Summer Particle Astrophysics Workshop 2024

Astroparticle Physics Overview

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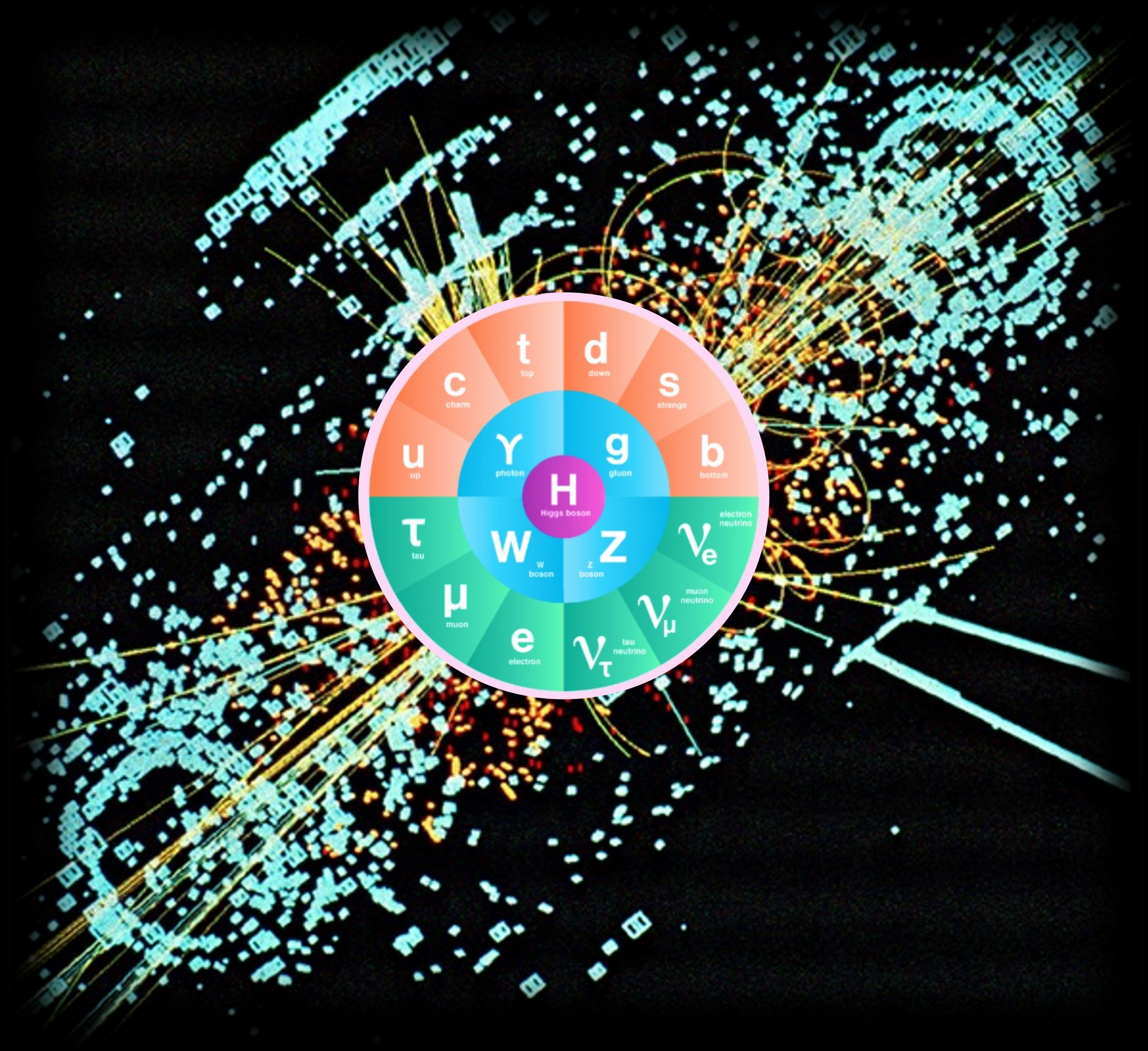
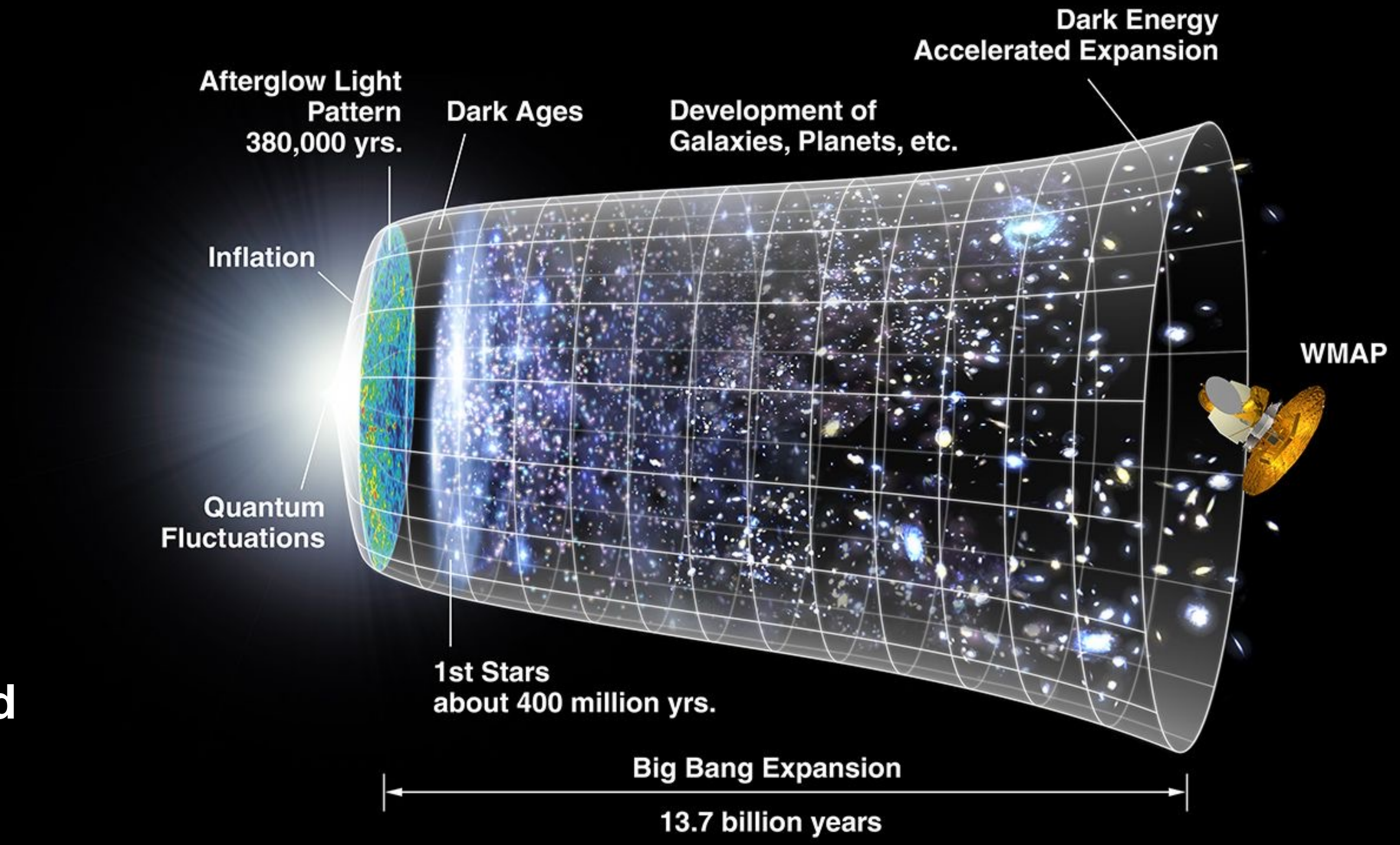
University of Oxford, UK



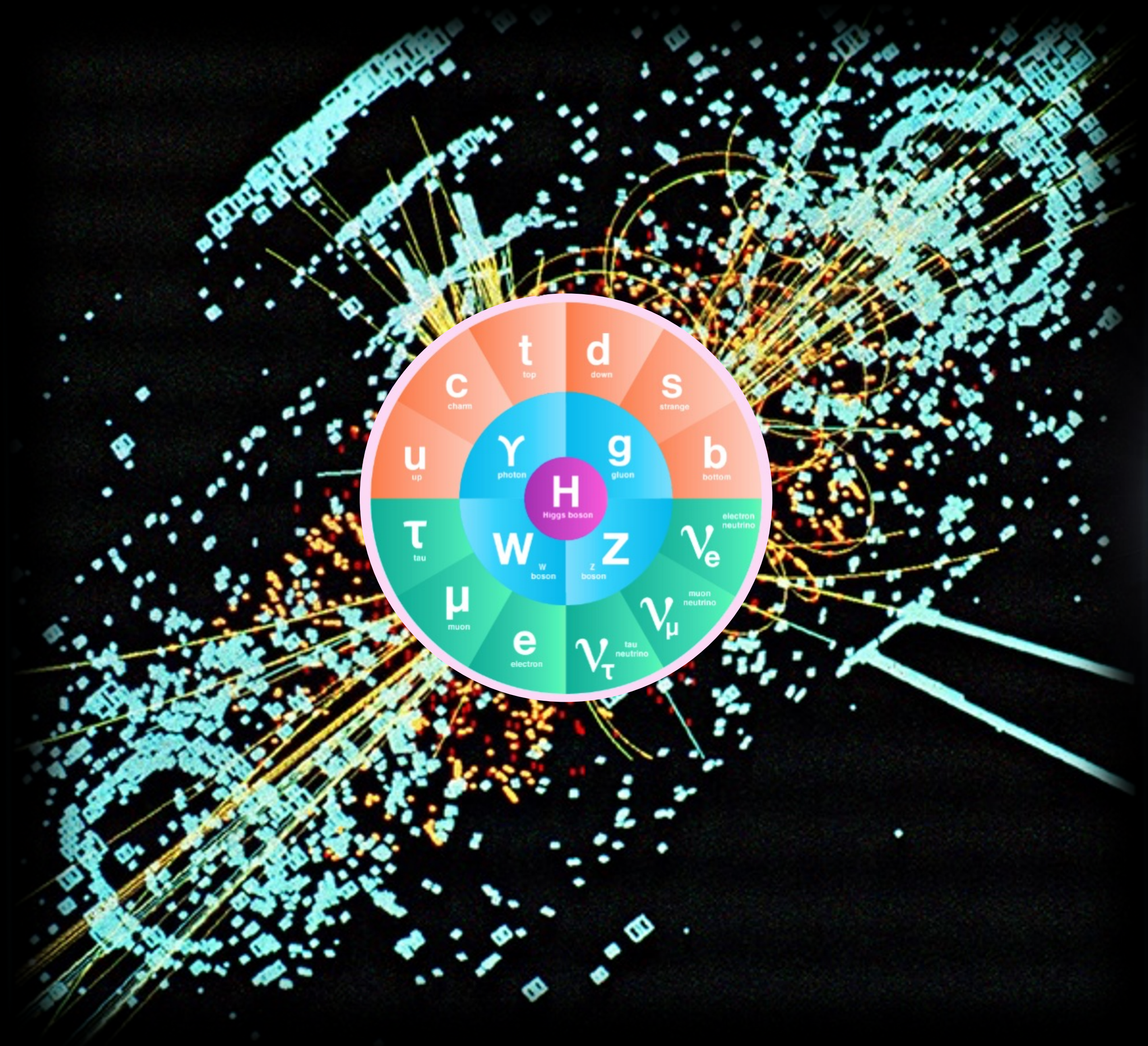
The Standard Model of Particle Physics has been incredibly successful over the past decades!

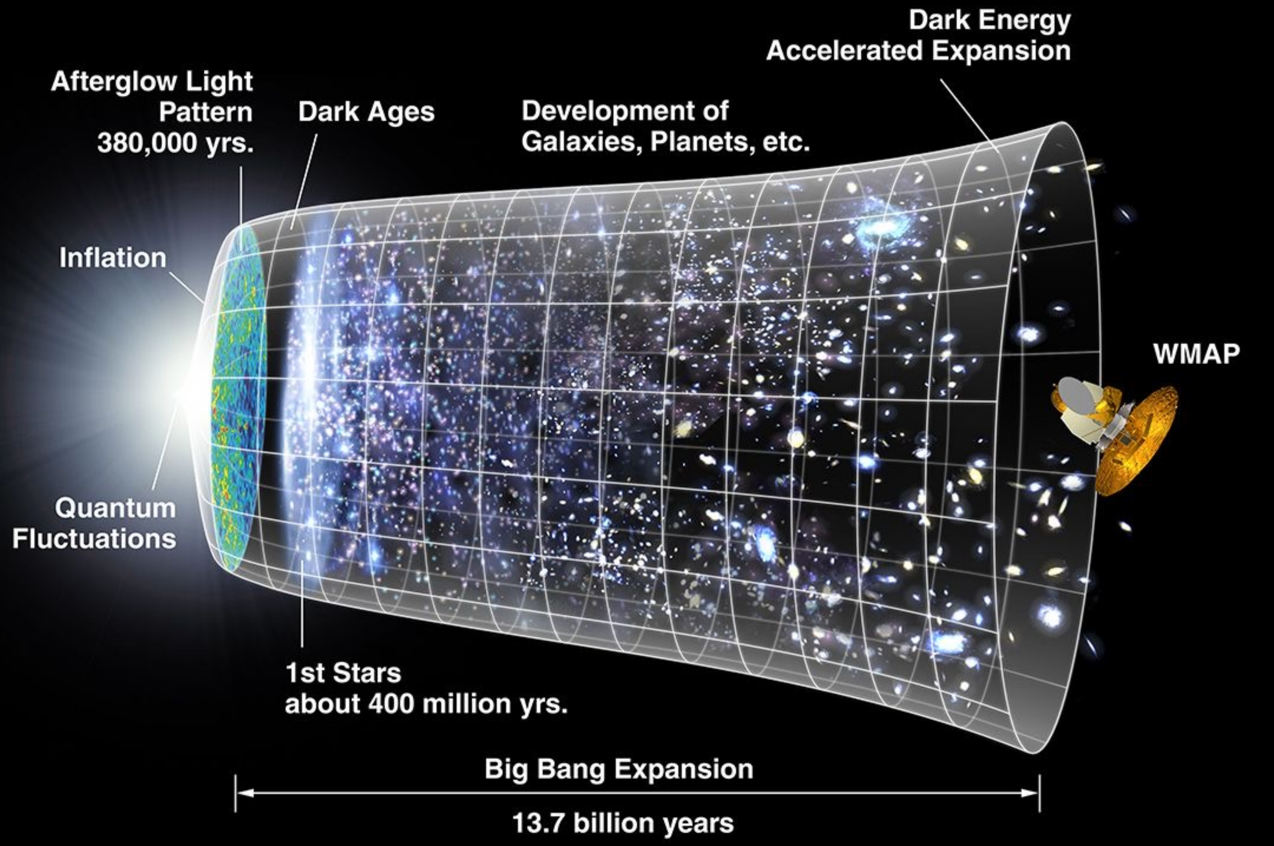
Predictions have been confirmed by experiments, multiple tests show its robustness in explaining particles and interactions.



Astrophysics and cosmology have shown an impressive evolution, driven by experiments and complemented by theories and models!

We have nowadays a “standard model of cosmology” which successfully describes the evolution of the Universe from a tiny time after its birth to any foreseeable future.



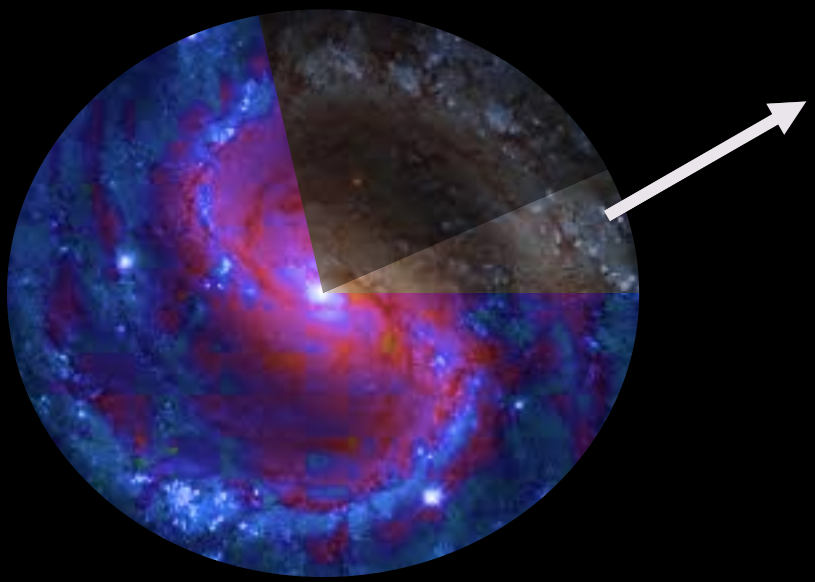


Yet, this is not the end of the story…

We have a lot of questions

We have a lot of questions

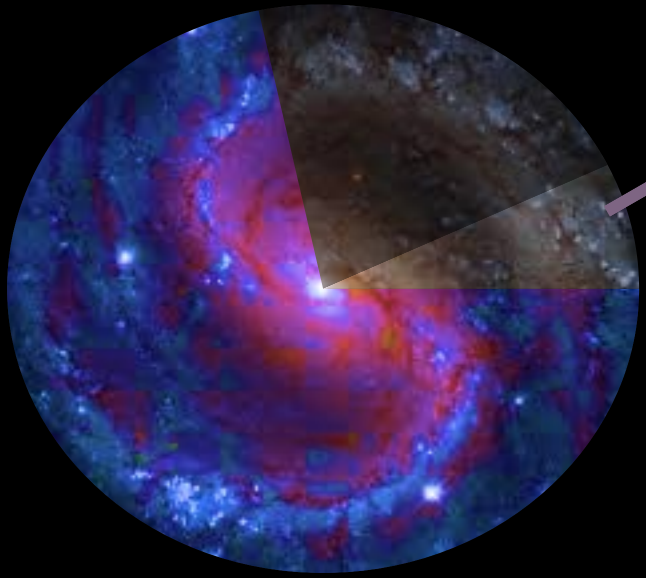
- What is the Universe made of?



We have a lot of questions

- What is the Universe made of?

What is Dark Matter?



What is it made of?

Is it a new particle? Several new particles?
… or something else?

How do we look for it?

We have a lot of questions

- What is the Universe made of?

Only 4% of the Universe is made of ordinary matter!

But just because we see it, does not mean that we know everything about it.

We have a lot of questions

- What is the Universe made of?
- What is dark matter?
- How can we explore and understand the extremes of the Universe?
- Are the particles described by the standard model fundamental, and how do they interact?
- What is mass – how do particles get heavy?
- Where does gravity fit into the standard model?
- What are the properties of neutrinos and what is their role in cosmic evolution?
- What is the origin of cosmic rays?
- Why is there an imbalance between the existence of antimatter and matter?
- How can high energy particles and gravitational waves tell us about the extreme universe?

Astroparticle Physics

Understand the nature, structure and dynamics of our Universe through the radiation/particles collected at Earth

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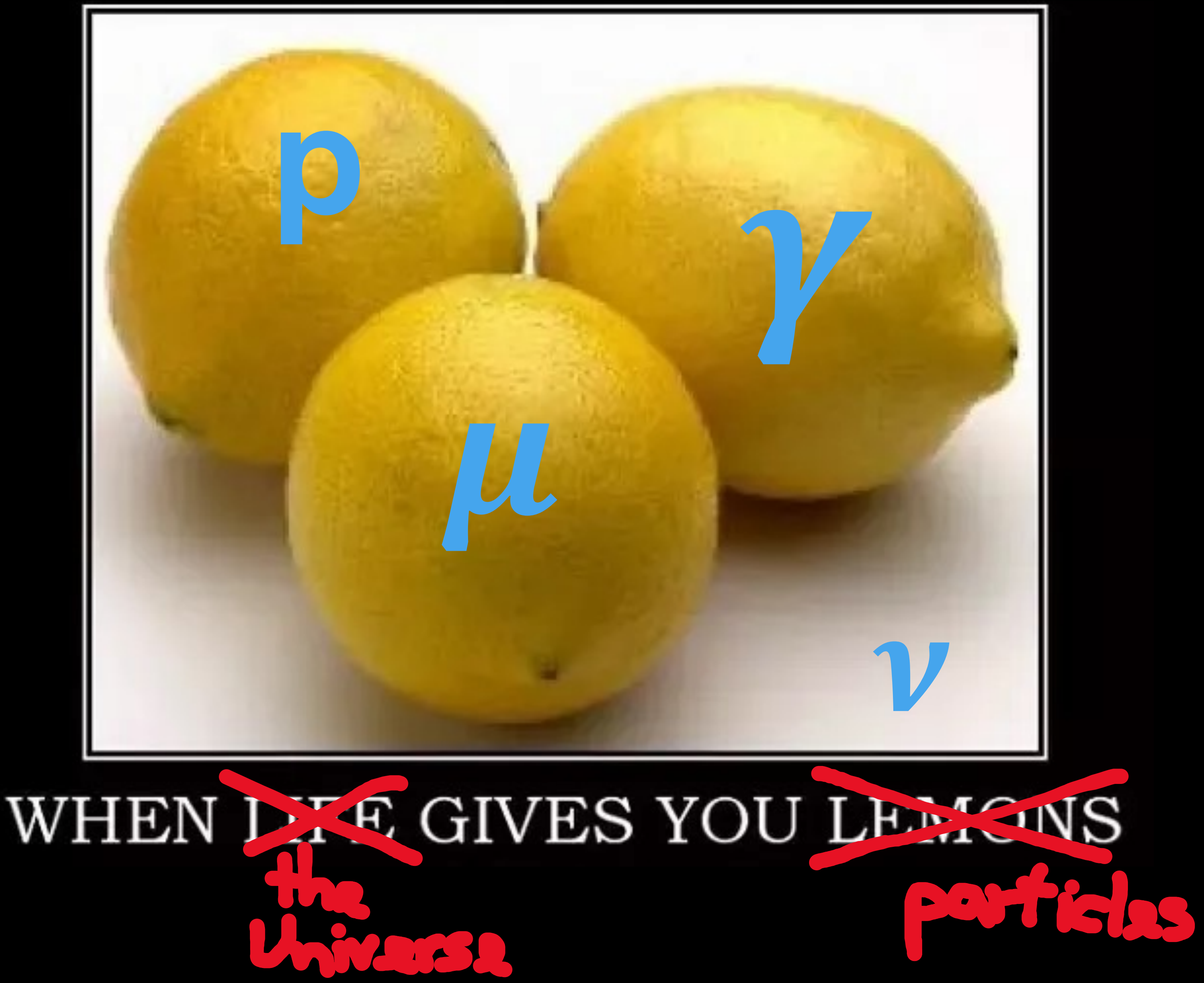
Understand the nature, structure and dynamics of our Universe through the radiation/particles collected at Earth

