Neutrinos: Exploring Origin of Matter and Space-time

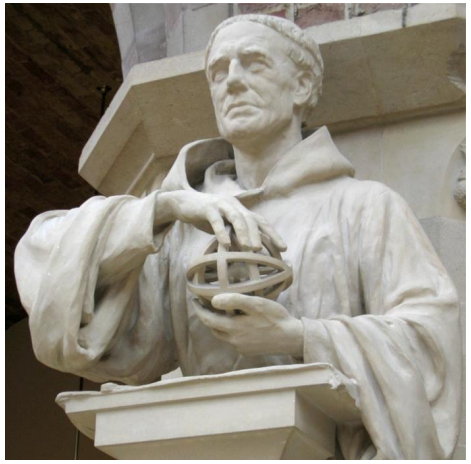
Hi, my name is Teppei Katori, I am a particle physicist
- Born and raised in Japan
- PhD in USA
- Lecturer in UK

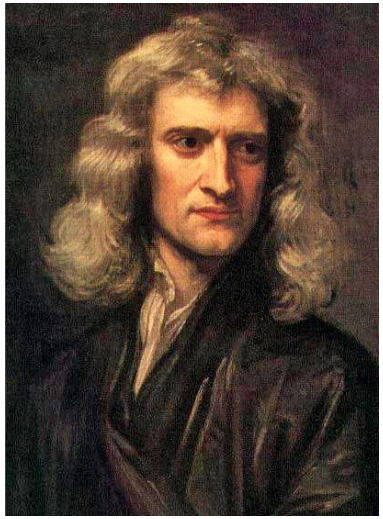
Teppei Katori (@teppeikatori)
King's College London
IOP West Midlands branch webinar, April 20, 2021

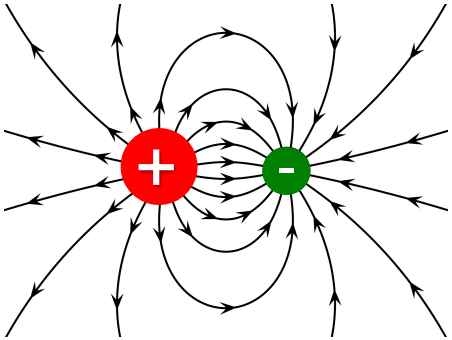
MicroBooNE PMT test stand
(photo by Reidar Hahn, Fermilab)

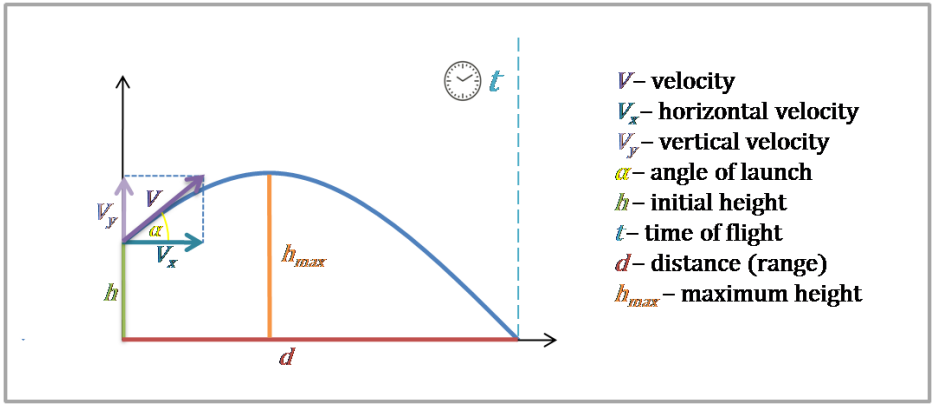
Where is Physics? Everywhere!

Physics is the subject to study the laws of Nature
- Every phenomenon in Nature is subject to the laws of physics









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Where is Physics? Everywhere!

Physics is the subject to study the laws of Nature
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Connection of logic allows reaching more intangible knowledge

Particle physics
Subject to study structure of matter and force in terms of elementary particles

This is the subject to reach the highest (most non-intuitive) knowledge by adding logics of ladders

Particle Physics

Subject to study structure of matter and force in terms of elementary particles
- matter → particles
- force → particles

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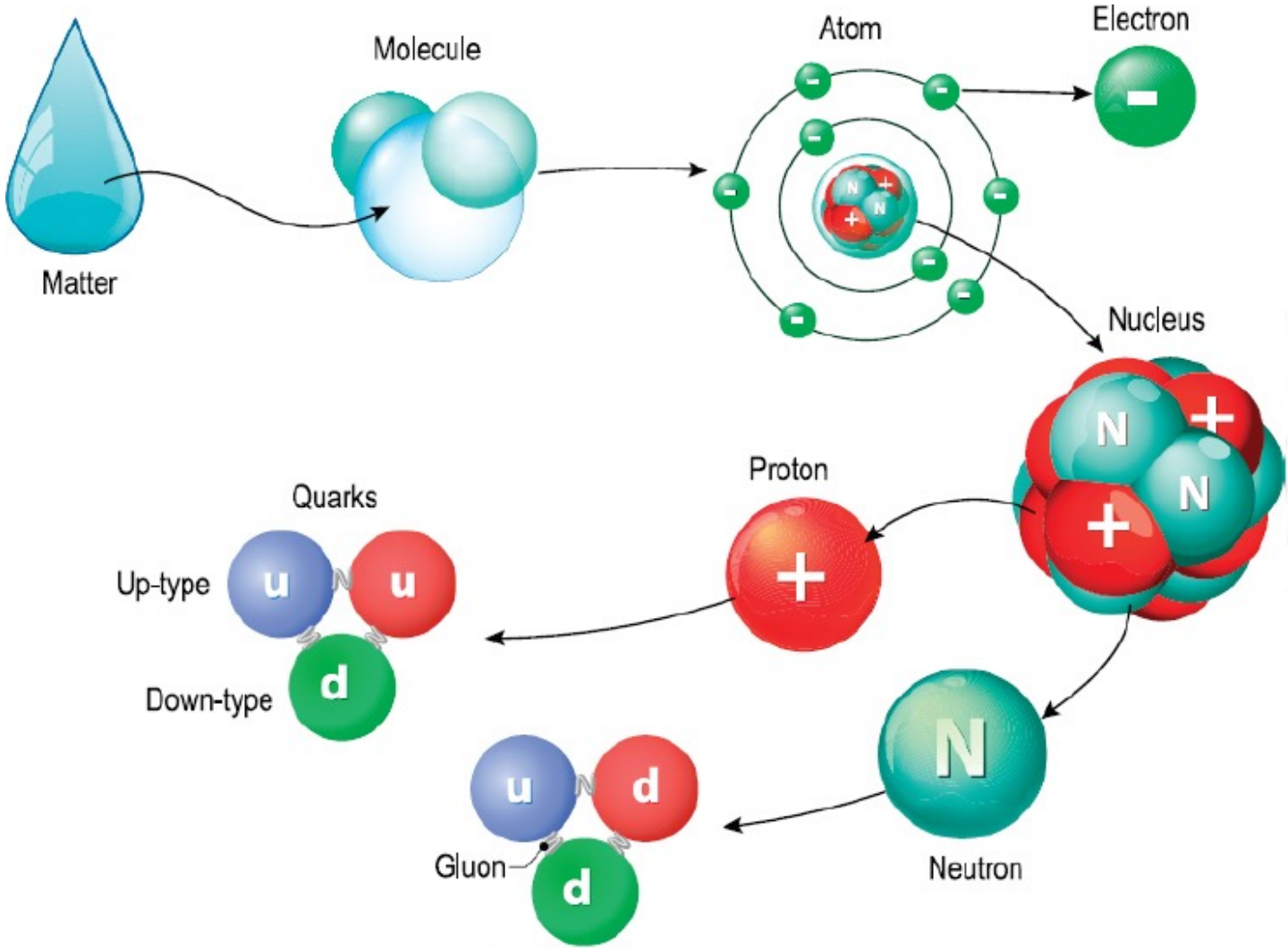

Particle Physics

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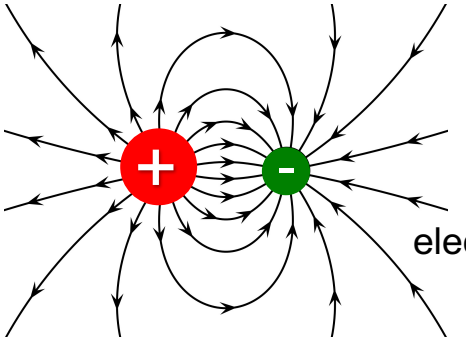
old view (Maxwell)

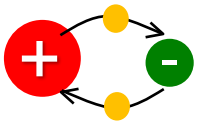
proton electron



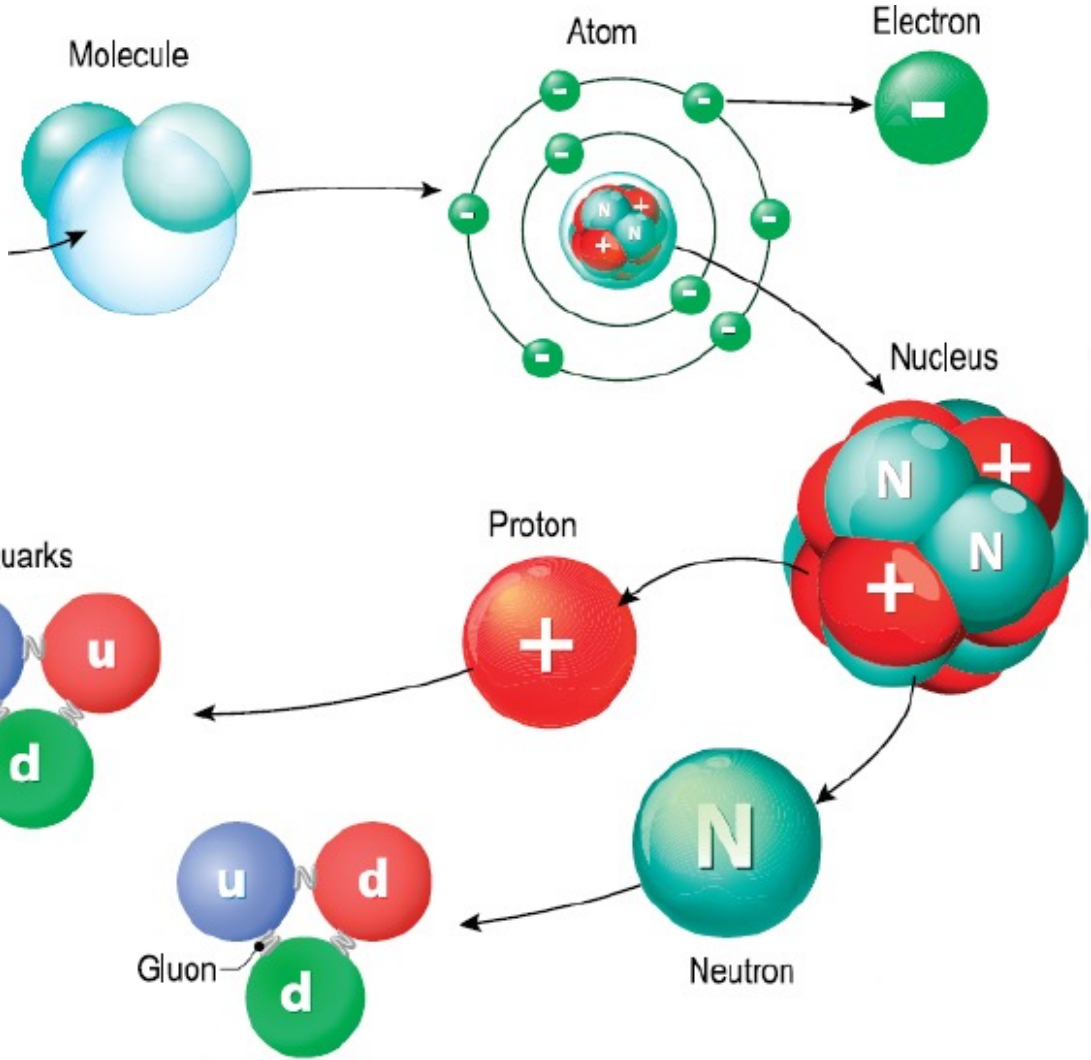
electromagnetic field

modern view (Yukawa)

proton electron

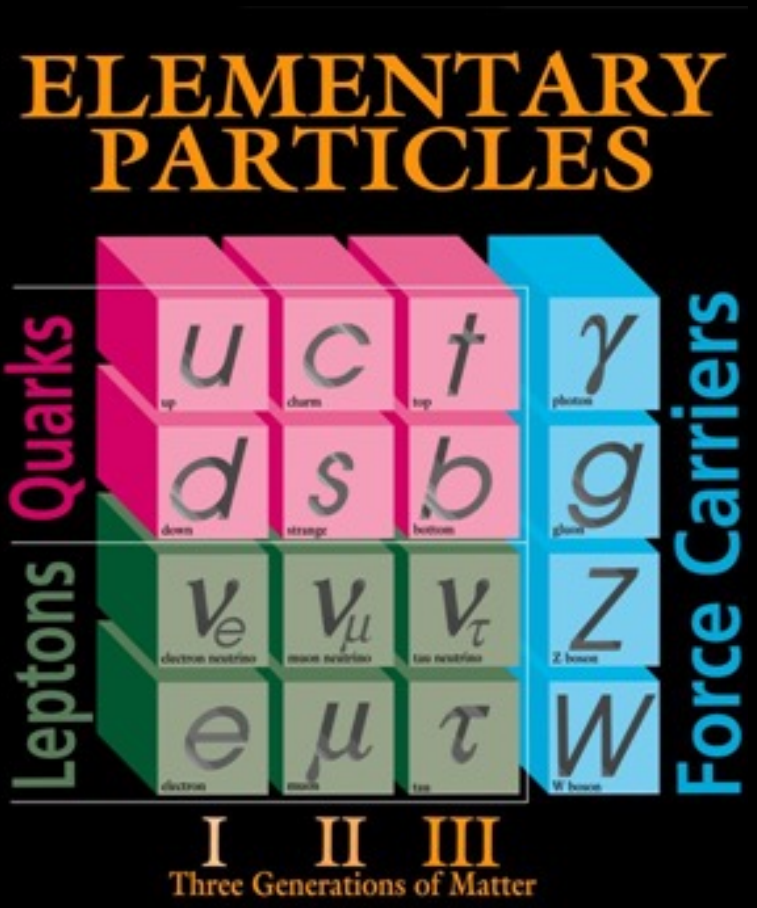


photon



The Standard Model, Elementary Particles of the Universe

- 6 Quarks
  - Up-quarks and Down-quarks make matter
- 6 Leptons
  - 3 Charged Leptons (electron is here)
  - 3 Neutrinos
- 3 Force carries (gauge bosons)
  - Gluon (Strong nuclear force, ~1)
  - Photon (light, ~0.01)
  - Weak bosons (Weak nuclear force, ~10^{-7})
  - Gravity is missing from this picture (~10^{-38})
- The Higgs boson
  - Higgs boson gives masses to other particles
  - Discovered in 2012



