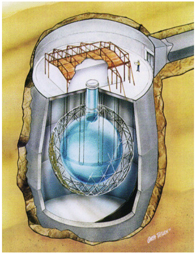
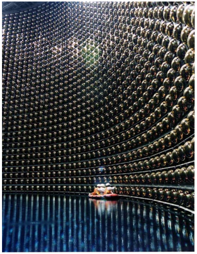
The changing flavours of neutrinos

The journey to Nobel 2015 and beyond

Amol Dighe
Department of Theoretical Physics
Tata Institute of Fundamental Research, Mumbai





Vijyoshi National Science Camp
IISER Kolkata, Dec 17, 2015

Nobel Prize in Physics 2015

Takaki Kajita
U. of Tokyo, Japan

Arthur McDonald
Queen's U., Canada

The Citation

" ... for the discovery of neutrino oscillations,
which shows that neutrinos have mass."

The mysteries of missing neutrinos

The extraordinary puzzles

- Where did the neutrinos from the Sun go ?
- Where did the neutrinos from the atmosphere go ?

The mysteries of missing neutrinos

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After efforts of more than 40 years ...

The extraordinary solution

- They "oscillated" to different "flavours"
- For this they must have nonzero mass

The mysteries of missing neutrinos

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- Where did the neutrinos from the atmosphere go ?

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- They "oscillated" to different "flavours"
- For this they must have nonzero mass

Now that we understand the solutions....

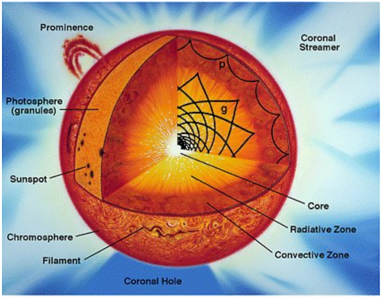
The extraordinary consequences

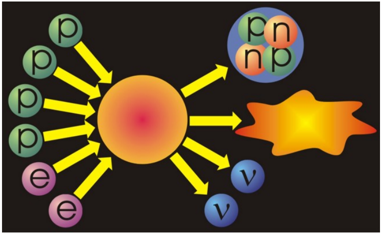
- Now we really are sure how the Sun shines
- Now we really don't know how neutrinos get their mass

The changing flavours of neutrinos

The changing flavours of neutrinos

How does the sun shine ?





- Nuclear fusion reactions: effectively

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

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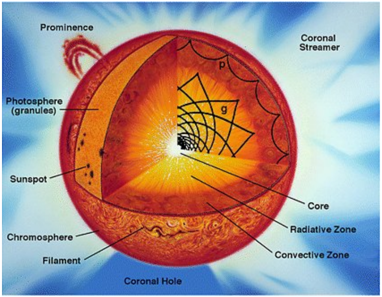

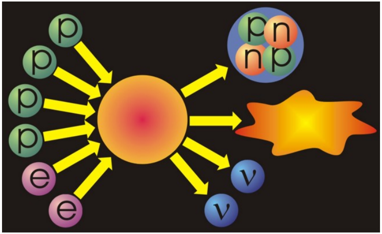

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- Neutrinos needed to conserve energy, momentum, angular momentum in all the steps

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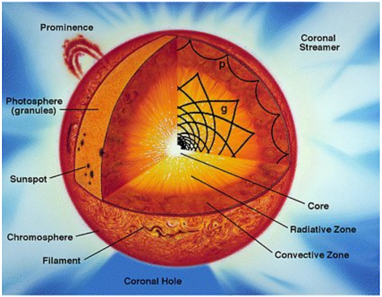

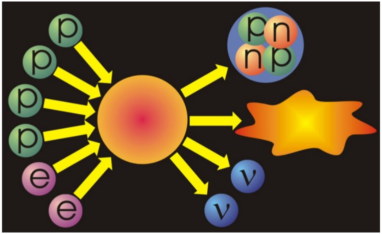

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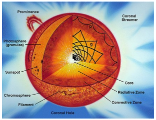
Neutrinos essential for the Sun to shine !!

Davis-Koshiba Nobel prize 2002

Neutrinos from the Sun



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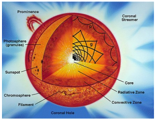

A very very large number of neutrinos

About hundred trillion through our body per second

Hundred trillion = 100 000 000 000 000

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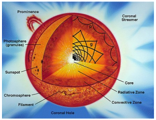

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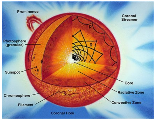

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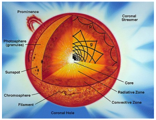
Neutrinos from the Sun



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Why do we not notice them ?

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 ?

Three questions about neutrinos

Pauli Dirac

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- Why do neutrinos from the Sun reach us during night ?
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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

The most weakly interacting particles

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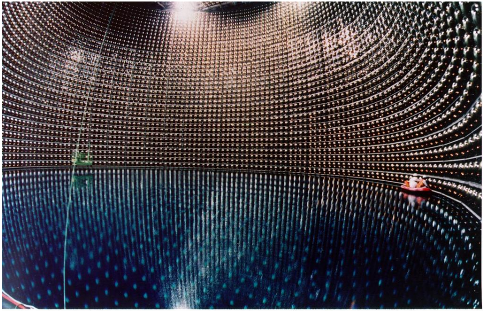
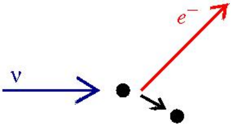
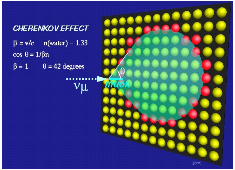
  Neutrinos pass through the Sun without interacting

How do we see the neutrinos then ?

