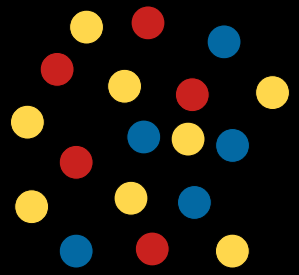
The Case of the Missing Antimatter

Steve Boyd
EPP Group

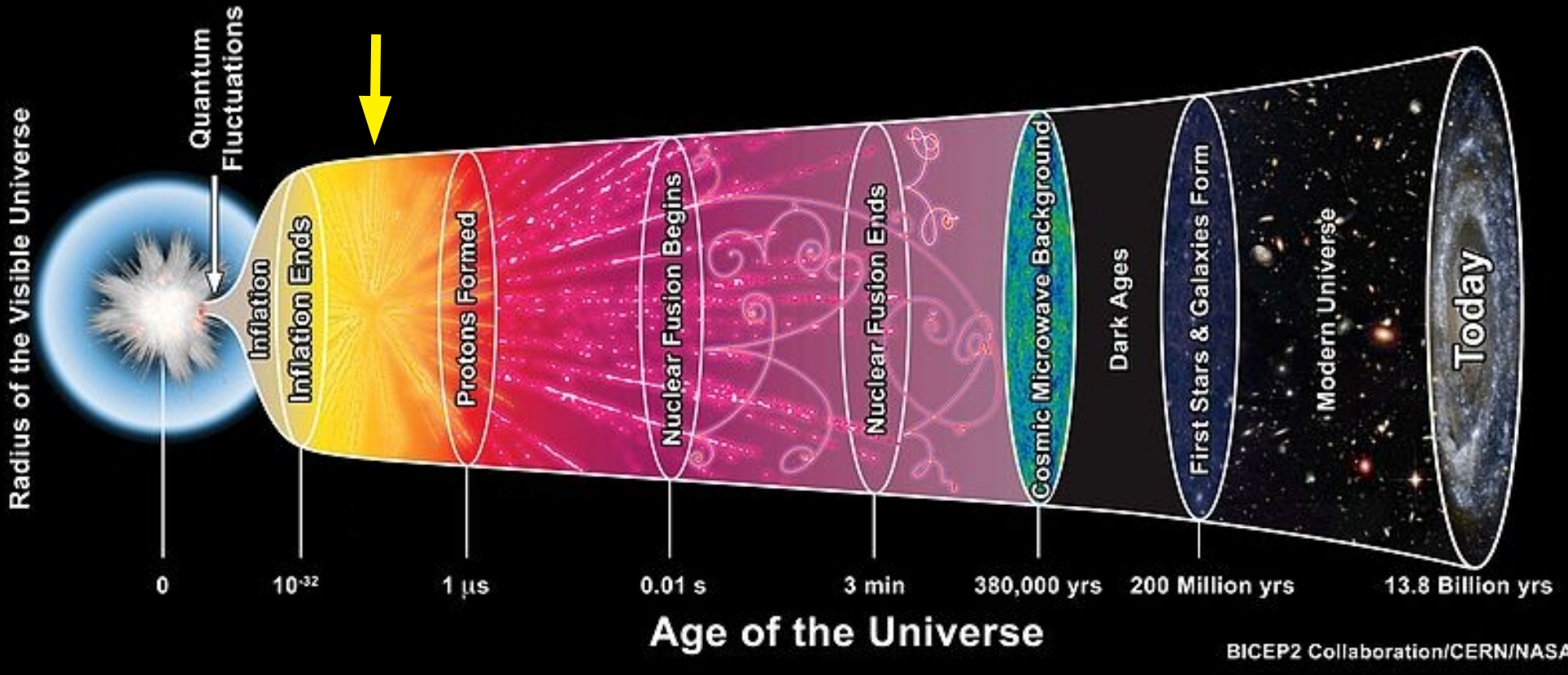

Where did all the antimatter go?

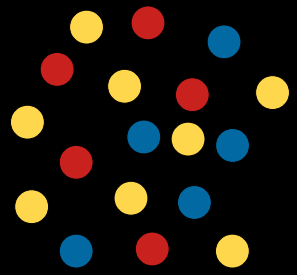


$T > m_e c^2$
$(10^{10}\ K)$

$$e^- + e^+ \Leftrightarrow \gamma + \gamma$$

Electroweak epoch ~ 10^{-15} s





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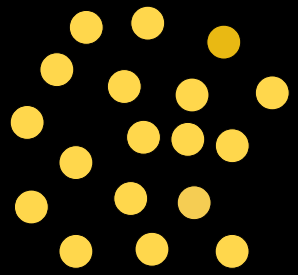

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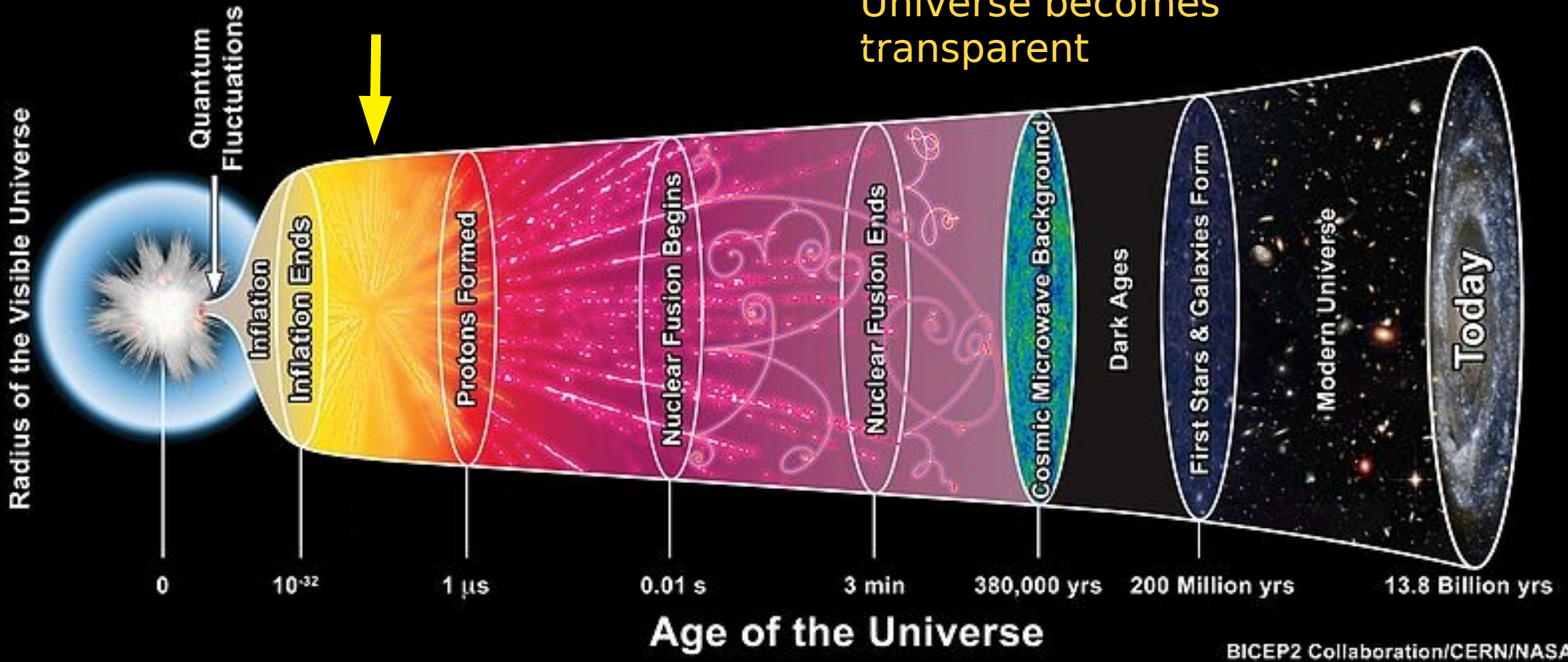
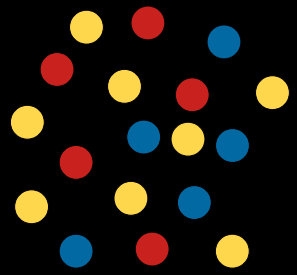
Electroweak epoch ~ 10^{-15} s

Photon decoupling
Universe becomes
transparent





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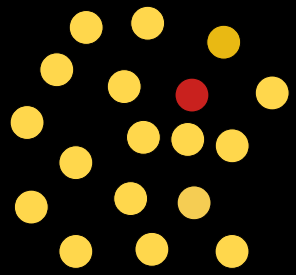

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Electroweak epoch ~ 10^{-15} s

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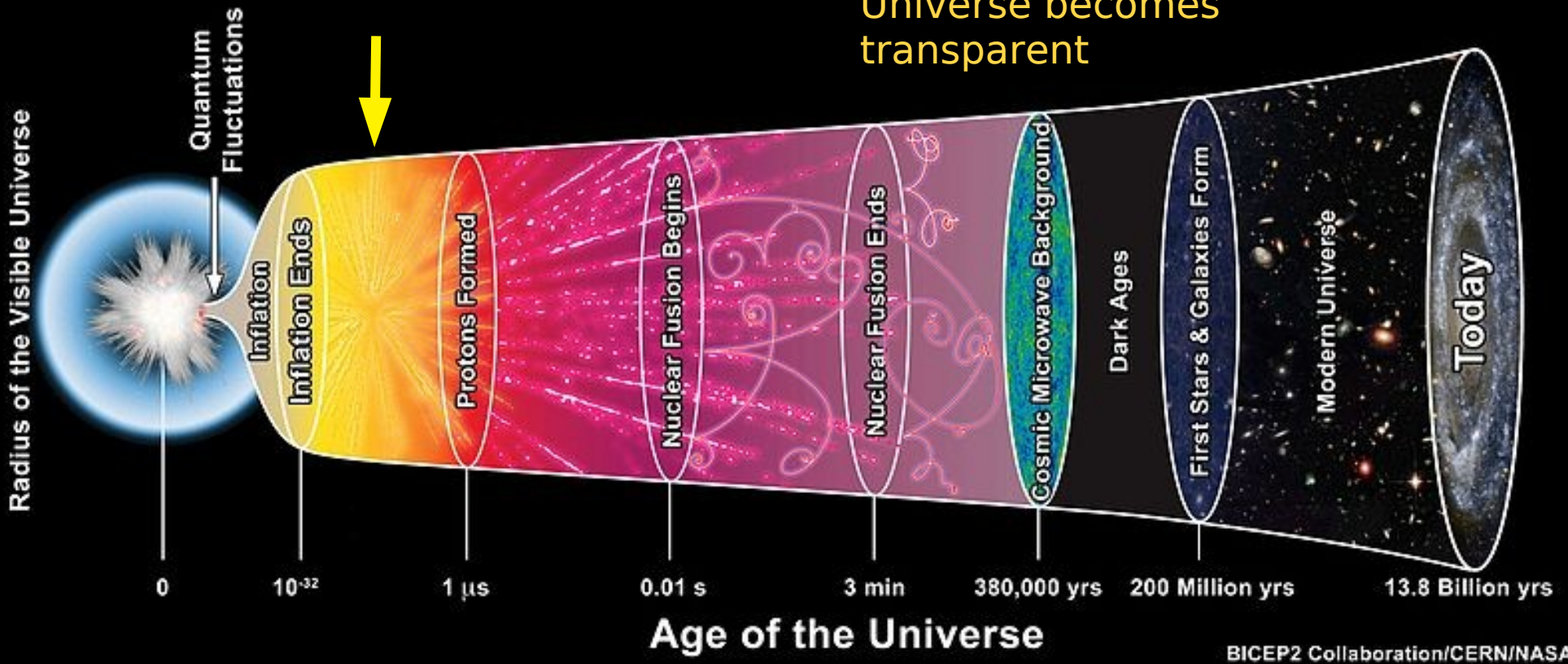
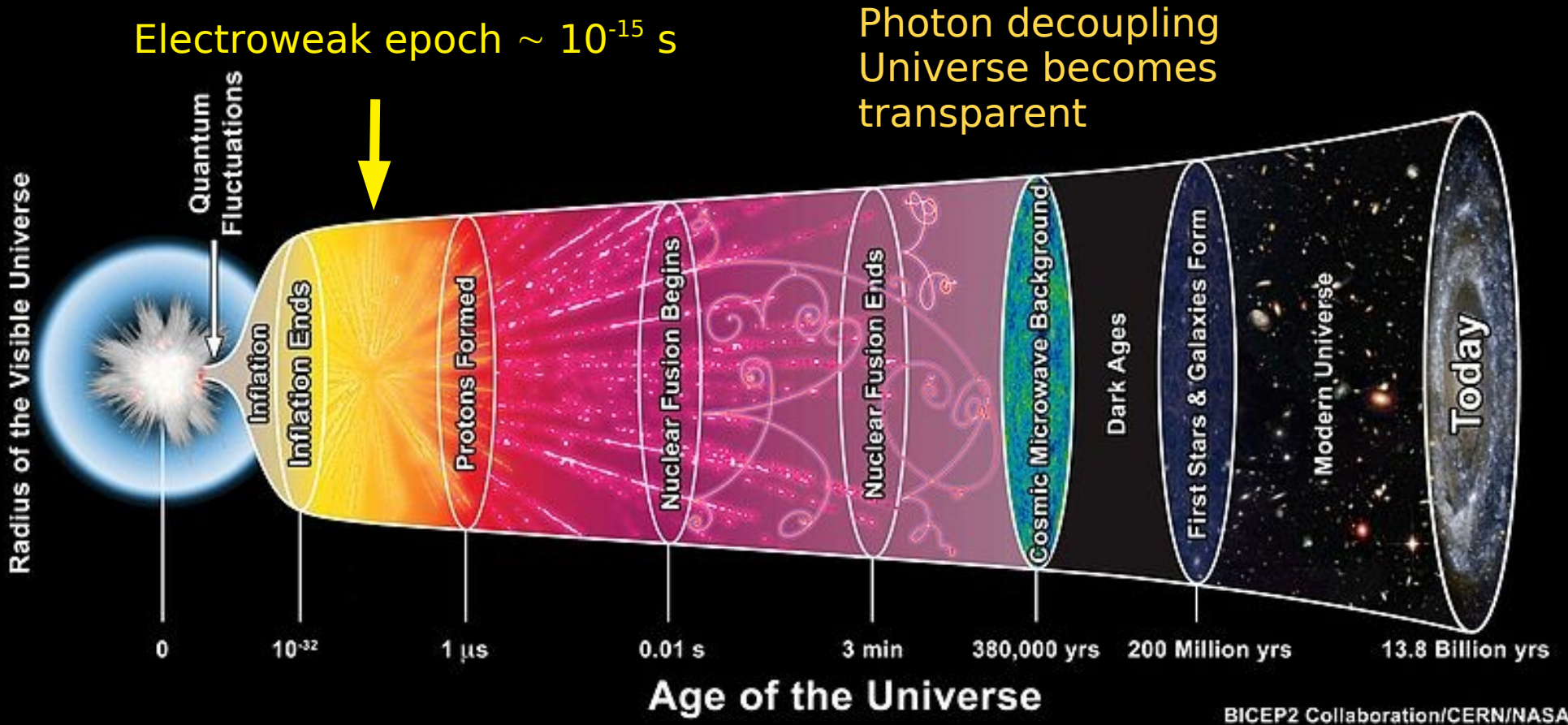
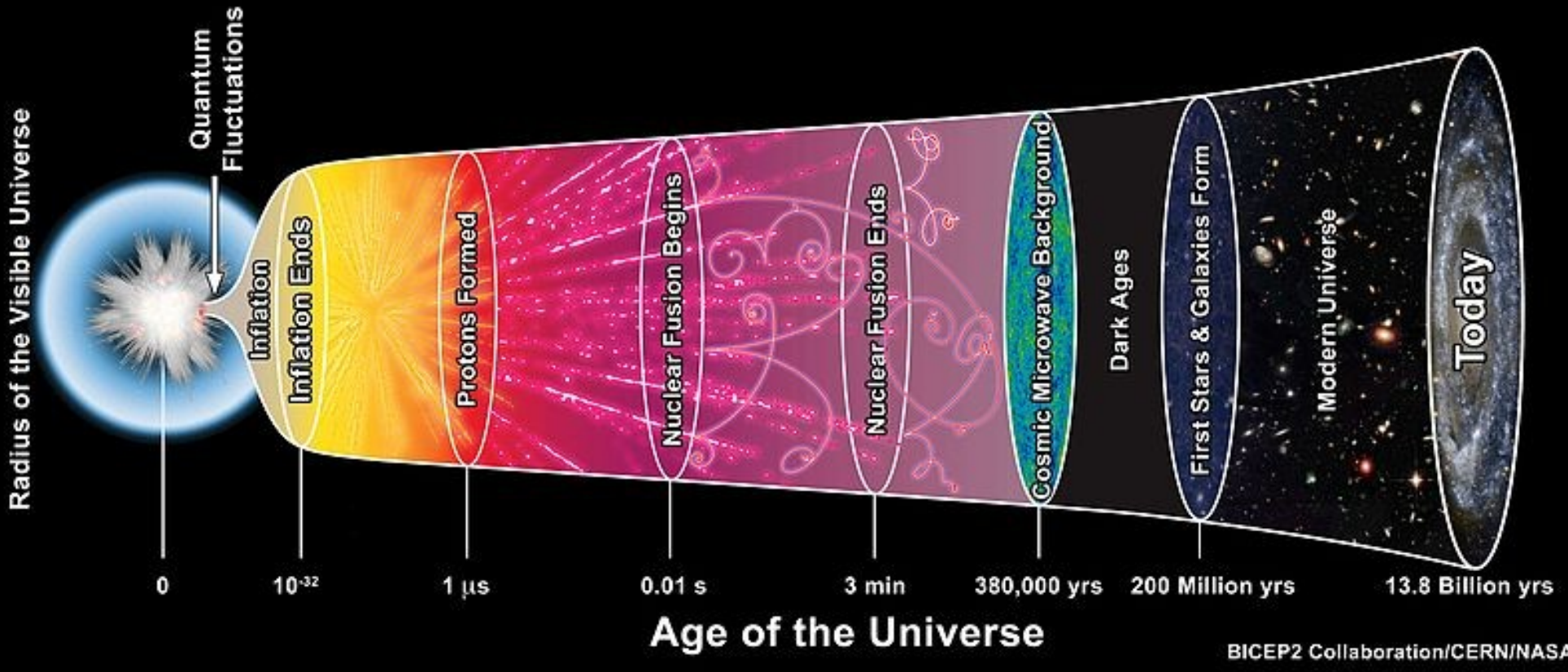


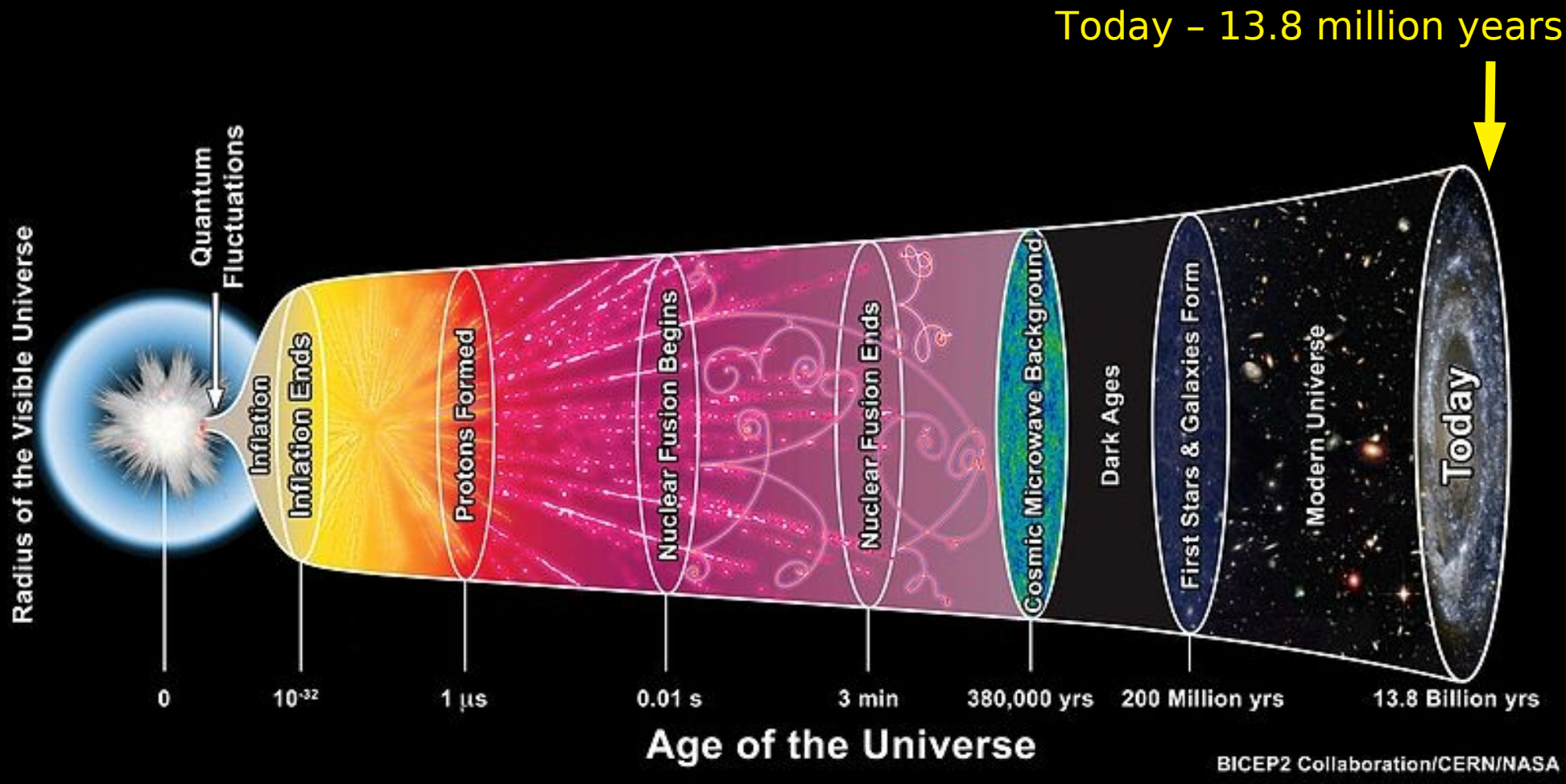
Did the laws of physics apply differently to matter than to anti-matter in the early Universe?



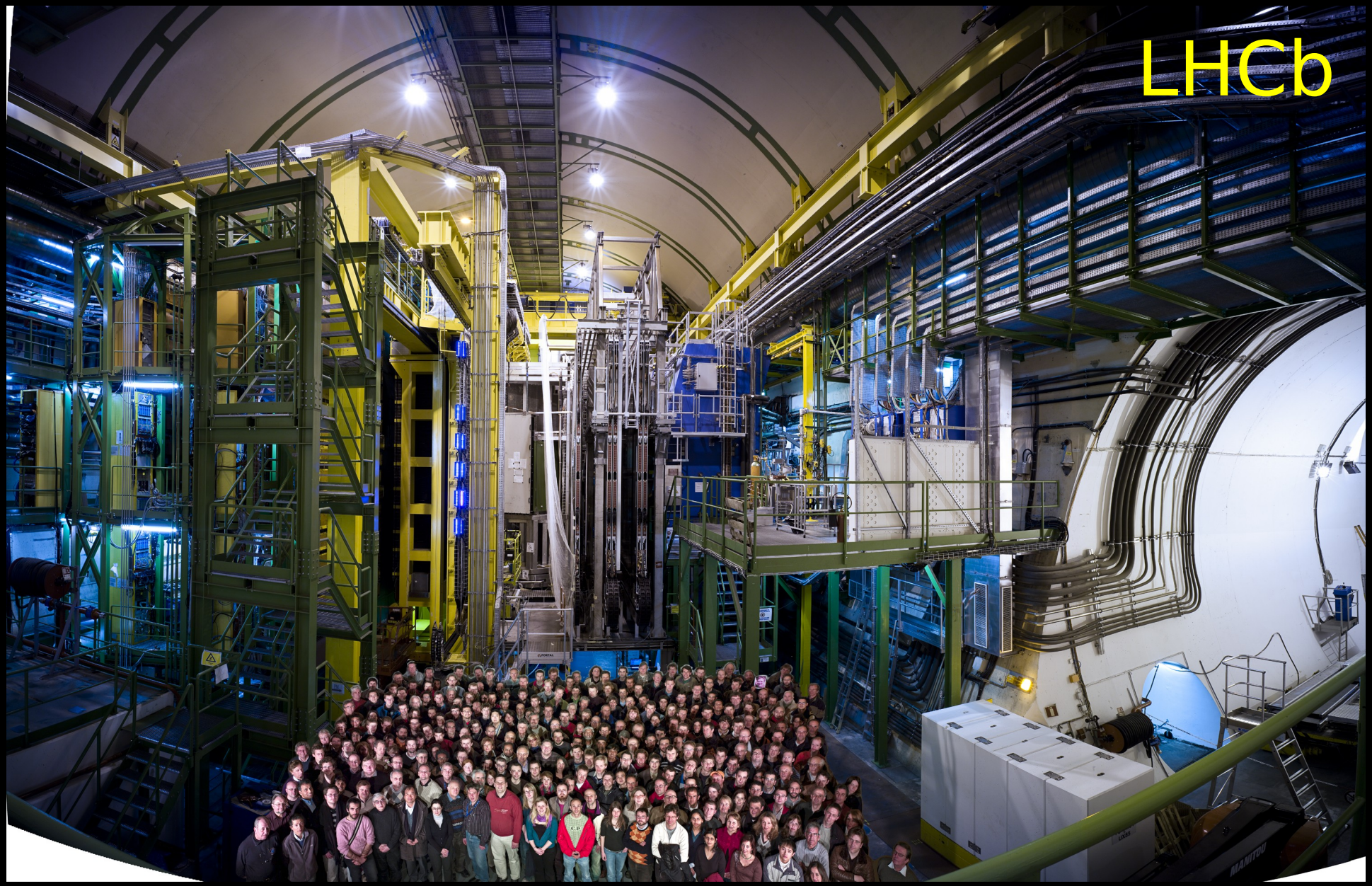
- Probably. But we can't recreate these conditions now.
- Perhaps, though, effects from this time still exist in the universal laws we have today?



Do the laws of physics apply differently to matter than to anti-matter now?



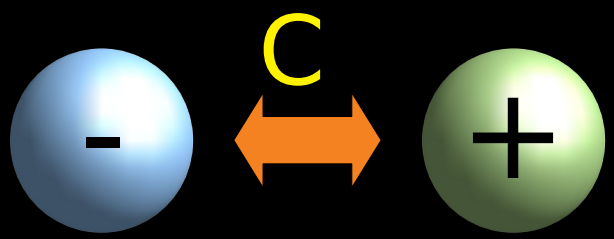
Yes. There is a difference. It is called *CP Violation*



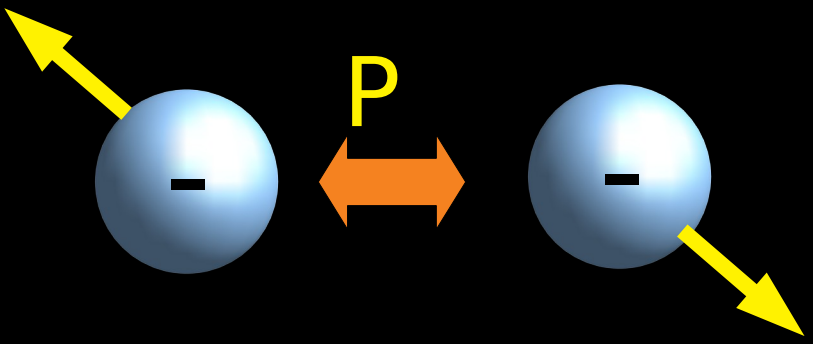
CP Violation

Symmetry operations :

- C (charge conjugation) :

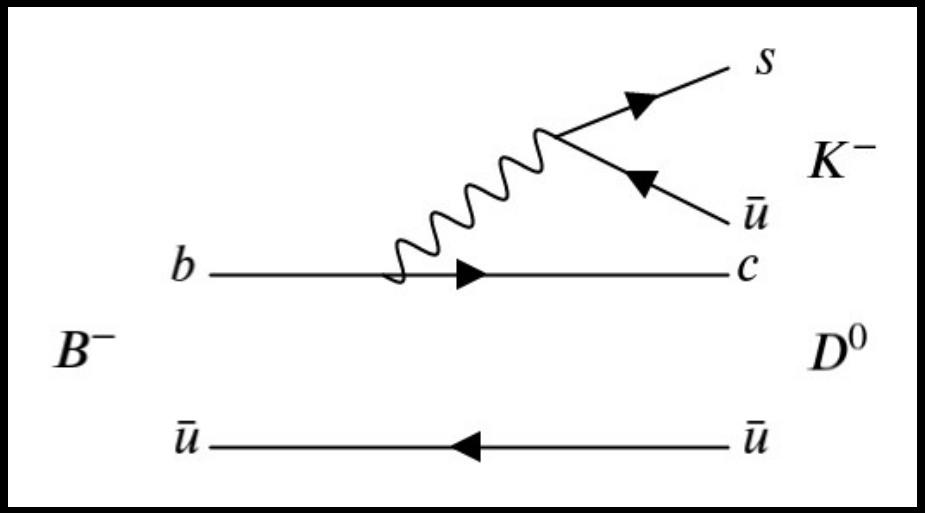


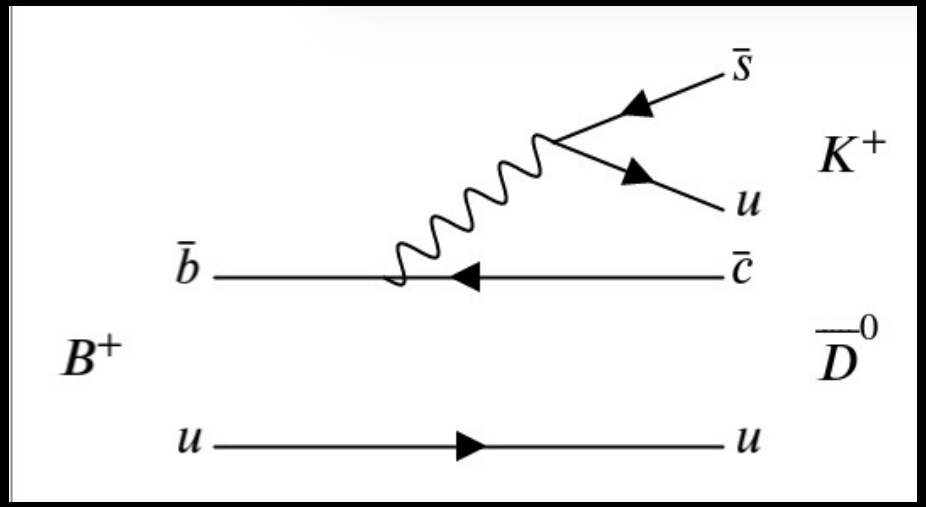
- P (parity) : $\mathbf{r} \rightarrow -\mathbf{r}$

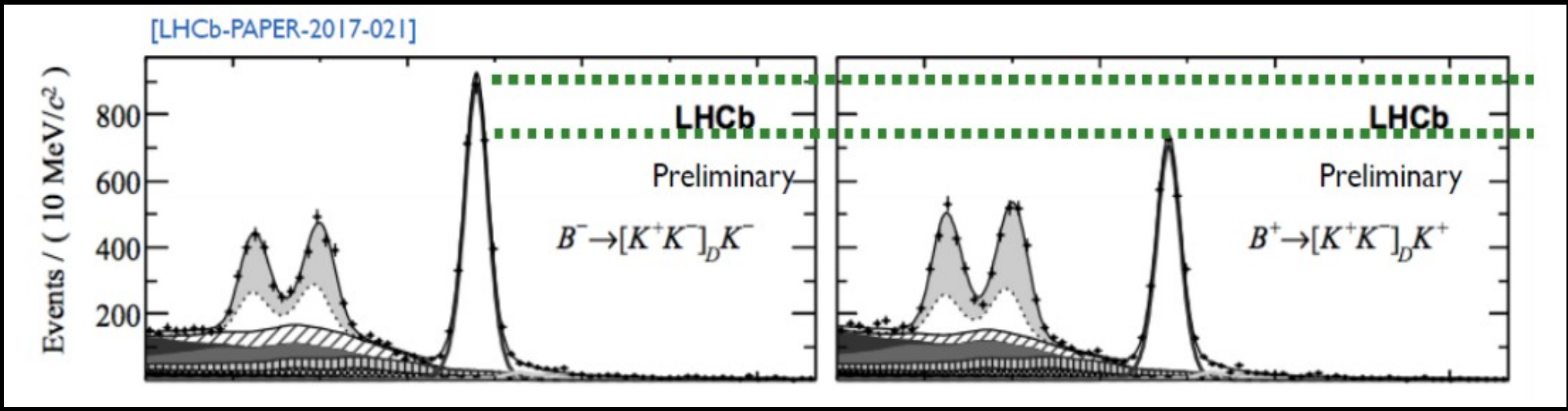


If universe is CP symmetric $\Rightarrow$ Prob(A $\rightarrow$ B) = Prob($\bar{A} \rightarrow \bar{B}$)

CP Violation







R. Aaij et al., Phys. Lett. B 777 (2018) 16-30

CP Violation

The Cosmic Microwave Background can be used to show that

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} = 10^{-10}$$

Measurements on quarks :

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} = 10^{-20}$$

Many many many orders of magnitude out!!!!!!

We need another source of CP violation

CP Violation

The Cosmic Microwave Background can be used to show that

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} = 10^{-10}$$

Measurements on quarks :

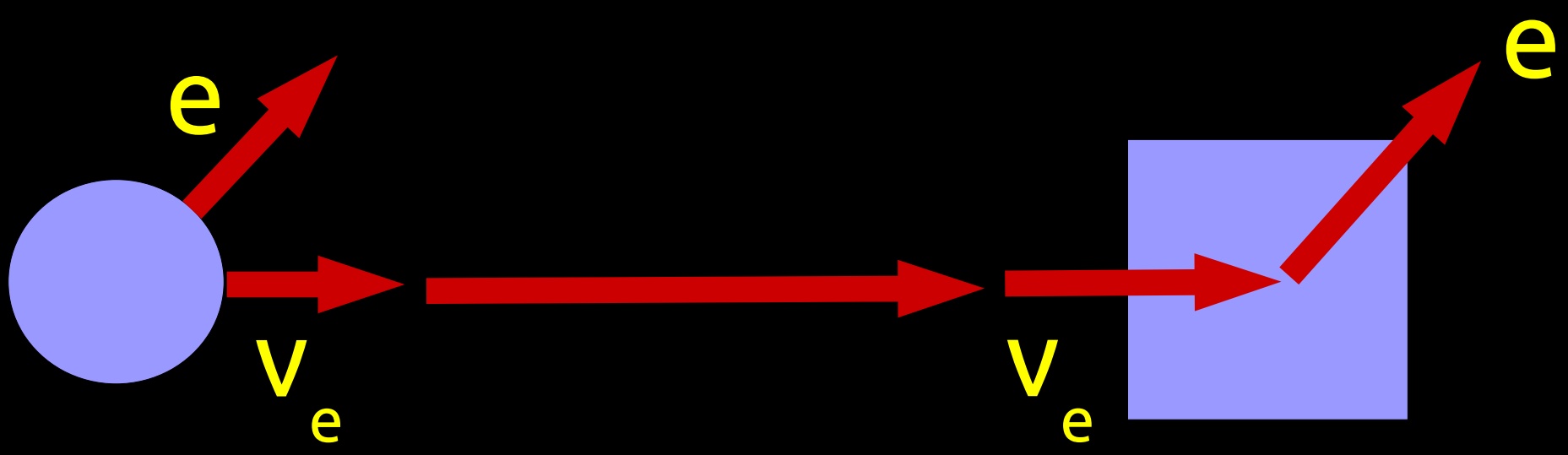
$$\frac{n_B - n_{\overline{B}}}{n_\gamma} = 10^{-20}$$

What about the leptons?

Neutrino reminder

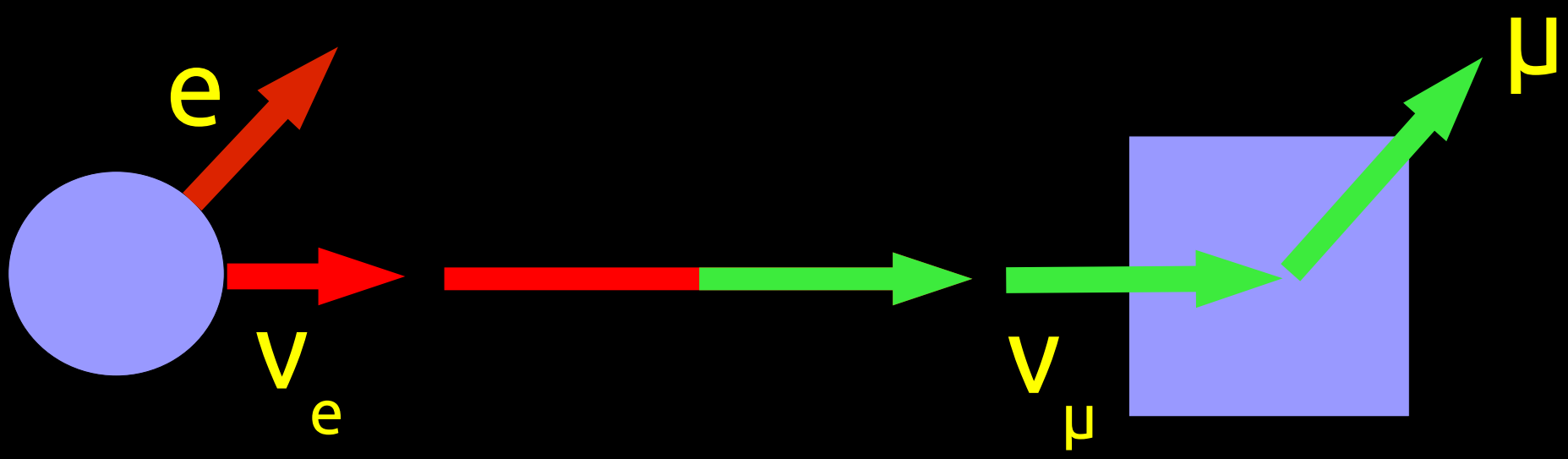
- Three flavours; associated with charged partner
- Lightest, electrically neutral fermions
- Masses less than 10’s of meV
- Extremely small interaction probabilities

Neutrino Flavour Oscillations



How we might view a typical neutrino experiment

Neutrino Flavour Oscillations



Neutrinos can change type as they travel through space

Two-Flavour Approximation

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta)\sin^2\left(1.27(\Delta m^2/eV^2)\frac{(L/km)}{(E/GeV)}\right)$$

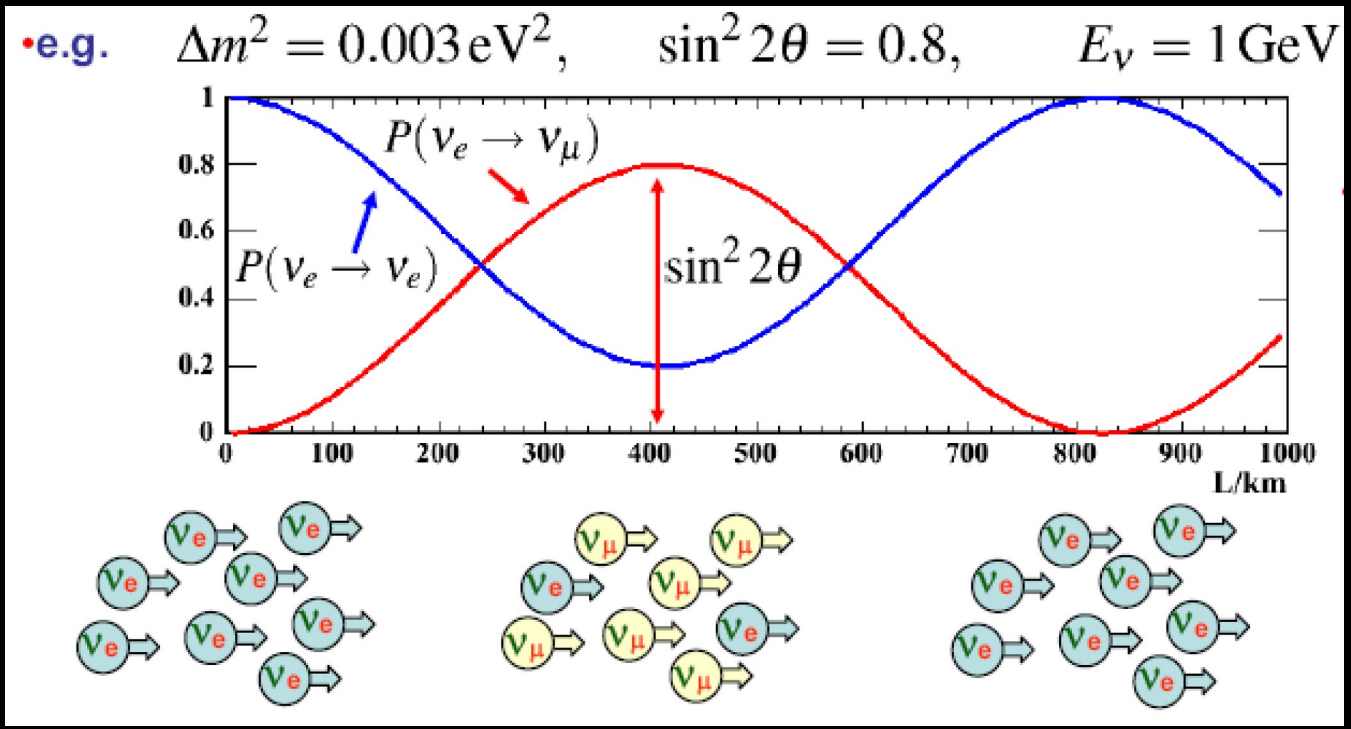
Oscillation amplitude

Oscillation wavelength

Δm^2: $m_1^2 - m_2^2$

L : flight distance

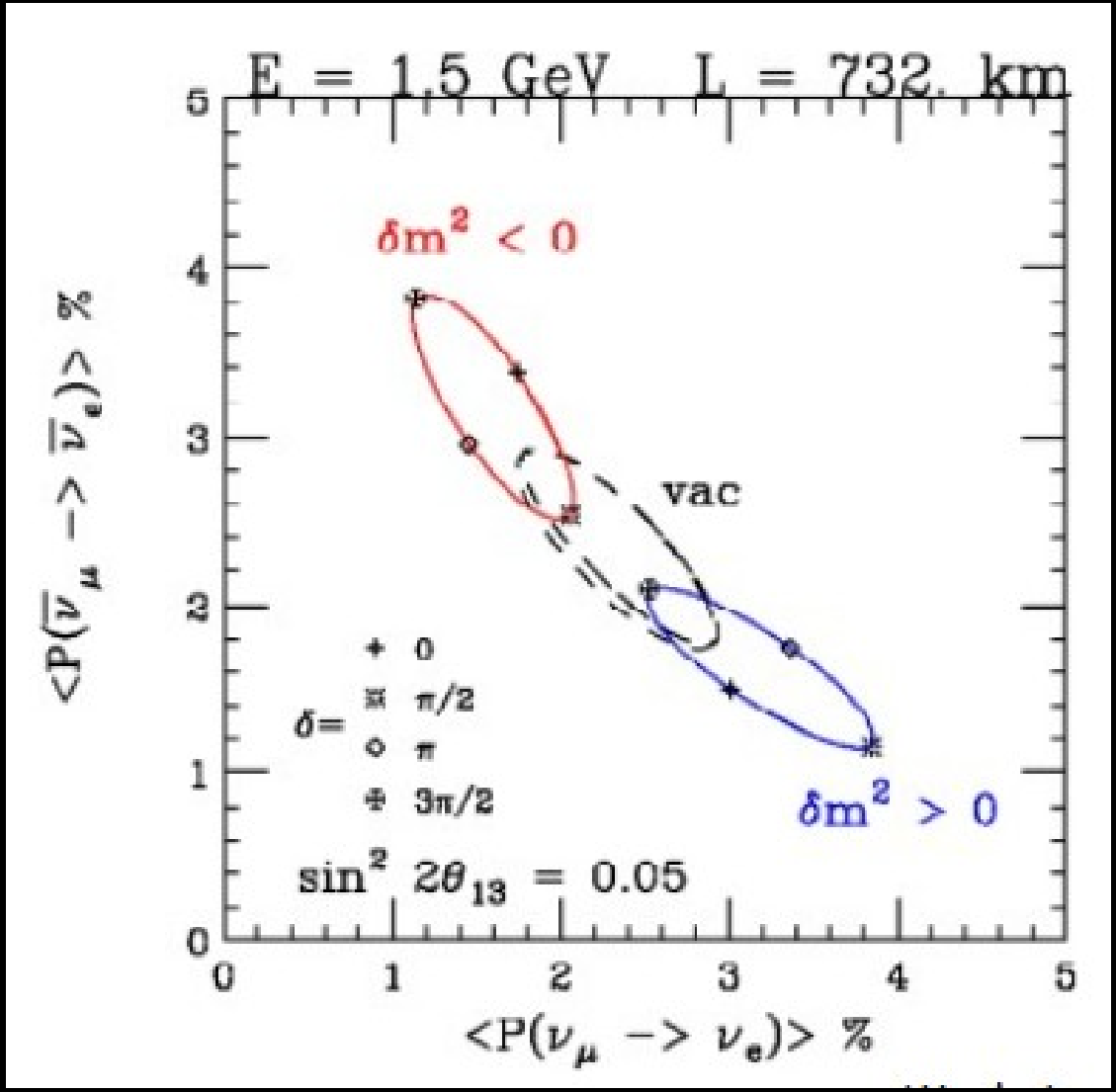
E : neutrino energy



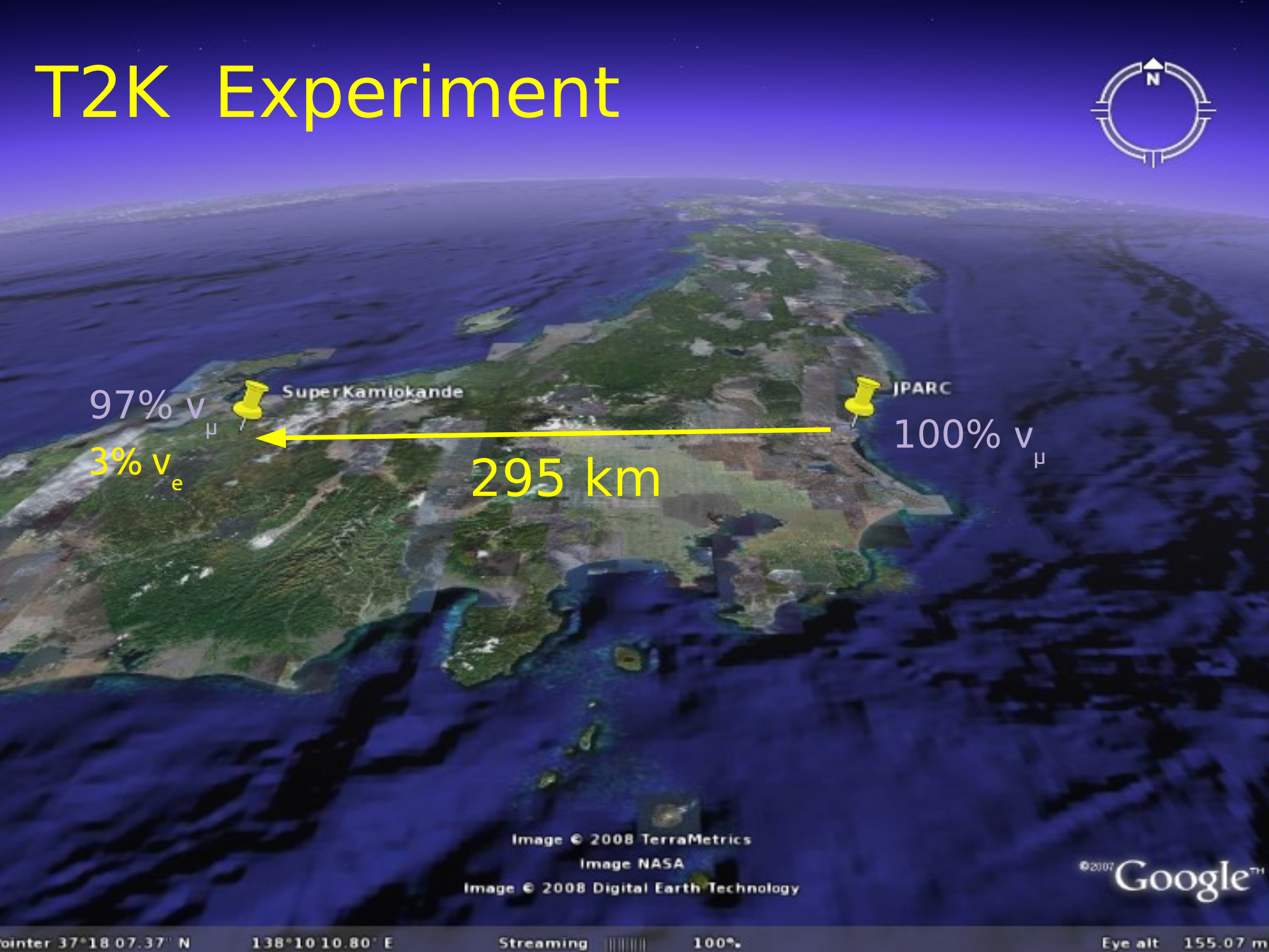
CP violation

- δ_{CP} : CP Phase
- $\delta_{CP} = 0 \Rightarrow$ No CP violation
- $\delta_{CP} = -\pi/2 \Rightarrow$ Maximum CP violation