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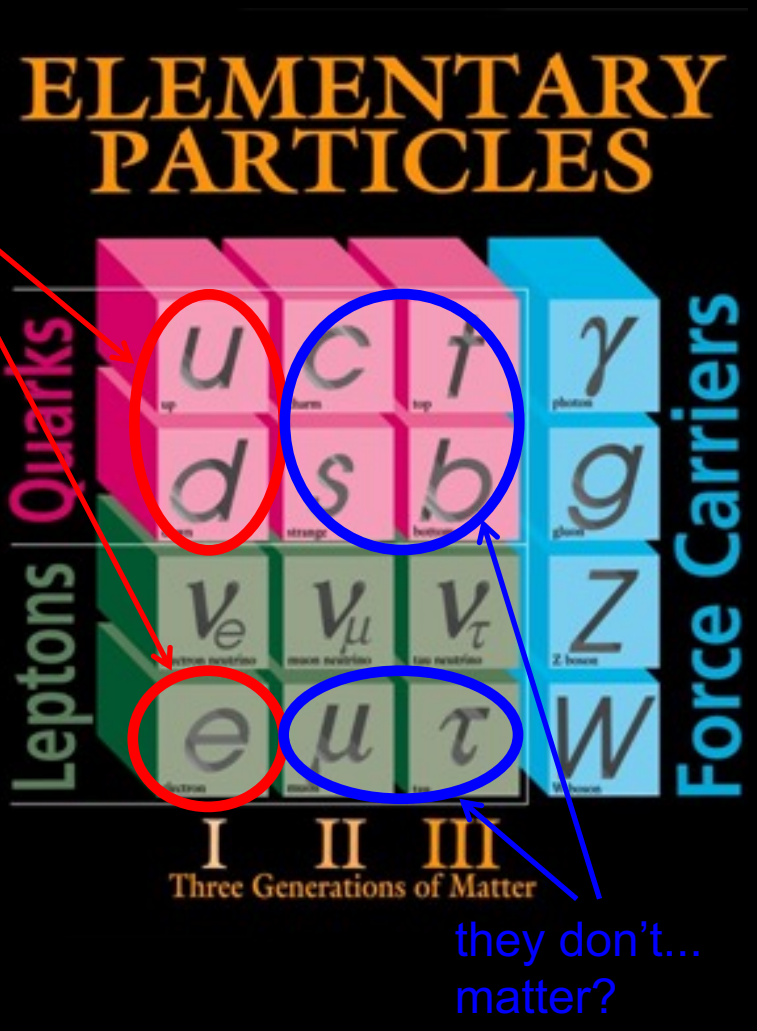

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today's talk

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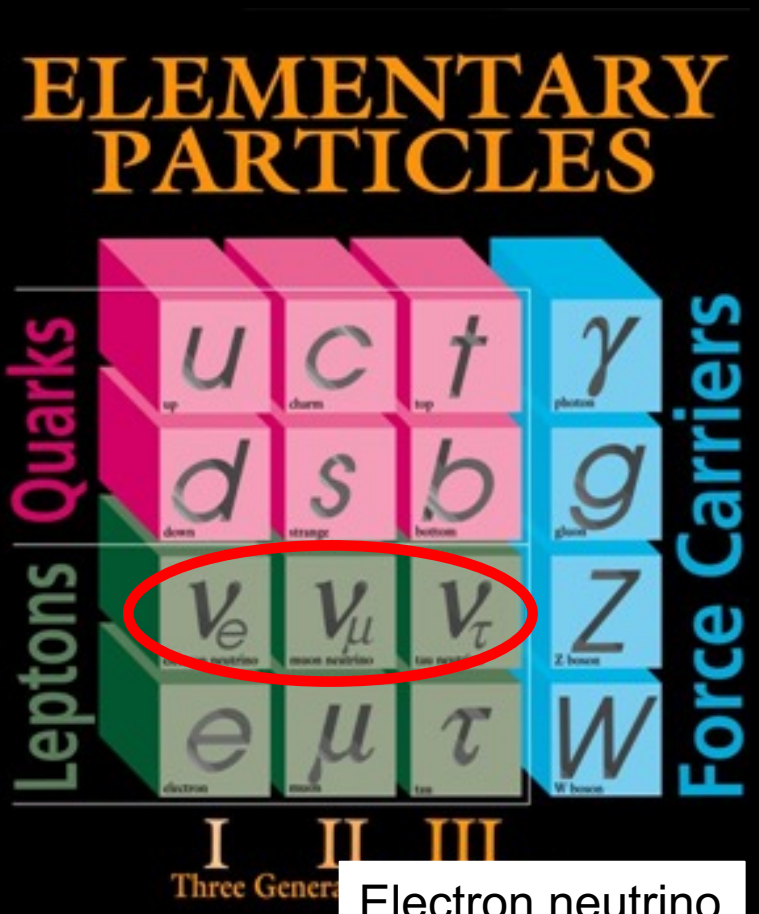

Electron neutrino
Muon neutrino
Tau neutrino

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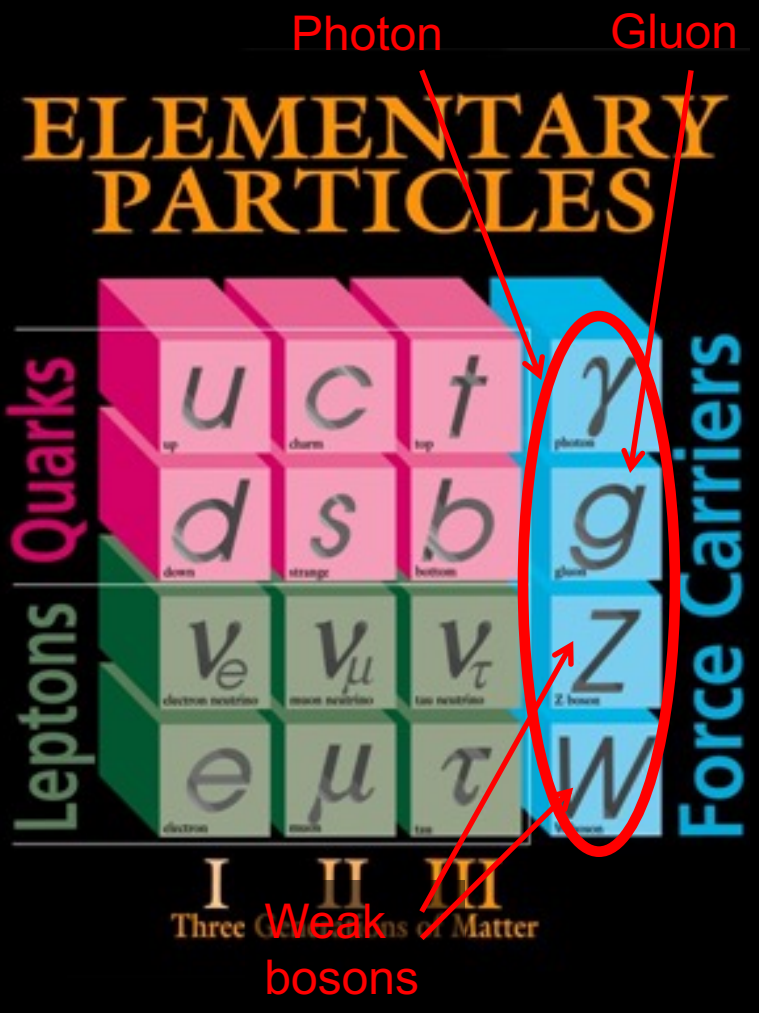

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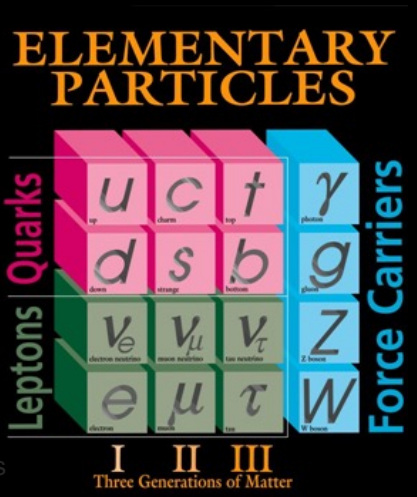

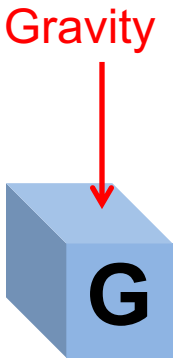

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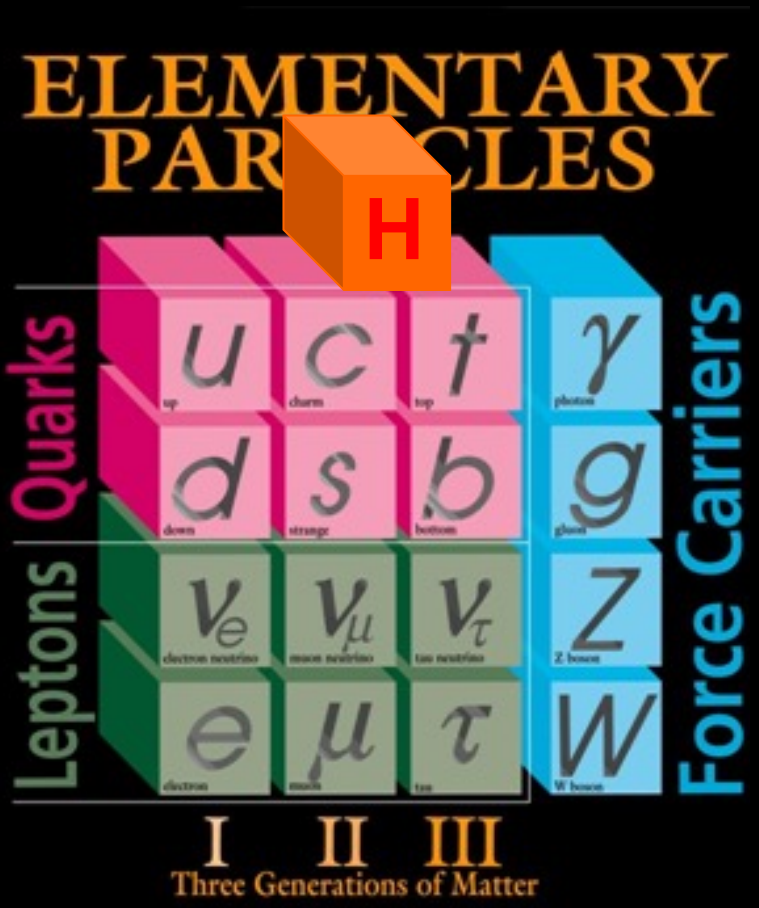

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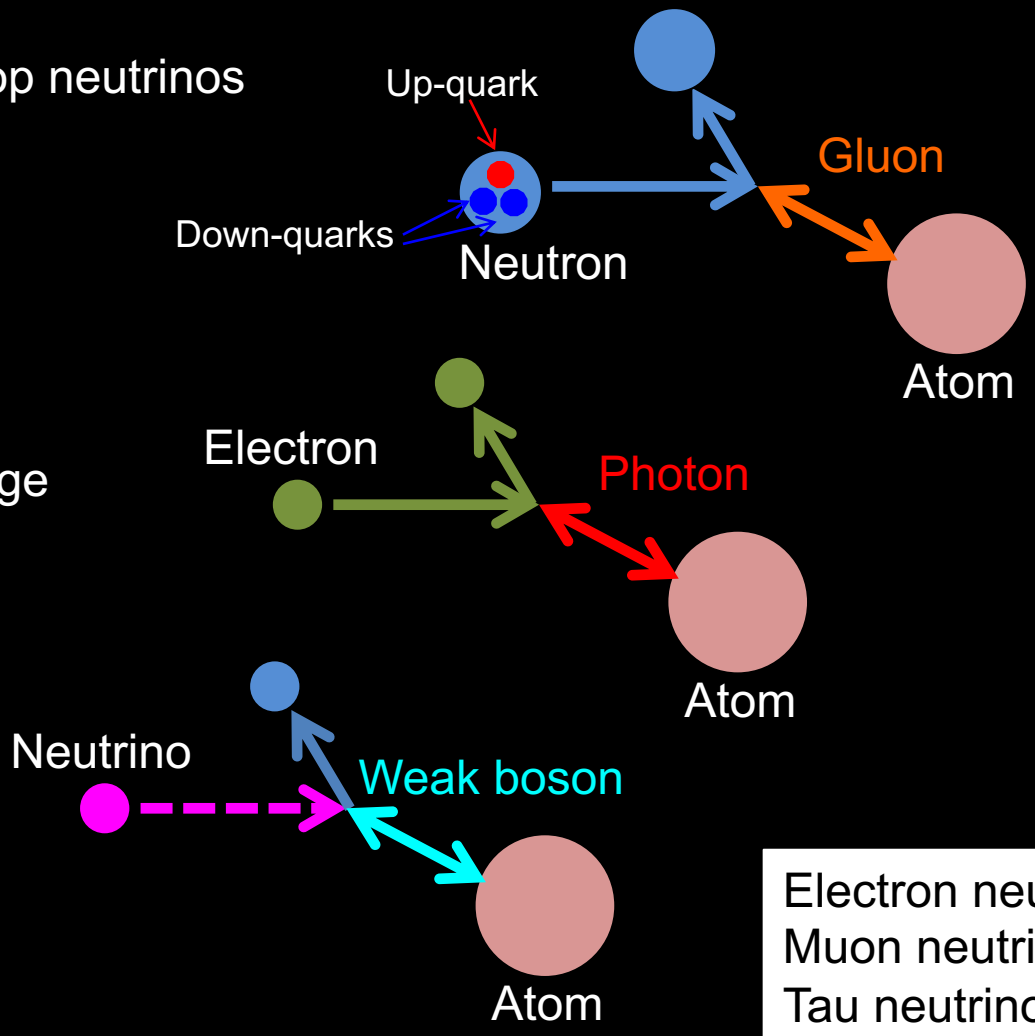
Neutrinos, Ghost particles

