Particle Astrophysics of Neutrinos

some selected aspects

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science without boundaries

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Omnipresent neutrinos

Unique features of 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: 50 cm
  - Neutrinos from the Sun: hundreds of light years !

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Neutrinos and the future of mankind

"Satnam has discovered that neutrinos from a massive solar flare are acting as microwaves, causing the temperature of the Earth's core to increase rapidly"

Statutory warning:
Taking Hollywood films seriously may be injurious to sanity

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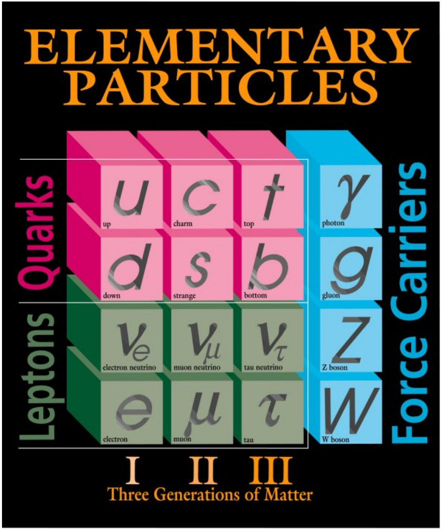
The Standard Model of Particle Physics



Fermilab 95-759

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

Neutrino physics – astrophysics interplay

1. Astrophysics puzzles, particle physics solutions
   - Atmospheric neutrino problem
   - The mystery of missing solar neutrinos
2. Physics and astrophysics of supernova neutrinos
   - Supernova explosion and neutrino emission
   - Neutrino flavour conversions
   - Physics potential of a galactic SN detection
3. Astrophysical neutrino sources: 10^{-4} eV – 10^{20} eV
   - Bigger and better detectors
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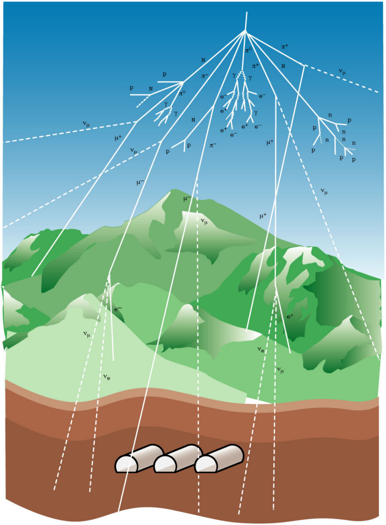
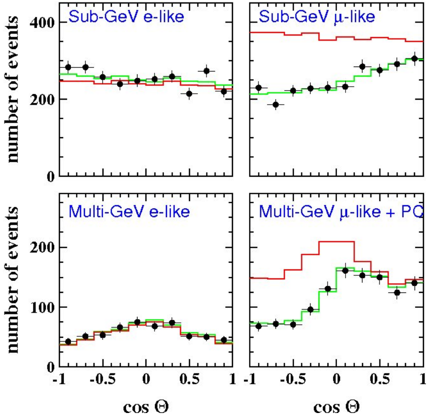
Neutrinos from cosmic rays (atmospheric neutrinos)

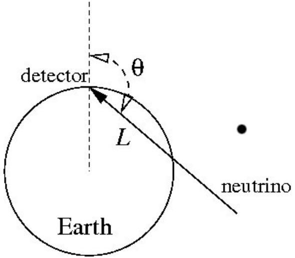


- $\pi^+ \to \mu^+ + \nu_\mu$
- $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$
- "ν_μ" flux $= 2\times$ "ν_e" flux
- "Down" flux = "Up" flux

Atmospheric neutrino puzzle

Zenith angle dependence:





Super-Kamiokande

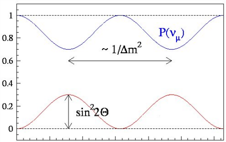
- Electron neutrinos match predictions
- Muon neutrinos lost while passing through the Earth !