SuperKamiokande: 50 000 000 litres of water







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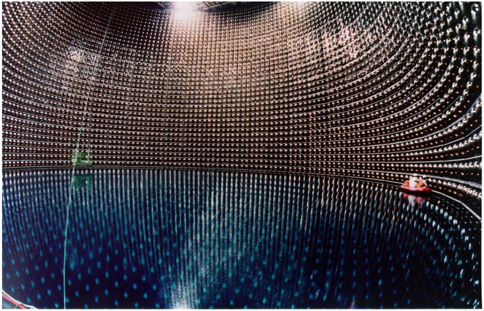
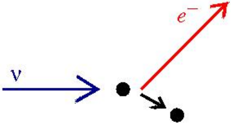
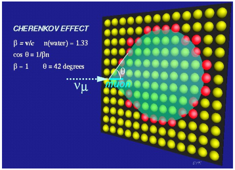




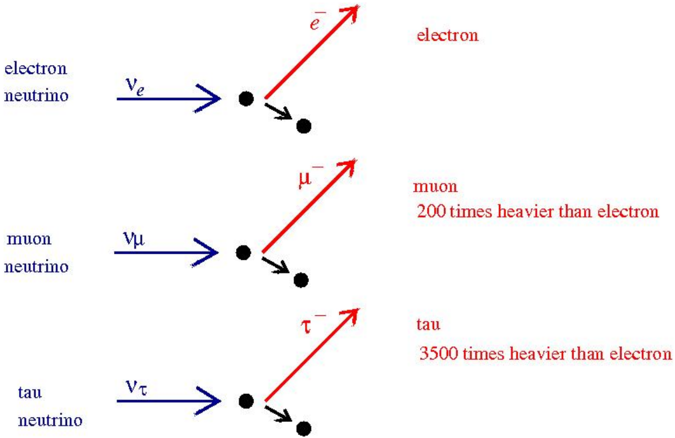


Recipe for observing neutrinos

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

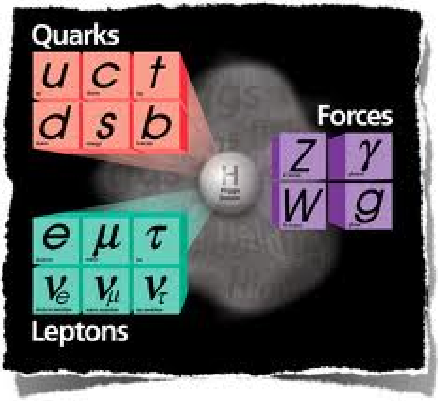
SuperKamiokande observes about 5-10 neutrinos per day

Three kinds ("flavours") of neutrinos: ν_e ν_μ ν_τ



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

The Standard Model of Particle Physics

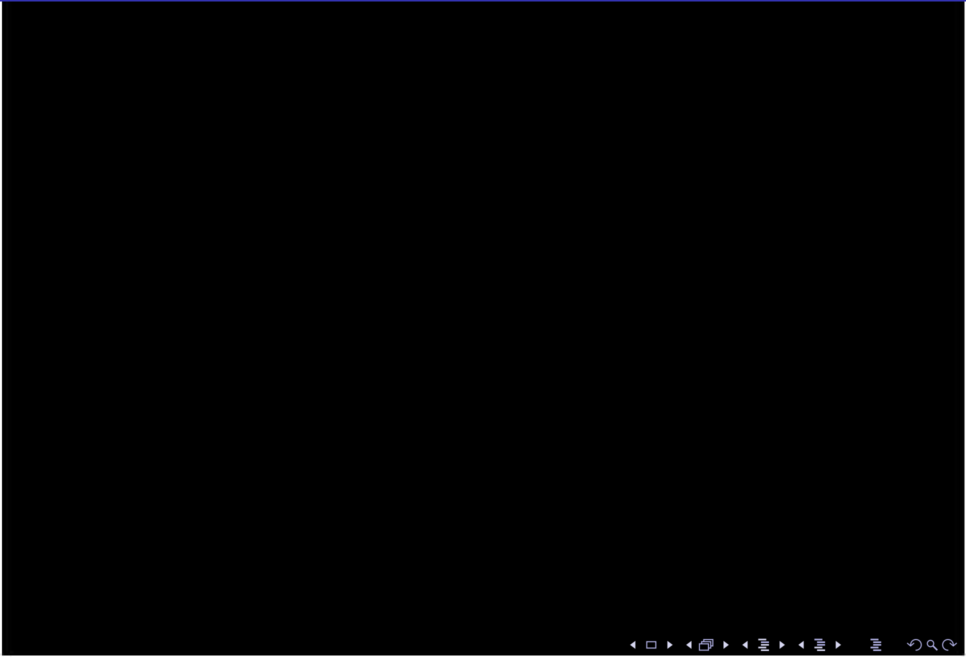


- 3 neutrinos:
  ν_e, ν_μ, ν_τ
- Zero charge
- spin 1/2
- almost massless:
  at least a million
  times lighter
  than electron