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$$

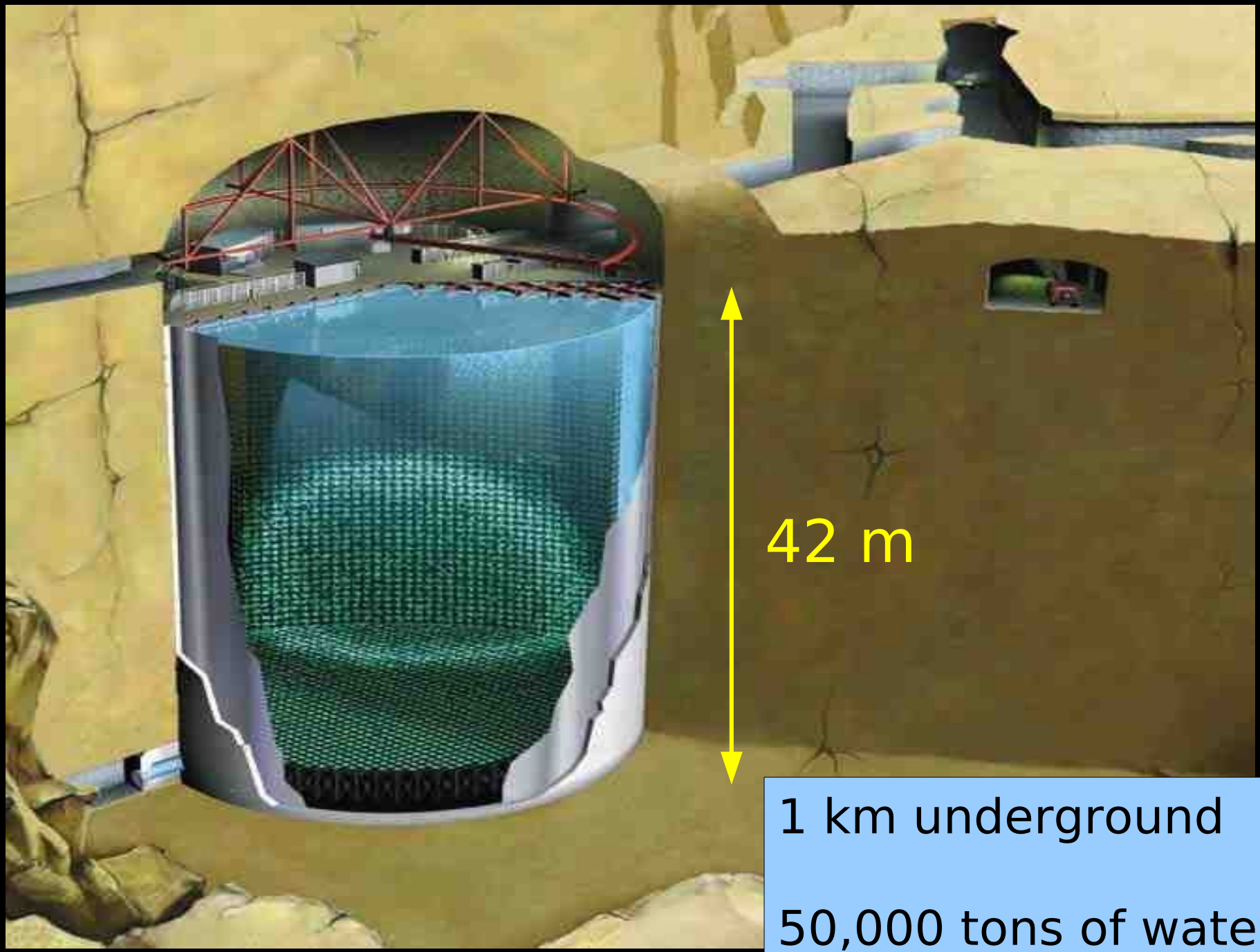


T2K Experiment



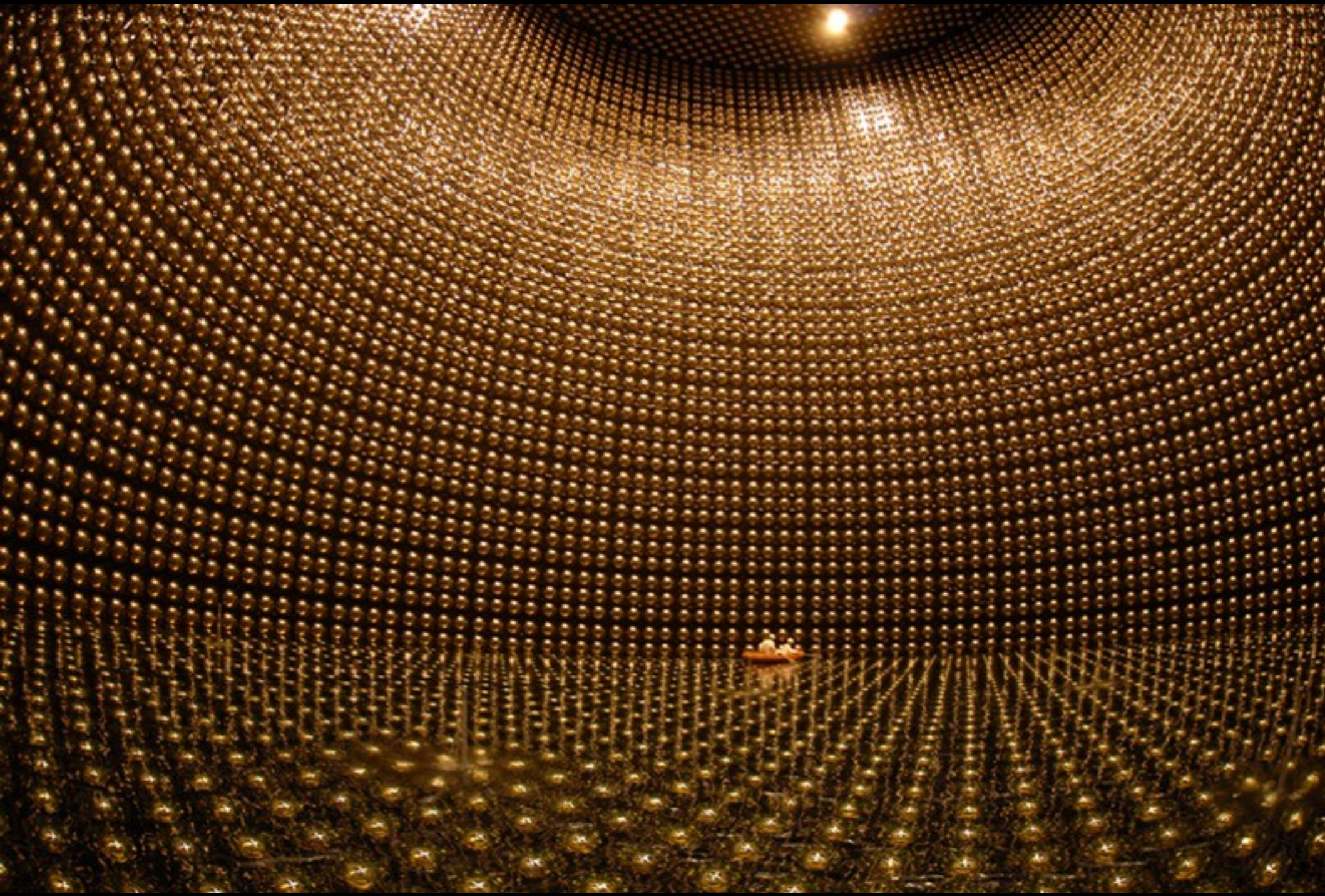
JPARC Facility in Japan

Super-Kamiokande

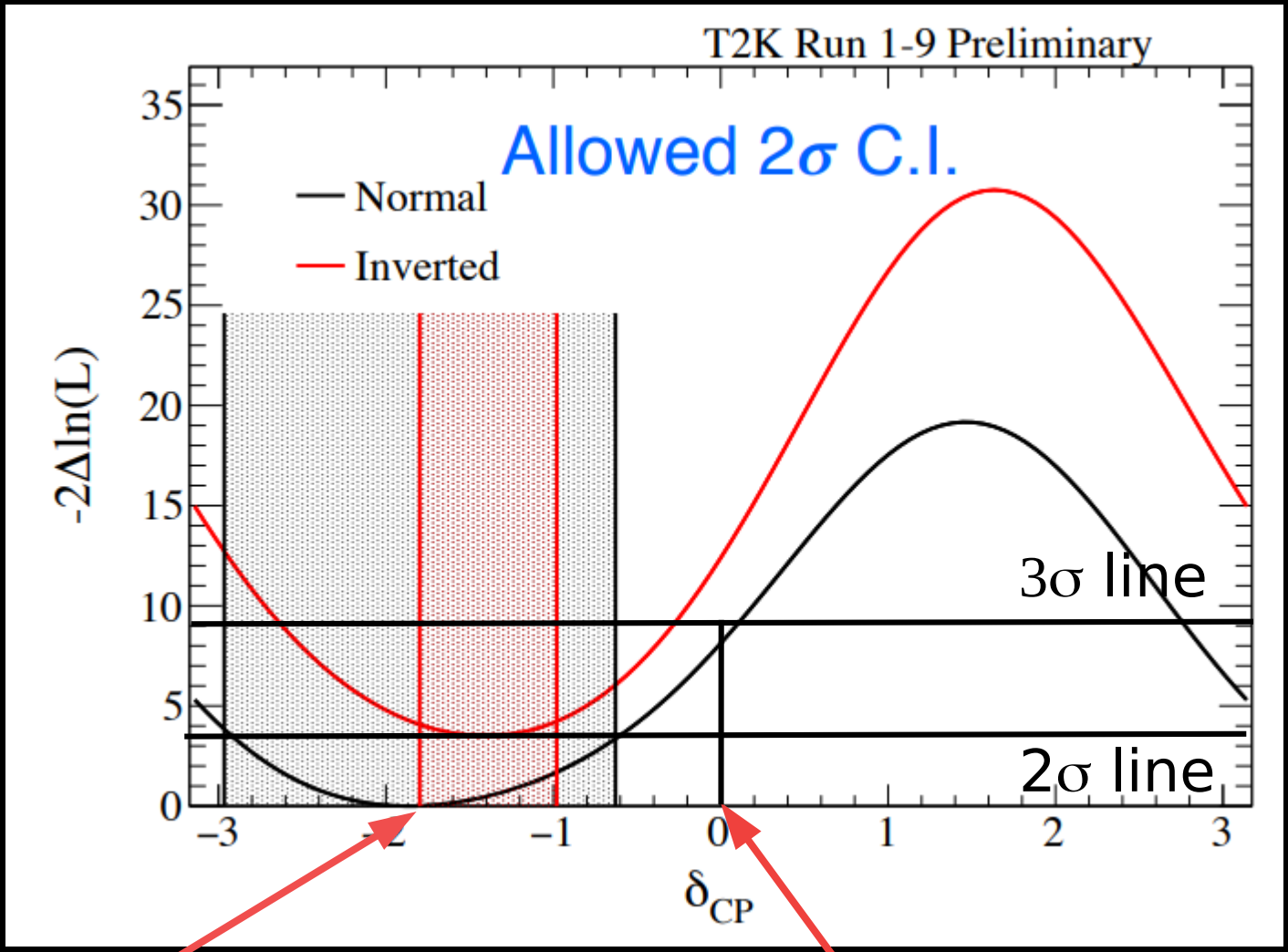


1 km underground

50,000 tons of water



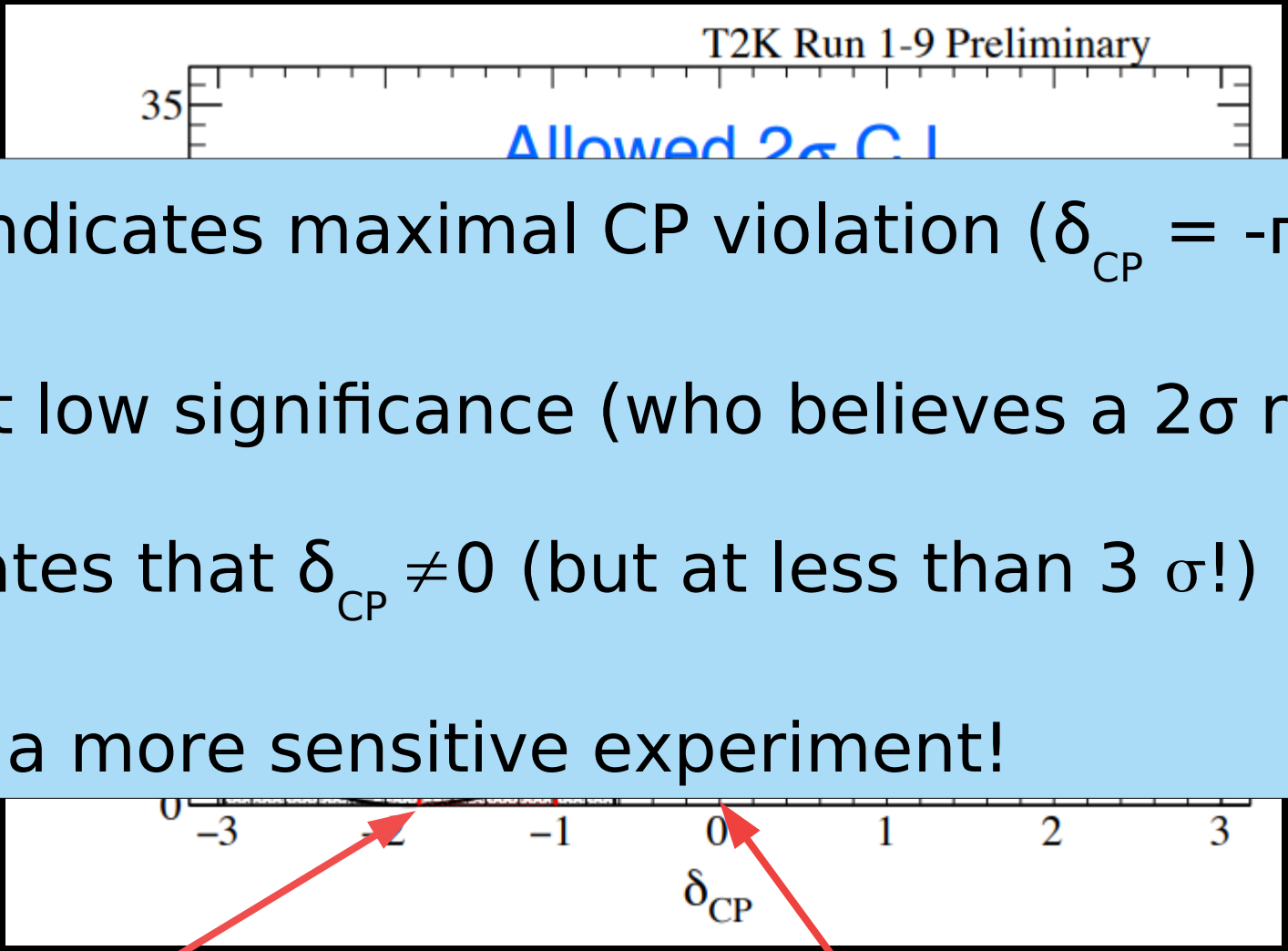
CP Measurement



Maximal CP violation
in neutrinos

CP Conserved
in neutrinos

CP Measurement

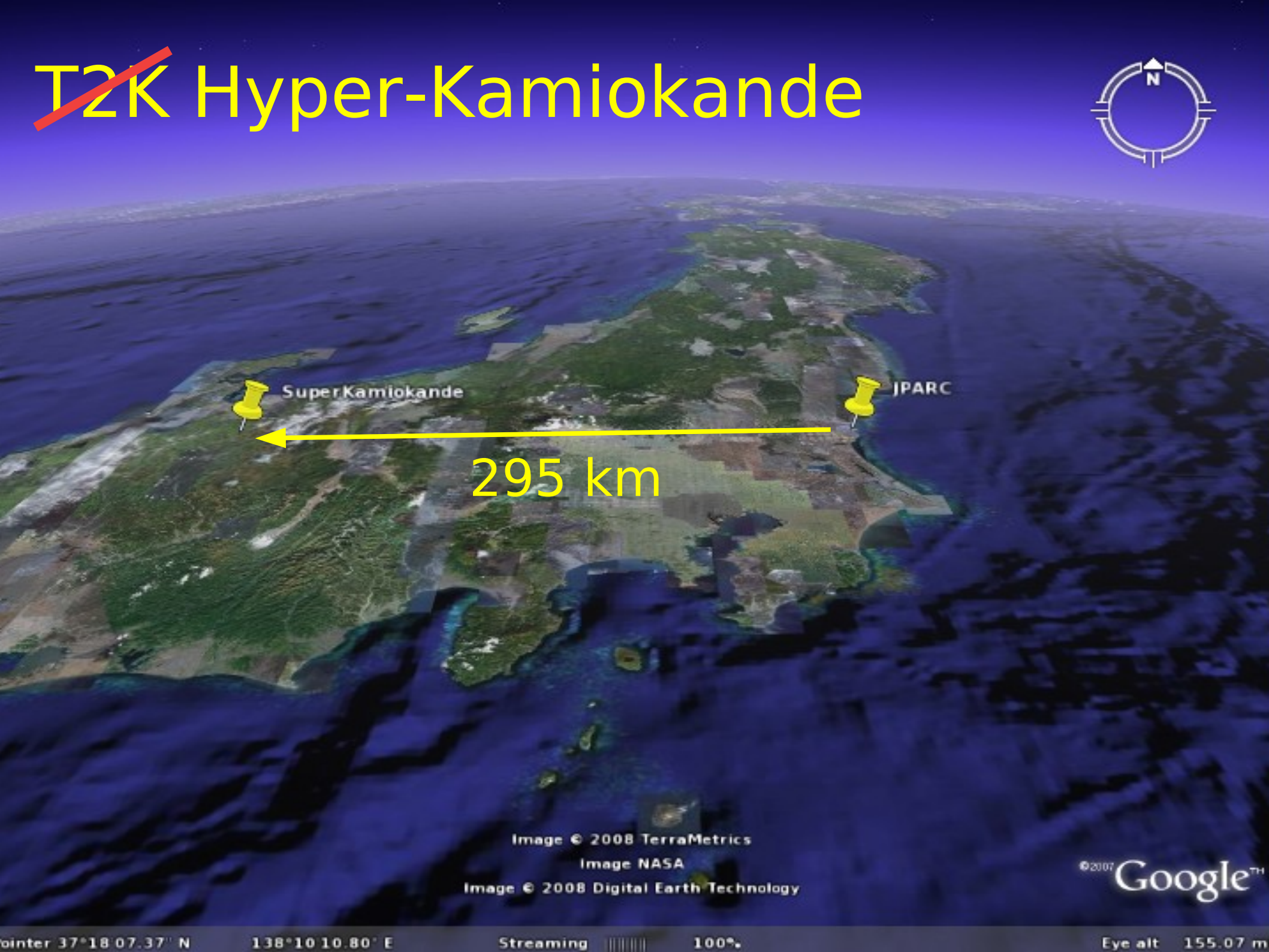


- T2K indicates maximal CP violation ($\delta_{CP} = -\pi/2$)
- But at low significance (who believes a 2σ result?)
- Indicates that $\delta_{CP} \neq 0$ (but at less than 3 σ!)
- Need a more sensitive experiment!

Maximal CP violation in neutrinos

CP Conserved in neutrinos

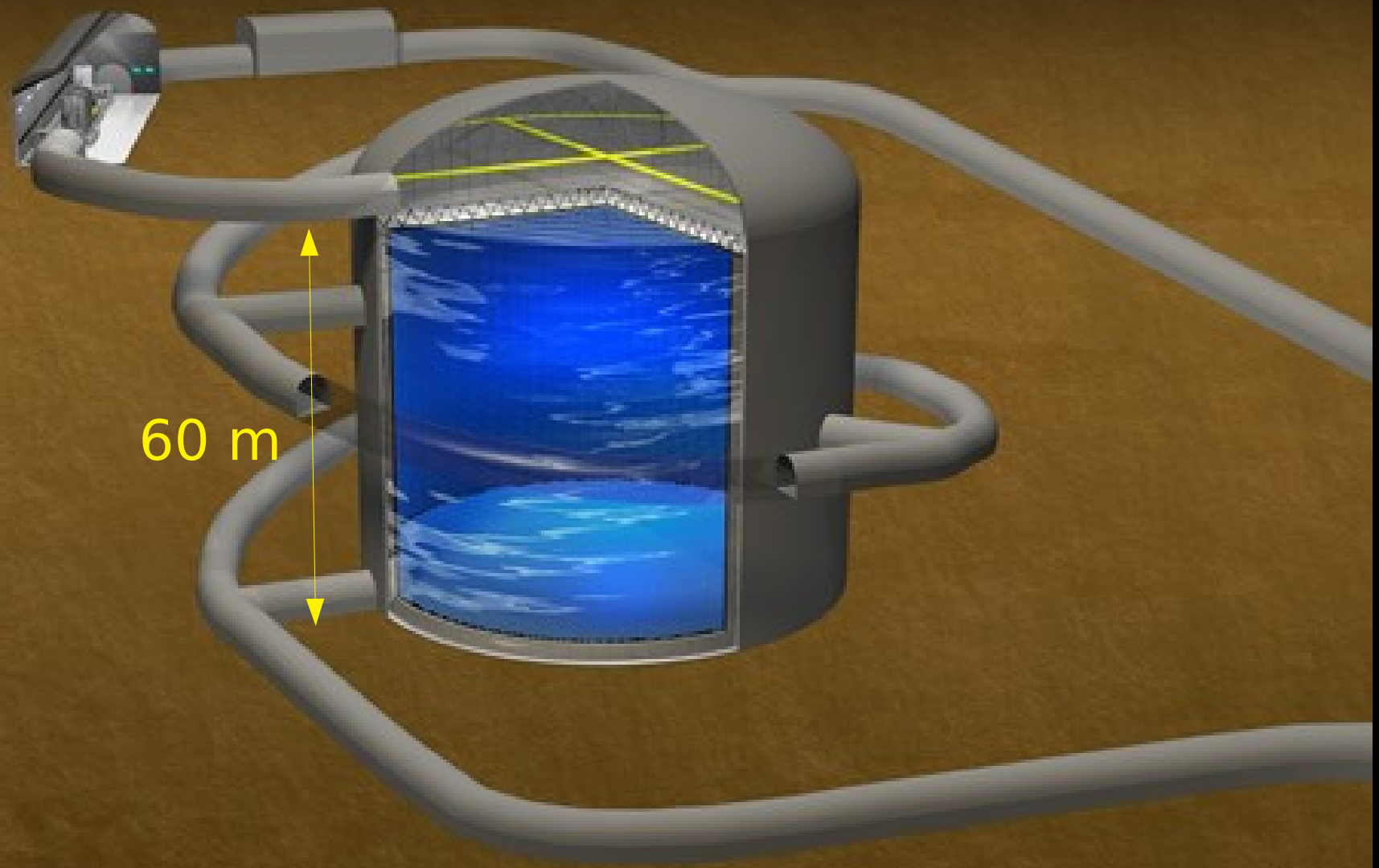
~~T2K~~ Hyper-Kamiokande



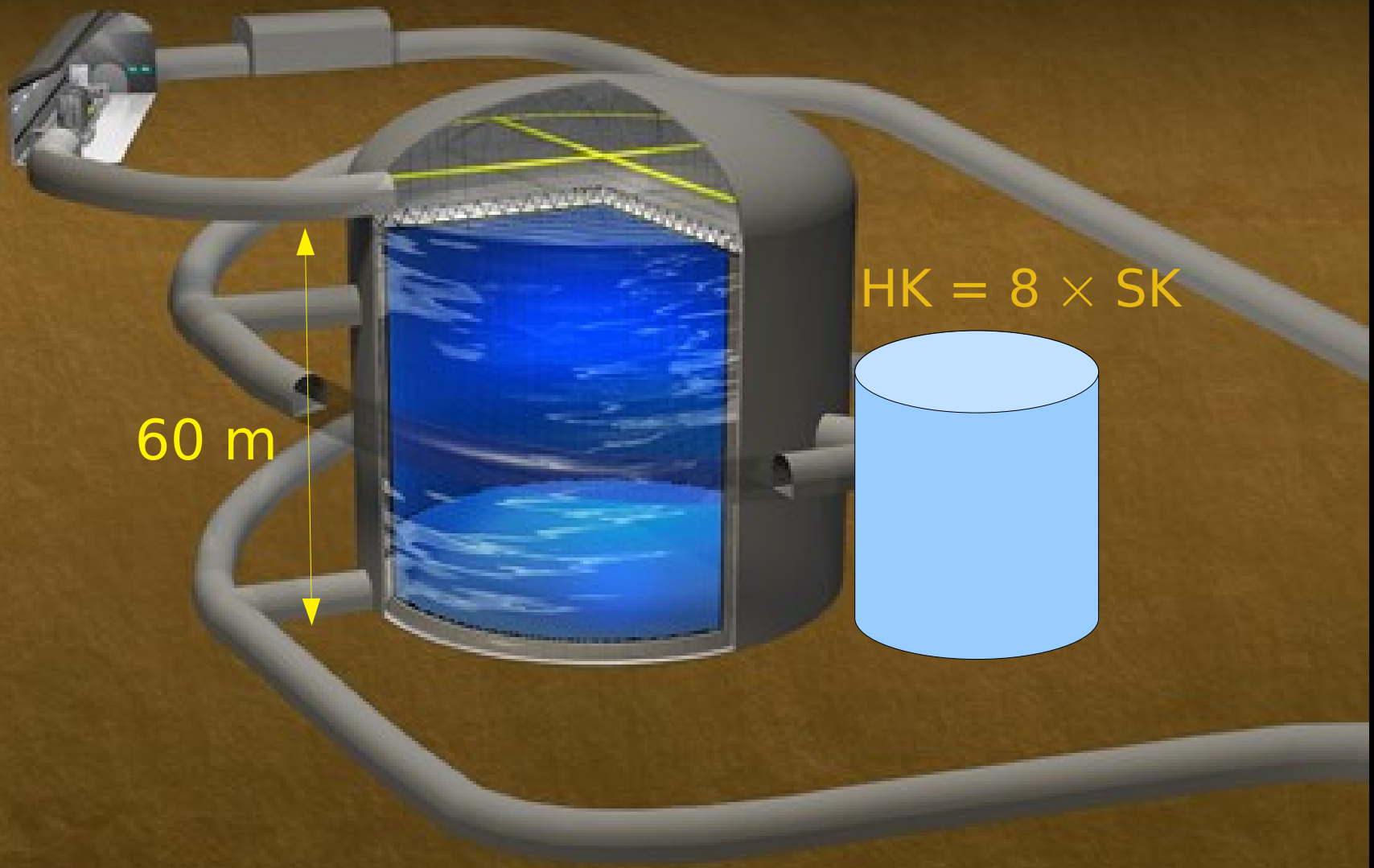
JPARC Facility in Japan

JPARC Facility in Japan

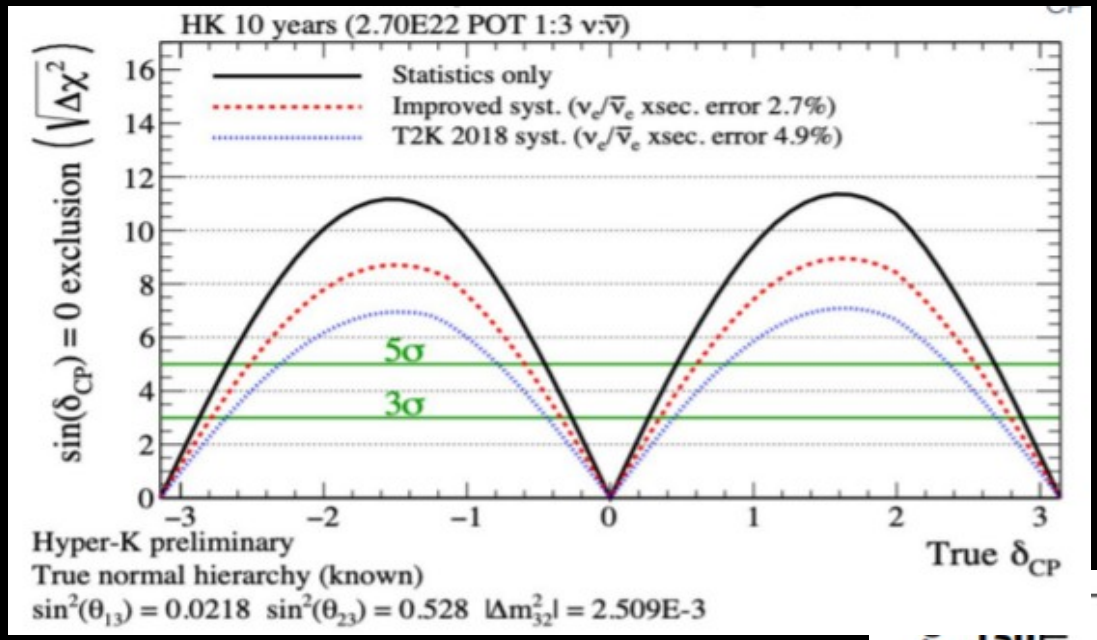
At the core of Mt Nijugo in Tochibora mine
Detector mass of 200 kton of pure water



At the core of Mt Nijugo in Tochibora mine
Detector mass of 260 kton of pure water

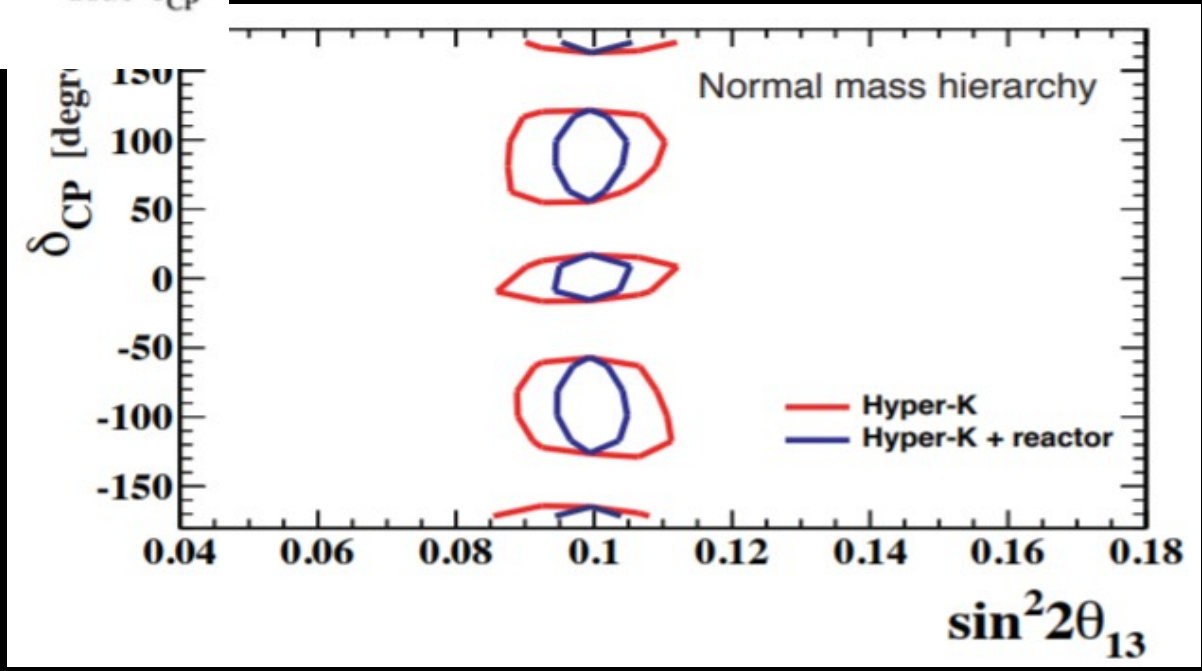


What can HK do?



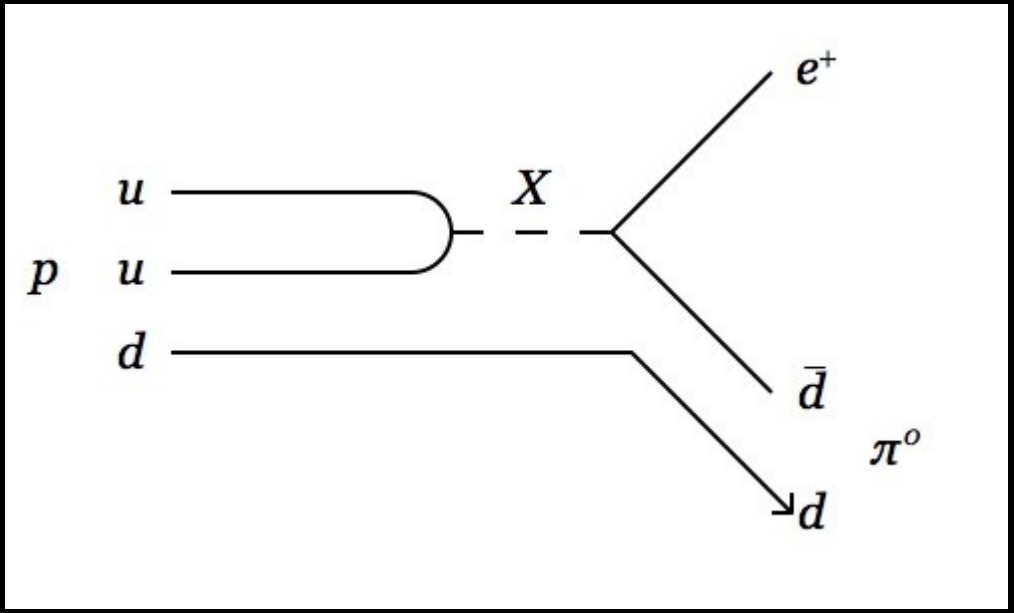
- Can exclude $\delta_{CP} = 0$ at 5σ after 3 years of operation
- 10σ after 10 years of operation

- Can measure δ_{CP} to around 20-30° after 5 years of operation.



Other physics – Proton decay

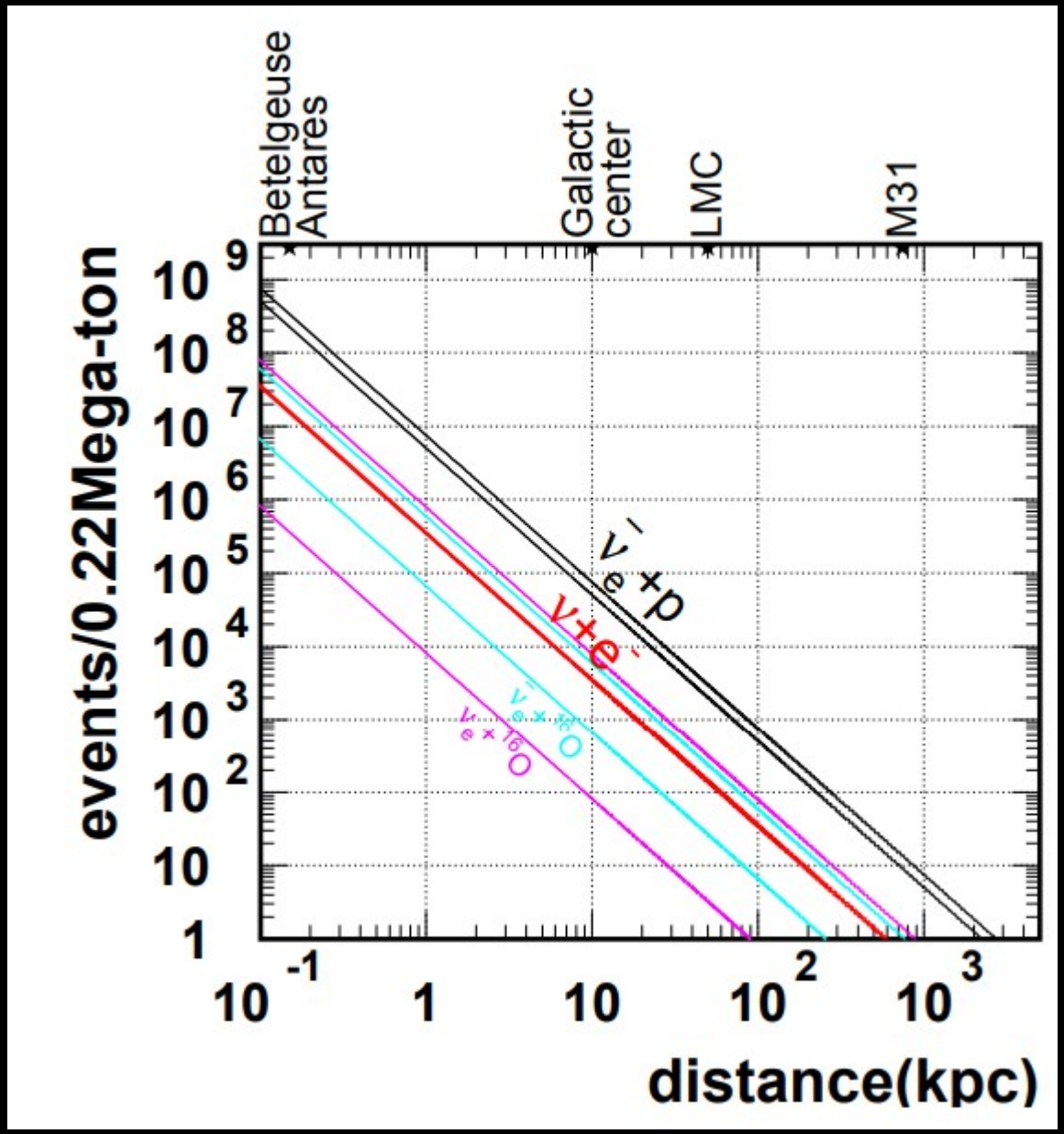
- Proton decay cannot happen in the current standard model of particle physics
- Observation of proton decay would indicate new physics



- Lifetime > 10^{34} yrs
- Greater sensitivity requires more protons

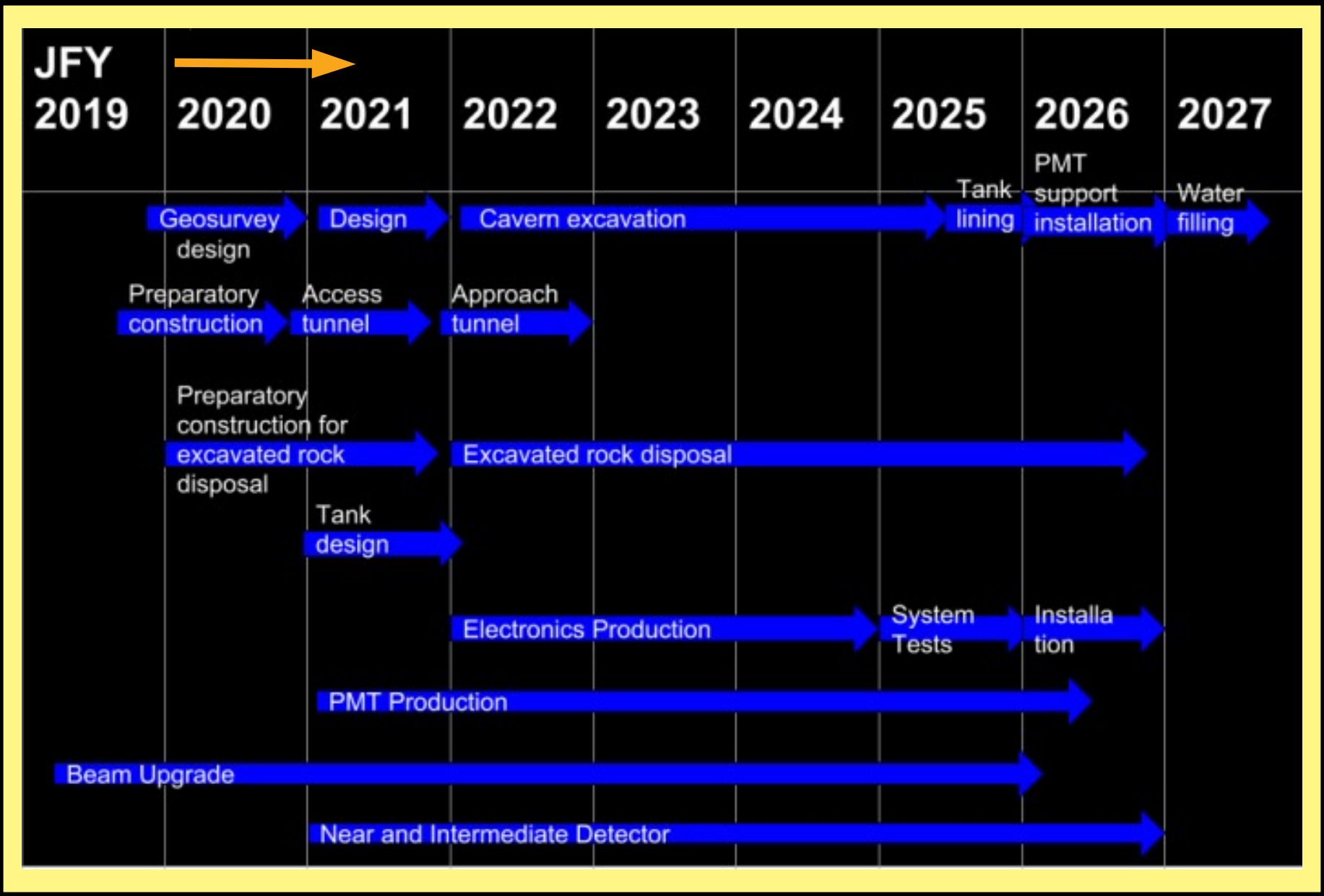
- Big tanks of water are perfect!

