FUTURE NEUTRINO OBSERVATIONS of the **supernova progenitor** prior to the ***core-collapse***

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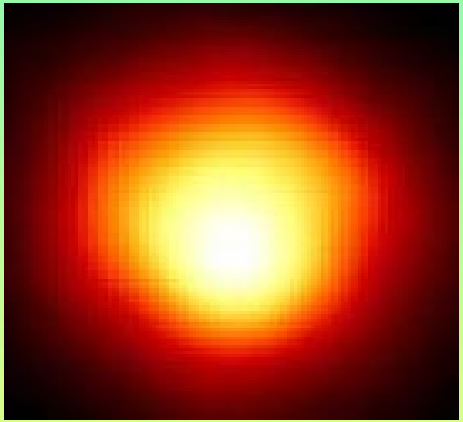
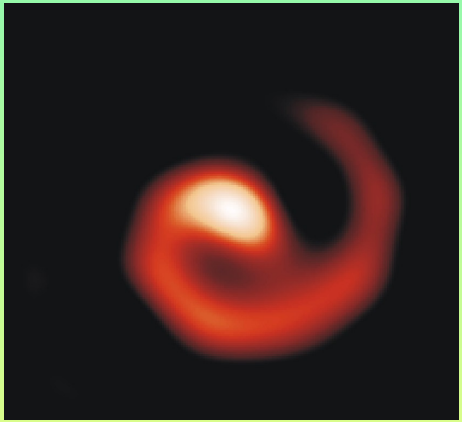
with M.Misiaszek, M. Kutschera

Detection possibility of the pair-annihilation neutrinos from neutrino-cooled pre-supernova star
Astroparticle Physics **21** 303-313 (2004)

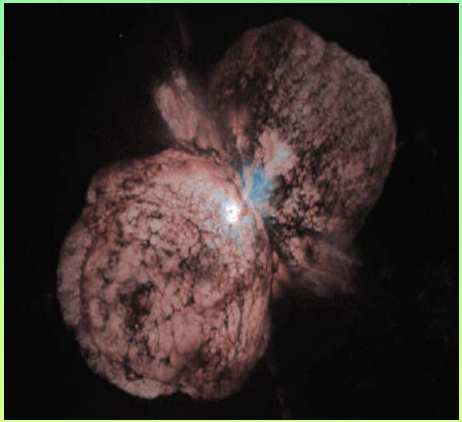
Betelgeuse 130 pc



WR 104 1.5 kpc



Eta Carina 2.7 kpc



NEUTRINO-COOLED STARS

Massive Star → Neutrino-Cooled Star → Pre-Supernova Star

definition:

↓ Could explode as *core-collapse* **supernova**

↓ **Massive star after carbon burning ignition**

↓ **Star prior to the collapse**

PRE-SUPERNOVA *versus* SUN

Sun – perfectly examined on observational and theoretical grounds *(EM, neutrinos, helioseismology)*.

Pre-Supernova – theoretical models only (no such a star known in Galaxy). Important observational results: SN 1987A *progenitor* and companion of the SN 1993J identified. Nature **427** (2004) 129-131

	Sun	Pre-Supernova
Lifetime	10^{10} yrs	300 yrs
Luminosity	$L_\odot$	$10^5 L_\odot$
L_ν	0.02 $L_\odot$	10^{12} $L_\odot$
Avg. ν energy	0.3 MeV	0.7-2 MeV

EVOLUTION OF THE MASSIVE STAR

Burning	$T_c\,[MeV]$	$\rho_c\,[g/cm^3]$	**Duration**	$L/L_\odot$	$L_\nu[erg/s]$
H	3.3×10^{-3}	3.8	5.8 mln yrs	40×10^3	$\sim 0.02L$
He	0.01	200	85 000 yrs	115×10^3	3.9×10^{33}
C	0.05	10^5	280 yrs	165×10^3	3.4×10^{38}
Ne	0.1	2×10^6	300 days	185×10^3	6.7×10^{41}
O	0.15	4×10^6	134 days	185×10^3	7.9×10^{42}
Si	0.24	3.2×10^7	30 hours	185×10^3	3.4×10^{44}
Shell **Si**	0.29	3.2×10^8	5.5 hour	185×10^3	–
Core-Collapse	0.14	1.6×10^9	$0.1 \ldots 0.5$ s	185×10^3	$> 10^{54}$

ESSENTIAL FACTORS

- Neutrino luminosity ($\sim 10^{12} L_\odot \simeq L_\odot$ at 100 light years)
- Stage duration (0.7…14 days)
- Distance (Galaxy: 0.1…30kpc)
- Avg. time between Galaxy events (10…200 years)
- Spectrum (E_ν = 0.7…2 MeV)
- Detector target mass (1 kiloton …16 gigaton)
- Detector threshold (1.8…5 MeV)

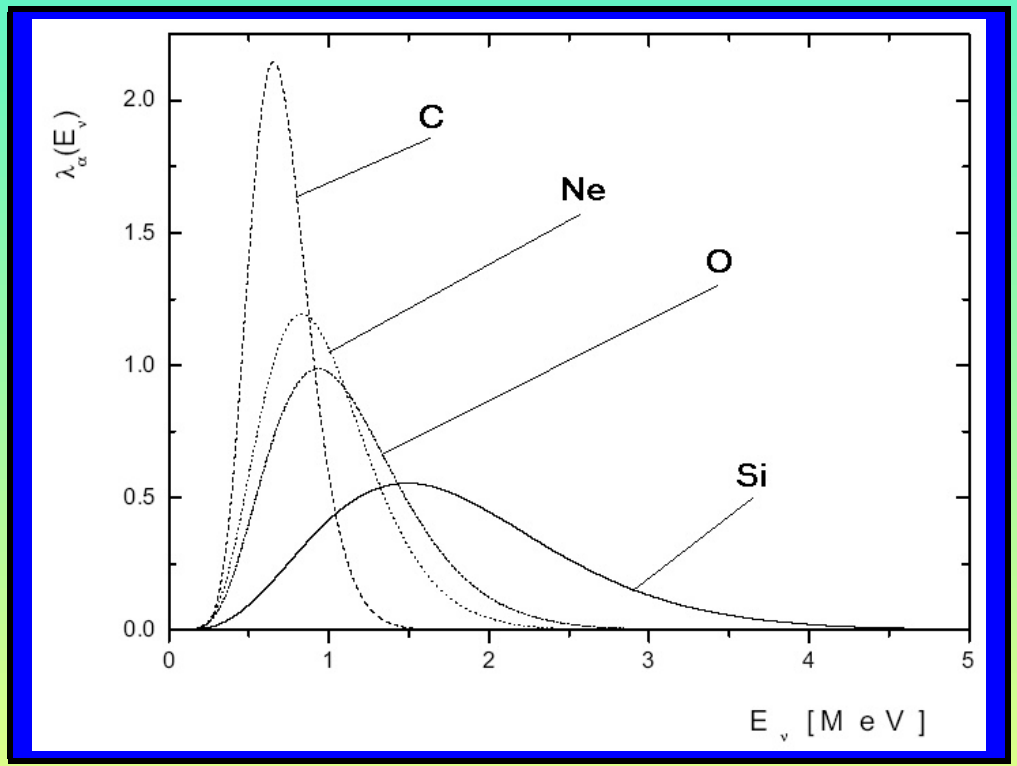
NEUTRINO LUMINOSITY

Nuclear burning stages:

