Particle Astrophysics of Neutrinos

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Indian Academy of Sciences
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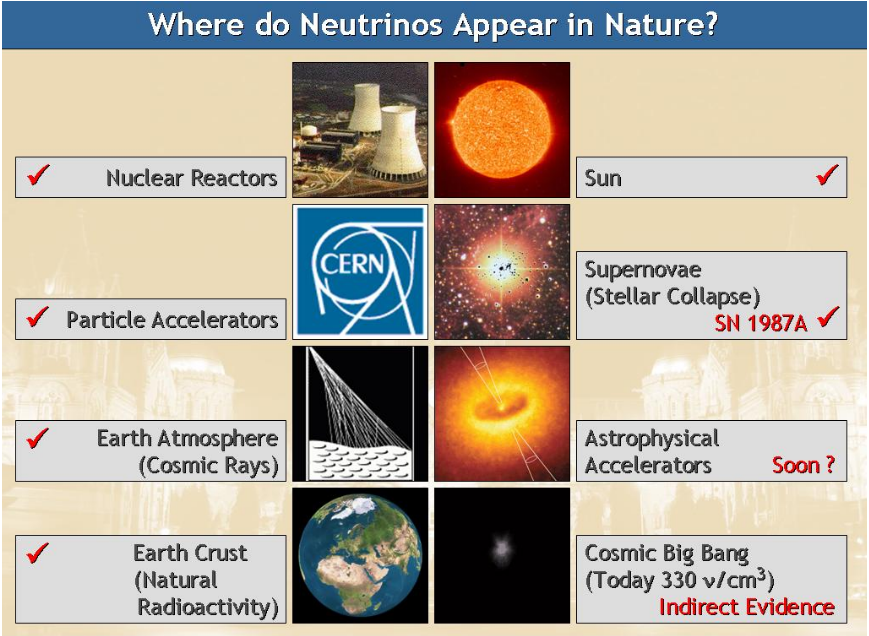
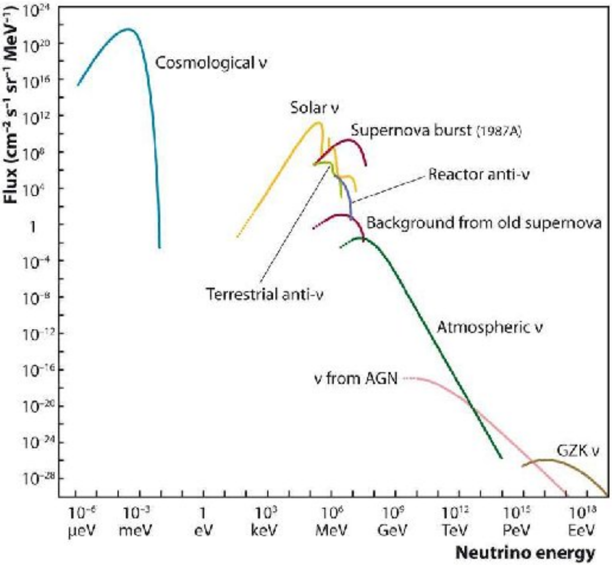
Omnipresent neutrinos



Energy spectra of neutrino sources



ASPERA

Some 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: $\sim$ 50 cm
  - Neutrinos from the Sun: light years !

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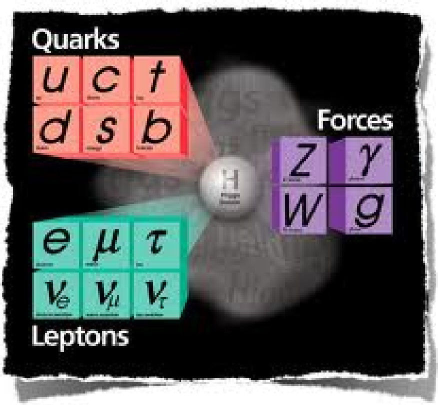
The Standard Model of Particle Physics



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

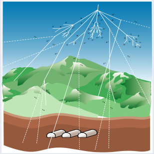
Particle astrophysics of neutrinos

1. Neutrinos that displayed oscillations
2. Neutrinos from a core collapse supernova
3. Neutrinos with extremely large / small energies
4. Exploring the universe in neutrinos

Particle astrophysics of neutrinos

The anomaly in atmospheric neutrinos (1–50 GeV)

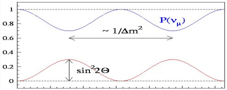
The source and the puzzle (1980s–1998)



- Cosmic rays $\oplus$ atmosphere $\Rightarrow$ pions and muons $\Rightarrow$ decay to neutrinos (ν_μ and ν_e)
- Expect almost isotropic flux of neutrinos
- Almost half the ν_μ are lost while passing through the Earth, no ν_e are lost.

