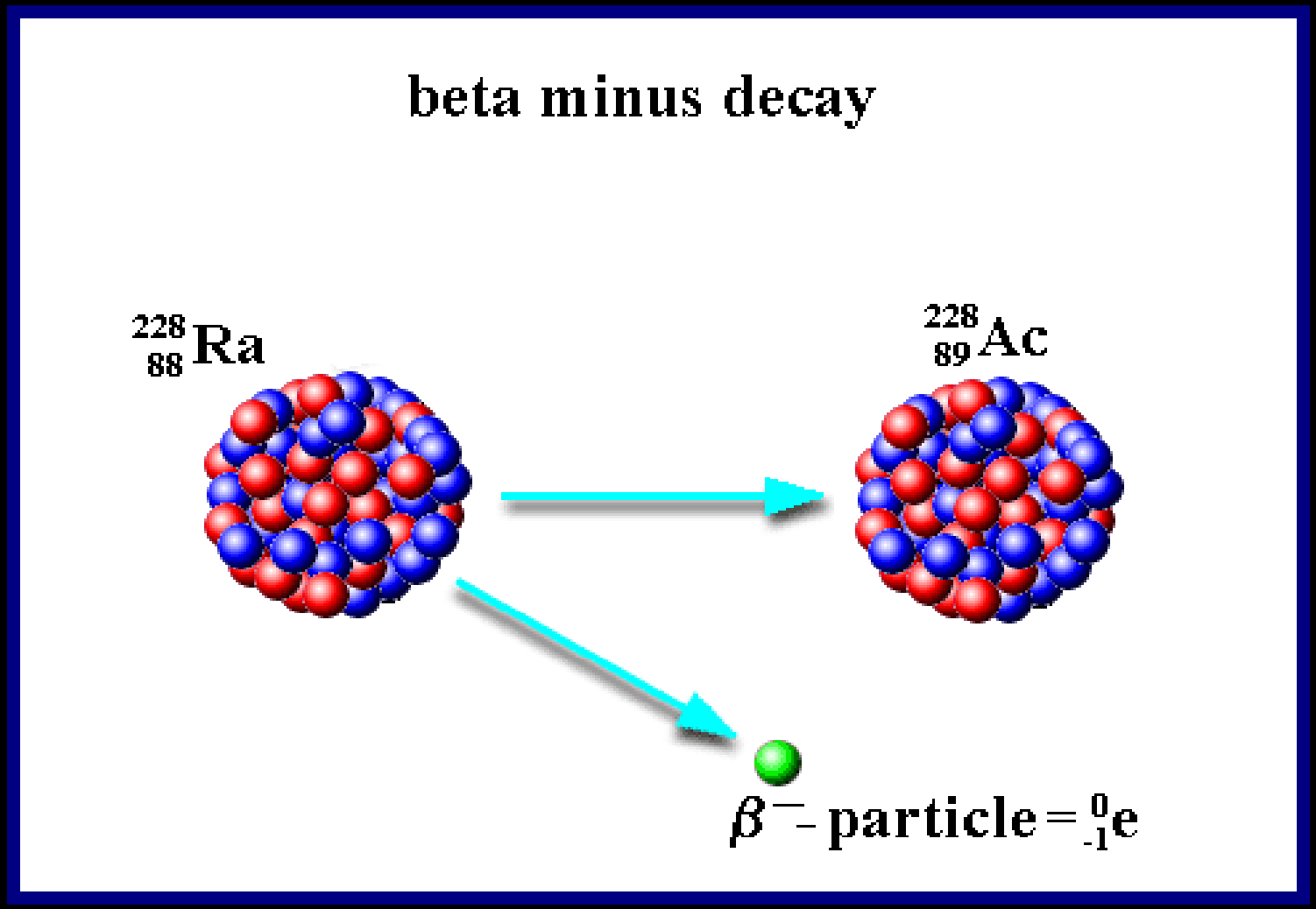
Neutrinos and the Case of the missing antimatter

Steve Boyd, University of Warwick

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


CRISIS



Energy(Ra) ≠ Energy(Ac)+Energy(e)

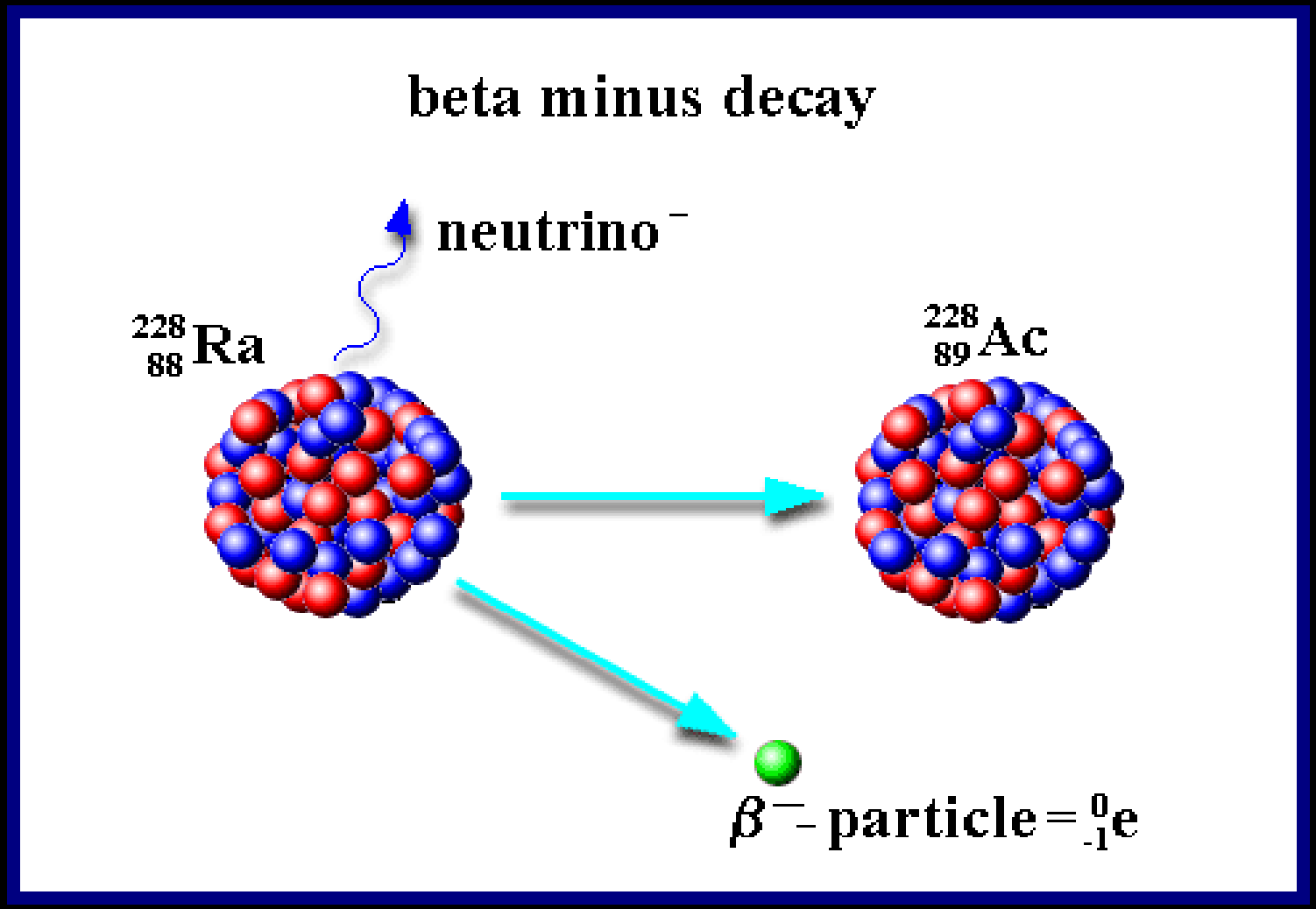
Neils Bohr

“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....”

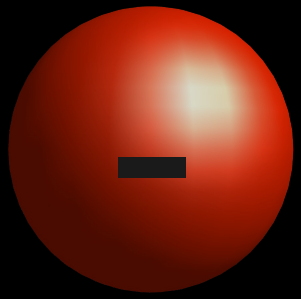
“You tell them. I'm off to a party”



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

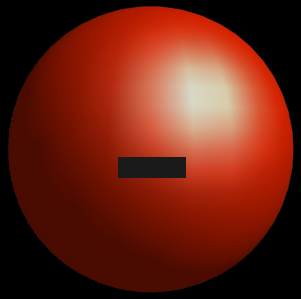
What are neutrinos?

Electron, e



Tiny mass (1)

Electron, e



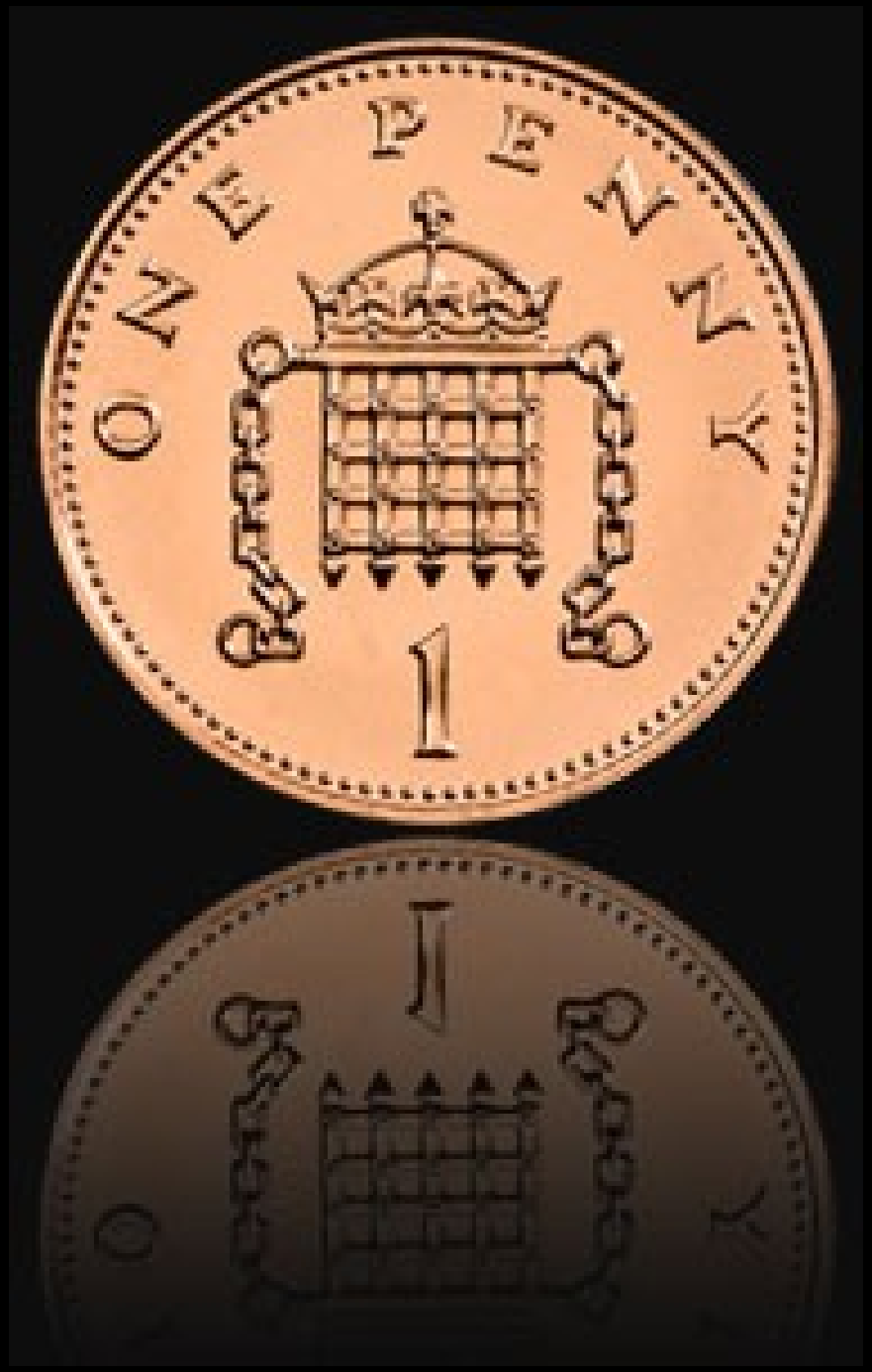
Tiny mass (1)

Electron Neutrino, ν_e

0

Very tiny mass
(<0.0000001)

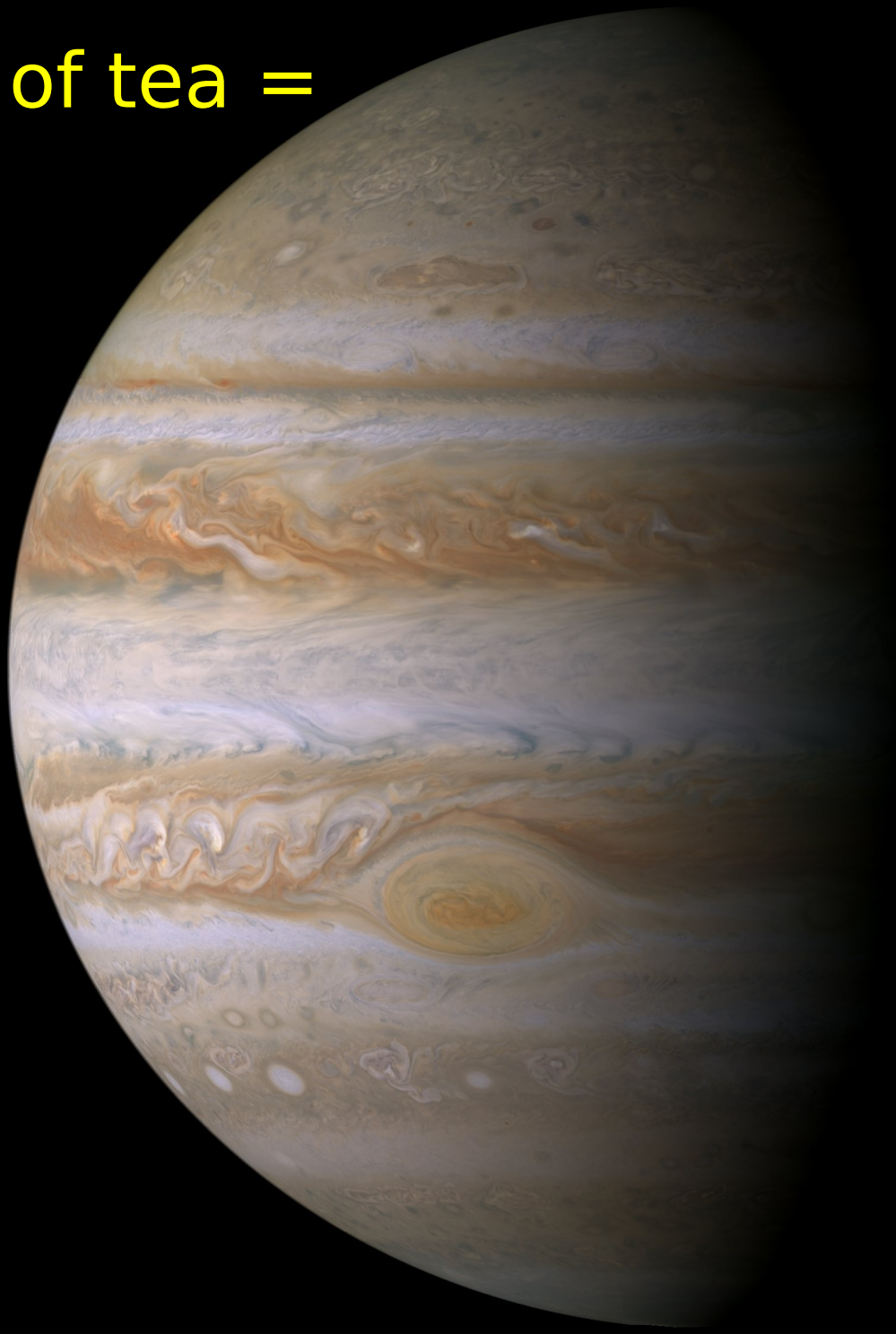
mass of a neutrino =



mass of an electron =

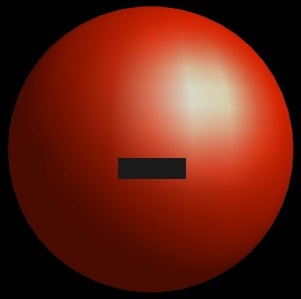
mass of a nice cup of tea =

mass of a nice cup of tea =



Electron, e

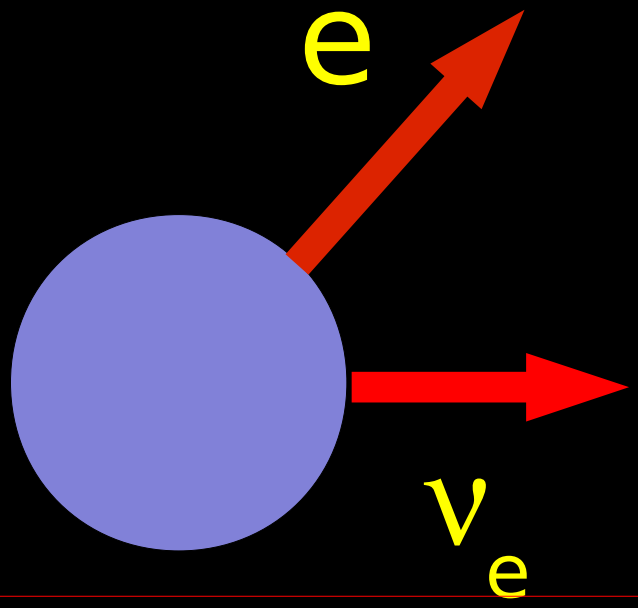
Electron Neutrino, ν_e

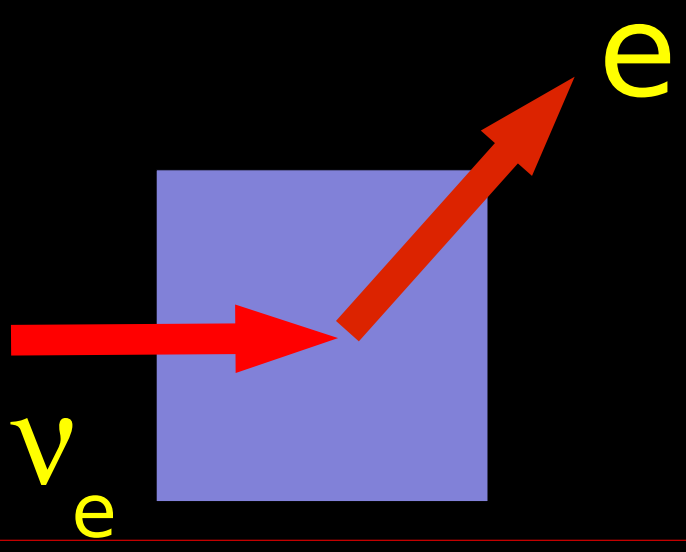


0

Tiny mass (1)

Very tiny mass
(<0.0000001)

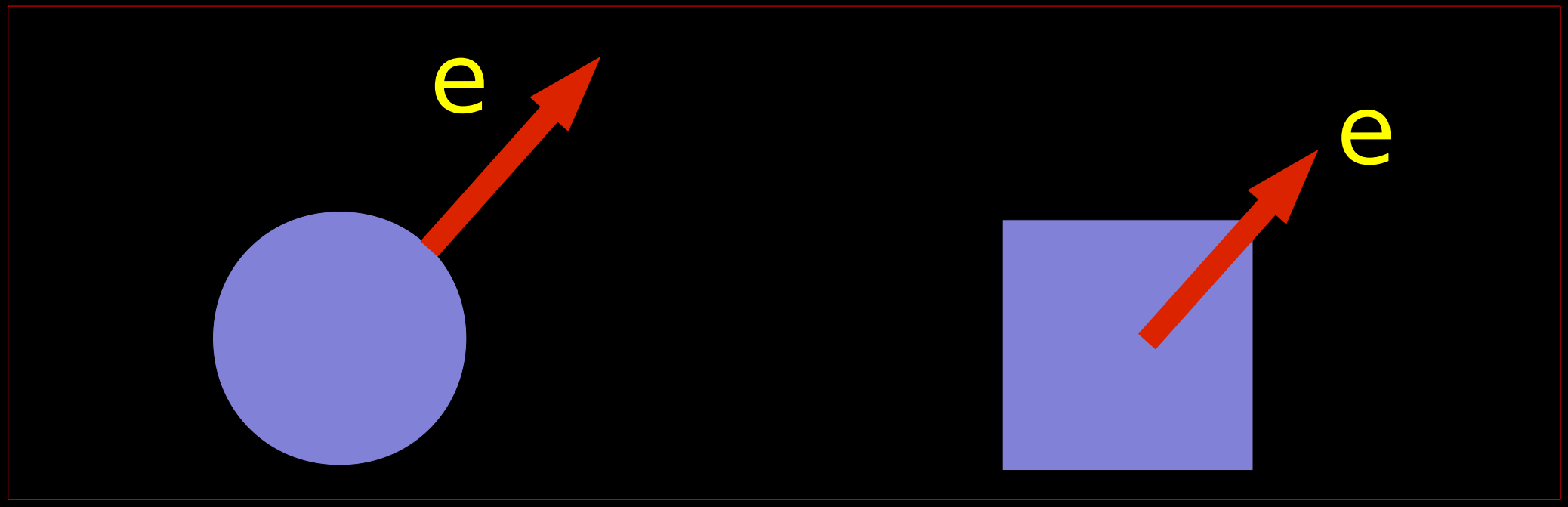




In experiments neutrinos are **NEVER** seen.