H	$\longrightarrow$	^{4}He
^{4}He	$\longrightarrow$	^{12}C, ^{16}O
^{12}C (^{16}O)	$\longrightarrow$	^{20}Ne, ^{24}Mg
^{20}Ne (^{16}O, ^{24}Mg)	$\longrightarrow$	^{16}O, ^{24}Mg
^{16}O (^{24}Mg, ^{28}Si)	$\longrightarrow$	^{28}Si
^{28}Si (^{32}S)	$\longrightarrow$	^{56}Ni, ^{56}Fe, ^{54}Fe

- Core mass 1...2 $M_\odot$, close to M_{Ch}=1.44 $M_\odot$
- Hoyle's formula: $E = 0.001Mc^2 \simeq 2 \cdot 10^{51}$ erg – total energy similar to Ia explosion
- SN Ia $\longrightarrow$ explosion energy (3 sec) • Pre-SN $\longrightarrow$ neutrinos (2 days)

PAIR-ANNIHILATION NEUTRINO SPECTRUM



Spectra and average $\bar{\nu}_e$ energy

	$\bar{E}_{\bar{\nu}_e}$ [MeV]	$\langle E_{\bar{\nu}_e} \rangle$ [MeV]	$E^{max}_{\bar{\nu}_e}$ [MeV]
C	0.71	0.74	0.6
Ne	0.97	1.08	0.8
O	1.11	1.25	0.9
Si	1.80	2.10	1.5

MONTE-CARLO SIMULATION

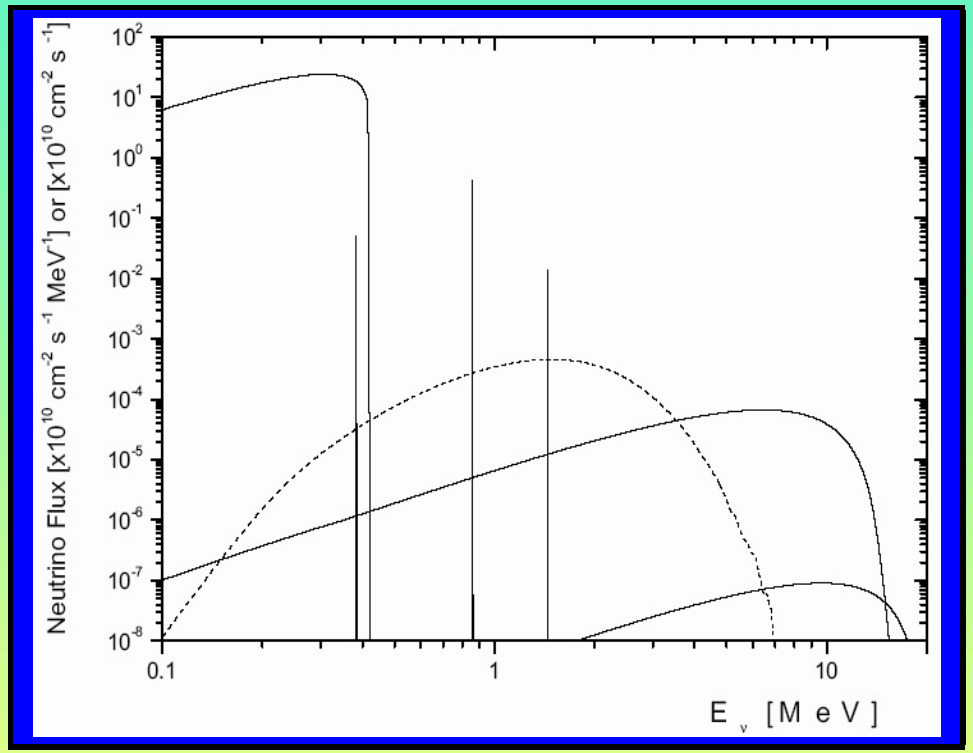
$$\frac{{G_F}^2}{2}\int \frac{d^3\mathbf{p}_1}{2E_1}\frac{d^3\mathbf{p}_2}{2E_2}\frac{d^3\mathbf{q}_1}{2\mathcal{E}_1}\frac{d^3\mathbf{q}_2}{2\mathcal{E}_2} \quad \Lambda\, f_{e^-} f_{e^+}\, \delta^4(P_1+P_2-Q_1-Q_2)\,|M|^2$$

1. Electron (positron) energy sampled according to Lorentz invariant phase space factor and Fermi-Dirac distribution:

$$\left[1+\exp\left(\frac{E\pm\mu_e}{kT}\right)\right]^{-1} \quad \frac{d^3\mathbf{p}}{2\,E}$$

2. 3-momentums $\mathbf{p}_1$, $\mathbf{p}_2$ in random direction
3. Lorentz transform to center-mass (CM) frame
4. In CM outcoming neutrino directed randomly
5. Inverse Lorentz transform back to plasma rest frame
6. $\bar{\nu}_e$ energy in plasma rest frame binned and event counted as $|M|^2$

NEUTRINO FLUX FROM 1 KPC



- Pair-annihilation neutrinos are conceptual equivalent of the solar pp neutrinos.
- We expect neutrino spectrum of the pre-supernova to be much more complicated than Solar.
- Significant fraction ($\sim 1/3$) of the **electron antineutrinos** ($\bar{\nu}_e$) emitted.

SCALABLE ANTINEUTRINO DETECTION METHOD

Reines-Cowan reaction (inverse β-decay):

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

1 event/kt H_2O
z 1 kpc

- KAMLAND (1 kt)
- BOREXINO (0.3 kt)
- SNO (1+1.7 kt)
- SUPER KAMIOKANDE (32 kt)
- HYPERK (540 kt)
- UNO (440 kt)
- GADZOOKS! (32 kt)
- *"Gigaton Array"* (10^6 kt)

GADZOOKS!

