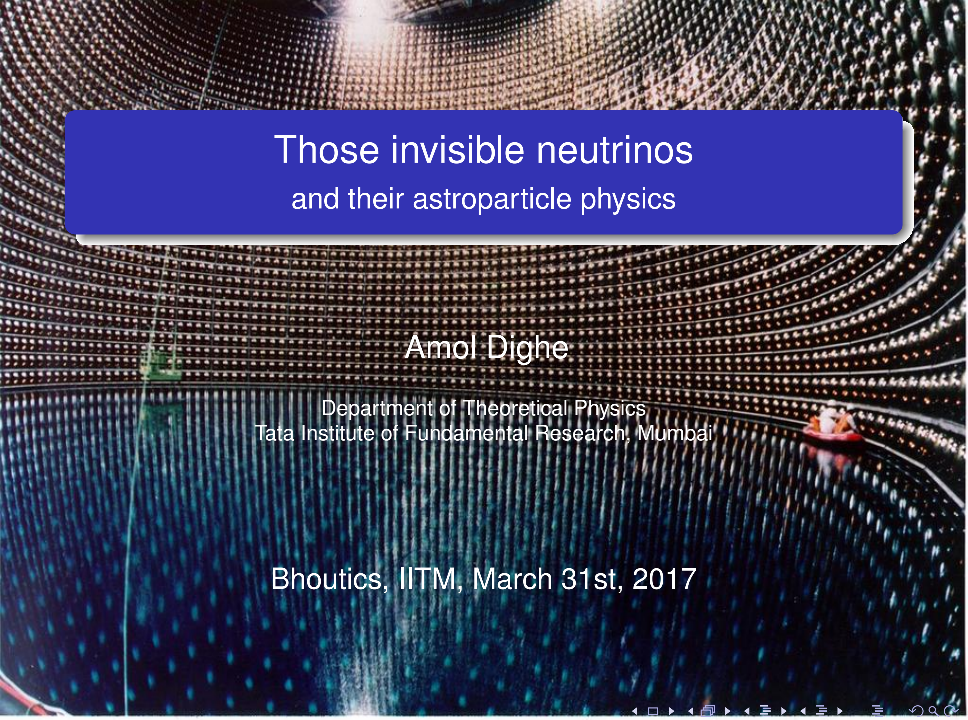

Those invisible neutrinos

and their astroparticle physics

Amol Dighe

Department of Theoretical Physics
Tata Institute of Fundamental Research, Mumbai

Bhoutics, IITM, March 31st, 2017

Those invisible neutrinos...

1. Neutrinos from the Sun
2. Neutrinos in astrophysics, cosmology, and particle physics
3. Neutrino mysteries that took decades to figure out
4. Neutrinos as messengers from the universe
5. The future of neutrino astronomy

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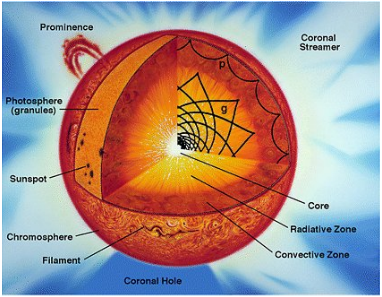
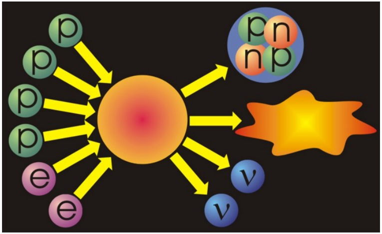
How does the Sun shine ?





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$$4\ {}^1_1\mathrm{H} + 2e^- \rightarrow {}^4_2\,\mathrm{He} + \mathrm{light}$$

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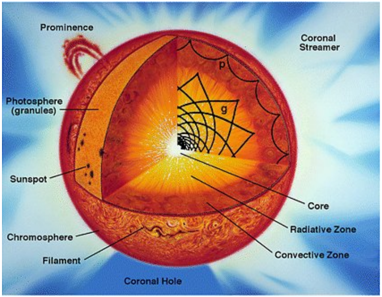

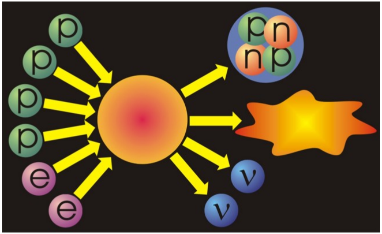

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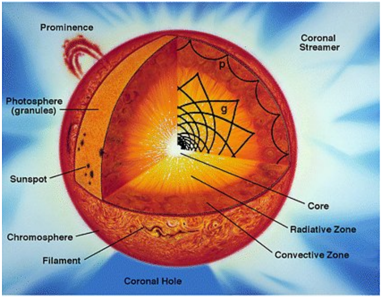