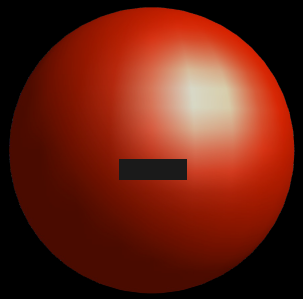
We can only detect them through the byproducts of their interactions with matter.

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



Electron, e

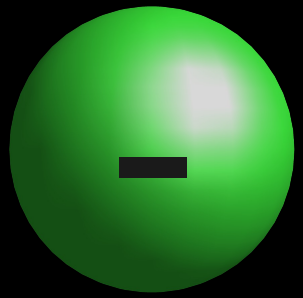
mass (1)



Electron
Neutrino, ν_e

Muon, μ

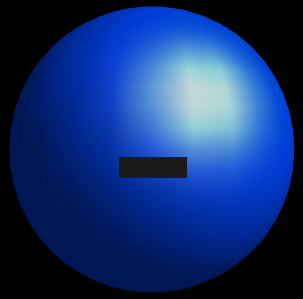
mass (200)



Muon
Neutrino, ν_μ

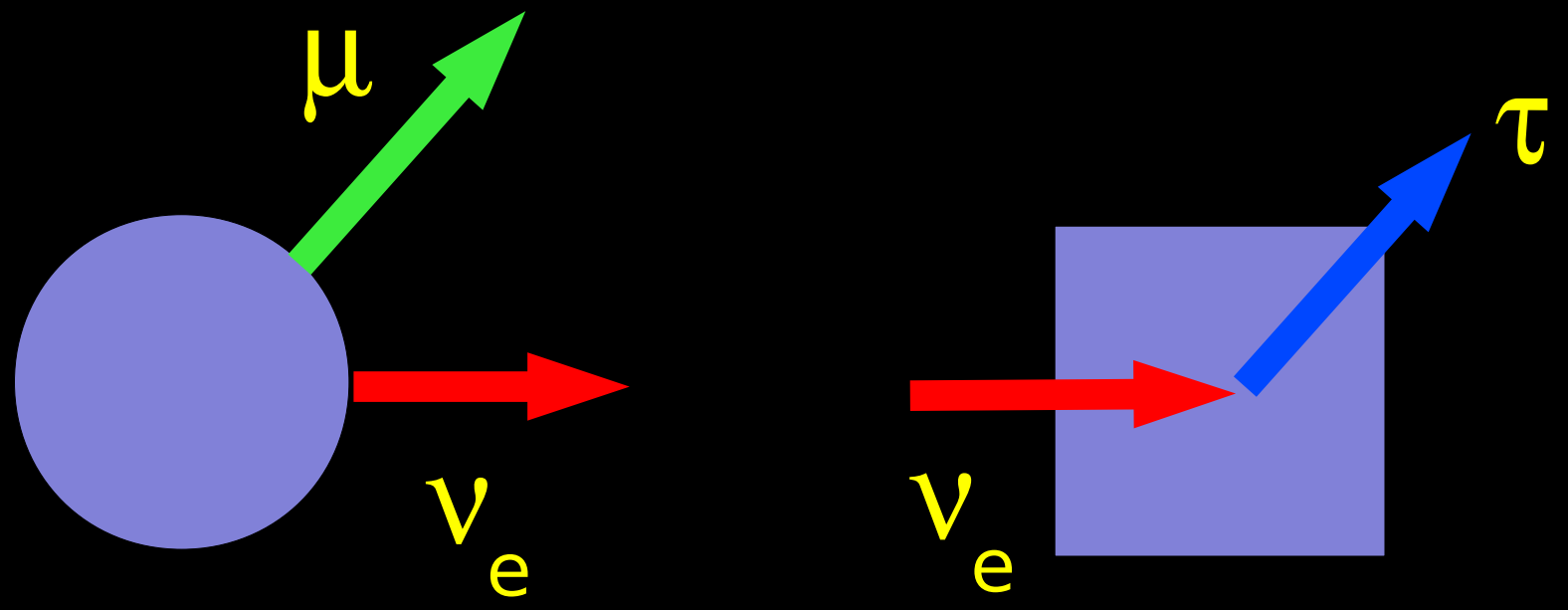
Tau, τ

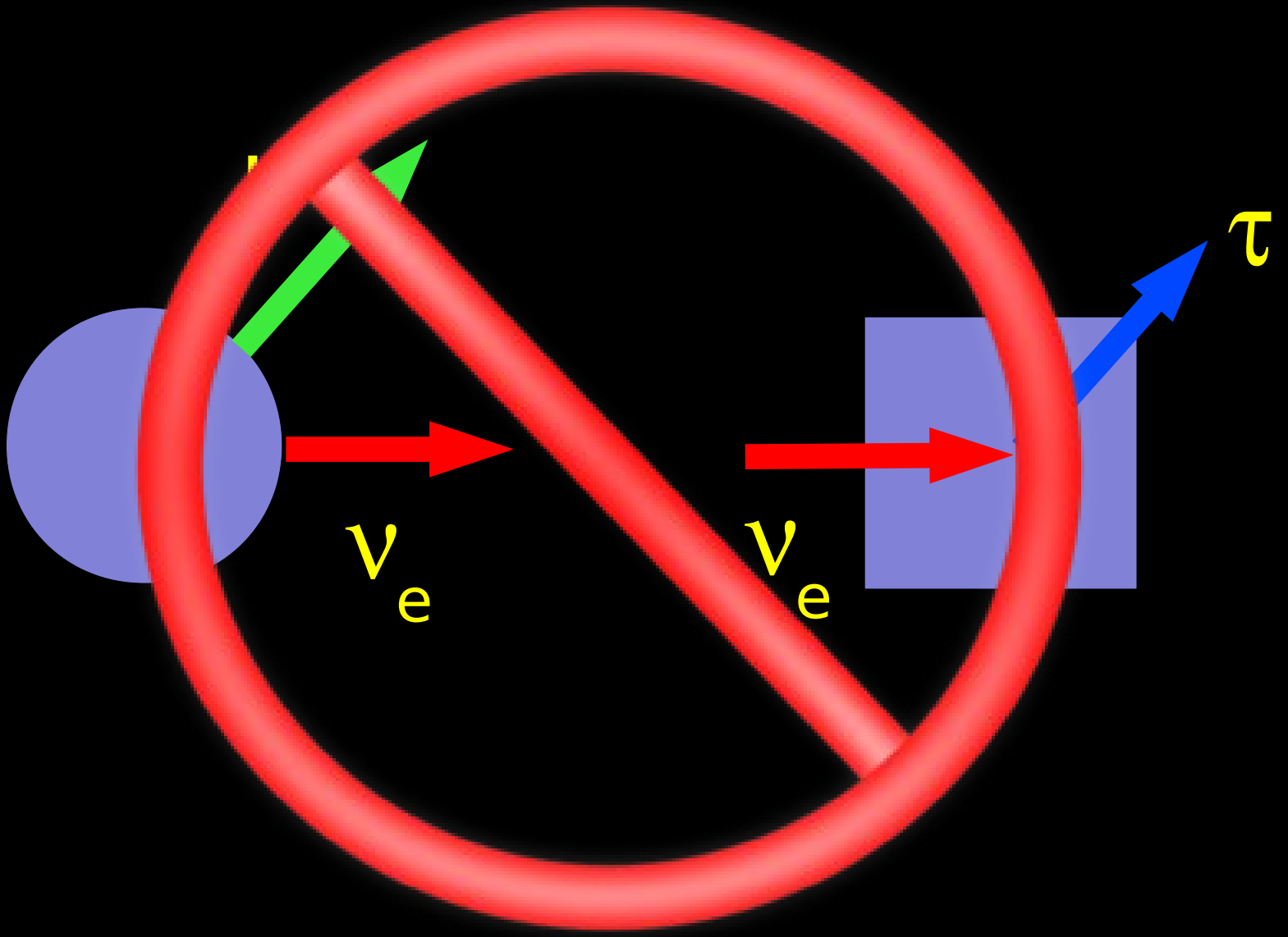
mass (3500)



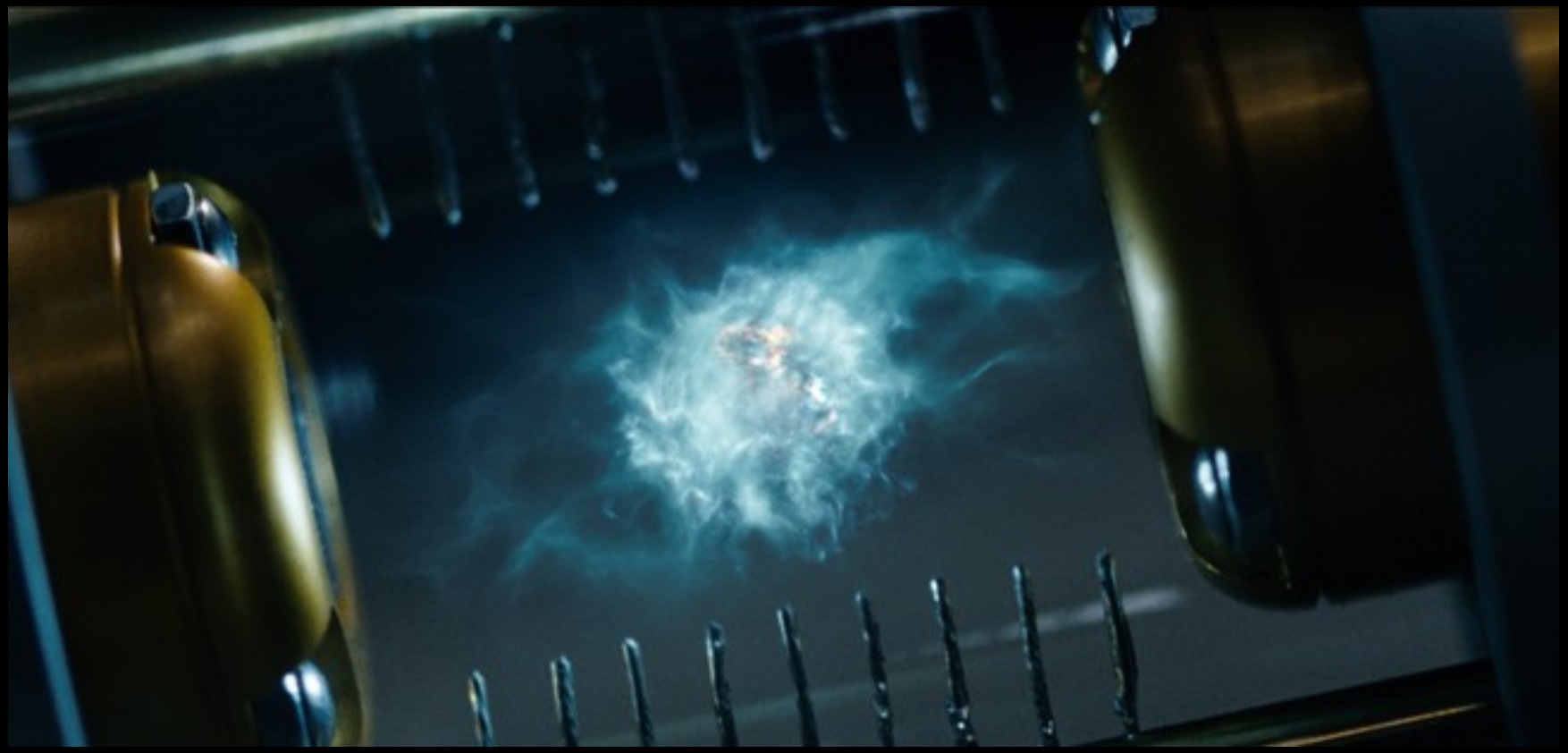
Tau
Neutrino, ν_τ

3 Lepton Types


μ
ν_e
τ
ν_e


τ
ν_e
ν_e

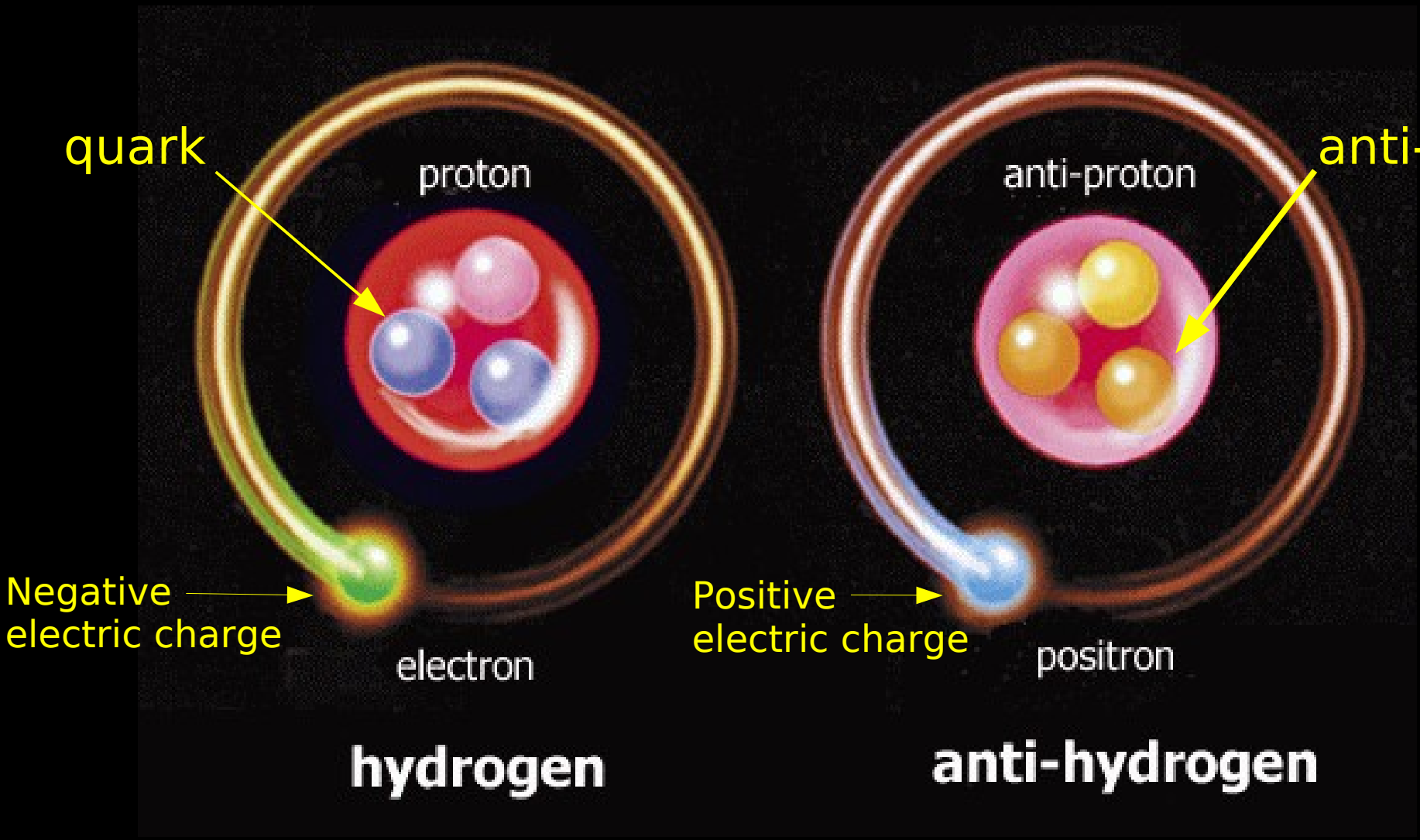
Antimatter is not....



From Angels and Demons, Dan Brown, 2009

Matter

Anti-Matter



Positron, e^+

mass (1)

Electron Antineutrino, ν_e

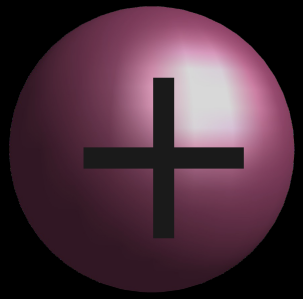
Muon, μ^+

mass (200)

Muon Antineutrino, ν_μ

Tau, τ^+

mass (3500)

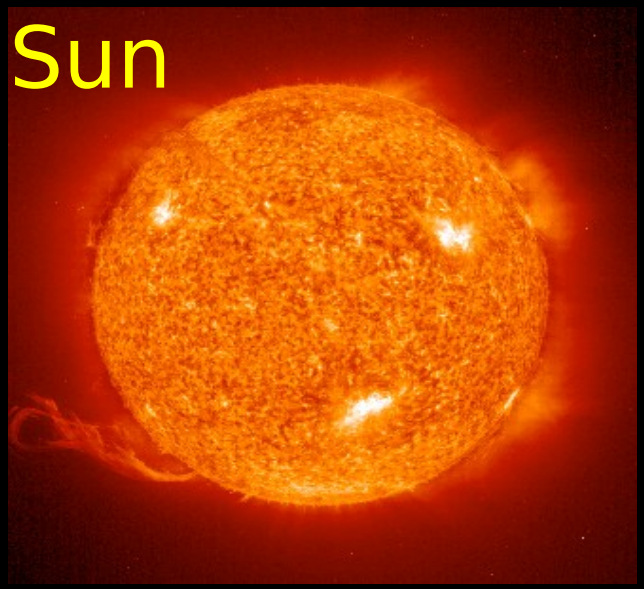


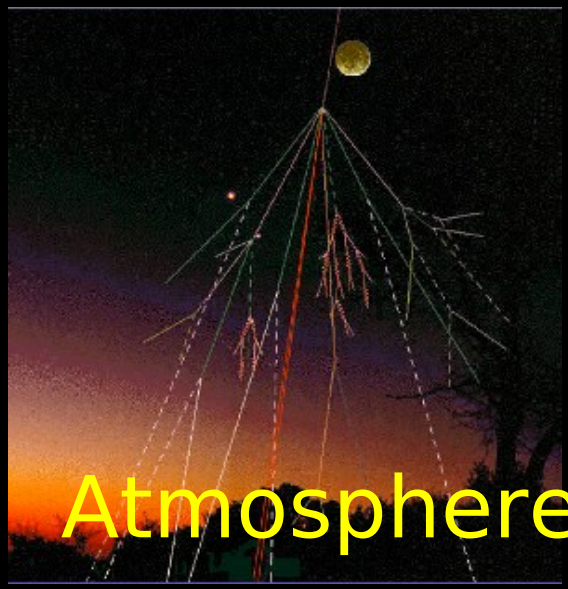
Tau Antineutrino, ν_μ

3 Antiparticles

Where do they come from?

Everywhere....