Inverse β-decay threshold $E_{th} = 1.8$ MeV while for water Cherenkov detectors $E_{th} \simeq 4$ MeV.

SOLUTION: (M. Vagins, Neutrino 2004)

Dissolving in pure H_2O efficient neutron absorber (chloride): $\boxed{GdCl_3}$ ($NaCl$, KCl) cause reaction:

$$\boxed{n + \mathrm{Gd(Cl)} \rightarrow \mathrm{Gd^*(Cl^*)} \rightarrow \mathrm{Gd(Cl)} + \gamma_i}$$

$$E_{tot} = \sum_i E_{\gamma_i} \simeq 8\,\mathrm{MeV}$$

Gamma-rays scatter off electrons $\Rightarrow$
Electrons emit Cherenkov light $\Rightarrow$
Light detected by photomultipliers

GADZOOKS! SCHEDULE

- 2004: U.S. DoE ADRP grant (*M. Vagins, UCI*)
- 2005: **K2K** testing 1kt:
  Gd - filtration, salt chemistry, corrosion, attenuation, ...
- 2008: **Full-scale** GADZOOKS! 32kt

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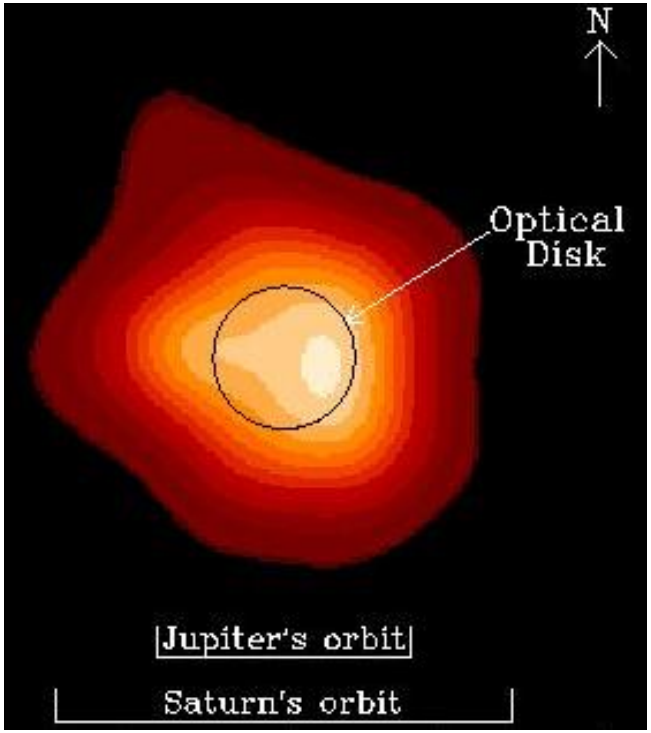
Neutrinos from pre-supernova: 3σ at 500 pc !

If GAZDOOKS! will start in 2008 we are able to
predict supernova explosion
for few nearby stars: β Ori, α Her, α Sco...

Unfortunately, explosion of the nearby star is **highly unlikely**
($\sim 10^{-4}$/year)

CAN STAR EXPLODE BEFORE 2008?



Military Importance of the Neutrino Astrophysics

Neutrinos and Arms Control Workshop

5-7 February 2004, University of Hawaii

Military Importance of the Neutrino Astrophysics

Neutrinos and Arms Control Workshop

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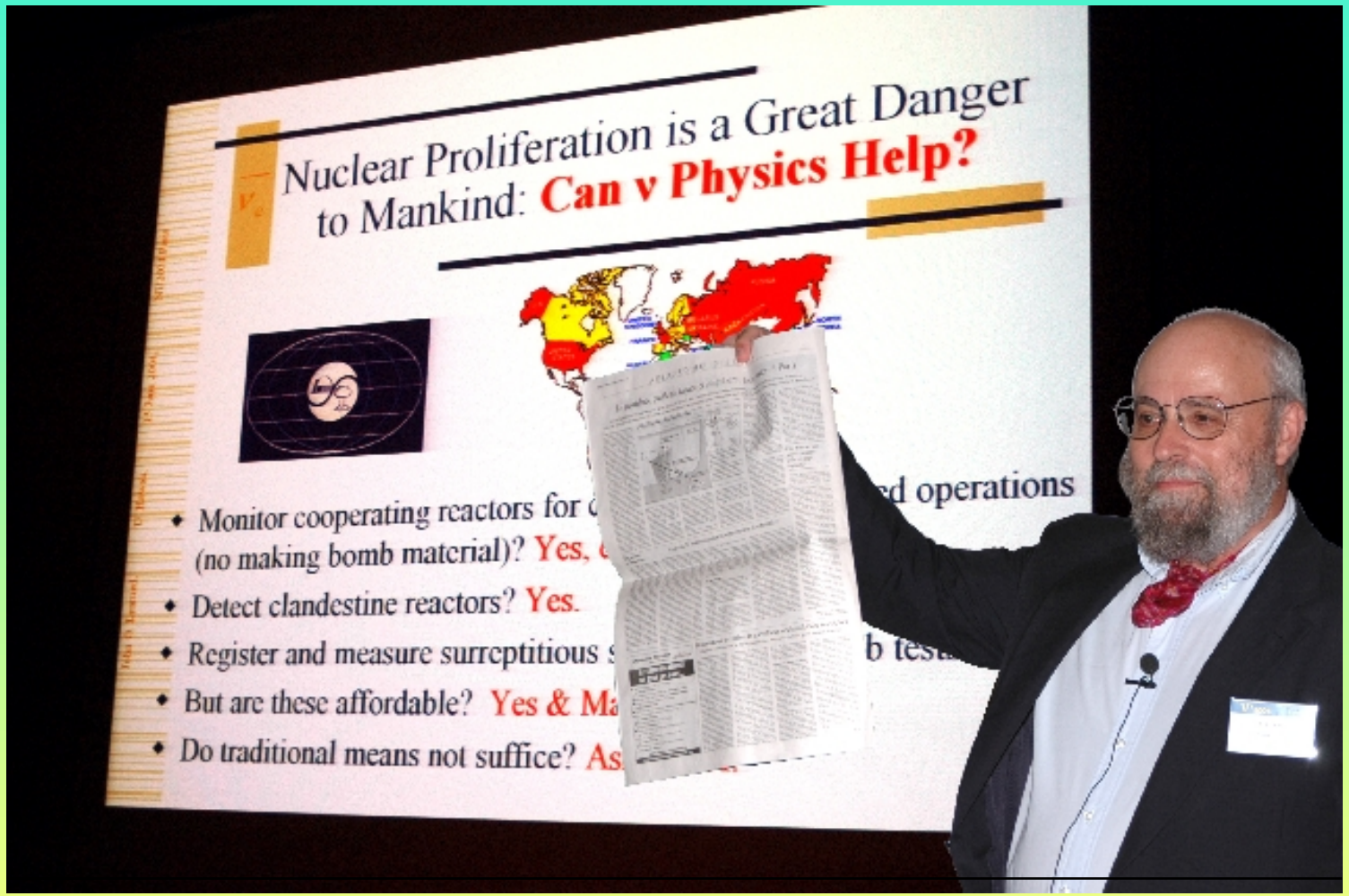
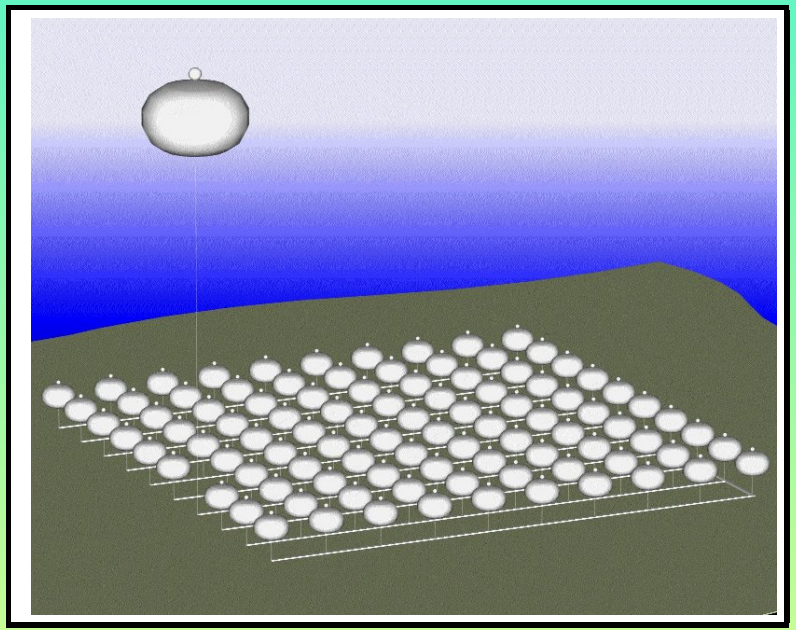
- Monitoring nuclear plants
- Search for clandestine reactors
- Hidden nuclear tests watch
- Tracking nuclear powered submarines
- Georeactor and Earth "tomography"
- Supernova prediction
- Neutrino SETI


