Neutrinos

A new window to see the Universe

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Tata Institute of Fundamental Research, Mumbai

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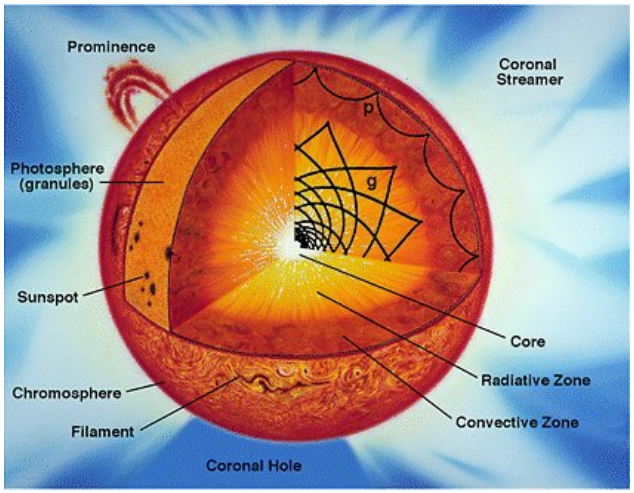
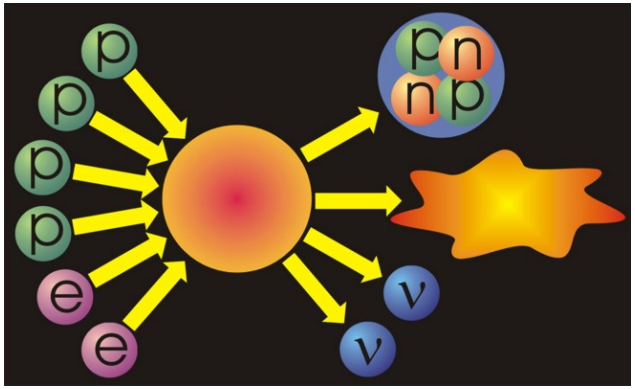
A new window to see the Universe

1. Neutrinos from the Sun
2. Neutrinos in astrophysics, cosmology, and particle physics
3. Neutrinos: the stuff mysteries are made of
4. Neutrinos as messengers from the Universe

A new window to see the Universe

How does the sun shine ?





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$$4\,{}^{1}_{1}\mathrm{H} + 2e^{-} \rightarrow {}^{4}_{2}\mathrm{He} + \mathrm{light}$$

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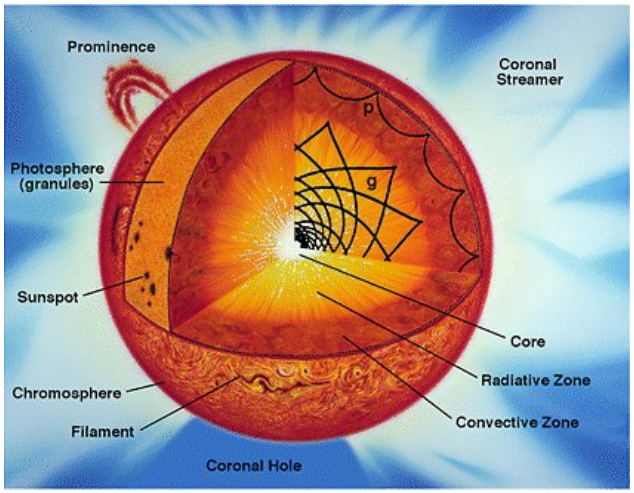

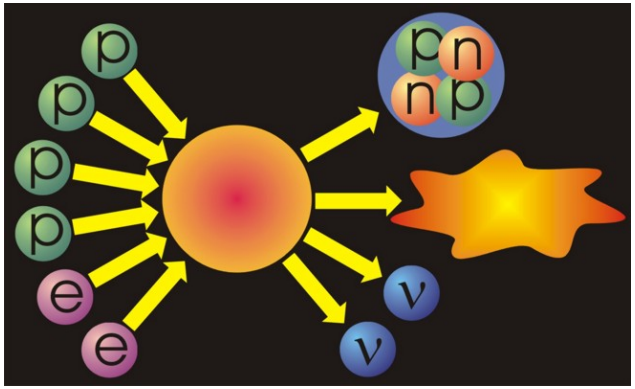

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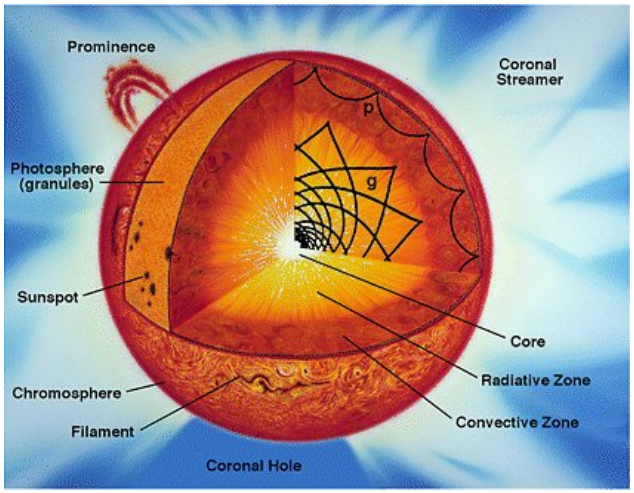

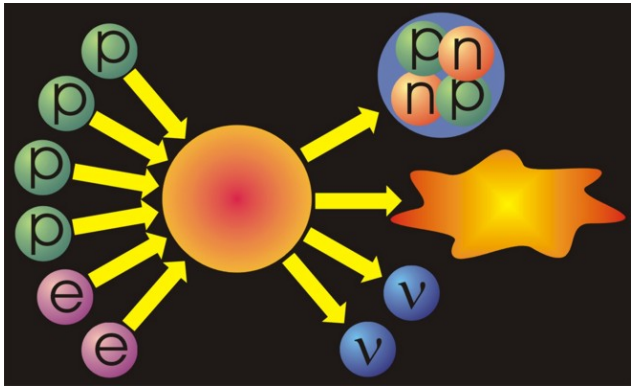

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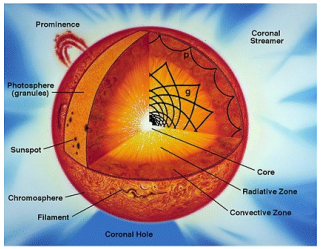
Neutrinos essential for the Sun to shine !!

Davis-Koshiba Nobel prize 2002

Neutrinos from the Sun: some interesting facts



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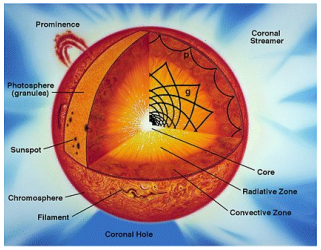

A very very large number of neutrinos

About hundred trillion through our body per second

Hundred trillion = 100 000 000 000 000

Why do we not notice them ?

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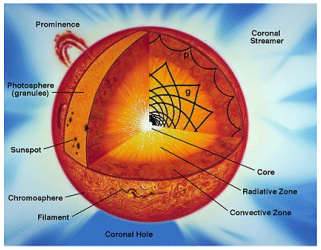

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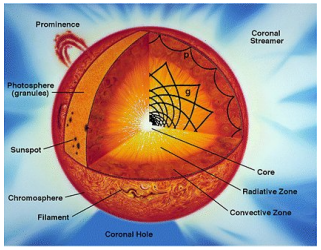

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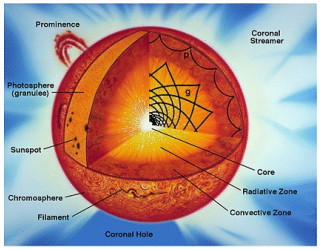

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What are the reasons for these confusing facts ?

Three questions, the same answer

- Why did the *roti* burn ?
- Why did the betel leaves *(paan)* rot ?
- Why could the horse not run ?

Three questions, the same answer

- Why did the *roti* burn ?
- Why did the betel leaves *(paan)* rot ?
- Why could the horse not run ?

Because they were not moved !

Three questions about neutrinos

Pauli Dirac

- Why do we not notice neutrinos passing through us?
- Why do neutrinos from the Sun reach us during night ?
- Why can we see “inside” the sun with neutrinos ?

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Because neutrinos interact extremely weakly !

The most weakly interacting particles

Stopping radiation with lead shielding

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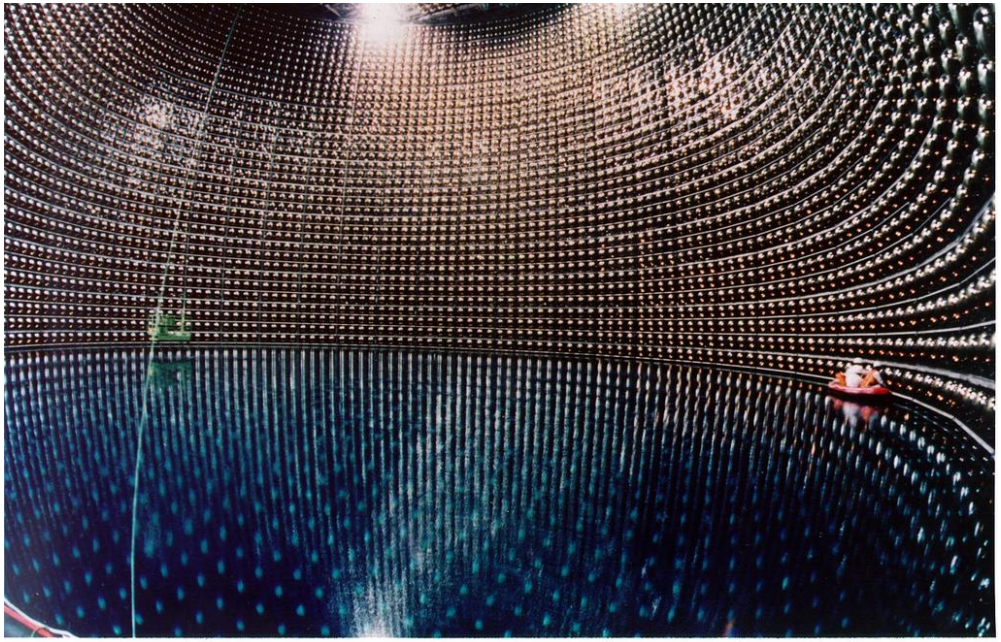
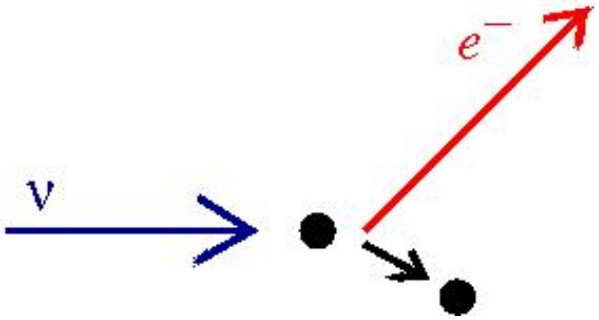
How do we see the neutrinos then ?

