Neutrino Astrophysics: Theoretical Status and Experimental Outlook

John Beacom
Theoretical Astrophysics Group, Fermilab
Introductory Remarks
Past Frontiers

• Bethe and Peierls, Nature (1934)
  “If [there are no new forces] ----
  one can conclude that there is no practically possible way of observing the neutrino.”

• 10 years ago
  Solar neutrino problem
  Atmospheric neutrino problem
  Large neutrino masses
  Nonzero magnetic moments, decay, etc.
Lucky Neutrinos

The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

Raymond Davis Jr.
1/4 of the prize
USA
University of Pennsylvania, Philadelphia, PA, USA
b. 1914

Masatoshi Koshina
1/4 of the prize
Japan
University of Tokyo, Tokyo, Japan
b. 1926

Riccardo Giacconi
1/2 of the prize
USA
Associated Universities Inc., Washington, DC, USA
b. 1931 (in Genoa, Italy)
State of the Field

“There is nothing new to be discovered in physics now, All that remains is more and more precise measurement.”

-- Kelvin, c. 1900

• We now understand neutrinos (Yeah, right)

• We now understand cosmology (Yeah, right)

• We now understand high-energy astrophysics (Yeah, right)
Neutrino Mixing

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix} = U_{\alpha j} \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
\]

\[
U = \begin{bmatrix}
\cos \theta & \sin \theta & s_{13} e^{-i\delta} \\
-s_\odot / \sqrt{2} & \cos \theta & 0 \\
s_\odot / \sqrt{2} & -c_\odot / \sqrt{2} & 0 \\
\end{bmatrix}
\]

\[
\theta_{\text{atm}} \approx 45^\circ, \quad \theta_{\text{solar}} \approx 35^\circ, \quad \theta_{13} \leq 10^\circ
\]

(graphic from Georg Raffelt)
Neutrino Masses

Normal Hierarchy

\[ m_1 = m_1 \]
\[ m_2 = \sqrt{m_1^2 + \delta m_{\text{solar}}^2} \]
\[ m_3 = \sqrt{m_1^2 + \delta m_{\text{solar}}^2 + \delta m_{\text{atm}}^2} \]

\[ \frac{m_3}{m_2} \leq \frac{\sqrt{\delta m_{\text{atm}}^2}}{\sqrt{\delta m_{\text{solar}}^2}} \leq 10 \]

Beacom and Bell, PRD 65, 113009 (2002)
Cosmological Parameters

\[ \Omega_{\text{total}} = 1.02 \pm 0.02 \]
\[ \Omega_{\text{matter}} h^2 = 0.14 \pm 0.01 \]
\[ \Omega_{\text{baryon}} h^2 = 0.022 \pm 0.001 \]
\[ \Omega_{\text{neutrino}} h^2 < 0.01 \]
\[ h = 0.71 \pm 0.04 \]
\[ \Omega_\Lambda = 0.7 \]
\[ m_\nu < 0.23 \text{ eV} \]

(WMAP)
Neutrino Number Densities

\[ \rho_{\nu} = \sum m_{\nu} n_{\nu} \]

\[ N_{\nu} < 4 \text{ (99\% CL) } \text{ BBN} \]

\[ 1.5 \leq N_{\nu} \leq 7.2 \text{ WMAP ++} \]
Crotty, Lesgourgues, and Pastor,

\[ n_{\nu} \approx n_{\bar{\nu}} \]
Dolgov et al., NPB 632, 363 (2002);
Wong, PRD 66, 025015 (2002);
Abazajian, Beacom, and Bell,
PRD 66, 013008 (2002)
Neutrino Dark Matter

\[ \rho_{\text{matter}} = \rho_{\text{CDM}} + \rho_{\text{baryons}} + \rho_{\text{neutrinos}} \]

\[ \rho_{\nu} = m_\nu n_\nu \]