Nuclear Proliferation is a Great Danger to Mankind: Can ν Physics Help?
Monitor cooperating reactors for
(no making bomb material)? Yes,
Detect clandestine reactors? Yes.
Register and measure surreptitious
But are these affordable? Yes & Ma
Do traditional means not suffice? As
d operations
b tes

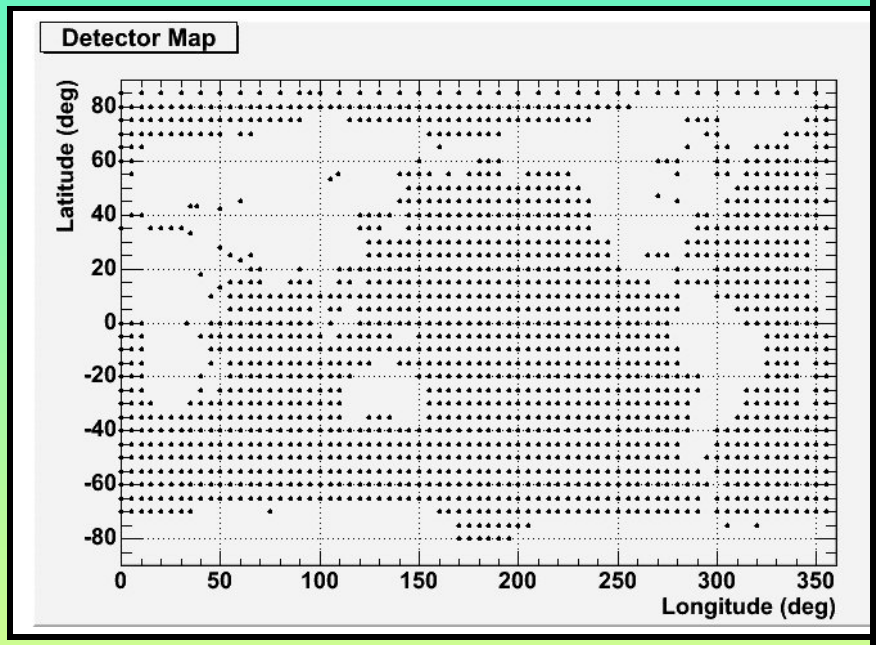
GIGATON ARRAY



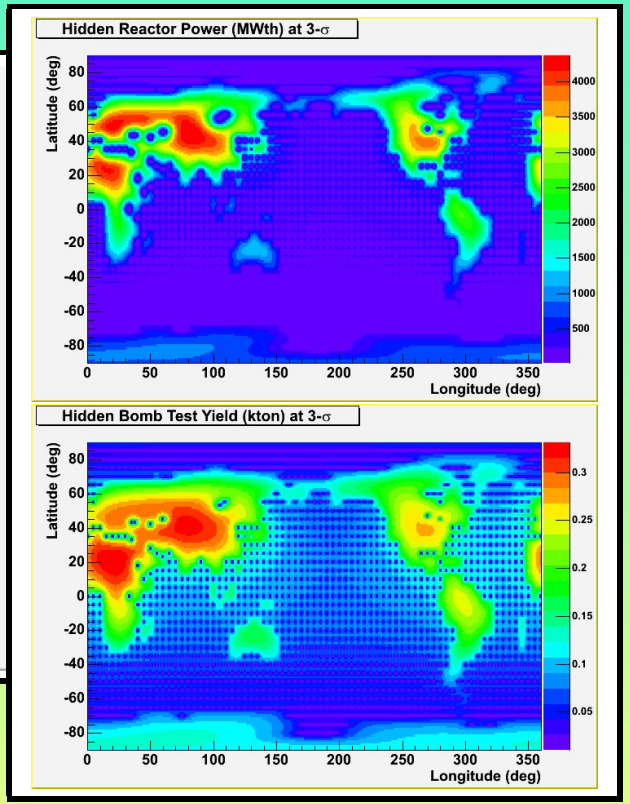
- Balloons (R=134 meters, 10 Mt) covered with photomultipliers
- At the bottom of the ocean, 4 km depth
- Dissolved ultra-low-^{40}KCl salt: reduce buoyancy, neutron capture
- Anchored on lines for maintenance

