

Supernova Neutrinos



Sanduleak -69 202



Tarantula Nebula

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



Sanduleak -69 202



Supernova 1987A

23 February 1987



- SN 1987A in the LMC the only certain identification of progenitor star
- SN 1993J in M81 another tentative case



Supernovae - Almost as Bright as Galaxies



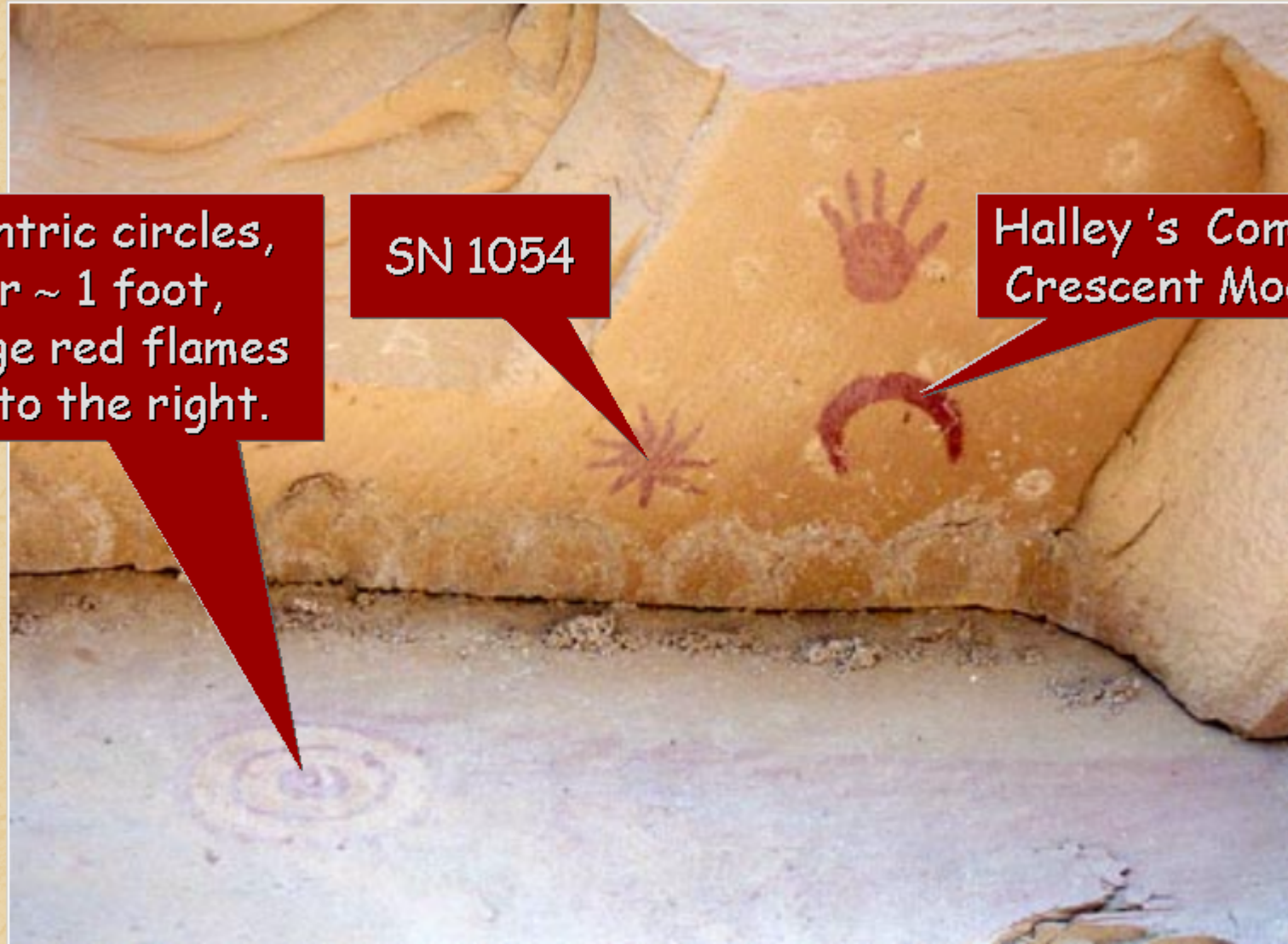
SN 1998S in NGC 3877



SN 1994D in NGC 4526

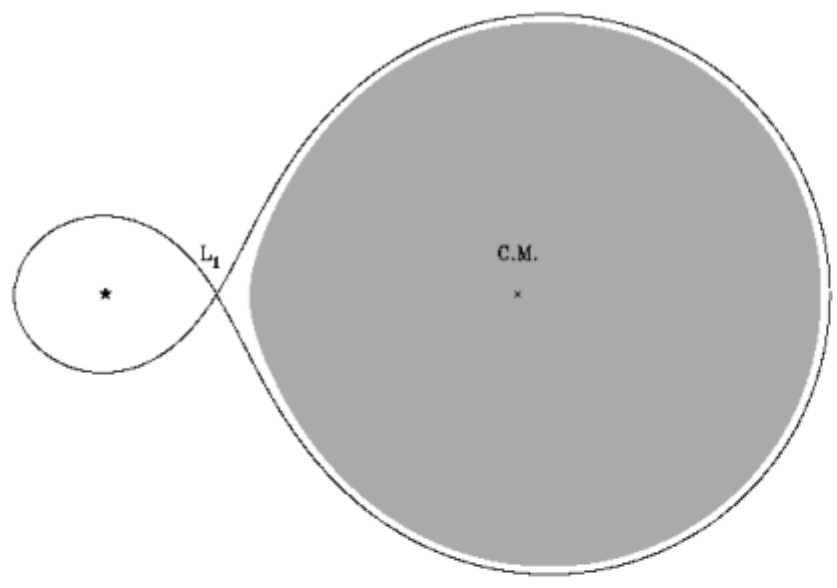
凡十一日没三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁没明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日没至和元年五月己丑出天關東南可數寸歲餘稍没熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

Supernova 1054 Petrograph

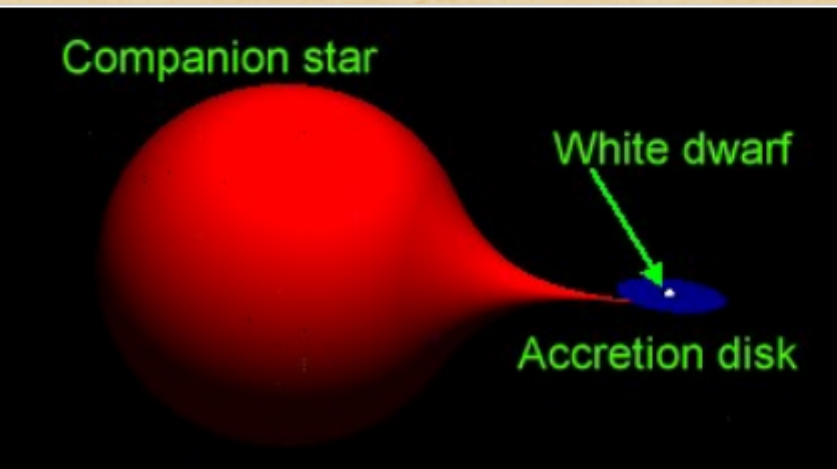


**Possible SN 1054 Petrograph by the Anasazi people
(Chaco Canyon, South-Western U.S.)**

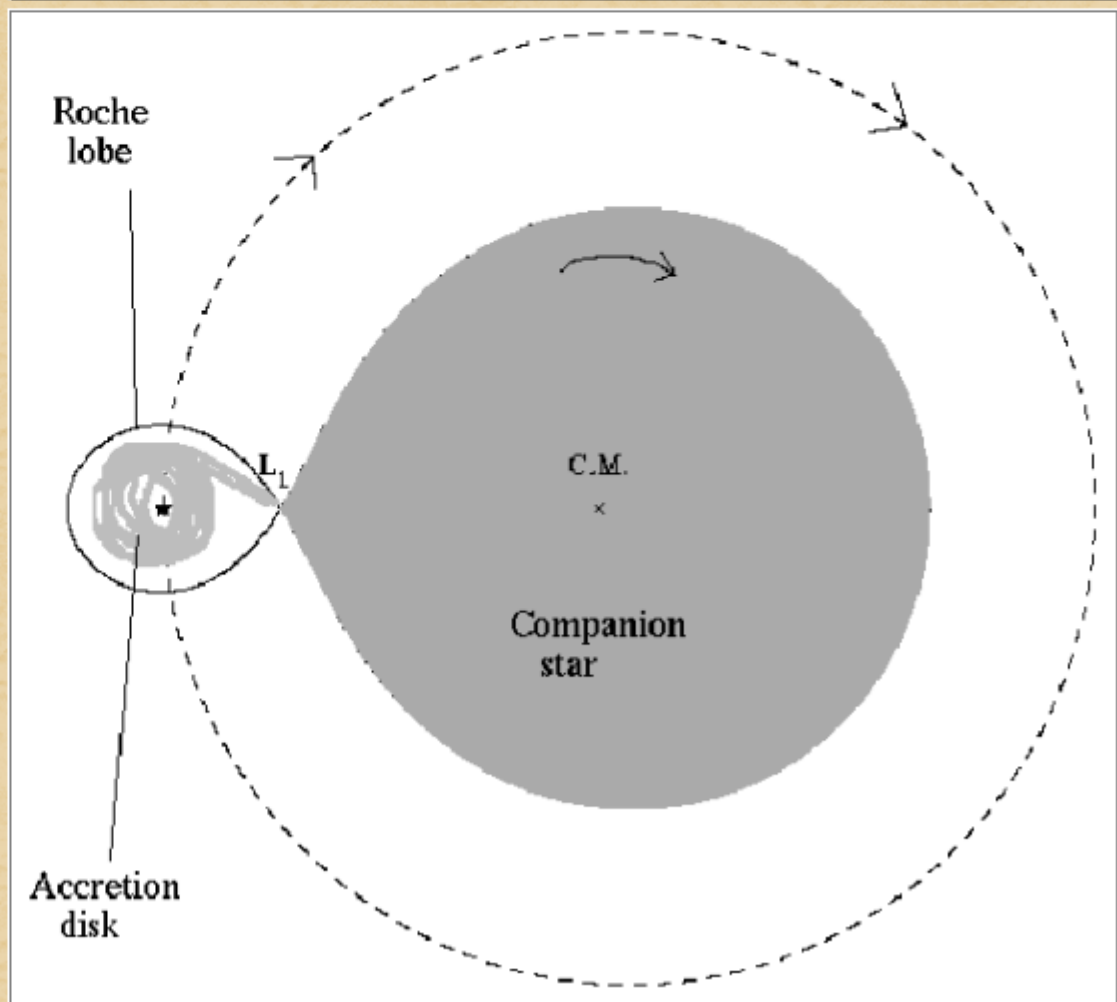
Mass Transfer in Binary Stars



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

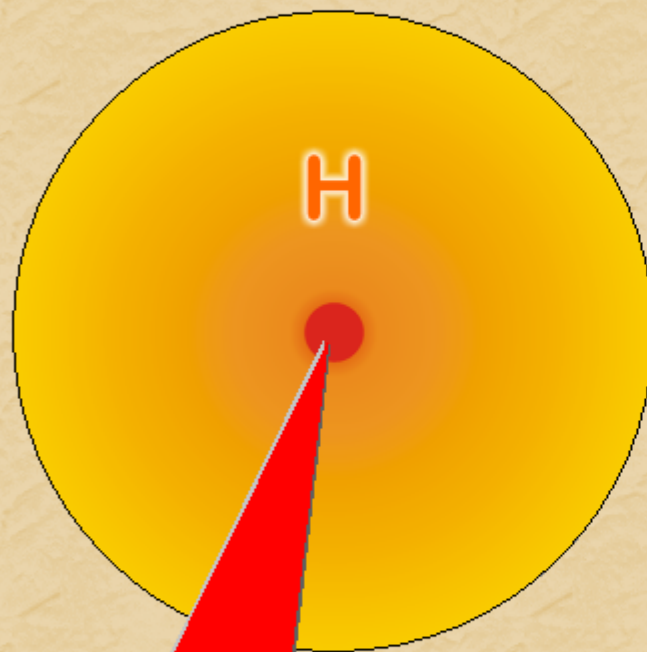


Roche-lobe overflow feeds mass to the compact star



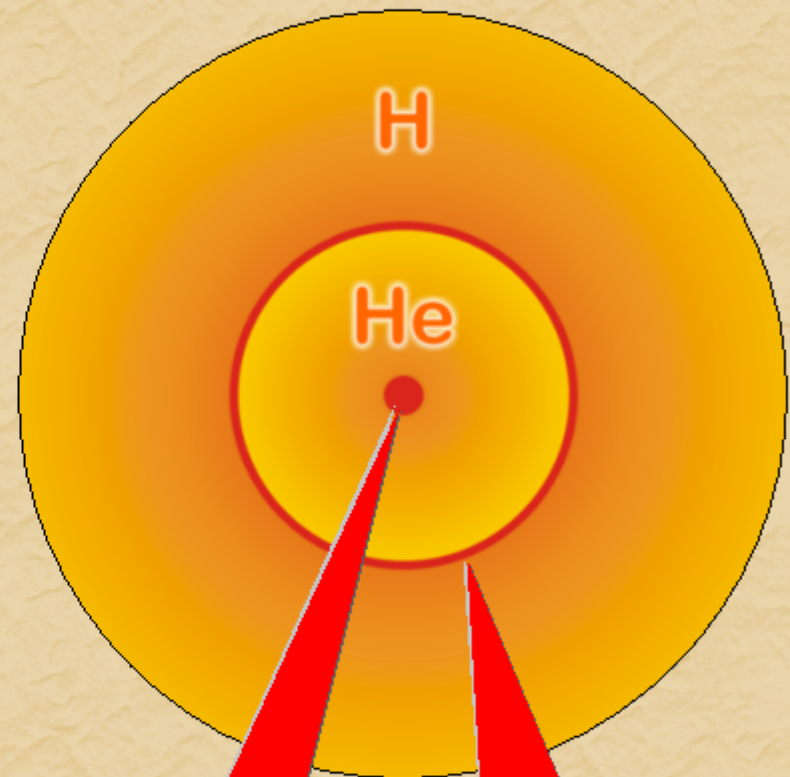
Stellar Collapse and Supernova Explosion

Main Sequence Star



Hydrogen Burning

Red Giant Star



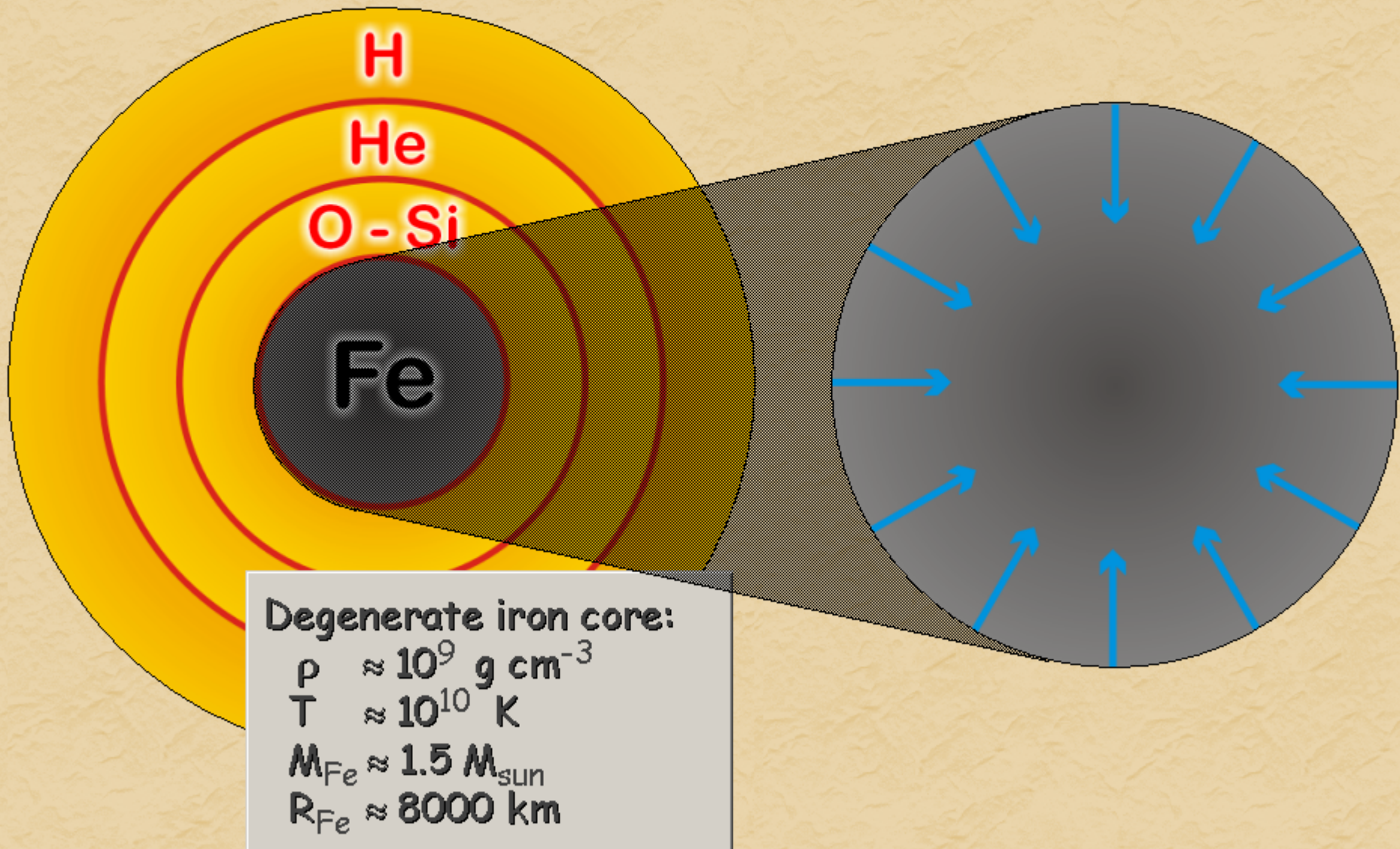
Helium
Burning

Hydrogen
Burning

Stellar Collapse and Supernova Explosion

Onion Structure

Collapse (Implosion)



Stellar Collapse and Supernova Explosion

Newborn Neutron Star

Explosion

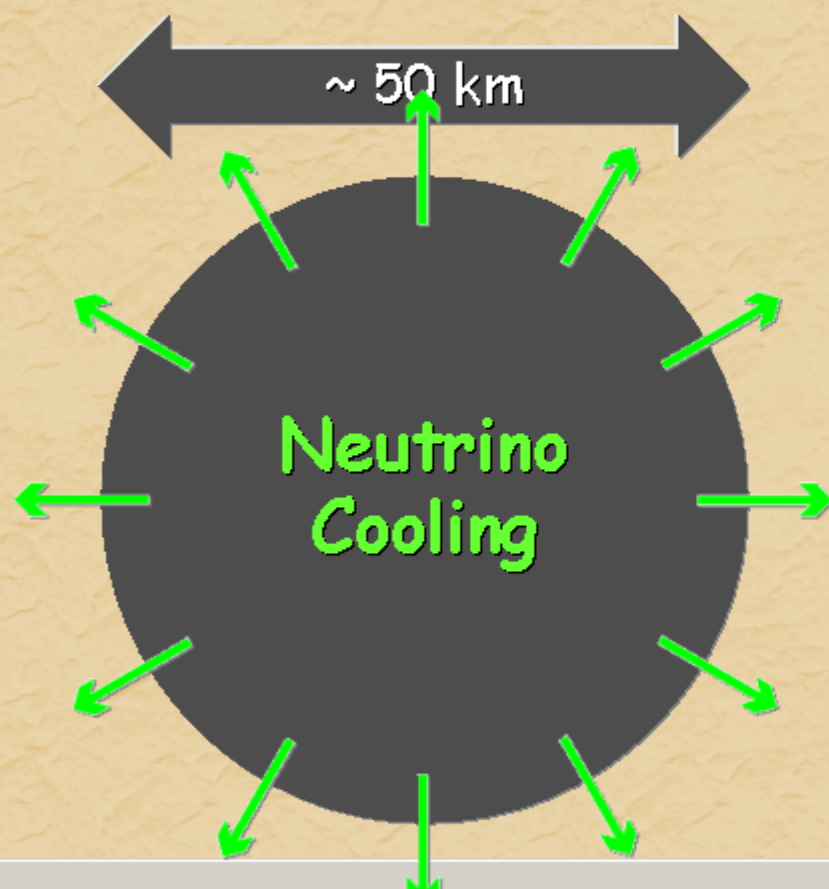
~ 50 km

Neutrino
Cooling

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

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



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

Gravitational binding energy

$$E_b \approx 3 \times 10^{53} \text{ erg} \approx 17\% M_{\text{SUN}} c^2$$

This shows up as

99% Neutrinos

1% Kinetic energy of explosion
(1% of this into cosmic rays)

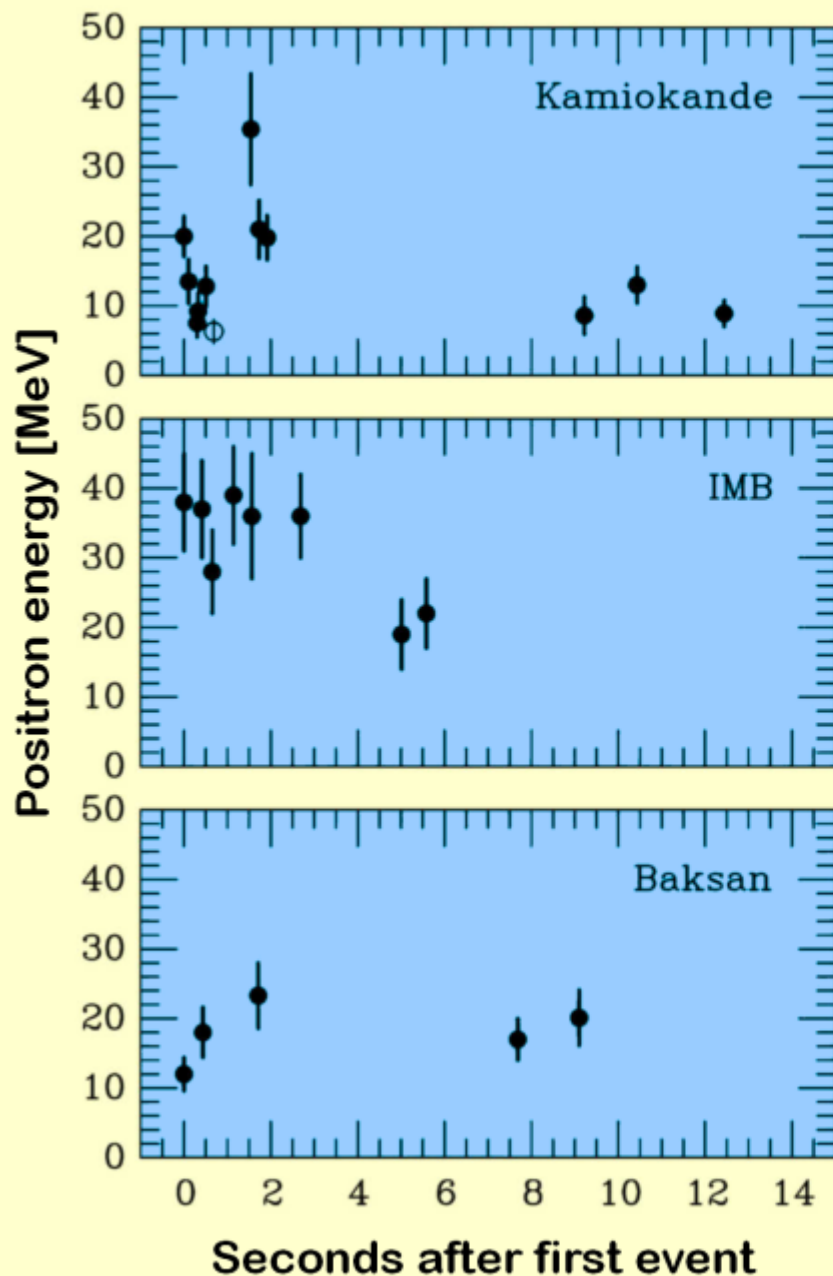
0.01% Photons, outshine host galaxy

Neutrino luminosity

$$L_\nu \approx 3 \times 10^{53} \text{ erg} / 3 \text{ sec} \\ \approx 3 \times 10^{19} L_{\text{SUN}}$$

While it lasts, outshines the entire visible universe

Neutrino Signal of Supernova 1987A



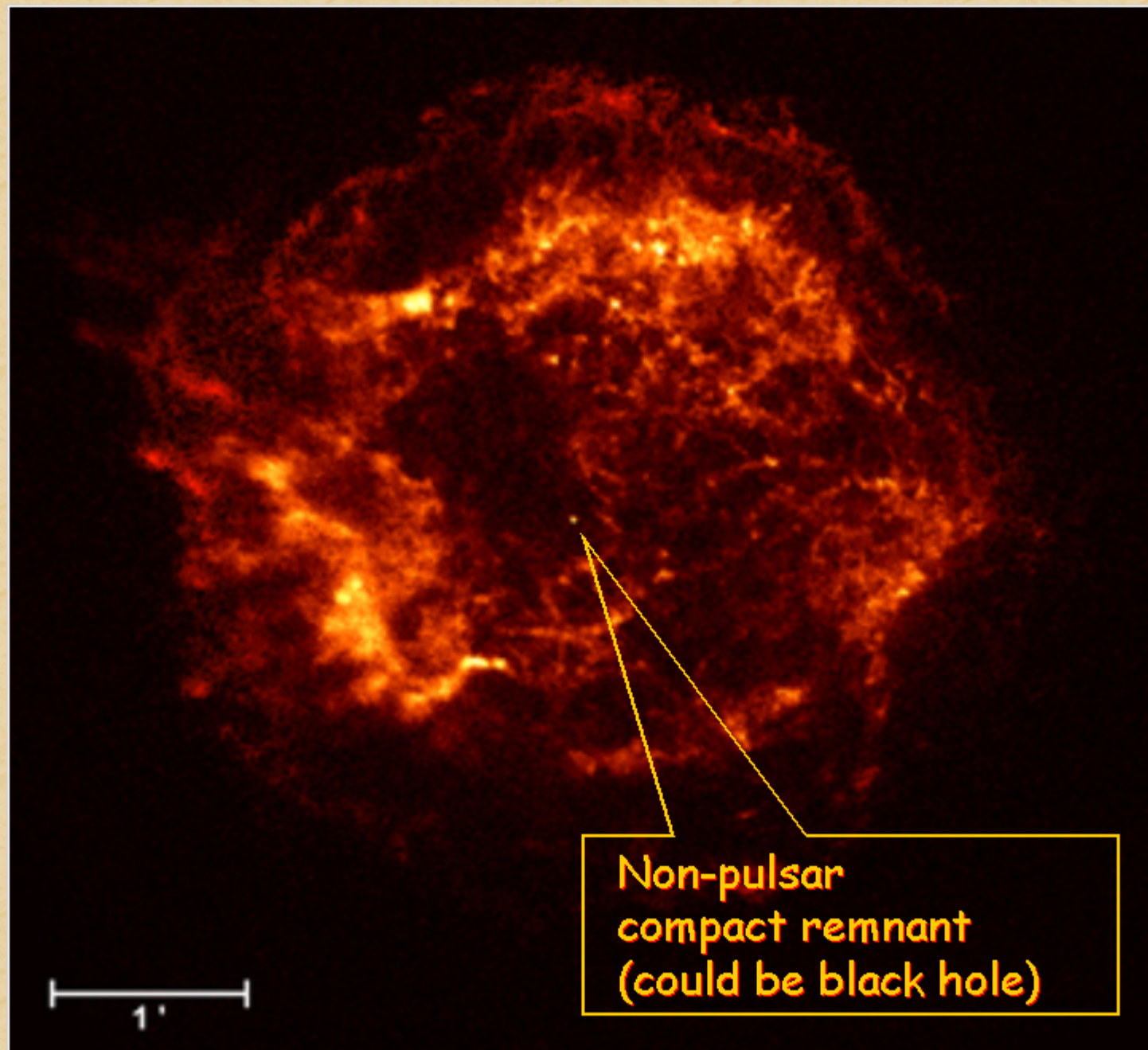
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ± 1 min

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



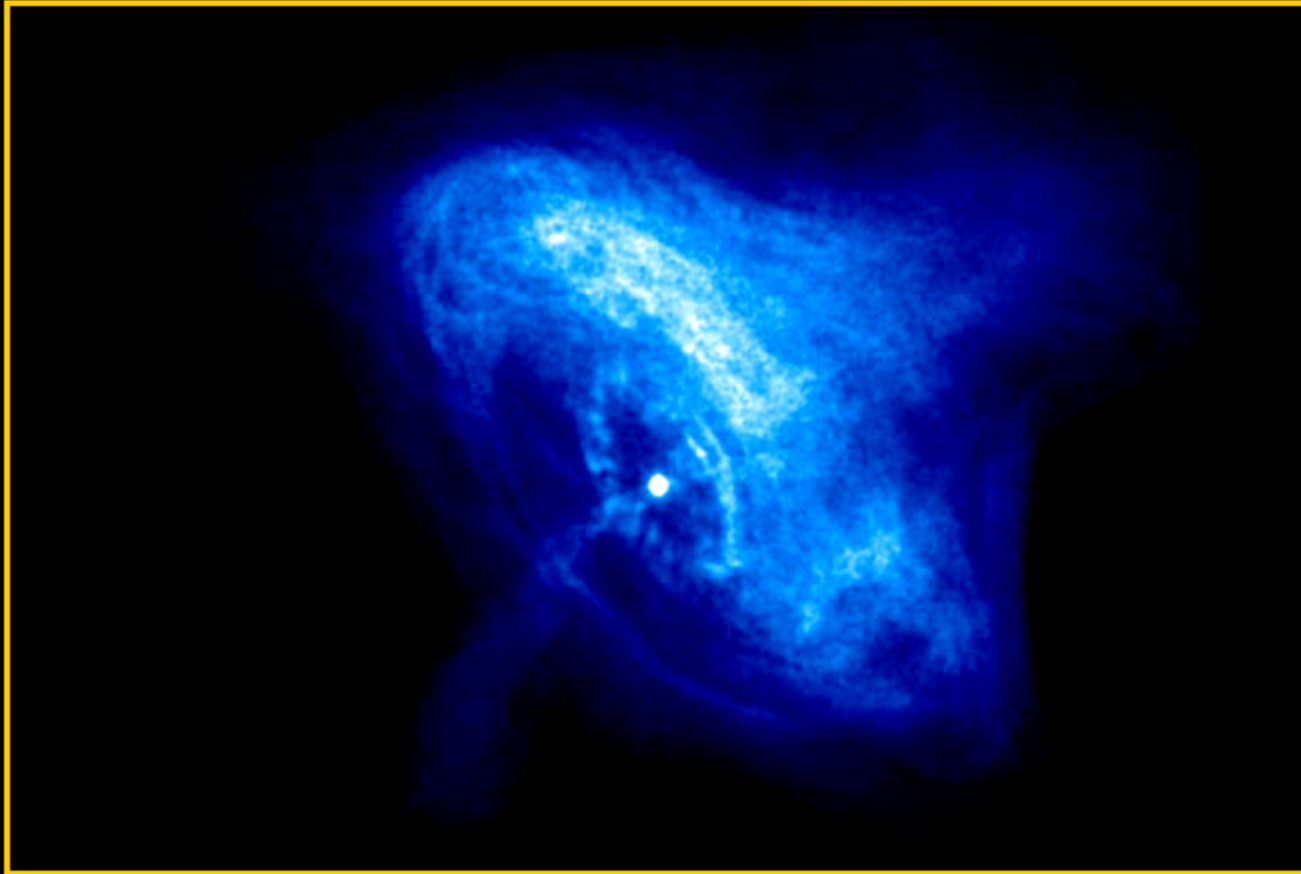
Walter Baade (1893-1960)



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



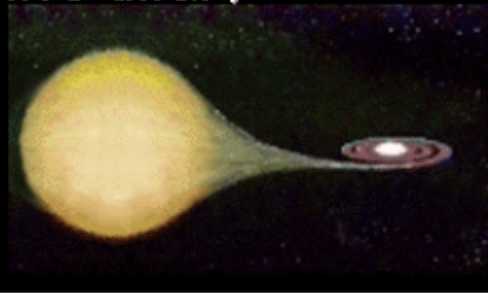
Chandra x-ray images



Type Ia vs. Core-Collapse Supernovae

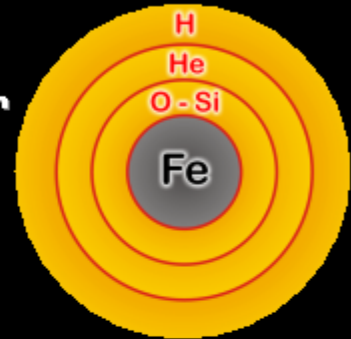
Type Ia

Carbon-oxygen white dwarf
(remnant of
low-mass star)
accretes matter
from companion



Core collapse (Type II, Ib/c)

Degenerate iron core
of evolved massive star
Accretes matter
by nuclear burning
at its surface



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

COLLAPSE SETS IN

Nuclear burning of C and O ignites
→ Nuclear deflagration
("Fusion bomb" triggered by collapse)

Powered by nuclear binding energy

Gain of nuclear binding energy
~ 1 MeV per nucleon

Collapse to nuclear density
Bounce & shock
Implosion → Explosion

Powered by gravity

Gain of gravitational binding energy
~ 100 MeV per nucleon
99% into neutrinos

Comparable "visible" energy release of $\sim 3 \times 10^{51} \text{erg}$

Supernovae the Power Supply for Cosmic Rays?

Required power supply

$$L_{\text{CR}} = V_{\text{D}} \rho_{\text{CR}} / \tau_{\text{res}} \\ \approx 5 \times 10^{40} \text{ erg/s} \approx 10^7 L_{\text{Sun}}$$

Disk volume

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

Energy density in CRs

$$\rho_{\text{CR}} \approx 1 \text{ eV} / \text{cm}^3$$

Residence time in galaxy

$$\tau_{\text{res}} \approx 6 \times 10^6 \text{ yrs}$$

Suggestive of supernovae:

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

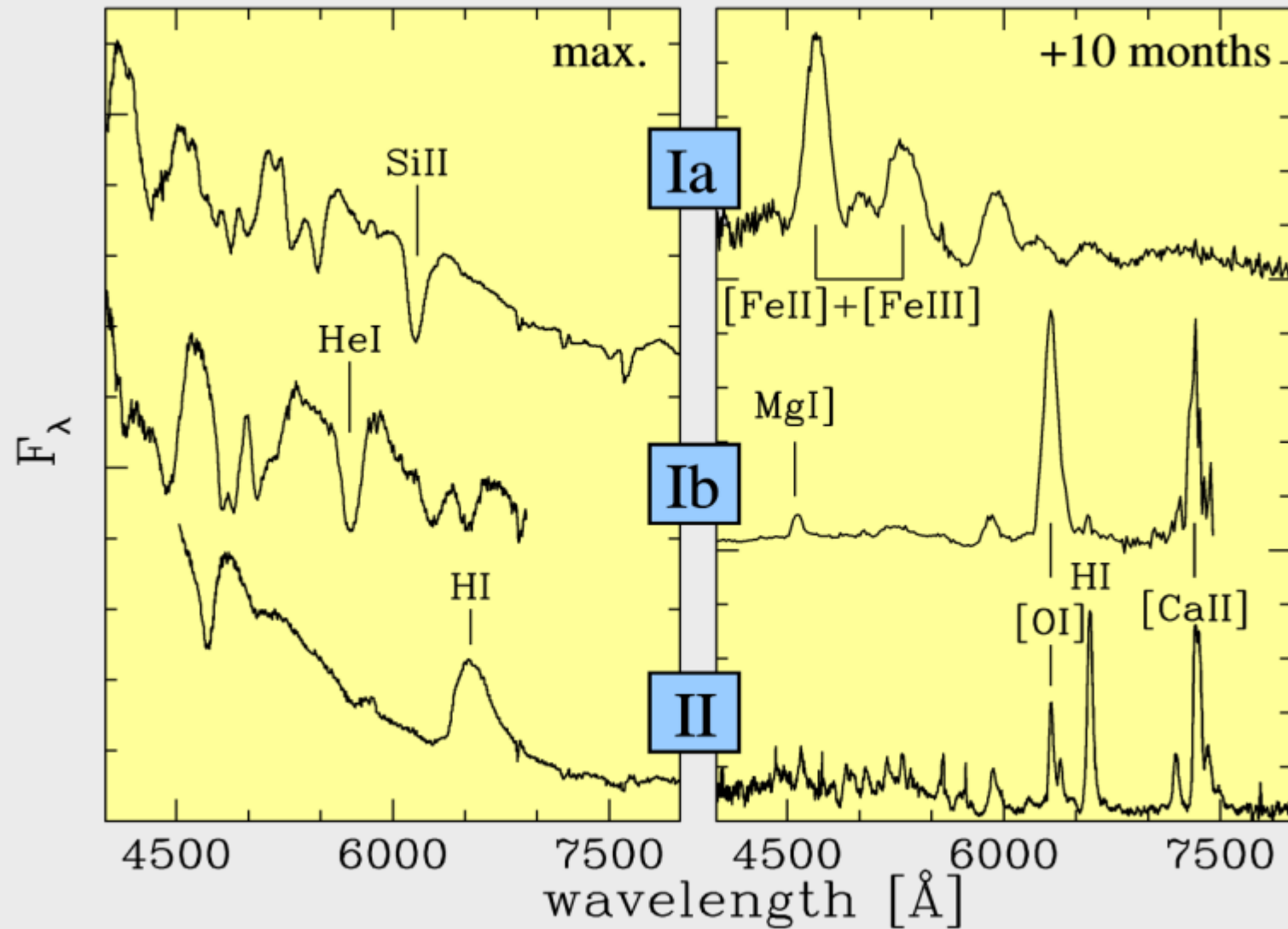
Total average energy deposition: $L_{\text{SN}} \approx 3 \times 10^{42} \text{ erg/s} \approx 50 L_{\text{CR}}$

Efficiency of a few percent required

Classification of Supernovae

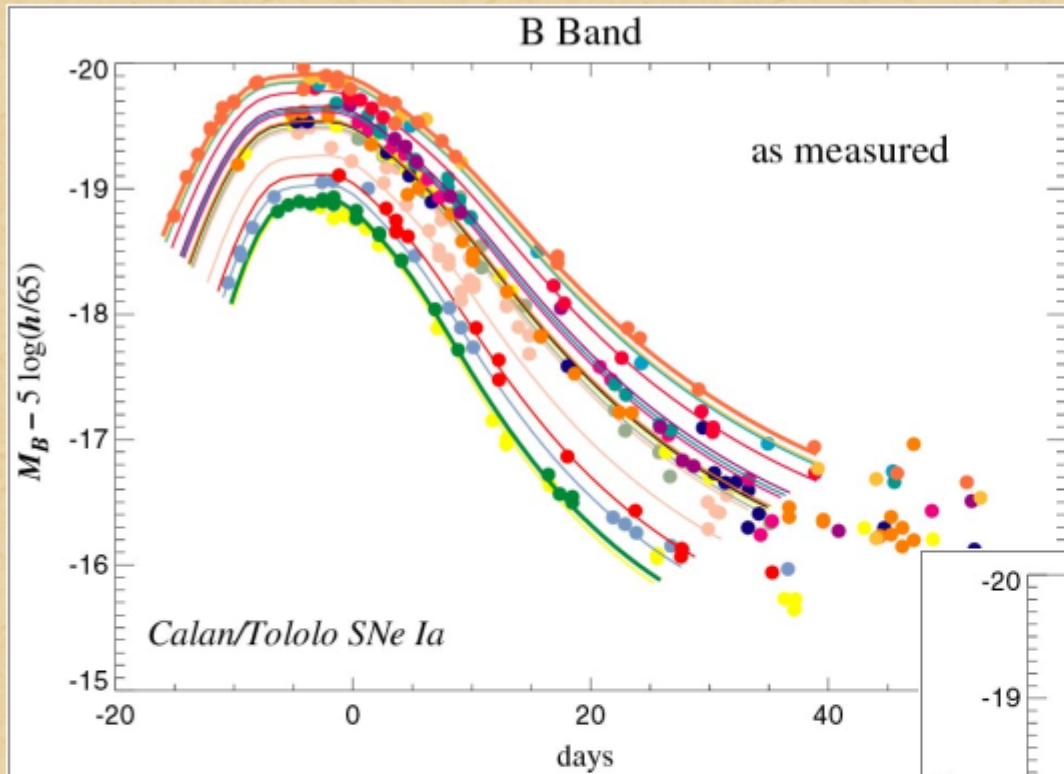
Spectral Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical Mechanism	Nuclear explosion of low-mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light Curve	Reproducible	Large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



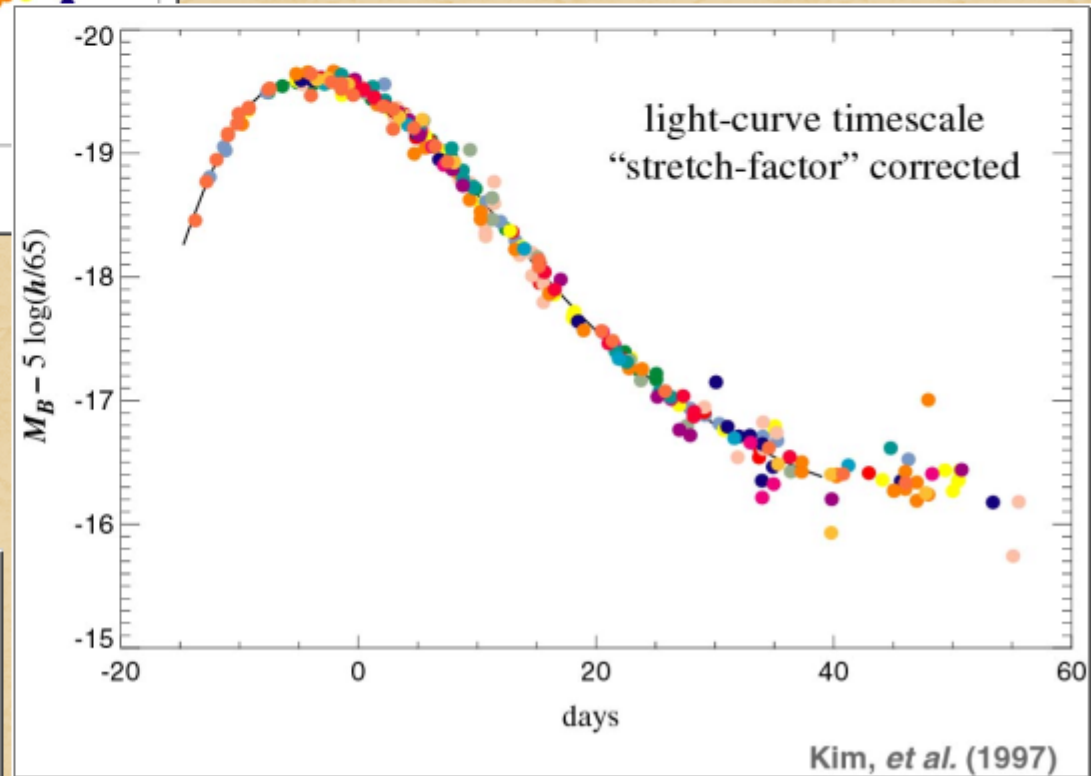
Cappellaro and Turatto, astro-ph/0012455

Universal Supernova Ia Light Curve

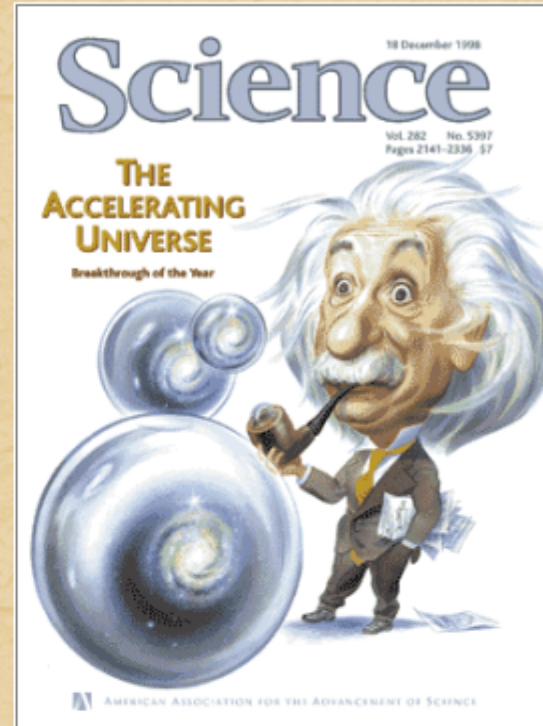
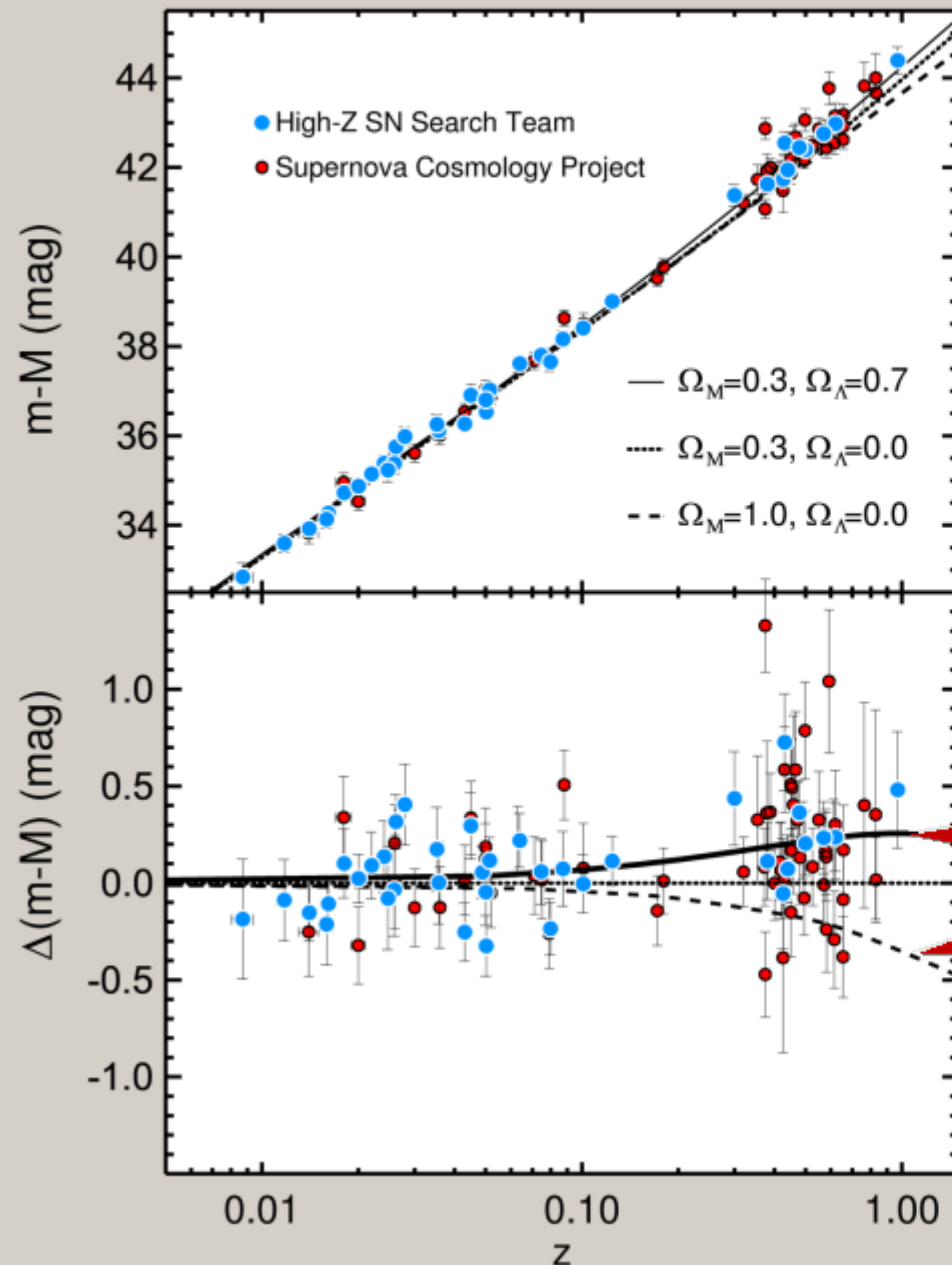


Measured supernova Ia light curves are empirically a 1-parameter family

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



Hubble Diagram - Accelerated Expansion

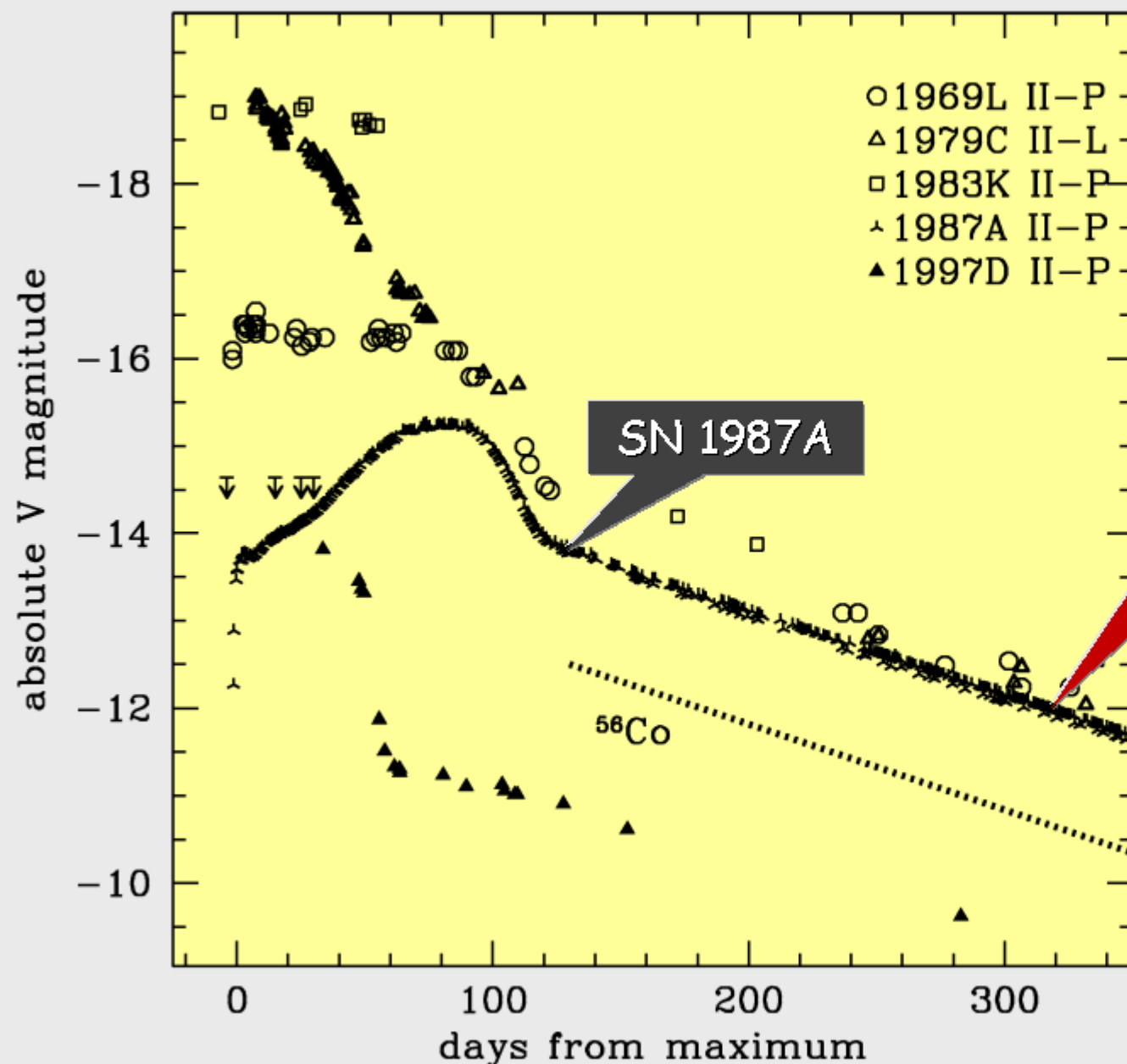


Accelerated expansion
(cosmological constant dominates)

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

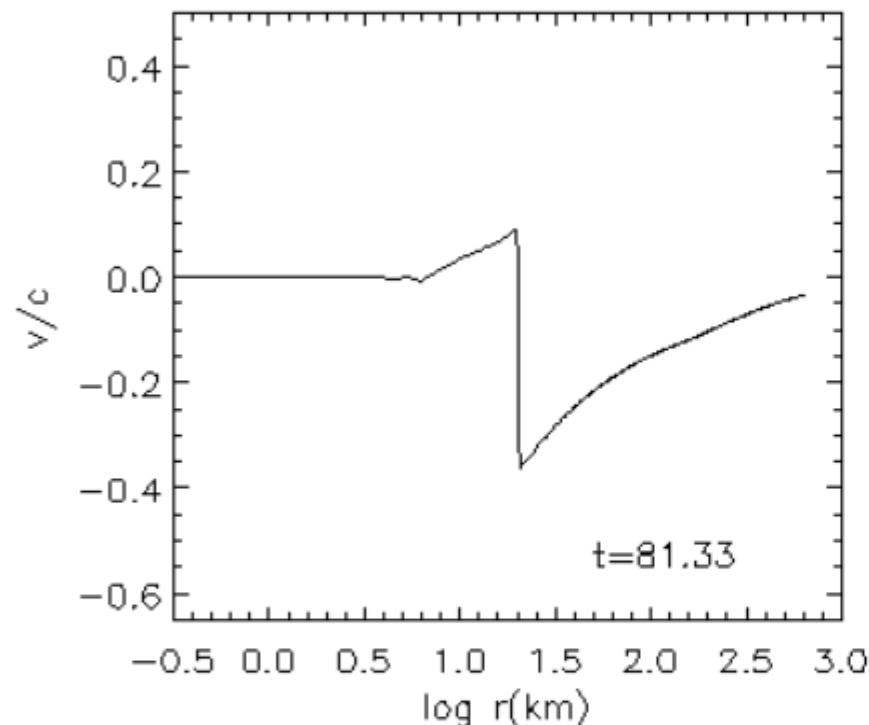
Cappellaro & Turatto,
astro-ph/0012455

Explosion Mechanism for Core-Collapse SNe

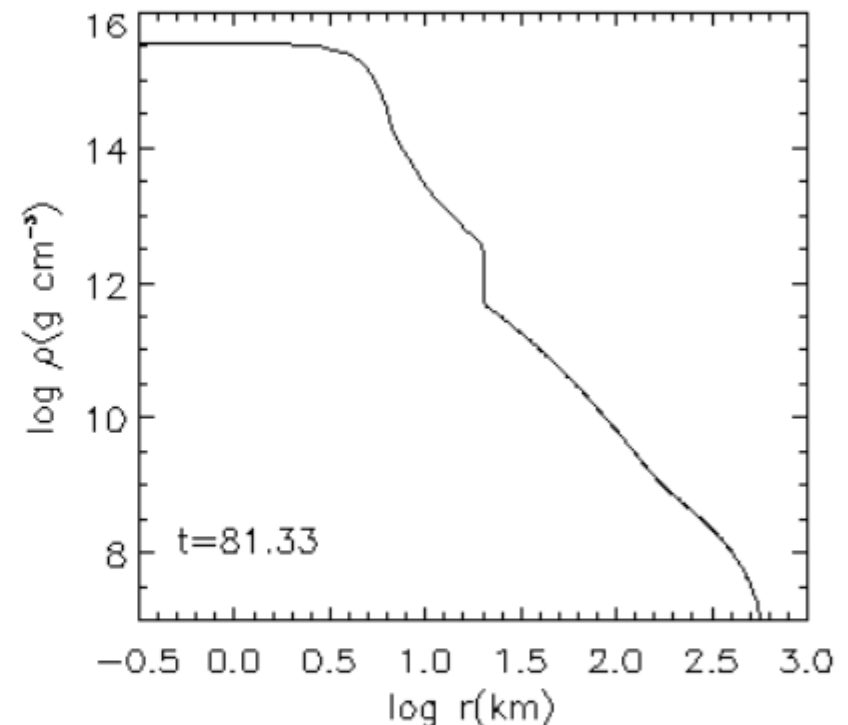


Collapse and Prompt Explosion

Velocity



Density

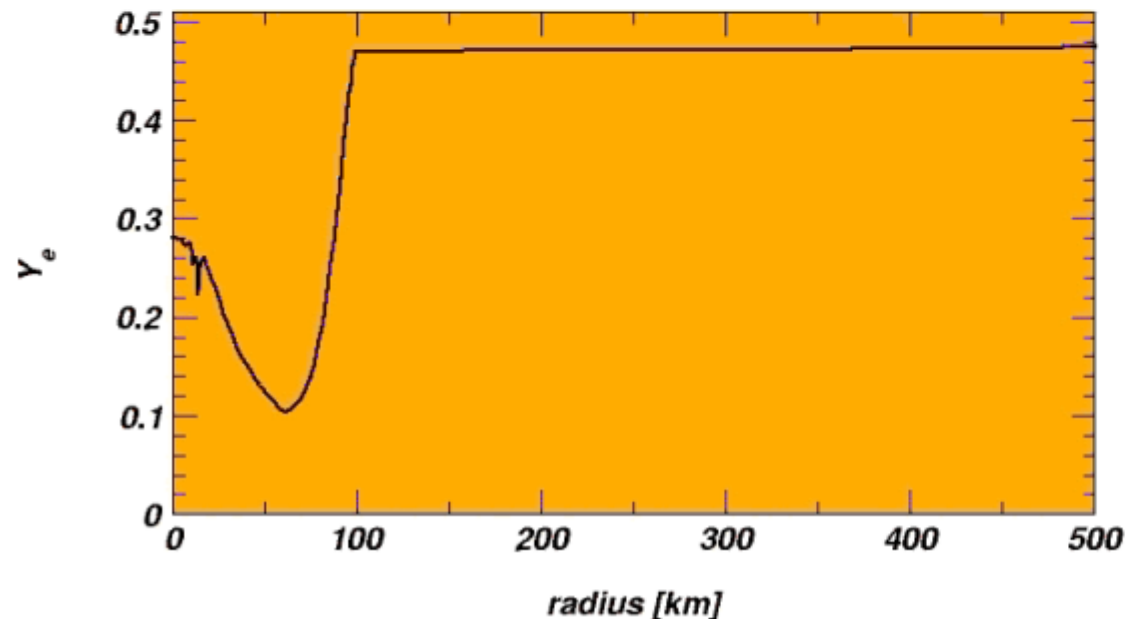
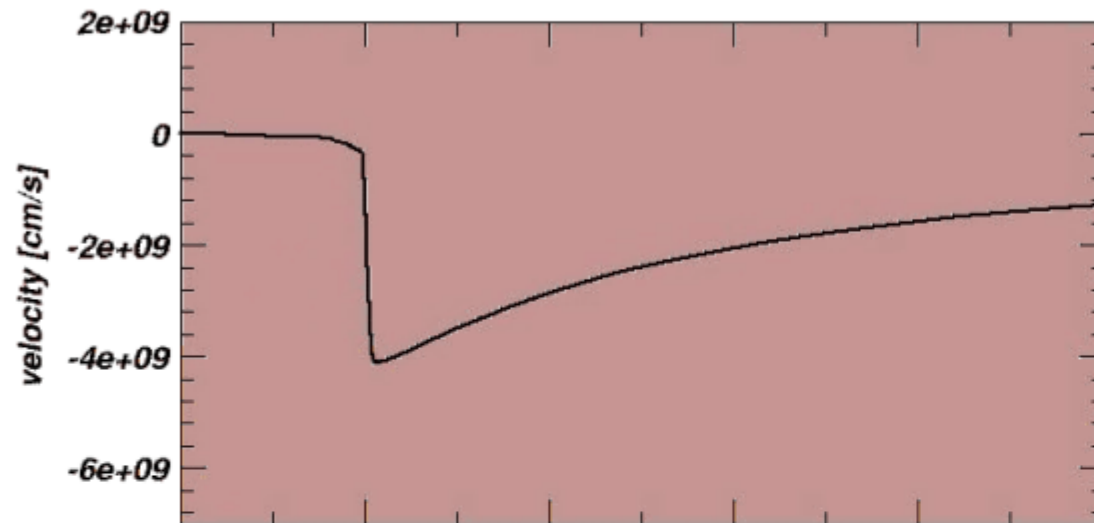


Supernova explosion primarily a hydrodynamical phenomenon

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

Failed Explosion

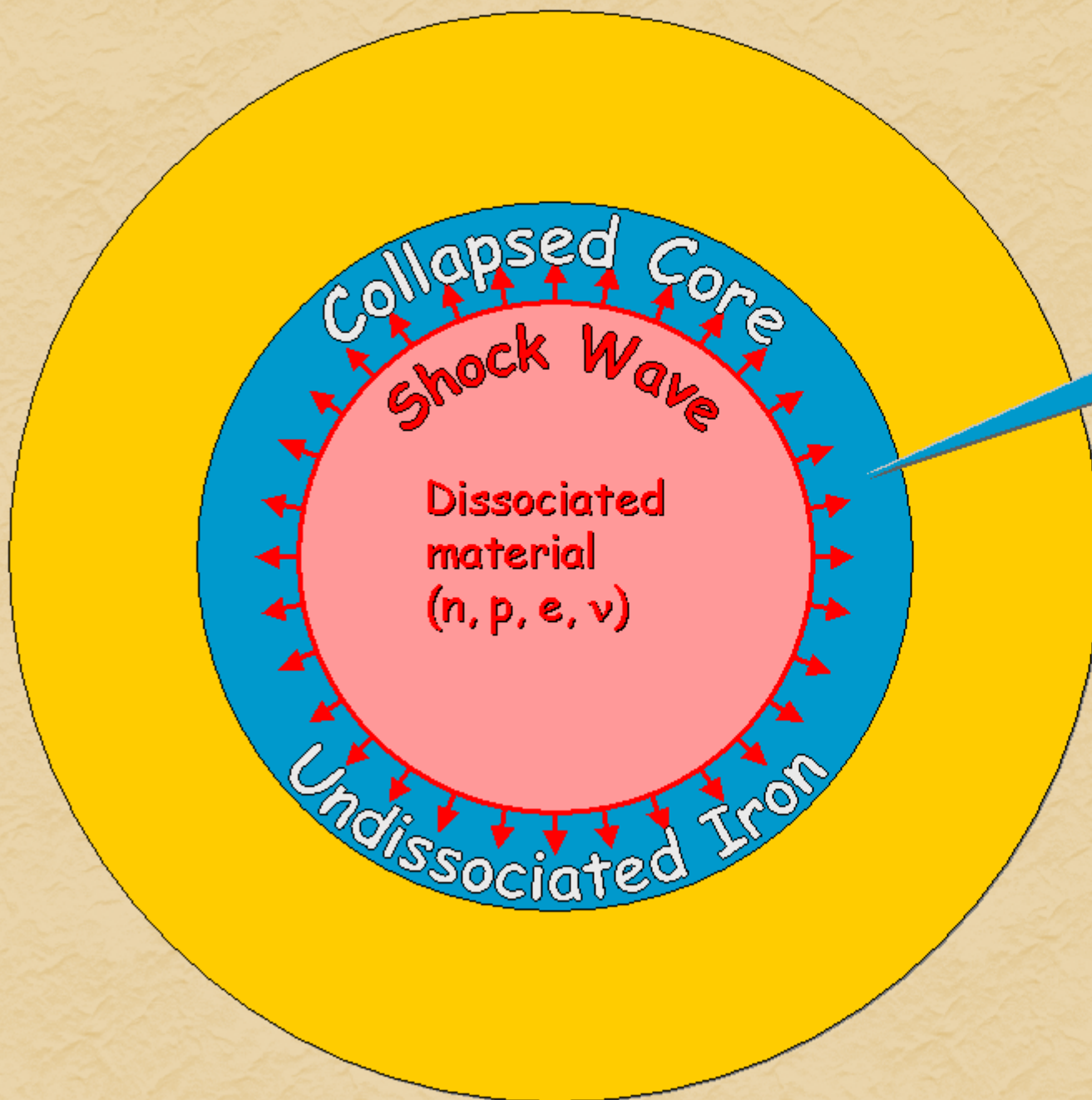
83.8 ms



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

Movie courtesy of
Bronson Messer,
Oakridge group (2001)

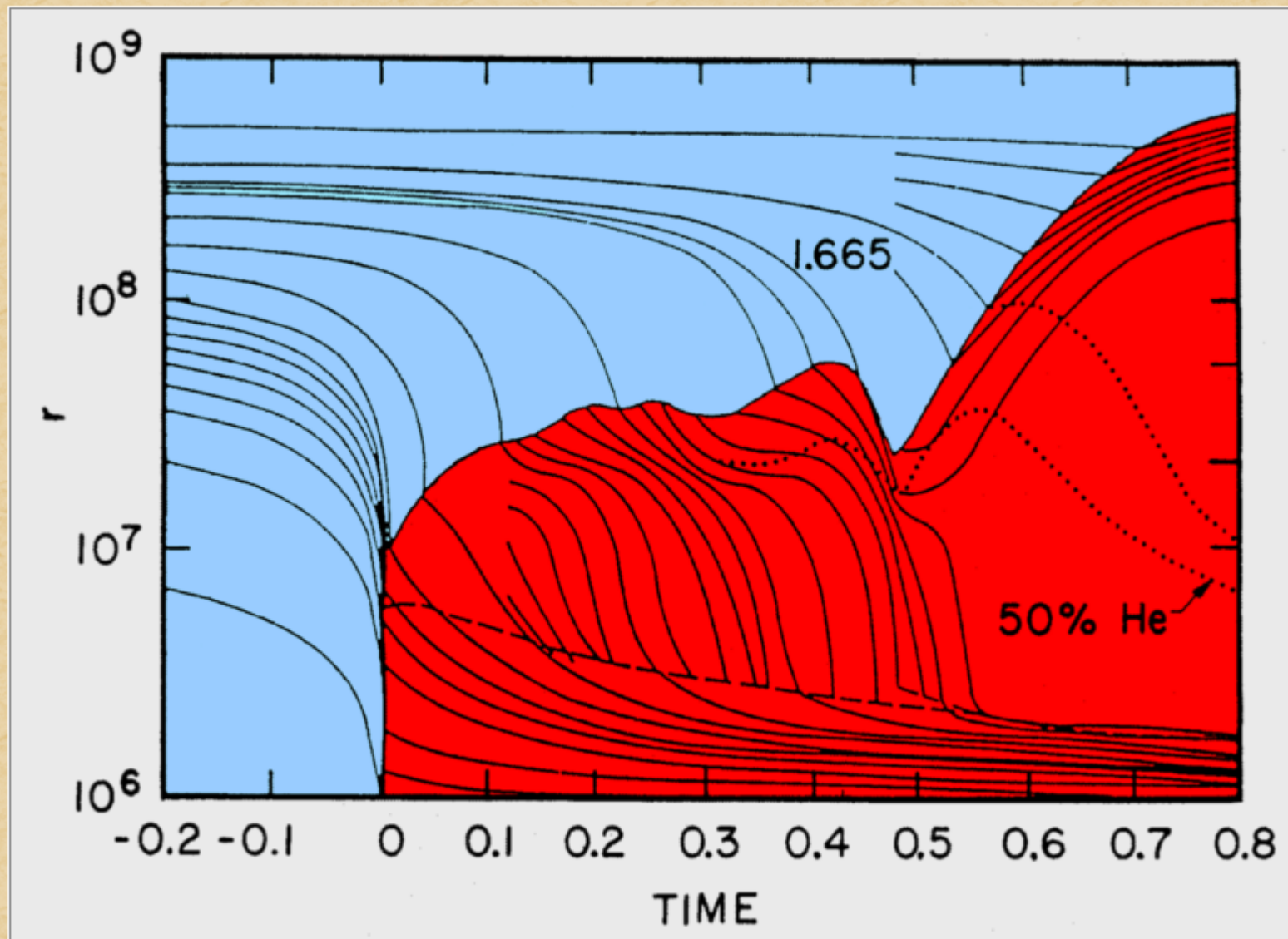
Why No Prompt Explosion?



