Supernova Neutrinos Detection: a brief overview

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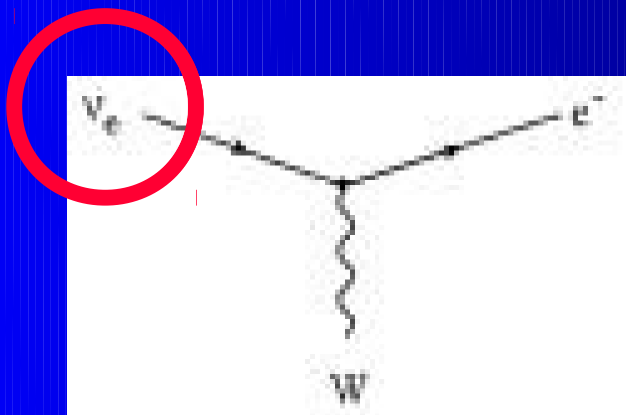
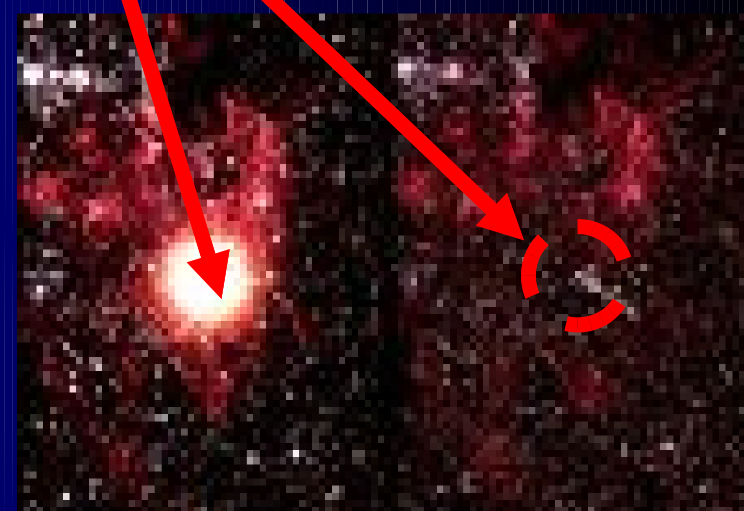
Supernovae and Neutrinos



The relations between the most elusive particle and one of the most “thundering” events of the universe...



PHYSICS MOTIVATIONS:
Astroparticle Physics

* Use cosmic particles as probes of extreme astrophysical environments

ν !

- They scape from innermost regions of astrophysical objects (photon cross section is 20 x greater...)

* Better source knowledge: getting information about the probe

ν properties

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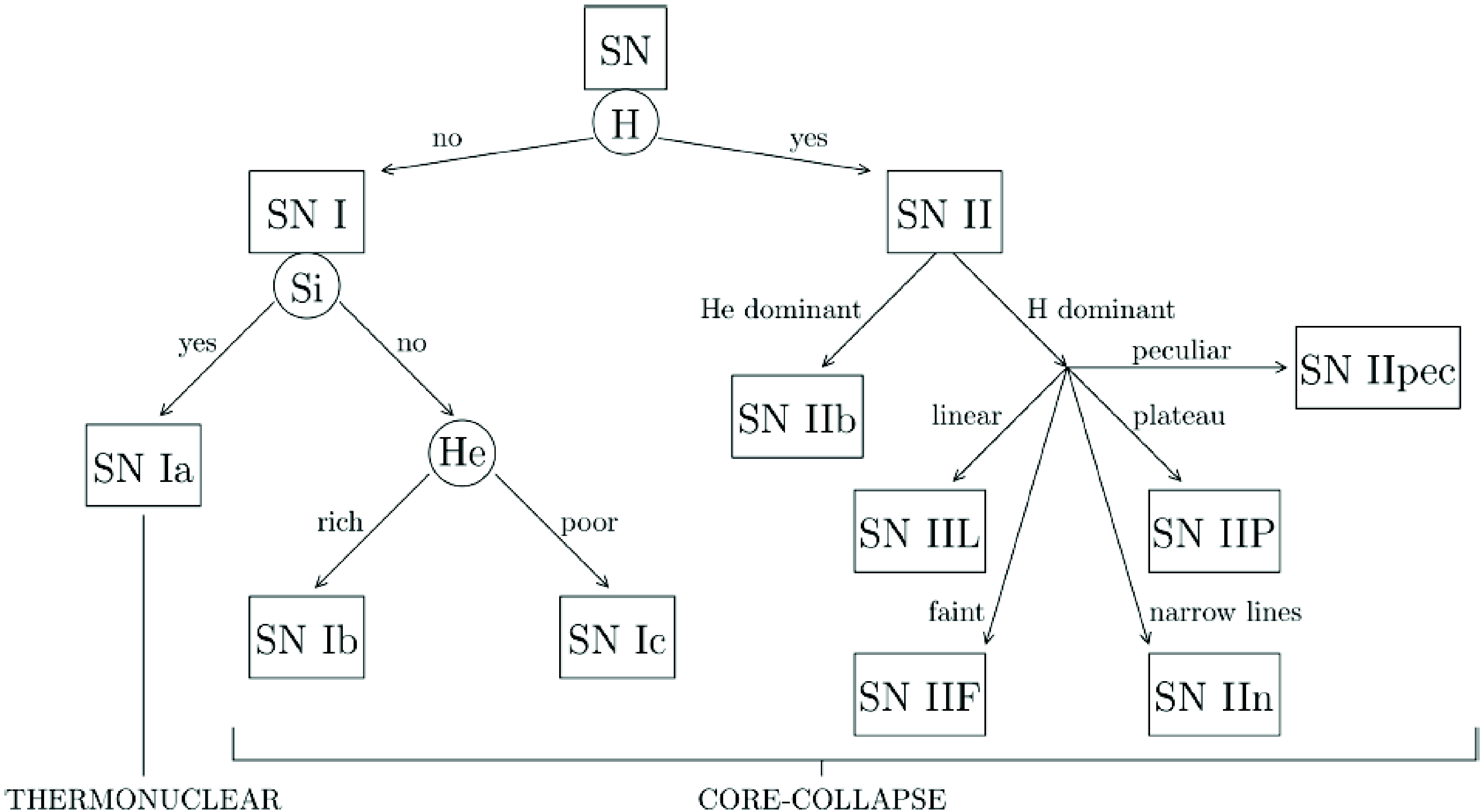
Overview

- Introduction
  - Stellar evolution
  - Supernova mechanism (type II): gravitational collapse
  - SN neutrinos: main features
- SN 1987 A
  - Detection
  - What we have learned
- Neutrinos Telescopes
  - Guidelines
  - Techniques: Cherenkov , Scintillators
- Current experimental scenario
  - Who is running
  - SNEWS
- Conclusions

Thanks for M. Selvi, LVD-Bologna,and W. Fulgione LVD-Torino for many slides in this presentation

SN Classification



From Giunti and Kim - Fundamentals on Neutrino Physics and Astrophysics

Thermonuclear Evolution and Stellar Structure

- Thermonuclear reaction sequence:

  H → He → C → O (Ne) → Si → Fe

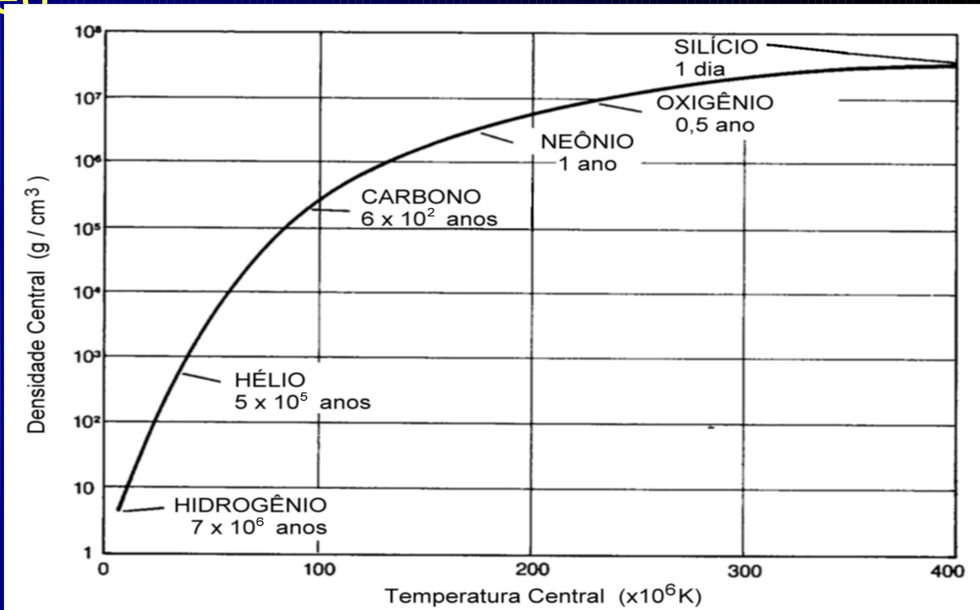
Since one light element is completely burned, the stellar core contracts, the temperature increases, and the burning of the heavier element in the sequnce is triggered

The cycle is always shorter

- CNO cycle:
  - He → C
    - $3\alpha \rightarrow C+\gamma$ (~ 5 x 10^5 y),

  C→ Ne and O
    - $C+\alpha \rightarrow O+\gamma$ ~ (600 y),
    - Si (~ 1 ano)
  - Last stage:

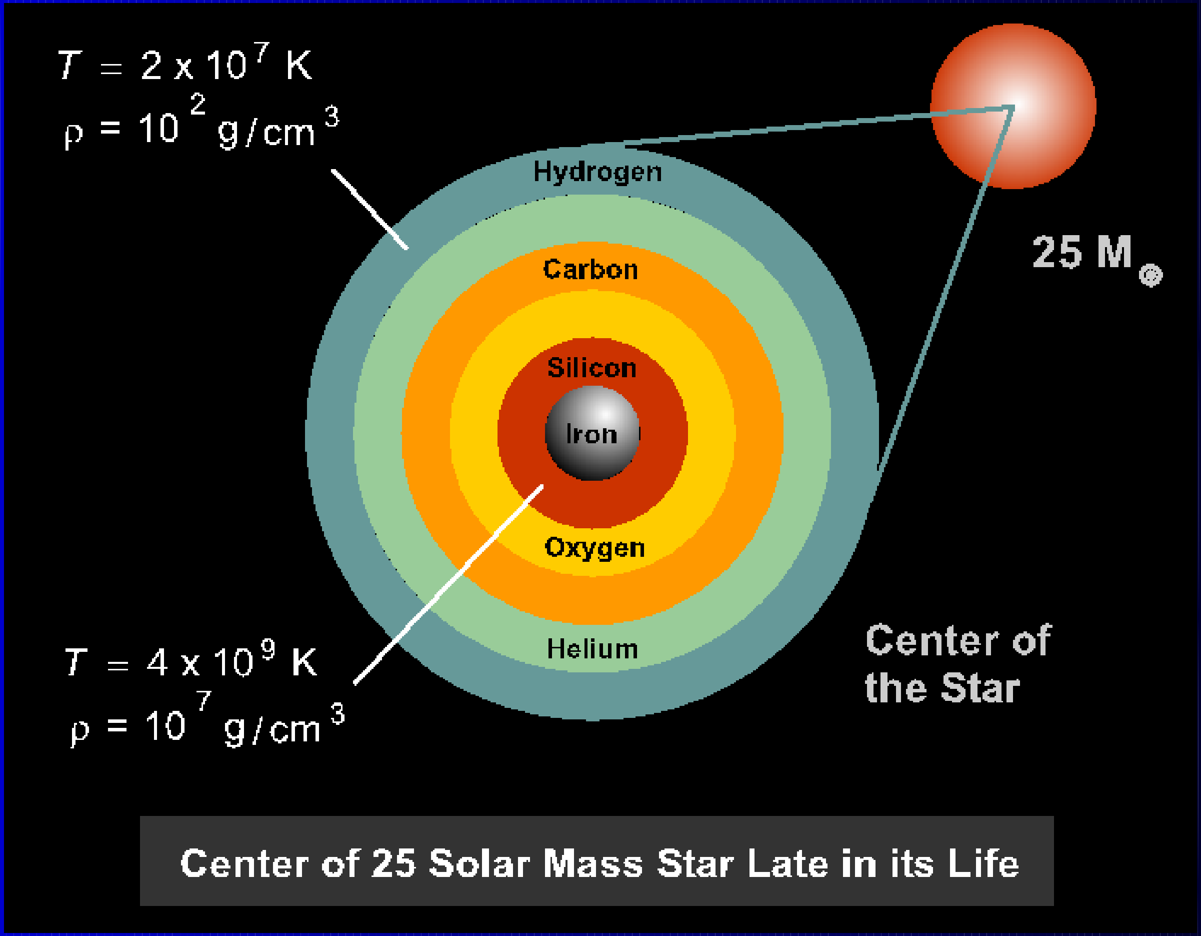
    Si → Fe (~ 1 day).