J. G. Learned, Neutrino 2004

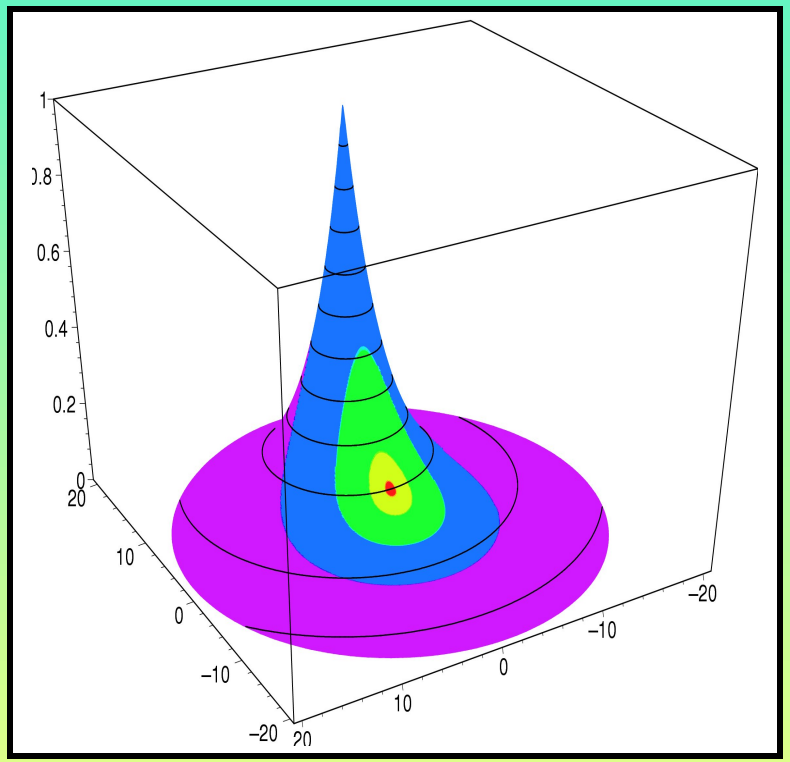
GLOBAL DETECTOR NETWORK



1596×10 Mt



GALAXY COVERAGE



Observation range:

- Red – GADZOOKS! [32 kt]
- Yellow – Hyper-Kamiokande [0.5 kt]
- Green - H-K (very optimistic)
- Blue – Single ocean balloon [10 Mt]
- Purple – *Gigaton Array* [1 Gt]

PRE-SUPERNOVA MONITORING

Assuming only $\bar{\nu}_e$ from e^+e^- annihilation are detectable

	Target mass	Maximum distance	Galaxy coverage
GADZOOKS!	32 kt	0.5 kpc	0.1%
HYPER-KAMIOKANDE	0.5 Mt	2 kpc	2%
SINGLE OCEANIC BALLOON	10 Mt	10 kpc	50%
GIGATON ARRAY	1 Gt	100 kpc	100%

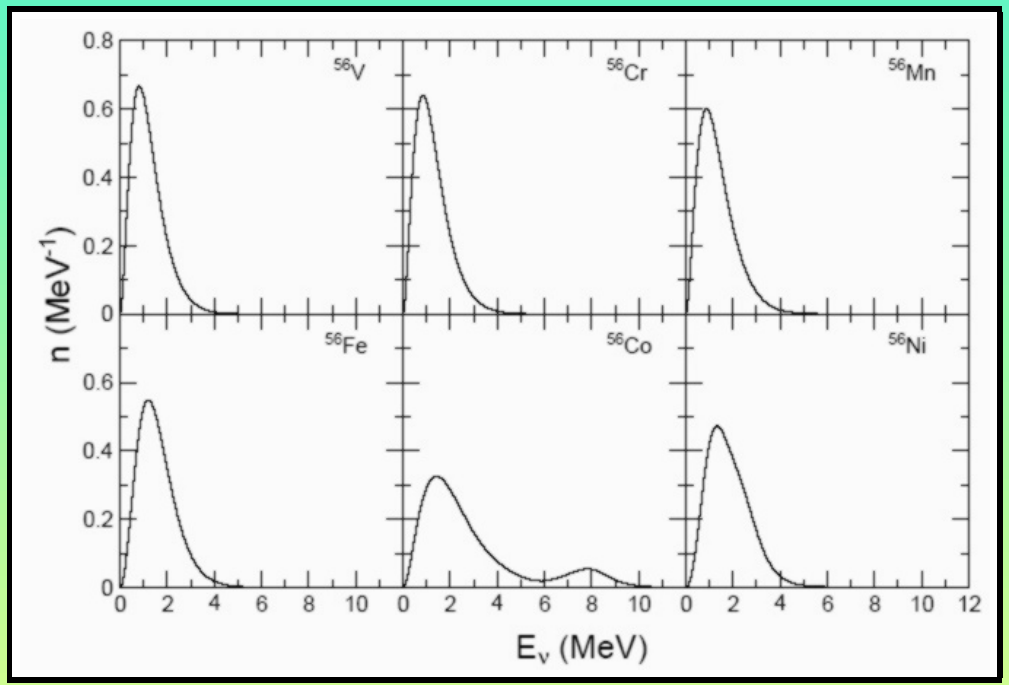
Expected observation range at 3σ (99%) confidence level

NEUTRINO ASTRONOMY IN THE "GIGATON ERA"

- Solar neutrino flux variations $\left(\frac{0.13\%}{\sqrt{\text{days}}}\right)$
- Supernova every 20 days from the Virgo Supercluster
- Cosmological supernova background
- Si burning 1-14 days before core-collapse from the Galaxy
- O/Ne burning *a year before supernova* up to few kpc
- Supernova shock front tracking – ,,pre-supernova" tomography
- Protoneutron star cooling neutrinos
- UHE neutrinos
- . . . possibly much more than we can imagine now

