Neutrinos and Supernovae

- Introduction, basic characteristics of a SN.
- Detection of SN neutrinos: How to determine, for all three flavors, the flux and temperatures.
- Other issues: Oscillations, neutronization pulse. Mass determination by the time-of-flight method. Pointing.
- Relic SN neutrinos.

Petr Vogel, Caltech
NNPSS-TSI-Lecture 3

Supernovae are fascinating objects. Their study is very important in astrophysics, neutrino physics, and for the understanding of the r-process nucleosynthesis.

- The SN core collapse is one of the most violent events known. Its theoretical description is challenging and so far poorly understood.
- The energy release, mostly in neutrinos, is so large that when averaged over > 100 years, the total neutrino energy per galaxy is comparable to the energy in light over the same time interval
- SN represent probably the longest possible neutrino baseline. Observation of SN neutrino could give information about neutrino masses and mixing.
- It is likely that after the SN collapse about half of all elements heavier than iron are formed in the r-process. There are many unresolved theoretical issues in the description of the r-process nucleosynthesis.

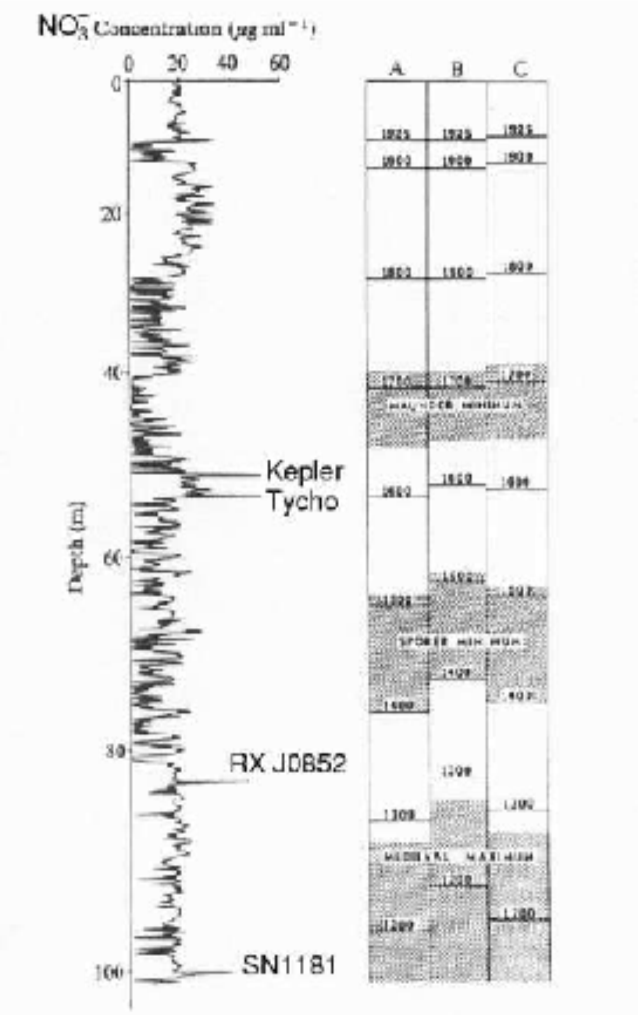
However, the galactic SN neutrinos are observable for less than one minute per century. Large detectors are needed to observe them, and they must be operational continuosly for very long time.

Note: $L_{sun} = 3.8 \times 10^{33}$ erg/s, $L_{galaxy} = 10^{44-45}$ erg/s, $L_{SN} = \sim 3 \times 10^{53}$ erg

Historical supernovae

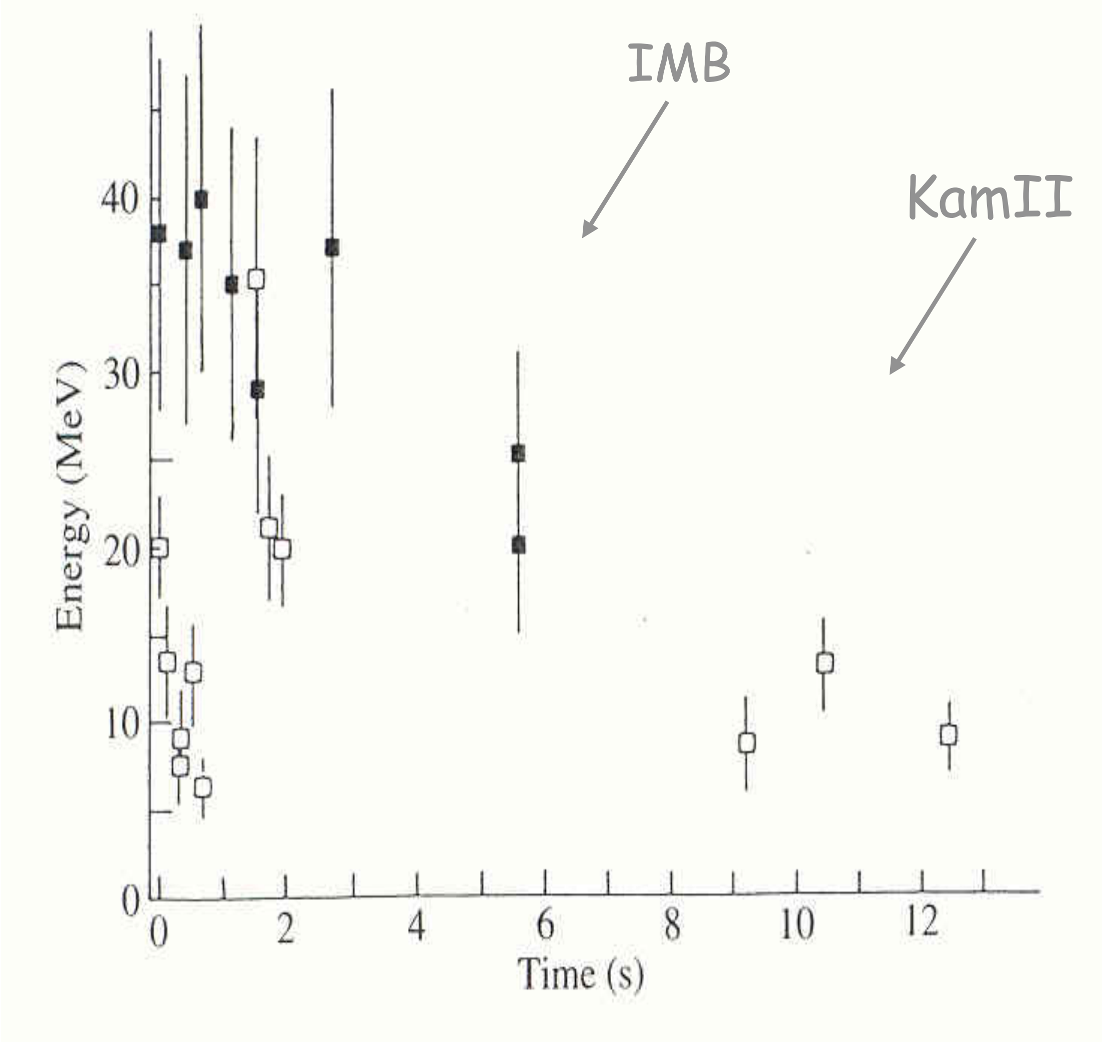
date	length of visibility	Historical records
1006	3 years	Chinese, Japanese, Arabic
1054 (Crab)	21 months	Chinese, Japanese
1181	6 months	Chinese, Japanese
∼1300		(discovered 1998)
1572	18 months	Tycho Brahe
1604	12 months	Johannes ~~Kleper~~ Kepler
∼1680 (Cas A)	Flamsteed?	
1987		

Discovered by observing ^{44}Ti, $T_{1/2}$=60y decay lines. Must have been very close, yet no historical record. Probably wrong.



One supernova each 30 years.

Supernova Neutrino Detection



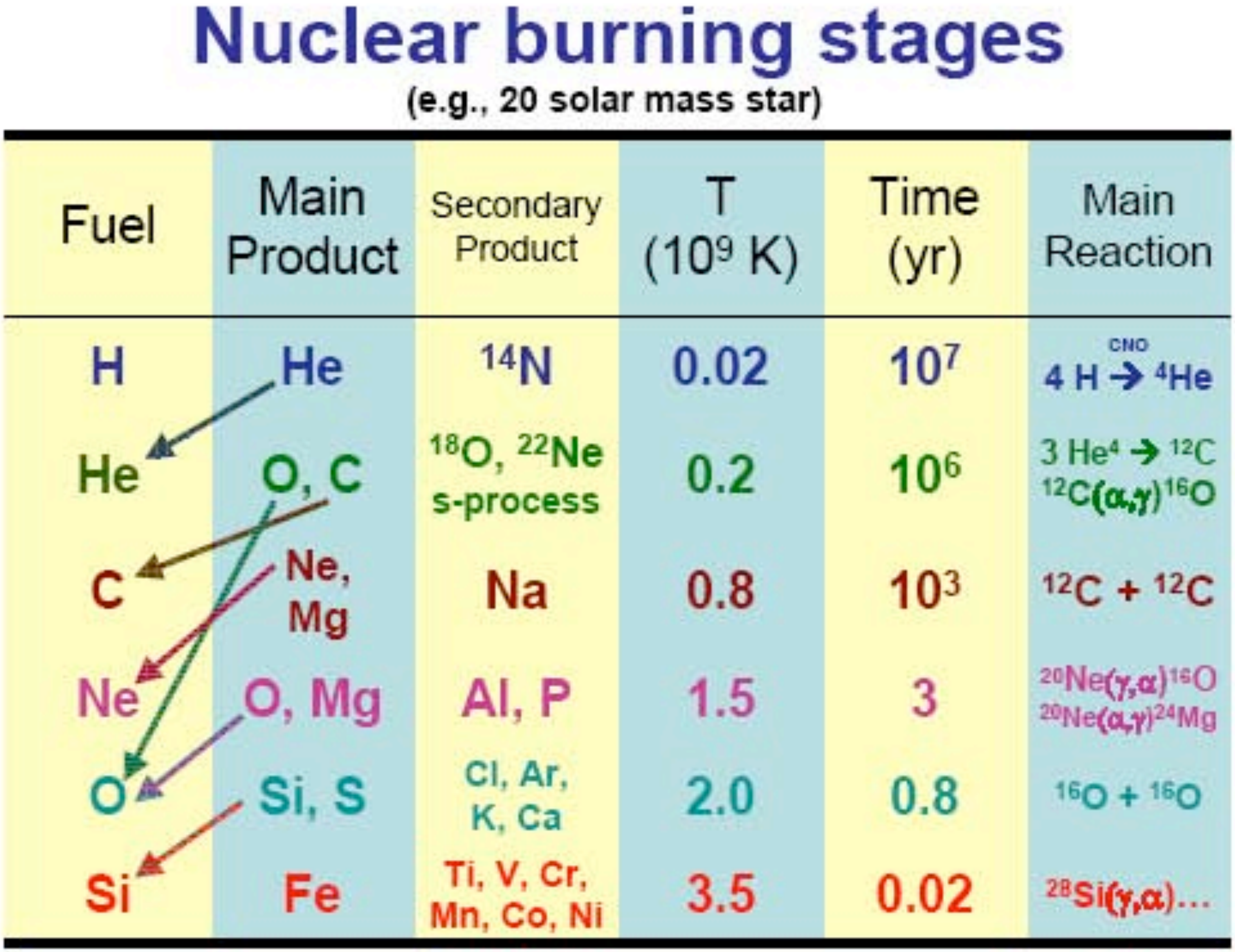
SN1987A:

~ 20 $\bar{\nu}_e p \rightarrow e^+ n$ events

SN200??:

~ 10^4 CC events

~ 10^3 NC events



Nuclear burning stages

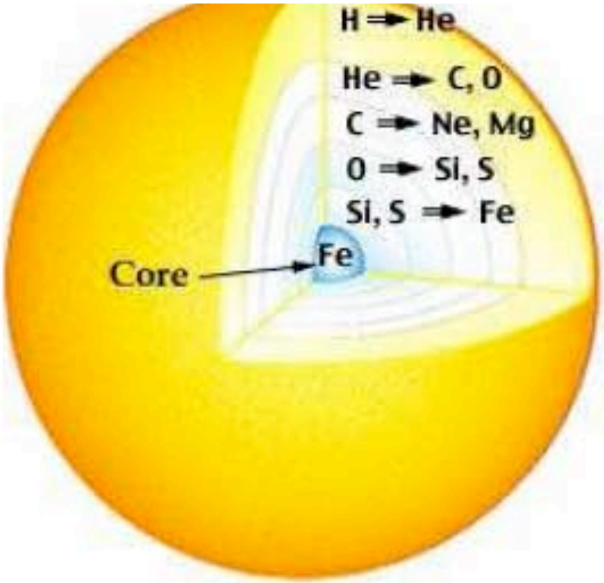
(e.g., 20 solar mass star)

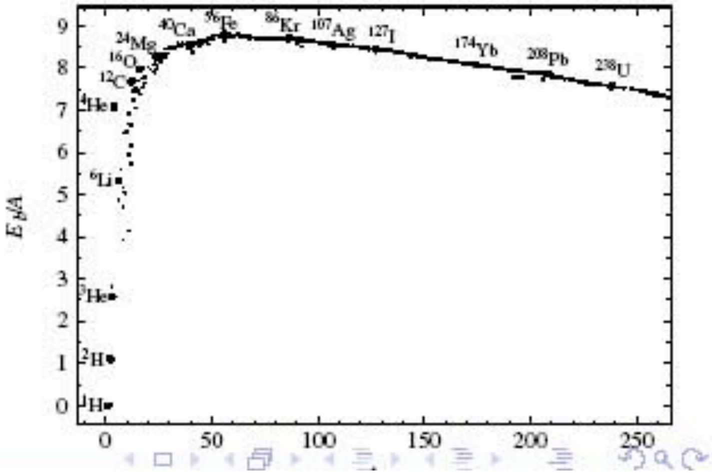
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)\ldots$

Reminder 10^9K = 86 keV, central temperature in Sun = 16×10^6K

Presupernova star $M>8M_\odot$

- Star has an onion-like structure.
- Iron is the final product of the different burning processes.
- As the mass of the iron core grows it becomes unstable and collapses ionce it grows above around 1.4 solar masses.





Reminder: binding energy per nucleon has a maximum near Fe

- The core is made of heavy nuclei (iron-mass range $A \sim 45 - 65$) and electrons. There are Y_e electrons per nucleon.
- The mass of the core M_c is determined by the nucleons.
- There is no nuclear energy source which adds to the pressure. Thus, the pressure is mainly due to the degenerate electrons, with a small correction from the electrostatic interaction between electrons and nuclei.
- As long as $M_c < M_{ch} = 1.44(2Y_e)^2 M_\odot$ (plus slight corrections for finite temperature), the core can be stabilized by the degeneracy pressure of the electrons.

However, there are two processes which make the situation unstable.

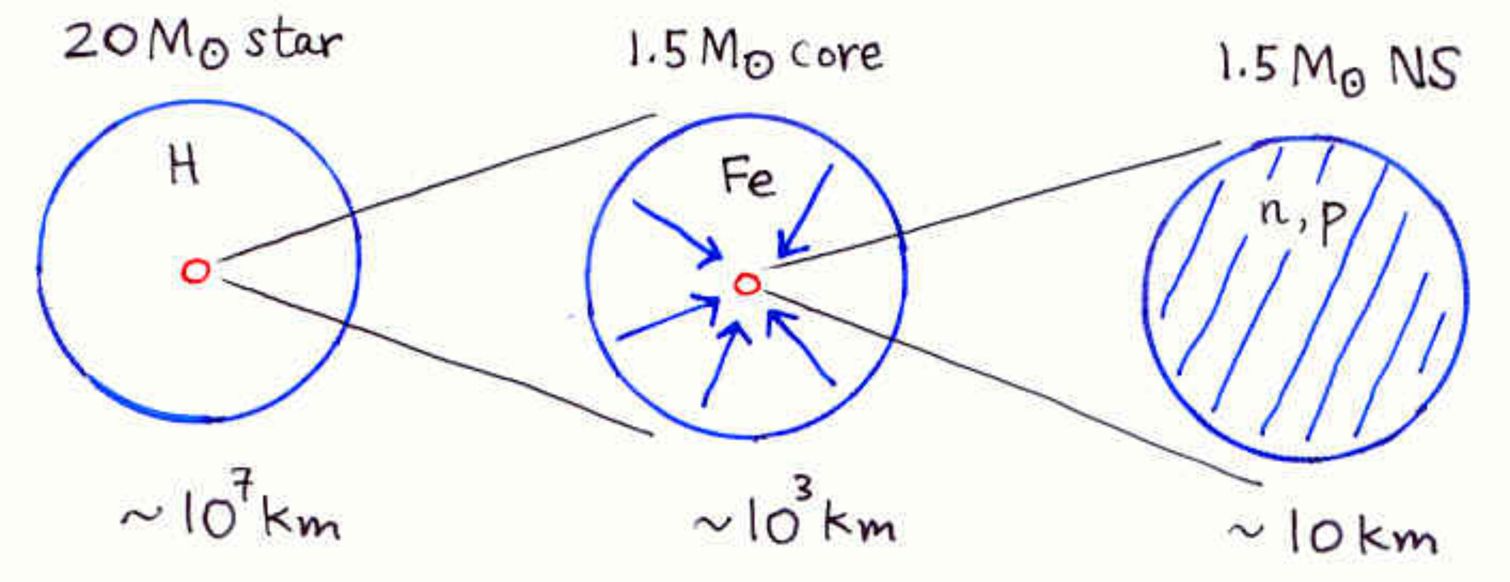
1. Silicon burning is continuing in a shell around the iron core. This adds mass to the iron core, thus M_c grows.
2. Electrons can be captured by nuclei.

$$e^- + (Z, A) \rightarrow (Z - 1, A) + \nu_e$$

This reduces the pressure and cools the core, as the neutrinos leave. In other words, Y_e and hence the Chandrasekhar mass M_{ch} is reduced.