Supernovae

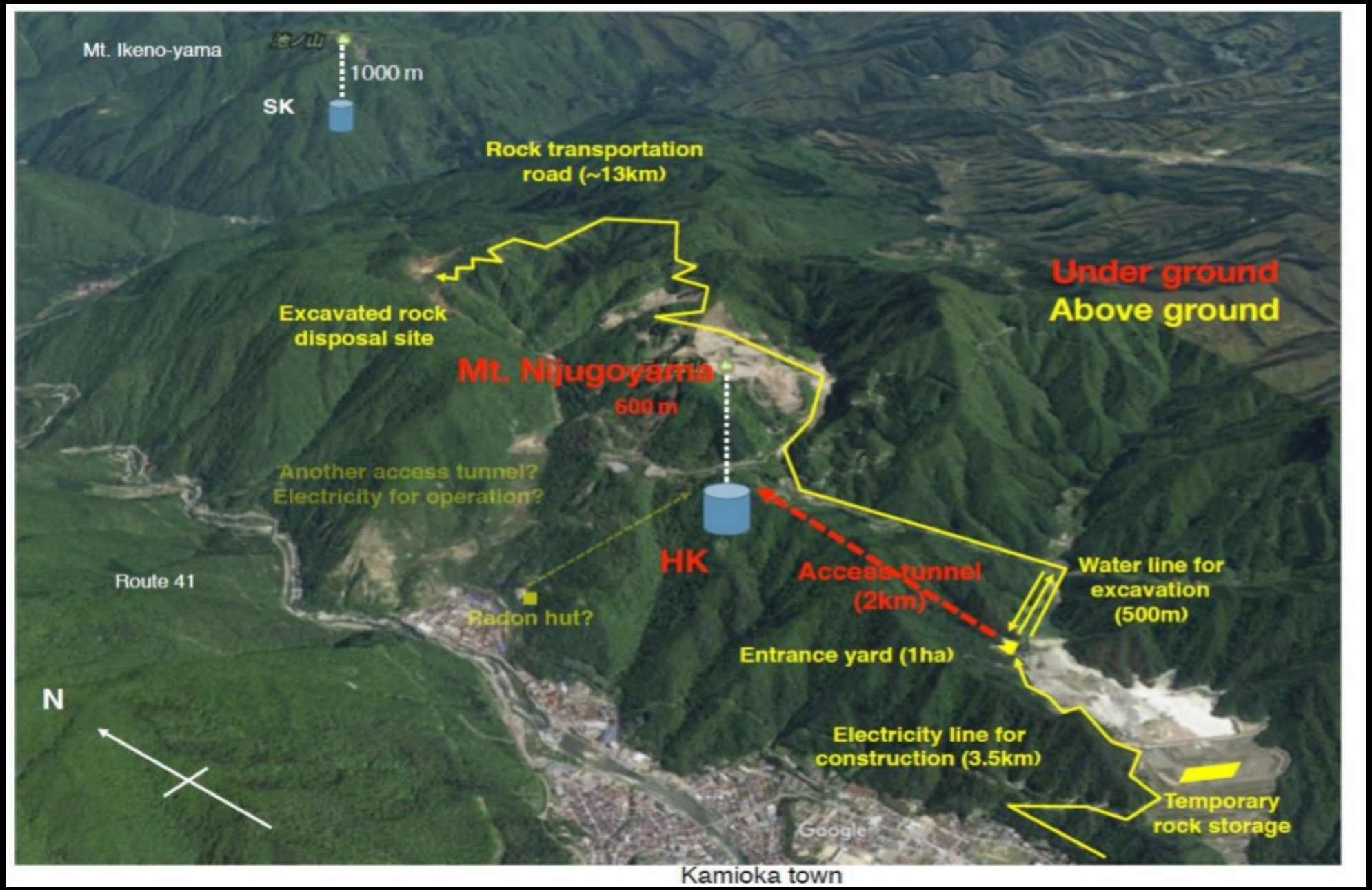


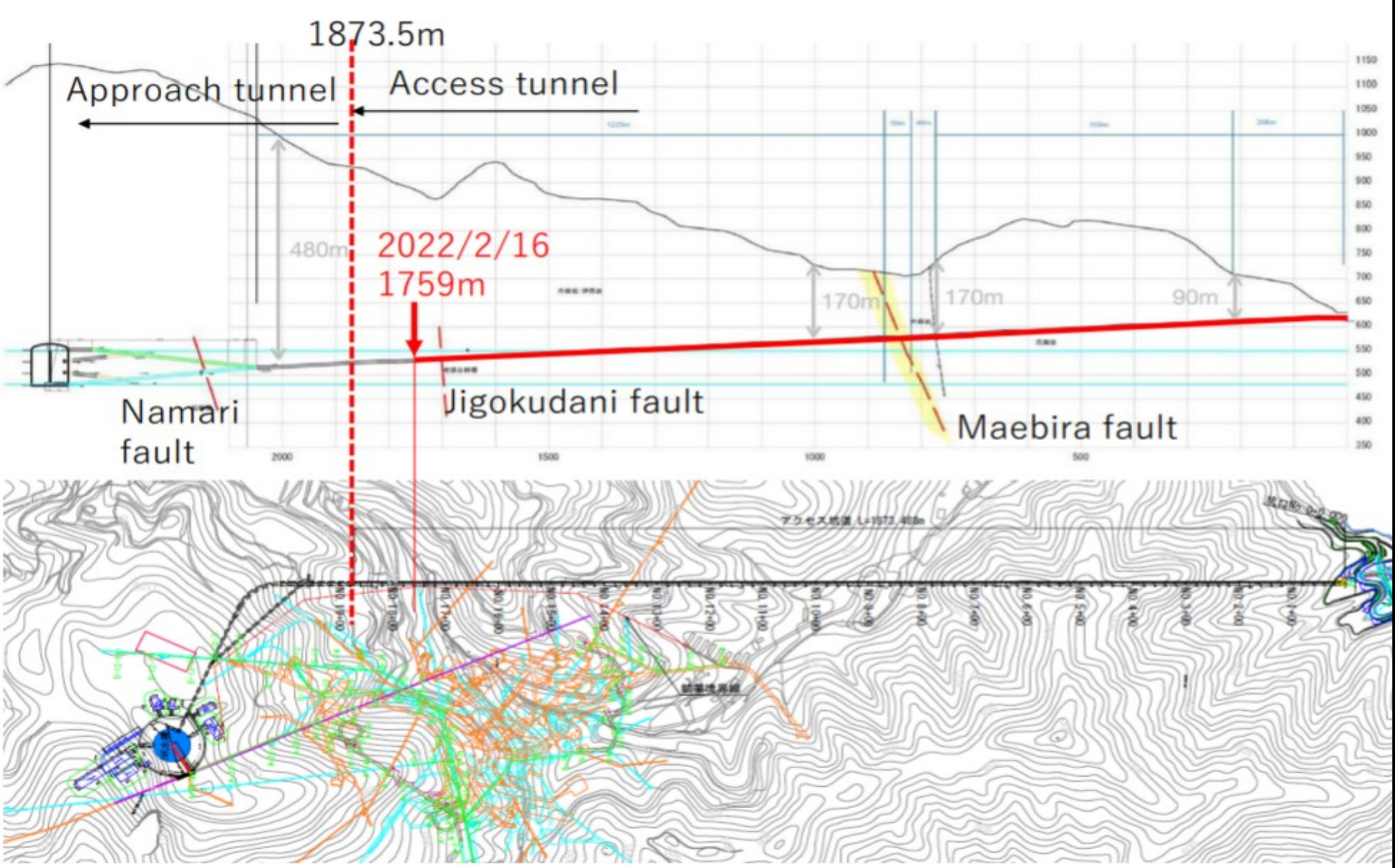
- HK would see 2-3 thousand events from SN in the LMC
- SN in galactic center would give us about 100k events (in tens of seconds)
- Integrate with global Supernova Early Warning (SNEWS) system

Schedule


JFY
2019
2020
2021
2022
2023
2024
2025
2026
2027
Geosurvey design
Design
Cavern excavation
Tank lining
PMT support installation
Water filling
Preparatory construction
Access tunnel
Approach tunnel
Preparatory construction for excavated rock disposal
Excavated rock disposal
Tank design
Electronics Production
System Tests
Installation
PMT Production
Beam Upgrade
Near and Intermediate Detector

Construction is Underway




1873.5m
Approach tunnel
Access tunnel
480m
2022/2/16
1759m
170m
170m
90m
Namari
fault
Jigokudani fault
Maebira fault


1873.5m
Approach tunnel
Access tunnel
480m
2022/2/16
1759m
170m
170m
90m


Air
Power and network line
Water

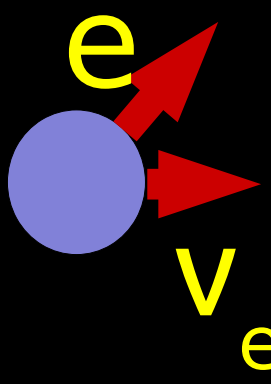

1873.5m
Approach tunnel
Access tunnel
Access Tunnel Completed - 25/2/2022
ハイ バー カミ オカ ンデ
祝 アクセス坑道掘削完了
L= 187 3.4 88m
Air
Water

Summary

- Why are we here? Disappearance of all the antimatter is a Big Question™ in physics.
- CP violation in the neutrino sector?
- Our current experiment, T2K, provides tantalising indications that CP violation is large in the neutrino sector.
- Hyper-Kamiokande (and DUNE), a next gen experiment, will tell us. Data taking begins in 2027. Construction is already under way.

This sparked an idea from Bruno Pontecorvo in 1969

Suppose the (assumed) particle with definite flavour is actually generated as one of three particles with definite mass : ν_1, ν_2 and ν_3



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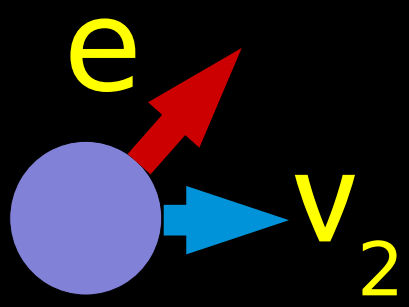
or



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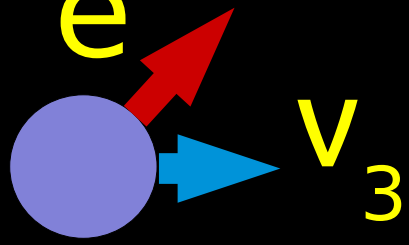
or



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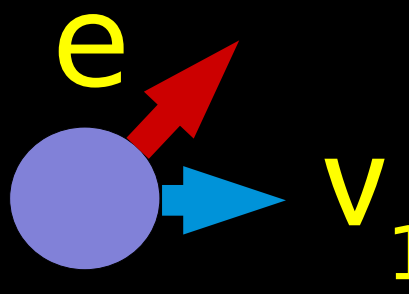

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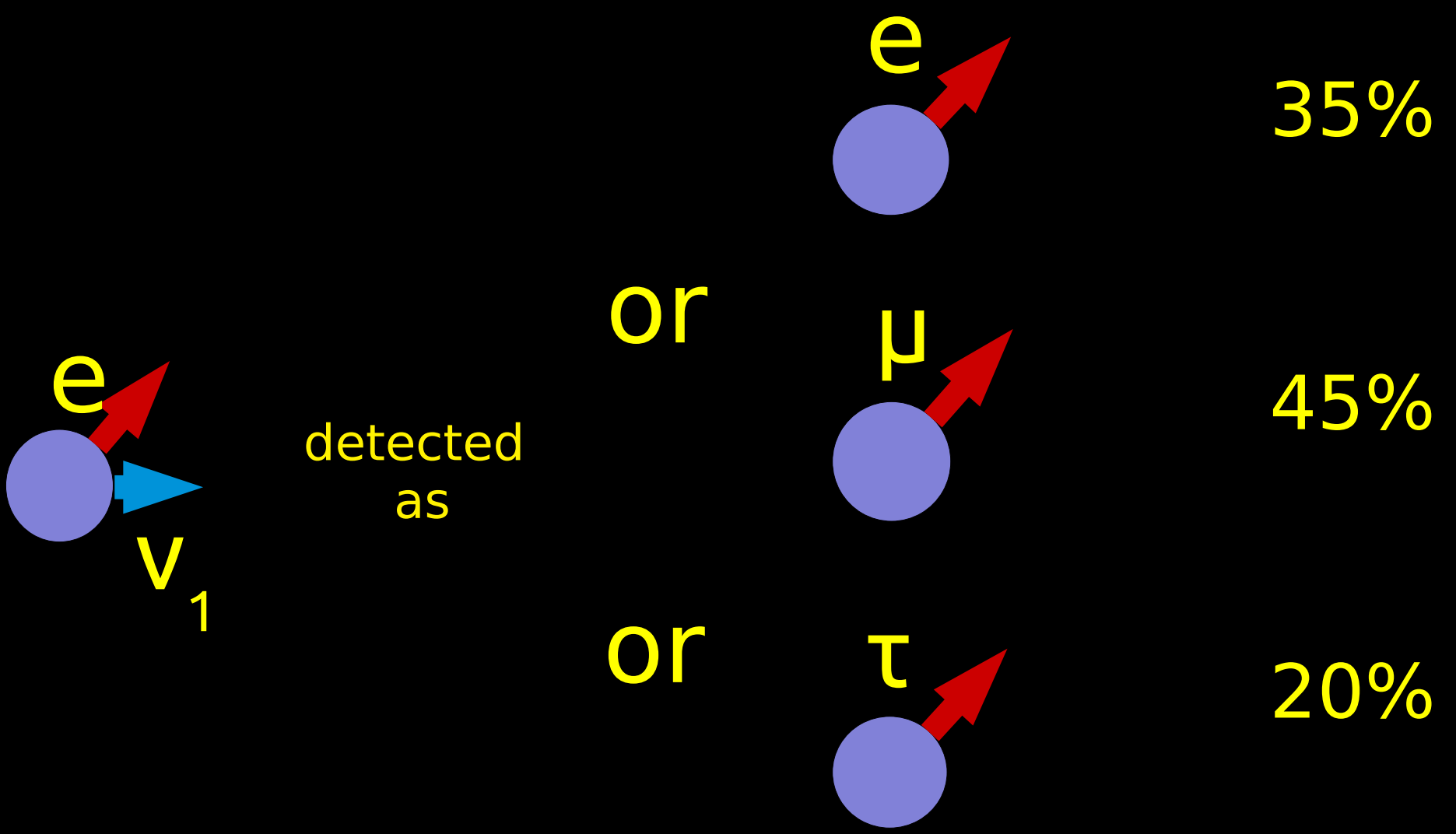
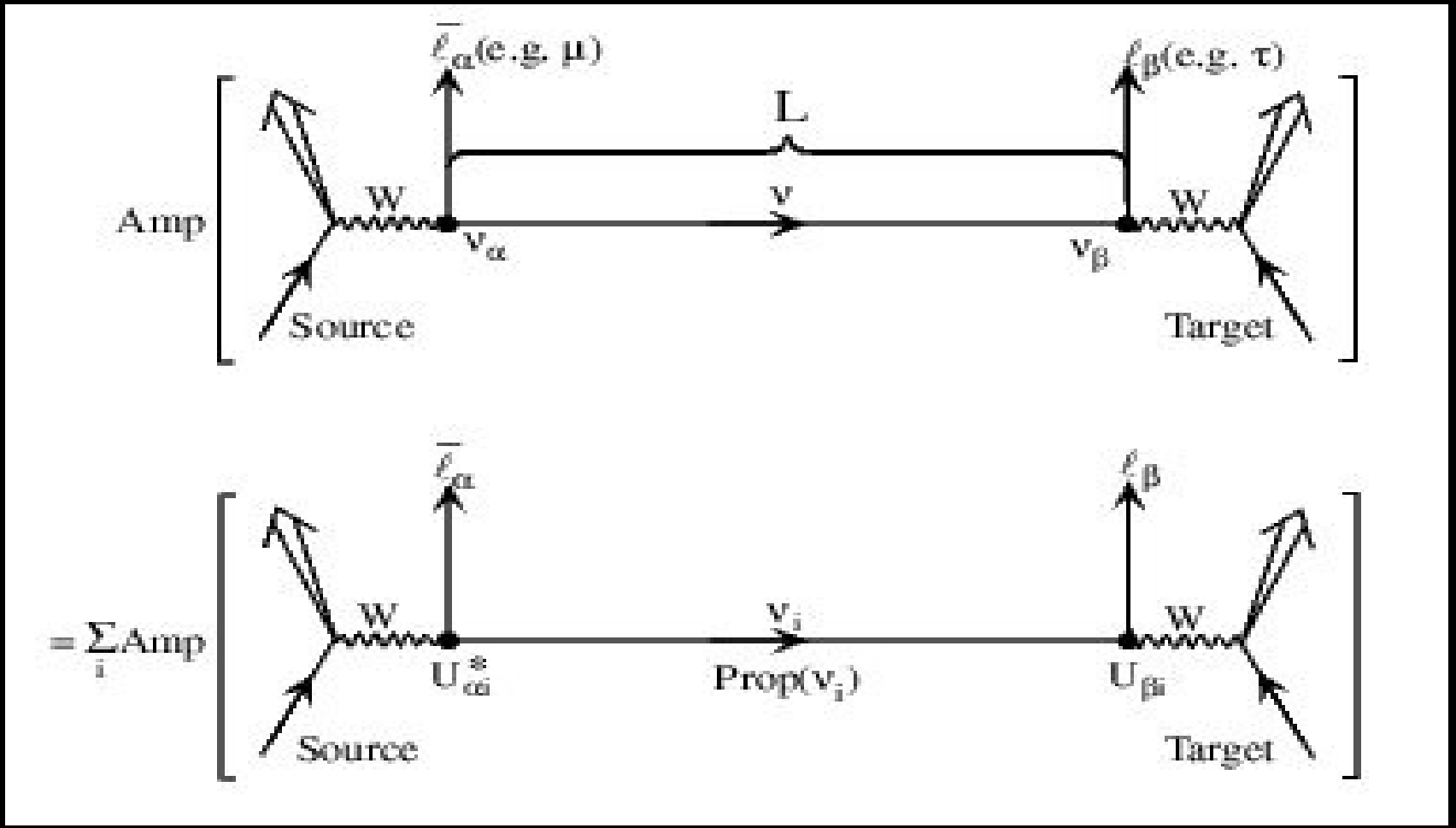
Crucially, because of quantum, the idea works the other way too

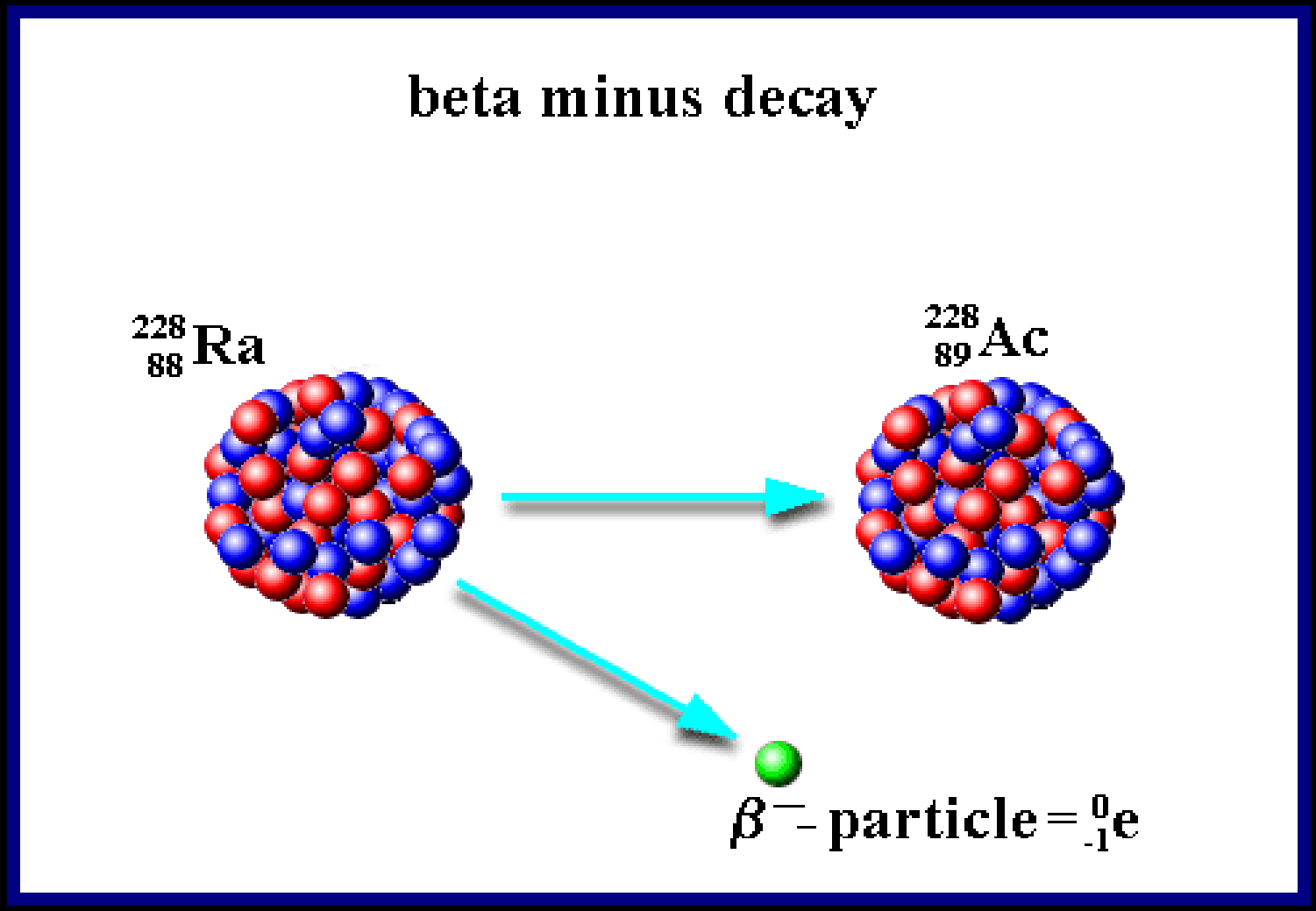


Neutrino Oscillations



$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_{i=1}^{3} Amp(\nu_\alpha \rightarrow \nu_i \rightarrow \nu_\beta) \right|^2$$


CRASH

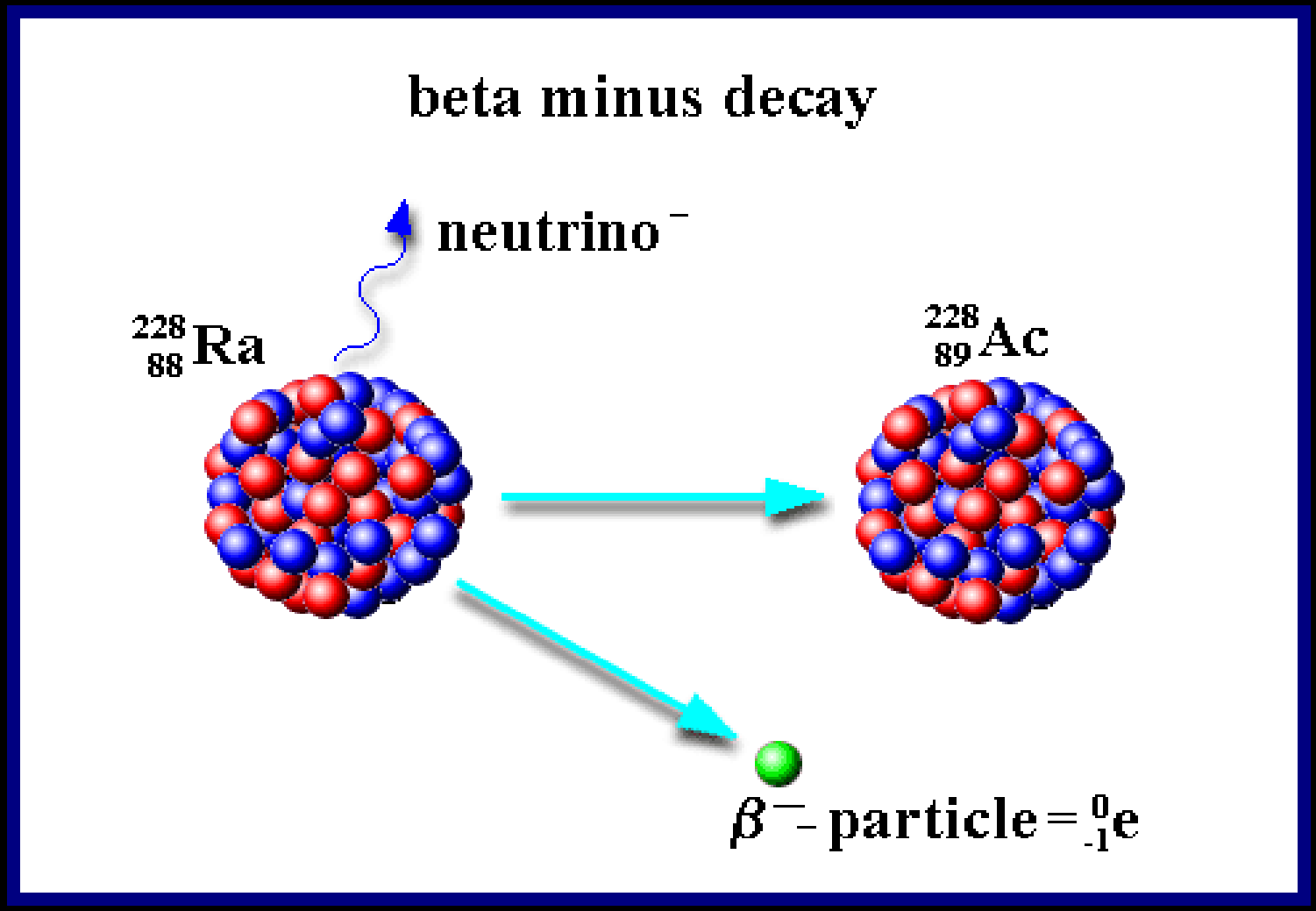


Energy(Ra) ≠ Energy(Ac)+Energy(e)

Wolfgang Pauli

“Desperate remedy.....”
“I do not dare publish this idea....”
“I admit my way out may look improbable....”
“Weigh it and pass sentence....”

“You tell them. I'm off to a party”

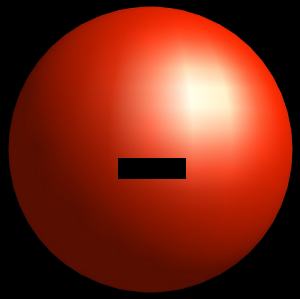


Energy(Ra) = Energy(Ac)+Energy(e)
+ Energy(Neutrino)

What are neutrinos?

Electron, e

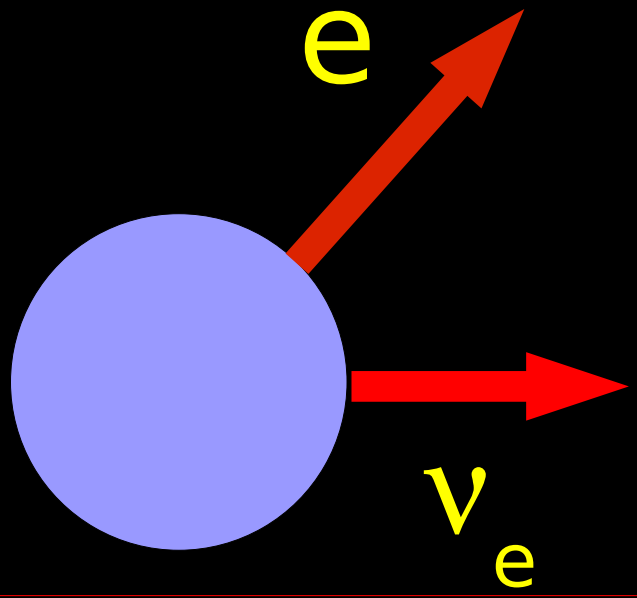
Electron Neutrino, ν_e

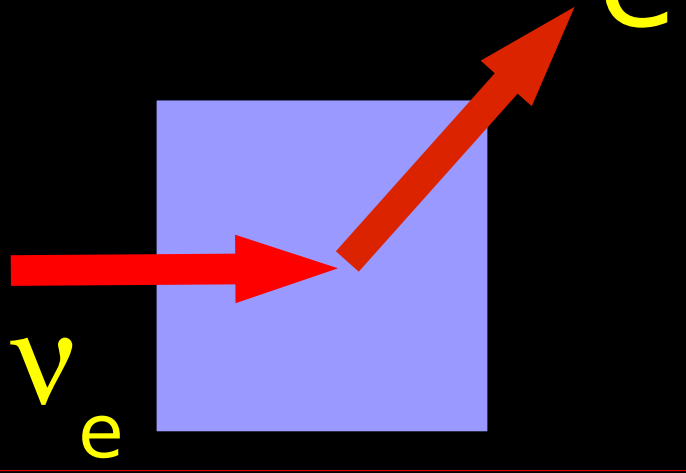


0

Tiny mass (1)

Very tiny mass
(<0.0000001)

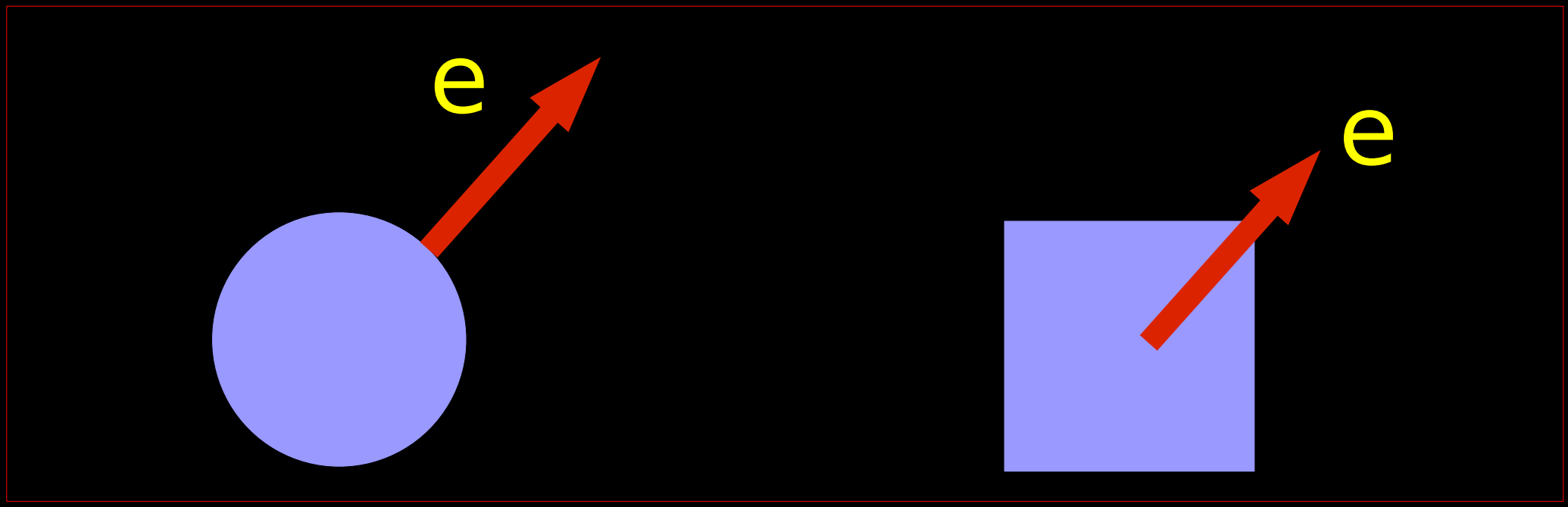




In experiments neutrinos are **NEVER** seen.

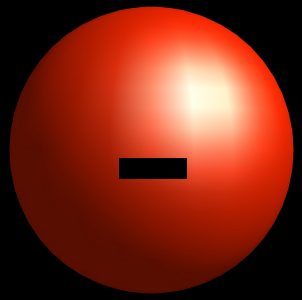
We can only detect them through the byproducts of their interactions with matter.

Type of the charged particle detected used to infer the type of incoming neutrino.



Electron, e

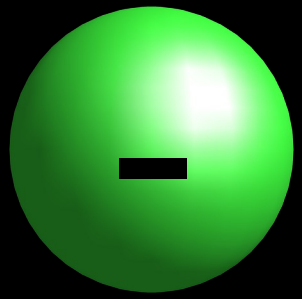
mass (1)



Electron Neutrino, ν_e

Muon, μ

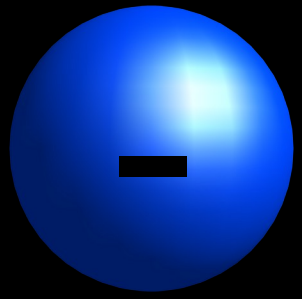
mass (200)



Muon Neutrino, ν_μ

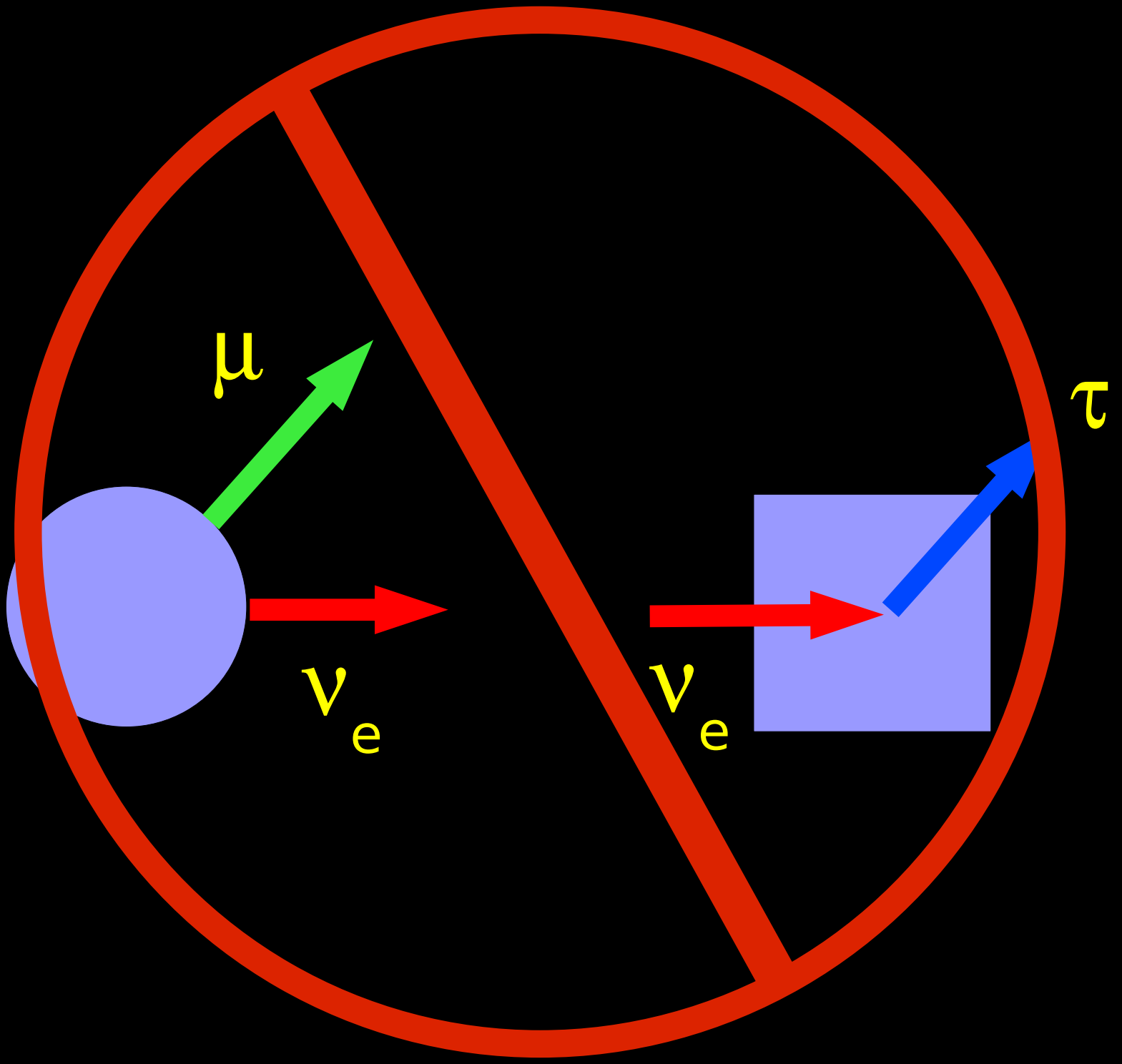
Tau, τ

mass (3500)



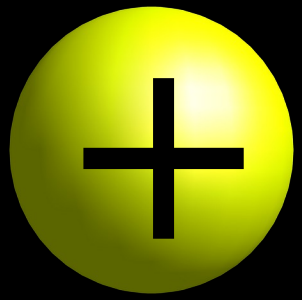
Tau Neutrino, ν_τ

3 Lepton Types


μ
τ
ν_e
ν_e

Positron, e^+

mass (1)



Electron Antineutrino, $\overline{\nu}_e$

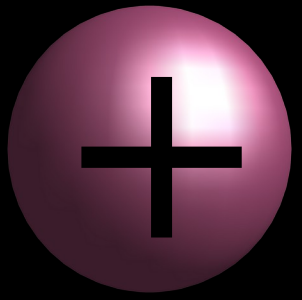
Muon, μ^+

mass (200)

Muon Antineutrino, $\overline{\nu}_\mu$

Tau, τ^+

mass (3500)



Tau Antineutrino, $\overline{\nu}_\mu$

3 Antiparticles

Where do they come from?

Everywhere!

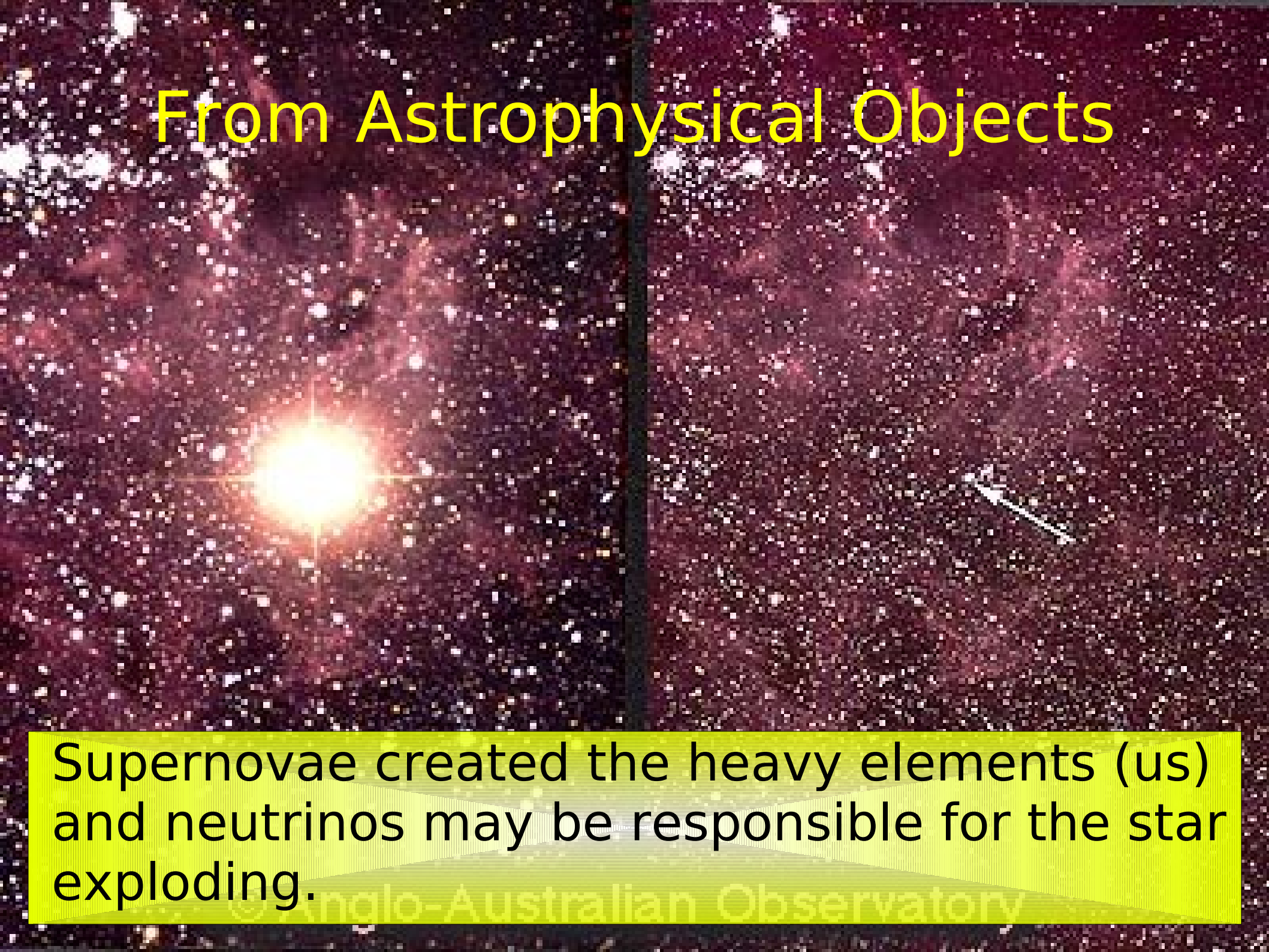

From the Big Bang
Artist's conception

From the Big Bang

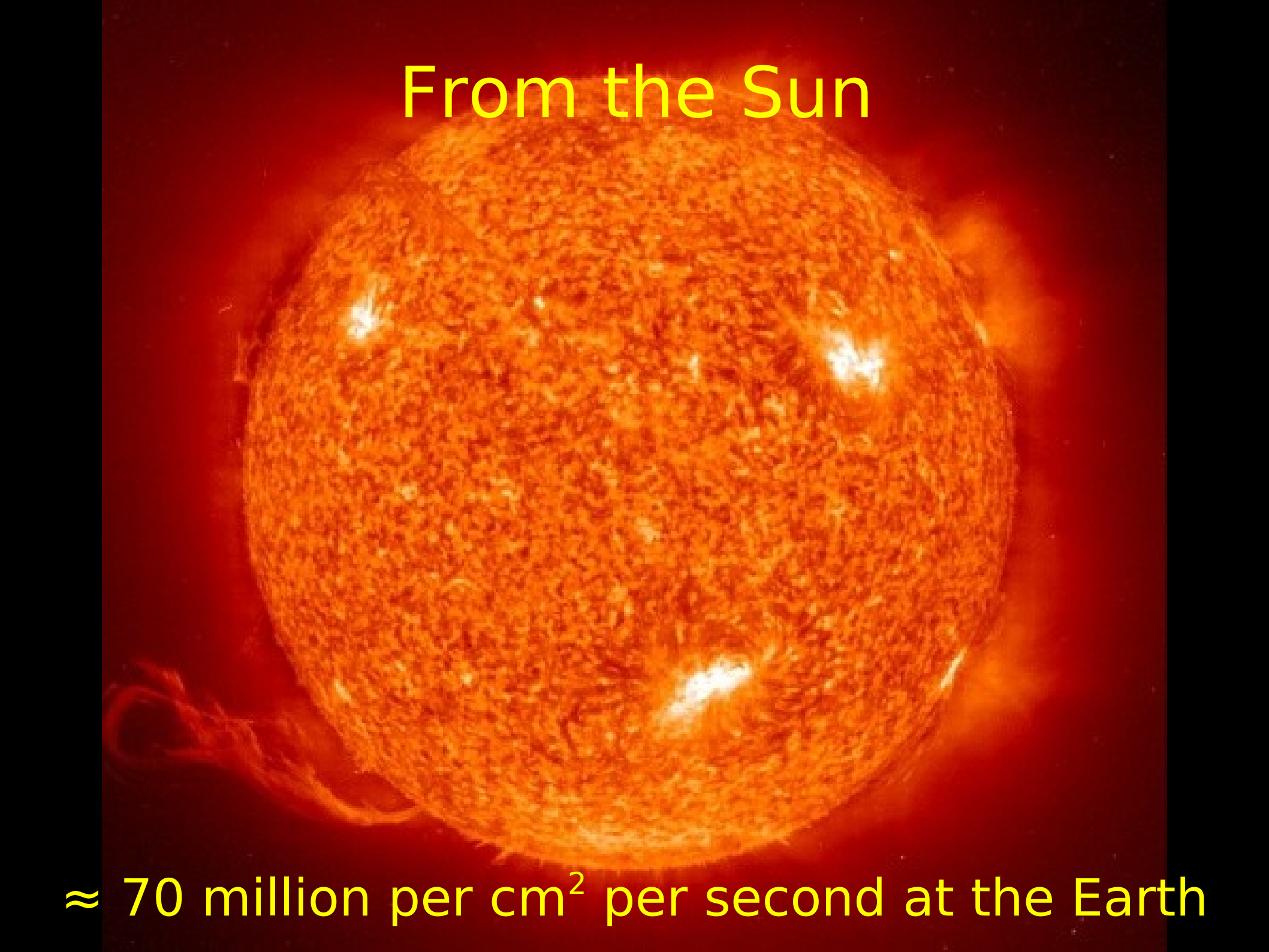
One cubic foot of space contains about 10,000,000 neutrinos left over from the Big Bang.

