Neutrinos: Nature's Ghost particles

Julia Gehrlein

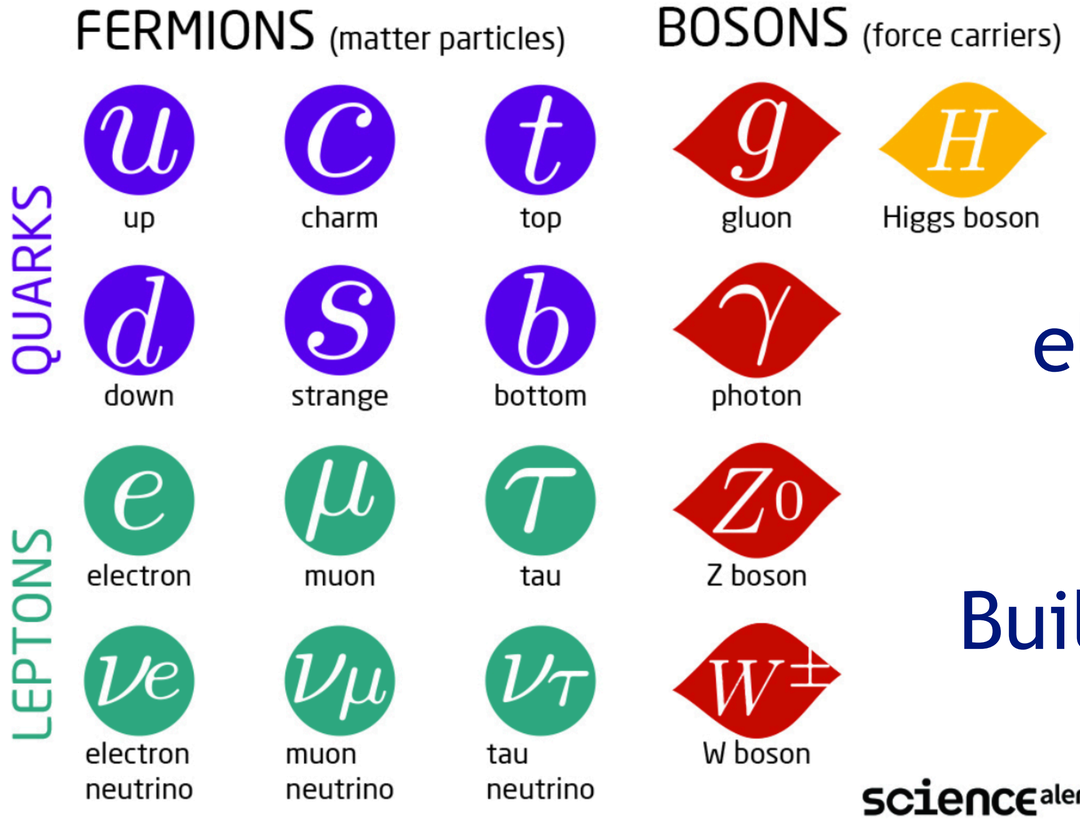
CO/WY AAPT annual section meeting

November 4 2023

COLORADO STATE UNIVERSITY

Everything around us

Current understanding of nature at smallest scales encoded in Standard Model of particle physics



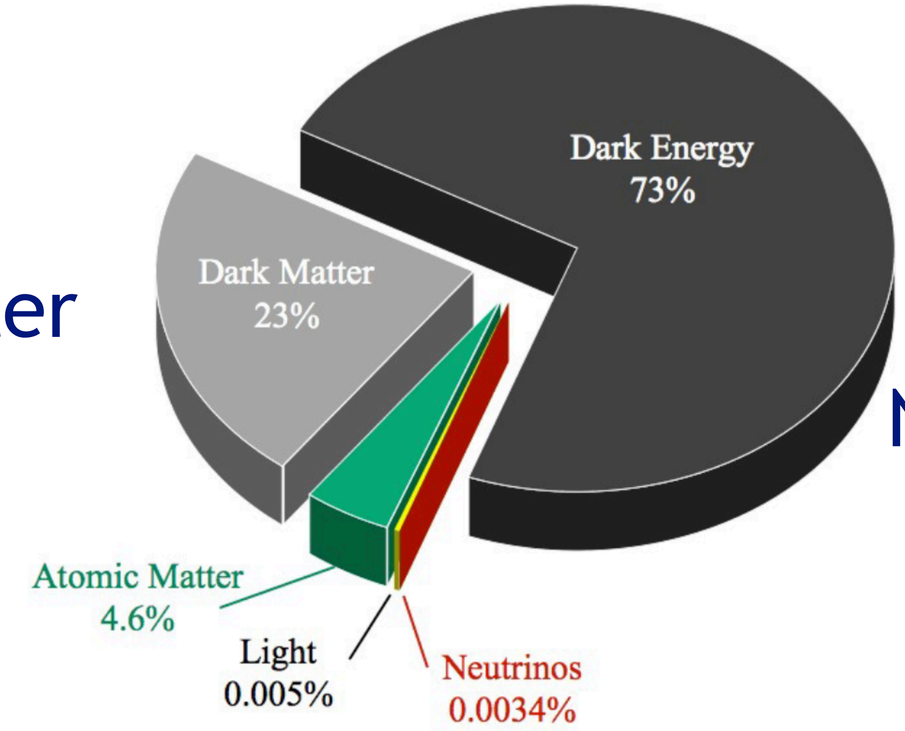
Includes all elementary particles we know so far

Building blocks of nature

Everything around us

Current understanding of nature at smallest scales encoded in Standard Model of particle physics

Describes ~5% of matter in Universe



Neutrinos second most abundant elementary SM particle in Universe

About me (neutrino)

Name: Neutrino (small neutral one)

About me (neutrino)

Size: Point-like, elementary particle

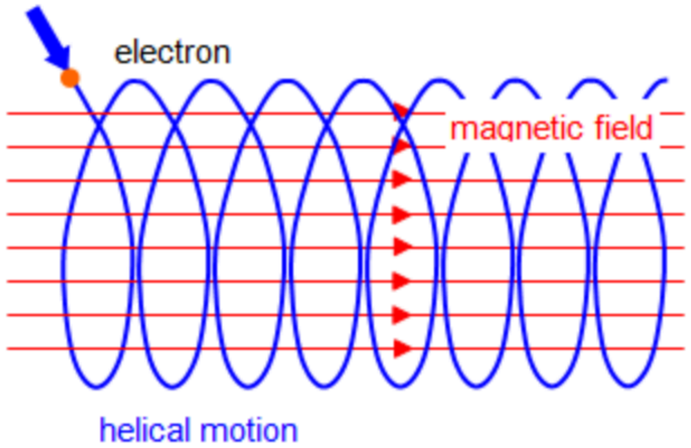
Cannot be split into subcomponents, no substructure!

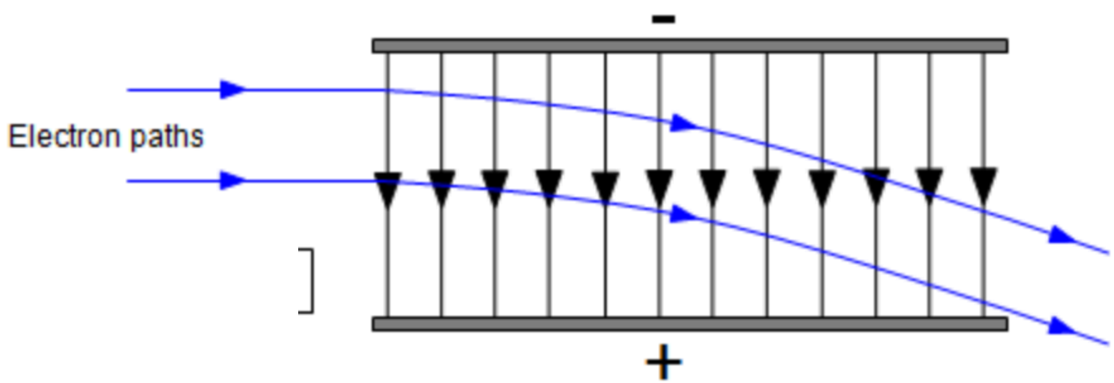
About me (neutrino)

Characteristics: electrically neutral

Not affected by electric or magnetic fields
unlike electrons

Neutrinos travel on a straight line





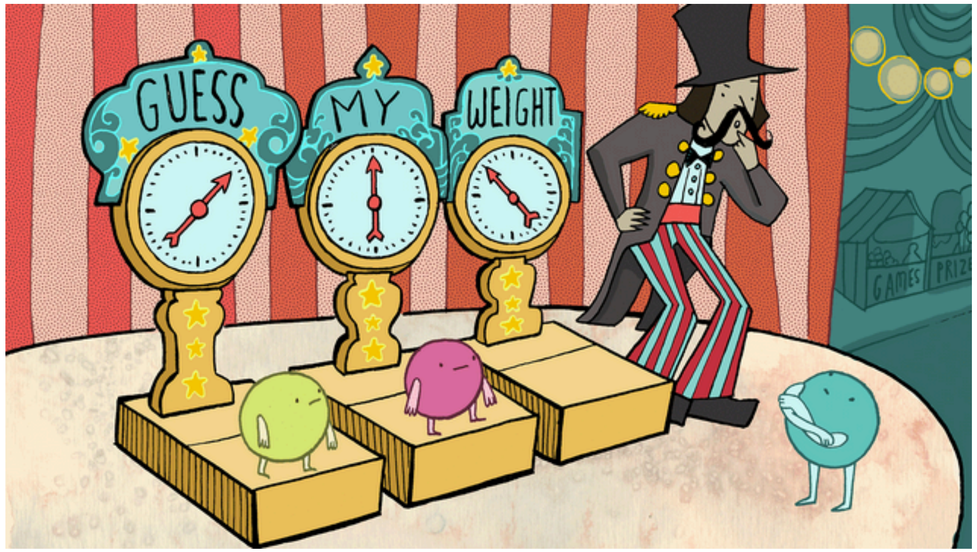
About me (neutrino)

Family: at least three types of neutrinos

types="flavor"

About me (neutrino)

Mass: very light but we don't know its value



Future experiments
will measure neutrino mass!