Solution through "vacuum oscillations"

Prerequisites

- Neutrino flavours mix with each other
- Neutrinos have different masses
- ν_e do not participate in the oscillations

Neutrino oscillations: ν_μ oscillate into ν_τ



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

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

Mixing parameters

$\Delta m^2_{\mathrm{atm}} \approx (1.3\text{–}3.4) \times 10^{-3}\ \mathrm{eV}^2$

Mixing angle $\theta_{\mathrm{atm}} \approx 36^\circ\text{–}54^\circ$

Confirmed by "short baseline" experiments (K2K, MINOS)

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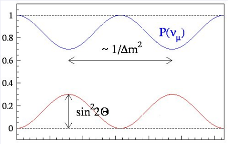

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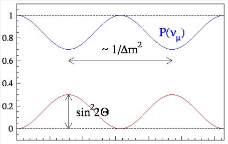

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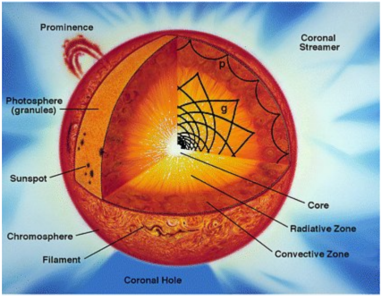
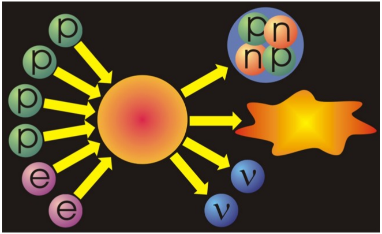
Neutrinos from the Sun (Solar neutrinos)



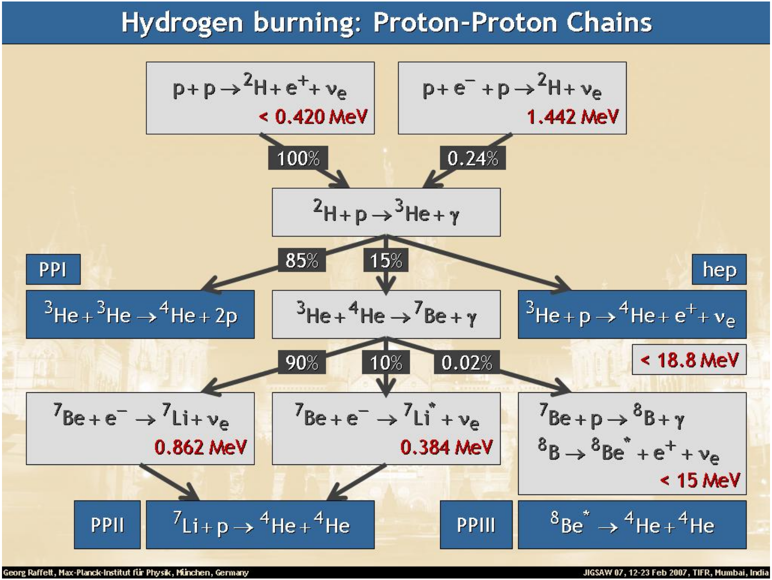


- Nuclear fusion reactions: effectively

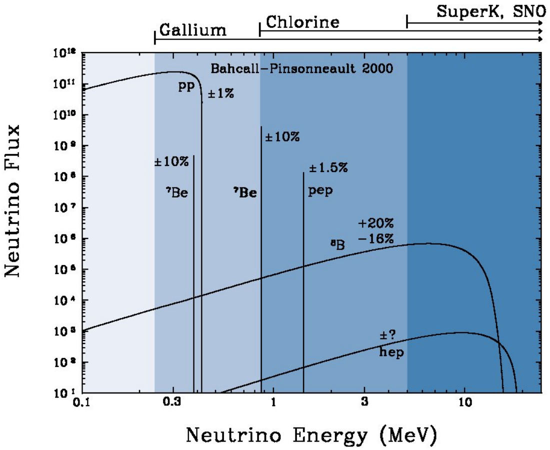
$$4\ {}^1_1\mathrm{H} + 2e^- \rightarrow {}^4_2\,\mathrm{He} + 2\nu_e + \mathrm{light}$$