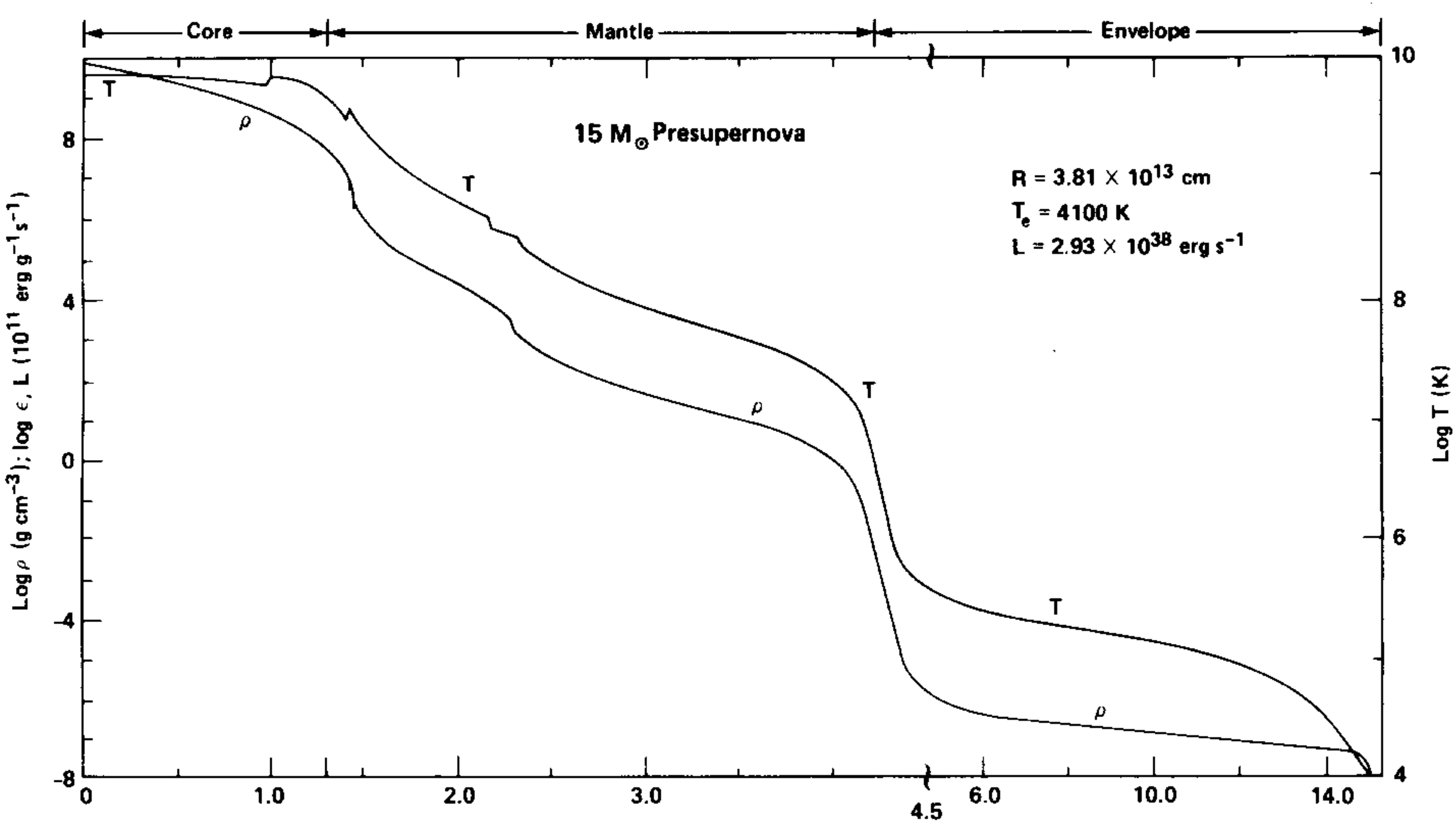
- J. N. Bahcall, *Neutrino Astrophysics*, Cambridge University Press, E.U.A. (1989).

Thermonuclear Evolution and Stellar Structure

- “Onion” configuration:



Physical and Chemical Profiles:



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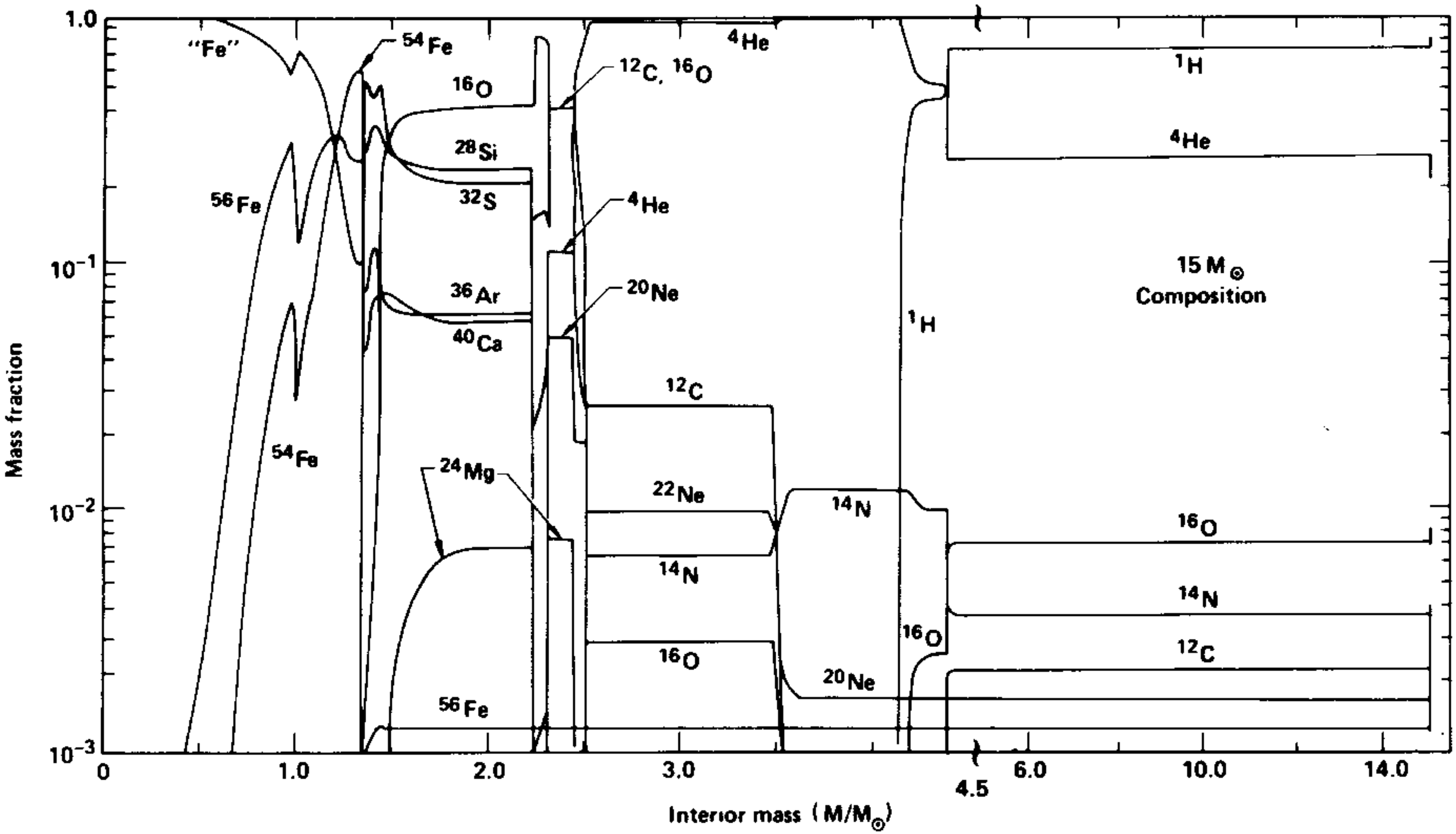


Explosion: I

- ν trapping

  $\rho_a \sim 6\times10^{11}$ g/cm^3 $\rightarrow$ $\lambda \sim$ 1 km

  $R_{Fe} \sim$ 100 km

  Neutrinosphere

$$\tau(R_\nu) = \int_{R_\nu}^{\infty} \frac{dr}{\lambda_\nu} = \frac{2}{3}$$

Explosion: II

- Phase transition of nuclear matter

Central Density:
$\rho_c \sim 2{,}7\times10^{14}$ g/cm^3

$$P = k\,\rho^{\gamma}$$

change of pressure main contribution

P_{e-} ; $\gamma = 4/3 \rightarrow P_n$; $\gamma = 5/3$

stiffness of stellar core

BOUCING $\rightarrow$ EXPLOSION

(shock wave) (ν re-heating)

Explosion: III

- Prompt explosion: pure hydrodinamical mechanism (?)
- Delayed explosion: shock is revitalized by neutrinos

$$\frac{d\dot{E}}{dm} = K(T_\nu)\left[\frac{L_\nu}{4\pi R_m^2} - \left(\frac{T_m}{T_\nu}\right)^2 a T_m^4 c\right]\frac{\text{erg}}{g \cdot s}$$

R : distance to the center
T : temperature [MeV]
K: neutrino absortion coeficient

Lν : Nu flux luminosity.

- First term: energy gain;
- Second term: looses by emmision from neutrino capture;
- Net gain: where ?

  R ~ 150 km (out of neutrinospheres !)
- The power released by neutrinos (~ 50 MeV s^{-1} / nucleon), revival the shock after ~250 ms.

Hydrodinamical mechanism (?)

Astro-ph/0510687

A NEW MECHANISM FOR CORE-COLLAPSE SUPERNOVA EXPLOSIONS

A. Burrows[1], E. Livne[2], L. Dessart[1], C.D. Ott[3], J. Murphy[1]

Accepted to Ap.J.

