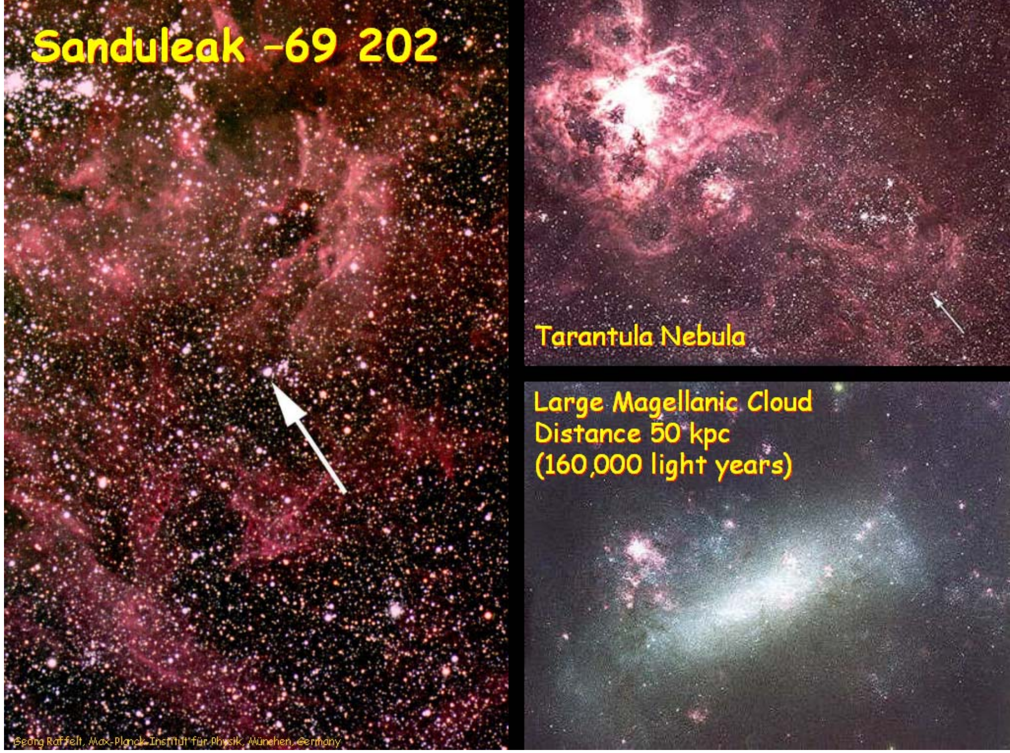
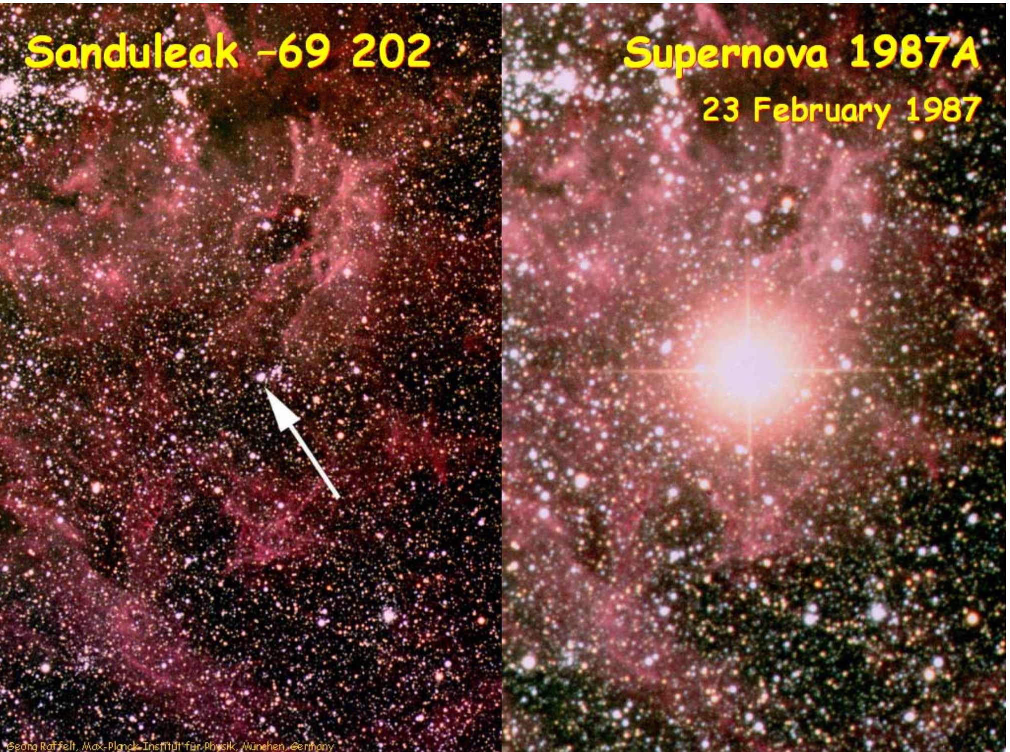

Supernova Neutrinos


Sanduleak -69 202
Tarantula Nebula
Large Magellanic Cloud
Distance 50 kpc
(160,000 light years)
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

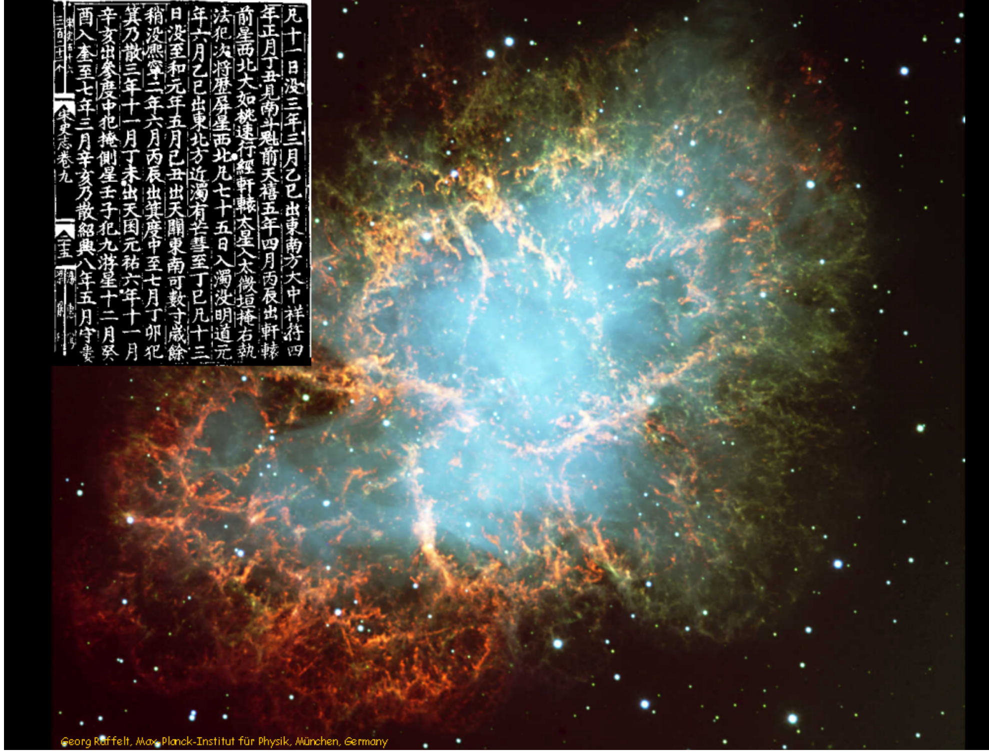

Sanduleak -69 202
Supernova 1987A
23 February 1987
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany


• SN 1987A in the LMC the only certain identification of progenitor star
• SN 1993J in M81 another tentative case
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

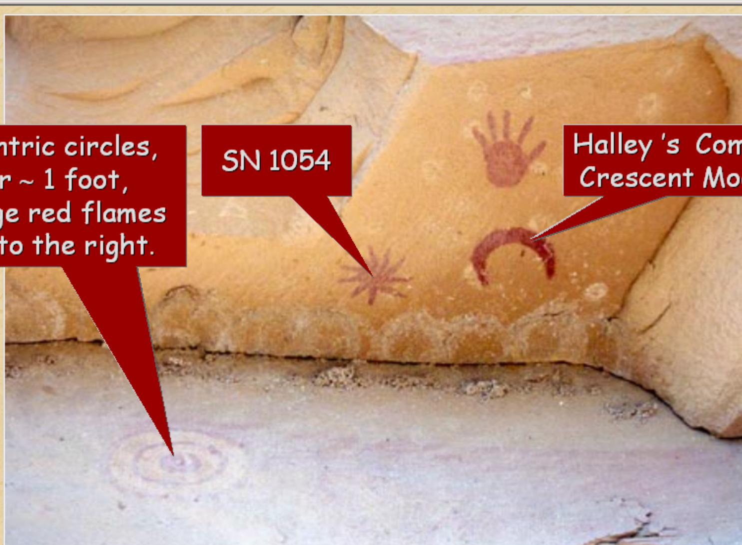
Supernovae – Almost as Bright as Galaxies

SN 1998S in NGC 3877

SN 1994D in NGC 4526

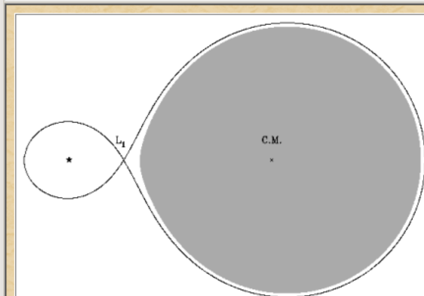


Supernova 1054 Petrograph

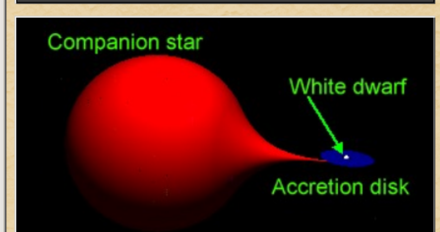


Possible SN 1054 Petrograph by the Anasazi people
(Chaco Canyon, South-Western U.S.)

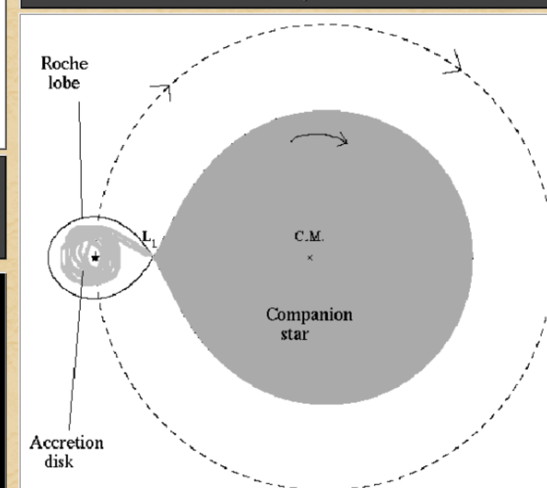
Mass Transfer in Binary Stars

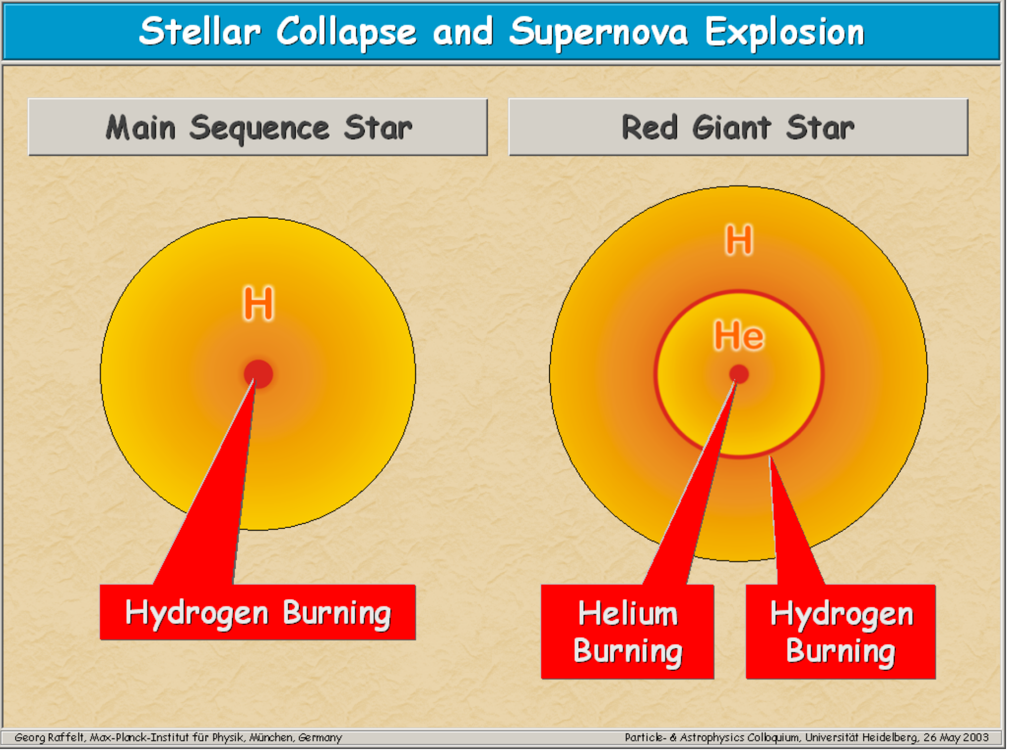


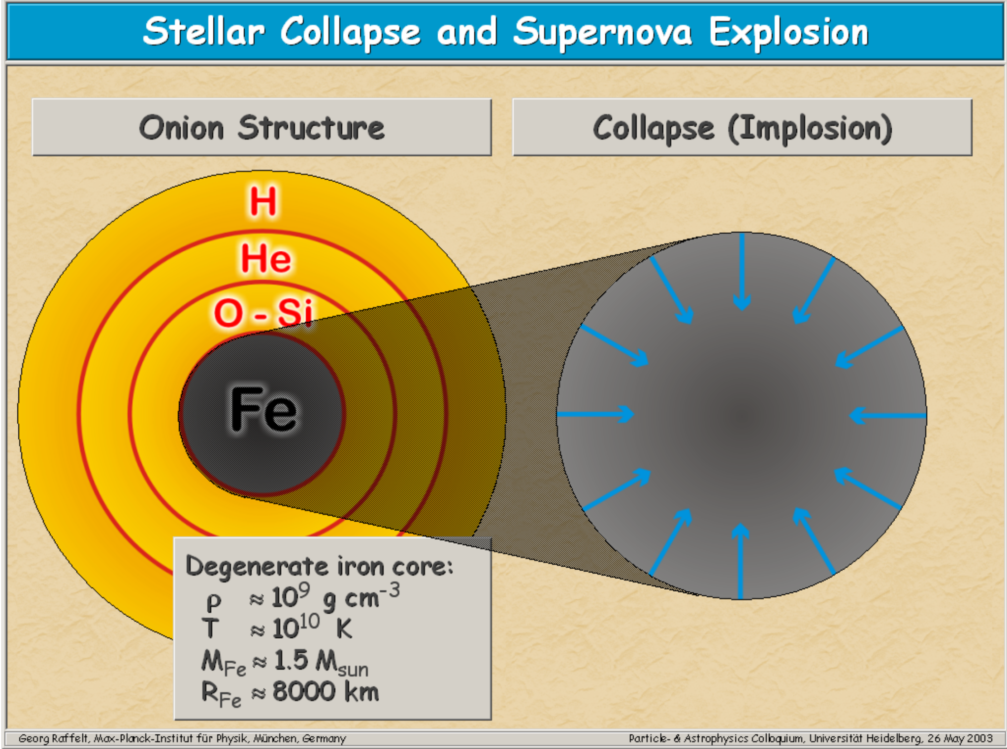
Binary system of white dwarf and evolved companion star, beginning to fill the "Roche lobe"

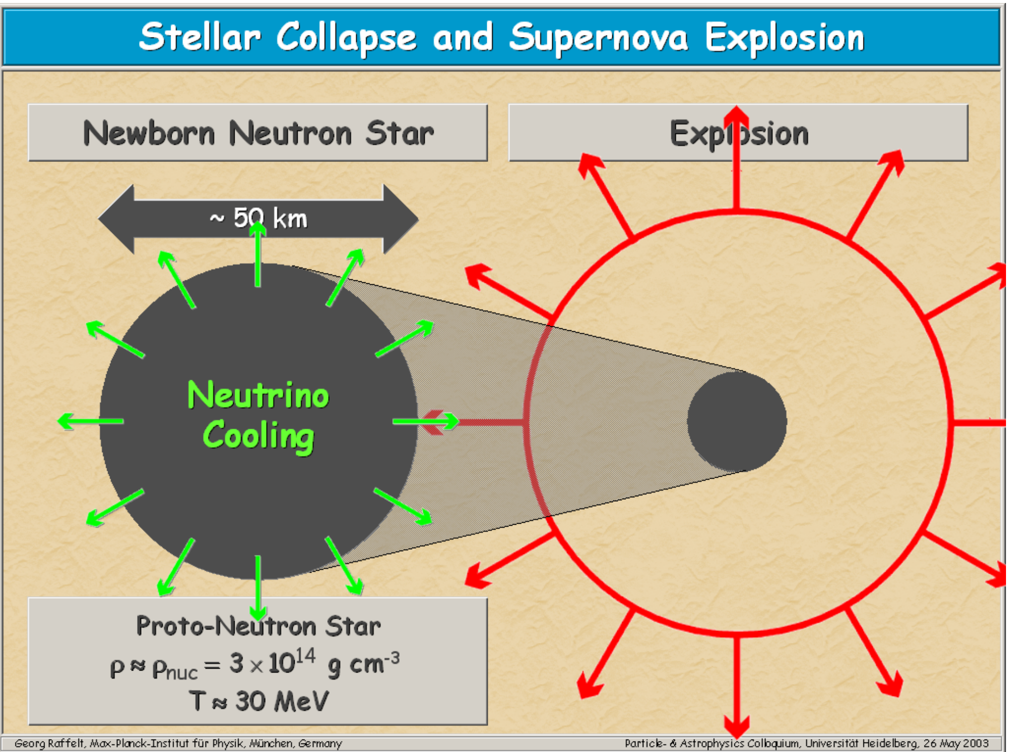


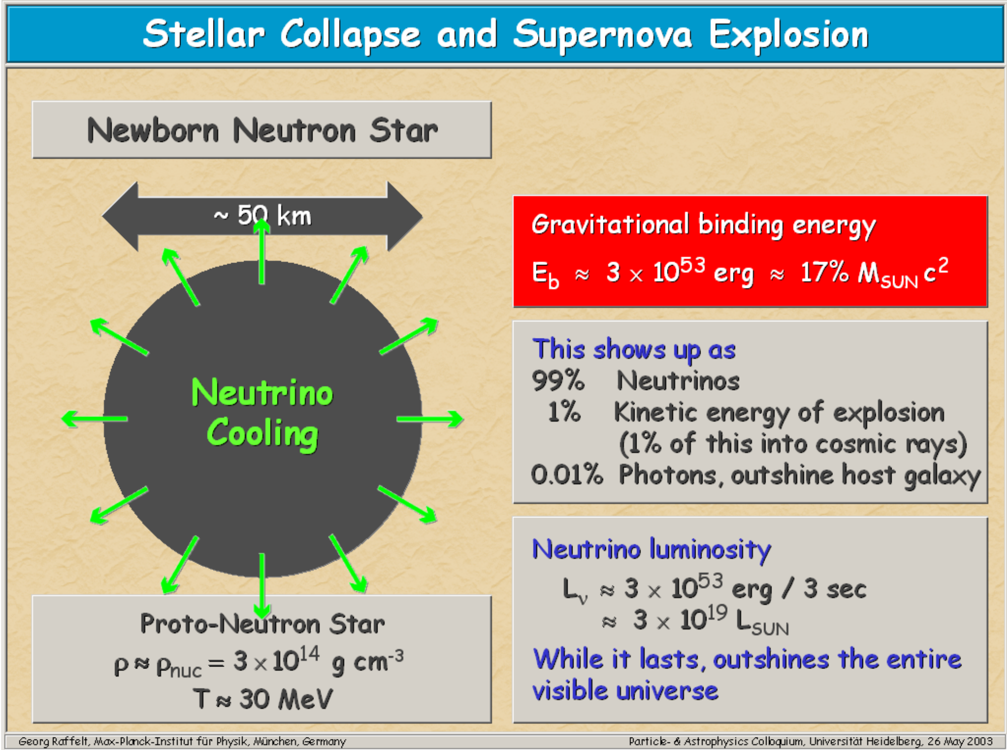
Roche-lobe overflow feeds mass to the compact star



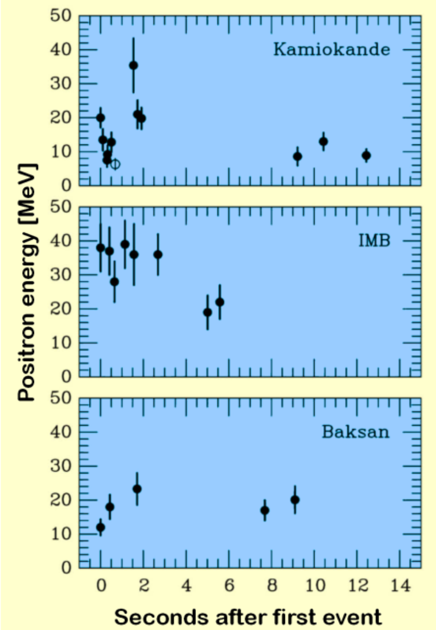

Stellar Collapse and Supernova Explosion
Main Sequence Star
Red Giant Star
H
H
He
Hydrogen Burning
Helium Burning
Hydrogen Burning
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003


Stellar Collapse and Supernova Explosion
Onion Structure
Collapse (Implosion)
H
He
O - Si
Fe
Degenerate iron core:
$\rho \approx 10^9$ g cm^{-3}
$T \approx 10^{10}$ K
$M_{Fe} \approx 1.5\ M_{sun}$
$R_{Fe} \approx 8000$ km
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003


Stellar Collapse and Supernova Explosion
Newborn Neutron Star
Explosion
~ 50 km
Neutrino Cooling
Proto-Neutron Star
$\rho \approx \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}
$T \approx 30$ MeV
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003


Stellar Collapse and Supernova Explosion
Newborn Neutron Star
~ 50 km
Neutrino Cooling
Proto-Neutron Star
$\rho \approx \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}
$T \approx 30$ MeV
Gravitational binding energy
$E_b \approx 3 \times 10^{53}$ 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
$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec
$\approx 3 \times 10^{19}\ L_{SUN}$
While it lasts, outshines the entire visible universe
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Neutrino Signal of Supernova 1987A



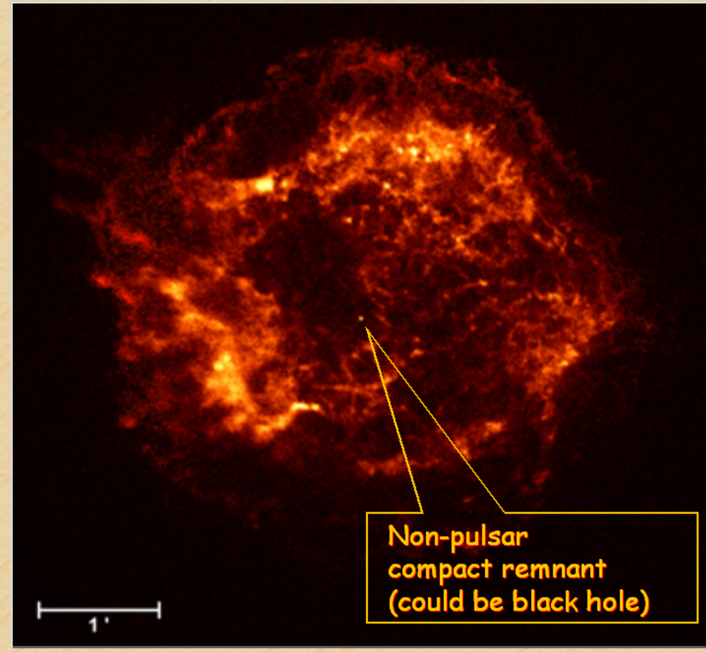
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

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

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

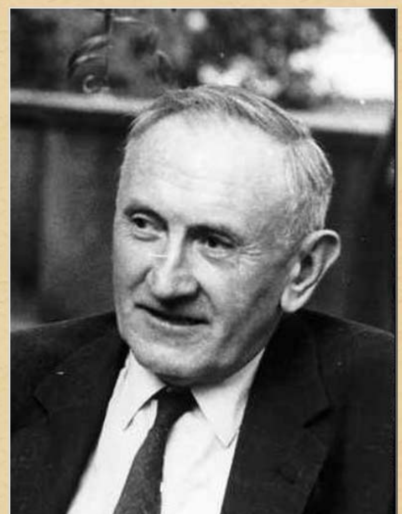
Within clock uncertainties, signals are contemporaneous

Supernova Remnant in Cas A (SN 1667?)



Chandra
x-ray image

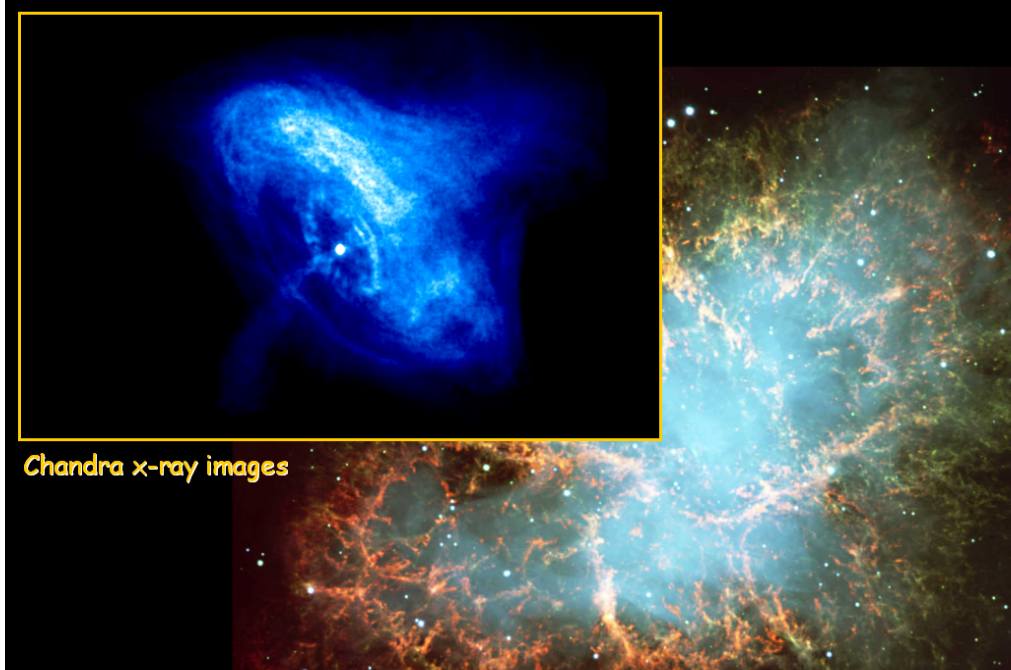
Walter Baade (1893-1960)



Fritz Zwicky (1898-1974)

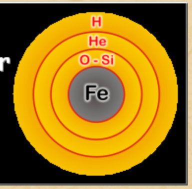
Baade and Zwicky were the first to speculate about a connection between supernova explosions and neutron-star formation [Phys. Rev. 45 (1934) 138]

The Crab Pulsar



Type Ia vs. Core-Collapse Supernovae

Type Ia	Core collapse (Type II, Ib/c)
Carbon-oxygen white dwarf (remnant of low-mass star) accretes matter from companion	Degenerate iron core of evolved massive star Accretes matter by nuclear burning at its surface



Chandrasekhar limit is reached - $M_{Ch} \approx 1.5\ M_{sun}\ (2Y_e)^2$

C O L L A P S E   S E T S   I N

Type Ia	Core collapse
Nuclear burning of C and O ignites → Nuclear deflagration ("Fusion bomb" triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy ~ 1 MeV per nucleon	Gain of gravitational binding energy ~ 100 MeV per nucleon 99% into neutrinos

Comparable "visible" energy release of ~ 3×10^{51} erg

Supernovae the Power Supply for Cosmic Rays?

Required power supply $L_{CR} = V_D\, \rho_{CR} / \tau_{res}$
$\approx 5 \times 10^{40}$ erg/s $\approx 10^7\ L_{Sun}$

Disk volume $V_D = \pi R^2 d \approx \pi\,(15\ \text{kpc})^2\ 200\ \text{pc}$
$\approx 4 \times 10^{66}\ \text{cm}^3$

Energy density in CRs $\rho_{CR} \approx 1\ \text{eV}/\text{cm}^3$

Residence time in galaxy $\tau_{res} \approx 6 \times 10^6$ yrs

Suggestive of supernovae:

- One SN explosion deposits ~ 3×10^{51} erg in kinetic energy of ejecta into the interstellar medium (ISM)
- Rate approx. 1 SN / 30 years / galaxy

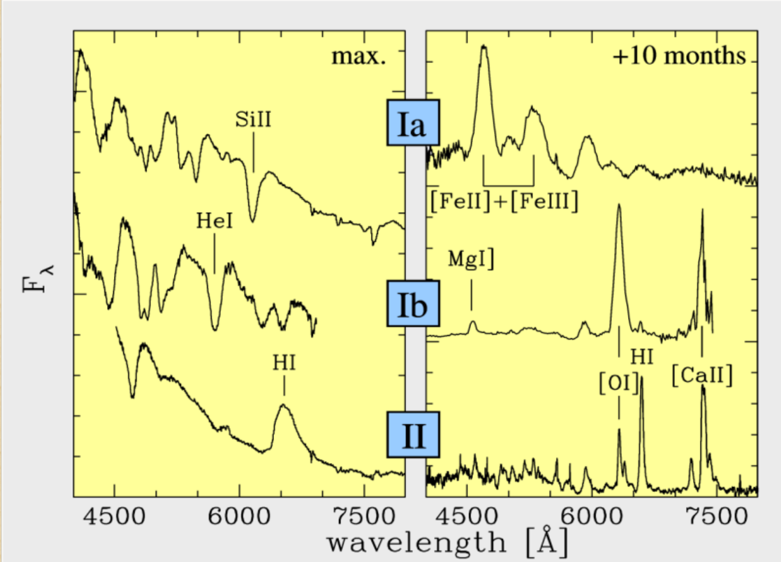
Total average energy deposition: $L_{SN} \approx 3 \times 10^{42}$ erg/s $\approx 50\ L_{CR}$

Efficiency of a few percent required

Classification of Supernovae

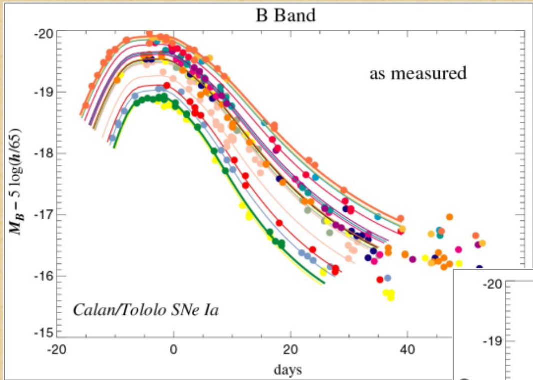
Spectral Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen	No Hydrogen	No Hydrogen	Hydrogen
	Silicon	No Silicon	No Silicon	
		Helium	No Helium	
Physical Mechanism	Nuclear explosion of low-mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
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)			

Typical Spectra of Different Supernova Types

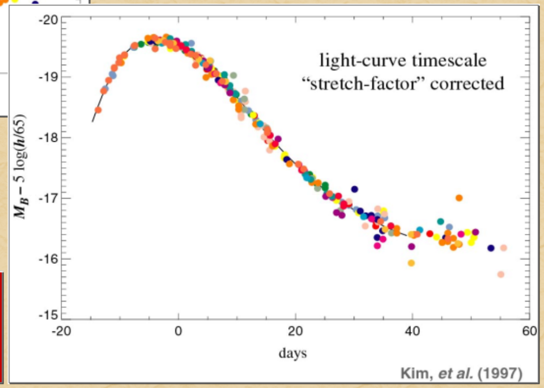


Cappellaro and Turatto, astro-ph/0012455

Universal Supernova Ia Light Curve

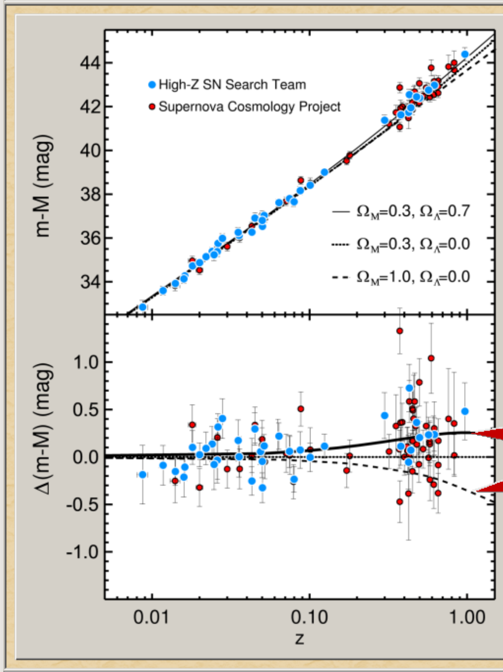


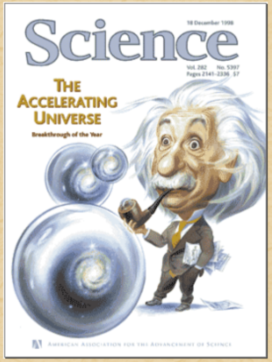
Measured supernova Ia light curves are empirically a 1-parameter family



After transformation becomes a universal light curve, i.e. a de-facto standard candle

