Neutrino Astrophysics

Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany
Where do Neutrinos Appear in Nature?

<table>
<thead>
<tr>
<th>Neutrinos Appearance</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Reactors</td>
<td>Sun</td>
</tr>
<tr>
<td>CERN</td>
<td>Supernovae (Stellar Collapse) SN 1987A</td>
</tr>
<tr>
<td>Earth Atmosphere (Cosmic Rays)</td>
<td>Astrophysical Accelerators Soon?</td>
</tr>
<tr>
<td>Earth Crust (Natural Radioactivity)</td>
<td>Cosmic Big Bang (Today 330 ν/cm³) Indirect Evidence</td>
</tr>
</tbody>
</table>

2002?
Neutrino Astrophysics

Lecture I: Physics with Supernovae

Lecture II: Cosmological Neutrinos
Sanduleak -69 202

Large Magellanic Cloud
Distance 50 kpc
(160,000 light years)

Tarantula Nebula
Supernova 1054 Petrograph

3 concentric circles, diameter ~ 1 foot, with huge red flames trailing to the right.

SN 1054

Halley’s Comet? Crescent Moon?

Possible SN 1054 Petrograph by the Anasazi people (Chaco Canyon, South-Western U.S.)
# Classification of Supernovae

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Ia</th>
<th>Ib</th>
<th>Ic</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum</td>
<td>No Hydrogen</td>
<td>No Silicon</td>
<td>Helium</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>Physical Mechanism</td>
<td>Nuclear explosion of low-mass star</td>
<td>Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Curve</td>
<td>Reproducible</td>
<td>Large variations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutrinos</td>
<td>Insignificant</td>
<td>~ 100 × Visible energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compact Remnant</td>
<td>None</td>
<td>Neutron star (typically appears as pulsar) Sometimes black hole ?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate / h² SNu</td>
<td>0.36 ± 0.11</td>
<td>0.14 ± 0.07</td>
<td>0.71 ± 0.34</td>
<td></td>
</tr>
<tr>
<td>Observed</td>
<td>Total ~ 2000 as of today (nowadays ~200/year)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Supernova Discoveries 1885-2000

Naming convention for supernovae:
SN 2000A, SN 2000B ... SN 2000Z,
SN 2000aa, SN 2000ab ... SN 2000az, SN 2000ba ... SN 2000fq
Lecture I: Physics with Supernovae

- Physical Mechanism of Core-Collapse Supernovae
- Supernova Neutrino Detection
- Limits on Particle Properties
- Flavor Oscillations of Supernova Neutrinos
Stellar Collapse and Supernova Explosion

Main Sequence Star

Hydrogen Burning

Red Giant Star

Helium Burning

Hydrogen Burning
Stellar Collapse and Supernova Explosion

Onion Structure

Degenerate iron core:
\[ \rho \approx 10^9 \text{ g cm}^{-3} \]
\[ T \approx 10^{10} \text{ K} \]
\[ M_{\text{Fe}} \approx 1.5 M_{\odot} \]
\[ R_{\text{Fe}} \approx 8000 \text{ km} \]

Collapse (Implosion)
Stellar Collapse and Supernova Explosion

Newborn Neutron Star

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

Explosion

~ 50 km

Neutrino Cooling
Stellar Collapse and Supernova Explosion

Newborn Neutron Star

~ 50 km

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
\[ L_\nu \approx 3 \times 10^{53} \text{ erg / 3 sec} \approx 3 \times 10^{19} L_\odot \]
While it lasts, outshines the entire visible universe

Proto-Neutron Star
\[ \rho \approx \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3} \]
\[ T \approx 30 \text{ MeV} \]
Baade and Zwicky were the first to speculate about a connection between supernova explosions and neutron-star formation

[Phys. Rev. 45 (1934) 138]
Supernova explosion primarily a hydrodynamical phenomenon

Movies by J.A.Font, Numerical Hydrodynamics in General Relativity
http://www.livingreviews.org
Why No Prompt Explosion?

- 0.1 $M_{\text{sun}}$ Fe has nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

Shock wave forms within the iron core
Dissipates its energy by dissociating the remaining layer of iron

Dissociated material $(n, p, e, \nu)$
Failed Explosion

Spherically symmetric simulation of a 15 $M_{\odot}$ stellar model with state-of-the-art neutrino transport.

