Astroparticle physics of neutrinos

Nobel Prize 2015 and beyond

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Department of Theoretical Physics
Tata Institute of Fundamental Research

ICTS Colloquium, Nov 4, 2015

Nobel Prize in Physics 2015

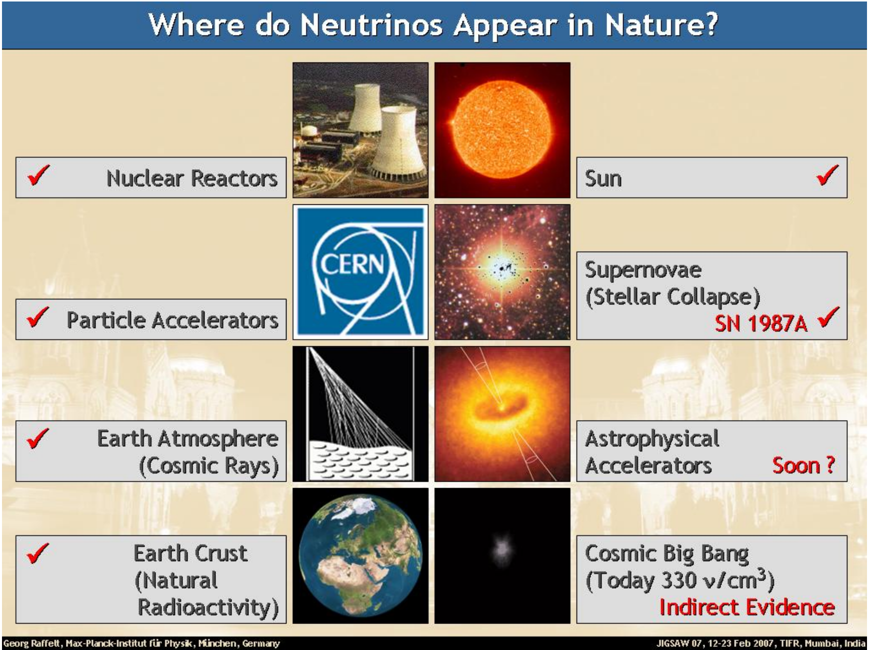
Takaki Kajita
U. of Tokyo, Japan

Arthur McDonald
Queen's U., Canada

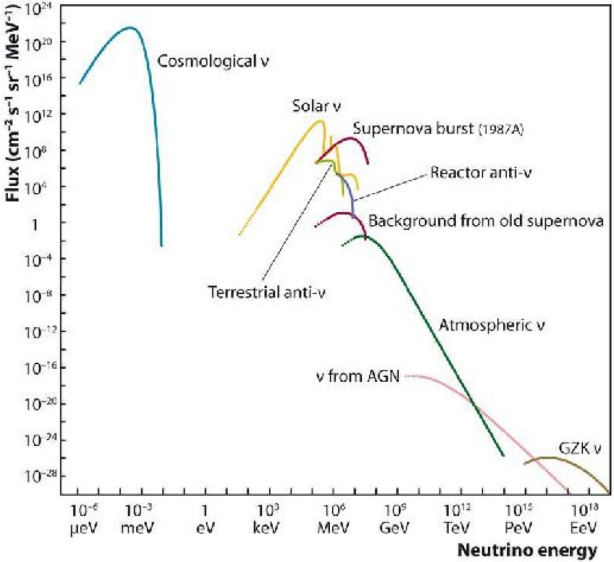
The Citation

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

Omnipresent neutrinos



Energy spectra of neutrino sources



Some interesting tidbits about neutrinos

The second most abundant particles in the universe

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

- Do not interact with light $\Rightarrow$ Dark matter
- Stopping radiation with lead shielding:
  - α, β, γ from radioactivity: $\sim$ 50 cm
  - Neutrinos from the Sun: light years !

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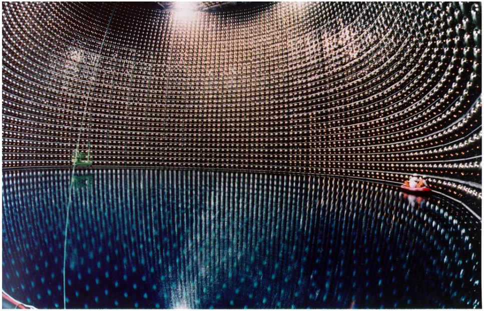
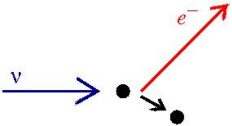
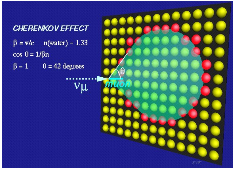
SuperKamiokande: 50 000 000 litres of water







Recipe for observing neutrinos

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

- Neutrinos from the Sun:
  ∼ 100 trillion through a human body per second
- SuperKamiokande observes about 5-10 neutrinos per day

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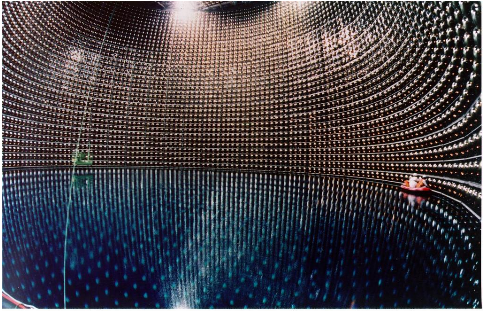

