

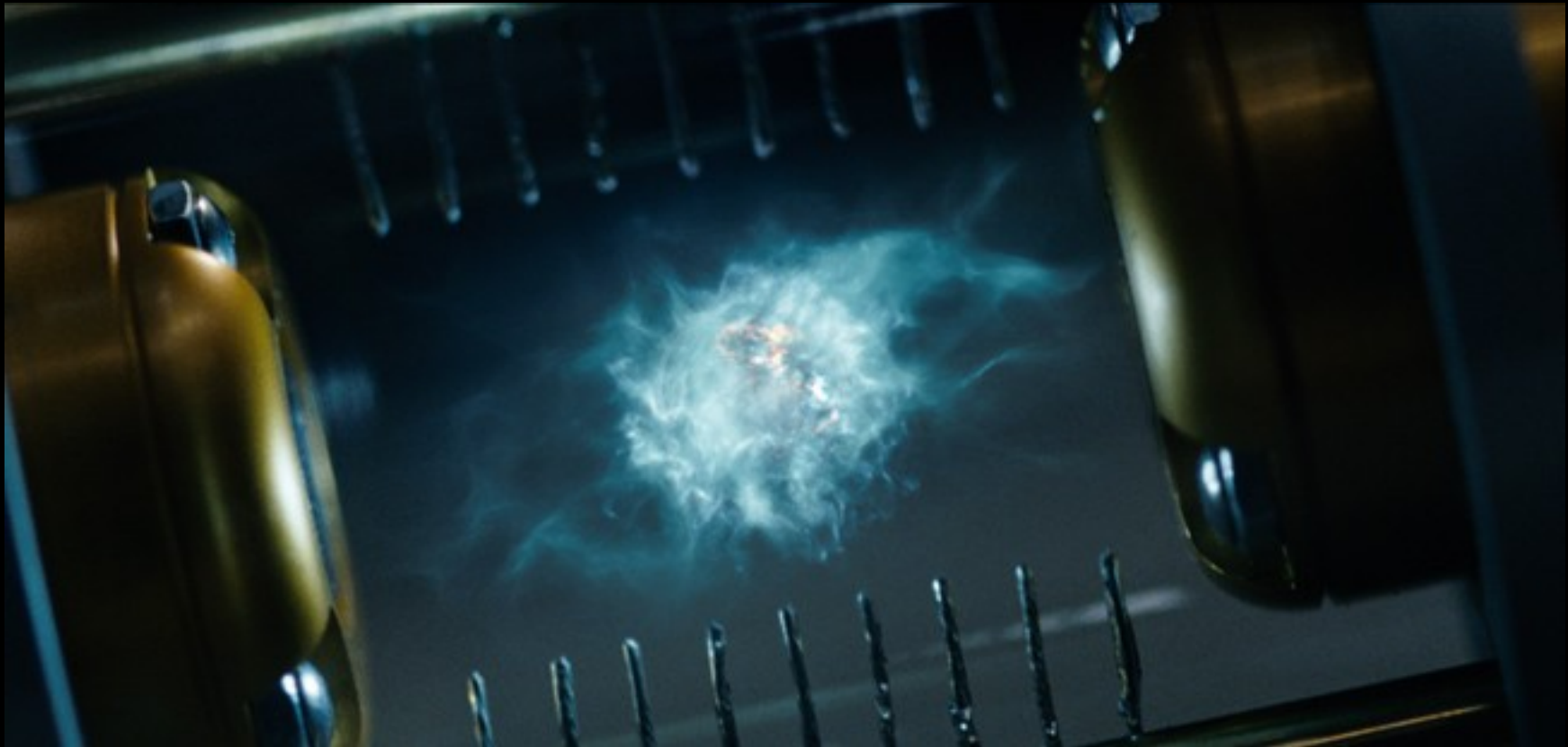
Neutrinos and the Case of the Missing Antimatter

Steve Boyd, University of Warwick

WARWICK

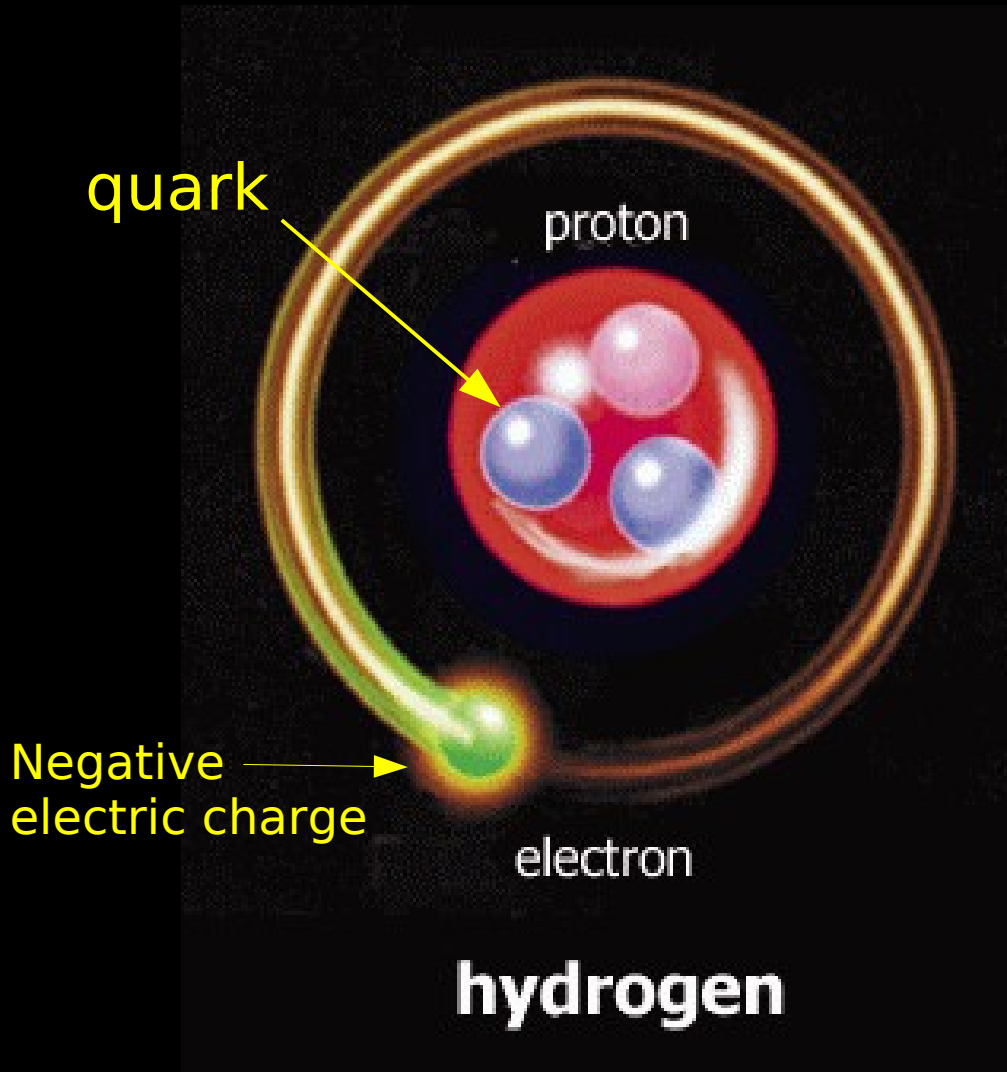


Not this...



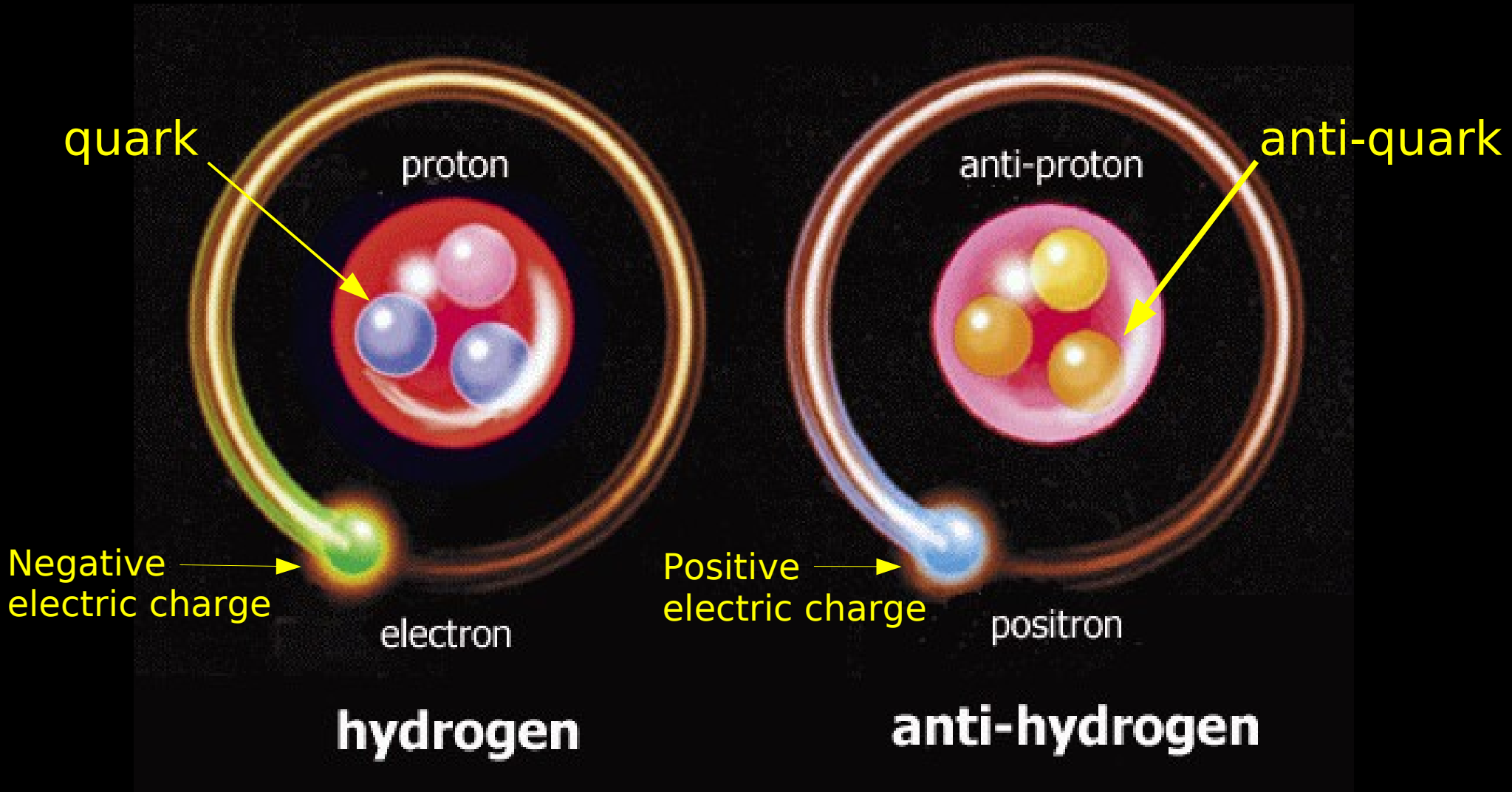
Angels and Demons, 2009

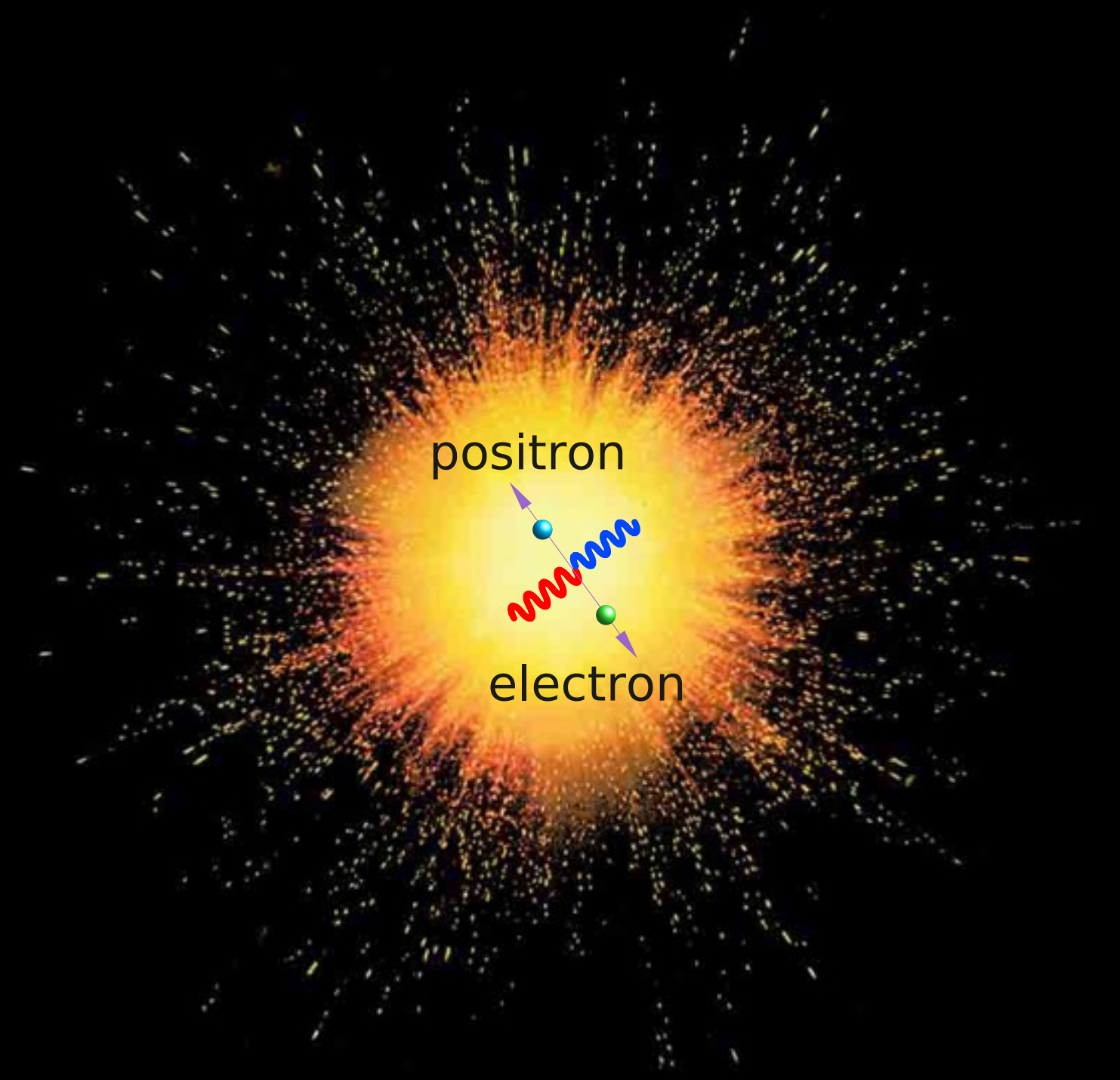
Matter



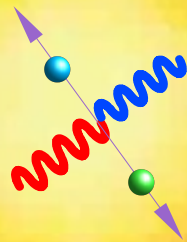
Matter

Anti-Matter





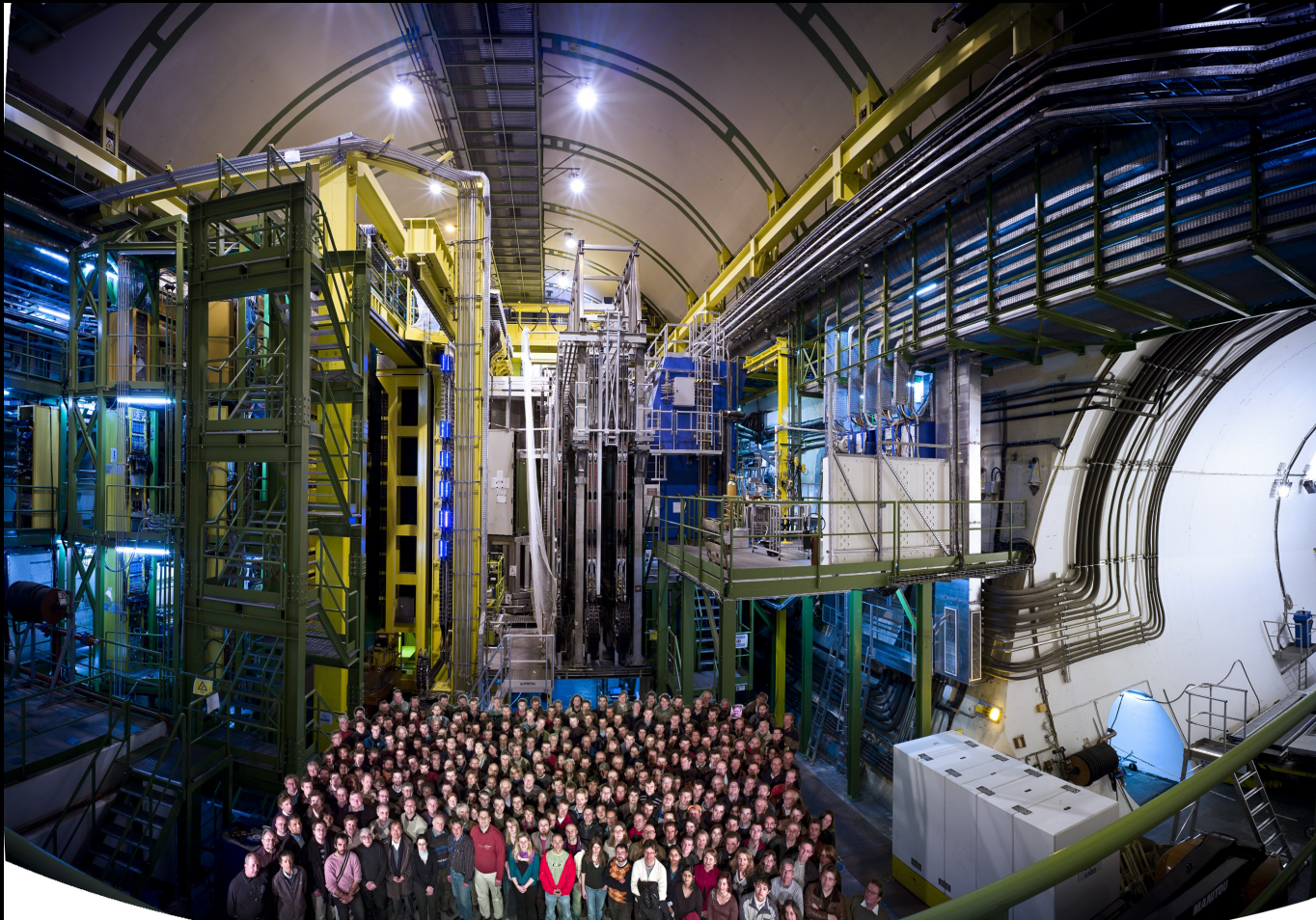
positron



electron

There *is* a difference between the physics of matter and antimatter. It's name is *CP Violation*

LHCb



The LHC will study this by looking differences between particles called B^0 and \bar{B}^0 mesons

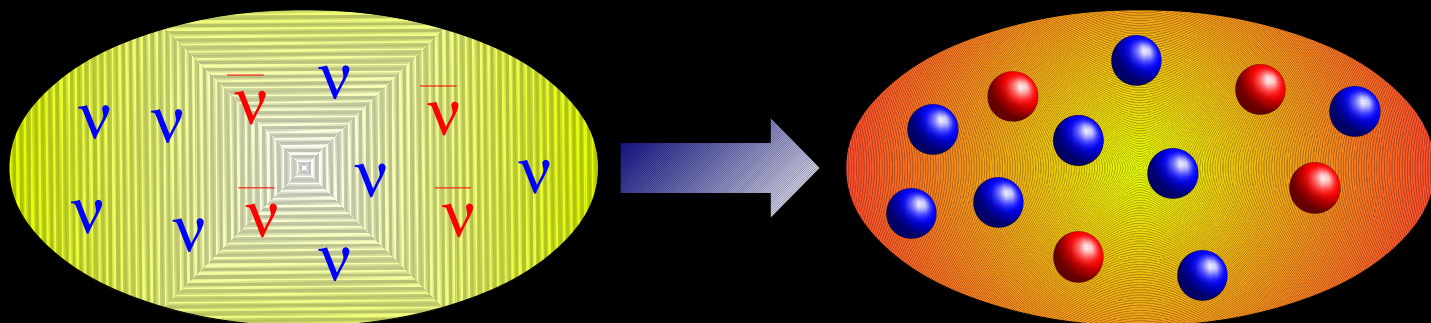
But.....

We might be looking in the wrong place....

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

Matter-Antimatter Asymmetry

A idea called "*Leptogenesis*" suggests that the asymmetry we see between matter and antimatter could have been generated by an asymmetry between *neutrinos* and *anti-neutrinos* at the beginning of things.



So what is a neutrino?

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

Electron, e

-1



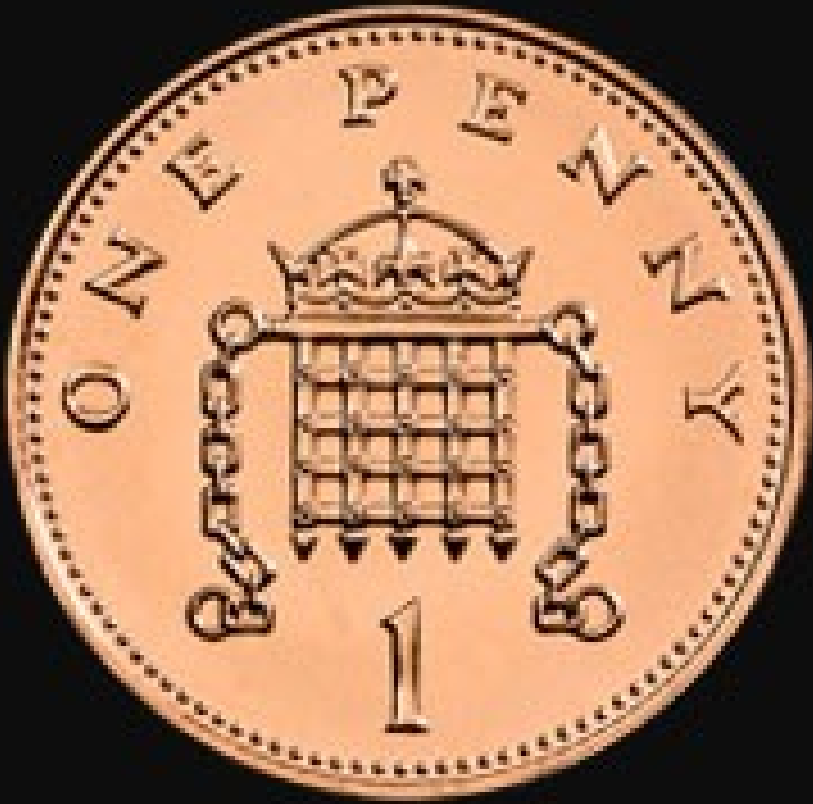
Tiny mass (1)

Electron Neutrino, ν_e



0

Very tiny mass
(<0.0000001)



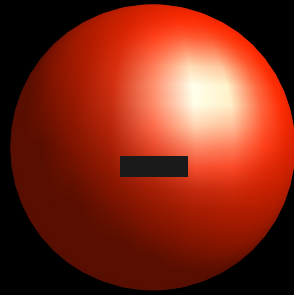




x 500

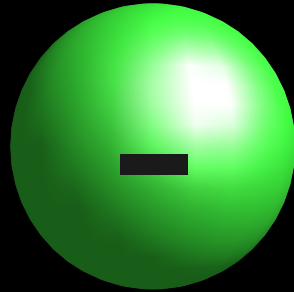


Electron, e
mass (1)



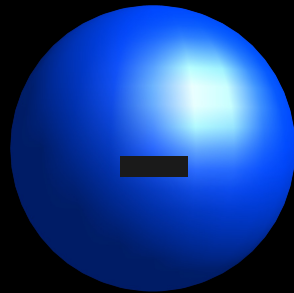
Electron
Neutrino, ν_e

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, $\bar{\nu}_e$

Muon
Neutrino, ν_μ



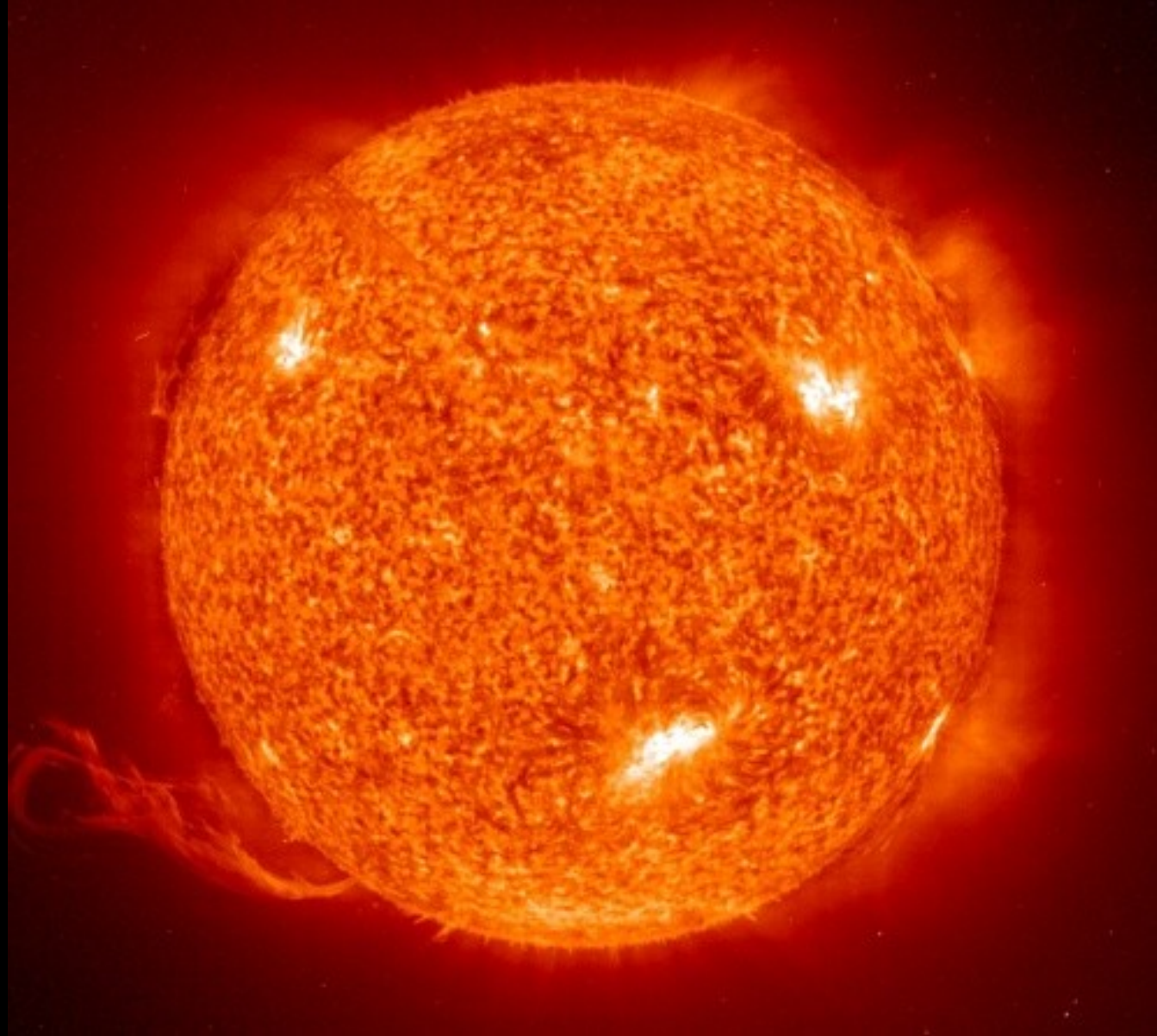
Muon
Antineutrino, $\bar{\nu}_\mu$

Tau
Neutrino, ν_τ



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

3 neutrino Flavours




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

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.