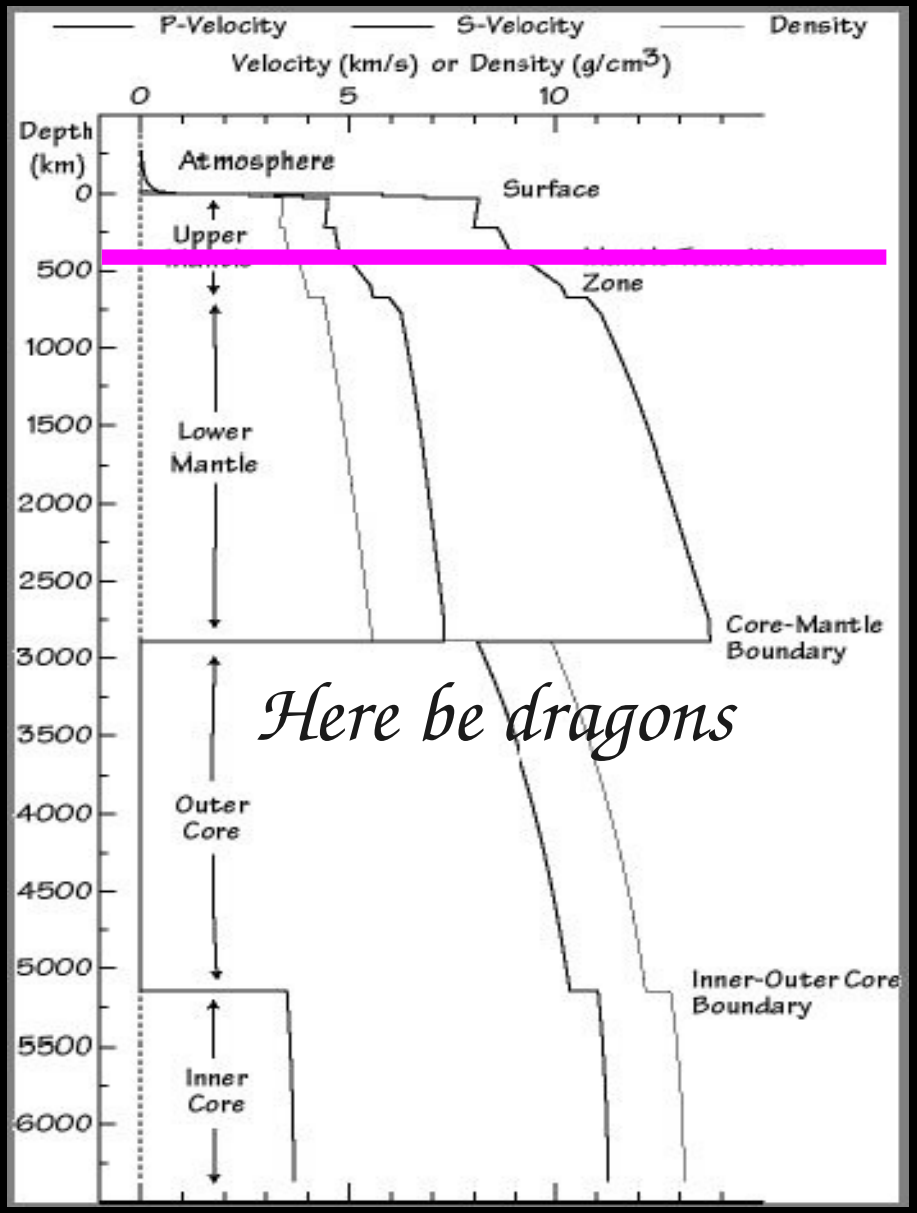


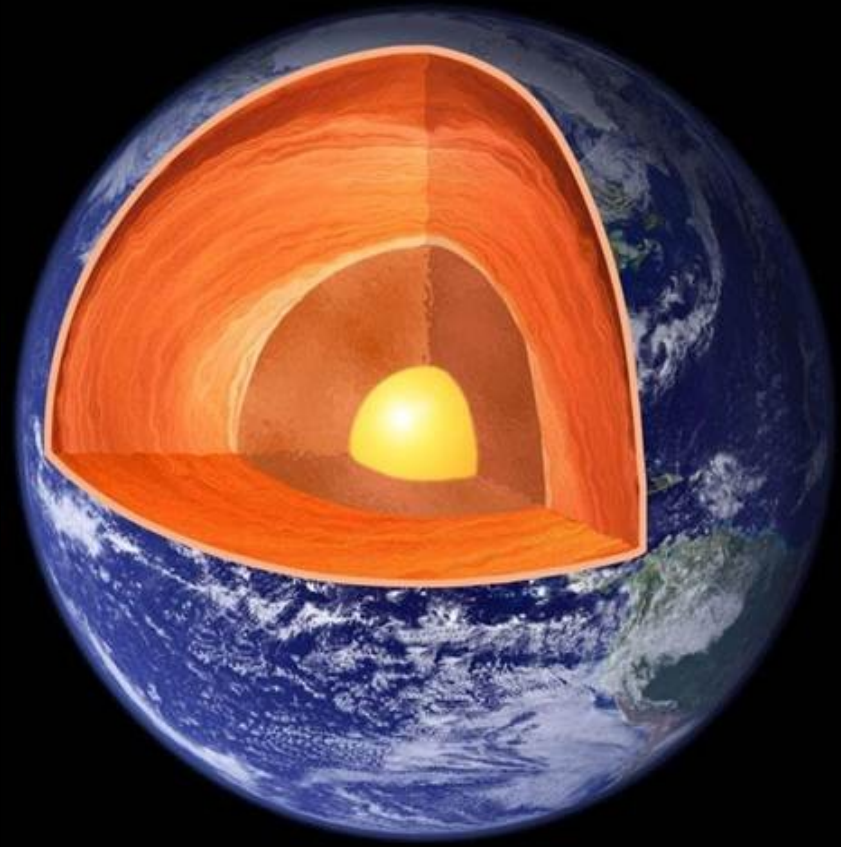


Reactors

Accelerators

Geoneutrinos





Earth's heat source is probably radioactive decay....which generates neutrinos

They are present in vast numbers

≈ 5 billion per cm^2 per second at the Earth


5,000,000,000,000,000,000 solar ν just
went through you

So why don't we notice?

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

The probability of a single neutrino to interact with a single target is less than 1 in 10^{40}

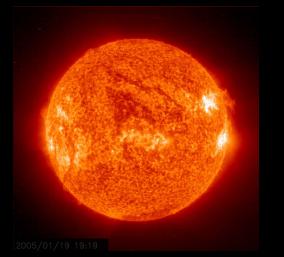
To a neutrino a planet is mostly empty space.

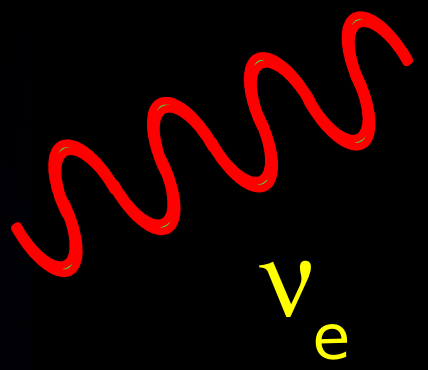
"The chances of a neutrino actually hitting something as it travels through all this howling emptiness are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich."

Douglas Adams

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

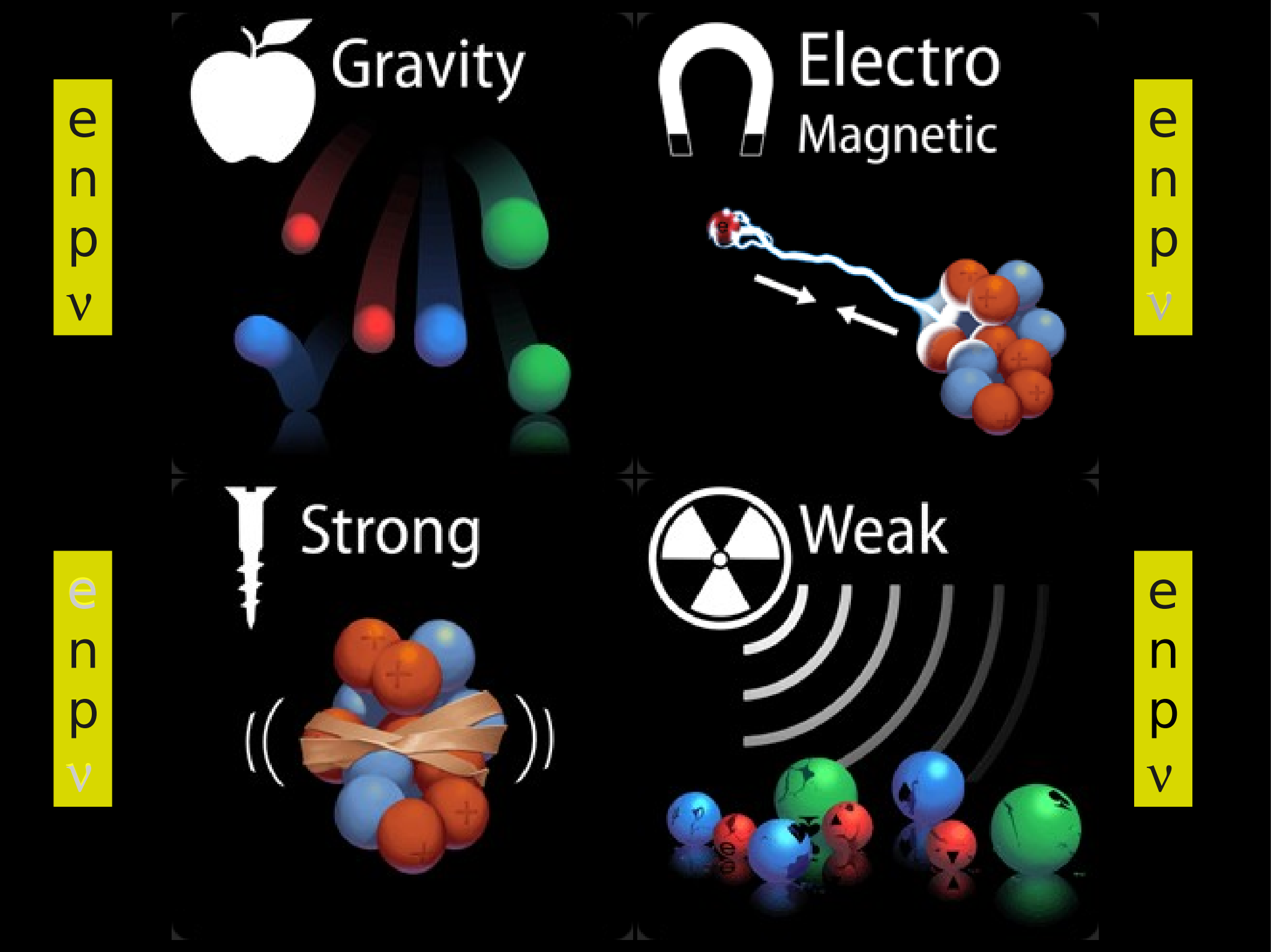
$= 0.000000000000005$





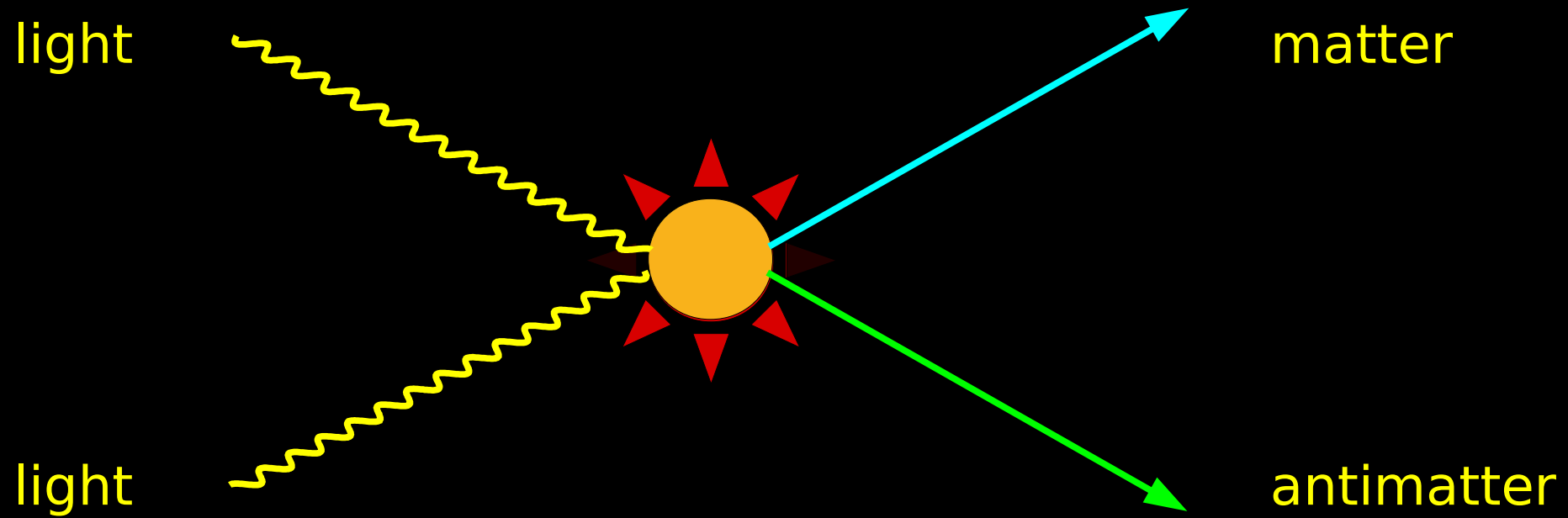

FreeFoto.com

Probability ≈ 2×10^{-13}


Gravity
Electro
Magnetic
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



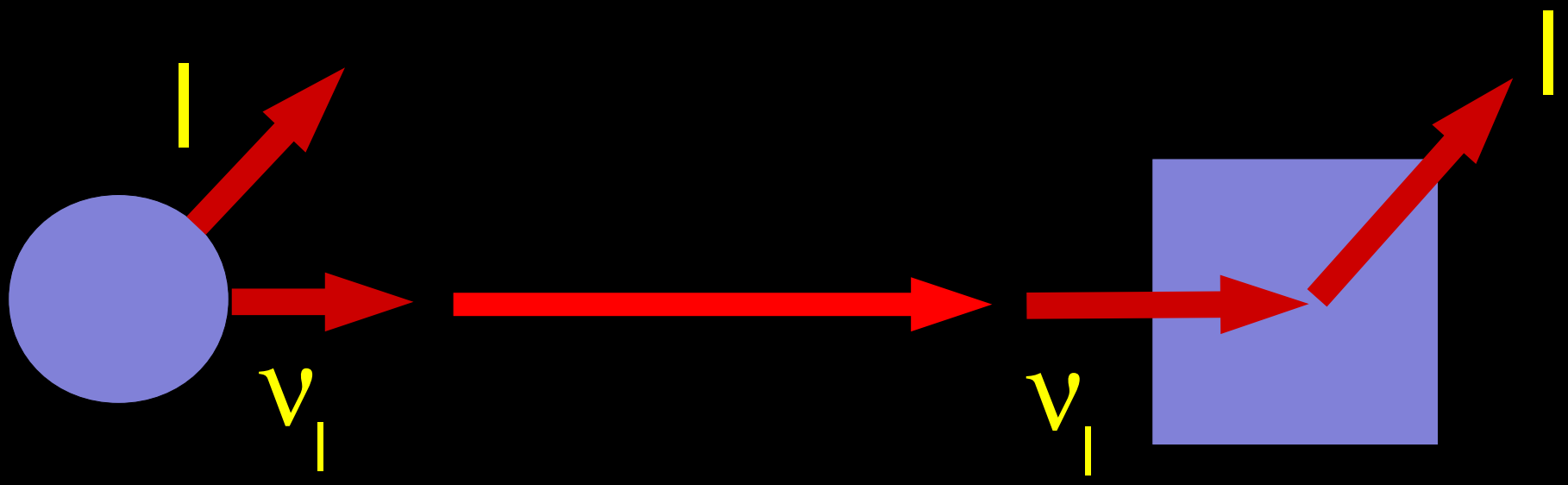
Equal amounts created - but no antimatter now - so matter and antimatter must behave differently after creation

Understanding this is a *Big Physics Question*™

How are we going to study this?

Neutrino Oscillations

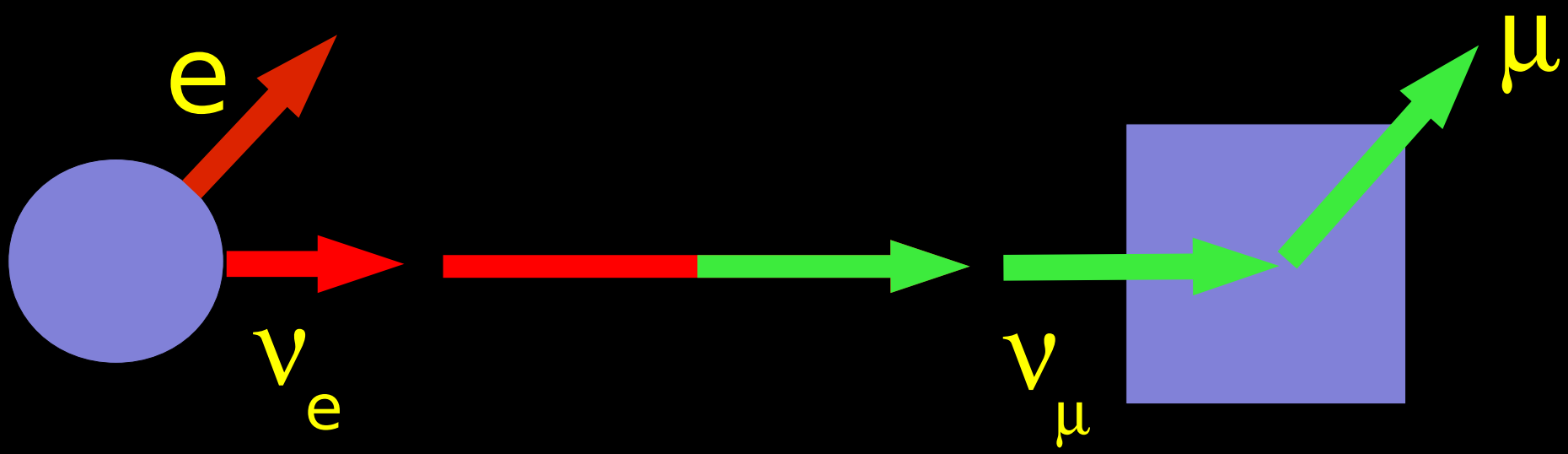
THE discovery in neutrinos of the last 20 years



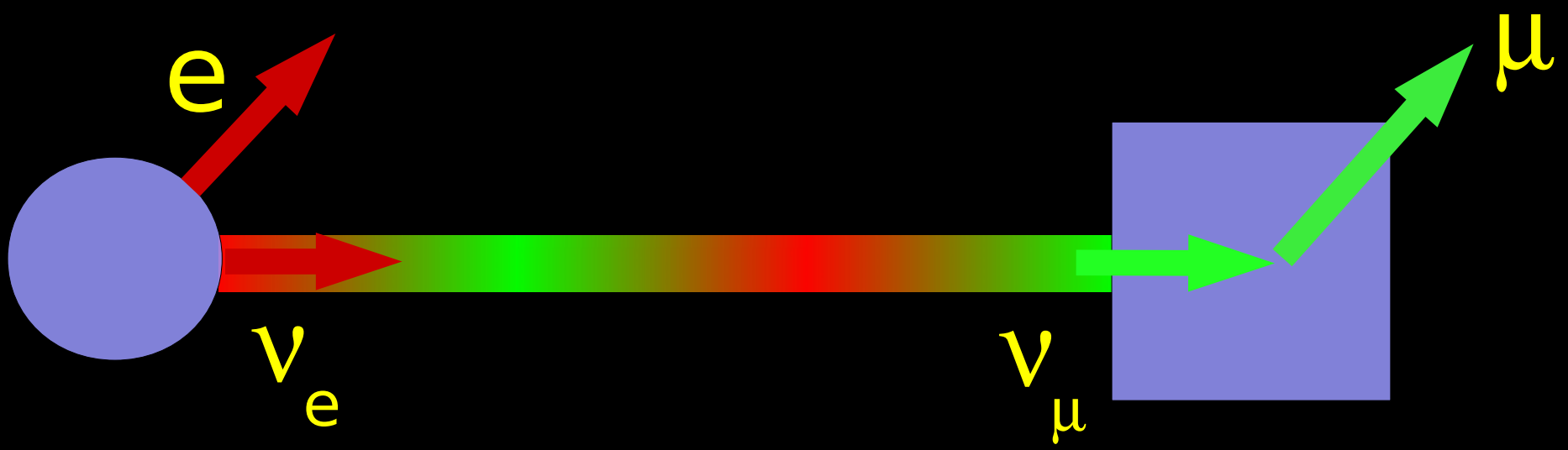
A typical neutrino experiment

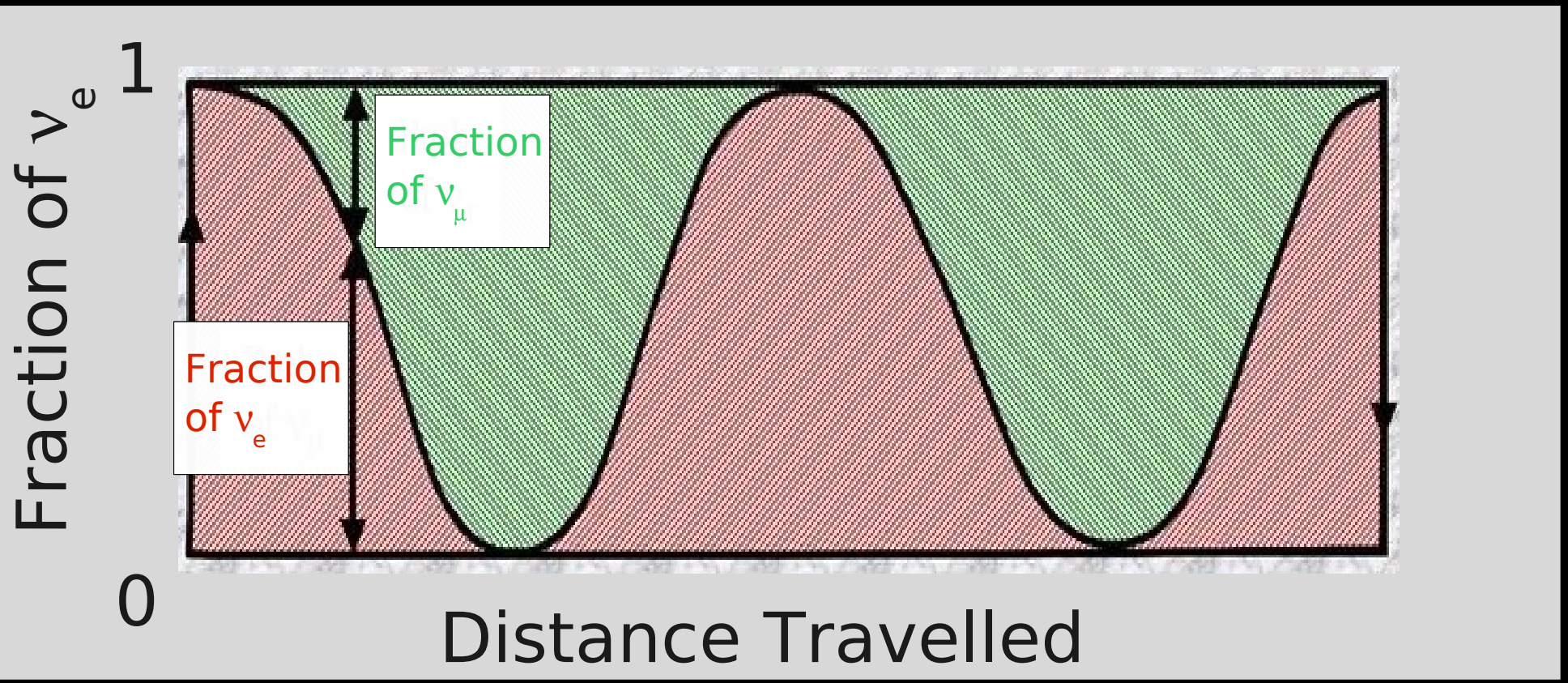
Neutrino Oscillations

THE discovery in neutrinos of the last 20 years



Neutrinos were changing flavour between sun and detector!


e
μ
ν e
ν μ


Fraction of ν e
1
0
Fraction of ν μ
Fraction of ν e
Distance Travelled

Oh Come on, pull the other one!

