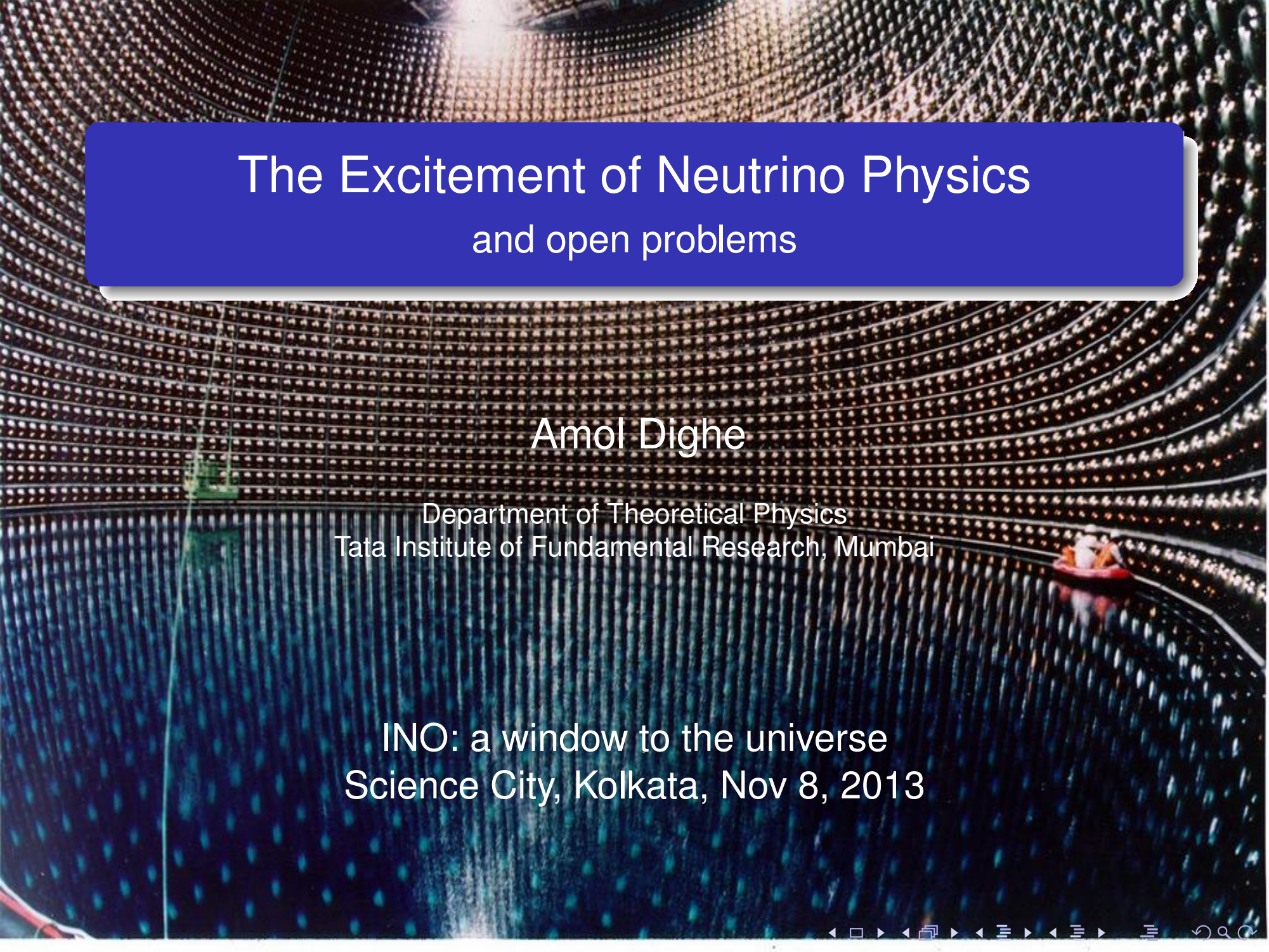


The Excitement of Neutrino Physics

and open problems

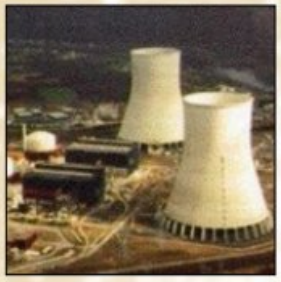
Amol Dighe

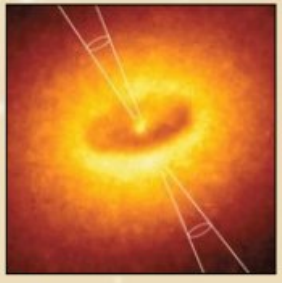
Department of Theoretical Physics
Tata Institute of Fundamental Research, Mumbai

INO: a window to the universe
Science City, Kolkata, Nov 8, 2013

Neutrinos everywhere

Where do Neutrinos Appear in Nature?





- ✓ Earth Crust (Natural Radioactivity)
- ✓ Nuclear Reactors
- ✓ Particle Accelerators
- ✓ Earth Atmosphere (Cosmic Rays)
- Sun ✓
- Supernovae (Stellar Collapse) SN 1987A ✓
- Cosmic Big Bang (Today 330 ν/cm^3) Indirect Evidence
- Astrophysical Accelerators Soon ?

Some interesting titbits about neutrinos

The second most abundant particles in the universe

- Cosmic microwave background photons: 400 / cm^3
- Cosmic microwave background neutrinos: 330 / cm^3

The lightest massive particles

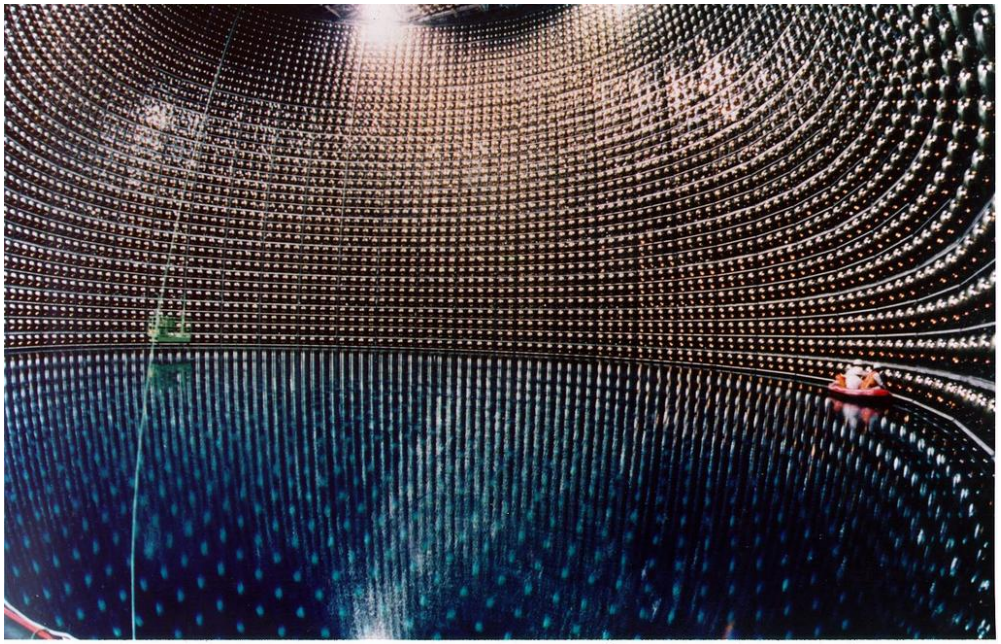
- A million times lighter than the electron
- No direct mass measurement yet

