Neutrinos

a new window to see the Universe

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

"Scienter" Stage, Vigyan Samagam
Nehru Science Centre, Mumbai, May 8th, 2019

Neutrinos: a new window to see the Universe

1. Neutrinos in particle physics, astrophysics, cosmology
2. Neutrino masses and mixing
3. Looking at the sky in neutrinos

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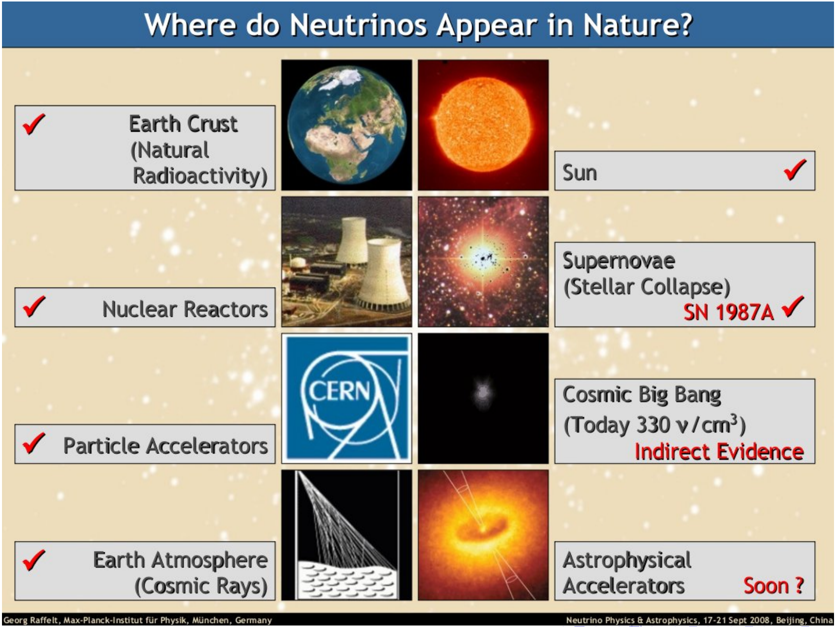
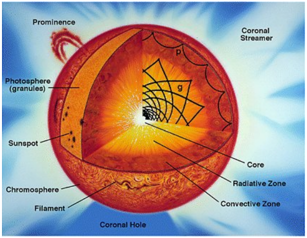
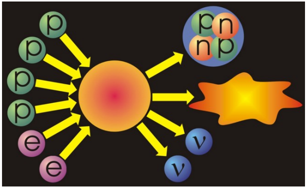
Omnipresent neutrinos



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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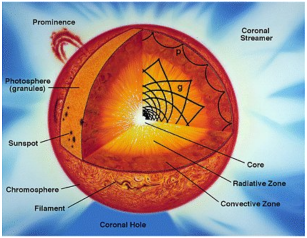
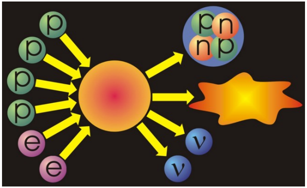


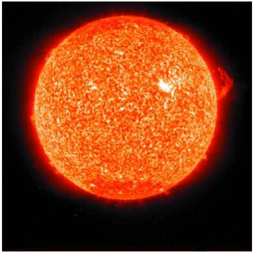


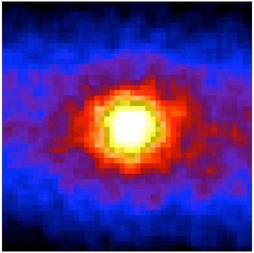
- Nuclear fusion reactions: effectively
$$4\ {}^1_1\mathrm{H} + 2e^- \rightarrow {}^4_2\,\mathrm{He} + \mathrm{light}$$
$$+2\nu_e$$
- Neutrinos needed to conserve energy, momentum, angular momentum in all the steps

Neutrinos essential for the Sun to shine !!

