united nations
educational, scientific
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organization

international atomic
energy agency

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abdus salam
international centre for theoretical physics

SMR.1317 - 25

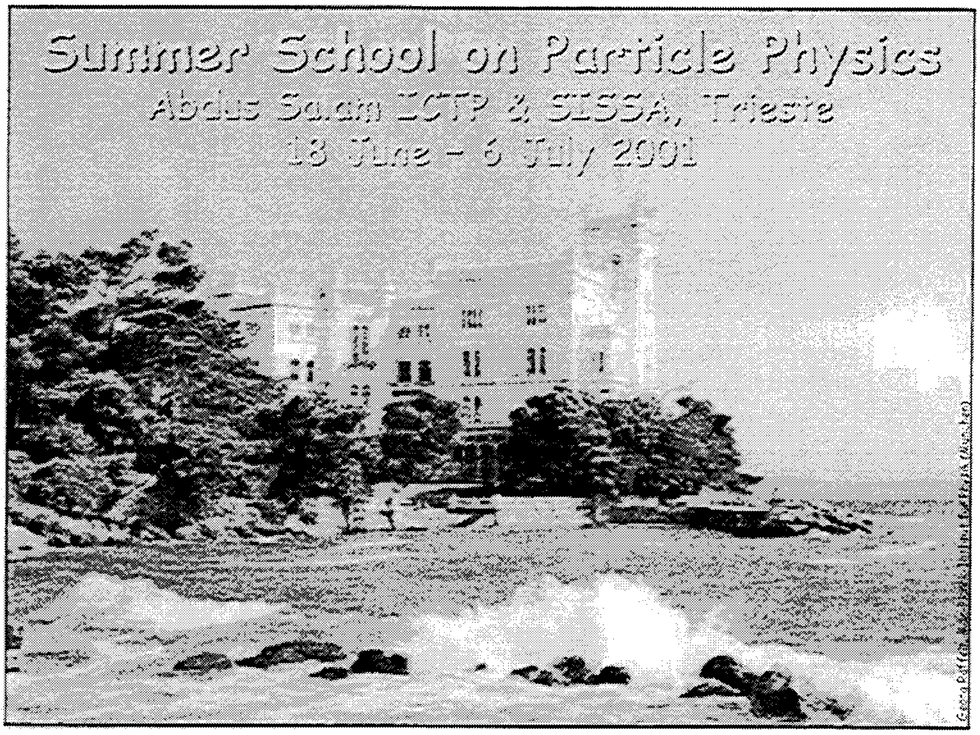
SUMMER SCHOOL ON PARTICLE PHYSICS

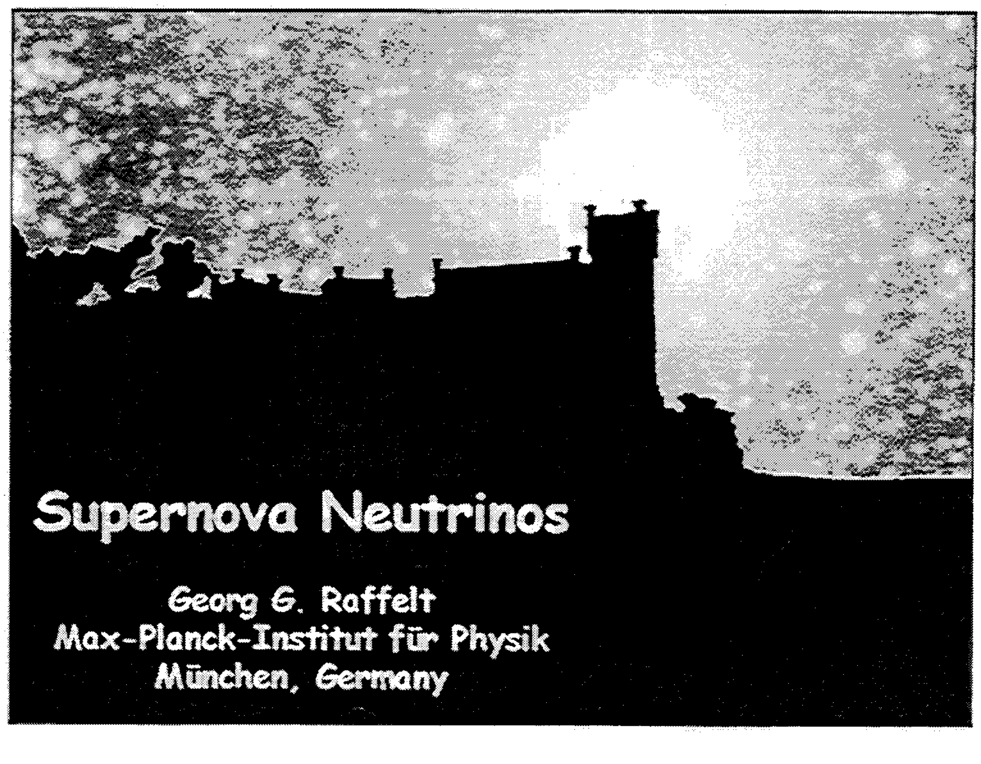
18 June - 6 July 2001

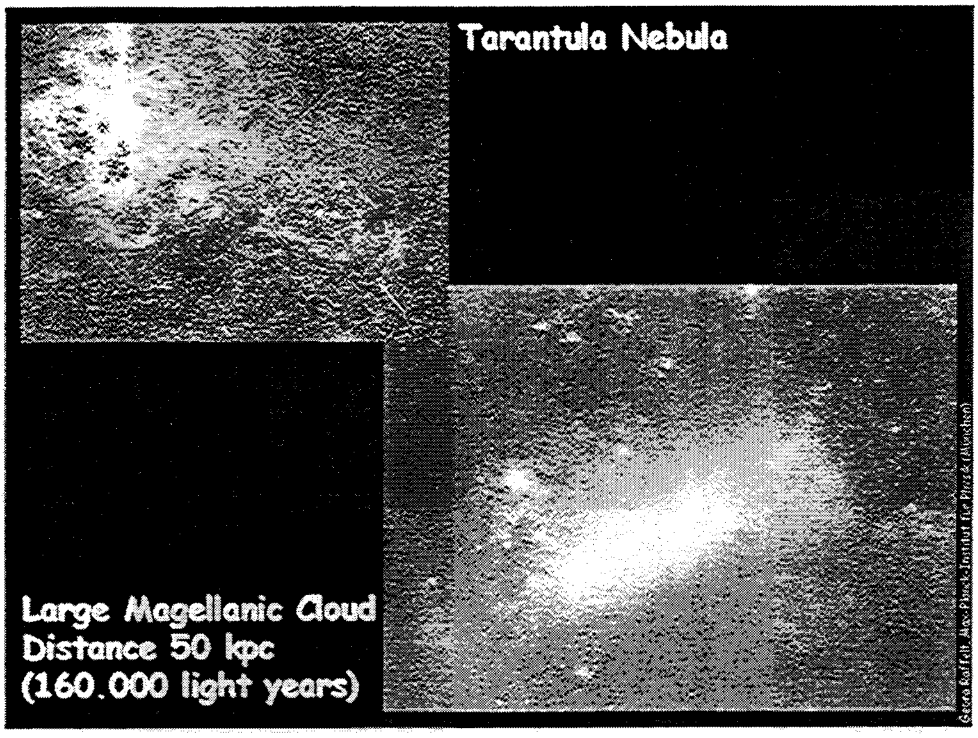
SUPERNOVA NEUTRINOS

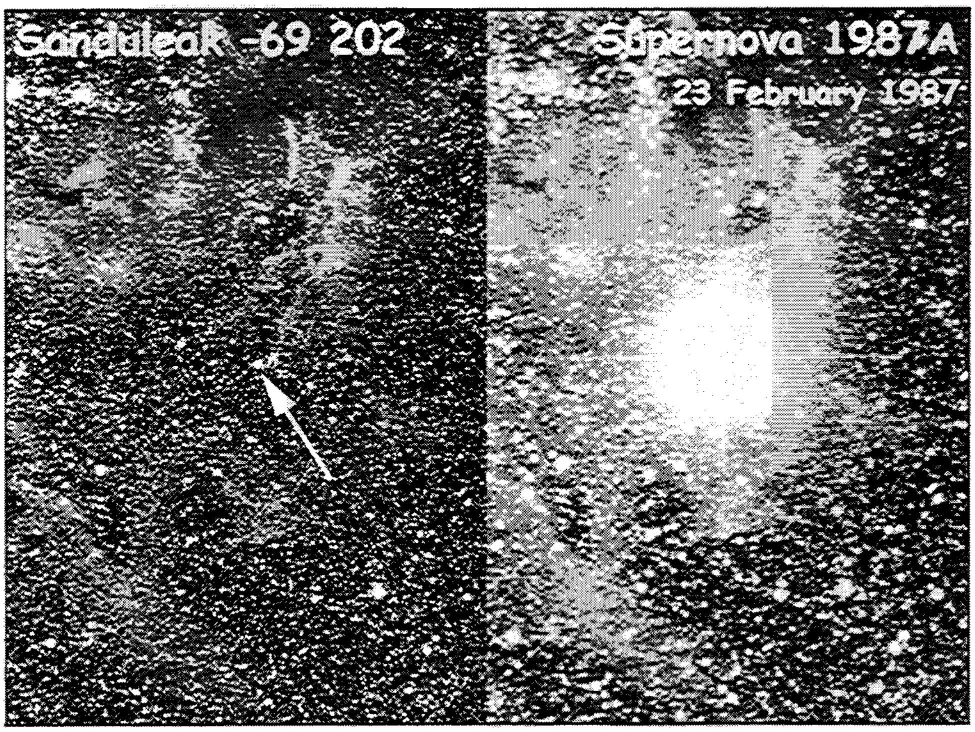
G. RAFFELT
Max-Planck-Institut für Physik
München, GERMANY

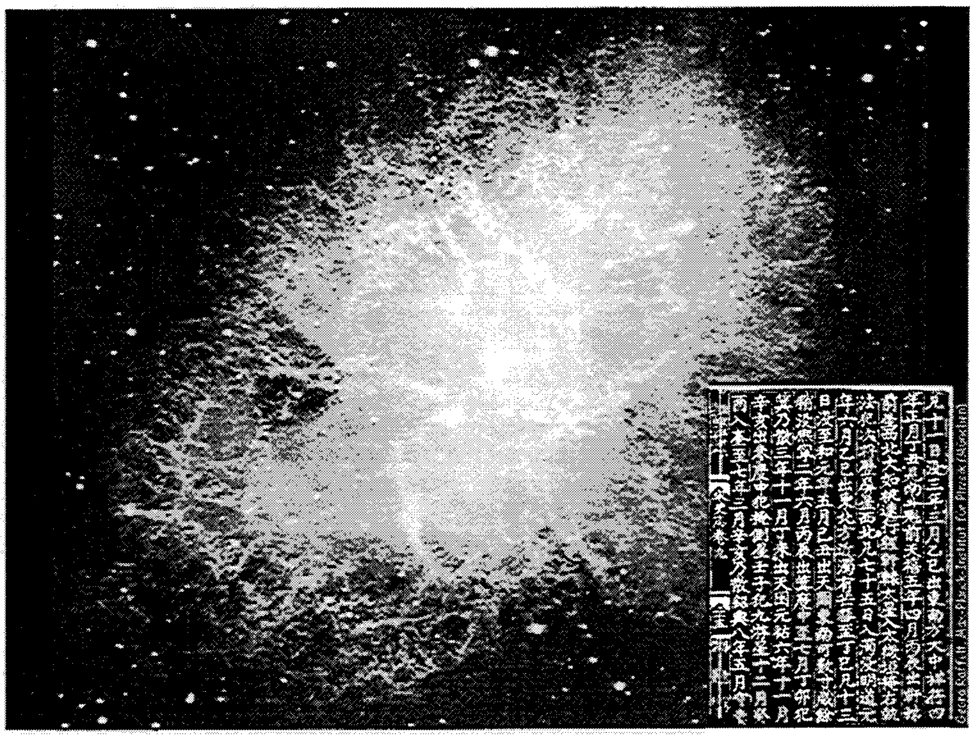
Please note: These are preliminary notes intended for internal distribution only.


Summer School on Particle Physics
Abdus Salam ICTP & SISSA, Trieste
18 June - 6 July 2001


Supernova Neutrinos
Georg G. Raffelt
Max-Planck-Institut für Physik
München, Germany


Tarantula Nebula
Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)


Sanduleak -69 202
Supernova 1987A
23 February 1987

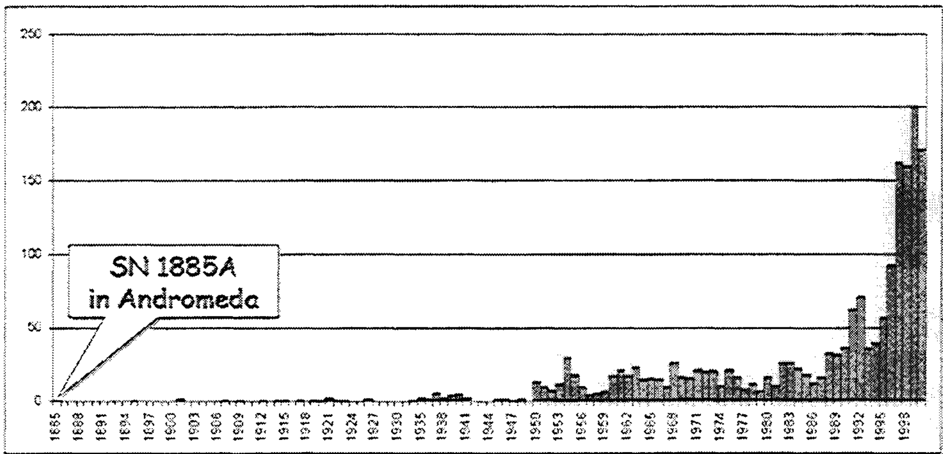



What are Supernovae?