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

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

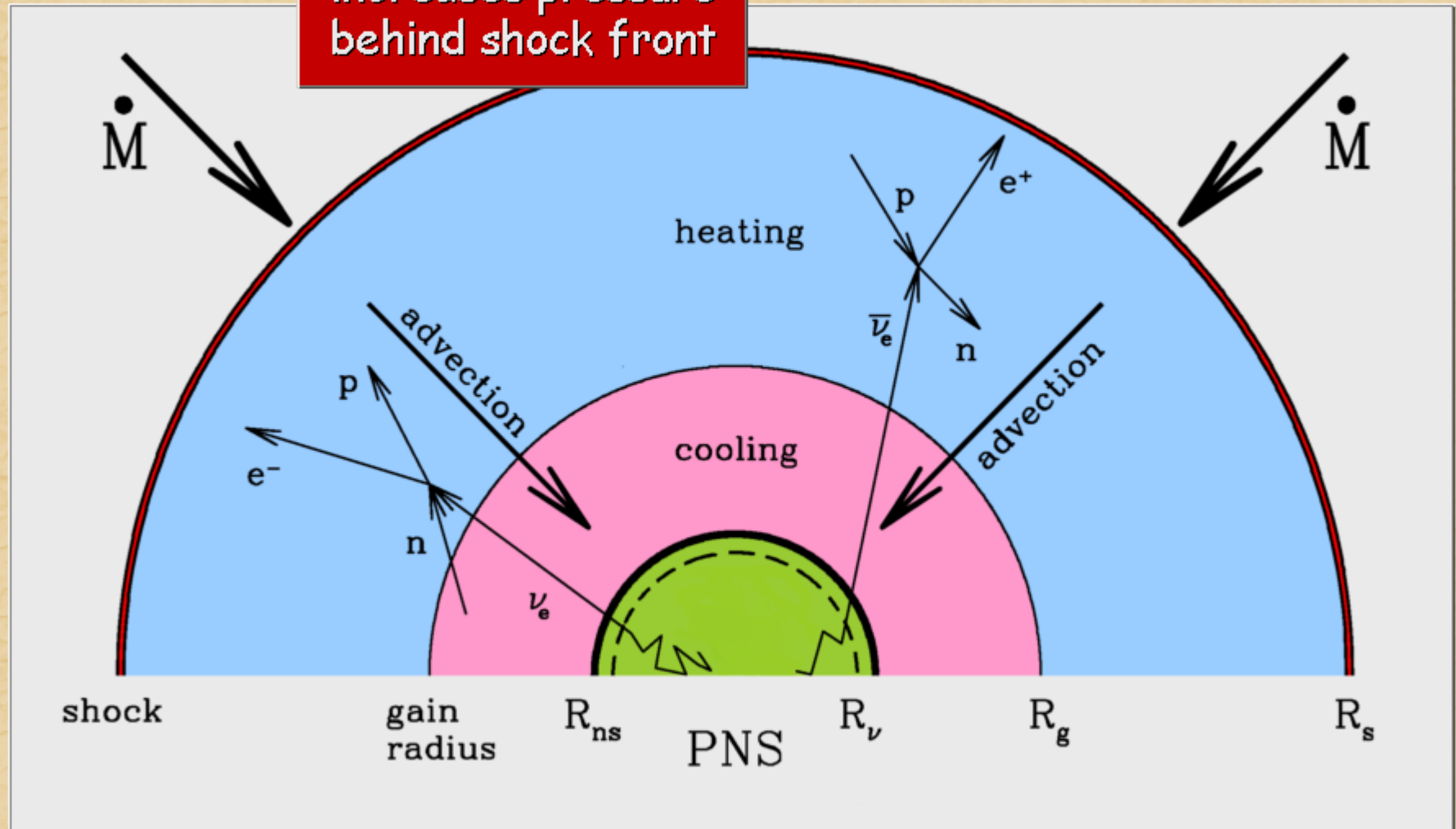
Delayed Explosion



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

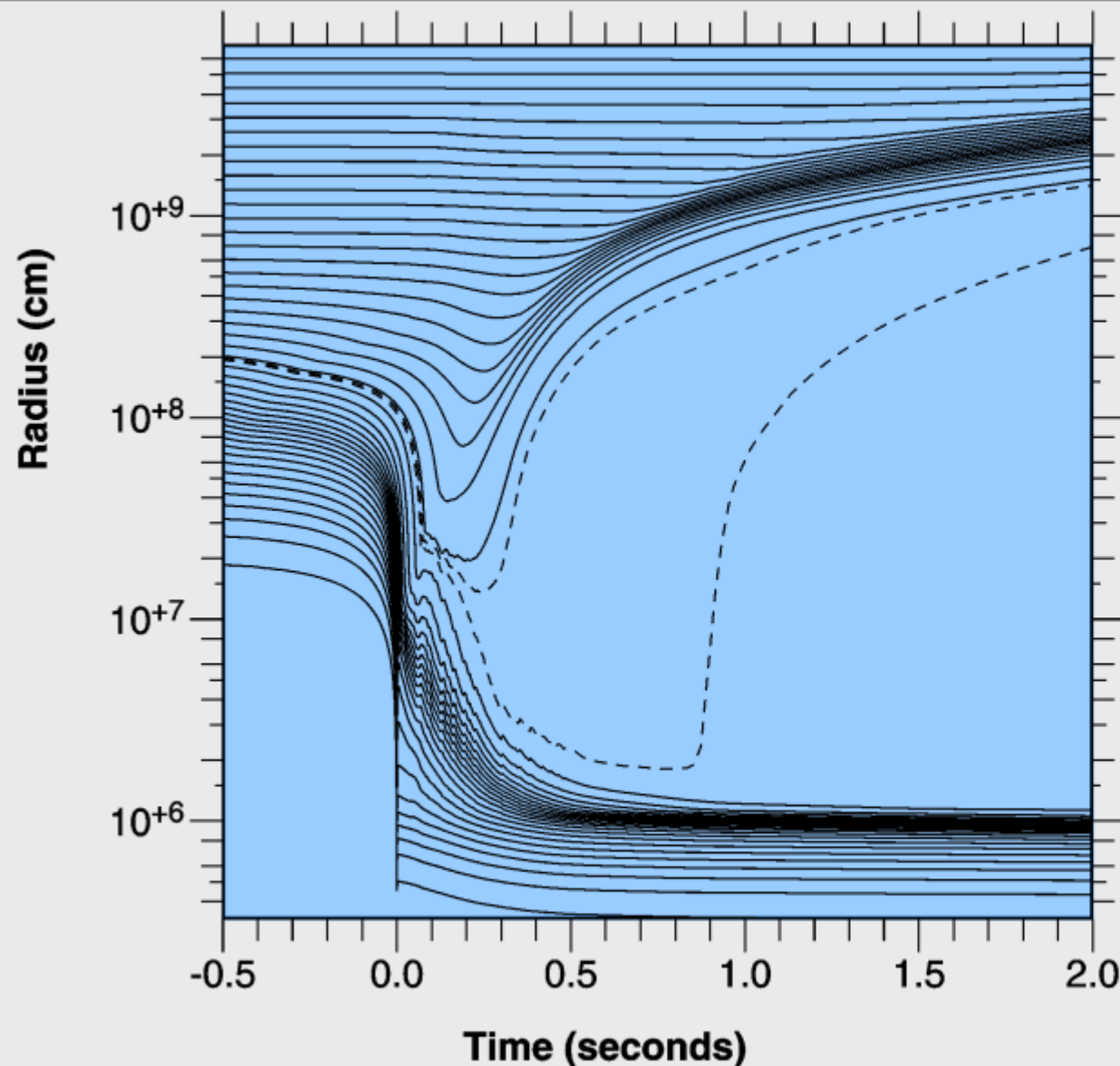
Neutrinos to the Rescue

Neutrino heating
increases pressure
behind shock front



Picture adapted from Janka, astro-ph/0008432

Explosion in Recent Livermore Simulation

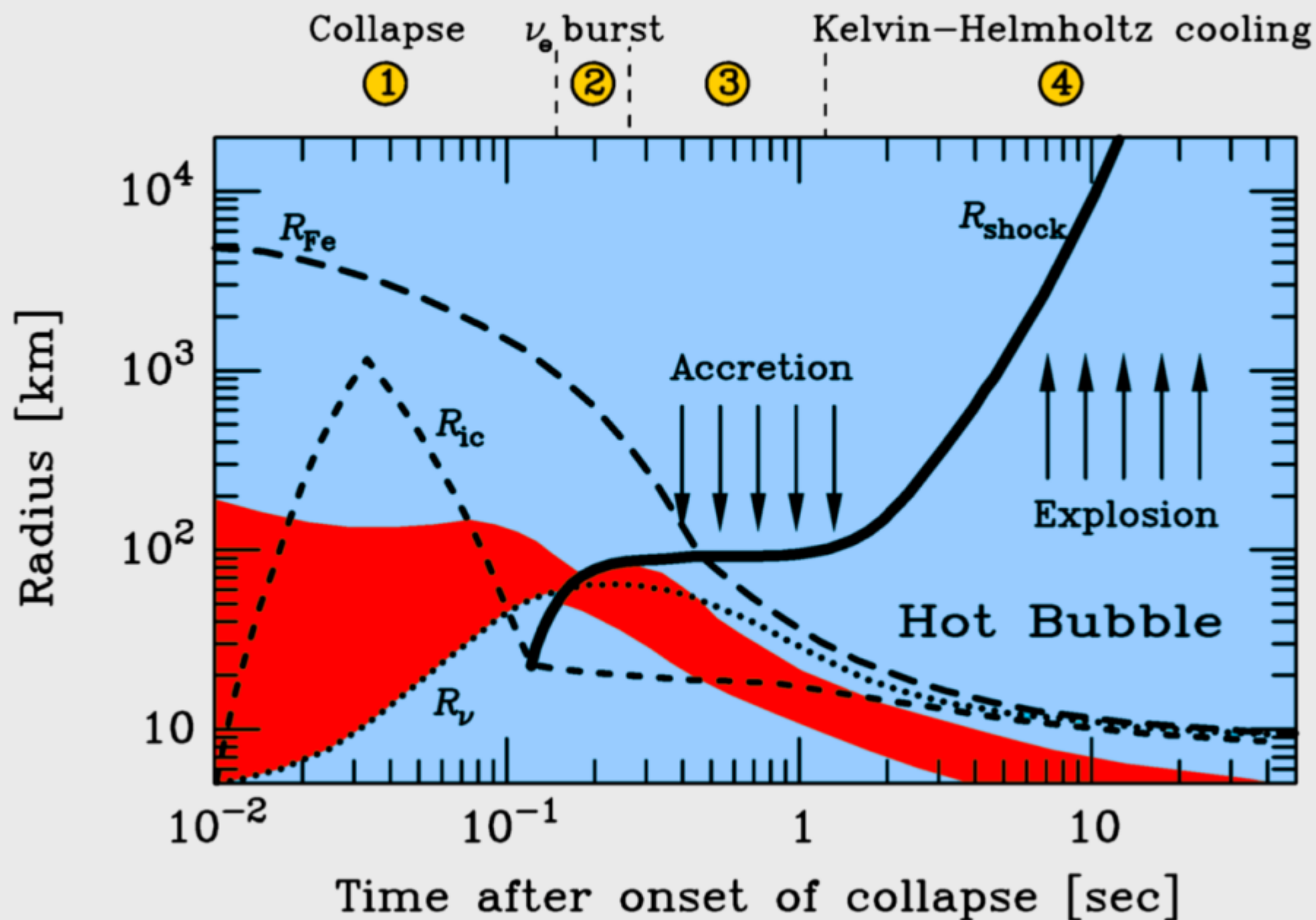


Livermore group obtains robust delayed explosions with 1-D code of Mayle & Wilson

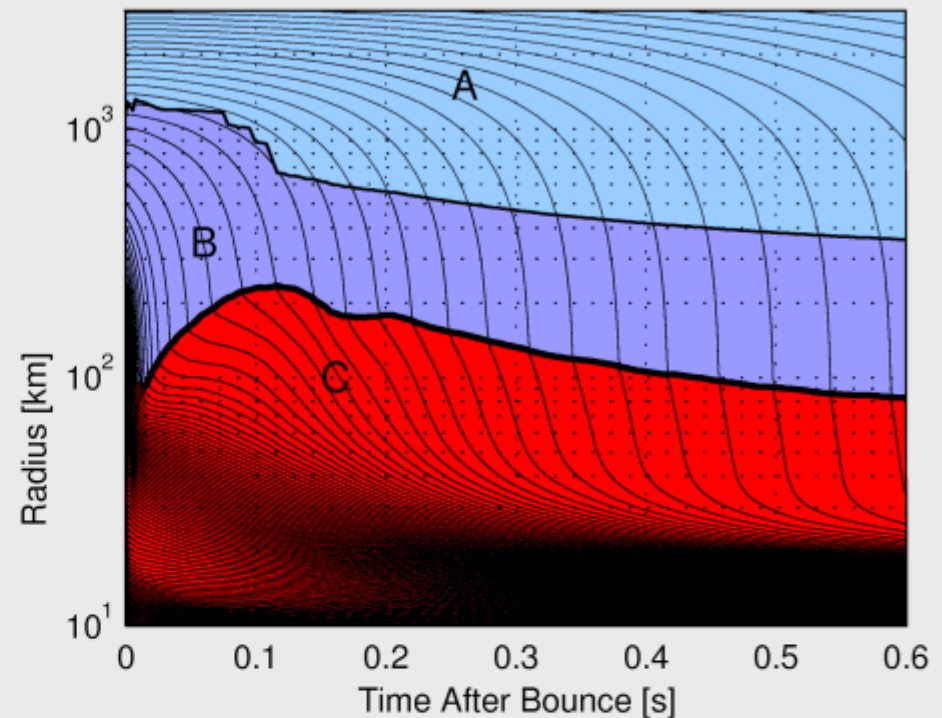
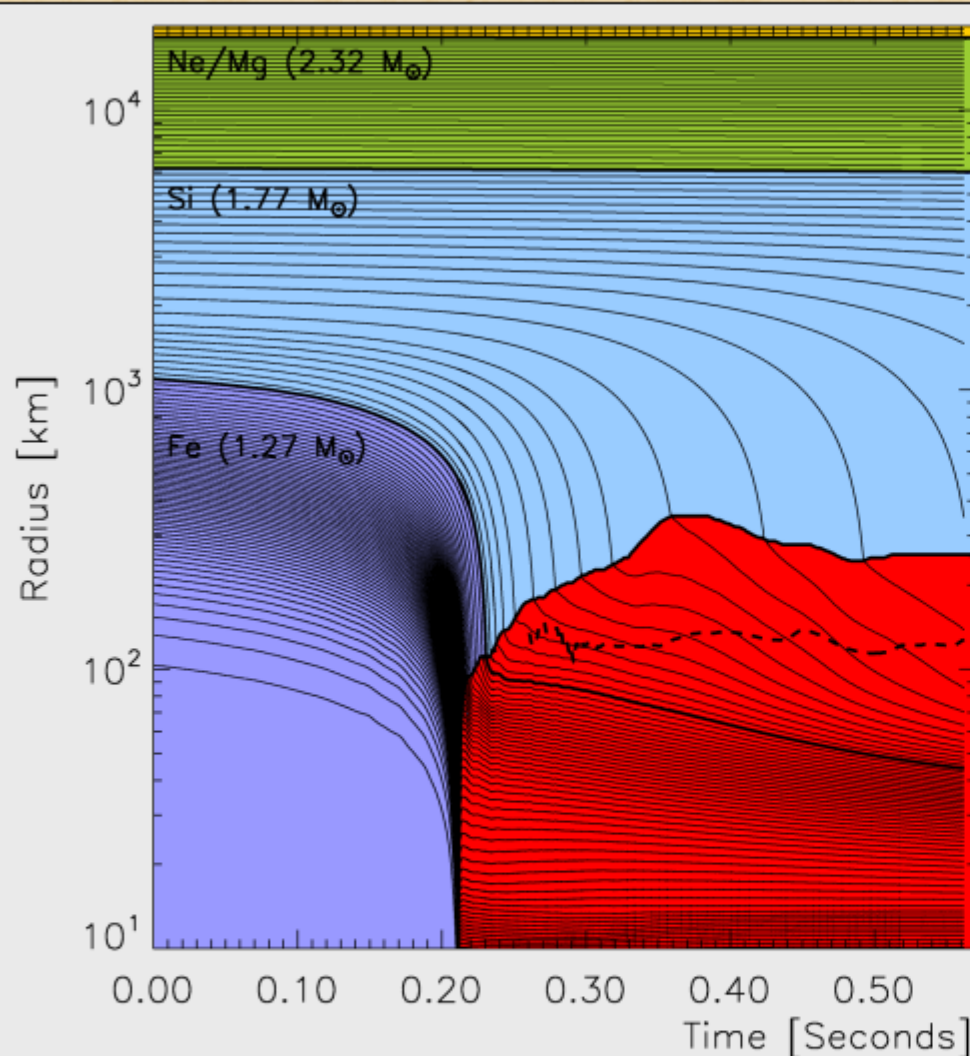
Neutrino luminosity is enhanced by "neutron finger convection" in proto neutron star

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

Supernova Delayed Explosion Scenario



Failed Explosions in Spherical Symmetry



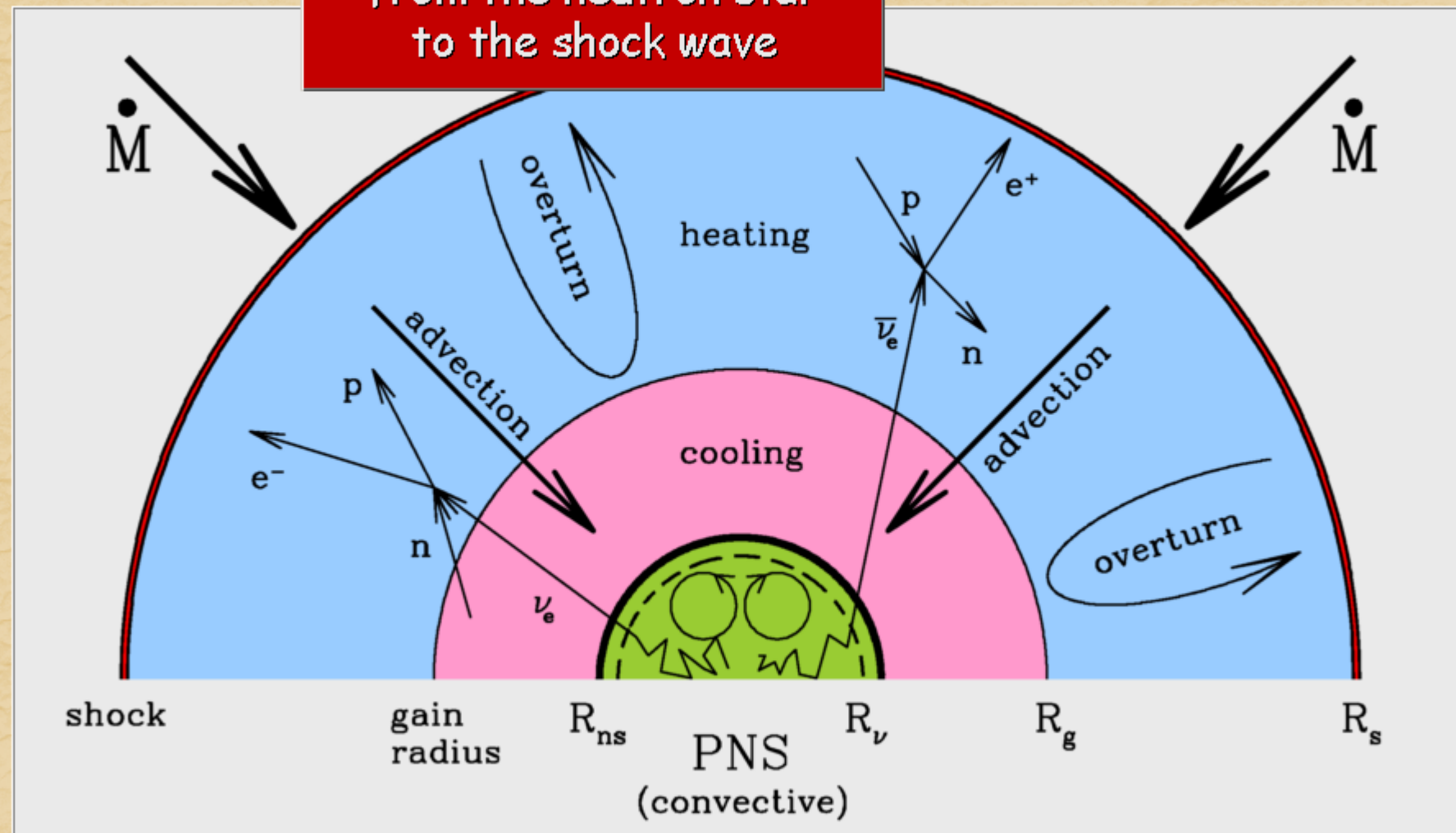
Mezzacappa et al., PRL 86 (2001) 1935

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

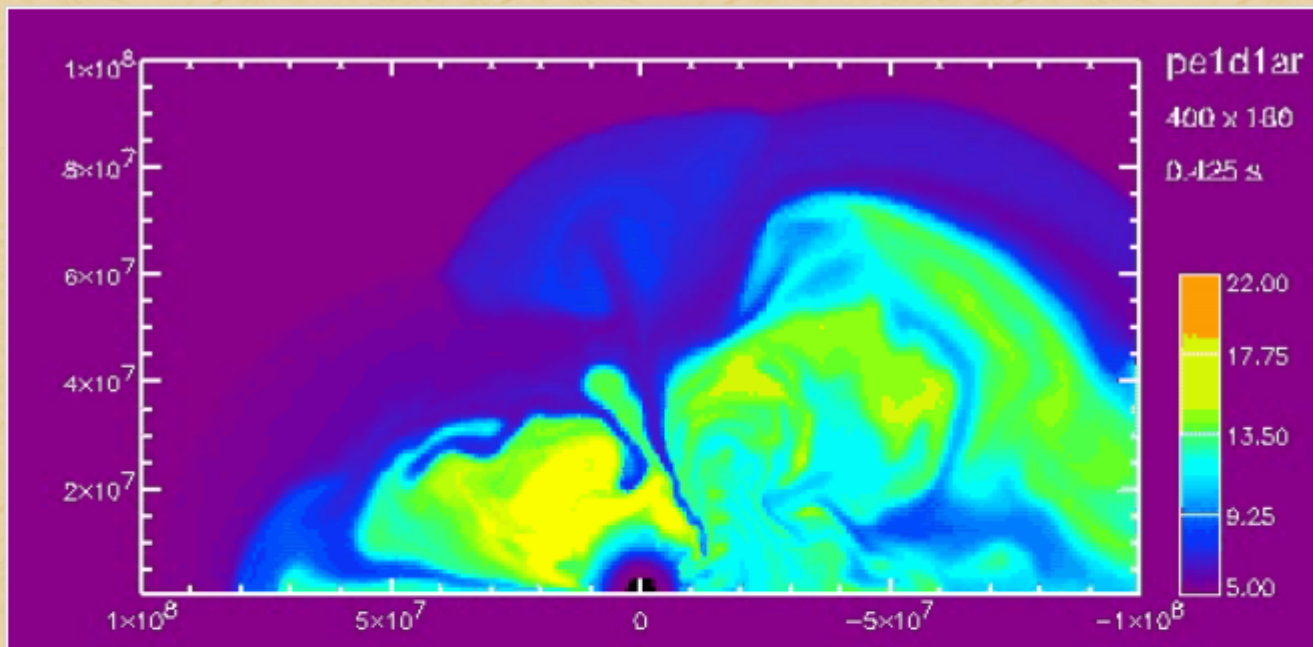
Convection dredges energy from the neutron star to the shock wave



Picture adapted from Janka, astro-ph/0008432

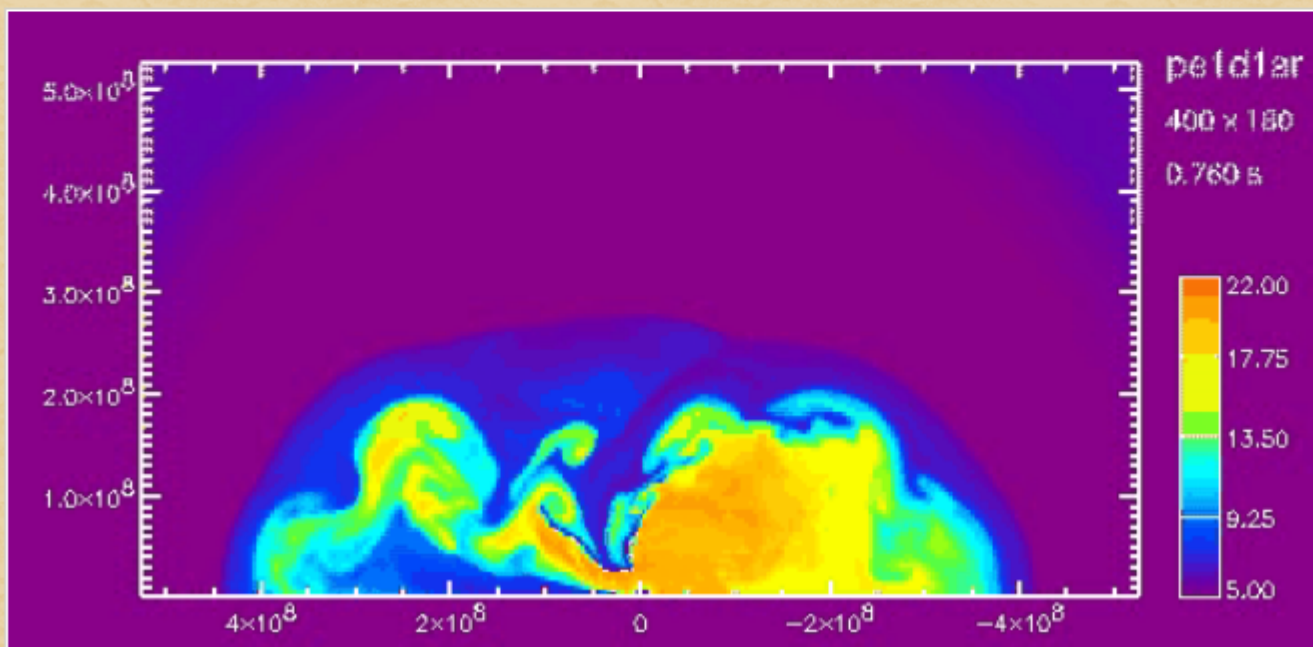
Convection in Supernovae (2-D Simulation)

1000 km



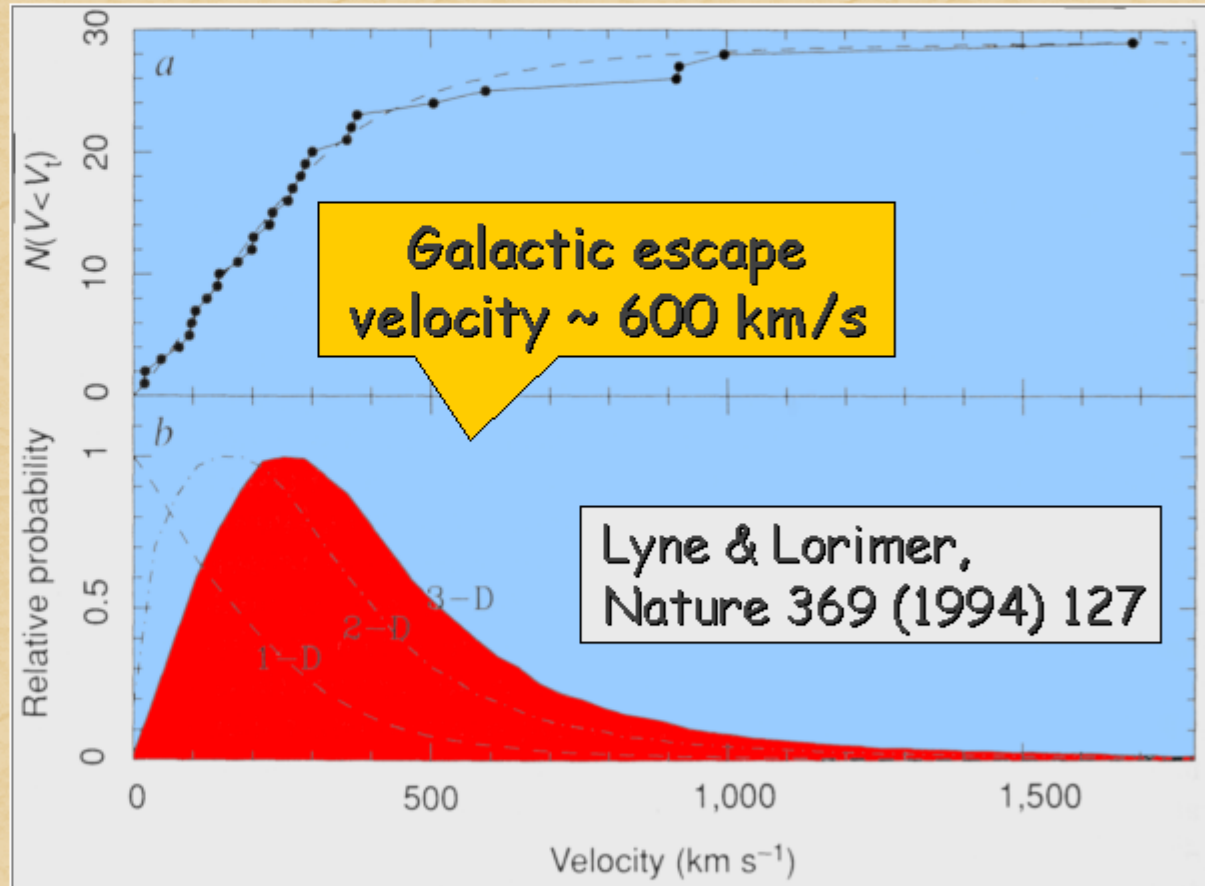
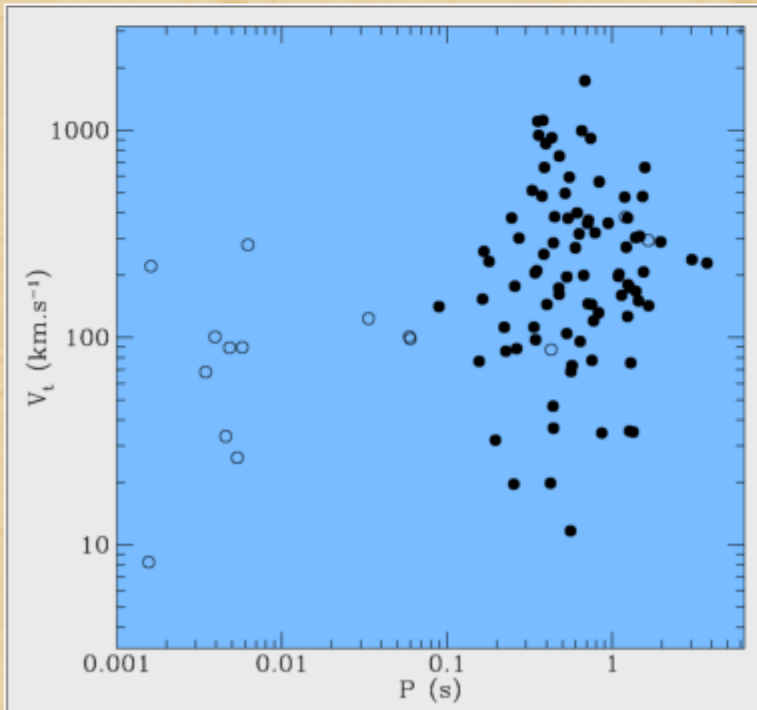
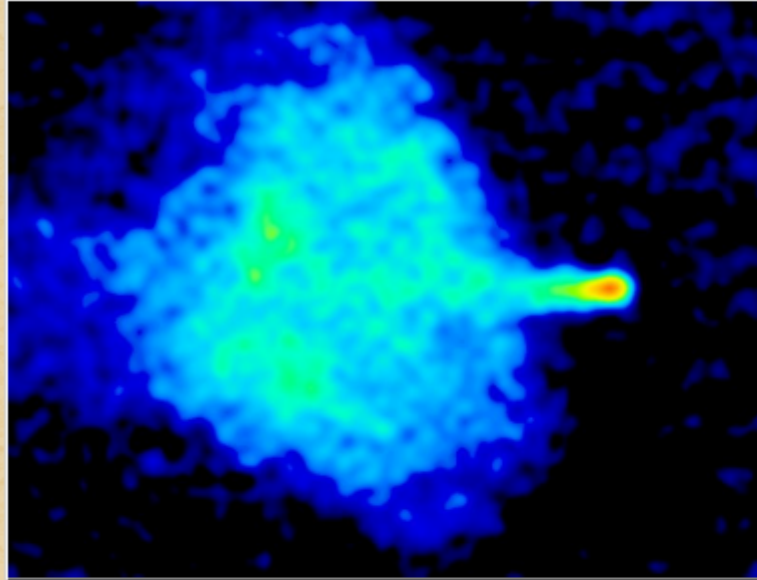
Entropy
contours

Artificially
triggered
explosion



Movies
courtesy
H.-T. Janka

High-Velocity Pulsars



Pulsar velocity distribution

What Accelerates the Pulsars?

Neutrino Rocket

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

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

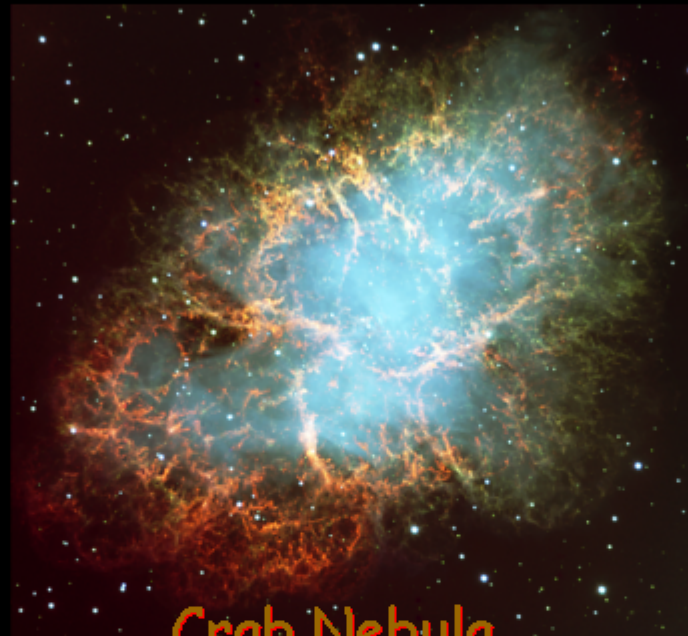
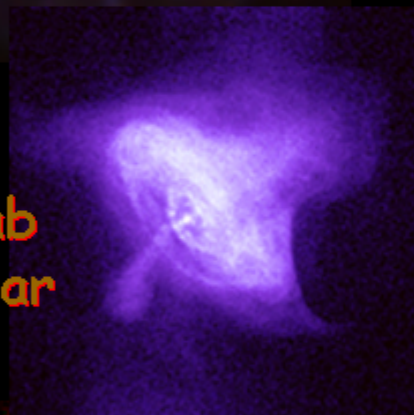
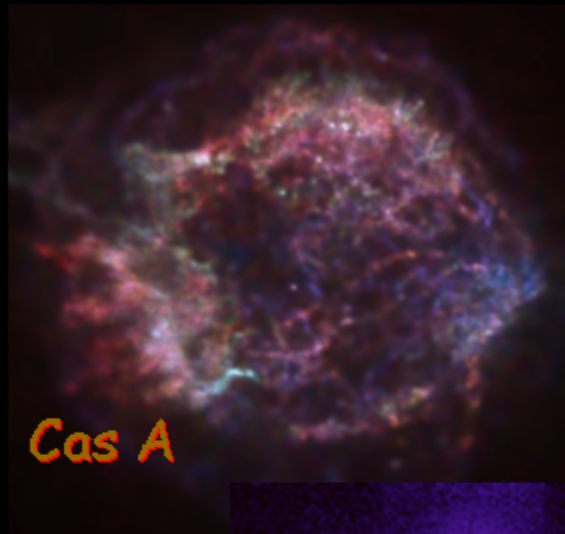
Electromagnetically driven acceleration:

Off-center global magnetic dipole moment & rotation accelerates star in one direction.

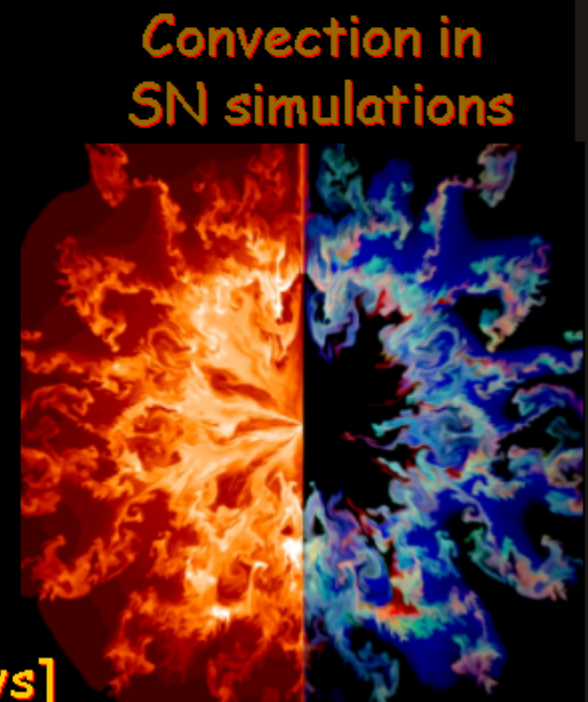
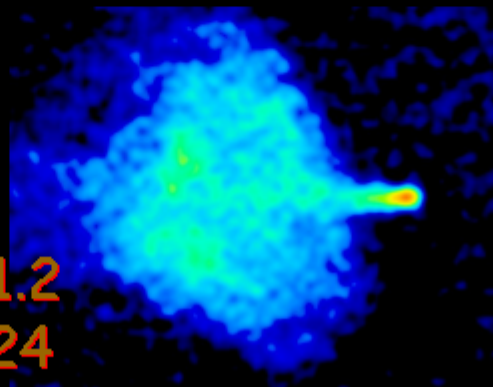
(Slow process - not a "kick")

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

Spherical Symmetry in Astrophysics :-)

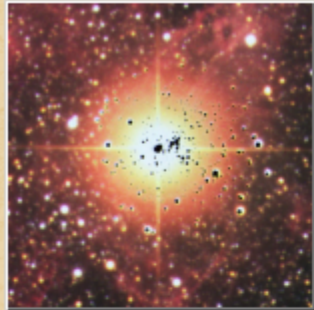


SNR G5.4-1.2
PSR 1757-24

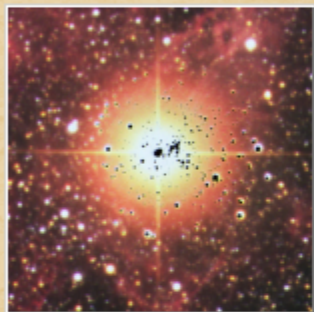


[Adapted after a slide by A. Burrows]

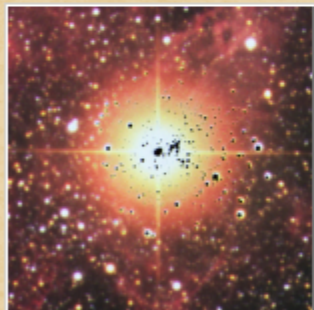
Theoretical Status of Supernova Explosions



- 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 ($\sim$ factor 2)



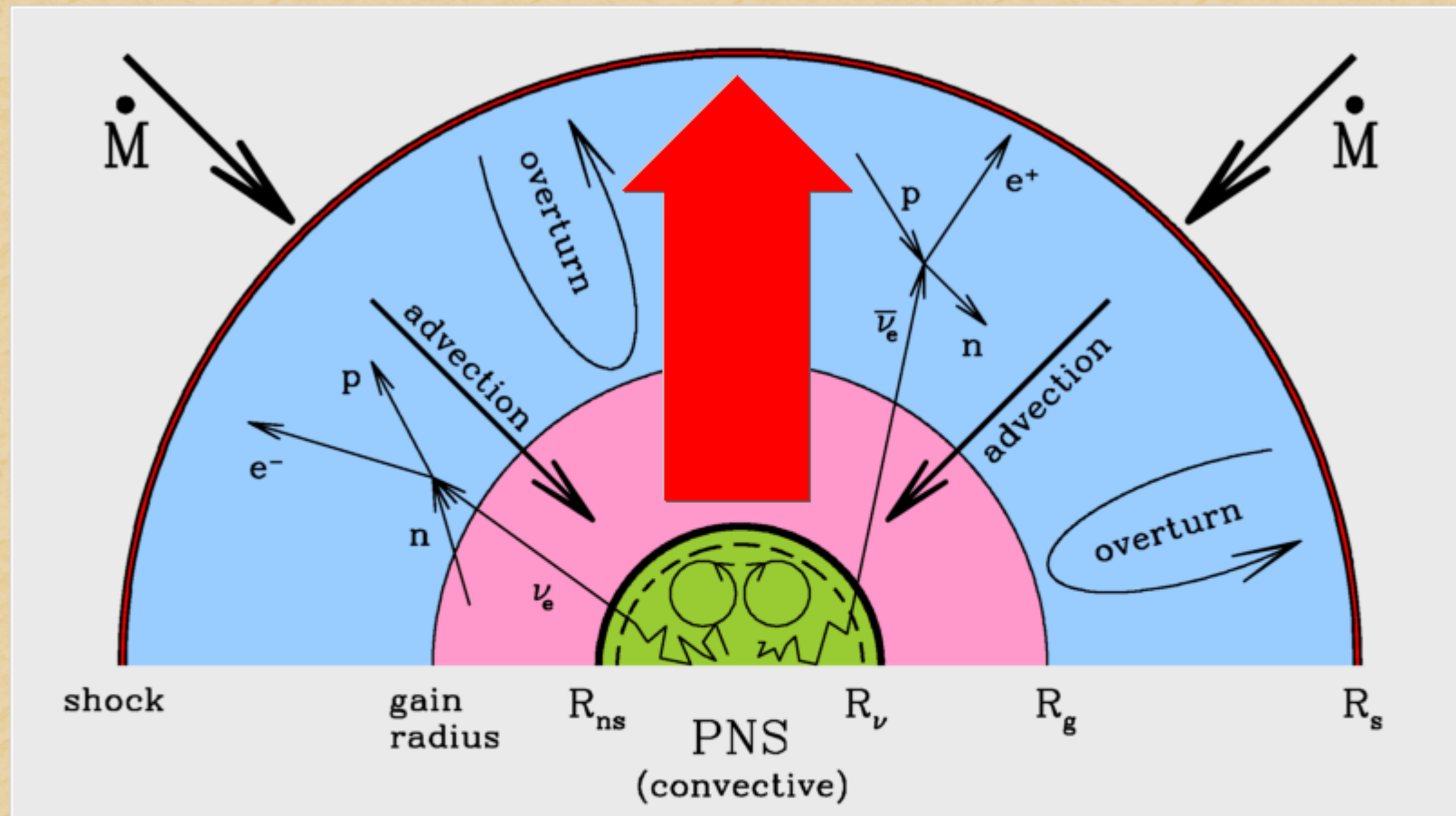
- Convection between proto neutron star (PNS) and shock wave and perhaps within PNS helps
- But 2-D simulations self-consistently coupled with state-of-the-art neutrino transport do not explode either



- 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
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SUPERNOVAE INDUCED BY AXION-LIKE PARTICLES

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The University of Chicago

AND

JAMES R. WILSON
Lawrence Livermore Laboratory

Received 1981 December 22; accepted 1982 April 1

ABSTRACT

It is shown that a new type of particle which may have been seen in a recent accelerator experiment may, if truly present, provide a mechanism whereby gravitationally collapsing massive stars may eject their outer mantles and envelopes in supernova explosions of $\sim 10^{51}$ ergs while leaving the cores to form neutron star remnants. These particles are “axion-like,” which means they interact semiweakly, decay to two photons with lifetimes $\sim 10^{-3}$ s, and have masses $0.15 \leq M_a \lesssim 1$ 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
 $N + N \rightarrow N + N + a$

**Thermal flux of axion-like
particles from "axion sphere"**

Decay
 $a \rightarrow e^+ + e^-$

Stalling
shock
wave

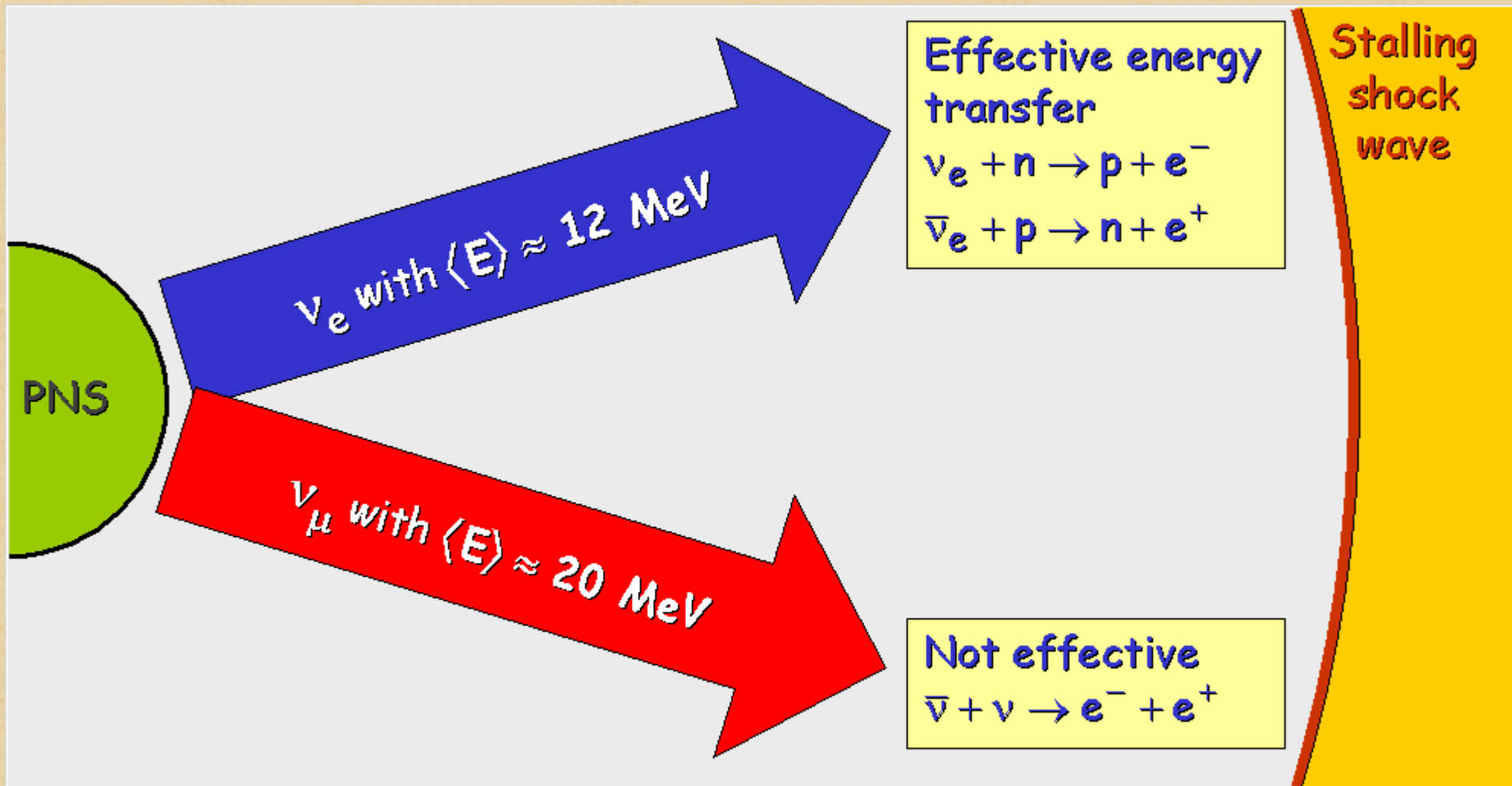
$$\mathcal{L} = \frac{1}{f} \bar{\Psi}_N \gamma_5 \gamma^\mu \Psi_N \partial_\mu a$$

$$\mathcal{L} = \frac{1}{f} \bar{\Psi}_e \gamma_5 \gamma^\mu \Psi_e \partial_\mu a$$

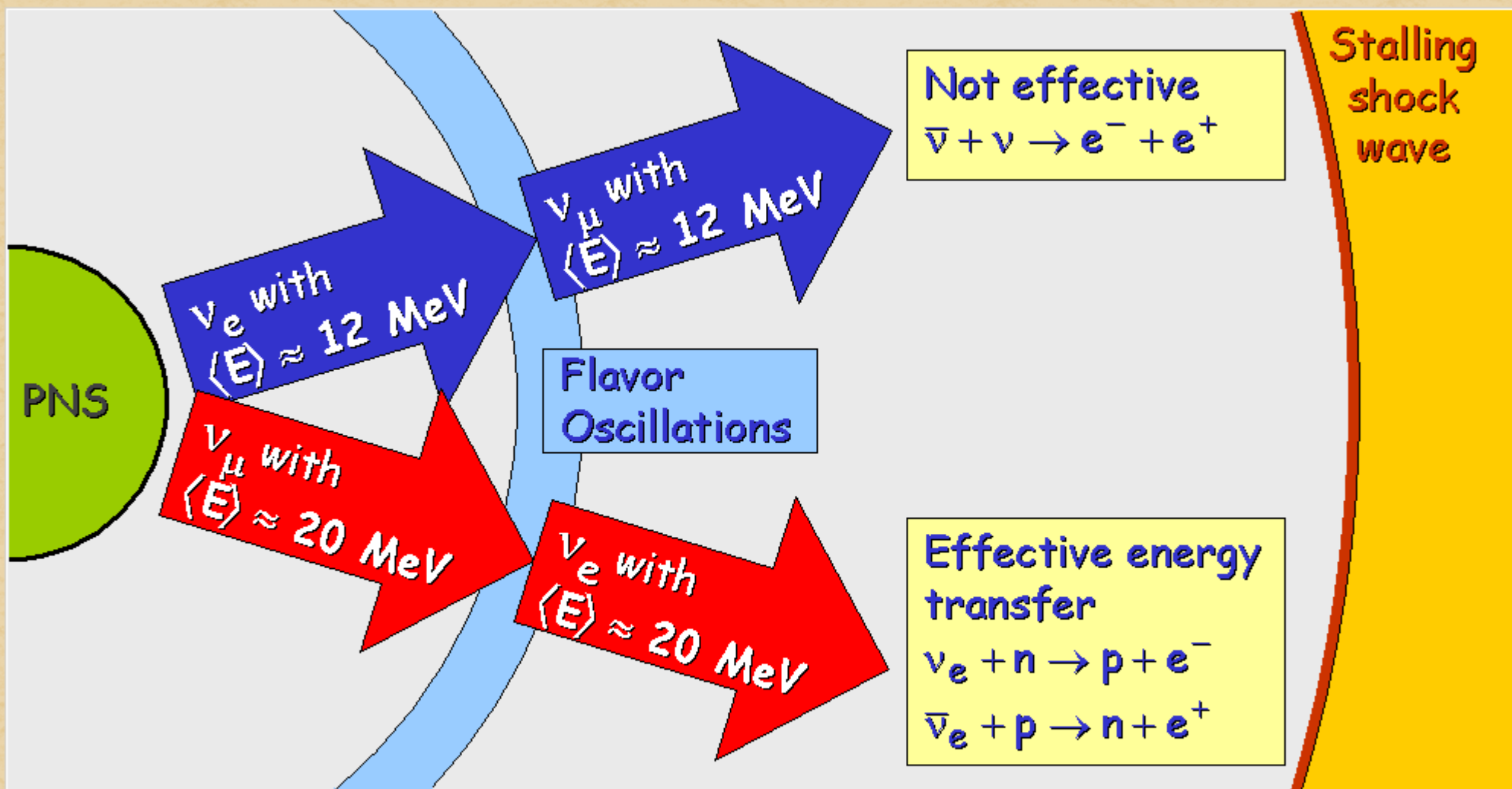
Apparently consistent with $f = \text{few } 10^5 \text{ GeV}$ and $m = \text{few MeV}$
Not excluded by other arguments, but also not independently motivated

Bereziani & Drago, PLB 473 (2000) 281

Swapping Neutrino Spectra by Oscillations

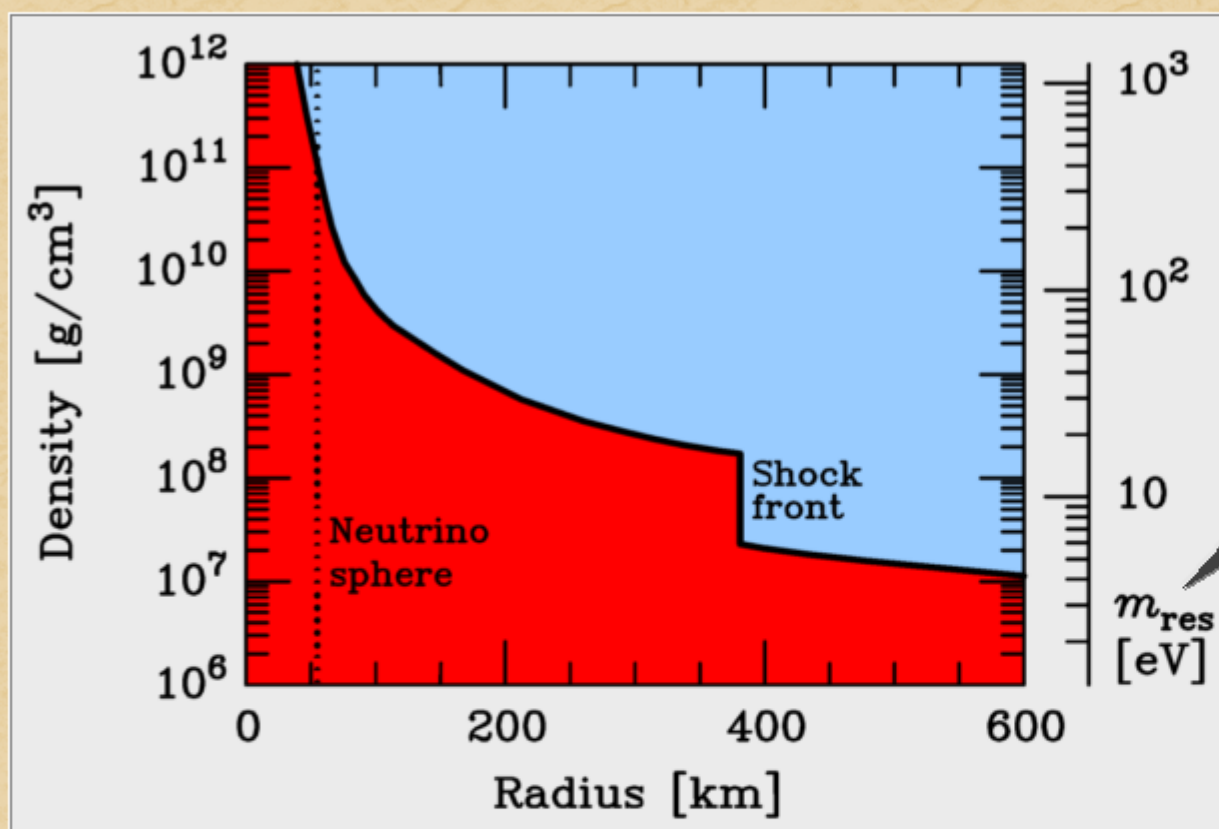


Swapping Neutrino Spectra by Oscillations



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

Matter Effect on Flavor Oscillations



"Effective neutrino mass"
from weak potential

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

($E_\nu = 10 \text{ MeV}$ 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

Further Reading

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

astro-ph/0103015

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

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

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Neutrinos and Supernova Theory
Phys. Rept. 333-334 (2000) 63-75.

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(Springer, 1990)

G. Raffelt
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Physics
(University of Chicago Press, 1996)

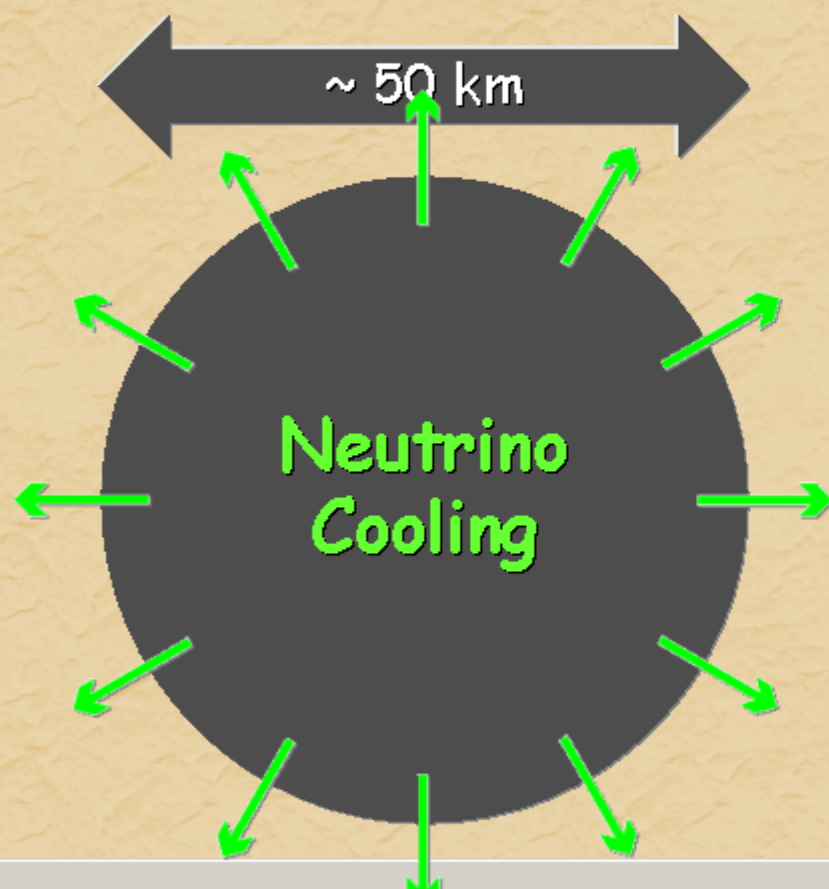
M. Koshiya
Observational Neutrino Astrophysics
Physics Reports 220 (1992) 229-402

Neutrinos from Core-Collapse Supernovae



Stellar Collapse and Supernova Explosion

Newborn Neutron Star



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

Gravitational binding energy

$$E_b \approx 3 \times 10^{53} \text{ erg} \approx 17\% M_{\text{SUN}} c^2$$

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

$$L_\nu \approx 3 \times 10^{53} \text{ erg} / 3 \text{ sec} \\ \approx 3 \times 10^{19} L_{\text{SUN}}$$

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: $M_{\text{Ch}} \approx G_N^{-3/2} m_N^{-2} = m_{\text{Pl}}^3 m_N^{-2} \approx 1.5 M_\odot$

Coincidentally same number from zero-T polytropic model

Density

Supported by nucleon degeneracy pressure

Nuclear density $\rho \approx \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3}$

Radius

$$\frac{4\pi}{3} \rho_{\text{nuc}} R^3 = M_{\text{Ch}}$$

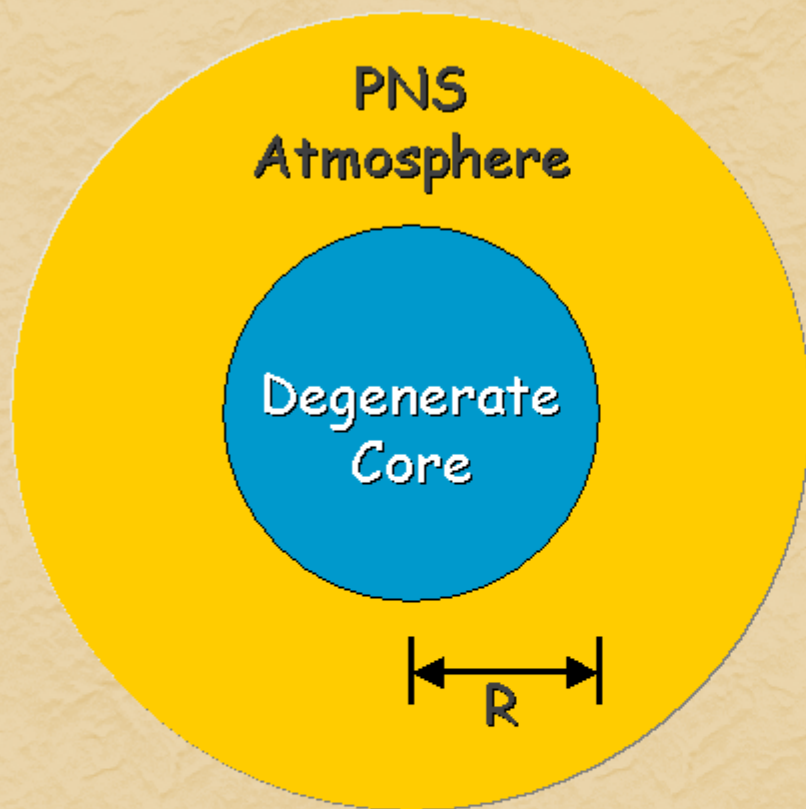
$$R \approx 10.6 \text{ km}$$

Schwarzschild
Radius

General $R_S = 2G_N M$

Here $R_S = 2G_N M_{\text{Ch}} = 2 m_{\text{Pl}} m_N^{-2} = 4.6 \text{ km}$

What determines the neutrino energies?



Gravitational potential of a given nucleon

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

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

$$\Phi \approx -27 \text{ MeV}$$

Virial theorem (hydrostatic equilibrium),
assuming nondegenerate conditions,

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

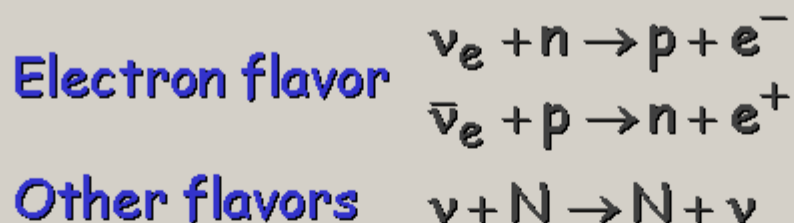
Thermal equilibrium

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

- 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 $\sim 10 \text{ MeV}$ range
- Core contracts by accretion and/or cooling $\rightarrow T$ increases

What determines the time scale?

Main neutrino reactions



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

$$n_B = \frac{\rho_{\text{nuc}}}{m_N} \approx 1.8 \times 10^{38} \text{ cm}^{-3}$$

Scattering rate

$$\Gamma = \sigma n_B \approx 1.1 \times 10^9 \text{ s}^{-1} \left(\frac{E_\nu}{100 \text{ MeV}} \right)^2$$

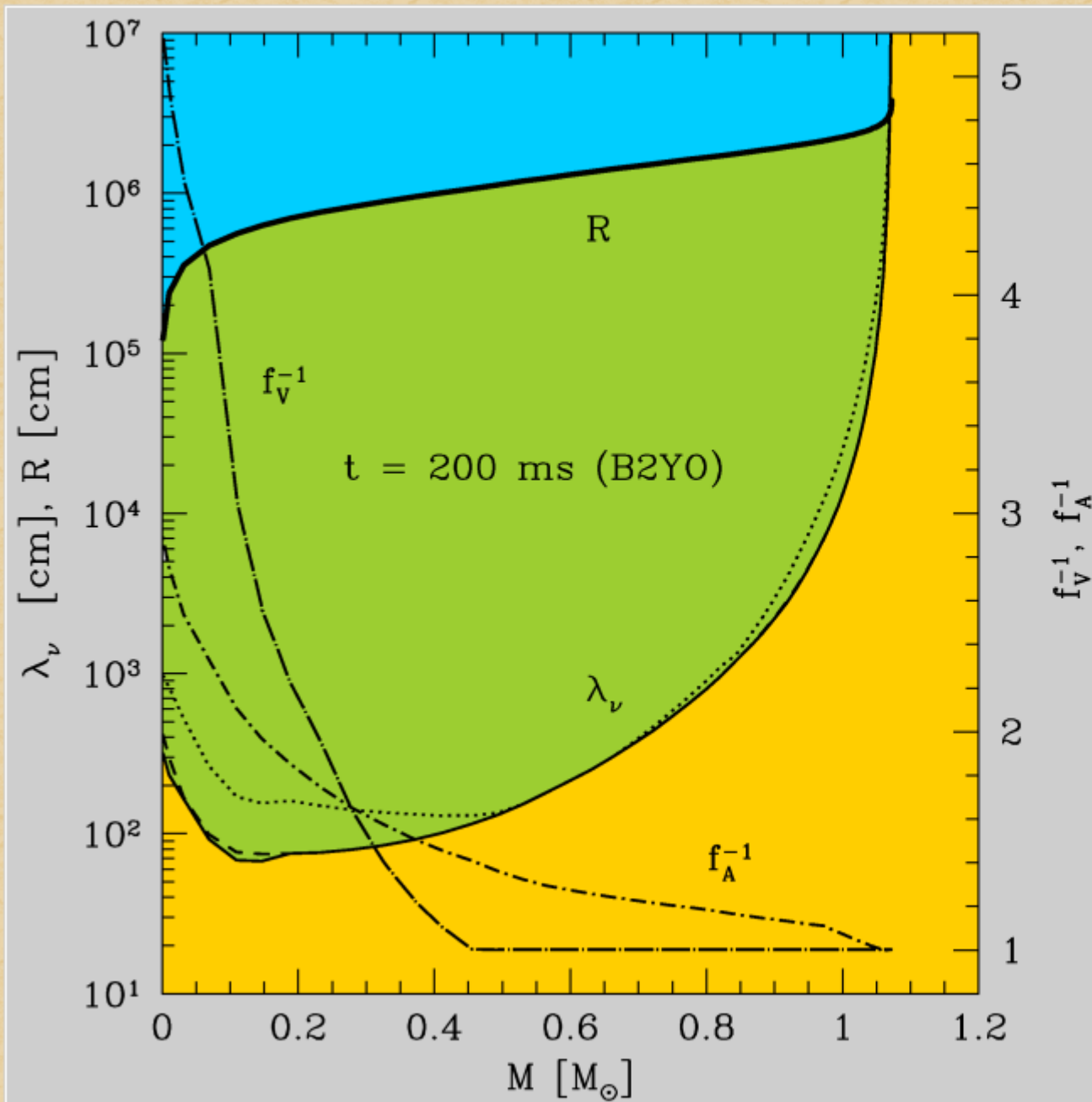
Mean free path

$$\lambda = (\sigma n_B)^{-1} \approx 28 \text{ cm} \left(\frac{100 \text{ MeV}}{E_\nu} \right)^2$$

Diffusion time

$$t_{\text{diff}} \approx \frac{R^2}{\lambda} \approx 1.2 \text{ sec} \left(\frac{R}{10 \text{ km}} \right)^2 \left(\frac{E_\nu}{100 \text{ MeV}} \right)^2$$

Neutrino Mean Free Path in a Supernova Core



Main processes:

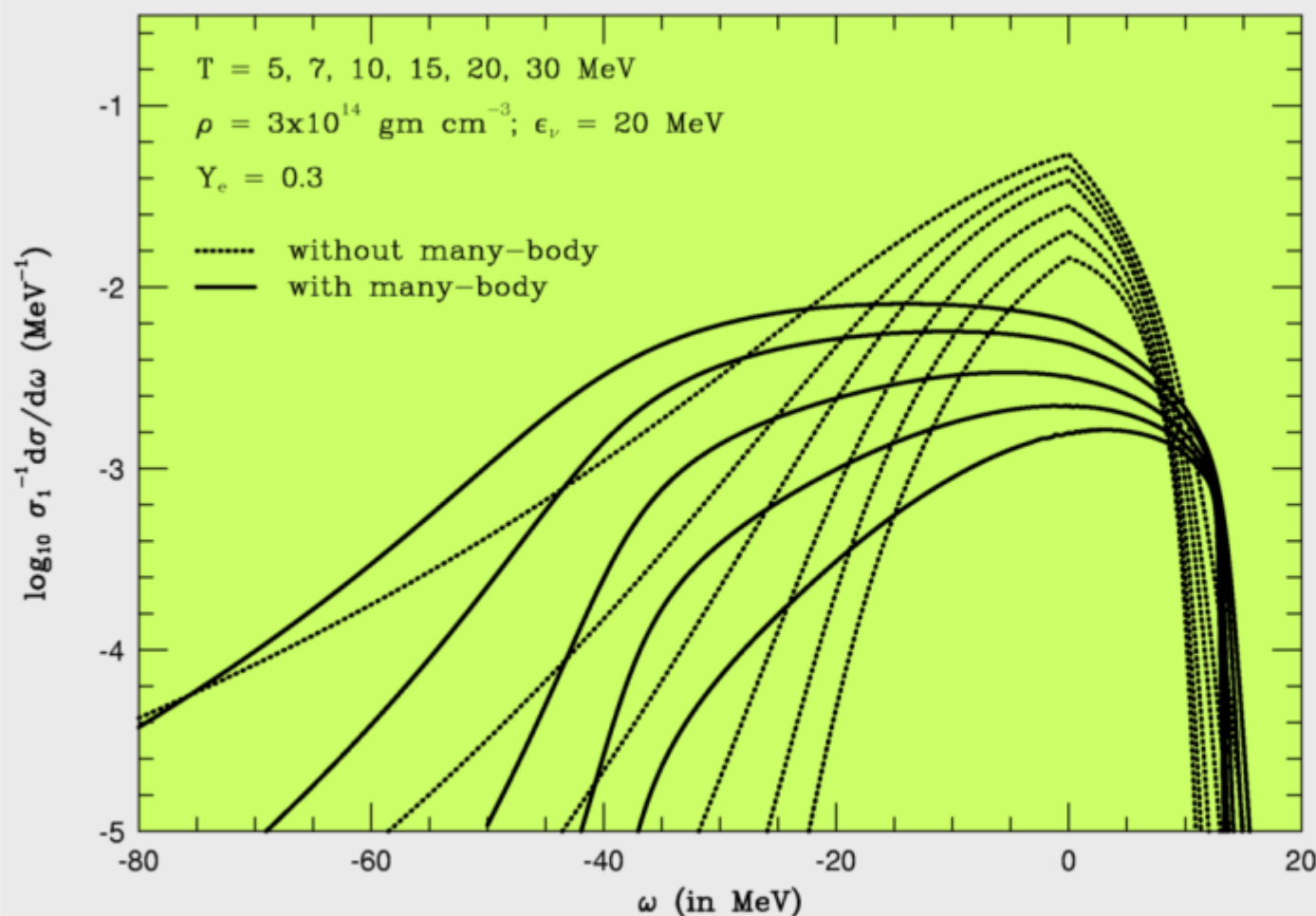
$\nu N \rightarrow N \nu$ all flavors

$\nu_e n \rightarrow p e^-$

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

Janka, Yamada & Keil
(1999)

Many-Body Effects on Neutrino Opacities

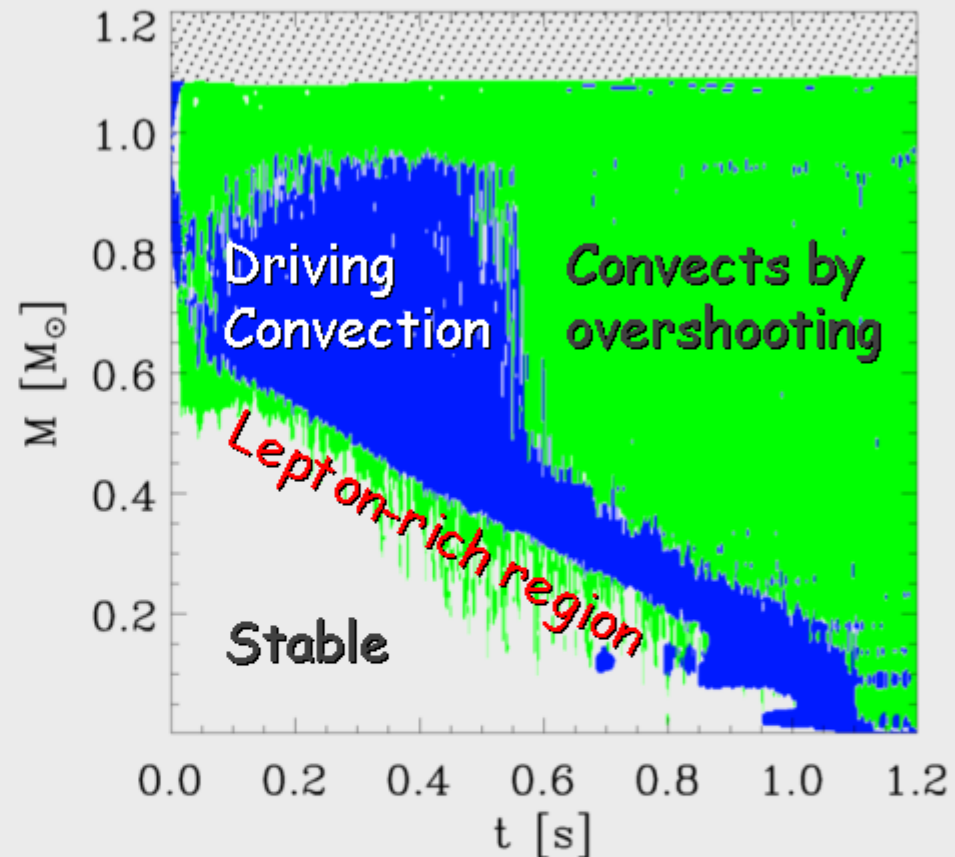
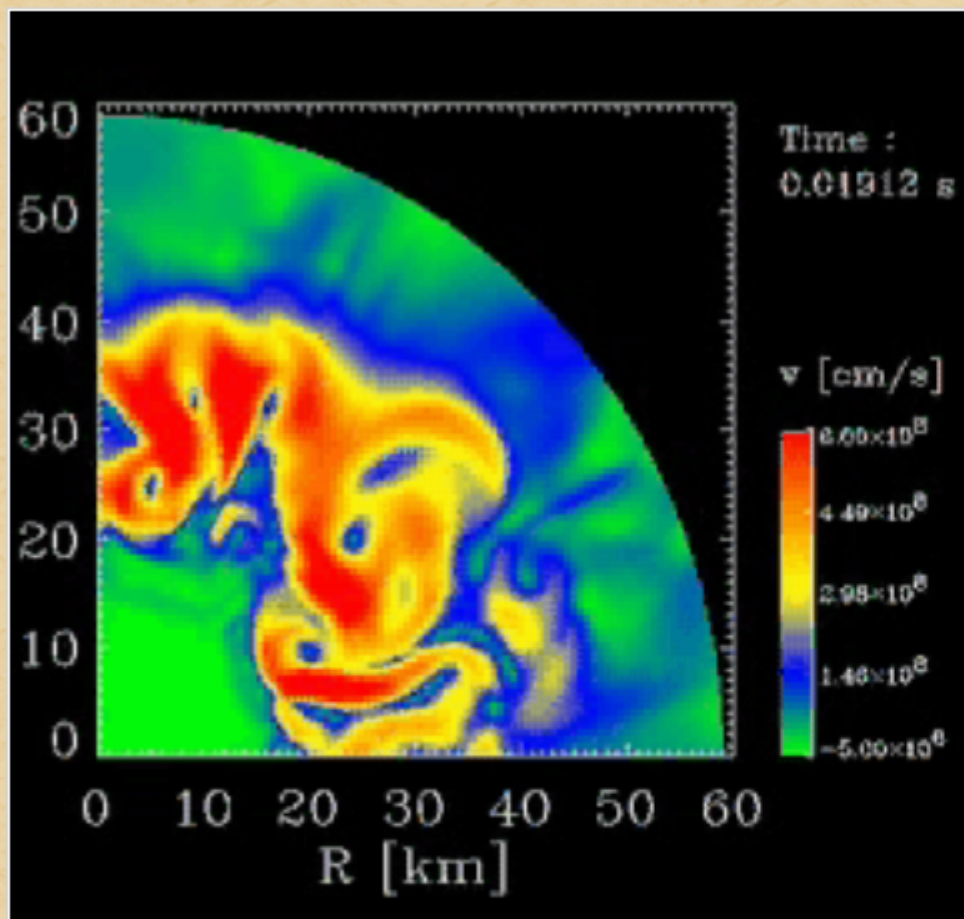