Davis-Koshiba Nobel prize 2002

Looking inside the Sun with neutrinos





- A few hundred trillion solar neutrinos per second through the human body, go undetected

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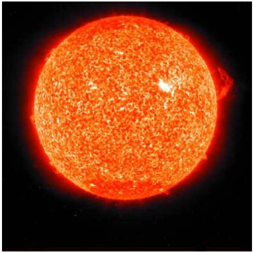
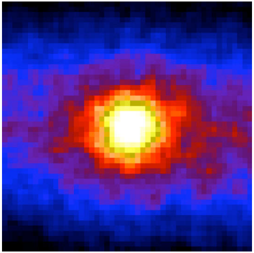
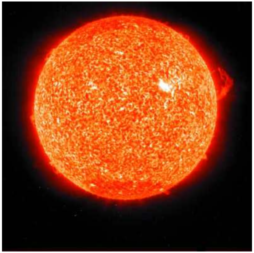
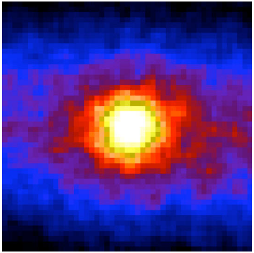




- A few hundred trillion solar neutrinos per second through the human body, go undetected
- The same number of neutrinos during the day and the night !

Looking inside the Sun with neutrinos





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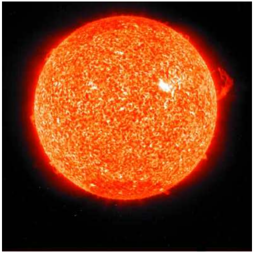
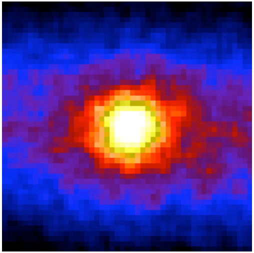
- The same number of neutrinos during the day and the night !
- Light from the Sun's surface: due to nuclear reactions millions of years ago
- Neutrinos from the Sun's core: due to nuclear reactions 8 minutes ago

Looking inside the Sun with neutrinos





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How to make sense of these features ?

The most weakly interacting particles

Stopping radiation with lead shielding

- Stopping α, β, γ radiation: 50 cm

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Understanding the three features

- Why do we not notice neutrinos passing through us?
  Neutrinos pass through our bodies without interacting
- Why do neutrinos from the Sun reach us during night ?
  Neutrinos pass through the Earth without interacting
- Why can the neutrinos reach us from the core of the Sun ?
  Neutrinos pass through the Sun without interacting

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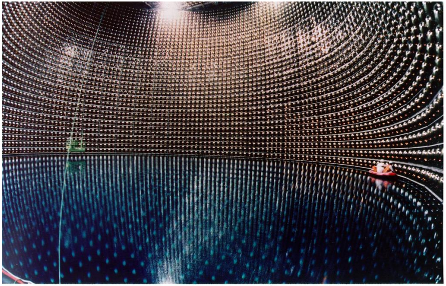
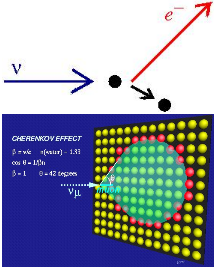
How do we see the neutrinos then ?

How to detect neutrinos: wait till they interact !





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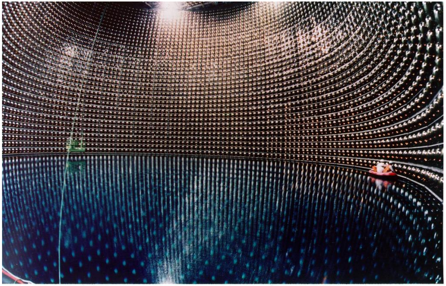

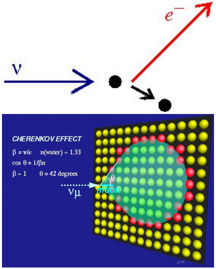

SuperKamiokande: 50 000 000 litres of water

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- SuperKamiokande observes about 5-10 neutrinos per day

