Detection of Supernova Neutrinos

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OUTLINE

- Characteristic of the neutrino signal from a stellar core collapse
- Detectors for SN neutrinos
- Observation of the SN1987A
- Future observations

The gravitational collapse

- A massive star ($M \approx 10M_{\odot}$) with an iron core ($M_C \approx 1.5M_{\odot}$) undergoes a gravitational collapse
  (at t=0 T_C~1MeV, ρ_C~10^{10} g/cm^3)
- Gravitational collapse speeds up due to photo-disintegration and e-capture:
  $\gamma + {}^{56}Fe \to 13\,{}^{4}He + 4n - 124.4\,MeV$
  $e^- + p \to n + \nu_e$
- Collapse is supposed to create a neutron-star remnant

Energy released by the collapse

$$E_B \equiv \Delta E \approx \frac{3}{5} G \frac{M_{NS}^2}{R_{NS}} \sim 2 \cdot 10^{53} erg \left(\frac{M_{NS}}{M_{Sun}}\right)^2 \left(\frac{10km}{R_{NS}}\right)$$

Energy balance:

- photo-disintegration:

  $E_\gamma < 1.5 M_{Sun} N_A$ (124.4/56) MeV~2%E_B

- explosion:

  $E_{exp} \approx (10M_{Sun}) v^2_{ej}/2 \sim (10M_{Sun})(1000 km/s)^2/2 \sim 1\% E_B$

- **ν-emission: >90%E_B**

ν Trapping and ν-sphere

- Core density > 10^{12} g/cm^3
- $\nu + (A,Z) \rightarrow \nu + (A,Z)$ large $\sigma \sim 10^{-42}$ cm^2(E/10MeV)^2
- $\lambda \sim 300$ m /ρ(10^{13} g/cm^3)
- ν trapped inside a sphere with radius R_ν which defines the surface of last scattering
- each neutrino type has its own R_ν
  - due to e-capture ν_e have larger R_ν

Stellar collapse and ν emission

4 phases:

- **Infall**: free-fall time scale ~ 100ms
- **Falling material on inner stiff core and bounce**
  - Shock wave in outer core
  - Early emission of ν_e: $e^- p \to n\nu_e$
- **Accretion and delayed shock revival** ~ 500ms
  - $e^+ + n \to p +$ anti-ν_e
  - $e^+ + e^- \to \nu_i +$ anti-ν_i
- **Cooling** ~10s
  - $e^+ + n \to p +$ anti-ν_e and $e^- + p \to n + \nu_e$
  - $e^+ + e^- \to \nu_i +$ anti-ν_i

PROMPT EMISSION

LATE THERMAL EMISSION

ν Energy and Fluence

$$T_\nu = \left(\frac{E_B}{\tau_{cooling}} \cdot \frac{1}{4\pi\sigma_{S-B} R_C^2} \cdot \frac{1}{g_\nu} \right)^{1/4} \approx 4 \text{ MeV}$$

$$\mathrm{E}_\nu = 3.15 T_\nu \approx 13 \text{ MeV}$$

$$F_\nu = \frac{1}{4\pi d^2} \cdot \frac{E_B}{E_\nu} \approx 10^{12} cm^{-2} \left(\frac{10kpc}{d} \right)^2$$

SN ν detection: is it possible?

1kton water detector :

$$\sigma(\bar{\nu}_e + p \rightarrow e^+ + n) \approx 9.3 \cdot 10^{-42} cm^2 \left(\frac{E_\nu}{10 MeV} \right)^2$$

Expected events at 10kpc : $0.8 \left(\frac{N_A}{18} \cdot 2 \cdot 10^9 \right) \cdot (1.57 \cdot 10^{-41} cm^2) \cdot 10^{12} cm^{-2} \approx 800$

Main features of emitted ν's

- All ν types emitted by CC and NC processes
- Energy hierarchy: $\langle E_e \rangle < \langle E_{\bar{e}} \rangle < \langle E_x \rangle$ with $x = \{\mu, \tau\}$
  - ν_e has a larger ν-sphere due to neutron rich material and large e-capture cross-section

$$\langle E_e \rangle = 10 - 12\,MeV$$
$$\langle E_{\bar{e}} \rangle = 12 - 15\,MeV$$
$$\langle E_x \rangle = 15 - 28\,MeV$$