ABSTRACT

In this paper, we present a new mechanism for core-collapse supernova explosions that relies upon acoustic power generated in the inner core as the driver. In our simulation using an 11-$M_\odot$ progenitor, an advective-acoustic oscillation à la Foglizzo with a period of ~25–30 milliseconds (ms) arises ~200 ms after bounce. Its growth saturates due to the generation of secondary shocks, and kinks in the resulting shock structure funnel and regulate subsequent accretion onto the inner core. However, this instability is not the primary agent of explosion. Rather, it is the acoustic power generated early on in the inner turbulent region stirred by the accretion plumes, and most importantly, but later on, by the excitation and sonic damping of core g-mode oscillations. An $\ell = 1$ mode with a period of ~3 ms grows at late times to be prominent around ~500 ms after bounce. The accreting protoneutron star is a self-excited oscillator, "tuned" to the most easily excited core g-mode. The associated acoustic power seen in our 11-$M_\odot$ simulation is sufficient to drive the explosion >550 milliseconds after bounce. The angular distribution of the emitted sound is fundamentally aspherical. The sound pulses radiated from the core steepen into shock waves that merge as they propagate into the outer mantle and deposit their energy and momentum with high efficiency. The ultimate source of the acoustic power is the gravitational energy of infall and the core oscillation acts like a transducer to convert this accretion energy into sound. An advantage of the acoustic mechanism is that acoustic power does not abate until accretion subsides, so that it is available as long as it may be needed to explode the star. This suggests a natural means by which the supernova is self-regulating.

Subject headings: supernovae, neutrinos, multi-dimensional radiation hydrodynamics, stellar pulsations

SN ν's spectrum: numerical simulations

Numerical integration or Monte-Carlo using the Boltzmann transport equation:

$$\frac{1}{c}\frac{\partial f}{\partial t}+\hat{p}.\nabla f=k_a\rho(b-f)-f\int(1-f')\rho\kappa_s(E,\Omega\rightarrow E',\Omega')\frac{d^3p'}{h^3}+(1-f)\int f'\rho\kappa_s(E',\Omega'\rightarrow E,\Omega)\frac{d^3p'}{h^3}$$

First term : nu absorption and emmision by free nucleons, *b* is the distribution function (similar to *f*) in the case of emmision.

Second and third terms: nu scattering (E, Ω) → (E', Ω')
κs is the opacity

- Constraints on particle number:

$$\int f(x,p,t)\frac{d^3p}{h^3}=N$$

$$f(x,p,t)=\frac{1}{e^{\left(\frac{E-m_\nu}{kT}\right)}+1}$$

SN ν's spectrum: numerical simulations

- General behaviour obtained for neutrino fluxes (from different groups!) can be reasonable described by the function:

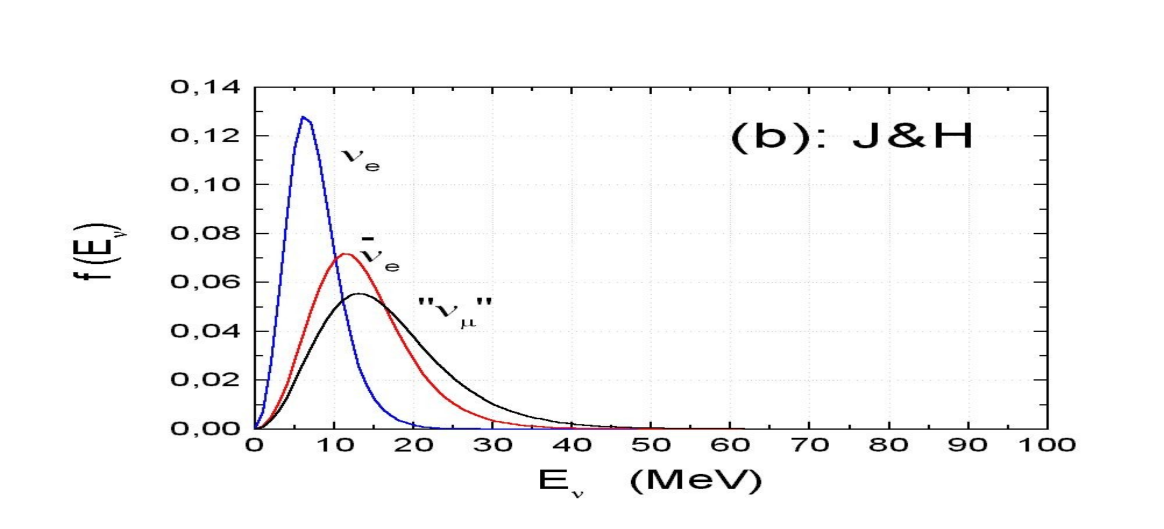
$$\frac{dN_\nu}{dE} = A \frac{E^2}{1 + e^{x-h}}$$

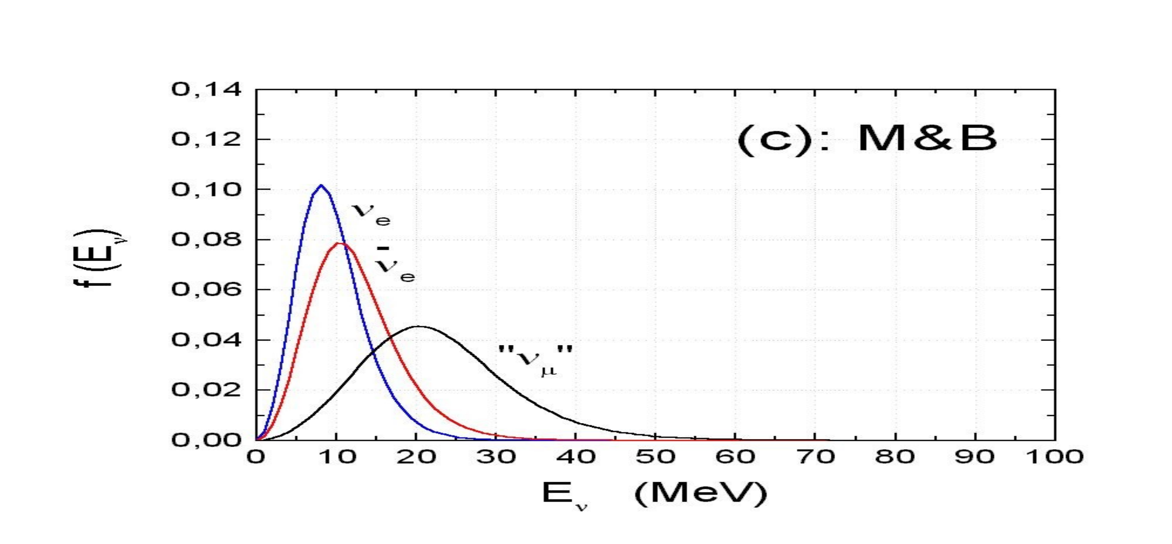
  - A $\rightarrow$ *normalization factor* ;

    energy boundary: $E_{total} \sim 3 \times 10^{53}$ erg

  - x = E / T $\rightarrow$ *spectral temperature ;*
  - η $\rightarrow$ *pseudo-degeneracy* ;

SN υ's spectrum





SN ν main features

The hierarchy of the temperatures: $T_{\nu e} < T_{\bar{\nu e}} < T_{\nu x}$.

Recent studies with an improved treatment of neutrino transport, microphysics, the inclusion of nuclear bremsstrahlung, and the energy transfer by recoils find somewhat smaller differences between the ν_e and ν_x spectra (see for example astro-ph/0303226).

The approximate equipartition of energy among flavors:

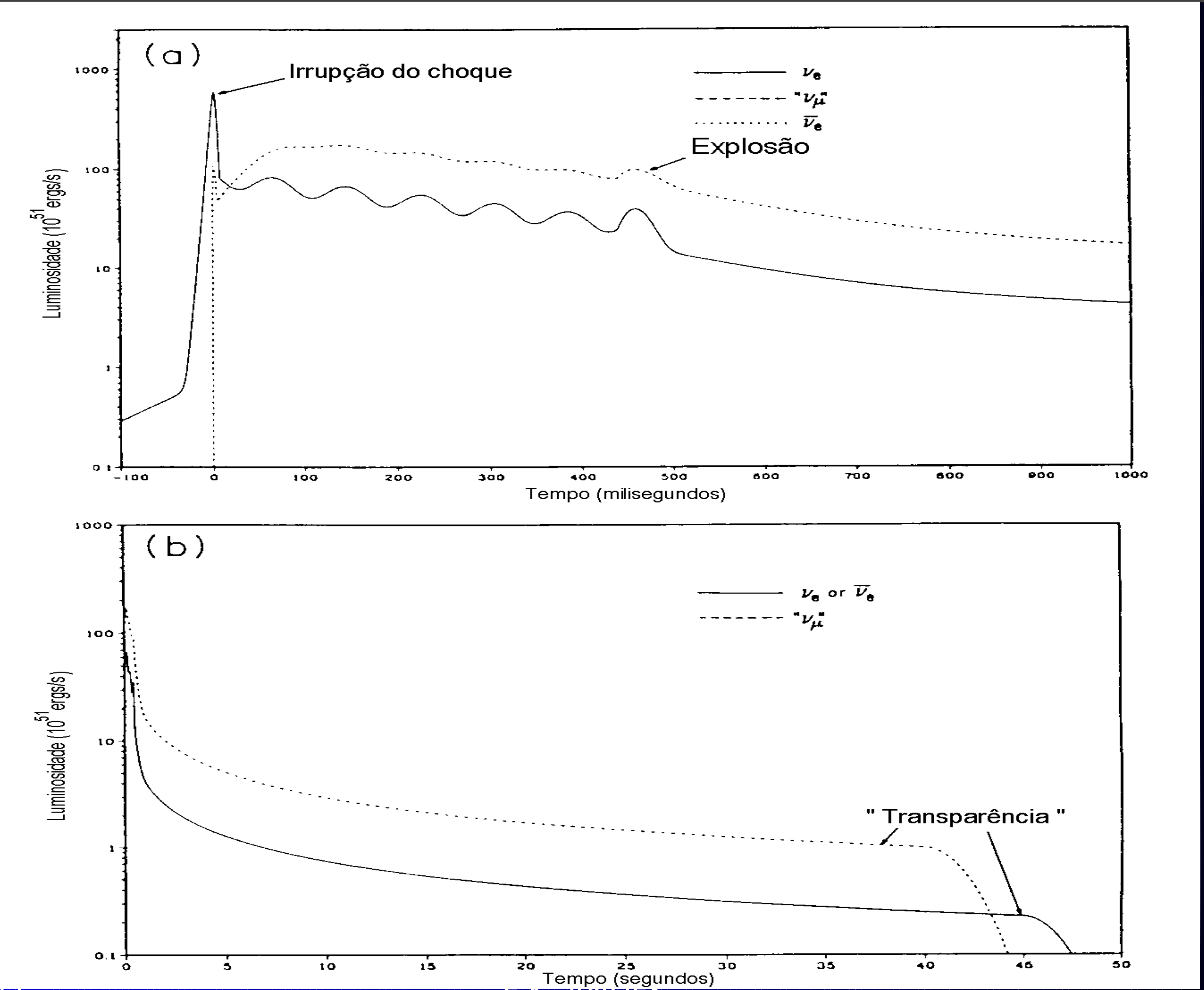
$L_{\nu e} \cong L_{\nu e} \cong L_{\nu x} \cong E_B/6$.

a binding energy of $E_B = 3 \times 10^{53}$ erg,

Ratios are

$T_{\nu x}/T_{\nu e} \sim 1.5$, $T_{\nu e}/T_{\bar{\nu e}} \sim 0.8$ and $T_{\nu e} \sim 3$ MeV