— — —

WEAK NUCLEAR NEUTRINOS



Langanke et. al. Phys.Rev. C64 (2001) 055801

Neutrino spectrum: electron capture during Si shell burning

NEUTRINO LUMINOSITY

TABLE 1

MAJOR NUCLEAR BURNING STAGES FOR 15 AND 25 $M_\odot$ POPULATION I STARS*

Burning Stage	Central Temperature (K)	Central Density (g cm^{-3})	Neutrino Luminosity† (erg s^{-1})	Optical Luminosity (erg s^{-1})	Effective Temperature (K)	Photospheric Radius (cm)	Time Scale (s)
Hydrogen	3.4 (7)	5.9 (0)	----	8.1 (37)	3.26 (4)	3.2 (11)	3.9 (14)
	3.7 (7)	3.8 (0)	----	3.1 (38)	3.98 (4)	4.2 (11)	2.3 (14)
Helium	1.6 (8)	1.3 (3)	3.9 (33)	2.3 (38)	1.59 (4)	2.2 (12)	4.2 (13)
	1.8 (8)	6.2 (2)	7.3 (34)	9.5 (38)	1.58 (4)	4.7 (12)	2.1 (13)
Carbon	6.2 (8)	1.7 (5)	3.4 (38)	3.3 (38)	4.26 (3)	3.7 (13)	2.0 (11)
	7.2 (8)	6.4 (5)	1.0 (40)	1.2 (39)	4.36 (3)	6.7 (13)	5.2 (9)
Neon	1.3 (9)	1.6 (7)	6.7 (41)	3.7 (38)	4.28 (3)	3.9 (13)	2.2 (8)
	1.4 (9)	3.7 (6)	7.8 (42)	1.2 (39)	4.36 (3)	6.7 (13)	3.9 (7)
Oxygen	1.9 (9)	9.7 (6)	7.9 (42)	3.7 (38)	4.28 (3)	3.9 (13)	5.5 (7)
	1.8 (9)	1.3 (7)	2.3 (43)	1.2 (39)	4.36 (3)	6.7 (13)	1.6 (7)
Silicon	3.1 (9)	2.3 (8)	3.4 (44)	3.7 (38)	4.28 (3)	3.9 (13)	5.2 (5)
	3.4 (9)	1.1 (8)	3.8 (45)	1.2 (39)	4.36 (3)	6.7 (13)	1.2 (5)
Collapse	8.3 (9)	6.0 (9)	6.8 (48)	3.7 (38)	4.28 (3)	3.9 (13)	3.0 (-1)
	8.3 (9)	3.5 (9)	8.1 (48)	1.2 (39)	4.36 (3)	6.7 (13)	3.5 (-1)

*All physical parameters refer to conditions just after the core ignition of each fuel, except the time scale which is the period between successive ignitions. The value for the 15 $M_\odot$ star is listed first in each case.

†Excluding neutrino losses during hydrogen burning.

Weaver, Zimmermann and Woosley 1978

SN1987A review, Table 1. Bahcall, Arnett, Kirshner, Woosley, ARA&A.

Table 1 Burning stages in the evolution of a 20-$M_\odot$ star

Fuel	ρ_c (g cm^{-3})	T_c (10^9 K)	τ (yr)	L_{phot} (erg s^{-1})	L_ν (erg s^{-1})
Hydrogen	5.6(0)	0.040	1.0(7)	2.7(38)	—
Helium	9.4(2)	0.19	9.5(5)	5.3(38)	<1.0(36)
Carbon	2.7(5)	0.81	3.0(2)	4.3(38)	7.4(39)
Neon	4.0(6)	1.7	3.8(−1)	4.4(38)	1.2(43)
Oxygen	6.0(6)	2.1	5.0(−1)	4.4(38)	7.4(43)
Silicon	4.9(7)	3.7	2 days	4.4(38)	3.1(45)

• C, Ne, O and Si burning belong to neutrino-cooled stage; star itself is referred to as pre-supernova ($v_{\mathrm{R}}(\mathrm{Fe}) < -1000$ km/s).

• Star surface "frozen":

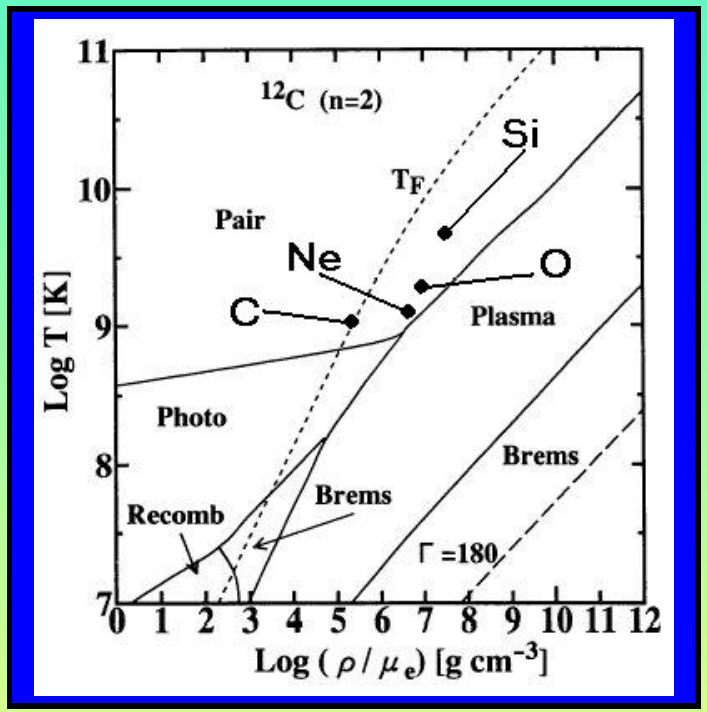
$\tau_{\mathrm{K-H}} \sim 10\,000$ yrs for hydrogen envelope $\mathrm{R} \sim 10 \ldots 100$ mln km.

• Accelerated evolution in the central region $\mathrm{R} \sim 10\,000$ km.

