Astroparticle physics of neutrinos

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Recent Issues in Nuclear and Particle Physics (RINP2)
Visva Bharati, Feb 4th, 2019
The knowns and unknowns of neutrinos

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

- $\Delta m_{\text{atm}}^2 \approx 2.4 \times 10^{-3} \text{ eV}^2$
- $\Delta m_{\odot}^2 \approx 8 \times 10^{-5} \text{ eV}^2$
- $\theta_{\text{atm}} \approx 45^\circ$
- $\theta_{\odot} \approx 32^\circ$
- $\theta_{\text{reactor}} \approx 9^\circ$

- Mass ordering: Normal (N) or Inverted (I) ?
- What are the absolute neutrino masses ?
- Are there more than 3 neutrinos ?
- Is there leptonic CP violation ?
- Can neutrinos be their own antiparticles ?
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Neutrinos come from many sources...

### Where do Neutrinos Appear in Nature?

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<th>Source</th>
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<td>Cosmic Big Bang (Today 330 $\text{v/cm}^3$) Indirect Evidence</td>
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Neutrinos as messengers from astrophysical sources

- No bending in magnetic fields ⇒ point back to the source
- Minimal obstruction / scattering ⇒ can arrive directly from regions from where light cannot come
Spectra of neutrino sources

- Cosmological $\nu$
- Solar $\nu$
- Supernova burst (1987A)
- Reactor anti-$\nu$
- Background from old supernova
- Terrestrial anti-$\nu$
- Atmospheric $\nu$
- $\nu$ from AGN
- GZK $\nu$

Flux (cm$^{-2}$ s$^{-1}$ sr$^{-1}$ MeV$^{-1}$)

Neutrino energy:
- $10^{-6}$ meV
- $10^{-3}$ meV
- 1 eV
- $10^3$ keV
- $10^6$ MeV
- $10^9$ GeV
- $10^{12}$ TeV
- $10^{15}$ PeV
- $10^{13}$ EeV
Astroparticle Physics of Neutrinos

1. Neutrinos from a core collapse supernova
2. Astrophysical neutrinos with ultra-high energies
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4. Multi-messenger astronomy
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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

Three Phases of Neutrino Emission

- **Prompt $\nu_e$ burst**
  - Shock breakout
  - De-leptonization of outer core layers

- **Accretion**
  - Shock stalls $\sim 150$ km
  - Neutrinos powered by infalling matter

- **Cooling**
  - Cooling on neutrino diffusion time scale

- Spherically symmetric model ($10.8 M_\odot$) with Boltzmann neutrino transport
- Explosion manually triggered by enhanced CC interaction rate
  
  Fischer et al. (Basel group), A&A 517:A80, 2010 [arxiv:0908.1871]

- 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*)
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
  ⊕ electron neutrino cross section higher
  ⇒ After conversion, greater push to the shock wave

- Deeper the conversions, greater the neutrino push

- MSW resonances: \( \sim 1000 \text{ km} \),
  Neutrino-neutrino collective effects: \( \sim 100 \text{ km} \)

- “Fast conversions”: \( \sim 10 \text{ km} \)
  (Angular anisotropies needed, but quite naturally possible)
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SN1987A: neutrinos and light

Neutrinos: Feb 23, 1987

Light curve: 1987-1997
SN1987A: what did we learn?

- 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, Majorons, axions, extra dimensions, ...)

Hubble image: now
Supernova neutrino detectors

- SNO+ (300)
- HALO (tens)
- LVD (400) Borexino (100)
- Baksan (100)
- Super-K ($10^4$) KamLAND (400)
- Daya Bay (100)

In brackets events for a “fiducial SN” at distance 10 kpc

Image Courtesy: Raffelt

Slide by Georg Raffelt
What a galactic SN can tell us

**On neutrino masses and mixing**
- Instant identification of neutrino mass ordering \((N \text{ or } I)\), through
  - Neutronization burst: (almost) disappears if \(N\)
  - Shock wave effects: in \(\nu (\bar{\nu})\) 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)
- Possible identification of QCD phase transition, SASI (Standing Accetion Shock) instabilities
- Hints on heavy element nucleosynthesis (r-process)
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High / Ultrahigh energy neutrinos ($E \gtrsim \text{TeV}$)

Sources of UHE neutrinos

- Primary protons interacting within the source
  \[ \Rightarrow \pi^\pm \Rightarrow \text{Decay to } \nu \]
- Primary protons interacting with CMB photons
  \[ \Rightarrow \pi^\pm \Rightarrow \text{Decay to } \nu \text{ (GZK)} \]
- 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
Below the antarctic ice: Gigaton IceCube