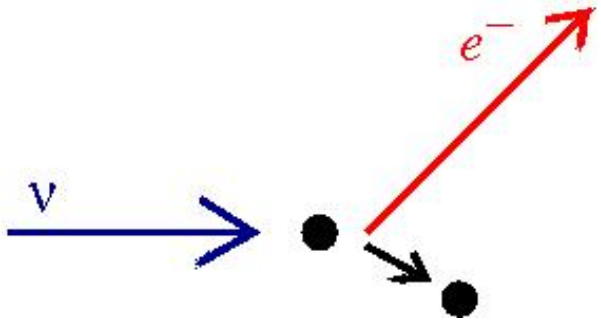
The most weakly interacting particles

- Invisible: do not interact with light
- Stopping radiation with lead shielding:
  - Stopping α, β, γ radiation: 50 cm
  - Stopping neutrinos from the Sun: light years !

How to detect neutrinos: an example

SuperKamiokande: 50 000 000 litres of water



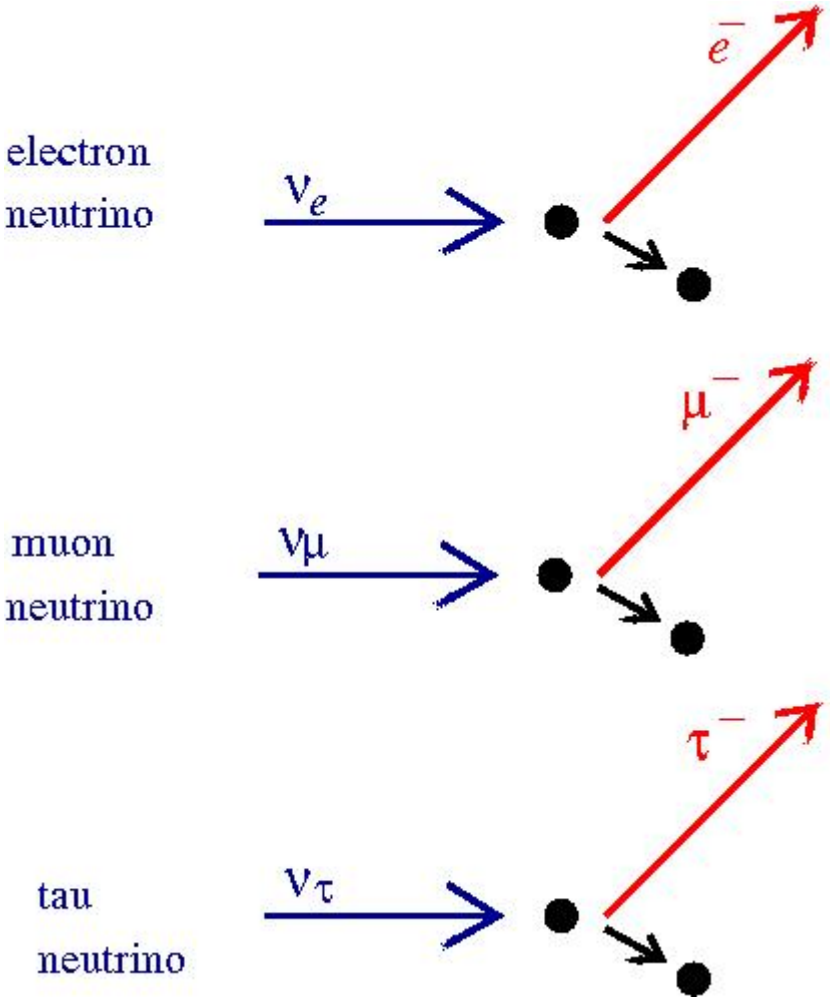


Observes about 5-10 neutrinos per day
(out of $\gtrsim 10^{25}$ neutrinos passing through)