Classification of Supernovae

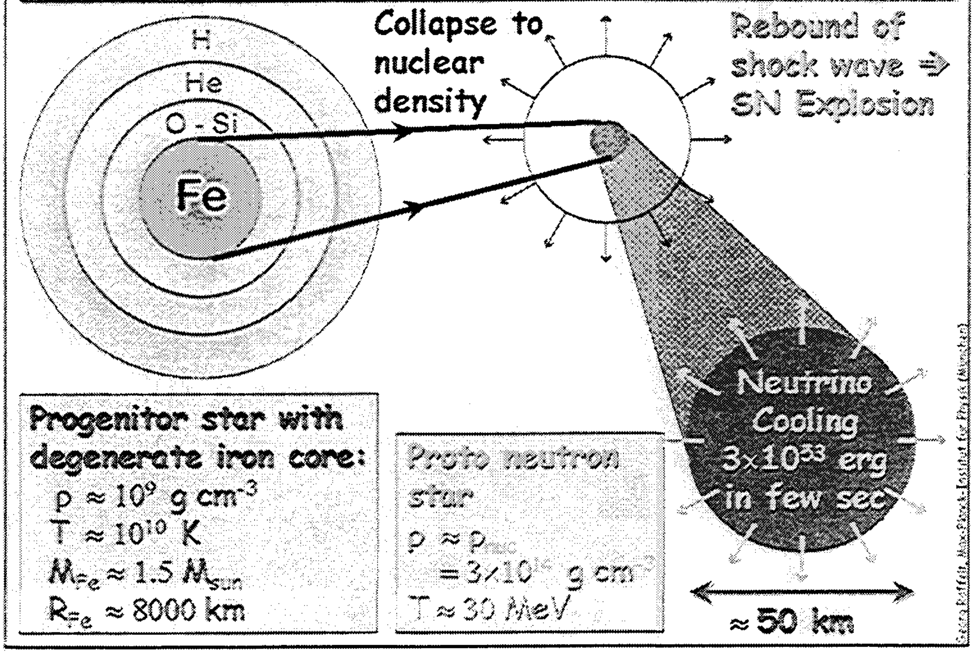
Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen	No Hydrogen	No Hydrogen	Hydrogen
	Silicon	No Silicon	No Silicon	
		Helium	No Helium	
Physical mechanism	Nuclear explosion of low mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light curve	Reproducible	Large Variations		
Neutrinos	Insignificant	~ 100 × Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole ?		
Rate/h^2 SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34
Observed	Total ~ 2000 as of today (nowadays ~200/year)			

Supernova Discoveries 1885-2000



Naming convention for supernovae:
SN 2000A, SN 2000B ... SN 2000Z,
SN 2000aa, SN 2000ab ... SN 2000az, SN 2000ba ... SN 2000fq

Stellar Collapse and Supernova Explosion



Core Collapse Supernova Energetics

Liberated gravitational binding energy of neutron star:
$E_b \approx 3\times10^{53}$ erg $\approx$ 17% $M_{SUN}c^2$

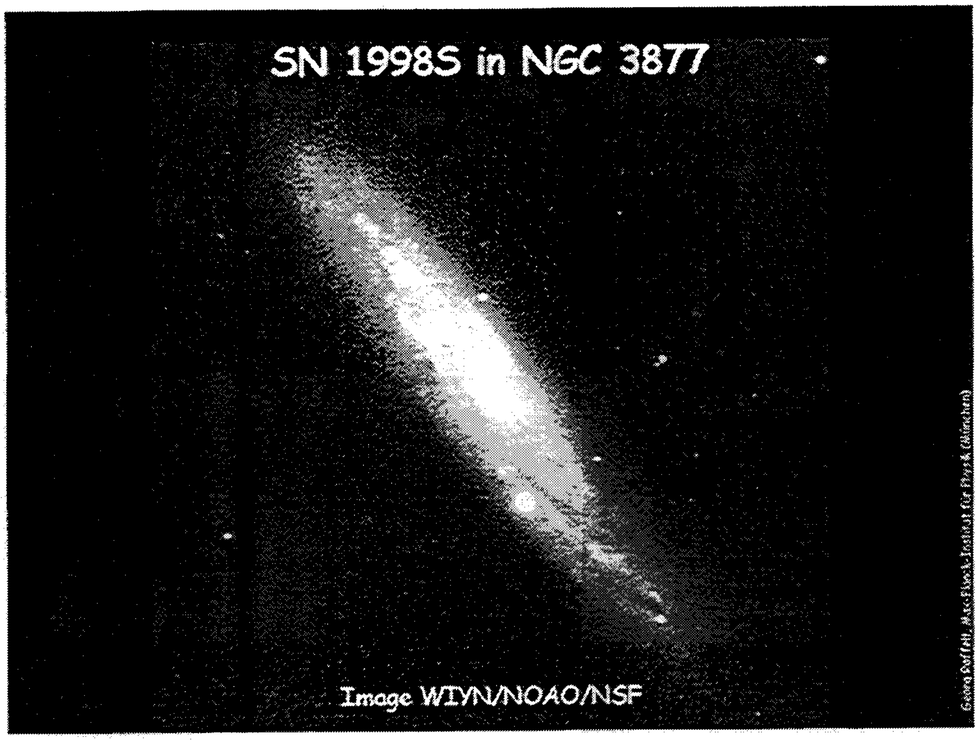
This shows up as

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

Neutrino luminosity

$L_\nu \approx 3\times10^{53}$ erg / 3 sec $\approx 3\times10^{19}\ L_{SUN}$

While it lasts, outshines the photon luminosity of the entire visible universe!



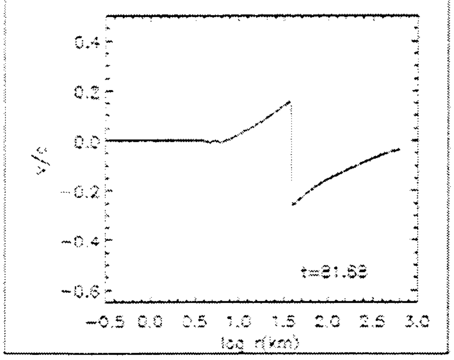
Walter Baade (1893-1960)

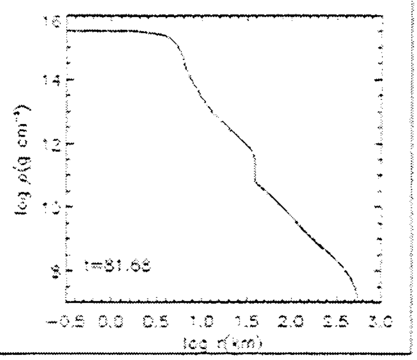
Fritz Zwicky (1898-1974)

Baade and Zwicky were the first to speculate about a connection between supernova explosions and neutron-star formation [Phys. Rev. 45 (1934) 138]

Collapse and Prompt Explosion

Velocity	Density

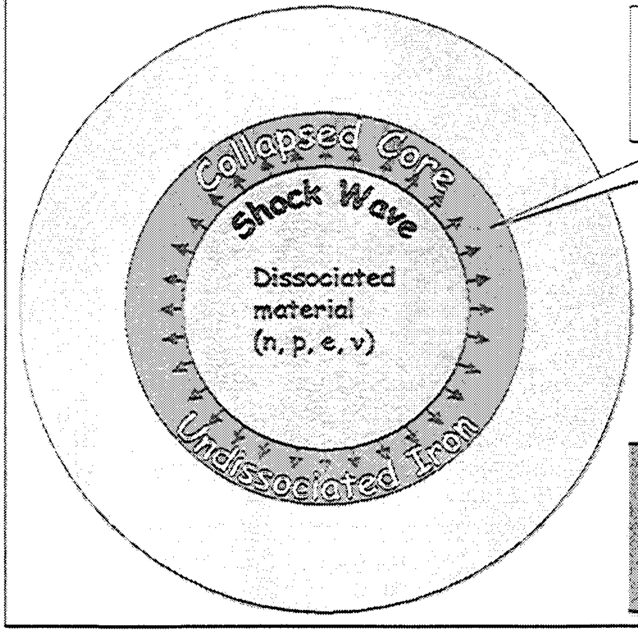




Movies by J.A.Font, Numerical Hydrodynamics in General Relativity
http://www.livingreviews.org

Supernova explosion primarily a hydrodynamical phenomenon

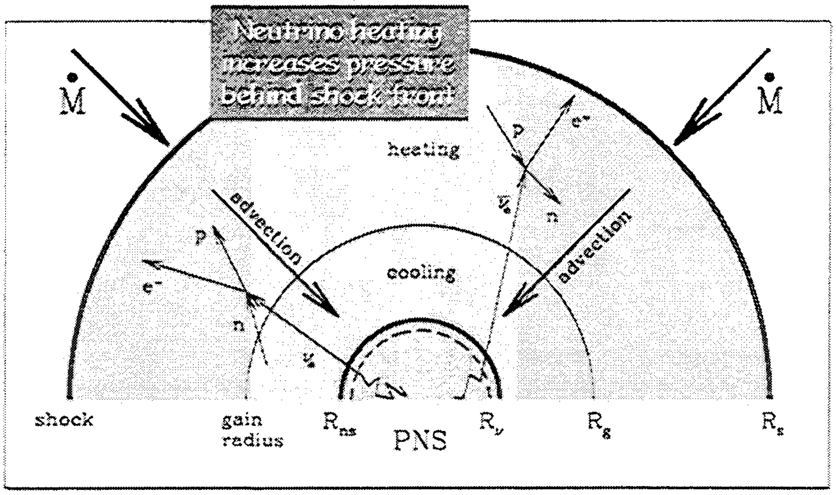
Why No Prompt Explosion?



Nuclear binding energy of 0.1 M_{sun} of iron $\approx 1.7\times 10^{51}$ erg

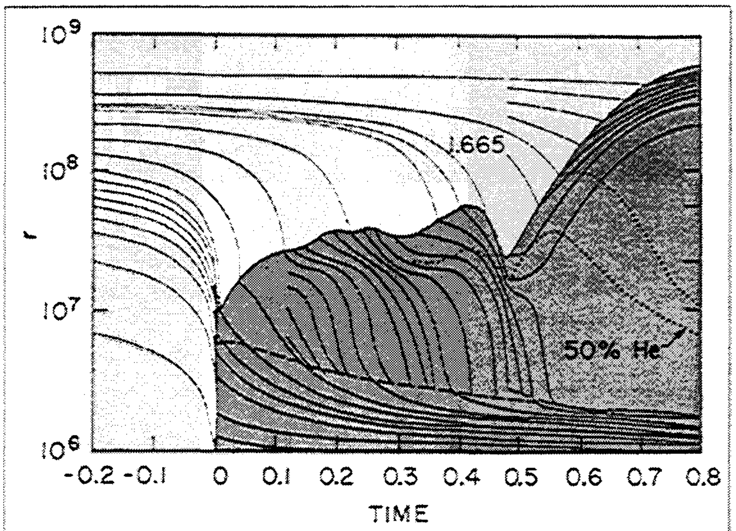
Shock wave forms within the iron core. Dissipates its energy by dissociating the remaining layer of iron.

Neutrinos to the Rescue



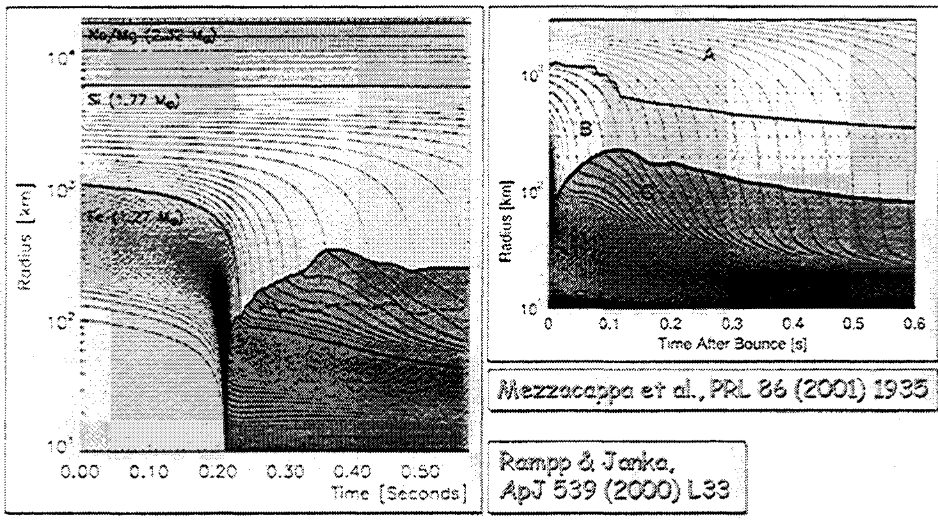
Picture adapted from Janka, astro-ph/0008432

Revival of a Stalled Supernova Shock by Neutrino Heating



Wilson, Proc. Univ. Illinois Meeting on Numerical Astrophysics (1982)
Bethe & Wilson, ApJ 295 (1985) 14

Failed Explosions

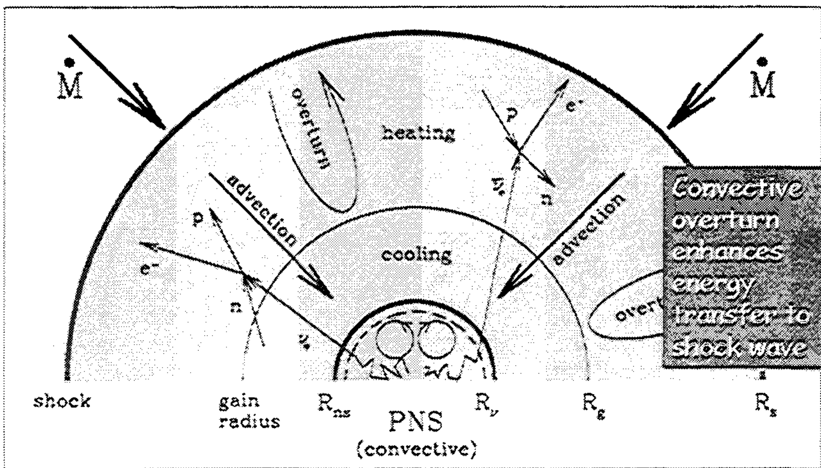


Mezzacappa et al., PRL 86 (2001) 1935

Rampp & Janka, ApJ 539 (2000) L33

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

Processes Relevant for Shock Revival

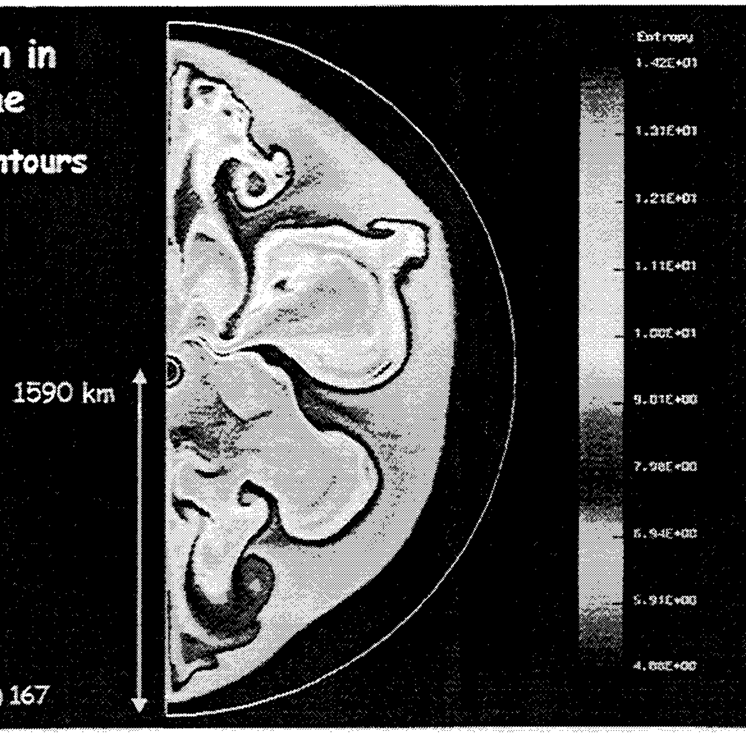


Convective overturn enhances energy transfer to shock wave

Picture adapted from Janka, astro-ph/0008432

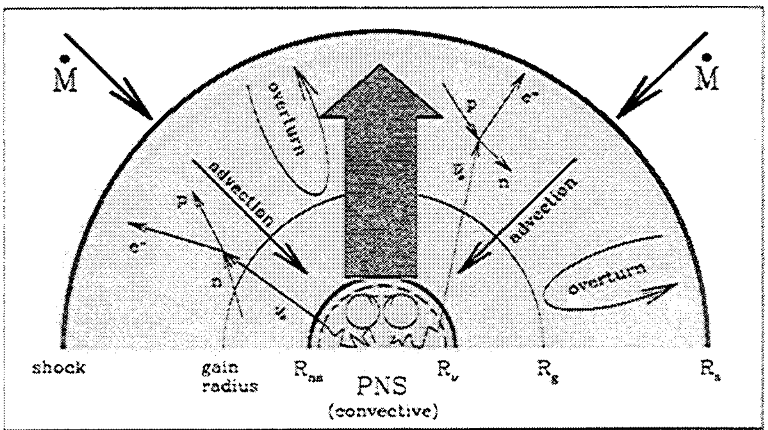
Convection in Supernovae

Entropy Contours



Janka & Müller, A&A 306 (1996) 167

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 tranfer too much energy → Limits on decaying neutrinos
[Falk & Schramm, PLB 79 (1978) 511]

Shock Revival by Novel Particles?