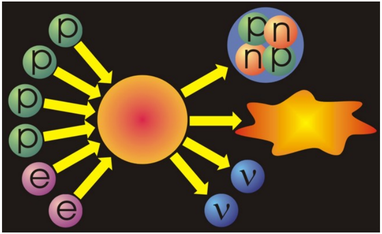

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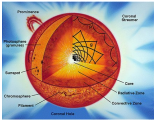
Neutrinos essential for the Sun to shine !!

Davis-Koshiba Nobel prize 2002

Neutrinos from the Sun: some interesting facts



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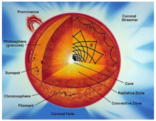

A very very large number of neutrinos

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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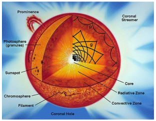

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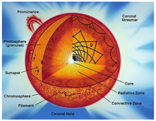

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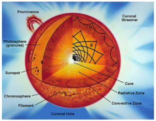

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What are the reasons for these confusing facts ?

Three questions, the same answer

- Why did the *roti* 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

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Because neutrinos interact extremely weakly !

The most weakly interacting particles

Stopping radiation with lead shielding

- Stopping α, β, γ radiation: 50 cm

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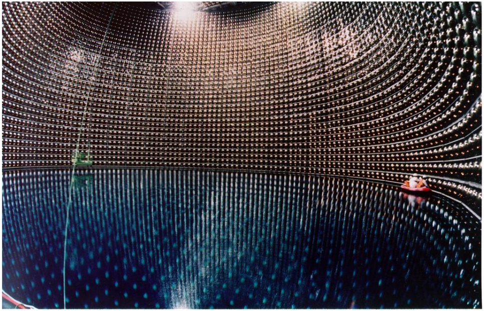
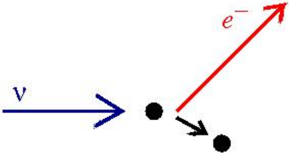
How do we see the neutrinos then ?

SuperKamiokande: 50 000 000 litres of water





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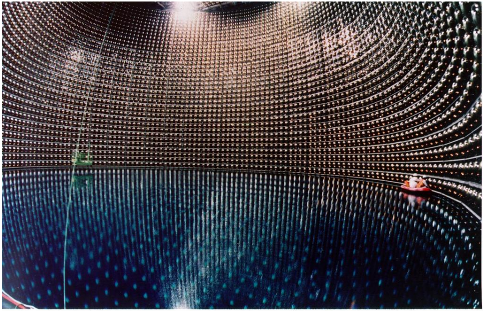

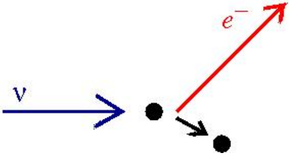

A very rare observation

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

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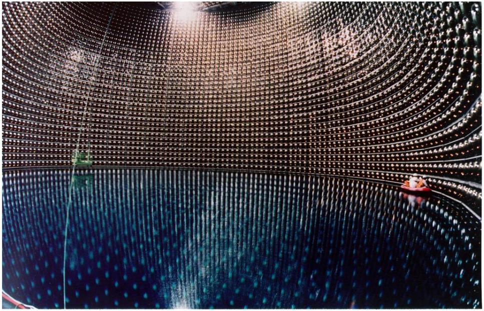