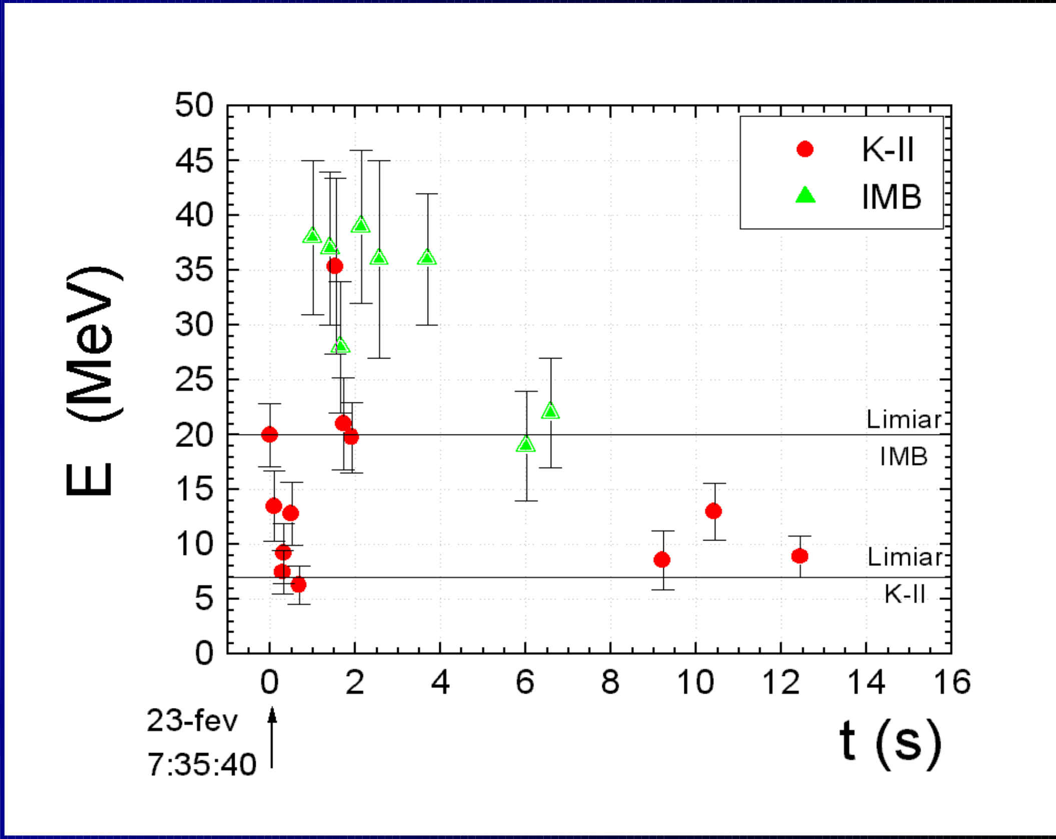
Luminosity and ‹E›



SN 1987A

- **ν's from Shelton Supernova – SN 1987A, arrived on Earth in Feb-23-1987, 07:35:35 UT**

Experiment	# events
Kamiokande-II	12
IMB	8
Baksan (?)	5
LSD (??)	5



What an analysis of a handful of events can show us: ...

Collapse Dynamics

- Total Energy ✓
- Duration ✓

Time Structure **(SK, Icecube ?)** *.. open ..*

Spectrum ✓

- Thermal characteristics (black body ??)
- Temperatures ✓

- **Energetic Partition** *.. open ..*

✓ : ... Checked by SN1987A

Our handful of events yet ... Neutrino Properties

- Delayed explosion 100$\times$ more probable than prompt explosion.
- Average energy $\langle E_{\bar{\nu}_e} \rangle \approx 15\,\mathrm{MeV}$.
- Neutrinos emitted $N_{\bar{\nu}_e} \approx 3 \cdot 10^{57}$.
- Energy emitted $E = 3 \cdot 10^{53}$ erg.
- Time scales
  - accretion of mass $\Delta t = 0.7\,\mathrm{s}$,
  - cooling phase $\Delta t = 4\,\mathrm{s}$

Neutrino mass:

Model independent $m_{\nu_e} \lesssim 30\,\mathrm{eV}$.

Model dependent $m_{\nu_e} < 5.7\,\mathrm{eV} \qquad (95\%\ \mathrm{CL})$.

Our handful of events yet ... Neutrino Properties

Several other properties of neutrinos are constrained

- Lifetime of electron antineutrino

$$\tau_{\bar{\nu}_e} \gtrsim 1.6 \cdot 10^5 \frac{m_{\nu_e}}{E_{\bar{\nu}_e}} \,\mathrm{yr},$$

- Number of flavours $N_\nu \lesssim 6$,
- Magnetic moment

$$\mu_{\nu_e} \lesssim 10^{-12} \mu_B,$$

- Charge radius of right-handed neutrinos

$$\langle r^2 \rangle_R \lesssim 2 \times 10^{-33} \,\mathrm{cm}^2,$$

- Electric charge of electron neutrino

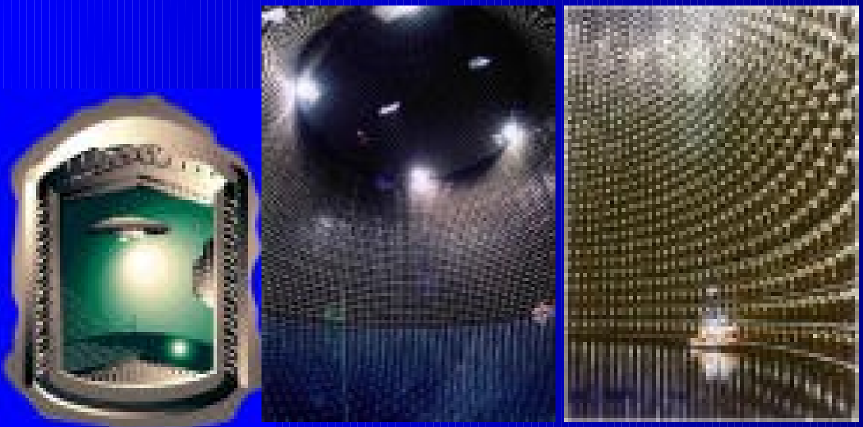
$$q_{\nu_e} \lesssim 10^{-17} e.$$

Neutrino Telescopes

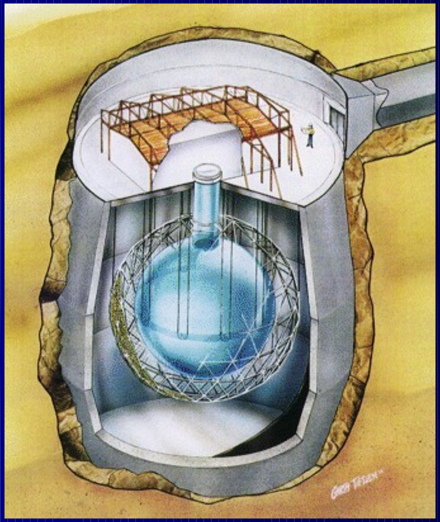
Why getting down on Earth to see stars ???

Neutrino Telescopes

SuperKamiokande

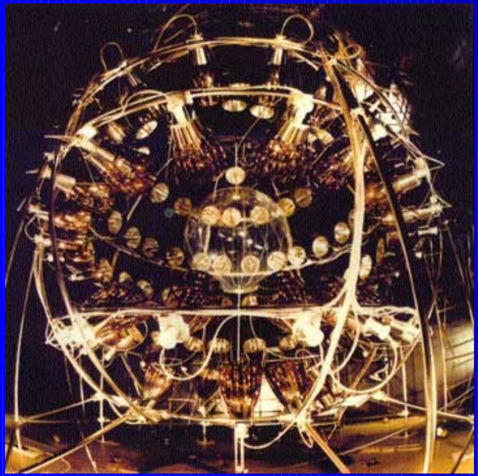


Amanda

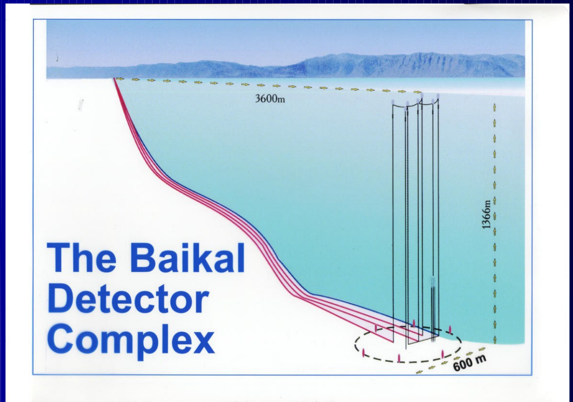


SNO

LVD



Borexino



ν-Telescopes: minimum requirements

- Large Mass:
  - due ν small cross-section

    $\sim 10^{-41} \div 10^{-44}\ cm^2$
- Big Depths:
  - Low radiation environments
  - Shielding for cosmic radiation

Typical Dimensions

$$N_\nu = \sigma_\nu F N_A \frac{M}{A} n_T$$

* $N\nu$: number of expected events
* $\sigma\nu$: cross section
* F : flux
* N_A : Avogadro's number
* M , A : total mass , molecular weight of the target
* n_T : number of targets particles / molecule

• to have ~ 100 events via inverse β-decay in liquid scintillator:

$\sigma\nu = 10^{-41}$ cm^{-2},

F ~ 10^{11} cm^{-2} (collapse in the galactic center),

A = 14 (CH2 scintillator),

n_T = 2 (H protons),

M ~ 1 kton → 10 m size cube

Detector additional requirements

Burrows' prescriptions, 1992:

A. Burrows, D. Klein e R. Gandhi, *Phys. Rev.*, **45D**, 3361 (1992).

"Beyond material, mass and depth, a Supernova neutrino telescope must have: .."

- **buffers adequate to handle high throughoutput**
- **short deadtime**
- **accurate absolute and relative timing**
- **good energy resolution**
- **low maintenance cost and a high duty cycle**

Latter, consense adds :

- **ability to distinguish among flavors**

Detectors for stellar collapse ν

Experiment	Mass (t)	Target	Lab
Super-Kamiokande	32000	H_2O	Kamioka Mines
SNO	1400 , 1000	H_2O , D_2O	Sudbury
LVD	1000	“H_nC_{2n+2}”	LNGS
Kamland	1000	“H_nC_{2n+2}”	Kamioka
MiniBoone	500	“H_nC_{2n+2}”	FermiLab
Baksan (SN in the Galaxy best limit < 0.13 / y)	330	“H_nC_{2n+2}”	Russia

Borexino (300 t of C_9H_{12}) is working,

Icarus (600 t of Lar) has been aprooved

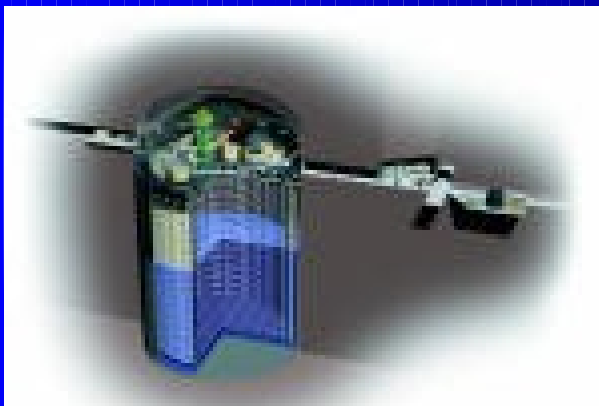
Icecube may observe a statistical enhance in the PM counting rate.

