Exploring the smallest things with the largest microscopes

Particle Physics: the Smallest to the Largest
Past 100 Years in Scientific Innovation and Outlook

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The University of Chicago

The Smallest Things

play a crucial role
to understand how the world works

fundamental entities
building blocks
elementary particles

interactions among them
their laws

Democritus's atom (400 BC)

Indivisible and Invisible

Democritus
(460 BC – 370 BC, Greece)

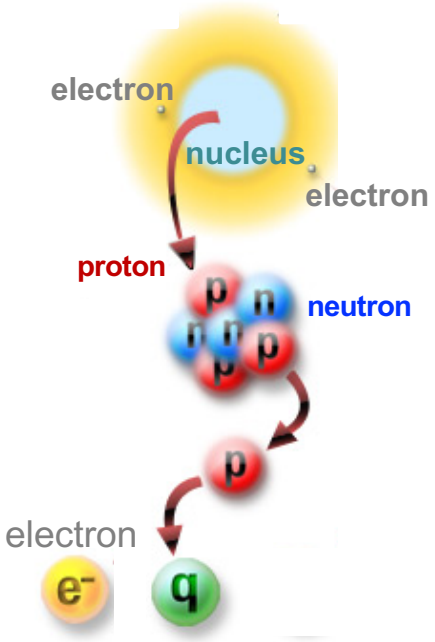
The universe is composed of the atoms and the void

Atoms were thought to be building blocks of the world.
The conception of the atom has been modified in several essential respects, but the philosophy remains the foundation of modern science.

Building Blocks

Dominant Forces

Discovery of electrons 1897



atom
10^{-10} meter

Discovery **(year)**

nuclei
10^{-14} meter
1909

protons
neutrons
10^{-15} meter
1932

quarks
(up & down quarks)
< 10^{-18} meter
1960s

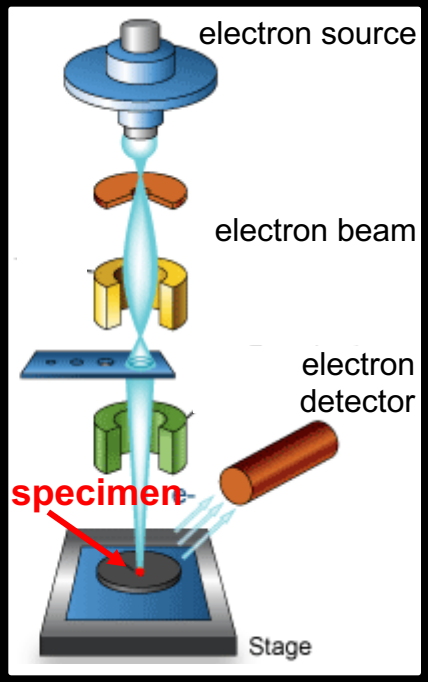
nano meter

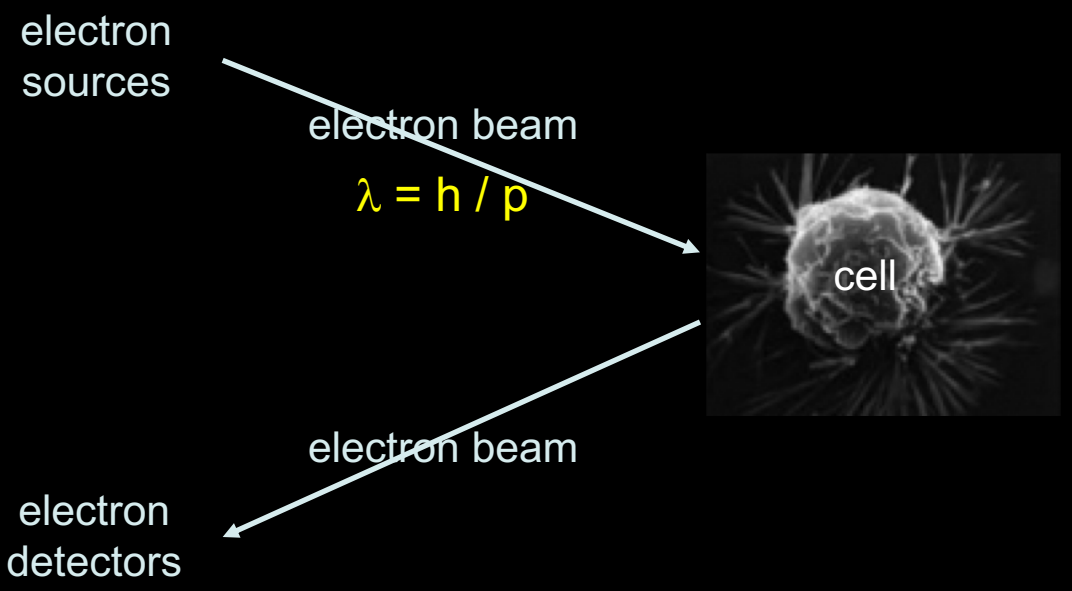
nano nano meter

Electromagnetic Force

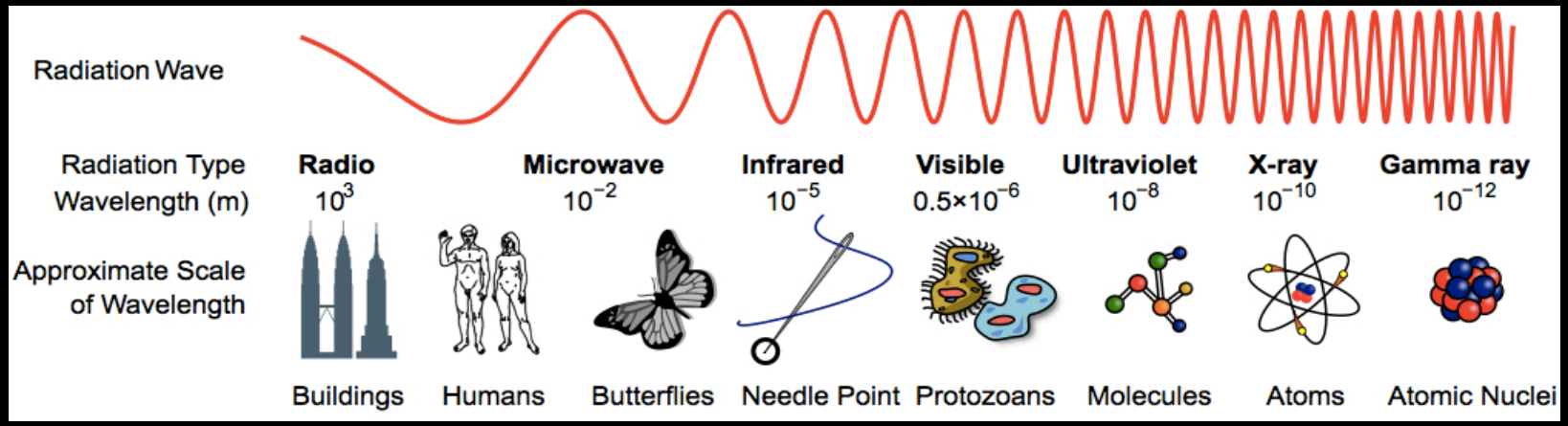
Strong Force
Weak Force

Seeing the “small” invisible by a “high” energy beam produced by particle accelerators (“super microscope”)

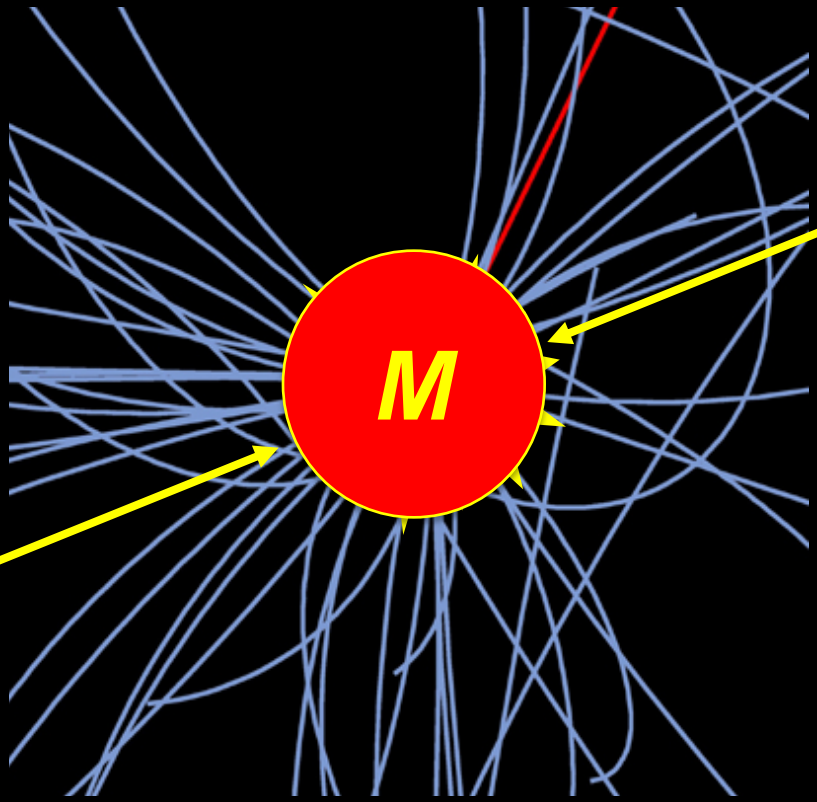




Higher E, Shorter λ (10^{-18}m)



Producing particles last seen in the earliest moments of the universe with a high energy collider (“time machine”)

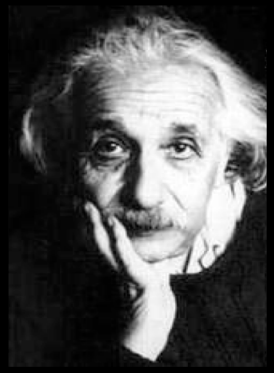


anti particle

$\frac{1}{2}E$

particle

$\frac{1}{2}E$



$E = Mc^2$

History of the Universe

Early Universe

0.00000000001 seconds

Current Universe

1,0000,000,000,000 seconds
(~14 billion years)

Big Bang

Building blocks existed in the early universe

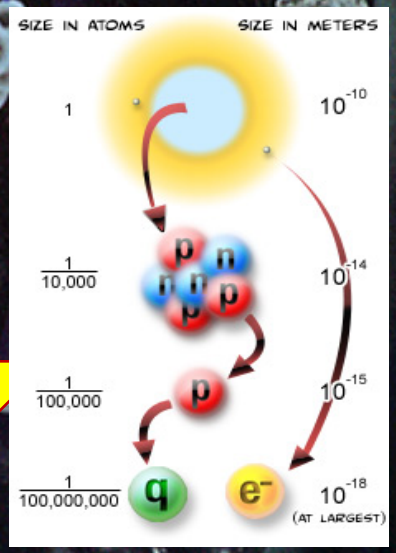
Top quark
Z boson
W boson
Higgs boson
…..

