Neutrino Physics: an Introduction

Lecture 3: Neutrinos in astrophysics and cosmology

Amol Dighe

Department of Theoretical Physics
Tata Institute of Fundamental Research, Mumbai

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Lecture 1: Neutrino detection and basic properties

- Unique properties
- Discovery of neutrino flavours
- Measuring mass, helicity, interactions

Lecture 2: Neutrino mixing and oscillations

- Solar and atmospheric puzzles and solutions
- Neutrino mixing, oscillations, flavour conversions
- The three-neutrino mixing picture

Lecture 3: Neutrinos in astrophysics and cosmology

- Low-energy (meV) cosmological neutrinos
- Medium-energy (MeV) supernova neutrinos
- High-energy ($>$ TeV) astrophysical neutrinos

1. Matter effects and future detectors
2. Low-energy (meV) cosmological neutrinos
3. Medium-energy (MeV) supernova neutrinos
4. High-energy (> TeV) astrophysical neutrinos

Effect of matter on mixing angle and Δm^2, Resonance

Constant matter density: $\Delta \equiv \frac{\Delta m^2}{4E}, \quad V_C \equiv \sqrt{2} G_F N_e$

Neutrinos

- $$\tan 2\theta_m = \frac{2\Delta \sin 2\theta}{2\Delta \cos 2\theta - V_C}$$
- $$\Delta_m = \sqrt{(\Delta \cos 2\theta - \frac{V_C}{2})^2 + (\Delta \sin 2\theta)^2}$$

Antineutrinos

- $$\tan 2\theta_m = \frac{2\Delta \sin 2\theta}{2\Delta \cos 2\theta + V_C}$$
- $$\Delta_m = \sqrt{(\Delta \cos 2\theta + \frac{V_C}{2})^2 + (\Delta \sin 2\theta)^2}$$

Conversion probability and CP violation

$$
\begin{aligned}
P_{e\mu} \simeq\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
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$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$, $\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$, $\hat{A} \equiv \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}}$

(Cervera et al. 2000; Freund, Huber, Lindner, 2000; Huber, Winter, 2003; Akhmedov et al, 2004)

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- Silver: $P_{e\tau} = P_{e\mu}(s^2_{23} \leftrightarrow c^2_{23}, \sin 2\theta_{23} \rightarrow -\sin 2\theta_{23})$

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- Platinum, Superb.: $P_{\mu e} = P_{e\mu}(\delta_{CP}, \rightarrow -\delta_{CP})$

(Cervera et al. 2000; Freund, Huber, Lindner, 2000; Huber, Winter, 2003; Akhmedov et al, 2004)

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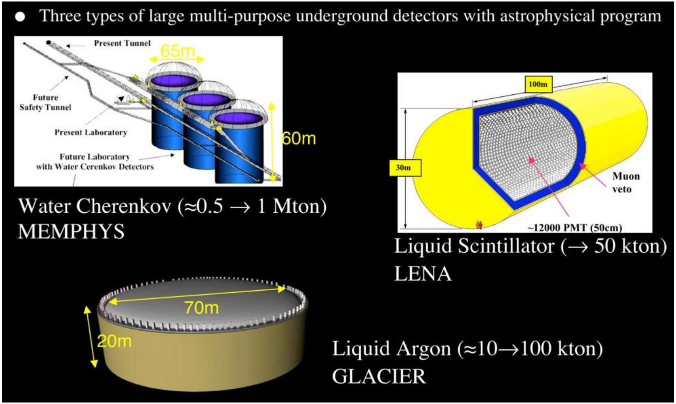
Future directions of multipurpose detectors



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

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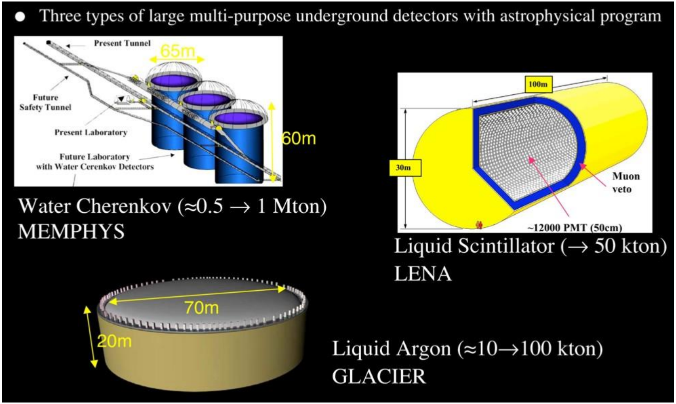
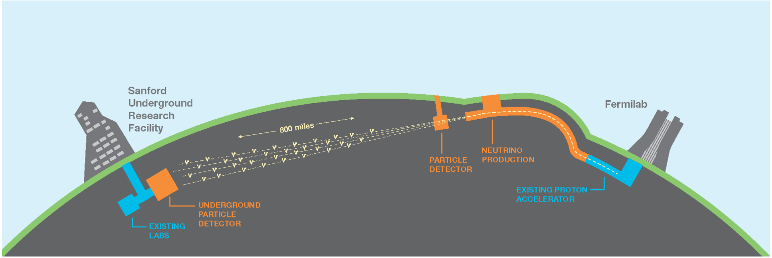


