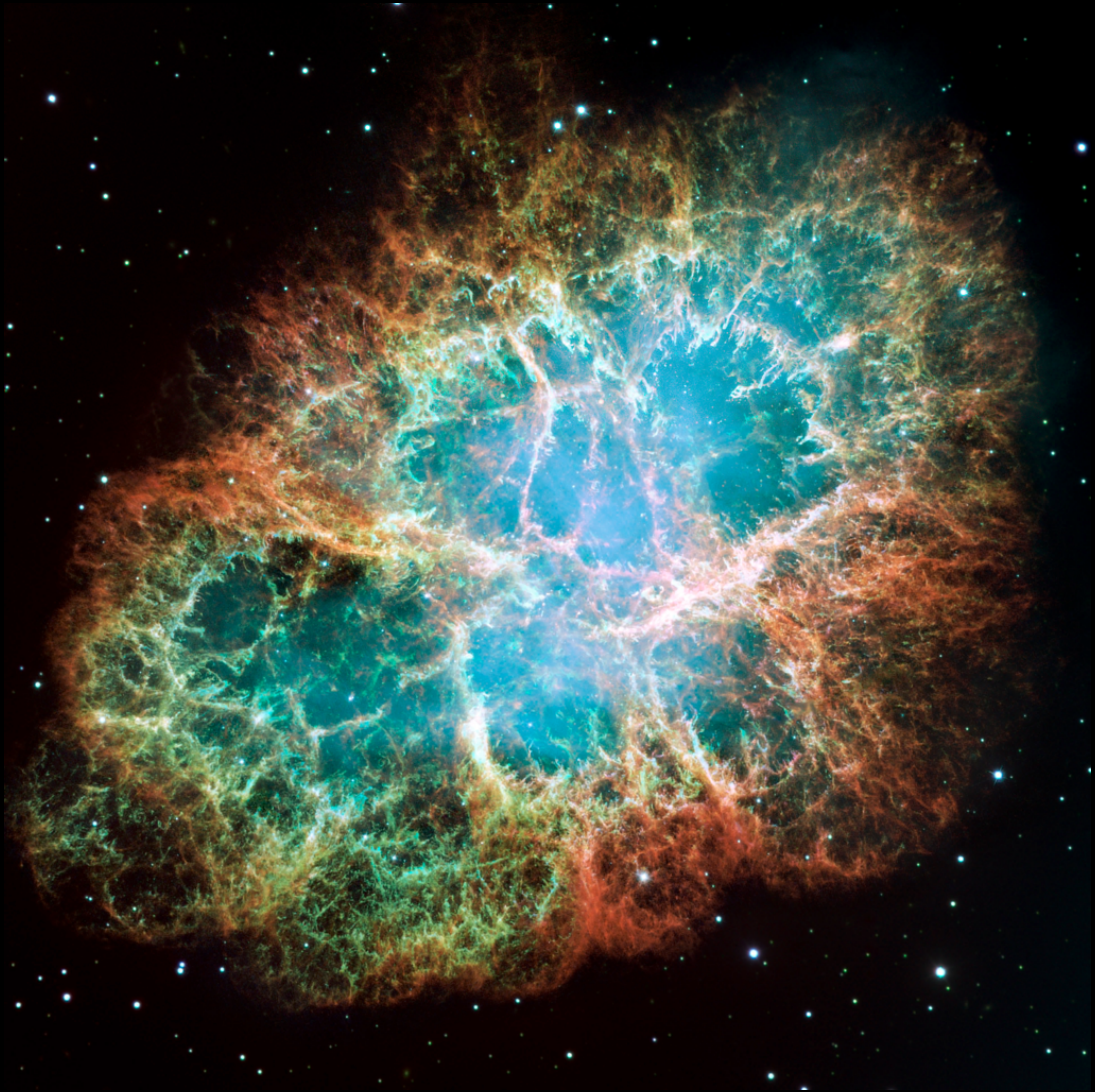
Searching for Matter Creation

How the neutrino may help unlock the mystery of our existence

Jason Detwiler, University of Washington
Seattle Art Institute, April 19, 2018



J. Detwiler

Credit: NASA

Matter and Antimatter

Early Universe

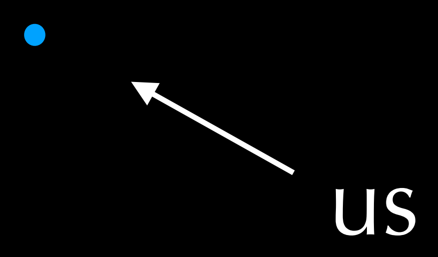
1,000,000,001
particles

for every

1,000,000,000
anti-particles

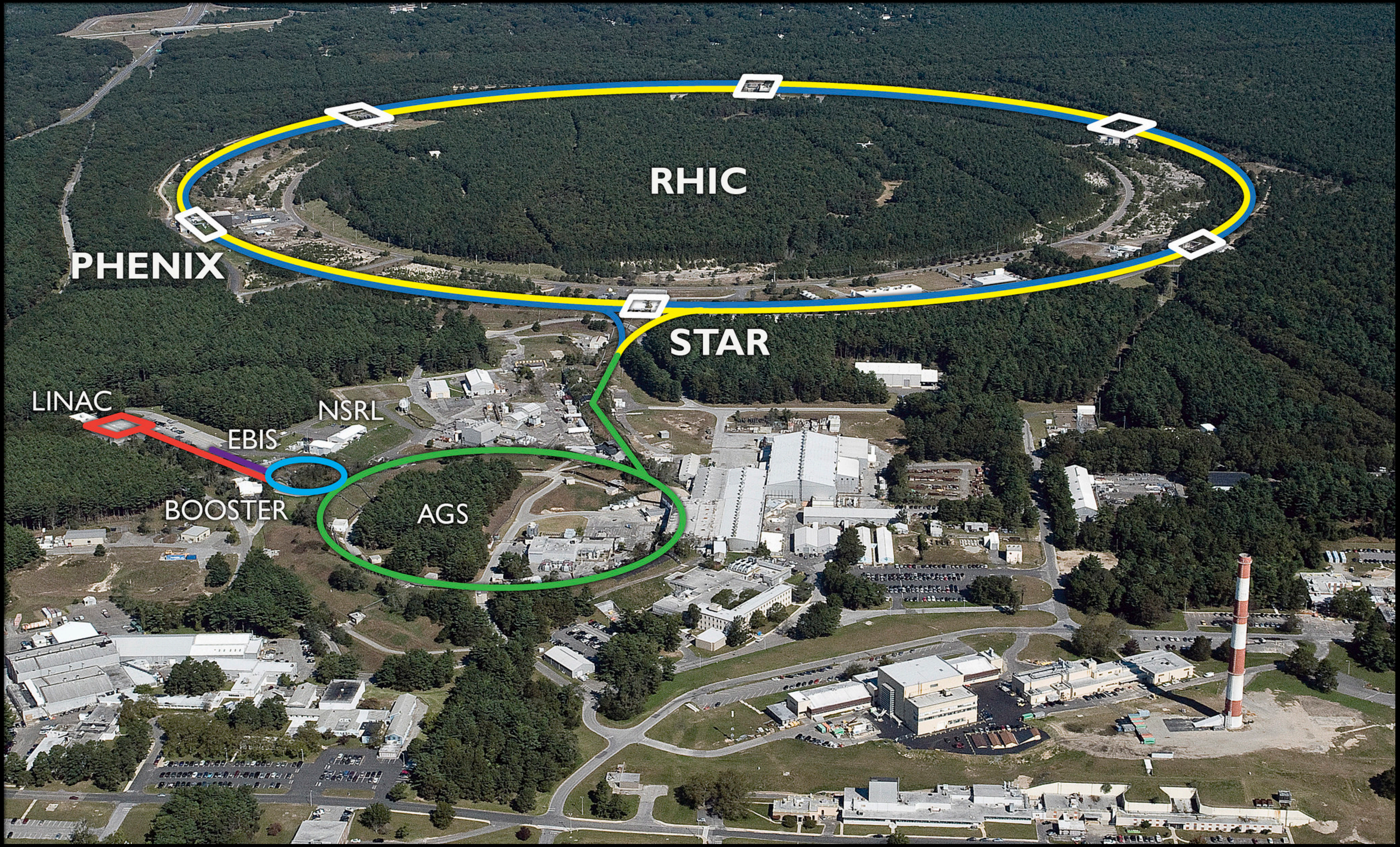
Matter and Antimatter

Current Universe



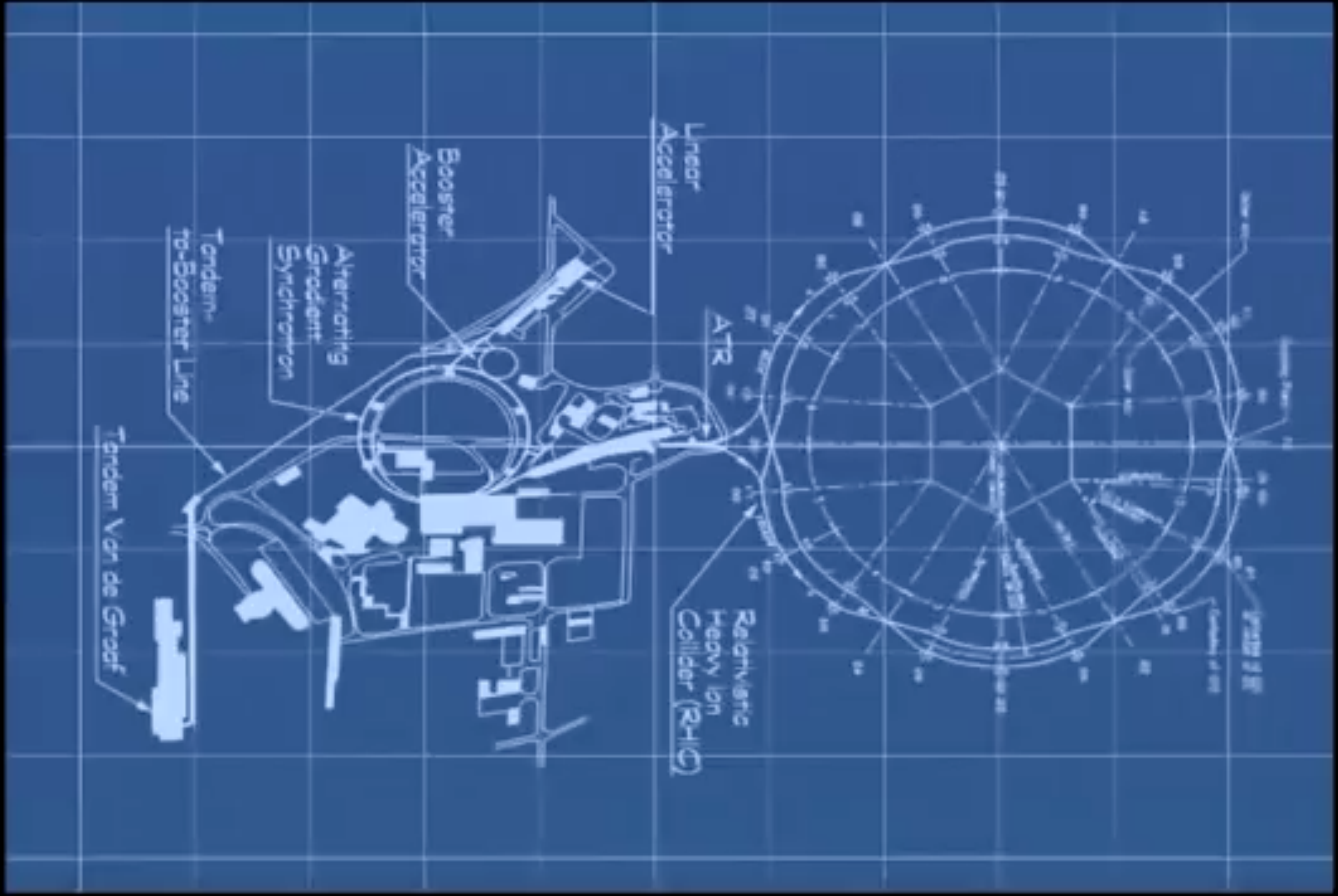
"The Great Annihilation"

Recreating the Big Bang



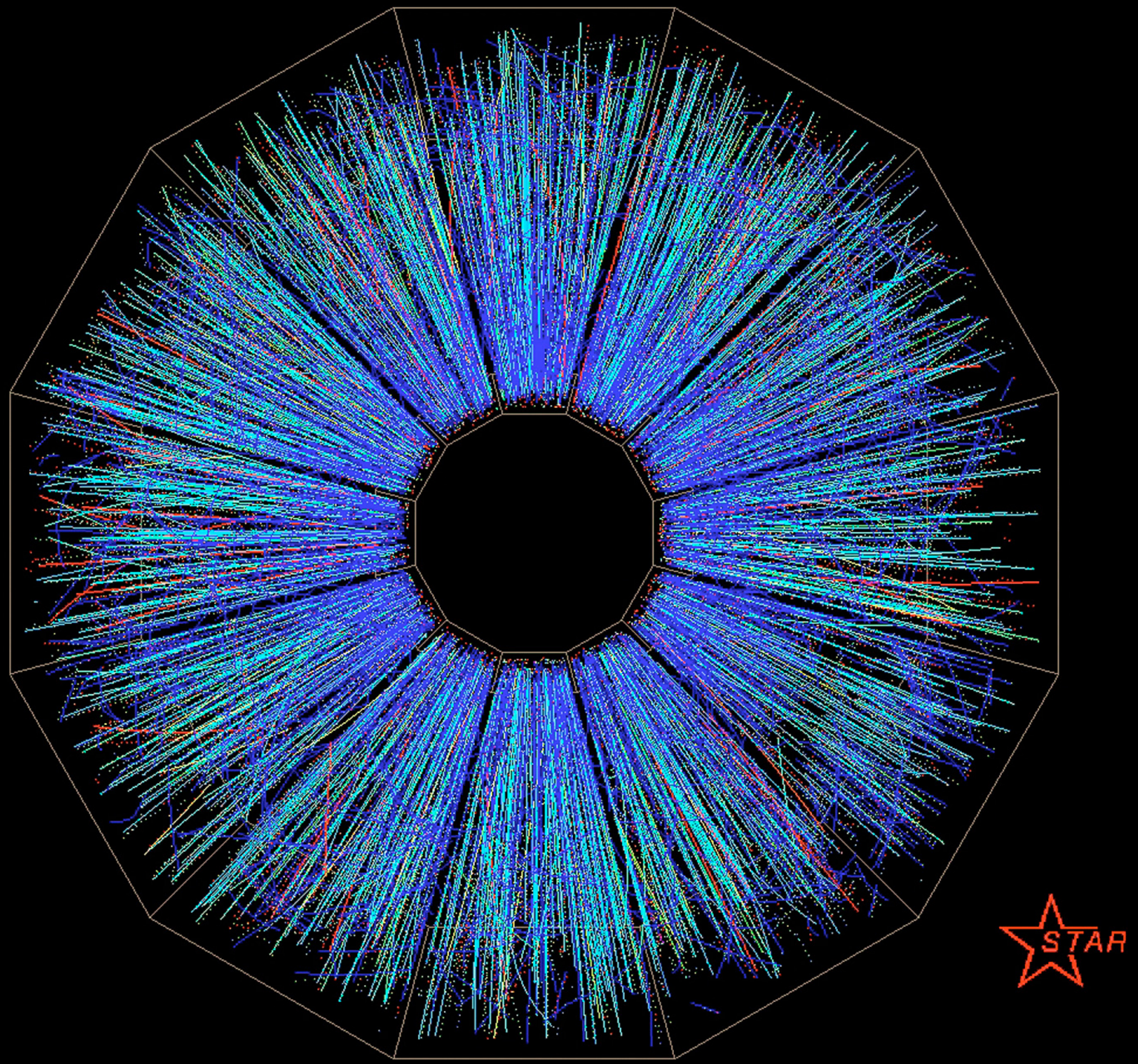
Credit: Brookhaven National Laboratory

Recreating the Big Bang



Credit: Brookhaven National Laboratory

Recreating the Big Bang



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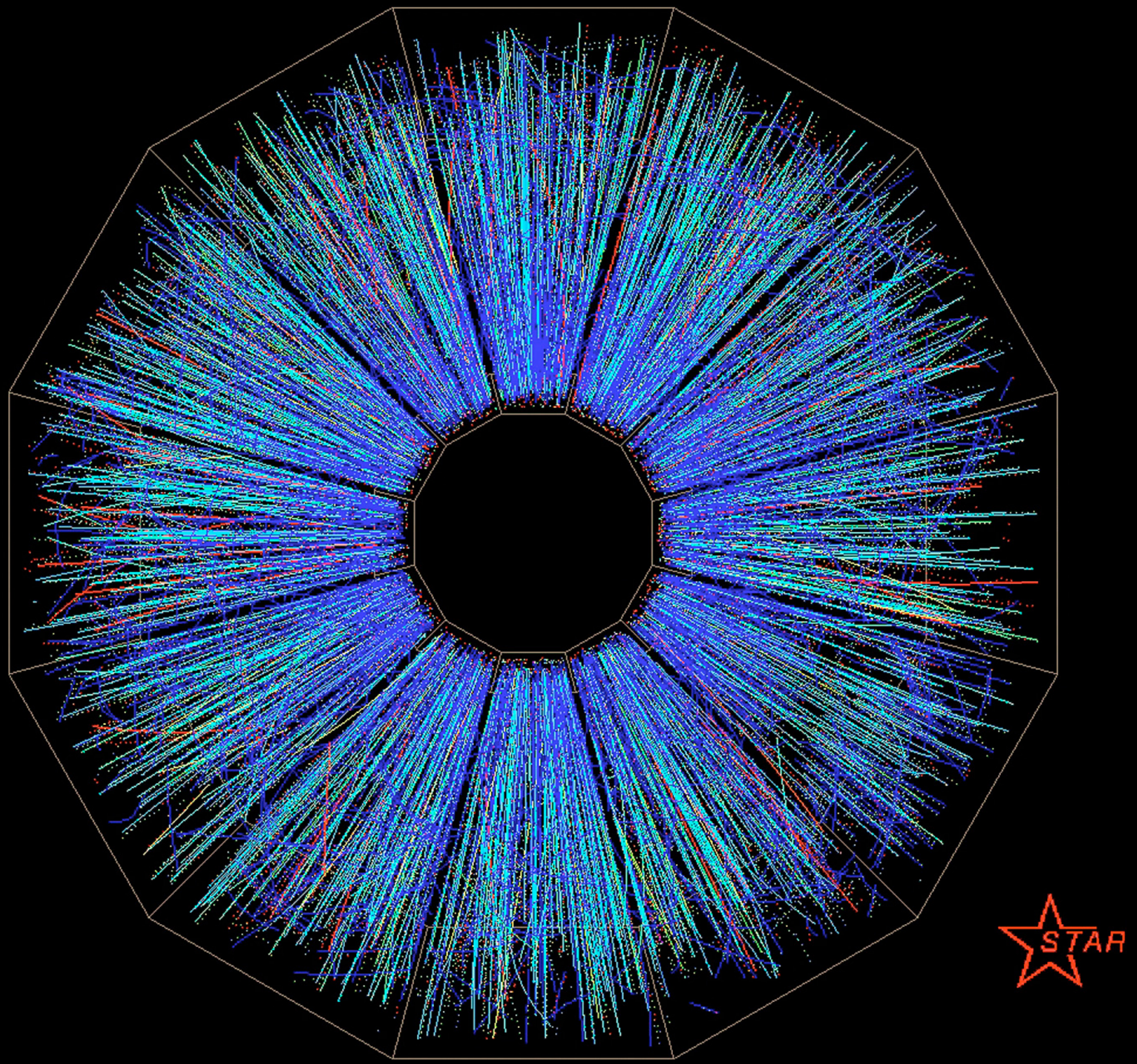
Credit: Brookhaven National Laboratory

Recreating the Big Bang

The universe
~0.00001 seconds
after the Big Bang

Temperature:
4,000,000,000,000 C



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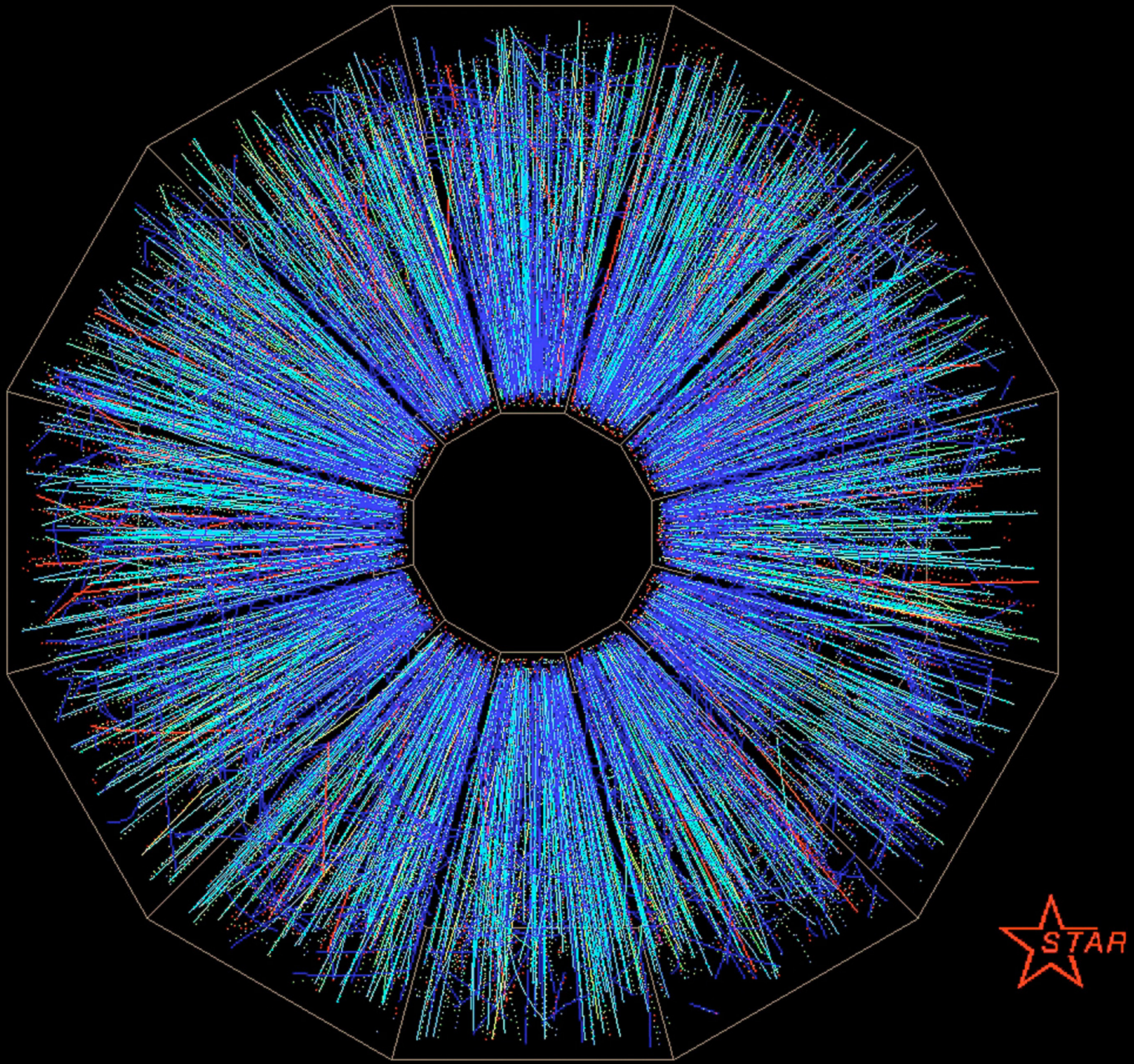
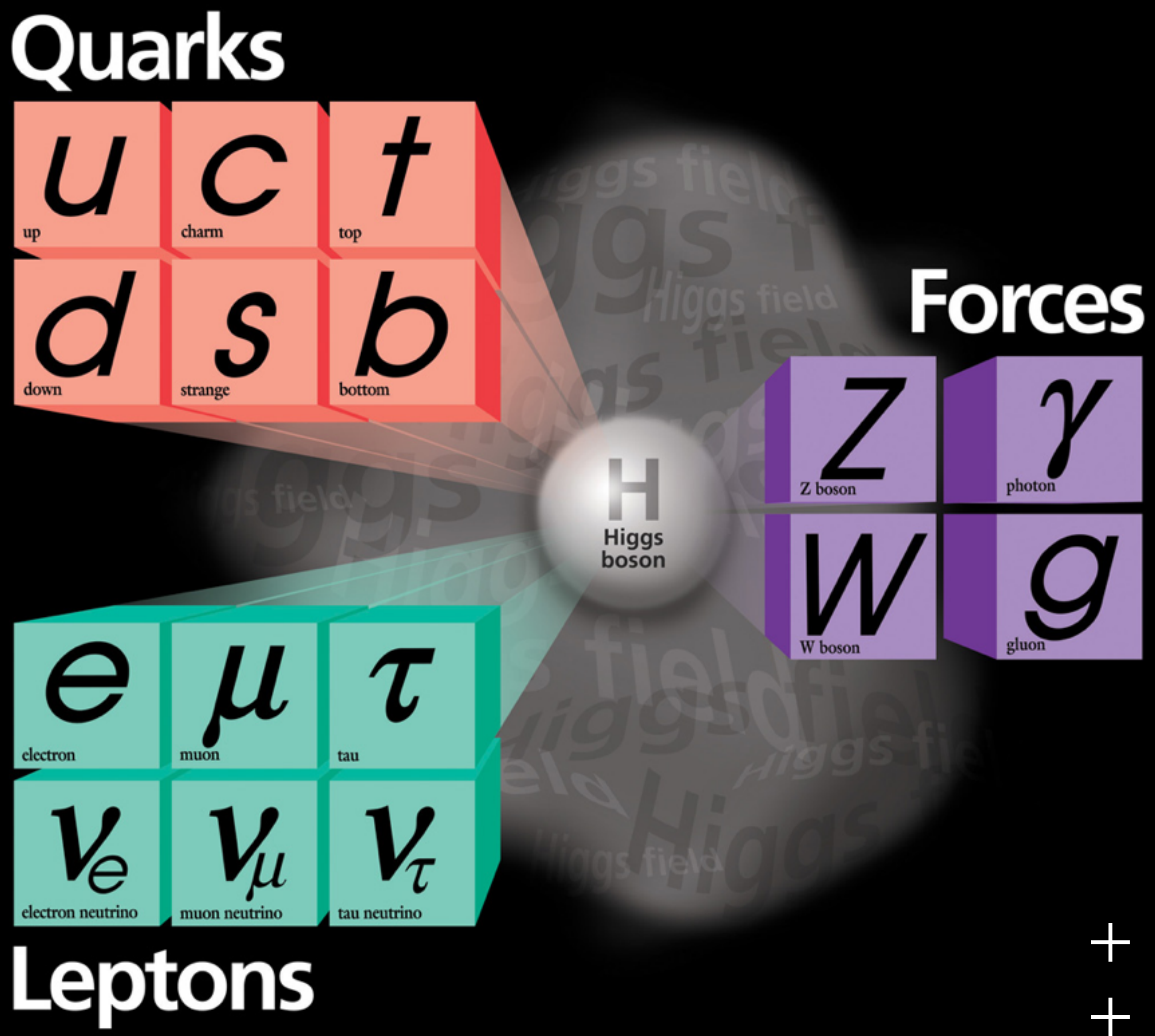


Matter and antimatter are
always created in pairs.