SuperKamiokande: 50 000 000 litres of water





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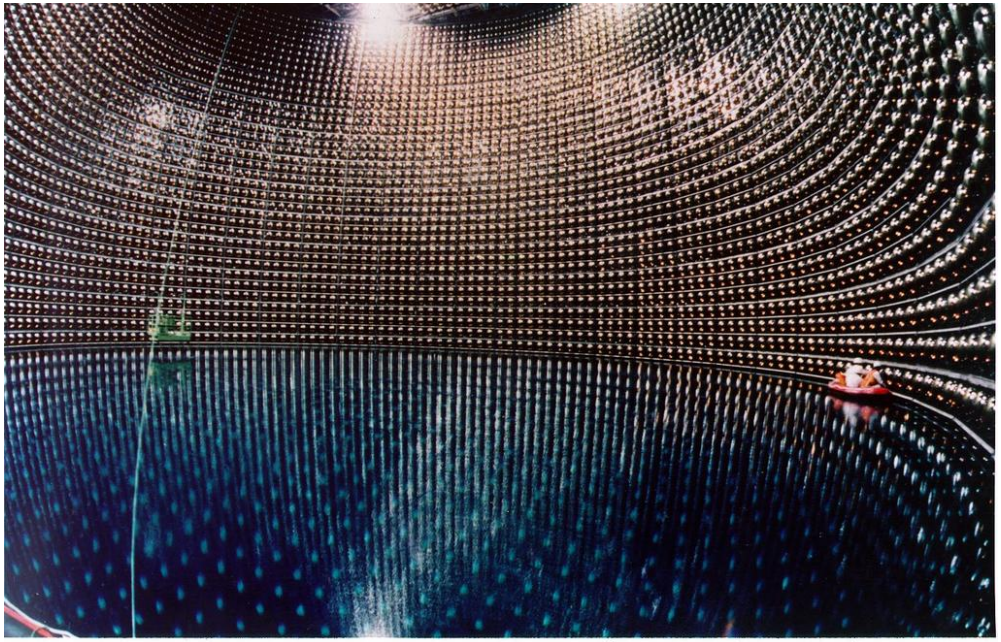

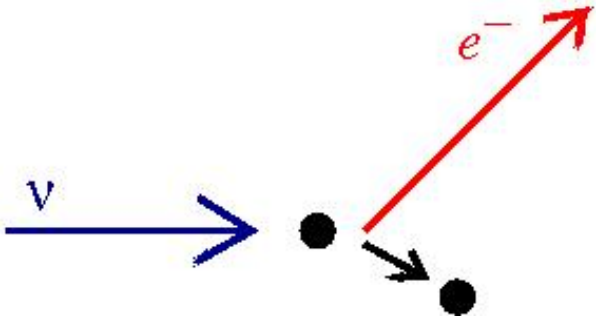

A very rare observation

- About 10^{25} neutrinos pass through SK every day.
- About 5–10 neutrinos interact in SK every day.

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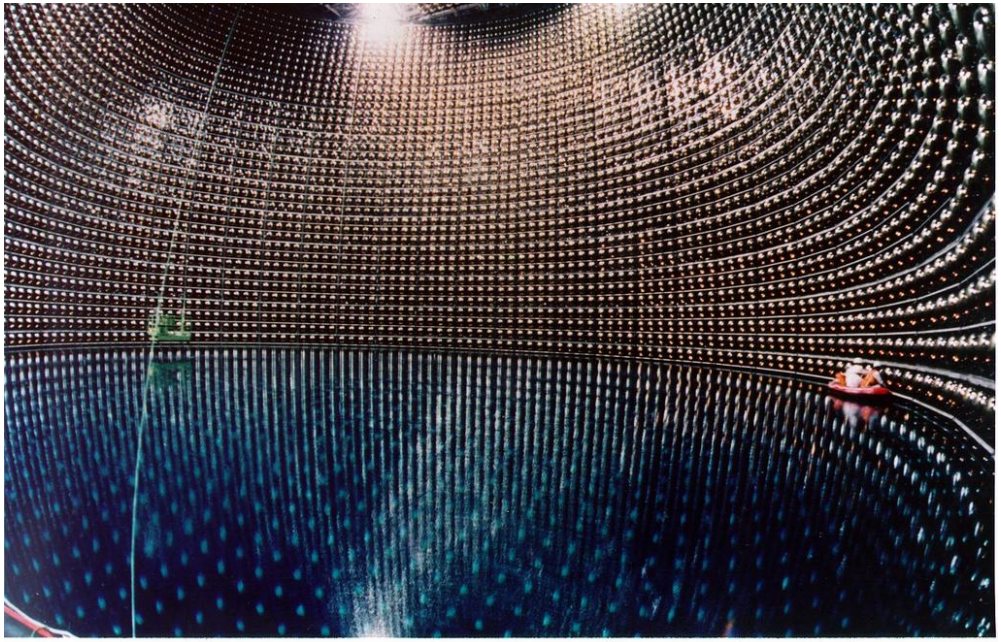

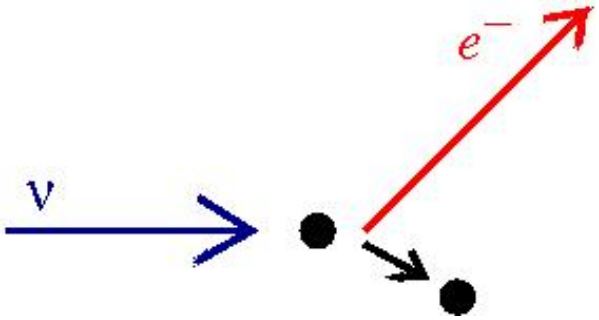

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Recipe for observing neutrinos

- Build very large detectors
- Wait for a very long time

A new window to see the Universe

A view from the Hubble telescope

The world without neutrinos

The world without neutrinos

Role of neutrinos in creating atoms

Neutrinos helped create the matter-antimatter asymmetry, without which, no atoms, no stars, no planets, no galaxies

Role of neutrinos in creating the Earth

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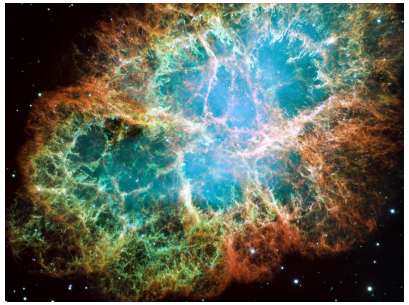
- A supernova must have exploded bilions of years ago whose fragments formed the solar system



Role of neutrinos in creating the Earth

- Elements heavier than oxygen can only be formed inside massive stars
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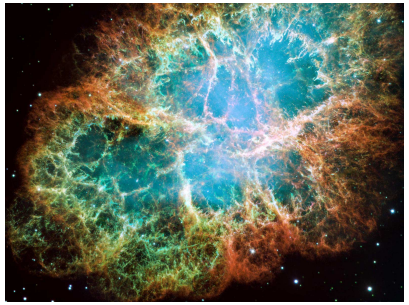
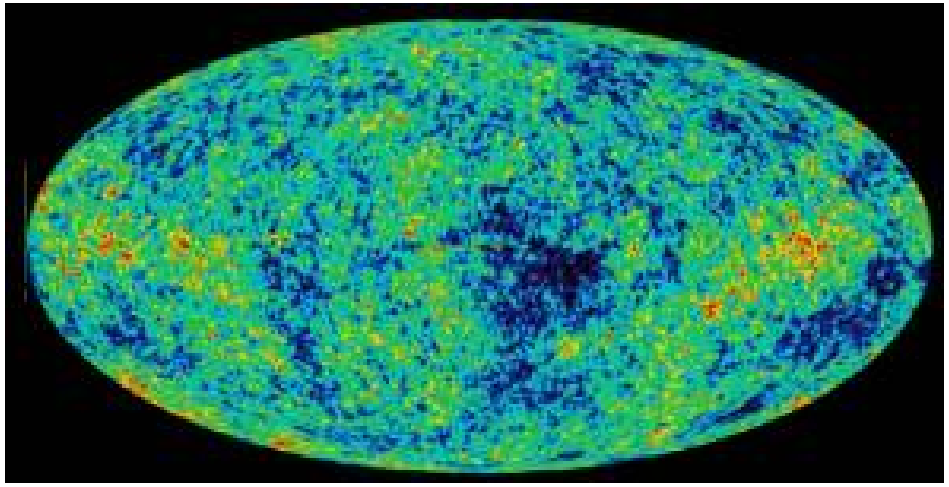


Supernovae explode because ...
neutrinos push the shock wave from inside !

The second-most abundant particles in the universe



- Cosmic microwave background: 400 photons/ cm^3
  Temperature: $\sim$ 3 K

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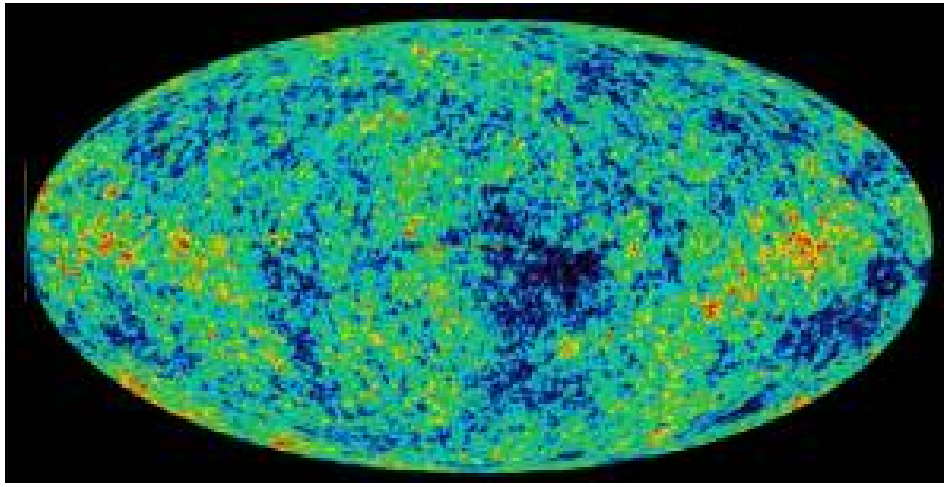


- Cosmic microwave background: 400 photons/ cm^3
  Temperature: $\sim$ 3 K
- Cosmic neutrino background: 300 neutrinos / cm^3
  Temperature: $\sim$ 2 K

Even empty space between galaxies is full of neutrinos !

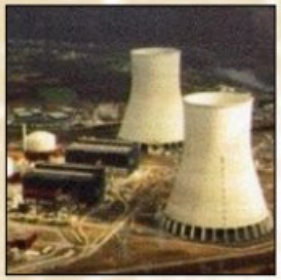
Neutrinos everywhere

Where do Neutrinos Appear in Nature?

✓ Earth Crust (Natural Radioactivity)