The core finally collapses.

Supernovae Type II- core collapse of massive star



See HW problem of Lars.
I will not consider the situation when BH is formed

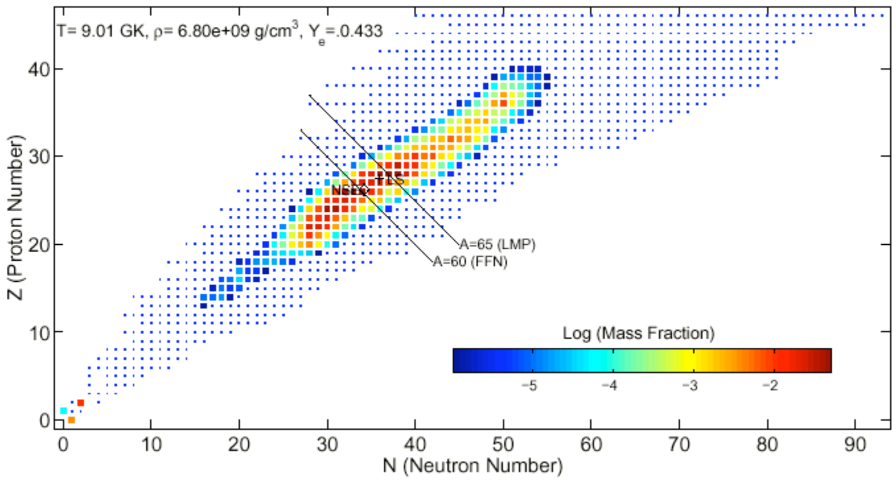
$$\Delta E_B \simeq \frac{3}{5}\frac{G M_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{G M_{NS}^2}{R_{core}} \simeq 3 \times 10^{53} \text{ ergs} \simeq 2 \times 10^{59} \text{ MeV}$$

$$\text{K.E. of explosion} \simeq 10^{-2}\,\Delta E_B$$

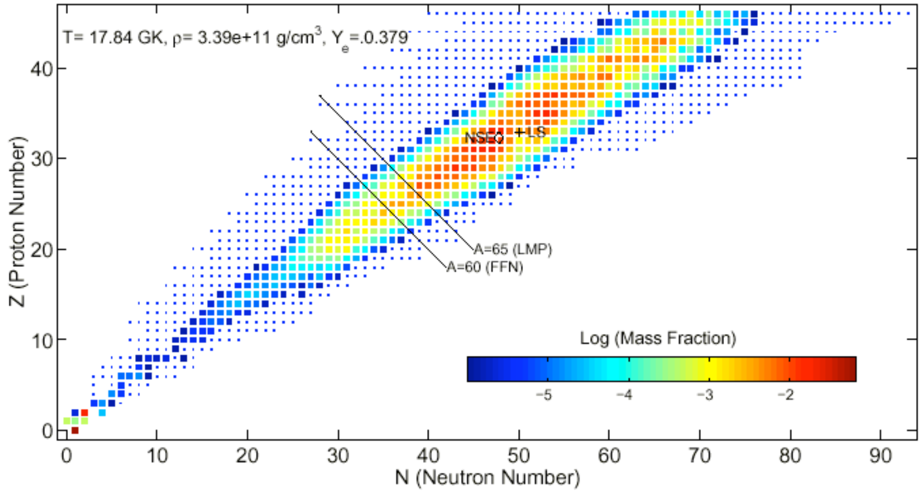
$$\text{E.M. radiation} \simeq 10^{-4}\,\Delta E_B$$

Nuclei responsible for electron capture during collapse

Near onset



Later

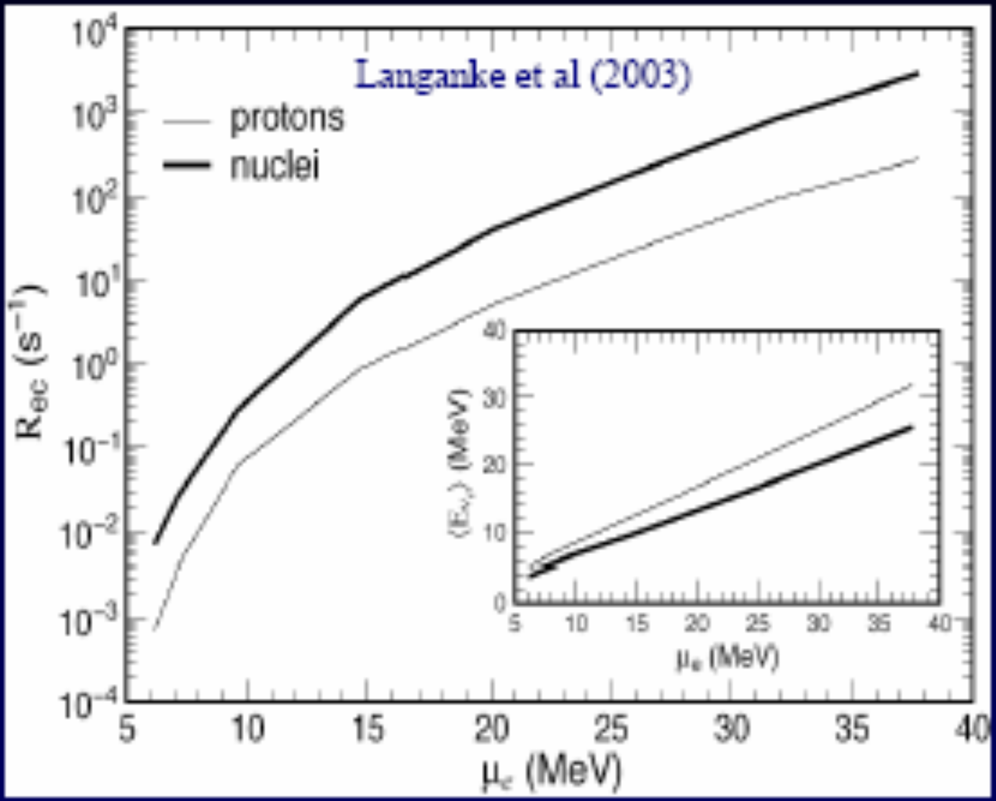


Need theory (and even better experiment but that is essentially impossible) to properly describe electron capture rates in heavier nuclei with electron that have high E_F.

Nuclear Electron Capture Rates

Shell Model calculations are currently limited to A~65.

Langanke et al (2003) have employed a hybrid of shell model (SMMC) and RPA to calculate a scattering of rates for A<110.



Electron capture on heavy nuclei remains important throughout collapse.

Back of the envelope estimates:

1) NS radius: nuclear radii = $1.2A^{1/3}$fm, V_n= 7.2×10^{-39}cm^3.

NS mass ~ M_{solar}~ 2×10^{30} kg~$1.2\times10^{57}M_p$

=> V_{NS}~8×10^{18}cm^3, R_{NS} ~ 13 km

See HW problem
of Lars

2) Mean free path: $\lambda=1/\rho\sigma$, $\rho=0.14\times10^{39}$cm^{-3},

$\sigma_{el} \sim G_F^2 c_A^2/\pi\,(hc)^2 E_\nu^2$ ~ 1.7×10^{-41}cm^2,

$c_A=1.27/2$, and for E_ν = 50 MeV, λ~4.3 m

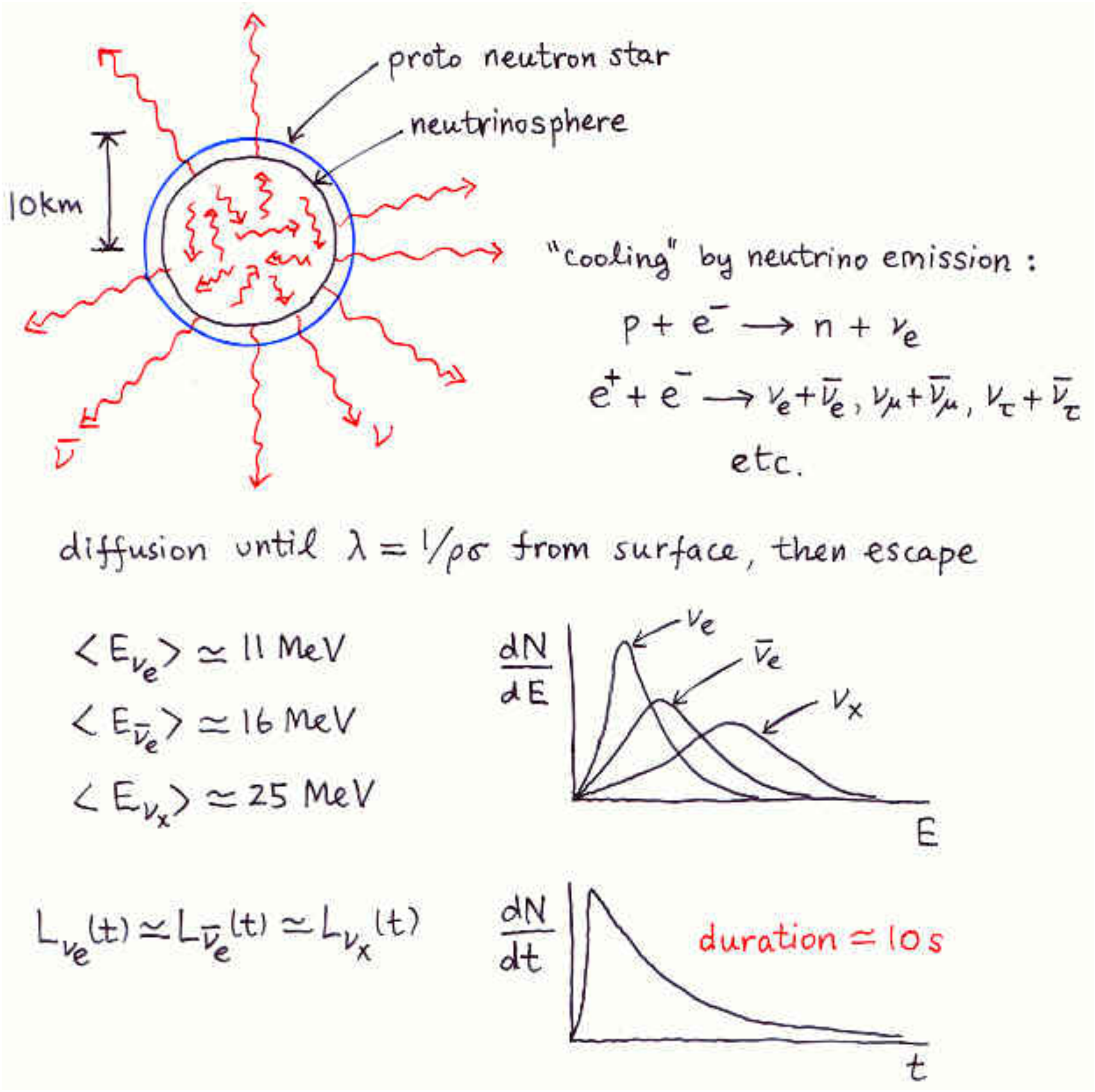
3) Diffusion time: $\tau \sim (R/\lambda)^2\,\lambda/c$ ~ 13 s

4) Assume thermal equilibrium =>`equal luminosity rule',

$L_\nu \sim L_{SN}/6$ ~ a few x 10^{51} erg/s on average

5) `Temperature hierarchy ': ν_μ and ν_τ have only neutral currents, they decouple deeper in the star and have higher temperature. Also, ν_e interact with neutrons, hence have shorter λ than $\bar{\nu}_e$ and lowest temperature.

Supernova Neutrino Emission



"cooling" by neutrino emission:

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

$$e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e,\ \nu_\mu + \bar{\nu}_\mu,\ \nu_\tau + \bar{\nu}_\tau$$

etc.

diffusion until $\lambda = 1/\rho\sigma$ from surface, then escape

$\langle E_{\nu_e} \rangle \simeq 11$ MeV

$\langle E_{\bar{\nu}_e} \rangle \simeq 16$ MeV

$\langle E_{\nu_x} \rangle \simeq 25$ MeV

$$L_{\nu_e}(t) \simeq L_{\bar{\nu}_e}(t) \simeq L_{\nu_x}(t)$$

duration ≃ 10 s

Comparison of different calculated flavor dependent average energies and fluxes

see Keil, Raffelt, and Janka, astro-ph/0208039

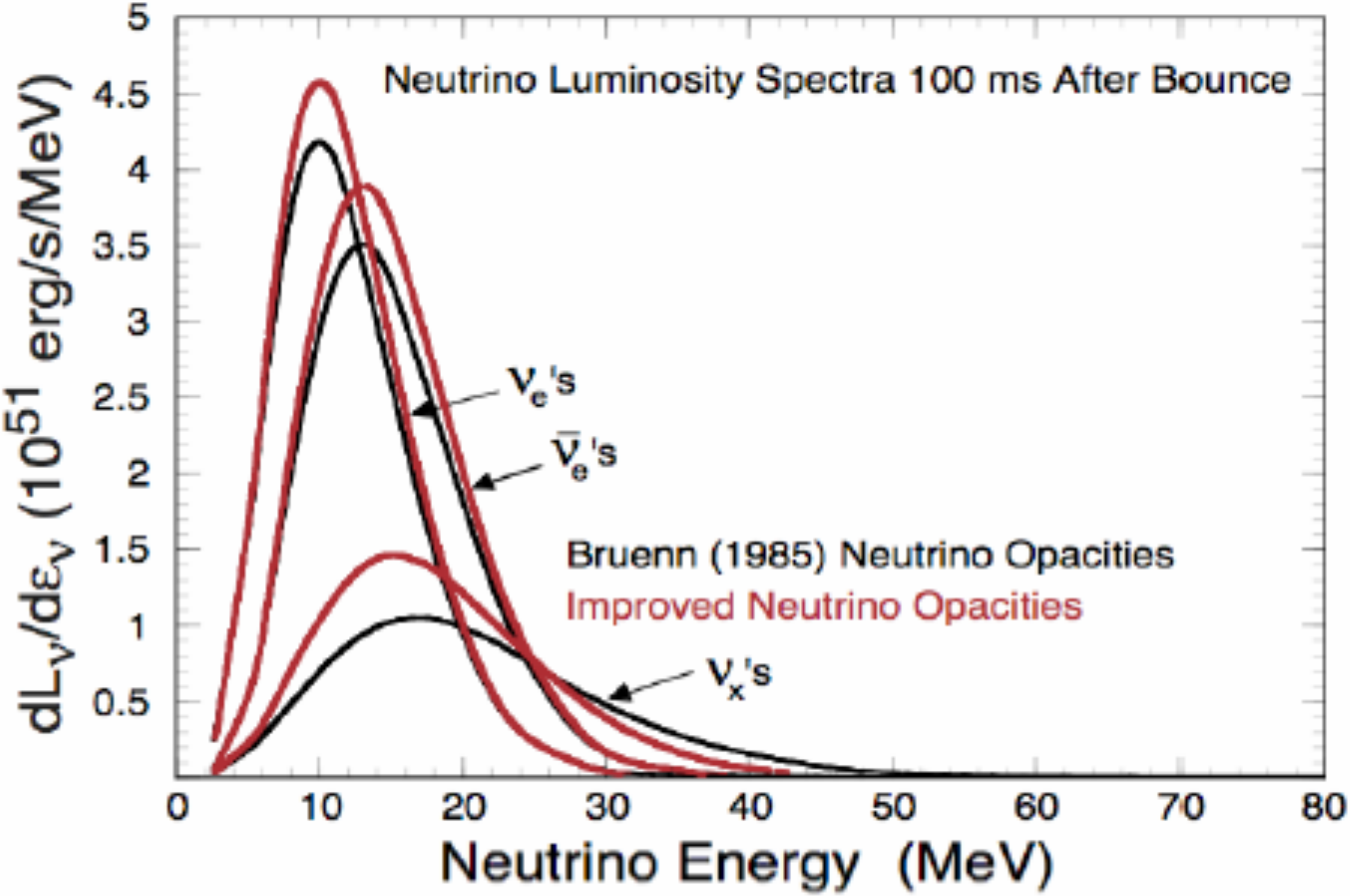
Table 1: Average energies of different flavors

	time pb	$\langle\nu_e\rangle$	$\langle\bar{\nu}_e\rangle$	$\langle\nu_x\rangle$
Mayle et al. (87)	1.0	12	24	22
Totani et al. (98)	0.3	12	15	19
Bruenn (87)	0.5	10	12	25
Suzuki (93)	1.0	9	12	13
Liebenhofer at al. (01)	0.5	19	21	24
Keil et al. I (02)	0.32	12	14	14
Keil et al. II (02)	0.15	13	15	16

