The 2021 Queen’s Summer Particle Astrophysics Workshop

Astroparticle Physics Overview

Ana Sofia Inácio

University of Lisbon and Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Portugal

Hello! I'm Ana Sofia

2015 – Bachelor Degree in Physics

Summer Internship at University of Zaragoza, Spain

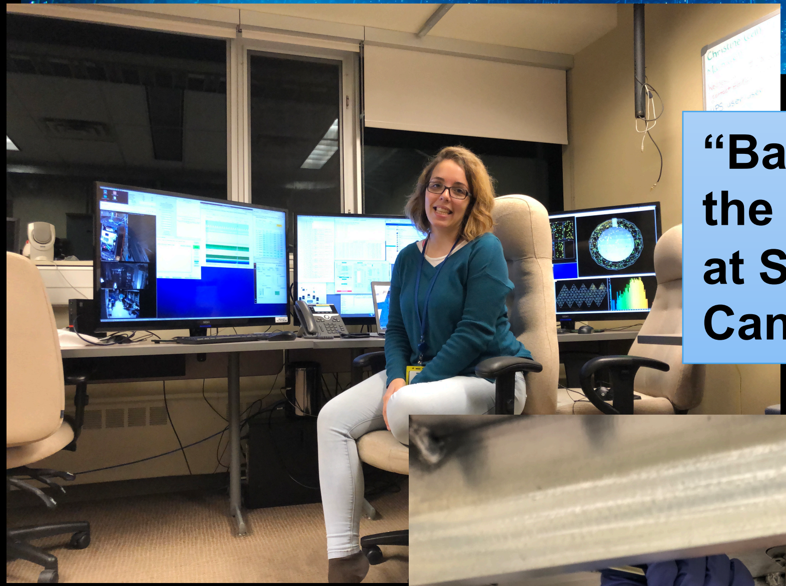
2017 – Master's Degree in Nuclear and Particle Physics

2018-… – PhD in Particle Physics

Working in the SNO+ Experiment

My favourite things:

- Detector Calibrations
- Radioactive Backgrounds
- Solar Neutrinos
- Double Beta Decay



"Babysitting" the detector at SNOLAB, Canada

Working with calibration hardware

What is

Astroparticle Physics

?

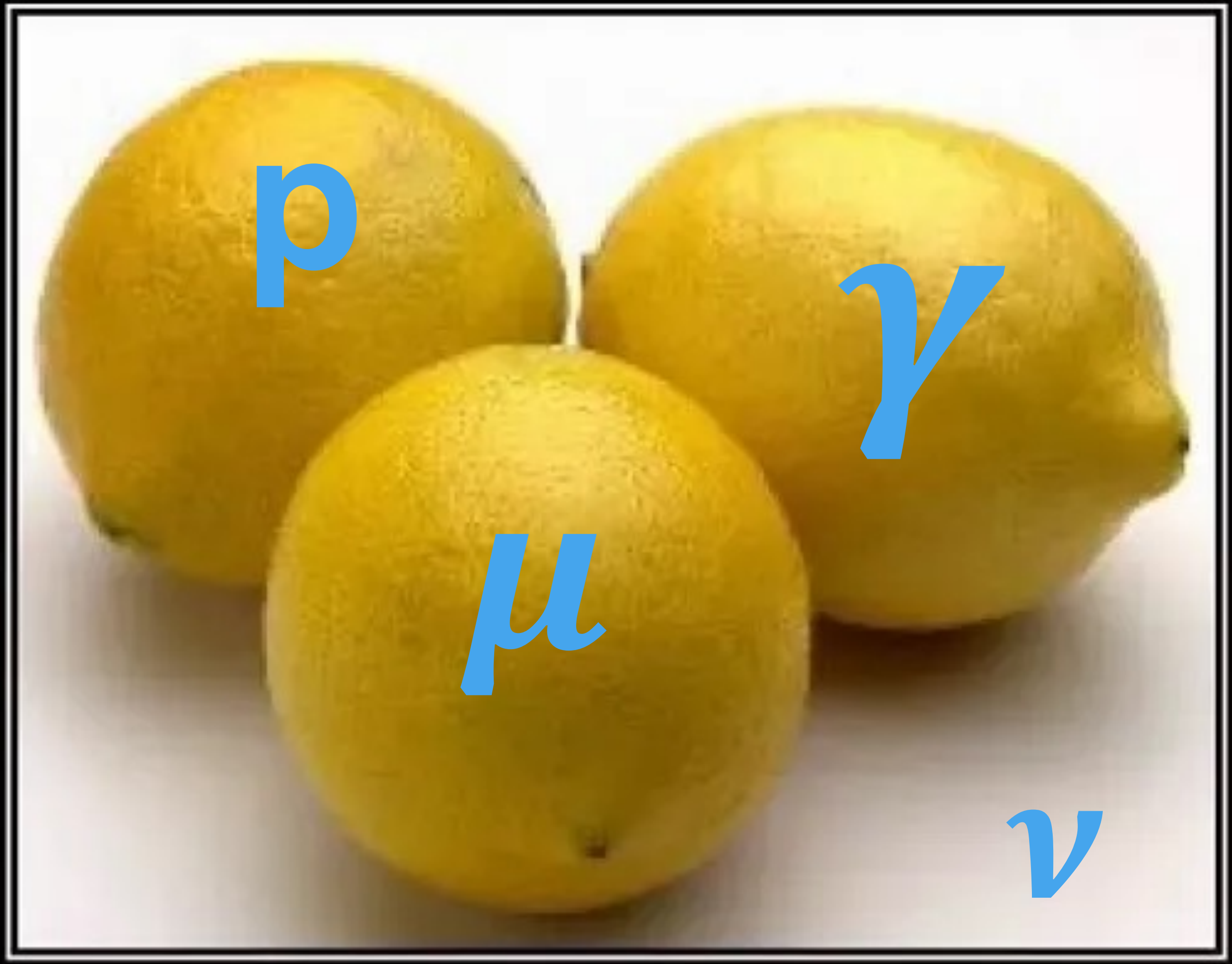
Understand the nature, structure and dynamics of our Universe through the radiation/particles collected at Earth

Astroparticle Physics

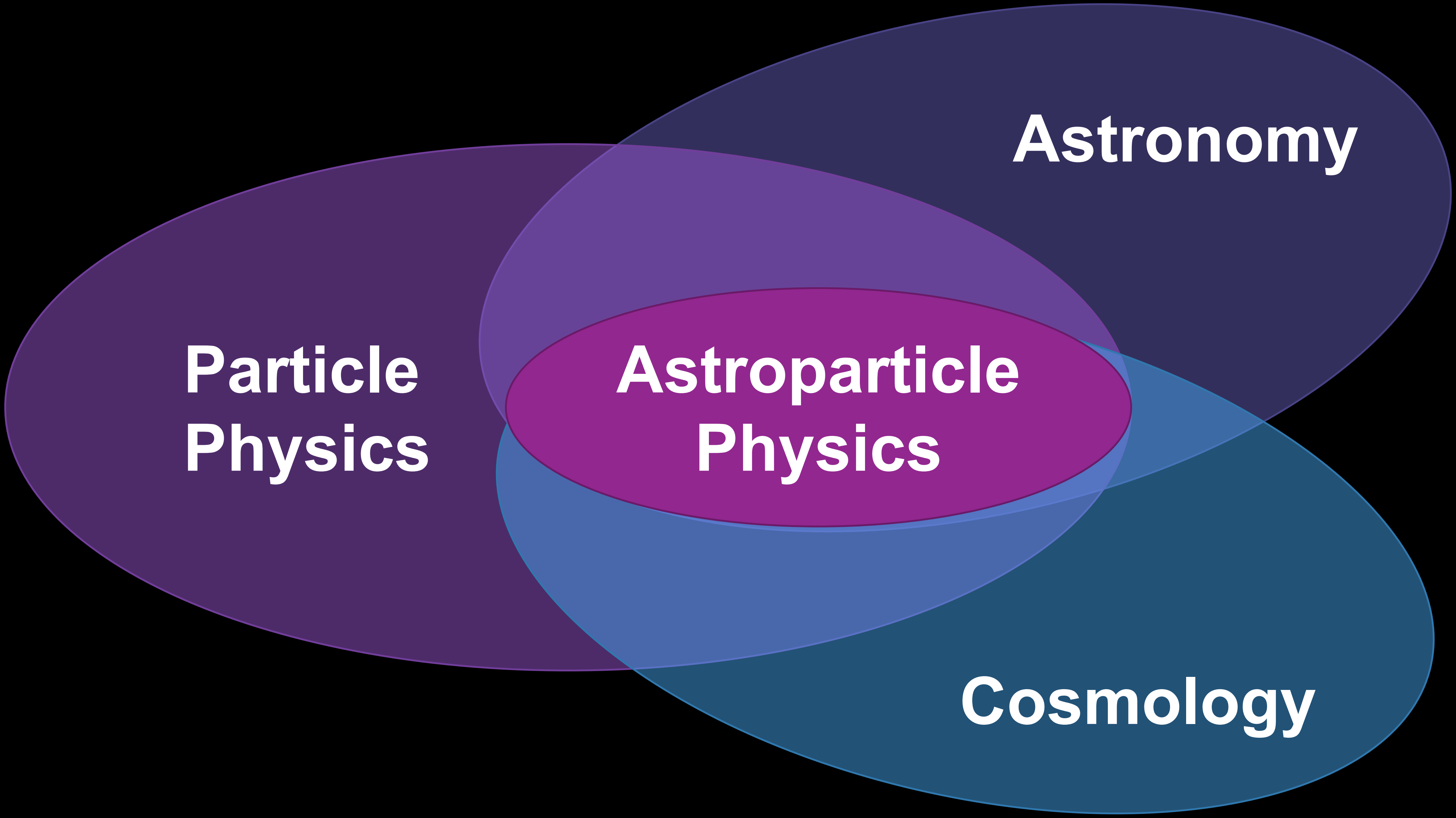
Understand the nature, structure and dynamics of our Universe through the radiation/particles collected at Earth

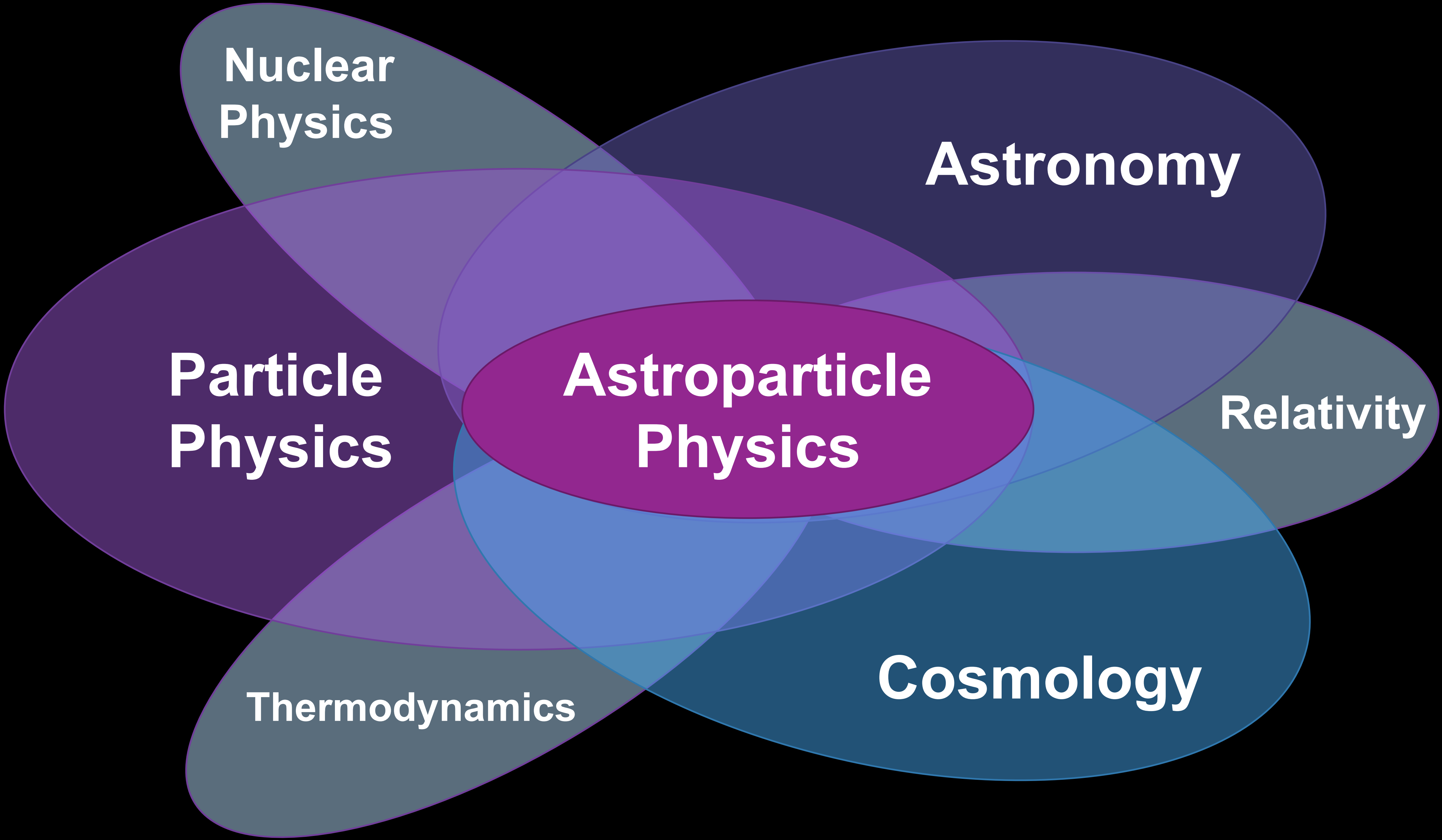
Astroparticle Physics

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



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


Astronomy
Particle Physics
Astroparticle Physics
Cosmology


Nuclear Physics
Astronomy
Particle Physics
Astroparticle Physics
Relativity
Thermodynamics
Cosmology

Why

Astroparticle Physics

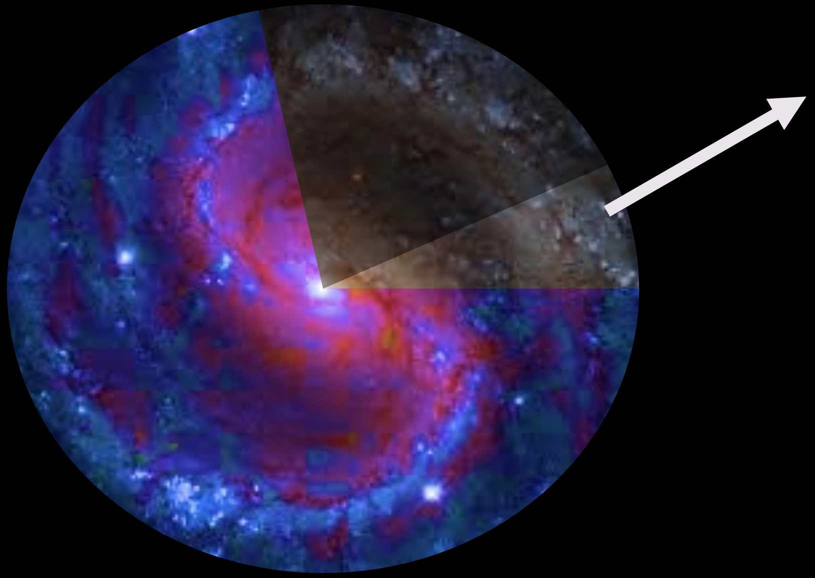
?

We have a lot of questions

We have a lot of questions

- What is the Universe made of?

23% Dark Matter



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

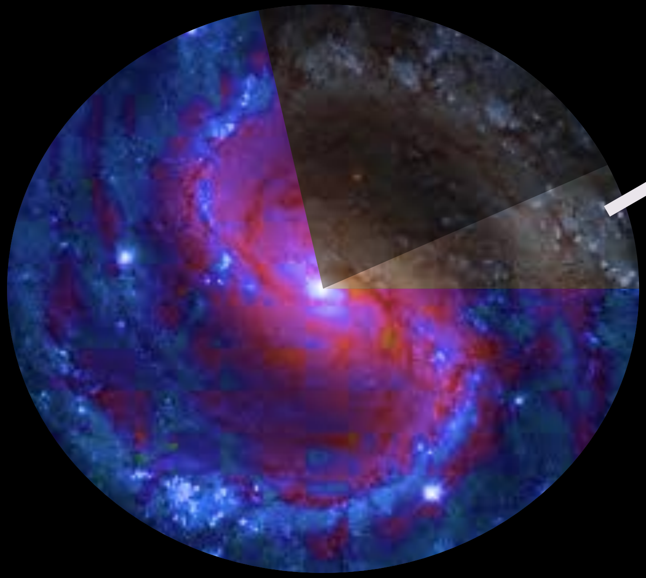
73% Dark Energy

We have a lot of questions

- What is the Universe made of?

What is Dark Matter?

23% Dark Matter



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

73% Dark Energy

This is what these experiments are trying to find out →

SBC
DEAP/Darkside
PICO
NEWS-G
SuperCDMS

How do we know Dark Matter exists?

Galaxy Clusters

Fritz Zwicky, 1933 – first to suspect the existence of dark matter.

Estimate the Mass { Speed of the Galaxies vs. Light emitted

Coma Cluster, NASA

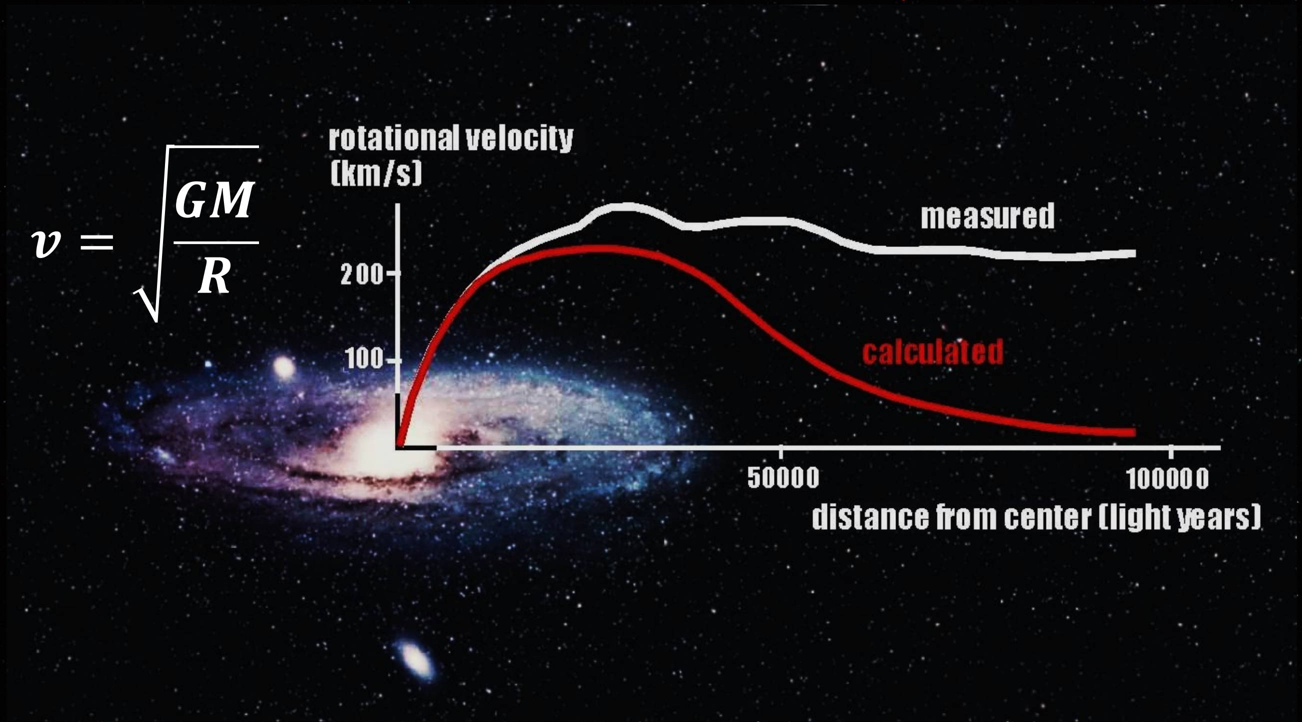
Galaxies of the Coma Cluster were moving too fast for the cluster to be bound together by the visible matter of its galaxies.

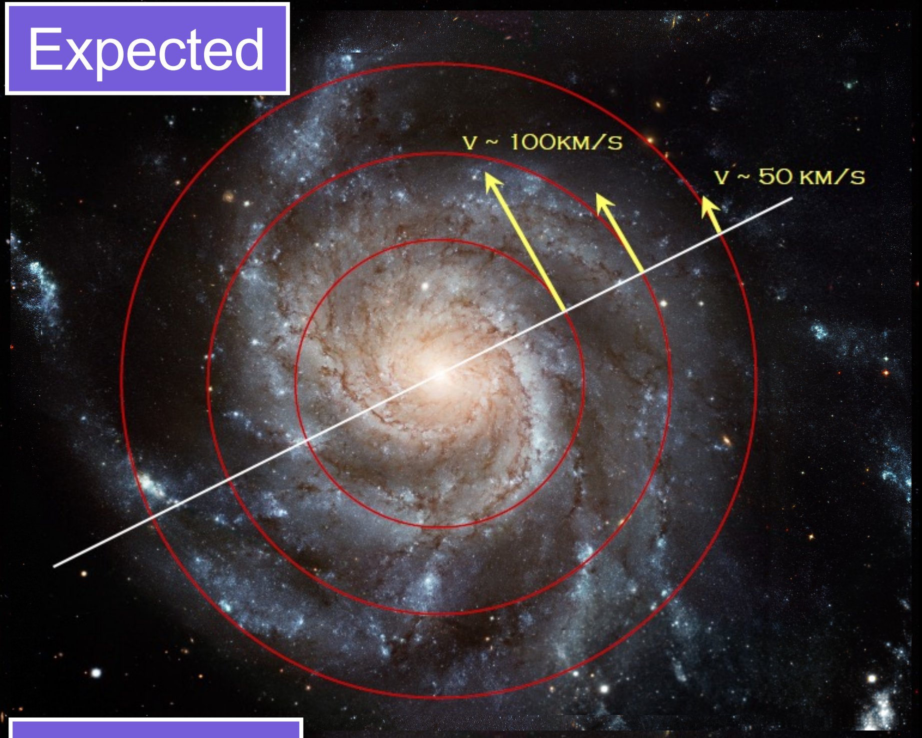
The cluster would evaporate! → *Unless there is more mass that we can't see...*

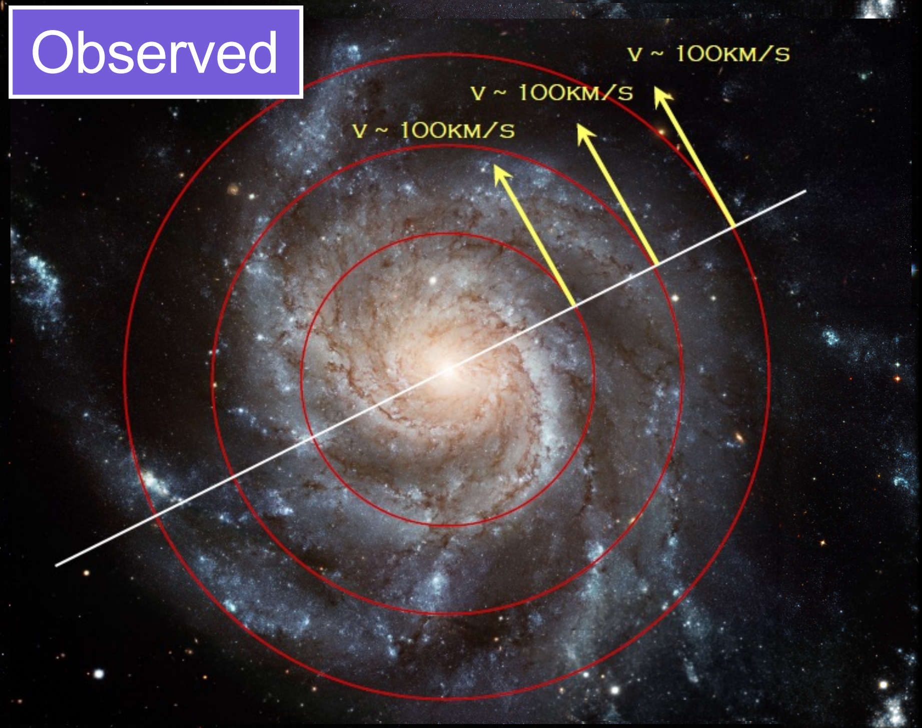
Velocity Curves of Spiral Galaxies

Vera Rubin, 1970

$$v = \sqrt{\frac{GM}{R}}$$





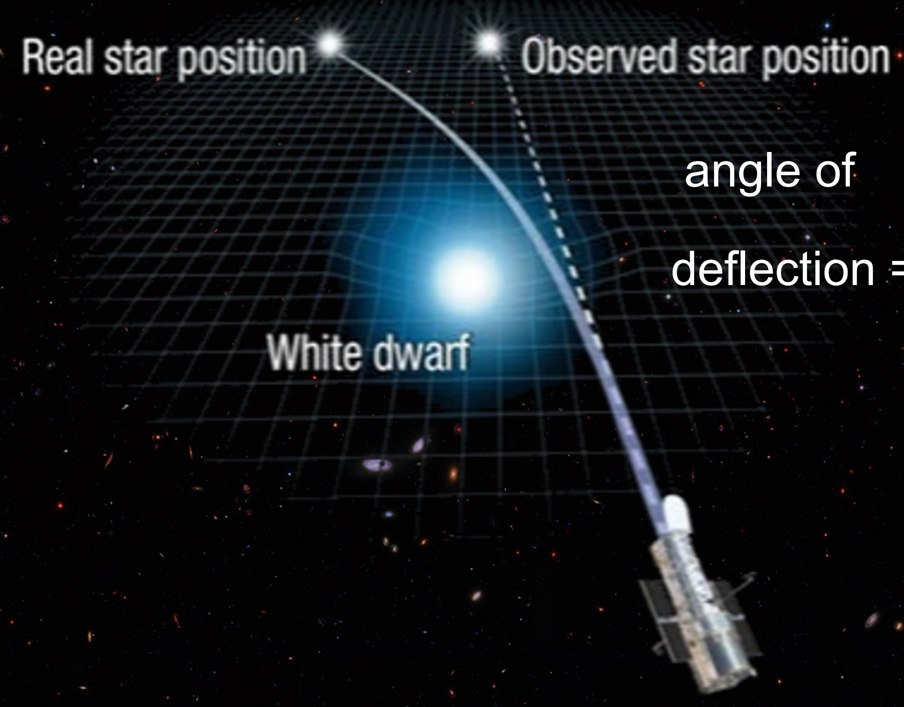


She concluded that there had to be more mass. Otherwise the galaxy would have fallen apart!