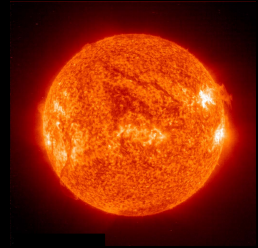



500,000,000,000,000 neutrinos
from the sun just went through
each and every one of you

"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-Mostly Harmless

Probability $\approx 5 \times 10^{-13}$




 ν_e



FreeFoto.com

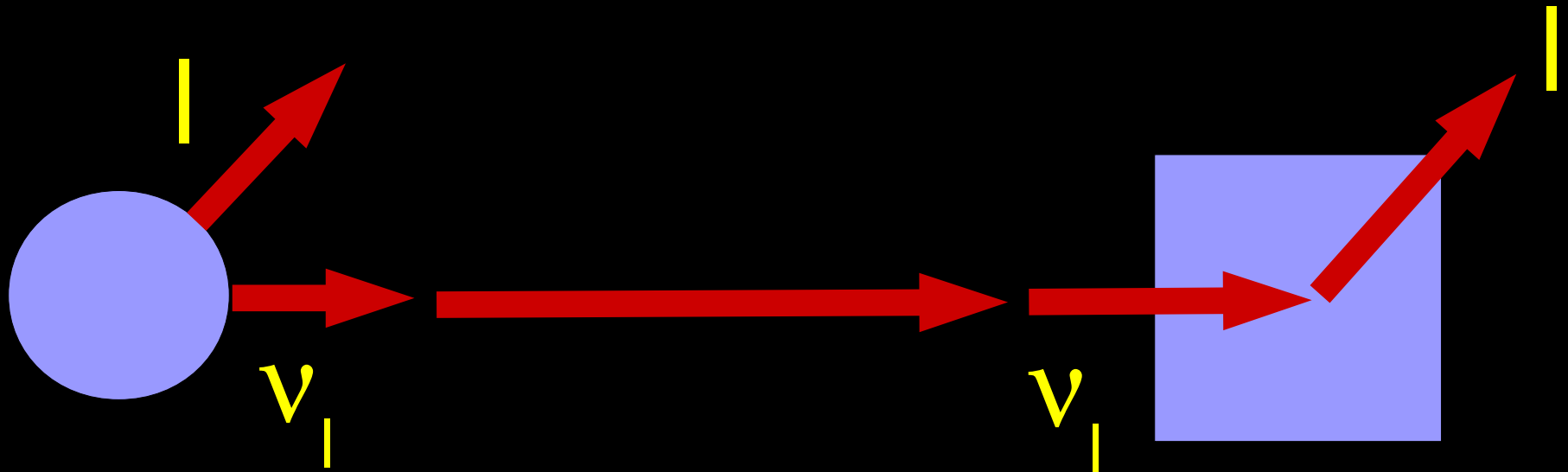
Probability $\approx 1 \times 10^{-13}$



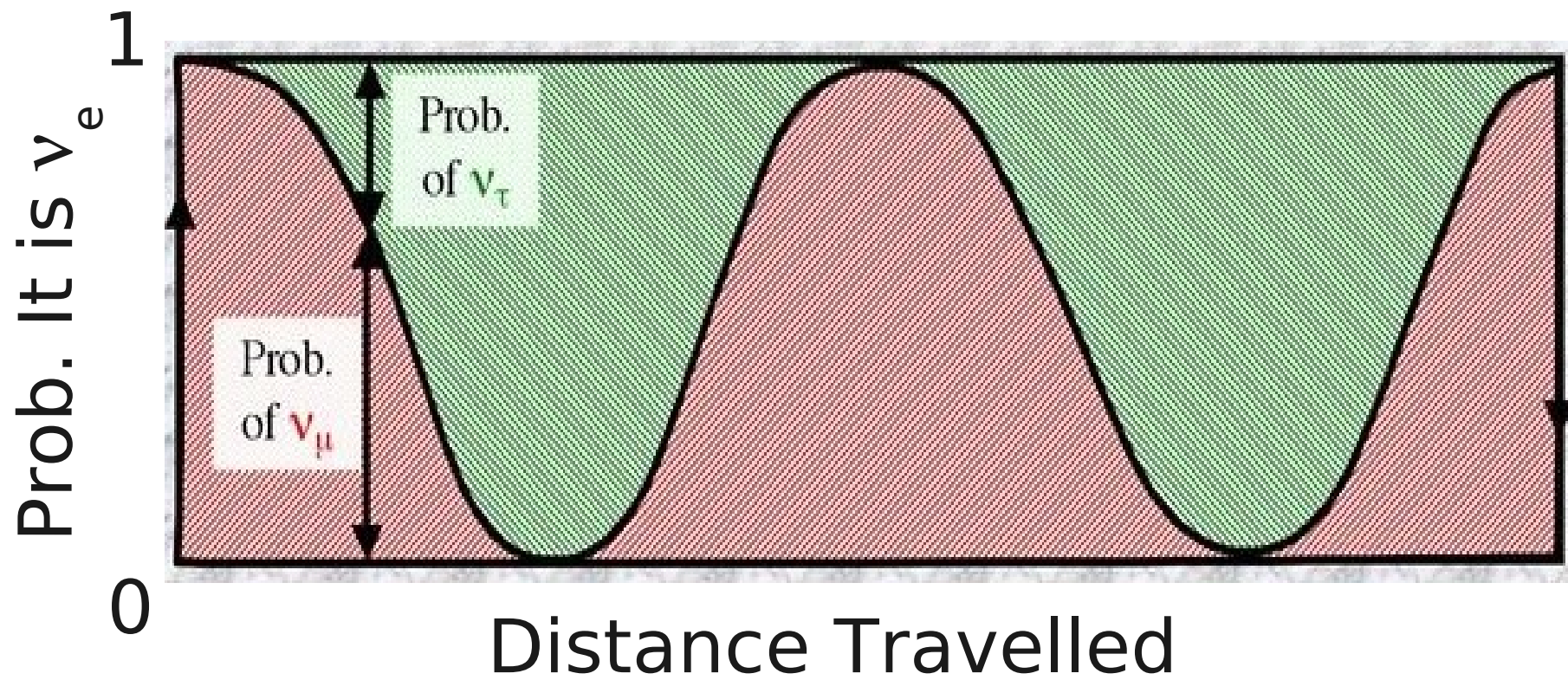
How do we use neutrinos to study CP violation?

Neutrino Oscillations

THE discovery in neutrinos of the last 20 years



A typical neutrino experiment



T2K Experiment



Image © 2008 TerraMetrics
Image NASA
Image © 2008 Digital Earth Technology

©2007 Google™

The Master Plan

Measure oscillations of neutrinos

Measure oscillations of anti-neutrinos

Difference between these two numbers indicates a difference between the physics of neutrino and anti-neutrinos

Can help show that leptogenesis works

Experiment is starting now....

But we still don't know much about the neutrino itself!

- What is the mass of a neutrino?
- 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?

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 & other 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

How do we exist?

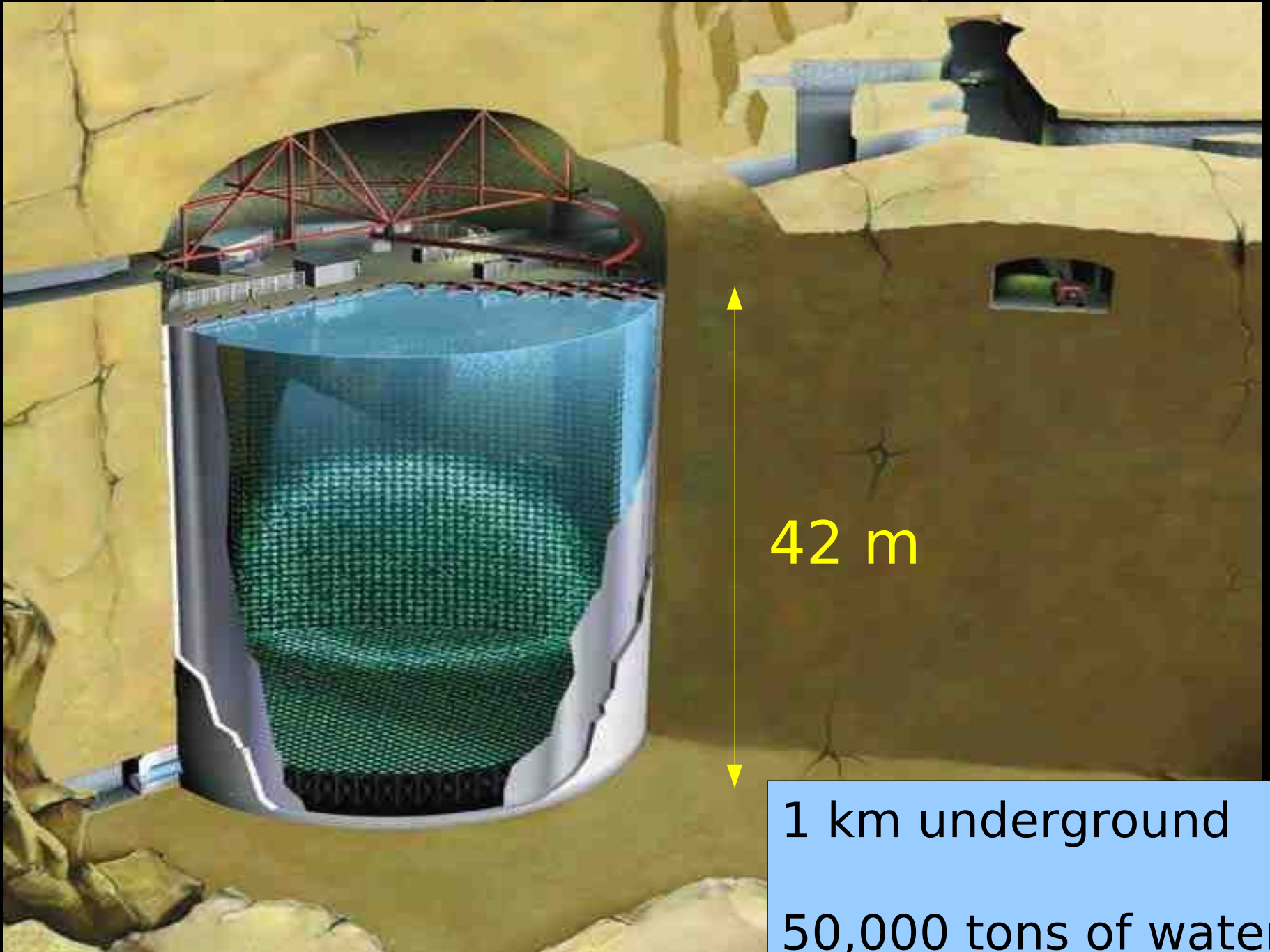
We don't know (yet) but we're working on it

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

JPARC Facility in Japan



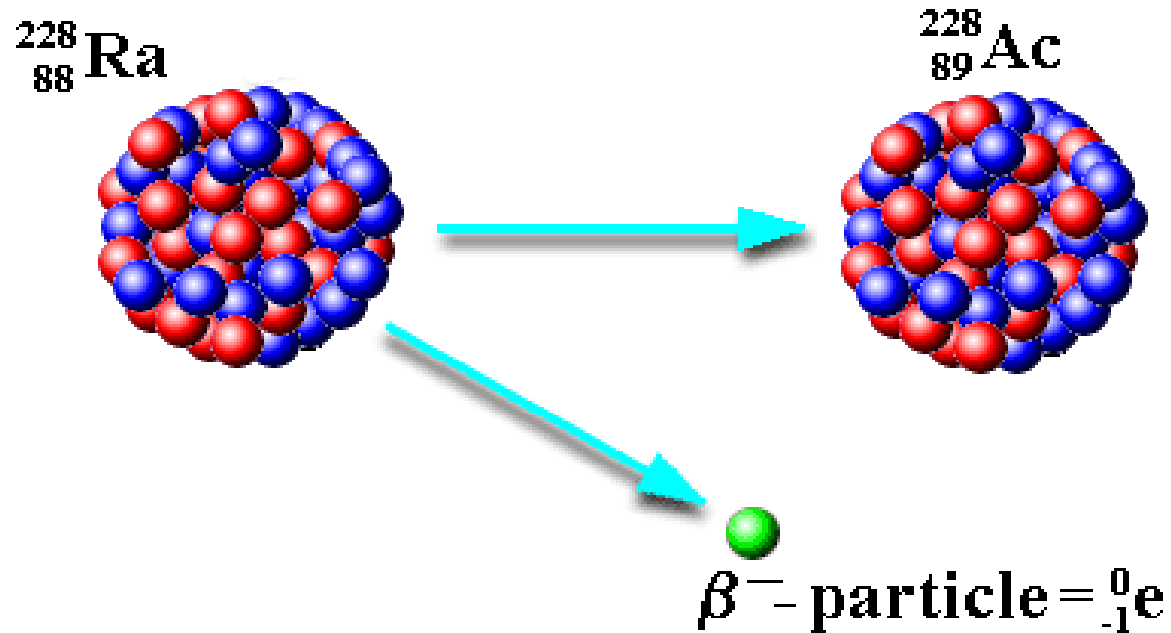
Super-Kamiokande



The image features a dark, star-filled night sky as a background. The stars are of various colors, including blue, orange, and white, and are scattered across the entire frame. In the center, the word "CRISIS" is written in large, bold, yellow capital letters. The letters are slightly transparent, allowing the stars behind them to be visible. The overall composition is simple and visually striking due to the contrast between the bright yellow text and the dark, multi-colored starry background.

CRISIS

beta minus decay



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

Wolfgang Pauli



“Desperate remedy....”

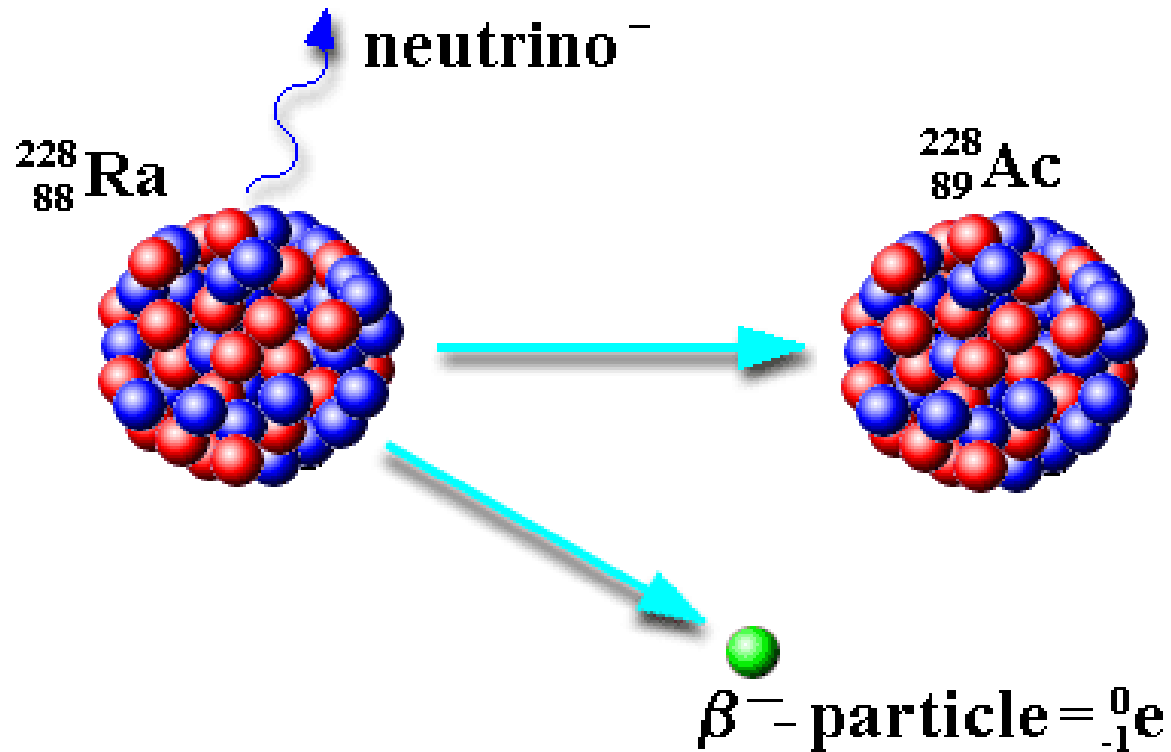
“I do not dare publish this idea....”

“I admit my way out may look improbable....”

“Weigh it and pass sentence....”

“You tell them. I'm off to a party”

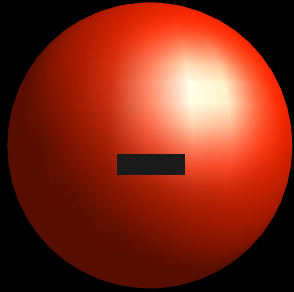
beta minus decay



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

What are neutrinos?

Electron, e



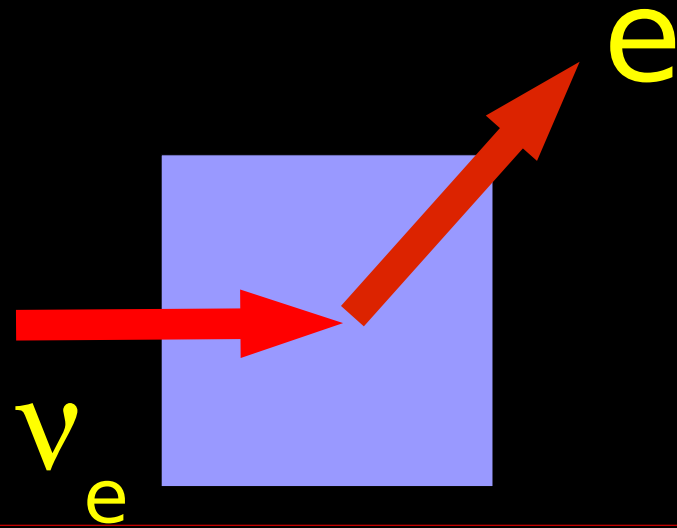
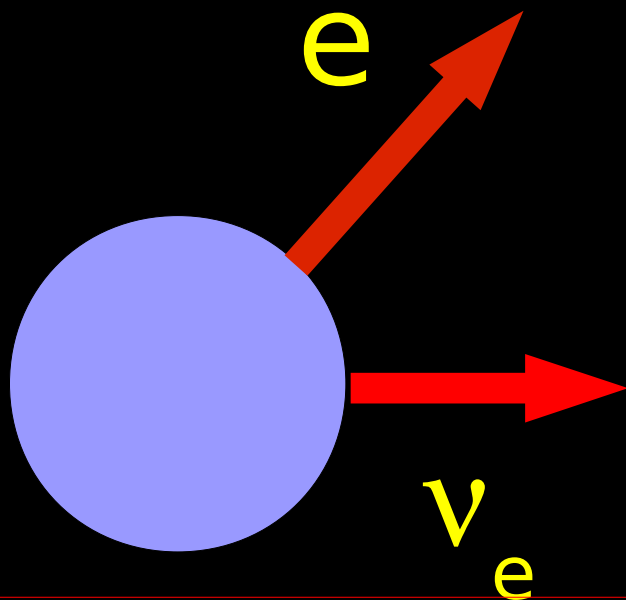
Tiny mass (1)

Electron Neutrino, ν_e



0

Very tiny mass
(<0.00000001)



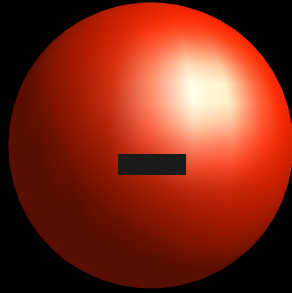
In experiments neutrinos are **NEVER** seen.

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.

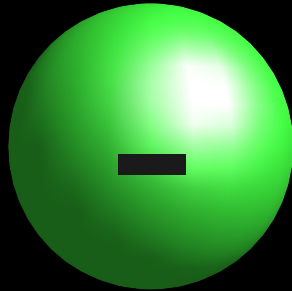


Electron, e
mass (1)



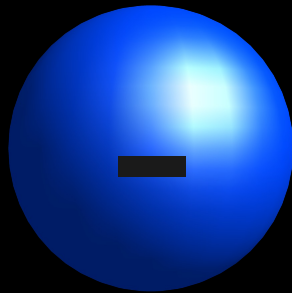
Electron
Neutrino, ν_e

Muon, μ
mass (200)



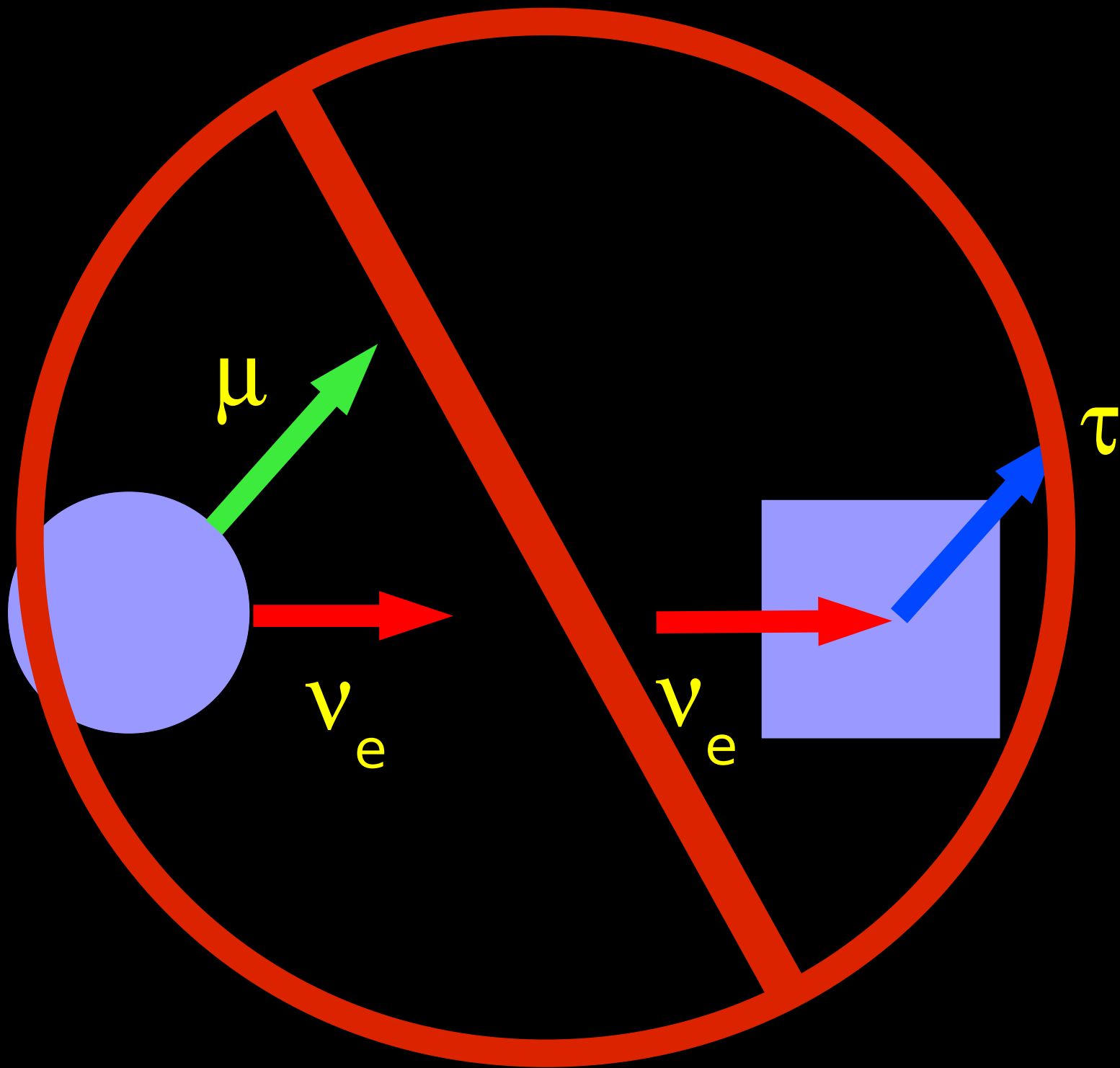
Muon
Neutrino, ν_μ

Tau, τ
mass (3500)



Tau
Neutrino, ν_τ

3 Lepton Types



Positron, e^+
mass (1)



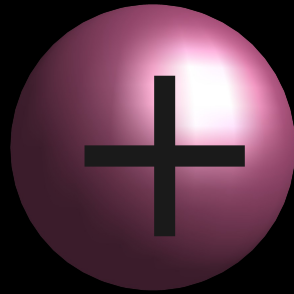
Electron
Antineutrino, $\bar{\nu}_e$

Muon, μ^+
mass (200)



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

Tau, τ^+
mass (3500)



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

3 Antiparticles

Where do they come
from?

Everywhere!

From the Big Bang



Artist's conception

From the Big Bang

An artist's conception of the Big Bang, showing a vast field of particles and energy expanding outwards from a central point. The background is dark, with numerous bright, multi-colored streaks (purple, blue, white) radiating from the center, creating a sense of intense energy and expansion.

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

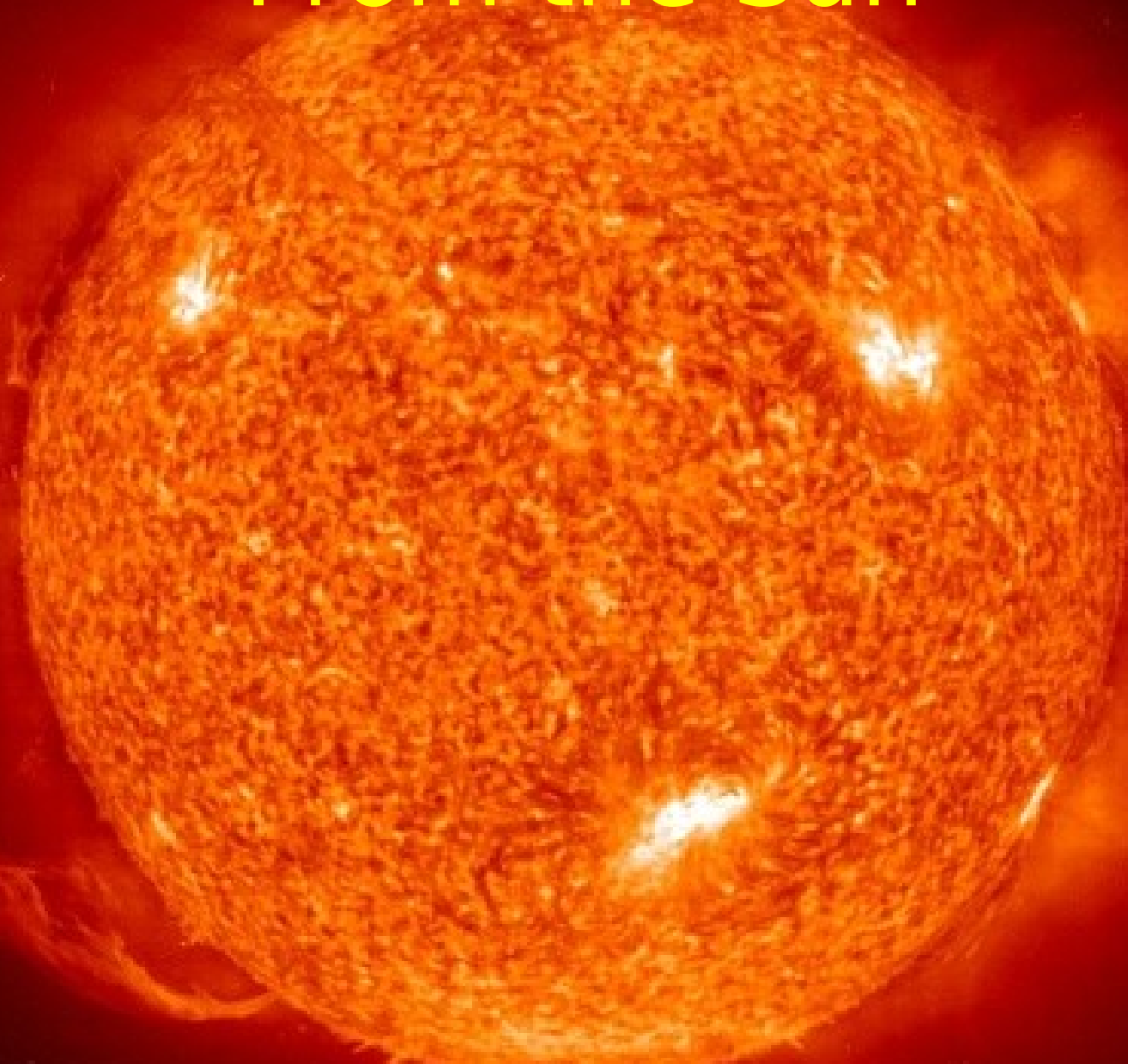
Artist's conception

From Astrophysical Objects

The image is split into two vertical panels. The left panel shows a dense field of stars with a prominent bright yellow star in the lower-left quadrant, exhibiting a four-pointed lens flare. The right panel shows a similar field of stars, but with a white arrow pointing to a specific, slightly dimmer star in the lower-right quadrant.

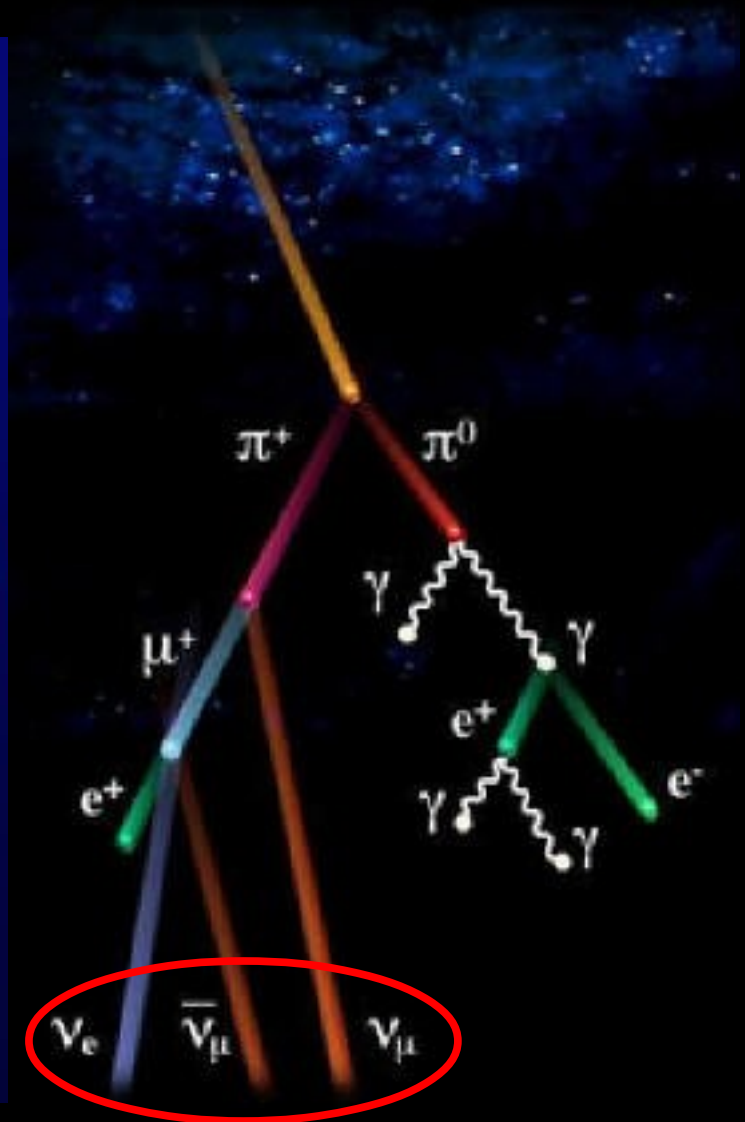
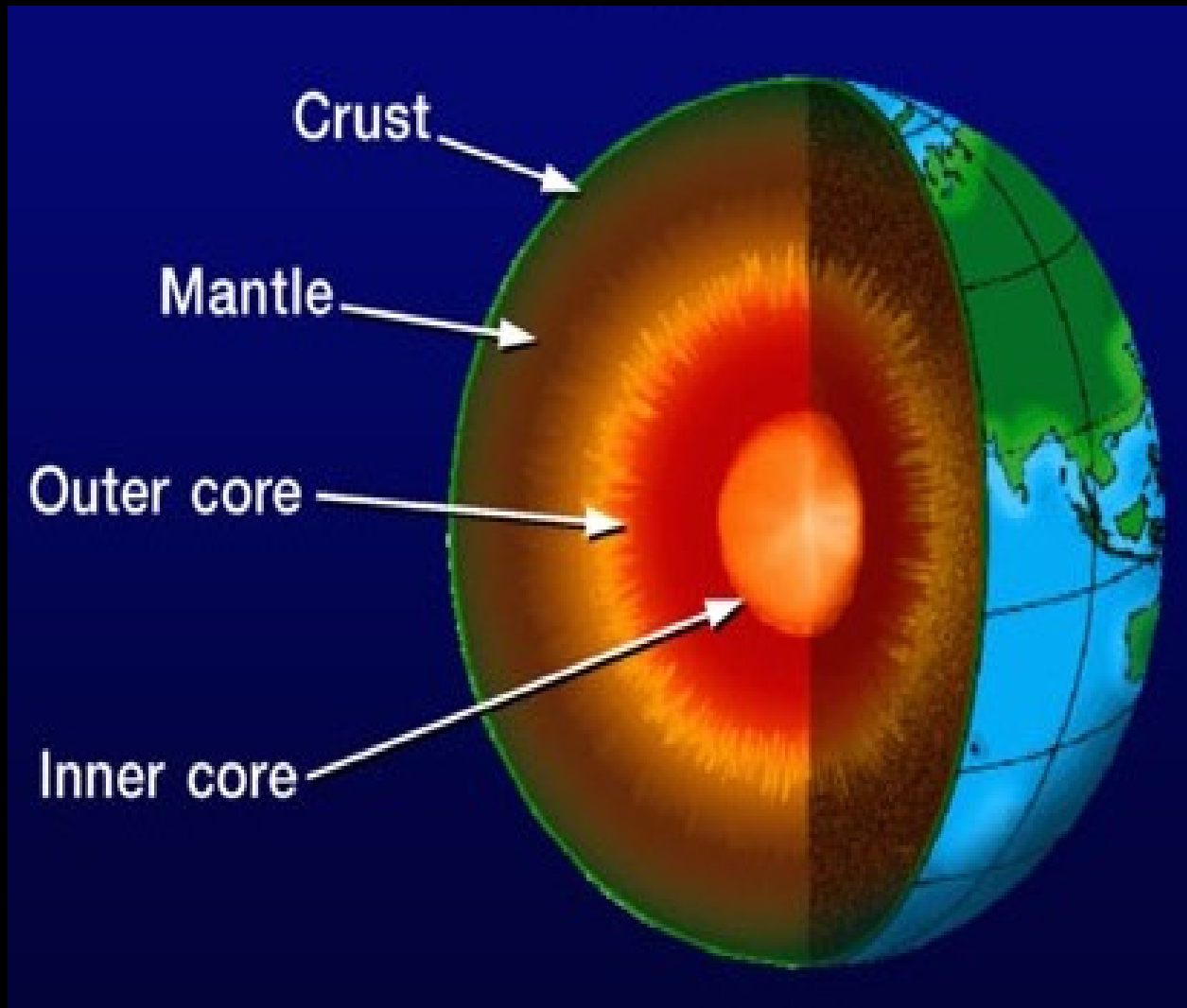
Supernovae created the heavy elements (us) and neutrinos may be responsible for the star exploding.