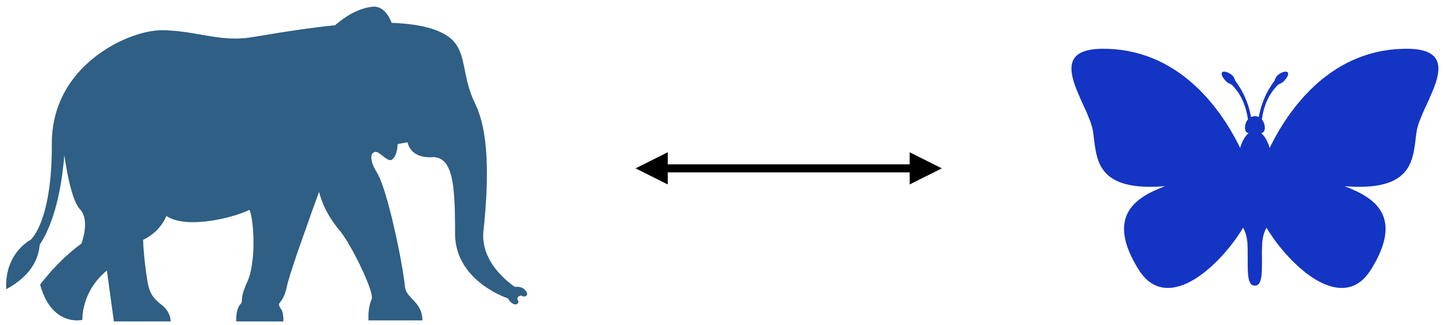
About me (neutrino)

Mass: very light but we don't know its value

Neutrinos weight less than 10^{-36} kg

10^{-36} kg=0.000000000000000000000000000000001 kg

Compared to second lightest particle (electron):



About me (neutrino)

Favorite thing to do:

travel through space and time

About me (neutrino)

Favorite thing to do:

travel through space and time

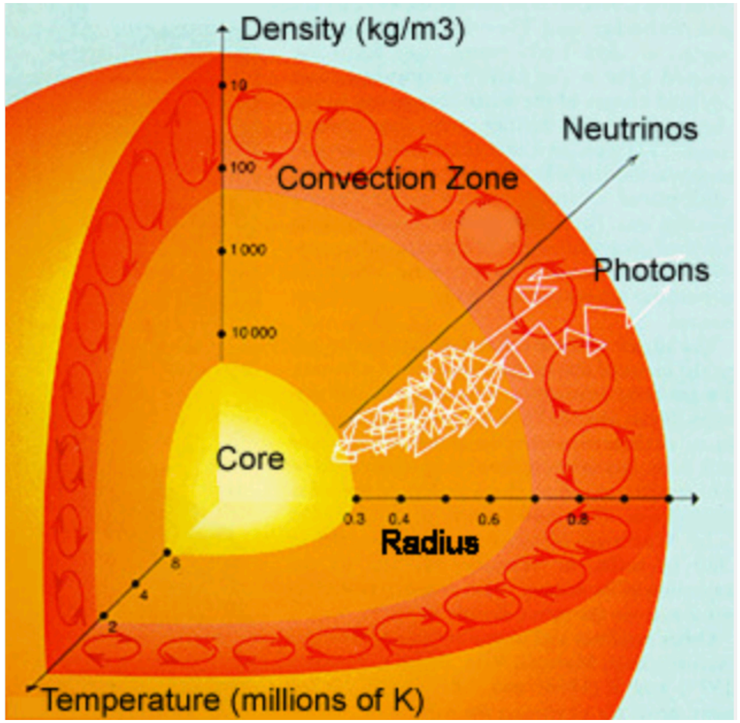
Least favorite thing to do:

interact!

Neutrinos are everywhere but interact only very rarely!

Neutrinos are everywhere

Produced for example in the Sun

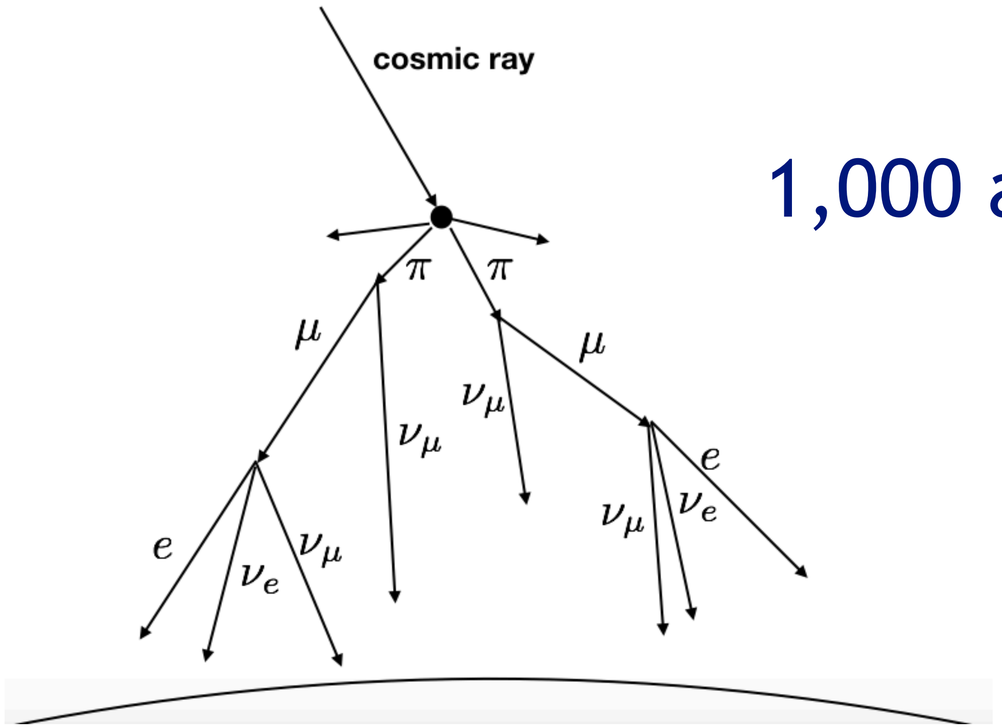


Neutrinos produced in nuclear fusion in the core of the Sun

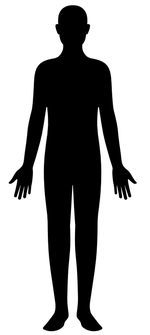
Each second 65 billion solar neutrinos pass through your fingernail!

Neutrinos are everywhere

Produced when high-energetic particle hit the atmosphere:
Atmospheric neutrinos



1,000 atmospheric neutrinos per human body per second



Neutrinos are everywhere

Produced in radioactive decays

small fraction of the potassium in bananas naturally occurs as the radioactive potassium-40 isotope → bananas produce neutrinos

(Living in brick or concrete building for a year: 700 banana equivalent doses)

Neutrinos are everywhere

100 trillion neutrinos flood through you per second!

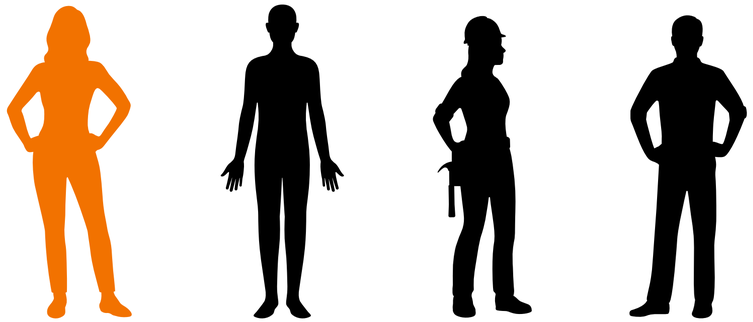
100 trillion=100,000,000,000,000 (14 zeros)

How many neutrinos interact with us?

Neutrinos interact rarely

How many neutrinos interact with us?

Chance neutrino interacts in your body at some point in your life is 1 in 4



Neutrinos interact rarely

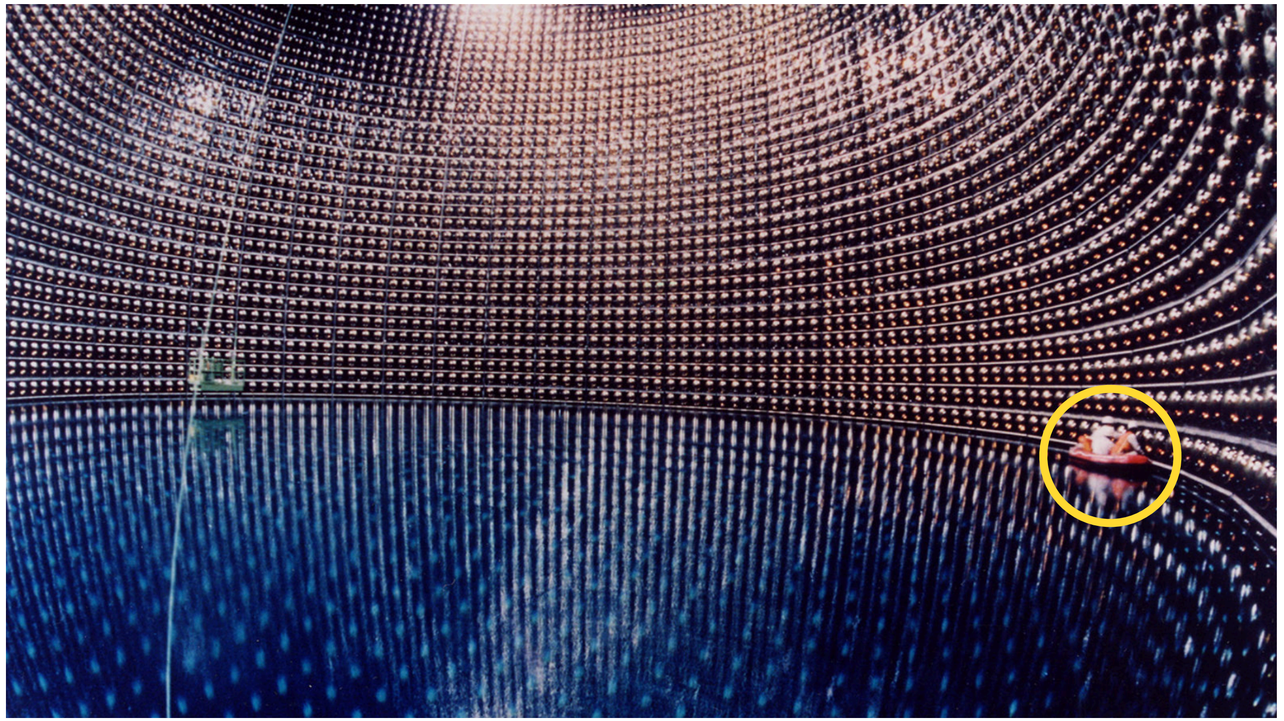
If neutrinos interact so rarely
how do we detect them?

