Probing New Physics with Astrophysical Neutrinos

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Introduction

New Physics $\Rightarrow$ New Particle Physics

Astrophysical Neutrinos $\Rightarrow$ Neutrinos from beyond the solar system
Neutrinos detected so far:

- MeV energies
  Neutrinos from the Sun and SN1987A

- Up to $\sim 1$ TeV (SuperK and others)
  & above 1 TeV (AMANDA, Frejus)
  Only atmospheric neutrinos

- Higher energies
  Upper limits on fluxes

BUT, excellent prospects for many experiments now coming on line
Astrophysical neutrino beam

- May eventually be as useful/revealing as the solar neutrino beam
- But we first need to detect and calibrate it!
Neutrino Sources

- “Cosmic beam dumps”, eg, active galactic nuclei, gamma ray bursts, supernovae remnants.
  - Optically thin sources → ν, γ and CR fluxes related. (e.g. Waxman & Bahcall; Mannheim, Protheroe & Rachen.)
  - Optically thick → “hidden” sources → neutrinos only

- Cosmogenic (GZK) neutrinos. (Guaranteed)
  → Interaction of cosmic rays with the cosmic microwave background

- Annihilation or decay of dark matter
  → Fluxes related to dark matter cross-sections and density distributions.
Astrophysical flux limits

AMANDA collaboration 2007
Above the electroweak scale

• UHE neutrinos probe energies far above the EW scale → Sensitivity to new physics via new contributions to cross-sections.

• Neutrino-nucleon cross-section must be extrapolated to energies where we have no experimental data points. (Ghandi, Quigg, Reno and Sarcevic)

• Suppressed cross-sections (w.r.t. simple parton model):
  → Possible new physics?
  → Saturation effects at high energy (Growth of cross-section with energy must saturate to preserve unitarity, Froissart bound.)

• Enhanced cross-sections:
  → Exchange of towers of Kaluza Klein gravitions (Feng & Shapere)
  → Black hole production (Banks & Fischler; Giddings & Thomas; Dimopoulos & Landsberg.)
  → Electroweak Instantons (Fodor, Katz, Ringwald, & Tu.)
Event rates $\rightarrow$ cross sections

- Event rates depend upon (flux)$\times$(cross-section)

How do we disentangle astrophysics from particle physics?

- Events rates for up and down going neutrinos depend differently on neutrino cross-sections.

- Enhanced cross-sections would:
  - increase down-going event rate
  - decrease up-going event rate (due to greater absorption in Earth)

- Amanda already provides constraints at 6 TeV CoM energy:
  \[ E_\nu = 10^{7.25} \text{ GeV} \quad \Rightarrow \quad \sqrt{s} = 6 \text{ TeV} \]
Cross-sections/fluxes at IceCube


\[ E_\nu = 10^{7.25} \text{ GeV} \]

\[ \frac{\sigma_{2\nu}}{\sigma_{\text{SM}}} \]

\[ \frac{\phi_\nu}{\phi_{\text{WB}}} \]
Neutrino probe of SUSY


• Neutrinos make NLSP pairs in the Earth

• NLSP is charged and long lived → long range.

Energetic NLSP pairs make a new signal in IceCube
→ Two parallel charged tracks, ~ 100 m apart.

Can also use atmospheric neutrinos. Ando, Beacom, Profumo, Rainwater, JCAP 0804, 029 (2008)
Neutrino Production

- pp and pγ interactions produce charged and neutral pions
  \[ pp \rightarrow NN + \text{pions}; \quad p\gamma \rightarrow p\pi^0, n\pi^+ \]
- Neutrinos from pion decay:
  \[ \pi^+ \rightarrow \nu_\mu + \mu^+ \]
  \[ \downarrow \]
  \[ \bar{\nu}_\mu + e^+ + \nu_e \]
- Expected flavor ratio at the source:
  \[ \nu_e : \nu_\mu : \nu_\tau = 1:2:0 \]
  \[ \nu_e : \nu_\mu : \nu_\tau = 1:1:1 \]

- After oscillations: \( \nu_\mu \leftrightarrow \nu_\tau \)
- For hadronic production, \( \phi_\nu \sim \phi_\gamma \)

Learned & Pakvasa
Deviations from 1:1:1
- Particle Physics

Exotic neutrino properties

• Neutrino decay  (Beacom, Bell, Hooper, Pakvasa, & Weiler)
• CPT violation  (Barenboim & Quigg)
• Oscillation to steriles  (Dutta, Reno and Sarcevic)
• Oscillations with tiny delta $\delta m^2$  (Crocker, Melia, & Volkas; Berezinsky et al.)
• Pseudo-Dirac mixing  (Beacom, Bell, Hooper, Learned, Pakvasa, & Weiler)
• Magnetic moment transitions  (Enqvist, Keränen, Maalampi)
• Mass varying neutrinos  (Fardon, Nelson & Weiner; Hung & Pas)
• ...
Neutrino invisible decays are not ruled out, and would greatly alter the ratios.