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."

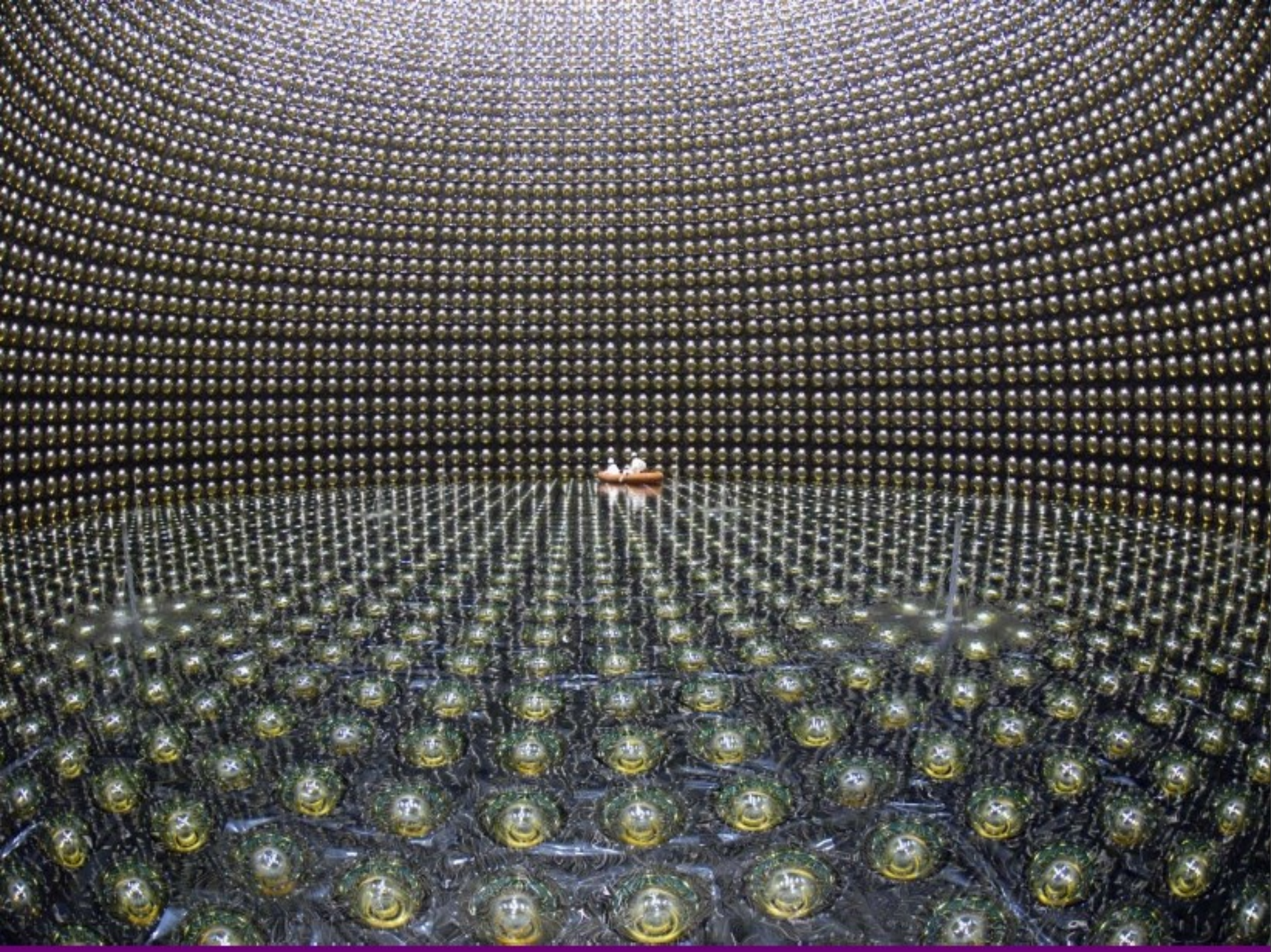
Douglas Adams



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

Super-Kamiokande



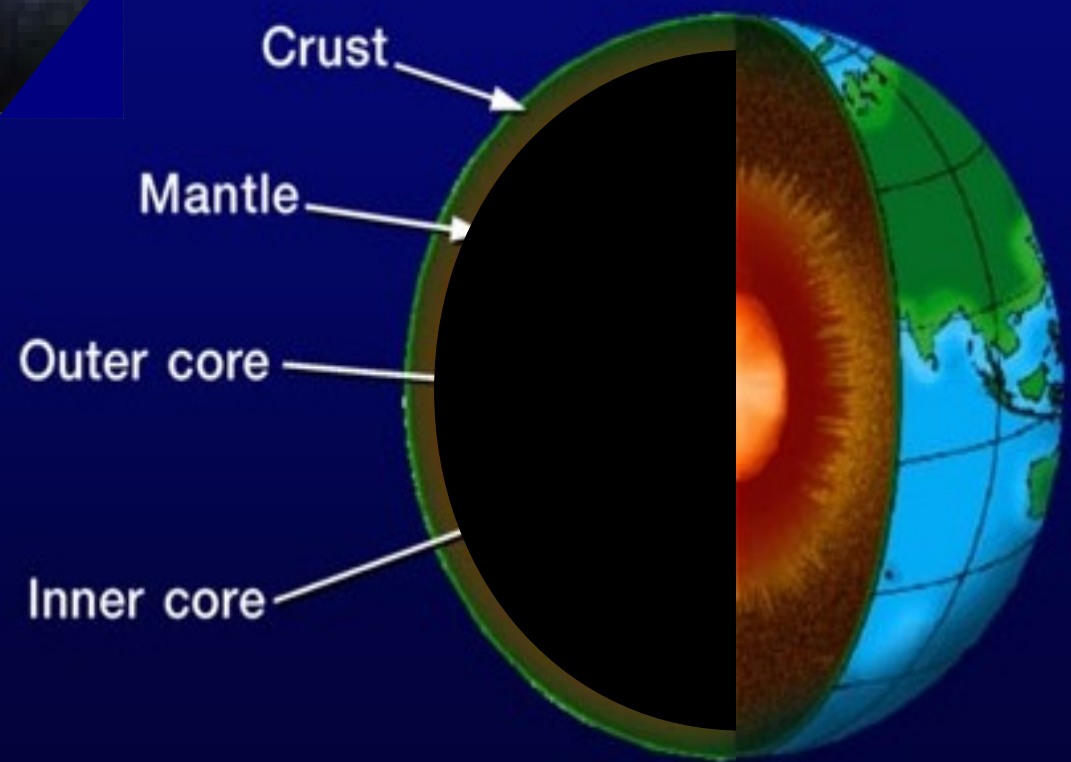


Why do we study
them?



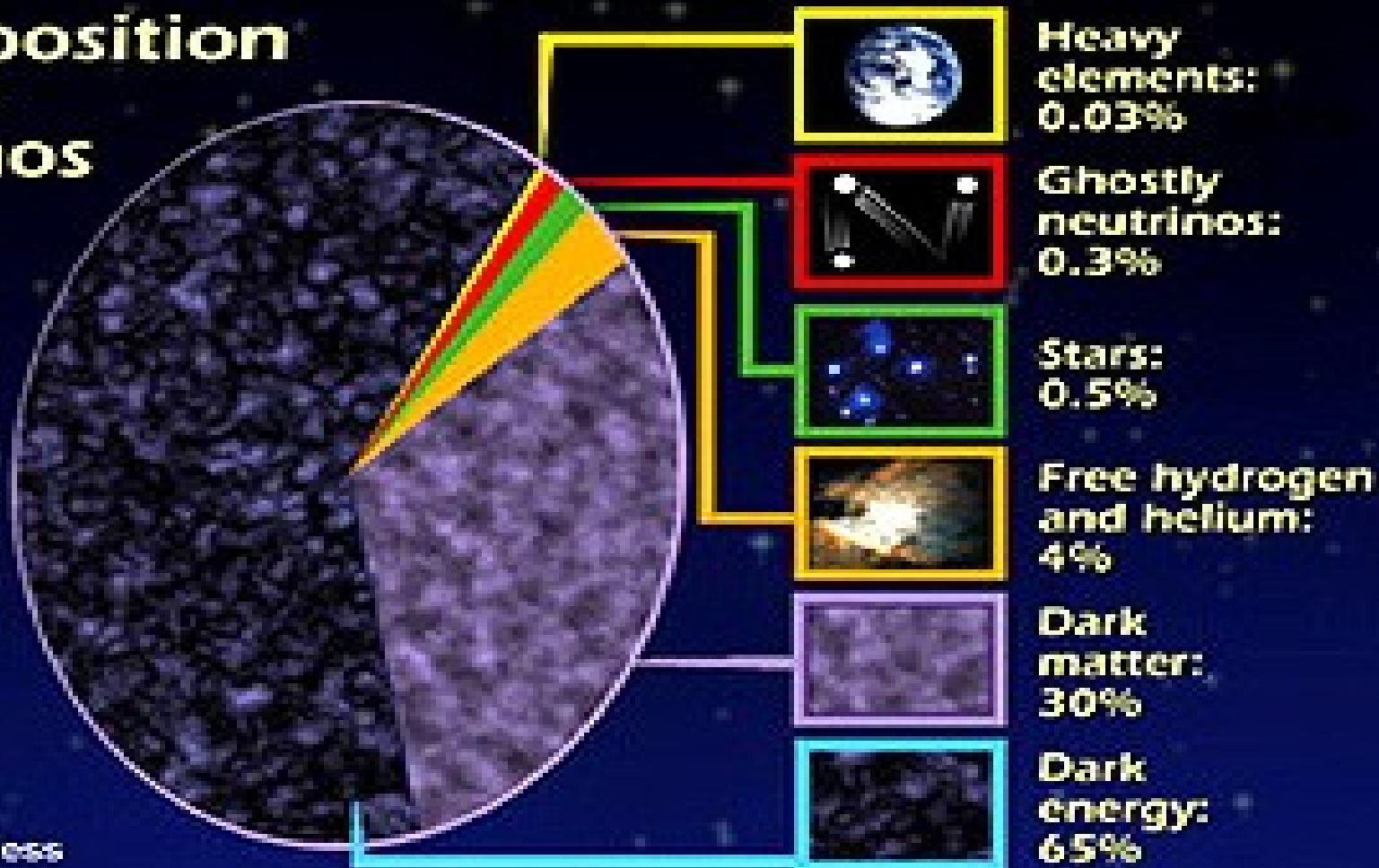
As Probes

Astrophysics
Geophysics
Cosmology
Particle Physics



Amount of matter in Universe

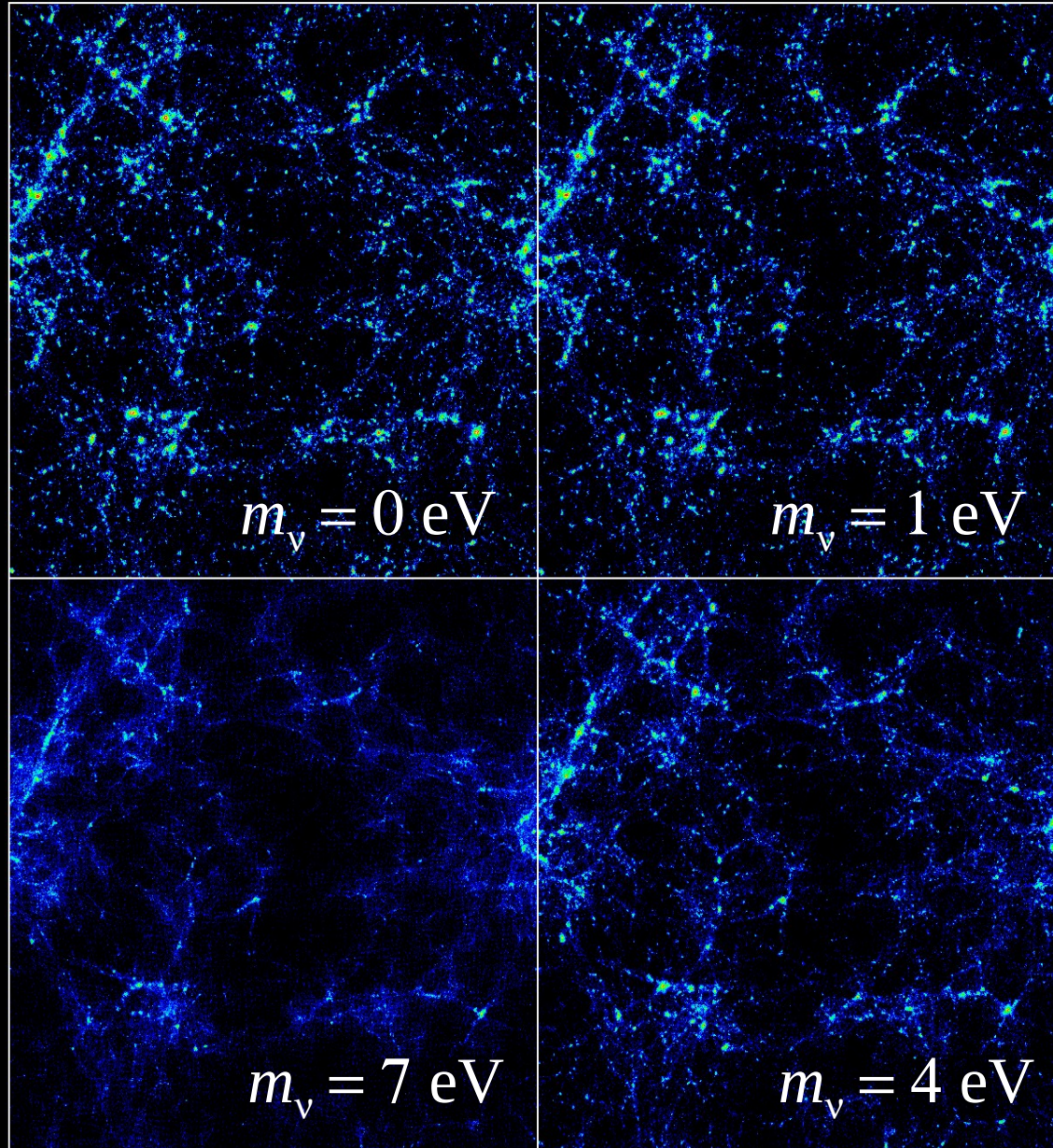
Composition of the Cosmos



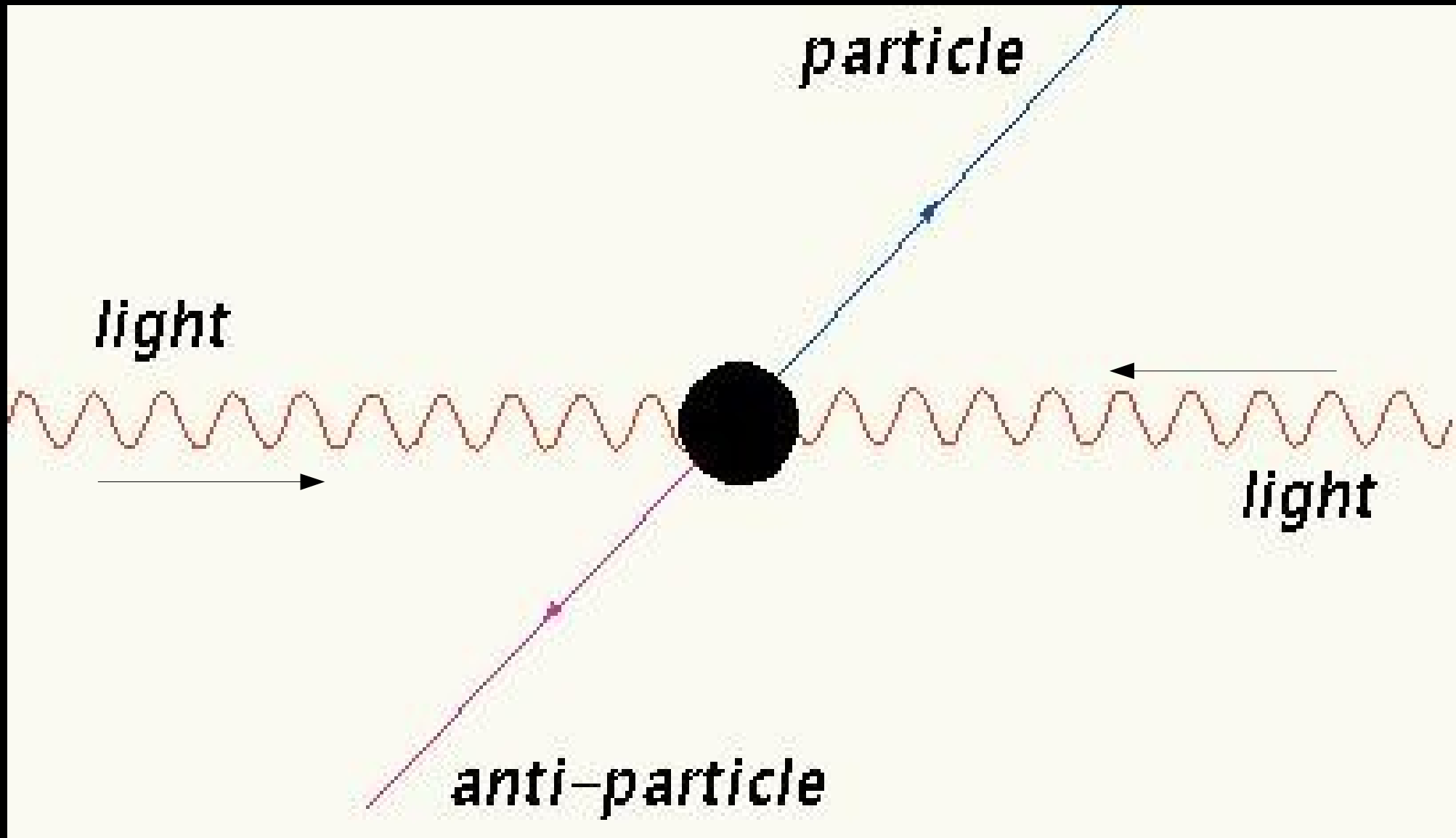
NASA/JPL, Riess

Second most common (known) particle in the universe

Universal Structure



Why is there more matter than antimatter?



Why is there more matter than antimatter?

10,000,000,001

Matter

10,000,000,000

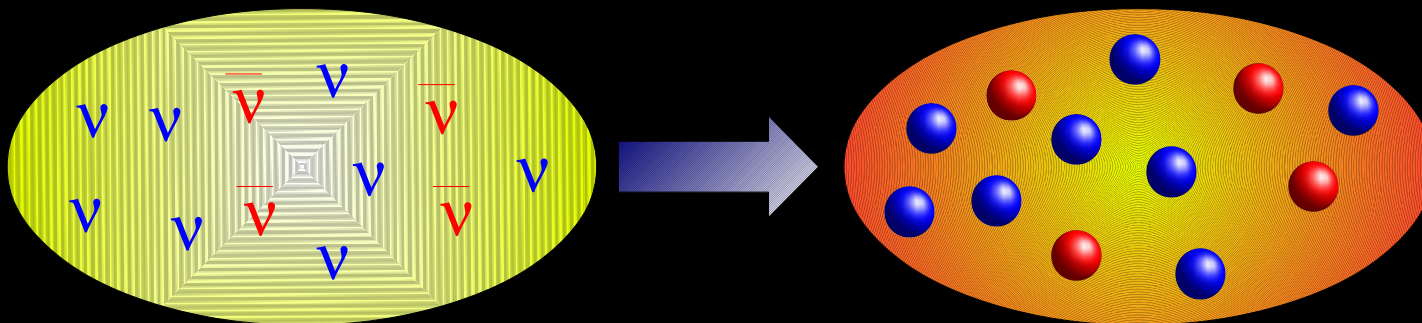
Antimatter

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.

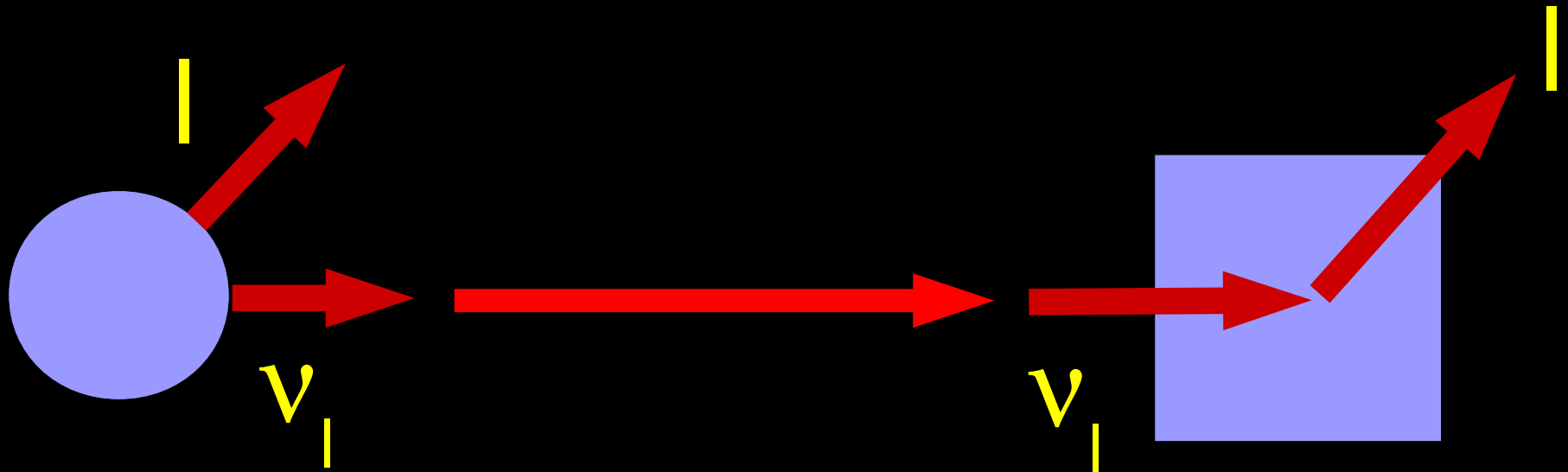


"Leptogenesis"

How to study this...?

Neutrino Oscillations

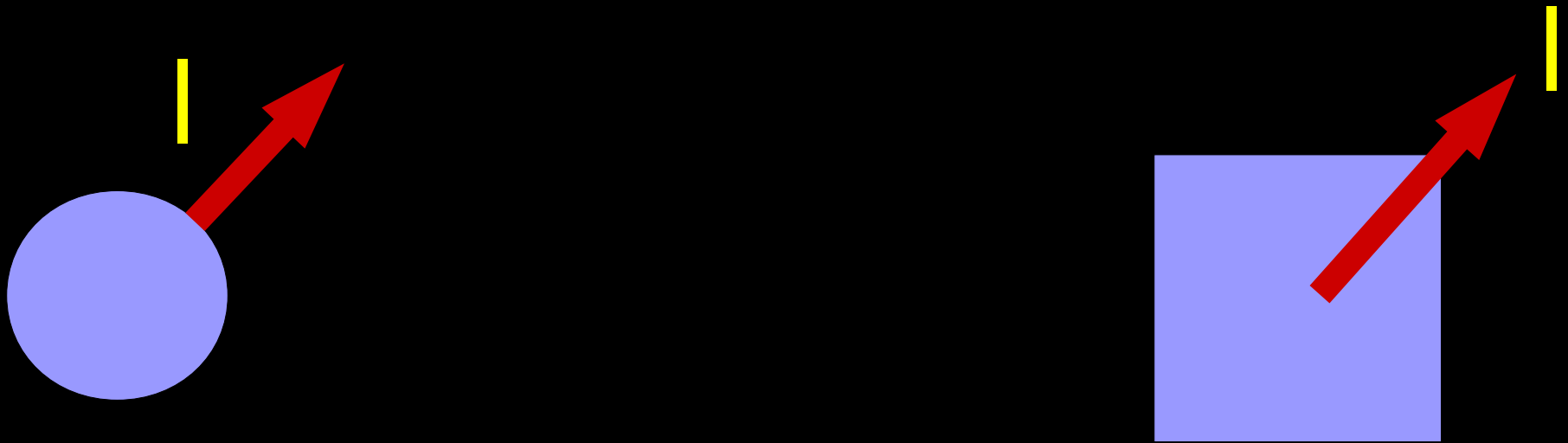
THE discovery in neutrinos of the last 20 years



A typical neutrino experiment

Neutrino Oscillations

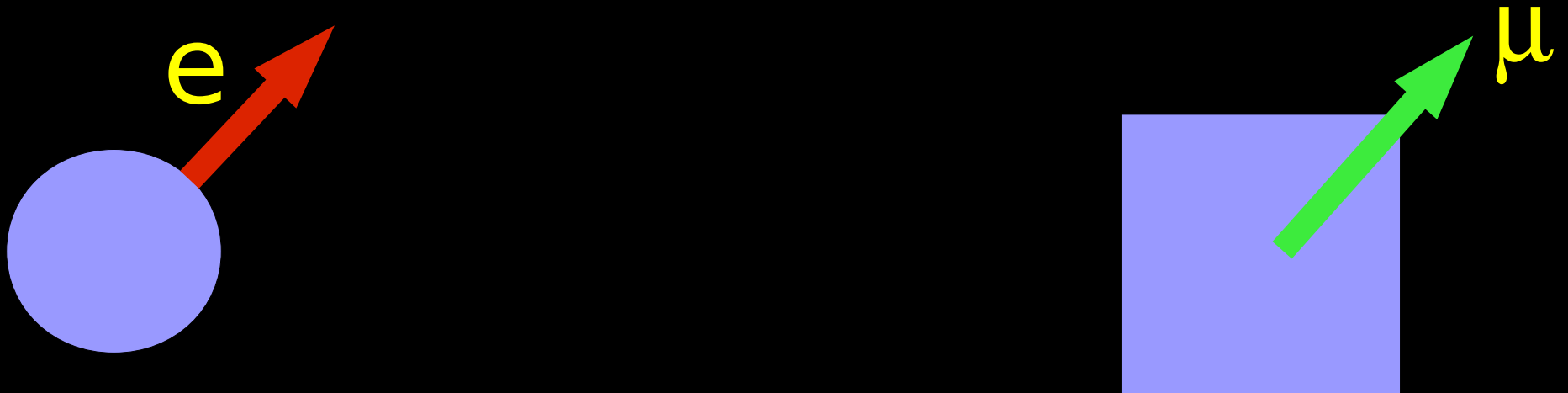
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A typical neutrino experiment