Solution through "vacuum oscillations"

- Neutrinos have different masses, ν_μ and ν_τ mix
- Quantum Mechanics predicts neutrino oscillations:



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

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

- Can measure $\Delta m^2_{\rm atm}$ and $\theta_{\rm atm}$

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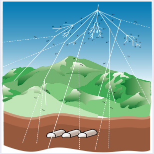

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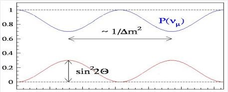

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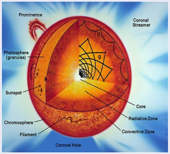
The mystery of missing Solar neutrinos (1-10 MeV)

The source and the puzzle (1960s–2002)



- Neutrinos essential for the sun to shine: many modes of producing ν_e
- Neutrino flux measured at the Earth only 30%–50% of the calculated value

Solution through "neutrino oscillations in matter"

- Neutrinos have different masses, ν_e mixes with others
- The matter inside the Sun affects Δm^2 and θ (MSW effect)
- A level crossing (resonance) takes place inside the Sun, which determines how many ν_e survive.
- Can measure $\Delta m^2_\odot$ and $\theta_\odot$

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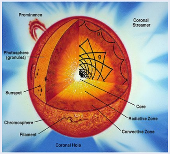

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Reactor neutrinos and Geo-neutrinos ($E \sim$ MeV)

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 $\theta_{\rm reactor}$:

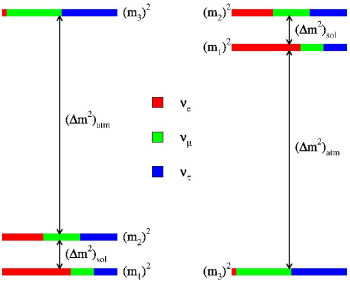
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{\rm reactor} \sin^2 \left(\frac{\Delta m^2_{\rm reactor} L}{4E} \right)$$

Geoneutrinos: $\bar{\nu}_e$

- Produced due to natural radioactivity in the Earth's crust
- Recently confirmed, after separating reactor neutrinos
- Useful for understanding Earth's radioactivity

The mixing picture and open questions

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) ?
- There are terrestrial experiments planned for this, which may give us an answer in 10-15 years, but some future astrophysical observations can decide the issue instantly !

Particle astrophysics of neutrinos

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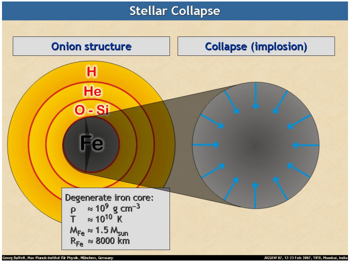
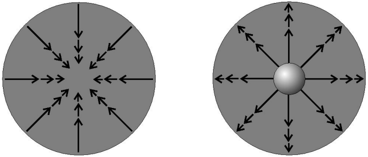
The death of a star: role of different forces

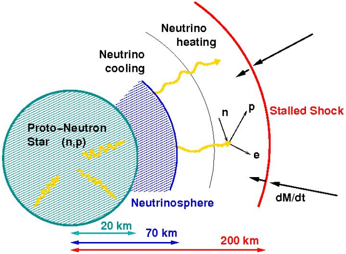
Gravity ⇒



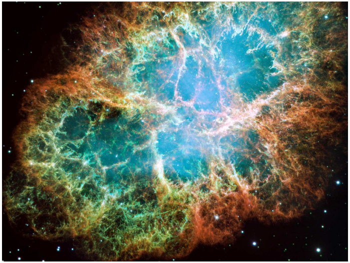
Nuclear forces ⇒



Neutrino push ⇒

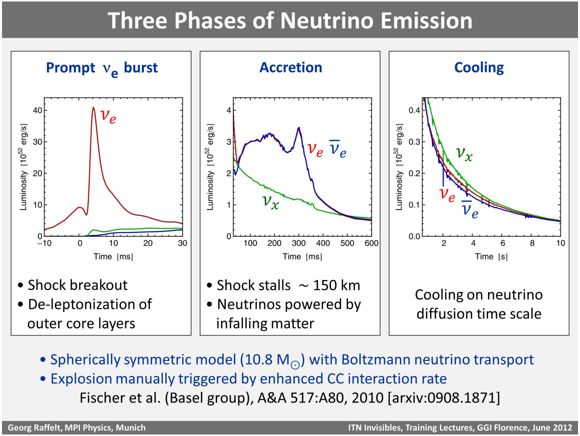


Hydrodynamics ⇒



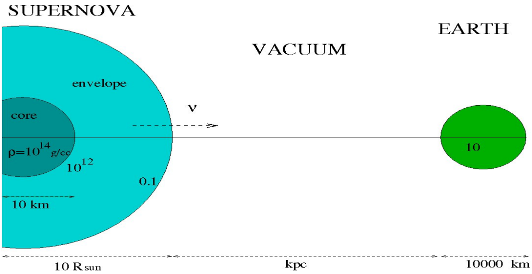
(Crab nebula, SN seen in 1054)