Other new physics can lead to different ratios.

Beacom, Bell, Hooper, Pakvasa, Weiler, PRL 90, 181301 (2003);
Ultimate long-baseline experiment

Astrophysical sources provide baselines almost as big as the visible universe.

This allows a sensitivity to oscillations with tiny $\delta m^2$

Eg. Oscillation modes that have a sub-dominant or completely negligible effect on the solar or atmospheric neutrinos may show up here.

Crocker, Melia and Volkas (2000, 2002)
Berezinsky, Narayan and Vissani (2002)
Keranen, Maalampi, Myyrylainen and Riittinen (2003)
Beacom, Bell, Hooper, Pakvasa, Learned, and Weiler (2004)
Pseudo-Dirac Neutrinos

Neutrinos appear to be Dirac, but in fact have subdominant Majorana mass terms.

- Oscillations driven by tiny mass differences.
- Would show up in astro-nu flavor ratios.
Deviations from 1:1:1

- Astrophysics

**Galactic $\beta$ beams:**
Photo-disintegration of heavy nuclei $\rightarrow$ neutrons $\rightarrow$ Pure $\bar{\nu}_e$ flux
$\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0 \rightarrow 5 : 2 : 2$ after oscillations

**Muon-damped source:**
If muons loose energy before decaying:
$\nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0 \rightarrow 1 : 2 : 2$ after oscillations

**We can do oscillation experiments with such sources!**
Measuring the 1-3 mixing angle and the CP phase:
e.g. Serpico & Kachelreiss, PRL 94, 21102 (2005); Winter, PRD 74, 033015 (2006);
Measuring mixing parameters with a $\beta$ beam source:

$\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$

$$R = \frac{\phi^D_\mu}{(\phi^D_e + \phi^D_\tau)}$$

Serpico & Kachelreiss, PRL 94, 21102 (2005);
Can we measure it?

**FLAVOR INFORMATION**

- **Muon tracks** – CC interactions of $\nu_{\mu}$
- **Showers** – neutral current interactions of all flavors, plus CC interactions of $\nu_e$ and $\nu_\tau$.
- **Double bang and lollipop events** - only $\nu_\tau$
- **Glashow resonance** – only $\bar{\nu}_e$, at $E=6.3$ PeV.

To determine the $\nu_e/\nu_\mu$ ratio → compare muon tracks to showers.
Muon Track  
Shower  
Double-Bang

\[ \nu_\mu, \nu_e, \nu_\mu, \nu_\tau, \nu_\tau \]

IceCube

Nicole Bell, The University of Melbourne  
Neutrino 2008, Christchurch, New Zealand, 30 May 2008
Muons/Showers rate for different electron fractions.
(Waxman-Bahcall flux, 1yr at Icecube)

Constraining Dark Matter with Neutrino Astrophysics

Dark Matter may be a source of high energy neutrinos
WIMP annihilation in the Sun/Earth

- WIMPS captured by the gravitational field of Sun
- Annihilation in Sun → all products absorbed except neutrinos

SuperK limits using upward-going neutrinos:

Neutrinos and Dark Matter - indirect detection

- Annihilation in our Galaxy
  - look for flux coming from Galactic center

- Annihilations in galaxies throughout the universe
  - cosmic diffuse flux

- Despite being harder to detect than gamma rays, neutrinos provide important information and strong bounds.
If the dark matter is the lightest new particle:

- All final states except neutrinos produce gamma rays,

→ Bound the total cross-section with the neutrino signal limit i.e. Assume $\text{Br}(\text{“invisible”}) = 100\%$
Upper bounds on the dark matter total annihilation cross-section


Also:


Kachelriess and Serpico, PRD 76, 063516 (2007).

Bell, Dent, Jacques, & Weiler, arXiv:0805.3423
Dark matter annihilation – MeV mass

Comparison of neutrino and photon limits on dark matter annihilation

Mack, Jacques, Beacom, Bell, and Yuksel, arXiv:0803.0157
Radiative corrections to neutrino processes give photons. 

\( \chi \chi \rightarrow \nu \bar{\nu} \) is accompanied by: 

\( \chi \chi \rightarrow \nu \bar{\nu} Z \rightarrow \text{gamma rays} \)

But direct neutrino limits are stronger!

Kachelriess and Serpico, PRD 76, 063516 (2007).

Bell, Dent, Jacques, & Weiler, arXiv:0805.3423
Dark Matter Lifetime

Photons $X \rightarrow X'\gamma$
... strong limit

Neutrinos $X \rightarrow \nu\nu$
... *model-independent* limit

Yuksel & Kistler

Palomares-Ruiz
Outlook

• Have not yet detected astrophysical neutrinos beyond the Sun and SN1987A.

• Many new detectors coming on line, with excellent prospects of seeing a signal.

• Will have complementary data from neutrinos, gamma rays and cosmic rays.

• Flavor discrimination important for both understanding the production mechanism, and probing exotic particle physics.

• High energy neutrino observation/limits provide important and restrictive dark matter limits.