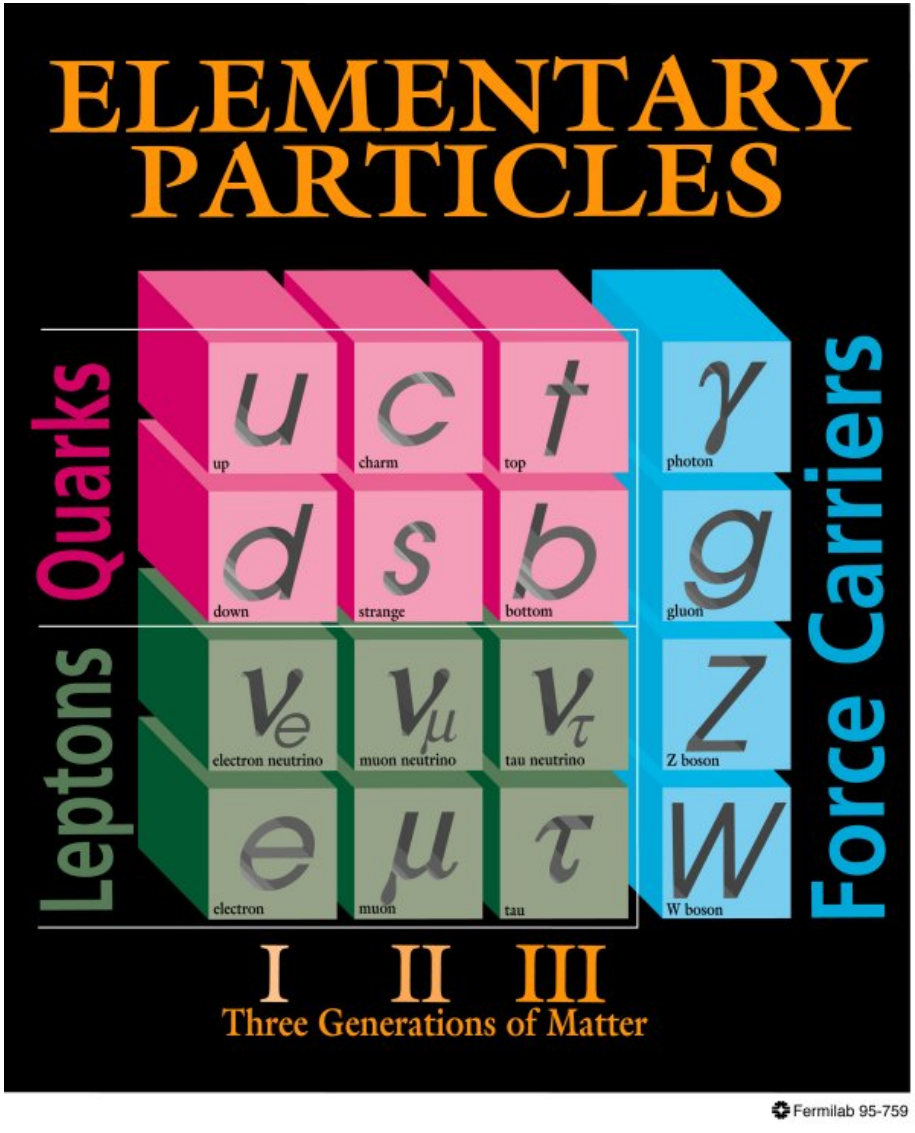
Recipe for observing neutrinos

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

Three kinds (flavours) of neutrinos: ν_e ν_μ ν_τ



The Standard Model of Particle Physics



+ Higgs

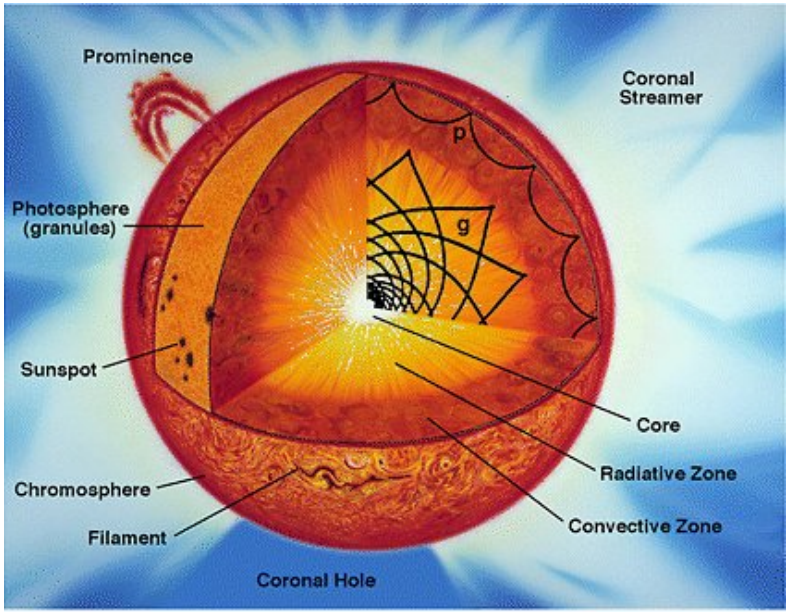
- 3 neutrinos:
  ν_e, ν_μ, ν_τ
- Zero charge
- spin 1/2
- almost massless:
  at least a million
  times lighter
  than electron

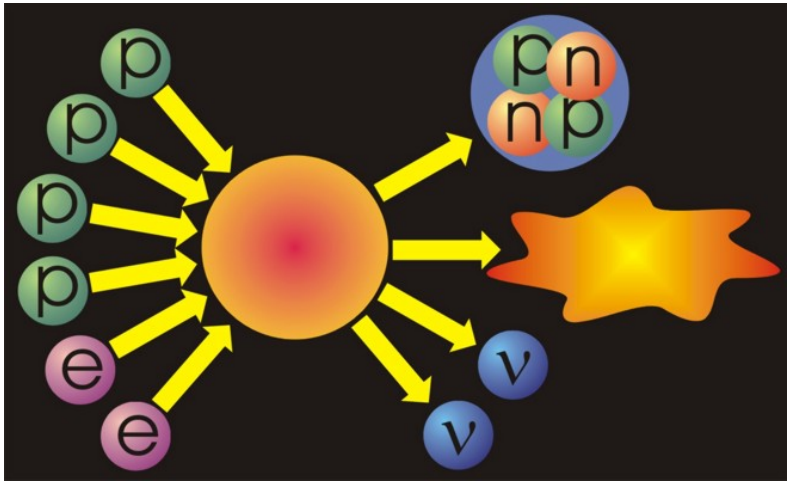
The excitement of neutrino physics

1. The neutrino mysteries
2. Neutrino masses and mixing: open problems
3. Neutrinos as messengers from the universe
4. The future of neutrino observations

The excitement of neutrino physics

How does the sun shine ?

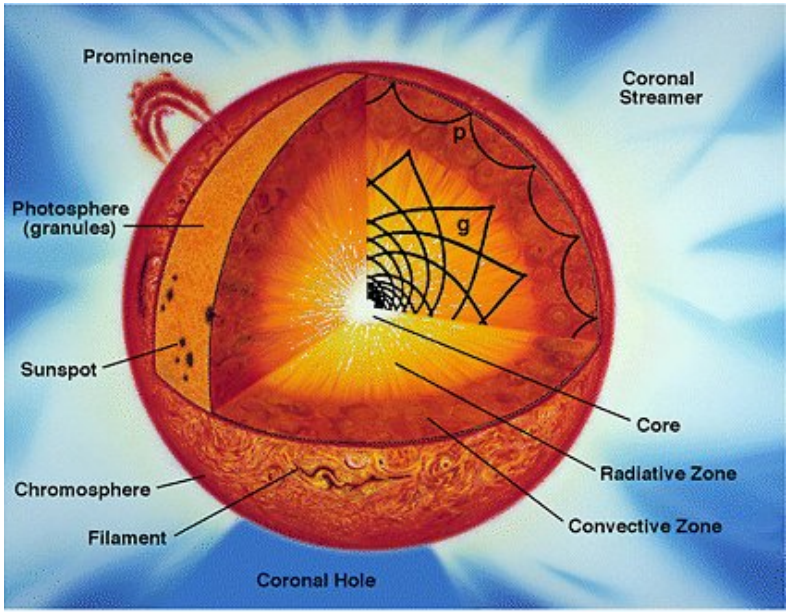


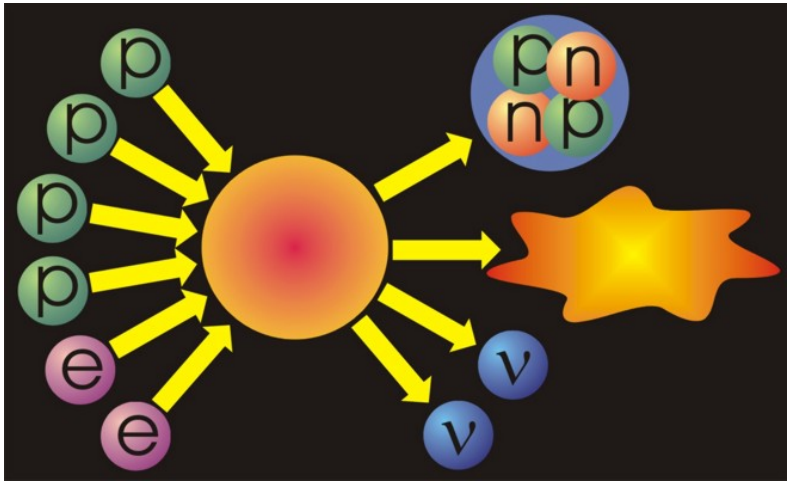


- Nuclear fusion reactions: mainly

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

How does the sun shine ?