M

Time Machine
(peeing backward in time)

Super Microscope
(peeing inward)

Standard Model

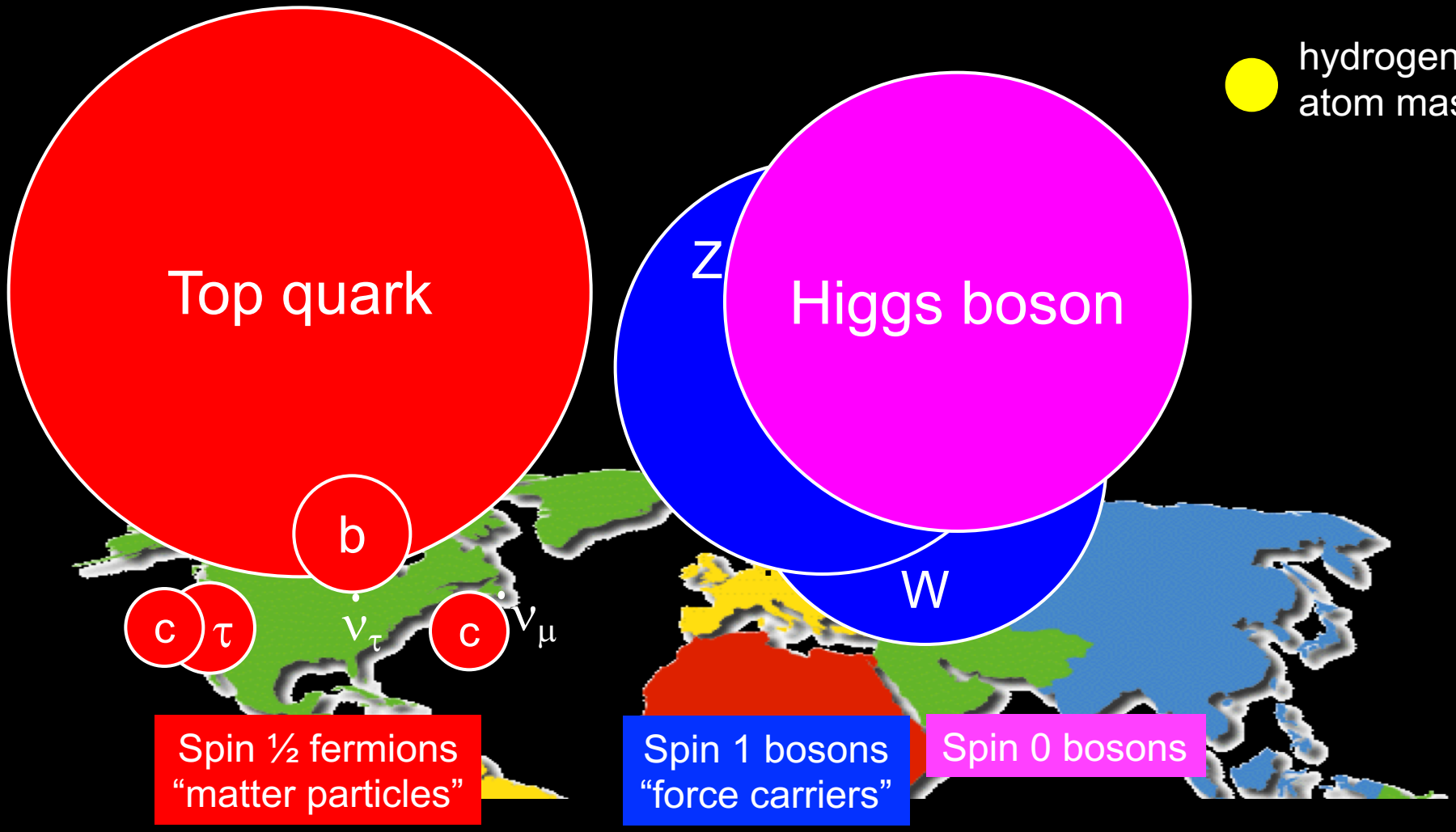


Particle Physics is where

- Current university meets early universe
- Inner world meets outer world
- Smallest thing meets biggest thing

up quark
down quark

Elementary particles discovered by accelerator-based experiments

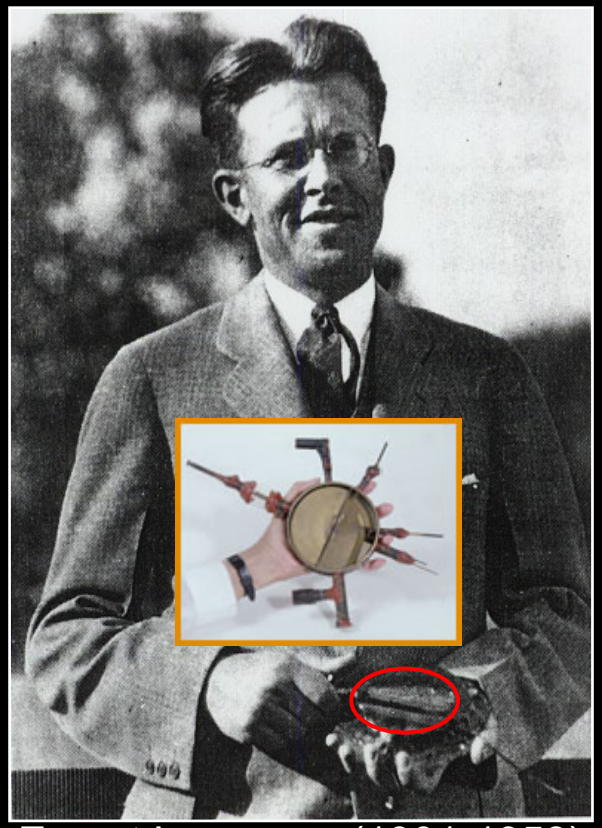


Particles are messengers: through them, we understand laws of nature

Discoveries made by their stories
(non accelerator-based & accelerator based)

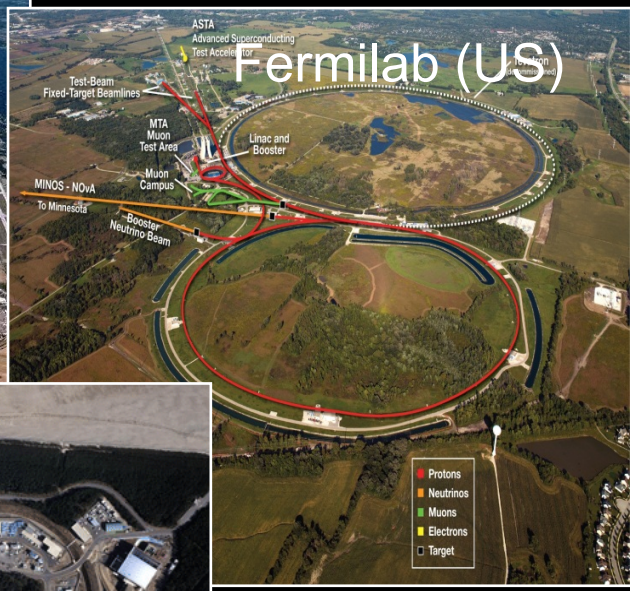
~100 Year History: Accelerators

1930

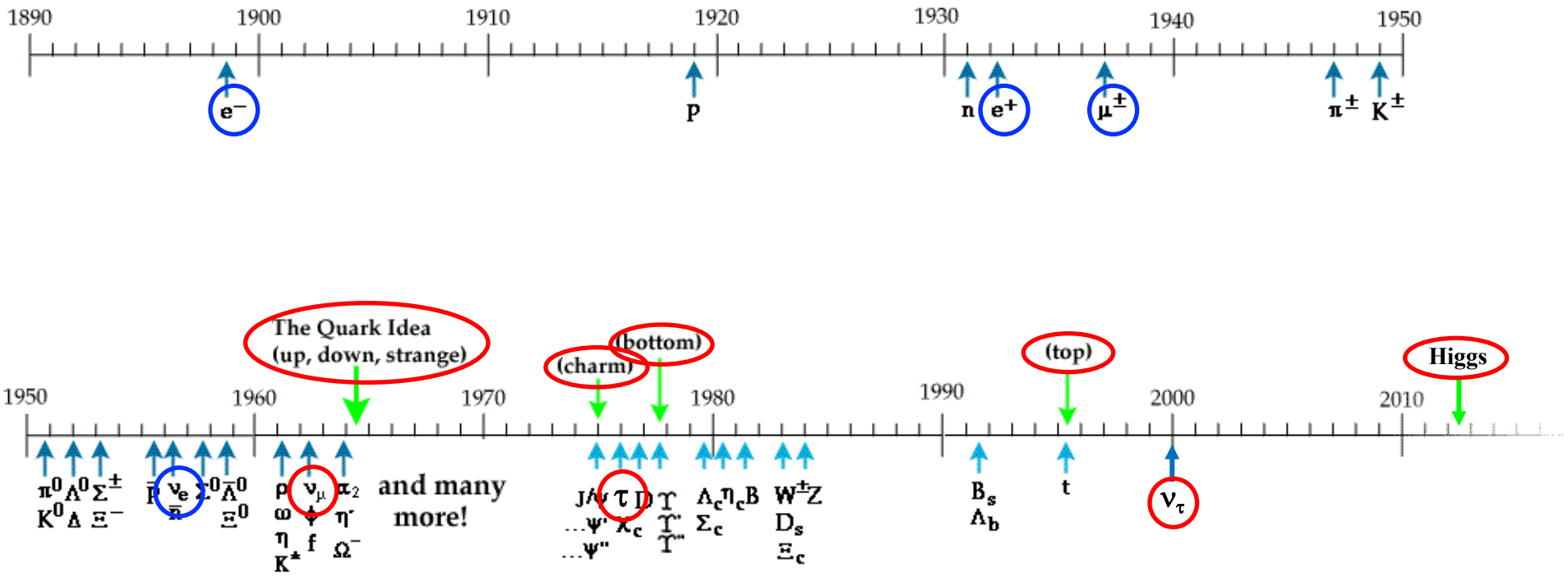


Ernest Lawrence (1901-1958)