Table 2: Luminosities of different flavors

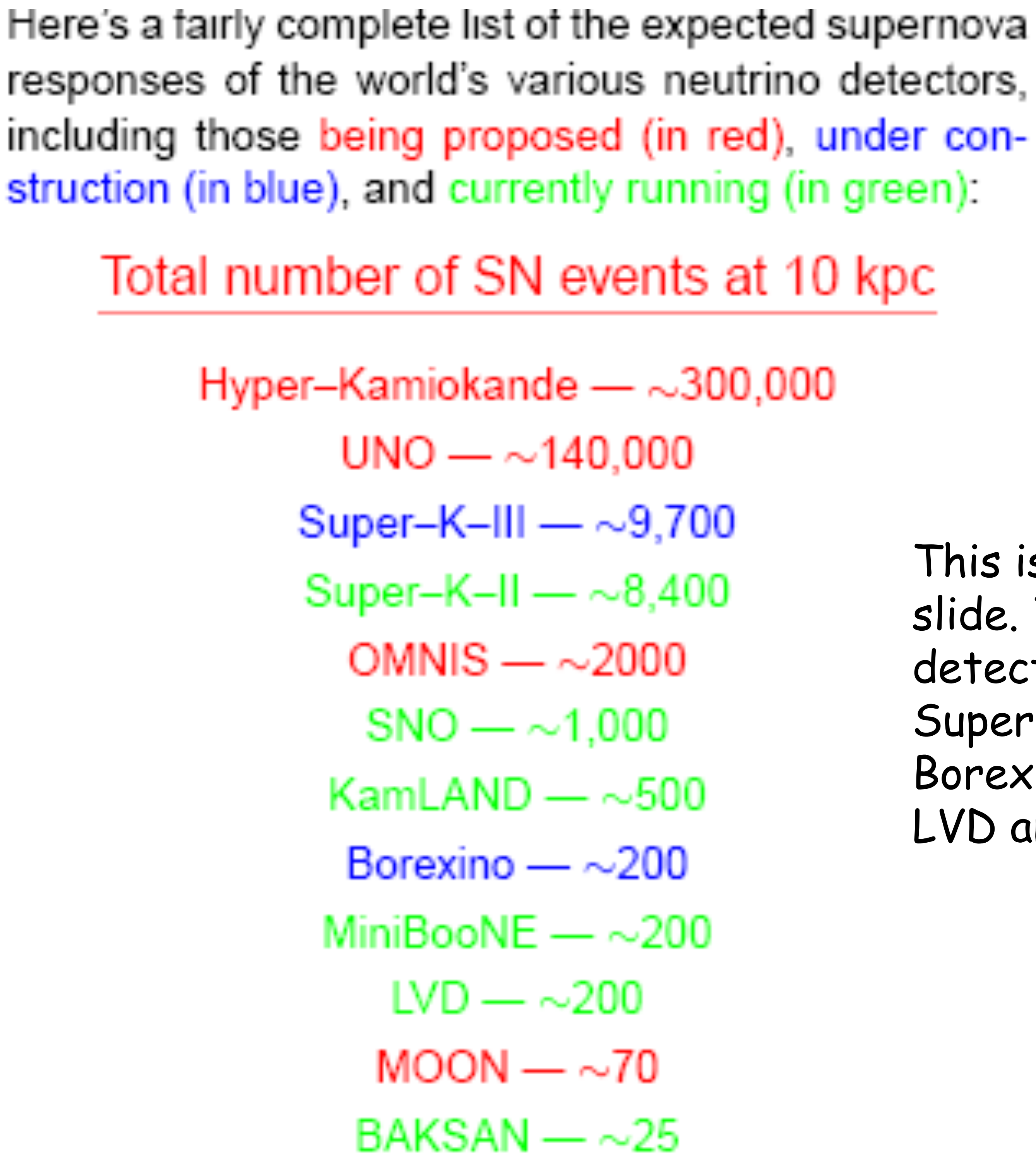
	time pb	L_{ν_e}	$L_{\bar{\nu}_e}$	$L\nu_x$
Mayle et al. (87)	1.0	20	20	20
Totani et al. (98)	0.3	20	20	20
Bruenn (87)	0.5	3	5	4
Suzuki (93)	1.0	3	3	3
Liebenhofer at al. (01)	0.5	30	30	10
Keil et al. I (02)	0.32	32	32	18
Keil et al. II (02)	0.15	74	74	28

time pb means ‘time post bounce in seconds’


Neutrino Luminosity Spectra 100 ms After Bounce
$dL_\nu/d\varepsilon_\nu$ (10^{51} erg/s/MeV)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
10
20
30
40
50
60
70
80
Neutrino Energy (MeV)
ν_e's
$\bar{\nu}_e$'s
ν_x's
Bruenn (1985) Neutrino Opacities
Improved Neutrino Opacities

Which SN neutrino signal could be detected and why?

- Electron antineutrinos $\bar{\nu}_e$ and neutrinos ν_e can be detected by the charged current reactions. If the energy of the created e^+ or e^- is measured, it is possible to determine both flux (L_ν/E_ν) and temperature of these flavors.
- All neutrino flavors can be detected by the neutral current (together). But there is no spectral information in that signal in general.
- The luminosities L_ν and average energies $\langle E_\nu \rangle$ depend on the emission process, and on oscillations at or near the SN, on the way to Earth, and possibly propagating through Earth.
- Given the uncertainties of the emission in SN, it seems to be difficult to obtain significant and reliable information on the neutrino mass and mixing this way, but many ingenious proposals have been made.
- In any case, the program for SN neutrino watch should contain, ideally, ways to determine six parameters (three luminosities and temperatures). This would significantly constrain the models of SN neutrino emission.
- We will make estimates for a 'standard' SN 10 kpc away (half of the stars in our galaxy are within that distance) with total energy 3×10^{53} ergs, with equal luminosity in all six flavors, and with the temperature hierarchy explained earlier.



Here's a fairly complete list of the expected supernova responses of the world's various neutrino detectors, including those being proposed (in red), under construction (in blue), and currently running (in green):

Total number of SN events at 10 kpc

Hyper–Kamiokande — $\sim$300,000
UNO — $\sim$140,000
Super–K–III — $\sim$9,700
Super–K–II — $\sim$8,400
OMNIS — $\sim$2000
SNO — $\sim$1,000
KamLAND — $\sim$500
Borexino — $\sim$200
MiniBooNE — $\sim$200
LVD — $\sim$200
MOON — $\sim$70
BAKSAN — $\sim$25

This is a bit out of date slide. The working SN detectors now are SuperK, KamLAND, Borexino, MiniBoone, LVD and IceCube.

Detecting electron antineutrinos $\bar{\nu}_e$ is relatively easy:

- The reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ has a relatively large and well understood (to 0.2% accuracy) cross section.
- ν_e energy is simply related to the positron energy, $E_\nu \approx E_e + M_n - M_p$. Thus by measuring the e^+ energy one can easily deduce the $\bar{\nu}_e$ energy.
- In SuperK there will be ~8000 events and in KamLAND (or SNO+) several hundred. It should be possible to determine the ν_e flux and temperature accurately, even their time dependence.

Detecting electron neutrinos ν_e is more difficult:

- Only targets that contain neutrons (i.e. complex nuclei) can be used.
- The cross sections are substantially smaller and, with few exceptions (deuternos, $^{12}C \rightarrow {}^{12}N_{gs}$) their magnitude is based on calculations.
- There are no active suitable detectors now (few events in KamLAND and Borexino).
- There are plans to develop lead based detectors. Numerous calculations of the cross section exist.
- If the electrons from $\nu_e + {}^{A}Pb \rightarrow e^- + {}^{A}Bi$ could be detected, one could determine the ν_e temperature.

Table 1: Calculated numbers of events expected in SK and SNO. In SNO events in 1 kton of D_2O and in 1.4 kton of H_2O are added. By ν_x we denote the combined effect of ν_μ and ν_τ, each accounts for half of the events. In all except the top row, the events caused by ν and $\bar{\nu}$ are added.

reaction	events in SK	events in SNO
$\bar{\nu}_e + p \to e^+ + n$	8300	365
$\nu_e + d \to e^- + p + p$ $\bar{\nu}_e + d \to e^+ + n + n$	-	160
$\nu_x + d \to \nu_x + n + p$	-	400
$\nu_x +^{16}\mathrm{O} \to \nu_x + \gamma + X$	710	50
$\nu_x +^{16}\mathrm{O} \to \nu_x + n +^{15}\mathrm{O}$	-	15
$\nu_e + e^- \to \nu_e + e^-$	200	15
$\nu_x + e^- \to \nu_x + e^-$	120	10

see J. Beacom and P.V., Phys. Rev. D **58**, 053010 (1998); ibid 093012 (1998)

How to detect ν_x (this is ν_μ and ν_τ and their antineutrinos)? Clearly, only through the neutral current.

The obvious requirements are: Sufficiently strong signal and the ability to distinguish it from the charged current events.

- ν scattering on electrons, $\nu + e \rightarrow \nu + e$.
  All detectors will have such signal, but it is often weak and it is difficult to separate the neutral and charged current events.
- ν NC excitation in water, with detection of γ, $\nu + {}^{16}O \rightarrow X + \nu + \gamma$

λ ν NC deuteron disintegration, with neutron detection,(SNO)
  $\nu + d \rightarrow n + p + \nu$

- ν elastic scattering on protons, $\nu + p \rightarrow \nu + p$, requires very low threshold (KamLAND, Borexino).
- ν NC excitation of a heavy nucleus (Pb) with the detection of evaporated neutron (or multiple neutrons), $\nu + {}^{208}Pb \rightarrow {}^{207}Pb + n + \nu$
  But the cross sections need be calculated (see Fuller, Haxton, McLauglin, Phys.Rev.D59,085005 or Kolbe, Langanke, Phys.Rev C63, 025802, the results differ by a factor of two)

There is (usually) no spectroscopic information in the NC signal

- In NC induced reaction, only the number of events is usually recorded.

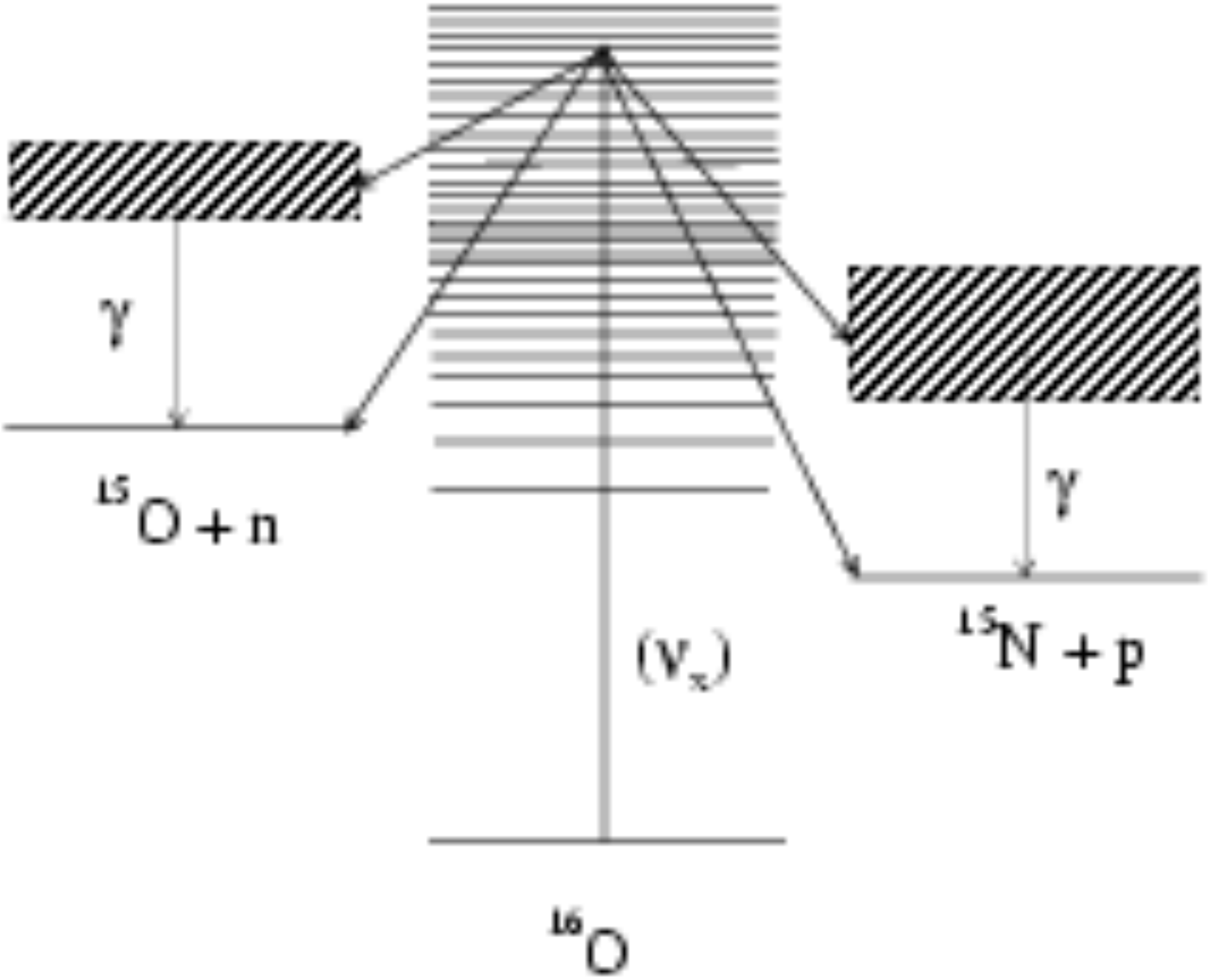
- The number of events depends on both luminosity and energy:

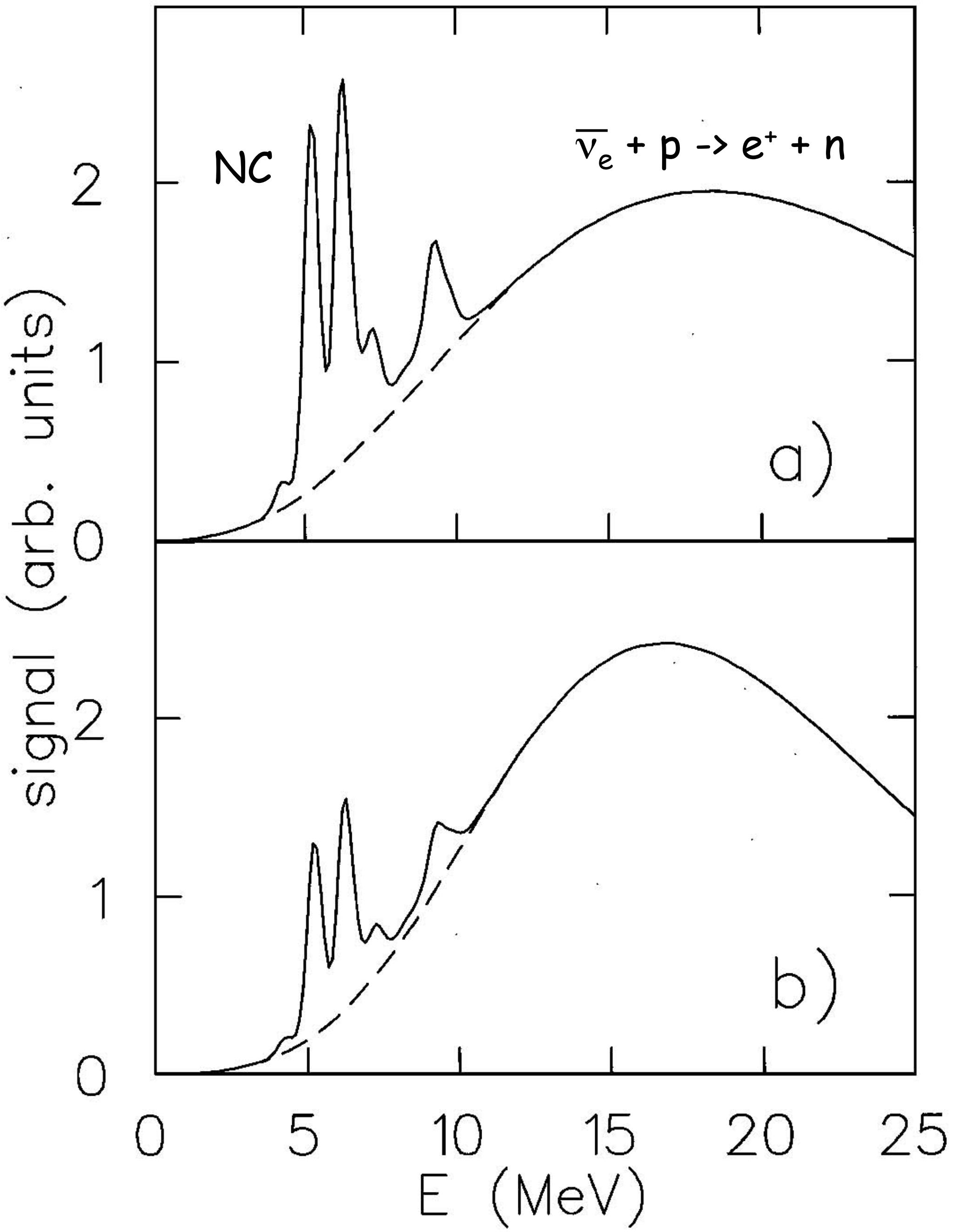
  $N \sim \frac{L}{D^2 \langle E_\nu \rangle} \int f(E_\nu) \sigma(E_\nu) dE_\nu$,

  where D is the distance, $f(E_\nu)$ is the neutrino energy spectrum, and $\sigma(E_\nu)$ is the cross section. Thus, there is a parameter degeneracy; higher average energy and lower luminosity can conspire to give the same number of events.

- Without spectral information it is difficult to determine the luminosity and average energy independently. (Perhaps by using reactions with different thresholds, often measured in different detectors, one can gain some insight).

Detecting ν_x by inelastic scattering on ^{16}O, followed by a nucleon emission and gamma radiation. All γ are between 5-10 MeV. There will be ~700 such events in SK.
See Langanke, P.V., Kolbe, PRL 76,2629(1996)

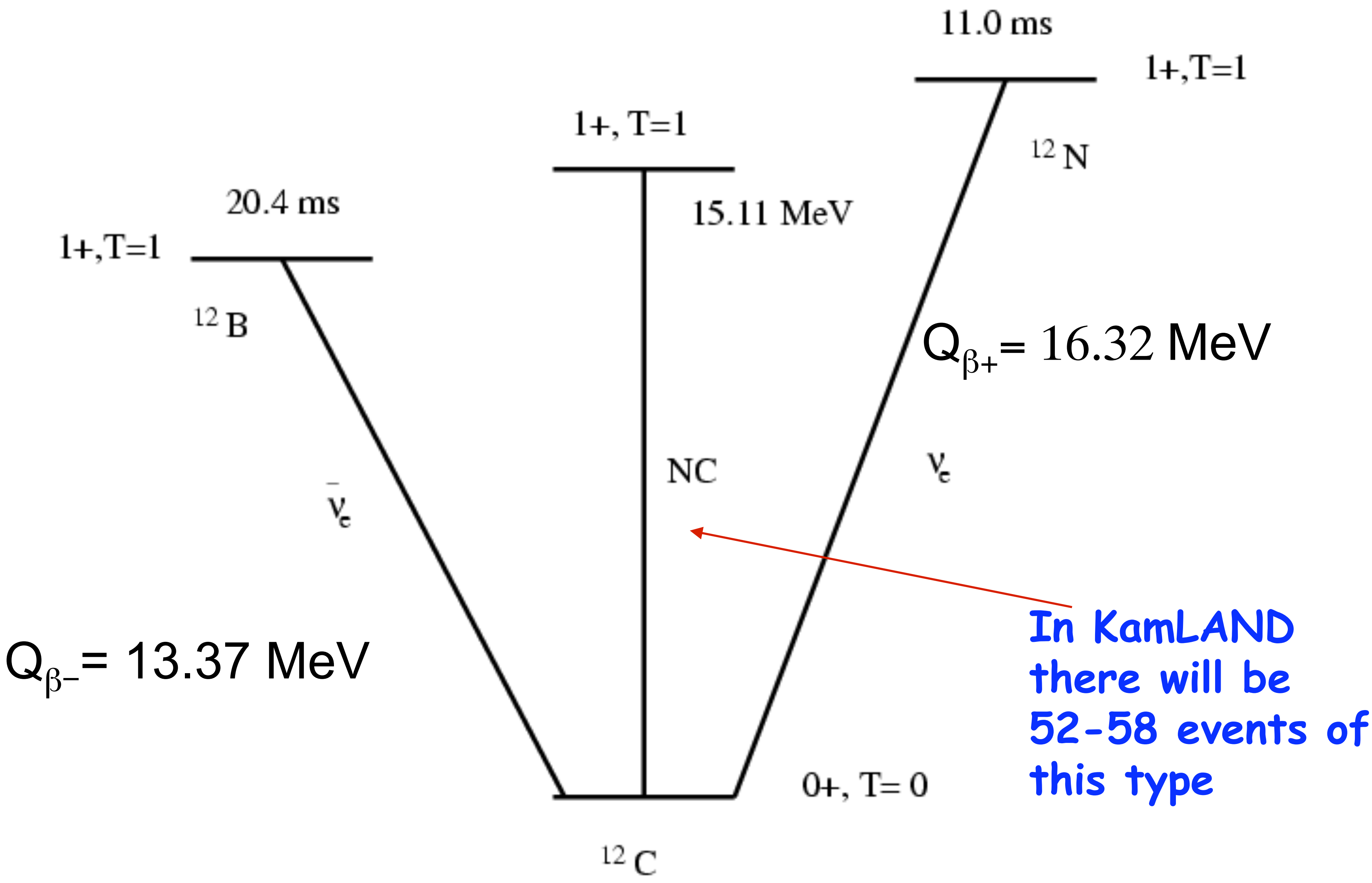




$T(\nu_x) = 8$ MeV
$T(\bar{\nu}_e) = 5$ MeV

$T(\nu_x) = 6.3$ MeV
$T(\bar{\nu}_e) = 4$ MeV
with $\mu = 3T$

A=12 triad



$Q_{\beta+}$= 16.32 MeV

$Q_{\beta-}$= 13.37 MeV

In KamLAND there will be 52-58 events of this type

Neutrino elastic scattering on protons, a chance for scintillator based detectors

see Beacom, Farr, P.V. Phys. Rev. D**66**, 033001 (2002)

Neutrinos will scatter on protons according to (to order E_ν/M)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T_p} = \frac{G_F^2 M}{\pi}\left[(c_A^2 + c_V^2) - (c_A^2 - c_V^2)\frac{T_p M}{2E_\nu^2} - (c_V \mp c_A)^2 \frac{T_p}{E_\nu} \pm 2 c_M c_A \frac{T_p}{E_\nu}\right] ,$$

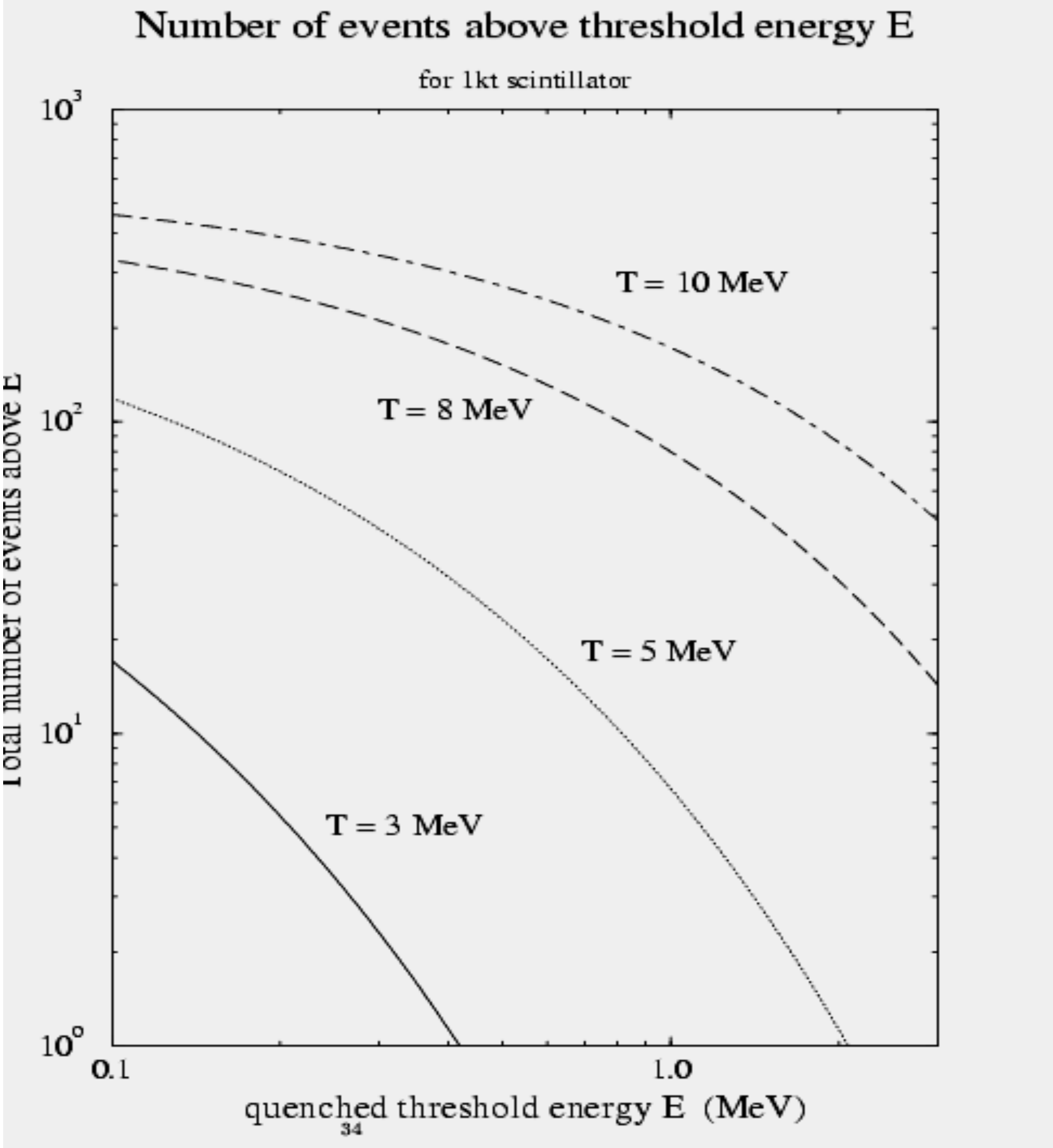
where $c_V = 1/2 - 2\sin^2\theta_W = 0.0375,\ c_A = 1.26/2,\ c_M \simeq -\mu_n/2.$

The proton recoil kinetic energy T_p is restricted from above by $\sim 2E_\nu^2/M$. Only the first two terms in the cross section formula are relevant for $E_\nu \ll M$.

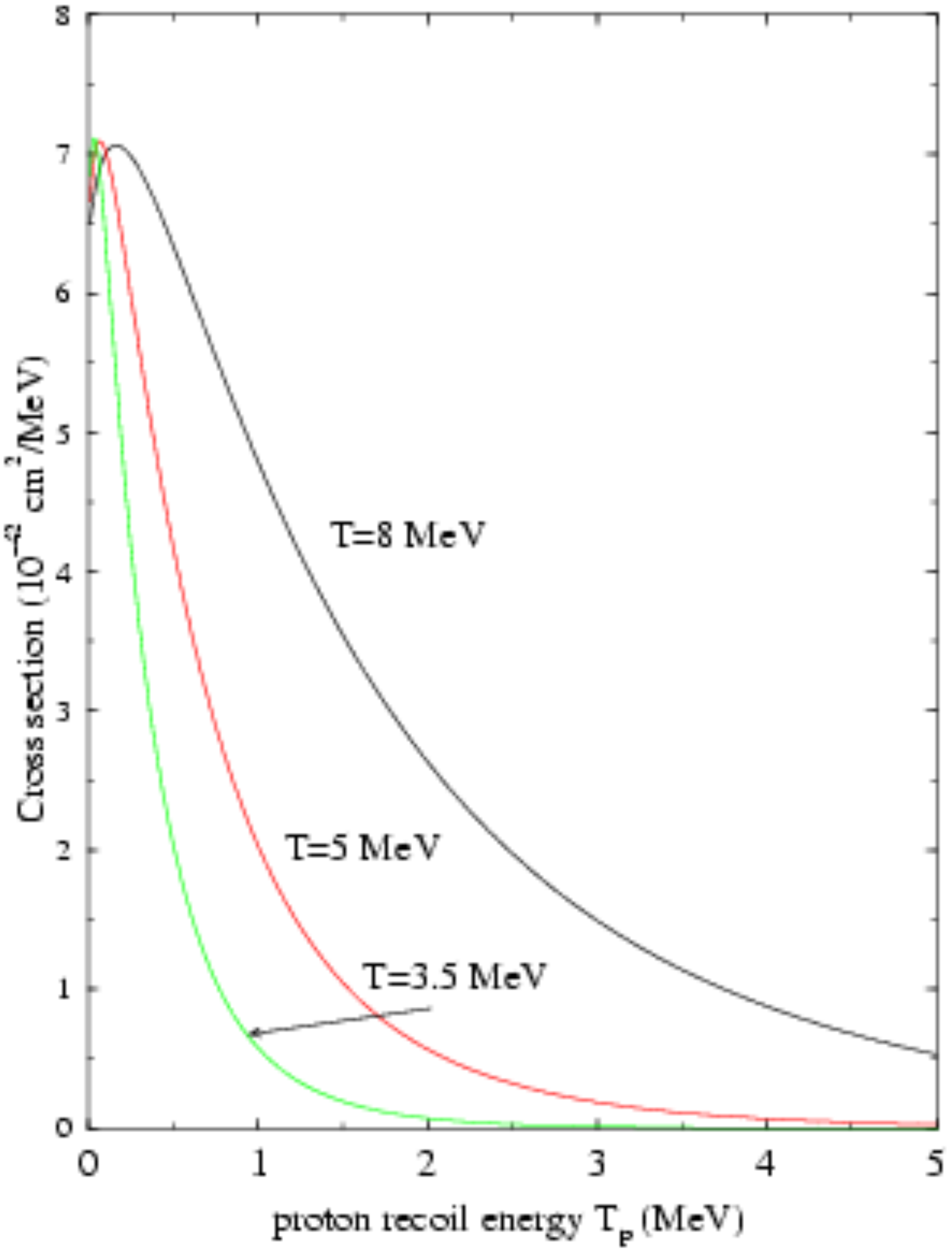
The recoiling protons do not emit Čerenkov radiation, but they will scintillate. However, the scintillation light is quenched, compared to electrons or γ. Thus, the relevant energies are ≤ 1 MeV.