Neutrino Oscillations

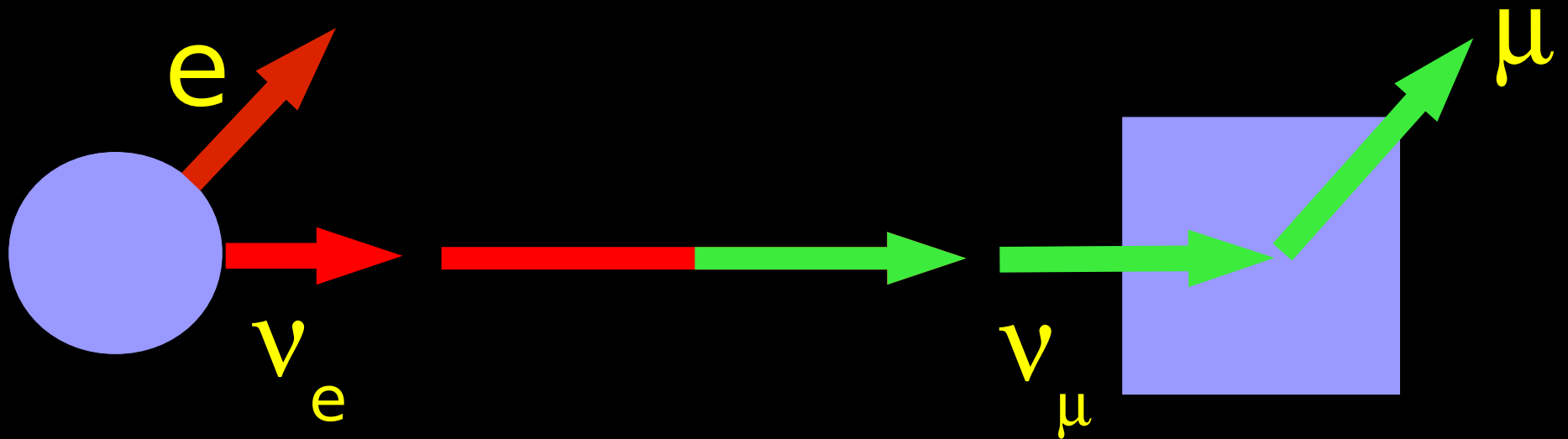
THE discovery in neutrinos of the last 20 years



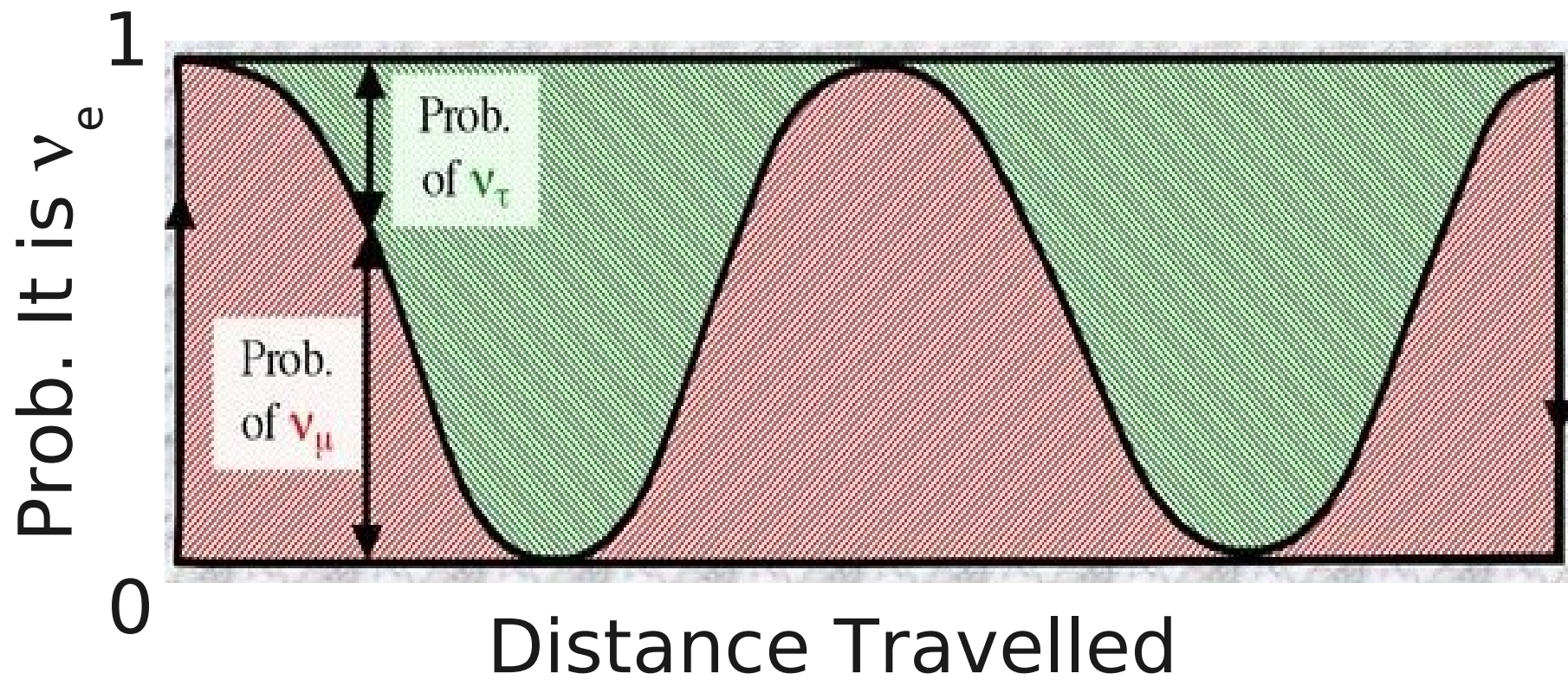
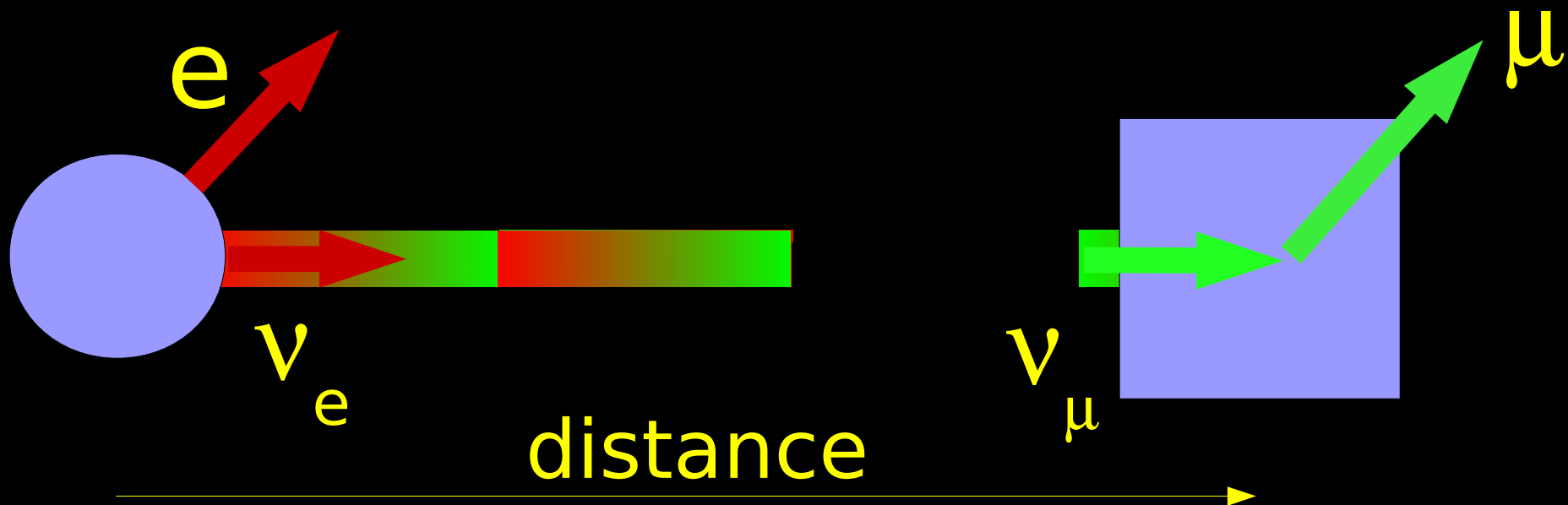
A typical neutrino experiment

Neutrino Oscillations

THE discovery in neutrinos of the last 20 years



Neutrinos change flavour between source and detector!



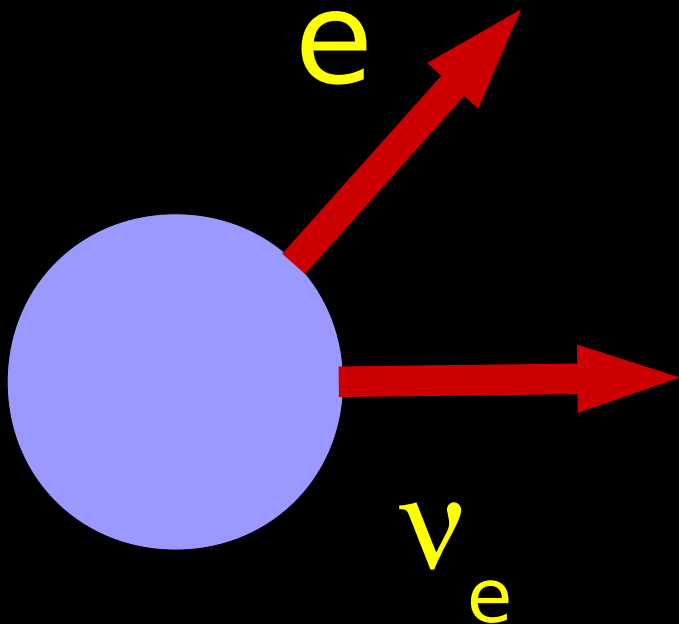
What the....?

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

What the....?

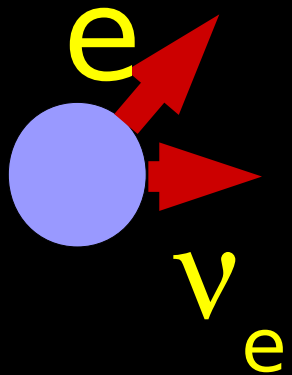
Q. How can a ν_e spontaneously turn into a ν_μ ?

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



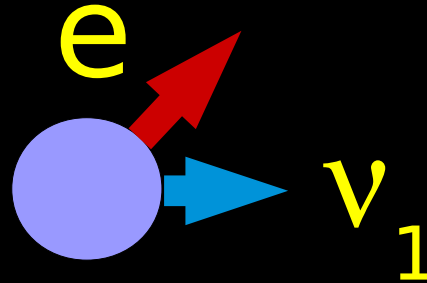
$\nu_e \equiv$ "that thing which was always produced/detected with an electron"

Quantum Stuff

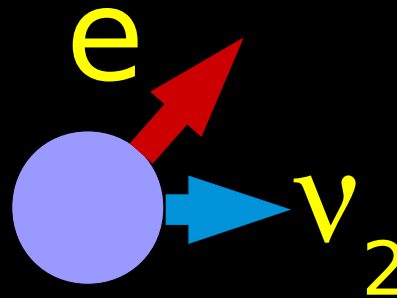


$=$

or

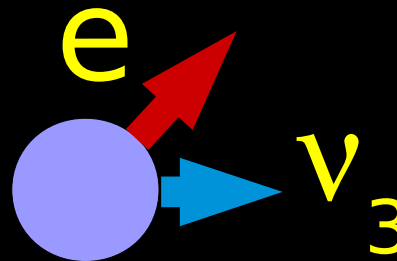


60%

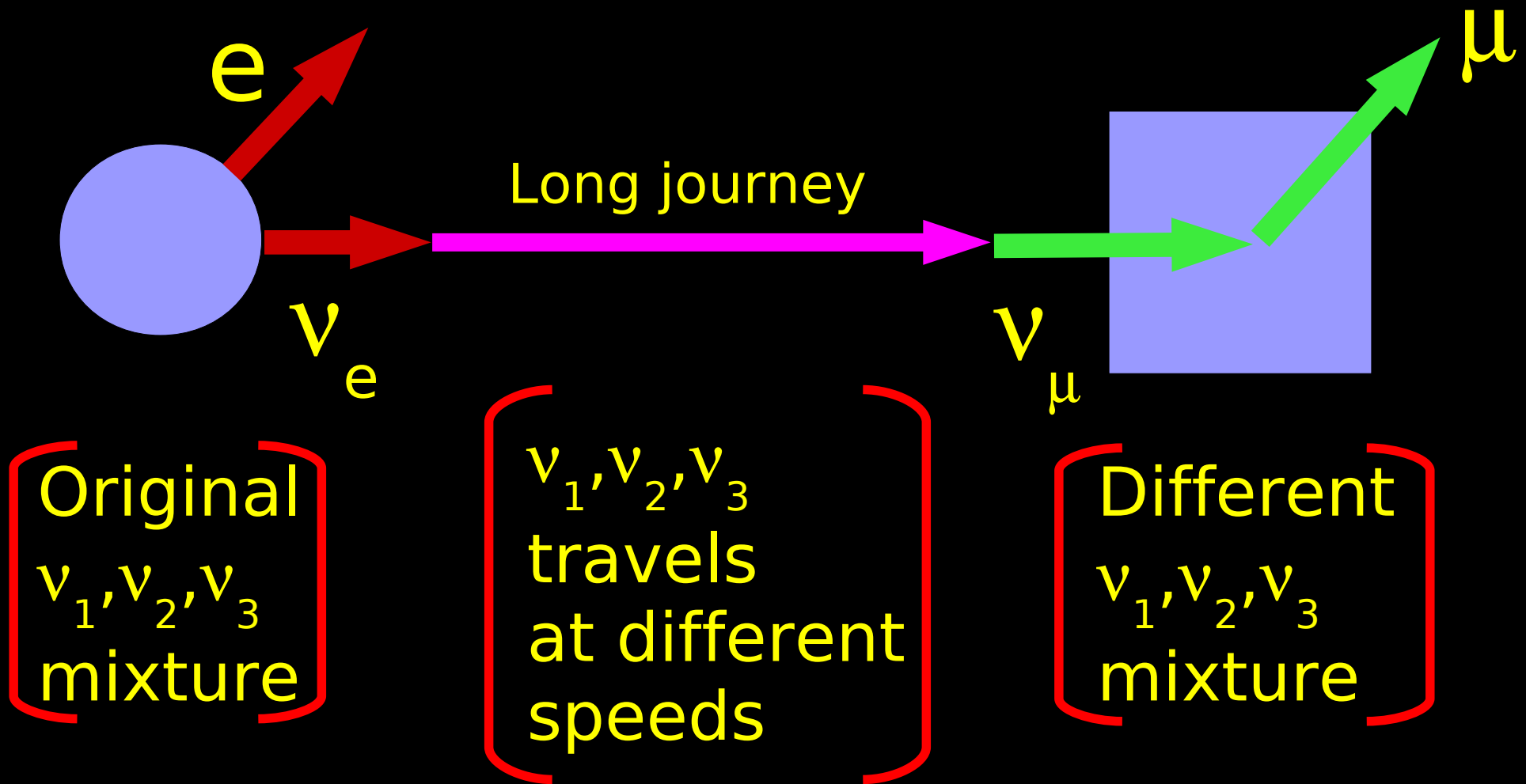


30%

or



10%



- This can only happen if v_1, v_2, v_3 have different masses
- Only gives us differences in masses

T2K



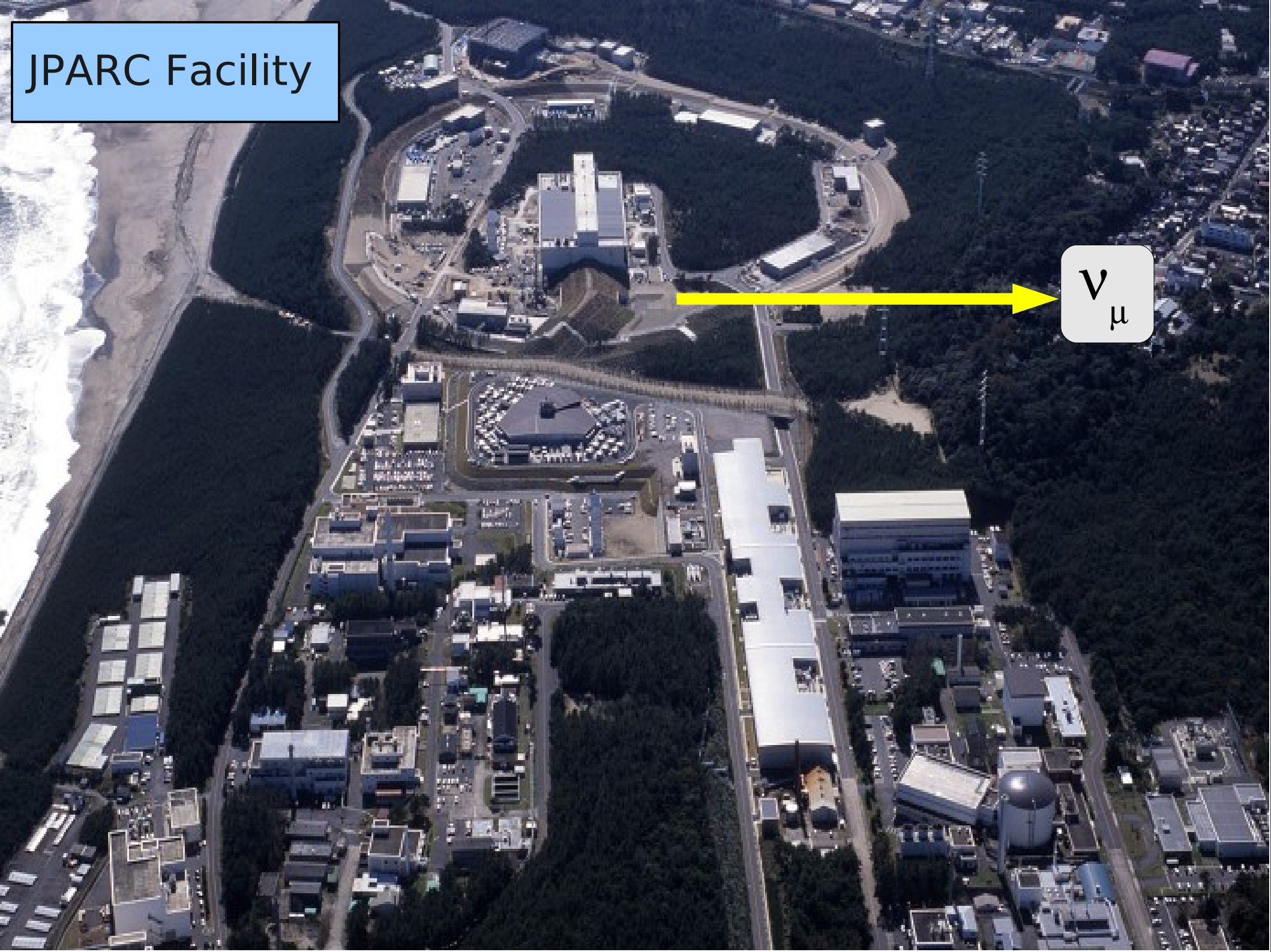
Image © 2008 TerraMetrics
Image NASA
Image © 2008 Digital Earth Technology

©2007 Google™

Things we still don't know

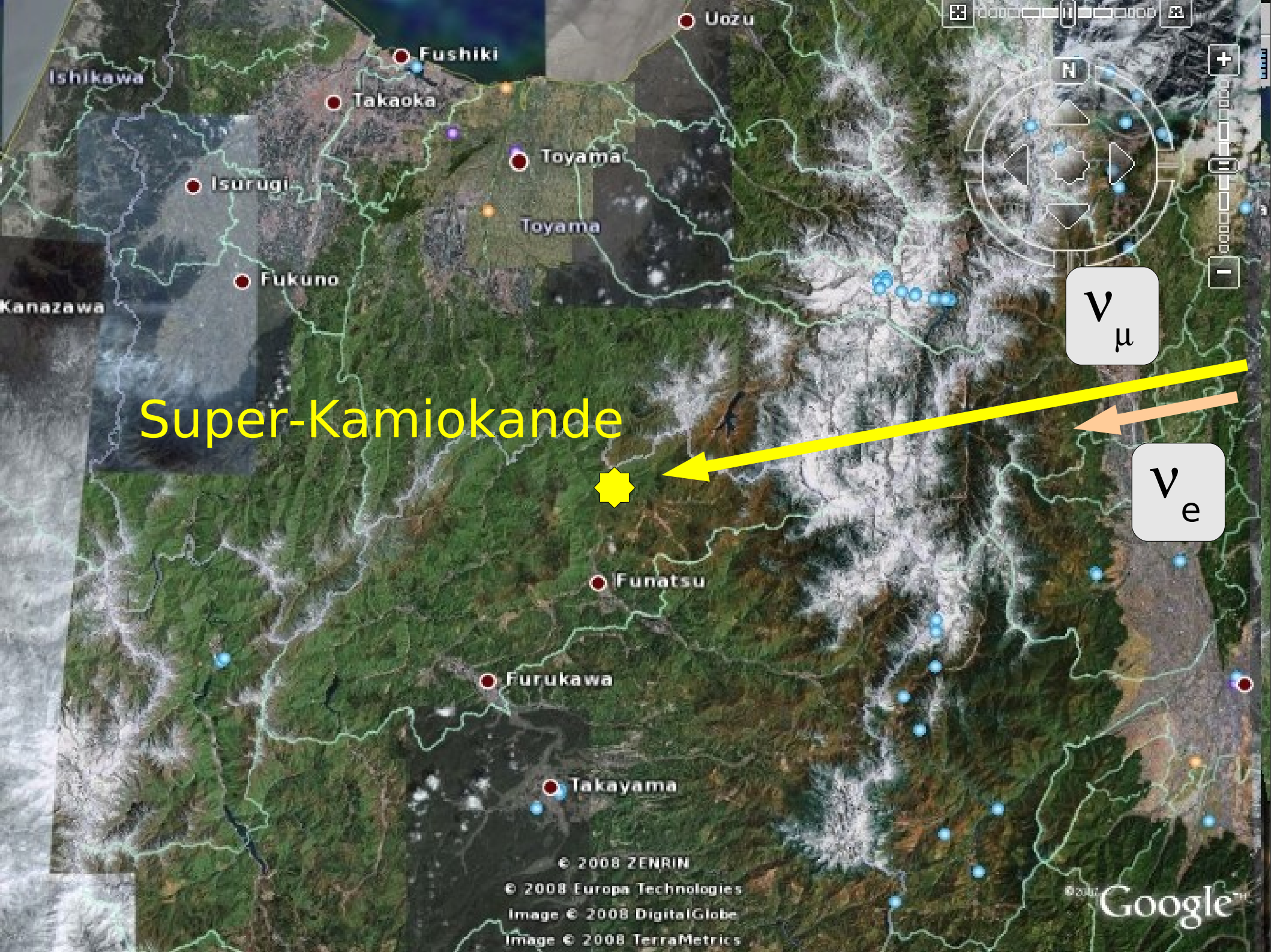
- How much do ν_1, ν_2 and ν_3 weigh?
- Why are they so much lighter than all the other massive particles?
- Are neutrinos the same as antineutrinos?
- Are neutrinos the reason we are here at all?

JPARC Facility



ν_{μ}

An aerial photograph of the JPARC (Japan Proton Accelerator Research Complex) facility. The facility is a large industrial and research complex with numerous buildings, parking lots, and a central circular structure. A yellow arrow originates from the central area of the facility and points towards a white rounded square containing the symbol for muon neutrino, ν_{μ} . The facility is situated near a coastline with waves visible on the left side.



Super-Kamiokande

ν_{μ}

ν_e

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

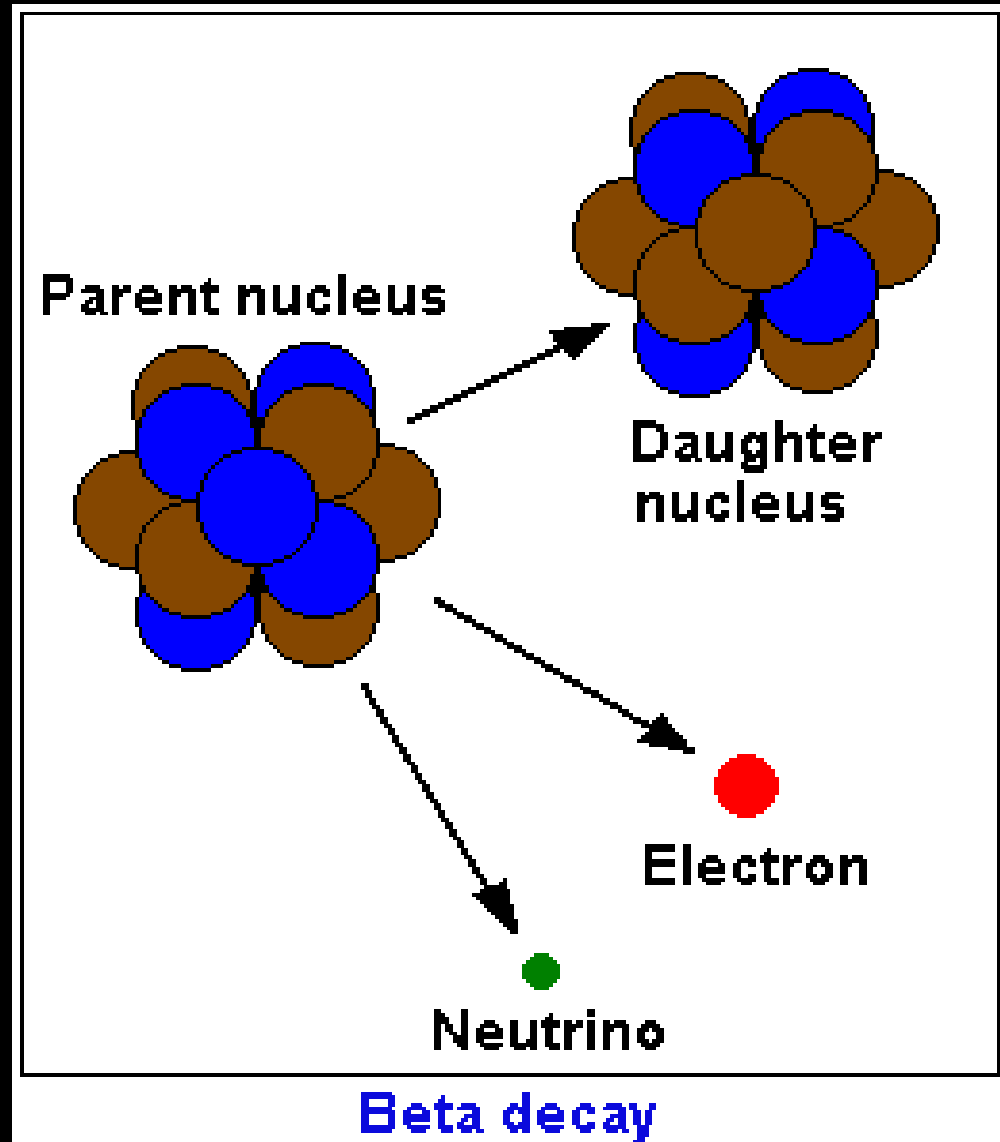
“...these kind of findings have implications that are not limited to the laboratory. They affect the whole of society — not only our economy, but our very view of life, our understanding of our relations with others, and our place in time.”