- Nuclear fusion reactions: mainly

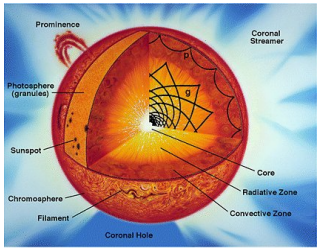
$$4\,{}^{1}_{1}\mathrm{H} + 2e^{-} \rightarrow {}^{4}_{2}\mathrm{He} + \text{light} + 2\nu_e$$

- Neutrinos needed to conserve energy, momentum, angular momentum

Neutrinos essential for the Sun to shine !!

Davis-Koshiba Nobel prize 2002

Neutrinos from the Sun: three interesting facts



A very very large number of neutrinos

About hundred trillion through our body per second

Hundred trillion = 100 000 000 000 000

Even during night !

Neutrinos during night = Neutrinos during day

Reach us directly from the core of the Sun

Light from the Sun's core cannot reach us directly

Why do we not notice them ?

Three questions, the same answer

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

Three questions, the same answer

- Why did the *roti* char ?
- 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 ?

Three questions about neutrinos

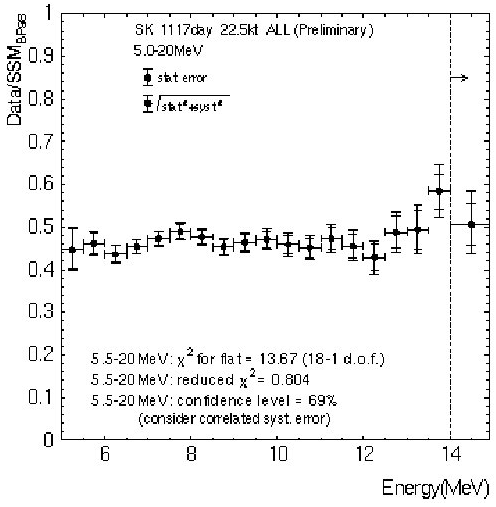
Pauli Dirac

- 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 ?

Because neutrinos interact extremely weakly !
(This is not the mystery)

Mystery of missing solar neutrinos

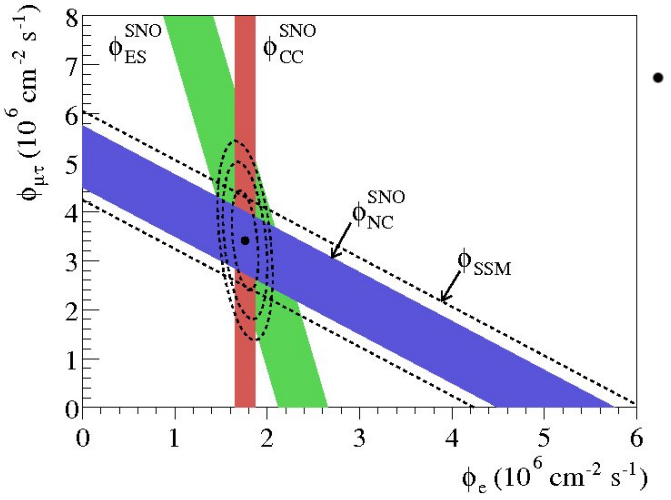
SuperKamiokande:



- Sun produces electron neutrinos (ν_e)
  $\Rightarrow$ Look for ν_e
- Where did the missing neutrinos (ν_e) go ?

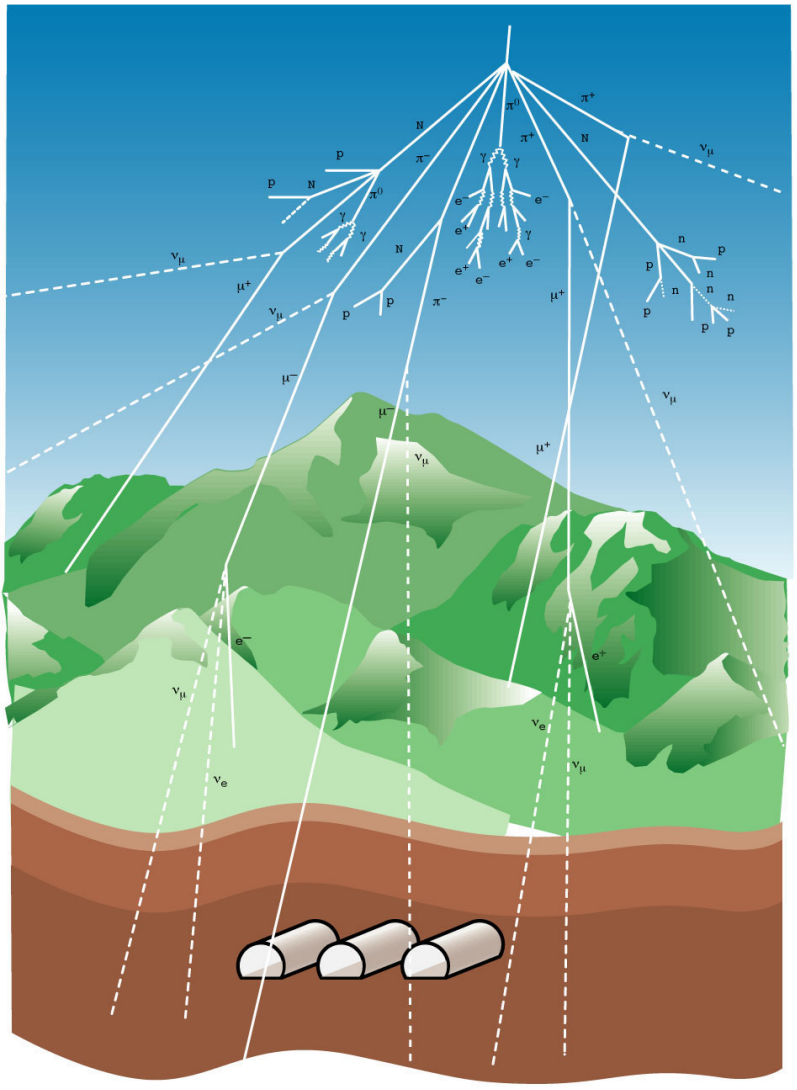
Neutrinos were missing from all experiments for 40 years !