Movie courtesy of Bronson Messer, Oakridge group (2001)
Neutrinos to the Rescue

Neutrino heating increases pressure behind shock front

Picture adapted from Janka, astro-ph/0008432
Revival of a Stalled Supernova Shock by Neutrino Heating

Supernova Collapse and Explosion

Collapse $\nu_e$ burst Kelvin–Helmholtz cooling

Nu source region

Radius [km]

Time after onset of collapse [sec]

Accretion

Explosion

Hot Bubble

$R_{Fe}$

$R_{ic}$

$R_{\nu}$

$R_{\text{shock}}$
Structure of Supernova Neutrino Signal

1. Collapse (infall phase)
2. Shock break out
3. Matter accretion
4. Kelvin-Helmholtz cooling

Traps neutrinos and lepton number of outer core layers

Collapsed Core
Shock Wave
Dissociated material (n, p, e, ν)
Undissociated Iron

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Neutrinos and Cosmology, Beijing, China (20-25 August 2002)
Failed Explosions in Spherical Symmetry

Spherically symmetric (1-D) simulations with state-of-the-art neutrino transport do not explode

Mezzacappa et al., PRL 86 (2001) 1935

Novel Forms of Energy Transfer?

New particles or neutrinos with novel properties could provide a new channel of energy transfer from proto neutron star to shock wave.

Must not transfer too much energy ⇒ Limits on decaying neutrinos

[Falk & Schramm, PLB 79 (1978) 511]
SUPERNOVAE INDUCED BY AXION-LIKE PARTICLES

DAVID N. SCHRAMM
The University of Chicago

AND

JAMES R. WILSON
Lawrence Livermore Laboratory

Received 1981 December 22; accepted 1982 April 1

ABSTRACT

It is shown that a new type of particle which may have been seen in a recent accelerator experiment may, if truly present, provide a mechanism whereby gravitationally collapsing massive stars may eject their outer mantles and envelopes in supernova explosions of \( \sim 10^{51} \) ergs while leaving the cores to form neutron star remnants. These particles are “axion-like,” which means they interact semiweakly, decay to two photons with lifetimes \( \sim 10^{-3} \) s, and have masses \( 0.15 \leq M_a \leq 1 \) MeV. It is hoped that future accelerator searches will be able to confirm or deny the existence of these particles, the presence of which would cause a dramatic solution to the long-standing gravitational-collapse supernova problem.

Subject headings: elementary particles — nuclear reactions — stars: collapsed — stars: supernovae
Livermore group obtains robust delayed explosions with 1-D code of Mayle & Wilson

Neutrino luminosity is enhanced by “neutron finger convection” in proto neutron star

Convection in Supernovae (2-D Simulation)

Entropy contours

Artificially triggered explosion

Movies courtesy H.-T. Janka
Theoretical Status of Supernova Explosions

- Spherically symmetric models do not explode, even with state-of-the-art Boltzmann solvers for neutrino transport.
- Delayed explosion scenario requires enhanced neutrino luminosity at early times (~ factor 2).
- Convection between proto neutron star (PNS) and shock wave and perhaps within PNS helps.
- Next steps: 2-D and 3-D simulations self-consistently coupled with state-of-the-art neutrino transport.
- Particle-physics models for new channel of energy transfer can be constructed.
- Simplest neutrino flavor-oscillation scenario suppressed by large matter effects relative to small $\Delta m$.
- New physical ingredients required?
- Explosion a magneto-hydrodynamical effect? (Strong B-fields and fast rotation possible).
Lecture I: Physics with Supernovae

- Physical Mechanism of Core-Collapse Supernovae
- Supernova Neutrino Detection
- Limits on Particle Properties
- Flavor Oscillations of Supernova Neutrinos
Cherenkov Effect

Water or Ice

Elastic Scattering or Reaction

Neutrino

Electron or Muon (Charged Particle)

Light

Light
SN 1987A Event No.9 in Kamiokande

Kamiokande Detector

Hirata et al., PRD 38 (1988) 448
Neutrino Signal of Supernova 1987A

Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty ±50 ms

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

Within clock uncertainties, signals are contemporaneous
Interpreting SN 1987A Neutrinos

