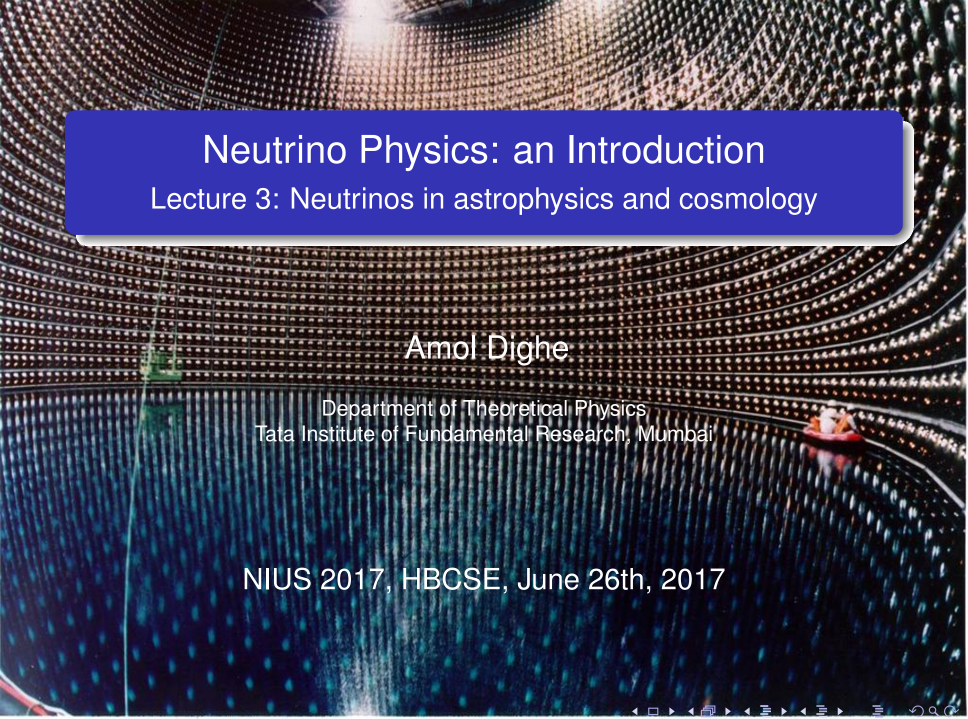

Neutrino Physics: an Introduction

Lecture 3: Neutrinos in astrophysics and cosmology

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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

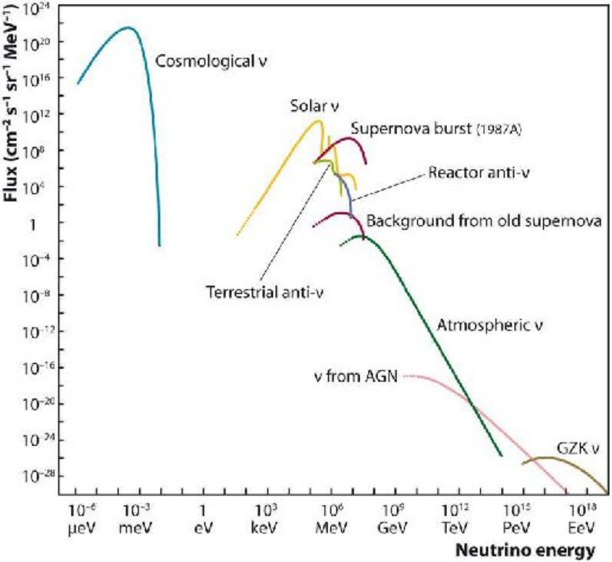
Lecture 3: Neutrinos in astrophysics and cosmology

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

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



1. Low-energy (meV) cosmological neutrinos
2. Medium-energy (MeV) supernova neutrinos
3. High-energy ($>$ TeV) astrophysical neutrinos
4. Some future directions...

