Particle and Nuclear Astrophysics with Supernova Neutrinos

John Beacom, Ohio State University
Why Is This Particle Different From All Other Particles?

Physics: Only weak interactions, so sensitive to feeble new forces
Astro/Cosmo: Probe great densities and distances without attenuation

Physics: Must accompany interconversions of protons and neutrons
Astro/Cosmo: Prodigious production in sources and the cosmos

Physics: Light masses are likely a clue about new physics
Astro/Cosmo: Low mass density preserves small-scale structure

Physics: Large quantum-mechanical mixing on macroscopic scales
Astro/Cosmo: Multiple flavors probe details of matter content
**Status of Neutrino Research: Physics**

### Knowns
- Three flavors: e, mu, tau
- Weak interactions only
- Large mixing angles
- Some masses nonzero
- Masses at or below eV scale
- Lots of exotica ruled out

**Much of this is very recent**

### Unknowns
- Are there sterile flavors?
- What is the mass scale?
- Dirac or Majorana masses?
- Exact angles, CP violation?
- Are there new interactions?
- **Big surprises?**

**Great progress coming soon**
# Status of Neutrino Research: Astro/Cosmo

## Knowns
- Solar fusion neutrino emission
- SN 1987A neutrino emission
- BBN fit has $N \sim 3$ species
- CMB fit has $N \sim 3$ species
- Dark matter is not neutrinos
- CMB+LSS fit has $M < 1$ eV

**Much of this is very recent**

## Unknowns
- Are there sterile flavors?
- What is the mass scale?
- Cosmological effects?
- Astrophysical sources?
- Are there new interactions?
- Big surprises?

**Great progress coming soon**
Four Promising Neutrino Frontiers

**Photons**

Lacki (2010)

- **meV scale cosmo:** “detected” by BBN, CMB
- **MeV scale astro:** near detection in Super-K
- **TeV-PeV scale astro:** maybe detected by IceCube
- **EeV scale astro:** near detection in ANITA
Neutrino Cosmology: Next Steps

Cosmology by physicists: CMB, 21cm

Cosmology by astronomers: stars ... clusters

Theory: synthesis

Laboratory: properties and interactions of neutrinos

Must reconcile N and M measurements – Are there sterile neutrinos?
Do Sterile Neutrinos Exist?

LSND/MiniBooNE not active neutrino mixing
Mixing with new sterile neutrinos possible
Other anomalies suggest something similar

First issue: total flavors $N$
Default is that these increase cosmo $N$
Planck says $N < 3.3$
Nominally rules out all but tiny mixing

Second issue: total mass $M$
Default is that these increase cosmo $M$
Planck and others say $M < 0.3$ eV
Nominally rules out all but tiny masses

If we’re lucky, there is a “big surprise” here
**Neutrino Astrophysics: Next Steps**

- **Astronomy by physicists:** neutrinos
- **Astronomy by astronomers:** EM radiation
- **Theory:** synthesis
- **Laboratory:** properties and interactions of neutrinos

**Must find new sources – How can sensitivity be improved?**
Do Astrophysical Neutrino Sources Exist?
Remaining Talk Outline

Introduction: Basics and Motivations

Introduction: Detection Modes

DSNB: Theoretical Predictions

DSNB: Experimental Limits

DSNB: Detection Strategy

Concluding Perspectives

(DSNB = Diffuse Supernova Neutrino Background)
Introduction: Basics and Motivations
Importance of Supernova Neutrino Detection

How do core-collapse supernovae explode?
How do they form neutron stars and black holes?
What are the nucleosynthesis products of supernovae?
What are the actions and properties of neutrinos?
What is the cosmic rate of black hole formation?
Which supernova-like events make neutrinos?
What else is out there that makes neutrinos?

... 