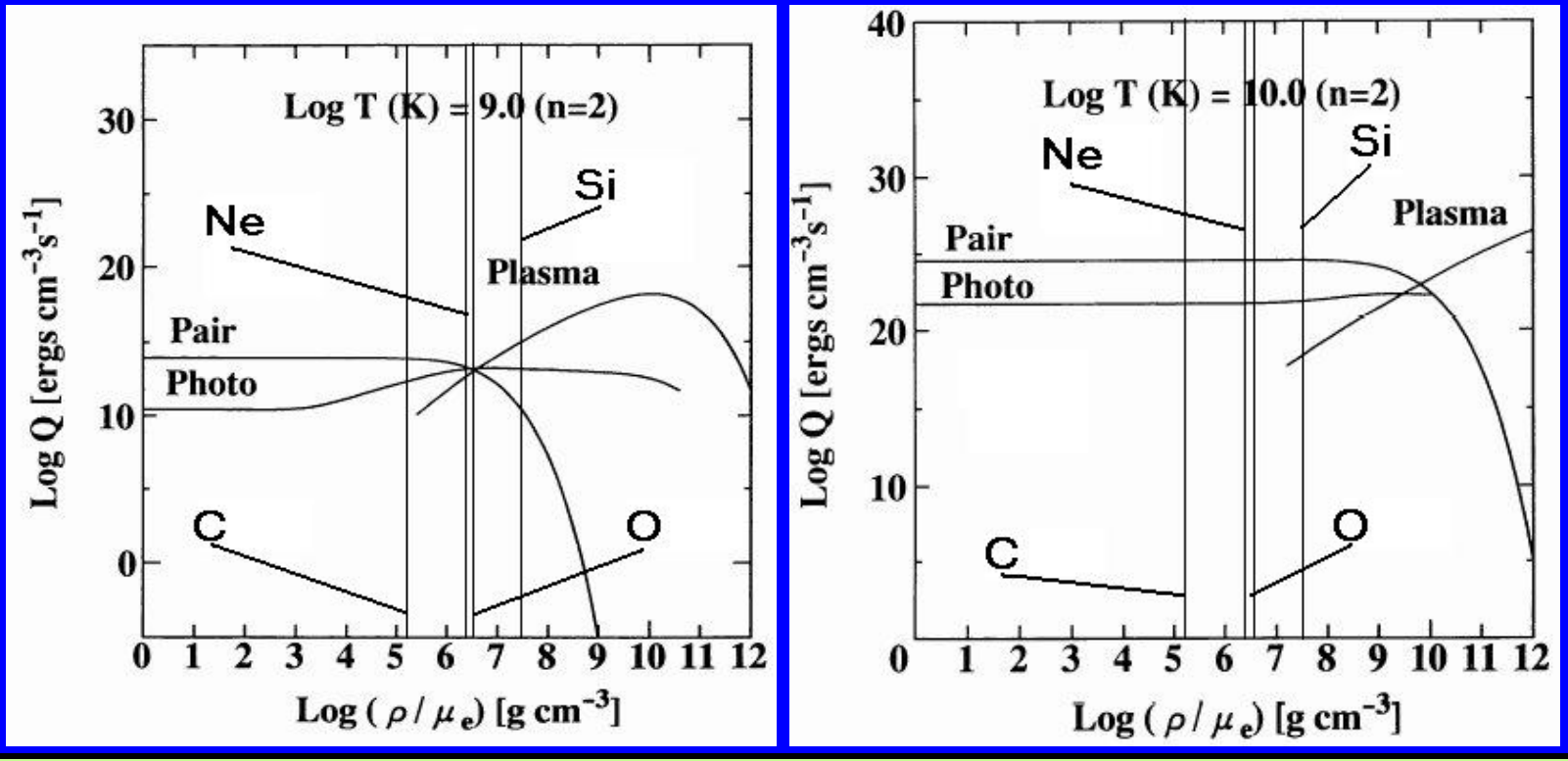
NEUTRINO COOLING

Thermal neutrinos :

- **pair-annihilation**
- plasmon decay
- photoneutrinos
- bremsstrahlung
- recombination



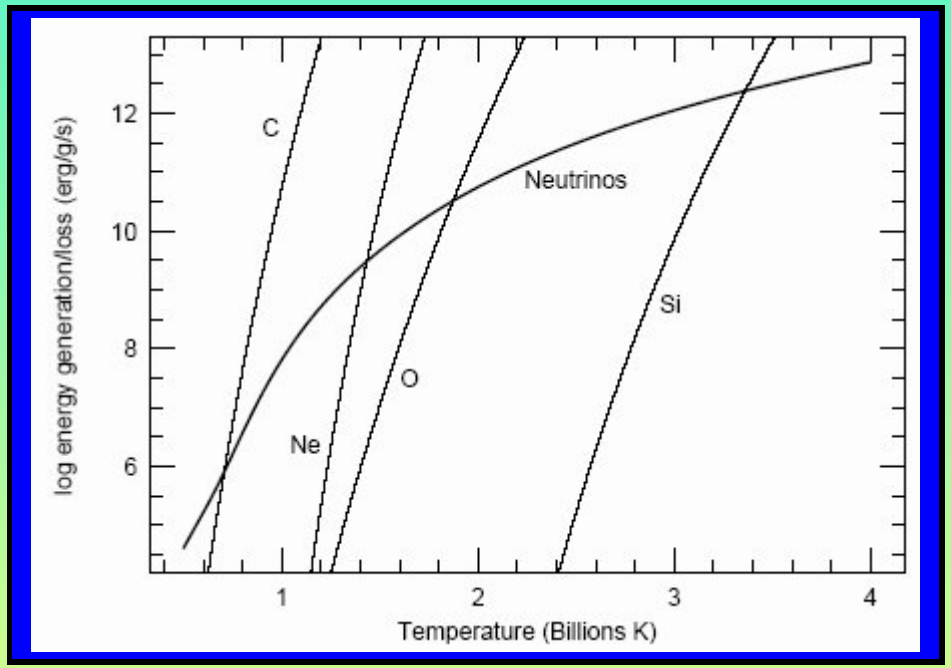
Itoh et.al, ApJSS, **102** (1996) p. 411



Burning C: $\log(T_c) = 8.9$, Ne: $\log(T_c) = 9.2$, O: $\log(T_c) = 9.3$, Si: $\log(T_c) = 9.6$. μ_e – mean molecular weight: $1/\mu_e = Y_e$.