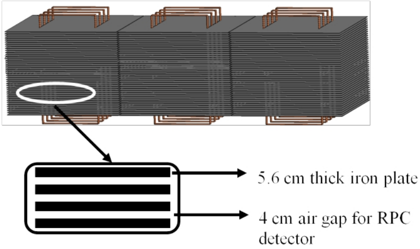
- Megaton water Cherenkov detectors
- 50 kiloton scintillator detectors
- 100 kiloton liquid Ar detectors
- Advantages ?

Long baseline experiments



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

Coming soon inside a mountain near you: INO



India-based Neutrino Observatory

- 1 km rock coverage from all sides
- 50 kiloton of magnetized iron (50 000 000 kg)

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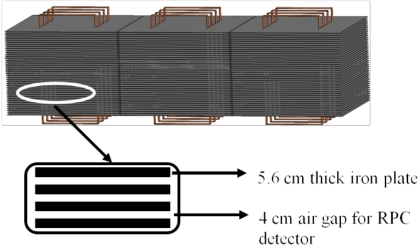

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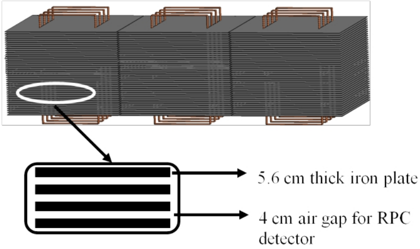

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- 50 kiloton of magnetized iron (50 000 000 kg)
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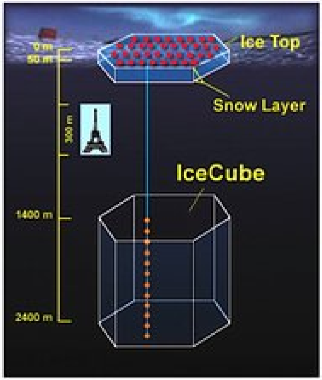
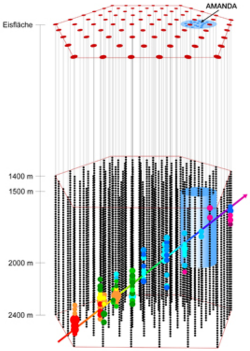
- Can distinguish neutrinos from antineutrinos
- Determining mass ordering from atmospheric neutrinos
- Can look for dark matter, magnetic monopoles, ...

Below the antarctic ice: Gigaton IceCube

1 000 000 000 000 litres of ice

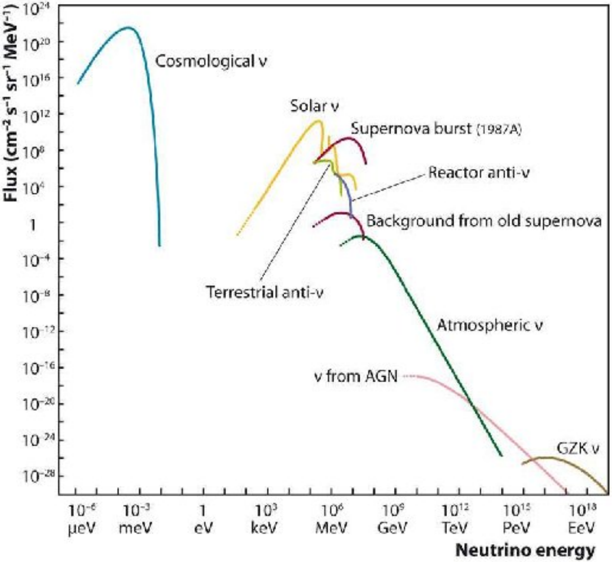




Neutrinos as messengers

- 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.