Astroparticle Physics

+ using the free particles that the Universe gives us to understand more about their fundamental properties


p
γ
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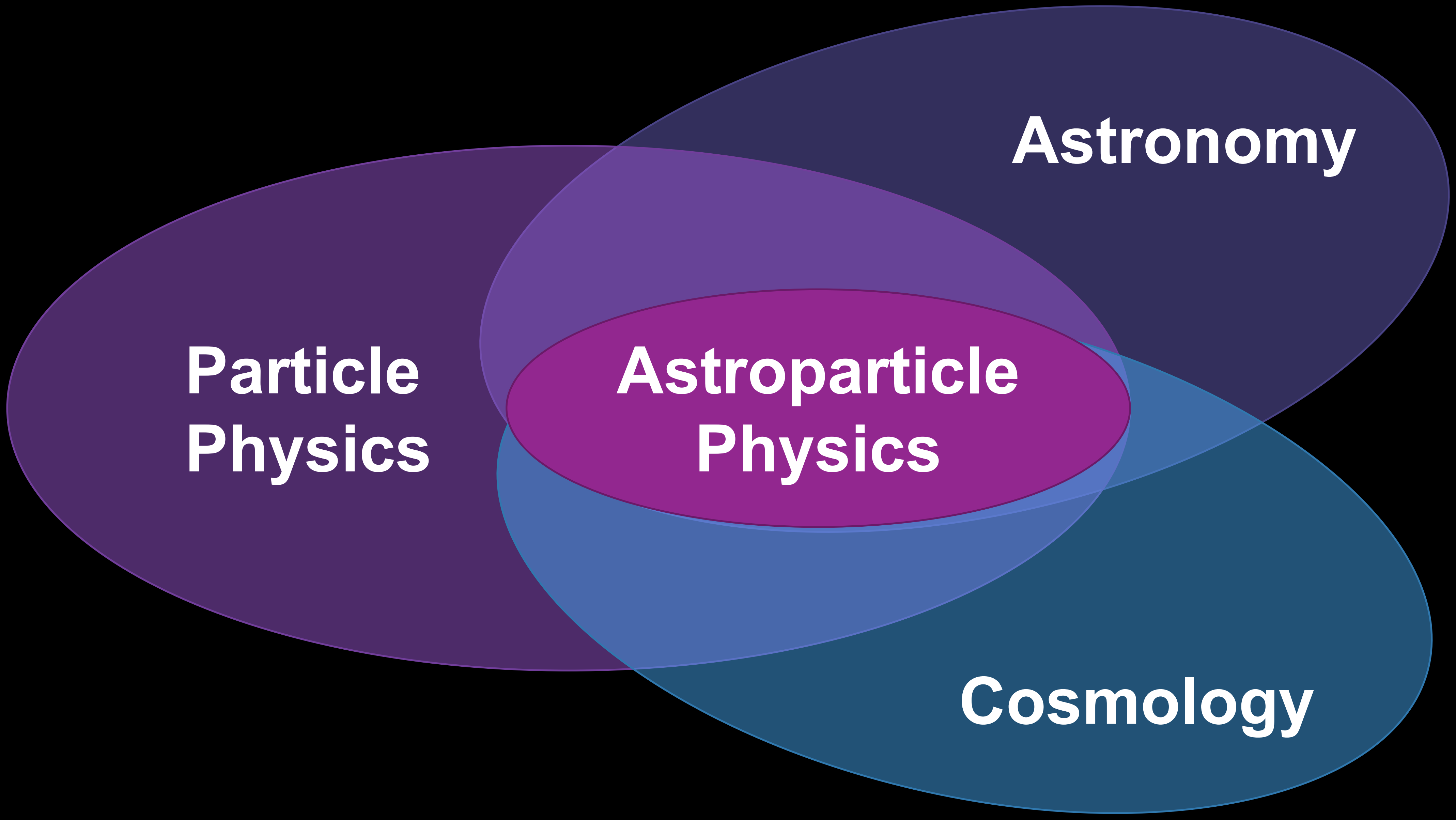
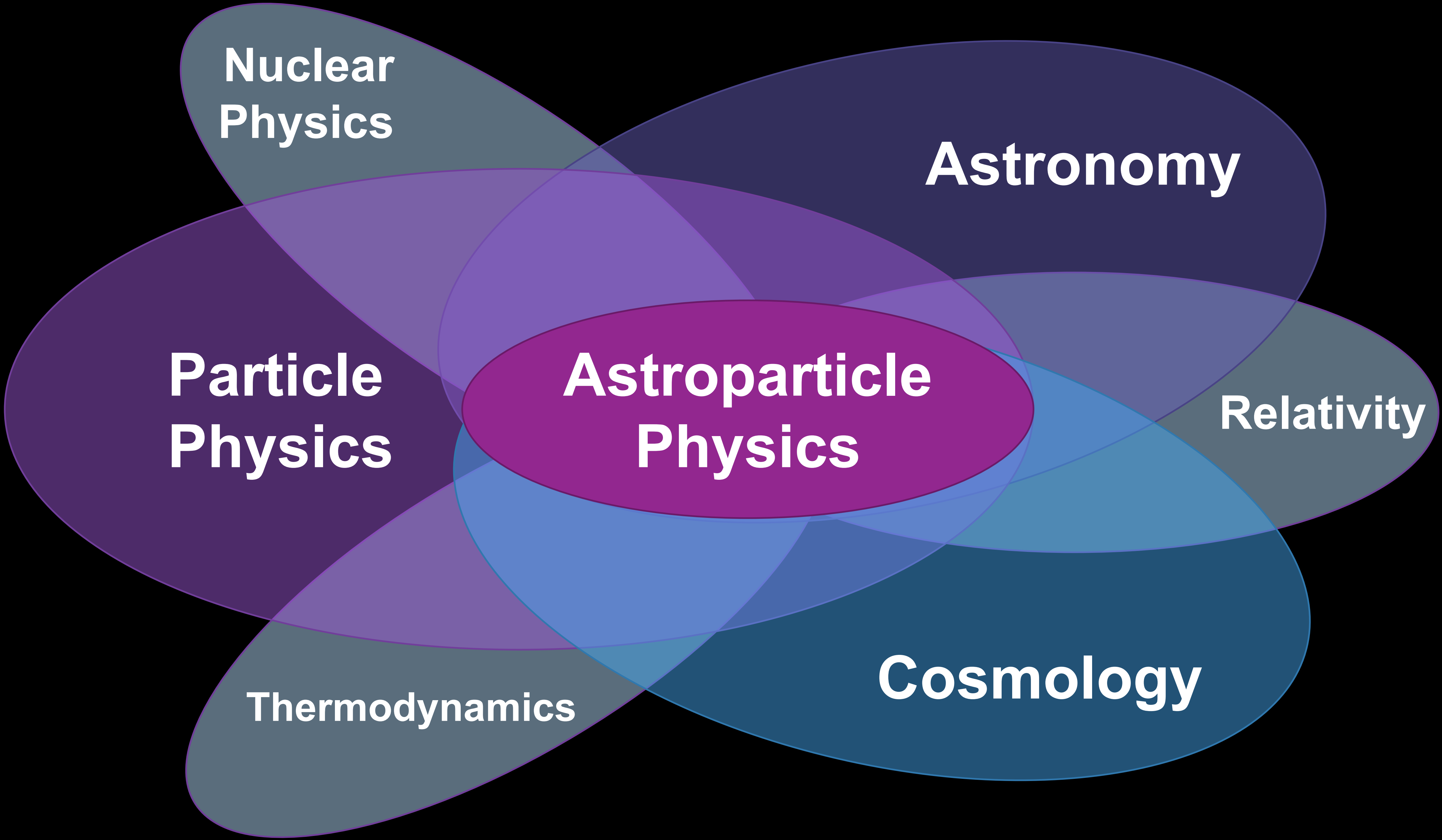
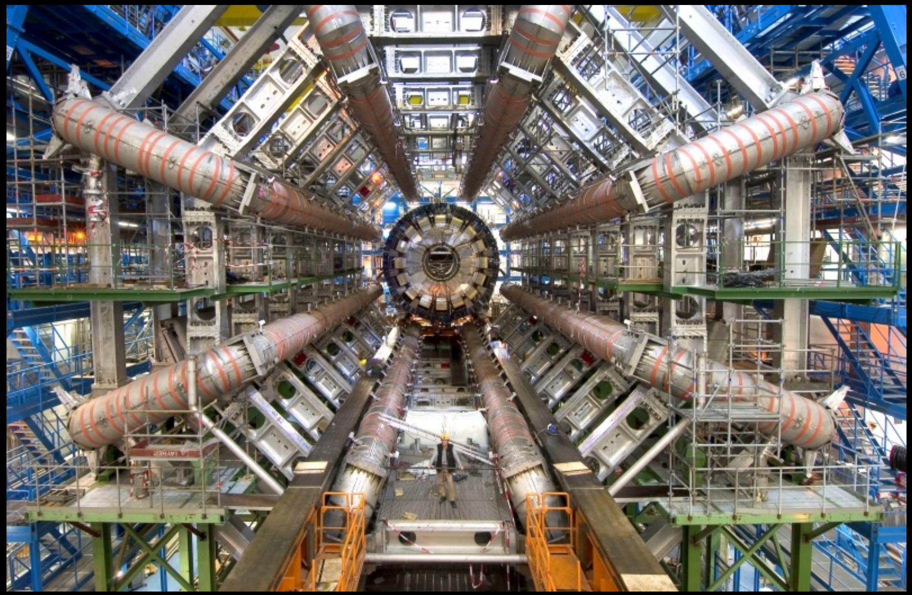
WHEN ~~LIFE~~ GIVES YOU ~~LEMONS~~
the Universe
particles


Astronomy
Particle Physics
Astroparticle Physics
Cosmology

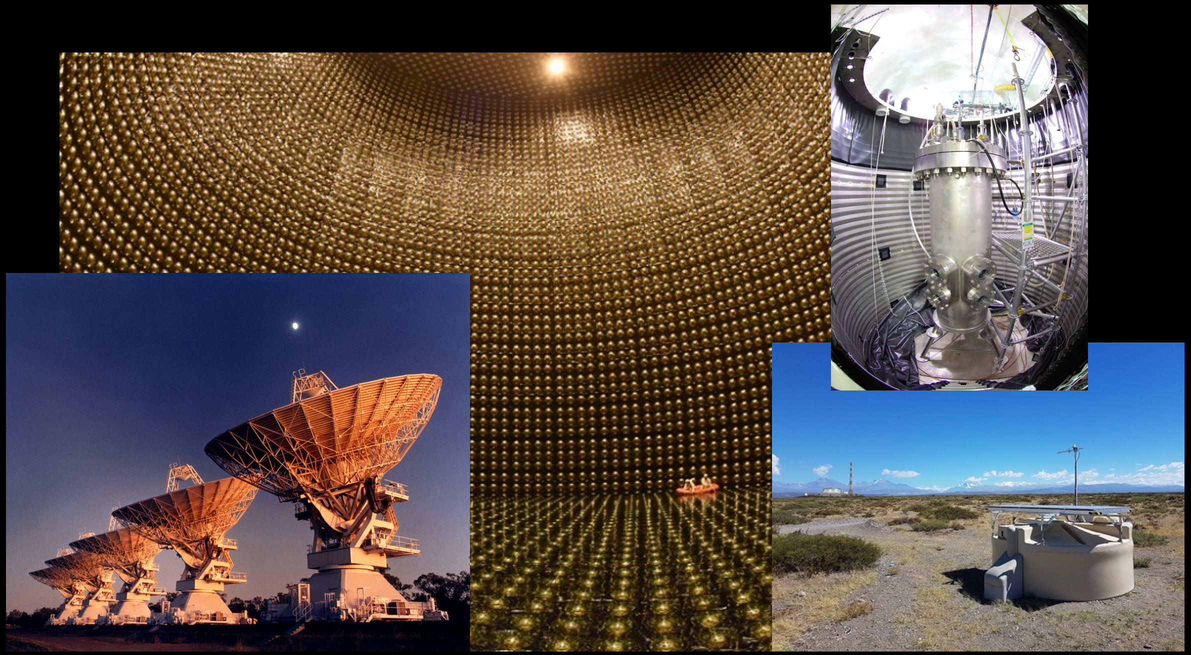

Nuclear Physics
Astronomy
Particle Physics
Astroparticle Physics
Relativity
Cosmology
Thermodynamics

Accelerator Experiments



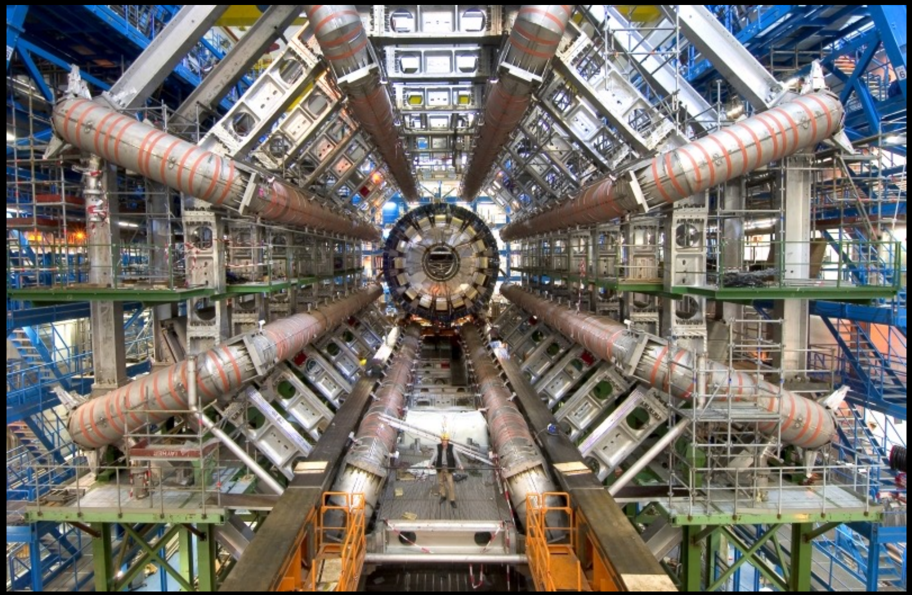
- Controlled environment:
  - Beam, backgrounds…

Astroparticle Experiments



- Access energy, space and time scales unattainable on Earth

Accelerator Experiments



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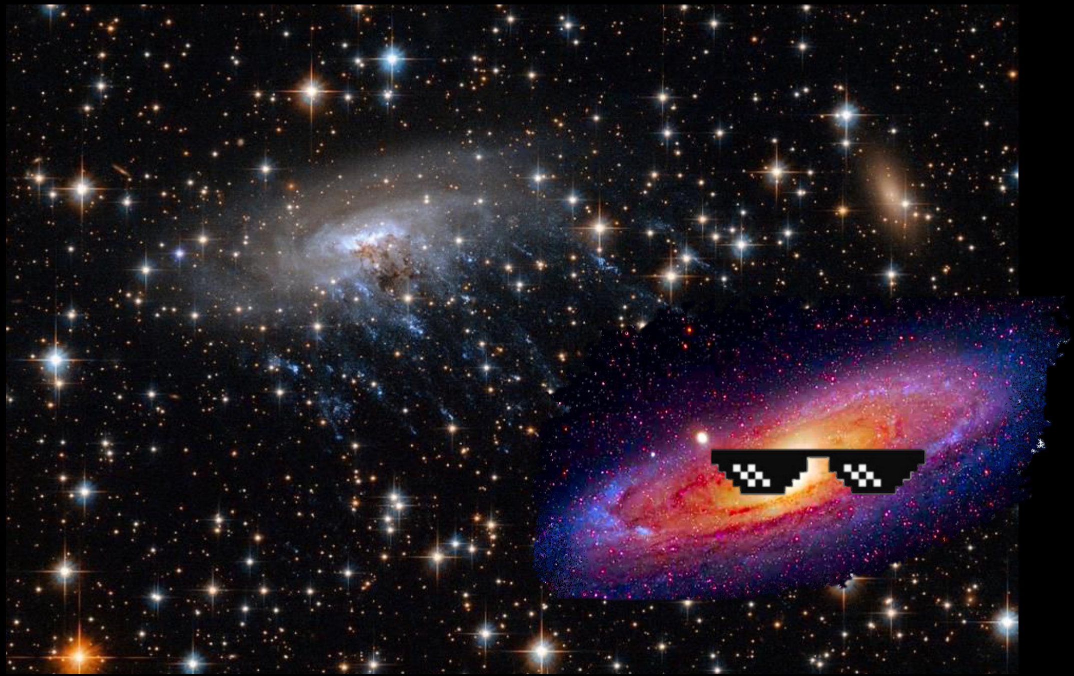
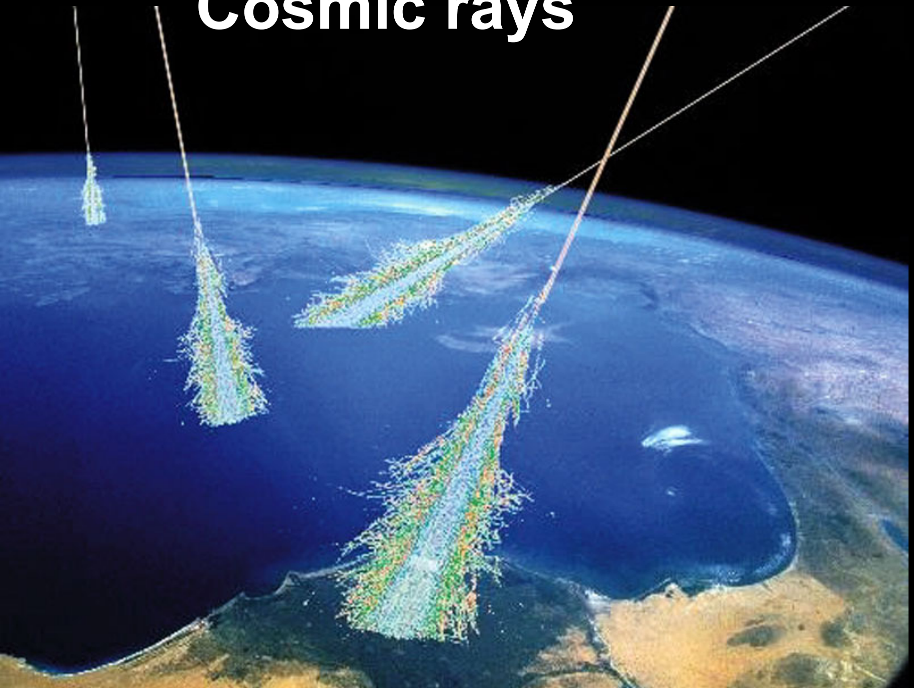
Astroparticle Experiments



We can do experimental particle physics with the most powerful accelerators of the Universe, testing physics far beyond the Earth laboratories capabilities.

Astroparticles

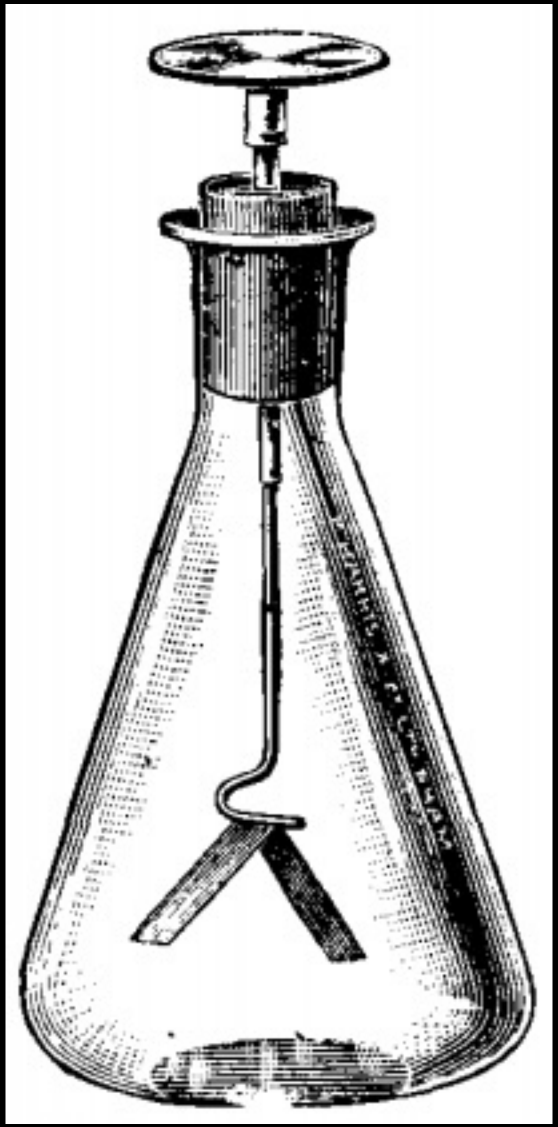
Cosmic rays



Neutrinos

Gamma Rays

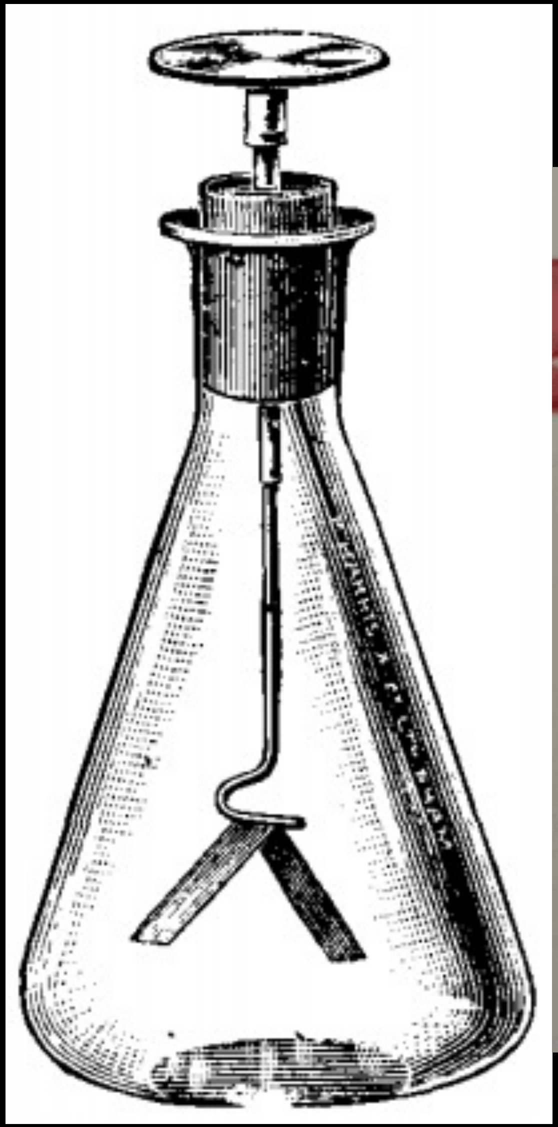
How did it start?

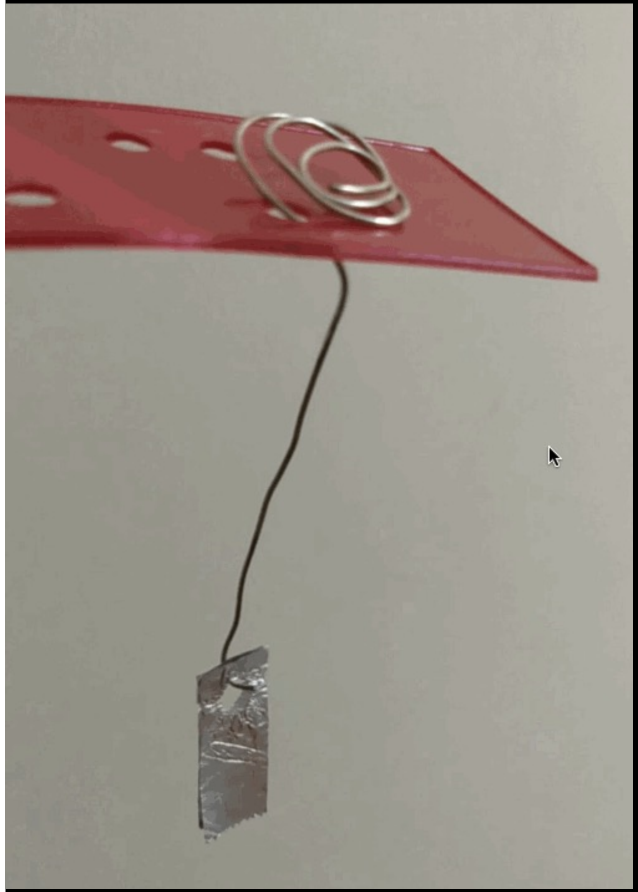


This is an electroscope

You can use it to measure electric charges.

You can build one at home: https://youtu.be/2PmWlPjV6n0

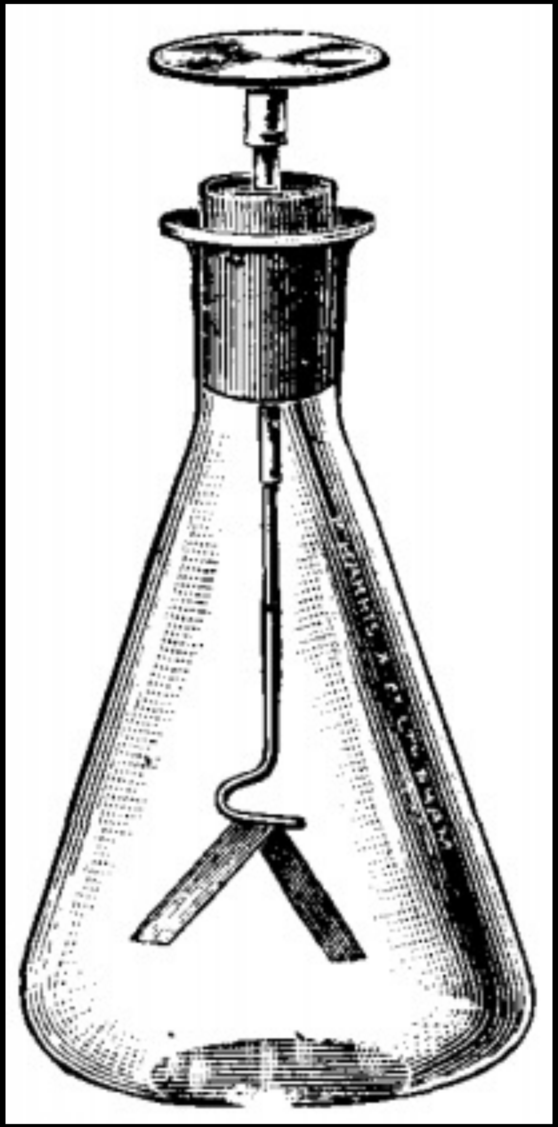




This is an electroscope

Charging
- Charged object touches the conductor
- Electric charge is induced to the leaves
- Leaves repel each other and separate

Discharging
- Ionization in air neutralizes the electroscope
- Leaves go back to uncharged position



This is an electroscope

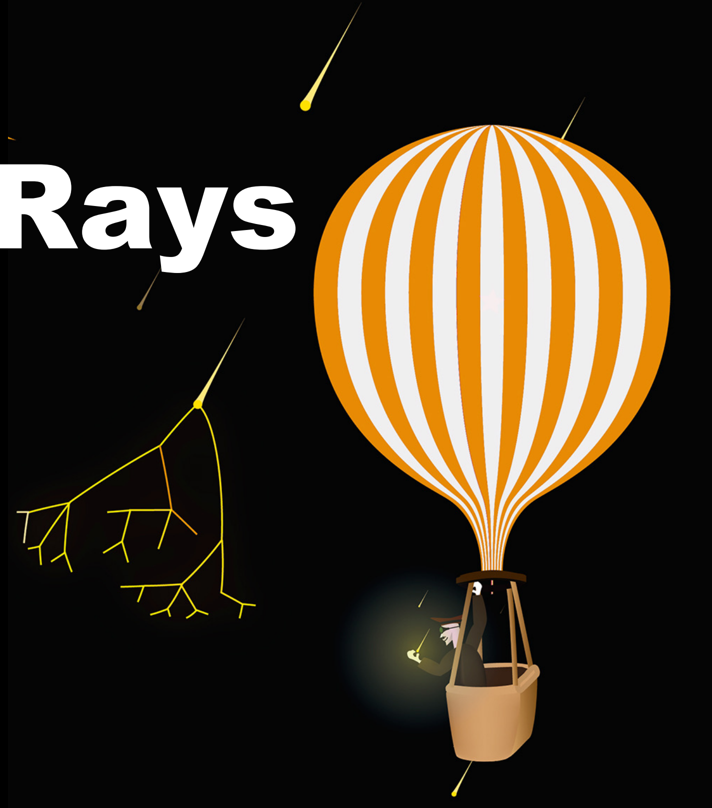
During the 19th century, scientists observed spontaneous discharge of the electroscopes, likely due to the ionization of the atmosphere. But what was the cause of this ionization?