Today's particle accelerators



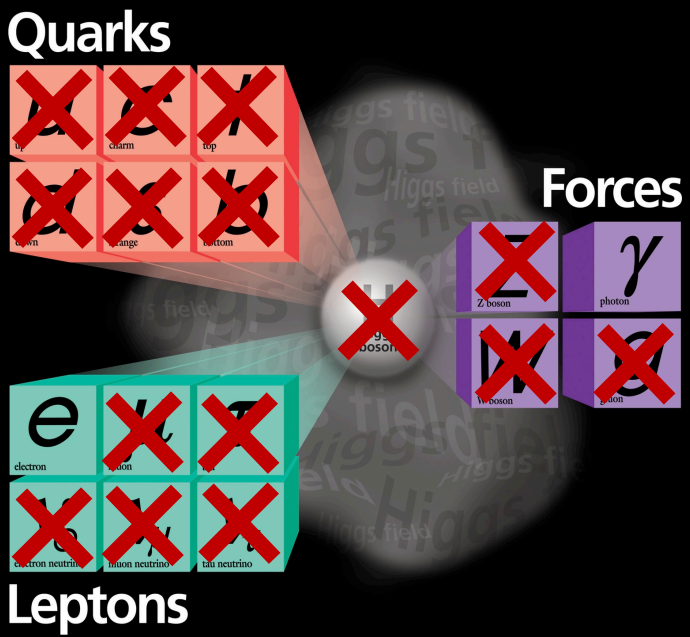
Discovery of Particles



Global

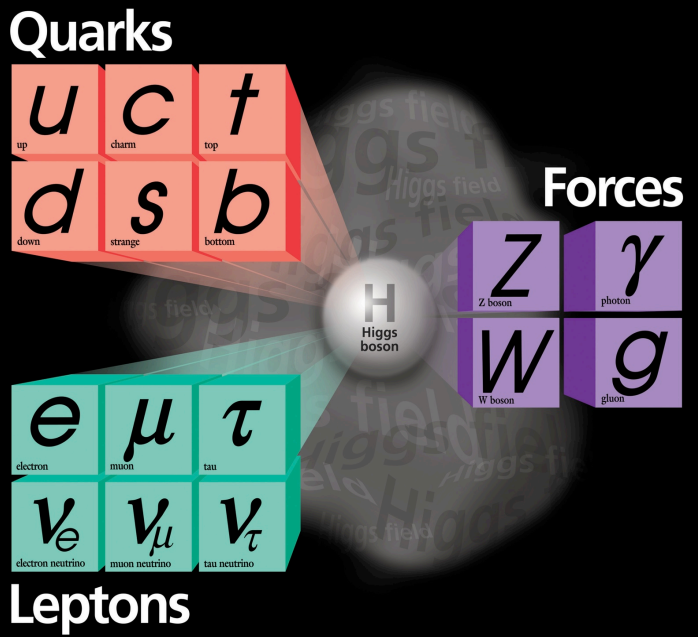
Last 100 Years

1922



2022

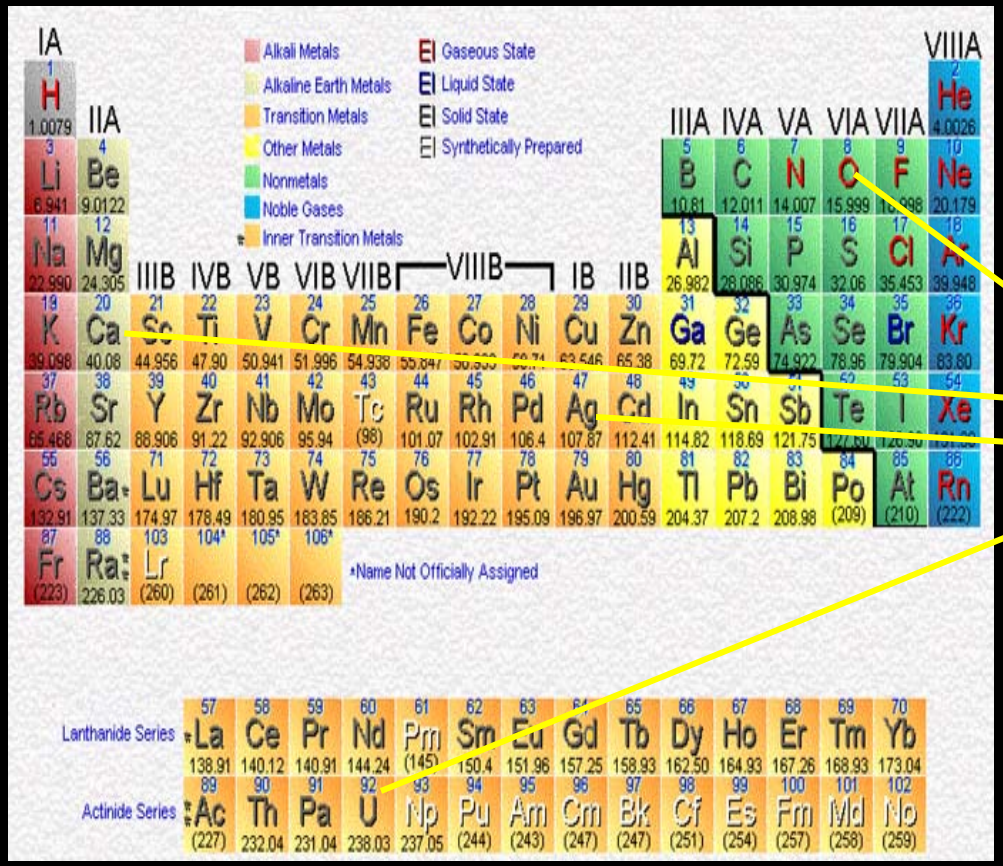
Standard Model of Particle Physics



Remarkable Achievements !!

Accomplishment
of the 19th Century

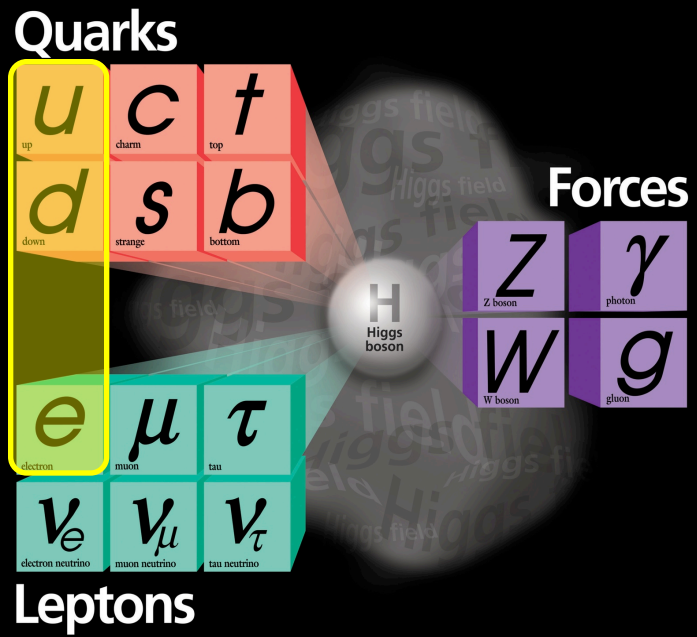
Periodic Table of Elements



Accomplishment
of the 20th Century

Table of Elementary Particles

Standard Model

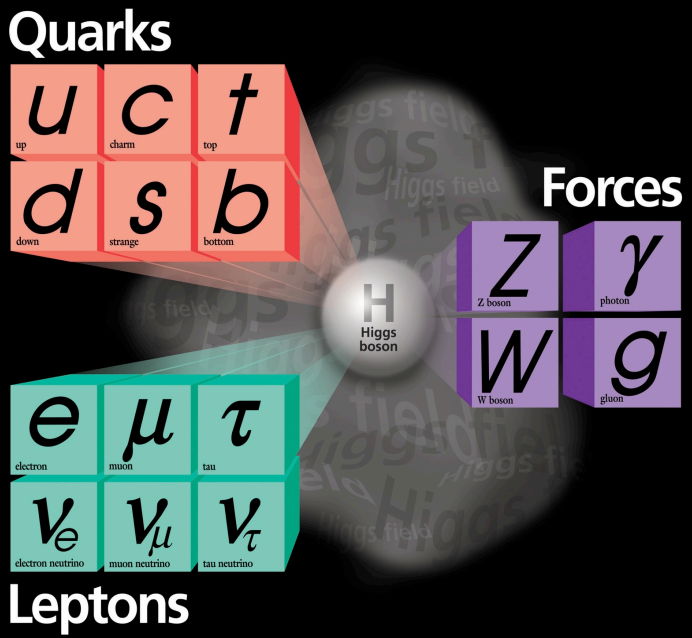


Remarkable Achievements !!

Standard Model & The Mysteries

Standard Model of Particle Physics

Working beautifully!



Remarkable Achievements !!

Phenomena in nature
that the Standard Model cannot explain.

WHY ?

- mass
- 6 quarks
- 3 families
- forces
- anti-matter
- neutrinos
- …..

WHAT ?