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

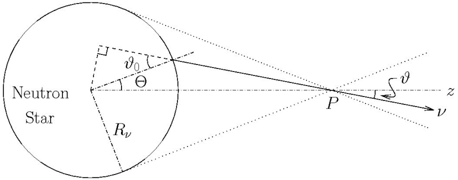
Inside the Earth: *flavour oscillations*

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

Non-linearity from neutrino-neutrino interactions

- Effective Hamiltonian: $H = H_{vac} + H_{MSW} + H_{\nu\nu}$

$$\begin{aligned} H_{vac}(\vec{p}) &= M^2/(2p) \\ H_{MSW} &= \sqrt{2} G_F n_{e^-} \, diag(1,0,0) \\ H_{\nu\nu}(\vec{p}) &= \sqrt{2} G_F \int \frac{d^3q}{(2\pi)^3} (1 - \cos\theta_{pq}) \left(\rho(\vec{q}) - \bar{\rho}(\vec{q})\right) \end{aligned}$$



Duan, Fuller, Carlson, Qian, PRD 2006

- Equation of motion:

$$\frac{d\rho}{dt} = i \left[H(\rho), \rho \right]$$

Note: ρ is a 3×3 matrix

“Collective” effects: qualitatively new phenomena

Synchronized oscillations:

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

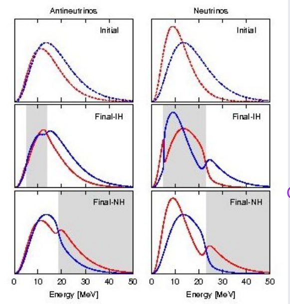
S. Pastor, G. Raffelt and D. Semikoz, PRD65, 053011 (2002)

Bipolar/pendular oscillations:

Coherent $\nu_e \bar{\nu}_e \leftrightarrow \nu_x \bar{\nu}_x$ oscillations

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

Multiple spectral split/swap:



ν_e and ν_x ($\bar{\nu}_e$ and $\bar{\nu}_x$) spectra interchange completely,
but 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)

Some new results/questions in collective effects

- New non-linear effects: can they be understood/modelled in terms of other phenomena (like superconductivity) ?

  Pehlivan, Balentekin et al, 2011

- Many answers known only with the single-angle approximation (all neutrinos at a point face the same average $\nu\nu$ potential independent of their direction).
  How does one reliably include multi-angle effects ?
- Linearized stability analysis: focussing on the onset of collective oscillations

  Banerjee, AD, Raffelt 2011, Sarikas Raffelt 2011

- Neutrinos that undergo scattering outside the neutrinosphere can have an effect on oscillations (Halo effect)

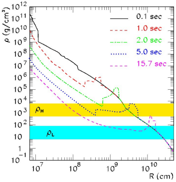
  Cherry et al 2012, Sarikas et al 2012

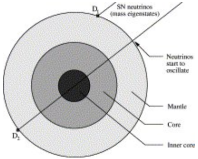
- "Collective" work in progress....

Oscillations: resonances, shock and earth effects

MSW resonances

- *H* resonance: $\rho \sim 10^3$–10^4 g/cc
  - In $\nu(\bar{\nu})$ for normal (inverted) hierarchy
- *L* resonance: $\rho \sim 10$–100 g/cc
  - Always in ν



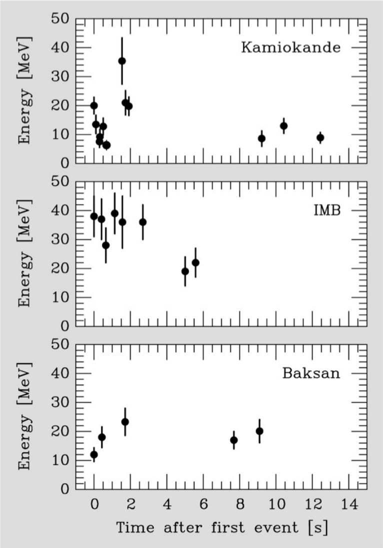


- During shock wave propagation, adiabaticity momentarily lost $\Rightarrow$ fluctuations in spectra.
- Turbulence behind the shock wave $\Rightarrow$ tends to make all flavors equal
- If the detector is shadowed by the Earth, matter-induced flavor oscillations inside the earth produce spectral modulations.