Future discovery range:
Kaplinghat, Knox & Song, astro-ph/0303344

See Abazajian parallel talk
Photon Windows

- Radio Continuum: 408 MHz Bonn, Jodrell Banks, & Parkes
- Atomic Hydrogen: 21 cm Leiden-Dwingeloo, Maryland-Parkes
- Radio Continuum: 2.4-2.7 GHz Bonn & Parkes
- Molecular Hydrogen: 115 GHz Columbia-GISS
- Infrared: 12, 60, 100 μm IRAS
- Near Infrared: 1.25, 2.2, 3.5 μm COBE/DIRBE
- Optical: Laustsen et al. Photomosaic
- X-Ray: 0.25, 0.75, 1.5 keV ROSAT/PSPC
- Gamma Ray: >100 MeV CGRO/EGRET
Neutrino Windows

Neutrino Facilities Assessment Committee, NAS (2002)
Astrophysical Neutrinos: Searching High
High Energy Messengers

Fluxes of Cosmic Rays

- Knee: 1 particle per m²-year
- Ankle: 1 particle per km²-year


Protons (diffuse)  Photons (Markarian 421)

John Beacom, Theoretical Astrophysics Group, Fermilab

Weak Interactions and Neutrinos Workshop, Lake Geneva, October 2003
Beyond the Veil


John Beacom, Theoretical Astrophysics Group, Fermilab
Weak Interactions and Neutrinos Workshop, Lake Geneva, October 2003
Active Galaxies

Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk

380 Arc Seconds
88,000 LIGHTYEARS

17 Arc Seconds
400 LIGHTYEARS
UHE Neutrinos

Initial fluxes are
\[ \phi_{v_e} : \phi_{v_\mu} : \phi_{v_\tau} = 1 : 2 : 0 \]

After oscillations
\[ \phi_{v_e} : \phi_{v_\mu} : \phi_{v_\tau} = 1 : 1 : 1 \]

Earth opacity effects above \( E \sim 100 \text{ TeV} \)
The Site:
5 cm of Powder, 2 km of Base, Never Rains, and Lots of Non-stop Sunshine

Aerial view of South Pole

IceCube

Ice Top

Snow Layer

IceCube

0 m
300 m
50 m
300 m
1400 m
2400 m
Flavor Identification

\[ \sim 100 \text{ TeV } \nu_e \quad \sim 10 \text{ TeV } \nu_\mu \quad \sim 10 \text{ PeV } \nu_\tau \]
IceCube Sensitivity

J. Ahrens et al. (IceCube), astro-ph/0305196
Neutrino-Gamma Connection

J. Ahrens et al. (AMANDA-II), astro-ph/0309585
Neutrino Decay

Normal

<table>
<thead>
<tr>
<th>3</th>
<th>μ</th>
<th>τ</th>
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</table>

Atmosphere

<table>
<thead>
<tr>
<th>2</th>
<th>e</th>
<th>μ</th>
<th>τ</th>
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</thead>
</table>

Sun

<table>
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<tr>
<th>1</th>
<th>e</th>
<th>μ</th>
<th>τ</th>
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Inverted

<table>
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<tr>
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<th>e</th>
<th>μ</th>
<th>τ</th>
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Atmosphere

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<tr>
<th>3</th>
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<th>τ</th>
</tr>
</thead>
</table>

~ 5:1:1

~ 0:1:1

Possible direct measurement of CP phase $\delta$ too!

Beacom, Bell, Hooper, Pakvasa, Weiler, PRL 90, 181301 (2003);
Beacom, Bell, Hooper, Pakvasa, Weiler, hep-ph/0309267
Nonstandard Flavor Ratios

Flavor ratios can also deviate from 1:1:1 due to:

• Tiny $\delta m^2$ mixing to steriles
  Crocker, Melia, Volkas, ApJS 130, 339 (2000); 141, 147 (2002);
  Berezinsky, Narayan, Vissani, NPB 658, 254 (2003);
  Keranen, Maalampi, Myyrylainen, Riittinen, hep-ph/0307041;
  Beacom, Bell, Hooper, Learned, Pakvasa, Weiler, hep-ph/0307151

• CPT violation
  Barenboim, Quigg, PRD 67, 073024 (2003)

• For these and astrophysical reasons, it is very important to test the flavor ratios directly!
  Barenboim, Quigg, PRD 67, 073024 (2003);
  Beacom, Bell, Hooper, Pakvasa, Weiler, hep-ph/0307025;
  Jones, Mocioiu, Reno, Sarcevic, hep-ph/0308042