Credit: Brookhaven National Laboratory


The Ubiquitous Neutrino
1 neutrino for every ~3 photons

All known forms of matter:



+ Dark Matter
+ Dark Energy

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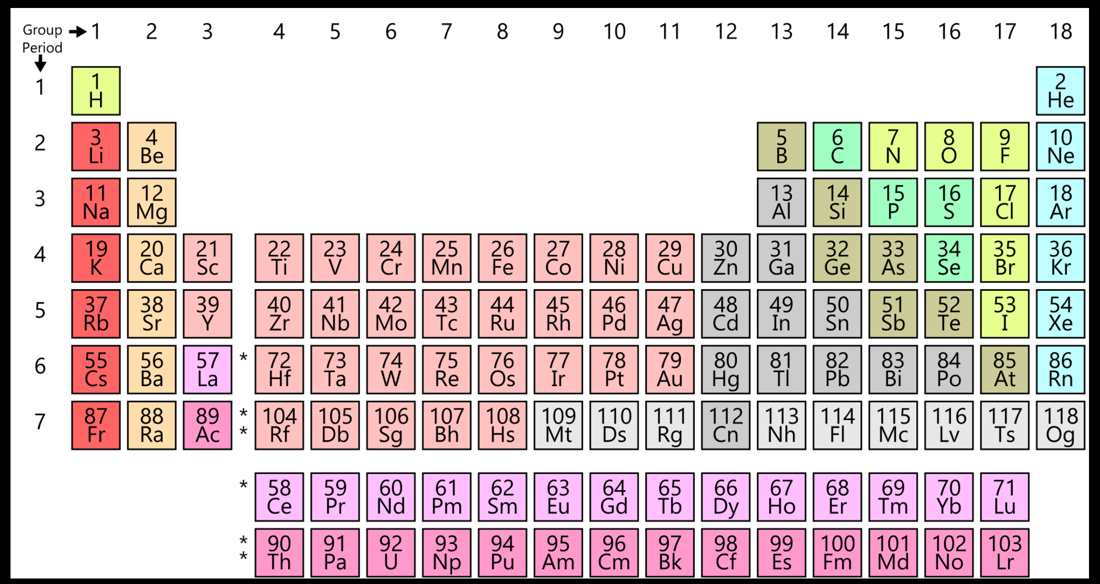
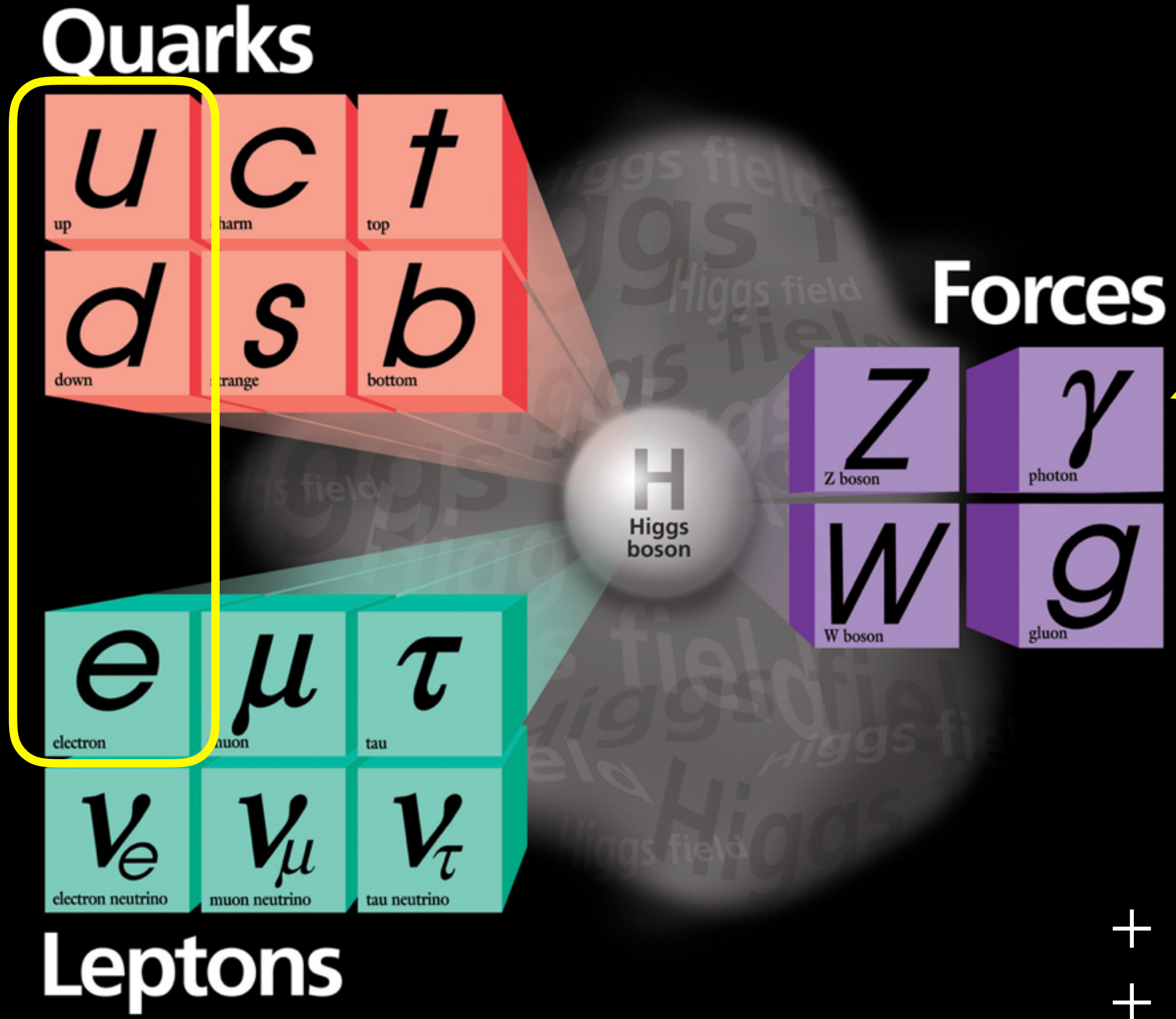
All known forms of matter:



Us



Light

+ Dark Matter
+ Dark Energy

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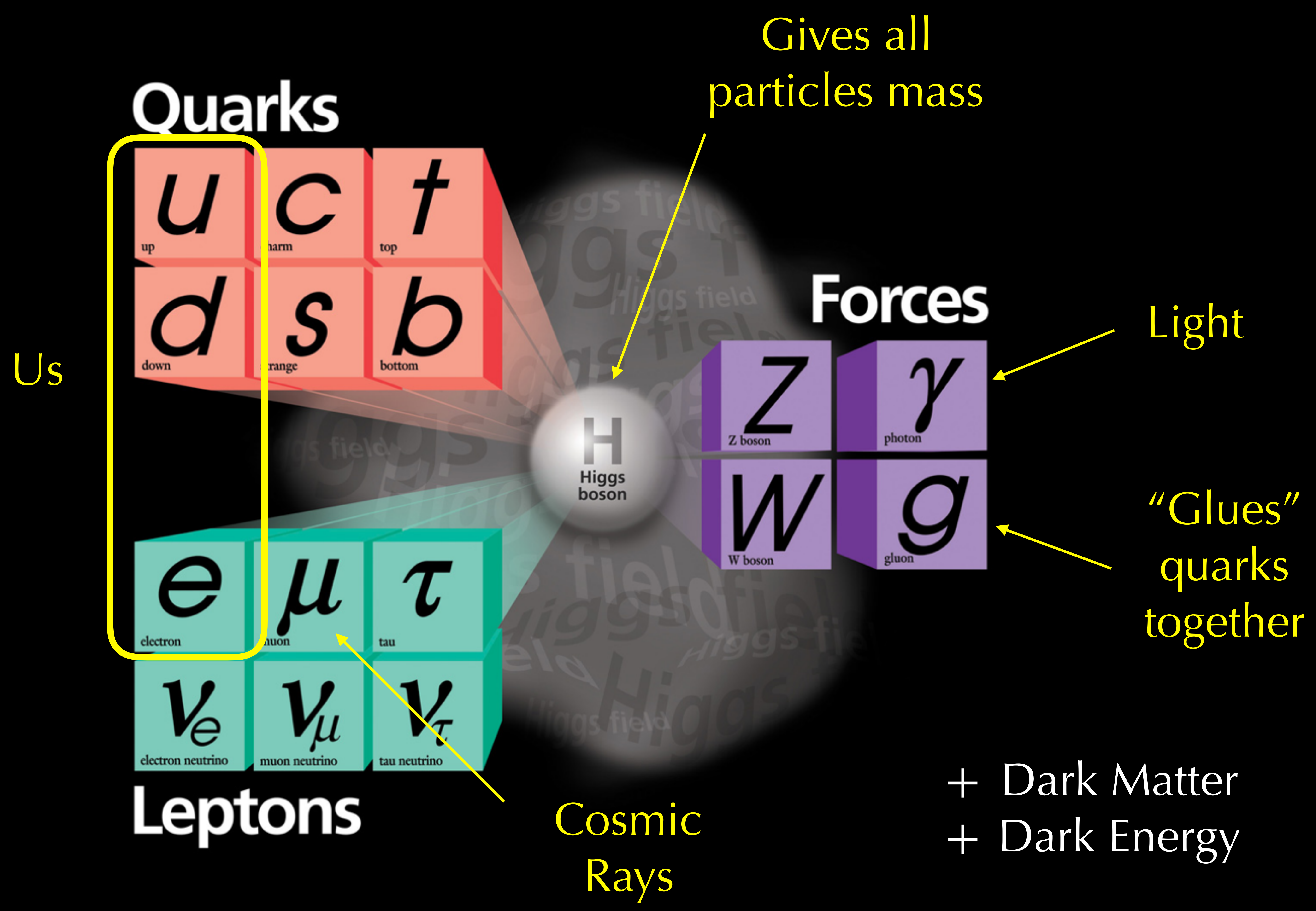
All known forms of matter:



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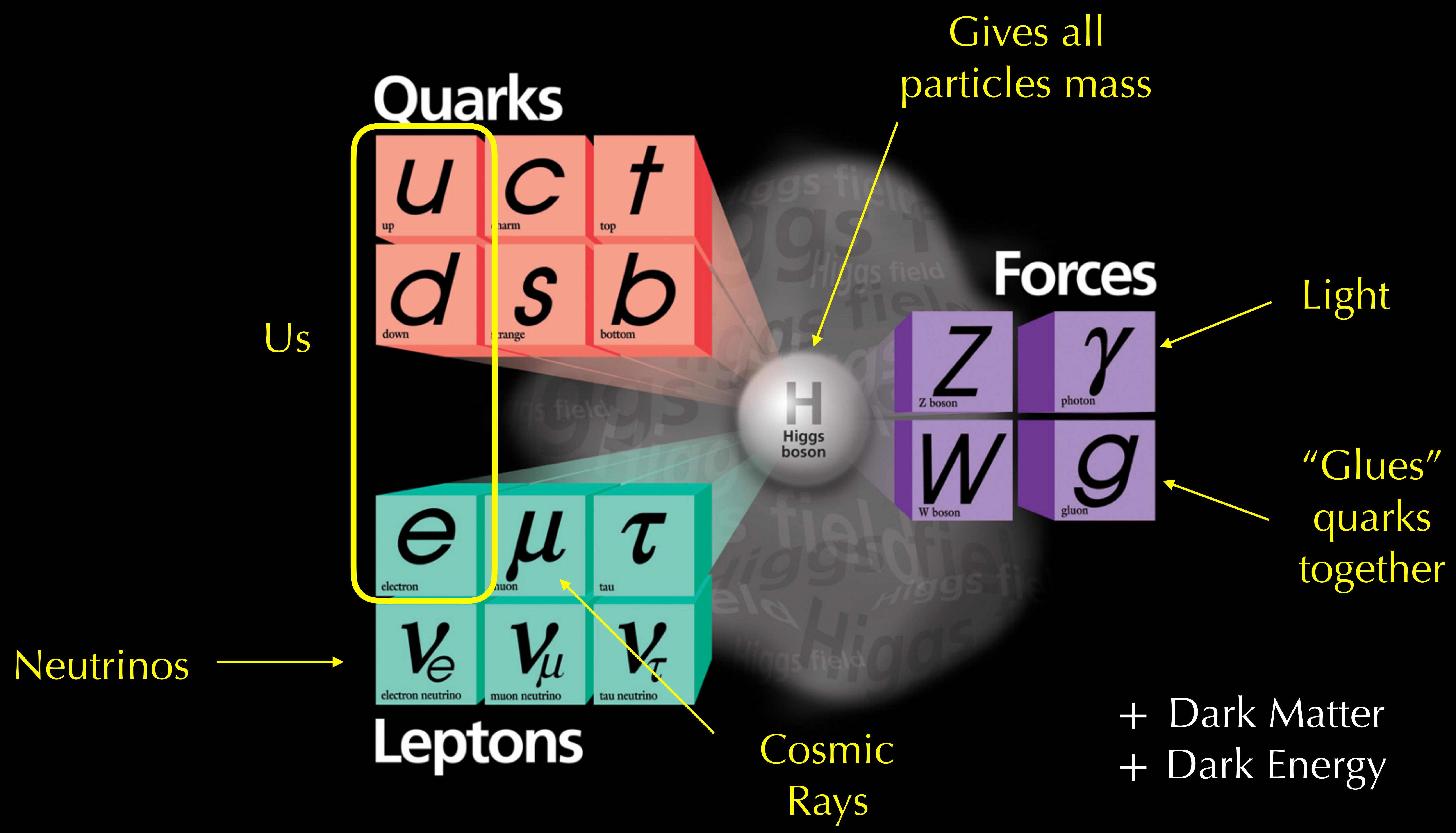
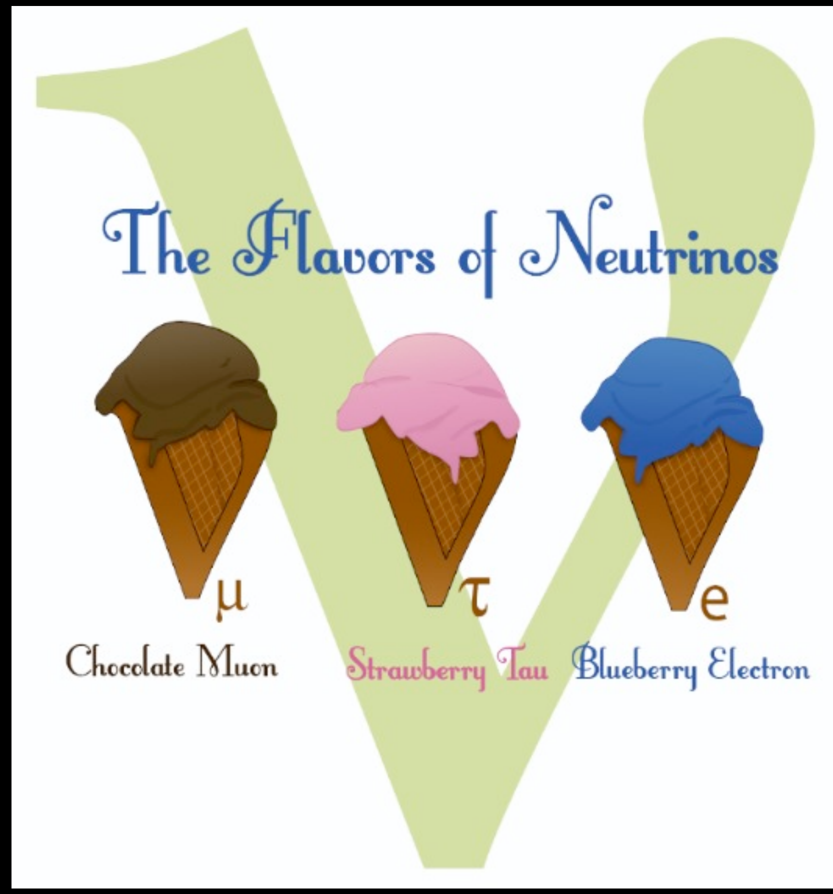
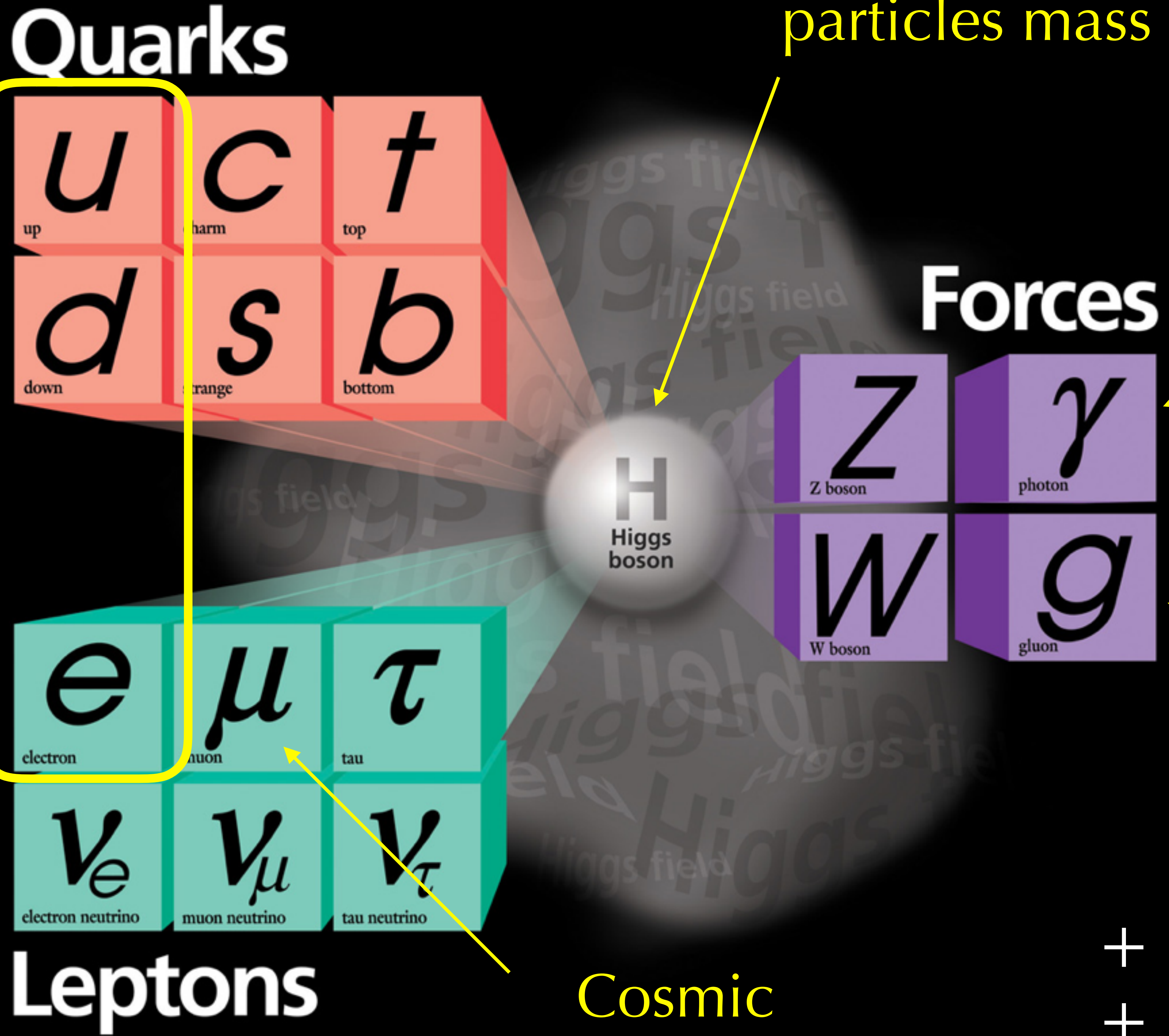
All known forms of matter:



+ Dark Matter
+ Dark Energy

All known forms of matter:





Us

Gives all particles mass

Light

"Glues" quarks together

Cosmic Rays

+ Dark Matter
+ Dark Energy

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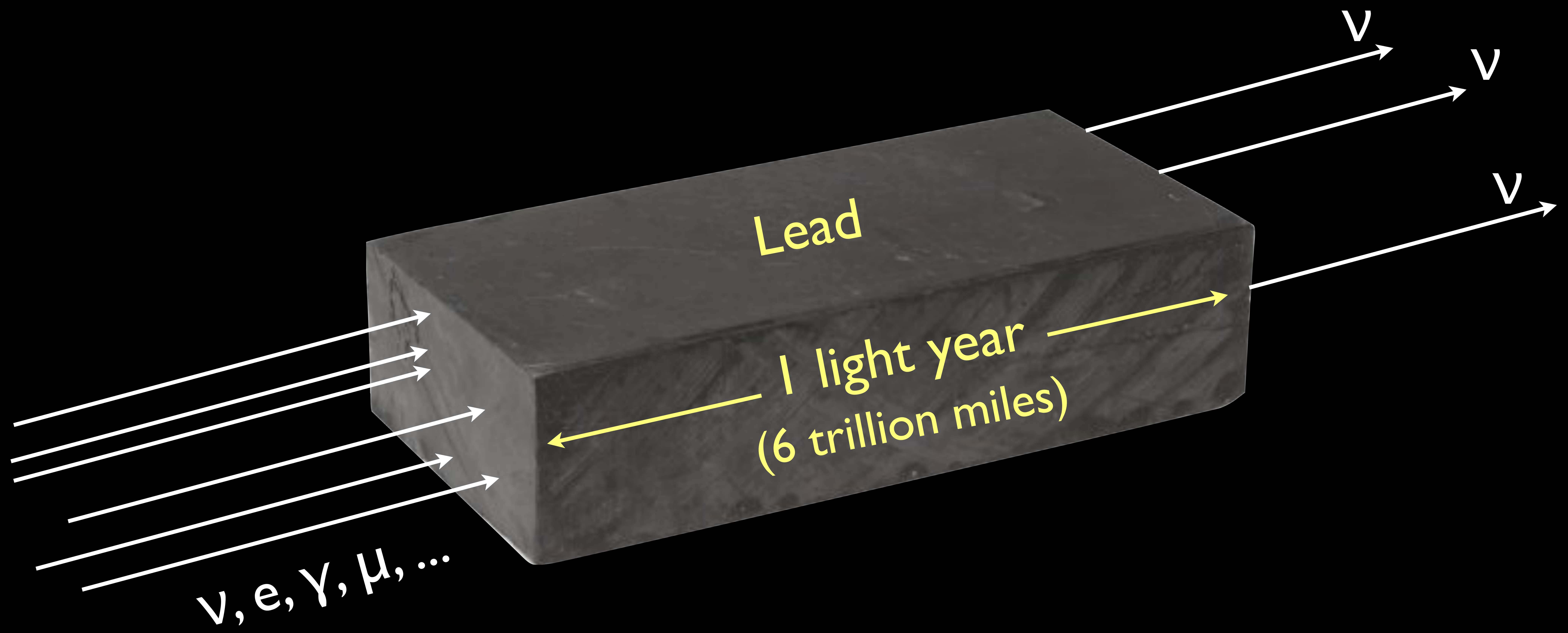

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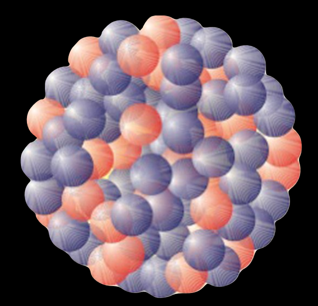
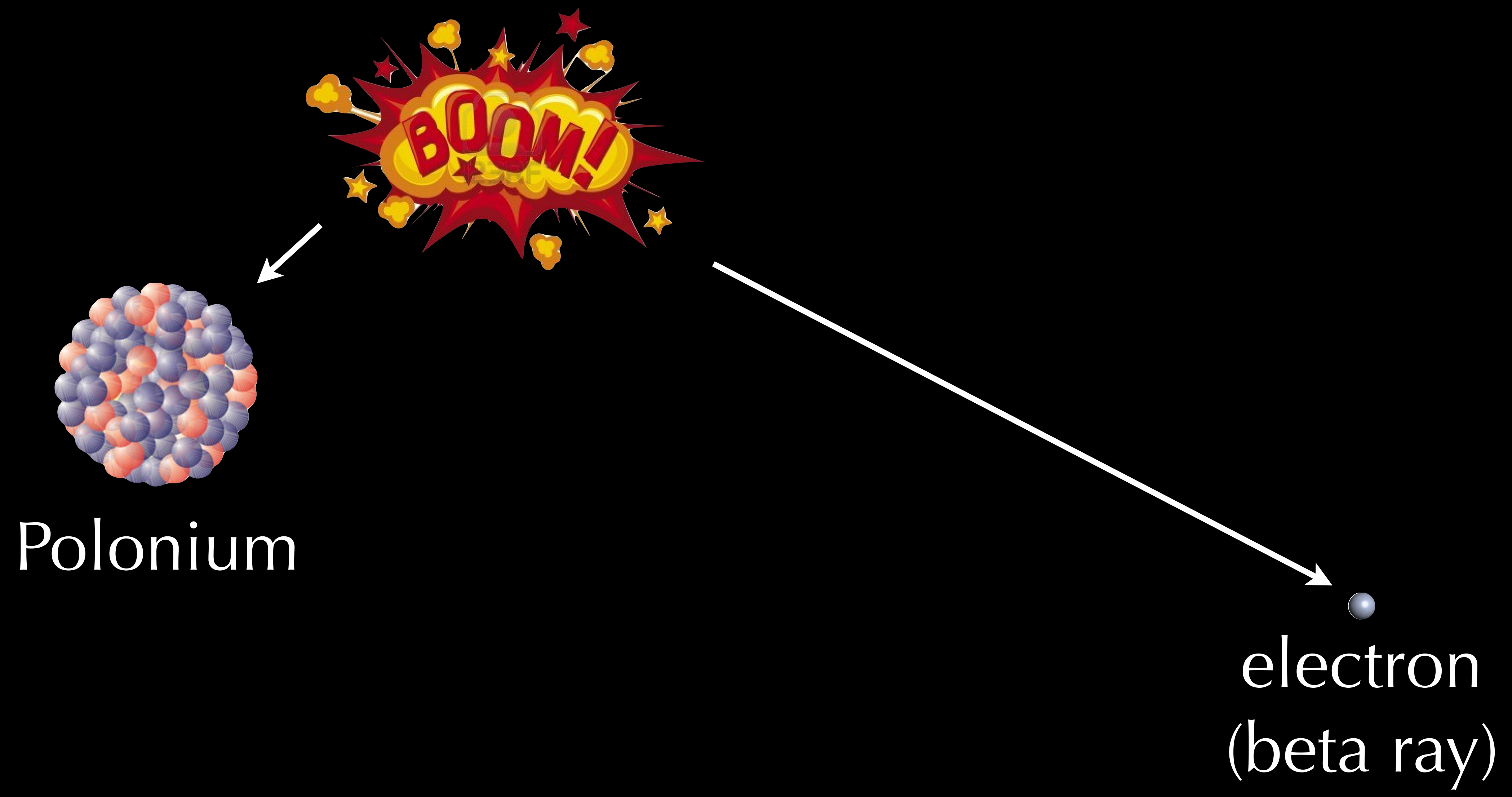
Beta Decay