Assume thermal spectra and equipartition of energy between the six degrees of freedom $\nu_e, \nu_\mu, \nu_\tau$ and their antiparticles.
Short History of Neutrino Astronomy

**High-E Cosmic Nus**
- Events from a SN at 10 kpc
- Many $\sigma$
- SN 1987A

**Water/Ice Cherenkov**
- Nestor
- Antares/Nemo
- Baikal
- Amanda / IceCube

**Solar Nus**
- IMB-3
- Kamiokande II+III
- SK I
- Super-K II
- SNO

**Scintillation**
- Borexino
- Kamland
- MiniBooNE
- MACRO
- LVD (Gran Sasso)
- Baksan Scintillator Telescope (BST)
- LSD (Mont Blanc)

**Radio chemical**
- Homestake
- GALLEX
- GNO
- SAGE

---

Events from a SN at 10 kpc
- Many $\sigma$
- SN 1987A
- IMB-3
- Kamiokande II+III
- SK I
- Super-K II
- SNO
- Borexino
- Kamland
- MiniBooNE
- MACRO
- LVD (Gran Sasso)
- Baksan Scintillator Telescope (BST)
- LSD (Mont Blanc)
- Homestake

---

1970
1975
1980
1985
1990
1995
2000
2005
2010

---

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Neutrinos and Cosmology, Beijing, China (20-25 August 2002)
Simulated Supernova Signal in Super-Kamiokande

Monte-Carlo simulation for Super-Kamiokande signal of SN at 10 kpc, based on a numerical Livermore model.

Total of about 8300 events for \( t < 18 \) s

Sudbury Neutrino Observatory (SNO)

1000 tons of heavy water

Events from a SN at 10 kpc (no flavor oscillations)

Heavy water (1 kt)

\[
\begin{align*}
CC: \; & v_e + d \rightarrow p + p + e^- & 72 \\
CC: \; & \bar{v}_e + d \rightarrow n + n + e^+ & 138 \\
NC: \; & v_e + d \rightarrow v_e + p + n & 30 \\
NC: \; & \bar{v}_e + d \rightarrow \bar{v}_e + p + n & 32 \\
NC: \; & v_x + d \rightarrow v_x + p + n & 164
\end{align*}
\]

Light water (1.4 kt)

\[
\begin{align*}
CC: \; & \bar{v}_e + p \rightarrow n + e^+ & 331
\end{align*}
\]
Each optical module (OM) picks up Cherenkov light from its neighborhood. SN appears as correlated “noise” between OMs.
Large Detectors for SN Neutrinos

- SNO & MiniBooNE
- LVD & Borexino
- Super-Kamiokande & Kamland
- Amanda (Antarctic ice)
Neutrino observation can alert astronomers several hours in advance to supernova. To avoid false alarms, require alarm from at least two experiments.

Supernova 1987A Early Light Curve

Super-K
Kamland
SNO
MiniBooNE
LVD
Borexino

KABOOM Server @ Kamioka

Alert

http://hep.bu.edu/~snnet
Estimates of the Galactic SN Rate

SN statistics in external galaxies
- Cappellaro et al. (1993)
- van den Bergh (1993)
- Muller et al. (1992)
- Cappellaro et al. (1999)
- Strom (1994)
- Tammann et al. (1994)
- Ratnatunga & vdB (1989)

Historical galactic SNe

Progenitor count in galaxy

No galactic neutrino bursts
- 90 % CL for 21 years observation
  (Only core collapse SNe)

SNe (all types) per century
- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12

Historical galactic SNe
Galactic Supernova Events

- 15 kpc ~ 83%
- 10 kpc ~ 53%
- 5 kpc ~ 10%

Most historical supernovae in ~ 10% of the galaxy

- Anomalously large rate in our galaxy?
- Small-number statistics?

• Adam Burrows

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Neutrinos and Cosmology, Beijing, China (20-25 August 2002)
The Future: A Megatonne Detector?