The changing flavours of 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

- Earth has elements heavier than iron, which cannot be created inside the Sun, or in any ordinary star

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- Earth has elements heavier than iron, which cannot be created inside the Sun, or in any ordinary star
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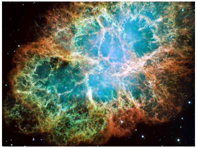
- This can happen only inside an exploding star (supernova)!
- A supernova must have exploded bilions of years ago whose fragments formed the solar system



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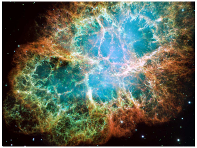
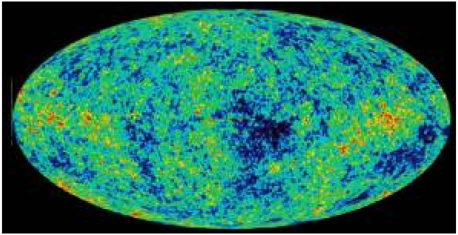


Supernovae explode because ...
neutrinos push the shock wave from inside !

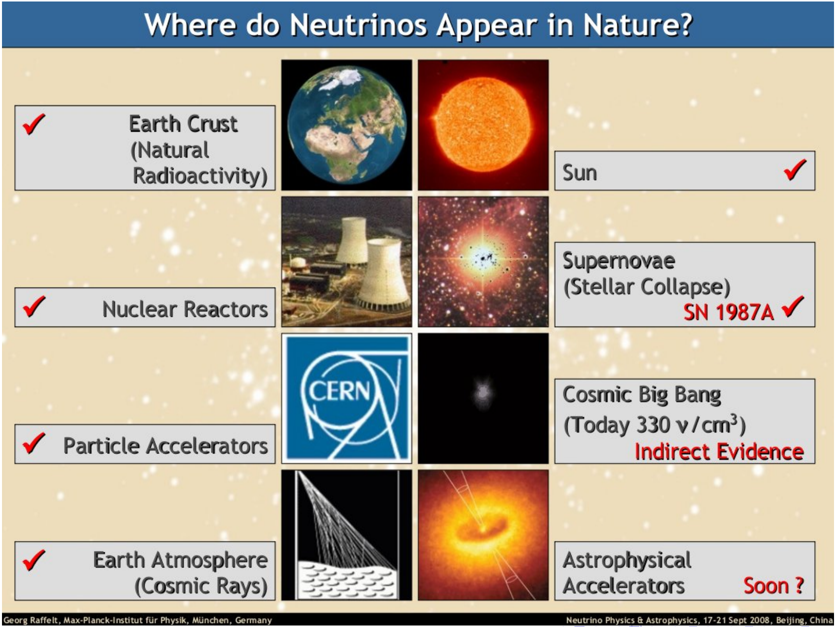
The second-most abundant particles in the universe



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

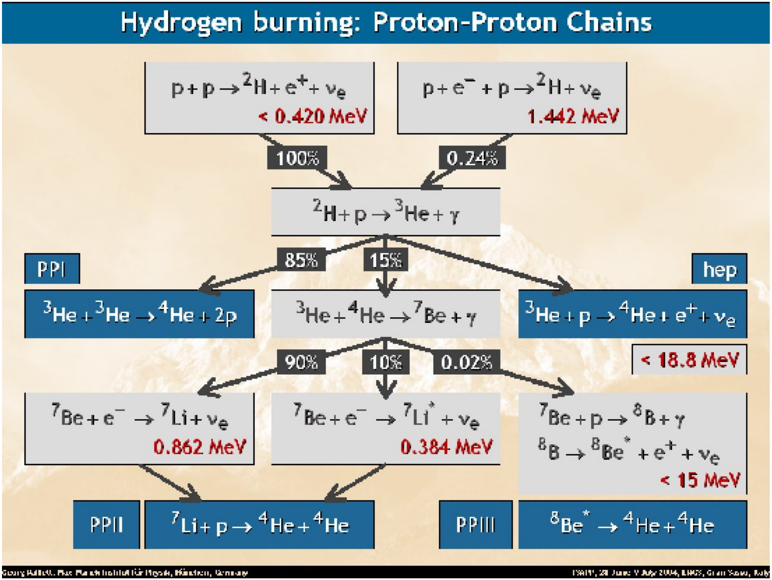
Even empty space between galaxies is full of neutrinos !

Neutrinos everywhere



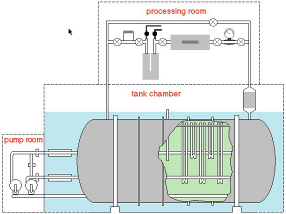
The changing flavours of neutrinos

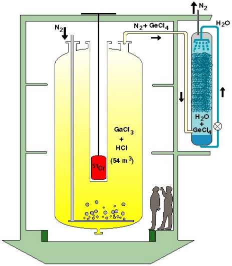
Neutrinos from the Sun

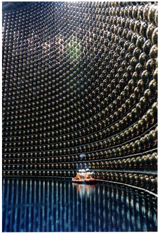


Detecting neutrinos from the Sun

- The Sun produces ν_e
- These ν_e can be detected at Earth: difficult, but possible