Bill Clinton

From Radioactive Decay



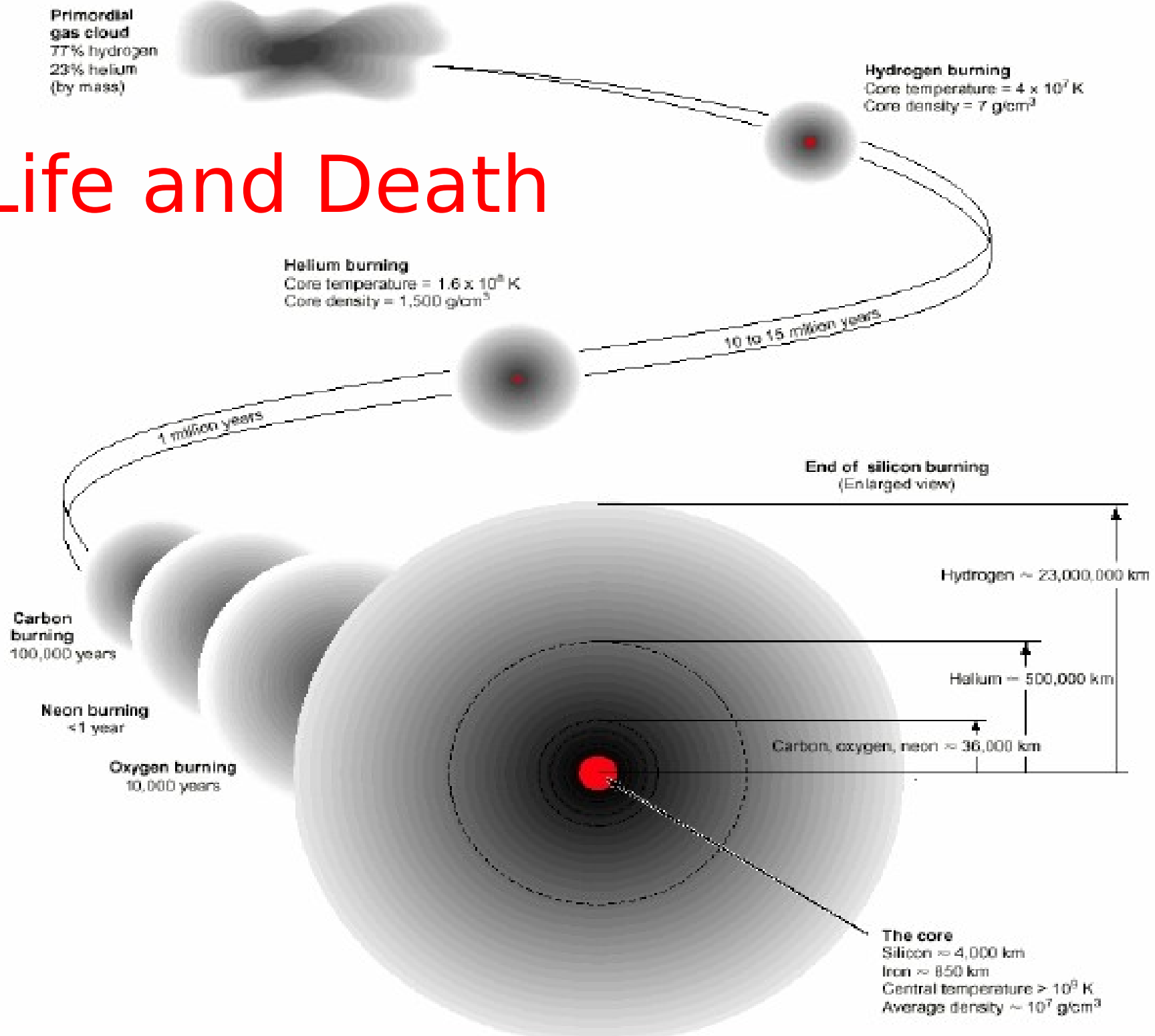
e.g. Decay of unstable nuclides in the core of the earth can tell us about its structure (Geoneutrinos)



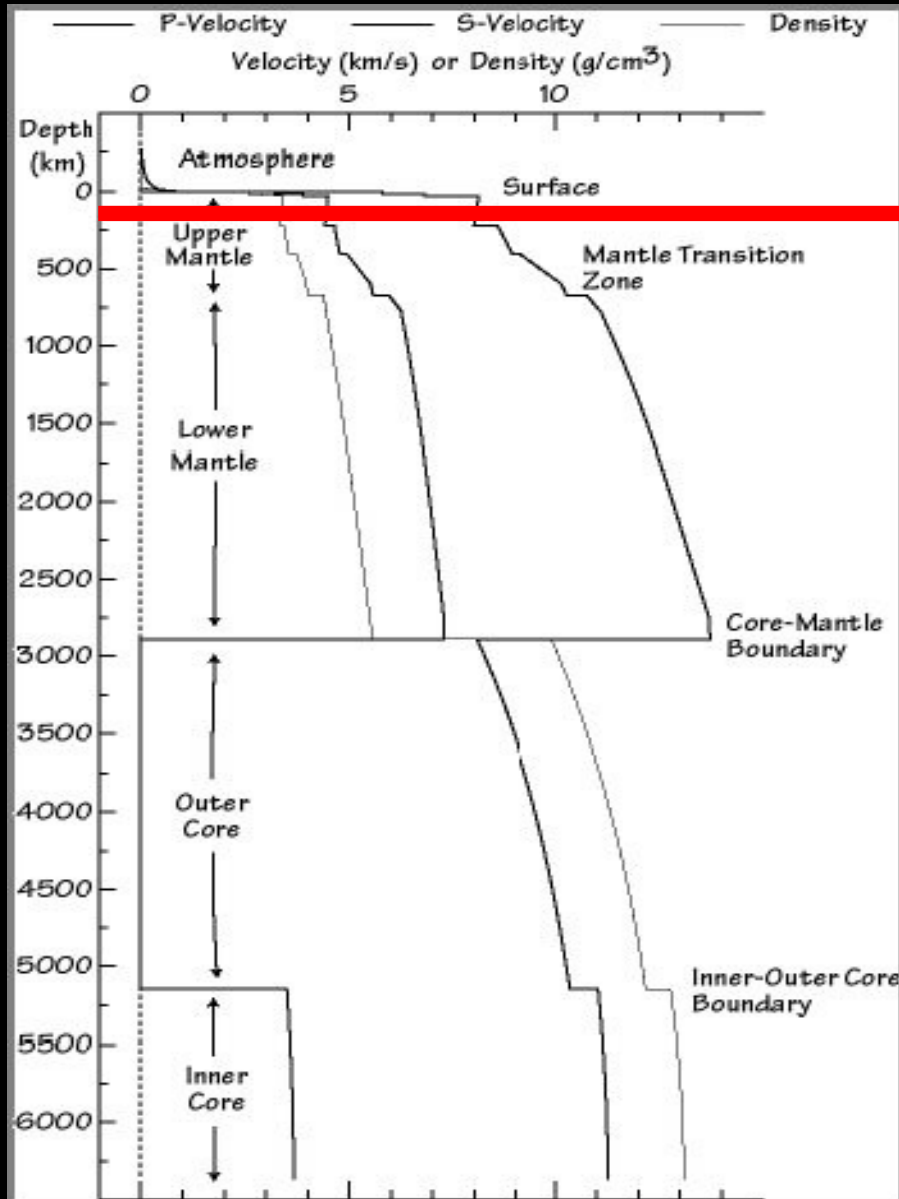


"Quarks. Neutrinos. Mesons. All those damn particles
you can't see. That's what drove me to drink.
But now I can see them!"

Life and Death



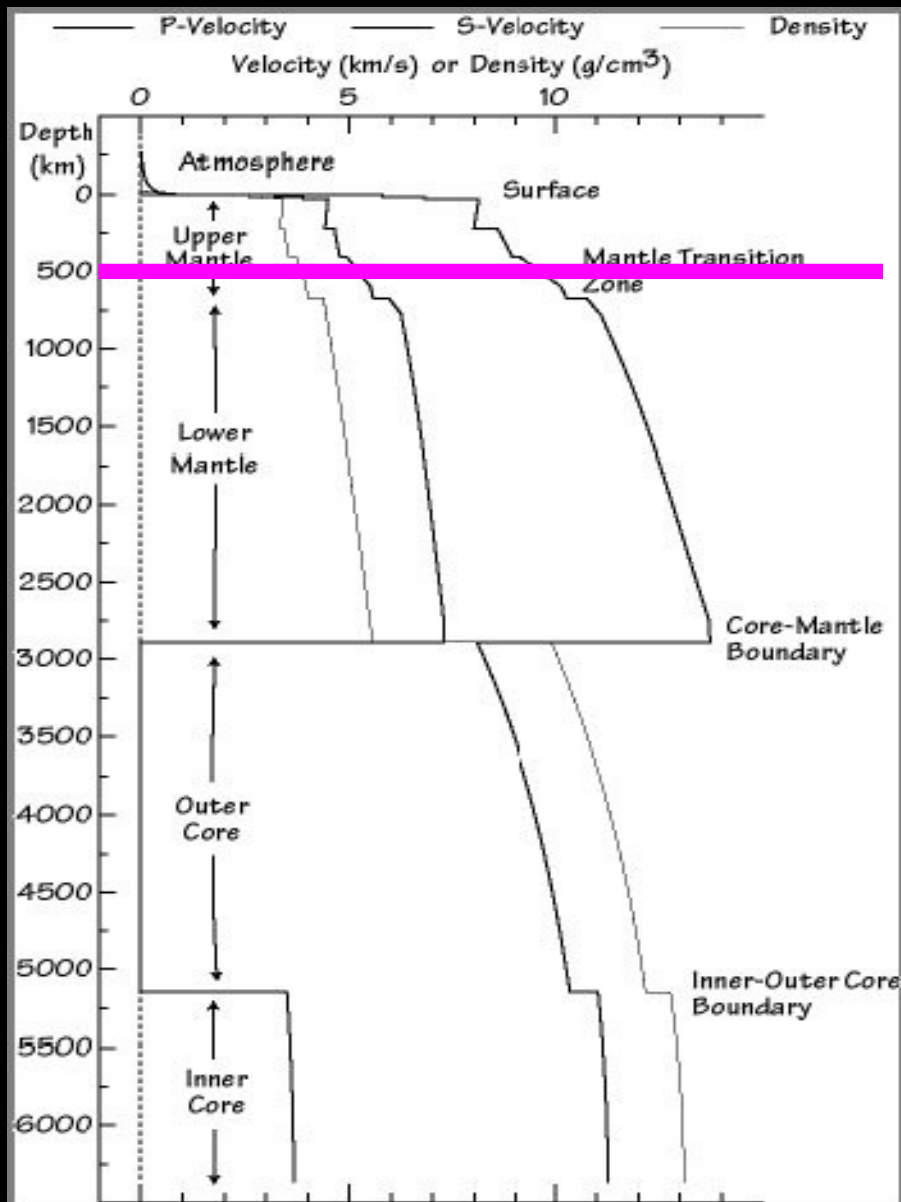
Geoneutrinos



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

A neutrino
experiment in Japan
measured
 25 ± 20 TW

Geoneutrinos



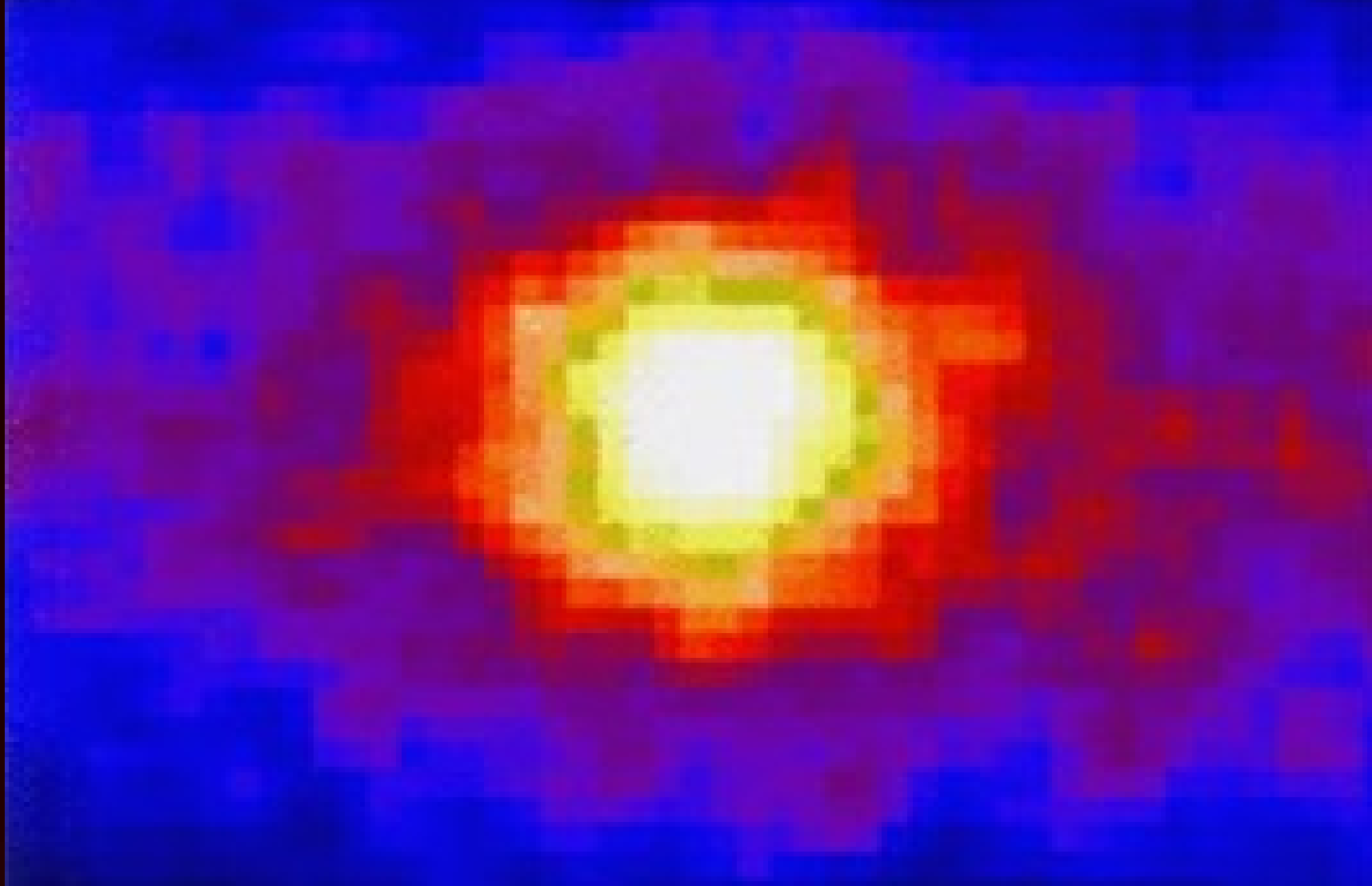
JPARC Facility



TARGET

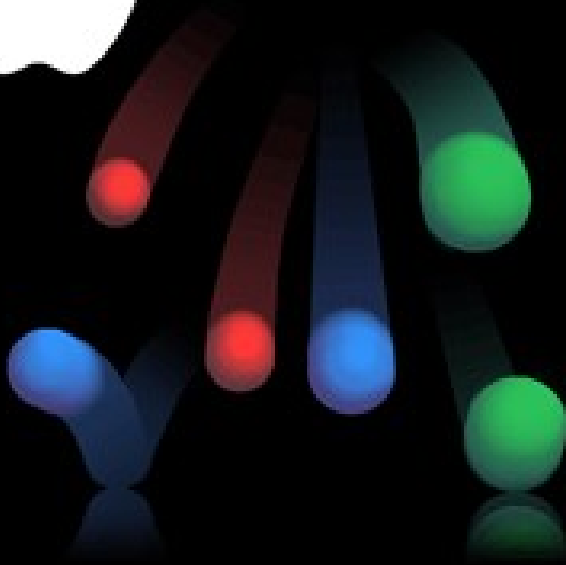


From the Sun





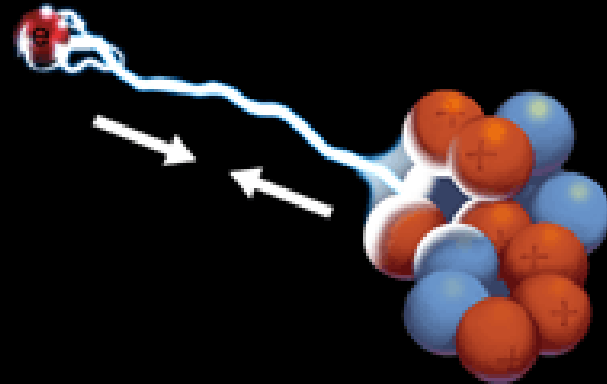
Gravity



e
n
p
v



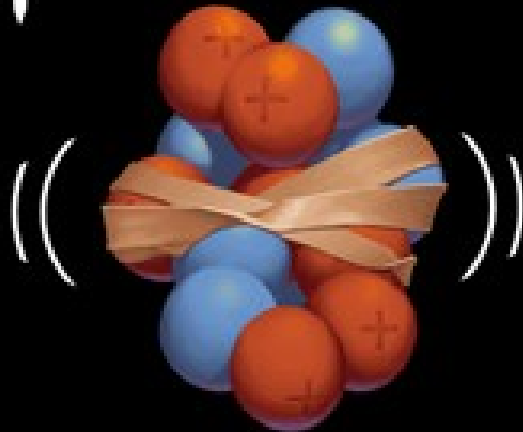
Electro
Magnetic



e
n
p
v



Strong



e
n
p
v



Weak

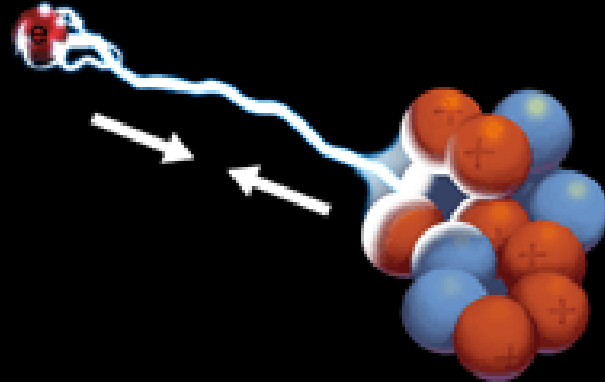


e
n
p
v



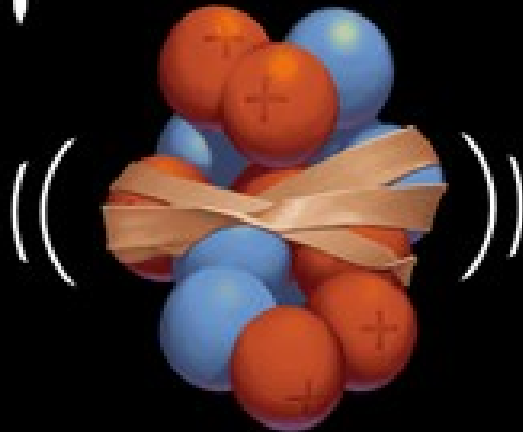
Electro
Magnetic

e
n
p
v



Strong

e
n
p
v

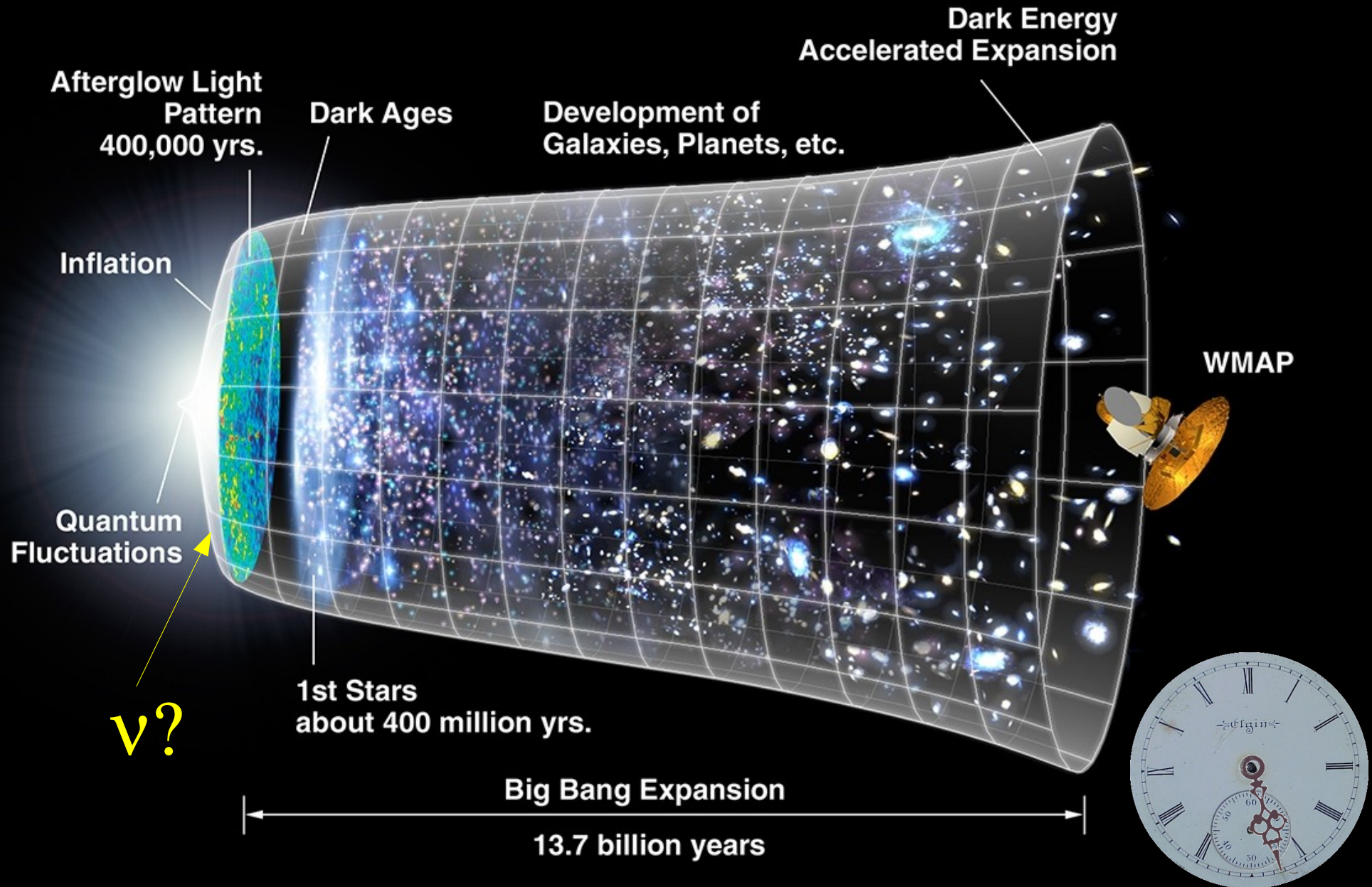


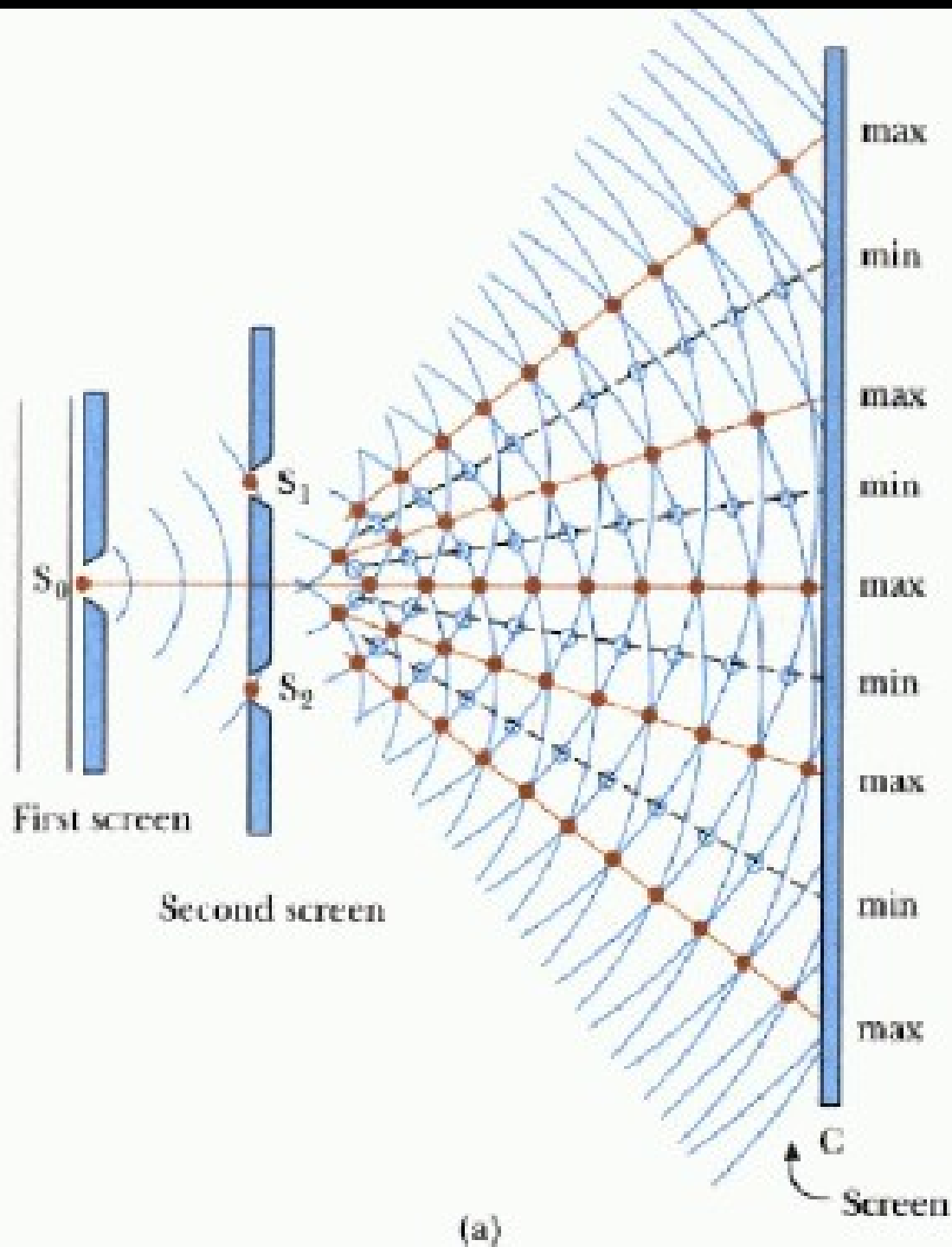
Weak

e
n
p
v

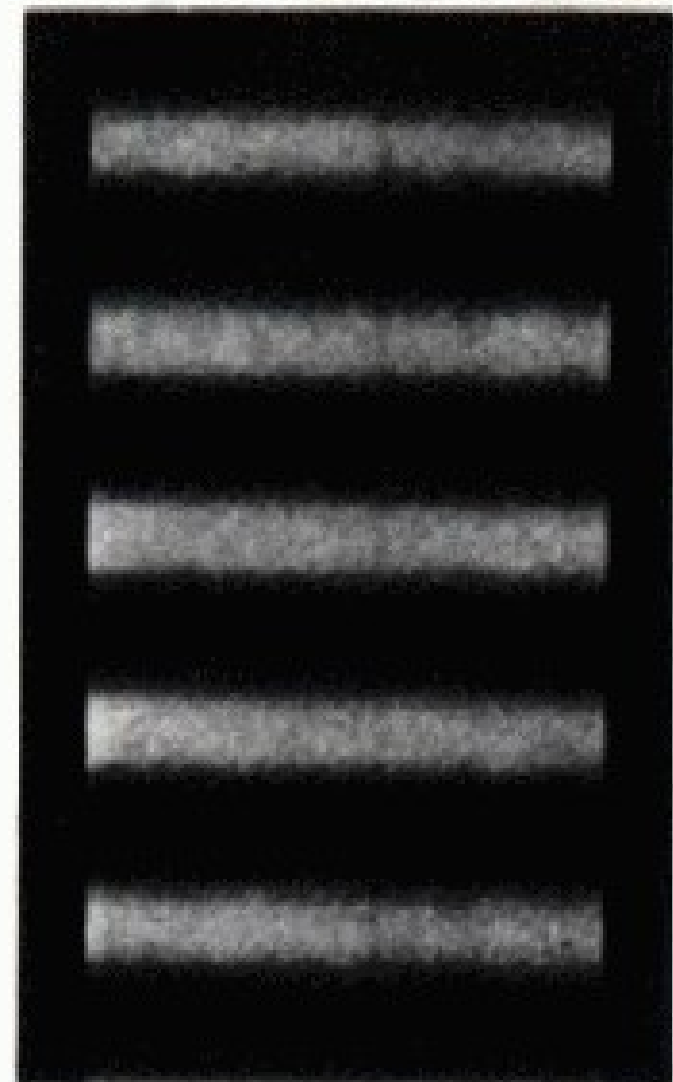


I give you...the Universe

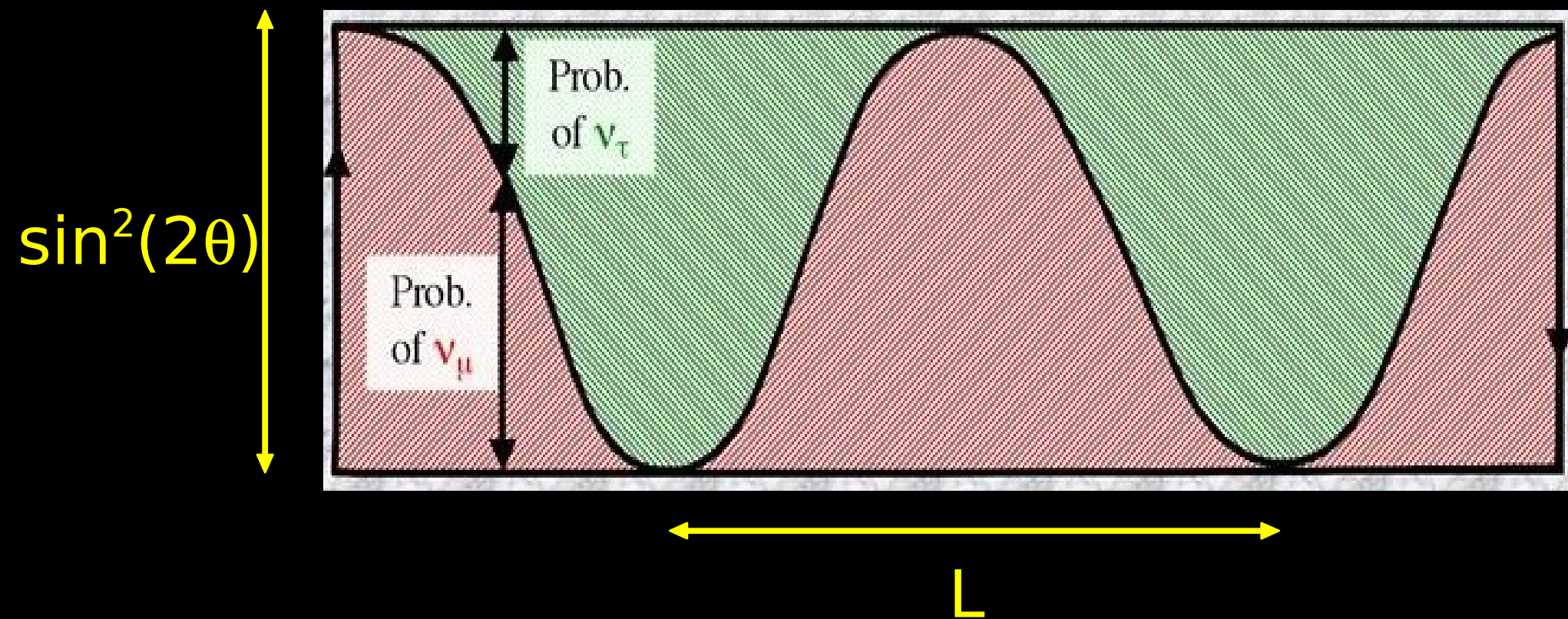




(a)



(b)



