The Ghostly Neutrino

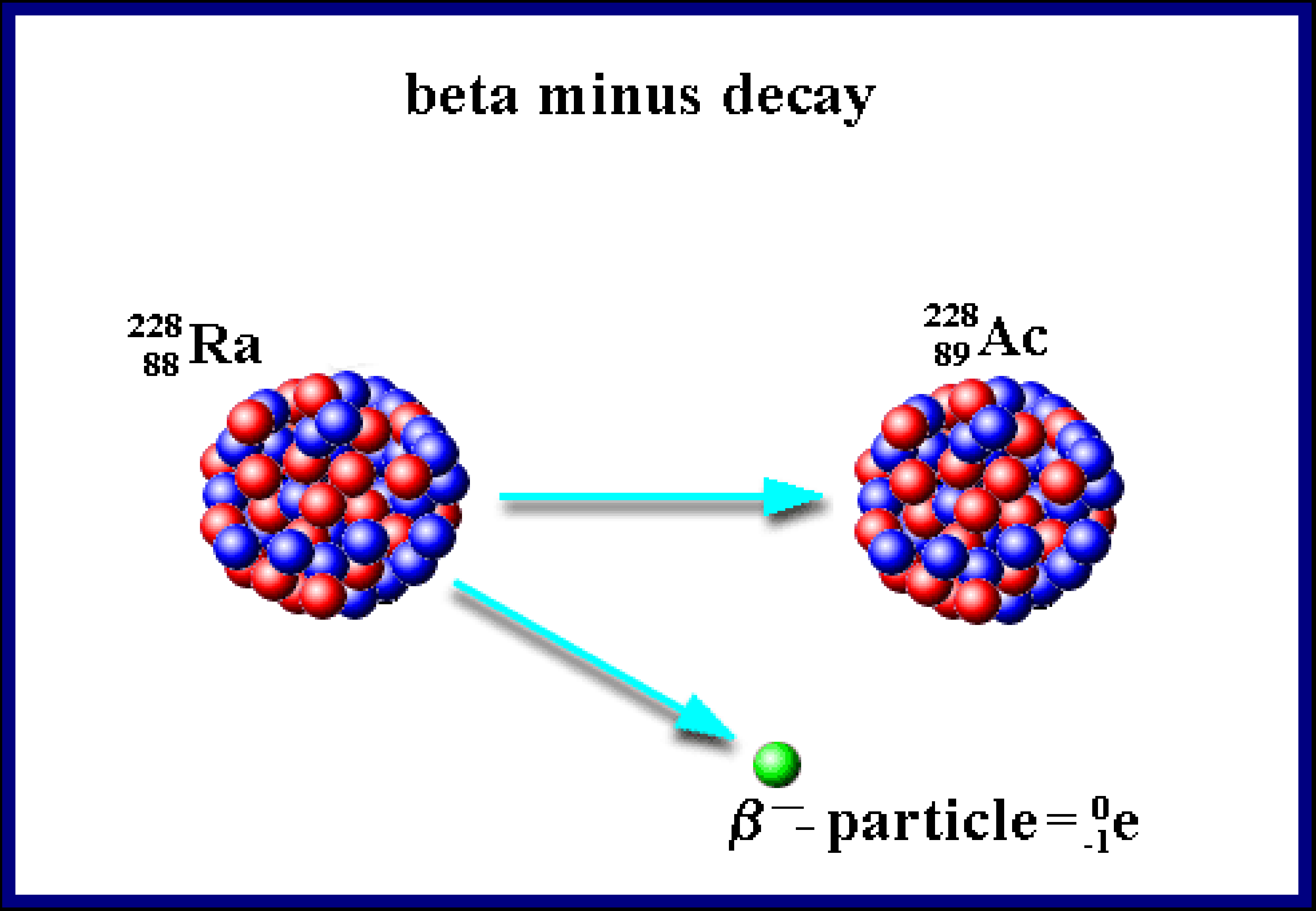
Steve Boyd, University of Warwick

“If we are to understand “why we are here” and the basic properties of the universe we live in, we must understand the neutrino.”

American Physical Society Report - 2004

- A little bit of history
- What are they?
- Where do they come from?
- Why study them?
- A recent surprise
- The T2K Project


CRISIS



$$\text{Energy(Ra)} \neq \text{Energy(Ac)} + \text{Energy(e)}$$

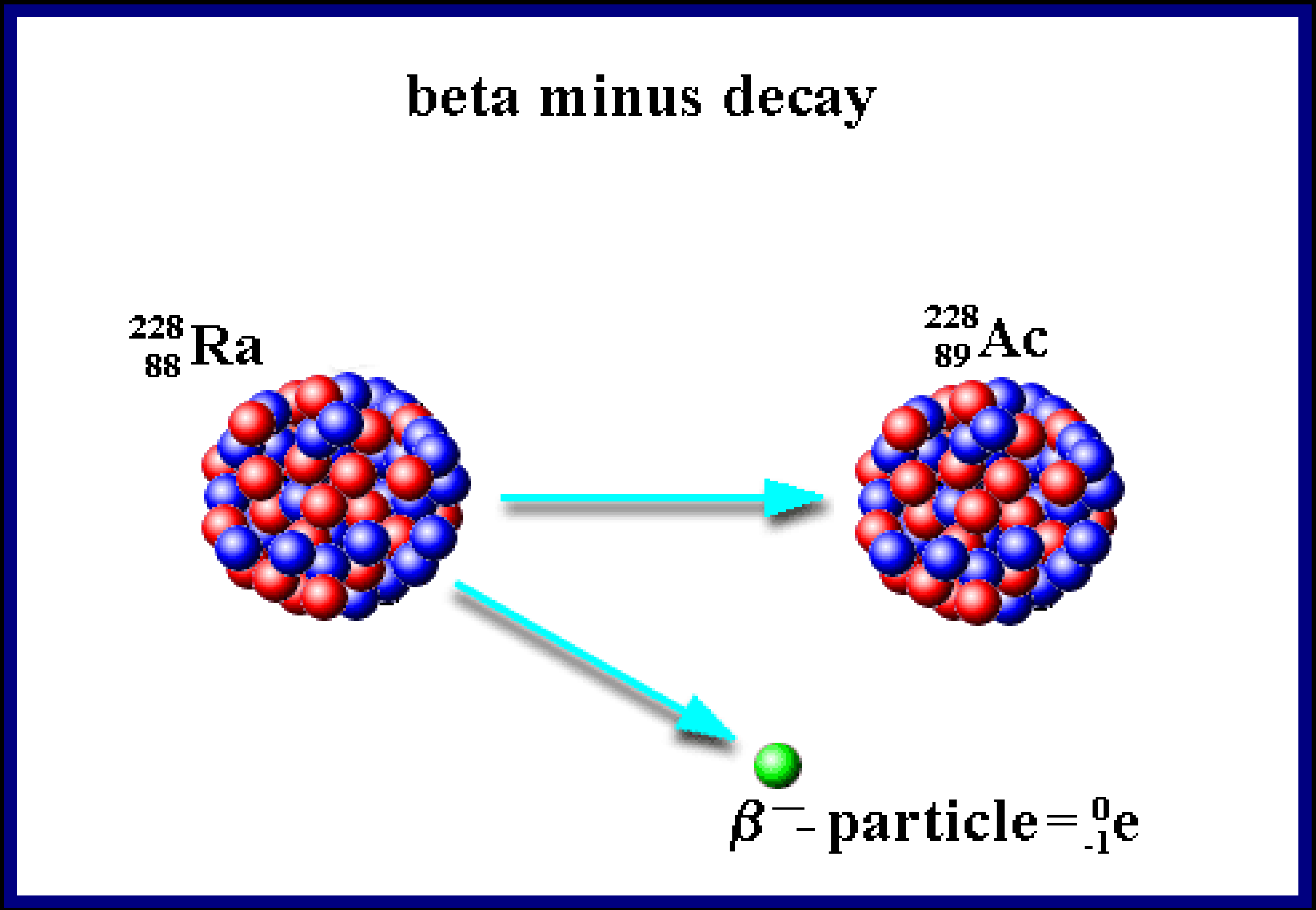
Neils Bohr

“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.”

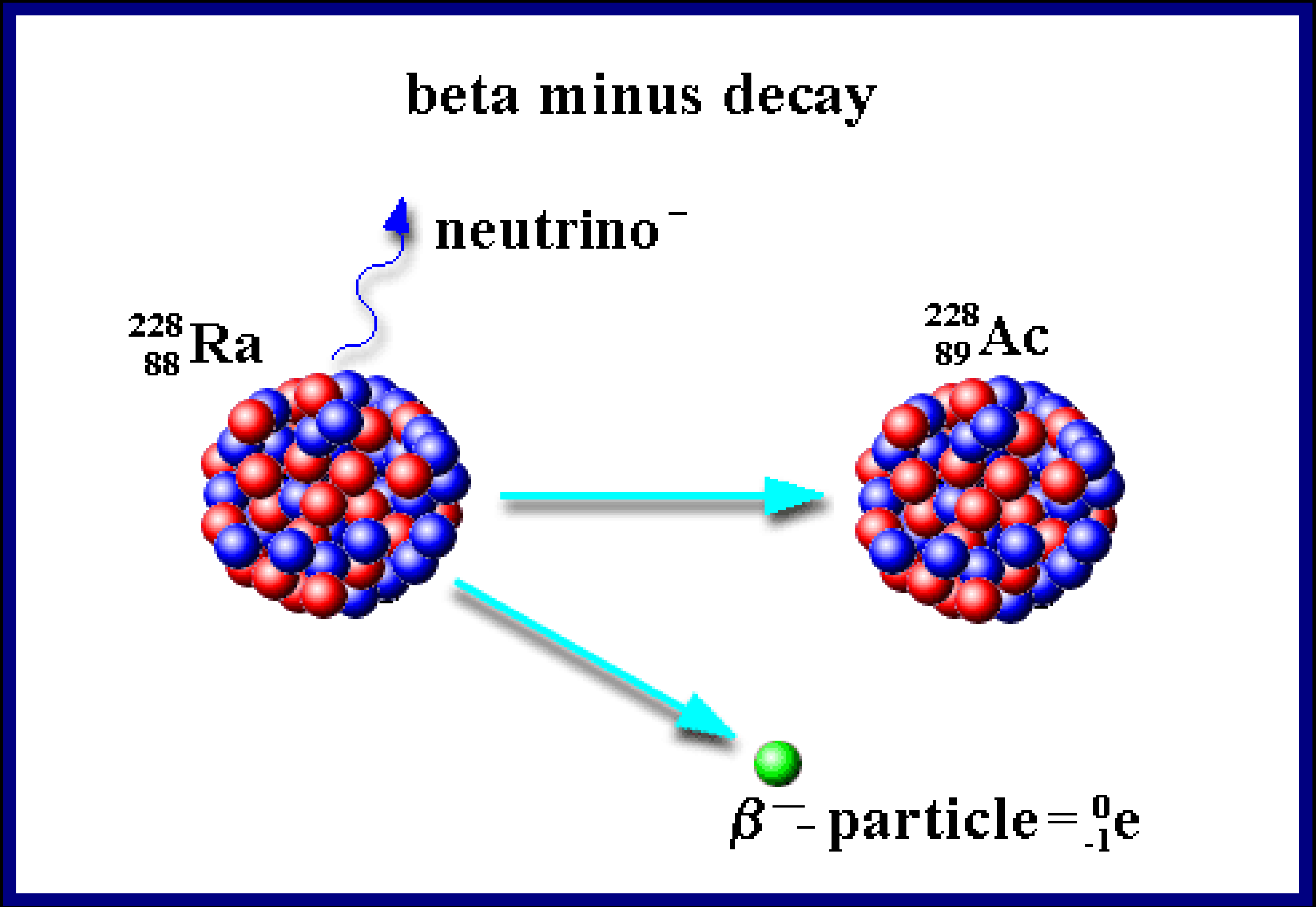
Wolfgang Pauli

"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"



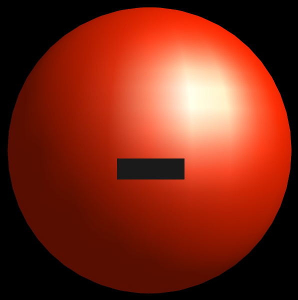
Energy(Ra) $\neq$ Energy(Ac)+Energy(e)



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

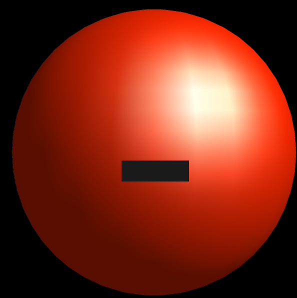
What are neutrinos?

Electron, e



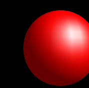
Tiny mass (1)

Electron, e



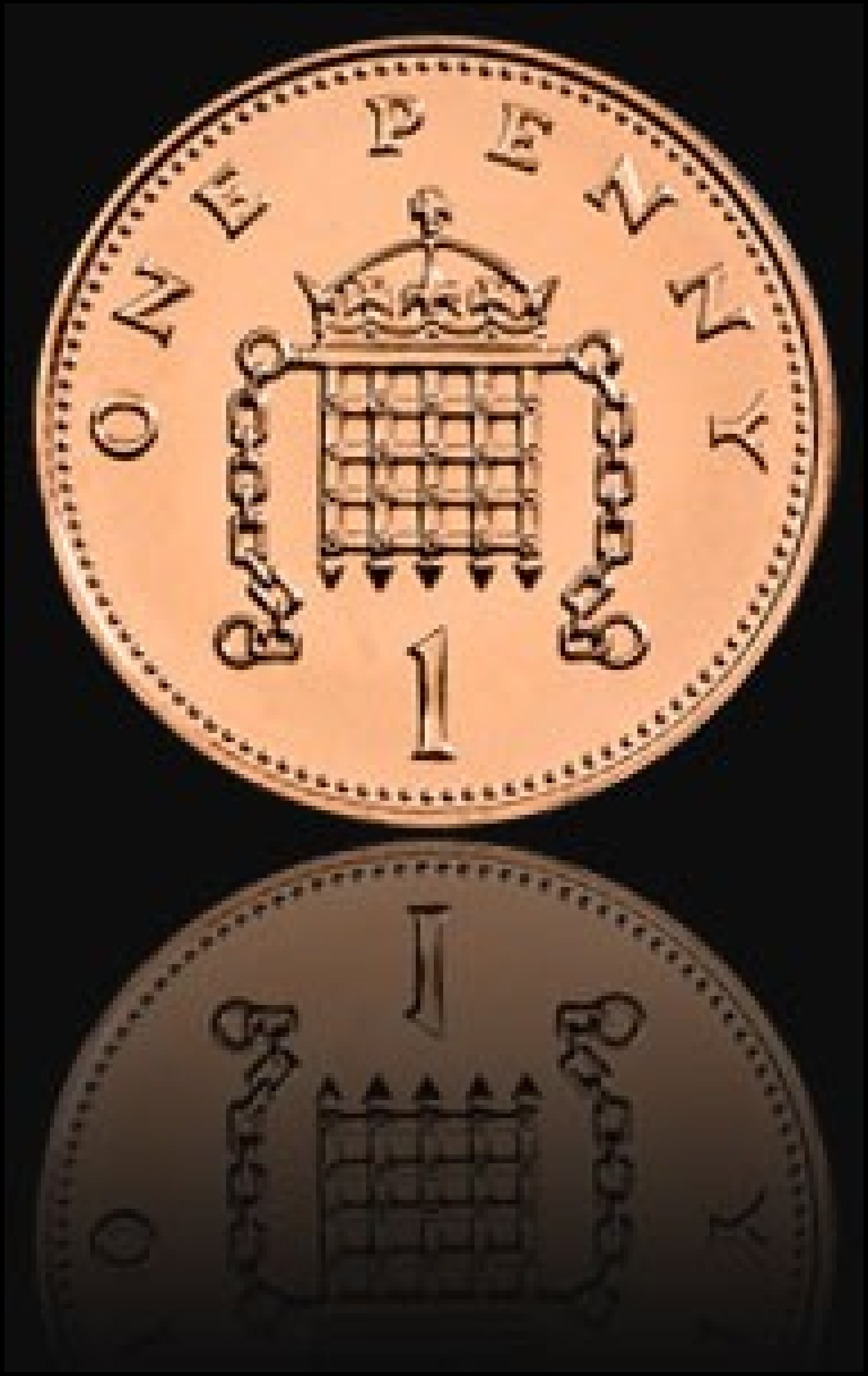
Tiny mass (1)

Electron Neutrino, ν_e



0

Very tiny mass
(<0.0000001)


ONE PENNY
1


www.2495.com
BUGATTI
18·4 EB 67
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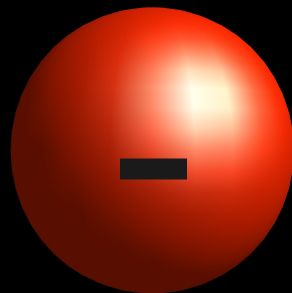
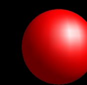
x 500

Electron, e

Electron Neutrino, ν_e

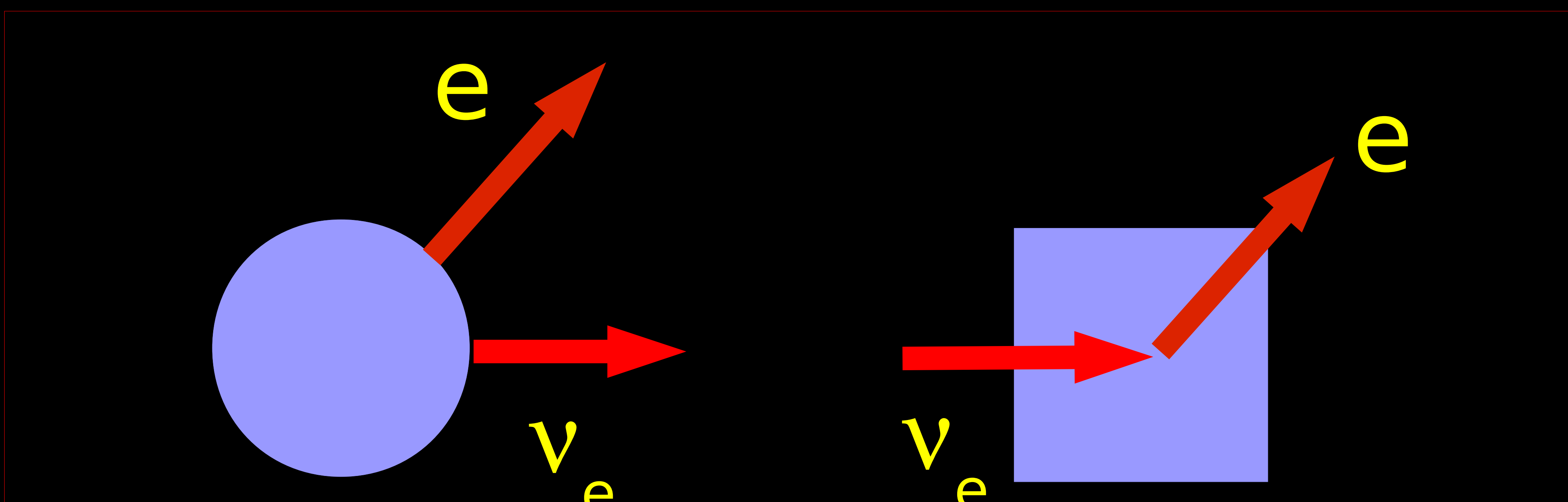




0

Tiny mass (1)