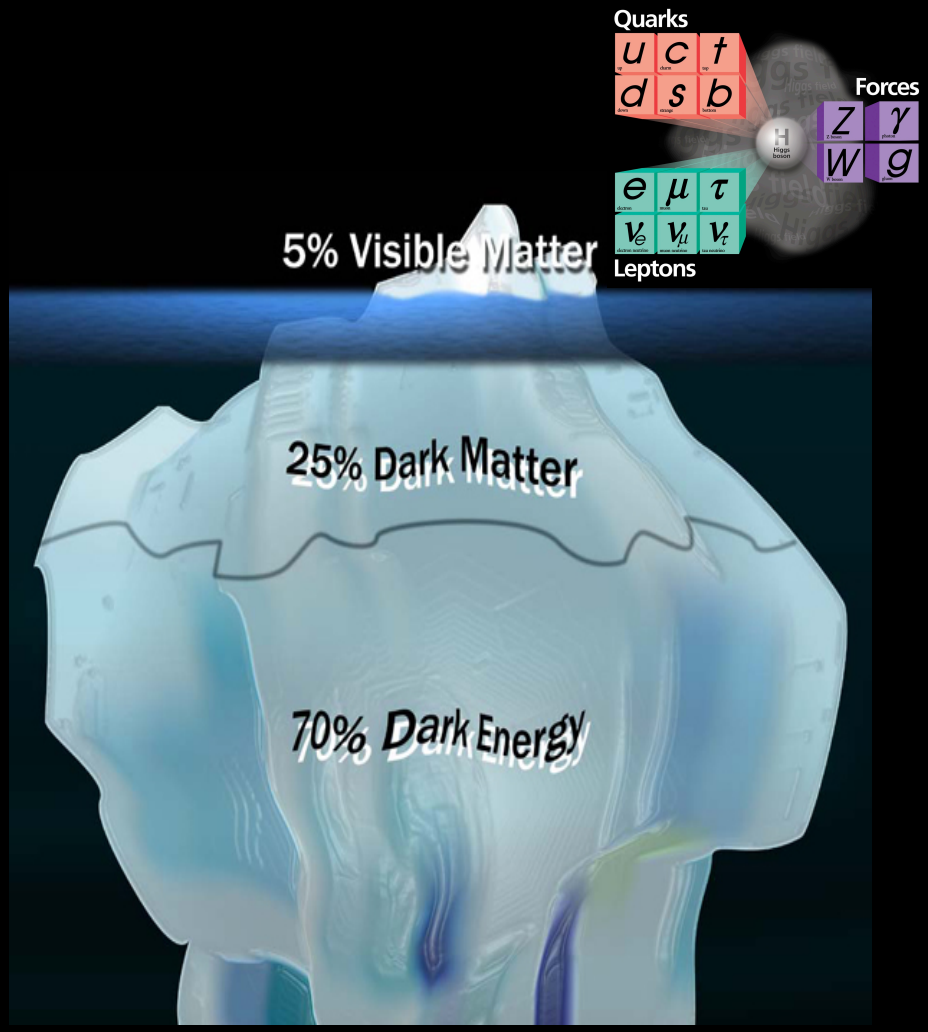
- dark matter
- dark energy

Standard Model & The Mysteries

Why ?

What ?

What ?



Visible Universe

Invisible Universe
(Dark Universe)

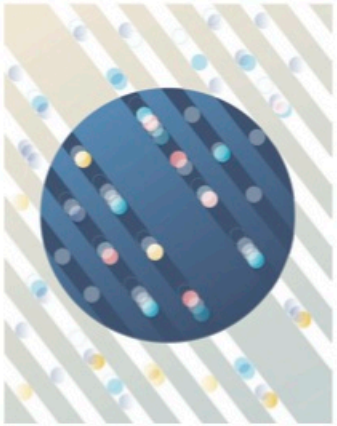
“The more you know, the more you know you don't know.”

Aristotle
Greek philosopher & scientist
(384 – 322 BC)

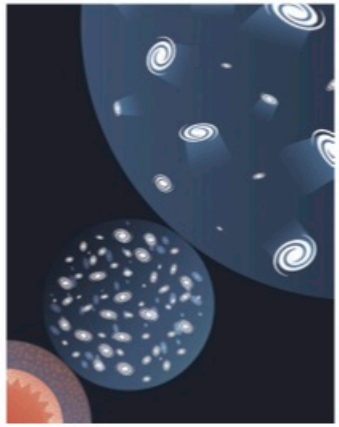
Intertwined Science Drivers in Particle Physics

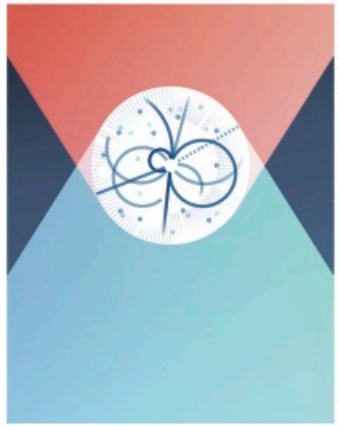
- Use the Higgs boson as a new tool for discovery
- Pursue the physics with neutrinos
- Identify the new physics of dark matter
- Understand cosmic acceleration (dark energy & inflation) and explore uncharted discovery space (gravitational waves)
- Explore the unknown: new particles, interactions, phys. principles