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

A. It's complicated...and can only be correctly described using the full mathematical machinery of quantum mechanics.

Neutrino Flavour Oscillations

$$|\nu_\alpha> = \sum_{i=1}^{3} U_{\alpha i} |\nu_i>$$ where $U_{\alpha i}$ is a unitary mixing matrix

Mass state ν_i travels from point (0,0) to (t,x) under the vacuum Schrodinger Equation

$$-\frac{\hbar^2}{2m}\frac{\partial^2 |\nu_k>}{\partial x^2} = E_k |\nu_k> = i\frac{\partial |\nu_k>}{\partial t} \quad \rightarrow \quad |\nu_k(t,x)> = e^{i(E_k t - p_k x)} |\nu_k(0,0)>$$

Hence $$P(\nu_\alpha(0,0) \rightarrow \nu_\beta(t,x)) = |<\nu_\beta(t,x)|\nu_\alpha(0,0)>|^2 = |\sum_k U_{\alpha k} e^{-i(E_k t - p_k x)} U^*_{\beta,k}|^2$$

Clearly $$P(\nu_\alpha(0,0) \rightarrow \nu_\beta(t,x)) = \sum_k \sum_j U_{\alpha k} U^*_{\alpha j} U_{\beta k} U^*_{\beta j} e^{i((E_j - E_k)t - (p_j - p_k)x)}$$

Given $$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \quad P(\nu_\alpha(0,0) \rightarrow \nu_\beta(t,x)) = \sin^2(2\theta)\sin^2\left(\frac{E_1 - E_2}{2}\right)$$

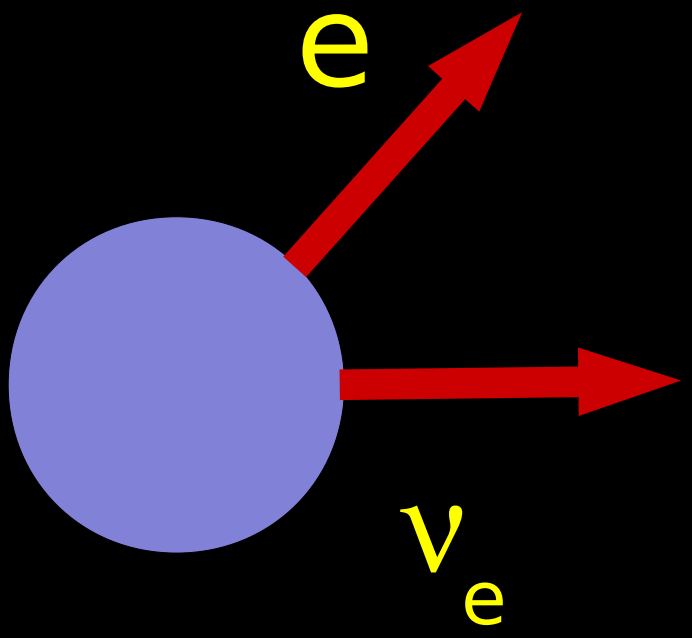
Assuming $p_1 \approx p_2$ we then have

$$P(\nu_\alpha(0,0) \rightarrow \nu_\beta(t,x)) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{12} L}{4E}\right)$$

In English this time?

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

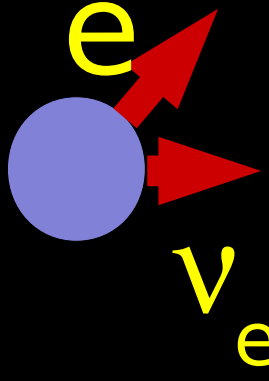
A. The ν_e isn't *a* particle. It's three!



ν_e ≡ “that thing which was always produced/detected with an electron but is never observed itself”

Quantum Stuff

Posit three other particles with definite mass : ν_1, ν_2 and ν_3



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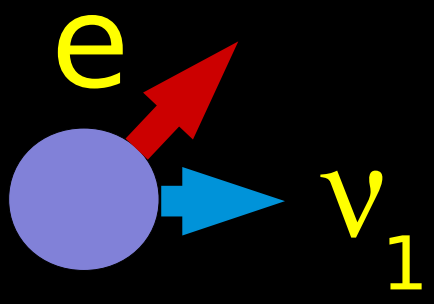
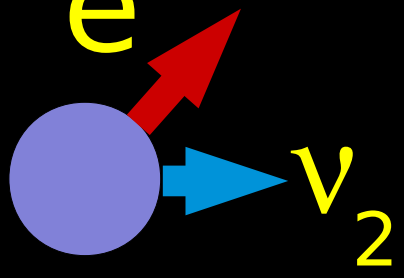


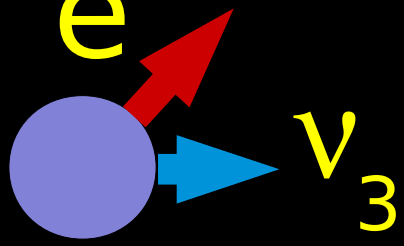
50%

or



30%

or

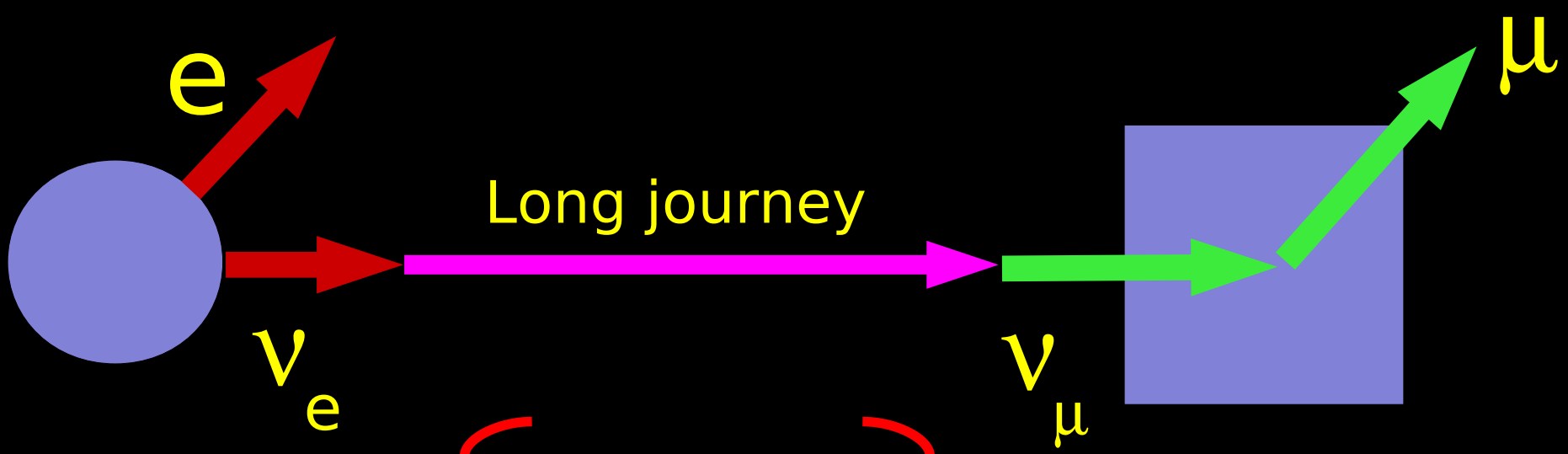


20%

Quantum Stuff

	ν_1	ν_2	ν_3
e	50%	30%	20%
μ	25%	30%	40%
τ	25%	30%	40%

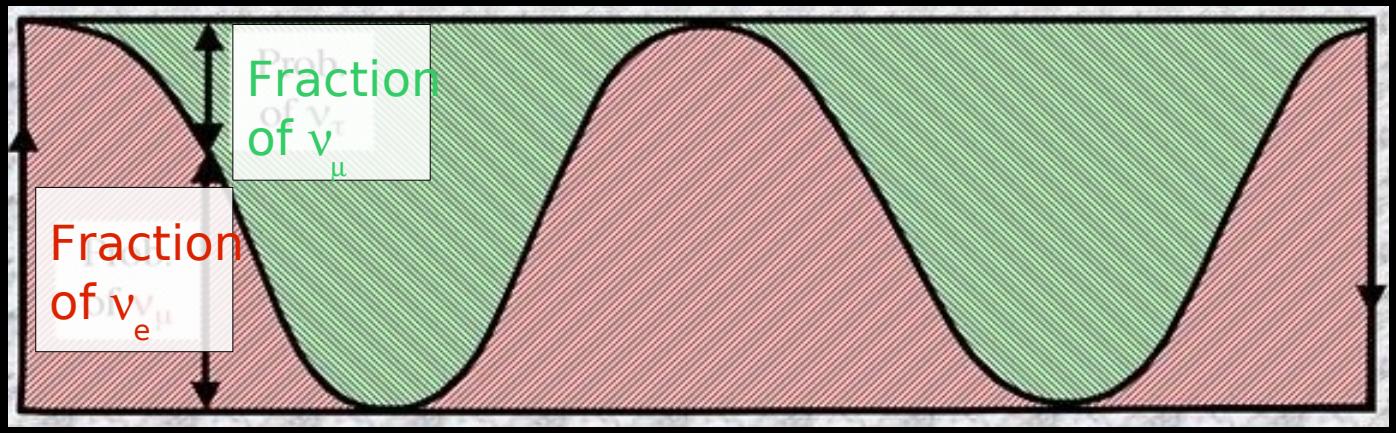
$P(e \rightarrow \nu_1 \rightarrow \mu) = (50\%) \times (25\%) = 12\%$



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



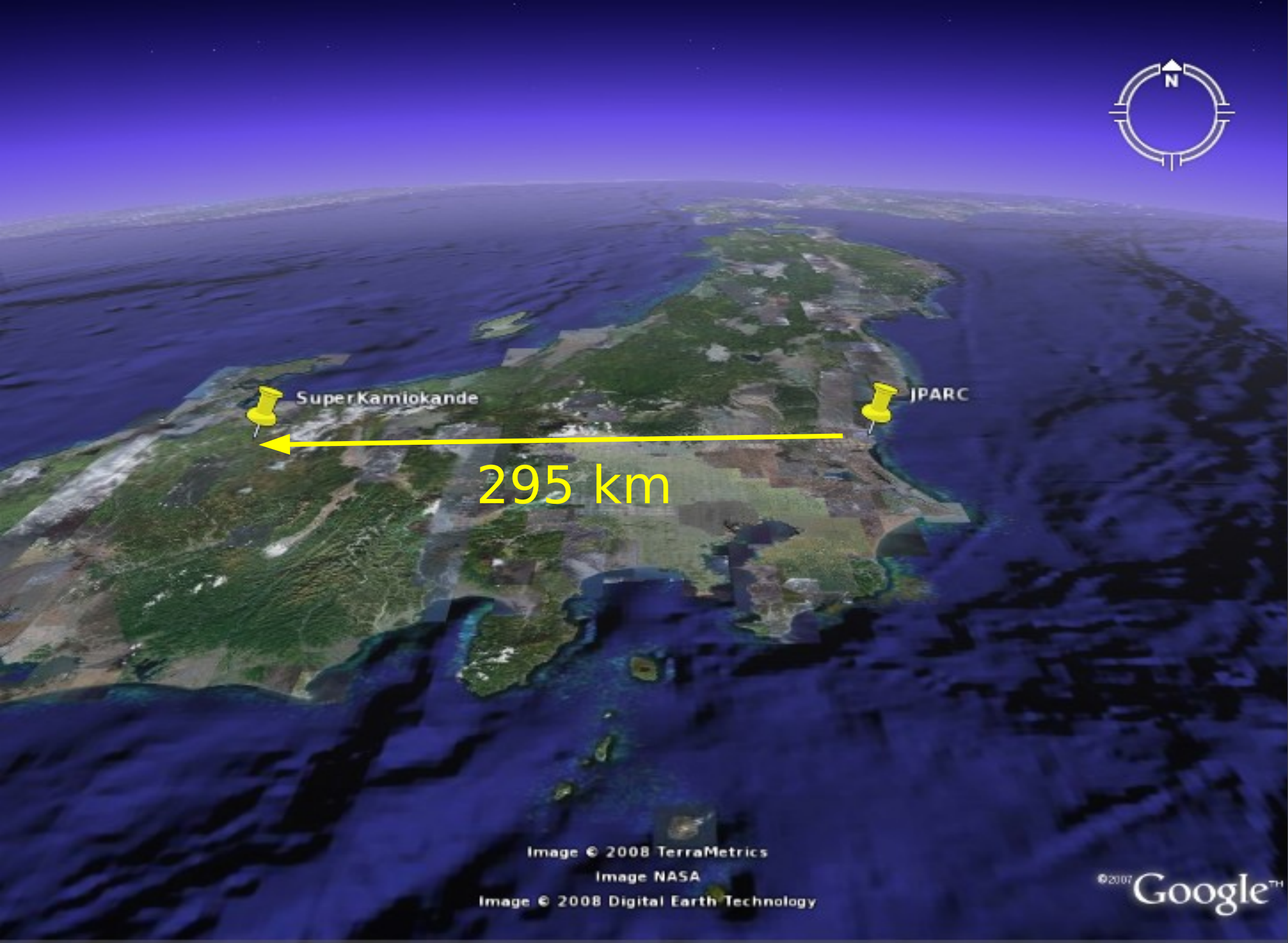
Why?

$$Prob\left(\nu_\mu \rightarrow \nu_e\right) \neq Prob\left(\overline{\nu_\mu} \rightarrow \overline{\nu_e}\right)$$

If oscillation probability of neutrinos is different from that of anti-neutrinos, then we have a handle to study the matter/ antimatter asymmetry

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


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

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?

“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


Thank you

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

‘‘...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

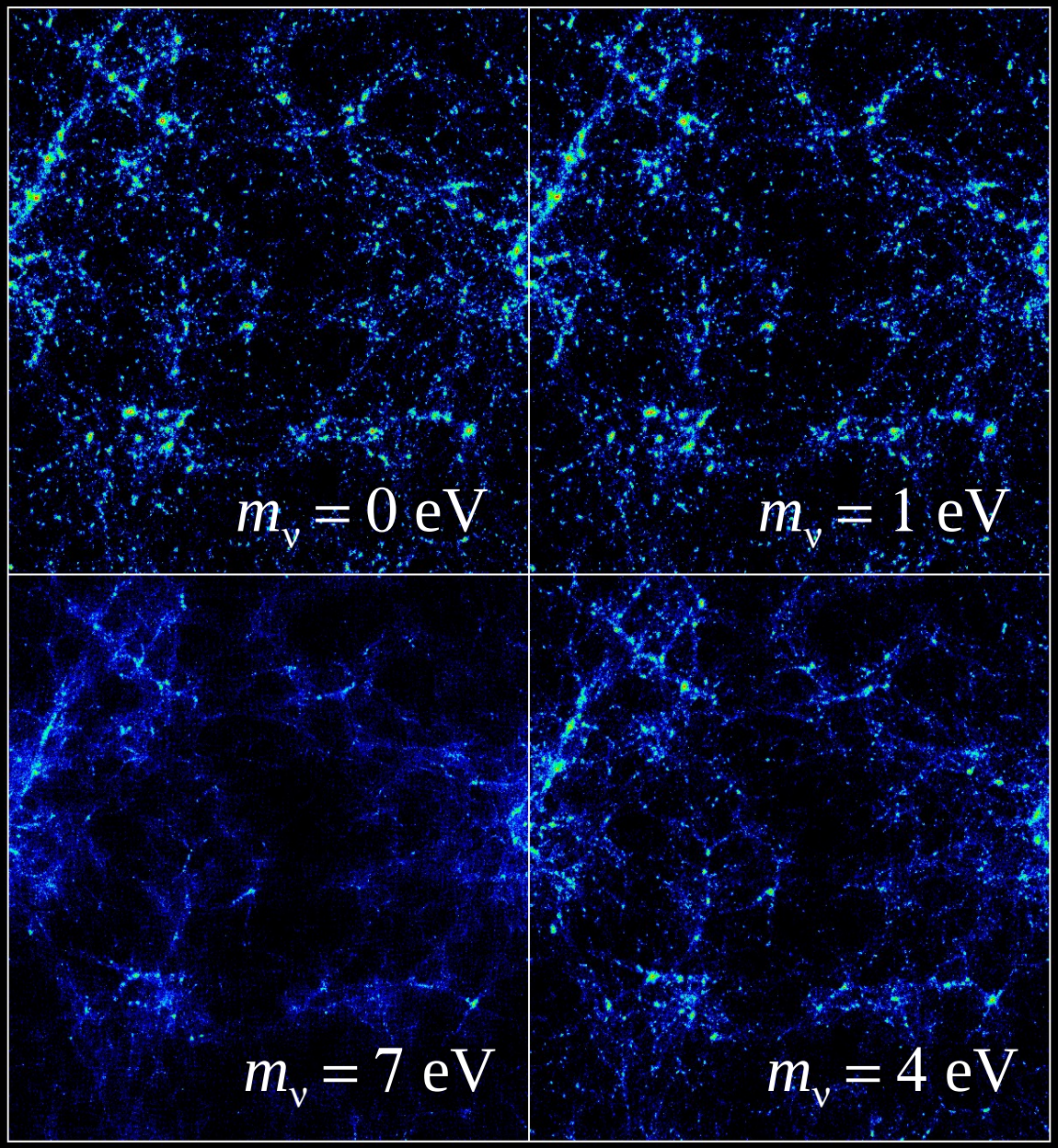
Why do blue sky research?

- Curiosity about the world around us.
- 5-10% 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
Security scanners
Rock Imaging
Cancer treatment using next gen cyclotrons