Their hypothesis: the Earth's crust has to be the source of the ionization levels that we measure in the atmosphere.

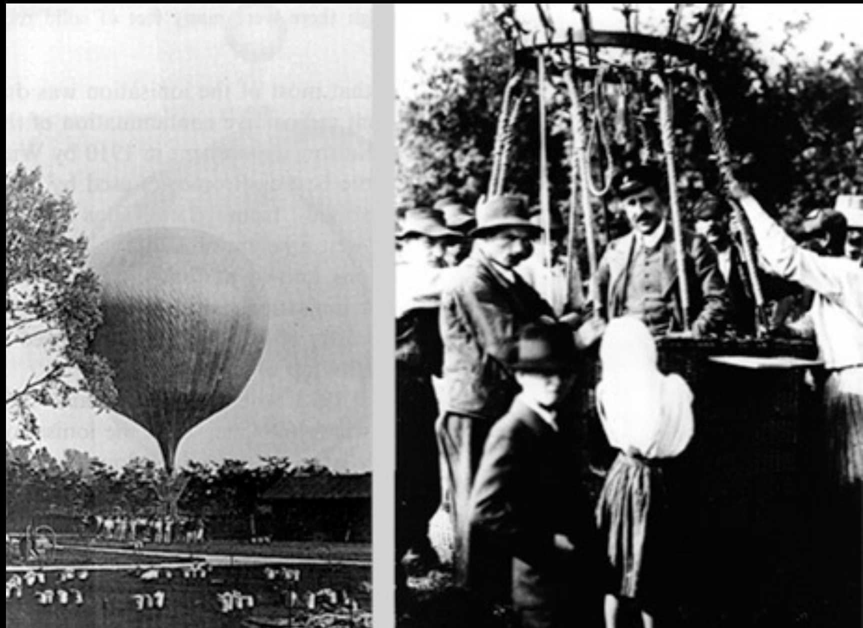
Testing the hypothesis: lowered electroscopes into lakes and oceans, carried them up mountains and took them to even greater heights in open baskets underneath hydrogen-filled balloons.

Results: conflicting, with some showing a decrease in ionization with altitude, others an increase.

The Discovery of Cosmic Rays



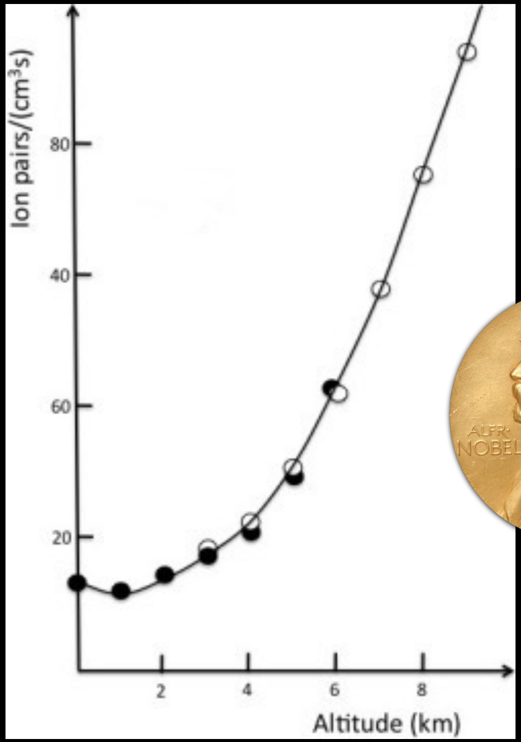
- Victor Hess,1912
  - He went up and down in the atmosphere in a balloon, measuring the radiation with an electroscope.
  - Measurements up to 5.3km, from 1911-12.



The Discovery of Cosmic Rays

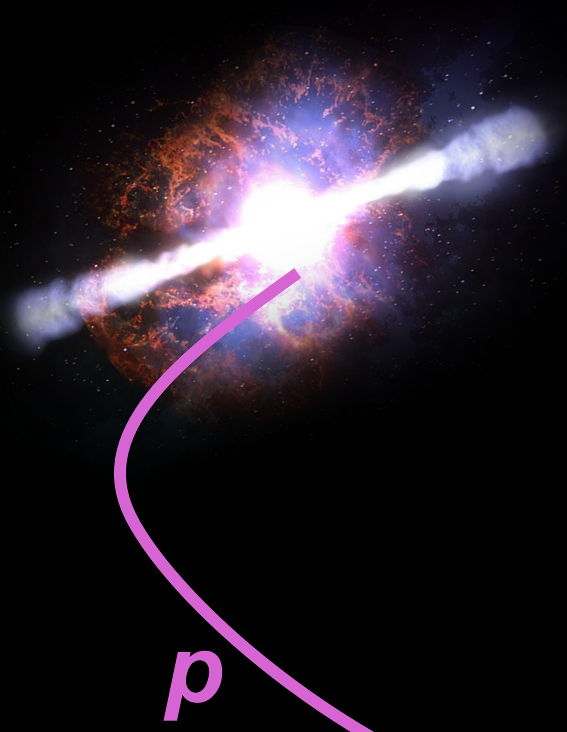
- Victor Hess,1912
  - He went up and down in the atmosphere in a balloon, measuring the radiation with an electroscope.
  - Measurements up to 5.3km, from 1911-12.

- The level of radiation decreased up to an altitude of about 1 km, but above that the level increased considerably, with the radiation detected at 5 km being about twice that at sea level.



Conclusion: there was radiation penetrating the atmosphere from outer space.

What are Cosmic Rays?



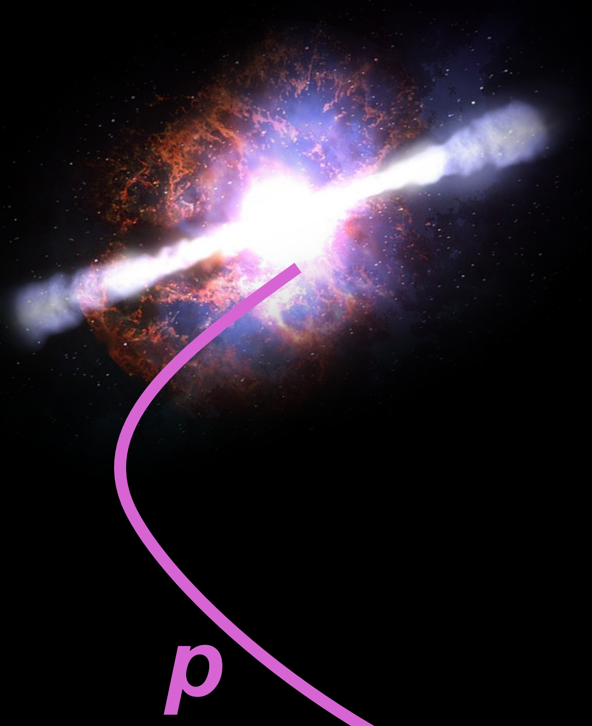
Cosmic rays are high-energy protons and atomic nuclei that move through space at nearly the speed of light.

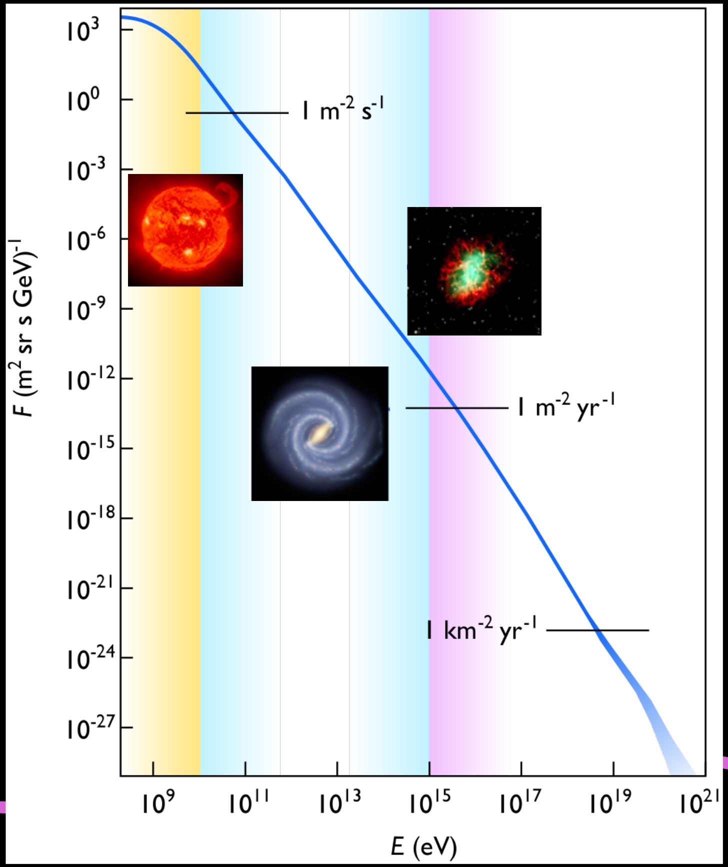
89% protons – nuclei of hydrogen, the lightest and most common element in the universe

10% nuclei of helium

1% heavier nuclei all the way up to uranium

What are Cosmic Rays?





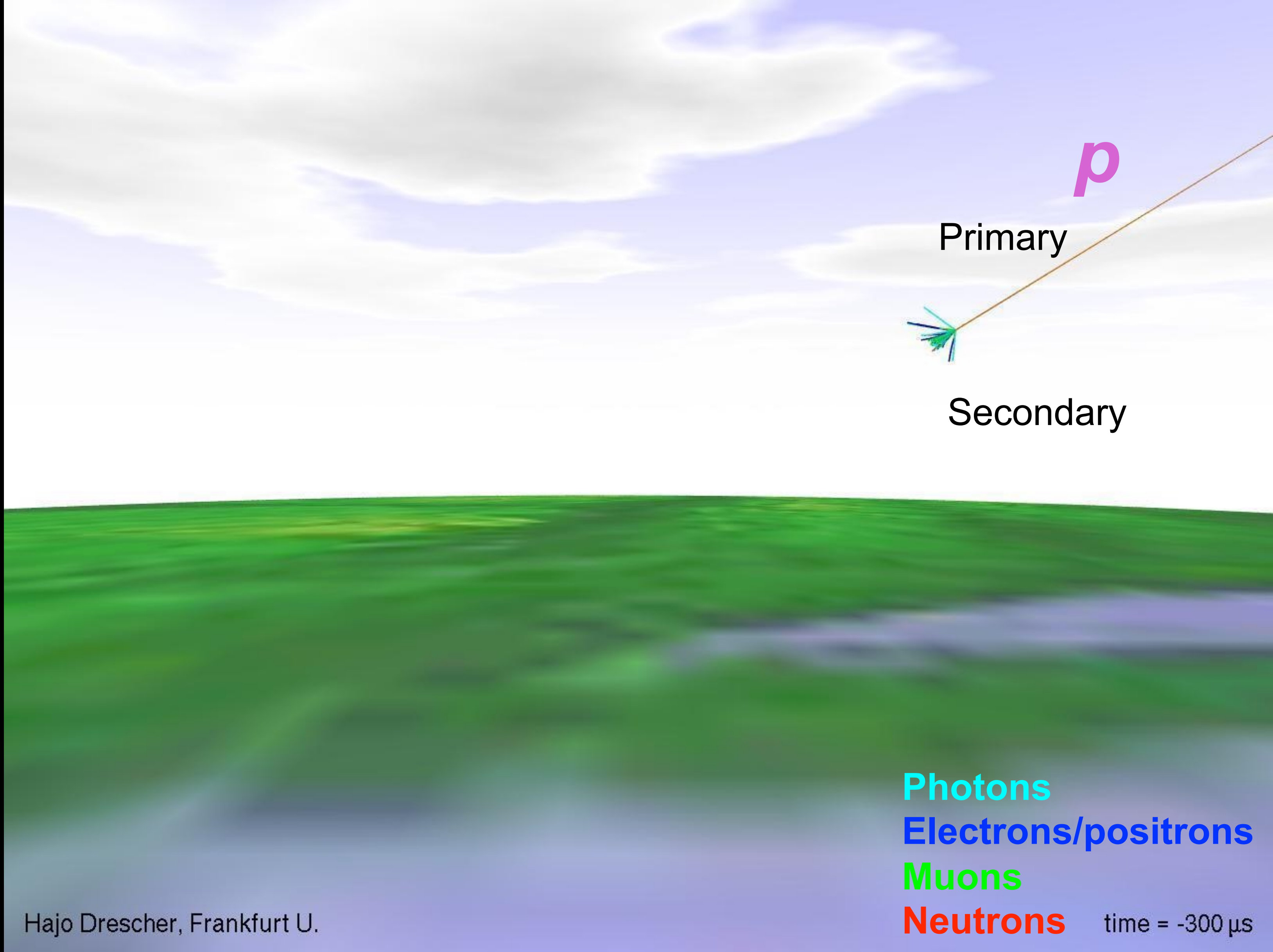
They originate from the sun, from outside of the solar system in our own galaxy, and from distant galaxies.

They are deflected by galactic magnetic fields (because they are charged).

What are Cosmic Rays?

- When these rays enter our atmosphere they hit oxygen and nitrogen molecules, creating secondary particles.

Creates mainly pions, π
- They interact with other molecules
- Or decay into muons and neutrinos



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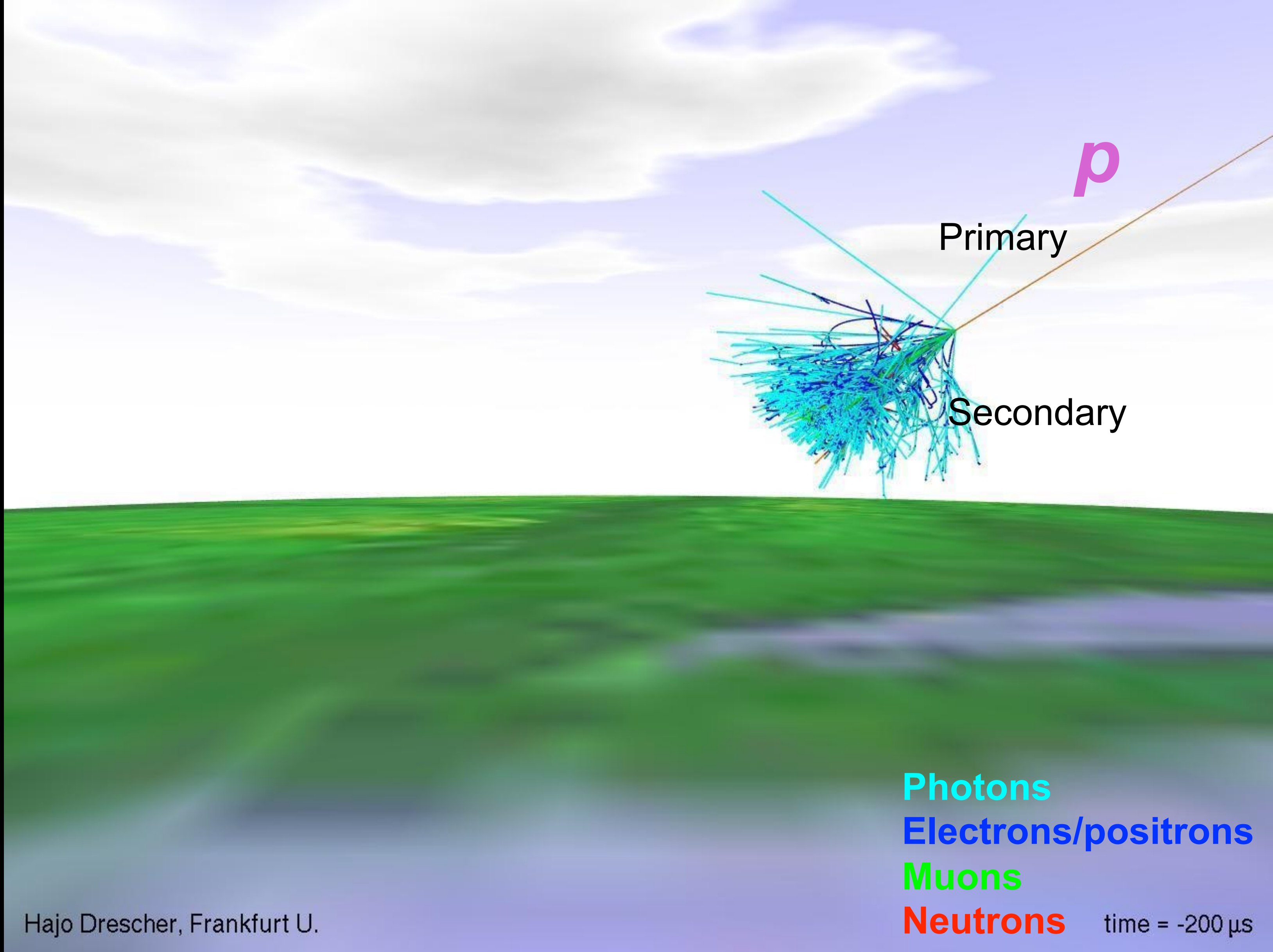
Very energetic muons may even go faster than the speed of light in the atmosphere, emiting a flash of Cherenkov light.



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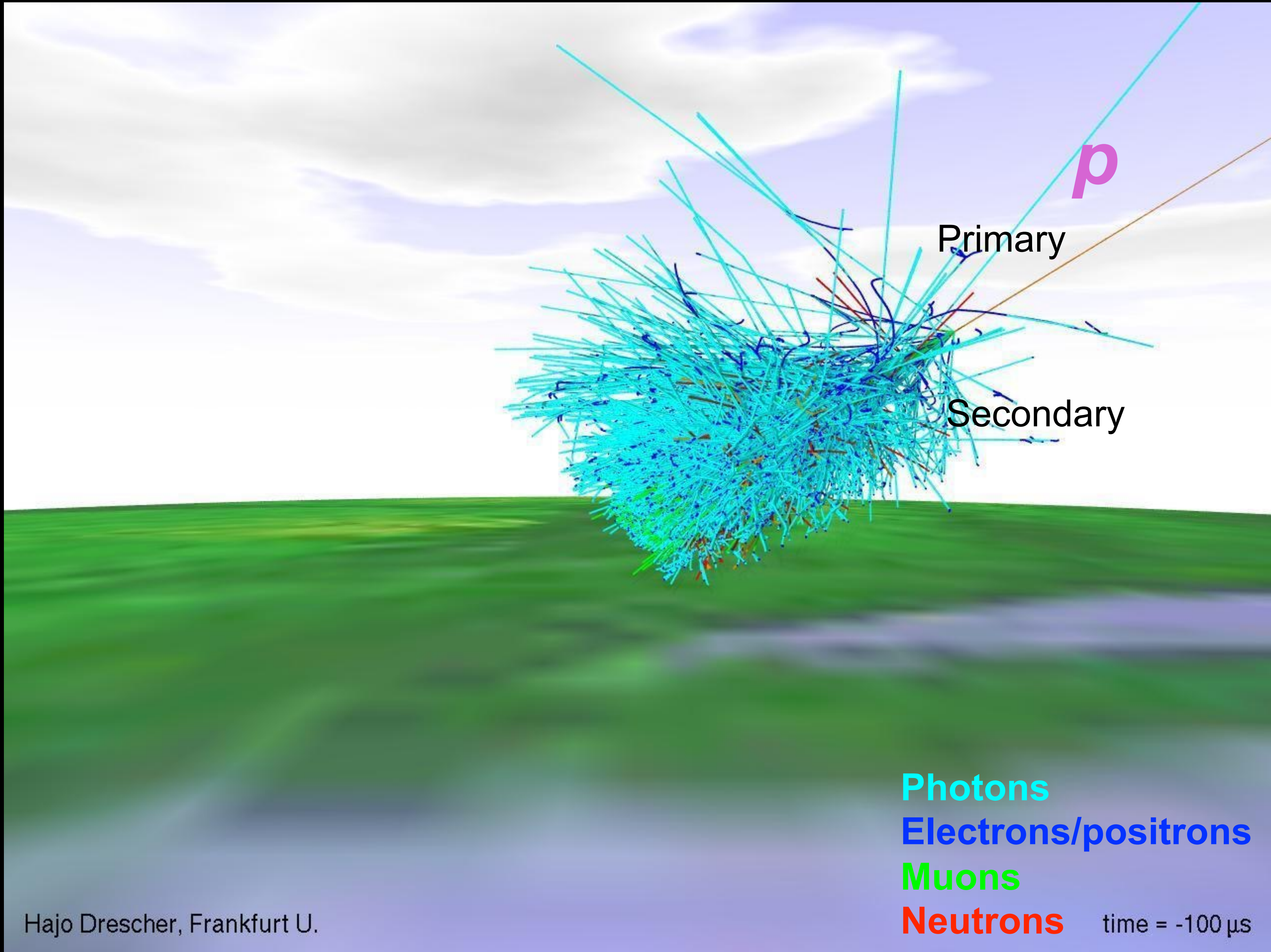

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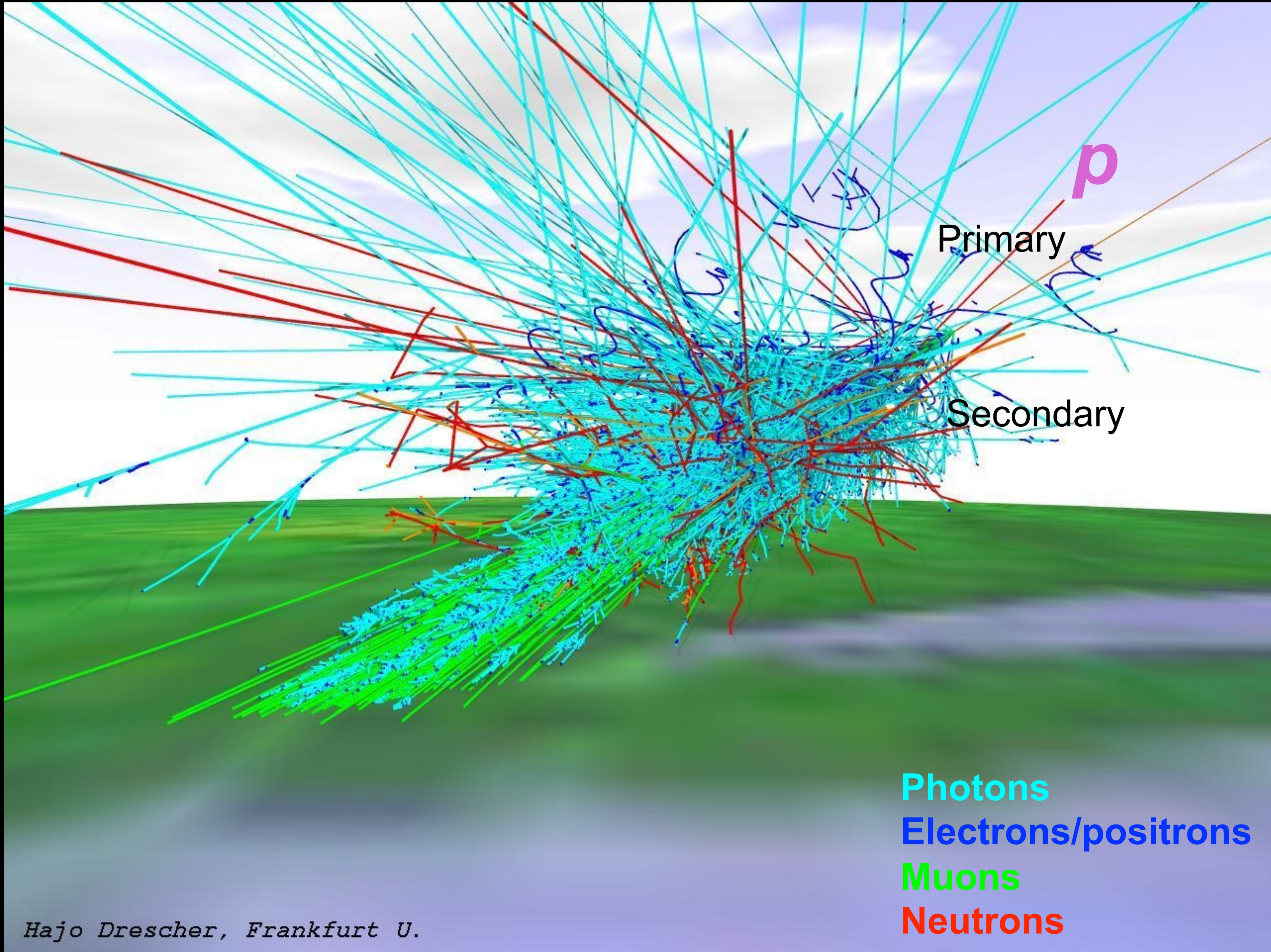
- When these rays enter our atmosphere they hit oxygen and nitrogen molecules, creating secondary particles.