- Equipartition: $E_i \approx E_B / 6$

ν Energy Spectra

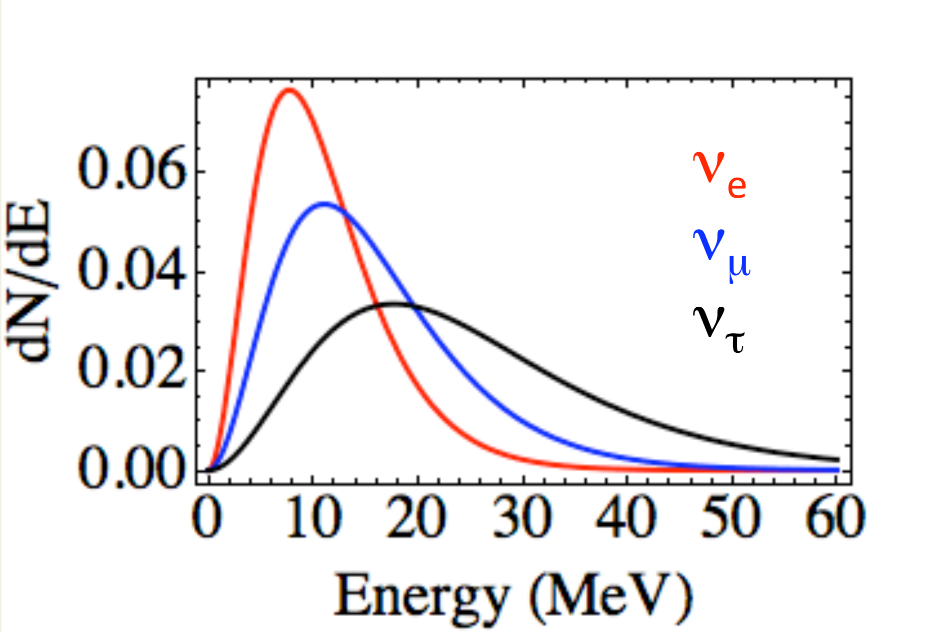
$$\left.\frac{d^2\phi_\nu^0}{dEdt}\right|_i = N\frac{L_i(t)}{4\pi d^2} f_i(E,T_i,\eta_i)$$

$$f(E,T,\eta) = \frac{E^2}{1+\exp(E/T-\eta)}$$

$$\text{Fluence}_\text{i} = \frac{1}{4\pi \text{d}^2}\cdot\frac{E_i}{\langle E_i\rangle}\cdot f_i(E,T_i,\eta_i)$$

$$\langle E_i\rangle = T_i\frac{F_3(\eta_i)}{F_2(\eta_i)}$$

$$T_{\bar{\nu}_e} = 5MeV,\ \text{T}_{\nu_\text{e}} = 0.7T_{\bar{\nu}_e},\ \text{T}_{\nu_\text{x}} = 1.6T_{\bar{\nu}_e}$$



SN Neutrino Oscillations

$$F_e^0 \rightarrow F_e = P_{ee}F_e^0 + P_{\mu e}F_\mu^0 + P_{\tau e}F_\tau^0$$

$$F_e = P_{ee}F_e^0 + (1 - P_{ee})F_x^0 \quad \text{with } \mathrm{F}_x^0 = F_\mu^0 = F_\tau^0$$

$$2F_x + F_e = 2\mathrm{F}_x^0 + F_e^0$$

For normal hierarchy with $\theta_{13} > 1^\circ$

$$F_{\bar{e}} = \cos^2\theta_{12}F_{\bar{e}}^0 + \sin^2\theta_{12}F_{\bar{x}}^0 \approx 0.7F_{\bar{e}}^0 + 0.3F_{\bar{x}}^0$$

$$F_e = \sin^2\theta_{13}F_e^0 + \cos^2\theta_{13}F_x^0 \approx F_x^0$$

SN rate in our galaxy

- From historical SN:

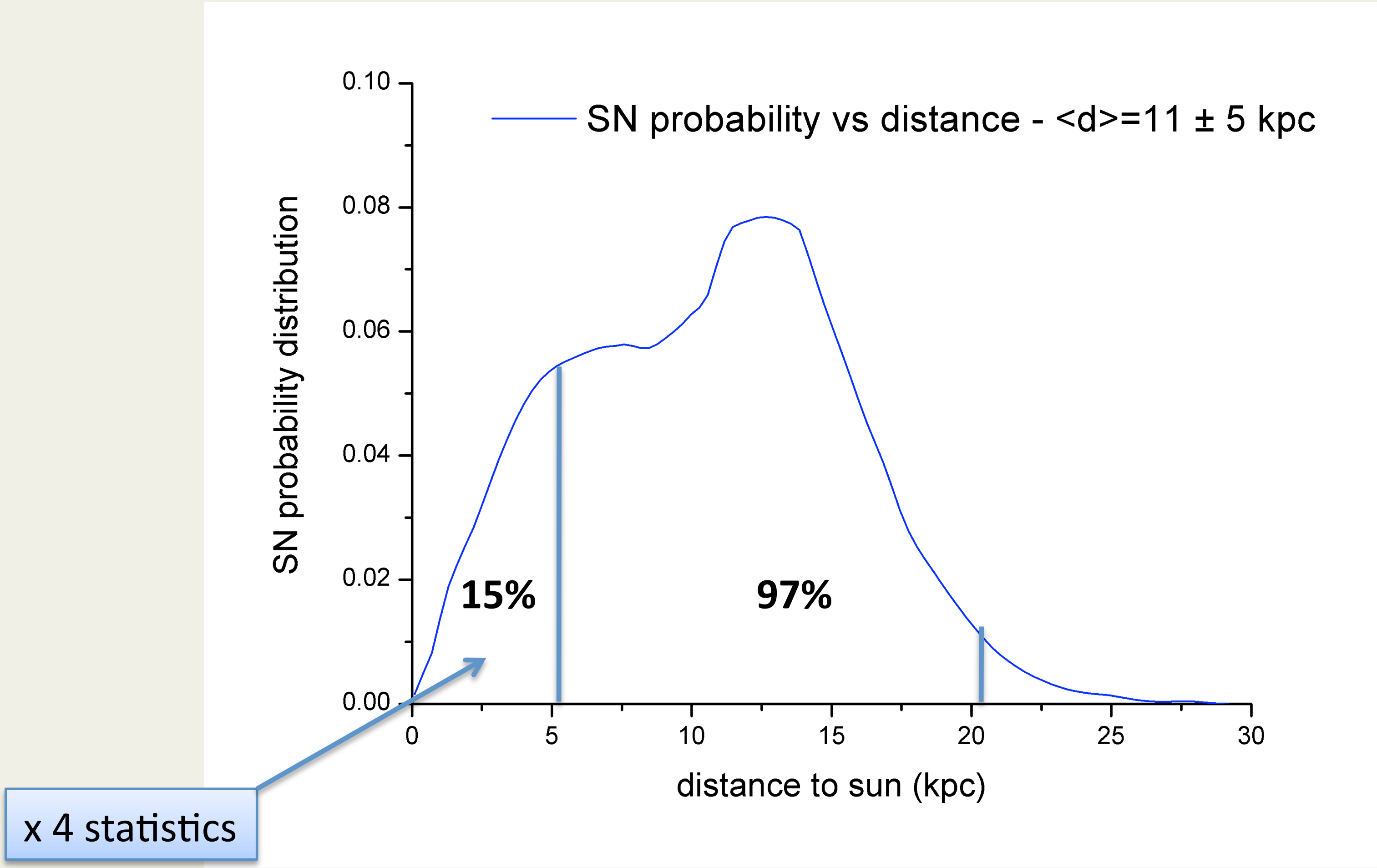
(6SN/1000yr) x 6 x 0.4 ~ 1/70yr

to accounts for obscuration (the 6) — only type II (the 0.4)

- From extragalactic observations:

1/30yr – 1/90yr

Galactic SN vs distance to the Sun



Mirizzi, Raffelt and Serpico, JCAP 0605,012(2006)

Detection techniques

Problem:

- Goal: search for a rare signal involving neutrinos
- Need sensitivity to 1-100 MeV range
- Need to be operational for > 10 years

