Neutrino Physics in Heaven

New Views of the Universe, 9-13 Dec 2005, Chicago
Kavli Institute Inaugural Symposium in Honor of David Schramm

\[ n \rightarrow p + e^- + \bar{\nu}_e \]
Sun Glasses for Neutrinos?

8.3 light minutes

1000 light years of lead needed to shield solar neutrinos

Bethe & Peierls 1934: "... this evidently means that one will never be able to observe a neutrino."
First Detection (1954 - 1956)

Clyde Cowan (1919 - 1974)

Fred Reines (1918 - 1998)
Nobel prize 1995

Anti-Electron Neutrinos from Hanford Nuclear Reactor

$\bar{\nu}_e + p \rightarrow n + Cd \rightarrow 3 \gamma$ in coincidence

$e^+ + e^- \rightarrow \gamma$
Where do Neutrinos Appear in Nature?

- Nuclear Reactors
- Sun
- Particle Accelerators
- Supernovae (Stellar Collapse) SN 1987A
- Earth Atmosphere (Cosmic Rays)
- Astrophysical Accelerators Soon?
- Earth Crust (Natural Radioactivity)
- Cosmic Big Bang (Today 330 ν/cm³) Indirect Evidence
Stellar Collapse and Supernova Explosion

**Onion structure**

- H
- He
- O - Si
- Fe

**Collapse (implosion)**

Degenerate iron core:
- $\rho \approx 10^9 \text{ g cm}^{-3}$
- $T \approx 10^{10} \text{ K}$
- $M_{Fe} \approx 1.5 M_{\text{sun}}$
- $R_{Fe} \approx 8000 \text{ km}$
Stellar Collapse and Supernova Explosion

Newborn Neutron Star

Explosion

~ 50 km

Neutrino Cooling

Proto-Neutron Star

\[ \rho \approx \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3} \]

\[ T \approx 30 \text{ MeV} \]
Stellar Collapse and Supernova Explosion

**Newborn Neutron Star**

- Neutrino Cooling
- Proto-Neutron Star
  - $\rho \approx \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3}$
  - $T \approx 30 \text{ MeV}$

**Gravitational binding energy**

$$E_b \approx 3 \times 10^{53} \text{ erg} \approx 17\% \, M_{\odot} c^2$$

This shows up as:

- 99% Neutrinos
- 1% Kinetic energy of explosion (1% of this into cosmic rays)
- 0.01% Photons, outshine host galaxy

**Neutrino luminosity**

$$L_\nu \approx 3 \times 10^{53} \frac{\text{erg}}{3 \text{ sec}} \approx 3 \times 10^{19} L_{\odot}$$

While it lasts, outshines the entire visible universe
Neutrino Signal of Supernova 1987A

Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty $\pm 1$ min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty $\pm 50$ ms

Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty $+2/-54$ s

Within clock uncertainties, signals are contemporaneous
Emission of very weakly interacting particles would “steal” energy from the neutrino burst and shorten it. (Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable
David Schramm (Editor Physics Reports)

“Why don’t you write a review on astrophysical particle limits?”
ASTROPHYSICAL METHODS TO CONSTRAIN AXIONS AND OTHER NOVEL
PARTICLE PHENOMENA

Georg G. RAFFELT
Max-Planck-Institut für Physik, Föhrstr. 40222, 8000 München 40, Germany

Editor: D.N. Schramm Received March 1990

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ASTROPHYSICAL METHODS TO CONSTRAIN AXIONS AND OTHER NOVEL PARTICLE PHENOMENA

Georg G. Raffelt
Max-Planck-Institut für Physik, Föhring 40, D-8000 Munich 40, Germany

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Single issue price DM 8,99, postage included.

Large Detectors for Supernova Neutrinos

- SNO (800)
- MiniBooNE (190)
- LVD (400)
- Borexino (80)
- Super-Kamiokande ($10^4$)
- Kamland (330)

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

Amanda
IceCube
Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model
Megatonne detector motivated by
- Long baseline neutrino oscillations
- Proton decay
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos
  (~10^5 events for SN at 10 kpc)

**1. Overview of the experiment**
(expect to start in 2007)

- Kamioka – 1 GeV ν beam
- Super-K: 22.5 kt
- Hyper-K: 1000 kt

Map showing locations:
- Kamioka
- Super-K
- Hyper-K
- JAERI
- KEK
- Yokohama
- Tokyo