Being 207 times heavier than electrons, muons are much less subject to the Bremsstrahlung effect which is the main source of deceleration for electrons and positrons of similar energy.

→ Cosmic muons travel far and easily reach the Earth’s surface



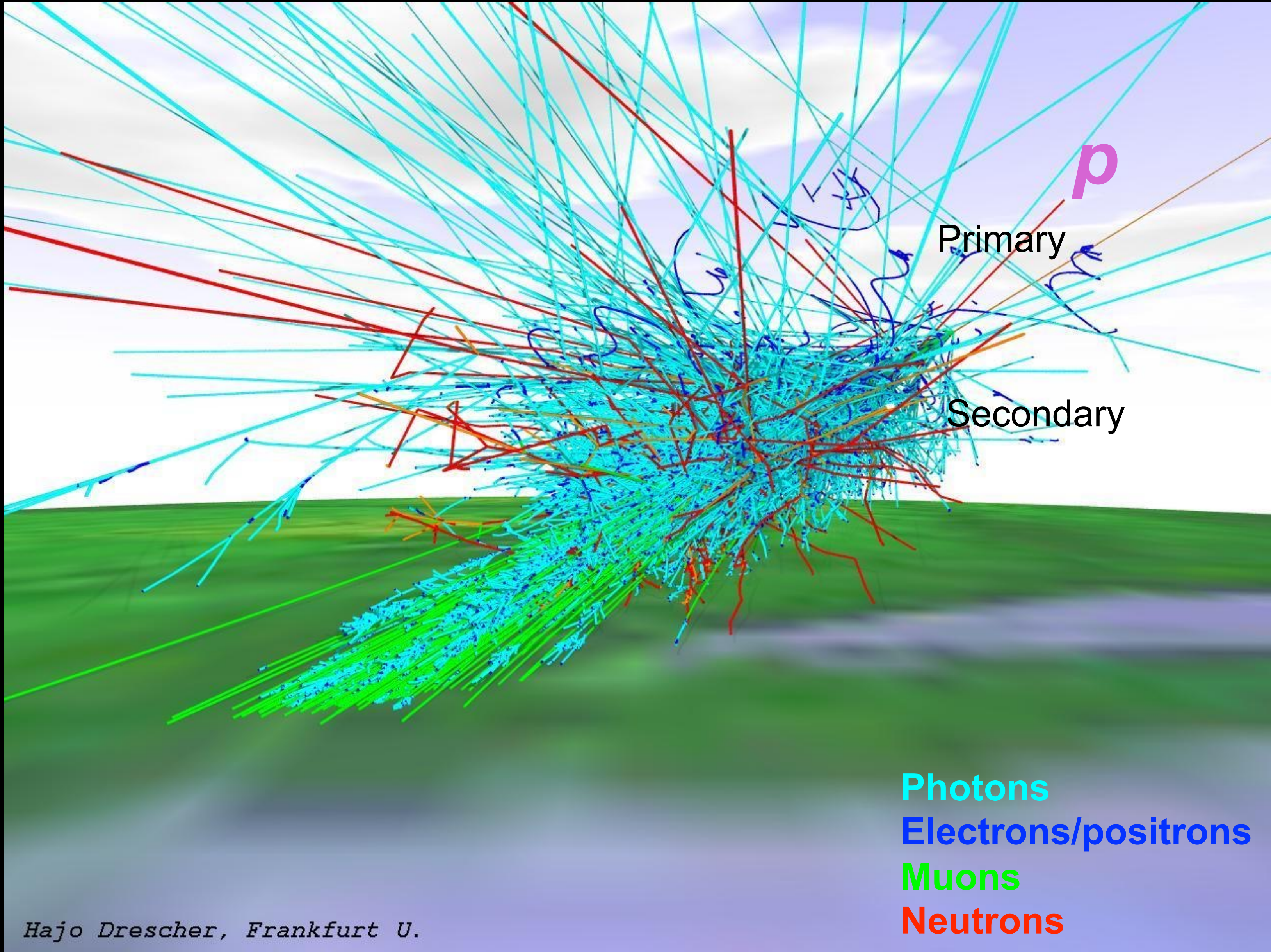
What are Cosmic Rays?

From the 1930s to the 1950s, before man-made particle accelerators reached very high energies, cosmic rays served as a source of particles for high energy physics investigations, and led to the discovery of subatomic particles.

1932 – discovery of the positron (the antielectron), the first particle of antimatter to be observed.

1937 – the muon.

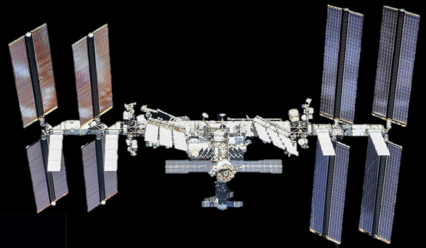
1947 – the pion and the kaon.



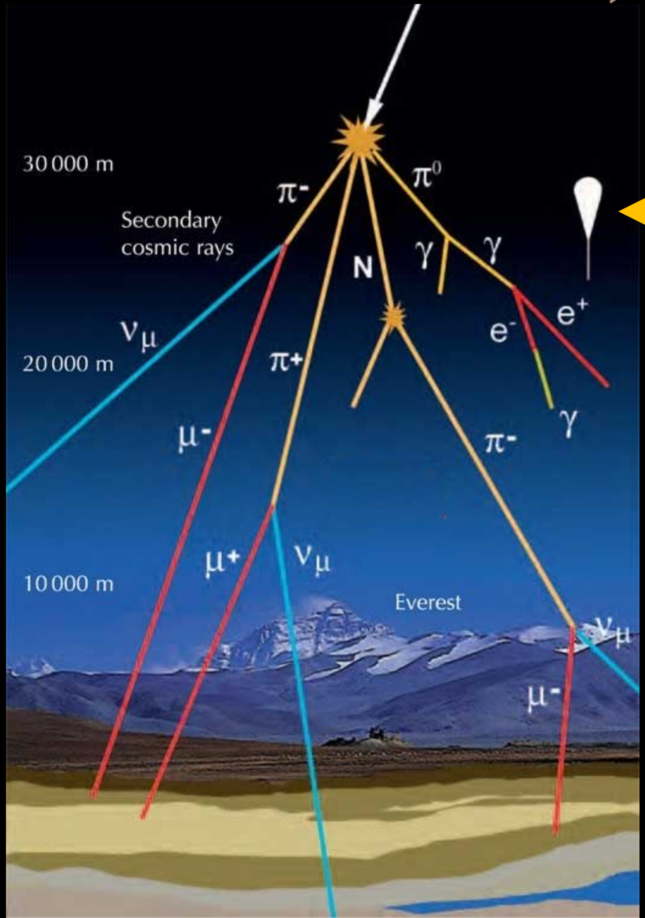
How to detect cosmic rays?

Satellites (e.g. Fermi)

At energies up to few 100 GeV:
direct detection above atmosphere
Limitations: size of the detector



AMS experiment on the
International Space Station



High altitude balloons

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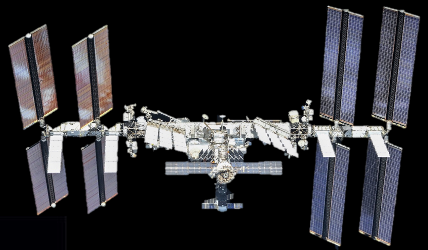
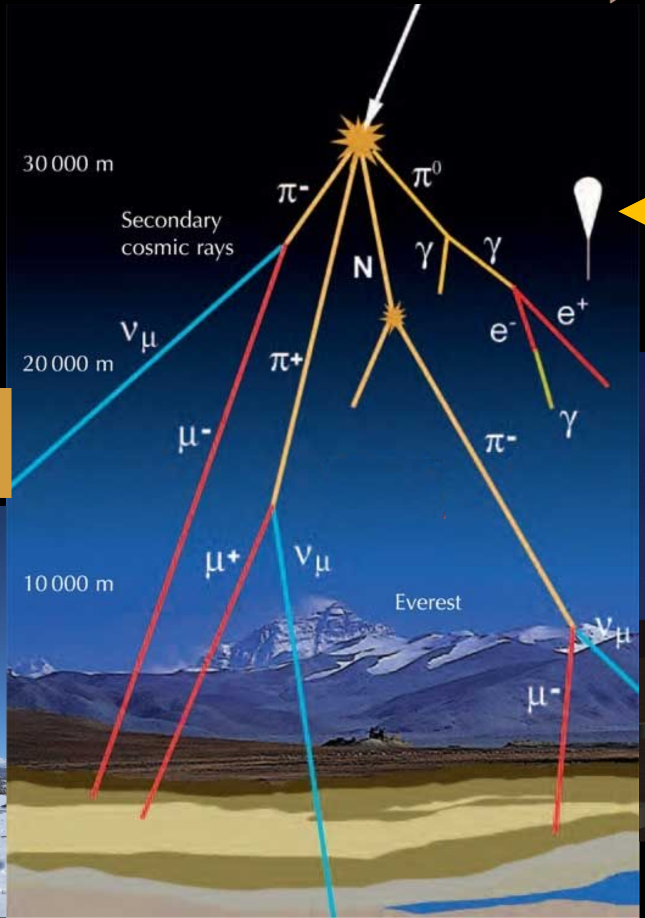
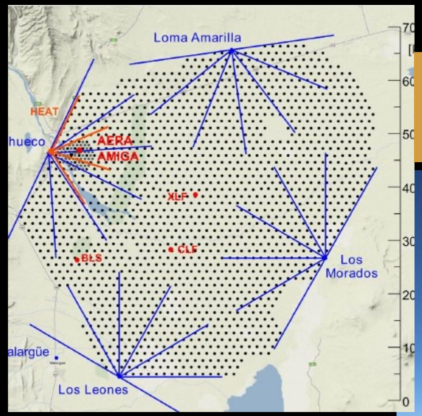


AMS experiment on the International Space Station



High altitude balloons

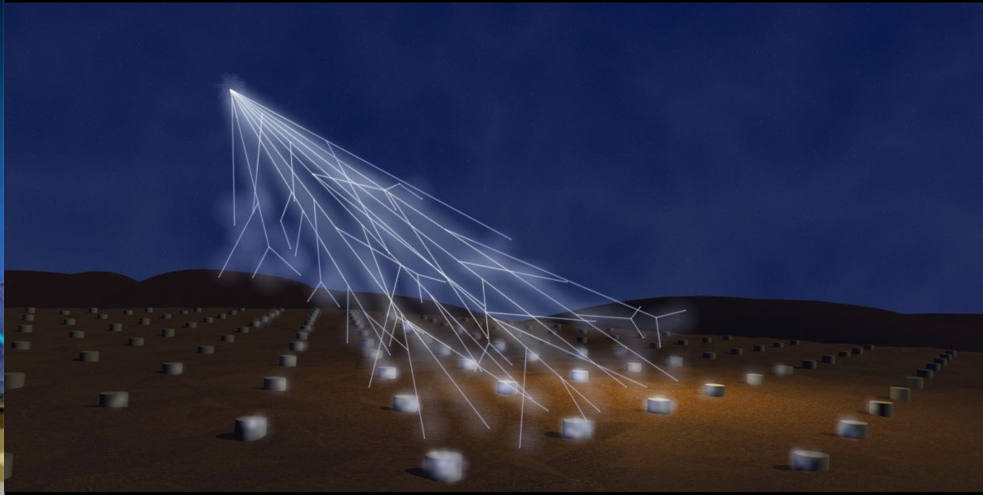
At energies above a few 100 GeV:
low rate requires large surface



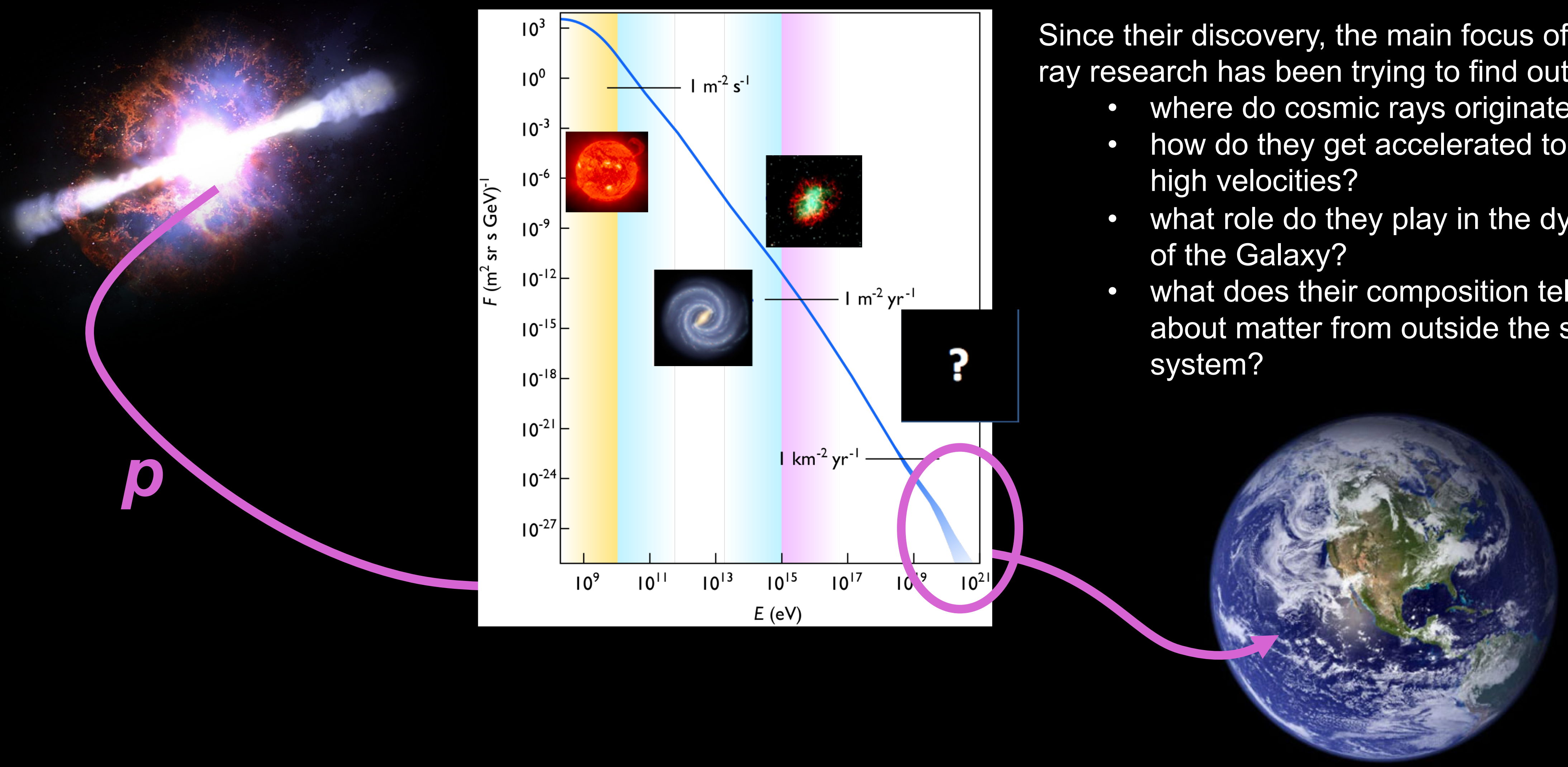
Pierre Auger Observatory, Argentina

Array of 1660 detector stations spread over an area of 3000 km² at an altitude of 1400 m

Detection of charged particles via the Cherenkov light they create in purified water.



But cosmic rays… How? Why?

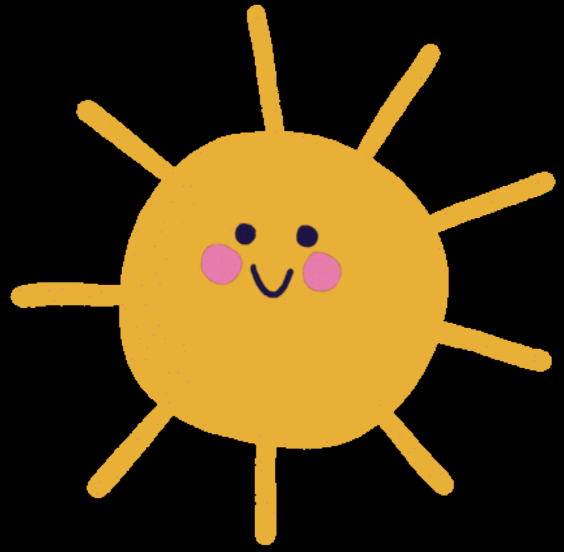


Since their discovery, the main focus of cosmic ray research has been trying to find out:

- where do cosmic rays originate?
- how do they get accelerated to such high velocities?
- what role do they play in the dynamics of the Galaxy?
- what does their composition tells us about matter from outside the solar system?

But, while some people were trying to figure out Cosmic Rays...

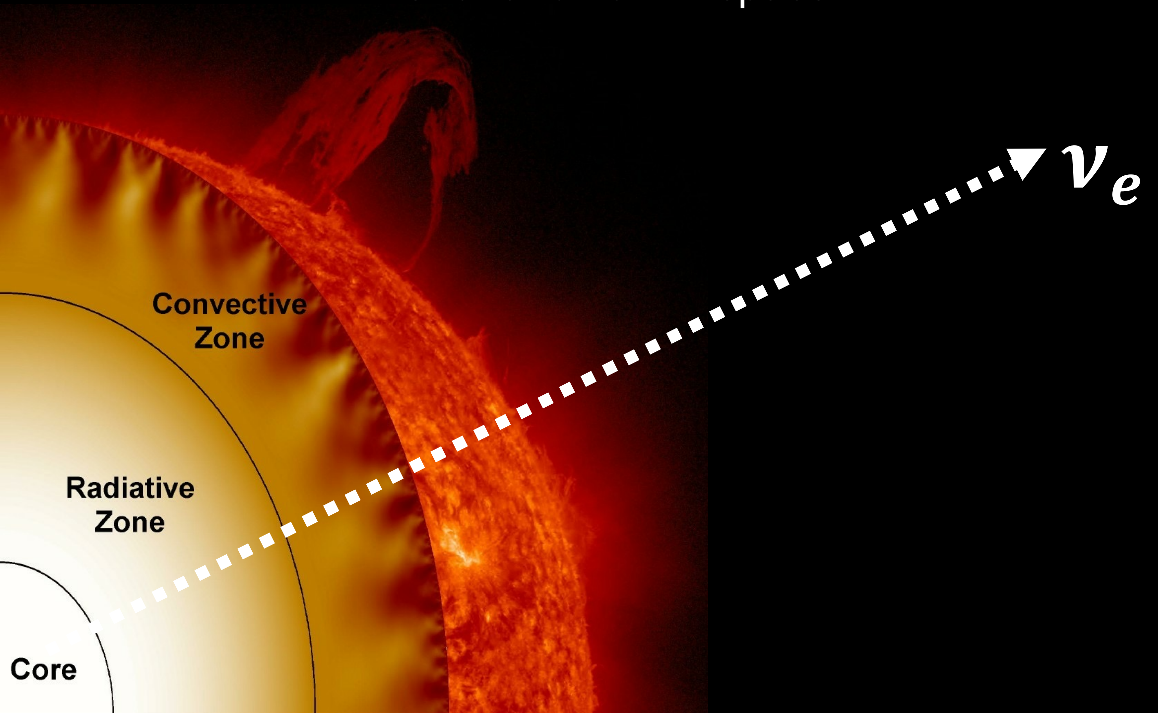
Other people were trying to figure out the Sun



The Sun is a Source of Neutrinos!

- Electron neutrinos with energy of the order of 1 MeV are produced in the thermonuclear fusion reactions in the solar core.
  - Hans Bethe (1930's): first solar model based on nuclear reactions
  - John Bahcall (1960's): increasingly detailed solar model calculations of the solar neutrino fluxes

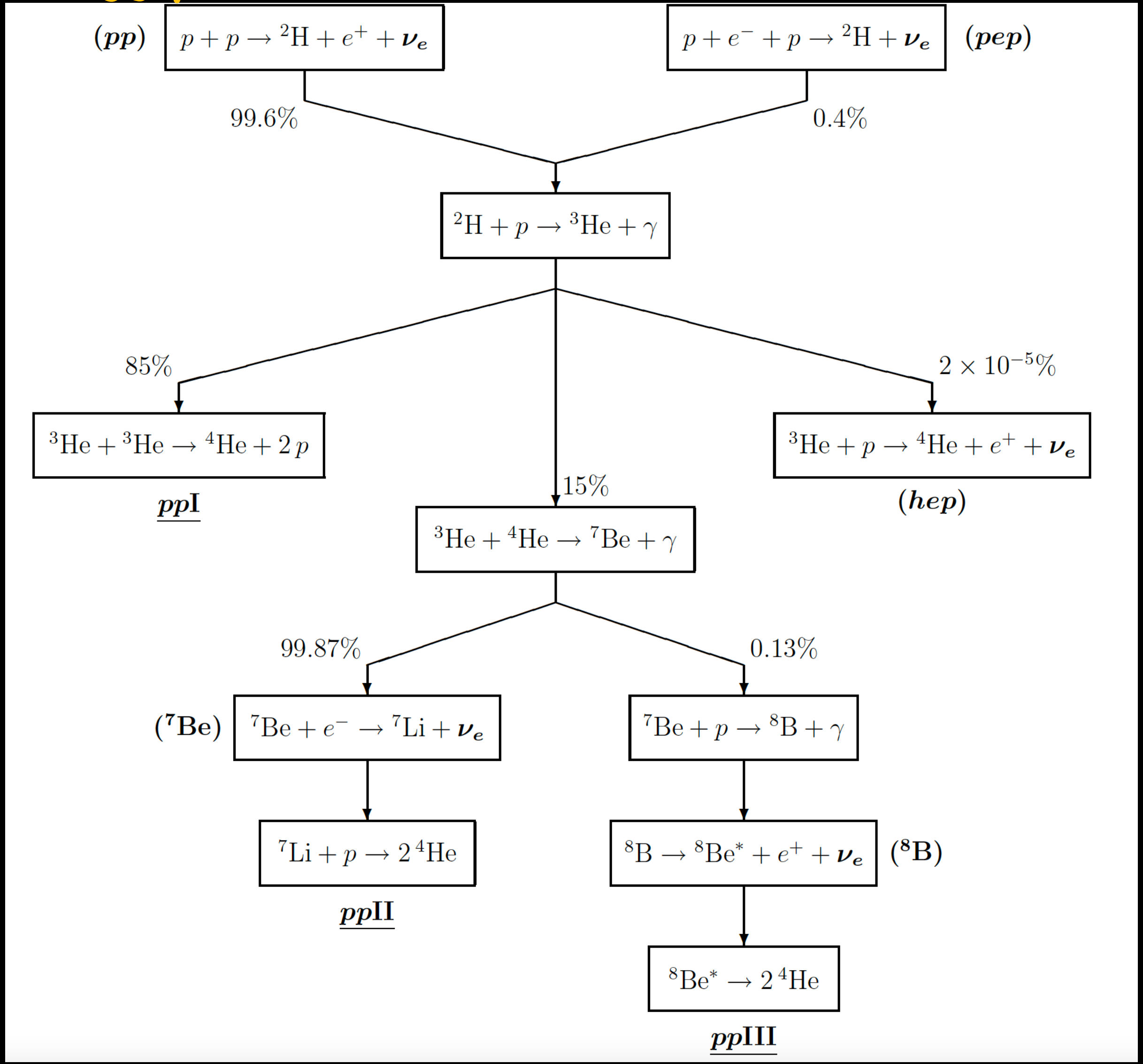
- Since neutrino interactions with matter is extremely weak, practically all the neutrinos produced in the core of the Sun pass undisturbed through the solar interior and flow in space.