Higgs boson


Neutrino mass

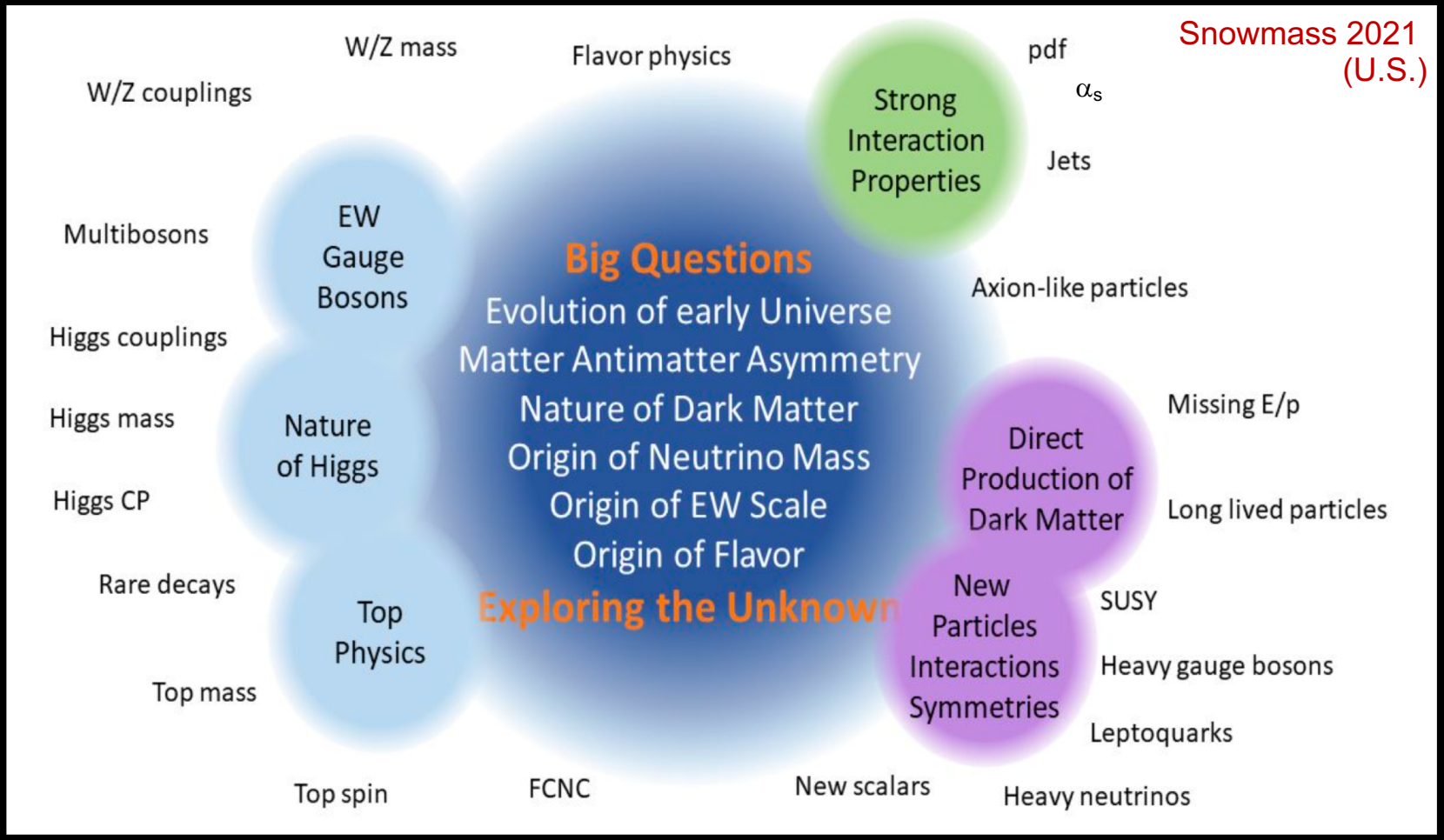

Dark matter


Cosmic acceleration


Explore the unknown

Energy Frontier

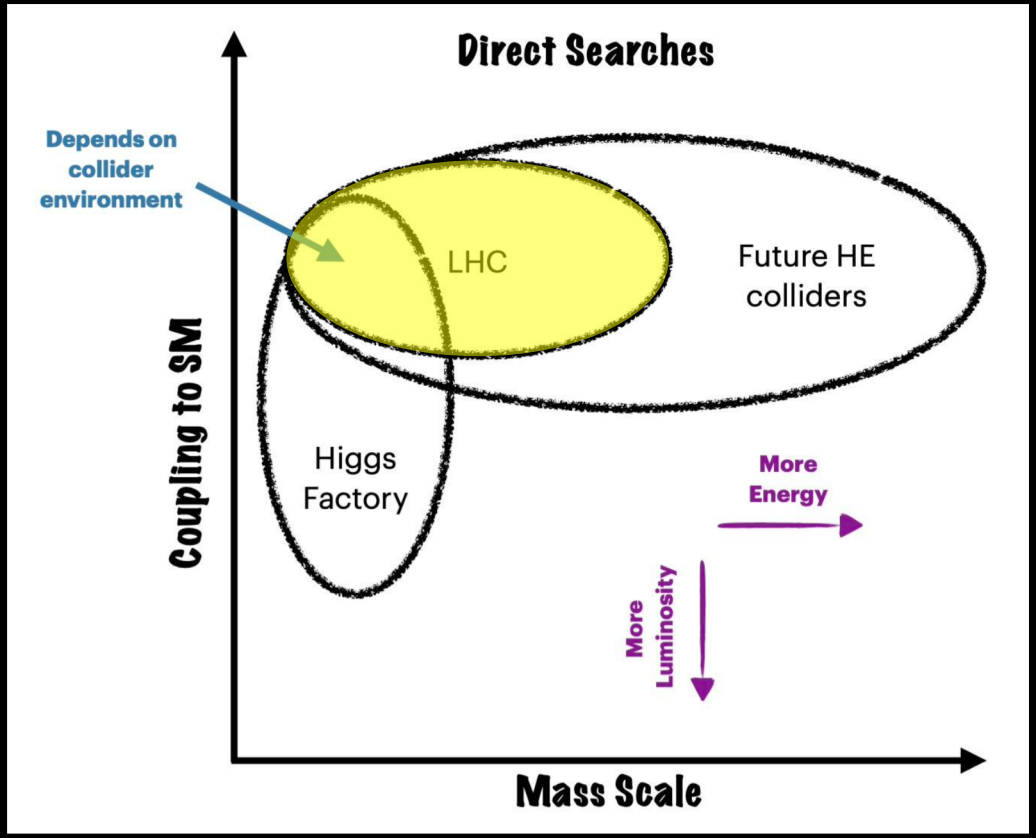
Explore the TeV energy scale and beyond
through the breadth and multitude of collider physics signatures



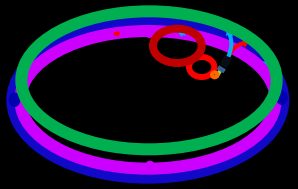
Energy Frontier Beyond LHC

Search for direct evidence of new physics

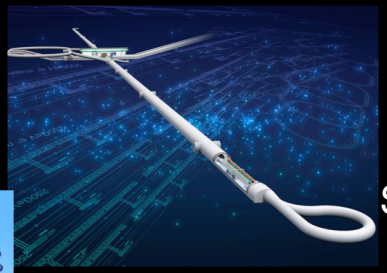
Search for indirect evidence of new physics via precision measurements (e.g., Higgs Factory)



Energy Frontier Beyond LHC

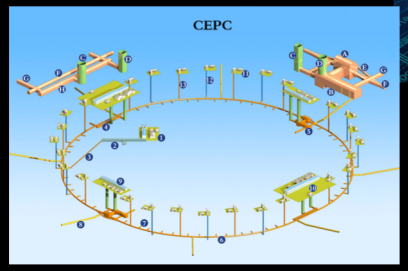


Muon collider
~10 TeV



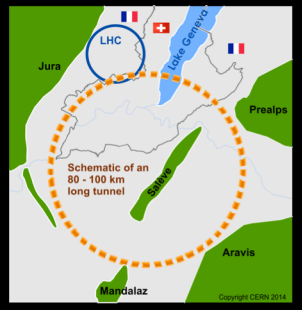
Super pp Collider (SppC)
E_{cm} ~100 TeV

2045



Compact Linear
Collider (CLIC)
e^+e^- $E_{cm} < 3$ TeV

2040



Circular Electron Positron Collider
(CEPC) $E_{cm} < 250$ GeV

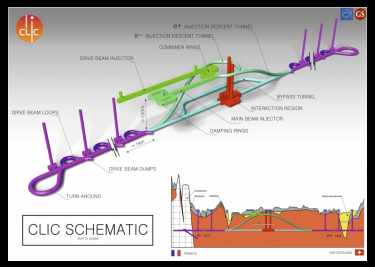
2035

Future Circular Collider (FCC)
e^+e^- $E_{cm} < 350$ GeV
pp E_{cm} ~100 TeV
AA E_{cm} ~40TeV