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

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

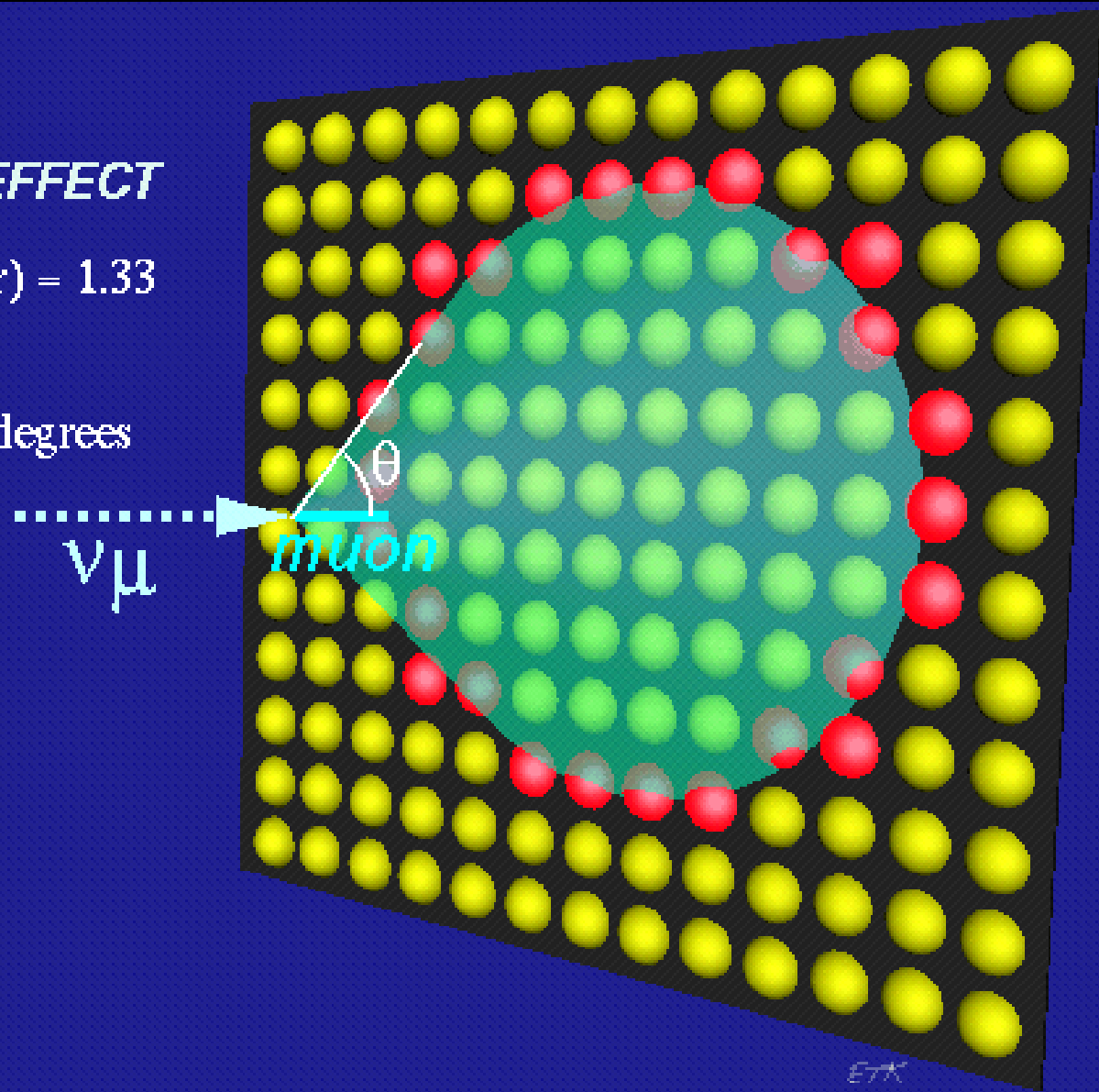
Water Cerenkov

CHERENKOV EFFECT

$$\beta = v/c \quad n(\text{water}) = 1.33$$

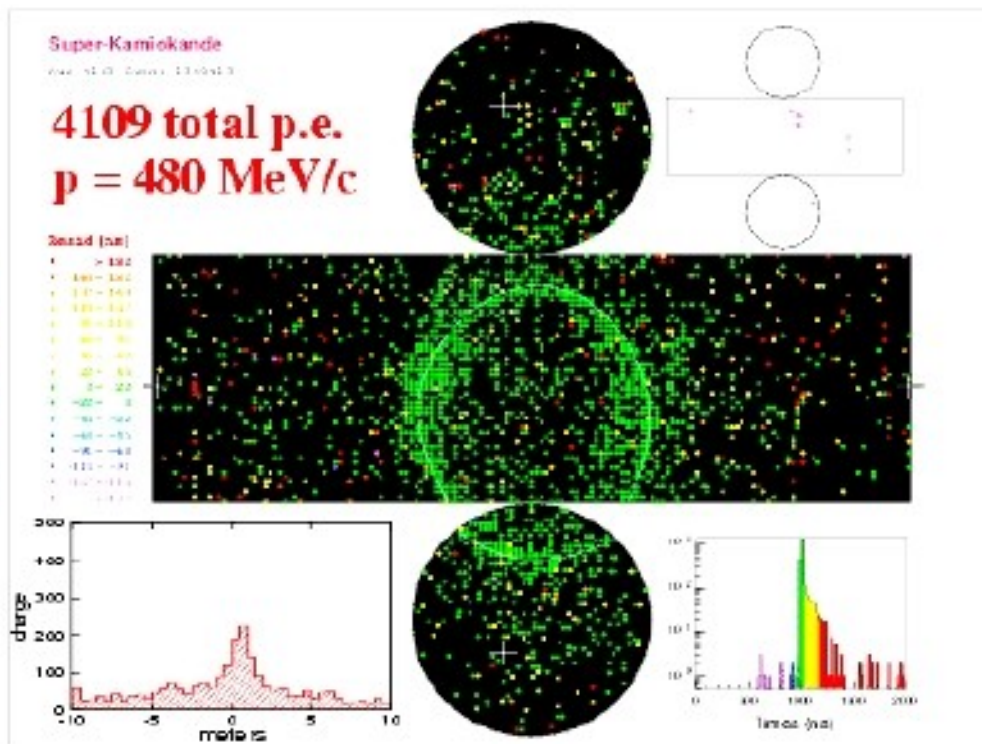
$$\cos \theta = 1/\beta n$$

$$\beta = 1 \quad \theta = 42 \text{ degrees}$$



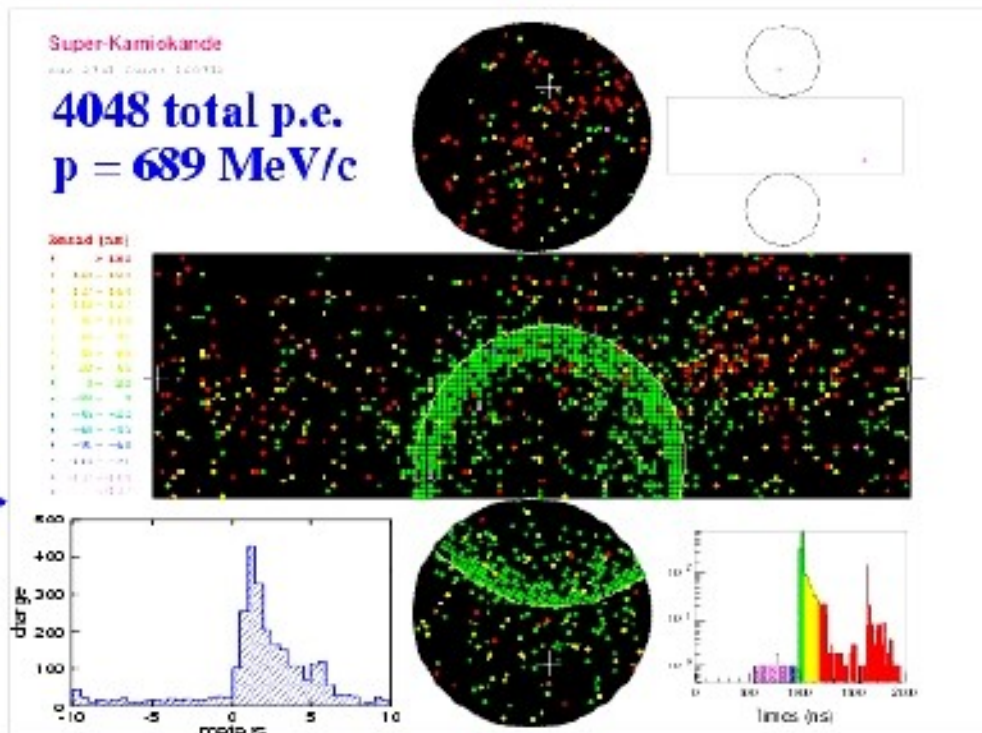
ETK

e-like



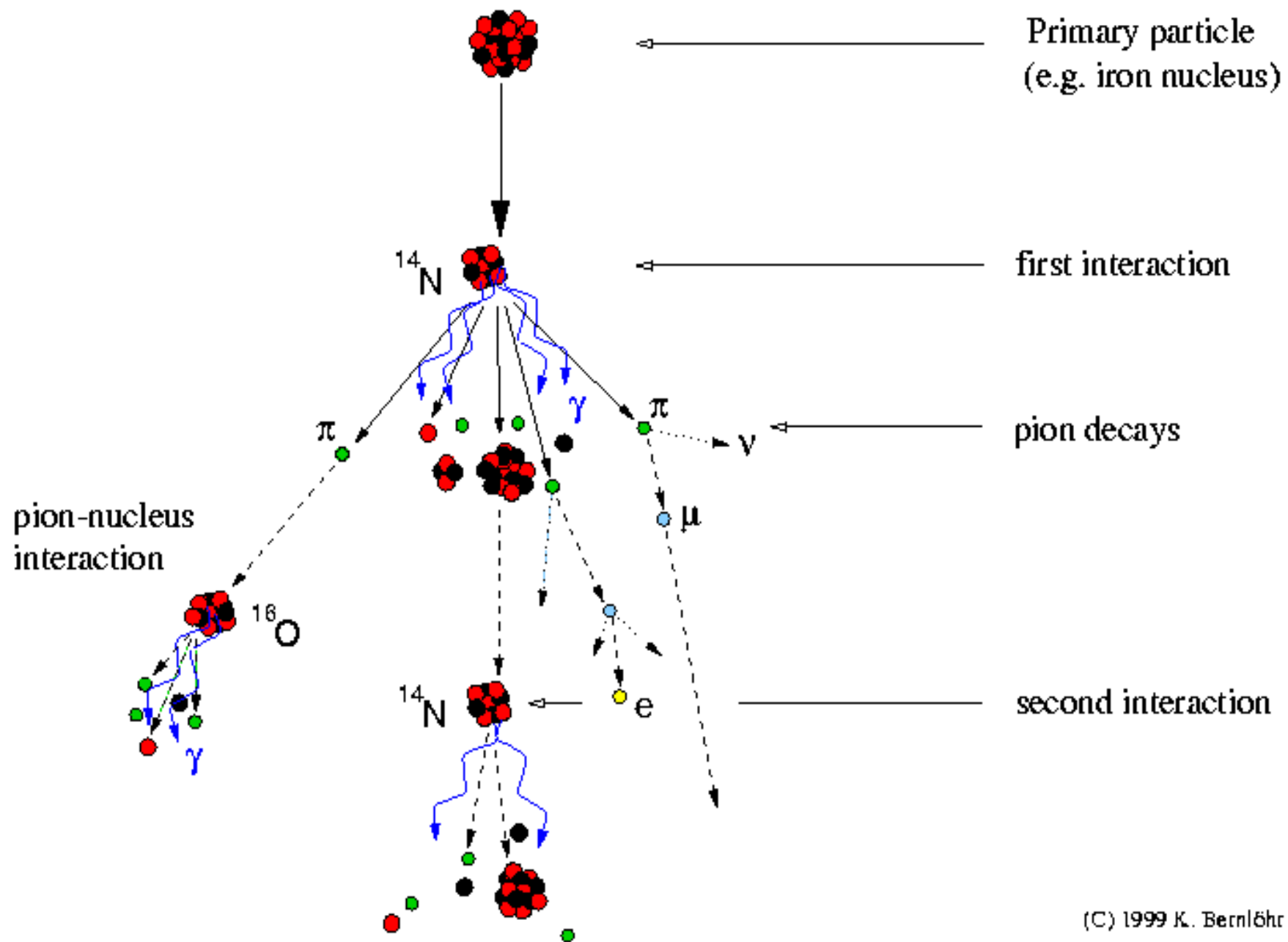
Electron-like : has a fuzzy ring

μ -like



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

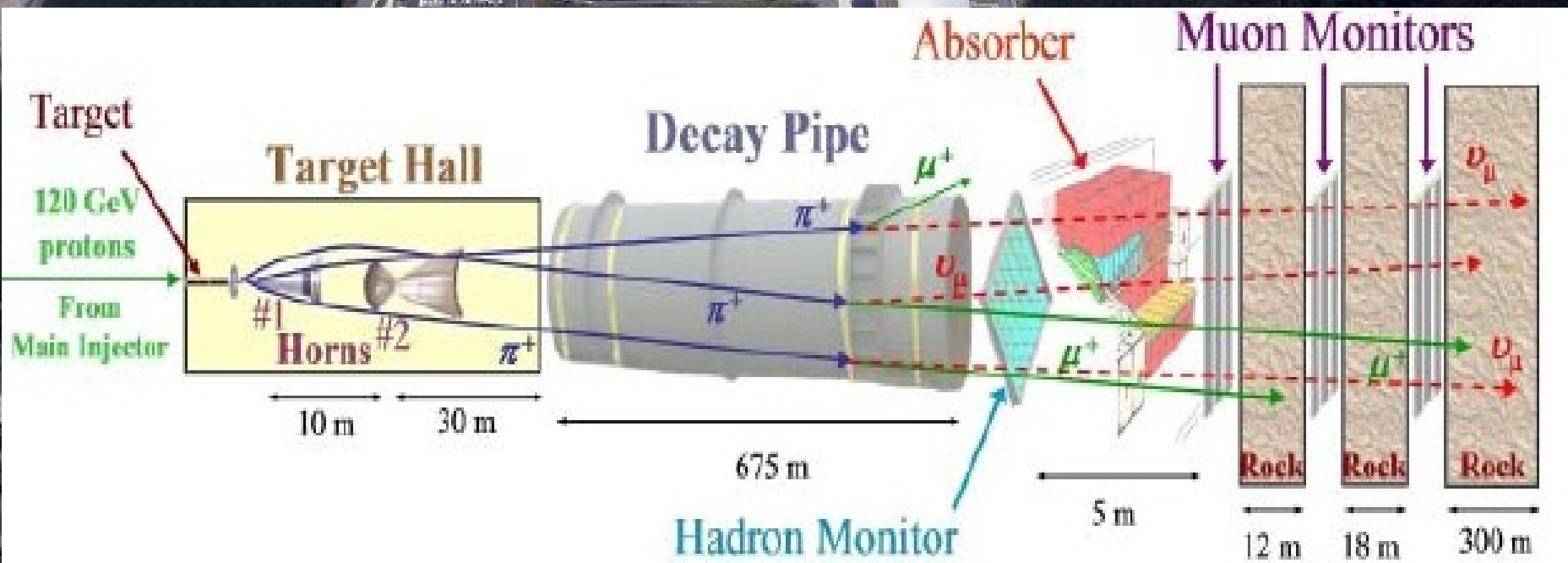
Development of cosmic-ray air showers



JPARC Facility

TARGET

ν_{μ}



Positron, e^+
mass (1)



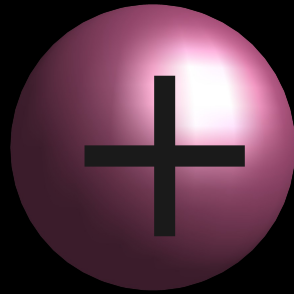
Electron
Antineutrino, $\bar{\nu}_e$

Muon, μ^+
mass (200)



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

Tau, τ^+
mass (3500)



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

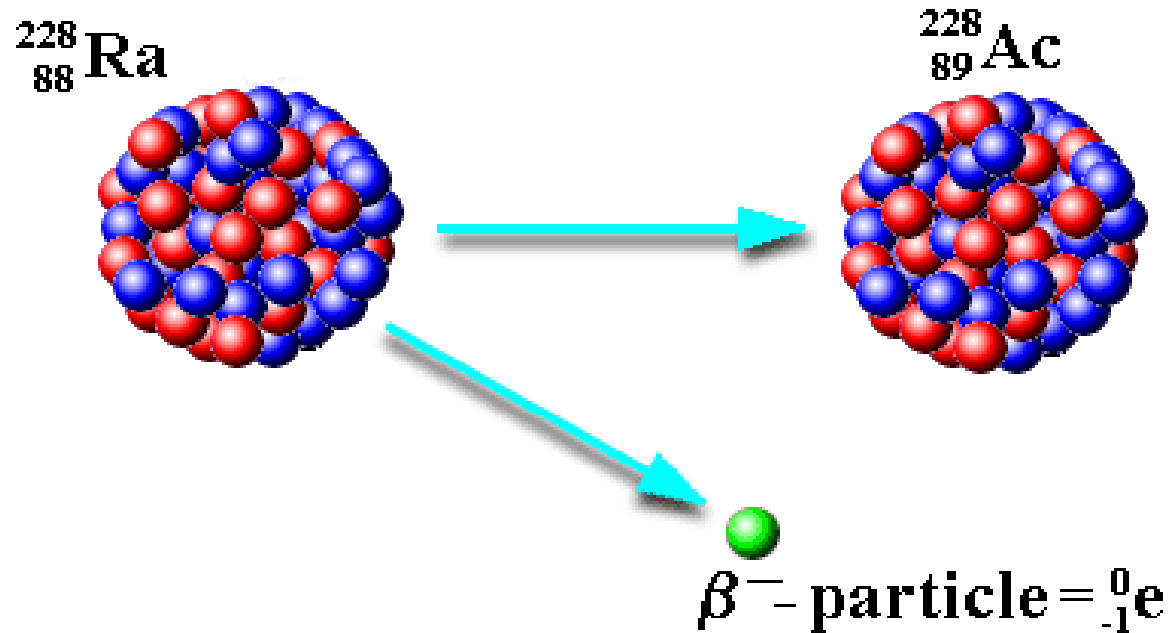
3 Antiparticles

Neils Bohr



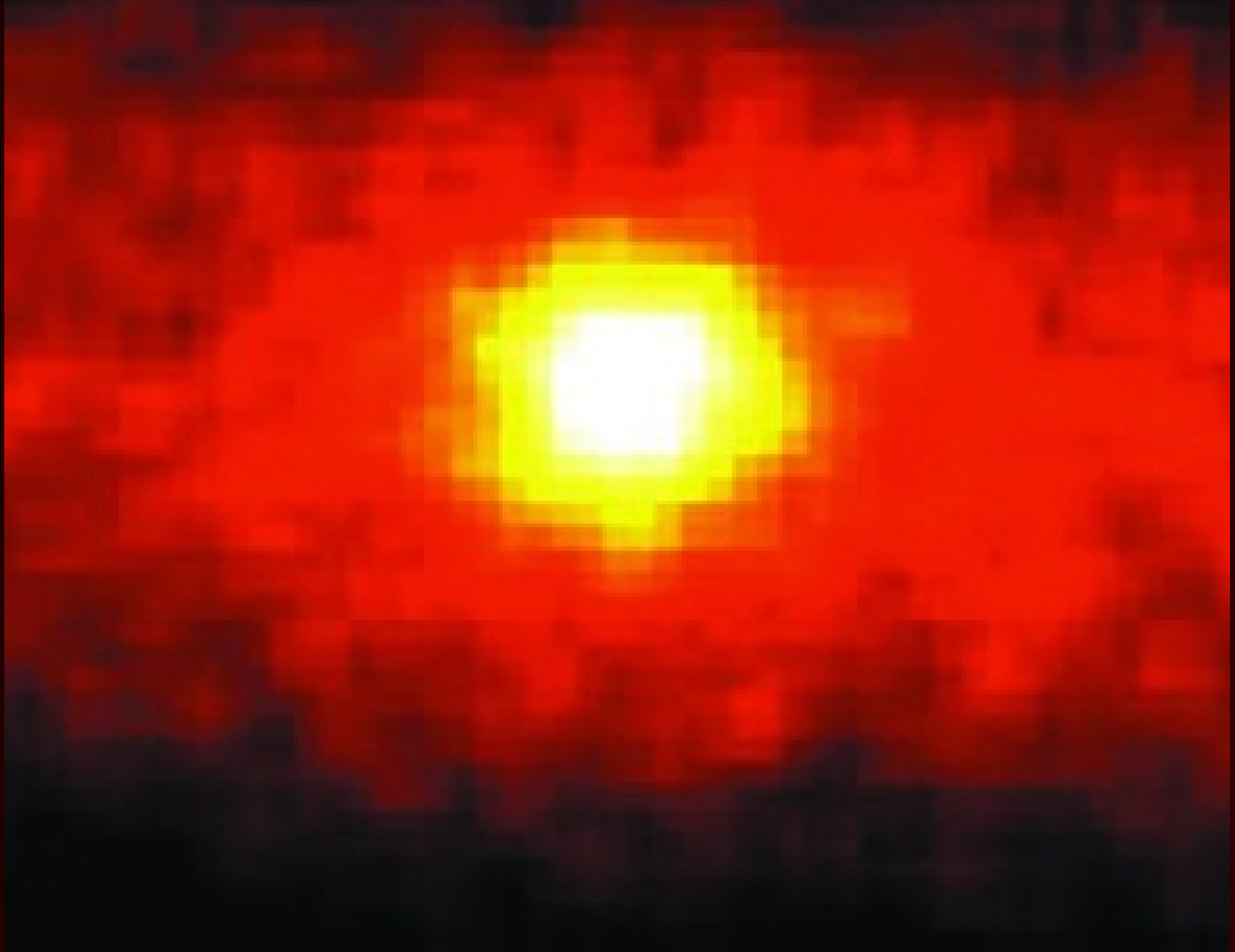
“At the present stage of atomic theory we have no arguments for upholding the concept of energy balance in the case of β -ray disintegrations.”

beta minus decay

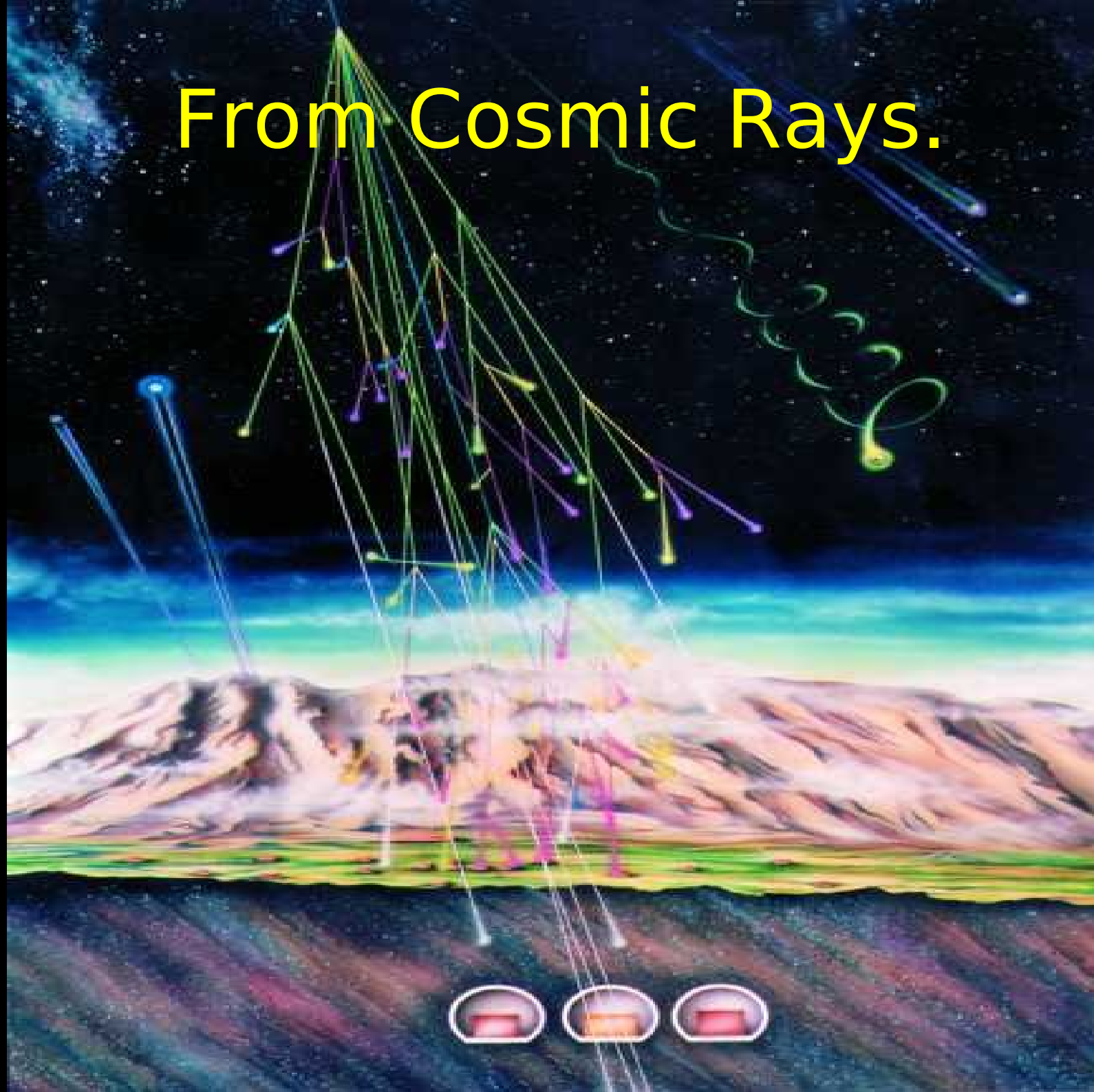


$$\text{Energy}(\text{Ra}) \neq \text{Energy}(\text{Ac}) + \text{Energy}(\text{e})$$

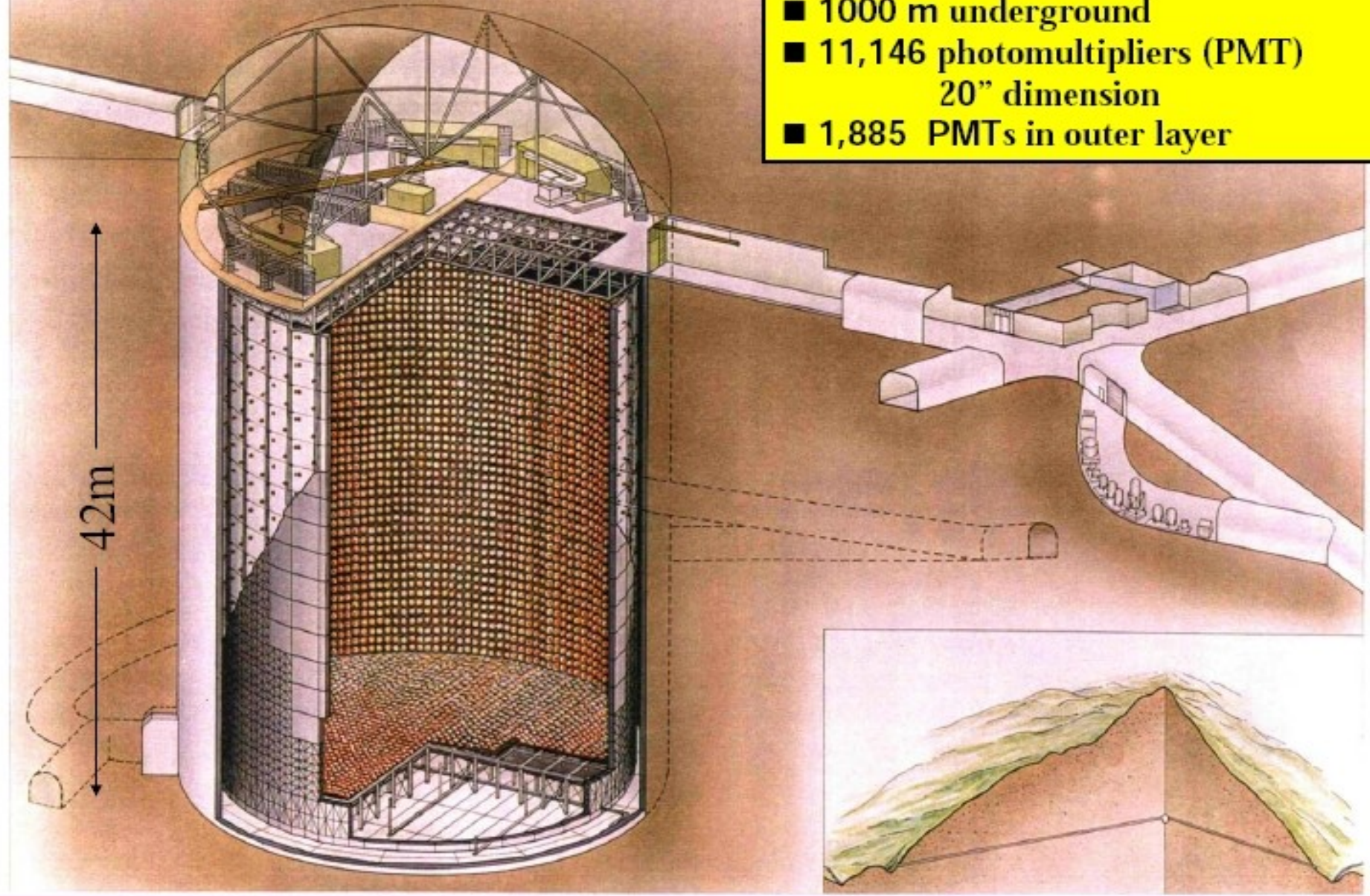
The Sun in Neutrinos

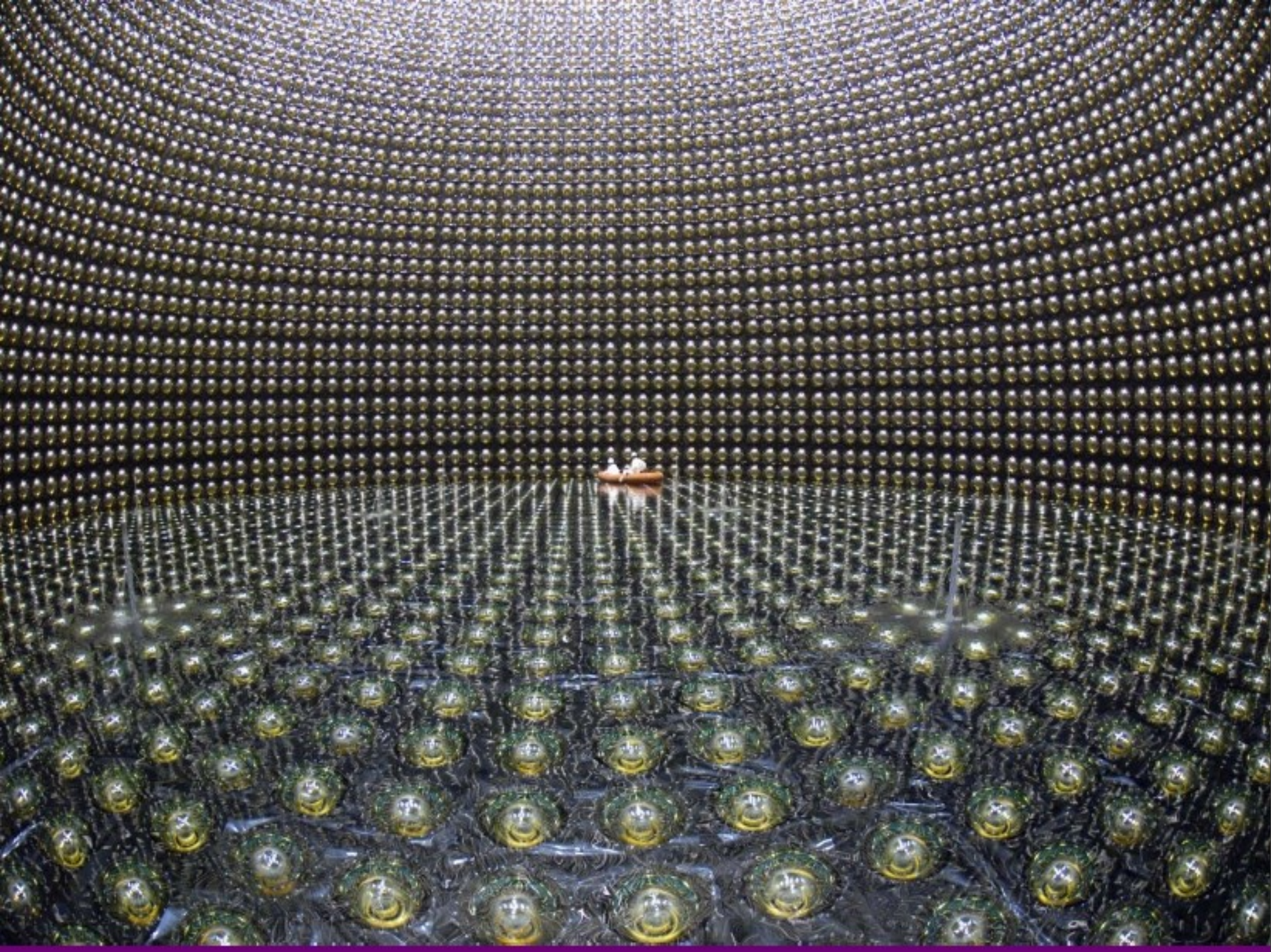


From Cosmic Rays.