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Source: abundance and temperature

- Relic density: $\sim$ 110 neutrinos /flavor /cm^3
- Temperature: $T_\nu = (4/11)^{1/3} T_{\mathrm{CMB}} \approx 1.95\ \mathrm{K} = 16.7\ \mathrm{meV}$
- 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

The inverse beta reaction

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

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

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

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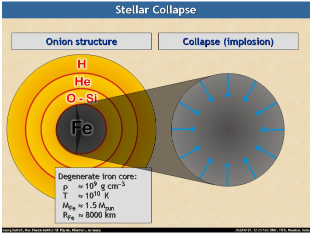
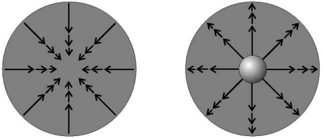
Supernova: the death of a star

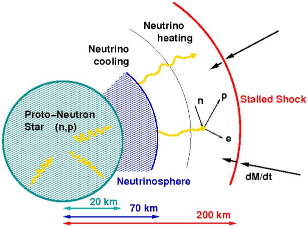
Gravity $\Rightarrow$



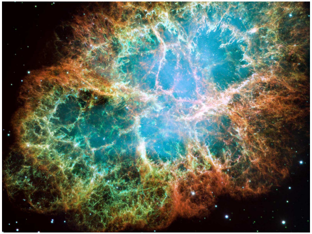
Strong nuclear force $\Rightarrow$



Weak nuclear force (Neutrino push) $\Rightarrow$

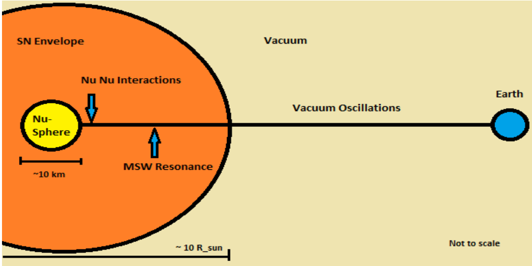


Electromagnetism (Hydrodynamics) $\Rightarrow$



(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*

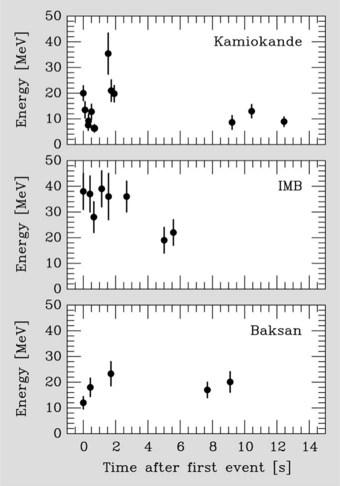
Resonant matter effects (*if detector is shadowed by the Earth*)

Can neutrino conversions affect SN explosions ?

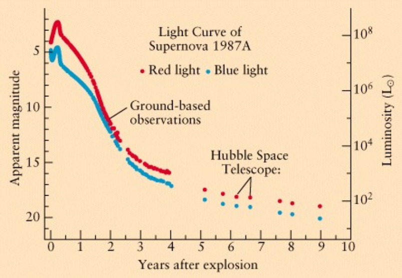
- Simulations of light SN have started giving explosions with the inclusions of 2D/3D large scale convections and hydrodynamic instabilities
- More push to the shock wave is still desirable.
- Non-electron neutrino primary spectra harder
  $\oplus$ electron neutrino cross section higher
  $\Rightarrow$ After conversion, greater push to the shock wave
- 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

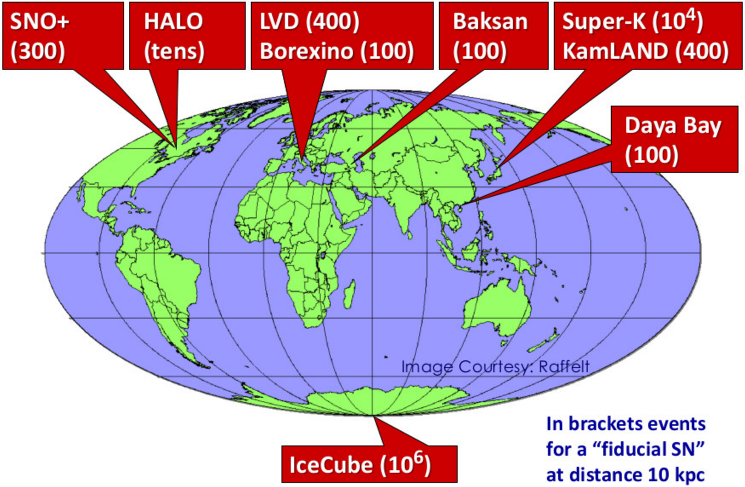


SN1987A: what did we learn ?