Bismuth

Meitner and Hahn, 1911

Beta Decay



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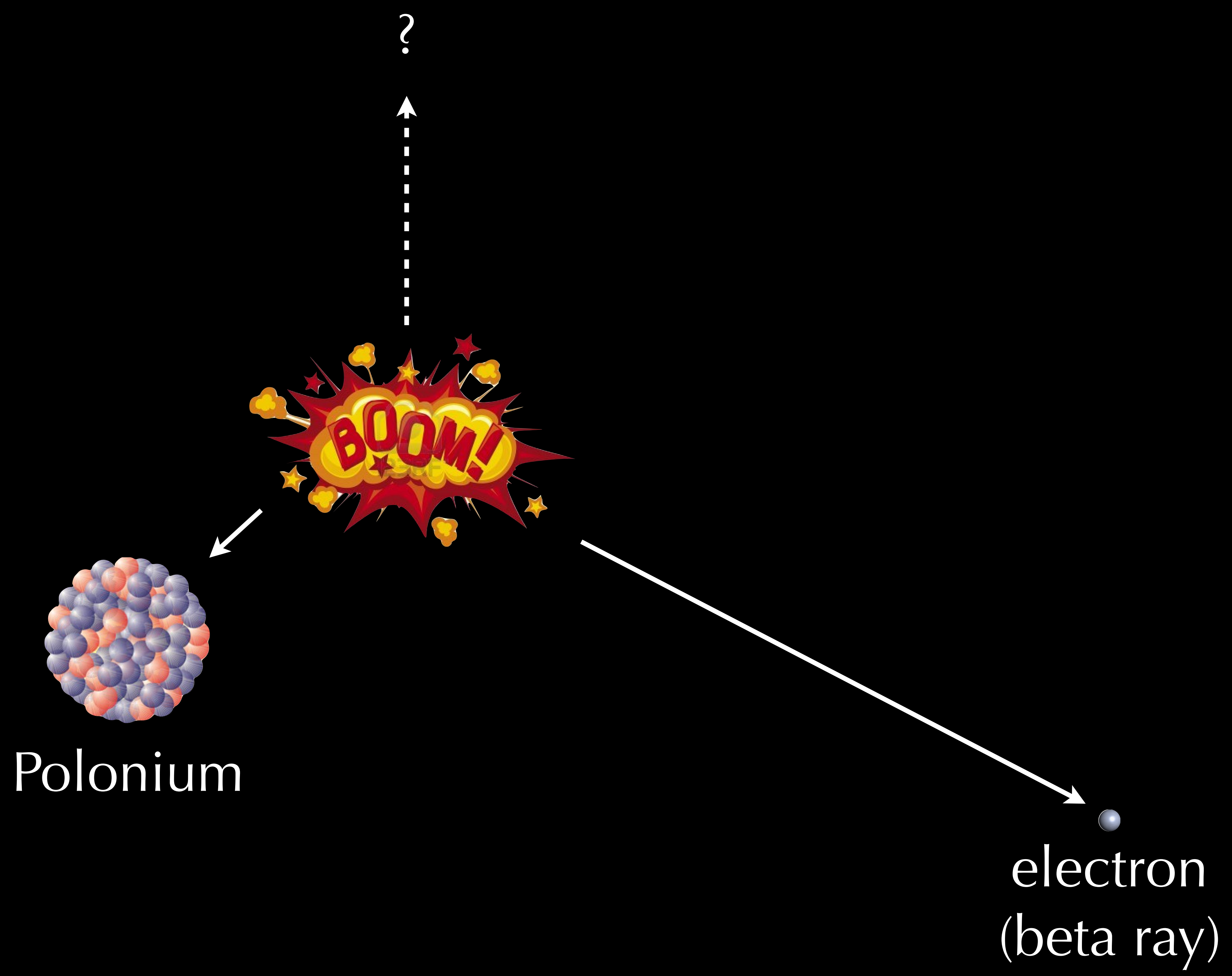

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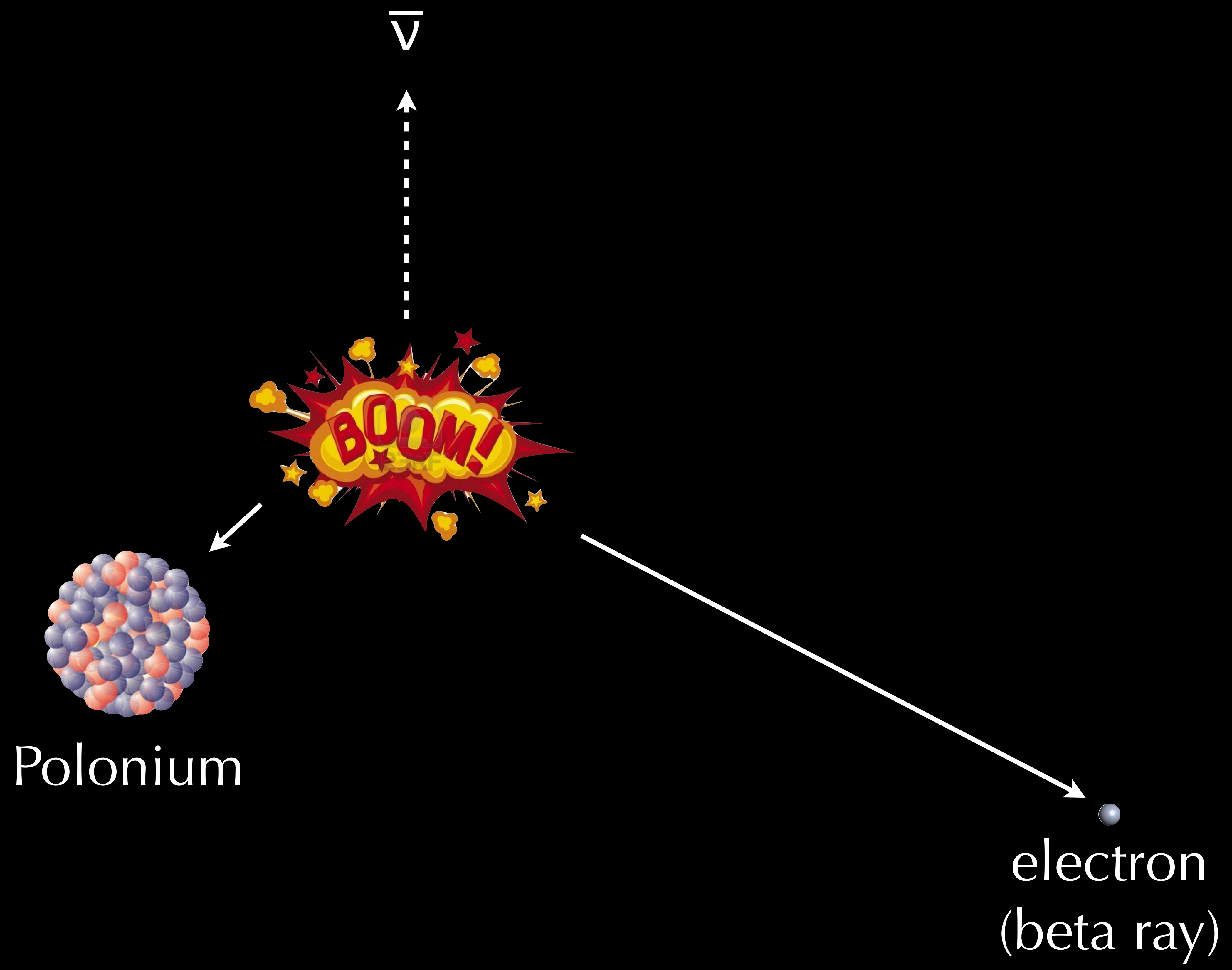
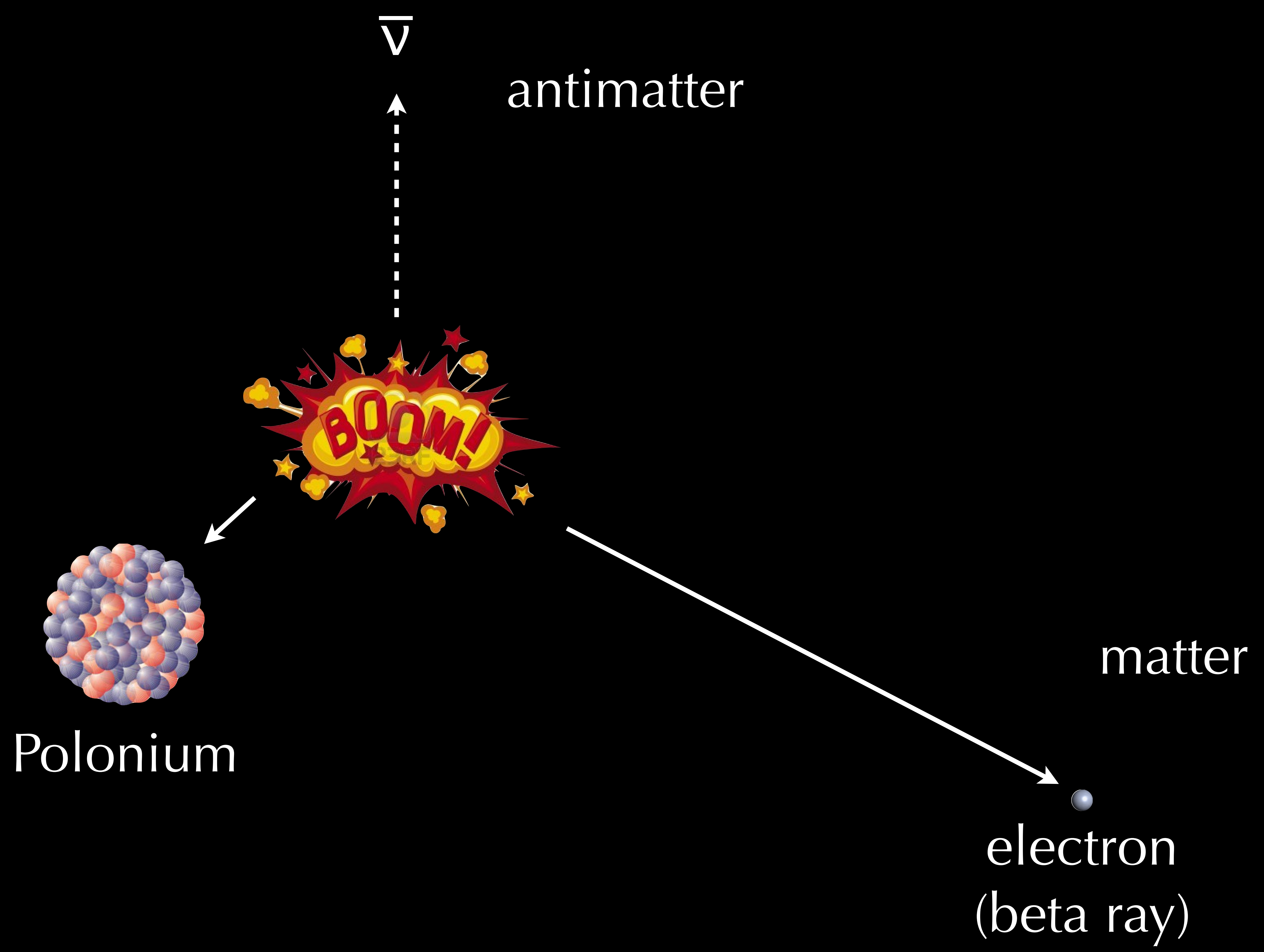


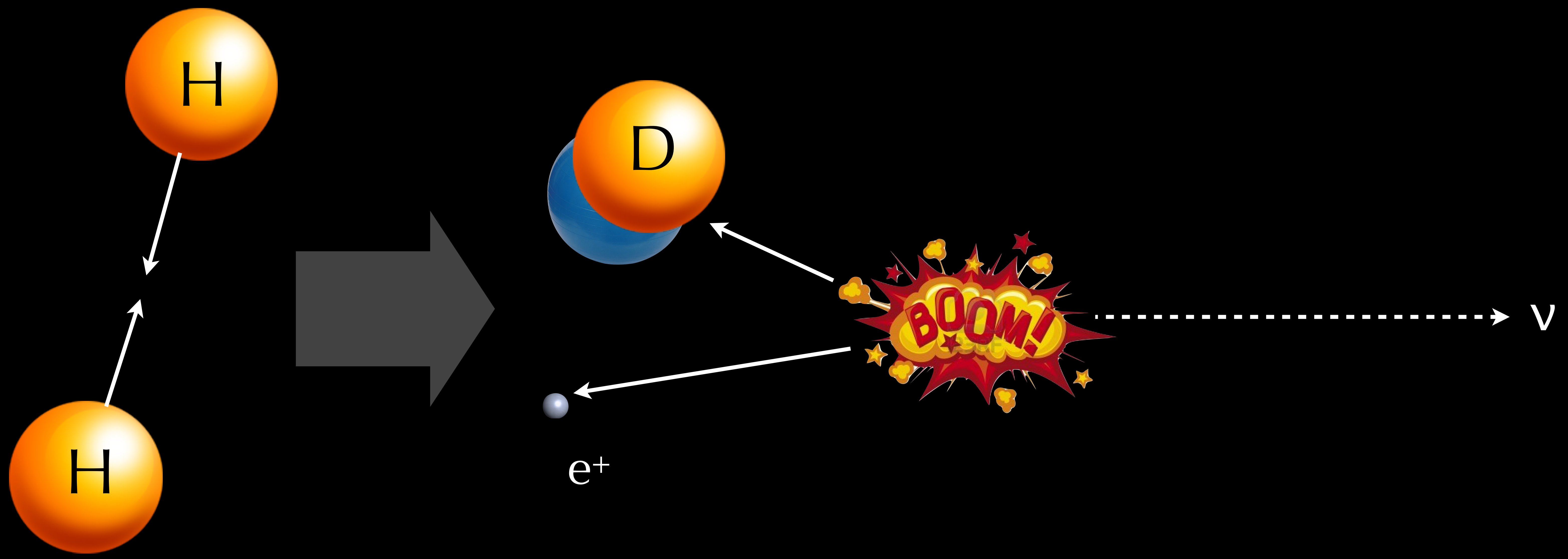
Wolfgang Pauli, 1931

Beta Decay



Wolfgang Pauli, 1931

Hydrogen Fusion



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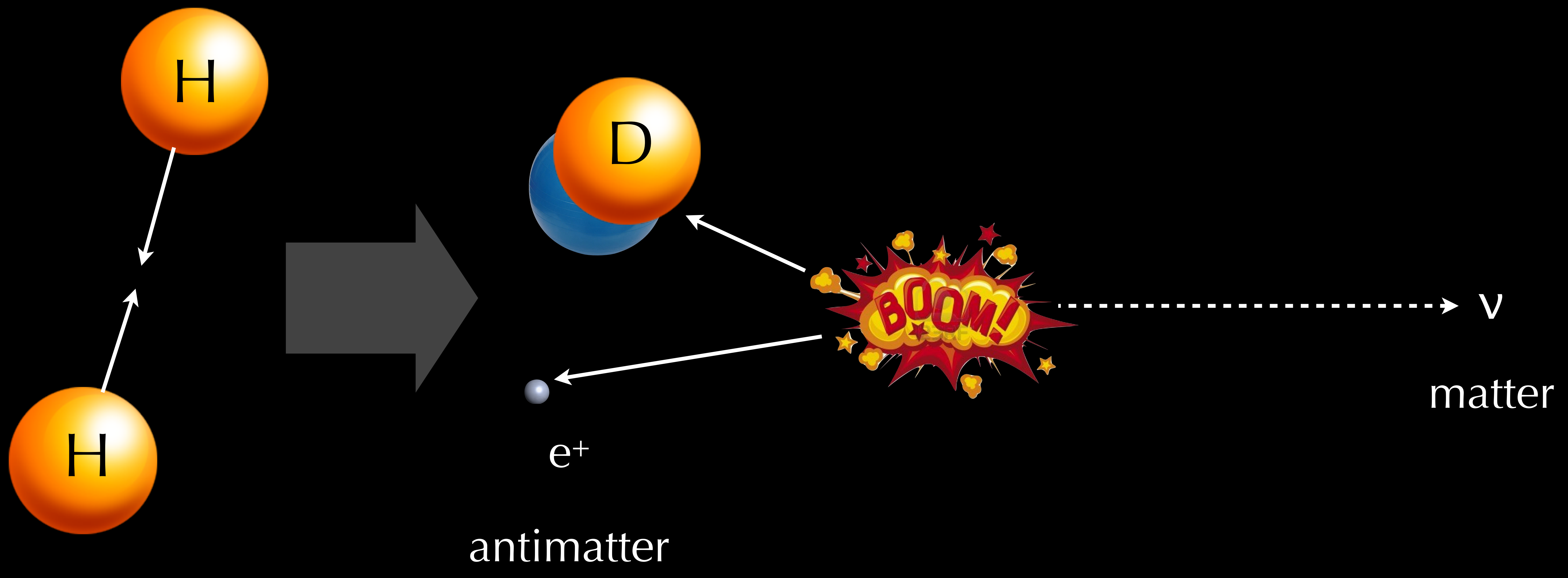
Hydrogen Fusion

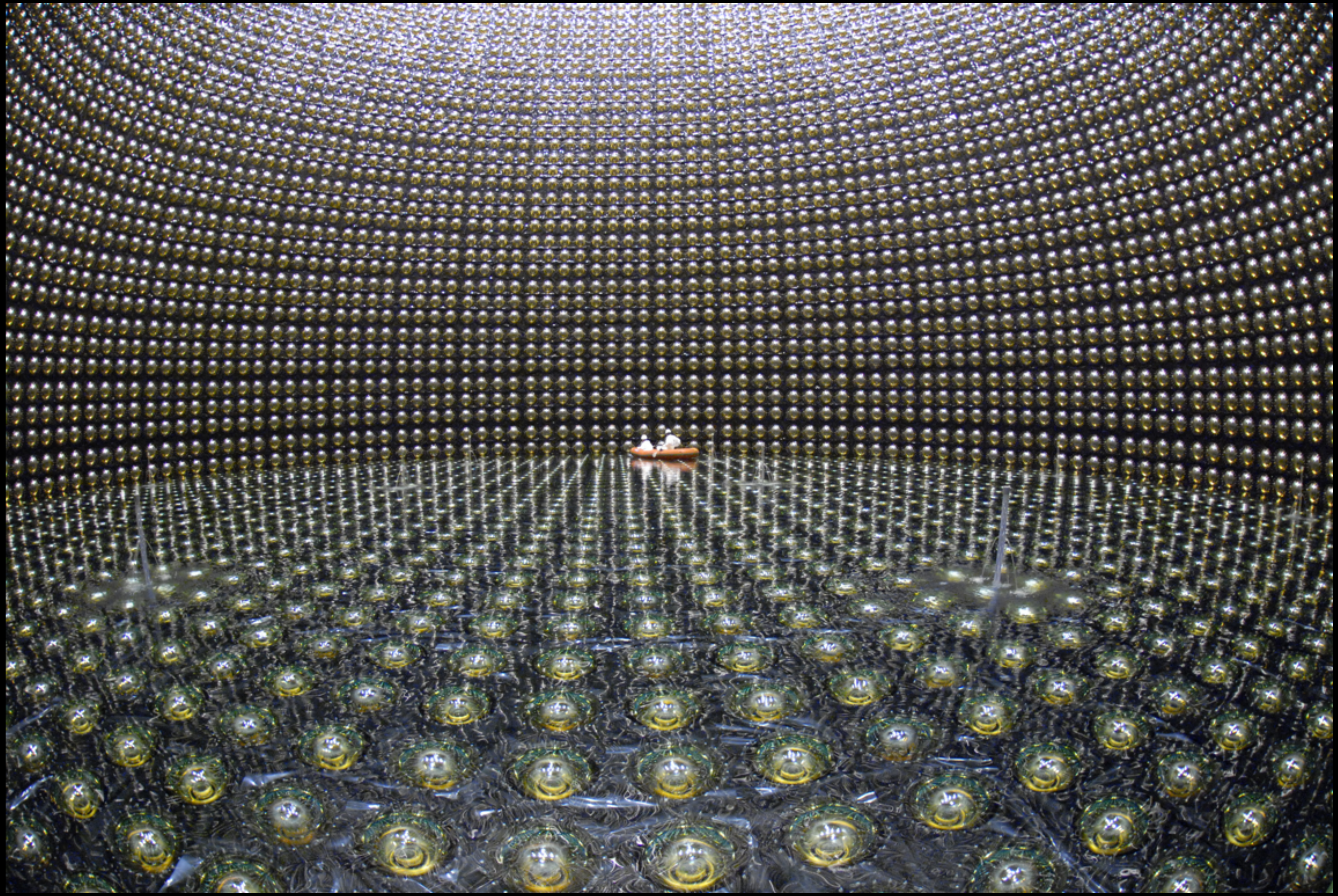


The Sun in Neutrinos

Actual size of sun:
~one pixel

Credit: Super-Kamiokande Collaboration

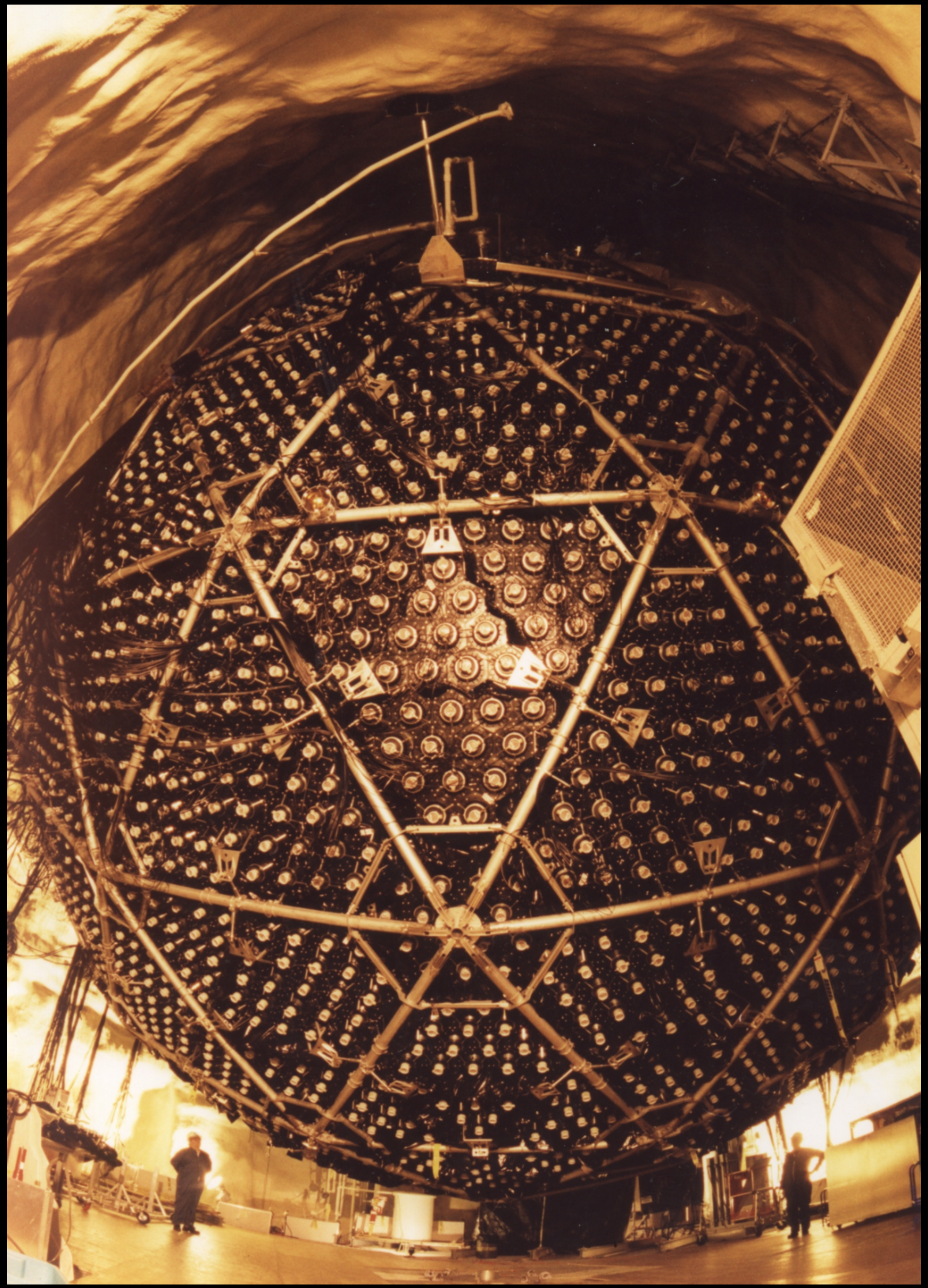
Super-Kamiokande



3,300 feet below Kamioka (Hida), Japan
50,000 tons of water, 11,000 light detectors

Credit: Super-Kamiokande Collaboration

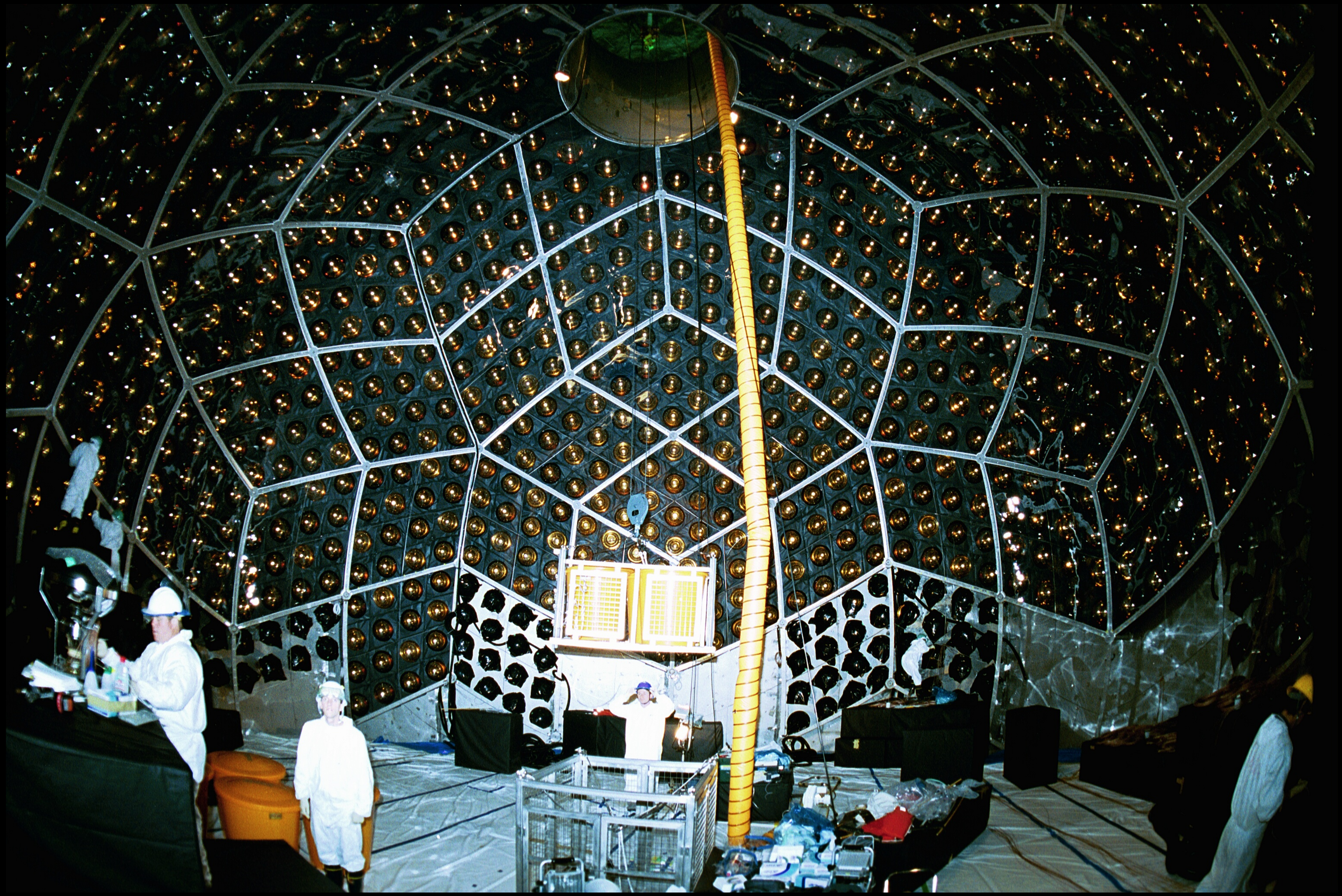
The Sudbury Neutrino Observatory (SNO)



6,800 feet below Sudbury, Ontario, Canada
1,000 tons of heavy water, 10,000 light detectors