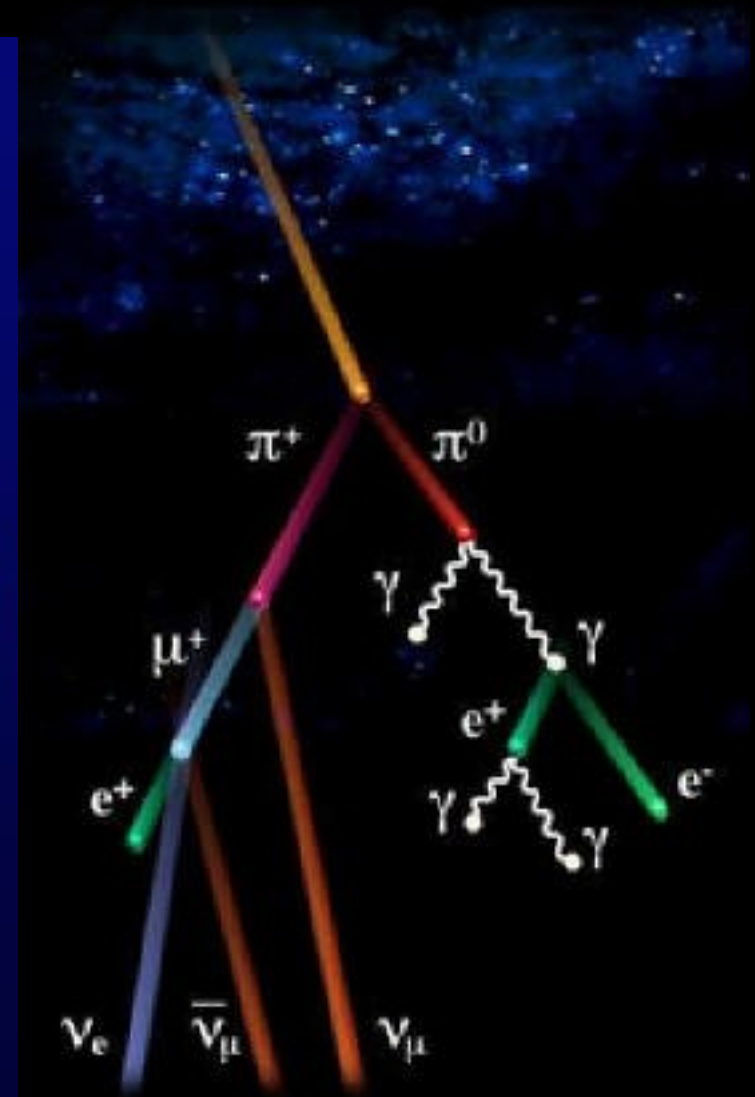
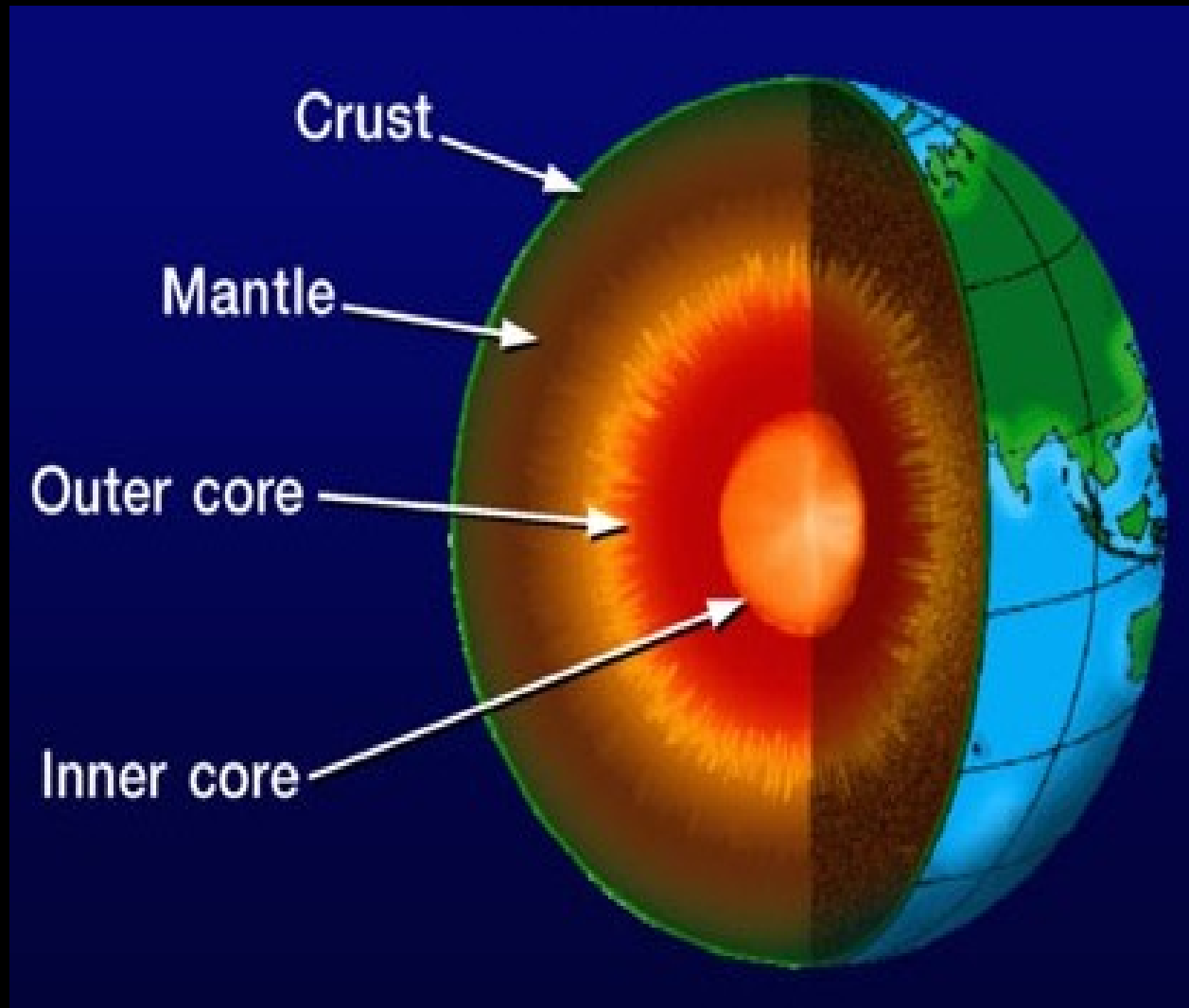


- 50,000 tons of ultra-pure water
- 1000 m underground
- 11,146 photomultipliers (PMT) 20" dimension
- 1,885 PMTs in outer layer





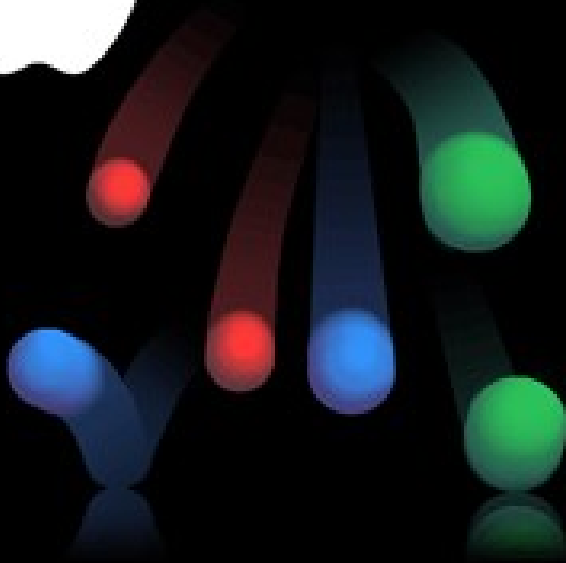
From The Earth



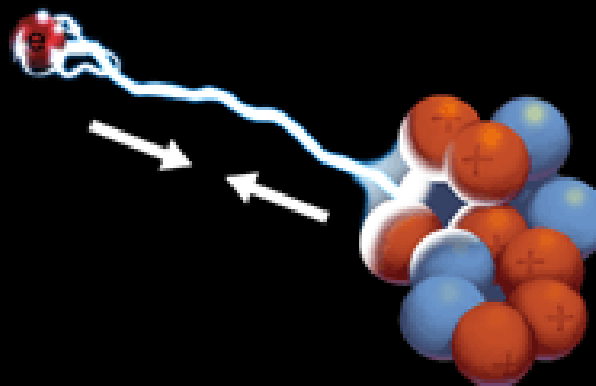
e
n
p
v



Gravity



Electro
Magnetic

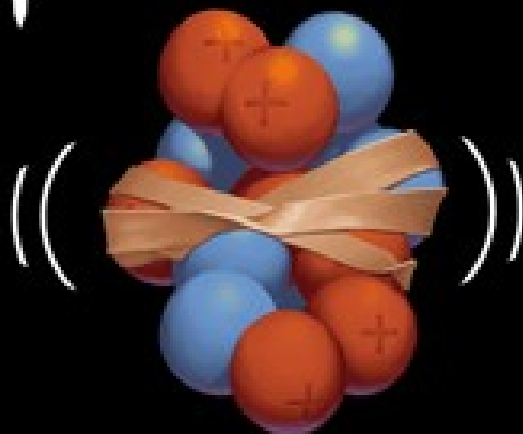


e
n
p
v

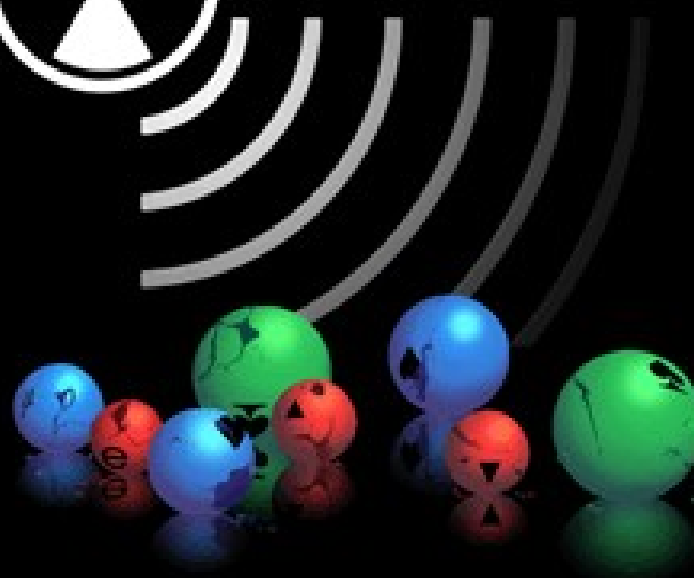
e
n
p
v



Strong



Weak



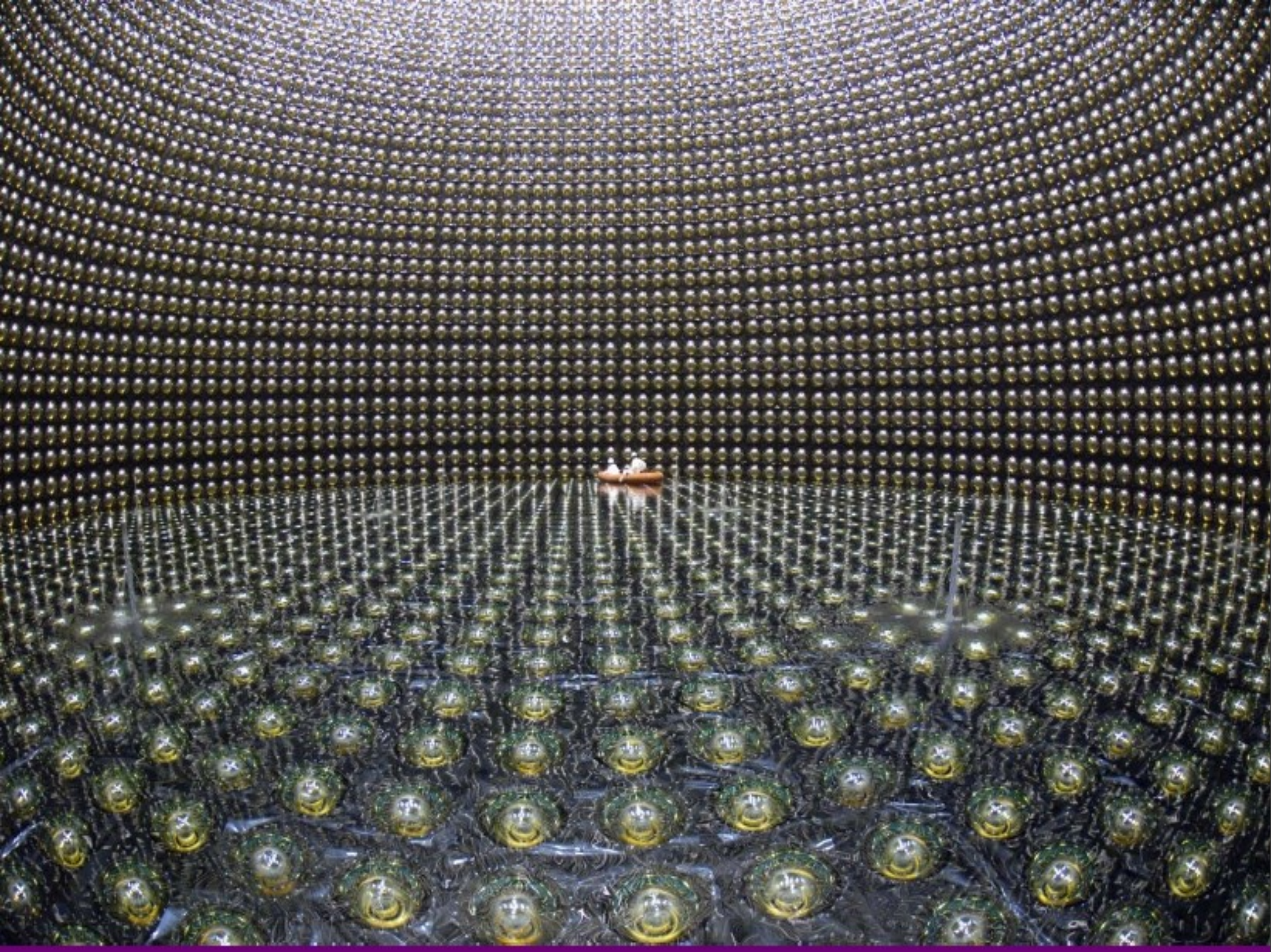
e
n
p
v

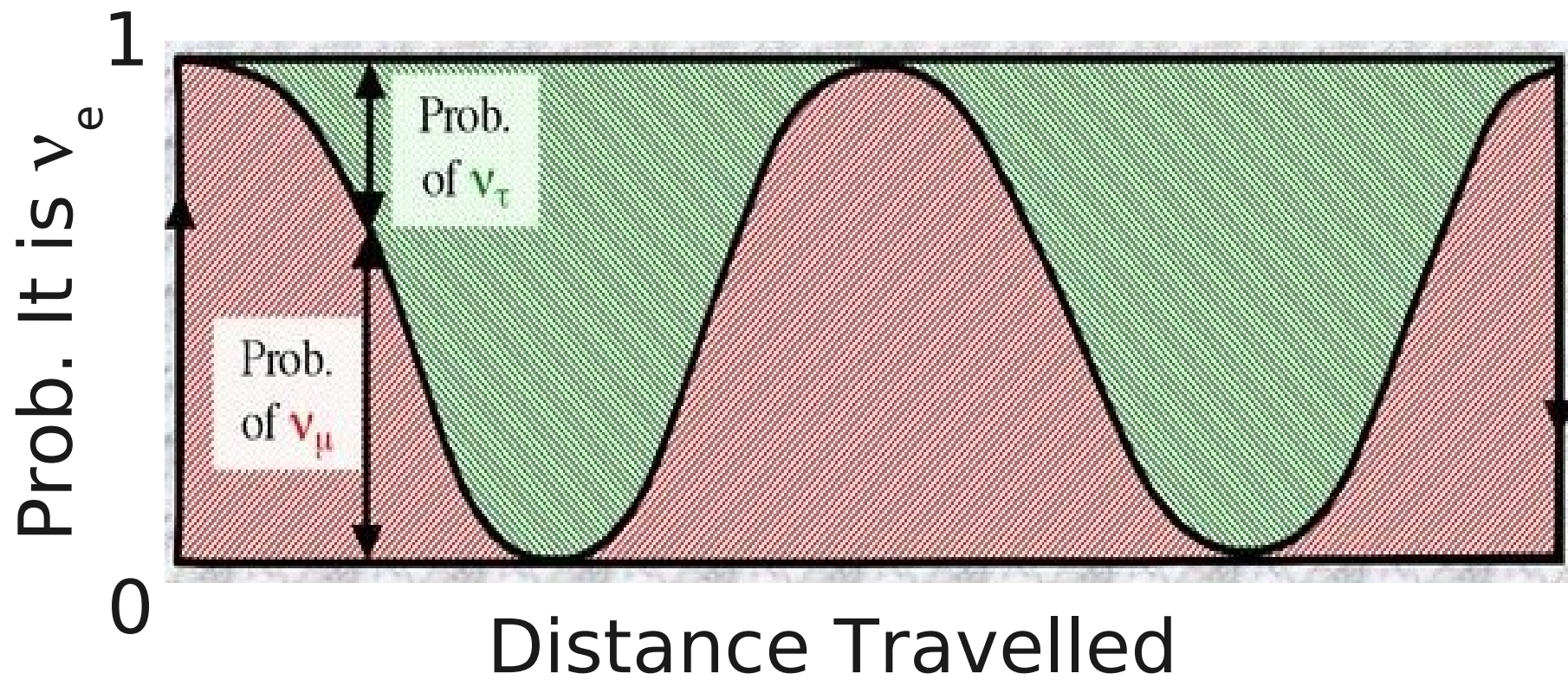




"The chances of a neutrino actually hitting something as it travels through all this howling emptiness are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich."

Douglas Adams





T2K



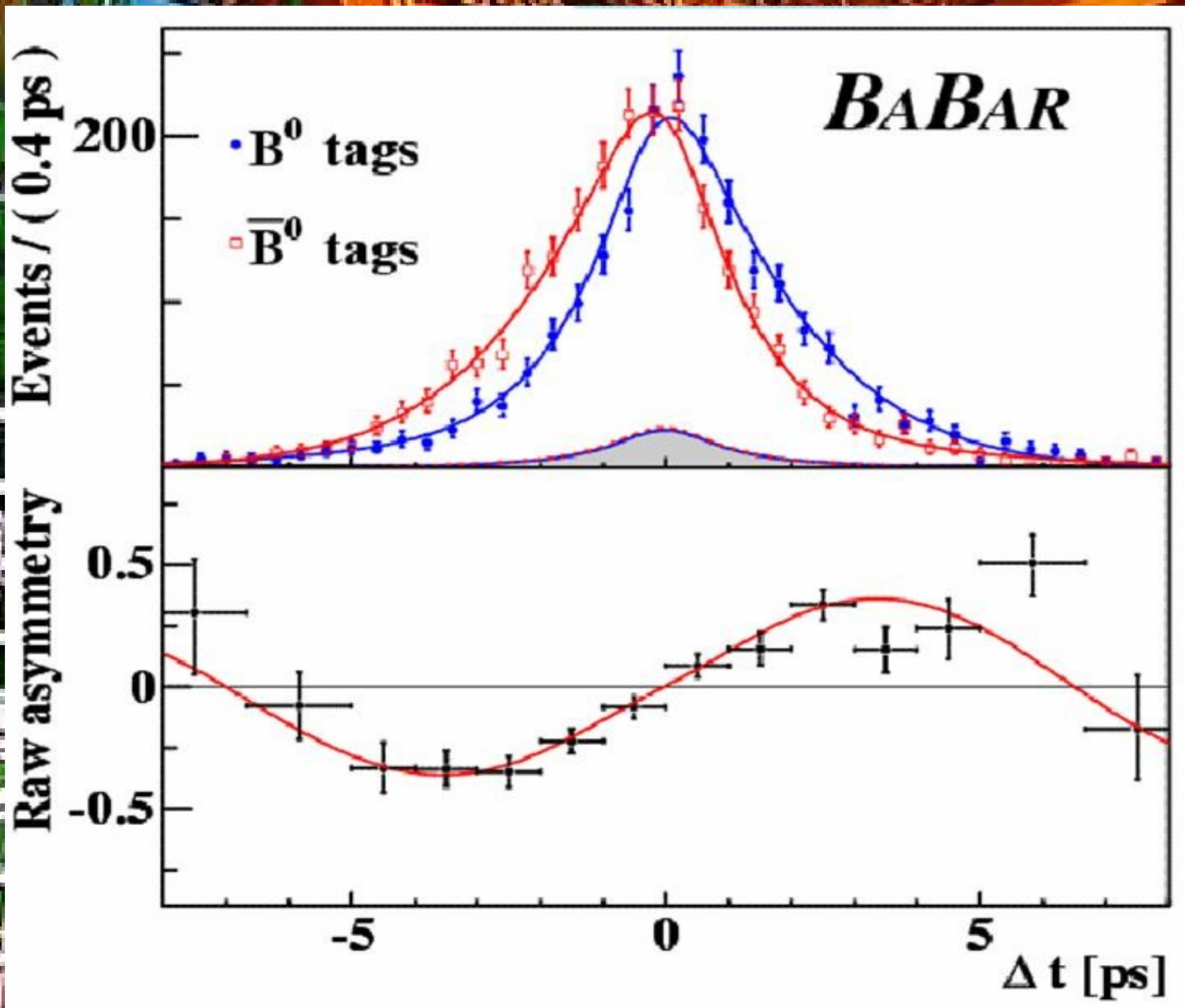
Image © 2008 TerraMetrics
Image NASA
Image © 2008 Digital Earth Technology

©2007 Google™

Super-Kamiokande

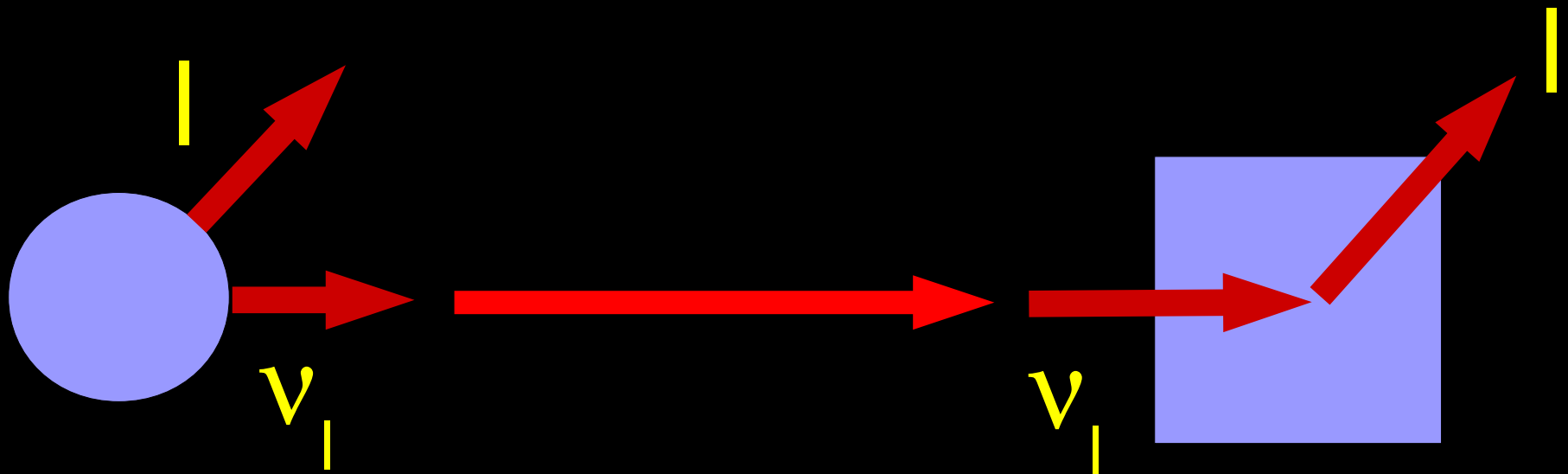


There is a difference between the physics of matter and antimatter




Neutrino Oscillations

THE discovery in neutrinos of the last 20 years



A typical neutrino experiment



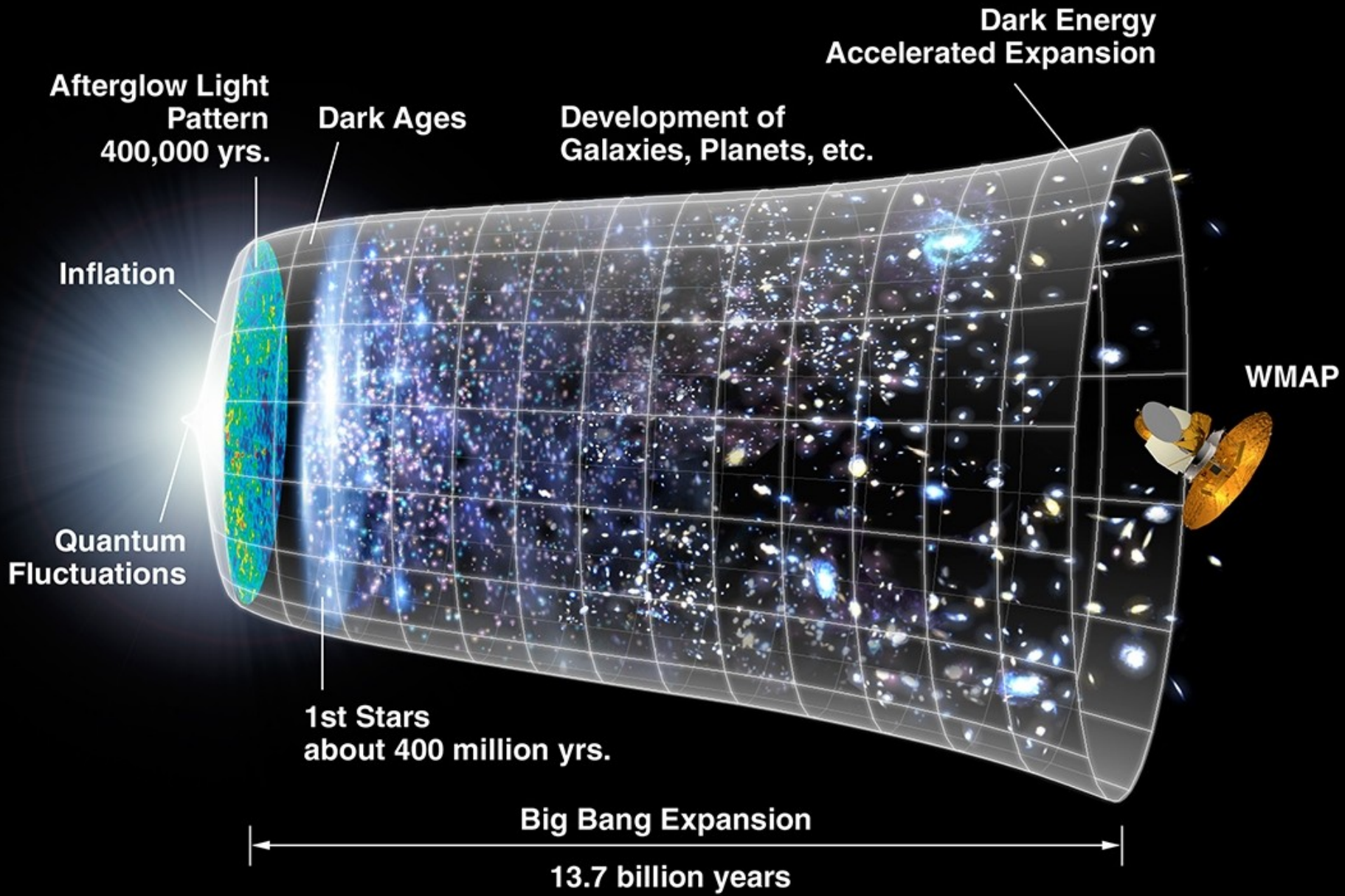


Neutrinos and the case of the missing antimatter

Steve Boyd, University of Warwick

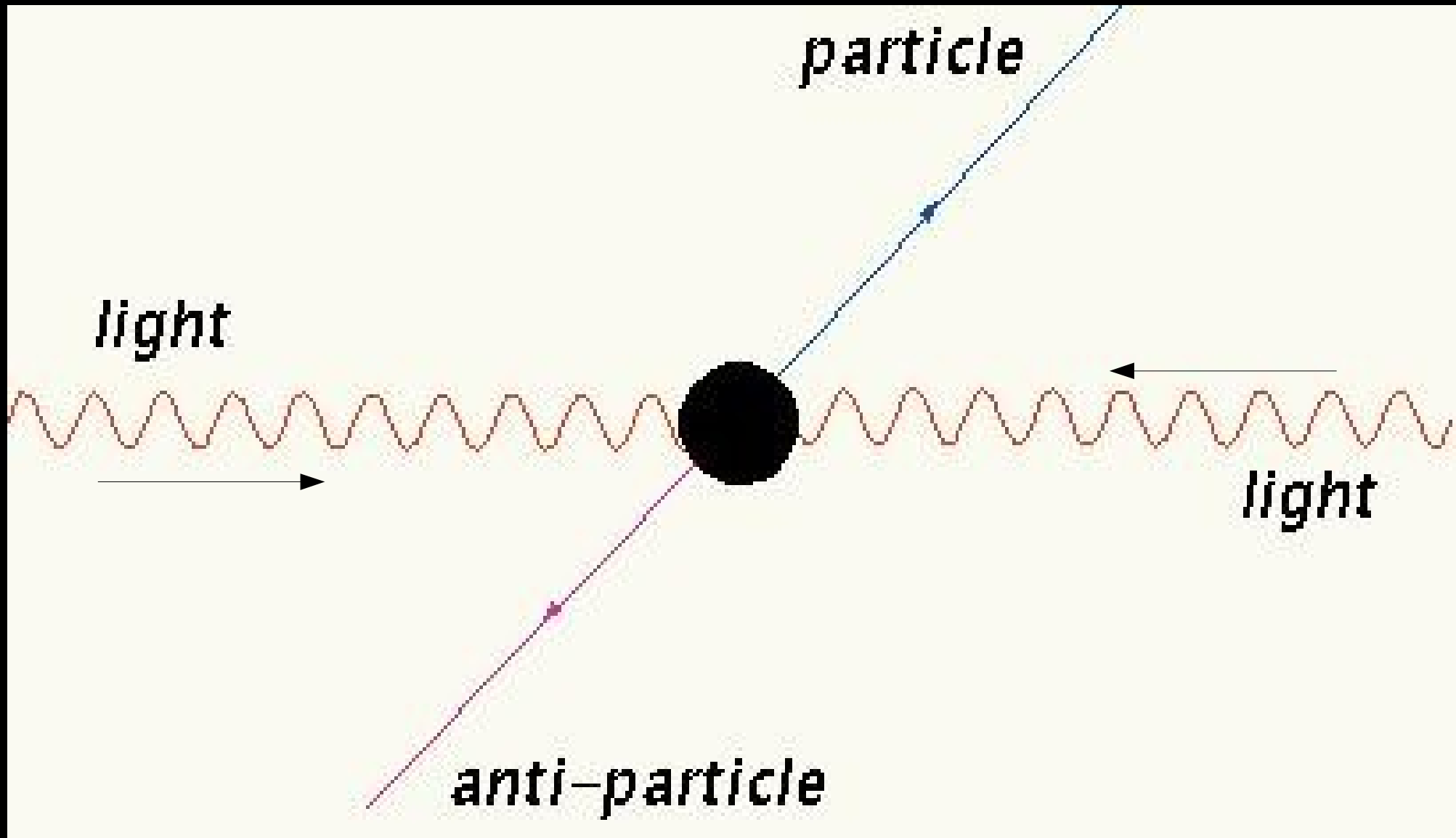
How do we exist?