(0.77 MW 50 GeV PS)
(4 MW 50 GeV PS)
(40 J serif)

Phase-I (0.77 MW + Super-K)
Phase-II (4 MW + Hyper-K) ~ Phase-I \times 200

Similar discussions in
- US (UNO project)
- Europe (MEMPHYS project)
Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km$^3$, 800 PMTs)

Future IceCube (1 km$^3$, 4800 PMTs)

AMANDA as of 2000
Effel Tower as comparison (true scaling)
AMANDA-A (top) zoomed in on
AMANDA-B10 (bottom) optical module (OM)

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
New Views of the Universe, 9-13 Dec 2005, Chicago, USA
Each optical module (OM) picks up Cherenkov light from its neighborhood. SN appears as “correlated noise”.

- 300 Cherenkov photons per OM from a SN at 10 kpc
- Noise per OM < 500 Hz

IceCube SN signal at 10 kpc, based on a numerical Livermore model [Dighe, Keil & Raffelt, hep-ph/0303210]
Three-Flavor Neutrino Parameters

\[
\begin{pmatrix}
    v_e \\
    v_\mu \\
    v_\tau
\end{pmatrix} =
\begin{pmatrix}
    1 \\
    C_{23} & S_{23} \\
    -S_{23} & C_{23}
\end{pmatrix}
\begin{pmatrix}
    C_{13} & e^{-i\delta}S_{13} \\
    -e^{i\delta}S_{13} & C_{13}
\end{pmatrix}
\begin{pmatrix}
    C_{12} & S_{12} \\
    -S_{12} & C_{12}
\end{pmatrix}
\begin{pmatrix}
    v_1 \\
    v_2 \\
    v_3
\end{pmatrix}
\]

\( C_{12} = \cos \theta_{12} \) etc., \( \delta \) CP-violating phase

**Atmospheric/K2K**
37° < \( \theta_{23} \) < 54°

**CHOOZ**
\( \theta_{13} \) < 11°

**Solar/KamLAND**
30° < \( \theta_{12} \) < 36°

**2\sigma ranges**
hep-ph/0405172

**Solar**
75–92

**Atmospheric**
1400–3000

**\( \Delta m^2 / \text{meV}^2 \)**

Tasks and Open Questions

- Precision for \( \theta_{12} \) and \( \theta_{23} \)
- How large is \( \theta_{13} \)?
- CP-violating phase \( \delta \)?
- Mass ordering?
  (normal vs inverted)
- Absolute masses?
  (hierarchical vs degenerate)
- Dirac or Majorana?
Oscillation of Supernova Anti-Neutrinos

Measured $\bar{\nu}_e$ spectrum at a detector like Super-Kamiokande

Assumed flux parameters
- Flux ratio $\bar{\nu}_e : \bar{\nu}_\mu = 0.8 : 1$
- $\langle E(\bar{\nu}_e) \rangle = 15$ MeV
- $\langle E(\bar{\nu}_x) \rangle = 18$ MeV

Mixing parameters
- $\Delta m^2_{\text{Sun}} = 60$ meV$^2$
- $\sin^2(2\theta) = 0.9$

No oscillations
Oscillations in SN envelope
Earth effects included


Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

New Views of the Universe, 9-13 Dec 2005, Chicago, USA
Supernova Shock Propagation and Neutrino Oscillations

Schirato & Fuller: Connection between supernova shocks, flavor transformation, and the neutrino signal [astro-ph/0205390]

Resonance density for $\Delta m^2_{atm}$

Experimental Limits on Relic Supernova Neutrinos

Super-K upper limit 29 cm$^{-2}$ s$^{-1}$ for Kaplinghat et al. spectrum [hep-ex/0209028]

Upper-limit flux of Kaplinghat et al., astro-ph/9912391
Integrated 54 cm$^{-2}$ s$^{-1}$

Cline, astro-ph/0103138
Improved Sensitivity with Neutron Tagging

Super-Kamiokande limited by
- Solar neutrinos for $E_\nu < 18\text{–}19$ MeV
- Sub-Cherenkov muons from atm nus $\mu \rightarrow e + \nu_e + \bar{\nu}_\mu$

Solution:
Neutron tagging $\bar{\nu}_e + p \rightarrow e^+ + n$

Water: Neutron capture on protons 2.2 MeV gammas, invisible in SK

Add gadolinium to SK:
- Efficient neutron capture
- 8 MeV gamma cascade, easily visible
- 0.1% (100 tons of Gd Cl$_3$) achieves $> 90\%$ tagging efficiency

SN relic nus: A few events per year in SK with no background at all

Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!