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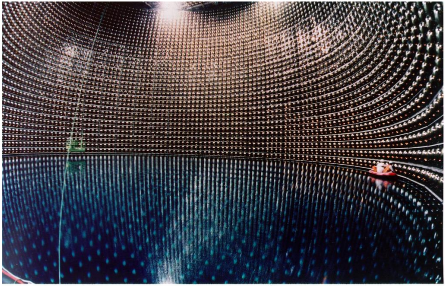

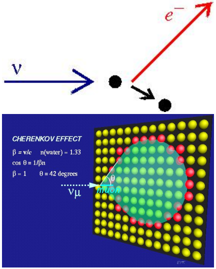

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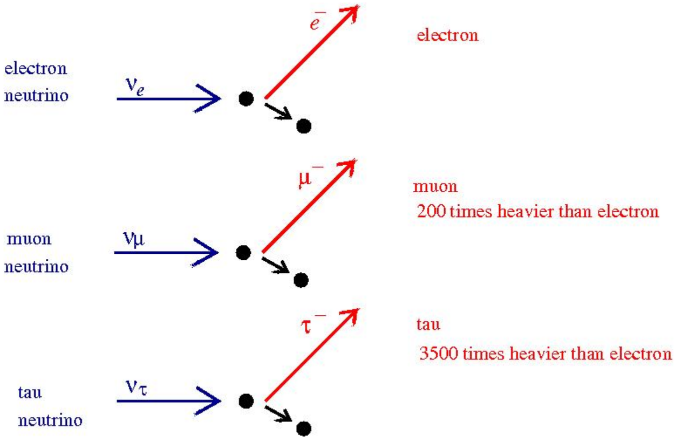
Recipe for observing neutrinos

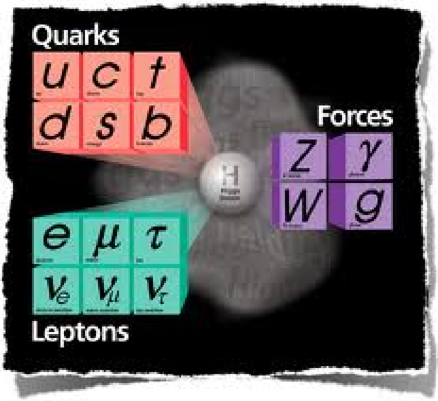
- Build very large detectors
- Wait for a very long time

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



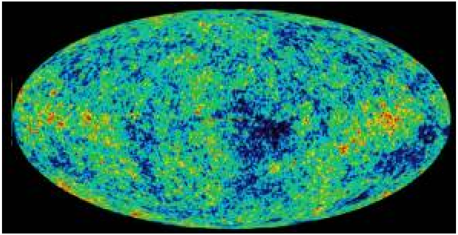
Antineutrinos $\overline{\nu}_e$, $\overline{\nu}_\mu$, $\overline{\nu}_\tau$ produce positively charged particles

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 second-most abundant particles in the universe

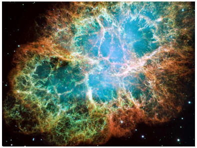


- Cosmic microwave background: 400 photons/ cm^3
  Temperature: $\sim$ 3 K
- Cosmic neutrino background: 300 neutrinos / cm^3
  Temperature: $\sim$ 2 K

Even empty space between galaxies is full of neutrinos !

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
- This can happen only inside an exploding star (supernova)!
- A supernova must have exploded billions of years ago whose fragments formed the solar system



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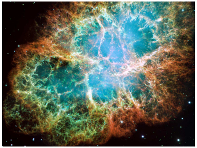
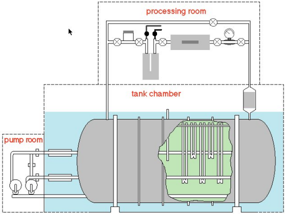


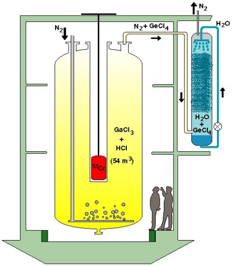
Supernovae explode because ...
neutrinos push the shock wave from inside !