3 types of neutrinos
- Extremely difficult to stop neutrinos

- Quarks exchange
  - Gluons, or
  - Photons, or
  - Weak bosons

- Charged leptons exchange
  - Photons, or
  - Weak bosons

- Neutrinos exchange
  - Weak bosons



Electron neutrino
Muon neutrino
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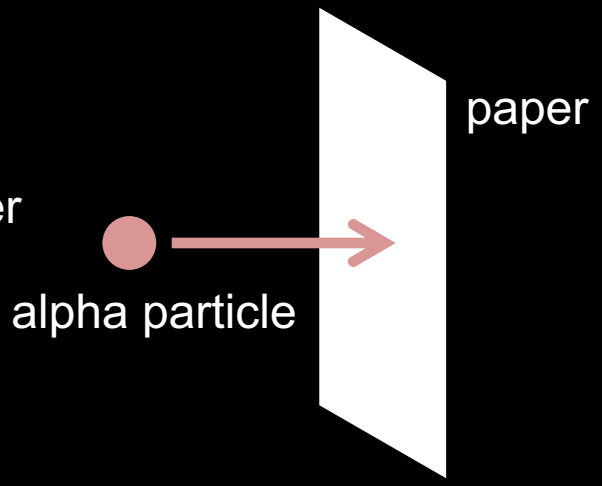
Neutrinos, Ghost particles

3 types of neutrinos
- Extremely difficult to stop neutrinos

Example: how to stop particles?
- Alpha particle (nuclei of Helium) → sheet of paper
- Beta particle (electron) → sheet of copper
- Gamma particle (photon) → chunk of lead
- Neutrino…?



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Example: how to stop particles?
- Alpha particle (nuclei of Helium) → sheet of paper
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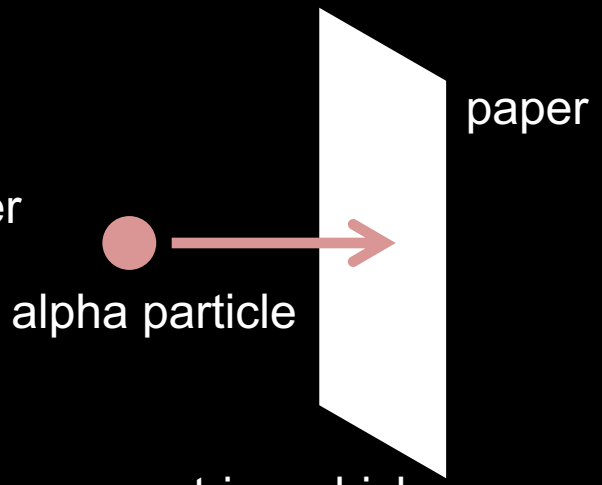
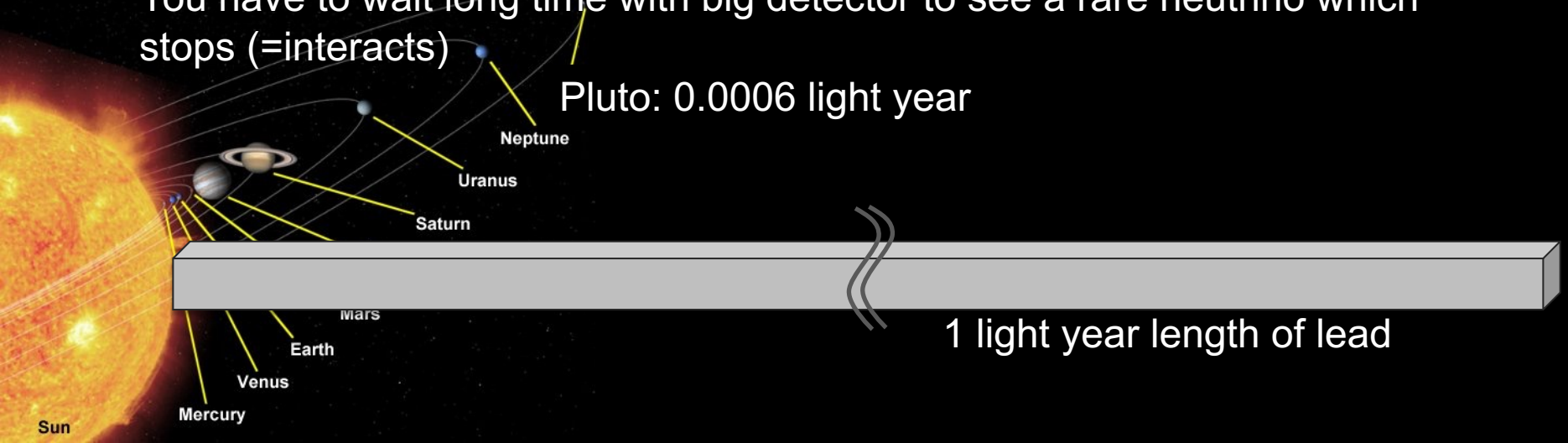
- Neutrino → 1 light year thickness of lead



You have to wait long time with big detector to see a rare neutrino which stops (=interacts)



Neutrinos, Ghost particles

3 types of neutrinos
- Extremely difficult to stop neutrinos

Neutrinos are everywhere, but they penetrate everything without leaving any traces.

Solar neutrinos
- 60 billion electron neutrinos from the Sun pass through every 1cm^2 of the Earth every second. However you have only a 25% chance for a neutrino to interact with your body in your lifetime.

Big bang neutrinos
- Every place in the Universe has ~330 neutrinos/cm^3 made by the Big Bang. Neutrinos are the second most abundant particle in the universe (photons~410/cm^3).

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Neutrinos, Ghost particles

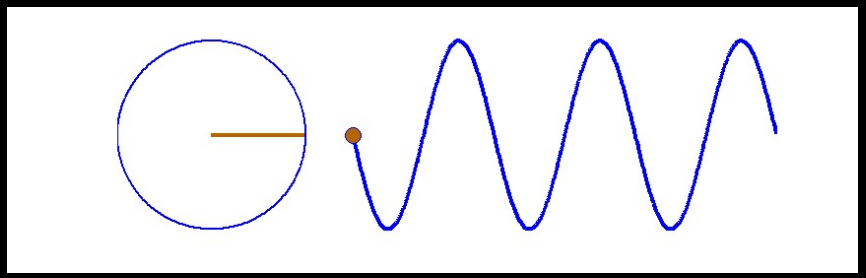
3 types of neutrinos
- Extremely difficult to stop neutrinos
- Extremely small mass

Tiny mass of weakly interacting neutrino cannot be measured by traditional methods, it can be measured only by neutrino oscillation, with a help of quantum mechanics

Neutrino Oscillations

Neutrinos obey quantum mechanics
- Neutrino is a particle, and a wave (wave-particle duality)

Plane wave looks like a wave



Wave packet looks like a particle

Neutrino Oscillations

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- State of neutrinos are not well-defined in space and time (Schrödinger's cat)

Schrödinger's cat
- There is a cat, a poison release device, and a radioactive material in the box. There is a 50% chance a nucleus in this radioactive material decays within a certain time, then this triggers the device to release the poison to kill the cat.

Quantum mechanically,

$$|Atom\rangle = |Decay\rangle + |Not\ decay\rangle$$

But in reality,

$$|Cat\rangle = |Dead\rangle + |Alive\rangle$$

But a cat cannot be Dead AND Alive!

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The state of neutrino

$$|\nu_\mu\rangle = |\nu_1\rangle + |\nu_2\rangle$$

Neutrino we observe

Neutrinos which propagate in space

Neutrino flavor eigenstate is not simultaneous eigenstate with Hamiltonian eigenstate

Neutrino Oscillations

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- Type of neutrino is not conserved with time
- If so, neutrinos have masses

Creation → Propagation → Propagation → Propagation… → Detection

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muon neutrino
electron neutrino

neutrino 1
neutrino 2

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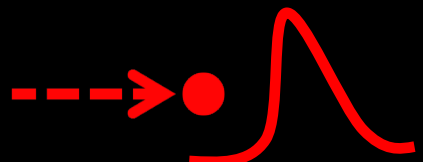

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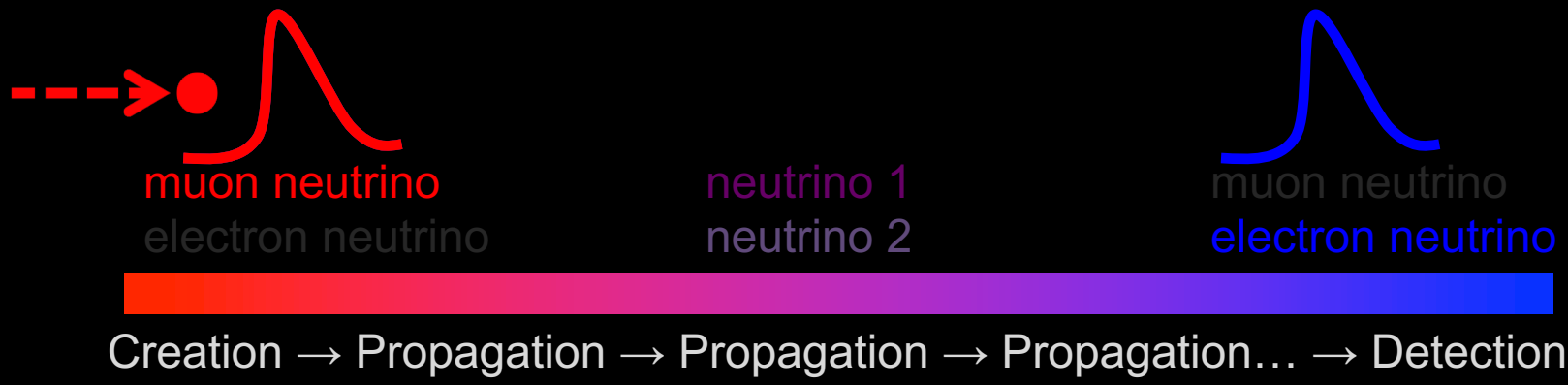

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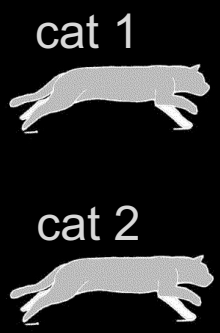

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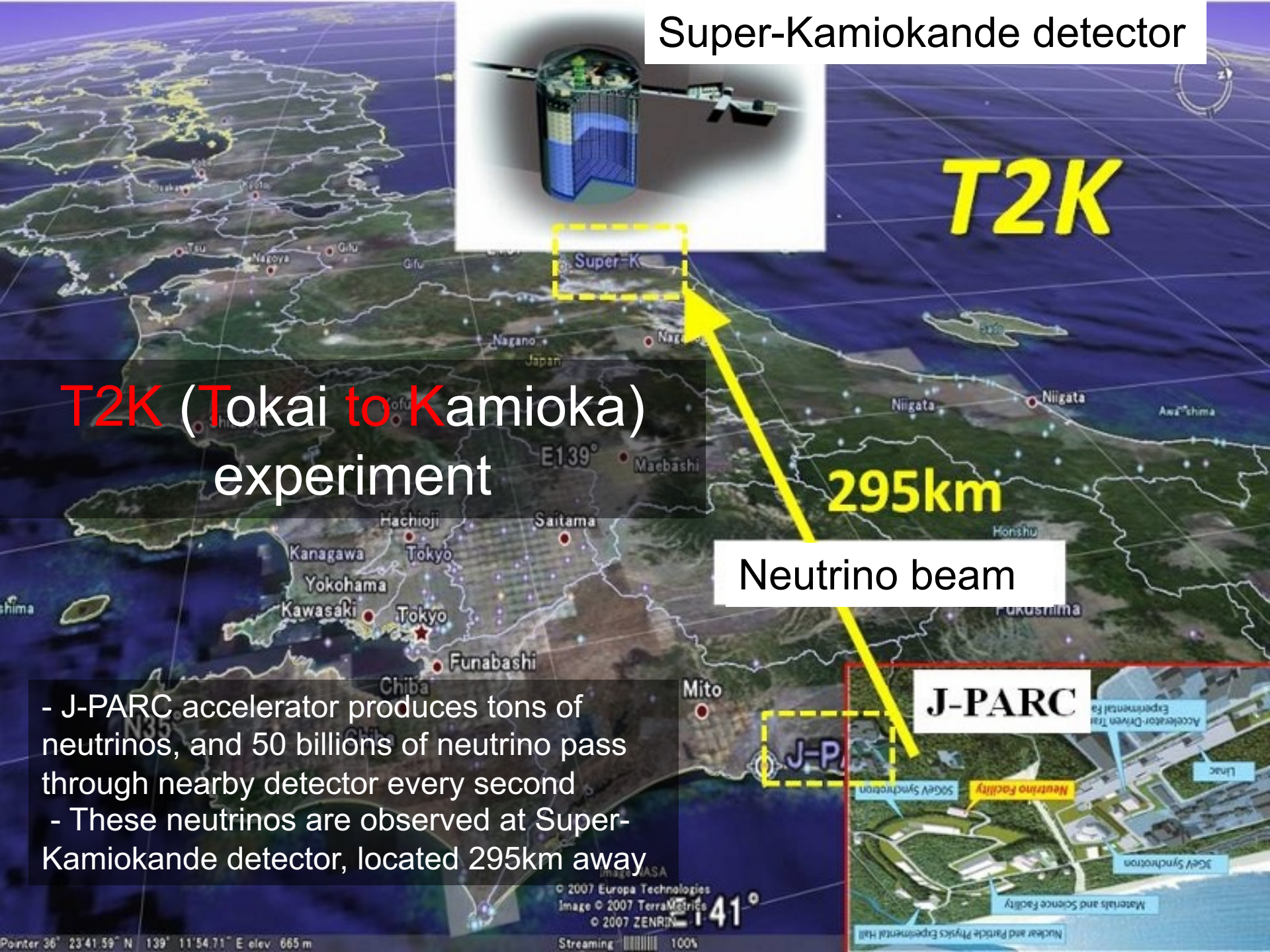
Creation → Propagation → Propagation → Propagation… → Detection