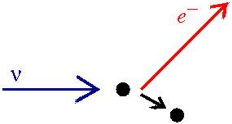

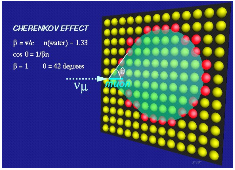

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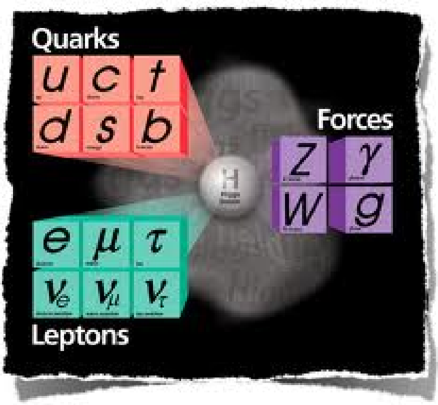
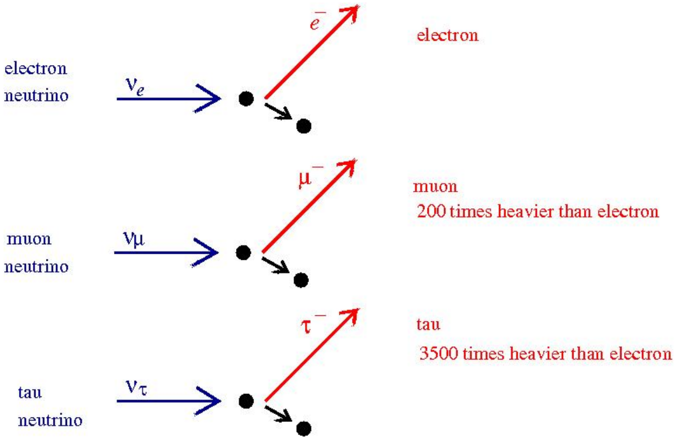
The Standard Model of Particle Physics



- 3 neutrinos: ν_e, ν_μ, ν_τ
- chargeless
- spin 1/2
- almost massless
- only weak interactions

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

Astroparticle physics of neutrinos

1. The Nobel Prize 2015
   - The solar neutrino puzzle
   - The atmospheric neutrino puzzle
   - Consolidation, implications and future
2. Neutrinos as messengers from the universe
   - Neutrinos from a core collapse supernova
   - Astrophysical neutrinos with ultra-high energies
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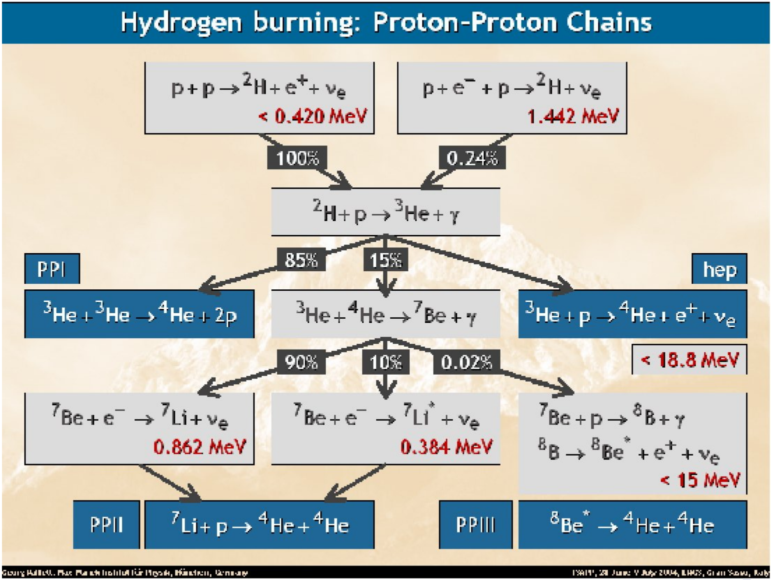
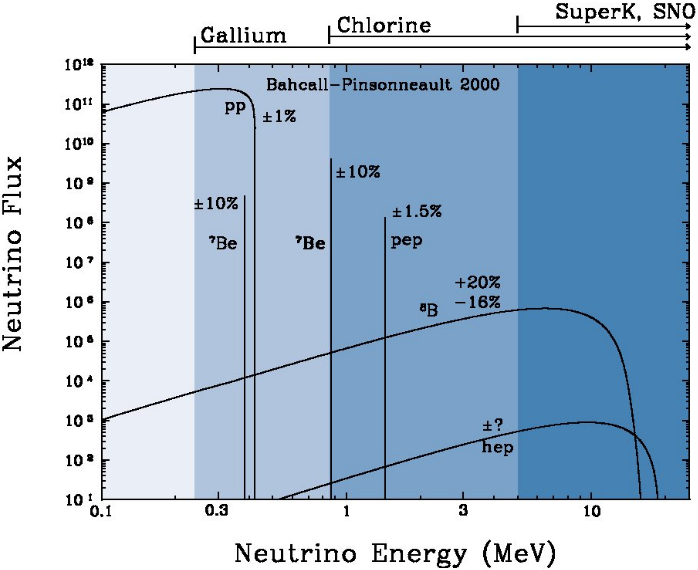
Neutrinos from the Sun