SNO:



- Look for all neutrino flavours
- Some of the ν_e seem to have become ν_μ/ν_τ

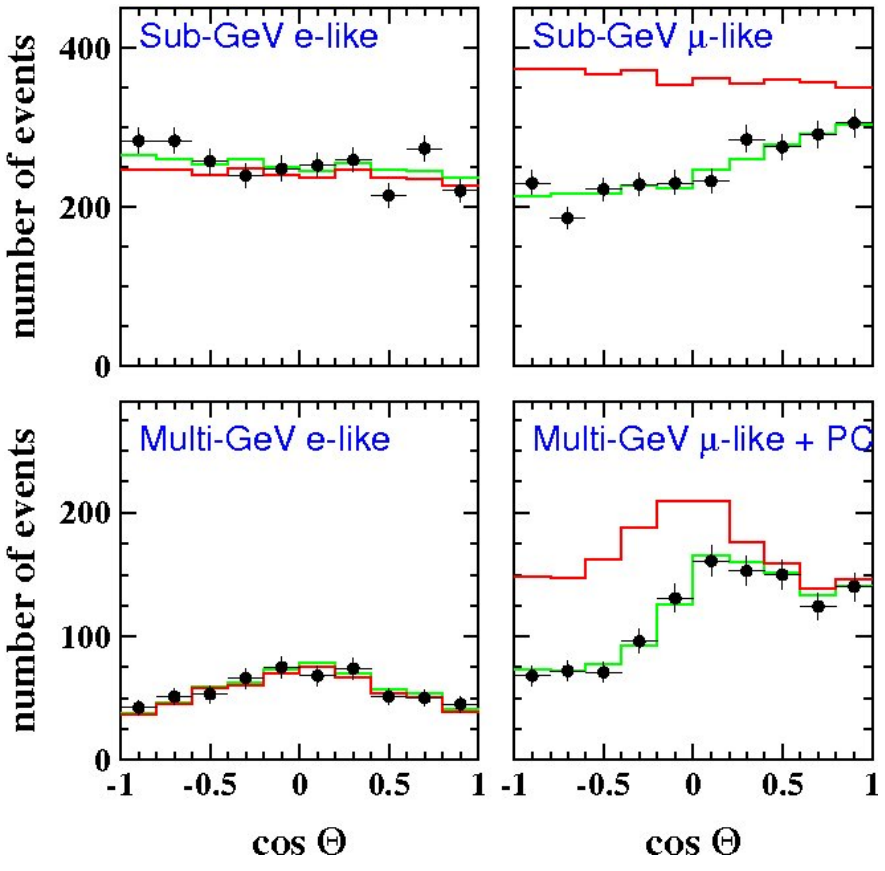
Neutrinos from cosmic rays (atmospheric neutrinos)

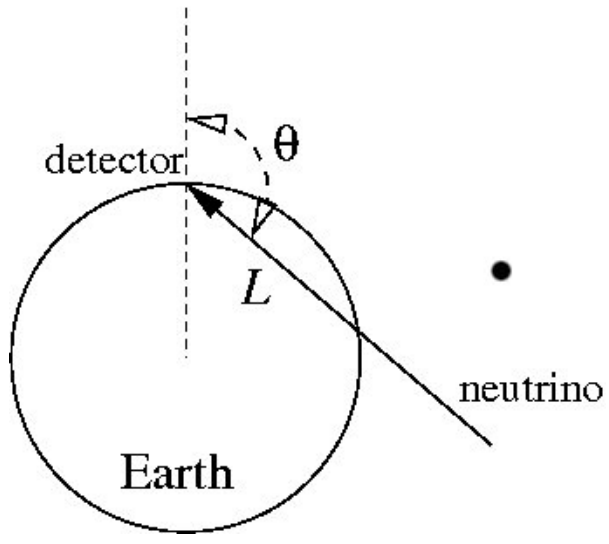


- $\pi^+ \to \mu^+ + \nu_\mu$
- $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$
- "ν_μ" flux $= 2\times$ "ν_e" flux
- "Down" flux = "Up" flux

The mystery of atmospheric neutrinos

Superkamiokande:

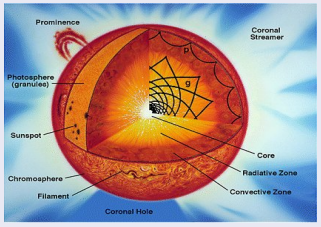




- Electron neutrinos match predictions
- Muon neutrinos lost while passing through the Earth !
- Muon neutrinos must have become tau neutrinos !

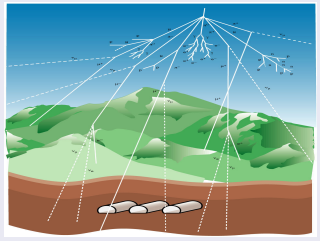
The long-term mysteries $\Rightarrow$ neutrino oscillations

Solar neutrino mystery: 1960s – 2002



- Only about half the expected ν_e observed!
- Possible solution: ν_e change to ν_μ/ν_τ

Atmospheric neutrino mystery: 1980s – 1998



- Half the ν_μ lost in the Earth!
- Possible solution: ν_μ change to ν_τ

Reactor neutrino experiments

- Breaking news of 2012:
  10% of reactor $\bar{\nu}_e$ are lost !
- Possible solution: $\bar{\nu}_e$ change to $\bar{\nu}_\mu/\bar{\nu}_\tau$

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 $\bar{\nu}_\mu/\bar{\nu}_\tau$?

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 $\bar{\nu}_\mu/\bar{\nu}_\tau$?

Because neutrinos have different masses and they mix !

$\Uparrow$

Quantum Mechanics

The excitement of neutrino physics

What is meant by neutrino mixing ?

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

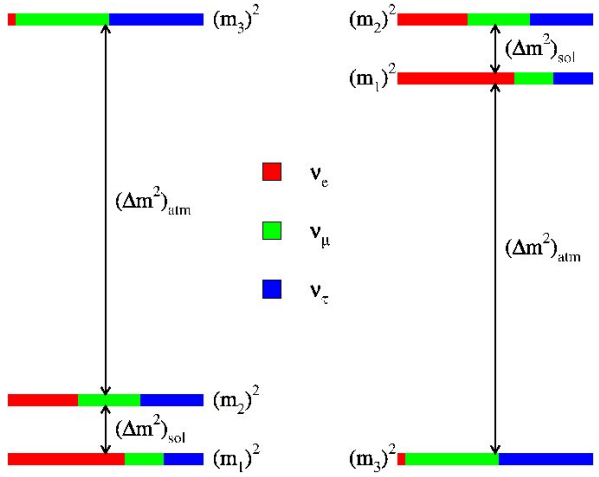
For example, ν_e–ν_μ mixing:

$$\nu_2 = -\nu_e \sin\theta + \nu_\mu \cos\theta$$

$$\nu_1 = \nu_e \cos\theta + \nu_\mu \sin\theta$$

Open questions about neutrino masses and mixing

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



- Mass ordering: Normal or Inverted ?
- What are the absolute neutrino masses ?
- Are there more than 3 neutrinos ?
- Is there leptonic CP violation ?
- Can neutrinos be their own antiparticles ?

