Particle Astrophysics of Neutrinos
some selected aspects

Amol Dighe

Department of Theoretical Physics
Tata Institute of Fundamental Research

science without boundaries
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Omnipresent neutrinos

- Nuclear Reactors
- Sun
- Particle Accelerators
- Supernovae (Stellar Collapse) \( \text{SN 1987A} \)
- Earth Atmosphere (Cosmic Rays)
- Astrophysical Accelerators \( \text{Soon?} \)
- Earth Crust (Natural Radioactivity)
- Cosmic Big Bang (Today 330 \( \nu \text{cm}^3 \)) \( \text{Indirect Evidence} \)
### 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 ⇒ Dark matter
- Stopping radiation with lead shielding:
  - \(\alpha, \beta, \gamma\) 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

- **3 neutrinos:** $\nu_e$, $\nu_\mu$, $\nu_\tau$
- 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
   - Theoretical challenges
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Neutrinos from cosmic rays (atmospheric neutrinos)

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

“\(\nu_\mu\)” flux = 2 × “\(\nu_e\)” flux

“Down” flux = “Up” flux
Atmospheric neutrino puzzle

Zenith angle dependence:

- 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
- $\nu_e$ do not participate in the oscillations

Neutrino oscillations: $\nu_\mu$ oscillate into $\nu_\tau$

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

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

Mixing parameters

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

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

Confirmed by “short baseline” experiments (K2K, MINOS)
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Neutrinos from the Sun (Solar neutrinos)

Nuclear fusion reactions: effectively

\[ 4 \, \text{^1H} + 2 \, \text{e}^- \rightarrow \frac{4}{2} \, \text{He} + 2 \nu_e + \text{light} \]

Neutrinos an essential part of all the sub-reactions:
Nuclear reactions inside the Sun

Hydrogen burning: Proton-Proton Chains

\[ p + p \rightarrow ^2H + e^+ + \nu_e \quad \text{< 0.420 MeV} \]

\[ p + e^- + p \rightarrow ^2H + \nu_e \quad 1.442 \text{ MeV} \]

100%  0.24%

\[ ^2H + p \rightarrow ^3He + \gamma \]

85%  15%

\[ ^3He + ^3He \rightarrow ^4He + 2p \]

90%  10%

\[ ^3He + ^4He \rightarrow ^7Be + \gamma \]

90%  10%  0.02%

\[ ^3He + p \rightarrow ^4He + e^+ + \nu_e \quad \text{< 18.8 MeV} \]

PPI

\[ ^7Be + e^- \rightarrow ^7Li + \nu_e \quad 0.862 \text{ MeV} \]

70%  30%

\[ ^7Be + e^- \rightarrow ^7Li^* + \nu_e \quad 0.384 \text{ MeV} \]

70%  30%  0.02%

\[ ^7Be + p \rightarrow ^8B + \gamma \quad 8B \rightarrow ^8Be^* + e^+ + \nu_e \quad \text{< 15 MeV} \]

PPII

\[ ^7Li + p \rightarrow ^4He + ^4He \]

PPIII

\[ ^8Be^* \rightarrow ^4He + ^4He \]
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 ($\nu_e$) 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 $\Phi_e$

- $\nu_{e,\mu,\tau} e^- \rightarrow \nu_{e,\mu,\tau} e^-$
  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)

- $\Phi_e + \Phi_{\mu\tau} = \text{constant}$, matches with Standard Solar Model

- $\nu_e$ convert into $\nu_\mu$ and $\nu_\tau$
### 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 $\nu_e$:
\[
P(\nu_e \rightarrow \nu_e) \approx P_f \cos^2 \theta_\odot + (1 - P_f) \sin^2 \theta_\odot
\]
- $P_f$ depends on: $\Delta m^2$, mixing angle $\theta_\odot$, density profile
- No oscillations! (Mass eigenstates have decohered)

#### Mixing parameters
\[
\Delta m^2_\odot \approx (7.2–9.5) \times 10^{-5} \text{ eV}^2
\]
- Mixing angle $\theta_\odot \approx 28^\circ–36^\circ$
- 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 “$\theta_{13}$” 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

Stellar Collapse

Onion structure

Collapse (implosion)

Degenerate iron core:

- $\rho \approx 10^9$ g cm$^{-3}$
- $T \approx 10^{10}$ K
- $M_{Fe} \approx 1.5 M_{\odot}$
- $R_{Fe} \approx 8000$ km
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: $\nu_e$ 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:
\( \nu \) and \( \bar{\nu} \) of all energies oscillate with the same frequency


Bipolar/pendular oscillations:
Coherent \( \nu_e \bar{\nu}_e \leftrightarrow \nu_x \bar{\nu}_x \) oscillations even for extremely small \( \theta_{13} \)


Spectral split/swap:
\( \nu_e \) and \( \nu_x \) (\( \bar{\nu}_e \) and \( \bar{\nu}_x \)) spectra interchange completely, only within certain energy ranges.


Collective effects influencing supernova astrophysics

- Nucleosynthesis of heavy elements (r-process)
- Shock wave propagation
**“Collective” effects: qualitatively new phenomena**

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Neutrino spectra exiting the supernova

B. Dasgupta, AD, G.Raffelt, A.Smirnov, PRL2009
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- Bigger and better detectors
- Theoretical challenges
A recent nearby supernova: SN1987A

- 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

(Hubble image)
Signal expected from a galactic SN (10 kpc)

### Water Cherenkov detector:
- $\bar{\nu}_e p \rightarrow ne^+: \approx 7000 - 12000^*$
- $\nu e^- \rightarrow \nu e^- : \approx 200 - 300^*$
- $\nu_e + ^{16}O \rightarrow X + e^- : \approx 150-800^*$

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

### Carbon-based scintillation detector:
- $\bar{\nu}_e p \rightarrow ne^+$
- $\nu + ^{12}C \rightarrow \nu + X + \gamma (15.11 \text{ MeV})$

### 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 $\theta_{13}$

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 $\theta_{13}$

## 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.
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SuperKamiokande: 40 kiloton of water

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

- Three types of large multi-purpose underground detectors with astrophysical program
  
  Water Cherenkov ($\approx 0.5 \rightarrow 1 \text{ Mton}$)
  MEMPHYS

  Liquid Scintillator ($\rightarrow 50 \text{ kton}$)
  LENA

  Liquid Argon ($\approx 10 \rightarrow 100 \text{ kton}$)
  GLACIER

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 $\nu$ 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