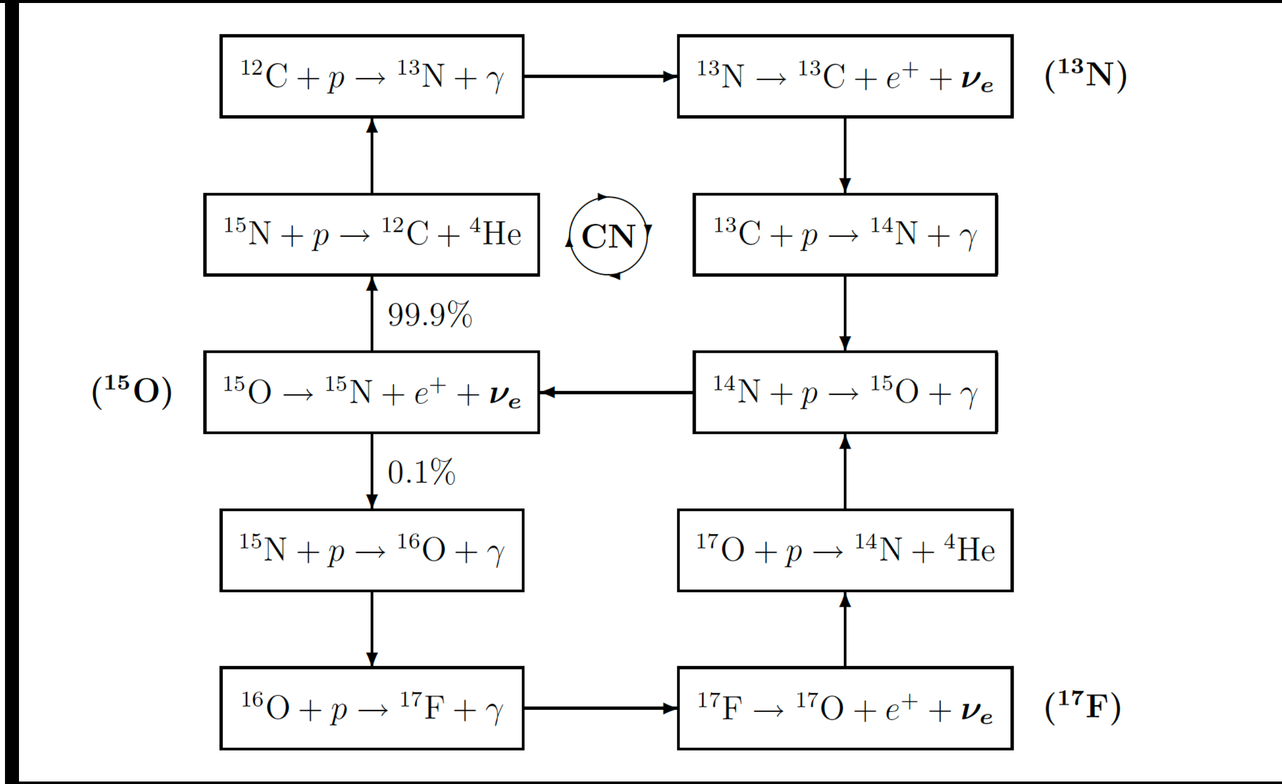
Only neutrinos, with their extremely small interaction cross-sections, can enable us to see into the interior of a star, and thus verify directly the hypothesis of nuclear energy generation in stars.
John N. Bahcall

The Sun is powered by two groups of thermonuclear reactions:

Dominates the energy production | pp chain



CNO cycle | **More important in stars bigger than the Sun**



The result of both processes is:

$$4p + 2e^- \to {}^4He + 2\nu_e + 26.7\ \text{MeV}$$

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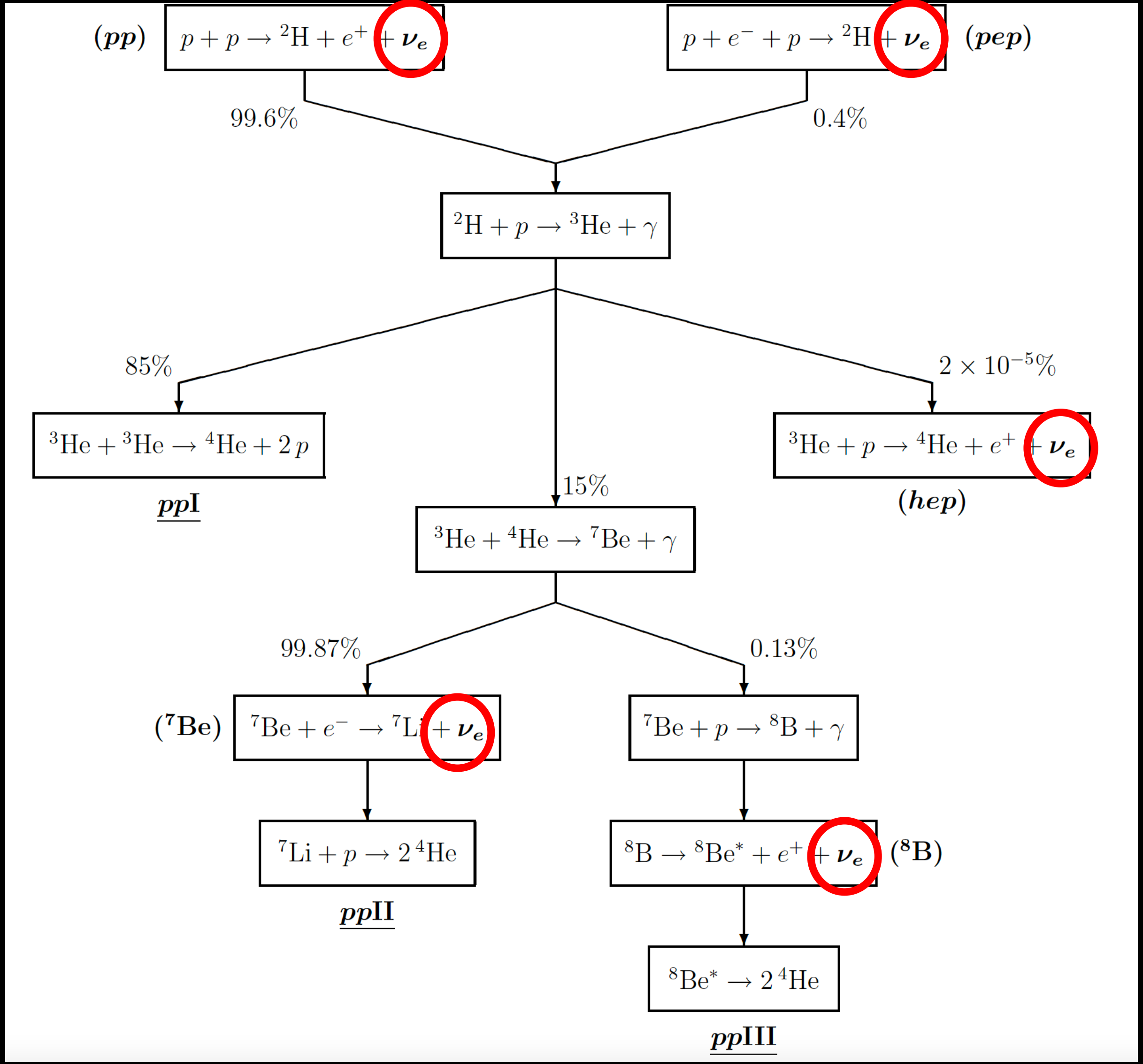
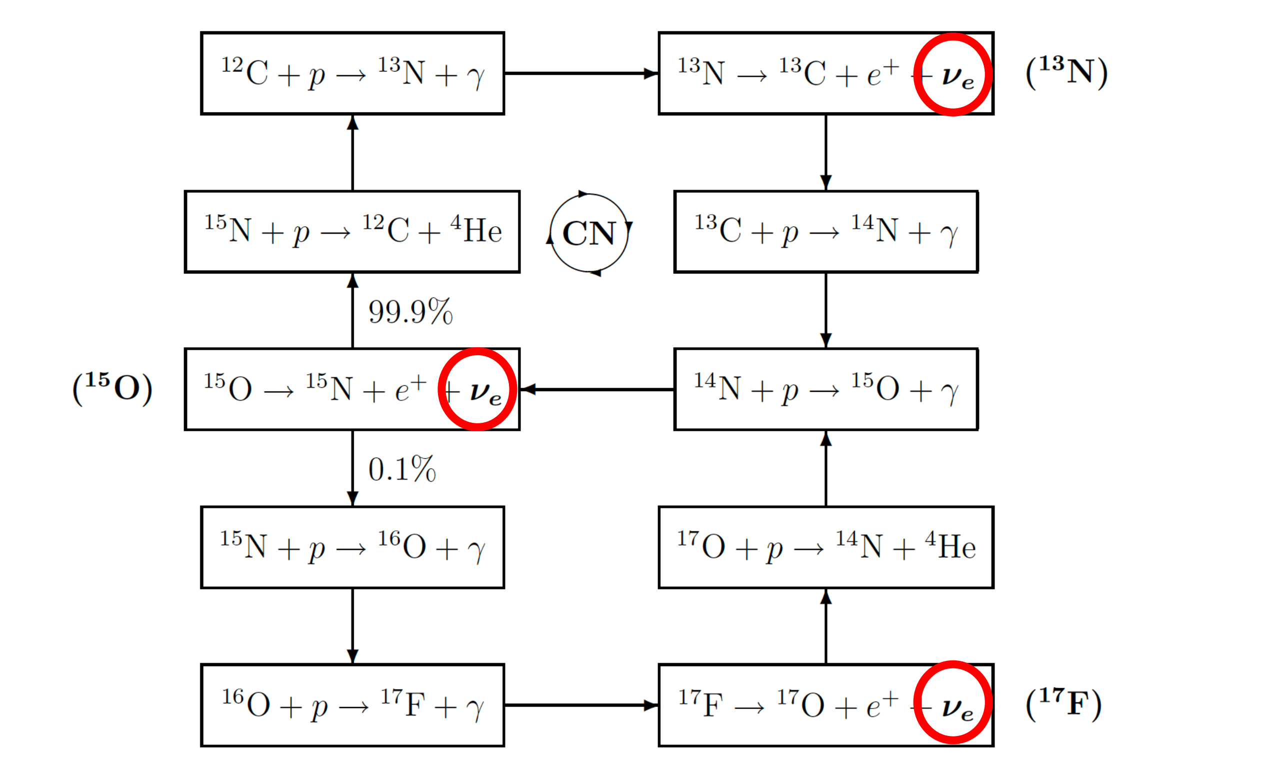
pp chain



CNO cycle



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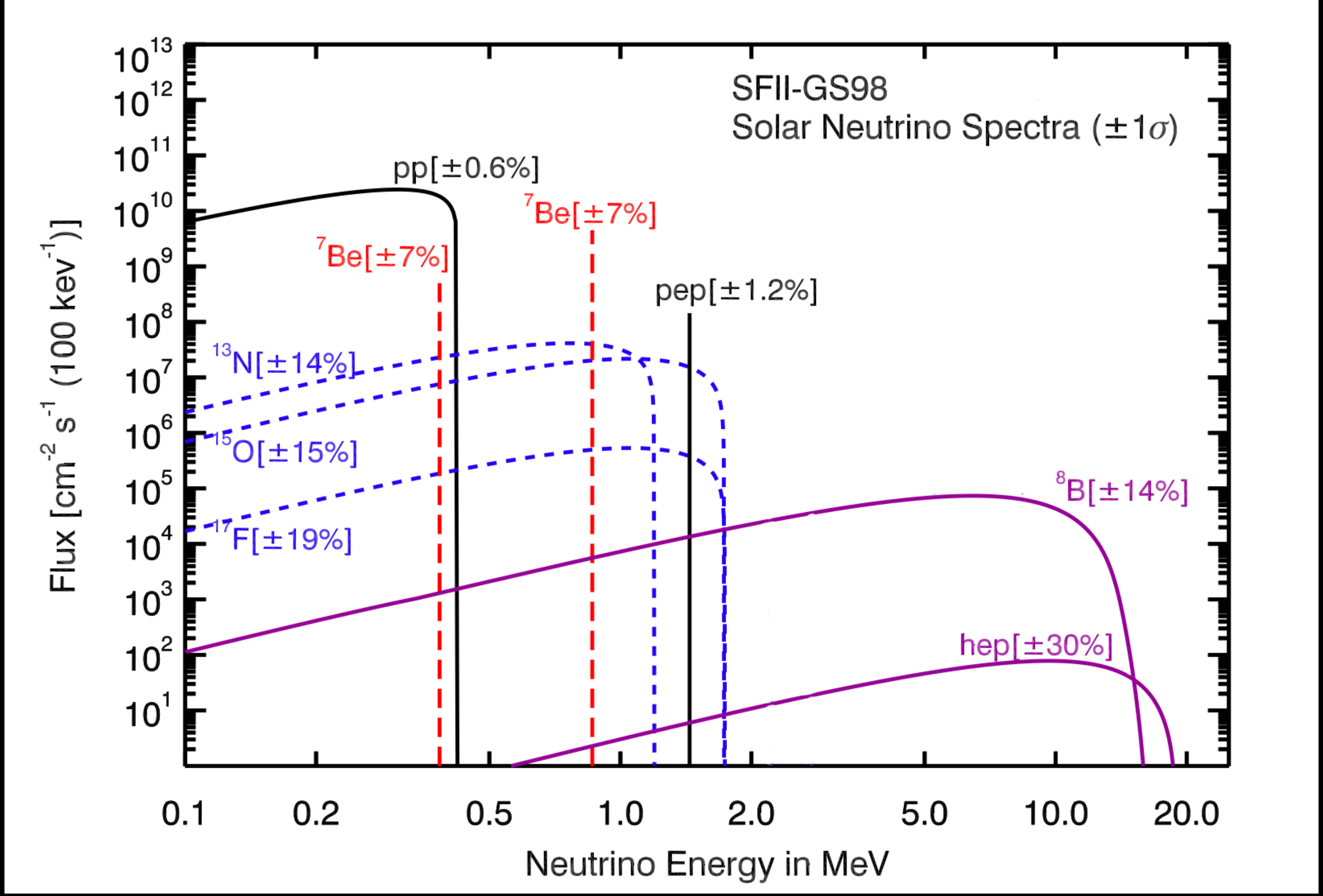
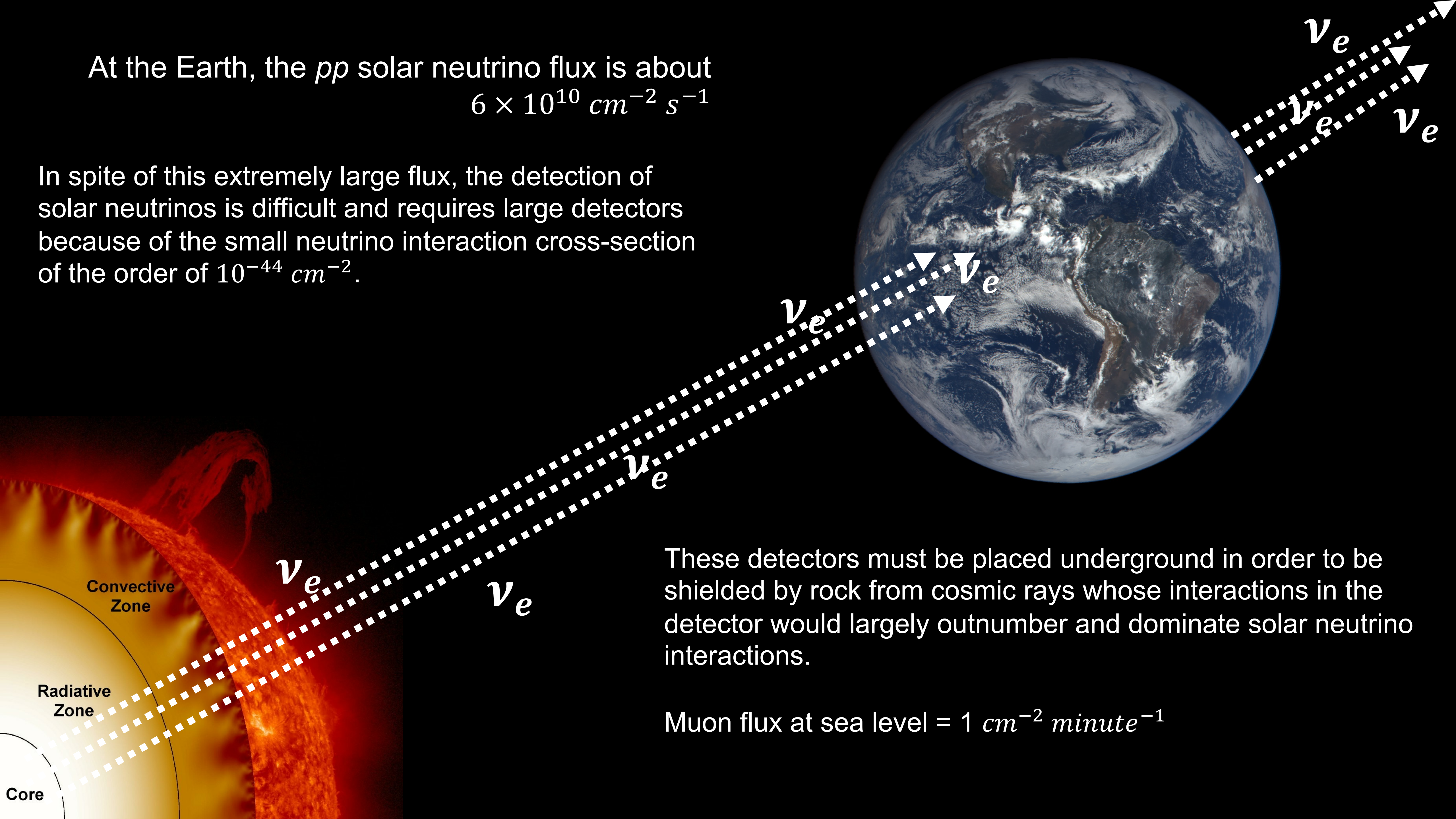


The detailed calculation of the solar neutrino fluxes has been done based on the Standard Solar Model (SSM). The SSM describes the structure and evolution of the Sun based on a variety of inputs such as the mass, luminosity, radius, surface temperature, age, and surface elemental abundances. In addition, the knowledge of the absolute nuclear reaction cross sections for the relevant fusion reactions and the radiative opacities are necessary.


At the Earth, the *pp* solar neutrino flux is about $6 \times 10^{10}\ cm^{-2}\ s^{-1}$
In spite of this extremely large flux, the detection of solar neutrinos is difficult and requires large detectors because of the small neutrino interaction cross-section of the order of $10^{-44}\ cm^{-2}$.
These detectors must be placed underground in order to be shielded by rock from cosmic rays whose interactions in the detector would largely outnumber and dominate solar neutrino interactions.
Muon flux at sea level = 1 $cm^{-2}\ minute^{-1}$
ν_e
ν_e
ν_e
ν_e
ν_e
ν_e
ν_e
ν_e
Convective Zone
Radiative Zone
Core


People who want to detect solar neutrinos
Cosmic rays just existing
imgflip.com

Solution:

Go inside a mine

First detection of Solar Neutrinos

Homestake Experiment

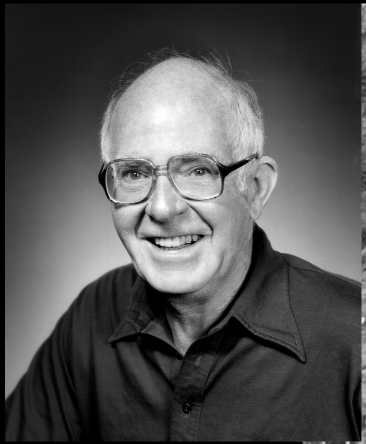
- Proposed in the 1970s by Ray Davis
- Radiochemical experiment looking for the inverse beta-decay reaction:

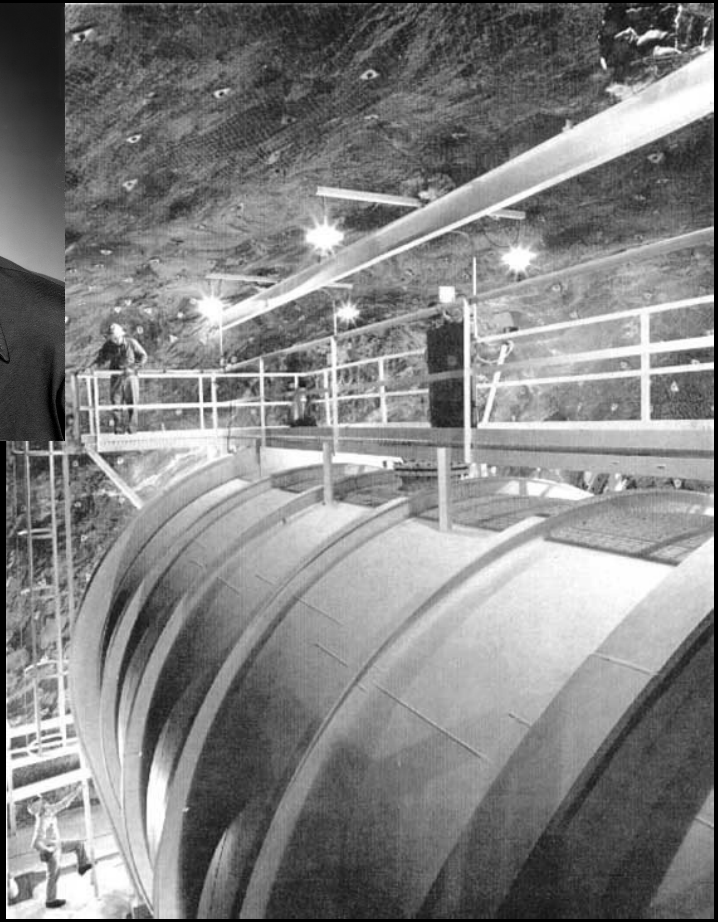
$$\nu_e + {}^{37}\mathrm{Cl} \mapsto {}^{37}\mathrm{Ar} + e^-$$

Neutrino energy threshold $E_\nu = 0.814$ MeV
Sensitive to ^{8}B and ^{7}Be solar neutrinos

- Expose large quantities of Chlorine
- Chemically extract the Argon
- Count the radioactive decays of ^{37}Ar = *number of solar neutrinos interacting*

Acquired data for 24 years!

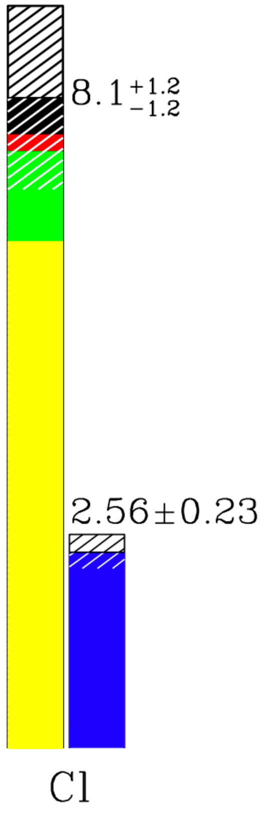




Homestake mine (USA), 1478 m deep

First detection of Solar Neutrinos

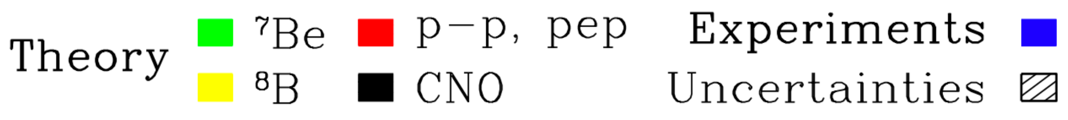
Homestake Experiment Results



Observe only 1/3 of the expected number of solar neutrinos!

Something wrong with:

- The experiment?
- The SSM?
- The neutrinos?