**Megatonne detector motivated by**
- Long baseline neutrino oscillations
- Proton decay
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos (~$10^5$ events for SN at 10 kpc)

**Similar discussions in**
- USA (UNO project)
- Europe (Frejus Tunnel)
Local Group of Galaxies

Events in a detector with $30 \times$ Super-K fiducial volume (8000 events in SK at 10 kpc)
Diffuse Background Flux of SN Neutrinos

1 SNu = 1 SN / 10^{10} L_{\text{sun, B}} / 100 \text{ years}

L_{\text{sun, B}} = 0.54 L_{\text{sun}} = 2 \times 10^{33} \text{ erg/s}

E_\nu \sim 3 \times 10^{53} \text{ erg per core-collapse SN}

1 SNu \sim 4 L_\nu / L_{\gamma, B}

Average neutrino luminosity of galaxies
\sim photon luminosity

For galaxies, average nuclear & gravitational energy release similar

Present-day SN rate of \sim 1 SNu, extrapolated to the entire universe,
corresponds to $\nu_e$ flux of \sim 1 cm^{-2} s^{-1}

Realistic flux dominated by much larger early star-formation rate

- Upper limit \sim 54 cm^{-2} s^{-1}
  [Kaplinghat et al., astro-ph/9912391]
- “Realistic estimate” \sim 10 cm^{-2} s^{-1}
  [Hartmann & Woosley, Astropart. Phys. 7 (1997) 137]

Measurement would tell us about early history of star formation

• Photons come from nuclear energy
• Neutrinos from gravitational energy
Experimental Limits on Relic SN Neutrinos

Preliminary Super-K upper limit of $39 \text{ cm}^{-2} \text{ s}^{-1}$ for Kaplinghat et al. spectrum (Totsuka, private comm.) ~ factor 30 improvement

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

Cline, astro-ph/0103138

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

Neutrino Energy (MeV)
Lecture I: Physics with Supernovae

- Physical Mechanism of Core-Collapse Supernovae
- Supernova Neutrino Detection
- Limits on Particle Properties
- Flavor Oscillations of Supernova Neutrinos
Neutrino Mass Limits by Signal Dispersion

Time-of-flight delay of massive neutrinos

\[ \Delta t = 2.57 s \left( \frac{D}{50 \text{kpc}} \right) \left( \frac{10 \text{MeV}}{E_\nu} \right)^2 \left( \frac{m_\nu}{10 \text{eV}} \right)^2 \]

SN 1987A

Graphs showing positron energy versus time for Kamiokande, IMB, and Baksan.
Neutrino Mass Limits by Signal Dispersion

Time-of-flight delay of massive neutrinos

\[ \Delta t = 2.57s \left( \frac{D}{50\text{kpc}} \right) \left( \frac{10\text{MeV}}{E_\nu} \right)^2 \left( \frac{m_\nu}{10\text{eV}} \right)^2 \]

SN 1987A

E \approx 20\text{ MeV}, \Delta t \approx 10\text{ s}, D \approx 50\text{ kpc}

Simple estimate or detailed maximum likelihood give similar results

Future Galactic SN (Super-K)

m_{\nu_e} < 20\text{ eV}
## Neutrino Mass Limits by Signal Dispersion

**Time-of-flight delay of massive neutrinos**

$$\Delta t = 2.57s \left( \frac{D}{50\text{kpc}} \right) \left( \frac{10\text{MeV}}{E_{\nu}} \right)^2 \left( \frac{m_{\nu}}{10\text{eV}} \right)^2$$

<table>
<thead>
<tr>
<th>Event</th>
<th>Neutrino Energy</th>
<th>Distance</th>
<th>Time Delay</th>
<th>Neutrino Mass Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 1987A</td>
<td>$\sim 20$ MeV</td>
<td>$\sim 50$ kpc</td>
<td>$\sim 10$ s</td>
<td>$m_{\nu_e} &lt; 20$ eV</td>
</tr>
<tr>
<td>Future Galactic SN</td>
<td>$\sim 10$ kpc</td>
<td></td>
<td>Rise-time 0.01 s</td>
<td>$m_{\nu_e} \sim 3$ eV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[T. Totani, PRL 80 (1998) 2040]</td>
</tr>
<tr>
<td>Future SN in Andromeda</td>
<td>$\sim 750$ kpc</td>
<td>$\sim 10$ s</td>
<td></td>
<td>$m_{\nu_e} \sim 1-2$ eV</td>
</tr>
</tbody>
</table>