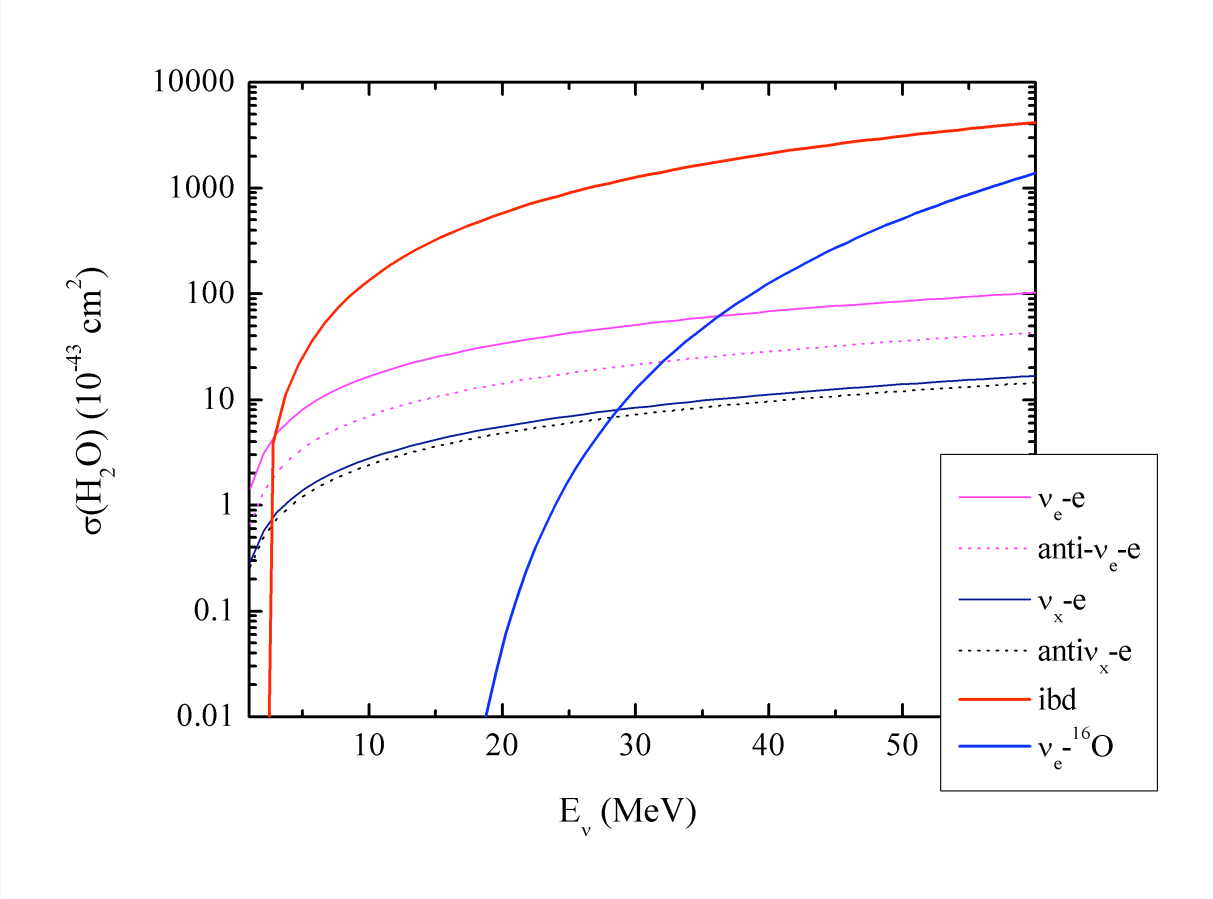
Solution:

- Look at inverse processes in SN ν production
- Use solar/reactor neutrino detection techniques
  - Massive Cherenkov
  - Massive liquid scintillators
  - Massive liquid nobles gases (Xe, Ar, Ne)