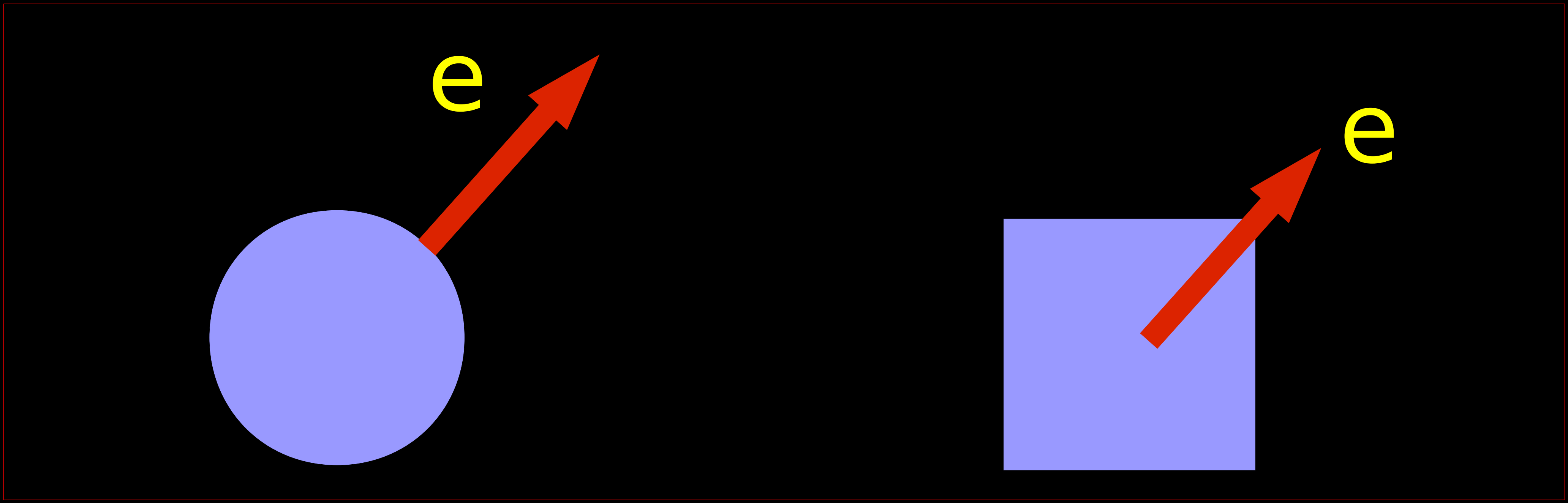
Very tiny mass (<0.0000001)



In experiments neutrinos are **NEVER** seen.

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

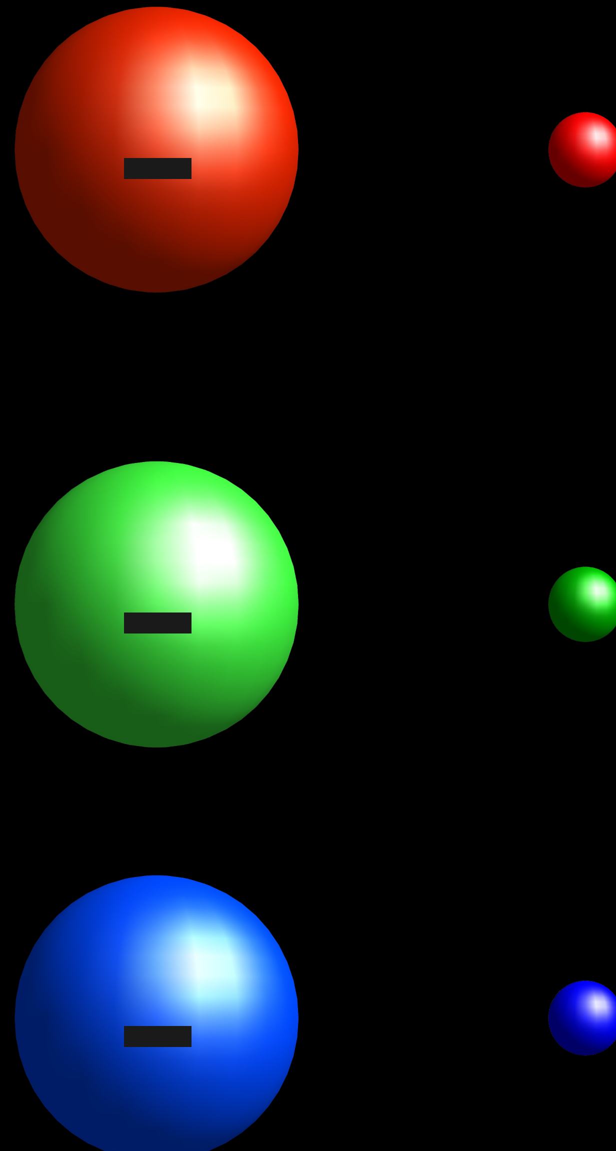
Type of the charged particle detected used to infer the type of incoming neutrino.



Electron, e
mass (1)

Muon, μ
mass (200)

Tau, τ
mass (3500)

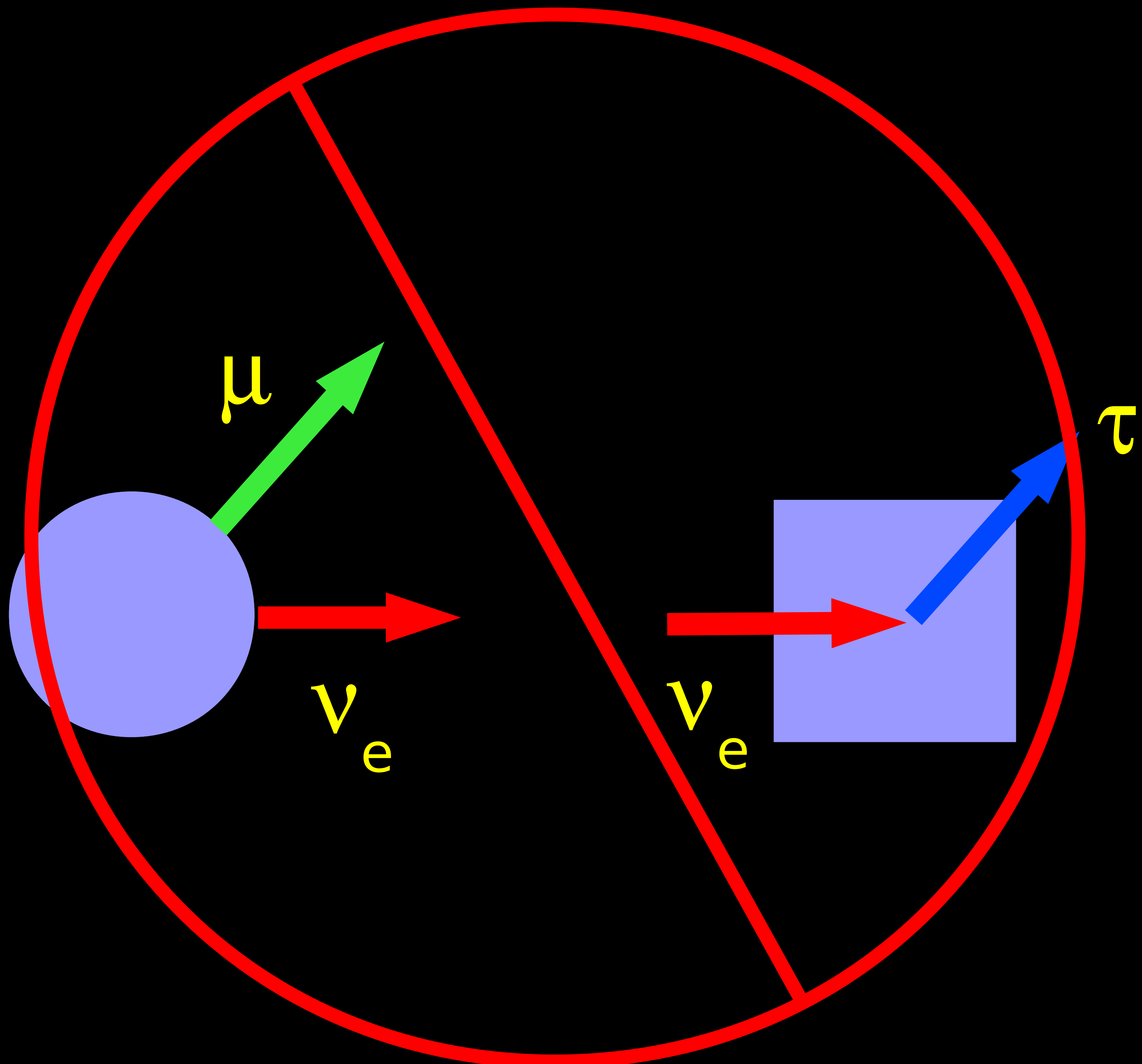


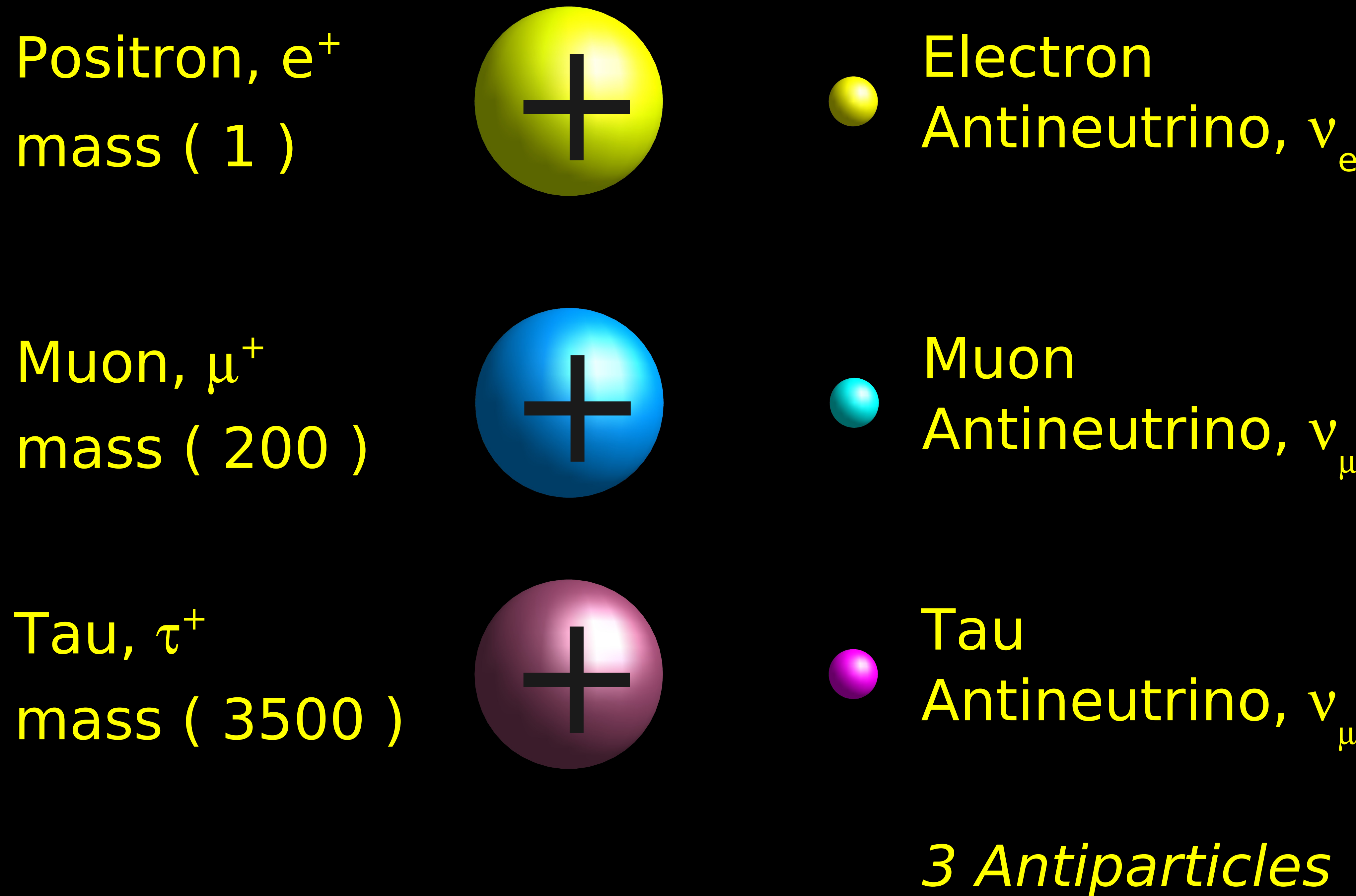
Electron Neutrino, ν_e

Muon Neutrino, ν_μ

Tau Neutrino, ν_τ

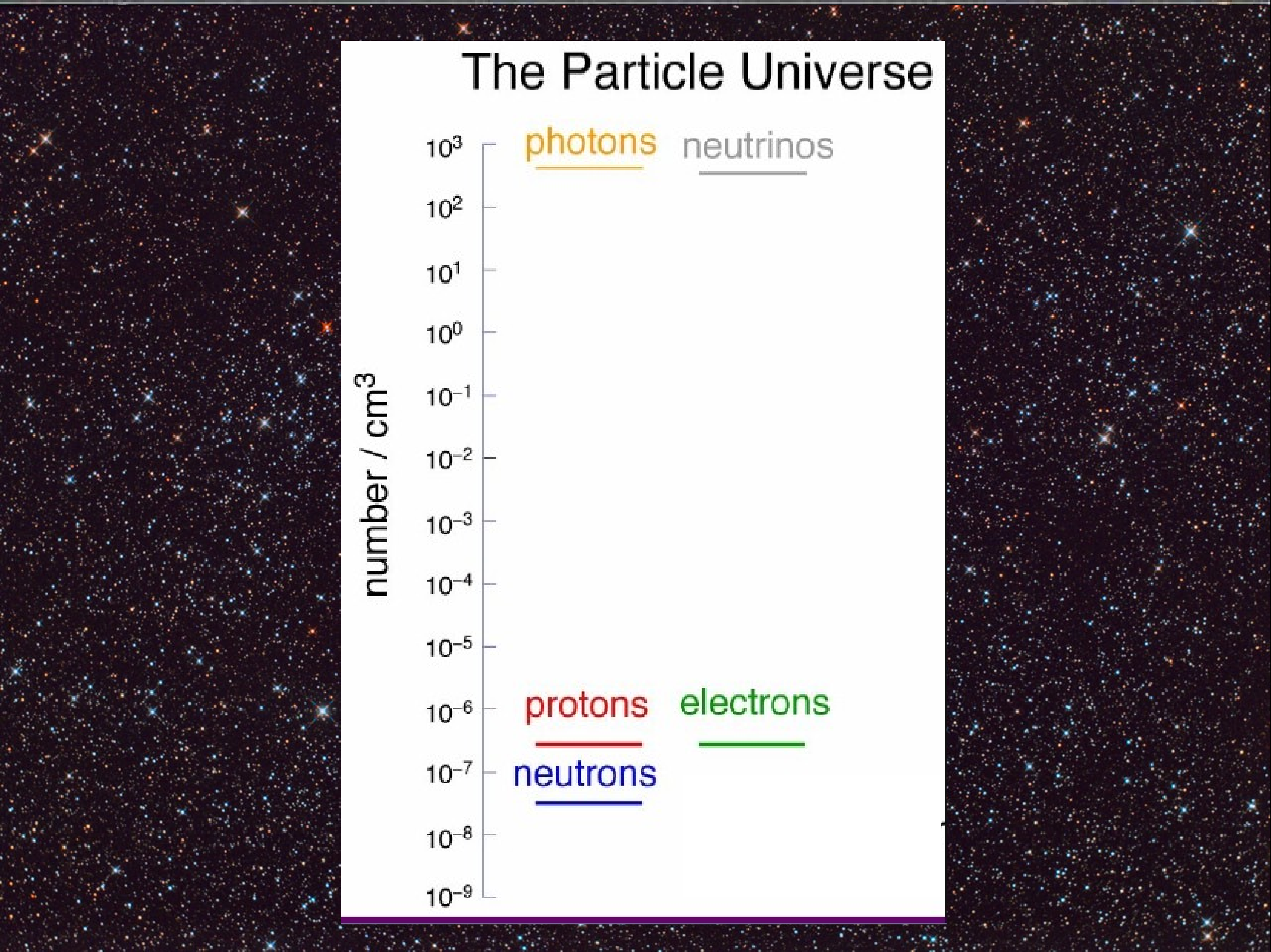
3 <u>Lepton</u> Types


μ
τ
ν_e
ν_e


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

Where do they come from?