THE ASTROPHYSICAL JOURNAL, 260:868–874, 1982 September 15

SUPERNOVAE INDUCED BY AXION-LIKE PARTICLES

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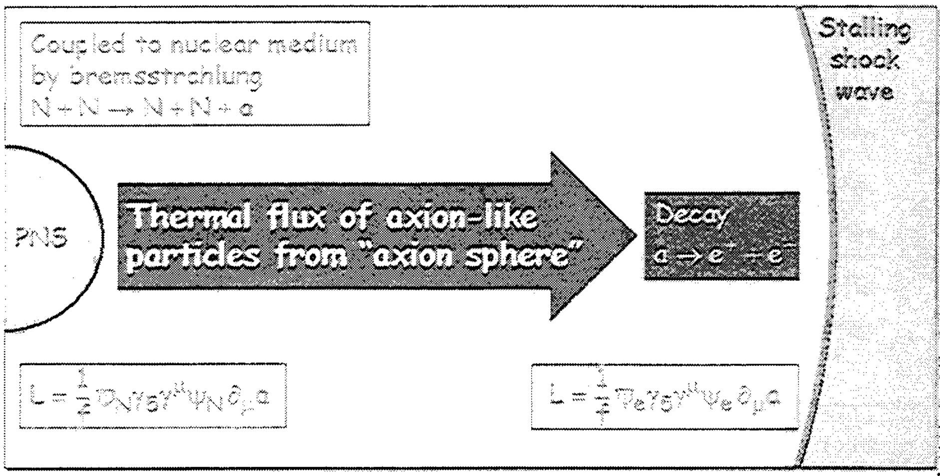
The University of Chicago
AND
JAMES R. WILSON
Lawrence Livermore Laboratory
Received 1981 December 22; accepted 1982 April 1

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 $0.15 \lesssim M_a \lesssim 1$ 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

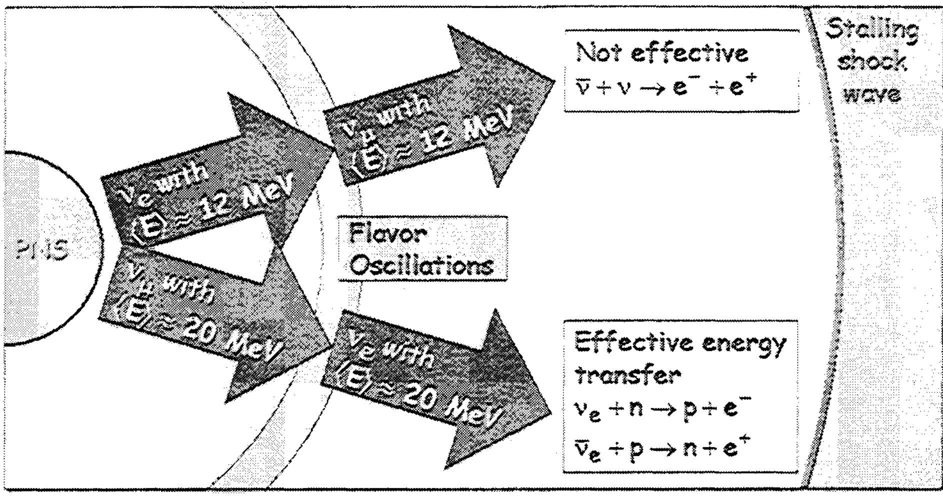
Viable Scenario with Axion-Like Particles



Apparently consistent with f = few 10^5 GeV and m = few MeV, not excluded by other arguments, but also not independently motivated

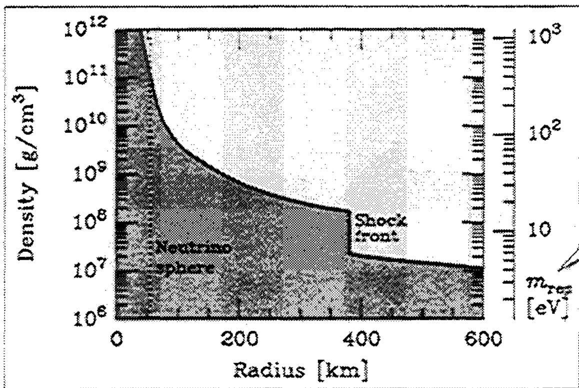
Berezhiani & Drago, PLB 473 (2000) 281

Swapping Neutrino Spectra by Oscillations



Swapping neutrino spectra by flavor oscillations enhances the rate of energy transfer to stalling shock wave [Fuller et al., ApJ 389 (1992) 517]

Matter Effect on Flavor Oscillations



"Effective neutrino mass" from weak potential

$$m_{res} = \sqrt{\sqrt{2} G_F n_e 2E_\nu}$$

(E_ν = 10 MeV and Y_e = 0.5)

Neutrino masses in the cosmologically interesting range of 10 - 100 eV would have been useful at rejuvenating the stalled shock wave

Conversely, for Δm in the now-favored sub-eV range, flavor oscillations between PNS and shock wave are suppressed by weak matter potential

Theoretical Status of Supernova Explosion

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)

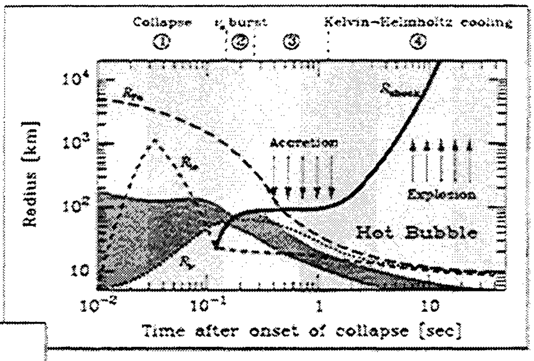
Convection between proto neutron star (PNS) and shock wave and within PNS helps.
Next steps: 2-D and 3-D simulations coupled with state-of-the-art neutrino transport.

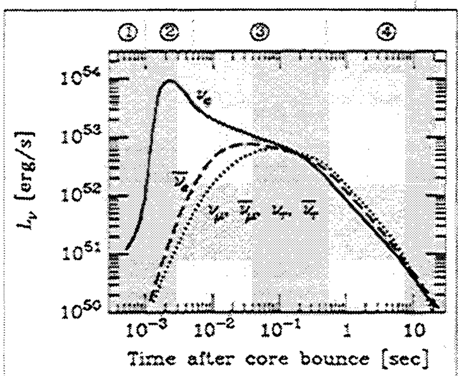
Particle-physics models for new channel of energy transfer can be constructed.
Simplest neutrino flavor-oscillation scenario suppressed by large matter effects relative to small Δm.

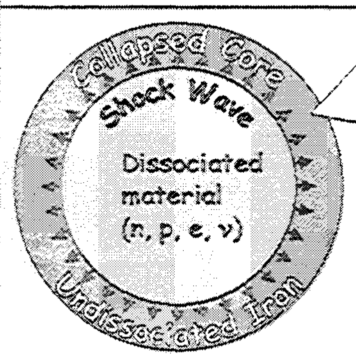
New astrophysics ingredients required?
Explosion a magneto-hydrodynamical effect?
(Strong B-fields and fast rotation possible)

Supernova Neutrino Signal

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

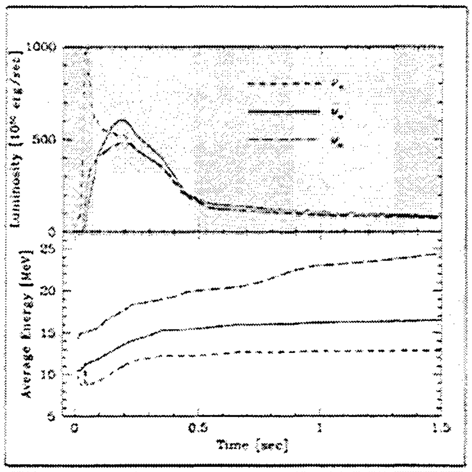




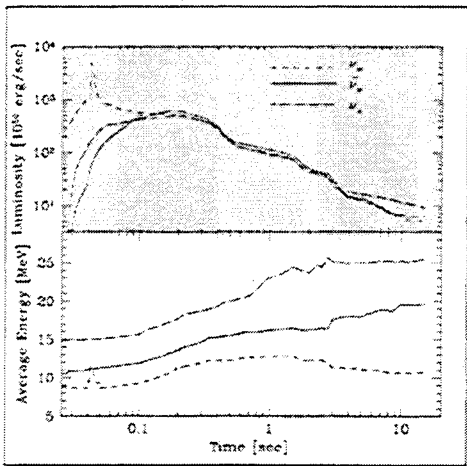


Traps neutrinos and lepton number of outer core layers

Numerical Neutrino Signal



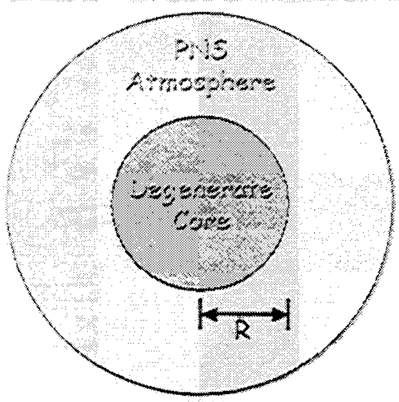
Linear Time & Luminosity Scale



Logarithmic Time & Luminosity

Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

What Determines the Neutrino Energies?



Gravitational potential of a given nucleon

$\Phi = -G_N M_{PNS} m_N R^{-1}$

With $M_{PNS} = 1\ M_{sun}$ and R = 20 km

$\Phi \approx -27$ MeV

Virial theorem (hydrostatic equilibrium), assuming nondegenerate conditions,

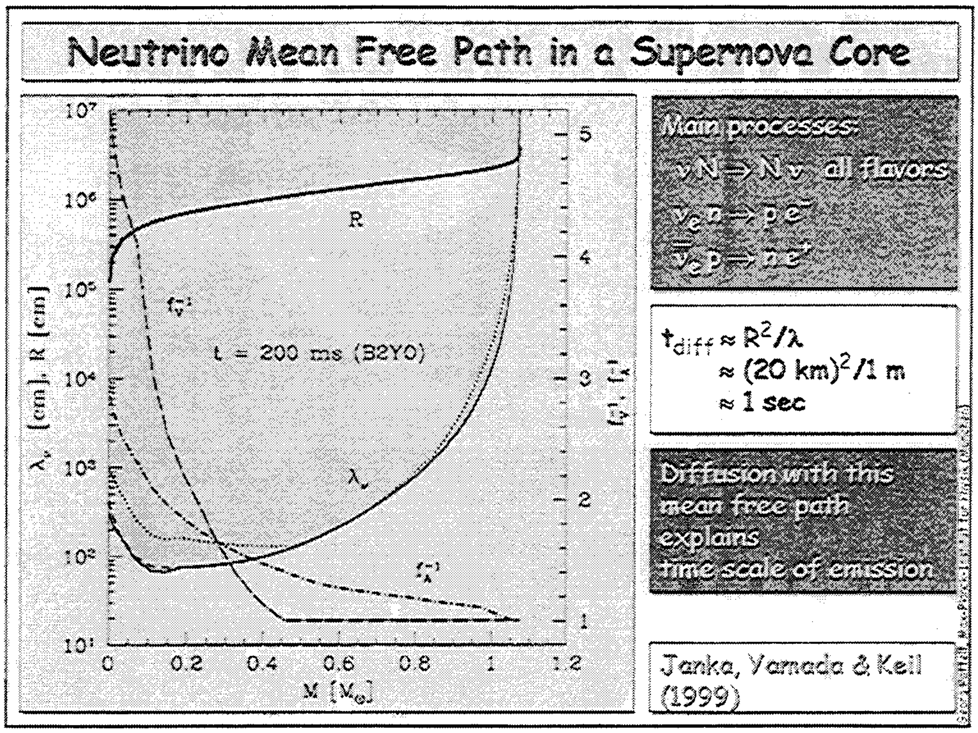
$\langle E_{kin} \rangle = -\frac{1}{2} \langle \Phi \rangle \approx 13$ MeV

Thermal equilibrium

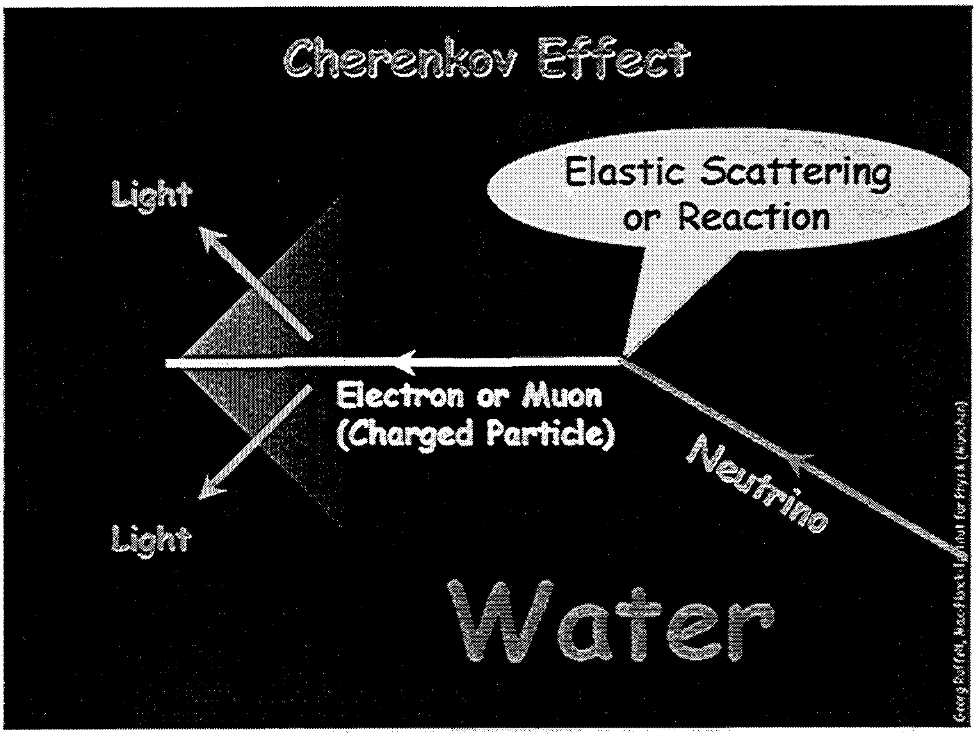
$T = (2/3) \langle E_{kin} \rangle \approx 9$ MeV

If the PNS atmosphere is nondegenerate, its temperature is determined by the gravitational potential at the surface of the degenerate core and found in the ~10 MeV range