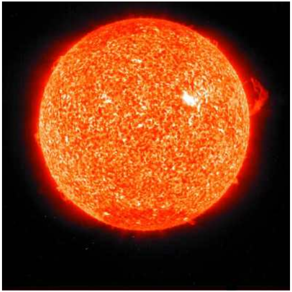


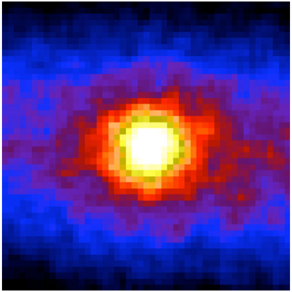
$\nu_e + \mathrm{Cl} \to \mathrm{Ar} + e^-$
Homestake

$\nu_e + \mathrm{Ga} \to \mathrm{Ge} + e^-$
Gallex

$\nu_e + e^- \to \nu_e + e^-$
SuperKamiokande

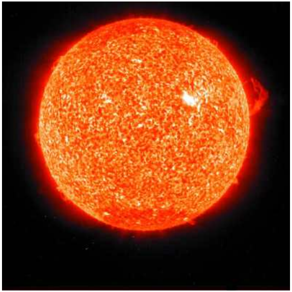
Seeing the Sun with neutrinos





- Light from the Sun's surface:
  due to nuclear reactions
  millions of years ago
- Neutrinos from the Sun's core:
  due to nuclear reactions
  8 minutes ago

Seeing the Sun with neutrinos



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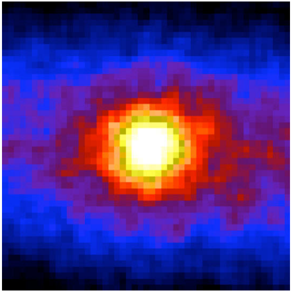
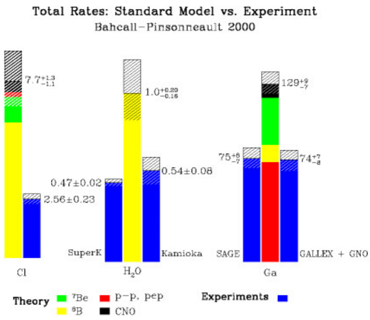
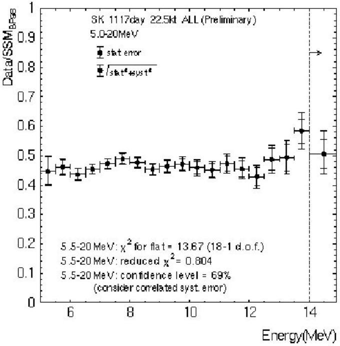


- We know how much light we get from the Sun...
- So we know how many neutrinos should arrive.

BUT...

Do we really understand how the Sun shines ?





Observations

- Only about 30%–50% of neutrinos from the Sun found
- Different experiments give different suppressions
  (They look at different energy ranges, of course..)
- SuperKamiokande shows suppression at all energies

Possible resolutions of the puzzle

- The astrophysicists cannot calculate accurately
- The experimentalists cannot measure accurately
- Neutrinos behave differently from what everyone thought !

.... remained unresolved for about 40 years !

The breakthrough idea

Bruno Pontecorvo

Maybe the neutrino flavours change !

- All the experiments are looking for ν_e
- What if ν_e are getting converted to other flavours of neutrinos (ν_μ or ν_τ) ?

The breakthrough idea

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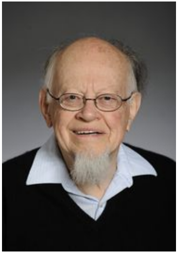
Maybe the neutrino flavours change !

- All the experiments are looking for ν_e
- What if ν_e are getting converted to other flavours of neutrinos (ν_μ or ν_τ) ?
- This is possible, but only if the neutrinos have different masses and they mix !

Neutrino flavour changes inside the Sun

John Bahcall

Lincoln Wolfenstein



Stanislav Mikheyev

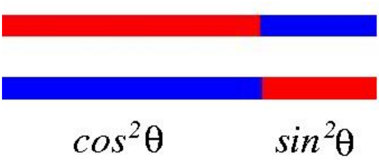
Alexei Smirnov

- Bahcall: Calculated the neutrino production inside the Sun in detail
- Wolfenstein: Showed that the neutrino mixing gets affected by the matter inside the Sun
- Mikheyev – Smirnov: Showed how these matter effects affect the neutrino flavour changes

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:



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

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

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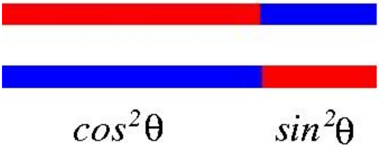
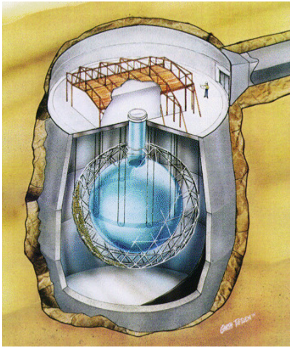


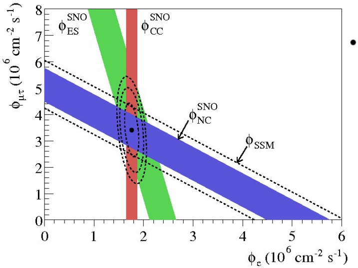
$$\nu_2 = -\nu_e \sin\theta + \nu_\mu \cos\theta$$

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

- Only ν_1 and ν_2 have fixed masses
- Then, if you produce ν_e, it may convert to ν_μ !
- How do we check this ?