Neutrino fluxes at different energies



Neutrino Physics: an Introduction (Lecture 3)

1. Matter effects and future detectors
2. Low-energy (meV) cosmological neutrinos
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Source: abundance and temperature

- Relic density: $\sim$ 110 neutrinos /flavor /cm^3
- Temperature: $T_\nu = (4/11)^{1/3} T_{\mathrm{CMB}} \approx 1.95\ \mathrm{K} = 0.16\ \mathrm{meV}$
- 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:

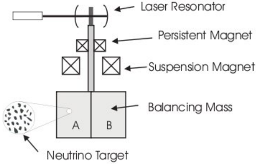
$$\Omega_\nu/\Omega_{\mathrm{baryon}} = 0.5 \left(\sum m_\nu/\mathrm{eV}\right)$$

- Looking really far back:

	Time	Temp	z
Relic neutrinos	0.18 s	$\sim$ 2 MeV	$\sim 10^{10}$
CMB photons	$\sim 4 \times 10^5$ years	0.26 eV	1100

Lazauskas, Vogel, Volpe, 2008

Detection of relic neutrinos: the torsion balance idea



- De Brogli wavelength of relic neutrinos: $\lambda \approx h/p \approx 1.5$mm.
- ν can interact coherently with a sphere of this size
- Measure force on such "spheres" due to the relic neutrino wind

- For iron spheres and 100 times local overdensity for ν, acceleration $a \lesssim 10^{-26}$ cm /s^2

Shvartsman et al 1982

- $\gtrsim$ 10 orders of magnitude smaller than the sensitivity of current torsion balance technology
- If neutrinos are Majorana, a further suppression by $v/c \approx 10^3$ (polarized target), $(v/c)^2 \approx 10^{-6}$ (unpolarized)

Hagmann, astro-ph/9901102

- The idea is essentially impractical.

The inverse beta reaction

- Need detection of low-energy neutrinos, so look for zero-threshold interactions
- Beta-capture on beta-decaying nuclei:

$$\nu_e + N_1(A, Z) \to N_2(A, Z+1) + e^-$$

End-point region ($E > M_{N_1} - M_{N_2}$) background-free. Energy resolution crucial.

Weinberg 1962, cocco, Mangano, Messina 2008, Lazauskas et al 2008, Hodak et al 2009

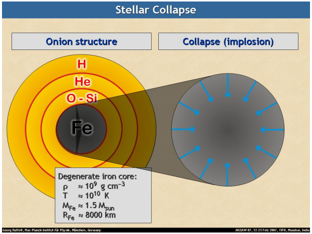
- Possible at ^{3}H experiments with 100 g of pure tritium but atomic tritium is neeed to avoid molecular energy levels

Lazauskas, Vogel, Volpe 2009, Hodak et al 2011

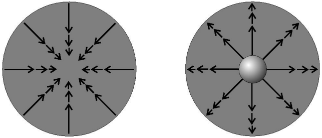
- PTOLEMY: Princeton Tritium Observatory for Light, Early-universe, Massive neutrino Yield

Supernova: the death of a star

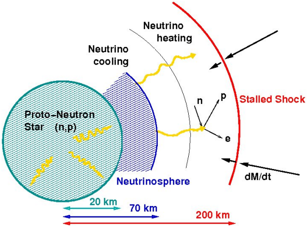
Gravity ⇒



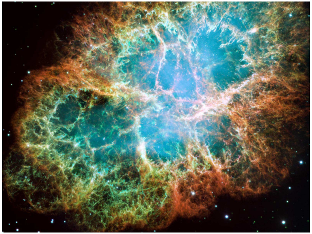
Strong nuclear force ⇒



Weak nuclear force (Neutrino push) ⇒

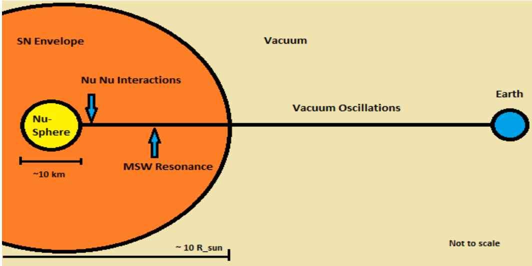


Electromagnetism (Hydrodynamics) ⇒



(Crab nebula, SN seen in 1054)

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*

Neutrino mass eigenstates travel independently

Inside the Earth: *flavour oscillations*

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

Can neutrino conversions affect SN explosions ?

- Simulations of light SN have started giving explosions with the inclusions of 2D/3D large scale convections and hydrodynamic instabilities
- More push to the shock wave is still desirable.