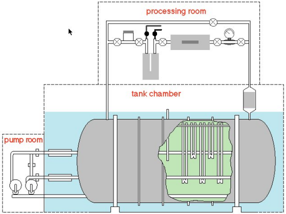
Spectra of solar neutrino fluxes

John Bahcall



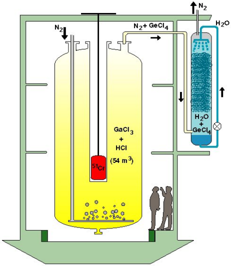
Detecting neutrinos from the Sun

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



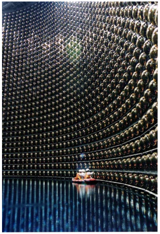
$\nu_e + \mathrm{Cl} \rightarrow \mathrm{Ar} + e^-$

Homestake



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

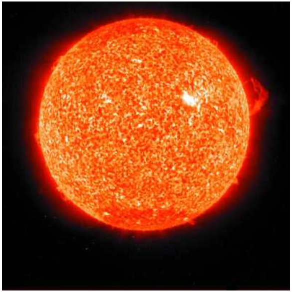
Gallex



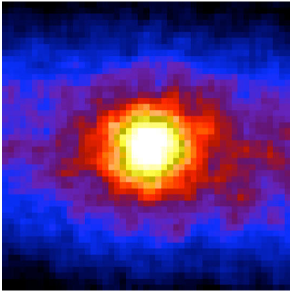
$\nu_e + e^- \rightarrow \nu_e + e^-$

SuperKamiokande

Seeing the Sun with neutrinos



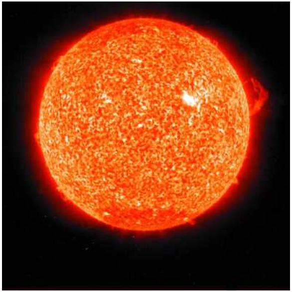
- Light from the Sun's surface:
  due to nuclear reactions
  millions of years ago
- Neutrinos from the Sun's core:
  due to nuclear reactions
  8 minutes ago



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

BUT...

Seeing the Sun with neutrinos



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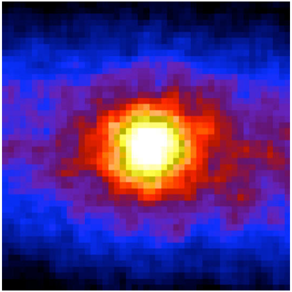

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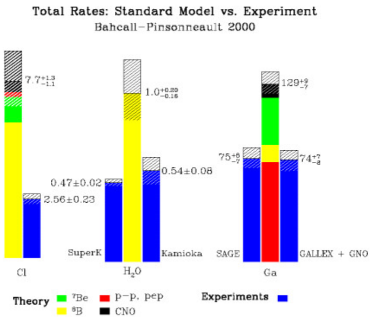
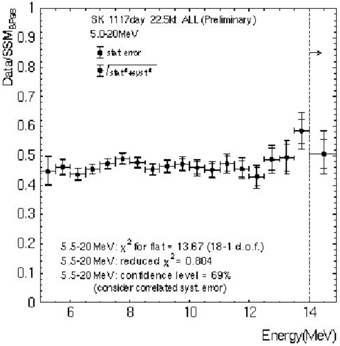
Do we really understand how the Sun shines ?





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) ?
- This is possible, but only if the neutrinos have different masses and they mix !

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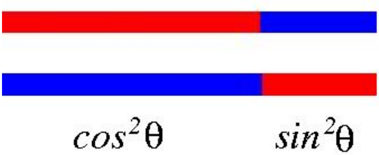
What is meant by neutrino mixing ?

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

For example, ν_e–ν_μ mixing:



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

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

- Only ν_1 and ν_2 have fixed masses
- Then, if you produce ν_e, it may convert to ν_μ !

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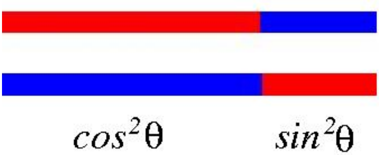

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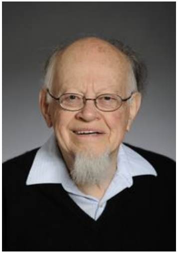
- Then, if you produce ν_e, it may convert to ν_μ !

Neutrino flavour changes inside the Sun

Lincoln Wolfenstein



Stanislav Mikheyev

Alexei Smirnov

- Neutrino mixing gets affected by the matter inside the Sun
- There is a resonance (level crossing) inside the Sun, where most of the flavour changes take place

How can we check that
flavour change is the cause of solar neutrino deficit ?

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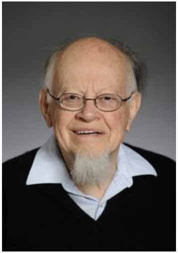

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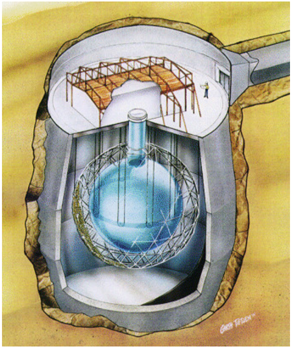
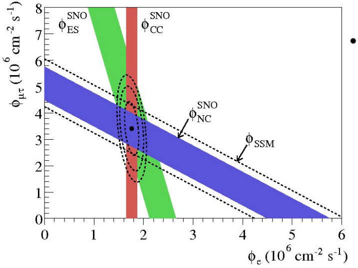
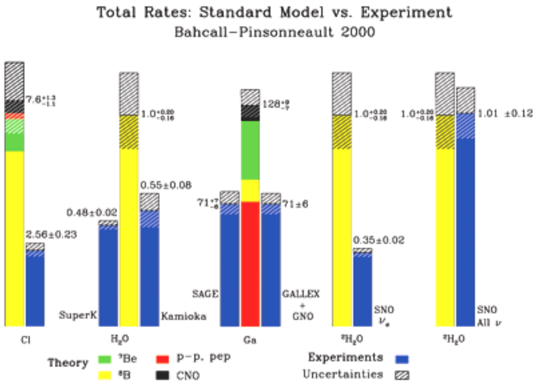
Heavy water Cherenkov experiment: SNO