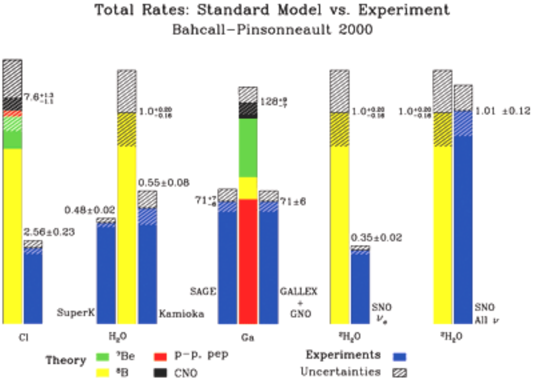
Heavy water Cherenkov experiment: SNO





- $\boxed{\text{Heavy water Cherenkov}}$
- $\nu_e\, D \rightarrow p\, p\, e^-$
  sensitive to Φ_e
- $\nu_{e,\mu,\tau}\ e^- \rightarrow \nu_{e,\mu,\tau}\ e^-$
  Sensitive to $\Phi_e + \Phi_{\mu\tau}/6$
- $\nu_{e,\mu,\tau}\ D \rightarrow n\, p\, \nu_{e,\mu,\tau}$
  sensitive to $\Phi_e + \Phi_{\mu\tau}$
- Neutral current: no effect of oscillations

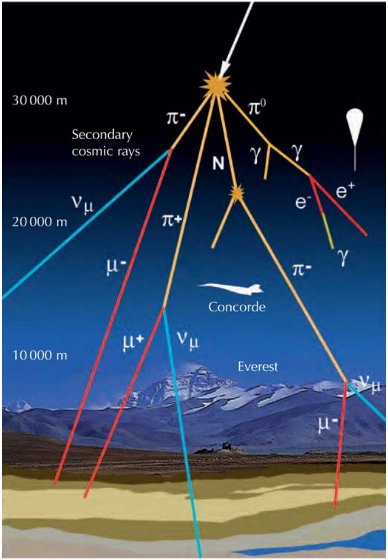
Solar neutrino problem settled (2002)



- All neutrinos from the Sun are now accounted for !
- Our understanding of the Sun is vindicated...

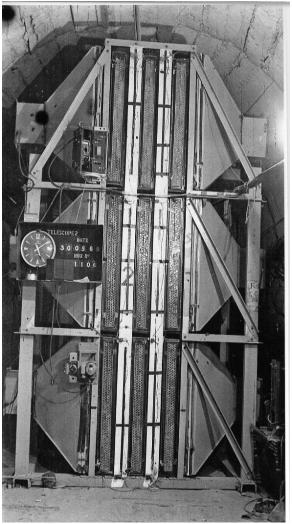
The changing flavours of neutrinos

Neutrinos from cosmic rays



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

The first “atmospheric” neutrinos detected in India



Detector in
Kolar Gold Fields

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Physics Letters 18, (1965) 196

(15th Aug 1965)

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

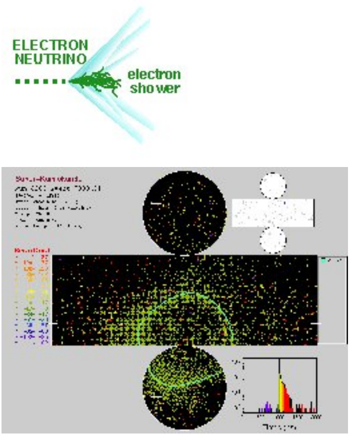
F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio
and
J. P. F. Sellschop and B. Meyer
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

PRL 15, (1965) 429

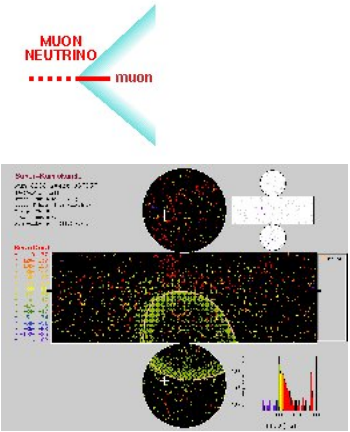
(30th Aug 1965)

Detecting ν_e and ν_μ through Cherenkov cones

SuperKamiokande: Water Cherenkov



Diffused ring



Sharp ring

Missing ν_μ from atmospheric neutrinos

Super-Kamiokande

$\boxed{\text{Multi-GeV}}$

- Fully contained ($E_{vis} > 1.33$ GeV)

	Data	MC
1 Ring e-like	290	236.0
1 Ring μ-like	230	297.5
Multi-Ring	533	560.1

- Partially contained

	Data	MC
Total = μ-like	301	371.6

$*$ CC $\overset{(-)}{\nu_\mu}$ / all p.c. = 0.98

$$\frac{(\mu/e)_D}{(\mu/e)_{MC}} = 0.65 \pm \underset{\text{stat}}{0.05} \pm \underset{\text{syst + MC stat}}{0.08}$$

Kam. $= 0.57 {}^{+0.08}_{-0.07} \pm 0.07$

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- Something wrong with detection ?
- Something wrong with our understanding of cosmic rays ?