- 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

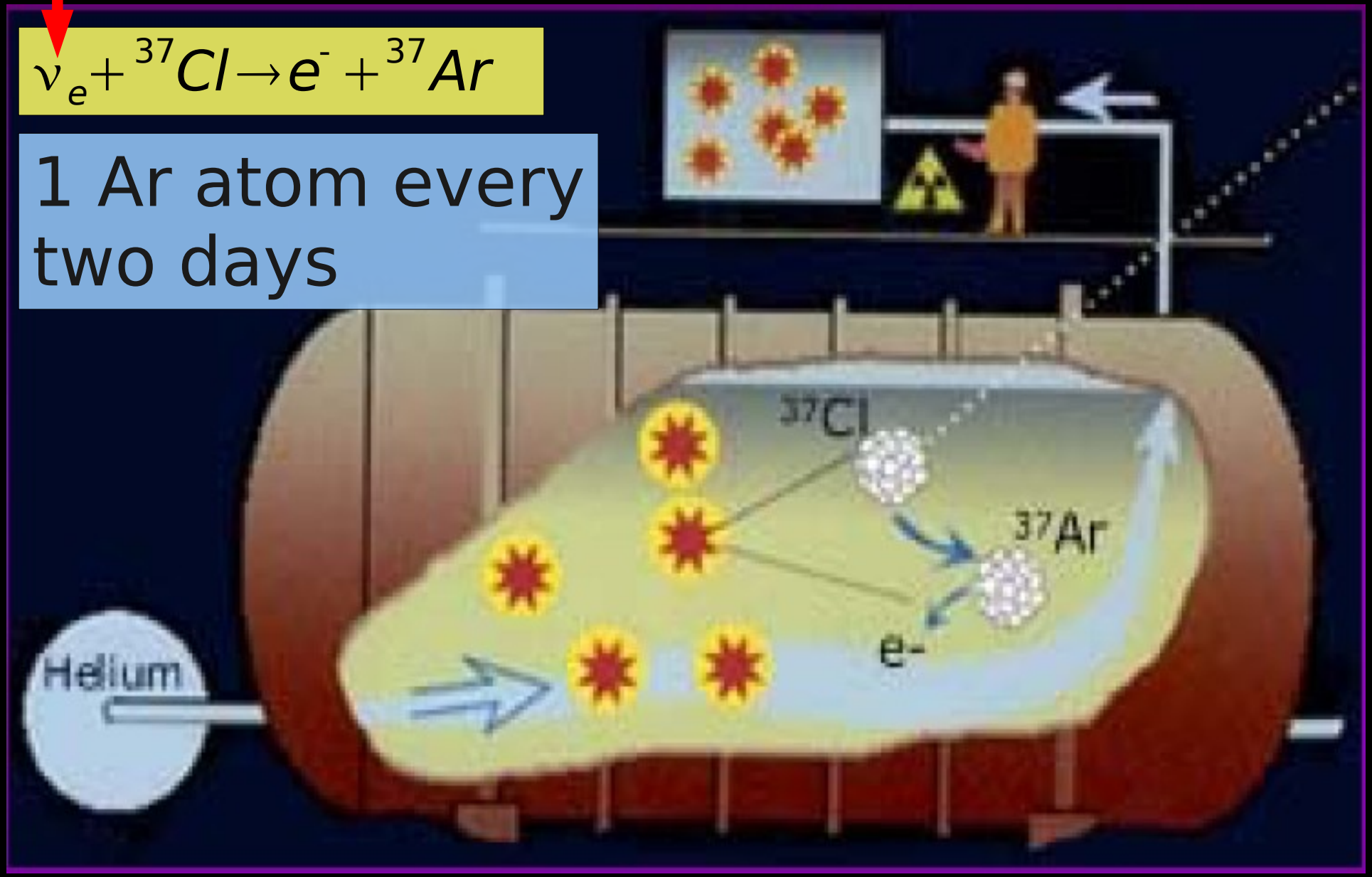


An atom a day

Only

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

1 Ar atom every two days



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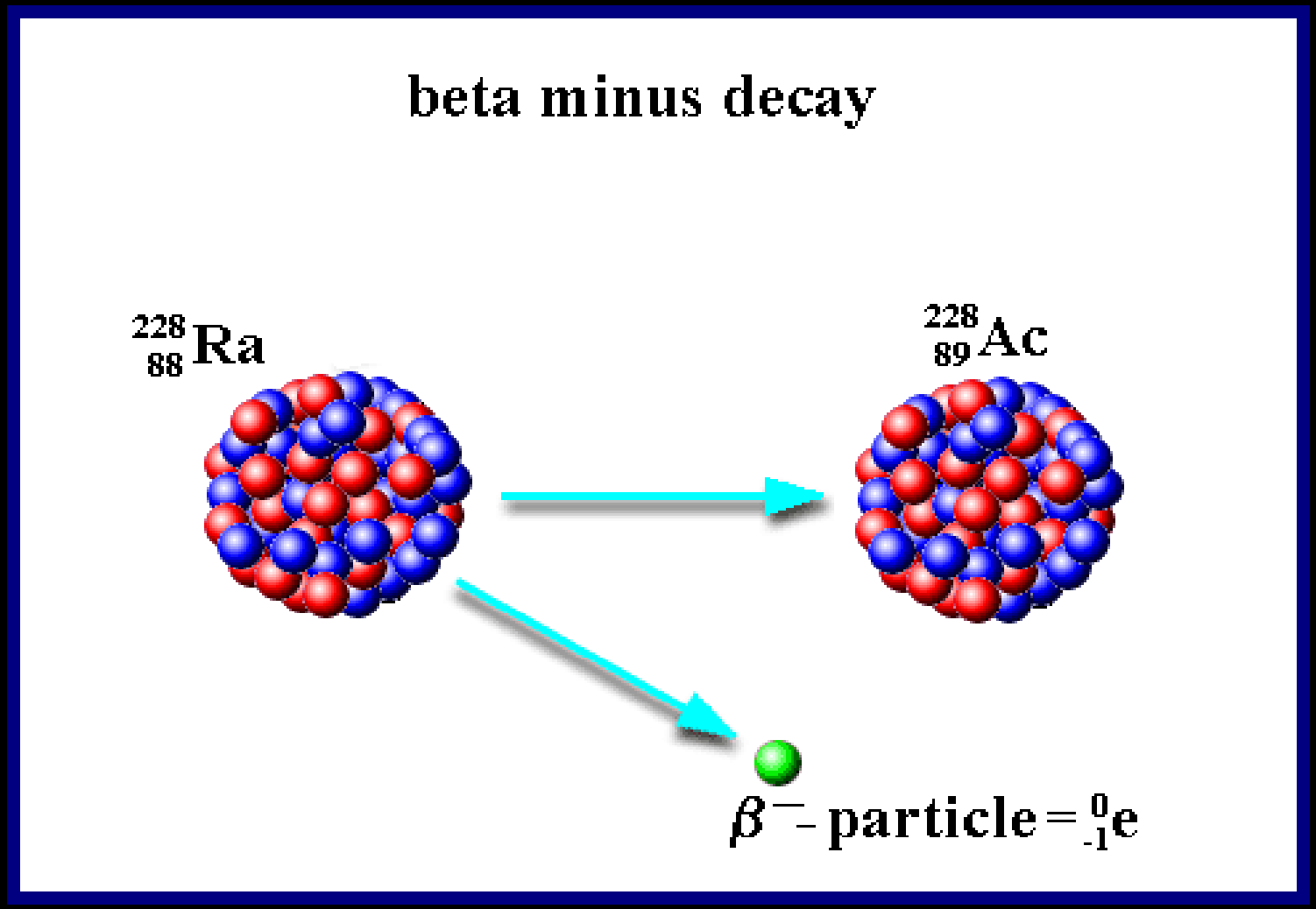

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Neils Bohr

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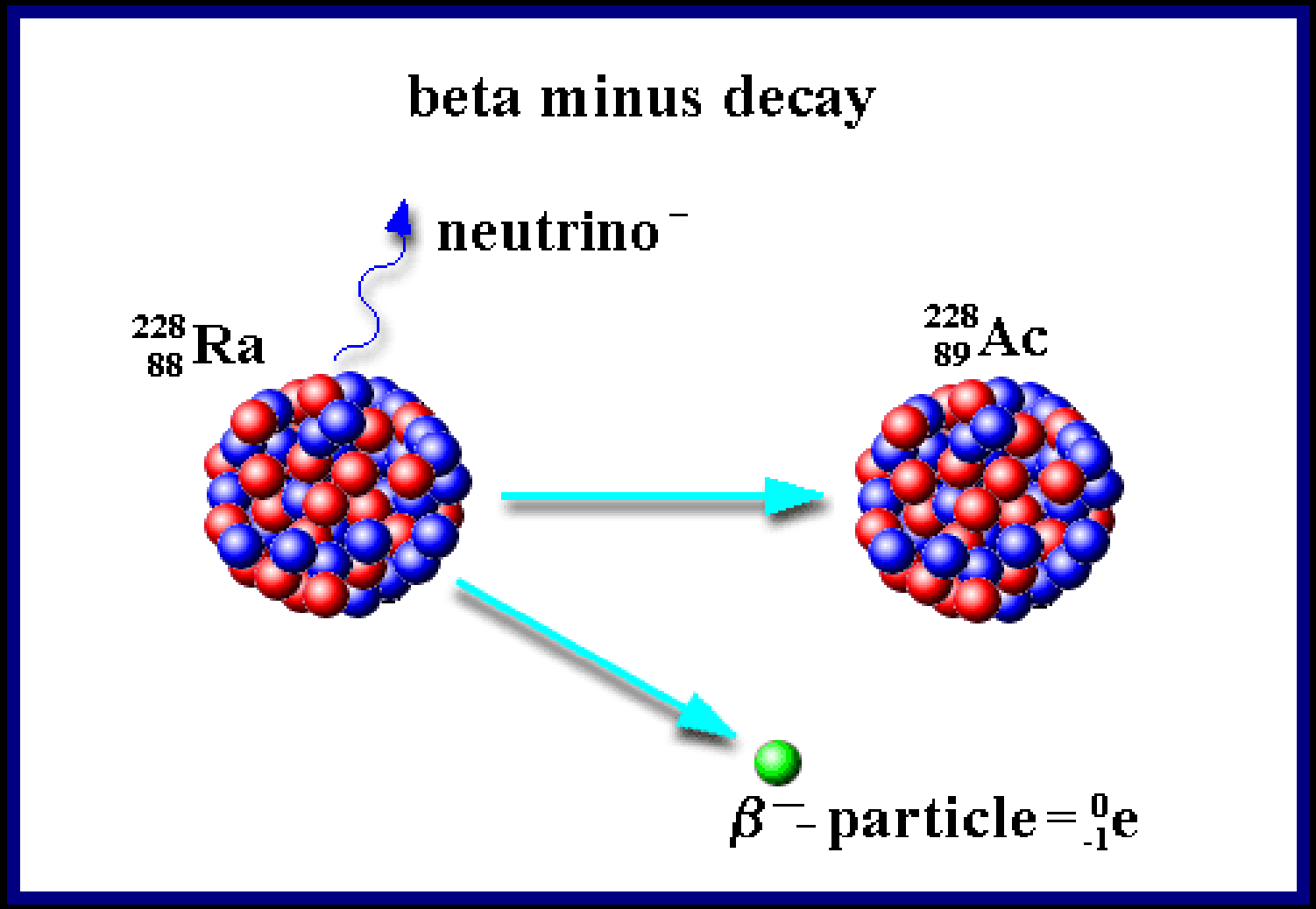
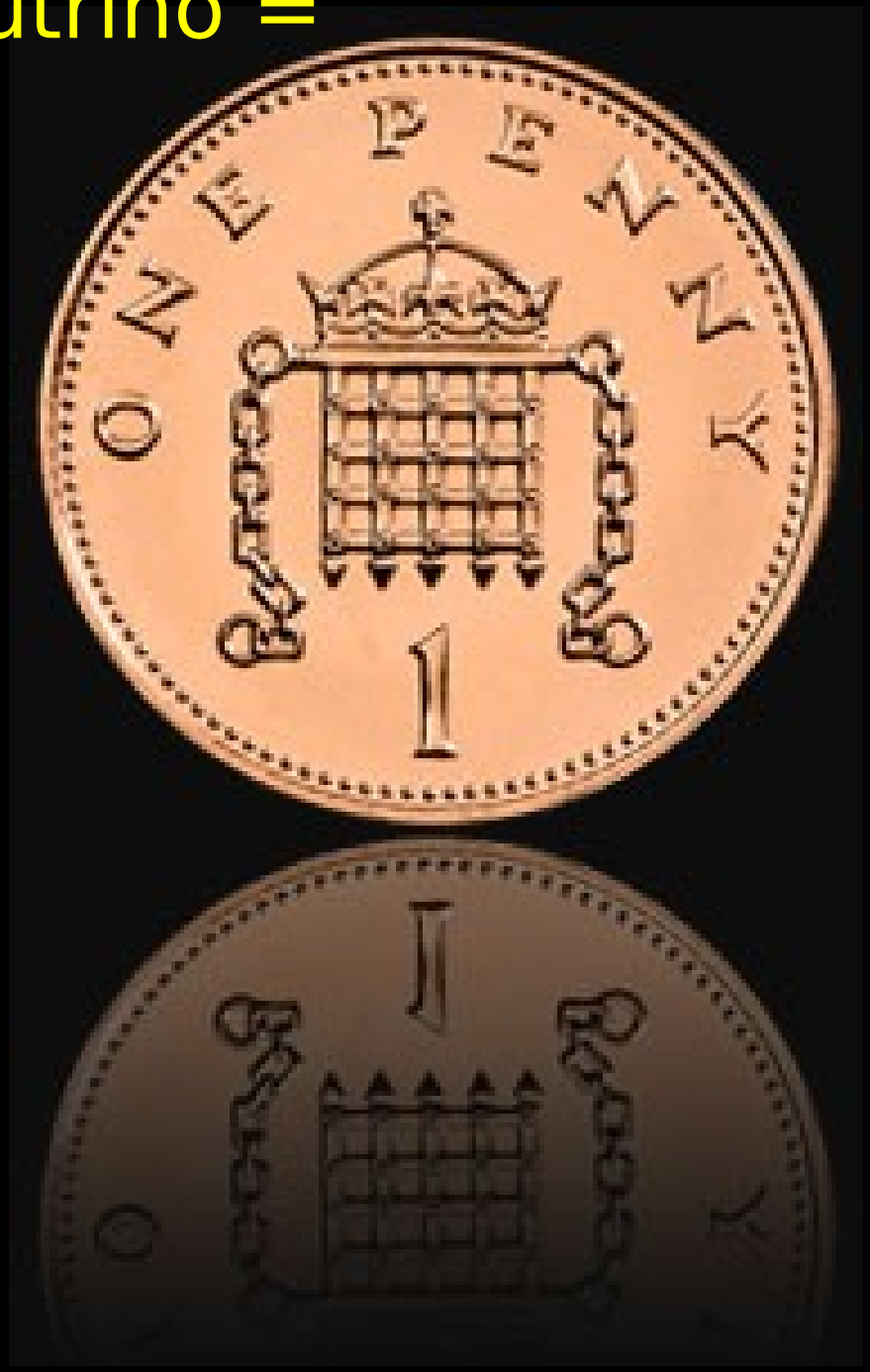


Energy(Ra) = Energy(Ac)+Energy(e)
+ Energy(Neutrino)

What are neutrinos?

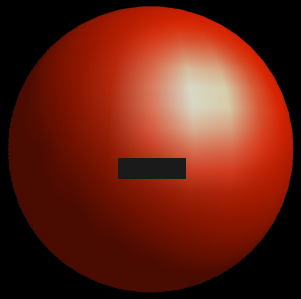
mass of a neutrino =



mass of an electron =

Electron, e

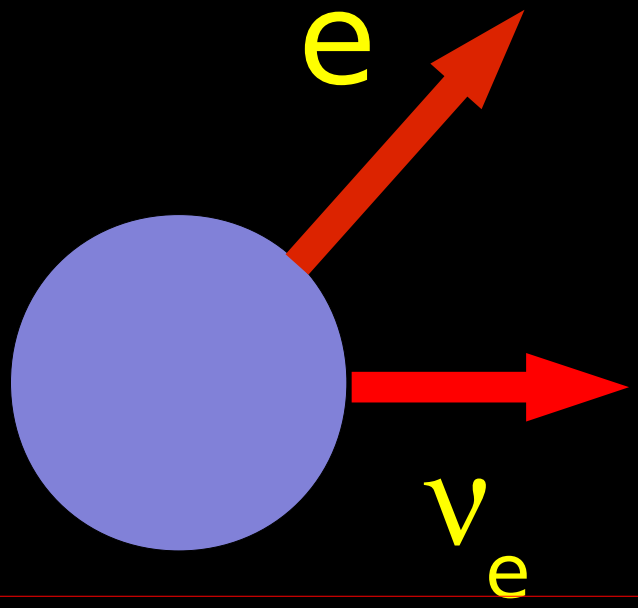
Electron Neutrino, ν_e

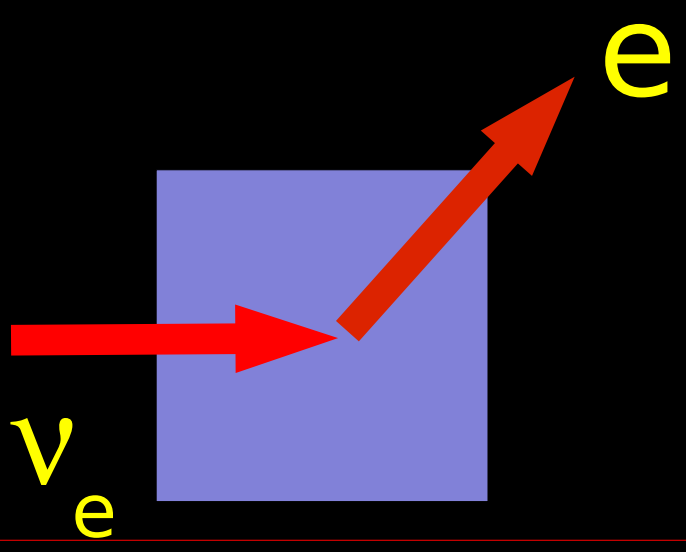


0

Tiny mass (1)

Very tiny mass
(<0.0000001)

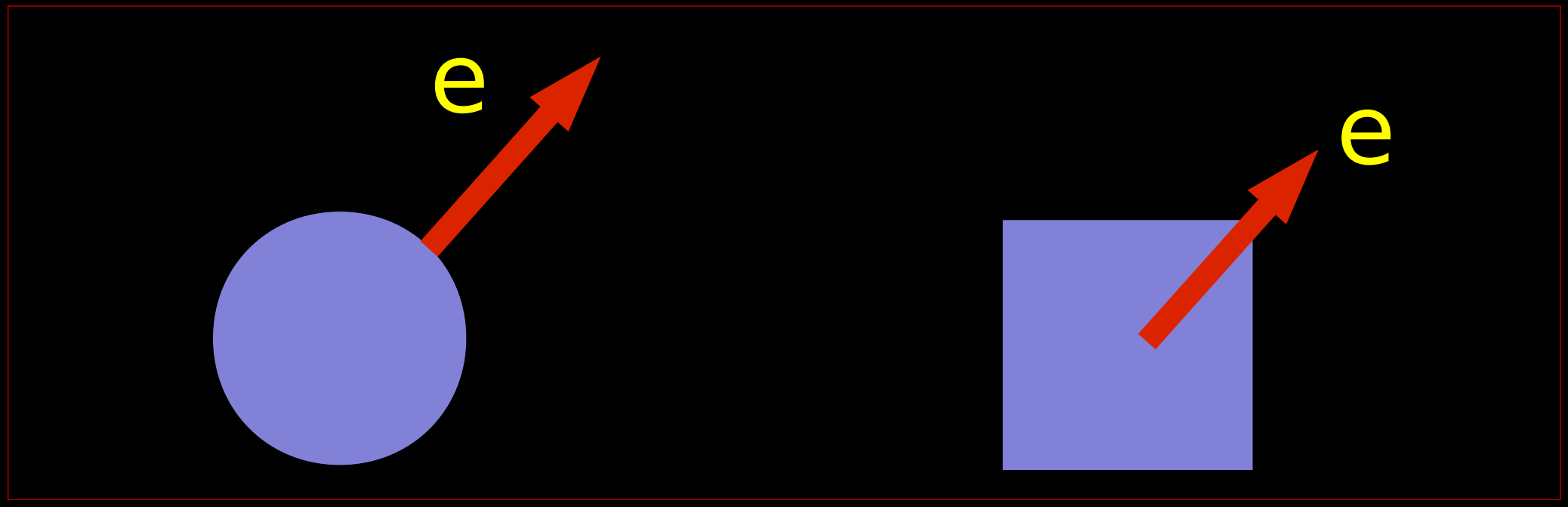


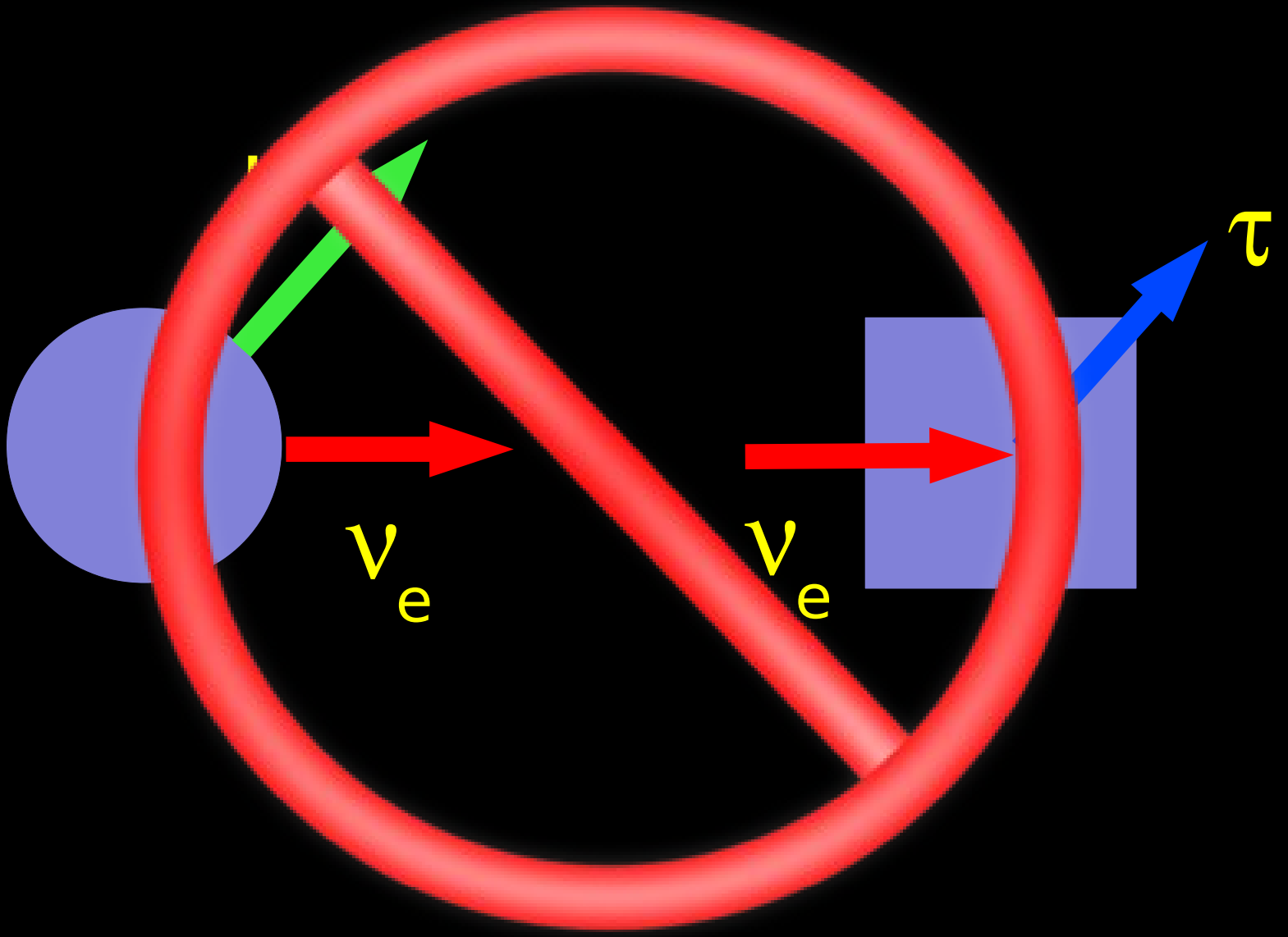


In experiments neutrinos are **NEVER** seen.

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.