- Heavy water Cherenkov
- $\nu_e\ D \to p\ p\ e^-$ sensitive to Φ_e
- $\nu_{e,\mu,\tau}\ e^- \to \nu_{e,\mu,\tau}\ e^-$ Sensitive to $\Phi_e + \Phi_{\mu\tau}/6$
- $\nu_{e,\mu,\tau}\ D \to n\ p\ \nu_{e,\mu,\tau}$ 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...

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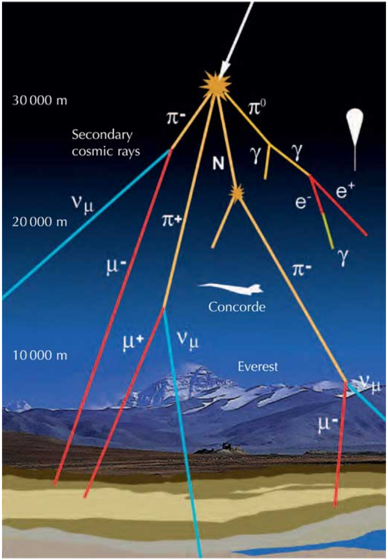
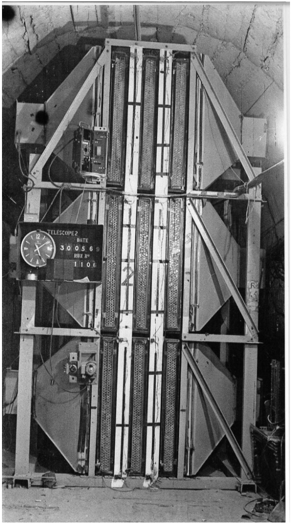
Neutrinos from cosmic rays



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

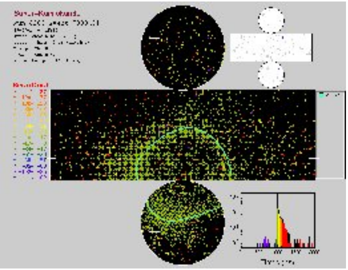
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

PRL 15, (1965) 429

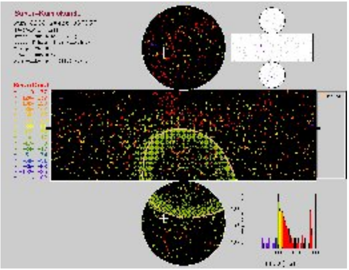
(30th Aug 1965)

Detecting ν_e and ν_μ through Cherenkov cones

SuperKamiokande: Water Cherenkov



Diffused ring



Sharp ring

Missing ν_μ from atmospheric neutrinos

Super-Kamiokande

Multi-GeV

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

	Data	MC
1 Ring e-like	290	236.0
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

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

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

- The ν_μ/ν_e ratio less than expected
- Something wrong with detection ?
- Something wrong with our understanding of cosmic rays ?
- Neutrinos behave differently from what everyone thought ??

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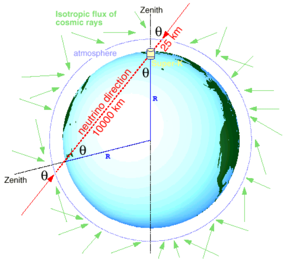

- Cosmic ray flux isotropic ⇒
  No. of "Down" neutrinos
  = No. of "Up" neutrinos
  (along a line)

- But if neutrinos have mass and they mix ⇒
  neutrinos travelling longer will have more time to convert to other neutrino flavours :

Neutrino oscillations

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

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

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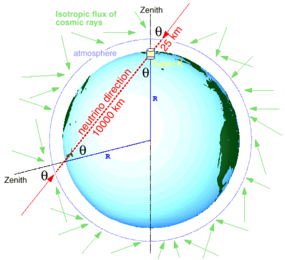

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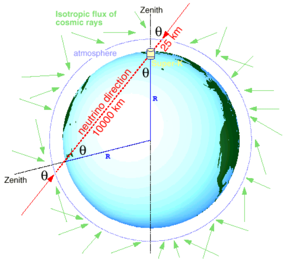

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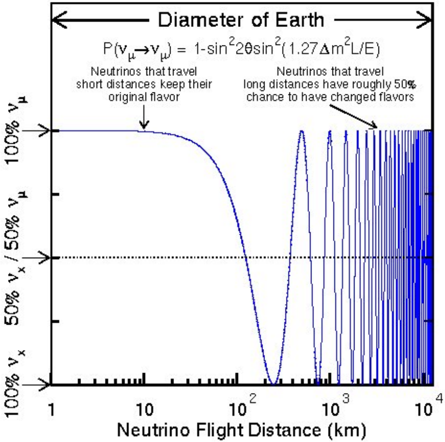
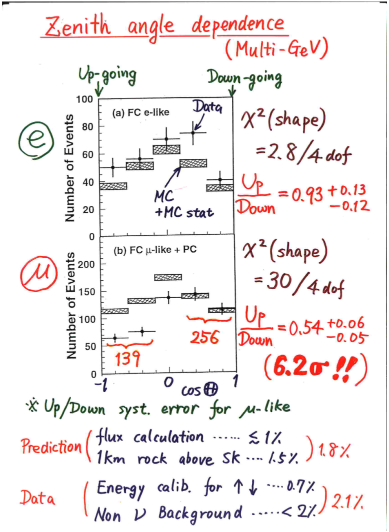
Neutrino oscillations as a function of distance travelled



- More neutrinos 'lost' when $\cos(\theta) < 0$

(θ : angle made with the zenith)

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 !