As core contracts (by accretion and/or cooling), T increases

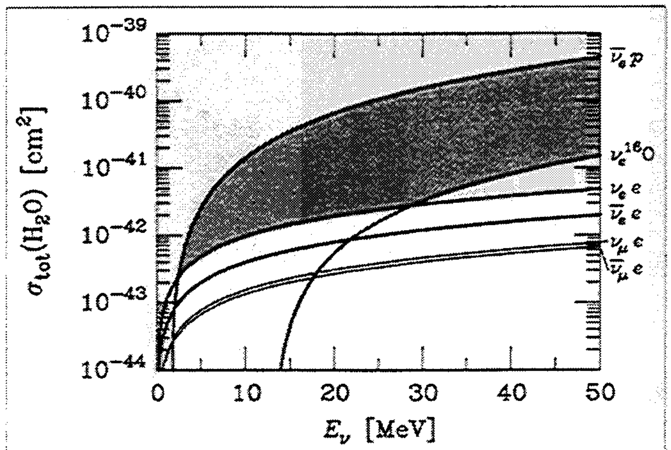

Neutrino Mean Free Path in a Supernova Core
Main processes:
νN ⇒ Nν all flavors
$\nu_e n \Rightarrow p e^-$
$\bar{\nu}_e p \Rightarrow n e^+$
$t_{diff} \approx R^2/\lambda$
$\approx (20\ \mathrm{km})^2/1\ \mathrm{m}$
$\approx 1\ \mathrm{sec}$
Diffusion with this
mean free path
explains
time scale of emission
Janka, Yamada & Keil
(1999)
t = 200 ms (B2Y0)
R
λ_ν
M [$M_\odot$]
λ_ν [cm], R [cm]


Supernova 1987A



Neutrino Cross Section in a Water Target

Cross section per water molecule

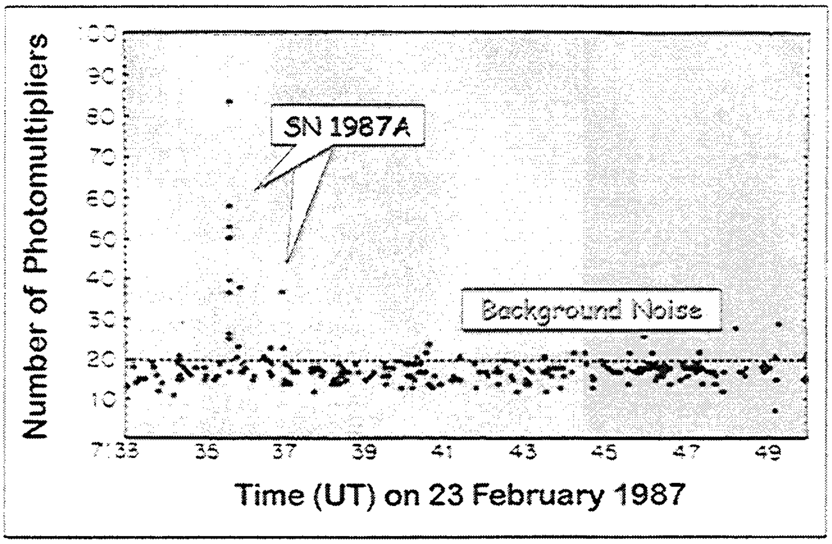


Main reactions: $\bar{\nu}_e + p \to n + e^+$ dominates for SN

$\nu_e + {}^{16}O \to {}^{16}F + e^-$

$\nu + e^- \to e^- + \nu$ dominates for Sun

Neutrino Signal of Supernova 1987A

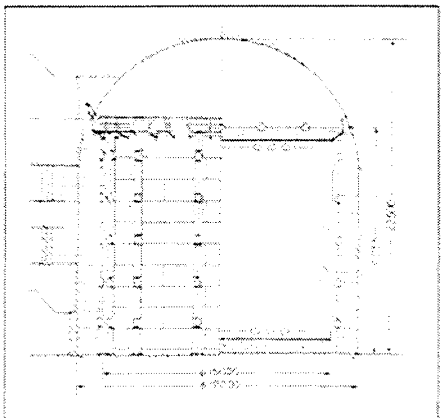


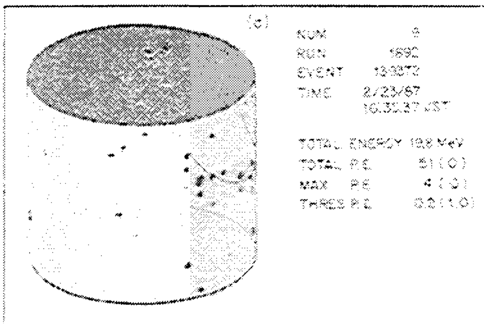
SN 1987A Neutrino Signal in Kamiokande

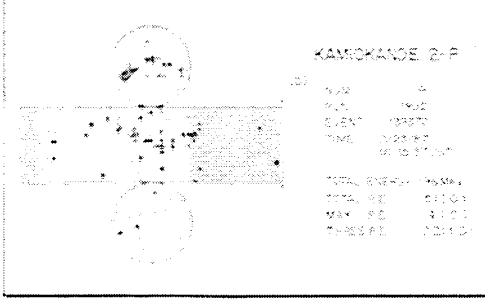
Georg Raffelt, Max-Planck-Institut für Physik (München)

SN 1987A Event No.9 in Kamiokande

Kamiokande Detector



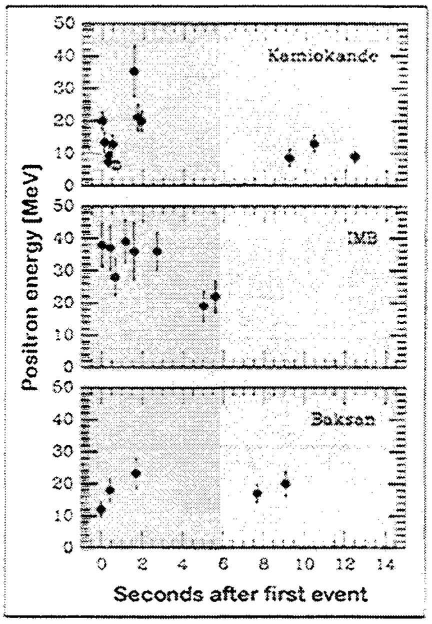




Hirata et al., PRD 38 (1988) 448

Georg Raffelt, Max-Planck-Institut für Physik (München)

Neutrino Signal of Supernova 1987A



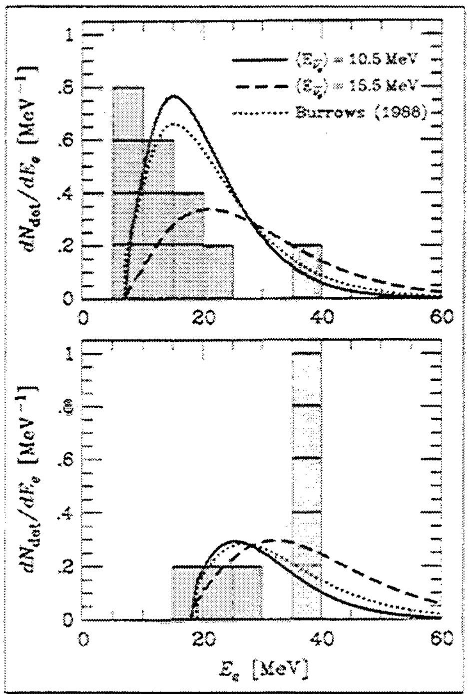
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

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

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

Within clock uncertainties, signals are contemporaneous

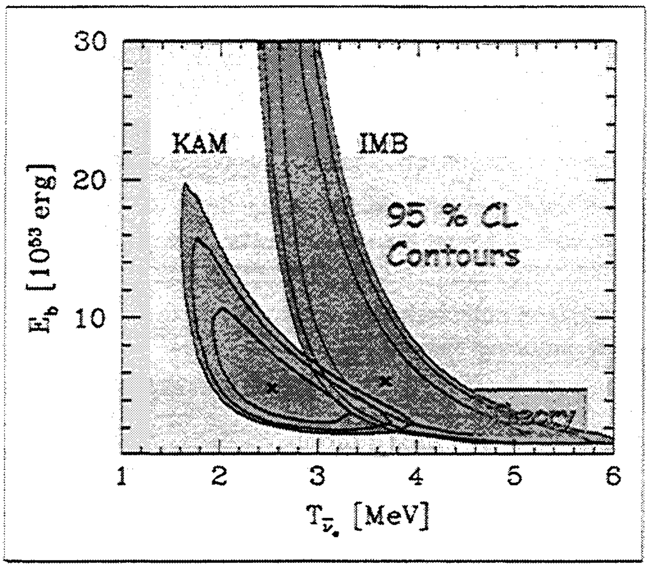
Energy Distribution of SN 1987A Neutrinos



Kamiokande II

IMB

Interpreting SN 1987A Neutrinos



Total Binding Energy

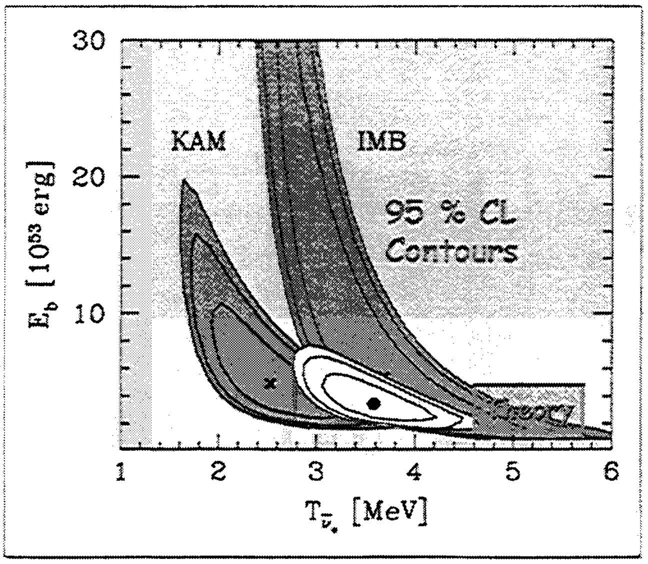
Spectral $\overline{\nu}_e$ Temperature

Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

Assume thermal spectrum and equipartition between the six degrees of freedom

ν_e, ν_μ, ν_τ and their antiparticles

Interpreting SN 1987A Neutrinos



Total Binding Energy

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ν_e, ν_μ, ν_τ and their antiparticles

Neutrino Limits by Intrinsic Signal Dispersion

Time of flight for massive neutrinos delayed by

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

SN 1987A: $E \approx 20$ MeV, $\Delta t \approx 10$ sec, $D \approx 50$ kpc

$m_{\nu_e} < 20$ eV

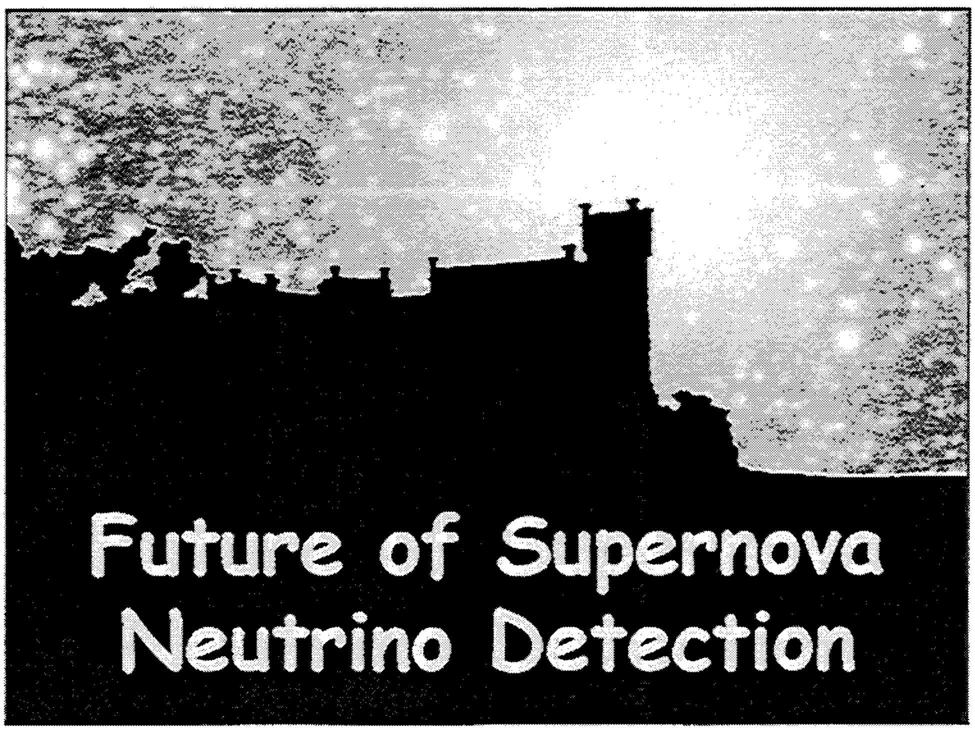
Detailed maximum-likelihood analysis yields similar limit. At the time of SN 1987A competitive with Tritium end-point limits, today $m_{\nu_e} < 3$ eV

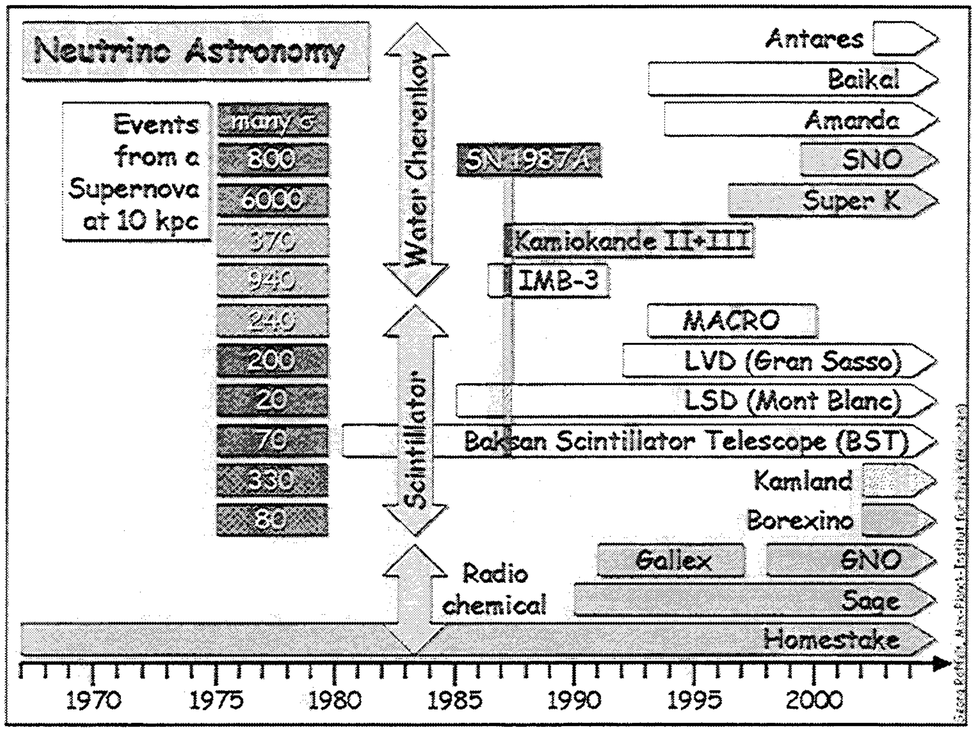
For "milli charged" neutrinos path bent by galactic magnetic field, inducing time delay