Sun ✓

✓ Nuclear Reactors

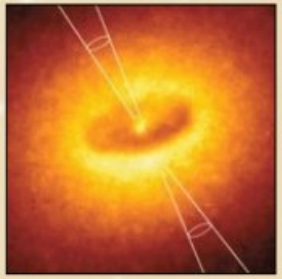


Supernovae (Stellar Collapse) SN 1987A ✓

✓ Particle Accelerators

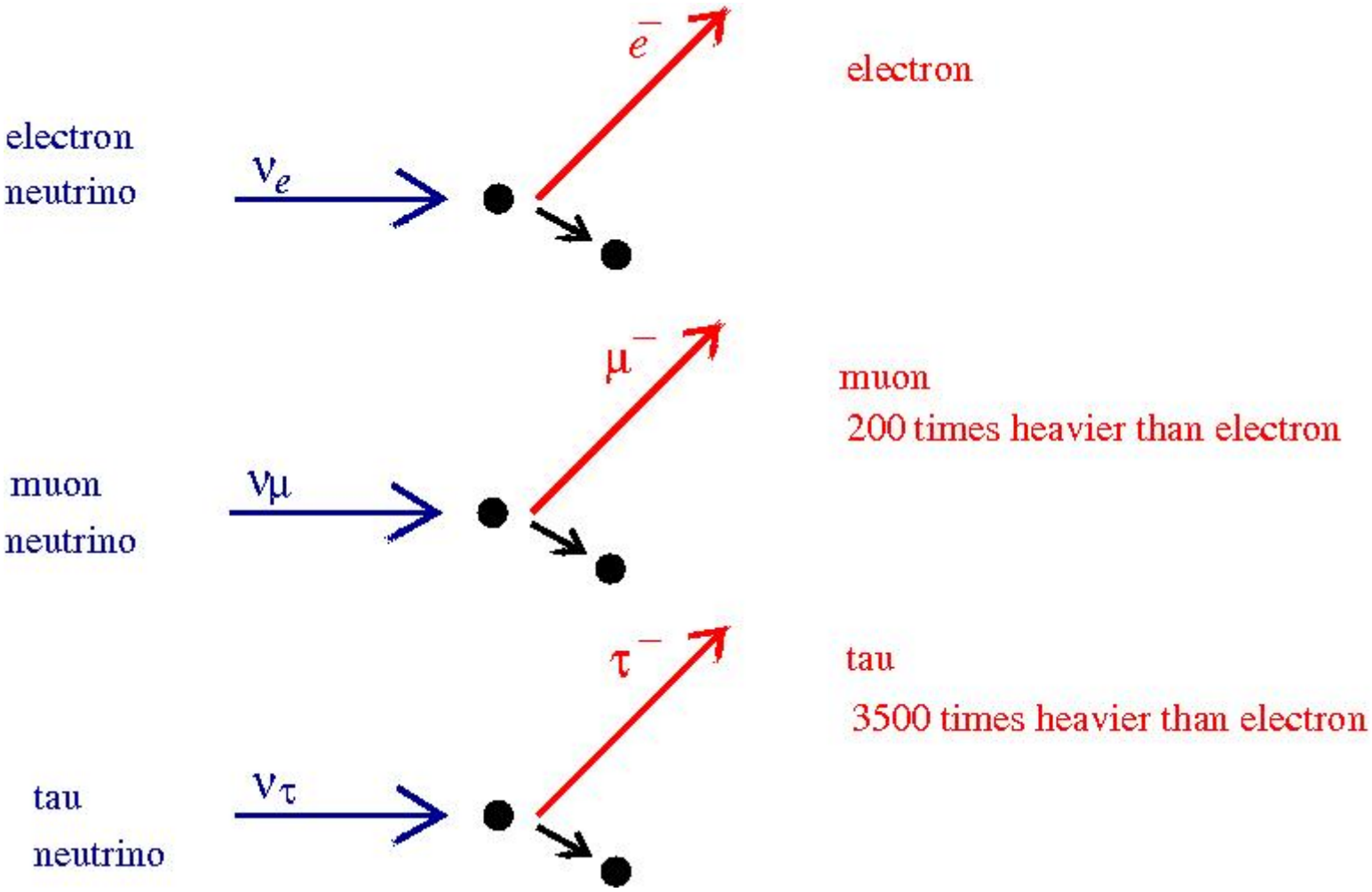
Cosmic Big Bang (Today 330 ν/cm^3) Indirect Evidence

✓ Earth Atmosphere (Cosmic Rays)



Astrophysical Accelerators Soon ?

Three kinds of neutrinos: ν_e ν_μ ν_τ



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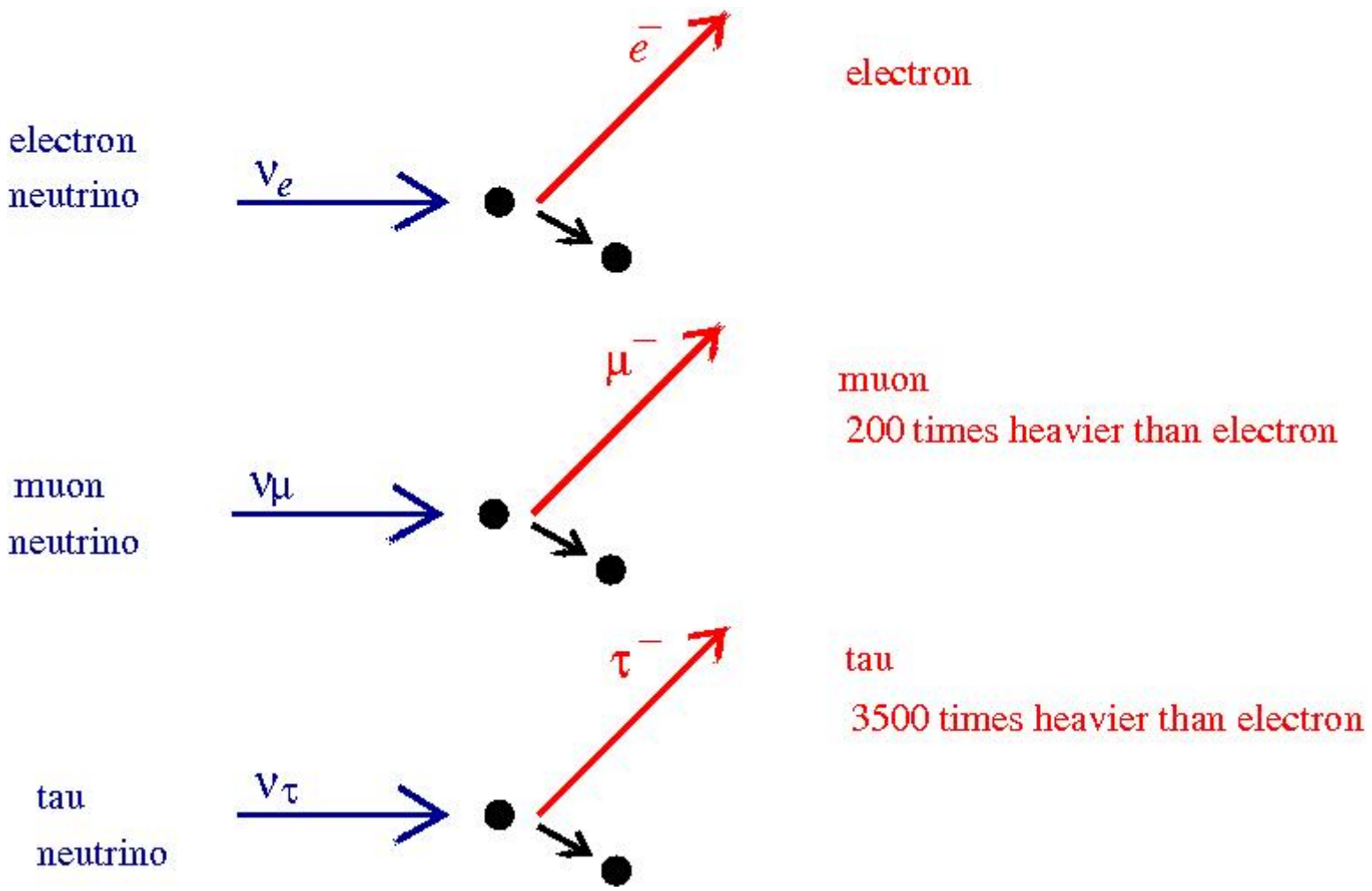
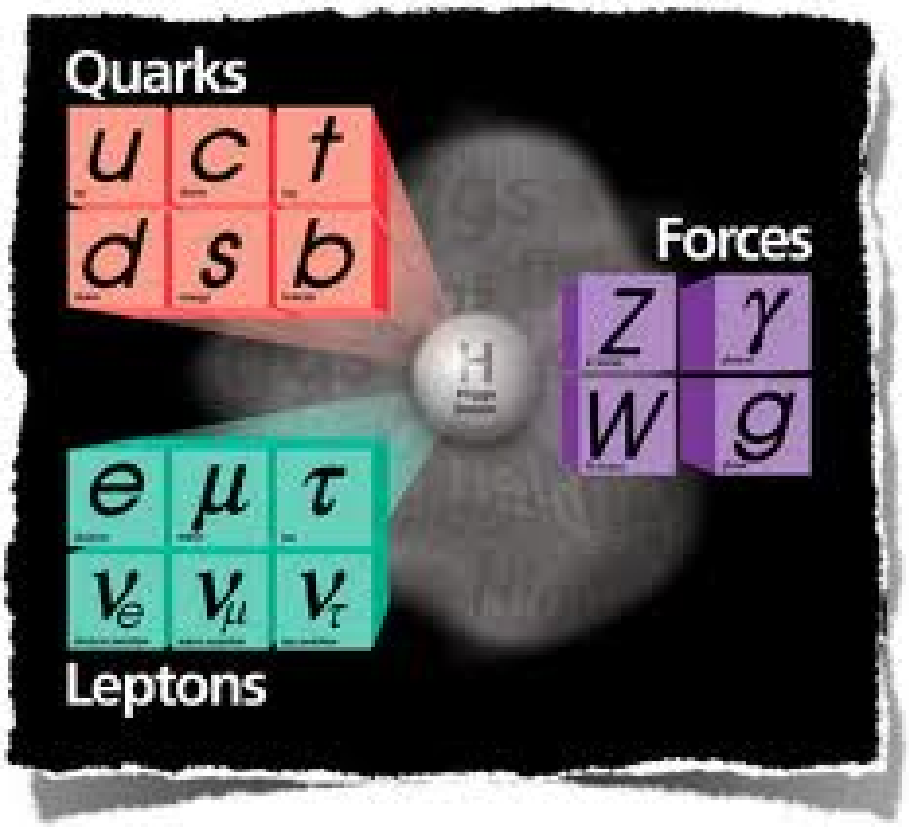


Antineutrinos $\overline{\nu}_e$, $\overline{\nu}_\mu$, $\overline{\nu}_\tau$ produce positively charged particles

The Standard Model of Particle Physics

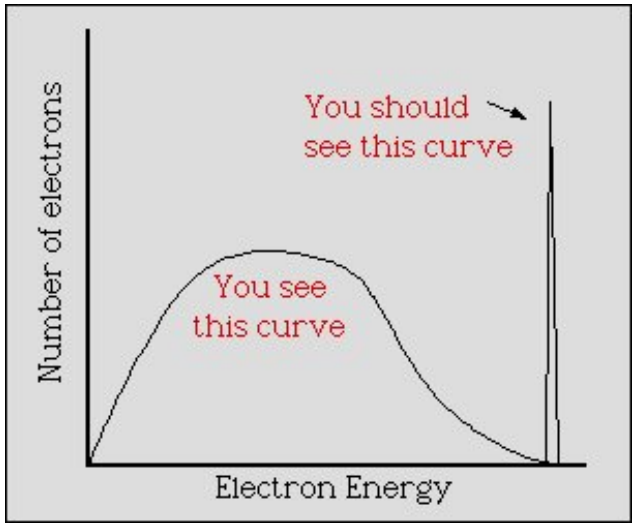


- 3 neutrinos: ν_e, ν_μ, ν_τ
- chargeless
- spin 1/2
- almost massless (at least a million times lighter than electrons)
- only weak interactions

A new window to see the Universe

The beta decay mystery: 1932

- Nuclear beta decay: $X \rightarrow Y + e^-$
- Conservation of energy and momentum $\Rightarrow$ Electrons have a fixed energy.
- But:



- Energy-momentum conservation in grave danger !!

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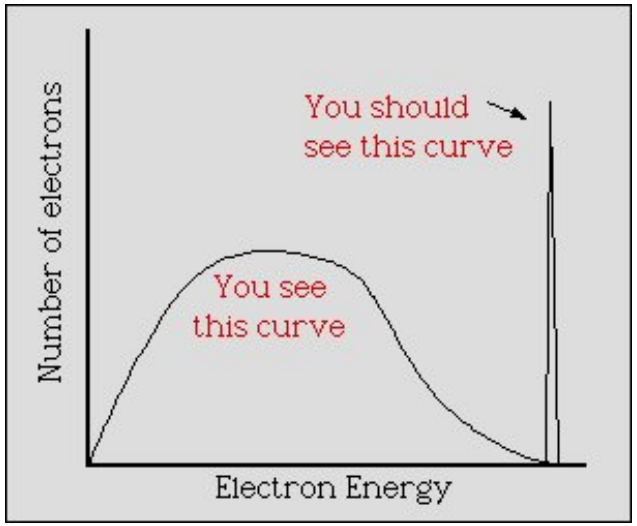


- Energy-momentum conservation in grave danger !!

A reluctant solution (Pauli): postulate a new particle

Does this new particle really exist ?