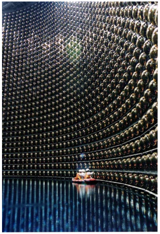
Role of neutrinos in creating matter

- Lack of antimatter in the universe cannot be accounted for by interactions of quarks
- Neutrinos have the potential to create the matter-antimatter asymmetry, essential for a universe made of matter

The solar neutrino puzzle (1960s – 2002)







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

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

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

- The sun produces ν_e, can detect at the Earth
- The number of neutrinos should match Sun's energy output

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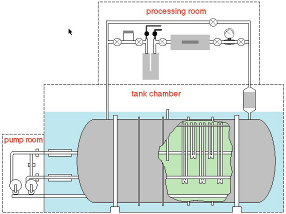

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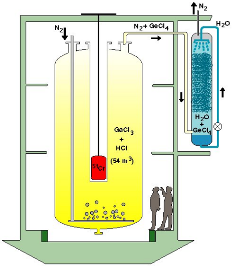

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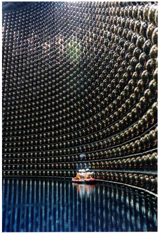


$\nu_e + e^- \to \nu_e + e^-$

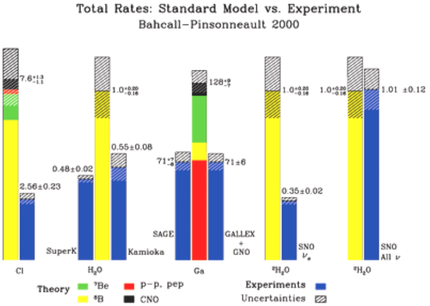
SuperKamiokande

- The sun produces ν_e, can detect at the Earth
- The number of neutrinos should match Sun's energy output
- A deficit of 30% – 50% at all detectors !
- Do we understand the Sun at all ?

Solar ν puzzle solution: neutrino flavor conversion

Maybe the neutrino flavors change !

- All the experiments are looking for ν_e
- Maybe ν_e are getting converted to (ν_μ or ν_τ) ?
- If we detect all neutrino flavors, numbers match $\Rightarrow$



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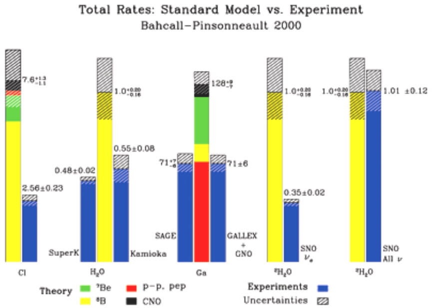
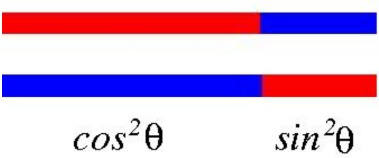


Possible, if the neutrinos have different masses and they mix !

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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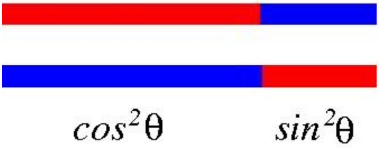
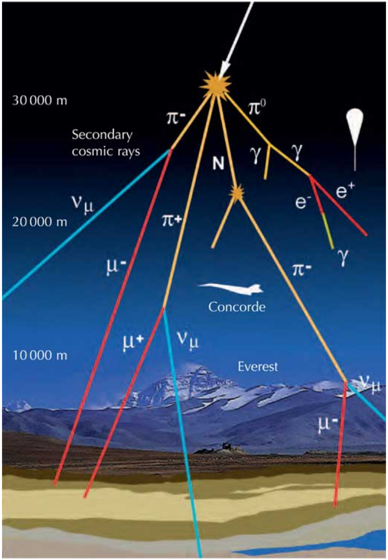


$$\nu_2 = -\nu_e \sin\theta + \nu_\mu \cos\theta$$

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

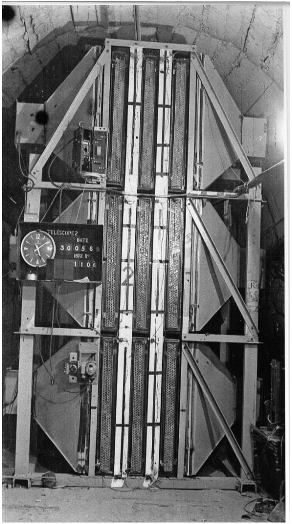
- Only ν_1 and ν_2 have fixed masses
  (*They are eigenstates of energy / eigenstates of evolution*)
- Then, if you produce ν_e, it may convert to ν_μ !
- **This is quantum mechanics at large length scales !**