Gravitational Lensing

General Relativity
Massive objects in space curve spacetime,
photon trajectories also follow spacetime curvature.

Can see this effect with compact objects: Black Holes, neutron stars, quasars, brown dwarfs, white dwarfs…

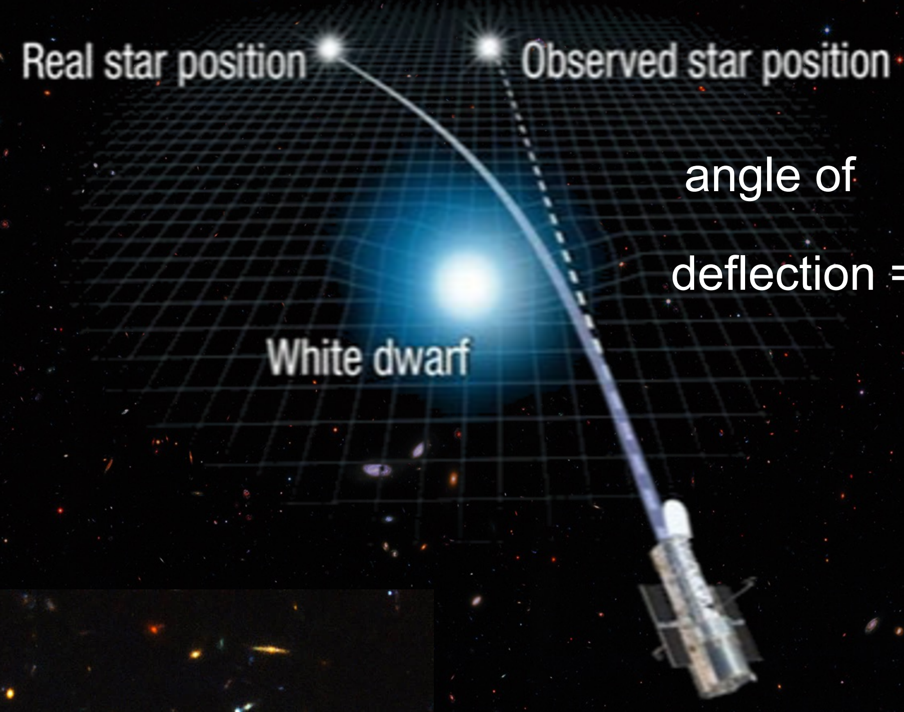


angle of deflection = $\frac{4GM}{rc^2}$

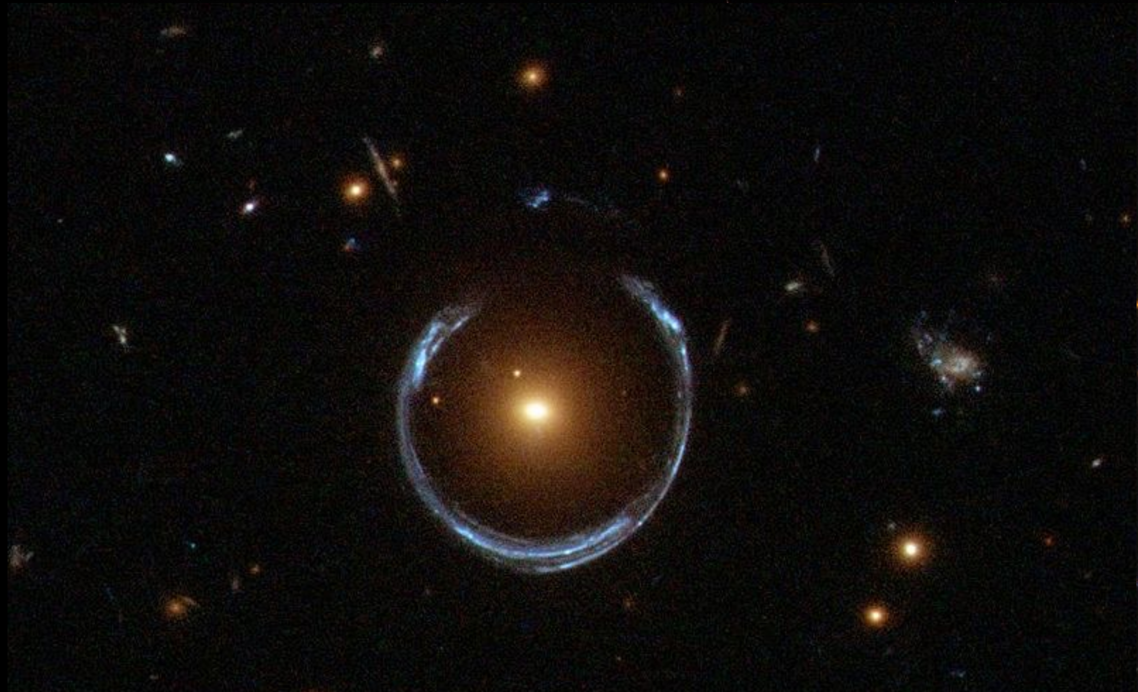
Gravitational Lensing

General Relativity
Massive objects in space curve spacetime,
photon trajectories also follow spacetime curvature.

Can see this effect with compact objects: Black Holes, neutron stars, quasars, brown dwarfs, white dwarfs…



$$\text{angle of deflection} = \frac{4GM}{rc^2}$$

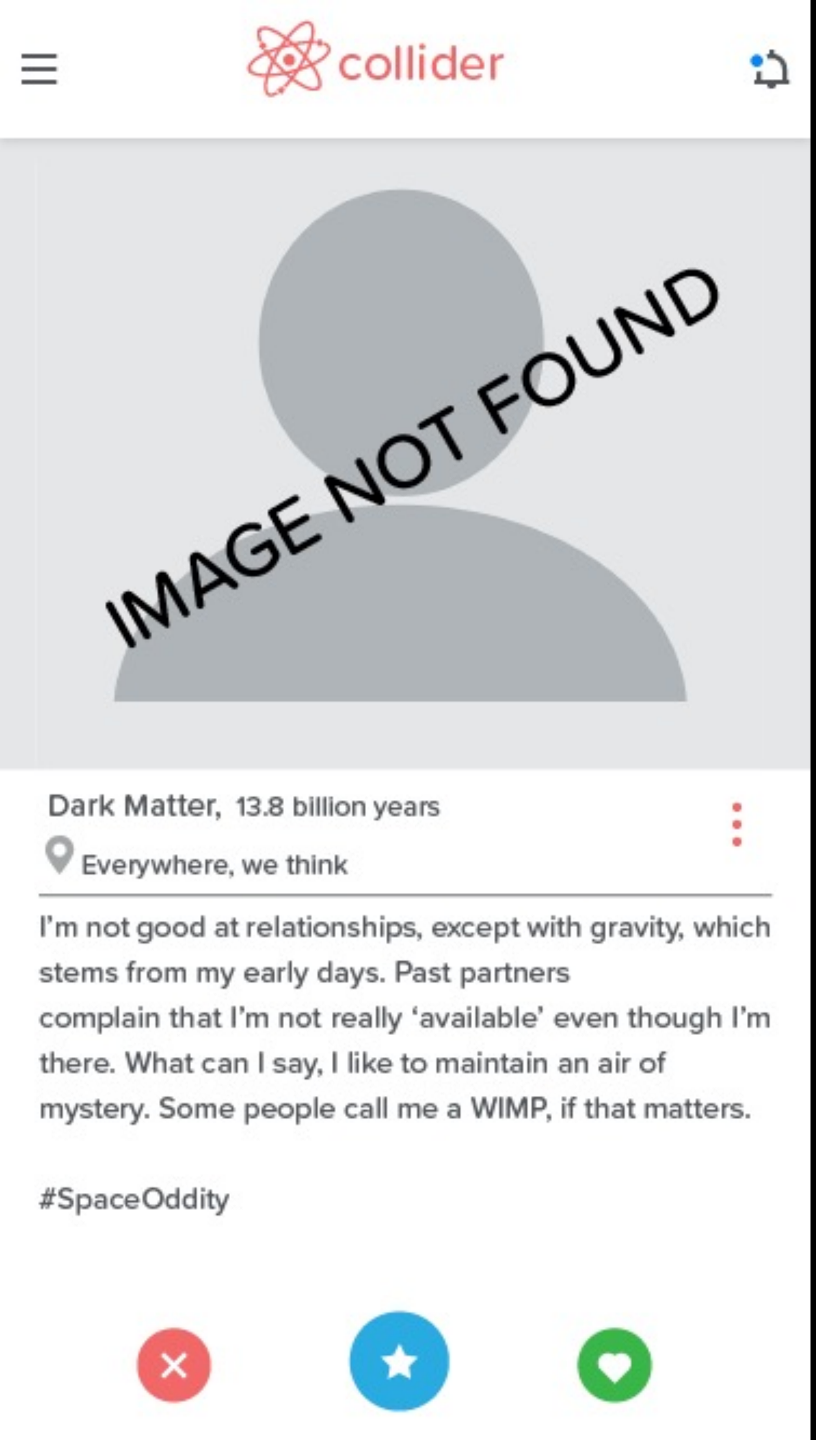


Einstein Ring, NASA

Galaxy Cluster SDSS J1038+4849, NASA

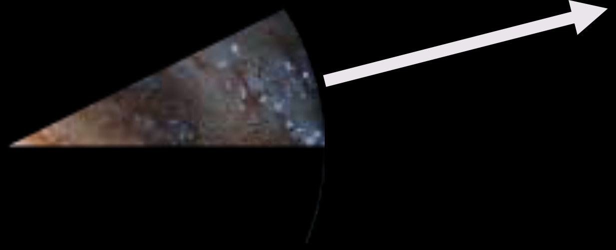
Candidates’ Criteria

1. Strong gravitational force
2. Weak interaction with other particles
3. Uncharged
4. Colour Force does not appear
5. Massive
6. Stable (13.8 billion years)



We have a lot of questions

- What is the Universe made of? In particular: What is dark matter?



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? In particular: What is dark matter?

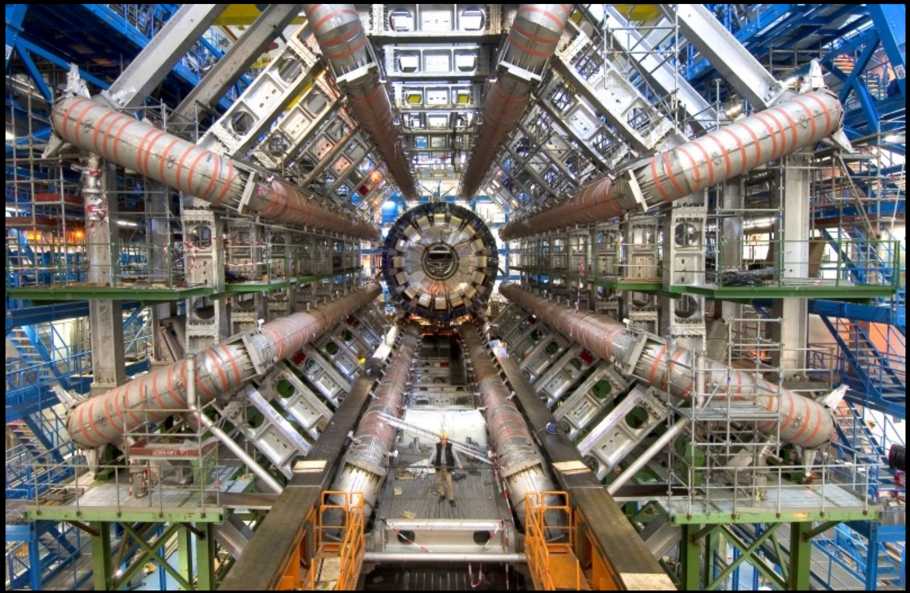
Only 4% of the Universe is made of ordinary matter!

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

- Do protons have a finite life time?
- What are the properties of neutrinos? What is their role in cosmic evolution?
- What do neutrinos tell us about the interior of the Sun and the Earth, and about Supernova explosions?
- What is the origin of cosmic rays? What is the view of the sky at extreme energies?
- What can gravitational waves tell us about violent cosmic processes and about the nature of gravity?

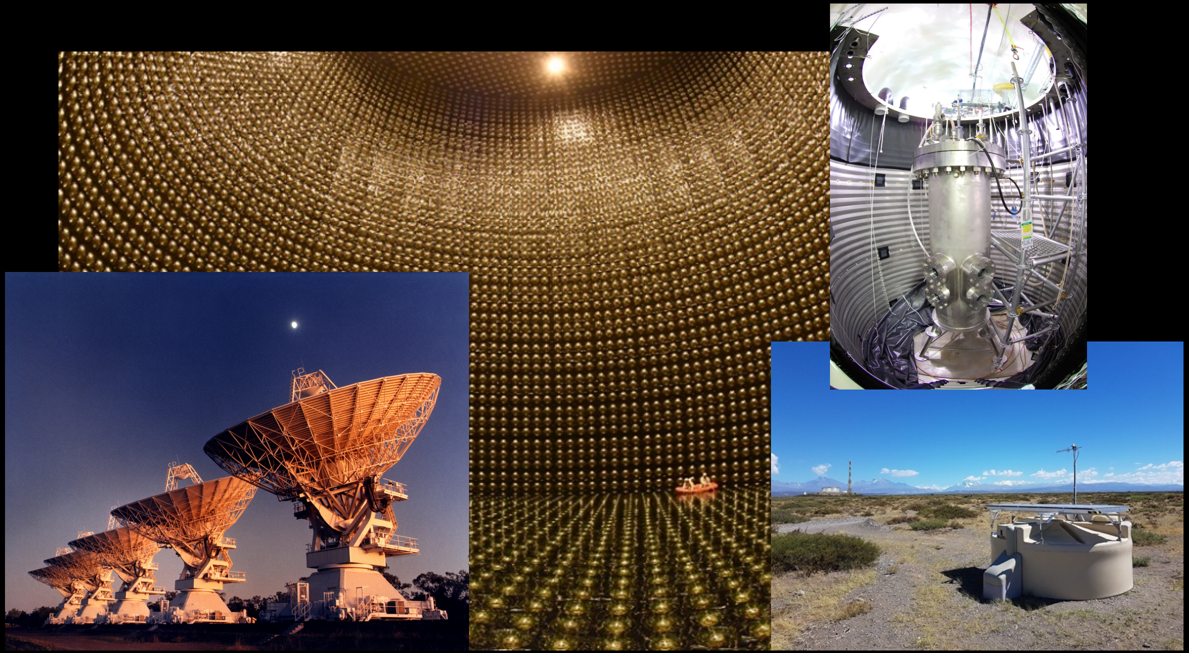
How do we find answers for these questions?

Accelerator Experiments



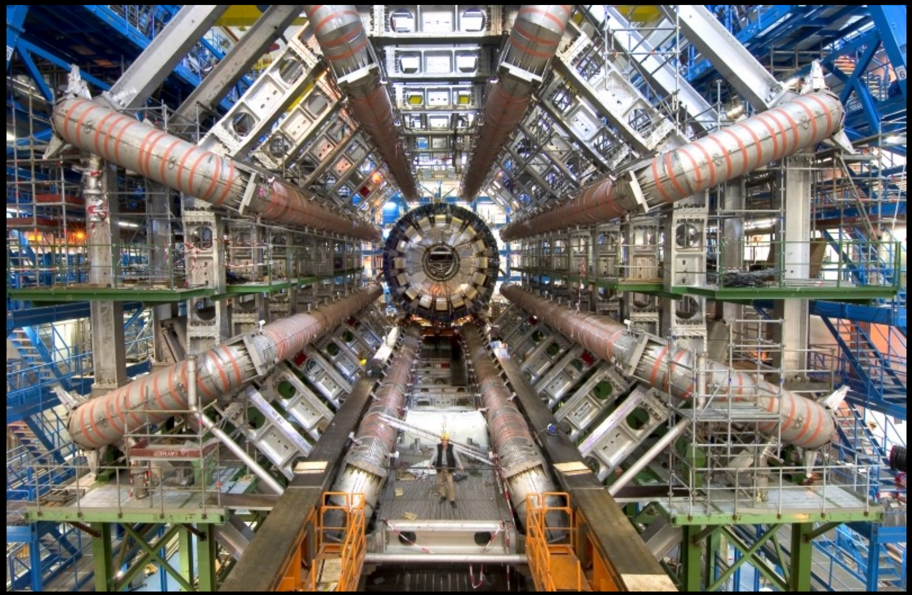
- Controlled environment:
  - Beam, backgrounds…

Astroparticle Experiments



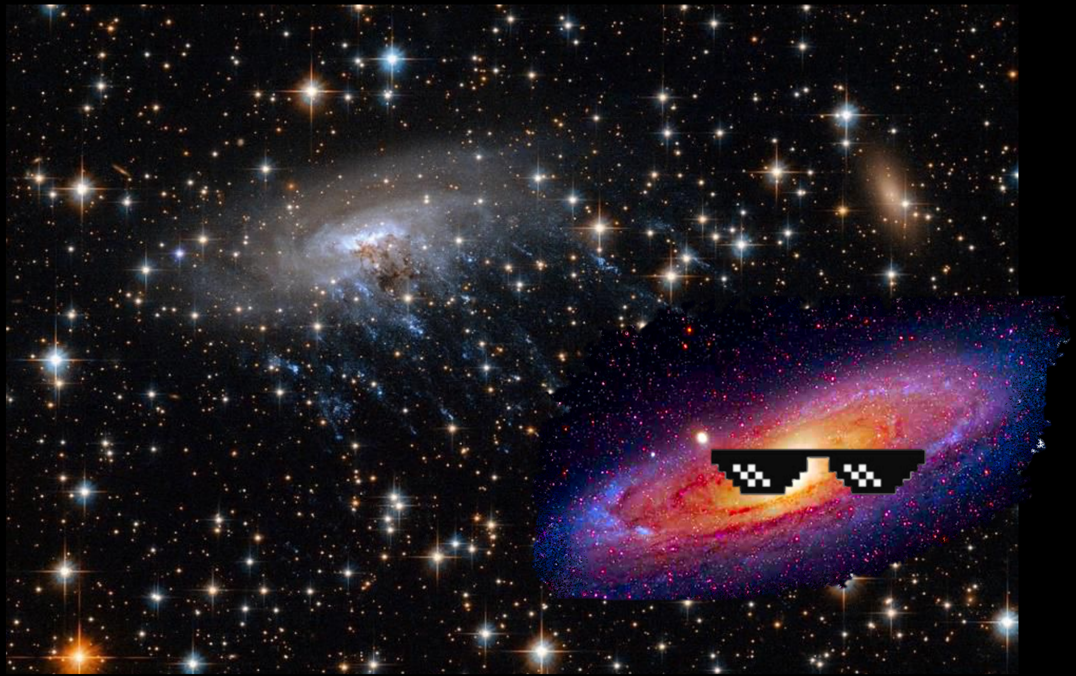
- Access energy, space and time scales unattainable on Earth

Accelerator Experiments



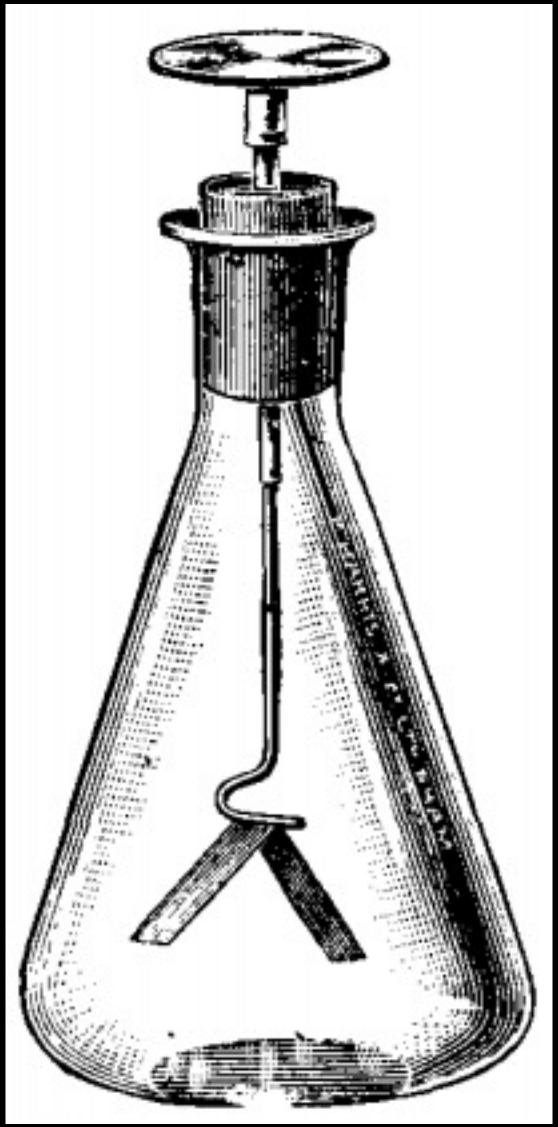
- Controlled environment:
  - Beam, backgrounds…

Astroparticle Experiments



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

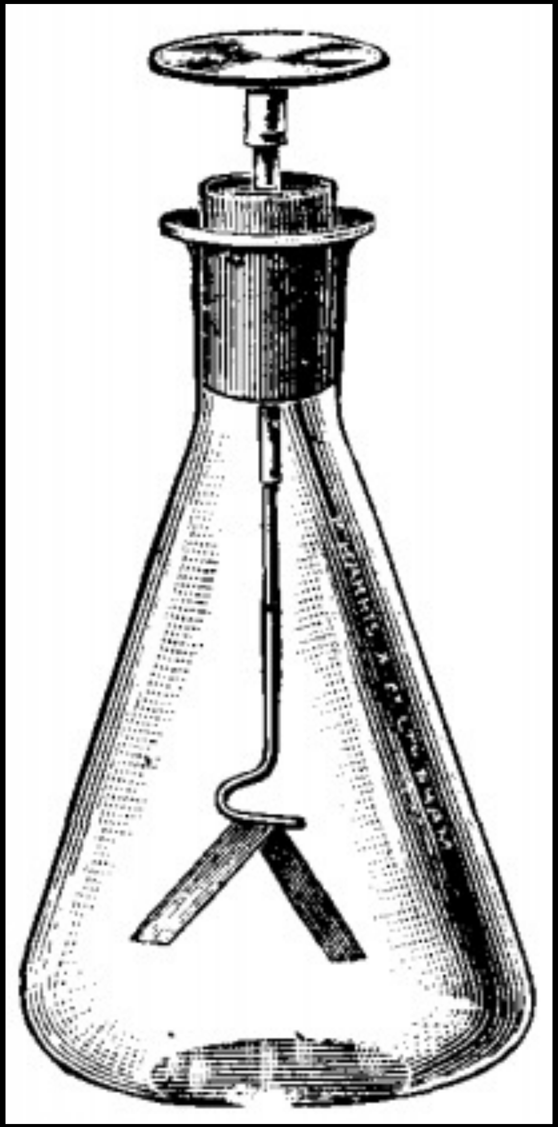
How did it start?



This is an electroscope

You can use it to measure electric charges.

You can build one at home: https://youtu.be/2PmWIPjV6n0



This is an electroscope

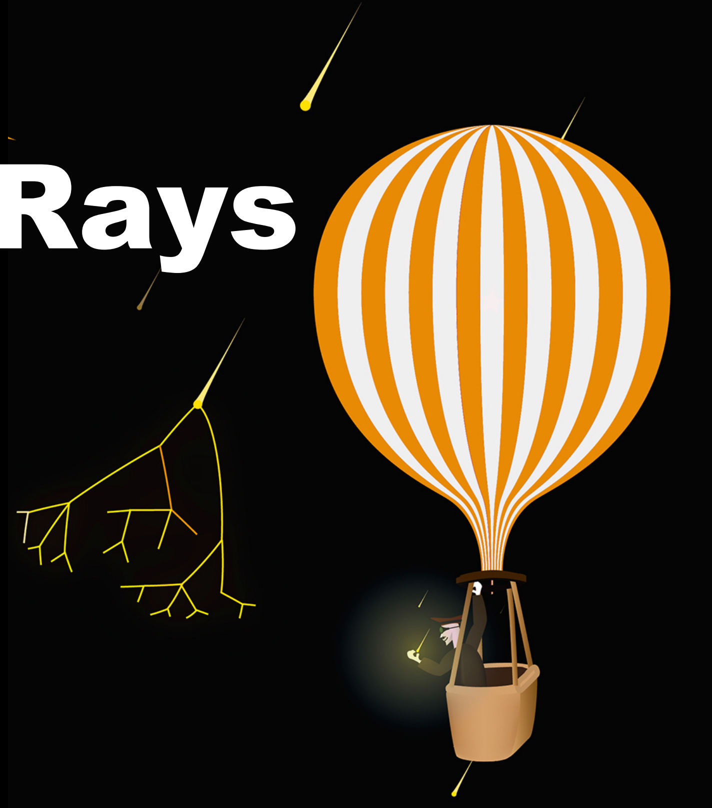
Scientists in the 1900’s noticed that the radioactive components of some rocks produced ionization.

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

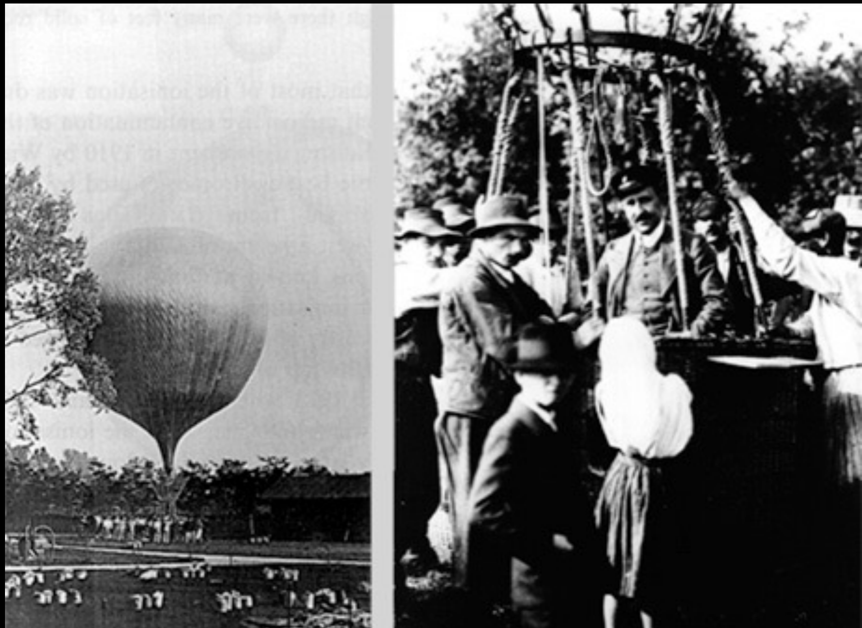
Testing the hypothesis: lowered electroscopes into lakes and oceans, carried them up mountains and took them to even greater heights in open baskets underneath hydrogen-filled balloons.