Credit: SNO Collaboration

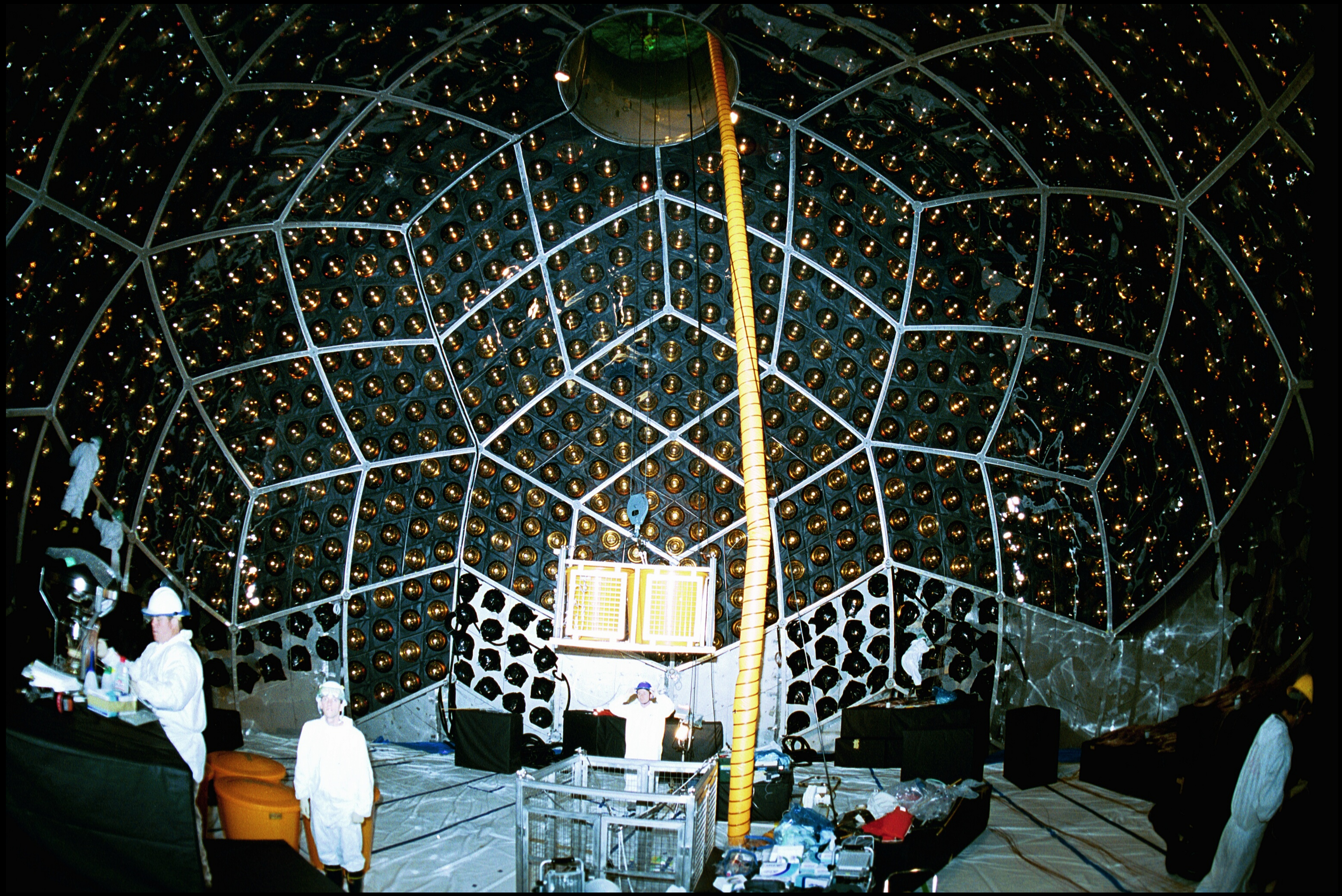
KamLAND



Just down the hall from Super-Kamiokande
1,000 tons of mineral oil, 2,000 light detectors

Credit: KamLAND Collaboration

KamLAND



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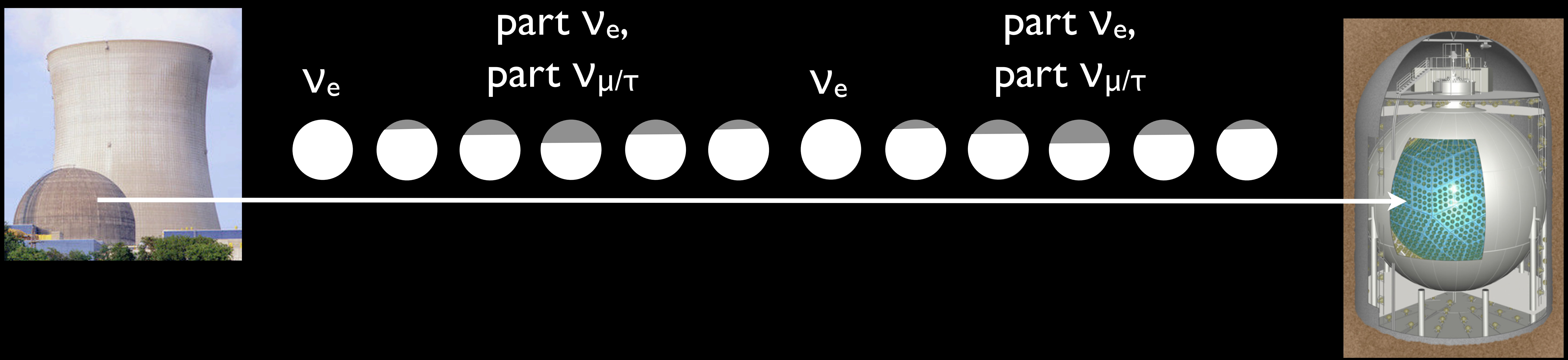
Neutrino Oscillation



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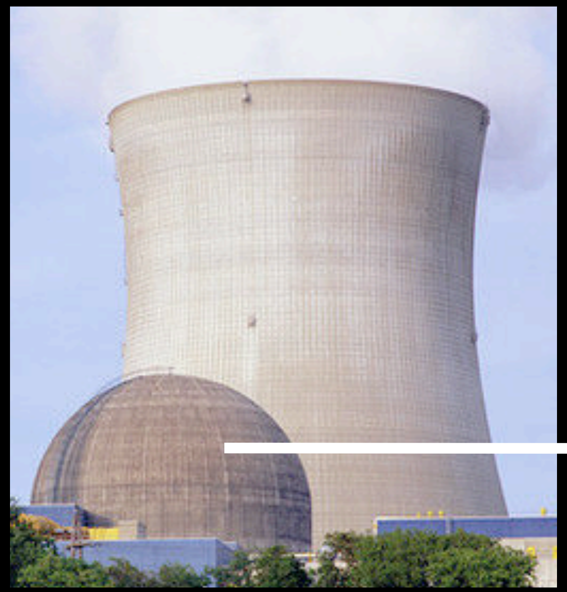
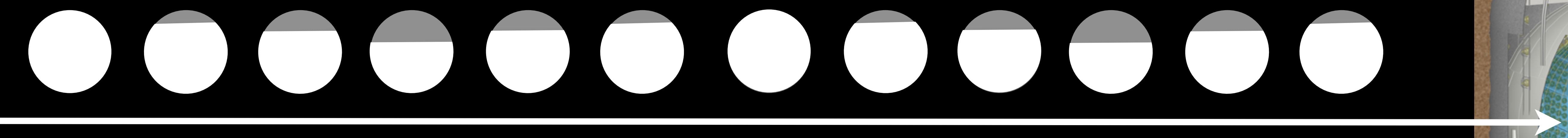
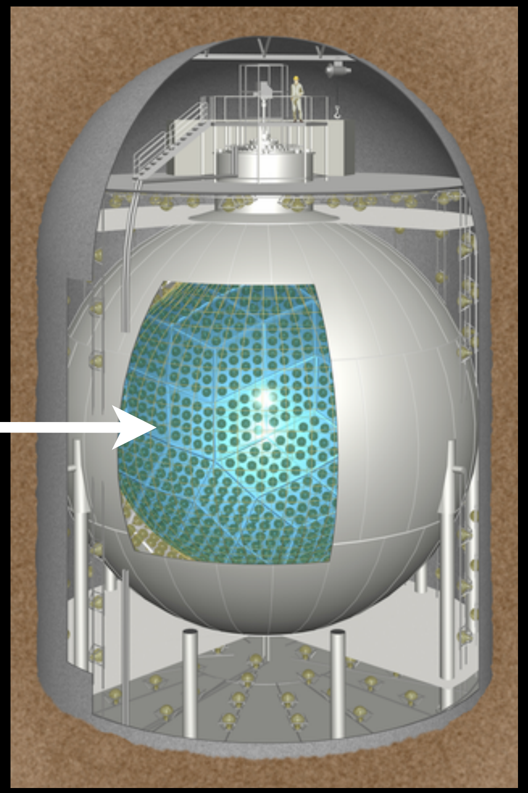
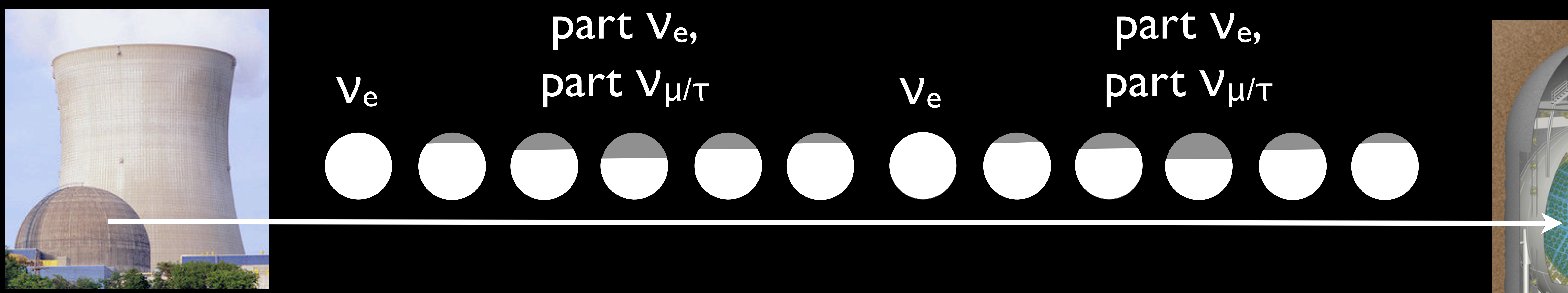


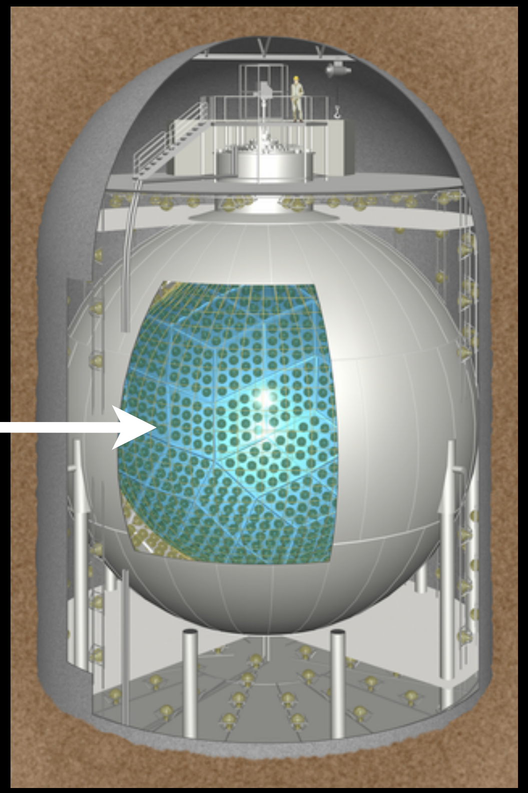




Requires neutrinos to have mass.

Neutrino Oscillation

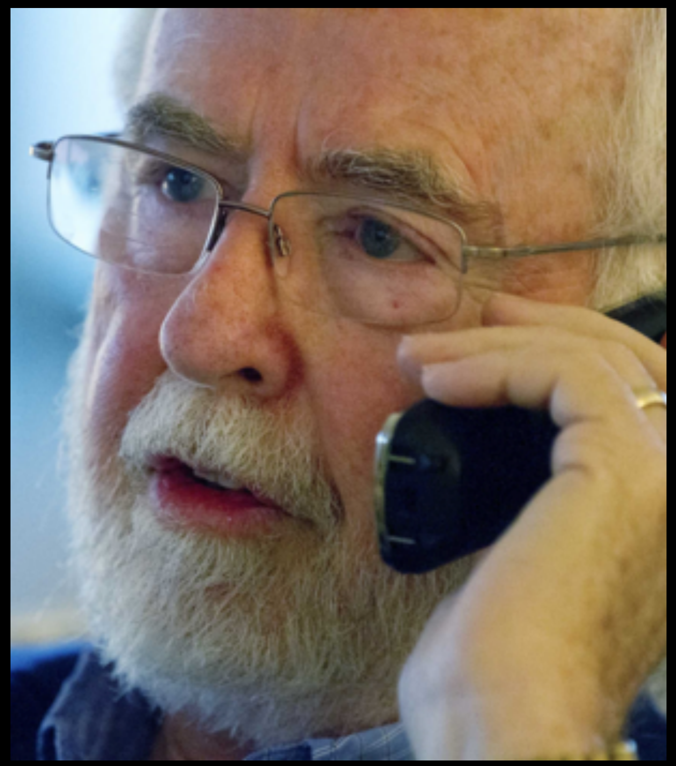




Requires neutrinos to have mass.

Kajita (SuperK)

2016



MacDonald (SNO)

Ettore Majorana

There are several categories of scientists in the world; those of second or third rank do their best but never get very far. Then there is the first rank, those who make important discoveries, fundamental to scientific progress. But then there are the geniuses, like Galilei and Newton. Majorana was one of these.

— (Enrico Fermi about Majorana, Rome 1938)

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- "Discovered" the neutron
- Invented "Majorana Particles"
- Mysteriously disappeared in 1938

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Argentina 1955

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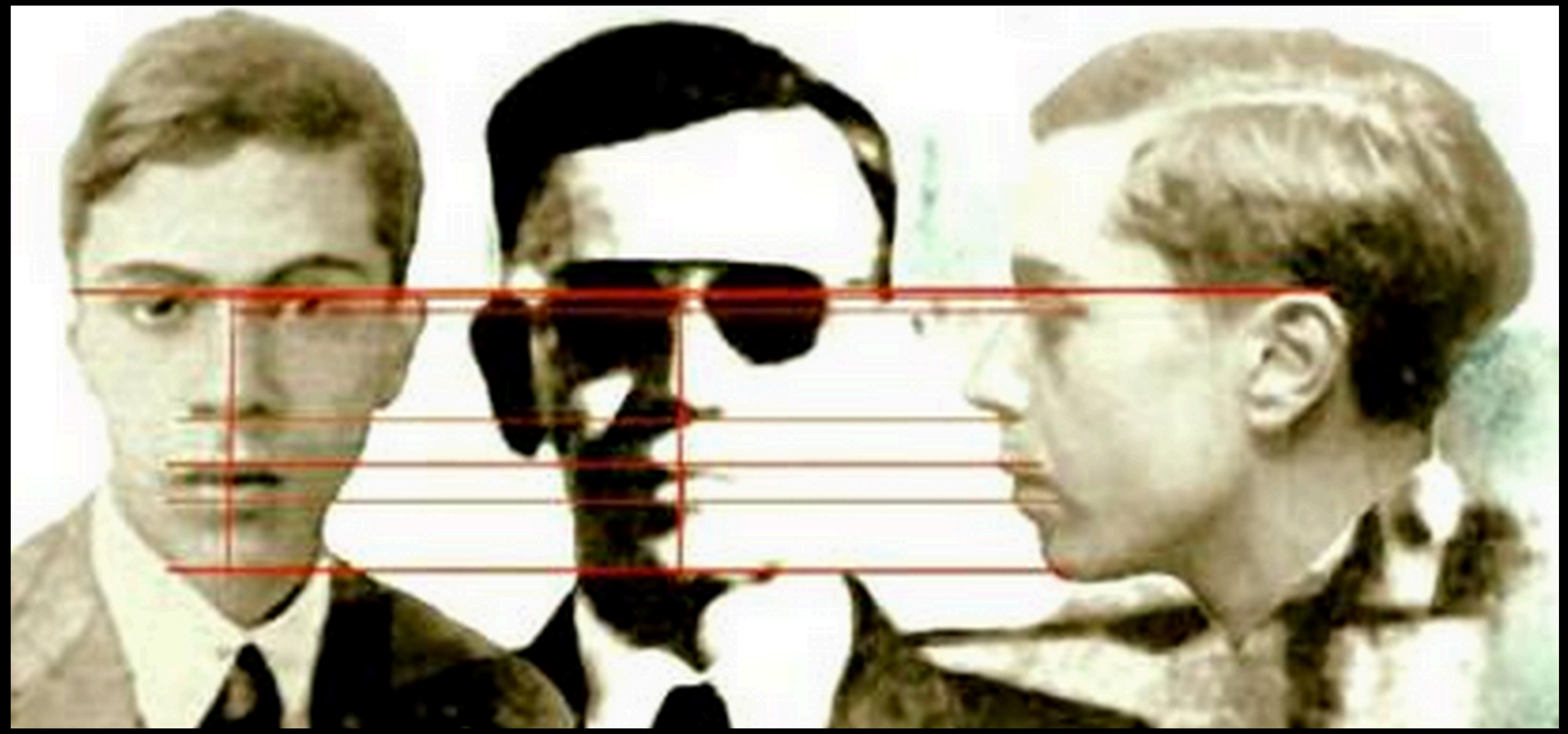
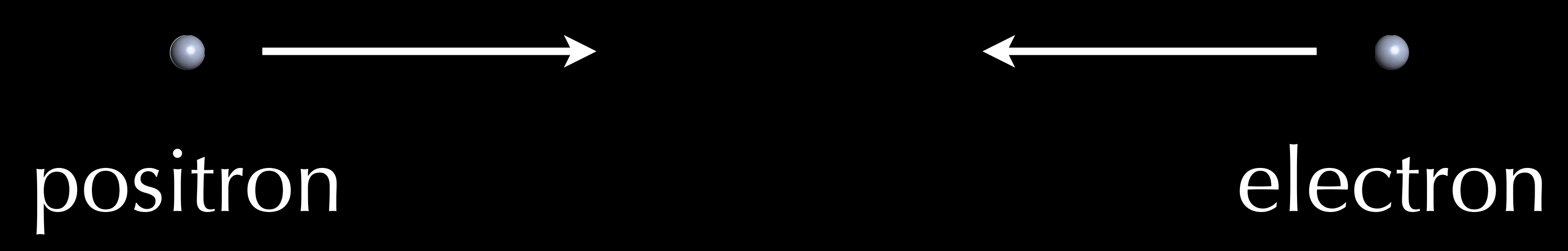
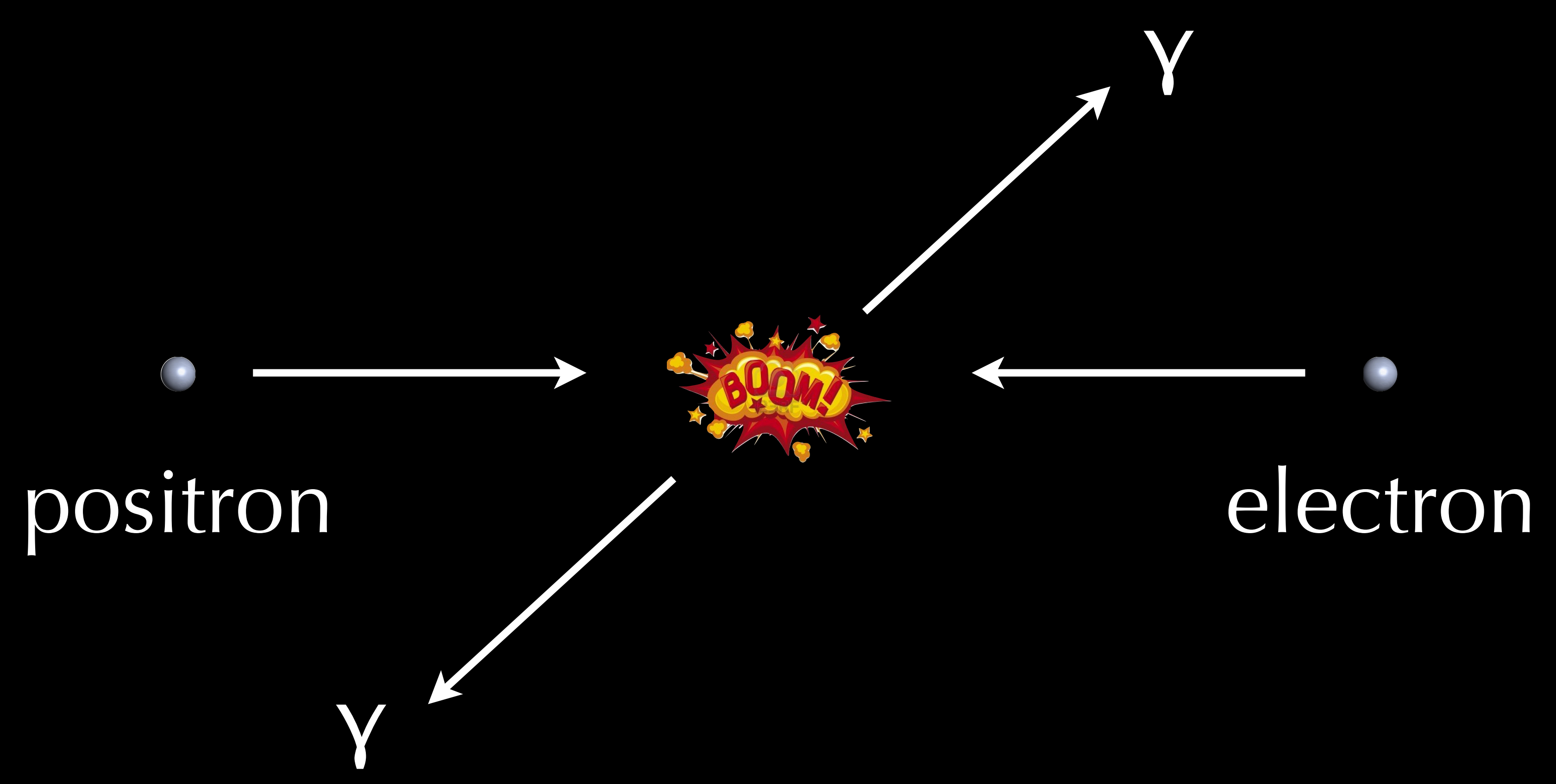