Cherenkov:

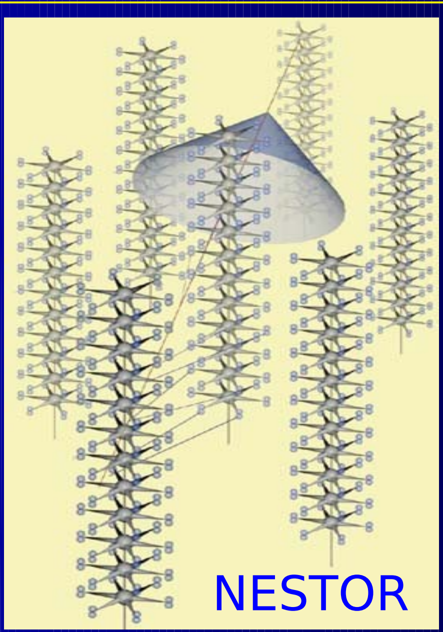
+) direction and energy   -) higher thresholds

- H2O :
  Tanks SuperKamiokande
  Ocean Nestor
  Lake Baikal
- D2O :
  SNO $\rightarrow$ "ν_μ" sensitivity
- Ice :
  Icecube

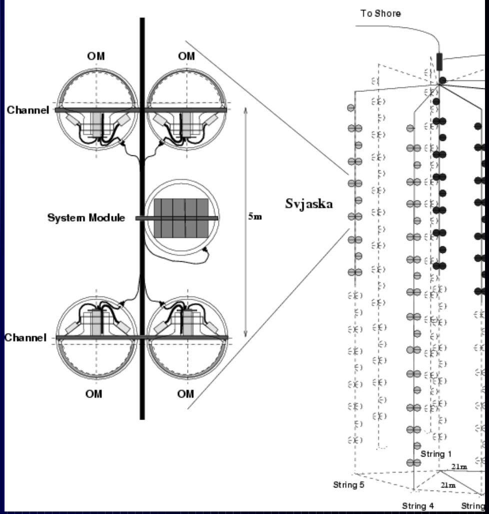
Cerenkov:
+) direction and energy / -) higher thresholds



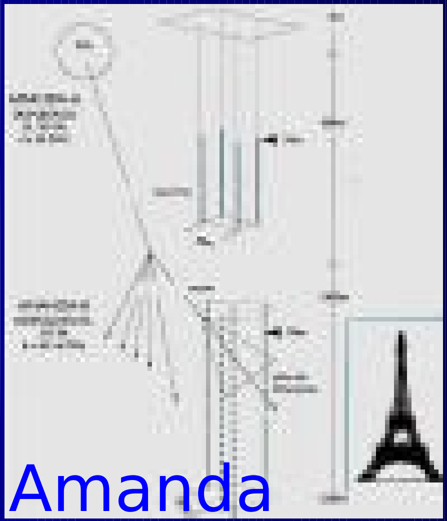
Superkamiokande



NESTOR

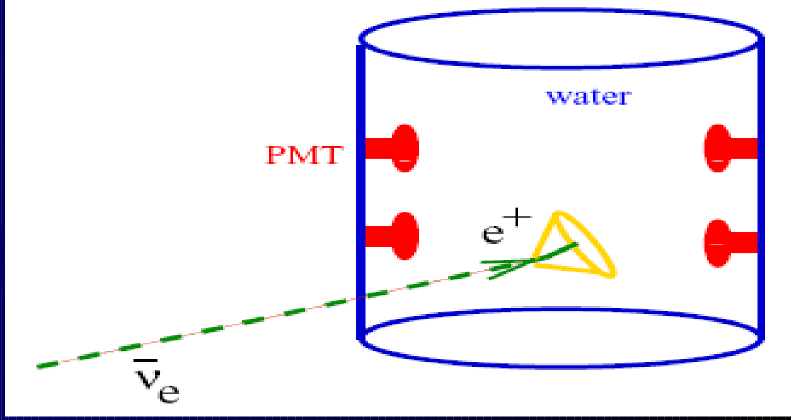


BAIKAL



Amanda

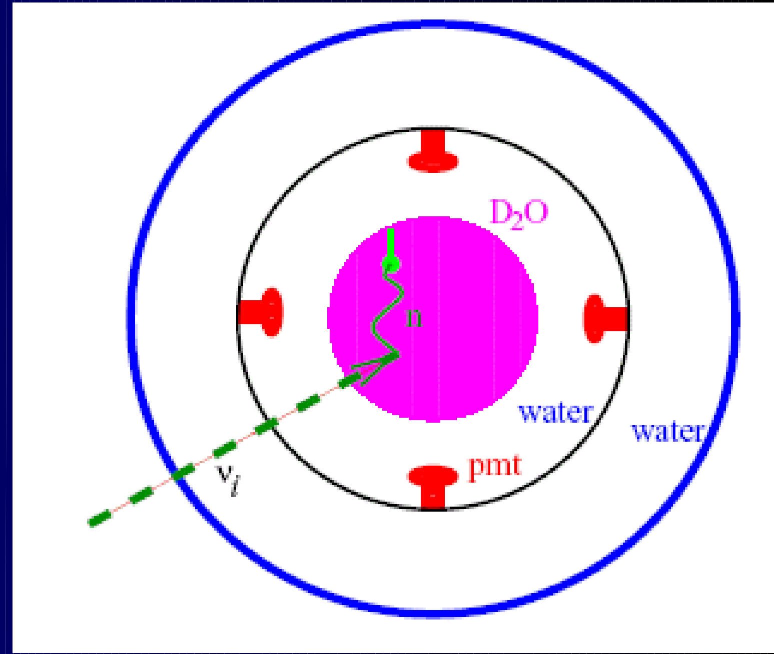
SN ν interactions in
Water Čerenkov



Interactions in H_2O	Int.	Energy threshold (MeV)
$\bar{\nu}_e + p \to n + e^+$	CC	1.8
$\nu_i + e^- \to \nu_i + e^-$	CC-NC	
$\nu_e + {}^{16}O \to {}^{16}F + e^-$	CC	15.4
$\nu_i + {}^{16}O \to \nu_i + \gamma + X$	NC	13.1 (Z(X) = 1^-) 16.1(Z(X) = 2^-)
$\bar{\nu}_e + {}^{16}O \to {}^{16}N + e^+$	CC	11.4

SN ν interactions in heavy water Čerenkov

(SNO)

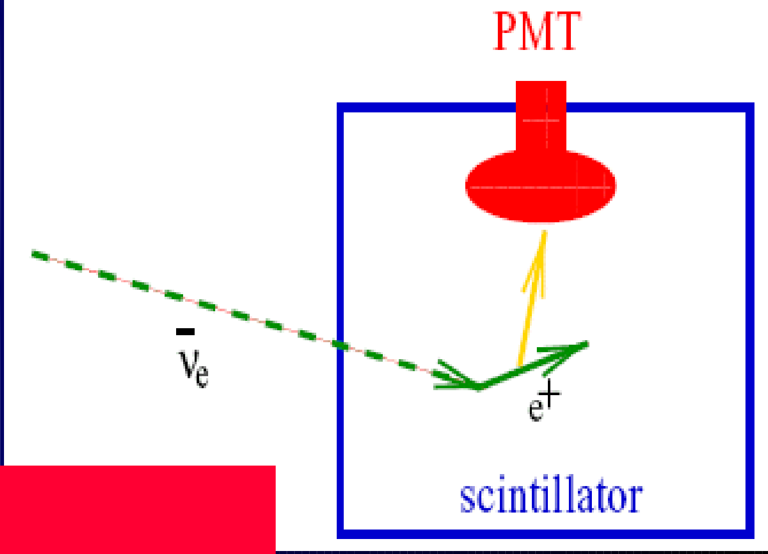


Interactions in D_2O	Int.	Energy threshold (MeV)
$\nu_i + d \rightarrow n + p + \nu_i$	NC	2.22
$\nu_e + d \rightarrow p + p + e^-$	CC	1.44
$\nu + d \rightarrow n + n + e^+$		

High statistic sample of all-flavors neutrinos

SN ν interactions in Liquid Scintillator

C_nH_{2n} volume surrounded by PMTs
(LENA, Kamland, LVD, Borexino, MiniBoone, Baksan)



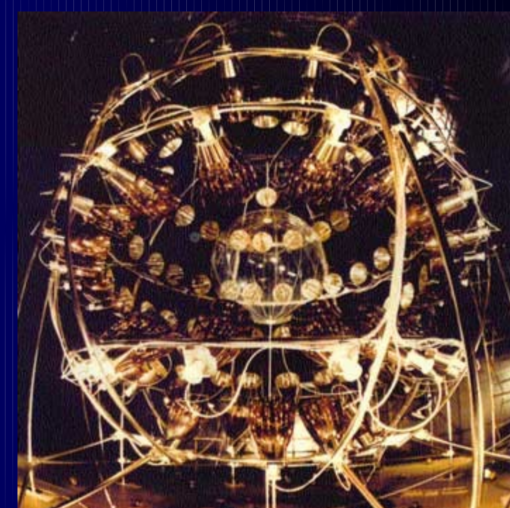
Interactions in liquid scintillator	Int.	Energy threshold (MeV)
$\bar{\nu}_e + p \rightarrow n + e^+$	CC	1.8
$\nu_i + p \rightarrow \nu_i + p$	NC	
$\nu_i + e^- \rightarrow \nu_i + e^-$	CC-NC	
$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$	CC	17.3
$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$	CC	14.4
$\nu_i + {}^{12}C \rightarrow \nu_i + {}^{12}C^*$		

Scintillator

+) Energy resolution, lower threshold, more target particles / molecule, time resolution

-) No direction

- LVD
- Borexino
- KamLAND



SN telecopes scenario

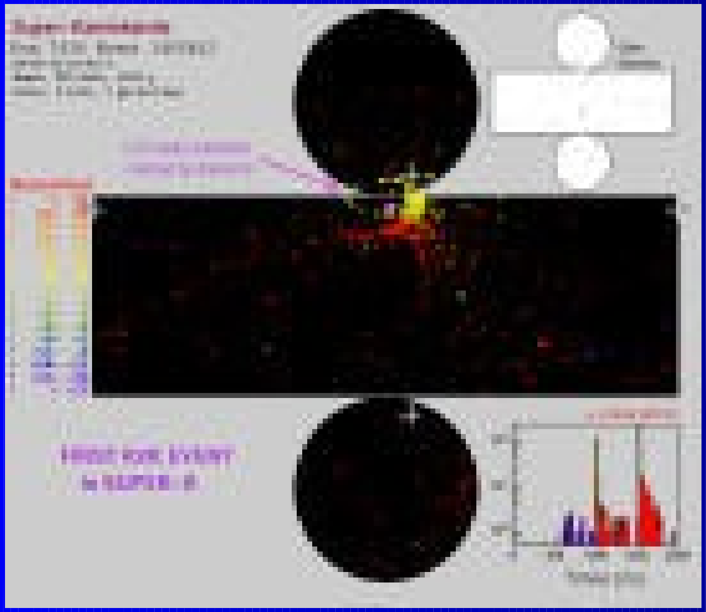
K.Scholberg, Journal of Physics: Conference Series 203 (2010) 012079

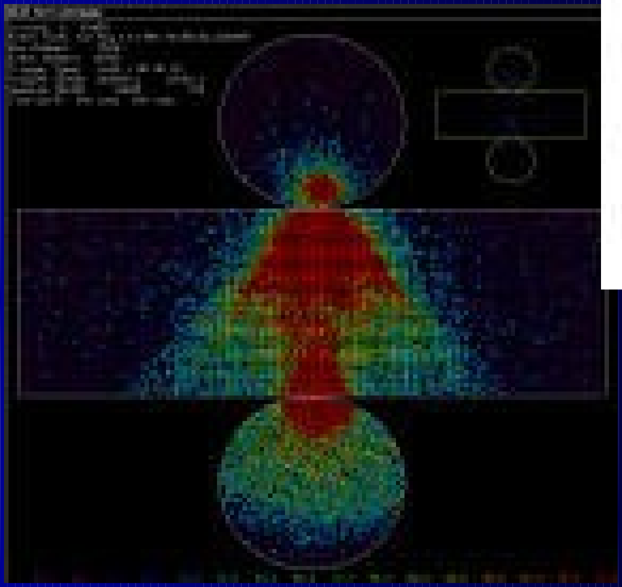
Table 1. Summary of neutrino detectors with supernova sensitivity. Neutrino event estimates are approximate and have a fairly large uncertainty. See reference [1] for individual detector references. Not included are are smaller detectors (*e.g.* reactor neutrino scintillator experiments) and detectors primarily sensitive to coherent elastic neutrino nucleus scattering.