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

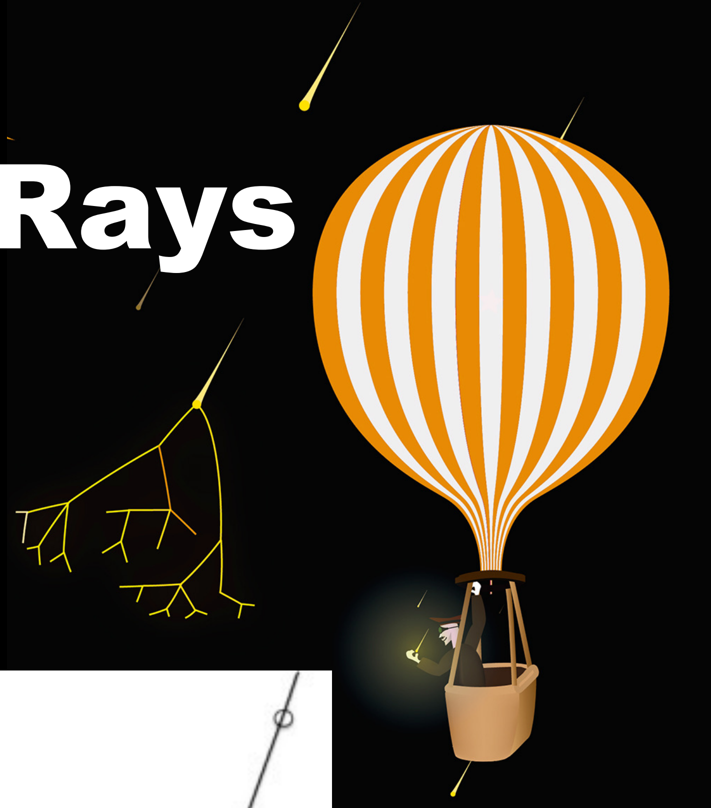
The Discovery of Cosmic Rays



- 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.



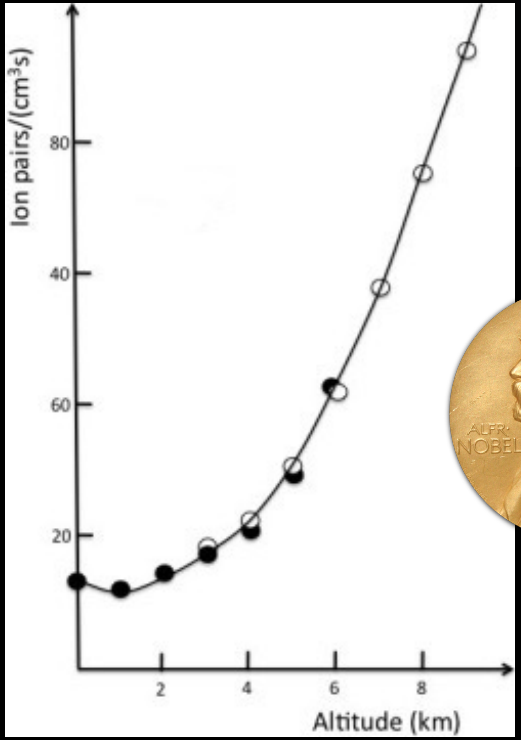
The Discovery of Cosmic Rays



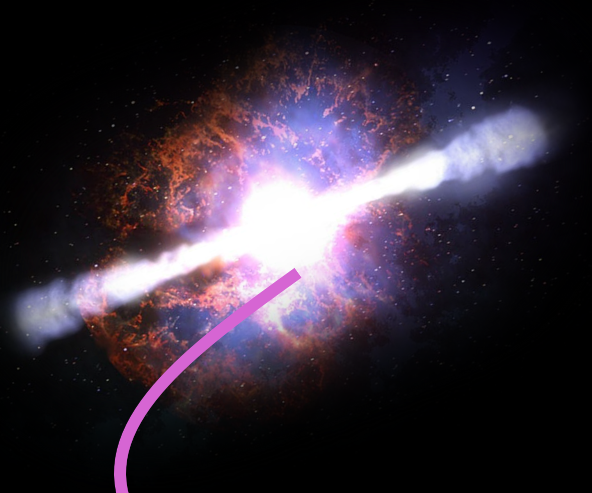
- Victor Hess,1912
  - He went up and down in the atmosphere in a balloon, measuring the radiation with an electroscope.
  - Measurements up to 5.3km, from 1911-12.

- 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.

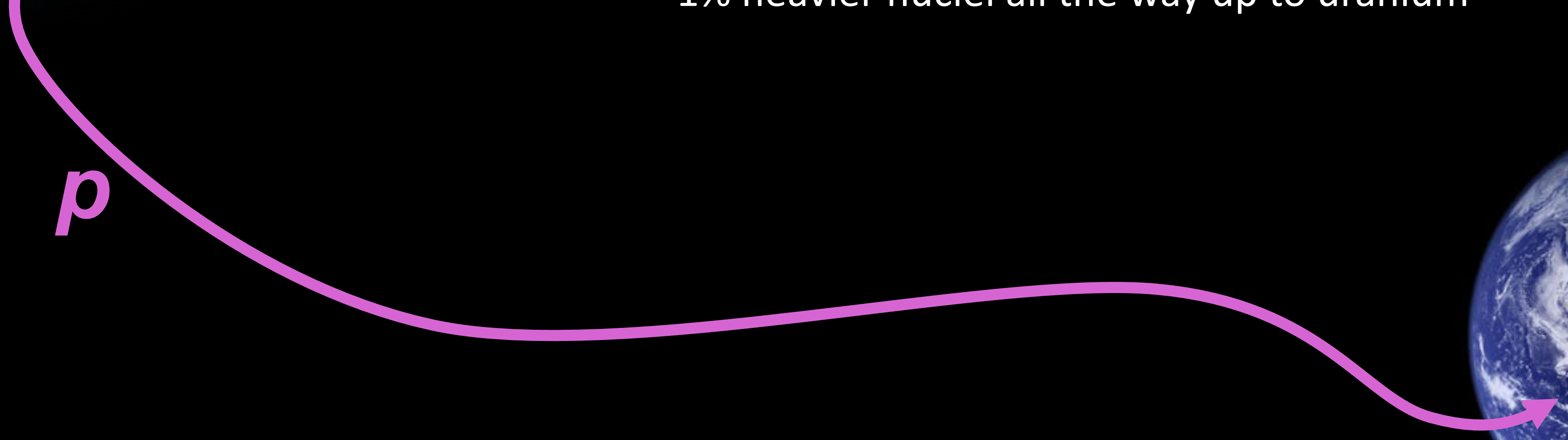


What are Cosmic Rays?

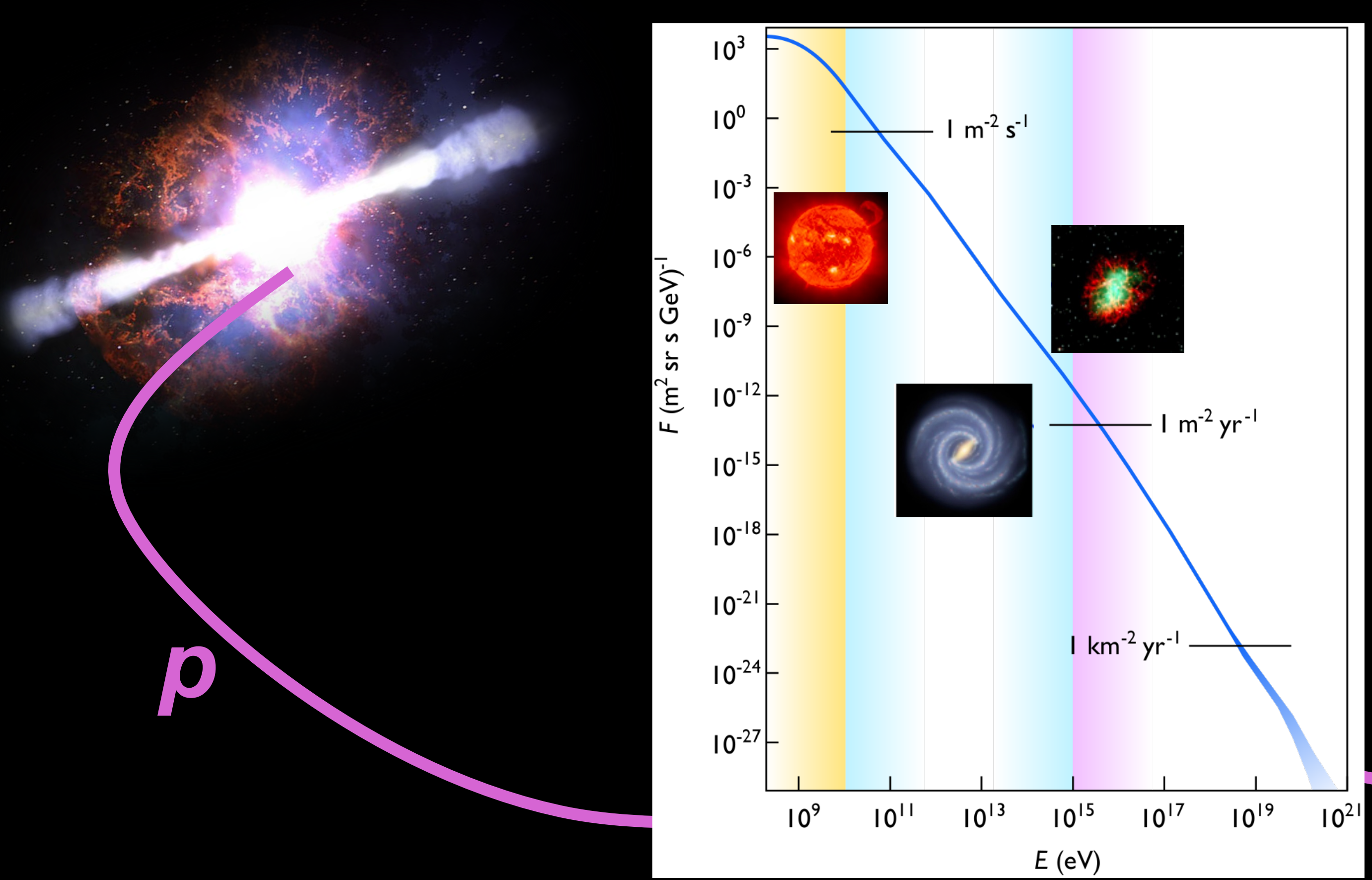


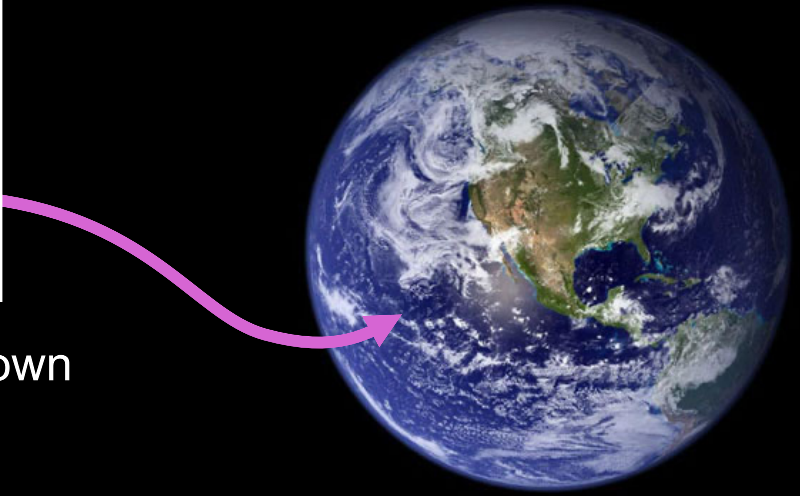
Cosmic rays are high-energy protons and atomic nuclei that move through space at nearly the speed of light.

- 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.

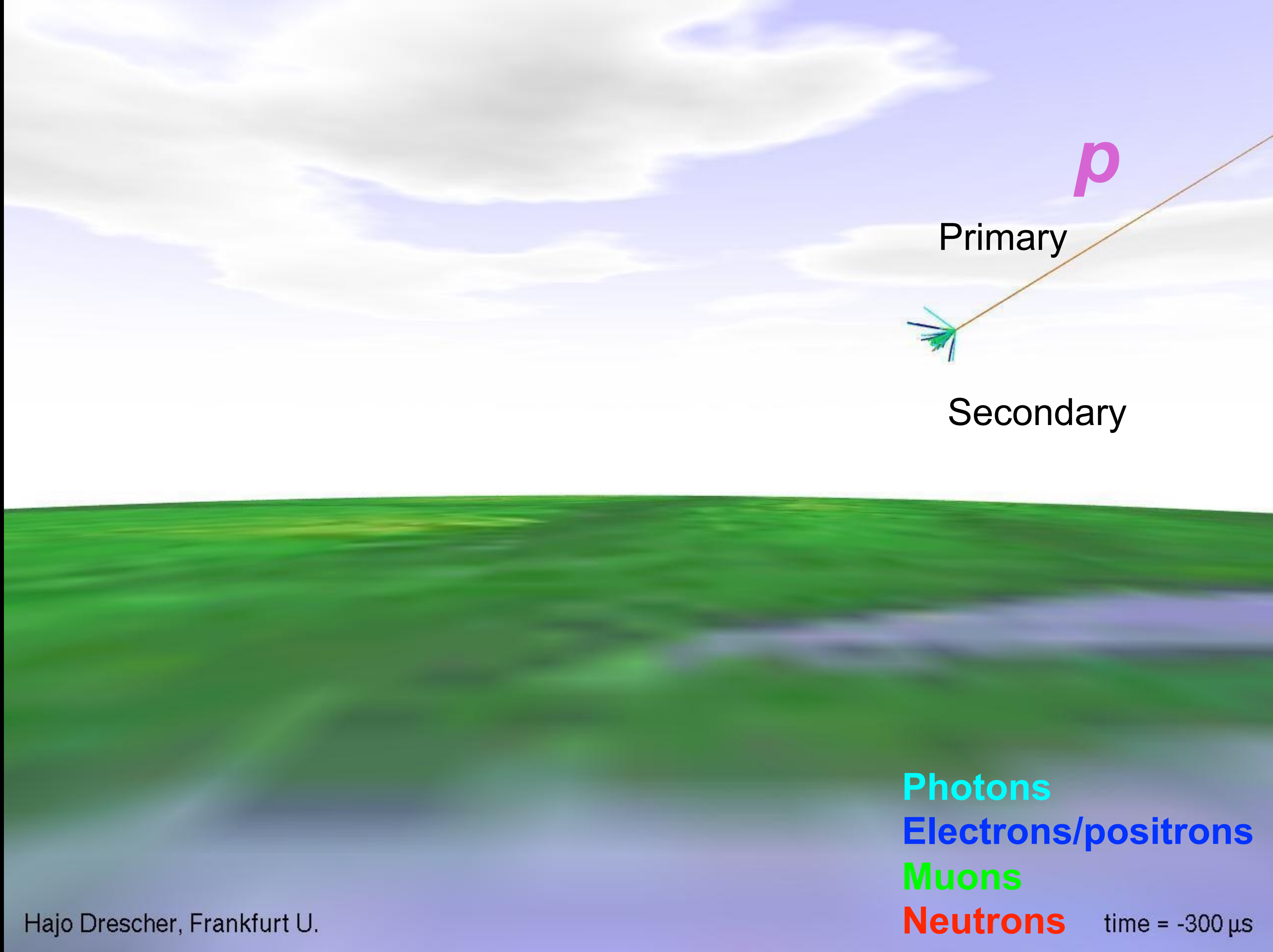
They are deflected by galactic magnetic fields (because they are charged particles).

What are Cosmic Rays?

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

Creates mainly pions, π

- They interact with other molecules
- Or decay into muons and neutrinos



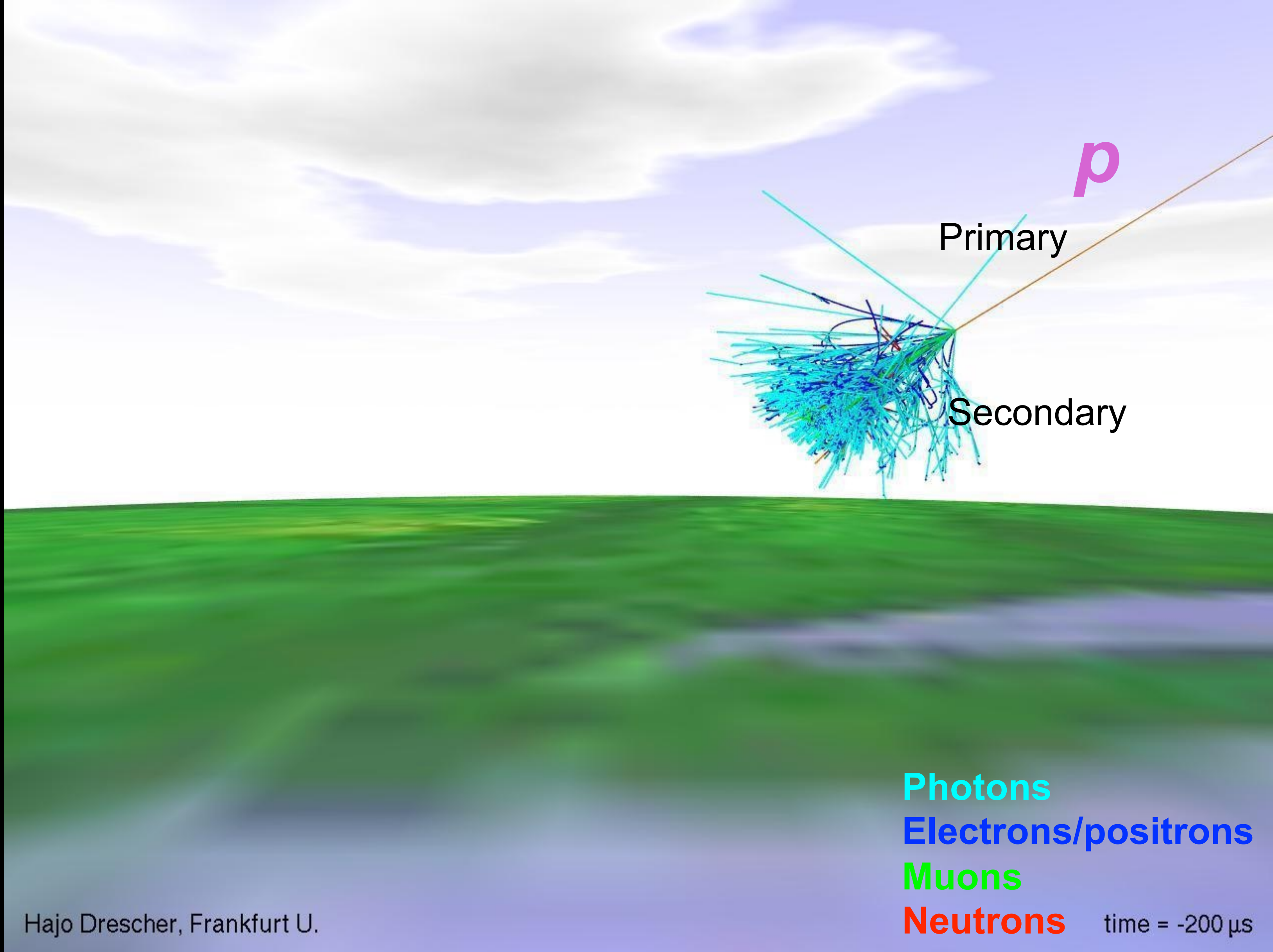
What are Cosmic Rays?

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

Creates mainly pions, π

- They interact with other molecules
- Or decay into muons and neutrinos

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



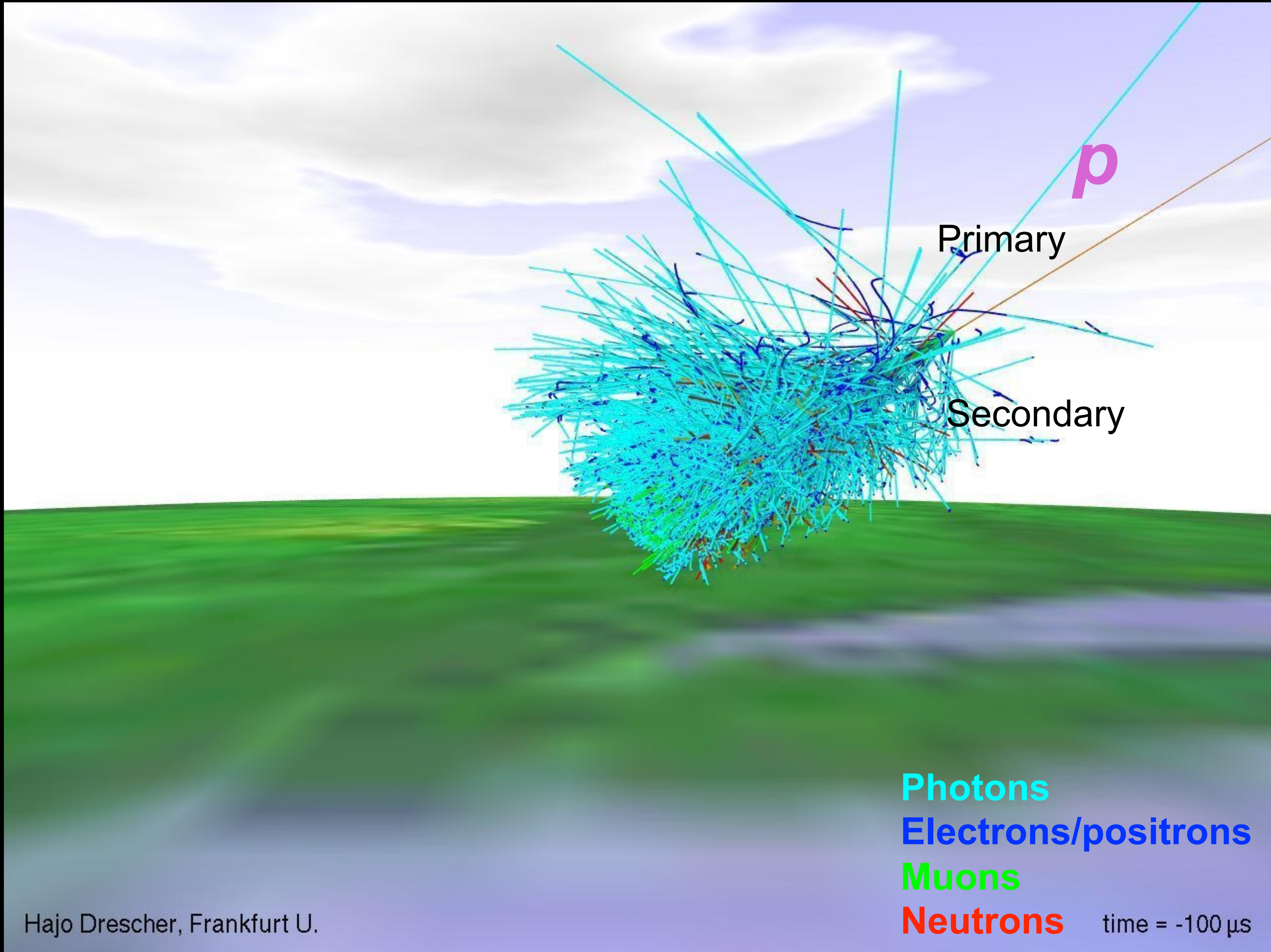
What are Cosmic Rays?

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

Creates mainly pions, π

- They interact with other molecules
- Or decay into muons and neutrinos

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

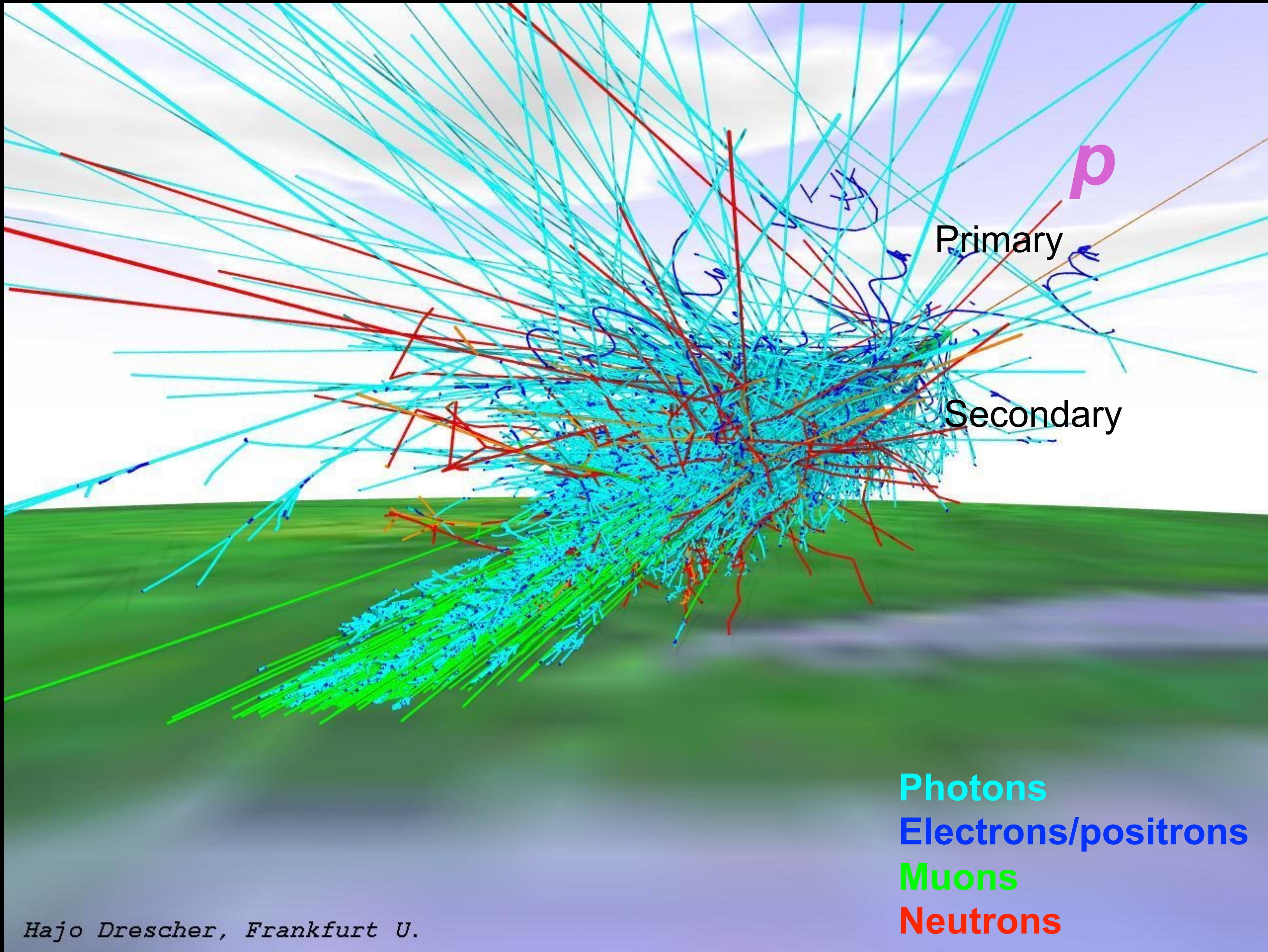


What are Cosmic Rays?