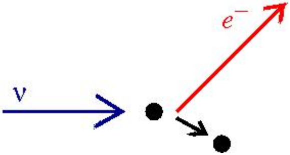

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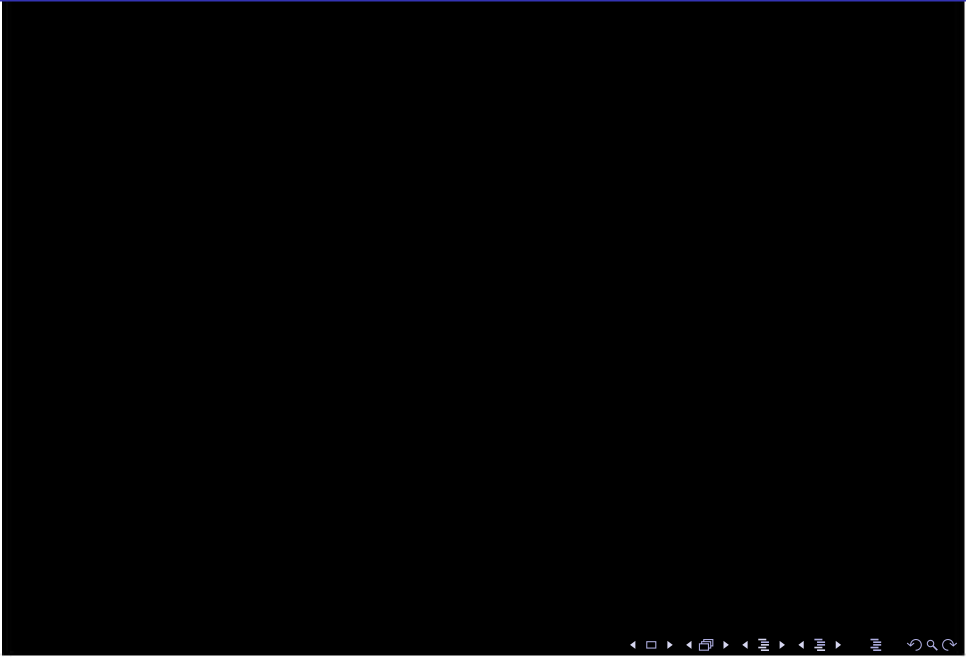
Recipe for observing neutrinos

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

Those invisible neutrinos...

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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- Earth has elements heavier than iron, which can be created only inside an exploding star (supernova)

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Role of neutrinos in creating the Earth

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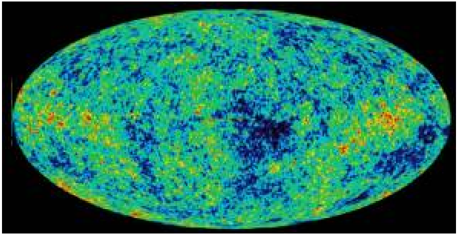
- A supernova must have exploded bilions of years ago whose fragments formed the solar system
- Supernovae explode because neutrinos push the shock wave from inside

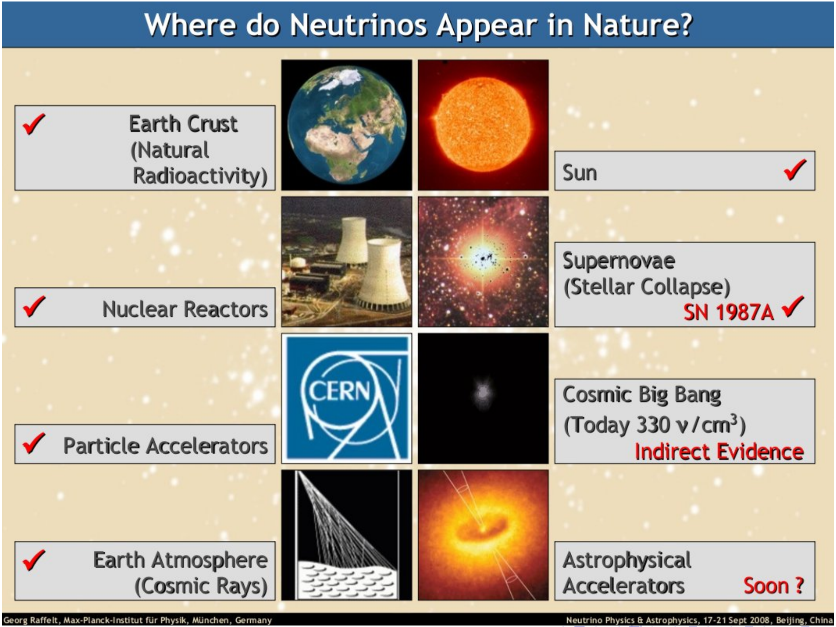
The second-most abundant particles in the universe