"But don't you see, **Wolfgang** *- if the particle is too* **weakly interacting** *to detect, we can't just take it on faith that you've discovered it."*

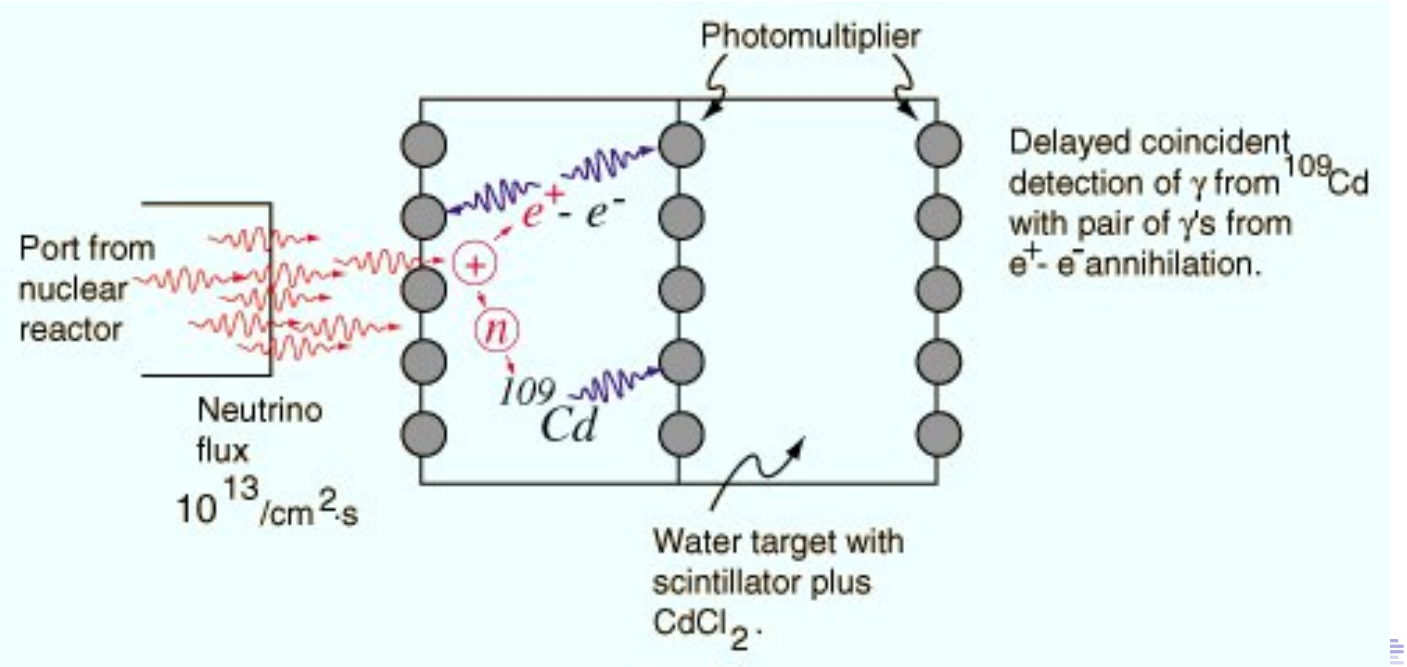
http://www.sciencecartoonsplus.com/pages/gallery.php

Discovery of electron neutrino: 1956

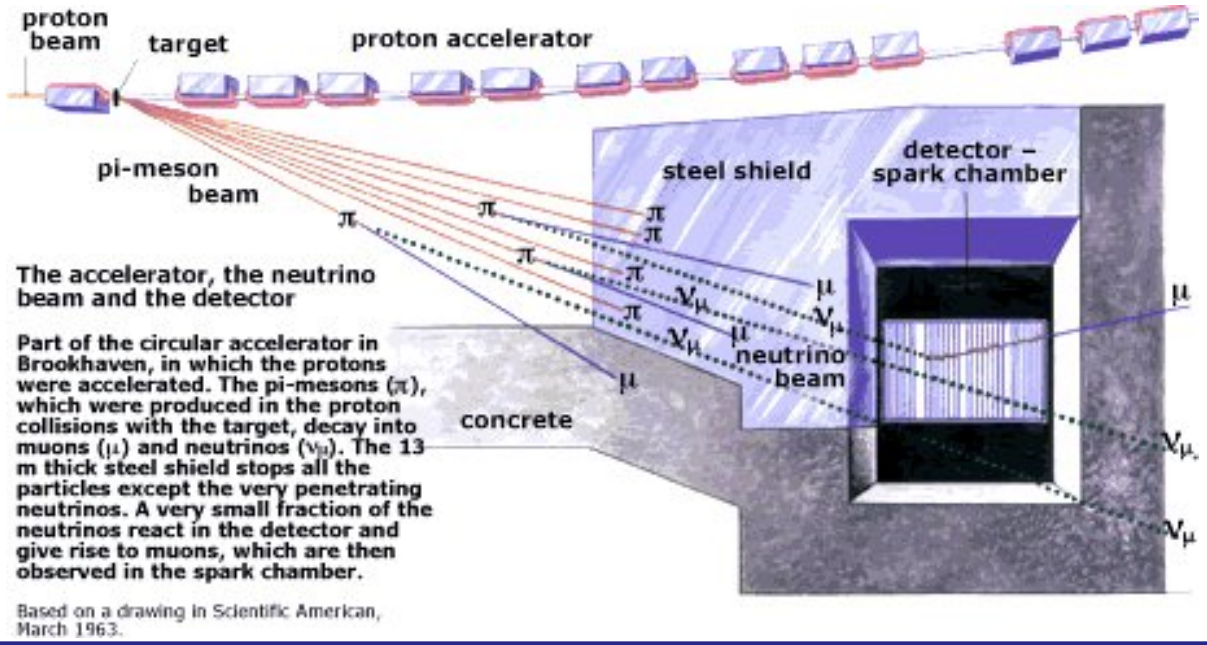
The million-dollar particle

- Reactor neutrinos: $\bar{\nu}_e + p \rightarrow n + e^+$
- $e^+ + e^- \rightarrow \gamma + \gamma$ (0.5 MeV each)
- $n + {}^{108}\mathrm{Cd} \rightarrow {}^{109}\mathrm{Cd}^* \rightarrow {}^{109}\mathrm{Cd} + \gamma$ (delayed)

Reines-Cowan: Nobel prize 1995



The “Who ordered muon neutrino ?” mystery: 1962



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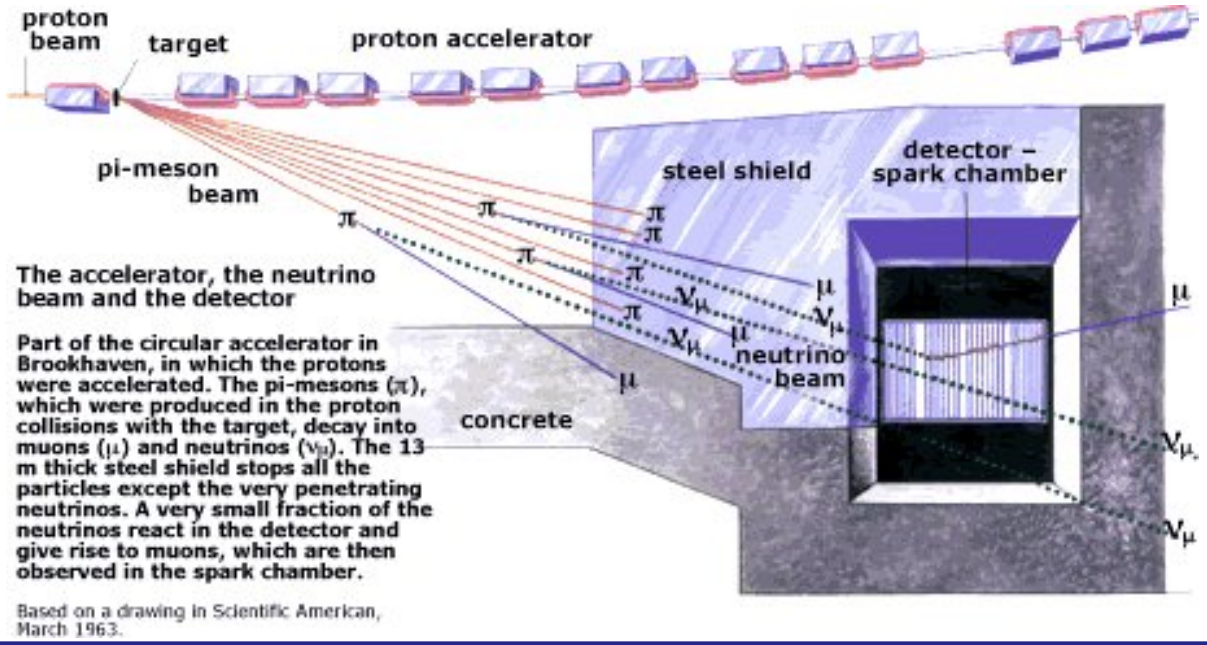

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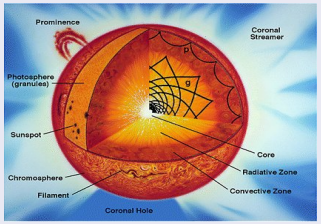
- Observed: always a muon, never an electron/positron
- This must be a new neutrino, not $\bar{\nu}_e$, but $\bar{\nu}_\mu$



Steinberger-Schwartz-Lederman Nobel 1988

The long-term mysteries ⇒ neutrino oscillations

Solar neutrino mystery: 1960s – 2002



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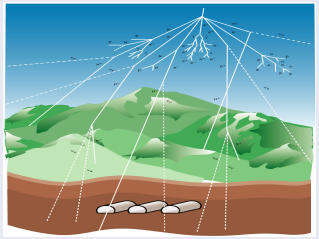
Atmospheric neutrino mystery: 1980s – 1998



- Half the ν_μ lost in the Earth!

Reactor neutrino experiments: 2012 +

- About 10% of reactor $\bar{\nu}_e$ are lost !

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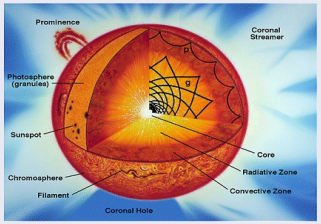

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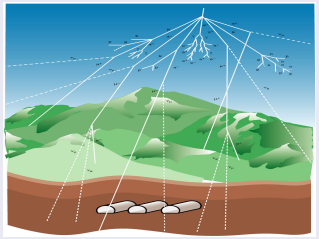

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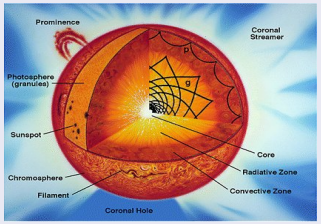

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- Nobel Prize 2015 (McDonald) 

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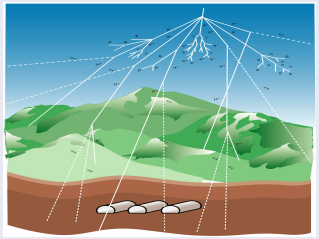

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Three questions, the same answer

ν conference participants

- Why did half the ν_e from the sun become ν_μ/ν_τ ?
- Why did half the ν_μ from the atmosphere become ν_τ ?
- Why did 10% $\bar{\nu}_e$ from the reactors become $\bar{\nu}_\mu/\bar{\nu}_\tau$?

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Because neutrinos have different masses and they mix !

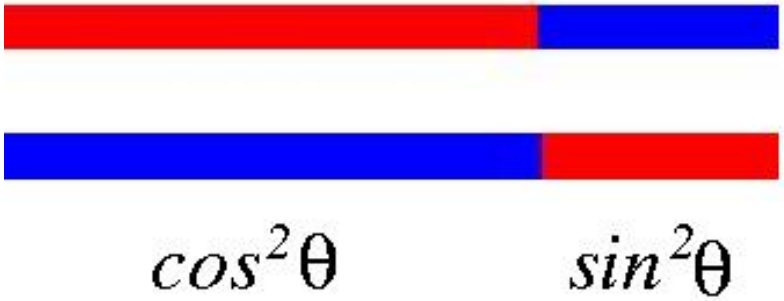
$\Uparrow$

Quantum Mechanics

What is meant by neutrino mixing ?