Credit: Rome Attorney's Office

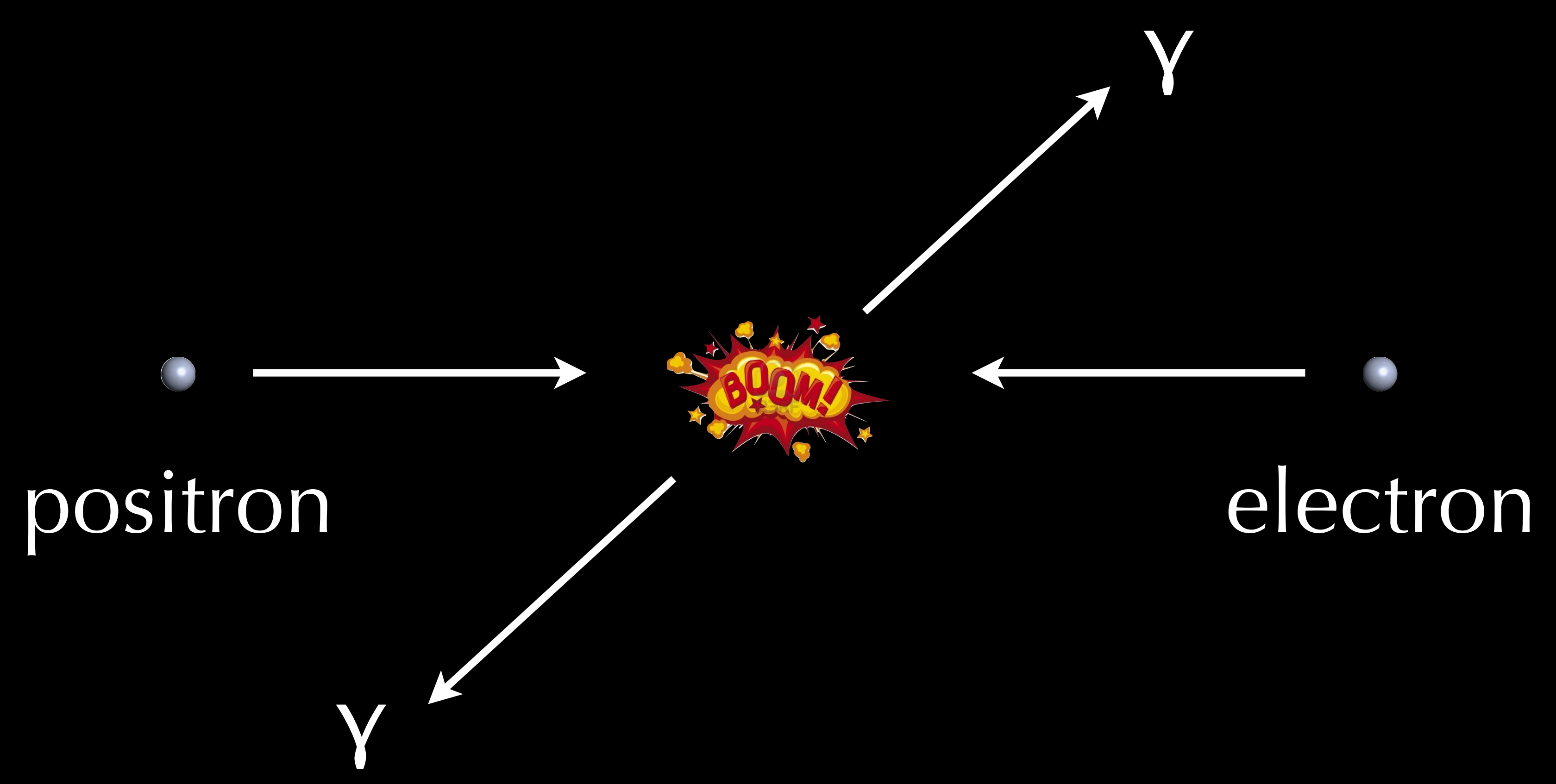
Annihilation

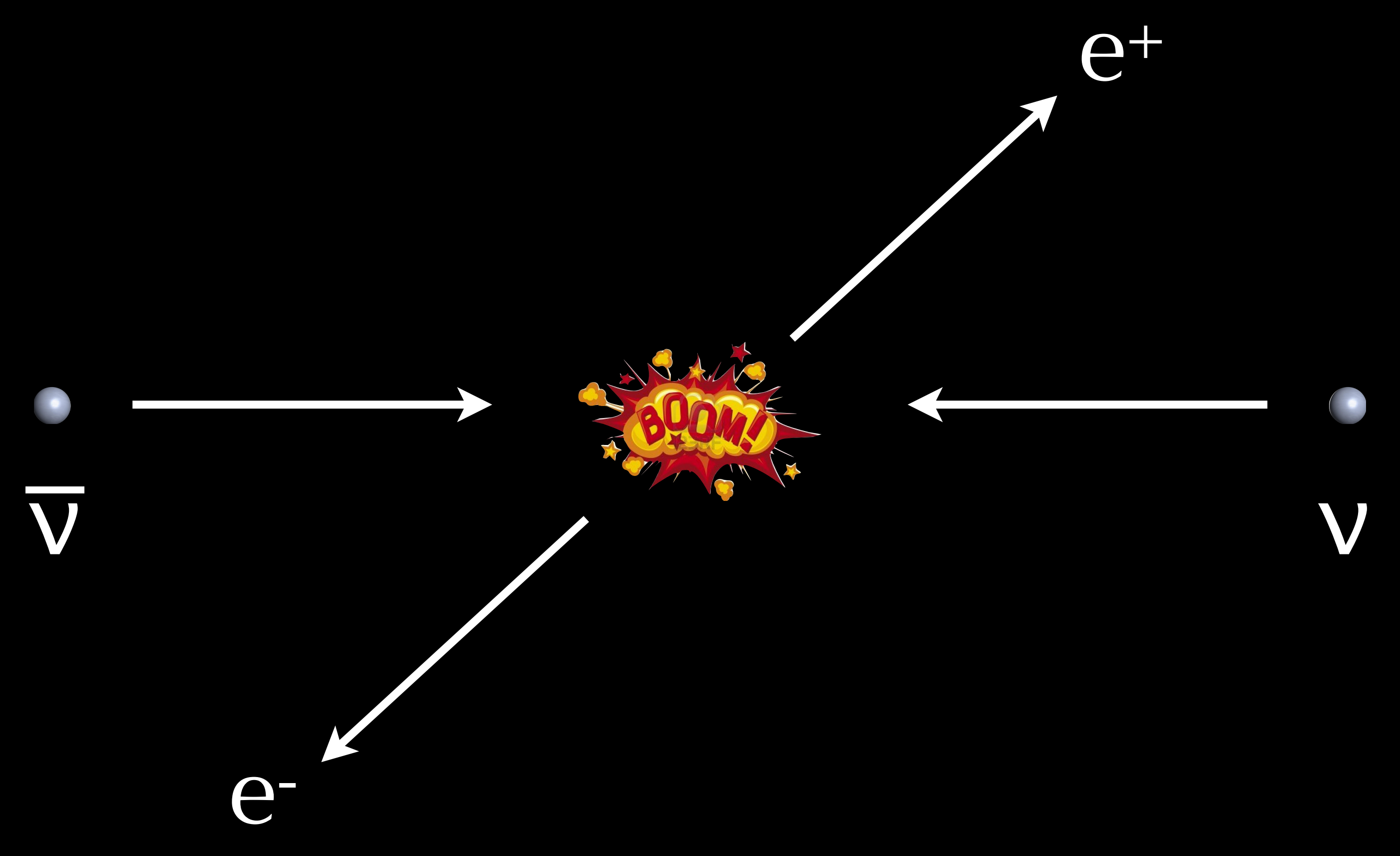


Annihilation



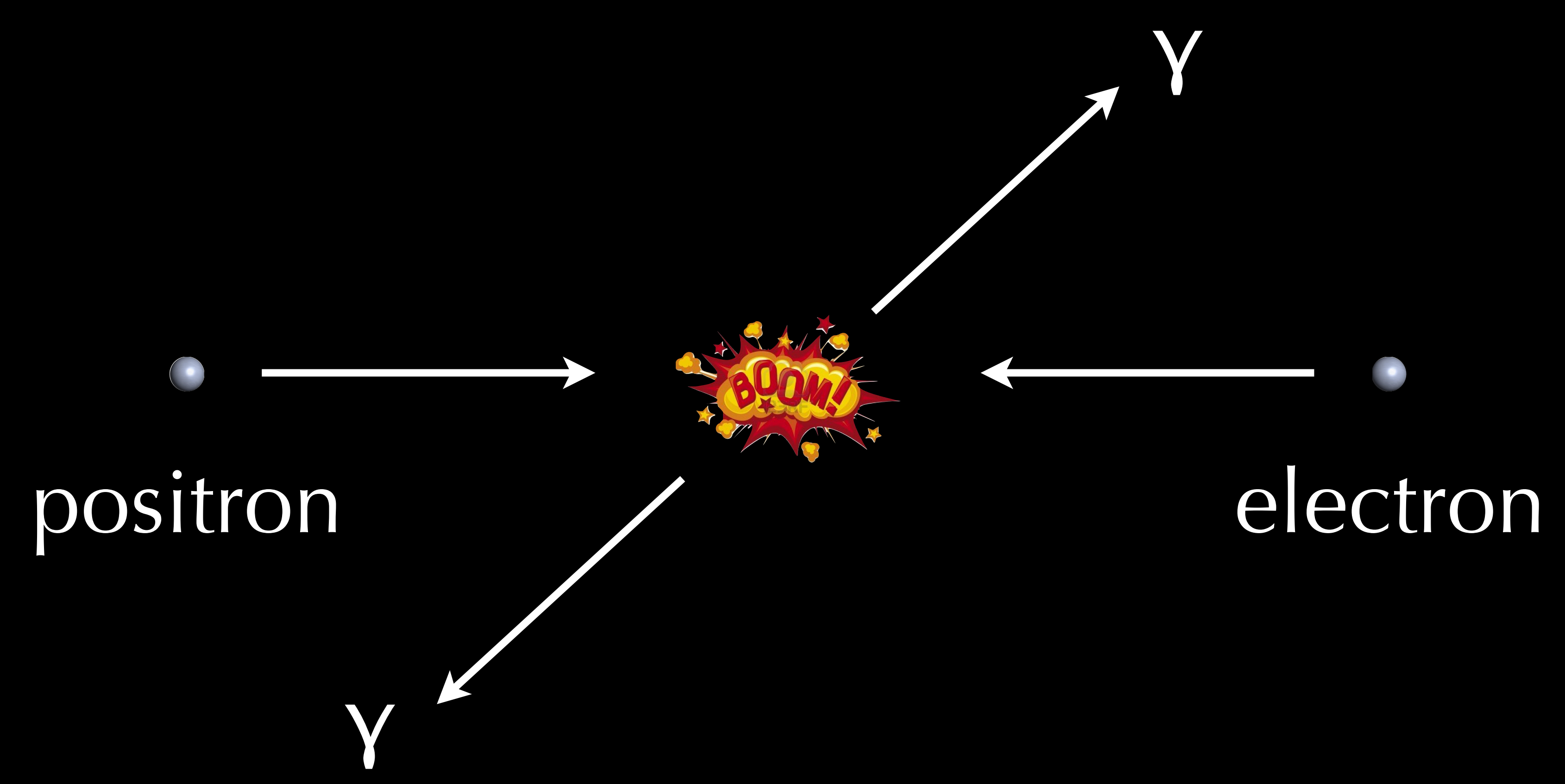
Annihilation

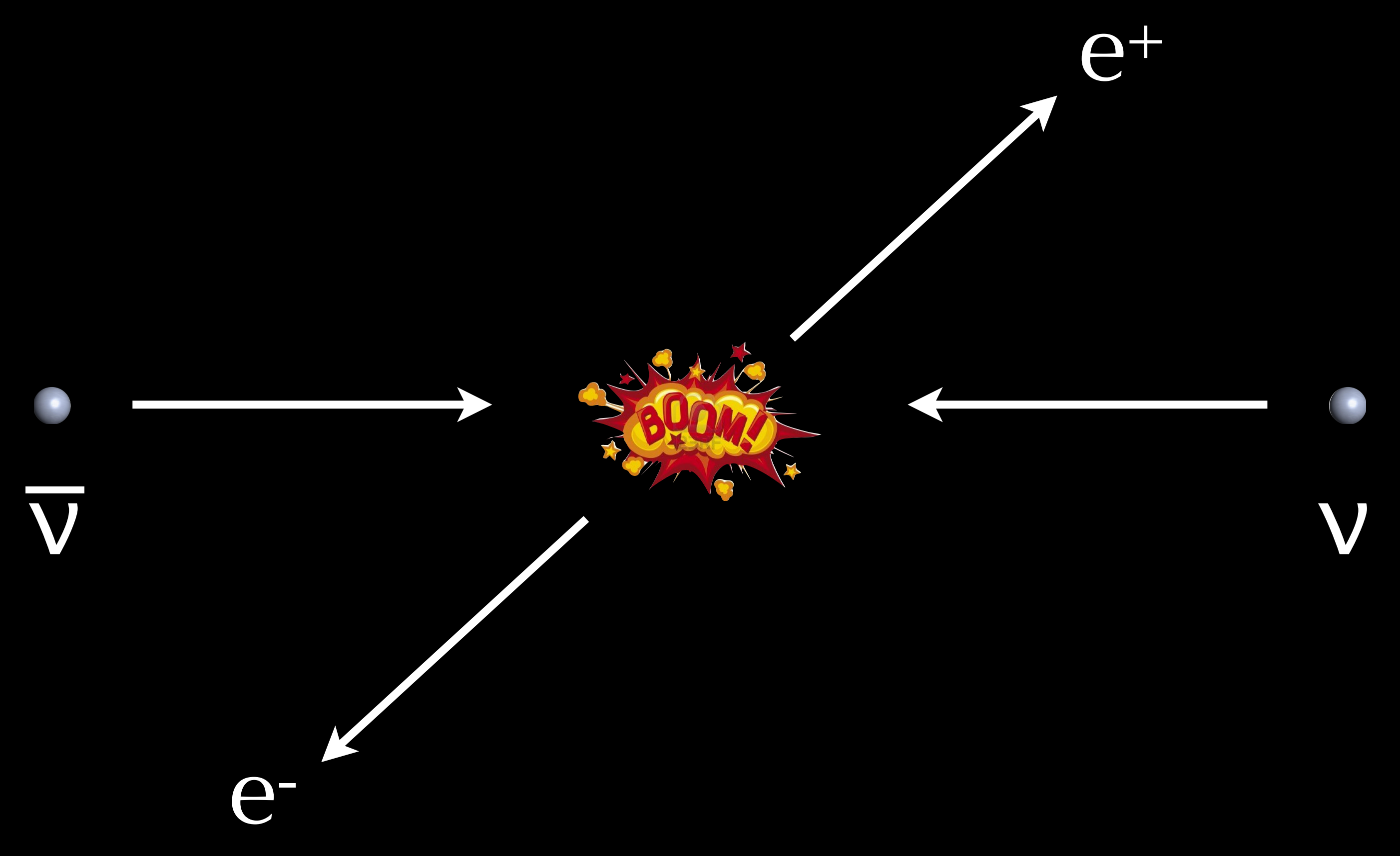




"Normal"
(Dirac)
neutrinos

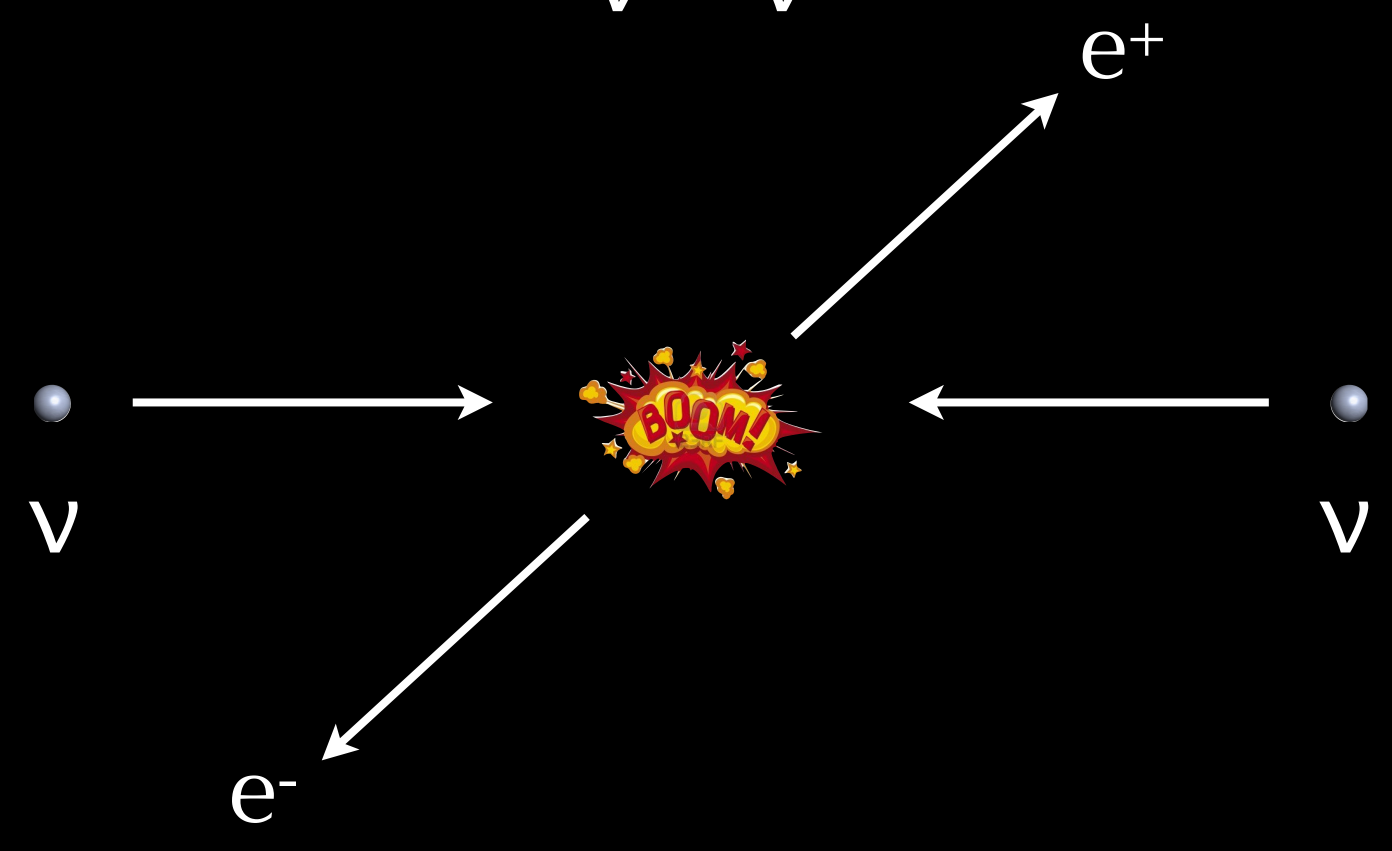
Annihilation





“Normal” (Dirac) neutrinos

Majorana neutrinos: $\nu = \bar{\nu}$



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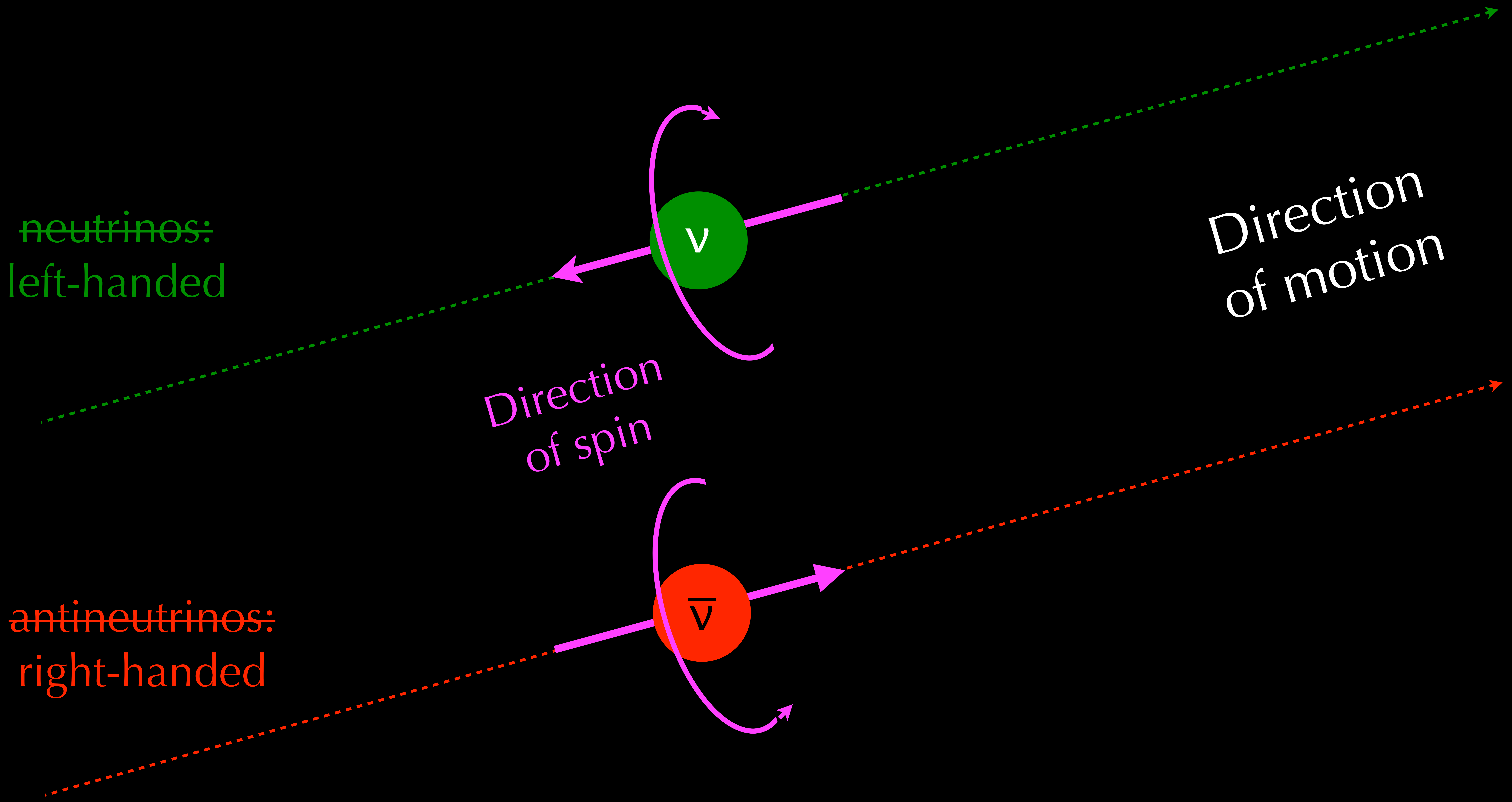
neutrinos:
left-handed
ν
Direction
of motion
Direction
of spin
antineutrinos:
right-handed
ν̄
J. Detwiler



~~neutrinos:~~
left-handed
ν
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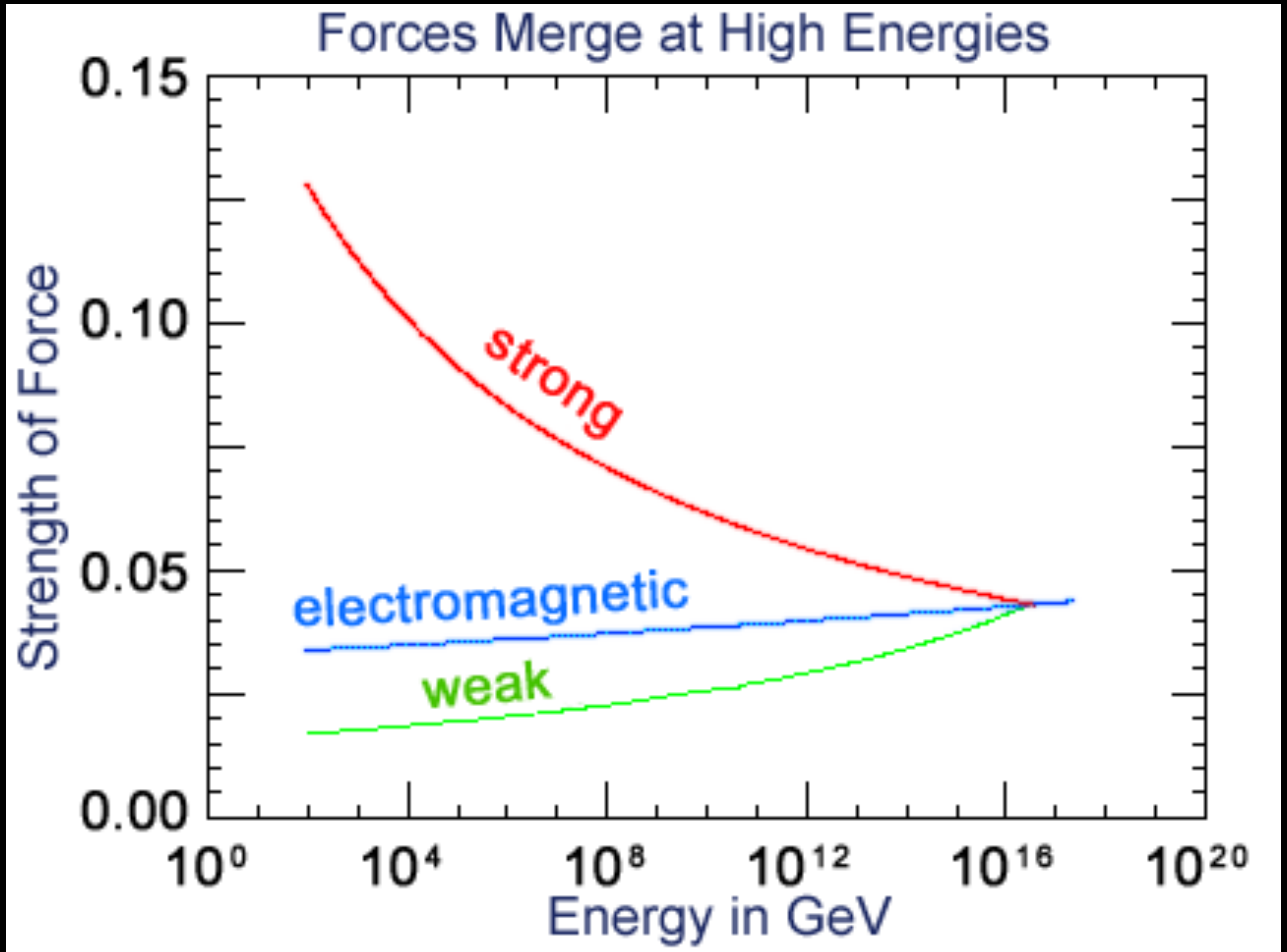
right-handed
ν̄

J. Detwiler

Grand Unification



1 proton = 1 GeV

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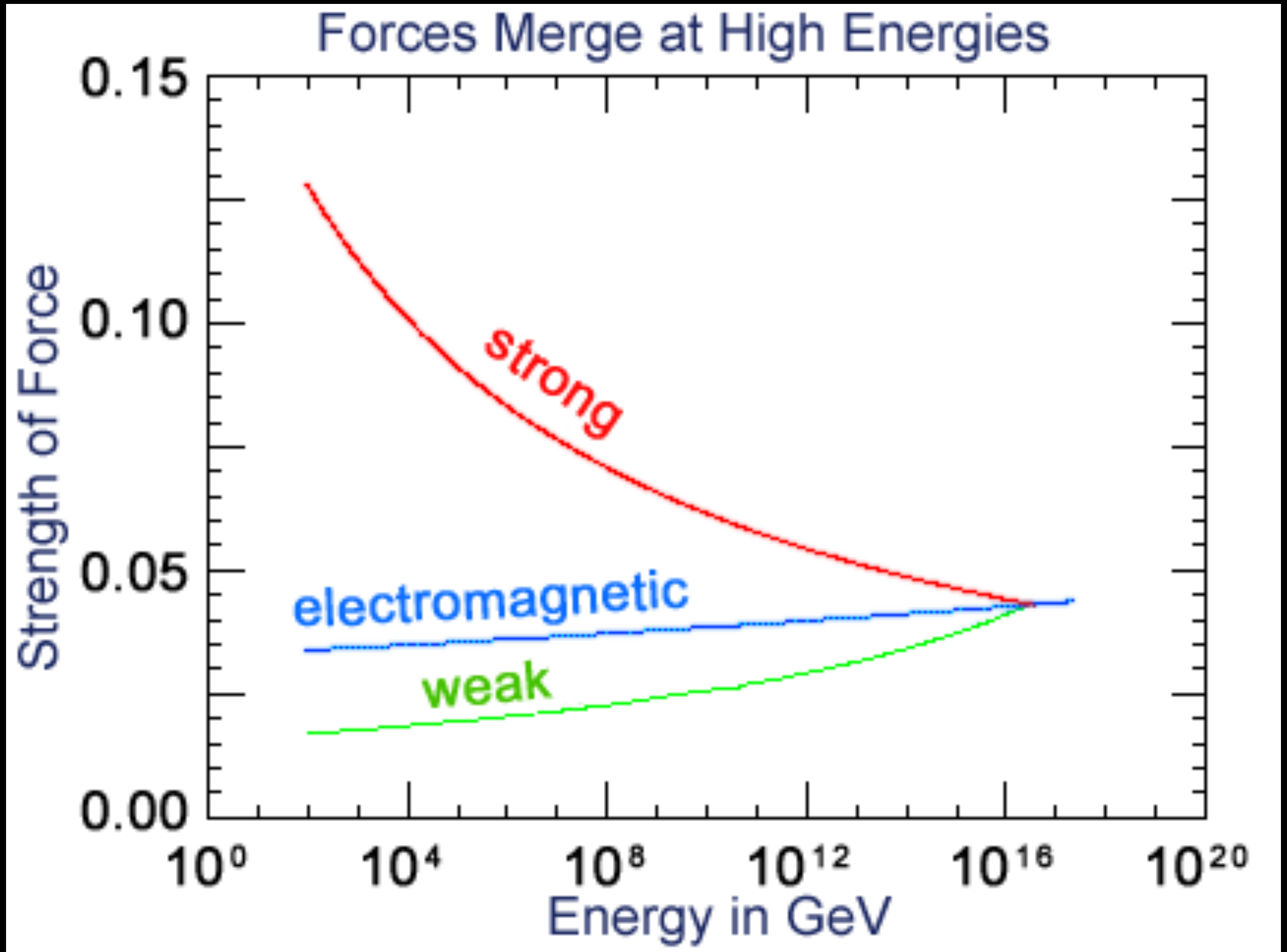
Grand Unification

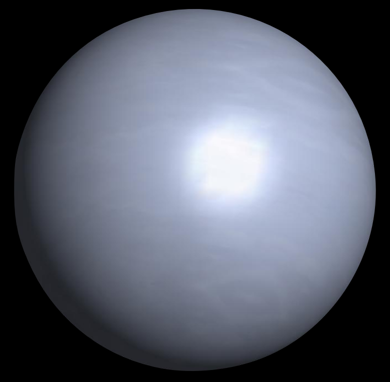


1 proton = 1 GeV

New particles are expected with masses >10^{16} times as heavy as a proton

These particles would have been present in the universe when the temperature was >10,000,000,000,000 C

Leptogenesis

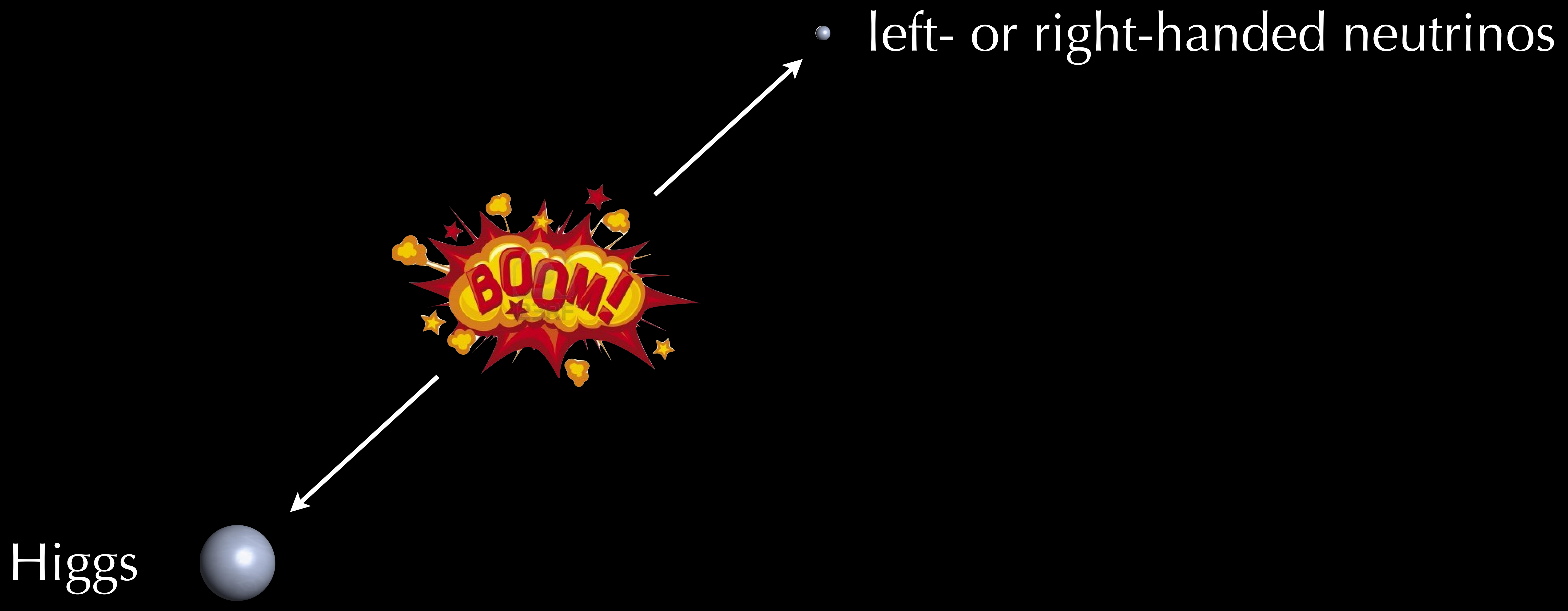


"N"