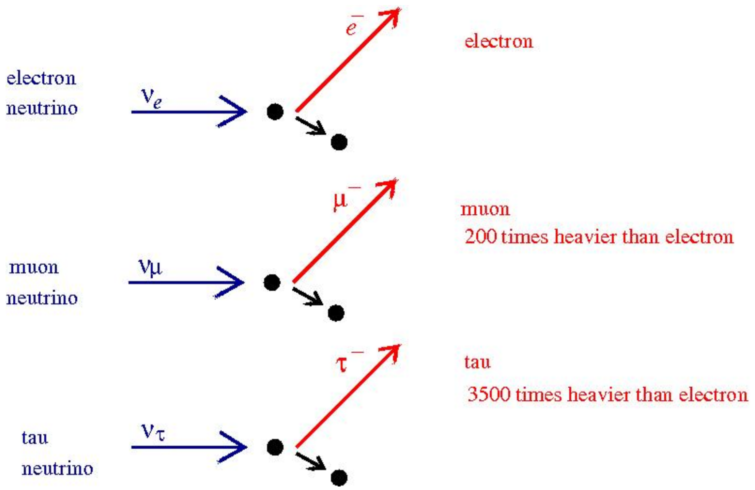
- Cosmic microwave background: 400 photons/ cm^3
  Temperature: $\sim$ 3 K
- Cosmic neutrino background: 300 neutrinos / cm^3
  Temperature: $\sim$ 2 K

Even empty space between galaxies is full of neutrinos !

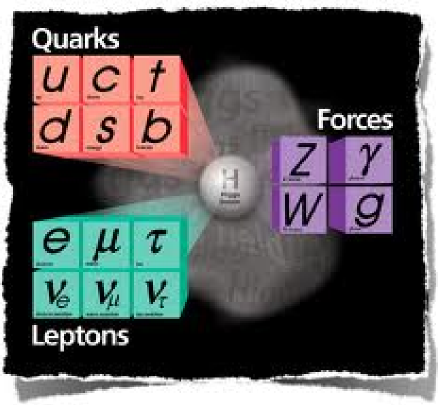
Neutrinos everywhere



Three kinds of neutrinos: ν_e ν_μ ν_τ



The Standard Model of Particle Physics

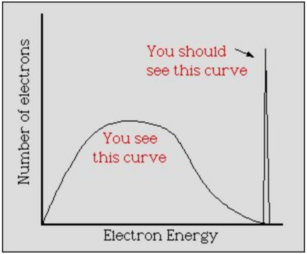


- 3 neutrinos: ν_e, ν_μ, ν_τ
- chargeless
- spin 1/2
- almost massless (at least a million times lighter than electrons)
- only weak interactions

Those invisible neutrinos...

The beta decay mystery: 1932

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



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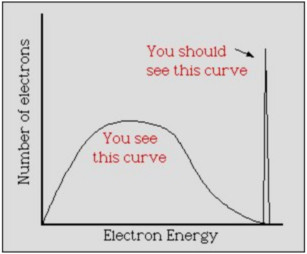


- Energy-momentum conservation in grave danger !!

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."

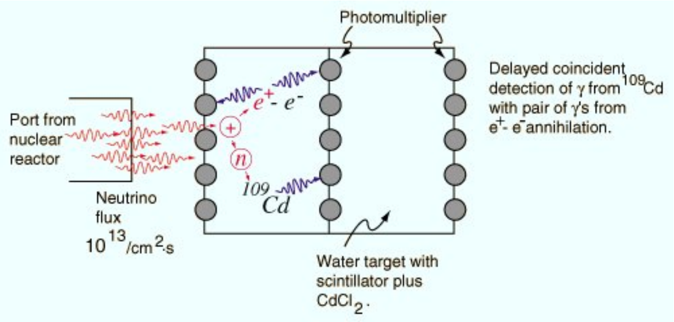
http://www.sciencecartoonsplus.com/pages/gallery.php

Discovery of electron neutrino: 1956

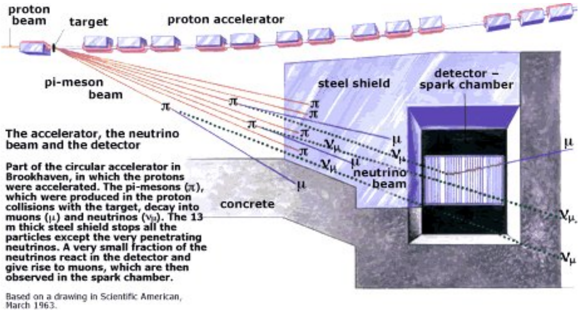
The million-dollar particle

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

Reines-Cowan: Nobel prize 1995



The “Who ordered muon neutrino ?” mystery: 1962



Muon neutrino: an unexpected discovery

- Neutrinos from pion decay: $\pi^- \to \mu^- + \bar{\nu}$
- Expected: $\bar{\nu} + N \to N' + e^+$??