- Neutrinos an essential part of all the sub-reactions:

Nuclear reactions inside the Sun

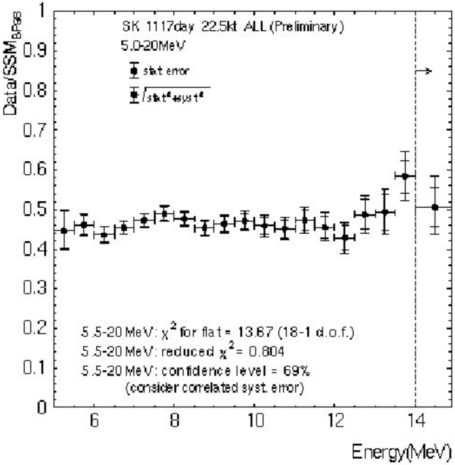


The solar neutrino spectra



- Magnitudes of fluxes depend on details of solar interior
- Spectral shapes robustly known

Mystery of missing solar neutrinos



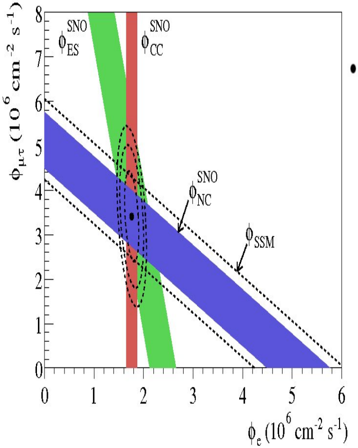
Super-Kamiokande

Where did the missing neutrinos (ν_e) go ?

Problem with our understanding of the Sun ?

Solar neutrino problem: unresolved for 40 years !

Solar neutrino puzzle: another jigsaw piece



- $\nu_e \, D \rightarrow p \, p \, e^-$
  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 $\Phi_e + \Phi_{\mu\tau}$

Sudbury Neutrino Observatory (SNO)

- $\Phi_e + \Phi_{\mu\tau} =$ constant, matches with Standard Solar Model
- ν_e convert into ν_μ and ν_τ

Solution through “MSW (matter) effect”

Prerequisites

- Neutrino flavours mix with each other
- Neutrinos have different masses
- Masses and mixing angles depend on matter density !

Survival probability of ν_e:

- $P(\nu_e \to \nu_e) \approx P_f \cos^2\theta_\odot + (1 - P_f)\sin^2\theta_\odot$
- P_f depends on: Δm^2, mixing angle $\theta_\odot$, density profile
- No oscillations ! (Mass eigenstates have decohered)

Mixing parameters

$$\Delta m^2_\odot \approx (7.2\text{–}9.5) \times 10^{-5}\ \mathrm{eV}^2$$

Mixing angle $\theta_\odot \approx 28°\text{–}36°$

Confirmed by “short baseline” experiments (KamLAND)

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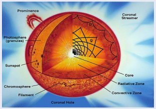
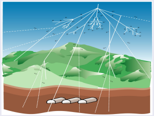
Summary of neutrino mixing parameters

Solar neutrino puzzle: 1960s – 2002



- $\Delta m^2_\odot \approx 8 \times 10^{-5}\ \text{eV}^2$, $\theta_\odot \approx 32^\circ$
- Mechanism: MSW (matter) effects

Atmospheric neutrino puzzle: 1980s – 1998



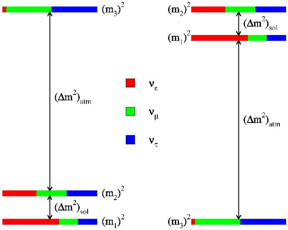
- $\Delta m^2_{\text{atm}} \approx 2 \times 10^{-3}\ \text{eV}^2$, $\theta_{\text{atm}} \approx 45^\circ$
- Mechanism: vacuum oscillations

Reactor neutrino experiments

- No $\bar{\nu}_e$ are lost
- The "third" mixing angle "θ_{13}" is very small ($\theta_{13} < 12^\circ$, may even be zero).