Neutrinos interact rarely

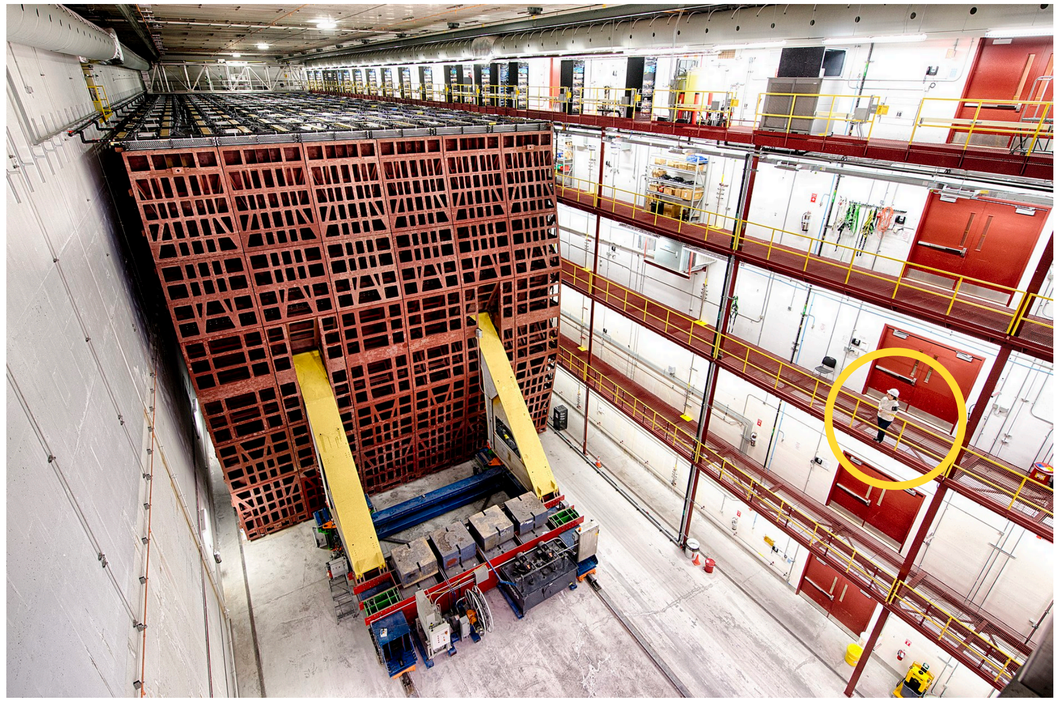
If neutrinos interact so rarely how do we detect them?

Increase probability of interaction → Build very big detectors!

SuperKamiokaNDE (Japan)



NOvA (MN)

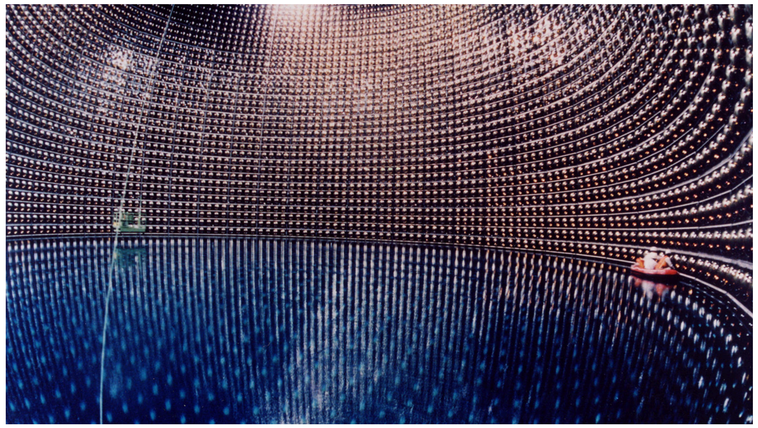


Neutrinos interact rarely

If neutrinos interact so rarely how do we detect them?

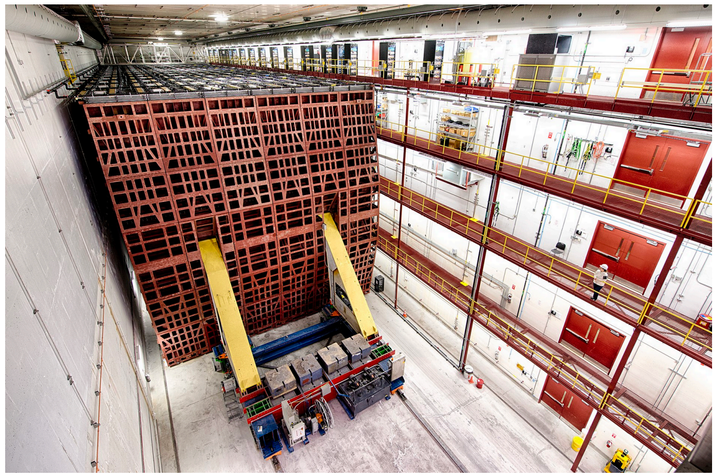
Increase probability of interaction → Build very big detectors!

SuperKamiokaNDE (Japan)



55,000 tons of water
in 136 ft tall and 129 ft diameter tank
3,300 ft underground

NOvA (MN)

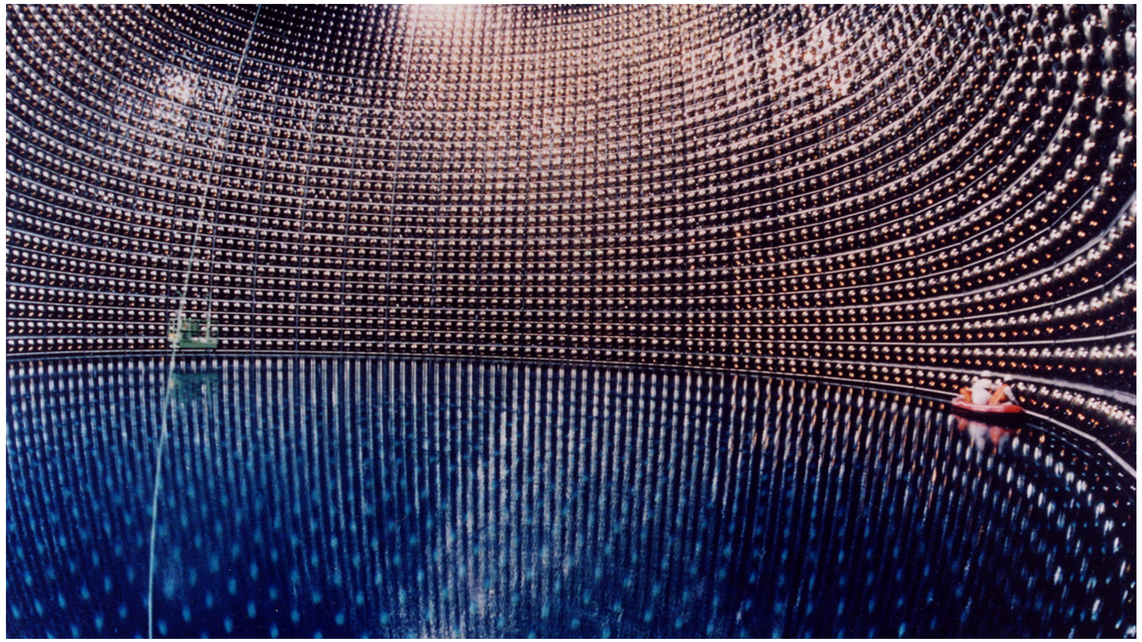


Underground, 14,000 tons (7,000 elephants)
50 ft tall, 196 ft long
(>2 blue whales long)

Neutrino detection

If neutrinos interact so rarely
how do we detect them?

Increase probability of interaction → Build very big detectors!

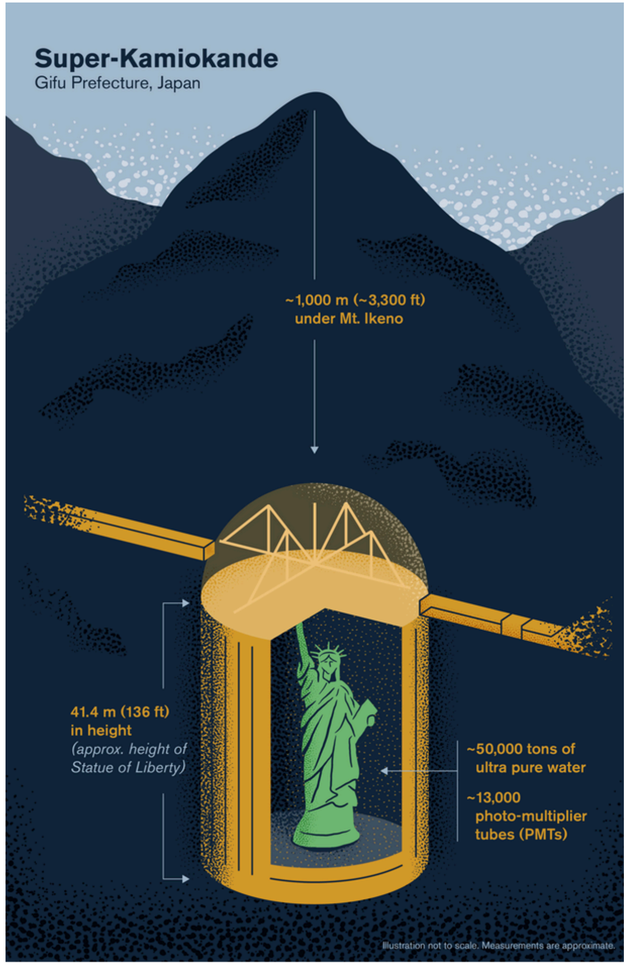


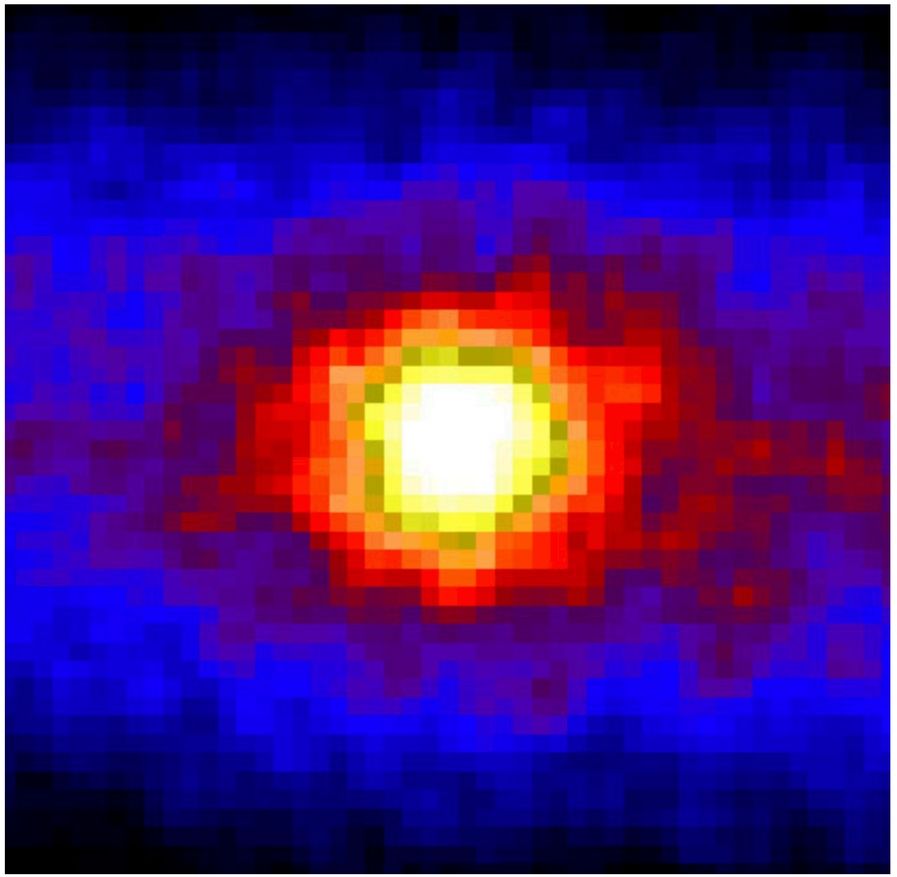
Solar neutrinos observed per day at SuperKamiokaNDE:
~10 neutrinos