Everywhere



The Particle Universe
number / cm3
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
photons
neutrinos
protons
electrons
neutrons

From the Big Bang

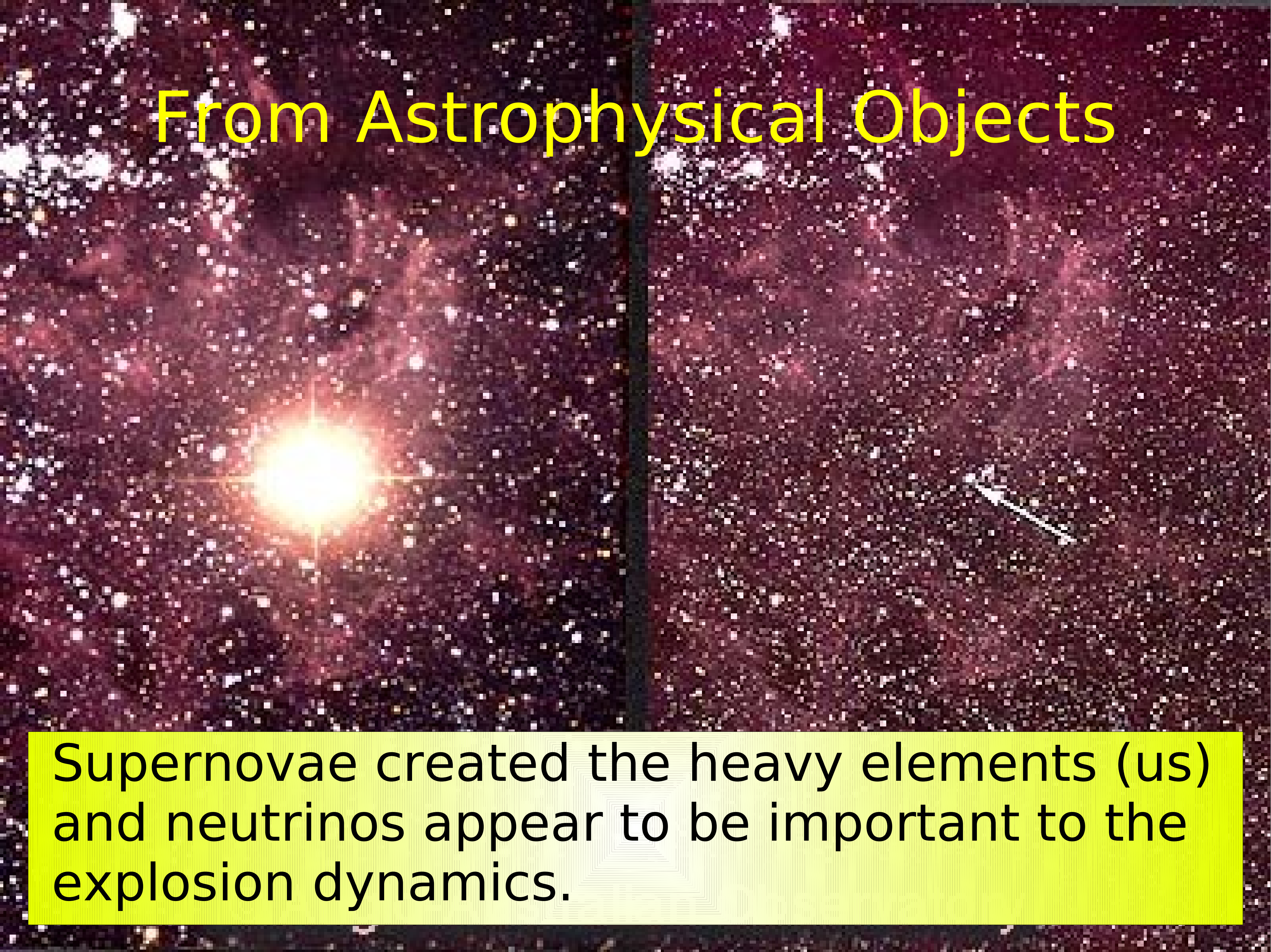
Artist's conception

From the Big Bang

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

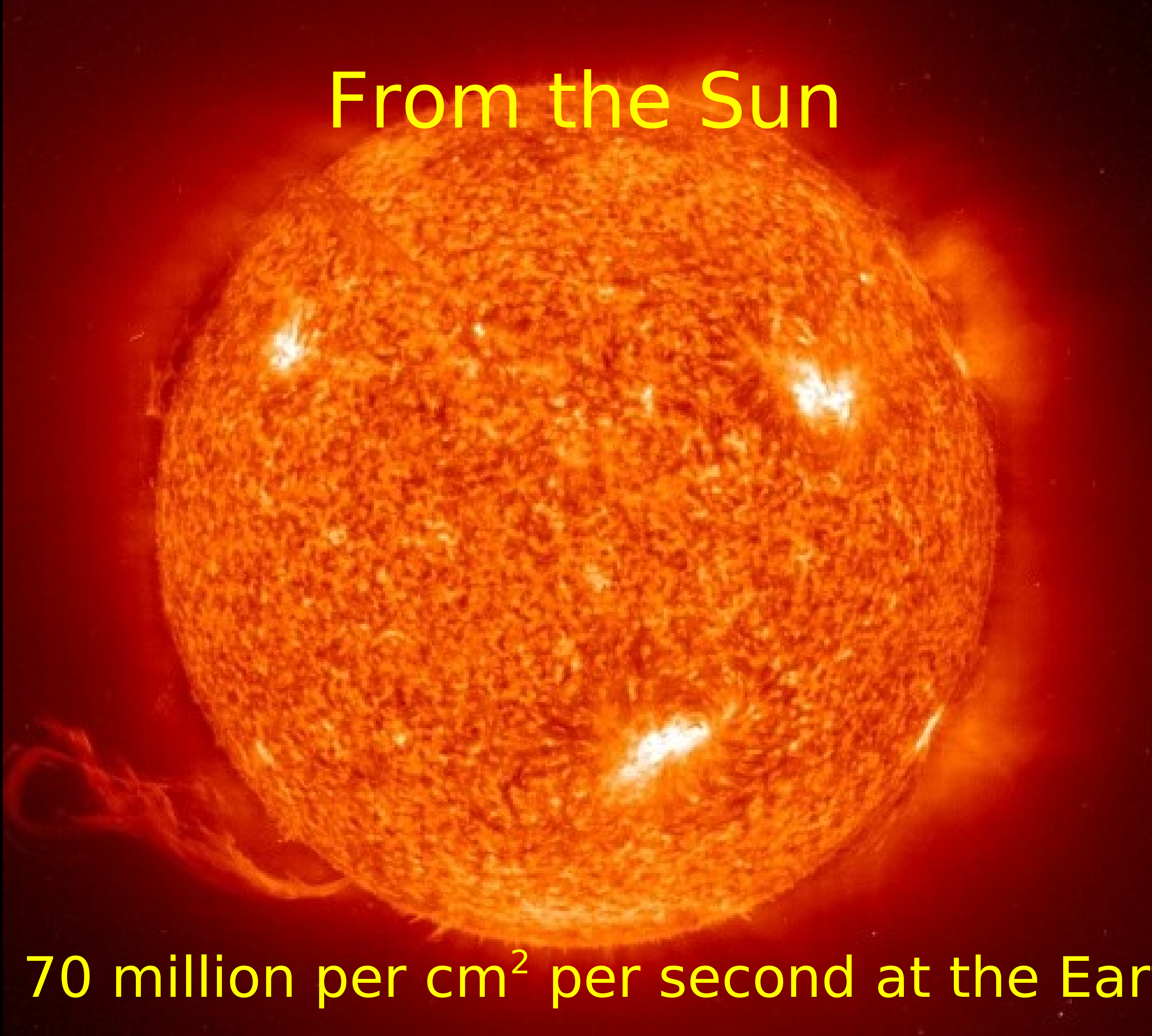
Artist's conception

From Astrophysical Objects

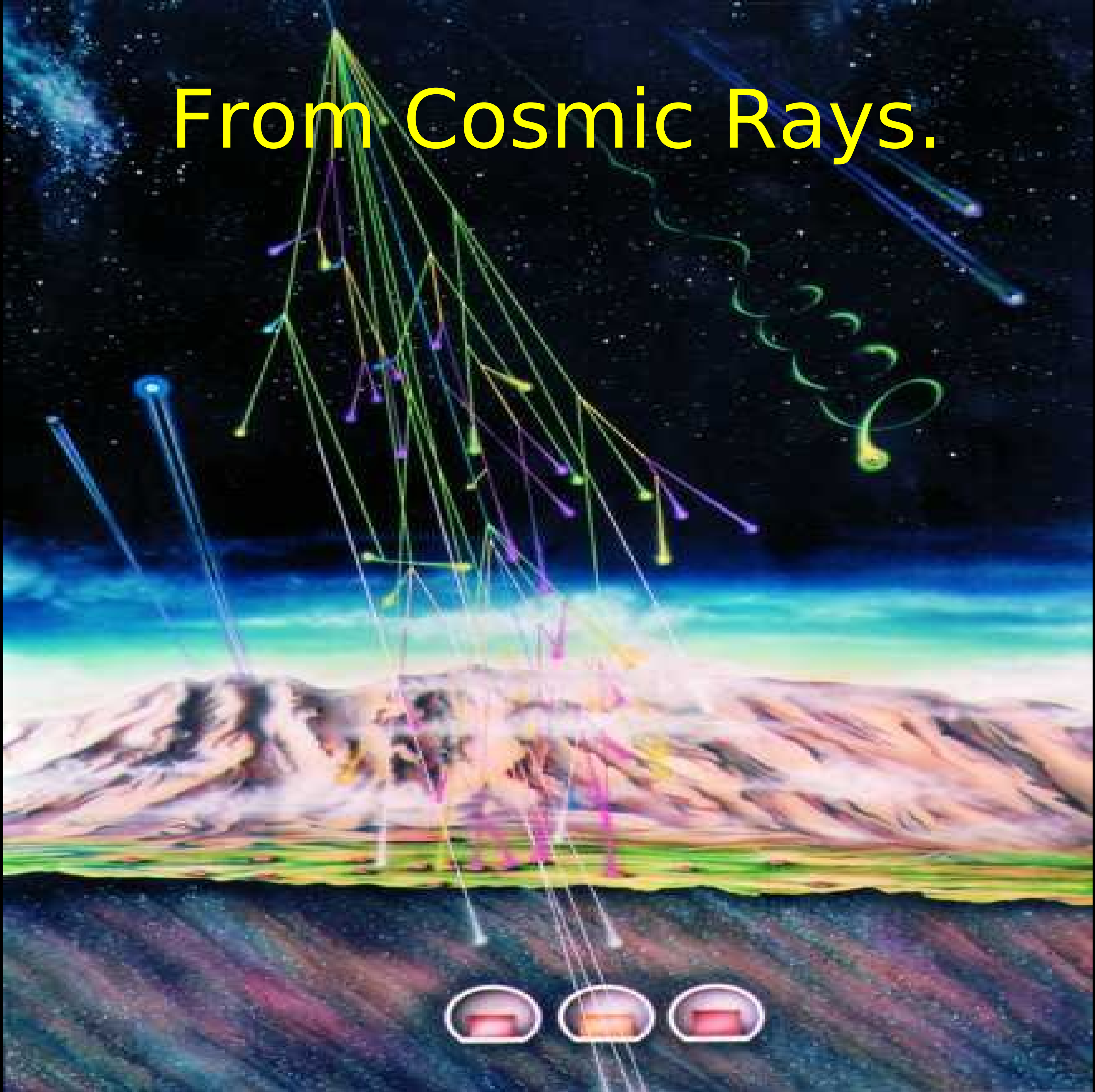


Supernovae created the heavy elements (us) and neutrinos appear to be important to the explosion dynamics.

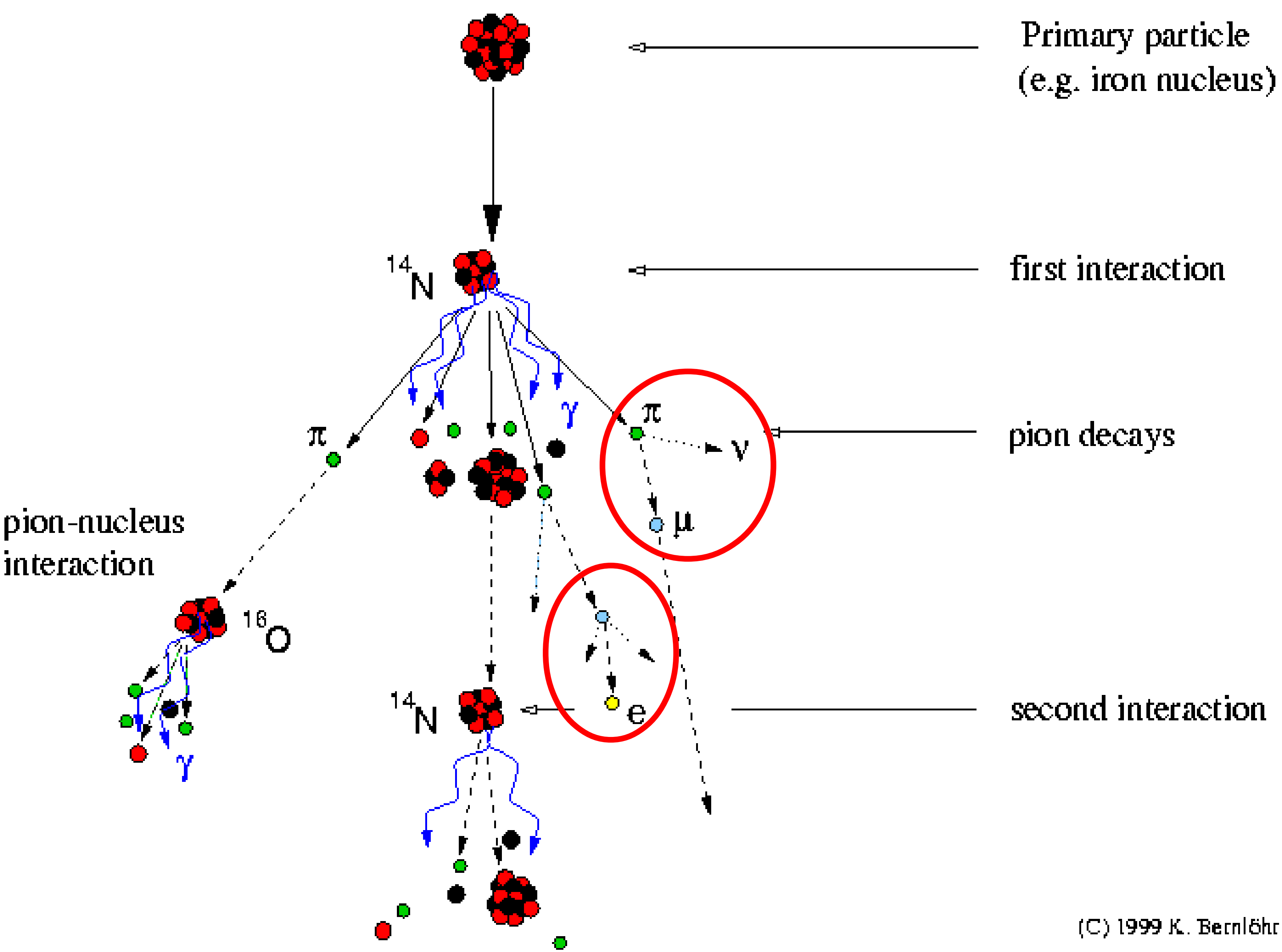
From the Sun



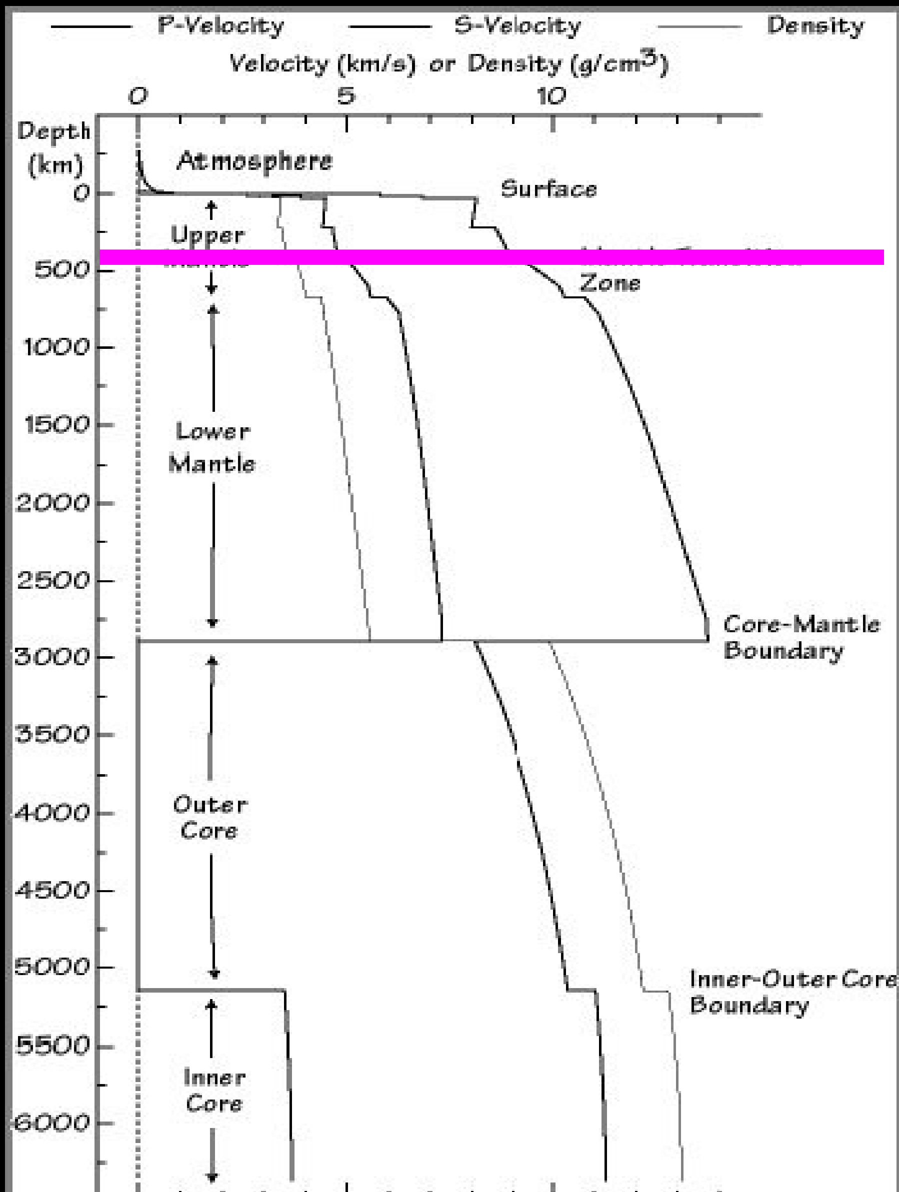
≈ 70 million per cm^2 per second at the Earth


From Cosmic Rays.

Development of cosmic-ray air showers



Geoneutrinos




From Us.

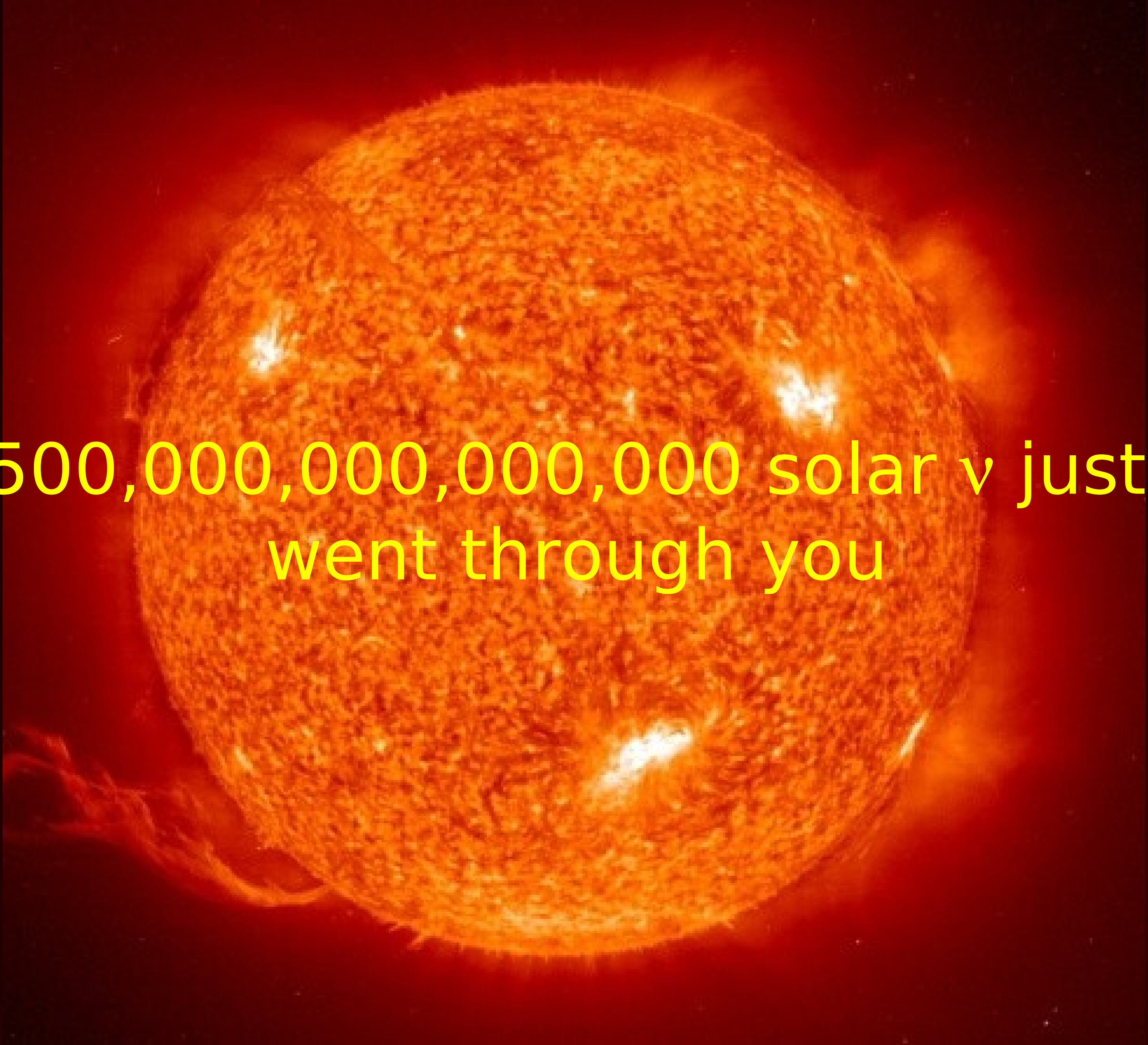
So why don't we notice?