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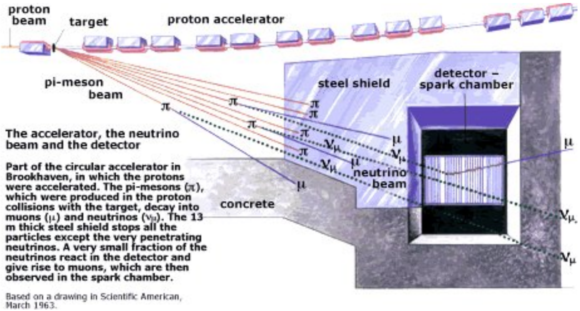

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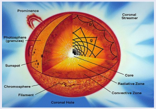
- Observed: always a muon, never an electron/positron
- This must be a new neutrino, not $\bar{\nu}_e$, but $\bar{\nu}_\mu$

Steinberger-Schwartz-Lederman Nobel prize 1988

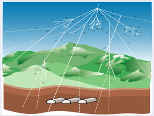
The long-term mysteries ⇒ neutrino oscillations

Solar neutrino mystery: 1960s – 2002



- Only about half the expected ν_e observed!

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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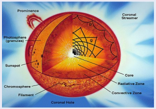

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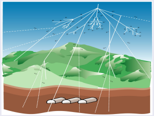

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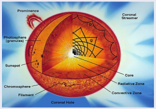

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- Nobel Prize 2015 (McDonald)

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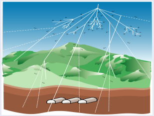

- Half the ν_μ lost in the Earth!
- Possible solution: ν_μ change to ν_τ
- Nobel Prize 2015 (Kajita)

Reactor neutrino experiments: 2012 +

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

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Because neutrinos have different masses and they mix !

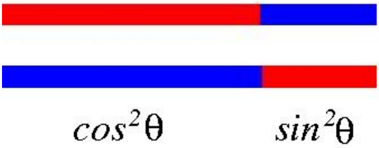
$\Uparrow$

Quantum Mechanics

What is meant by neutrino mixing ?

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

For example, ν_e–ν_μ mixing:

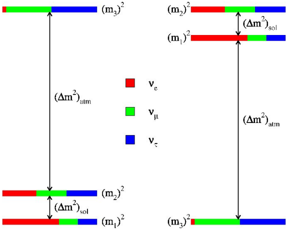


$$\nu_2 = -\nu_e \sin\theta + \nu_\mu \cos\theta$$

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

Still open mysteries about neutrino masses

Mixing of ν_e, ν_μ, ν_τ $\Rightarrow$ ν_1, ν_2, ν_3 (mass eigenstates)



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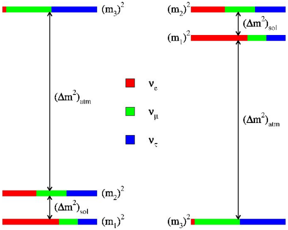
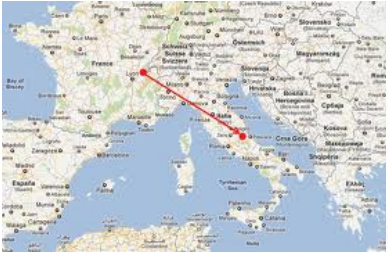
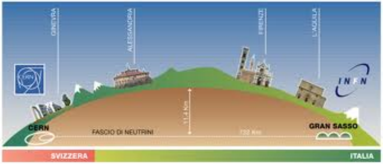


- Mass ordering: Normal or Inverted ?
- What are the absolute neutrino masses ?
- Are there more than 3 neutrinos ?
- Do neutrinos behave differently than antineutrinos ?
- Can neutrinos be their own antiparticles ?

A short-lived mystery (2011-12)





Superluminal neutrinos ?

The neutrinos do not travel faster than light

$\Uparrow$

Relativity

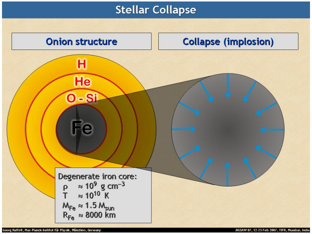
Those invisible neutrinos...

Neutrinos as messengers

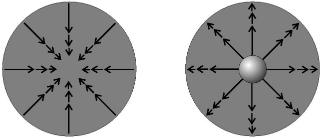
- No bending in magnetic fields $\Rightarrow$ point back to the source
- Minimal obstruction / scattering $\Rightarrow$ can arrive directly from regions from where light cannot come.