Neutrino masses and mixing: open questions

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



- Mass ordering: Normal or Inverted ?
- What are the absolute neutrino masses ?
- Are there more than 3 neutrinos ?
- Is there leptonic CP violation ?
- Is some new physics hidden in the data ?

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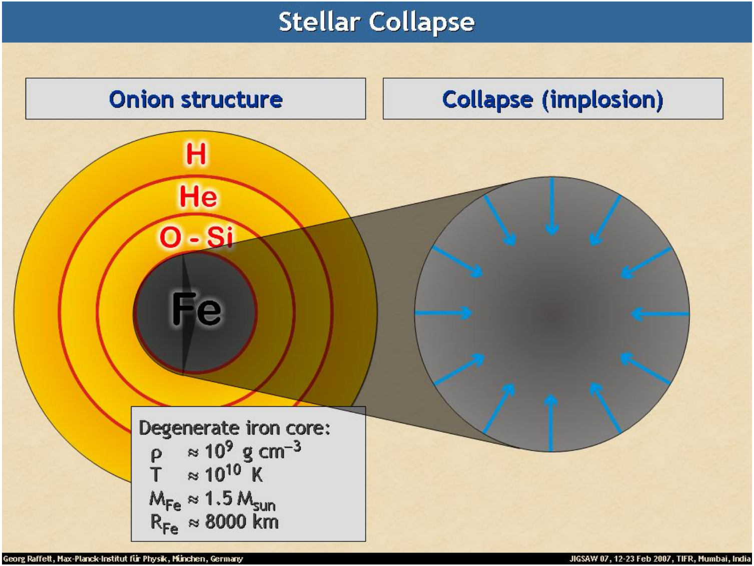
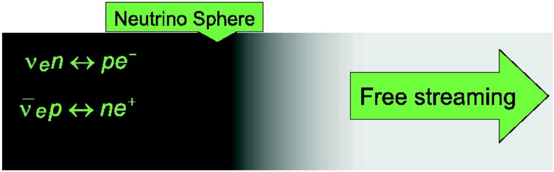
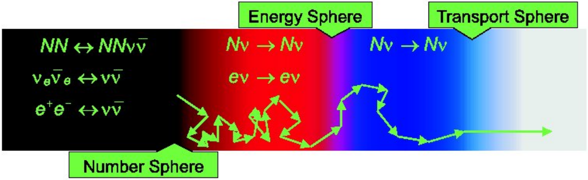
The would-be supernova before the collapse



Trapped neutrinos before the collapse

- Neutrinos trapped inside “neutrinospheres” around $\rho \sim 10^{10}$g/cc.

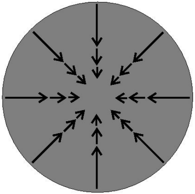


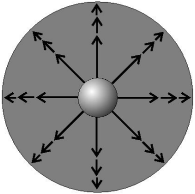


- Escaping neutrinos: $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

Core collapse and the shock wave

Gravitational core collapse $\Rightarrow$ Shock Wave





Neutronization burst: ν_e emitted for $\sim$ 10 ms

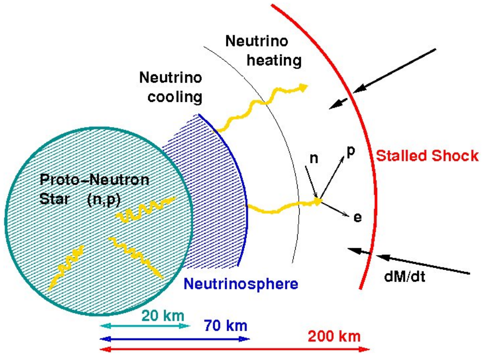
Cooling through neutrino emission: $\sim 10^{58}$ neutrinos