2030

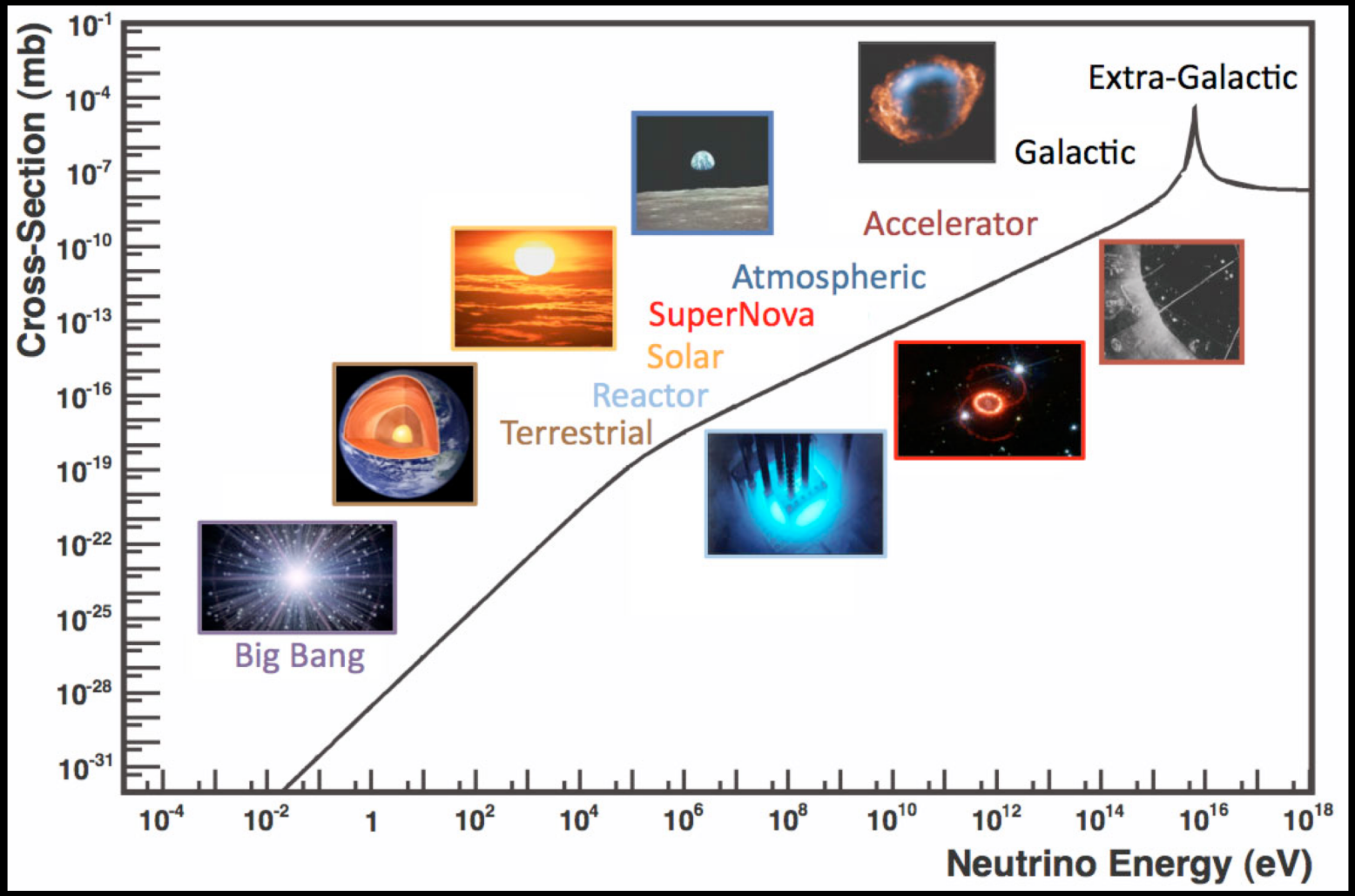
LHC

2025



International Linear Collider (ILC)
e^+e^- $E_{cm} < 1$ TeV

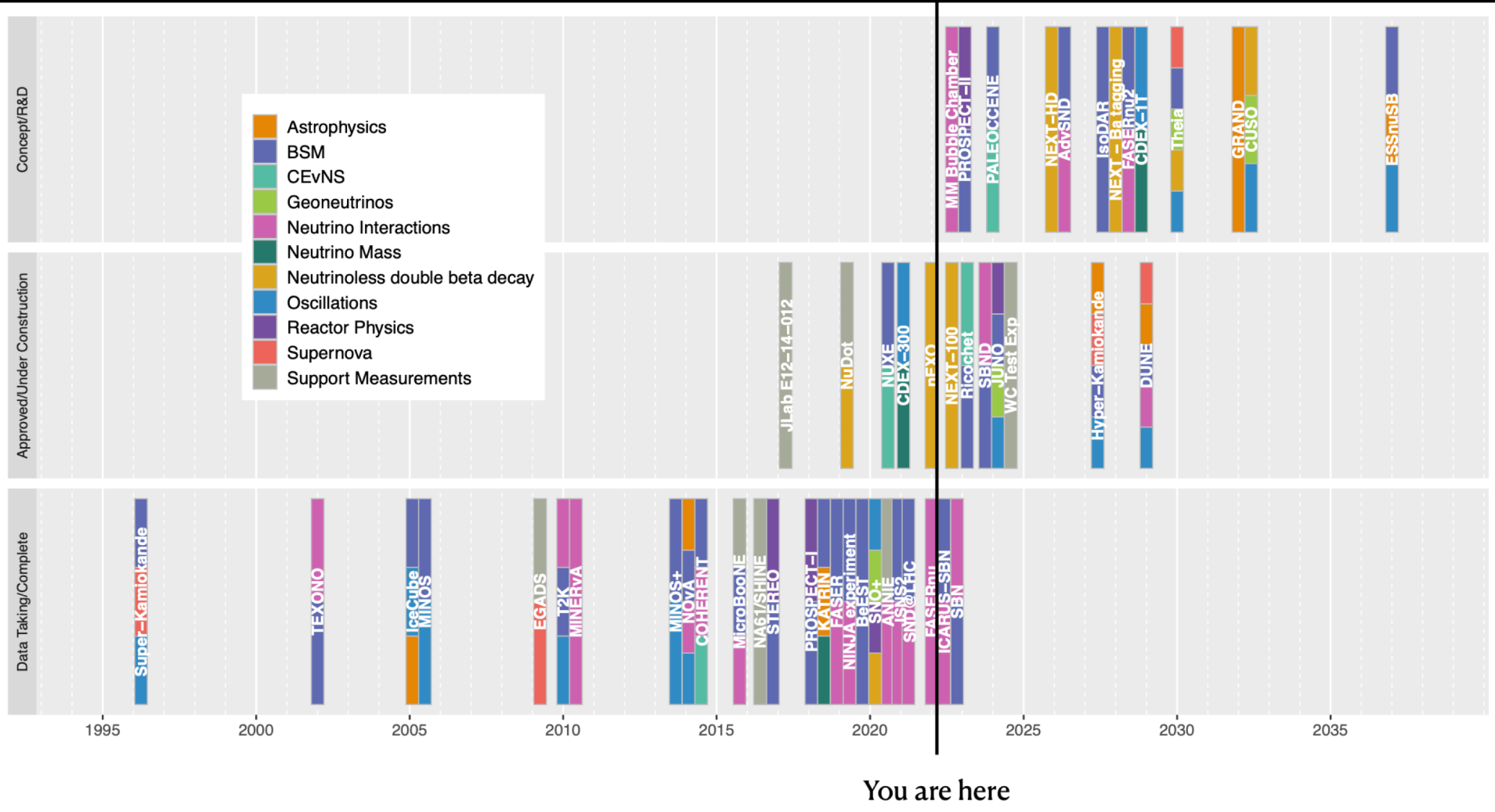
Neutrino Frontier



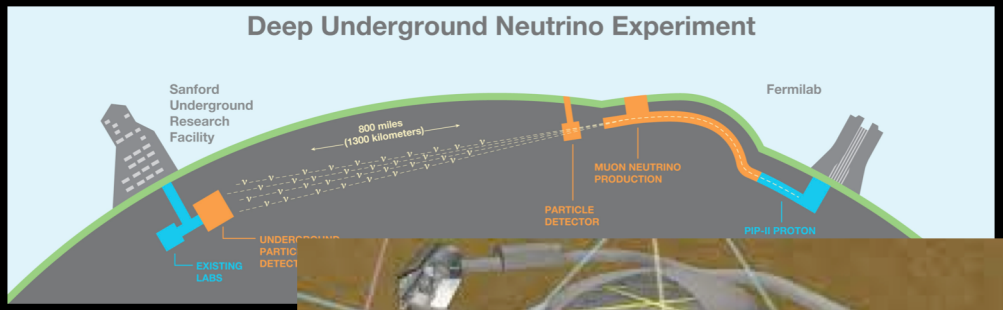
Credit: J.A. Formaggio & G.P. Zeller

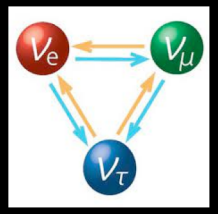
Neutrino Frontier

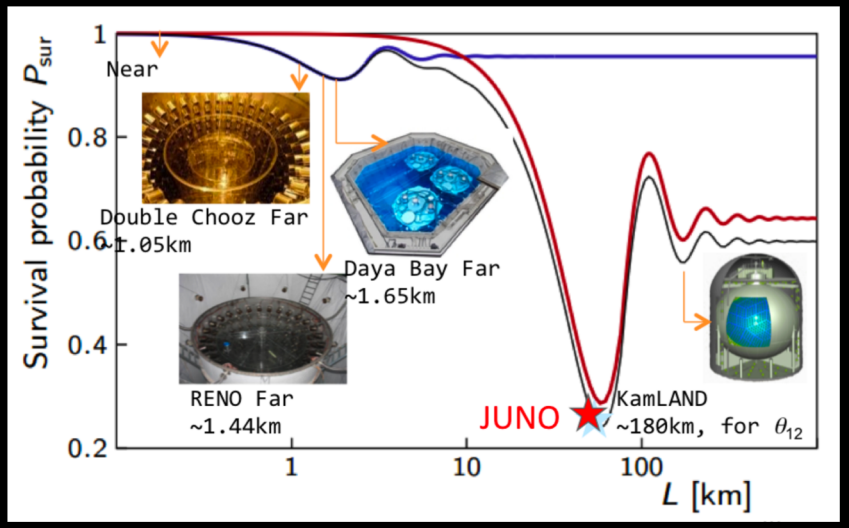
Snowmass 2022

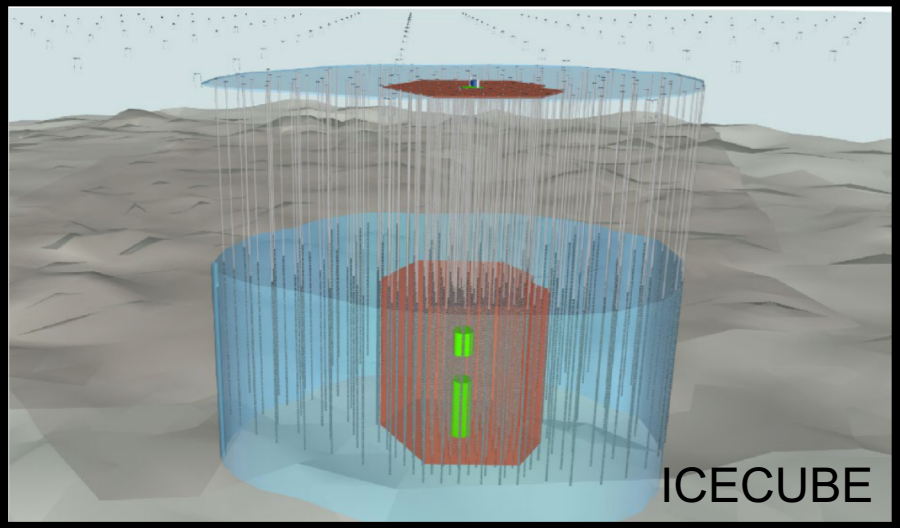


Neutrino Frontier





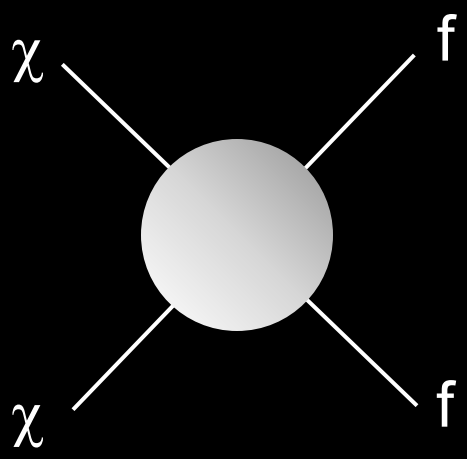




Dark Matter Searches

Indirect detection (space telescopes)

— annihilation →



scattering

Direct detection
(underground experiments)

Complementary
to each other

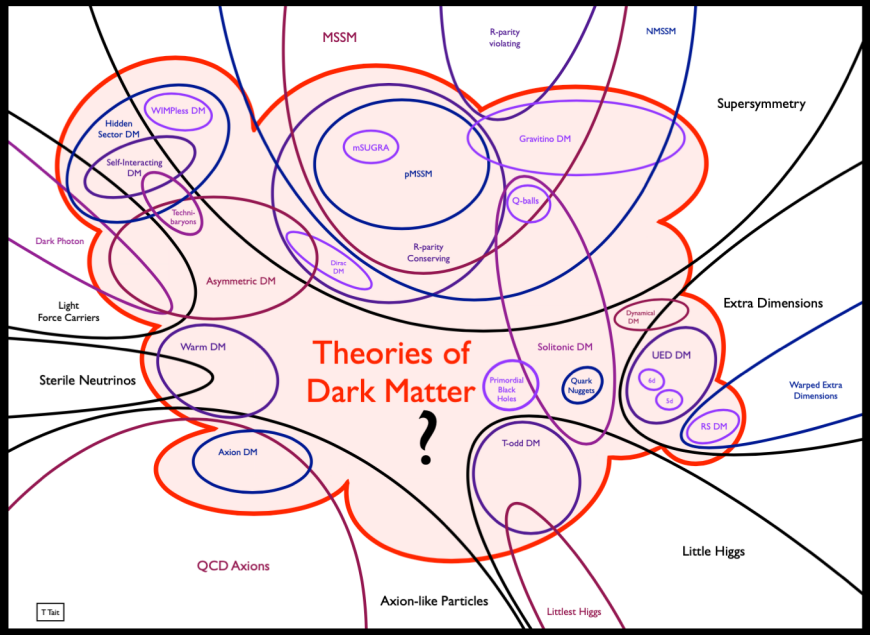
← production —

Particle accelerators (collider experiments)

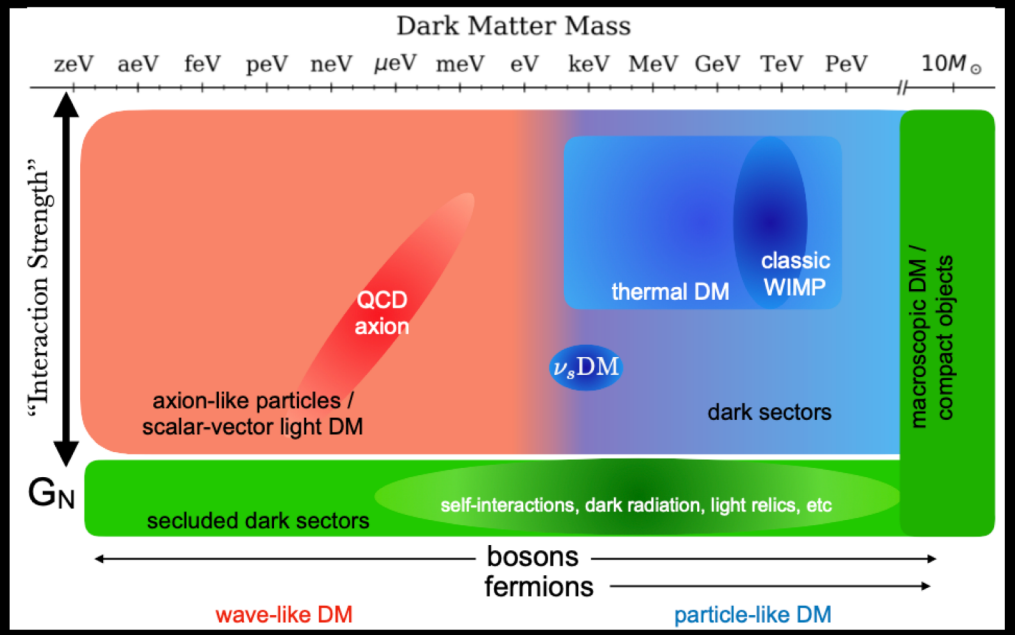
Dark Matter Searches

The Space of Dark Matter models encompasses a dizzying array of possibilities, representing many orders of mass and couplings