See Bell parallel talk
Astrophysical Neutrinos: Searching Very High
UHE Neutrino Prospects

Importance of neutrino mixing


See Besson parallel talk
GZK Neutrinos

\[ p_{\text{CR}} + \gamma_{\text{CMB}} \rightarrow \Delta \rightarrow p + \pi^0 \]
\[ \rightarrow n + \pi^+ \]
\[ \pi^0 \rightarrow \gamma \gamma \]
\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]

Connected observables:
- Protons
- Photons
- Neutrinos

Cronin
Protons, Photons, and Neutrinos

Semikoz, Sigl, hep-ph/0309328
Existing Neutrino Limits

Semikoz, Sigl, hep-ph/0309328
Future Neutrino Sensitivity

Semikoz, Sigl, hep-ph/0309328
ANITA

Funded 2003
Flies 2006
Other Physics

• Neutrino-nucleon cross section at high energies
  Domokos, Kovesi-Domokos, Burgett, Wrinkle, JHEP 0107, 017 (2001);
  Tyler, Olinto, Sigl, PRD 63, 055001 (2001);
  Jain, Kar, McKay, Panda, Ralston, PRD 66, 065018 (2002);
  Anchordoqui, Feng, Goldberg, Shapere, PRD 66, 103002 (2002);
  Friess, Han, Hooper, PLB 547, 31 (2002)

• Z-bursts, supermassive dark matter, top-down
  Gorbunov, Tinyakov, Troitsky, Astropart. Phys. 18, 463 (2003);
  Jones, Mocioiu, Reno, Sarcevic, hep-ph/0308042;
  Fodor, Katz, Ringwald, Tu, hep-ph/0309171

• New astrophysical sources

• New tests of neutrino properties
Astrophysical Neutrinos: Searching Very Low
Supernovae

SN Rates
SN Detection
Modeling (1d, 2d, 3d)

SN1999dk, z = 0.015
Supernova Energetics

\[ \Delta E_B \approx \frac{3}{5} \frac{G M_{NS}^2}{R_{NS}} - \frac{3}{5} \frac{G M_{NS}^2}{R_{core}} \approx 3 \times 10^{53} \text{ ergs} \approx 2 \times 10^{59} \text{ MeV} \]

K.E. of explosion \( \approx 10^{-2} \Delta E_B \)

E.M. radiation \( \approx 10^{-4} \Delta E_B \)
Supernova Neutrino Emission

"cooling" by neutrino emission:

\[ p + e^- \rightarrow n + \nu_e \]

\[ e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e, \nu_\mu + \bar{\nu}_\mu, \nu_\tau + \bar{\nu}_\tau \]

e tc.

diffusion until \( \lambda = 1/\rho \sigma \) from surface, then escape

\[ \langle E_{\nu_e} \rangle \approx 11 \text{ MeV} \]

\[ \langle E_{\bar{\nu}_e} \rangle \approx 16 \text{ MeV} \]

\[ \langle E_{\nu_x} \rangle \approx 25 \text{ MeV} \]

\[ L_{\nu_e}(t) \approx L_{\bar{\nu}_e}(t) \approx L_{\nu_x}(t) \]

duration = 10 s
Supernova Neutrino Detection

SN1987A:
\[ \sim 20 \bar{\nu}_e p \rightarrow e^+ n \] events

SN200??:
\[ \sim 10^4 \text{ CC events} \]
\[ \sim 10^3 \text{ NC events} \]

Supernova physics (models, black holes, progenitors...)

Particle physics (neutrino properties, new particles, ...)

John Beacom, Theoretical Astrophysics Group, Fermilab
Weak Interactions and Neutrinos Workshop, Lake Geneva, October 2003
"Everybody complains about the supernova rate, but nobody does anything about it."
Supernova Neutrino Background

Fig. 2. Supernova rate evolution on the cosmological time scale. These lines are for a $\Lambda$-dominated cosmology ($\Omega_m = 0.3, \Omega_\Lambda = 0.7$). The Hubble constant is taken to be 70 km s$^{-1}$ Mpc$^{-1}$.