Super-Kamiokande detector
T2K
T2K (Tokai to Kamioka) experiment
295km
Neutrino beam
- J-PARC accelerator produces tons of neutrinos, and 50 billions of neutrino pass through nearby detector every second
- These neutrinos are observed at Super-Kamiokande detector, located 295km away
J-PARC
Super-K
Nagoya
Nagano
Niigata
Maebashi
Hachioji
Saitama
Kanagawa
Tokyo
Yokohama
Kawasaki
Funabashi
Chiba
Mito
Honshu
E139°
E141°
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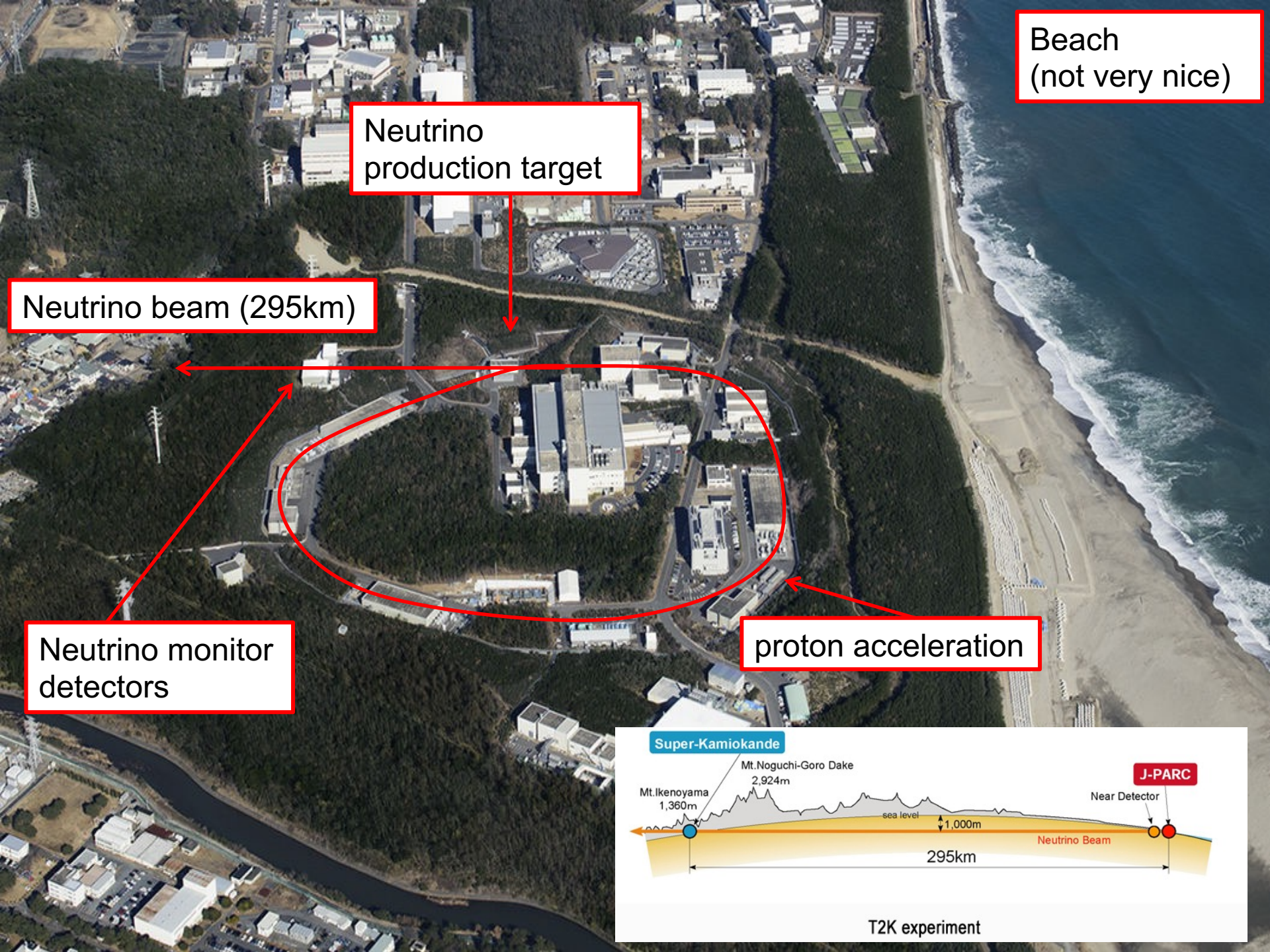
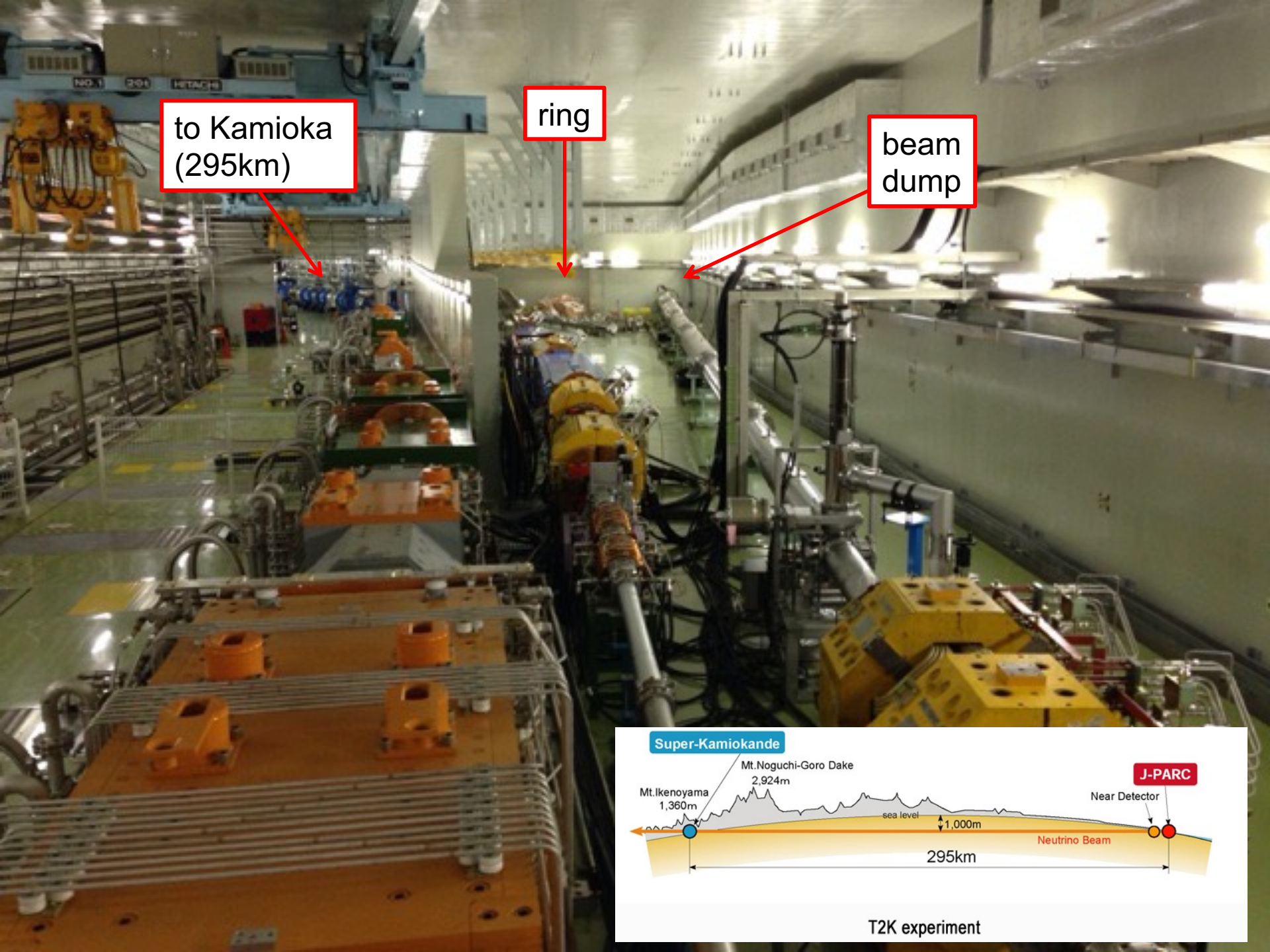

Beach
(not very nice)
Neutrino
production target
Neutrino beam (295km)
Neutrino monitor
detectors
proton acceleration
Super-Kamiokande
Mt.Noguchi-Goro Dake
2,924m
Mt.Ikenoyama
1,360m
J-PARC
Near Detector
sea level
1,000m
Neutrino Beam
295km
T2K experiment


to Kamioka
(295km)
ring
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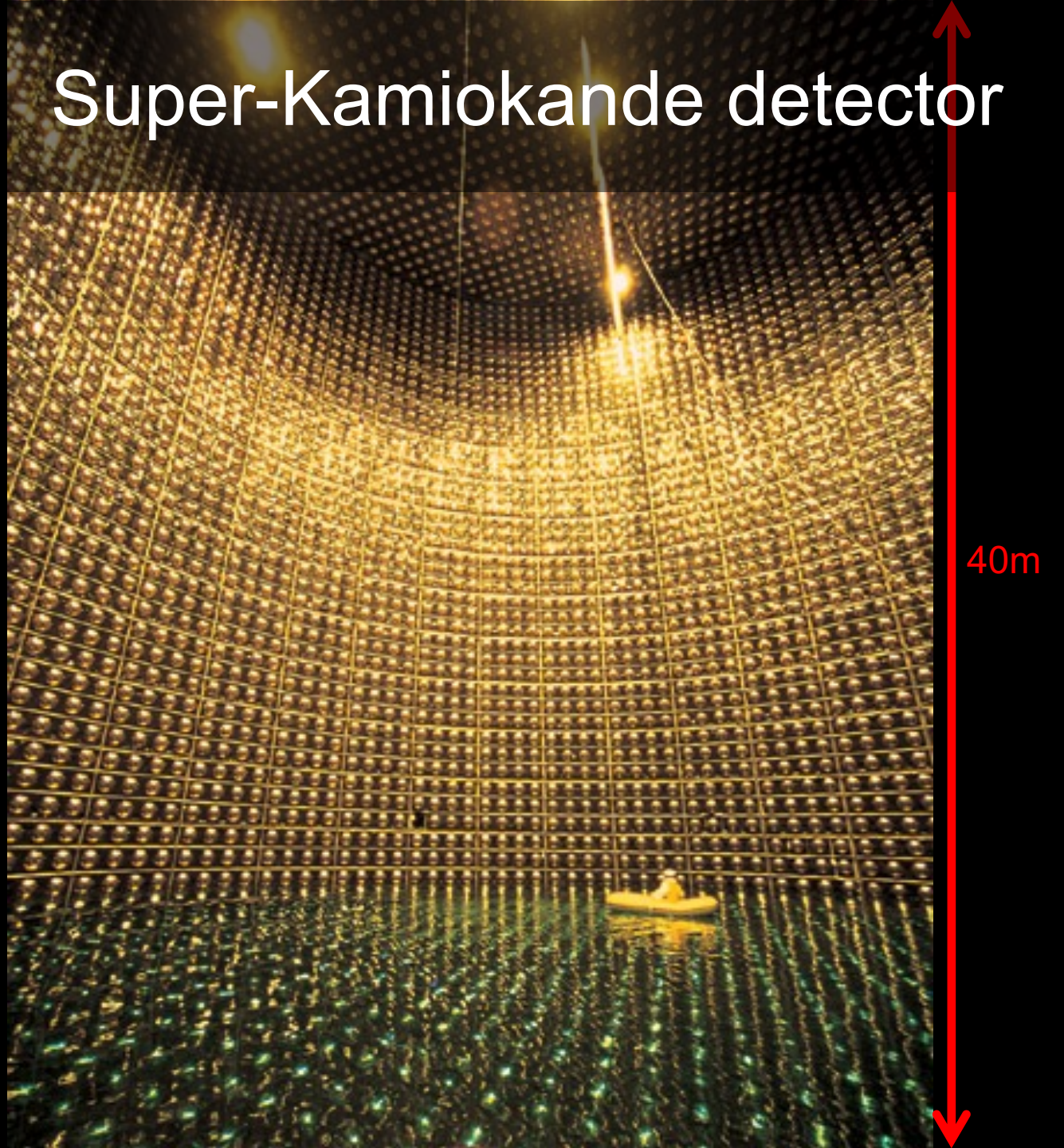
T2K experiment