Artist's conception

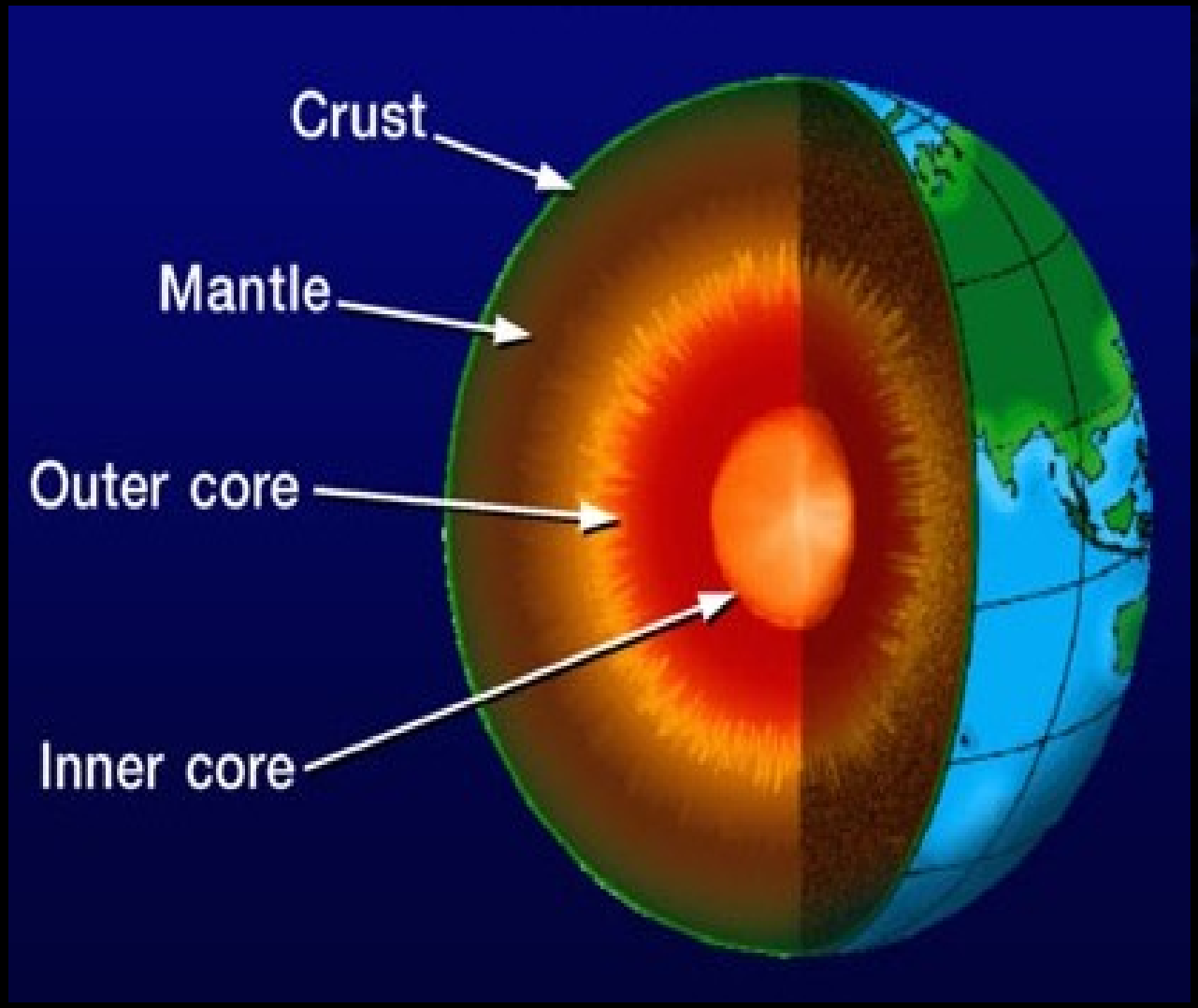
From Astrophysical Objects

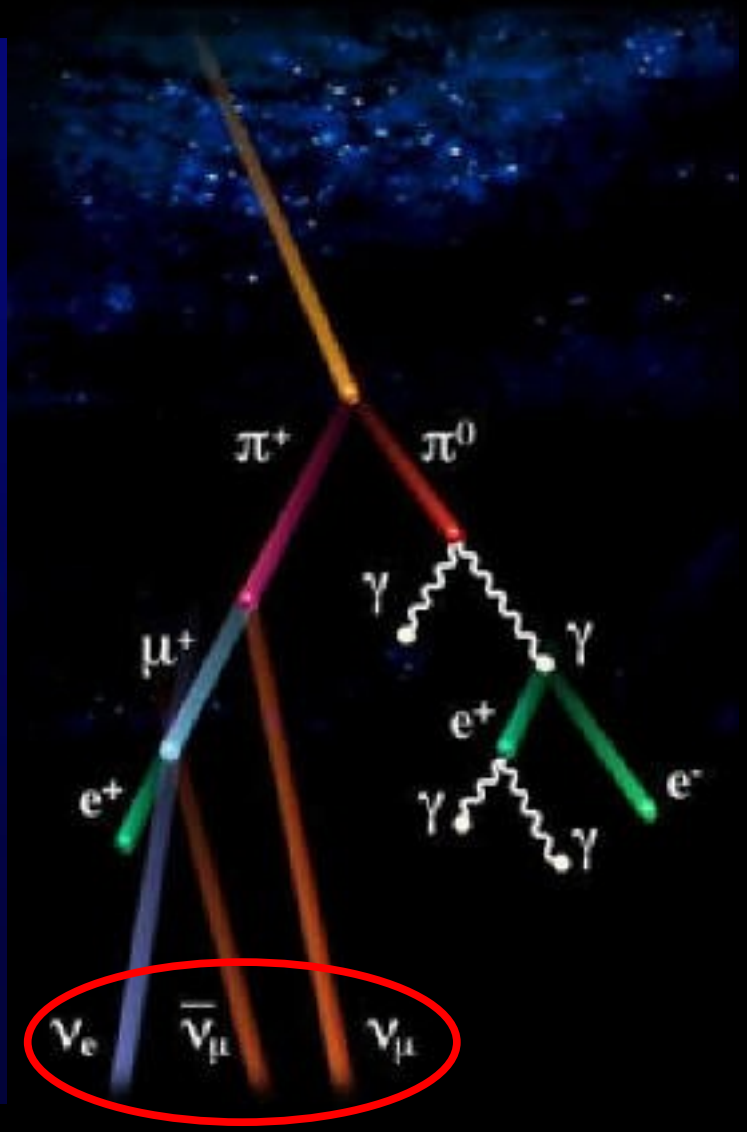


Supernovae created the heavy elements (us) and neutrinos may be responsible for the star exploding.


From the Sun
≈ 70 million per cm^2 per second at the Earth

From The Earth






From Us.

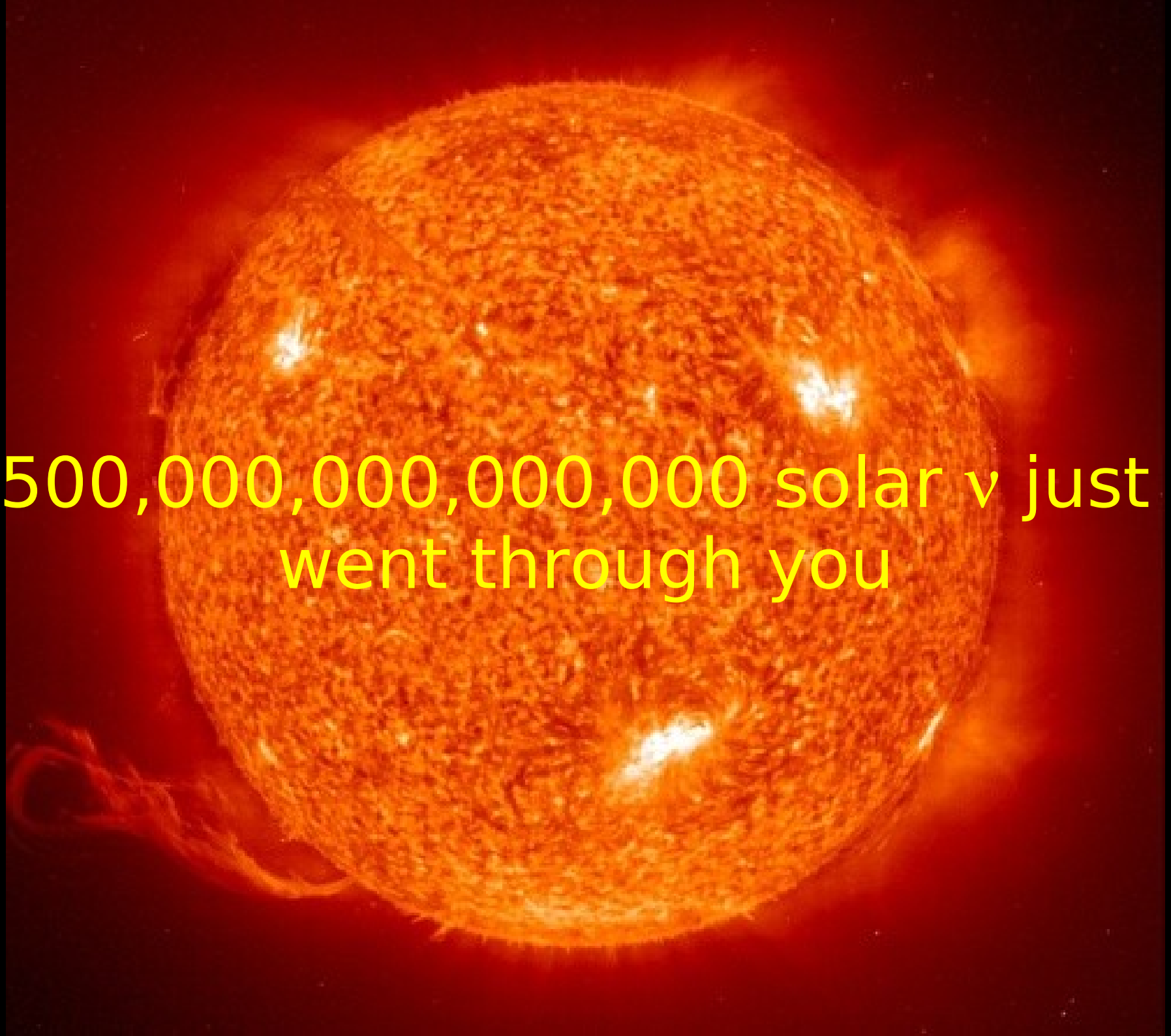
So why don't we notice?

ν are almost ghosts. They interact extremely weakly with matter.

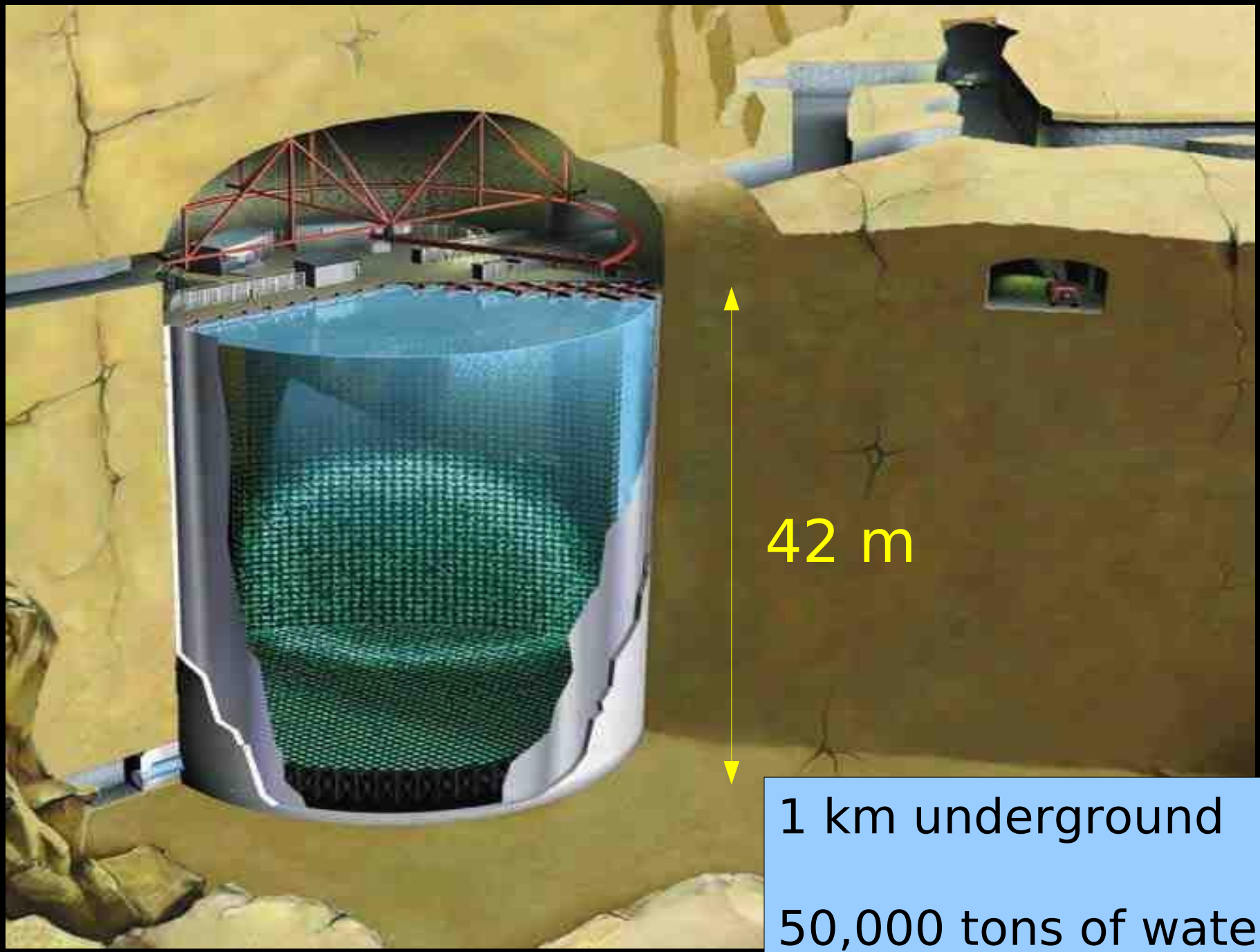
To a neutrino a planet is mostly empty space.

"The chances of a neutrino actually hitting something as it travels through all this howling emptiness are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich."

Douglas Adams

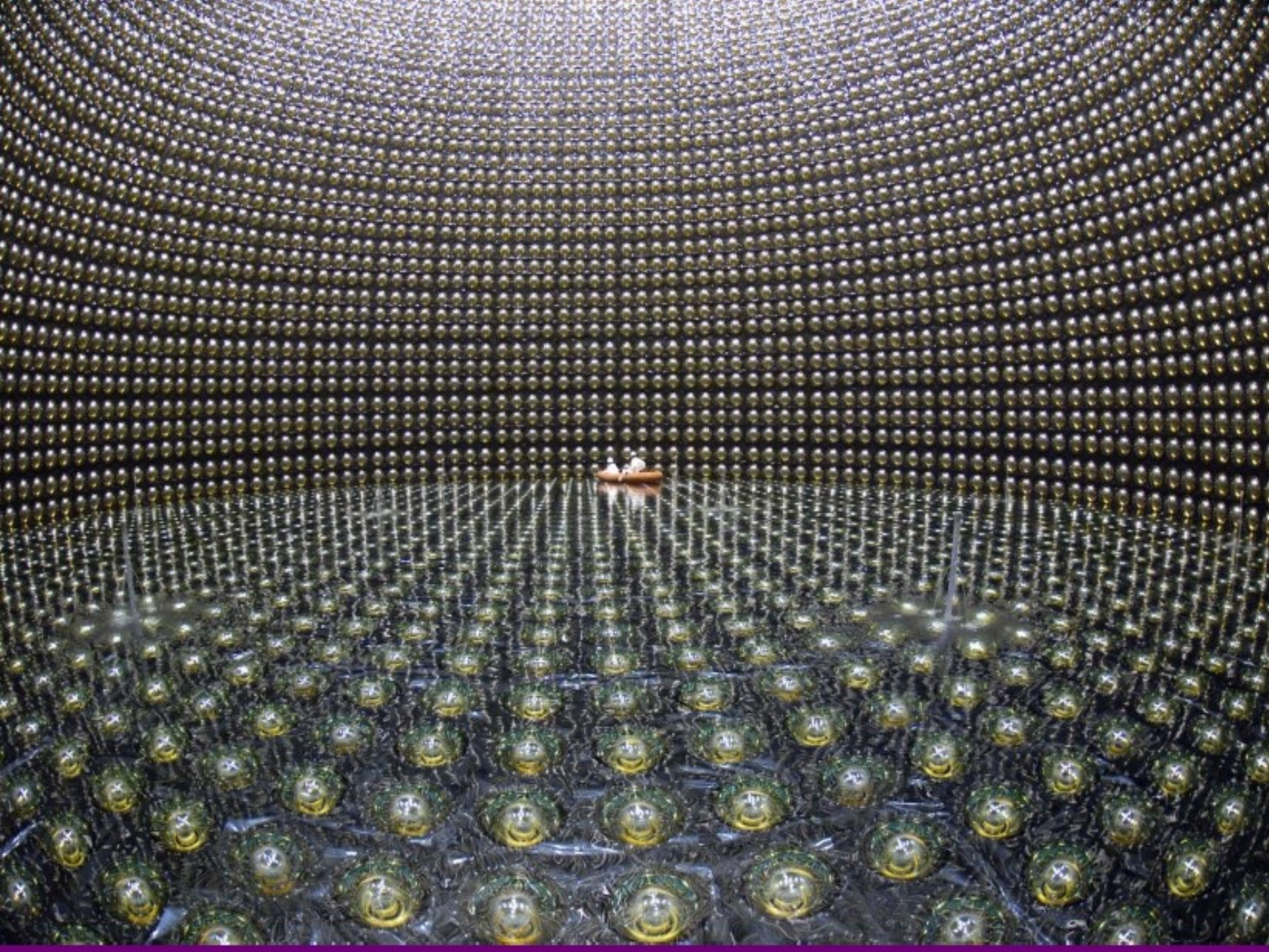

500,000,000,000,000 solar ν just
went through you

Super-Kamiokande



1 km underground

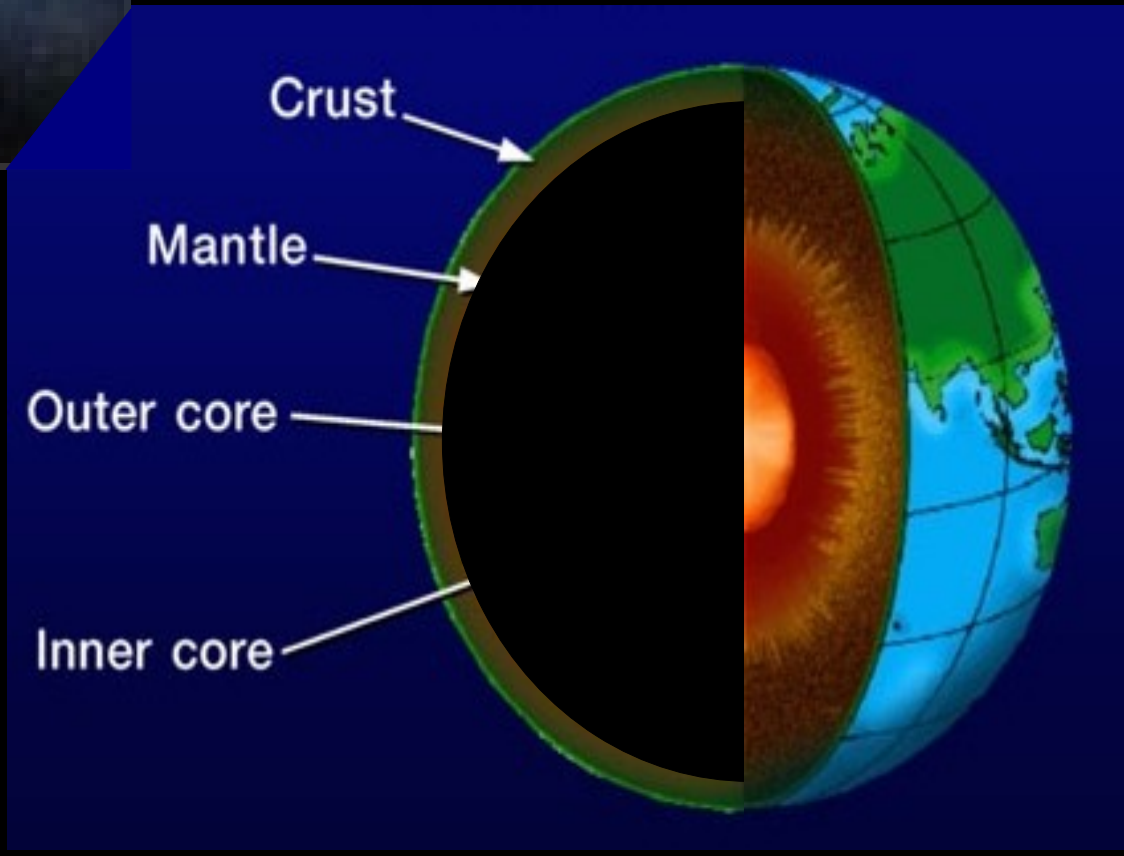
50,000 tons of water



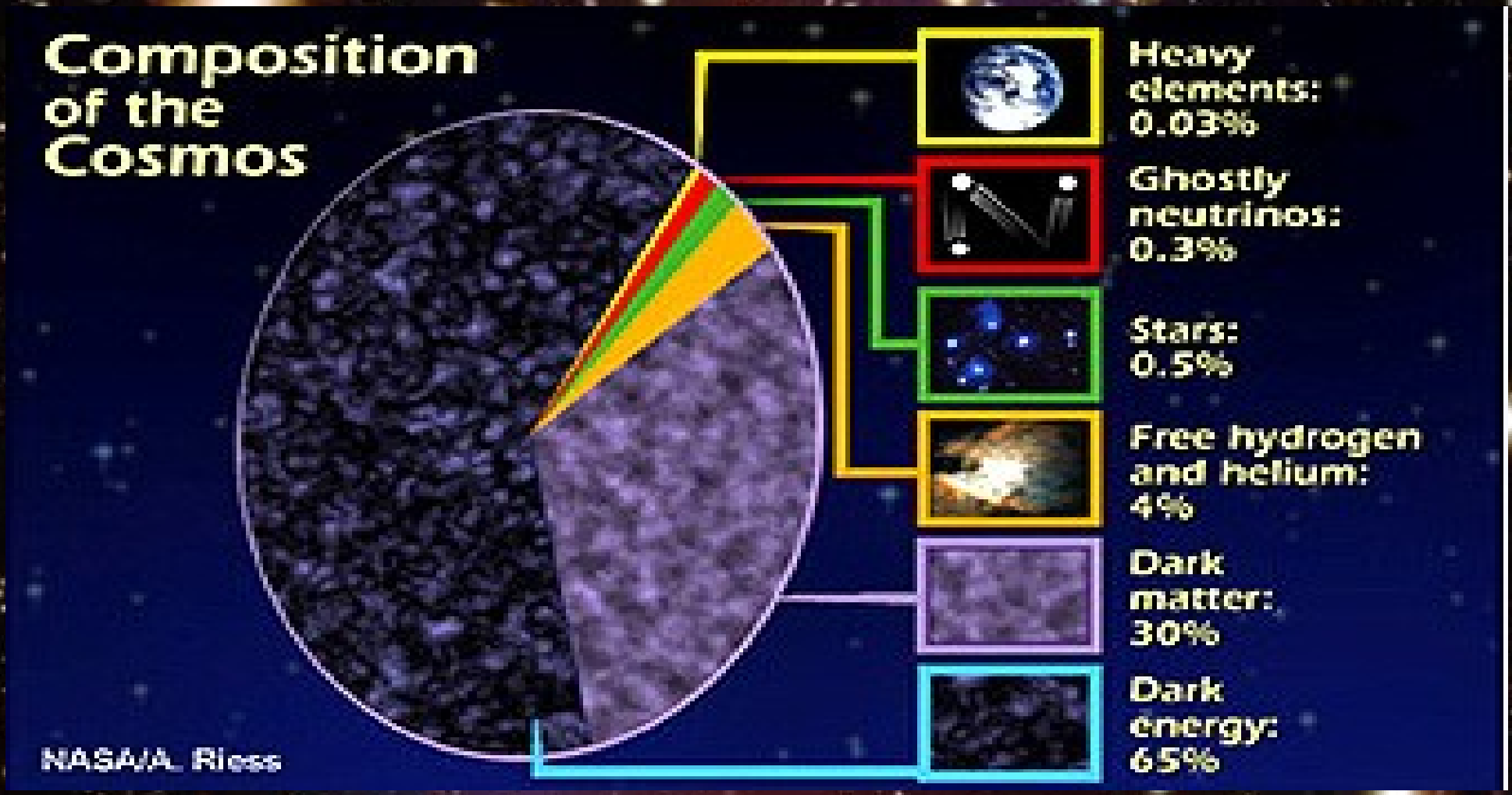
Why do we study them?

As Probes

Astrophysics
Geophysics
Cosmology
Particle Physics

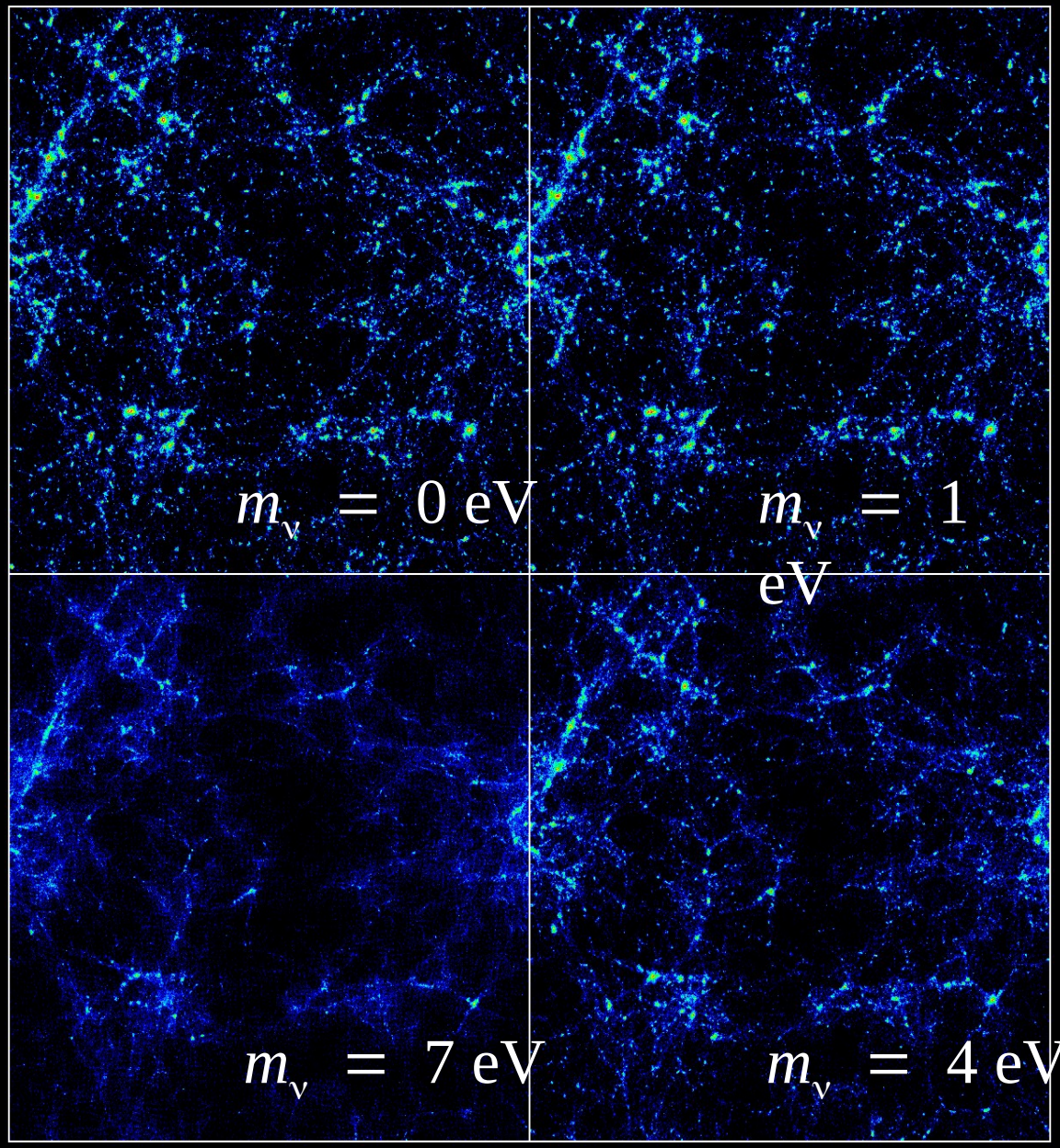


Amount of matter in Universe

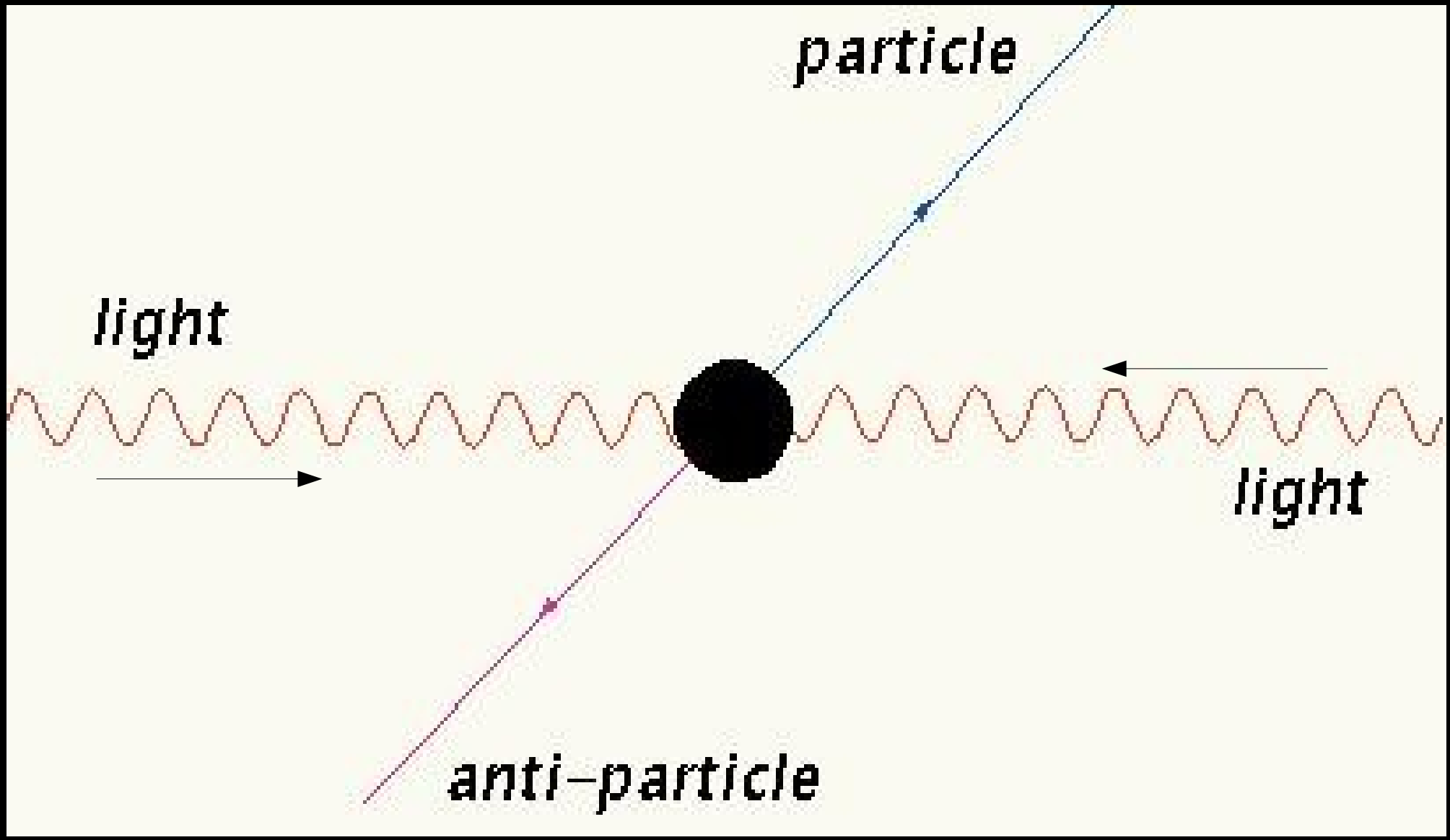


Second most common (known) particle in the universe

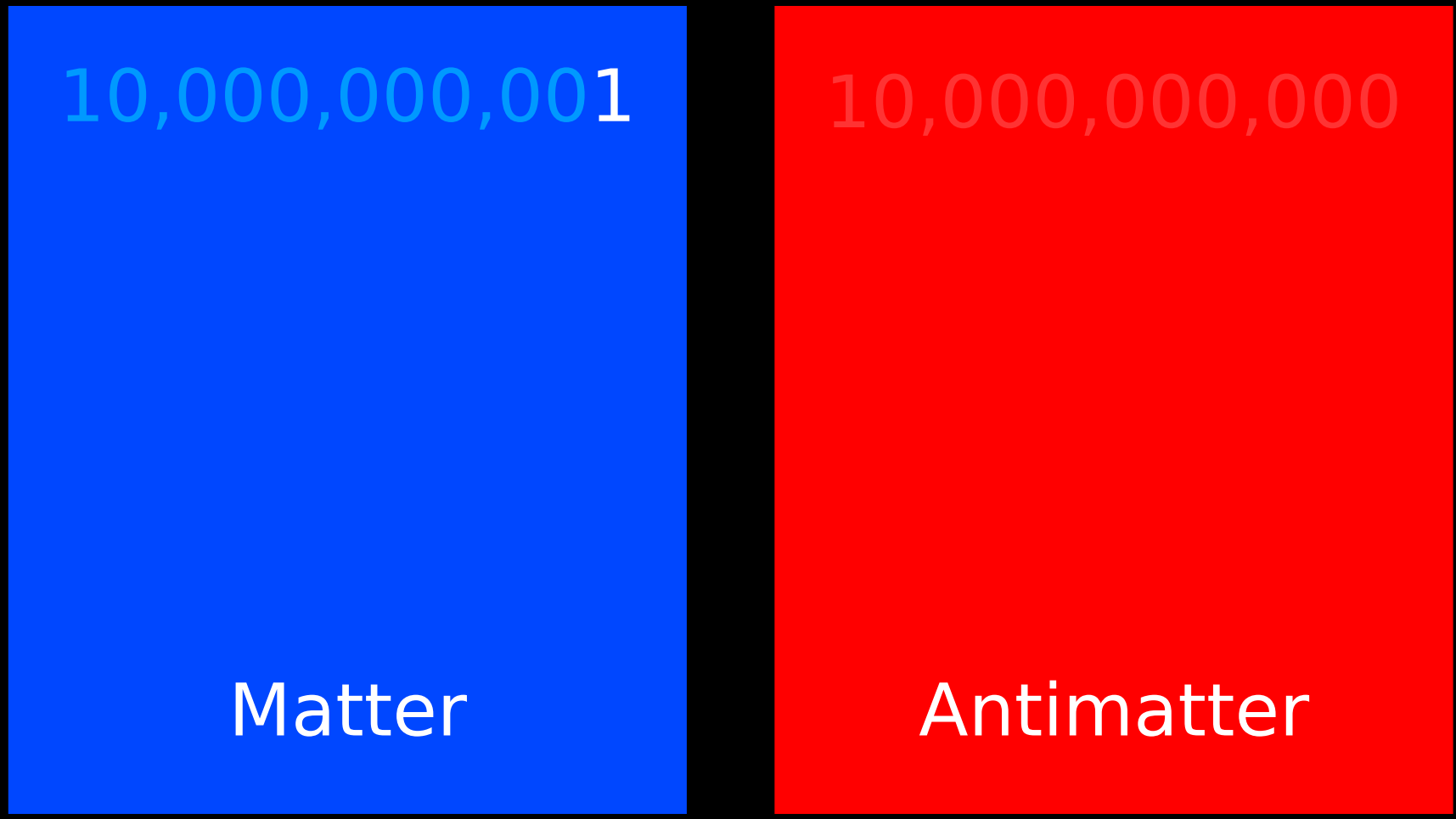
Universal Structure



Why is there more matter than antimatter?



Why is there more matter than antimatter?



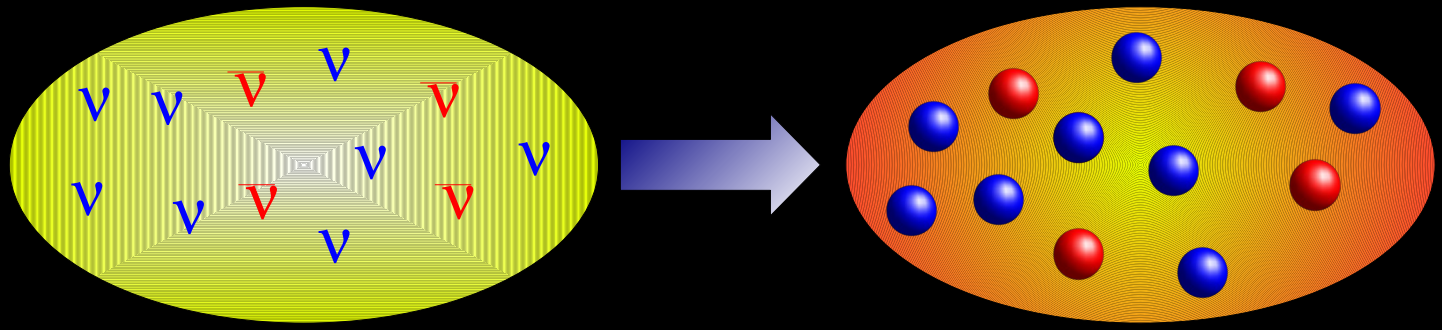
Thanks to Hitoshi Maruyama

Matter-Antimatter Asymmetry

Q. Is there a difference between
the physics of matter and antimatter?

A.Yes there is.

We've never seen it in neutrinos, though.

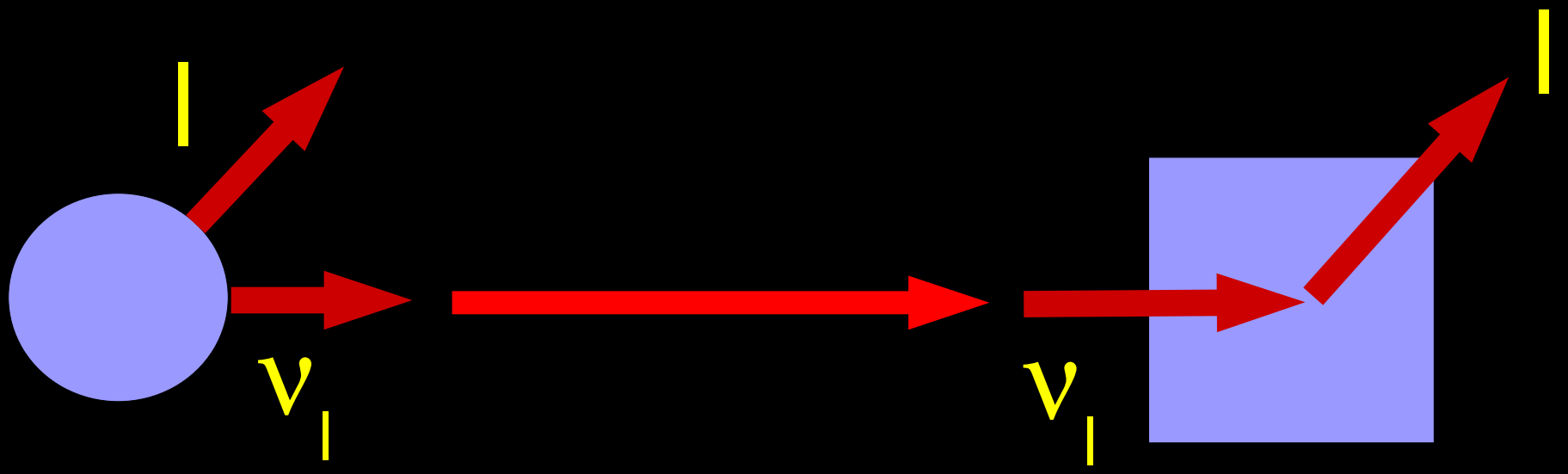


“Leptogenesis”

How to study this...?

Neutrino Oscillations

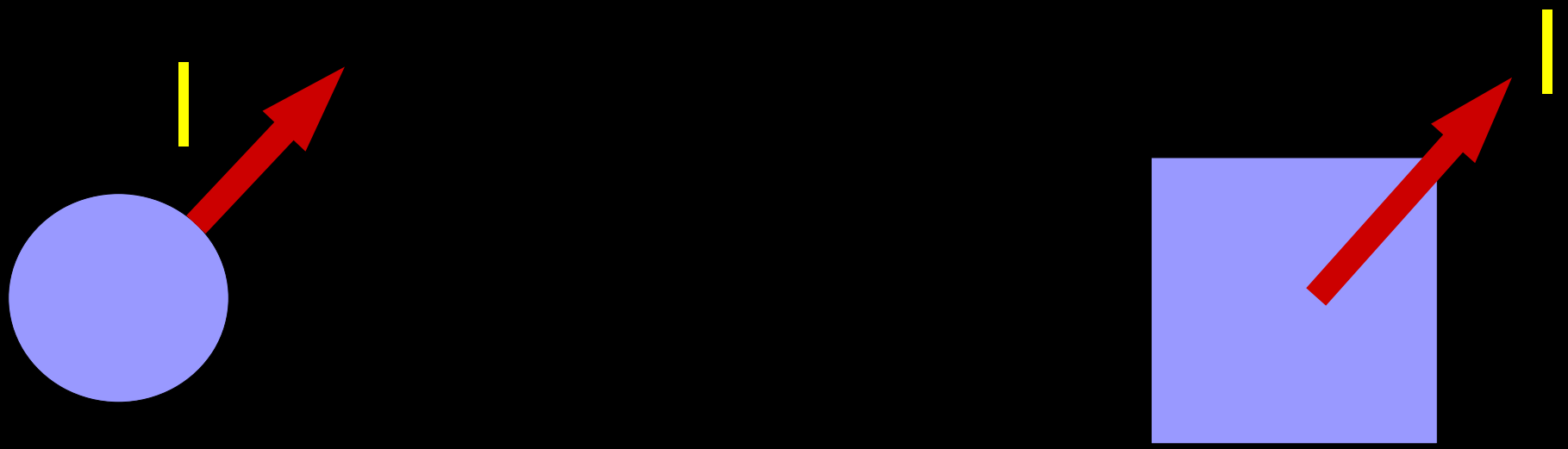
THE discovery in neutrinos of the last 20 years



A typical neutrino experiment

Neutrino Oscillations

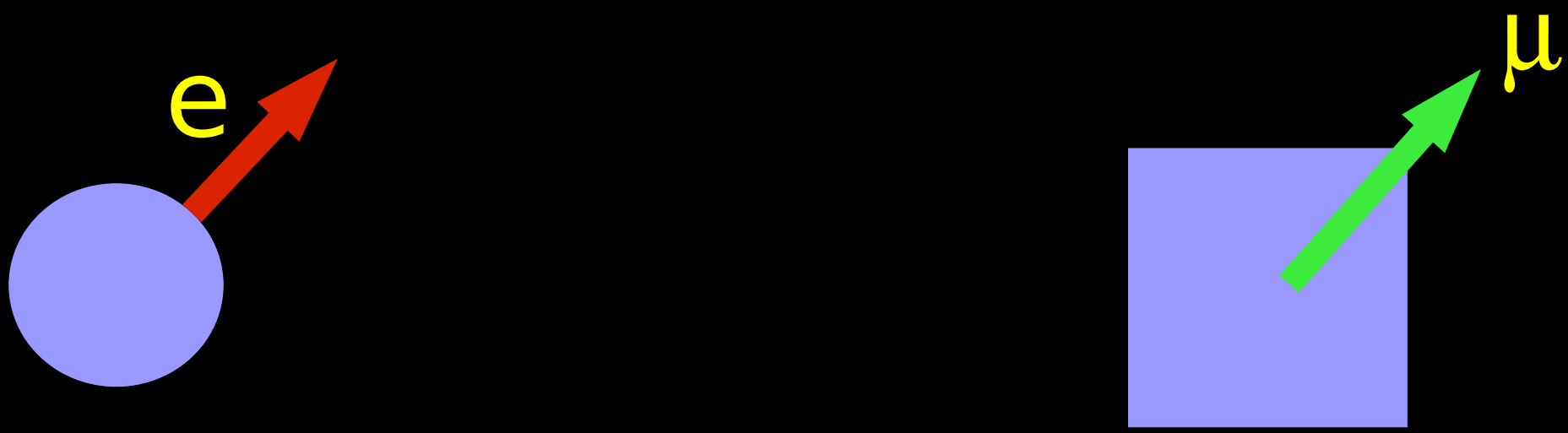
THE discovery in neutrinos of the last 20 years



A typical neutrino experiment

Neutrino Oscillations

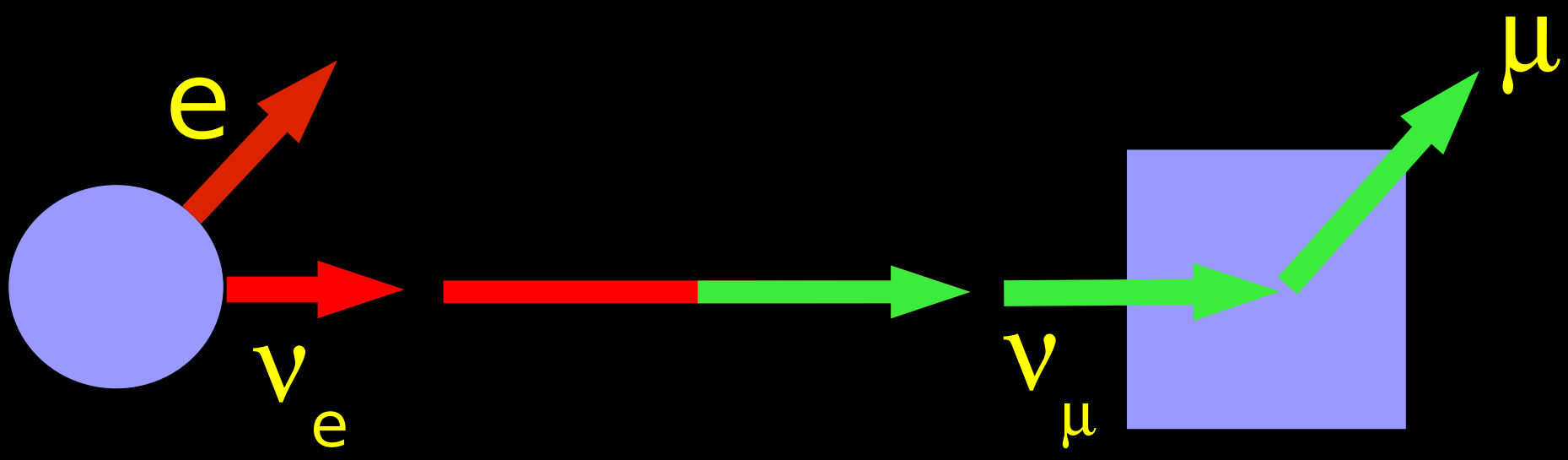
THE discovery in neutrinos of the last 20 years