1 000 000 000 000 litres of ice
Detection of HE neutrinos: water/ice Cherenkov

- Thresholds of $\sim 100$ GeV, controlled by the distance between optical modules

Sensitive energy ranges

- $10^{11} \text{ eV} \lesssim E \lesssim 10^{16} \text{ eV}$: up-going neutrinos
  - No background from cosmic rays
- $E \gtrsim 10^{16-17} \text{ eV}$: down-going neutrinos
  - Atmospheric neutrino background insignificant
  - Up-going neutrinos get absorbed in the Earth
The three PeV events at Icecube

- Three events at $\sim 1, 1.1, 2.2$ PeV energies found
- Cosmogenic? $\times$ Glashow resonance? $\times$ atmospheric?
  - Roulet et al 2013 ++ many
- IceCube analyzing 54 events from 30 TeV to 10 PeV
- Constraints on Lorentz violation: $\delta (\nu^2 - 1) \lesssim O(10^{-18})$
  - Borriello, Chakraborty, Mirizzi, 2013
Detection of UHE neutrinos: cosmic ray showers

- Neutrinos with $E \gtrsim 10^{17}$ eV can induce giant air showers (probability $\lesssim 10^{-4}$)
- Deep down-going muon showers
- Deep-going $\nu_\tau$ interacting in the mountains
- Up-going Earth-skimming $\nu_\tau$ shower
Detection through radio waves: ANITA

Charged particle shower $\Rightarrow$ Radio Askaryan: charged clouds emit coherent radio waves through interactions with $B_{\text{Earth}}$ or Cherenkov

Detectable for $E \gtrsim 10^{17}$ eV at balloon experiments like ANITA
Limits on UHE neutrino fluxes

Waxman-Bahcall, AMANDA, Antares, RICE, Auger, IceCube
Also expect complementary info from: ANITA, NEMO, NESTOR, KM3NET ...
Flavor information from UHE neutrinos

Flavor ratios $\nu_e : \nu_\mu : \nu_\tau$ at sources

- Neutron source (nS): $1 : 0 : 0$
- Pion source ($\pi$S): $1 : 2 : 0$
- Muon-absorbing sources ($\mu$DS): $0 : 1 : 0$

Flavor ratios at detectors (with neutrino mixing)

- 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
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Beacom et al, PRL 2003
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The big-bang relic neutrinos ($\sim 0.1$ meV)

- Relic density: $\sim 110$ neutrinos /flavor /cm$^3$
- Temperature: $T_\nu = (4/11)^{1/3} T_{\text{CMB}} \approx 1.95$ K = 0.17 meV
- The effective number of neutrino flavors:
  \[ N_{\text{eff}}(\text{SM}) = 3.074. \text{ Planck} \Rightarrow N_{\text{eff}} = 3.30 \pm 0.27. \]
- Contribution to dark matter density:
  \[ \Omega_\nu/\Omega_{\text{baryon}} = 0.5 \left( \sum m_\nu/\text{eV} \right) \]

Looking really far back:

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Detection of relic neutrinos: the torsion balance idea

- De Broglie wavelength of relic neutrinos: \( \lambda \approx \frac{h}{p} \approx 1.5\text{mm} \).
- \( \nu \) 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 \( \nu \), acceleration \( a \lesssim 10^{-26} \text{cm/s}^2 \) \cite{Shvartsman1982}.

\( \gtrsim 10 \) orders of magnitude smaller than the sensitivity of current torsion balance technology.

If neutrinos are Majorana, a further suppression by \( \nu/c \approx 10^3 \) (polarized target), \( (\nu/c)^2 \approx 10^{-6} \) (unpolarized) \cite{Hagmann1999}.

The idea is rather impractical at the moment.
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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.


- Possible at \(^3\text{H}\) experiments with 100 g of pure tritium but atomic tritium is needed to avoid molecular energy levels
- \(^{187}\text{Re}\) at MARE also suggested, but a lot more material will be needed
- Search for ways of detection still on ...

Lazauskas, Vogel, Volpe 2009, Hodak et al 2011
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Light, neutrinos, and gravitational waves
Follow-up detections of IC170922 based on public telegrams

- **IceCube**
  - September 22

- **Swift**
  - September 26

- **Fermi, ASAS-SN**
  - September 28

- **MAGIC**
  - October 4

- **Liverpool, AGILE**
  - September 29
Blazar at IceCube

Follow-up Observations of IceCube Alert IC170922

Observatories
- Earth Observatory
- Space Observatory

Detections
- Observations with detection
- Observations without detection

IceCube Neutrino Observatory
Astrophysical observations have played a crucial role in unravelling neutrino properties.

The knowledge of neutrino properties can now be used to learn about astrophysical phenomena.