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Solar neutrino solution (MeV): current status

- Solution through "neutrino oscillations in matter":
  - Neutrinos have different masses, ν_e mixes with others
  - The matter inside the Sun plays a major role in determining how many ν_e survive.

- Survival probability of electron neutrinos:

$$\boxed{P(\nu_e \to \nu_e) \approx P_f \cos^2\theta_\odot + (1 - P_f)\sin^2\theta_\odot}$$

P_f: "flip probability" at level crossing (Landau-Zener)

- Can measure $\Delta m^2_\odot$ and $\theta_\odot$:
  - Observed: $\Delta m^2_\odot \approx 8 \times 10^{-5}$ eV^2, $\theta_\odot \approx 30°$
  - Parameters confirmed by reactor neutrino experiments (KamLand)

Atmospheric neutrino solution (GeV): current status

- Solution through (mainly) vacuum oscillations:
  - ν_μ convert predominantly to ν_τ
  - More accurate experiments needed to detect Earth matter effects

- Survival probability of ν_μ :

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

- Can measure $\Delta m^2_{\rm atm}$ and $\theta_{\rm atm}$:
  - $\Delta m^2_{\rm atm} \approx 2.4 \times 10^{-3}$ eV^2, Mixing angle $\theta_{\rm atm} \approx 45^\circ$
  - Confirmed by "short baseline" experiments (K2K, MINOS, T2K)

Reactor neutrinos and Geo-neutrinos ($E \sim$ MeV)

Reactor neutrinos: $\bar{\nu}_e$

- Confirmed oscillations through solar neutrino parameters even in vacuum
- Discovery of 2012: $\sim$ 10% of the $\bar{\nu}_e$ lost even at short distances $\sim$ km
- Showed that there is one more nonzero mixing angle $\theta_{\rm reactor}$:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{\rm reactor} \sin^2\left(\frac{\Delta m^2_{\rm reactor} L}{4E}\right)$$

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- Produced due to natural radioactivity in the Earth's crust
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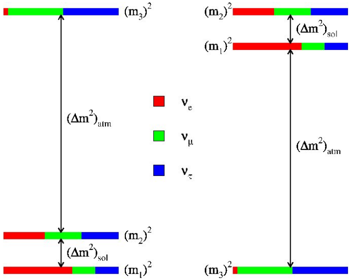
The three-neutrino mixing picture

Mixing of $\nu_e, \nu_\mu, \nu_\tau \Rightarrow \nu_1, \nu_2, \nu_3$ (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 ?

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.
- 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....

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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)

- Observe neutrinos from the first step: the p-p reaction
- 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.

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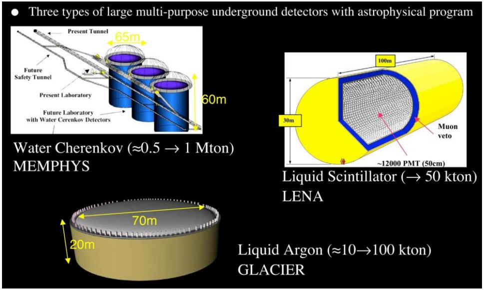
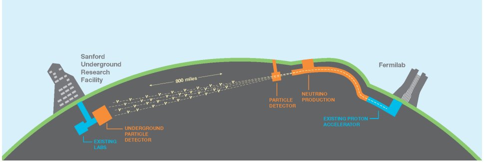
Bigger detectors, ambitious experiments



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



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

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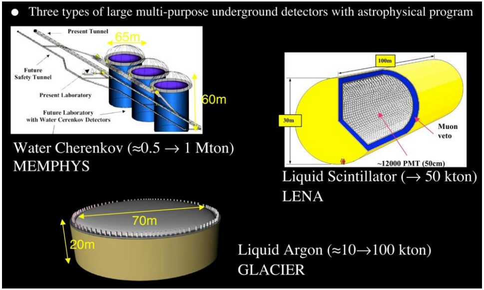

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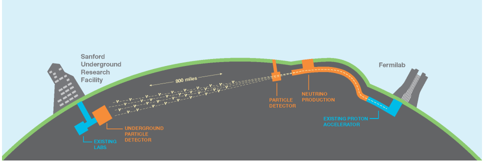