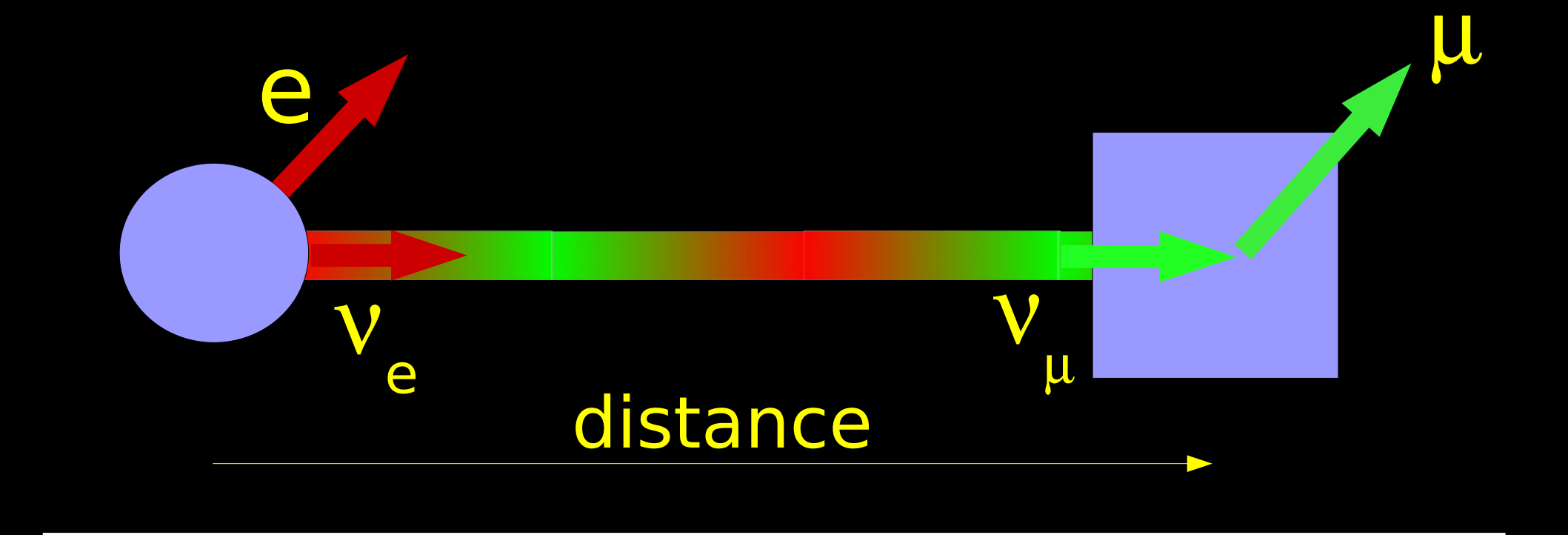
A typical neutrino experiment

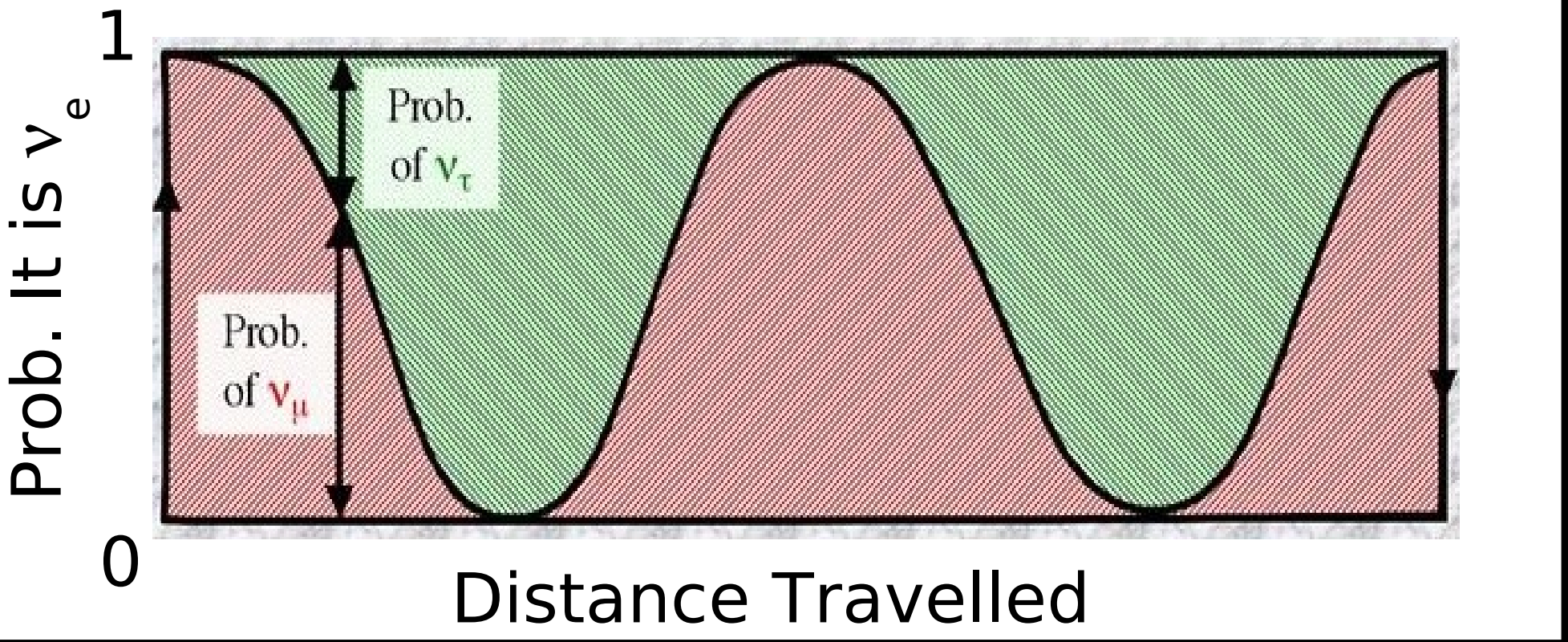
Neutrino Oscillations

THE discovery in neutrinos of the last 20 years



Neutrinos change flavour between source and detector!


e
μ
ν_e
ν_μ
distance


1
0
Prob. It is ν_e
Prob. of ν_τ
Prob. of ν_μ
Distance Travelled

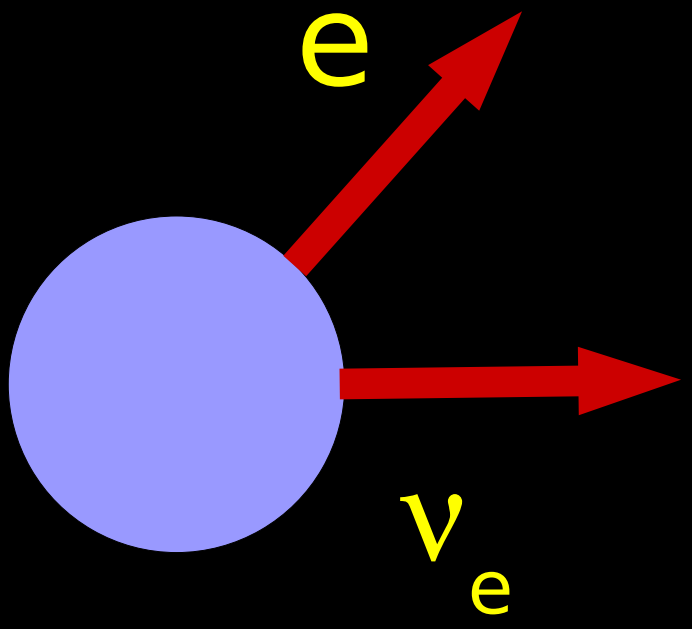
What the....?

Q. How can a ν_e spontaneously turn into a ν_μ?

What the....?

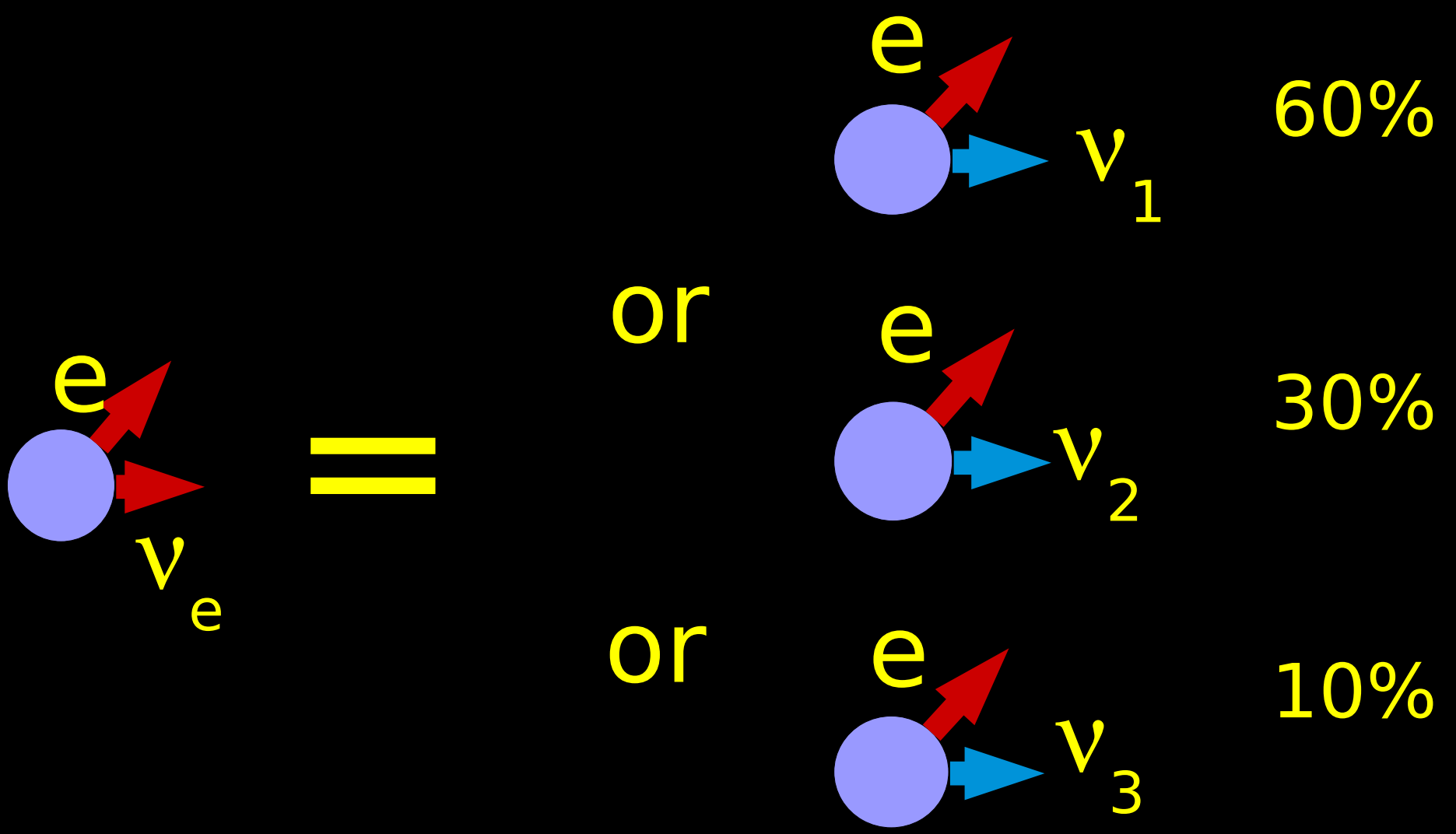
Q. How can a ν_e spontaneously turn into a ν_μ?

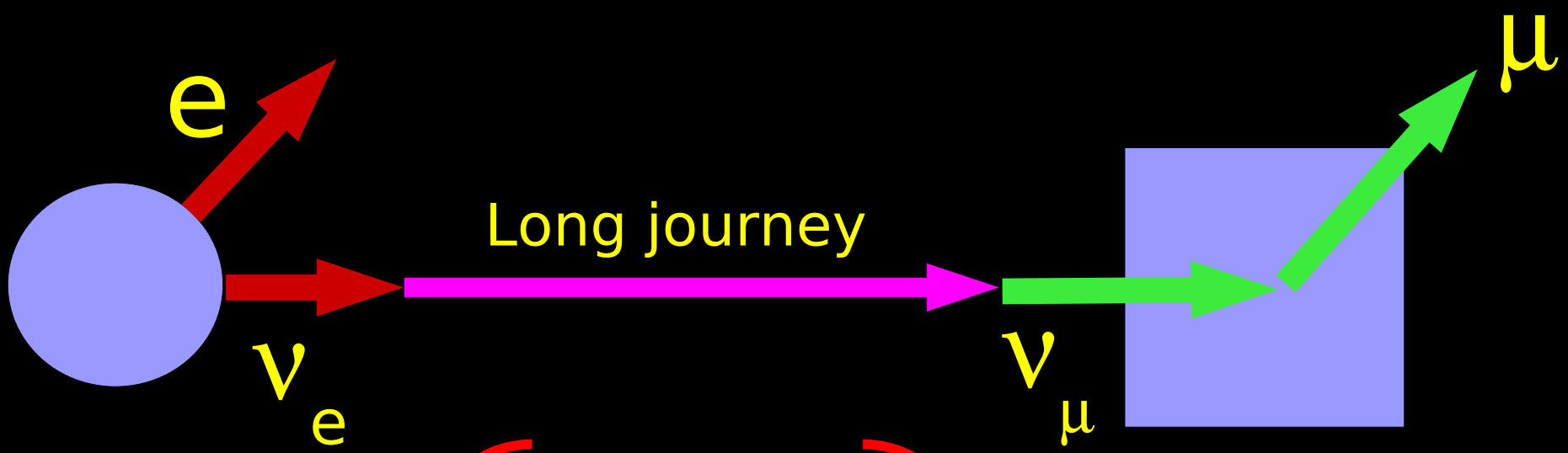
A. The ν_e isn't *a* particle. It's three!



$\nu_e \equiv$ “that thing which was always produced/detected with an electron”

Quantum Stuff



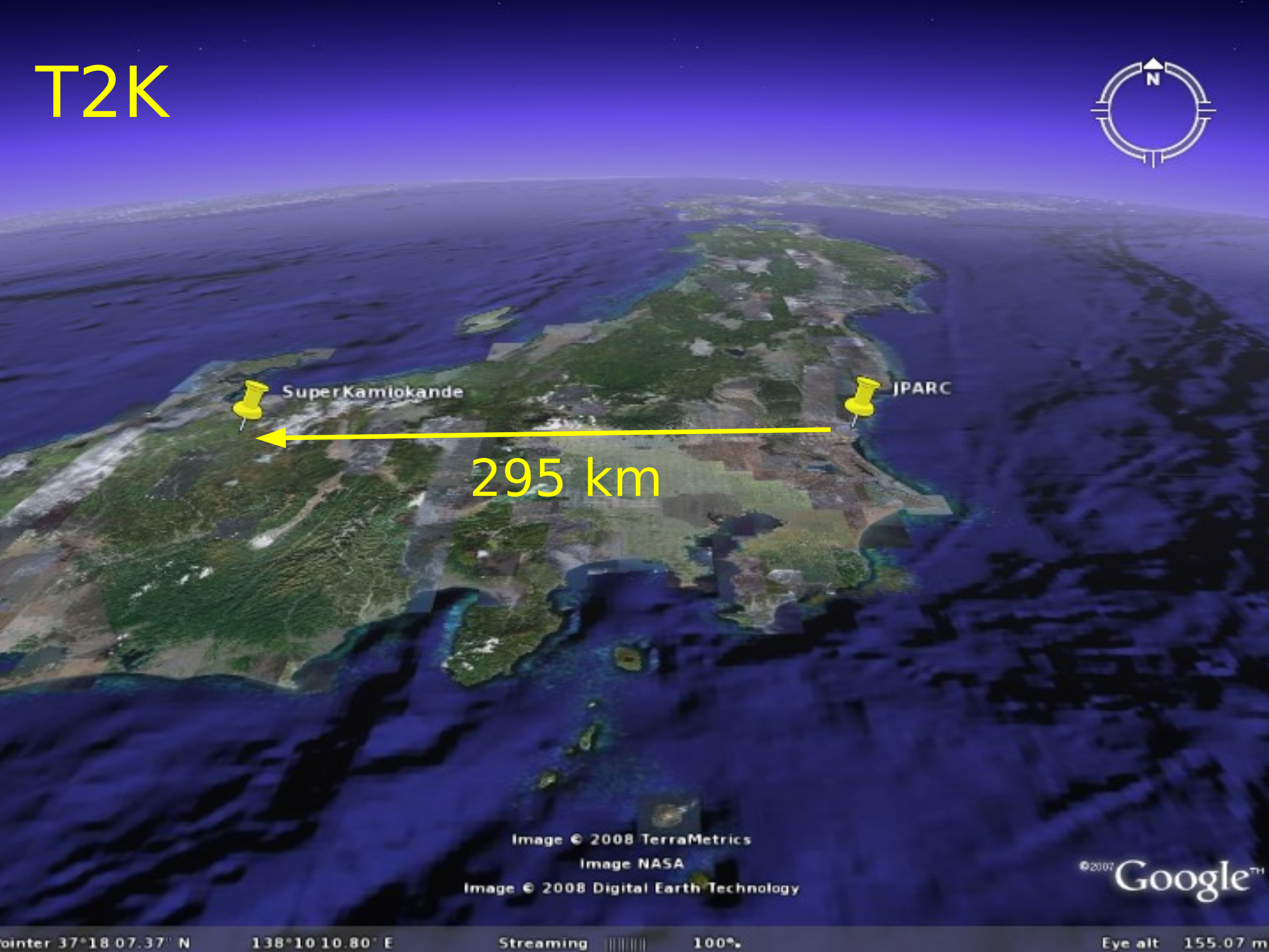


Original ν_1,ν_2,ν_3 mixture

ν_1,ν_2,ν_3 travels at different speeds

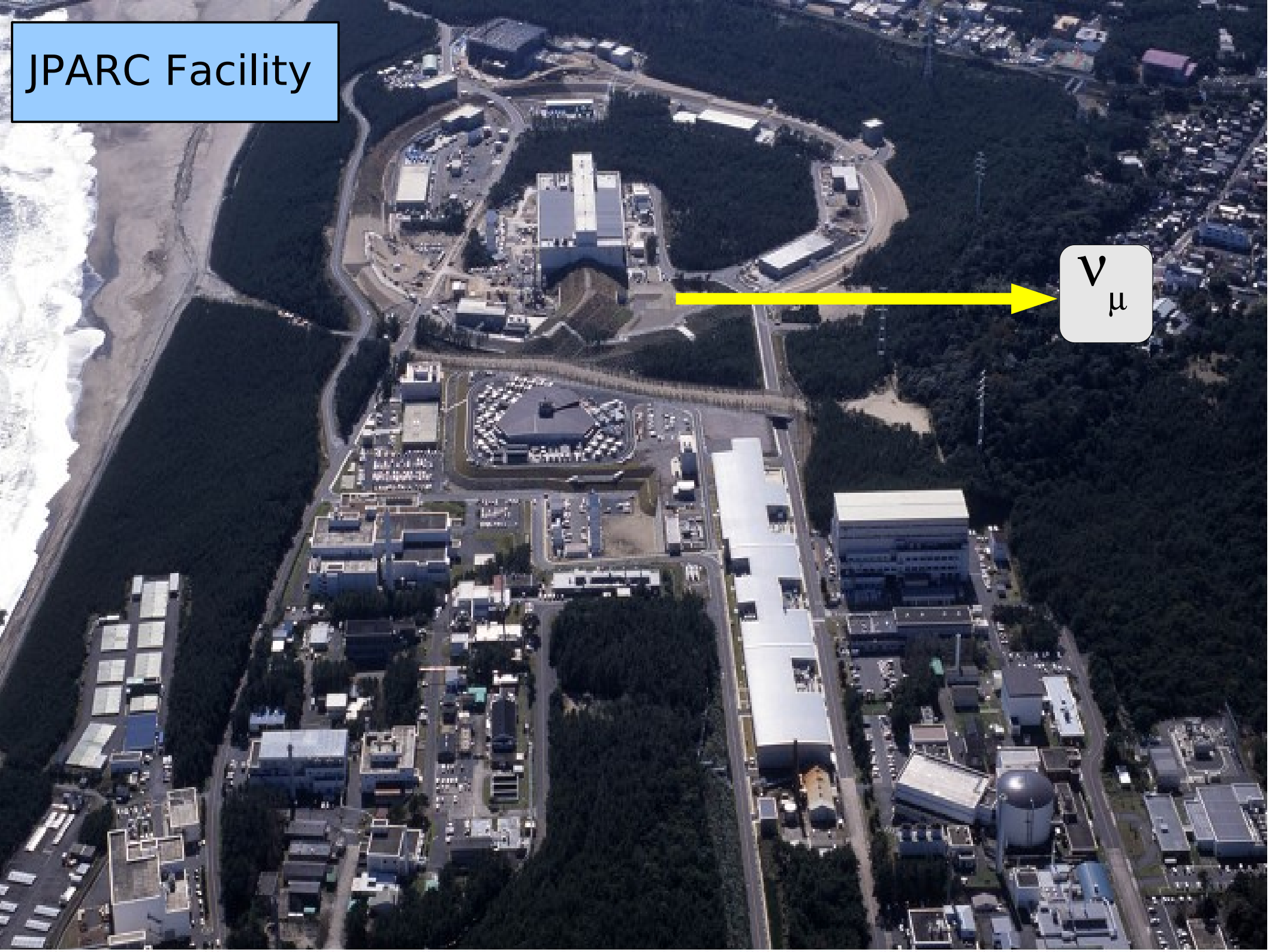
Different ν_1,ν_2,ν_3 mixture

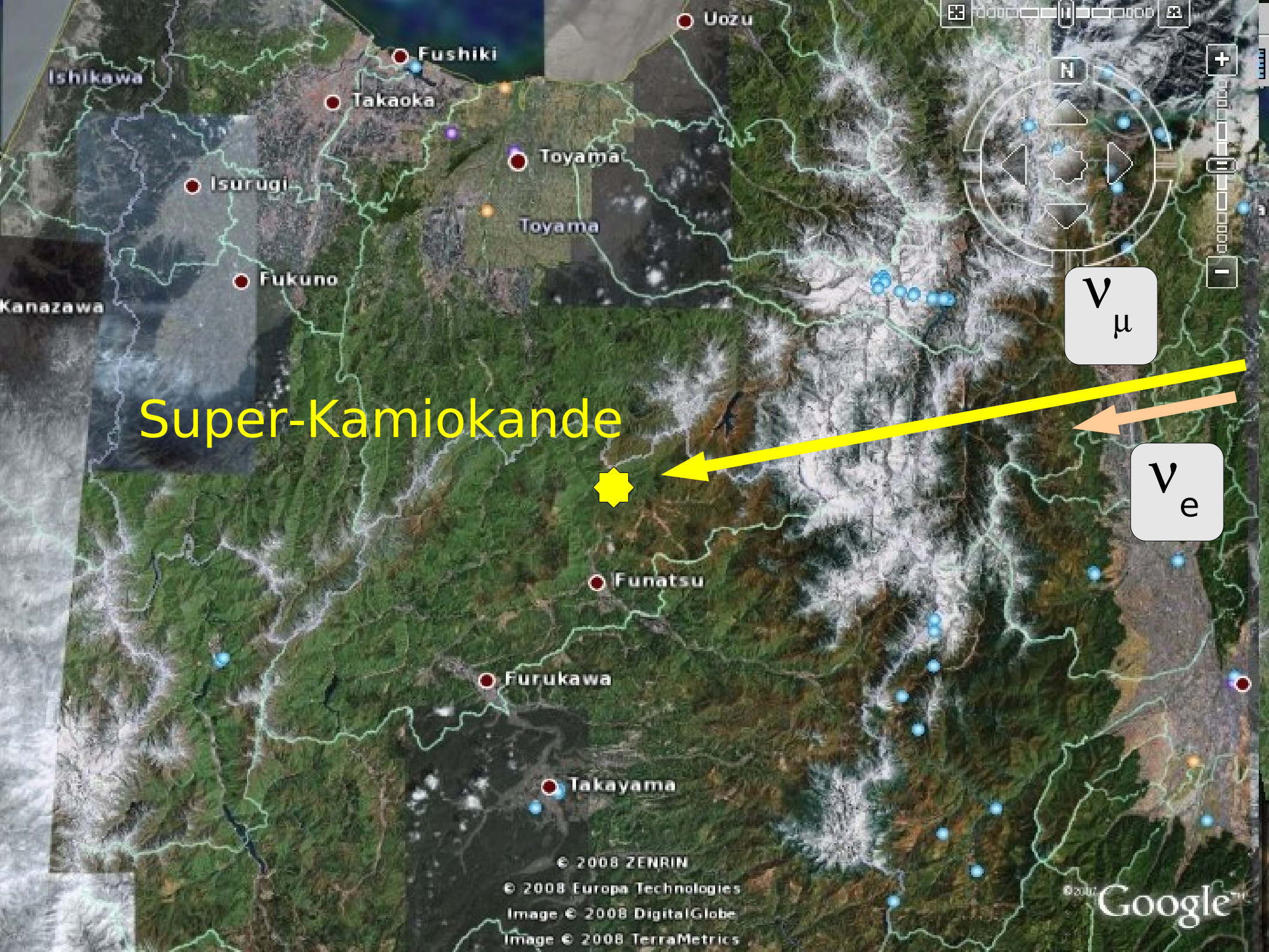
- This can only happen if ν_1,ν_2,ν_3 have different masses
- Only gives us differences in masses


T2K
N
SuperKamiokande
JPARC
295 km
Image © 2008 TerraMetrics
Image NASA
Image © 2008 Digital Earth Technology
©2007 Google™
Pointer 37°18'07.37" N 138°10'10.80" E
Streaming
100%
Eye alt 155.07 m

Things we still don't know

- How much do ν_1,ν_2 and ν_3 weigh?
- Why are they so much lighter than all the other massive particles?
- Are neutrinos the same as antineutrinos?
- Are neutrinos the reason we are here at all?


JPARC Facility
ν_μ


Uozu
Fushiki
Ishikawa
Takaoka
Toyama
Isurugi
Toyama
Fukuno
Kanazawa
Super-Kamiokande
ν_μ
ν_e
Funatsu
Furukawa
Takayama
© 2008 ZENRIN
© 2008 Europa Technologies
Image © 2008 DigitalGlobe
Image © 2008 TerraMetrics
Google

Economic Impacts

- 5% of jobs in UK are in physics-based sectors
- Gross added value from physics sector was estimated to be 70 billion pounds in 2005
- Synergy between PP projects and industry – industry acquires added skills base for other applications
- Training - 50% of PP PhDs go into other sectors

Radioisotope production
Sensors for medical applications
High level computing for biological/climate modelling
Spin off tools for other science (e.g. DIAMOND)
Nuclear fusion research
Muon tomography in border security
Airport scanners
Rock Imaging
Cancer treatment using next gen cyclotrons
proton therapy

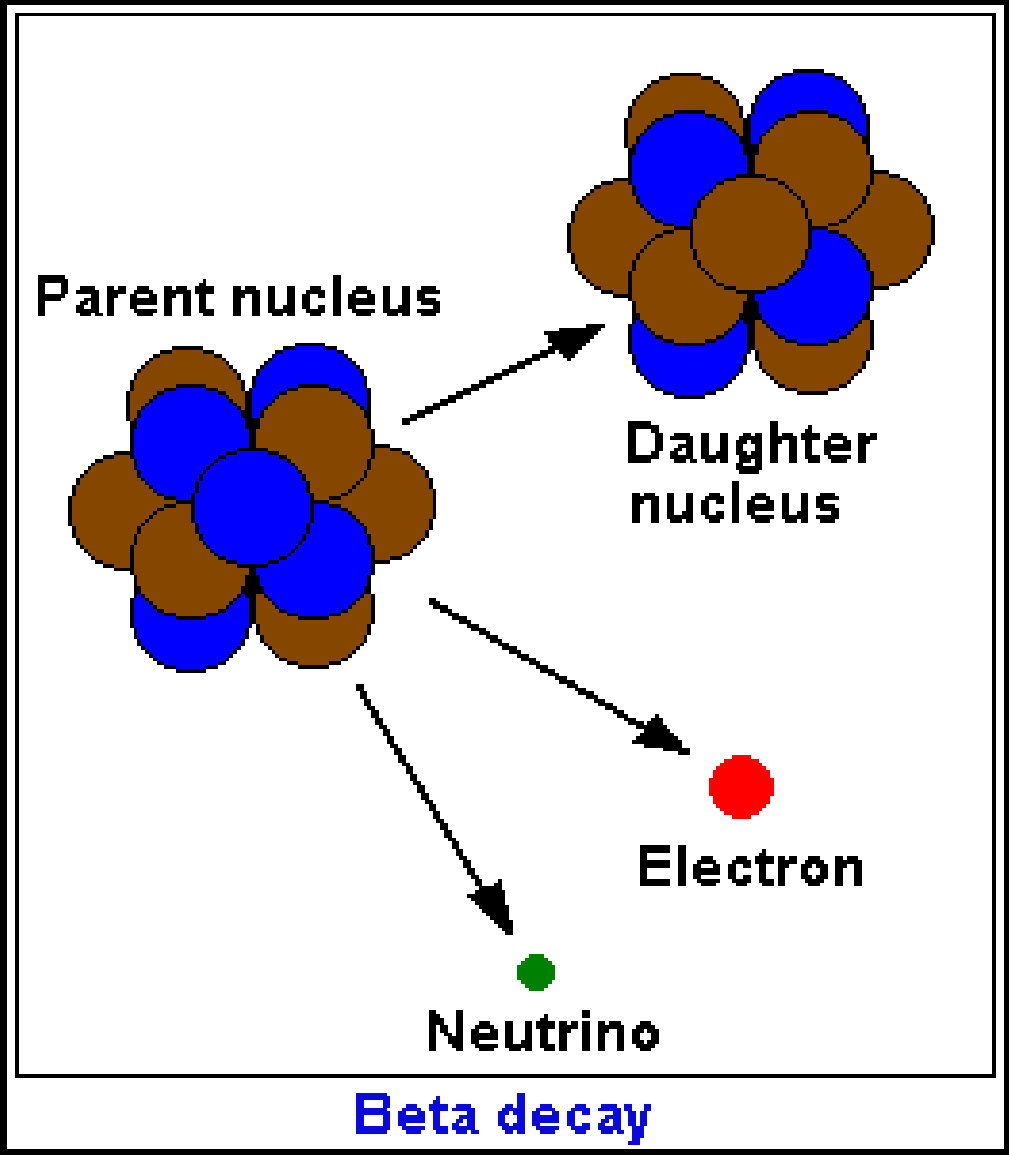
‘‘...these kind of findings have implications that are not limited to the laboratory. They affect the whole of society — not only our economy, but our very view of life, our understanding of our relations with others, and our place in time.’’

Bill Clinton

From Radioactive Decay

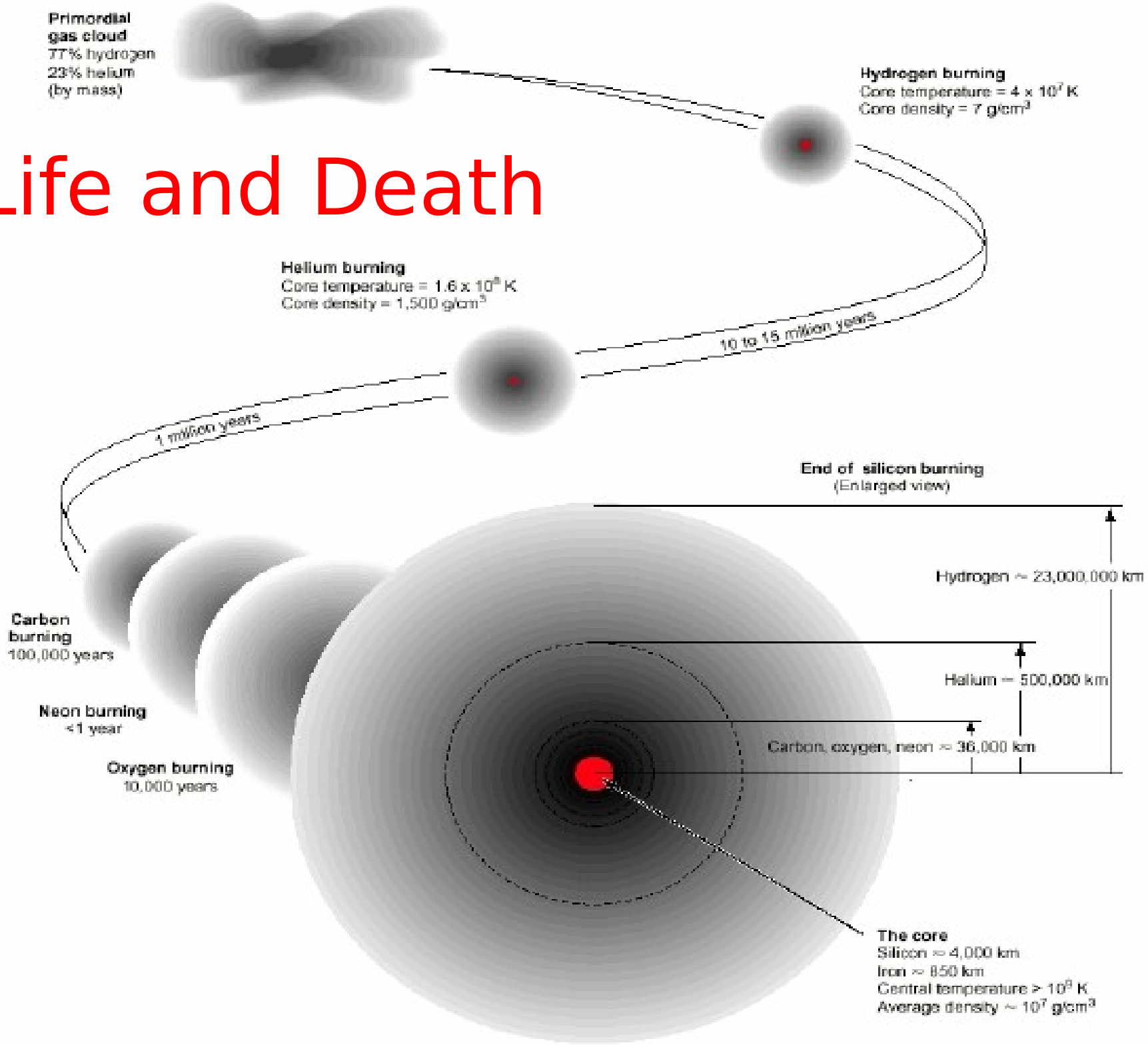
$$n \rightarrow p + e + \nu_e$$

e.g. Decay of unstable nuclides in the core of the earth can tell us about its structure (Geoneutrinos)

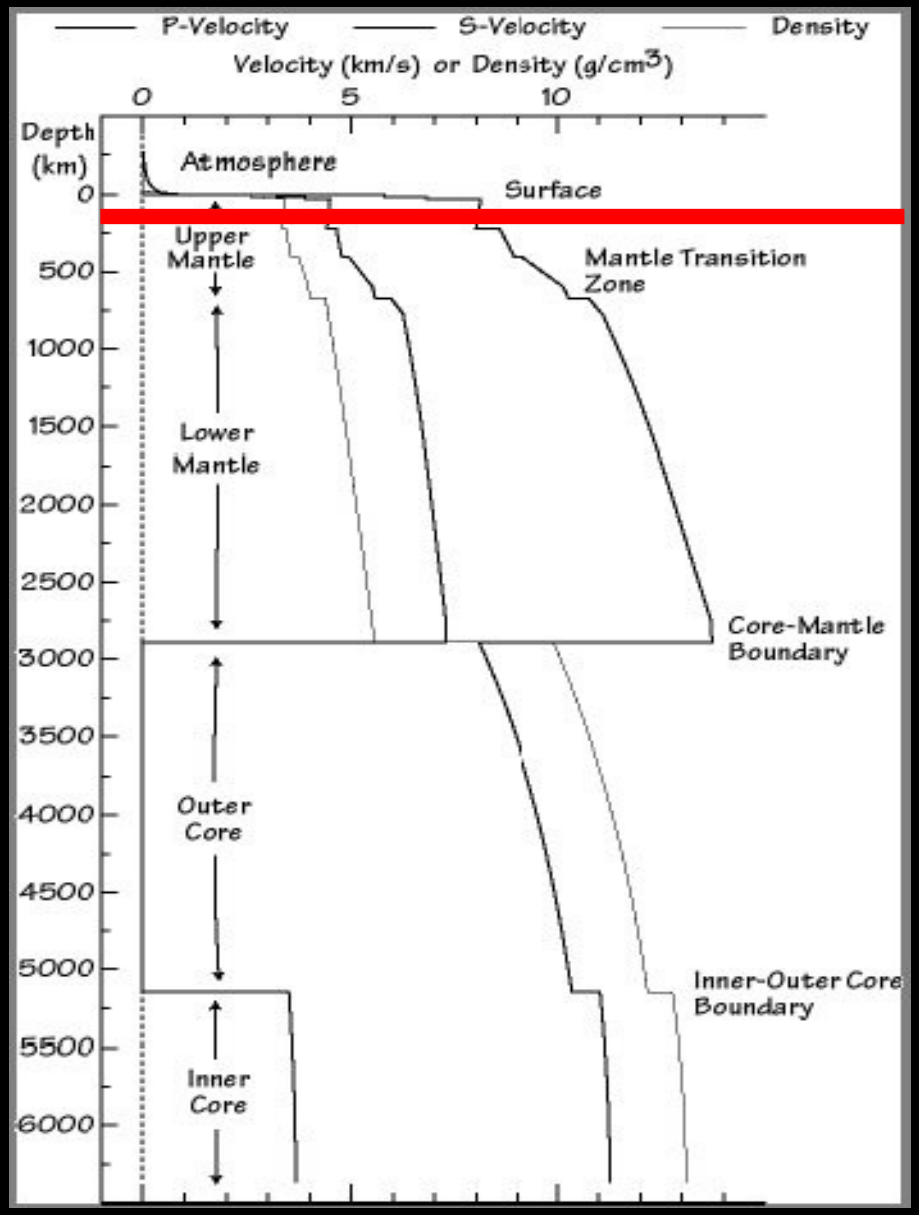


"Quarks. Neutrinos. Mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them!"

Life and Death



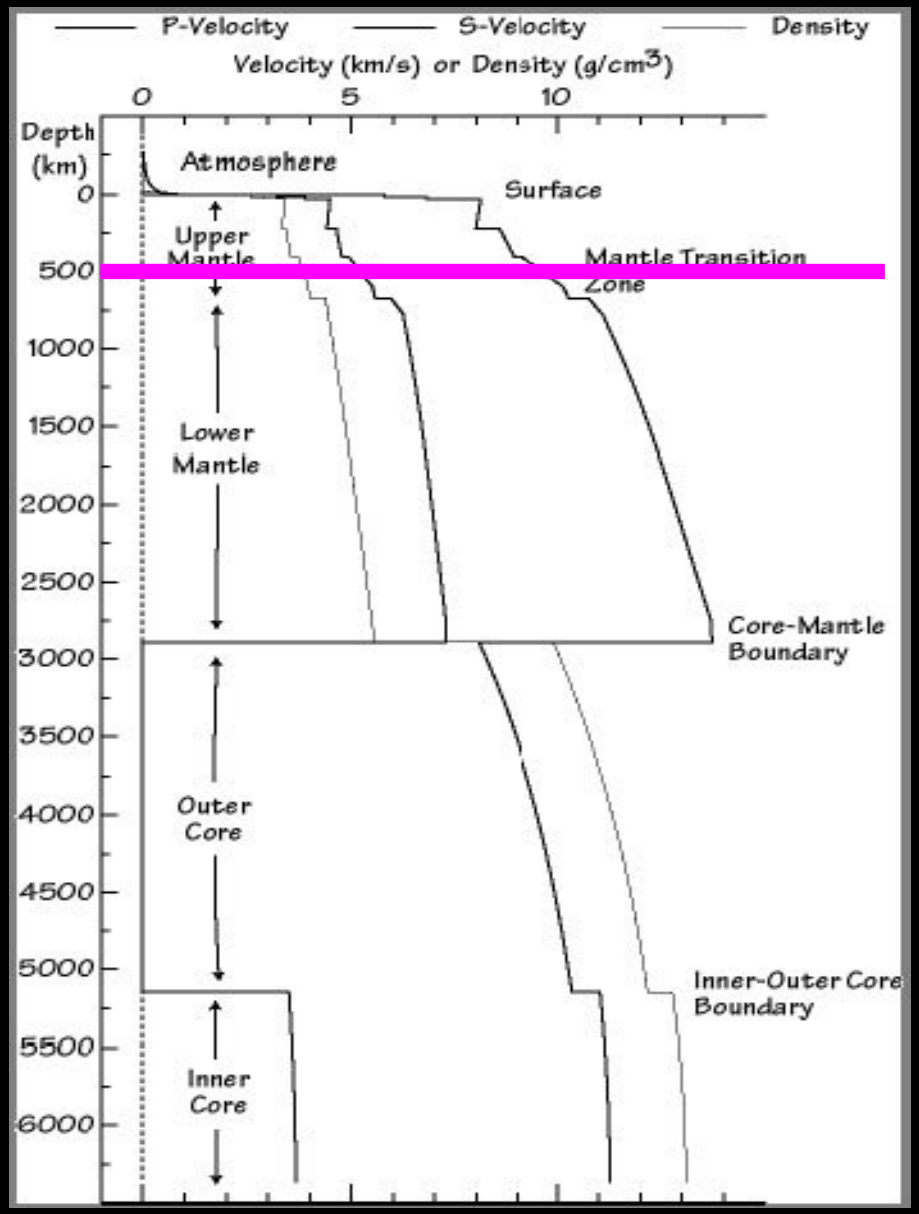
Geoneutrinos

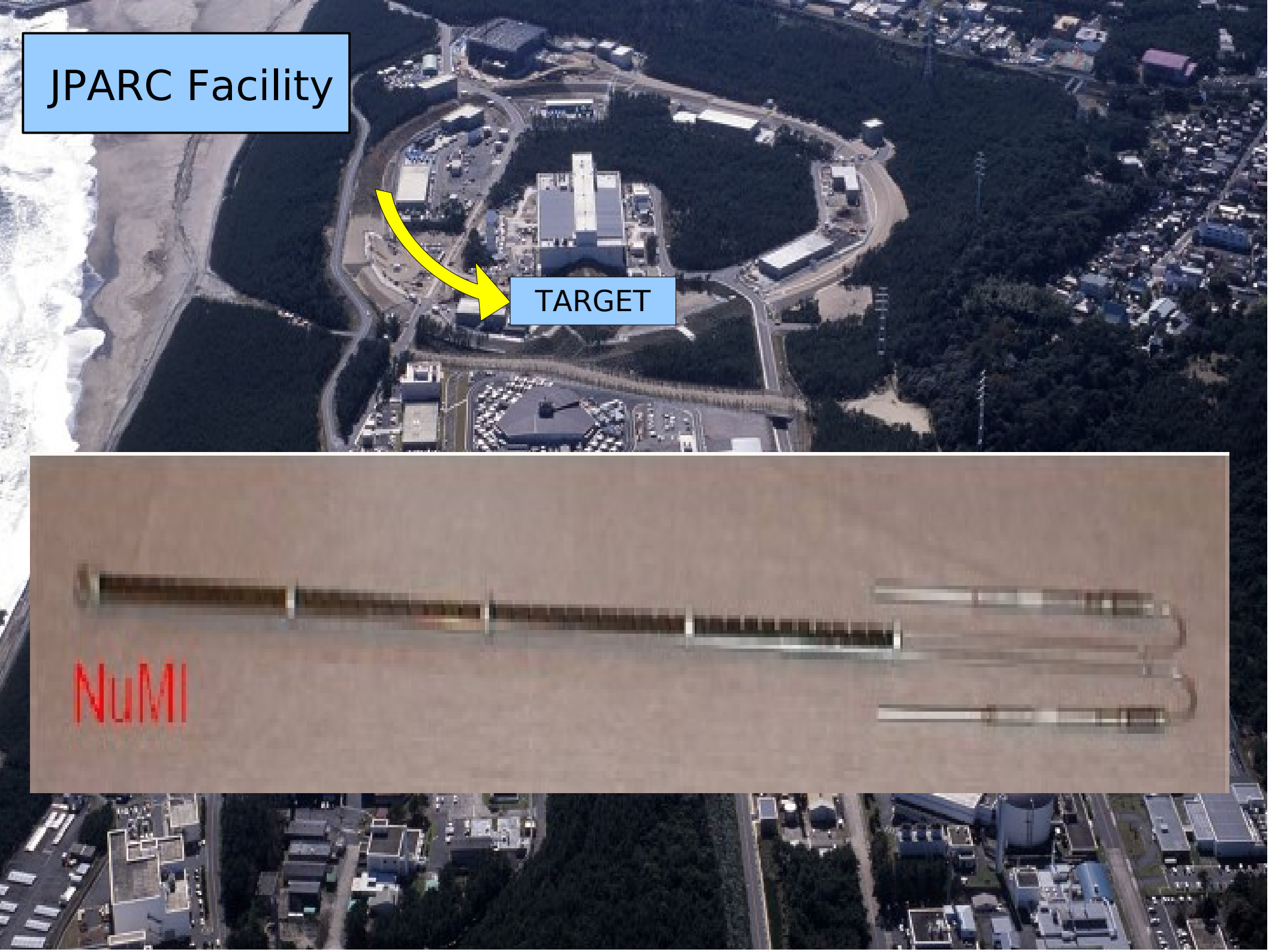


Models suggest
A total heatflow of
19 TW from radio-
active decay

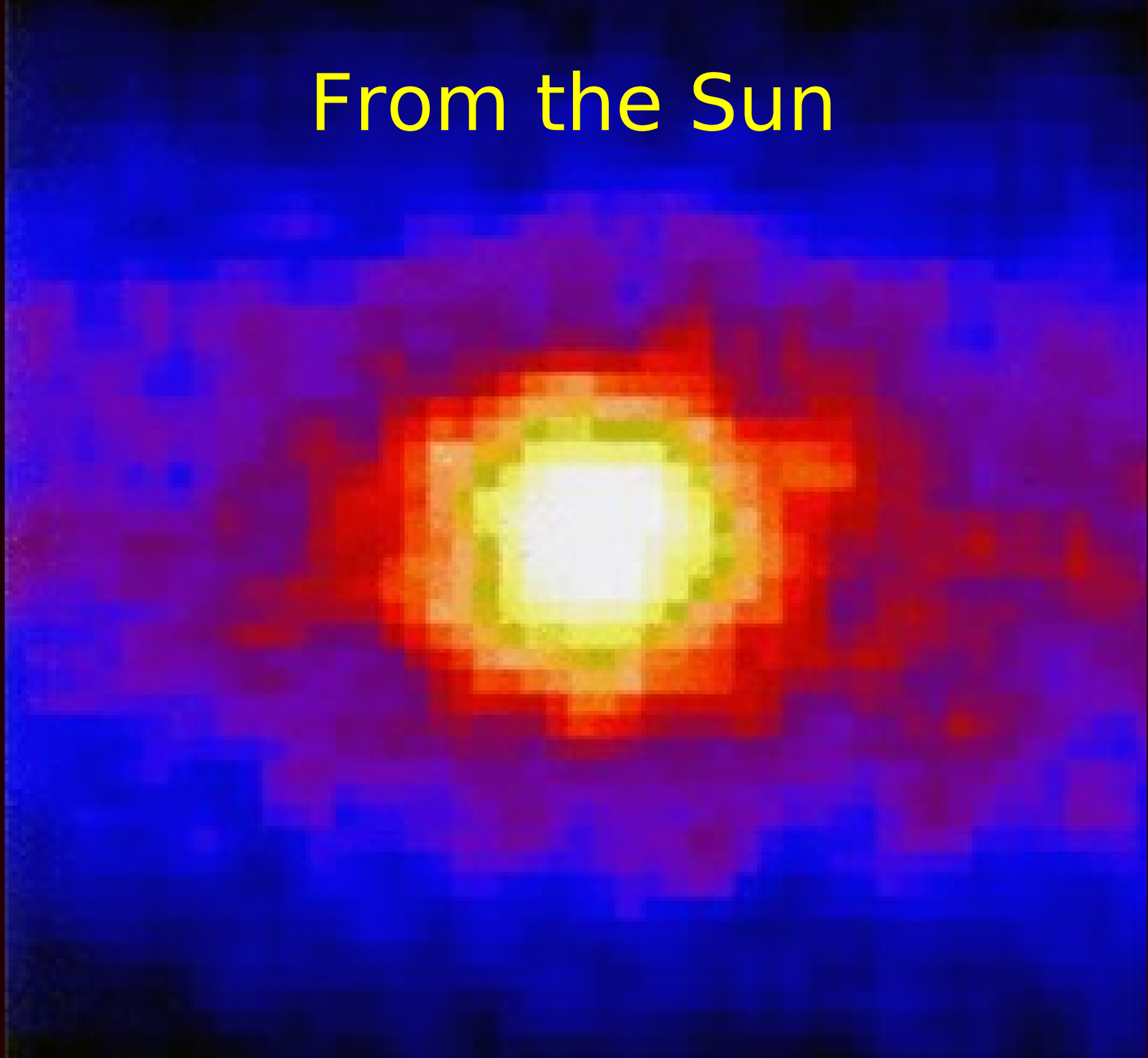
A neutrino
experiment in Japan
measured
25 ± 20 TW