$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ Duration: About 10 sec

Emission of 99% of the SN collapse energy in neutrinos

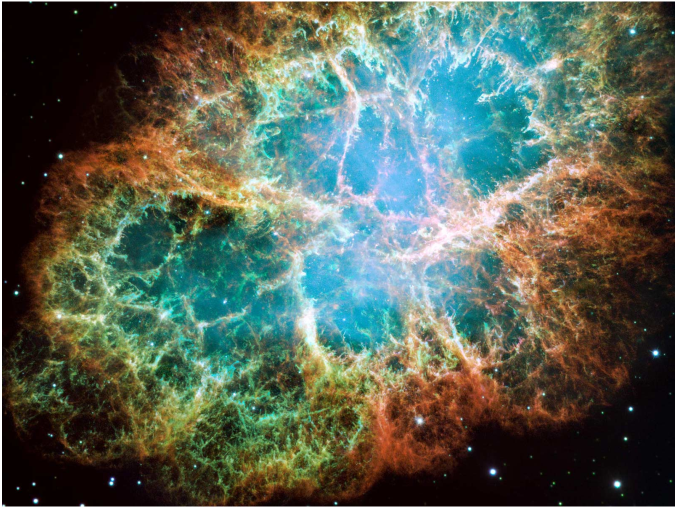
¿¿¿ Explosion ???

Role of neutrinos in explosion



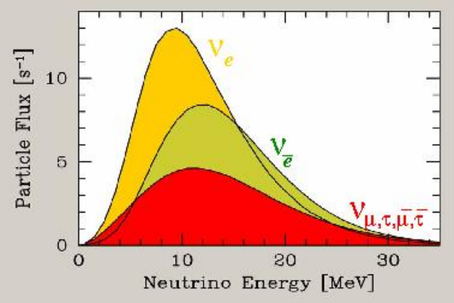
- Neutrino heating needed for pushing the shock wave
- Large scale convection also needed for explosion

The star after explosion



(Crab nebula, supernova seen in 1054)

Primary fluxes and spectra



- Almost blackbody spectra, slightly "pinched"
- Energy hierarchy: $E_0(\nu_e) < E_0(\bar{\nu}_e) < E_0(\nu_x)$
- $E_0(\nu_e) \approx$ 10–12 MeV
  $E_0(\bar{\nu}_e) \approx$ 13–16 MeV
  $E_0(\nu_x) \approx$ 15–25 MeV

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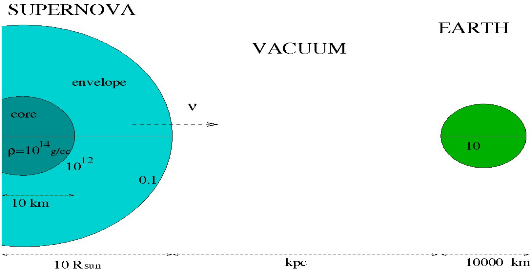
Neutrino oscillations in matter of varying density



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*)

“Collective” effects: qualitatively new phenomena

Synchronized oscillations:

ν and $\bar{\nu}$ of all energies oscillate with the same frequency

S. Pastor, G. Raffelt and D. Semikoz, PRD65, 053011 (2002)

Bipolar/pendular oscillations:

Coherent $\nu_e \bar{\nu}_e \leftrightarrow \nu_x \bar{\nu}_x$ oscillations even for extremely small θ_{13}

S. Hannestad, G. Raffelt, G. Sigl, Y. Wong, PRD74, 105010 (2006)

Spectral split/swap:

ν_e and ν_x ($\bar{\nu}_e$ and $\bar{\nu}_x$) spectra interchange completely, only within certain energy ranges.