FIG. 1: Spectra of low-energy $\bar{\nu}_e + p \rightarrow e^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.

Pushing the boundaries of neutrino astronomy to cosmological distances
Dark Energy 73%
(Cosmological Constant)

Normal Matter 4%
(of this about 10% luminous)

Neutrinos 0.1–2%

Dark Matter 23%
Structure forms by gravitational instability of primordial density fluctuations
Structure forms by gravitational instability of primordial density fluctuations.

A fraction of hot dark matter suppresses small-scale structure.
Power Spectrum of Cosmic Density Fluctuations

Current power spectrum $P(k) [(h^{-1} \text{ Mpc})^3]$

- Cosmic Microwave Background
- SDSS galaxies
- Cluster abundance
- Weak lensing
- Lyman Alpha Forest

Tegmark & Zaldarriaga, astro-ph/0207047 + updates

Wavenumber $k [h/\text{Mpc}]$

Wavelength $\lambda [h^{-1} \text{ Mpc}]$
Neutrino Free Streaming - Transfer Function

Power suppression for $\lambda_{FS} \lesssim 100$ Mpc/h

- $\Sigma m_\nu = 0$
- $\Sigma m_\nu = 0.3$ eV
- $\Sigma m_\nu = 1$ eV

Transfer function

$P(k) = T(k) P_0(k)$

Effect of neutrino free streaming on small scales

$T(k) \approx 1 - 8\Omega_\nu / \Omega_M$

valid for

$8\Omega_\nu / \Omega_M \ll 1$

Hannestad, Neutrinos in Cosmology, hep-ph/0404239
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<th>Study</th>
<th>$\Sigma m_\nu / eV$ (limit 95%CL)</th>
<th>Data / Priors</th>
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<tr>
<td>Ichikawa, Fukugita, Kawasaki 2004 [astro-ph/0409768]</td>
<td>2.0</td>
<td>WMAP</td>
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<td>Spergel et al. (WMAP) 2003 [astro-ph/0302209]</td>
<td>0.69</td>
<td>WMAP, CMB, 2dF, HST, $\sigma_8$</td>
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<tr>
<td>Barger et al. 2003 [hep-ph/0312065]</td>
<td>0.75</td>
<td>WMAP, CMB, 2dF, SDSS, HST</td>
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<tr>
<td>Crotty et al. 2004 [hep-ph/0402049]</td>
<td>1.0 0.6</td>
<td>WMAP, CMB, 2dF, SDSS &amp; HST, SN</td>
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<td>Hannestad 2004 [hep-ph/0409108]</td>
<td>0.65</td>
<td>WMAP, SDSS, SN Ia gold sample, Ly-\alpha data from Keck sample</td>
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<td>Seljak et al. 2004 [astro-ph/0407372]</td>
<td>0.42</td>
<td>WMAP, SDSS, Bias, Ly-\alpha data from SDSS sample</td>
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<td>Lesgourgues, Pastor &amp; Perotto</td>
<td>Planck &amp; SDSS</td>
<td>$\Sigma m_\nu &gt; 0.21$ eV detectable</td>
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<tr>
<td>&amp; Perotto, hep-ph/0403296</td>
<td>Ideal CMB &amp; 40 x SDSS</td>
<td>$\Sigma m_\nu &gt; 0.13$ eV detectable</td>
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<td>Abazajian &amp; Dodelson</td>
<td>Future weak lensing survey 4000 deg$^2$</td>
<td>$\sigma(m_\nu) \sim 0.1$ eV</td>
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<tr>
<td>astro-ph/0212216</td>
<td>CMB lensing</td>
<td>$\sigma(m_\nu) \sim 0.15$ eV (Planck)</td>
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<tr>
<td>$\sigma(m_\nu) \sim 0.044$ eV (CMBpol)</td>
<td>Weak-lensing selected sample of $&gt; 10^5$ clusters</td>
<td>$\sigma(m_\nu) \sim 0.03$ eV</td>
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<td>Kaplinghat, Knox &amp; Song</td>
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<tr>
<td>astro-ph/0303344</td>
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<tr>
<td>Wang, Haiman, Hu, Khoury &amp; May</td>
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<tr>
<td>astro-ph/0505390</td>
<td></td>
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</table>
“Weighing” Neutrinos with KATRIN