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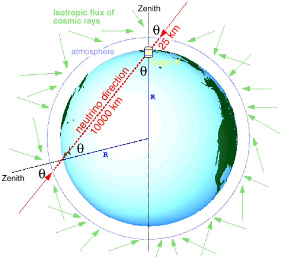
- Something wrong with detection ?
- Something wrong with our understanding of cosmic rays ?
- Neutrinos behave differently from what everyone thought ??

The breakthrough idea



- Cosmic ray flux isotropic ⇒
  No. of “Down” neutrinos
  = No. of “Up” neutrinos
  (along a line)

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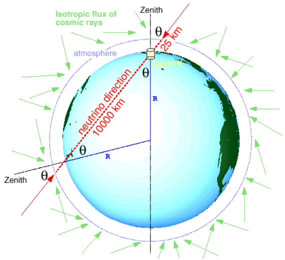

- Cosmic ray flux isotropic $\Rightarrow$
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- But if neutrinos have mass and they mix $\Rightarrow$
  neutrinos travelling longer will have more time to convert to other neutrino flavours :

Neutrino oscillations

$$P(\nu_\mu \to \nu_x) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad (\Delta m^2 = m_2^2 - m_1^2)$$

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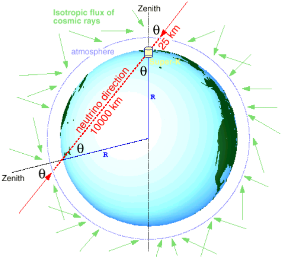

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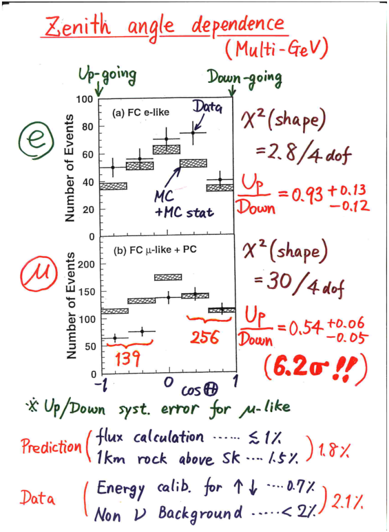
- More "Up" neutrinos travelling through the Earth will be lost, than those coming "Down" from above

The zenith angle dependence (1998) !

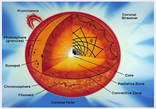


- Indeed more ν_μ travelling through the Earth are lost
- The zenith angle dependence fits the form of the probability expressions exactly
- Neutrino oscillation hypothesis proved !

The changing flavours of neutrinos

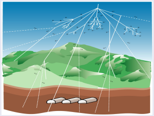
Neutrino puzzles ⇒ neutrino oscillations

Solar neutrino puzzle: 1960s – 2002



- Only about half the expected ν_e observed!

Atmospheric neutrino puzzle: 1980s – 1998



- Half the ν_μ lost in the Earth!

Reactor neutrino experiments

- Breaking news of 2012:
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Neutrino puzzles $\Rightarrow$ neutrino oscillations

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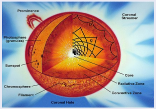

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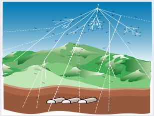

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Three questions, the same answer

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 ?
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$\Uparrow$

Quantum Mechanics (working at large distances !)

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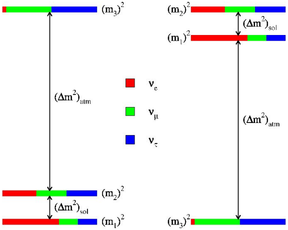
Quantum Mechanics (working at large distances !)

Experiments can measure Δm^2 and mixing angles

Still open mysteries about neutrino masses

$\boxed{\text{Mixing of } \nu_e, \nu_\mu, \nu_\tau \Rightarrow \nu_1, \nu_2, \nu_3 \text{ (mass eigenstates)}}$



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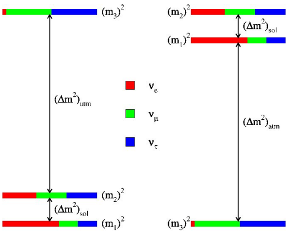

- Mass ordering: Normal or Inverted ?
- What are the absolute neutrino masses ?
- Are there more than 3 neutrinos ?
- Is there leptonic CP violation ?
- Can neutrinos be their own antiparticles ?

And how do neutrinos get their mass at all ?

- In Standard Model of particle physics, the mass arises from the interaction between a left-handed particle, a right-handed particle, and Higgs.
  For example, e_L, e_R and h come together to give mass to the electron, which contains both e_L and e_R.

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- But there is no right-handed neutrino !
  $\Rightarrow$ Higgs mechanism is not enough

- There *has to be* something beyond the Standard Model, perhaps even beyond our current imagination.

- Many further mysteries of neutrinos are definitely yet to present themelves....