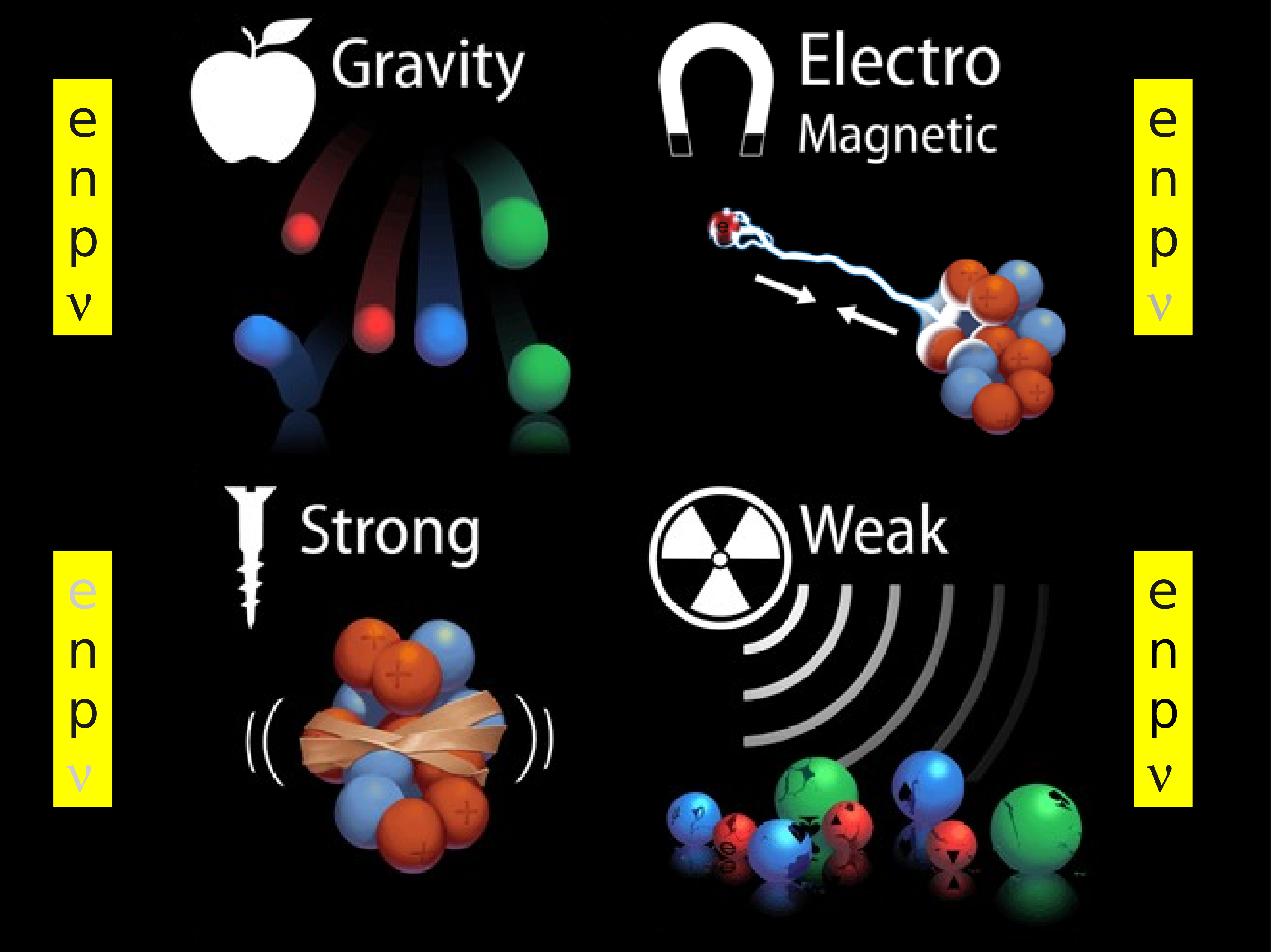
ν are almost ghosts. They interact extremely weakly with matter.

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

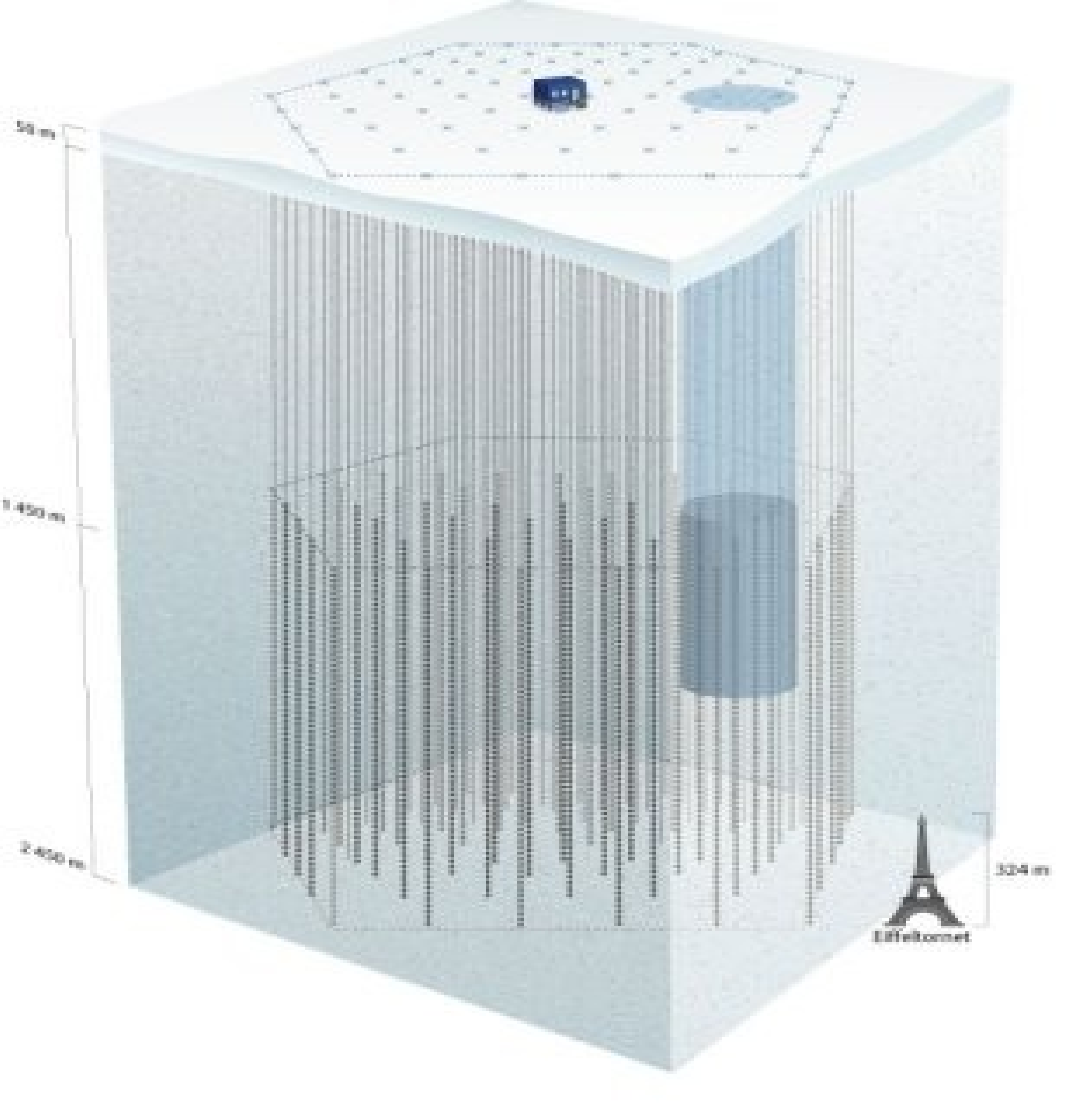

e n p ν
Gravity
Electro
Magnetic
e n p ν
e n p ν
Strong
Weak
e n p ν

Why do we study them?

- Probes of environments that we otherwise cannot see
- Probes of objects too far away for anything else
- Cosmological and astrophysical implications
- Matter/Antimatter imbalance

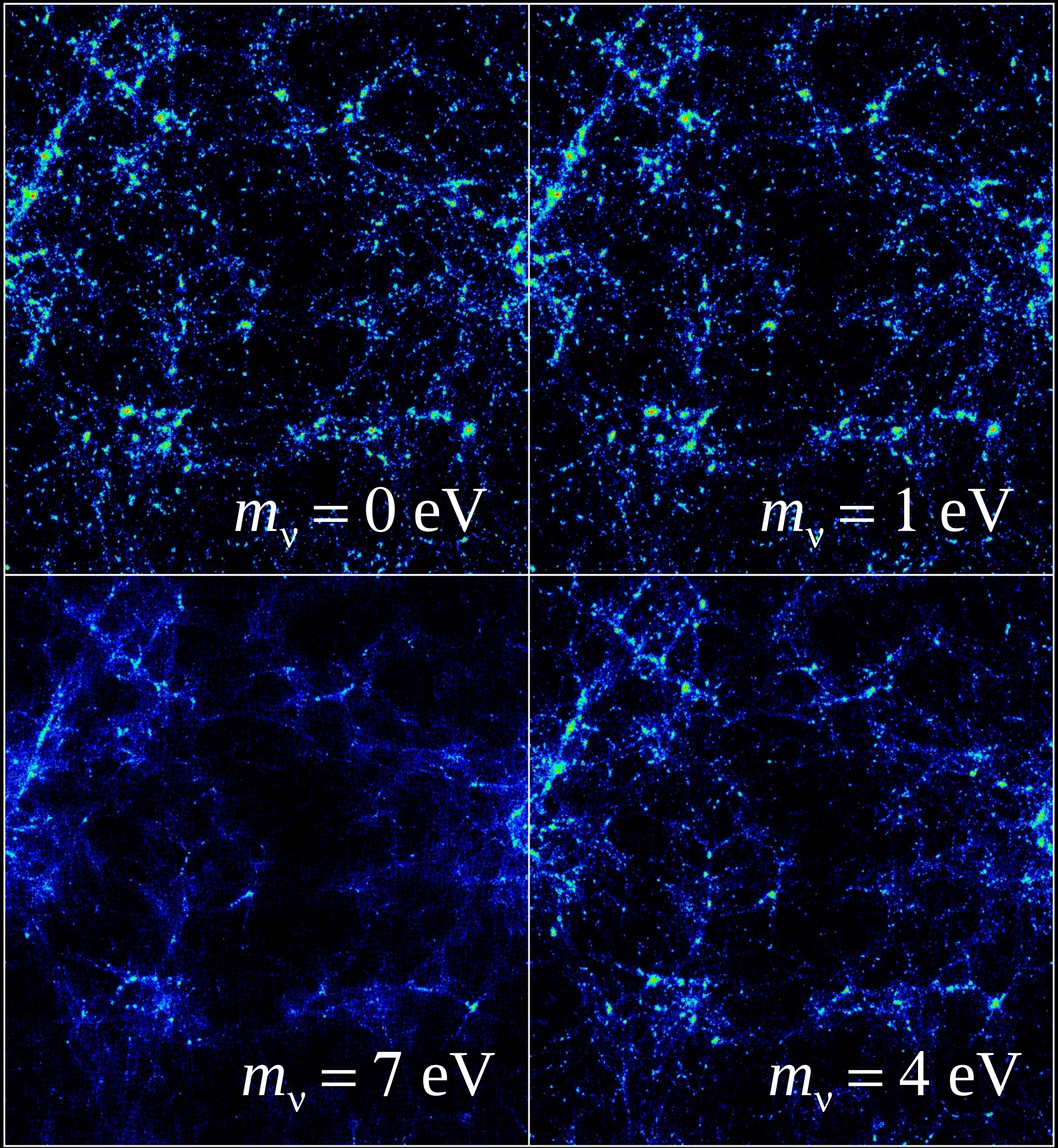
NEUTRINO ASTROPHYSICS

- Probes of environm… we otherwise cannot see
- Probes … al away for anything else
- Cosmological and astrophysical implications
- Matter/Antimatter imbalance


50 m
1 450 m
324 m
Eiffeltornet

- Probes of environments that we otherwise cannot see
- Probes of objects too far away for anything else
- Cosmological and astrophysical implications
- Matter/Antimatter imbalance

Universal Structure



- Probes of environments that we otherwise cannot see

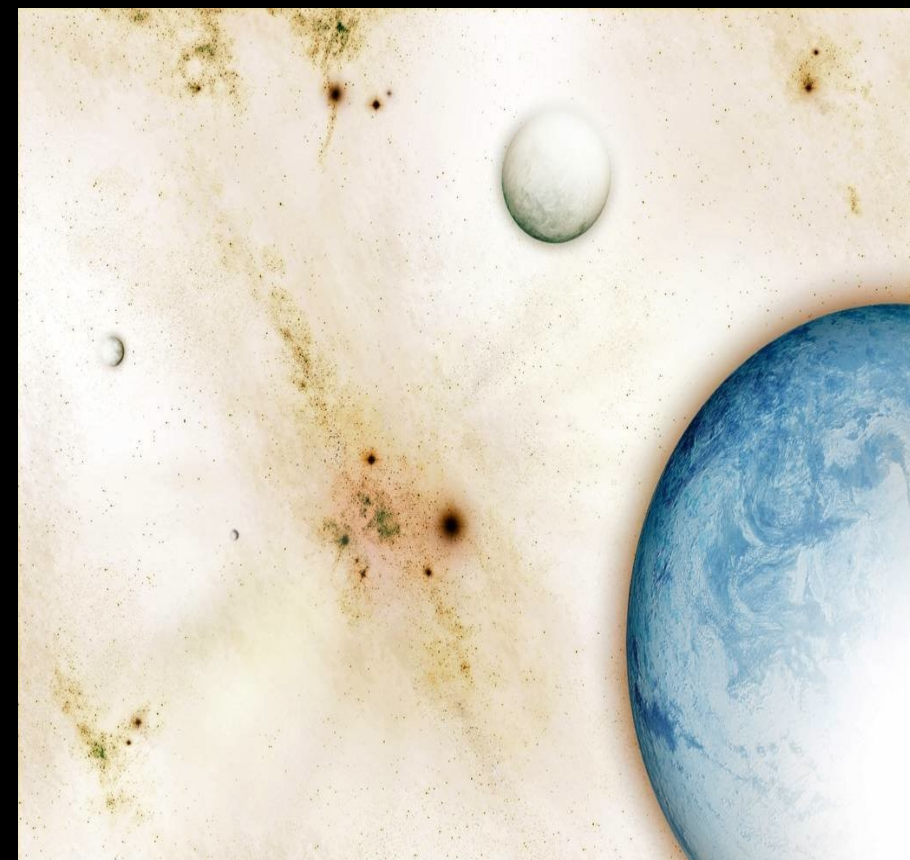
- Probes of objects too far away for anything else

- Cosmological and astrophysical implications

- Matter/Antimatter imbalance

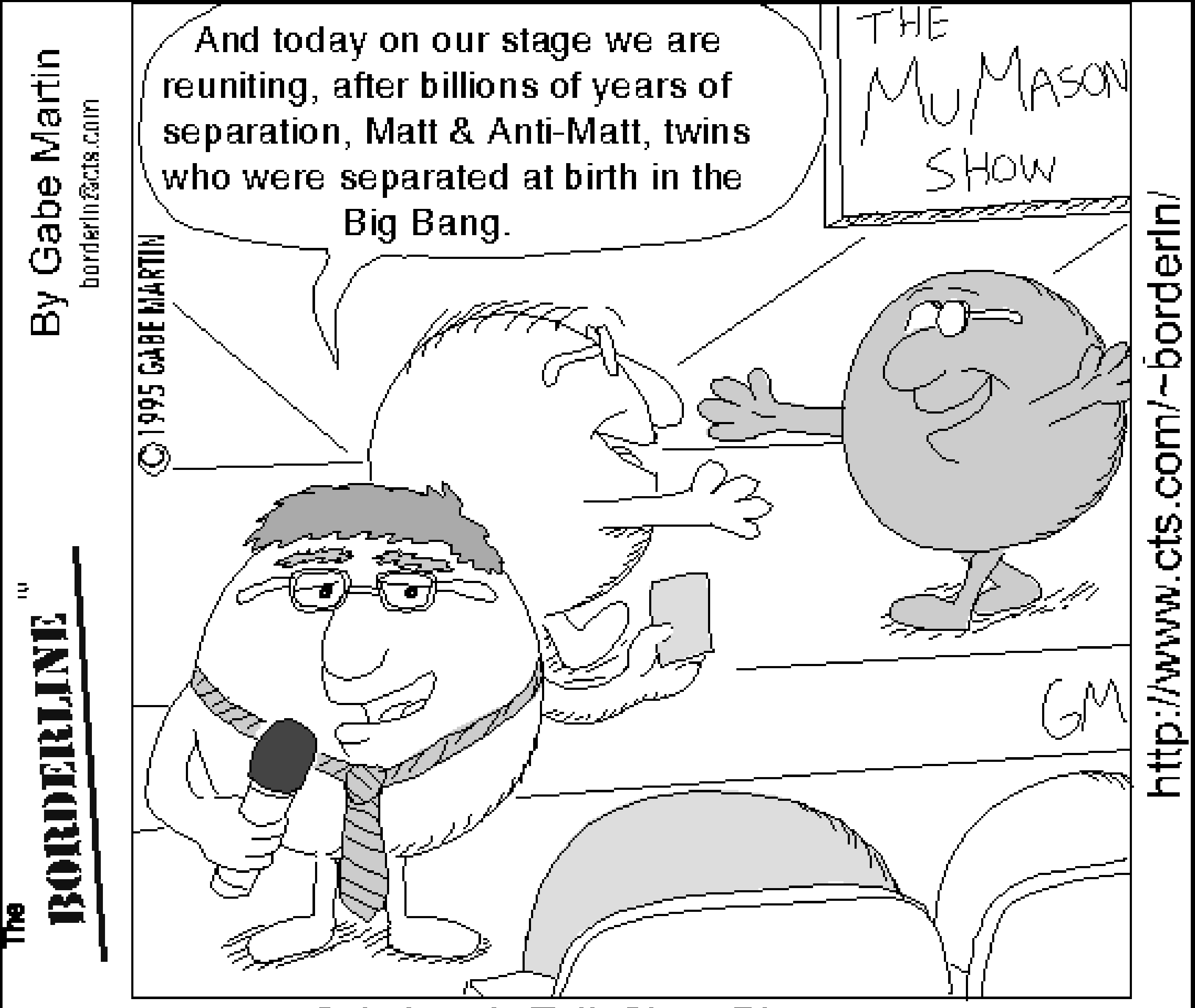
Why is there more matter than antimatter?