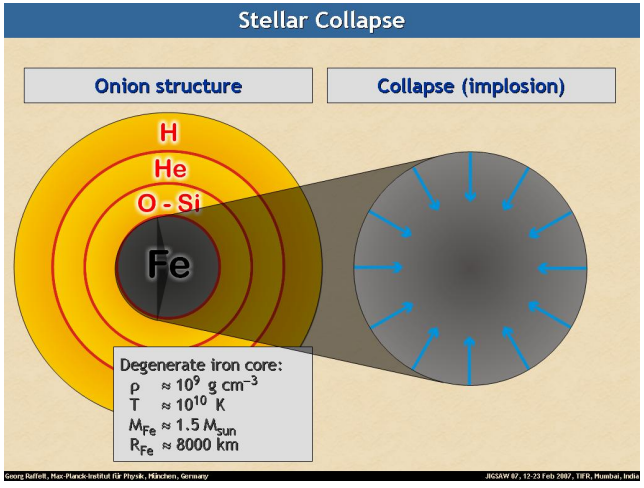
The excitement of neutrino physics

Neutrinos as messengers

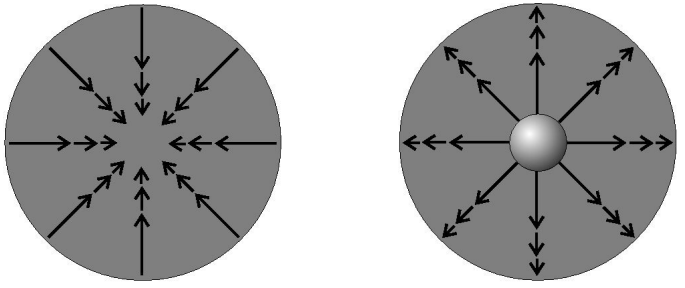
- No bending in magnetic fields $\Rightarrow$ point back to the source
- Minimal obstruction / scattering $\Rightarrow$ can arrive directly from regions from where light cannot come.

Supernova: the death of a star

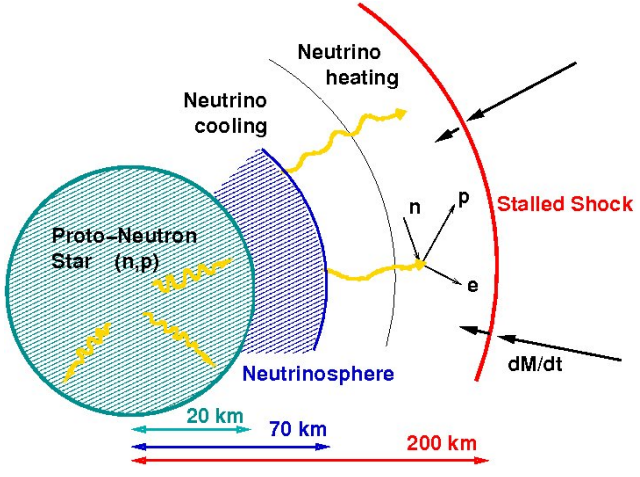
Gravity ⇒



Strong nuclear force ⇒



Weak nuclear force (Neutrino push) ⇒



Electromagnetism (Hydrodynamics) ⇒

(Crab nebula, SN seen in 1054)

Supernova neutrinos

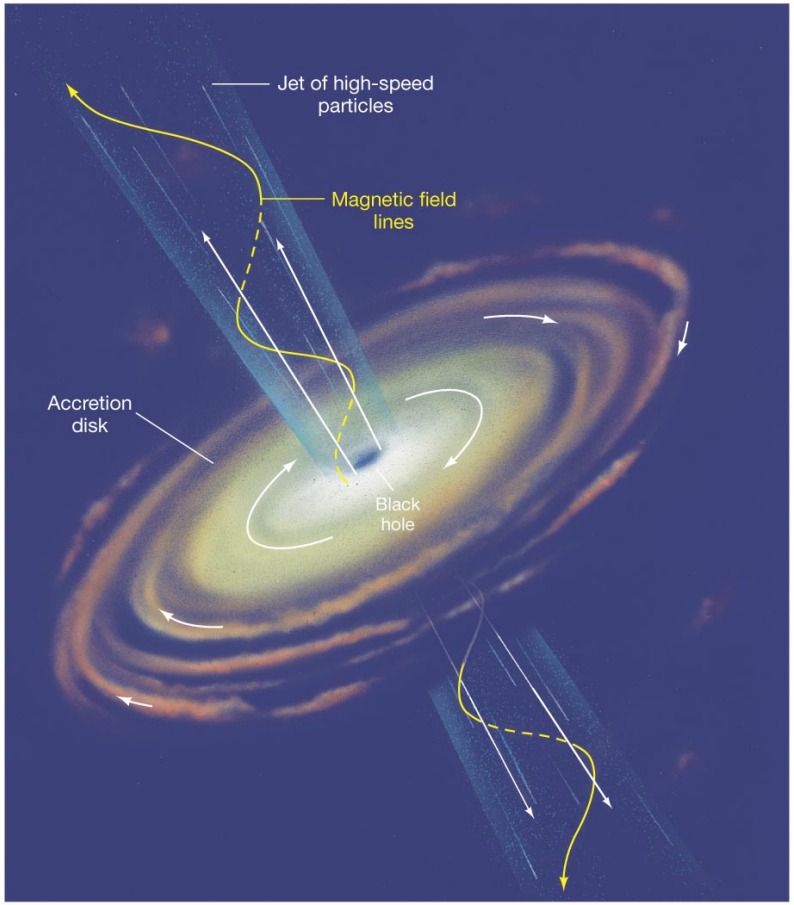
What they do

- Blow up the star (one such piece has become our Earth)
- Change flavour inside the star ($\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$)

How they can help us

- 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)
- Identify neutrino mass ordering: normal or inverted