We cannot solve key problems without detecting supernova neutrinos

The required detections are – surprisingly – within our reach
Detecting even a few neutrinos could often give decisive answers
Will open new frontiers in observational neutrino astrophysics
**SN 1987A: Our Rosetta Stone**

Observation: Type II supernova progenitors are massive stars

Observation: The neutrino precursor is very energetic

Theory: Core collapse makes a proto-neutron star and neutrinos
Introduction: Three Detection Modes
Distance Scales and Detection Strategies

N >> 1 : Burst
- Rate ~ 0.01/yr
- high statistics, all flavors

N ~ 1 : Mini-Burst
- Rate ~ 1/yr
- object identity, burst variety

N << 1 : DSNB
- Rate ~ 10^8/yr
- cosmic rate, average emission
**Simple Estimate: Milky Way Burst Yields**

**Super-Kamiokande (32 kton water)**
- $10^4$ inverse beta decay on free protons
- $10^2 - 10^3$ CC and NC with oxygen nuclei
- $10^2$ neutrino-electron elastic scattering (*crude directionality*)

**KamLAND, MiniBooNE, Borexino, SNO+, etc (~ 1 kton oil)**
- $10^2$ inverse beta decay on free protons
- $10^2$ neutron-proton elastic scattering
- $10 - 10^2$ CC and NC with carbon nuclei
- $10$ neutrino-electron elastic scattering

**IceCube (10^6 kton water)**
- Burst is significant increase over background rate
- Possibility of precise timing information

**Much larger or better detectors are being proposed now**
Simple Estimate: Extragalactic Mini-Burst Yields

Yield in Super-Kamiokande ~ 1 (Mpc/D)^2

A 5000-kton detector could see mini-bursts from galaxies within several Mpc, where the supernova rate is above one per year.

New considerations for such a detector as a dense infill for IceCube!

Kistler, Ando, Yuksel, Beacom, Suzuki (2011); builds on Yoichiro Suzuki’s ideas for Deep-TITAND
**Simple Estimate: DSNB Event Rate**

Super-Kamiokande rate in an **every 10 second interval**

\[ \left[ \frac{dN_\nu}{dt} \right]_{\text{DSNB}} \sim \left[ \frac{dN_\nu}{dt} \right]_{87A} \]

Kamiokande-II rate in a **special 10 second interval** \( \sim 1 \text{ s}^{-1} \)

\[ \left[ \frac{N_{SN} M_{det}}{4\pi D^2} \right]_{\text{DSNB}} \left[ \frac{N_{SN} M_{det}}{4\pi D^2} \right]_{87A} \]

For the DSNB relative to SN 1987A:

- \( N_{SN} \) up by \( \sim 100 \)
- \( M_{det} \) up by \( \sim 10 \)
- \( 1/D^2 \) down by \( \sim 10^{-10} \)

DSNB event rate in Super-Kamiokande is a few per year
Present: Standard Model of Predicted DSNB

See my 2010 article in Annual Reviews of Nuclear and Particle Science
Theoretical Framework

Signal rate spectrum in detector in terms of measured energy

\[
\frac{dN_e}{dE_e}(E_e) = N_p \sigma(E_\nu) \int_0^\infty \left[ (1 + z) \varphi[E_\nu(1 + z)] \right] R_{SN}(z) \left[ \left| \frac{c \, dt}{dz} \right| \, dz \right]
\]

Third ingredient: Detector Capabilities (well understood)

First ingredient: Neutrino spectrum (this is now the unknown)

Second ingredient: Supernova Rate (formerly very uncertain, but now known with good precision)


John Beacom, Ohio State University

ISMD13, Chicago, IL, September 2013 20
First Ingredient: Supernova Neutrino Emission

Core collapse releases \( \sim 3 \times 10^{53} \ \text{erg} \), shared by six flavors of neutrinos

Spectra quasi-thermal with average energies of \( \sim 15 \ \text{MeV} \)