Hubble Diagram – Accelerated Expansion



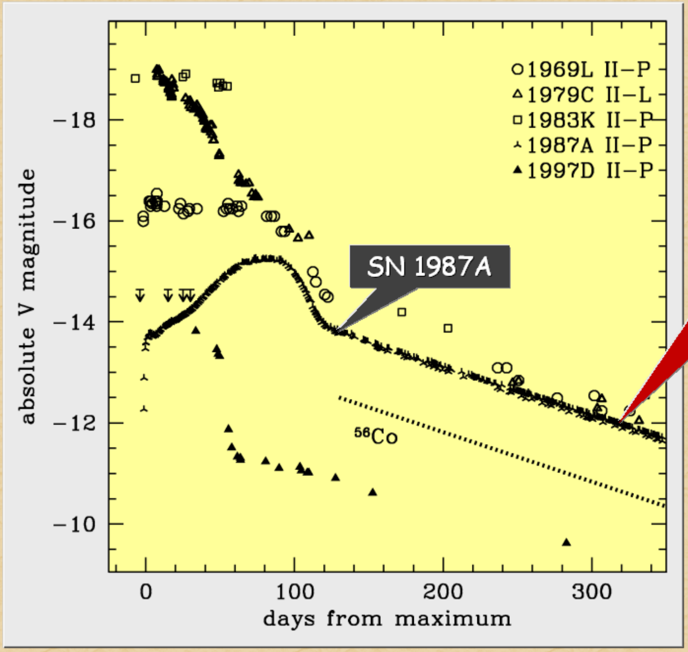


Accelerated expansion (cosmological constant dominates)

Decelerated expansion (for normal matter)

Supernovae type Ia as cosmological standard candles

Examples for SN II Light Curves



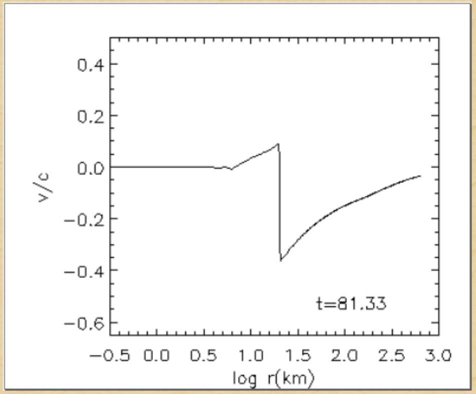
Powered by radioactive decay of ^{56}Co

Cappellaro & Turatto, astro-ph/0012455

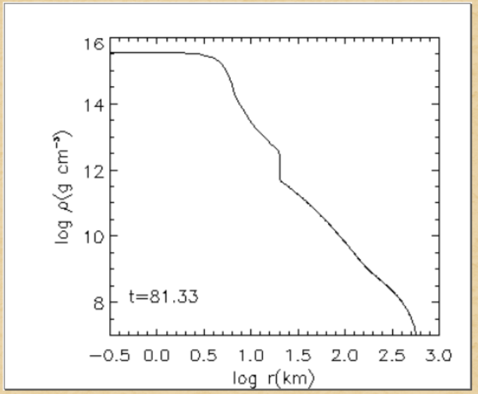
Explosion Mechanism for Core-Collapse SNe

Collapse and Prompt Explosion

Velocity



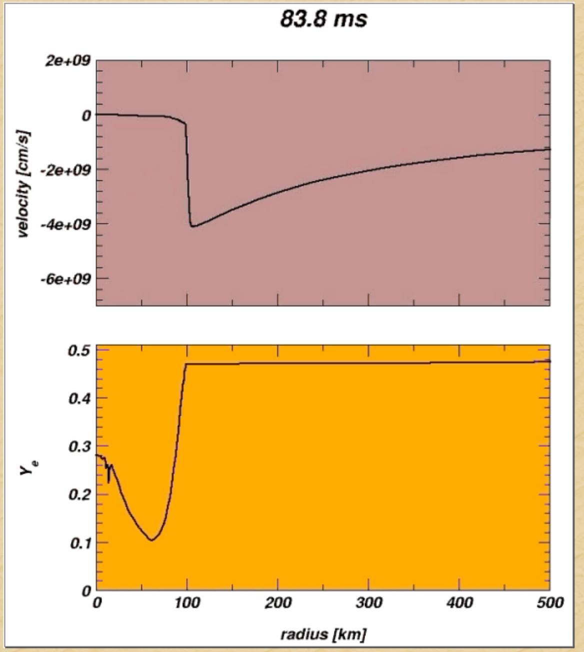
Density



Supernova explosion primarily a hydrodynamical phenomenon

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

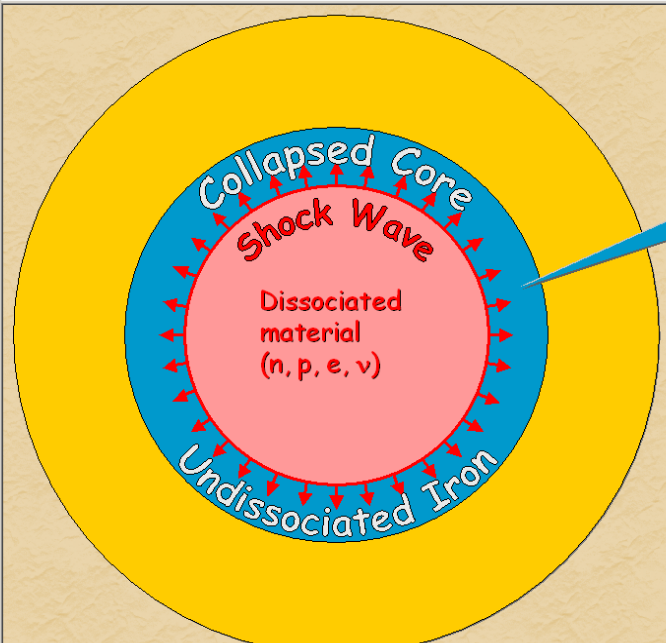
Failed Explosion



Spherically symmetric simulation of a 15 M_{sun} stellar model with state-of-the-art neutrino transport

Movie courtesy of Bronson Messer, Oakridge group (2001)

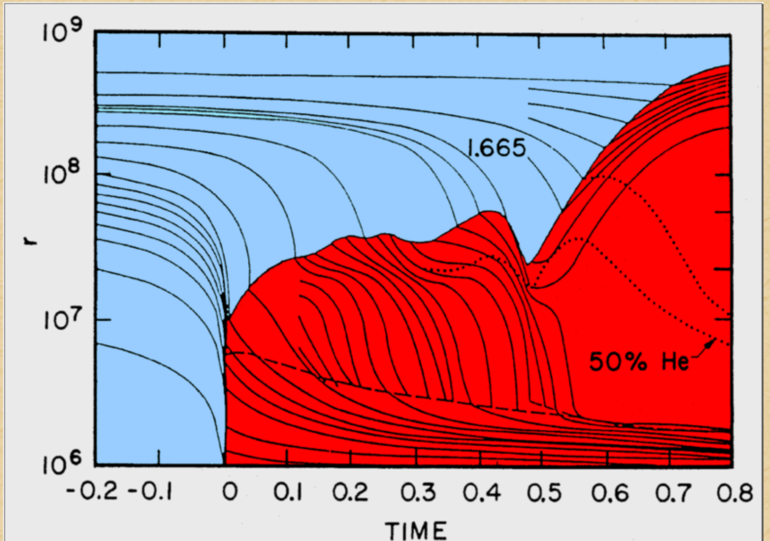
Why No Prompt Explosion?



- 0.1 M_{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

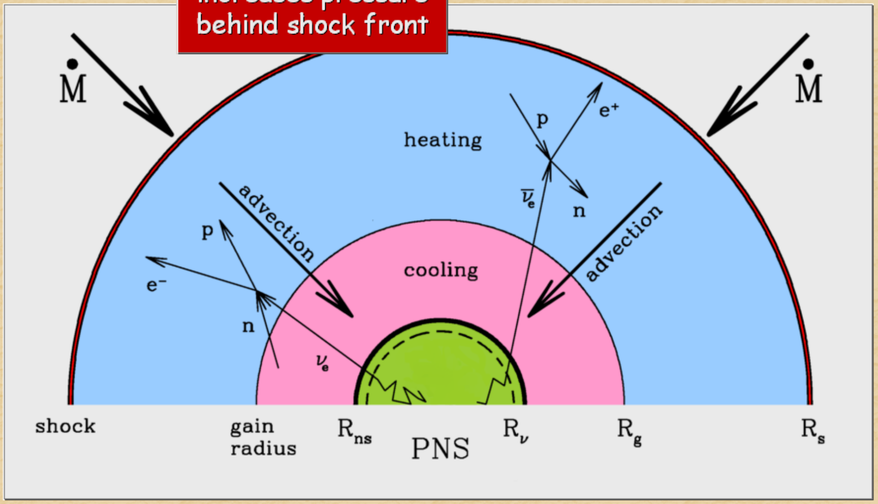
Delayed Explosion



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

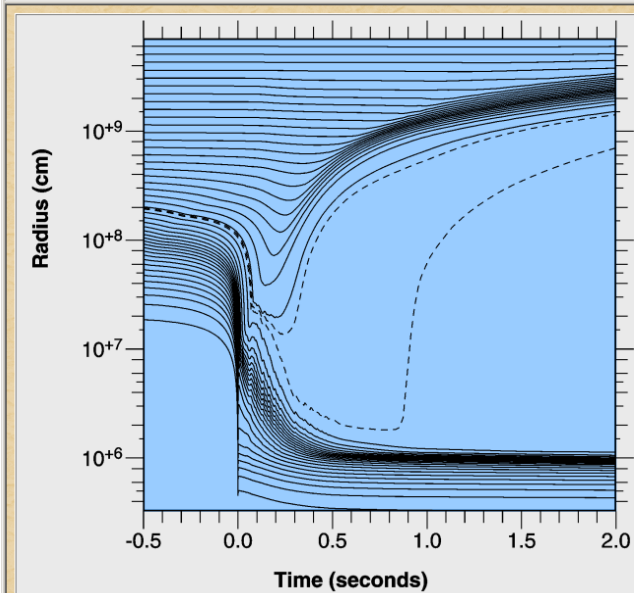
Neutrinos to the Rescue

Neutrino heating increases pressure behind shock front



Picture adapted from Janka, astro-ph/0008432

Explosion in Recent Livermore Simulation

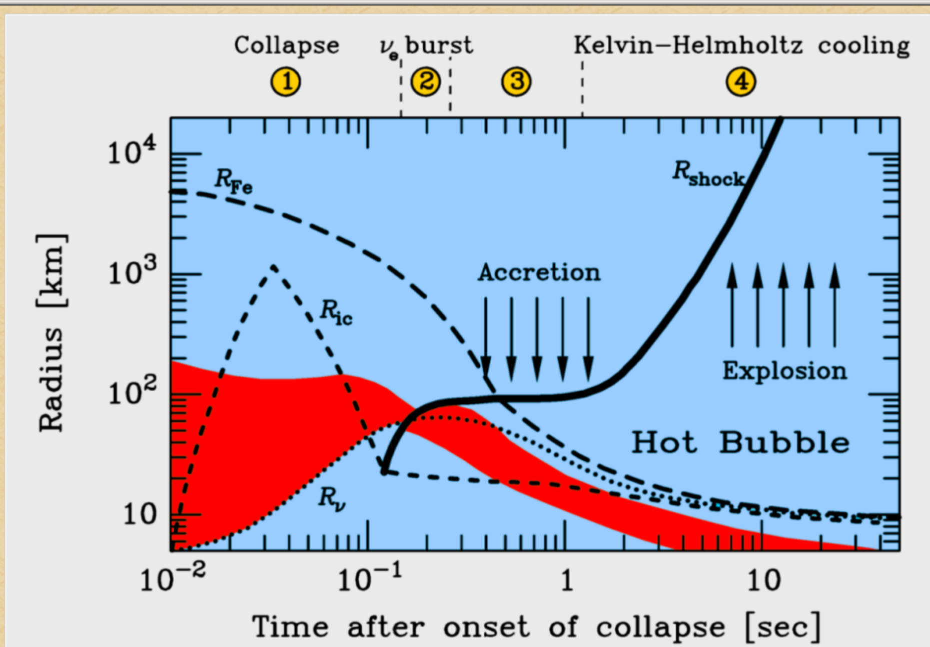


Livermore group obtains robust delayed explosions with 1-D code of Mayle & Wilson

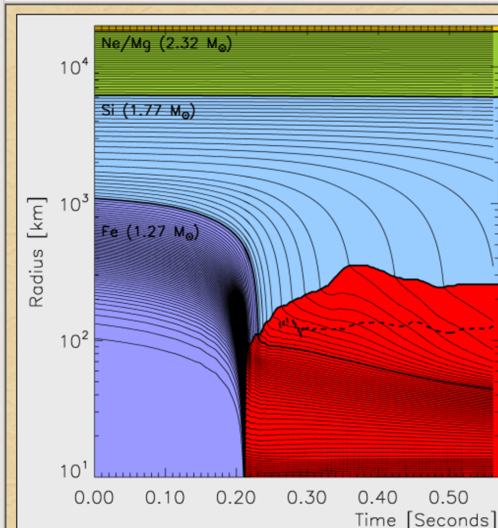
Neutrino luminosity is enhanced by "neutron finger convection" in proto neutron star

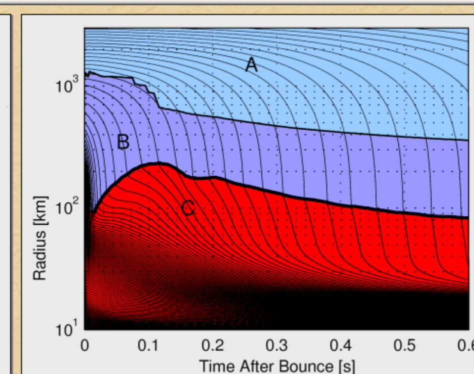
Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

Supernova Delayed Explosion Scenario



Failed Explosions in Spherical Symmetry





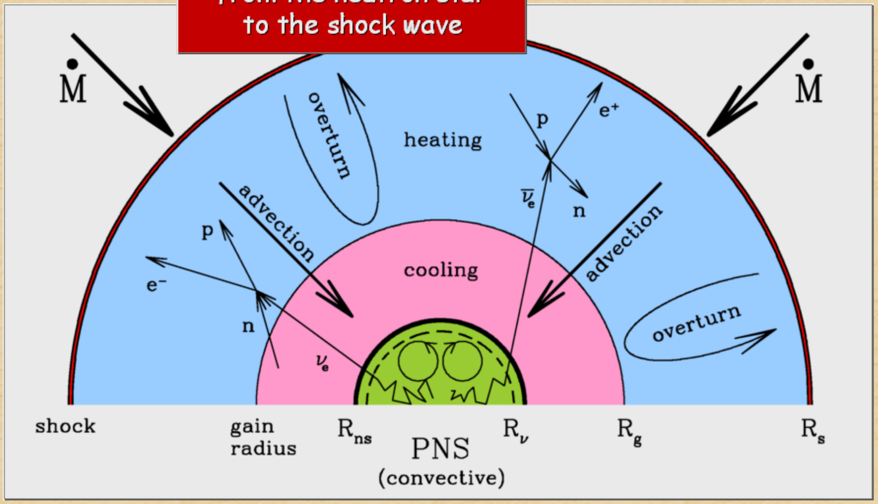
Mezzacappa et al., PRL 86 (2001) 1935

Rampp & Janka, ApJ 539 (2000) L33

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

Convection to the Rescue

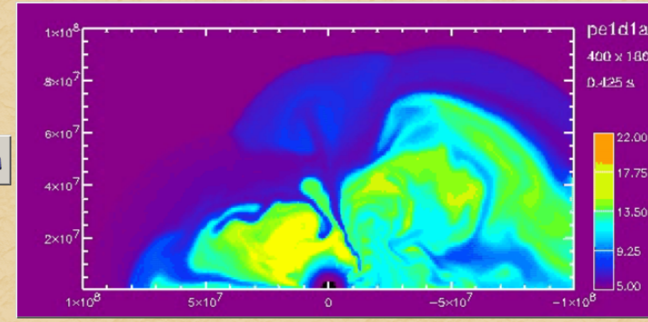
Convection dredges energy from the neutron star to the shock wave



Picture adapted from Janka, astro-ph/0008432

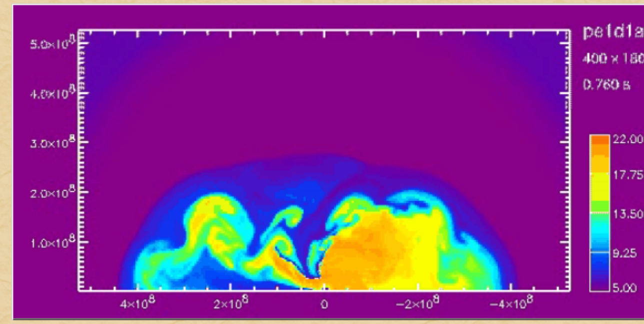
Convection in Supernovae (2-D Simulation)

1000 km



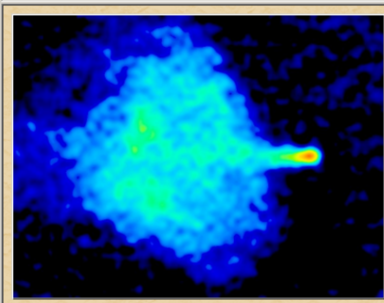
Entropy contours

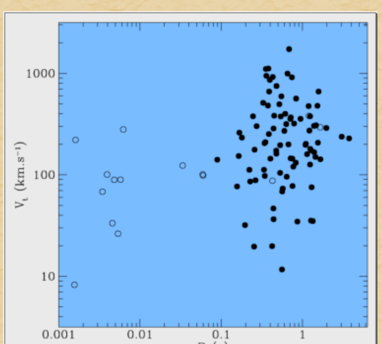
Artificially triggered explosion

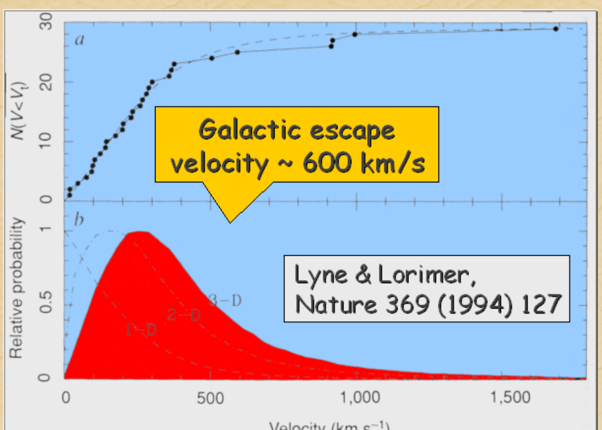


Movies courtesy H.-T. Janka

High-Velocity Pulsars







Pulsar velocity distribution

What Accelerates the Pulsars?

Neutrino Rocket

Required neutrino asymmetry $2.8\% \left(\frac{3\times 10^{53}\,\mathrm{erg}}{E_{tot}}\right)\left(\frac{v_{kick}}{1000\,\mathrm{km/s}}\right)$

Caused by B-field induced asymmetry of neutrino transport coefficients (parity violation, dispersion effects & oscillations, asymmetric field distribution, ...)?
Typically requires huge fields > 10^{15} Gauss

Matter Rocket

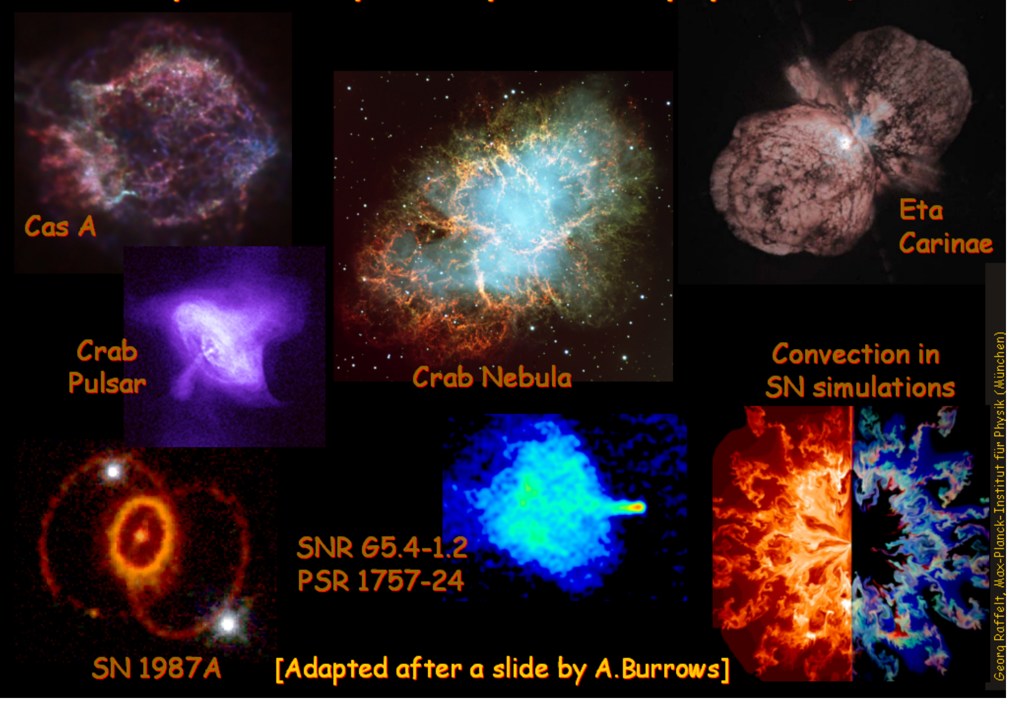
Hydrodynamically driven kicks
- Asymmetric matter ejection, but convection not enough (?)
- Pre-collapse asymmetry, perhaps caused by overstable oscillations of pre-supernova core?

Photon Rocket

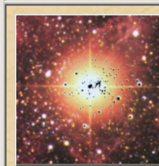
Electromagnetically driven acceleration:
Off-center global magnetic dipole moment & rotation accelerates star in one direction.
(Slow process – not a "kick")

Dong Lai, Neutron Star Kicks and Asymmetric Supernovae, astro-ph/0012049

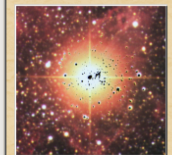
Spherical Symmetry in Astrophysics :-)



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)

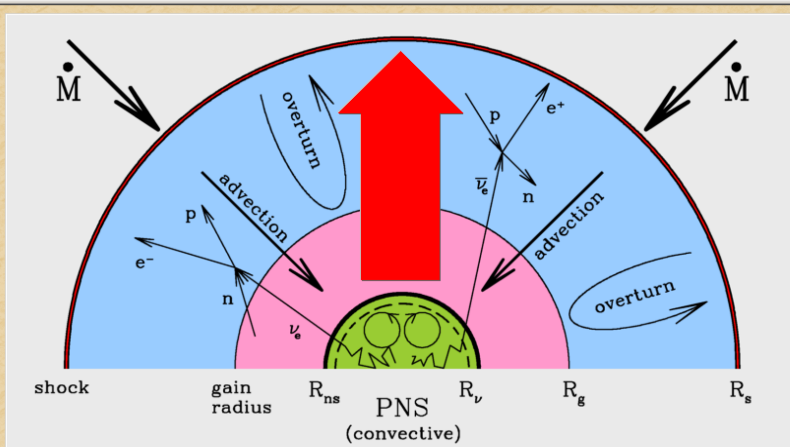


- Convection between proto neutron star (PNS) and shock wave and perhaps within PNS helps
- But 2-D simulations self-consistently coupled with state-of-the-art neutrino transport do not explode either

- New physical ingredients required?
- Explosion a magneto-hydrodynamical effect? (Strong B-fields and fast rotation possible)
- Nuclear equation of state very different?

Buras, Rampp, Janka & Kifonidis (MPA Garching),
Improved Models of Stellar Core Collapse and Still no Explosions:
What is Missing?
[astro-ph/0303171, Phys. Rev. Lett. 90, 241101 (20 June 2003)]

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]

Shock Revival by Novel Particles?

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

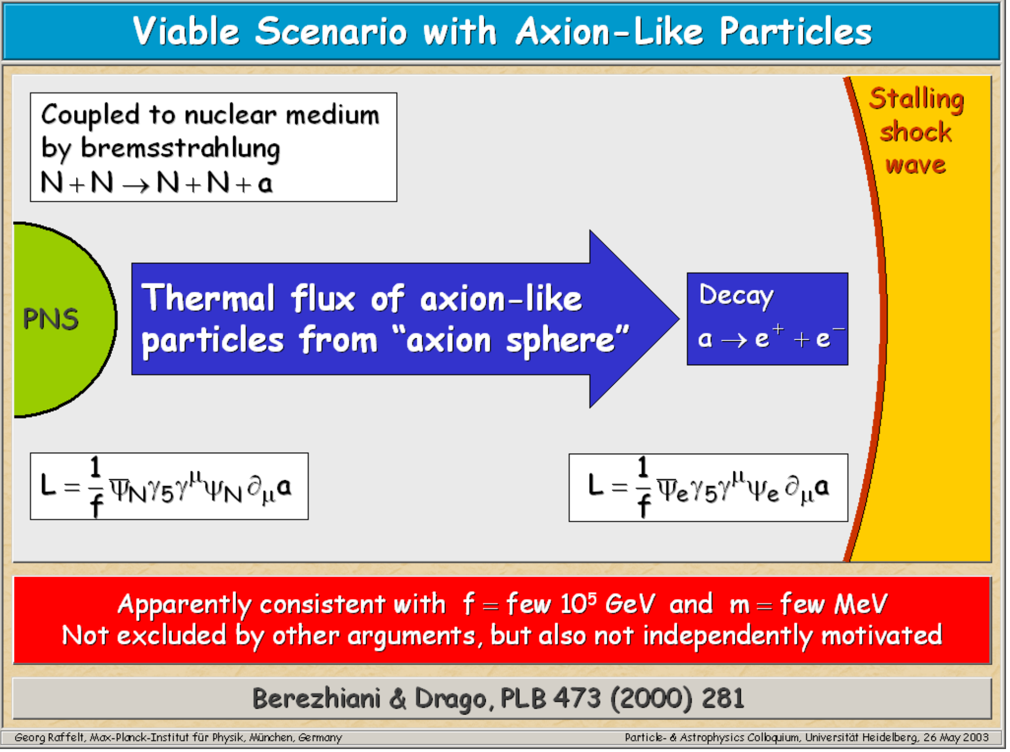
SUPERNOVAE INDUCED BY AXION-LIKE PARTICLES

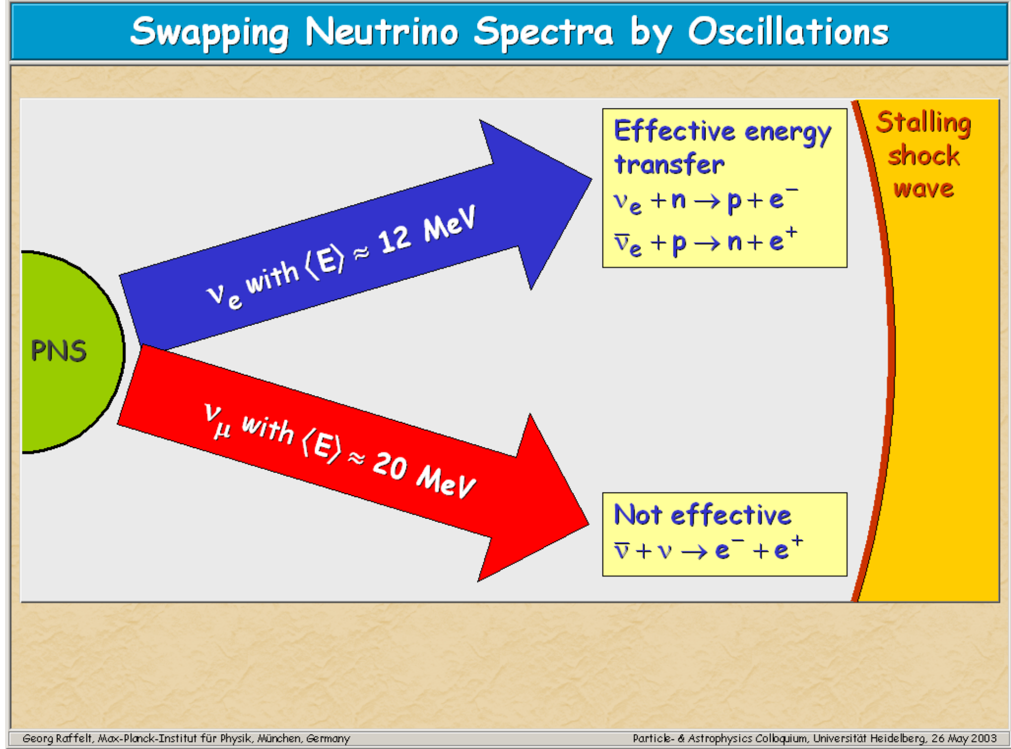
DAVID N. SCHRAMM
The University of Chicago
AND
JAMES R. WILSON
Lawrence Livermore Laboratory
Received 1981 December 22; accepted 1982 April 1

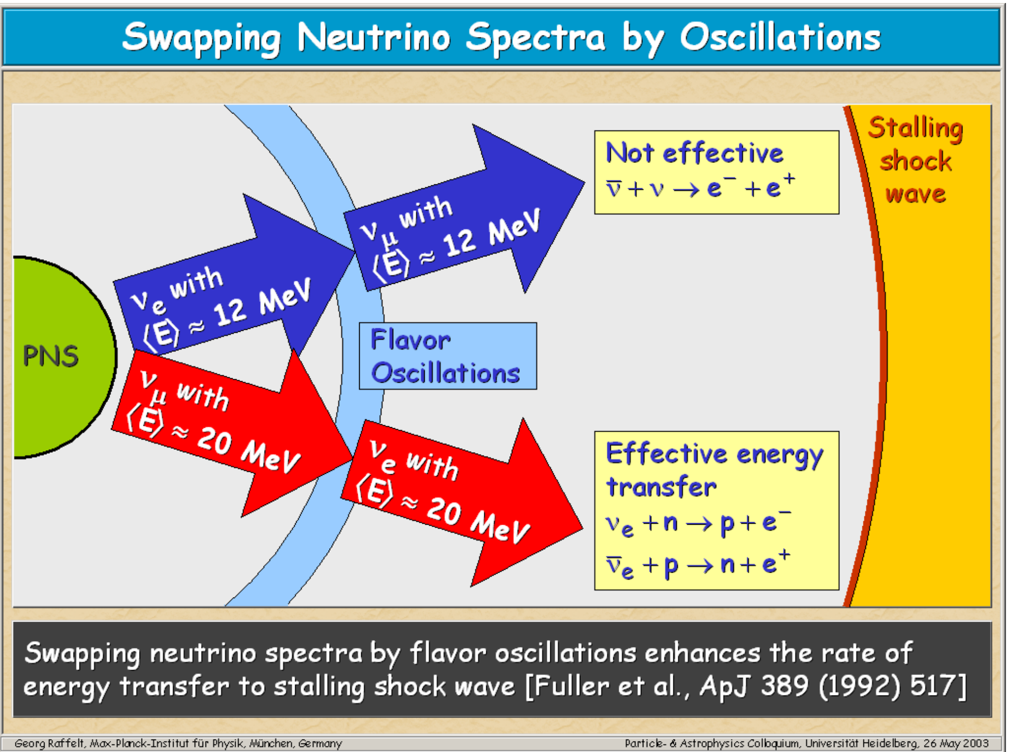
ABSTRACT

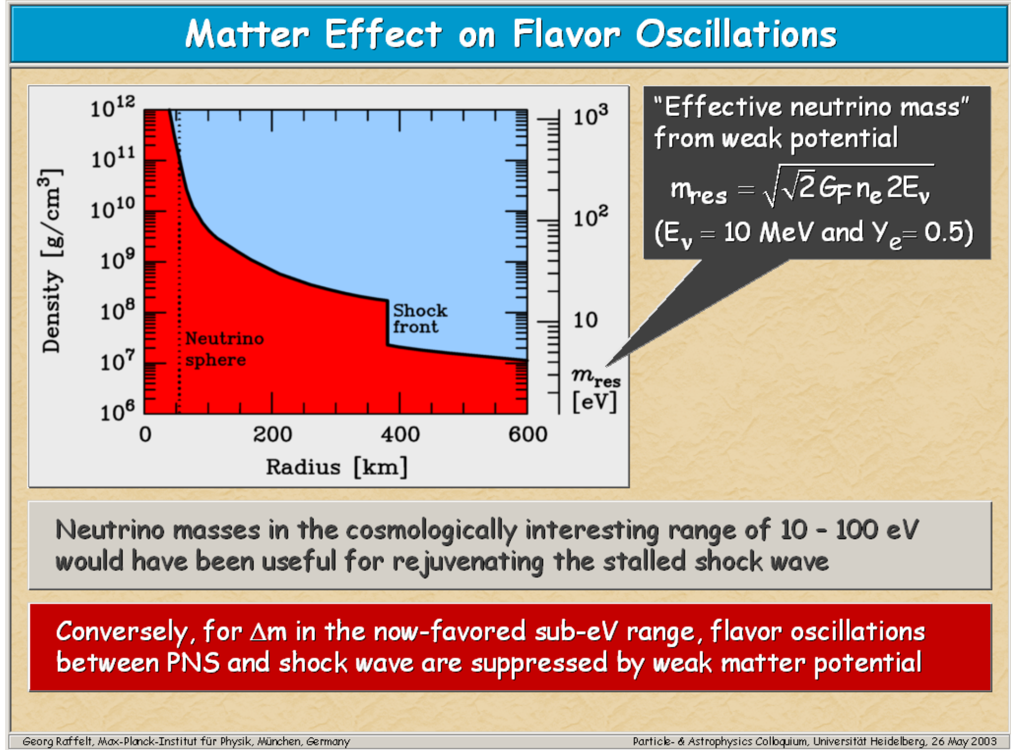
It is shown that a new type of particle which may have been seen in a recent accelerator experiment may, if truly present, provide a mechanism whereby gravitationally collapsing massive stars may eject their outer mantles and envelopes in supernova explosions of $\sim 10^{51}$ ergs while leaving the 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 $0.15 \leq M_a \lesssim 1$ 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
Coupled to nuclear medium by bremsstrahlung
$N+N \to N+N+a$
Stalling shock wave
PNS
Thermal flux of axion-like particles from "axion sphere"
Decay
$a \to e^+ + e^-$
$L = \frac{1}{f} \overline{\Psi}_N \gamma_5 \gamma^\mu \Psi_N \partial_\mu a$
$L = \frac{1}{f} \overline{\Psi}_e \gamma_5 \gamma^\mu \Psi_e \partial_\mu a$
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
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003


Swapping Neutrino Spectra by Oscillations
PNS
ν_e with $\langle E \rangle \approx 12$ MeV
ν_μ with $\langle E \rangle \approx 20$ MeV
Effective energy transfer
$\nu_e + n \to p + e^-$
$\overline{\nu}_e + p \to n + e^+$
Stalling shock wave
Not effective
$\overline{\nu} + \nu \to e^- + e^+$
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003


Swapping Neutrino Spectra by Oscillations
PNS
ν_e with $\langle E \rangle \approx 12$ MeV
ν_μ with $\langle E \rangle \approx 20$ MeV
ν_μ with $\langle E \rangle \approx 12$ MeV
ν_e with $\langle E \rangle \approx 20$ MeV
Flavor Oscillations
Not effective
$\overline{\nu} + \nu \to e^- + e^+$
Effective energy transfer
$\nu_e + n \to p + e^-$
$\overline{\nu}_e + p \to n + e^+$
Stalling shock wave
Swapping neutrino spectra by flavor oscillations enhances the rate of energy transfer to stalling shock wave [Fuller et al., ApJ 389 (1992) 517]
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003


Matter Effect on Flavor Oscillations
10^{12}
10^{11}
10^{10}
10^9
10^8
10^7
10^6
Density [g/cm^3]
0
200
400
600
Radius [km]
10^3
10^2
10
m_{res} [eV]
Shock front
Neutrino sphere
"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 for 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
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Further Reading

H.-T. Janka, K. Kifonidis & M. Rampp
Supernova Explosions and Neutron Star Formation
astro-ph/0103015

A. Burrows
Supernova Explosions in the Universe
Nature 403 (2000) 727-733

E. Cappellaro & M. Turrato
Supernova Types and Rates
astro-ph/0012455

G.E. Brown, H.A. Bethe & G. Baym
Supernova Theory
Nucl. Phys. A 375 (1982) 481-532

A. Burrows
Neutrinos from Supernova Explosions
Ann.Rev.Nucl.Part.Sci. 40 (1990) 181-212.

A. Burrows & T. Young
Neutrinos and Supernova Theory
Phys. Rept. 333-334 (2000) 63-75.

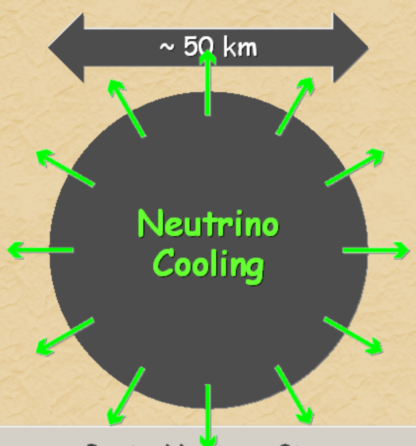
A.G. Petschek (ed.)
Supernovae
(Springer, 1990)

G. Raffelt
Stars as Laboratories for Fundamental Physics
(University of Chicago Press, 1996)

M. Koshiba
Observational Neutrino Astrophysics
Physics Reports 220 (1992) 229-402

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



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

Gravitational binding energy
$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN}\,c^2$

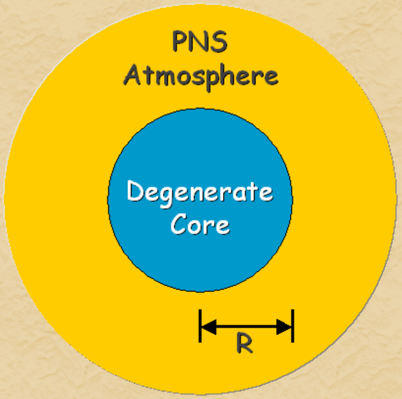
This shows up as
- 99% Neutrinos
- 1% Kinetic energy of explosion (1% of this into cosmic rays)
- 0.01% Photons, outshine host galaxy

Neutrino luminosity
$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec
$\approx 3 \times 10^{19}\ L_{SUN}$
While it lasts, outshines the entire visible universe

What determines the size of the PNS?