τ
ν_e
ν_e

Positron, e^+

mass (1)

Electron
Antineutrino, ν_e

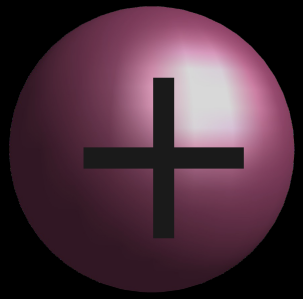
Muon, μ^+

mass (200)

Muon
Antineutrino, ν_μ

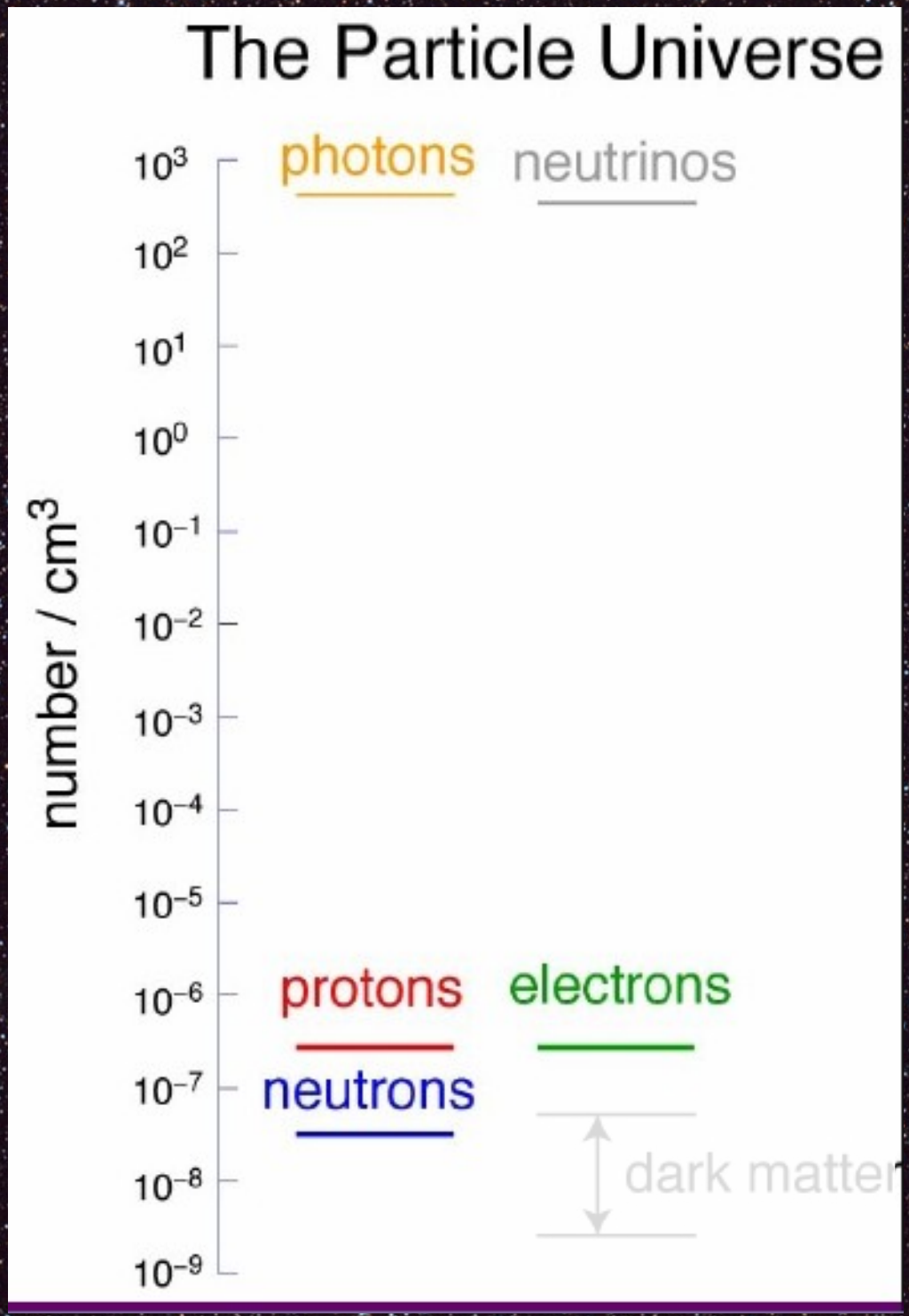
Tau, τ^+

mass (3500)



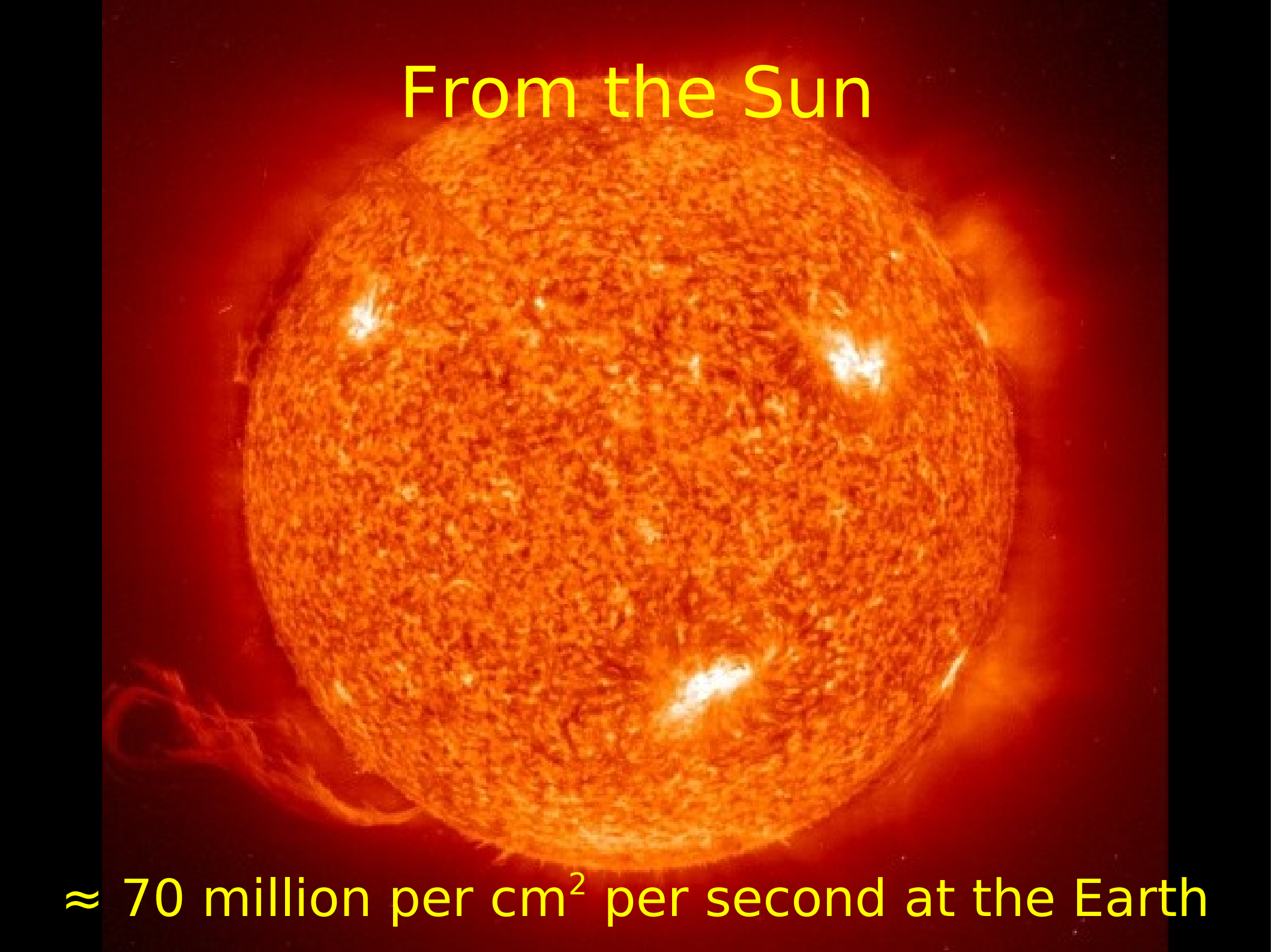
Tau
Antineutrino, ν_μ

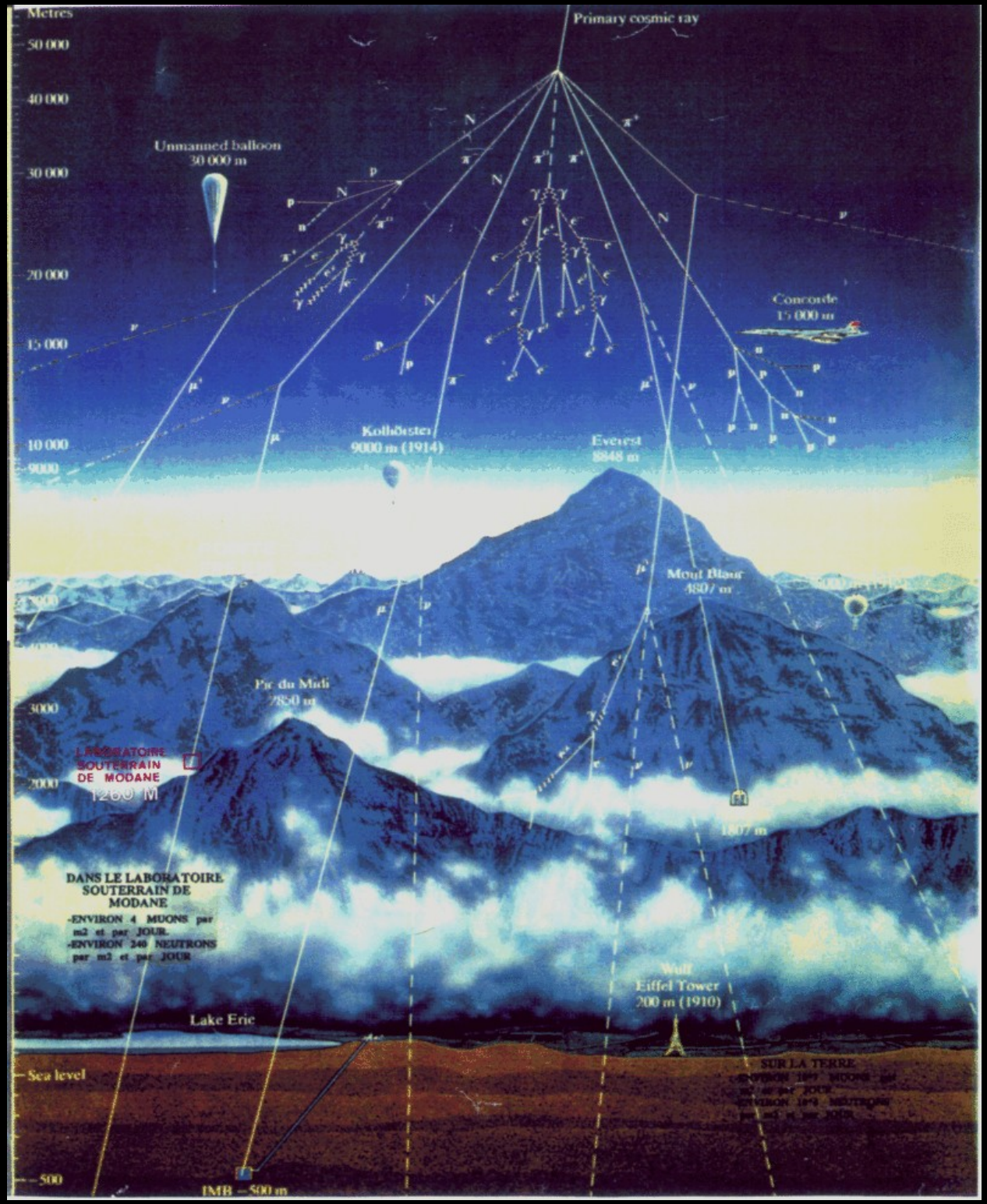
3 Antiparticles


The Particle Universe
photons
neutrinos
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}
number / cm^3
protons
electrons
neutrons
dark matter

From the Big Bang

Artist's conception


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



From Cosmic Rays.

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

Probability ≈ 2×10^{-13}


5,000,000,000,000,000,000 solar ν just
went through you

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

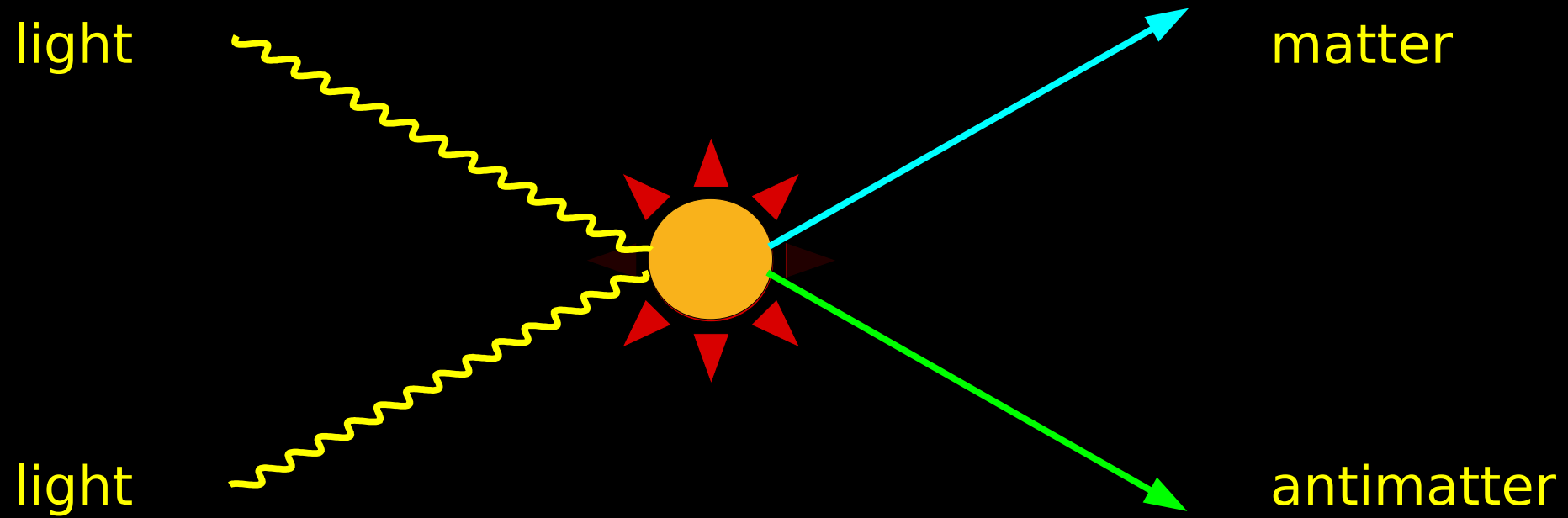
- Probes of environments that we otherwise cannot see
- Probes of objects too far away for anything else
- Cosmological and astrophysical implications
- Matter/Antimatter imbalance

NEUTRINO ASTROPHYSICS

The universe around us is composed of matter

But we think that equal amounts of matter and antimatter were produced in the Big Bang

Where's all the antimatter gone?



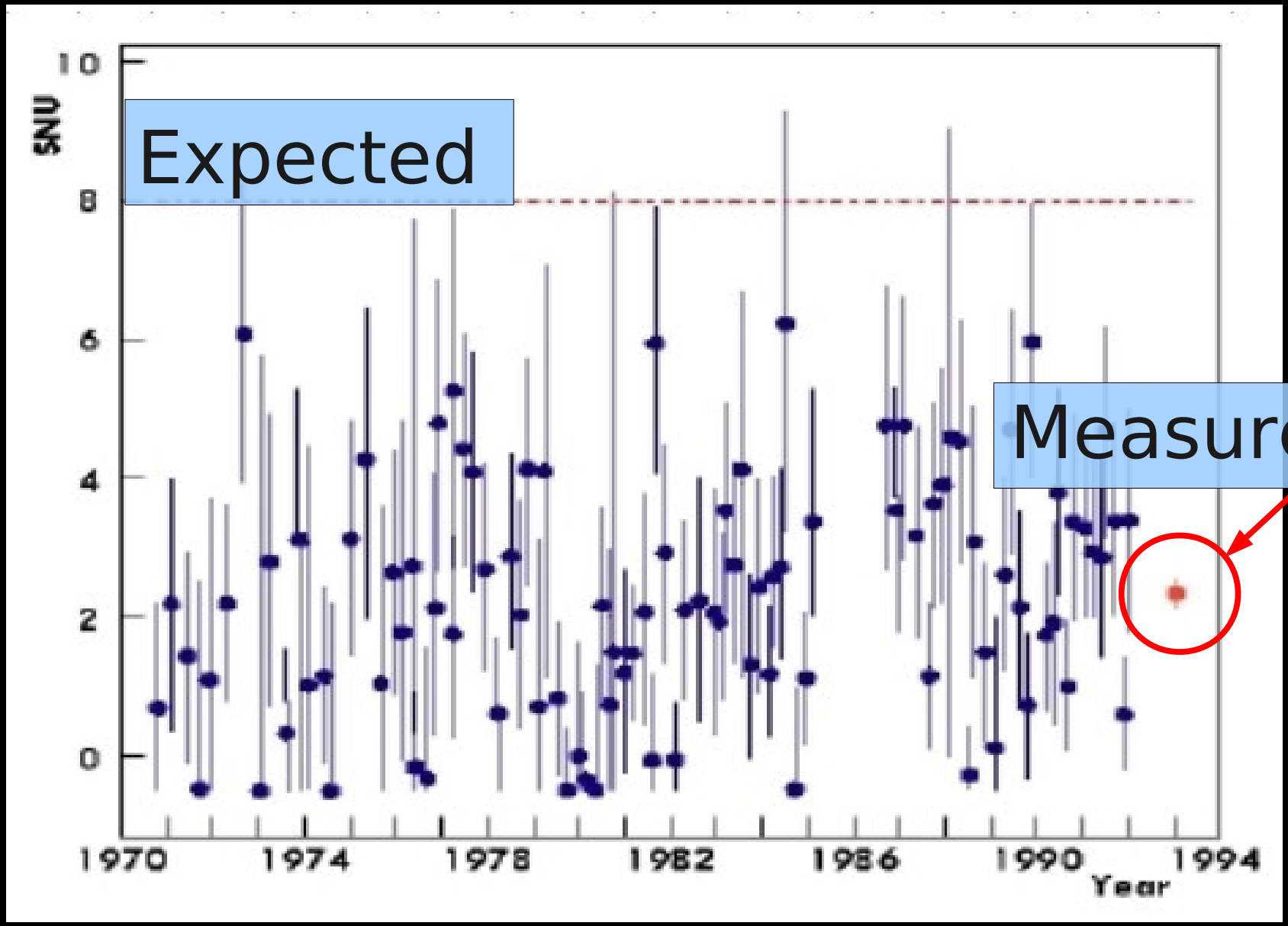
Equal amounts created - but no antimatter now - so matter and antimatter must behave differently after creation

Understanding this is a Big Question in Physics

The Sun is Broken!!!

Ray Davis – Early 1970s

Less than expected



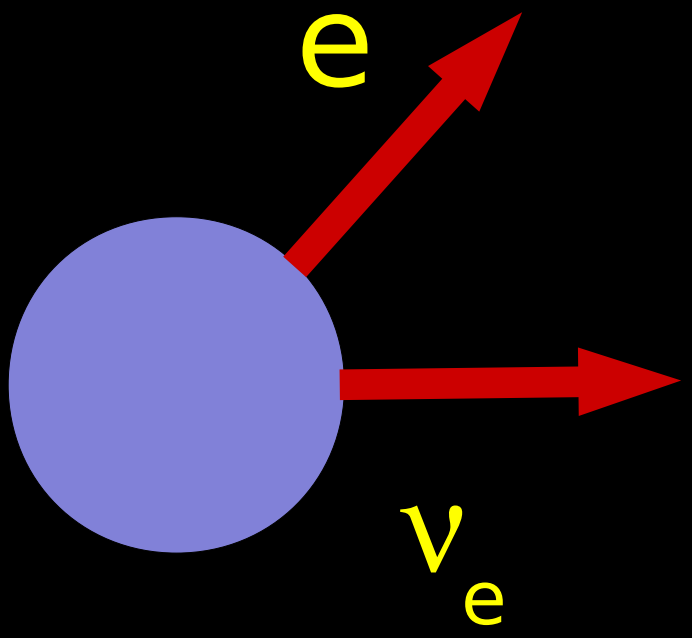
Oh Come on!

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

Oh Come on!