Neutrino mixing surely important but actual effects unknown

Goal is to measure the received spectrum

Yuksel, Beacom (2007)
Importance of the Neutrino Spectrum

- Experiment
  - SN 1987A data
- Experiment
  - DSNB data
- Experiment
  - SN 2012 data

Theory
- Supernova simulations (initial spectra)
  + Neutrino flavor change (effects of mixing)
  + Nucleosynthesis yields (neutrino interactions)
Second Ingredient: Cosmic Supernova Rate

Number of massive stars unchanging due to short lifetimes

\[
\left( \frac{dN}{dt} \right) = 0 = + \left( \frac{dN}{dt} \right)_{\text{star birth}} - \left( \frac{dN}{dt} \right)_{\text{bright collapse}} - \left( \frac{dN}{dt} \right)_{\text{dark collapse}}
\]

Measured from \( N/\tau \) using luminosity and spectrum of galaxies (now high precision)

Measured from the core collapse supernova rate (precision will improve rapidly)

Inferred from mismatch; can be measured by star disappearance; can be measured by DSNB (frontier research area)
Predictions from Cosmic Star Formation Rate

Total star formation rate deduced from massive stars using initial mass function (IMF)

Impressive agreement among results from different groups, techniques, and wavelengths

Integral of $R_{SF}$ agrees with EBL

$$R_{SN}(z) \simeq \frac{R_{SF}(z)}{143M_\odot}$$

IMF uncertainty on $R_{SN}$ small
**Third Ingredient: Neutrino Detection Capabilities**

Only Super-Kamiokande has large enough mass AND (nearly) low enough backgrounds

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

Free proton targets only  
Cross section grows as \( \sigma \sim E_\nu^2 \)  
Kinematics good, \( E_e \sim E_\nu \)  
Directionality isotropic

Vogel, Beacom (1999); Strumia, Vissani (2003)
Predicted Flux and Event Rate Spectra

Horiuchi, Beacom, Dwek (2009)

Bands show full uncertainty range arising from cosmic supernova rate
Present: Limits from Super-Kamiokande

See Bays et al. [Super-Kamiokande] (2012)
Measured Spectrum Including Backgrounds

Amazing background rejection: nothing but neutrinos despite huge ambient backgrounds

Amazing sensitivity: factor \(\sim 100\) over Kamiokande-II limit and first in realistic DSNB range

No terrible surprises

Challenges: Decrease backgrounds and energy threshold and increase efficiency and particle ID

Malek et al. [Super-Kamiokande] (2003); energy units changed in Beacom (2011) – use with care
Limits on Supernova Neutrino Emission

2003 Super-Kamiokande limit: $\Phi < 1.2 \text{ cm}^{-2} \text{ s}^{-1}$ (90% CL) for nuebar with $E_\nu > 19.3$ MeV

Supernova rate uncertainty is now subdominant; this limits the effective nuebar spectrum that includes mixing effects

Within range of expectations from theory and SN 1987A!

Also limits from KamLAND (lower energy) and SNO (nue)

New Super-Kamiokande Limits

Much improved analysis and more data
To be conservative, new limits are a factor ~ 2 worse than before

Bays et al. [Super-Kamiokande] (2012)

Must further decrease detector backgrounds and energy threshold
Emerging: Gadolinium in Super-Kamiokande?

See talks by Mark Vagins at HAvSE 2011 and LowNu 2011
The signal reaction produces a neutron, but most backgrounds do not.

Beacom and Vagins (2004): First proposal to use dissolved gadolinium in large light water detectors showing it could be practical and effective.