Mass	Chandrasekhar mass of iron core of progenitor star Dimensional analysis: $M_{Ch} \approx G_N^{-3/2} m_N^{-2} = m_{Pl}^3 m_N^{-2} \approx 1.5 M_\odot$ Coincidentally same number from zero-T polytropic model
Density	Supported by nucleon degeneracy pressure Nuclear density $\rho \approx \rho_{nuc} = 3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$
Radius	$\frac{4\pi}{3} \rho_{nuc} R^3 = M_{Ch}$ $R \approx 10.6$ km
Schwarzschild Radius	General $R_S = 2 G_N M$ Here $R_S = 2 G_N M_{Ch} = 2\, m_{Pl}\, m_N^{-2} = 4.6$ km

What determines the neutrino energies?



Gravitational potential of a given nucleon

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

With $M_{PNS} \approx 1.5\ M_{sun}$ and $R \approx 30$ 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

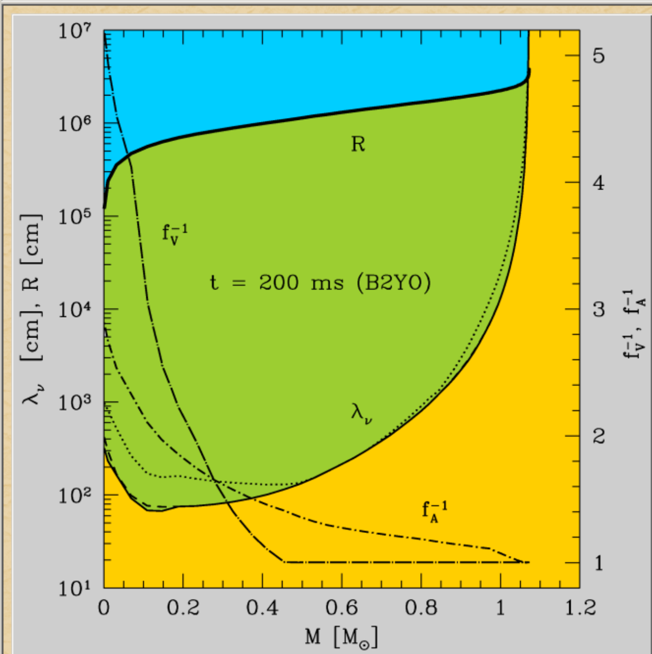
$T = (2/3) \langle E_{kin} \rangle \approx 9$ MeV

- If the proto-neutron star (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
- Core contracts by accretion and/or cooling $\rightarrow$ T increases

What determines the time scale?

Main neutrino reactions	Electron flavor: $\nu_e + n \rightarrow p + e^-$, $\bar{\nu}_e + p \rightarrow n + e^+$; Other flavors: $\nu + N \rightarrow N + \nu$
Neutral-current scattering cross section	$\sigma(\nu N \rightarrow N\nu) = \frac{C_V^2 + 3C_A^2}{\pi} G_F^2 E_\nu^2 \approx 2 \times 10^{-40}\,\text{cm}^2 \left(\frac{E_\nu}{100\ \text{MeV}}\right)^2$
Nucleon density	$n_B = \frac{\rho_{nuc}}{m_N} \approx 1.8 \times 10^{38}\,\text{cm}^{-3}$
Scattering rate	$\Gamma = \sigma n_B \approx 1.1 \times 10^9\,\text{s}^{-1} \left(\frac{E_\nu}{100\ \text{MeV}}\right)^2$
Mean free path	$\lambda = (\sigma n_B)^{-1} \approx 28\,\text{cm} \left(\frac{100\ \text{MeV}}{E_\nu}\right)^2$
Diffusion time	$t_{diff} \approx \frac{R^2}{\lambda} \approx 1.2\,\text{sec} \left(\frac{R}{10\ \text{km}}\right)^2 \left(\frac{E_\nu}{100\ \text{MeV}}\right)^2$

Neutrino Mean Free Path in a Supernova Core



Main processes:

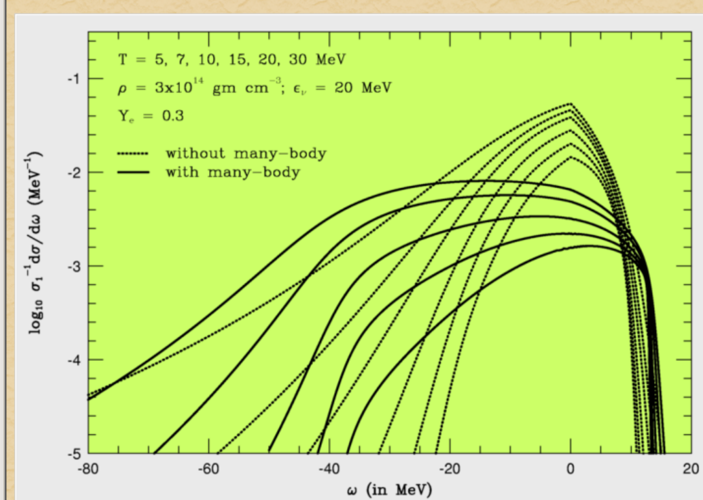
$\nu N \rightarrow N \nu$ all flavors

$\nu_e n \rightarrow p e^-$

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

Janka, Yamada & Keil (1999)

Many-Body Effects on Neutrino Opacities

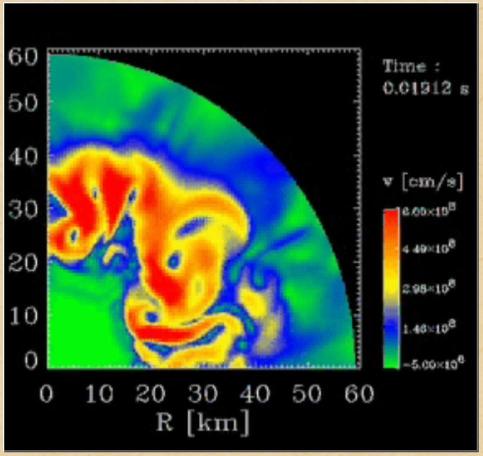


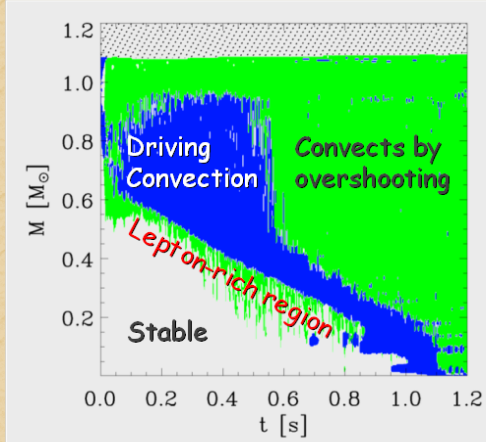
Burrows & Sawyer, astro-ph/9804264

See also Reddy, Prakash & Lattimer, PRD 58 (1998) 013009

Opacities with realistic many-body treatment not yet included in all numerical simulations

Convection in Proto Neutron Star

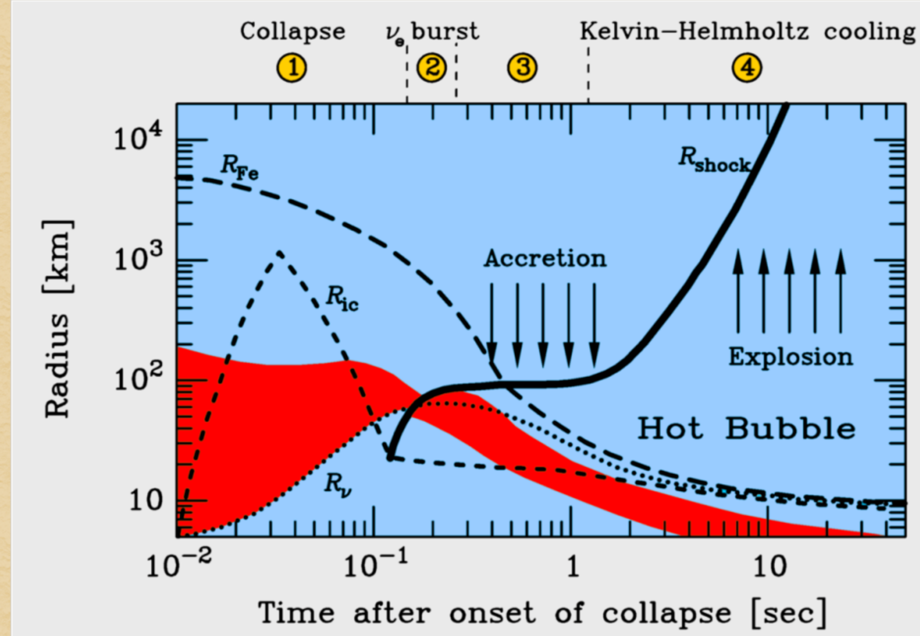




Time scale of deleptonization increased by ~ factor 2,
i.e. of same general magnitude as diffusion-dominated transport

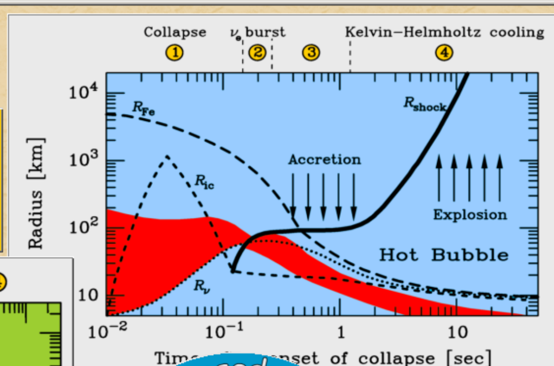
Keil, Janka & Müller, ApJ 473 (1996) L111

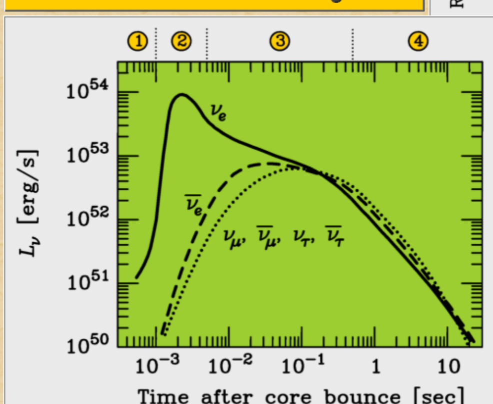
Supernova Delayed Explosion Scenario

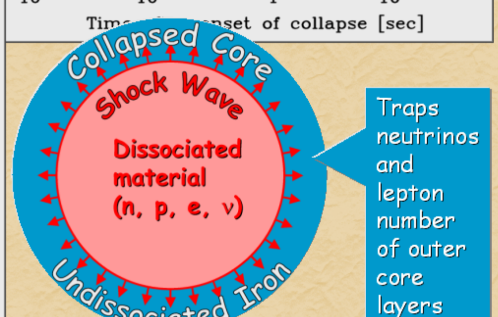


Structure of Supernova Neutrino Signal

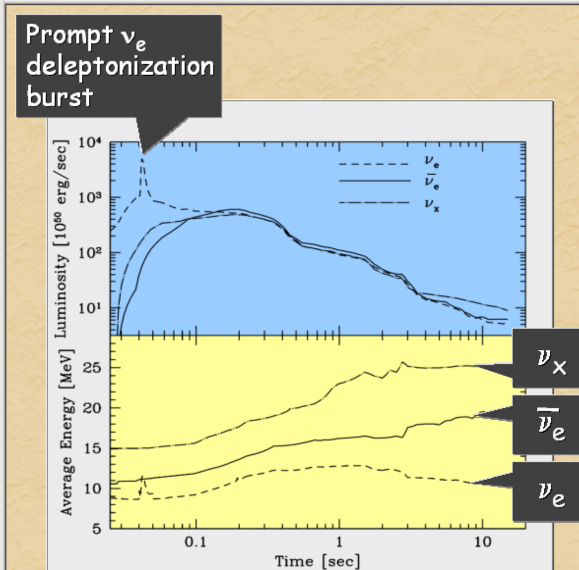
1. Collapse (infall phase)
2. Shock break out
3. Matter accretion
4. Kelvin-Helmholtz cooling







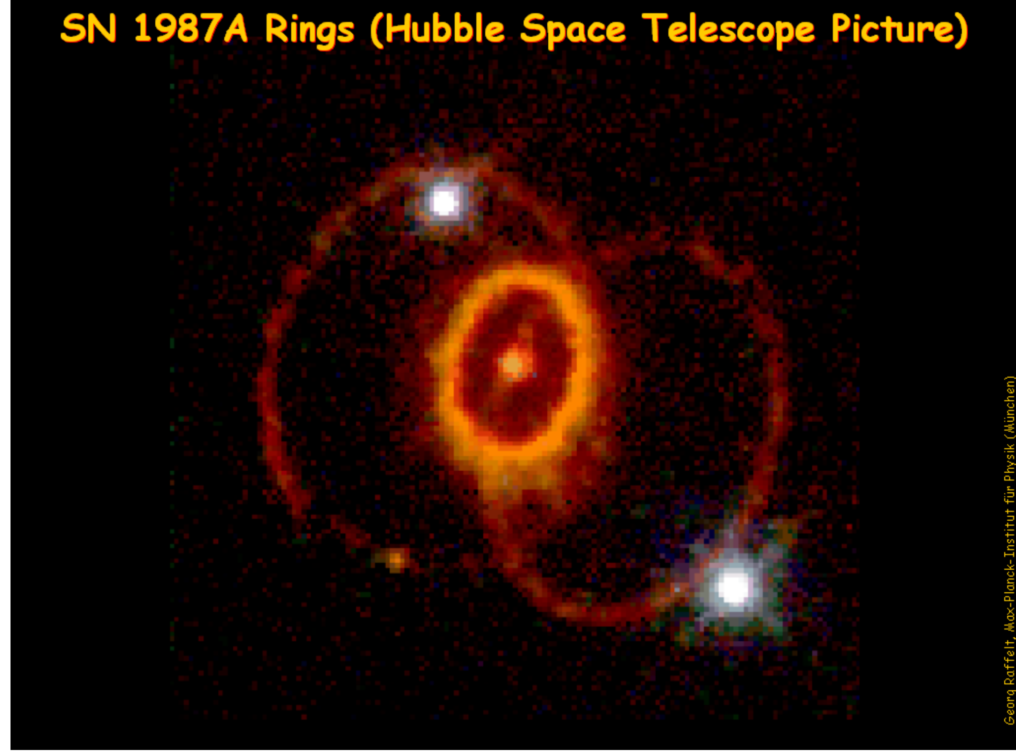
Structure of a Supernova Neutrino Burst

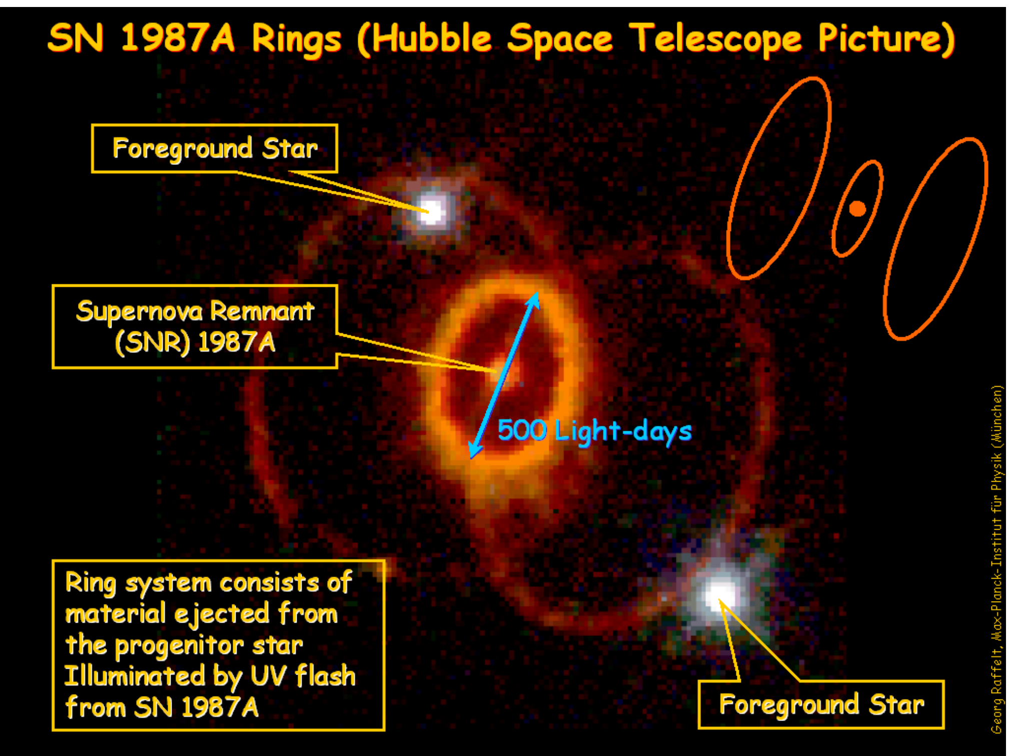


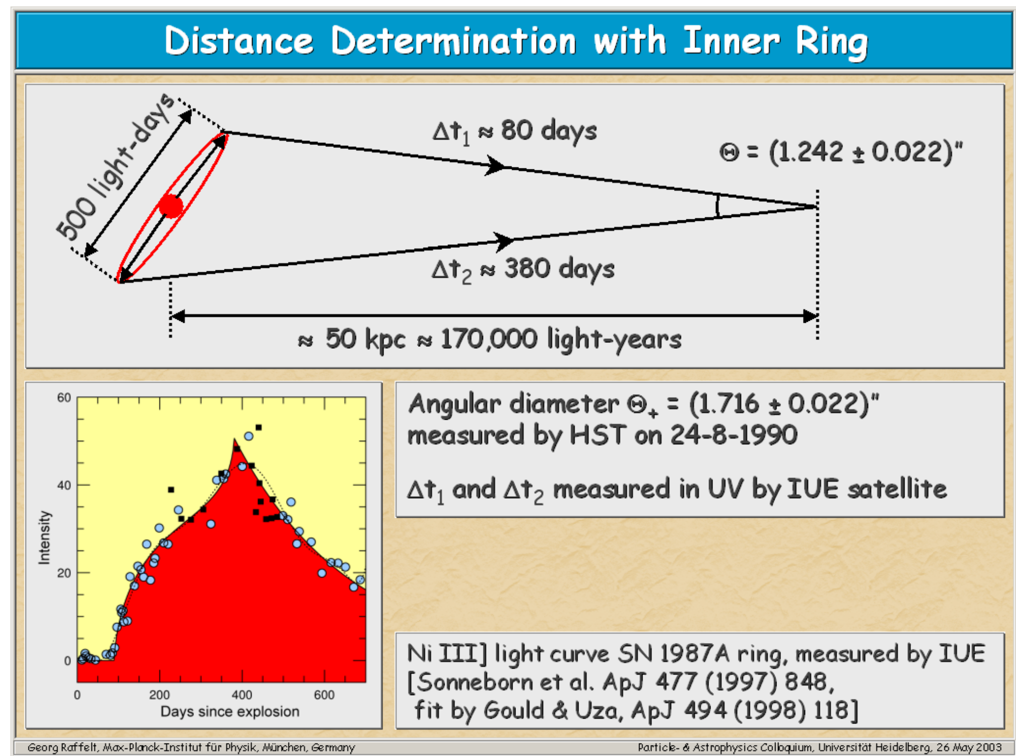
Broad characteristics
- Duration few seconds
- $\langle E_\nu \rangle$ ~ 10-20 MeV
- $\langle E_\nu \rangle$ increases with time
- Hierarchy
  $\langle E_{\nu_e} \rangle < \langle E_{\bar\nu_e} \rangle < \langle E_{\nu_x} \rangle$
- Approximate equipartition of energy between flavors

Livermore numerical model
ApJ 496 (1998) 216

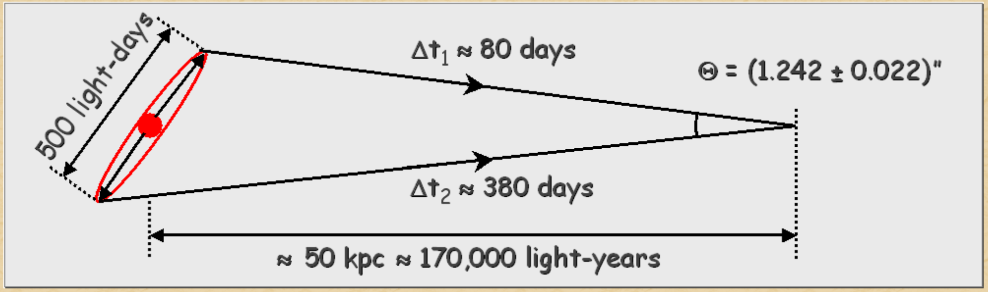

Supernova 1987A

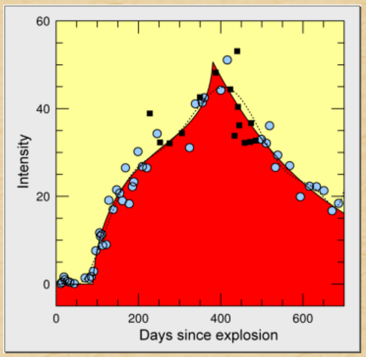

SN 1987A Rings (Hubble Space Telescope Picture)
Georg Raffelt, Max-Planck-Institut für Physik (München)


SN 1987A Rings (Hubble Space Telescope Picture)
Foreground Star
Supernova Remnant (SNR) 1987A
500 Light-days
Ring system consists of material ejected from the progenitor star Illuminated by UV flash from SN 1987A
Foreground Star
Georg Raffelt, Max-Planck-Institut für Physik (München)


Distance Determination with Inner Ring
500 light-days
Δt1 ≈ 80 days
Θ = (1.242 ± 0.022)"
Δt2 ≈ 380 days
≈ 50 kpc ≈ 170,000 light-years
60
40
20
0
Intensity
0
200
400
600
Days since explosion
Angular diameter Θ+ = (1.716 ± 0.022)" measured by HST on 24-8-1990
Δt1 and Δt2 measured in UV by IUE satellite
Ni III] light curve SN 1987A ring, measured by IUE [Sonneborn et al. ApJ 477 (1997) 848, fit by Gould & Uza, ApJ 494 (1998) 118]
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Distance Determination with Inner Ring





Distance to SN 1987A

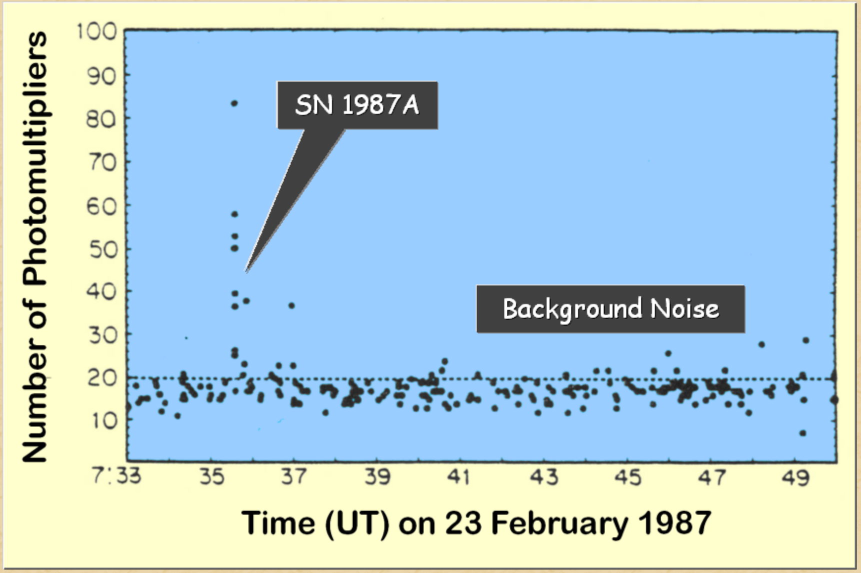
51.2 ± 3.1 kpc	Panagia et al., ApJ 380 (1991) L23
51.4 ± 1.2 kpc	Panagia, IAU Symposium 190 (1999)
47.2 ± 0.9 kpc	Gould & Uza, ApJ 494 (1998) 118

Ni III] light curve SN 1987A ring, measured by IUE [Sonneborn et al. ApJ 477 (1997) 848, fit by Gould & Uza, ApJ 494 (1998) 118]

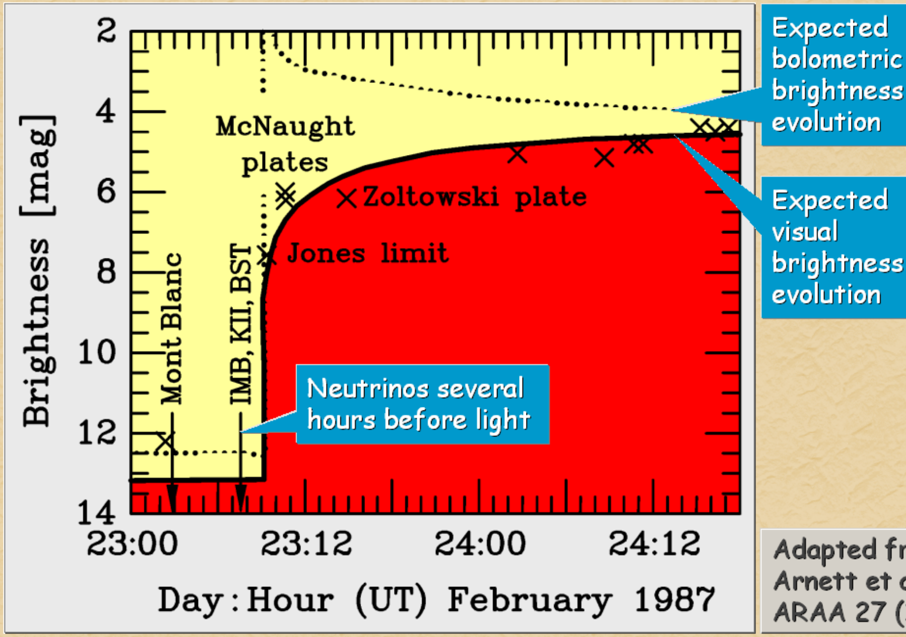
Animation of SN 1987A Explosion

Animation by T. Goertel
Space Telescope Science Institute
http://www.stsci.edu

Neutrino Signal of SN 1987A in Kamiokande



Early Lightcurve of SN 1987A



Adapted from Arnett et al., ARAA 27 (1989)

Dispersion between Neutrinos and Photons

Transit time for photons and neutrinos are equal to within ~ 3h

Total transit time ~ 5×10^{12} sec
→ Equal for photons and neutrinos within ~ 2×10^{-9}

(Longo 1987, Stodolsky 1988)

$$\left|\frac{c_\nu - c_\gamma}{c_\nu + c_\gamma}\right| < 10^{-9}$$

Shapiro time delay for particles moving through a gravitational potential

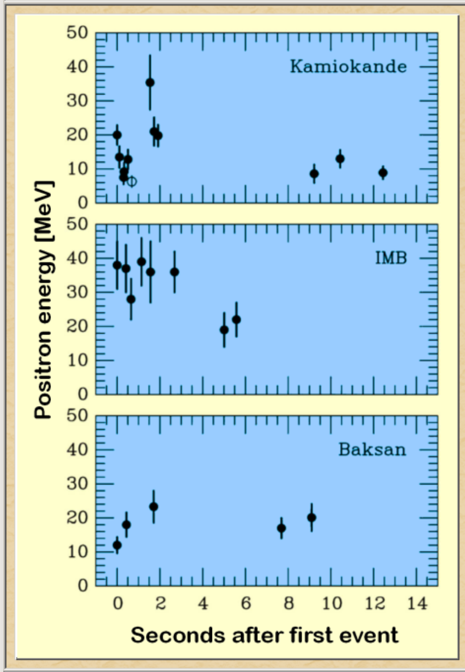
$$\Delta t_{\rm Shapiro} = -2\int_A^B U[r(t)]dt \approx 2 - 10 \times 10^6 \text{ sec}$$

(Krauss & Tremaine 1988)

Equal within ~ 1 – 4 $\times 10^{-3}$

- Provides limits on parameters of certain non-GR theories of gravitation
- Could be extended to neutrinos vs. anti-neutrinos or different flavors from signal of a future galactic SN

Neutrino Signal of Supernova 1987A



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

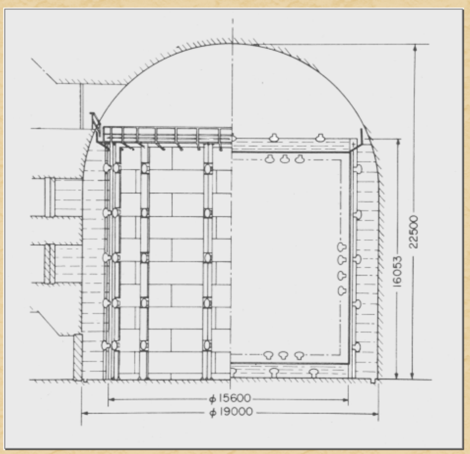
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty ±50 ms

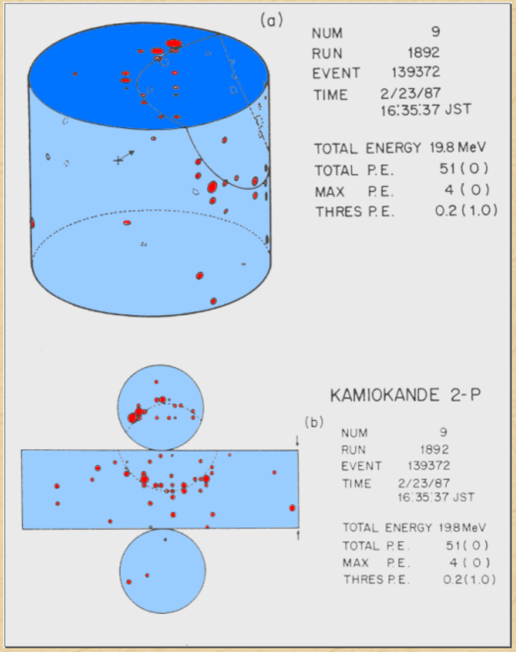
Baksan Scintillator Telescope (Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

SN 1987A Event No.9 in Kamiokande

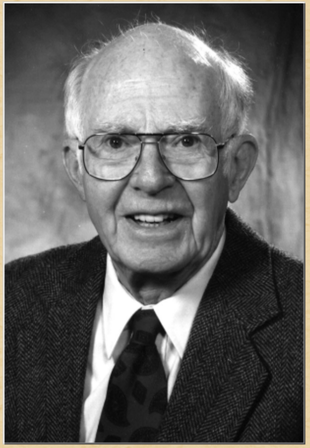
Kamiokande Detector





Hirata et al., PRD 38 (1988) 448

2002 Physics Nobel Prize for Neutrino Astronomy



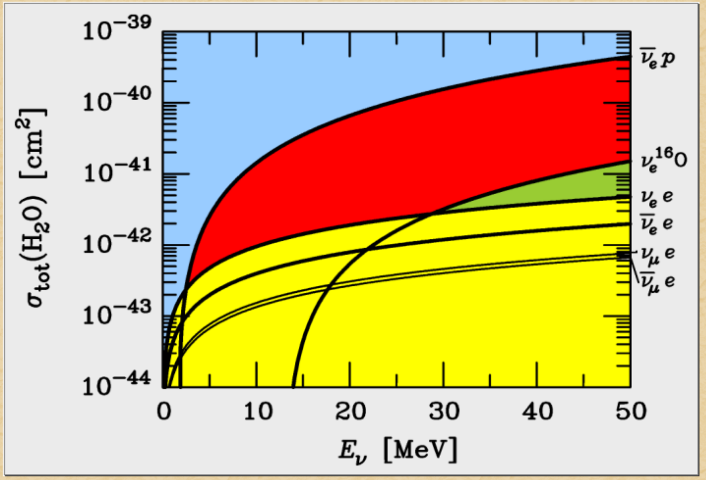
Ray Davis Jr.
(*1914)

Masatoshi Koshiba
(*1926)

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

Neutrino Cross Section in a Water Target

Cross section per water molecule

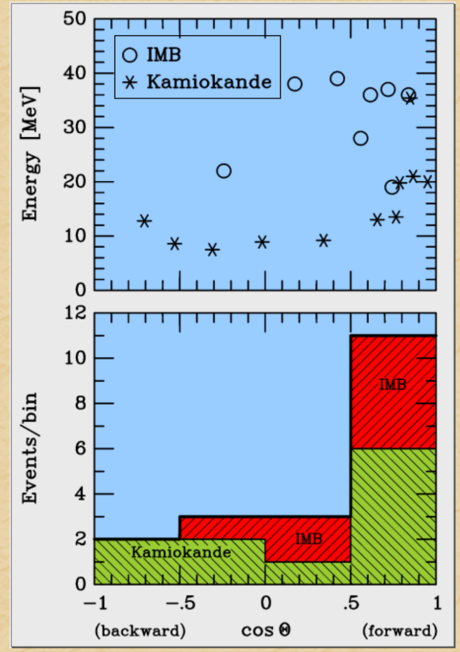


Main reactions: $\bar{\nu}_e + p \to n + e^+$ dominates for SN

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

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

Angular Distribution of SN 1987A Neutrinos



Main detection reaction

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

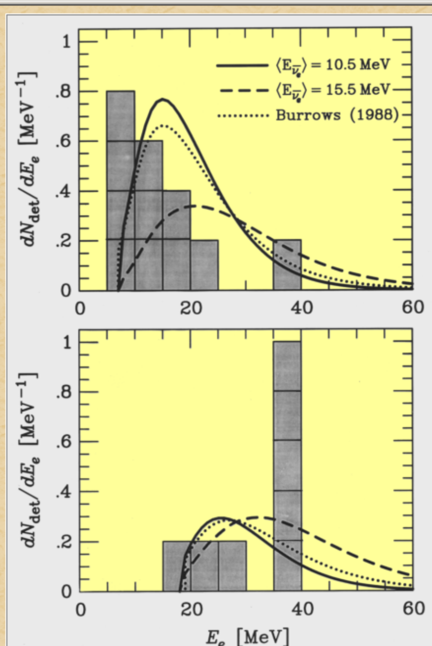
is essentially isotropic for the relevant energies.