Detector	Type	Mass (kton)	Location	Events at 8.5 kpc	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980-present
Super-K	H_2O	32	Japan	8000	1996-present
LVD	C_nH_{2n}	1	Italy	300	1992-present
KamLAND	C_nH_{2n}	1	Japan	300	2002-present
MiniBooNE	C_nH_{2n}	0.7	USA	200	2002-present
Borexino	C_nH_{2n}	0.3	Italy	100	2005-present
IceCube	Long string	0.4/PMT	South Pole	N/A	2007-present
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
HALO	Pb	0.07	Canada	80	Near future
Icarus	Ar	0.6	Italy	230	Near future
NOνA	C_nH_{2n}	15	USA	3000	Near future
LBNE LAr	Liquid argon	5	USA	1900	Future
LBNE WC	H_2O	300	USA	78,000	Future
MEMPHYS	H_2O	440	Europe	120,000	Future
Hyper-K	H_2O	500	Japan	130,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	38,000	Future

Pulse Recognition

- Cerenkov: Threshold and event topology





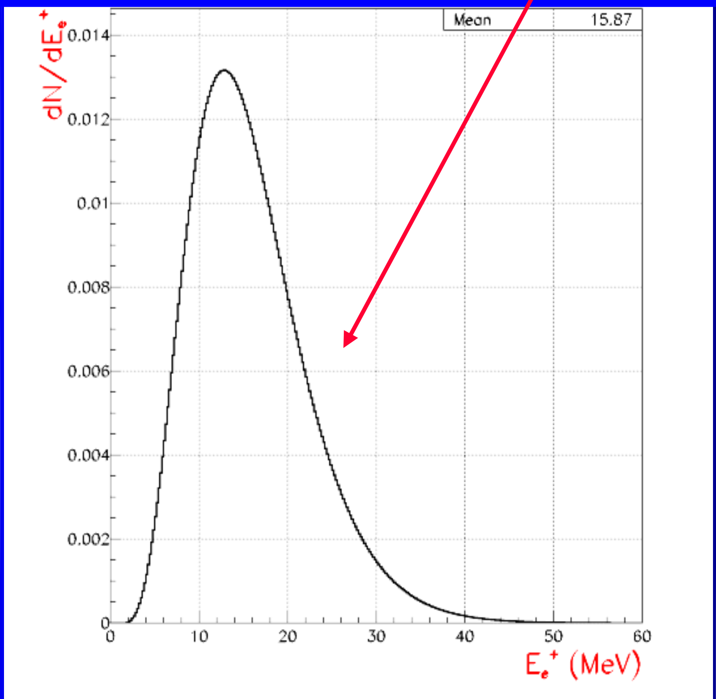
Inverse beta decay (double signature)

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

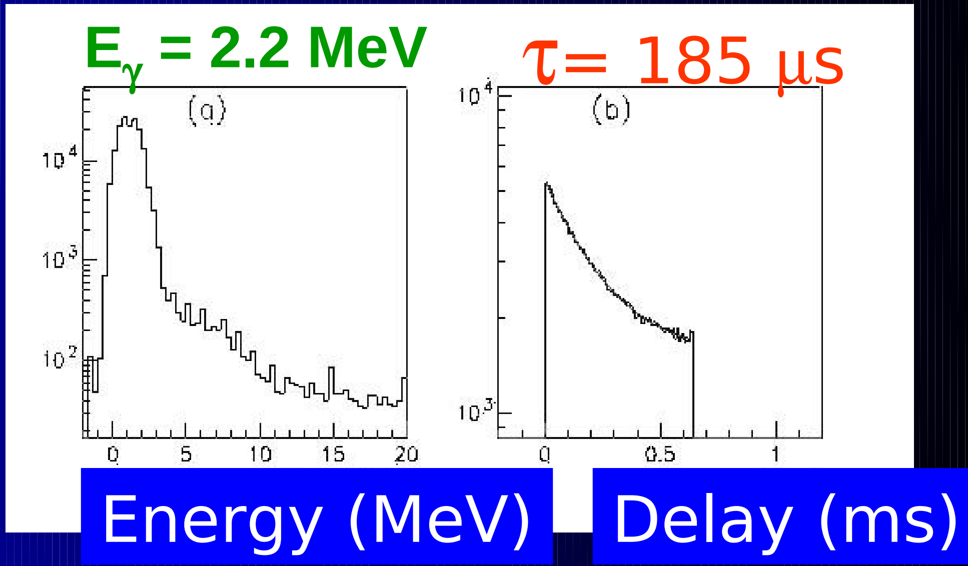
$$n + p \rightarrow d + \gamma$$

1. Positron detection

followed by …



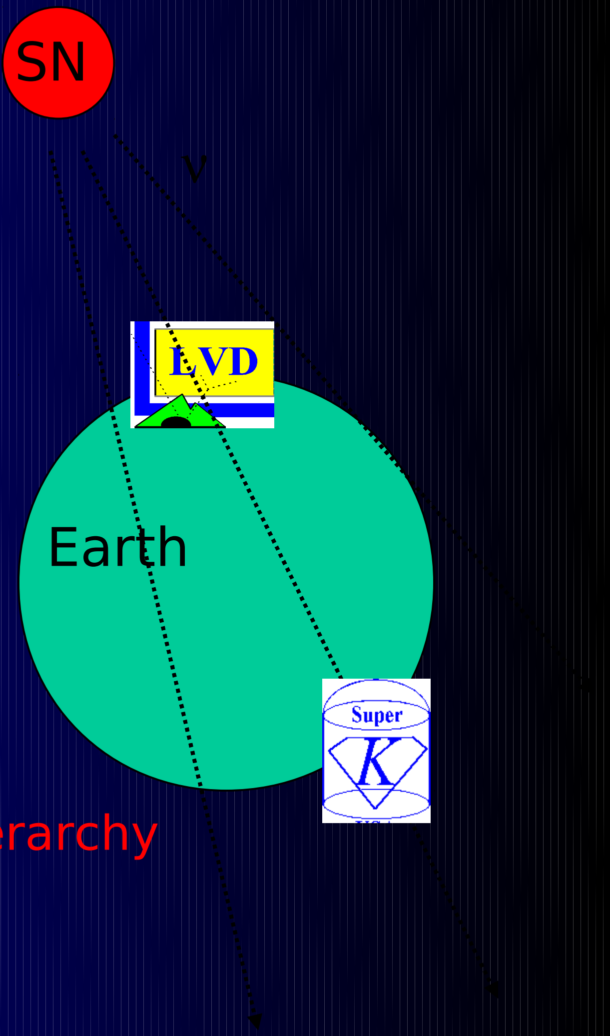
2. Gamma (2.2 MeV) from neutron capture (τ = 185 μs)



Neutron capture efficiency = 60% (from ^{252}Cf measurement)

Earth matter effects

If we consider the effect of Earth in the neutrino path to the detector, we must replace, in the detected flux estimation, U^2_{ei} with P_{ei} (i=1,2), the probability for the mass eigenstate ν_i to be detected as ν_e after path in the Earth, which depends on the solar oscillation parameters and on the travelled density profile through the Earth.



$$\begin{cases} F_e = P_H P_{e2} F^0_e + (1 - P_H P_{e2}) F^0_x \\ F_{\bar{e}} = P_{e1} F^0_{\bar{e}} + P_{e2} F^0_{\bar{x}} \end{cases}$$

for normal hierarchy

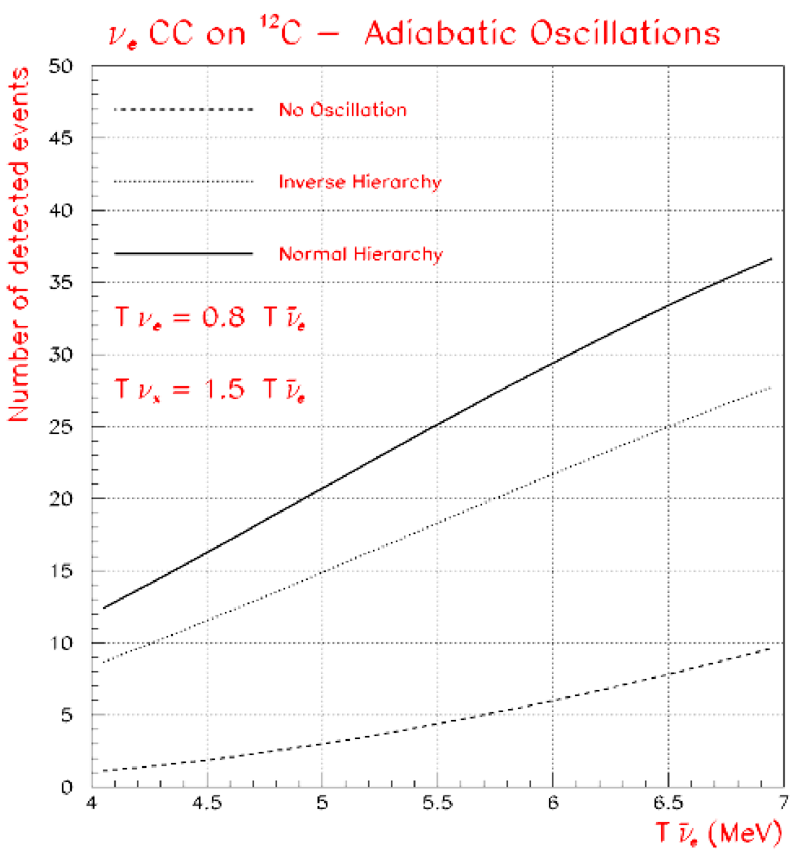
$$\begin{cases} F_e = P_{e2} F^0_e + P_{e1} F^0_x \\ F_{\bar{e}} = P_H P_{e1} F^0_{\bar{e}} + (1 - P_H P_{e1}) F^0_{\bar{x}} \end{cases}$$