40m height, 40m wide, 50k ton of pure water to observe neutrinos

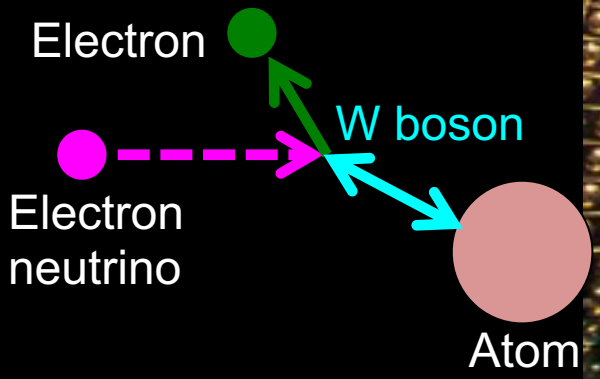
Super-Kamiokande detector

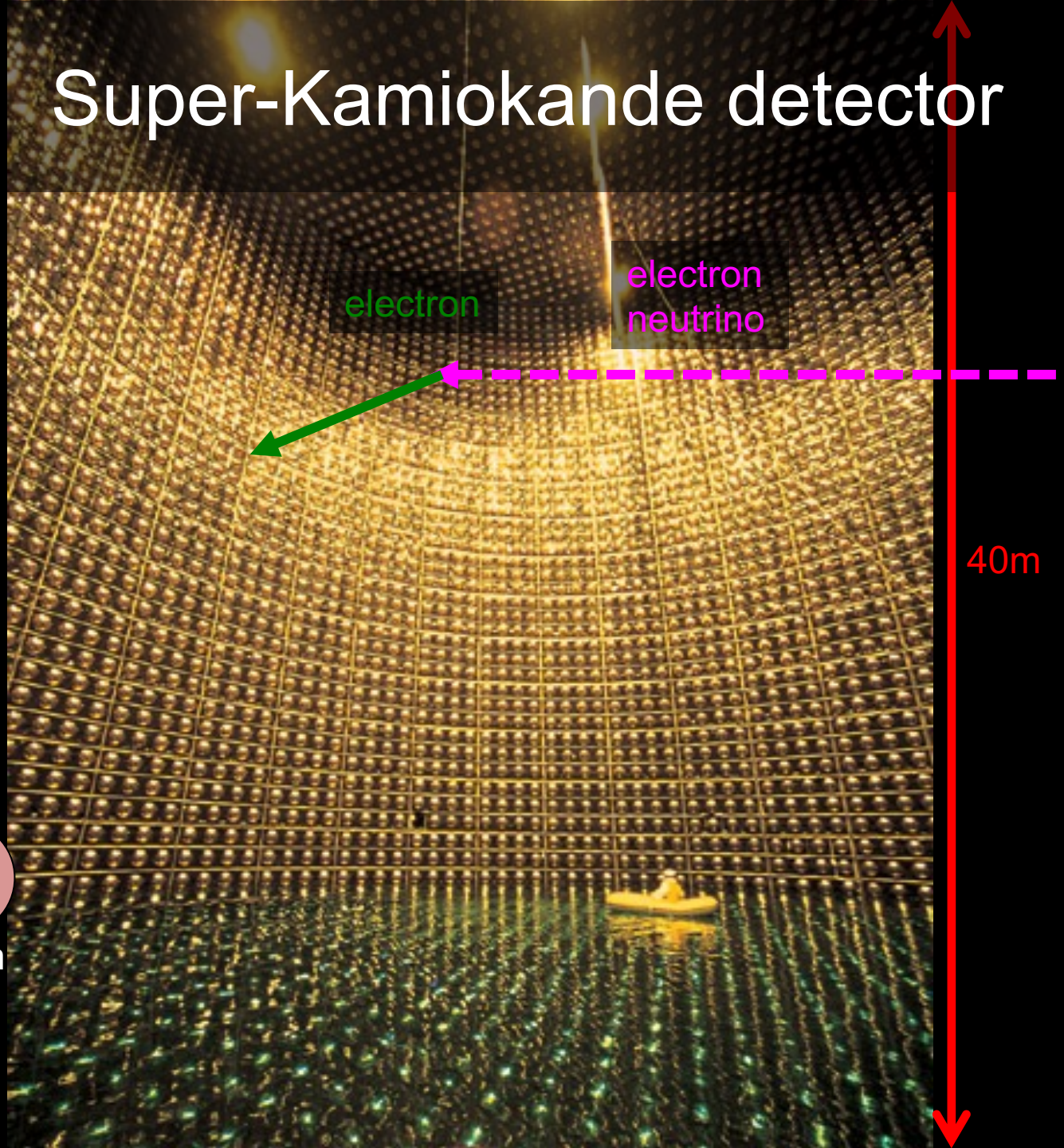


Super-Kamiokande detector

40m height, 40m wide, 50k ton of pure water to observe neutrinos

Neutrinos interact with water molecules, and produce charged particles





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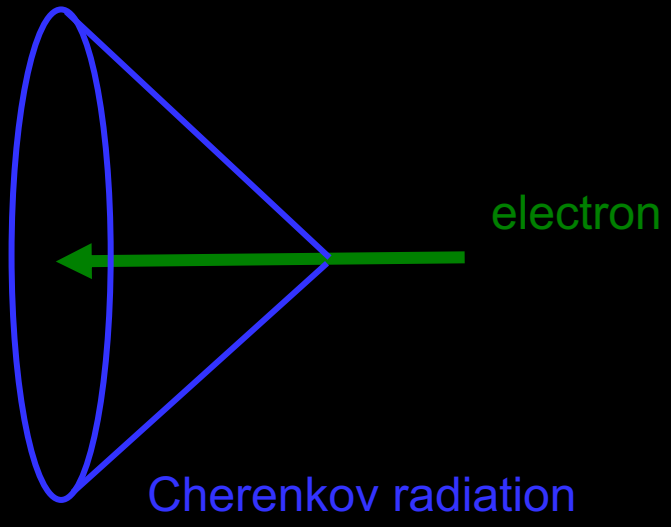
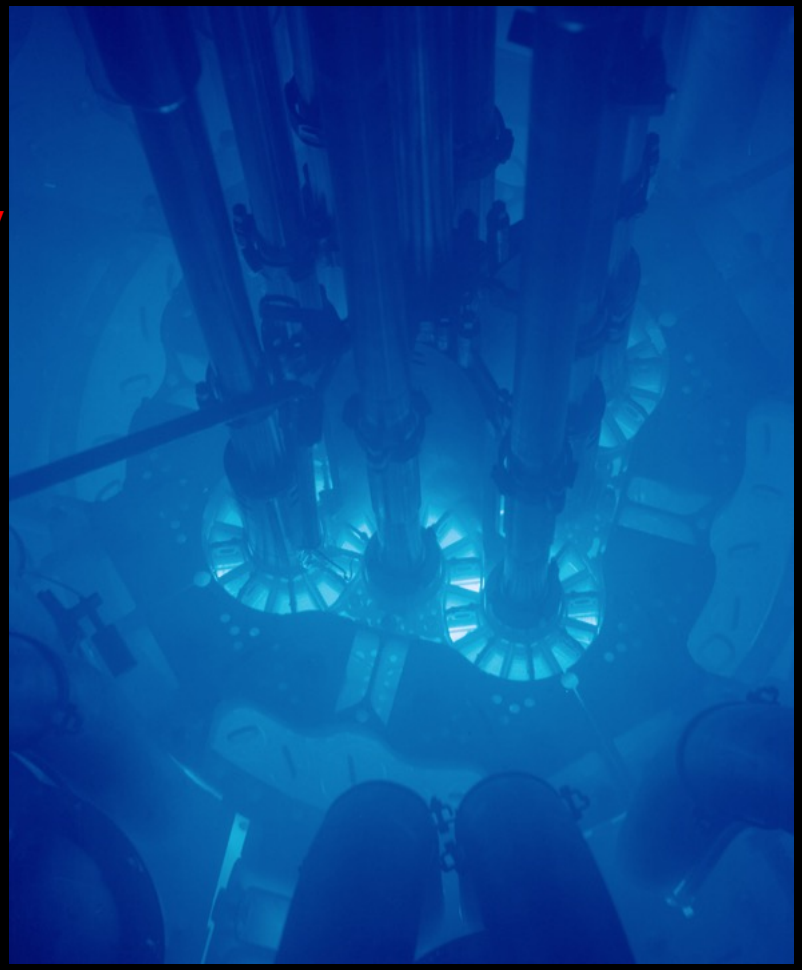
Cherenkov radiation

Speed of light is slower in media (=water), so high-energy charged particles could move faster than light

Particles emit sonic boom of light, Cherenkov radiations, to slow down in media.

The emission has characteristic cone shape (peak in blue spectrum in water)





Blue light in nuclear reactors are Cherenkov radiations from electrons

Super-Kamiokande detector

40m height, 40m wide, 50k ton of pure water to observe neutrinos

Neutrinos interact with water molecules, and produce charged particles

Charged particles produce Cherenkov radiations

11,000 of photo-multiplier tubes (PMTs) covered on the wall detect Cherenkov photons from Cherenkov radiation

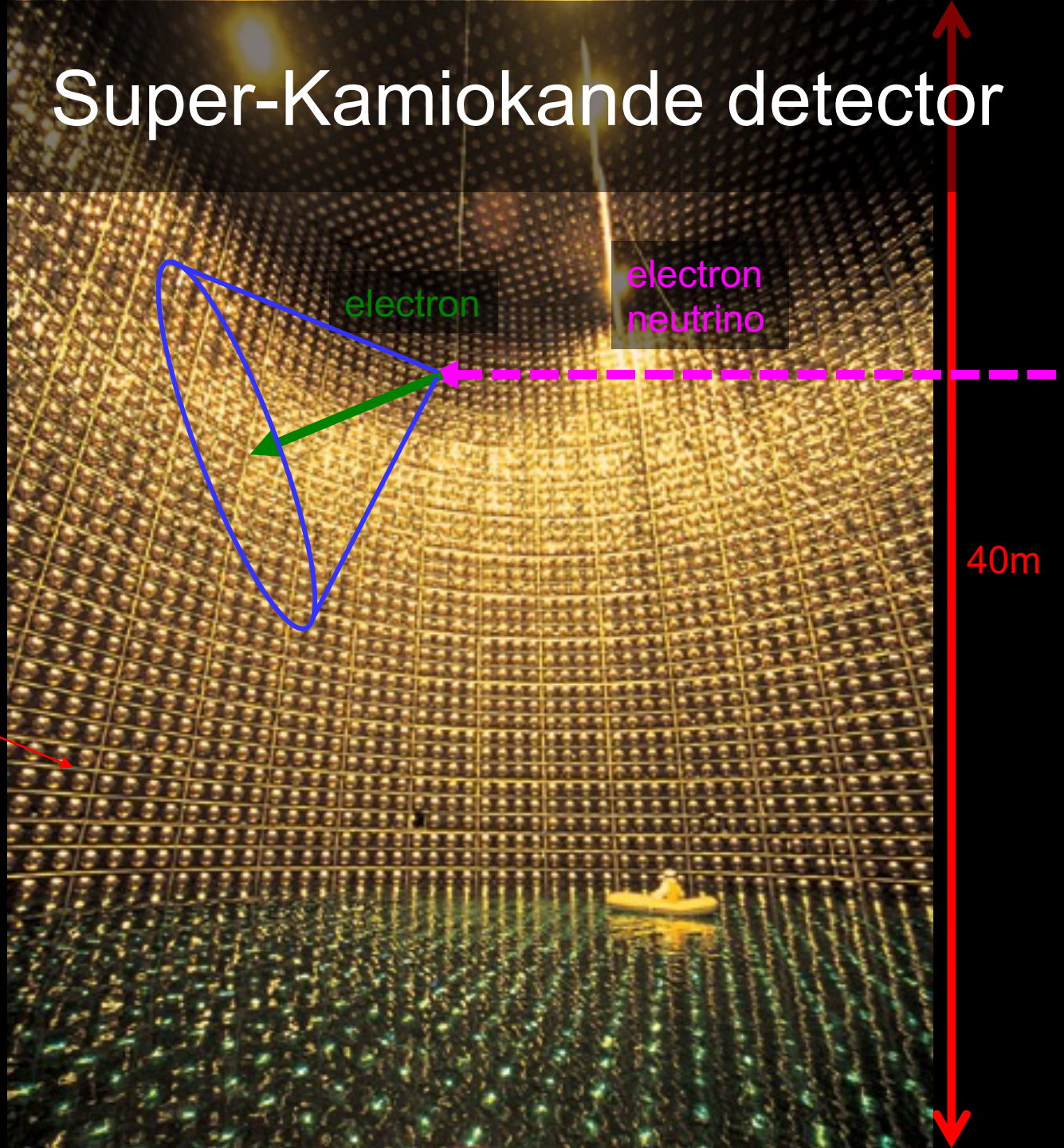


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Photo-multiplier tubes (PMTs)

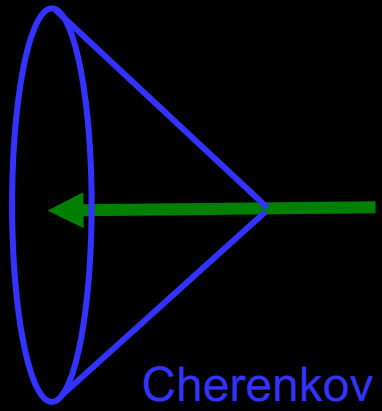
Charged particles make only several photons

Number of photons

10^0 10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} (/cm^2)

10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^0 10^2 10^4 10^6 (Lux)