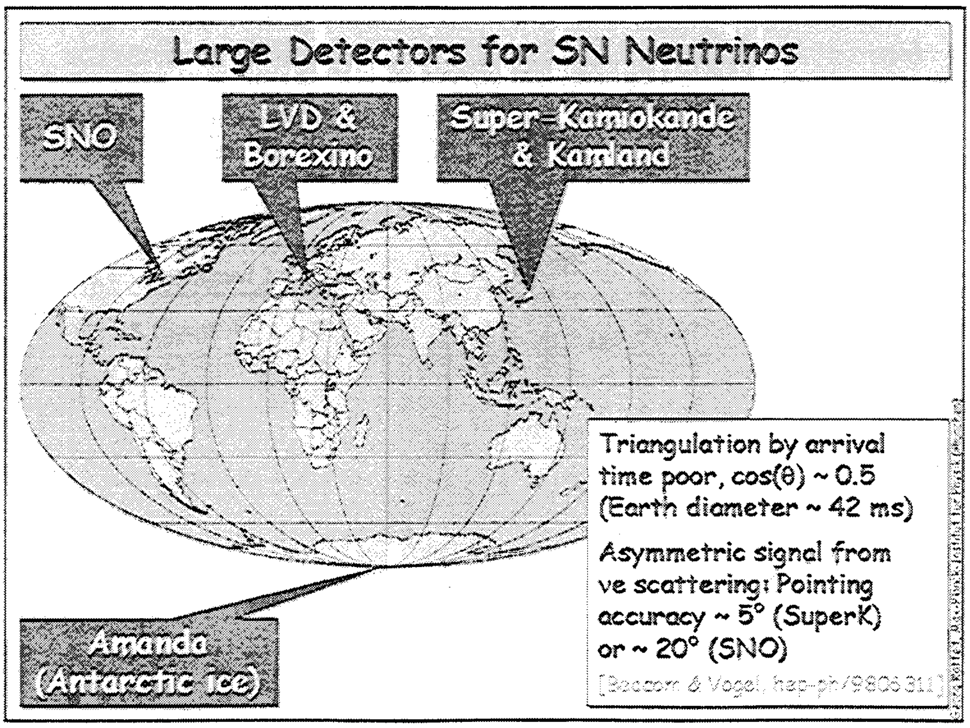
$$\frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp d_B)^2}{6E_\nu^2} < 3\times10^{-12}$$

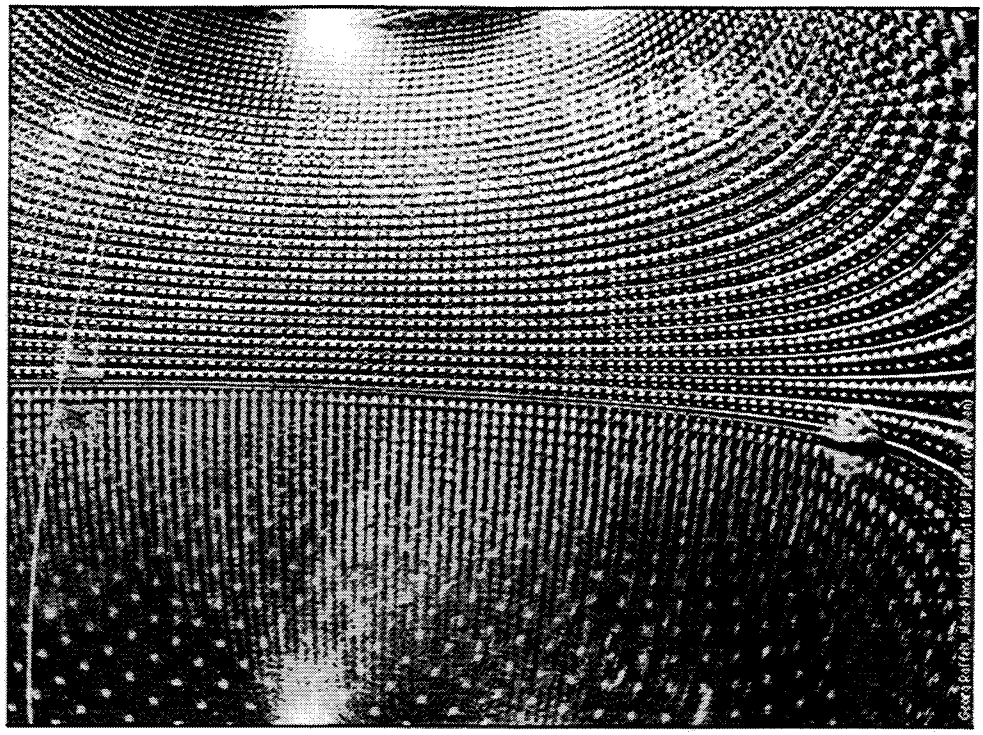
SN 1987A limit: $\frac{e_\nu}{e} < 3\times10^{-17}\left(\frac{1\,\mu G}{B_\perp}\right)\left(\frac{1\,kpc}{d_B}\right)$

Assuming electric charge conservation in neutron decay yields more restrictive limit of about 3×10^{-21} e

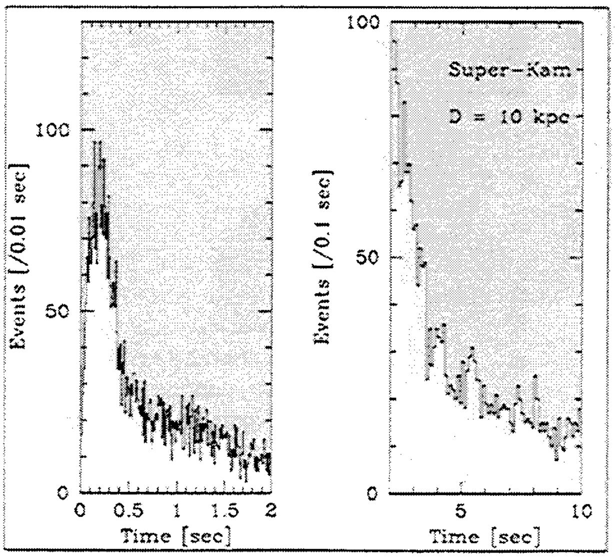



Neutrino Astronomy
Events from a Supernova at 10 kpc
many c
800
6000
370
940
240
200
20
70
330
80
Water Cherenkov
Scintillator
Radio chemical
SN 1987A
Antares
Baikal
Amanda
SNO
Super K
Kamiokande II+III
IMB-3
MACRO
LVD (Gran Sasso)
LSD (Mont Blanc)
Baksan Scintillator Telescope (BST)
Kamland
Borexino
Gallex
GNO
Sage
Homestake
1970
1975
1980
1985
1990
1995
2000


Large Detectors for SN Neutrinos
SNO
LVD & Borexino
Super-Kamiokande & Kamland
Amanda (Antarctic ice)
Triangulation by arrival time poor, cos(θ) ~ 0.5 (Earth diameter ~ 42 ms)
Asymmetric signal from νe scattering: Pointing accuracy ~ 5° (SuperK) or ~ 20° (SNO)
[Beacom & Vogel, hep-ph/9806311]



Galactic Supernova Signal in Super-Kamiokande

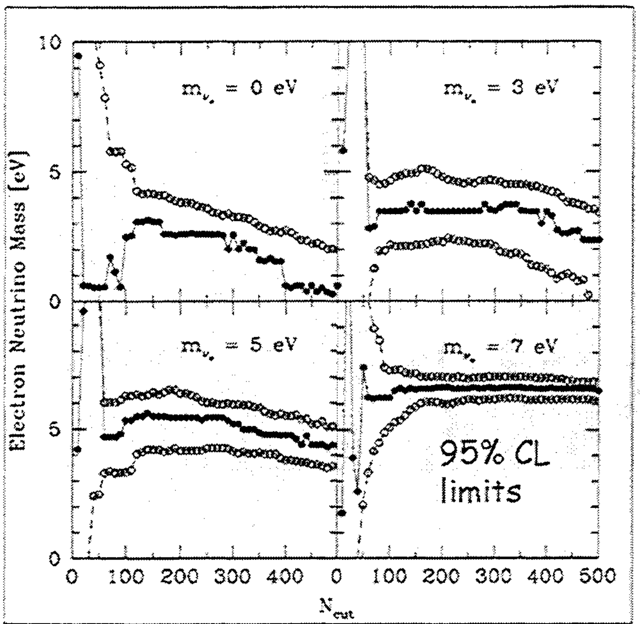


Monte-Carlo simulation for Super-K signal of SN at 10 kpc, based on a numerical model with Livermore code

Total of about 8300 events for t < 18 s

Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

Neutrino Mass from a Future Galactic SN

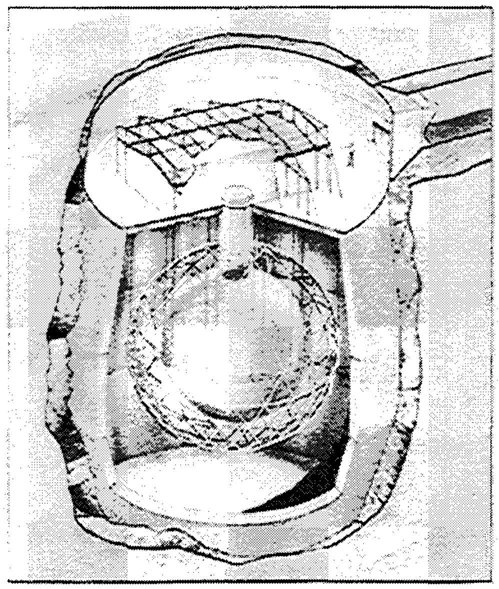


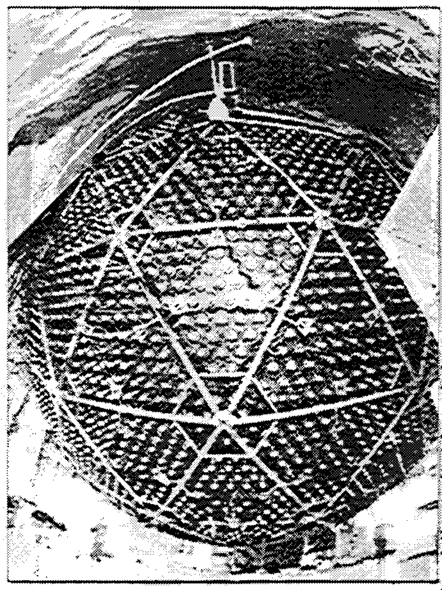
Use correlation between energy & time of arrival as a statistical measure of first N_{cut} events in Monte Carlo simulation of SN signal in SuperK

For SN at 10 kpc sensitive to approx. 3 eV

T. Totani, PRL 80 (1998) 2040

Sudbury Neutrino Observatory (SNO) (1000 tons of heavy water)





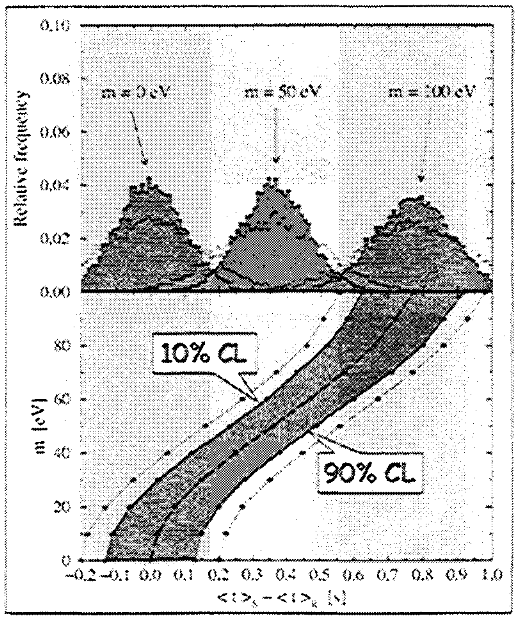
Flavor-Sensitive Detection at SNO

Sudbury Neutrino Observatory (SNO), Canada
Heavy-water Cherenkov detector (1000 tons)
9600 PMTs
Data taking since May 1999

Detection Reactions

$\nu + e \to \nu + e$	all flavors (ν_e cross section about 7× larger)
$\nu_e + d \to p + p + e$	only ν_e
$\nu + d \to p + n + e$	all flavors equally

Mu- and Tau-Neutrino Mass Sensitivity at SNO

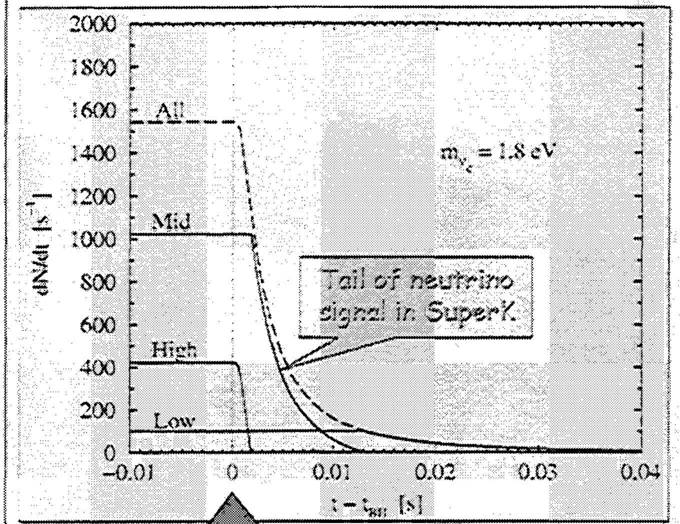


Measure difference between average arrival time $\langle t \rangle_R$ of reference signal from "massless" ν_e (from CC signal in SNO or better from SK) and $\langle t \rangle_S$ for ν_μ or ν_τ (from NC signal in SNO).