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



In brackets events for a "fiducial SN" at distance 10 kpc

What supernova neutrinos can tell us

On neutrino masses and mixing

- Identify neutrino mass ordering: normal or inverted

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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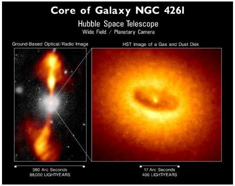
Sources of high-energy neutrinos



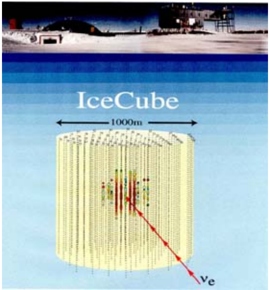
The origins

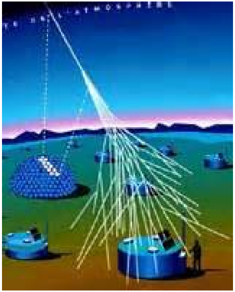
- Primary protons interacting within the source or with CMB photons $\Rightarrow \pi^{\pm} \Rightarrow$ Decay to ν
- Individual sources like AGNs and GRBs
- Diffused flux accumulated over the lifetime of universe

What we will learn

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

Detection of high energy neutrinos

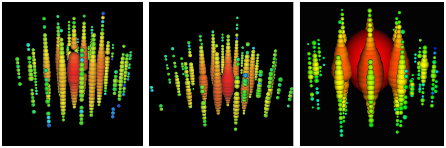




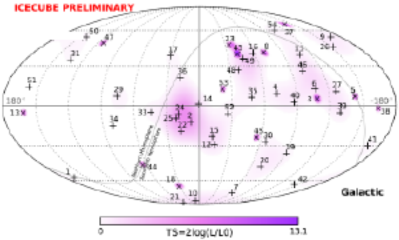
Detection techniques

- 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): $0 : 1 : 0$

Flavor ratios at detectors

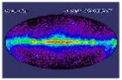
- Neutron source: $\approx 5 : 2 : 2$
- Pion source: $\approx 1 : 1 : 1$
- Muon-absorbing sources : $\approx 4 : 7 : 7$

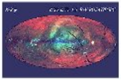
New physics effects

- 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

Dawn of multi-messenger astronomy

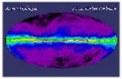

Gamma ray

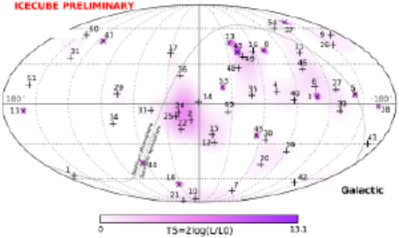

X-ray

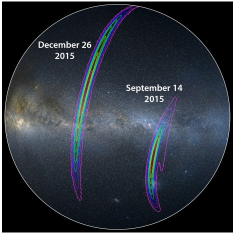

Visible


Near infrared


Infrared


Radio waves





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Possible threads in “Neutrinos in Astrophysics”

- Using neutrinos to learn about the Sun
- Neutrino conversions inside a supernova
- Interpretations of high-energy events at Icecube
- Leptogenesis and baryogenesis

Pre-requisites and post-requisites

Essential background skills

- Basic quantum mechanics, linear (matrix) algebra
- Numerical calculations and plots

Topics to be learnt on the way

- Standard Model of particle physics
- Matter effects on neutrino flavour conversions
- Statistics and data analysis