(only 0.00000000000000001% of neutrinos coming through)

Neutrino detection

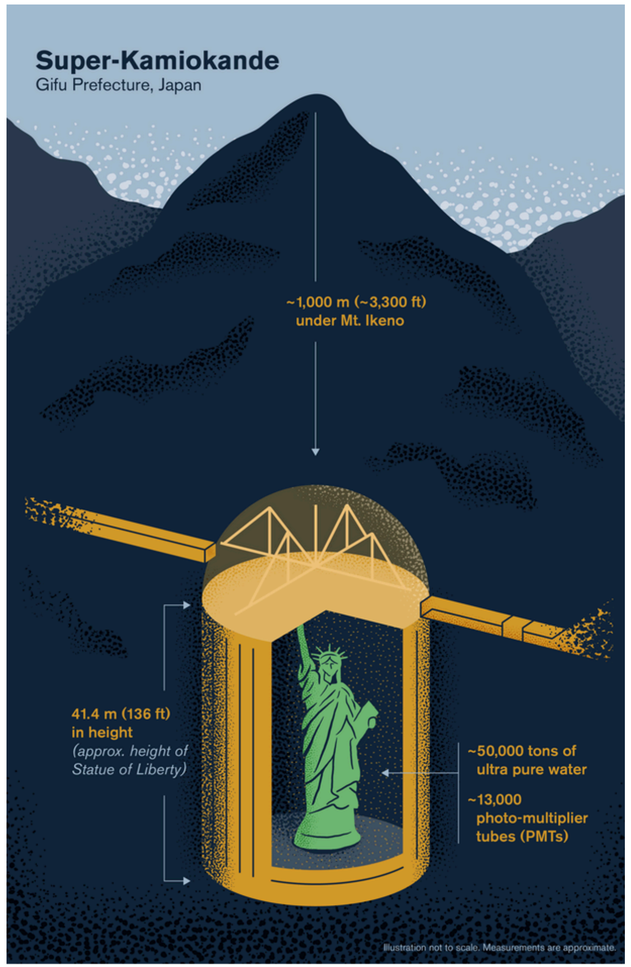
Center of Sun in neutrinos

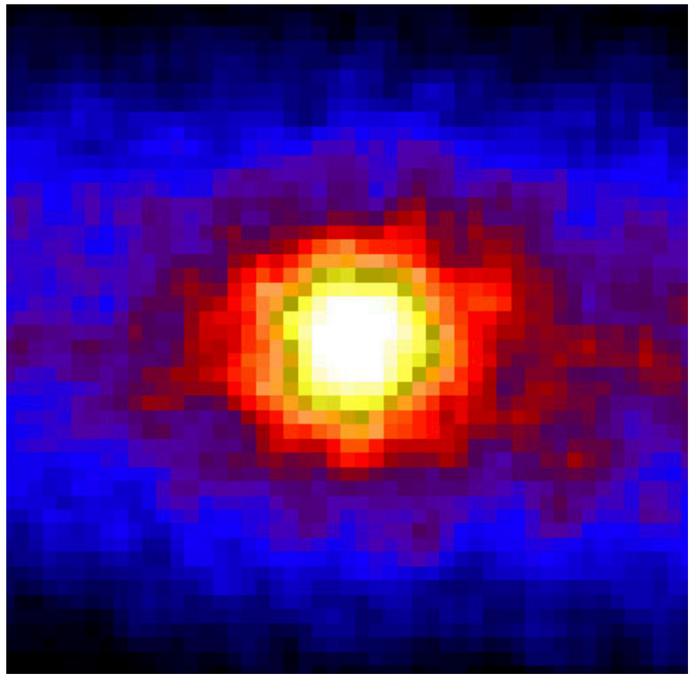




Neutrino detection

Center of Sun in neutrinos





Picture of Sun in neutrinos taken underground

Picture of Sun in visible light taken underground

Surprise!

Neutrinos change their flavor when propagating over a distance

For example electron neutrino can transform into muon neutrino

“Neutrino oscillations”

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Surprise!

Neutrinos change their flavor when propagating over a distance

Neutrino oscillations imply that
neutrinos have a non-vanishing mass

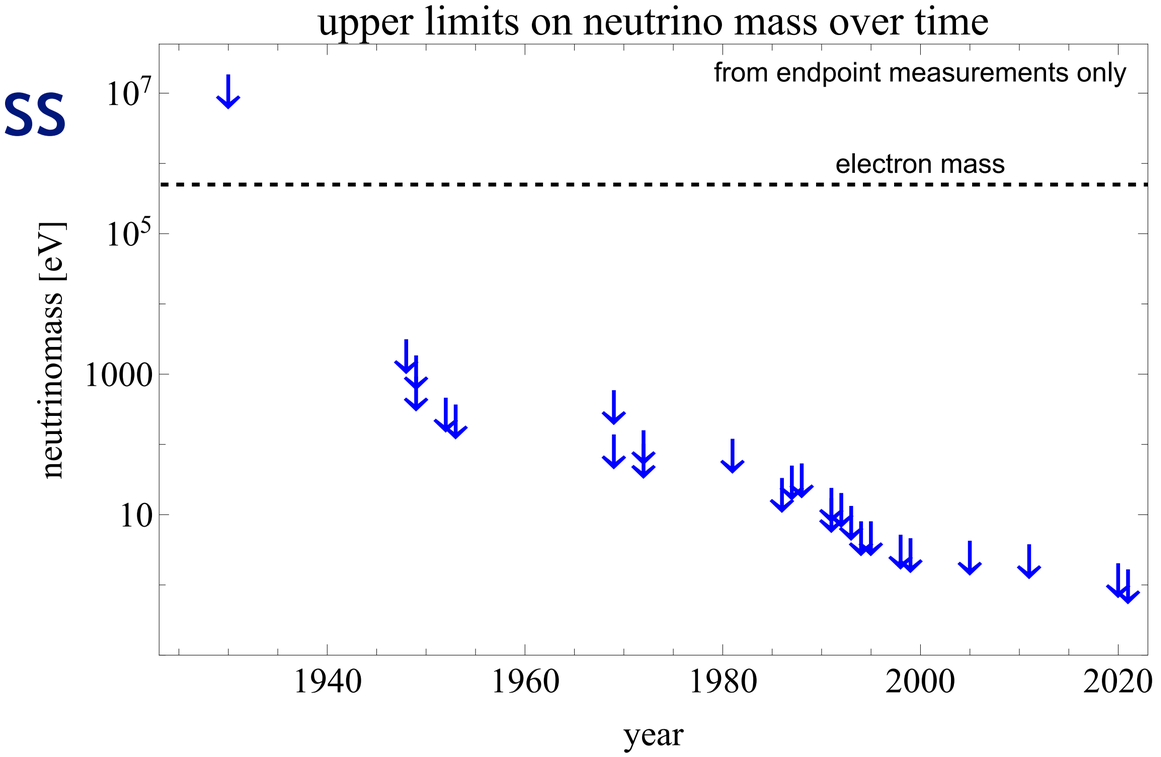
Surprise!

Neutrinos change their flavor when propagating over a distance

Neutrino oscillations imply that neutrinos have a non-vanishing mass

Unexpected as we have not seen neutrino masses directly

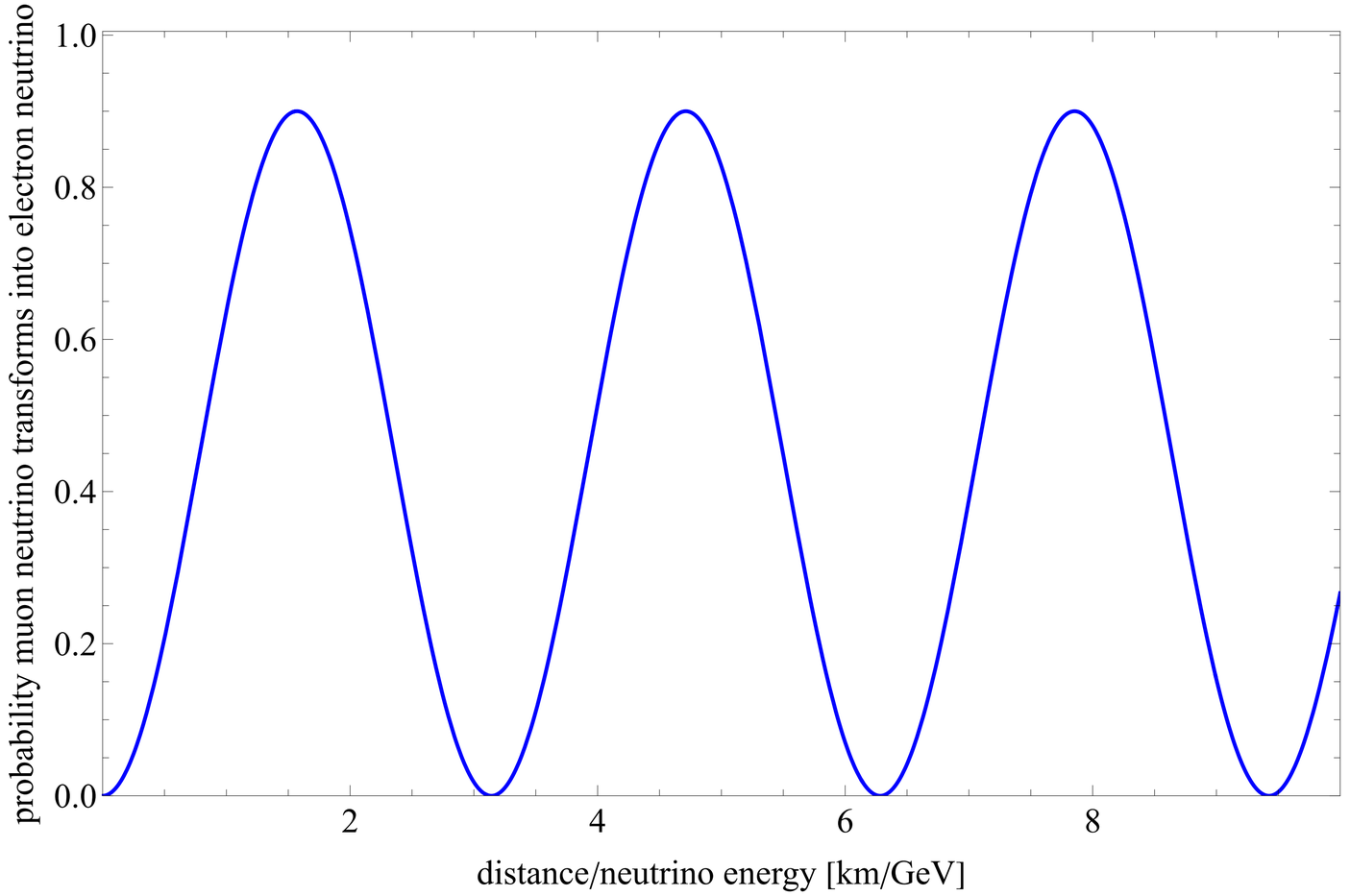
Ongoing research to measure neutrino mass!