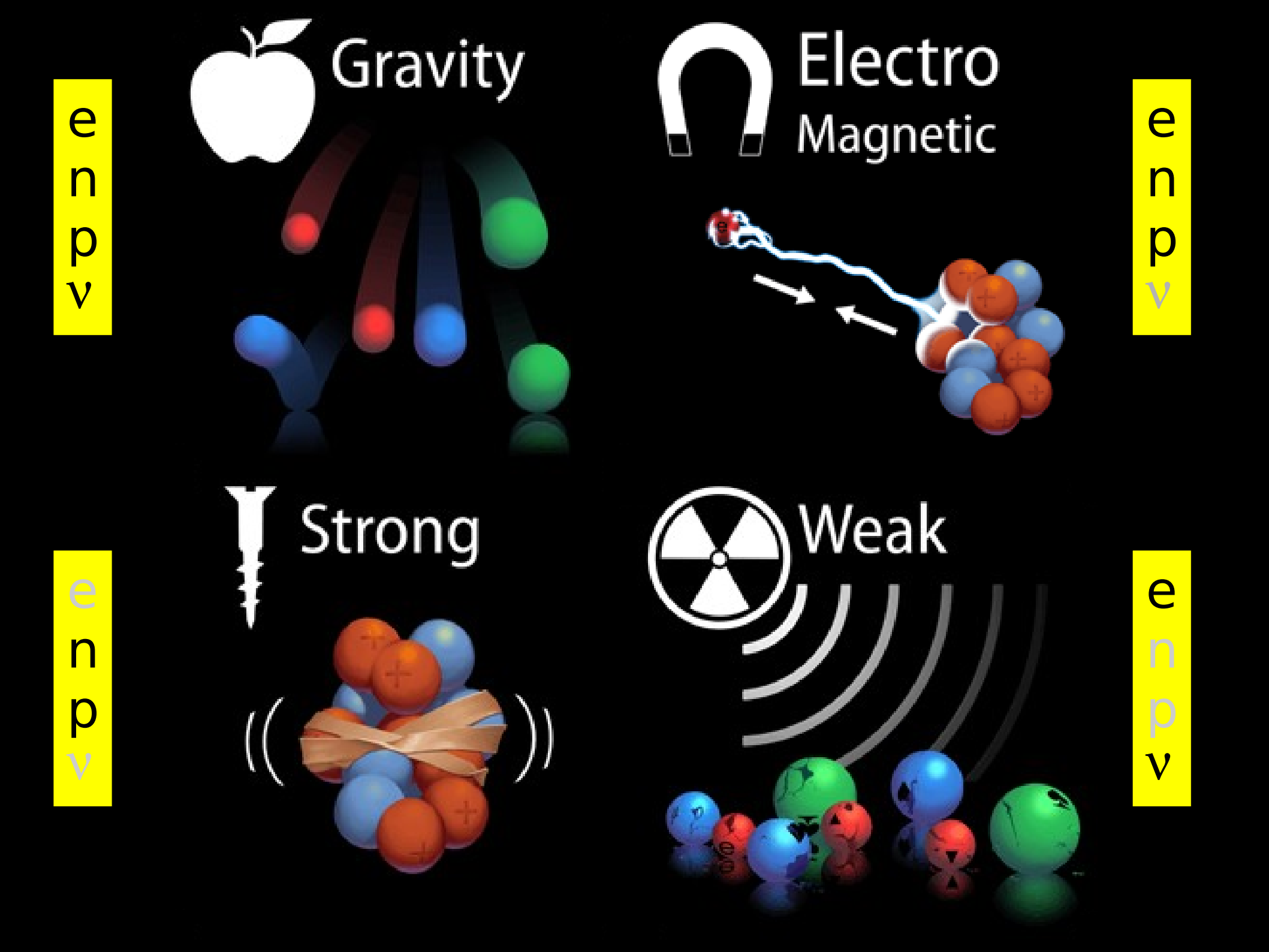
Geoneutrinos

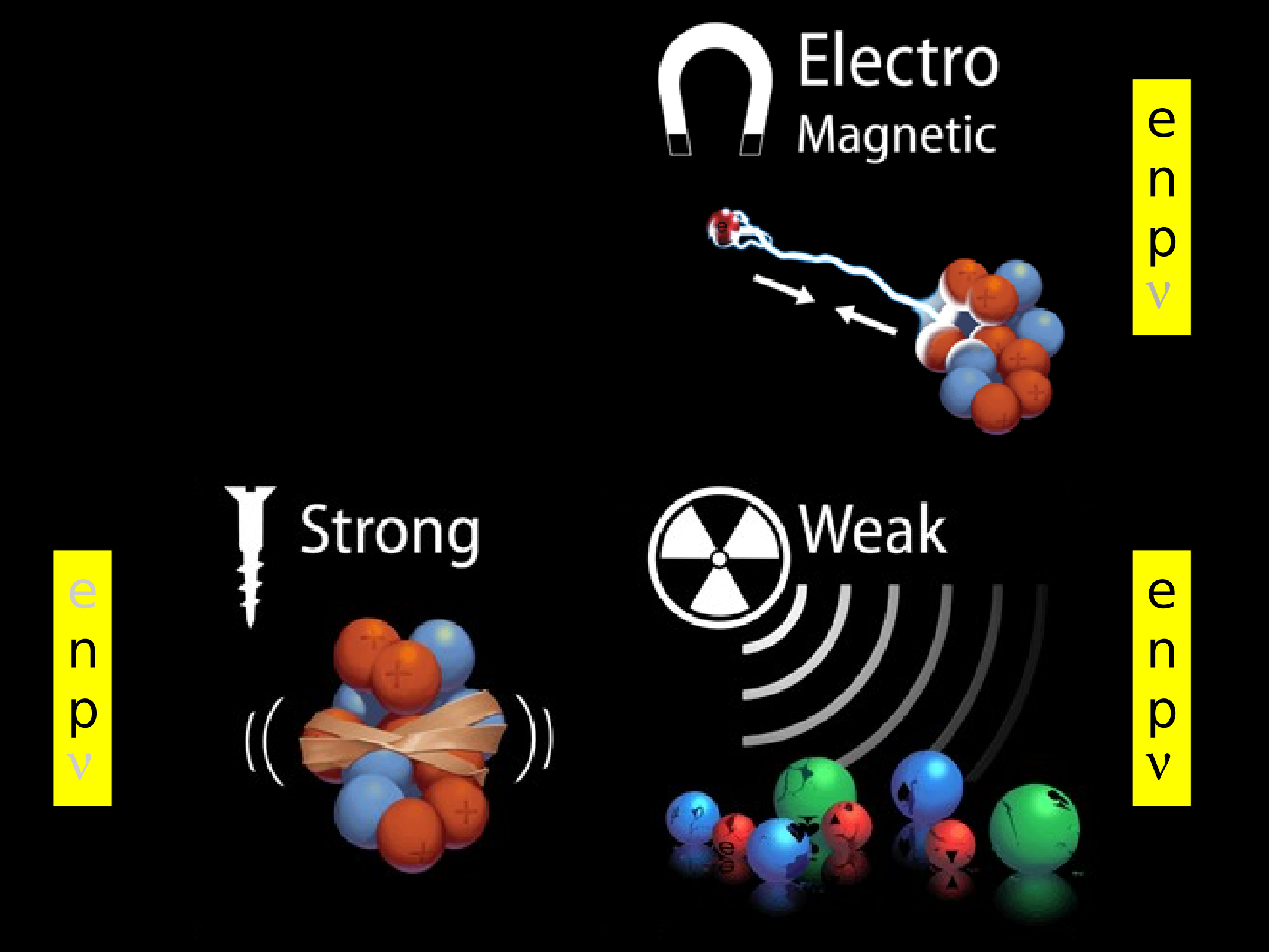



JPARC Facility
TARGET
NuMI

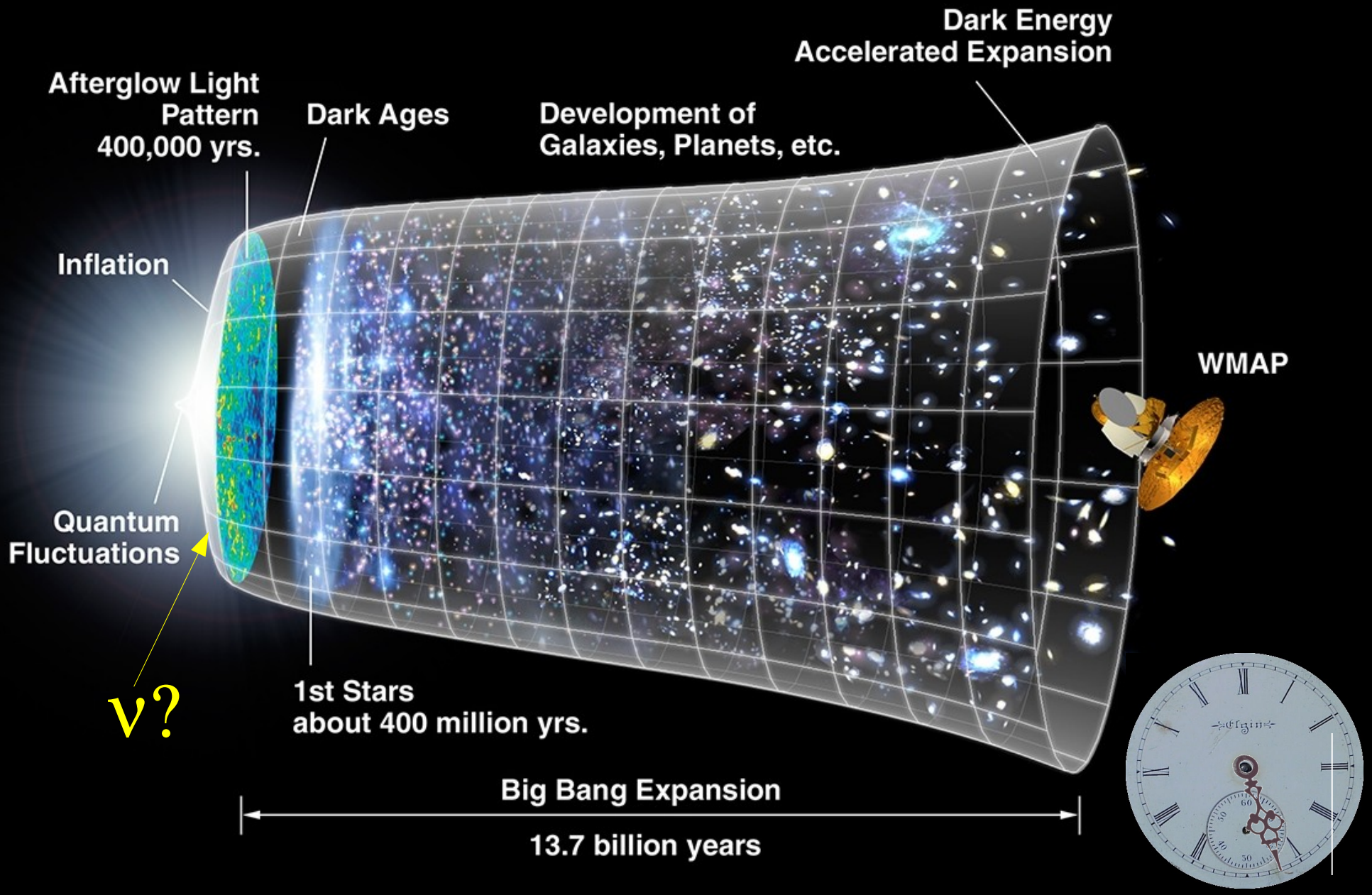
From the Sun

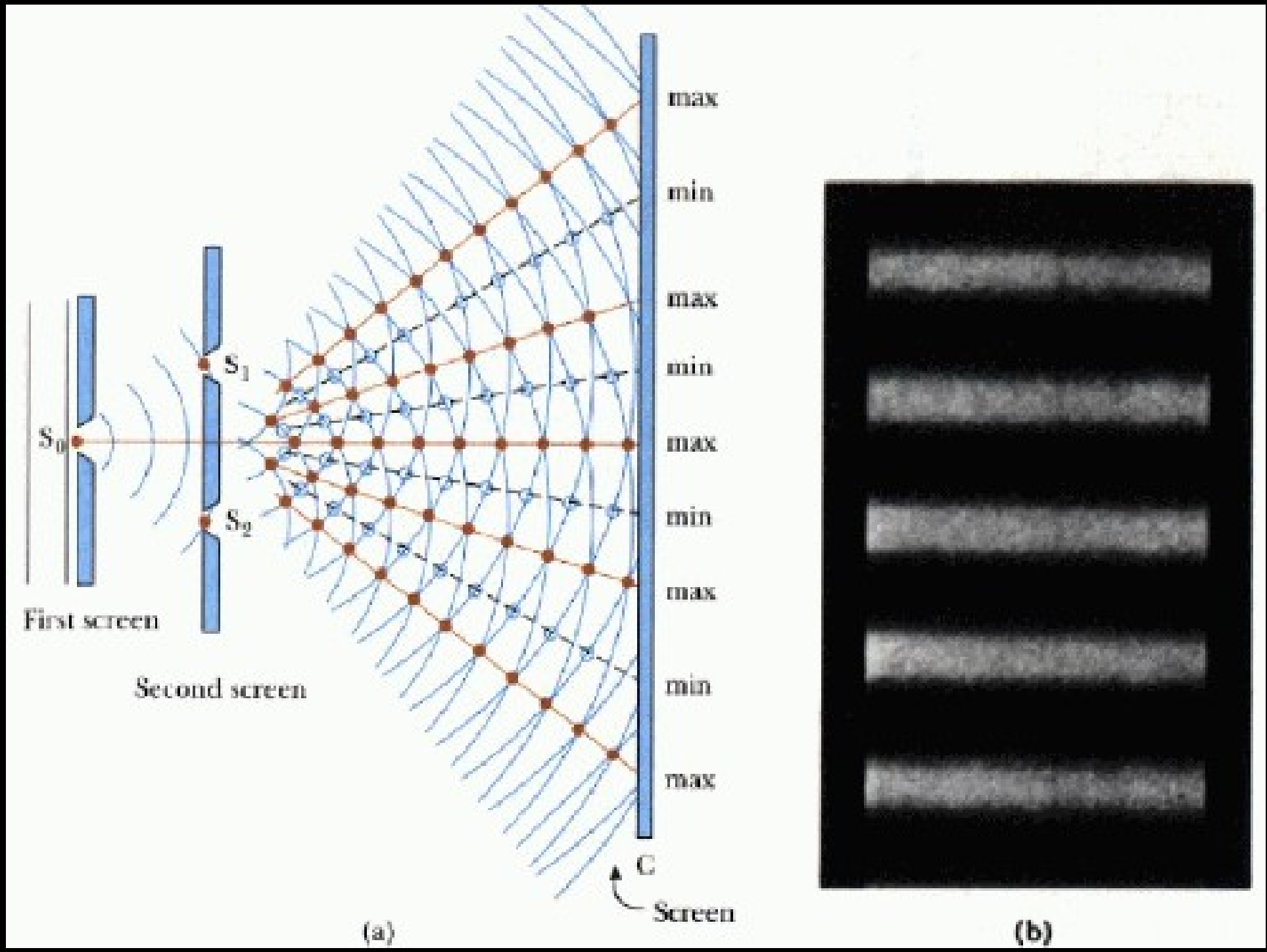


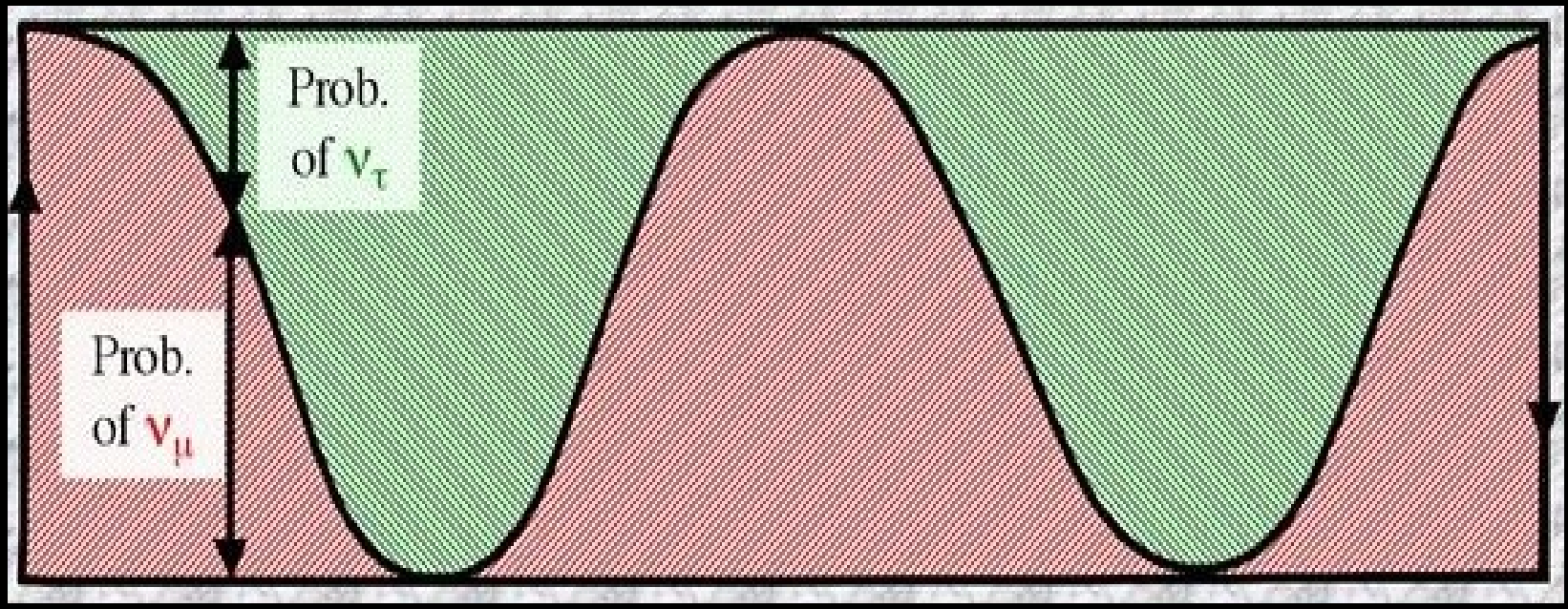

Gravity
Electro
Magnetic
Strong
Weak
e
n
p
ν


Electro
Magnetic
e
n
p
ν
Strong
e
n
p
ν
Weak
e
n
p
ν

I give you...the Universe




max
min
max
min
max
min
max
min
max
S_0
S_1
S_2
First screen
Second screen
C
Screen
(a)
(b)



$\sin^2(2\theta)$

L

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 \frac{L}{E})$$

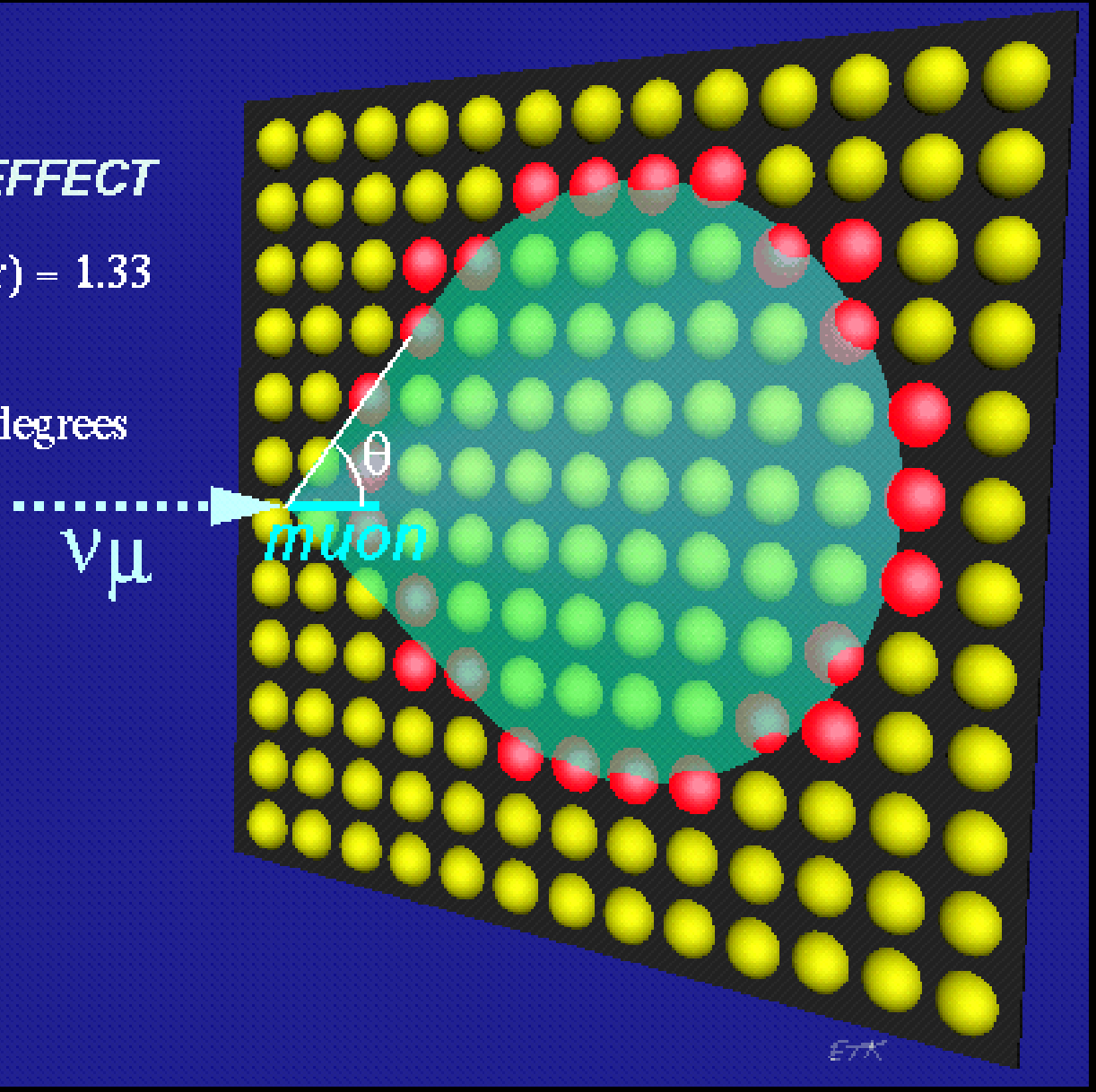
$\Delta m^2 = m_1^2 - m_2^2$

CHERENKOV EFFECT

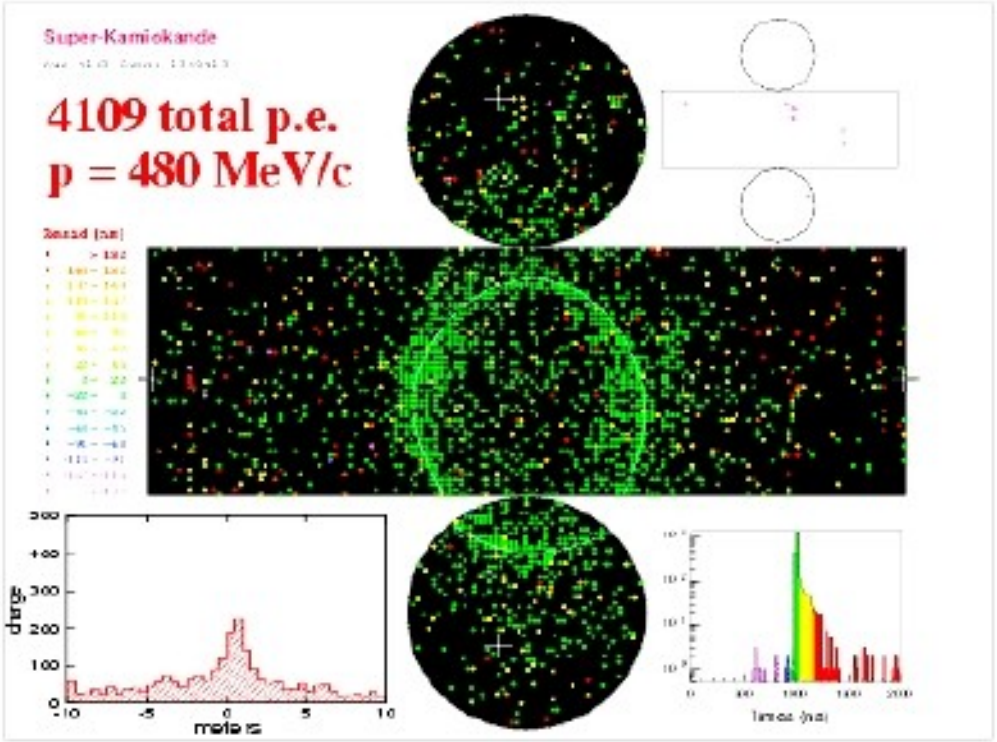
$\beta = v/c$ n(water) = 1.33

$\cos\ \theta = 1/\beta n$

$\beta = 1$ $\theta = 42$ degrees

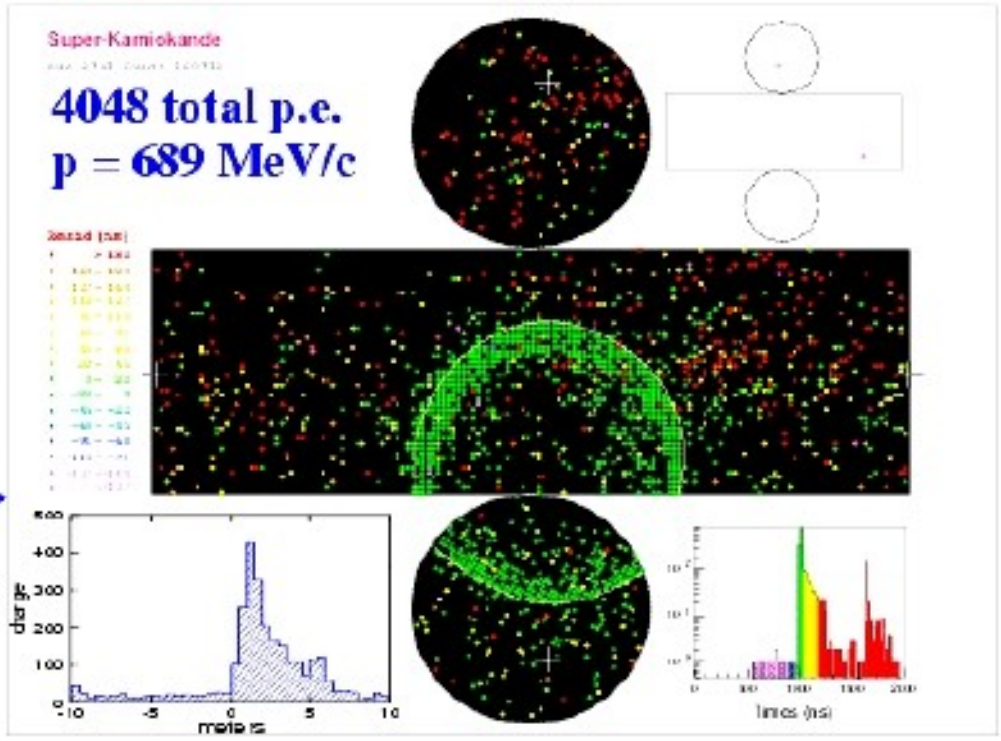


e–like



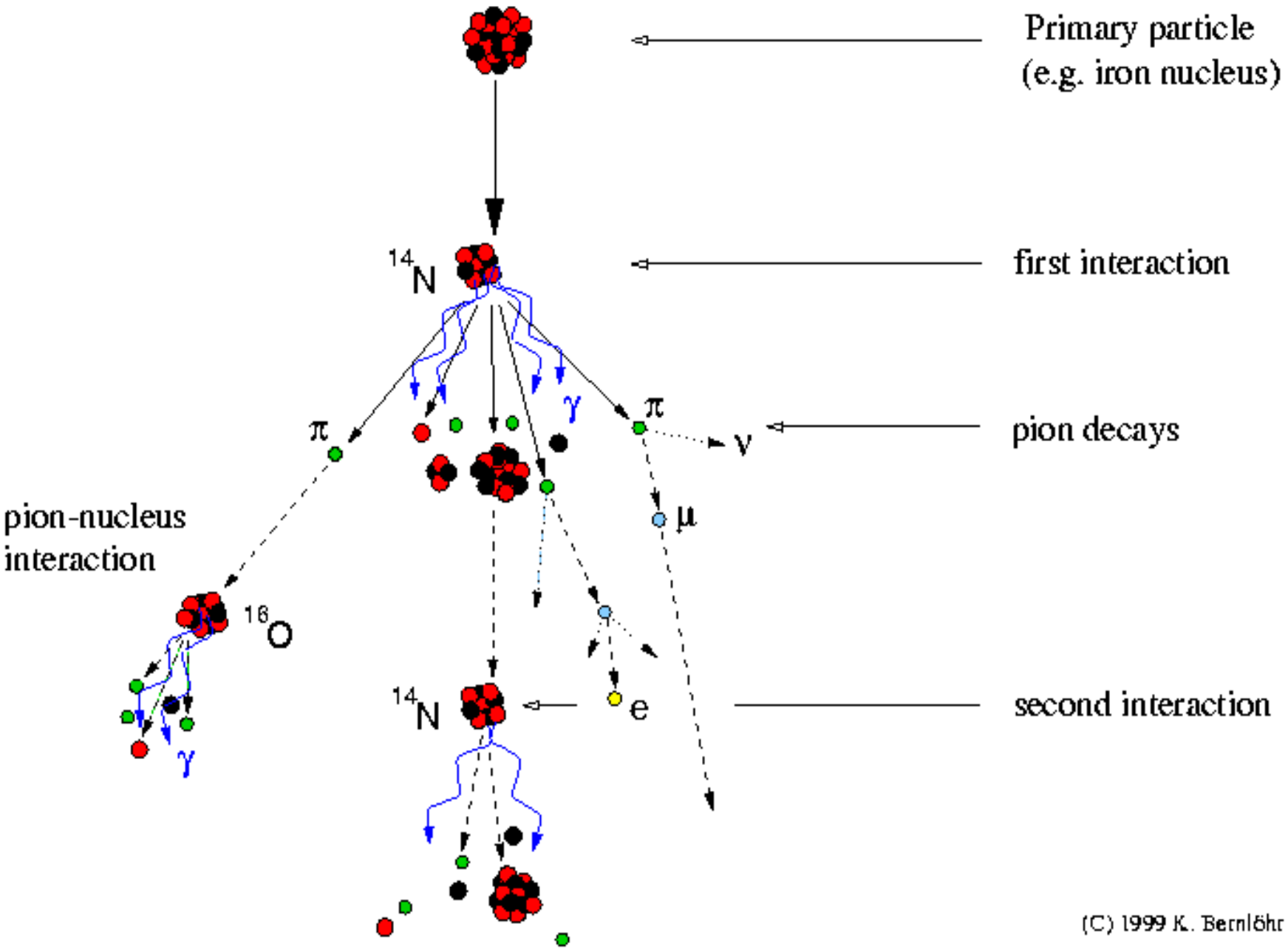
Electron-like : has a fuzzy ring

μ–like

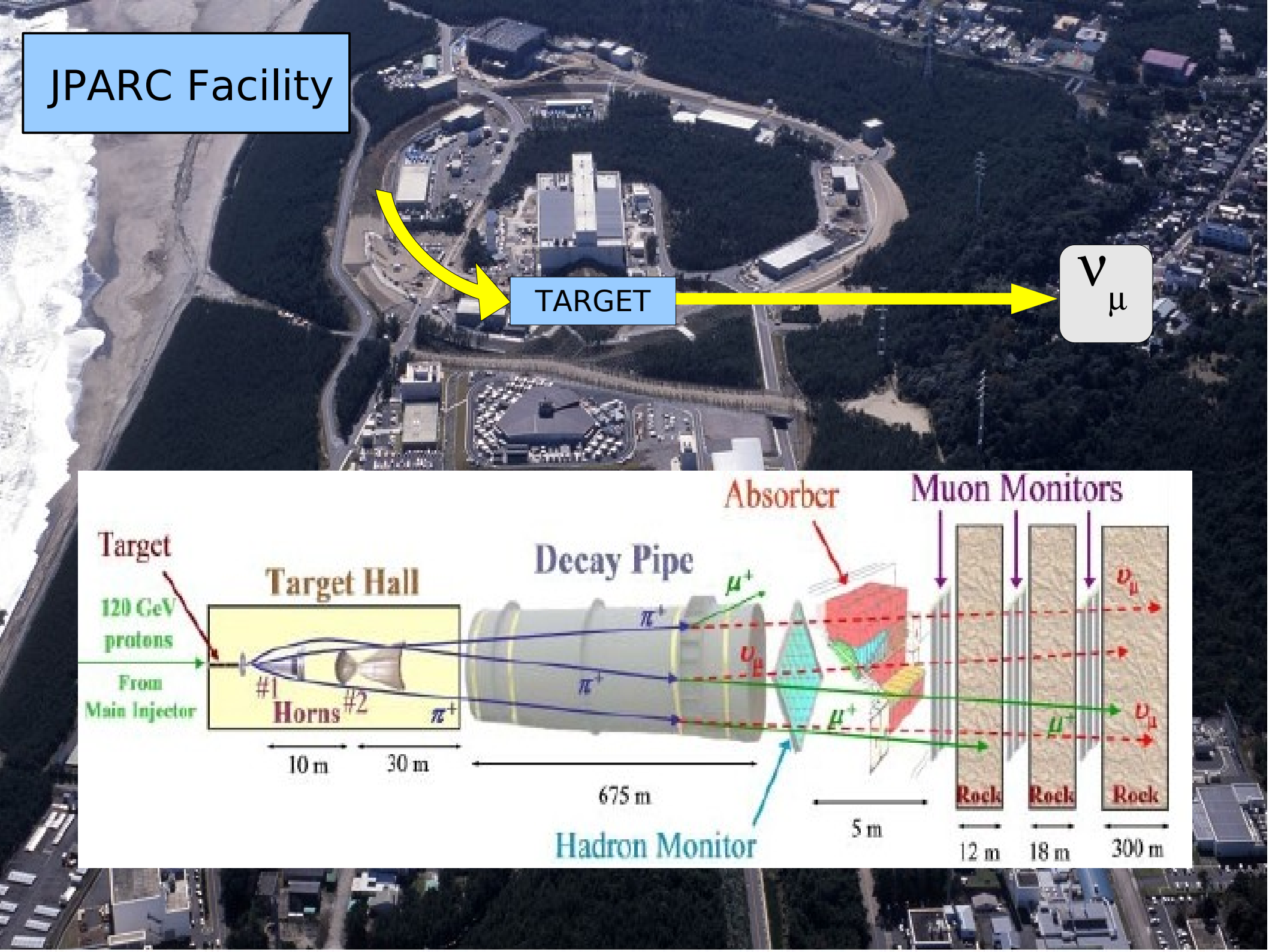


Muon-like : has a sharp edged ring and particle stopped in detector.

Development of cosmic-ray air showers

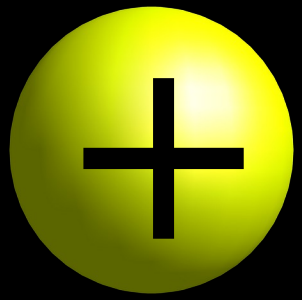


JPARC Facility



Positron, e^+

mass (1)



Electron Antineutrino, ν_e

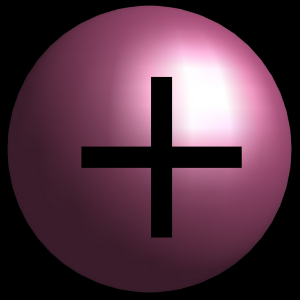
Muon, μ^+

mass (200)

Muon Antineutrino, ν_μ

Tau, τ^+

mass (3500)

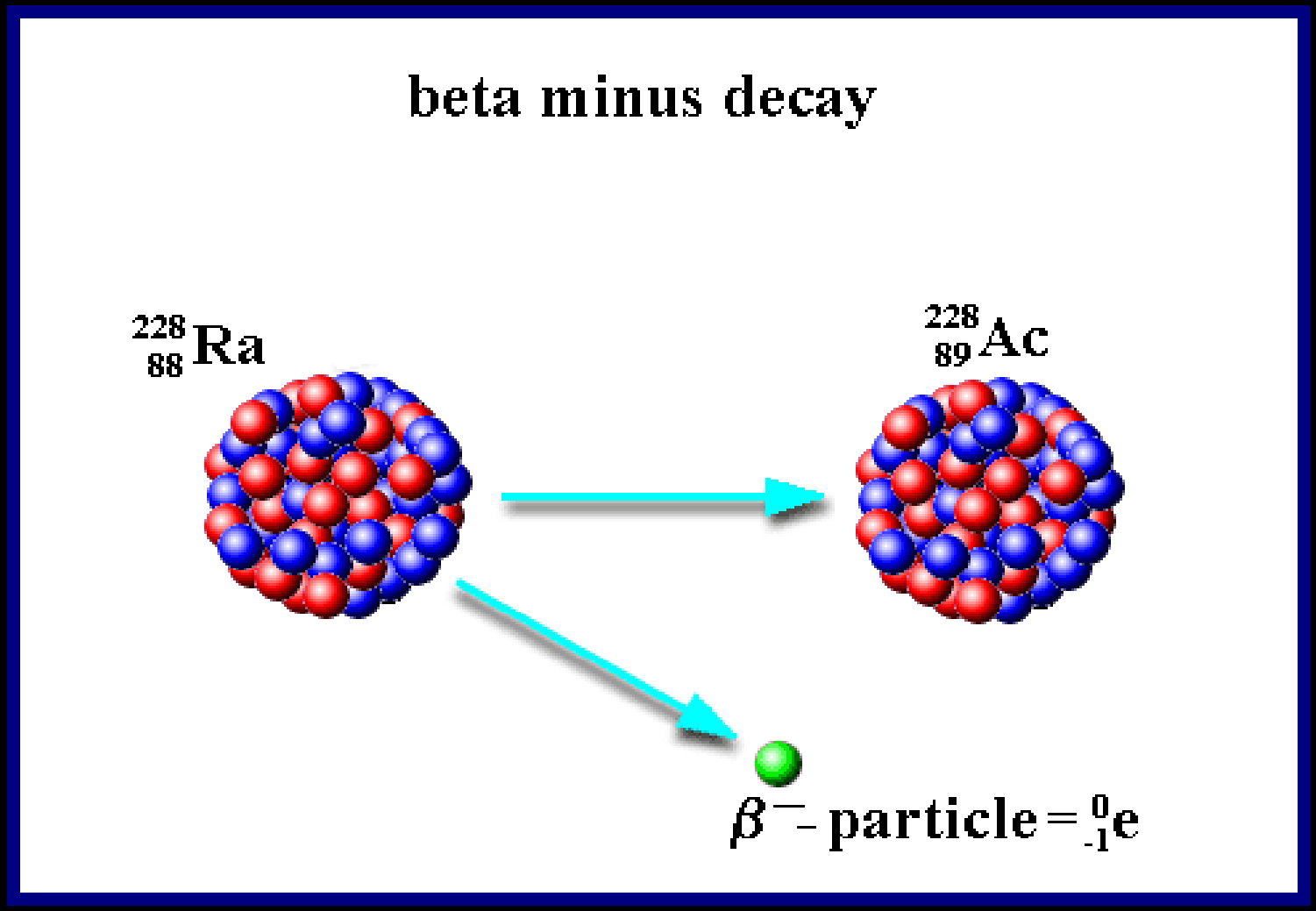


Tau Antineutrino, ν_μ

3 Antiparticles

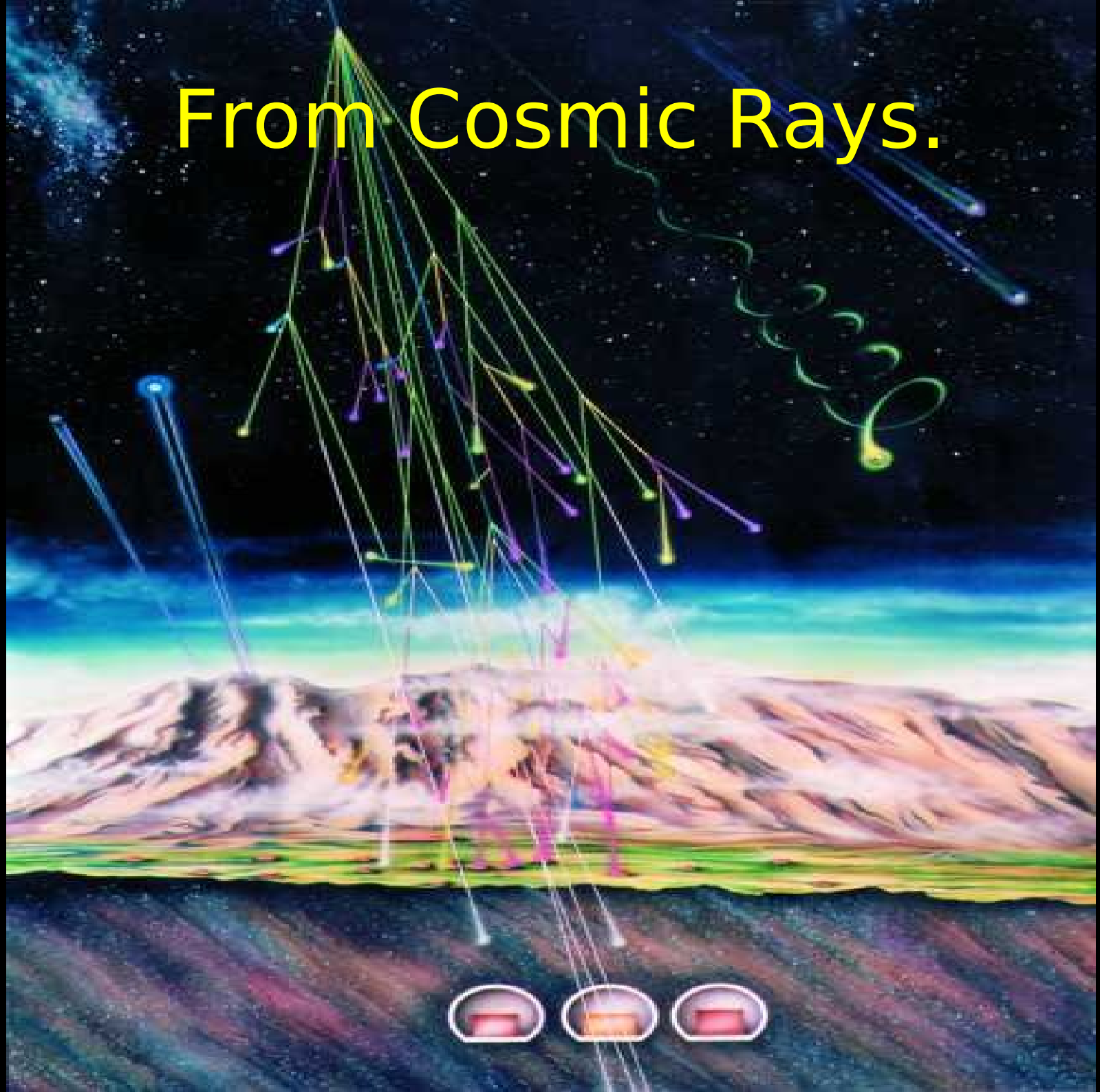
Neils Bohr

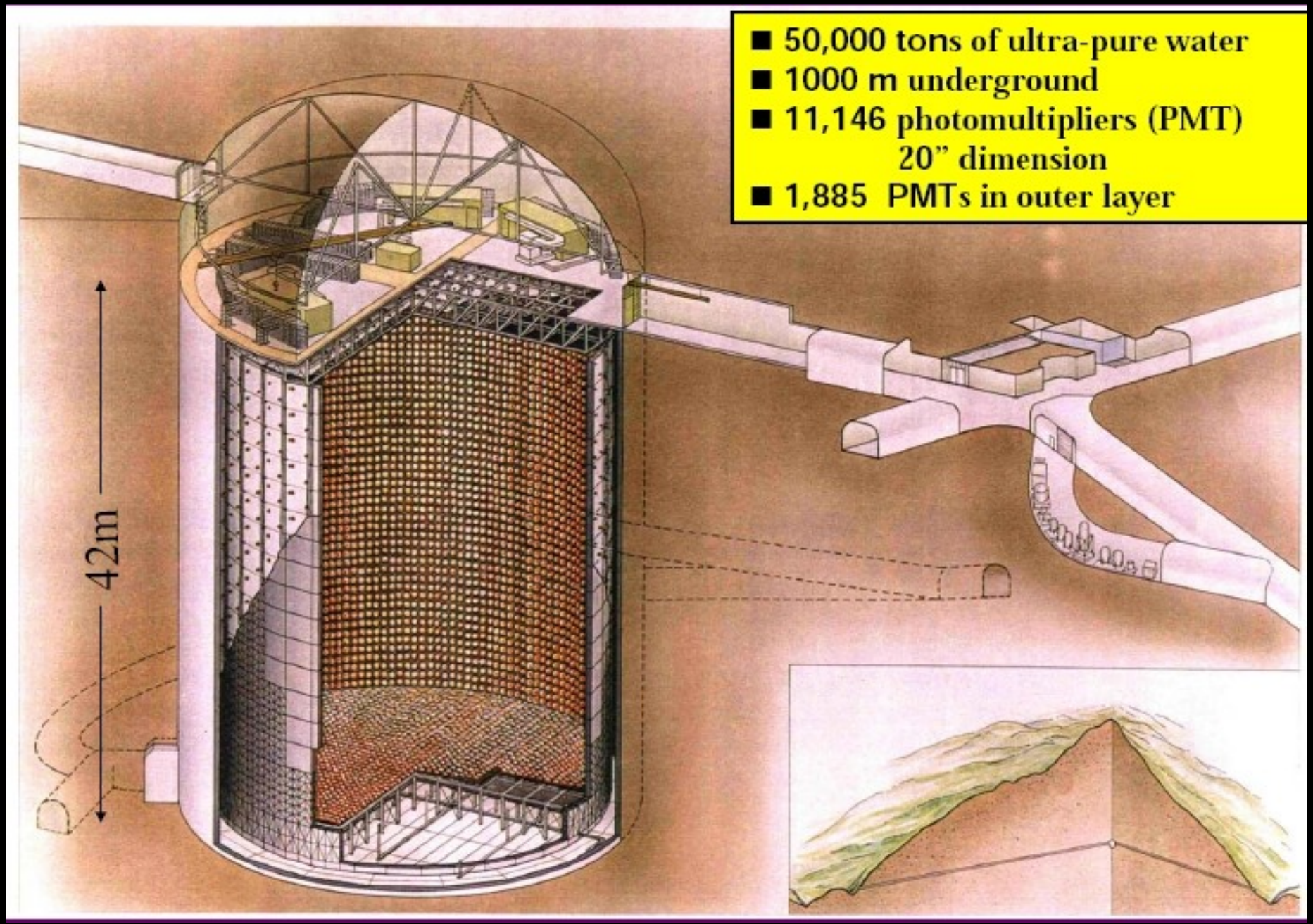
“At the present stage of atomic theory we have no arguments for upholding the concept of energy balance in the case of β-ray disintegrations.”