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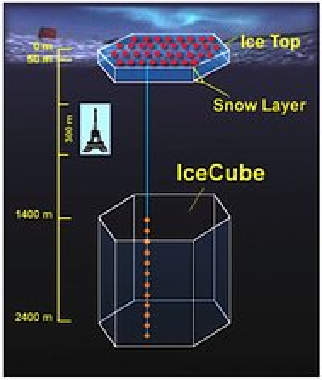
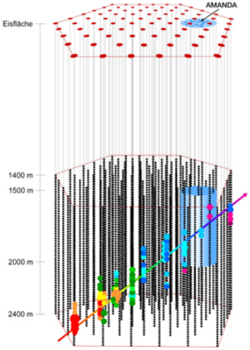
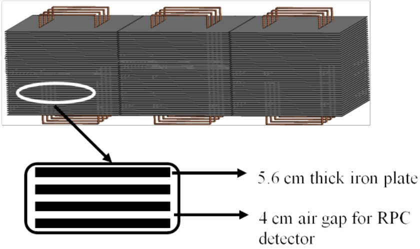
Below the antarctic ice: Gigaton IceCube

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

1. The Nobel Prize 2015
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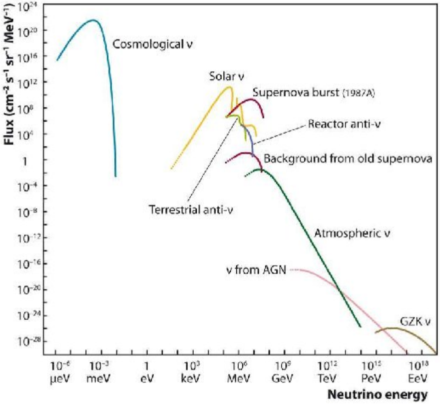
Neutrinos from the sky at all energies

Neutrinos as good messengers

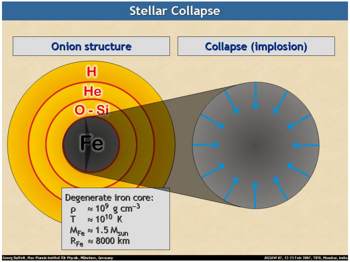
- No bending in magnetic fields $\Rightarrow$ point back to the source
- Minimal obstruction / scattering $\Rightarrow$ can arrive directly from regions from where light cannot come



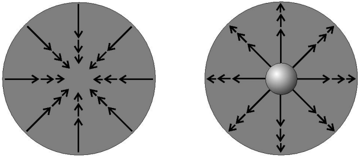
Astroparticle physics of neutrinos

The death of a star: role of different forces

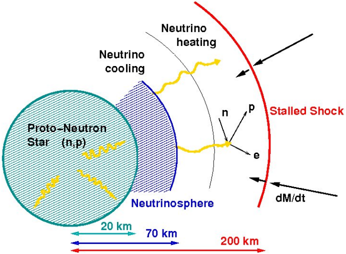
Gravity ⇒



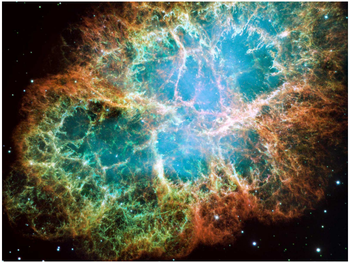
Nuclear forces ⇒



Neutrino push ⇒

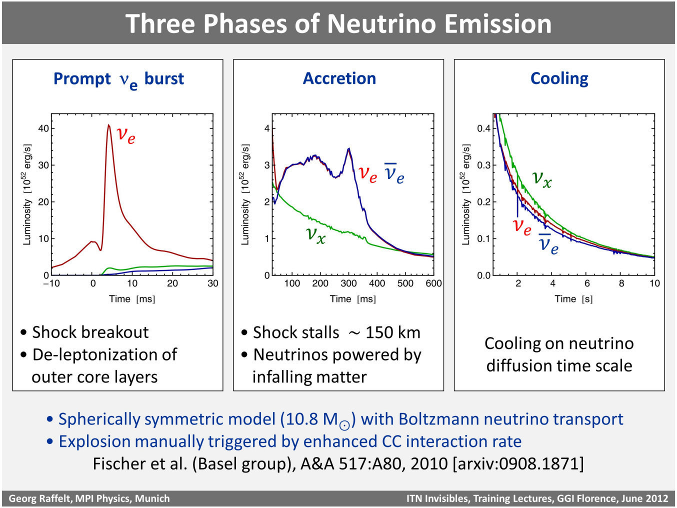


Hydrodynamics ⇒



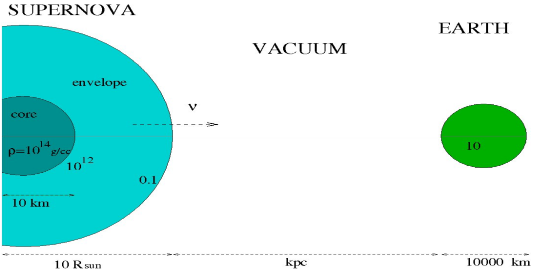
(Crab nebula, SN seen in 1054)

Neutrino fluxes: $\sim 10^{58}$ neutrinos in 10 sec



- Escaping neutrinos: $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

Neutrino oscillations in matter of varying density



Inside the SN: ***flavour conversion***

Non-linear “collective” effects and resonant matter effects

Between the SN and Earth: ***no flavour conversion***

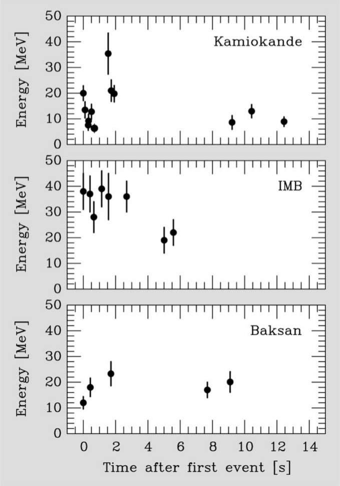
Mass eigenstates travel independently

Inside the Earth: ***flavour oscillations***

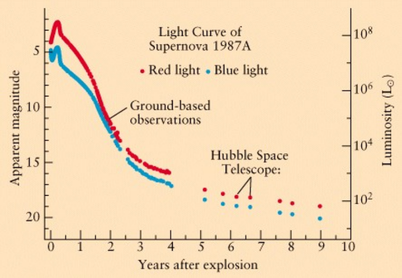
Resonant matter effects (*if detector is shadowed by the Earth*)

SN1987A: neutrinos and light

Neutrinos: Feb 23, 1987



Light curve: 1987-1997



SN1987A: what did we learn ?