Expect only a fraction of an event from forward-peaked reaction

$\nu + e^- \to e^- + \nu$

Observed signal compatible with isotropy only at approx. 0.1 % CL, but no alternative known

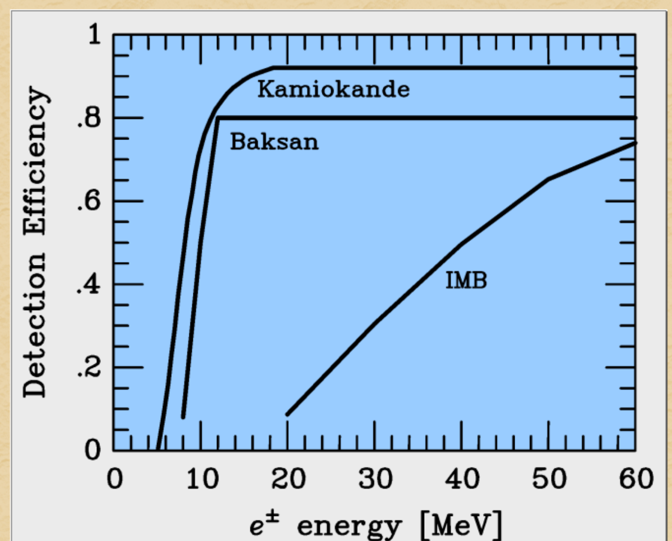
Energy Distribution of SN 1987A Neutrinos



Kamiokande II

IMB

Trigger Efficiencies at the Detectors



Fiducial volumes for SN 1987A detection

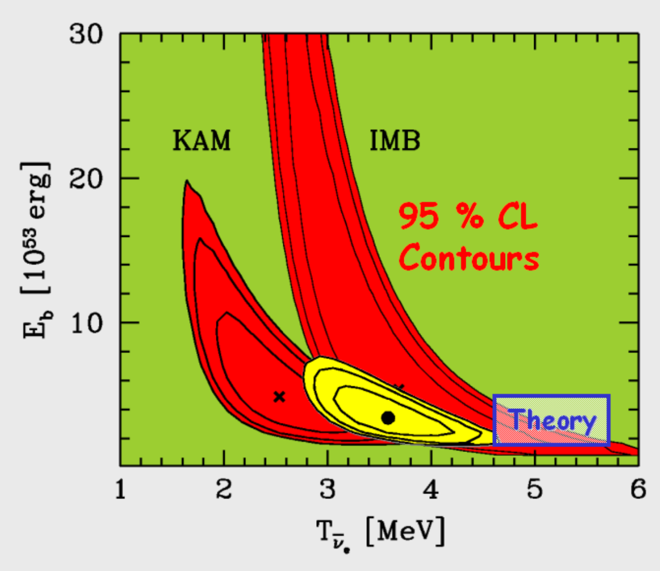
Kamiokande II
2140 tons water
(1.43×10^{32} protons)

IMB
6800 tons water
(4.6×10^{32} protons)

BST
200 tons scintillator
(1.88×10^{31} protons)

Interpreting SN 1987A Neutrinos

Total Binding Energy

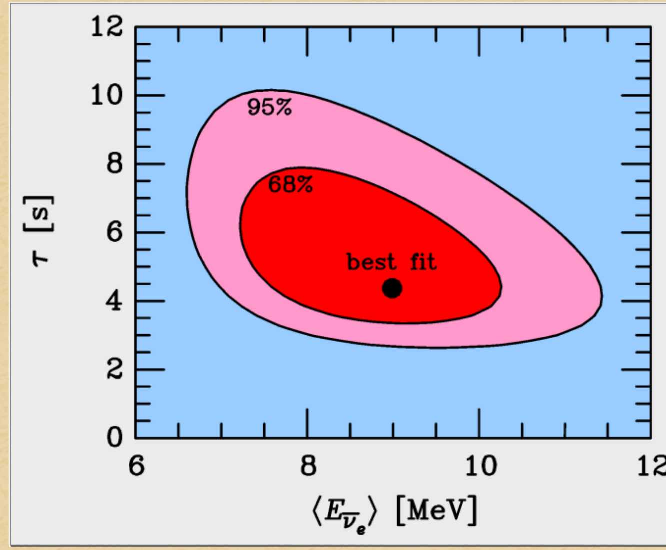


Spectral $\bar\nu_e$ Temperature

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

Assume thermal spectra and equipartition of energy between the six degrees of freedom ν_e, ν_μ, ν_τ and their antiparticles

Cooling Time Scale



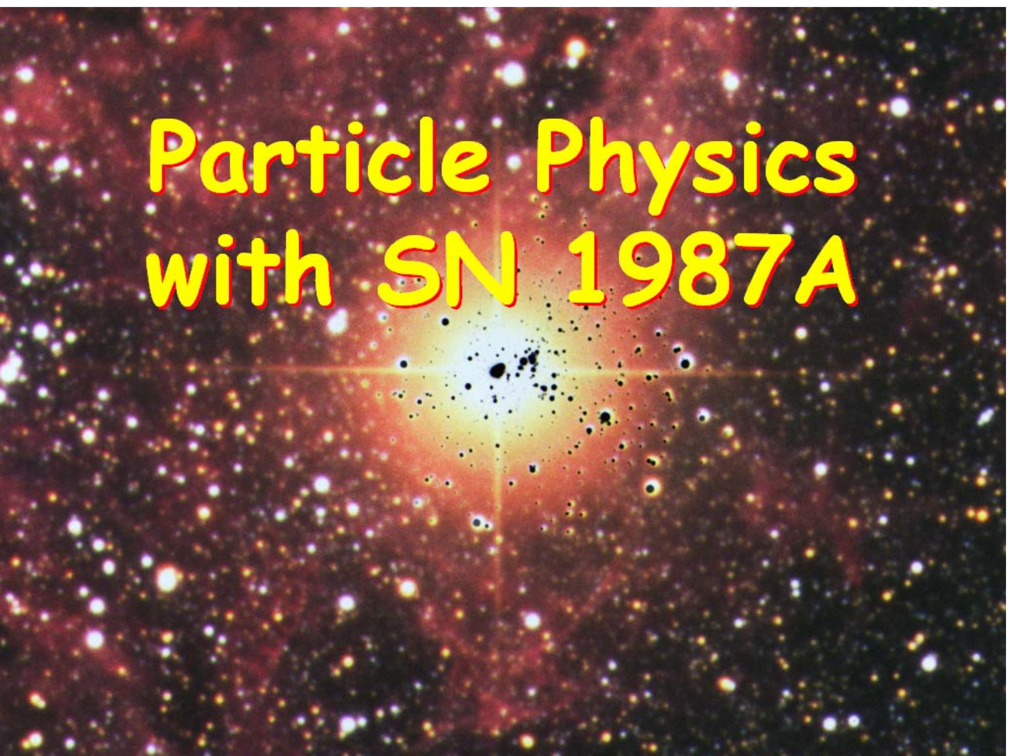
Exponential cooling model
- $T = T_0\, e^{-t/4\tau}$
- constant radius
- $L = L_0\, e^{-t/\tau}$

Fit parameters are
- T_0, τ, radius,
- 3 offset times for detectors

(Loredo & Lamb 95)

Similar results for more sophisticated cooling models

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003



Neutrino Limits by Intrinsic Signal Dispersion

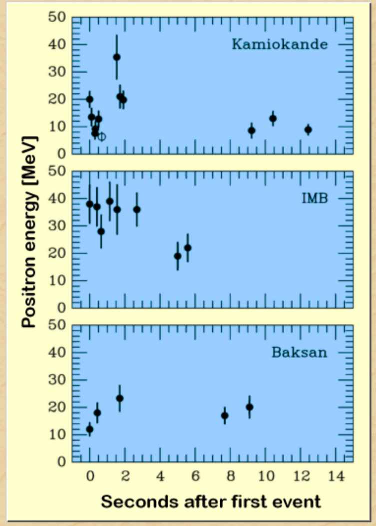
Time of flight delay by neutrino mass	For "milli charged" neutrinos, path bent by galactic magnetic field, inducing a time delay
$\Delta t = 2.57\,\mathrm{s} \left(\frac{D}{50\,\mathrm{kpc}}\right) \left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2 \left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$	$\frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp d_B)^2}{6 E_\nu^2} < 3 \times 10^{-12}$
$m_{\nu_e} < 20$ eV	$\frac{e_\nu}{e} < 3 \times 10^{-17} \left(\frac{1\,\mu\mathrm{G}}{B_\perp}\right) \left(\frac{1\,\mathrm{kpc}}{d_B}\right)$
• Detailed maximum-likelihood analysis yields similar limit • At the time of SN 1987A competitive with tritium end-point limits, today $m_{\nu_e} < 2.2$ eV • Cosmological limit today $m_\nu < 0.7$ eV	Assuming charge conservation in neutron decay yields a more restrictive limit of about 3×10^{-21} e

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Neutrino Mass Limits by Signal Dispersion

Time-of-flight delay of massive neutrinos $\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$

SN 1987A

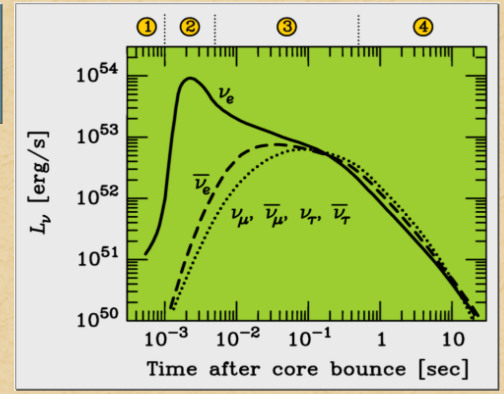


Neutrino Mass Limits by Signal Dispersion

Time-of-flight delay of massive neutrinos $\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$

SN 1987A	$E \approx 20$ MeV, $\Delta t \approx 10$ s, $D \approx 50$ kpc Simple estimate or detailed maximum likelihood analysis give similar results	$m_\nu < 20$ eV

Future Galactic SN (Super-K)

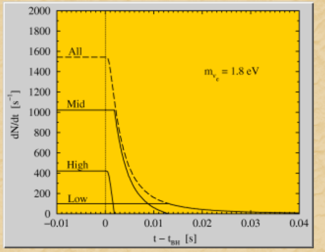


Neutrino Mass Limits by Signal Dispersion

Time-of-flight delay of massive neutrinos $\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$

SN 1987A	$E \approx 20$ MeV, $\Delta t \approx 10$ s, $D \approx 50$ kpc Simple estimate or detailed maximum likelihood analysis give similar results	$m_\nu < 20$ eV
Future Galactic SN (Super-K)	$D \approx 10$ kpc, Rise-time 0.01 s Sensitivity approximately [T.Totani, PRL 80 (1998) 2040]	$m_\nu \sim 3$ eV

With Black Hole Formation



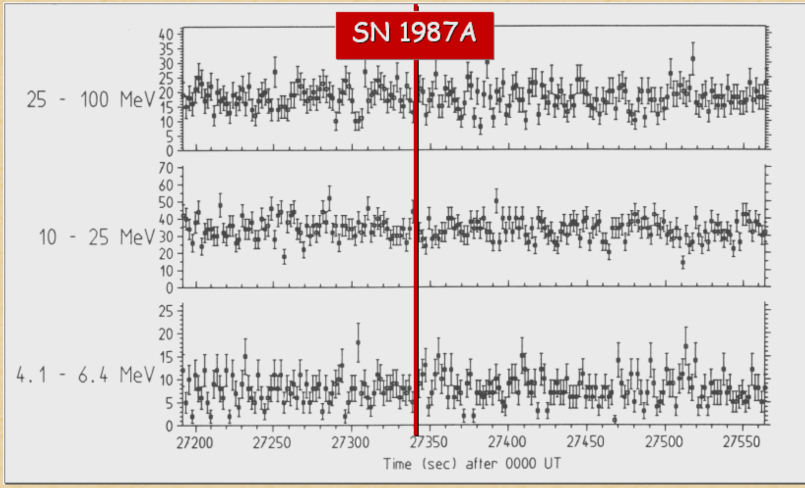
Neutrino Mass Limits by Signal Dispersion

Time-of-flight delay of massive neutrinos $\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$

SN 1987A	$E \approx 20$ MeV, $\Delta t \approx 10$ s, $D \approx 50$ kpc Simple estimate or detailed maximum likelihood analysis give similar results	$m_\nu < 20$ eV
Future Galactic SN (Super-K)	$D \approx 10$ kpc, Rise-time 0.01 s Sensitivity approximately [T.Totani, PRL 80 (1998) 2040]	$m_\nu \sim 3$ eV
With Black Hole Formation	$D \approx 10$ kpc, Cutoff "infinitely" fast Sensitivity approximately [Beacom et al., PRD 63 (2001) 073011]	$m_\nu \sim 2$ eV
Future SN in Andromeda (Megatonne)	$D \approx 750$ kpc, $\Delta t \approx 10$ s Sensitivity approximately	$m_\nu \sim$ 1-2 eV

Gamma-Ray Observations of SMM Satellite

Counts in the GRS instrument on the Solar Maximum Mission Satellite



10s fluence limit $0.9\ \mathrm{cm}^{-2}$

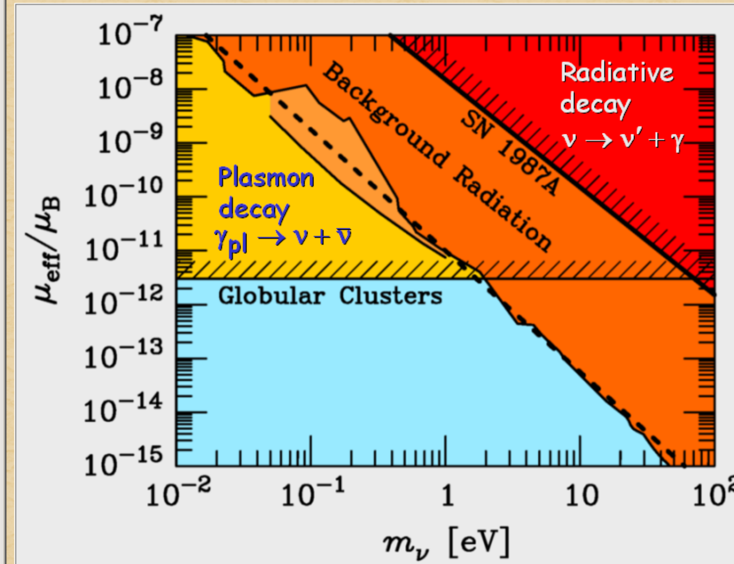
$0.4\ \mathrm{cm}^{-2}$

$0.6\ \mathrm{cm}^{-2}$

SN 1987A neutrino fluence ~ $10^{10}\ \mathrm{cm}^{-2}$

< 10^{-10} of neutrinos have decayed between SN and Earth

Neutrino Radiative Lifetime Limits

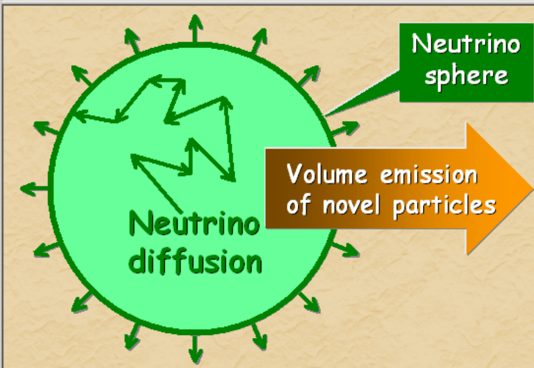


$$\Gamma_{\nu\to\nu'\gamma} = \frac{\mu_{eff}^2}{8\pi} m_\nu^3$$

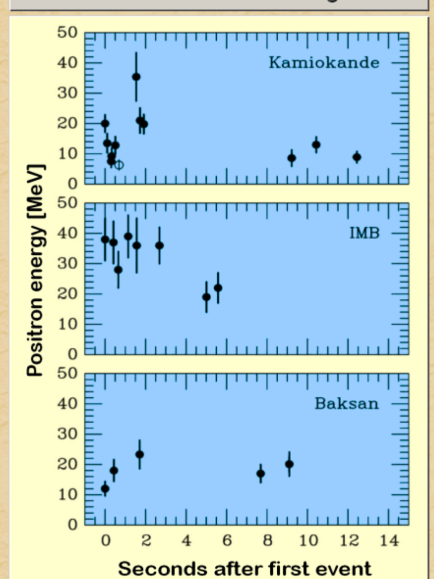
$$\Gamma_{\gamma\to\nu\bar\nu} = \frac{\mu_{eff}^2}{24\pi} \omega_{pl}^3$$

For low-mass neutrinos, plasmon decay in globular cluster stars yields most restrictive limits

The Energy-Loss Argument



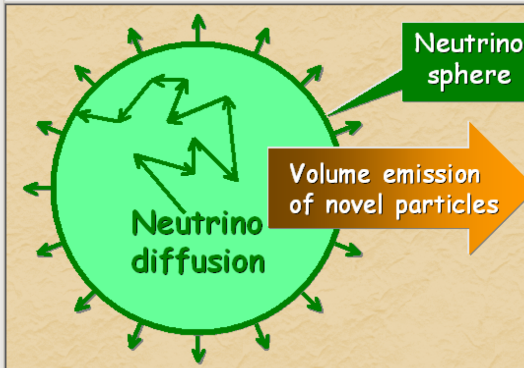
SN 1987A neutrino signal



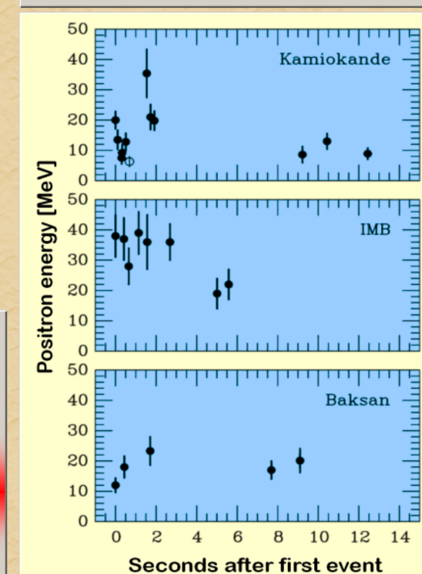
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

The Energy-Loss Argument



SN 1987A neutrino signal



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

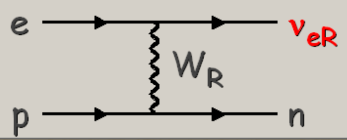
$$\epsilon_x < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

for $\rho \approx 3\times10^{14}\ \mathrm{g\ cm^{-3}}$ and $T \approx 30$ MeV

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Right-Handed Neutrinos (Dirac Neutrinos)

Right-handed currents



Average scattering rate in SN core involving ordinary left-handed neutrinos

$\Gamma_L \approx 10^{10}\,s^{-1}$

For right-handed neutrinos

$\Gamma_R \approx \frac{G_R^2}{G_F^2}\Gamma_L$

To avoid complete energy loss in ~ 1 s

$\frac{G_R^2}{G_F^2} 10^{10}\,s^{-1} < 1\,s^{-1}$

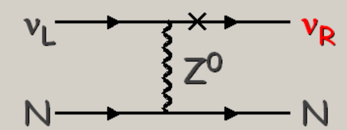
$G_R < 10^{-5}\,G_F$

Right-Handed Neutrinos (Dirac Neutrinos)

Right-handed currents

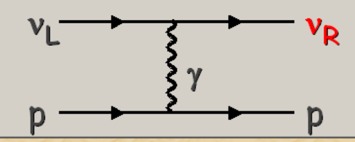
$G_R < 10^{-5}\,G_F$

Dirac mass term



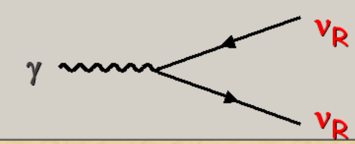
$m_D < 30$ keV

Magnetic moment



$\mu_\nu < 10^{-12}\,\mu_B$

Milli-charges



$e_\nu < 10^{-9}\,e$

Right-Handed Neutrinos in the Early Universe

- If neutrinos are Dirac particles, will the right-handed components achieve thermal equilibrium in the early universe before big-bang nucleosythesis?
- This would modify the light-element abundances in significant ways, notably increase the helium abundance

	Required strength	SN 1987A limit
Right-handed charged current	$G_R \sim 10^{-3}\,G_F$	$G_R < 10^{-5}\,G_F$
Dirac mass	few 100 keV	30 keV
Dipole moment	$\sim 0.5 \times 10^{-10}\,\mu_B$	$10^{-12}\,\mu_B$

Sterile Neutrinos

Sterile (right-handed) neutrinos may exist that are not a Dirac partner to an ordinary neutrino

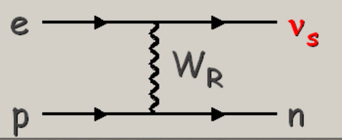
- Unknown mass m_s
- Unknown mixing angles with ordinary neutrinos Θ_{es}, $\Theta_{\mu s}$, and $\Theta_{\tau s}$

Consequences and applications

- May (partially) account for some experimental oscillation results
- Hot, warm, or cold dark matter contribution
- May affect big-bang nucleosynthesis
- Emission from supernova cores
- Affects r-process nucleosynthesis in the SN hot bubble
- Radiative decays → potentially detectable

Sterile Neutrinos

Active-sterile mixing



Average scattering rate in SN core involving ordinary left-handed neutrinos

$$\Gamma_L \approx 10^{10}\,\mathrm{s}^{-1}$$

Electron neutrino appears as sterile neutrino in $\frac{1}{2}\sin^2(2\Theta_{es})$ of all cases

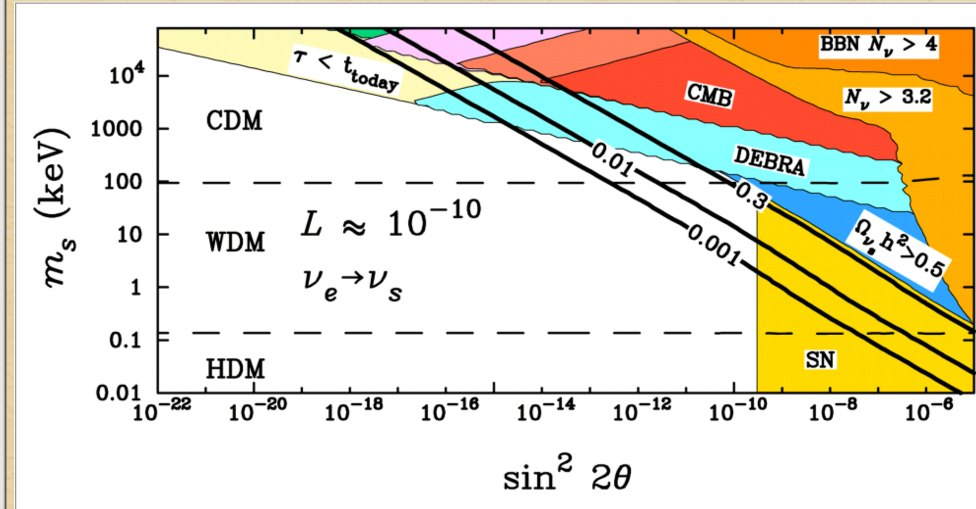
$$\Gamma_s \approx \frac{1}{2}\sin^2(2\Theta_{es})\,\Gamma_L$$

To avoid complete energy loss in ~ 1 s

$$\frac{1}{2}\sin^2(2\Theta_{es})\,10^{10}\,\mathrm{s}^{-1} < 1\,\mathrm{s}^{-1}$$

$$\sin^2(2\Theta_{es}) < 3\times10^{-10}$$

Sterile Neutrinos as Dark Matter



Abazajian, Fuller & Patel, Sterile neutrino hot, warm, and cold dark matter astro-ph/0101524

Oscillation Suppression in Supernovae

Neutrino mixing angle in a medium

$$\sin^2(2\Theta) = \frac{\sin^2(2\Theta_{vac})}{\sin^2(2\Theta_{vac}) + \left[\cos^2(2\Theta_{vac}) - A\right]^2}$$

For ν_s–ν_e–mixing:

$$A = \pm\sqrt{2}G_F\left(n_e + 2n_{\nu_e} - \tfrac{1}{2}n_n\right)\frac{2E_\nu}{\Delta m^2}$$

$$= \pm1.53\times10^9\,\frac{\left(Y_e + 2Y_{\nu_e} - \frac{1}{2}Y_n\right)\rho}{10^{14}\,\mathrm{g\,cm^{-3}}}\,\frac{E_\nu}{100\,\mathrm{MeV}}\,\frac{1\,\mathrm{eV}^2}{\Delta m^2}$$

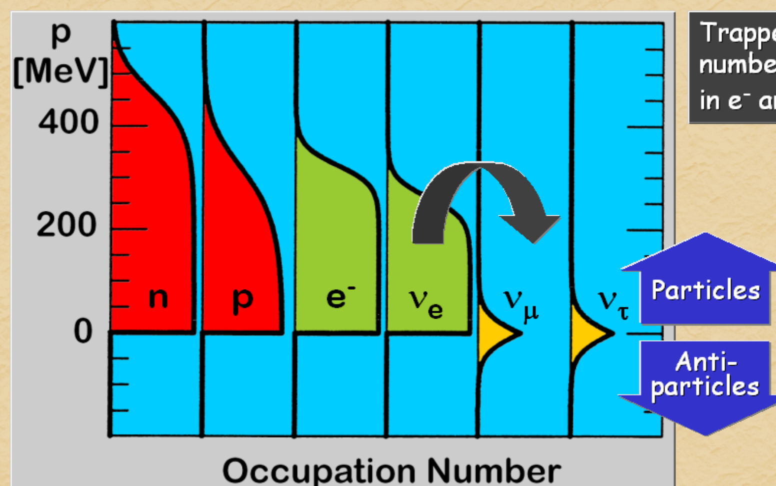
Large medium effect ($|A| \gg 1$) and large sterile mass ($m_s \gg m_\nu$)

$$\frac{\sin^2(2\Theta)}{\sin^2(2\Theta_{vac})} = A^{-2}$$

$$= 4.3\times10^{-19}\left(\frac{10^{14}\,\mathrm{g\,cm^{-3}}}{\left(Y_e + 2Y_{\nu_e} - \frac{1}{2}Y_n\right)\rho}\right)^2\left(\frac{100\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_s}{1\,\mathrm{eV}}\right)^4$$

- Strong medium effects for $m_s < 30$ keV
- No effective SN emission for $m_s < 100$ eV

Degenerate Fermi Seas in a Supernova Core



Trapped lepton number is stored in e^- and ν_e

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

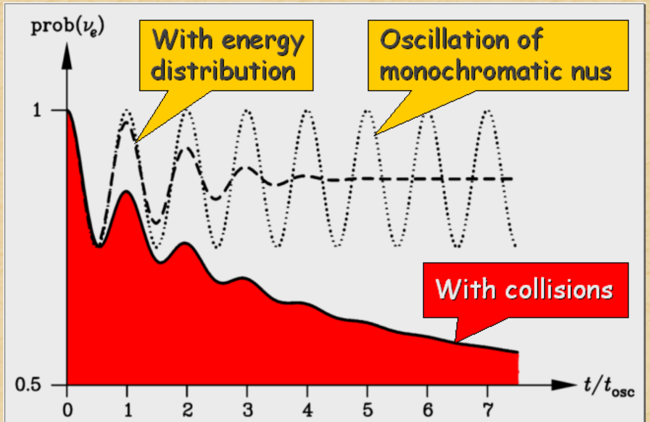
Time scale to achieve flavor equilibrium?

Flavor Relaxation in a Supernova Core

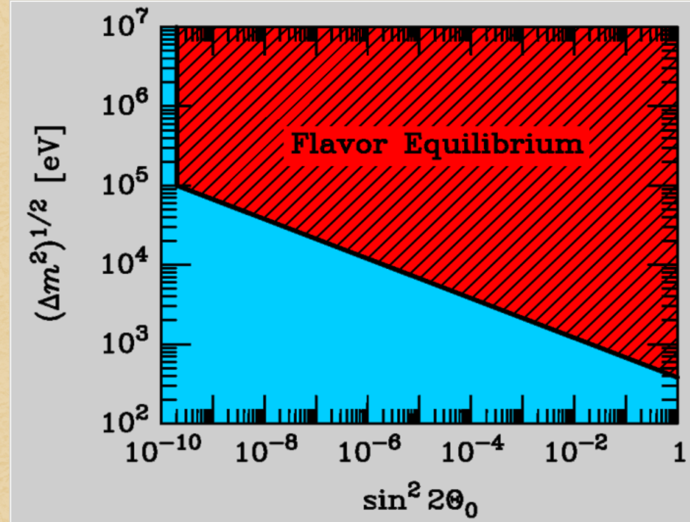
Neutrinos suffer collisions in a medium that can interrupt the coherence of flavor oscillations: The flavor content is "measured" and oscillations start from scratch from the "collapsed state".