The atmospheric neutrinos



- $\pi^+ \to \mu^+ + \nu_\mu$
- $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

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)

Atmospheric neutrino puzzle and its solution

The puzzle

- Half of the ν_μ lost when coming “up” through the Earth
- All ν_e, and down-going ν_μ accounted for !

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- Half of the ν_μ lost when coming "up" through the Earth
- All ν_e, and down-going ν_μ accounted for !

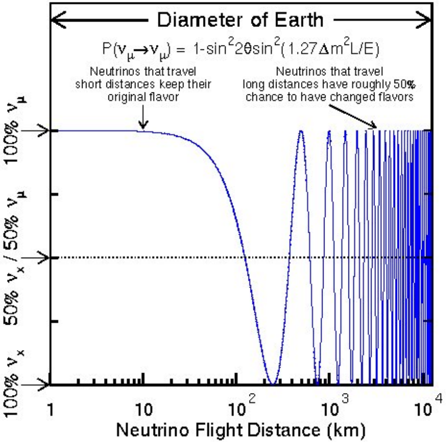
If neutrinos have masses and they mix...

- Neutrinos travelling longer will have more time to convert to other neutrino flavours
- More "Up" neutrinos travelling through the Earth will be lost, than those coming "Down" from above
- The loss must be
  mainly through $\nu_\mu \to \nu_\tau$, and
  not much through $\nu_\mu \to \nu_e$.

Neutrino "oscillations"

Neutrino flavours "oscillate"

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



Nobel Prize in Physics 2015

Takaki Kajita
U. of Tokyo, Japan

Arthur McDonald
Queen's U., Canada

The Citation

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which shows that neutrinos have mass."

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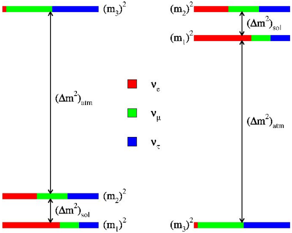
How do neutrinos get their mass ? .... unresolved question

The three-neutrino mixing picture: consolidation

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



- $\Delta m^2_{\rm atm} \approx 2.4 \times 10^{-3}$ eV^2
- $\Delta m^2_{\odot} \approx 8 \times 10^{-5}$ eV^2
- $\theta_{\rm atm} \approx 45°$
- $\theta_{\odot} \approx 32°$
- $\theta_{\rm reactor} \approx 9°$

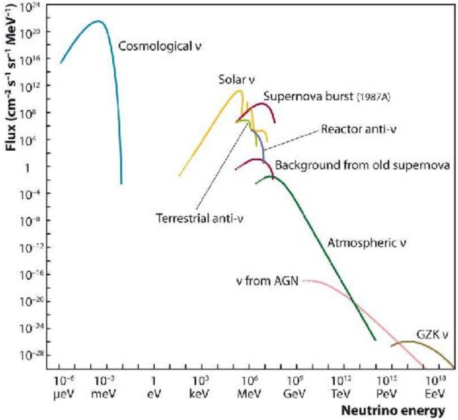
- Mass ordering: Normal (N) or Inverted (I) ?
- What are the absolute neutrino masses ?
- Are there more than 3 neutrinos ?
- Is there leptonic CP violation ?
- Can neutrinos be their own antiparticles ?

