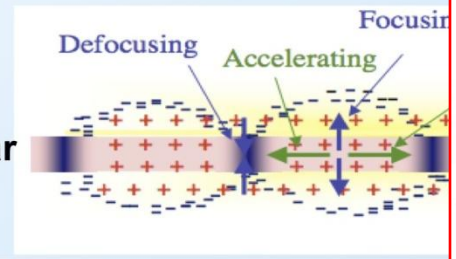
## Principle of laser/plasma wakefield accelerators

**Linear**



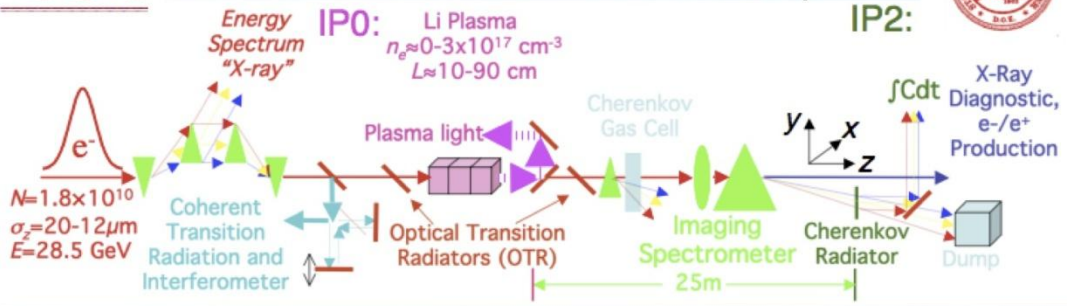

- Laser driver--Tajima&Dawson, PRL'79
- E-fields:
- Beam driver--P. Chen et al., PRL'85
- Phase v

**Non-Linear**

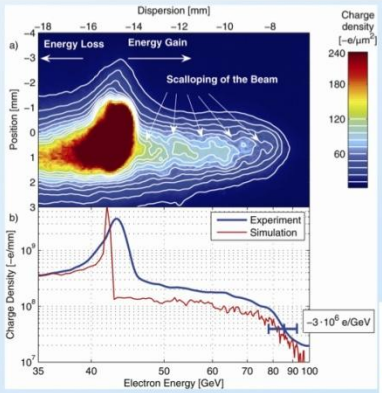



# Plasma Wakefield Accelerators

## Plasma wakefield accelerator expt




- Used 42 GeV FFTB beam
- Li plasma
- Most electrons decelerated
- Few % accelerated
- Highest energy observed ~ 85 GeV




*Blumenfeld et al., Nature 2007*

# Closing Remarks

- Particle accelerators are of fundamental importance to basic physics research, medicine, materials research, chemistry, and biology
- Their importance is growing, with breakthrough applications like proton/ion therapy and (Thorium reactors)
- Next-generation accelerators will get more “bang for the buck”, making medical linacs smaller and “energy frontier” machines affordable
- The traditional R&D model, that particle physics does the R&D and others benefit, is still working.