Sensitive to $m_\nu > 30$ eV

Beacom & Vogel, hep-ph/9806311

SN Neutrino Mass from Early Black Hole Formation



Black Hole Formation

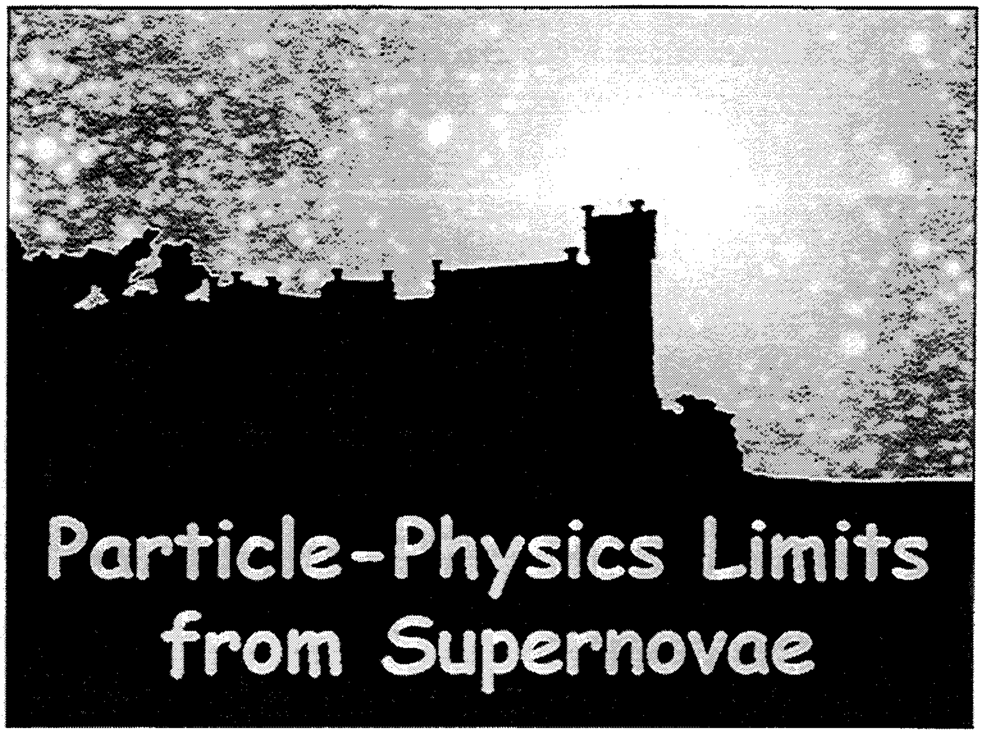
Beacom, Boyd & Mezzacappa, hep-ph/0006015

Super-Kamiokande ν_e mass sensitivity 1.8 eV

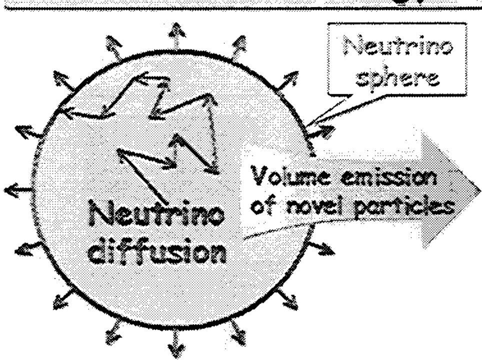
OMNIS ν_μ and ν_τ mass sensitivity 6 eV

Neutrino Mass Limits

	"ν_e"	"ν_μ"	"ν_τ"
Direct kinematical	2.8 eV	160 keV	18 MeV
	0.3 eV	?	?
Cosmological	$\Sigma m_\nu < 4$ eV		
	$\Sigma m_\nu < 0.3$ eV or even less?		
SN time of flight	20 eV		
	3 eV	30 eV	
with black hole	2 eV	6 eV	



The Energy-Loss Argument



Emission of very weakly interacting particles would "steal" energy from the observable neutrino burst and shorten it.

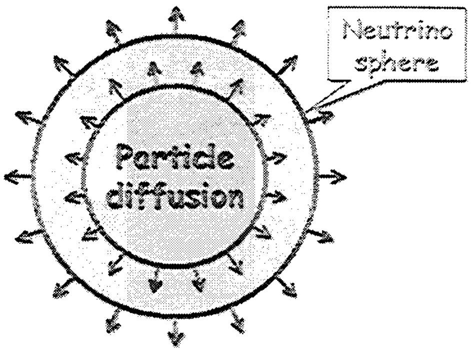
Early neutrino burst powered by accretion and energy near surface, not sensitive to volume energy loss.

Late-time signal most sensitive observable.

Assuming that the neutrino burst was not shortened by more than ~ ½ leads to an approximate requirement on a novel energy-loss rate:

$$\epsilon_x < 10^{19}\ \mathrm{erg\,g^{-1}\,s^{-1}} \quad \text{for} \quad \rho \approx 3\times10^{14}\ \mathrm{g\,cm^{-3}} \quad \text{and} \quad T \approx 30\ \mathrm{MeV}$$

The Energy-Loss Argument in the Trapping Limit



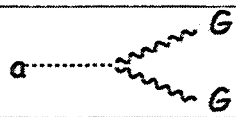
If mean-free-path < geometric dimension, new particles are more important for energy transfer than neutrinos.

Efficiency of energy transfer must be ~ less than of nus, or else speed up cooling of PNS.

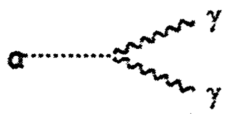
If coupling comparable to nus,
- may be important during infall
- may cause additional events in detectors

Axion Properties

Most generic property:
Coupling to gluons $L_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$

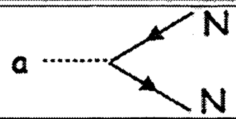


Mass (from mixing with π^0)
$m_a \approx 6\ \text{eV} \times 10^6\ \text{GeV} / f_a \approx m_\pi f_\pi / f_a$

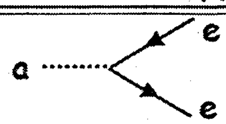


Photon coupling
$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F\tilde{F}a = g_{a\gamma} \vec{E}\cdot\vec{B}\, a, \quad g_{a\gamma} = \frac{\alpha}{2\pi f_a} (E/N - 1.92)$

Nucleon coupling (axial vector) $L_{aN} = \frac{C_N}{2f_a} \overline{\Psi}_N \gamma^\mu \gamma_5 \Psi_N \partial_\mu a$



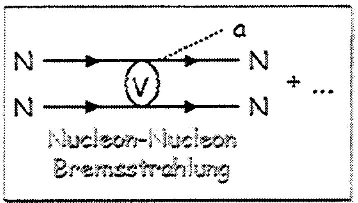
Electron coupling (optional) $L_{ae} = \frac{C_e}{2f_a} \overline{\Psi}_e \gamma^\mu \gamma_5 \Psi_e \partial_\mu a$



Axion Emission from Nuclear Medium

Axion-nucleon interaction of current-current form:

$$\mathcal{L}_{int} = \frac{C_N}{2f_a}\bar{\Psi}_N\gamma_\mu\gamma_5\Psi_N\,\partial^\mu a = \frac{C_N}{2f_a}J^A_\mu\partial^\mu a$$



Energy loss rate (erg cm^{-3} s^{-1})

$$Q = \int d\Gamma_a \int d\Gamma_{Nucleons}\,|M|^2\,\omega$$

$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2}\int_0^\infty d\omega\,\omega^4 S(-\omega)$$

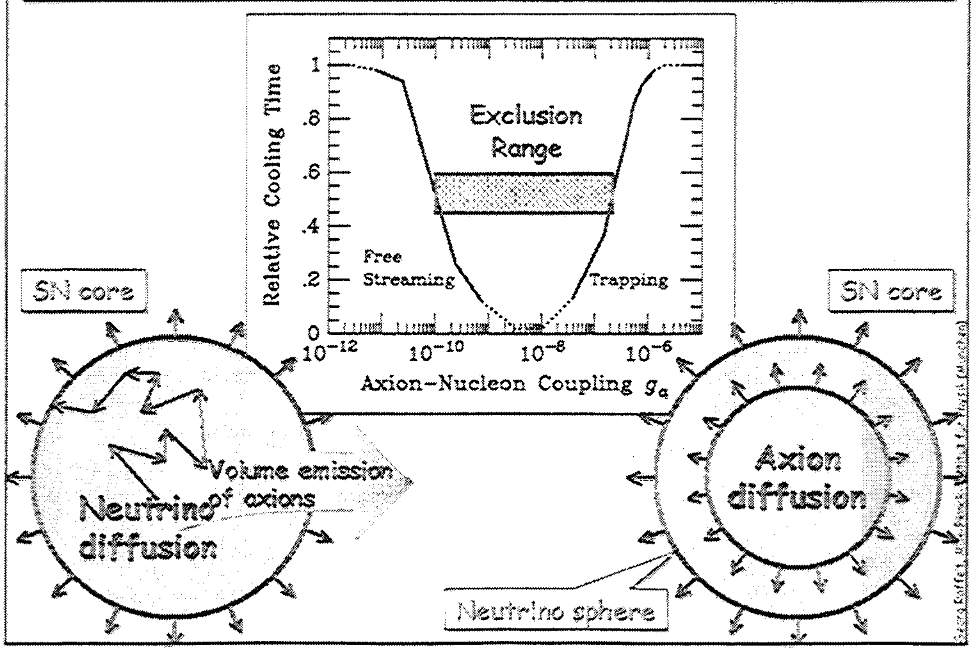
axion energy

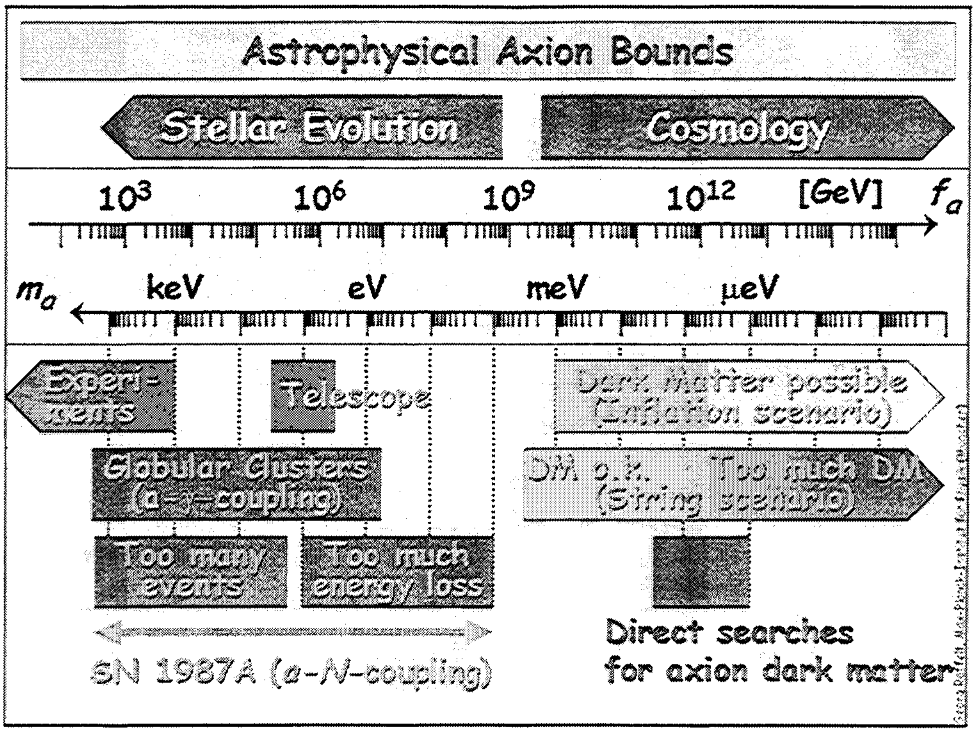
dynamical structure function

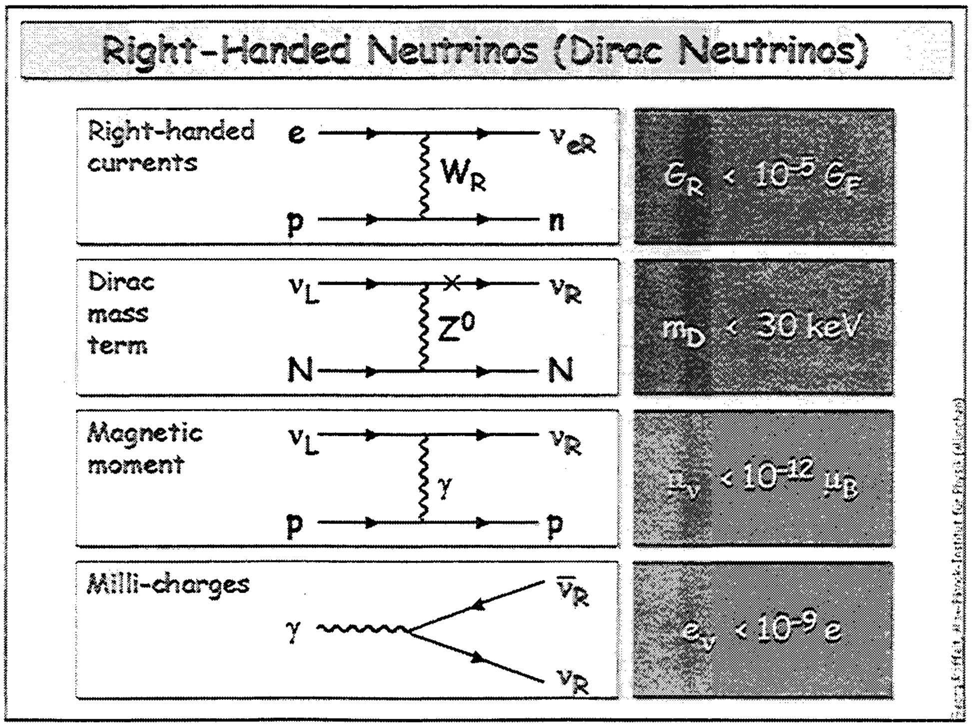
Difficulties include:

- Realistic nucleon-nucleon interaction potential (even in vacuum)
- Many-body effects (effective mass, spin-spin correlations ...)
- Axion couplings in the nuclear medium
- Multiple-scattering effects:
  Frequency of NN collisions exceeds typical axion energy: $\tau_{coll} < \omega^{-1}$
  Expect LPM-type destructive interference effects

SN 1987A Axion Limits




Astrophysical Axion Bounds
Stellar Evolution
Cosmology
10^3
10^6
10^9
10^{12}
[GeV]
f_a
m_a
keV
eV
meV
μeV
Experi-
ments
Telescope
Dark Matter possible
(Inflation scenario)
Globular Clusters
(a-γ-coupling)
DM o.k.
Too much DM
(String scenario)
Too many
events
Too much
energy loss
SN 1987A (a-N-coupling)
Direct searches
for axion dark matter


Right-Handed Neutrinos (Dirac Neutrinos)
Right-handed
currents
e
ν_{eR}
W_R
p
n
$G_R < 10^{-5}\,G_F$
Dirac
mass
term
ν_L
ν_R
Z^0
N
N
$m_D < 30$ keV
Magnetic
moment
ν_L
ν_R
γ
p
p
$\mu_\nu < 10^{-12}\,\mu_B$
Milli-charges
γ
$\bar{\nu}_R$
ν_R
$e_\nu < 10^{-9}\,e$

Spin and Spin-Flavor Oscillations

In macroscopic magnetic or electric fields, neutrinos spin-precess if they have a magnetic moment μ. Spin-reversal after a distance

$L_{flip} = 5.36 \times 10^3$ cm (μ_B Gauss)/(μB)

with $\mu_B = e/2m_e$ the Bohr magneton and B the transverse field.

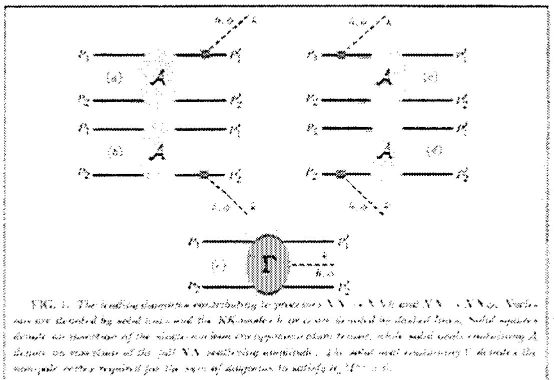
Galactic magnetic field ~ 1 μGauss, coherence length ~ 1 kpc = 3×10^{21} cm
Significant spin reversal if $\mu > 2 \times 10^{-12}\ \mu_B$
Stellar cooling limits $\mu < 3 \times 10^{-12}\ \mu_B$

- Magnetic field between neutron star and shock wave could be large
- Relevant length scale ~ 100 km
- Significant spin reversal for $\mu B > 10^{-3}\ \mu_B$ Gauss
- Easily satisfied if $\mu \sim 10^{-12}\ \mu_B$ and $B > 10^{12}$ Gauss
- However, suppressed by medium weak potential, except if resonance condition can be satisfied.