Burrows & Sawyer,
astro-ph/9804264

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

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

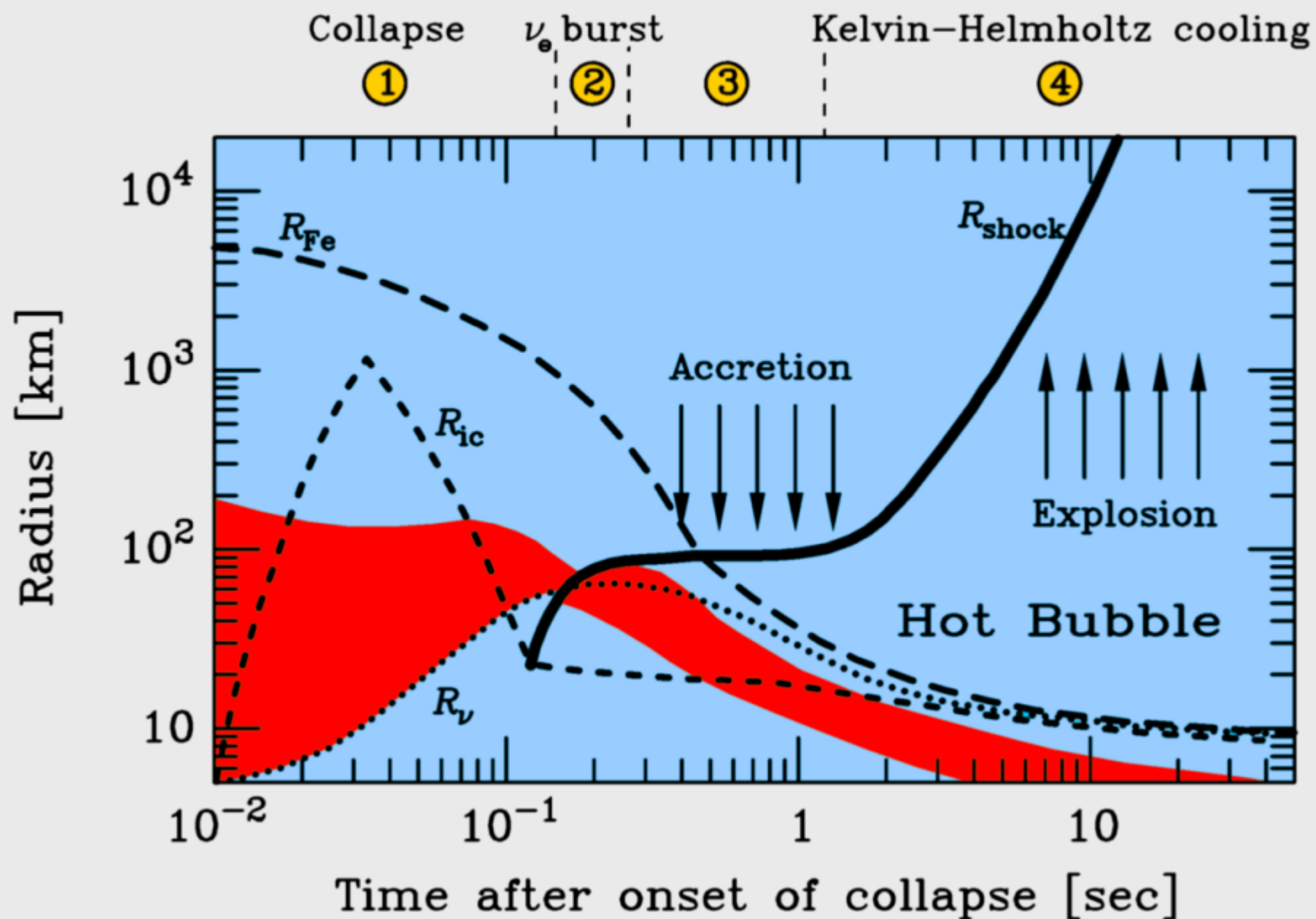
Convection in Proto Neutron Star



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

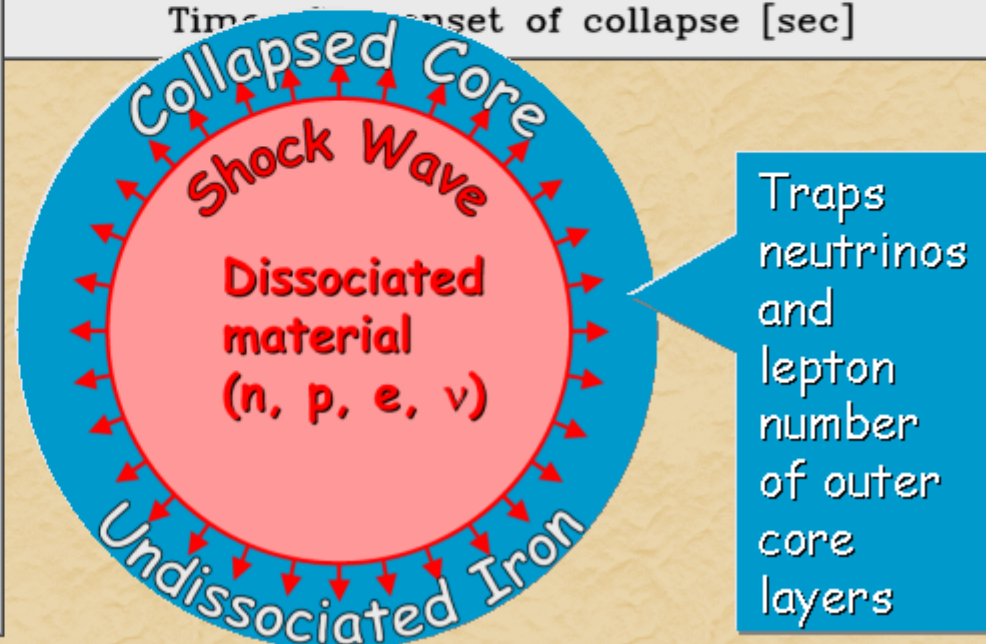
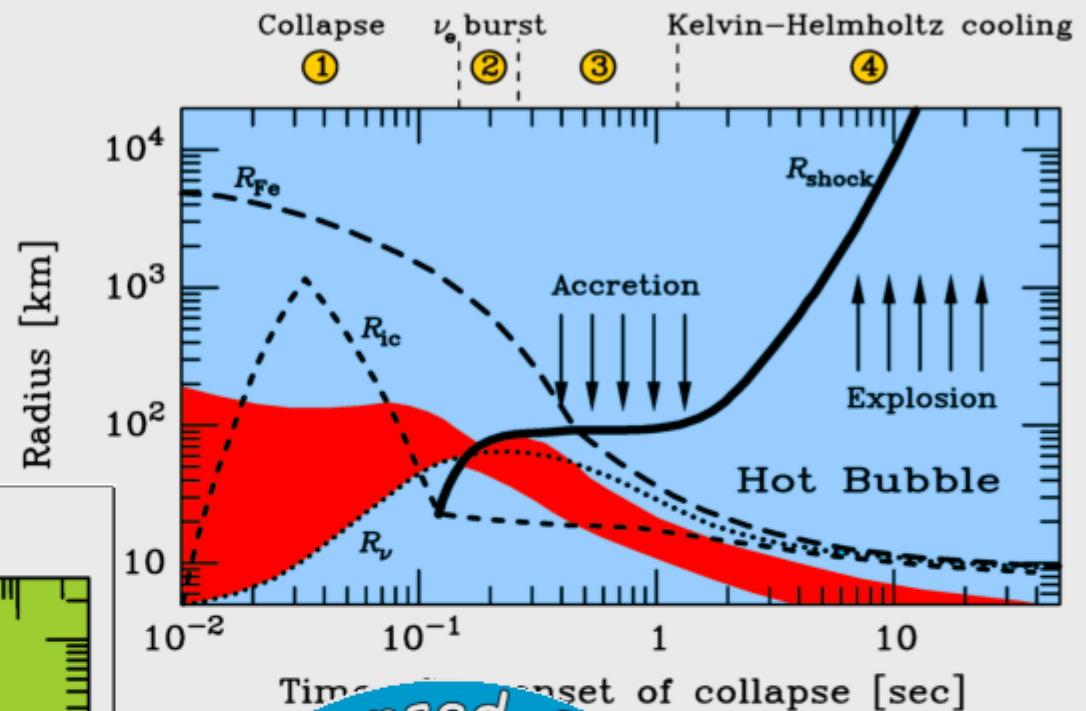
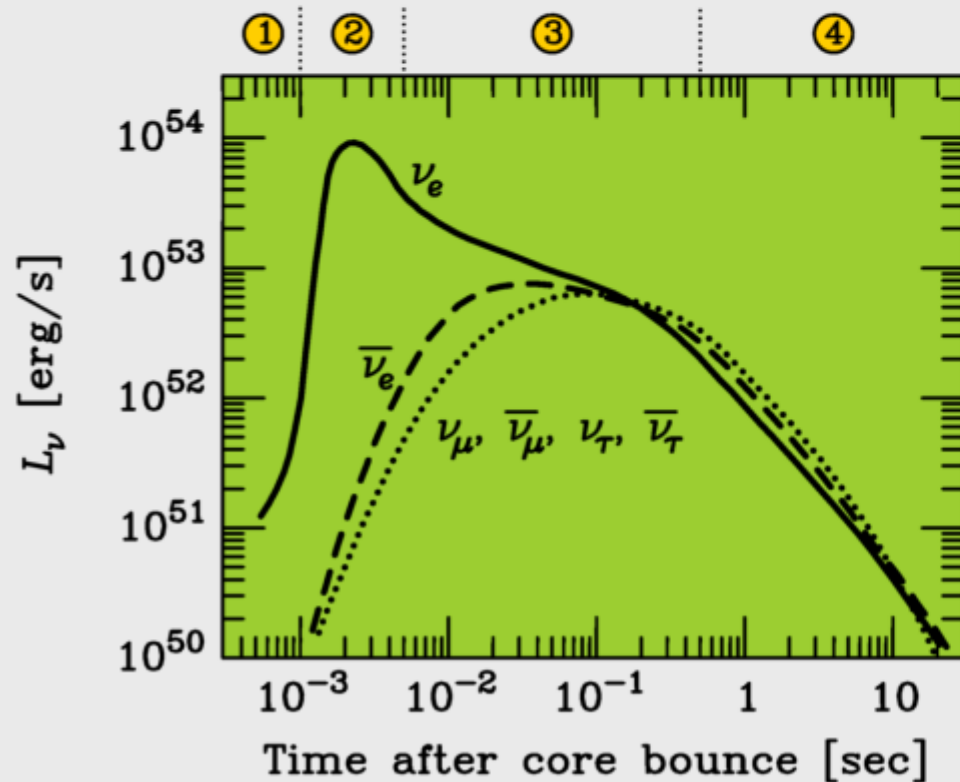
Keil, Janka & Müller, ApJ 473 (1996) L111

Supernova Delayed Explosion Scenario



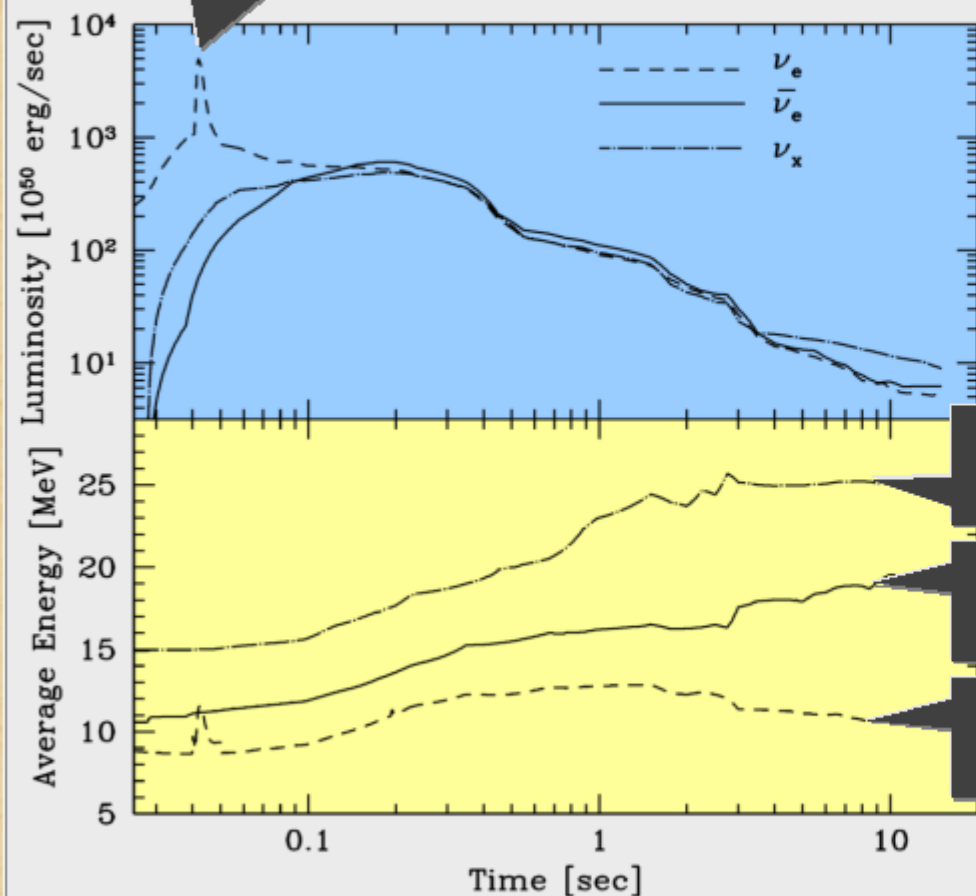
Structure of Supernova Neutrino Signal

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



Structure of a Supernova Neutrino Burst

Prompt ν_e
deleptonization
burst



Broad characteristics

- Duration few seconds
- $\langle E_\nu \rangle \sim 10\text{-}20$ 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

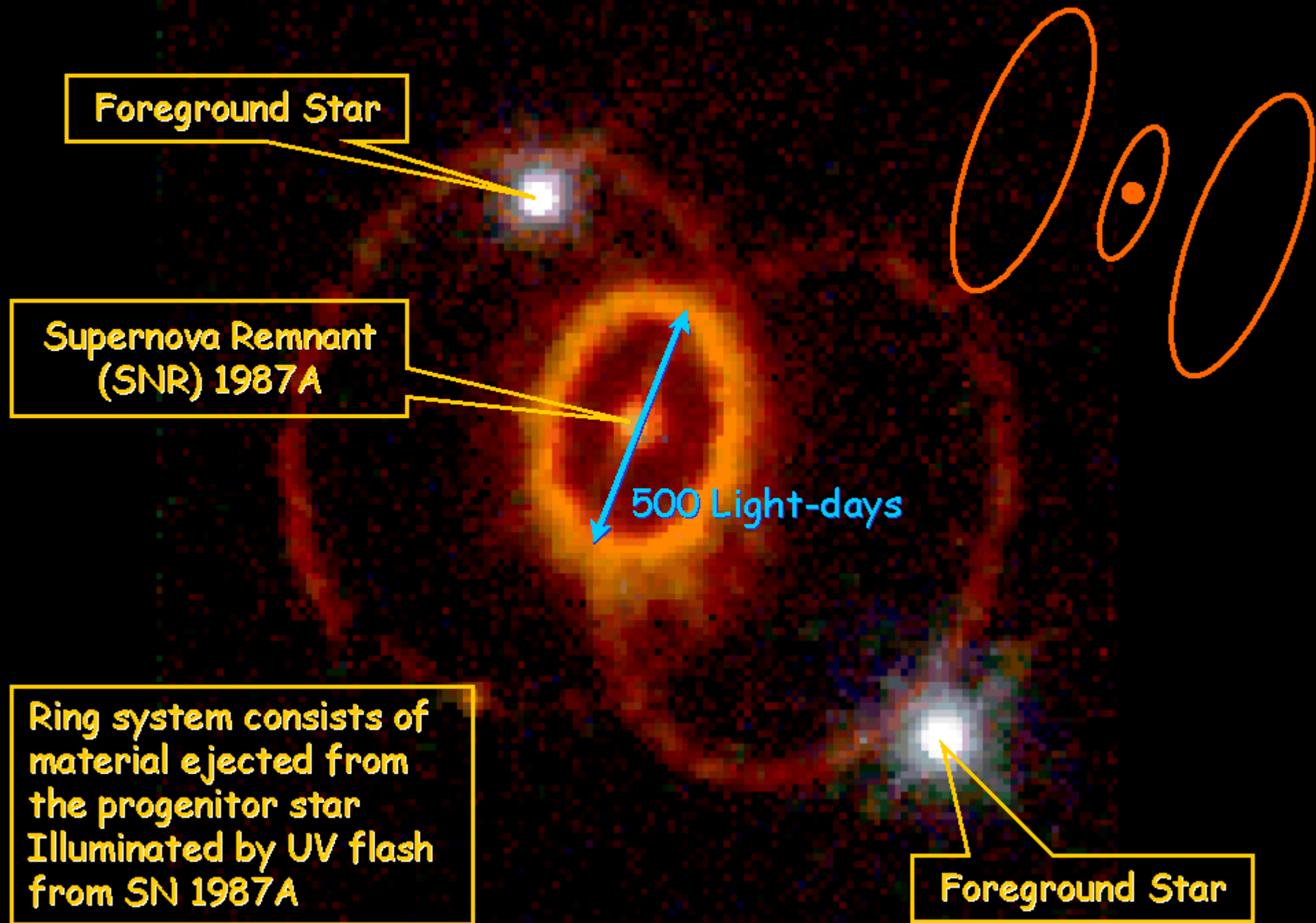
Supernova 1987A



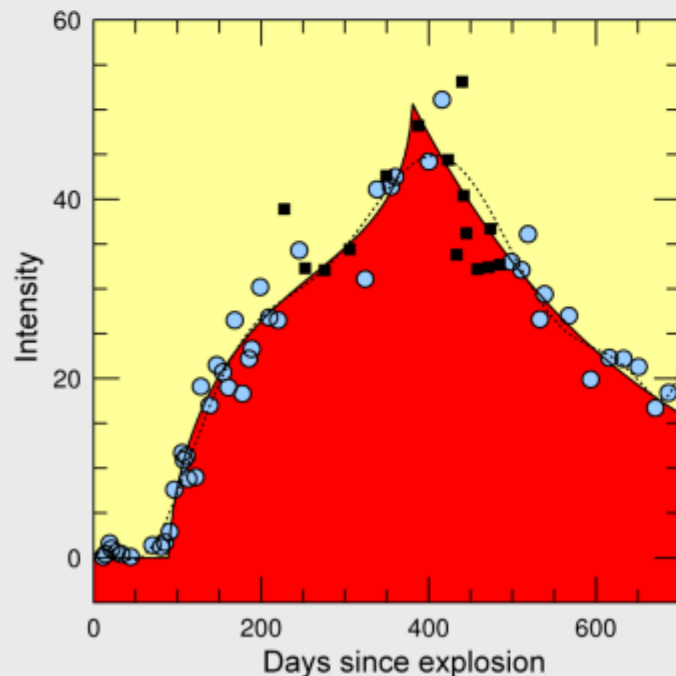
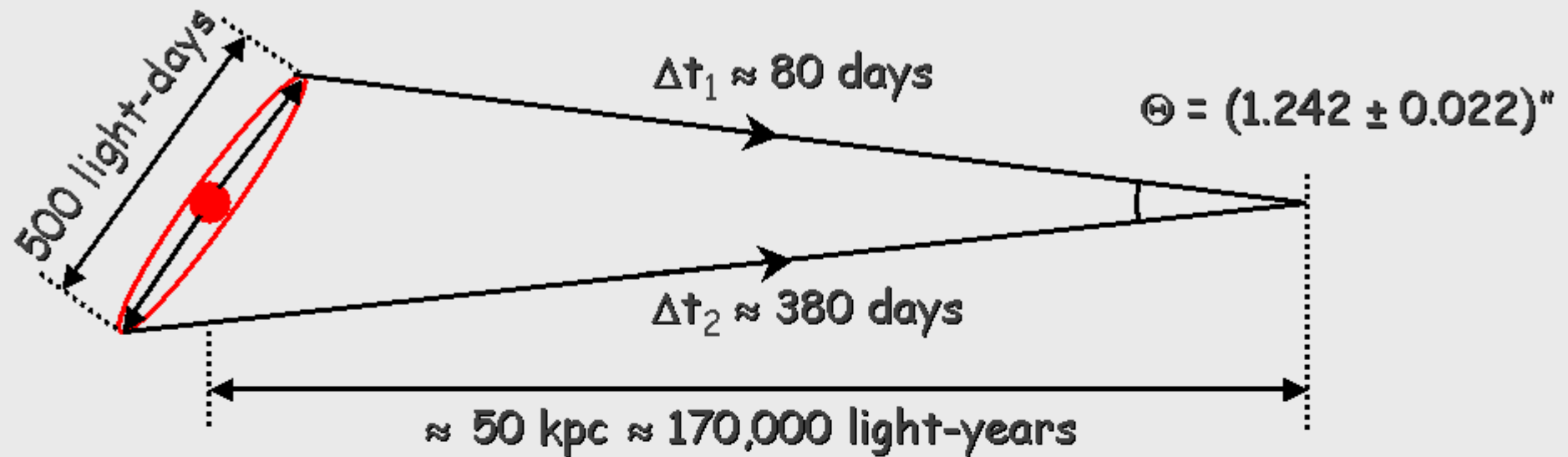
SN 1987A Rings (Hubble Space Telescope Picture)



SN 1987A Rings (Hubble Space Telescope Picture)



Distance Determination with Inner Ring

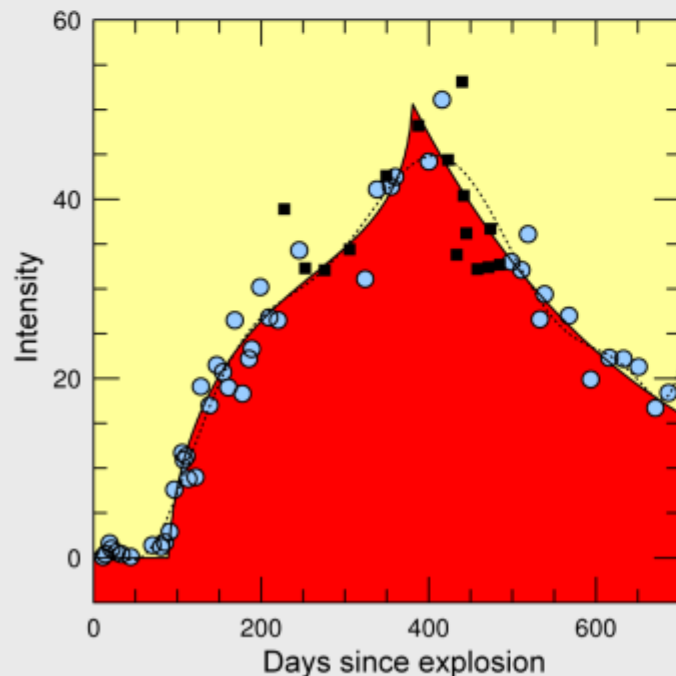
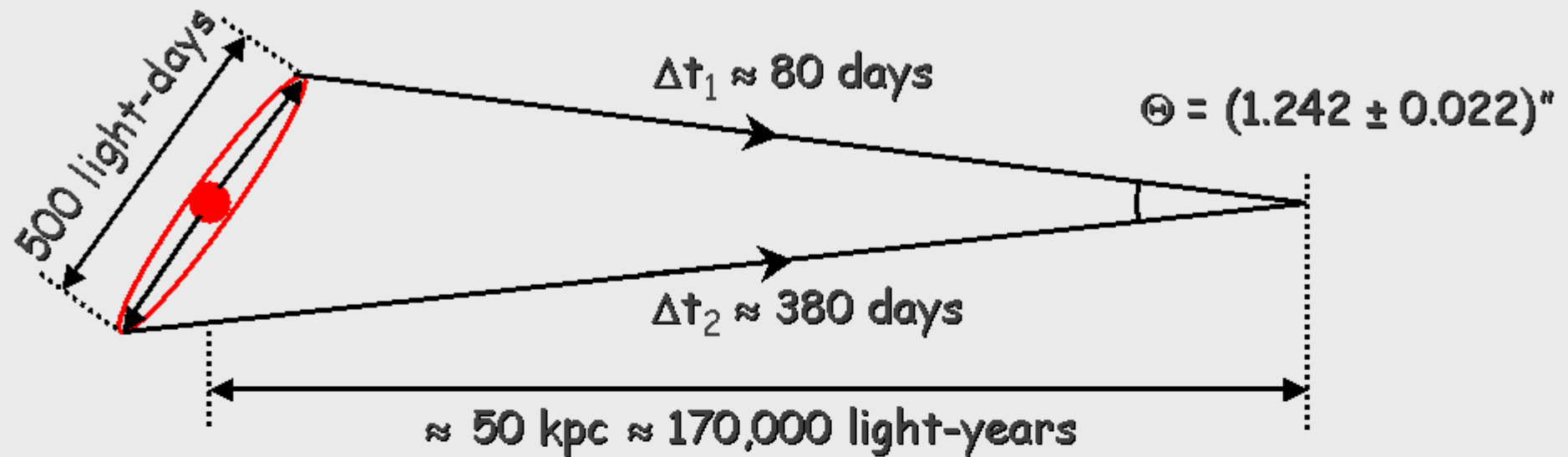


Angular diameter $\Theta_+ = (1.716 \pm 0.022)''$
measured by HST on 24-8-1990

Δt_1 and Δt_2 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]

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

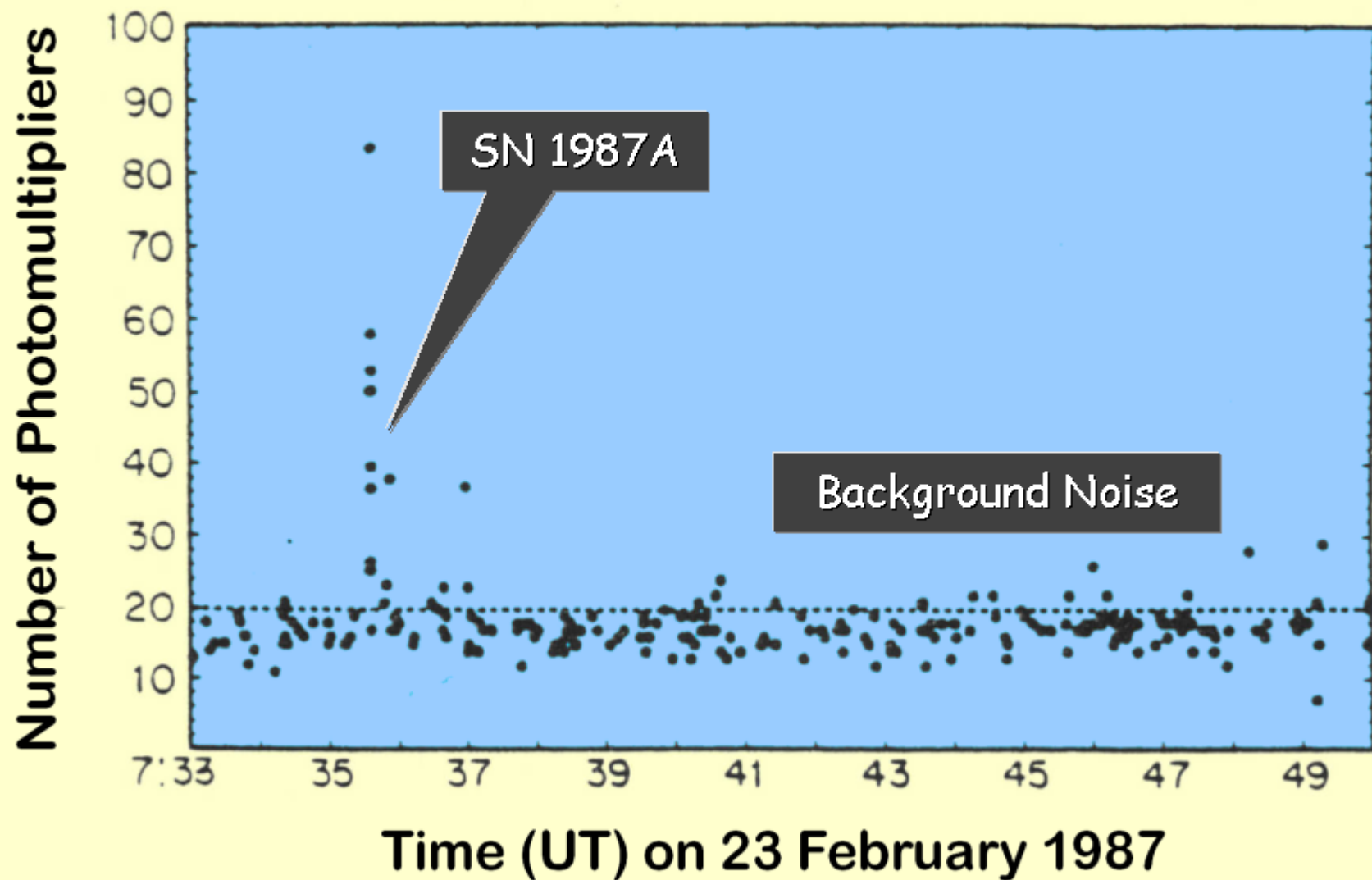
Ni III] light curve SN 1987A ring, measured by IUE
[Sonneborn et al. ApJ 477 (1997) 848,
fit by Gould & Uza, ApJ 494 (1998) 118]

Animation of SN 1987A Explosion

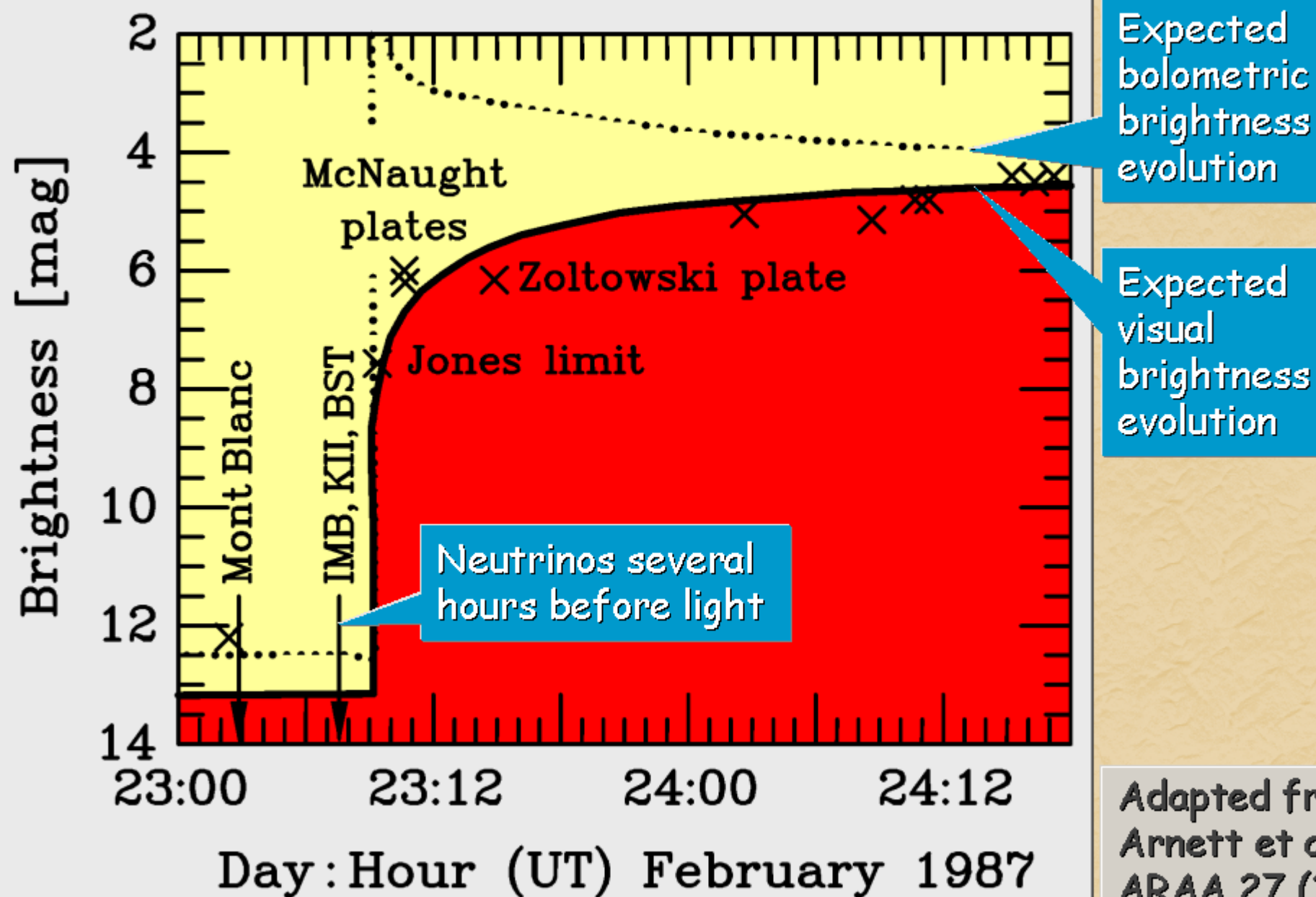


Animation by T. Goertel
Space Telescope Science Institute
<http://www.stsci.edu>

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 $\sim 3h$

Total transit time $\sim 5 \times 10^{12}$ sec
→ Equal for photons and neutrinos
within $\sim 2 \times 10^{-9}$

(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

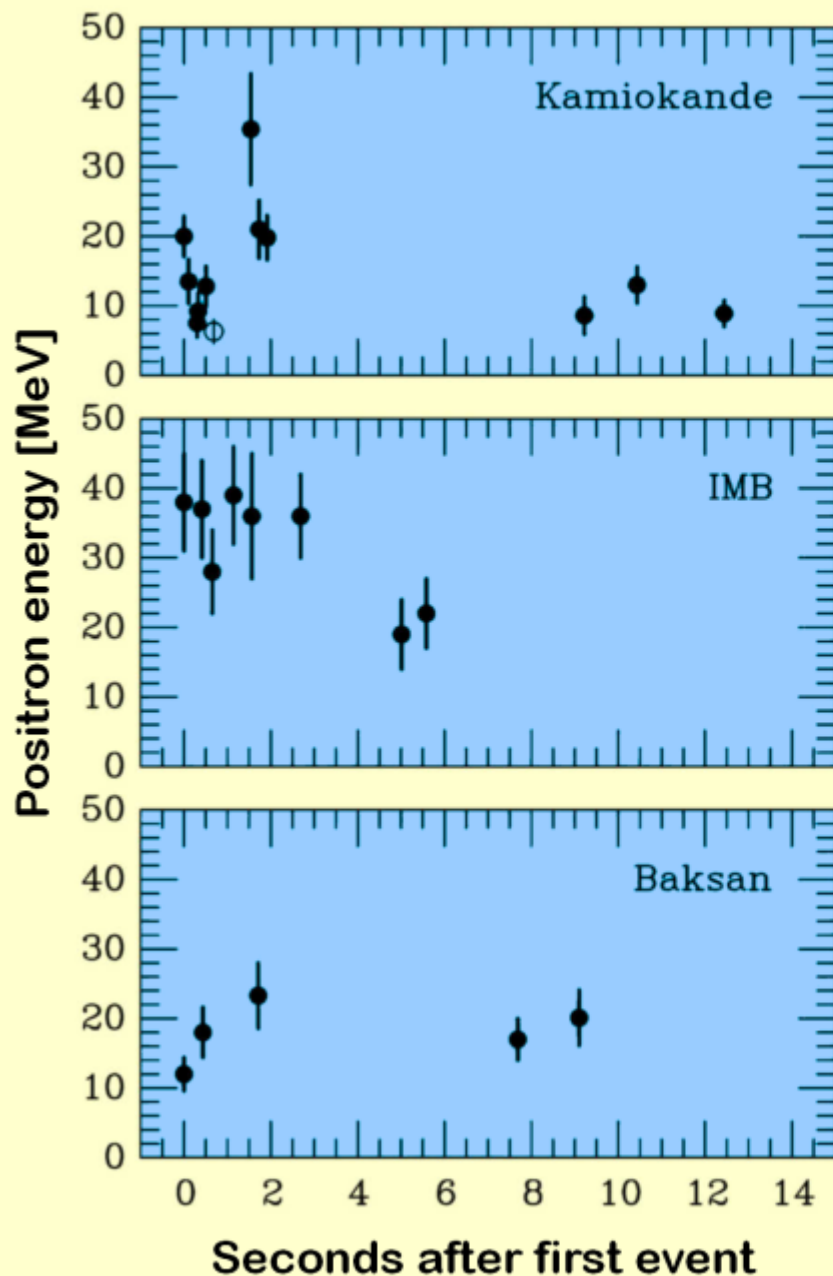
$$\Delta t_{\text{Shapiro}} = -2 \int_A^B U[r(t)] dt \approx 2 - 10 \times 10^6 \text{ sec}$$

(Krauss & Tremaine 1988)

Equal within $\sim 1 - 4 \times 10^{-3}$

- 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

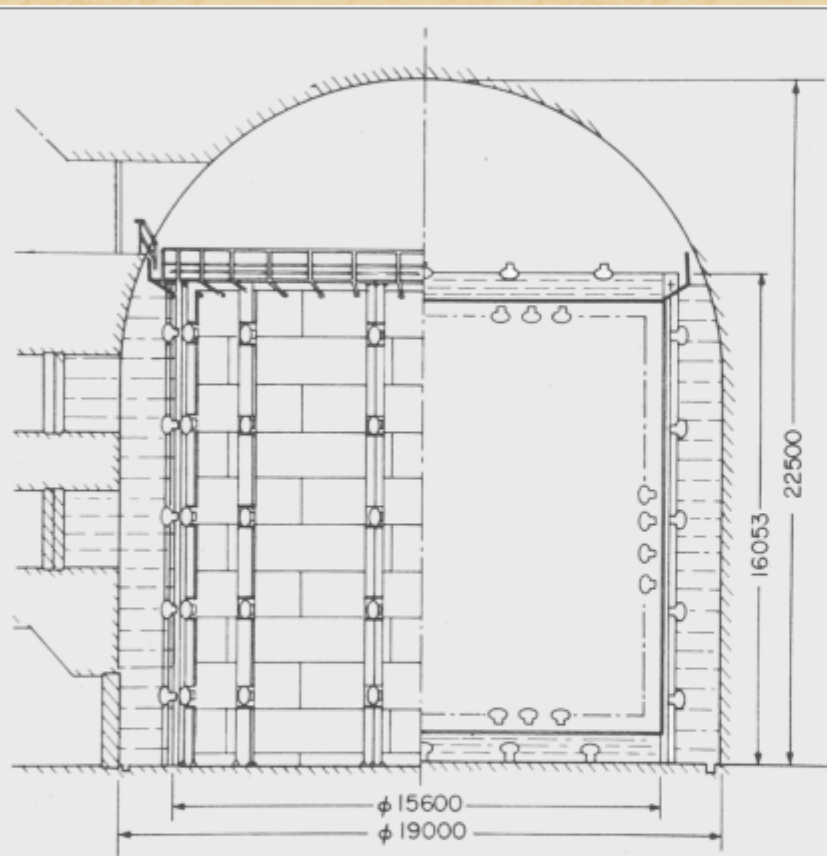
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty ± 50 ms

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

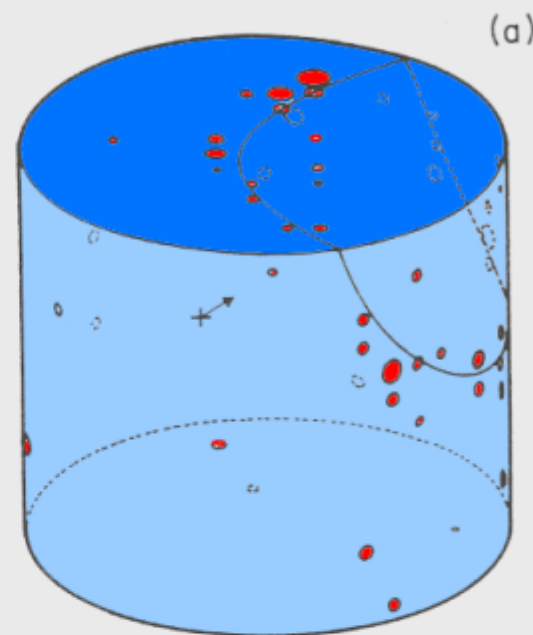
Within clock uncertainties,
signals are contemporaneous

SN 1987A Event No.9 in Kamiokande

Kamiokande Detector

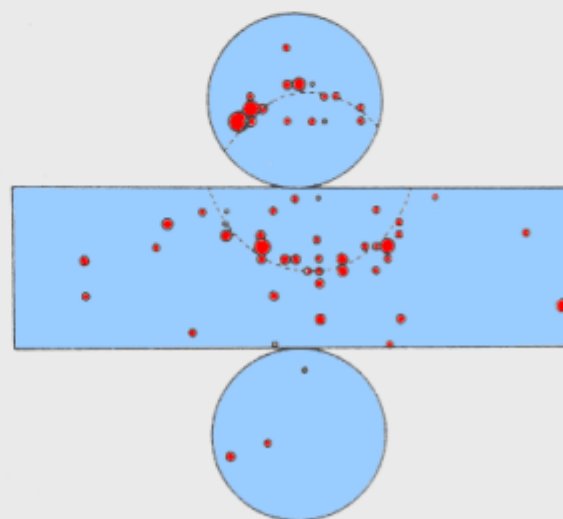


Hirata et al., PRD 38 (1988) 448



NUM 9
RUN 1892
EVENT 139372
TIME 2/23/87
16:35:37 JST

TOTAL ENERGY 19.8 MeV
TOTAL P.E. 51 (0)
MAX P.E. 4 (0)
THRES P.E. 0.2 (1.0)

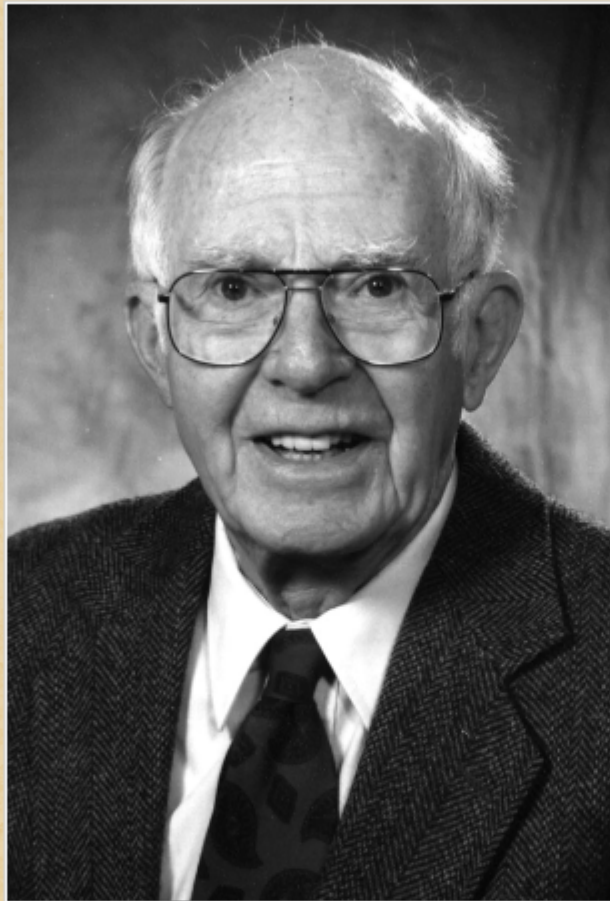


KAMIOKANDE 2-P

NUM 9
RUN 1892
EVENT 139372
TIME 2/23/87
16:35:37 JST

TOTAL ENERGY 19.8 MeV
TOTAL P.E. 51 (0)
MAX P.E. 4 (0)
THRES P.E. 0.2 (1.0)

2002 Physics Nobel Prize for Neutrino Astronomy



Ray Davis Jr.
(*1914)



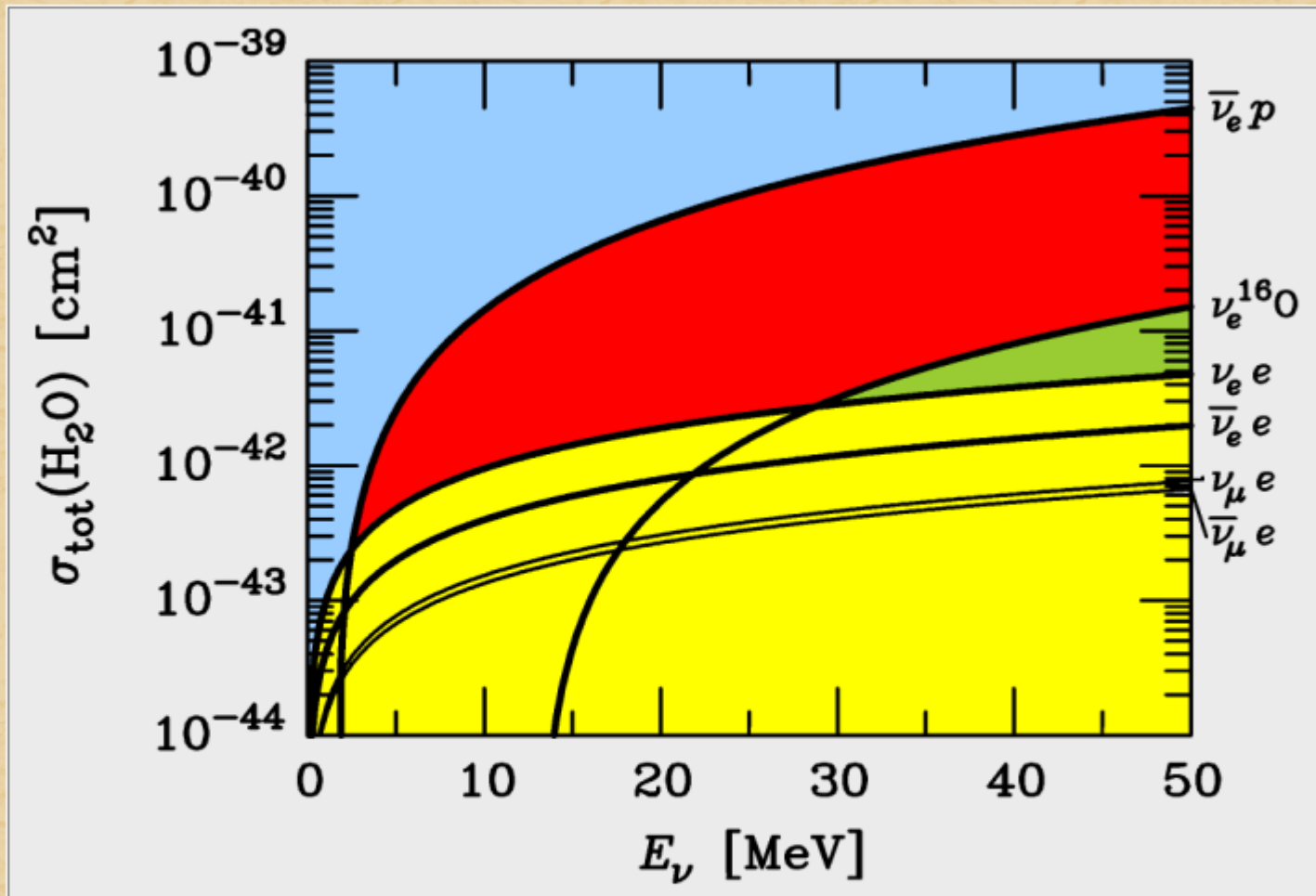
Masatoshi Koshihara
(*1926)



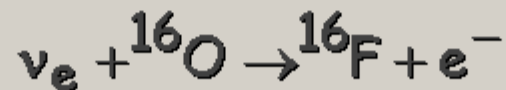
"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

Neutrino Cross Section in a Water Target

Cross
section
per
water
molecule

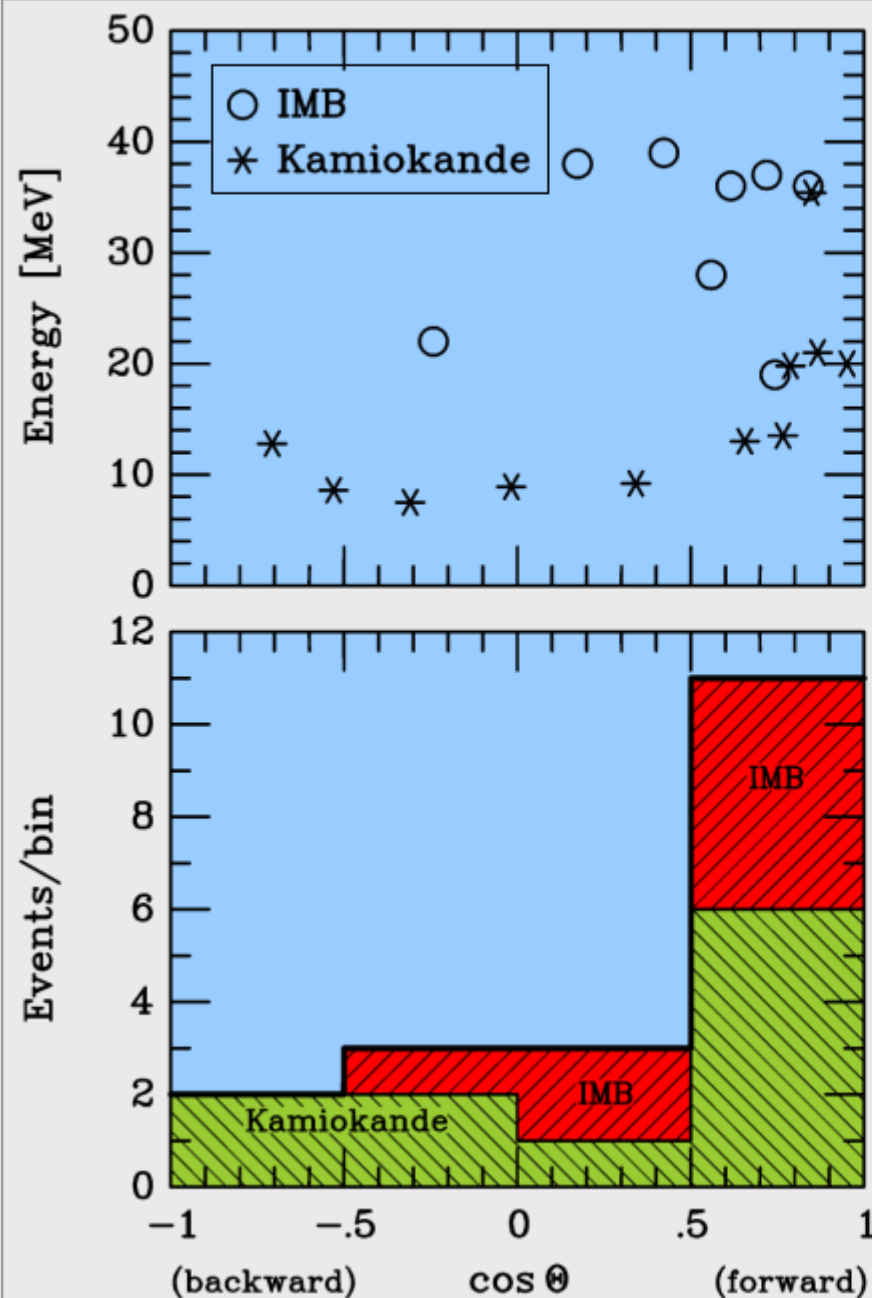


Main reactions: $\bar{\nu}_e + p \rightarrow n + e^+$ dominates for SN



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

Angular Distribution of SN 1987A Neutrinos



Main detection reaction



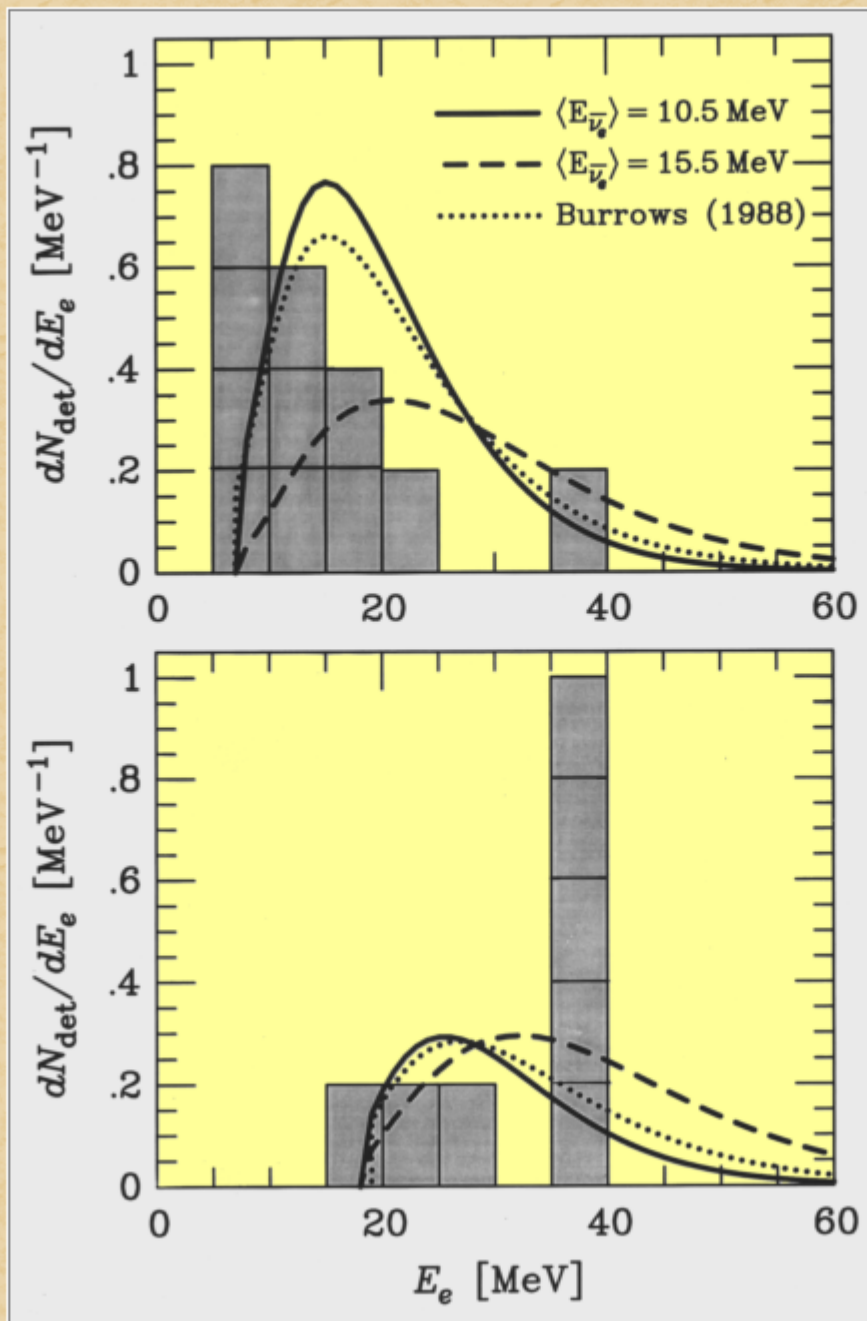
is essentially isotropic for the relevant energies.

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



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

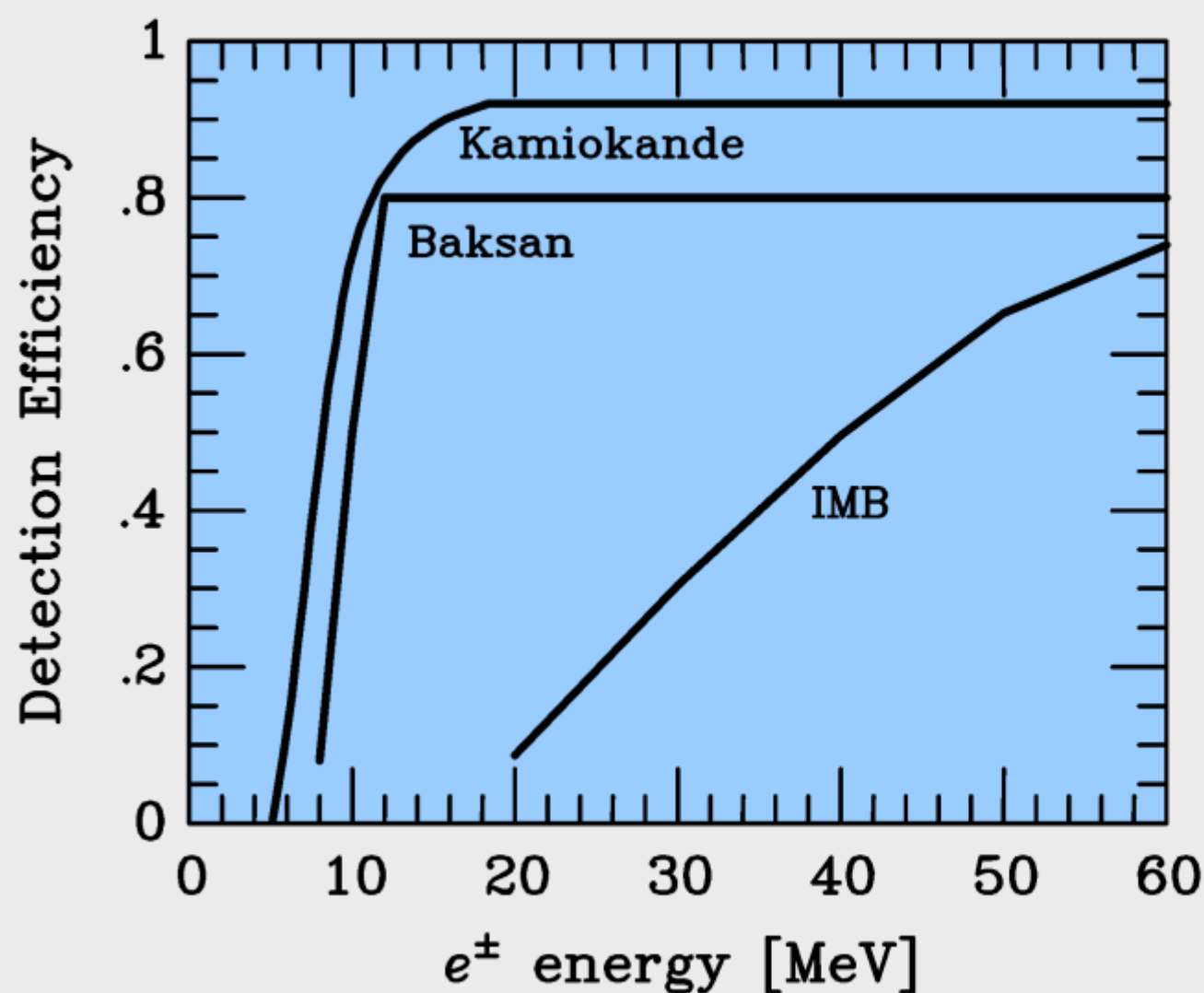
Energy Distribution of SN 1987A Neutrinos



Kamiokande II

IMB

Trigger Efficiencies at the Detectors



Fiducial volumes for
SN 1987A detection

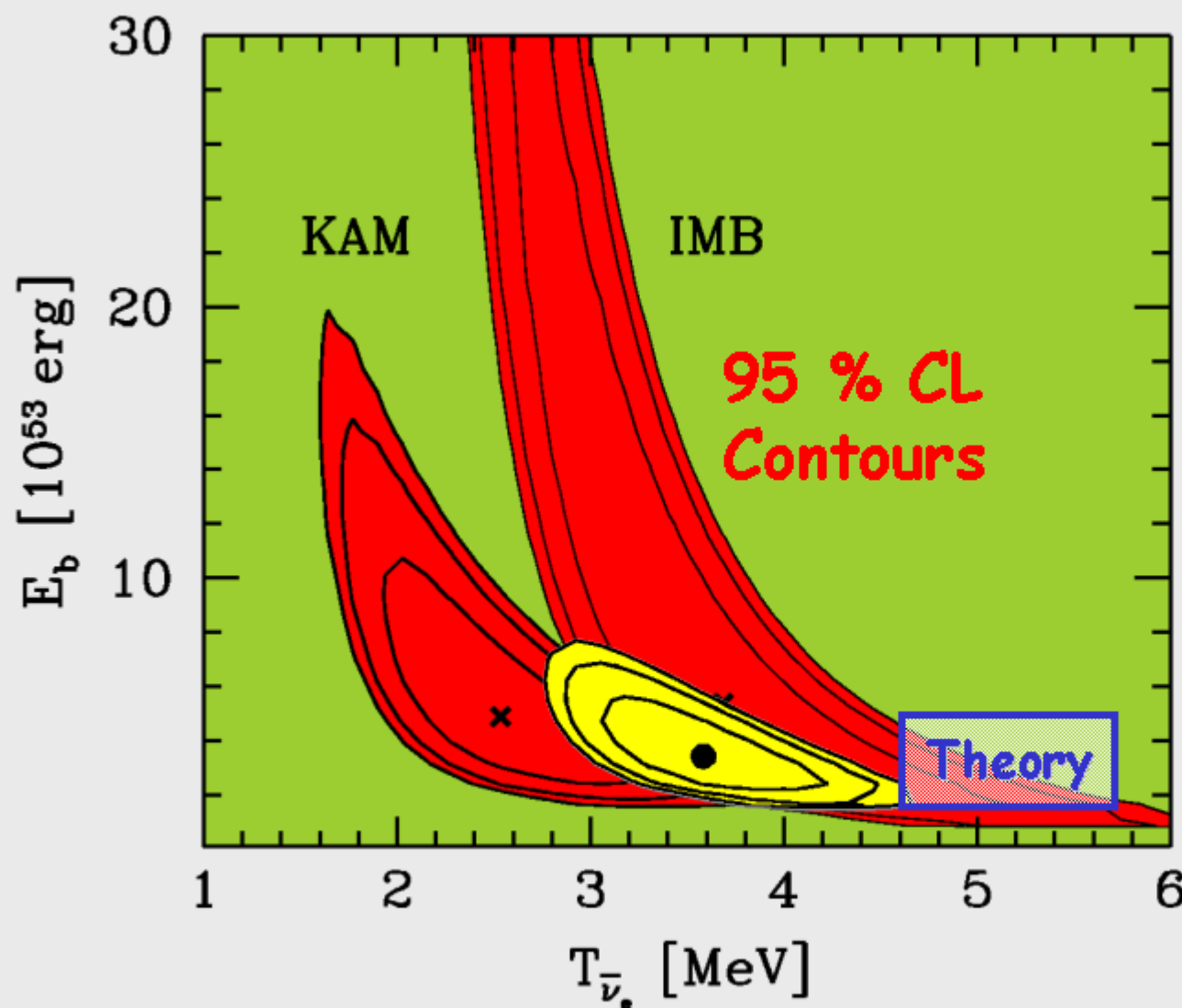
Kamiokande II
2140 tons water
(1.43×10^{32} protons)

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

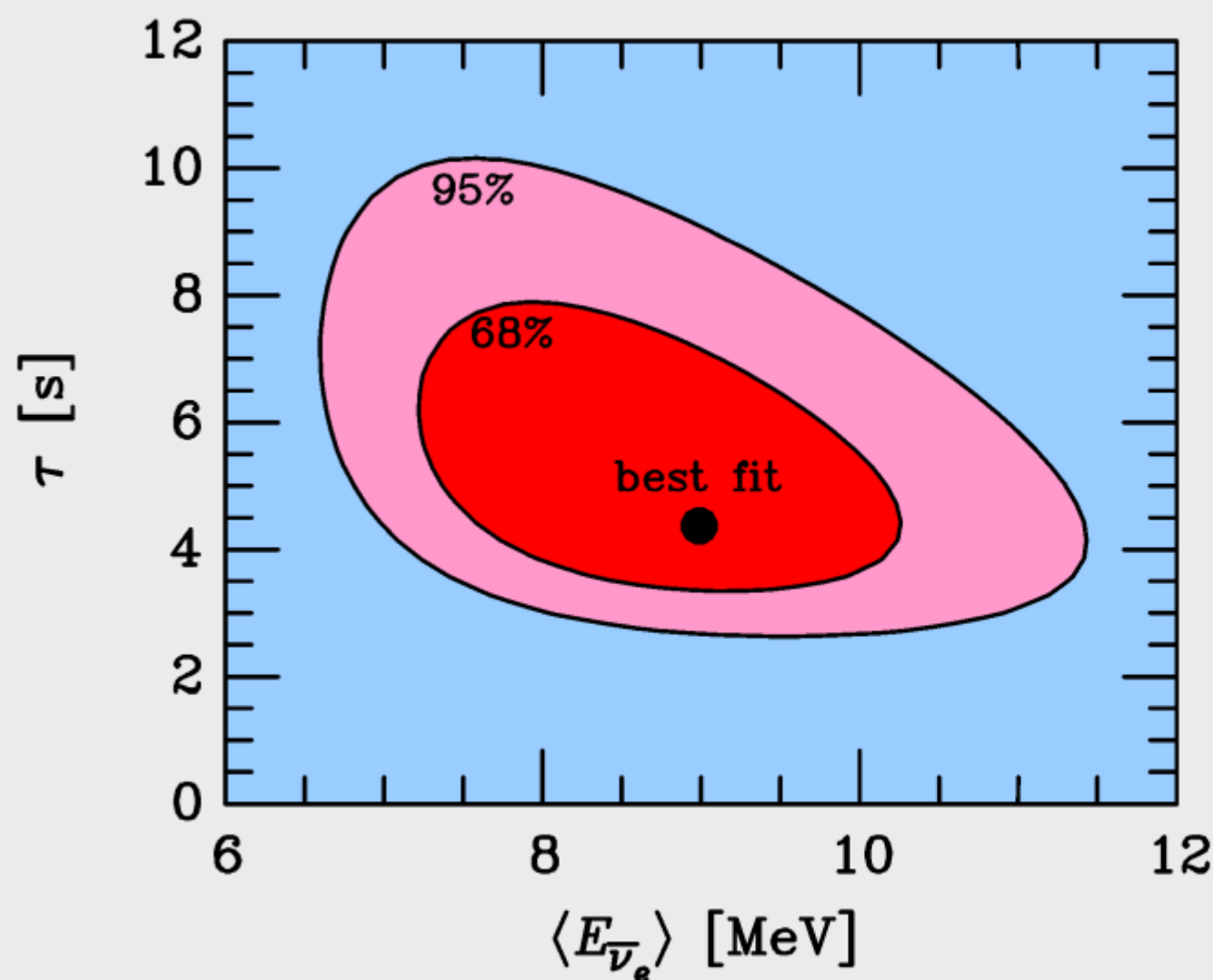


Jegerlehner,
Neubig & Raffelt,
PRD 54 (1996) 1194

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

Spectral $\bar{\nu}_e$ Temperature

Cooling Time Scale



Exponential cooling model

$$T = T_0 e^{-t/4\tau}$$

constant radius

$$L = L_0 e^{-t/\tau}$$

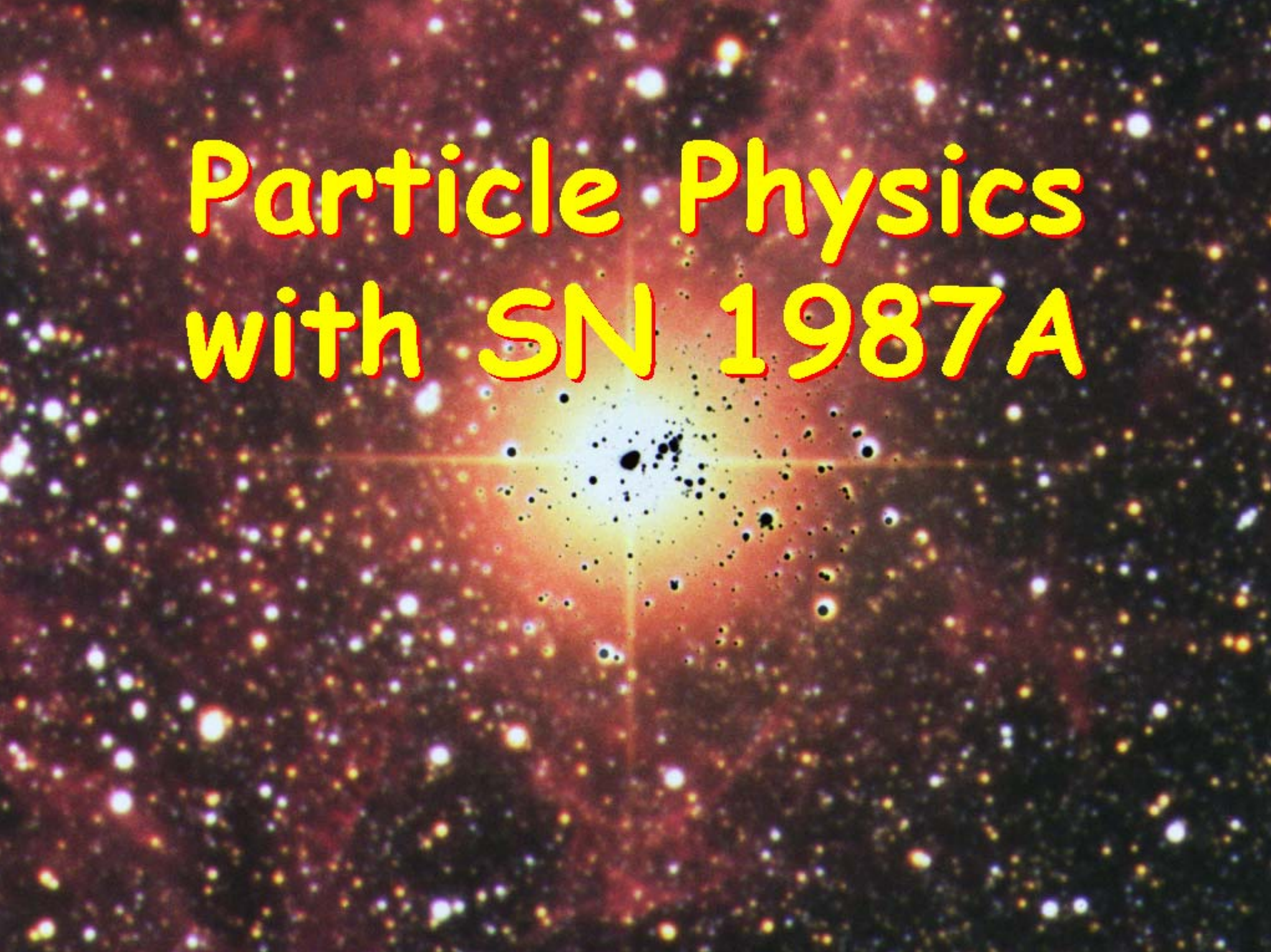
Fit parameters are

T_0 , τ , radius,
3 offset times
for detectors

(Loredo & Lamb 95)