=



Why is there more matter than antimatter?

Sub-Atomic Talk Show Disasters

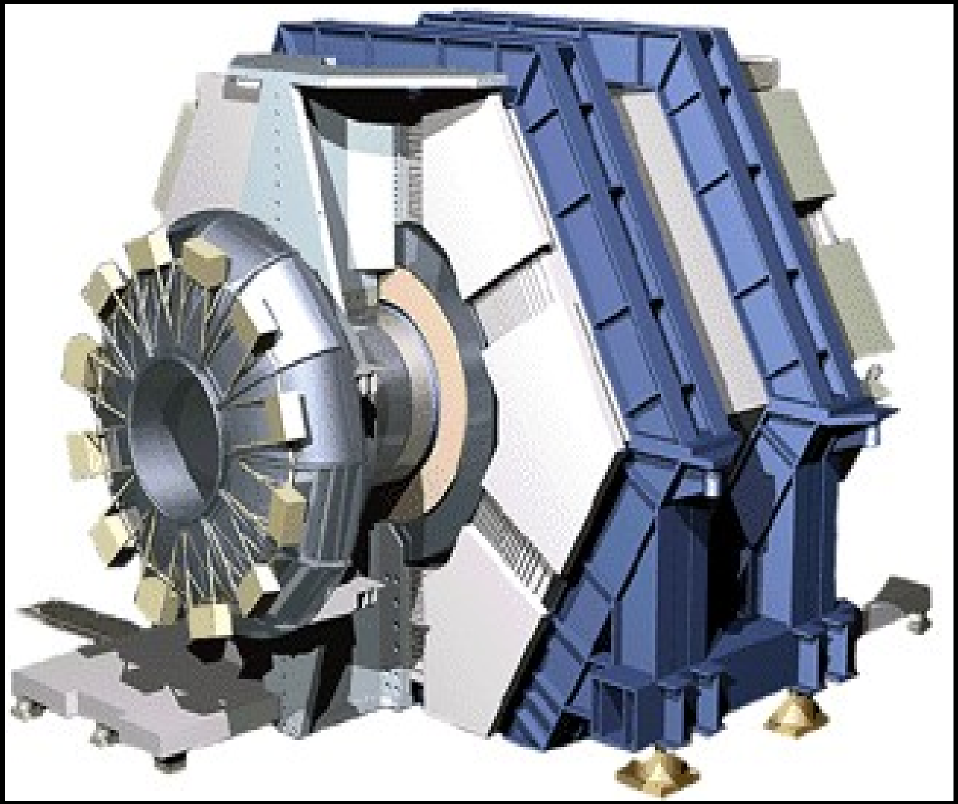


Sub-Atomic Talk-Show Disasters

CP Violation

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

A. Yes there is.



We study this here with an experiment called BaBar

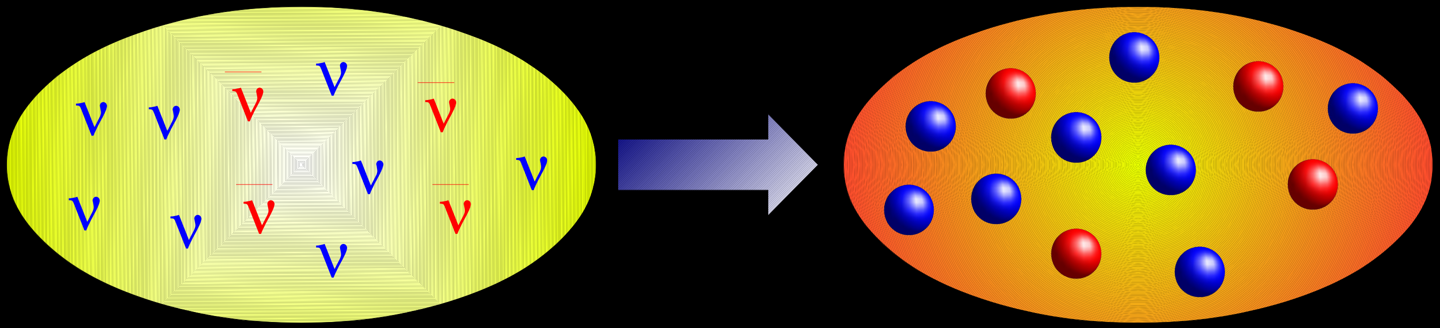
“B_0 / $\bar{B}_0$ mixing”

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.

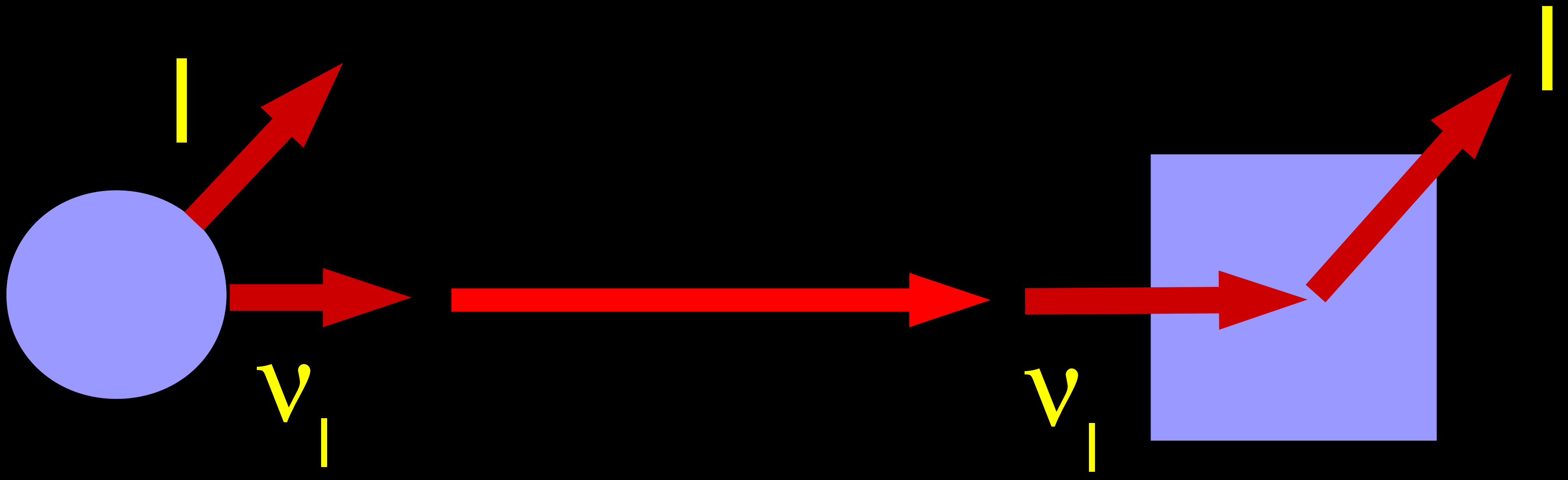


"Leptogenesis"

How to study this?

Neutrino Oscillations

THE discovery in neutrinos of the last 20 years



A typical neutrino experiment

The Sun is Broken!!!

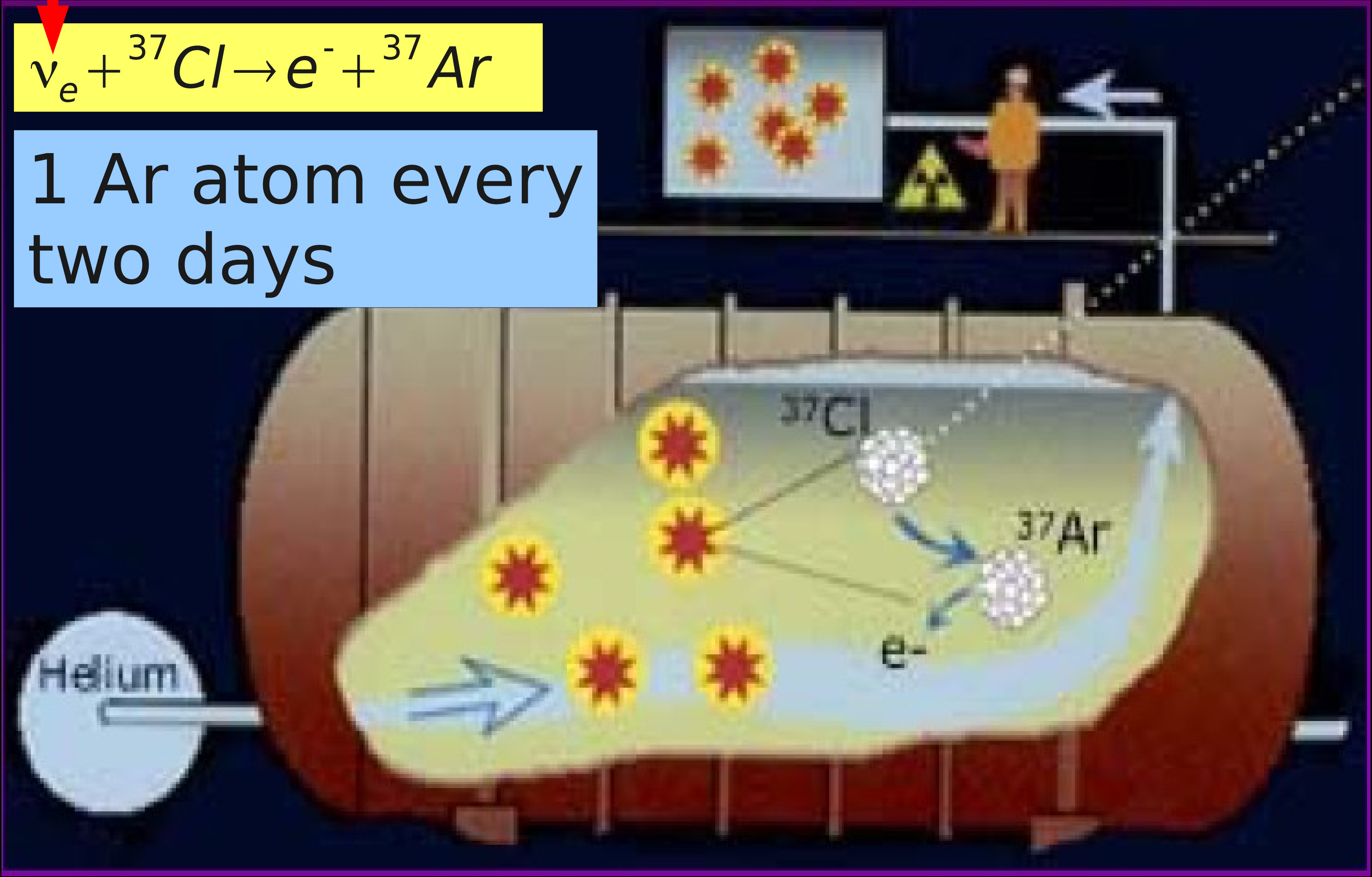
Ray Davis – Early 1970s

An atom a day

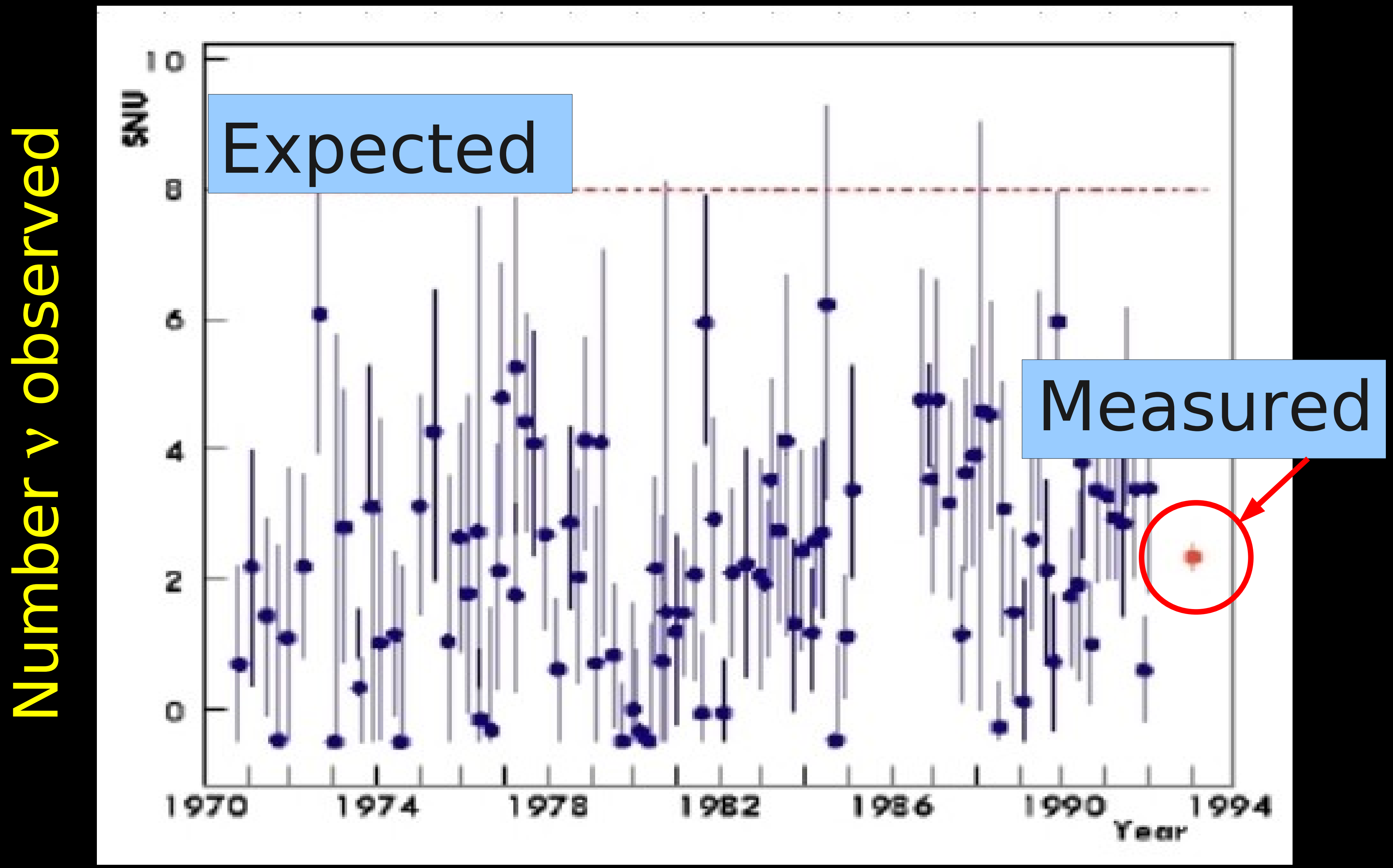
Only

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

1 Ar atom every two days

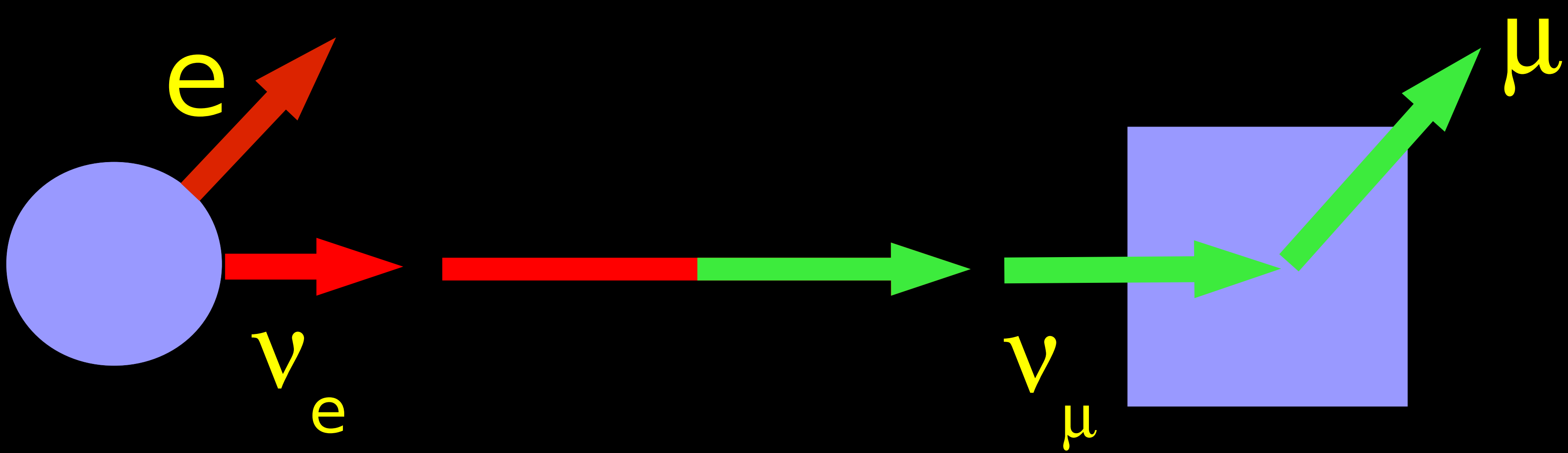


Less than expected

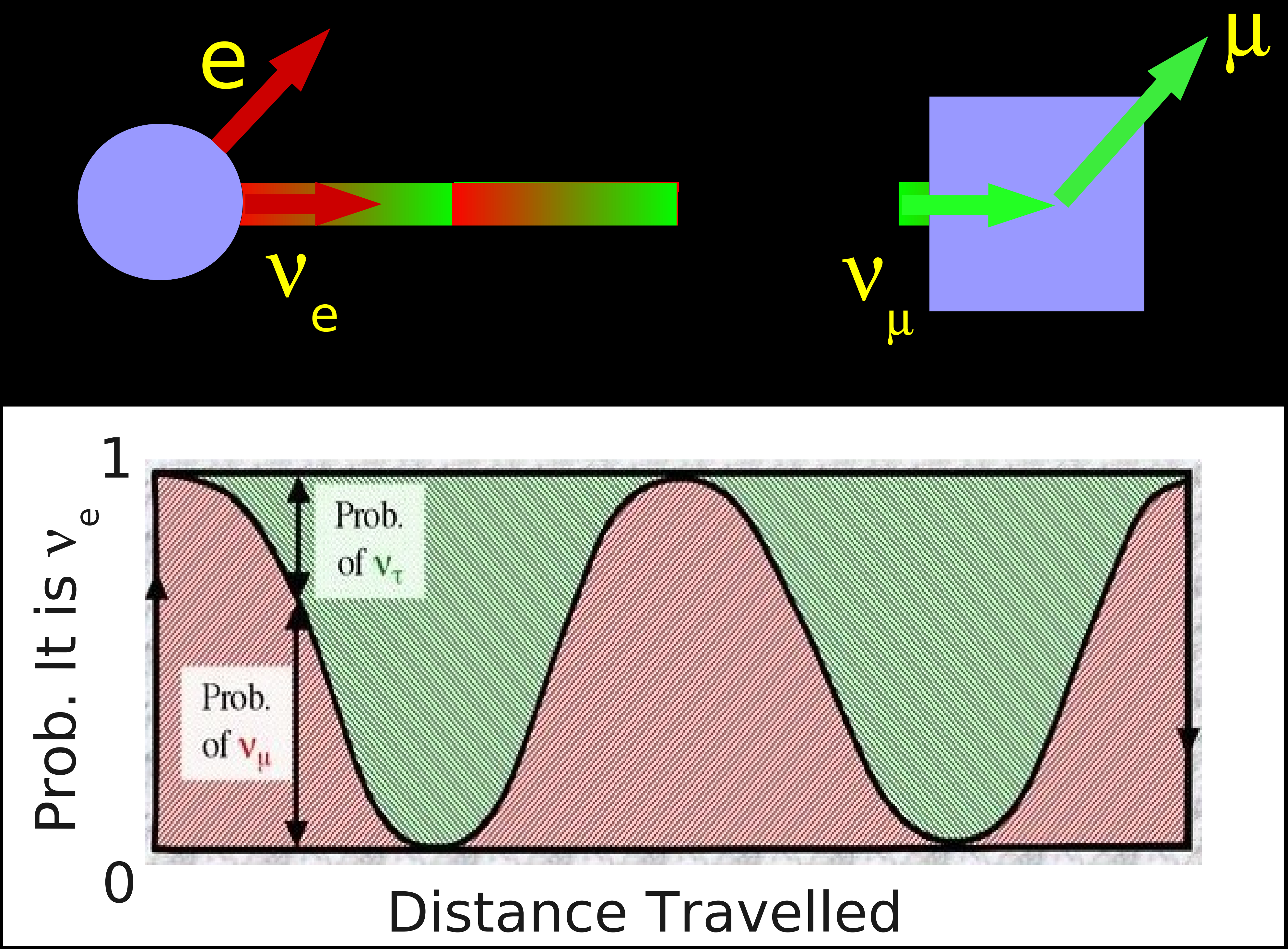


Neutrino Oscillations

THE discovery in neutrinos of the last 20 years



Neutrinos were changing flavour between sun and detector!