Fig. 3. Number flux of $\nu_\alpha$'s for the three supernova rate models, assuming “no oscillation” case.

Relative Spectra

Solar $^8\text{B}$
Solar hep
Atmospheric $\nu_e$

$\uparrow$ SRN predictions

(M. Malek)
SK Data Limit

- 4.1 years of SK data
- Background limited
- Some improvement is possible

Malek et al. (SK), PRL 90, 061101 (2003)
**SNB Flux Limit**

- Predictions roughly agree on spectrum shape

- **Main question is normalization of**

  \[ \bar{\nu}_e / \text{cm}^2 / \text{s}, \quad E_\nu > 19.3 \text{ MeV} \]

  2.2 Kaplinghat, Steigman, Walker, PRD 62, 043001 (2000)

  \(< 1.2 \quad \text{Malek et al. (SK), PRL 90, 061101 (2003)}\)


- **Last two based on multiwavelength measurements of the star formation rate as a function of redshift**
Inverse Beta Decay

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

• Cross section is "large" and "spectral"
  \[ \sigma \approx 0.095(E_\nu - 1.3\text{MeV})^2 \times 10^{-42}\text{cm}^2 \]
  \[ E_e = E_\nu - 1.3\text{MeV} \]

Corrections in Vogel and Beacom, PRD 60, 053003 (1999)

• We must detect the neutron, but how?
A Proposed Solution

John Beacom and Mark Vagins, hep-ph/0309300
Add Gadolinium to SK?

GADZOOKS!

Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!
Neutron Capture

Capture on H:

\[ \sigma = 0.3 \text{ barns} \]
\[ E_{\gamma} = 2.2 \text{ MeV} \]

Capture on Gd:

\[ \sigma = 49100 \text{ barns} \]
\[ E_{\gamma} = 8 \text{ MeV} \]
(Equivalent \( E_e \sim 5 \text{ MeV} \))

\[
\frac{1}{\lambda_{\text{total}}} = \frac{1}{\lambda_H} + \frac{1}{\lambda_{\text{Gd}}} = n_H \sigma_H + n_{\text{Gd}} \sigma_{\text{Gd}}
\]

At 0.2% GdCl\(_3\):

Capture fraction = 90%

\[
\lambda = 4 \text{ cm}, \tau = 20 \mu s
\]
## Cost of Gd

Based on 100 tons of GdCl₃ in SK (0.2% by mass)

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost/kg</th>
<th>Cost/SK</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>$4,000/kg</td>
<td>$400,000,000/SK</td>
</tr>
<tr>
<td>1993</td>
<td>$485/kg</td>
<td>$48,500,000/SK</td>
</tr>
<tr>
<td>1999</td>
<td>$115/kg</td>
<td>$11,500,000/SK</td>
</tr>
<tr>
<td>2002</td>
<td>$4/kg</td>
<td>$400,000/SK</td>
</tr>
</tbody>
</table>
Important $\text{GdCl}_3$ Properties

- *Soluble* in water (unlike mineral oil)
- Initial chemical and radiological purity excellent
- Initial water transparency tests excellent
- 100 tons? No problem
- Gadolinium used in MRI contrasting agents
- You could drink 12 liters of *GADZOOKS!* water every day
Gadolinium Supplements

Try “gadolinium health buy” in Google

1.25 ng/liter Gadolinium

“Supports healthy cellular functions”

“Not carcinogenic”

Note: sea water is 0.7 ng/liter Gadolinium

But it doesn’t come in raspberry flavor
Neutron Backgrounds in SK

Don’t want captures on Gd to dilute the solar signal

How many neutrons are in SK anyway?

• Spallation \( \sim 10^5 \text{/day} \) but can be easily cut

• Reactor \( \sim 20 \text{/day} \) (more likely a signal!)