Similar results for
more sophisticated
cooling models

Particle Physics with SN 1987A



Neutrino Limits by Intrinsic Signal Dispersion

Time of flight delay by neutrino mass

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

$$m_{\nu_e} < 20 \text{ eV}$$

- Detailed maximum-likelihood analysis yields similar limit
- At the time of SN 1987A competitive with tritium end-point limits, today $m_{\nu_e} < 2.2 \text{ eV}$
- Cosmological limit today $m_\nu < 0.7 \text{ eV}$

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

$$\frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp d_B)^2}{6 E_\nu^2} < 3 \times 10^{-12}$$

$$\frac{e_\nu}{e} < 3 \times 10^{-17} \left(\frac{1 \mu\text{G}}{B_\perp} \right) \left(\frac{1 \text{ kpc}}{d_B} \right)$$

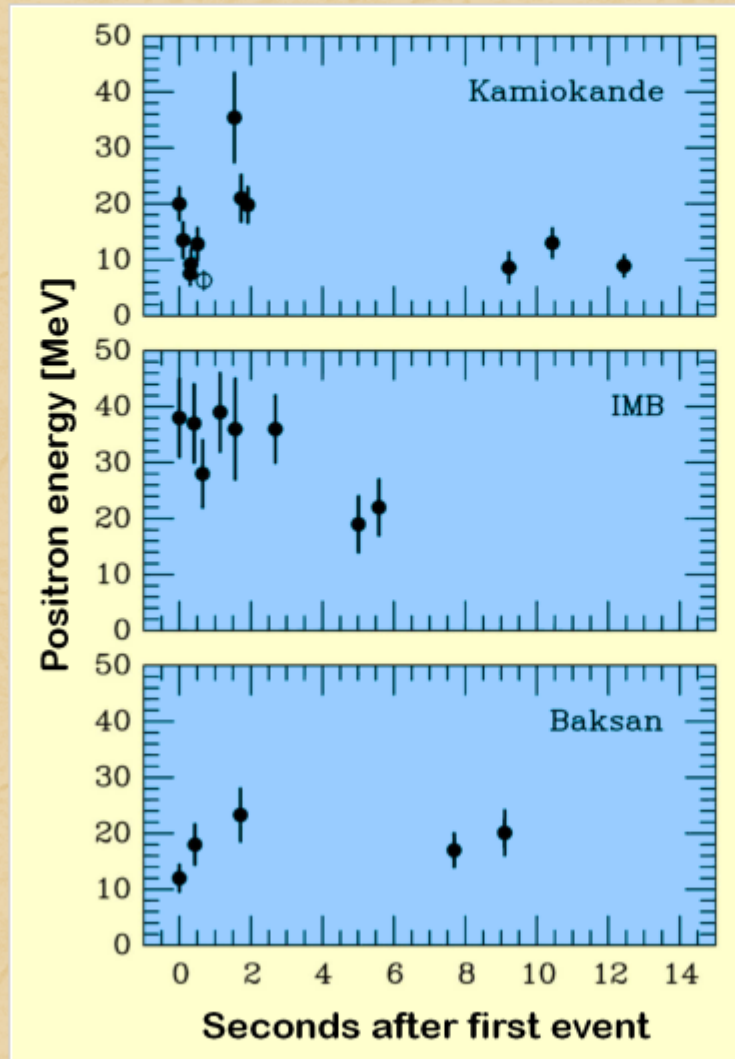
Assuming charge conservation in neutron decay yields a more restrictive limit of about $3 \times 10^{-21} e$

Neutrino Mass Limits by Signal Dispersion

Time-of-flight delay
of massive neutrinos

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

SN 1987A



Neutrino Mass Limits by Signal Dispersion

Time-of-flight delay
of massive neutrinos

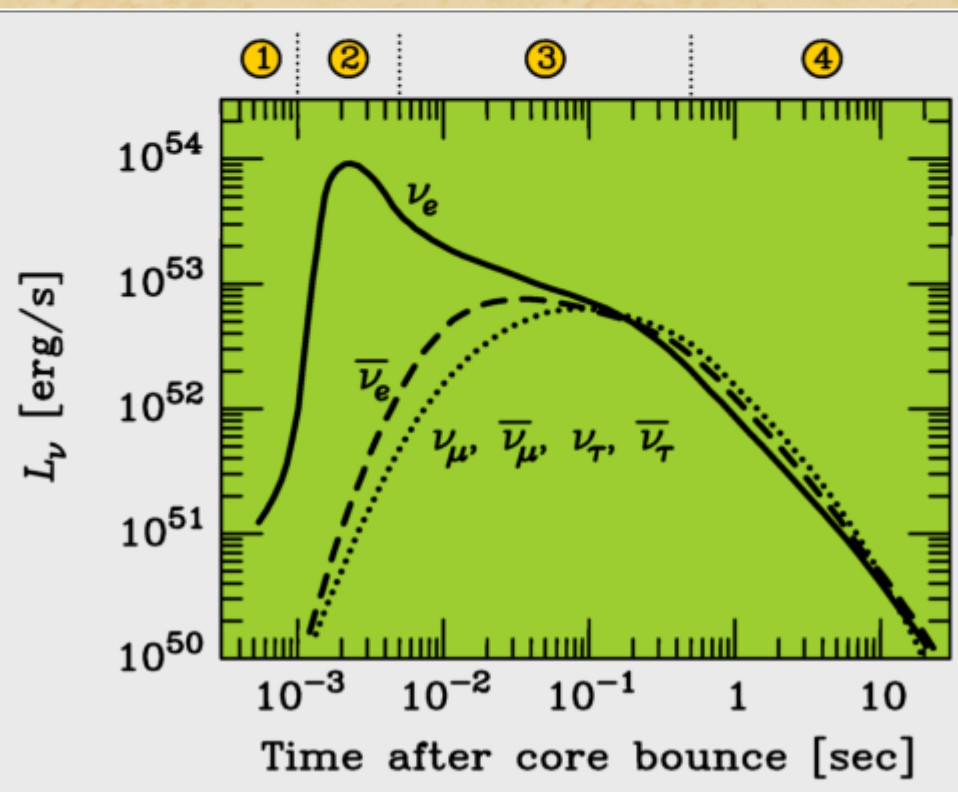
$$\Delta t = 2.57 \text{ s} \left(\frac{D}{50 \text{ kpc}} \right) \left(\frac{10 \text{ MeV}}{E_\nu} \right)^2 \left(\frac{m_\nu}{10 \text{ eV}} \right)^2$$

SN 1987A

$E \approx 20 \text{ MeV}$, $\Delta t \approx 10 \text{ s}$, $D \approx 50 \text{ kpc}$
Simple estimate or detailed maximum
likelihood analysis give similar results

$$m_\nu < 20 \text{ eV}$$

Future
Galactic SN
(Super-K)



Neutrino Mass Limits by Signal Dispersion

Time-of-flight delay
of massive neutrinos

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

SN 1987A

$E \approx 20 \text{ MeV}$, $\Delta t \approx 10 \text{ s}$, $D \approx 50 \text{ kpc}$
Simple estimate or detailed maximum likelihood analysis give similar results

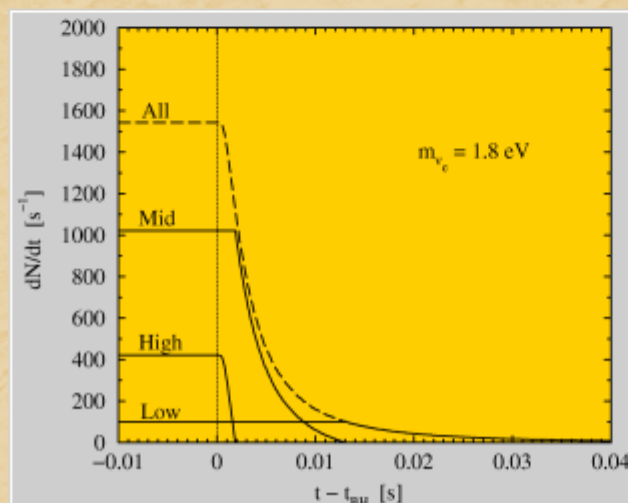
$m_\nu < 20 \text{ eV}$

Future
Galactic SN
(Super-K)

$D \approx 10 \text{ kpc}$, Rise-time 0.01 s
Sensitivity approximately
[T.Totani, PRL 80 (1998) 2040]

$m_\nu \sim 3 \text{ eV}$

With
Black Hole
Formation



Neutrino Mass Limits by Signal Dispersion

Time-of-flight delay
of massive neutrinos

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

SN 1987A

$E \approx 20 \text{ MeV}$, $\Delta t \approx 10 \text{ s}$, $D \approx 50 \text{ kpc}$
Simple estimate or detailed maximum likelihood analysis give similar results

$m_\nu < 20 \text{ eV}$

Future
Galactic SN
(Super-K)

$D \approx 10 \text{ kpc}$, Rise-time 0.01 s
Sensitivity approximately
[T.Totani, PRL 80 (1998) 2040]

$m_\nu \sim 3 \text{ eV}$

With
Black Hole
Formation

$D \approx 10 \text{ kpc}$, Cutoff "infinitely" fast
Sensitivity approximately
[Beacom et al., PRD 63 (2001) 073011]

$m_\nu \sim 2 \text{ eV}$

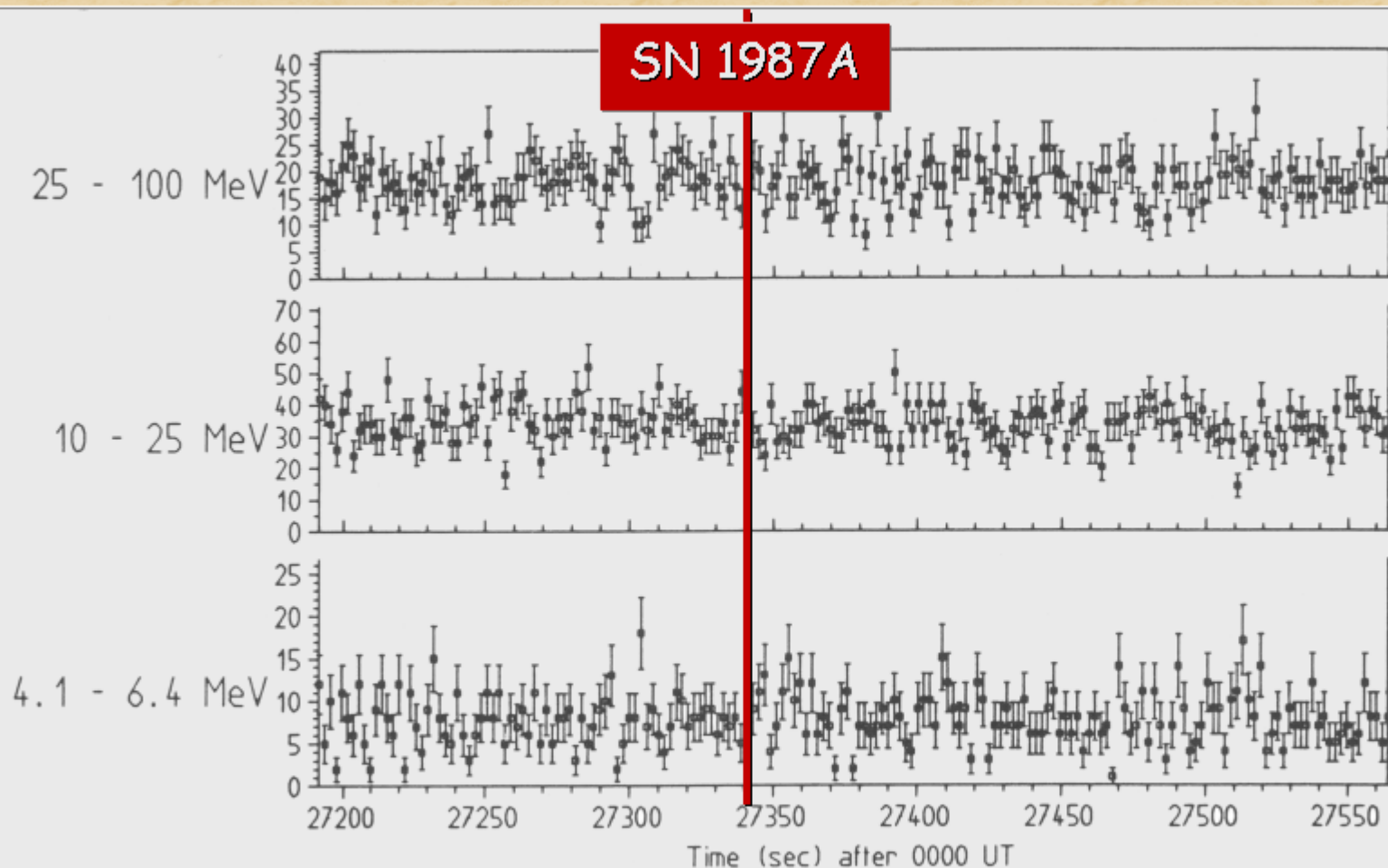
Future SN
in Andromeda
(Megatonne)

$D \approx 750 \text{ kpc}$, $\Delta t \approx 10 \text{ s}$
Sensitivity approximately

$m_\nu \sim 1\text{-}2 \text{ eV}$

Gamma-Ray Observations of SMM Satellite

Counts in the GRS instrument on the Solar Maximum Mission Satellite



10s fluence
limit
 0.9 cm^{-2}

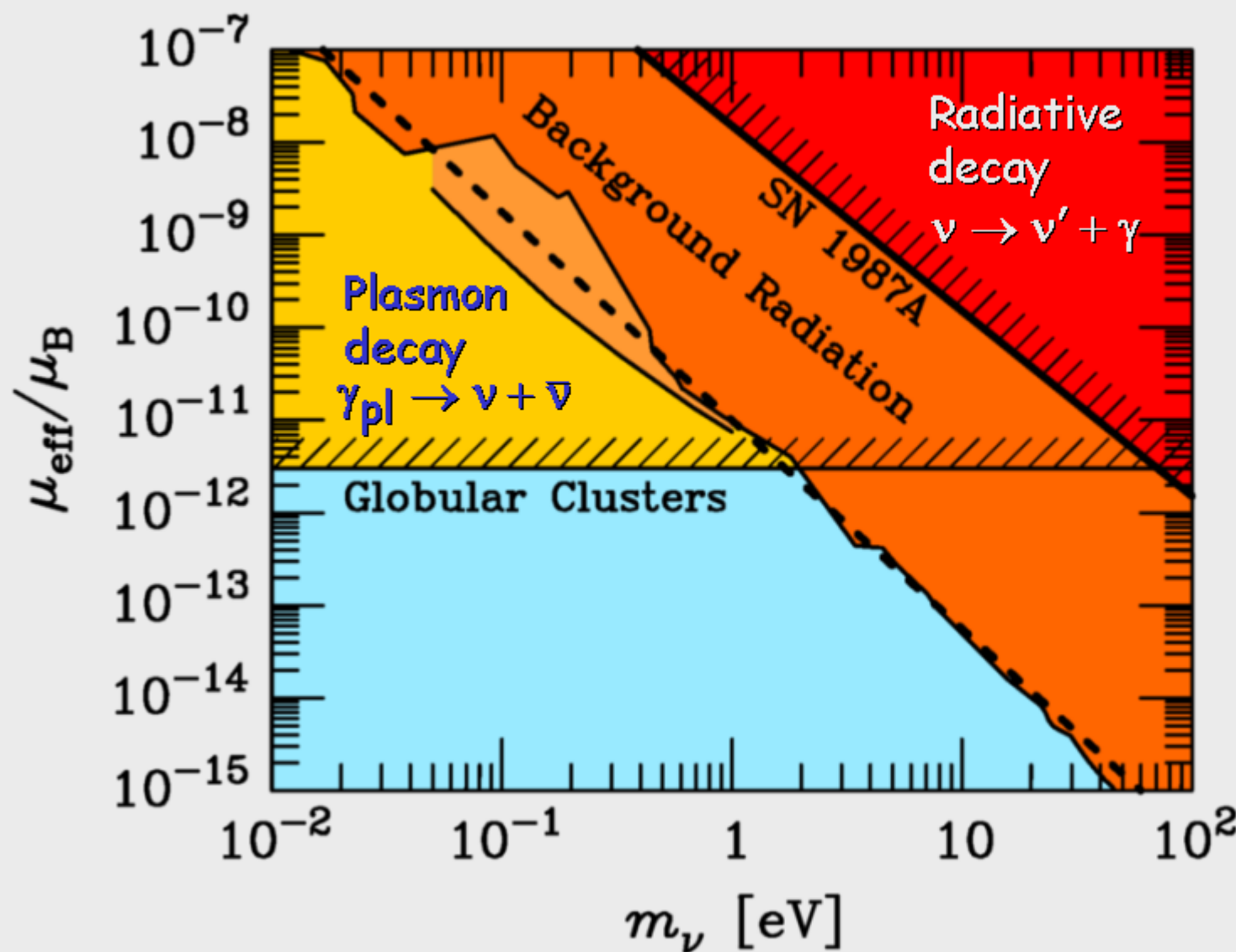
0.4 cm^{-2}

0.6 cm^{-2}

SN 1987A neutrino fluence $\sim 10^{10} \text{ cm}^{-2}$

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

Neutrino Radiative Lifetime Limits

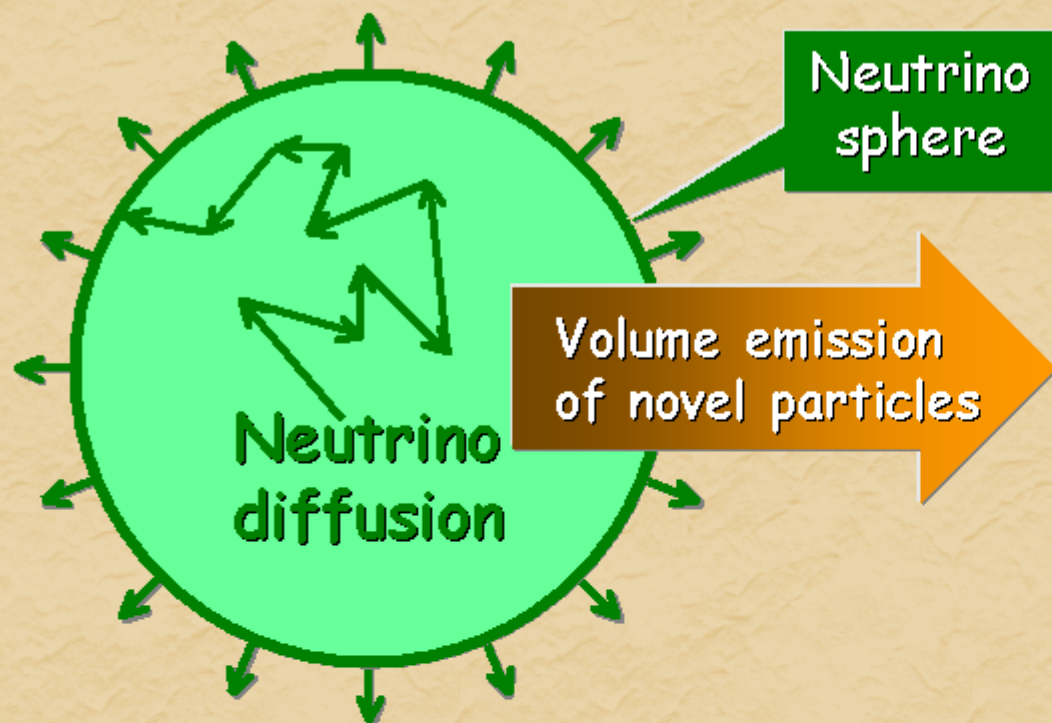


$$\Gamma_{\nu \rightarrow \nu' \gamma} = \frac{\mu_{\text{eff}}^2}{8\pi} m_\nu^3$$

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

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

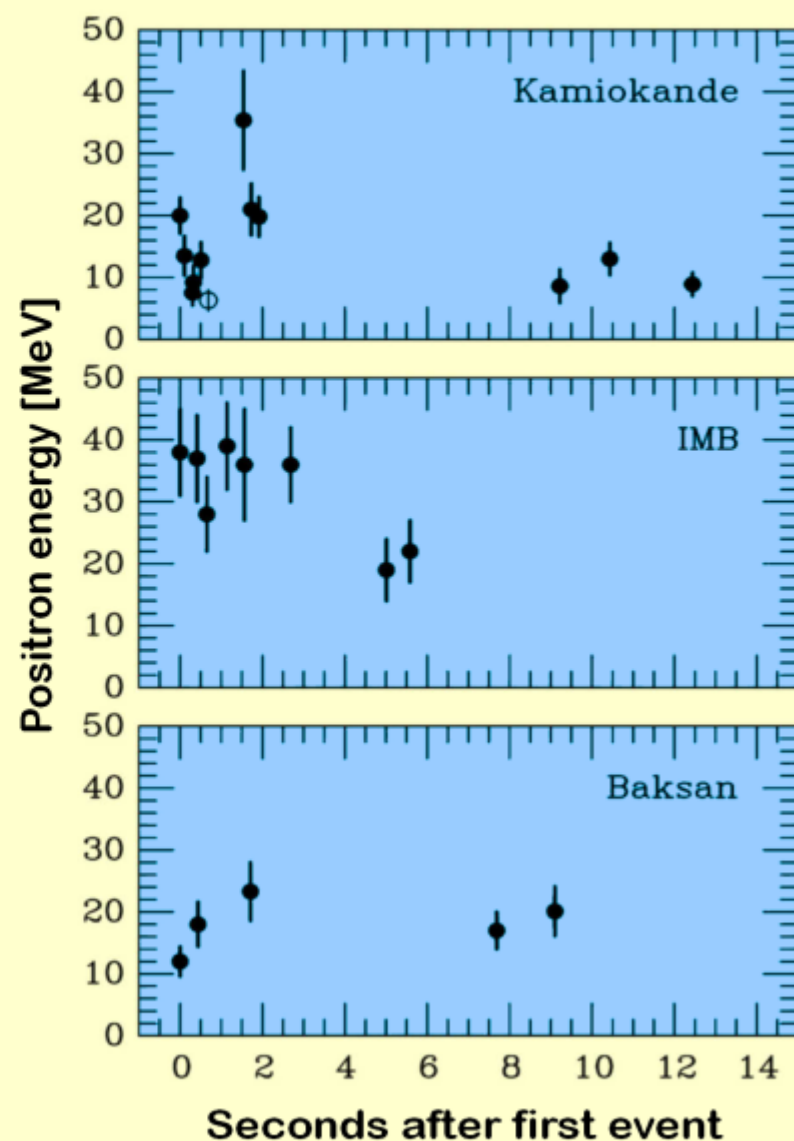
The Energy-Loss Argument



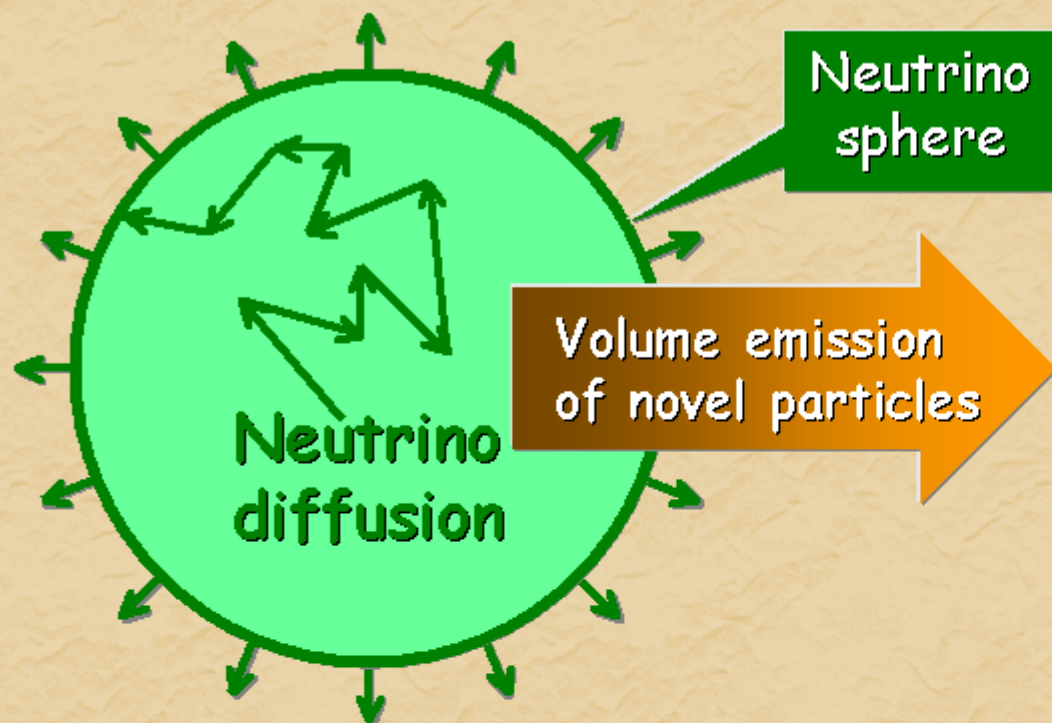
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

SN 1987A neutrino signal



The Energy-Loss Argument

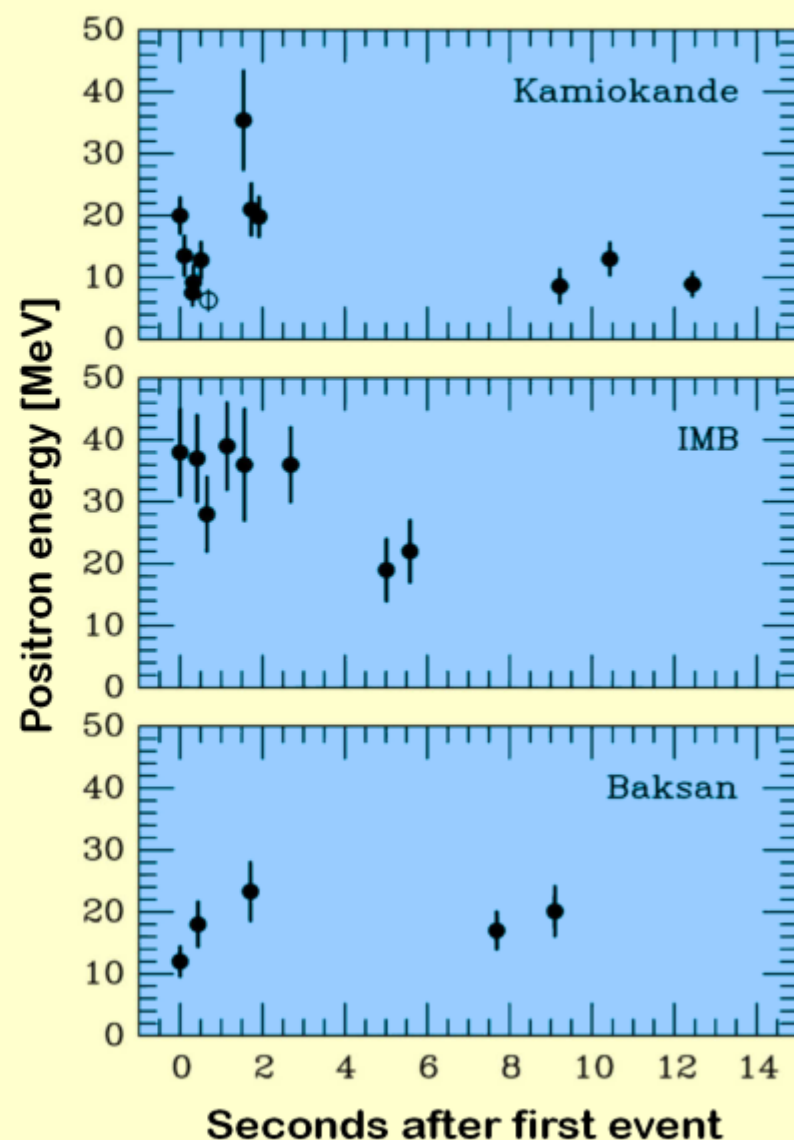


Assuming that the neutrino burst was not shortened by more than $\sim \frac{1}{2}$ leads to an approximate requirement on a novel energy-loss rate

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

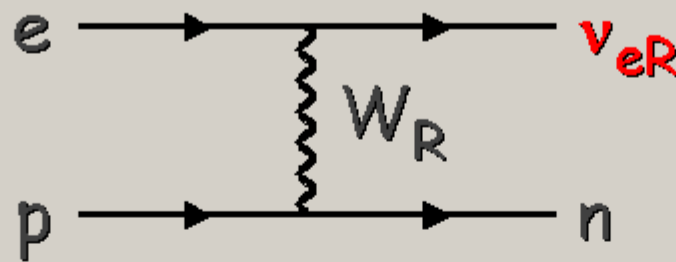
for $\rho \approx 3 \times 10^{14} \text{ g cm}^{-3}$ and $T \approx 30 \text{ MeV}$

SN 1987A neutrino signal



Right-Handed Neutrinos (Dirac Neutrinos)

Right-handed
currents



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

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

For right-handed neutrinos

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

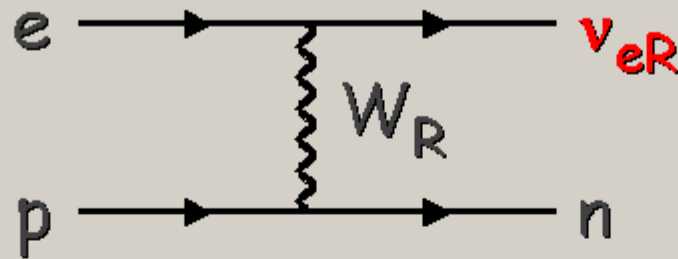
To avoid complete energy loss in $\sim 1 \text{ s}$

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

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

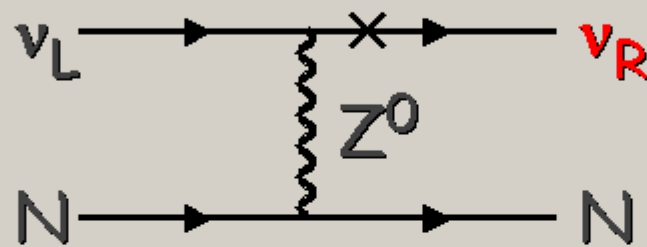
Right-Handed Neutrinos (Dirac Neutrinos)

Right-handed
currents



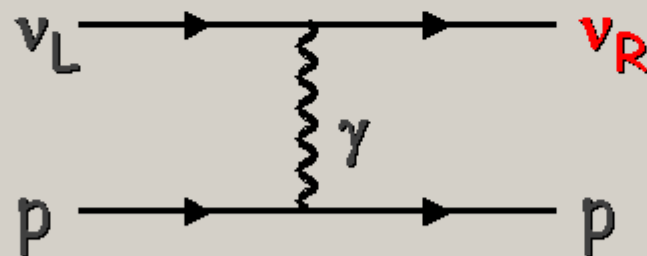
$$G_R < 10^{-5} G_F$$

Dirac
mass
term



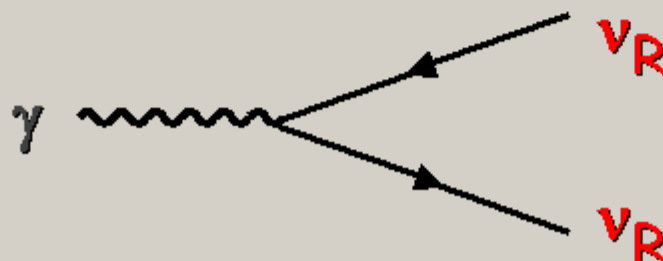
$$m_D < 30 \text{ keV}$$

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 nucleosynthesis?
- 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 $\rightarrow$ potentially detectable

Sterile Neutrinos

Active-sterile
mixing



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

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

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

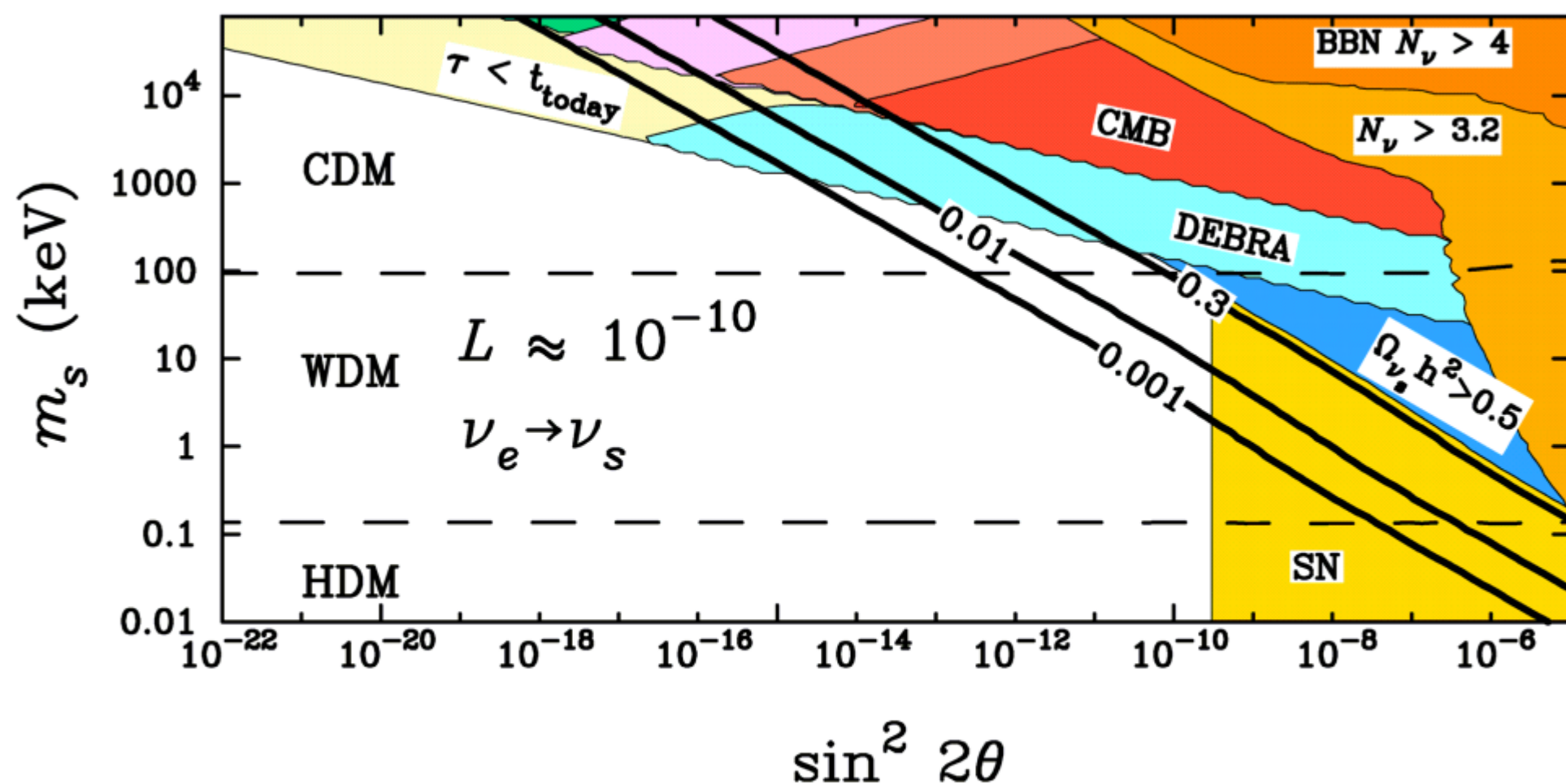
$$\Gamma_s \approx \frac{1}{2} \sin^2(2\Theta_{es}) \Gamma_L$$

To avoid complete energy loss in $\sim 1 \text{ s}$

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

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

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

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

For ν_s - ν_e -mixing:

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

$$= \pm 1.53 \times 10^9 \frac{(\gamma_e + 2\gamma_{\nu_e} - \frac{1}{2}\gamma_h) \rho}{10^{14} \text{ g cm}^{-3}} \frac{E_\nu}{100 \text{ MeV}} \frac{1 \text{ eV}^2}{\Delta m^2}$$

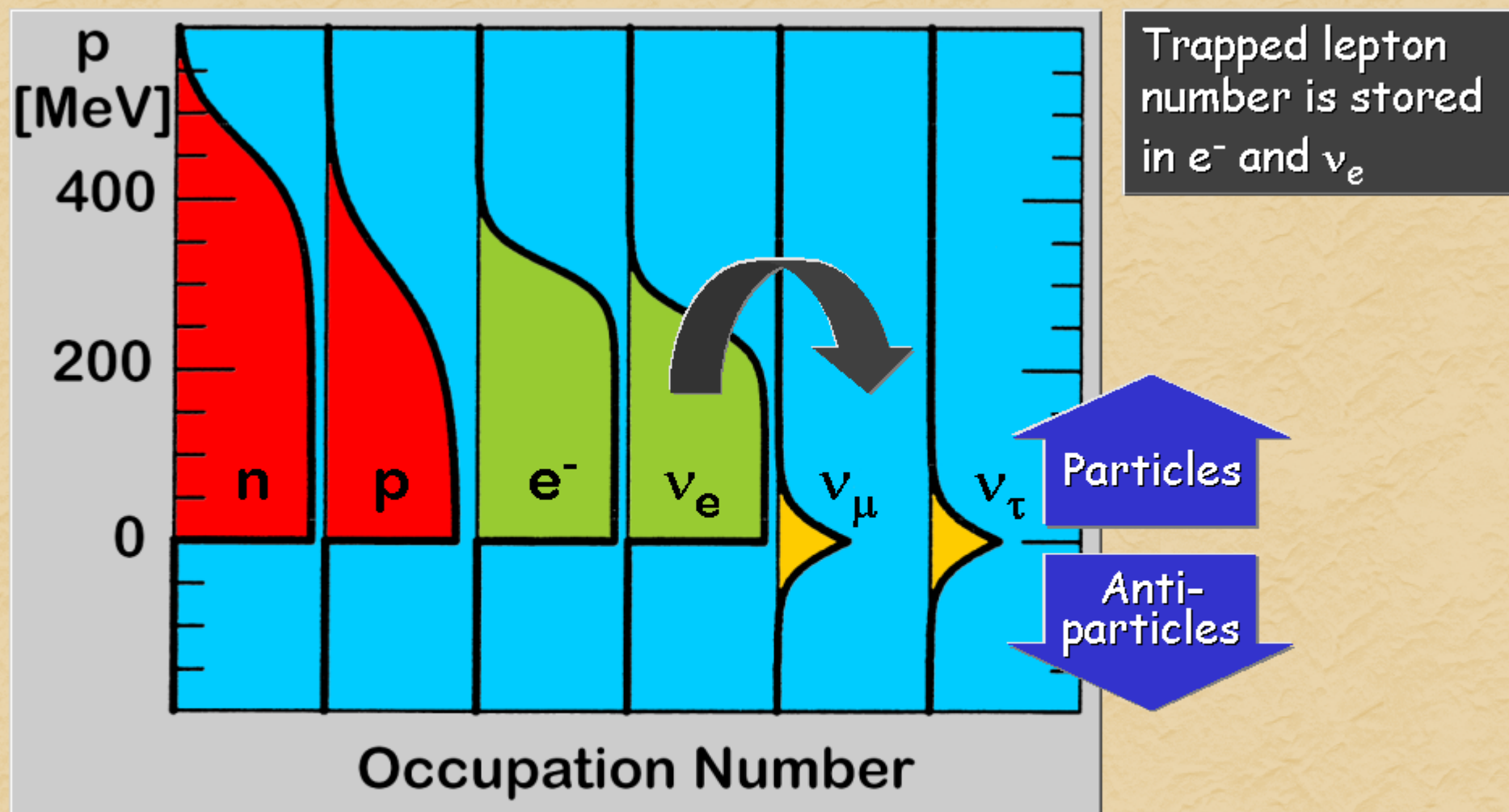
Large medium
effect ($|A| \gg 1$)
and large sterile
mass ($m_s \gg m_\nu$)

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

$$= 4.3 \times 10^{-19} \left(\frac{10^{14} \text{ g cm}^{-3}}{(\gamma_e + 2\gamma_{\nu_e} - \frac{1}{2}\gamma_h) \rho} \right)^2 \left(\frac{100 \text{ MeV}}{E_\nu} \right)^2 \left(\frac{m_s}{1 \text{ eV}} \right)^4$$

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

Degenerate Fermi Seas in a Supernova Core



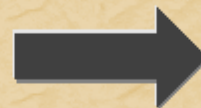
In true thermal equilibrium with flavor mixing only one chemical potential for charged leptons and one for neutrinos

Time scale to achieve flavor equilibrium?

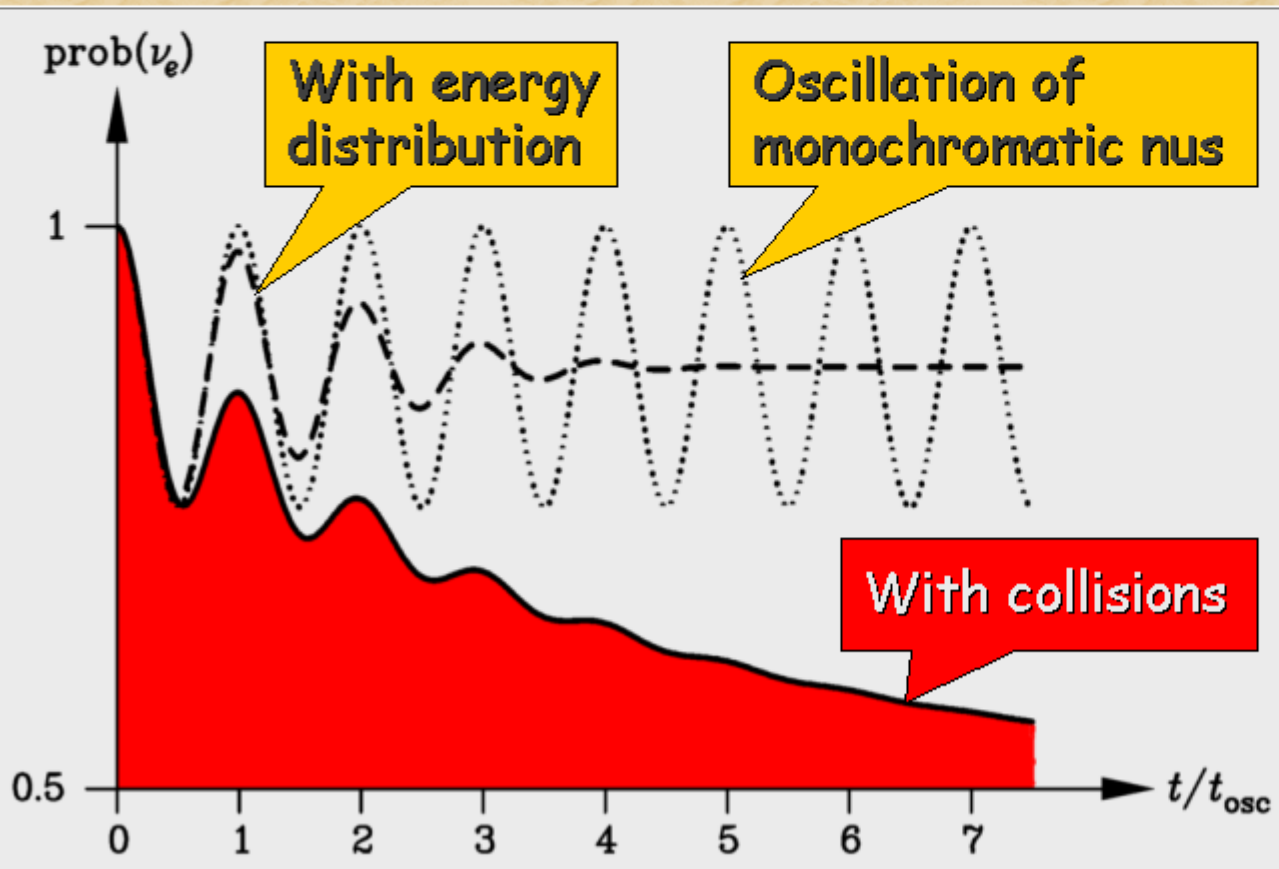
Flavor Relaxation in a Supernova Core

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".

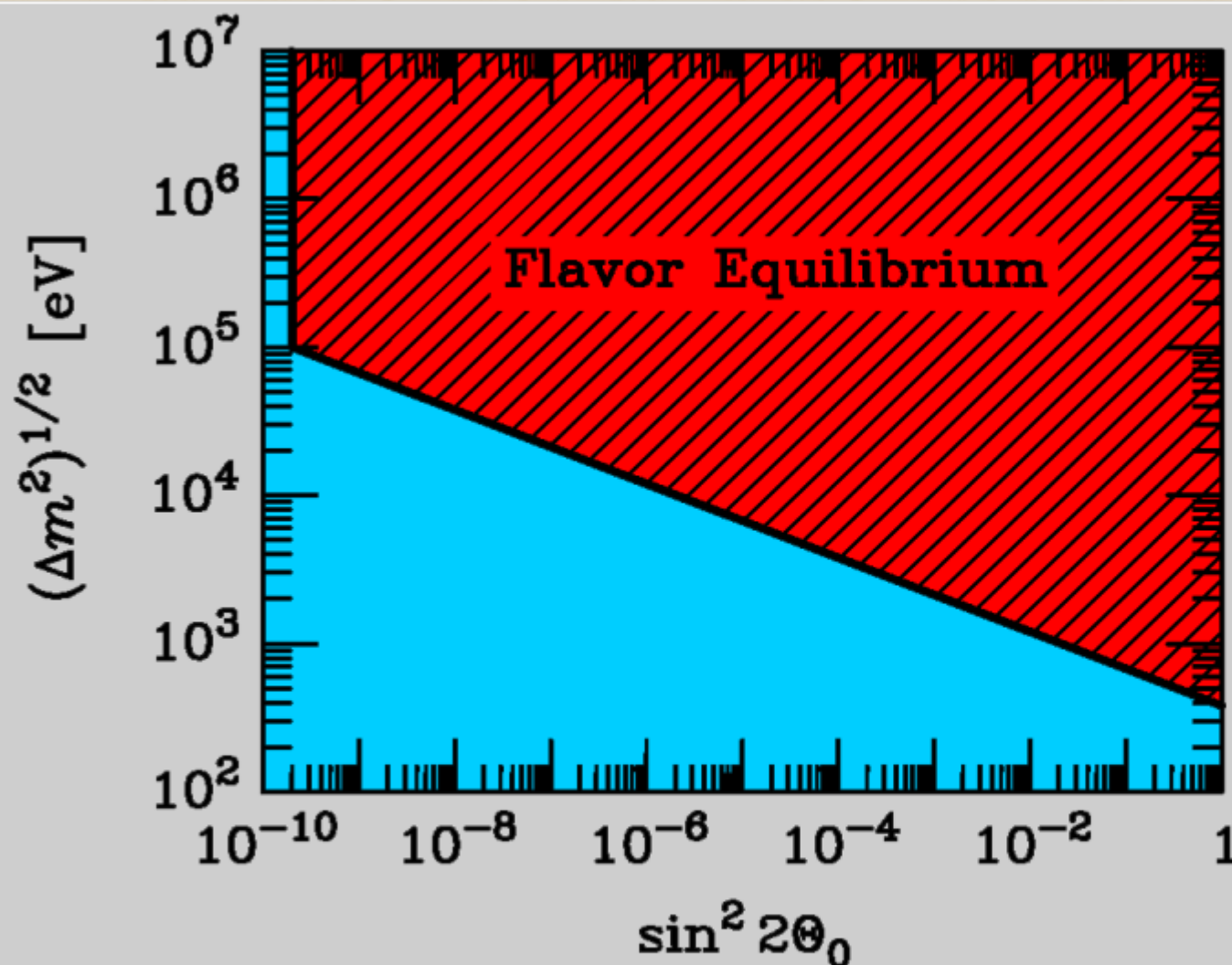
Average oscillation probability $\frac{1}{2} \sin^2(2\Theta)$
Collision rate $\sim$ damping rate Γ



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



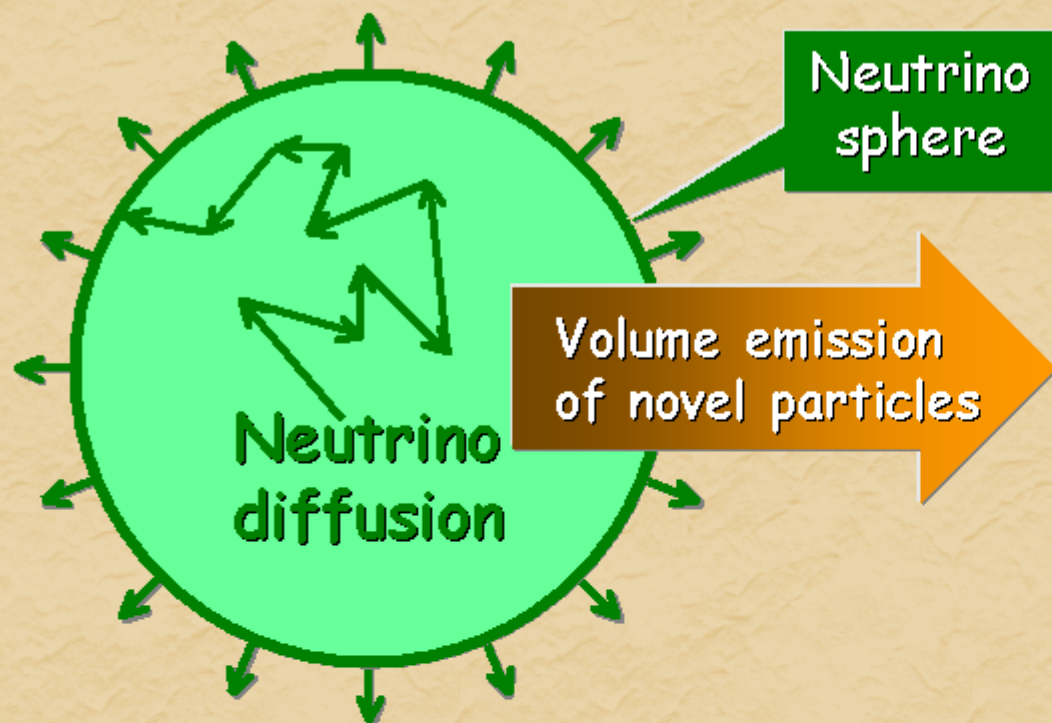
Flavor Conversion in a Supernova Core



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

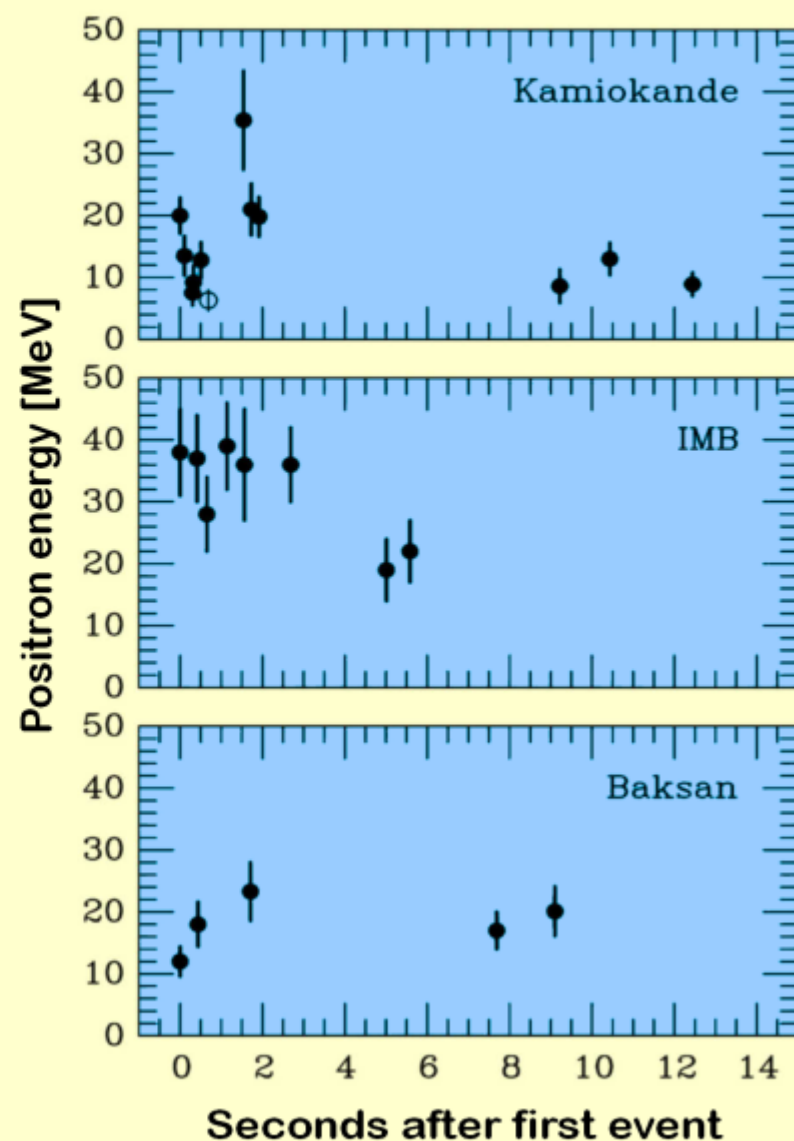
The Energy-Loss Argument



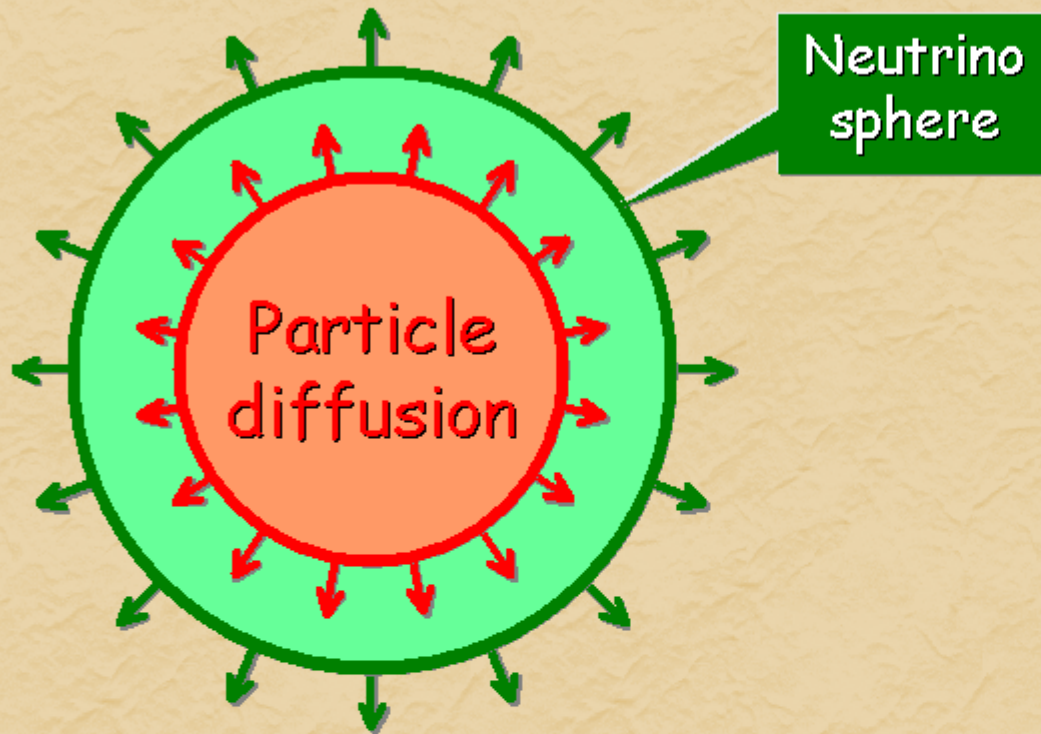
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

SN 1987A neutrino signal



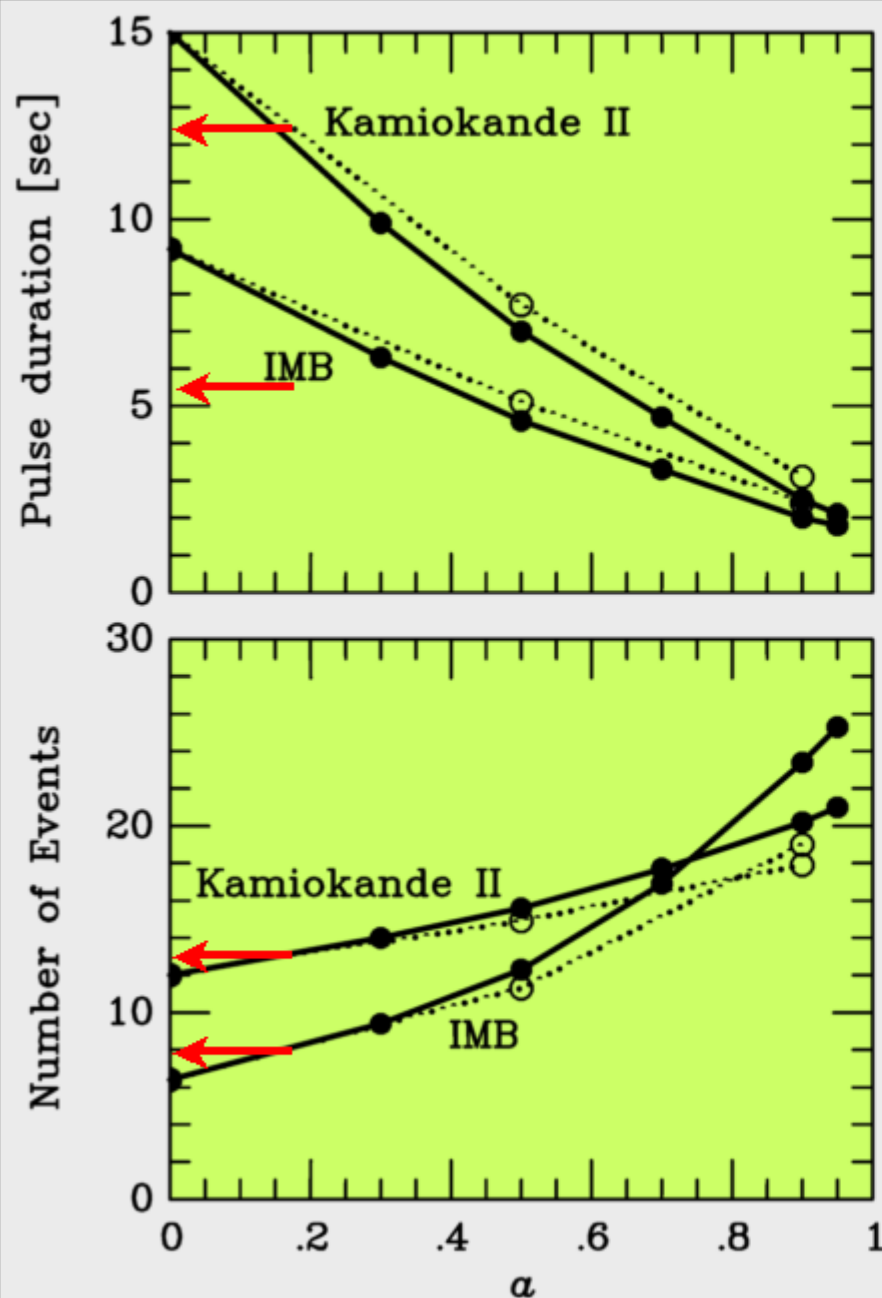
The Energy-Loss Argument in the Trapping Limit



**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

Enhanced Neutrino Energy Transfer



Neutrino opacities reduced in dense regions by a suppression factor $(1 - \alpha)$
Reduced opacities (increased energy transfer)

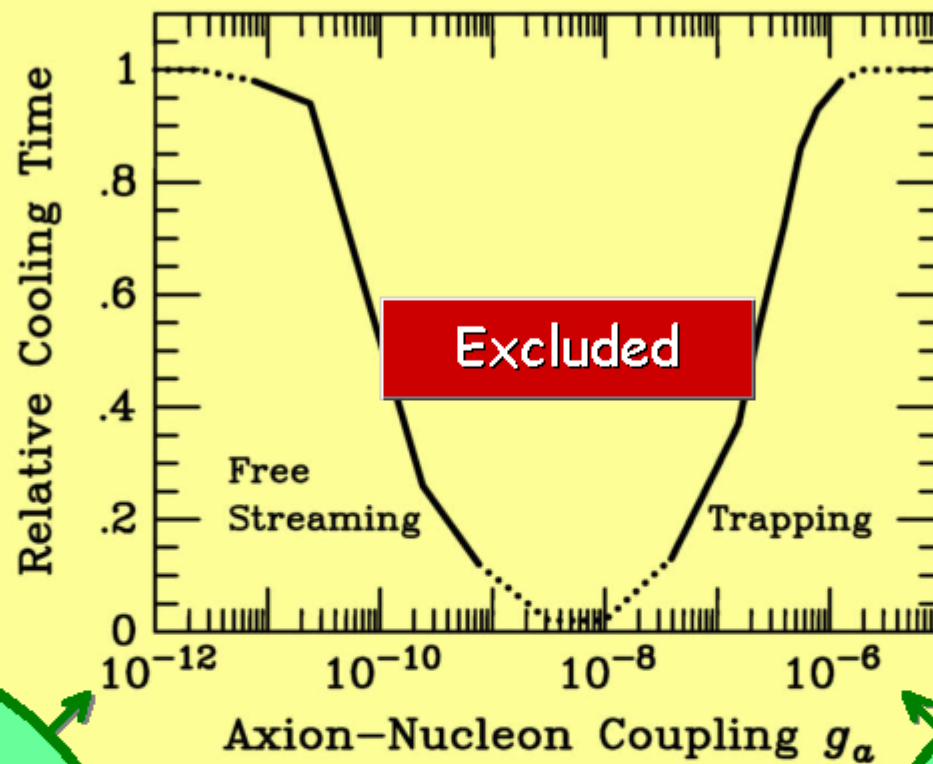
- Reduces signal duration
- Increases number of events (larger energies by heating of neutrino sphere)

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

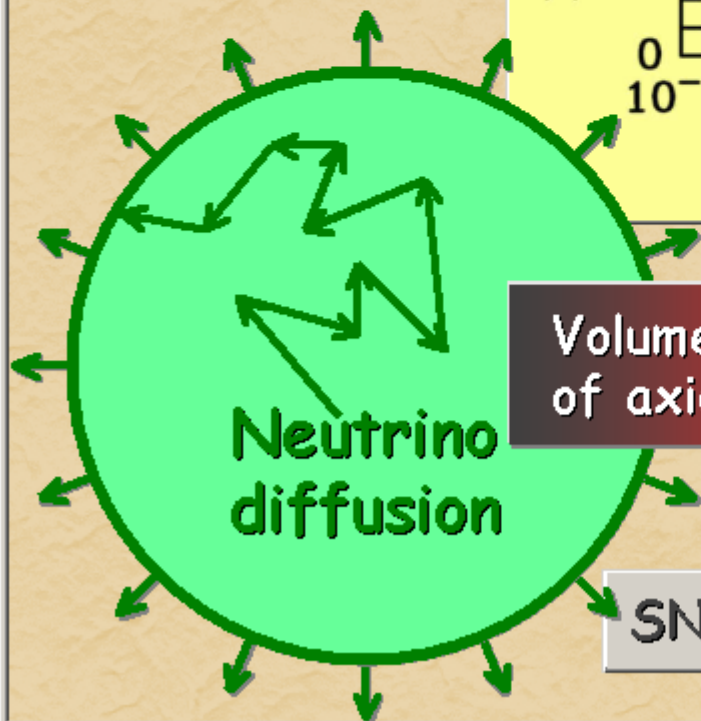
Keil, Janka & Raffelt, PRD 51 (1995) 6635

SN 1987A Axion Limits

Free streaming

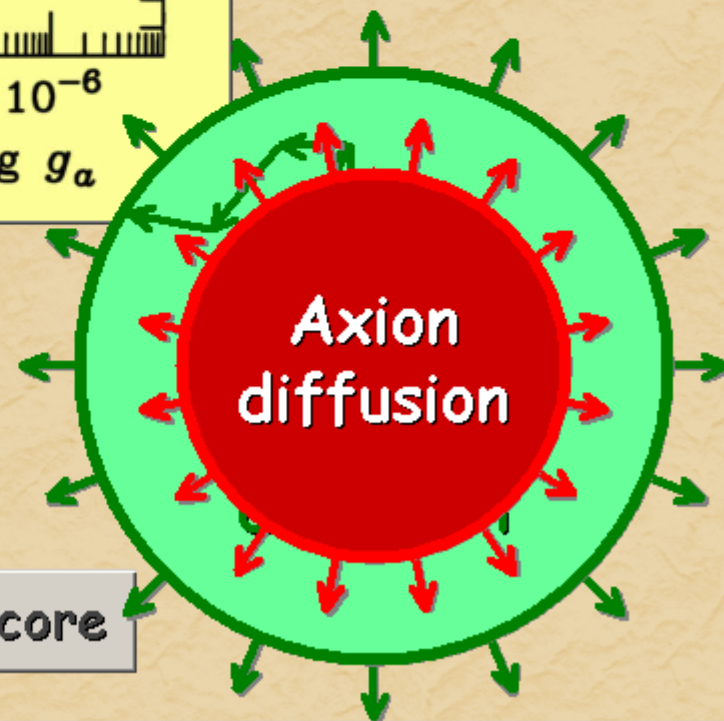


Trapping



Volume emission
of axions

SN core



Axion
diffusion

SN core

Axion Properties

Coupling to gluons
(Most generic
axion property)

$$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$$



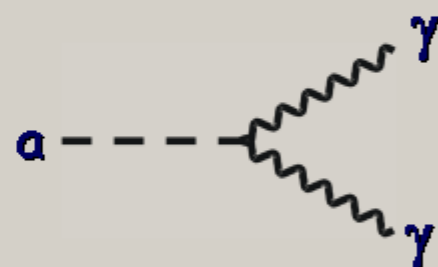
Mass

$$m_a = \frac{0.6 \text{ eV}}{f_a / 10^7 \text{ GeV}} \approx \frac{m_\pi f_\pi}{f_a}$$

Photon coupling

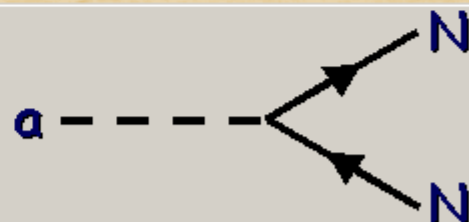
$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma} \vec{E} \cdot \vec{B} a$$

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} \left(\frac{E}{B} - 1.92 \right)$$



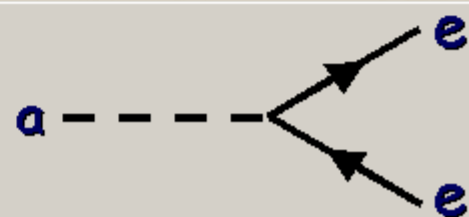
Nucleon coupling
(axial vector)

$$\mathcal{L}_{aN} = \frac{C_N}{2f_a} \bar{\Psi}_N \gamma^\mu \gamma_5 \Psi_N \partial_\mu a$$



Electron coupling
(optional)

$$\mathcal{L}_{ae} = \frac{C_e}{2f_a} \bar{\Psi}_e \gamma^\mu \gamma_5 \Psi_e \partial_\mu a$$

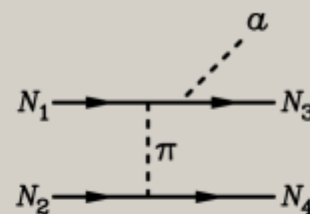


Axion Emission Processes in Stars

Nucleons

$$\frac{C_N}{2f_a} \bar{\Psi}_N \gamma_\mu \gamma_5 \Psi_N \partial^\mu a$$

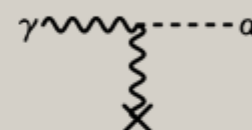
Nucleon
Bremsstrahlung



Photons

$$\frac{C_e}{2f_a} \bar{\Psi}_e \gamma_\mu \gamma_5 \Psi_e \partial^\mu a$$

Primakoff



Electrons

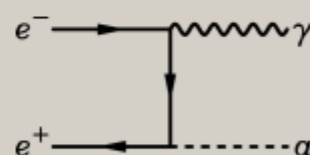
$$C_\gamma \frac{\alpha}{2\pi f_a} \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$

$$= -C_\gamma \frac{\alpha}{2\pi f_a} \vec{E} \cdot \vec{B} a$$

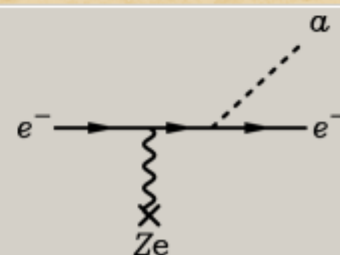
Compton



Pair
Annihilation



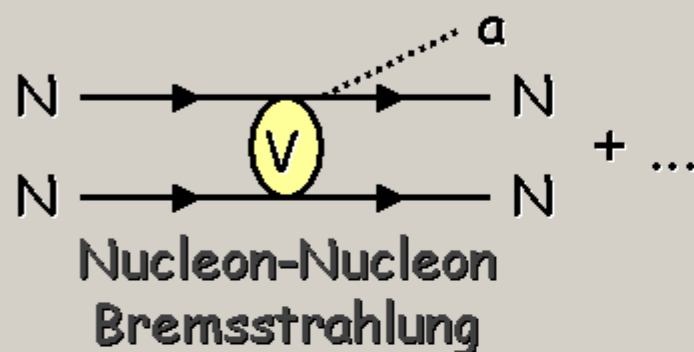
Electromagnetic
Bremsstrahlung



Axion Emission from Nuclear Medium

Axion-nucleon interaction
of current-current form:

$$\mathcal{L}_{\text{int}} = \frac{C_N}{2f_a} \bar{\Psi}_N \gamma_\mu \gamma_5 \Psi_N \partial^\mu a = \frac{C_N}{2f_a} J_\mu^A \partial^\mu a$$



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

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

axion
energy

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

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

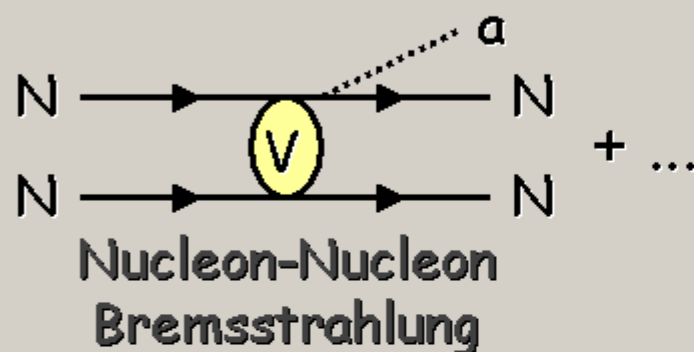
$$\tau_{\text{coll}} < \omega^{-1}$$

Expect LPM-type destructive interference effects

Axion Emission from Nuclear Medium

Axion-nucleon interaction
of current-current form:

$$\mathcal{L}_{\text{int}} = \frac{C_N}{2f_a} \bar{\Psi}_N \gamma_\mu \gamma_5 \Psi_N \partial^\mu a = \frac{C_N}{2f_a} J_\mu^A \partial^\mu a$$



Energy loss rate (erg cm⁻³ s⁻¹)

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

axion
energy

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

dynamical
structure
function

Fundamentally the dynamical structure function is
a correlator of the nucleon axial current

Non-relativistic nucleons: $\sim$ 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
($k \rightarrow 0$)

$$\bar{S}(\omega) = \frac{4}{3} \int_{-\infty}^{+\infty} dt e^{i\omega t} \left\langle \frac{s(t) \cdot s(0) + s(0) \cdot s(t)}{2} \right\rangle$$