ENERGY BUDGET

- Neutrino emission ballaning nuclear reactions.
- Nuclear reaction rate grows faster with T_c than neutrino cooling



Woosley, Heger, Weaver, RMP **74** (2002) p. 1015

CONVECTIVE CORE

Some details of the $e^+ + e^- \rightarrow \nu_x + \bar{\nu}_x$ cooling

1. Nuclear burning ignited in the central region
2. Neutrinos unable to carry out energy
3. Gas expanding due to heating
4. Burning bubble moves upward
5. Nuclear reactions ceased
6. Energy liberated as pair-annihilation neutrinos

SIMPLE NEUTRINO EMISSION MODEL

1. Central temperature T_c and density ρ_c from stellar model
2. Chemical potential μ_e computed under assumption $\mathrm{Y}_e = 0.5$

$$\frac{\rho_c \mathrm{Y}_e}{m_p} = \frac{8\pi}{h^3 c^3} \left(10^6 q_e\right)^3 \int_0^\infty \frac{(E+m_e)\sqrt{E^2+2m_e E}}{exp\left(\frac{E-\mu_e}{k_B \mathrm{T}_c}\right)+1} dE$$

3. Electrons and positrons in thermal equilibrium $\mu_{e^-} = \mu_e$, $\mu_{e^+} = -\mu_e - 2m_e c^2$.

ANNIHILATION INTO NEUTRINOS

D. Dicus, Phys. Rev. D, **6** (1972) p. 941

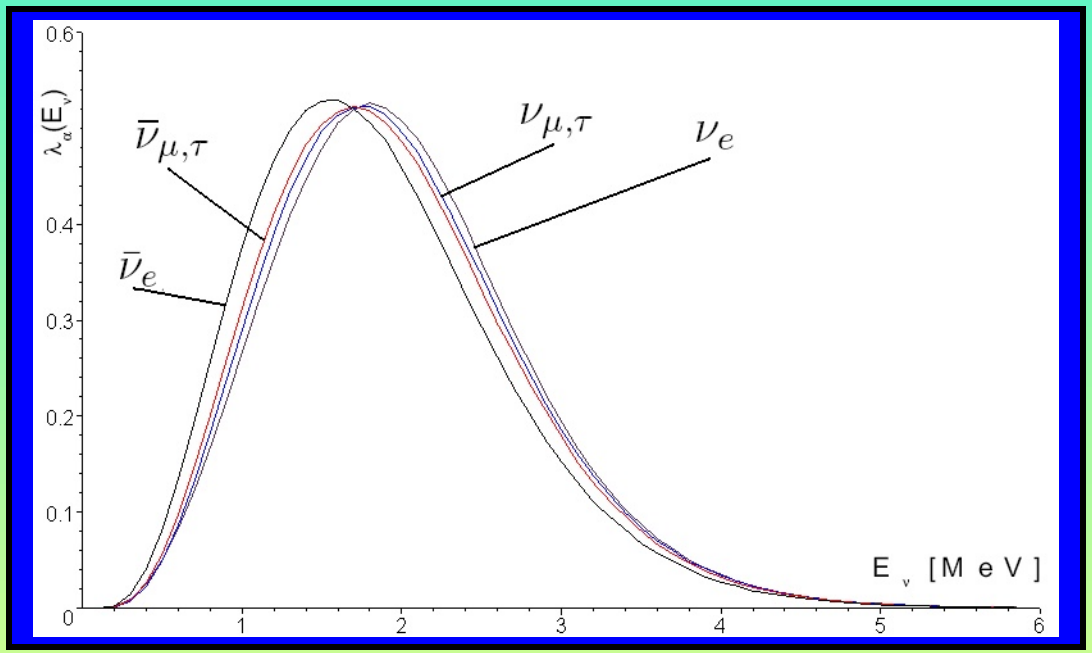
$$M = \frac{i\,g^2}{8{m_W}^2}\bar{u_\nu}(q)\gamma^\alpha(1-\gamma_5)v_\nu(q^{'}) \times \bar{v_e}(p^{'})\gamma_\alpha(C_V - C_A\gamma_5)u_e(p)$$

$$\begin{gathered}|M|^2 \propto \ (C_A - C_V)^2(p_{e^-}\cdot q_{\nu_x})(p_{e^+}\cdot q_{\bar{\nu}_x}) + (C_A + C_V)^2(p_{e^+}\cdot q_{\nu_x})(p_{e^-}\cdot q_{\bar{\nu}_x}) \ + \\ {m_e}^2({C_V}^2 - {C_A}^2)q_{\nu_x}\cdot q_{\bar{\nu}_x} = \\ ({C_A}^2 + {C_V}^2)\left[(p_{e^-}\cdot q_{\nu_x})(p_{e^+}\cdot q_{\bar{\nu}_x}) + (p_{e^+}\cdot q_{\nu_x})(p_{e^-}\cdot q_{\bar{\nu}_x})\right] \\ -2\,C_V C_A\left[(p_{e^-}\cdot q_{\nu_x})(p_{e^+}\cdot q_{\bar{\nu}_x}) - (p_{e^+}\cdot q_{\nu_x})(p_{e^-}\cdot q_{\bar{\nu}_x})\right] \\ +{m_e}^2({C_V}^2 - {C_A}^2)q_{\nu_x}\cdot q_{\bar{\nu}_x}\end{gathered}$$

$$C_V = \frac{1}{2} \pm 2\,\sin^2\theta_W \ = 0.5 \pm 0.4448, \qquad C_A = \frac{1}{2},$$

p, q 4-momenta, m_e – electron mass, θ_W Weinberg angle $\sin^2\theta_W = 0.2224$.

SPECTRUM $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$



	$\bar{E}_\nu$ [MeV]
$\bar{\nu}_e$	1.80
$\bar{\nu}_{\mu,\tau}$	1.87
$\nu_{\mu,\tau}$	1.89
ν_e	1.89

C: $\nu_{\mu,\tau}/\nu_e = 1 : 11.4$, 42.5% ν_e, Ne: $\nu_{\mu,\tau}/\nu_e = 1 : 7.8$, 39.8% ν_e,
O: $\nu_{\mu,\tau}/\nu_e = 1 : 6.9$, 38.9% ν_e, Si: $\nu_{\mu,\tau}/\nu_e = 1 : 5.4$, 36.3% ν_e.

REQUIREMENTS FOR PRE-SUPERNOVA OBSERVATION

- ν_e or $\bar{\nu}_e$ detection in 0.5-6 MeV range.
- More than N>>1 events/day.
- Long lasting experiment

ENHANCED SUPER-KAMIOKANDE

Antineutrinos detected by inverse β-decay: $\bar{\nu}_e + p \rightarrow n + e^+ \quad (\star)$

Spectrum averaged cross-section:

$$\bar{\sigma}_{\mathrm{Si}} = \int_{E_{min}}^{\infty} \sigma(E)\lambda_{\mathrm{Si}}(E)\, dE = 0.7 \cdot 10^{-43}\ \mathrm{cm}^2$$

$E_{min} = 1.8\,\mathrm{MeV}$. Reaction $(\star)$ gives 41 events/day at D=1kpc