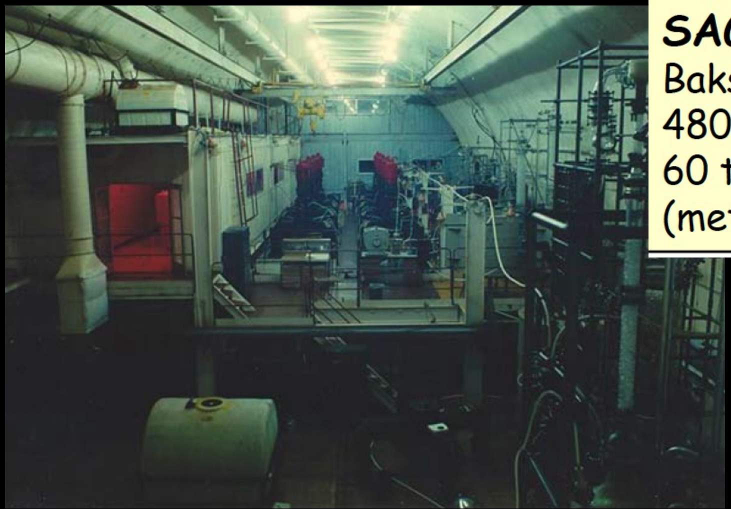


Gallium Experiments

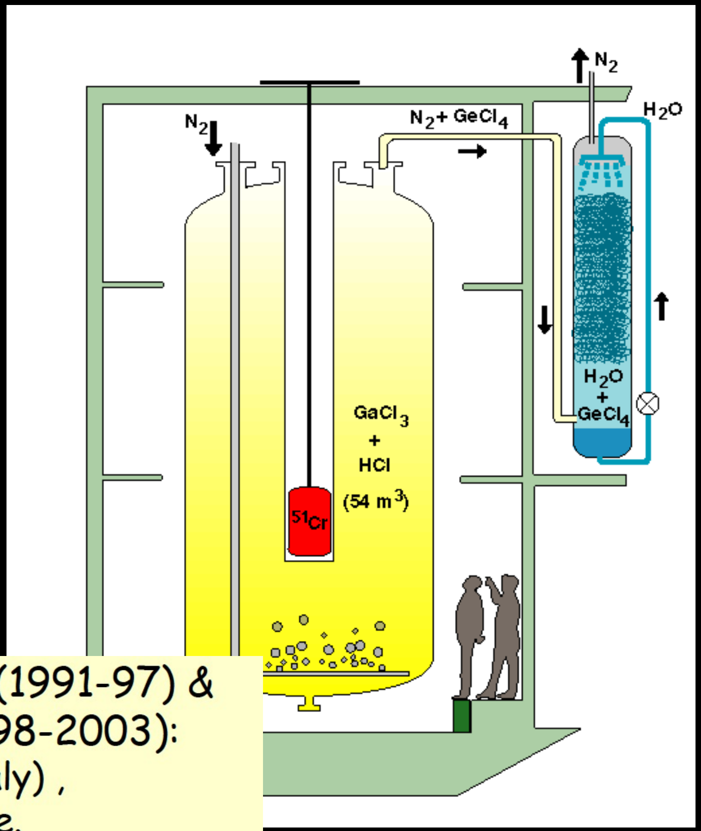
- Similar to Homestake, but using the Gallium reaction

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$

Neutrino energy threshold $E_\nu = 0.233$ MeV
Sensitive to ^{8}B, ^{7}Be and high energy pp solar neutrinos



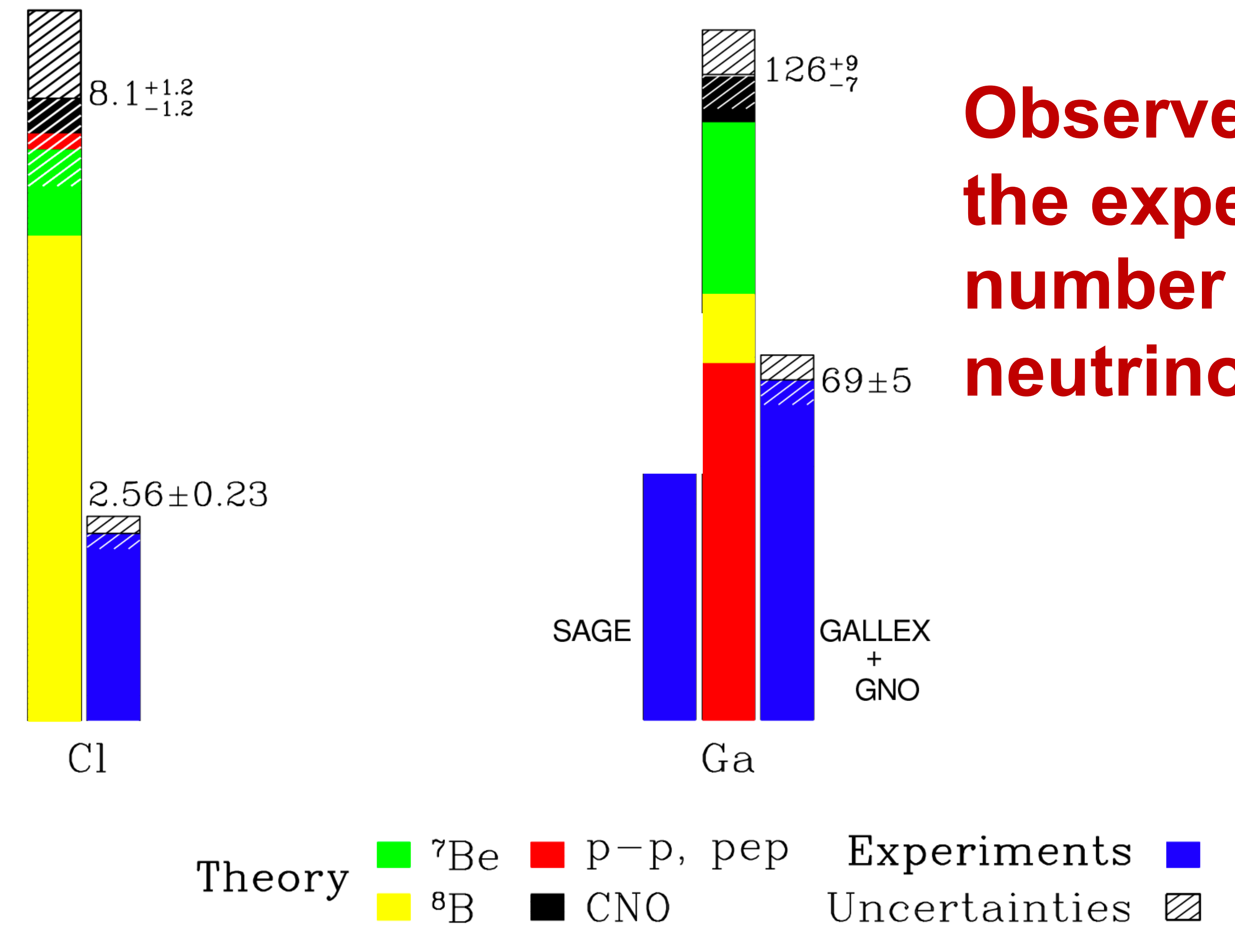
SAGE (1991-93):
Baksan (Russia)
4800 m.w.e.
60 tons of gallium
(metal Ga target)



GALLEX (1991-97) &
GNO (1998-2003):
LNGS (Italy) ,
3200 m.w.e.
30 tons of gallium
(water solution of $GaCl_3$)

SAGE uses metallic gallium (which becomes a liquid at just above room temperature), while GALLEX uses gallium in a liquid-chloride form. The different forms of the gallium are susceptible to very different types of backgrounds, and thus the two experiments provide a check for each other.

Gallium Experiments



Observe 1/2 of the expected number of solar neutrinos!

Water Cherenkov Detectors

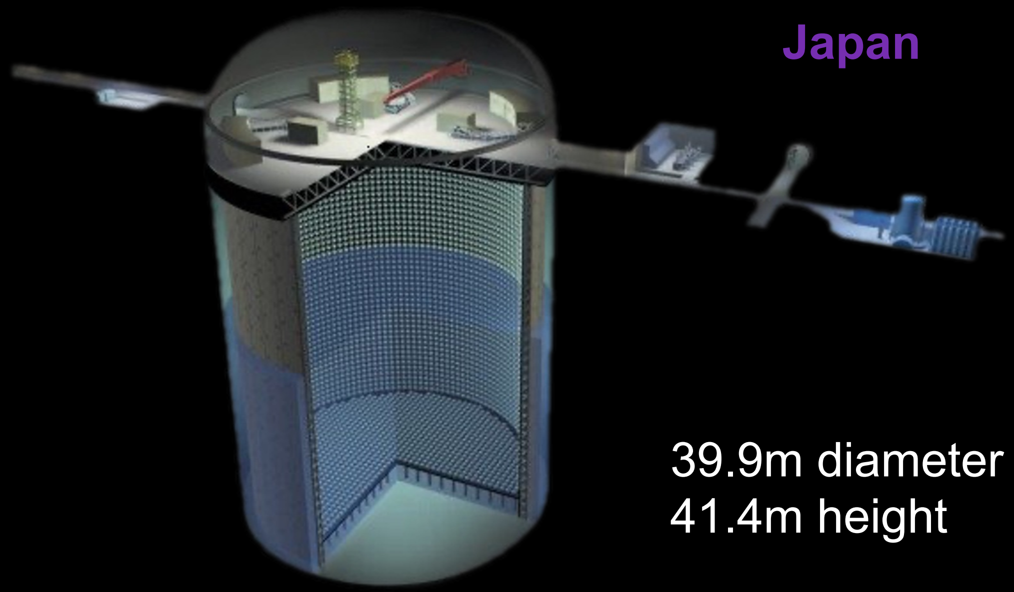
- 1987 Kamiokande
- 1997 Super-Kamiokande
  - Several phases

- Detects neutrino-electron scatterings

$$\nu_l + e^- \rightarrow \nu_l + e^-$$

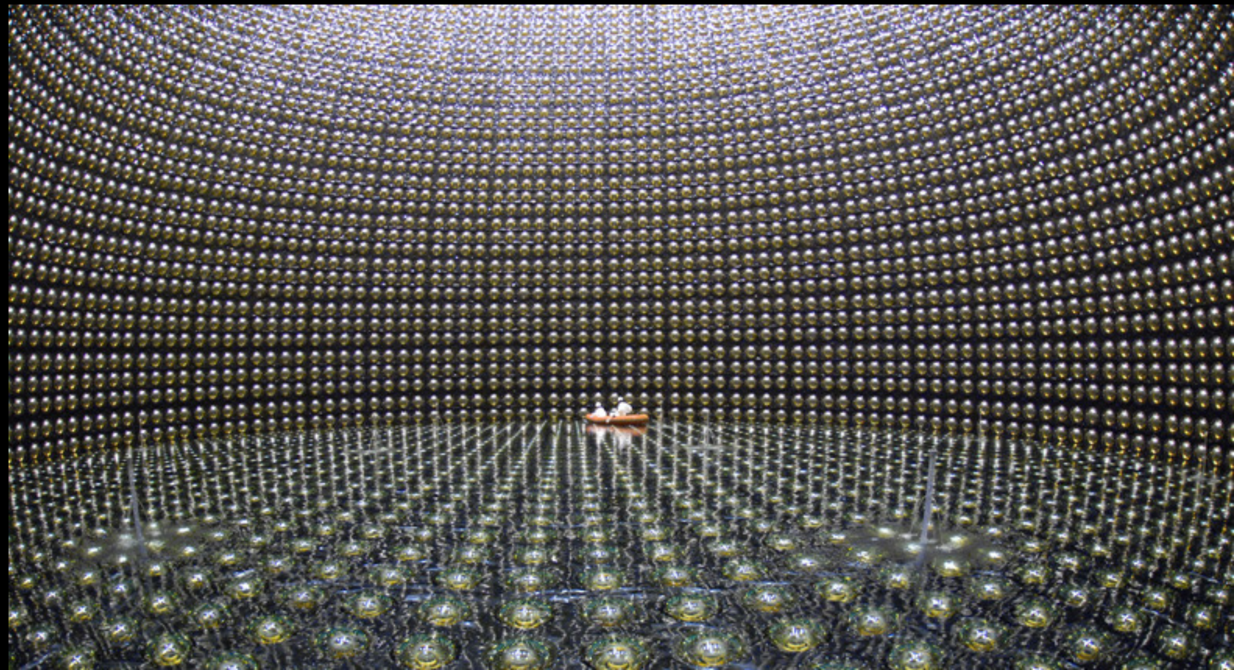
- Sensitive to all neutrino flavours, but mainly ν_e

Japan



39.9m diameter
41.4m height

11000 photomultipliers
50000 tons of water

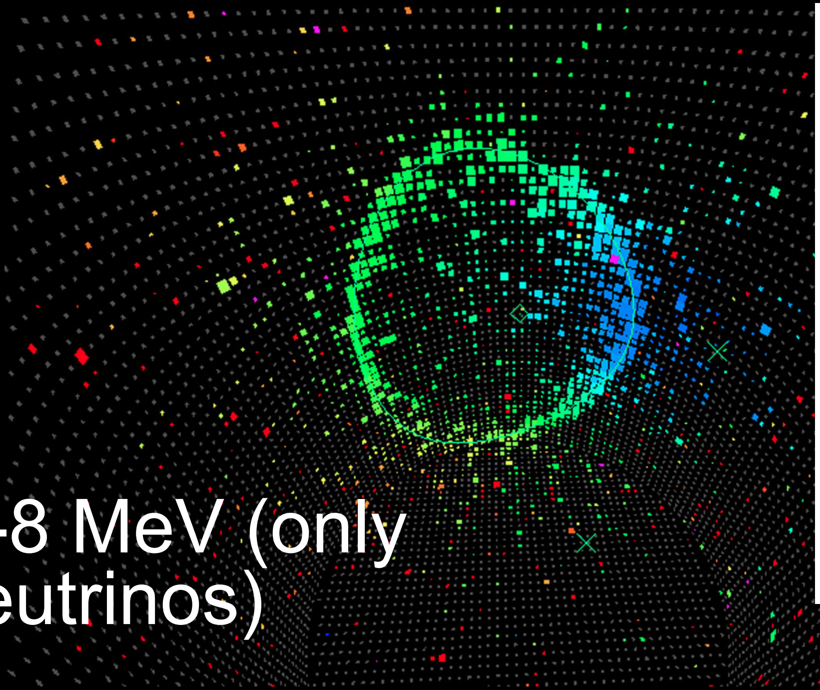


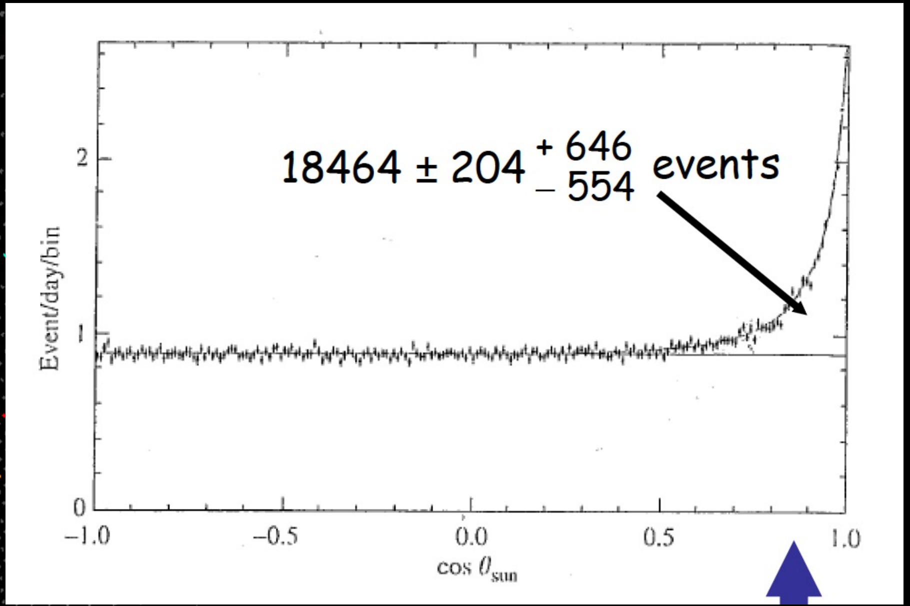
Water Cherenkov Detectors

- The scattered electrons produce Cherenkov radiation

- Allow to know:
  - Directionality
  - Arrival Time
  - Energy

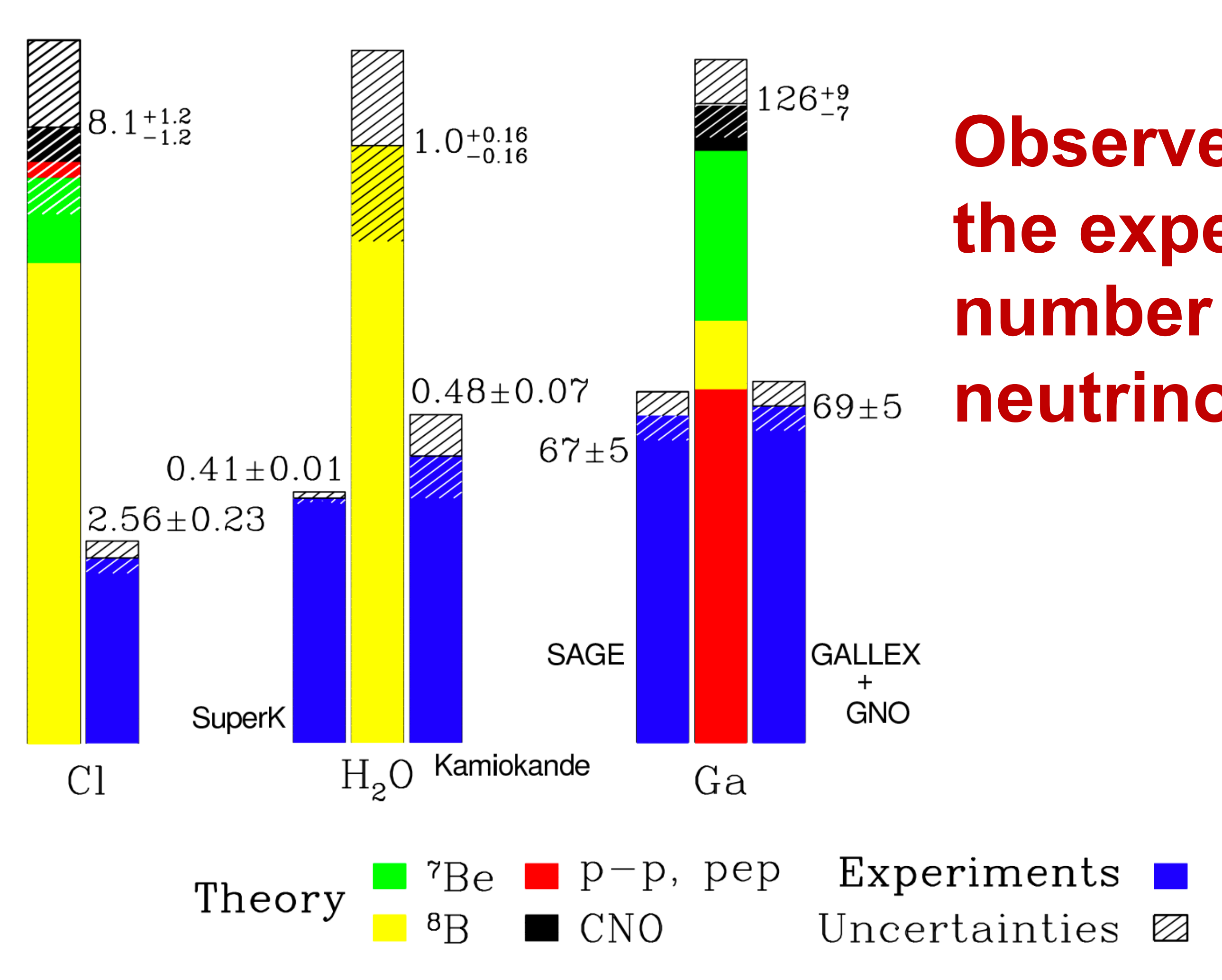
- High threshold 5-8 MeV (only sensitive to ^{8}B neutrinos)





They could see the events along the direction of the Sun – they are solar $\nu's$

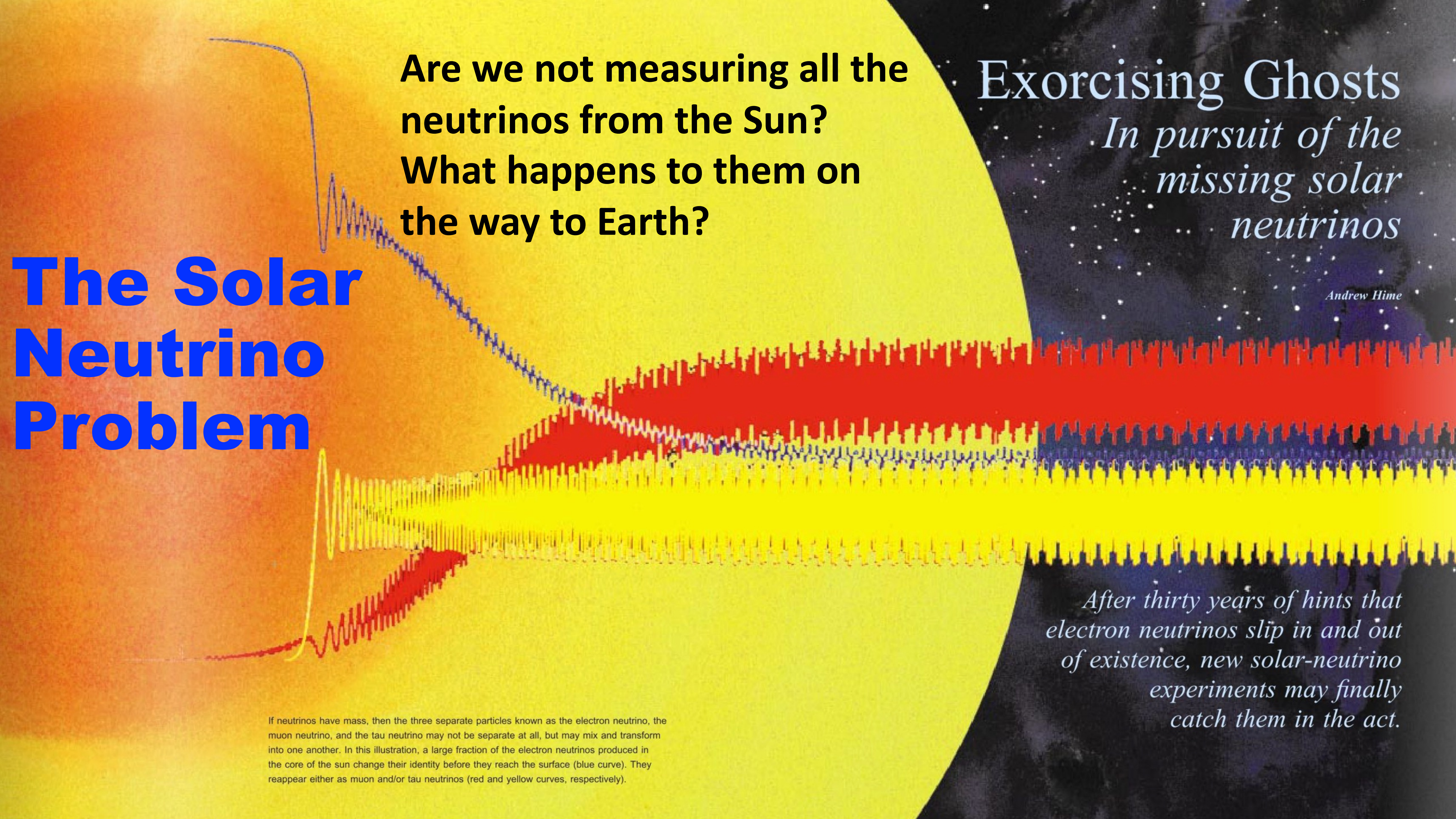
Water Cherenkov Detectors



Observe 1/2 of the expected number of solar neutrinos!

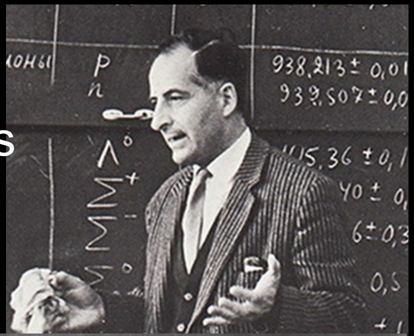
The Solar Neutrino Problem

Are we not measuring all the neutrinos from the Sun? What happens to them on the way to Earth?



Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations

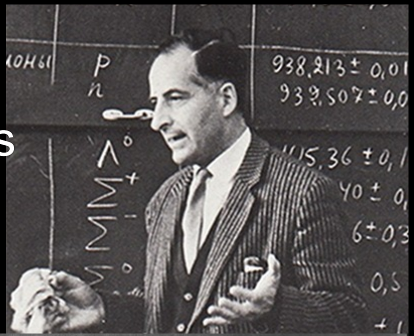


Three flavours of Neutrinos

ν_e ν_μ ν_τ

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



S. Sakata 1911-1970
Z. Maki 1929-2005
M. Nakagawa 1932-2001

Three flavours of Neutrinos

$$\boldsymbol{\nu_e} \quad \boldsymbol{\nu_\mu} \quad \boldsymbol{\nu_\tau}$$

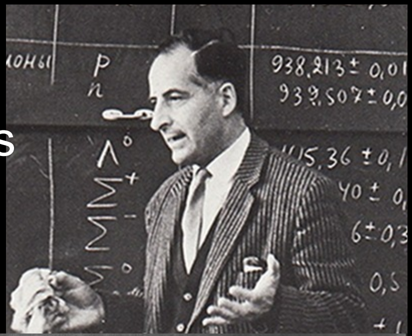
Are a linear combination of three neutrino mass states

$$\boldsymbol{\nu_1} \quad \boldsymbol{\nu_2} \quad \boldsymbol{\nu_3}$$

$$\boldsymbol{\nu_e} = a\boldsymbol{\nu_1} + b\boldsymbol{\nu_2} + c\boldsymbol{\nu_3}$$
$$\boldsymbol{\nu_\mu} = d\boldsymbol{\nu_1} + e\boldsymbol{\nu_2} + f\boldsymbol{\nu_3}$$
$$\boldsymbol{\nu_\tau} = g\boldsymbol{\nu_1} + h\boldsymbol{\nu_2} + i\boldsymbol{\nu_3}$$

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



Three flavours of Neutrinos

$$\nu_e \qquad \nu_\mu \qquad \nu_\tau$$

Are a linear combination of three neutrino mass states

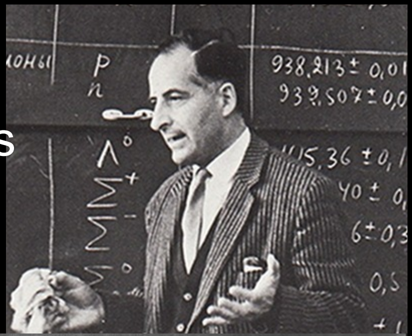
$$\nu_1 \qquad \nu_2 \qquad \nu_3$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The PMNS Matrix

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



Courtesy of Sakata Memorial Archival Library

S. Sakata 1911-1970 | Z. Maki 1929-2005 | M. Nakagawa 1932-2001

Three flavours of Neutrinos

ν_e ν_μ ν_τ

Are a linear combination of three neutrino mass states

ν_1 ν_2 ν_3

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

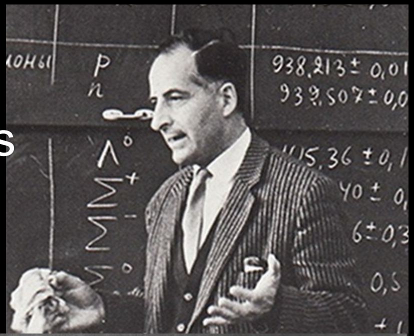
(that looks more like this)

The PMNS Matrix

Neutrinos Oscillate

When neutrinos travel, they change from one flavour to the other.