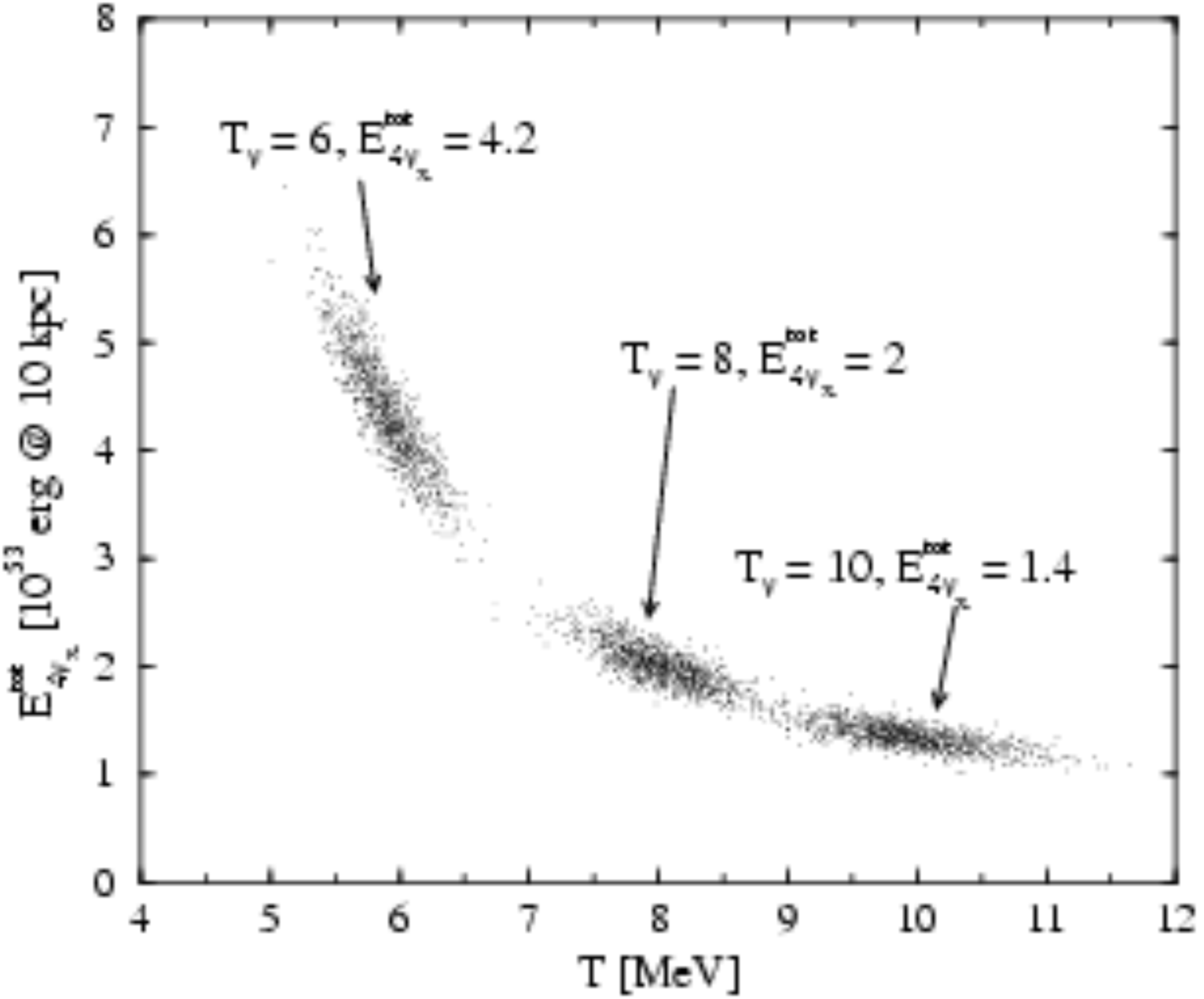
The total cross section is proportional to E_ν^2, so the signal will be dominated by ν_x, particularly above reasonable detection thresholds.

In a sensitive detector one might be able not only to count the number of events, but observe the proton recoil spectrum. In that case one will be able to determine both the ν_x temperature and luminosity.


Number of events above threshold energy E
for 1kt scintillator
Total number of events above E
10^3
10^2
10^1
10^0
T = 10 MeV
T = 8 MeV
T = 5 MeV
T = 3 MeV
0.1
1.0
quenched threshold energy E (MeV)

$d\sigma/dT_p$ averaged over F−D spectrum





, Beacom, Farr, and Vogel, PRD 66) 033001 (2002)

Measuring neutrino mass by TOF

The time delay, with respect to massless particle, is
$\Delta t(E) = 0.514\ (m_\nu/E_\nu)^2 D$,
where m is in eV, E in MeV, D in 10 kpc, and Δt in sec.

But there are no massless particles emitted by SN at the same time as neutrinos. Alternatively, we might look for a time delay between the charged current signal (i.e. ν_e) and the neutral current signal (dominated by ν_x).
Alternatively, one might look for a broadening of the signal, and rearrangement according to the neutrino energy.

Time delay between the neutral and charged current events; constraint on the mass difference of ν_e and ν_x neutrinos

- First requirement is a clear separation of the CC and NC current signals. That is only partially possible, typically the weaker NC signal will be somewhat contaminated by the CC current events with a similar signature.

- The most efficient way to decide whether there is a delay or not is to determine the mean arrival time of the two kinds of events:

  $\langle t \rangle_{NC} = \Sigma_k t_k / N_{NC}$

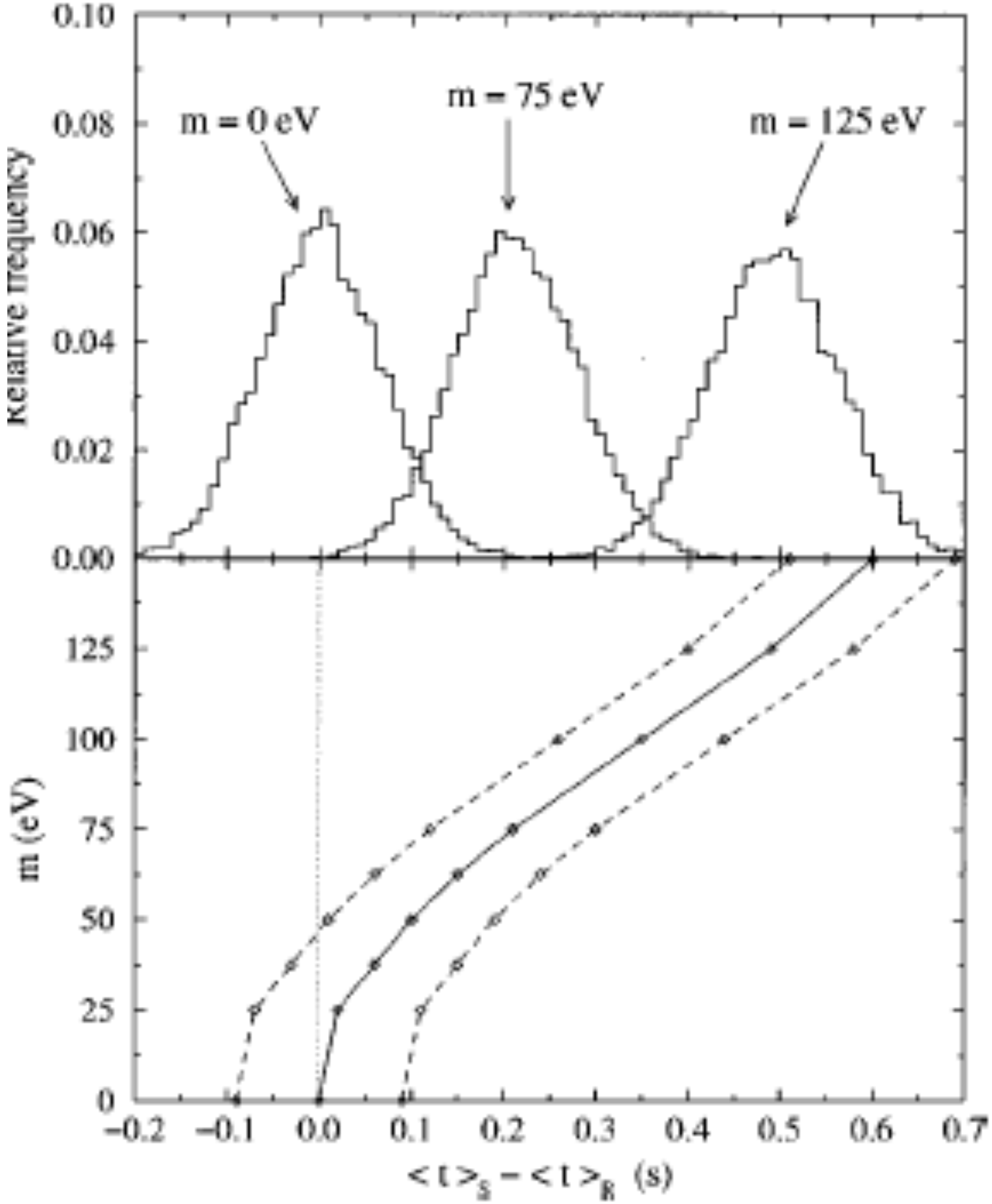
  $\langle t \rangle_{CC} = \Sigma_k t_k / N_{CC}$

- The signature of neutrino mass is then

  $\langle t \rangle_{NC} > \langle t \rangle_{CC}$

  with significance beyond the statistical fluctuations.

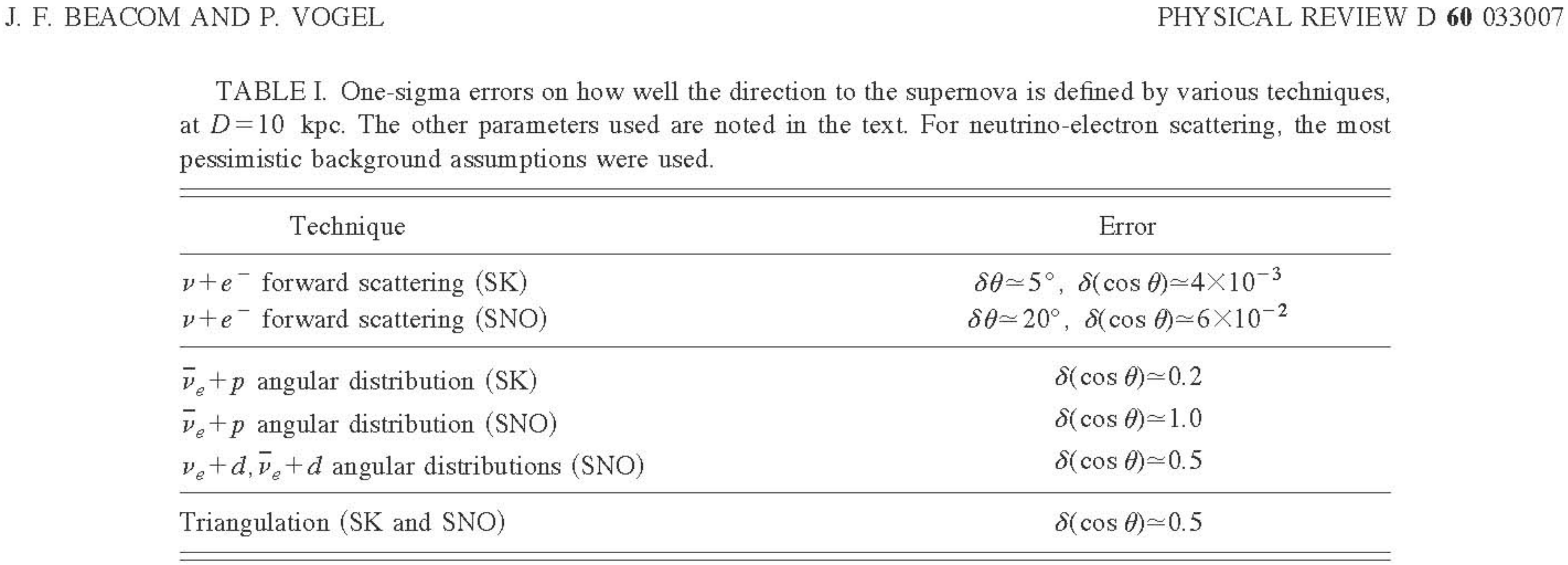
- For the existing detectors (SK,SNO) and the 'standard' scenario, one arrives (neglecting oscillations) at a sensitivity of ~ 20 eV for the mass difference.



$<t>_{signal} - <t>_{reference}$
for several mass values
Lower part shows the range
of the deduced masses.
The dashed lines are 10%
and 90% CL.
See, Beacom & P.V.,
Phys.Rev.D58,053010(1998)

Locating supernova by its neutrino signal?

(difficult and not very accurate)



J. F. BEACOM AND P. VOGEL PHYSICAL REVIEW D **60** 033007

TABLE I. One-sigma errors on how well the direction to the supernova is defined by various techniques, at $D=10$ kpc. The other parameters used are noted in the text. For neutrino-electron scattering, the most pessimistic background assumptions were used.

Technique	Error
$\nu+e^-$ forward scattering (SK)	$\delta\theta\simeq5°$, $\delta(\cos\theta)\simeq4\times10^{-3}$
$\nu+e^-$ forward scattering (SNO)	$\delta\theta\simeq20°$, $\delta(\cos\theta)\simeq6\times10^{-2}$
$\bar{\nu}_e+p$ angular distribution (SK)	$\delta(\cos\theta)\simeq0.2$
$\bar{\nu}_e+p$ angular distribution (SNO)	$\delta(\cos\theta)\simeq1.0$
$\nu_e+d, \bar{\nu}_e+d$ angular distributions (SNO)	$\delta(\cos\theta)\simeq0.5$
Triangulation (SK and SNO)	$\delta(\cos\theta)\simeq0.5$

Oscillations of SN neutrinos

SN neutrinos undergo oscillations on their way out of the star, in the interstellar space, and possibly when they propagate through Earth. Thus, in principle they carry information about the oscillation parameters. However, since the uncertainties in the primary spectra are large, only the most robust features are potentially useful for extracting oscillation information.

Some of these features are:

- The neutronization pulse is pure ν_e when formed.
- The 'spectrum hierarchy' should exist, but the magnitude of the energy separation is uncertain.
- Generally, the initial spectra should be 'pinched', i.e. they should be depleted at higher energies when compared to the pure thermal spectrum.

Now, when there is a consensus that atmospheric neutrinos involve essentially $\nu_\mu \to \nu_\tau$ oscillations with $\Delta m^2 \sim 10^{-3}$ eV^2 and a large mixing angle, and that the LMA is the correct solution to the solar neutrino puzzle, two issues remain:

i) Is the pattern of masses 'normal' or 'inverted'?

ii) How small is the mixing angle θ_{13}?

Observation of the SN neutrinos can, perhaps, help in answering these questions, but the description how to do it is lengthy and thus beyond this talk. The relevant references are e.g.,

Dinghe and Smirnov, Phys. Rev. D**62**, 033007 (2000),
Lunardini and Smirnov, hep-ph/0302033,
Dinghe, Keil and Raffelt, hep-ph/0304150.

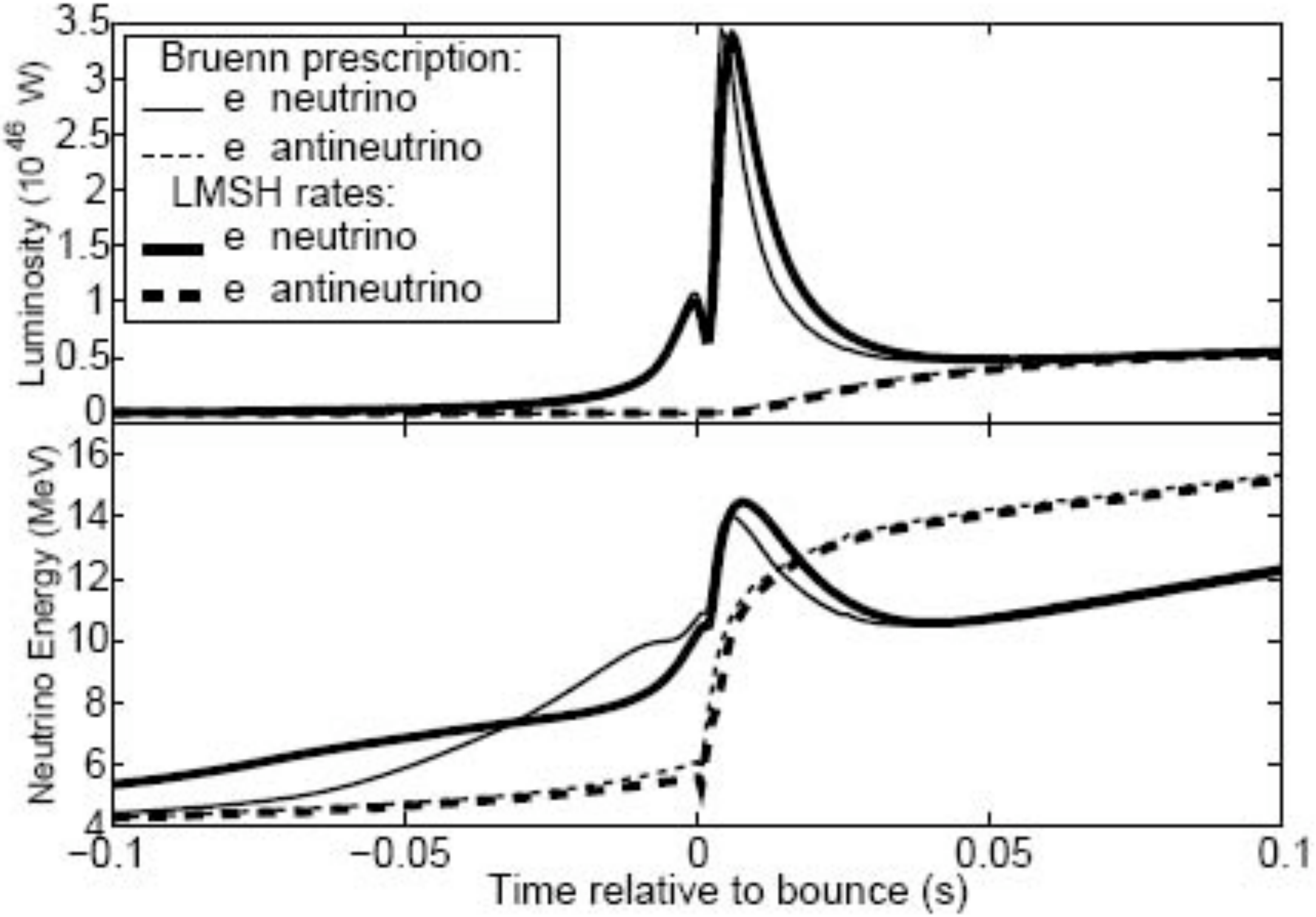
Neutronization pulse

In the early stages of the core collapse electrons are captured on the core nuclei, and the resulting ν_e escape. Eventually the density of the core increases so much that the neutrinos are trapped. However, outside the outgoing shock the ν_e created by the electron captures still escape, forming a very narrow ($\sim$0.01 s) and intense pulse. This pulse represents $2-5\times10^{51}$ ergs of energy, i.e. perhaps $5-10\%$ of the total energy of the ν_e neutrinos.