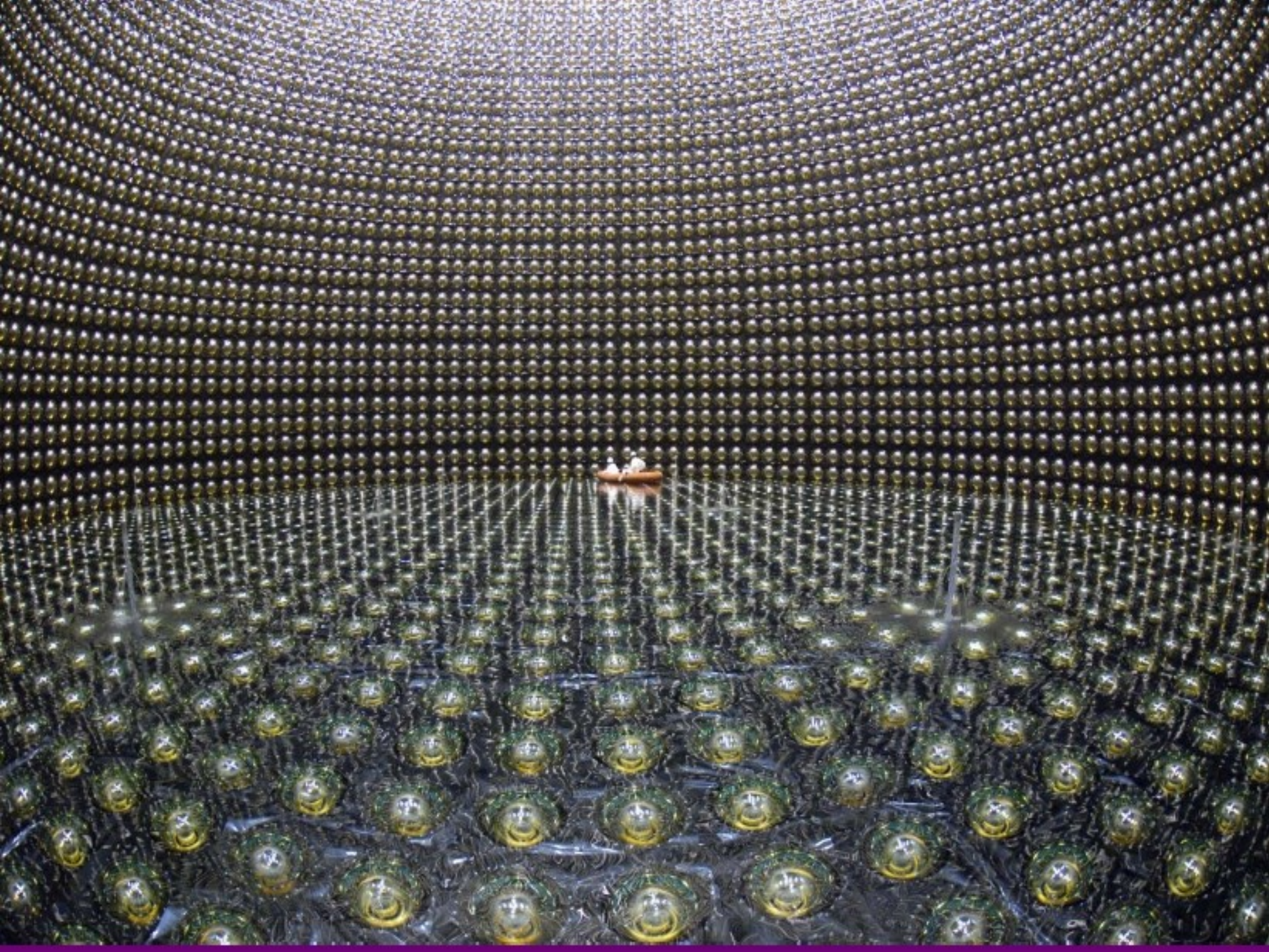


Energy(Ra) ≠ Energy(Ac)+Energy(e)

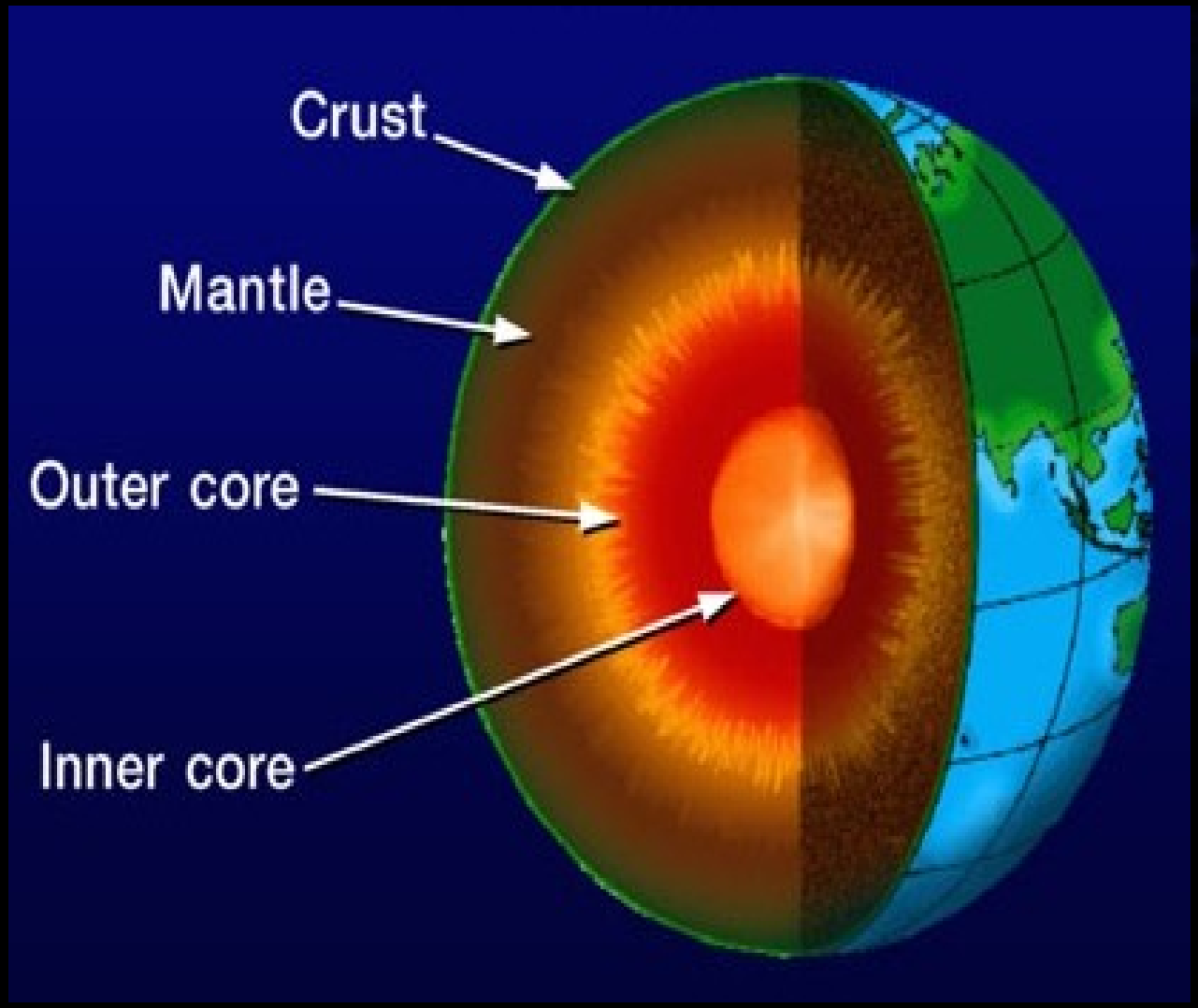
The Sun in Neutrinos

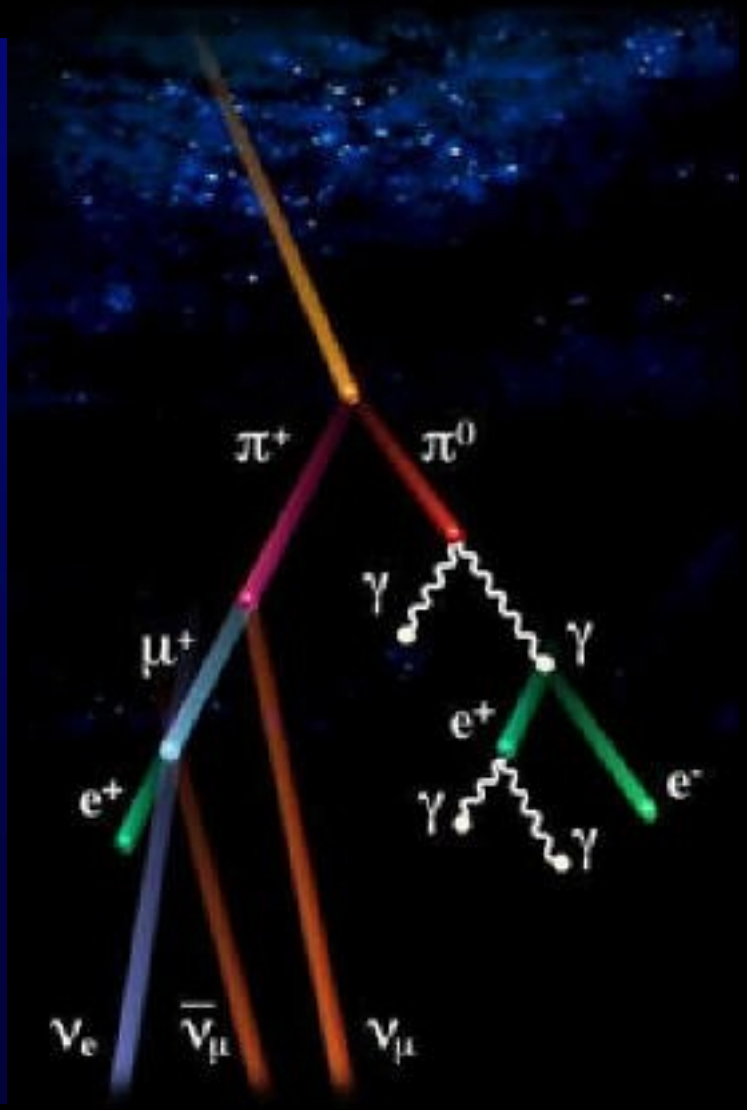

From Cosmic Rays.

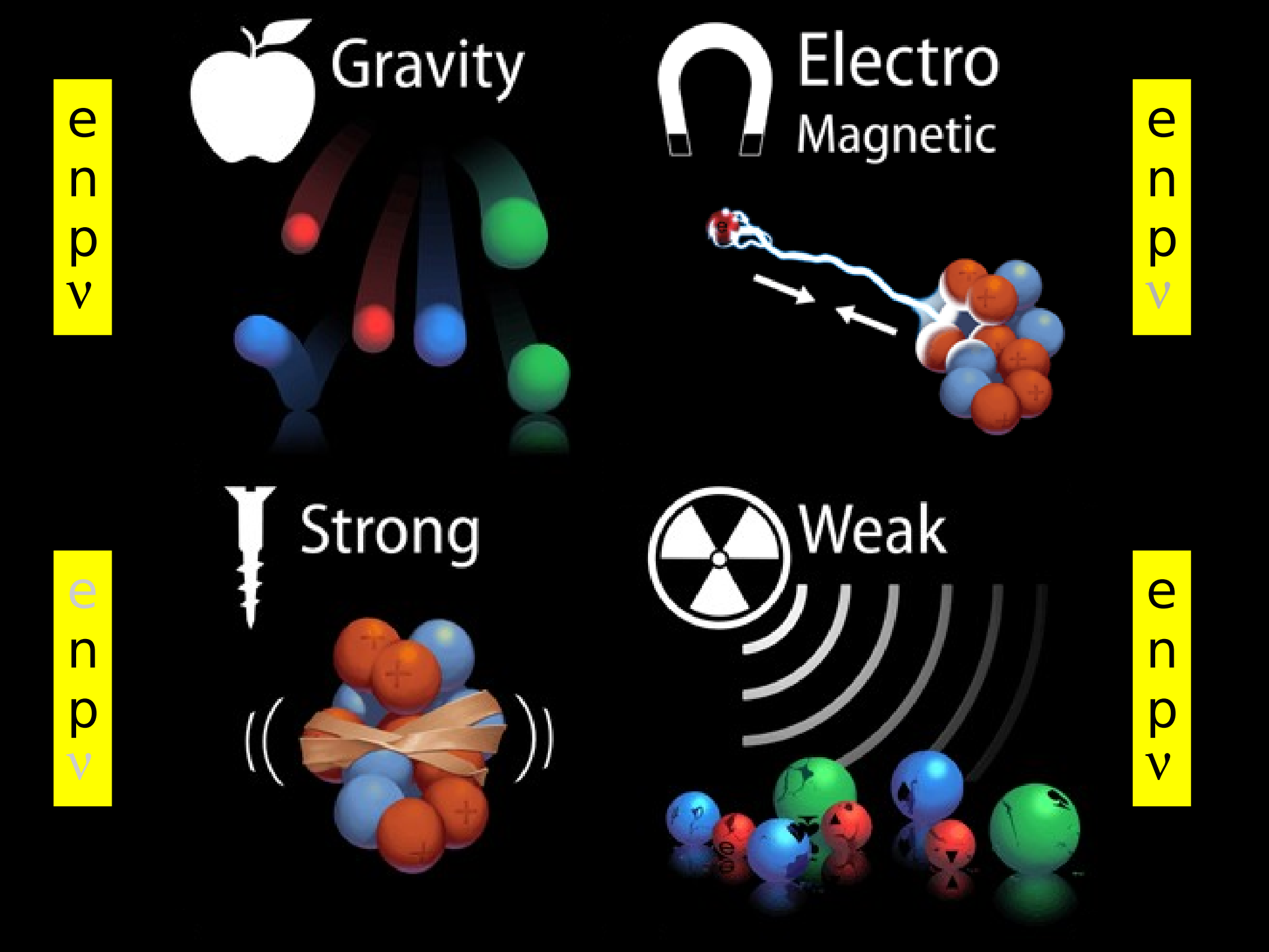

■ 50,000 tons of ultra-pure water
■ 1000 m underground
■ 11,146 photomultipliers (PMT)
20" dimension
■ 1,885 PMTs in outer layer
42m



From The Earth



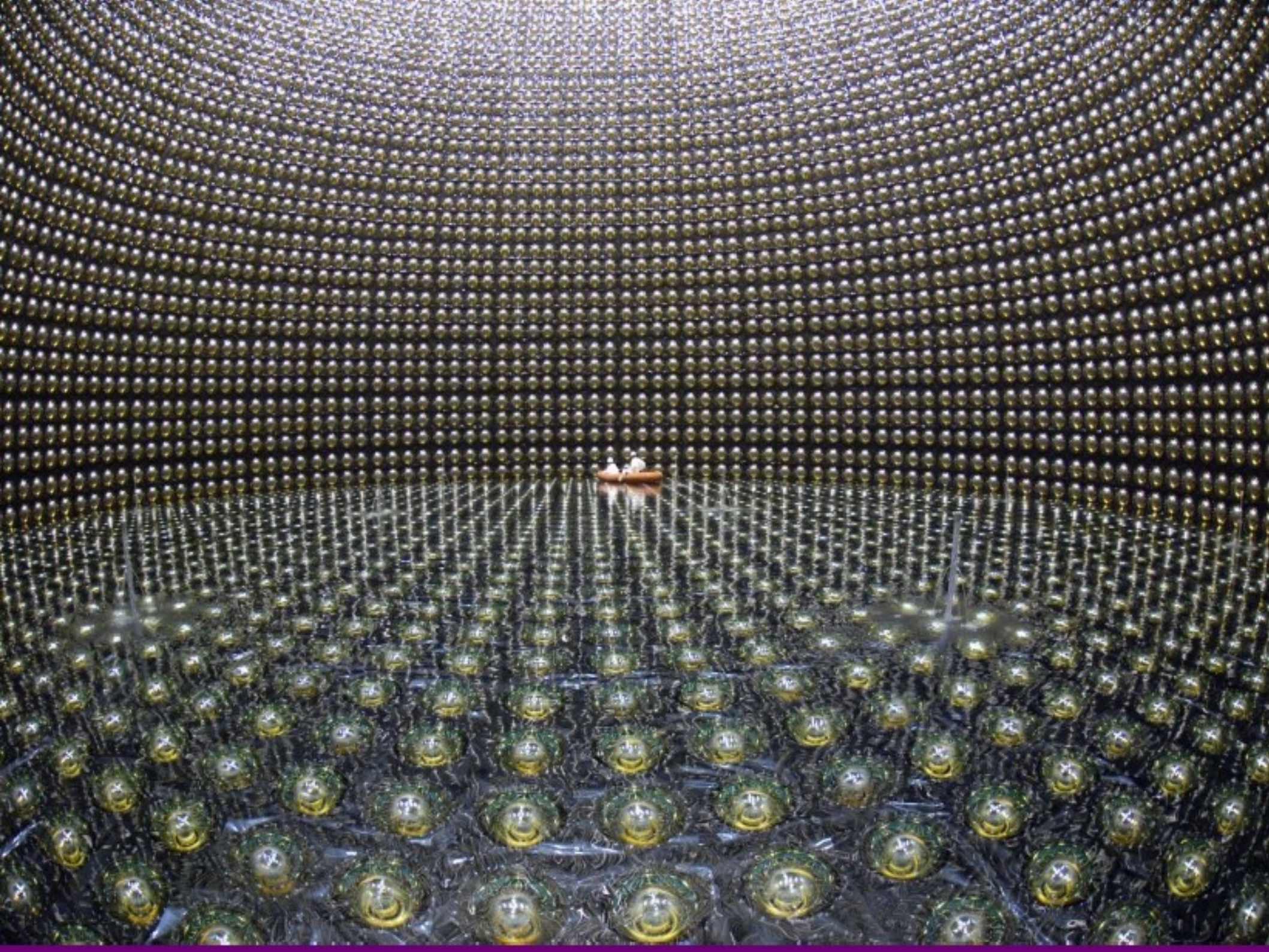


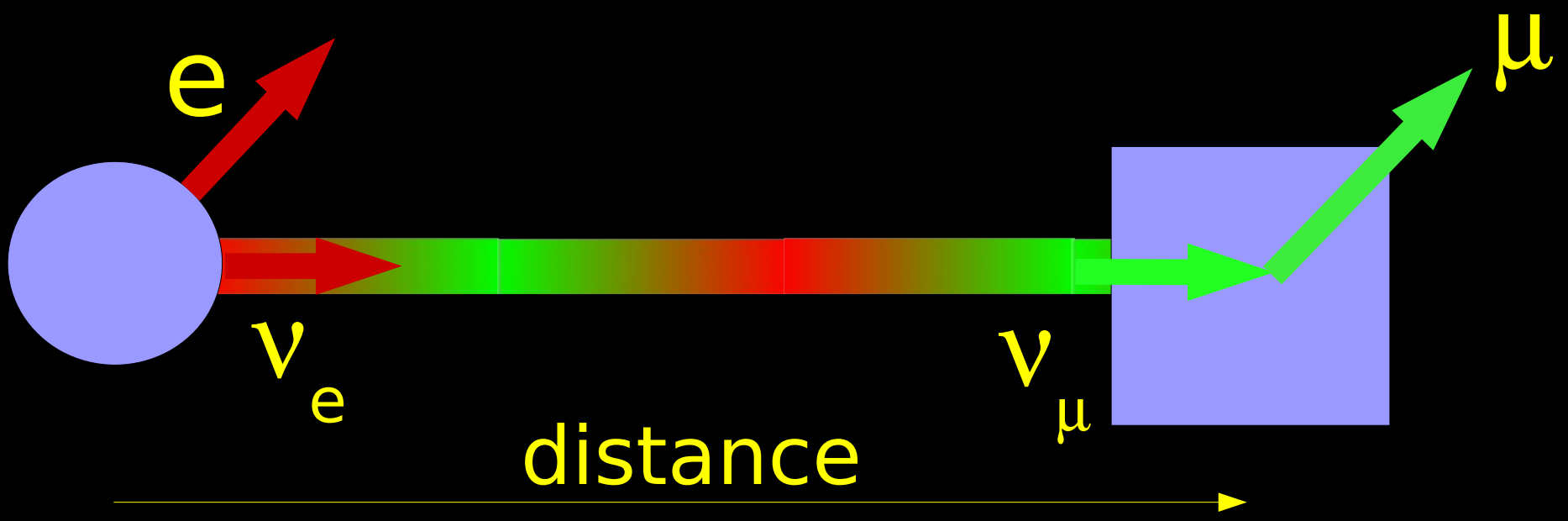

Gravity
Electro
Magnetic
Strong
Weak
e
n
p
ν

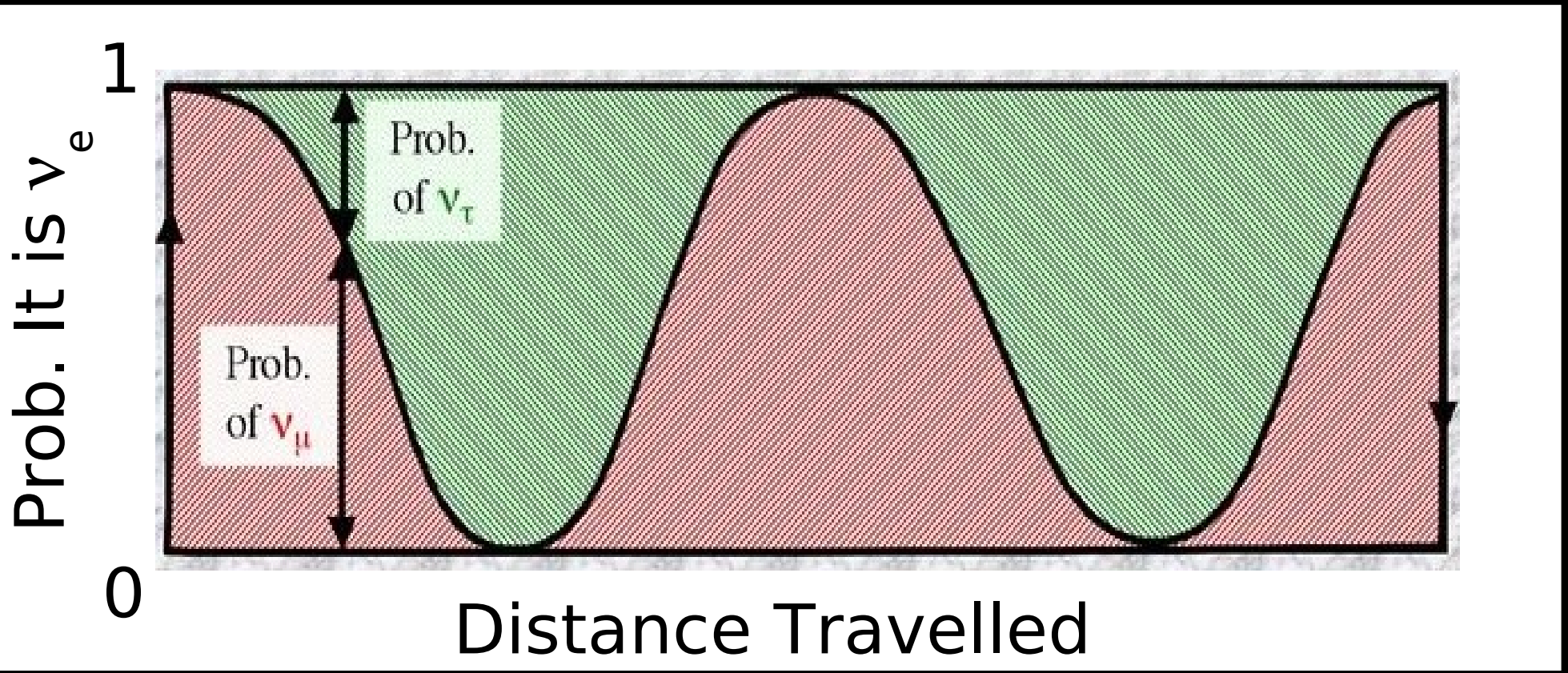

BUGATTI
18·4 EB 67

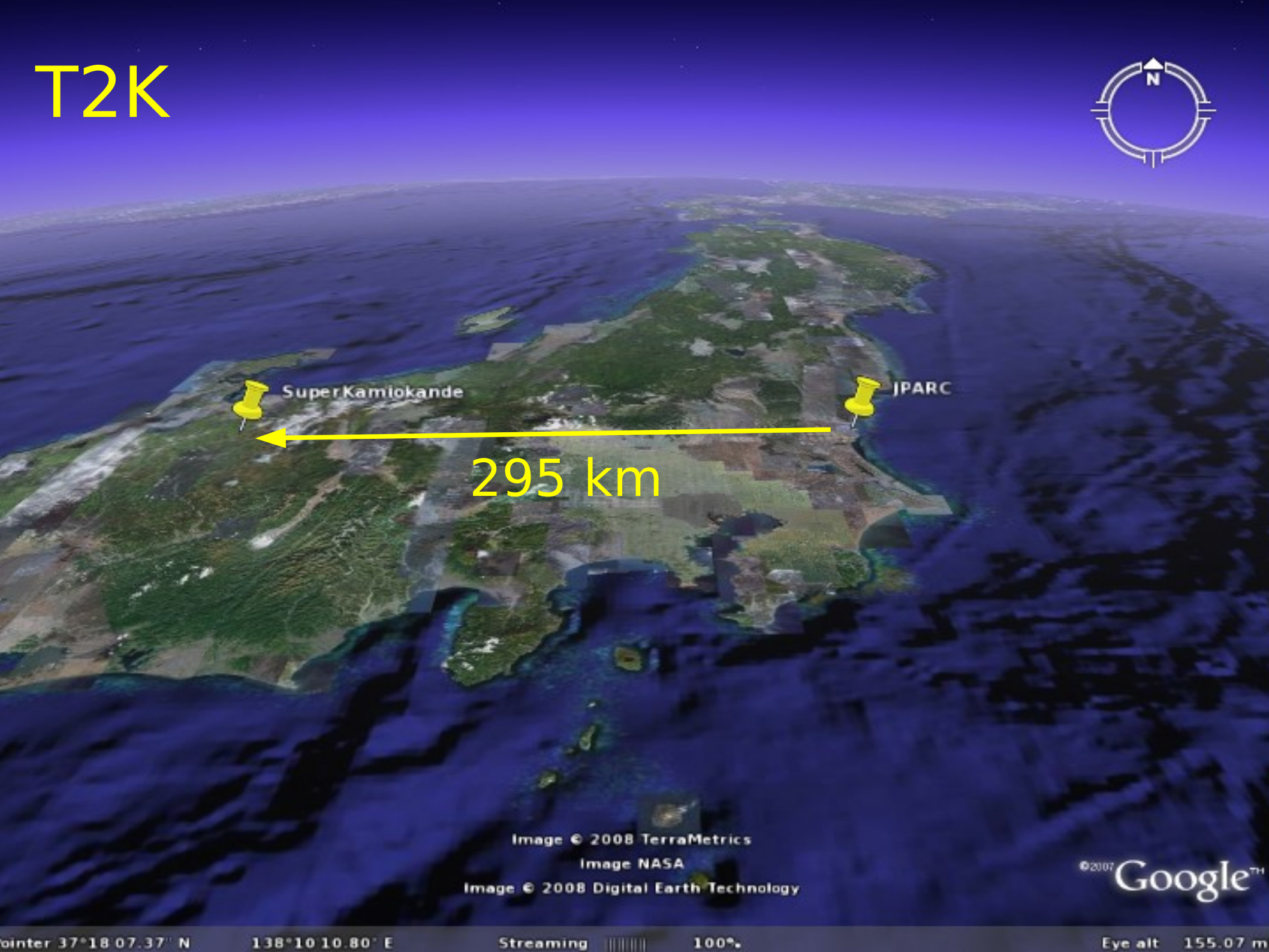
"The chances of a neutrino actually hitting something as it travels through all this howling emptiness are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich."

Douglas Adams

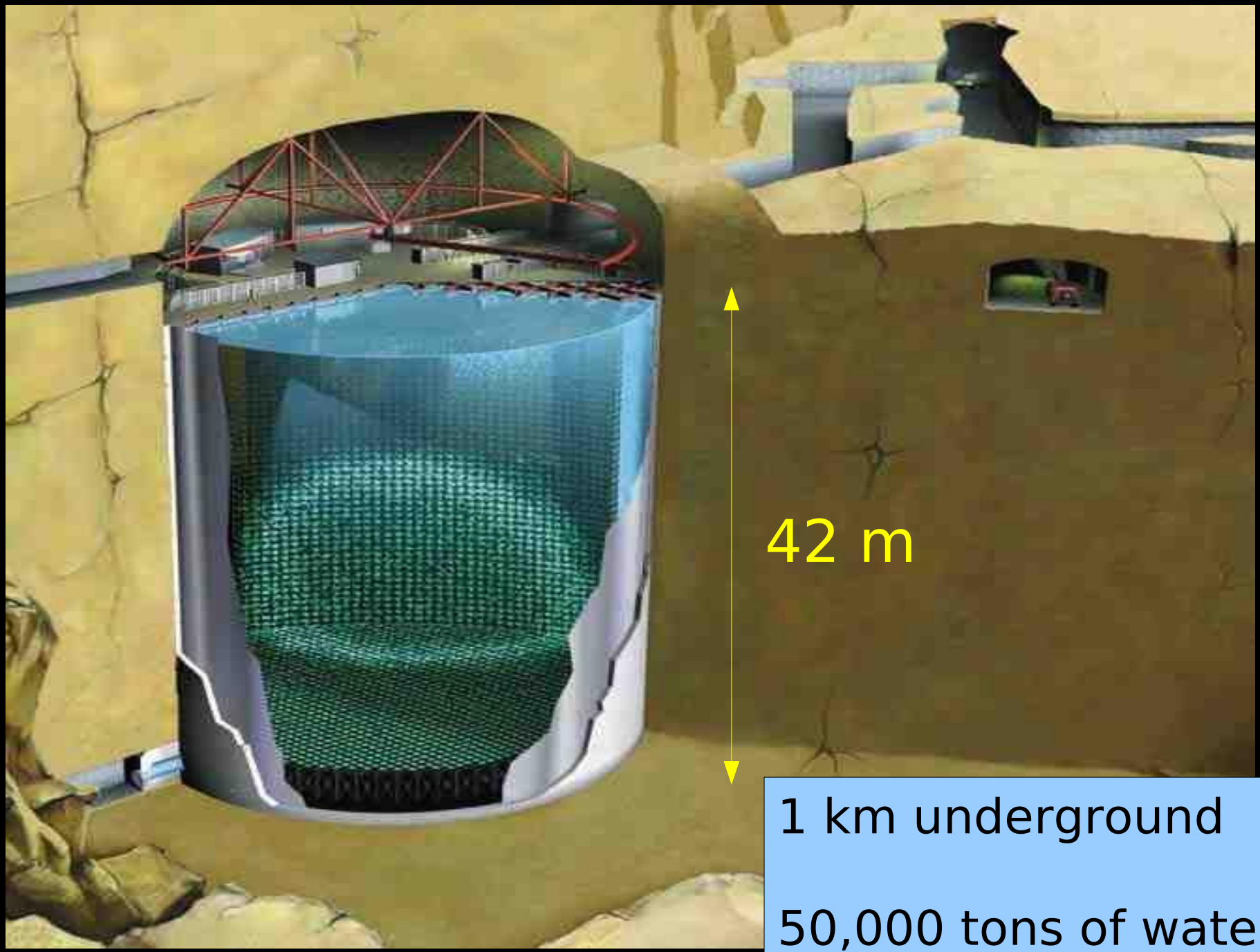



e
μ
ν_e
ν_μ
distance


1
0
Prob. It is ν_e
Prob. of ν_τ
Prob. of ν_μ
Distance Travelled


T2K
N
SuperKamiokande
JPARC
295 km
Image © 2008 TerraMetrics
Image NASA
Image © 2008 Digital Earth Technology
©2007 Google™
Pointer 37°18'07.37" N 138°10'10.80" E
Streaming
100%
Eye alt 155.07 m

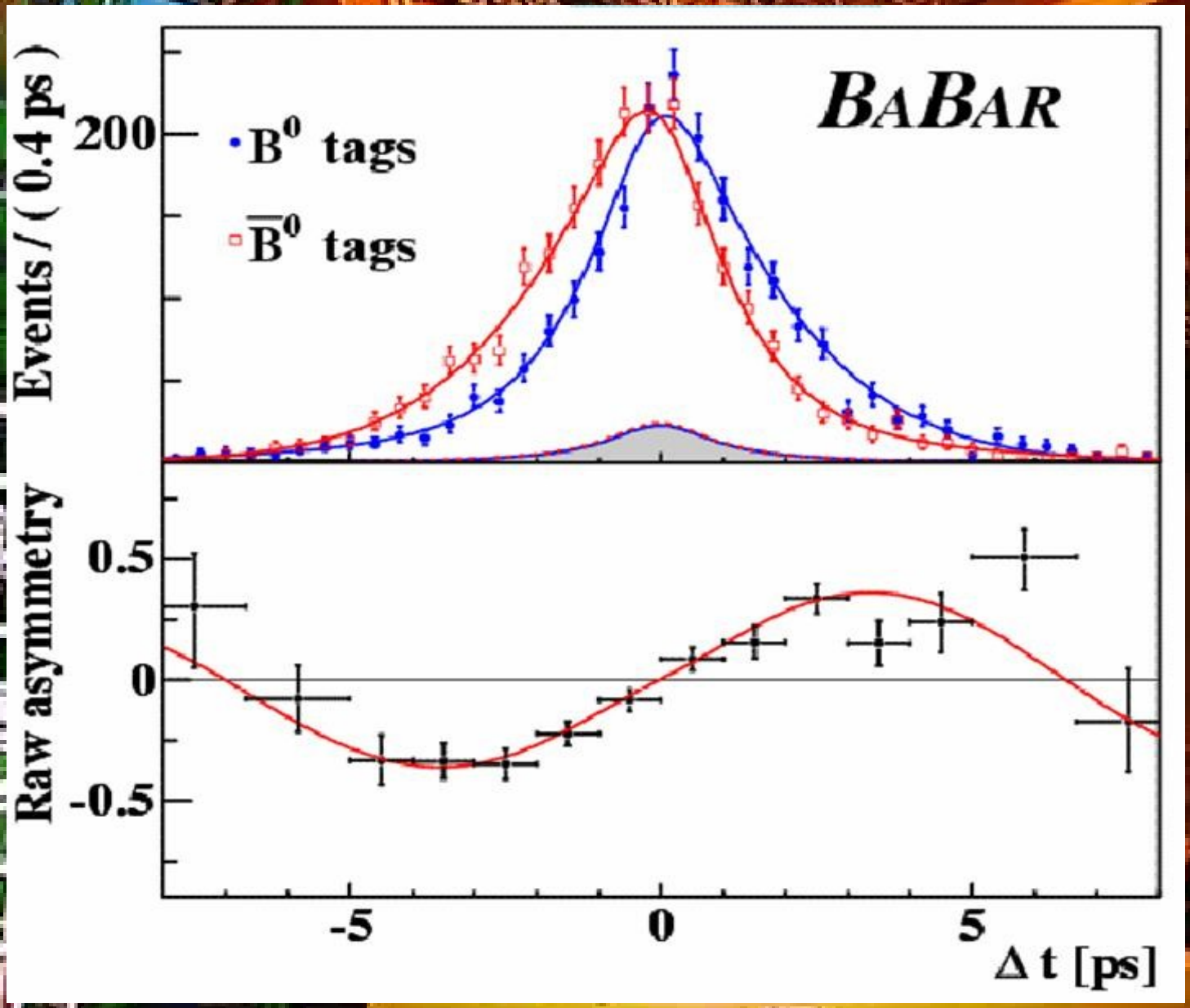
Super-Kamiokande



1 km underground

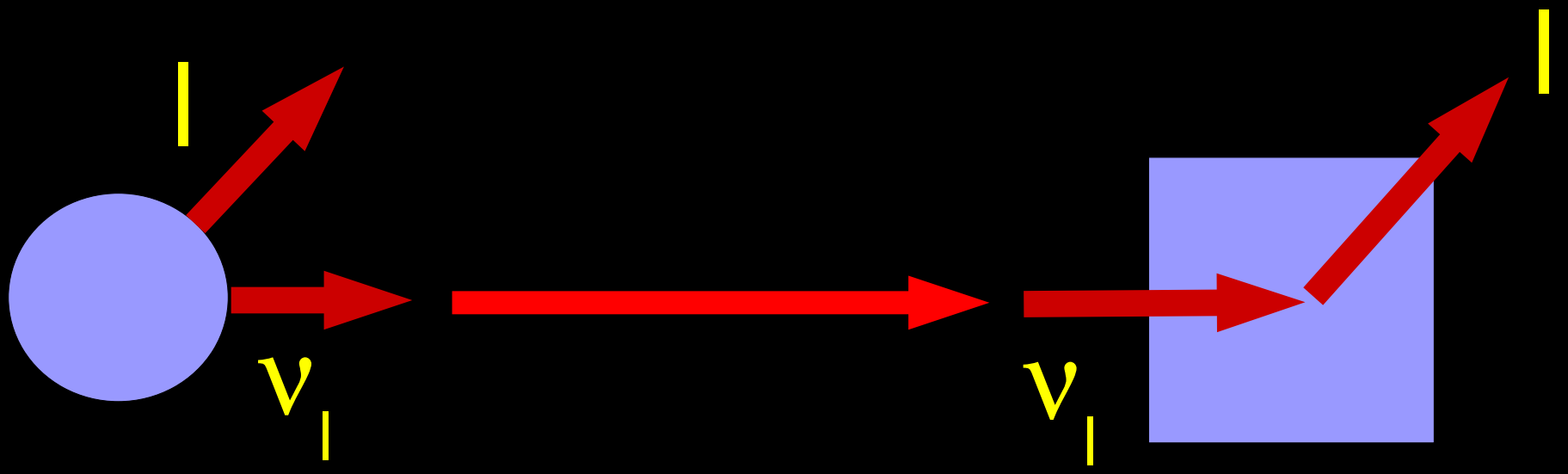
50,000 tons of water

There is a difference between the physics of matter and antimatter



Neutrino Oscillations

THE discovery in neutrinos of the last 20 years



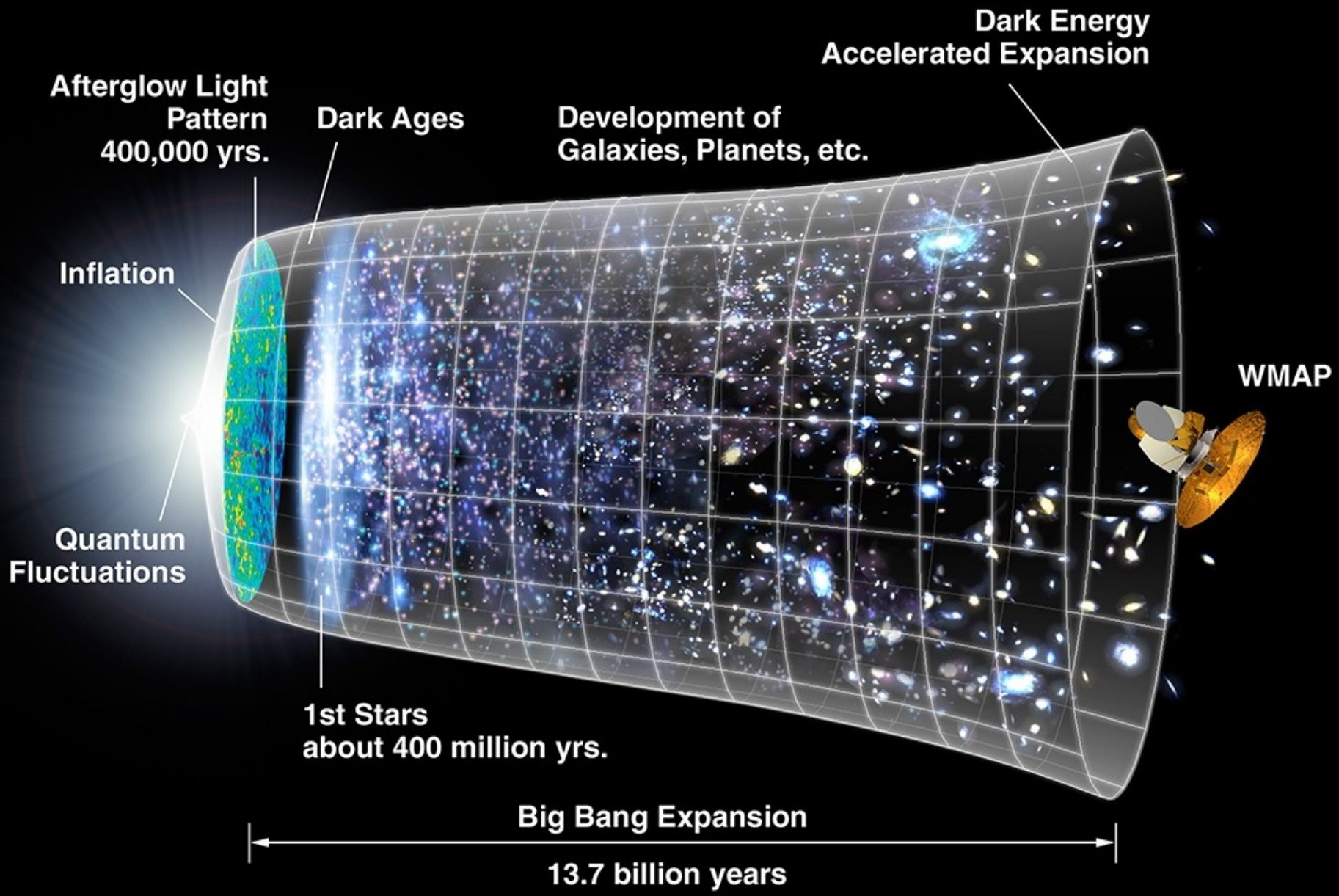
A typical neutrino experiment

Neutrinos and the case of the missing antimatter

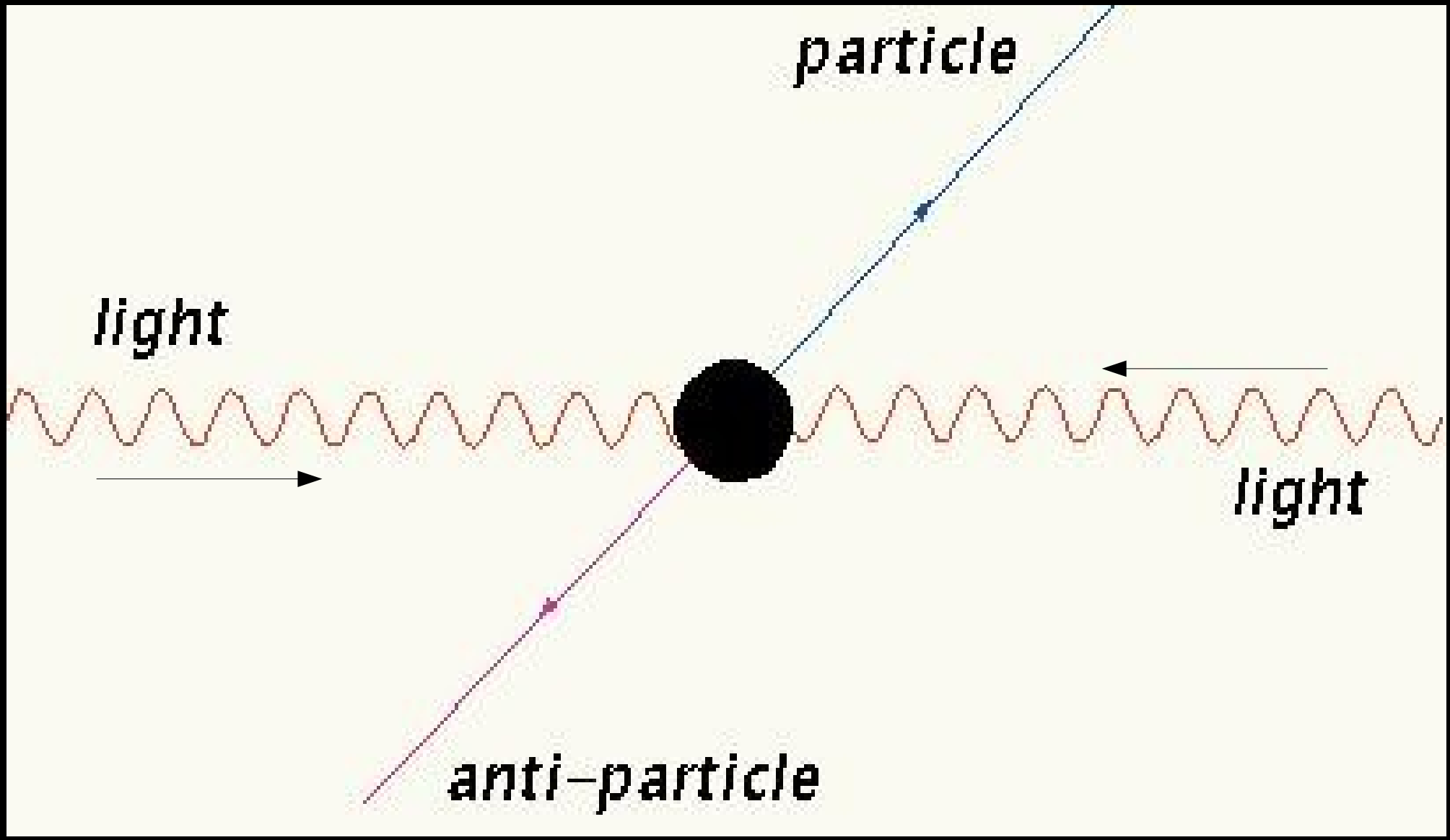
Steve Boyd, University of Warwick

How do we exist?