Neutrino oscillations

Neutrinos change their type (flavor) when propagating over distance

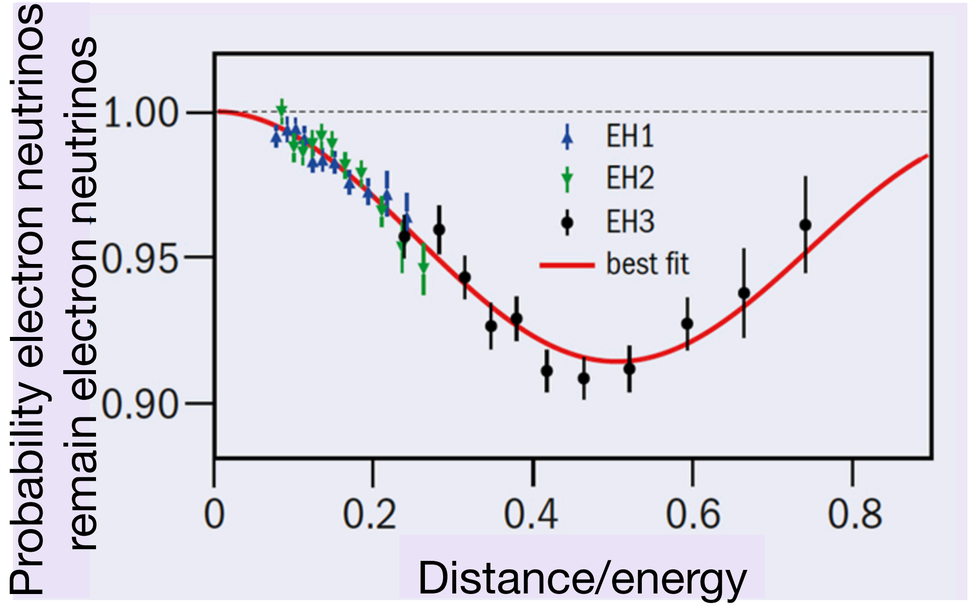
Probability of change depends on neutrino energy, distance traveled, fundamental neutrino parameters



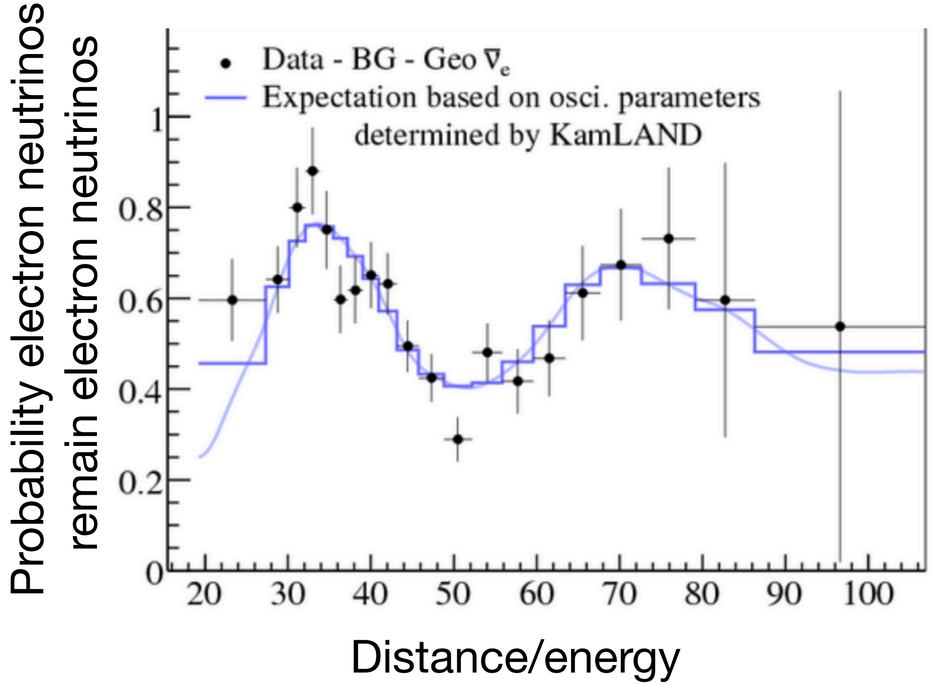
Neutrino oscillations

Neutrinos change their type (flavor) when propagating over distance

Oscillations seen at many experiments → learned about neutrino parameters



Reactor neutrinos traveling to detector



Daya Bay (China)

KamLand (Japan) [KamLand 0801.4589].

Neutrino oscillations

Neutrinos change their type (flavor) when propagating over distance

Oscillations seen at many experiments → learned about neutrino parameters

Still don’t know all fundamental neutrino parameters

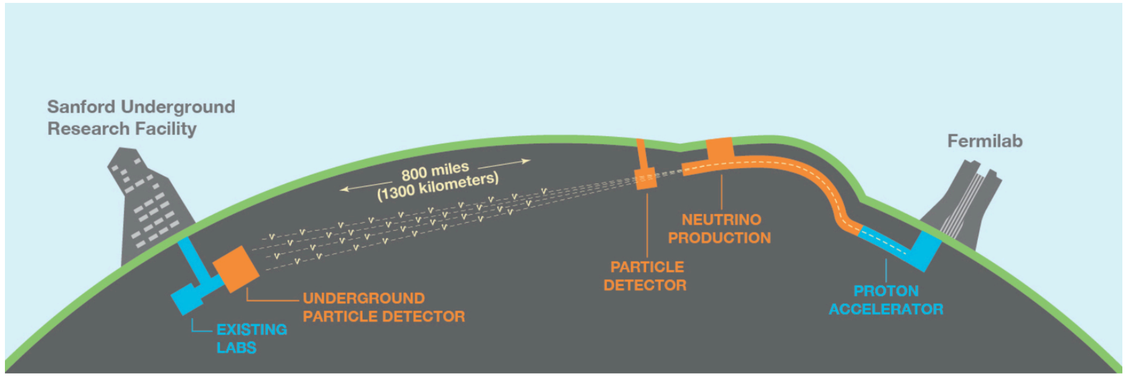
→ build new optimized experiments to measure them

Future of neutrinos

Example: DUNE
Deep Underground Neutrino Experiment

Build neutrino detector 1 mile underground in South Dakota

Detect neutrinos produced 800 miles away in Illinois



Future of neutrinos

Example: DUNE
Deep Underground Neutrino Experiment

Compare neutrinos detected in SD to neutrinos produced in IL

How many of the produced muon neutrinos are still muon neutrinos?

How many have transformed into electron neutrinos or tau neutrinos?

Learn about unknown
fundamental neutrino parameters

Future of neutrinos

Example: DUNE
Deep Underground Neutrino Experiment

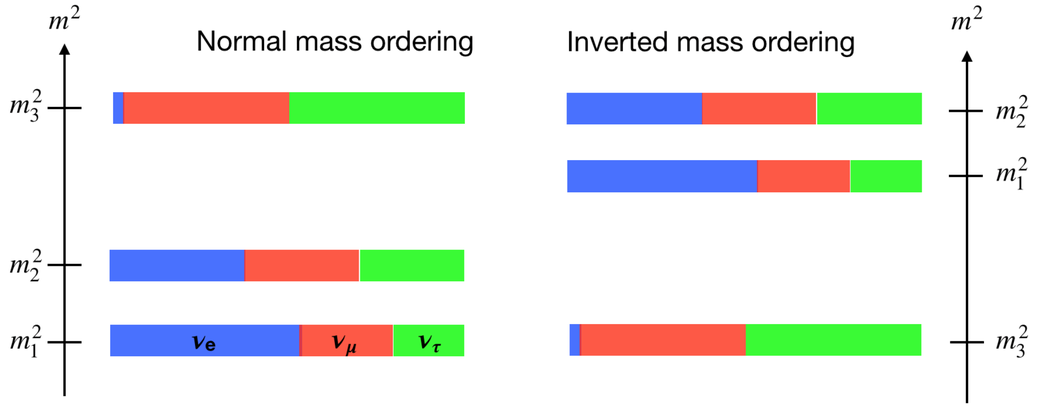
Learn about unknown
fundamental neutrino parameters

Do neutrinos and antineutrinos behave differently?

Which neutrino mass eigenstate is the lightest?

Are there extra neutrinos?

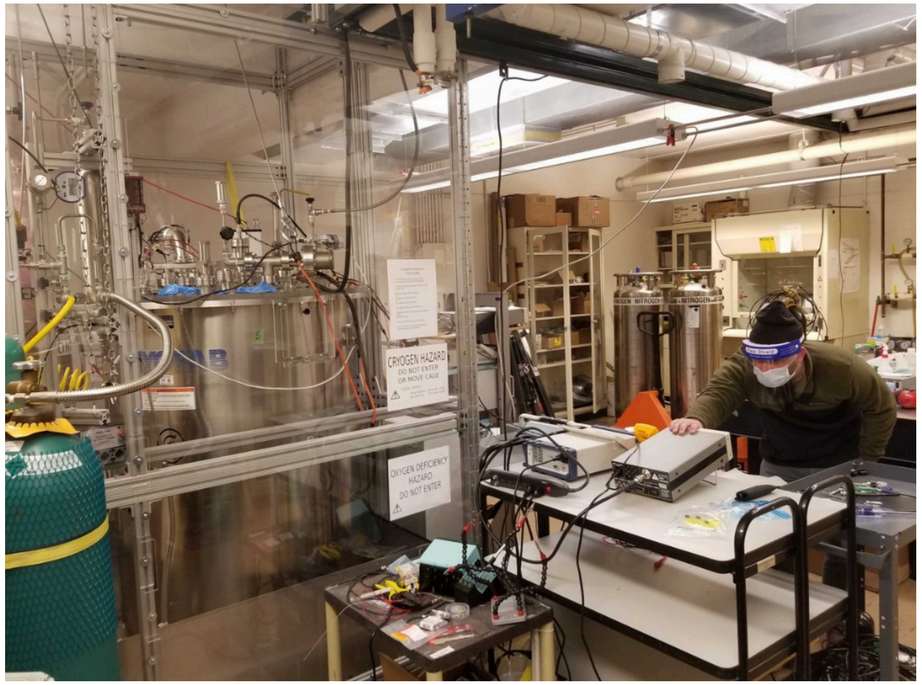
Do neutrinos have new interactions?