Scaling the usually predicted yields I estimate that such a pulse could result in ~ 10 neutrino-electron scattering events in SK, recognizable by their clustering in time, and by their characteristic narrow angular distribution. (Obviously, that yield estimate has a substantial error margin.)

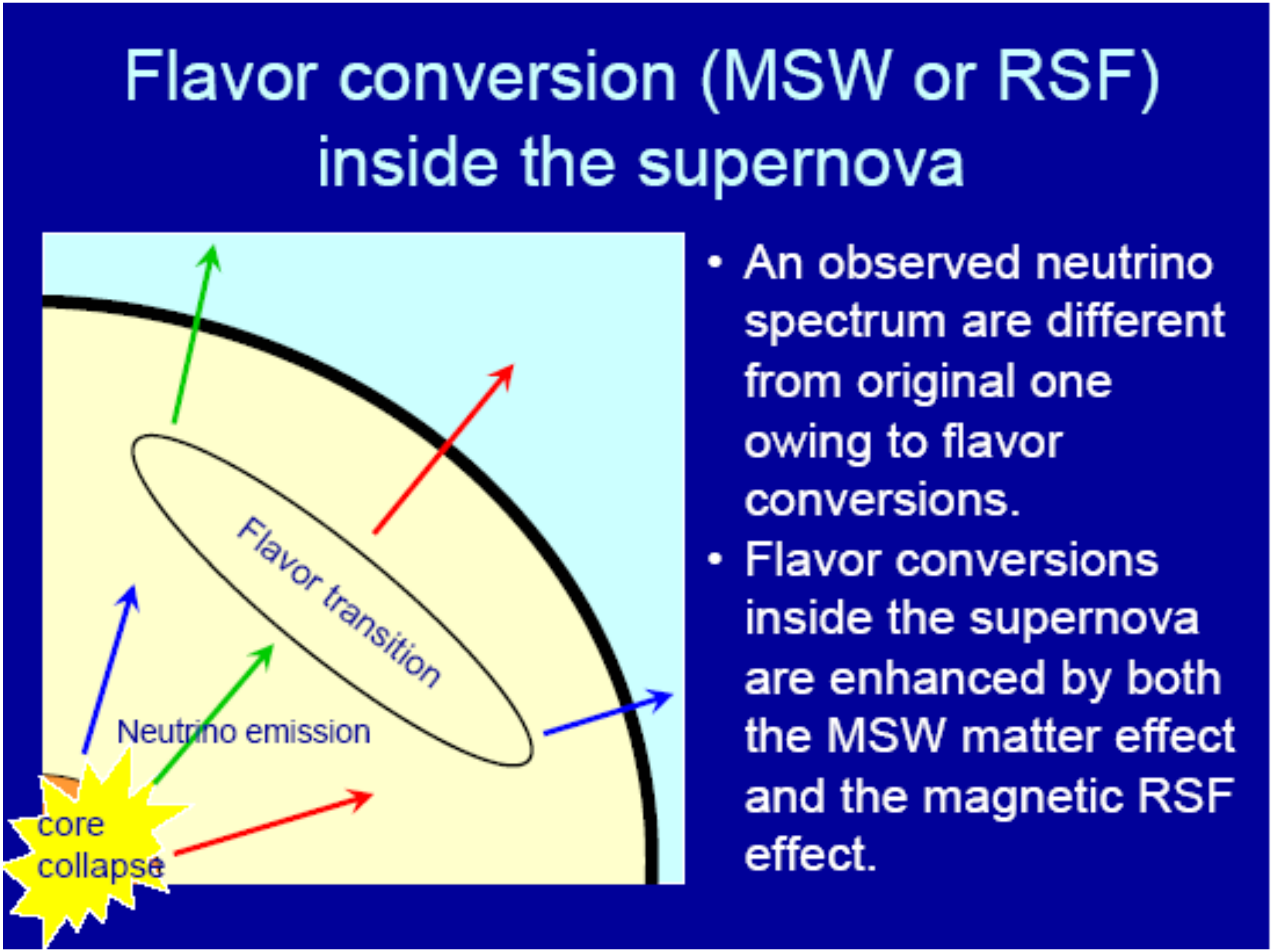
Clearly, observation of the neutronization pulse would be valuable for understanding the mechanism of the core collapse and bounce.

If the flavor of the neutrinos in the neutronization pulse at Earth could be determined (not clear how, scattering on electrons cannot be used for that purpose), one could make a definitive statement about the conversion probability caused by oscillations, since the pulse, unlike the later cooling emission, is at the SN pure ν_e.



(PRL **91** 201102)

Luminosity and energy of the neutronization pulse. Note the smooth increase for $\bar{\nu}_e$ and the peak structure for ν_e.



Flavor conversion (MSW or RSF) inside the supernova

- An observed neutrino spectrum are different from original one owing to flavor conversions.
- Flavor conversions inside the supernova are enhanced by both the MSW matter effect and the magnetic RSF effect.

Neutrino densities are so high that neutrino-neutrino interactions become Important. Theoretical treatment is challenging, but very interesting.

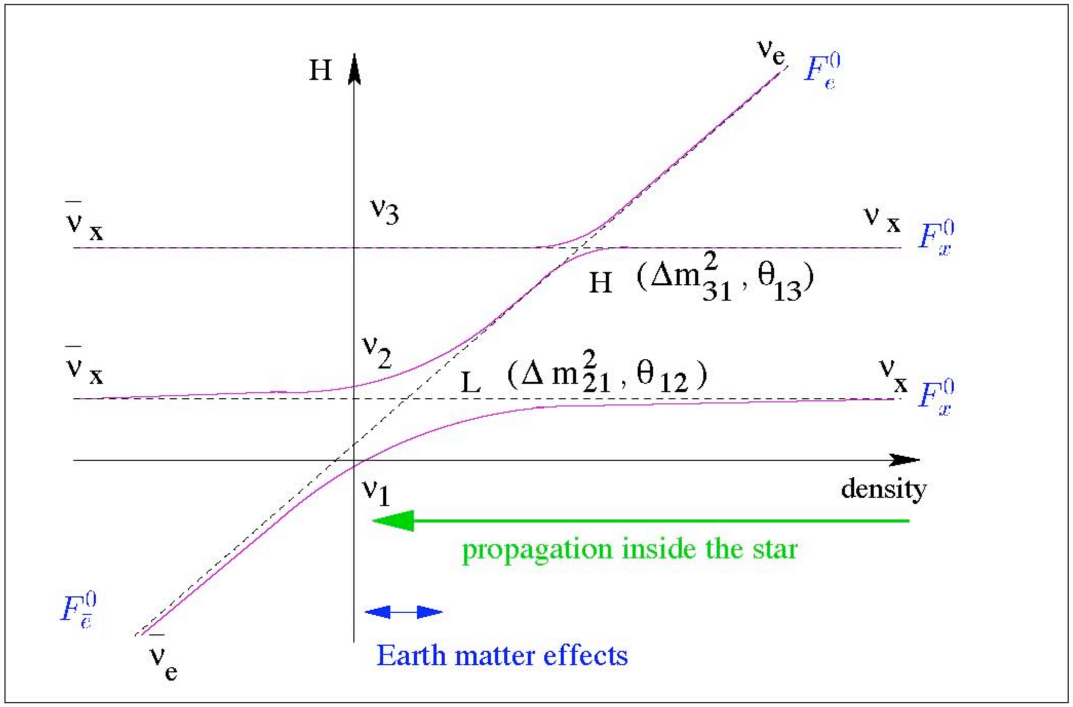
MSW conversion (between ν_e and $\nu_{\mu,\tau}$)

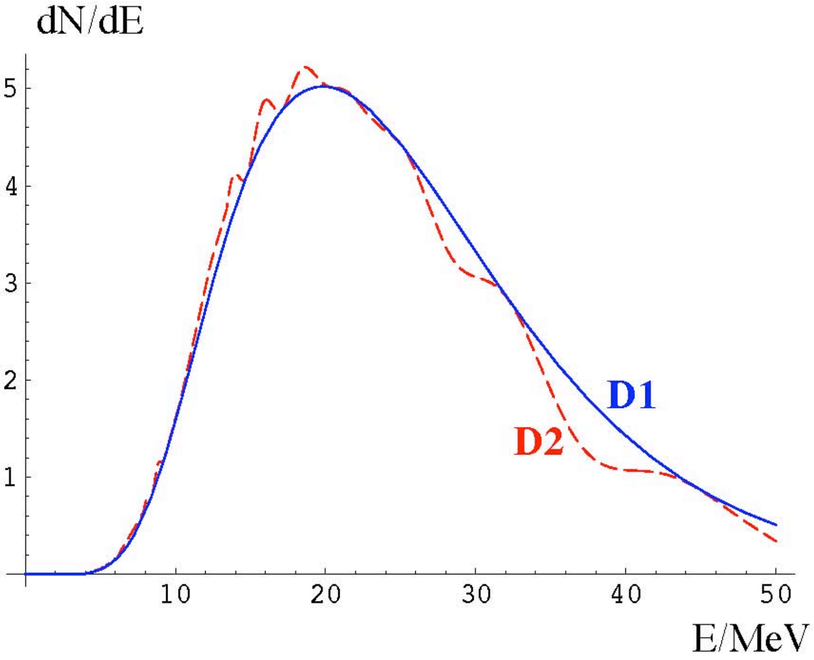
$$\frac{\Delta m^2}{E_\nu} \simeq G_F n_B \underline{Y_e}$$

Since there are two Δm^2 values, there are two conversion densities.

This for normal hierarchy.
Inside the SN neutrinos
are in flavor states, they
emerge in mass eigenstates.

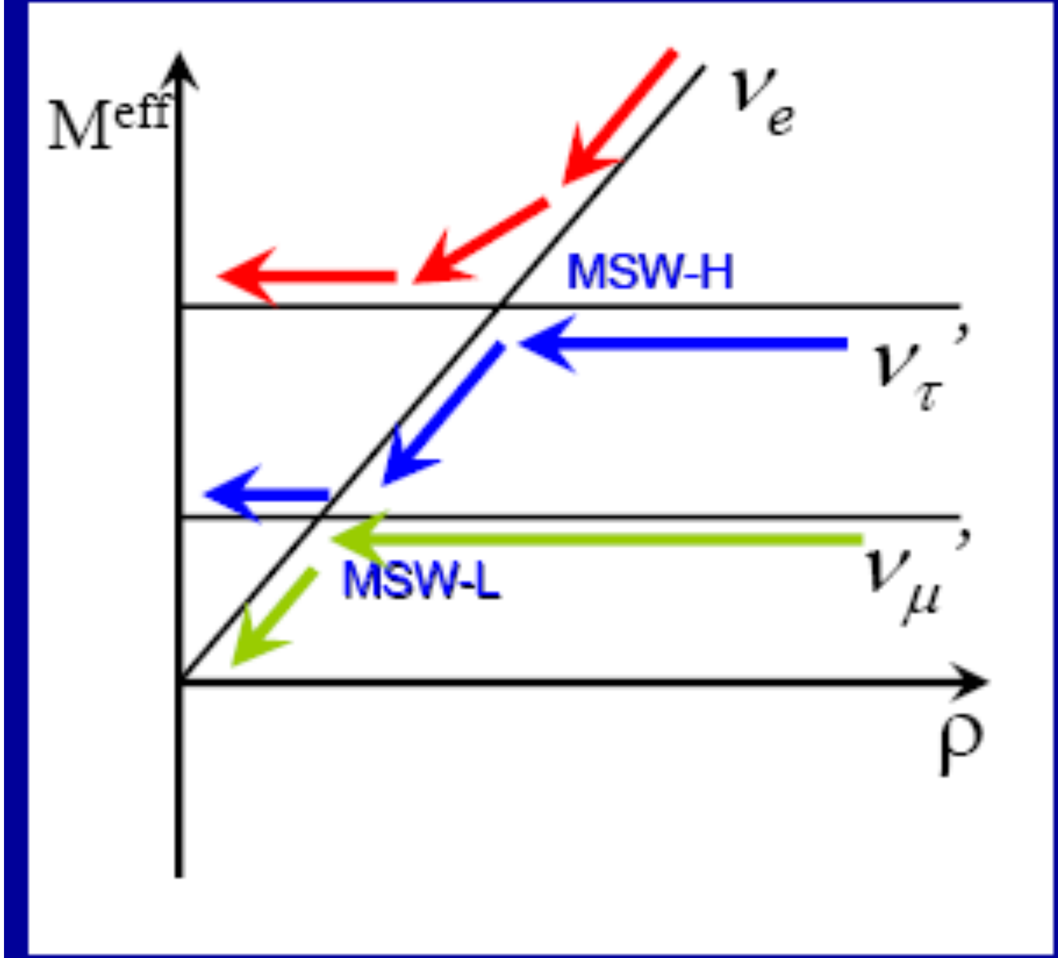
Effect of earth on the
e^+ spectrum from ν_e + p