Neutrino flavours ν_e, ν_μ, ν_τ do not have fixed masses !!

For example, ν_e–ν_μ mixing:



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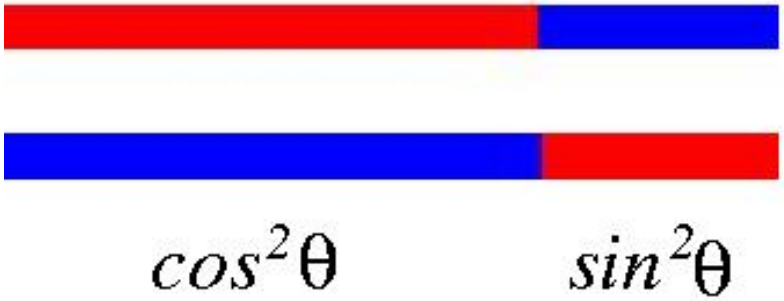

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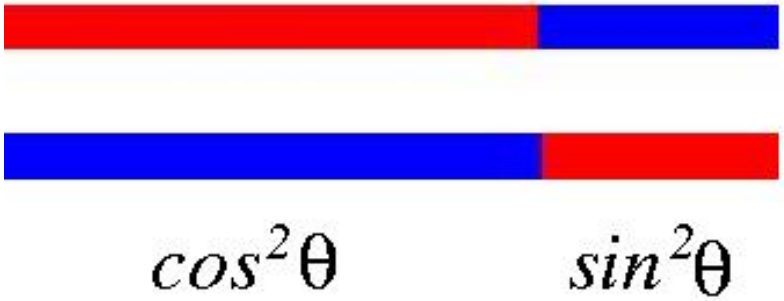

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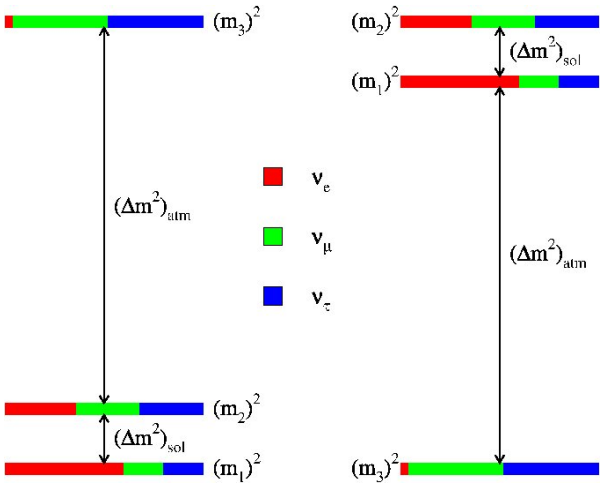
- **This is quantum mechanics at large length scales !**

Still open mysteries about neutrino masses

Mixing of ν_e, ν_μ, $\nu_\tau \Rightarrow \nu_1, \nu_2, \nu_3$ (mass eigenstates)



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- $\theta_{\text{atm}} \approx 45^\circ$
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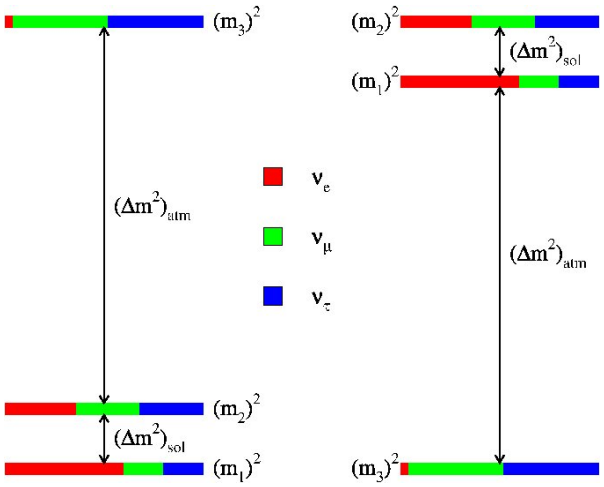

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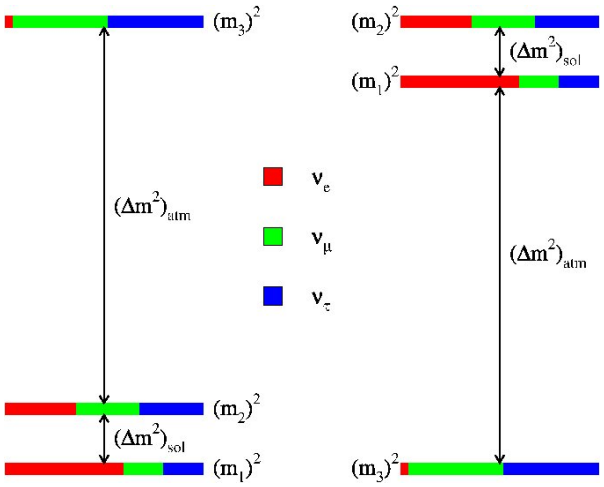

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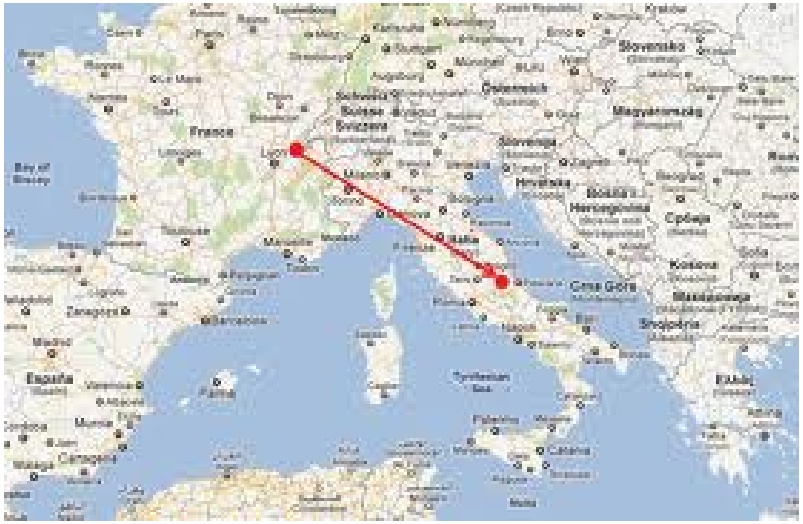
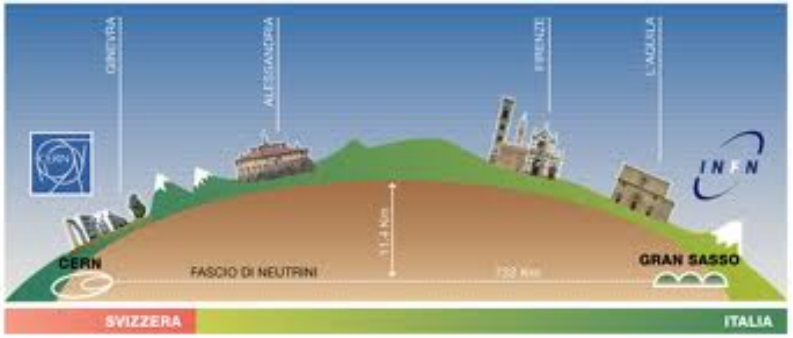
- How do neutrinos get their mass ?

A short-lived mystery (2011-12)





Superluminal neutrinos ?

The neutrinos do not travel faster than light

$\Uparrow$

Relativity

A new window to see the Universe

Looking at the sky in neutrinos

Neutrinos as good messengers

- No bending in magnetic fields $\Rightarrow$ point back to the source
- Minimal obstruction / scattering $\Rightarrow$ can arrive directly from regions from where light cannot come

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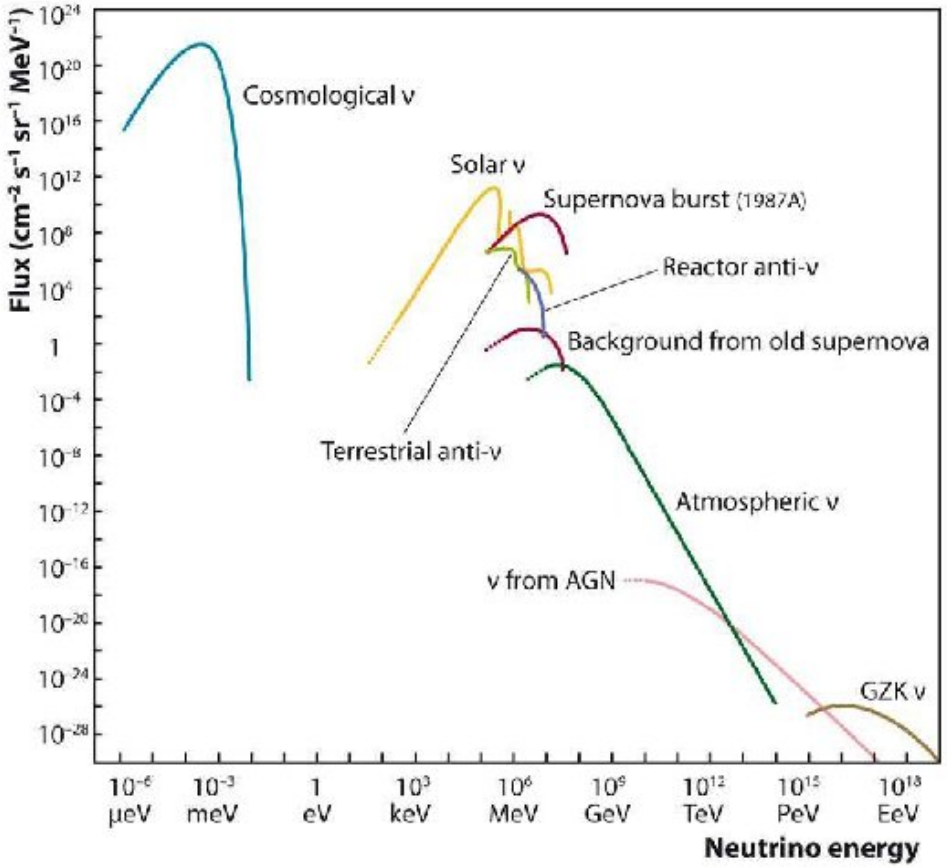
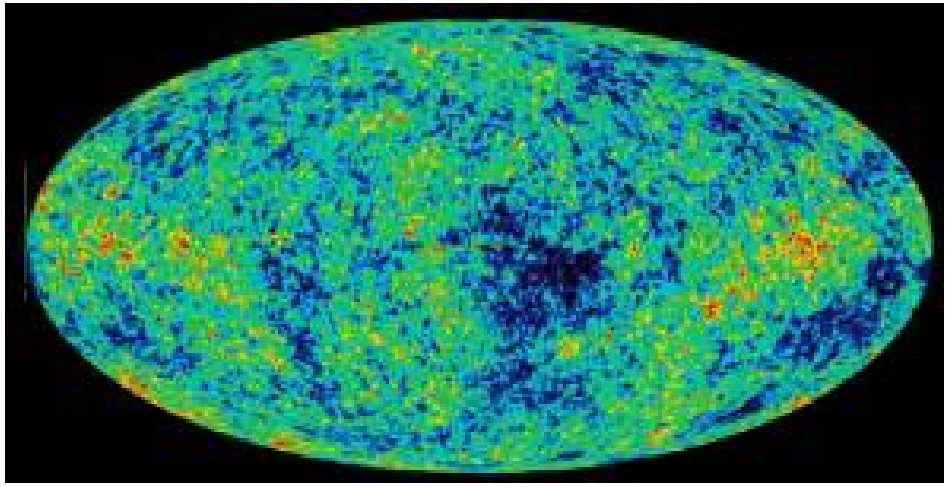


ASPERA

Cosmological neutrinos (big-bang relics $\sim$ 0.1 meV)

Empty space between galaxies is full of light and neutrinos



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  Temperature: $\sim$ 3 K
- Tell us about the universe when it was *only* 400,000 years old (Now it is $\sim$ 14 000 000 000 years old.)