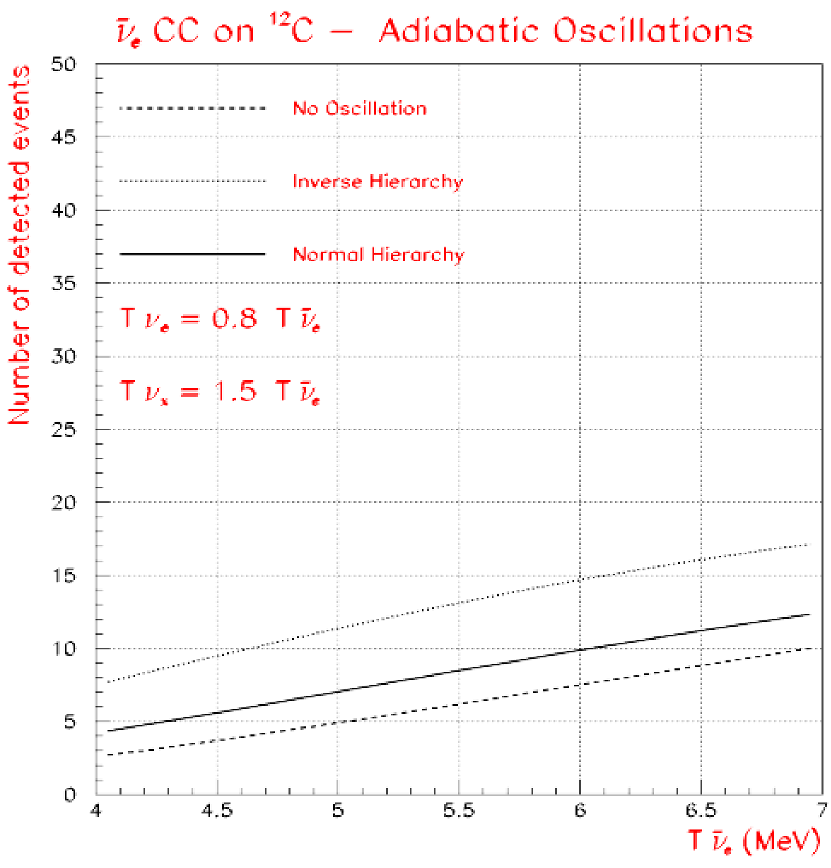
for inverted hierarchy

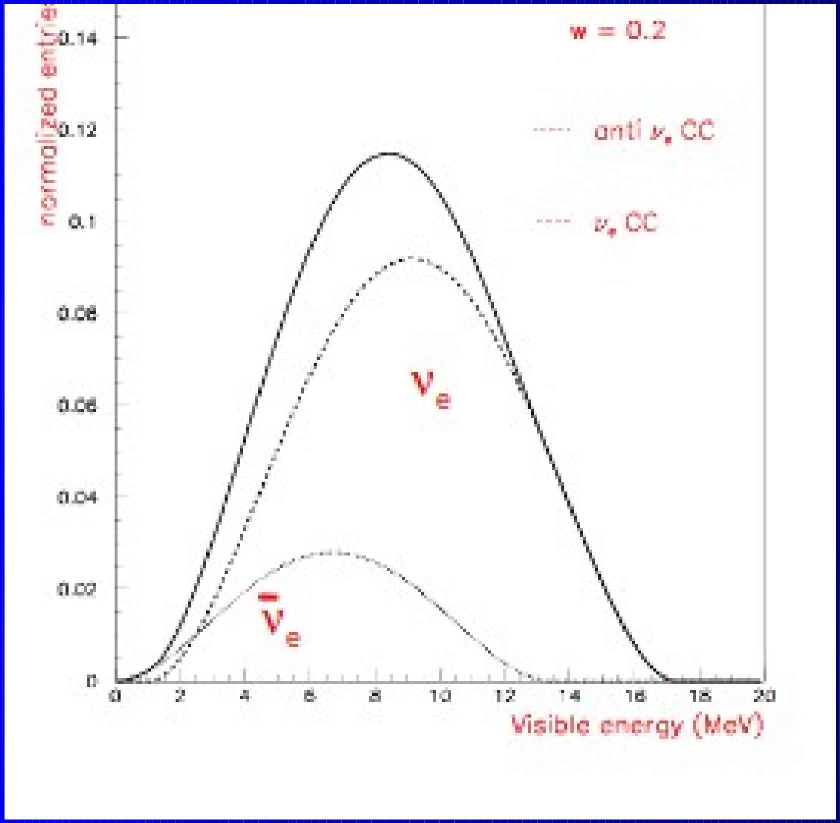
CC with ^{12}C

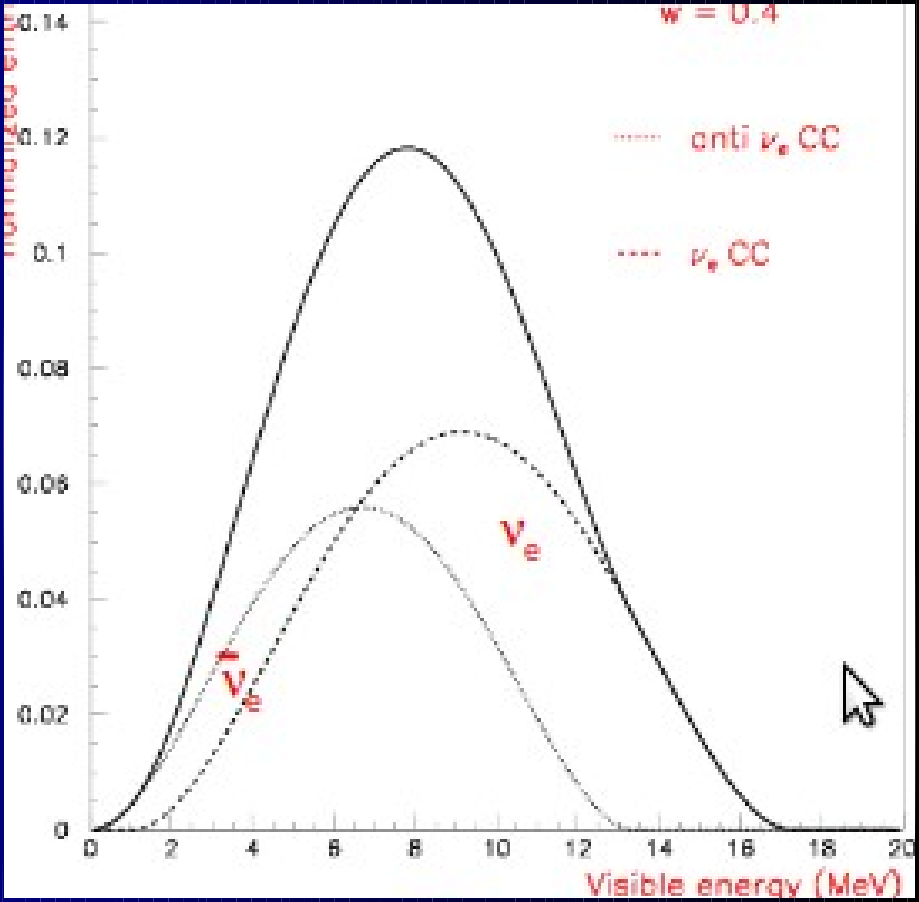
At $T_{\bar{\nu}_e}$=5 MeV W = $\bar{\nu}_e / (\nu_e + \bar{\nu}_e)$

	ν_e	$\bar{\nu}_e$	tot	w
NH	22	6	28	0.2
IH	15	11	26	0.4



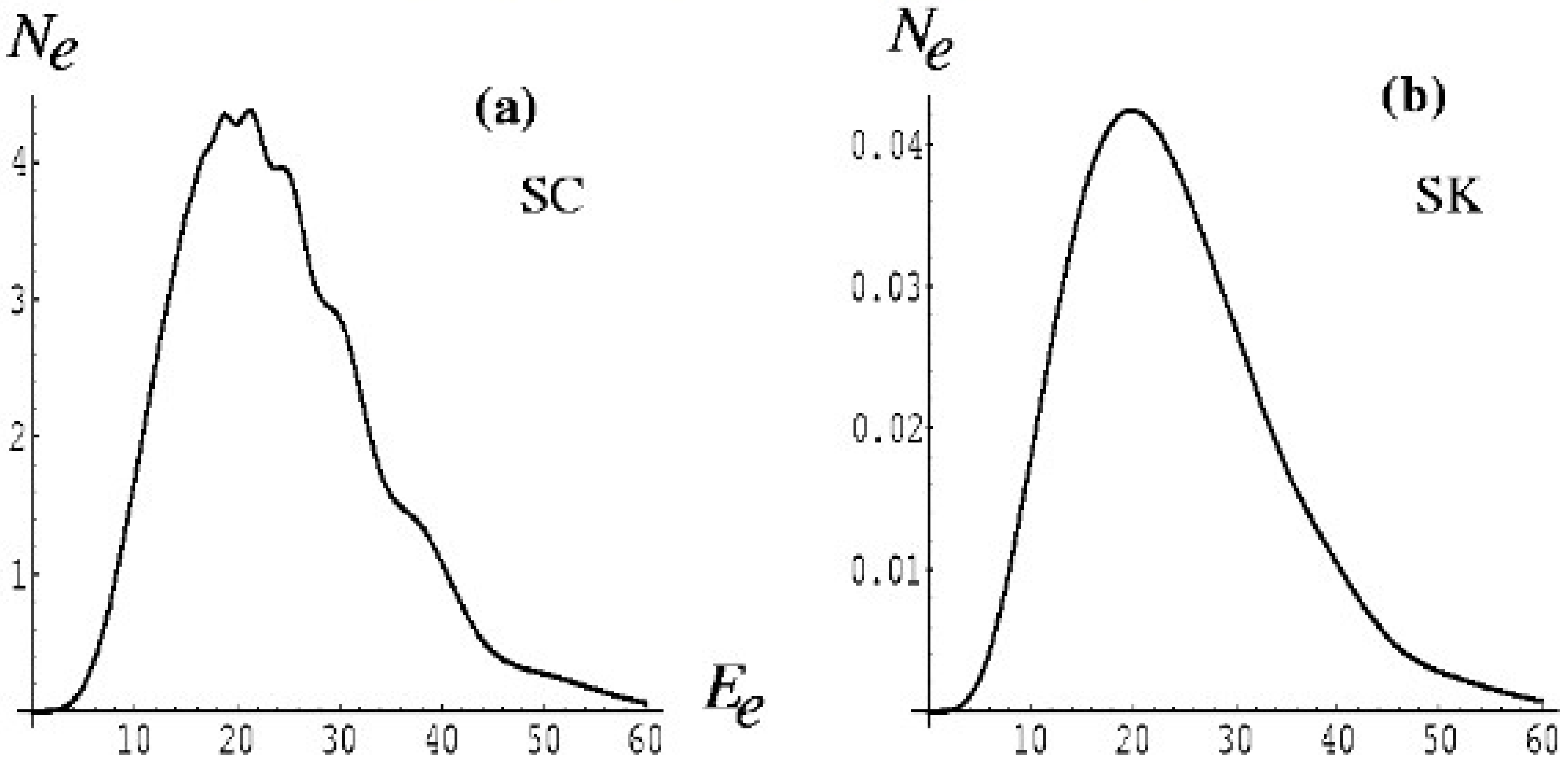



w = 0.2
anti ν_e CC
ν_e CC
normalized entries
Visible energy (MeV)
ν_e
$\bar{\nu}_e$


w = 0.4
anti ν_e CC
ν_e CC
Visible energy (MeV)
ν_e
$\bar{\nu}_e$

SN ν oscillations and Earth matter effects

(Dighe, Keil, Raffelt hep-ph/0304150)