Supernova: the death of a star

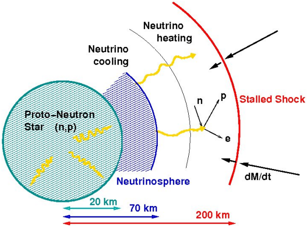
Gravity $\Rightarrow$



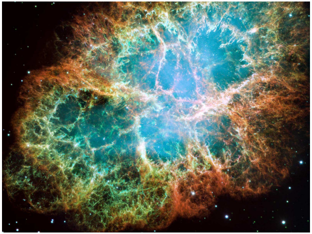
Strong nuclear force $\Rightarrow$



Weak nuclear force (Neutrino push) $\Rightarrow$



Electromagnetism (Hydrodynamics) $\Rightarrow$



(Crab nebula, SN seen in 1054)

What supernova neutrinos can tell us

On neutrino masses and mixing

- Identify neutrino mass ordering: normal or inverted

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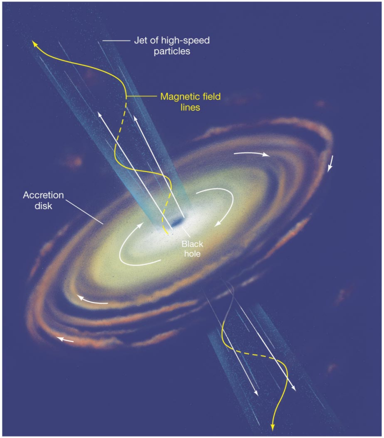
On neutrino masses and mixing

- Identify neutrino mass ordering: normal or inverted

On supernova astrophysics

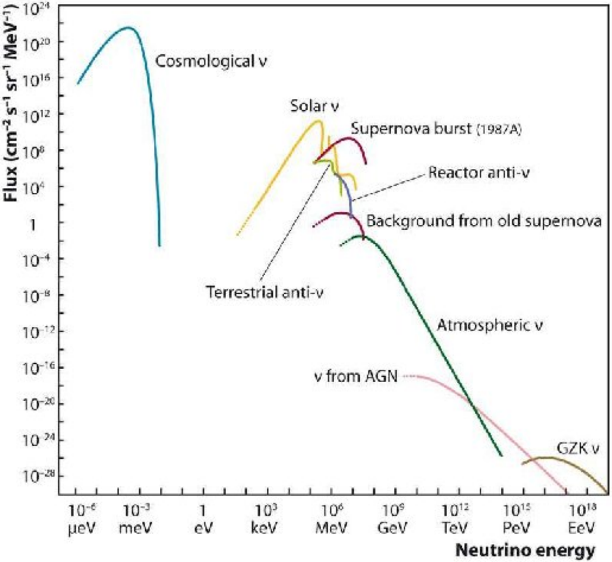
- Locate a supernova hours before the light arrives
- Track the shock wave through neutrinos while it is still inside the mantle (Not possible with light)
- How a neutron star is formed (Is there a QCD phase transition ?)

Active Galactic Nuclei (AGNs)



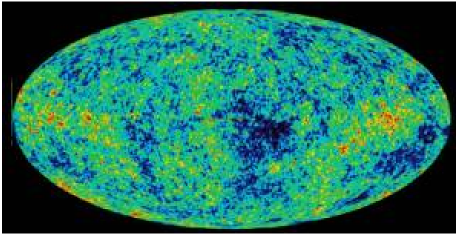
- The most powerful, long-lived objects in the universe
- Study of neutrinos will allow us to probe them deeper inside
- We might have seen the first neutrinos from AGNs in the last few years !!

Astrophysical neutrinos at all energies



The cosmological neutrinos (big-bang relics)

Empty space between galaxies is full of light and neutrinos



- Cosmic microwave background: 400 photons/ cm^3
  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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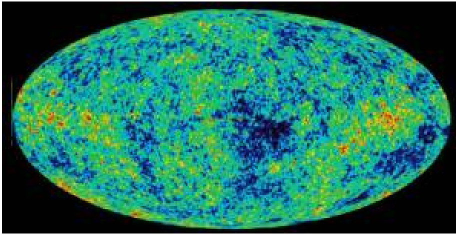
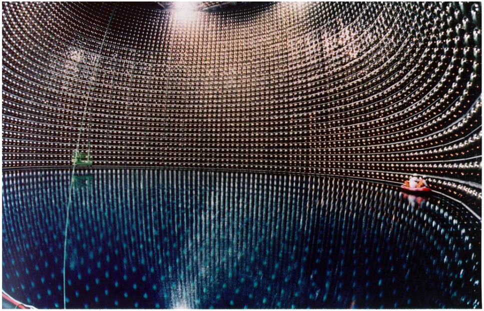
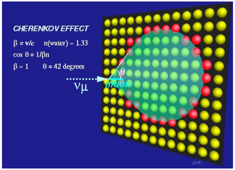