Tim Tait

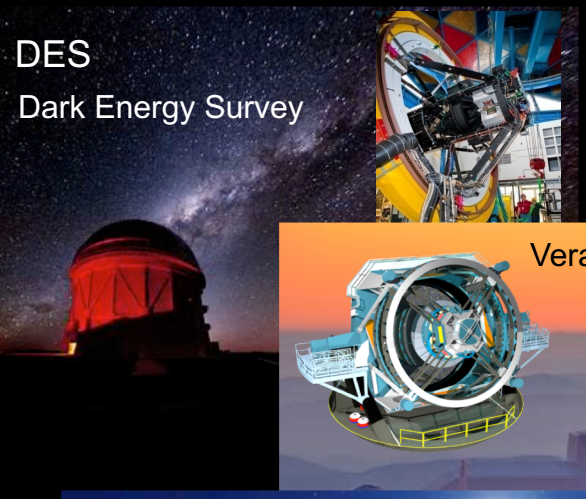


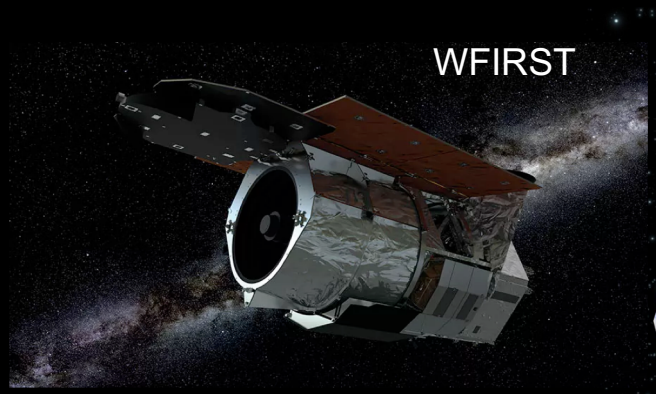
Snowmass 2022 (US)

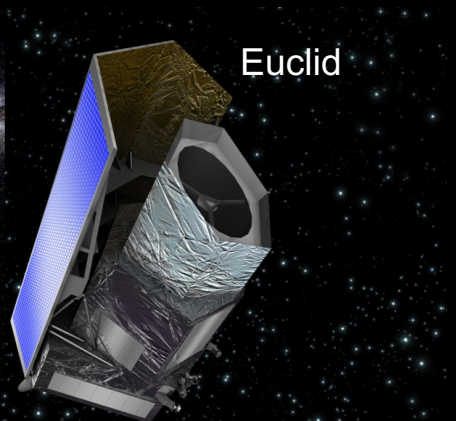


Cosmological Probes

Cosmic Expansion History
Cosmic Microwave Background
Growth of Structure
Gravitational Waves



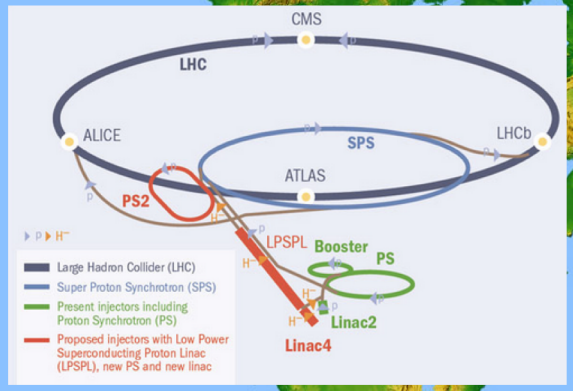




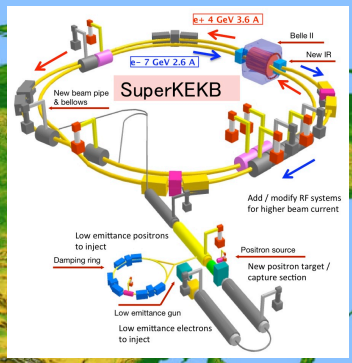
Searches for New Particles and New Phenomena
Direct (Energy Frontier)
Indirect (Neutrinos, Precision Measurements, Rare Processes)

Fermilab

CERN
Energy Frontier



Intensity Frontier



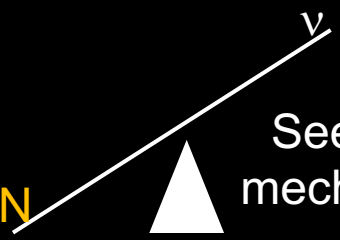
KEK

Other accelerators: VEPP-2000, VEPP-4M, BEPC-II, DAΦNE, PSI, TRIUMF Cyclotrons, …

Intensity Frontier:
Extremely high intensity beams
Probe high energy indirectly

Large E → Rare

E x Δt ~ h



Seesaw mechanism

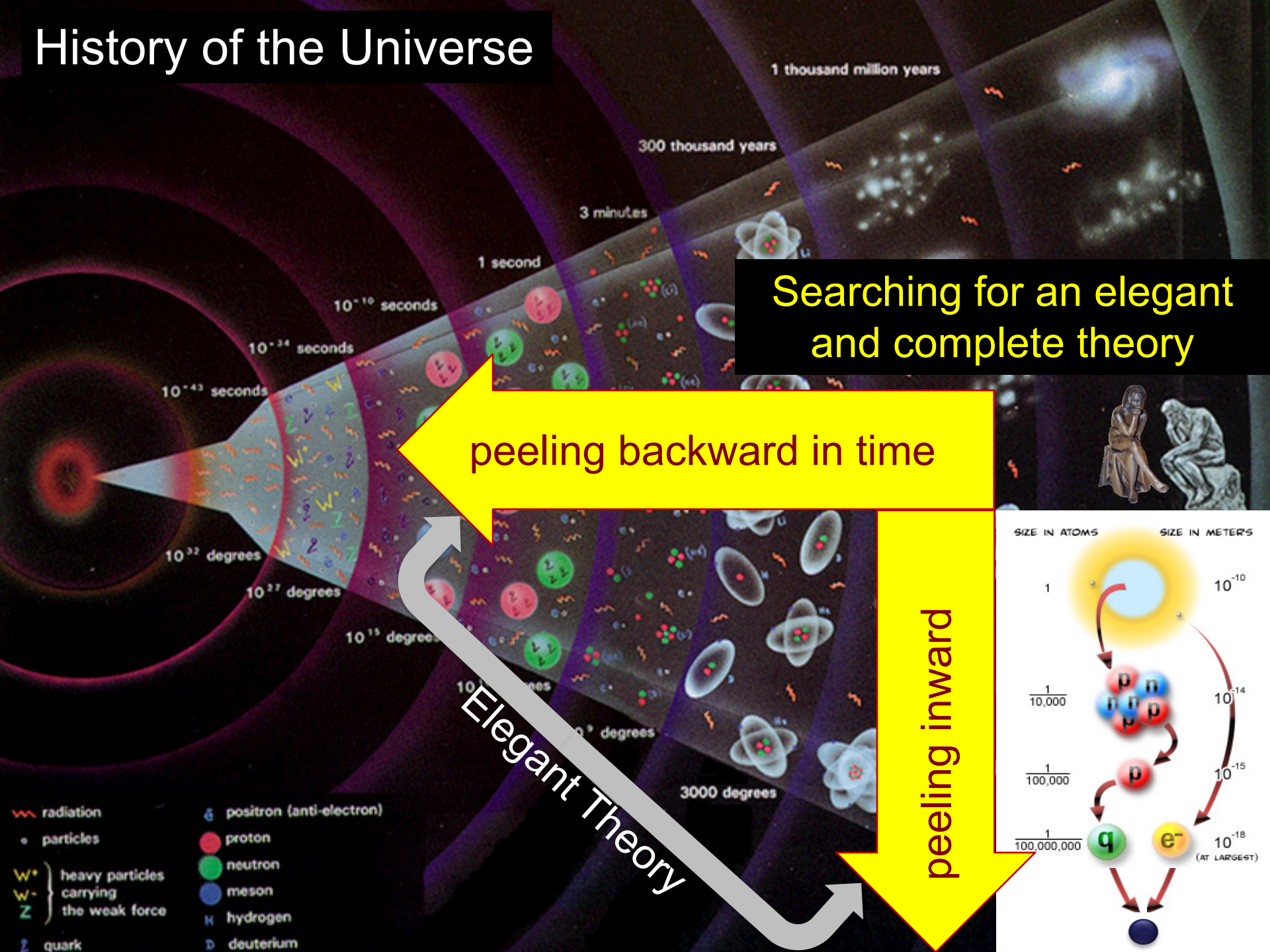
Conclusions

- Over 100 years in particle physics
  - The Standard Model has been constructed and is complete
  - Our knowledge of the Standard Model and our knowledge of the cosmos and its connection to particle physics have increased tremendously.
  - Remarkable achievements!
  - Move to deeper questions

- New Discoveries
  - Dark Matter exists, its grav. interactions being mapped by a host of cosmic probes
  - Neutrinos have unusually small mass; we are measuring their interactions and generational properties and narrowing down their masses.
  - Our Universe has an anti-matter deficit, and is accelerating
  - Gravitational waves, connection to fundamental questions in particle physics
  - These discoveries will enlarge our model of the Universe.