See for example Akhmedov et al., PRD 55 (1997) 515.
Nunokawa, Tomas & Valle, astro-ph/9811181

Limits on Large Extra Dimensions

Hierarchy problem solved by true Planck scale M being close to electro-weak 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 $G_N^{-1} = M_{Pl}^2 = 4\pi M^{n+2} R^n$

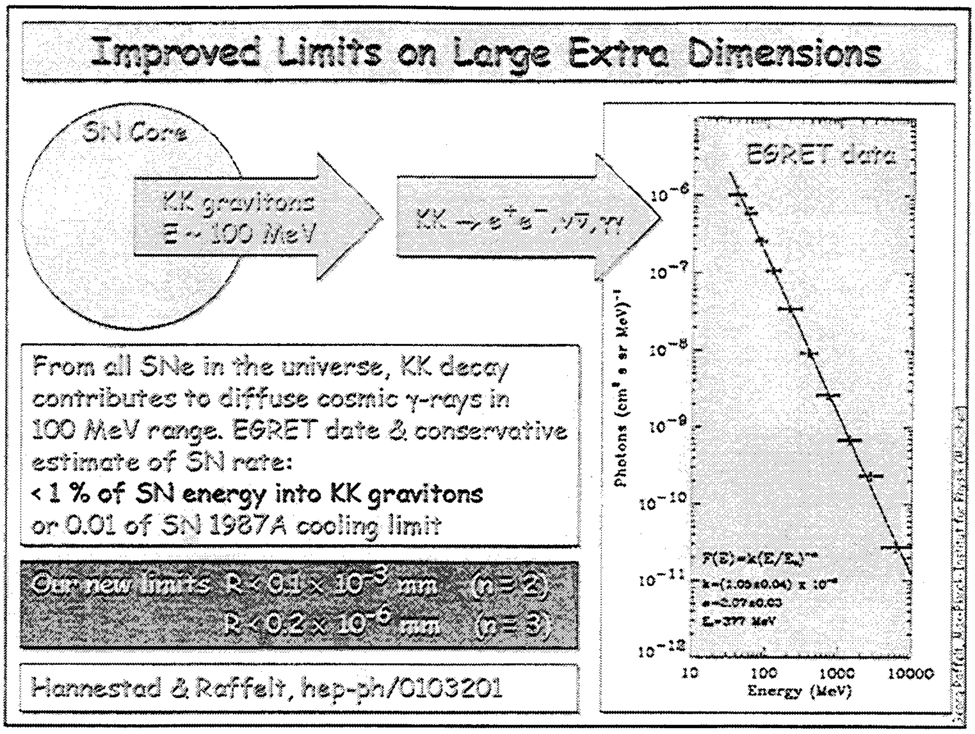


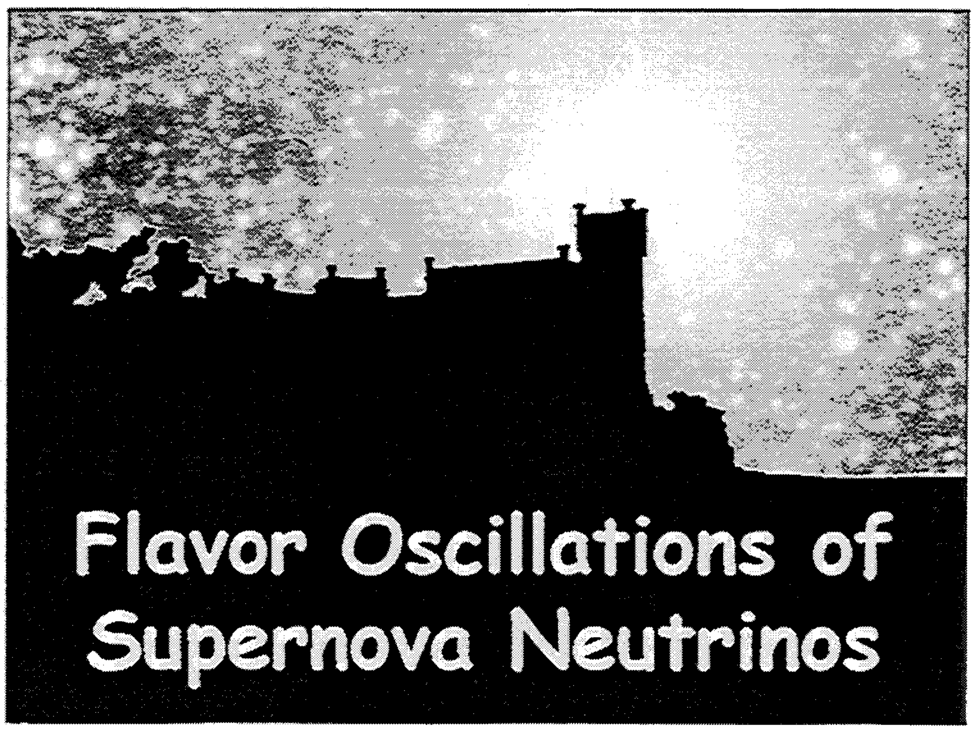
Cullen & Perelstein, hep-ph/9904422
Hanhart et al., nucl-th/0007016

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

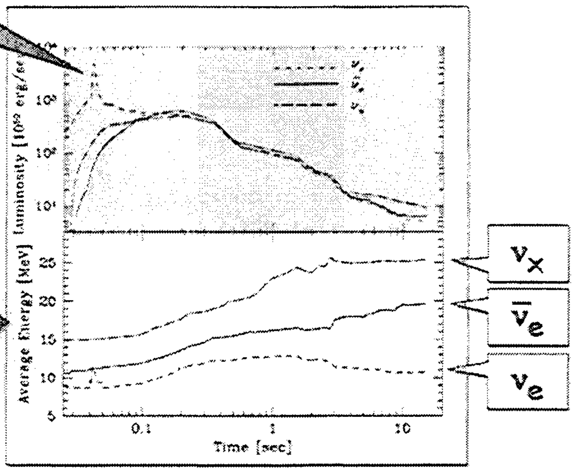

Improved Limits on Large Extra Dimensions
SN Core
KK gravitons
E ~ 100 MeV
KK → e⁺e⁻, νν̄, γγ
EGRET data
From all SNe in the universe, KK decay contributes to diffuse cosmic γ-rays in 100 MeV range. EGRET date & conservative estimate of SN rate:
< 1 % of SN energy into KK gravitons
or 0.01 of SN 1987A cooling limit
Our new limits R < 0.1 × 10⁻³ mm (n = 2)
R < 0.2 × 10⁻⁶ mm (n = 3)
Hannestad & Raffelt, hep-ph/0103201
Photons (cm² s sr MeV)⁻¹
Energy (MeV)


Flavor Oscillations of
Supernova Neutrinos

Flavor Oscillations and SN Neutrinos

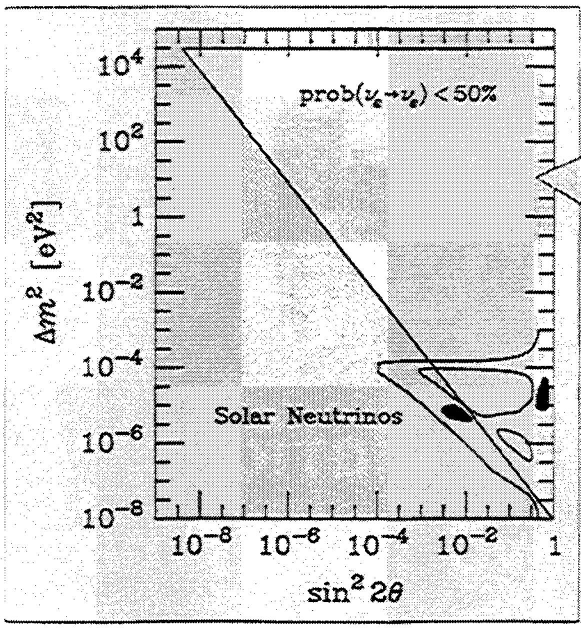
Prompt ν_e deleptonization burst

Flavor-dependent neutrino spectra



Numerical model of Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

Resonant Oscillations in a Supernova Envelope



Adiabatic oscillations for a large range of mixing parameters

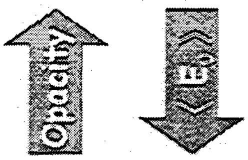
Neutrino Spectra from a Supernova Core

Different flavors are trapped by different reactions

$\nu_e + n \rightarrow p + e^-$

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

$\nu_{\mu,\tau}\ (\bar{\nu}_{\mu,\tau}) + N \rightarrow N + \nu_{\mu,\tau}\ (\bar{\nu}_{\mu,\tau})$

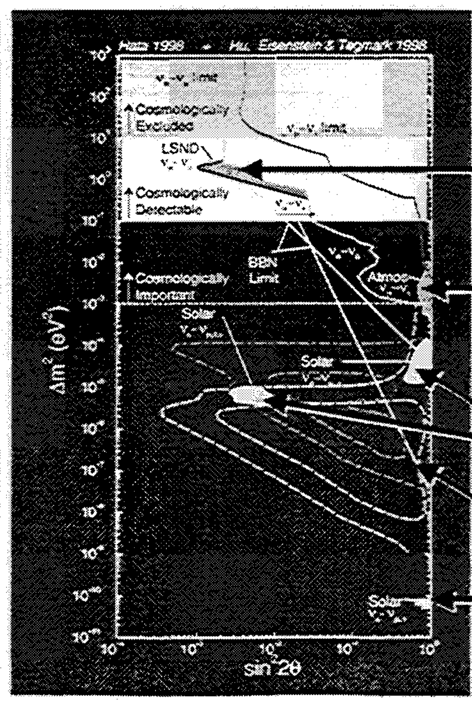


Beta reactions are more efficient than neutral-current scattering, and there are more n than p. Typical SN simulations yield a hierarchy of spectral temperatures

$$\langle E_\nu \rangle = \begin{cases} 10-12\ \text{MeV} & \text{for } \nu_e \\ 14-17\ \text{MeV} & \text{for } \bar{\nu}_e \\ 24-27\ \text{MeV} & \text{for } \nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau \end{cases}$$

Approximate equipartition of energy among flavors

Neutrino oscillations can partially swap spectra



Current Indications for Neutrino Oscillations

LSND Experiment

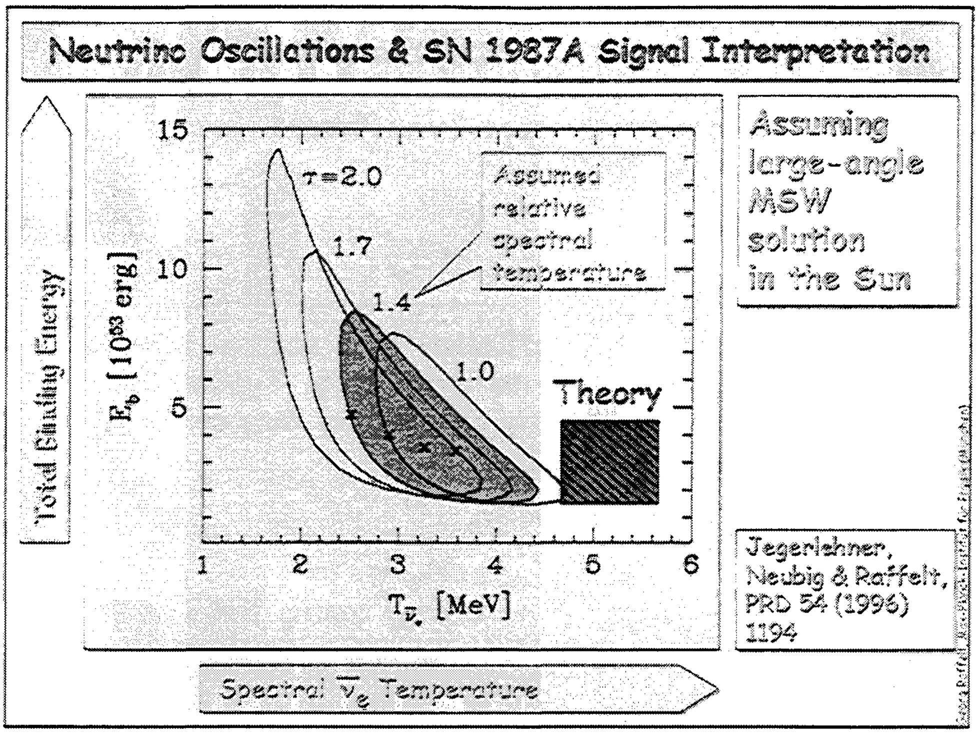
Atmospheric Neutrino Anomaly

Solar Neutrinos:

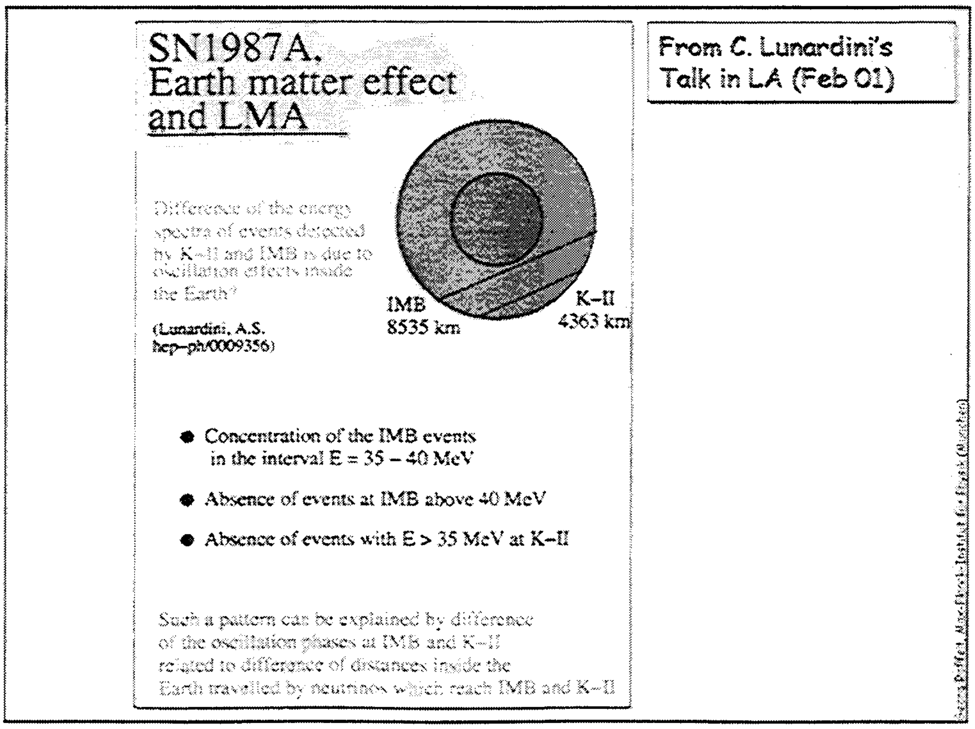
MSW Solutions (Matter effects important)