Simple estimate or detailed maximum likelihood give similar results.
Neutrino Mass from Early Black Hole Formation

Beacom, Boyd & Mezzacappa, hep-ph/0006015

Tail of neutrino signal in Super-K

Super-Kamiokande sensitivity $m_V \sim 1.8$ eV

Black hole formation

Neutrino mass $m_{\nu_e} = 1.8$ eV

dN/dt [s$^{-1}$]

$-0.01$ $0$ $0.01$ $0.02$ $0.03$ $0.04$

t - $t_{BH}$ [s]
# Neutrino Mass Limits and Future Sensitivity

## Tritium endpoint
- **Mainz/Troitsk**: 2.5 eV
- **KATRIN**: 0.3 eV

## Supernova Nus Time-of-flight
- **SN 1987A**: 20 eV
- **Super-Kamiokande**
  - With black hole: 2 eV
  - With gravity waves: 1 eV

## Cosmic structure
- **2dF Redshift Survey**: 0.8 eV
- **Sloan Digital Sky Survey**: 0.3 eV

- Assume 3 mass eigenstates with very small mass differences as indicated by atmospheric and solar neutrinos.
- The cosmological limit refers to $m_\nu = \Sigma m_\nu / 3$.
The Energy-Loss Argument

Assuming that the neutrino burst was not shortened by more than \( \sim \frac{1}{2} \) leads to an approximate requirement on a novel energy-loss rate

\[ \varepsilon_x < 10^{19} \text{ erg g}^{-1} \text{ s}^{-1} \]

for \( \rho \approx 3 \times 10^{14} \text{ g cm}^{-3} \) and \( T \approx 30 \text{ MeV} \)
### Axion Emission Processes in Stars

<table>
<thead>
<tr>
<th>Nucleons</th>
<th>$\frac{C_N}{2f_a} \overline{\Psi} N \gamma_\mu \gamma_5 \Psi N \delta^\mu a$</th>
<th>Nucleon Bremsstrahlung</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>$\frac{C_e}{2f_a} \overline{\Psi} e \gamma_\mu \gamma_5 \Psi e \delta^\mu a$</td>
<td>Primakoff</td>
</tr>
<tr>
<td>Electrons</td>
<td>$C_\gamma \frac{\alpha}{2\pi f_a} \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a$</td>
<td>Compton</td>
</tr>
<tr>
<td></td>
<td>$= -C_\gamma \frac{\alpha}{2\pi f_a} \vec{E} \cdot \vec{B} a$</td>
<td>Pair Annihilation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electromagnetic Bremsstrahlung</td>
</tr>
</tbody>
</table>
SN 1987A Axion Limits

- Neutrino diffusion
- Free streaming
- Trapping
- Axion diffusion
- Volume emission of axions
- Excluded

Axion–Nucleon Coupling $g_\alpha$

Relative Cooling Time

$10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$
Astrophysical Axion Bounds

Stellar Evolution

Cosmology

\[m_a\]

keV eV meV [GeV] \(f_a\)

Experiments

Telescope

Globular clusters (\(a-\gamma\)-coupling)

Too many events

SN 1987A (\(a-N\)-coupling)

Axion dark matter possible (Late inflation scenario)

DM o.k. (String scenario)

Too much DM

Direct search

Too much energy loss
Large Extra Dimensions

- Fundamentally, space-time can have more than 4 dimensions (e.g. 10 or 11 in string theories)
- If standard model fields are confined to 4D brane in (4+n) D space-time, and only gravity propagates in the (4+n) D bulk, the compactification scale could be macroscopic.
Hierarchy problem solved by true Planck scale $M$ being close to electroweak scale in space with $n$ extra dimensions, assumed to be compactified on $n$ tori with periodicities $2\pi R$.

Newton's law at large distances governed by

$$G_N^{-1} = M_{Pl}^2 \approx M^{n+2} R^n$$

- SN core emits large flux of KK gravity modes by nucleon-nucleon bremsstrahlung
- Large multiplicity of modes

**SN 1987A energy-loss argument:**

- $R < 0.7 \times 10^{-3}$ mm ($n = 2$)
- $R < 0.8 \times 10^{-6}$ mm ($n = 3$)

Is the most restrictive limit on such theories, except for cosmological arguments.