e
νe
μ
νμ
1
0
Prob. It is νe
Prob.
of ντ
Prob.
of νμ
Distance Travelled

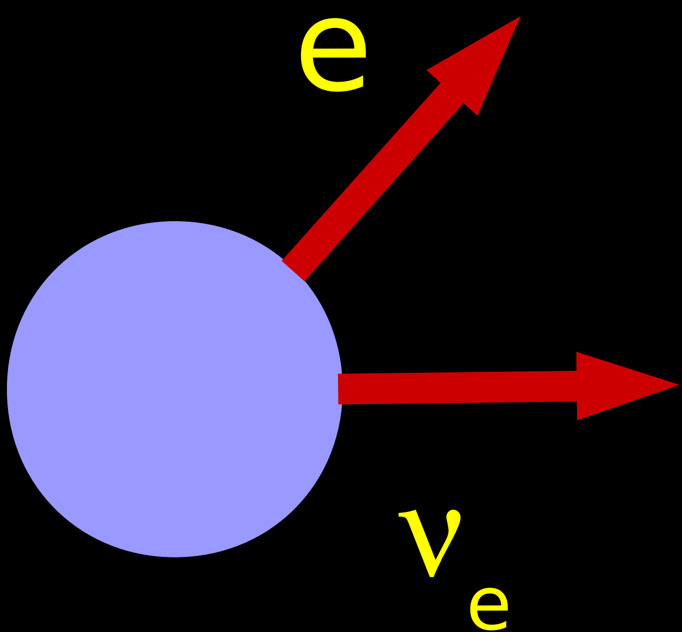
Eh?

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

Eh?

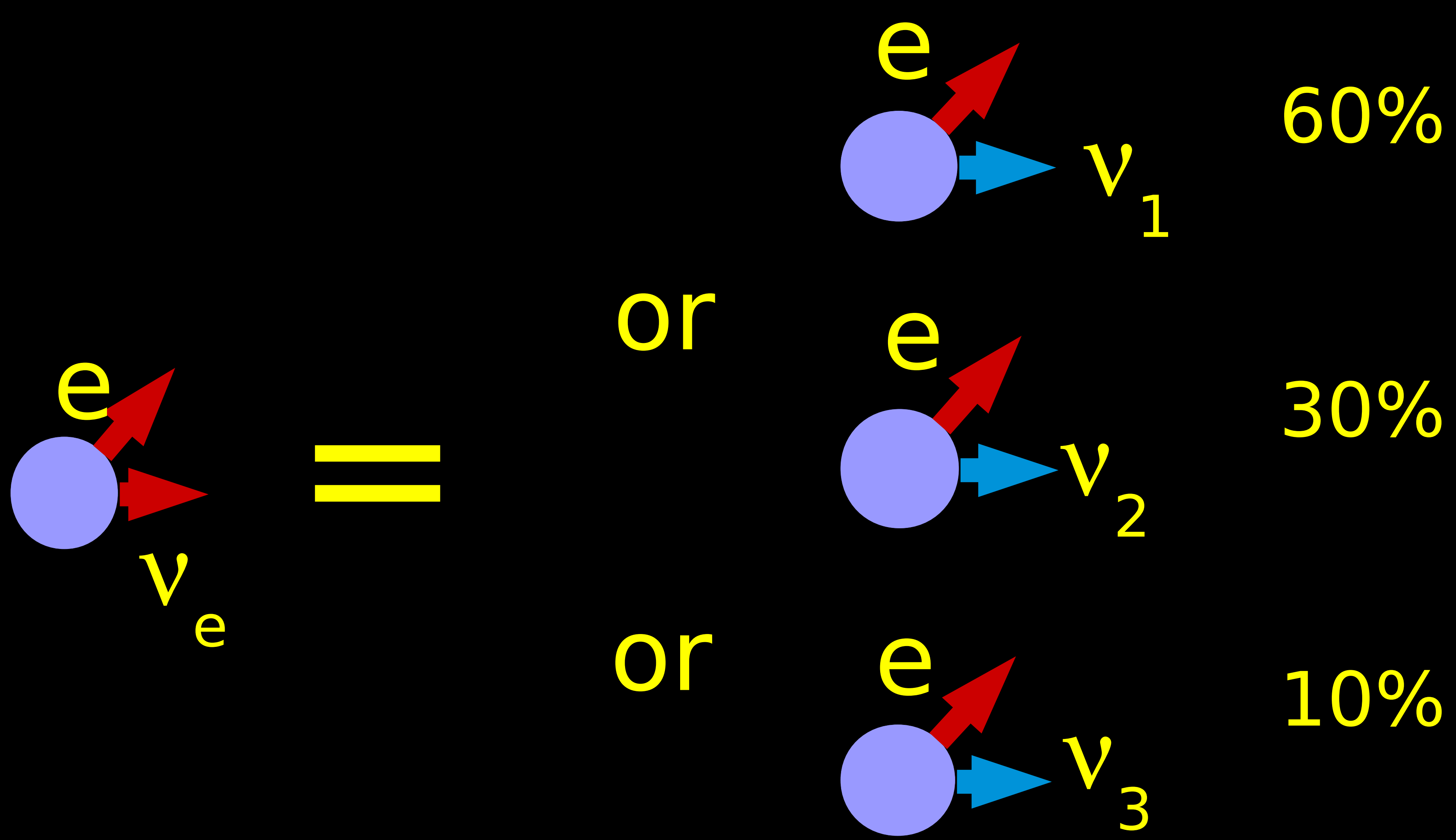
Q. How can a ν_e spontaneously turn into a ν_μ?

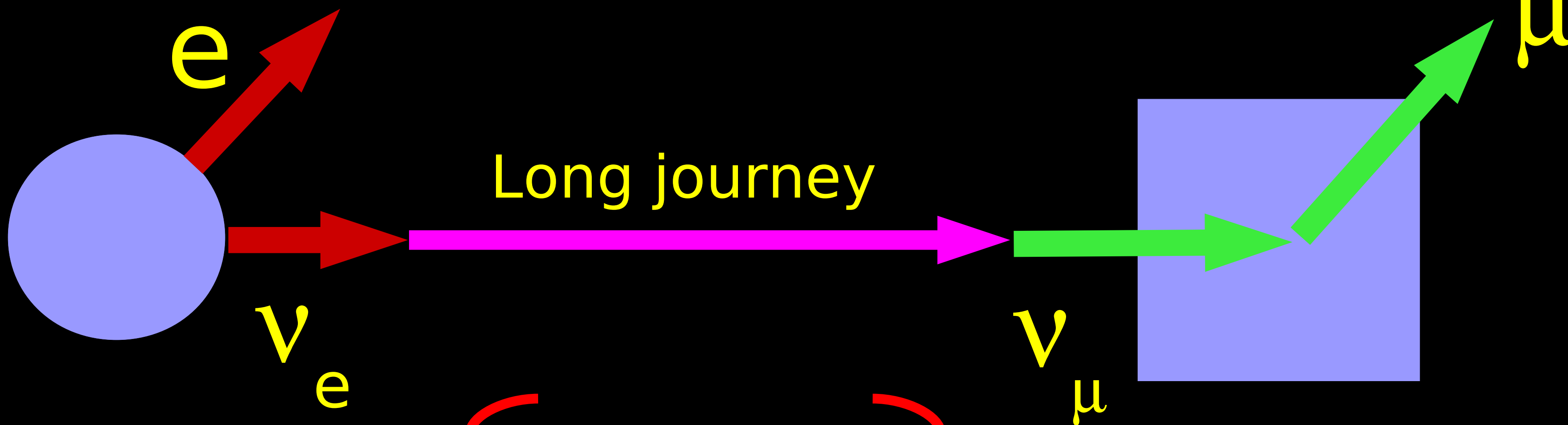
A. The ν_e isn't *a* particle. It's three!



ν_e ≡ “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

Why so important?

- The Standard Model of Particle Physics has no explanation for a non-zero, but tiny, neutrino mass – so we are in “unknown physics” territory.

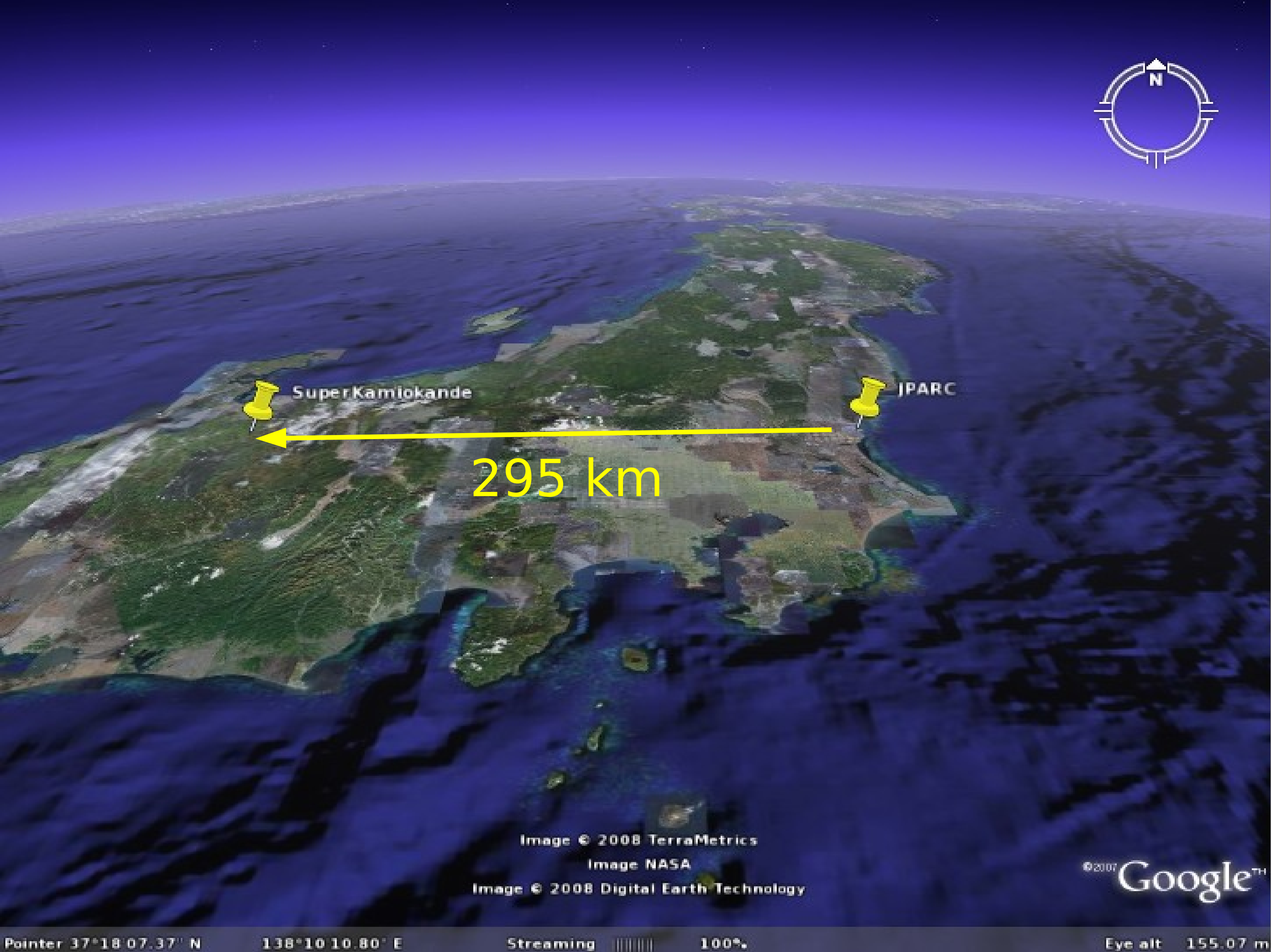
- Neutrino masses link to GUT theories.

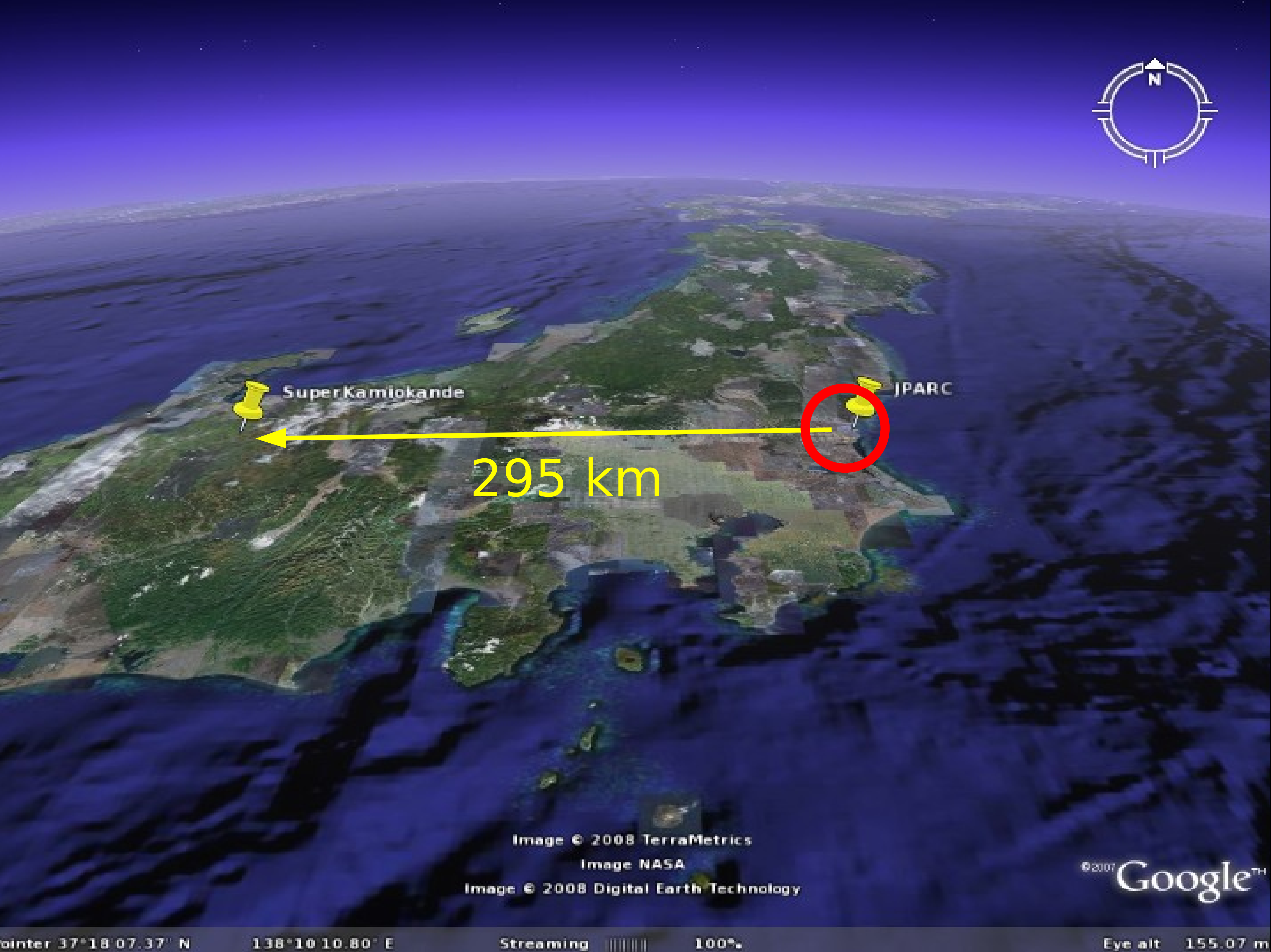
- Has cosmological implications (mass balance, structure)

$$P_{osc}\left(\nu_{\mu} \rightarrow \nu_{e}\right) \neq P_{osc}\left(\overline{\nu_{\mu}} \rightarrow \overline{\nu_{e}}\right)$$

The T2K Experiment

- University of Warwick
- University of Sheffield
- Imperial College, University of London
- Oxford University
- University of Liverpool
- University of Lancaster
- Queen Mary College, University of London
- Rutherford-Appleton Laboratories


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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SuperKamiokande
JPARC
295 km
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138°10'10.80" E
Streaming
100%
Eye alt
155.07 m