G.Raffelt, A.Smirnov, PRD76, 081301 (2007), PRD76, 125008 (2007)

B. Dasgupta, AD, G.Raffelt, A.Smirnov, PRL103,051105 (2009)

Collective effects influencing supernova astrophysics

- Nucleosynthesis of heavy elements (r-process)
- Shock wave propagation

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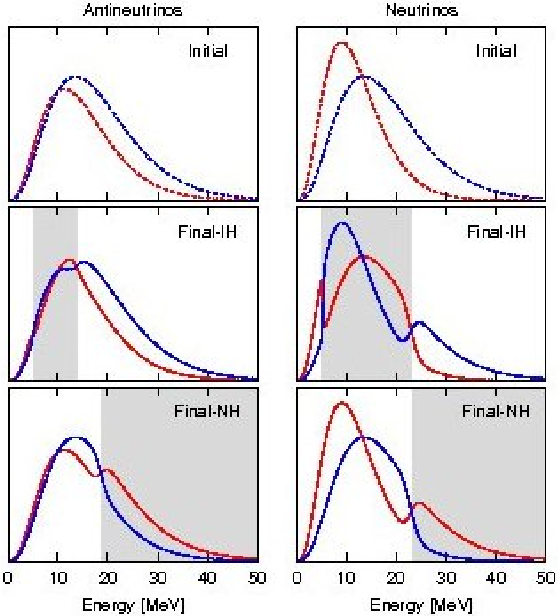
Neutrino spectra exiting the supernova



B. Dasgupta, AD, G.Raffelt, A.Smirnov, PRL2009

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A recent nearby supernova: SN1987A

(Hubble image)

- 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

Signal expected from a galactic SN (10 kpc)

Water Cherenkov detector:

- $\bar{\nu}_e p \rightarrow n e^+$: $\approx 7000 - 12000^*$
- $\nu e^- \rightarrow \nu e^-$: $\approx 200 - 300^*$
- $\nu_e + ^{16}O \rightarrow X + e^-$: $\approx$ 150–800*

* Events expected at Super-Kamiokande with a galactic SN at 10 kpc

Carbon-based scintillation detector:

- $\bar{\nu}_e p \rightarrow n e^+$
- $\nu + {}^{12}C \rightarrow \nu + X + \gamma$ (15.11 MeV)

Liquid Argon detector:

- $\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$

What supernova neutrinos can tell us

On neutrino masses and mixing

- Identify neutrino mass ordering: normal or inverted even for extremely small θ_{13}

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)

Inverse supernova neutrino problem

Observe the neutrino spectra, deduce neutrino mixing parameters, primary neutrino spectra, shock wave propagation

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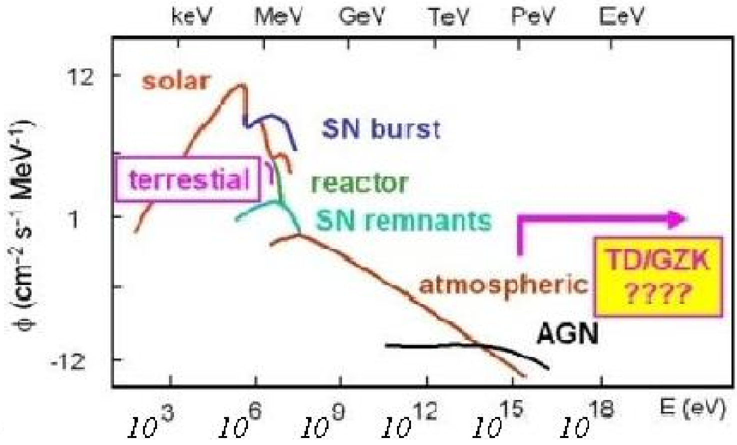
Spectra of astrophysical neutrinos



Ongoing activities in neutrino physics

keV-energy neutrinos

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

MeV-energy neutrinos

- Measuring the energy of the sun in neutrinos
- Geoneutrinos: neutrinos from the Earth's radioactivity
- Reactor neutrino experiments for θ_{13}

GeV-energy neutrinos

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

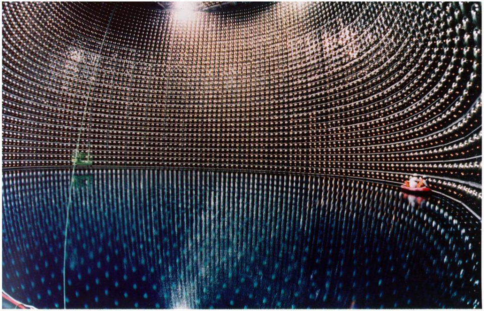
TeV-energy neutrinos

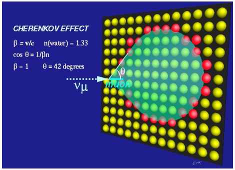
Astrophysical neutrinos: supernovae, GRBs, etc.