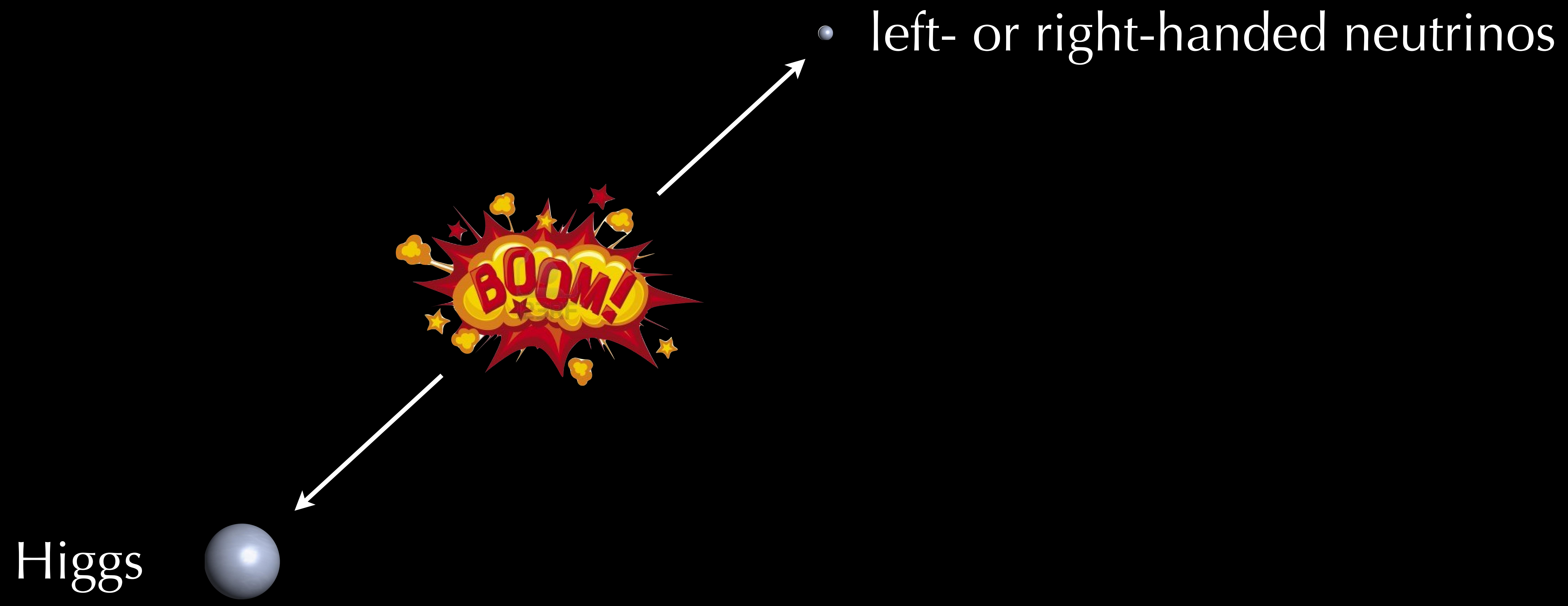
Super-heavy version of the neutrino

A Majorana particle: $N = \bar{N}$

Leptogenesis



Leptogenesis



N decays violate Charge-Parity symmetry:
decays to left-handed particles happens more often than decays to right-handed anti-particles

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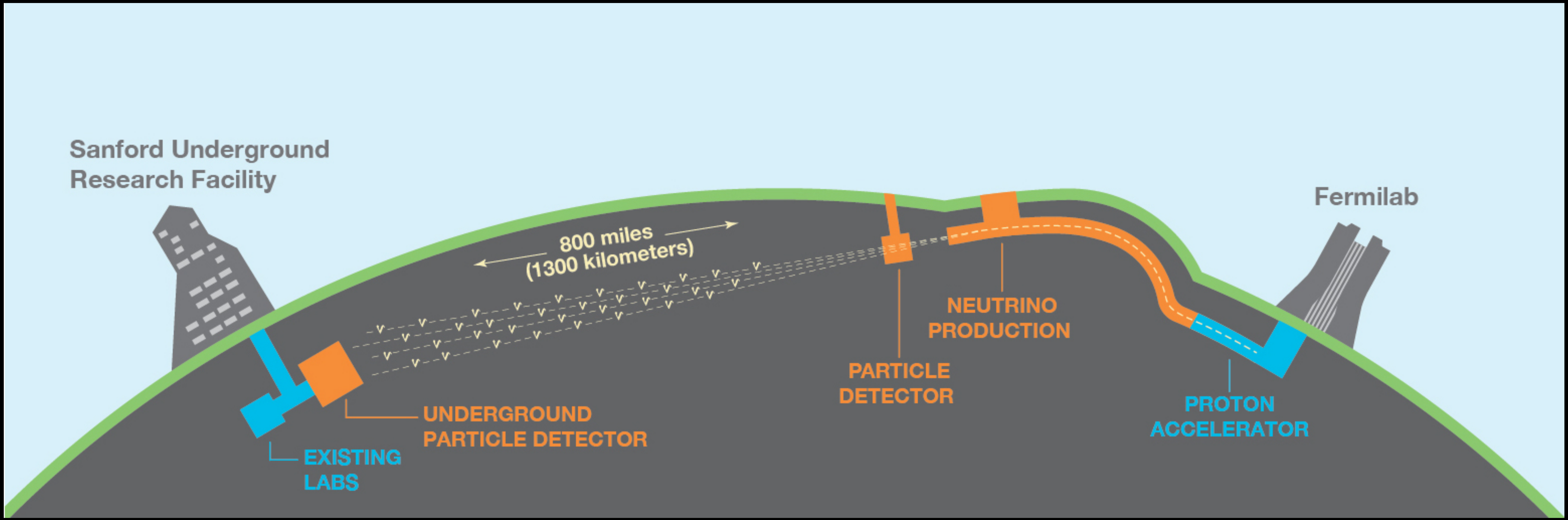
Leptogenesis

- N would have existed in copious amounts in the early universe
- The Higgs field causes the N to mix with neutrinos and confer its properties onto the neutrinos
- Predictions:
  - Neutrino oscillations will differ from antineutrino oscillations (CP violation)
  - Neutrinos would also be Majorana particles

Testing Neutrino CP Violation: DUNE



Beyond the scope of this talk.

dunescience.org

Testing the Majorana Nature of the Neutrino

- Cross two beam of neutrinos and see if they annihilate each other
- Move faster than the neutrino to get it to spin the “wrong” way, and see if that particle generates any positrons
- Search for neutrinoless double-beta decay

Testing the Majorana Nature of the Neutrino

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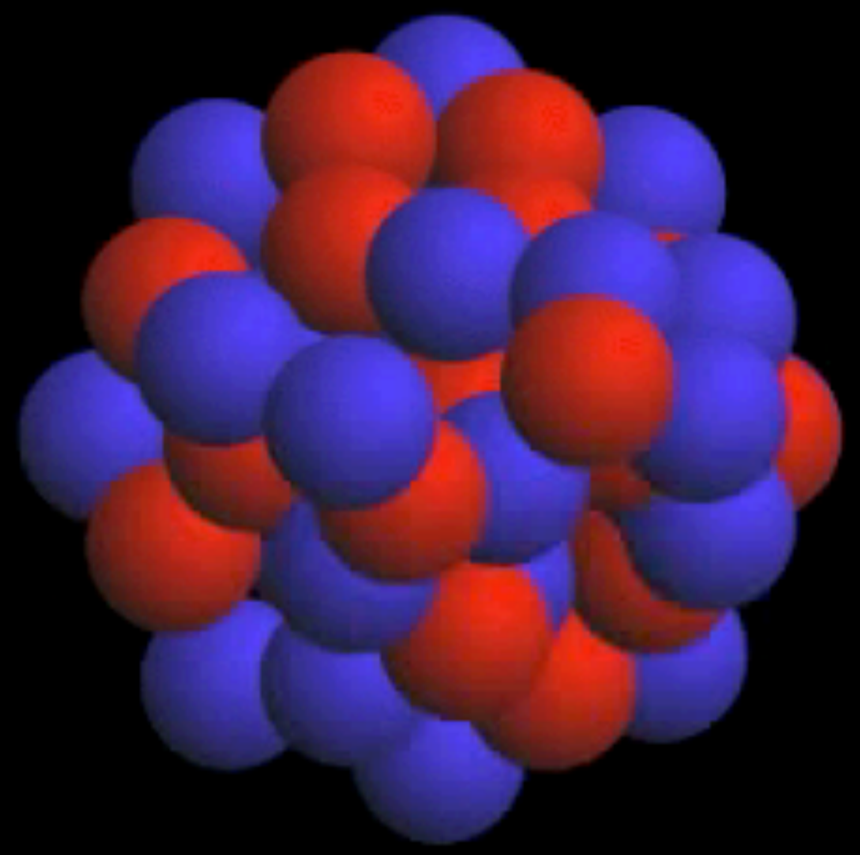
Nuclear Beta Decay

Blue: neutrons
Red: protons



Example: $^{76}As \rightarrow {}^{76}Se$

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Nuclear Beta Decay

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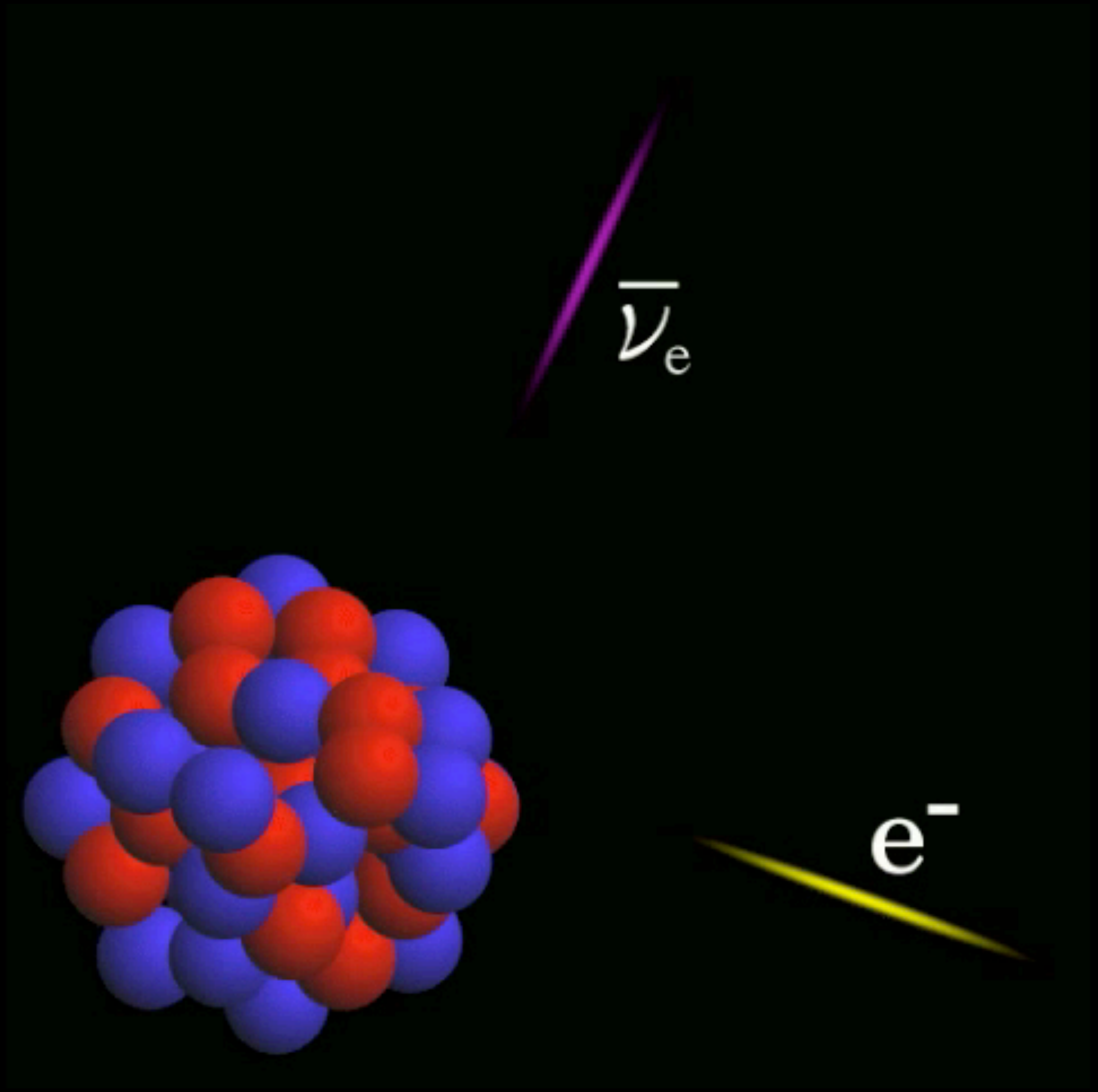
Red: protons



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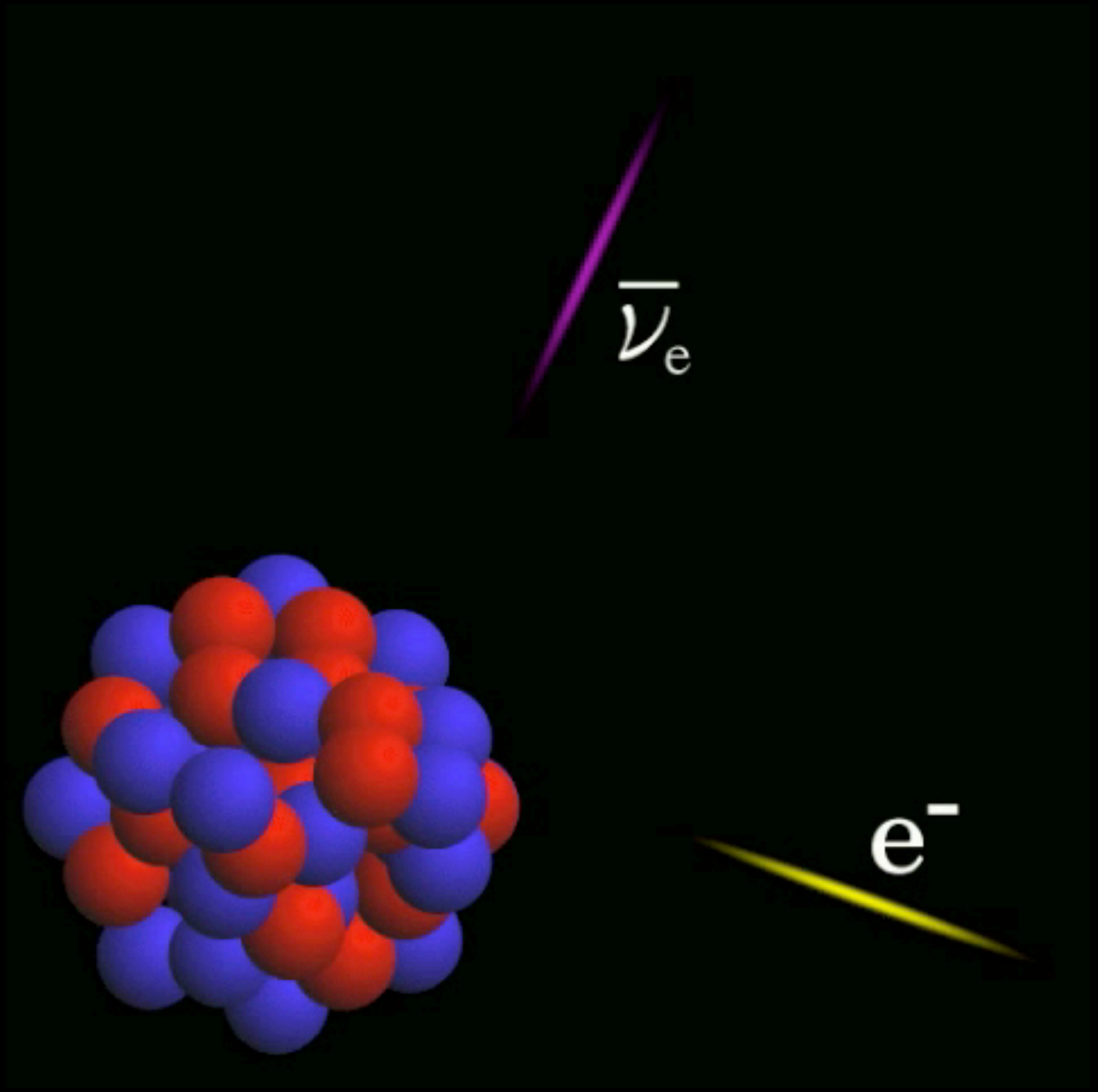


Blue: neutrons
Red: protons

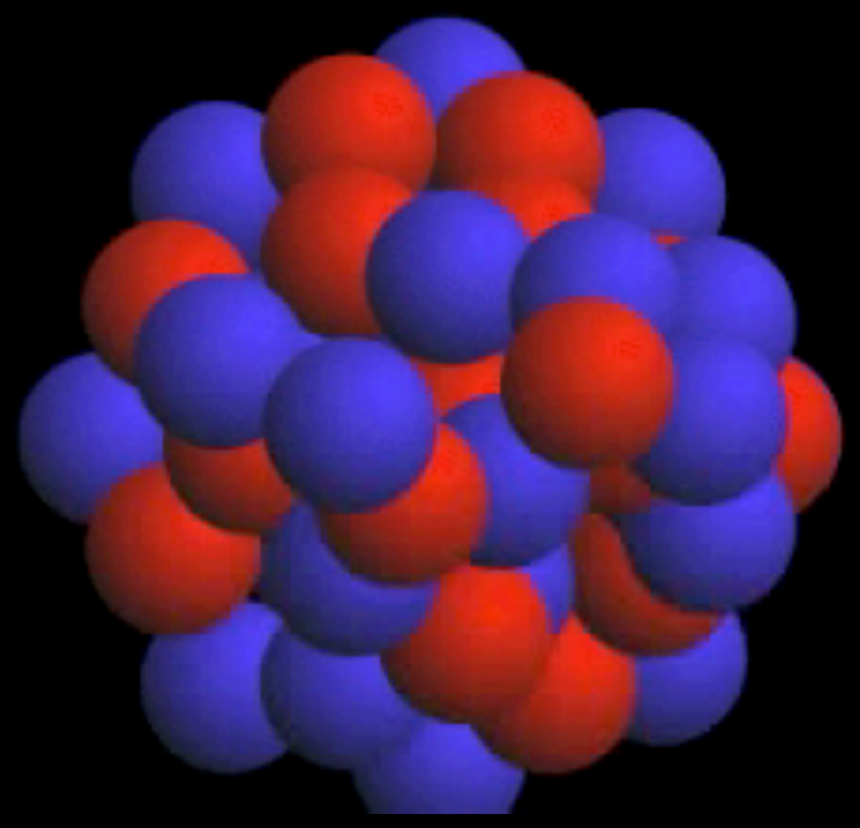
Example: $^{76}As \rightarrow {}^{76}Se$

Possible because
^{76}As is 0.004% heavier
than ^{76}Se: $E = mc^2$

Half life: 1 day

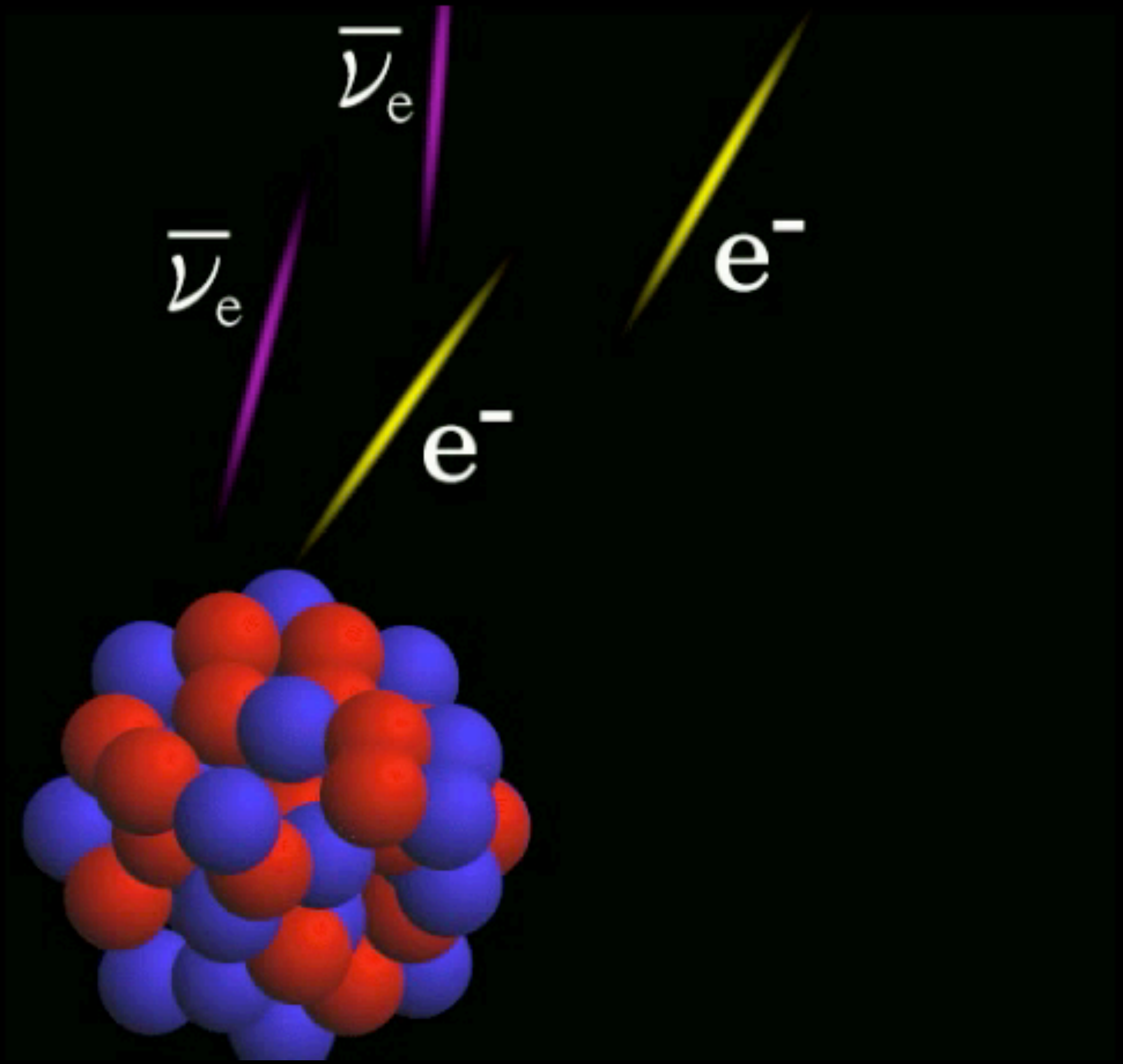
Double Beta Decay

Blue: neutrons
Red: protons



Example: $^{76}Ge \rightarrow {}^{76}Se$

Double Beta Decay



Blue: neutrons
Red: protons

Example: $^{76}Ge \rightarrow {}^{76}Se$

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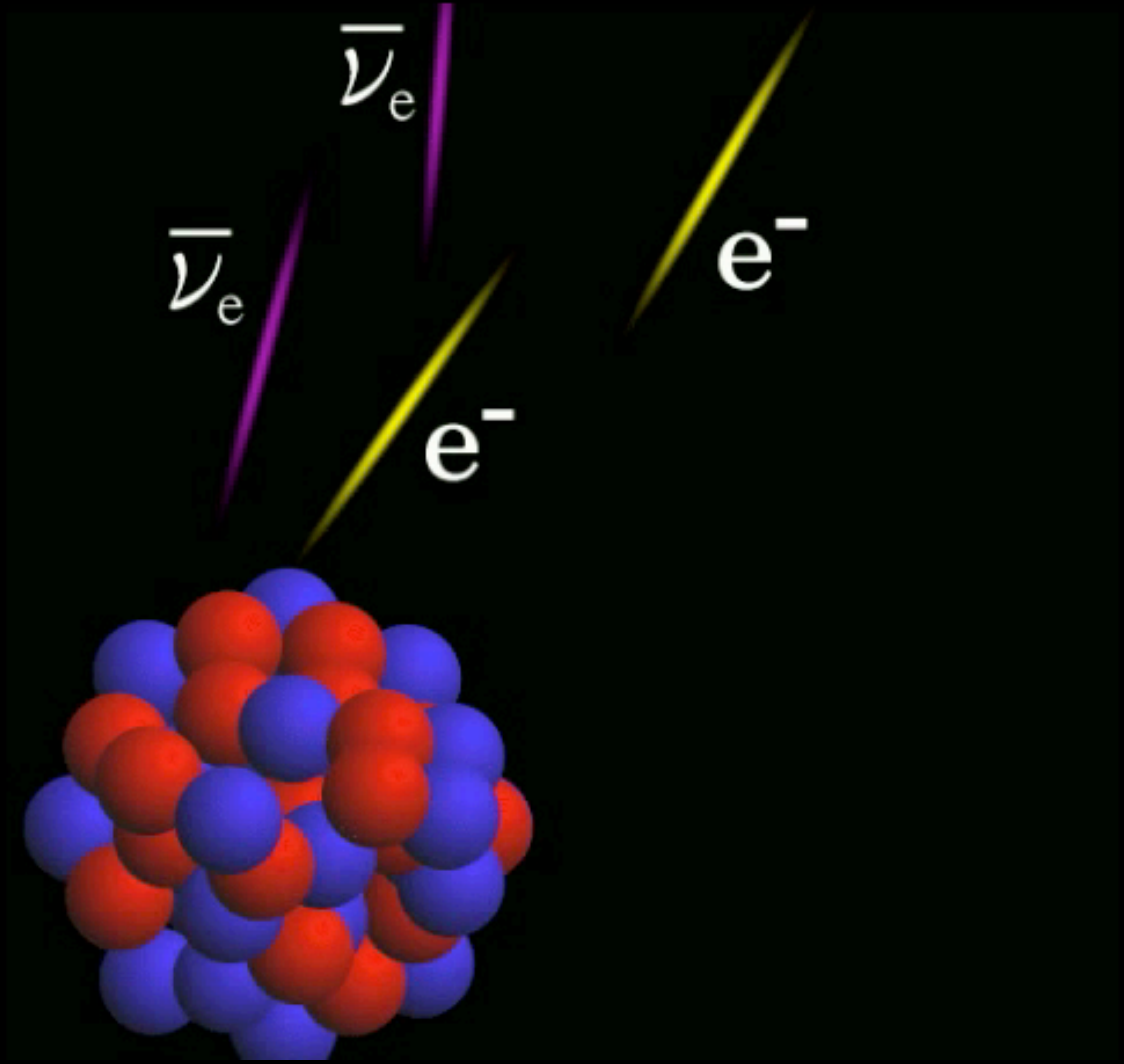
Double Beta Decay

Blue: neutrons
Red: protons



Example: $^{76}Ge \rightarrow {}^{76}Se$

Possible because ^{76}Ge is 0.003% heavier than ^{76}Se (but lighter than ^{76}As)

Half life: 10^{21} years!