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

New general tool for particle ID
Rich new physics program

Neutron capture on protons
Gamma-ray energy 2.2 MeV
Hard to detect in SK

Neutron capture on gadolinium
Gamma-ray energy \( \sim 8 \) MeV
Easily detectable coincidence separated by \( \sim 4 \) cm and \( \sim 20 \) µs
Benefits of Neutron Tagging for DSNB

Solar neutrinos:
eliminated

Spallation daughter decays:
essentially eliminated

Reactor neutrinos:
now a visible signal

Atmospheric neutrinos:
significantly reduced

DSNB:
*More signal, less background!*

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(DSNB predictions now at upper edge of band)

John Beacom, Ohio State University
EGADS Proposal

EGADS Facility

Masayuki Nakahata, Mark Vagins, others

In June of 2009 we received full funding (390,000,000 yen = ~$4,300,000) for this effort.

Gd Pretreatment System

240 50-cm PMT’s

Selective Water+Gd Filtration System

200 ton (6.5 m X 6.5 m) water tank (SUS304)

Transparency Measurement
EGADS Detector

Hall E and EGADS

12/2009

2/2010

6/2010

12/2010
Adding 383 grams $\text{Gd}_2(\text{SO}_4)_3$ to 191 liters of $\text{H}_2\text{O}$; January 5th, 2011
Water and Gadolinium Filtration System

EGADS Selective Filtration System

June 2011

200 ton EGADS Test Tank

0.5 ton Collection Buffer Tank

0.5 ton Buffer Tank

RO Permeate Lines

Recycles RO Reject Lines

Concentrated Gd NF Reject Lines

UF#2 Reject

Conveying Pump (~0.35 MPa, >4 ton/hr)

UF#1 Reject Line

0.2 μm 2nd Stage Filter

5 μm 1st Stage Filter

Intake Pump (>4 ton/hr)

Repressurization Pump (>0.6 MPa, >3 ton/hr)

Repressurization Pump (>0.9 MPa, >2 ton/hr)

TOC

DI #1

0.2 μm Filter

DI #2

RO #2

0.2 μm Filter

Repressurization Pump (>0.9 MPa, >1.5 ton/hr)

RO #1

Concentrated Gd NF Reject Lines

Nanofilter #2

A product of seven years of R&D at UC Irvine

Nanofilter #1

Ultrafilter #2

Membrane Degas

Ultrafilter #1

Chiller

John Beacom, Ohio State University

ISMD13, Chicago, IL, September 2013
Recent News from Vagins

Filtration System – Pure Water:
Transparency of filtered pure water in EGADS equivalent to SK

Gadolinium Water Small-Batch Brew System:
Gadolinium dissolved with no problems in 15-ton holding tank

Gadolinium Removal System:
Demonstrated factor $10^6$ removal of gadolinium in a single pass

Filtration System – Gadolinium Water:
Gadolinium water circulation already has 99.97% efficient return

Gadolinium Water Transparency:
Transparency for filtered gadolinium water is already very high

On track for full test of EGADS with gadolinium water
Concluding Perspectives
Prospects for First Detection of the DSNB

Guaranteed signal:
SK has a few DSNB nuebar signal interactions per year
Astrophysical uncertainties are small and shrinking quickly

Super-Kamiokande upgrade:
Possibility of adding gadolinium is seriously considered
Research and development work very promising so far

Supernova implications:
New measurement of cosmic core-collapse rate (and more?)
Direct test of the average neutrino emission per supernova

Broader context:
Possible first detections besides Sun and SN 1987A
Non-observation of a signal would require a big surprise
Broader Vision

Understanding neutrino properties and interactions is essential to nuclear and particle physics

Understanding neutrino production and presence is essential to astrophysics and cosmology

Active synthesis and exploitation of extreme scales will bring a new era of precision ... and discovery
Center for Cosmology and Astroparticle Physics

New faculty Linda Carpenter, Chris Hirata, and Annika Peter

Postdoctoral Fellowship applications welcomed in Fall

ccapp.osu.edu

Some (rough) statistics that may surprise

Columbus, Ohio: 0.8 million people (city), 1.8 million people (metro)
Ohio State University: 56,000 students on Columbus campus
Physics: 55 faculty, Astronomy: 20 faculty
CCAPP: 20 faculty, 10 postdocs from both departments