Average oscillation probability $\frac{1}{2}\sin^2(2\Theta)$
Collision rate ~ damping rate Γ

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



Flavor Conversion in a Supernova Core

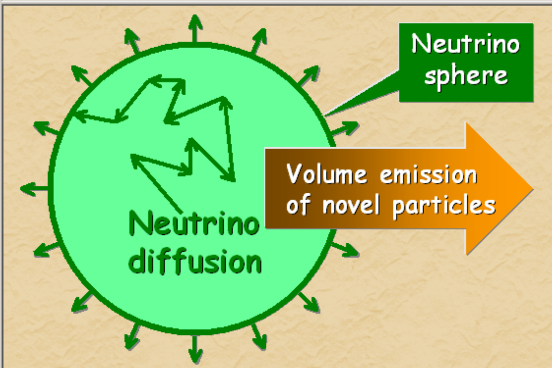


Within ~ 1 sec flavor equilibrium is achieved between ν_e and ν_μ or ν_τ

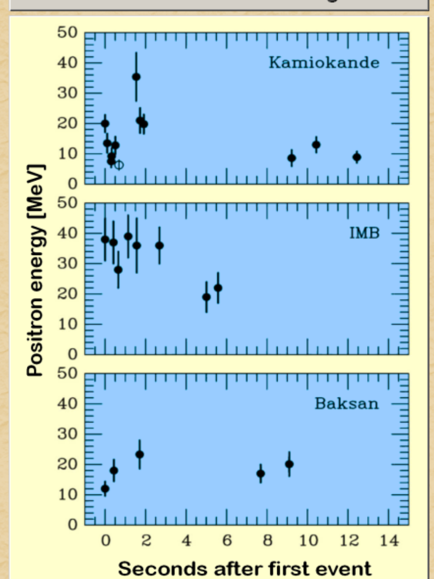
Suppression of mixing angle by medium effects responsible for flavor-lepton number conservation in a supernova core

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

The Energy-Loss Argument



SN 1987A neutrino signal



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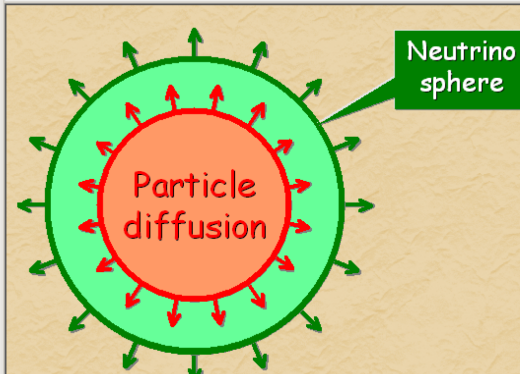
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

The Energy-Loss Argument in the Trapping Limit

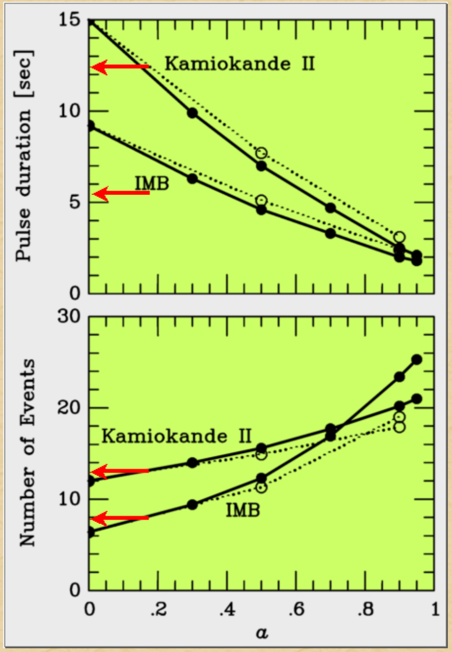


Mean-free-path of new particles < geometric dimension of star

- New particles are more important for energy transfer than neutrinos (Energy transfer $\propto$ mfp)
- Efficiency of energy transfer must be less than of neutrinos or else speed up cooling of PNS, again shortening the observed SN 1987A signal

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Enhanced Neutrino Energy Transfer



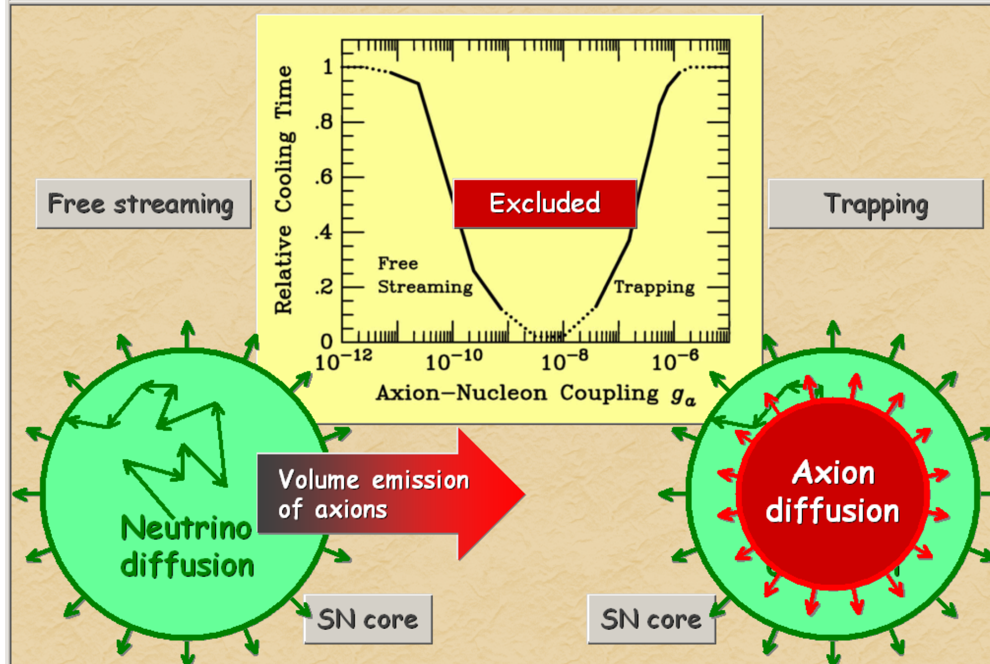
Neutrino opacities reduced in dense regions by a suppression factor (1 - a)

Reduced opacities (increased energy transfer)
- Reduces signal duration
- Increases number of events (larger energies by heating of neutrino sphere)

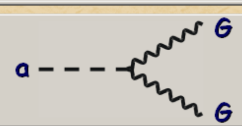
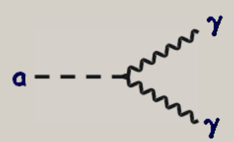
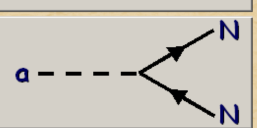
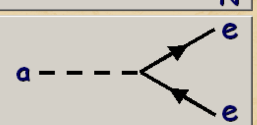
SN 1987A signal indicates that energy transfer should not be much more effective than standard

Keil, Janka & Raffelt, PRD 51 (1995) 6635

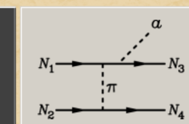
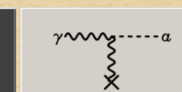
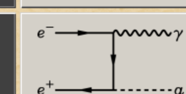
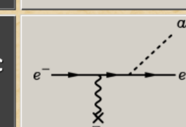
SN 1987A Axion Limits



Axion Properties

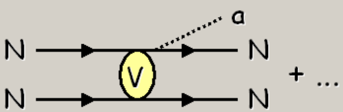
Coupling to gluons (Most generic axion property)	$L_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G} a$	
Mass	$m_a = \frac{0.6\ \mathrm{eV}}{f_a/10^7\ \mathrm{GeV}} \approx \frac{m_\pi f_\pi}{f_a}$	
Photon coupling	$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F} a = g_{a\gamma} \vec{E}\cdot\vec{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{B} - 1.92\right)$	
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 Processes in Stars

Nucleons	$\frac{C_N}{2f_a} \overline{\Psi}_N \gamma_\mu \gamma_5 \Psi_N \partial^\mu a$	Nucleon Bremsstrahlung	
Photons	$\frac{C_e}{2f_a} \overline{\Psi}_e \gamma_\mu \gamma_5 \Psi_e \partial^\mu a$	Primakoff	
Electrons	$C_\gamma \frac{\alpha}{2\pi f_a} \frac{1}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} a = -C_\gamma \frac{\alpha}{2\pi f_a} \vec{E}\cdot\vec{B}\, a$	Compton	
		Pair Annihilation	
		Electromagnetic Bremsstrahlung	

Axion Emission from Nuclear Medium

Axion-nucleon interaction of current-current form: $\mathcal{L}_{int} = \frac{C_N}{2f_a}\bar{\Psi}_N\gamma_\mu\gamma_5\Psi_N\partial^\mu a = \frac{C_N}{2f_a}J^A_\mu\partial^\mu a$



+ ...

Nucleon-Nucleon Bremsstrahlung

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

Axion Emission from Nuclear Medium

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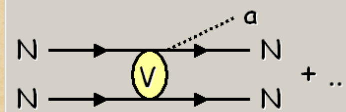

+ ...

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axion energy

dynamical structure function

Fundamentally the dynamical structure function is a correlator of the nucleon axial current
Non-relativistic nucleons: ~ nucleon spin density operator σ

$$S(\omega,k) = \frac{4}{3n_B}\int_{-\infty}^{+\infty} dt\, e^{i\omega t}\langle\sigma(t,k)\cdot\sigma(0,-k)\rangle$$

Example for the Fluctuation and Dissipation Theorem of linear-response theory: Axion emission determined by spontaneous nucleon spin fluctuations

Properties of the Dynamical Structure Function

Nucleon spin-density autocorrelation function	$S(\omega,k) = \frac{4}{3n_B}\int_{-\infty}^{+\infty} dt\, e^{i\omega t}\langle\sigma(t,k)\cdot\sigma(0,-k)\rangle$	
Normalization, ignoring many-body correlations	$\int_{-\infty}^{+\infty}\frac{d\omega}{2\pi}S(\omega,k) = \frac{1}{n_B}\int\frac{2d^3p}{(2\pi)^3}f_p(1-f_{p+k})$	
Detailed balancing	$S(-\omega,k) = e^{-\omega/T}S(\omega,k)$	consequence of non-commuting $\sigma(t)$ at different times
Symmetric form	$\bar{S}(\omega,k) = \frac{S(-\omega,k)+S(\omega,k)}{2}$	$\rightarrow S(\omega,k) = \frac{2\bar{S}(\omega,k)}{1+e^{-\omega/T}}$
Long-wavelength limit ($k \to 0$)	$\bar{S}(\omega) = \frac{4}{3}\int_{-\infty}^{+\infty} dt\, e^{i\omega t}\left\langle\frac{s(t)\cdot s(0)+s(0)\cdot s(t)}{2}\right\rangle$	
Is Fourier transform of single-nucleon spin correlation function	$\bar{R}(t) = \frac{4}{3}\left\langle\frac{s(t)\cdot s(0)+s(0)\cdot s(t)}{2}\right\rangle$	

Spin Relaxation Rate

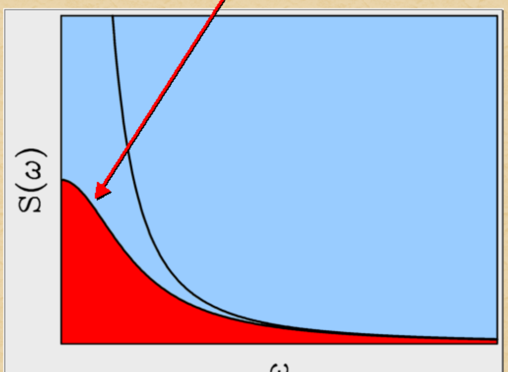
A spin immersed in a bath of scatterers with spin-dependent forces relaxes exponentially for uncorrelated kicks (Markov chain)

$$\bar{R}(t) = e^{-|\Gamma t|}$$

with Γ the "spin relaxation rate", leading to the Fourier transform

$$\bar{S}(\omega) = \frac{2\Gamma}{\omega^2+\Gamma^2}$$

Lorentzian structure function, includes multiple scattering effects



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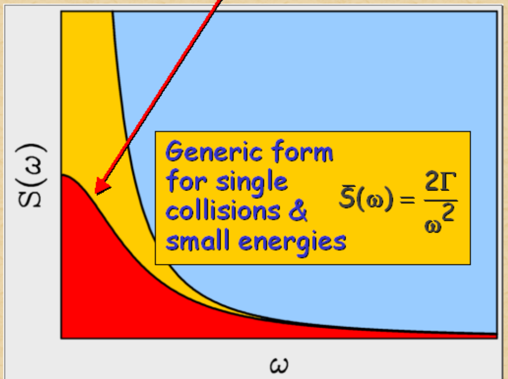
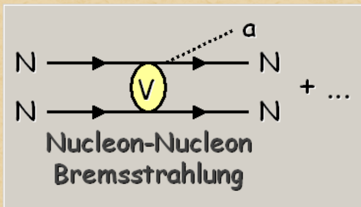




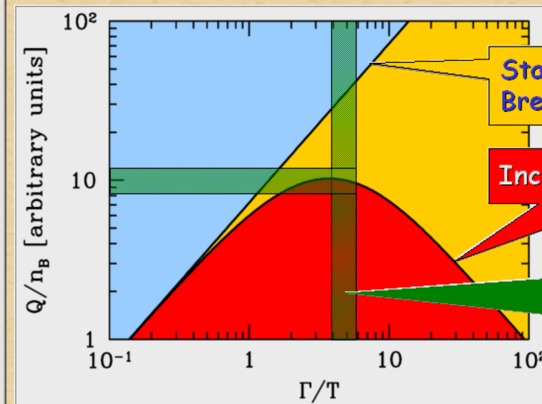
Identify coefficient Γ from bremsstrahlung calculation with spin relaxation rate

Axion Emission Rate

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

$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 \frac{2\Gamma}{\omega^2+\Gamma^2} \frac{2}{1+e^{\omega/T}} \propto \begin{cases} n_B^2 & \text{for small density} \\ n_B^{-1} & \text{for large density} \end{cases}$$

Axionic volume energy loss rate of nuclear medium



Standard behavior: Bremsstrahlung rate $\propto \rho^2$

Including LPM effect

One-pion exchange potential in Born approximation:

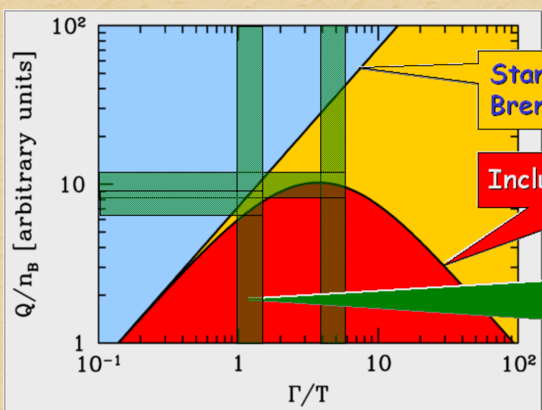
$$\frac{\Gamma}{T} \approx 1.25 \frac{\rho}{10^{14}\,\text{g cm}^{-3}} \sqrt{\frac{30\,\text{MeV}}{T}}$$

Axion Emission Rate

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

$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 \frac{2\Gamma}{\omega^2+\Gamma^2} \frac{2}{1+e^{\omega/T}} \propto \begin{cases} n_B^2 & \text{for small density} \\ n_B^{-1} & \text{for large density} \end{cases}$$

Axionic volume energy loss rate of nuclear medium

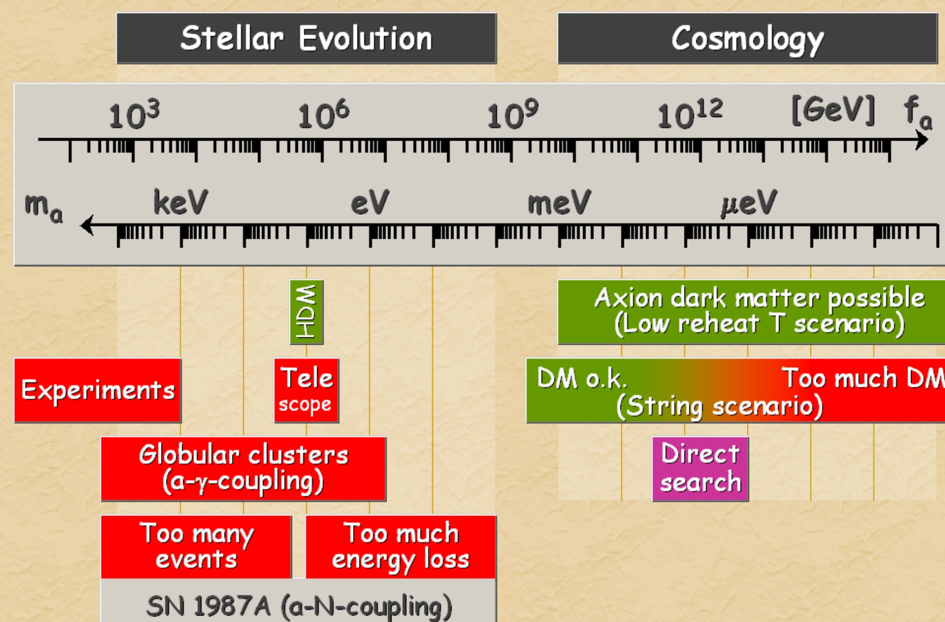


Standard behavior: Bremsstrahlung rate $\propto \rho^2$

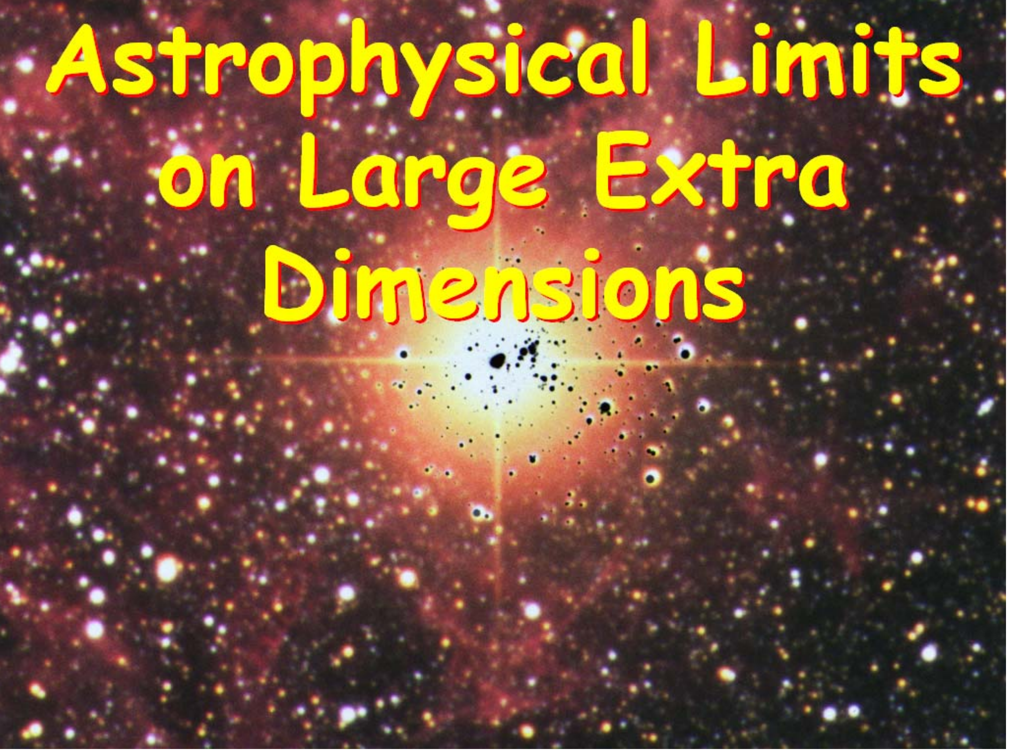
Including LPM effect

Using phase shifts from nuclear scattering data [Hanhart, Phillips & Reddy, astro-ph/0003445]

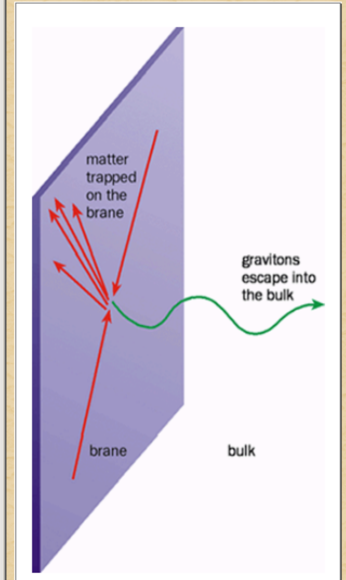
Astrophysical Axion Bounds



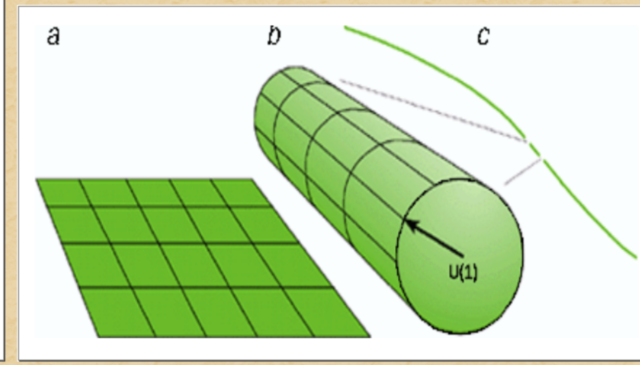
Astrophysical Limits on Large Extra Dimensions



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



Planck Mass and Compactification Scale

Gauss' Law

$$M_{Pl}^2 = (2.4\times10^{18}\,\mathrm{GeV})^2 = (2\pi R)^n M^{2+n}$$

- Reduced Planck mass $M_{Pl} = m_{Pl}/(8\pi)^{1/2}$
- Compactification radius
- Scale of fundamental physics

Gravity is strong (comparable to electroweak interaction), but looks weak because it leaks into large extra dimensions

If scale of fundamental physics ~ 1 TeV to solve the hierarchy problem, then experimentally

$n = 1$	$R_1 \sim 10^{13}$ cm	excluded
$n = 2$	$R_2 \sim 1$ mm	marginally allowed
$n = 3$	$R_3 \sim 10^{-6}$ mm	allowed
...		

Kaluza-Klein (KK) Gravitons

Bulk particles have discrete momenta in extra dimensions

$$\phi = \exp(ip\cdot x)\,\exp\left(i\sum_{j=1}^{n}\frac{n_j y_j}{R}\right)$$

Assuming toroidal compactification with dimenion $2\pi R$

- p 4D energy-momentum
- x 4D coordinate
- y_j extra dimensional coordinate
- n_j whole number

Klein-Gordon Equation for massless bulk particle in 4+nD

$$\left(\frac{\partial^2}{\partial t^2} - \sum_{j=1}^{3+n}\frac{\partial^2}{\partial x_j^2}\right)\phi = \left(p^2 - \sum_{j=1}^{n}\frac{n_j^2}{R^2}\right)\phi = 0$$

- There are many massless modes, appearing in 4D as massive particles, e.g. a "tower of Kaluza-Klein gravitons"
- Are weakly coupled like normal gravitons, but may be astrophysically important because of huge number of modes

Supernova Limit on Large Extra Dimensions

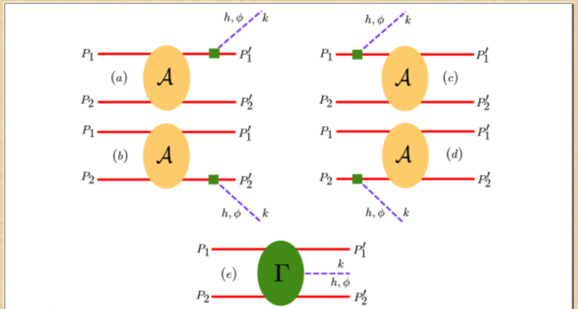


FIG. 1. The leading diagrams contributing to processes $NN \to NNh$ and $NN \to NN\phi$. Nucleons are denoted by solid lines and the KK-modes h or ϕ are denoted by dashed lines. Solid squares denote an insertion of the single-nucleon energy-momentum tensor, while solid ovals containing $\mathcal{A}$ denote an insertion of the full NN scattering amplitude. The solid oval containing Γ denotes the non-pole vertex required for the sum of diagrams to satisfy $\partial_\mu M^{\mu\nu} = 0$.

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

Rate $\propto M_{Pl}^{-2}$

Large multiplicity of modes

$RT \sim 10^{11}$

for R ~ 1 mm, T ~ 30 MeV

$$\text{Rate} \propto \frac{(RT)^n}{M_{Pl}^2} \propto \frac{T^n}{M^{2+n}}$$

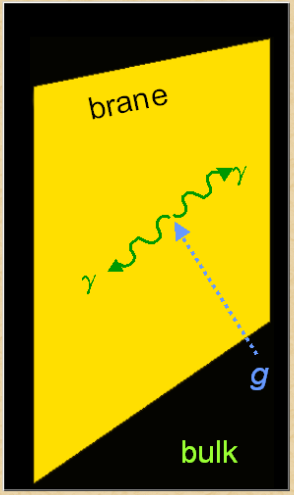
Cullen & Perelstein, hep-ph/9904422
Hanhart et al., nucl-th/0007016

SN 1987A energy-loss argument:
$R < 1\ \mu m$, $M > 9$ TeV $(n = 2)$
$R < 1$ nm, $M > 0.7$ TeV $(n = 3)$

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

Kaluza-Klein Graviton Decays

Gravitons are stable in the bulk, but can decay when they are within a Compton wavelength of the brane

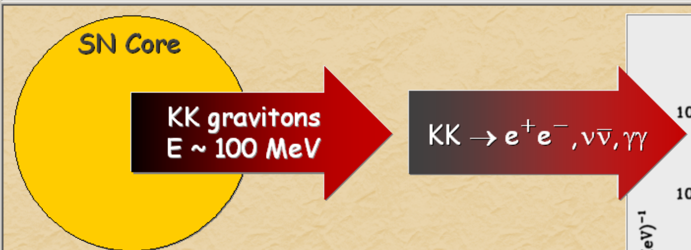


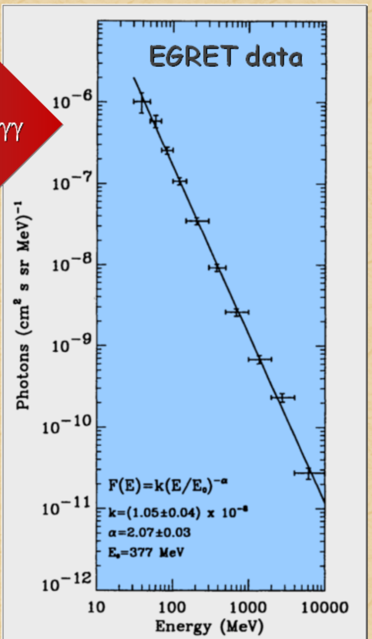
$$\Gamma_{tot} \sim P_{wall}\Gamma_{brane} \sim (mR)^{-n} \times \frac{m^{n+3}}{M_{nD}^{n+2}} \sim \frac{m^3}{M_{Pl}^2}$$

$$\tau_{2\gamma} \sim 6 \times 10^9\ \text{yr}\,(m/100\ \text{MeV})^{-3}$$

Most gravitons produced by cosmological supernovae have decayed and produced γ rays

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

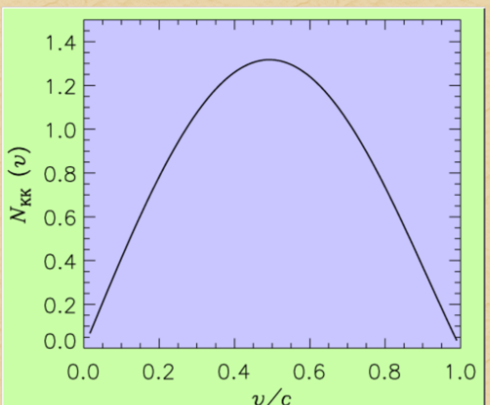
Our new limits $R < 0.1\ \mu m$, $M > 28$ TeV $(n = 2)$
$R < 0.2$ nm, $M > 1.7$ TeV $(n = 3)$

Hannestad & Raffelt, hep-ph/0103201

KK Graviton Retention by Neutron Star

$$v_{escape} = \sqrt{\frac{2GM}{R}} \approx 0.6c$$

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

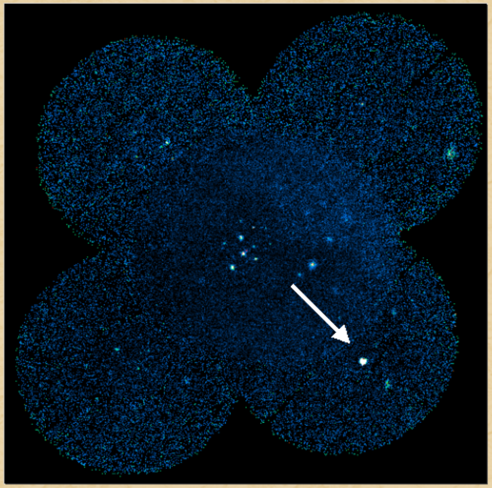


Velocity distribution of KK-gravitons emitted by supernova

Nearby Neutron Star RX J185635-3754

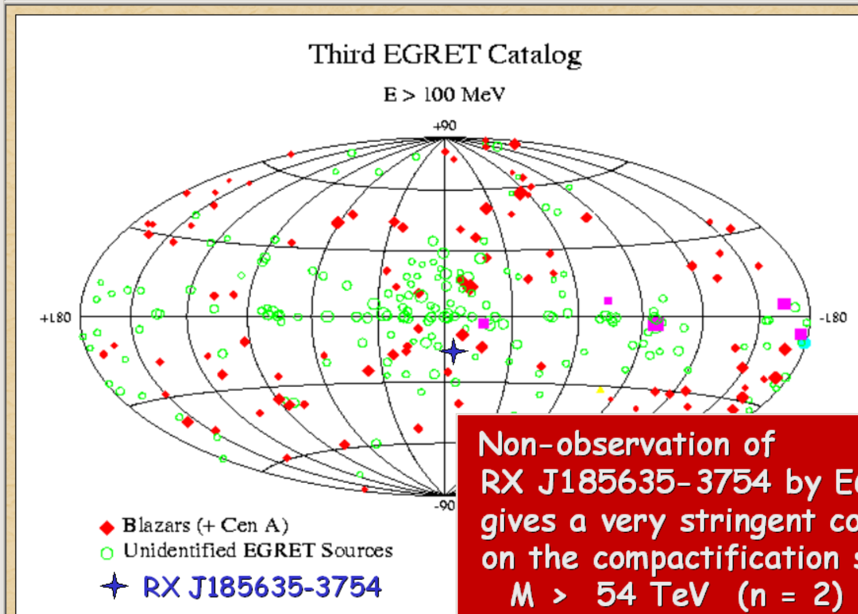
D = 120 pc (closest known neutron star), Age ~ 1.2×10^6 yr

HST Image
(Walter & Matthews 1997)



ROSAT Image
(Walter, Wolk & Neuhauser 1996)

Third EGRET Catalog (Hartmann et al. 1999)



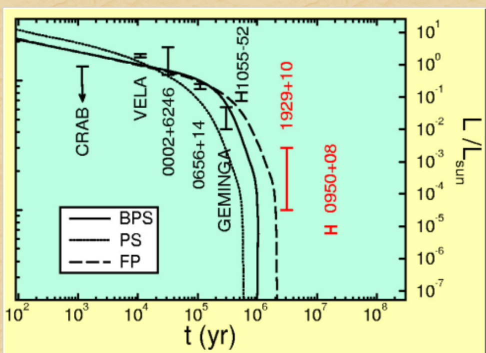
Non-observation of RX J185635-3754 by EGRET gives a very stringent constraint on the compactification scale:
M > 54 TeV (n = 2)
M > 3.5 TeV (n = 3)

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Neutron Star Excess Heat

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

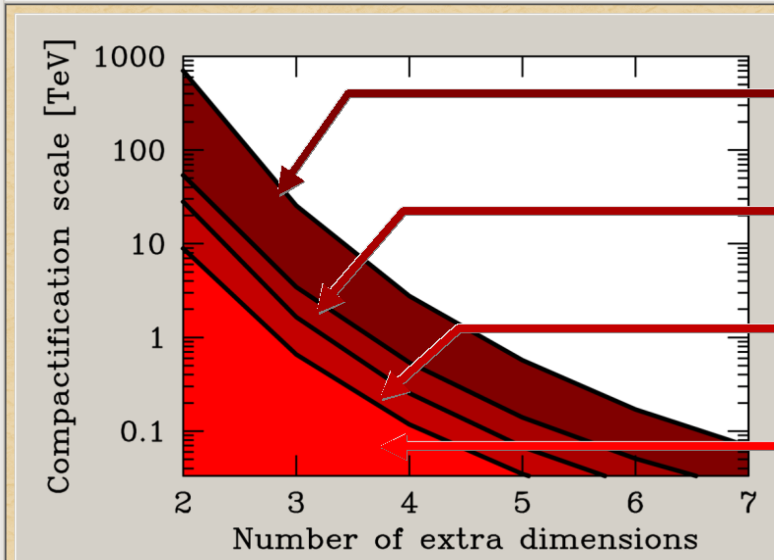
Neutron star cooling calculations vs. observations (Pavlov, Stringfellow & Cordova 1996, Larson & Link 1999)



To avoid excess heating by KK decay
M > 700 TeV (n = 2)
M > 26 TeV (n = 3)

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Summary of Limits on Large Extra Dimensions



Neutron star excess heat

Gamma rays from close pulsars

Gamma rays from all cosmic SNe

SN 1987A Energy loss

Hannestad & Raffelt, PRD (2003) [hep-ph/0304029]

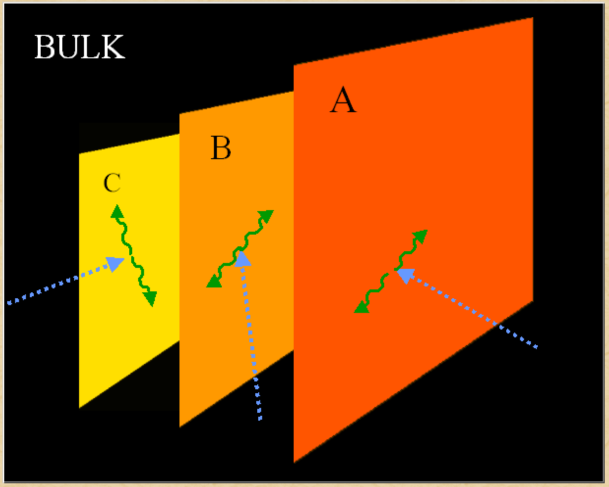
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Loop Holes

In other than toroidal compactifications, processes such as
$G(m_1) \to G(m_2) + G(m_3)$
can be much faster than radiative decays so that all KK states cascade to lower-mass KK states.