LOW solution

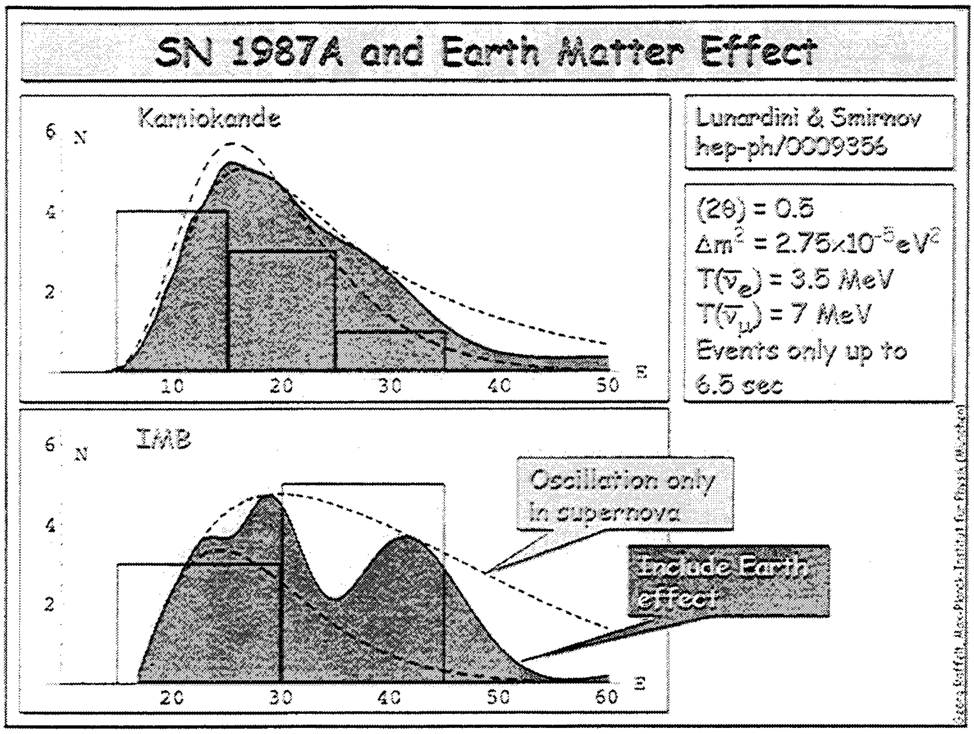
Vacuum Solution

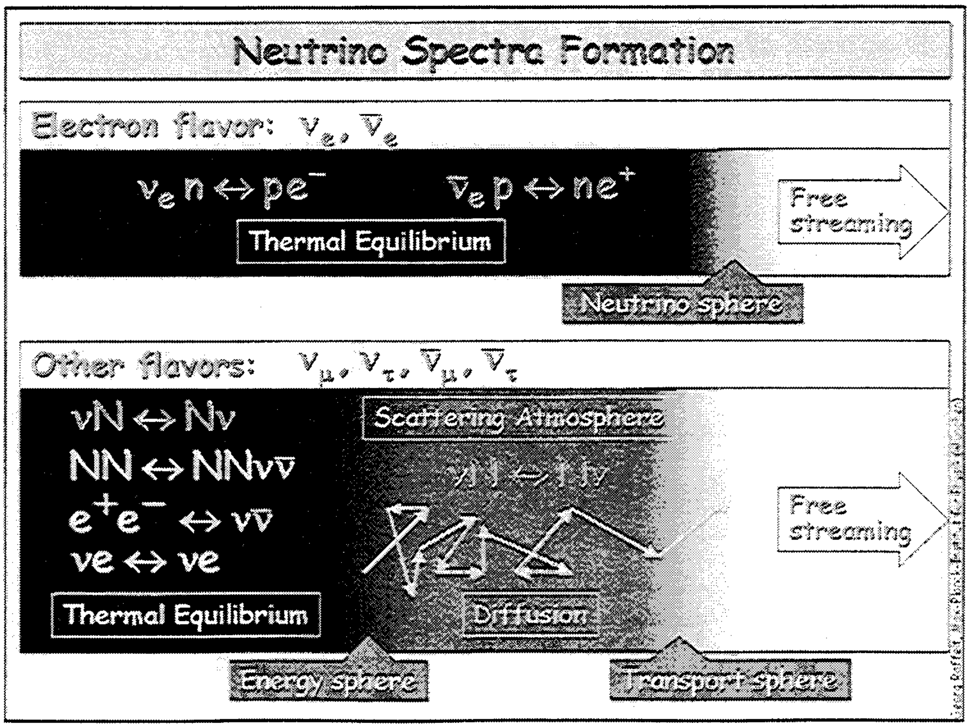


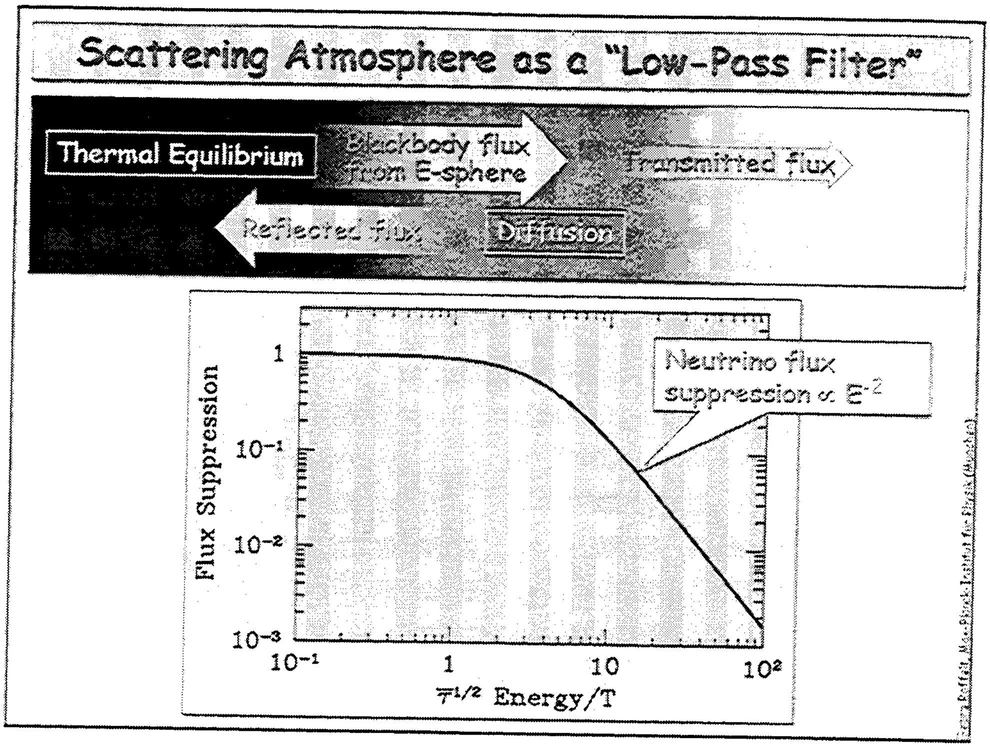
Neutrino Oscillations & SN 1987A Signal Interpretation
Assuming large-angle MSW solution in the Sun
15
10
5
1
2
3
4
5
6
τ=2.0
1.7
1.4
1.0
Assumed relative spectral temperature
Theory
E_b [10^{53} erg]
$T_{\bar{\nu}_e}$ [MeV]
Total Binding Energy
Spectral $\bar{\nu}_e$ Temperature
Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

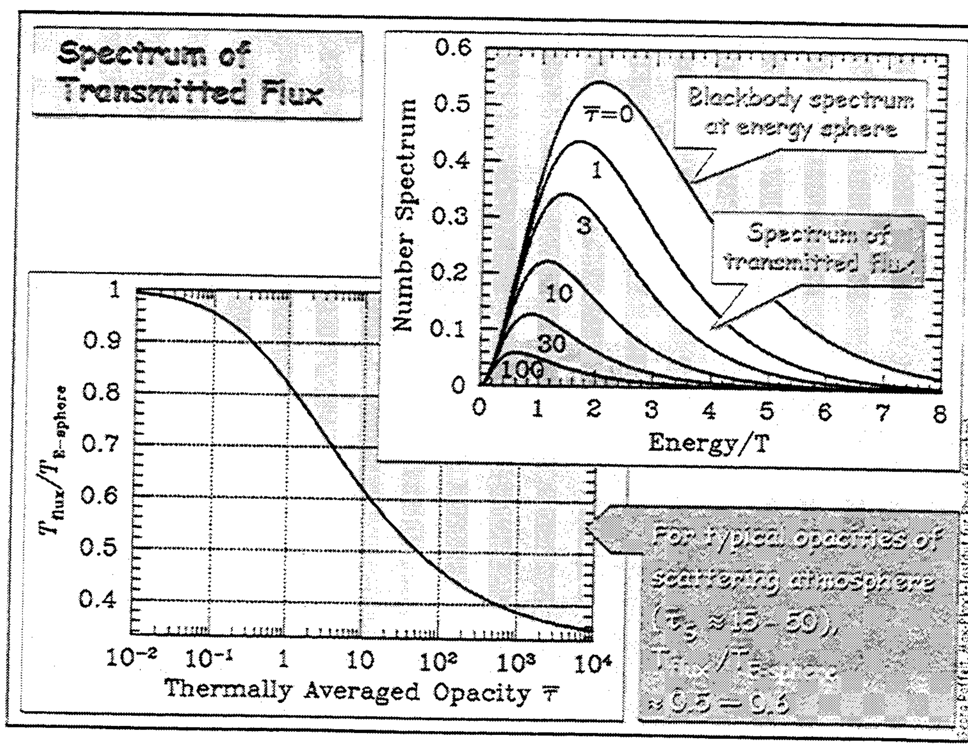


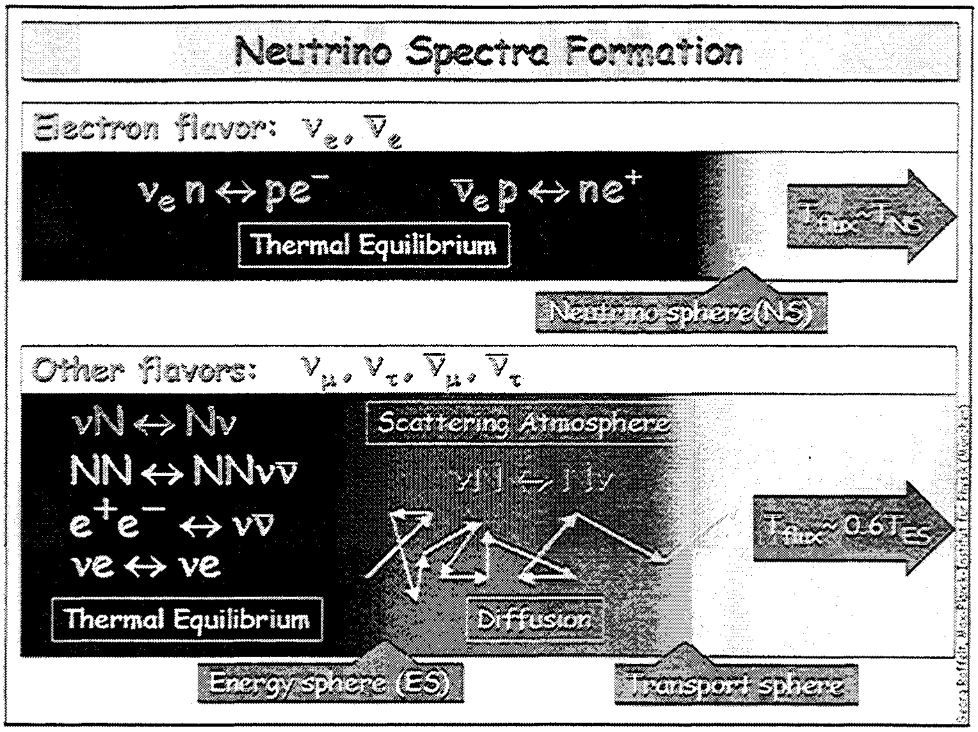
SN1987A.
Earth matter effect and LMA
From C. Lunardini's Talk in LA (Feb 01)
Difference of the energy spectra of events detected by K–II and IMB is due to oscillation effects inside the Earth?
(Lunardini, A.S. hep–ph/0009356)
IMB 8535 km
K–II 4363 km
Concentration of the IMB events in the interval E = 35 – 40 MeV
Absence of events at IMB above 40 MeV
Absence of events with E > 35 MeV at K–II
Such a pattern can be explained by difference of the oscillation phases at IMB and K–II related to difference of distances inside the Earth travelled by neutrinos which reach IMB and K–II


SN 1987A and Earth Matter Effect
Kamiokande
N
E
IMB
Lunardini & Smirnov
hep-ph/0009356
(2θ) = 0.5
Δm² = 2.75×10⁻⁵eV²
T(ν̄e) = 3.5 MeV
T(ν̄μ) = 7 MeV
Events only up to
6.5 sec
Oscillation only
in supernova
Include Earth
effect

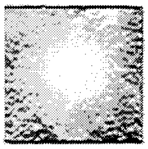

Neutrino Spectra Formation
Electron flavor: νe, ν̄e
νe n ↔ pe⁻
ν̄e p ↔ ne⁺
Thermal Equilibrium
Free
streaming
Neutrino sphere
Other flavors: νμ, ντ, ν̄μ, ν̄τ
νN ↔ Nν
NN ↔ NNνν̄
e⁺e⁻ ↔ νν̄
νe ↔ νe
Thermal Equilibrium
Scattering Atmosphere
Diffusion
Free
streaming
Energy sphere
Transport sphere


Scattering Atmosphere as a "Low-Pass Filter"
Thermal Equilibrium
Blackbody flux from E-sphere
Transmitted flux
Reflected flux
Diffusion
Neutrino flux suppression ∝ E^-2
Flux Suppression
1
10^-1
10^-2
10^-3
10^-1
1
10
10^2
τ^1/2 Energy/T

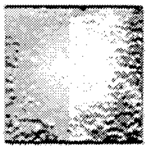

Spectrum of Transmitted Flux
Number Spectrum
0.6
0.5
0.4
0.3
0.2
0.1
0
τ=0
1
3
10
30
100
Blackbody spectrum at energy sphere
Spectrum of transmitted flux
0 1 2 3 4 5 6 7 8
Energy/T
T_flux/T_E-sphere
1
0.9
0.8
0.7
0.6
0.5
0.4
10^-2 10^-1 1 10 10^2 10^3 10^4
Thermally Averaged Opacity τ
For typical opacities of scattering atmosphere (τ_S ≈ 15 - 50), T_flux/T_E-sphere ≈ 0.5 — 0.6



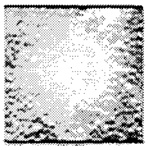
Conclusions



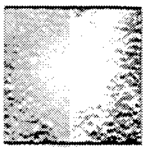
Type II supernova explosions probably explained by neutrino-driven delayed explosion mechanism, but thus far no working numerical standard model. Convection key to successful explosion? Completely new physics needed?



If neutrino mixing parameters in currently favored regions
- Neutrino flavor oscillations not important for SN physics
- But crucial for detector signal interpretation
- Sterile nus and/or dipole moments can have strong effects



High-statistics observation of a galactic SN is
- crucial for empirical study of core-collapse event
- not sensitive to sub-eV neutrino masses
- probably differentiates between some mixing scenarios
- information on possible late phase transitions and such



Particle emission by supernova cores continues to provide most restrictive limits on various theories (axions, r.h. neutrinos, extra dimensions ...)
High-statistics observation would put these on firm grounds.

Further Reading

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astro-ph/0103015

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