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



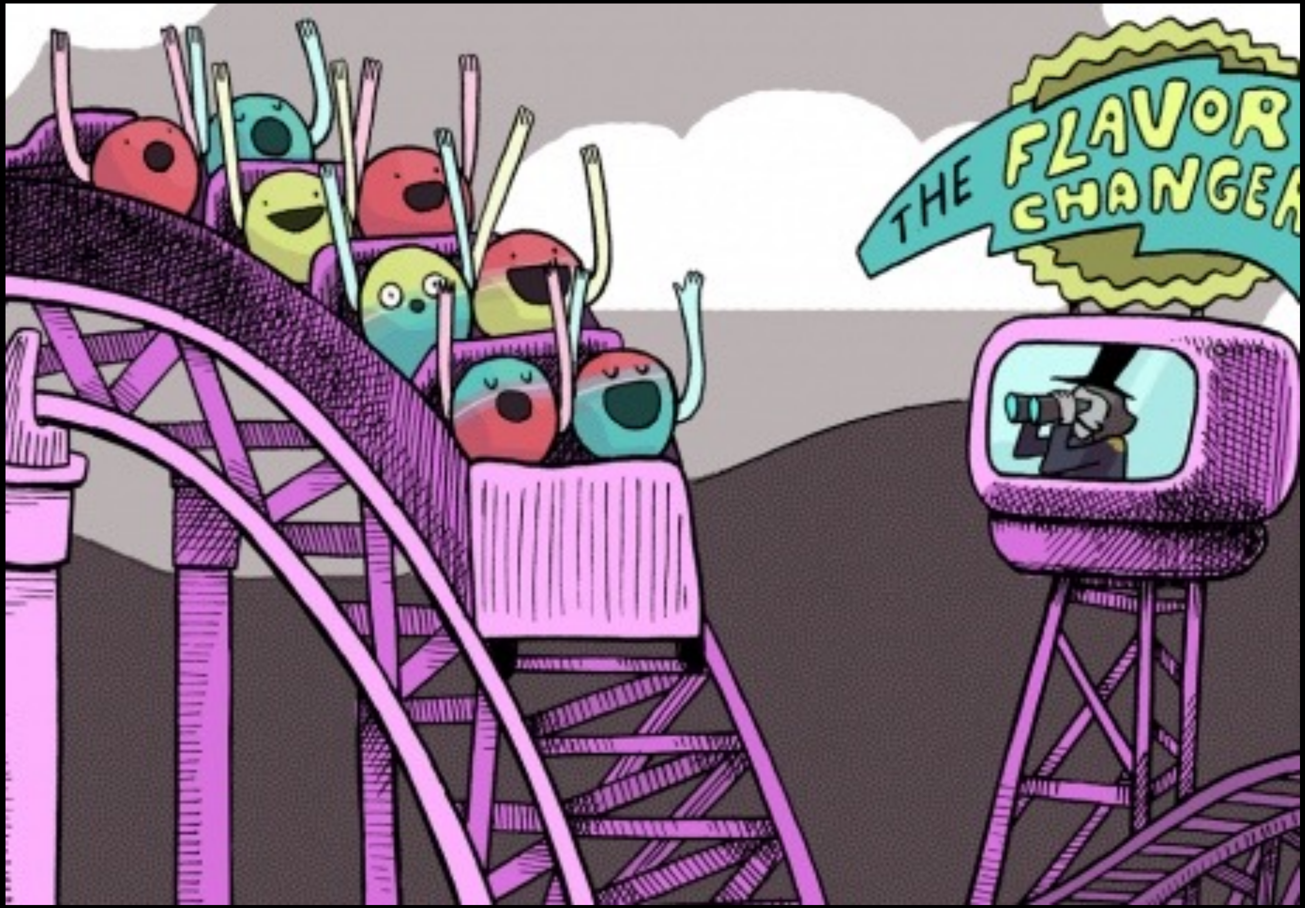
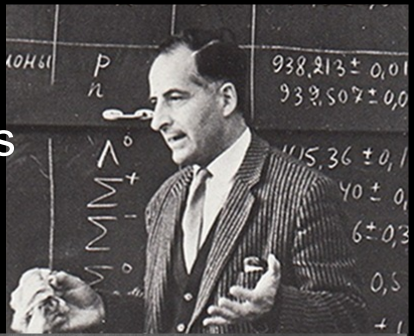


Image from Symmetry Magazine

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations

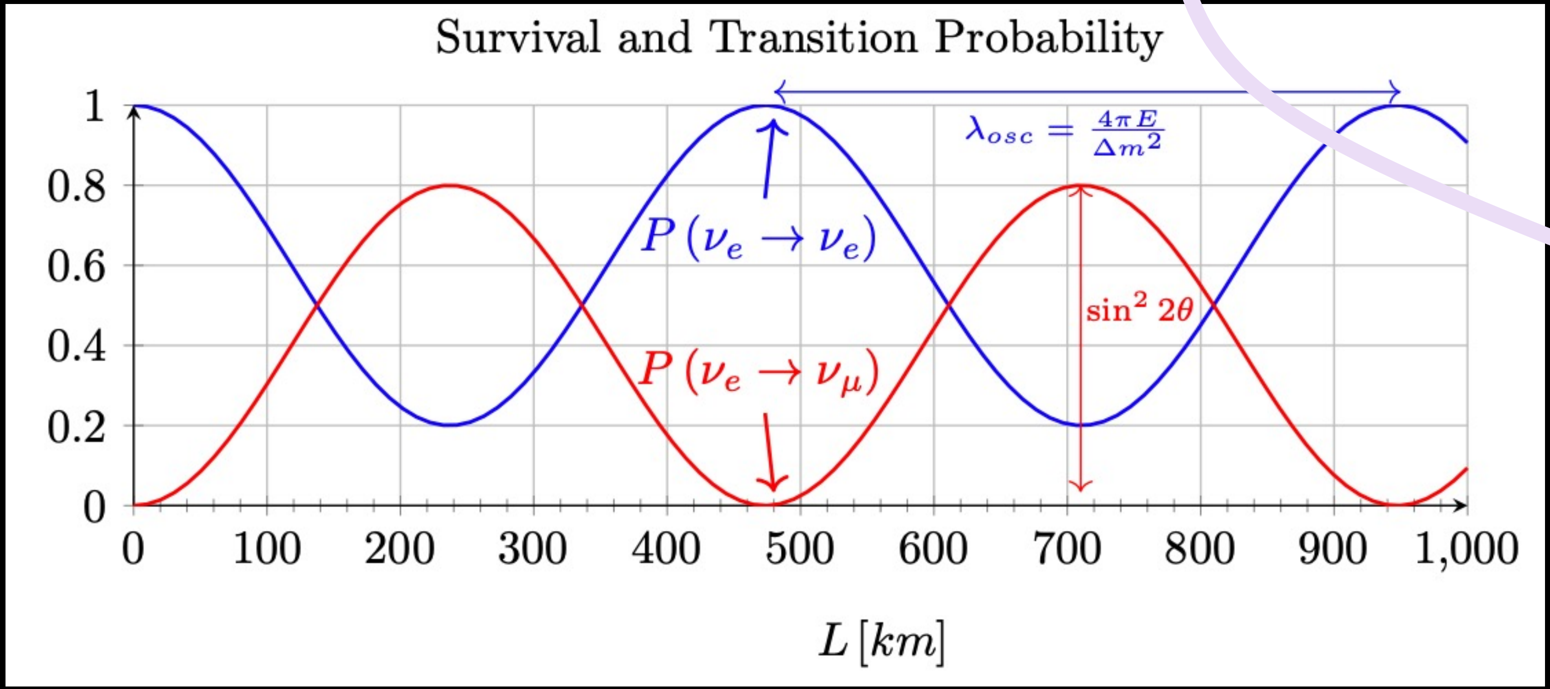


When neutrinos travel, they change from one flavour to the other.

Two neutrino case:

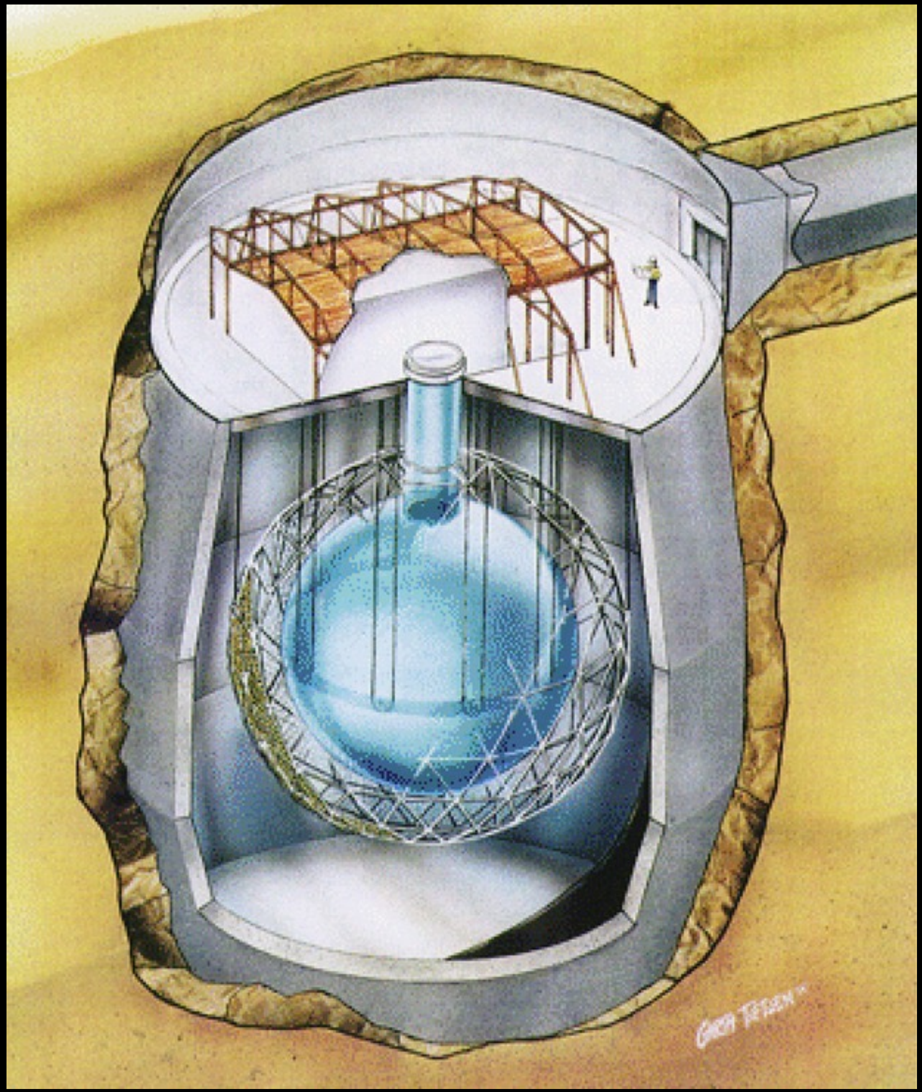
$$P_{oscillation}(\boldsymbol{\nu_e} \rightarrow \boldsymbol{\nu_\mu}) = sin^2 2\theta_{12} sin^2\left(1.27\Delta m^2_{21}[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

$m_2^2 - m_1^2$



SNO – Sudbury Neutrino Observatory

- 1000 tonnes of Heavy Water (D_2O)
  - Inside a 12 m diameter acrylic sphere
- Seen by 9500 PMTs
- Volume outside the acrylic vessel (AV) filled with water
- 2 km underground inside a Nickel mine in Canada

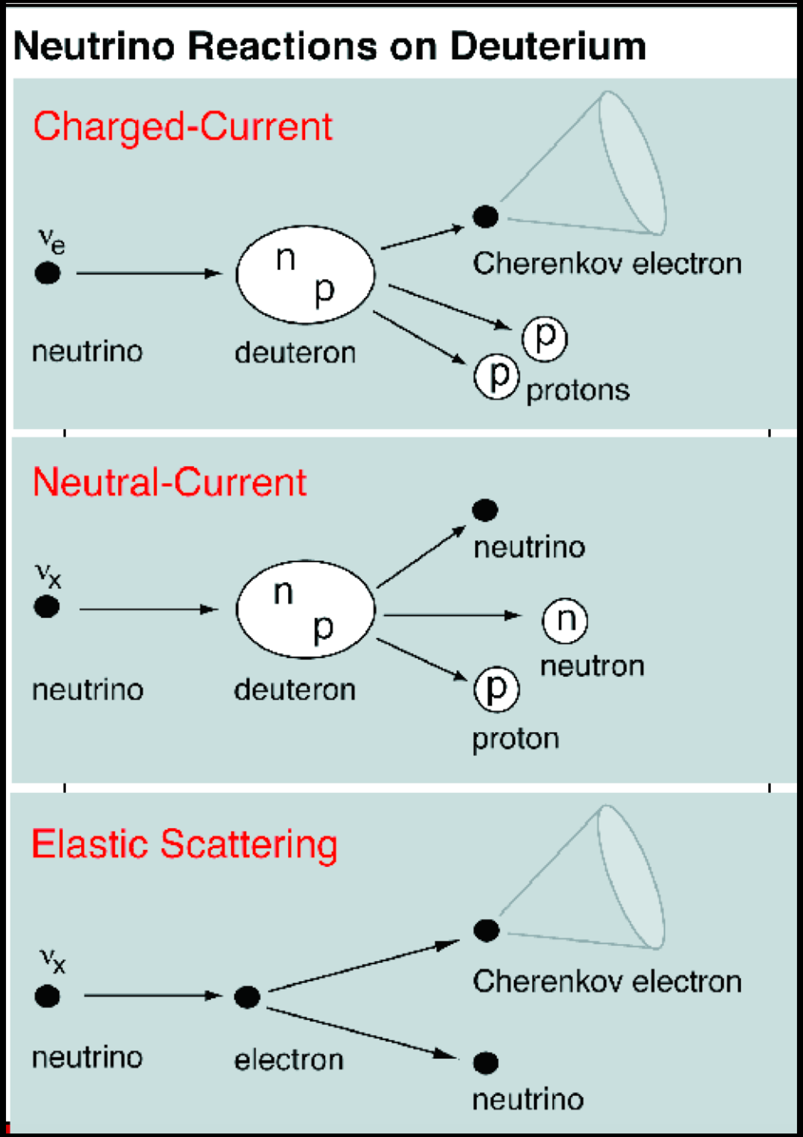


Neutrino Reactions in SNO

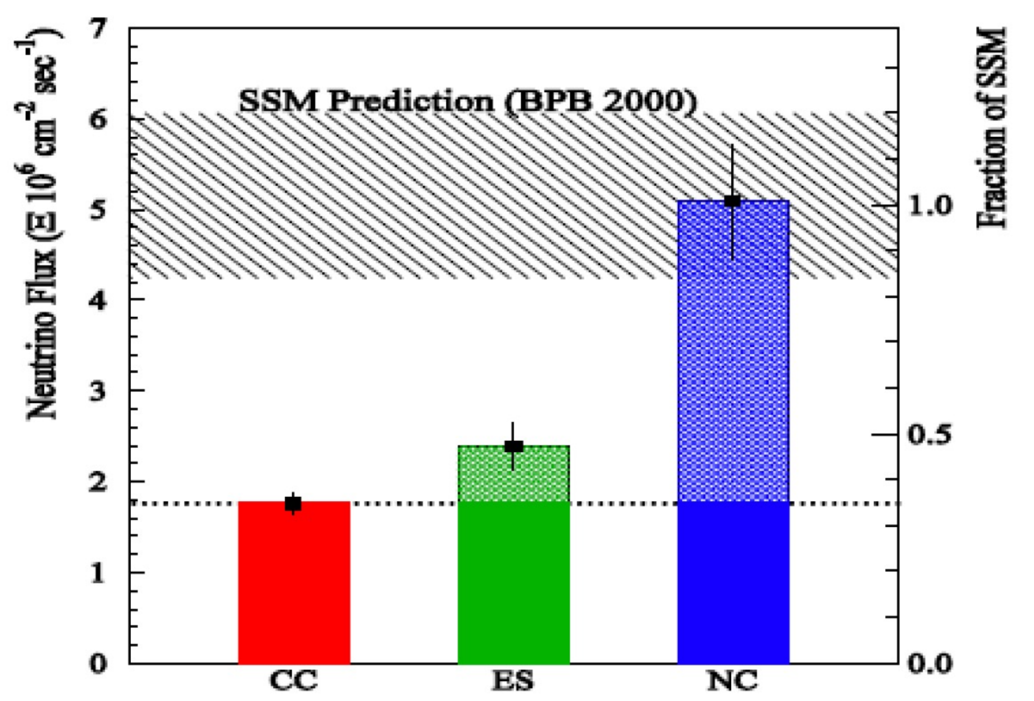
- $\nu_e + d \rightarrow p + p + e^-$
  - Signal: Cherenkov light from electron
  - Only sensitive to ν_e
  - Measured ν_e flux

- $\nu_l + d \rightarrow \nu_l + p + n$
  - Signal: neutron capture (6.25 MeV γ) and Cherenkov light from electrons scattered by the γ
  - Measured total neutrino flux

- $\nu_l + e^- \rightarrow \nu_l + e^-$
  - Signal: Cherenkov light from electron
  - Mainly sensitive to ν_e , some ν_μ and ν_τ



SNO Results

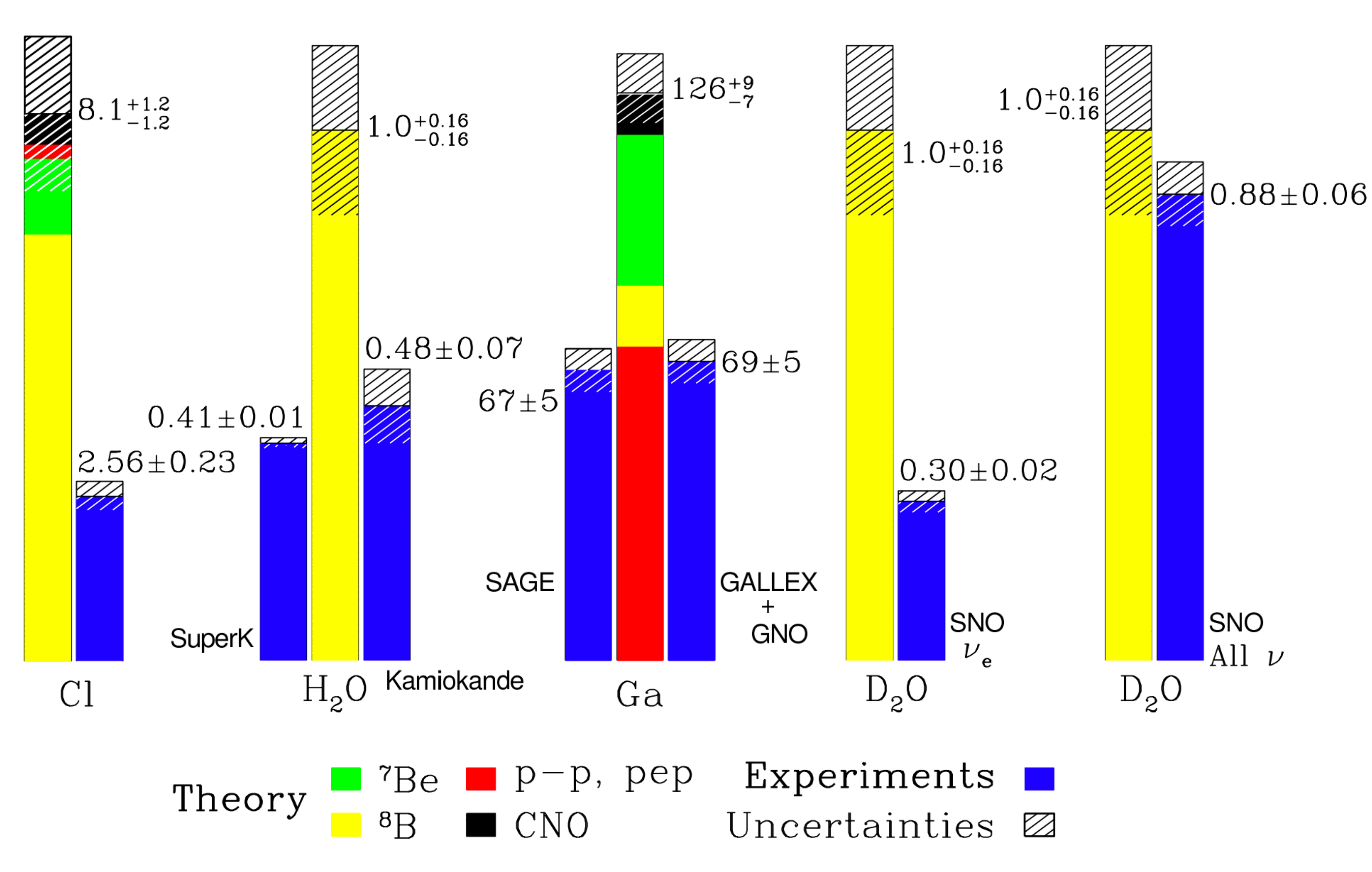


5.3 σ appearance of $\nu_{\mu\tau}$ in a ν_e beam

Roughly 70% of ν_e oscillates away

- Clear evidence for a flux of ν_μ and/or ν_τ from the sun
- Total neutrino flux is consistent with expectation from SSM
- Clear evidence of $\nu_e \rightarrow \nu_\mu$ and/or $\nu_e \rightarrow \nu_\tau$ neutrino transitions

The Solar Neutrino Problem is Solved!

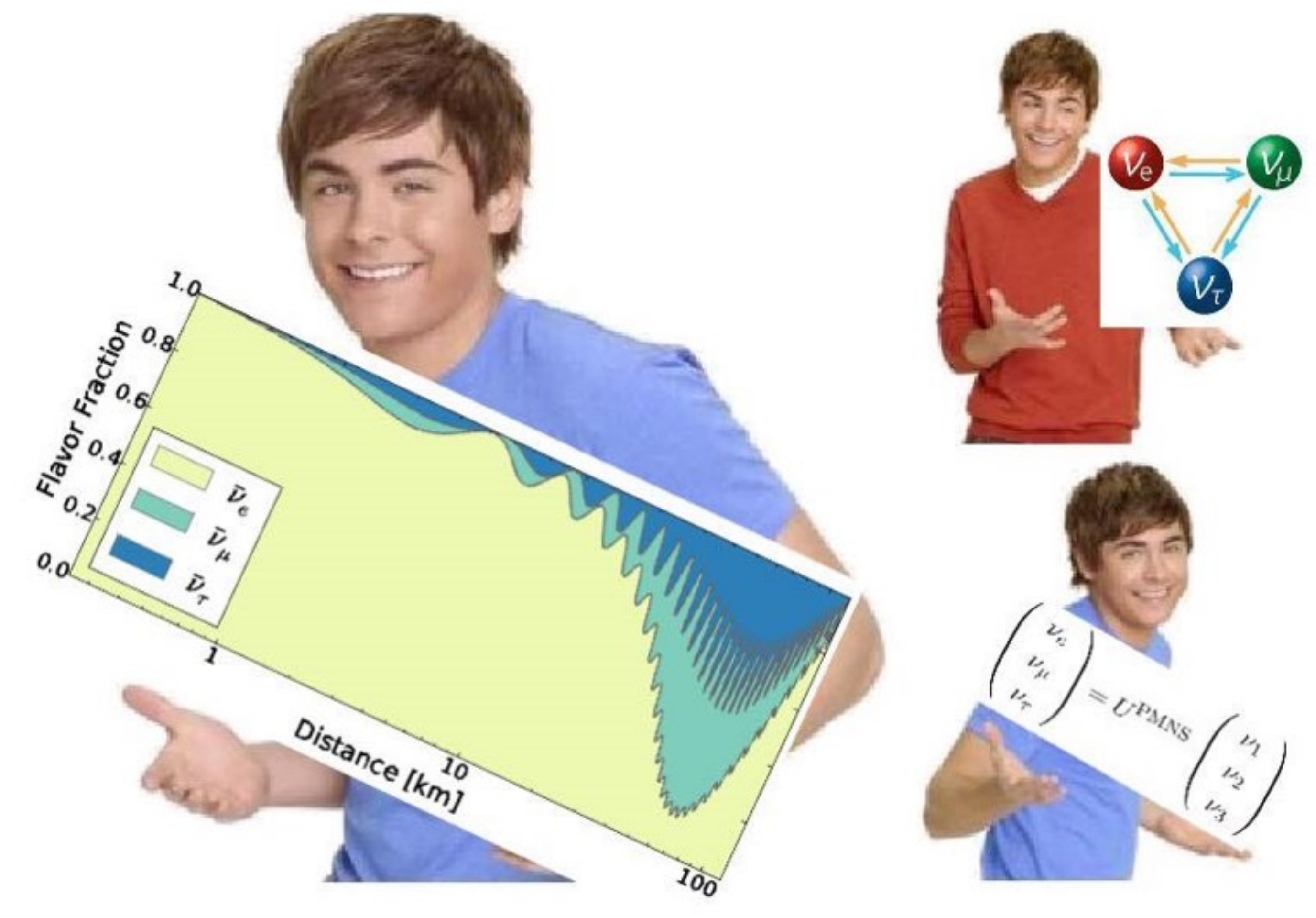


Neutrino Oscillations Discovered!