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”

Why bother?

$$P_{osc}(\nu_\mu \rightarrow \nu_e) \neq P_{osc}(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$$

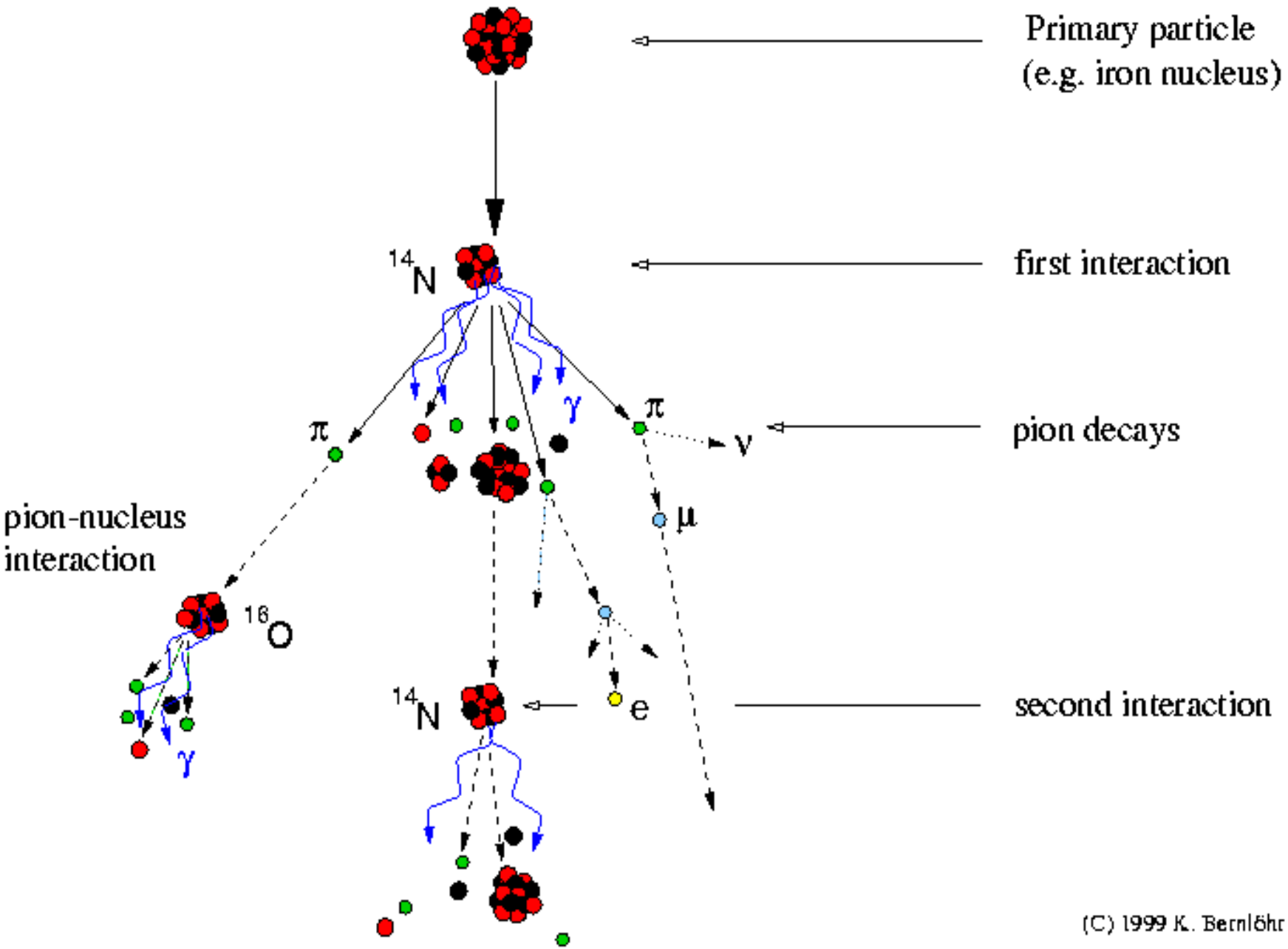
If oscillation probability of neutrinos is different from that of anti-neutrinos, then we have a handle to study the matter/ antimatter asymmetry

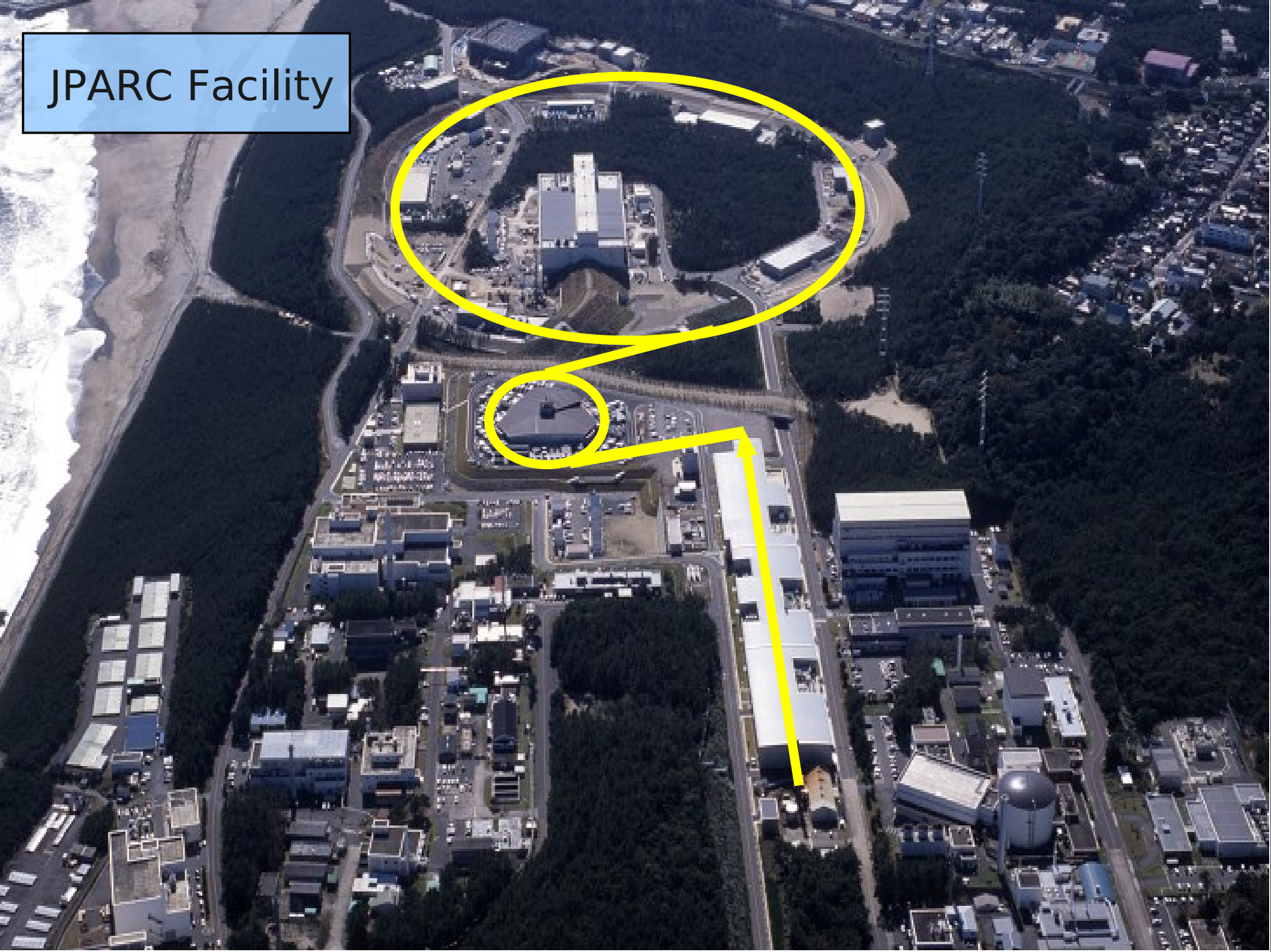
The T2K Experiment


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

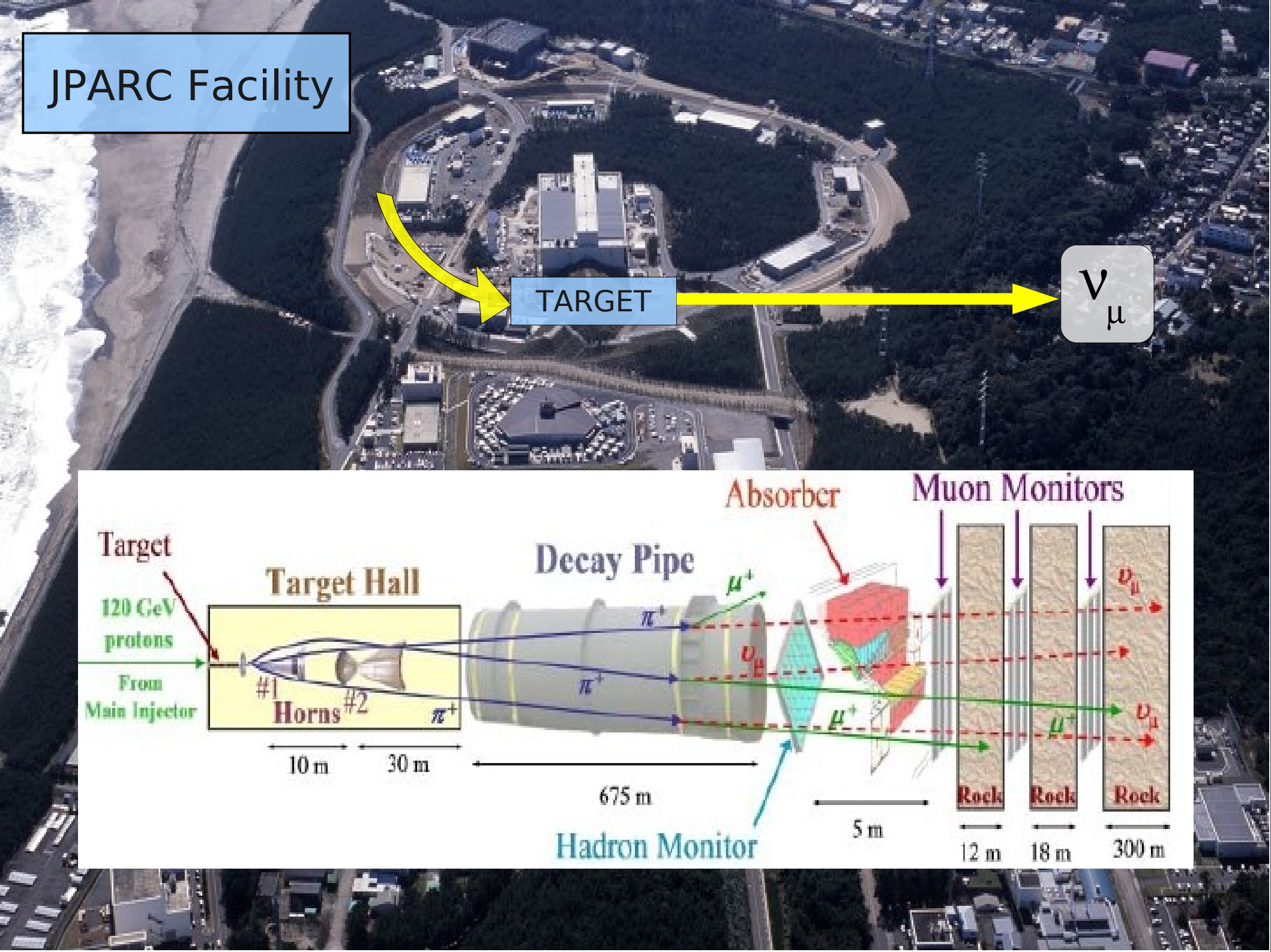

Tokai-mura
Shirane
N
© 2008 ZENRIN
© 2008 Europa Technologies
Image © 2008 DigitalGlobe
©2007 Google™