- When these rays enter our atmosphere they hit other particles like 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



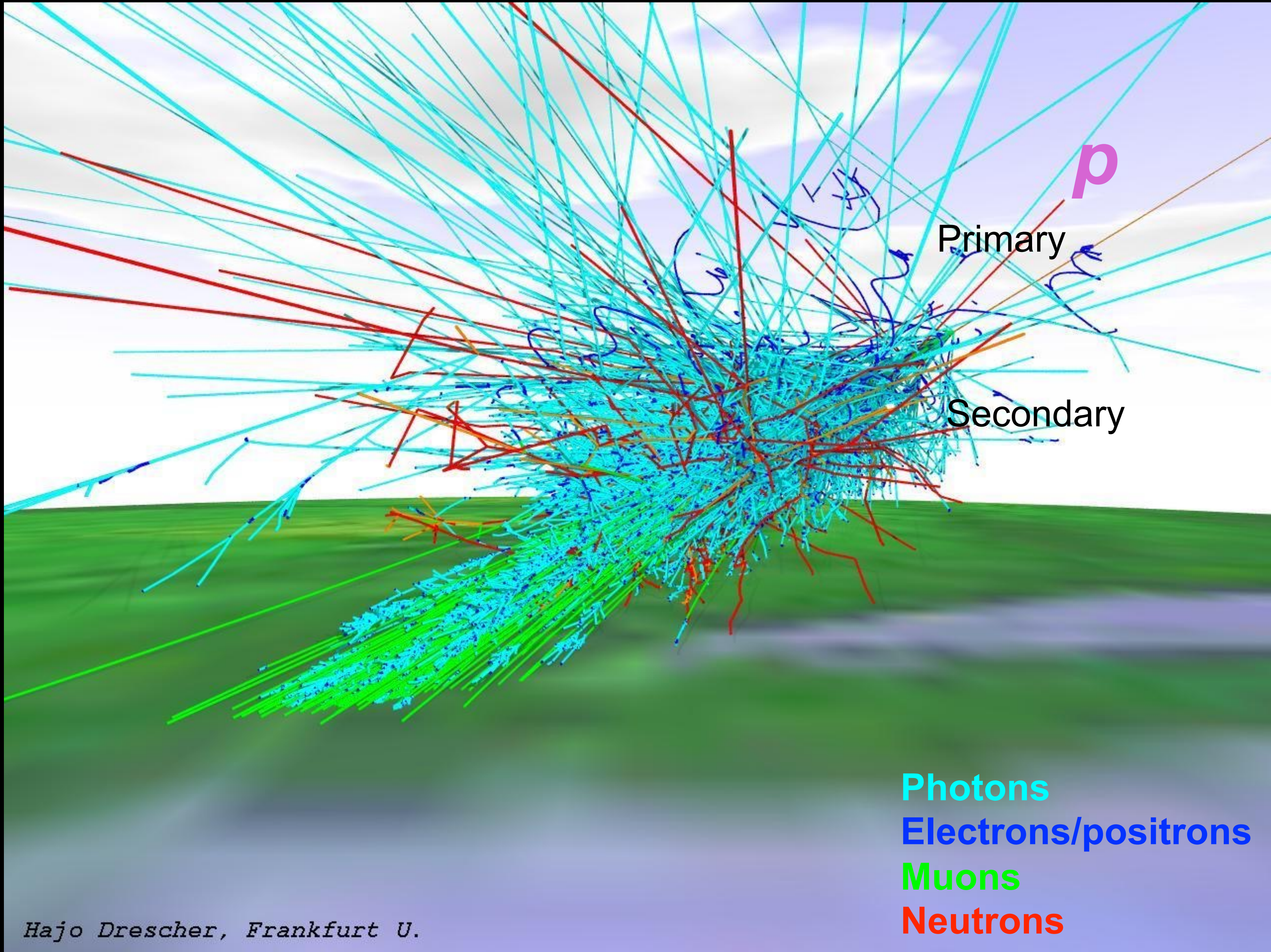
What are Cosmic Rays?

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.

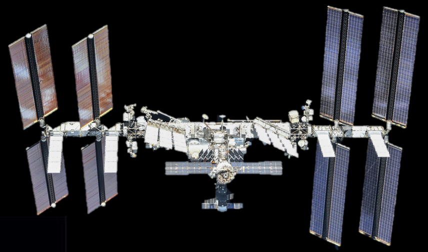
1947 – the pion and the kaon.



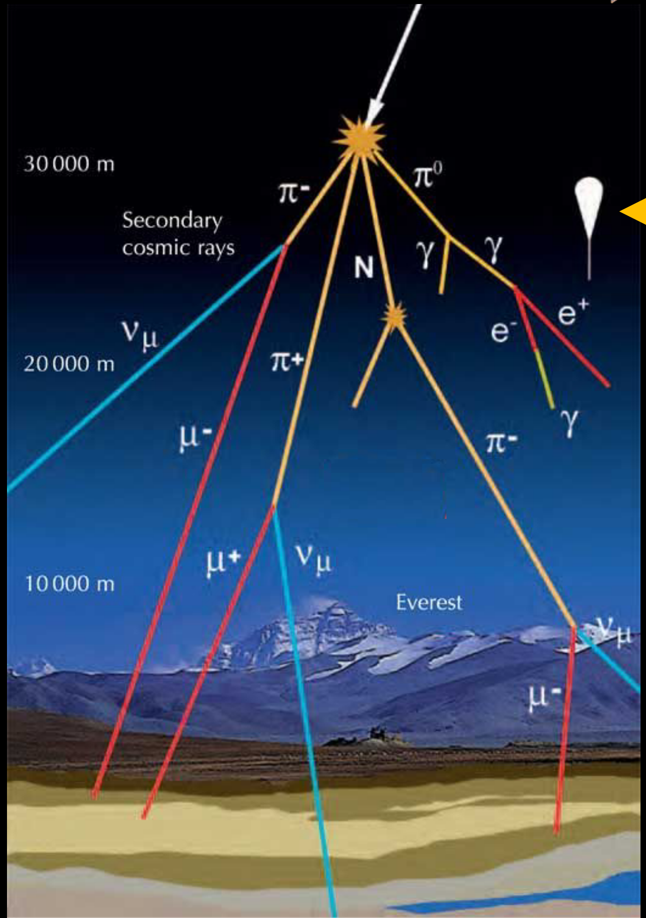
How to detect cosmic rays?

Satellites (e.g. Fermi)

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



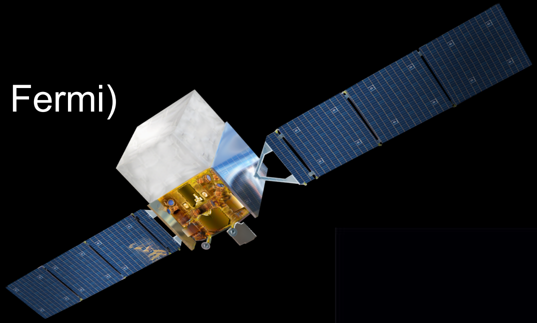
AMS experiment on the
International Space Station



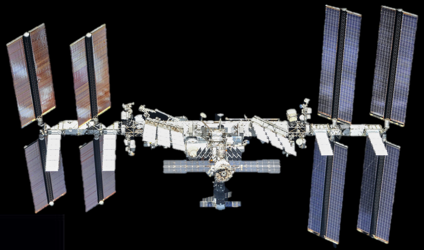
High altitude balloons

How to detect cosmic rays?

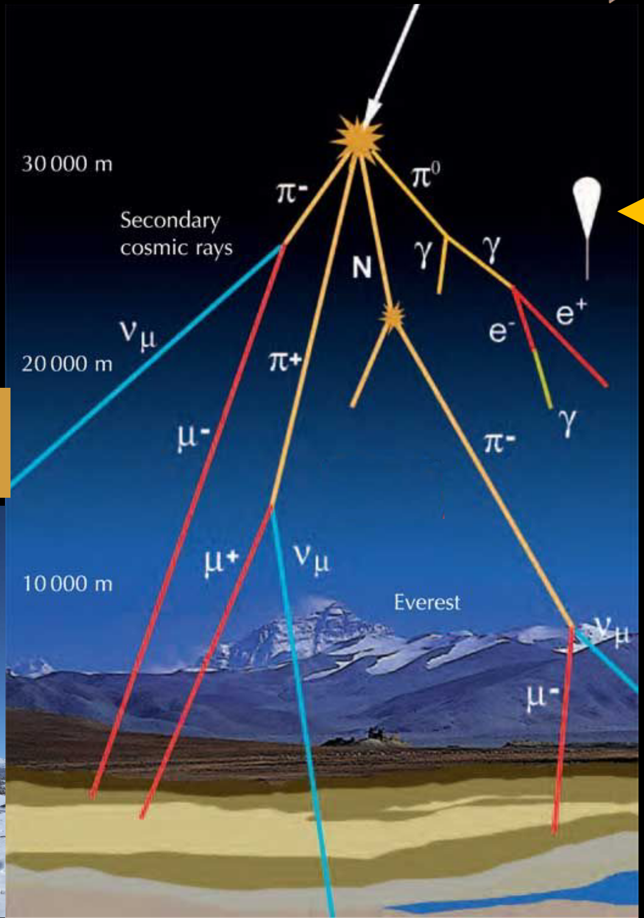
Satellites (e.g. Fermi)



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

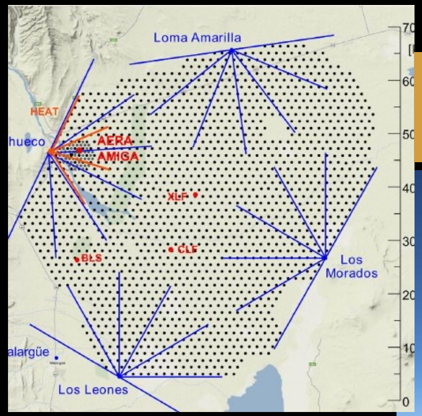


AMS experiment on the
International Space Station



High altitude balloons

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

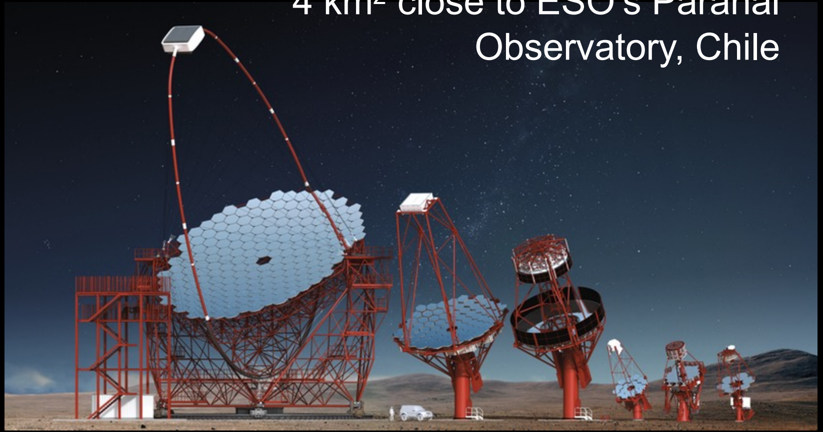


Pierre Auger Observatory, Argentina

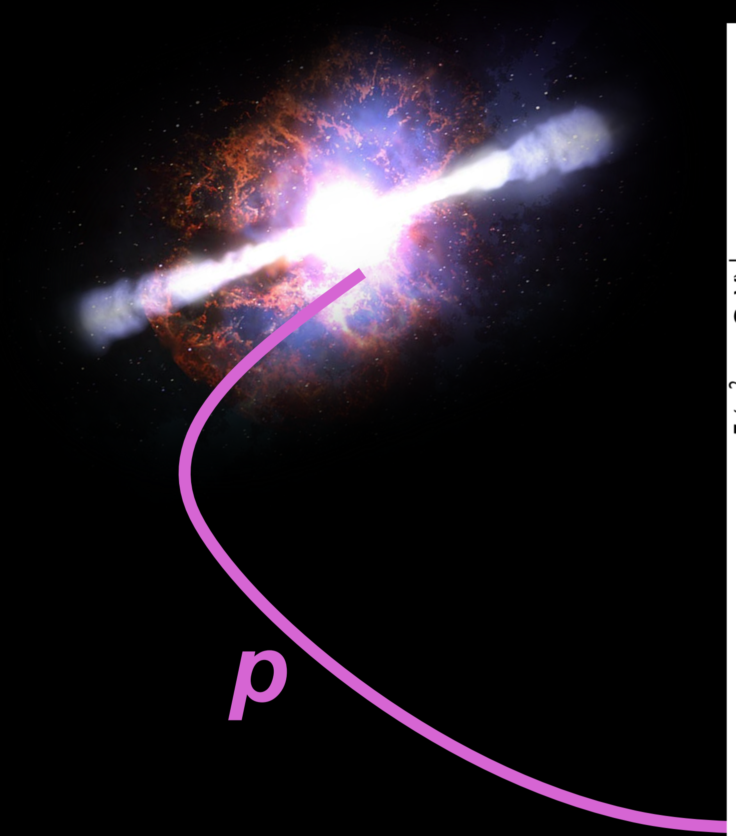
Array of 1660 detector stations spread over an area of 3000 km^2 at an altitude of 1400 m

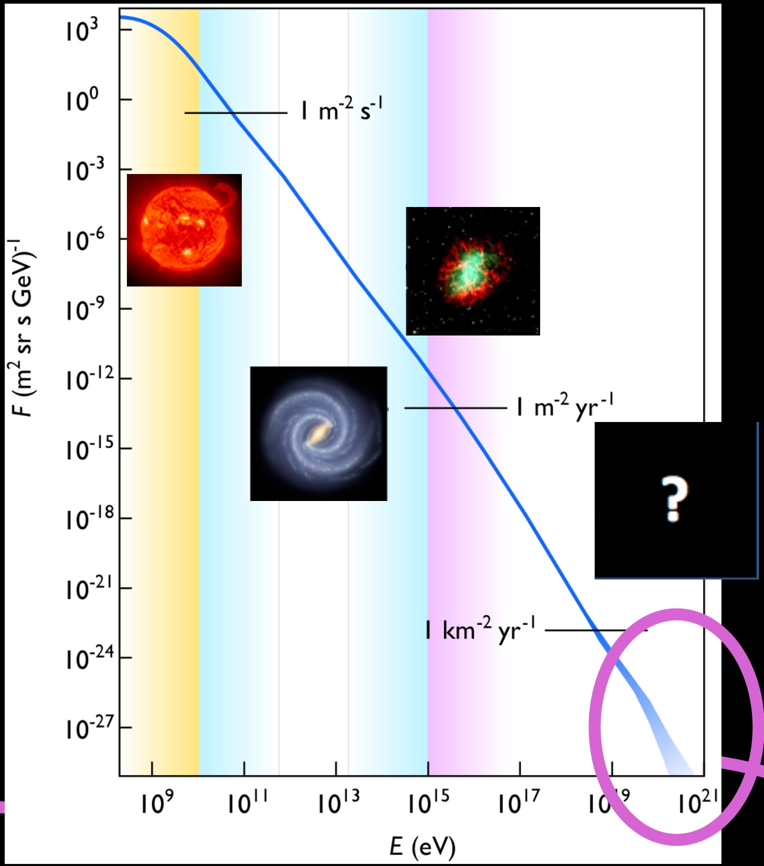
Detection of charged particles via the Cherenkov light they create in purified water.

In planning / preparation:
Array of 100 optical telescopes of different diameter (4–23 m) spread over an area of 4 km^2 close to ESO’s Paranal Observatory, Chile



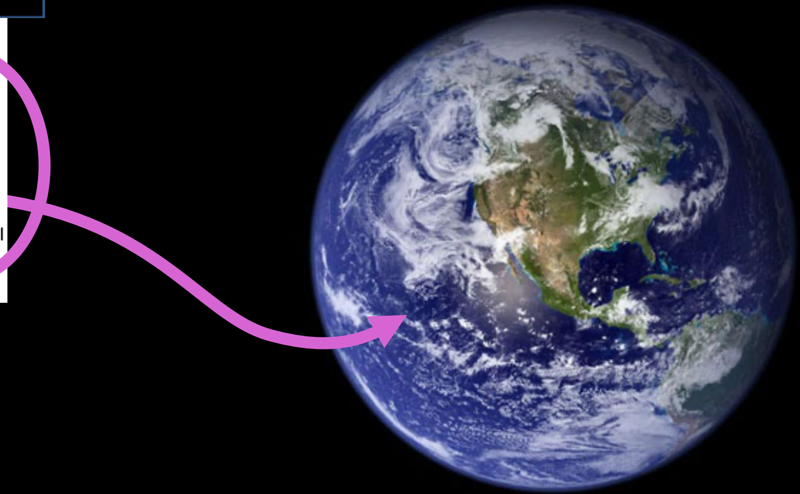
What are Cosmic Rays?





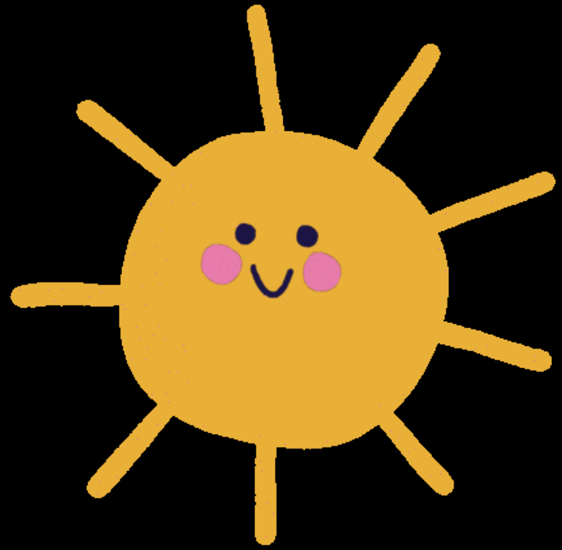
Since their discovery, the main focus of cosmic ray research has been trying to find out:

- 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



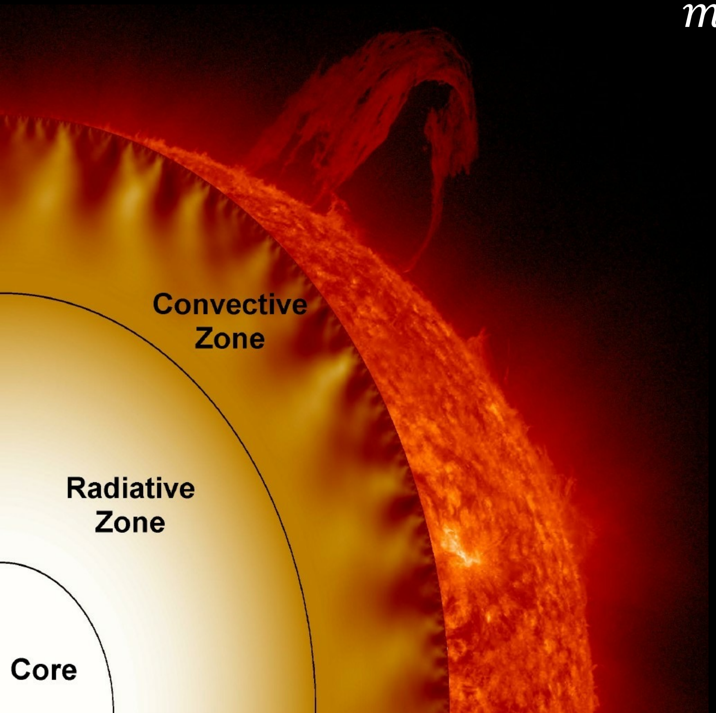
The Sun is a Source of Neutrinos!

- 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

- Thermonuclear reactions release energy because the total mass of a nucleus is less than the total mass of the constituent nucleons:

$$m(A,Z) = Zm_p + (A-Z)m_n - B(A,Z)$$

A – atomic mass
Z – atomic number (number of protons)
m_p – proton mass
m_n – neutron mass
$B(A,Z)$ – nuclear binding energy



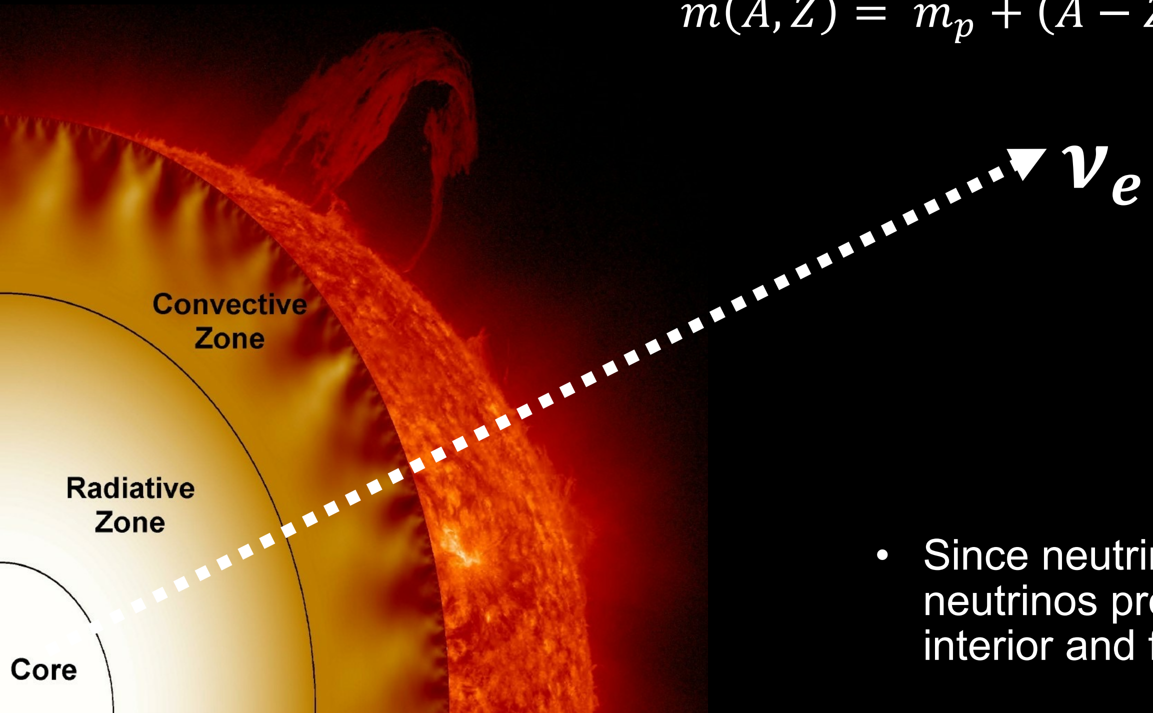
Only neutrinos, with their extremely small interaction cross-sections, can enable us to see into the interior of a star, and thus verify directly the hypothesis of nuclear energy generation in stars.
John N. Bahcall

The Sun is 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

- Thermonuclear reactions release energy because the total mass of a nucleus is less than the total mass of the constituent nucleons:

$$m(A,Z) = m_p + (A-Z)m_n - B(A,Z)$$



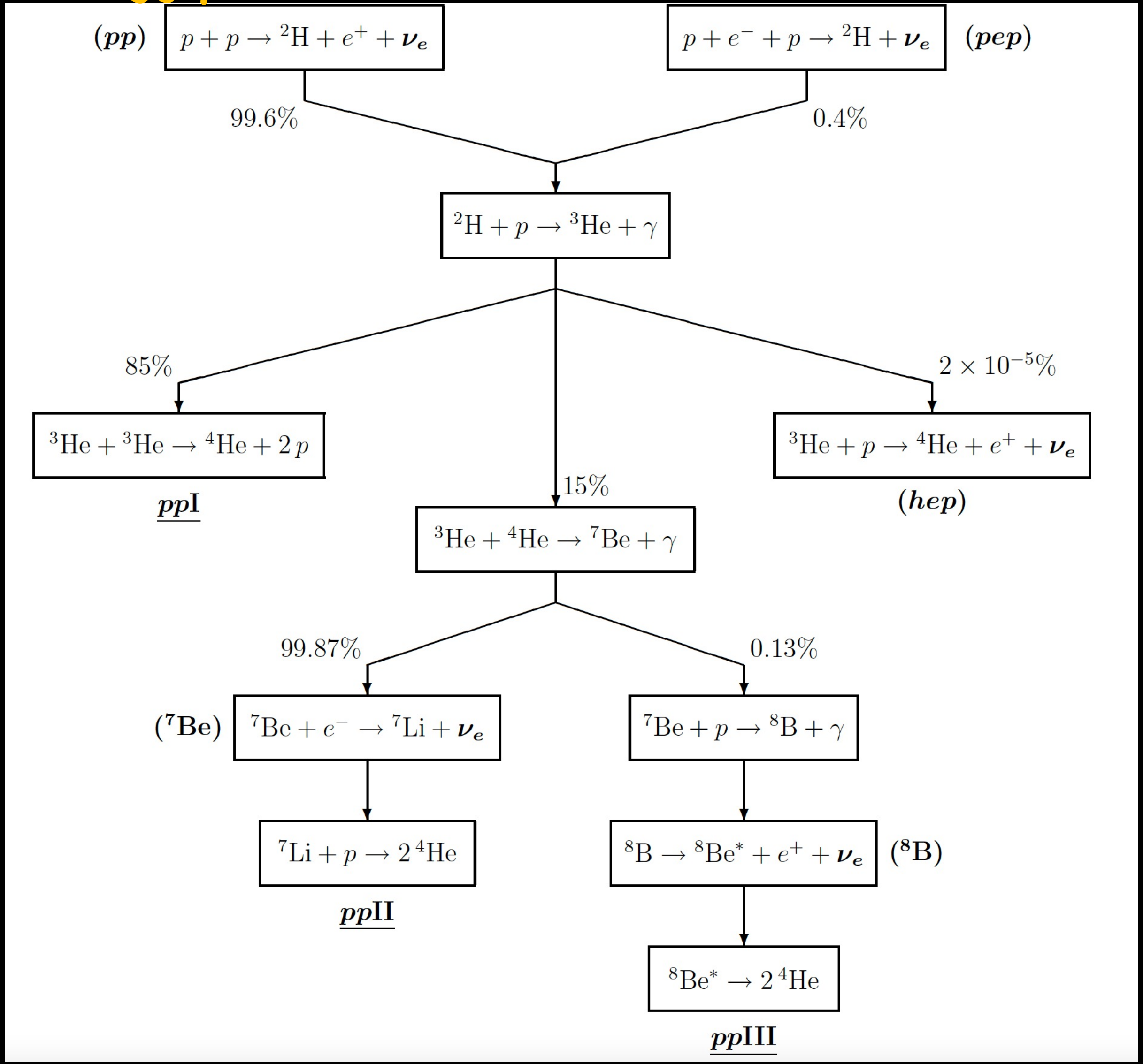
Only neutrinos, with their extremely small interaction cross-sections, can enable us to see into the interior of a star, and thus verify directly the hypothesis of nuclear energy generation in stars.
John N. Bahcall

- 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.