Three-flavor formulation

- If both MSW resonances are adiabatic

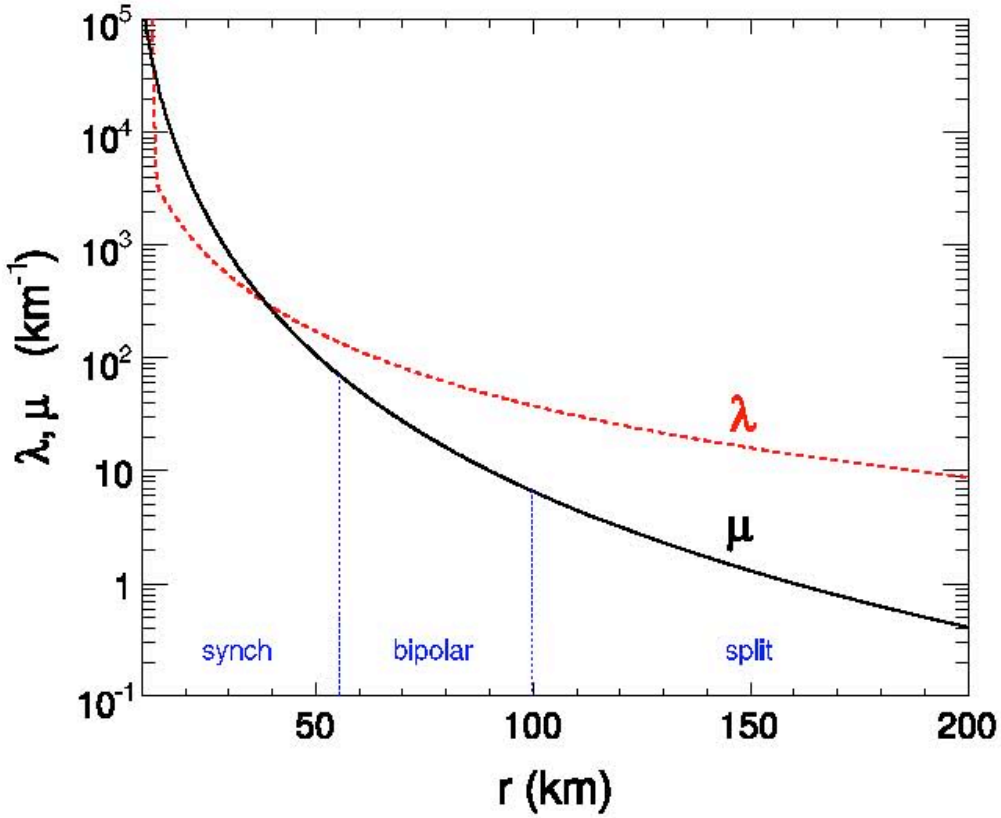


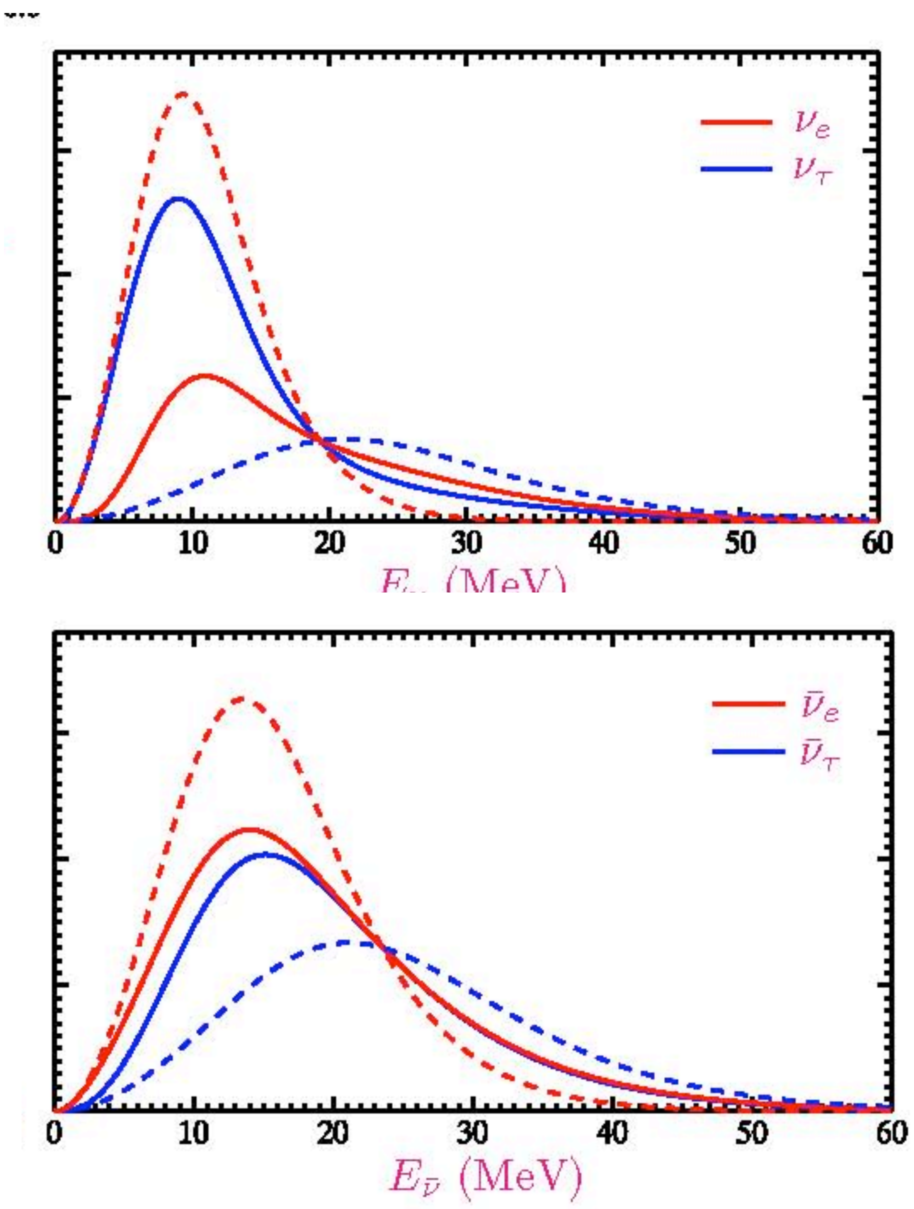
- Produced ν_e becomes the heaviest mass eigenstate ν_3.
- Non-electron neutrinos (ν_x) are mainly converted into the observed ν_e.

$$\nu_e \rightarrow \nu_3$$
$$\nu_x \rightarrow \nu_{1,2}$$

About neutrino selfinteraction in SN:
The selfinteraction strength
$\mu = \sqrt{2}G_F(N_\nu + \bar{N}_\nu)$ is compared to the matter oscillation strength
$\lambda = \sqrt{2}G_F N_e$ as a function of distance above the SN

Effect of selfinteraction:
Original spectra are dashed, final full lines, note the change for ν_τ. Here for normal hierarchy





Relic supernova neutrino flux

- Neutrinos emitted by the core collapse SN are moving freely and accumulate continuously throughout the universe.
- When averaged over contributions of at least 10^8 (10^8 ~ 30 years/10 seconds) galaxies form an isotropic and time independent flux.
- This flux is naturally cut-off by the redshift, $E = E_{in}/(1 + z)$, and eventually becomes unobservable.
- If it can be observed, it will provide information about the average SN rate till z ~ 1, I.e. over a substantial part of the history of the universe.
- A crude estimate of the diffuse ν_e flux gives 'a few' ν_e/cm^2 s resulting in ~0.5 counts per kt per year. — —
- SuperKamiokande (Malek et al. PRL90, 0611001(2003)) gives an upper limit of $1.2/cm^2$ s for energies above 19 MeV. This limit, background limited, is approaching the prediction of various SN relic flux models.

Back of the envelope estimate of the relic flux

- Typical SN has ~$2\text{x}10^{57}$ M_p
- Number of emitted ν_e happens to be also $2\text{x}10^{57}$ ($5\text{x}10^{52}$erg = $30\text{x}10^{57}$MeV, <E> ~ 15 MeV)
- Assume that SN cores contain ~1% of the mass of luminous stars, which in turn have Ω_*~0.005~ 25eV/cm^3
- The ν_e density is the $\rho_\nu \sim \Omega_*/(100\ M_p) \sim$ $2.5\text{x}10^{-10}\nu$/cm3
- The flux is $c\rho_\nu \sim 8\nu/(\text{cm}^2\text{s})$

Relic Supernova Neutrinos

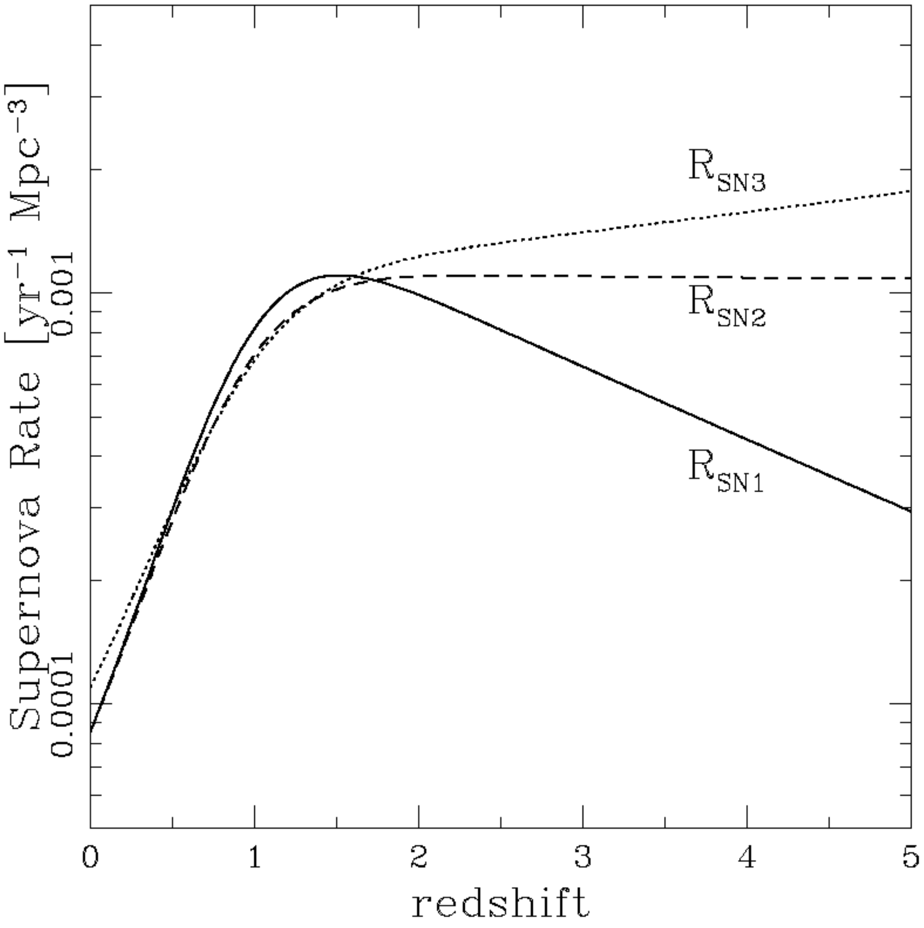


Fig. 2. Supernova rate evolution on the cosmological time scale. These lines are for a Λ-dominated cosmology ($\Omega_m = 0.3, \Omega_\lambda = 0.7$). The Hubble constant is taken to be 70 km s^{-1} Mpc^{-1}.

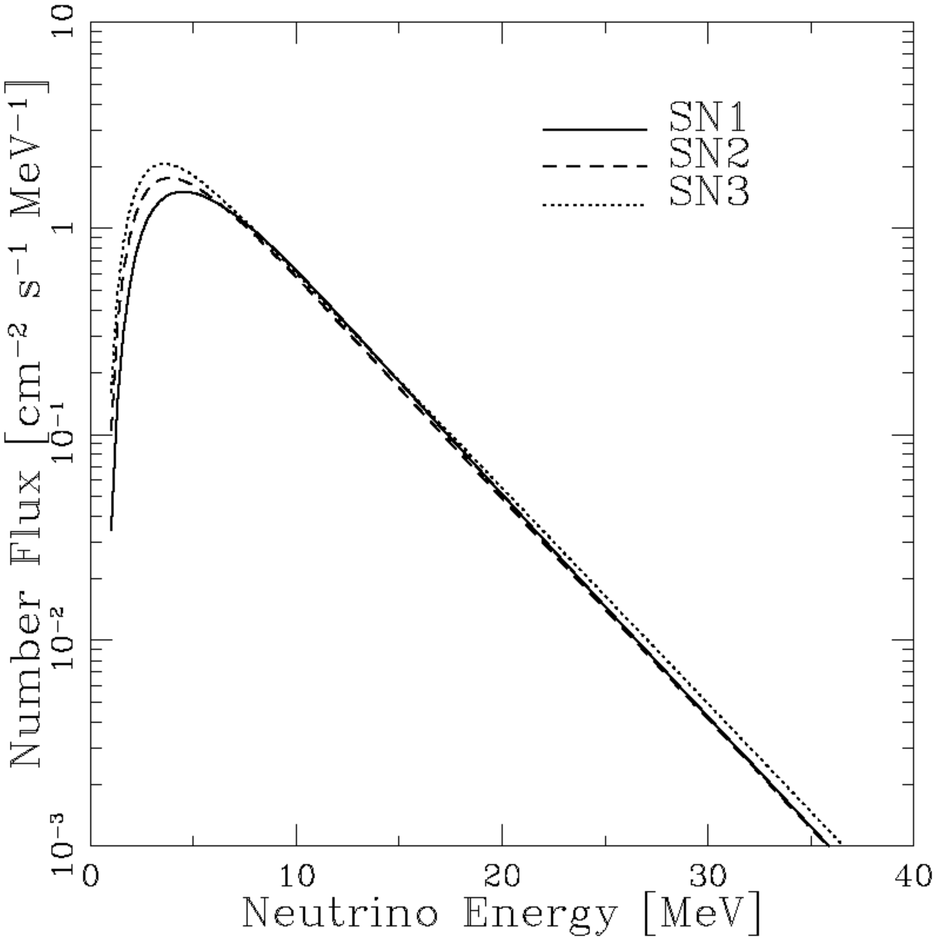
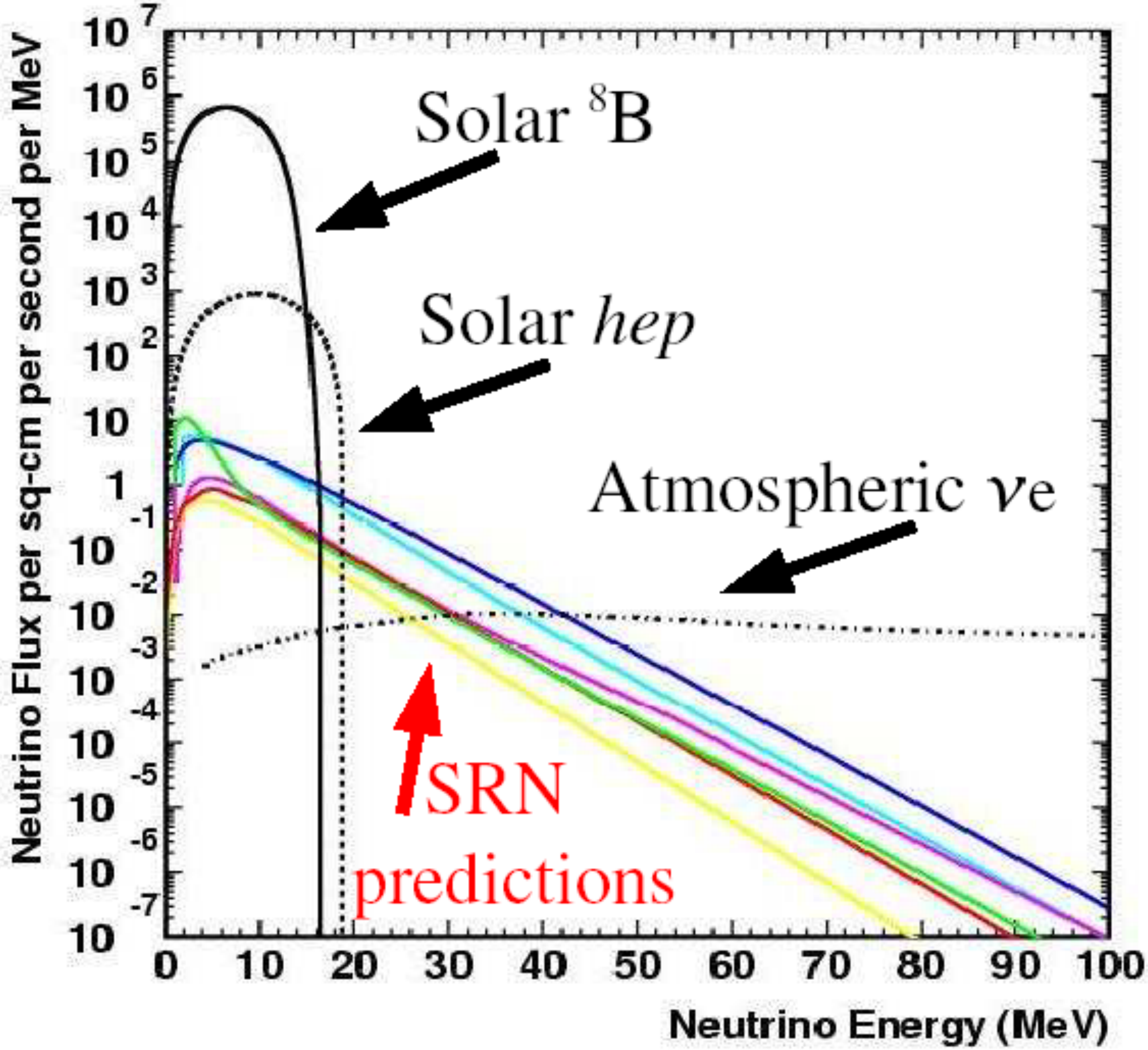


Fig. 3. Number flux of $\bar{\nu}_e$'s for the three supernova rate models, assuming "no oscillation" case.