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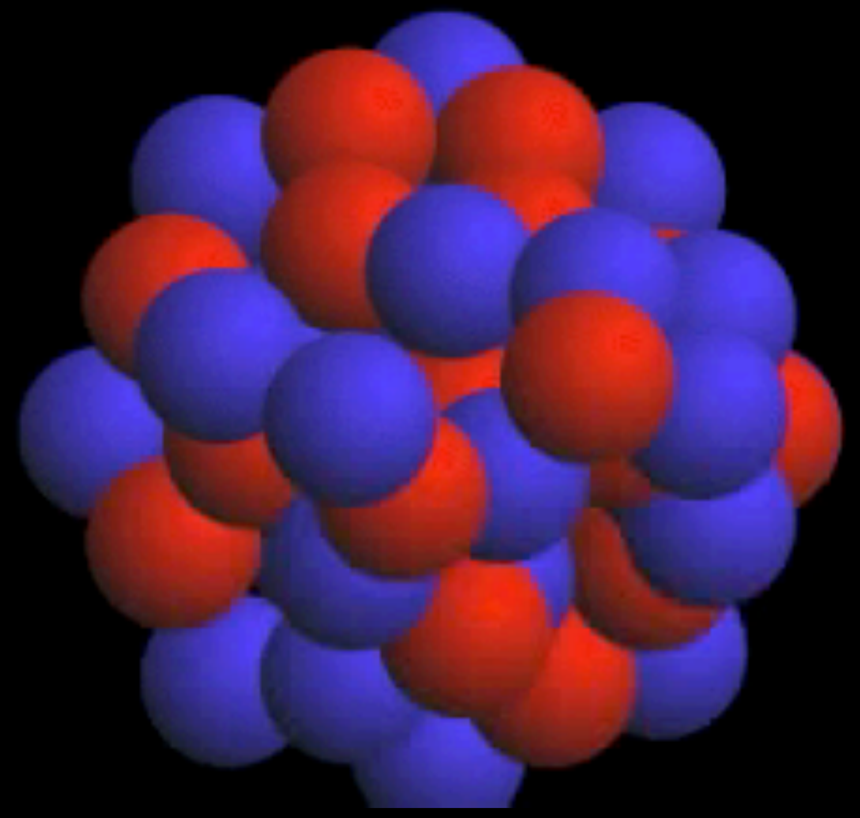
Neutrinoless Double Beta Decay

Blue: neutrons
Red: protons



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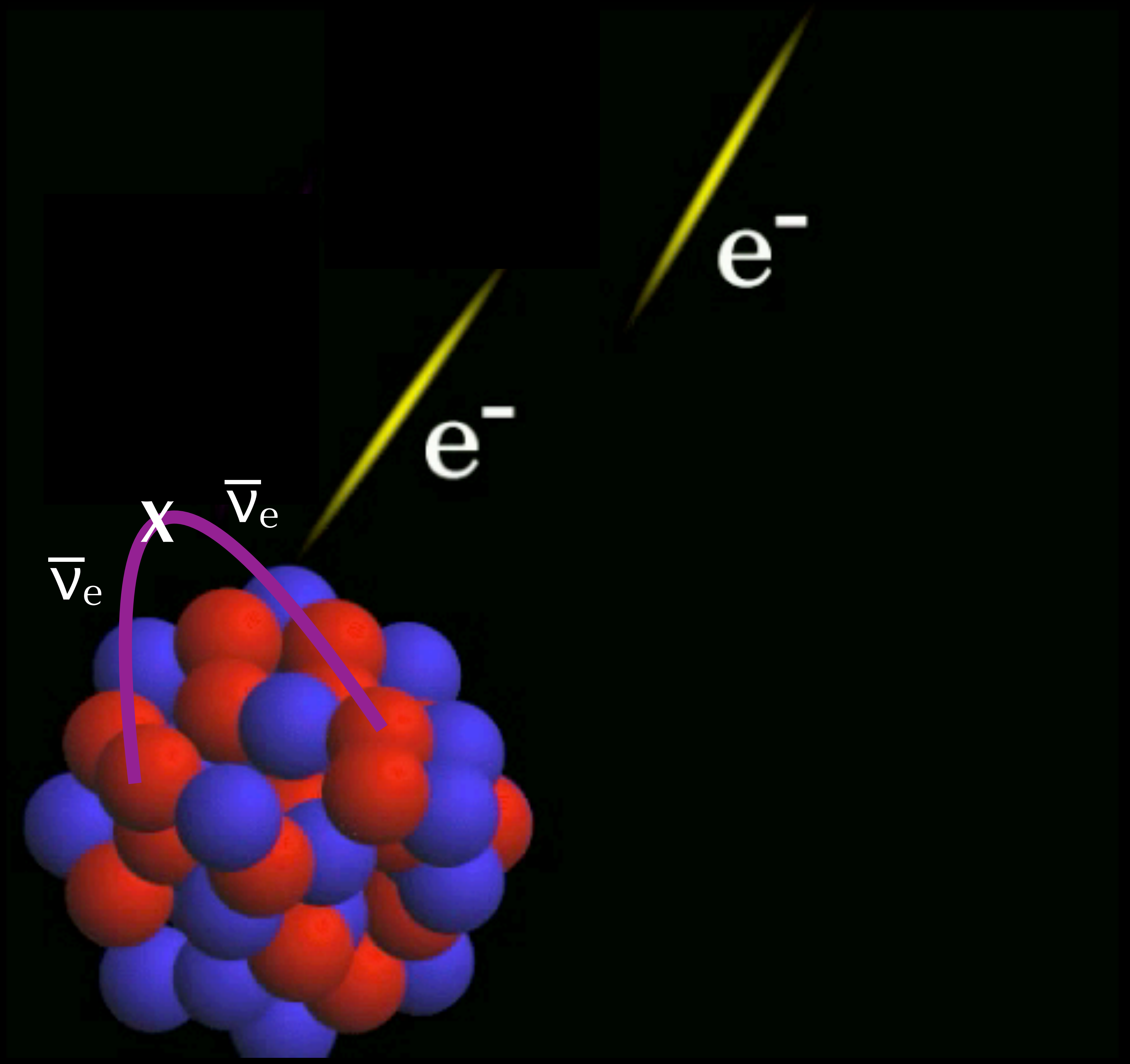

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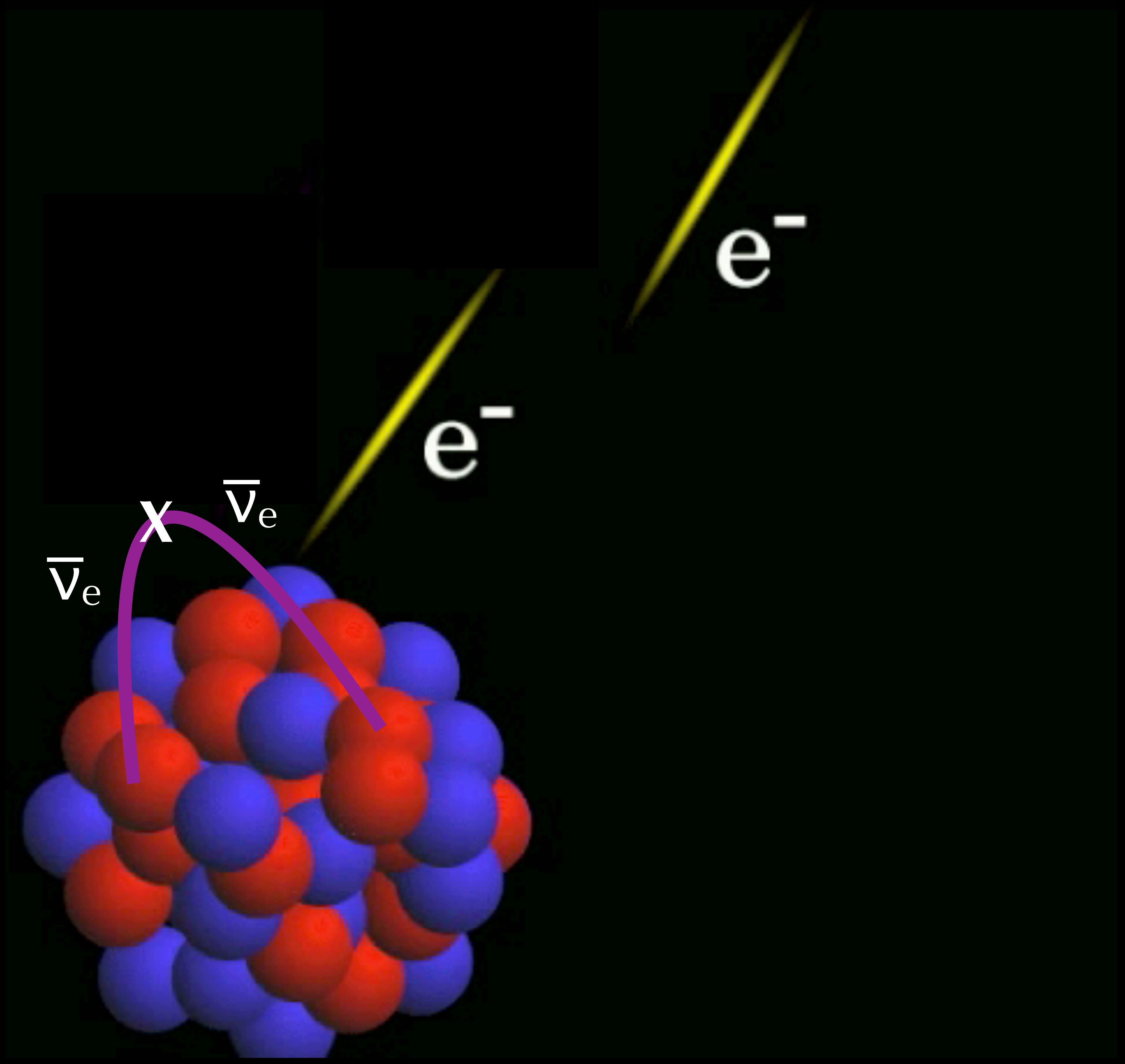


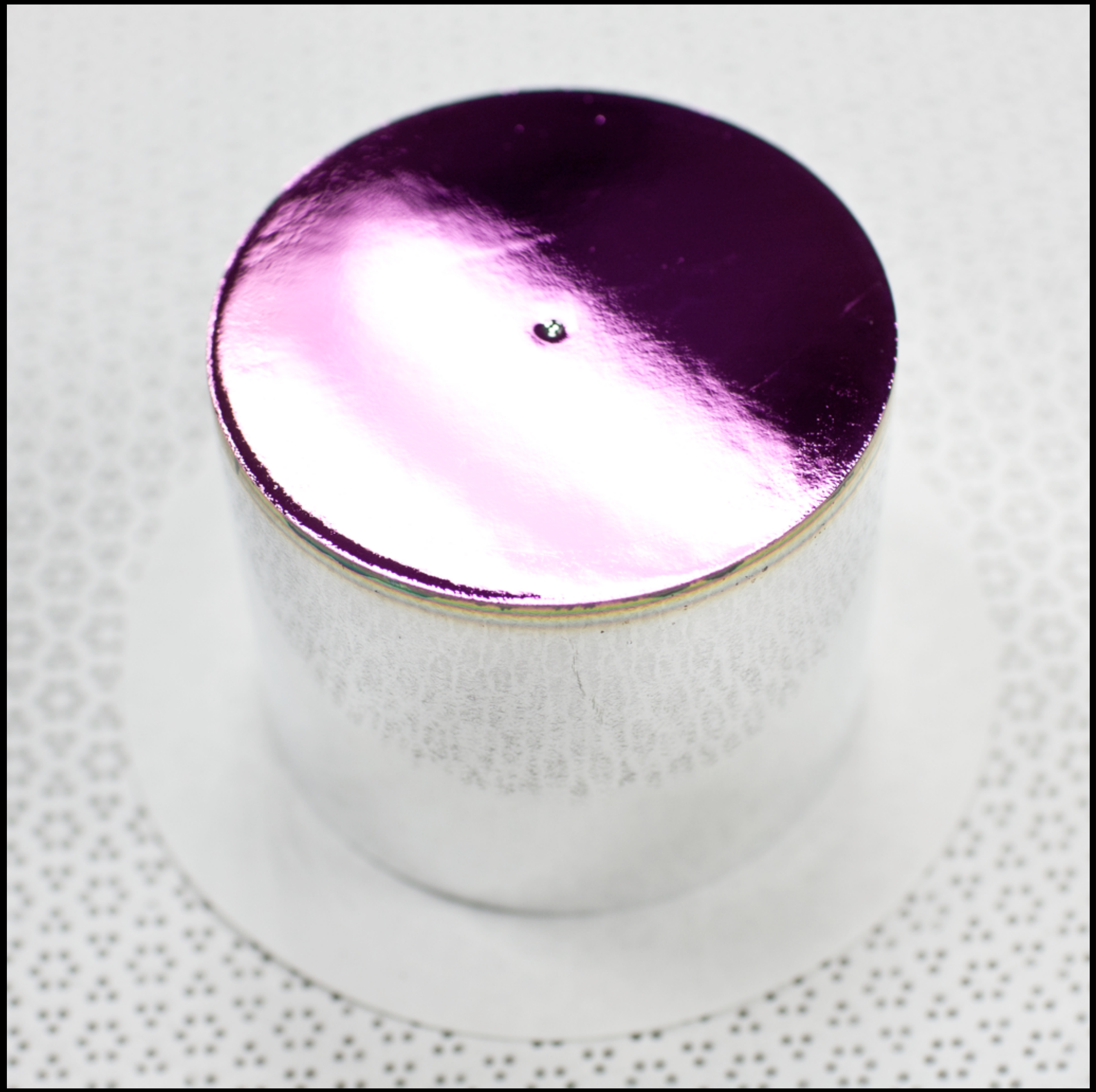
Matter Creation!

Half life: >10^{26} years

Example: $^{76}Ge \rightarrow {}^{76}Se$

J. Detwiler

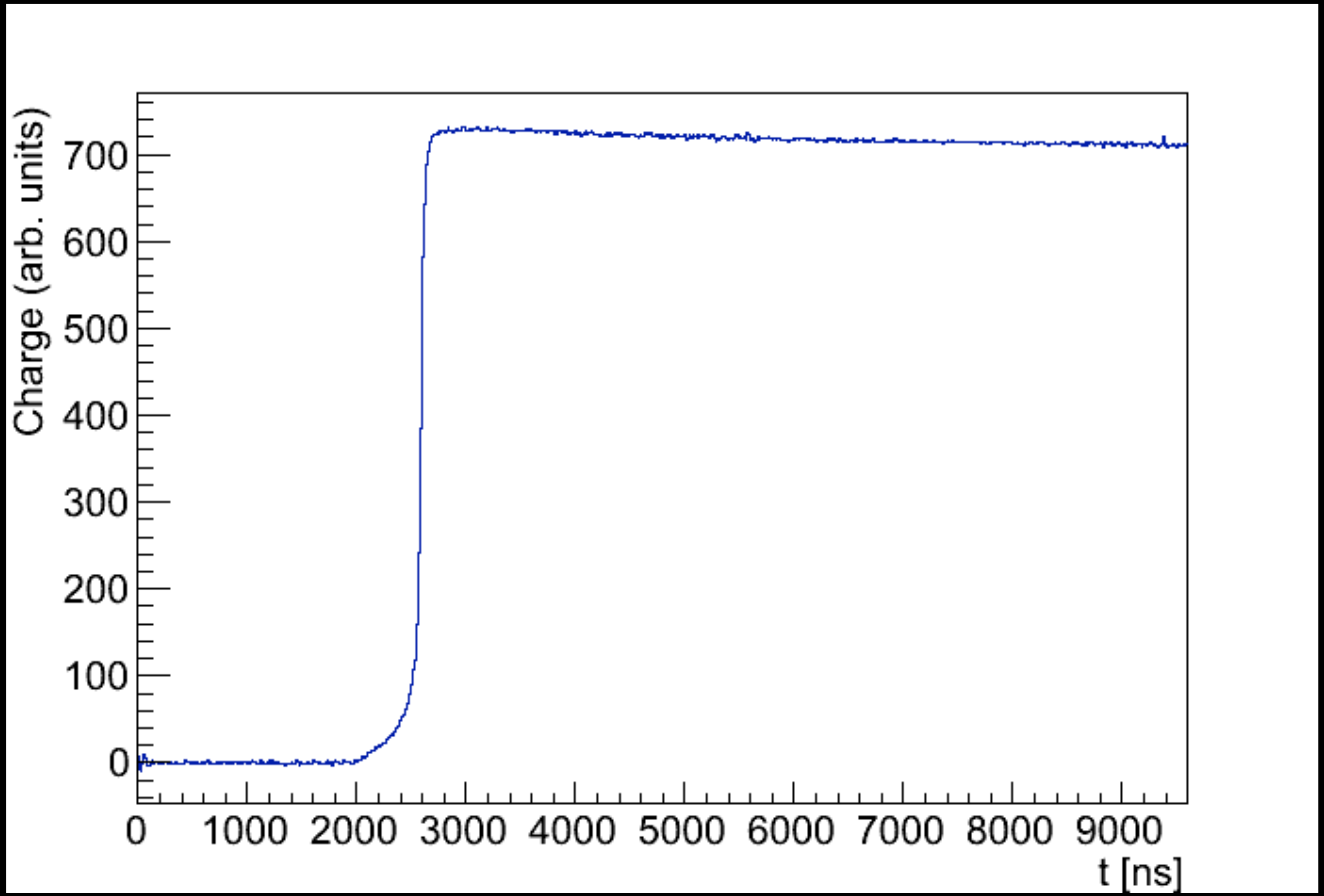
Germanium Detectors



- ~1 kg detector: a giant single crystal containing ~10^{25} Ge nuclei
- A decay generates an electronic pulse
- The pulse size is proportional to the energies (speeds) of the two electrons

J. Detwiler

Germanium Detectors



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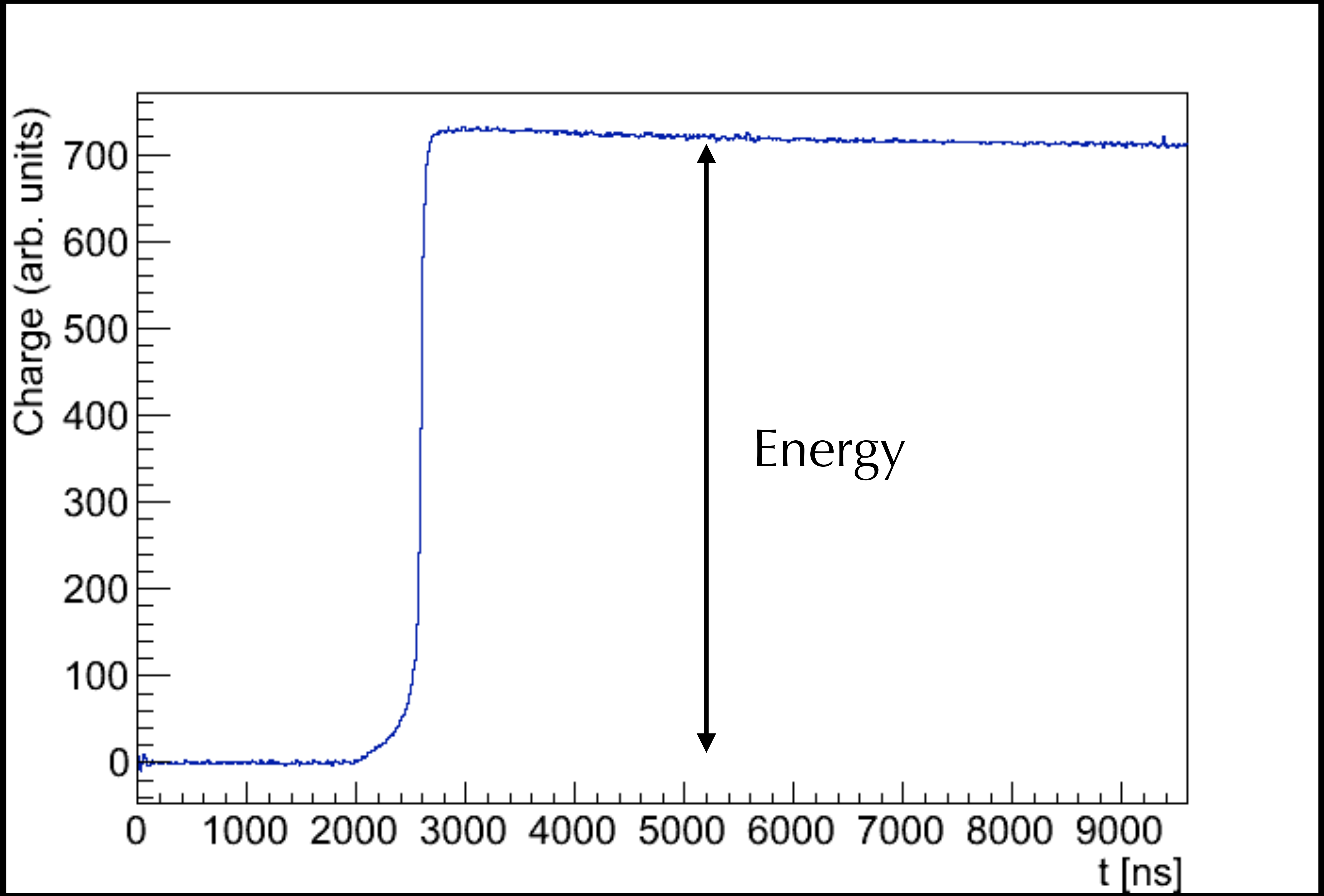

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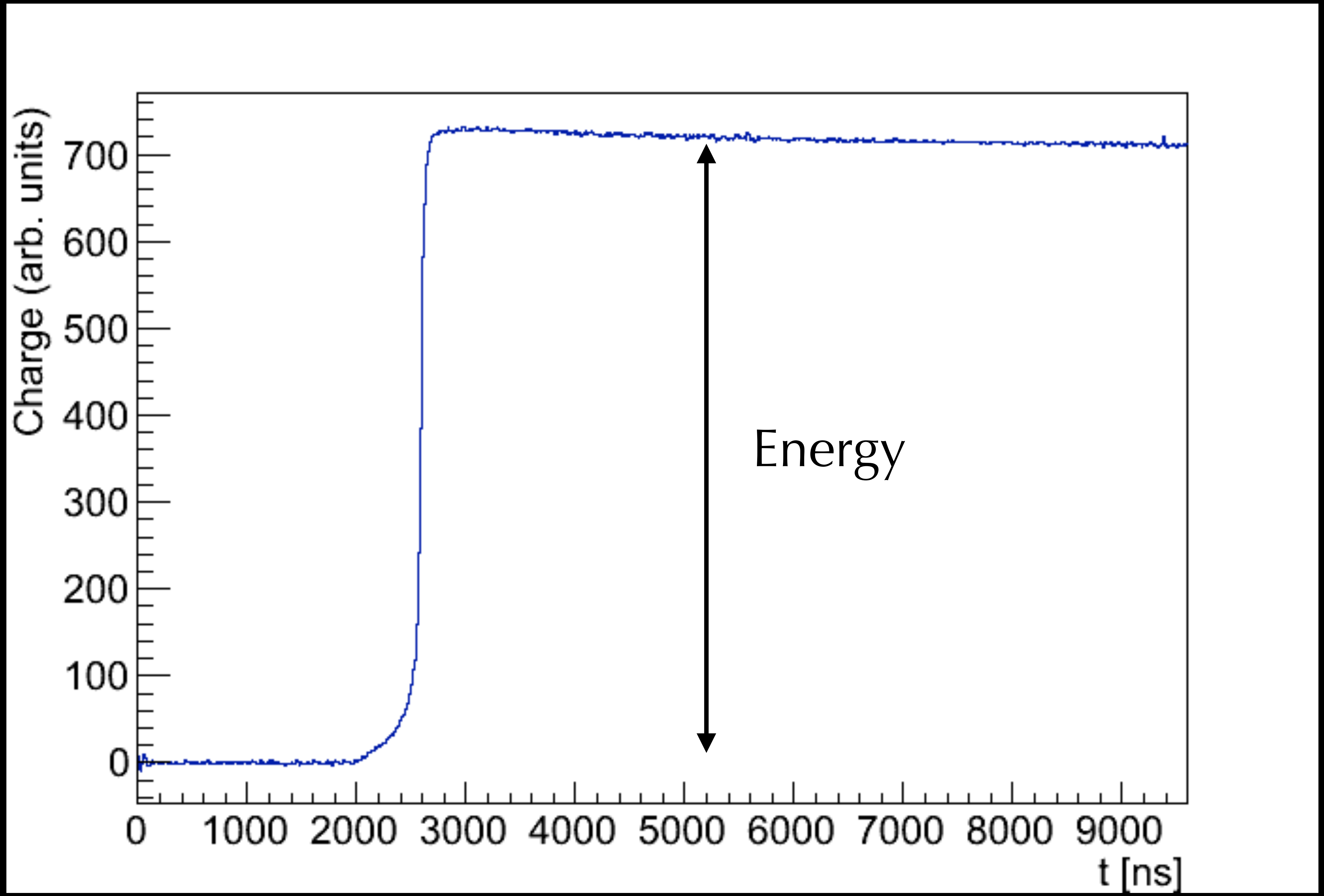
Germanium Detectors

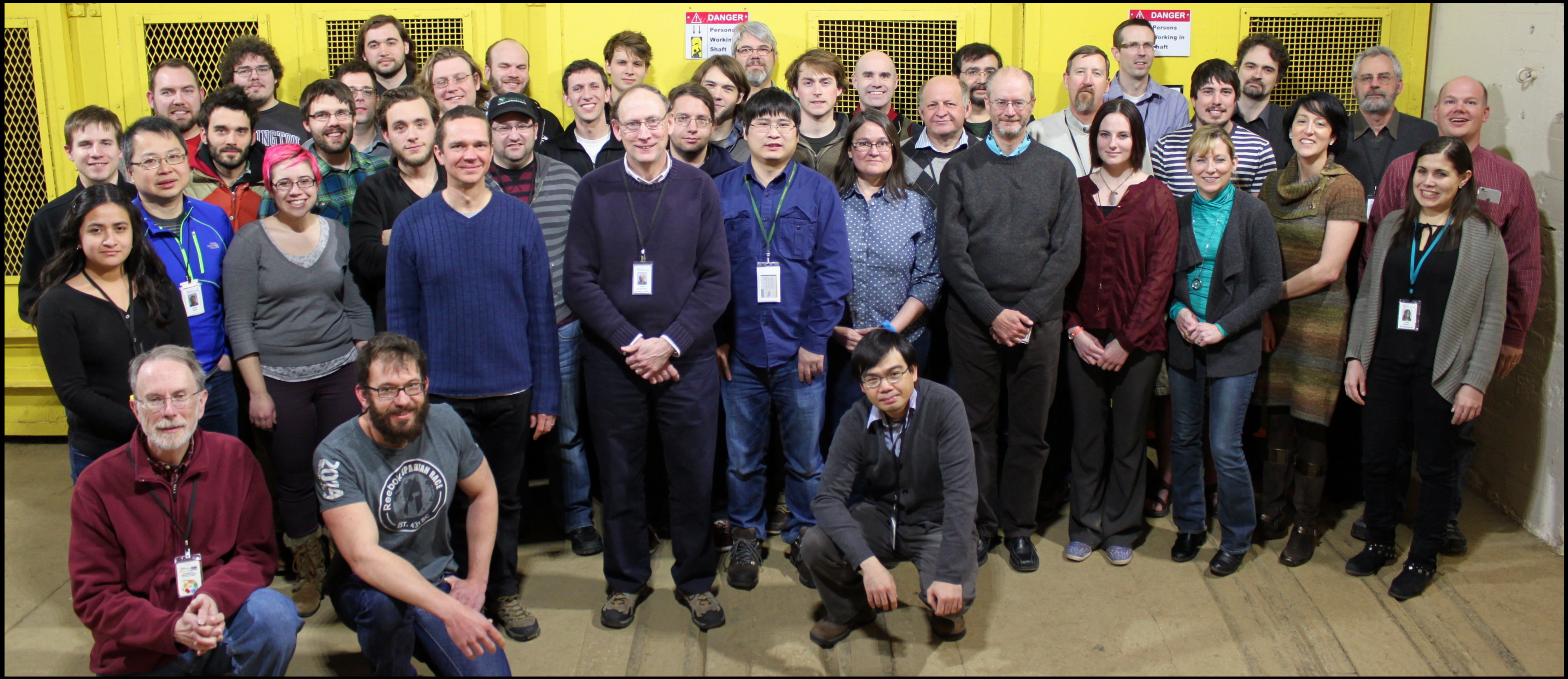


- "Standard" double beta decay: the neutrinos carry away some of the energy
- Neutrinoless double beta decay: no "missing" energy
- Search for pulses with energy equal to $(M_{Ge} - M_{Se} - 2\ m_e)c^2$

Challenges

- Need to eliminate all other sources of pulses with the same energy
- Need to measure the energy very well
- Need dozens of detectors (complex and pricey)