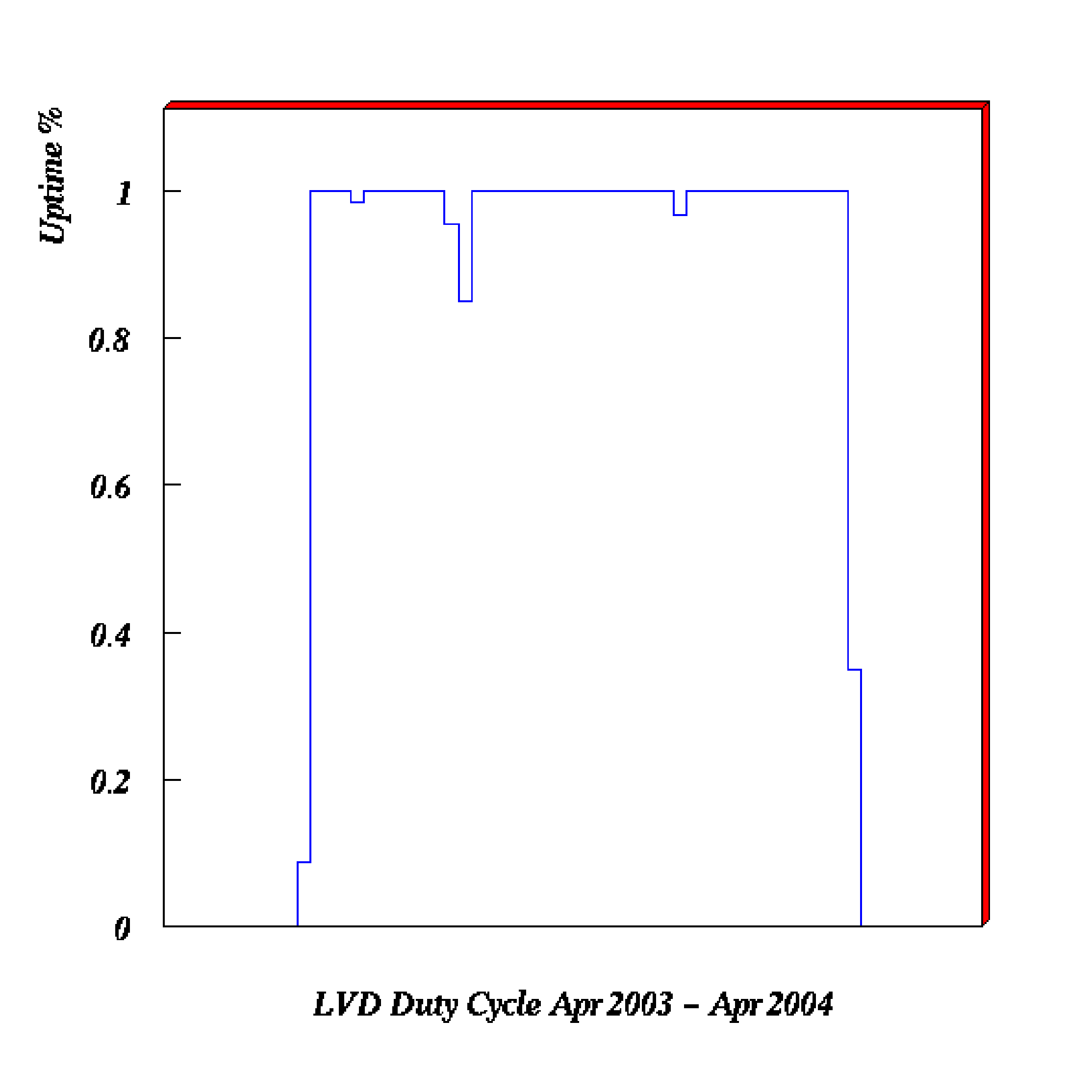
The modulation can be seen by one single detector only if the energy resolution is good enough → scintillator detectors

Up-time

ν beam characteristics:

- 1 bunch each 20-30 years
- bunch duration: 10 – 60 s
- T_0 ?

High duty cicle needed!

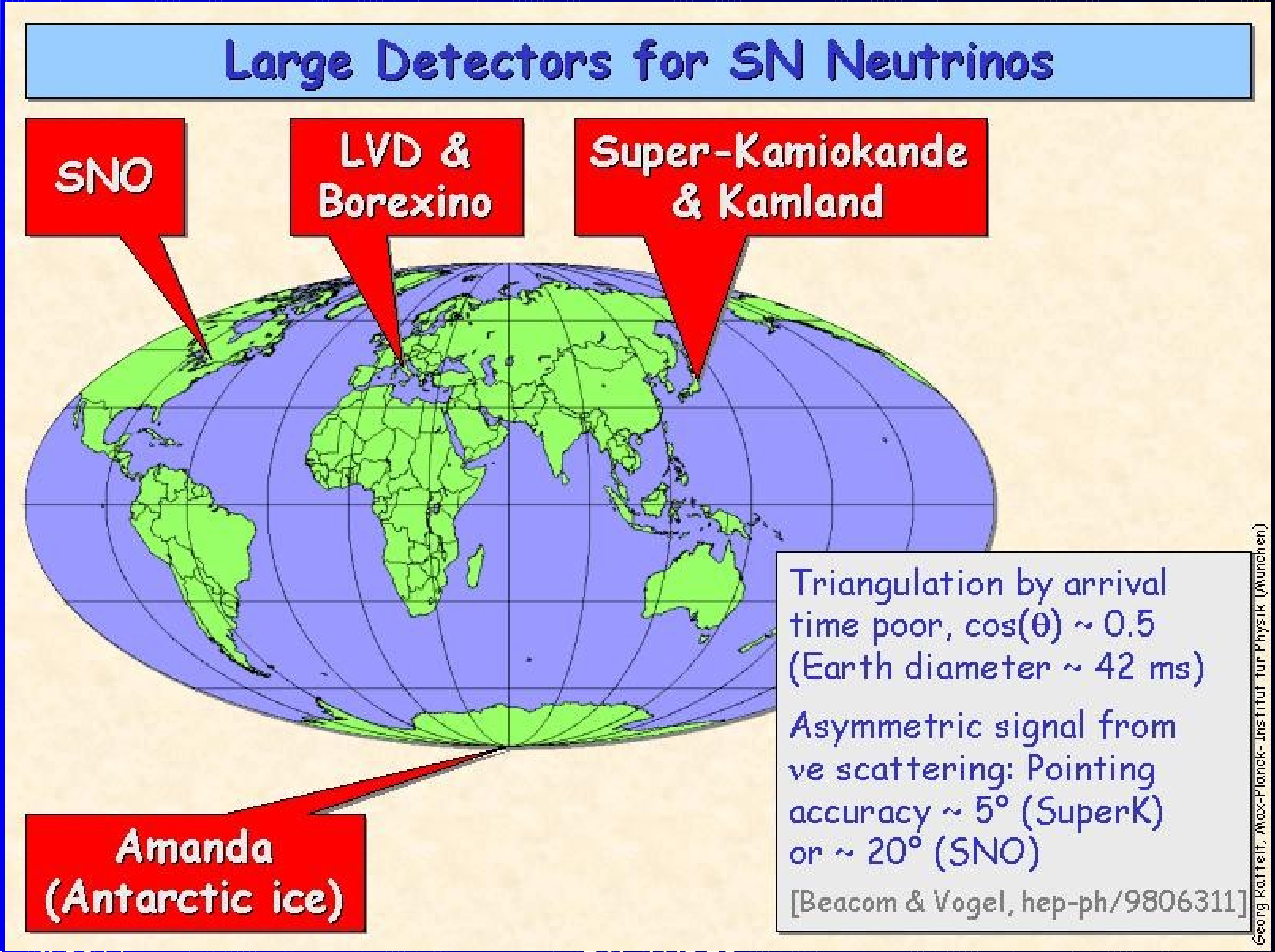


SNEWS

- SUPERNOVA EARLY WARNING SYSTEM

SK, LVD, Borexino, SNO, KamLAND, have defined a common protocol (SN candidates trigger rates) to warn IAU

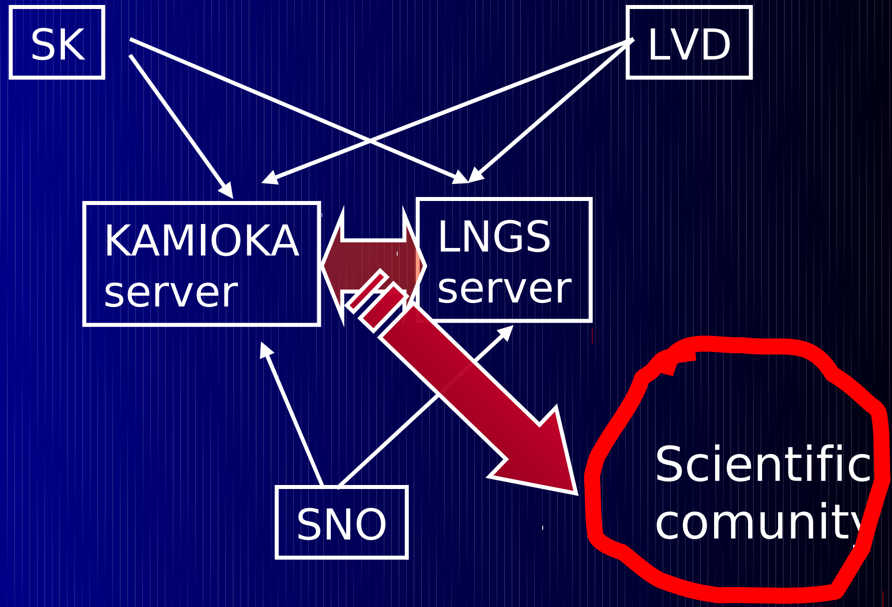
SNEWS



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

The SNEWS system

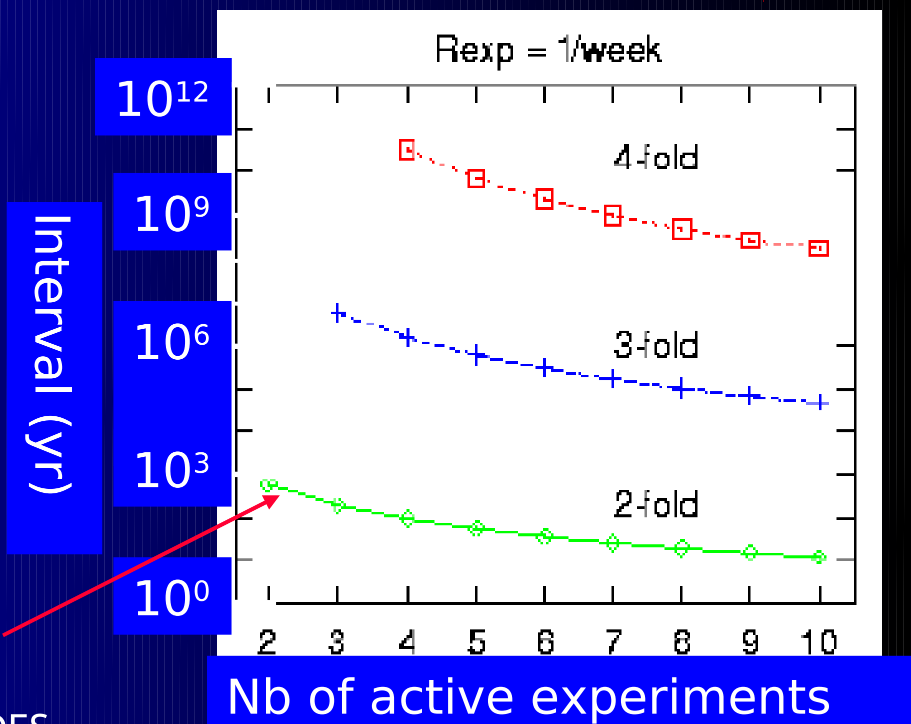
SuperNova Early Warning System: working group between experiments looking for SN burst
(currently LVD, SK, SNO, but Borexino, Amanda, MiniBoone, KamLand expected to join)



Every experiment looks for SN burst and send alarm at average rate of 1/week
Network as much as possible fault tolerant

Give prompt information to astronomical comunity.
Doing online twofold coincidence allows to send a prompt alarm and to reduce to around zero fake alarms!

Triangulation possible but $\delta\theta \approx 50\%$



Future detection

Expected number of events:

O(10^4) for a galactic collapse

Scale of the future experiments: MEGATONS

LENA, Hyper-K, DUSEL

Is better save lots of space in ANDES

Neutrino oscillations (Theta – 13)

Mass hierarchy

Supernova dynamics (acretion phase)

Supernova spectrum (blackbody ?)

Conclusions

* Supernova neutrinos are a rich probe for particle physics and astrophysics
* Under____
ground, water, ice experiments are necessary
* Collaboration and coordination among different experiments is a reality
* Southern hemisphere measuments should be very interesting