The Sun is powered by two groups of thermonuclear reactions:

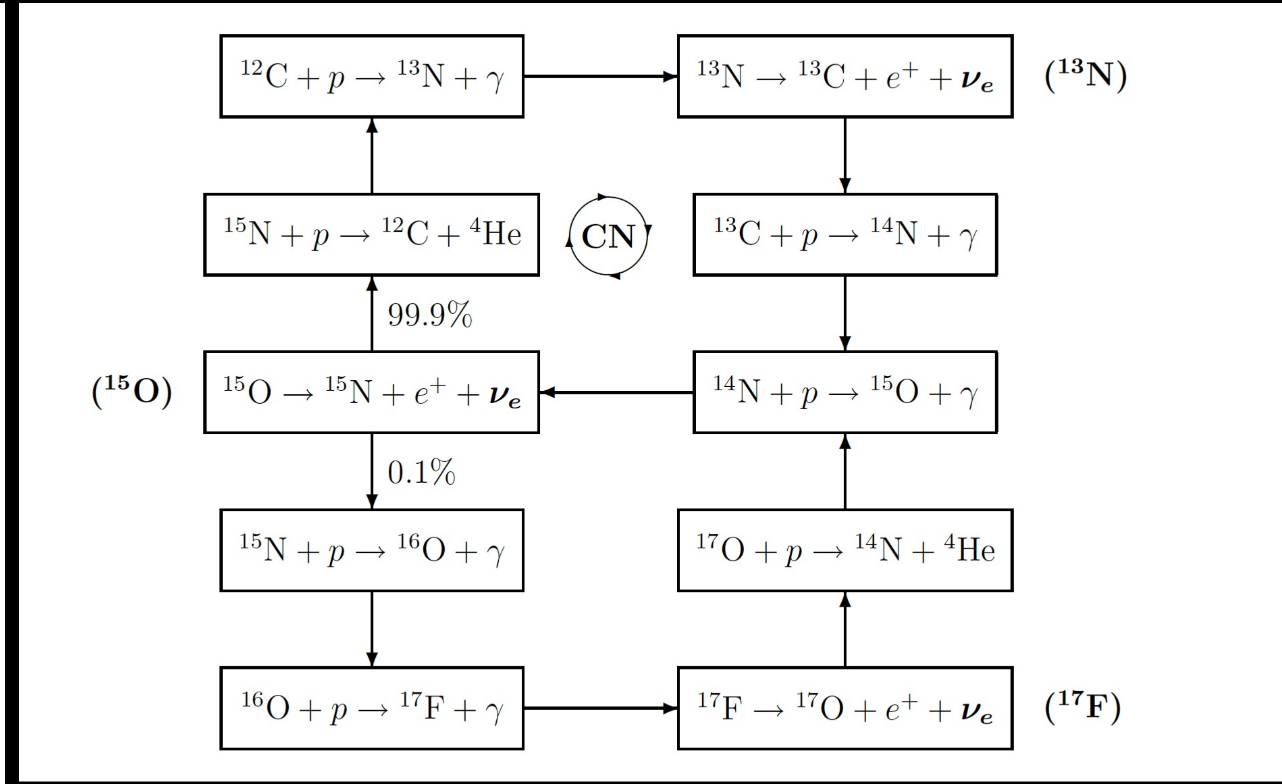
Dominates the energy production

pp chain



CNO cycle

More important in stars bigger than the Sun

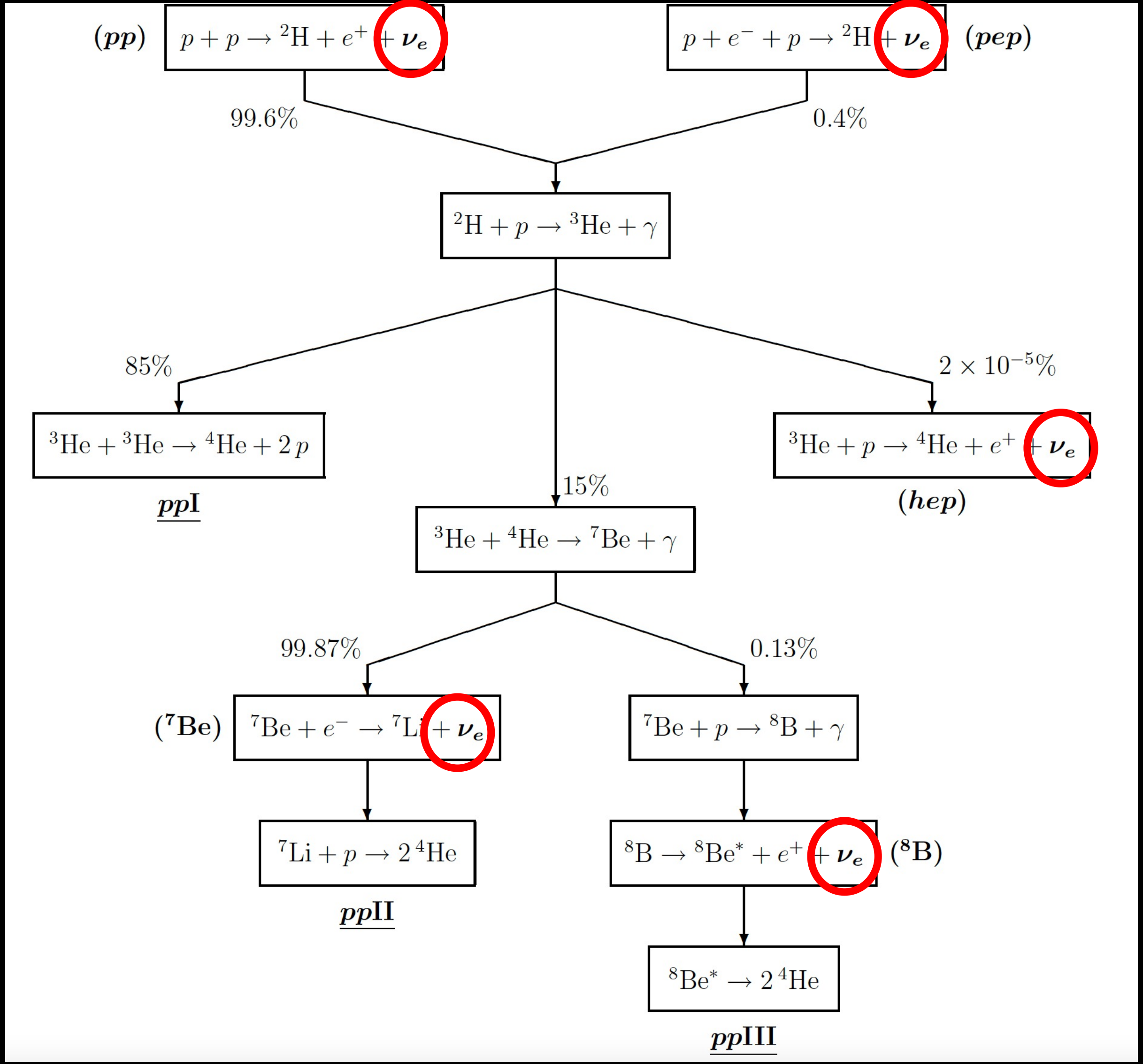


The result of both processes is:

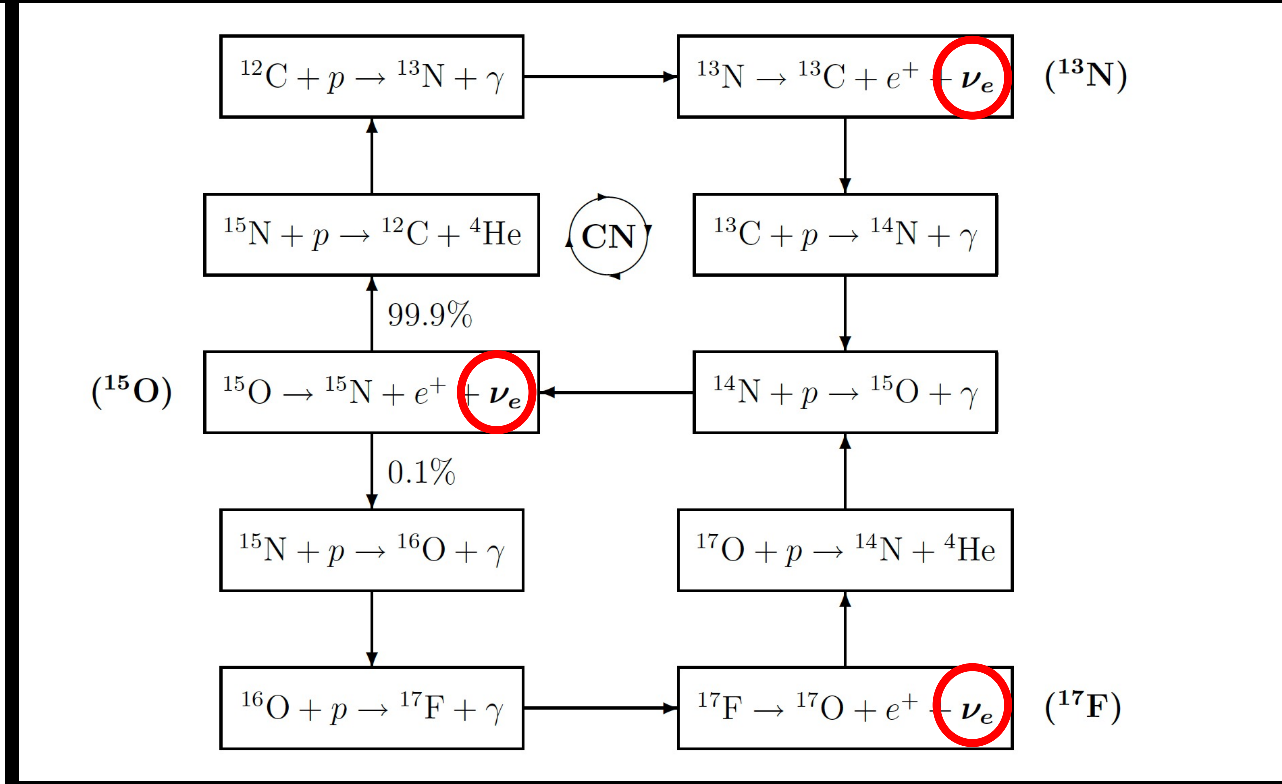
$$4p + 2e^- \to {}^4\mathrm{He} + 2\nu_e + 26.7\ \mathrm{MeV}$$

The Sun is powered by two groups of thermonuclear reactions:

pp chain

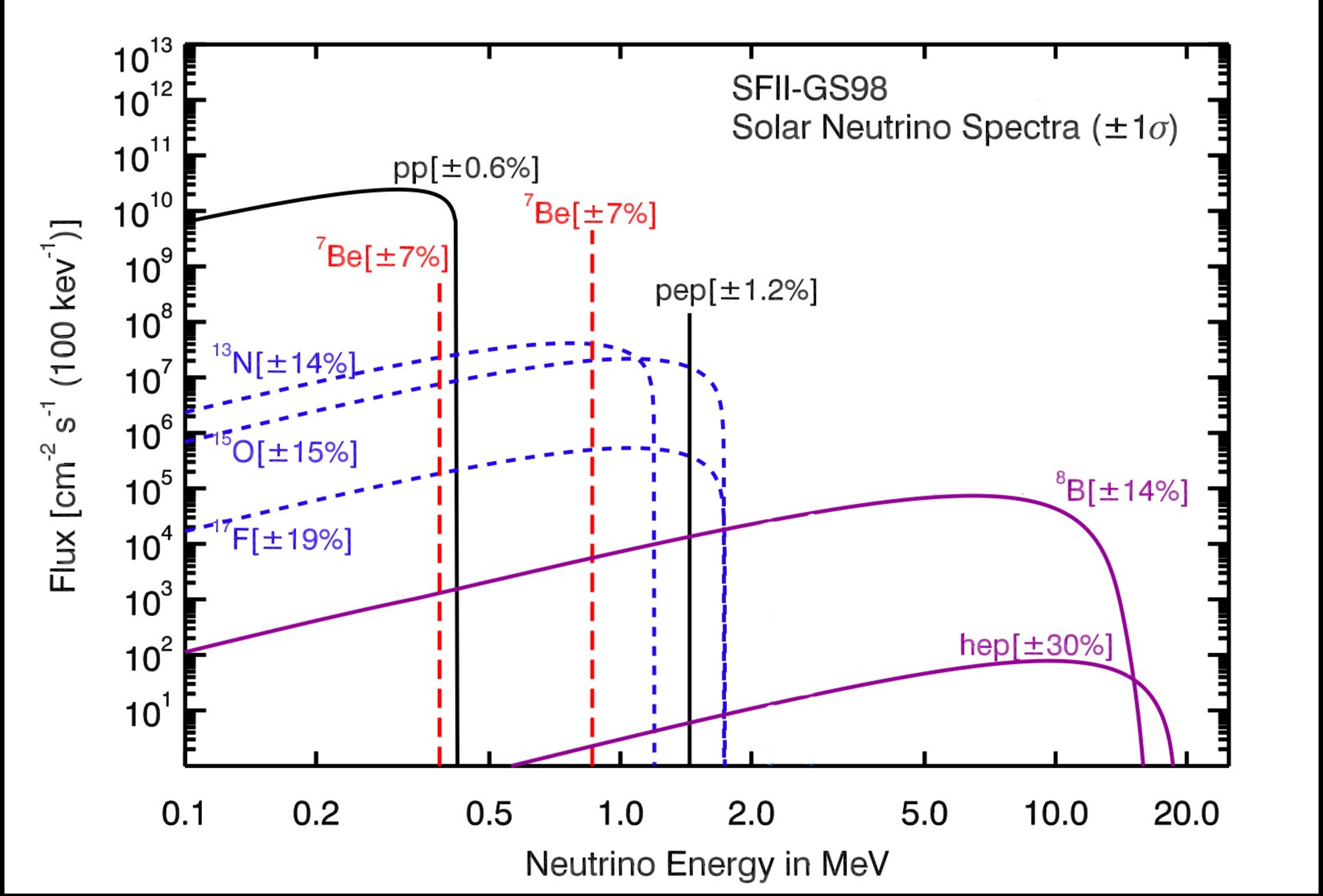


CNO cycle



The result of both processes is:

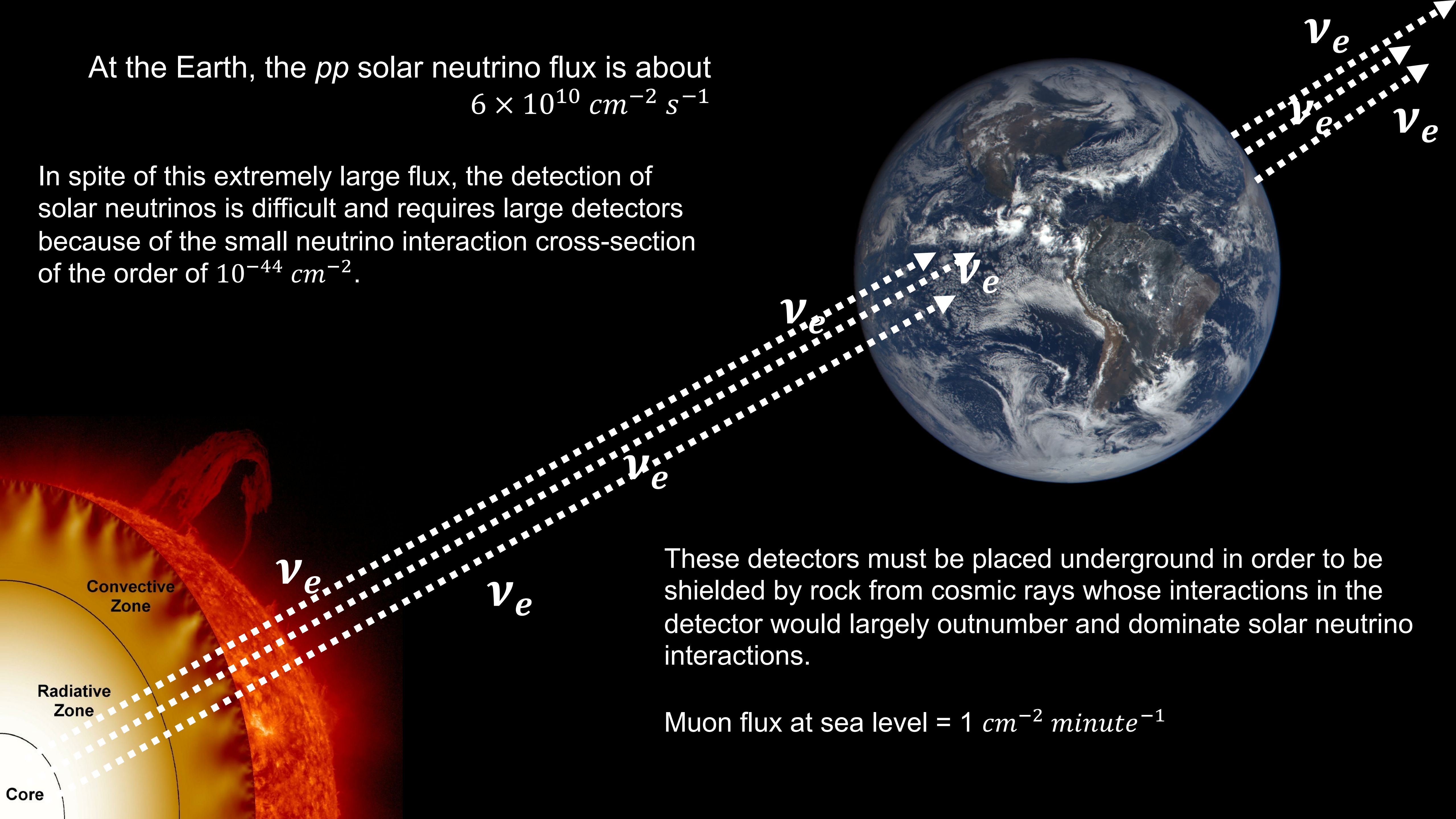
$$4p + 2e^- \to {}^4\mathrm{He} + 2\nu_e + 26.7\ \mathrm{MeV}$$



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 $cm^{-2}\ minute^{-1}$

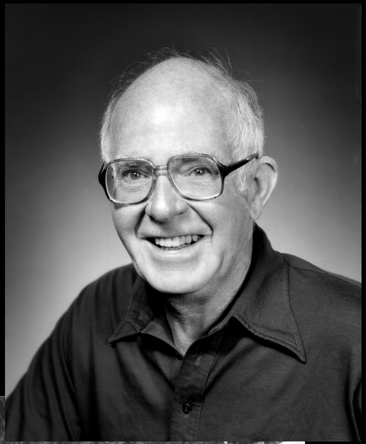

People who want to detect solar neutrinos
Cosmic rays just existing
imgflip.com

Solution:

Go inside a mine

First detection of Solar Neutrinos

Homestake Experiment



- Proposed in the 70s by Ray Davis
- Radiochemical experiment looking for the Pontecorvo-Alvarez inverse beta-decay Cl-Ar reaction:

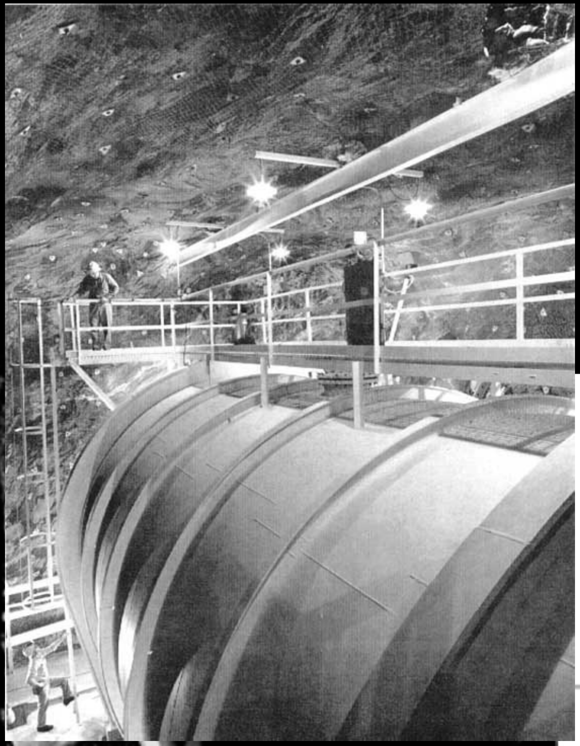
$$\nu_e + {}^{37}\mathrm{Cl} \mapsto {}^{37}\mathrm{Ar} + e^-$$

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

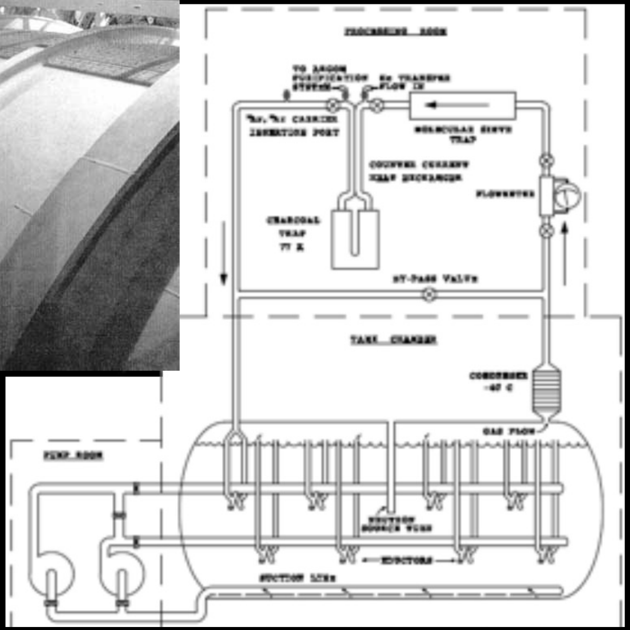
- Expose large quantities of Chlorine
- Chemically extract the Argon
- Count the radioactive decays of ^{37}Ar

First detection of Solar Neutrinos

Homestake Experiment



- Homestake mine (USA), 1478 m deep
- Used 600 tons of CCl4 (cleaning liquid)
- Flush the Argon out of the tanks using helium, every two to three months (efficiency of 95%)



Volume 21, Number 36

Published by the BNL Public Relations Office

9-1307-66

Solar Neutrinos Are Counted At Brookhaven

Dr. Ray Davis of Chemistry is shown placing a low level counter in a cut-down navy gun barrel which acts as a shield from stray cosmic radiation. This equipment is used in the Brookhaven Solar

The extracted Argon is measured in a counter

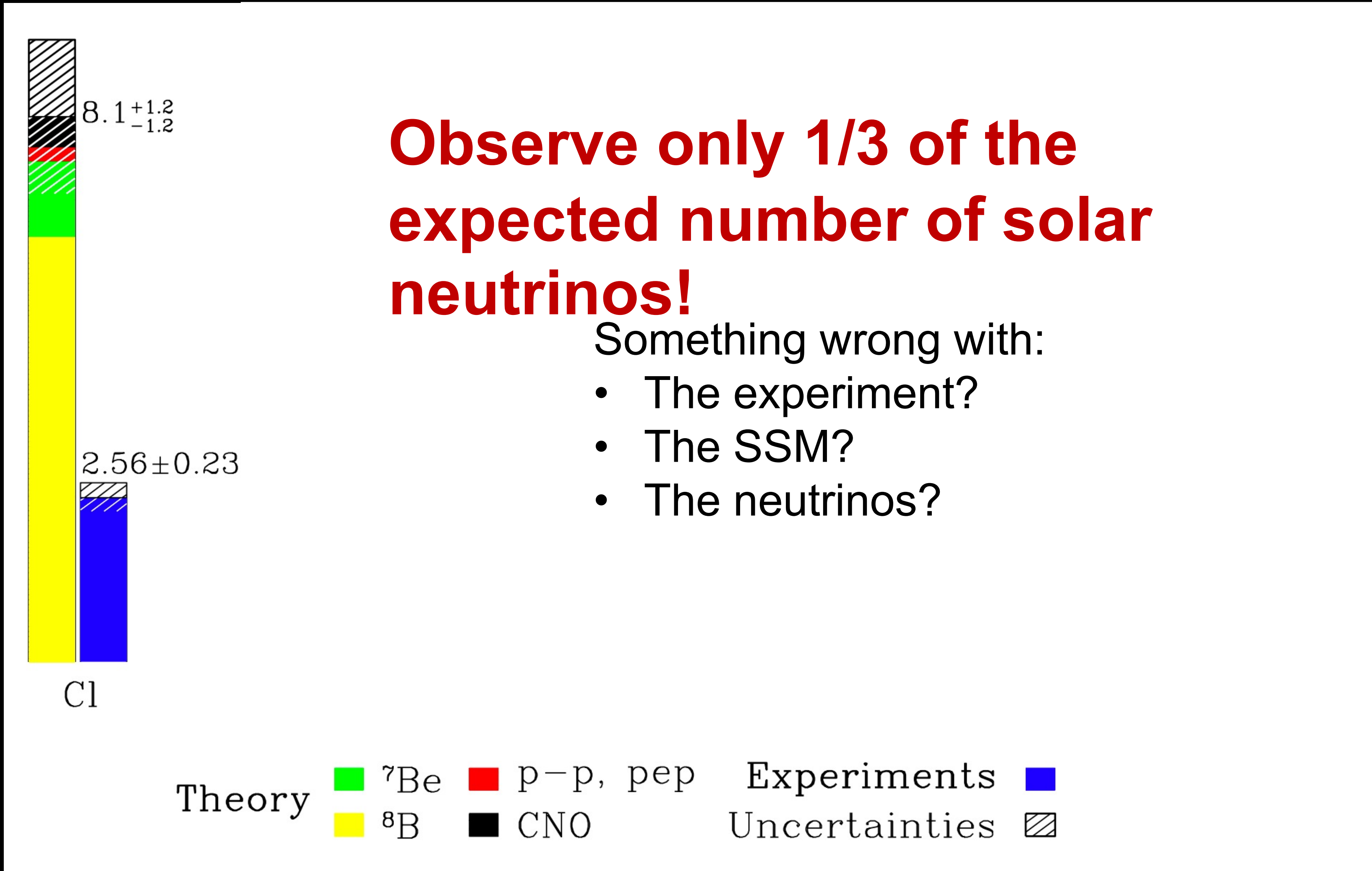
$$^{37}Ar + e^{-} \rightarrow \nu_e + {}^{37}Cl$$

$$(T_{1/2} = 35d)$$

Acquired data for 24 years!