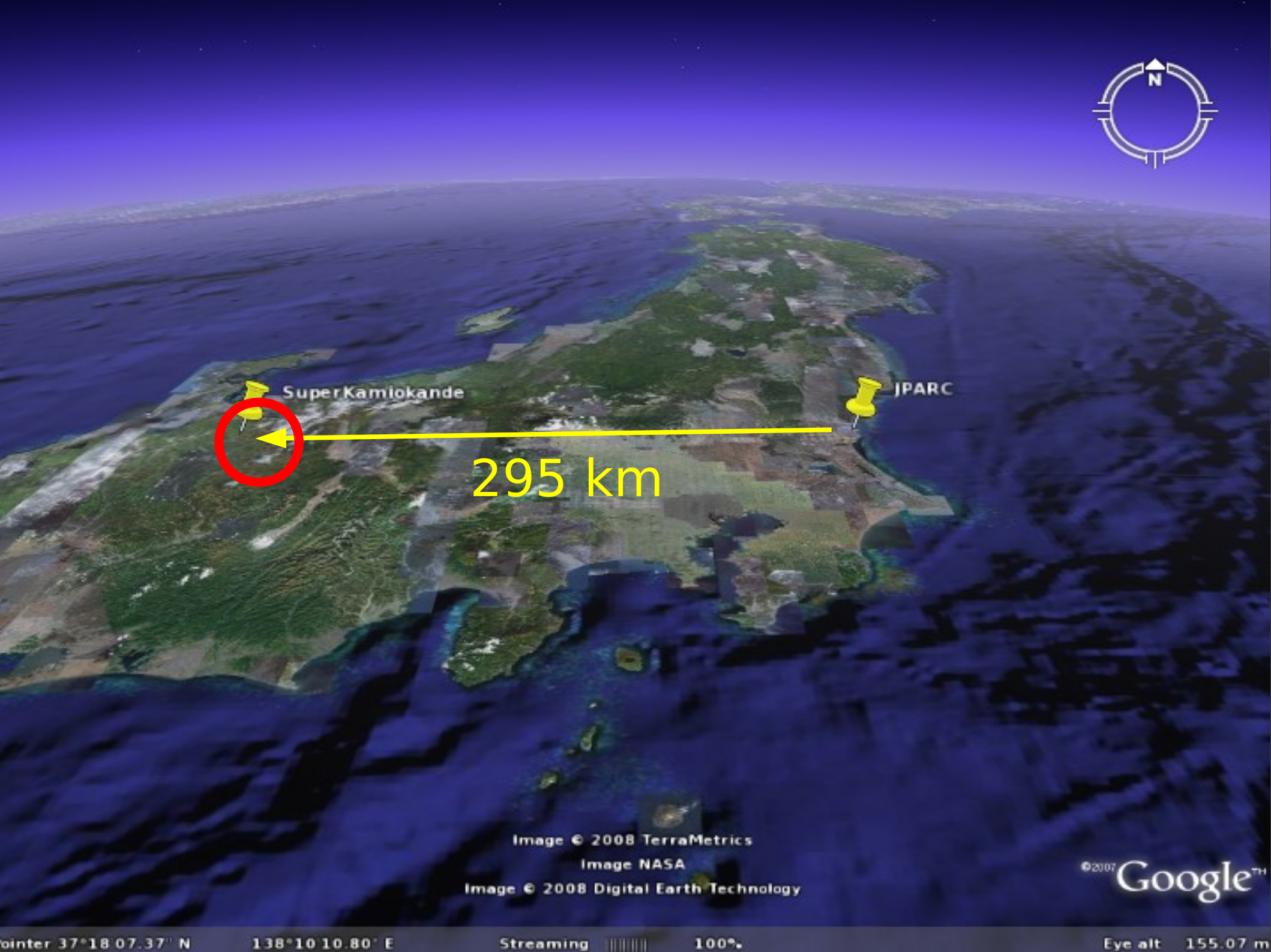
Development of cosmic-ray air showers




JPARC Facility

JPARC Facility

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295 km
Image © 2008 TerraMetrics
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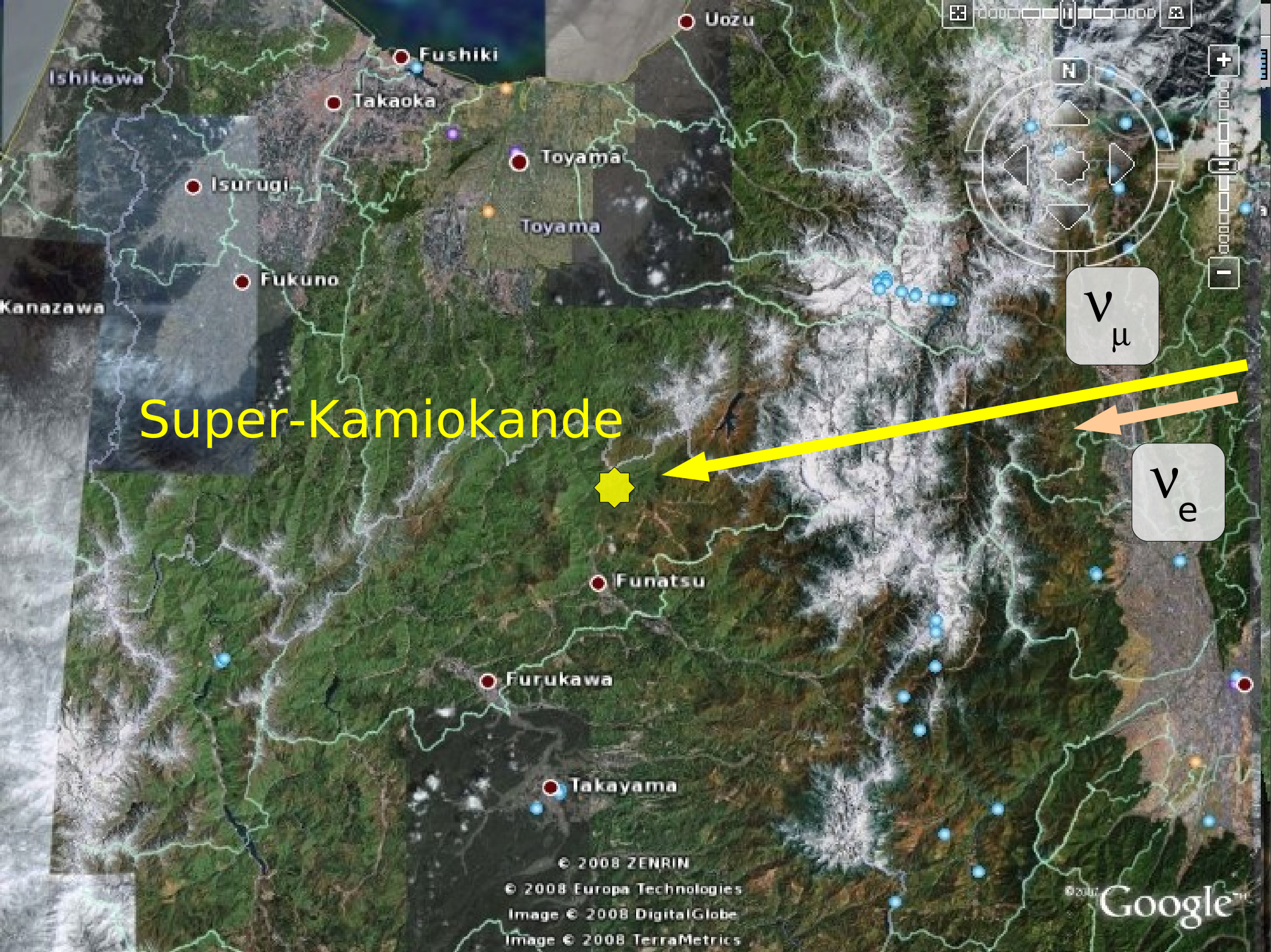
Uozu
Fushiki
Ishikawa
Takaoka
Toyama
Isurugi
Toyama
Fukuno
Kanazawa
ν_μ
Super-Kamiokande
ν_e
Funatsu
Furukawa
Takayama
© 2008 ZENRIN
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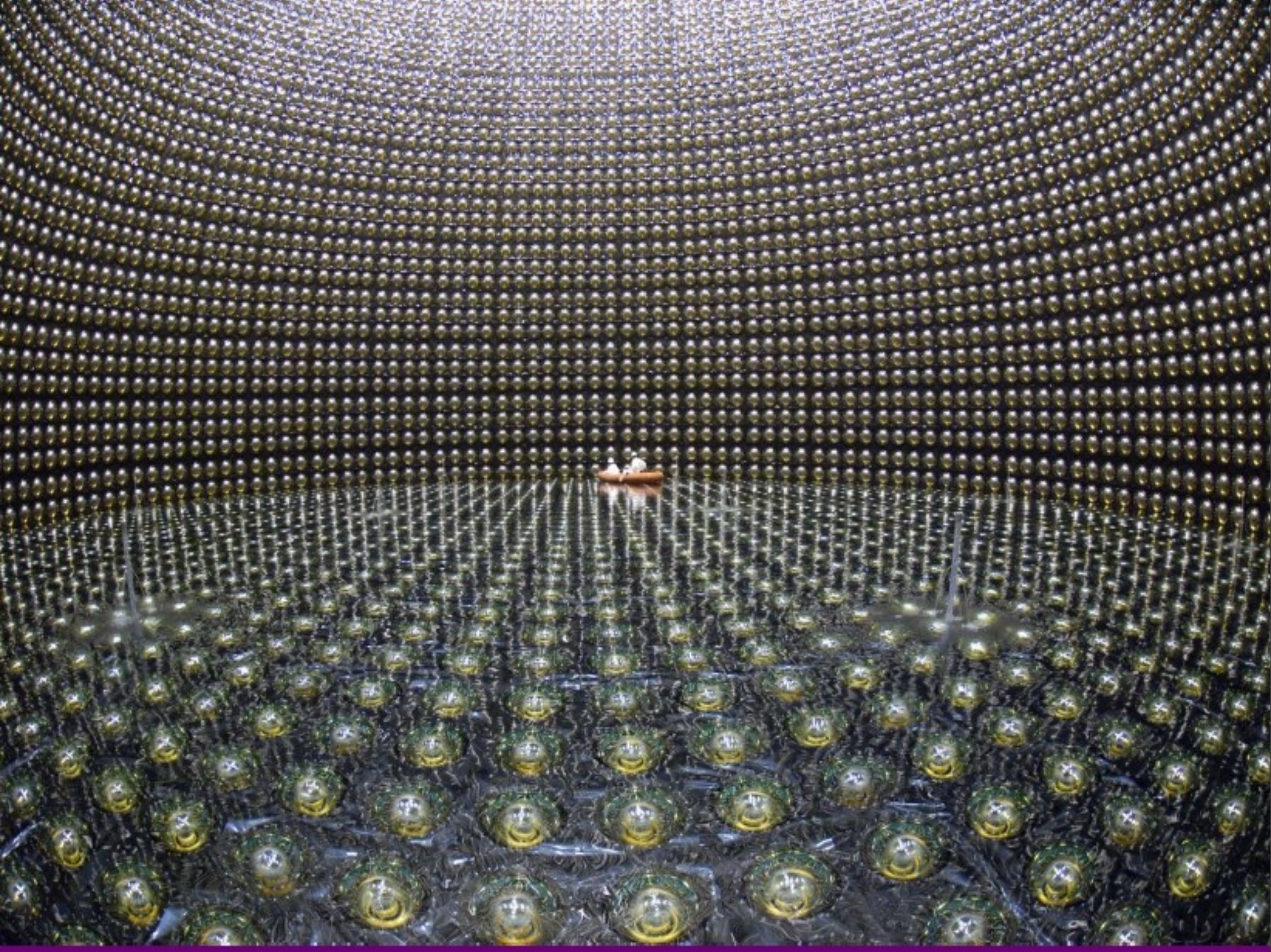
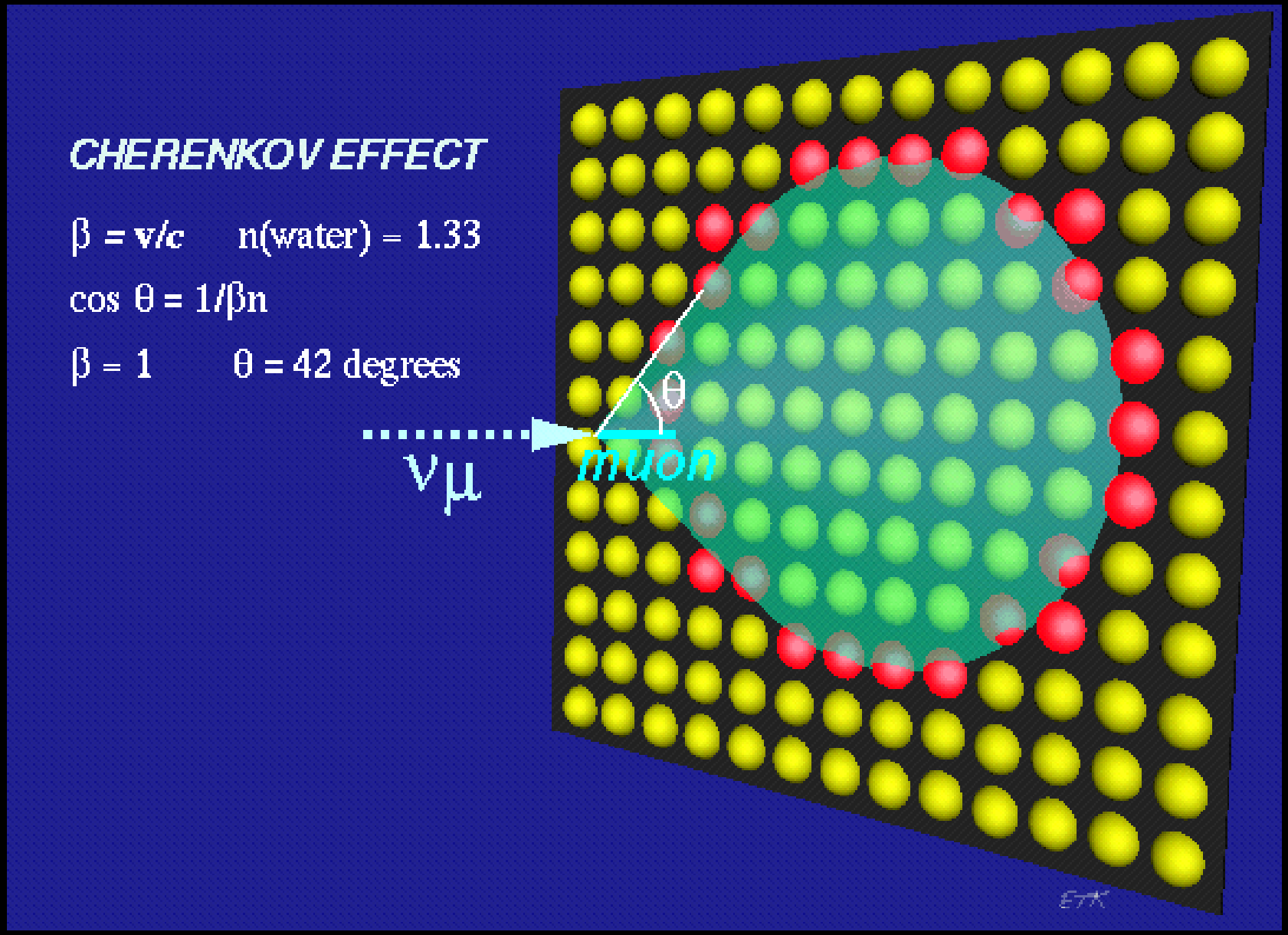
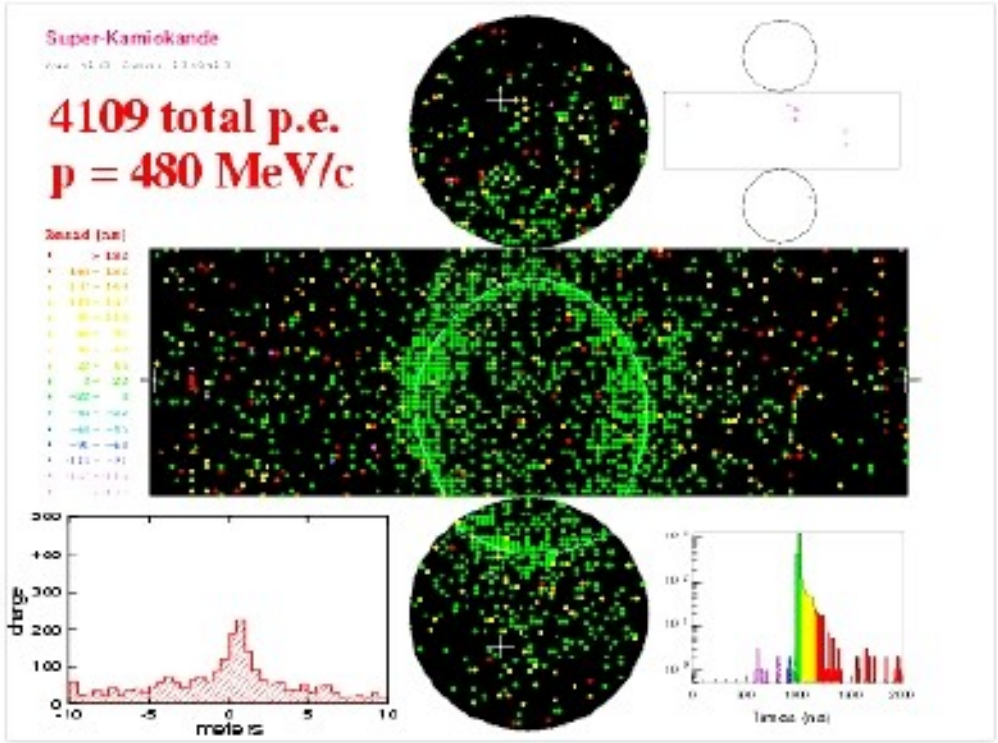


Water Cerenkov

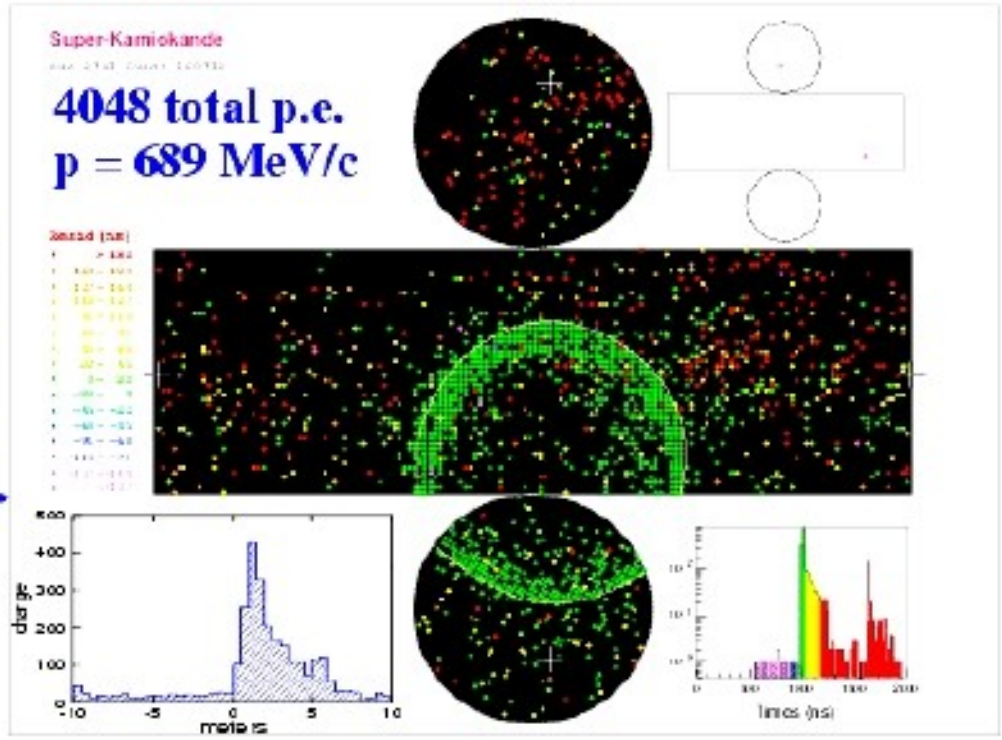


e–like



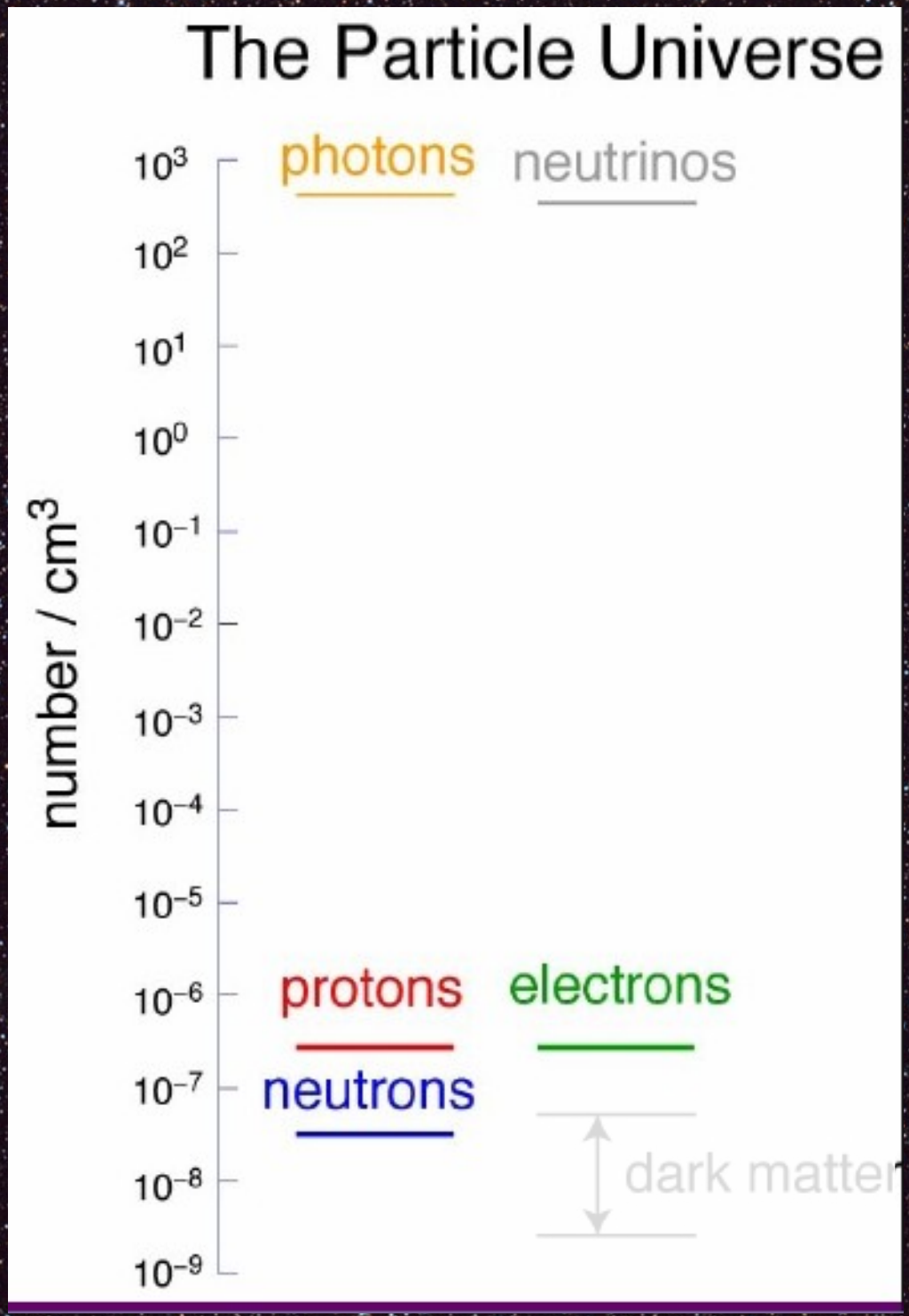
Electron-like : has a fuzzy ring

μ–like



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

Everywhere


The Particle Universe
photons
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10^{-7}
10^{-8}
10^{-9}
number / cm^3
protons
electrons
neutrons
dark matter

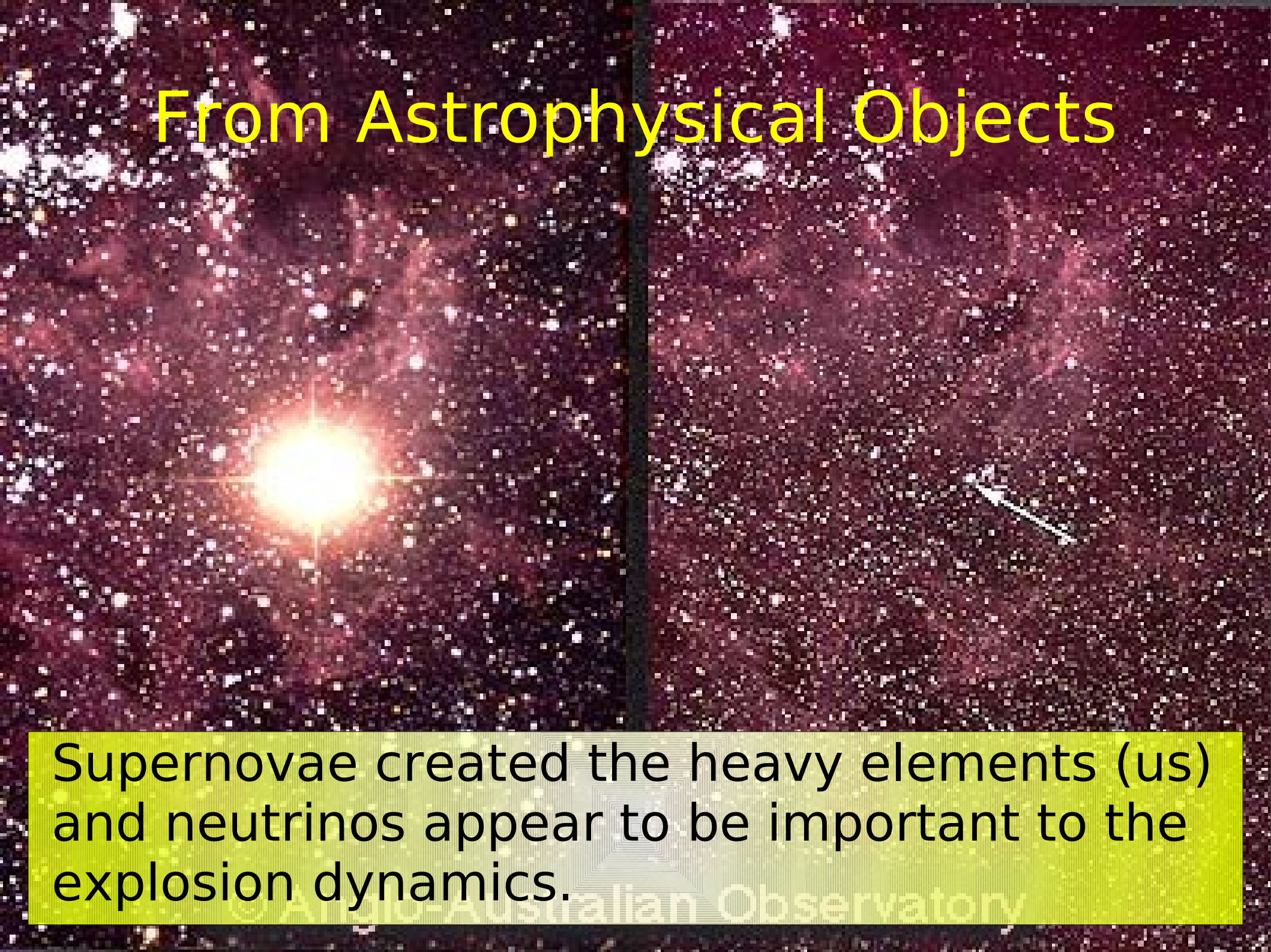
From the Big Bang

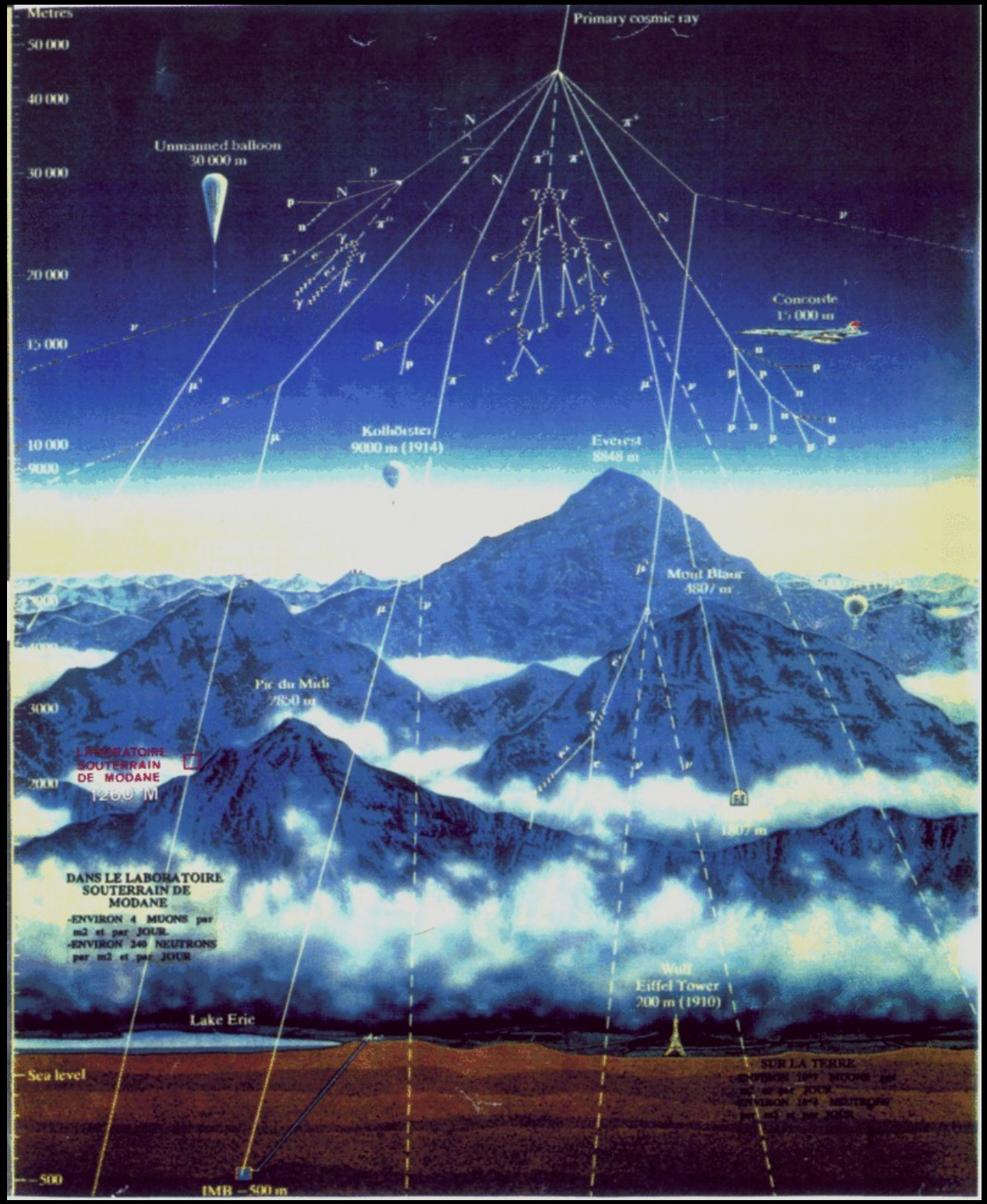
Artist's conception

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.
© Anglo-Australian Observatory



From Cosmic Rays.


From Us.

‘‘...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

Ray Davis in his solar neutrino detector – Early 1970s

Less than expected

The sun only produces ν_e