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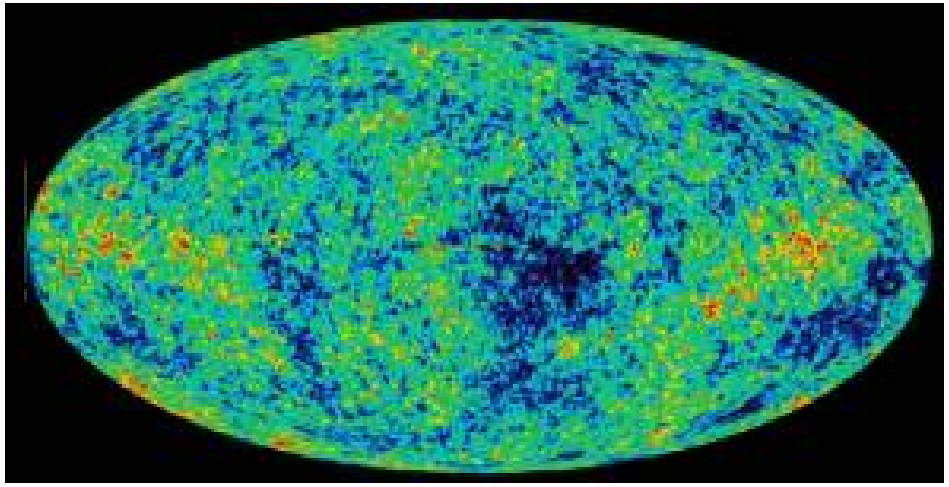

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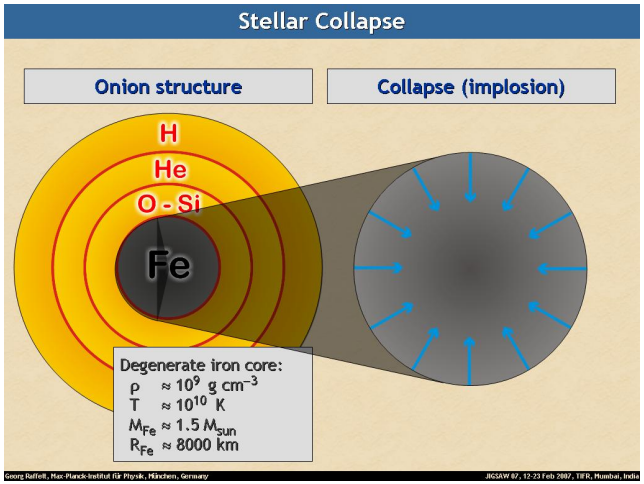
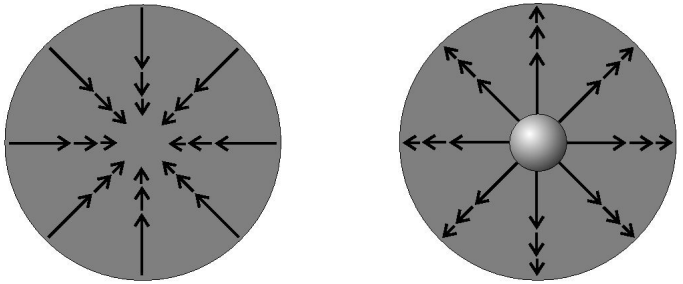
- Cosmic neutrino background: 300 neutrinos / cm^3
  Temperature: $\sim$ 2 K
- Can tell us about the universe when it was $\sim$ 0.2 sec old !

Supernova: the death of a star

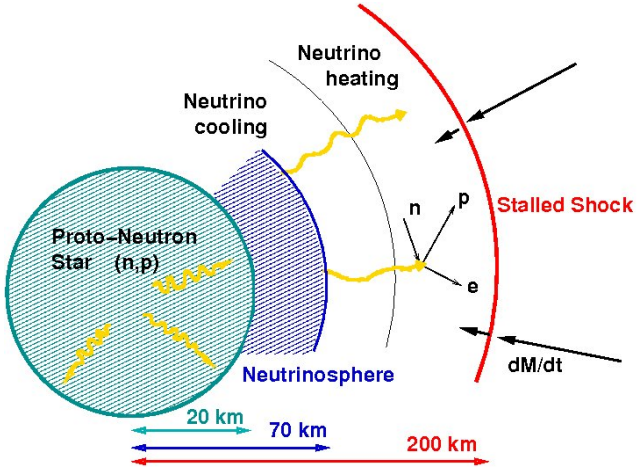
Gravity ⇒



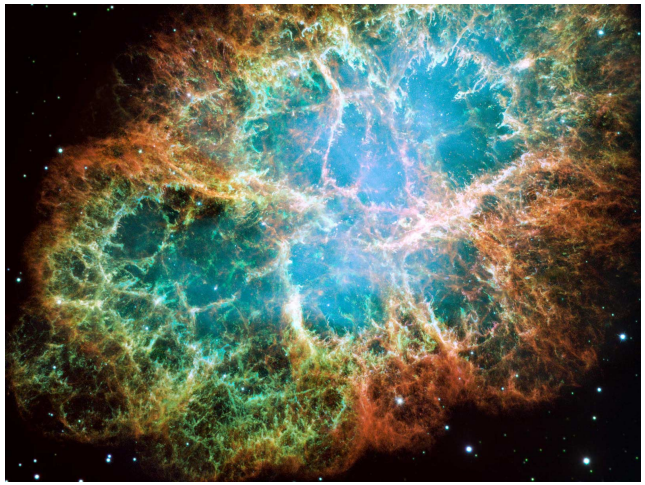
Strong nuclear force ⇒



Weak nuclear force (Neutrino push) ⇒

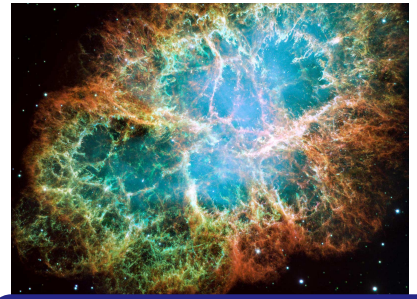


Electromagnetism (Hydrodynamics) ⇒



(Crab nebula, SN seen in 1054)

Neutrinos from a galactic supernova ($\sim$ 10 MeV)



10^{58} neutrinos emitted within the first 10 seconds !

On neutrino masses and mixing

- Instant identification of neutrino mass ordering (N or I), through
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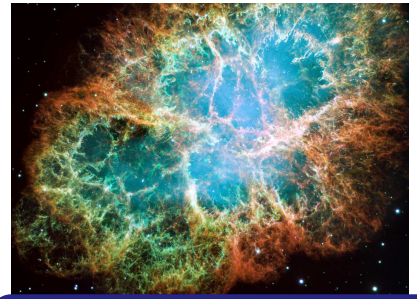

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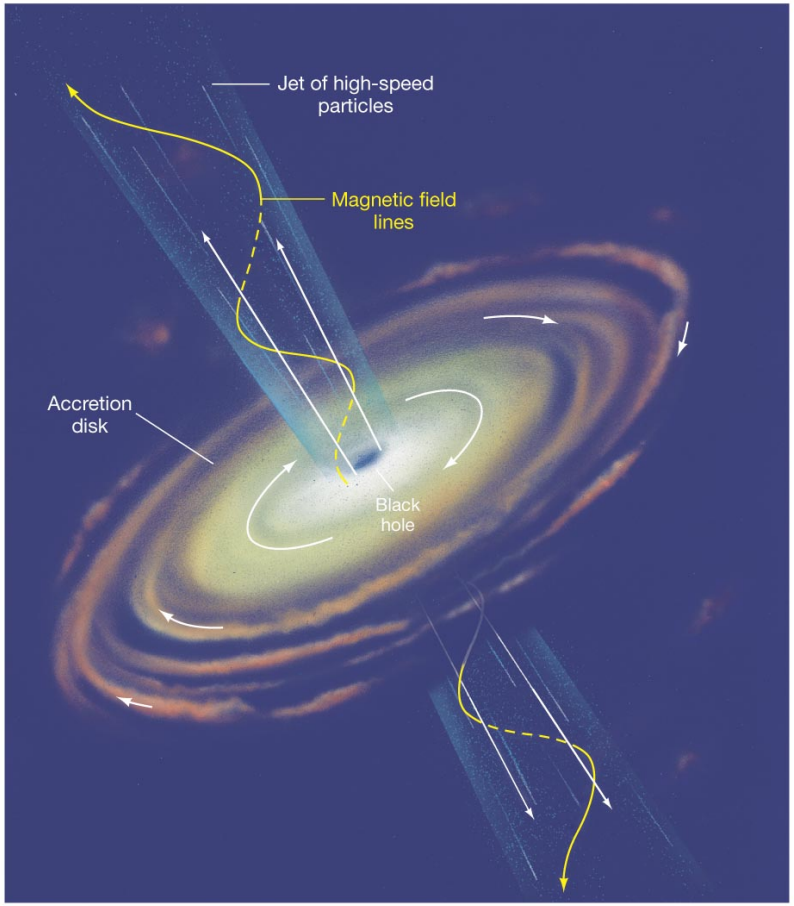
On supernova astrophysics

- Locate a supernova hours before the light arrives
- Track the shock wave through neutrinos while it is still inside the mantle (Not possible with light)
- Possible identification of QCD phase transition, SASI (Standing Accetion Shock) instabilities
- Hints on heavy element nucleosynthesis (r-process)

Active Galactic Nuclei (AGNs)



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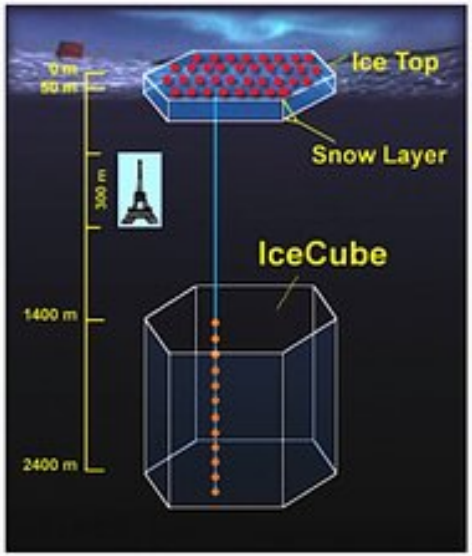
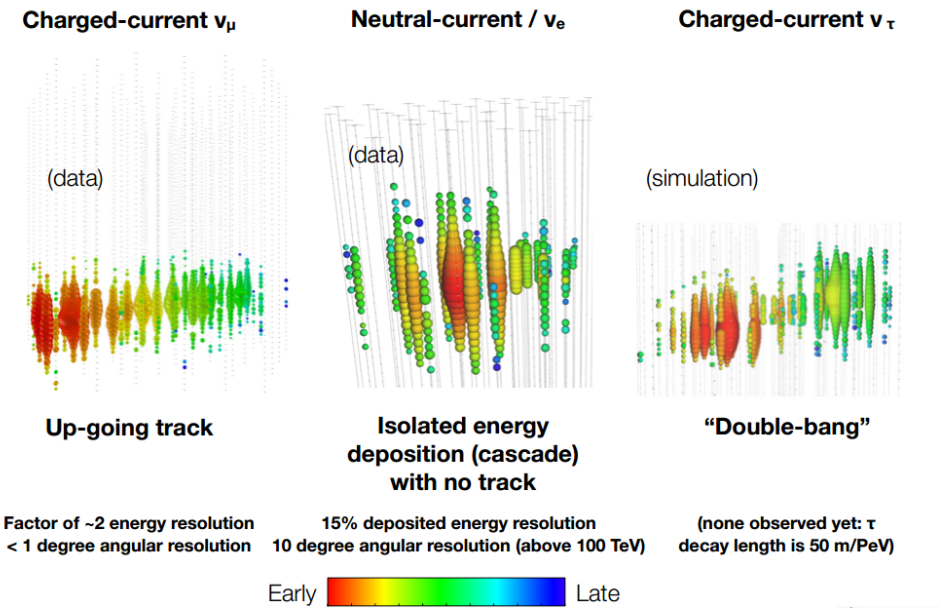
- The most powerful, long-lived objects in the universe
- Study of neutrinos will allow us to probe them deeper inside
- We might have seen the first neutrinos from AGNs in the last few years !!