Cherenkov radiation from 1 charged lepton




New moon


Full moon


Cloudy London


Desk lamp


Sunny Brighton

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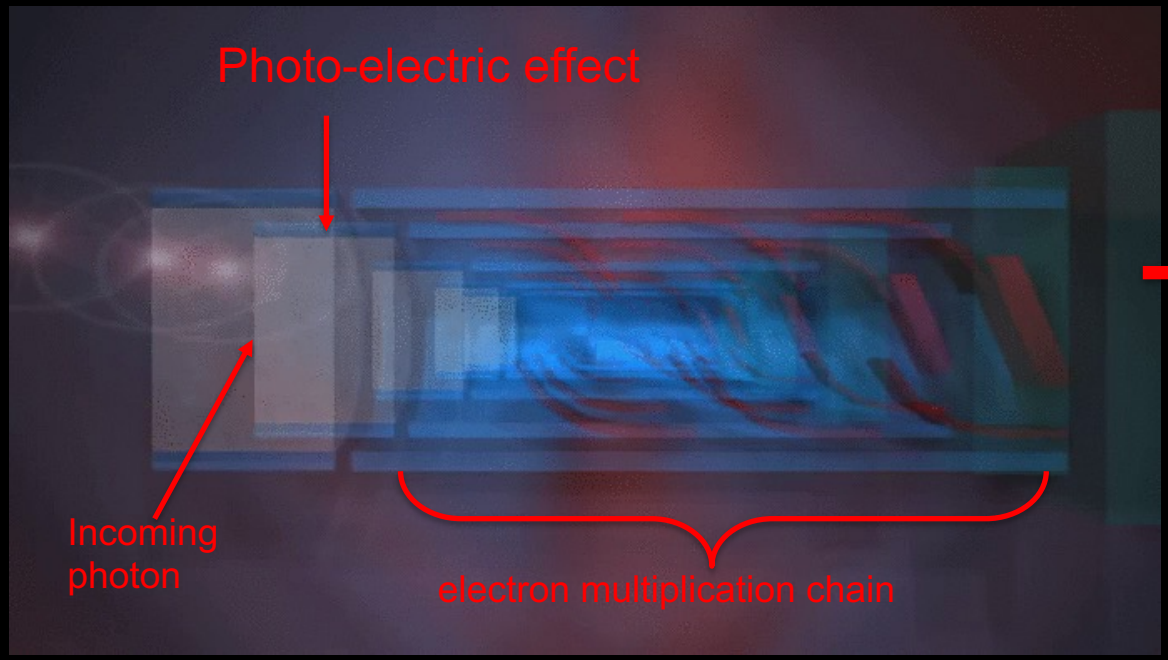
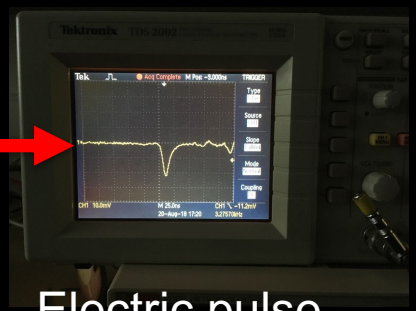
Photo-multiplier tubes (PMTs)

Charged particles make only several photons

Photo-multiplier tube converts photons to electrons by photo-electric effect

High-voltage accelerates electrons to collide on metallic place to release more electrons. This process repeats, and produce ~10^7 electrons from a photon, and strong electric pulse is produced and observed





Electric pulse (signal)

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Particle Physicists = Jack of all trades

Charged particles make only several photons

Photo-multiplier tube converts photons to electrons by photo-electric effect

High-voltage accelerates electrons to collide on metallic place to release more electrons. This process repeats, and produce ~10^7 electrons from a photon, and strong electric pulse is produced and observed

Particle physics

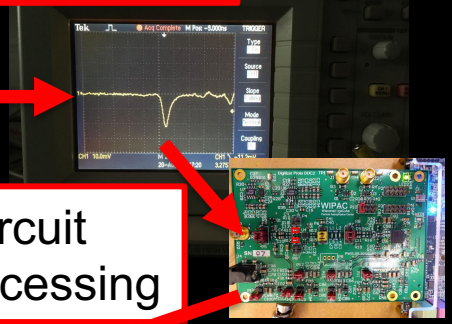
Photo-electric effect

Material science

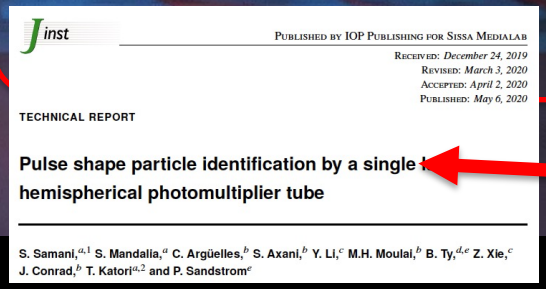
Signal transmission
Analog signal circuit

Quantum mechanics

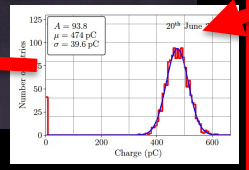
Electromagnetism



Digital circuit
Data processing



Scientific writing
Editing
Graphic



Simulation
Programming
Statistical analysis

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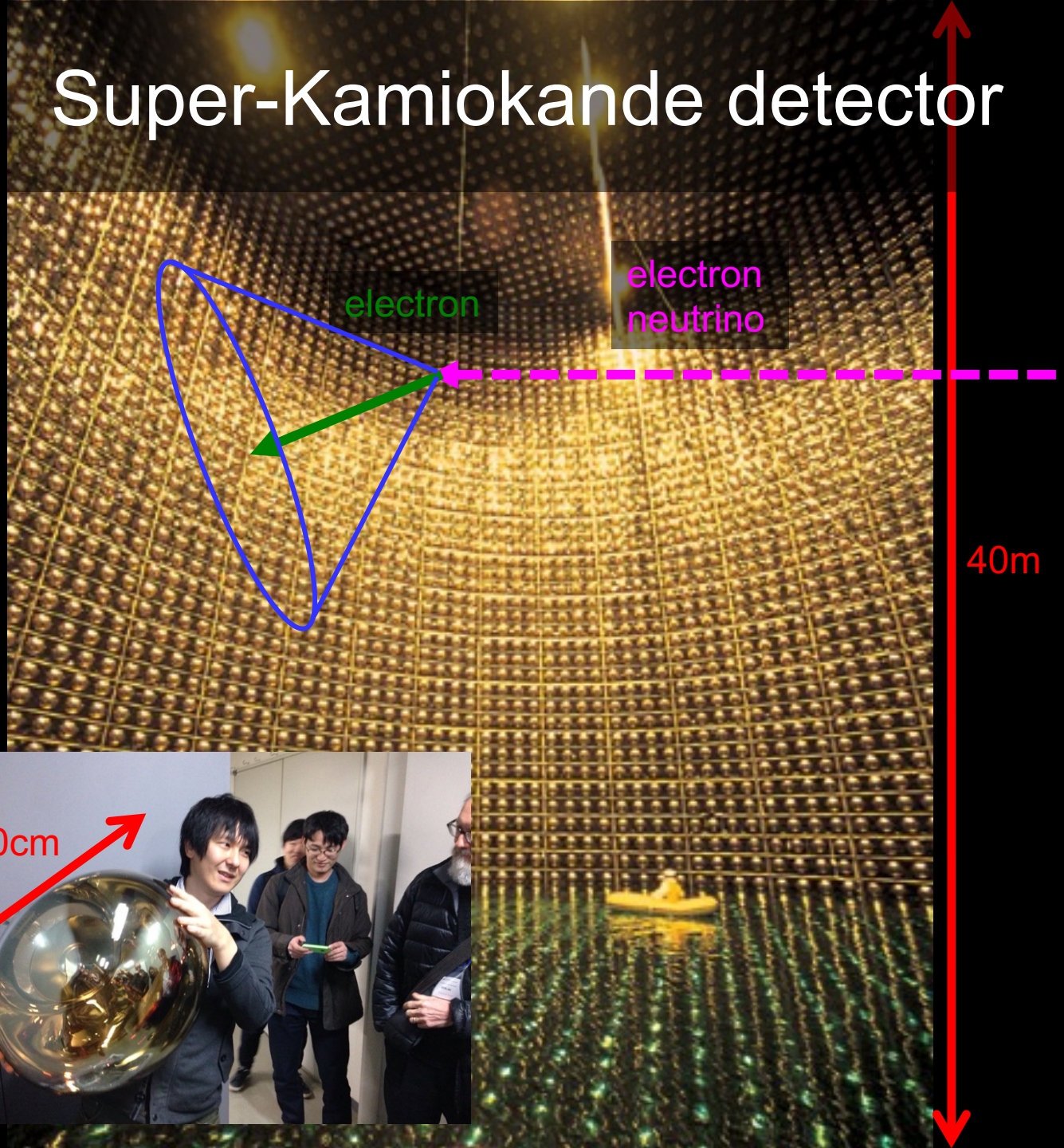
Super-Kamiokande detector

40m height, 40m wide, 50k ton of pure water to observe neutrinos

Neutrinos interact with water molecules, and produce charged particles

Charged particles produce Cherenkov radiations

11,000 of photo-multiplier tubes (PMTs) covered on the wall detect Cherenkov photons from Cherenkov radiation



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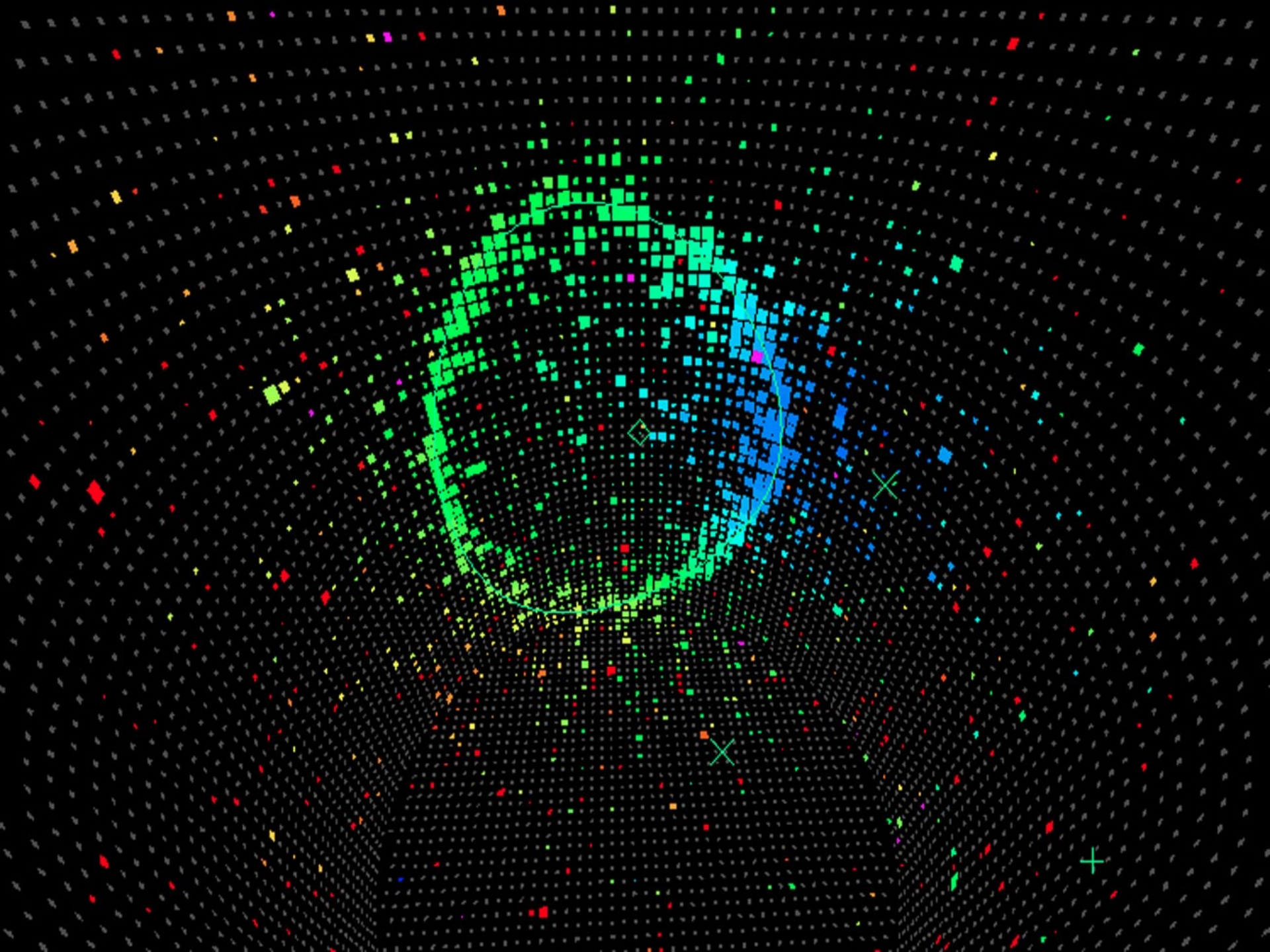

Super-Kamiokande detector

obel Prize in Physics 2015

aki Kajita, Arthur B. McDonald

Share this: 1.6K

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

40m

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Super-Kamiokande detector

obel Prize in Physics 2015

aki Kajita, Arthur B. McDonald

Share this: 1.6K

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel P

Kajita and A

oscillations,

BREAKTHROUGH PRIZE

The Nobel Prize in Physics 1988

Leon M. Lederman

Prize share: 1/3

Melvin Schwartz

Prize share: 1/3

Jack Steinberger

Prize share: 1/3

The Nobel Prize in Physics 1995

© University of California Regents

Frederick Reines

Prize share: 1/2

The Nobel Prize in Physics 2002

Raymond Davis Jr.