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

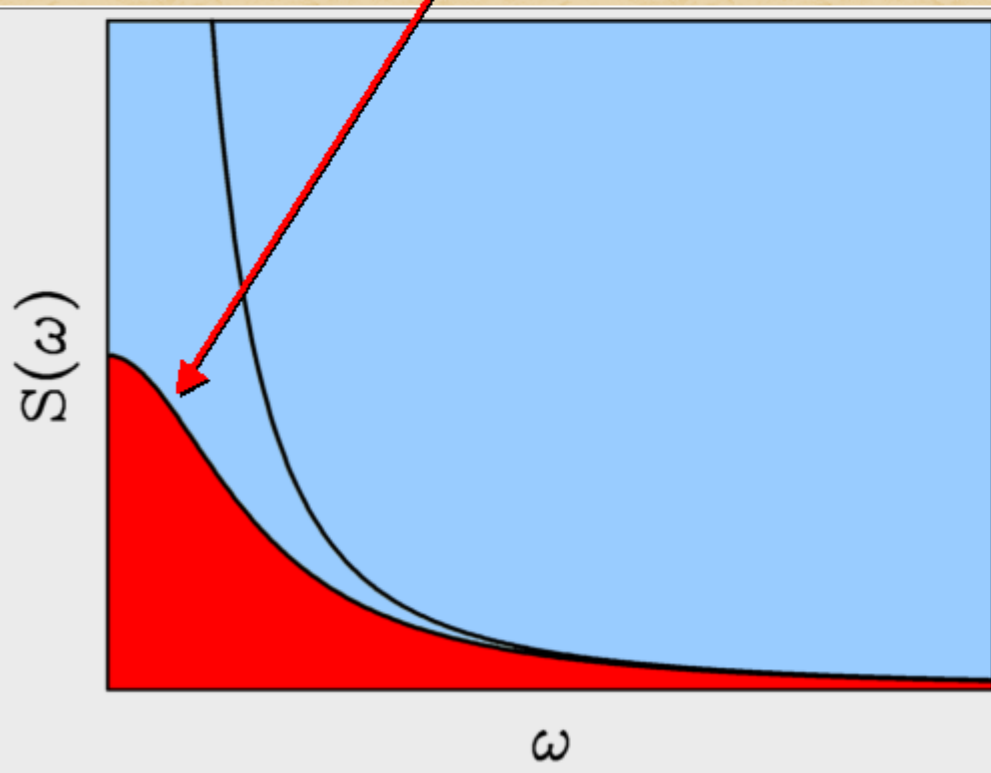
A spin immersed in a bath of scatterers with spin-dependent forces relaxes exponentially for uncorrelated kicks (Markov chain)

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

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



Spin Relaxation Rate

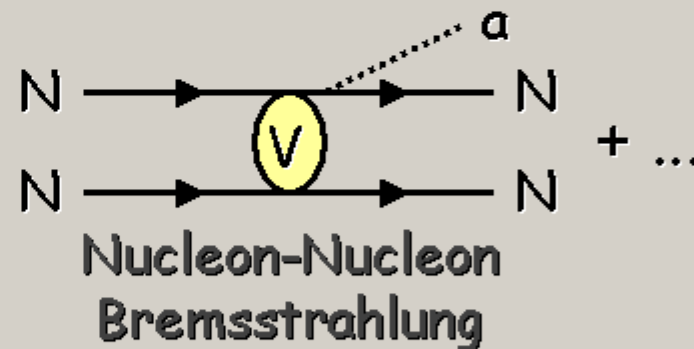
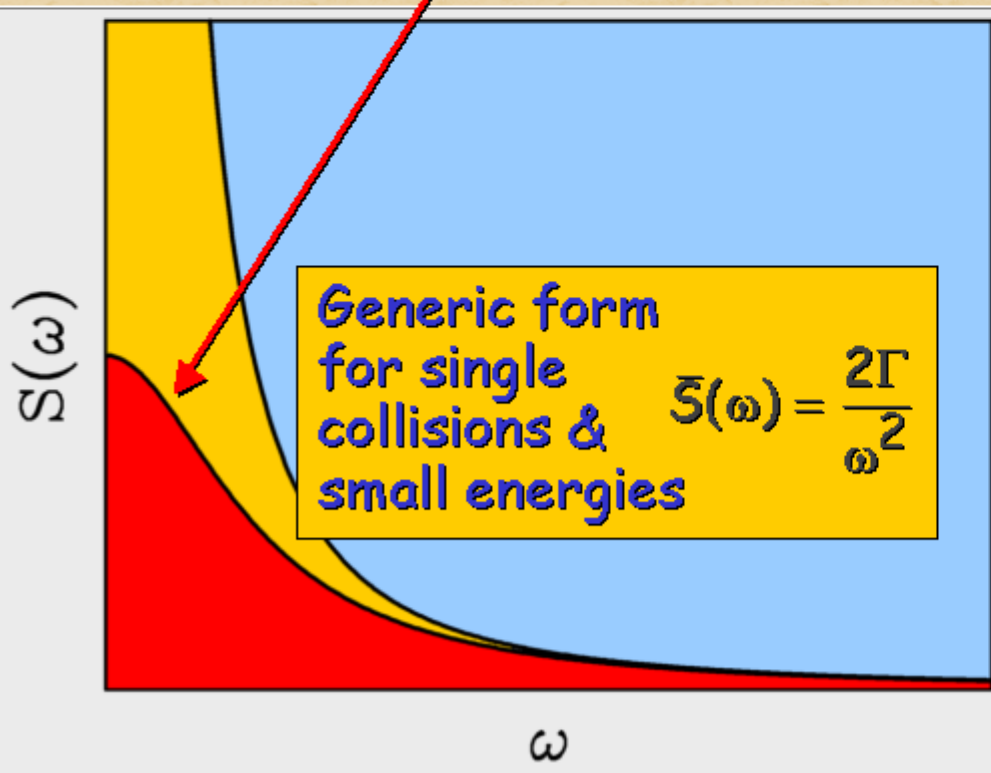
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Lorentzian structure function,
includes multiple scattering effects



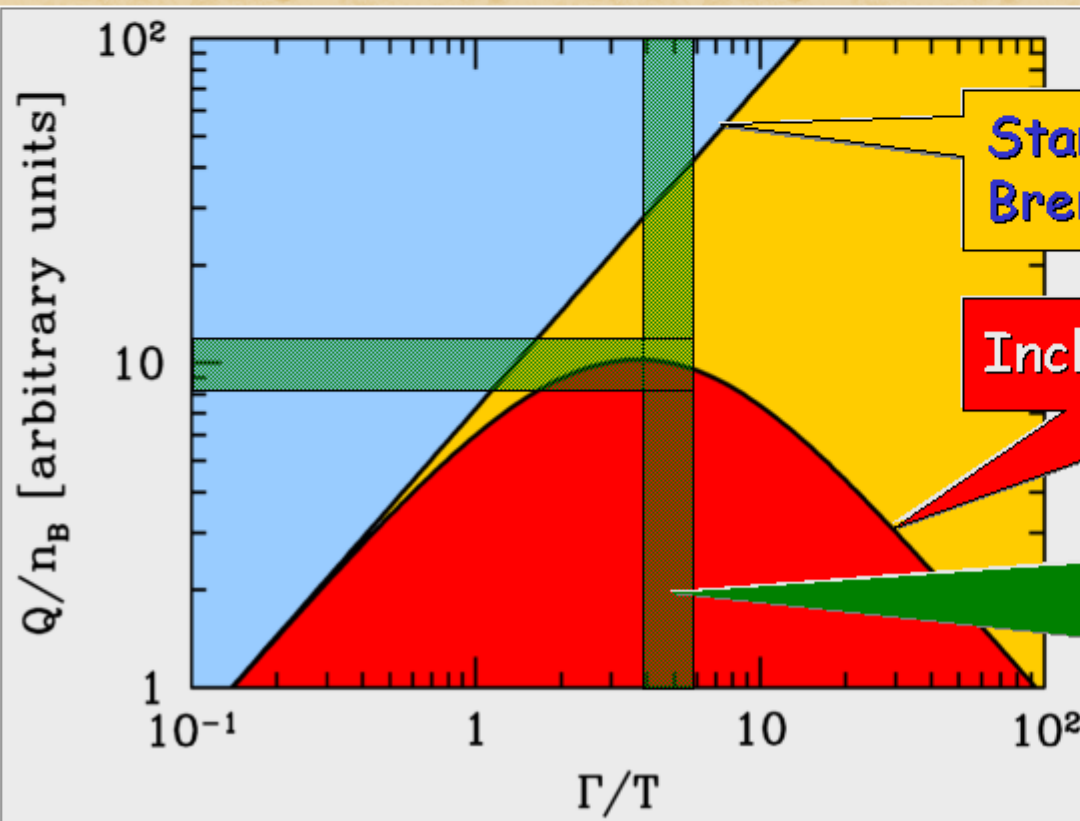
Identify coefficient Γ
from bremsstrahlung
calculation with spin
relaxation rate

Axion Emission Rate

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

Axionic volume energy loss rate of nuclear medium

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



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

Including LPM effect

One-pion exchange potential in Born approximation:

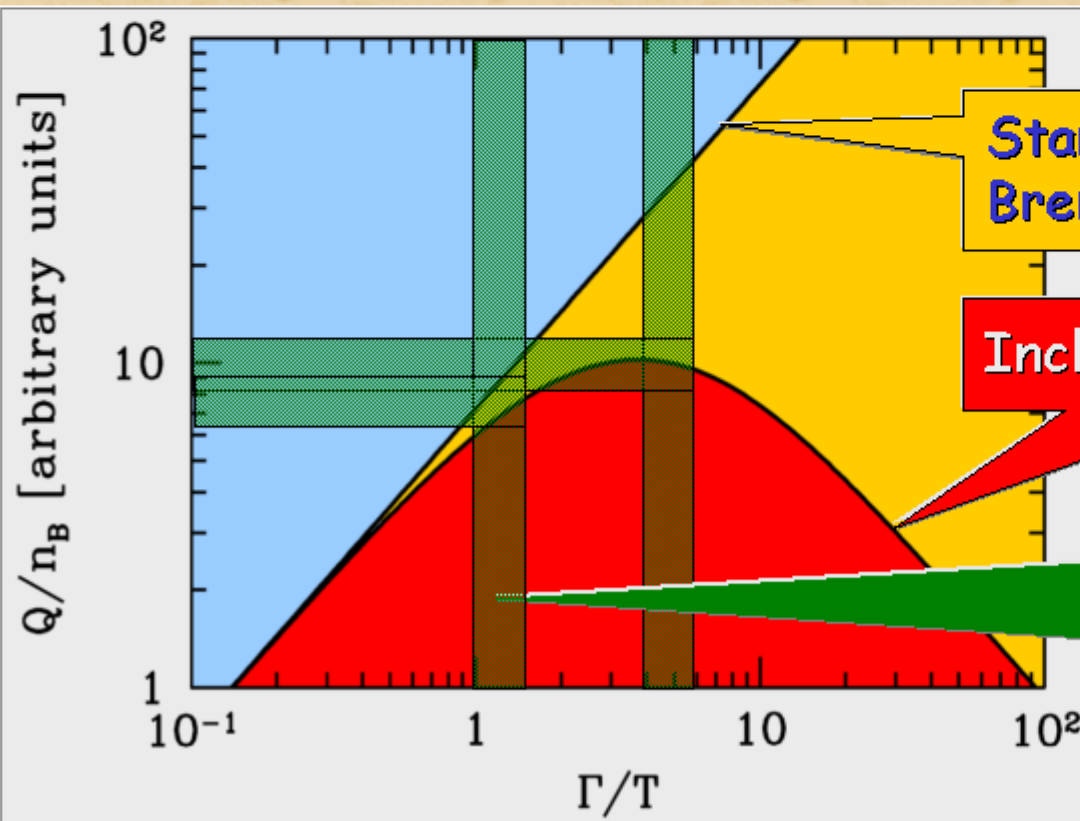
$$\frac{\Gamma}{T} \approx 1.25 \frac{\rho}{10^{14} \text{ g cm}^{-3}} \sqrt{\frac{30 \text{ MeV}}{T}}$$

Axion Emission Rate

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

Axionic volume energy loss rate of nuclear medium

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



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

Stellar Evolution

Cosmology



HDM

Axion dark matter possible
(Low reheat T scenario)

Experiments

Tele
scope

DM o.k.

Too much DM
(String scenario)

Globular clusters
(α - γ -coupling)

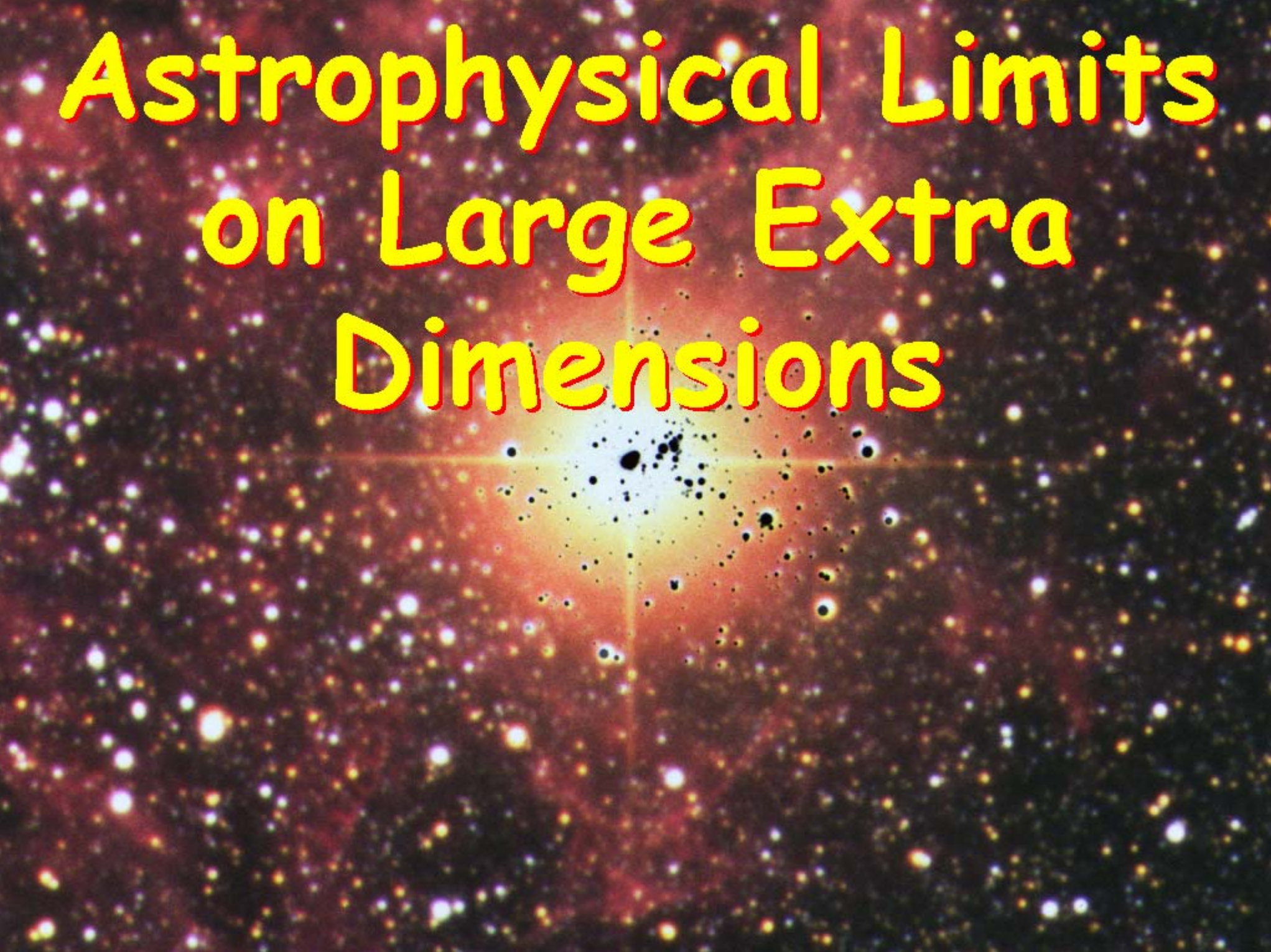
Direct
search

Too many
events

Too much
energy loss

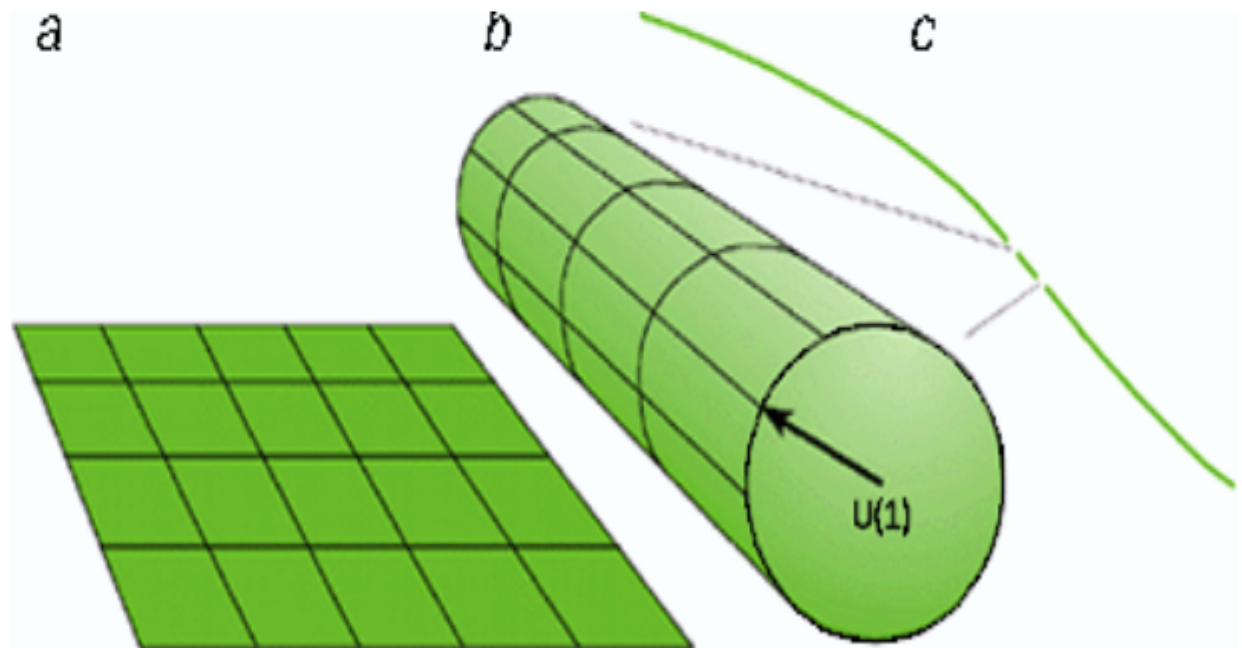
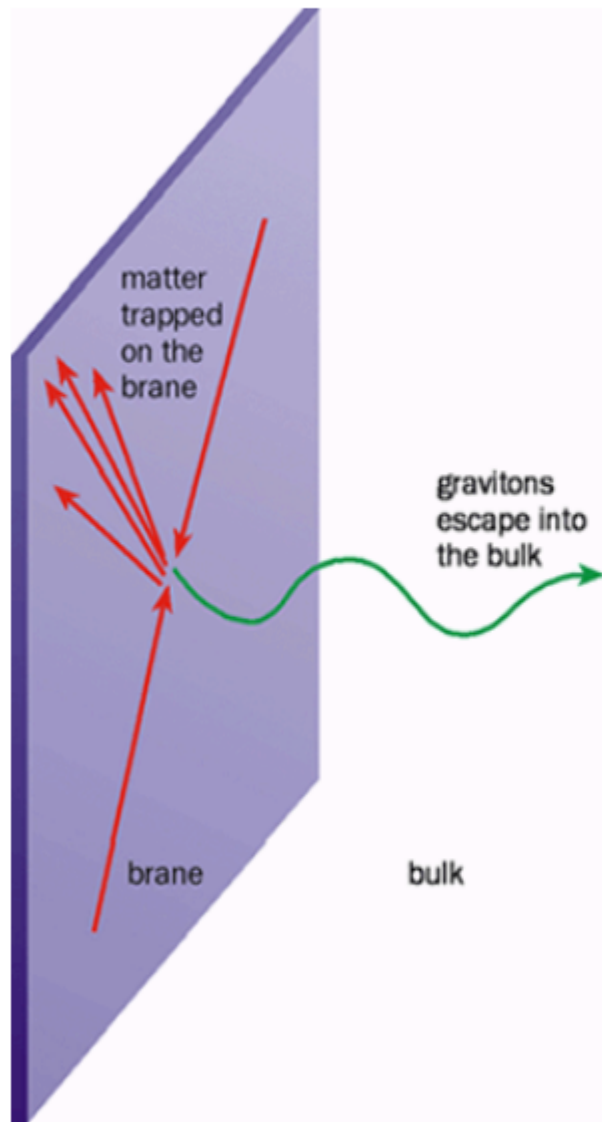
SN 1987A (α -N-coupling)

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

$$M_{\text{Pl}}^2 = (2.4 \times 10^{18} \text{ GeV})^2 = (2\pi R)^n M^{2+n}$$

Reduced
Planck mass

$$M_{\text{Pl}} = m_{\text{Pl}} / (8\pi)^{1/2}$$

Compacti-
fication
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 $\sim 1 \text{ TeV}$ to solve the hierarchy
problem, then experimentally

$n = 1$ $R_1 \sim 10^{13} \text{ cm}$ excluded

$n = 2$ $R_2 \sim 1 \text{ mm}$ marginally allowed

$n = 3$ $R_3 \sim 10^{-6} \text{ mm}$ allowed

...

Kaluza-Klein (KK) Gravitons

Bulk particles have discrete momenta in extra dimensions

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

Assuming toroidal compactification with dimension $2\pi R$

p 4D energy-momentum
 x 4D coordinate
 γ_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

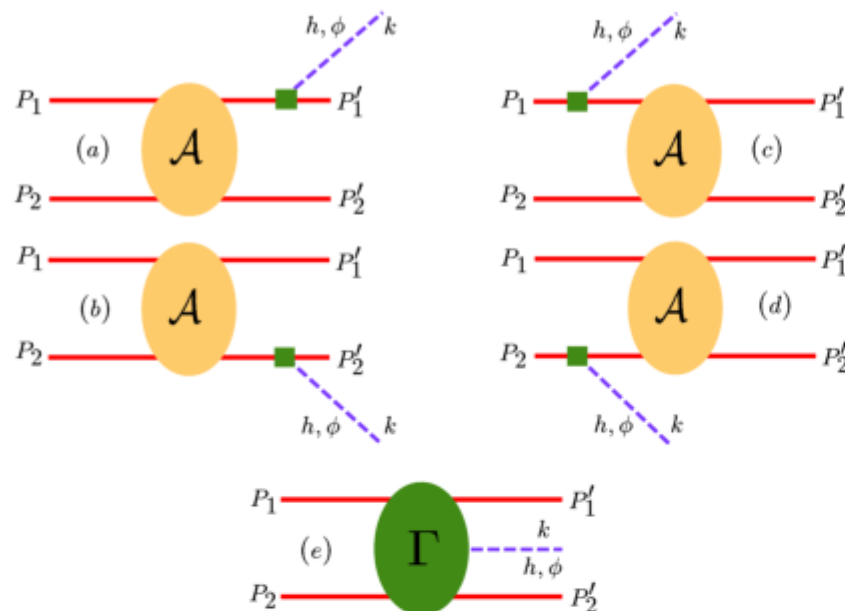


FIG. 1. The leading diagrams contributing to processes $NN \rightarrow NNh$ and $NN \rightarrow NN\phi$. Nucleons are denoted by solid lines and the KK-modes h or ϕ are denoted by dashed lines. Solid squares denote an insertion of the single-nucleon energy-momentum tensor, while solid ovals containing 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

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

Large multiplicity of modes

$$RT \sim 10^{11}$$

for $R \sim 1 \text{ mm}$, $T \sim 30 \text{ MeV}$

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

Cullen & Perelstein, hep-ph/9904422

Hanhart et al., nucl-th/0007016

SN 1987A energy-loss argument:

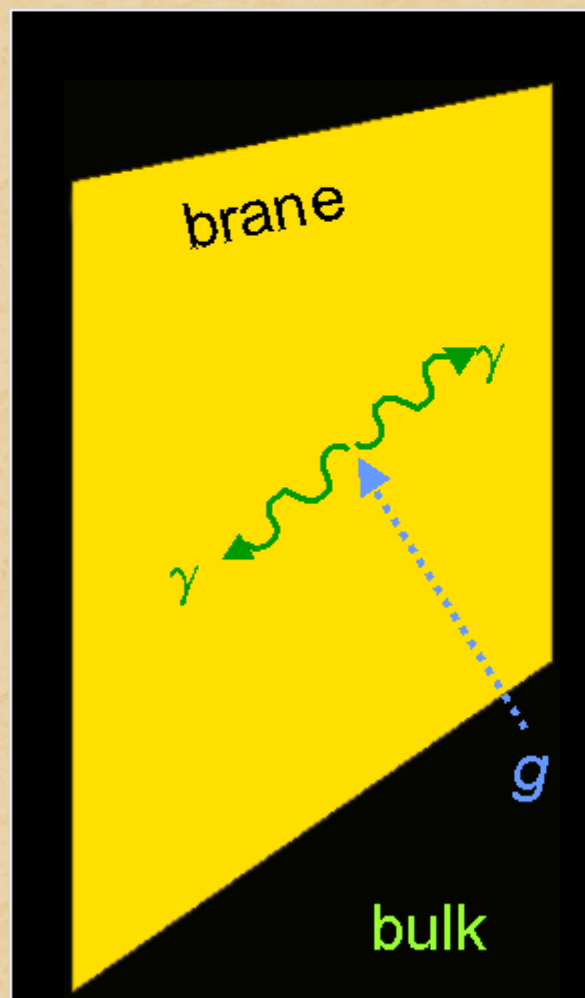
$$R < 1 \text{ } \mu\text{m}, \quad M > 9 \text{ TeV} \quad (n = 2)$$

$$R < 1 \text{ nm}, \quad M > 0.7 \text{ TeV} \quad (n = 3)$$

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



$$\Gamma_{\text{tot}} \sim P_{\text{wall}} \Gamma_{\text{brane}}$$

$$\sim (mR)^{-n} \times \frac{m^{n+3}}{M_{\text{hD}}^{n+2}} \sim \frac{m^3}{M_{\text{Pl}}^2}$$

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

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

Improved Limits on Large Extra Dimensions

SN Core

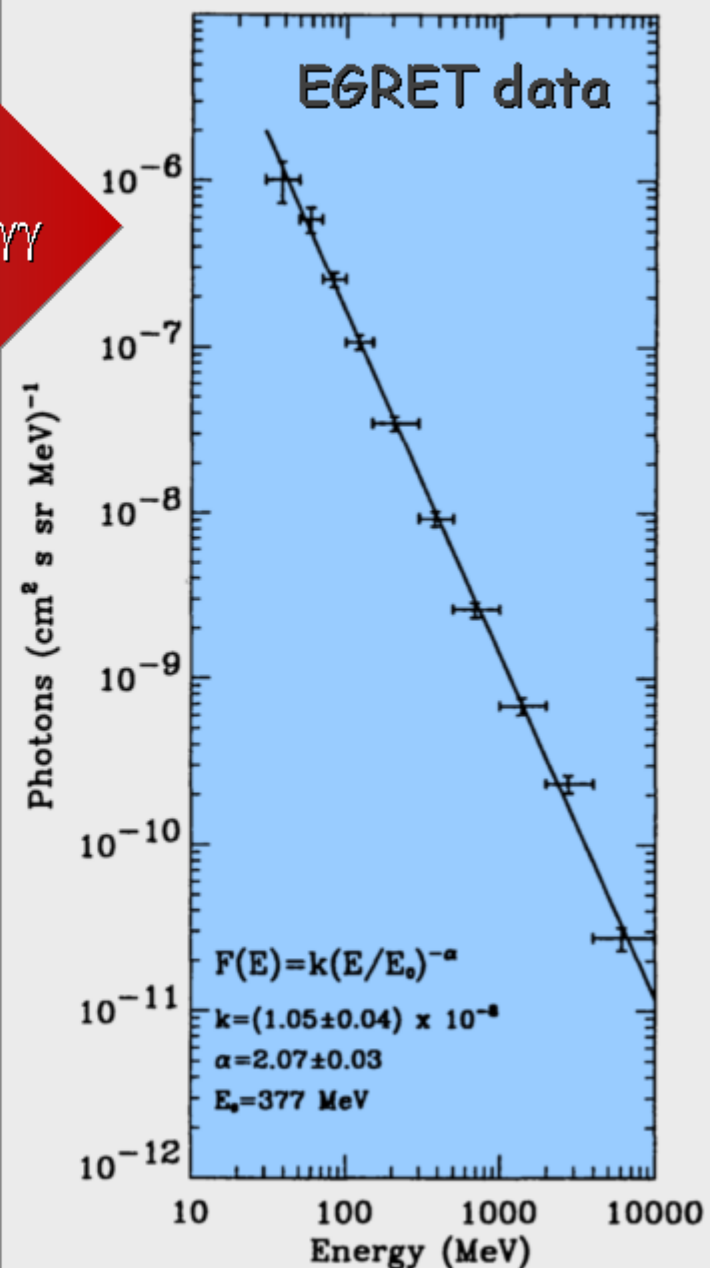
KK gravitons
 $E \sim 100 \text{ MeV}$

$KK \rightarrow e^+e^-, \nu\bar{\nu}, \gamma\gamma$

- 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 $R < 0.1 \mu\text{m}$, $M > 28 \text{ TeV}$ ($n = 2$)
 $R < 0.2 \text{ nm}$, $M > 1.7 \text{ TeV}$ ($n = 3$)

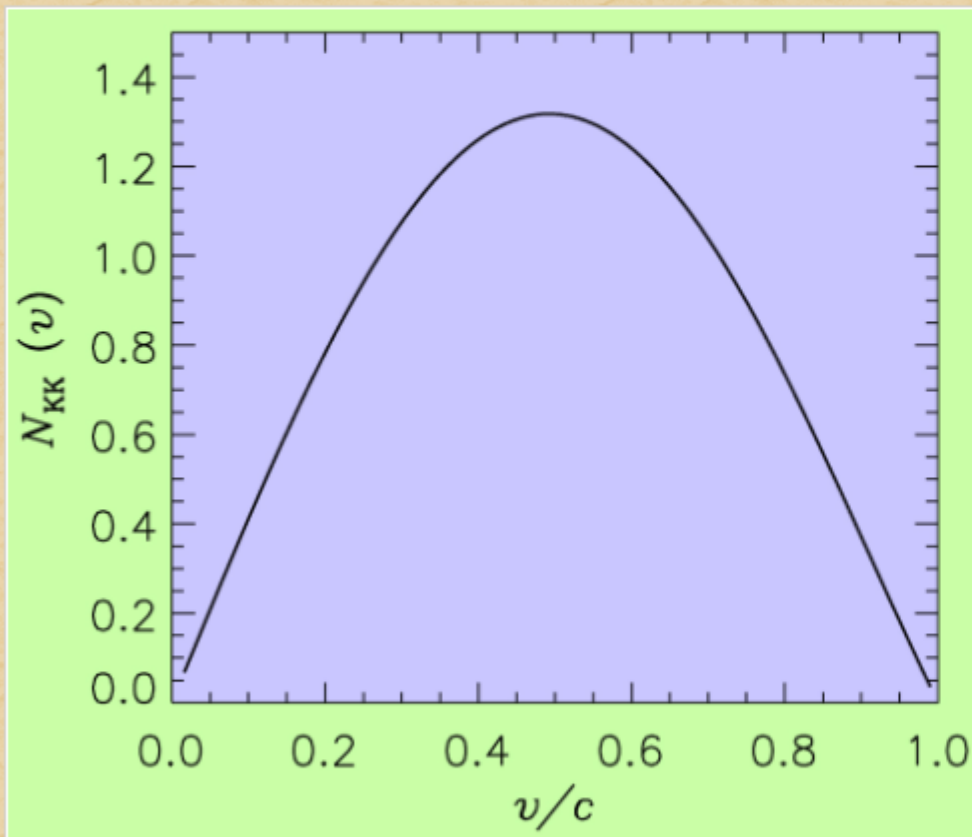
Hannestad & Raffelt, hep-ph/0103201



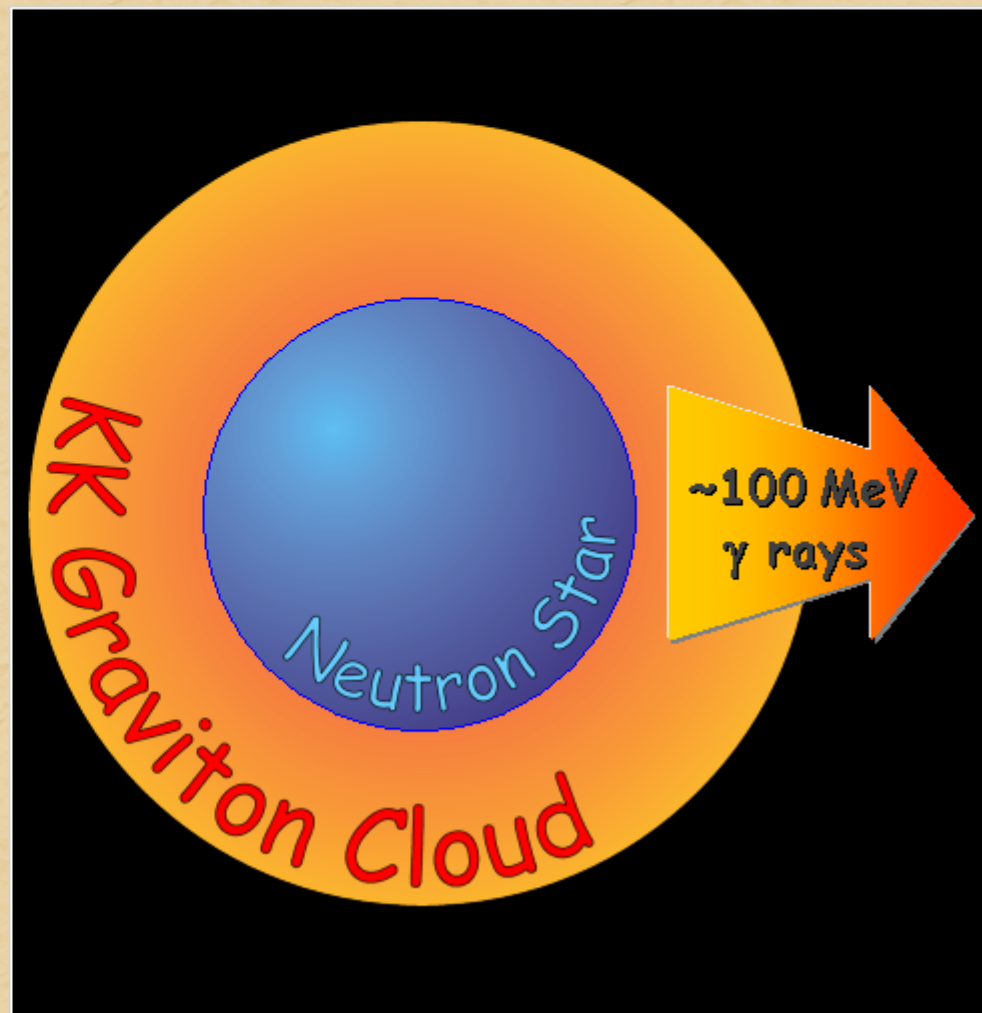
KK Graviton Retention by Neutron Star

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

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

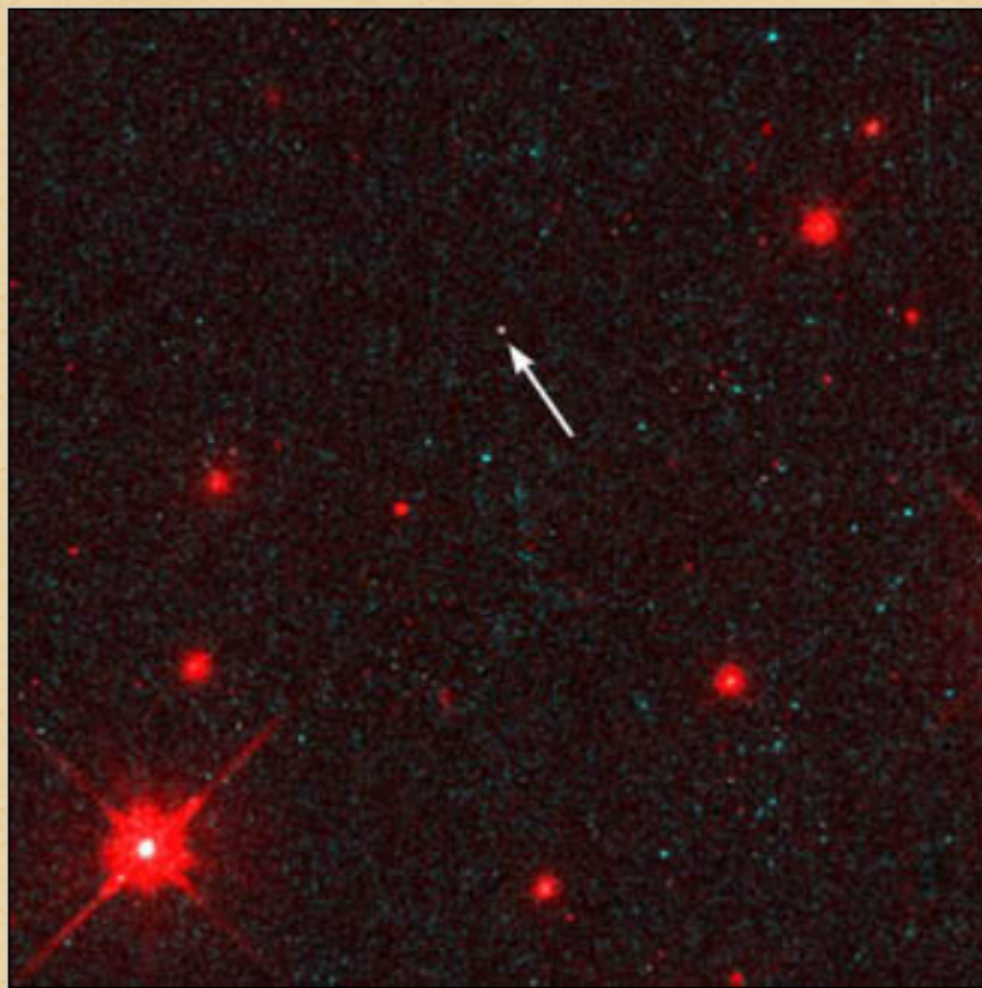


Velocity distribution of KK-gravitons emitted by supernova

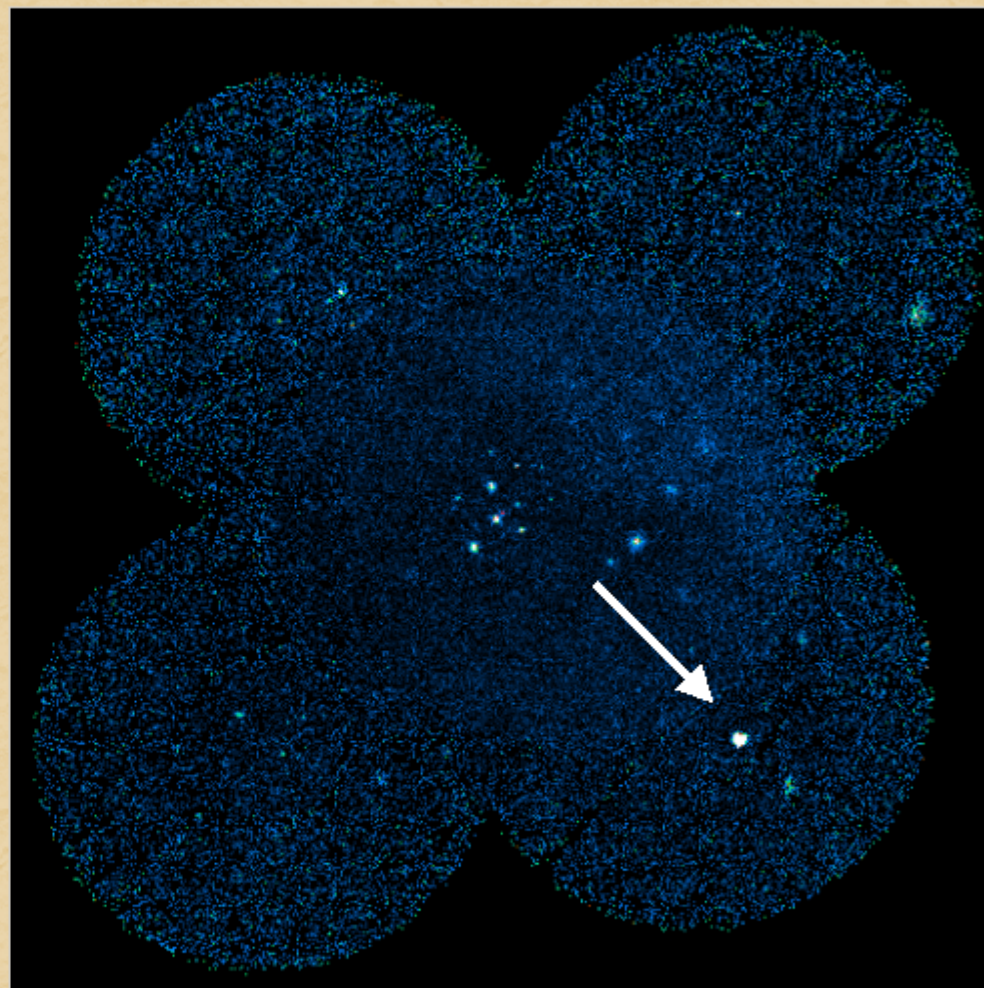


Nearby Neutron Star RX J185635-3754

$D = 120$ pc (closest known neutron star), Age $\sim 1.2 \times 10^6$ yr



HST Image
(Walter & Matthews 1997)

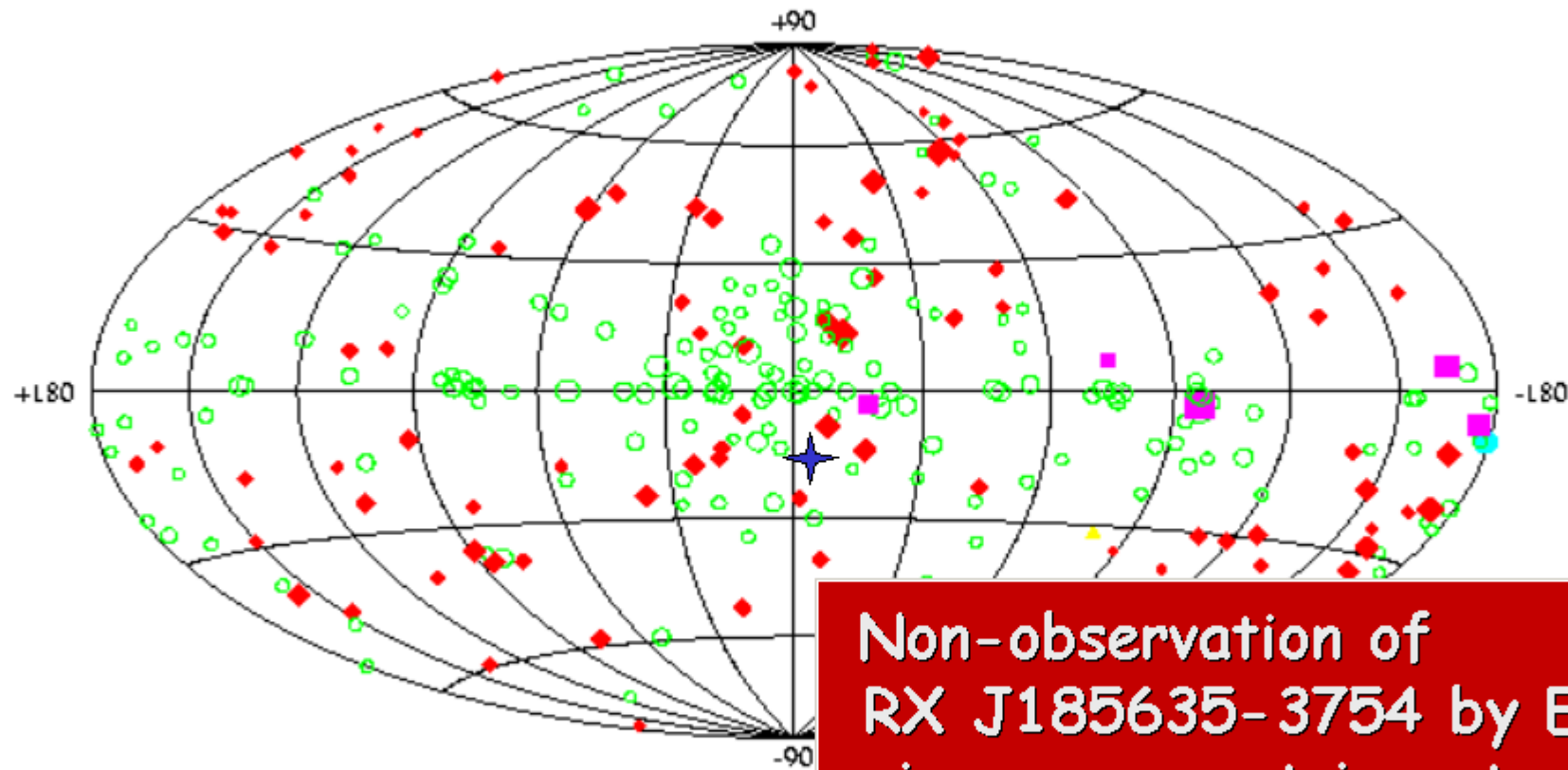


ROSAT Image
(Walter, Wolk & Neuhauser 1996)

Third EGRET Catalog (Hartmann et al. 1999)

Third EGRET Catalog

$E > 100 \text{ MeV}$



- ◆ Blazars (+ Cen A)
- Unidentified EGRET Sources
- ★ **RX J185635-3754**

Non-observation of
RX J185635-3754 by EGRET
gives a very stringent constraint
on the compactification scale:

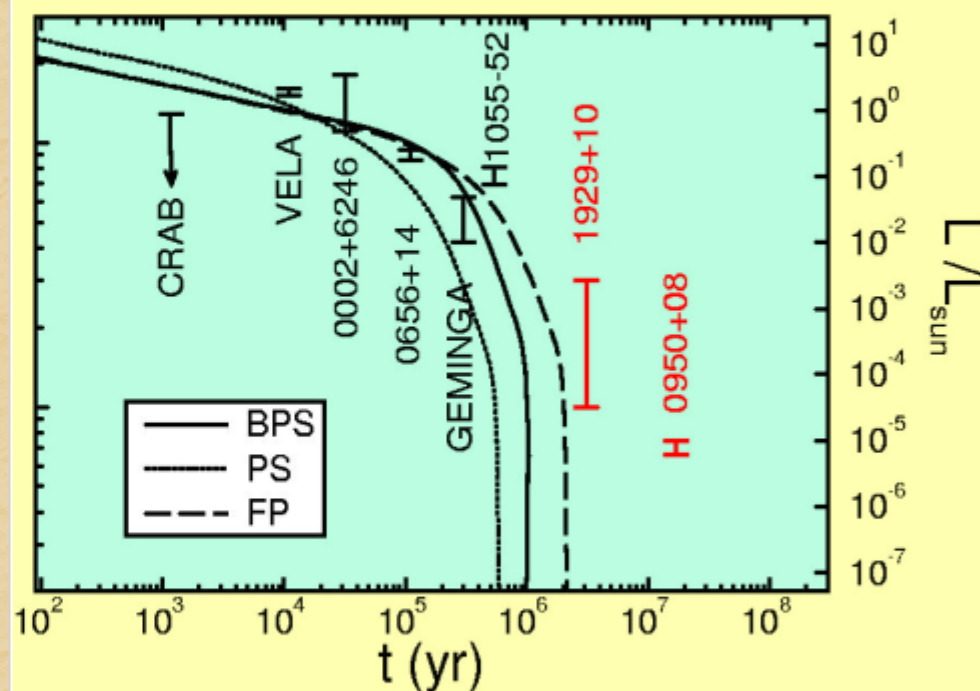
$$M > 54 \text{ TeV} \quad (n = 2)$$

$$M > 3.5 \text{ TeV} \quad (n = 3)$$

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)

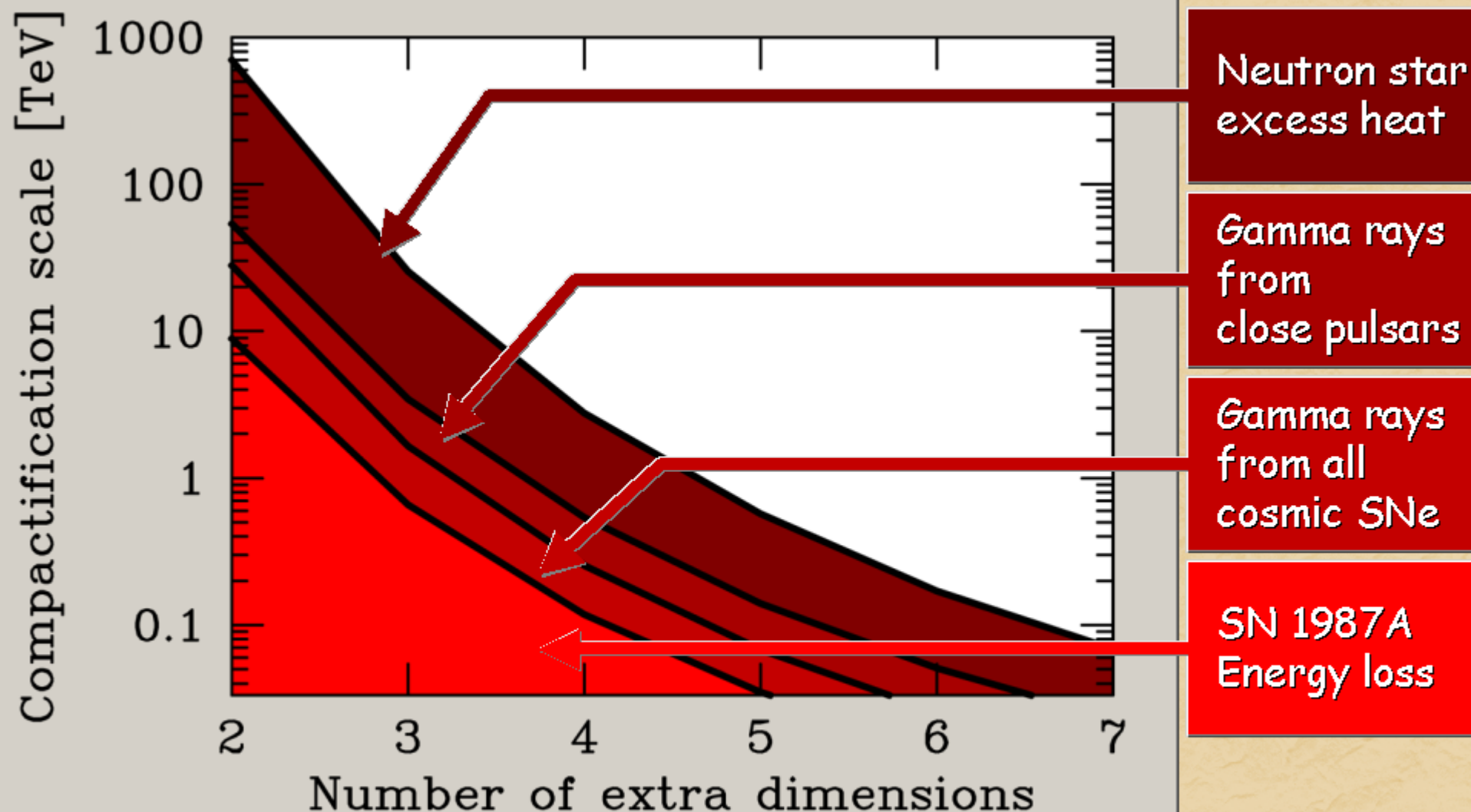


To avoid excess heating by KK decay

$$M > 700 \text{ TeV} \quad (n = 2)$$

$$M > 26 \text{ TeV} \quad (n = 3)$$

Summary of Limits on Large Extra Dimensions



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

Loop Holes

In other than toroidal compactifications, processes such as

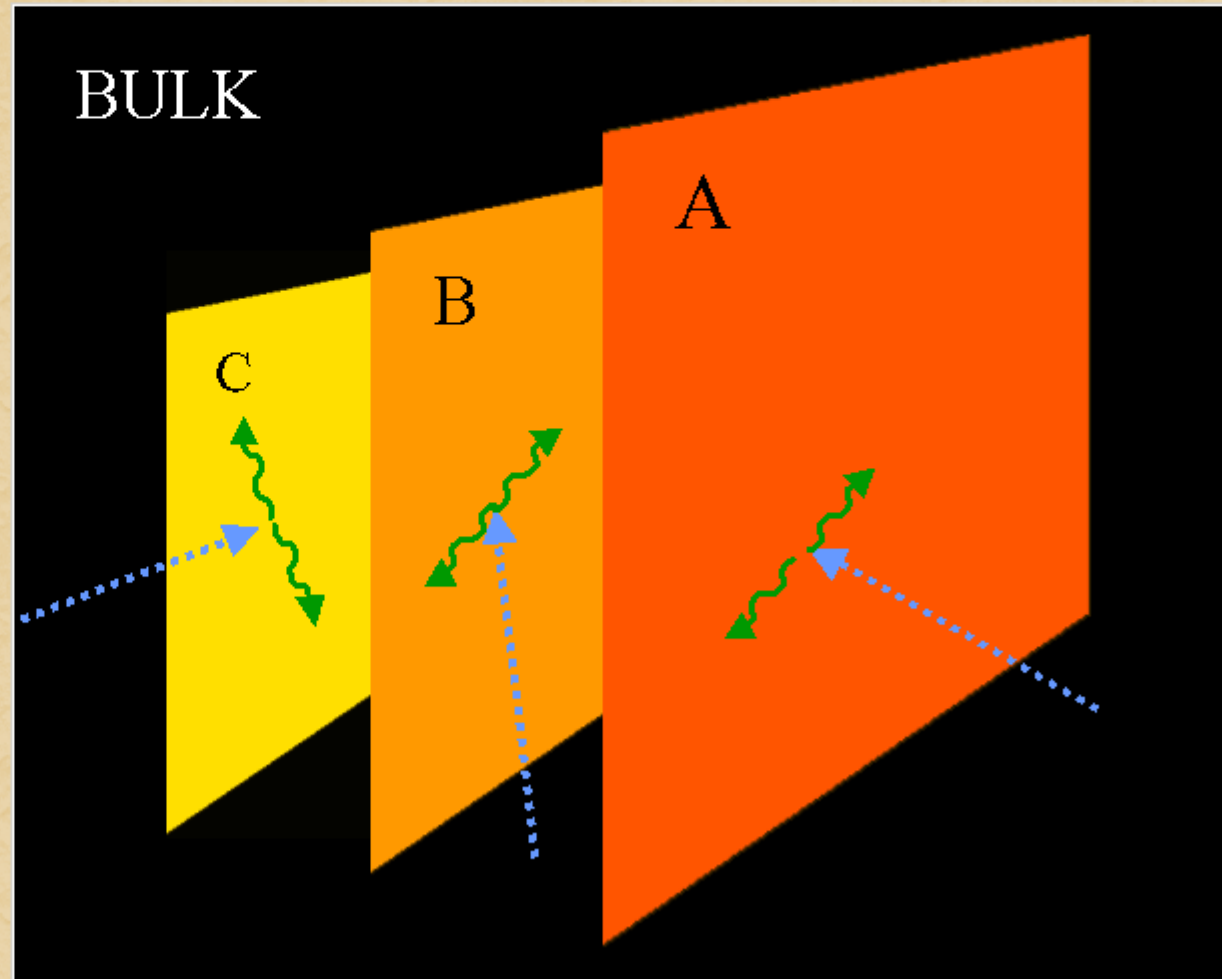
$$G(m_1) \rightarrow G(m_2) + G(m_3)$$

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

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

For ν_s - ν_e -mixing:

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

$$= \pm 1.53 \times 10^9 \frac{(\gamma_e + 2\gamma_{\nu_e} - \frac{1}{2}\gamma_n) \rho}{10^{14} \text{ g cm}^{-3}} \frac{E_\nu}{100 \text{ MeV}} \frac{1 \text{ eV}^2}{\Delta m^2}$$

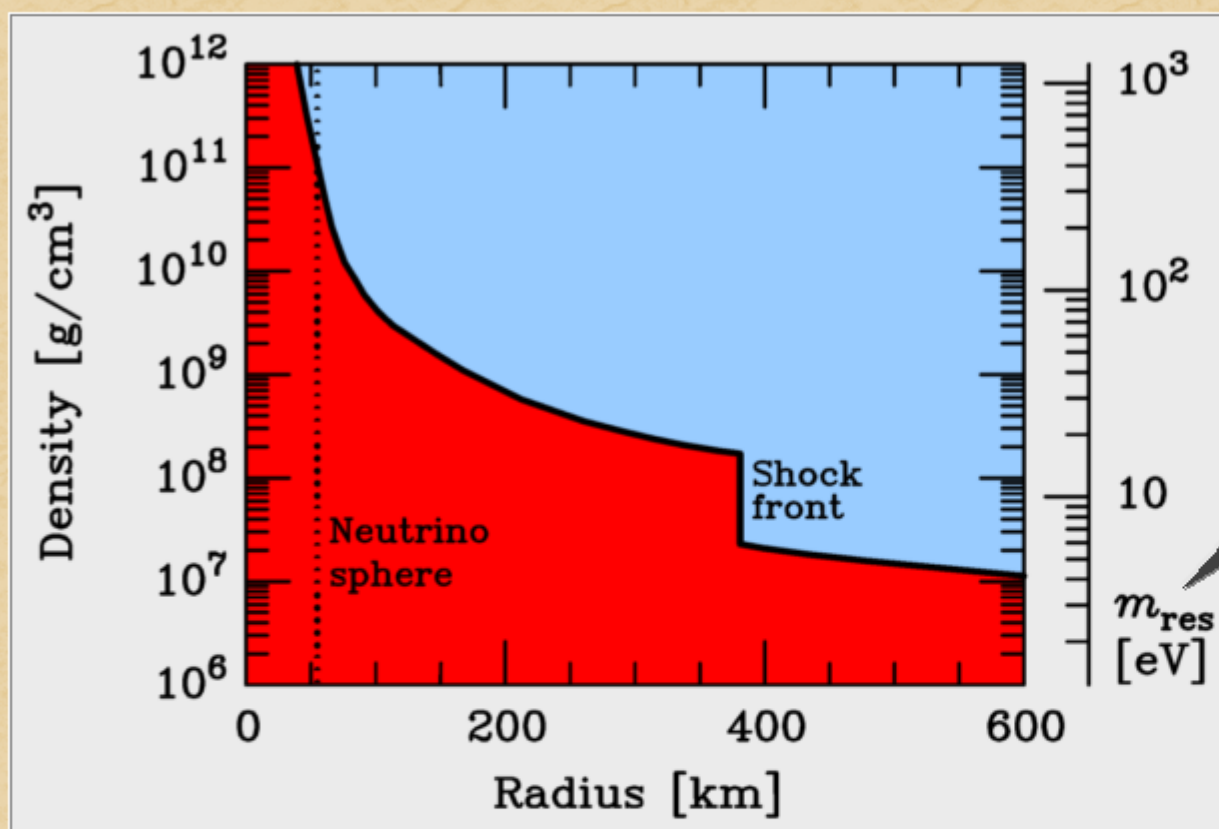
Large medium
effect ($|A| \gg 1$)
and large sterile
mass ($m_s \gg m_\nu$)

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

$$= 4.3 \times 10^{-19} \left(\frac{10^{14} \text{ g cm}^{-3}}{(\gamma_e + 2\gamma_{\nu_e} - \frac{1}{2}\gamma_n) \rho} \right)^2 \left(\frac{100 \text{ MeV}}{E_\nu} \right)^2 \left(\frac{m_s}{1 \text{ eV}} \right)^4$$

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

Matter Effect on Flavor Oscillations



"Effective neutrino mass"
from weak potential

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

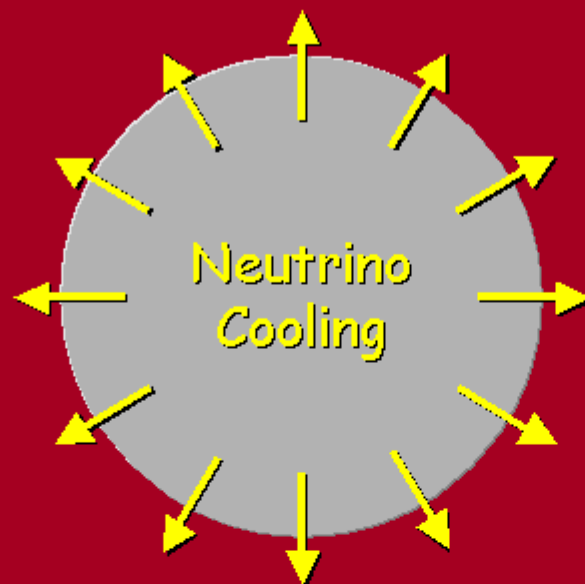
($E_\nu = 10 \text{ MeV}$ and $Y_e = 0.5$)

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

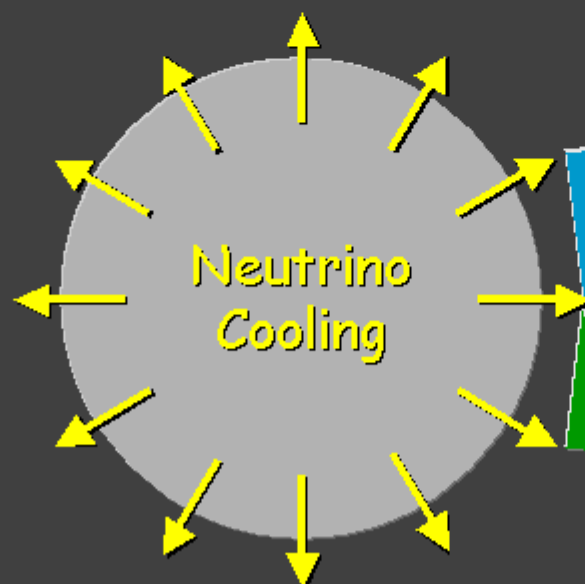
R-Process Nucleosynthesis in Supernovae

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

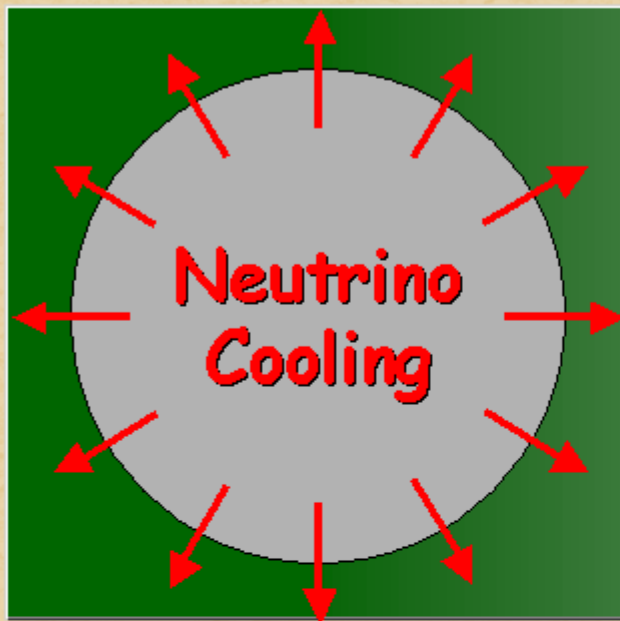


ν_μ with
 $\langle E \rangle \approx 20 \text{ MeV}$

ν_e with
 $\langle E \rangle \approx 20 \text{ MeV}$

$\bar{\nu}_e$ with
 $\langle E \rangle \approx 17 \text{ MeV}$

R-Process Nucleosynthesis in Supernovae



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



R-process destroyed by α -effect



(1) Protons trapped in α -particles

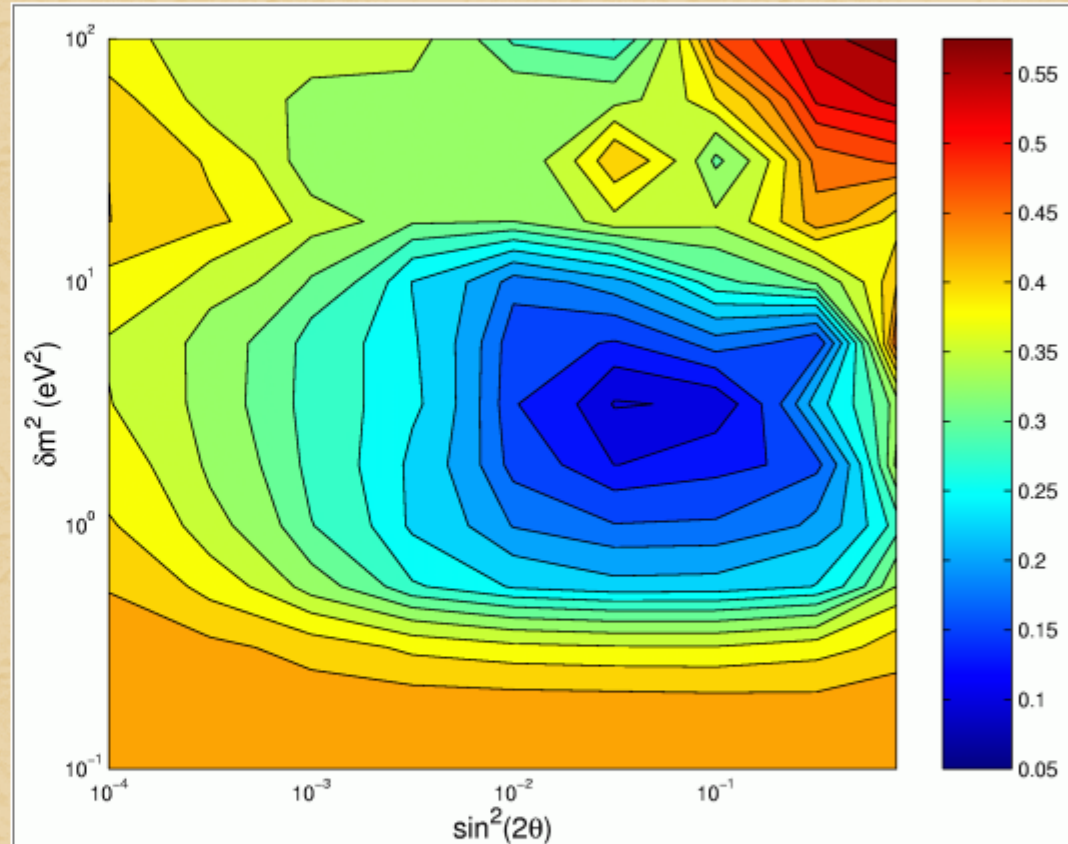
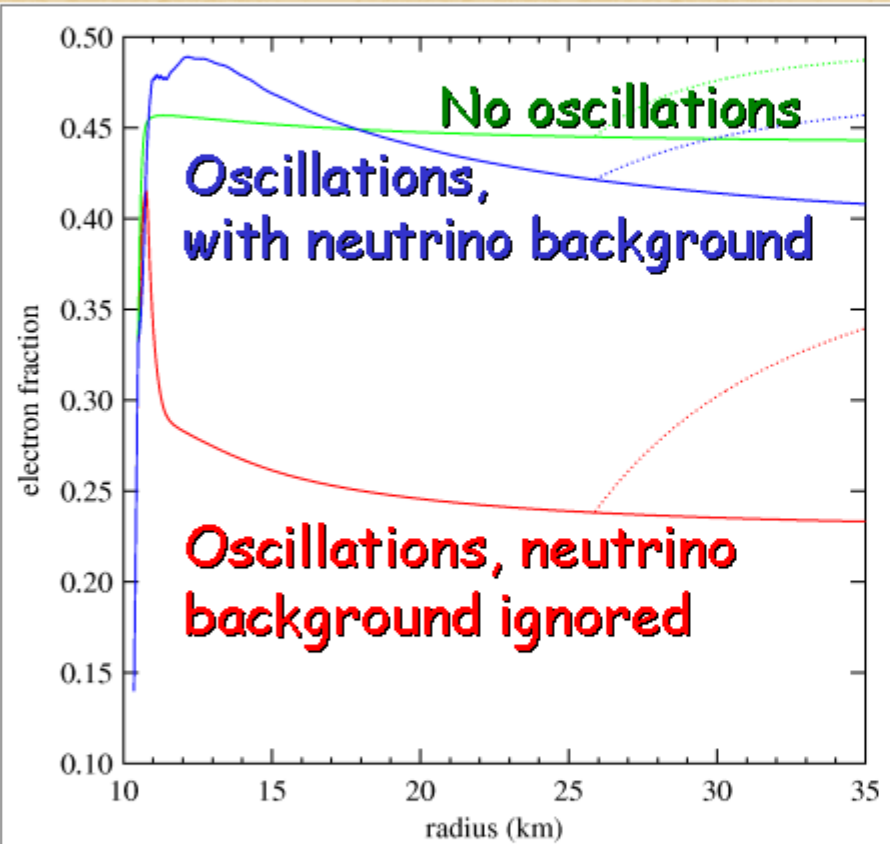
(2) Neutrons $\rightarrow$ protons by β -reactions

$\rightarrow$ Neutron concentration too low

Oscillations $\nu_e \rightarrow \nu_s$ (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 $\nu_e + n \leftrightarrow p + e^-$

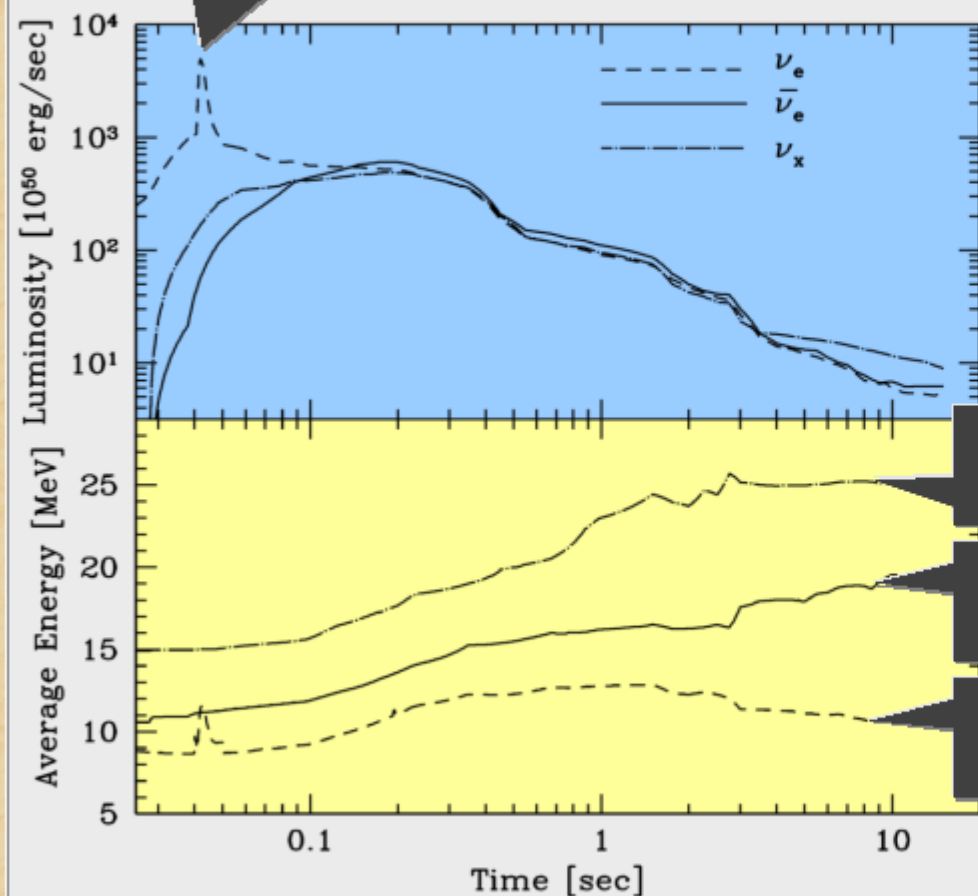


Neutrino background ignored

Patel & Fuller, hep-ph/0003034

Structure of a Supernova Neutrino Burst

Prompt ν_e
deleptonization
burst

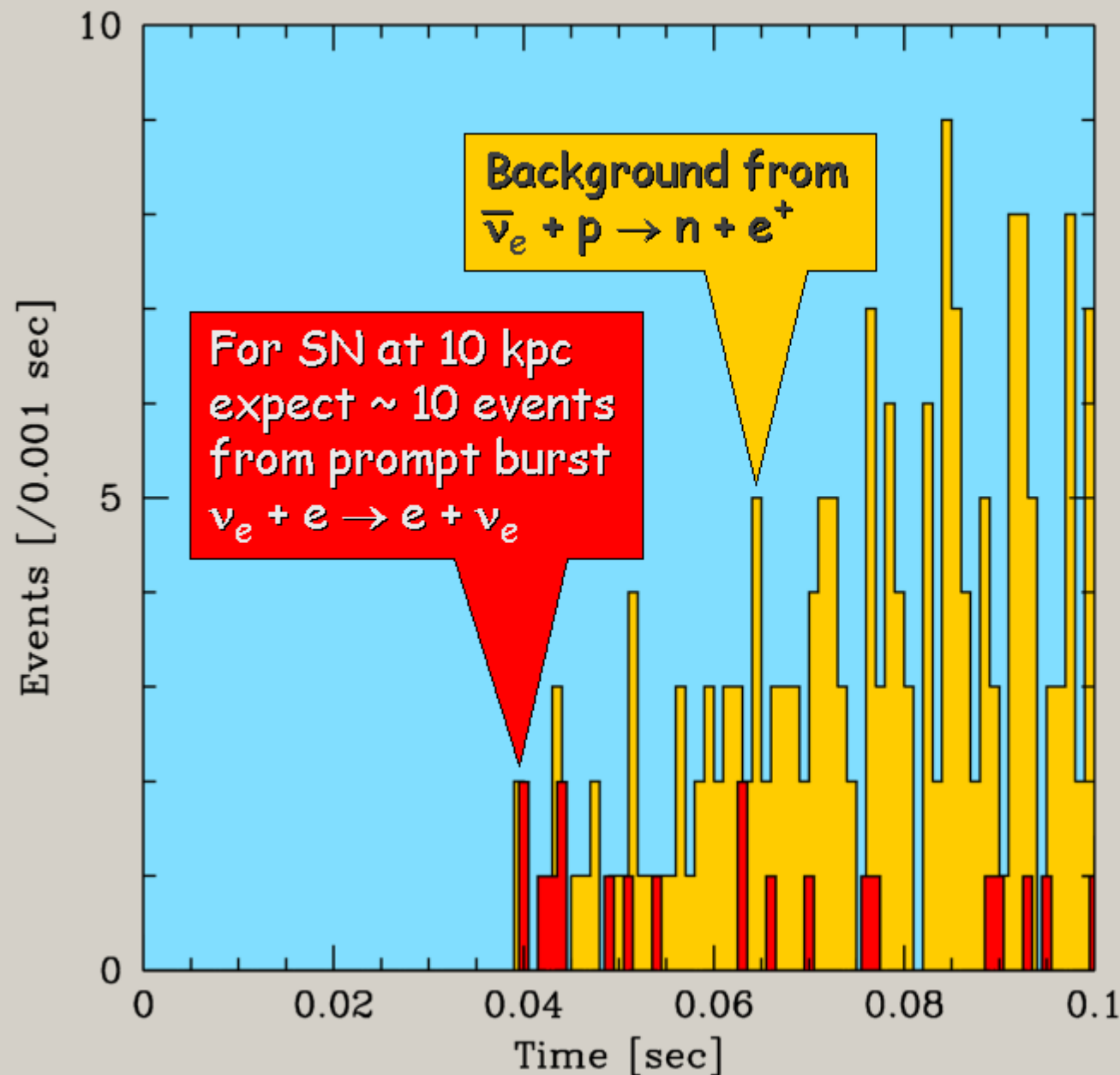


Broad characteristics

- Duration few seconds
- $\langle E_{\nu} \rangle \sim 10\text{-}20$ 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

Can we see the prompt neutrino burst?