"...the research group in Canada led by Arthur B. McDonald could demonstrate that the neutrinos from the Sun were not disappearing on their way to Earth. Instead they were captured with a different identity when arriving to the Sudbury Neutrino Observatory."

"...Takaaki Kajita presented the discovery that neutrinos from the atmosphere switch between two identities on their way to the Super-Kamiokande detector in Japan."

when your parents ask where all your electron neutrinos went



But this proves that neutrinos have mass…

$$P_{oscillation}(\boldsymbol{\nu_e} \rightarrow \boldsymbol{\nu_\mu}) = sin^2 2\theta_{12} sin^2 \left(1.27 \Delta m_{21}^2 [\mathrm{eV}^2] \frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

$m_2^2 - m_1^2$

But this proves that neutrinos have mass…

- What is the value of the mass?

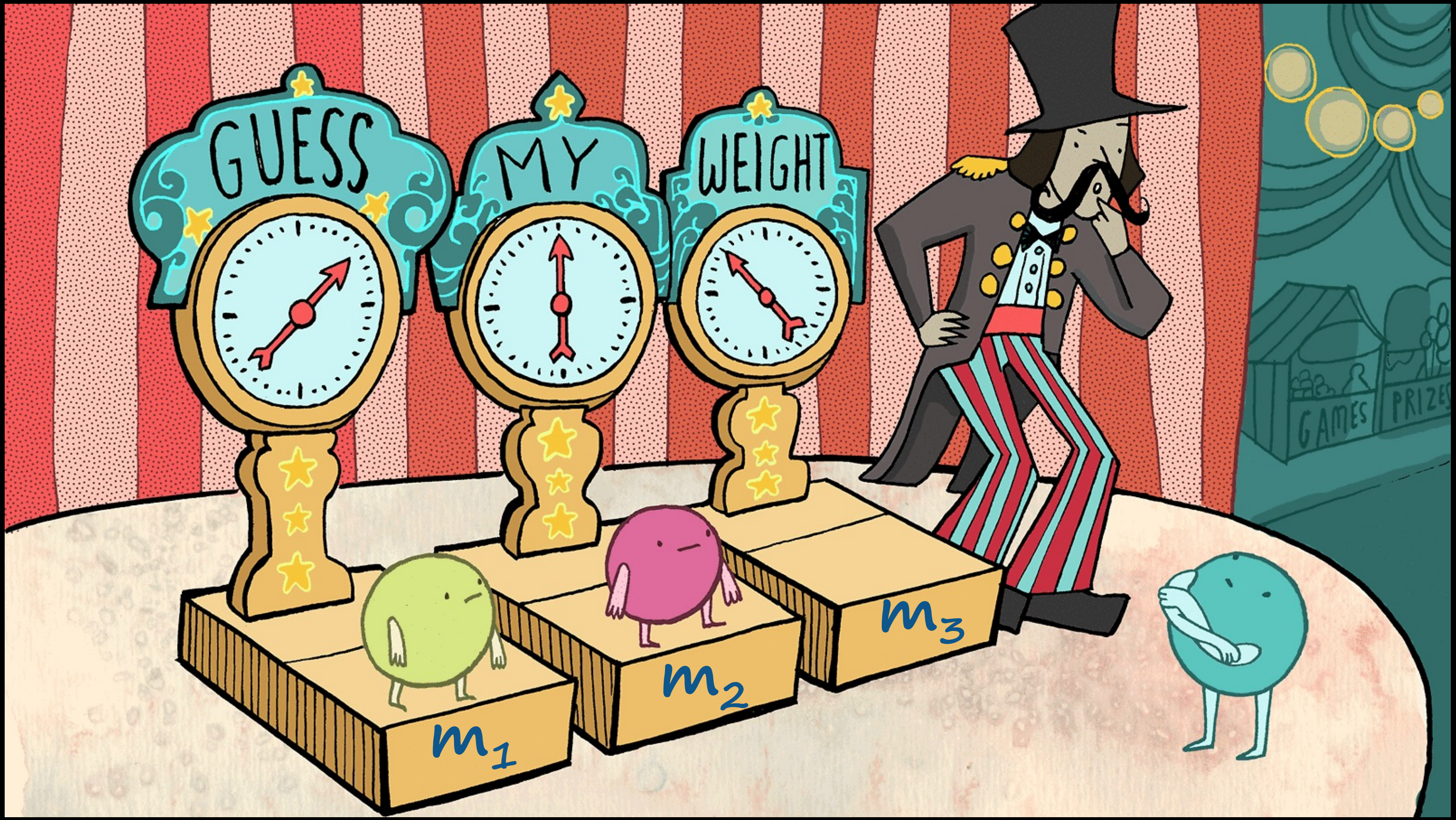
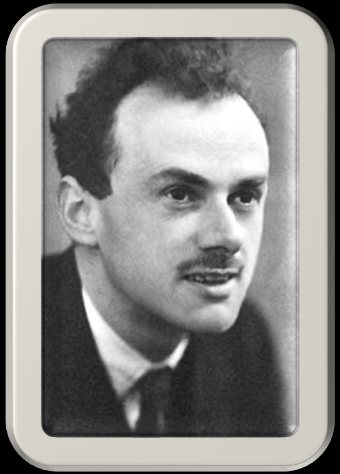


Image from Symmetry Magazine

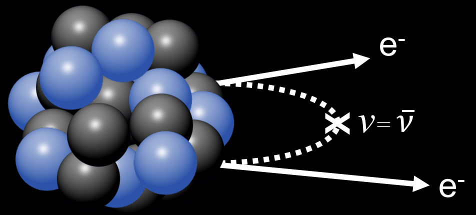
But this proves that neutrinos have mass...

- What is the value of the mass?
- Where do Neutrino masses come from?



Dirac Neutrinos
Lepton number conservation
Neutrino ≠ anti-neutrino

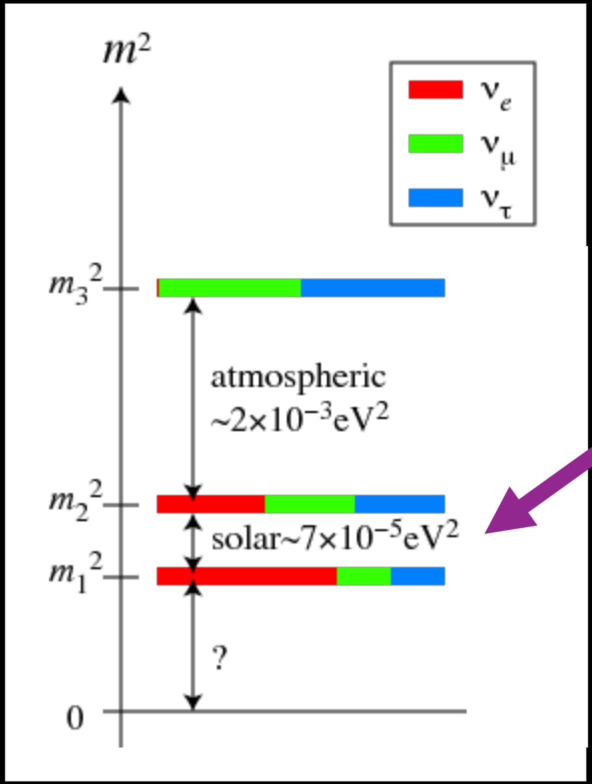
Majorana Neutrinos
Lepton number violation
Neutrino = anti-neutrino



Search for neutrinoless double beta decay

But this proves that neutrinos have mass...

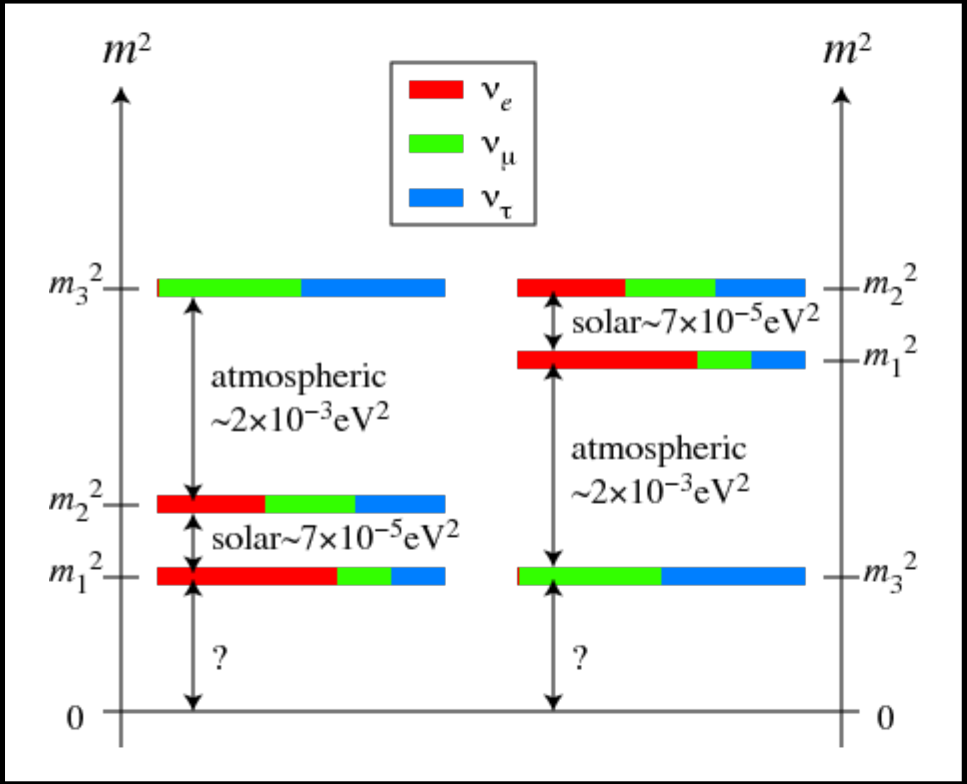
- How are the masses ordered?



Solar experiments have fixed the order between m_1 and m_2

But this proves that neutrinos have mass…

- How are the masses ordered?



But this proves that neutrinos have mass...

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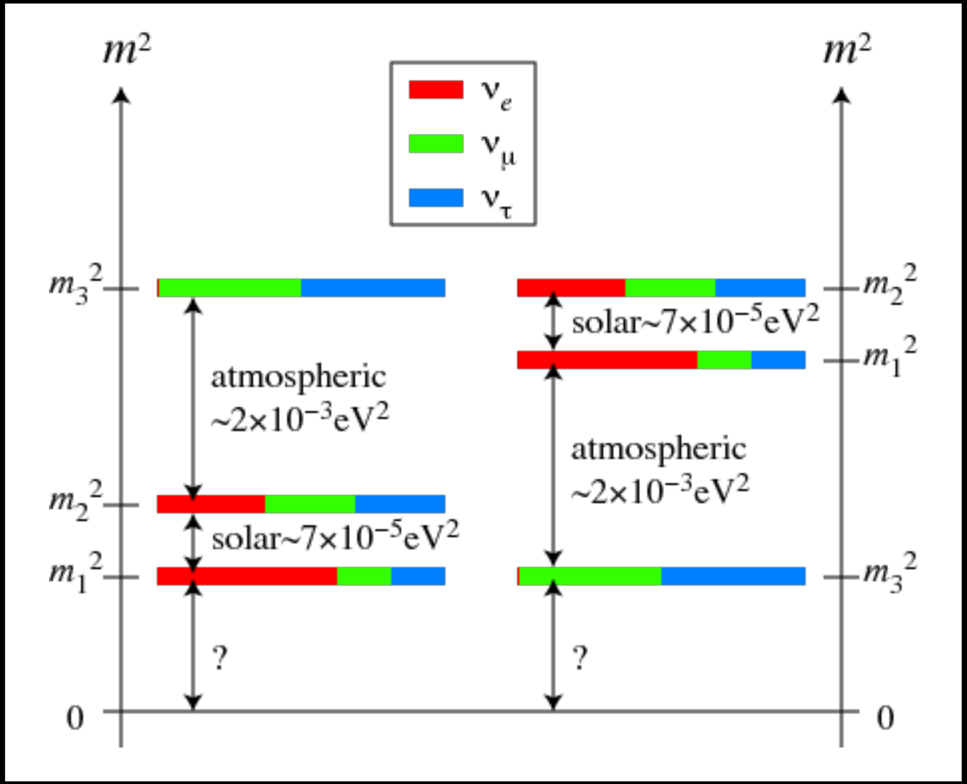
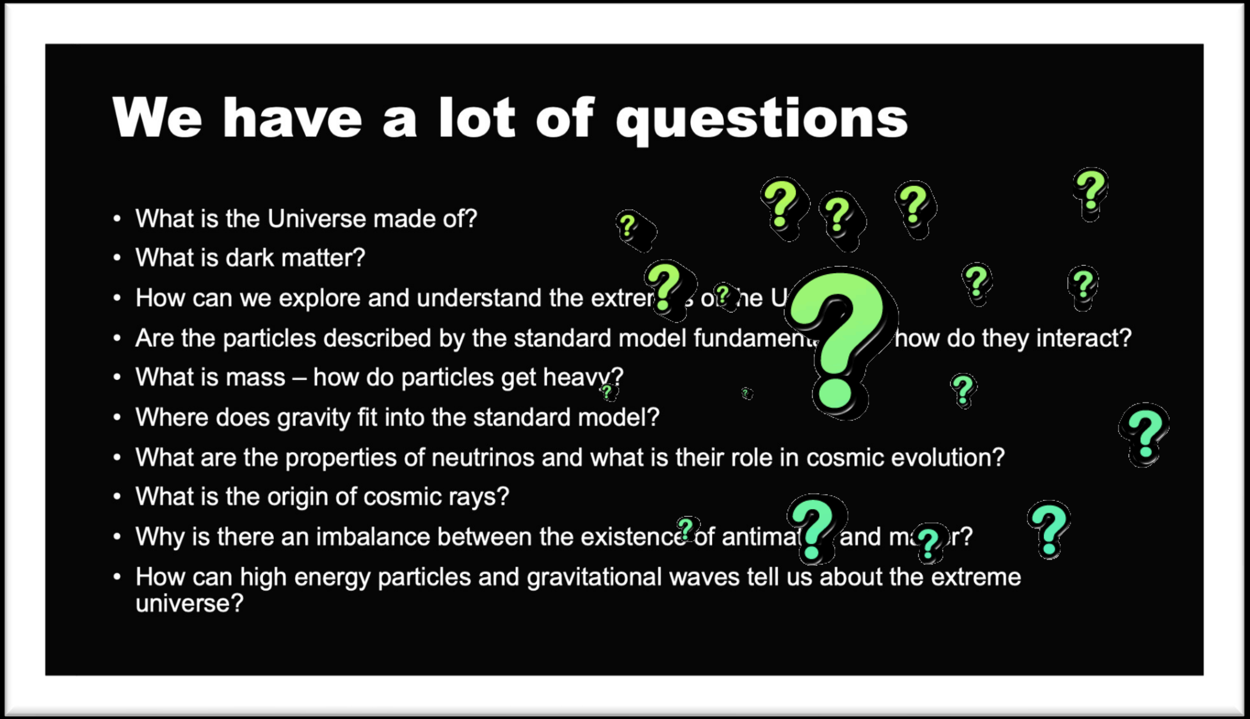


study of differences between neutrino and antineutrino oscillations

- Is there CP violation in the lepton sector?
- What are the precise values of the neutrino mixing parameters?

~~How did it start?~~

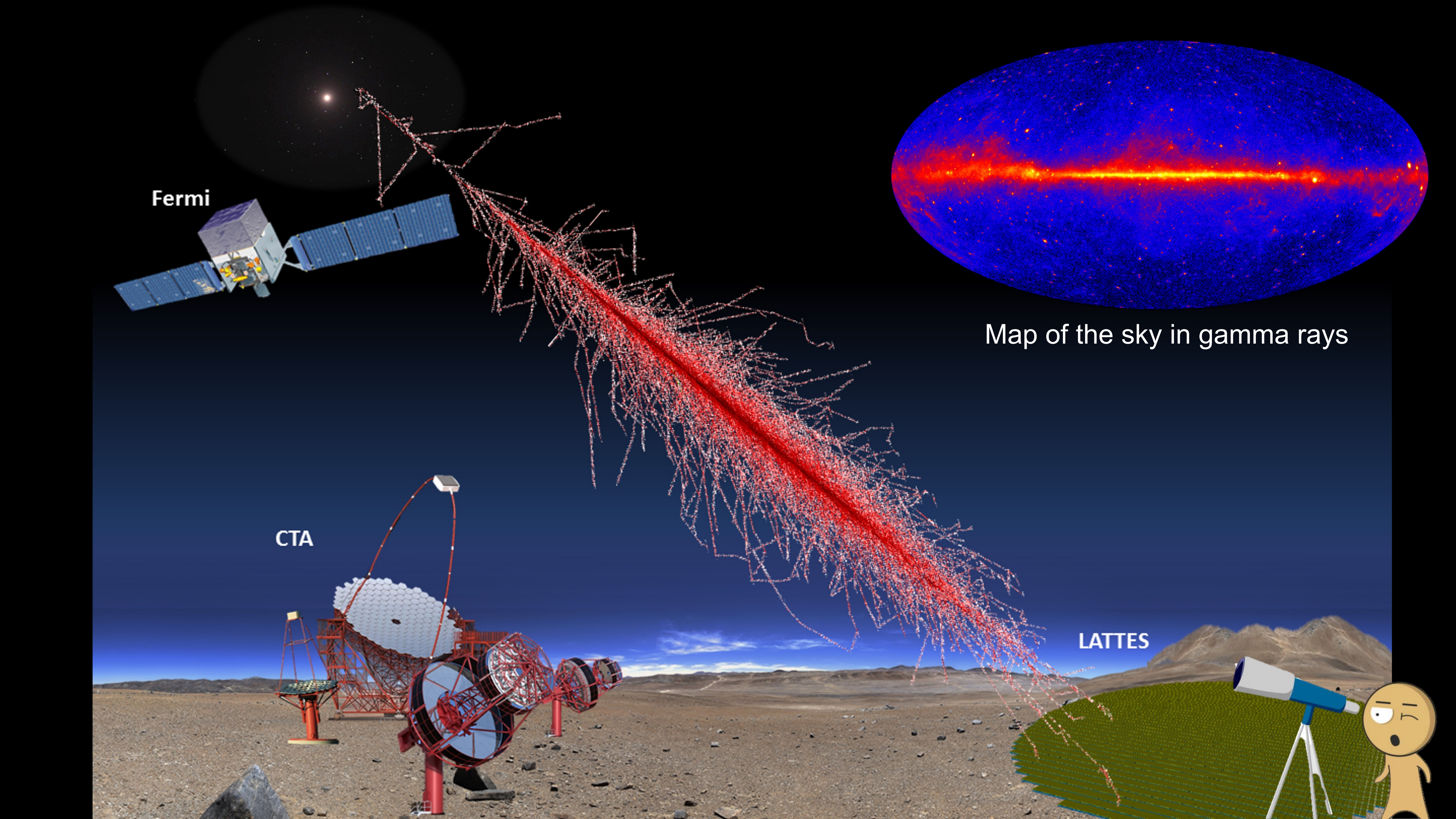
Where is it heading?



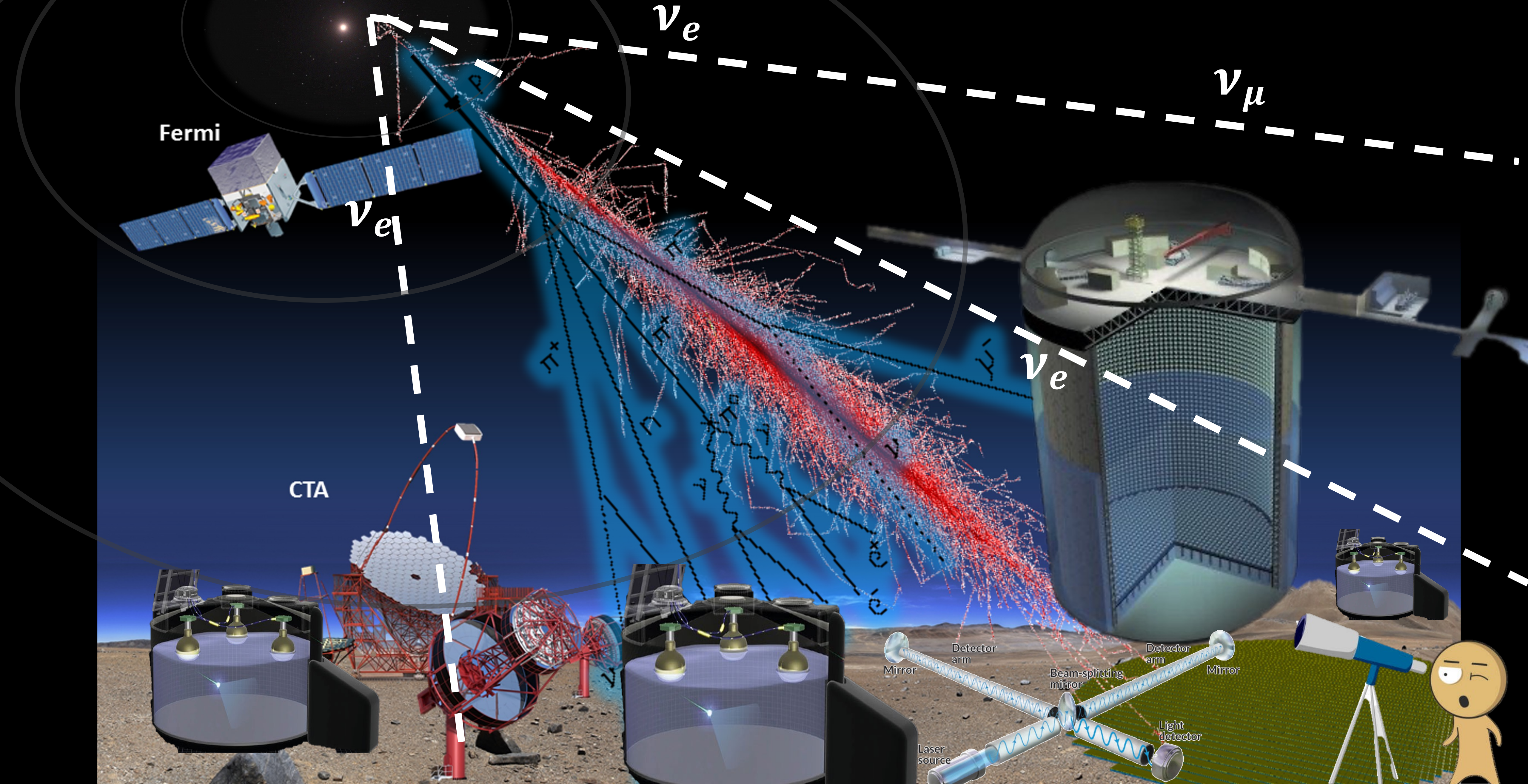
But thankfully we have nice experiments to search for answers

A lot of research activity in:

- High-energy cosmic-ray physics and astrophysics;
- Particle cosmology;
- Particle astrophysics;
- Related astrophysics: supernova, active galactic nuclei, cosmic abundances, dark matter etc.;
- High-energy, VHE and UHE gamma-ray astronomy;
- High- and low-energy neutrino astronomy;
- Instrumentation and detector developments related to the above-mentioned fields.


Fermi
Map of the sky in gamma rays
CTA
LATTES

Multi-messenger astrophysics



Summary

- Astroparticle physics is the study of fundamental particles travelling through space, particularly those that reach the Earth.
  - Neutrinos
  - Cosmic Rays
  - Gamma Rays
- Use them to answer fundamental questions about our universe.
  - And with the era of multi-messenger physics, research is this field is getting more and more exciting!
- During the workshop you will learn about some of the best, world-renowned experiments in astroparticle physics trying to solve the mysteries of the universe!

Thank you!