In non-toroidal geometries, the mode spacing can be much larger
→ KK gravitons are not produced astrophysically

If there are more branes, photons can be produced on all of them, leaving fewer in our world, weakening the limits



Neutrino Oscillations and a Future Galactic Supernova

Oscillation Suppression in Supernovae

Neutrino mixing angle in a medium

$$\sin^2(2\Theta) = \frac{\sin^2(2\Theta_{vac})}{\sin^2(2\Theta_{vac}) + \left[\cos^2(2\Theta_{vac}) - A\right]^2}$$

For $\nu_s - \nu_e$-mixing:

$$A = \pm\sqrt{2}G_F\left(n_e + 2n_{\nu_e} - \tfrac{1}{2}n_n\right)\frac{2E_\nu}{\Delta m^2}$$

$$= \pm 1.53\times10^9\,\frac{\left(Y_e + 2Y_{\nu_e} - \tfrac{1}{2}Y_n\right)\rho}{10^{14}\,\mathrm{g\,cm^{-3}}}\,\frac{E_\nu}{100\,\mathrm{MeV}}\,\frac{1\,\mathrm{eV}^2}{\Delta m^2}$$

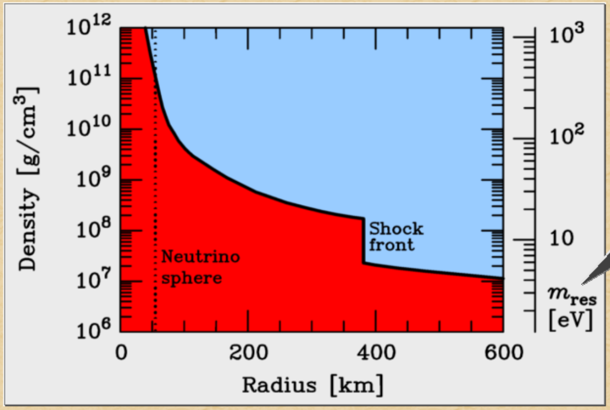
Large medium effect ($|A| \gg 1$) and large sterile mass ($m_s \gg m_\nu$)

$$\frac{\sin^2(2\Theta)}{\sin^2(2\Theta_{vac})} = A^{-2}$$

$$= 4.3\times10^{-19}\left(\frac{10^{14}\,\mathrm{g\,cm^{-3}}}{\left(Y_e + 2Y_{\nu_e} - \tfrac{1}{2}Y_n\right)\rho}\right)^2\left(\frac{100\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_s}{1\,\mathrm{eV}}\right)^4$$

- Strong medium effects for $m_s < 30$ keV
- No effective SN emission for $m_s < 100$ eV

Matter Effect on Flavor Oscillations



"Effective neutrino mass" from weak potential

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

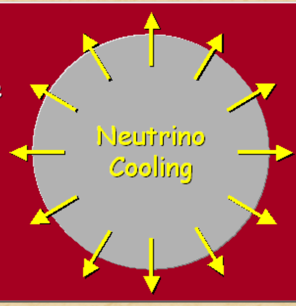
($E_\nu = 10$ MeV and $Y_e = 0.5$)

Neutrino masses in the cosmologically interesting range of 10 - 100 eV would have been useful for 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

R-Process Nucleosynthesis in Supernovae

Hot-bubble region outside of SN core after explosion possible site for r-process nucleosynthesis of heavy elements



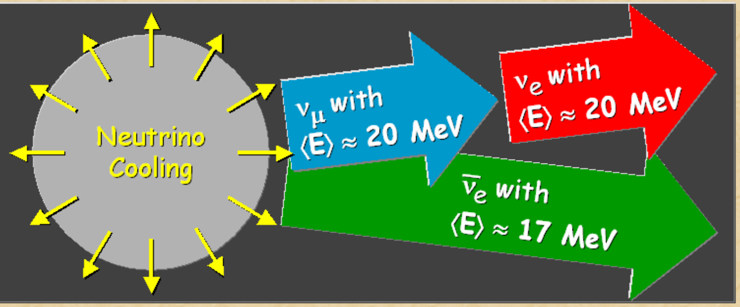
- Neutrino-driven wind
- Neutron fraction governed by beta reactions

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

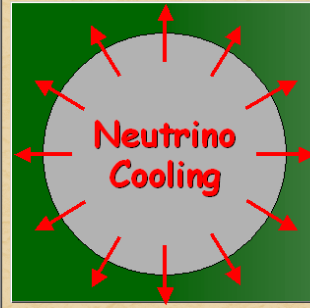
$\bar{\nu}_e + p \to n + e^+$

- Neutron-rich material because $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle$

Swapping of neutrino spectra by flavor oscillations can force neutrino-driven wind to become proton-rich



R-Process Nucleosynthesis in Supernovae

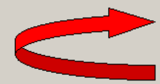


Neutrino driven wind
neutron-rich material
neutron fraction governed by beta reactions

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

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

R-process destroyed by α-effect



(1) Protons trapped in α-particles

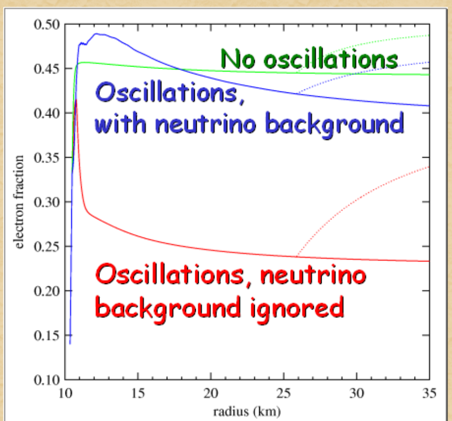
(2) Neutrons → protons by β-reactions

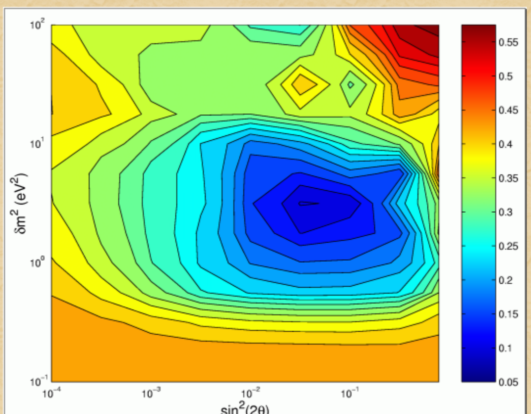
➔ Neutron concentration too low

Oscillations $\nu_e \to \nu_s$ (sterile neutrinos) quenches β-rates
Specific mass scheme required (resonance condition)

Sterile Neutrinos and r-Process Nucleosynthesis

Electron fraction Y_e in SN neutrino-driven wind, assuming oscillations $\nu_e \leftrightarrow \nu_s$ (resonant) and $\bar{\nu}_e \leftrightarrow \bar{\nu}_s$, affecting beta equilibrium $\nu_e + n \leftrightarrow p + e^-$



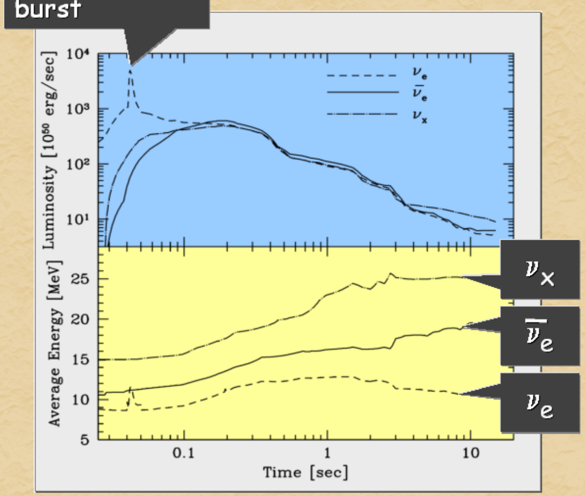


Neutrino background ignored

Patel & Fuller, hep-ph/0003034

Structure of a Supernova Neutrino Burst

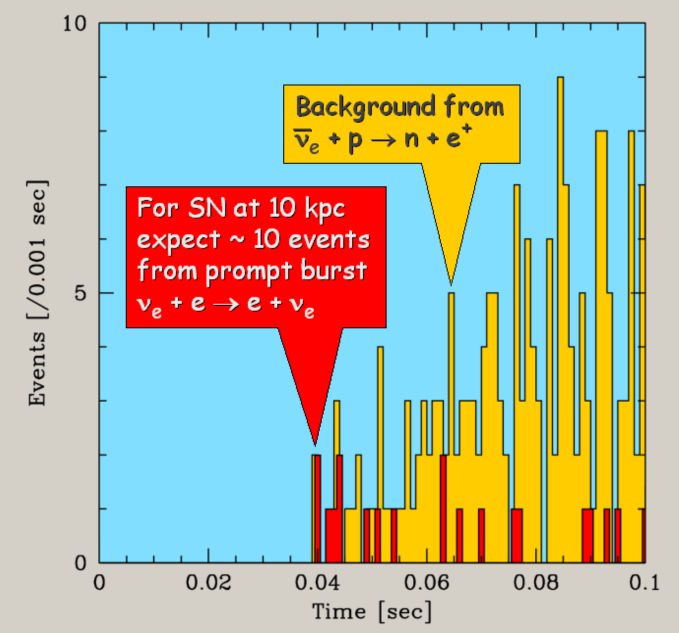
Prompt ν_e deleptonization burst



Livermore numerical model
ApJ 496 (1998) 216

Broad characteristics
- Duration few seconds
- $\langle E_\nu \rangle$ ~ 10-20 MeV
- $\langle E_\nu \rangle$ increases with time
- Hierarchy $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$
- Approximate equipartition of energy between flavors

Can we see the prompt neutrino burst?

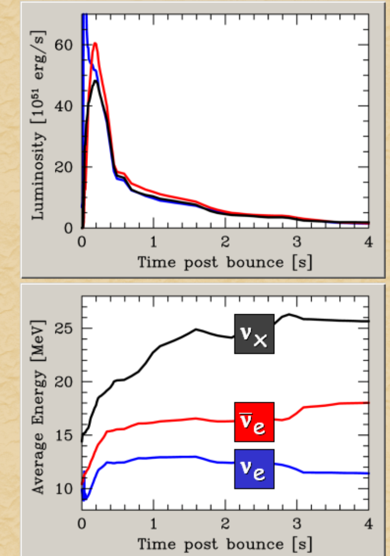


Monte-Carlo example for early SN signal in Super-Kamiokande

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

Flavor-Dependent Fluxes and Spectra

Livermore num. simulation [ApJ 496 (1998) 216]



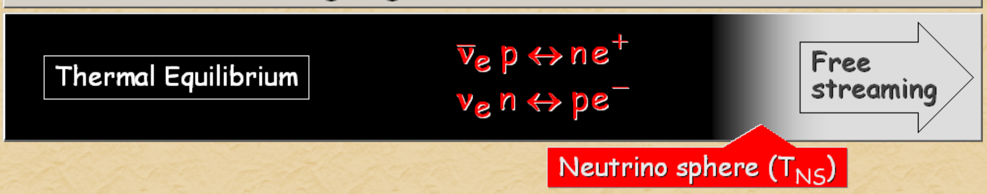
From these and similar studies the "standard" assumptions are
- Almost exact equipartition of energy among flavors
- Pronounced hierarchy of average energies

However, in traditional simulations the transport of ν_x (ν_μ and ν_τ) is rather schematic
- Incomplete microphysics
- Crude numerics to couple nu transport with hydro code

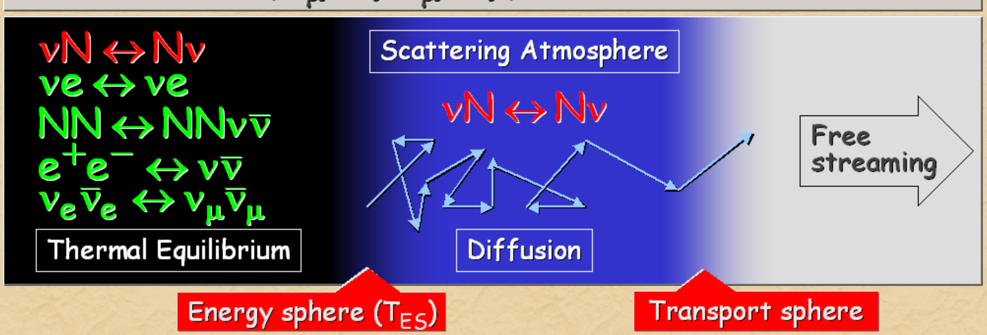
Neutrino Spectra Formation

G.Raffelt astro-ph/0105250

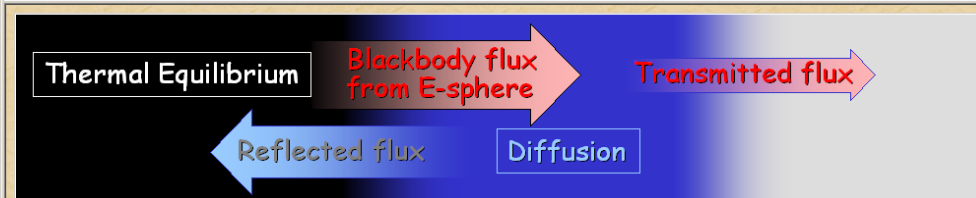
Electron flavor $(\nu_e, \bar{\nu}_e)$

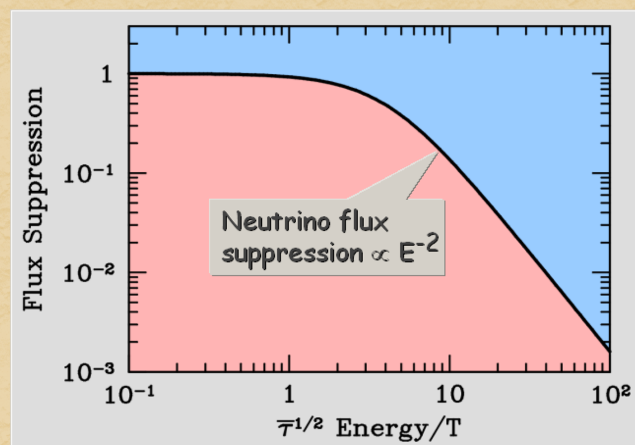


Other flavors $(\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)$

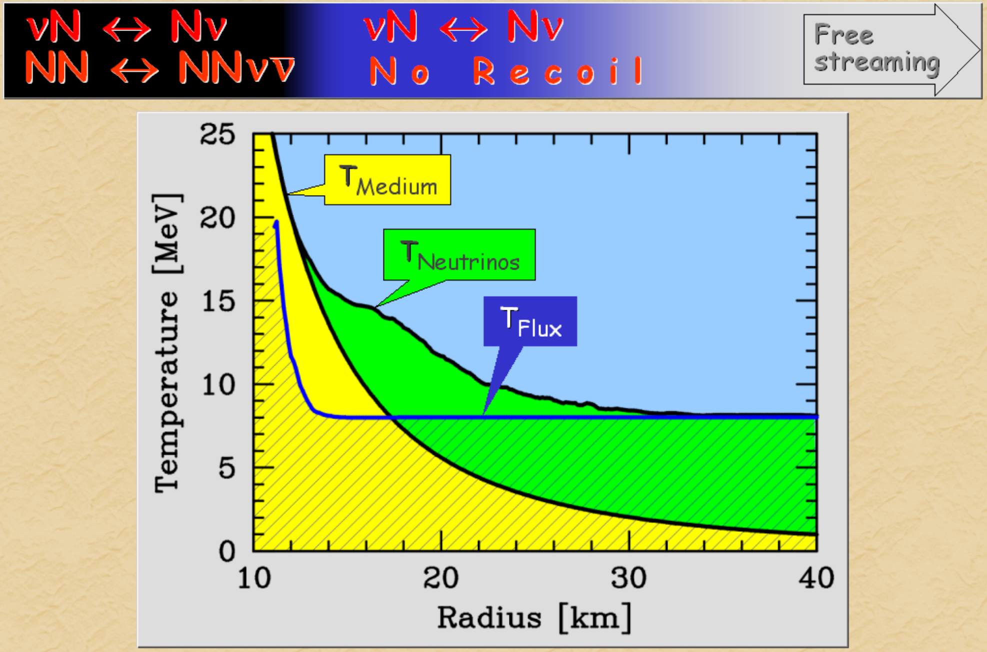


Scattering Atmosphere as a "Low-Pass Filter"



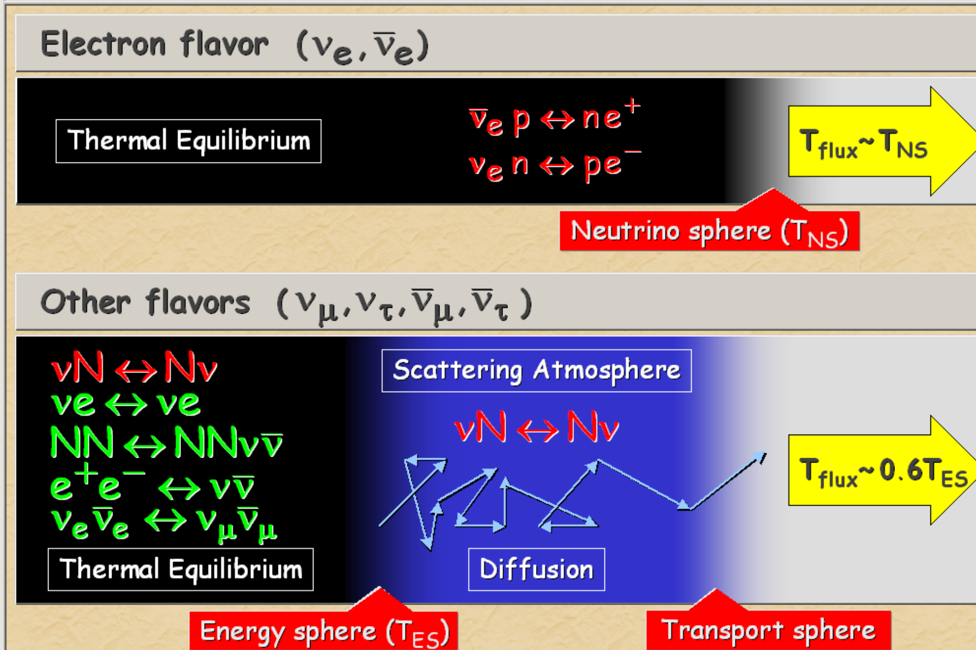


Scattering Atmpsphere as Low-Pass Filter

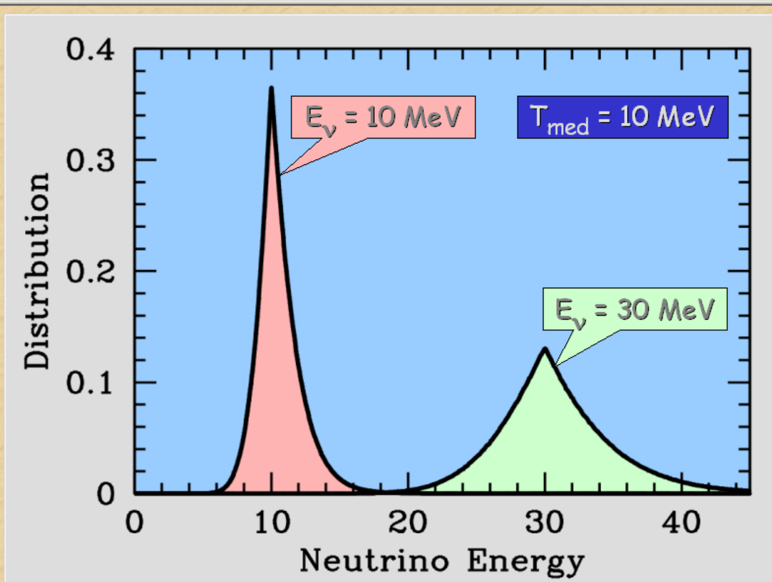


Neutrino Spectra Formation

G.Raffelt
astro-ph/0105250



Energy Transfer by Nucleon Recoils



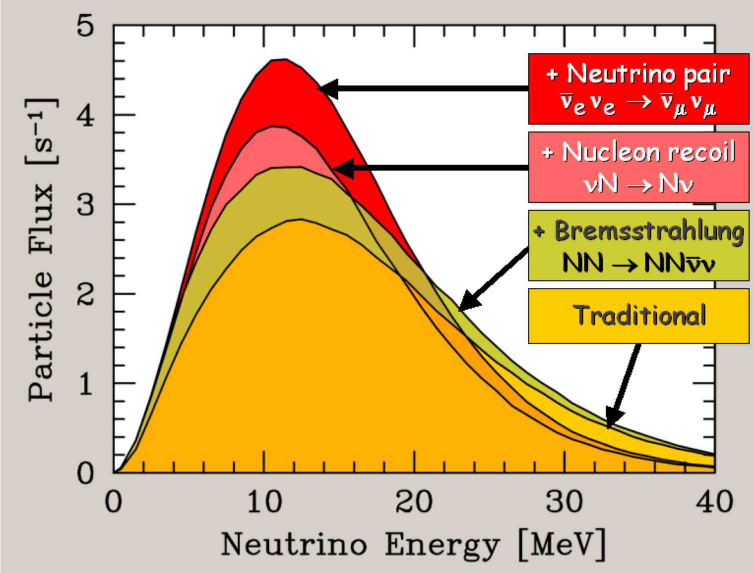
Energy transfer in νN collisions not insignificant

Microphysics for Mu- and Tau-Neutrino Transport

	Traditional treatment	Dominant processes
Main opacity	$\nu + N \to N + \nu$	$\nu + N \to N + \nu$
Energy exchange	$\nu + e \to e + \nu$	$\nu + e \to e + \nu$ Recoil $\nu + N \to N + \nu$ [2,6,7]
Pair production	$e^+ + e^- \to \bar\nu + \nu$	$N + N \to N + N + \bar\nu + \nu$ [1-4] $\bar\nu_e + \nu_e \to \bar\nu + \nu$ [6,7]

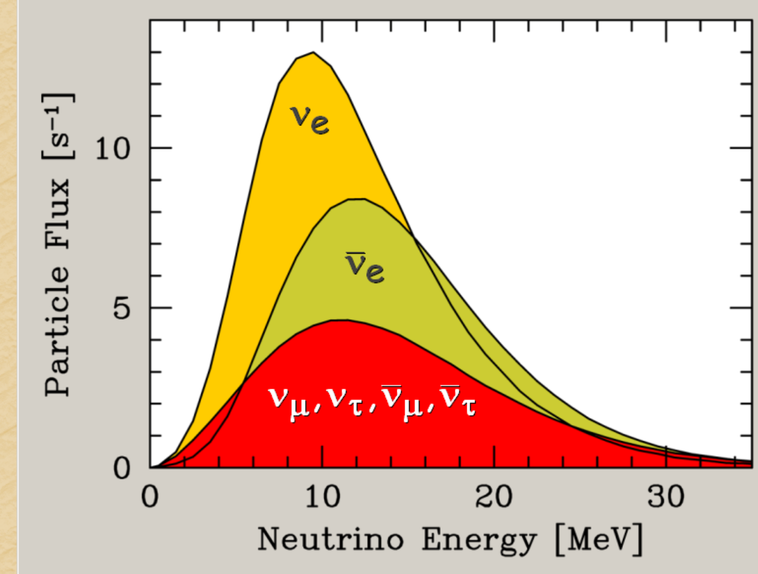
[1] Suzuki, Num. Astrophys. Japan 2 (1991) 267
[2] Janka, W.Keil, Raffelt & Seckel, PRL 76 (1996) 2621 [astro-ph/9507023]
[3] Hannestad & Raffelt, ApJ 507 (1998) 339 [astro-ph/9711132]
[4] Thompson, Burrows & Horvath, PRC 62 (2000) 035802 [astro-ph/0003054]
[6] Raffelt, ApJ 561 (2001) 890 [astro-ph/0105250]
[6] Buras, Janka, M.Keil, Raffelt & Rampp, ApJ (2003) [astro-ph/0205006]
[7] M.Keil, Raffelt & Janka, ApJ submitted (2003) [astro-ph/0208035]

Flux and Spectra Modification by New Processes



Keil, Raffelt & Janka, ApJ (2003) [astro-ph/0208035]

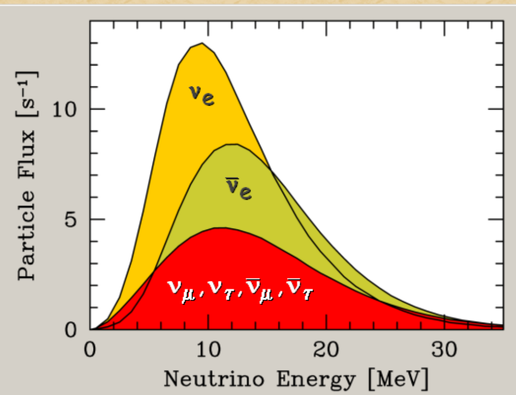
Flavor-Dependent Fluxes in an Accretion-Phase Model



Keil, Raffelt & Janka, ApJ (2003) [astro-ph/0208035]

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

What Are The Spectral Flux Characteristics?



The spectra are crudely thermal, but how to characterize in detail?

Commonly used global parameters

- Total luminosity L_ν
- Average energy $\langle E \rangle$
- General energy moments $\langle E^n \rangle$
- "RMS energy" $E_{rms} = \sqrt{\frac{\langle E^3 \rangle}{\langle E \rangle}}$

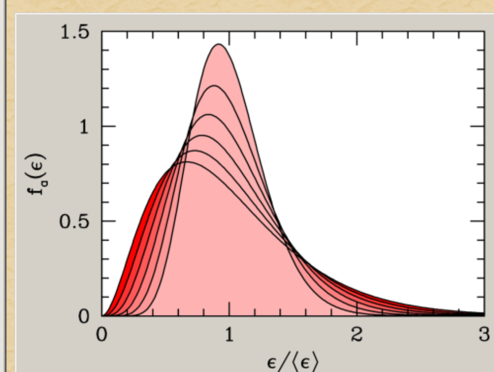
Two-parameter fits (Normalization is third parameter)	Thermal spectrum, i.e. Fermi-Dirac shape (η fit)	$F(E) \propto \frac{E^2}{1+e^{-\eta+E/T}}$
	Quasi power law (α fit)	$F(E) \propto E^\alpha \exp\left[-(\alpha+1)\frac{E}{\bar E}\right]$

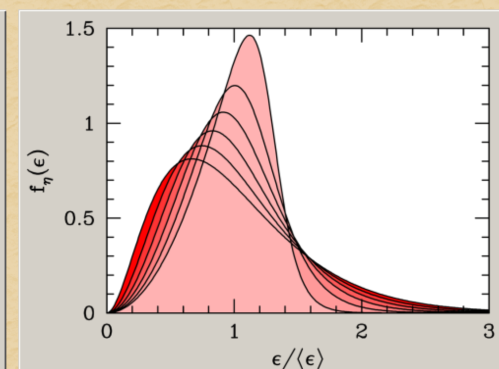
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Alpha vs. Eta Fit

$$F(E) \propto E^\alpha \exp\left[-(\alpha+1)\frac{E}{\bar E}\right]$$

$$F(E) \propto \frac{E^2}{1+e^{-\eta+E/T}}$$





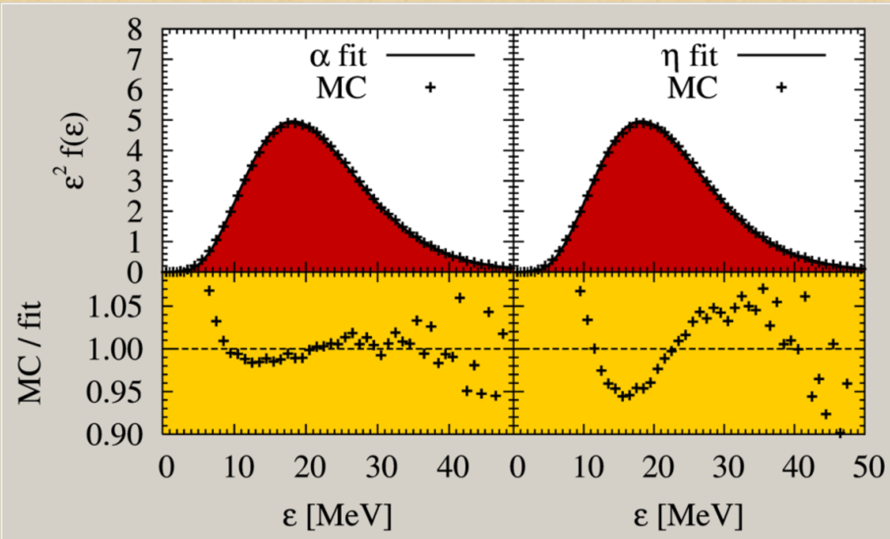
Starting with $F(E) \propto E^2 \exp\left(-3\frac{E}{\bar E}\right)$ the width is reduced in 10% steps

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

How Good are the Two-Parameter Global Fits?

$F(E) \propto E^{\alpha} \exp\left[-(\alpha+1)\frac{E}{\overline{E}}\right]$

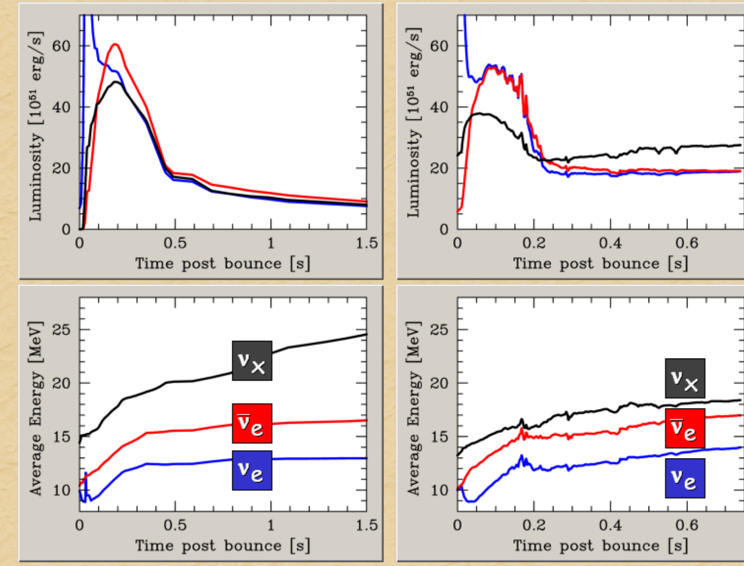
$F(E) \propto \frac{E^2}{1+e^{-\eta+E/T}}$



Keil, Raffelt & Janka, astro-ph/0208035

Fluxes and Spectra from Numerical Simulations

Livermore (traditional) [ApJ 496 (1998) 216]	Garching (new microphyiscs) [astro-ph/0303226]



Three-Flavor Neutrino Parameters (Ignoring LSND)

Atmospheric	Chooz Limit	Solar	3σ ranges
$32° < \theta_{23} < 60°$	$\theta_{13} < 14°$	$27° < \theta_{12} < 41°$	hep-ph/0211054

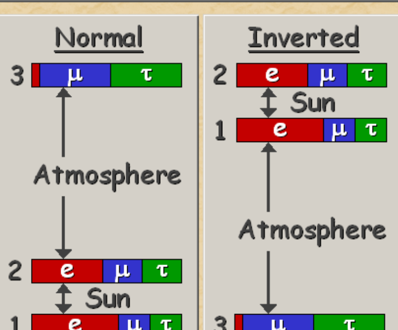
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & e^{-i\delta}s_{13}\\ & 1 & \\ -e^{i\delta}s_{13} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

Solar 24 - 240

Atmospheric 1400 - 6000

$\Delta m^2/\text{meV}^2$

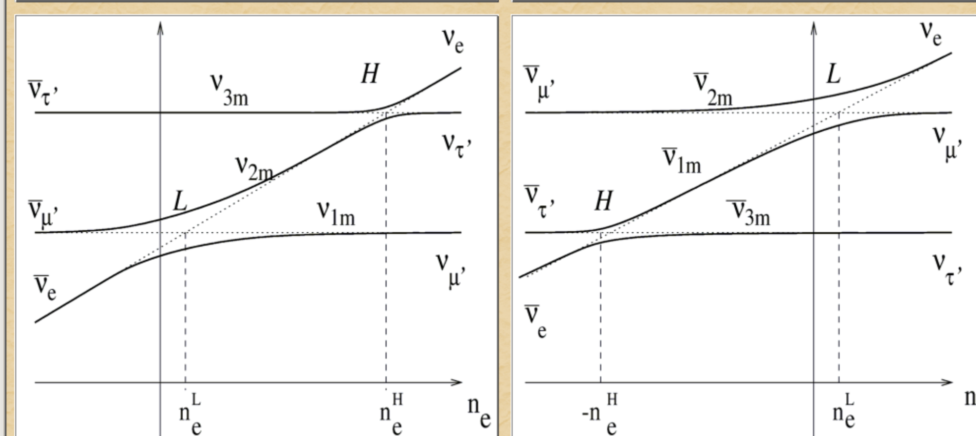


Tasks and Open Questions

- Precision for θ_{12} and θ_{23} ($\theta_{12} < 45°$ and $\theta_{23} = 45°$?)
- How large is θ_{13}?
- CP-violating phase?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?