High energy astrophysical neutrinos ($\gtrsim$ 100 GeV)

Gigaton IceCube: 1 000 000 000 000 litres of ice





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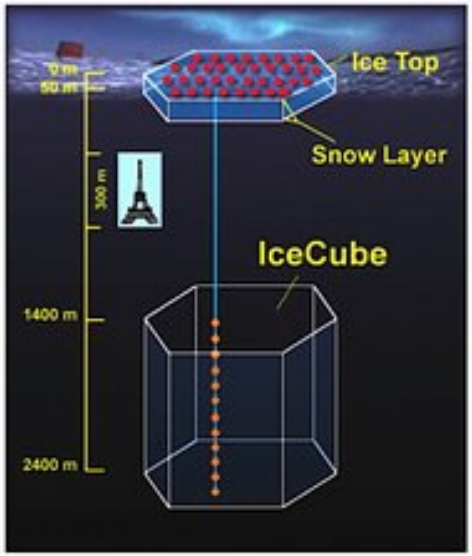
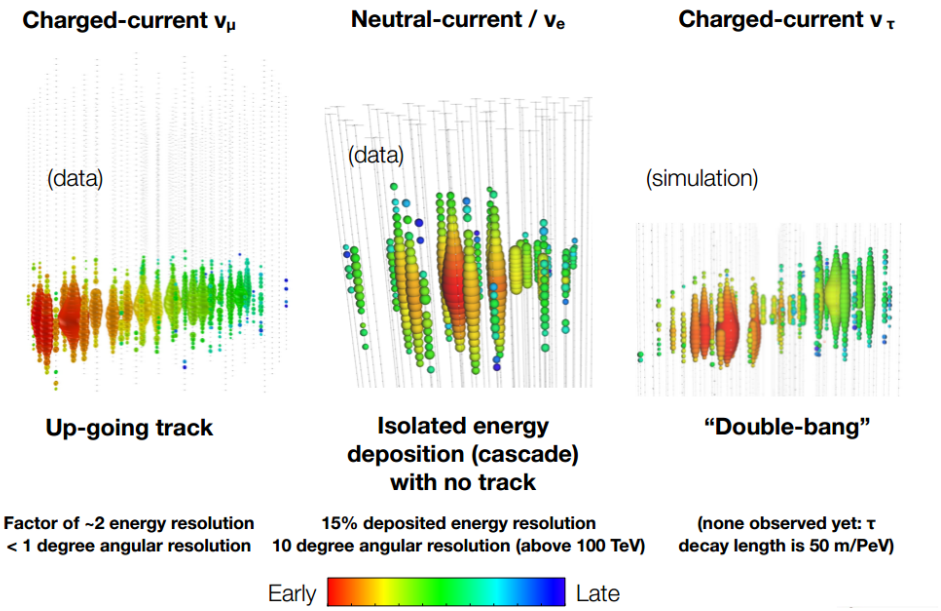
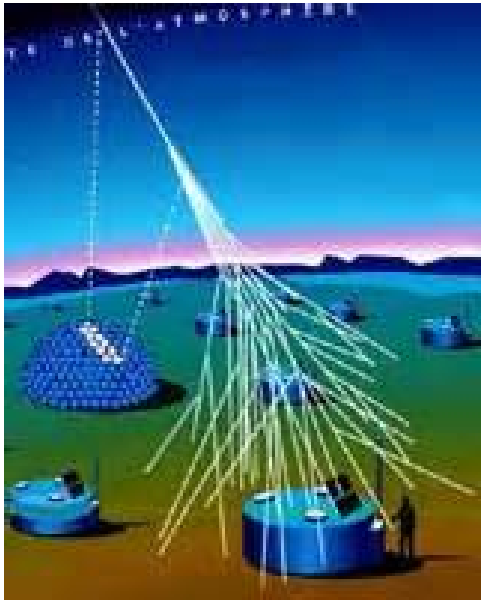


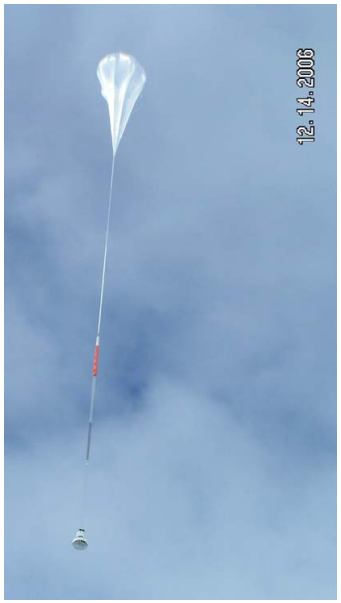


- Look for high energy neutrinos from astrophysical events (AGNs, gamma ray bursts, supernovae, neutron star mergers...)
- Search for origin, correlations with directions of UHECR
- Tell us about sources, possible new physics (Lorentz violation, neutrino decay, ...)

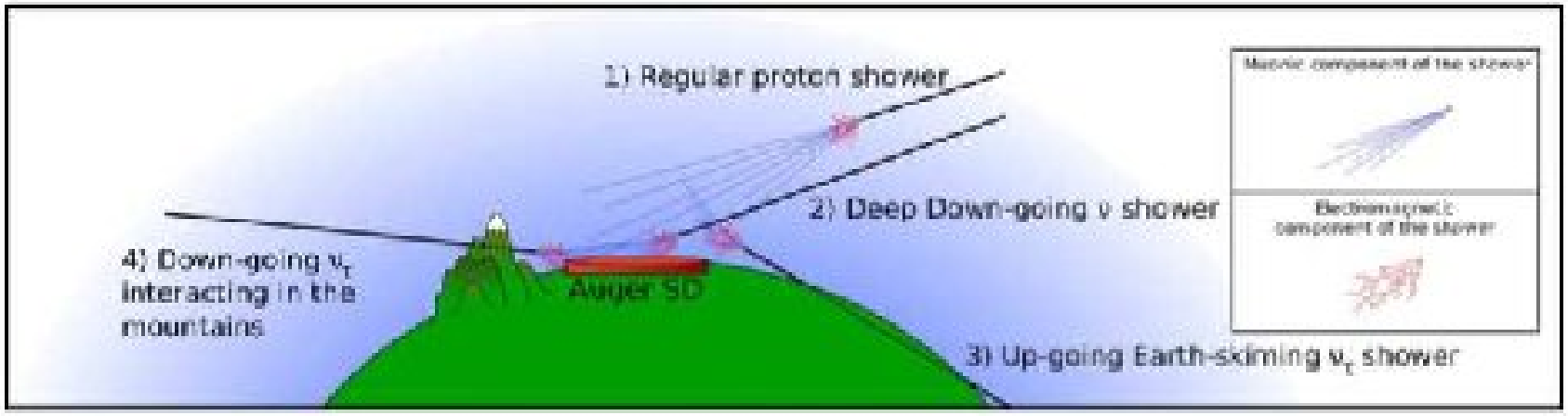
Ultrahigh energy neutrinos ($\gtrsim 10^{16}$ eV)



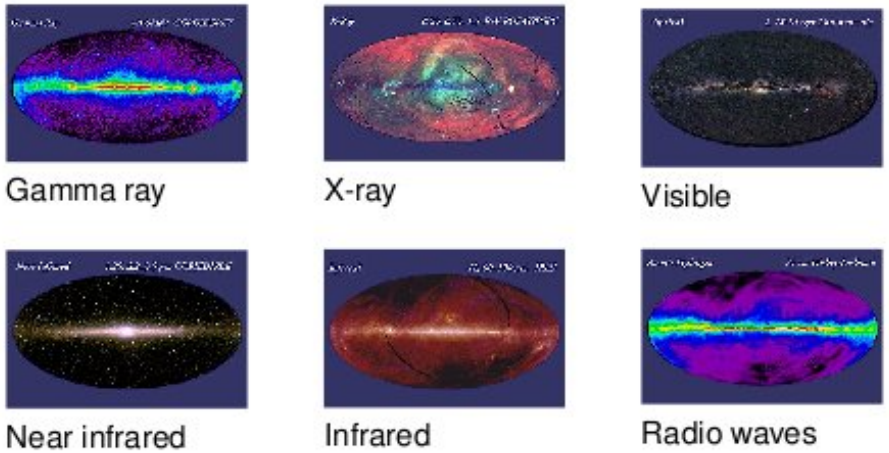
Auger

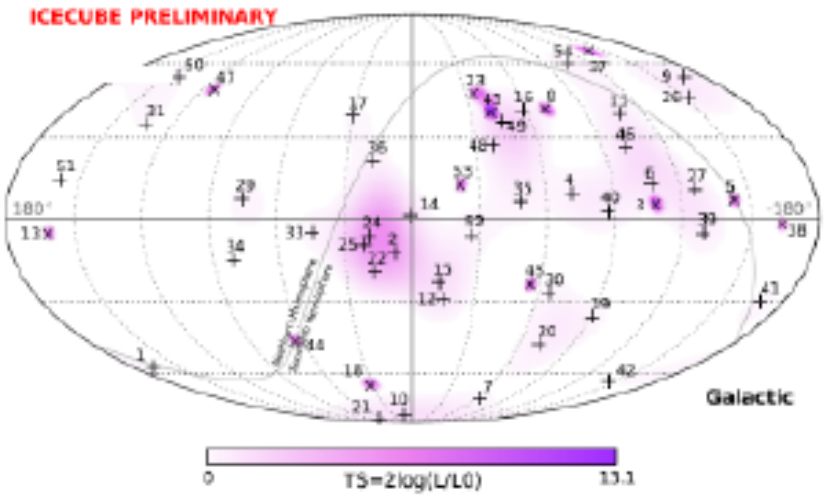


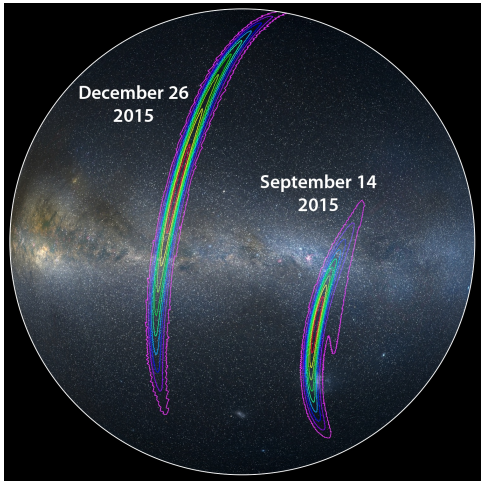
ANITA (balloon)