Neutrinos: a new window to see the Universe

Neutrinos as messengers from the universe

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



ASPERA

The big-bang relic neutrinos ($\sim$ 0.1 meV)

- Relic density: $\sim$ 110 neutrinos /flavor /cm^3
- Temperature: $T_\nu = (4/11)^{1/3} T_{\rm CMB} \approx 1.95\ {\rm K} = 0.17\ {\rm meV}$

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- The effective number of neutrino flavors: $N_{\mathrm{eff}}(\mathrm{SM}) = 3.074$. Planck $\Rightarrow$ $N_{\mathrm{eff}} = 3.30 \pm 0.27$.
- Contribution to dark matter density:

$$\Omega_\nu / \Omega_{\mathrm{baryon}} = 0.5 \left(\sum m_\nu / \mathrm{eV} \right)$$

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- Looking really far back:

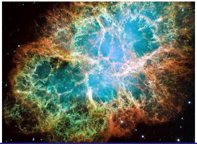
	Time	$T_{\rm decoupling}$	z
CMB photons	$\sim 400,000$ years	0.26 eV	1100
Relic neutrinos	0.18 s	~ 2 MeV	$\sim 10^{10}$

Lazauskas, Vogel, Volpe, 2008

Experiments with induced inverse beta decay end-point

$$\nu_e + {}^A_Z X \to {}^A_{Z+1} Y + e^-$$

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



On neutrino masses and mixing

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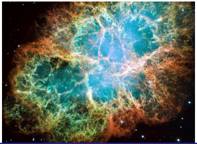

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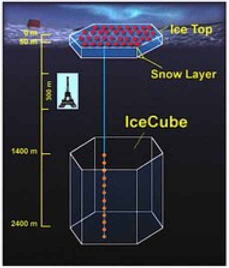
On supernova astrophysics

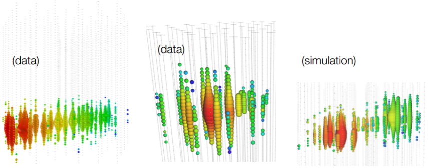
- Locate a supernova hours before the light arrives
- Track the shock wave through neutrinos while it is still inside the mantle (Not possible with light)
- Possible identification of QCD phase transition, SASI (Standing Accetion Shock) instabilities
- Hints on heavy element nucleosynthesis (r-process)

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

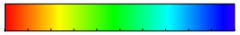
Gigaton IceCube: 1 000 000 000 000 litres of ice



Charged-current ν_μ	Neutral-current / ν_e	Charged-current ν_τ

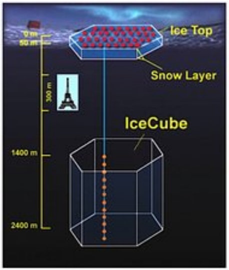


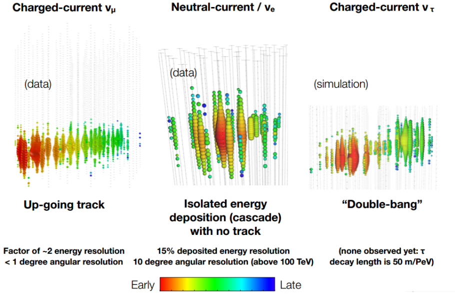
Up-going track	Isolated energy deposition (cascade) with no track	"Double-bang"
Factor of ~2 energy resolution < 1 degree angular resolution	15% deposited energy resolution 10 degree angular resolution (above 100 TeV)	(none observed yet: τ decay length is 50 m/PeV)

Early  Late

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

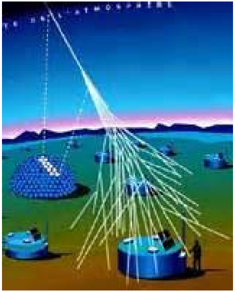
Gigaton IceCube: 1 000 000 000 000 litres of ice



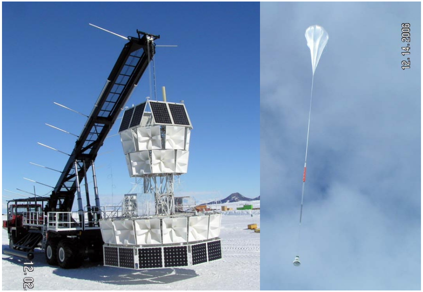


- Three events at $\sim 1, 1.1, 2.2$ PeV energies found
- Search for origin, correlations with directions of UHECR
- Constraints on Lorentz violation: $\delta(v^2-1) \lesssim \mathcal{O}(10^{-18})$
- Flavor ratios tell about sources, possible new physics