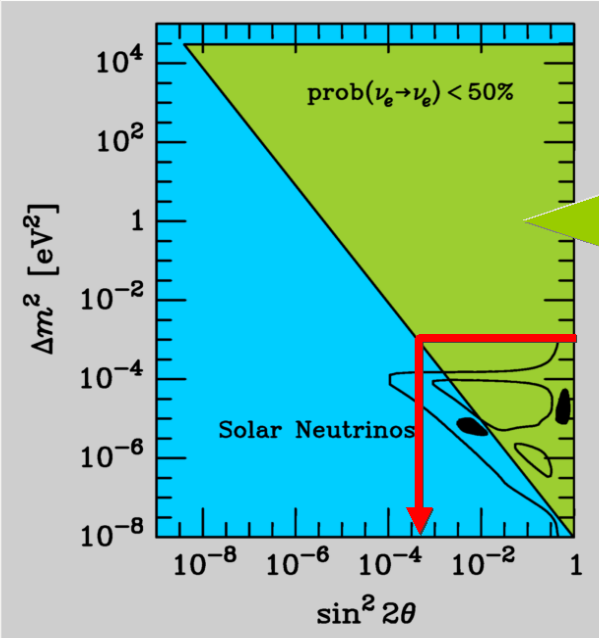
Level-Crossing Diagram in a SN Envelope

Normal mass hierarchy	Inverted mass hierarchy



Dighe & Smirnov, Identifying the neutrino mass spectrum from a supernova neutrino burst, astro-ph/9907423

Resonant Oscillations in a Supernova Envelope



Adiabatic oscillations for a large range of mixing parameters

- 13-oscillations involve atmospheric mass difference
- Adiabatic for $\sin^2(2\Theta_{13}) > 10^{-3}$

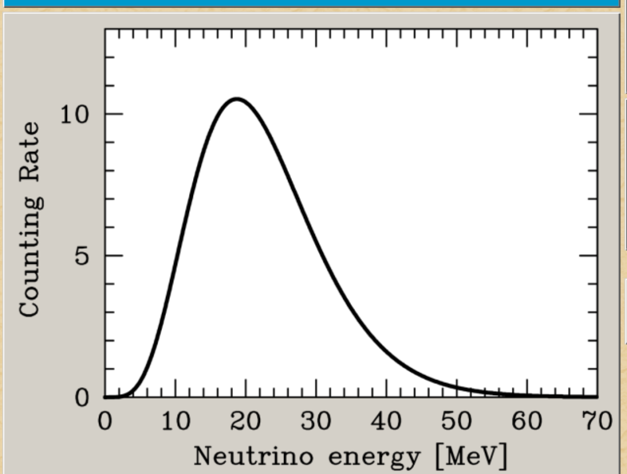
Spectra Emerging from Supernova

Assume primary fluxes	F_e^0 for ν_e $F_{\bar e}^0$ for $\bar\nu_e$ F_x^0 for $\nu_\mu, \bar\nu_\mu, \nu_\tau, \bar\nu_\tau$
After leaving the supernova envelope, the fluxes are partially swapped	$F_e = p\,F_e^0 + (1-p)\,F_x^0$ $F_{\bar e} = \bar p\,F_{\bar e}^0 + (1-\bar p)\,F_x^0$ $\frac{1}{4}\sum F_x = \frac{2+p+\bar p}{4} F_x^0 + \frac{1-p}{4} F_e^0 + \frac{1-\bar p}{4} F_{\bar e}^0$

$\sin^2(2\Theta_{13})$	Mass hierarchy	p	$\bar p$
$\gg 10^{-3}$	Normal	0	$\cos^2(\Theta_{12})$
	Inverted	$\sin^2(\Theta_{12})$	0
$\ll 10^{-3}$	Either	$\sin^2(\Theta_{12})$	$\cos^2(\Theta_{12})$

Oscillation of Supernova Anti-Neutrinos

Measured $\bar\nu_e$ spectrum at a detector like Super-Kamiokande



Assumed flux parameters:

Flux ratio $\bar\nu_e : \bar\nu_x = 0.8 : 1$

$\langle E(\bar\nu_e)\rangle = 15\,\text{MeV}$

$\langle E(\bar\nu_x)\rangle = 18\,\text{MeV}$

Mixing parameters:

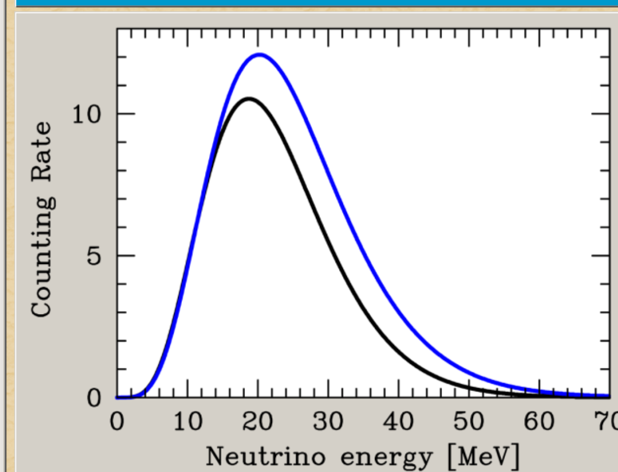
$\Delta m^2_{sun} = 60\,\text{meV}^2$

$\sin^2(2\theta) = 0.9$

No oscillations

Oscillation of Supernova Anti-Neutrinos

Measured $\bar\nu_e$ spectrum at a detector like Super-Kamiokande



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No oscillations

Oscillations in SN envelope

Oscillation of Supernova Anti-Neutrinos

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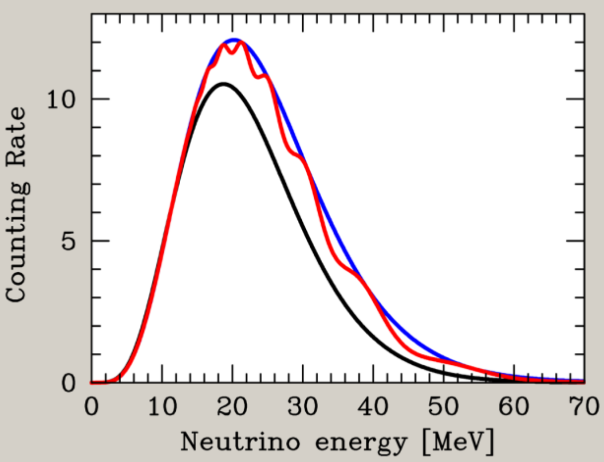

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$\Delta m^2_{\text{sun}} = 60\,\text{meV}^2$

$\sin^2(2\theta) = 0.9$

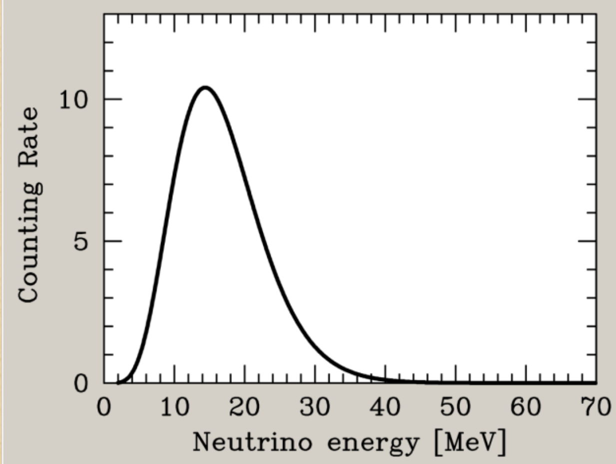
No oscillations

Oscillations in SN envelope

Earth effects included

Oscillation of Supernova Neutrinos

Measured ν_e spectrum at a detector like SNO, considering only CC reactions



Assumed flux parameters:

Flux ratio $\nu_e : \nu_x = 0.9:1$

$\langle E(\nu_e)\rangle = 12\,\text{MeV}$

$\langle E(\nu_x)\rangle = 18\,\text{MeV}$

Mixing parameters:

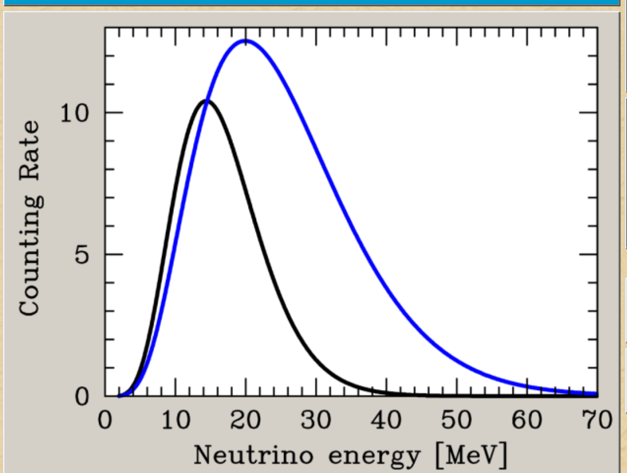
$\Delta m^2_{\text{sun}} = 60\,\text{meV}^2$

$\sin^2(2\theta) = 0.9$

No oscillations

Oscillation of Supernova Neutrinos

Measured ν_e spectrum at a detector like SNO, considering only CC reactions



Assumed flux parameters:

Flux ratio $\nu_e : \nu_x = 0.9:1$

$\langle E(\nu_e)\rangle = 12\,\text{MeV}$

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Oscillations in SN envelope

Oscillation of Supernova Neutrinos

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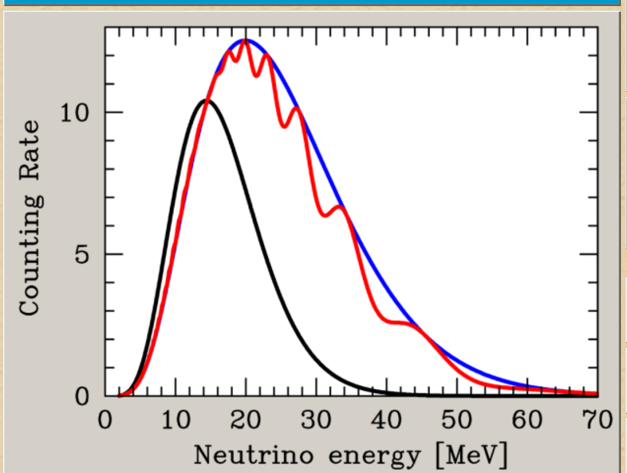

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$\langle E(\nu_e)\rangle = 12\,\text{MeV}$

$\langle E(\nu_x)\rangle = 18\,\text{MeV}$

Mixing parameters:

$\Delta m^2_{\text{sun}} = 60\,\text{meV}^2$

$\sin^2(2\theta) = 0.9$

No oscillations

Oscillations in SN envelope

Earth effects included

Implications of Observing Earth Effects

	normal hierarchy	inverted hierarchy	
Supernova nus: Earth effects appear in channels	$\bar\nu_e$	ν_e	$\sin^2(\theta_{13}) > 10^{-3}$
	ν_e and $\bar\nu_e$	ν_e and $\bar\nu_e$	$\sin^2(\theta_{13}) < 10^{-3}$

One plausible scenario

$\sin^2(\theta_{13}) > 10^{-3}$ established e.g. by long-baseline reactor expt.	Earth effects observed in $\bar\nu_e$ channel ?	Yes: Normal hierarchy
		No: Inverted hierarchy or SN source spectra "anomalous"

Positively observing Earth effects in SN neutrinos gives us unique information about neutrino parameters

Not observing the effects in a SN signal is ambiguous: Can always be blamed on SN source spectra

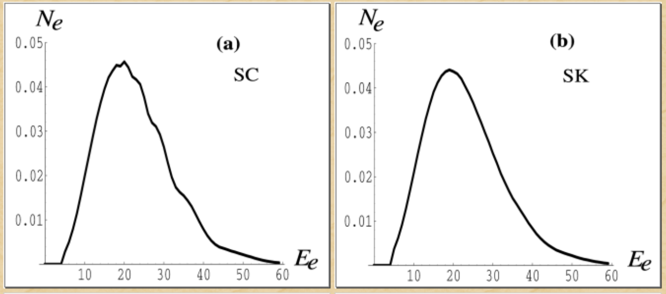
Robust Strategies for Observing Earth Effects

One detector observes SN shadowed by Earth

Another detector observes SN directly

Identify Earth effects by comparing signals

Identify "wiggles" in signal of single detector
Problem: Smearing by limited energy resolution

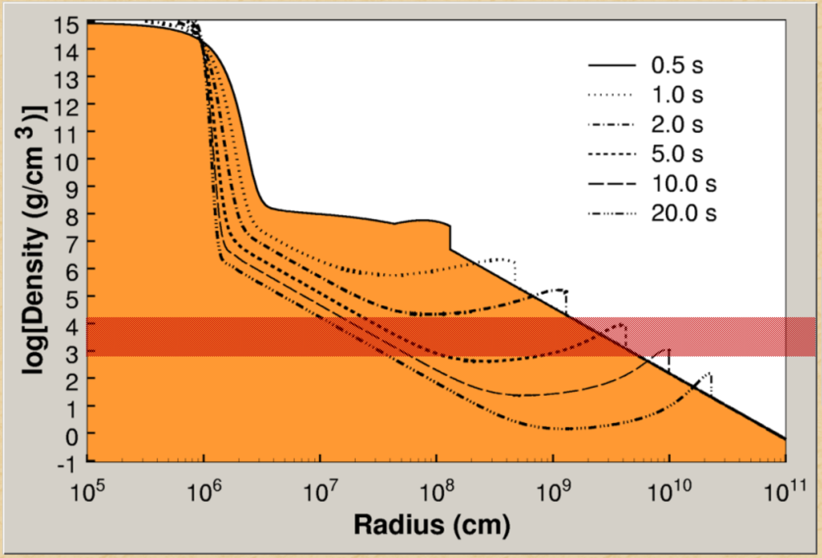


Scintillation detector ~ 2000 events may be enough

Water Cherenkov: Need Hyper-Kamiokande with ~ 10^5 events

Dighe, Keil & Raffelt: "Identifying Earth matter effects on supernova neutrinos at a single detector" [hep-ph/0304150]

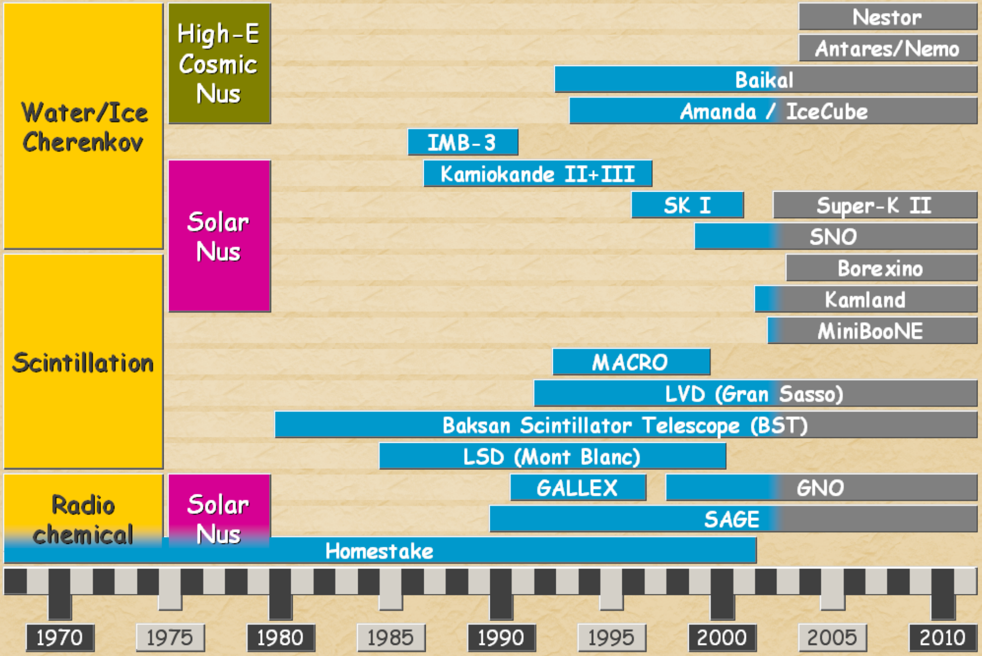
SN Shock Propagation and Neutrino Oscillations



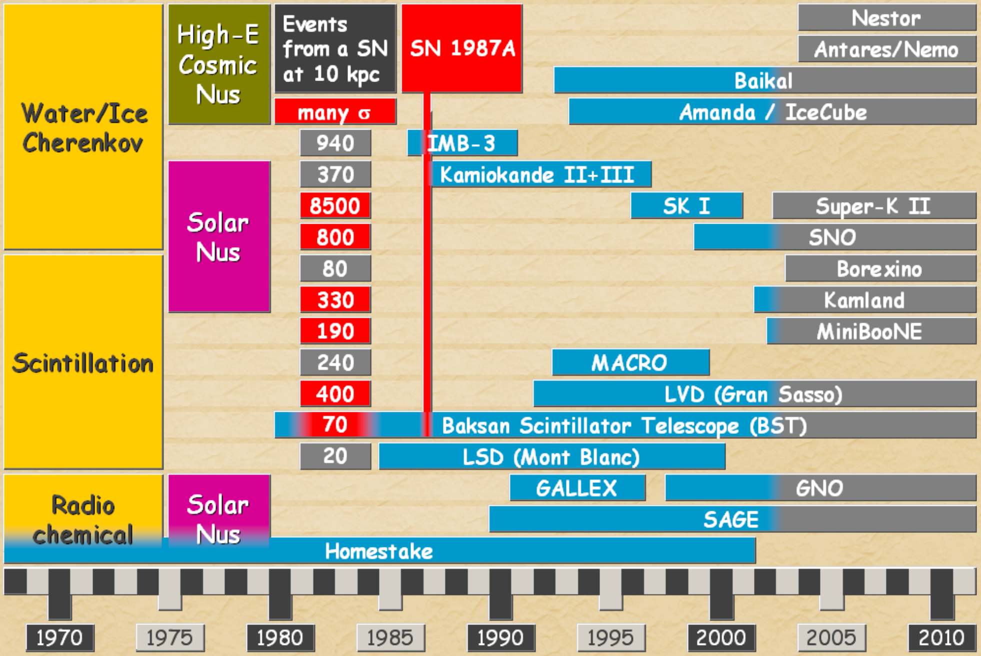
Resonance density for Δm^2_{atm}

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

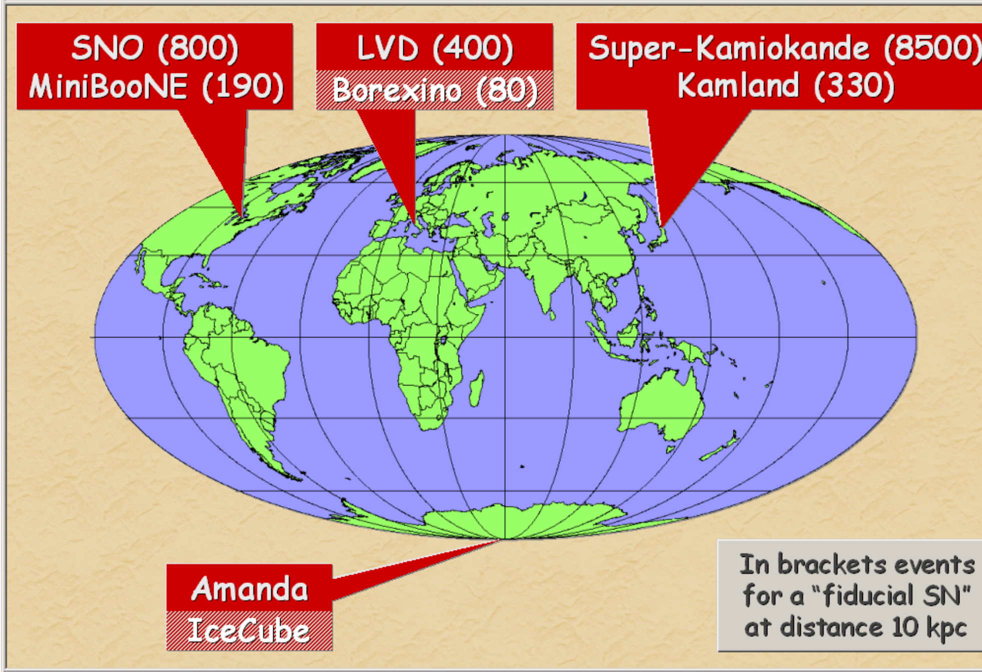
Brief History of Neutrino Astronomy



Brief History of Neutrino Astronomy

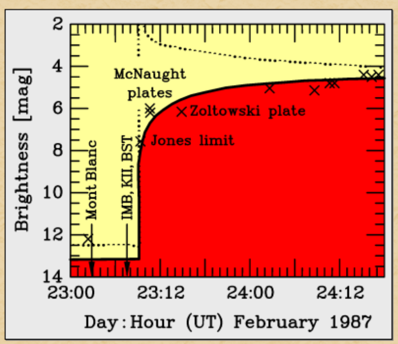


Large Detectors for SN Neutrinos



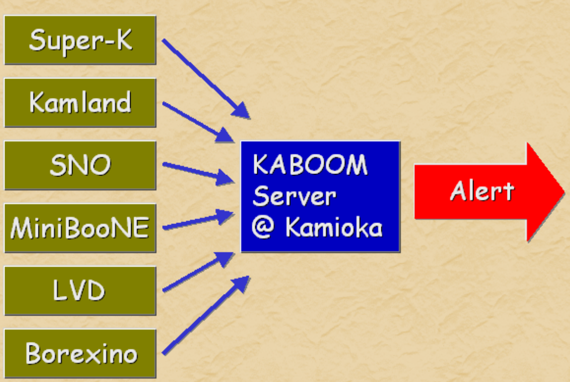
In brackets events for a "fiducial SN" at distance 10 kpc

SuperNova Early Warning System (SNEWS)



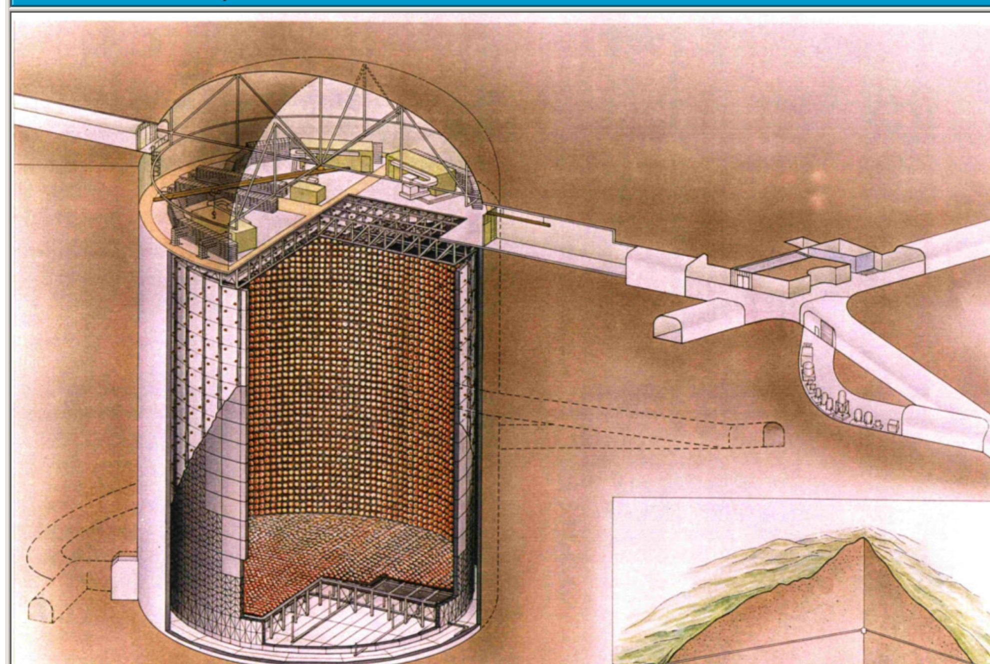
Supernova 1987A Early Light Curve

Neutrino observation can alert astronomers several hours in advance to supernova. To avoid false alarms, require alarm from at least two experiments.

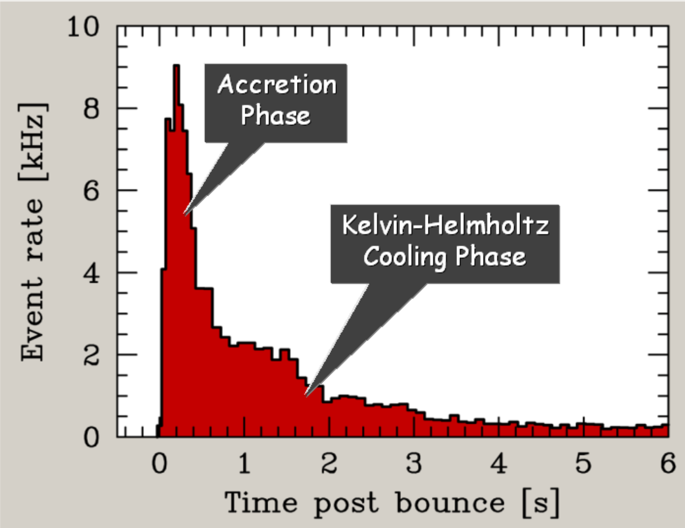


http://hep.bu.edu/~snnet

Super-Kamiokande Neutrino Detector

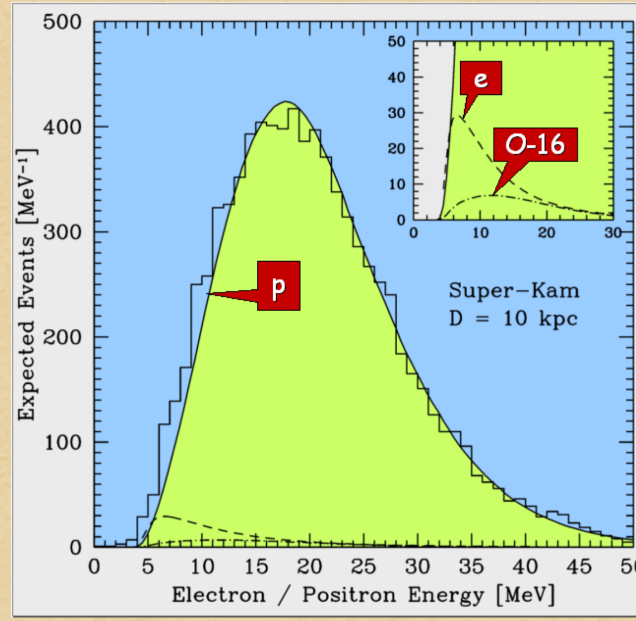


Simulated Supernova Signal at Super-Kamiokande



Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

Galactic Supernova Signal in Super-Kamiokande

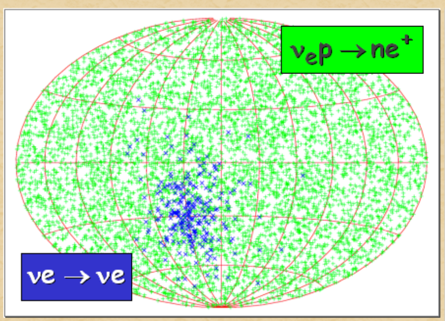


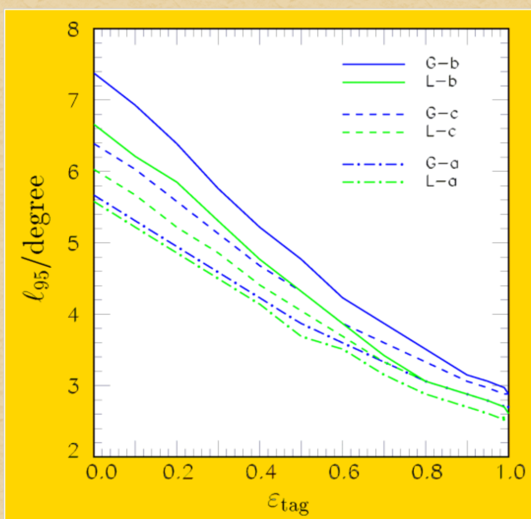
Monte-Carlo simulation for Super-Kamiokande signal of SN at 10 kpc, based on a numerical model with Livermore code

Total of about 8300 events for t < 18 s

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

Supernova Pointing with Neutrinos



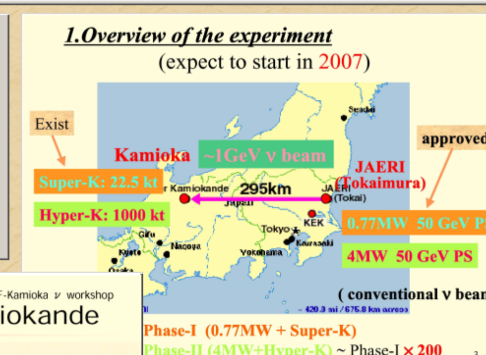


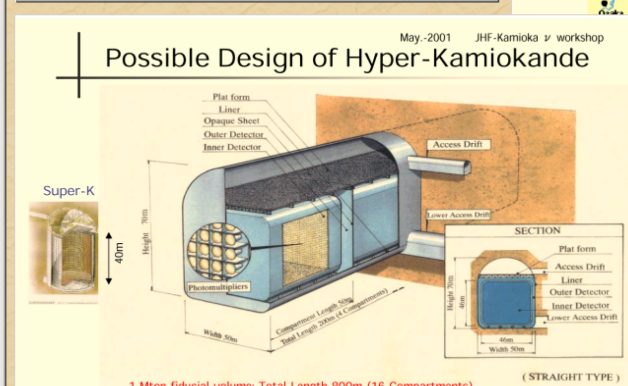
95% CL pointing accuracy for different assumed fluxes and mixing scenarios
Assume that neutrons can be tagged with efficiency ϵ_{tag}

Tomas, Semikoz, Raffelt, Kachelriess & Dighe, Supernova pointing with low- and high-energy neutrino detectors [hep-ph/0307050]

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)

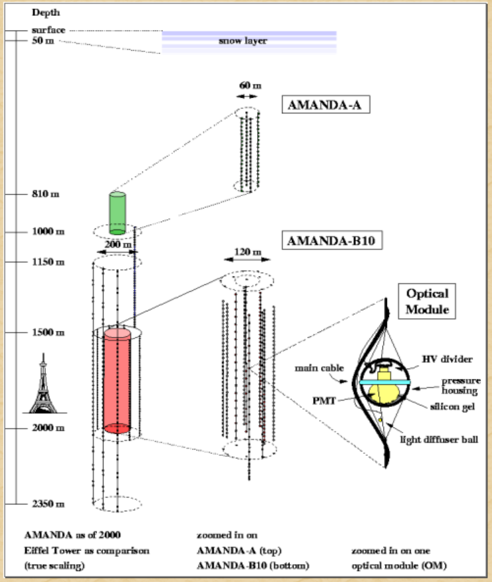


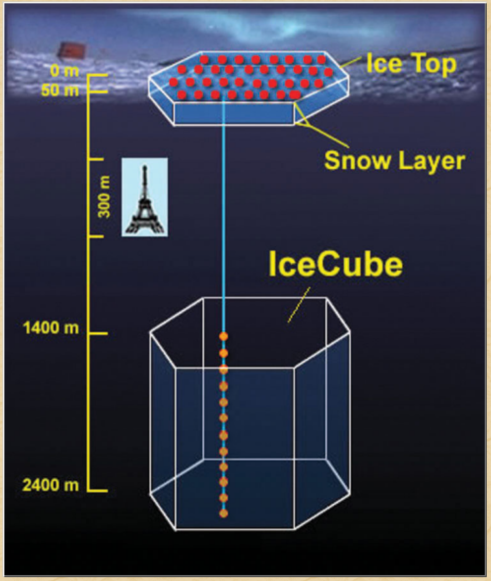


Similar discussions in
- USA (UNO project)
- Europe (Frejus Tunnel)

Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km^3, 800 PMTs)	Future IceCube (1 km^3, 4800 PMTs)



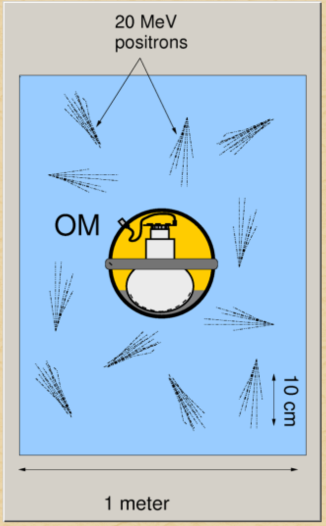


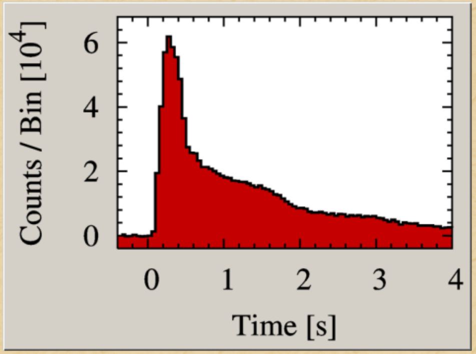
IceCube as a Supernova Neutrino Detector

Each optical module (OM) picks up Cherenkov light from its neighborhood. SN appears as "correlated noise".