- Huge New Opportunities (Now and Future), Exciting Time!
  - We have new tools to measure matter, energy and space-time at all epochs

History of the Universe



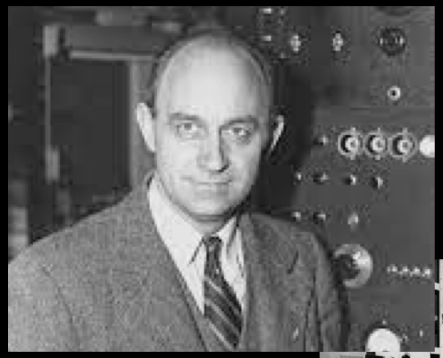
Searching for an elegant and complete theory

peeling backward in time

Elegant Theory

peeling inward

Science & Technology Breakthroughs

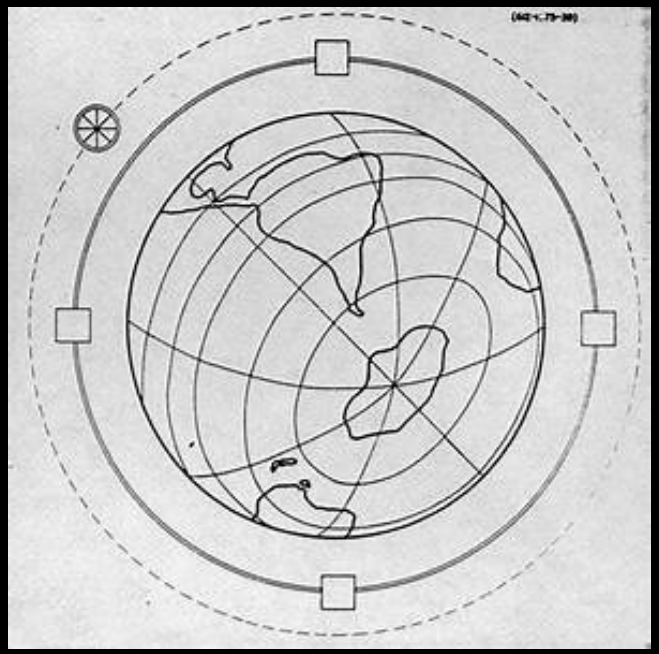


Enrico Fermi
(1901 – 1954)

APS President in 1953

The only way to access new physics is through the development of higher- and higher-energy accelerators

Fermi's Globatron (Projection):
~1 TeV, ~40,000 km, ~1994,
~170B 1954 $ (~1,000B 2022 $)



Actual ~1 TeV Accelerators:
Tevatron: ~10 km, ~1985, ~a few B 2022 $

Dramatically smaller and cheaper
thanks to Science & Technology Breakthroughs

Equity, Diversity and Inclusion for Better Science and Technology

Gender Gap

The Nobel Prize in Physics has been awarded to 221 individuals until 2022

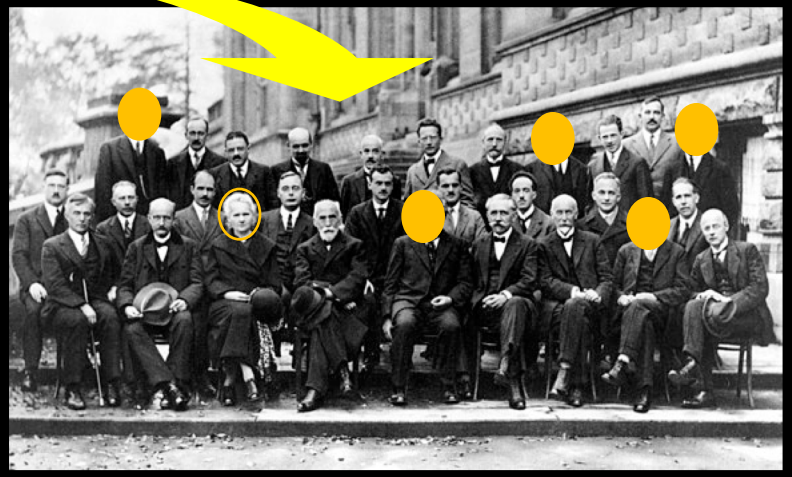
4 women received the Nobel Prize in Physics (2%)

Marie Curie (1903) → 60 years later: Maria Goeppert-Mayer (1963)

→ 55 years later: Donna Strickland (2018) → 2 years later: Andrea Ghez (2020)

Progress in gender balance in the last 100 years

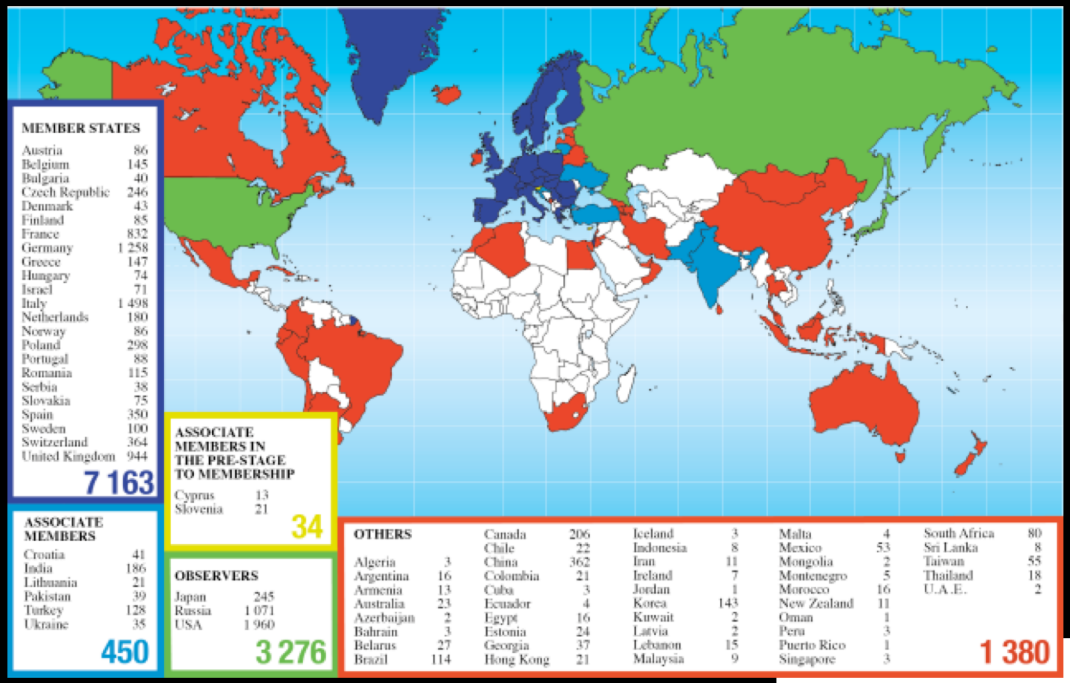
Solvay Conference (1927)



Now (2022: ~20%)

Racial and Regional Gap

“Particle Physics is Global!” Opportunities to Reduce Gaps



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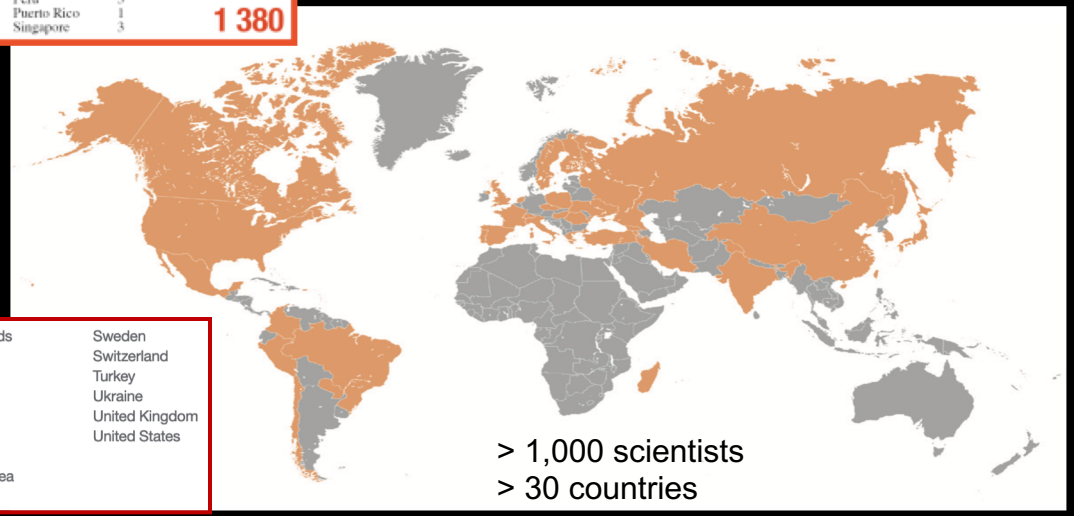

Armenia	Georgia	Netherlands	Sweden
Brazil	Greece	Paraguay	Switzerland
Canada	Hungary	Peru	Turkey
Chile	India	Poland	Ukraine
China	Iran	Portugal	United Kingdom
Colombia	Italy	Romania	United States
Czech Republic	Japan	Russia	
Finland	Madagascar	South Korea	
France	Mexico	Spain	

> 1,000 scientists
> 30 countries

The International Year of Basic Sciences for Sustainable Development

The UN adopted 2022 as the International Year of Basic Sciences for Sustainable Development, recognizing that basic sciences are vital to attain sustainable development and to improve the quality of life for people all over the world.

Globalization has been an influential development in recent decades as science and technology have enabled people to work and communicate across great distances and as the pace of the international economy has accelerated.

The pandemic highlighted how inter-connected the world is right now and how science, technology, society, policy, and politics are all connected. However, it has widened the gap between regions and countries, and erected walls between them. Geopolitical tensions further raised these walls. We are at a critical juncture, when the world faces major global challenges and needs global collaborative responses to meet them.

Basic science can play towards global collaboration for the emerging sustainability sciences during this era of gaps and tensions and on how our past experiences can help guide us for the future.