First detection of Solar Neutrinos

Homestake Experiment Results



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

Something wrong with:

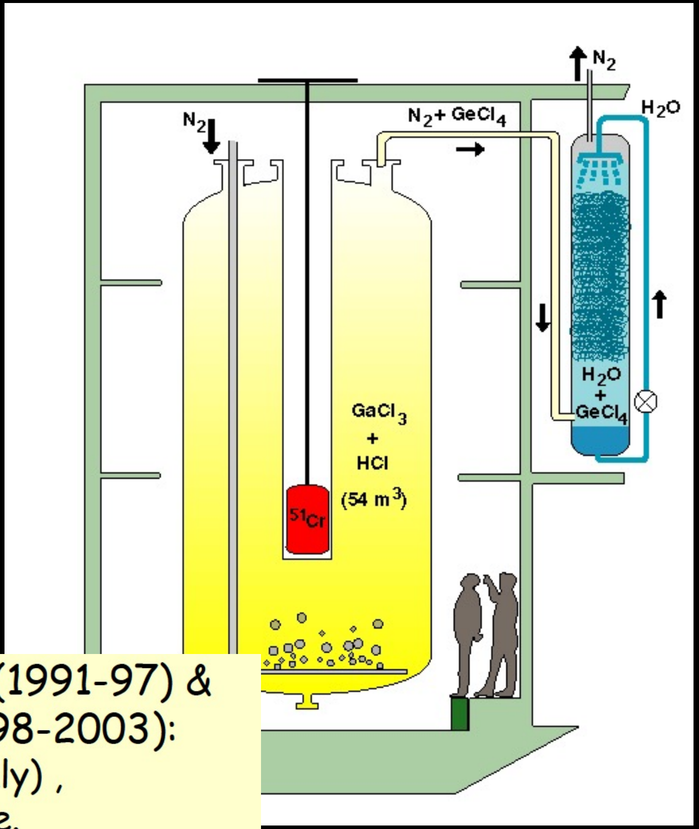
- The experiment?
- The SSM?
- The neutrinos?

Gallium Experiments

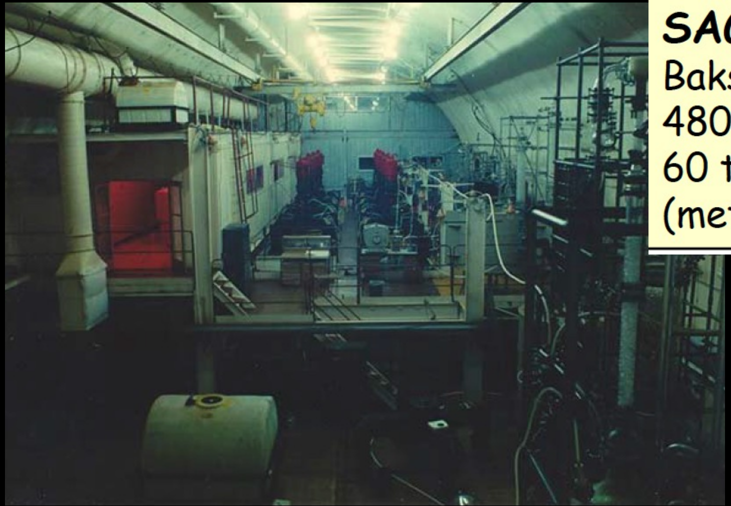
- Similar to Homestake, but using the Gallium reaction

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

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



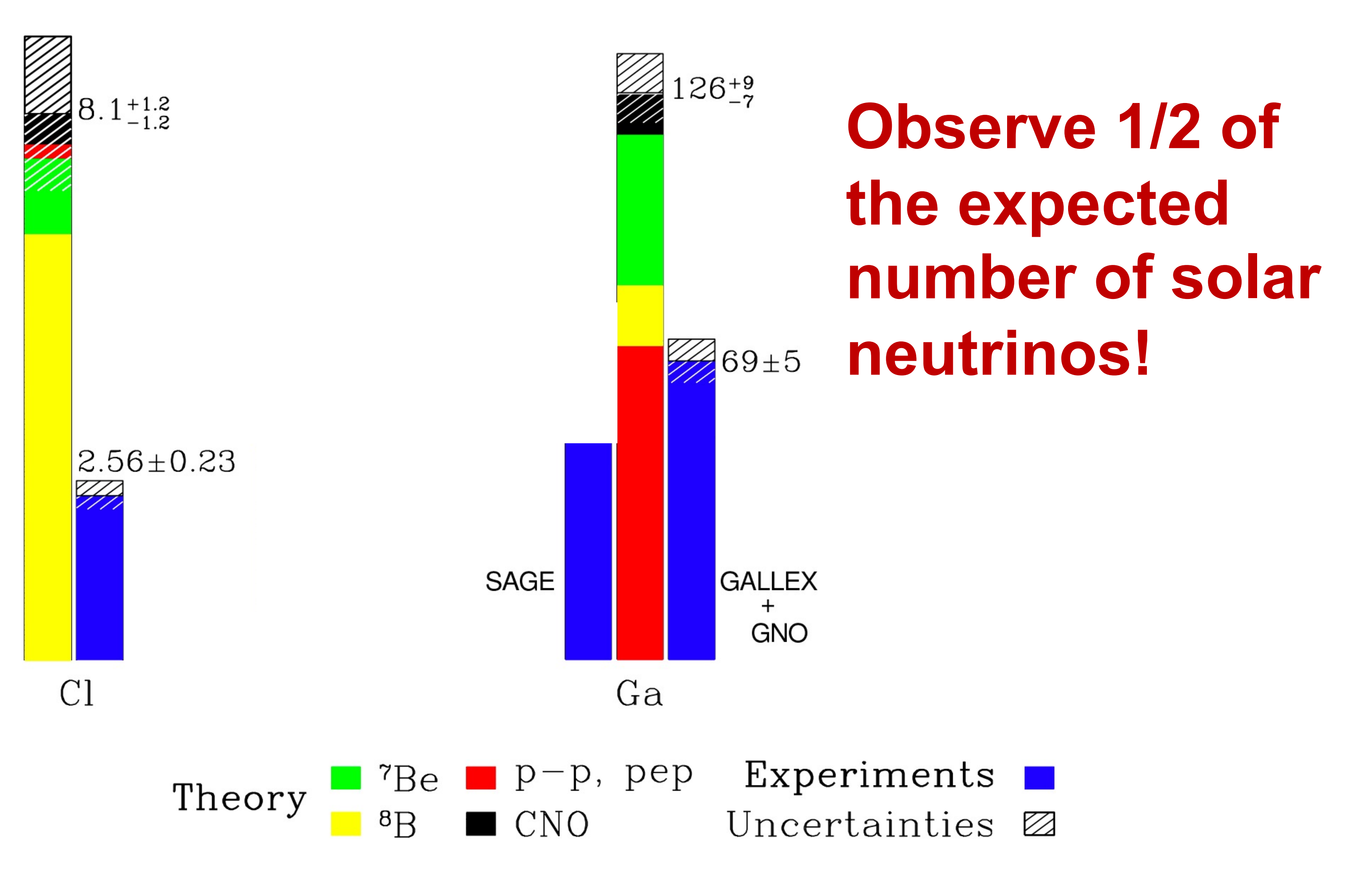
GALLEX (1991-97) &
GNO (1998-2003):
LNGS (Italy) ,
3200 m.w.e.
30 tons of gallium
(water solution of $GaCl_3$)



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

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

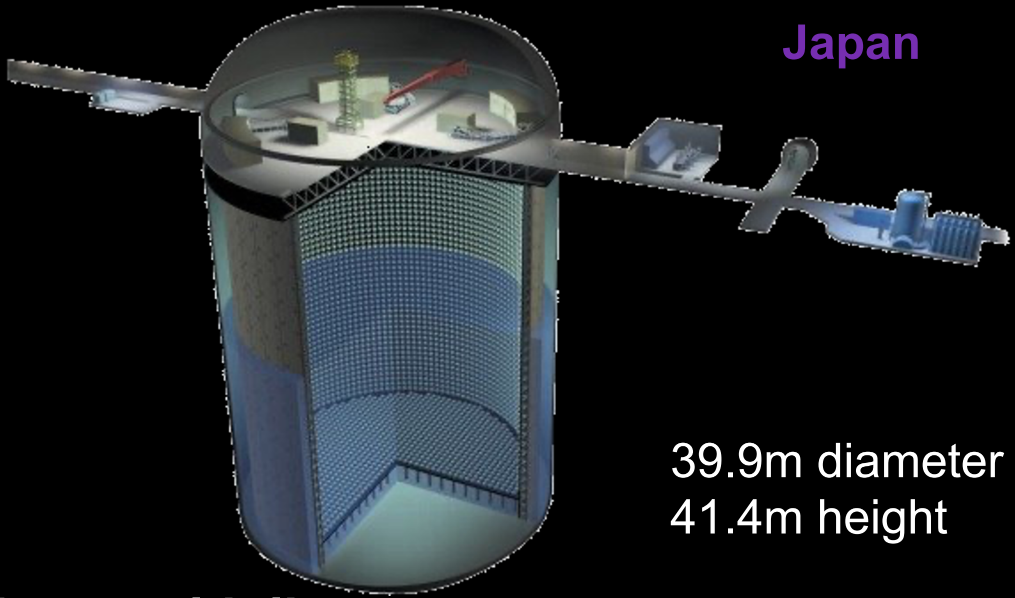
- 1987 Kamiokande
- 1997 Super-Kamiokande
  - Several phases

- Detects neutrino-electron scatterings

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

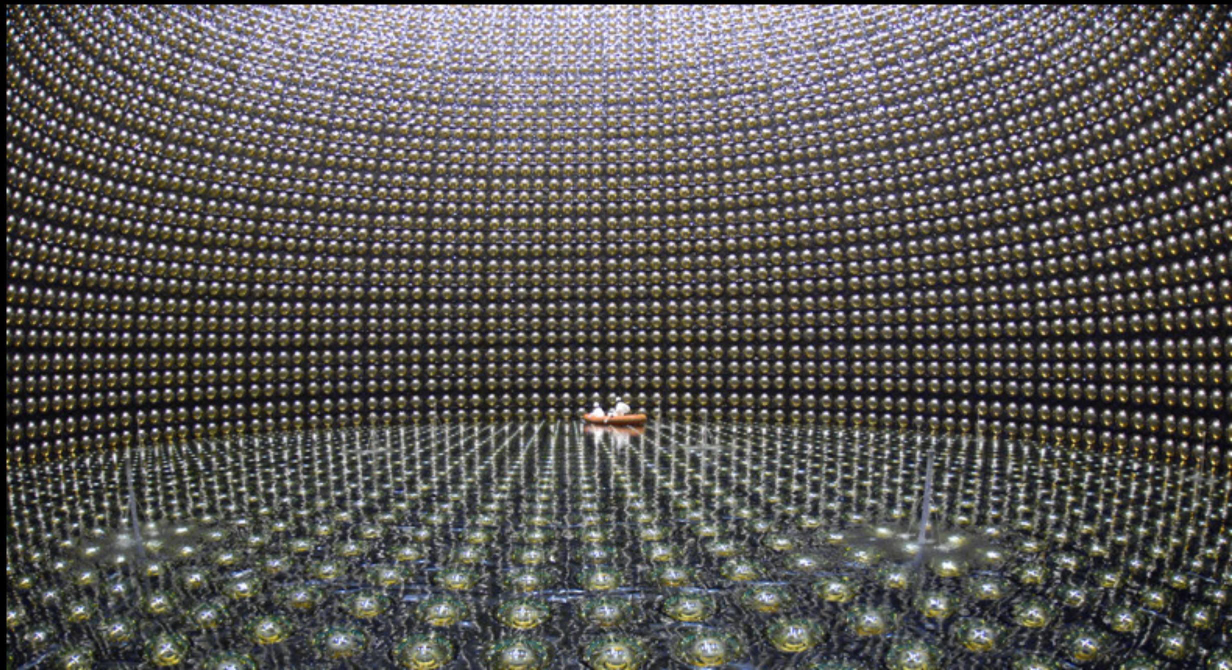
- Sensitive to all neutrino flavours, but mainly ν_e

Japan



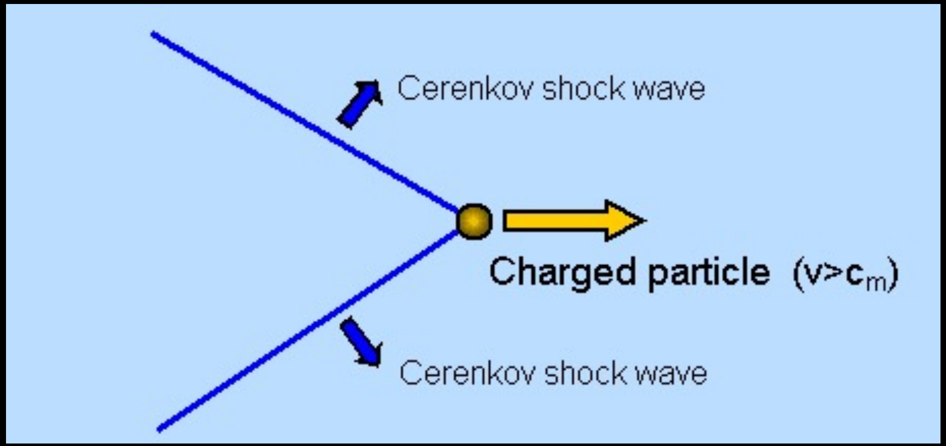
39.9m diameter
41.4m height

11000 photomultipliers
50000 tons of water



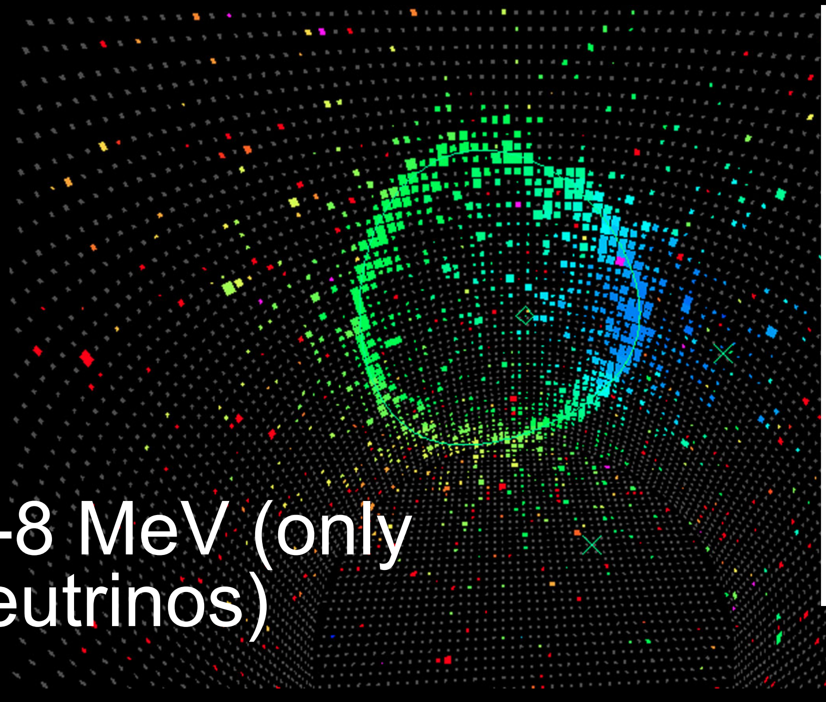
Water Cherenkov Detectors

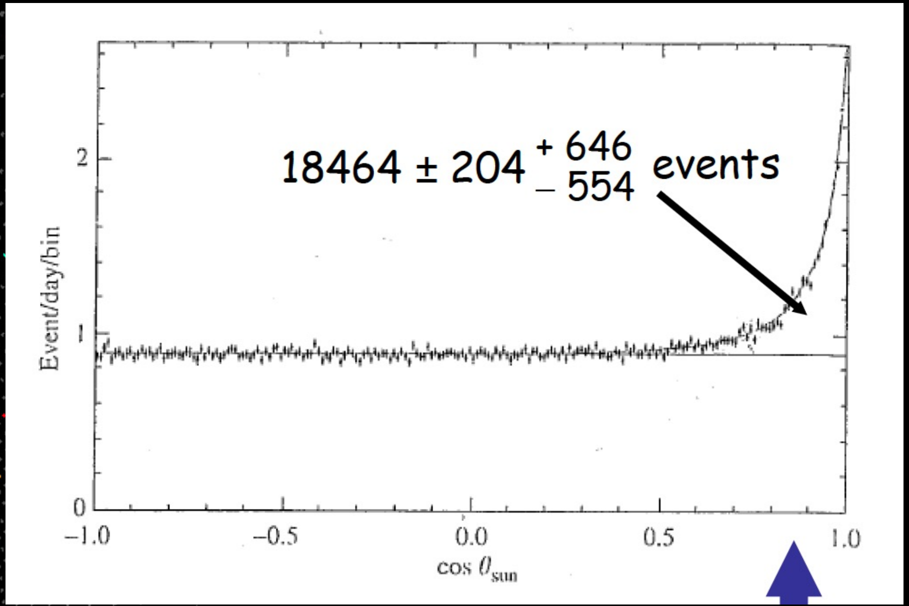
- The scattered electrons produce Cherenkov radiation



Cherenkov radiation is electromagnetic radiation emitted when a charged particle passes through a dielectric medium at a speed greater than the phase velocity of light in that medium

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

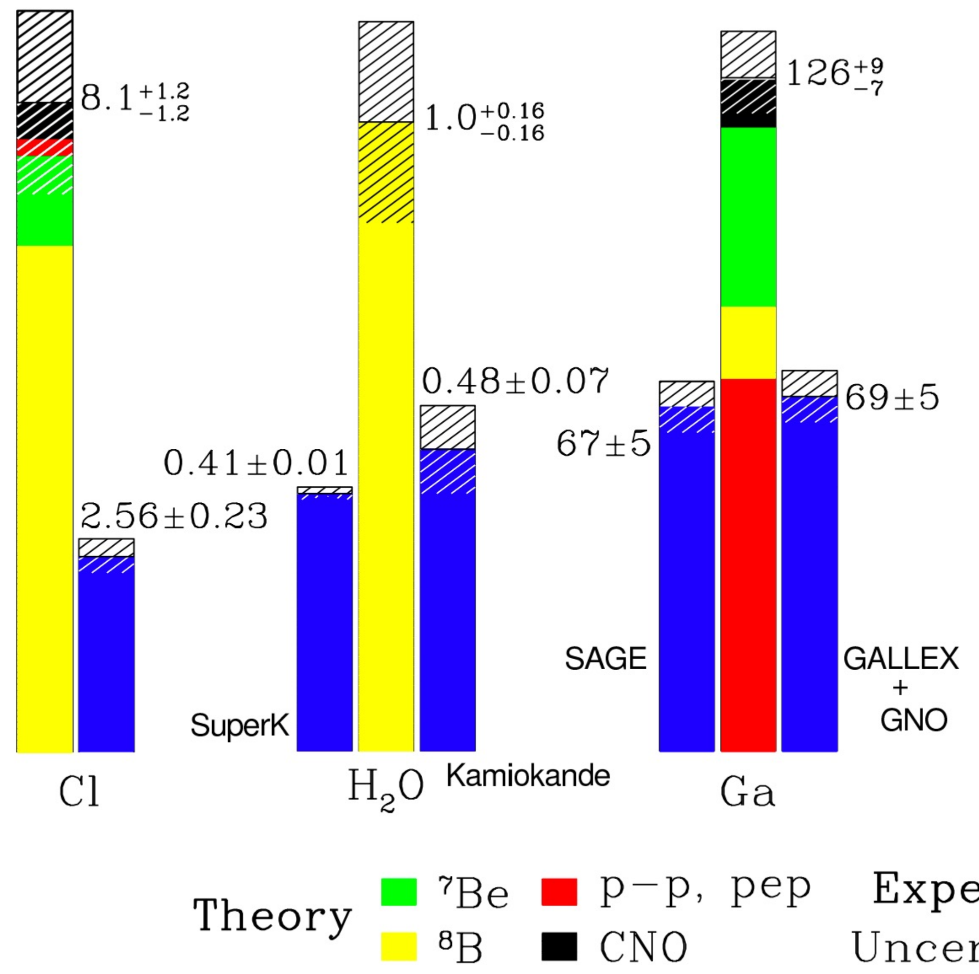




- High threshold 5-8 MeV (only sensitive to ^{8}B neutrinos)

They could see the events along the direction of the Sun – they are solar ν

Water Cherenkov Detectors



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

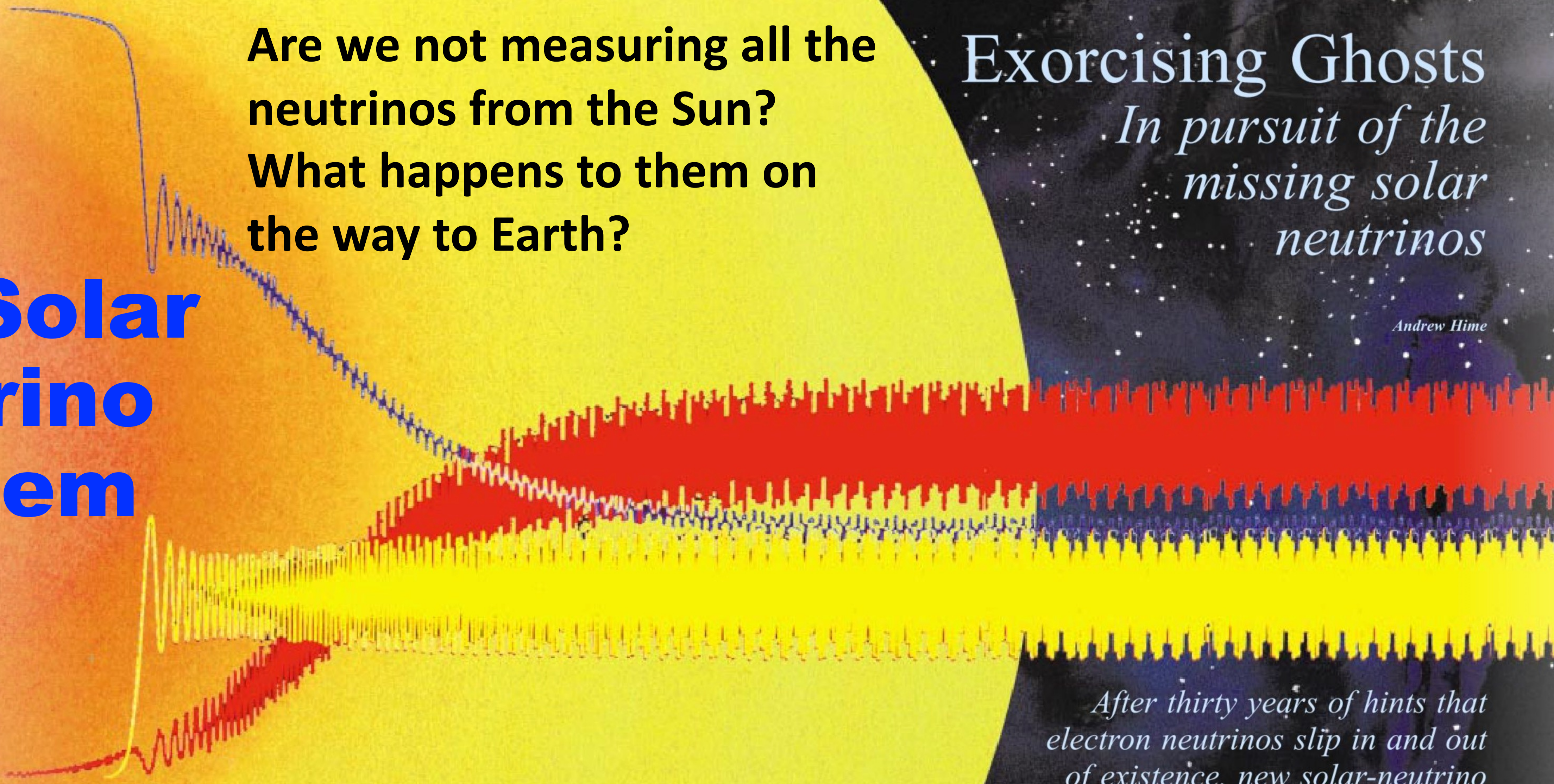
The Solar Neutrino Problem

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

Exorcising Ghosts

In pursuit of the missing solar neutrinos

Andrew Hime

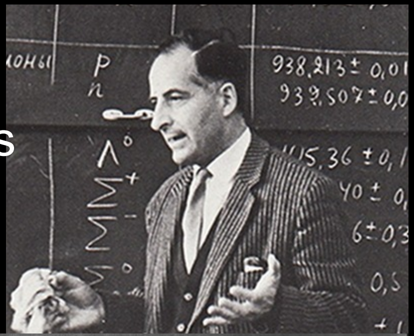


If neutrinos have mass, then the three separate particles known as the electron neutrino, the muon neutrino, and the tau neutrino may not be separate at all, but may mix and transform into one another. In this illustration, a large fraction of the electron neutrinos produced in the core of the sun change their identity before they reach the surface (blue curve). They reappear either as muon and/or tau neutrinos (red and yellow curves, respectively).

After thirty years of hints that electron neutrinos slip in and out of existence, new solar-neutrino experiments may finally catch them in the act.