- Cosmic microwave background: 400 photons/ cm^3
  Temperature: $\sim$ 3 K
- Tell us about the universe when it was *only* 400,000 years old (Now it is $\sim$ 14 000 000 000 years old.)
- Cosmic neutrino background: 300 neutrinos / cm^3
  Temperature: $\sim$ 2 K
- Can tell us about the universe when it was 0.18 sec old !

Those invisible neutrinos...

SuperKamiokande: 50 kiloton of water





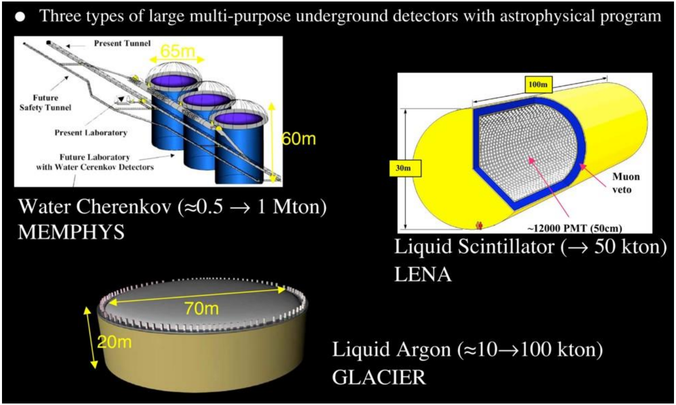
Cherenkov radiation

With 50 000 000 litres of water

- Neutrinos passing through SK per day: 10^{25}
- Neutrino interactions in SK per day: 5-10

Need bigger and better detectors !

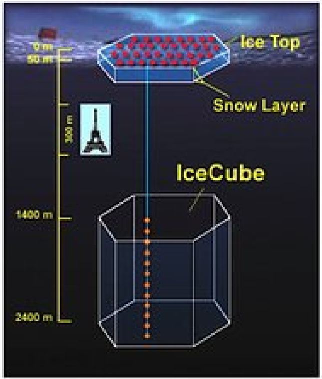
Directions of multi-purpose detector development

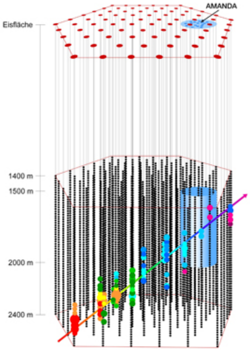


Sensitivity to MeV – 100 GeV neutrinos

- Measuring the energy of the sun in neutrinos
- Supernova neutrino detection

Below the antarctic ice: Gigaton IceCube

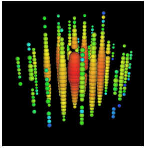




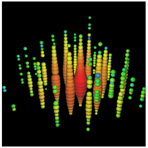
Sensitivity to $E \gtrsim 100$ GeV

- Neutrinos from Gamma Ray Bursts, late SN neutrinos
- Luminosity of SN neutrino burst

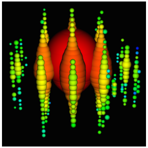
The three PeV (10^{15} eV) events at Icecube



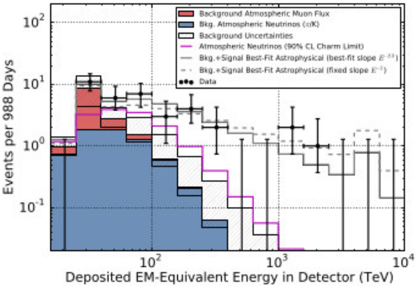
Bert



Ernie



Big Bird

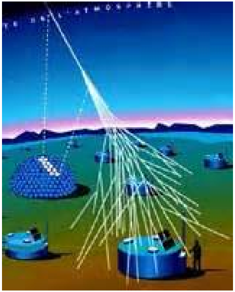


- Three events at $\sim 1, 1.1, 2.2$ PeV energies found
- Cosmogenic ? X Glashow resonance? X atmospheric ?