Hubble image: now

- Confirmed the SN cooling mechanism through neutrinos
- Number of events too small to say anything concrete about neutrino mixing
- Some constraints on SN parameters obtained
- Strong constraints on new physics models obtained (neutrino decay, Majorans, axions, extra dimensions, ...)

What a galactic SN can tell us

On neutrino masses and mixing

- Instant identification of neutrino mass ordering (N or I), through
  - Neutronization burst: disappears if I
  - Shock wave effects: in ν ($\bar{\nu}$) for N (I)

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)

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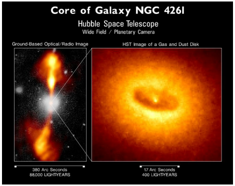
High / Ultrahigh energy neutrinos ($E \gtrsim$ TeV)



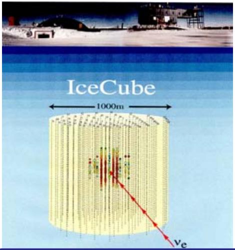
Sources of HE neutrinos

- Primary protons interacting within the source or with CMB photons $\Rightarrow \pi^{\pm} \Rightarrow$ Decay to ν
- Individual sources like AGNs and GRBs
- Diffused flux accumulated over the lifetime of universe

What we will learn

- Mechanisms of astrophysical phenomena
- Limits on neutrino decay, Lorentz violation, etc

Detection of HE neutrinos: water/ice Cherenkov



- Thresholds of $\sim$ 100 GeV, controlled by the distance between optical modules

Sensitive energy ranges

- Down-going neutrinos: atmospheric muon background becomes insignificant only for $E \gtrsim 10^{16-17}$ eV
- Up-going neutrinos: $E \lesssim 10^{16}$ eV, since more energetic neutrinos get absorbed in the Earth

Flavour information

- Track for ν_μ
- Cascade for ν_e, hadrons, ν_τ
- Double-bang for ν_τ ?

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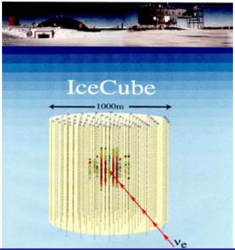

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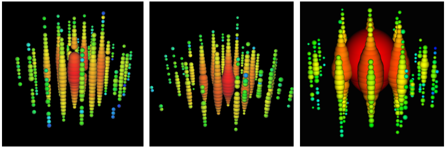
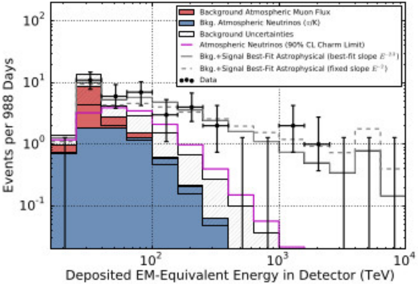
The three PeV events at Icecube



Bert Ernie Big Bird

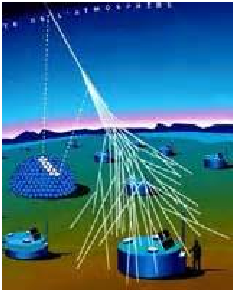


- Three events at $\sim 1, 1.1, 2.2$ PeV energies found
- Cosmogenic ? X Glashow resonance? X atmospheric ?

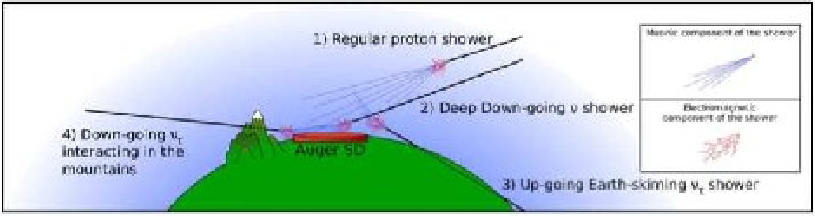
  Roulet et al 2013 ++ many
- IceCube analyzing 54 events from 30 TeV to 10 PeV
- Constraints on Lorentz violation: $\delta(v^2 - 1) \lesssim \mathcal{O}(10^{-18})$