Neutrinos Oscillate

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



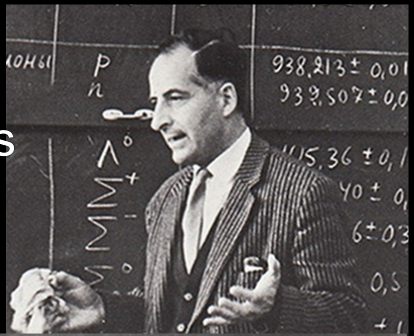
S. Sakata 1911-1970
Z. Maki 1929-2005
M. Nakagawa 1932-2001

Three flavours of Neutrinos

ν_e ν_μ ν_τ

Neutrinos Oscillate

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



Three flavours of Neutrinos

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

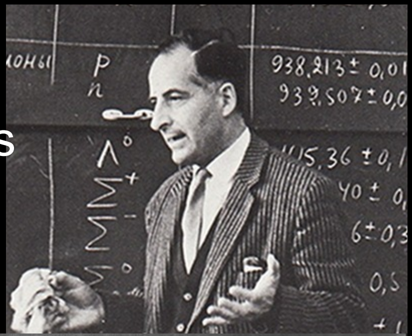
Are a linear combination of three neutrino mass states

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

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

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

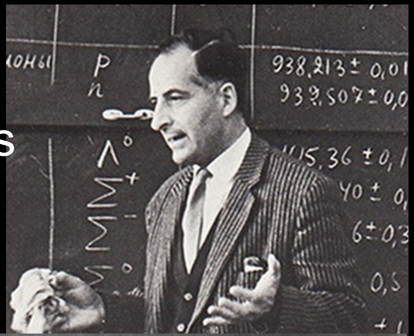
$$\nu_1 \qquad \nu_2 \qquad \nu_3$$

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

The PMNS Matrix

Neutrinos Oscillate

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



Three flavours of Neutrinos

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

Are a linear combination of three neutrino mass states

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

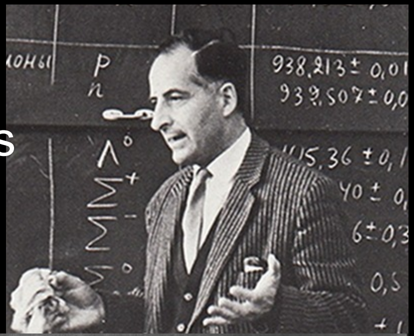
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12}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

(that looks more like this)

The PMNS Matrix

Neutrinos Oscillate

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



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

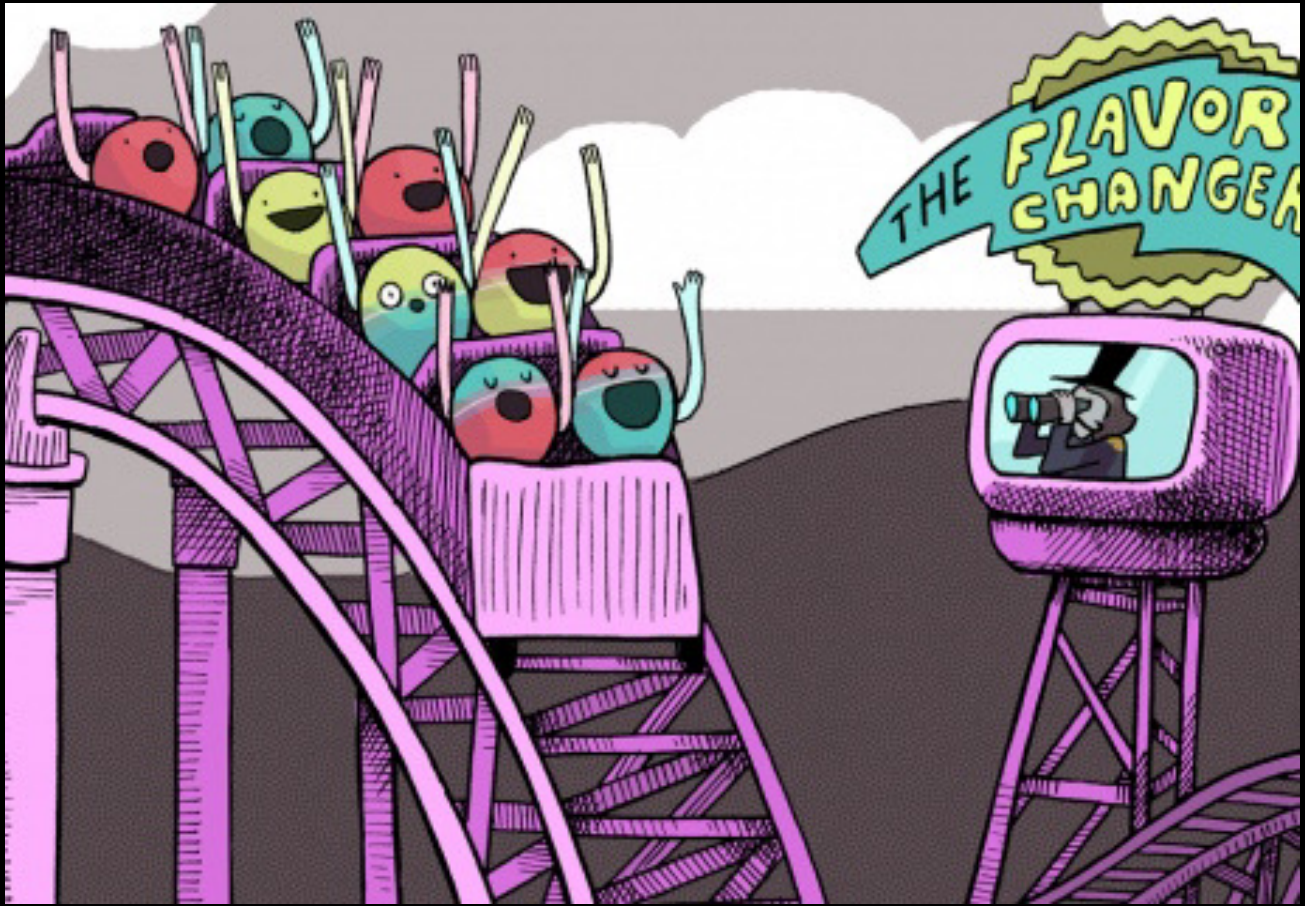
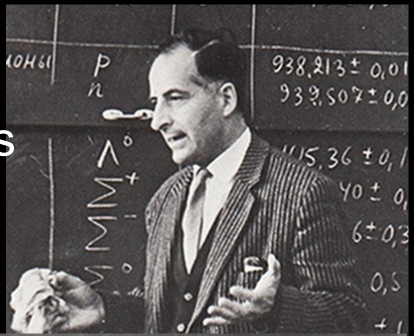


Image from Symmetry Magazine

Neutrinos Oscillate

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



Courtesy of Sakata Memorial Archival Library

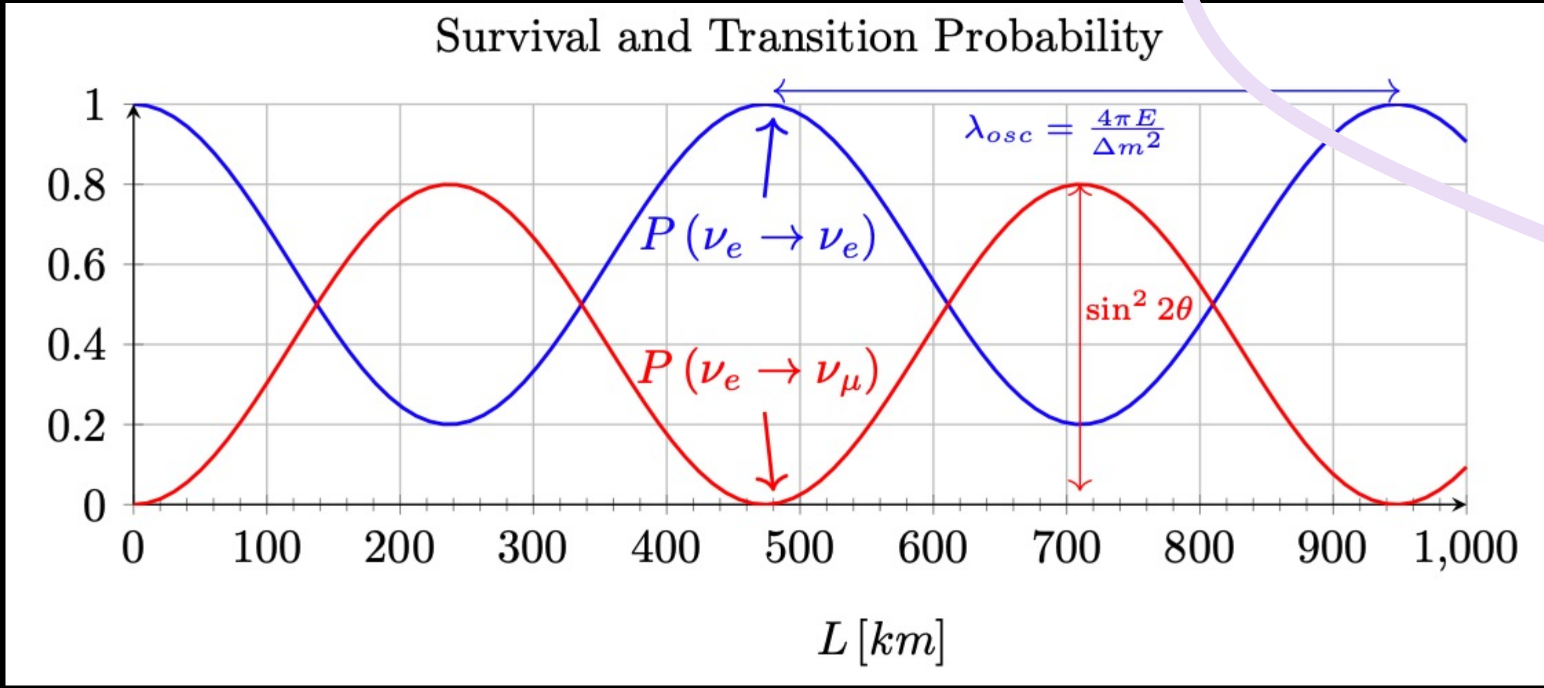
S. Sakata 1911-1970 | Z. Maki 1929-2005 | M. Nakagawa 1932-2001

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

Two neutrino case:

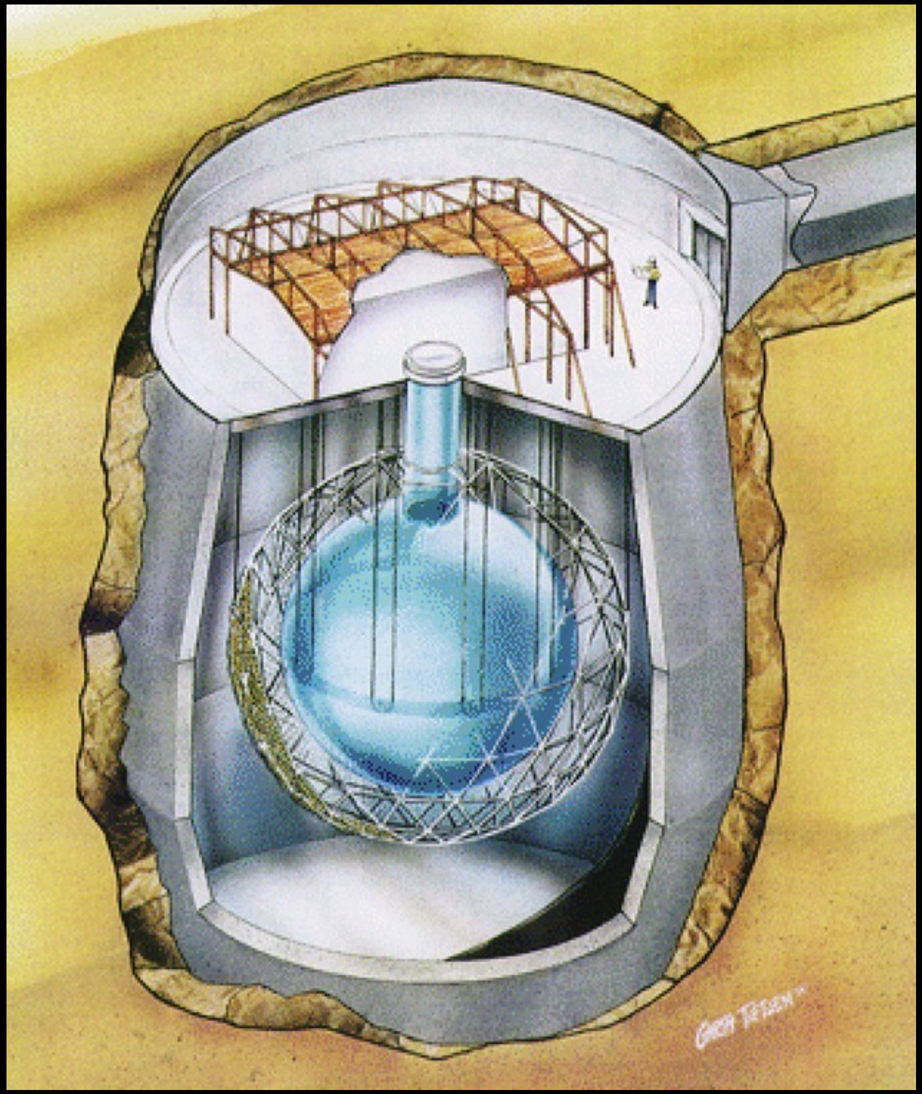
$$P_{oscillation}(\boldsymbol{\nu_e} \rightarrow \boldsymbol{\nu_\mu}) = sin^2 2\theta_{12} sin^2\left(1.27\Delta m^2_{21}[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

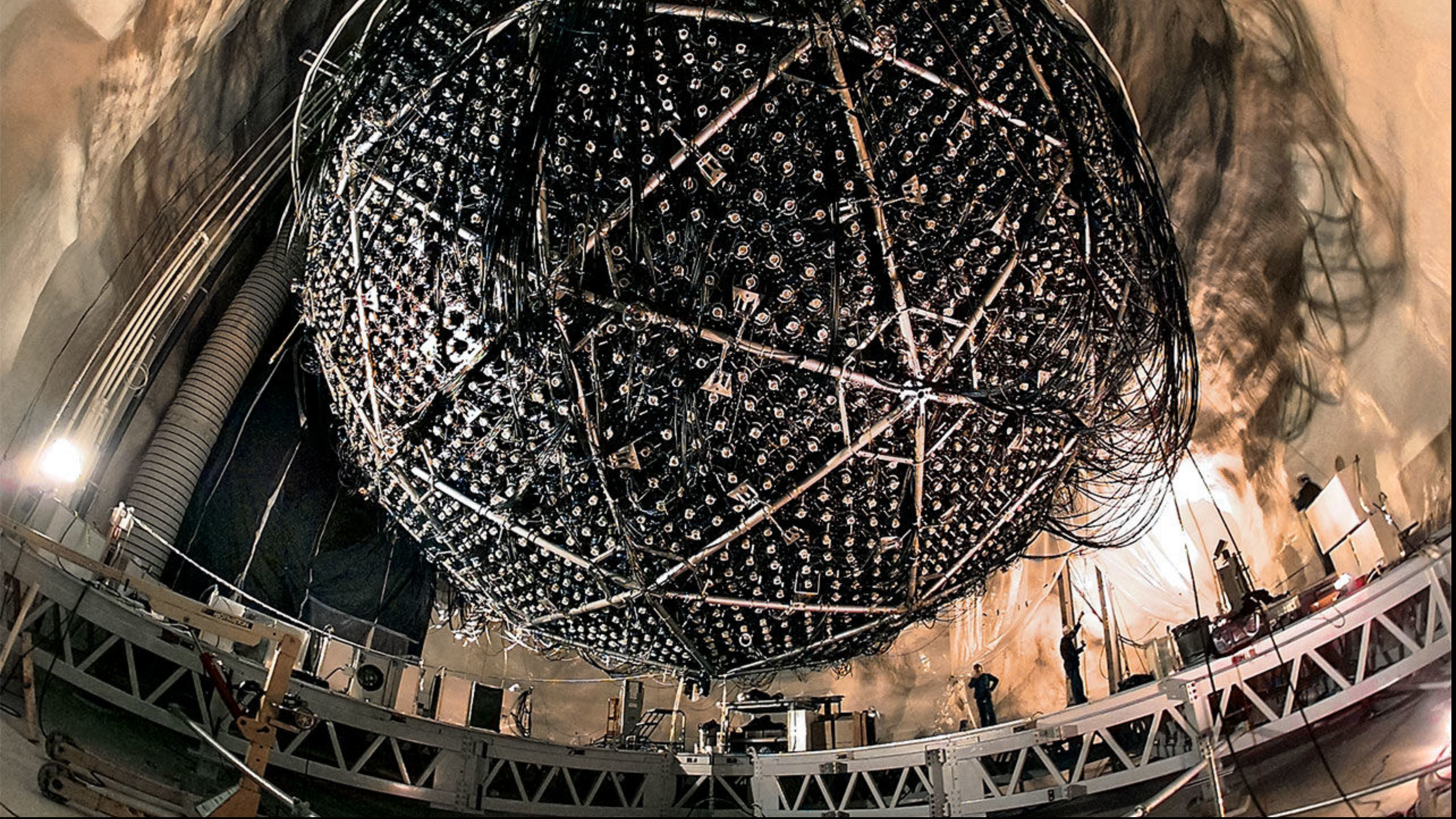
$m_2^2 - m_1^2$



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

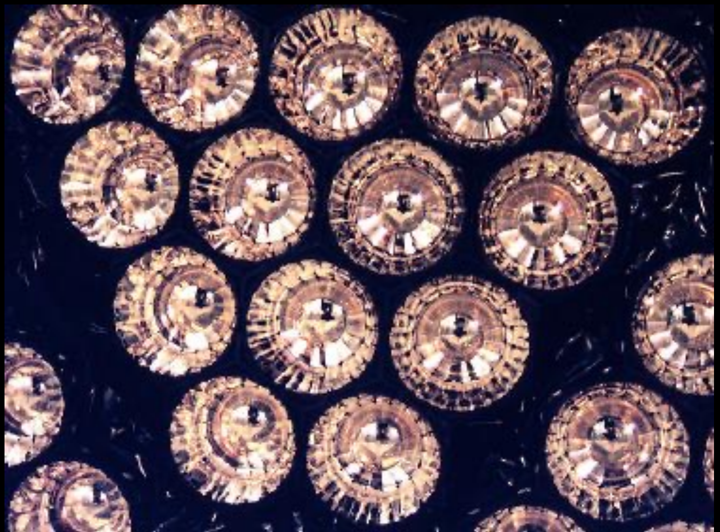


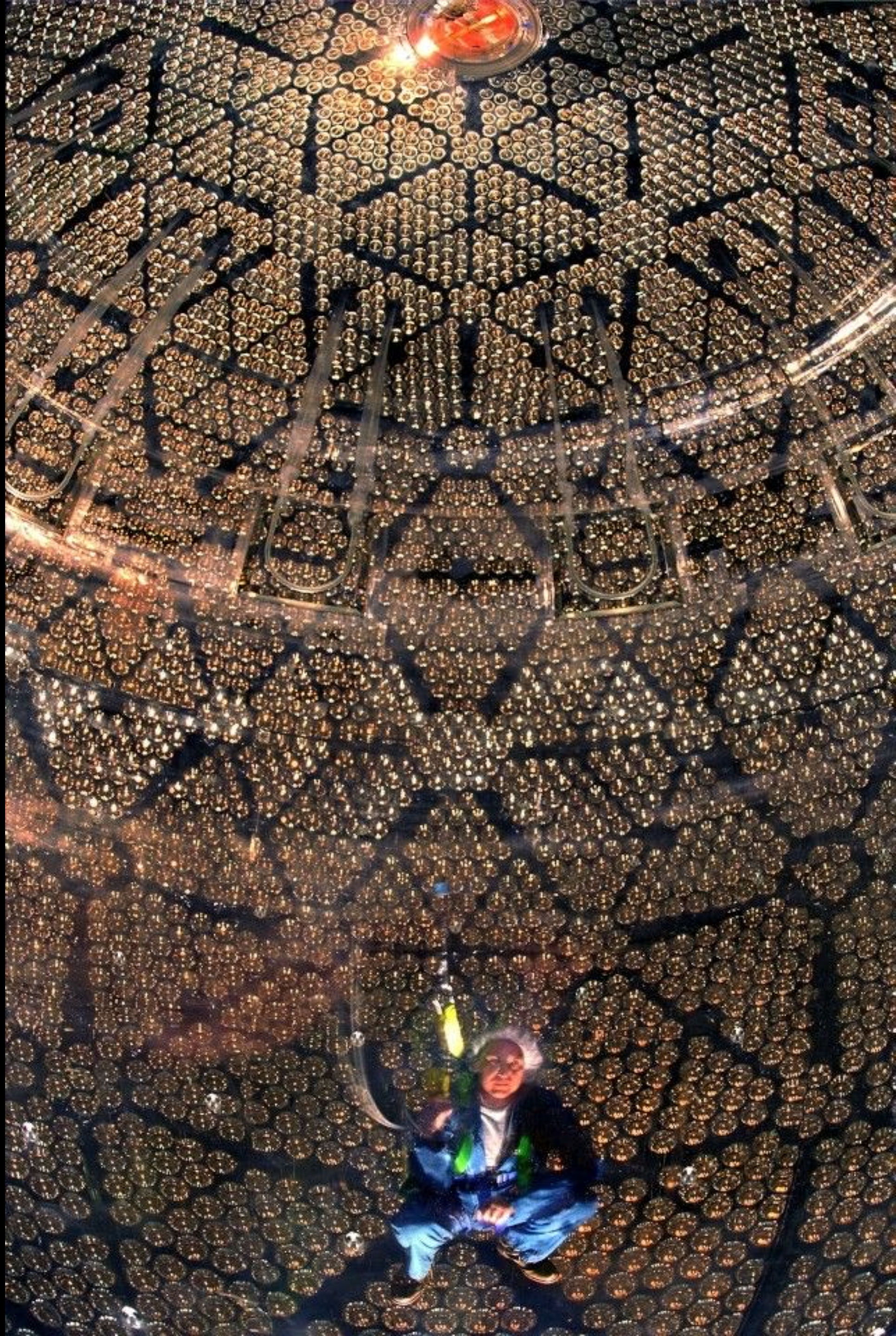


The PMTs – photomultiplier tubes

20 cm diameter

Have light concentrators around to increase detector efficiency



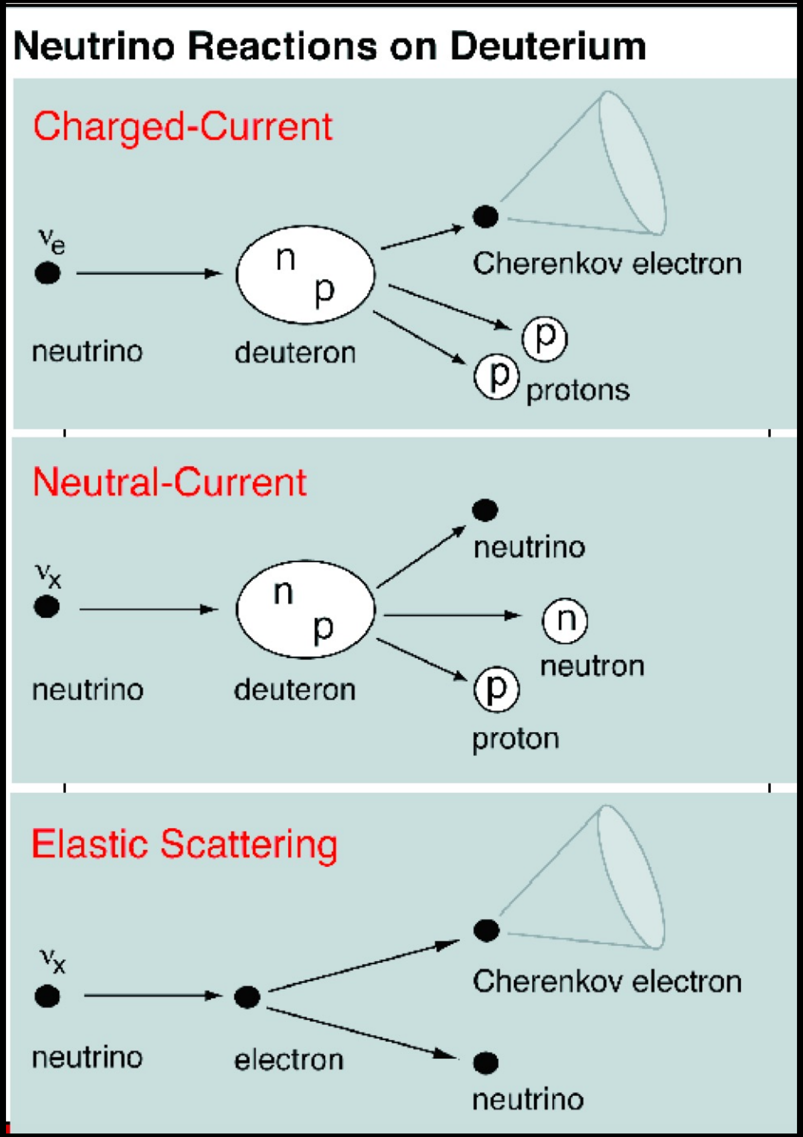


Neutrino Reactions in SNO

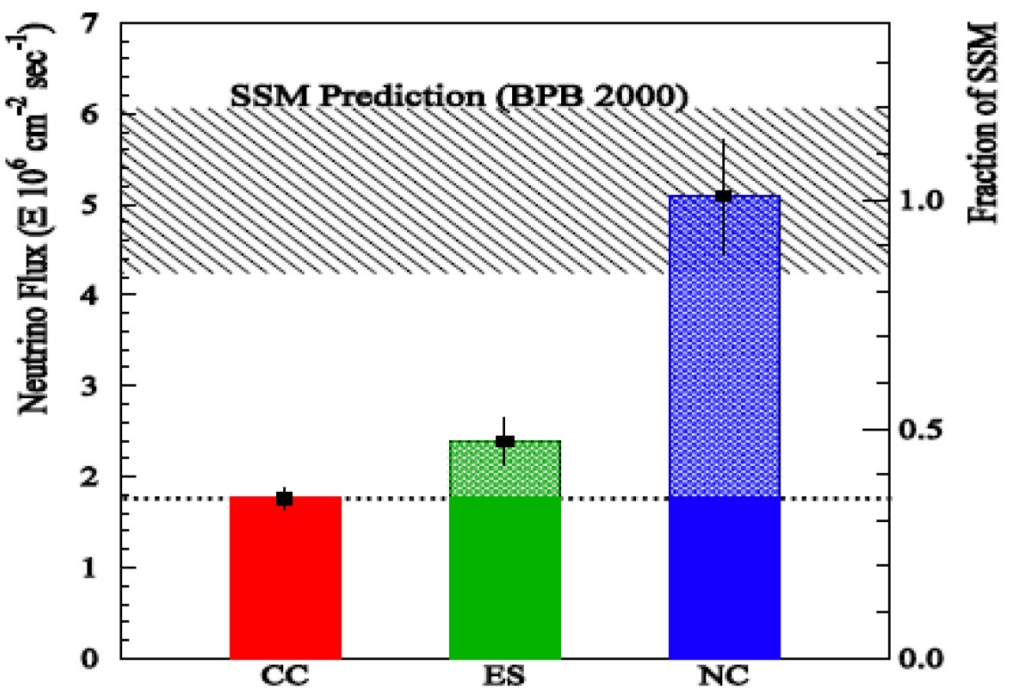
- $\nu_e + d \rightarrow p + p + e^-$
  - Signal: Cherenkov light from electron
  - Only sensitive to ν_e
  - Measured ν_e flux

- $\nu_l + d \rightarrow \nu_l + p + n$
  - 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