Neutrino physics – astrophysics interplay

1. Astrophysics puzzles, particle physics solutions
   - Atmospheric neutrino problem
   - The mystery of missing solar neutrinos
2. Physics and astrophysics of supernova neutrinos
   - Supernova explosion and neutrino emission
   - Neutrino flavour conversions
   - Physics potential of a galactic SN detection
3. Astrophysical neutrino sources: 10^{-4} eV – 10^{20} eV
   - Bigger and better detectors
   - Theoretical challenges

SuperKamiokande: 40 kiloton of water





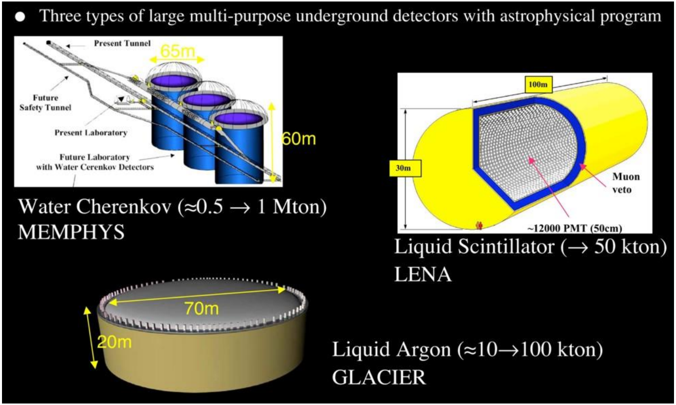
Cherenkov radiation

With 40 000 000 litres of water

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

Need bigger and better detectors !

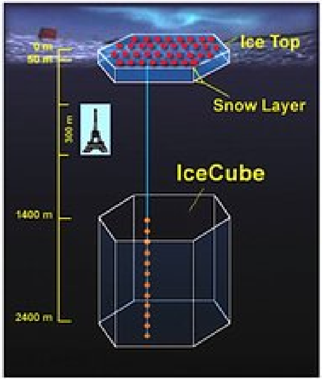
Directions of multi-purpose detector development

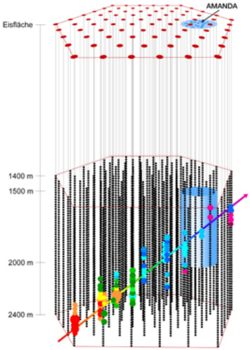


Sensitivity to MeV – 100 GeV neutrinos

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

Below the antarctic ice: Gigaton IceCube

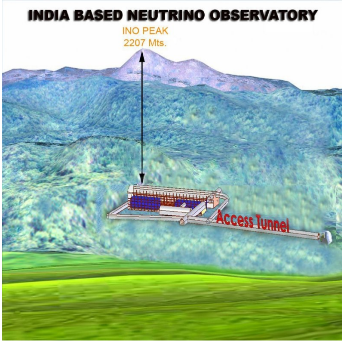


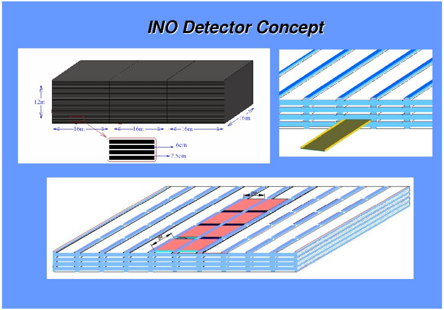


Sensitivity to $E \gtrsim 100$ GeV

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

Coming soon inside a mountain near you: INO





India-based Neutrino Observatory

- In a tunnel below a peak
- 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

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Some open issues in neutrino physics

Neutrino masses and mixing

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

Astrophysics and cosmology

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

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Neutrinos: providing windows for looking at the sky