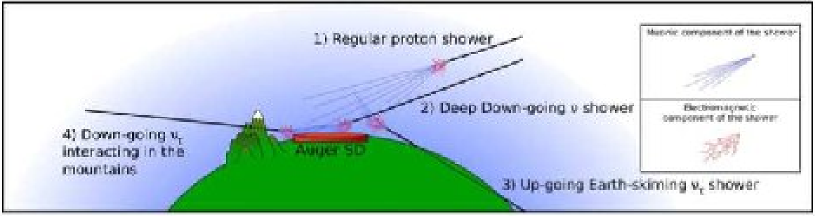
Ultrahigh energy neutrinos ($\gtrsim 10^{16}$ eV)



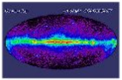
Auger

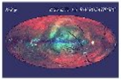


ANITA (balloon)



Multimessenger astronomy

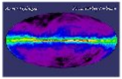

Gamma ray

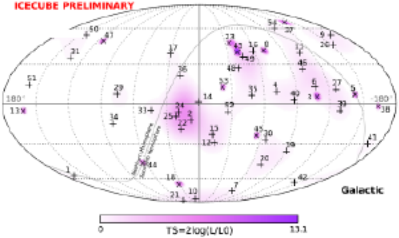

X-ray

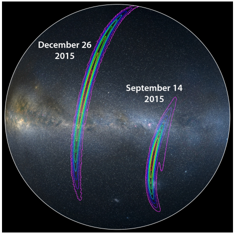

Visible


Near infrared

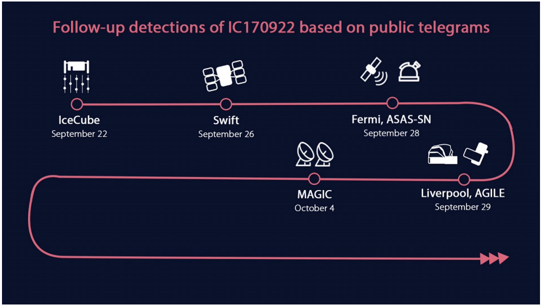

Infrared

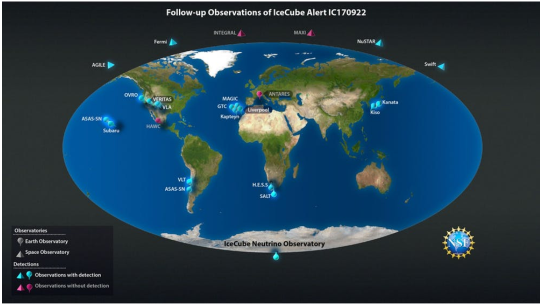

Radio waves





Blazar at IceCube, followup by telescopes





Role of atmospheric neutrino ($\sim$ 1 GeV) experiments

ATMOSPHERIC NEUTRINO DETECTORS

PRECISION MEASUREMENTS OF MIXING PARAMETERS

Secondary role to LBL ?
Parameter degeneracies ?
Synergy: can 1 + 1 > 2 ?

UNDERSTANDING STANDARD PHYSICS

Fluxes, Cross sections, Inelasticities
Earth tomography

TESTS OF STANDARD OSCILLATION FRAMEWORK

Exploiting large L & E range

NEUTRINO PROPERTIES BEYOND STANDARD MODEL

Sterile neutrinos,
Non-standard interactions,
Neutrino decays,
Lorentz / CPT violation

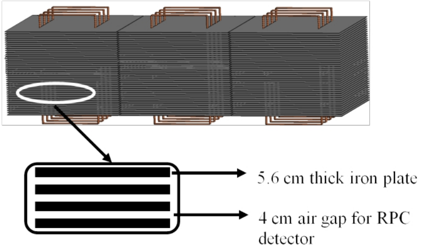
NEW PHYSICS SEARCHES BEYOND NEUTRINOS

Dark matter, Long-lived particles, Magnetic monopoles

MULTI-MESSENGER ASTRONOMY

Long-term versatile detector keeping its eyes open
Supernovae, GRBs, AGNs, Blazars, ..

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

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, ...