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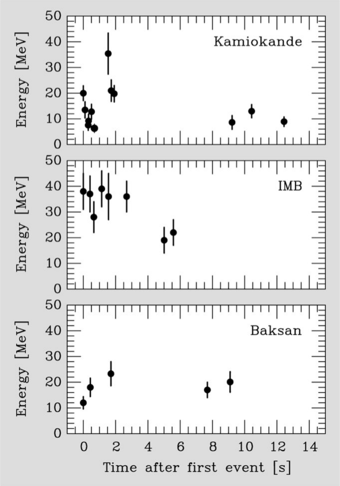
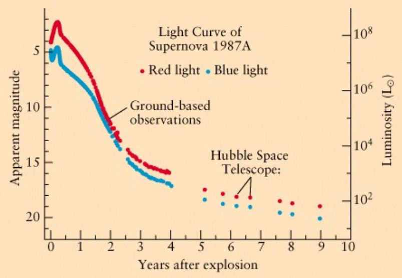
- Deeper the conversions, greater the neutrino push
- Neutrino flavour conversions in extremely dense media:
  - MSW resonances: 1000 km,
  - Neutrino-neutrino collective effects: 100 km
  - “Fast conversions”: 10 km [Angular anisotropies needed, but quite naturally possible]

SN1987A: neutrinos and light

Neutrinos: Feb 23, 1987



Light curve: 1987-1997

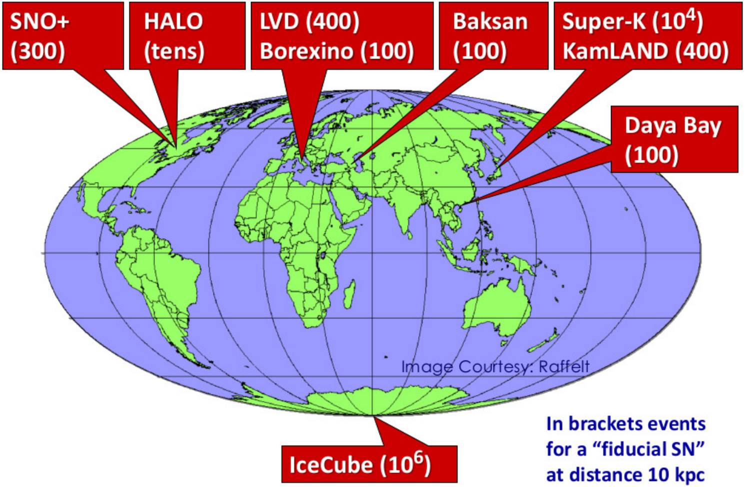


SN1987A: what did we learn ?

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, ...)

Supernova neutrino detectors



What supernova neutrinos can tell us

On neutrino masses and mixing

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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)
- How is a neutron star / black hole formed ? Is there a QCD phase transition ?
- How are heavy elements formed ?

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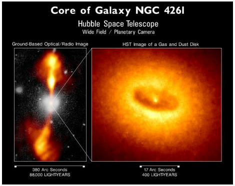
Sources of high-energy neutrinos



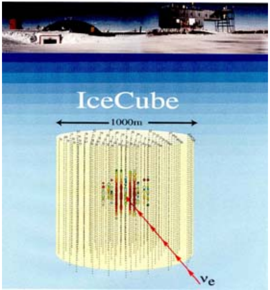
The origins

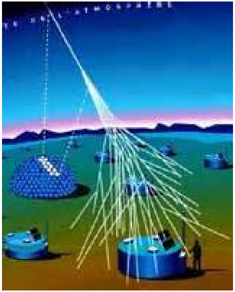
- Primary protons interacting within the source or with CMB photons $\Rightarrow \pi^{\pm} \Rightarrow$ Decay to ν
- Individual sources like AGNs and GRBs
- Diffused flux accumulated over the lifetime of universe

What we will learn

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

Detection of high energy neutrinos

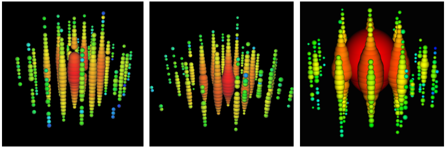




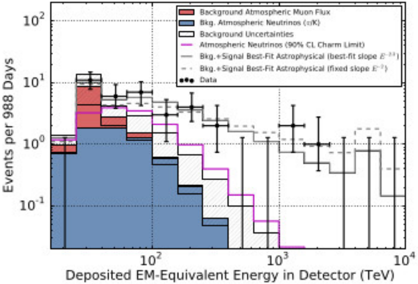
Detection techniques

- 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)

Highest energy neutrinos observed till now



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

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): $0 : 1 : 0$

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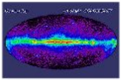
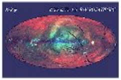
New physics effects

- 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

Dawn of multi-messenger astronomy

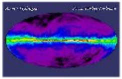

Gamma ray


X-ray


Visible


Near infrared


Infrared


Radio waves