Prize share: 1/4

Masatoshi Koshiba

Prize share: 1/4

Kamiokande detector

Koichiro Nishikawa and the K2K and T2K Collaboration

Atsuto Suzuki and the KamLAND Collaboration

Kam-Biu Luk and the Daya Bay Collaboration

Yoichiro Suzuki and the Super K Collaboration

Yifang Wang and the Daya Bay Collaboration

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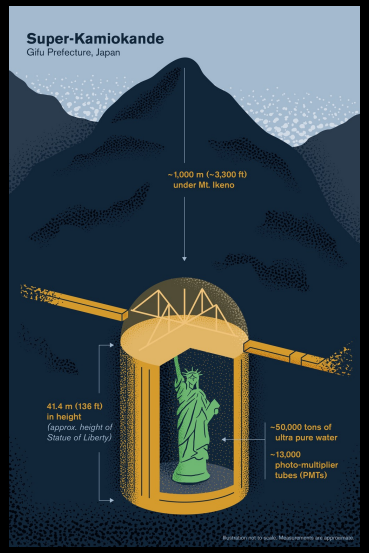
Super-Kamiokande detector

Kamioka (神岡),
Gifu prefecture (岐阜県),
Japan

Deep mountain area, and the detector is located in a former mine in the Ikenoyama mountain (池ノ山), roughly 1km from the mountain top



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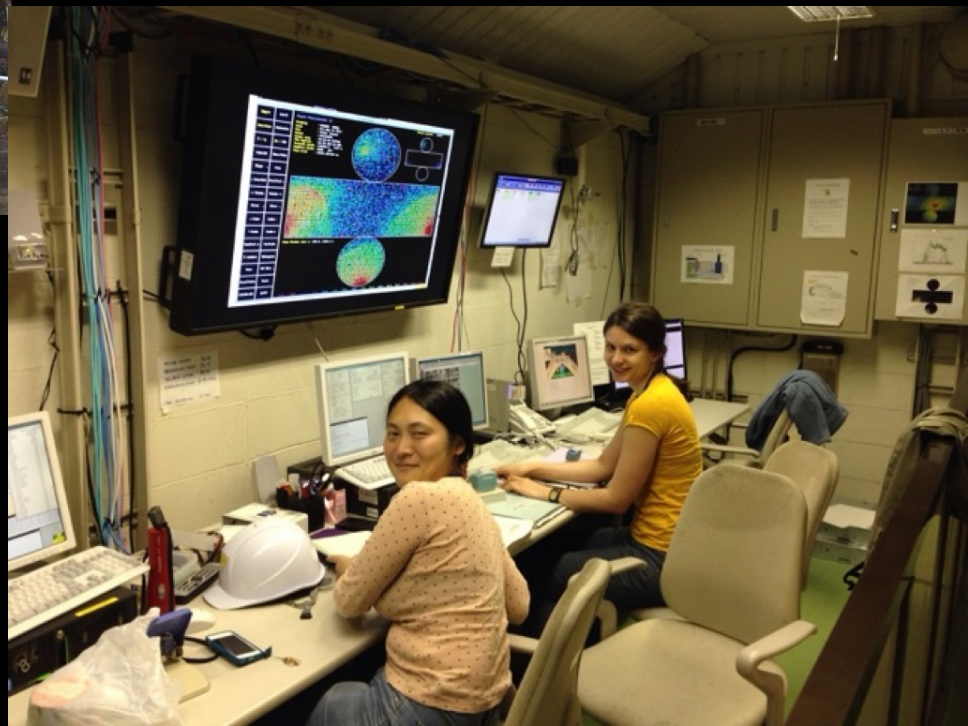
Super-Kamiokande detector



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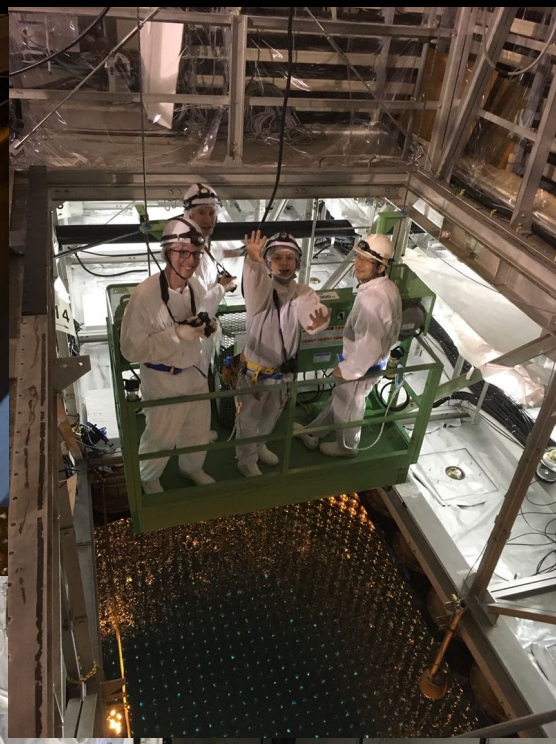
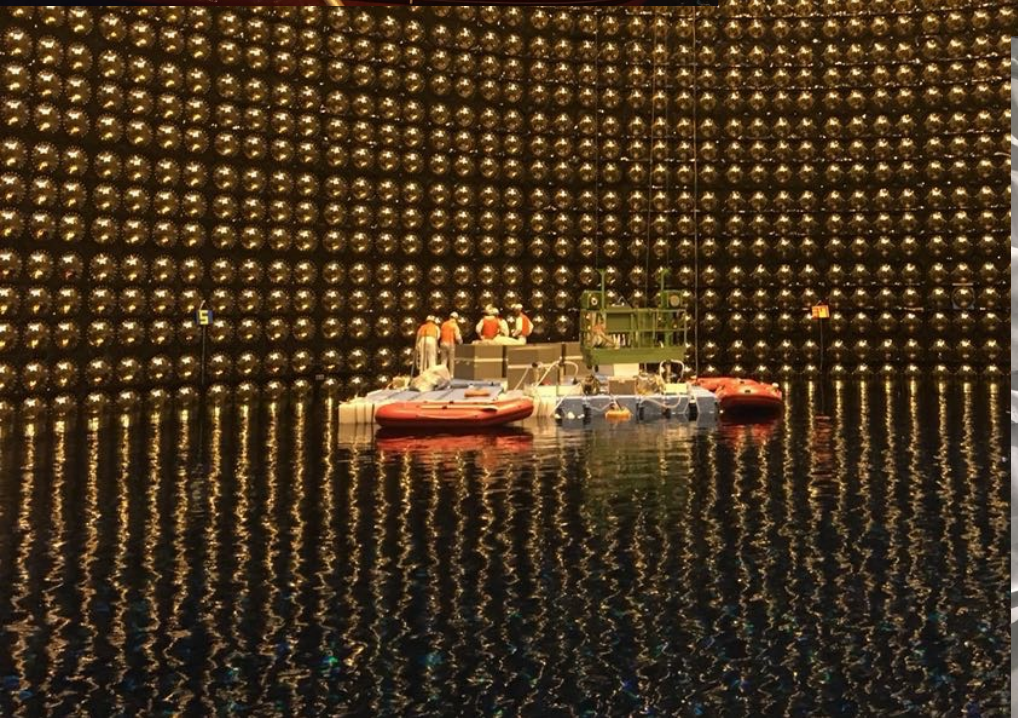
Super-Kamiokande detector refurbishment 2018

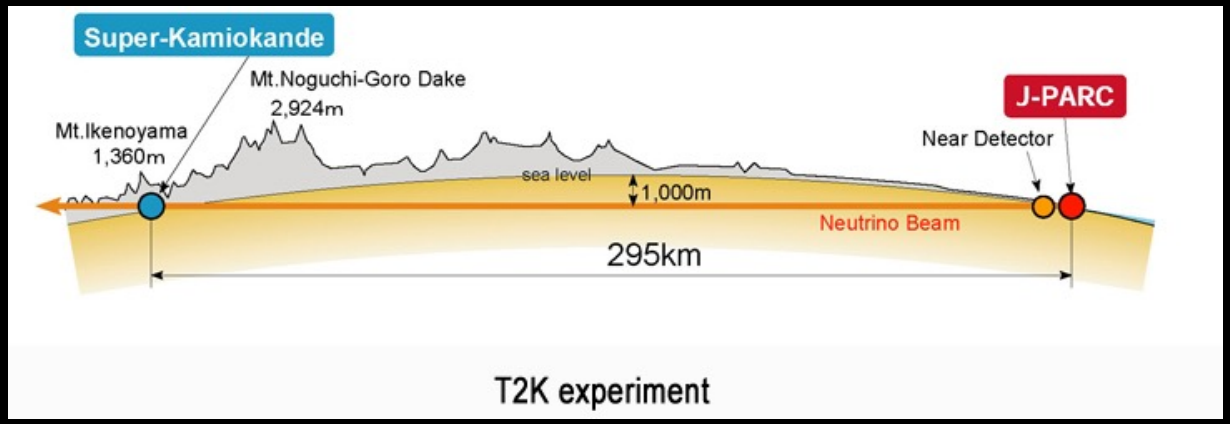




New type of neutrino oscillation is observed!

T2K experiment measured electron neutrinos from muon neutrino beam ($\nu_\mu \rightarrow \nu_e$)
T2K also measured electron anti-neutrino from muon anti-neutrino beam ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

Furthermore, these 2 neutrino oscillations look slightly different (later)



T2K experiment

Confirmation of these results need more data...

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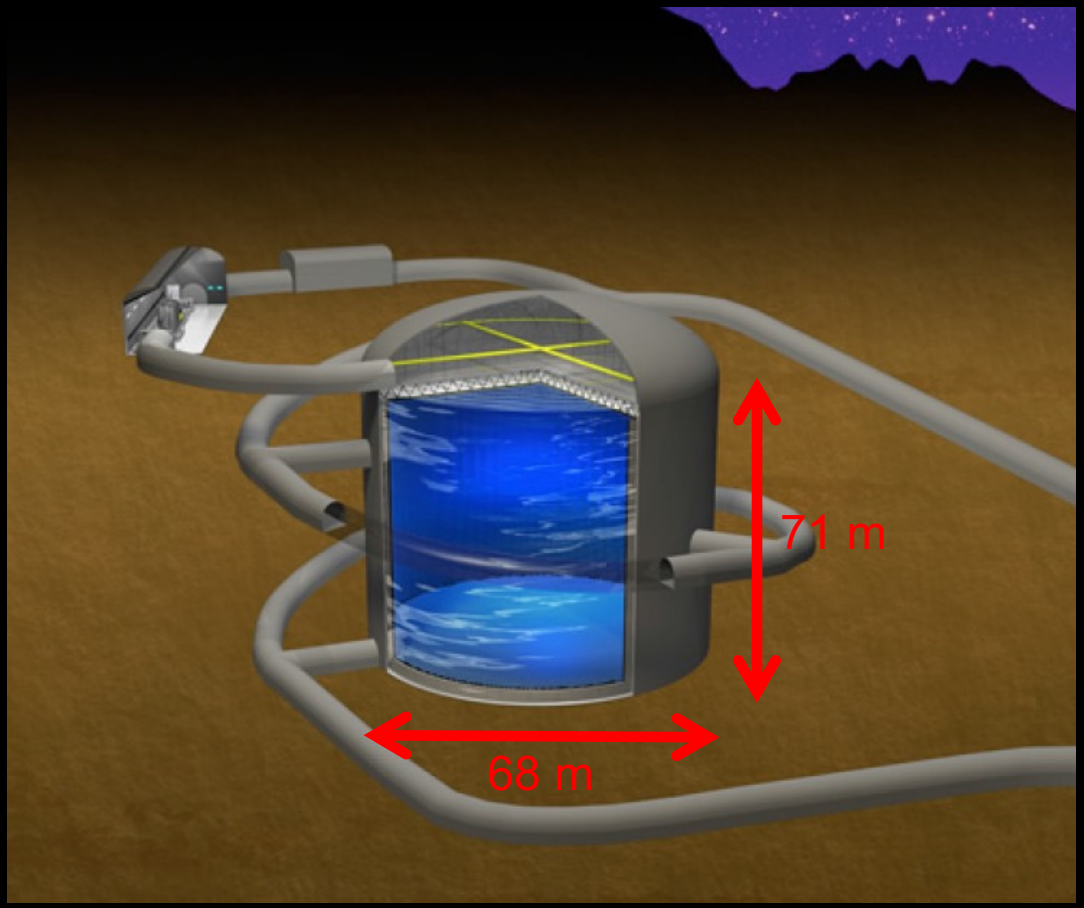
Hyper-Kamiokande detector

We are building a new 230 kton water tank

- More data to investigate the origin of matter and space-time
- It detects neutrinos from the Sun, atmosphere, supernova, etc



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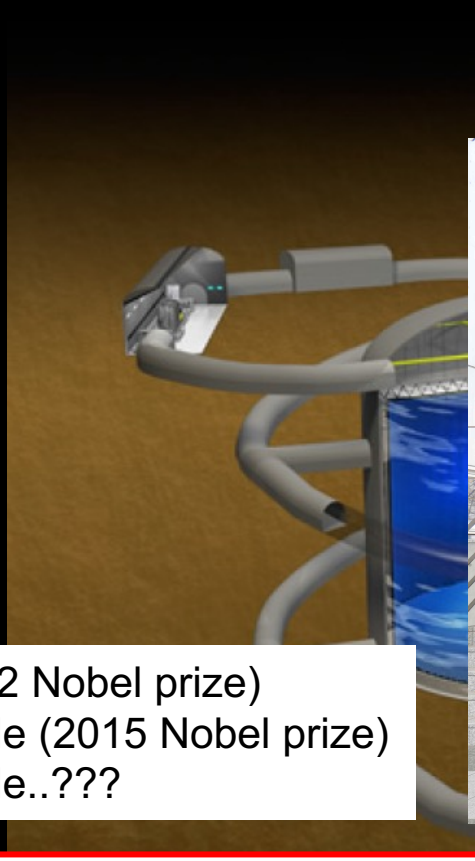

Collaboration meeting (Jan. 2020)

Kamiokande (2002 Nobel prize)
Super-Kamiokande (2015 Nobel prize)
Hyper-Kamiokande..???

KING'S College LONDON

We are moving to a new endeavor, new discovery, and new excitement!
(and more Nobel prize!)

Hyper-Kamiokande detector

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- More data to investigate th matter and space
- detects s from the mosphere, supernova,

laboration meeting (Jan. 2020)

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Super-Kamiokande (2015 Nobel prize)
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KING'S College LONDON

We are moving to a new endeavor, new discovery, and new excitement!
(and more Nobel prize!)