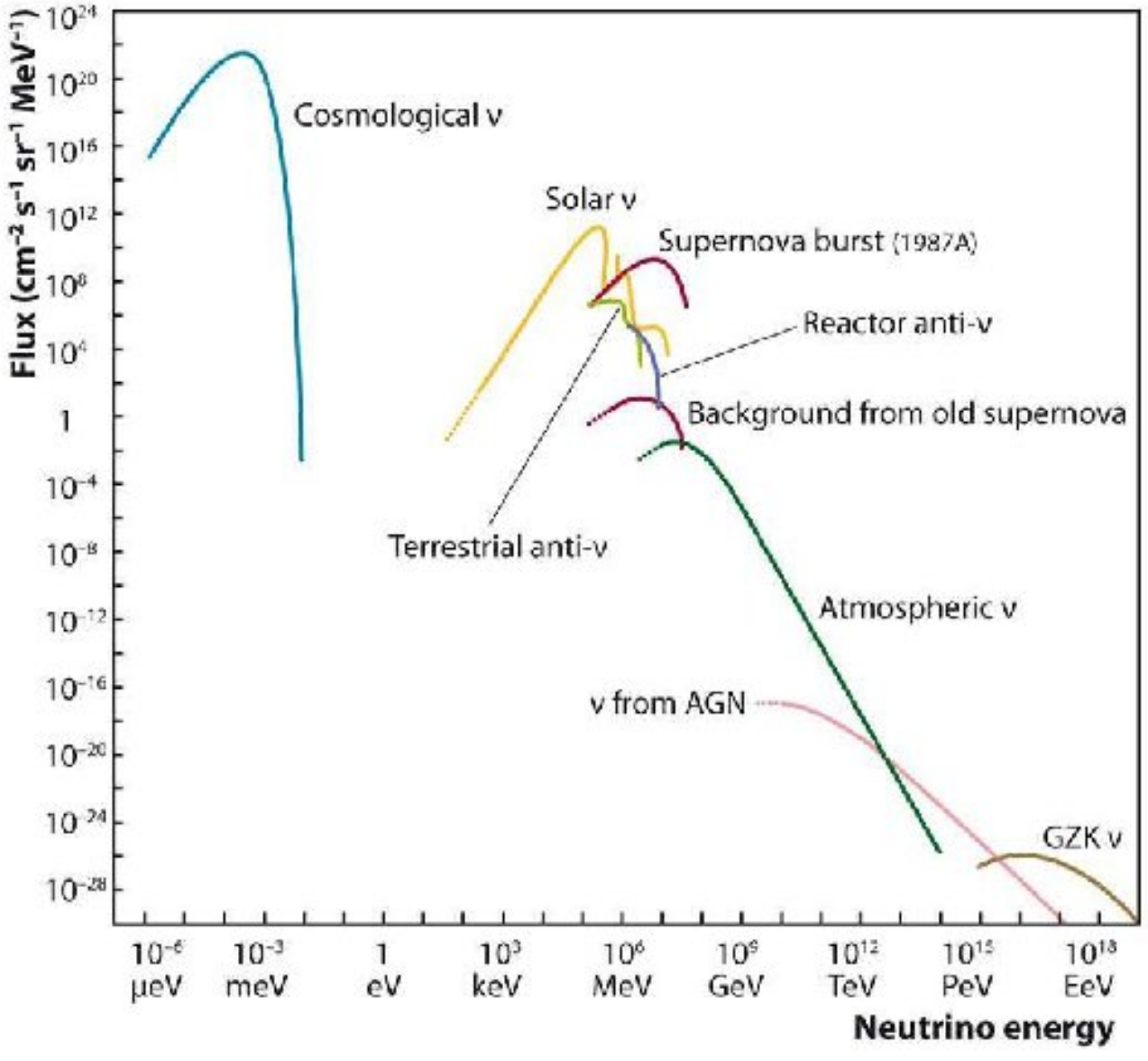
Active Galactic Nuclei (AGNs)



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

The excitement of neutrino physics

Neutrinos at all energies



Exploration of neutrinos over a wide energy range

keV-energy neutrinos (10^3 eV)

- Neutrinoless double beta decay experiments:
  to determine if neutrinos are their own antiparticles

MeV-energy neutrinos (10^6 eV)

- Measuring the energy of the sun in neutrinos
- Geoneutrinos: neutrinos from the Earth's radioactivity
- Reactor neutrino experiments

GeV-energy neutrinos (10^9 eV)

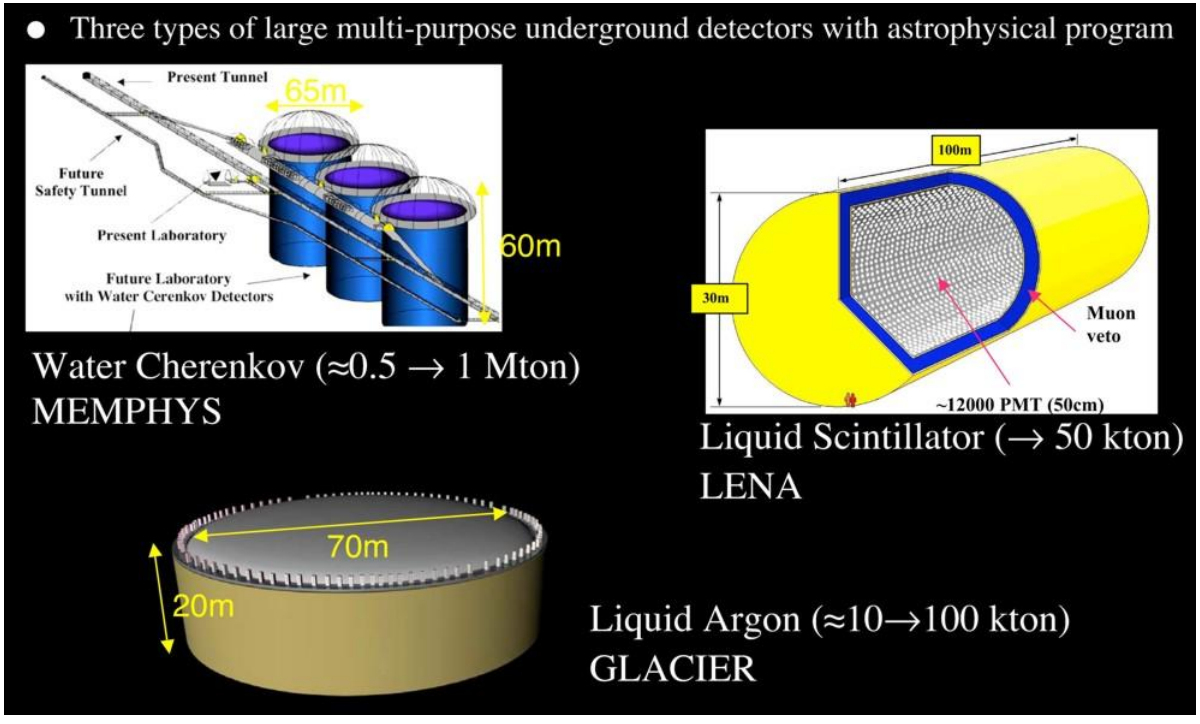
- Atmospheric neutrino measurements for mass ordering
- Long baseline experiments: production-detection distance $\sim$ 1000–10000 km

TeV-PeV-EeV energy neutrinos ($\gtrsim 10^{12}$ eV)

Astrophysical neutrinos: supernovae, AGNs, etc.