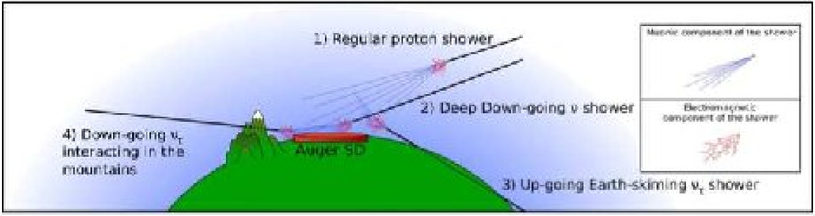
  Roulet et al 2013 ++ many
- IceCube analyzing 54 events from 30 TeV to 10 PeV
- Constraints on Lorentz violation: $\delta(v^2 - 1) \lesssim \mathcal{O}(10^{-18})$

  Borriello, Chakraborty, Mirizzi, 2013

Detection of UHE neutrinos: cosmic ray showers



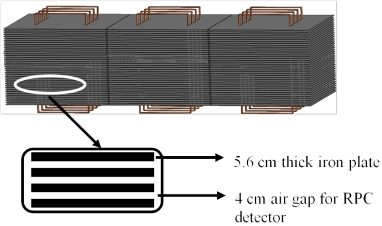
- Neutrinos with $E \gtrsim 10^{17}$ eV can induce giant air showers (probability $\lesssim 10^{-4}$)
- Deep down-going muon showers
- Deep-going ν_τ interacting in the mountains
- Up-going Earth-skimming ν_τ shower



Detection through radio waves: ANITA

- Charged particle shower $\Rightarrow$ Radio Askaryan: charged clouds emit coherent radio waves through interactions with $\mathbf{B}_{\rm Earth}$ or Cherenkov
- Detectable for $E \gtrsim 10^{17}$ eV at balloon experiments like ANITA

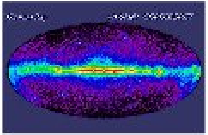
Coming soon(?) inside a mountain near you: INO

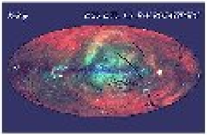


India-based Neutrino Observatory

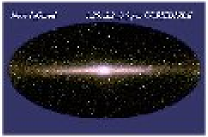
- In a tunnel below a peak (Bodi West Hills, near Madurai)
- 1 km rock coverage from all sides
- 50 kiloton of magnetized iron (50 000 000 kg)
- Can distinguish neutrinos from antineutrinos
- Determining mass hierarchy from atmospheric neutrinos

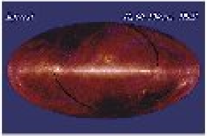
Mapping the universe with EM waves

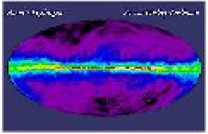

Gamma ray


X-ray

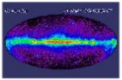

Visible

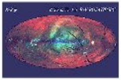

Near infrared


Infrared


Radio waves

Mapping the universe with neutrinos

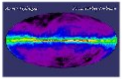

Gamma ray


X-ray

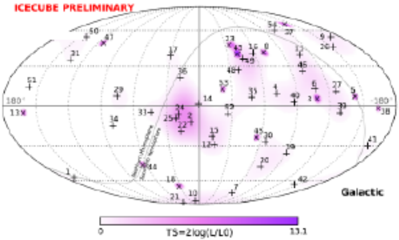

Visible

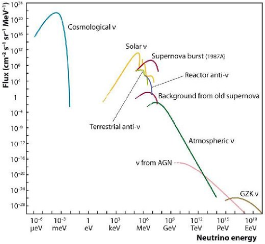

Near infrared


Infrared

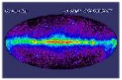

Radio waves

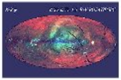
Neutrinos are entering this domain, slowly but surely...





Mapping the universe with neutrinos

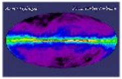

Gamma ray


X-ray


Visible


Near infrared


Infrared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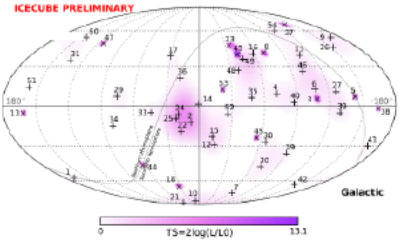

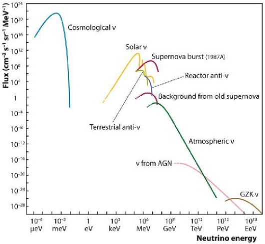

... and should be adding more colours to the universe...