• \(^{152}\text{Gd} \) decay \( 10^{10} \text{ alpha/day} \), \( P(\text{alpha,n}) \) on \(^{17}\text{O} \) is \( 10^{-10} \)

• U/Th contamination in GdCl\(_3\) must be controlled

Solar \( \nu + e^- \rightarrow \nu + e^- \)

~ 10 / day

Backgrounds

\( \sim 100 \text{ / day} \)
Correlated Backgrounds

• Singles event rate above 5 MeV is \( \sim 1/\text{ton/year} \) so accidental background rate is vanishing

• \(^{8}\text{He}/^{9}\text{Li}/^{11}\text{Li}\) produced by spallation
  Beta decay followed by neutron emission
  Rare, controlled by timing and energy cuts

• Reactor \( \nu e + p \rightarrow e^+ + n \)

• Atmospheric \( \nu e + p \rightarrow e^+ + n \)

• Atmospheric \( \nu \mu + p_{\text{bound}} \rightarrow \mu^+_{\text{invisible}} + n_{\text{free}} + \text{invisible} \)
Spectrum With GADZOOKS!

Beacom and Vagins, hep-ph/0309300
Reactor Antineutrinos

KamLAND first data
0.16 kton yr

Just 3 days in SK GADZOOKS!

“High” energies only, less resolution

Eguchi et al. (KamLAND), PRL 90, 021802 (2003)
Galactic Supernova Detection

\[ \approx 8000 \quad \bar{\nu}_e + p \rightarrow e^+ + n \]

\[ \approx 700 \quad \nu + ^{16}O \rightarrow \nu + \gamma + X \quad (E = 5 - 10 \text{ MeV}) \]

\[ \approx 300 \quad \nu + e^- \rightarrow \nu + e^- \quad (e^- \text{ is forward}) \]

\[ \sim 100 \quad \nu_e + ^{16}O \rightarrow e^- + X \quad (\text{buried}) \]

\[ \bar{\nu}_e + ^{16}O \rightarrow e^+ + X \]

With GADZOOKS!, we can separate reactions

Real chance to see CC reactions on $^{16}O$

Haxton, PRD 36, 2283 (1987)

Oscillations can increase those yields by $\sim 10$
Atm. Neutrinos and Proton Decay

• Atmospheric neutrino charged-current interactions

\[ \bar{\nu}_\ell + p_{\text{bound}}(^{16}\text{O}) \rightarrow \ell^+ + n_{\text{free}} + X \]
\[ \nu_\ell + n_{\text{bound}}(^{16}\text{O}) \rightarrow \ell^- + p_{\text{free}} + X \]

Flux ratio predictions
Matter effects in oscillations
CPT violation (Barenboim, Lykken, et al.) tests

• Nucleon decay

\[ \gamma, \gamma p, \gamma n \text{ from } ^{15}\text{O and } ^{15}\text{N} \]
following \( N \rightarrow K \nu \)
Conclusions

• **GADZOOKS!**
  Propose to add 0.2% GdCl$_3$ to Super-Kamiokande (Beacom and Vagins, paper in preparation)

• Potentially quick and inexpensive

• *Detect* the Supernova Neutrino Background (SNB)
  Astrophysical neutrinos from redshift $z \sim 0.5$
  Unique probe of the *dark* supernova rate
  Measurement of supernova neutrino spectrum
  New tests of neutrino properties

• New results on reactor, solar, atmospheric, and nucleon decay
Conclusions

Neutrinos are central to many important questions:

- **Beyond the Standard Model**
  What chooses the neutrino masses and mixing angles?
  Are neutrinos Majorana or Dirac particles?
  Tests for exotic neutrino properties

- **Cosmology**
  Cosmological parameter determination
  Dark matter properties
  Dark energy? \( \Lambda \sim (1 \text{ meV})^4 \sim m^4 \)?

- **High-energy astrophysics**
  Conventional sources at highest energies, densities, and distances
  Unconventional sources, e.g., dark matter decay or annihilation
  Origins of the high-energy gamma and proton fluxes

And best of all...there's data aplenty!
Conclusions

Not the beginning of the end in neutrino physics, but just the end of the beginning.

Neutrino astrophysics, lots of data just ahead,
On three frontiers:
1-10^4 TeV: AGN, GRB, etc in IceCube, others
10^6 TeV: GZK, Z-burst, SDM, etc
10^-6 TeV: supernova in GADZOOKS!

Neutrino telescopes approaching comparable sensitivity to photon observations.

Also key for testing dark matter models.
Lutefisk

Codfish soaked in lye (HNaO, see Material Safety Data Sheet)