The Universe

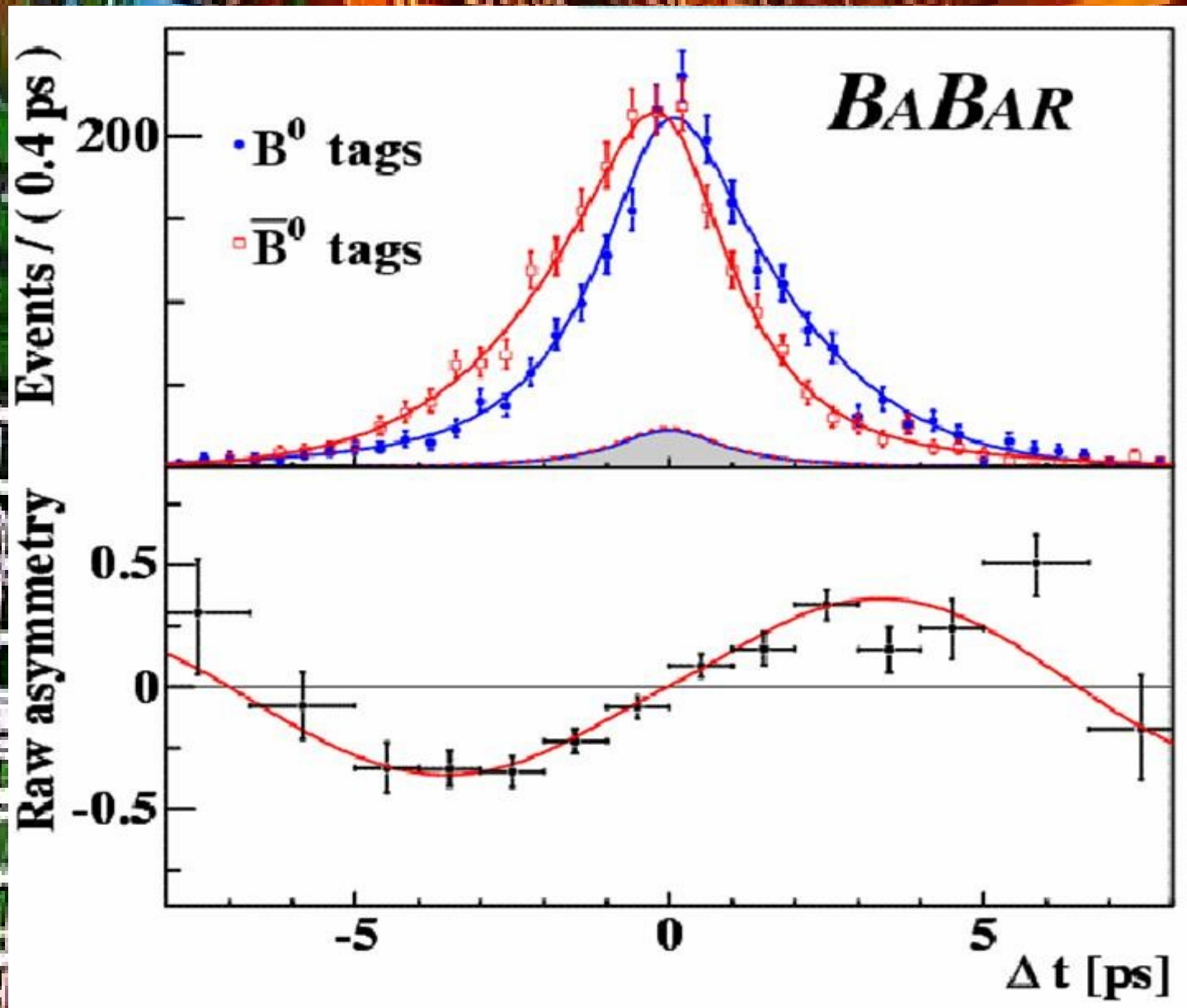




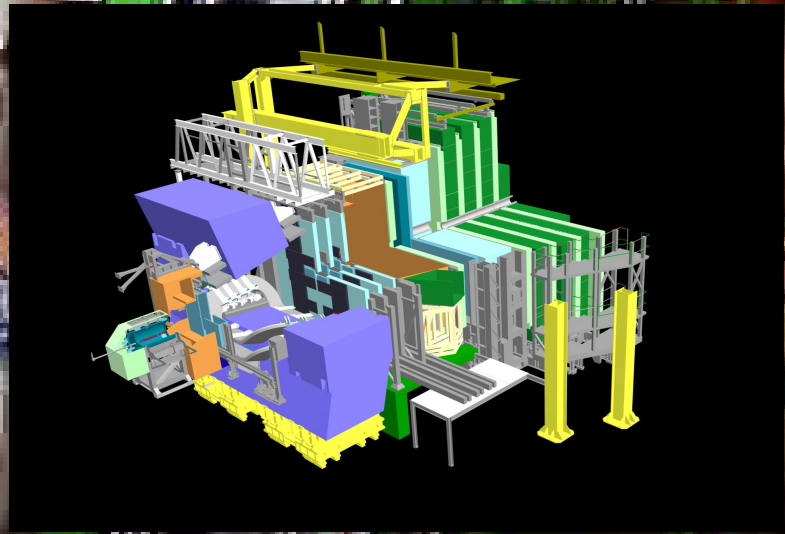
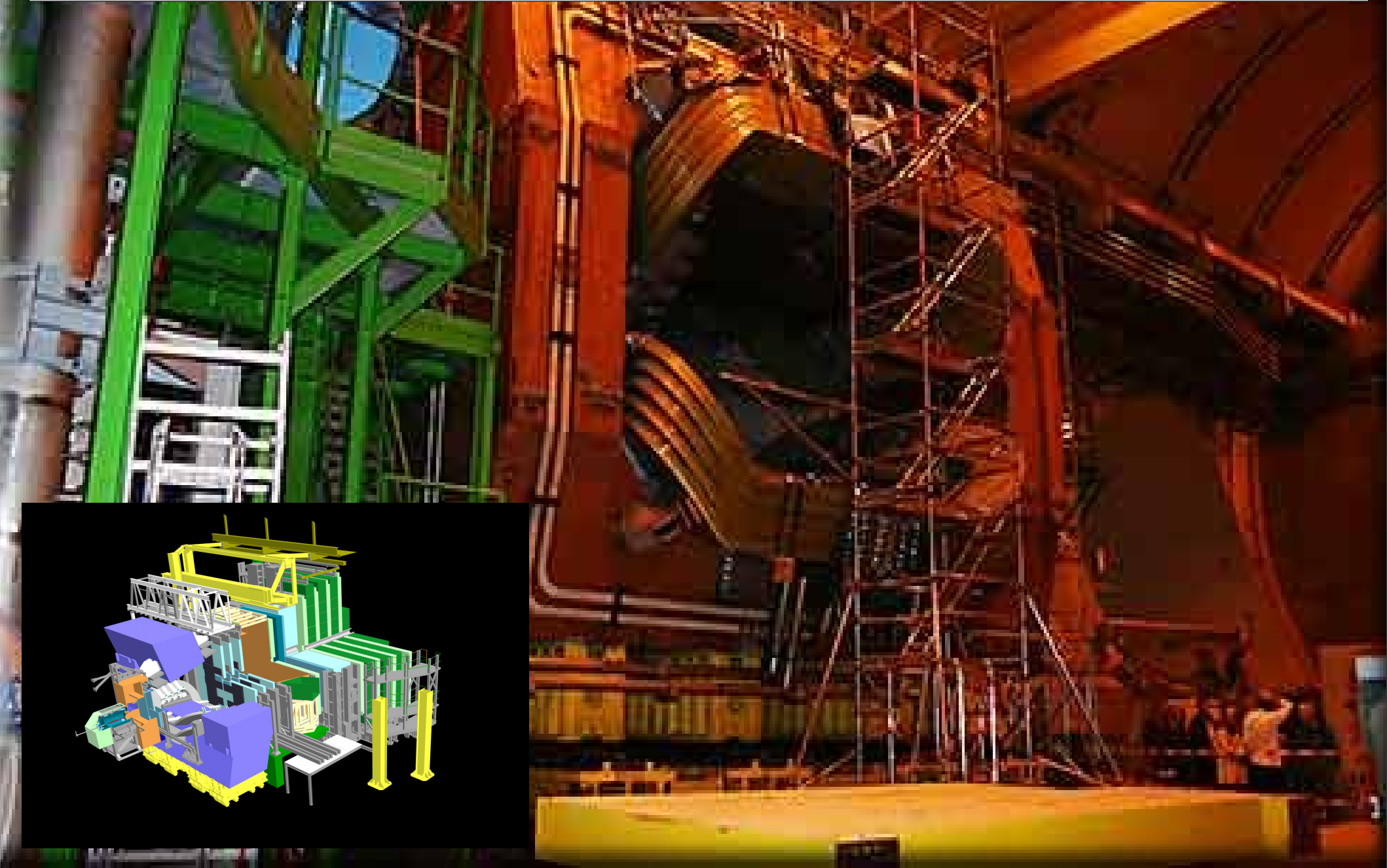
Why is there more matter than antimatter?



There is a difference between the physics of matter and antimatter



There is a difference between the physics of matter and antimatter



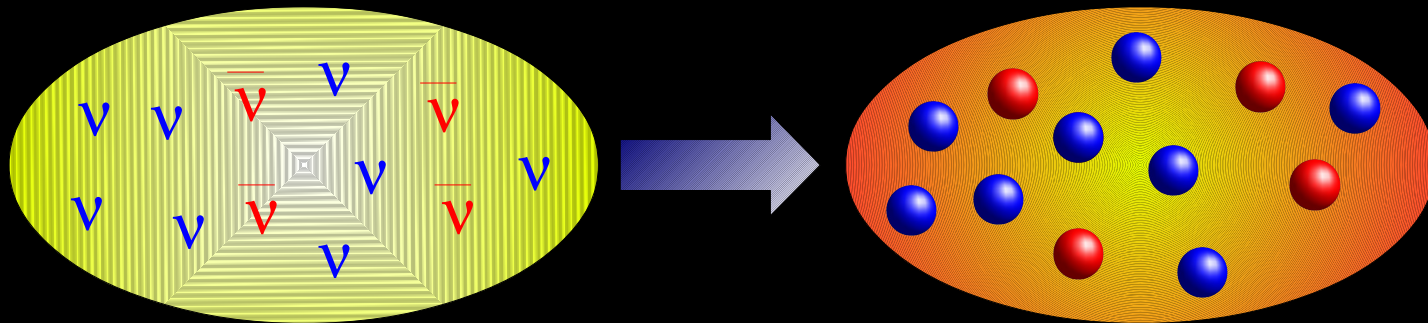
How do we exist?

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 wherever you have radioactive decays

Electron, e

-1



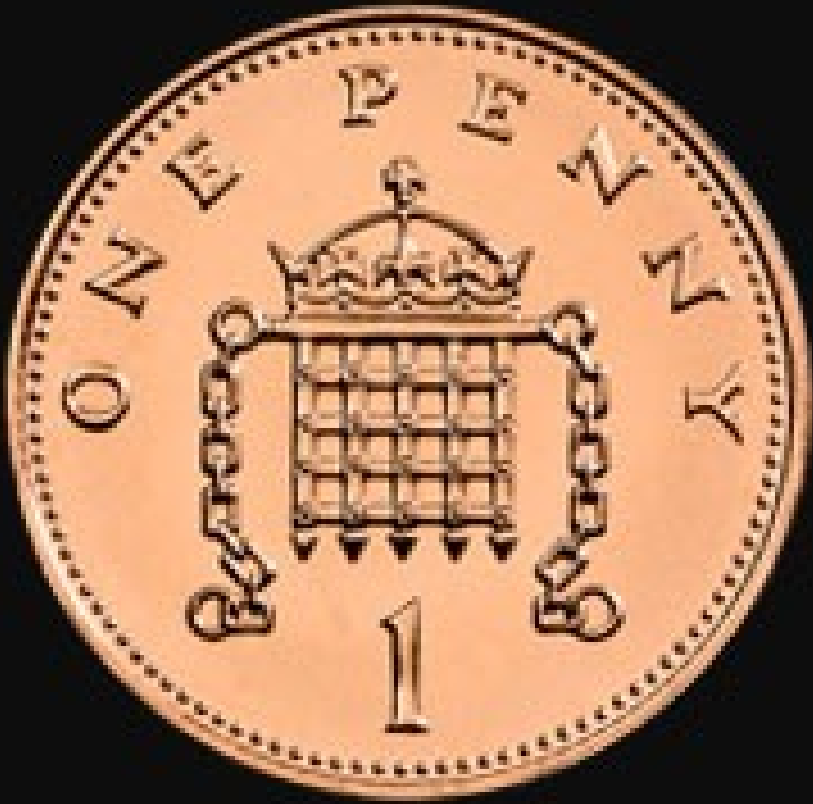
Tiny mass (1)

Electron Neutrino, ν_e



0

Very tiny mass
(<0.0000001)



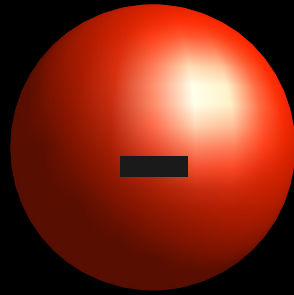




x 500

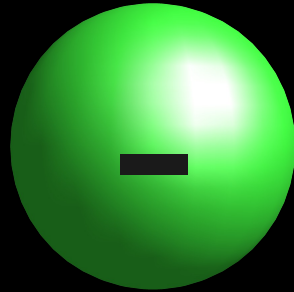


Electron, e
mass (1)



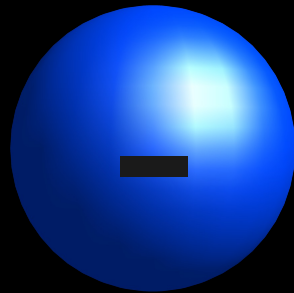
Electron
Neutrino, ν_e

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, $\bar{\nu}_\tau$

3 neutrino Flavours

From the Big Bang

An artist's conception of the Big Bang, showing a vast field of particles and energy expanding outwards from a central point. The background is dark, with numerous bright, multi-colored streaks (purple, blue, white) radiating from the center, creating a sense of intense energy and expansion.


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

Artist's conception

From Astrophysical Objects

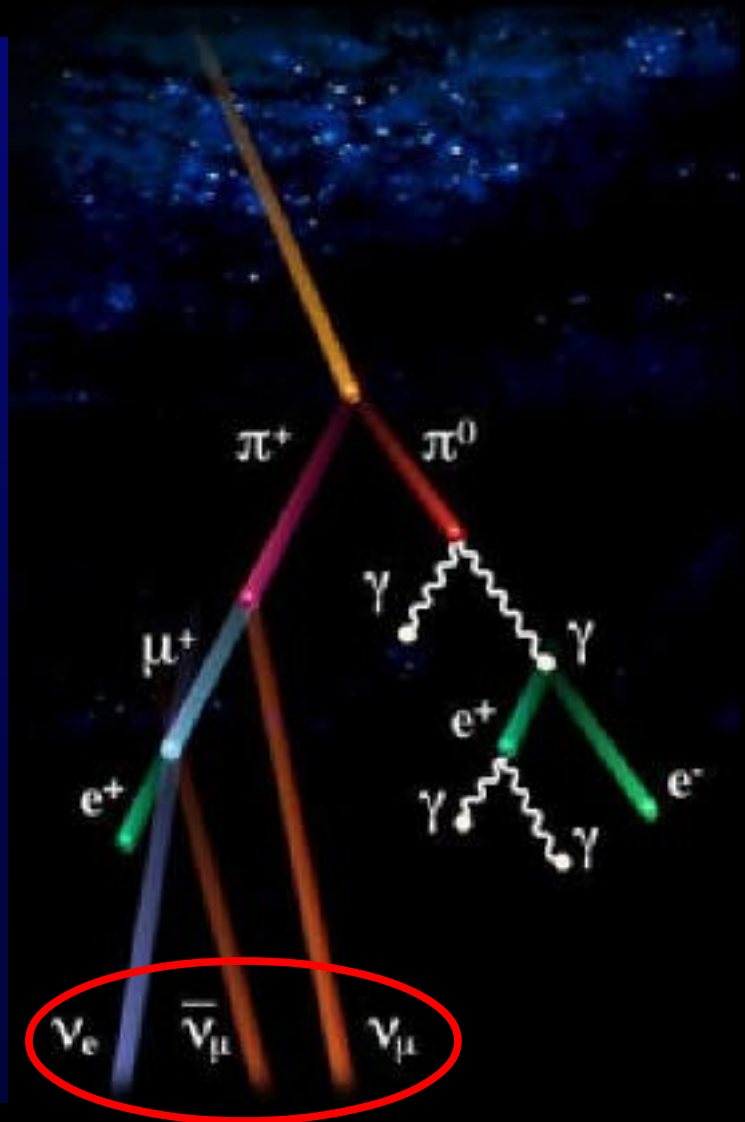
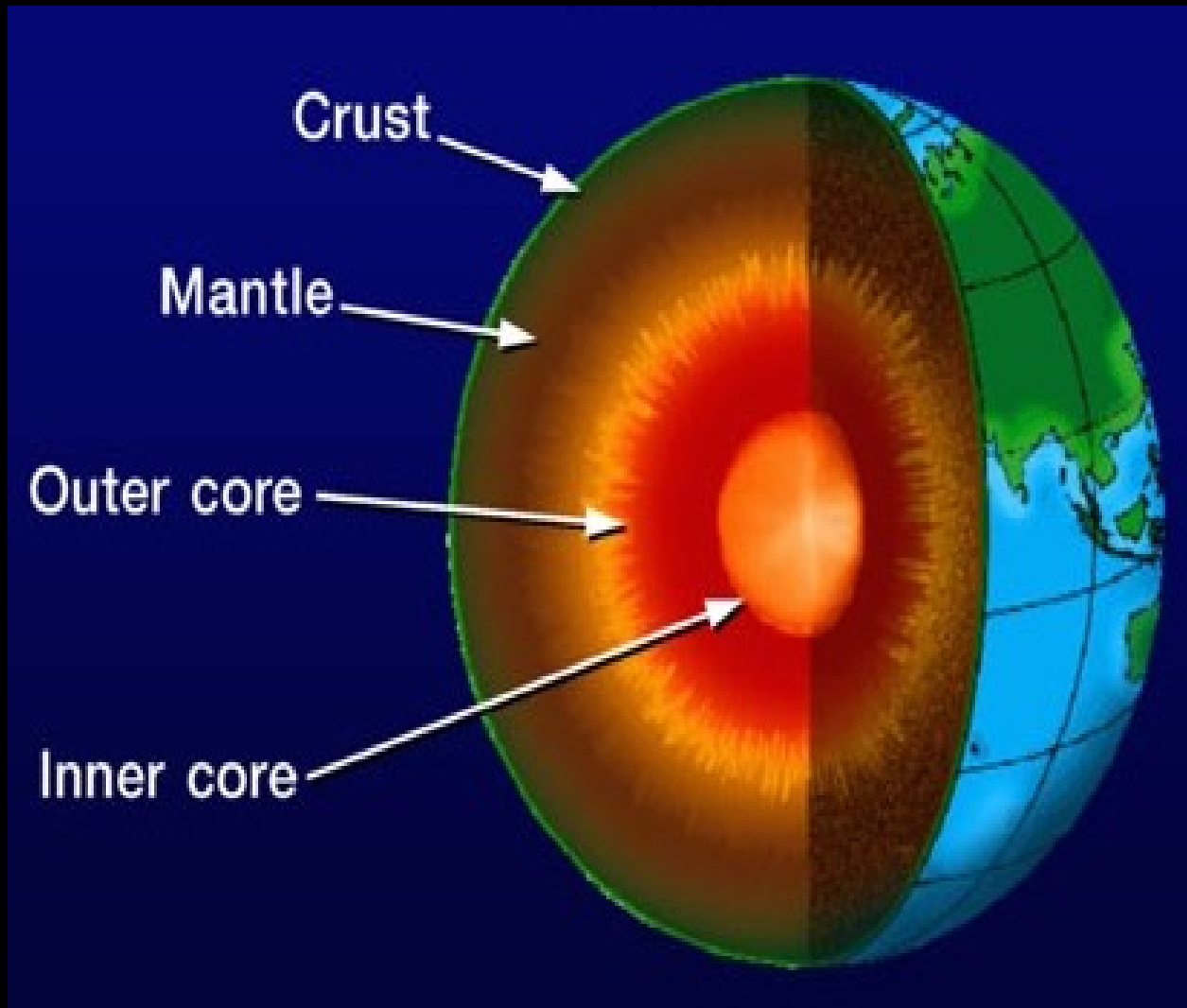


Supernovae created the heavy elements (us) and neutrinos may be responsible for the star exploding.



500,000,000,000,000 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



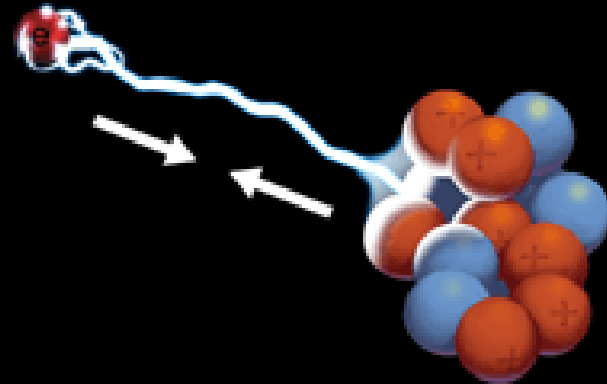
Gravity



e
n
p
v



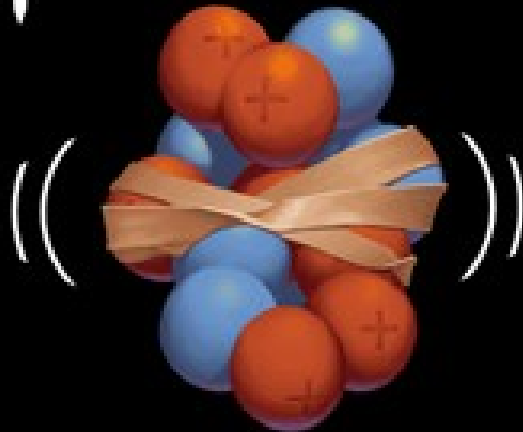
Electro
Magnetic



e
n
p
v



Strong



e
n
p
v



Weak



e
n
p
v

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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egg sandwich lifetime – 20 minutes

9000 egg sandwiches at any time

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9000 egg sandwiches at any time

Area of egg sandwich – 15 cm x 15cm

186 m² total egg-sandwich area

Surface area of earth

500 million km²

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

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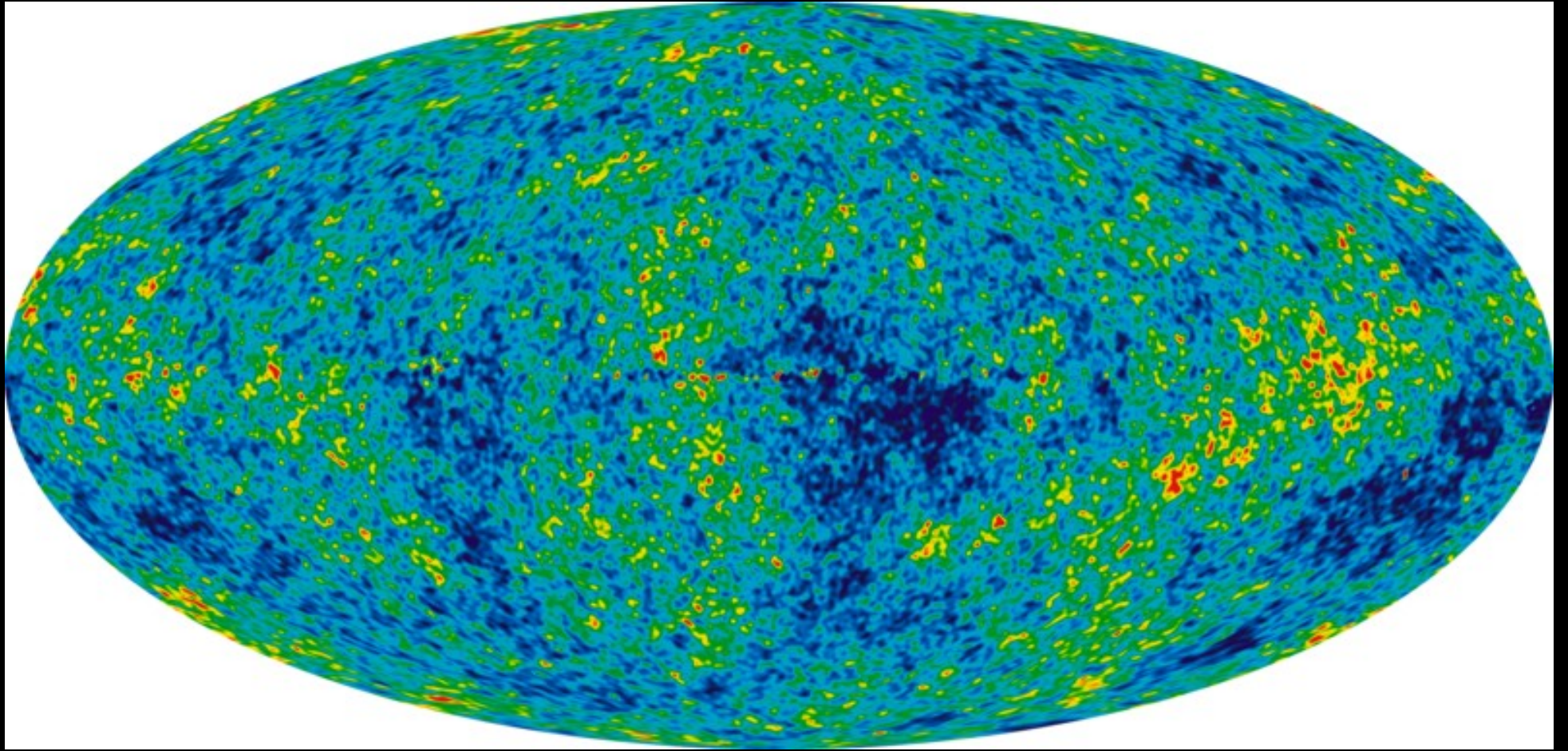
Suppose flight paths cover area of earth uniformly

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.