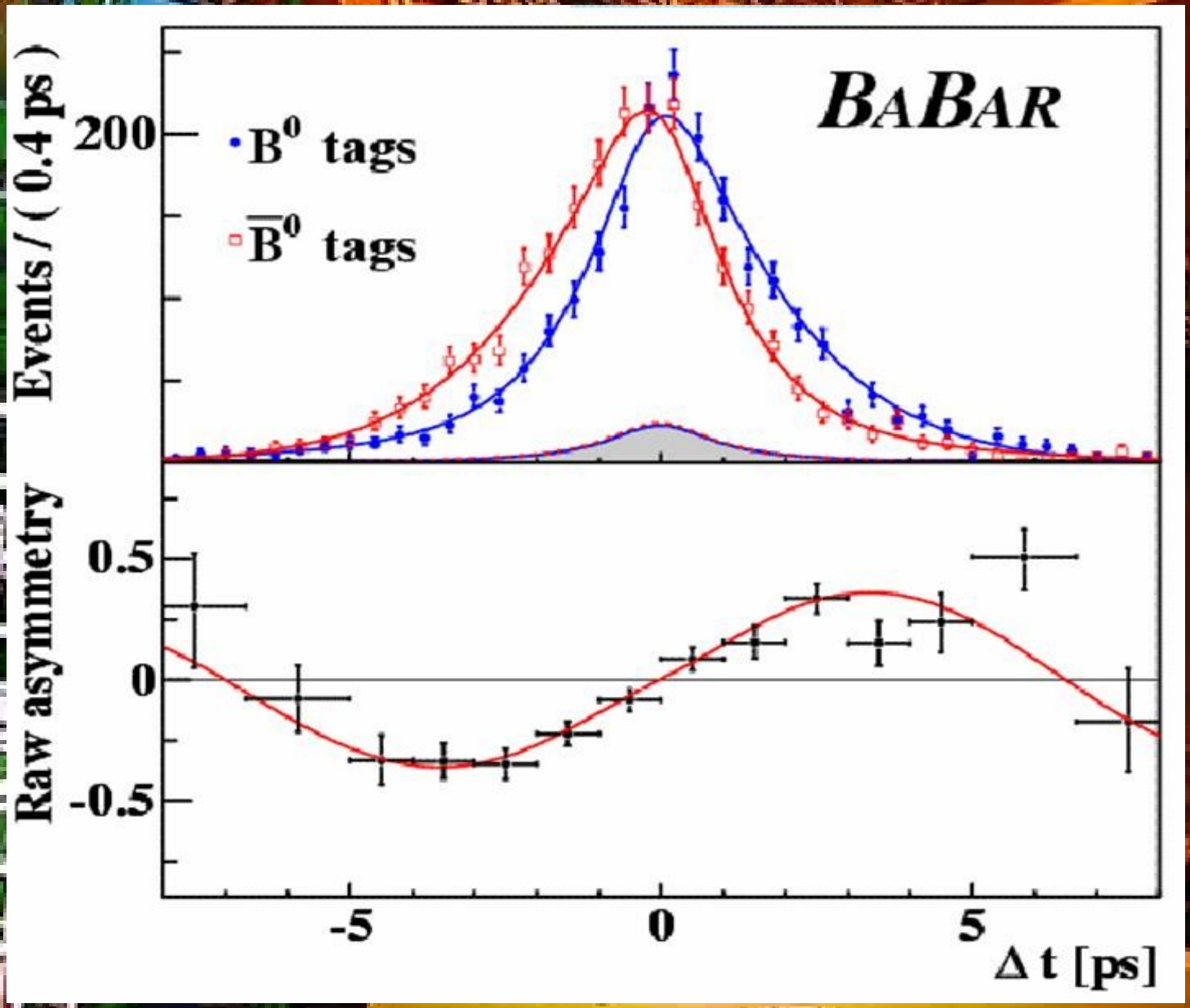
The Universe



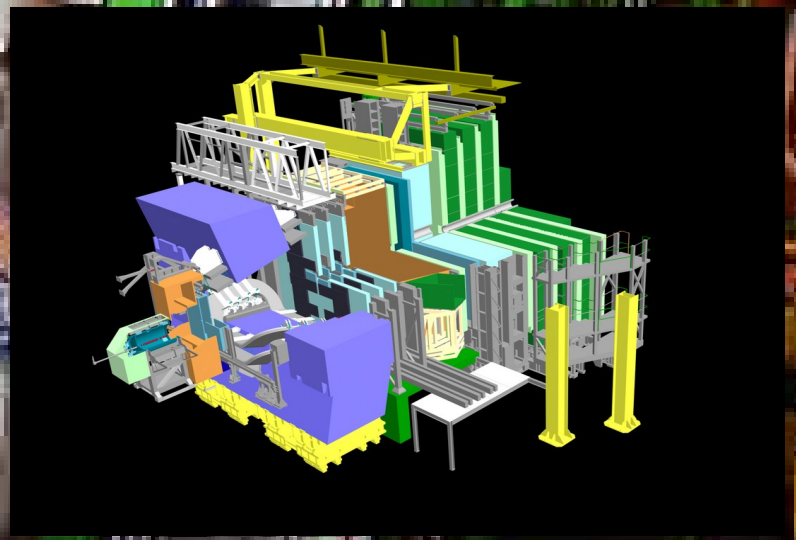
Why is there more matter than antimatter?



There is a difference between the physics of matter and antimatter



There is a difference between the physics of matter and antimatter



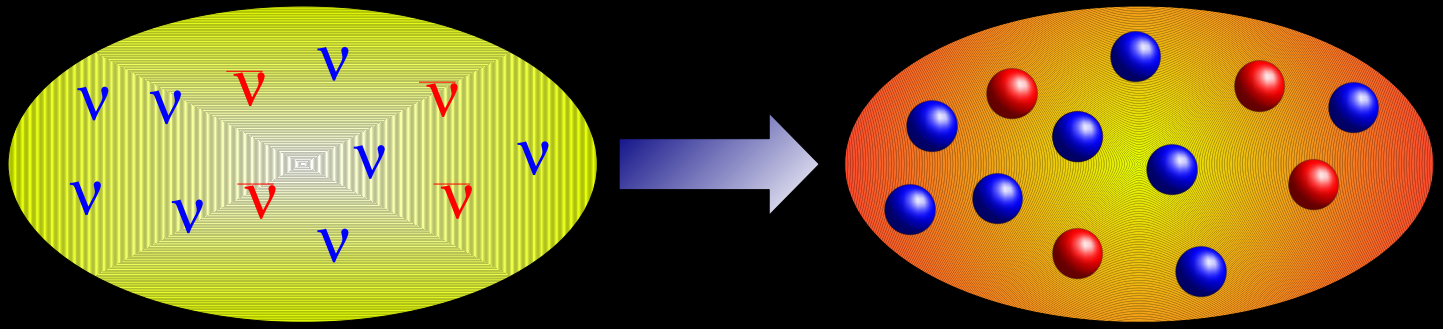
How do we exist?

We don't know (yet) but we're working on it

The smallest, most insignificant (yet most common) particle in the cosmos may just hold the reason!

Matter-Antimatter Asymmetry

A theory called “Leptogenesis” suggests that the asymmetry we see was generated by an asymmetry between *neutrinos* and *anti-neutrinos* at the beginning of things.



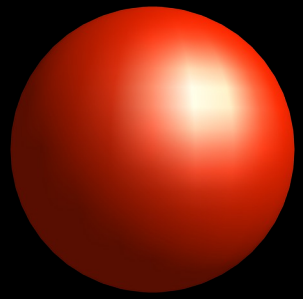
What is a neutrino?

Neutrinos are the second most common particle in the universe. Produced whereever you have radioactive decays

Electron, e

Electron Neutrino, ν_e

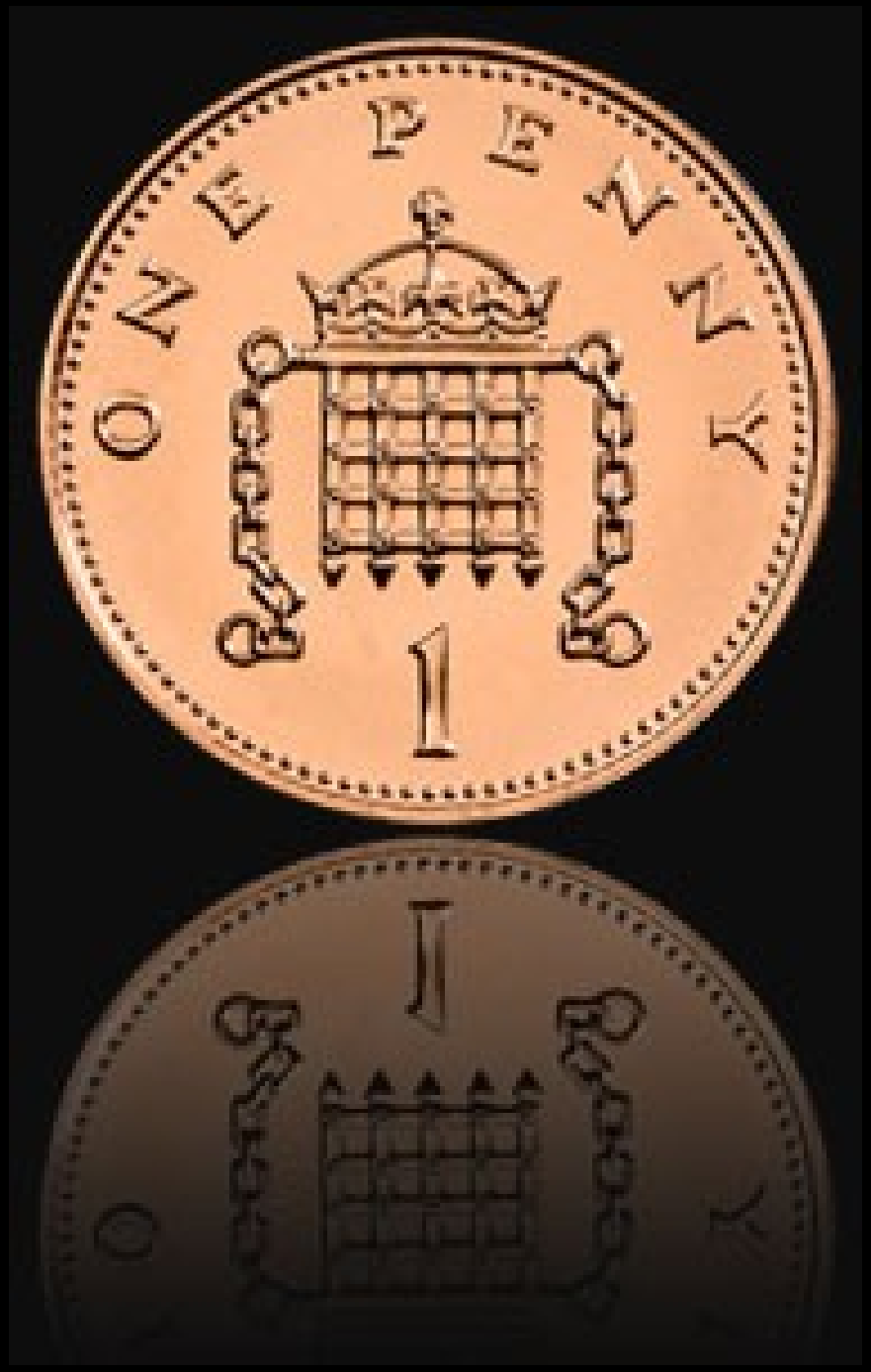
-1



0

Tiny mass (1)

Very tiny mass
(<0.0000001)

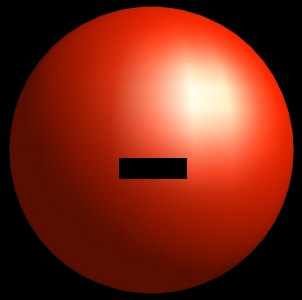

ONE PENNY
1


BUGATTI
F 18·4 EB 67


x 500

Electron, e

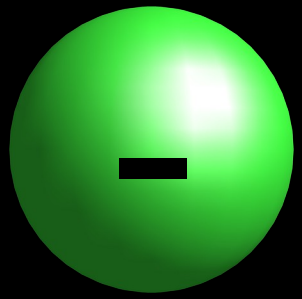
mass (1)



Electron Neutrino, ν_e

Muon, μ

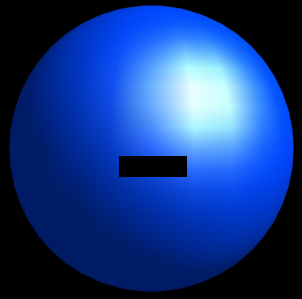
mass (200)



Muon Neutrino, ν_μ

Tau, τ

mass (3500)



Tau Neutrino, ν_τ

3 Lepton Types

Electron Neutrino, ν_e

Electron Antineutrino, $\bar{\nu}_e$

Muon Neutrino, ν_μ

Muon Antineutrino, $\bar{\nu}_\mu$

Tau Neutrino, ν_τ

Tau Antineutrino, $\bar{\nu}_\mu$

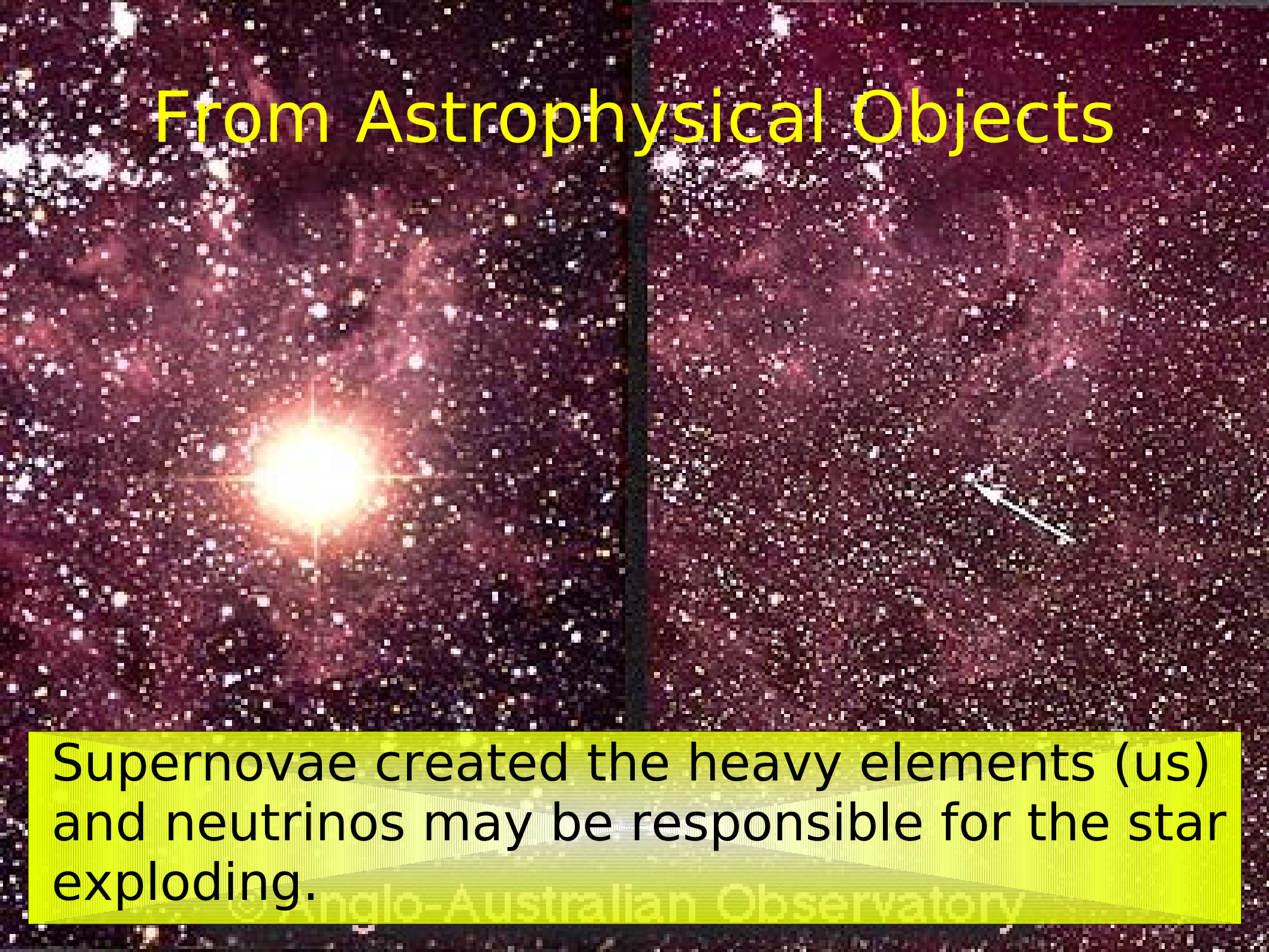
3 neutrino Flavours

From the Big Bang

One cubic foot of space contains about 10,000,000 neutrinos left over from the Big Bang.

Artist's conception

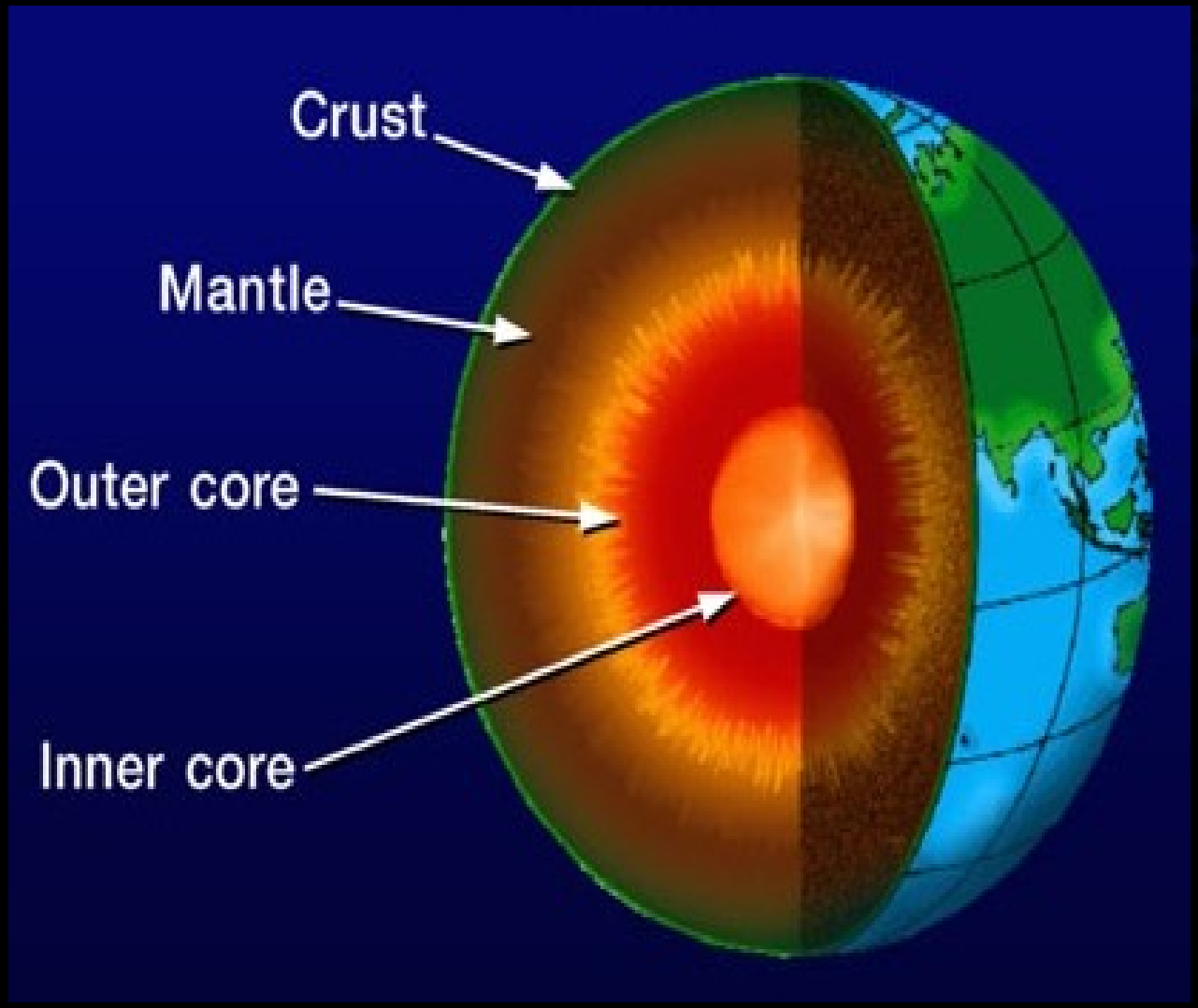
From Astrophysical Objects

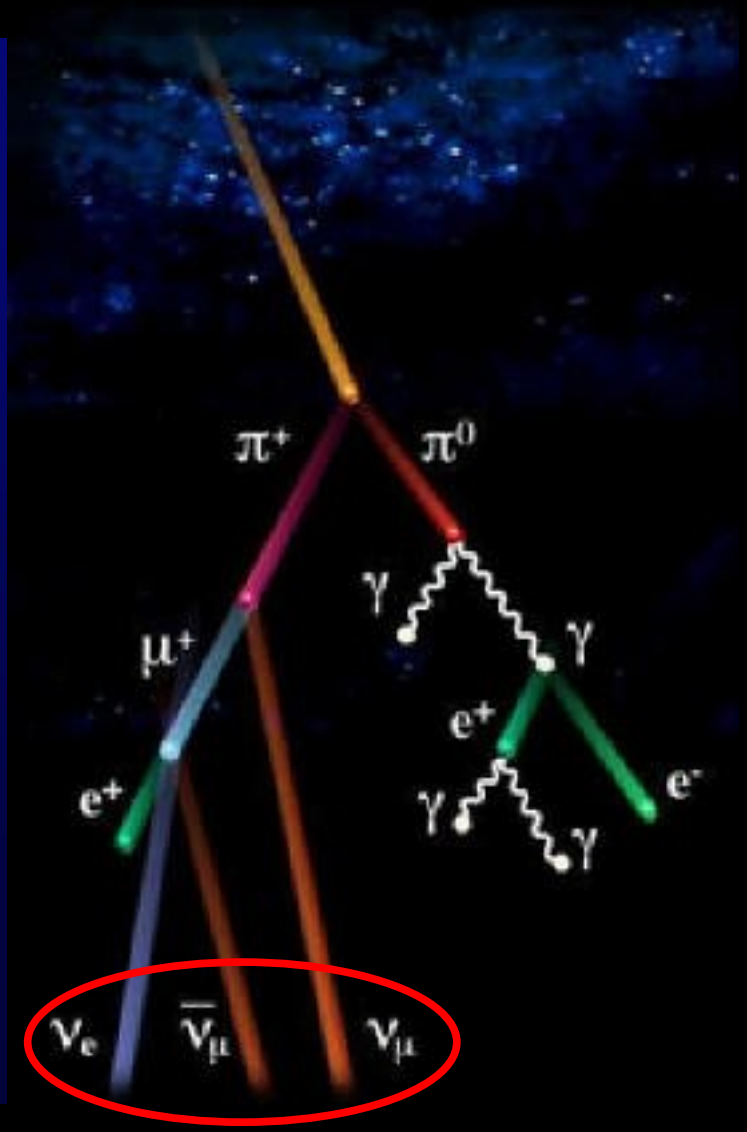


Supernovae created the heavy elements (us) and neutrinos may be responsible for the star exploding.


500,000,000,000,000,000 neutrinos
from the sun just went through
each and every one of you

From The Earth






From Us.

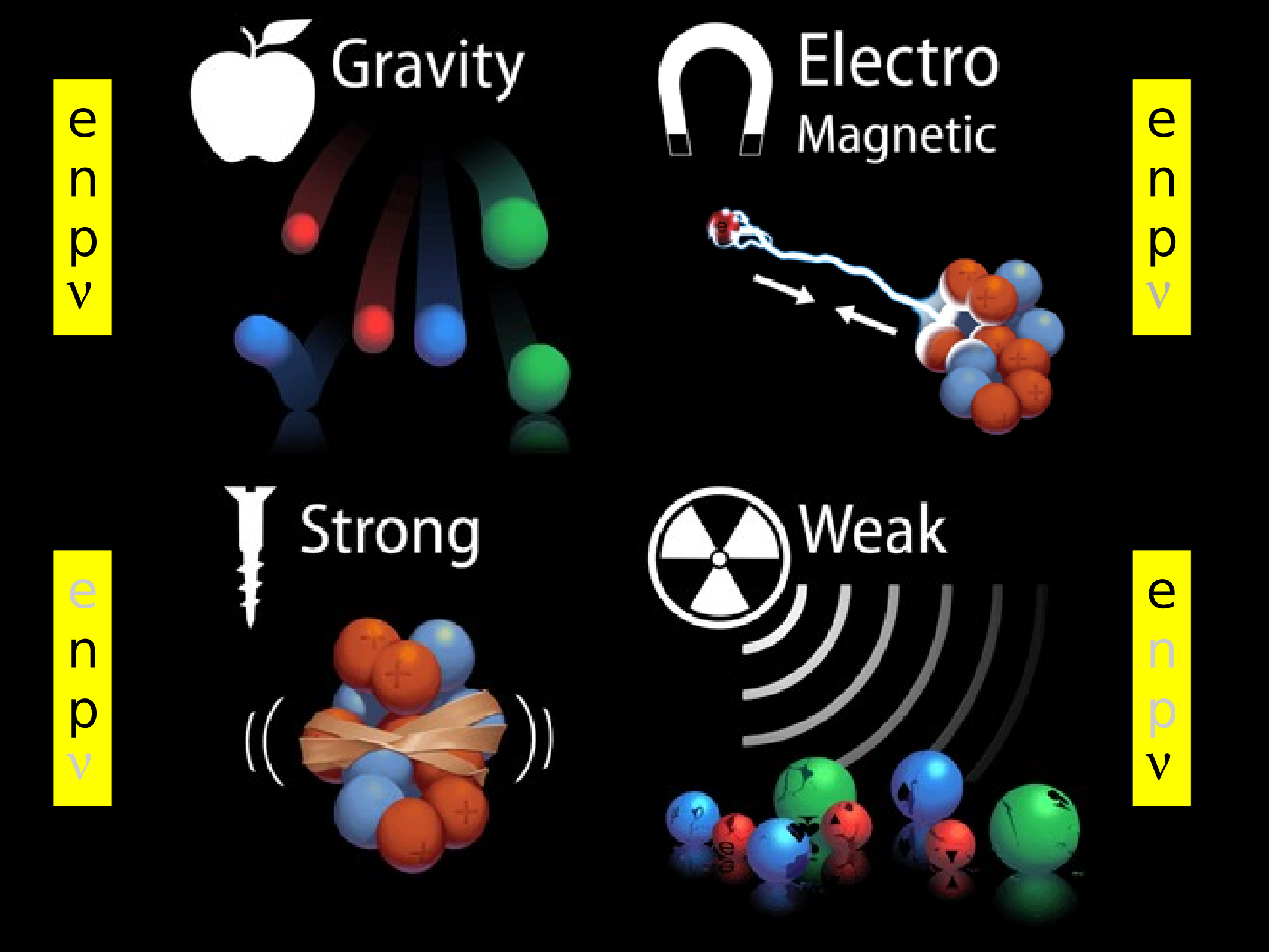
So why don't we notice?

ν are almost ghosts. They interact extremely weakly with matter.

To a neutrino a planet is mostly empty space.

"The chances of a neutrino actually hitting something as it travels through all this howling emptiness are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich."

Douglas Adams


Gravity
Electro
Magnetic
Strong
Weak
e
n
p
ν

Assume 1 billion people eat an egg sandwich every 3 months

1.67×10^7 egg sandwiches/day

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Let's say that 3 months of the year people can eat outside, and that they picnic one day every week

600,000 external egg sandwiches/day

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600,000 external egg sandwiches/day

egg sandwich lifetime – 20 minutes

9000 egg sandwiches at any time

Assume 1 billion people eat an egg sandwich every 3 months

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Area of egg sandwich – 15 cm x 15cm

186 m^2 total egg-sandwich area

Surface area of earth

500 million km^2

Suppose flight paths cover area of earth uniformly

Probability of egg-sandwich/ ball bearing intersection

3×10^{-13}

Assume 1 billion people eat an egg sandwich every 3 months

1.67×10^7 egg sandwiches/day

Let's say that 3 months of the year people can eat outside, and that they picnic one day every week

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Surface area of earth

500 million km^2

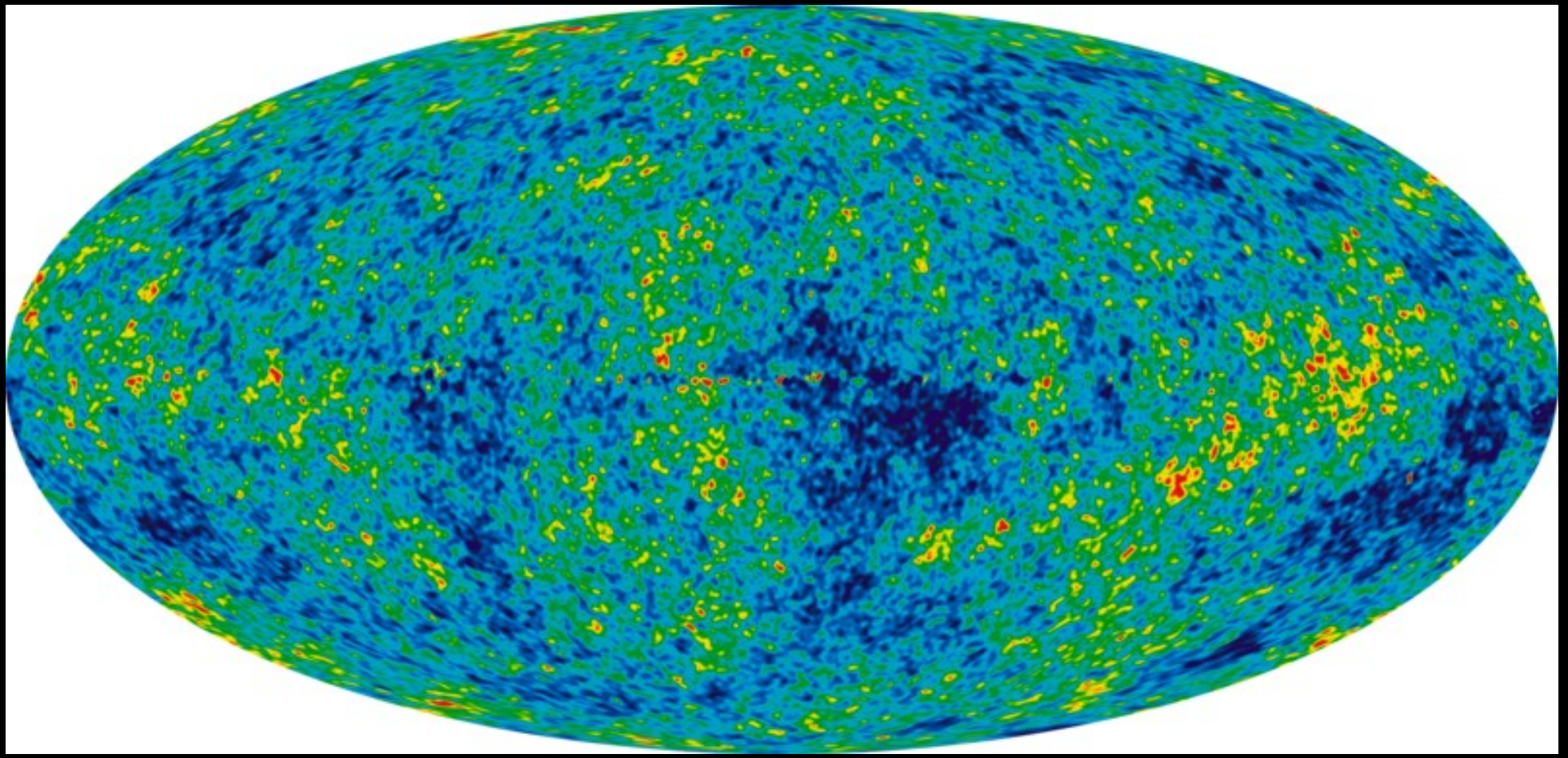
Suppose flight paths cover area of earth uniformly

Probability of egg-sandwich/ ball bearing intersection

3×10^{-13}

Probability of average solar neutrino interaction

5×10^{-13}



One cubic foot of space contains about 10,000,000 neutrinos left over from the Big Bang.

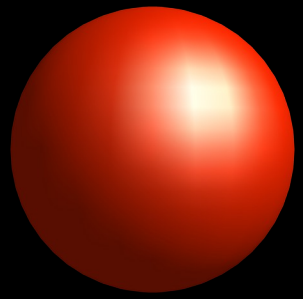
So what is a neutrino?

Neutrinos are the second most common particle in the universe. They are produced whenever something radioactively decays

Electron, e

Electron Neutrino, ν_e

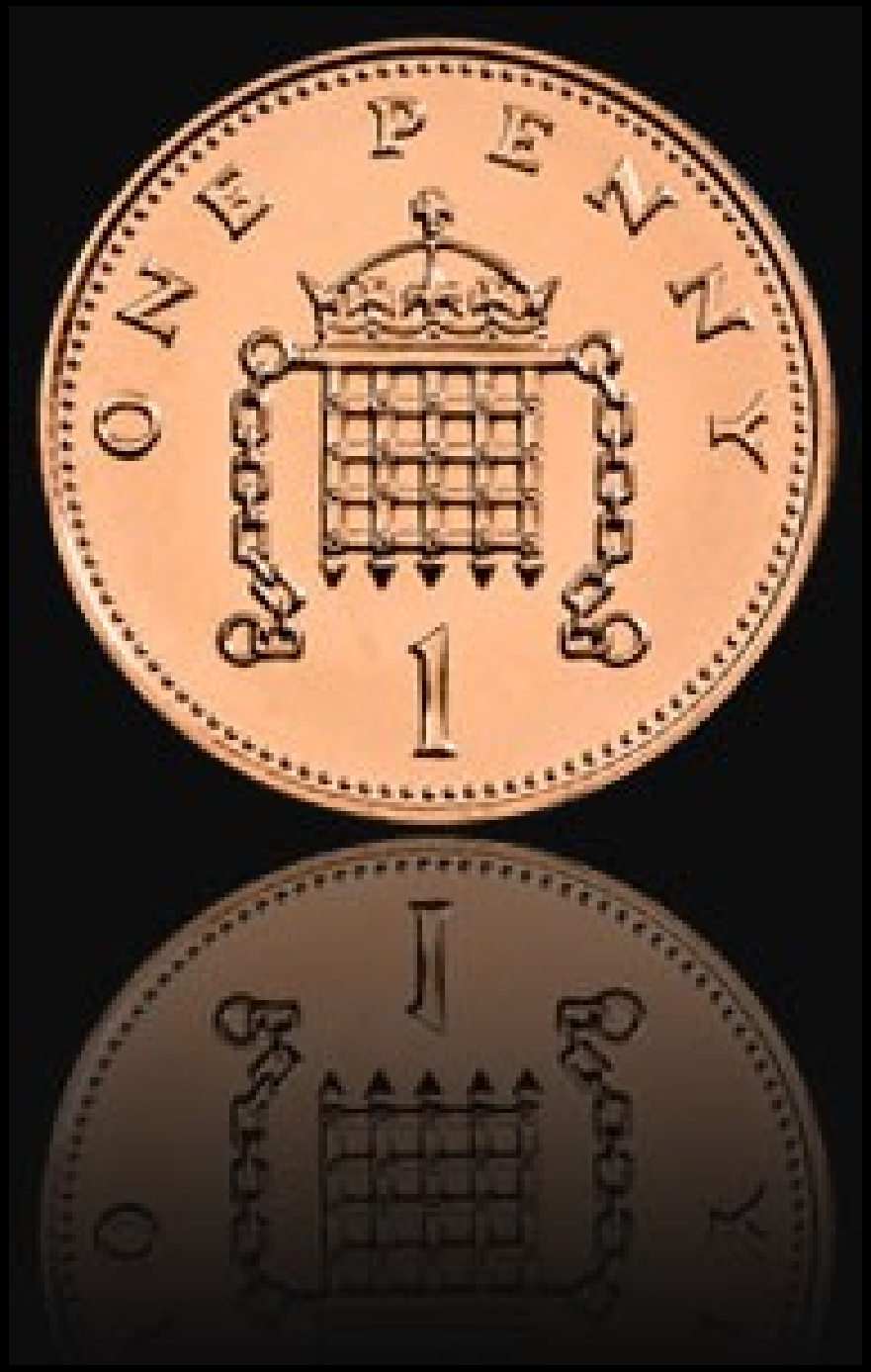
-1



0

Tiny mass (1)

Very tiny mass
(<0.0000001)

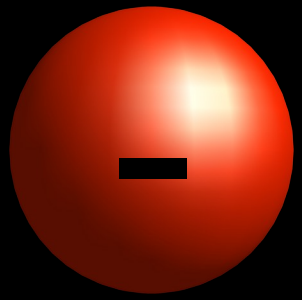

ONE PENNY
1


BUGATTI
F 18·4 EB 67


x 500

Electron, e

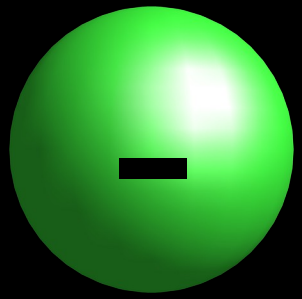
mass (1)



Electron
Neutrino, ν_e

Muon, μ

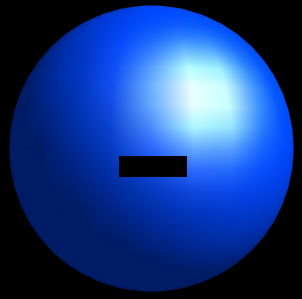
mass (200)



Muon
Neutrino, ν_μ

Tau, τ

mass (3500)



Tau
Neutrino, ν_τ

3 Lepton Flavours
+ anti-leptons

Electron Neutrino, ν_e

Electron Antineutrino, $\overline{\nu}_e$

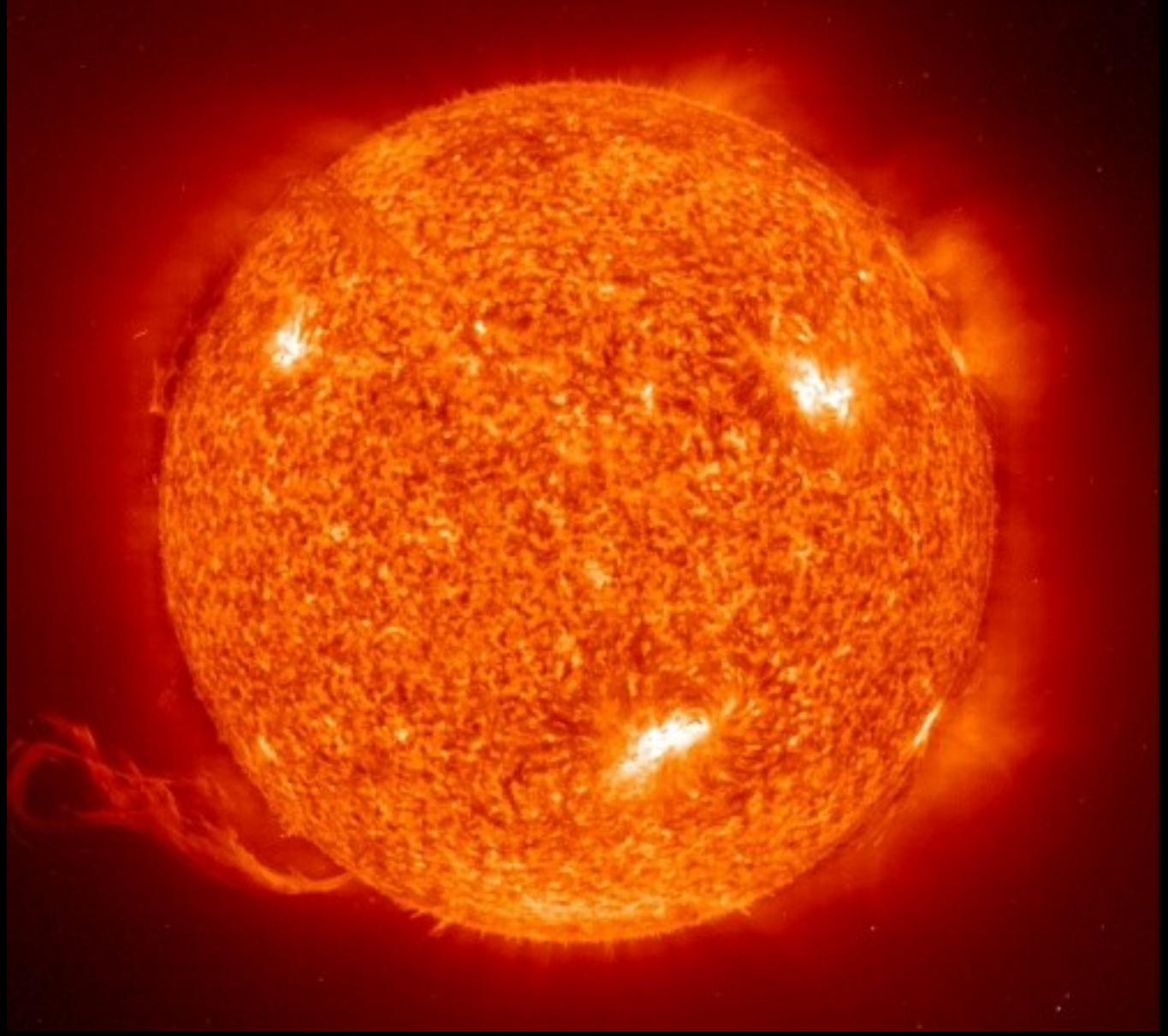
Muon Neutrino, ν_μ

Muon Antineutrino, $\overline{\nu}_\mu$

Tau Neutrino, ν_τ

Tau Antineutrino, $\overline{\nu}_\mu$

3 neutrino Flavours



The sun generates about 2×10^{38} neutrinos/s as byproducts of the fusion processes that make the star shine.