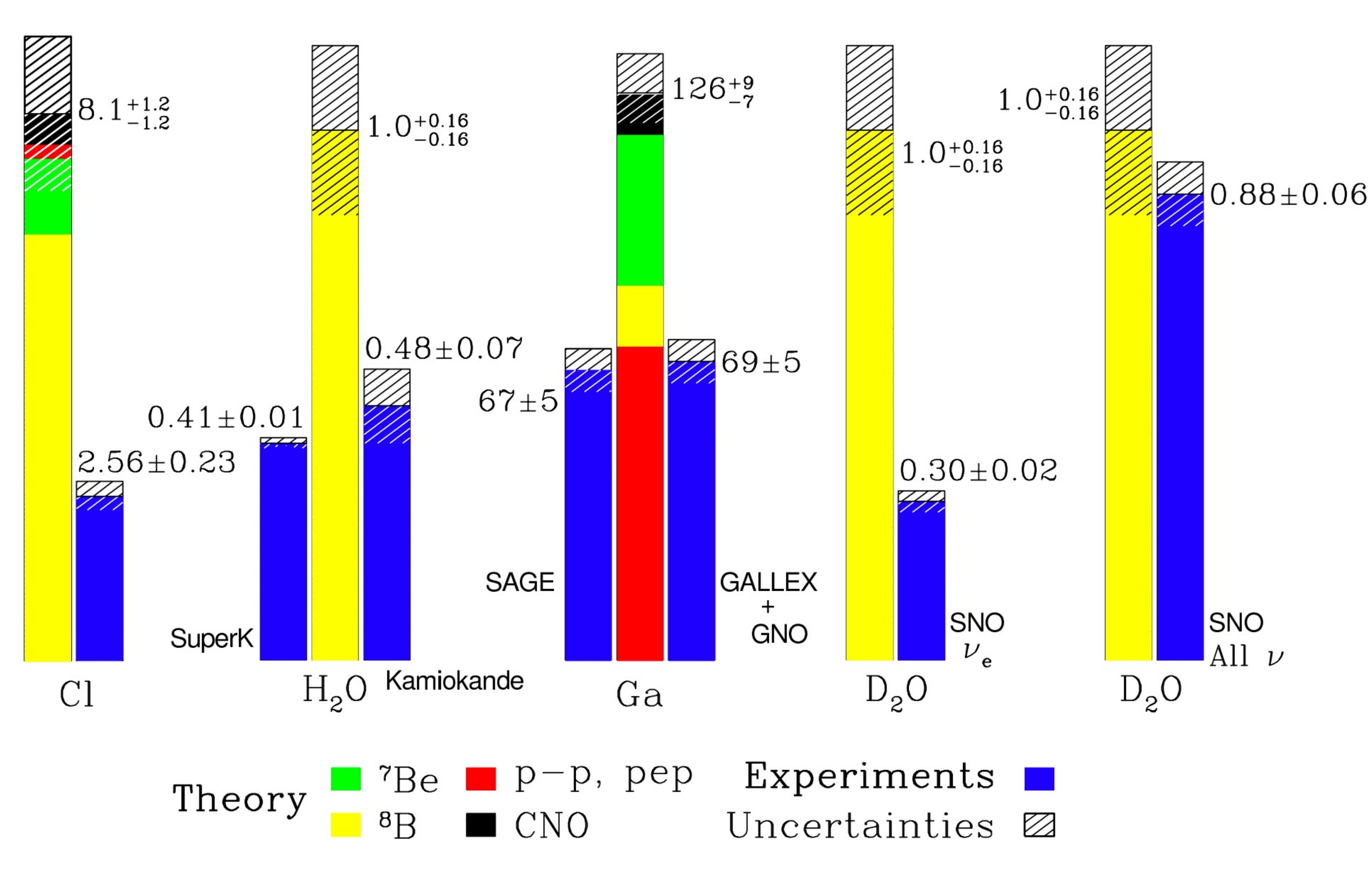


5.3 σ appearance of $\nu_{\mu\tau}$ in a ν_e beam

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…

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

$m_2^2-m_1^2$

But this proves that neutrinos have mass…

- What is the value of the mass?

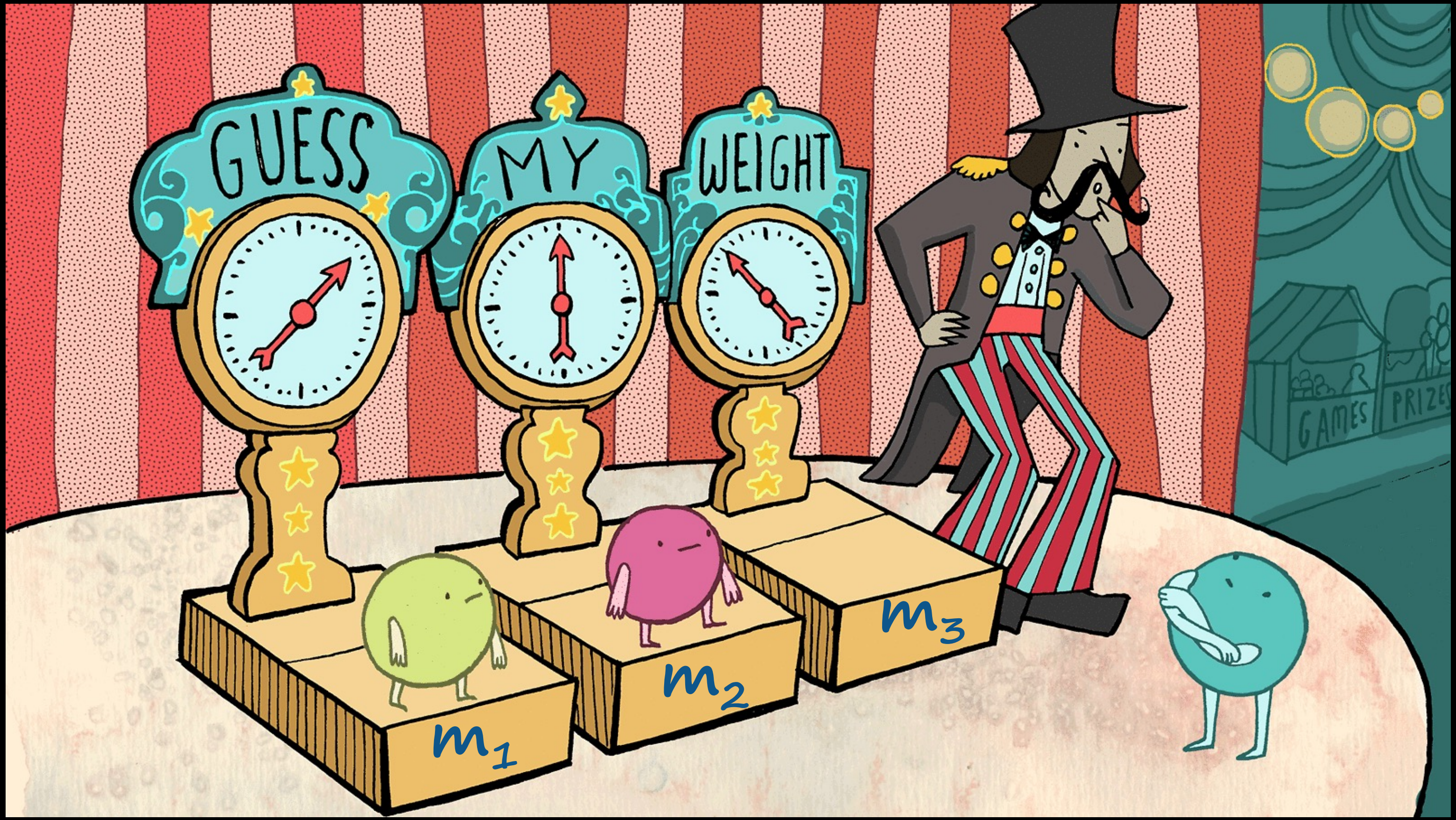
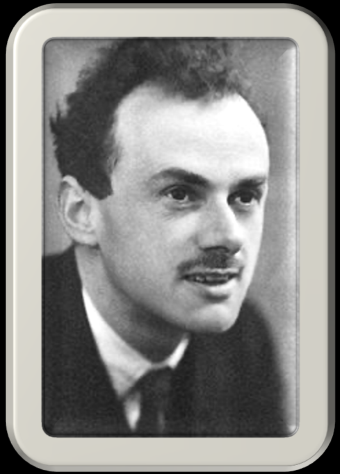


Image from Symmetry Magazine

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 Double Beta Decay

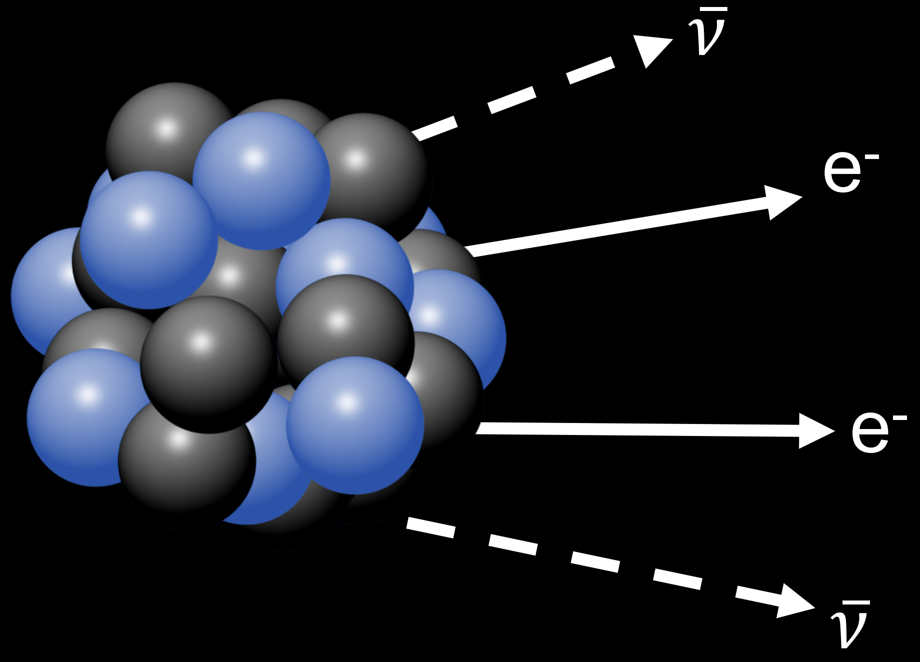
SNO+

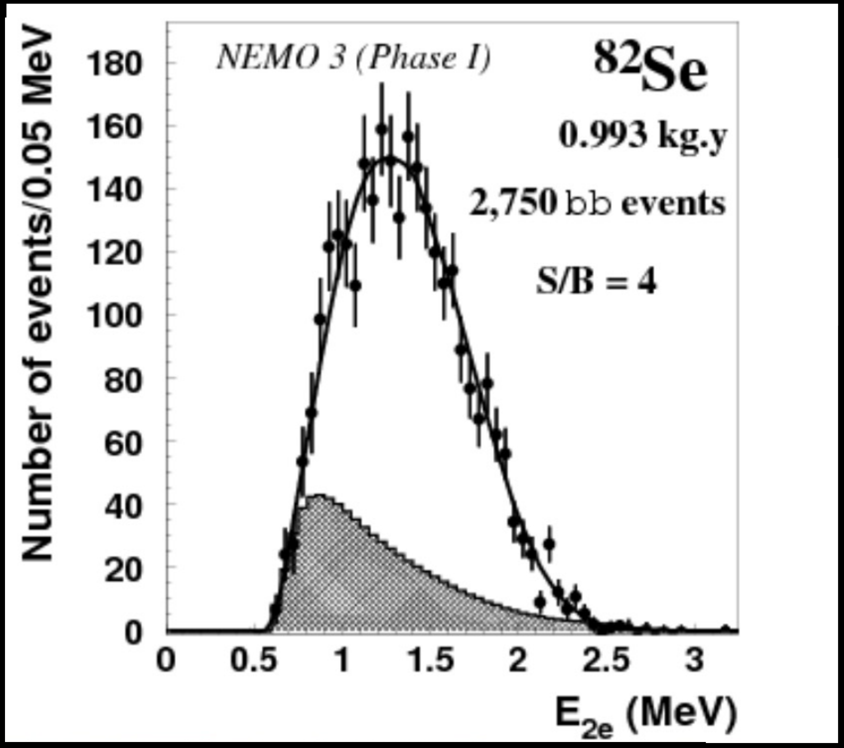
nEXO

Majorana/Legend

2ν Double Beta Decay

A rare nuclear decay through which some nuclei reach stability.

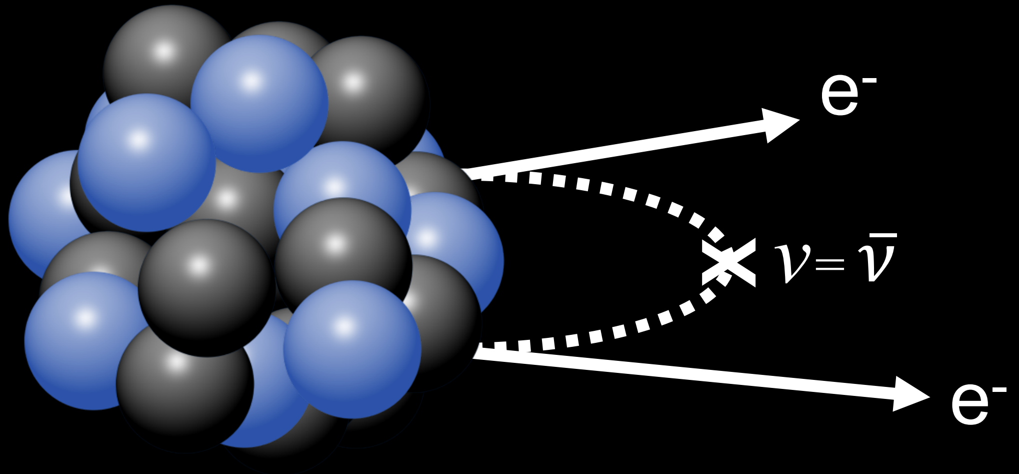


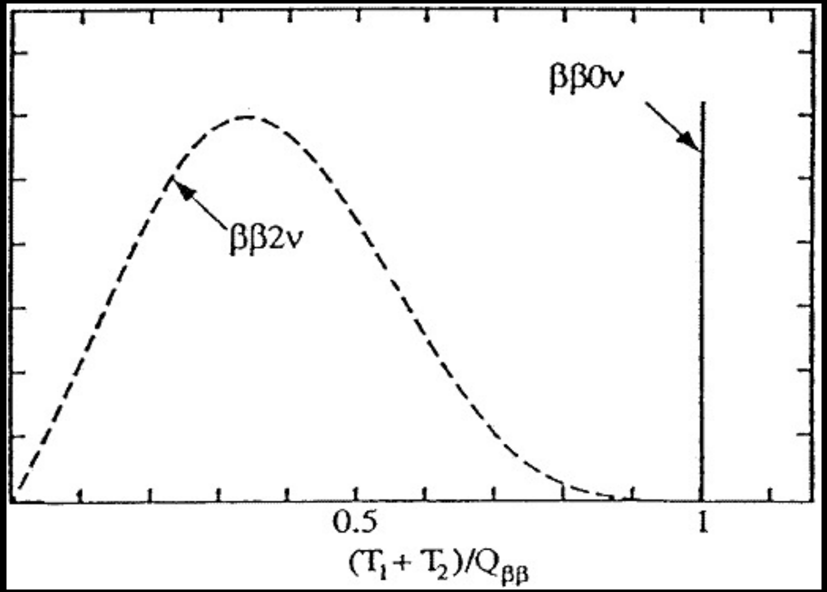


Detected Kinetic Energy of the Two Electrons/Q

- Possible when normal beta decay is not energetically allowed.
- Can happen for 35 natural isotopes.
  Observed in 11: ^{48}Ca, ^{76}Ge, ^{130}Te, ^{136}Xe...
- Long half-lives between 10^{19} and 10^{24} years.

0ν Double Beta Decay





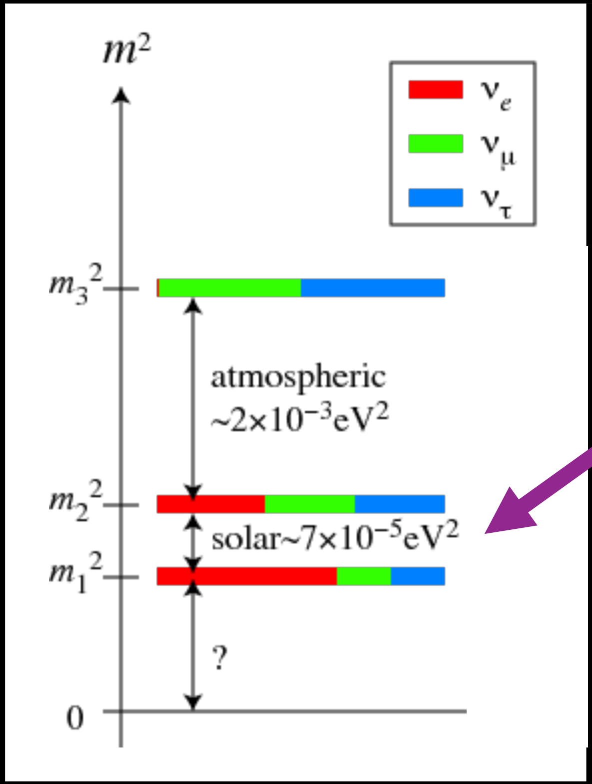
- Possible if neutrinos are Majorana particles (their own anti-particles).
- Violates lepton number conservation.
- Rate depends on the effective electron neutrino Majorana mass.

$$\left[T^{1/2}_{0\nu}\right]^{-1} = G_{0\nu}|\mathcal{M}_{0\nu}|^2\left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

$$m_{\beta\beta} = \left|\sum_{i=1,2,3} e^{i\xi_i}|U^2_{ei}|m_i\right|$$

But this proves that neutrinos have mass...

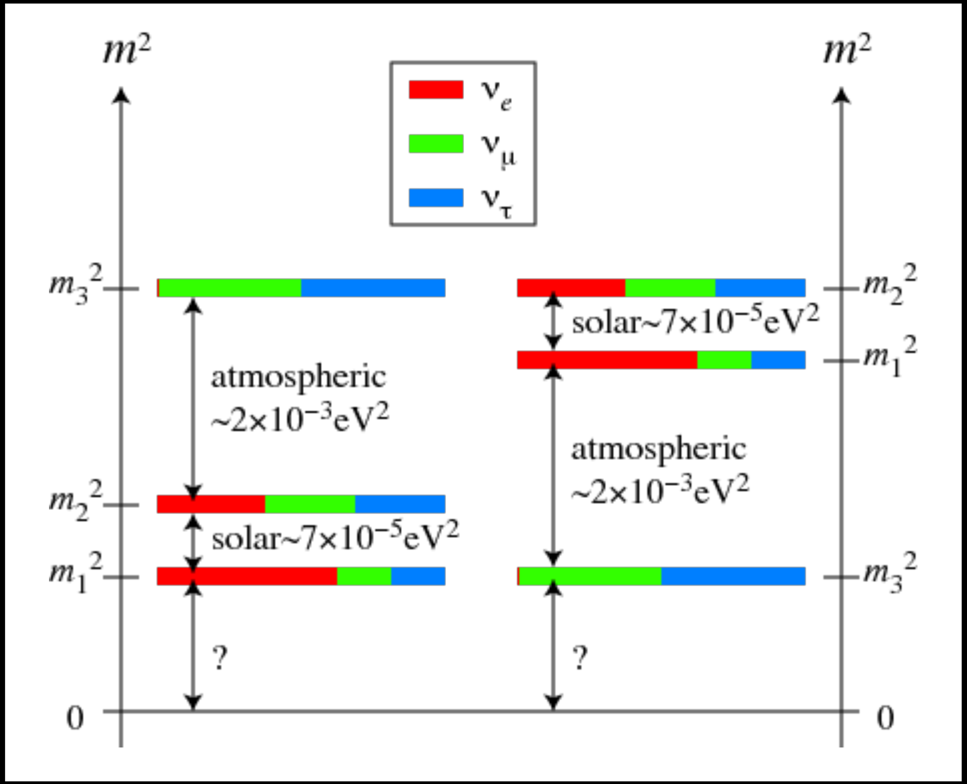
- How are the masses ordered?



Solar experiments have fixed the order between m_1 and m_2

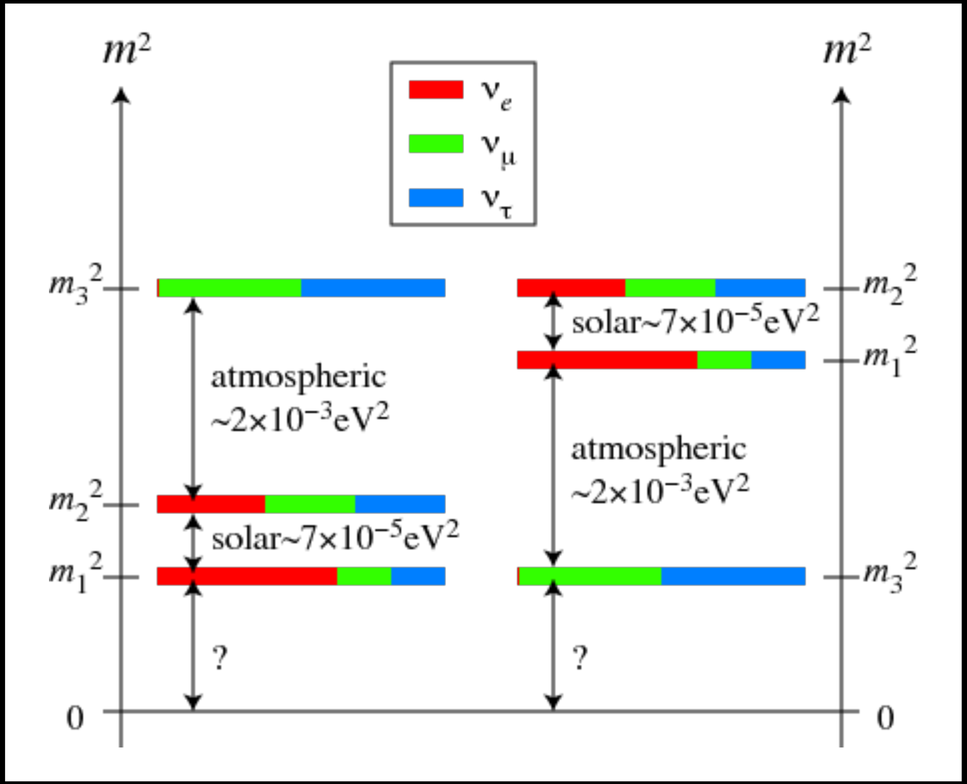
But this proves that neutrinos have mass...

- How are the masses ordered?



But this proves that neutrinos have mass…

- How are the masses ordered?

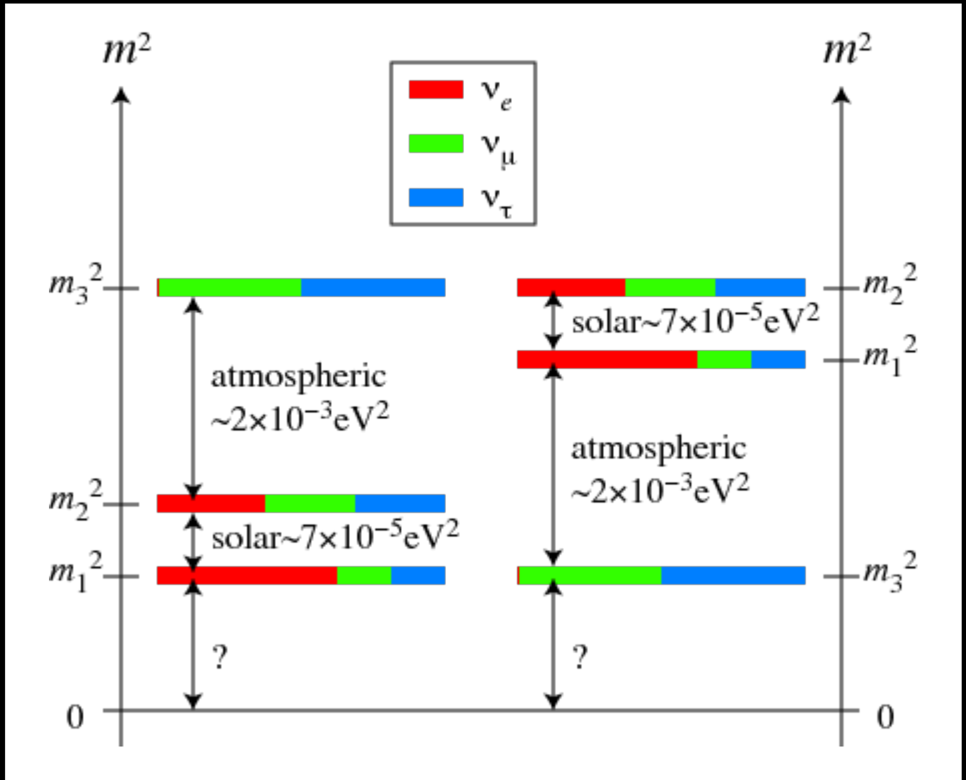


study of differences between neutrino and antineutrino oscillations

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

But this proves that neutrinos have mass...

- How are the masses ordered?



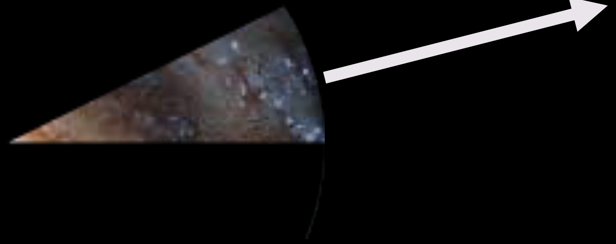
- Is there CP violation in the lepton sector?
- What are the precise values of the neutrino mixing parameters?

Hyper-Kamiokande

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

We have a lot of questions

- What is the Universe made of? In particular: What is dark matter?



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.

- Do protons have a finite life time?
- What are the properties of neutrinos? What is their role in cosmic evolution?
- What do neutrinos tell us about the interior of the Sun and the Earth, and about Supernova explosions?
- What is the origin of cosmic rays? What is the view of the sky at extreme energies?
- What can gravitational waves tell us about violent cosmic processes and about the nature of gravity?

Summary

Astroparticle physics is an exciting field!

There are a lot of puzzling questions that we need to answer!

You can be the one finding the answers in the future.

In the next lectures you will hear all about the cool experiments trying to solve the mysteries of the universe.

"The World is sailing beyond a new horizon in physics." –~~Cool quote I heard at the opening talk of a conference~~

Stolen from Ben, who heard it at a conference