*Cullen & Perelstein, hep-ph/9904422*  
*Hanhart et al., nucl-th/0007016*
Improved Limits on Large Extra Dimensions

- From all SNe in the universe, KK decay contributes to diffuse cosmic γ-rays in 100 MeV range
- EGRET data & conservative estimate of SN rate:
  < 1 % of SN energy into KK gravitons
  i.e. 0.01 of SN 1987A cooling limit

Our new limits

- $R < 0.1 \times 10^{-3}$ mm  \( (n = 2) \)
- $R < 0.2 \times 10^{-6}$ mm  \( (n = 3) \)

Hannestad & Raffelt, hep-ph/0103201
**KK Graviton Retention by Neutron Star**

\[ V_{\text{escape}} = \sqrt{\frac{2GM}{R}} \approx 0.6c \]

- Neutron stars retain 50-60% of KK gravitons in a halo
- Emits \( \gamma \) rays by KK decays

**Velocity distribution of KK-gravitons emitted by supernova**

\[ N_{KK}(v) \]

\[ 0.0 \leq v/c \leq 1.0 \]

~100 MeV \( \gamma \) rays

\( \approx 100 \) MeV \( \gamma \) rays

Neutrons and Cosmology, Beijing, China (20-25 August 2002)
Nearby Neutron Star RX J185635-3754

\[ D = 61 \text{ pc} \text{ (closest known neutron star), } \text{Age} \approx 1.2 \times 10^6 \text{ yr} \]

HST Image
(Walter & Matthews 1997)

ROSAT Image
(Walter, Wolk & Neuhauser 1996)
Non-observation of RX J185635-3754 by EGRET gives a very stringent constraint on the compactification scale:

- $M > 300 \text{ TeV (} n = 2\right)$
- $M > 20 \text{ TeV (} n = 3\right)$
Neutron Star Excess Heat

- Neutron stars retain 50-60% of KK gravitons in a halo
- Emits $\gamma$ rays by KK decays

Neutron star cooling calculations vs. observations (Pavlov, Stringfellow & Cordova 1996, Larson & Link 1999)

To avoid excess heating by KK decay

$M > 1600 \text{ TeV} \ (n = 2)$
$M > 60 \text{ TeV} \ (n = 3)$
## Summary of Limits on Large Extra Dimensions

<table>
<thead>
<tr>
<th>Source</th>
<th>( M_{\text{min}} ) [TeV]</th>
<th>( R_{\text{max}} ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laboratory experiments</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SN 1987A neutrino signal</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>EGRET</td>
<td>30, 84, 73, 300, 454</td>
<td>7 \times 10^{-4}, 8 \times 10^{-5}, 1 \times 10^{-4}, 8 \times 10^{-6}, 3 \times 10^{-6}</td>
</tr>
<tr>
<td>Cas A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSR J0953+0755</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX J185635-3754</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excess heat PSR J0953+0755</td>
<td>1680, 60</td>
<td>2 \times 10^{-7}, 5 \times 10^{-9}</td>
</tr>
</tbody>
</table>

Lecture I: Physics with Supernovae

- Physical Mechanism of Core-Collapse Supernovae
- Supernova Neutrino Detection
- Limits on Particle Properties
- Flavor Oscillations of Supernova Neutrinos
Flavor-Dependent Fluxes and Spectra

Prompt $\nu_e$ deleptonization burst

Can we see the prompt neutrino burst?

Background from $\bar{\nu}_e + p \rightarrow n + e^+$

For SN at 10 kpc expect ~ 10 events from prompt burst $\nu_e + e \rightarrow e + \nu_e$

Monte-Carlo example for early SN signal in Super-Kamiokande

Neutrino Spectra Formation

**Electron flavor** \((\nu_e, \bar{\nu}_e)\)

- Thermal Equilibrium
- \(\bar{\nu}_e p \leftrightarrow n e^+\)
- \(\nu_e n \leftrightarrow p e^-\)

**Neutrino sphere (NS)**

**Other flavors** \((\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)\)

- \(\nu N \leftrightarrow N \nu\)
- \(\nu e \leftrightarrow \bar{\nu} e\)
- \(NN \leftrightarrow NN \nu \bar{\nu}\)
- \(e^+e^- \leftrightarrow \nu \bar{\nu}\)
- Thermal Equilibrium