Future of neutrinos

Neutrino research at CSU

Building DUNE



Important parts of DUNE detector built and tested in CSU labs

Theory research in neutrinos at CSU

Neutrinos

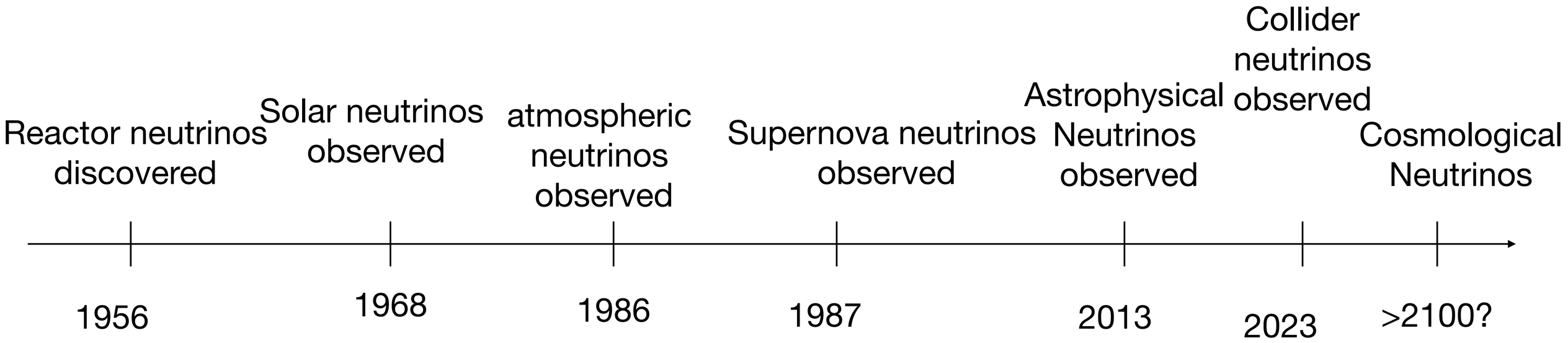
- Very abundant particles: produced in many different sources
- Very elusive: interact extremely rarely
- Very interesting: we don't know everything about neutrinos yet!
- Play neutrino game: NuOdyssey
- Neutrino rap

Thanks for your attention!

Appendix: Neutrino timeline

Theoretical prediction
of neutrino in 1930

Three generations of neutrinos discovered
in 1956, 1962, 2000

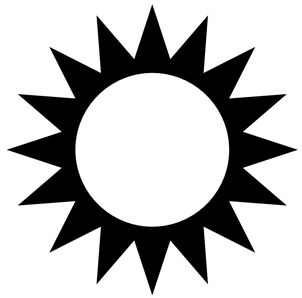


Appendix: Neutrinos interact rarely

Neutrinos travel unimpeded on a straight line pointing back to where they came from

Neutrinos can travel through lead without interacting for

1.6 light-years=100,000 times Earth-Sun distance

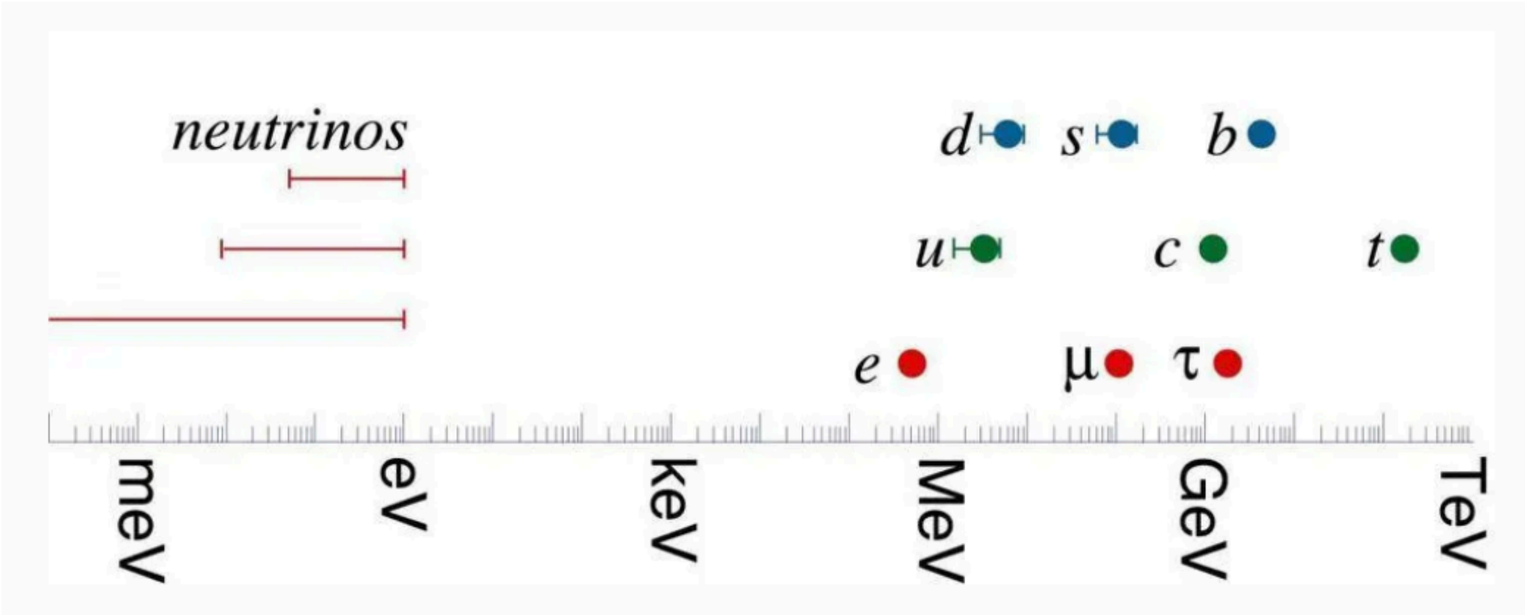


Lead shield to block neutrinos

~10 million years by car to travel along the shield from beginning to end

Appendix: Neutrino mass

SM particle masses



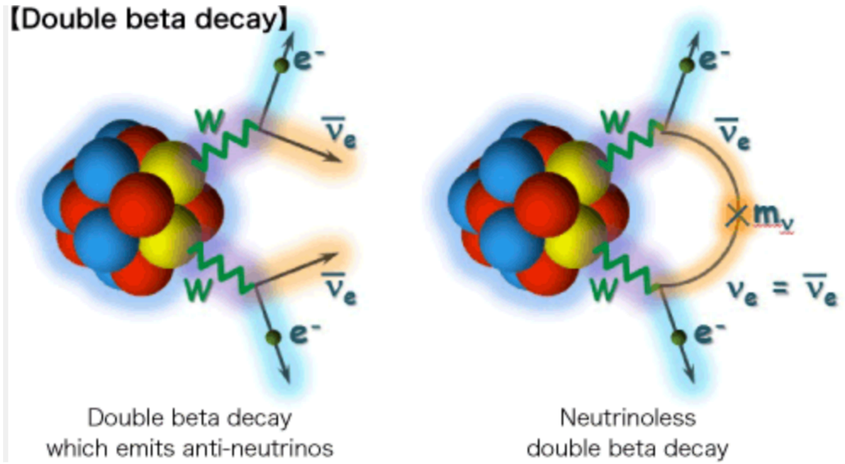
We know:

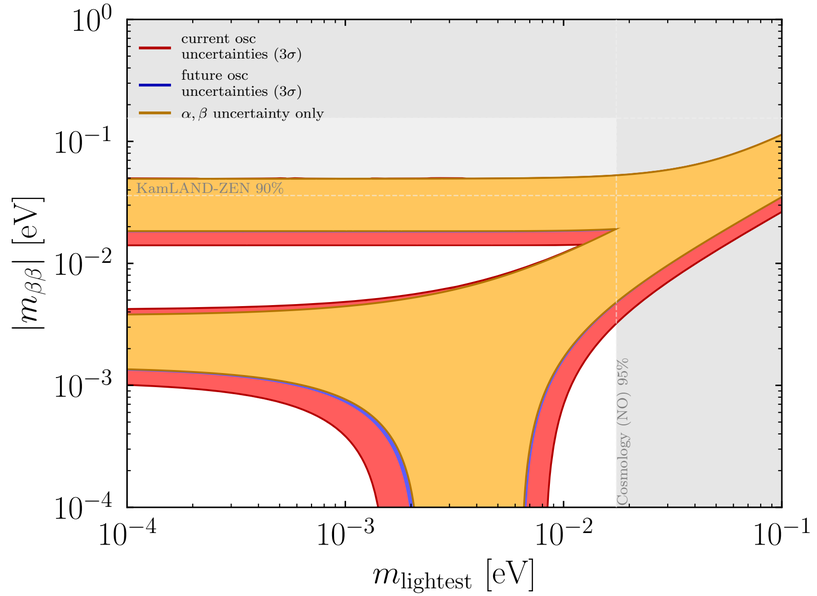
- Neutrinos have a mass (they are massless in SM)
- Neutrinos are very light

Appendix: Neutrino mass

Neutrinos are the only SM (matter) particles which have no electric charge
Opens possibility that neutrinos are their own antiparticles!
neutrino=antineutrino!?

Look for neutrinoless double beta decay
No observation so far!





Appendix: Neutrino mass

Neutrinos are the only SM (matter) particles which have no electric charge
Opens possibility that neutrinos are their own anti particles!
neutrino=antineutrino!?

If neutrinos are their own antiparticles they could have a different kind of mass term (Majorana mass term vs Dirac mass term)

$$m_\nu^M = M_M \bar{\nu}_L^c \nu_L$$
$$m_\nu^D = M_D \bar{\nu}_L \nu_R$$

Appendix: Neutrino mass

If neutrinos are their own antiparticles they could have a different kind of mass term (Majorana mass term vs Dirac mass term)

Dirac mass term generated via interaction with Higgs field

$$y_\nu \bar{L}_L \tilde{H} \nu_R \rightarrow M_D \bar{\nu}_L \nu_R \, (M_D = y_\nu v_H)$$

There is no ν_R in the SM!

Give mass to neutrinos but
need very very weak coupling of neutrinos to Higgs field!

Appendix: Neutrino mass

If neutrinos are their own antiparticles they could have a different kind of mass term (Majorana mass term vs Dirac mass term)

Dirac mass term generated via interaction with Higgs field

$$y_\nu \bar{L}_L \tilde{H} \nu_R \rightarrow M_D \bar{\nu}_L \nu_R \; (M_D = y_\nu v_H)$$

Majorana mass term cannot be generated following basic rules of QFT/SM without introducing new particles

$$\cancel{M_M \bar{L}_L^c L_L}$$

Appendix: Neutrino mass

Majorana mass term cannot be generated following basic rules of QFT/SM without introducing new particles

$\Rightarrow$ introduce new particles

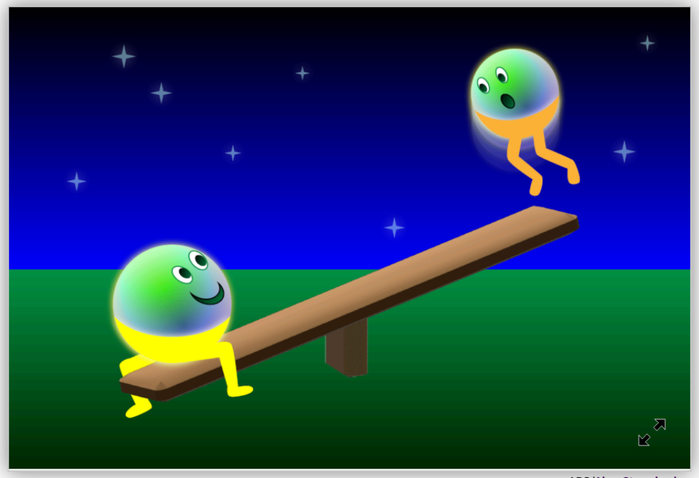
For example sterile neutrino (not charged under SM)