Tokai-mura
Shirane
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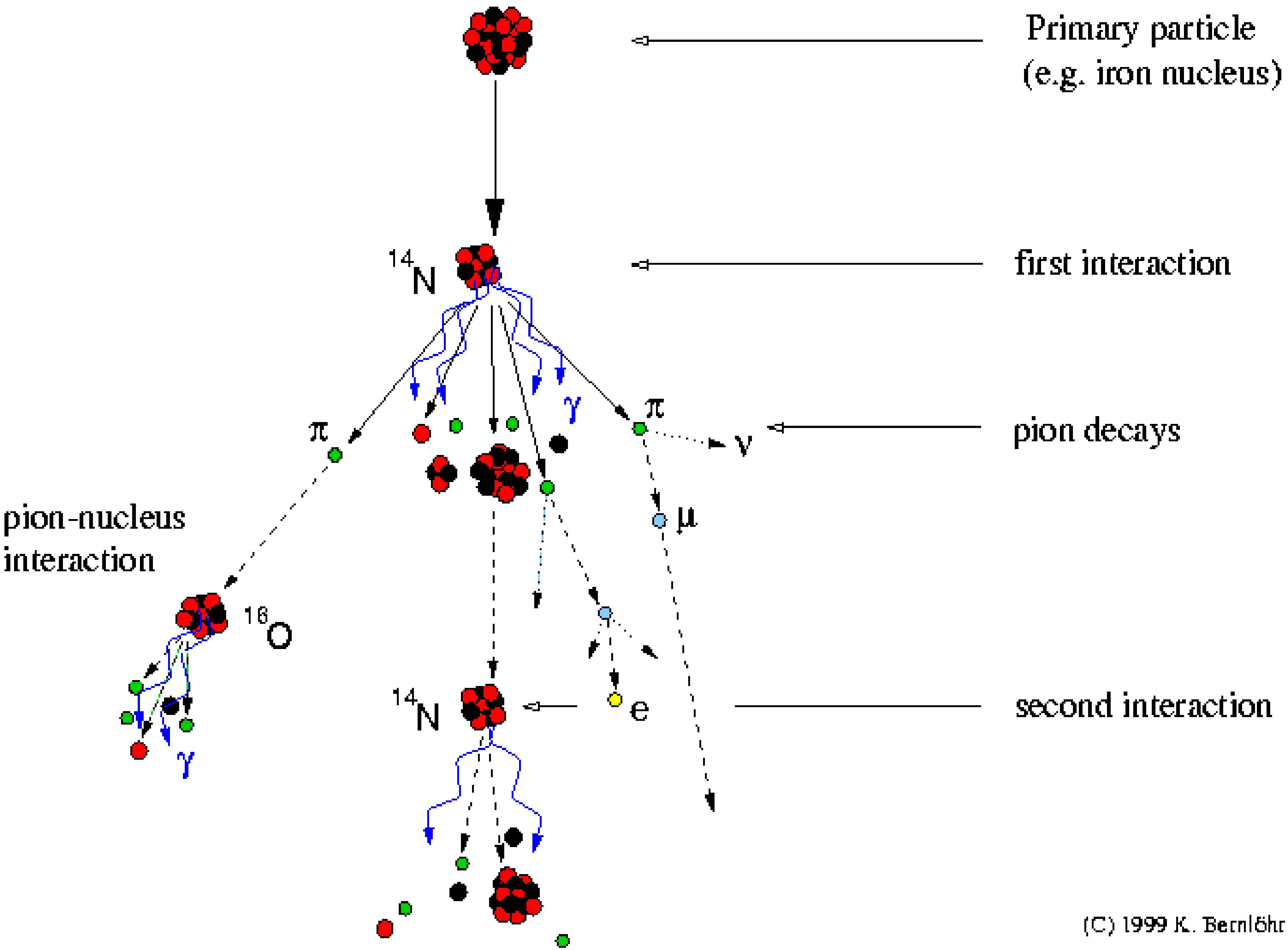
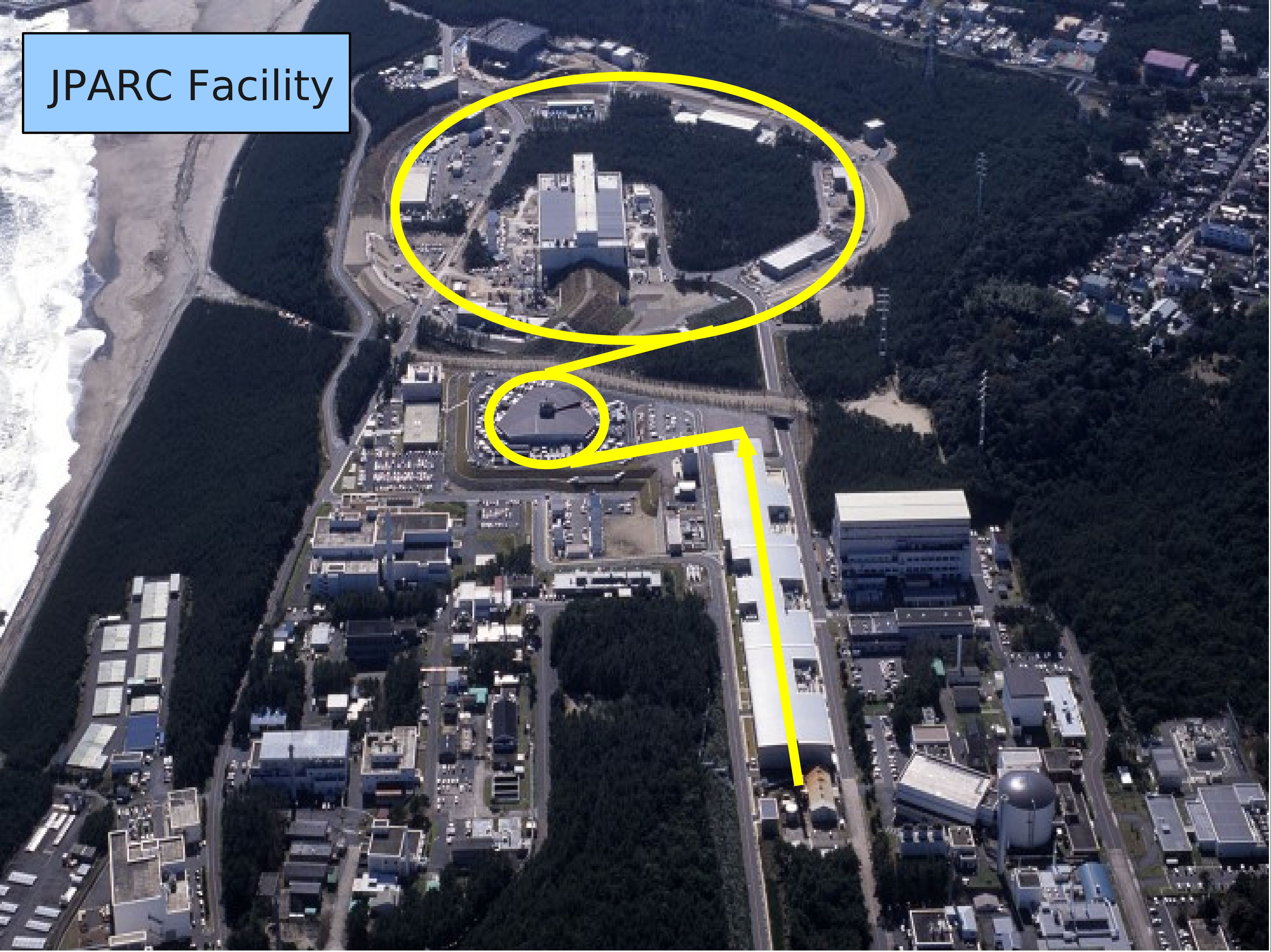
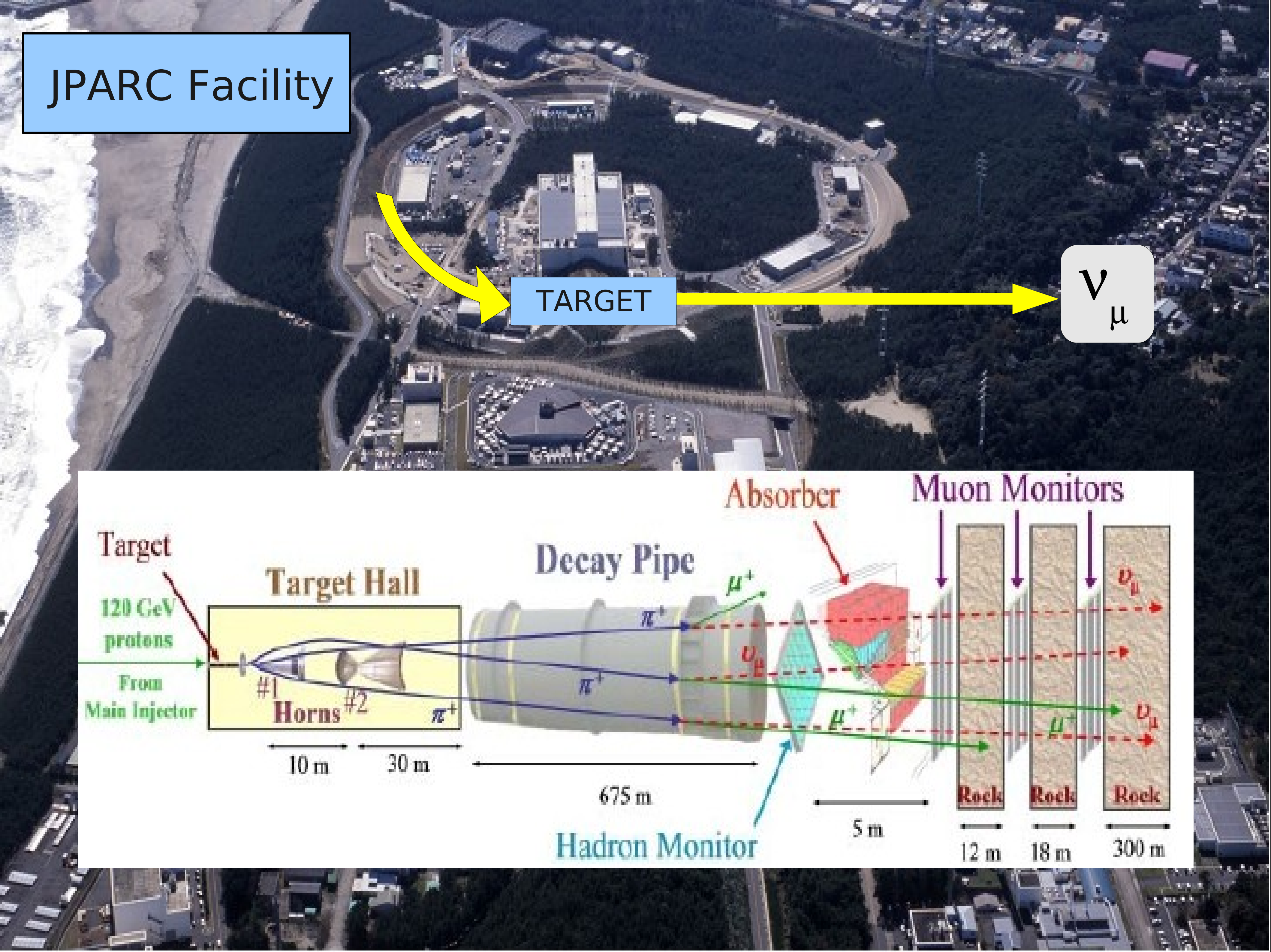
Development of cosmic-ray air showers

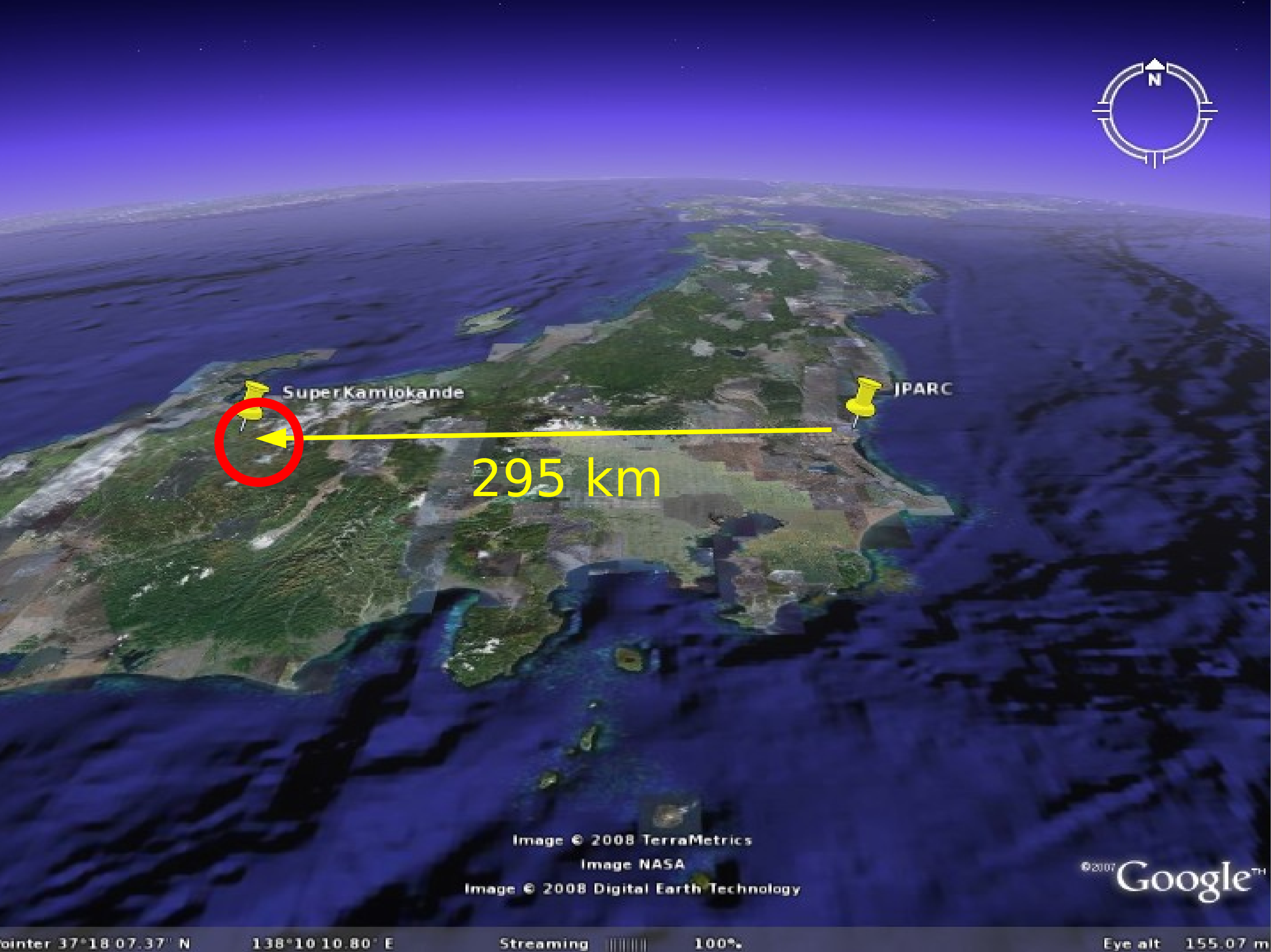


JPARC Facility





JPARC Facility
TARGET
ν_μ
Target
Target Hall
Decay Pipe
Absorber
Muon Monitors
120 GeV protons
From Main Injector
#1
Horns
#2
π^+
π^+
π^+
π^+
μ^+
υ_μ
υ_μ
υ_μ
μ^+
μ^+
Rock
Rock
Rock
10 m
30 m
675 m
5 m
12 m
18 m
300 m
Hadron Monitor