Ando, Sato, and Totani, Astropart. Phys. 18, 307 (2003)

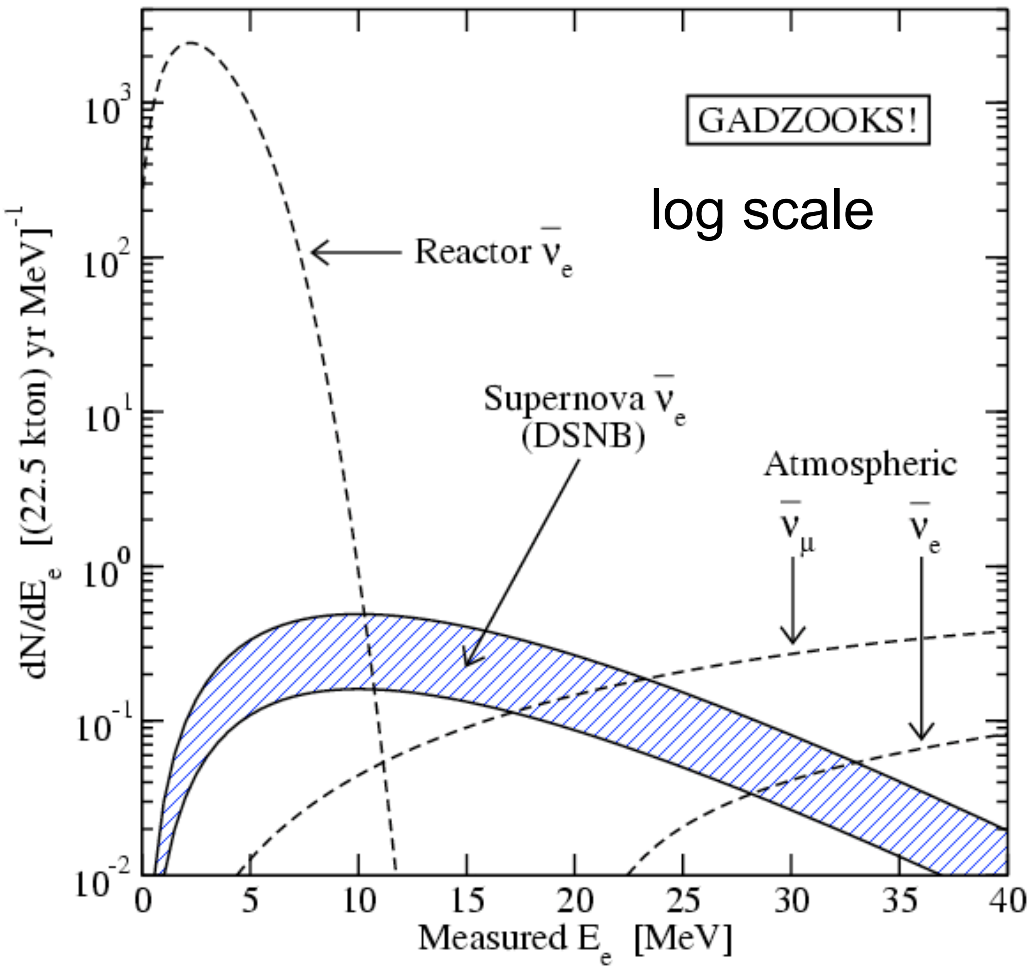
Relative Spectra in SK

(M. Malek)

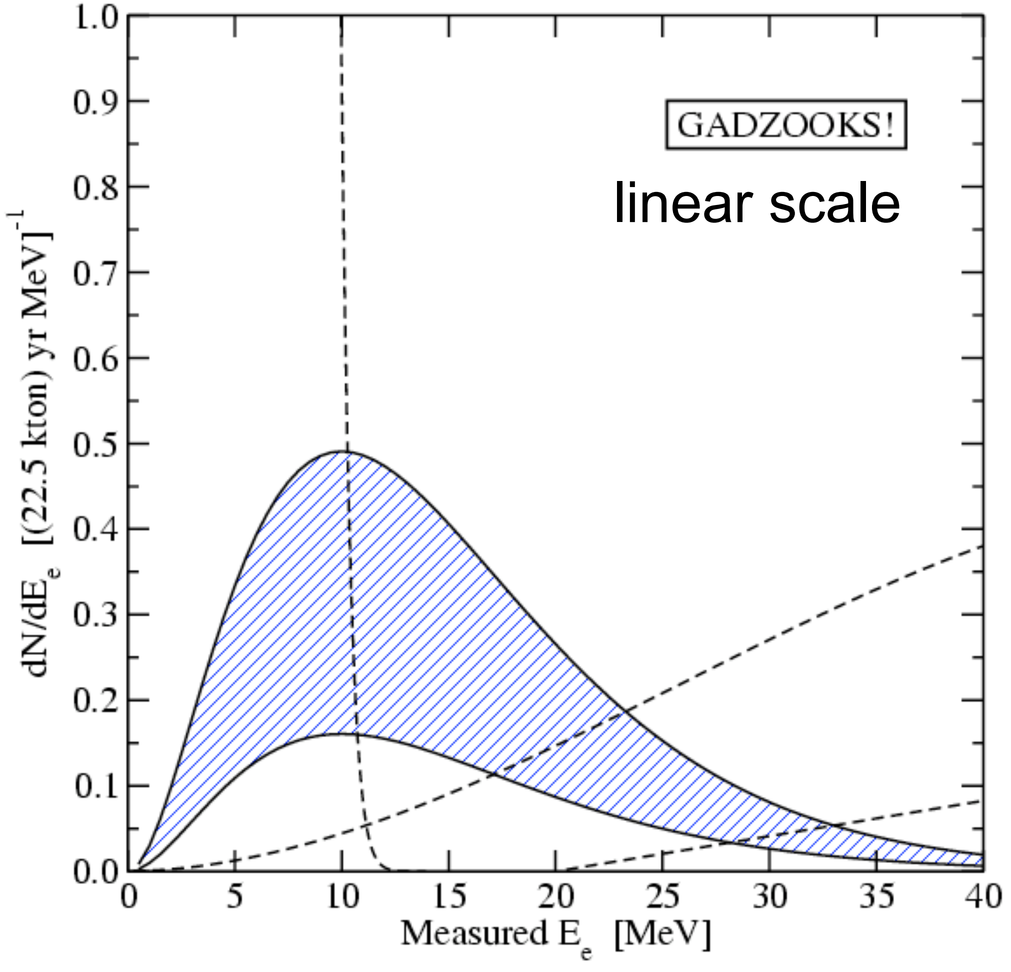


Expect 3-4 events in 22kt of water per year (SK)

SRN Spectrum With GADZOOKS!



log scale



linear scale

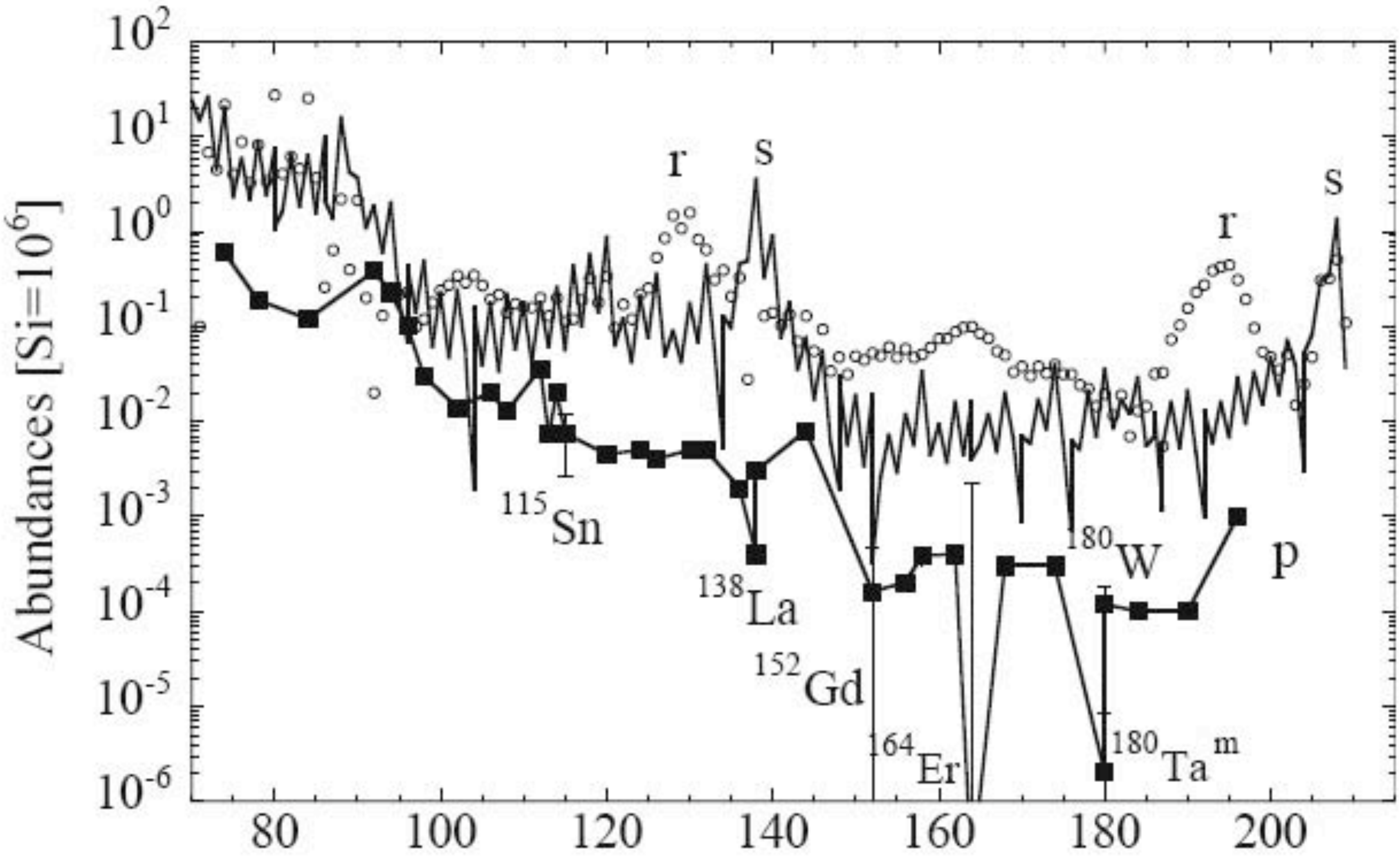
Beacom and Vagins, hep-ph/0309300, PRL93,171101(2004)

Gd added to water to make $\bar{\nu}_e$ detection unambiguous

Conclusions

- Signals corresponding to the charged current reactions induced by the $\bar{\nu}_e$ and ν_e neutrinos, as well as the neutral current reactions induced by all active neutrinos can be separately observed, even though at the present time not all needed detectors exist.
- Both luminosity and average energy of the $\underline{\nu}_e$ component can be accurately determined by SuperK, with important additional signals in all existing detectors.
- It is more difficult to do the same for the ν_e component. In fact no suitable detector for this exist at present.
- In liquid scintillator detectors with very low threshold the elastic scattering on protons is observable. This contains, in principle, spectroscopic information as well.
- It is difficult or impossible to use the time-of-flight to determine sub-eV neutrino masses. The pointing with neutrinos is also crude.
- With even larger detectors one could observe the neutronization relic SN neutrino flux, and perhaps extract oscillation parameters.

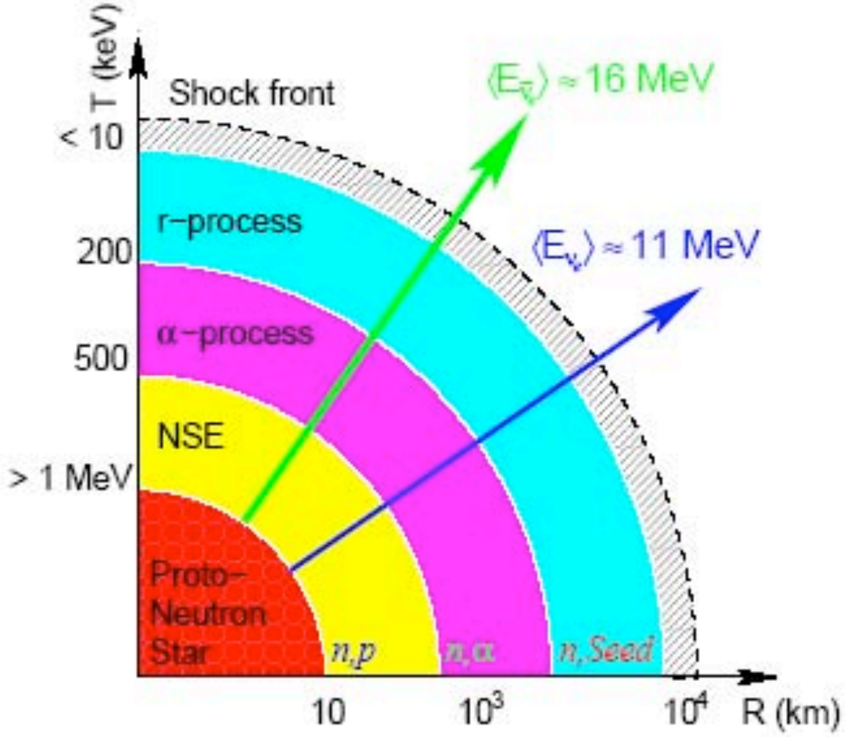
SN neutrinos and the r-process nucleosynthesis



Abundance of heavy elements in the solar system. Approximately equal amounts originate from the s-process (slow) and r-process (rapid). Note the shifted abundance peaks related to the magic numbers.

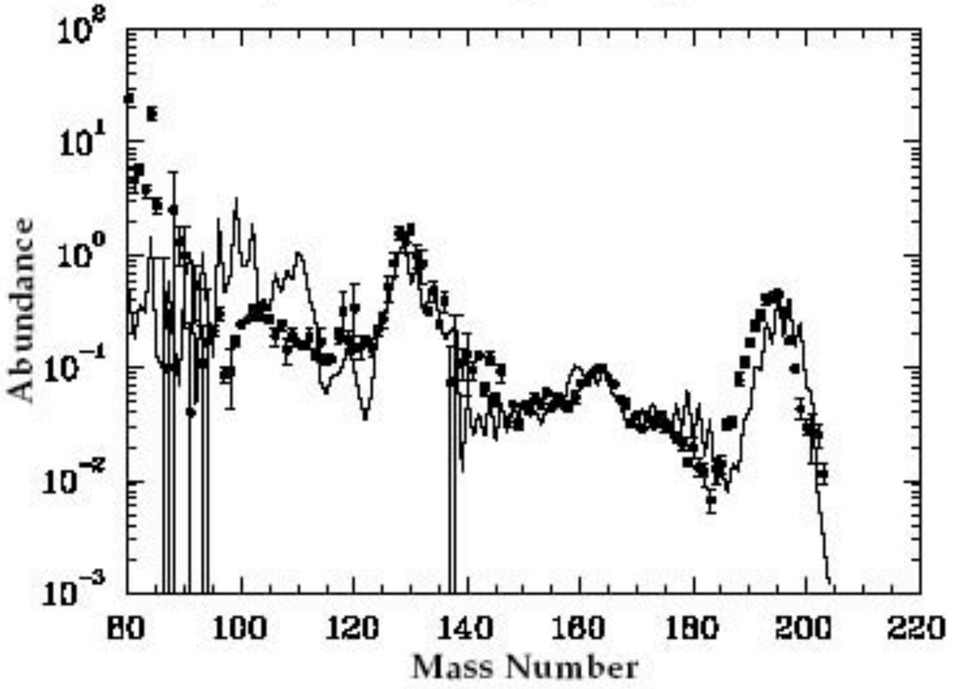
The r-process requires exceptionally explosive conditions:
$\rho(n) \sim 10^{20\text{-}24}$ cm^{-3}, T ~ 10^9 K, t ~ 1 sec

Neutrino-driven wind



- Neutrino-wind from (cooling) NS
  $\nu_e + n \rightarrow e^- + p$
  $\bar\nu_e + p \rightarrow e^+ + n$
- α-process (formation seed nuclei)
  $\alpha + \alpha + n \rightarrow {}^9\mathrm{Be} + \gamma$
  $\alpha + {}^9\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + n$

(S. Woosley *et al*)



- Expansion adiabatic (Entropy constant) and $r \sim e^{t/\tau}$.
- Main parameter determining the nucleosynthesis is the neutron to seed ratio

r-process in the SN neutrino driven wind. Since the $\overline{\nu_e}$ have larger energy than the ν_e the wind will be neutron rich. Modeling realistic r-process abundance without forcing parameters is difficult. But this scenario of the r-process is still the most likely one.