Seesaw mechanism: mass of sterile neutrino suppresses mass of light neutrino

Get natural suppression of neutrino mass

Give mass to neutrino+explain smallness

Have not observed sterile neutrino



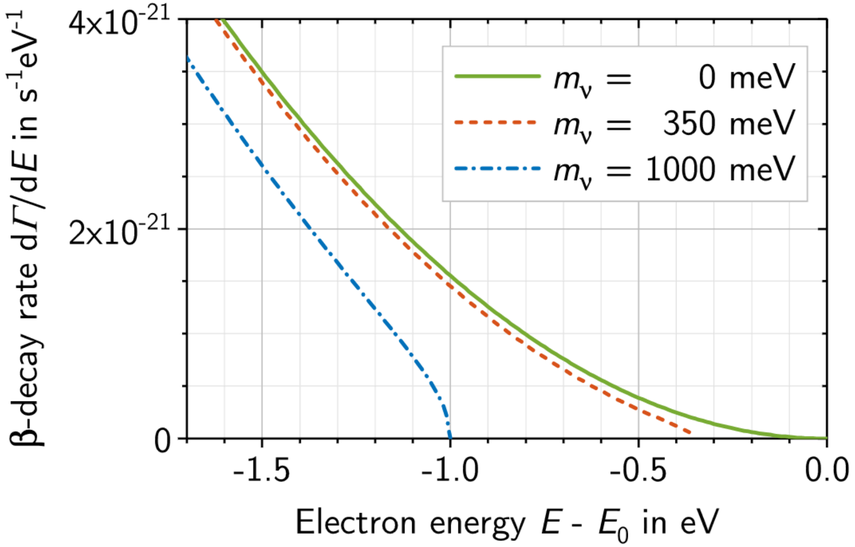
APS/Alan Stonebraker

Appendix: Neutrino mass measurement

Neutrinos emitted in radioactive decay of element together with electron

Energy-momentum conservation requires total energy to be conserved

measure energy of electron → maximal electron energy is total energy of process minus energy contained in neutrino mass

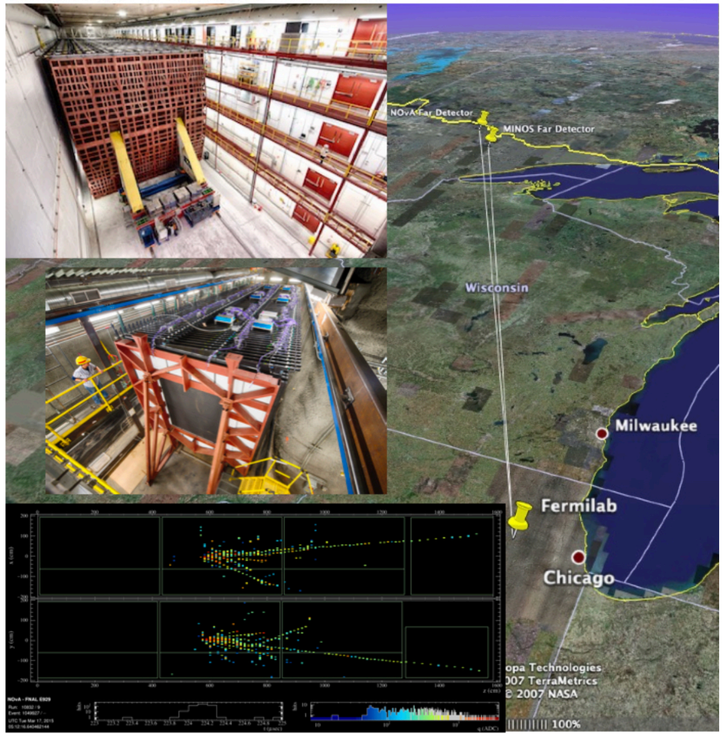


Appendix: Neutrino oscillations

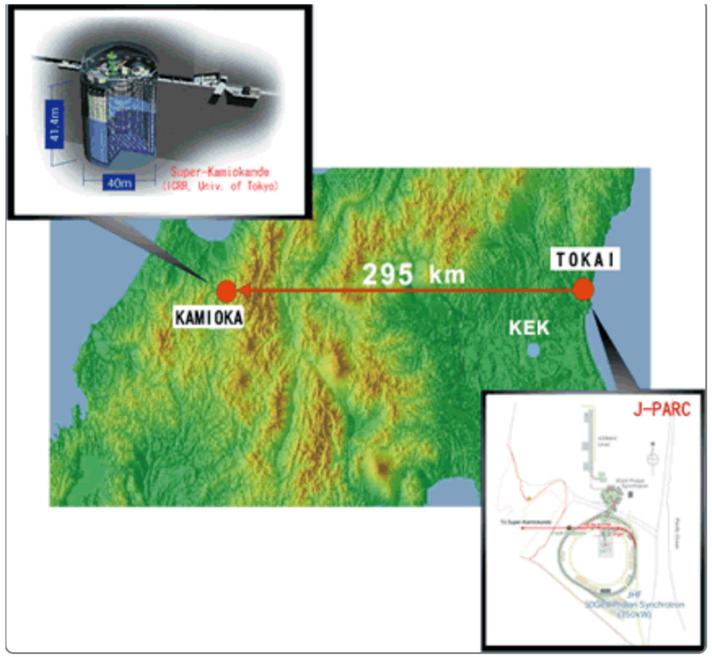
Several experiments aim to measure same parameters