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

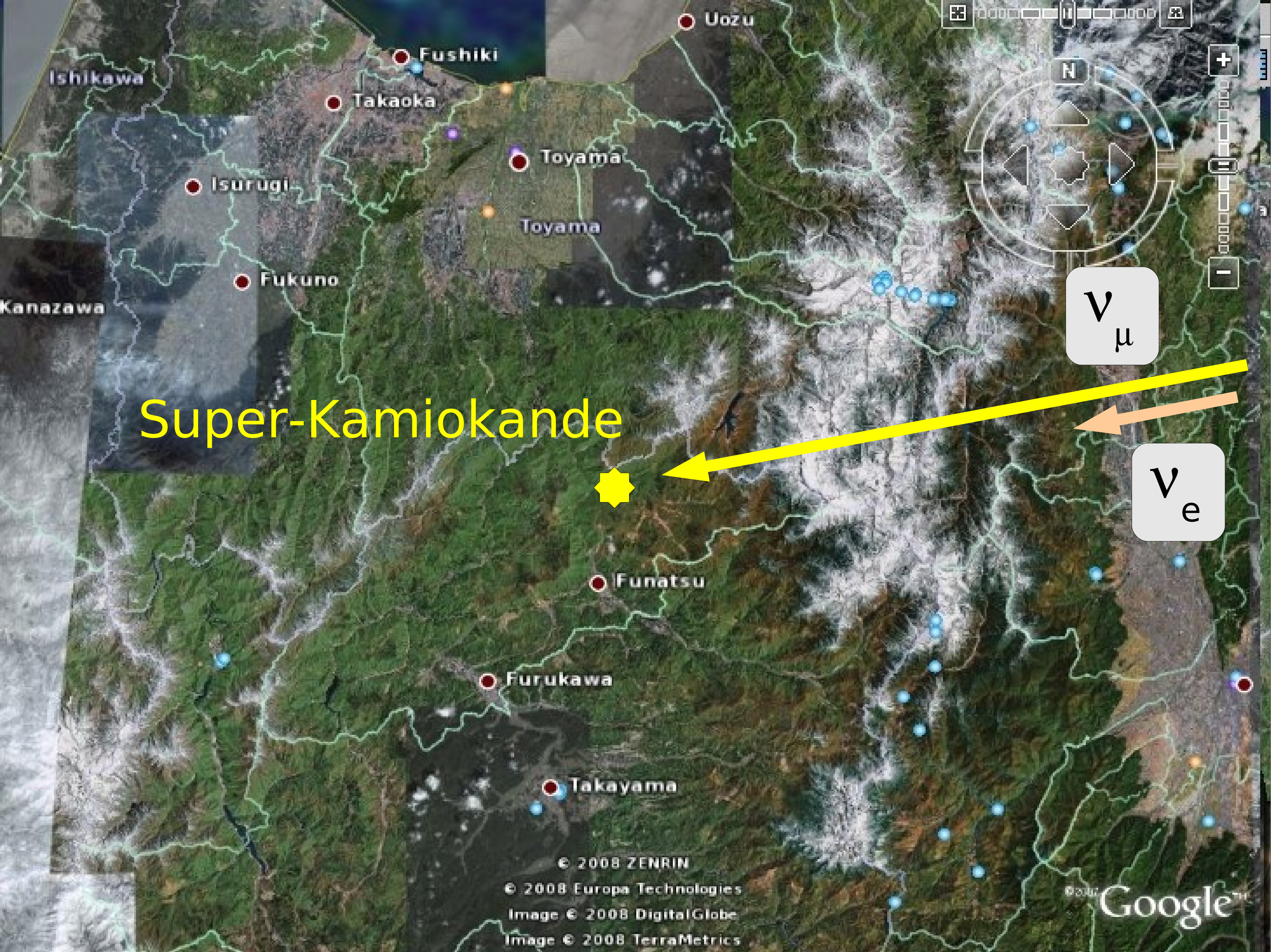
Super-Kamiokande
ν_μ
ν_e
Uozu
Fushiki
Ishikawa
Takaoka
Toyama
Isurugi
Toyama
Fukuno
Kanazawa
Funatsu
Furukawa
Takayama
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Image © 2008 DigitalGlobe
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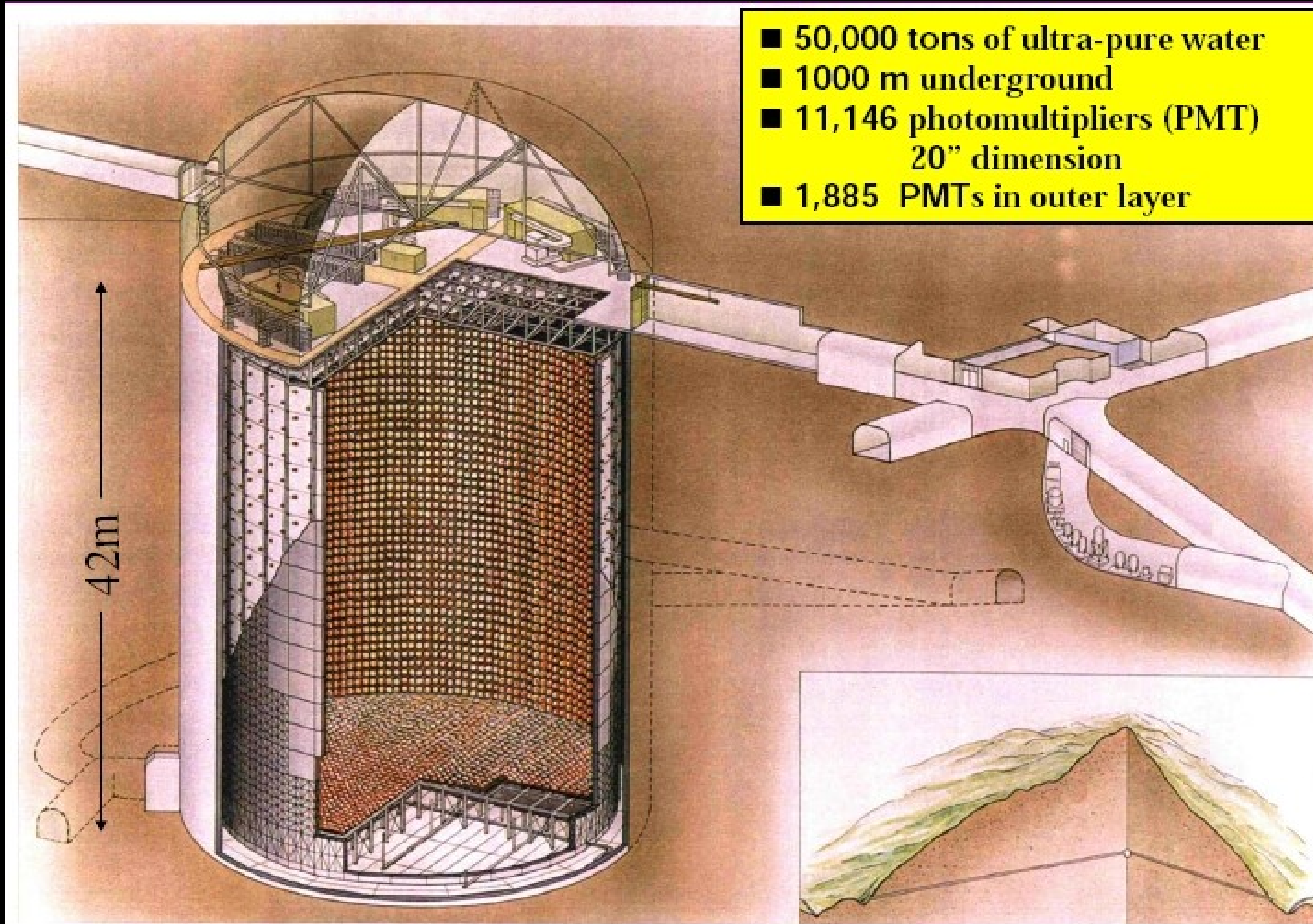
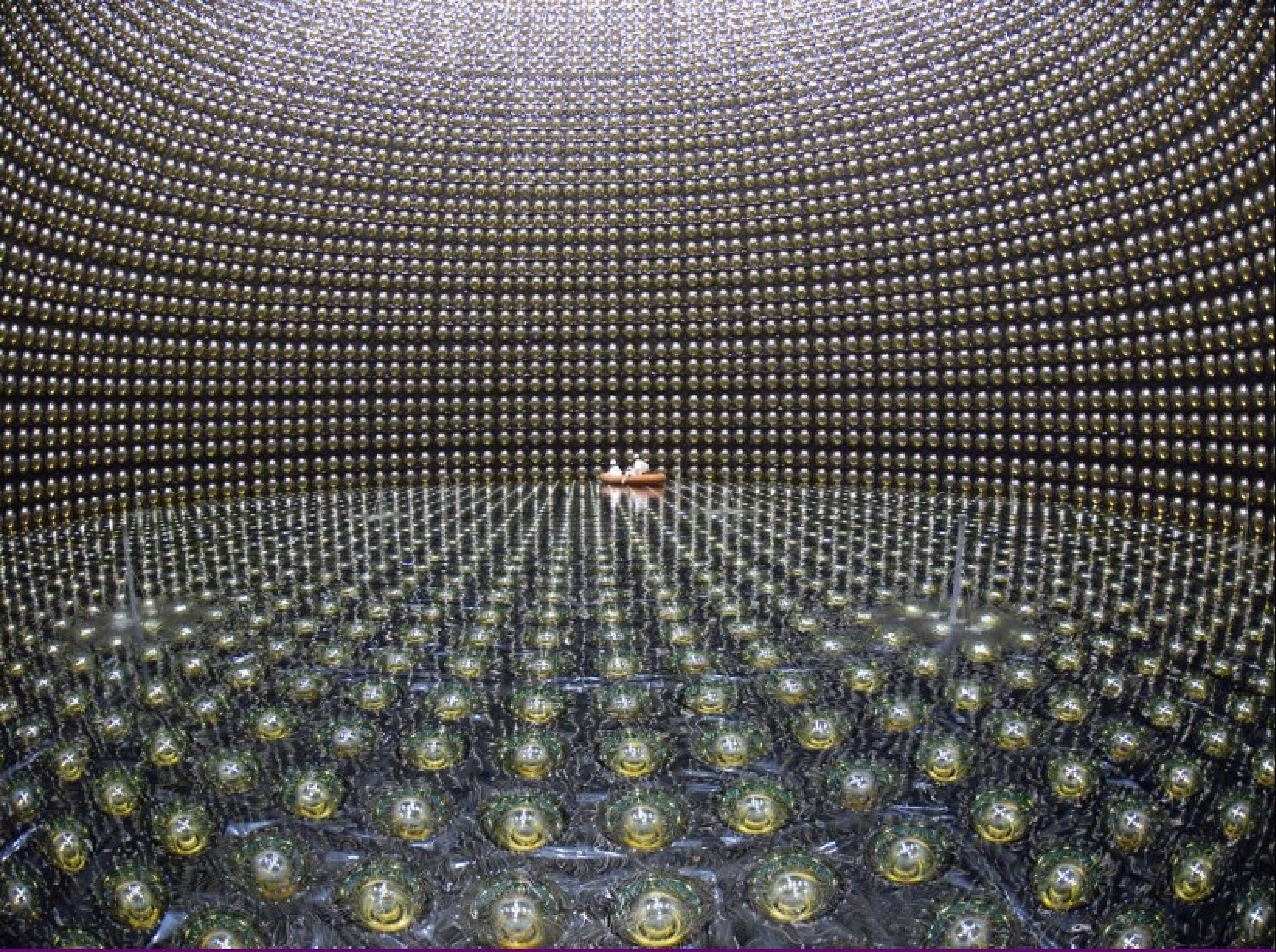
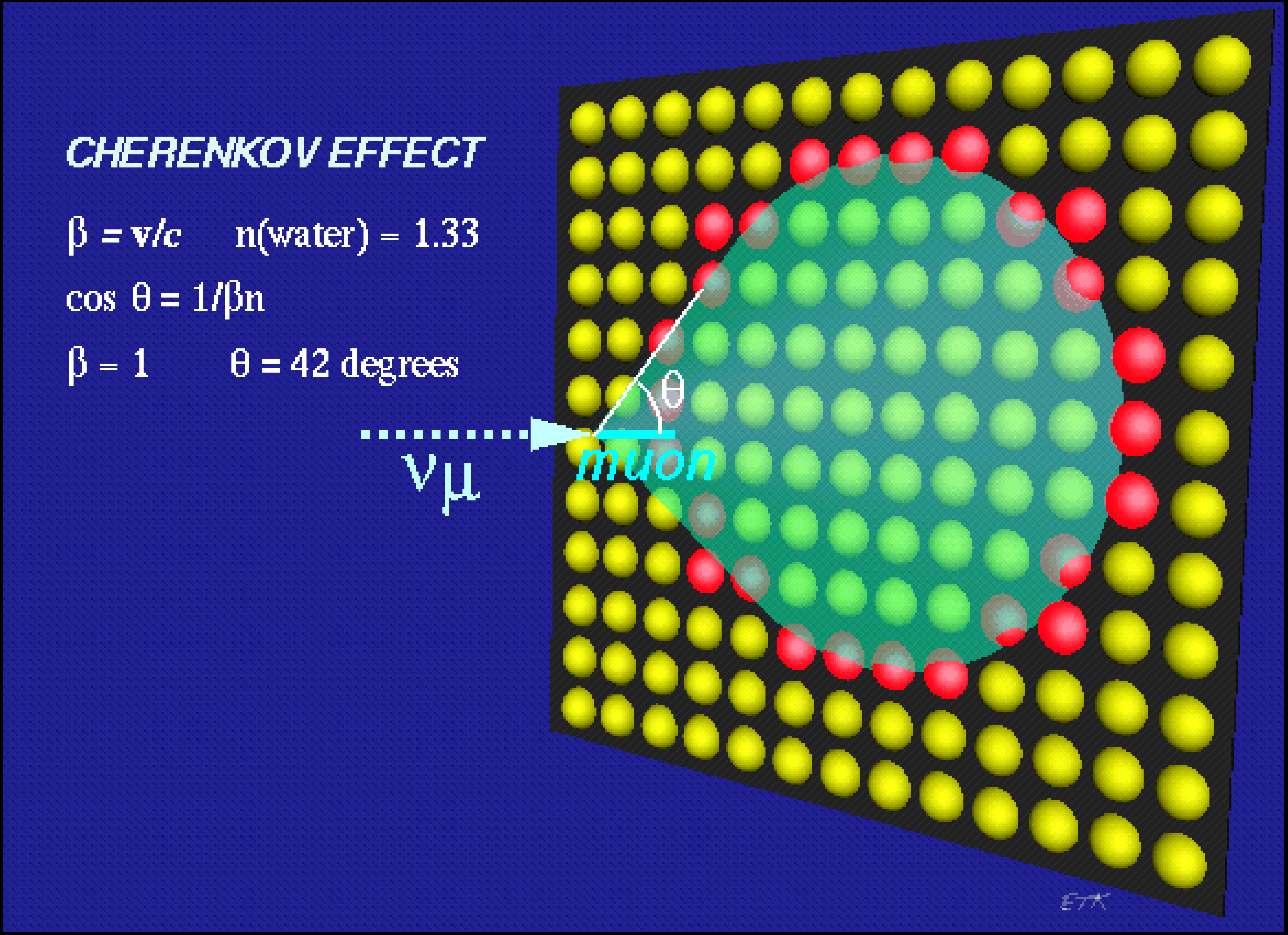
Google

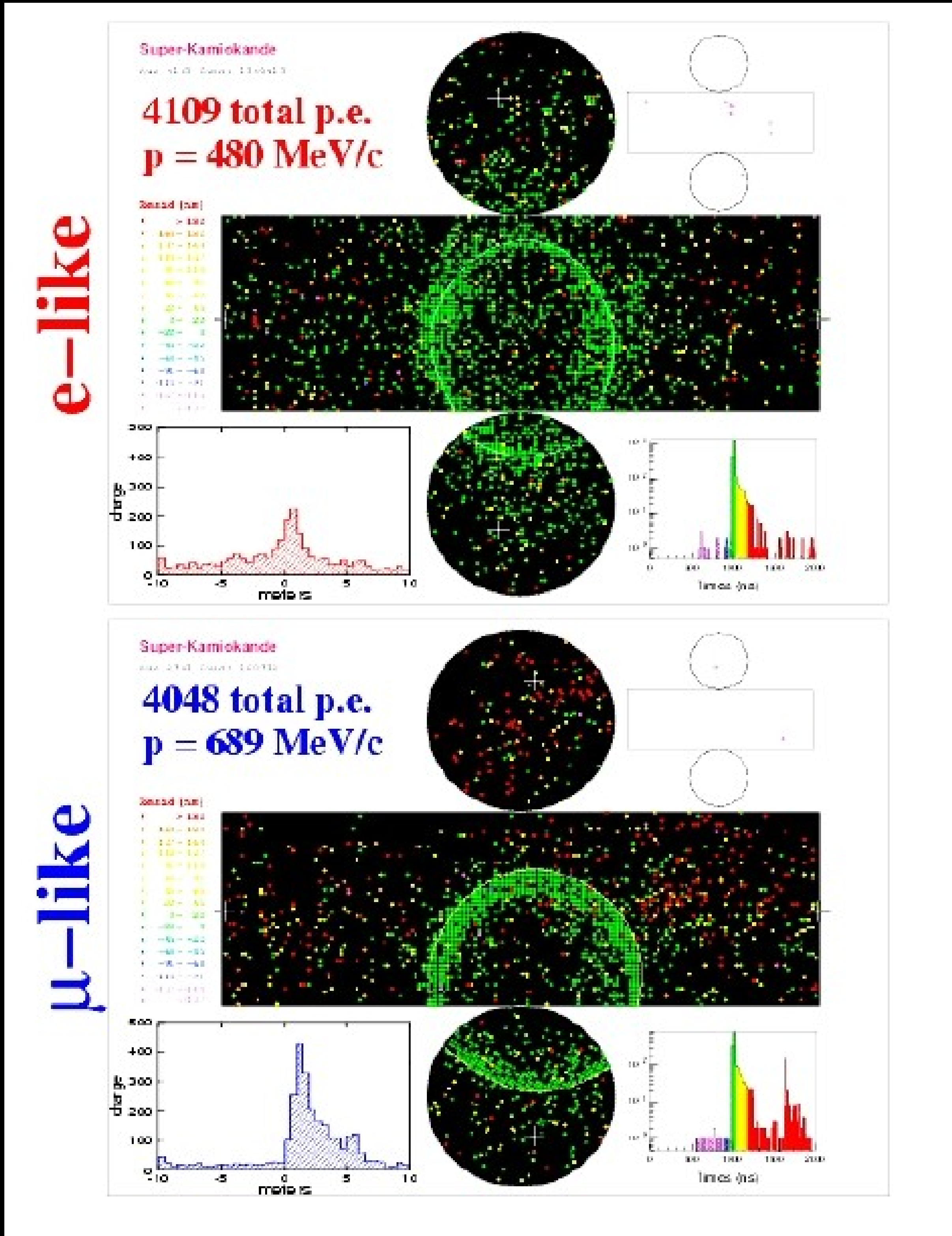
- 50,000 tons of ultra-pure water
- 1000 m underground
- 11,146 photomultipliers (PMT) 20” dimension
- 1,885 PMTs in outer layer





Water Cerenkov





Electron-like : has a fuzzy ring

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

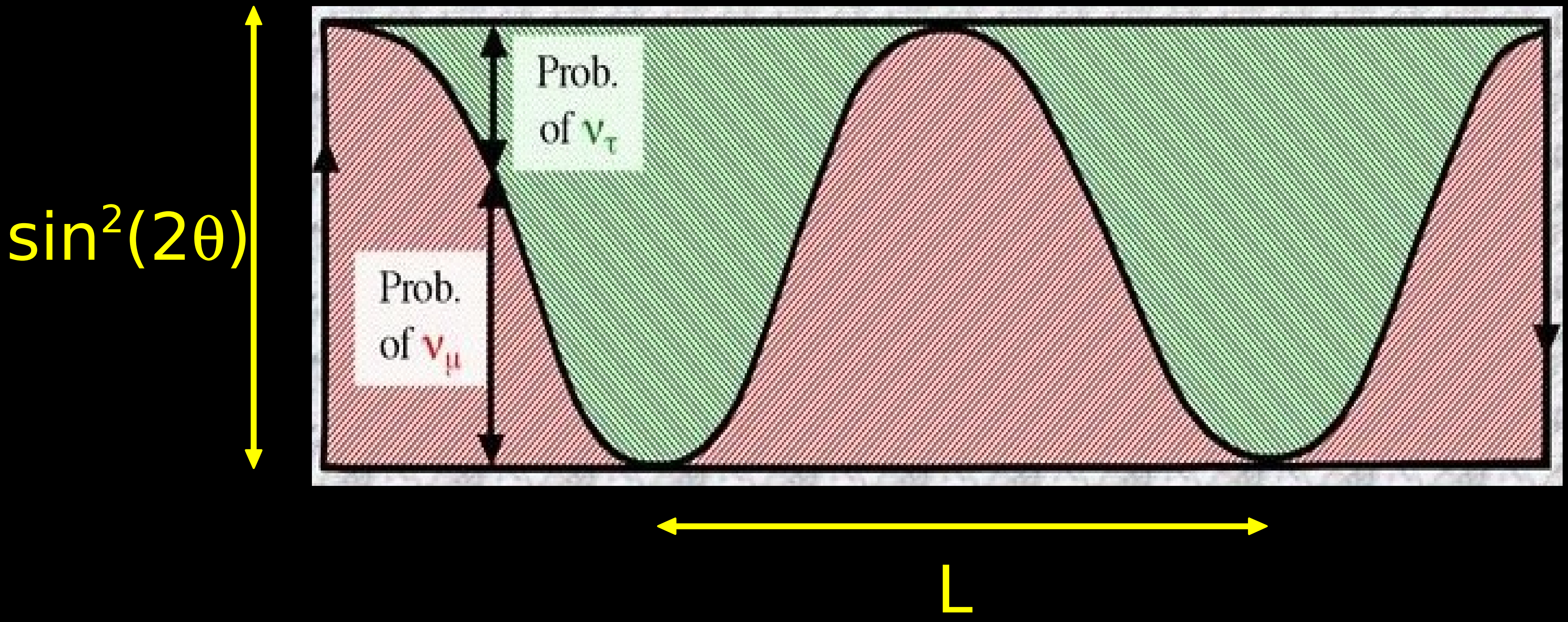
Open Questions

- 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?

‘‘...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

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



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

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

Why do blue sky research?

- 5% of jobs in UK are in physics-based sectors
- Gross added value from physics sectors 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 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