  Borriello, Chakraborty, Mirizzi, 2013

Detection of UHE neutrinos: cosmic ray showers



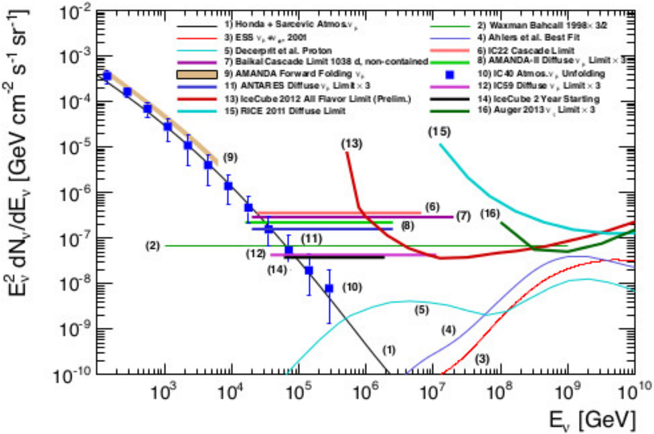
- Neutrinos with $E \gtrsim 10^{17}$ eV can induce giant air showers (probability $\lesssim 10^{-4}$)
- Deep down-going muon showers
- Deep-going ν_τ interacting in the mountains
- Up-going Earth-skimming ν_τ shower



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

Limits on UHE neutrino fluxes



Waxman-Bahcall, AMANDA, Antares, RICE, Auger, IceCube
Also expect complementary info from: ANITA, NEMO, NESTOR, KM3NET ...

Flavor information from UHE neutrinos

Flavor ratios $\nu_e : \nu_\mu : \nu_\tau$ at sources

- Neutron source (nS): $1 : 0 : 0$
- Pion source (πS): $1 : 2 : 0$,
- Muon-absorbing sources (μDS): $0 : 1 : 0$

Flavor ratios at detectors (with neutrino mixing)

- Neutron source: $\approx 5 : 2 : 2$
- Pion source: $\approx 1 : 1 : 1$
- Muon-absorbing sources : $\approx 4 : 7 : 7$

New physics effects

- Decaying neutrinos can skew the flavor ratio even further: as extreme as $6 : 1 : 1$ or $0 : 1 : 1$
  Ratio measurement $\Rightarrow$ improved limits on neutrino lifetimes

Beacom et al, PRL 2003

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Big bang relic neutrinos

Source

- Relic density: $\sim$ 110 neutrinos /flavor /cm^3
- Temperature: $T_\nu \approx 1.95\,\mathrm{K} \equiv 16.7\,\mathrm{meV}$
- Contribution to dark matter density:
  $\Omega_\nu/\Omega_{\mathrm{baryon}} = 0.5\,(\sum m_\nu/\mathrm{eV})$
- Looking really far back: 0.18 sec after Big Bang, as opposed to 400,000 years for CMB photons

Detection

- Torsion-balance ideas impractical
- Zero-threshold reactions needed:
  inverse β-capture on β-decaying nuclei:
  $\nu_e + N_1(A, Z) \rightarrow N_2(A, Z+1) + e^-$
- End-point region ($E > M_{N_1} - M_{N_2}$) background-free.
  Energy resolution crucial

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Neutrinos from the sky

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 reach us.

Supernova neutrinos

- Rich SN astrophysics and ν oscillation phenomenology
- Instant identification of mass hierarchy possible
- Unique way of extracting information on SN dynamics

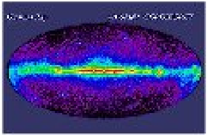
Astrophysical ultrahigh-energy neutrinos

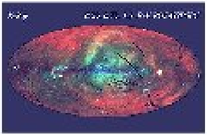
- Cerenkov ν telescopes, large cosmic ray detector arrays
- Flavor identification for sources and ν properties

Cosmological ultra-low energy neutrinos

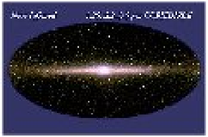
- For one more confirmation of the big-bang picture

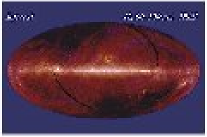
Mapping the universe with EM waves

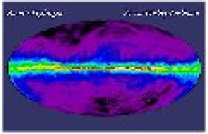

Gamma ray


X-ray

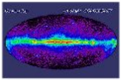

Visible


Near infrared


Infrared


Radio waves

Mapping the universe with neutrinos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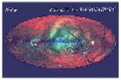
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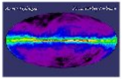
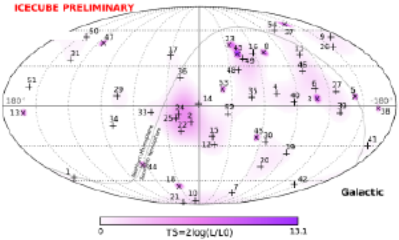
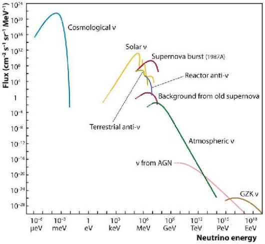
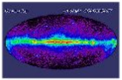

Radio waves

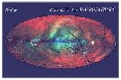
Neutrinos are entering this domain, slowly but surely...





Mapping the universe with neutrinos

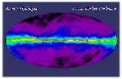

Gamma ray


X-ray

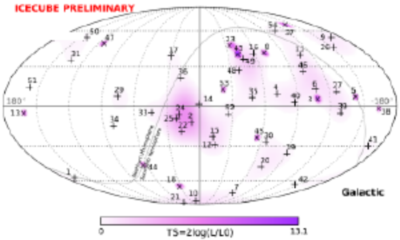

Visible

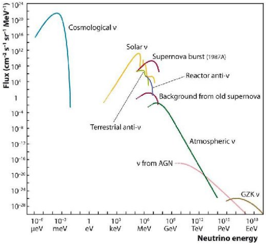

Near infrared


Infrared


Radio waves

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





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