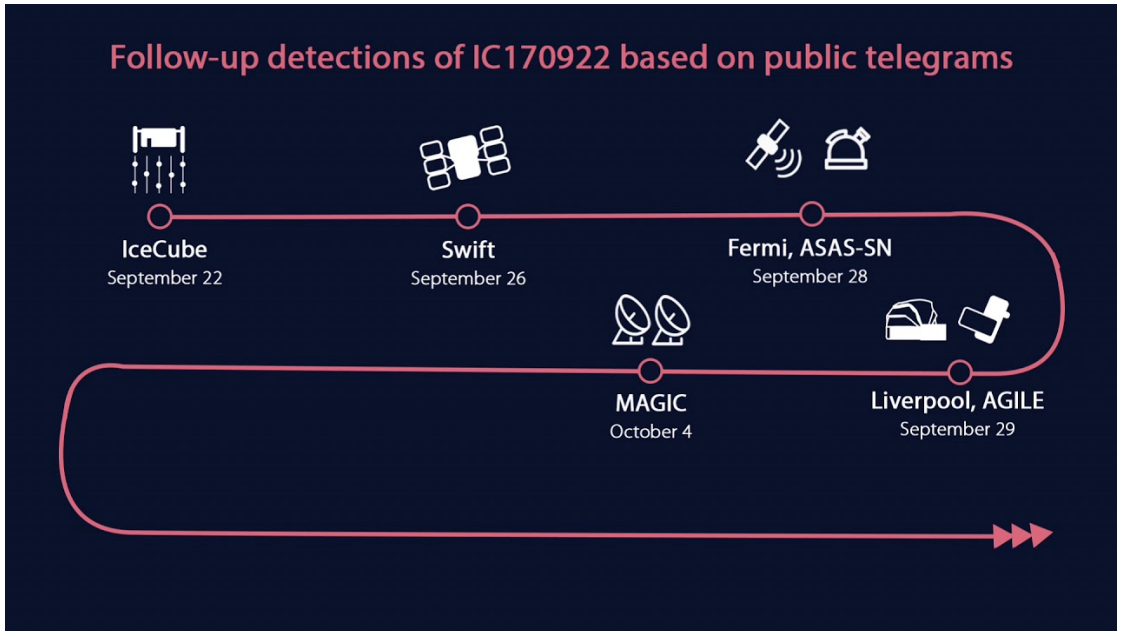
Multimessenger astronomy

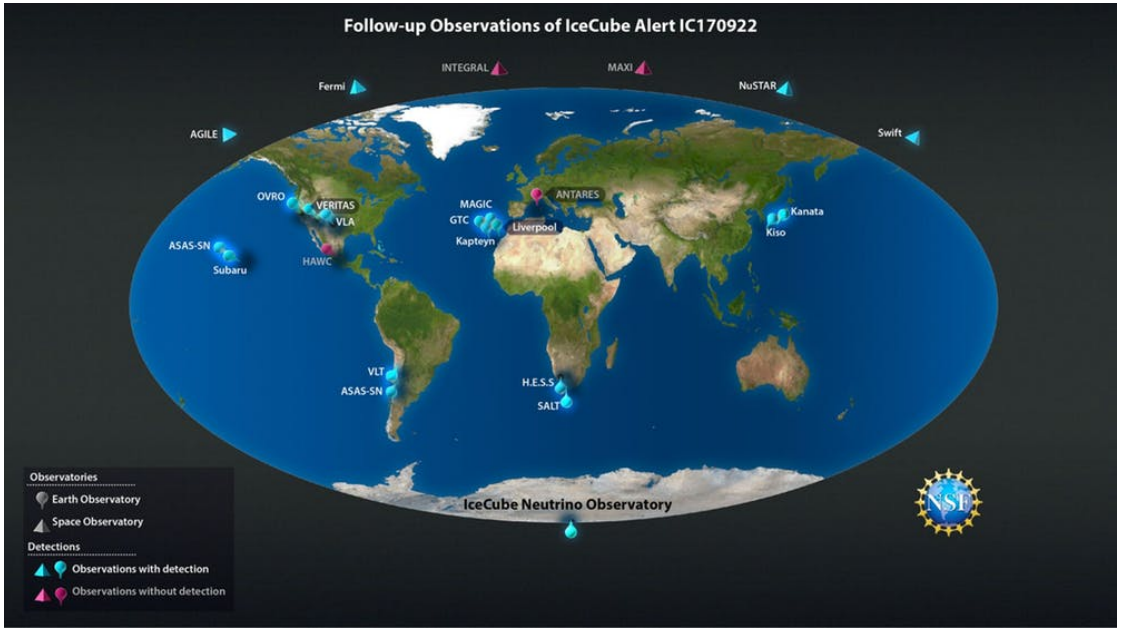




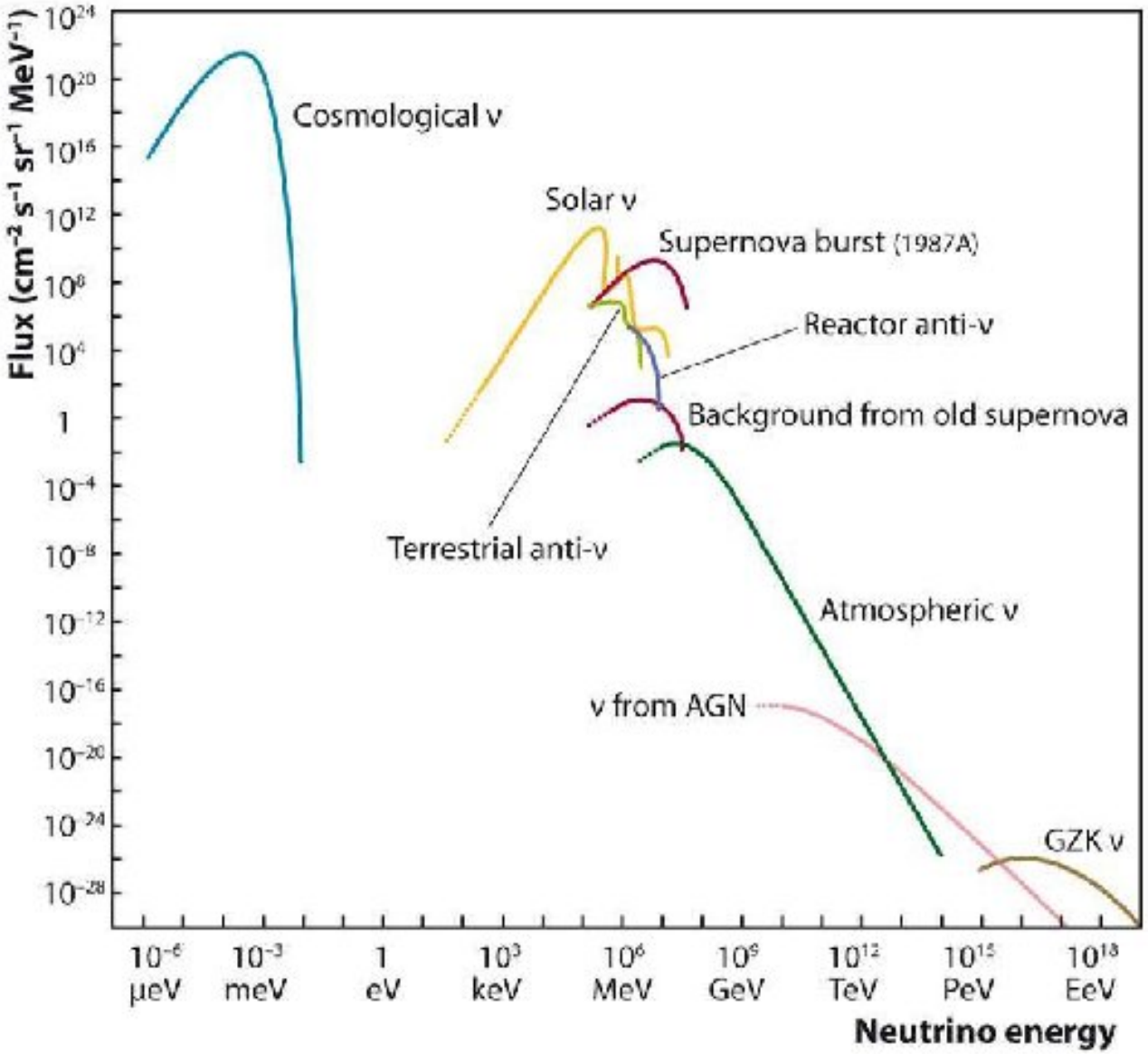


Blazar at IceCube, followup by telescopes



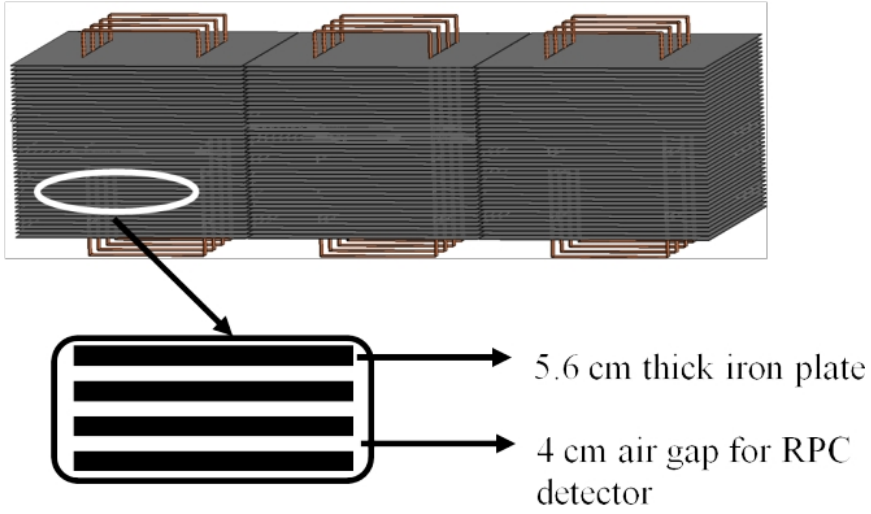


Neutrinos at all energies



ASPERA

Atmospheric neutrinos ($\sim 1 - 100$ GeV)

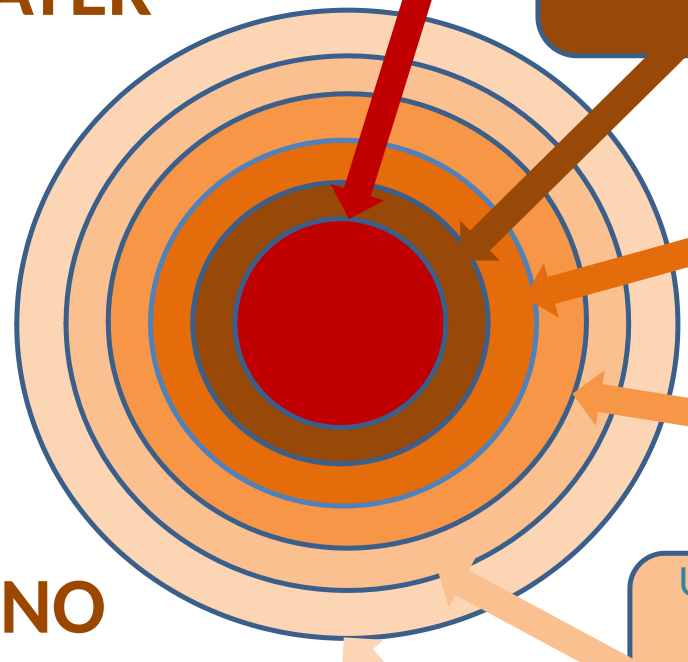


India-based Neutrino Observatory (INO)

- In a tunnel below a peak (Bodi West Hills, near Madurai)
- 1 km rock coverage from all sides
- 50 kiloton of magnetized iron (50 000 000 kg)
- Can distinguish neutrinos from antineutrinos
- Determining mass hierarchy from atmospheric neutrinos

Multi-layer goals of INO

MULTI-LAYER



INO GOALS

Determining neutrino mass ordering / Independent verification in neutrinos and antineutrinos / Detection of Earth matter effects

Measuring neutrino properties: Mixing parameters, Non-standard interactions, CPT violation, decay, decoherence, Sterile neutrinos, long range forces.
*Earth Tomography

Searching for physics beyond the Standard Model (beyond neutrinos): Magnetic monopoles, long-lived particles, dark matter annihilation

Act as a long-term detector looking for atmospheric and astrophysical phenomena: Searching for unknown,
*Multimessenger astronomy

Underground, radiation-free lab infrastructure useful for other experiments: High energy physics, Biology, Material Science, Geology.
*Readiness for future opportunities

A large scale international experiment running in India for development of Experimental physics manpower, Detector development expertise.
*Education and training hub for students all over India

ICAL @ INO

INO

Neutrinos: a new window to the Universe

- At extremely small scales: identifying mechanism for generating neutrino masses and mixing pattern
- At extremely large scales: understanding astrophysical / cosmological phenomena
- Speculative applications: nuclear non-proliferation, Earth tomography, oil exploration, communication, ...