Tritium β-decay

$^{3}\text{H} \rightarrow ^{3}\text{He} + e^- + \bar{\nu}_e$

Electron spectrum

- Sensitive to common mass scale $m$ for all flavors because of small mass differences from oscillations
- Best limit from Mainz und Troitsk $m < 2.2 \text{ eV} \ (95\% \ CL)$
- KATRIN can reach 0.2 eV
- Under construction
- Data taking foreseen to begin in 2007

http://www-ik.fzk.de/katrin/
Extending the Mass Bound to Other Low-Mass Particles

Assume a generic hot dark matter particle that was in thermal equilibrium at some cosmological epoch

- Internal particle degrees of freedom (e.g. spin states) $g_X$
- Mass $m_X$
- Effective number of thermal degrees of freedom at freeze-out $g^*$_

**Contribution to cosmic mass density**

$$\Omega_X h^2 = \frac{m_X g_X}{183 \text{ eV}} \frac{10.75}{g_X} \times \begin{cases} 1 & \text{for fermions} \\ 4/3 & \text{for bosons} \end{cases}$$

**Free-streaming length**

$$\lambda_{FS} \approx \frac{20 \text{ Mpc}}{\Omega_X h^2} \left( \frac{T_X}{T_Y} \right)^4 \left[ 1 + \log \left( 3.9 \frac{\Omega_X}{\Omega_m} \frac{T_Y^2}{T_X^2} \right) \right]$$

**Perform maximum likelihood analysis for different choices of $g_X$ and $g^*$ to derive cosmological limit on $m_X$**
Axion Freeze-Out

Cosmic thermal degrees of freedom

Freeze-out temperature

\[ L_{a\pi} = \frac{C_{a\pi}}{f_a f_{\pi}} \left( \pi^0 \pi^+ \partial_\mu \pi^- + \pi^0 \pi^- \partial_\mu \pi^+ \right) \]

\[ \rho, \pi^0, \rho, \eta, K^*, \omega, \rho, \pi, \pi^0 \]

\[ \nu, \gamma, e^\pm \]

\[ T_o (\text{MeV}) \]

\[ T_o (\text{MeV}) \]

\[ g^*(T) \]

\[ f_a (\text{MeV}) \]

\[ f_a (\text{MeV}) \]

\[ g_0 (f_a) (\text{MeV}) \]

Cosmic thermal degrees of freedom at axion freeze-out

\[ C_{a\pi} = \frac{1 - z}{3(1 + z)} \approx 0.094 \]

Chang & Choi, PLB 316 (1993) 51

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

New Views of the Universe, 9-13 Dec 2003, Chicago, USA
Mass Limits on Hot Dark Matter Axions and Neutrinos

Hannestad, Mirizzi & Raffelt
hep-ph/0504059

Hannestad, astro-ph/0409108
(Seesaw proceedings, Paris, 2004)

Axions

\[ m_a < 1.05 \text{ eV (95\% CL)} \]

Neutrinos

\[ \Sigma m_\nu < 0.65 \text{ eV (95\% CL)} \]
Search for Solar Axions

Primakoff production

Axion flux

Sun

Axion Helioscope (Sikivie 1983)
Axion-Photon-Oscillation

N
Magnet S

→ Tokyo Axion Helioscope
(Results since 1998)

→ CERN Axion Solar Telescope (CAST)
(Result since 2003)

Alternative technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments
(SOLAX, COSME, DAMA, ...)

Axion energy [keV]

0 2 4 6 8 10

0 2 4 6 8 10

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
New Views of the Universe, 9-13 Dec 2005, Chicago, USA
Results and Prospects of the CAST Experiment

CAST Collaboration:
First results from the CERN Axion Solar Telescope (CAST)

CAST Phase II and future cosmological sensitivity probably connect
Dark Energy 73% (Cosmological Constant)

Ordinary Matter 4% (of this only about 10% luminous)

Dark Matter 23%

Neutrinos 0.1–2%

The Standard Model of Elementary Particles

force carriers

The Standard Model of Elementary Particles

force carriers

Leptogenesis
Astrophysics & Cosmology

Elementary Particle Physics

Cosmic Rays