→ Cross checks, systematic uncertainties

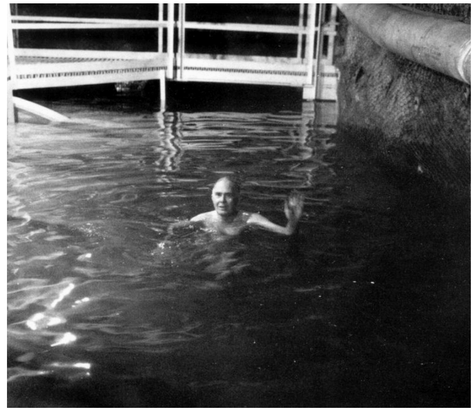
US experiment

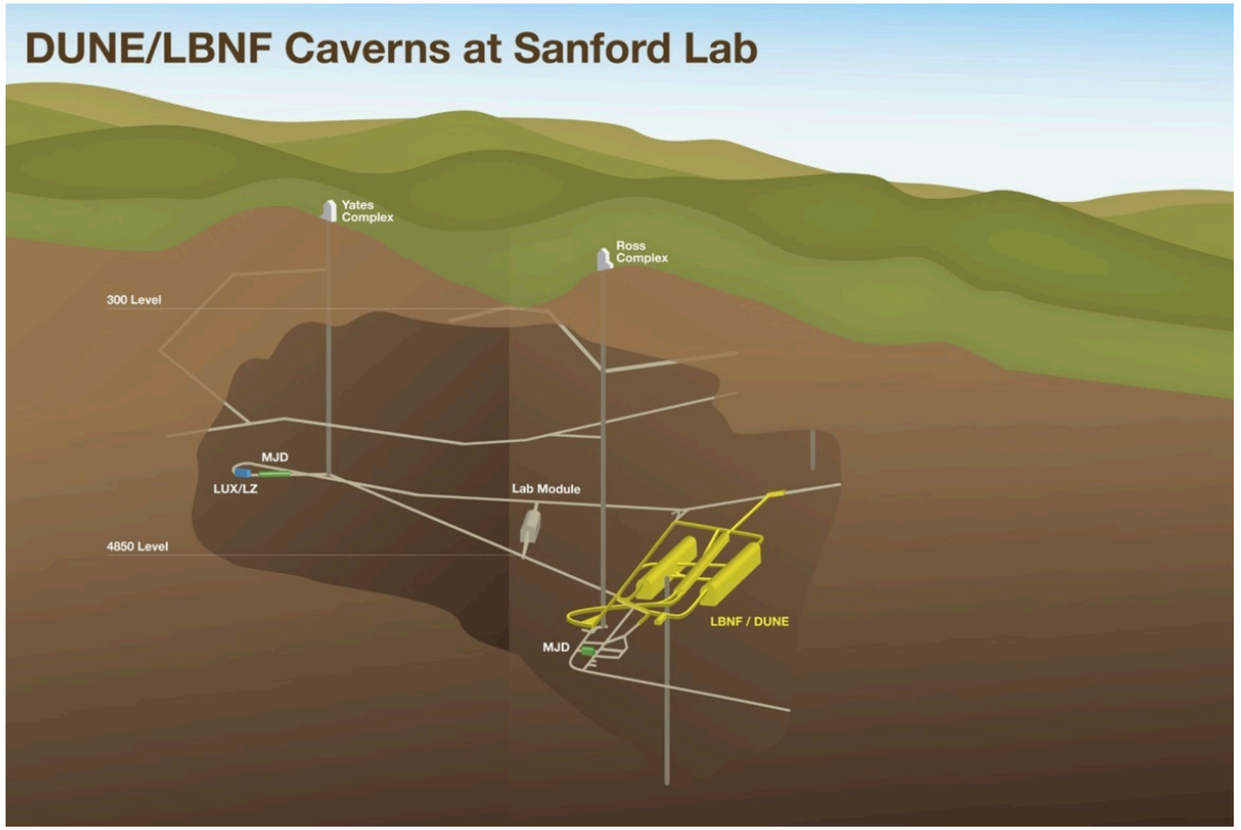


Japanese experiment

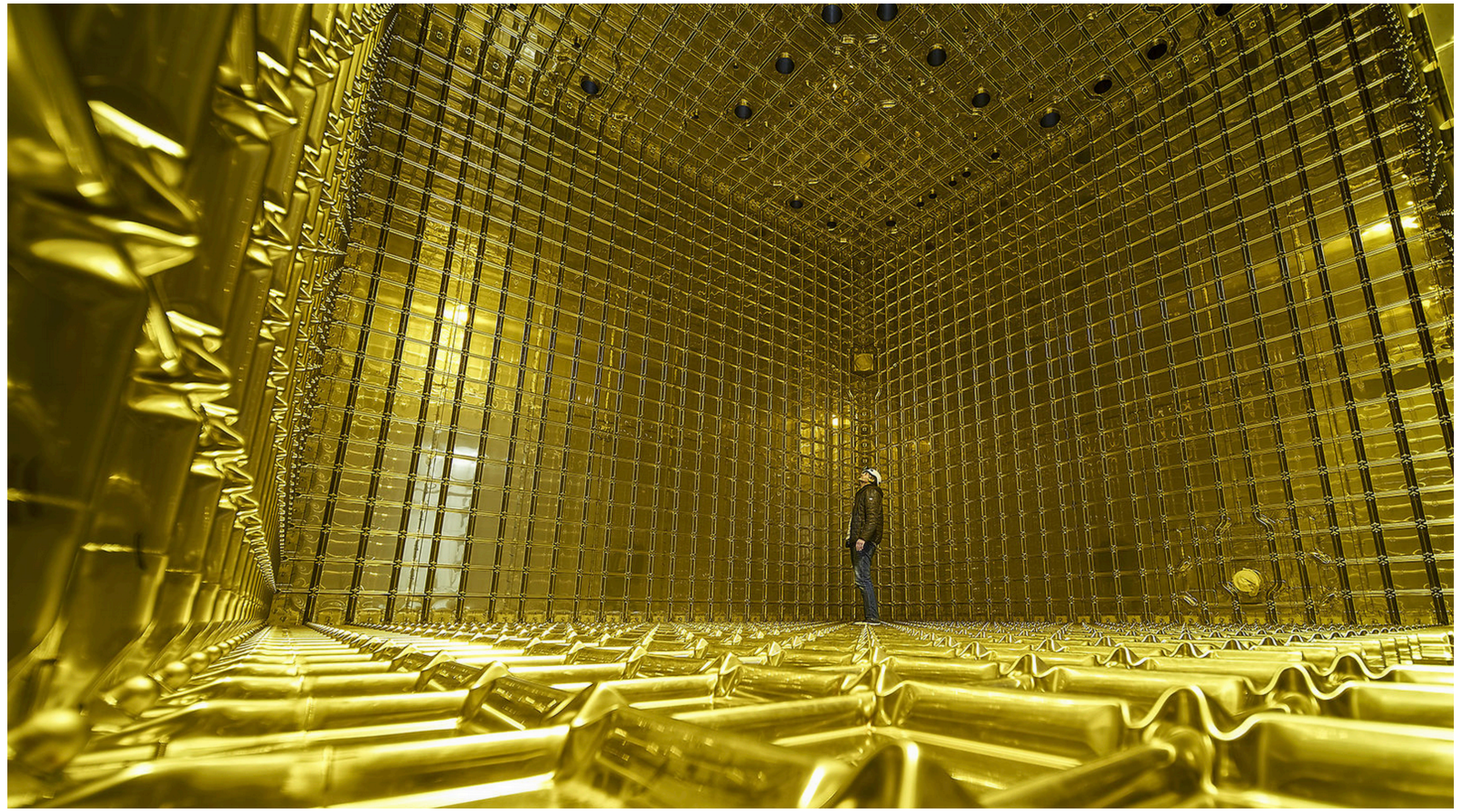


Appendix: SURF





Appendix: DUNE



ProtoDUNE at CERN

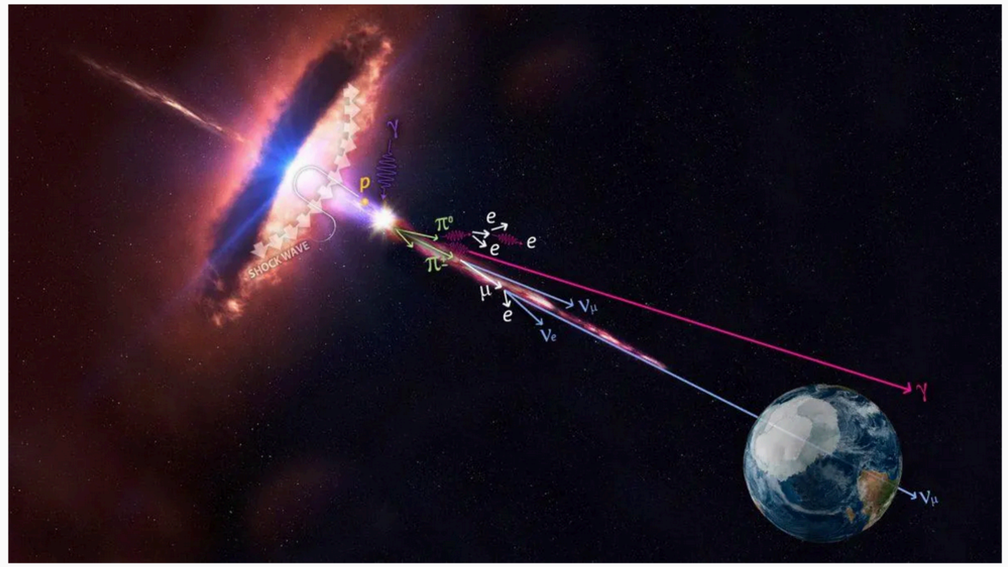
Appendix: Neutrinos

Astrophysical neutrinos
High-energy neutrinos produced in astrophysical sources

>1000 times more energy than
neutrinos from colliders

Very rare events: few events per year per km^2

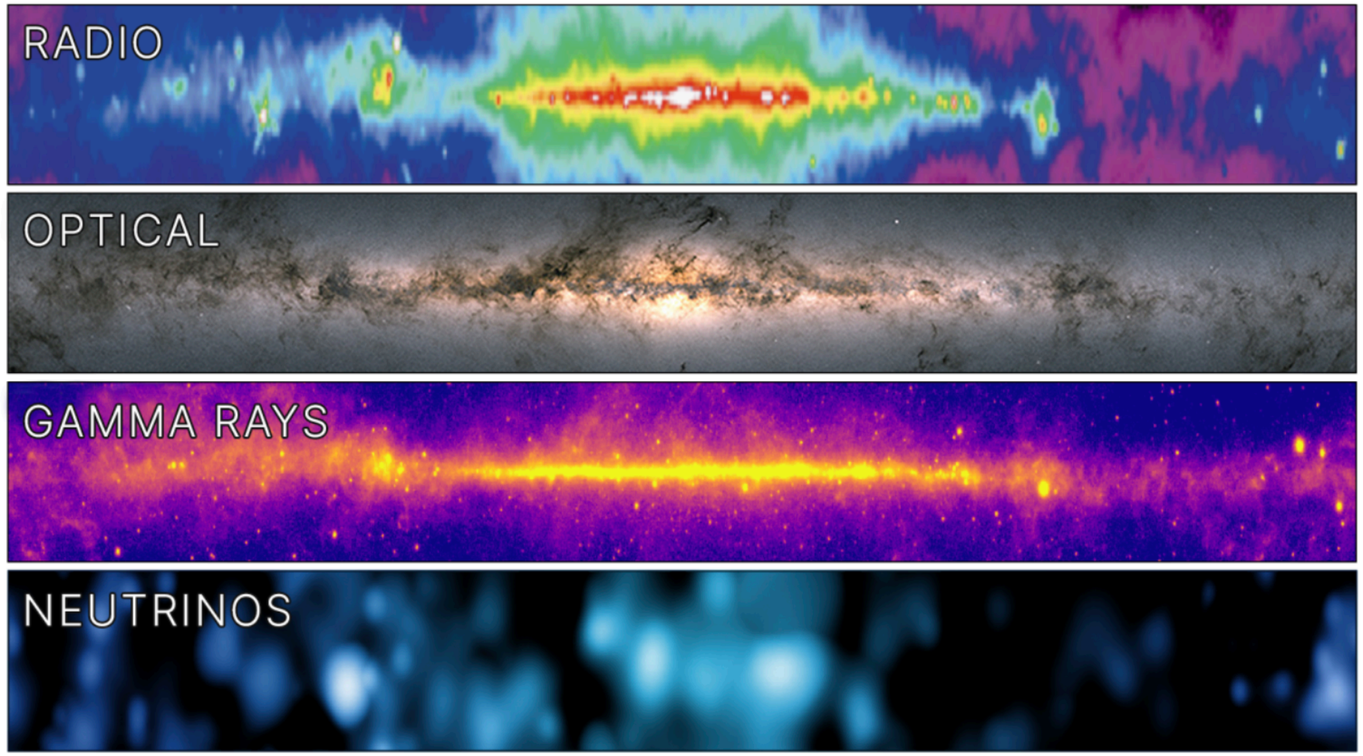
Travel very long distances:
come from outside of our galaxy



Neutrinos not affected by magnetic fields
in Universe → point back to source

Appendix: Neutrinos

Milky Way



Ice Cube Collaboration

Appendix: Neutrinos

At the birth of the elements in the universe:
Cosmic neutrino background

relic of big bang (age of Universe=1 sec)

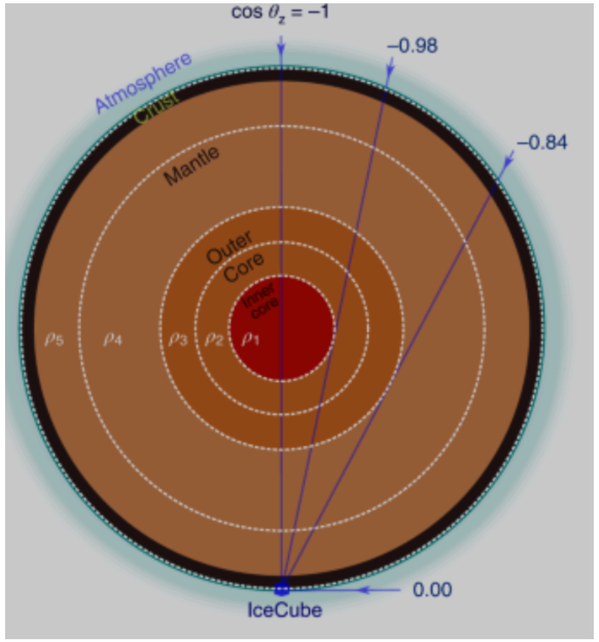
Density of relic neutrinos: 336 ν per cm^3
(Not observed yet!)

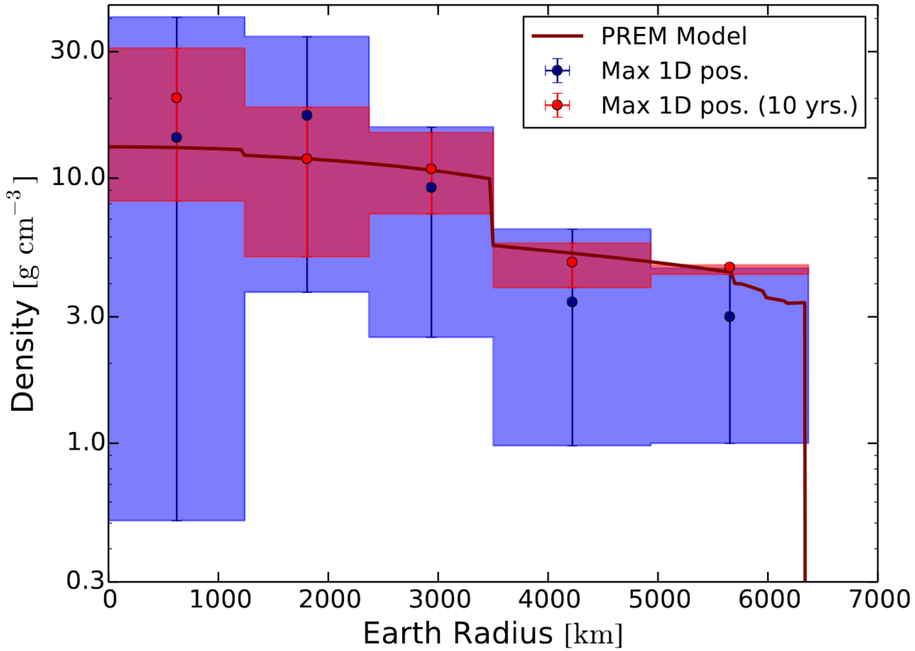
Photon background (Cosmic microwave background)
age of universe=379,000 years

Appendix: Neutrinos

Atmospheric neutrinos:

Particle physics at high energy (larger than collider energies)
Earth tomography





[Donini, Palomarez-Ruiz, Salvado 1803.05901]