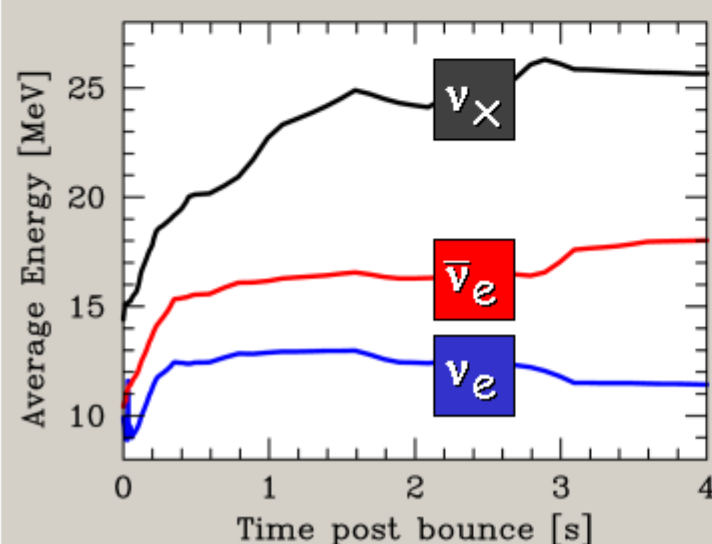
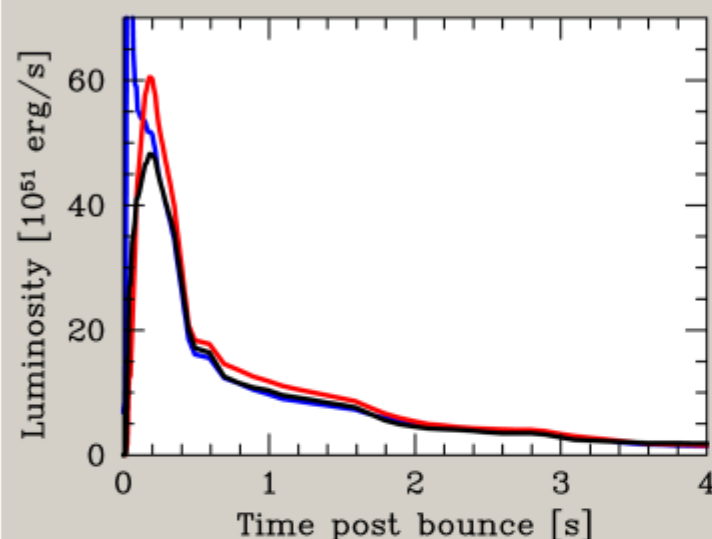


Monte-Carlo example
for early SN signal
in Super-Kamiokande

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

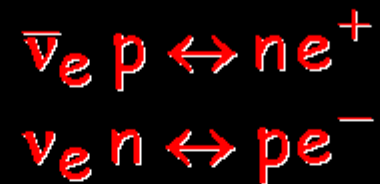
- Almost exact equipartition of energy among flavors
- Pronounced hierarchy of average energies

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

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

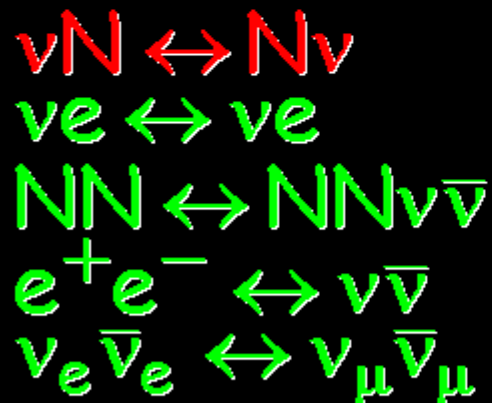
Thermal Equilibrium



Free
streaming

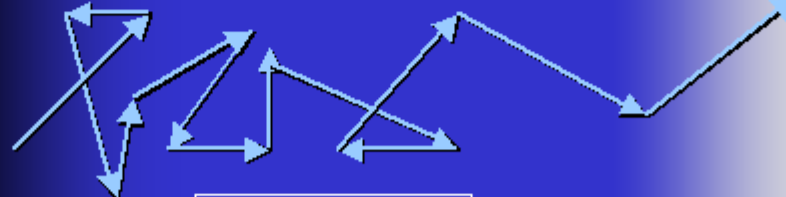
Neutrino sphere (T_{NS})

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



Thermal Equilibrium

Scattering Atmosphere



Diffusion

Free
streaming

Energy sphere (T_{ES})

Transport sphere

Scattering Atmosphere as a "Low-Pass Filter"

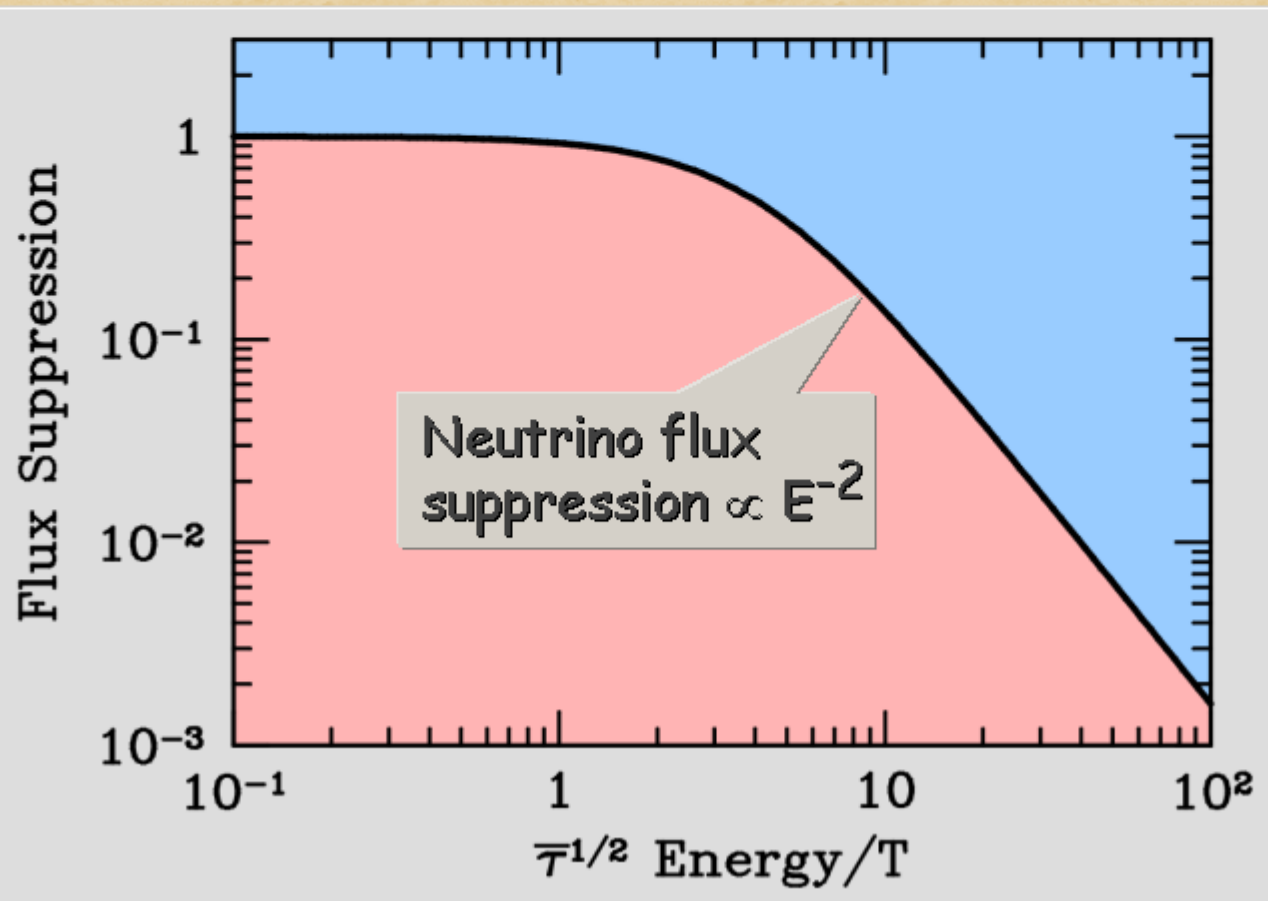
Thermal Equilibrium

Blackbody flux
from E-sphere

Transmitted flux

Reflected flux

Diffusion



Scattering Atmosphere as Low-Pass Filter

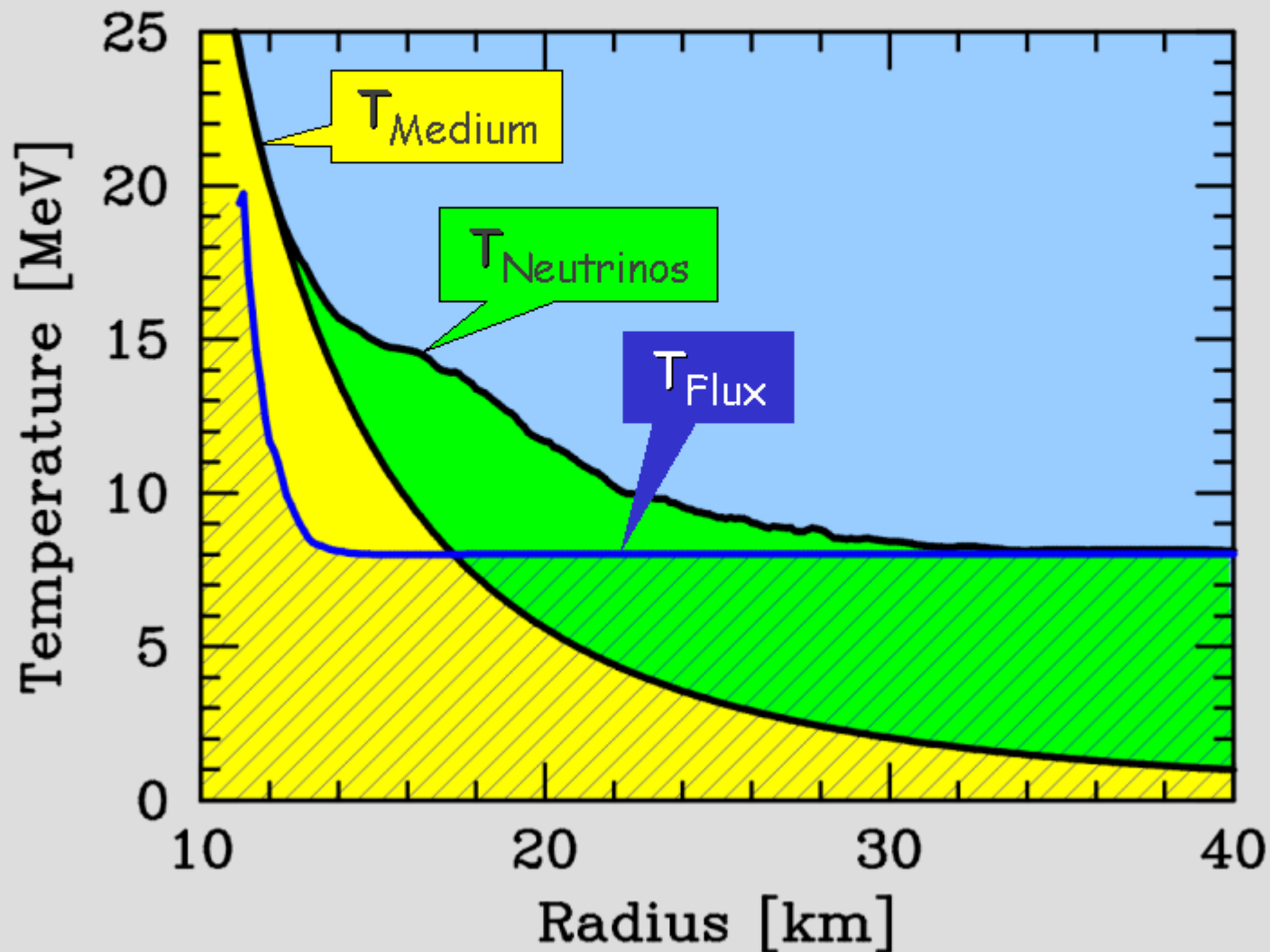
$\nu N \leftrightarrow N \nu$

$NN \leftrightarrow NN\nu\bar{\nu}$

$\nu N \leftrightarrow N \nu$

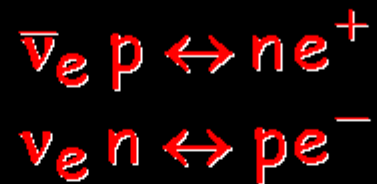
No Recoil

Free
streaming



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

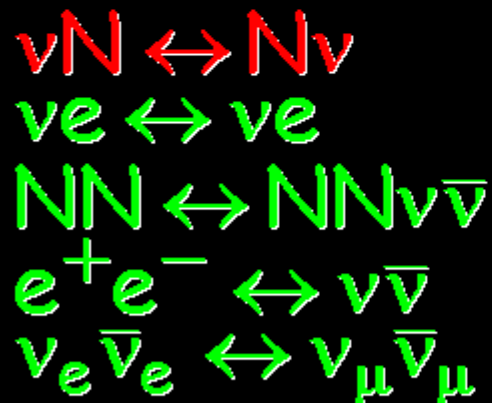
Thermal Equilibrium



$$T_{\text{flux}} \sim T_{\text{NS}}$$

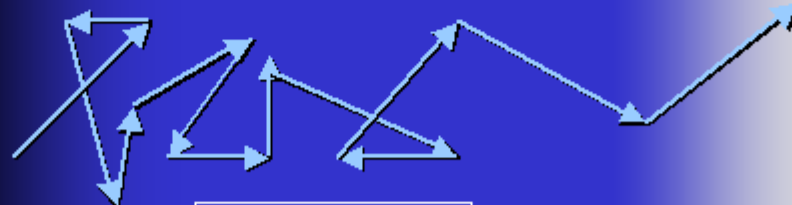
Neutrino sphere (T_{NS})

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



Thermal Equilibrium

Scattering Atmosphere



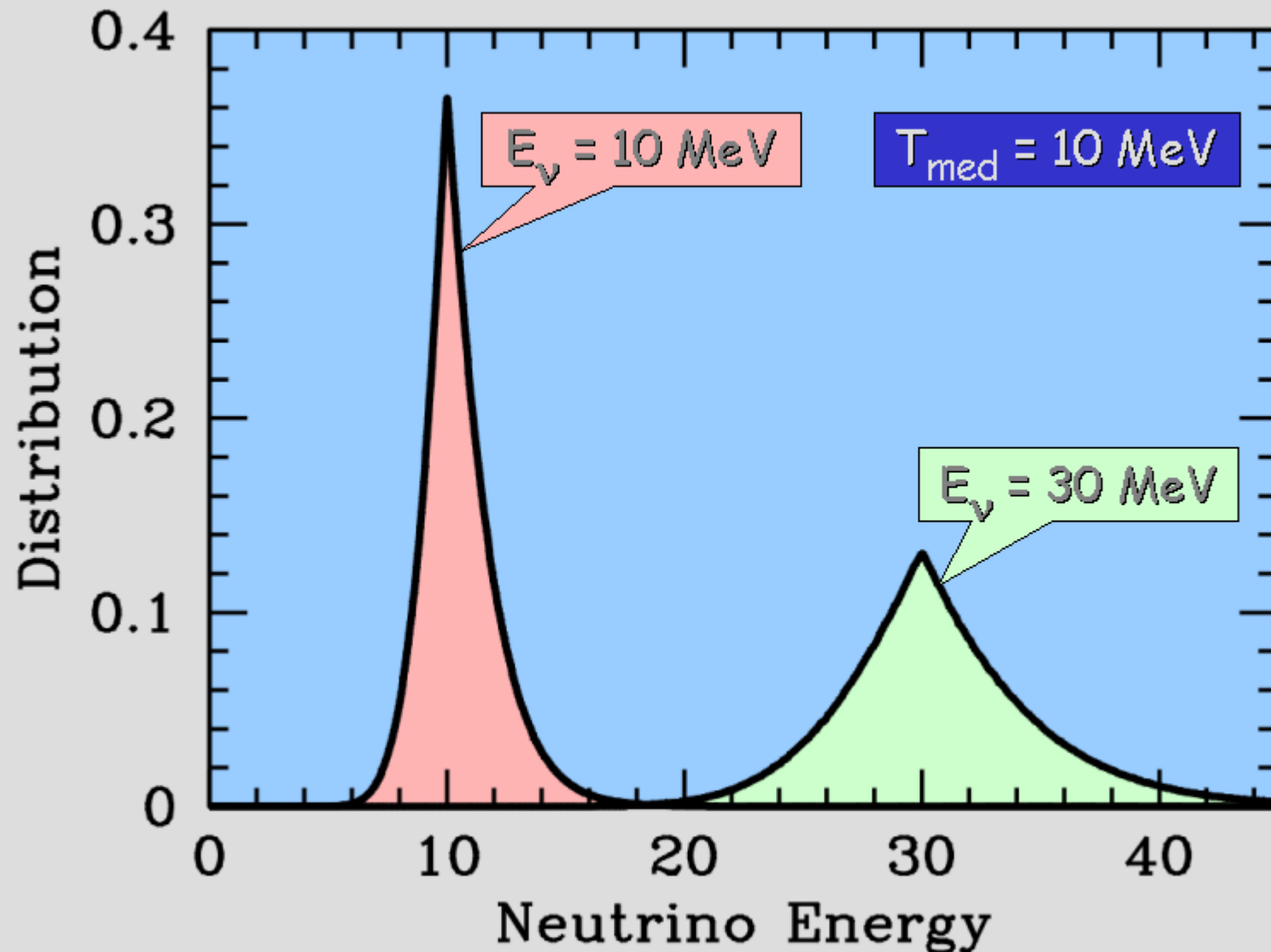
Diffusion

$$T_{\text{flux}} \sim 0.6 T_{\text{ES}}$$

Energy sphere (T_{ES})

Transport sphere

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	$\nu + N \rightarrow N + \nu$	$\nu + N \rightarrow N + \nu$
Energy exchange	$\nu + e \rightarrow e + \nu$	$\nu + e \rightarrow e + \nu$ Recoil $\nu + N \rightarrow N + \nu$ [2,6,7]
Pair production	$e^+ + e^- \rightarrow \bar{\nu} + \nu$	$N + N \rightarrow N + N + \bar{\nu} + \nu$ [1-4] $\bar{\nu}_e + \nu_e \rightarrow \bar{\nu} + \nu$ [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]

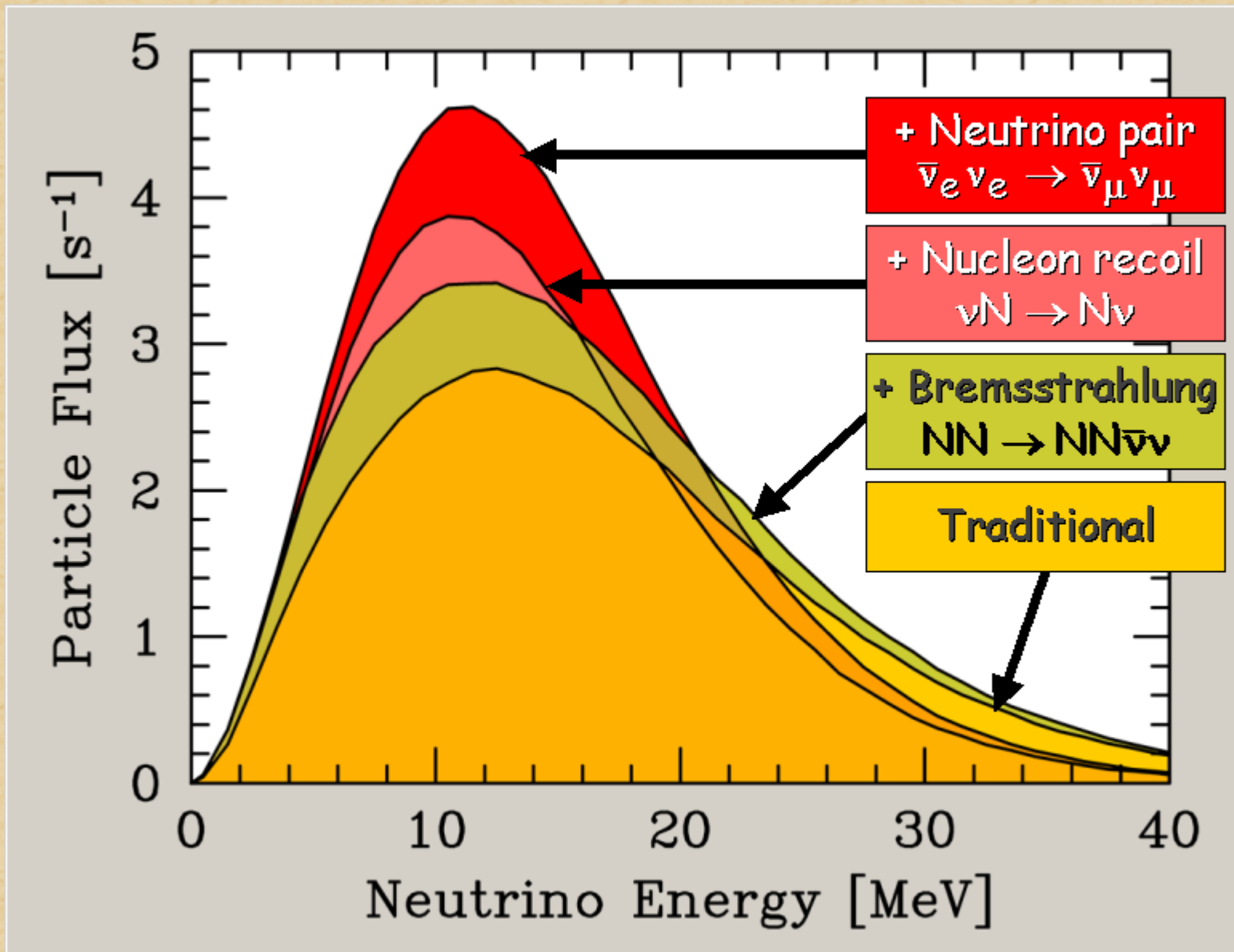
[4] Thompson, Burrows & Horvath, PRC 62 (2000) 035802 [astro-ph/0003054]

[6] Raffelt, ApJ 561 (2001) 890 [astro-ph/0105250]

[6] Buras, Janka, M.Keil, Raffelt & Rampp, ApJ (2003) [astro-ph/0205006]

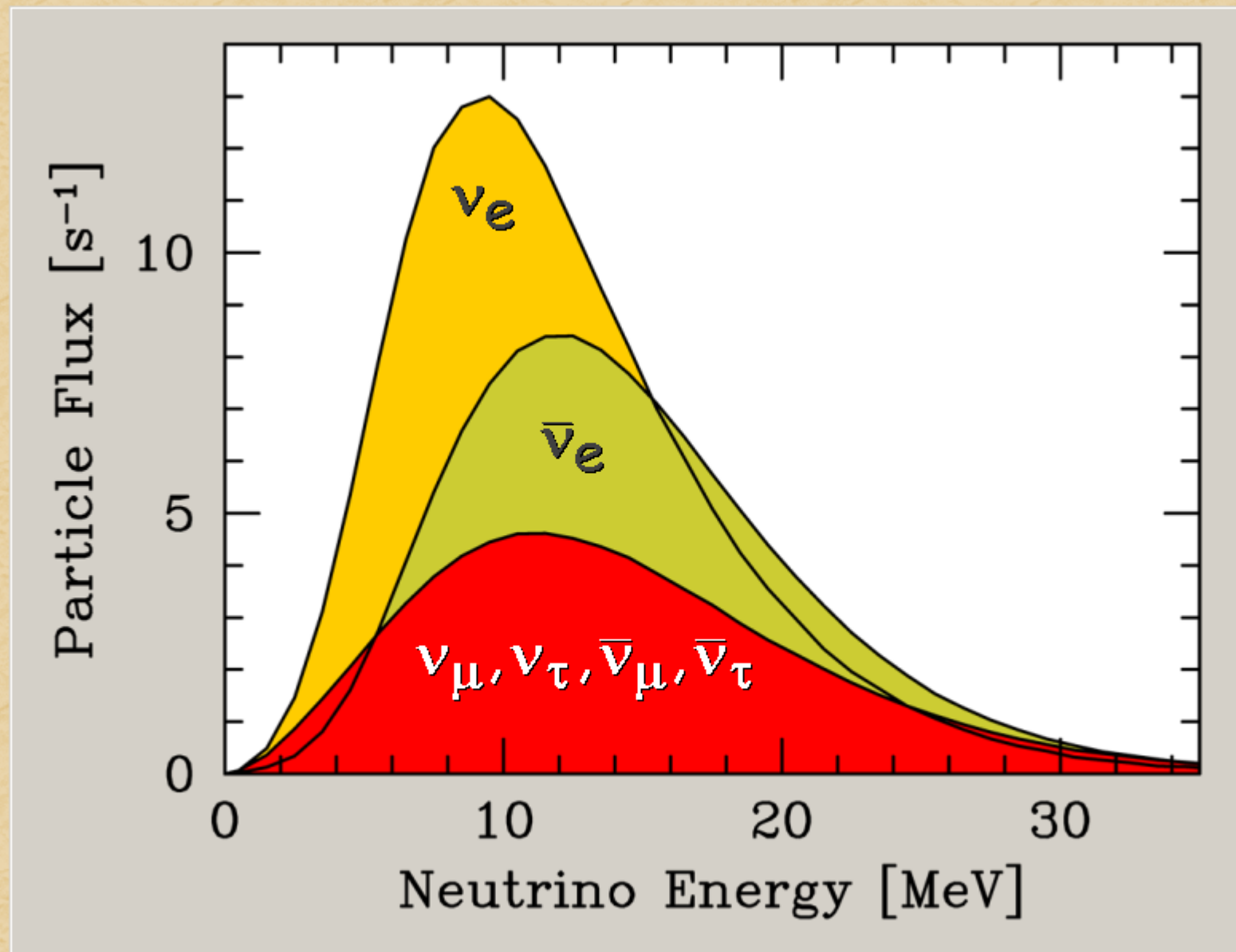
[7] M.Keil, Raffelt & Janka, ApJ submitted (2003) [astro-ph/0208035]

Flux and Spectra Modification by New Processes



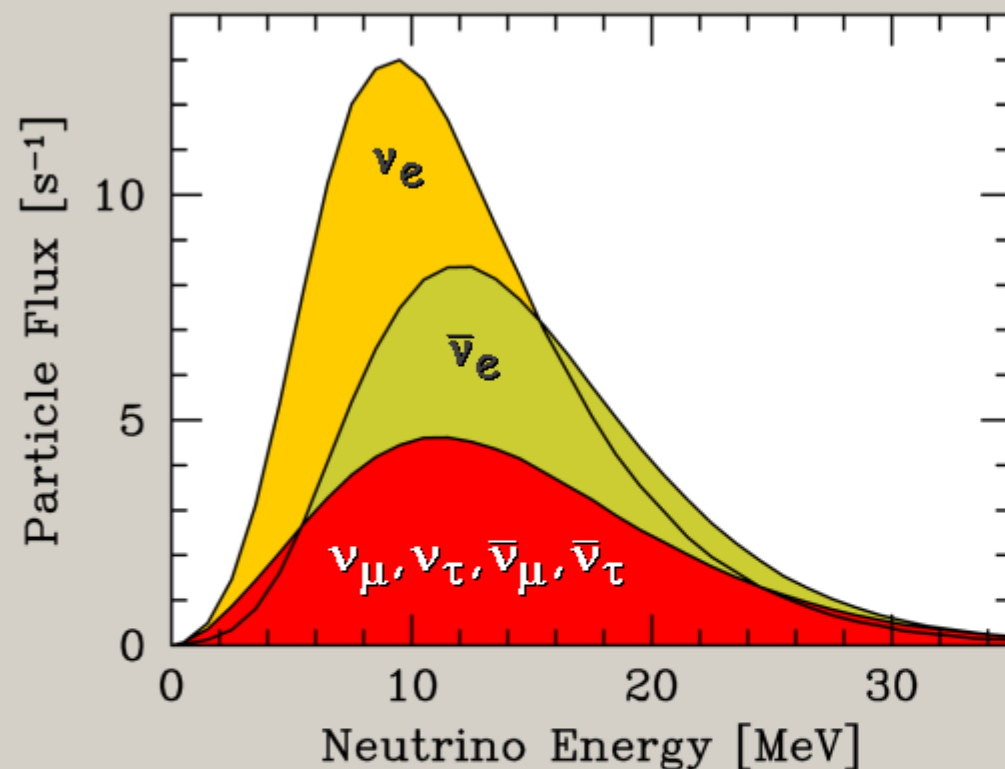
Keil, Raffelt & Janka, ApJ (2003) [astro-ph/0208035]

Flavor-Dependent Fluxes in an Accretion-Phase Model



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

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)

Quasi power law
(α fit)

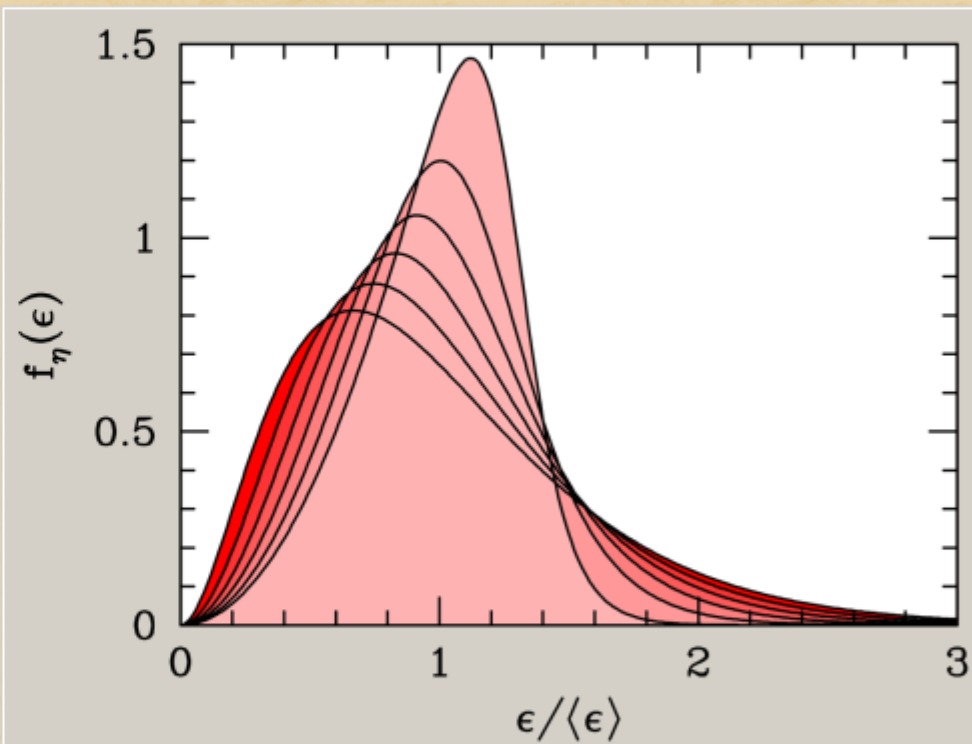
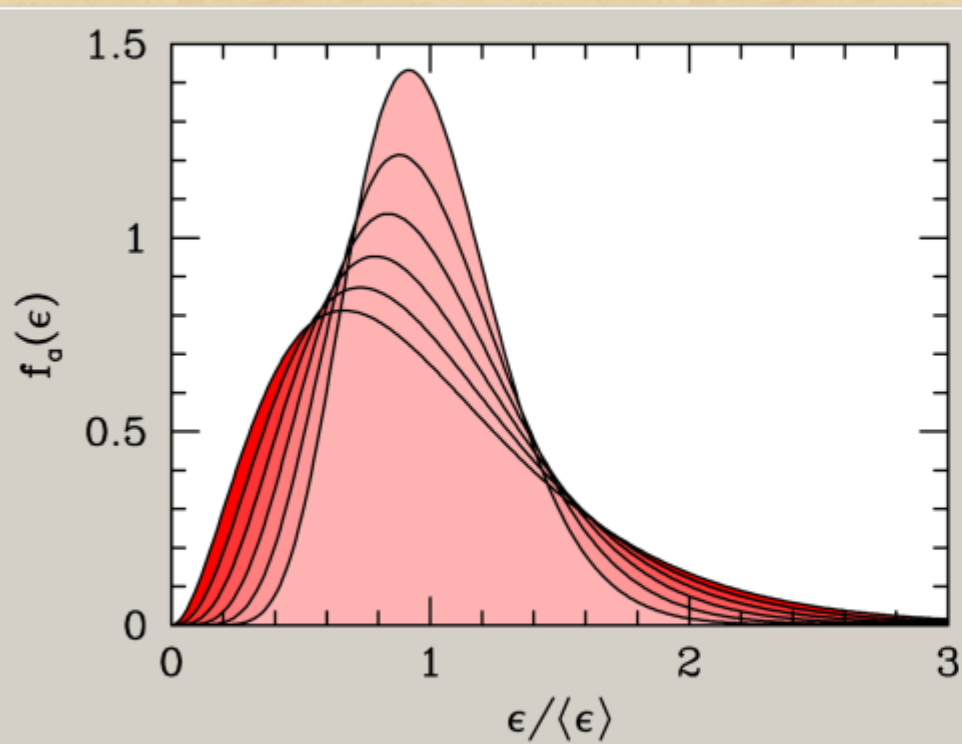
$$F(E) \propto \frac{E^2}{1 + e^{-\eta + E/T}}$$

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

Alpha vs. Eta Fit

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

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

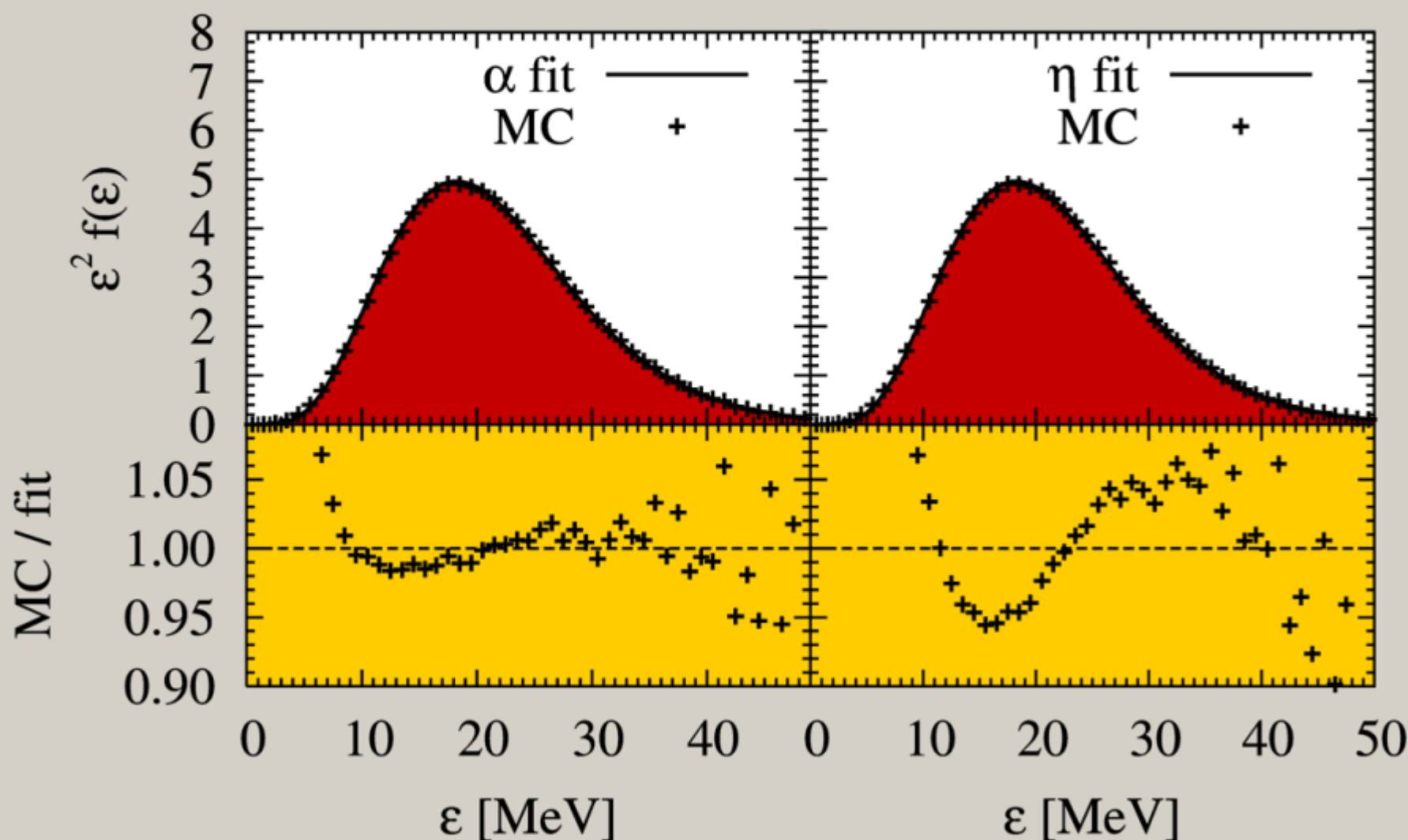


Starting with $F(E) \propto E^2 \exp\left(-3\frac{E}{\bar{E}}\right)$ the width is reduced in 10% steps

How Good are the Two-Parameter Global Fits?

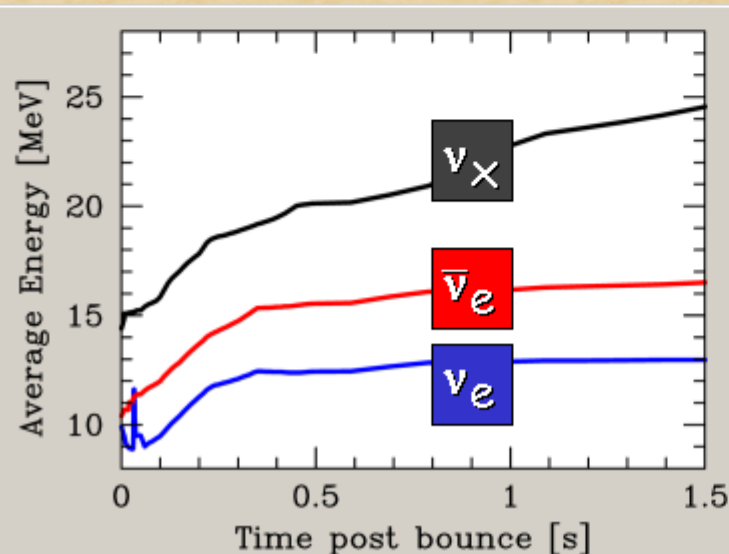
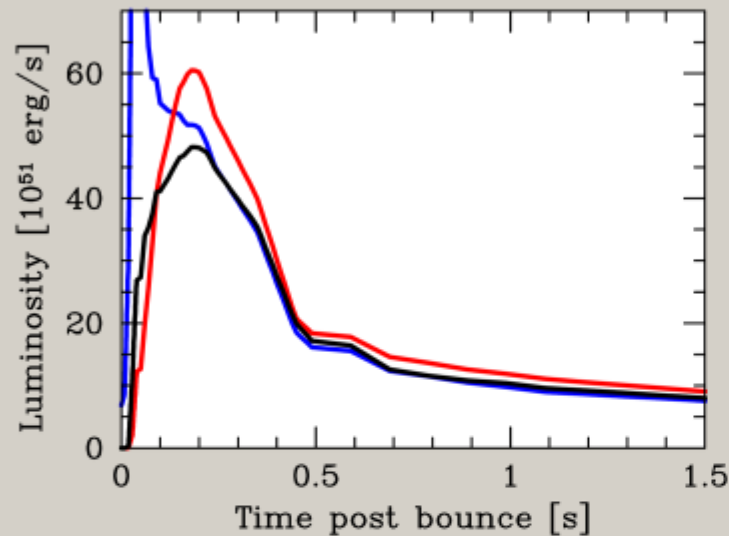
$$F(E) \propto E^\alpha \exp\left[-(\alpha+1)\frac{E}{\bar{E}}\right]$$

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

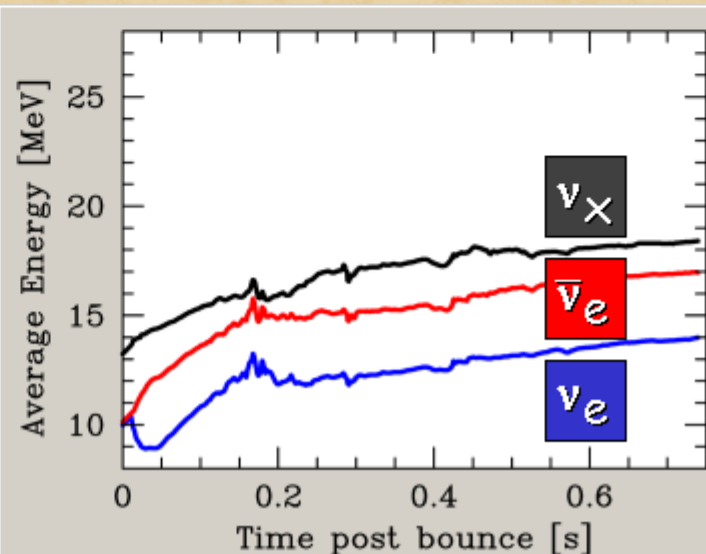
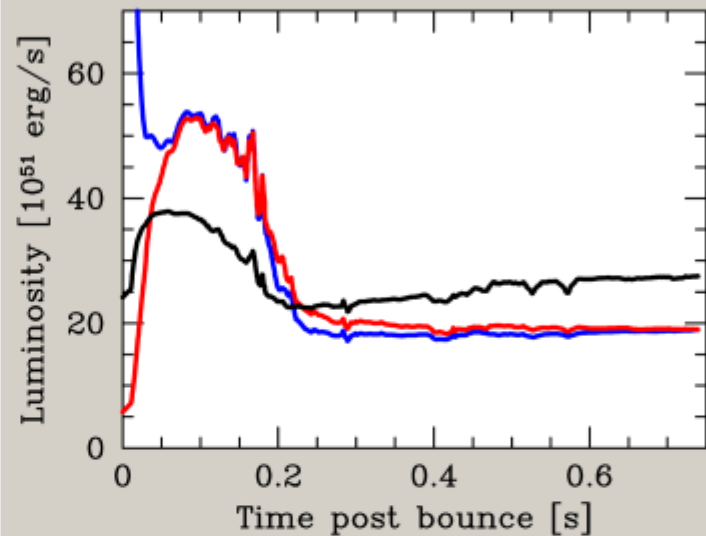


Fluxes and Spectra from Numerical Simulations

Livermore (traditional)
[ApJ 496 (1998) 216]



Garching (new microphysics)
[astro-ph/0303226]



Three-Flavor Neutrino Parameters (Ignoring LSND)

Atmospheric
 $32^\circ < \theta_{23} < 60^\circ$

Chooz Limit
 $\theta_{13} < 14^\circ$

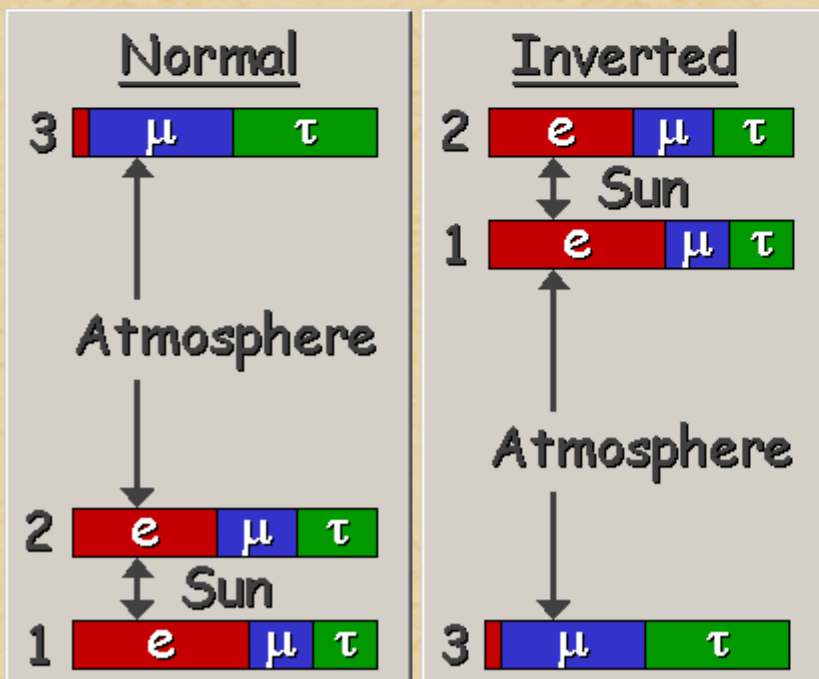
Solar
 $27^\circ < \theta_{12} < 41^\circ$

3σ ranges
 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
 $\Delta m^2 / \text{meV}^2$

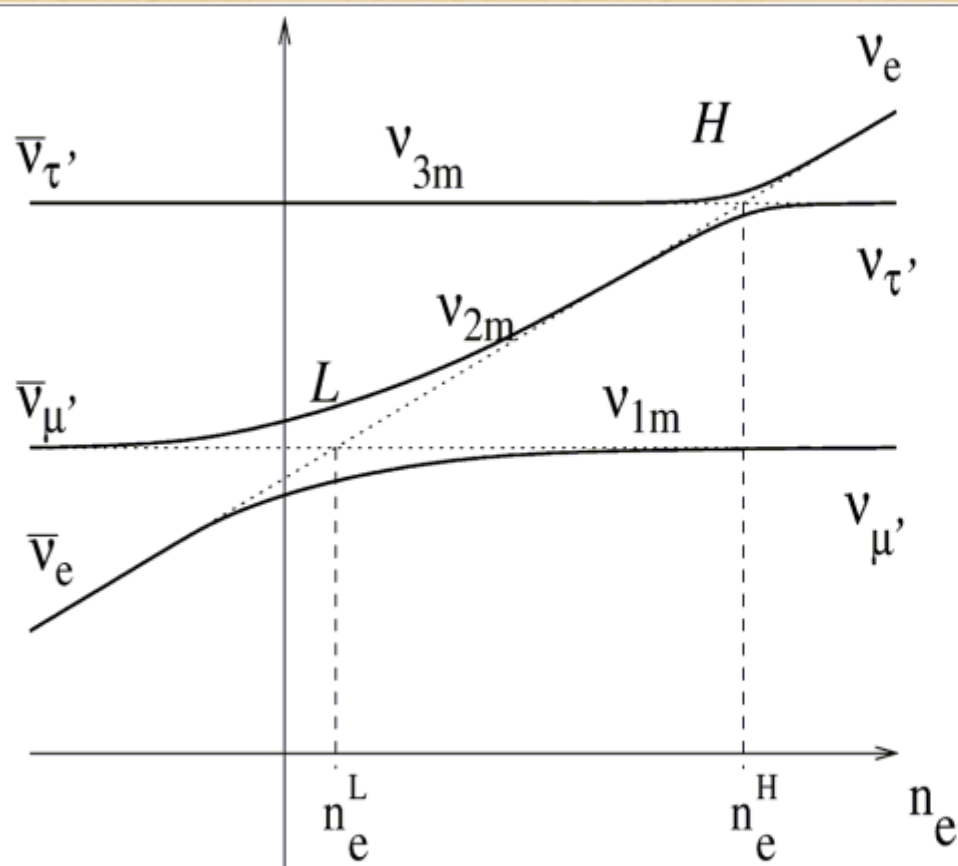


Tasks and Open Questions

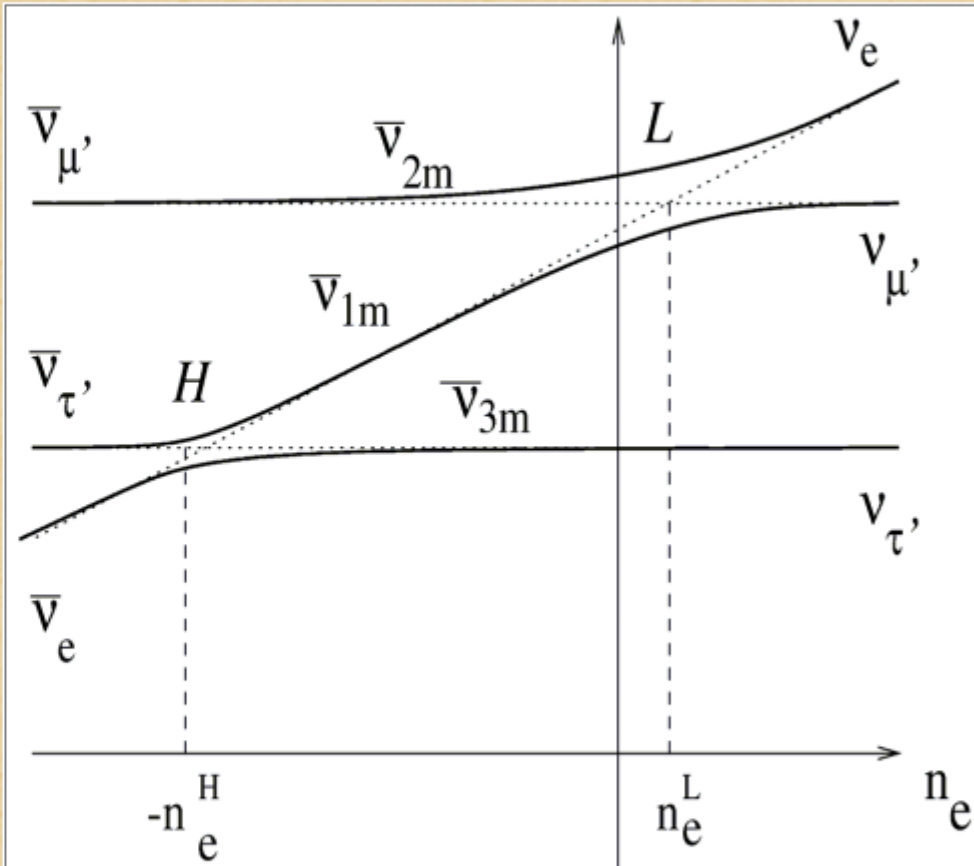
- Precision for θ_{12} and θ_{23} ($\theta_{12} < 45^\circ$ and $\theta_{23} = 45^\circ$?)
- How large is θ_{13} ?
- CP-violating phase?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?

Level-Crossing Diagram in a SN Envelope

Normal mass hierarchy

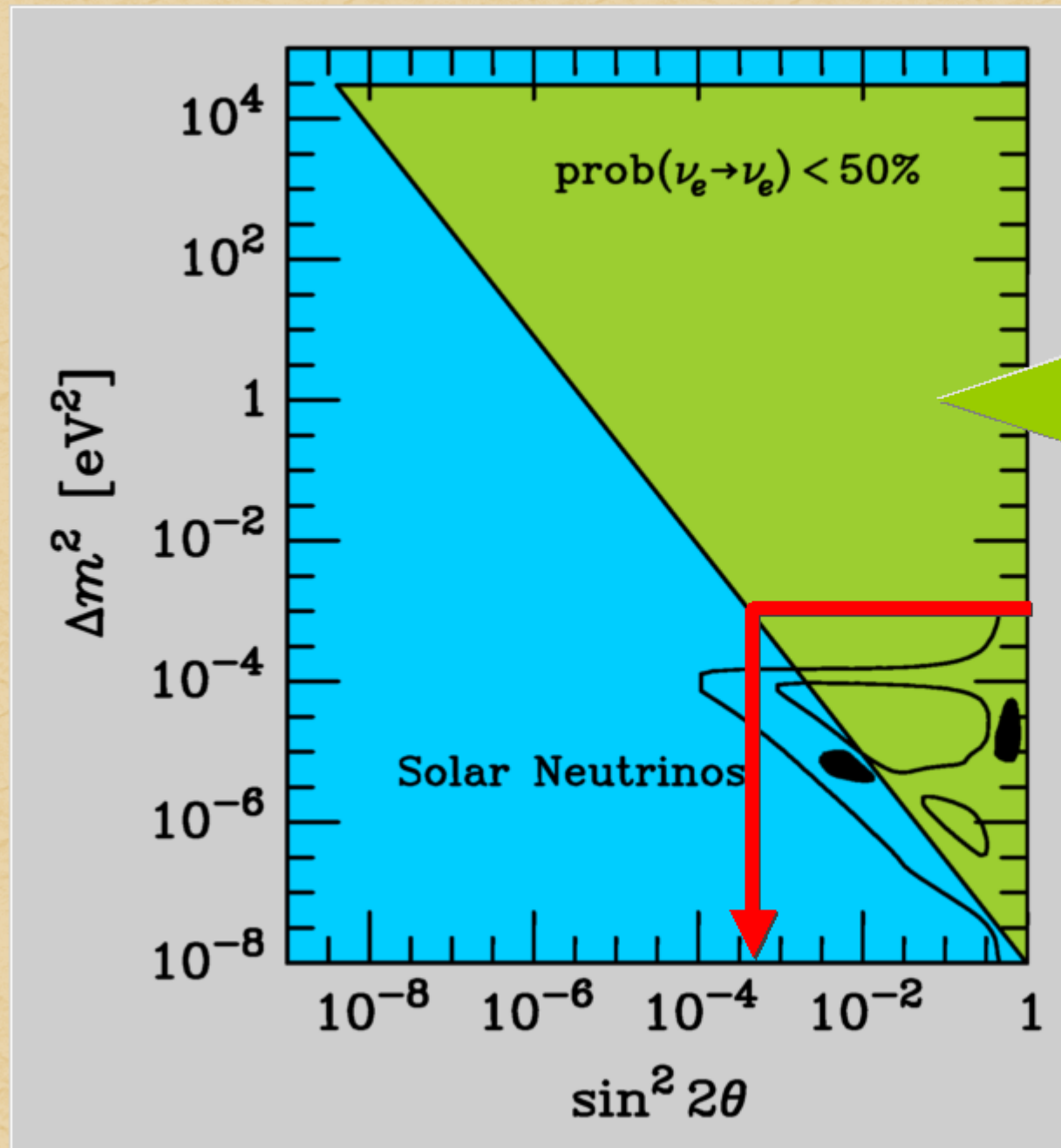


Inverted mass hierarchy



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

$$F_e^0 \text{ for } \nu_e$$

$$F_{\bar{e}}^0 \text{ for } \bar{\nu}_e$$

$$F_x^0 \text{ for } \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$$

After leaving the supernova envelope, the fluxes are partially swapped

$$F_e = p F_e^0 + (1-p) F_x^0$$

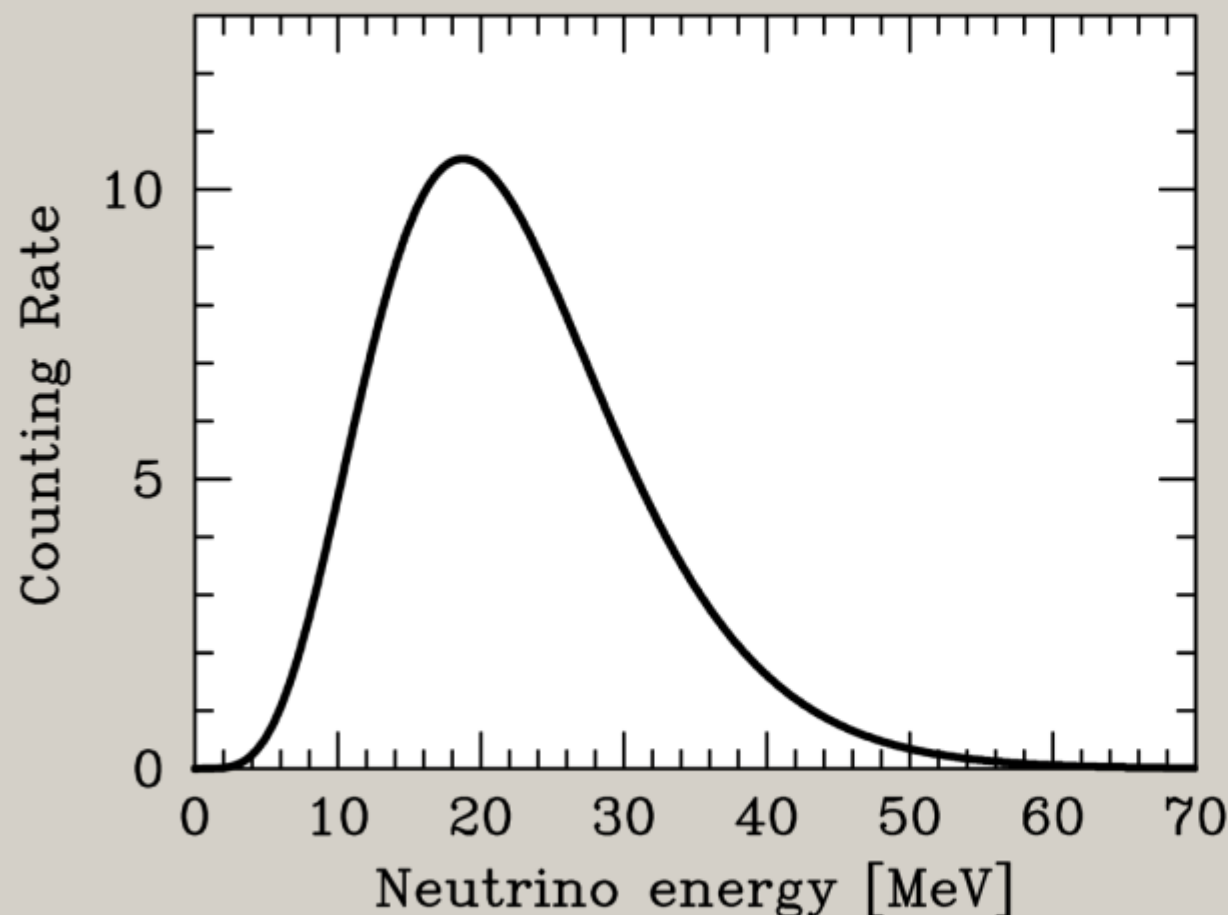
$$F_{\bar{e}} = \bar{p} F_{\bar{e}}^0 + (1-\bar{p}) F_x^0$$

$$\frac{1}{4} \sum F_x = \frac{2+p+\bar{p}}{4} F_x^0 + \frac{1-p}{4} F_e^0 + \frac{1-\bar{p}}{4} F_{\bar{e}}^0$$

$\sin^2(2\Theta_{13})$	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:

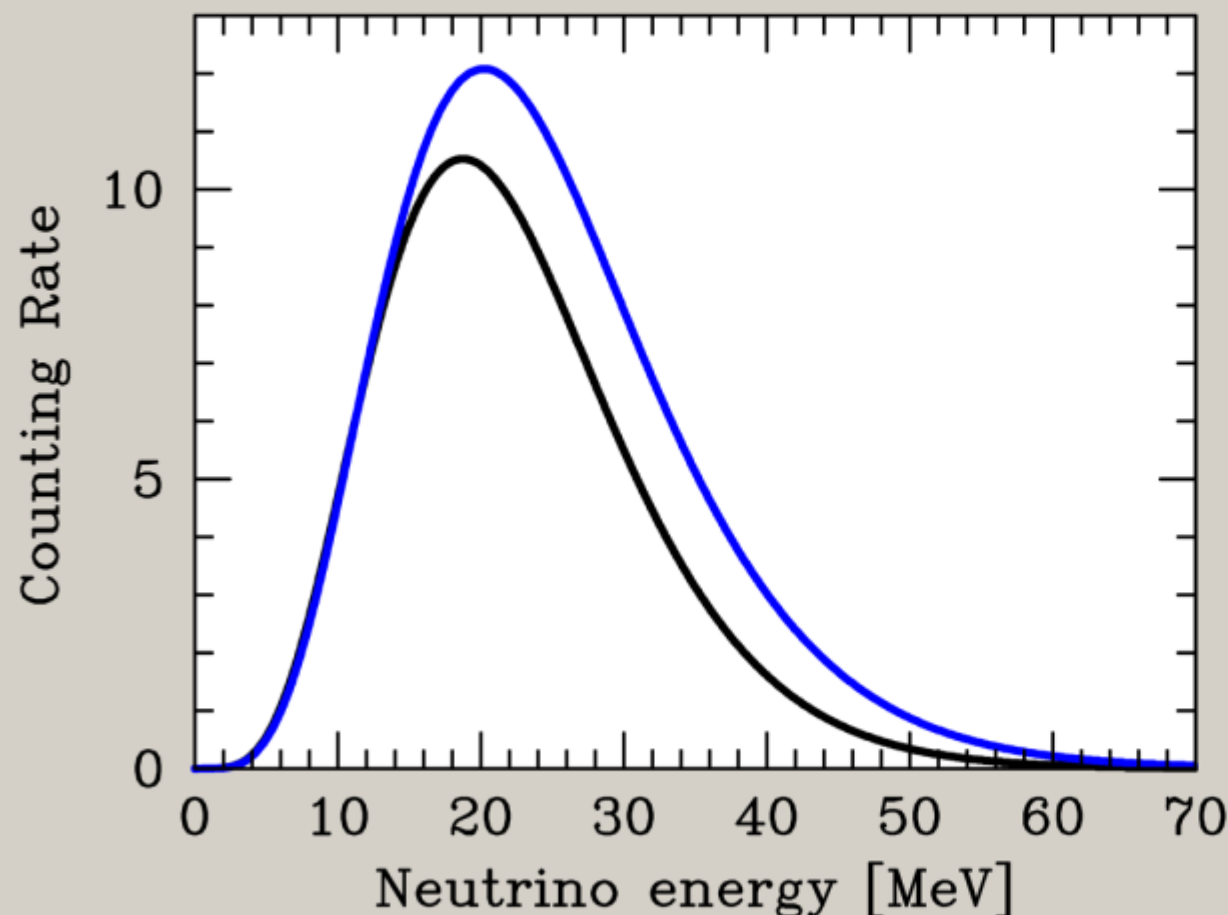
$\Delta m_{\text{sun}}^2 = 60 \text{ meV}^2$

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

No oscillations

Oscillation of Supernova Anti-Neutrinos

Measured $\bar{\nu}_e$ spectrum at a detector like Super-Kamiokande



Assumed flux parameters:

Flux ratio $\bar{\nu}_e : \bar{\nu}_x = 0.8 : 1$

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$\langle E(\bar{\nu}_x) \rangle = 18 \text{ MeV}$

Mixing parameters:

$\Delta m_{\text{sun}}^2 = 60 \text{ meV}^2$

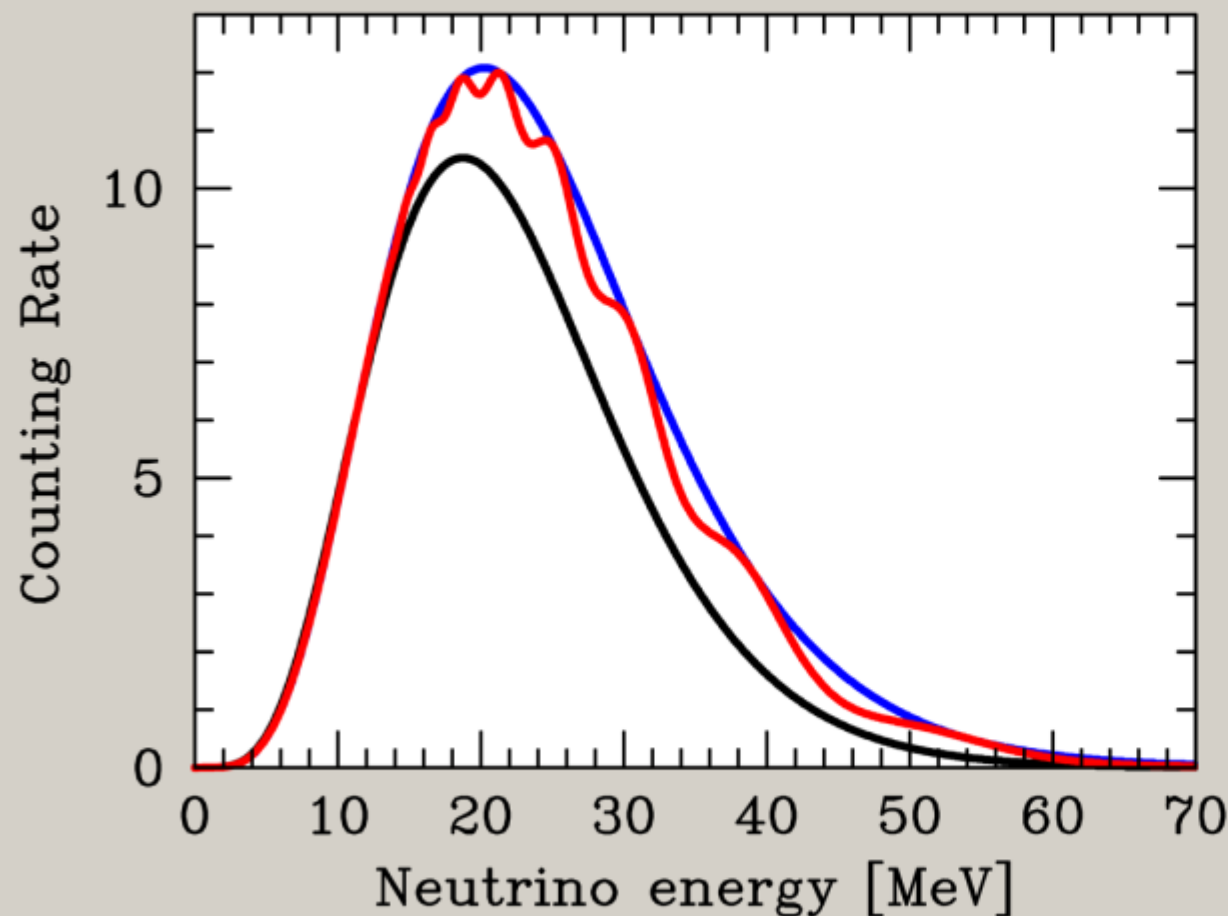
$\sin^2(2\theta) = 0.9$

No oscillations

Oscillations in SN envelope

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:

$\Delta m_{\text{sun}}^2 = 60 \text{ meV}^2$

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

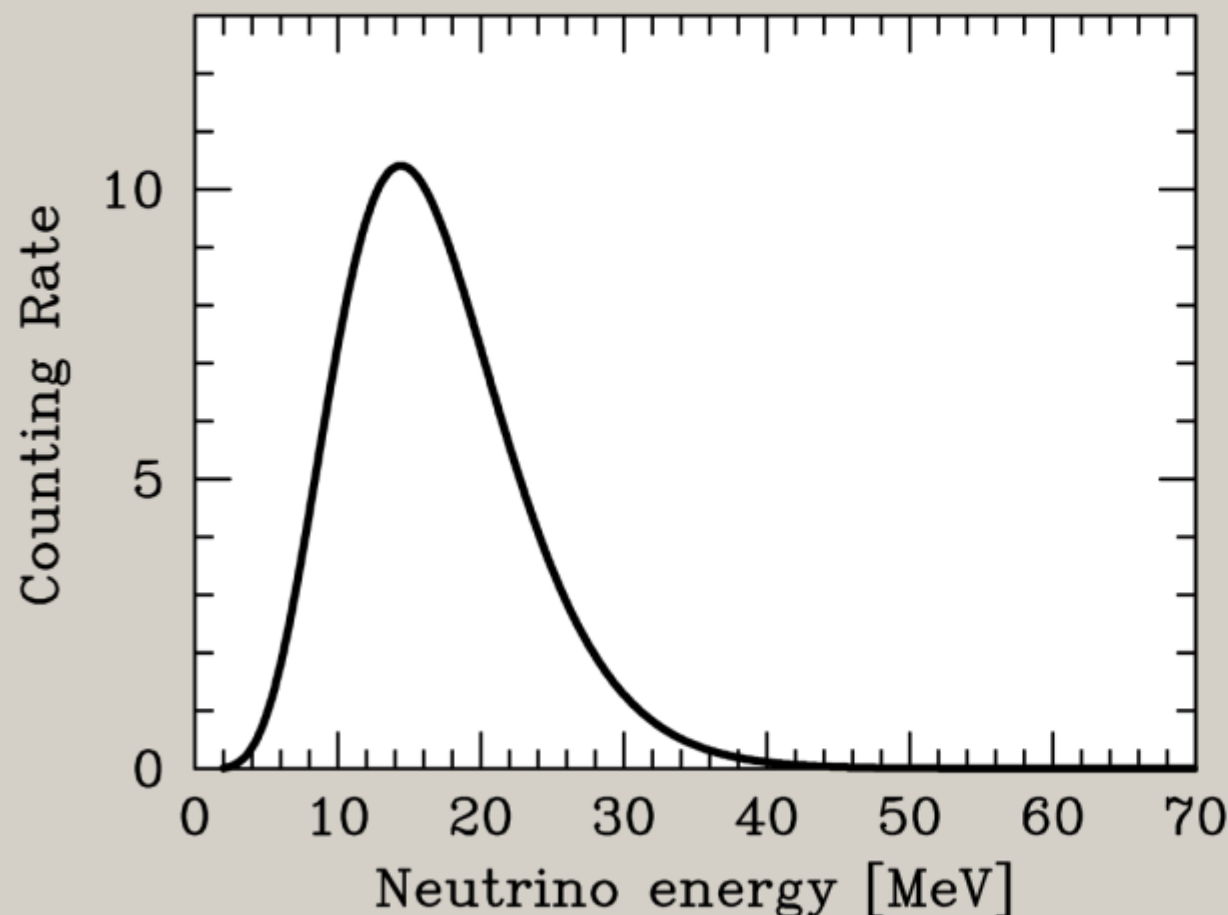
No oscillations

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:

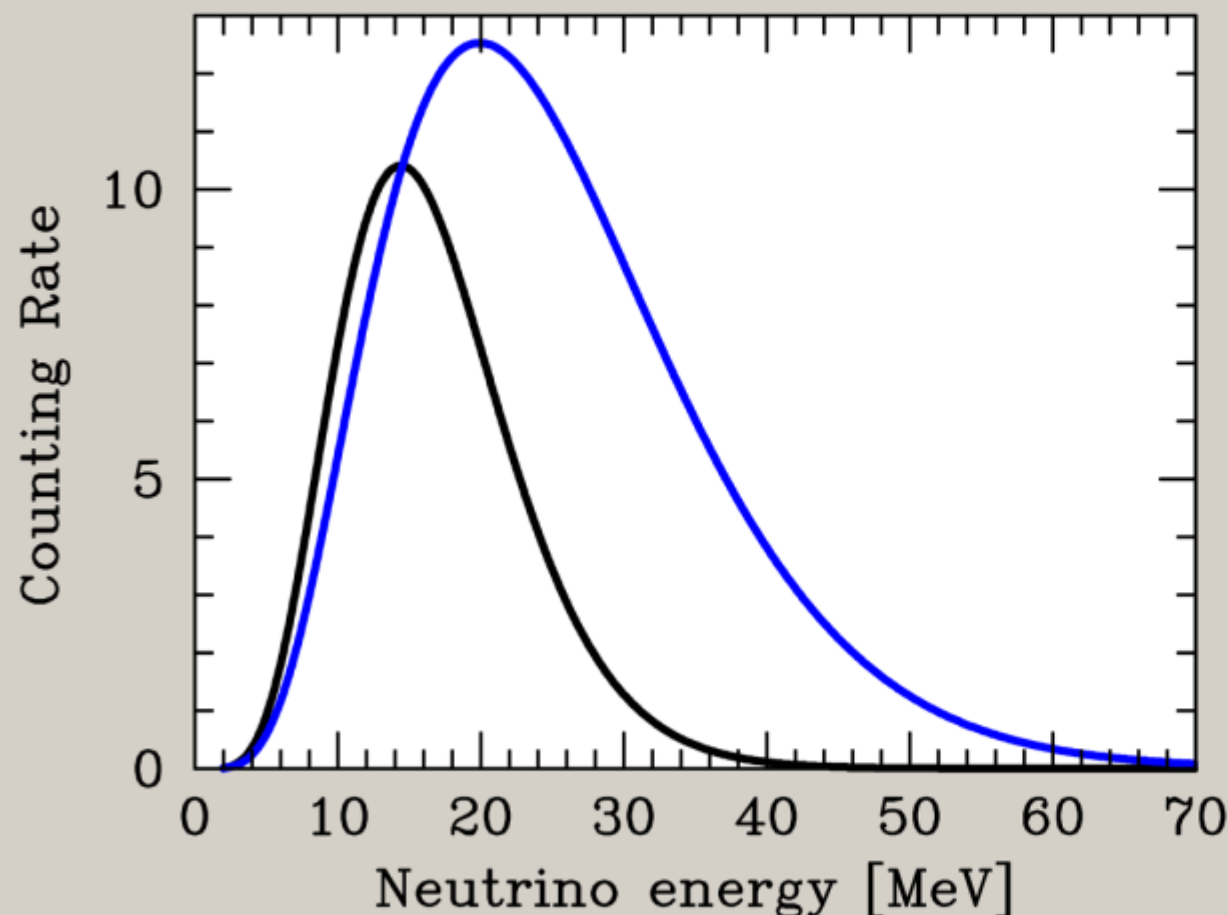
$\Delta m_{\text{sun}}^2 = 60 \text{ meV}^2$

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

No oscillations

Oscillation of Supernova Neutrinos

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



Assumed flux parameters:

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

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

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

Mixing parameters:

$\Delta m_{\text{sun}}^2 = 60 \text{ meV}^2$

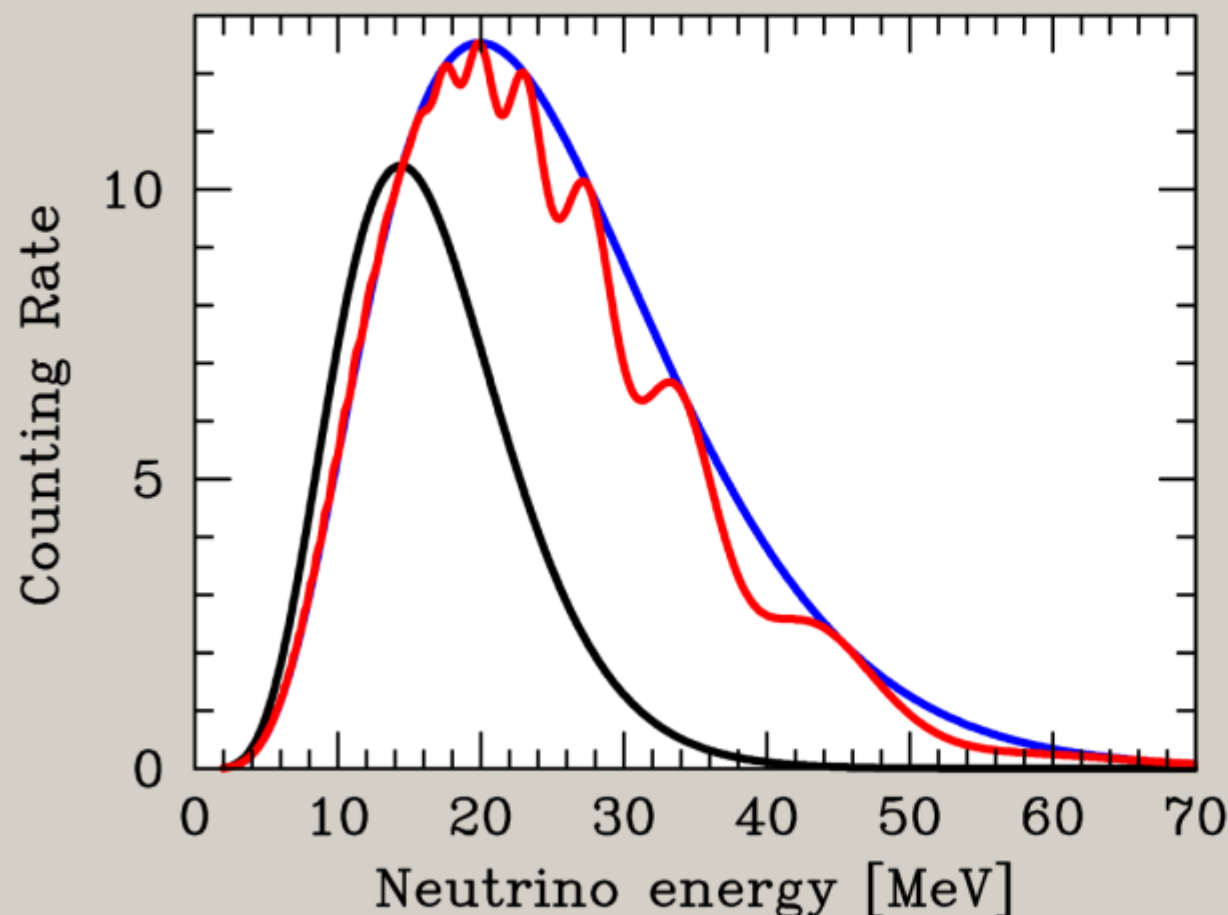
$\sin^2(2\theta) = 0.9$

No oscillations

Oscillations in SN envelope

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:

$\Delta m_{\text{sun}}^2 = 60 \text{ meV}^2$

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

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

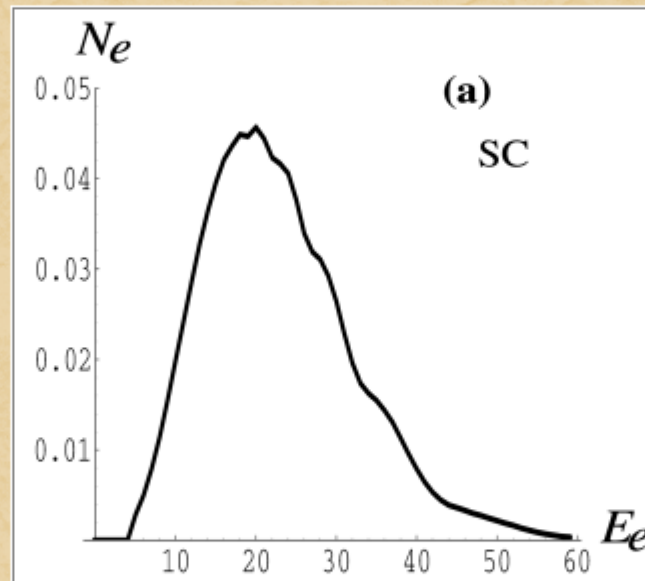
Robust Strategies for Observing Earth Effects

One detector observes SN shadowed by Earth

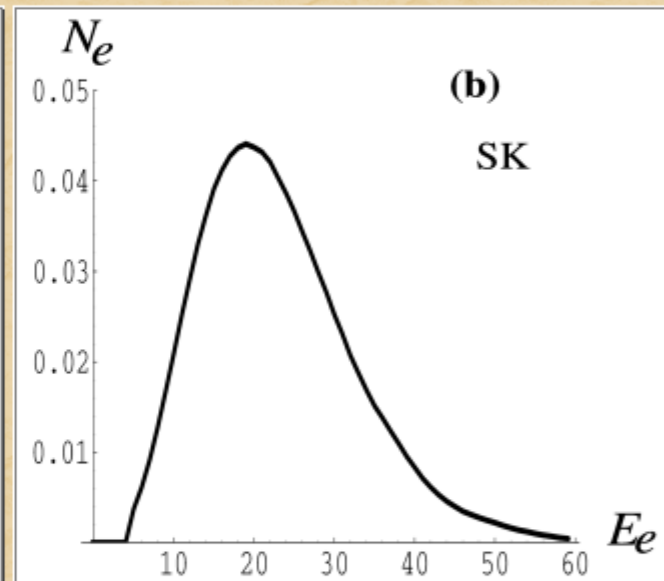
Another detector
observes SN directly

Identify
Earth effects
by comparing signals

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



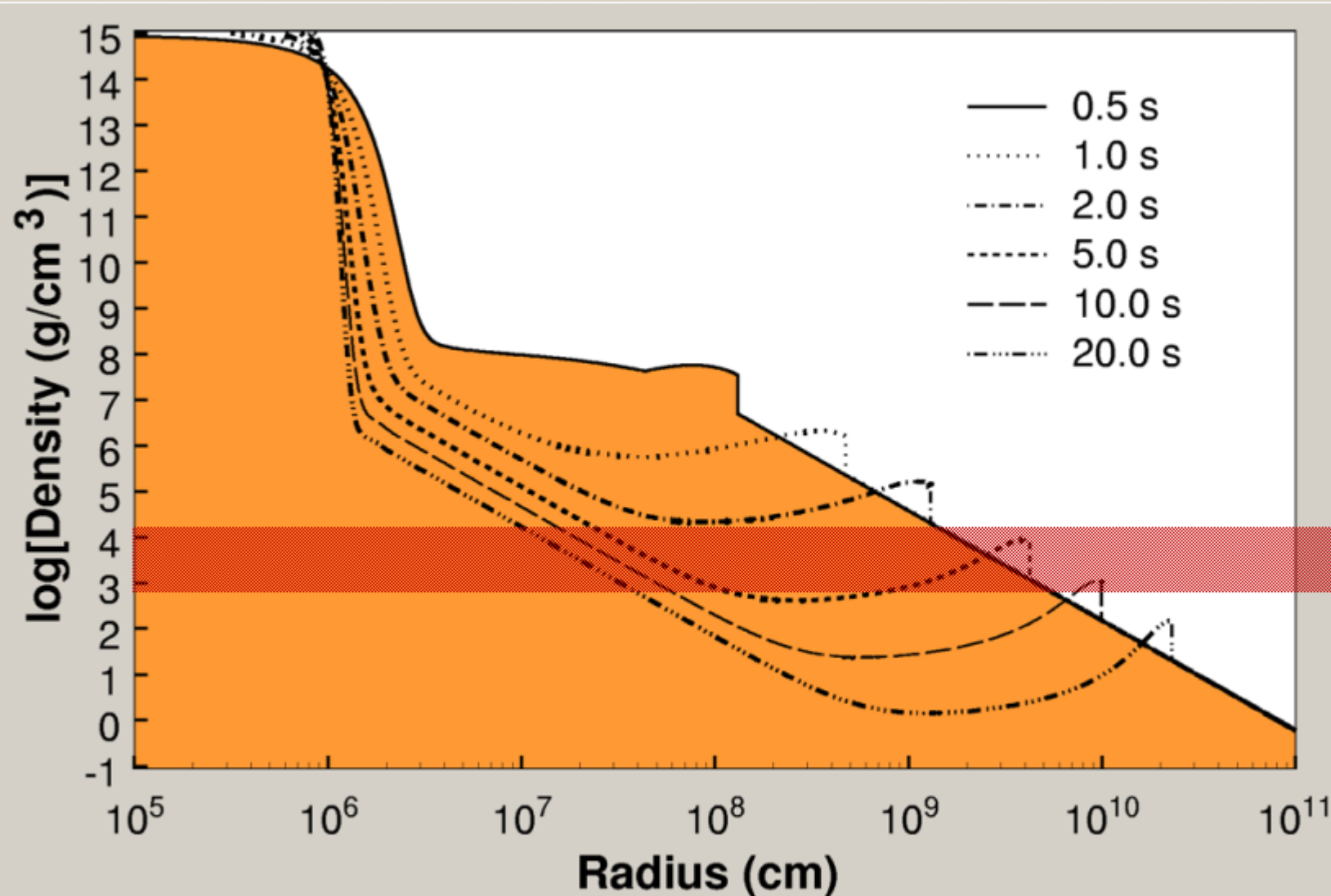
Scintillation detector
~ 2000 events
may be enough



Water Cherenkov:
Need Hyper-Kamiokande
with $\sim 10^5$ events

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

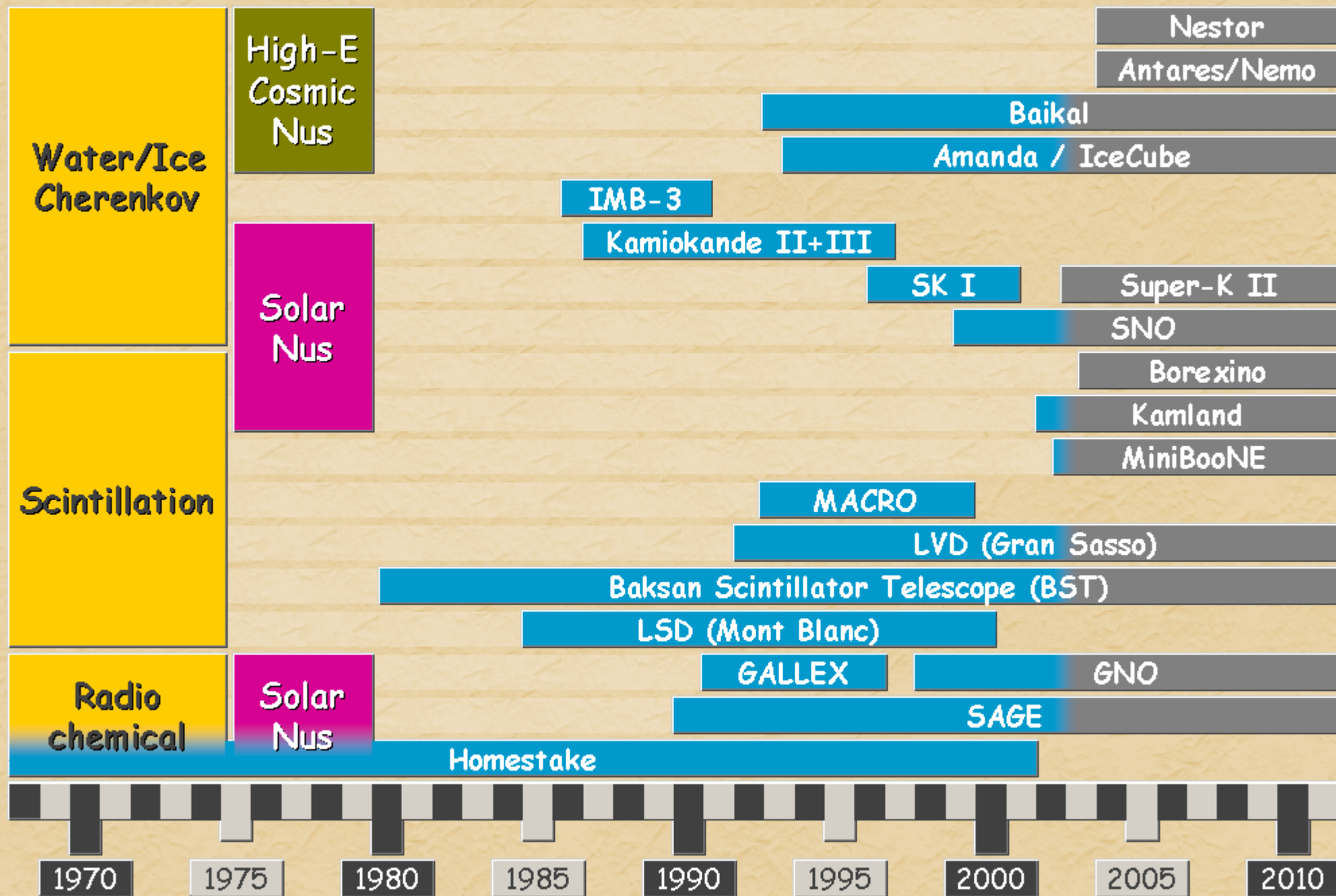
SN Shock Propagation and Neutrino Oscillations



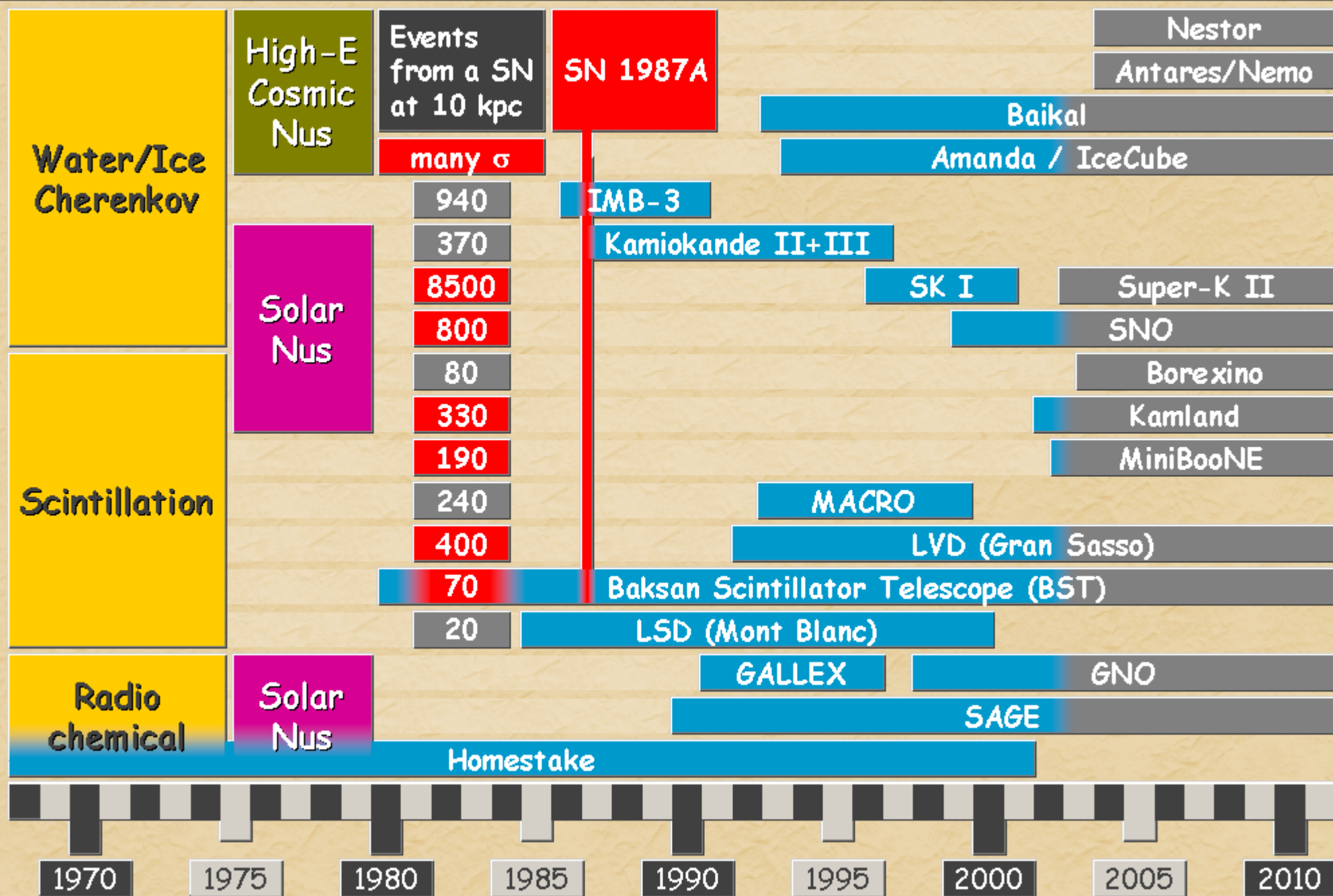
Resonance
density for
 Δm^2_{atm}

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

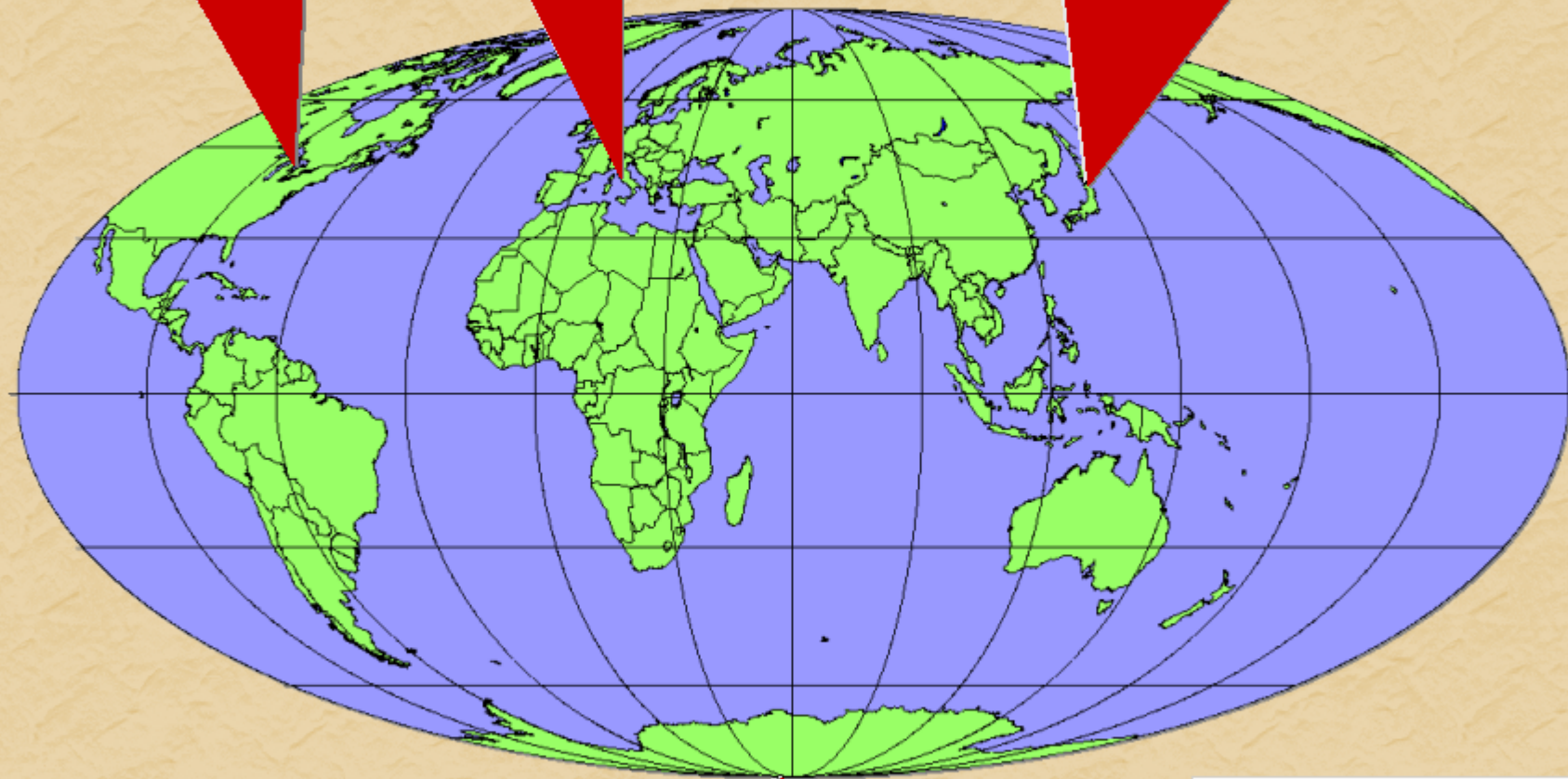


Large Detectors for SN Neutrinos

SNO (800)
MiniBooNE (190)

LVD (400)
Borexino (80)

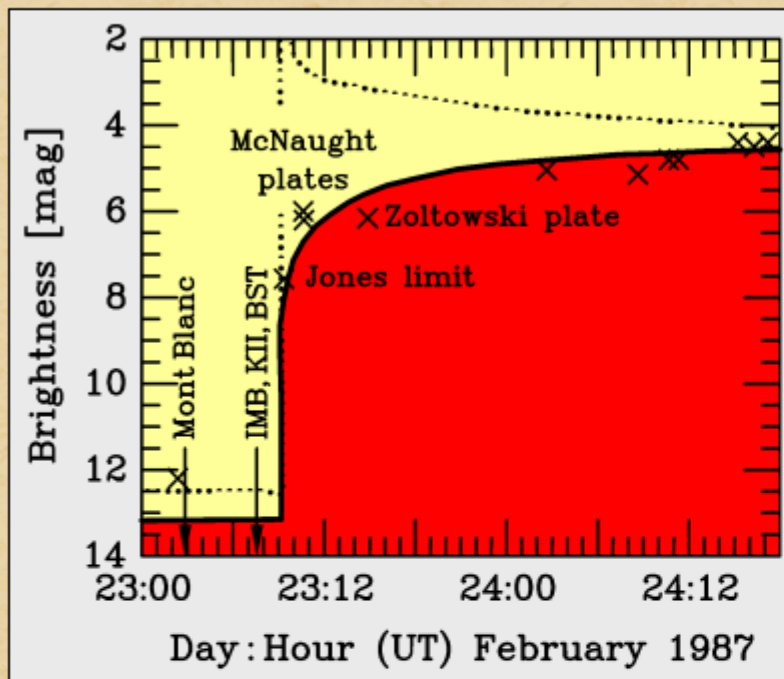
Super-Kamiokande (8500)
Kamland (330)



Amanda
IceCube

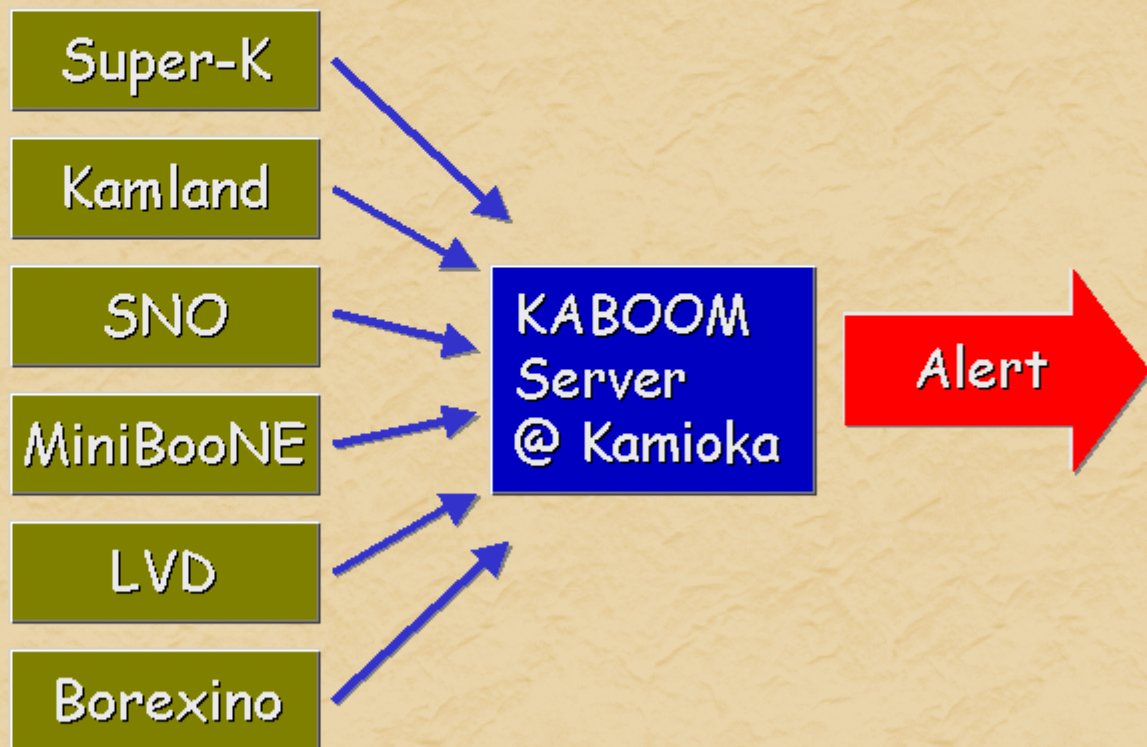
In brackets events
for a "fiducial SN"
at distance 10 kpc

SuperNova Early Warning System (SNEWS)



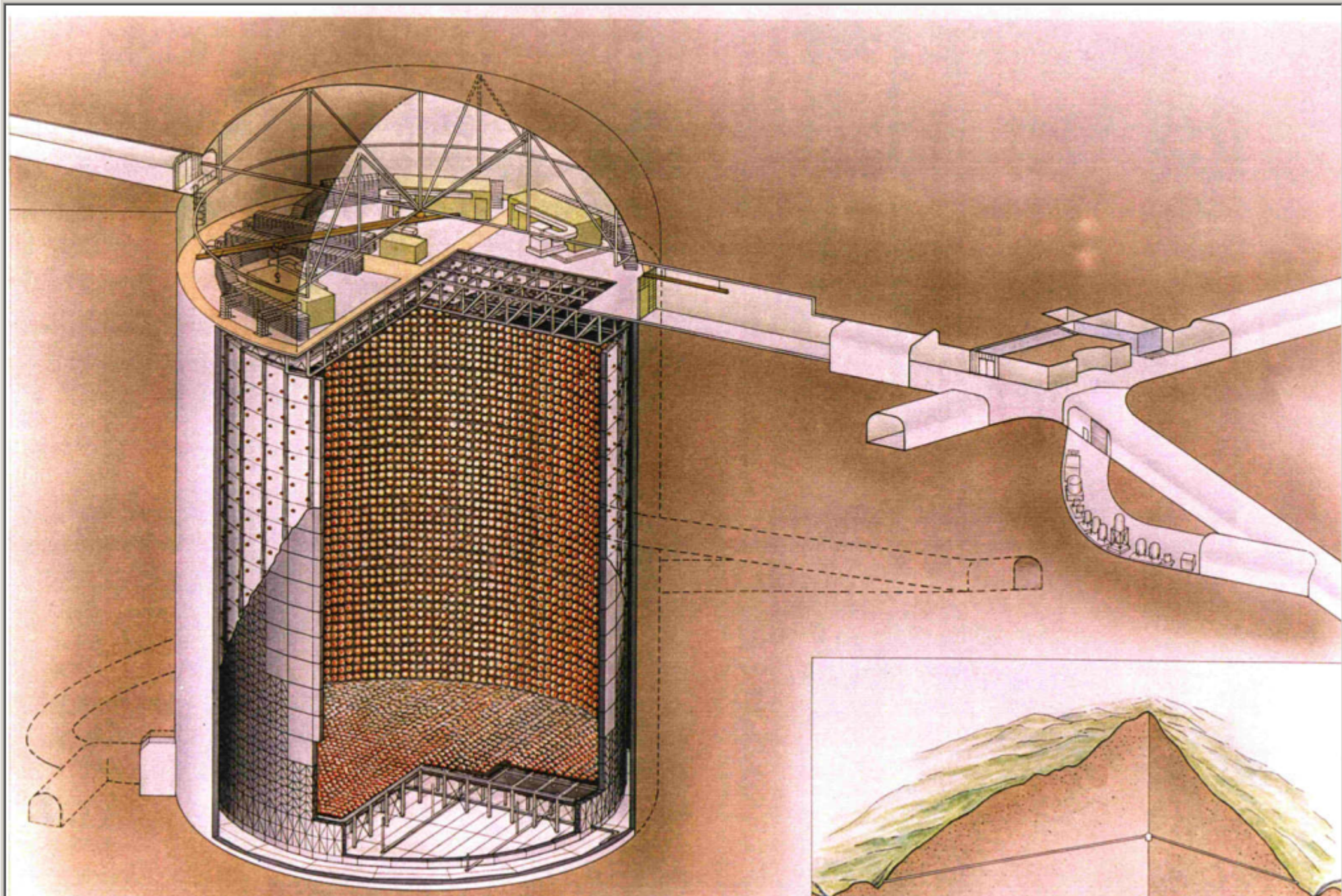
Supernova 1987A
Early Light Curve

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

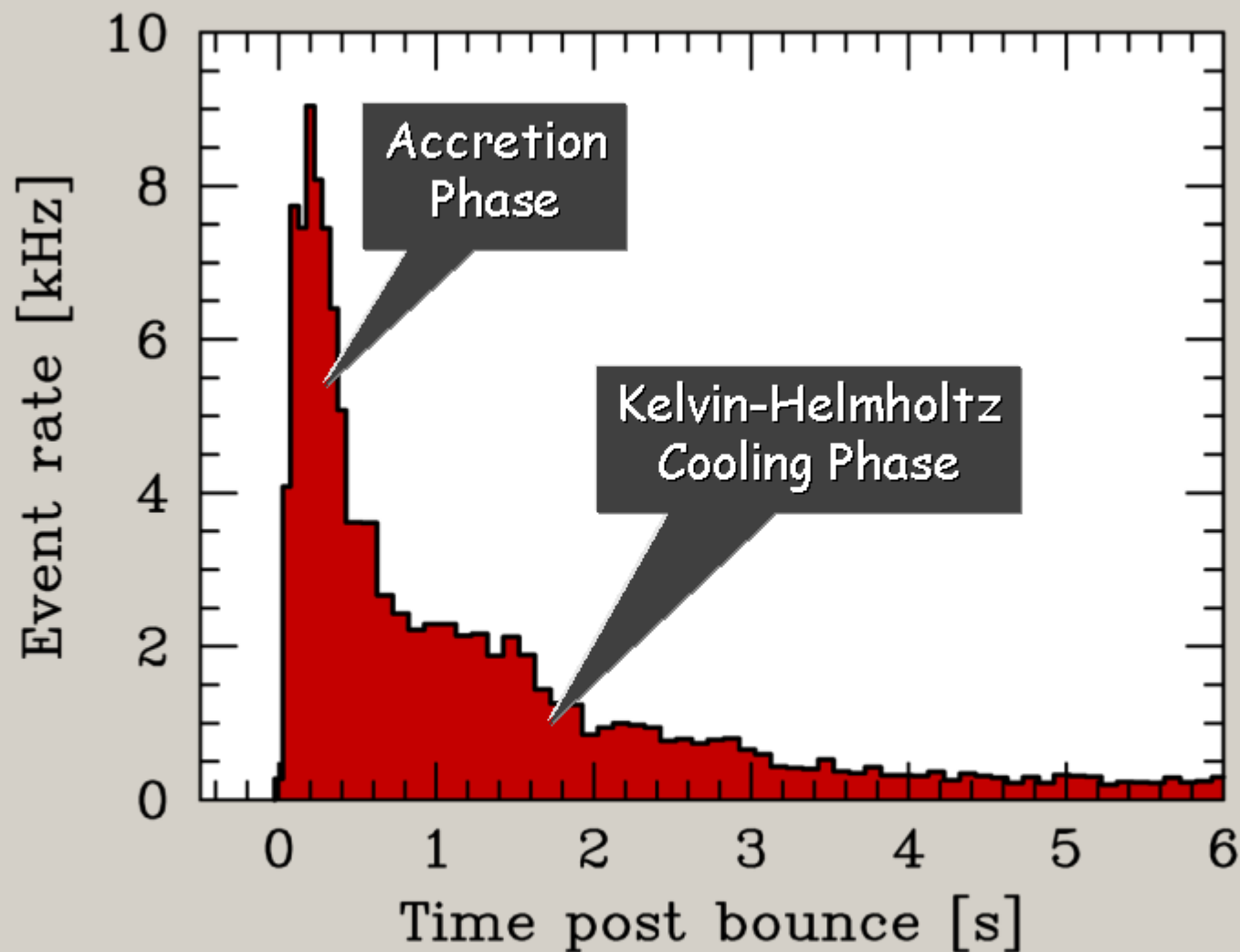


<http://hep.bu.edu/~snnet>

Super-Kamiokande Neutrino Detector

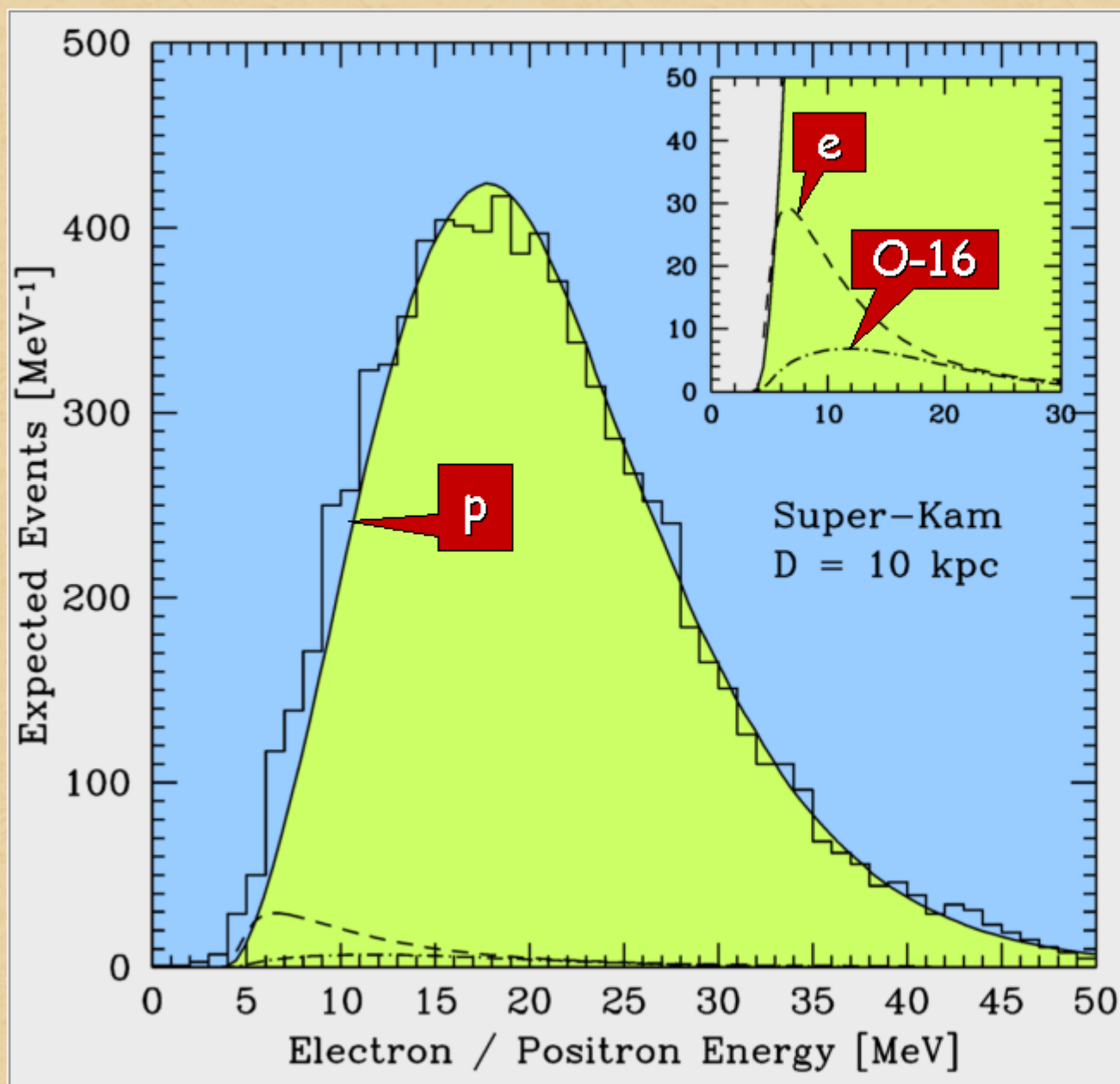


Simulated Supernova Signal at Super-Kamiokande



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

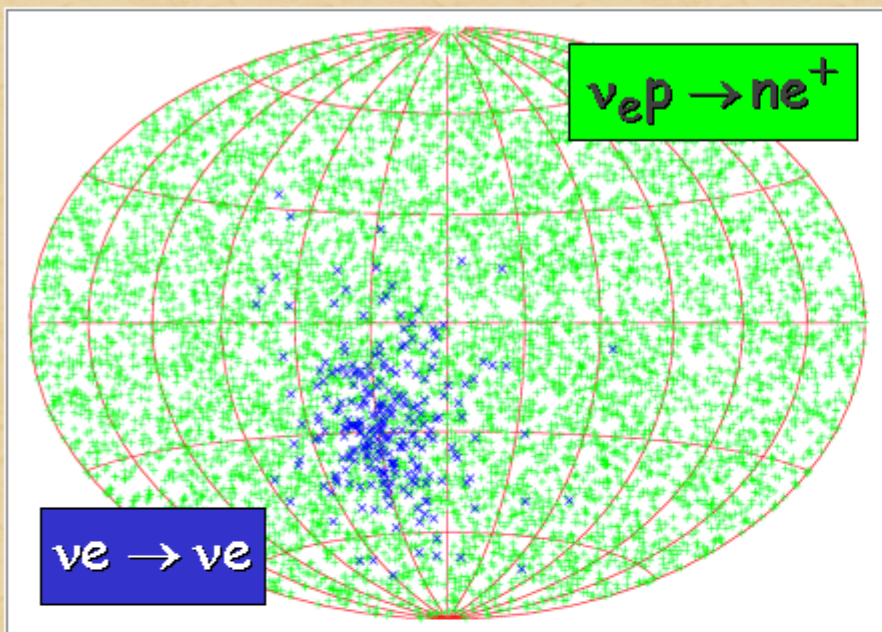


Monte-Carlo simulation
for Super-Kamiokande
signal of SN at 10 kpc,
based on a numerical
model with Livermore
code

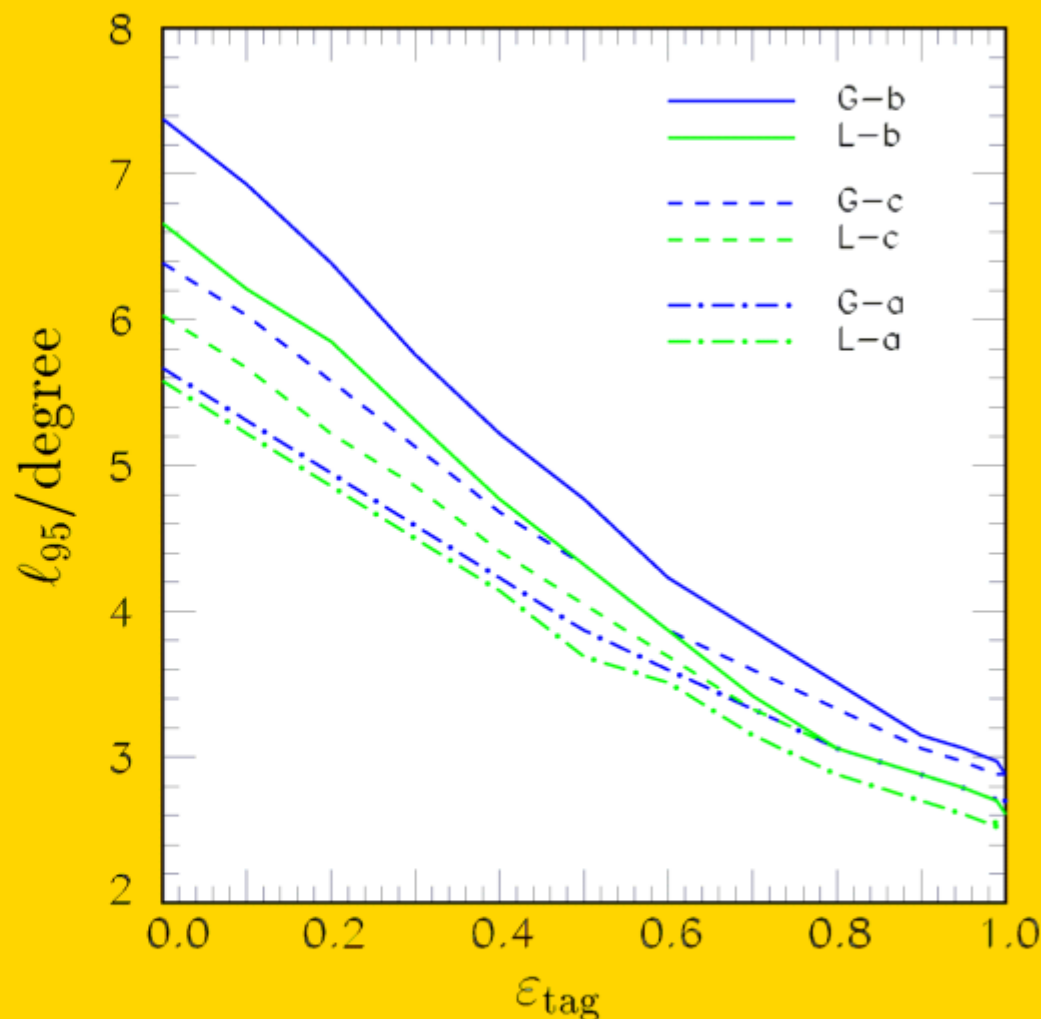
Total of about 8300
events for $t < 18$ s

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

($\sim 10^5$ events for SN at 10 kpc)

1. Overview of the experiment

(expect to start in 2007)



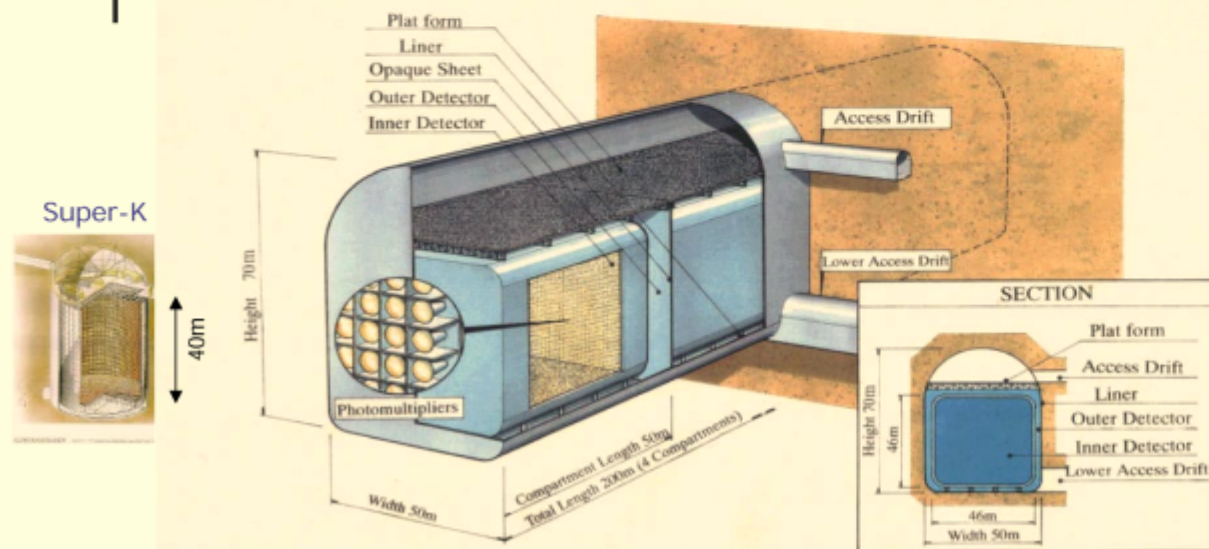
Phase-I (0.77MW + Super-K)

Phase-II (4MW+Hyper-K) $\sim$ Phase-I $\times 200$

3

Possible Design of Hyper-Kamiokande

May.-2001 JHF-Kamiooka ν workshop



(STRAIGHT TYPE)

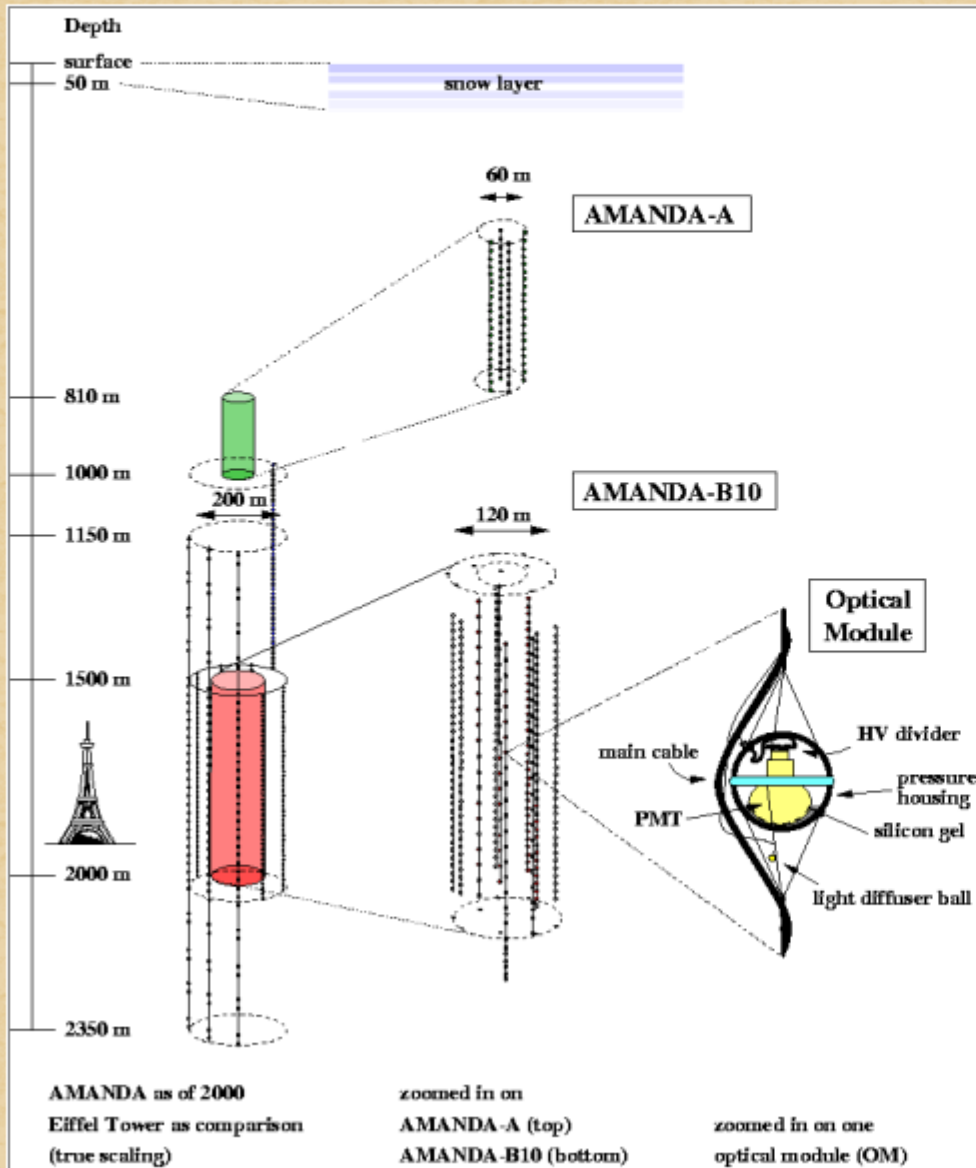
1 Mton fiducial volume: Total Length 800m (16 Compartments)

Similar discussions in

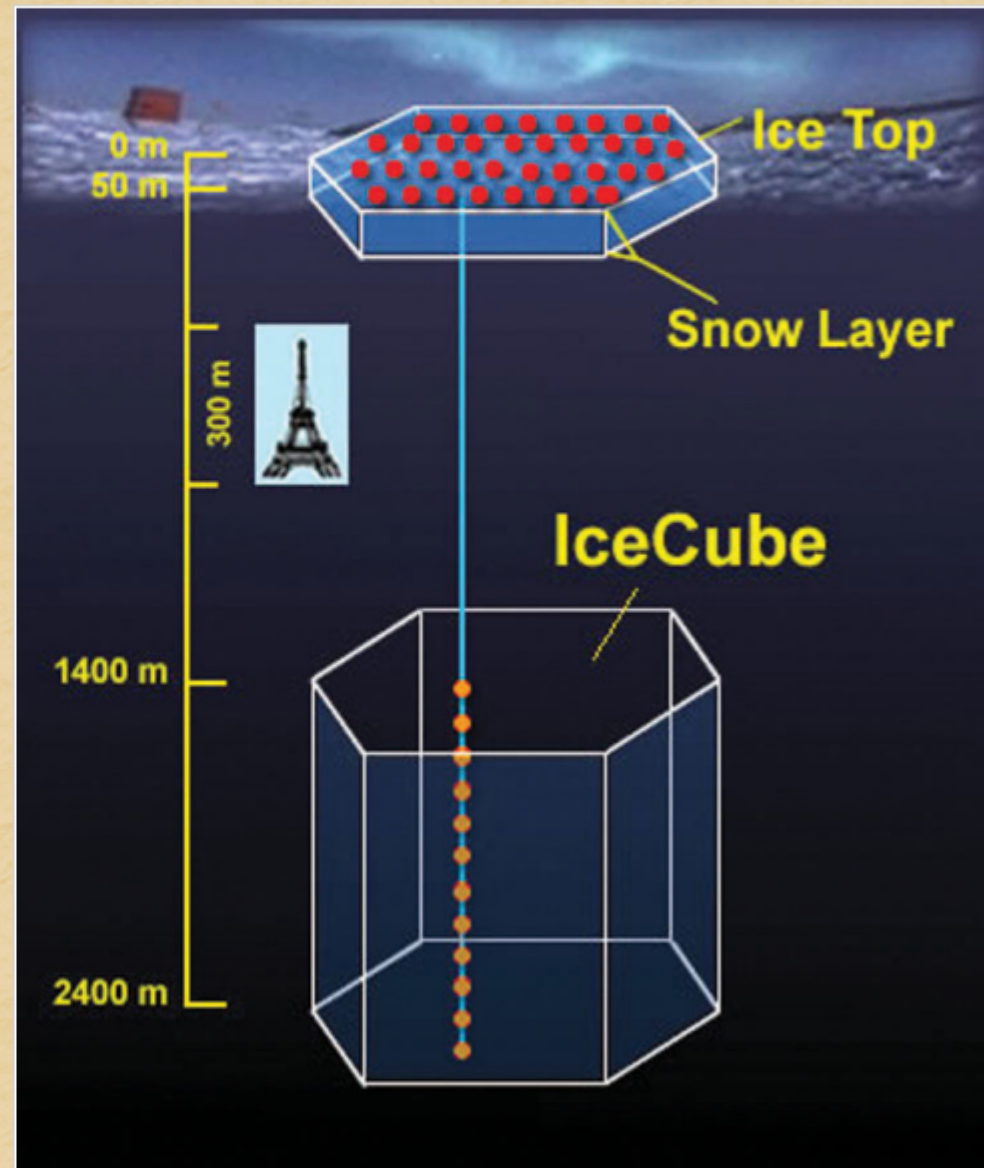
- USA (UNO project)
- Europe (Frejus Tunnel)

Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km^3 , 800 PMTs)



Future IceCube (1 km^3 , 4800 PMTs)

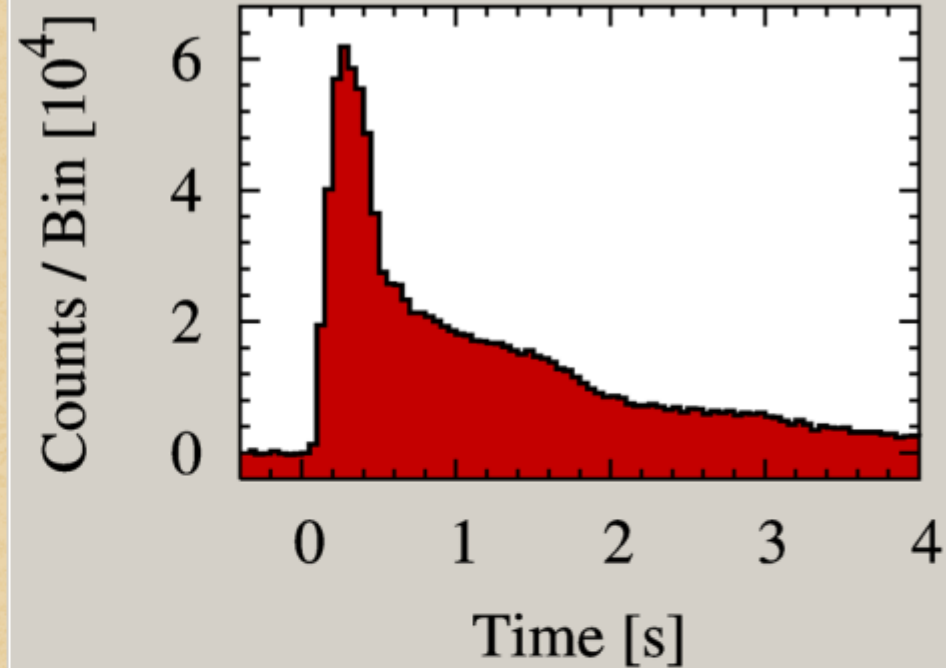
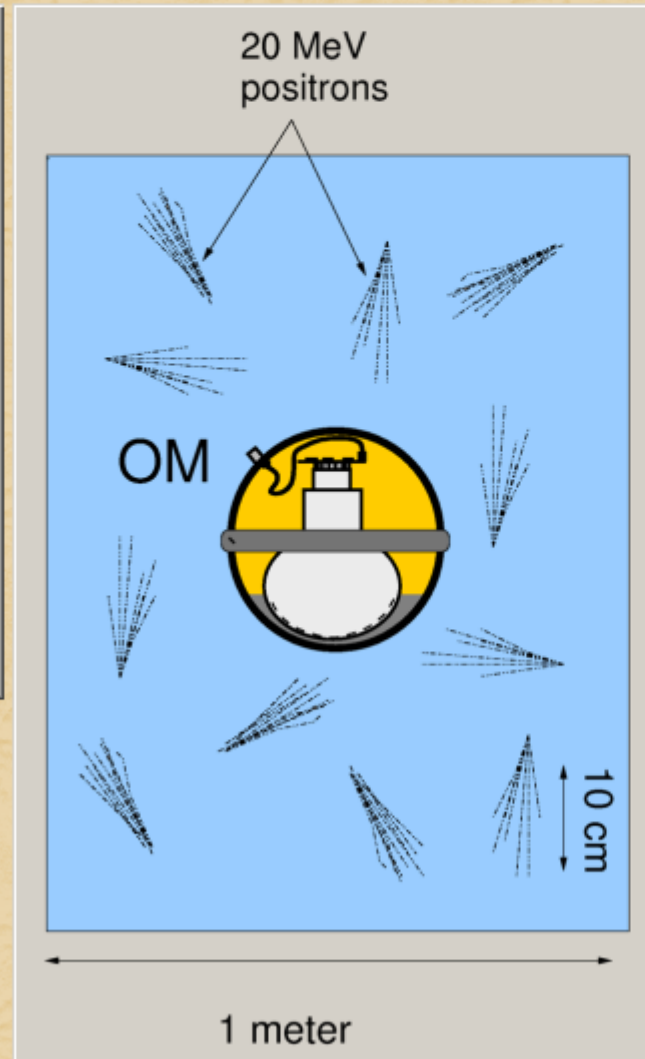


IceCube as a Supernova Neutrino Detector

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

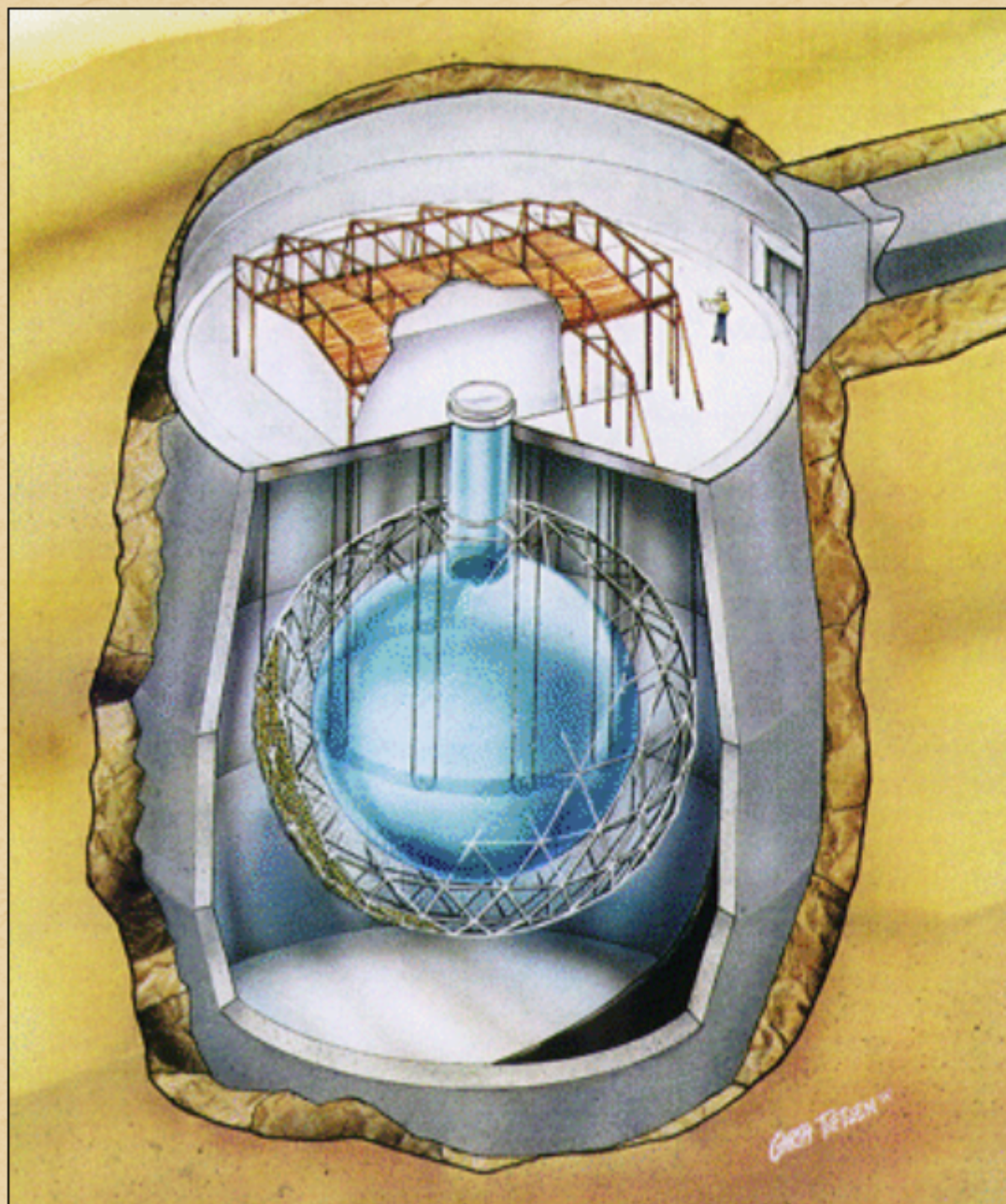
~ 300
Cherenkov
photons
per OM
from SN
at 10 kpc

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)



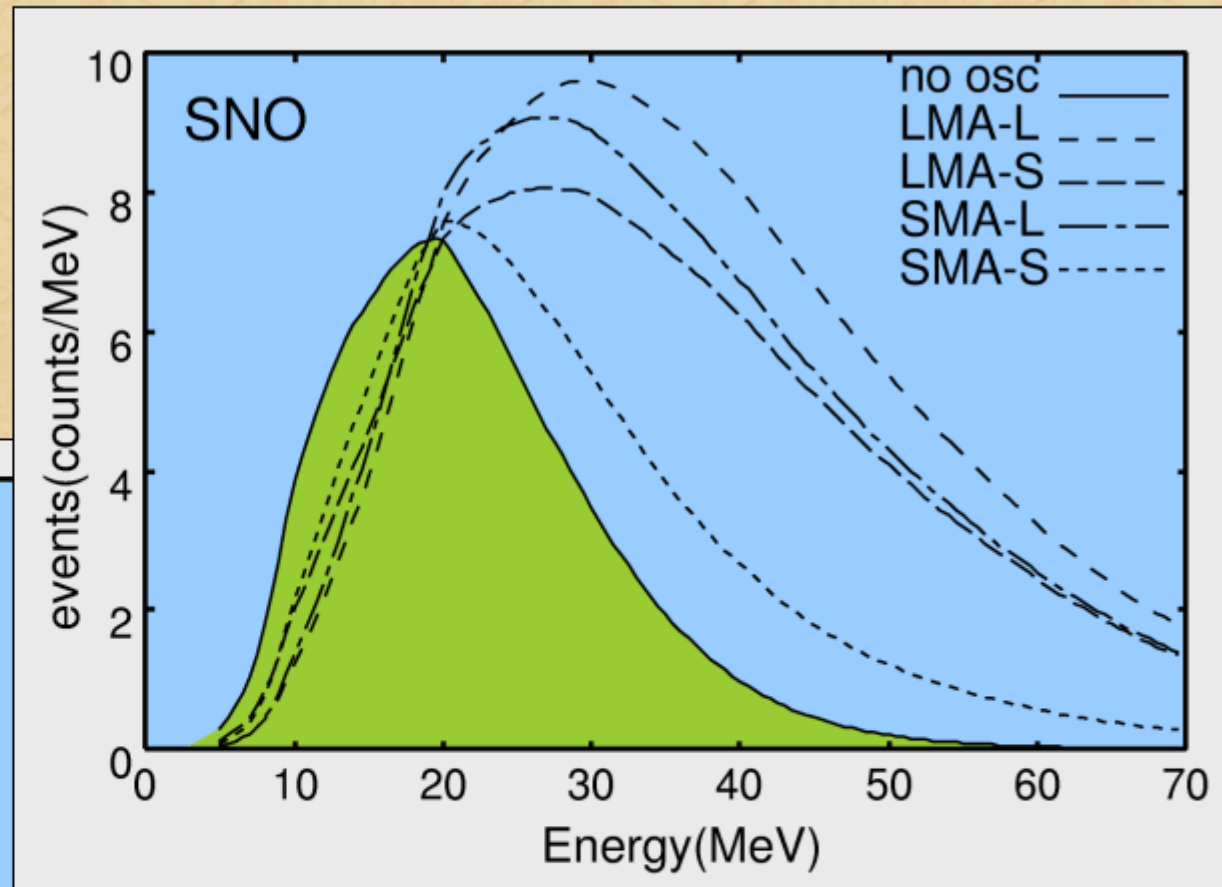
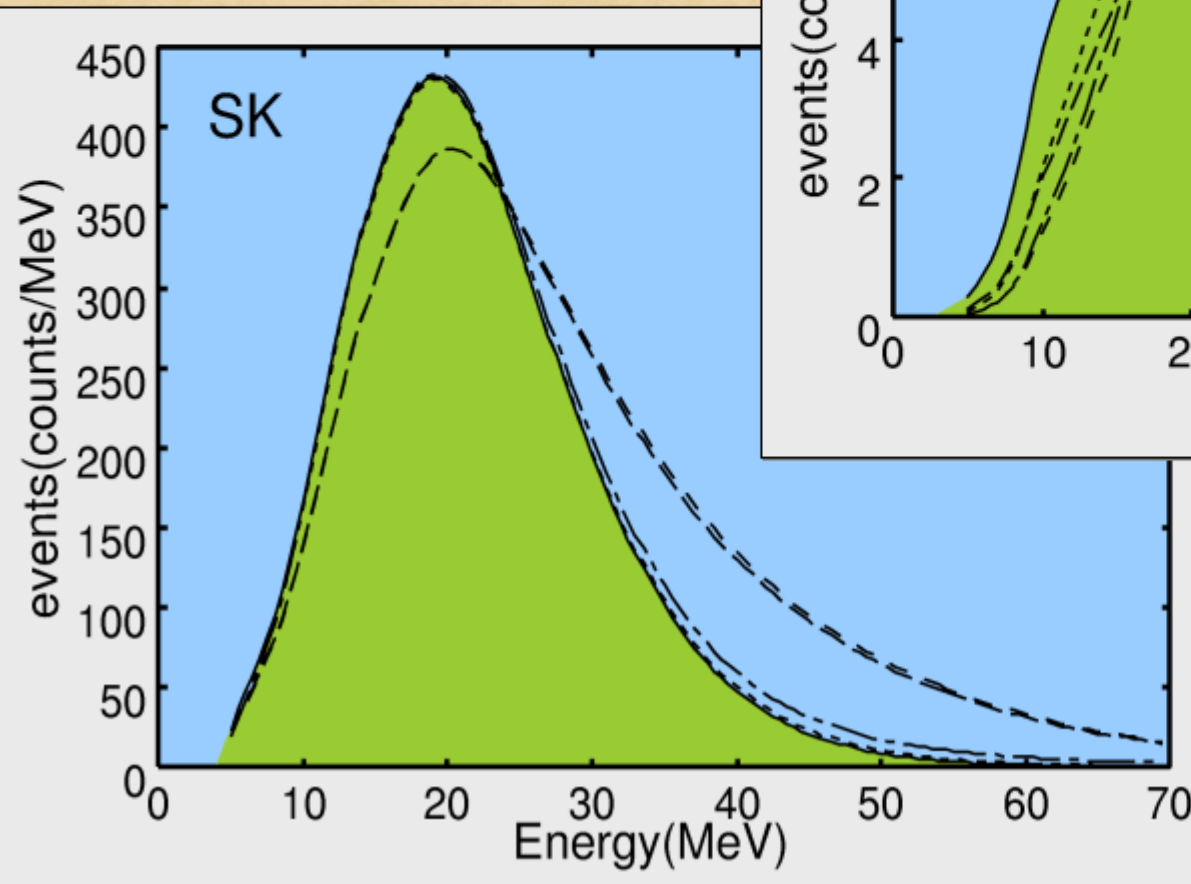
1000 tons of heavy water