Exploration of neutrinos over a wide energy range

keV-energy neutrinos (10^3 eV)

- Neutrinoless double beta decay experiments:
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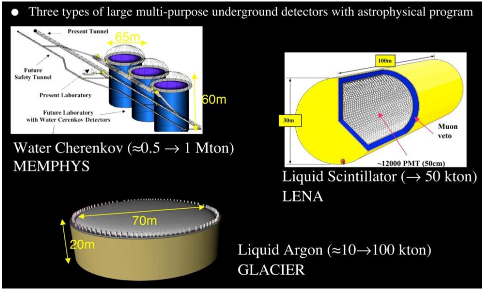
TeV-PeV-EeV energy neutrinos ($\gtrsim 10^{12}$ eV)

Astrophysical neutrinos: supernovae, AGNs, etc.

Bigger detectors, ambitious experiments



- Megaton water Cherenkov detectors
- 50 kiloton scintillator detectors
- 100 kiloton liquid Ar detectors

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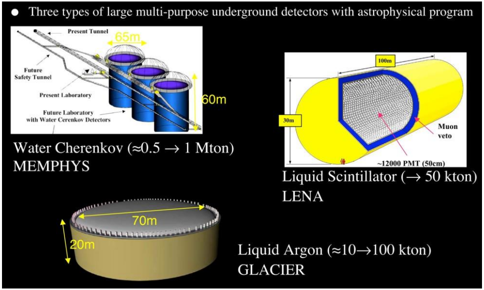

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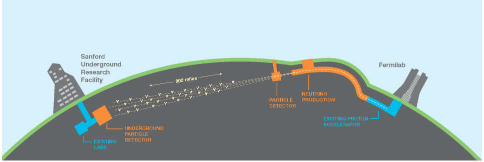
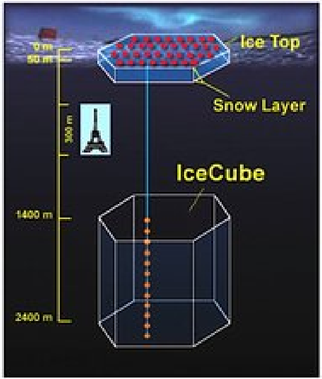
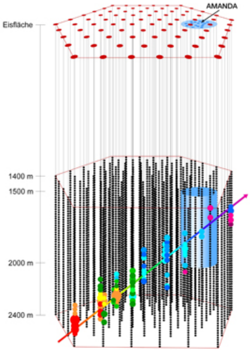


- Deep Underground Neutrino Experiment (DUNE)
- Detector 1600 km away from source

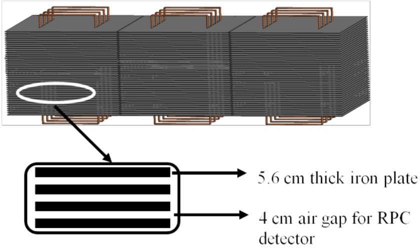
Below the antarctic ice: Gigaton IceCube

1 000 000 000 000 litres of ice





Coming soon inside a mountain near you: INO



India-based Neutrino Observatory

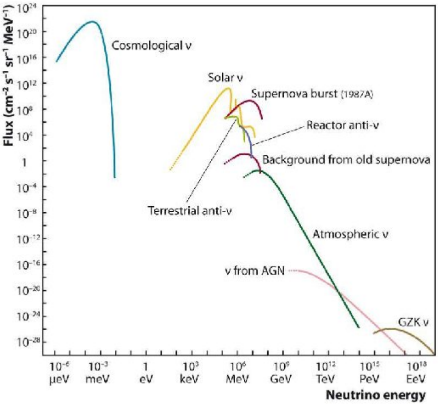
- In a tunnel below a peak (Bodi West Hills, near Madurai)
- 1 km rock coverage from all sides
- 50 kiloton of magnetized iron (50 000 000 kg)
- Can distinguish neutrinos from antineutrinos
- Determining mass hierarchy from atmospheric neutrinos

The changing flavours of neutrinos

Neutrinos from the sky at all energies

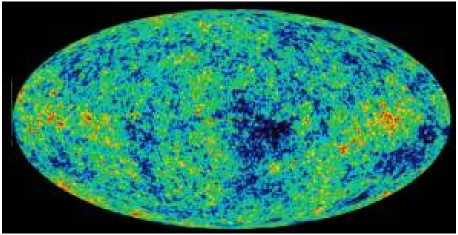
Neutrinos as good messengers

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



The big-bang neutrinos

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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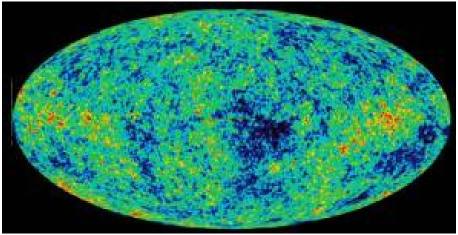

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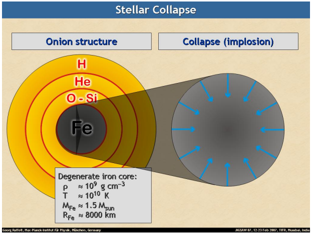
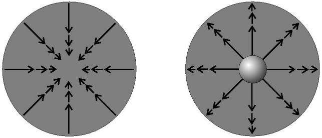
- Cosmic neutrino background: 300 neutrinos / cm^3
  Temperature: $\sim$ 2 K
- Can tell us about the universe when it was 0.18 sec old !