Bigger and better detectors

1 Megaton water = 1 000 000 000 litres

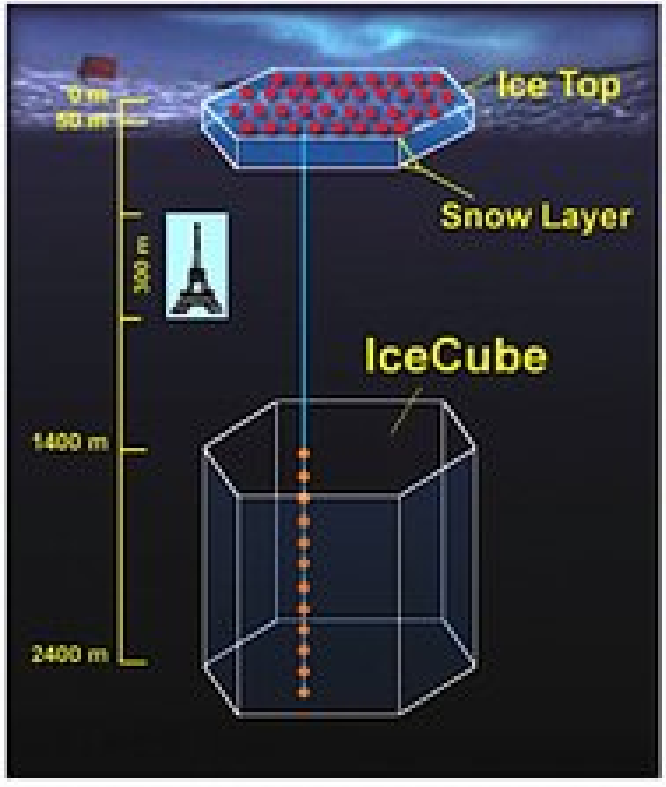


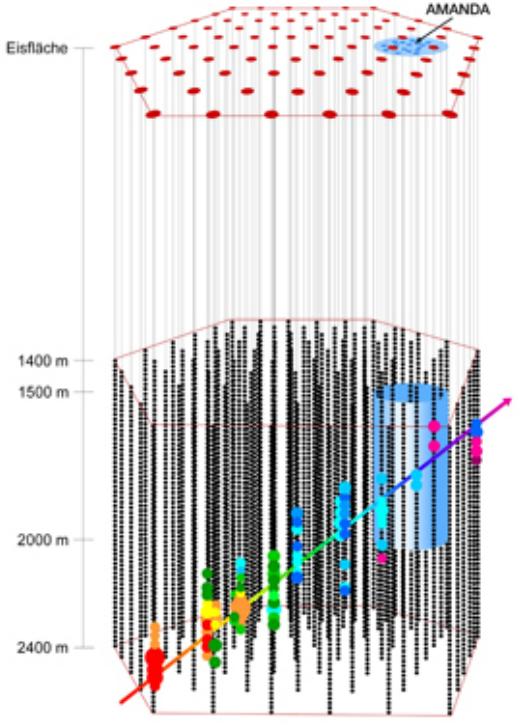
Long baseline experiments

- “Manufacture” a lot of neutrinos
- See how many of them survive after travelling the “long baseline” ($\sim$ 1000–10000 km)

Below the antarctic ice: Gigaton IceCube

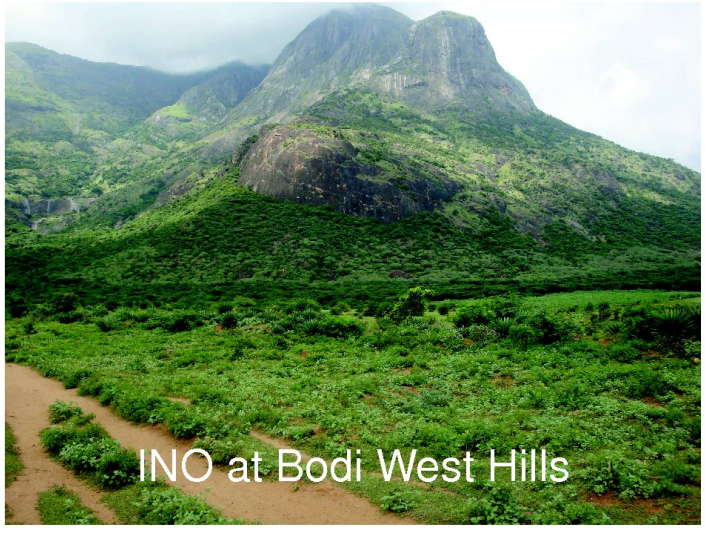
1 gigaton water = 1 000 000 000 000 litres

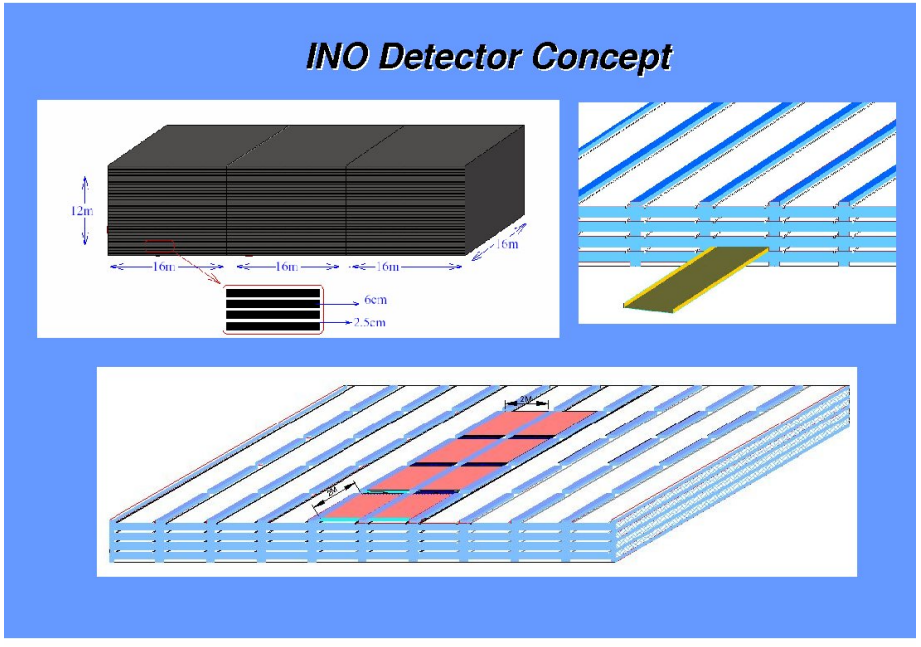




There are many more experiments around the world,
I have just shown a sample.

Coming soon inside a mountain near you: INO





India-based Neutrino Observatory

- Under a mountain, inside a tunnel (Bodi Hills, TN)
- 1 km rock coverage from all sides
- 50 kiloton of magnetized iron (50 000 000 kg)
- $\gtrsim$ 25 years: a lifelong project

Future results to look forward to

Neutrino masses and mixing

- Determination of masses and mixing parameters from data
- Are neutrinos their own antiparticles (Majorana) ?
- Signals of physics beyond the Standard Model
- Models for small ν masses and the mixing pattern

Astrophysics and cosmology

- Effect of neutrino mixing on SN explosion mechanism
- Nucleosynthesis of heavy elements
- Nature of astrophysical phenomena like AGNs
- Creation of the matter-antimatter asymmetry