~ 300 Cherenkov photons per OM from SN at 10 kpc

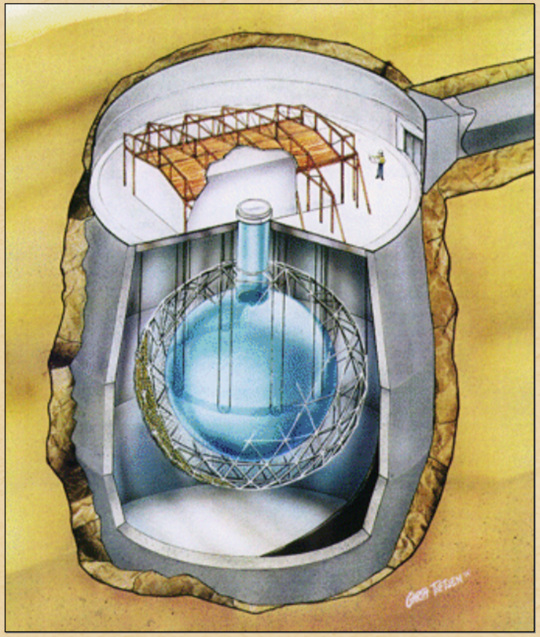
Noise per OM < 500 Hz





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

Sudbury Neutrino Observatory (SNO)

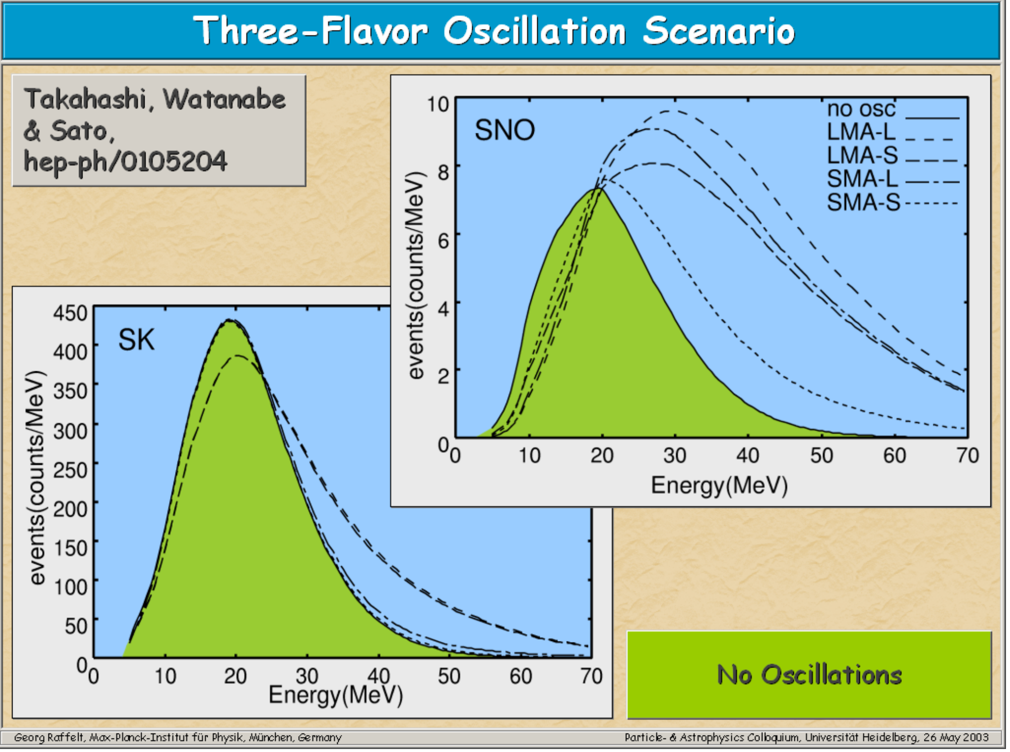


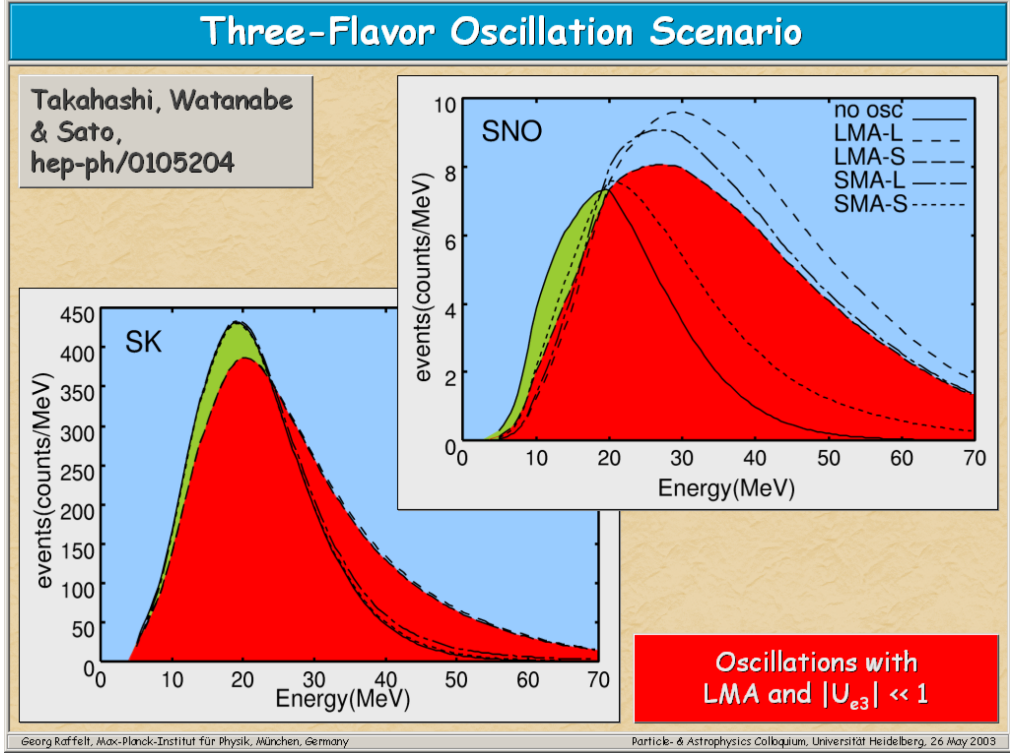
1000 tons of heavy water

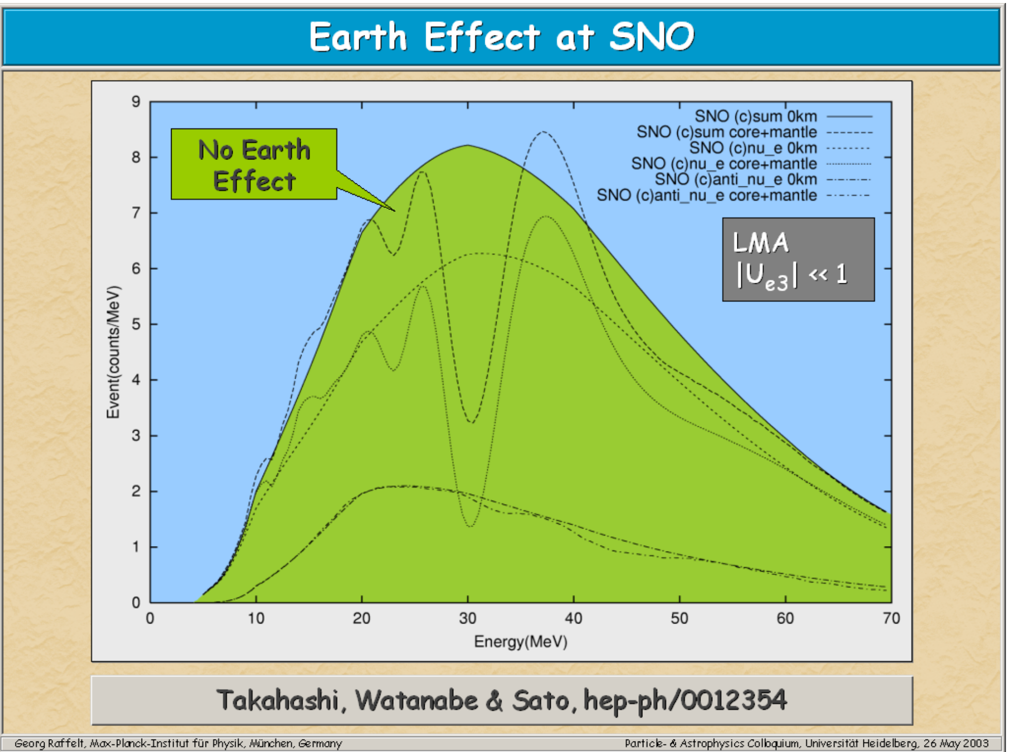
Events from a SN at 10 kpc
(no flavor oscillations)

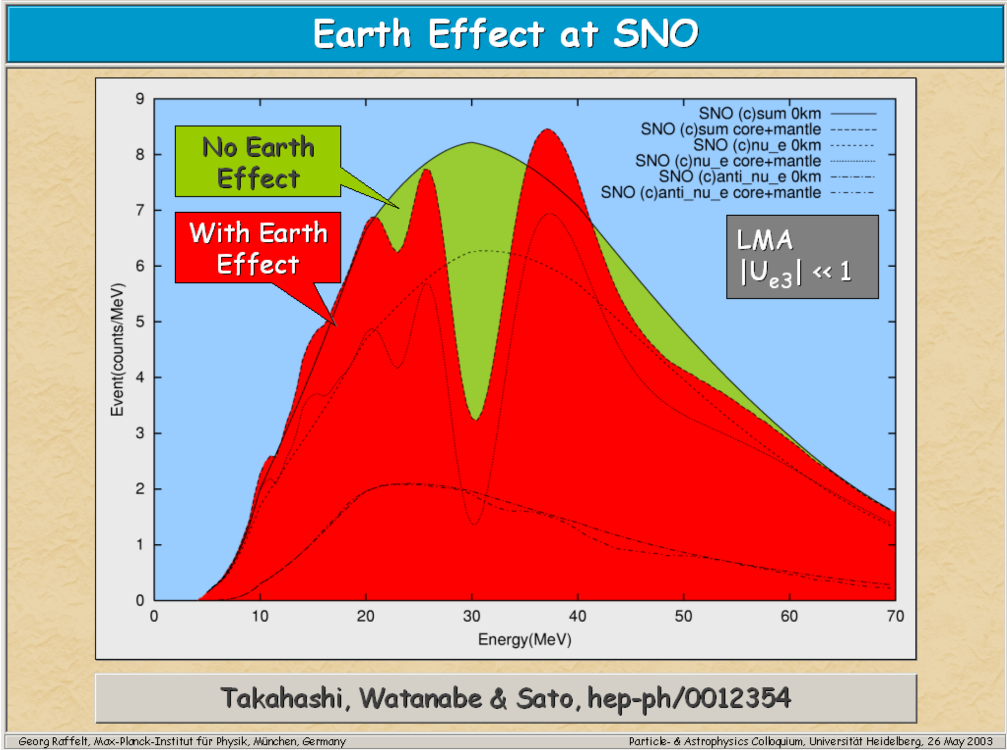
Heavy water (1 kt)	Events:
CC: $\nu_e + d \to p + p + e^-$	72
CC: $\overline{\nu}_e + d \to n + n + e^+$	138
NC: $\nu_e + d \to \nu_e + p + n$	30
NC: $\overline{\nu}_e + d \to \overline{\nu}_e + p + n$	32
NC: $\nu_x + d \to \nu_x + p + n$	164

Light water (1.4 kt)	Events:
CC: $\overline{\nu}_e + p \to n + e^+$	331

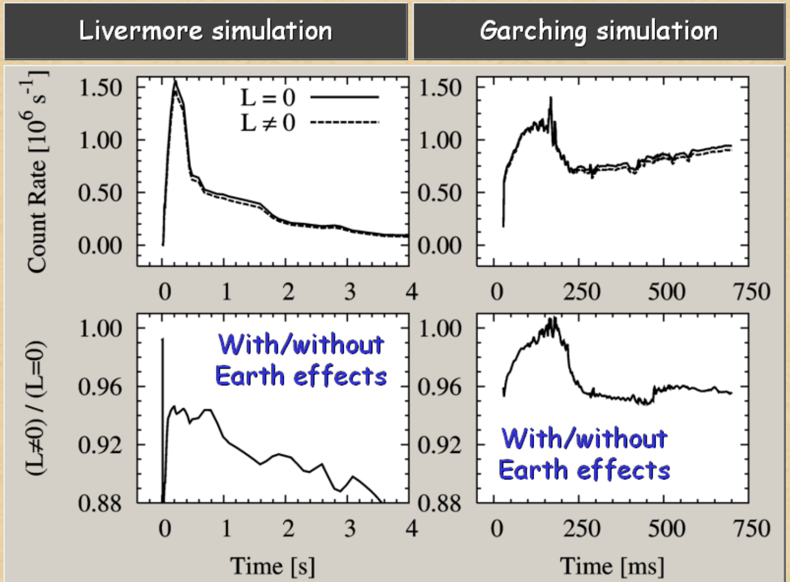

Three-Flavor Oscillation Scenario
Takahashi, Watanabe & Sato, hep-ph/0105204
SNO
SK
no osc
LMA-L
LMA-S
SMA-L
SMA-S
events(counts/MeV)
Energy(MeV)
No Oscillations
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003


Three-Flavor Oscillation Scenario
Takahashi, Watanabe & Sato, hep-ph/0105204
SNO
SK
no osc
LMA-L
LMA-S
SMA-L
SMA-S
events(counts/MeV)
Energy(MeV)
Oscillations with LMA and $|U_{e3}| \ll 1$
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003


Earth Effect at SNO
SNO (c)sum 0km
SNO (c)sum core+mantle
SNO (c)nu_e 0km
SNO (c)nu_e core+mantle
SNO (c)anti_nu_e 0km
SNO (c)anti_nu_e core+mantle
No Earth Effect
LMA $|U_{e3}| \ll 1$
Event(counts/MeV)
Energy(MeV)
Takahashi, Watanabe & Sato, hep-ph/0012354
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003


Earth Effect at SNO
SNO (c)sum 0km
SNO (c)sum core+mantle
SNO (c)nu_e 0km
SNO (c)nu_e core+mantle
SNO (c)anti_nu_e 0km
SNO (c)anti_nu_e core+mantle
No Earth Effect
With Earth Effect
LMA $|U_{e3}| \ll 1$
Event(counts/MeV)
Energy(MeV)
Takahashi, Watanabe & Sato, hep-ph/0012354
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

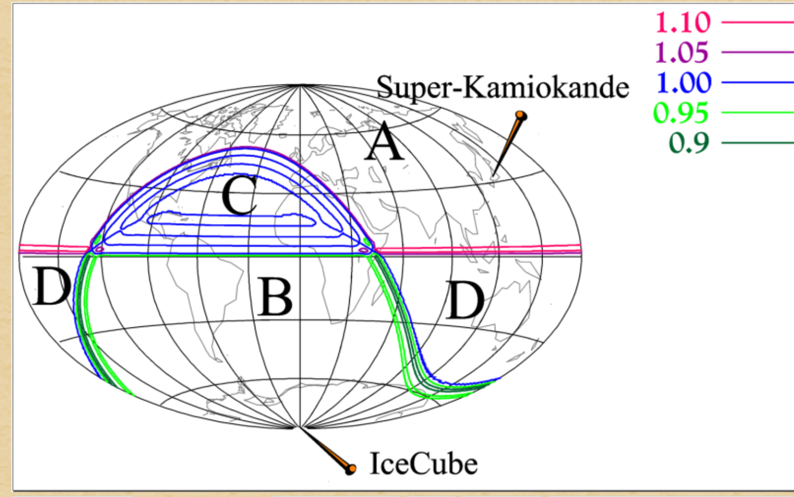
Observing the Earth Effects in IceCube



Dighe, Keil, Raffelt hep-ph/0303210

Statistical IceCube signal precision < 1%

Two-Detector Sky Coverage with Super-K & IceCube



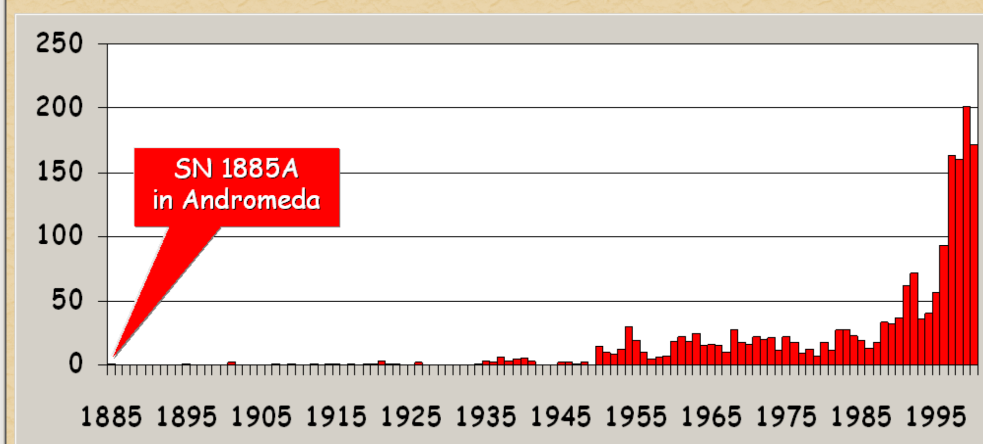
Dighe, Keil, Raffelt hep-ph/0303210

Earth effects appear in				
	IceCube	A	35%	Suitable for two-detector method
Super-K		B	35%	
Super-K	IceCube	C	15%	Approx. same signal in both detectors
		D	15%	

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany   Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

The Galactic Supernova Rate

Supernova Discoveries 1885-2000



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

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany   Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

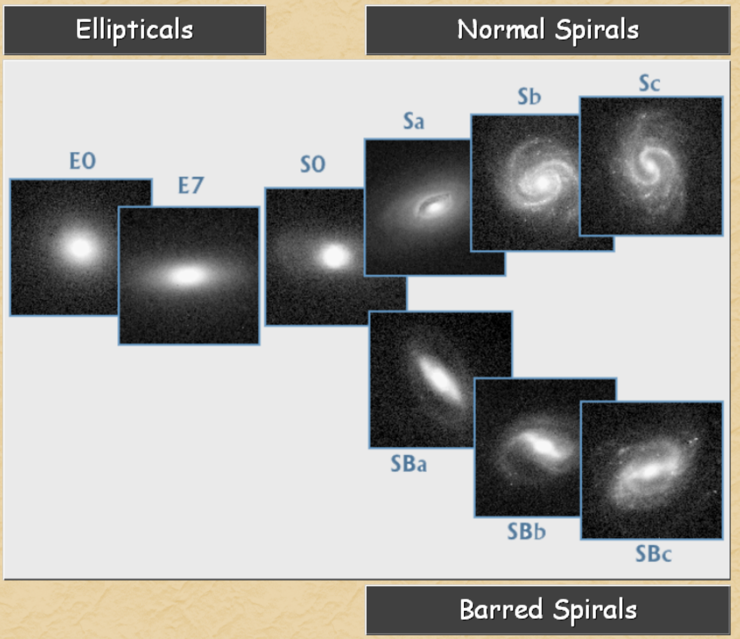
SN Statistics in External Galaxies

Cappellaro, Evans & Turatto, Astron. Astrophys. 351 (1999) 459
is latest study with largest sample

Limited controlled samples useful for this task:
- Photographic searches (7319 galaxies, 94 SNe)
- Evans' visual search 1980-1998 (3068 galaxies, 54 SNe)

Difficulties include:
- Galaxy blue luminosity (internal absorption)
- Distances (value of Hubble constant)
- Correction for inclination of galaxy (losing some SNe)
- Galaxy morphological classification
- Saturation in dense regions of photographic plates (galaxy cores)
- Limiting discovery brightness
- Intrinsic luminosity distribution of core-collapse SNe (many faint ones ?)
- Blue luminosity of Milky Way uncertain ($2.3 \pm 0.6 \times 10^{10}\ L_{sun}$)
- Morphological type of Milky Way

Hubble Sequence of Galaxy Types



Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Supernova Rates

Multiply numbers with h^2

Galaxy Type	Supernova Type: Ia	Core Collapse: Ib/c	Core Collapse: II	All
E-S0	0.32 ± .11	< 0.02	< 0.04	0.32 ± .11
S0a-Sb	0.32 ± .12	0.20 ± .11	0.75 ± .34	1.28 ± .37
SBc-Sd	0.37 ± .14	0.25 ± .12	1.53 ± .62	2.15 ± .66
All	0.36 ± .11	0.14 ± .07	0.71 ± .34	1.21 ± .36

Measured in SuperNova unit: 1 SNu = 1 SN / $10^{10}\ L_{sun,B}$ / 100 years

Milky Way Galaxy:
Type Sb-Sbc, $L_B = 2.3 \times 10^{10}\ L_{sun,B}$, $h = 0.75$
About 2.0 ± 1.0 core-collapse SNe per century

Cappellaro & Turatto, Supernova Types and Rates, astro-ph/0012455

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

Some Galaxies with Many Observed Supernovae

M83 (Southern Pinwheel)
D = 4.6 Mpc

Observed Supernovae:
1923A, 1945B, 1950B, 1957D, 1968L, 1983N

NGC 6946
D = 3.0 Mpc

Observed Supernovae:
1917A, 1939D, 1948B, 1968D, 1969P, 1980K

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Particle- & Astrophysics Colloquium, Universität Heidelberg, 26 May 2003

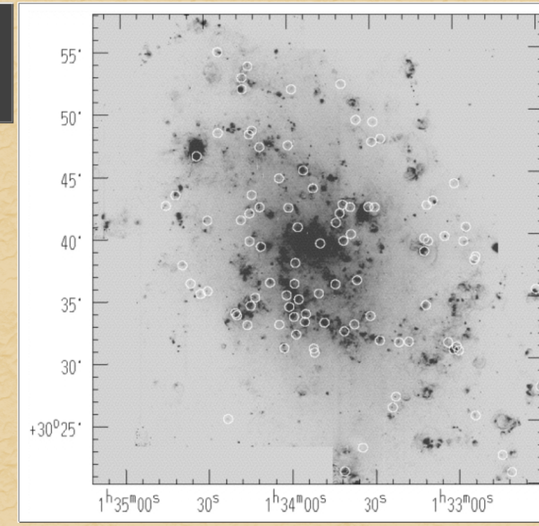
Andromeda Galaxy (M31)

- SN 1885A is the only historical SN in Andromeda (M31) (distance 760 kpc)
- We see all of the galaxy - one probably would not have missed a SN by obscuration
- Probably low star formation rate (low FIR luminosity)

~ 1.2 SN/century
Tammann et al.
Ap. J. Suppl. Ser. 92 (1994) 487

Supernova Remnants in M33 (Triangulum)

Hα image of M33 (Triangulum)



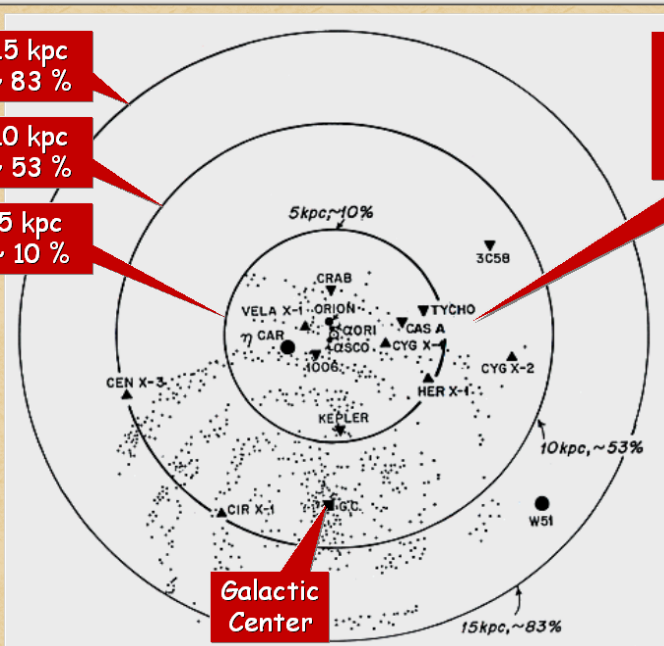
S.M. Gordon et al.,
A New Optical Sample of Supernova Remnants in M33
Astrophys. J. Suppl. 117 (1998) 89.

Galactic Supernova Events

15 kpc
~ 83 %

10 kpc
~ 53 %

5 kpc
~ 10 %



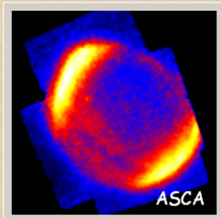
Most historical supernovae in ~ 10% of the galaxy

Anomalously large rate in our galaxy?

Small-number statistics?

Adam Burrows

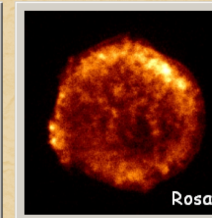
Historical Supernovae (Local Group) since AD 1000



SN 1006
1.5 kpc

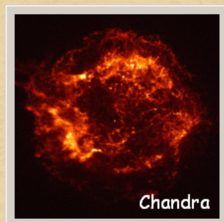
SN 1054 Crab
Type II 2 kpc
Pulsar

SN 1181 3C 58
8 kpc



SN 1572 Tycho
Type Ia 3 kpc

SN 1604 Kepler
Type II ? 4-8 kpc

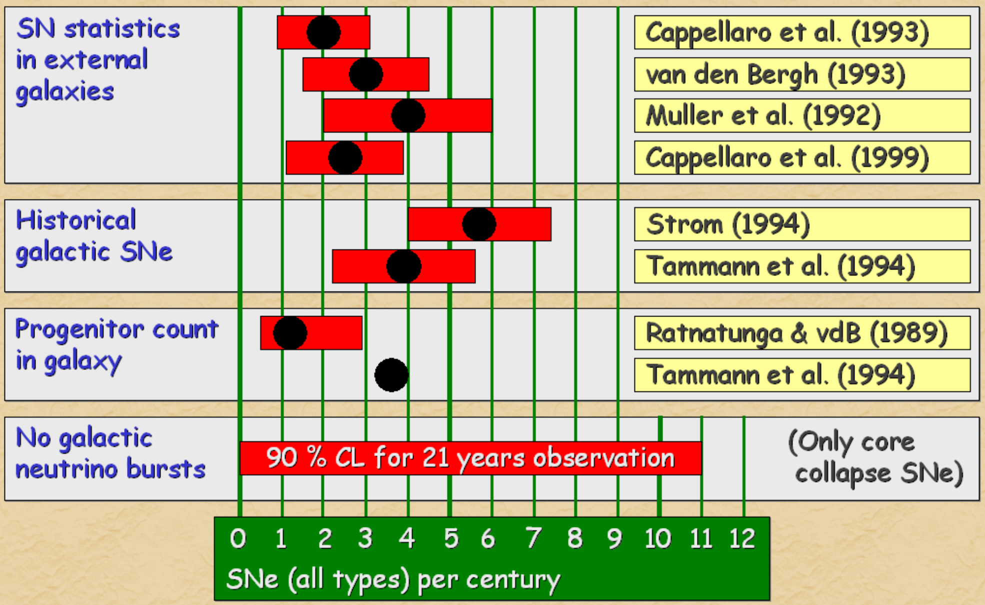


SN 1680? Cas A
Type II 2.8 kpc
Neutron Star

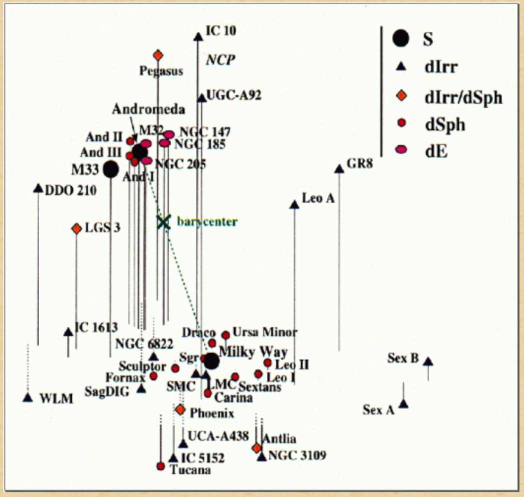
SN 1885
Andromeda
760 kpc

SN 1987A LMC
Type II 50 kpc
No pulsar

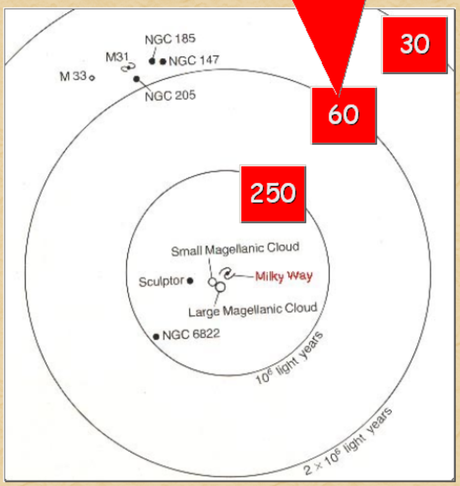
Estimates of the Galactic SN Rate



Local Group of Galaxies



Events in a detector with 30 × Super-K fiducial volume, e.g. Hyper-Kamiokande

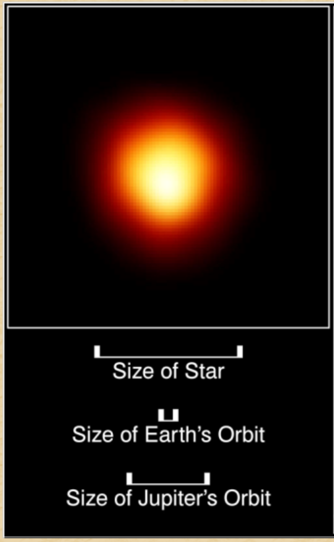


Brightest Members of Local Group

	Type	Lumin	D [kpc]	Neutrino events	SNe (all types) per century
Milky Way	S(B)bc	1	8.5	330,000	1-6
LMC	Ir	0.11	50	9,600	0.1 / 0.23 / 0.49
SMC	Ir	0.030	60	6,600	0.065 / 0.12
NGC 6822	Ir	0.011	500	96	0.04
IC 10 (UGC 192)	Ir	0.015	660	55	0.082-0.11
NGC 205	Sph	0.016	760	42	
M32 (NGC 221)	E2	0.017	760	42	
Andromeda (M31)	Sb	1.3	760	42	0.9 / 1.21 / 1.25
Triangulum (M33)	Sc	0.16	790	38	0.28 / 0.35 / 0.68

- Luminosity: Visual in units of the Milky Way
- Neutrino events in 30 × SK fiducial volume (8000 events in SK for SN at 10 kpc)
- Refs. for SN rates in Pavlidou & Fields, Ap. J. 558 (2001) 63.

The Red Supergiant Betelgeuse (Alpha Orionis)



First resolved image of a star other than Sun

Distance (Hipparcos) 130 pc (425 lyr)

If Betelgeuse goes Supernova 6×10^7 neutrino events in Super-Kamiokande

Neutrinos From All Cosmic Supernovae

Diffuse Background Flux of SN Neutrinos

1 SNu = 1 SN / 10^{10} $L_{sun,B}$ / 100 years
$L_{sun,B}$ = 0.54 L_{sun} = 2 × 10^{33} erg/s
E_ν ~ 3 × 10^{53} erg per core-collapse SN

→ 1 SNu ~ 4 L_ν / $L_{\gamma,B}$
Average neutrino luminosity of galaxies ~ photon luminosity

- Photons come from nuclear energy
- Neutrinos from gravitational energy

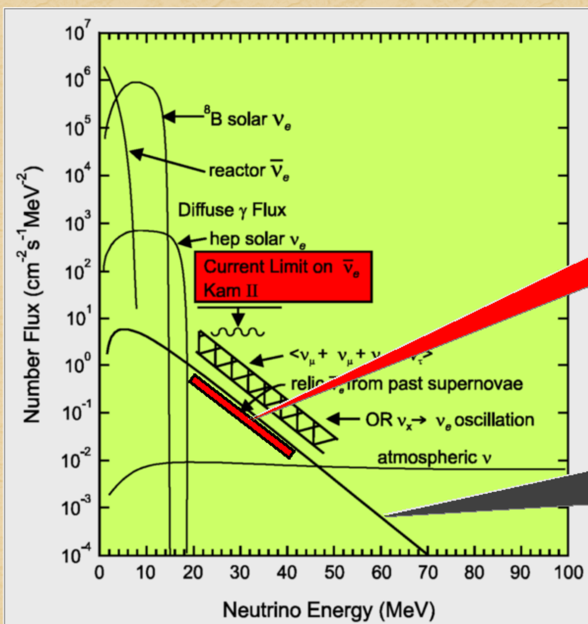
→ For galaxies, average nuclear & gravitational energy release similar

Present-day SN rate of ~ 1 SNu, extrapolated to the entire universe, corresponds to ν_e flux of ~ 1 cm^{-2} s^{-1}

Realistic flux dominated by much larger early star-formation rate
- Upper limit ~ 54 cm^{-2} s^{-1}
  [Kaplinghat et al., astro-ph/9912391]
- "Realistic estimate" ~ 10 cm^{-2} s^{-1}
  [Hartmann & Woosley, Astropart. Phys. 7 (1997) 137]

Measurement would tell us about early history of star formation

Experimental Limits on Relic SN Neutrinos



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

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

Cline, astro-ph/0103138

Search for Cosmic SN Nus at Super-Kamiokande

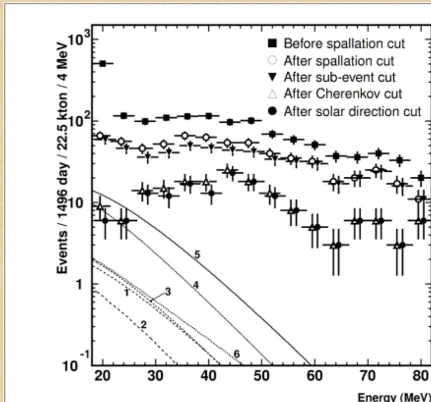


FIG. 1: Energy spectrum at each reduction step. In the final data set, the spallation cut and solar direction cut are only applied in the first four bins. The numbered lines represent the corresponding theoretical predictions from Table I.

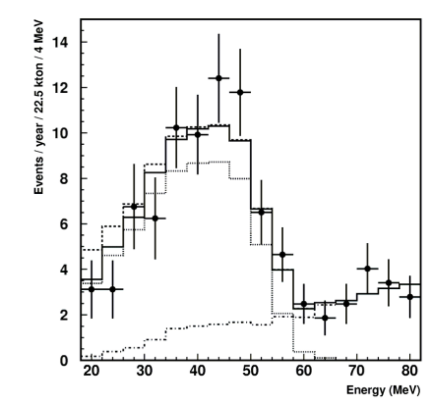


FIG. 2: Energy spectrum of SRN candidates. The dotted and dash-dot histograms are the fitted backgrounds from invisible muons and atmospheric ν_e. The solid histogram is the sum of these two backgrounds. The dashed line shows the sum of the total background and the 90% upper limit of the SRN signal.

hep-ex/0209028

Search for Cosmic SN Nus at Super-Kamiokande

TABLE I: The SRN search results are presented for six theoretical models. The first column describes the method used to calculate the SRN flux. The second column shows the efficiency-corrected limit on the SRN event rate at SK. The third column is the flux limit set by SK, which can be compared with the theoretical predictions that are shown in the fourth column. The fifth column shows the flux predictions above a threshold of $E_\nu > 19.3$ MeV . Note that the heavy metal abundance calculation only sets a theoretical upper bound on the SRN flux [7].

Theoretical model	Event rate limit (90% C.L.)	SRN flux limit (90% C.L.)	Predicted flux	Predicted flux ($E_\nu > 19.3$ MeV)
Galaxy evolution [4]	< 3.2 events/year	$< 130\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$44\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$0.41\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$
Cosmic gas infall [5]	< 2.8 events/year	$< 32\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$5.4\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$0.20\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$
Cosmic chemical evolution [6]	< 3.3 events/year	$< 25\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$8.3\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$0.39\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$
Heavy metal abundance [7]	< 3.0 events/year	$< 29\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$< 54\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$< 2.2\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$
Constant supernova rate [4]	< 3.4 events/year	$< 20\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$52\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$3.1\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$
Large mixing angle osc. [8]	< 3.5 events/year	$< 31\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$11\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$	$0.43\ \bar\nu_e\ \mathrm{cm^{-2}\ s^{-1}}$

hep-ex/0209028

Improved Sensitivity with Neutron Tagging

M.Vagins, Talk at NOON 2003, http://www-sk.icrr.u-tokyo.ac.jp/noon2003/

Super-Kamiokande limited by
- Solar neutrinos for E_ν < 18-19 MeV
- Sub-Cherenkov muons from atm nus $\mu \to e + \nu_e + \bar\nu_\mu$

Solution:
Neutron tagging $\bar\nu_e + p \to e^+ + n$

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

Add gadolinium to SK:
- Efficient neutron capture
- 8 MeV gamma cascade, easily visible
- 0.1 % (100 tons of Gd Cl_3) achieves > 90% tagging efficiency

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

A Modest Proposal

Pouring a bunch of stuff into Super–K is a big step, and not to be done lightly, no matter how promising things may look initially.

Here's what comes next:

1) Spend the next year or so exploring the chemistry, stability, and optical properties of $GdCl_3$ in detail.
2) Understand any changes needed in the SK water system and Monte Carlo the modified detector's response using what's learned above as input.
3) Build a small test tank (one supermodule) with exactly the same materials as in SK. Put in PMT's, cables, water, and $GdCl_3$ and let it sit for two years. Check for $GdCl_3$-induced damage.
4) If everything looks good, in the last month(s) of SK–II put in 9 tons of $GdCl_3$ to make sure we really understand our backgrounds. Look for reactor antineutrinos!

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

Onward, Ever Onward

Finally, if every test *still* looks good, mix 100 tons of $GdCl_3$ into SK–III and prepare for the bright new days of supernova and reactor neutrino data ahead!