Supernova: the death of a star

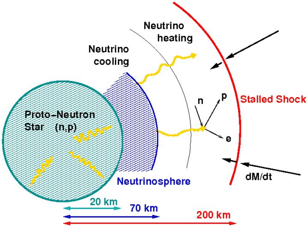
Gravity ⇒



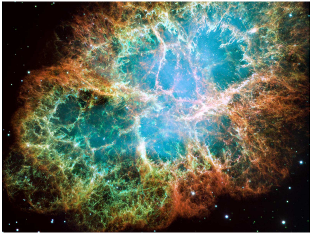
Strong nuclear force ⇒



Weak nuclear force
(Neutrino push) ⇒



Electromagnetism
(Hydrodynamics) ⇒



(Crab nebula, SN seen in 1054)

What supernova neutrinos can tell us

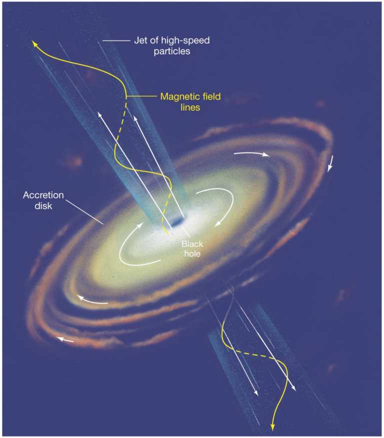
On neutrino masses and mixing

- Identify neutrino mass ordering: normal or inverted

On supernova astrophysics

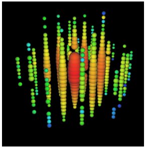
- Locate a supernova hours before the light arrives
- Track the shock wave through neutrinos while it is still inside the mantle (Not possible with light)

Active Galactic Nuclei (AGNs)

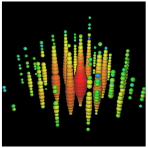


- The most powerful, long-lived objects in the universe
- Study of neutrinos will allow us to probe them deeper inside
- We might just have seen the first neutrinos from AGNs last year !!

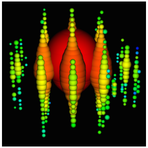
The three PeV events at Icecube



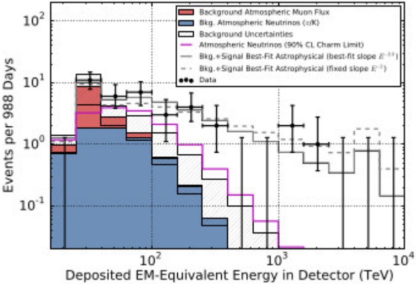
Bert



Ernie



Big Bird

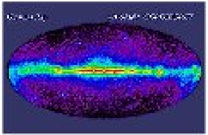


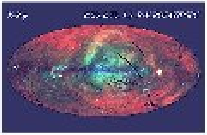
- Three events at $\sim 1, 1.1, 2.2$ PeV energies found
- Cosmogenic ? X Glashow resonance? X atmospheric ?

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

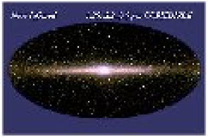
  Borriello, Chakraborty, Mirizzi, 2013

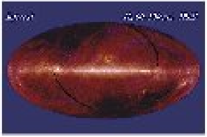
Mapping the universe in light waves

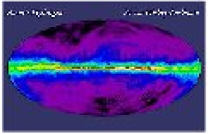

Gamma ray


X-ray

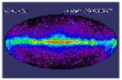

Visible


Near infrared


Infrared


Radio waves

Mapping the universe in neutrinos



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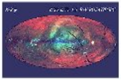

X-ray

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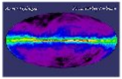
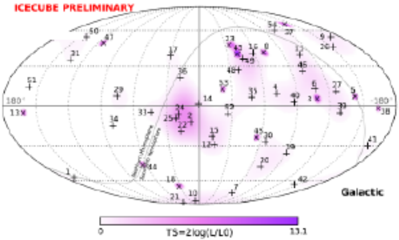
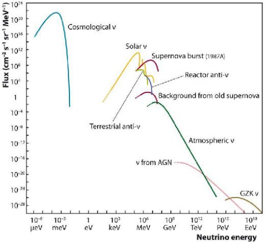


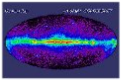
Radio waves

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





Mapping the universe in neutrinos



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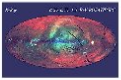

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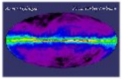

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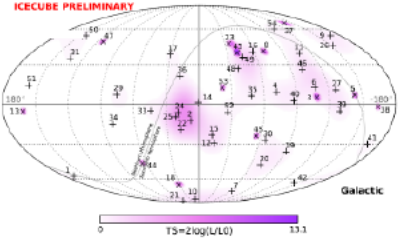

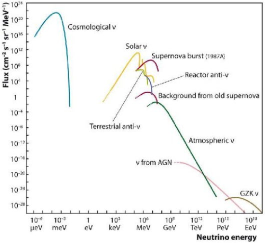

... and should be adding more colors to the universe...

Menu of neutrino flavours for future

- Determining neutrino properties (more surprises ?)
- Using neutrinos to see the universe
- Figuring out the neutrino mass puzzle
- Speculative applications: nuclear non-proliferation, Earth tomography, oil exploration, communication, ...

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Something not-thought-of-yet is bound to turn up ...