**Scattering Atmosphere**

**Energy sphere (ES)**

**Transport sphere**

**Free streaming**
Neutrino Spectra Formation

Electron flavor \((\nu_e, \bar{\nu_e})\)

Thermal Equilibrium

\[
\begin{align*}
\bar{\nu}_e + p &\leftrightarrow n + e^+ \\
\nu_e + n &\leftrightarrow p + e^-
\end{align*}
\]

\(T_{\text{NS}}\) \hspace{1cm} \(T_{\text{flux}} \approx T_{\text{NS}}\)

Neutrino sphere (NS)

Other flavors \((\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)\)

\[
\begin{align*}
\nu N &\leftrightarrow N \nu \\
\nu e &\leftrightarrow \bar{\nu} e \\
N N &\leftrightarrow N N \nu \bar{\nu} \\
e^+ + e^- &\leftrightarrow \nu \bar{\nu}
\end{align*}
\]

Thermal Equilibrium

Scattering Atmosphere

\(T_{\text{ES}}\)

\(T_{\text{flux}} \approx 0.6 T_{\text{ES}}\)

Energy sphere (ES)

Transport sphere

Diffusion
Three-Flavor Oscillation Scenario

Takahashi, Watanabe & Sato, hep-ph/0105204

No Oscillations

SNO

Energy (MeV)

Events (counts/MeV)

SK

Energy (MeV)

Events (counts/MeV)

No Oscillations
Three-Flavor Oscillation Scenario

Takahashi, Watanabe & Sato, hep-ph/0105204

Oscillations with LMA and $|U_{e3}| \ll 1$
Earth Effect at SNO

No Earth Effect

Takahashi, Watanabe & Sato, hep-ph/0012354
Earth Effect at SNO

With Earth Effect

No Earth Effect

Takahashi, Watanabe & Sato, hep-ph/0012354
Degenerate Fermi Seas in a Supernova Core

In true thermal equilibrium with flavor mixing only one chemical potential for charged leptons and one for neutrinos.

Trapped lepton number is stored in $e^-$ and $\nu_e$.

Time scale to achieve flavor equilibrium?
Neutrinos suffer collisions in a medium that can interrupt the coherence of flavor oscillations: The flavor content is “measured” and oscillations start from scratch from the “collapsed state”.

Average oscillation probability \( \frac{1}{2} \sin^2(2\Theta) \)

Collision rate \( \sim \) damping rate \( \Gamma \)

Conversion rate \( \frac{1}{2} \sin^2(2\Theta) \Gamma \)

\( \Theta \) is the mixing angle in the medium.
In a SN core, the weak potential corresponds to \( \Delta m \sim 10-100 \text{ keV} \)

Vast suppression of flavor conversion for sub-eV masses.

With energy distribution

Oscillation of monochromatic nus

With collisions
Flavor Conversion in a Supernova Core

Within ~ 1 sec flavor equilibrium is achieved between $\nu_e$ and $\nu_\mu$ or $\nu_\tau$.

Suppression of mixing angle by medium effects responsible for flavor-lepton number conservation in a supernova core.
## Conclusions of Lecture I

1. **Core-collapse supernova explosions probably explained by neutrino-driven delayed explosion mechanism**
2. **But thus far no working numerical standard model**
3. **Convection key to successful explosion?**

<table>
<thead>
<tr>
<th>High-statistics observation of a galactic SN is</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crucial for empirical study of core-collapse event</strong></td>
</tr>
<tr>
<td><strong>Not sensitive to sub-eV neutrino masses</strong></td>
</tr>
<tr>
<td><strong>May differentiate between some mixing scenarios</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>If neutrino mixing parameters in currently favored regions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Neutrino flavor oscillations not important for SN physics</strong></td>
</tr>
<tr>
<td><strong>But crucial for detector signal interpretation</strong></td>
</tr>
<tr>
<td><strong>Sterile nus and/or dipole moments can have strong effects</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle emission by supernova cores continues to provide most restrictive limits on various theories</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(axions, r.h. neutrinos, extra dimensions, ... )</strong></td>
</tr>
<tr>
<td><strong>High-statistics observation would put these on firm grounds</strong></td>
</tr>
</tbody>
</table>