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

<u>Heavy water (1 kt)</u>	<u>Events:</u>
CC: $\nu_e + d \rightarrow p + p + e^-$	72
CC: $\bar{\nu}_e + d \rightarrow n + n + e^+$	138
NC: $\nu_e + d \rightarrow \nu_e + p + n$	30
NC: $\bar{\nu}_e + d \rightarrow \bar{\nu}_e + p + n$	32
NC: $\nu_x + d \rightarrow \nu_x + p + n$	164
 <u>Light water (1.4 kt)</u>	 <u>Events:</u>
CC: $\bar{\nu}_e + p \rightarrow n + e^+$	331

Three-Flavor Oscillation Scenario

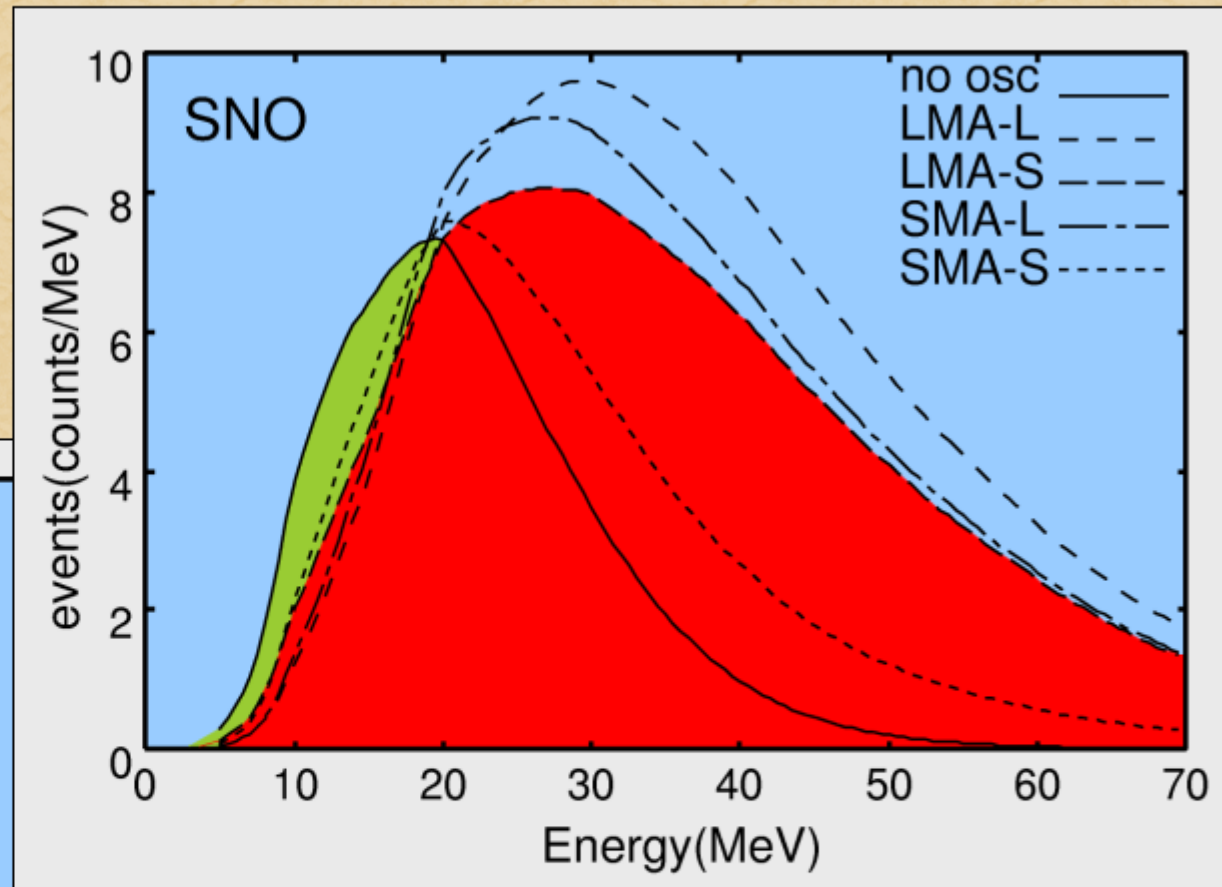
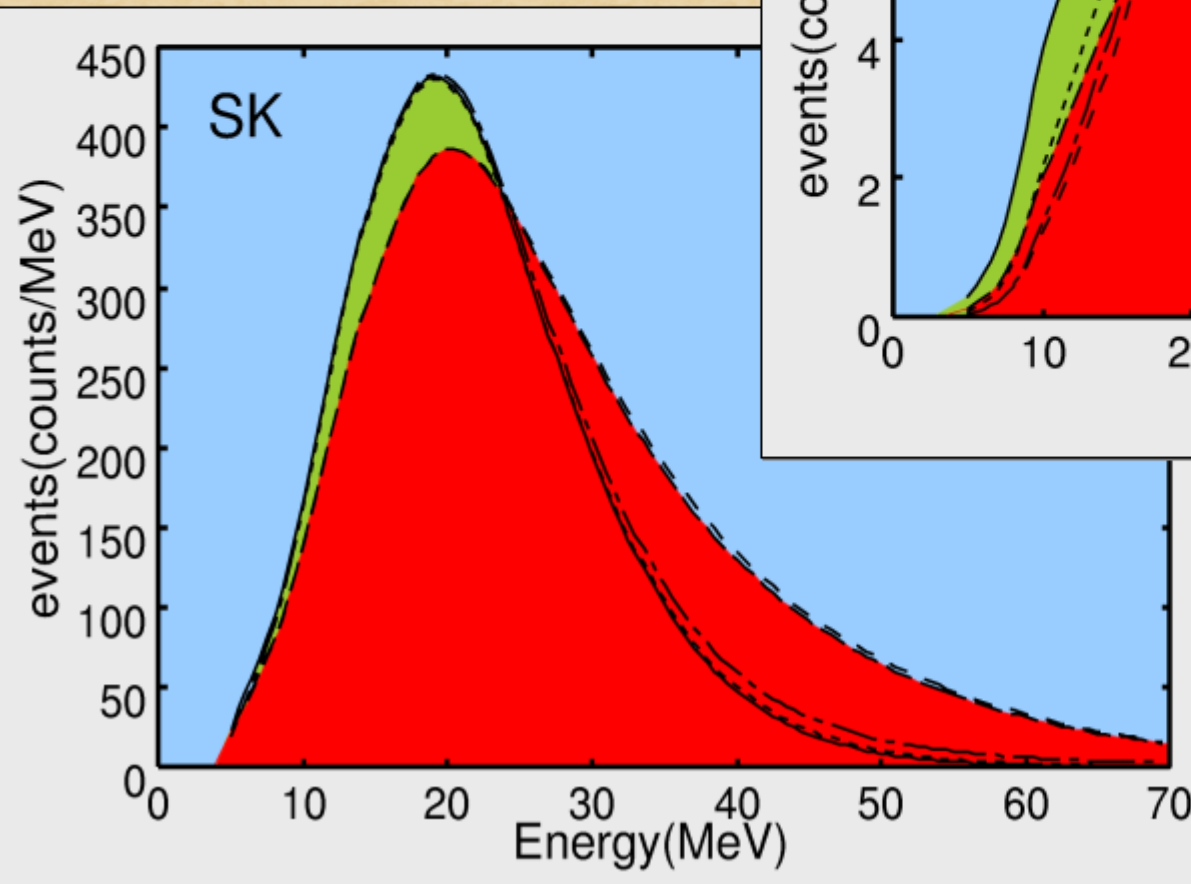
Takahashi, Watanabe
& Sato,
hep-ph/0105204



No Oscillations

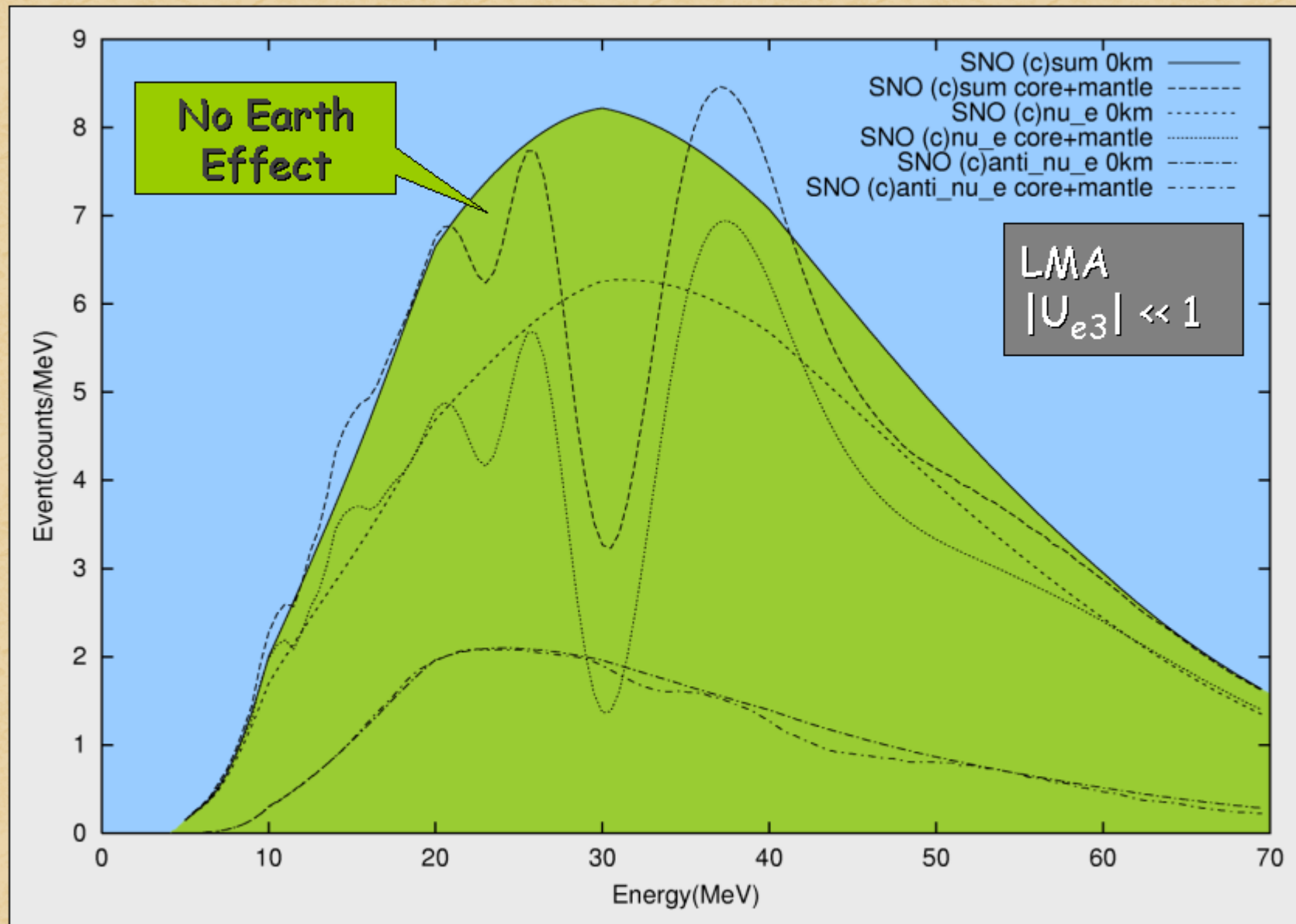
Three-Flavor Oscillation Scenario

Takahashi, Watanabe
& Sato,
hep-ph/0105204



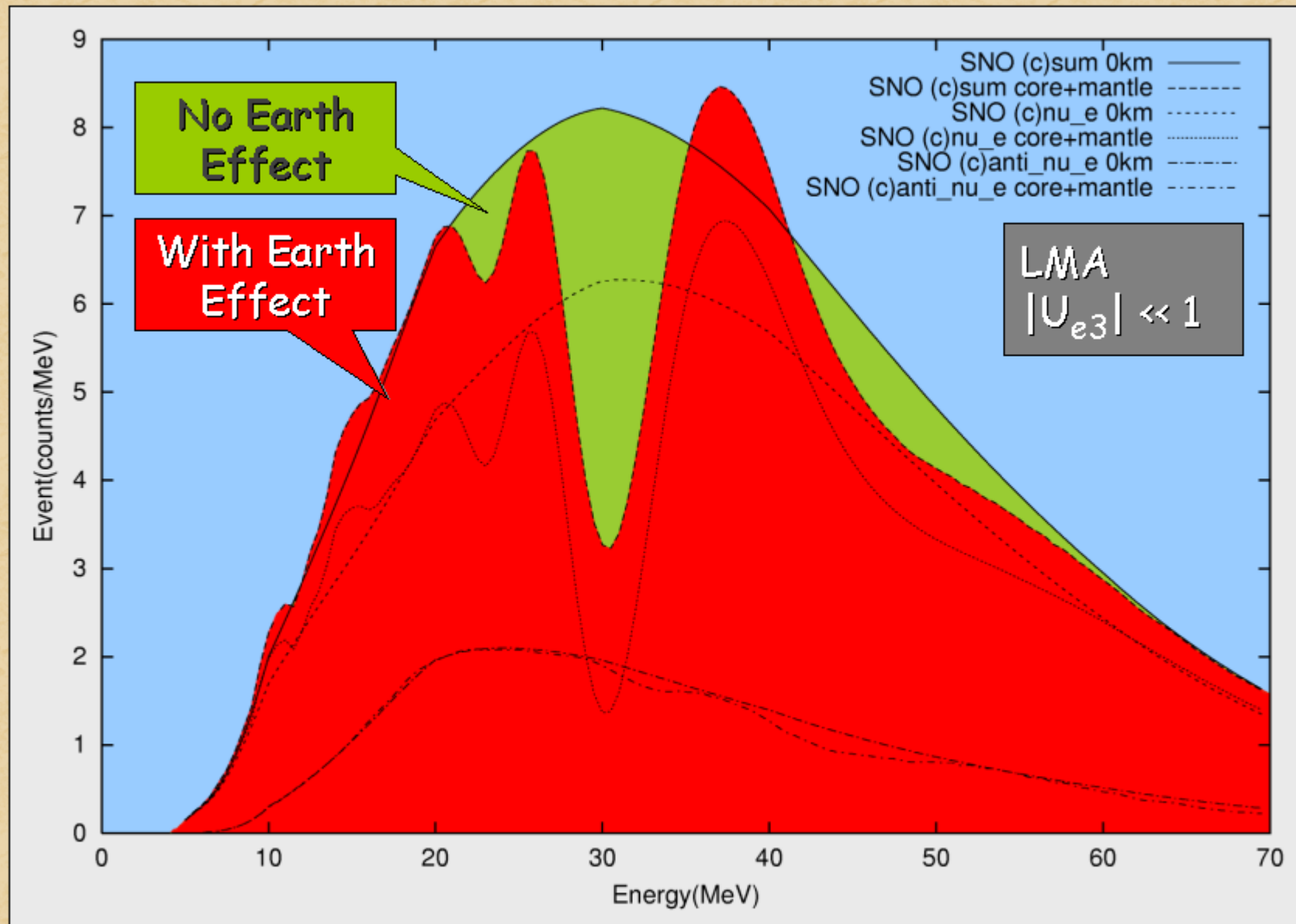
Oscillations with
LMA and $|U_{e3}| \ll 1$

Earth Effect at SNO



Takahashi, Watanabe & Sato, hep-ph/0012354

Earth Effect at SNO

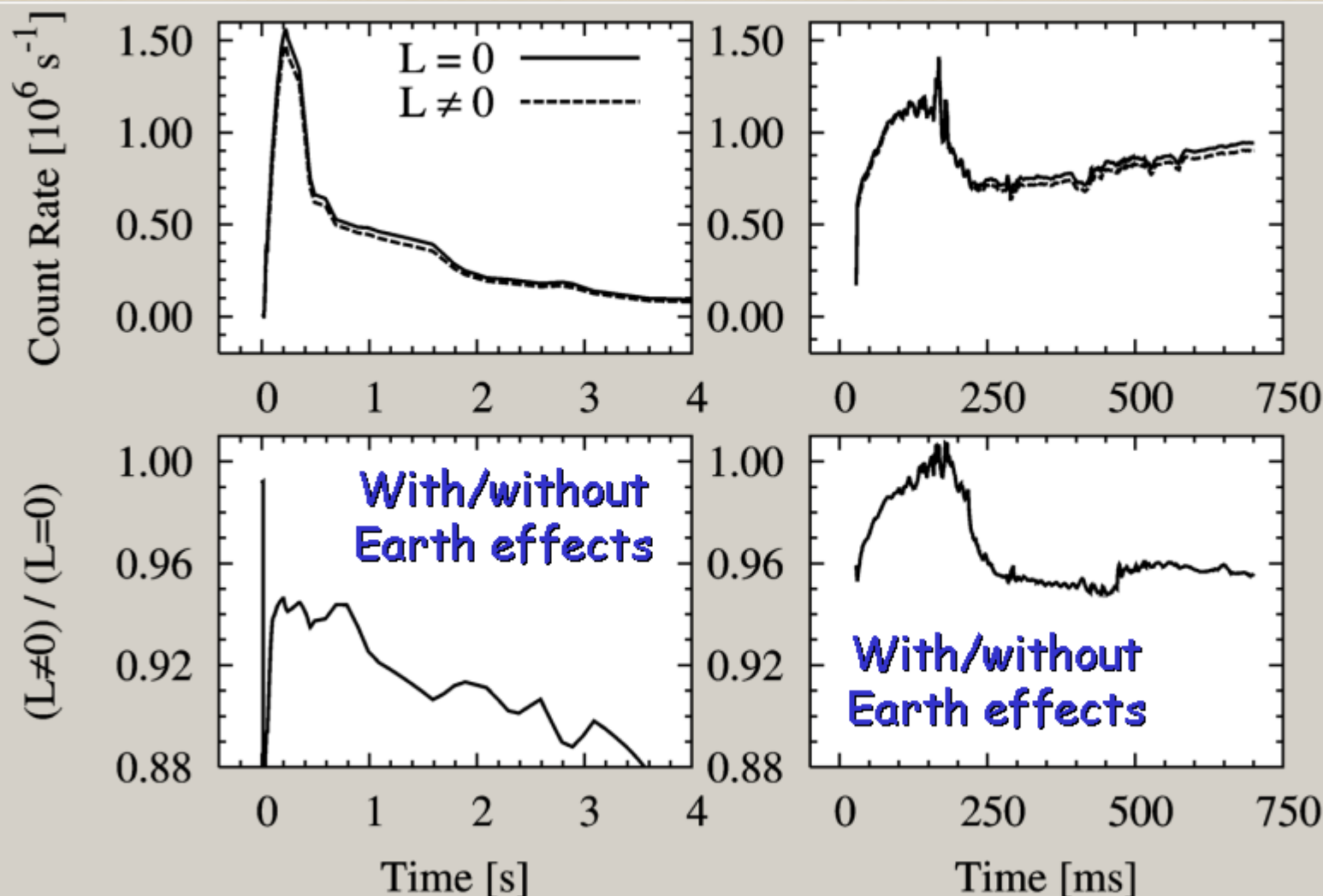


Takahashi, Watanabe & Sato, hep-ph/0012354

Observing the Earth Effects in IceCube

Livermore simulation

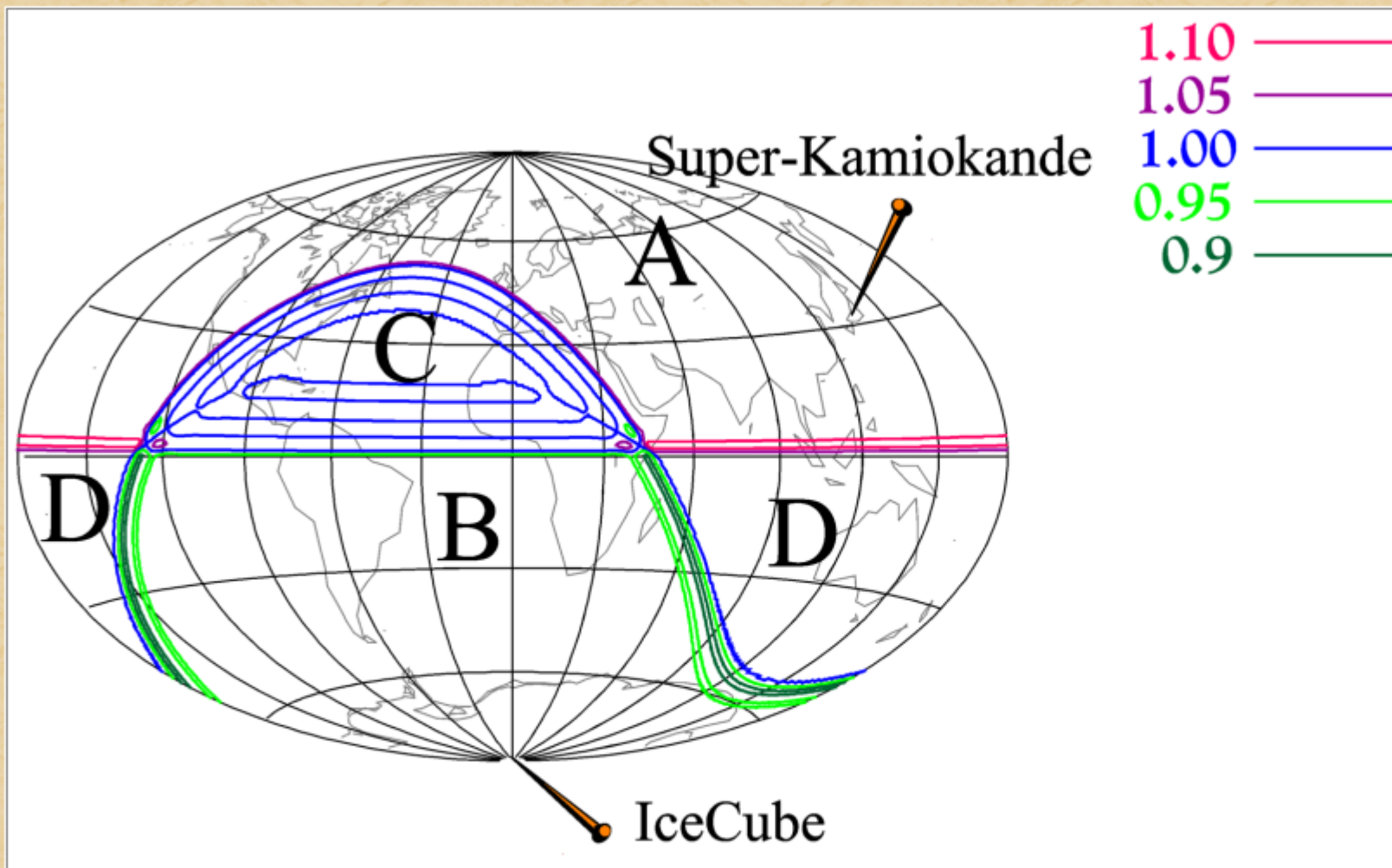
Garching simulation



Dighe,
Keil,
Raffelt
hep-ph/
0303210

Statistical IceCube signal precision $< 1\%$

Two-Detector Sky Coverage with Super-K & IceCube

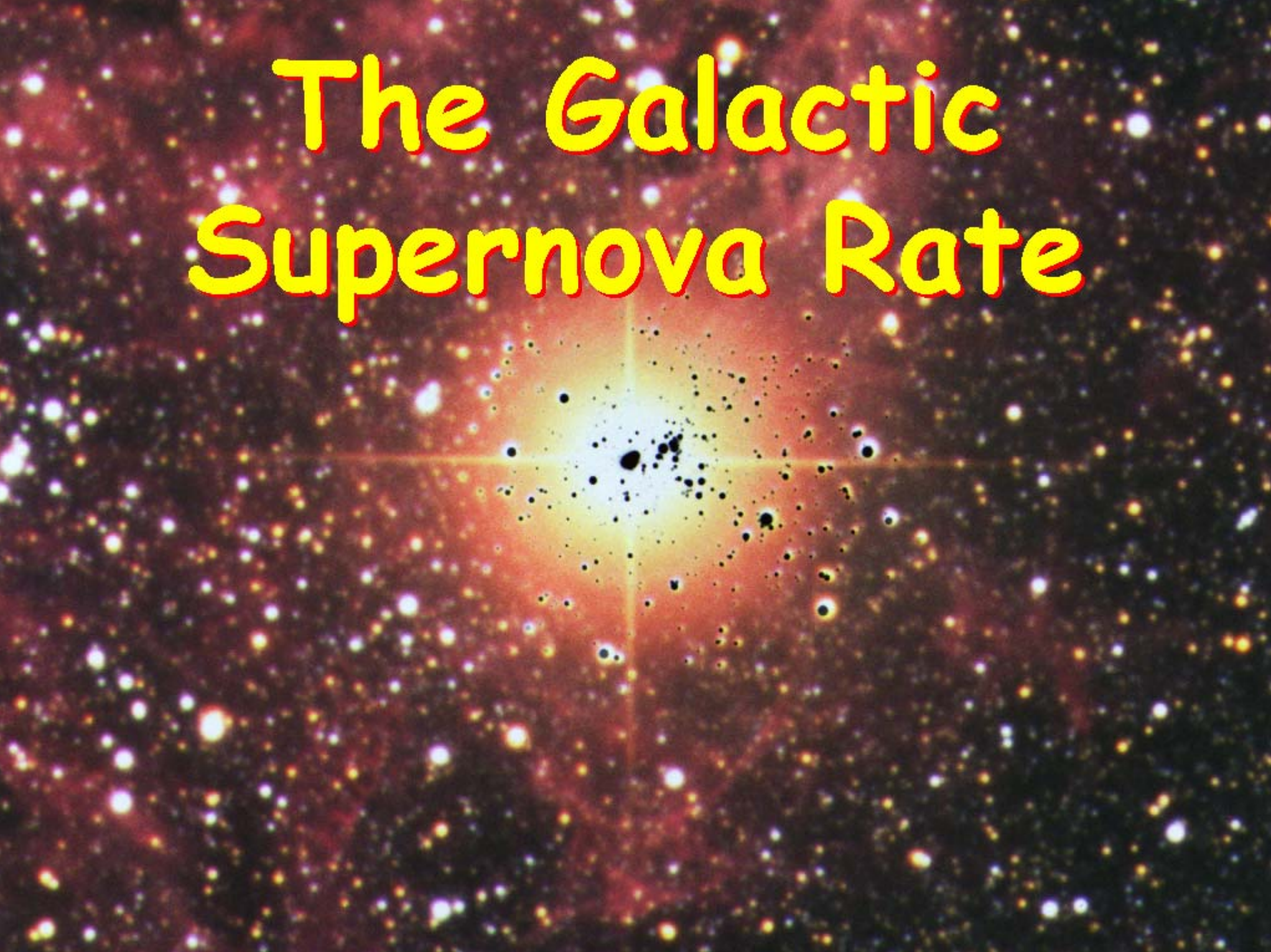


Dighe,
Keil,
Raffelt
hep-ph/
0303210

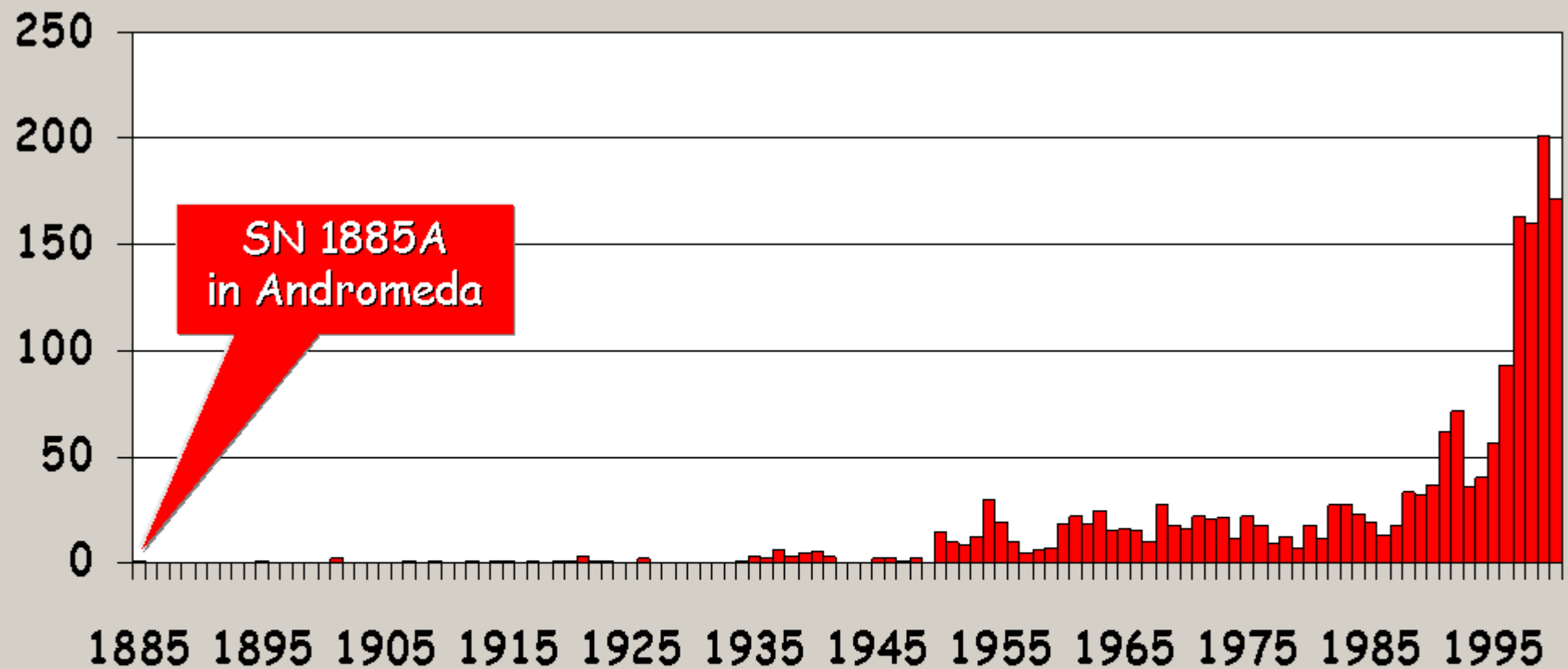
Earth
effects
appear
in

	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%	

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

SN Statistics in External Galaxies

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

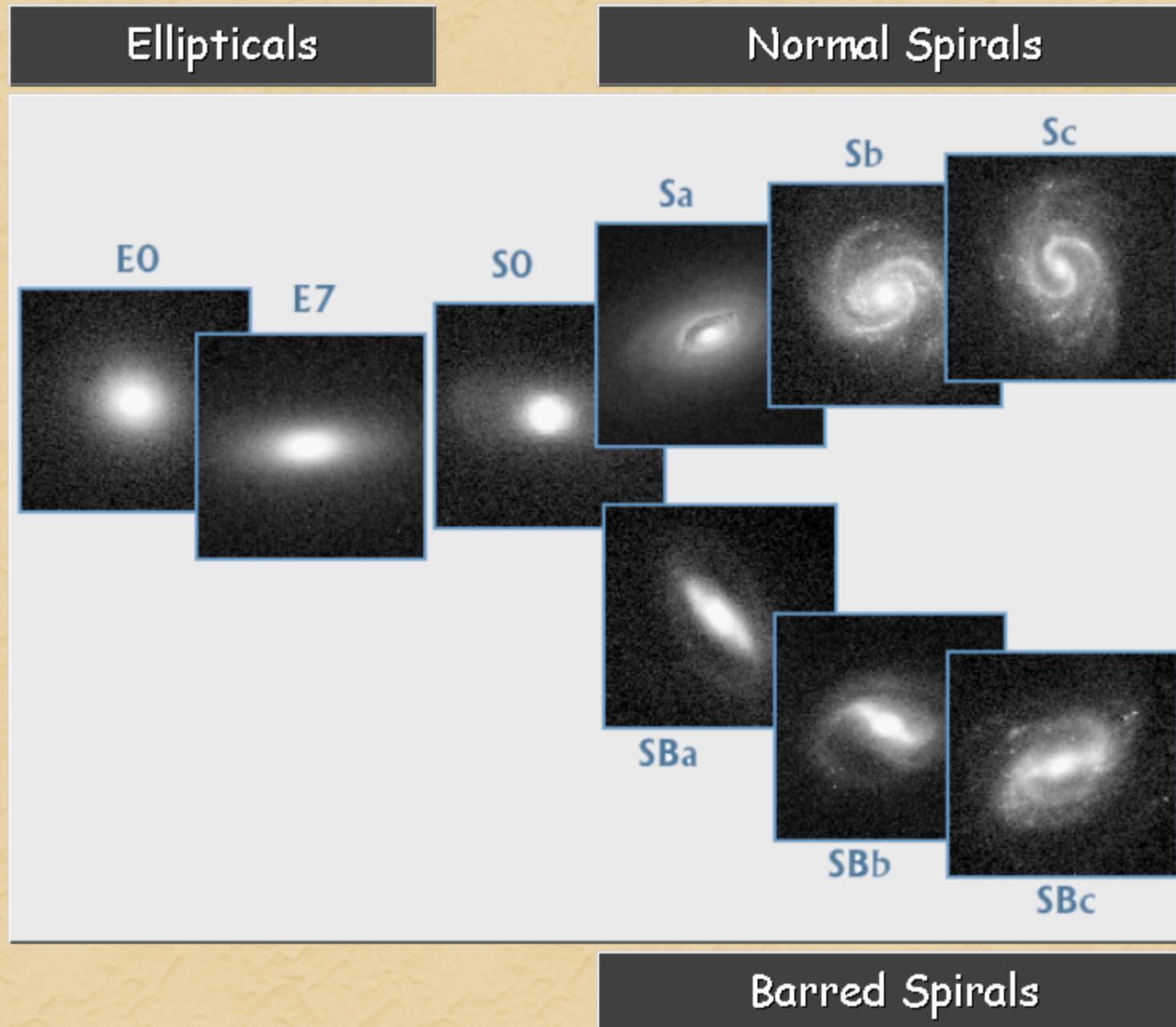
Limited controlled samples useful for this task:

- 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 ($2.3 \pm 0.6 \times 10^{10} L_{\text{sun}}$)
- Morphological type of Milky Way

Hubble Sequence of Galaxy Types



Supernova Rates

Multiply numbers with h^2		Supernova Type			
		Ia	Core Collapse		All
			Ib/c	II	
Galaxy Type	E-S0	$0.32 \pm .11$	< 0.02	< 0.04	$0.32 \pm .11$
	S0a-Sb	$0.32 \pm .12$	$0.20 \pm .11$	$0.75 \pm .34$	$1.28 \pm .37$
	SBc-Sd	$0.37 \pm .14$	$0.25 \pm .12$	$1.53 \pm .62$	$2.15 \pm .66$
	All	$0.36 \pm .11$	$0.14 \pm .07$	$0.71 \pm .34$	$1.21 \pm .36$

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

Milky Way Galaxy:

Type Sb-Sbc, $L_B = 2.3 \times 10^{10} L_{\text{sun,B}}$, $h = 0.75$

About 2.0 ± 1.0 core-collapse SNe per century

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

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

Andromeda Galaxy (M31)

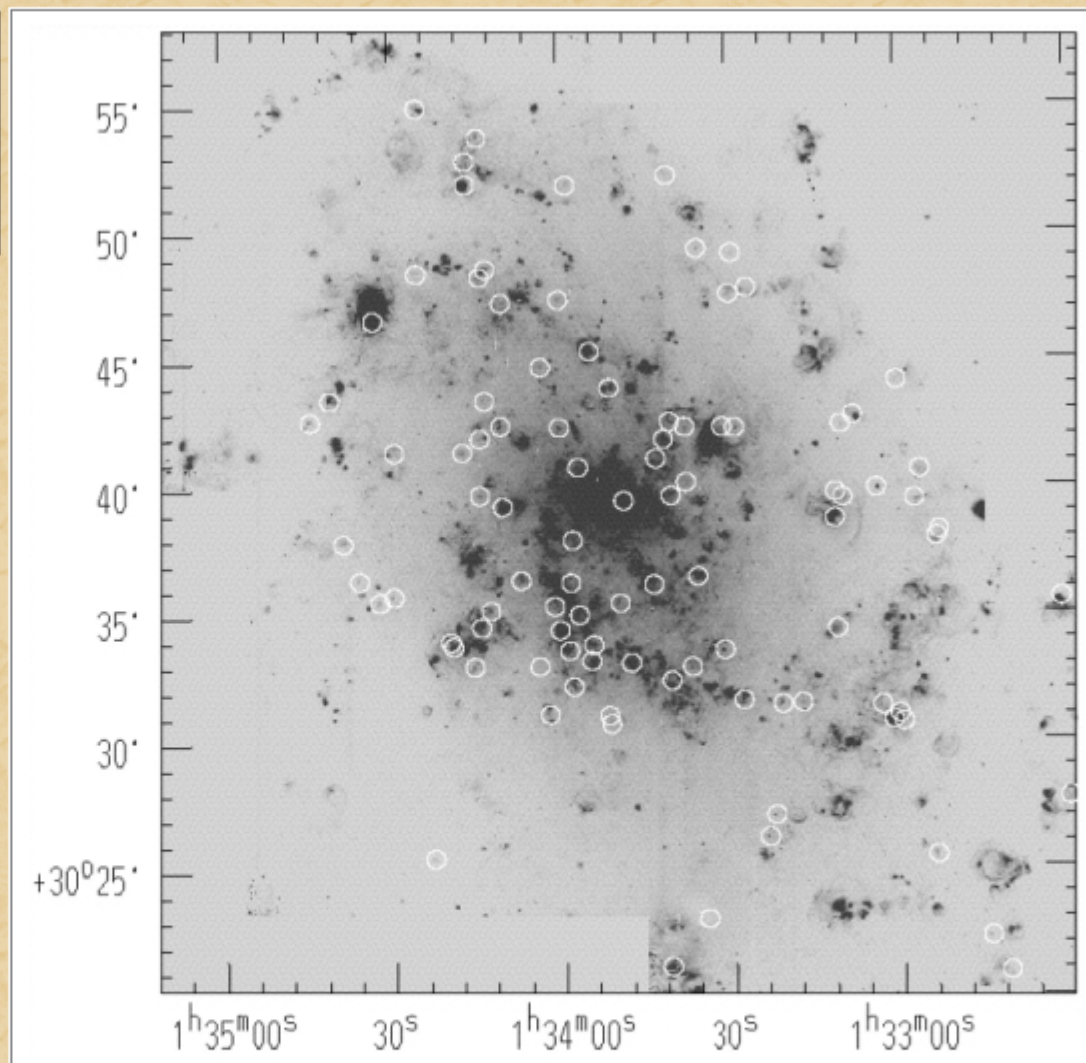


- SN 1885A is the only historical SN in Andromeda (M31) (distance 760 kpc)
- We see all of the galaxy - one probably would not have missed a SN by obscuration
- Probably low star formation rate (low FIR luminosity)

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

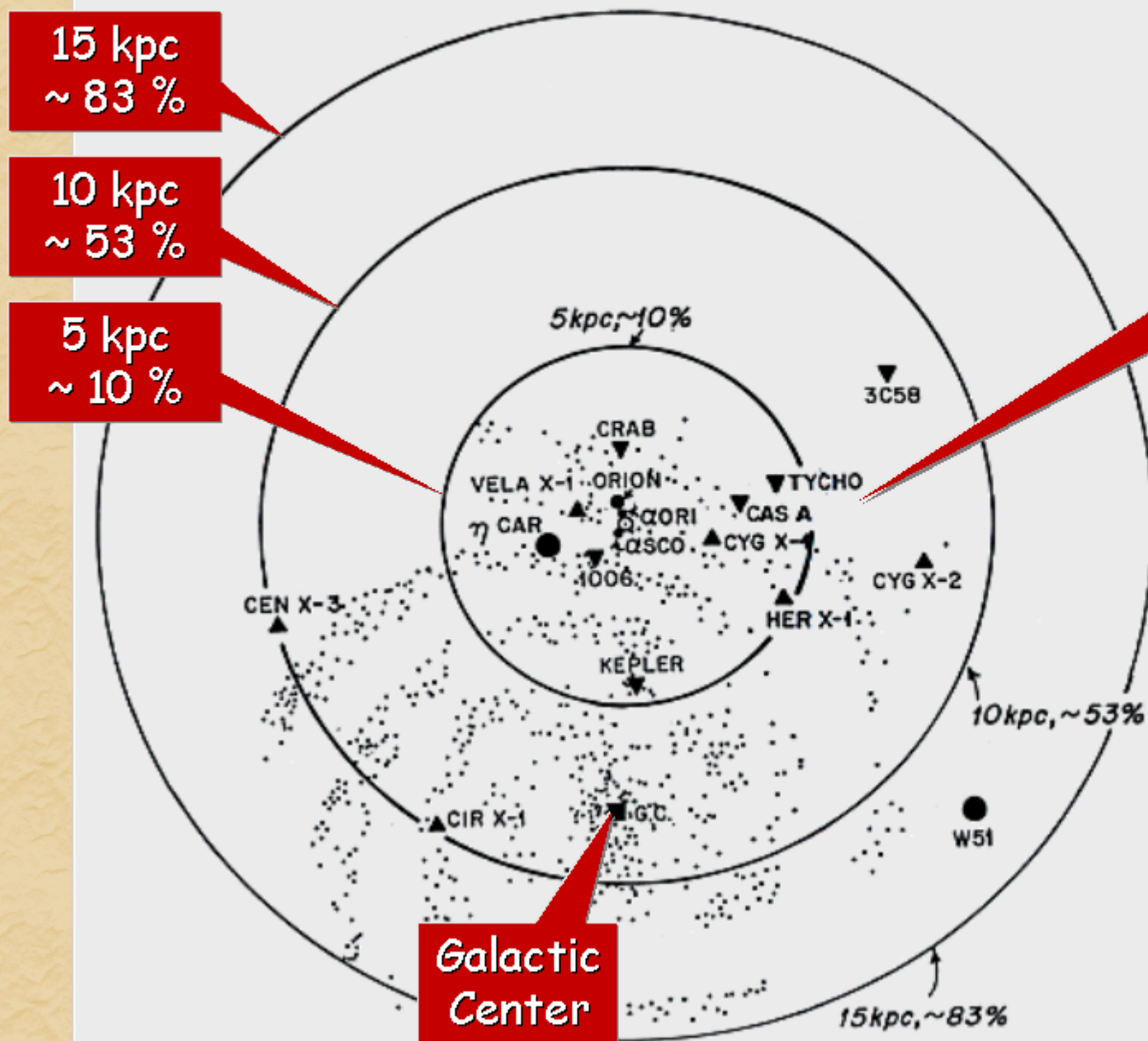
Supernova Remnants in M33 (Triangulum)

H α 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

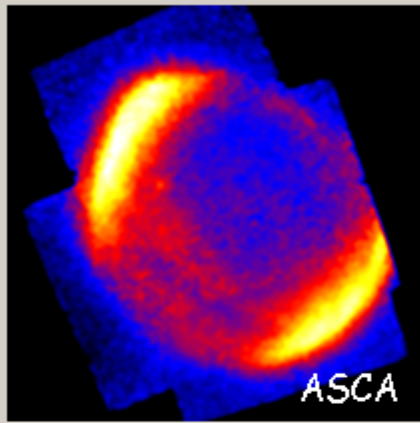


Most historical supernovae in $\sim 10\%$ of the galaxy

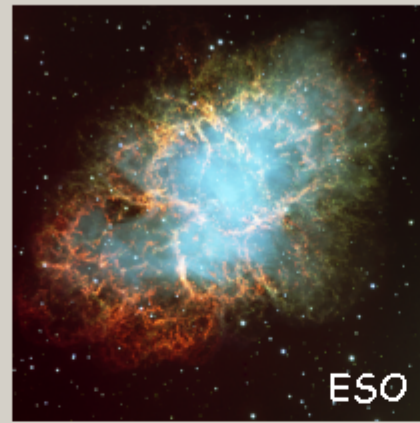
Anomalously large rate in our galaxy?
Small-number statistics?

Adam Burrows

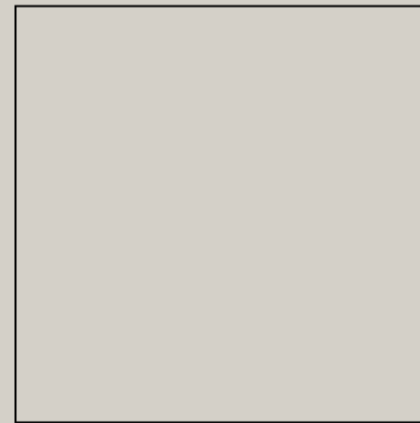
Historical Supernovae (Local Group) since AD 1000



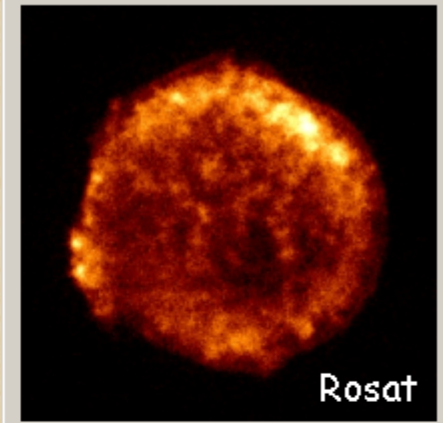
SN 1006
1.5 kpc



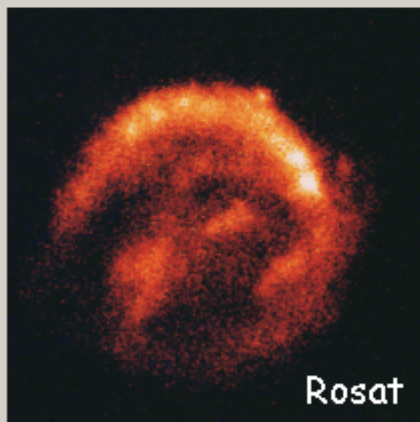
SN 1054 Crab
Type II Pulsar
2 kpc



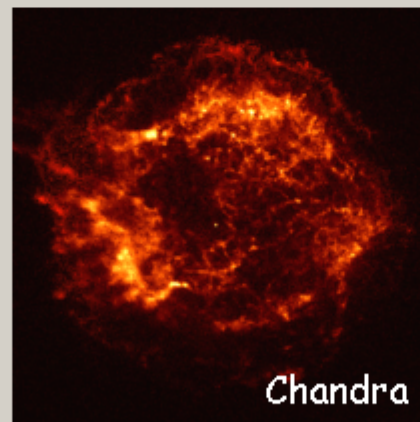
SN 1181 3C 58
8 kpc



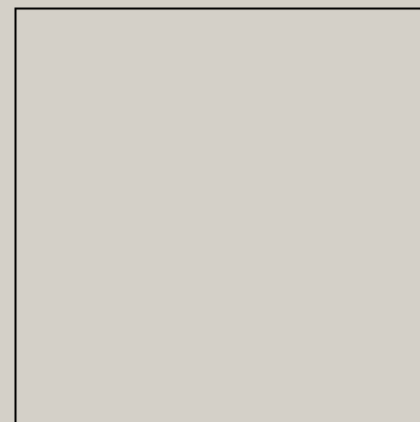
SN 1572 Tycho
Type Ia
3 kpc



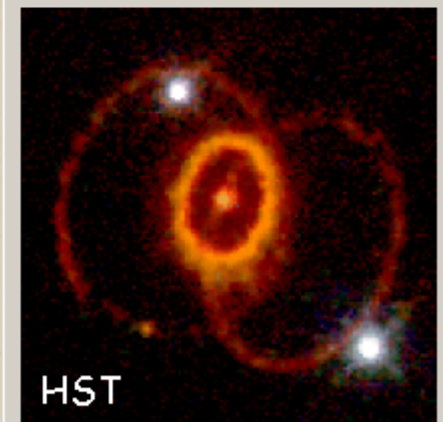
SN 1604 Kepler
Type II? 4-8 kpc



SN 1680? Cas A
Type II Neutron Star
2.8 kpc

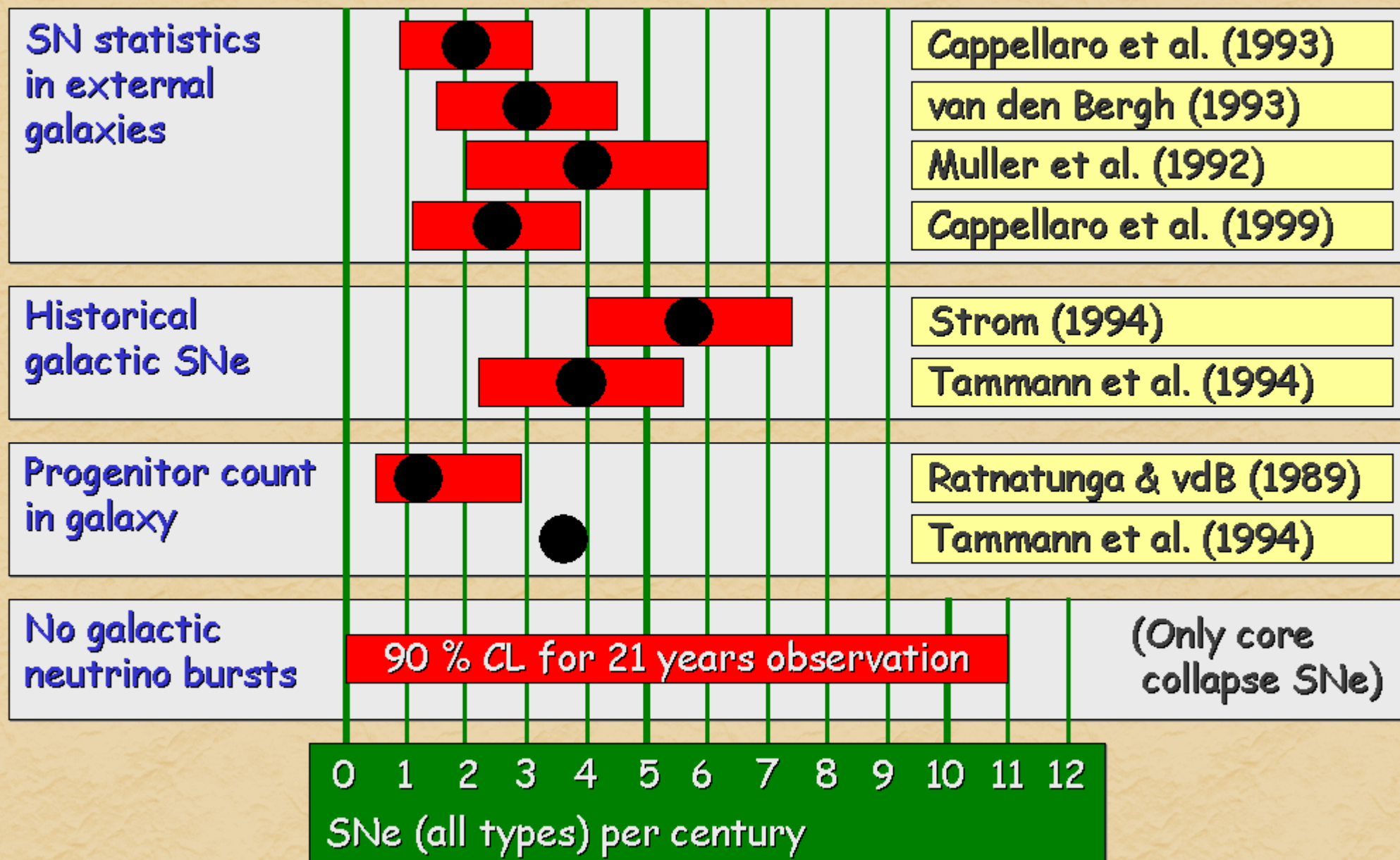


SN 1885 Andromeda
760 kpc

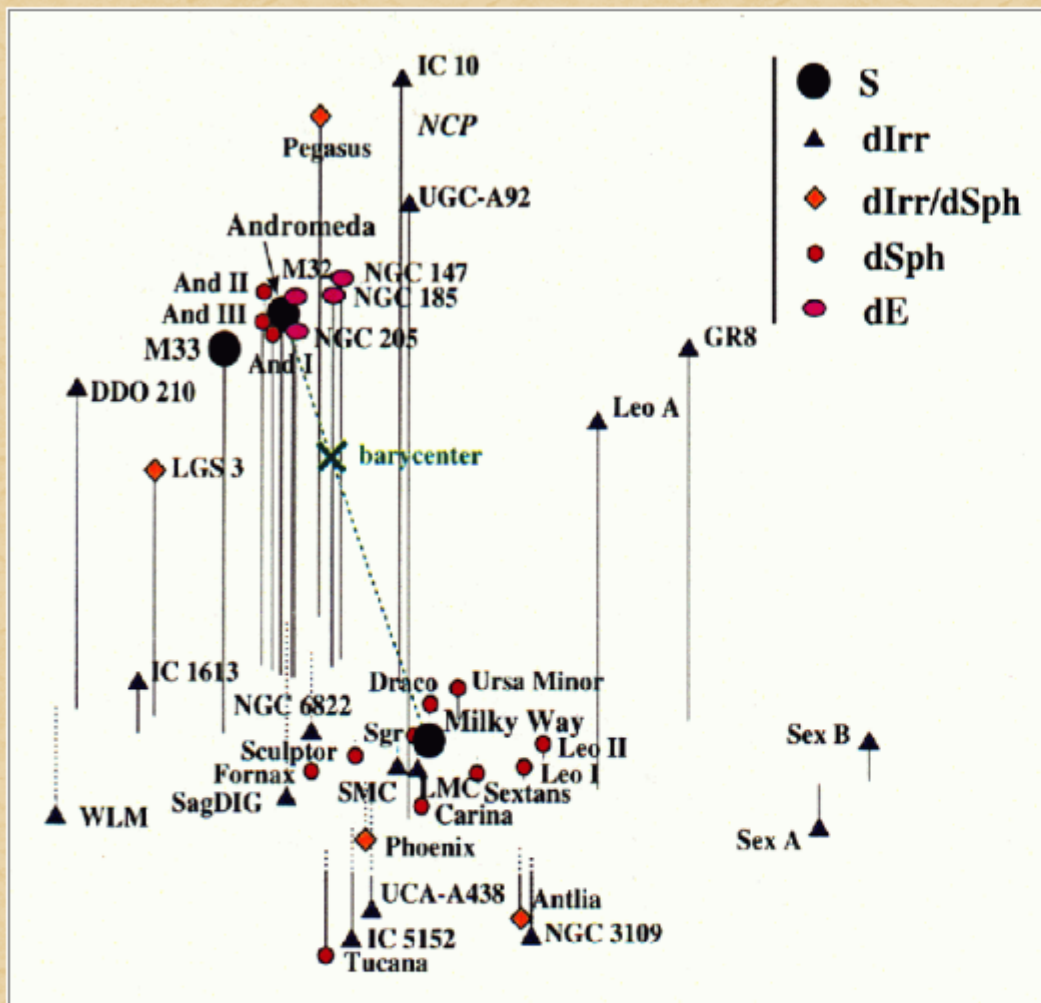


SN 1987A LMC
Type II No pulsar
50 kpc

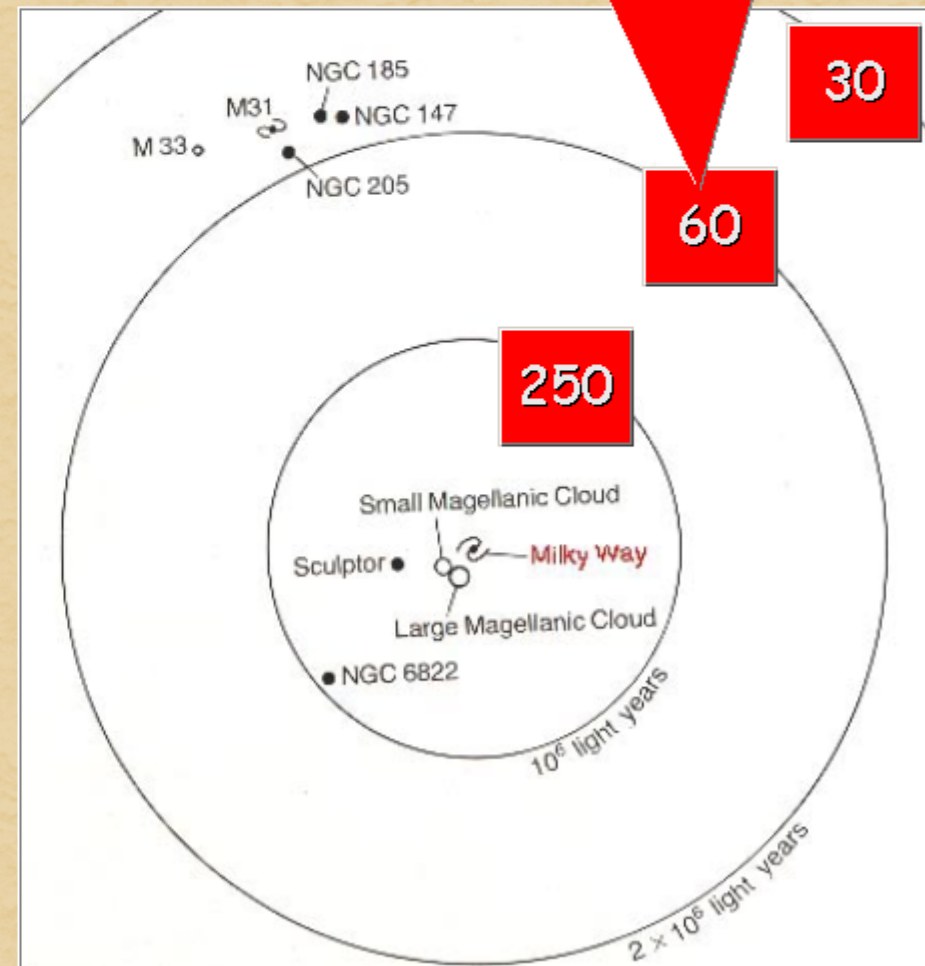
Estimates of the Galactic SN Rate



Local Group of Galaxies



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

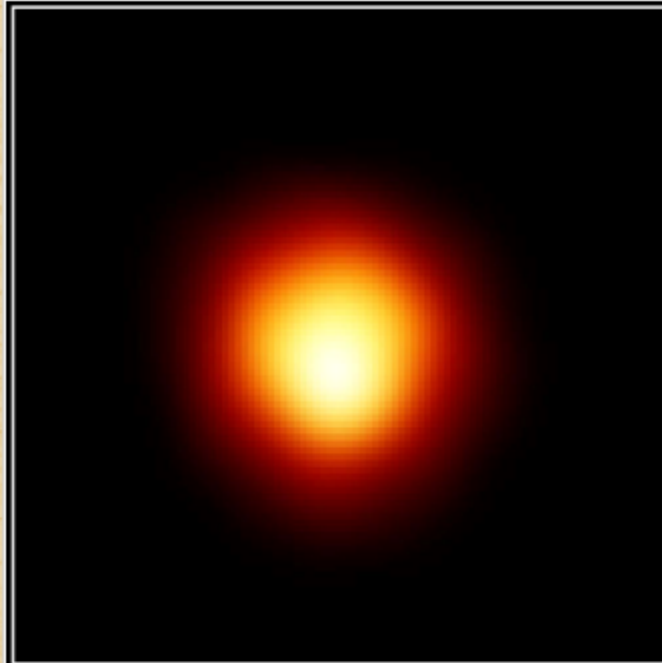


Brightest Members of Local Group

	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 $30 \times$ 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)



Size of Star



Size of Earth's Orbit



Size of Jupiter's Orbit



First resolved
image of a star
other than Sun

Distance
(Hipparcos)
130 pc (425 lyr)

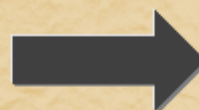
If Betelgeuse goes Supernova
 6×10^7 neutrino events
in Super-Kamiokande

Neutrinos From All Cosmic Supernovae



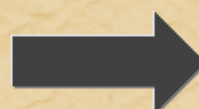
Diffuse Background Flux of SN Neutrinos

$$1 \text{ SNU} = 1 \text{ SN} / 10^{10} L_{\text{sun},B} / 100 \text{ years}$$
$$L_{\text{sun},B} = 0.54 L_{\text{sun}} = 2 \times 10^{33} \text{ erg/s}$$
$$E_{\nu} \sim 3 \times 10^{53} \text{ erg per core-collapse SN}$$



$1 \text{ SNU} \sim 4 L_{\nu} / L_{\gamma,B}$
Average neutrino
luminosity of galaxies
 $\sim$ photon luminosity

- Photons come from nuclear energy
- Neutrinos from gravitational energy



For galaxies, average
nuclear & gravitational
energy release similar

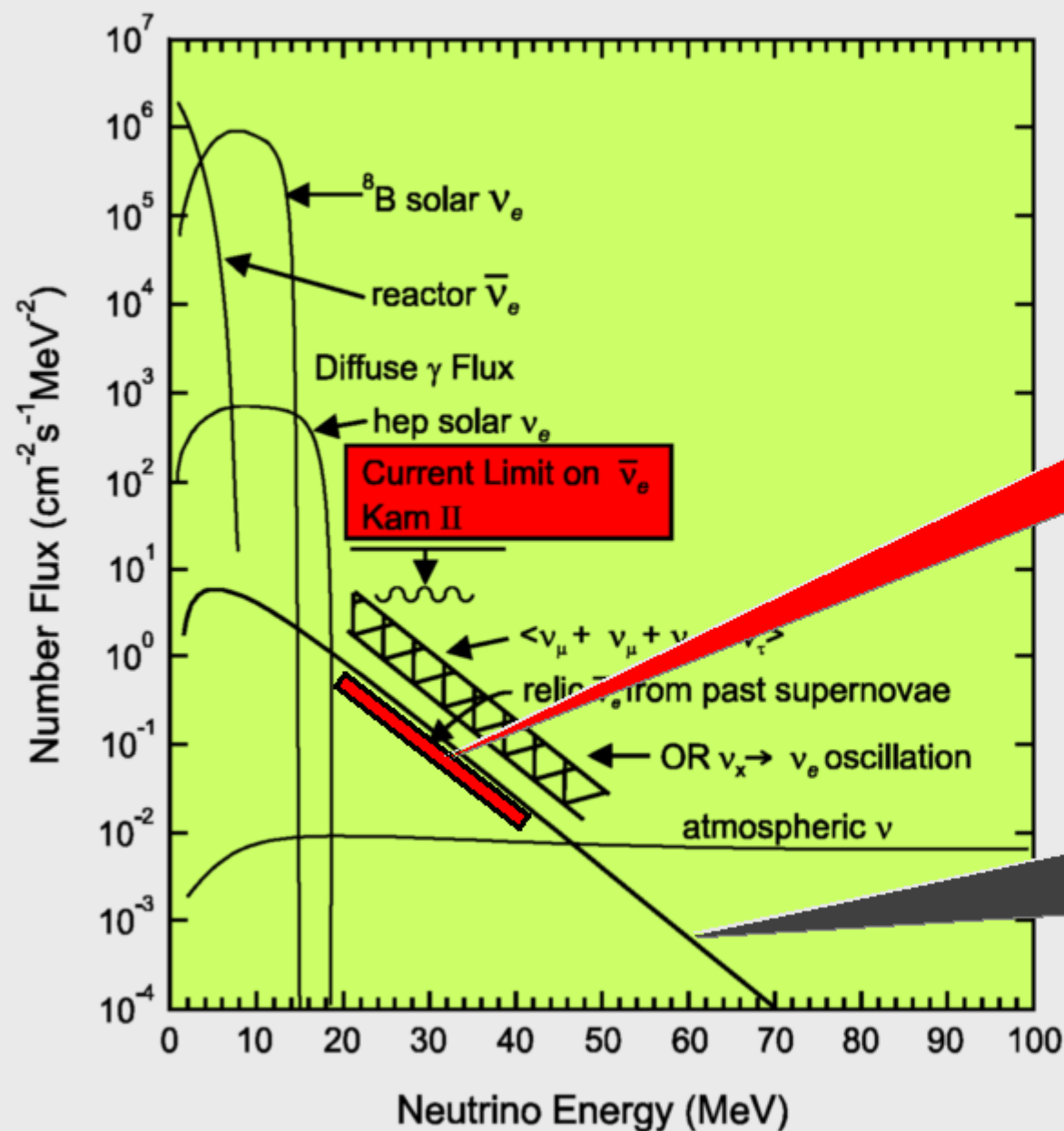
Present-day SN rate of $\sim 1 \text{ SNU}$, extrapolated to the entire universe,
corresponds to ν_e flux of $\sim 1 \text{ cm}^{-2} \text{ s}^{-1}$

Realistic flux dominated by much larger early star-formation rate

- Upper limit $\sim 54 \text{ cm}^{-2} \text{ s}^{-1}$
[Kaplinghat et al., astro-ph/9912391]
- "Realistic estimate" $\sim 10 \text{ cm}^{-2} \text{ s}^{-1}$
[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
 $29 \text{ cm}^{-2} \text{ s}^{-1}$ for
Kaplinghat et al. spectrum
[hep-ex/0209028]

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

Cline, astro-ph/0103138

Search for Cosmic SN Nus at Super-Kamiokande

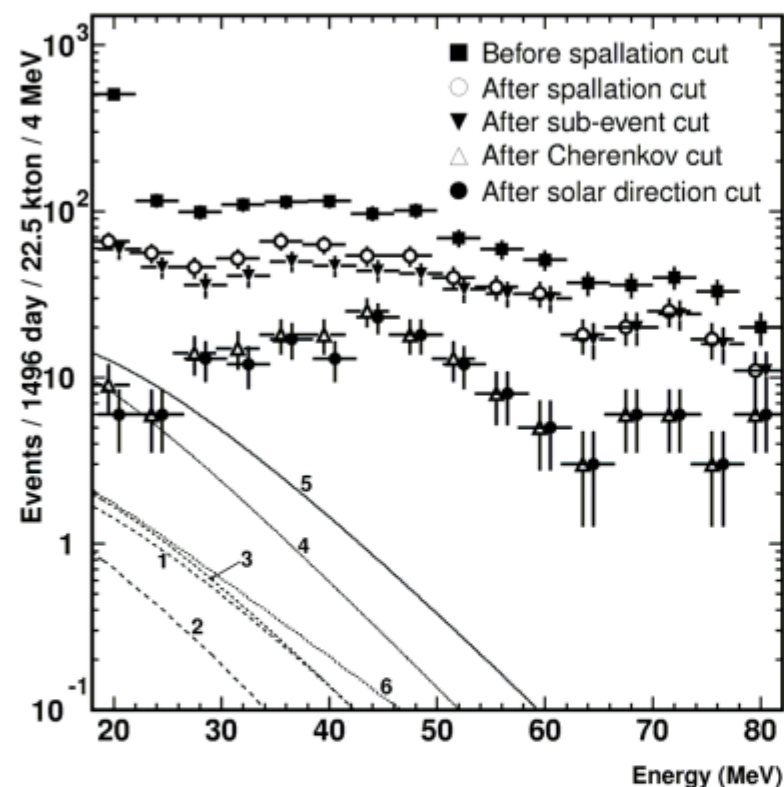


FIG. 1: Energy spectrum at each reduction step. In the final data set, the spallation cut and solar direction cut are only applied in the first four bins. The numbered lines represent the corresponding theoretical predictions from Table I.

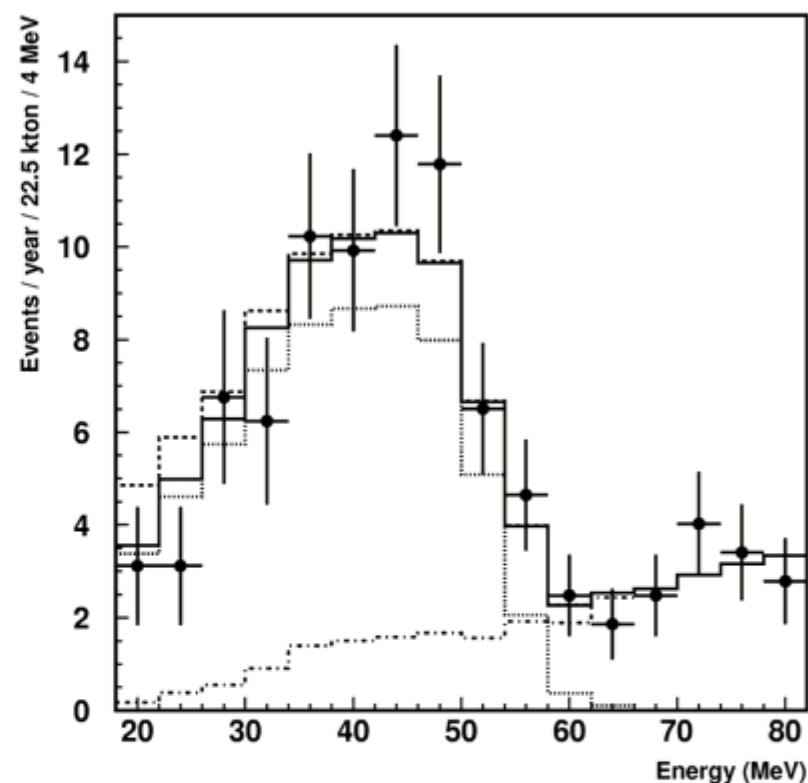


FIG. 2: Energy spectrum of SRN candidates. The dotted and dash-dot histograms are the fitted backgrounds from invisible muons and atmospheric ν_e . The solid histogram is the sum of these two backgrounds. The dashed line shows the sum of the total background and the 90% upper limit of the SRN signal.

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	$< 130 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$44 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$0.41 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$
Cosmic gas infall [5]	< 2.8 events/year	$< 32 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$5.4 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$0.20 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$
Cosmic chemical evolution [6]	< 3.3 events/year	$< 25 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$8.3 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$0.39 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$
Heavy metal abundance [7]	< 3.0 events/year	$< 29 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$< 54 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$< 2.2 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$
Constant supernova rate [4]	< 3.4 events/year	$< 20 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$52 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$3.1 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$
Large mixing angle osc. [8]	< 3.5 events/year	$< 31 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$11 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$0.43 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$

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 $E_\nu < 18\text{-}19\text{ MeV}$
- Sub-Cherenkov muons from atm nus
 $\mu \rightarrow e + \nu_e + \bar{\nu}_\mu$

Solution:

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

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 GdCl_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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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!