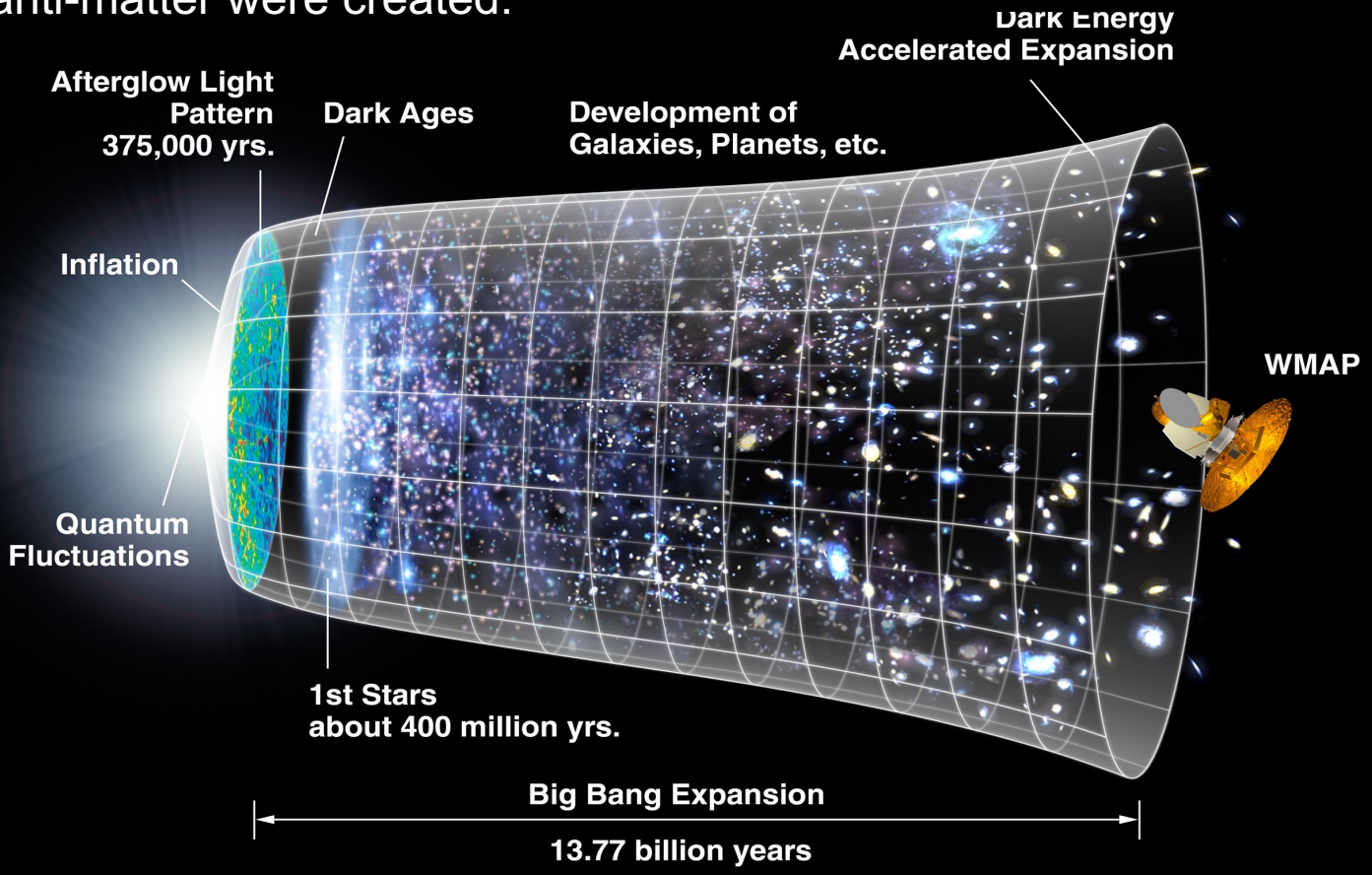
Big questions neutrinos may answer

Neutrinos may answer big questions...

- Origin of matter
- Grand Unification
- Quantum Gravity

Neutrinos and Origin of Matter

All matter was created by the energy of the Big Bang, and equal amount of matter and anti-matter were created.



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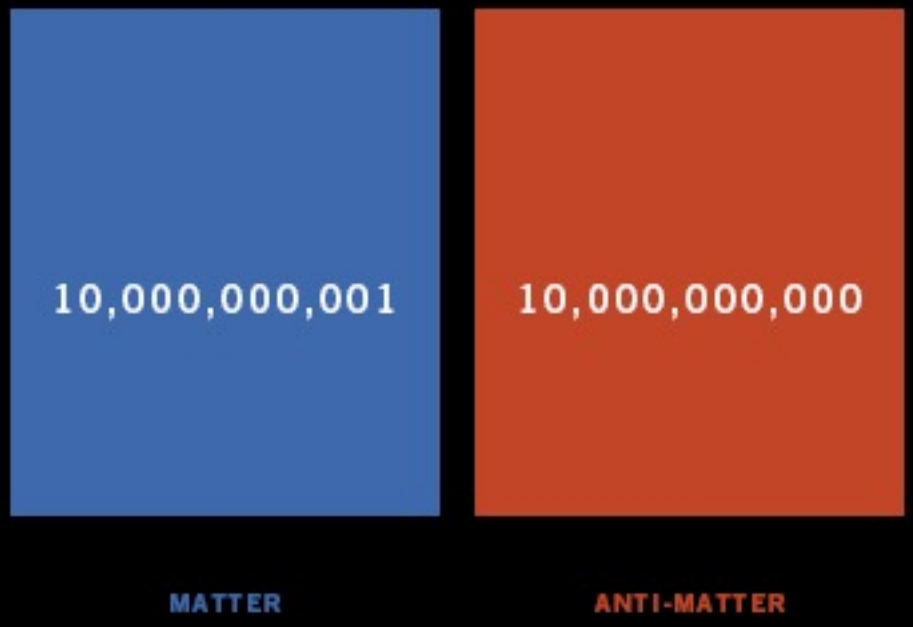
Neutrinos and Origin of Matter

Every matter was created by the energy of the Big Bang, and equal amount of matter and anti-matter were created.

But there is not anti-matter in the universe…, where are they?
In fact, slightly more matter was created than anti-matter…, Why? and how?



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Neutrinos and Origin of Matter

Every matter was created by the energy of the Big Bang, and equal amount of matter and anti-matter were created.

But there is not anti-matter in the universe…, where are they?
In fact, slightly more matter was created than anti-matter…, Why? and how?

Theorists speculate the difference of neutrino oscillations and anti-neutrino oscillations may be the key to understanding the matter-antimatter asymmetry of the universe

Recently, T2K experiment first time found an indication that these 2 oscillations are slightly different. Confirmation need more data.

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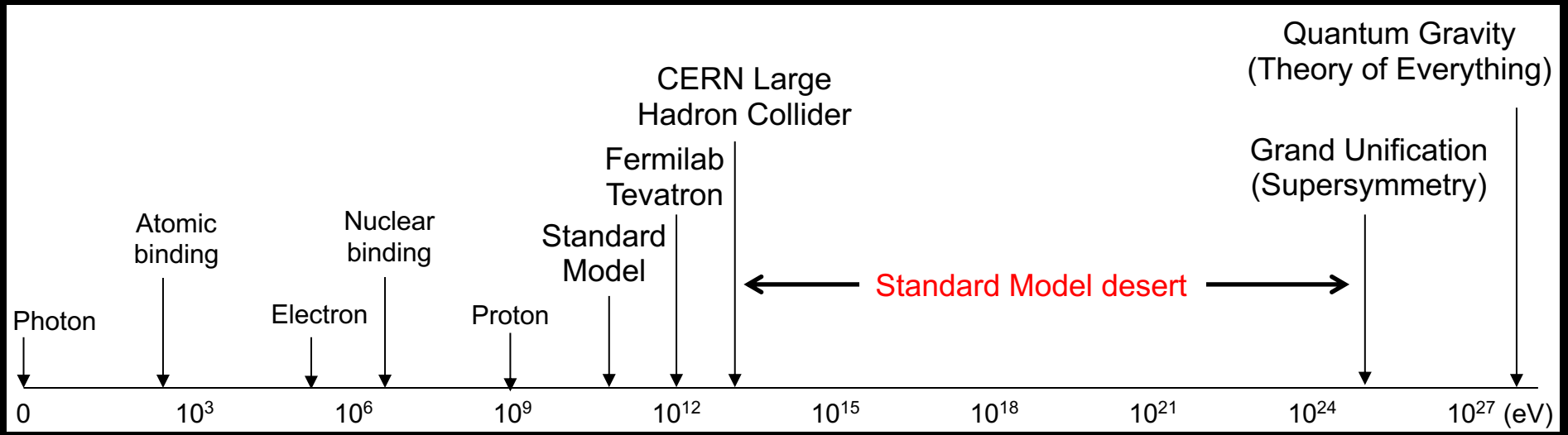
Neutrinos may be the origin of all matter in the universe (matter-antimatter asymmetry)

Neutrinos and Grand Unification Theory

- Neutrino masses are not predicted by the Standard Model
- Extremely small neutrino masses are related with Grand Unification Theory?

$$M(\text{neutrino}) \sim \frac{(\text{Energy scale of Standard Model})^2}{(\text{Energy scale of Grand unification})}$$



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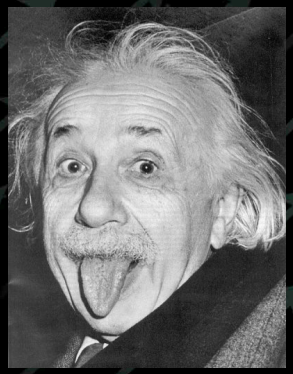
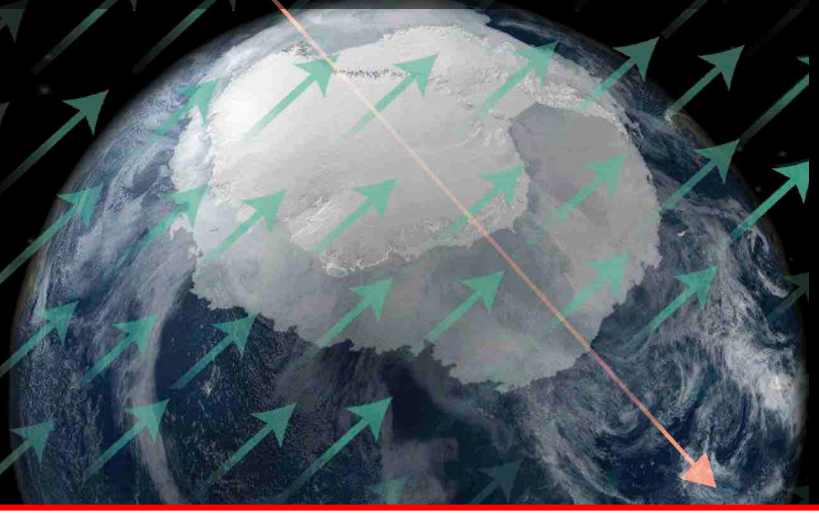
Neutrinos may be related to unification of three forces (electromagnetic force, weak nuclear force, strong nuclear force) in Standard Model?

Neutrinos and Quantum Gravity

Neutrinos from distance galaxies propagate long distance without interactions.
This feature is useful to test space-time structure (Lorentz symmetry)

- Lorentz symmetry is a perfect symmetry in Einstein's Special Relativity
- Violation of Lorentz symmetry is allowed in ultra high energy theories, such as quantum gravity theories including string theory
- If so, can astrophysical neutrinos investigate new space-time structure?
- Einstein may be wrong? Hawking may be happier?





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Using neutrinos, we experimentally investigate Theory of Everything (quantum gravity)

Neutrino projects, all over the world!

There are neutrino experiments in Belgium, Canada, China, France, Germany, India, Italy, Japan, Korea, Russia, Spain, UK, USA etc, even at the South Pole! Sometimes we compete, but mostly we are good friends!

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End

Neutrinos are ghostly elementary particles, penetrating everything

Neutrinos change species when they propagate. This is called neutrino oscillation, and this is due to small neutrino masses.

Neutrinos may be related to the origin of matter: matter-antimatter asymmetry.

Neutrinos can look for a tiny new space-time effect (violation of Lorenz symmetry)

Research of neutrinos is a new field, and all excitement continues to the future!


Back up

Neutrino applications

EUROPHYSICS LETTERS

Europhys. Lett., **60** (1), pp. 34–39 (2002)

Paper Number: IAEA-CN-184/27

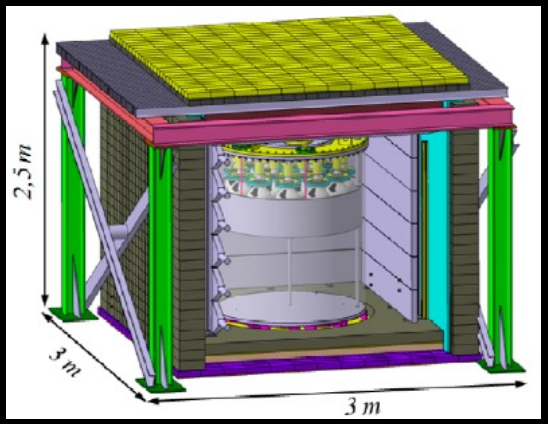
Reactor Neutrino Detection for Non Proliferation with the NUCIFER Experiment

Th. Lasserre, V.M. Bui, M. Cribier, A. Cucoanes, M. Fallot, M. Fechner, J. Gaffiot, L. Giot, R. Granelli, A. Letourneau, D. Lhuillier, J. Martino, G. Mention, D. Motta, Th.A. Mueller, A. Porta, R. Queval, J. L. Sida, C. Varignon, F. Yermia

Could one find petroleum using neutrino oscillations in matter?

T. Ohlsson(*) and W. Winter(**)

Institut für Theoretische Physik, Physik-Department, Technische Universität München James-Franck-Straße, 85748 Garching bei München, Germany



Modern Physics Letters A
Vol. 27, No. 12 (2012) 1250077 (10 pages)

DOI: 10.1142/S0217732312500770

World Scientific
www.worldscientific.com

Letters B 671 (2009) 15–19

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www.elsevier.com/locate/physletb

DEMONSTRATION OF COMMUNICATION USING NEUTRINOS

Submarine neutrino communication

Patrick Huber

Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA

Galactic neutrino communication

John G. Learned [a], Sandip Pakvasa [a,*], A. Zee [b]

[a] *Department of Physics and Astronomy, University of Hawaii, 2505 Correa Road, Honolulu, HI 96822, USA*
[b] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*

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Neutrinos, Ghost particles

3 types of neutrinos
- Extremely difficult to stop neutrinos
- Extremely small mass

Tiny mass of weakly interacting neutrino cannot be measured by traditional methods, it can be measured only by neutrino oscillation, with a help of quantum mechanics