AD, Smirnov 2000

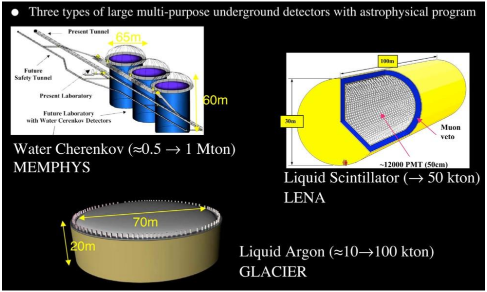
SN1987A: the neutrino observation

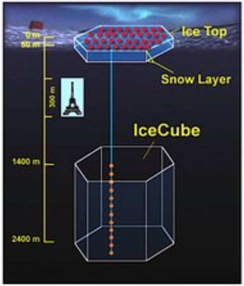
Neutrinos: Feb 23, 1987



- Neutrinos reached a few hours before the light
- Confirmed the SN cooling mechanism through neutrinos
- Number of events too small to say anything concrete about neutrino mixing
- Some constraints on SN parameters, strong constraints on new physics models (neutrino decay, Majorans, axions, extra dimensions, ...)

Preparing for future SN neutrino detection





- Water Cherenkov / liquid scintillator / liquid Ar detectors for tracking individual neutrinos
- Large-volume ice Cherenkov for determining luminosity to a high accuracy (integrated Cherenkov glow)

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)

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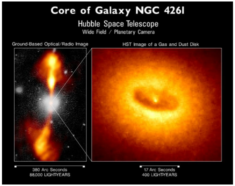
High / Ultrahigh energy neutrinos ($E \gtrsim$ TeV)



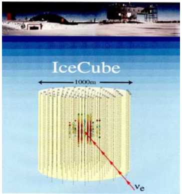
Sources of HE neutrinos

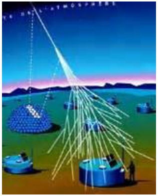
- Primary protons interacting within the source or with CMB photons $\Rightarrow \pi^{\pm} \Rightarrow$ Decay to ν
- Individual sources like AGNs and GRBs
- Diffused flux accumulated over the lifetime of universe

What we will learn

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

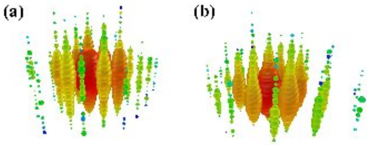
Detection of high energy neutrinos






Detection techniques

- Water Cherenkov like IceCube: 10^{11} eV $\lesssim E \lesssim 10^{16}$ eV
- Cosmic ray arrays for $E \gtrsim 10^{17}$ eV
- Radio detection from balloon experiments (Askaryan)



- Two events at $\sim 10^{15}$ eV energies found
- First observation of HEν (2011-12) !!!

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:
  $\Omega_\nu/\Omega_{\mathrm{baryon}} = 0.5\left(\sum m_\nu/\mathrm{eV}\right)$
- Looking really far back: 0.18 sec after Big Bang, as opposed to 400,000 years for CMB photons

Detection: beta-capture on beta-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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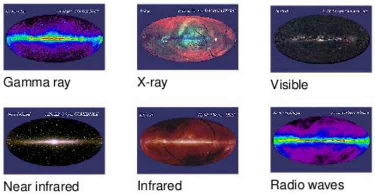
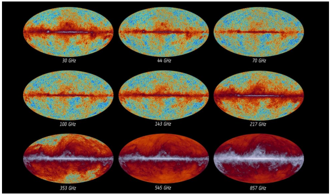
Neutrinos as messengers

- No bending in magnetic fields $\Rightarrow$ point back to the source
- Minimal obstruction / scattering $\Rightarrow$ can arrive directly from regions from where light cannot come.
- This messenger may have unknown interesting properties !

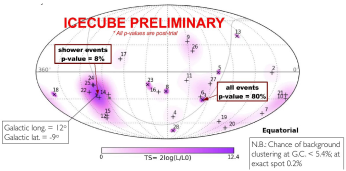
Mapping the universe

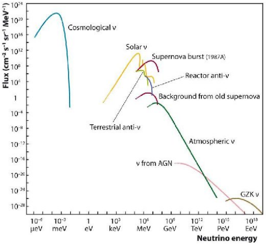




CMB from Planck

Neutrinos entering this domain, slowly but surely...





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