Hunting for Neutrinoless Double-Beta Decay



The MAJORANA Collaboration at the Homestake Mine

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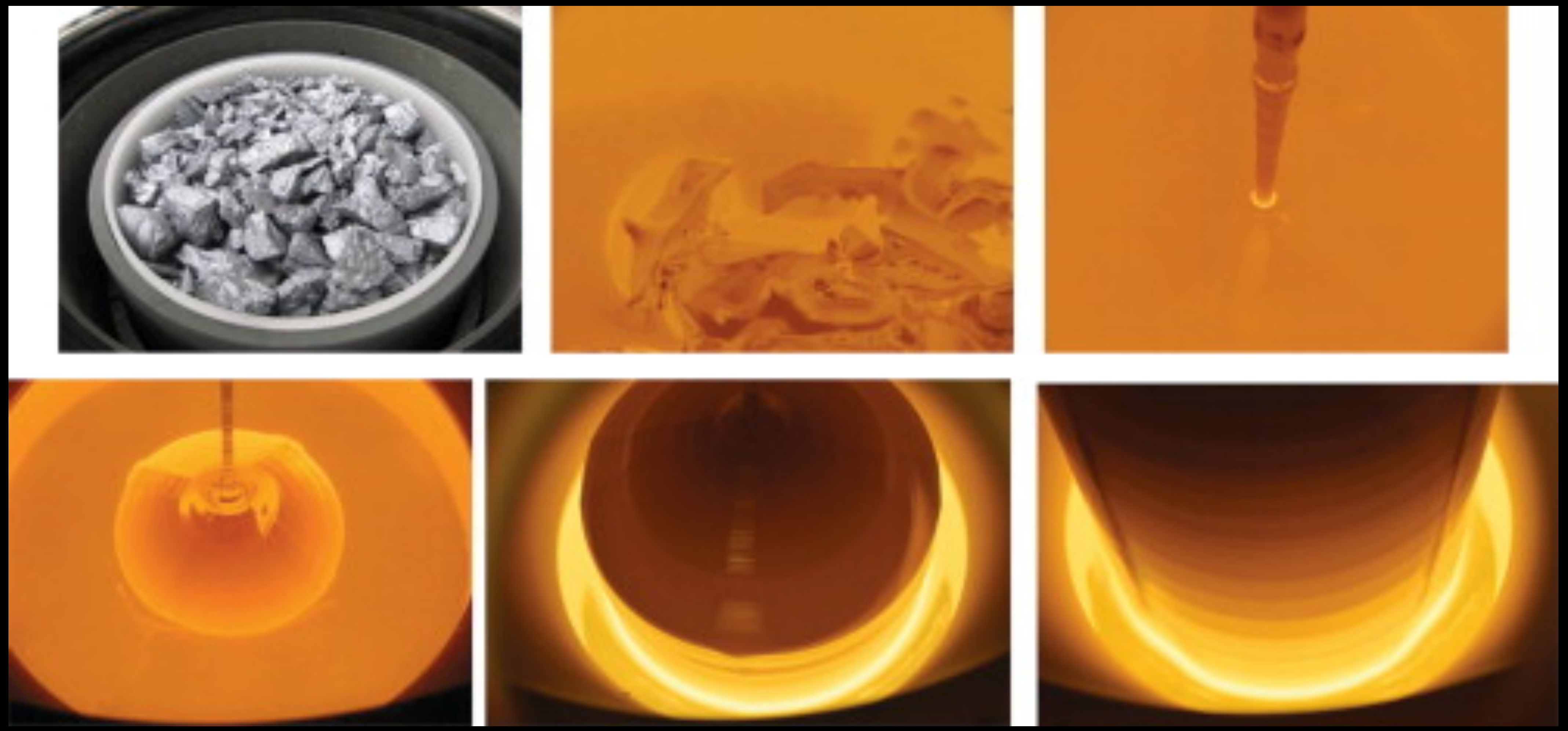
Getting the Ge Detectors

$^{nat}Ge \rightarrow {}^{nat}GeF_4$ gas $\rightarrow {}^{76}GeF_4$ gas $\rightarrow {}^{76}GeO_2$

Ultracentrifuge facility in Krasnoyarsk, Russia

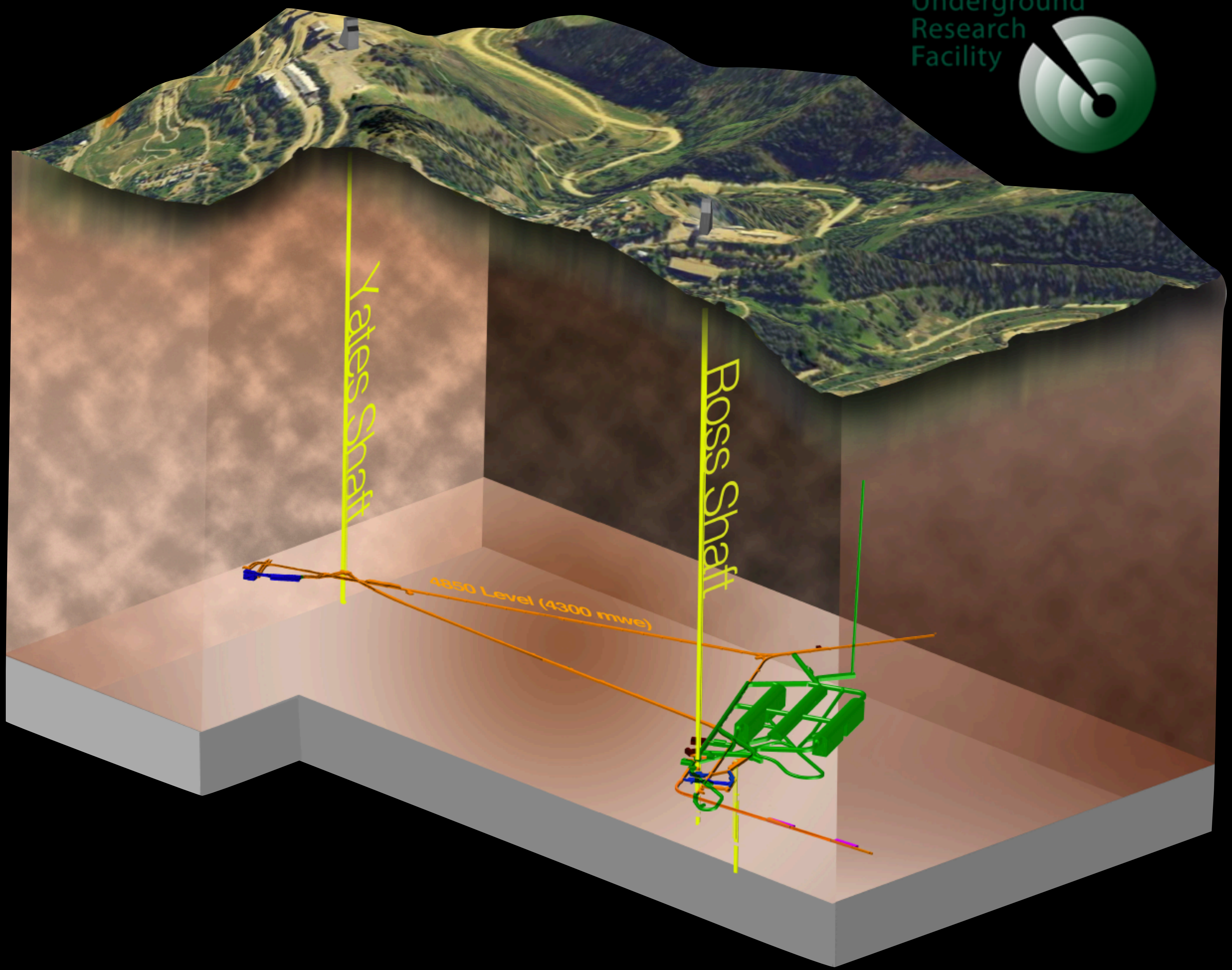
$^{76}GeO_2 \rightarrow {}^{76}Ge$ metal $\rightarrow$ Single crystal ^{76}Ge



Czochralski crystal growth method

Blocking Natural Radiation

Sanford Underground Research Facility



Block cosmic rays: go 1 mile underground

Shield gamma radiation and use ultra pure materials

Credit: M. Kapust, SURF

Working 1 Mile Underground

UW student Khang Nguyen

Ultra-Clean Materials

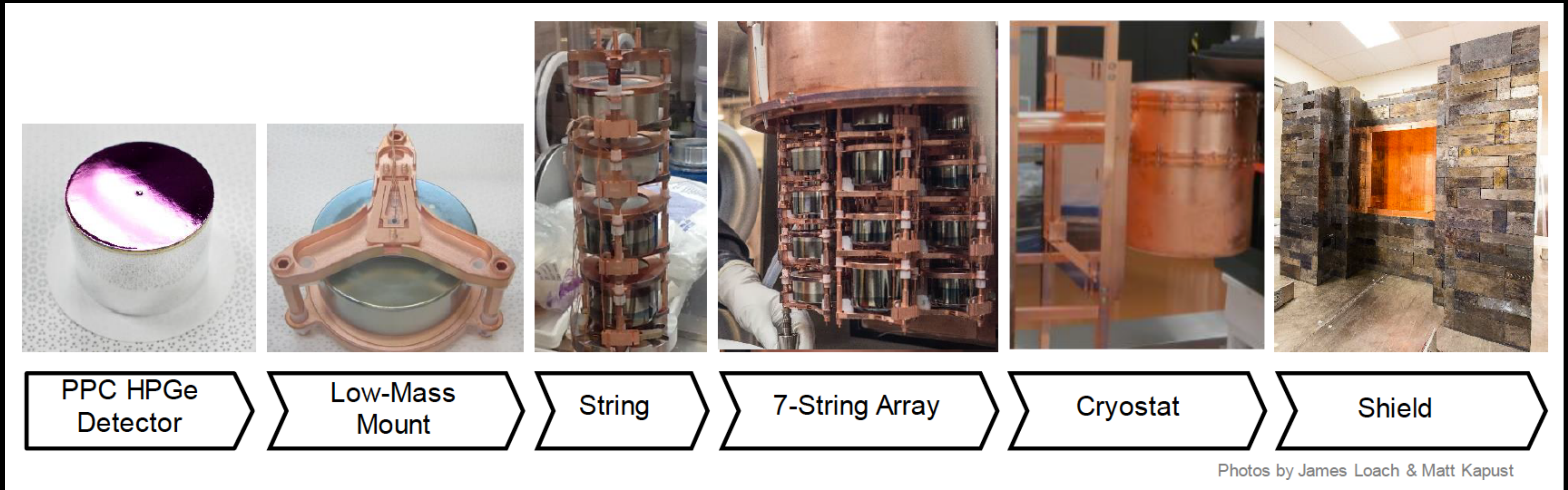
Make the world's cleanest copper 30x cleaner

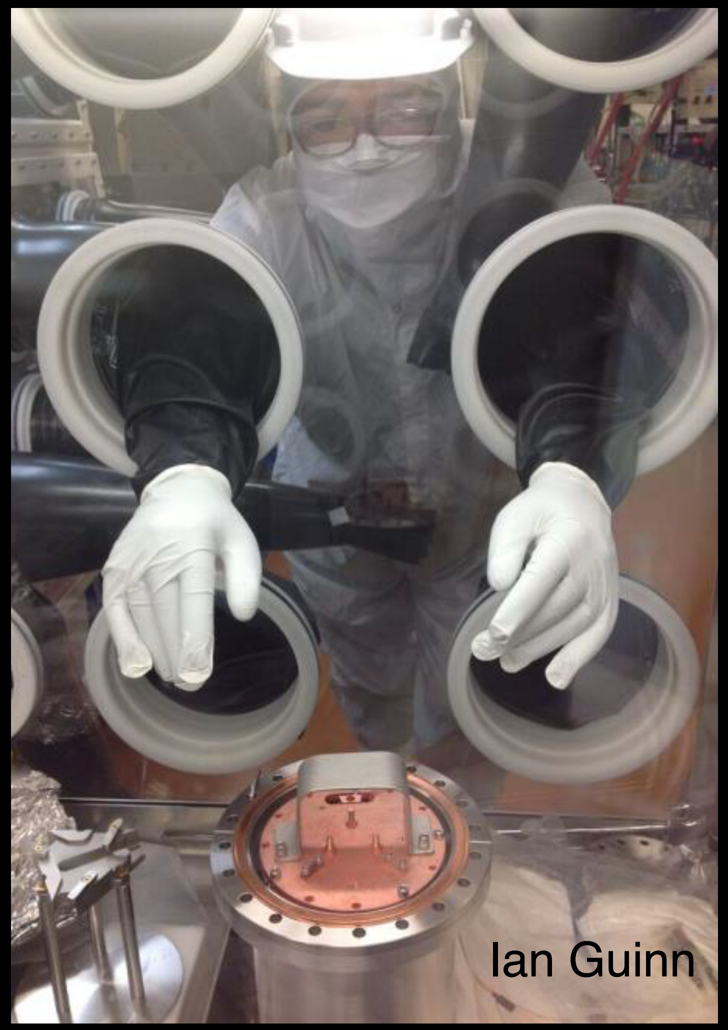
Parts stored under nitrogen cover gas

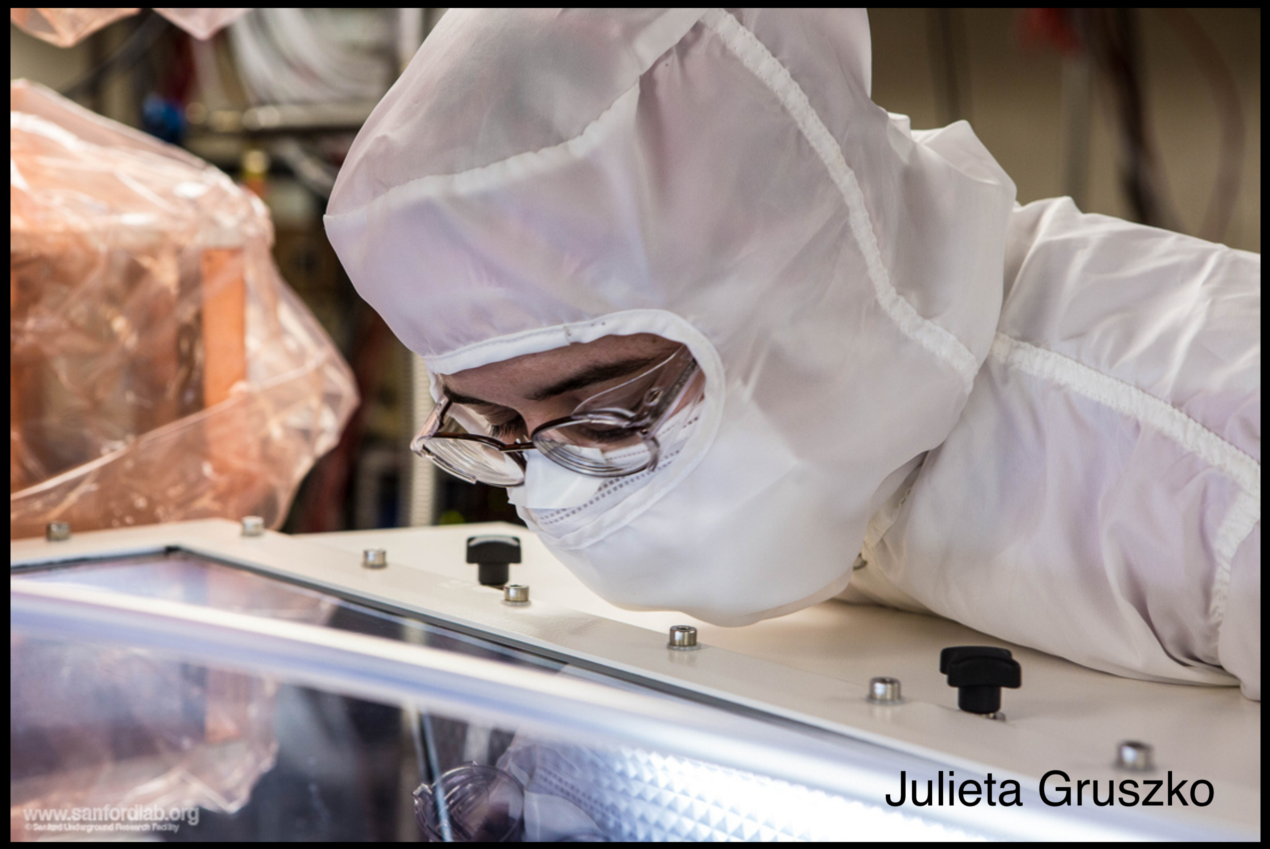
Also: ultra-clean plastics, cables, connectors, electronics boards, vacuum seals, bolt thread coatings…

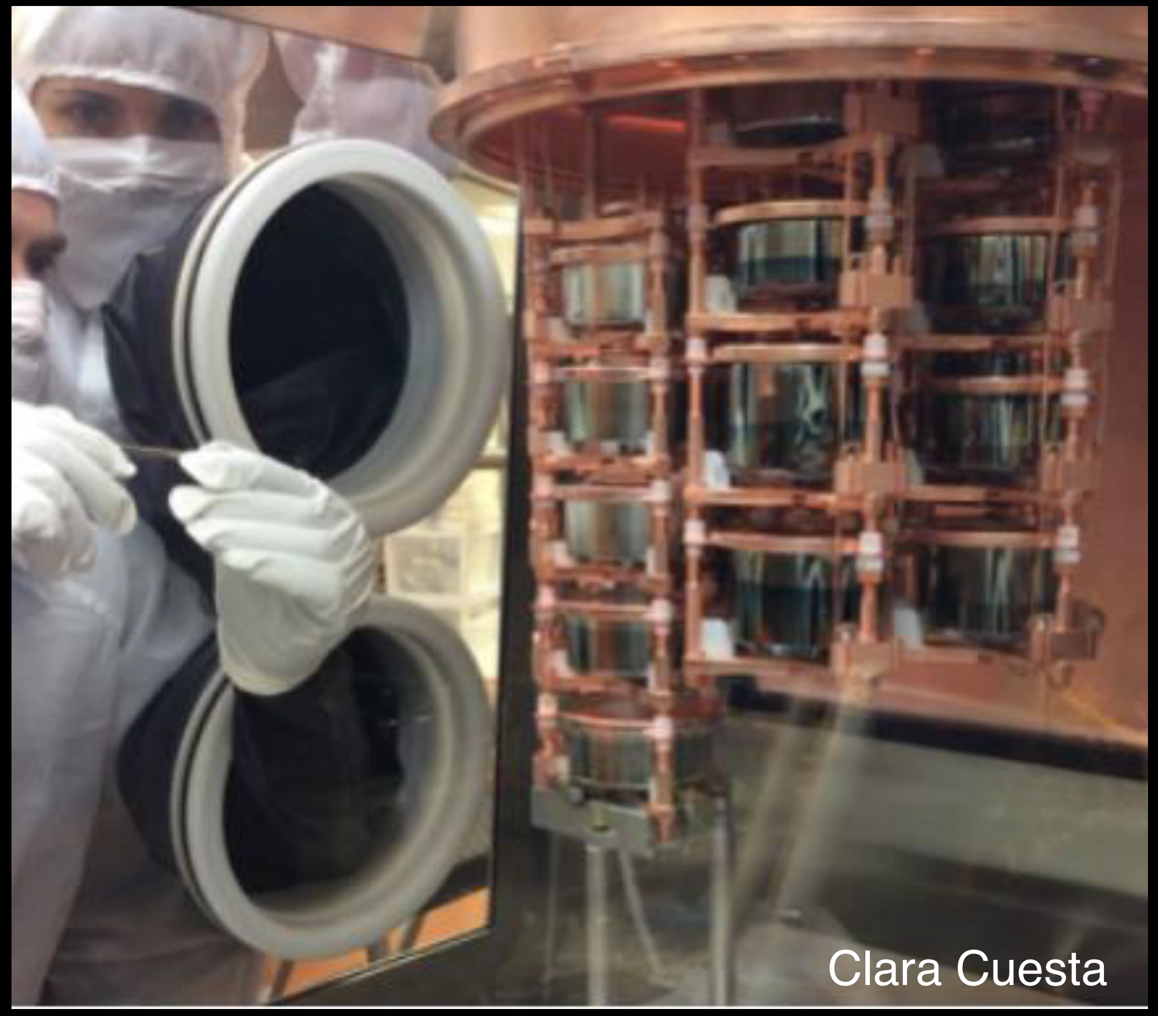
Credit: M. Kapust, SURF

Building the Detector









First Results

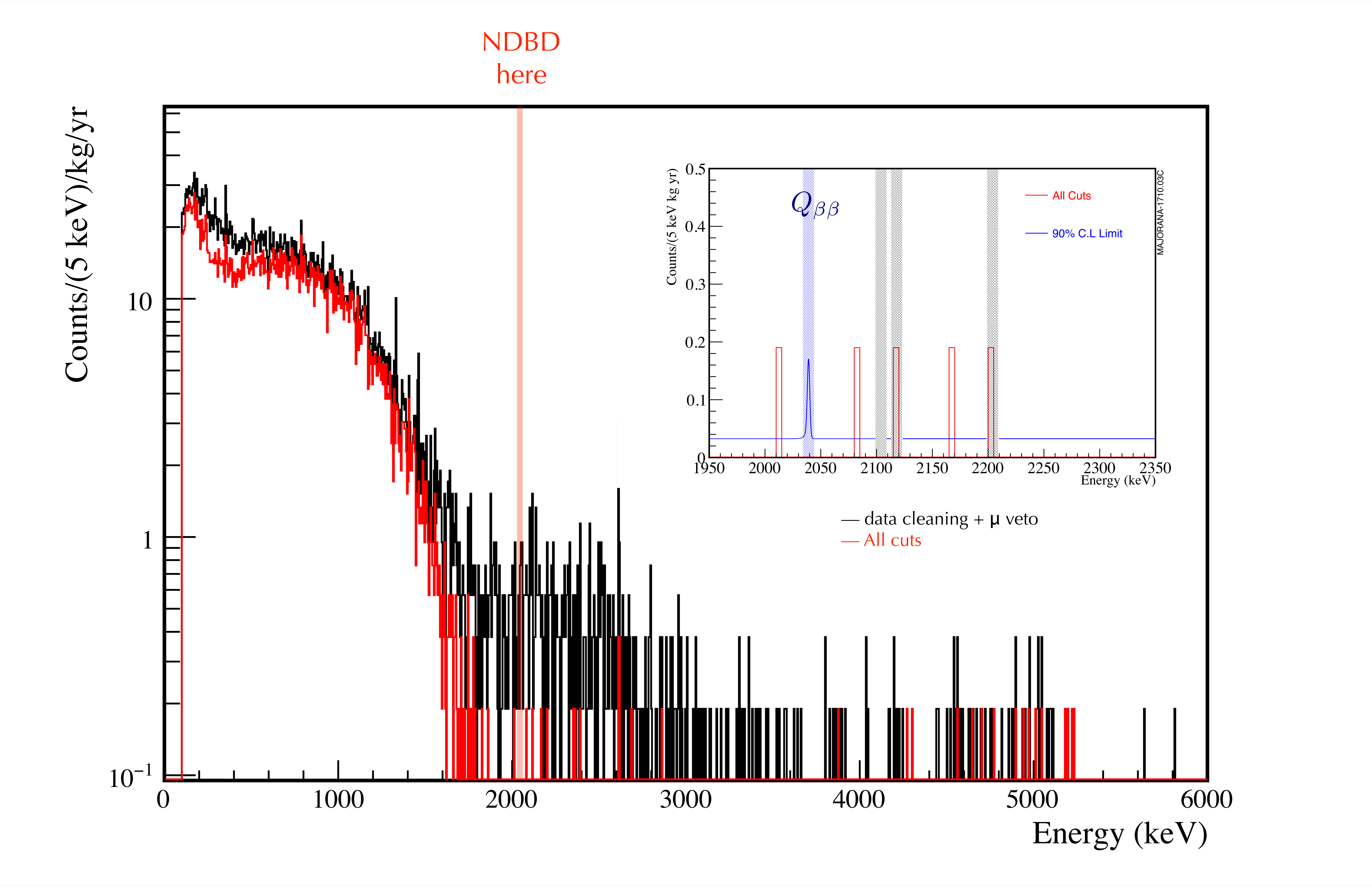
Featured in Physics | Editors' Suggestion

Search for Neutrinoless Double-β Decay in ^{76}Ge with the MAJORANA DEMONSTRATOR

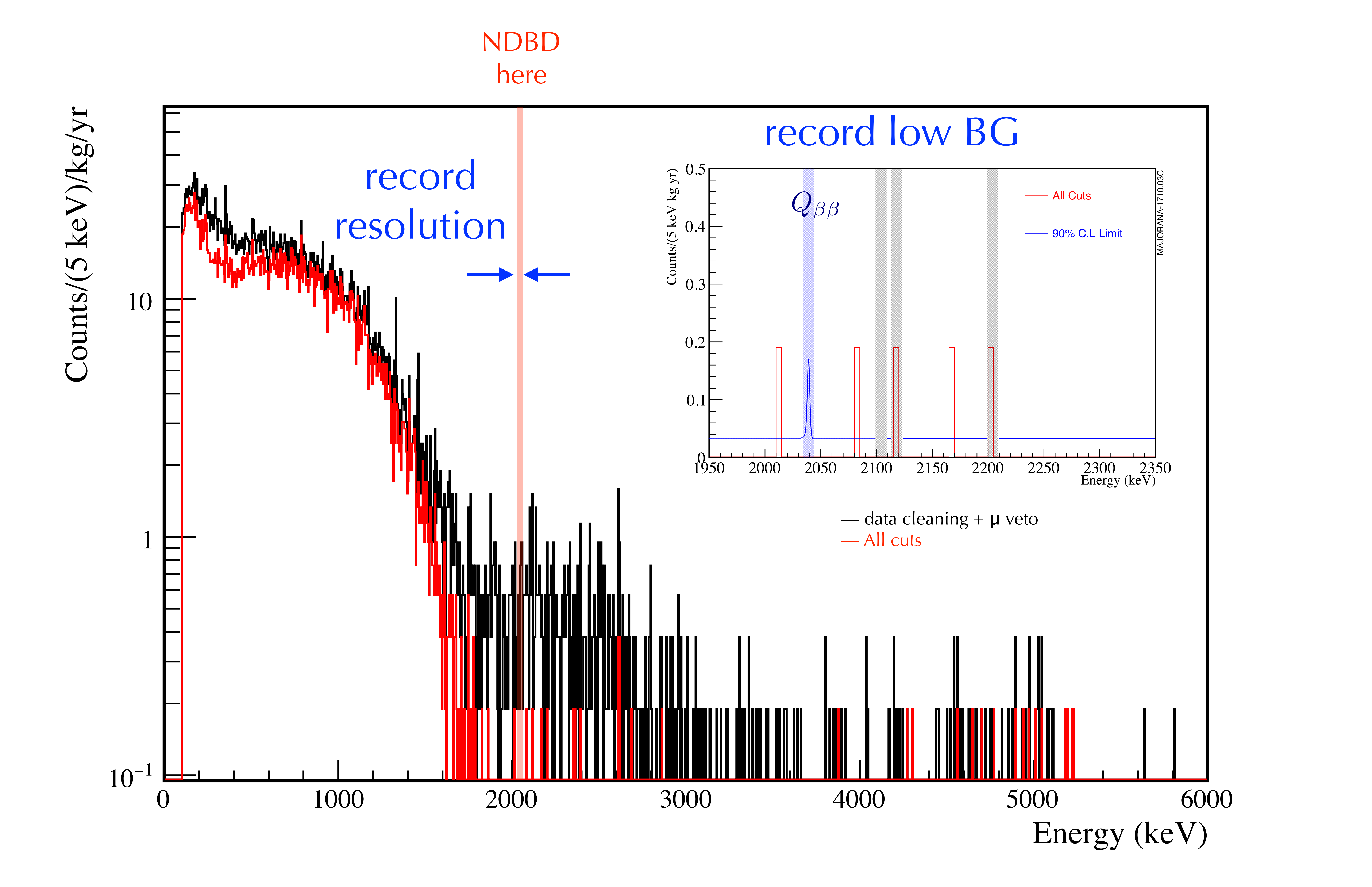
C. E. Aalseth *et al.* (Majorana Collaboration)
Phys. Rev. Lett. **120**, 132502 – Published 26 March 2018

Physics See Viewpoint: The Hunt for No Neutrinos

First Results



First Results



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Future Plans

LEGEND

- Join forces with a similar experiment in Europe
- Use hundreds of detectors
- Test ~50-75%* of theoretical predictions

* somewhat subjective

Summary

- Leading theories explaining the matter asymmetry of the universe predict that neutrinos are Majorana particles
- The only known method of testing the Majorana nature of the neutrino is searches for neutrinoless double-beta decay
- A massive international campaign is underway to search for this novel process. Discovery could come at any time!