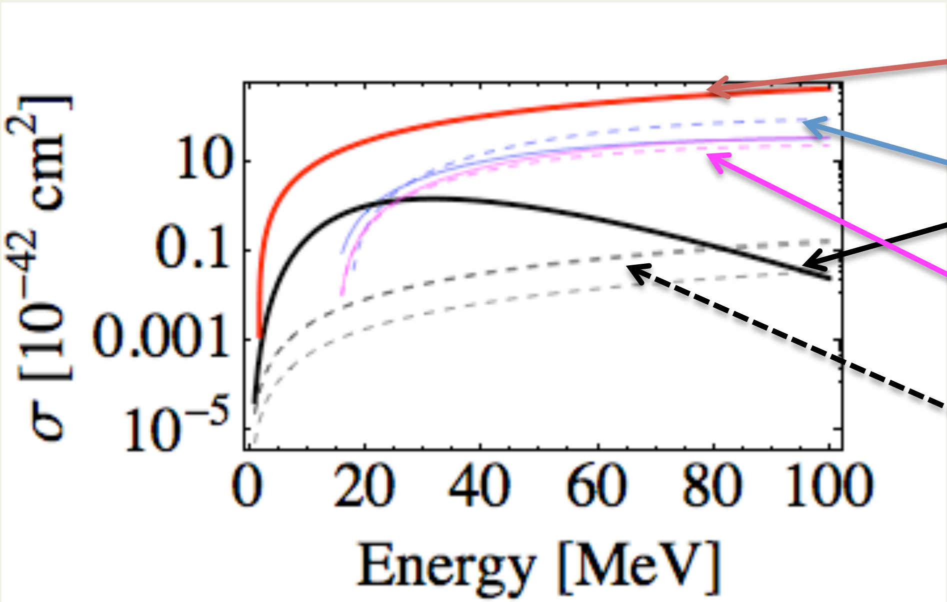
Detection channels

CC	NC	ES
$\nu_e + n \rightarrow e^- + p$	$\nu + p \rightarrow \nu + p$	$\nu_x + e^- \rightarrow \nu_x + e^-$
$\bar{\nu}_e + p \rightarrow e^+ + n$	$\nu + (A,Z) \rightarrow \nu + (A,Z)^*$	
$\bar{\nu}_e + (A,Z) \rightarrow e^+ + (A,Z-1)$	$\bar{\nu} + (A,Z) \rightarrow \bar{\nu} + (A,Z)^*$	
$\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)$	$\nu + (A,Z) \rightarrow \nu + (A,Z)$	

Cross-sections for a water Cherenkov



Cross-sections for a LS detector



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

$$\nu + p \rightarrow \nu + p$$

$$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$$

$$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$$

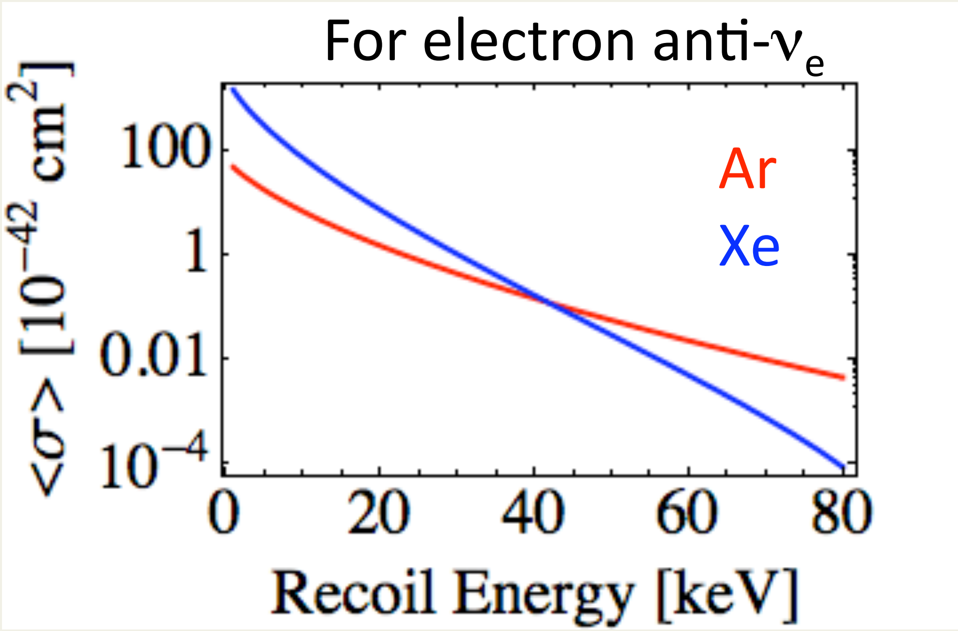
$$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$$

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

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

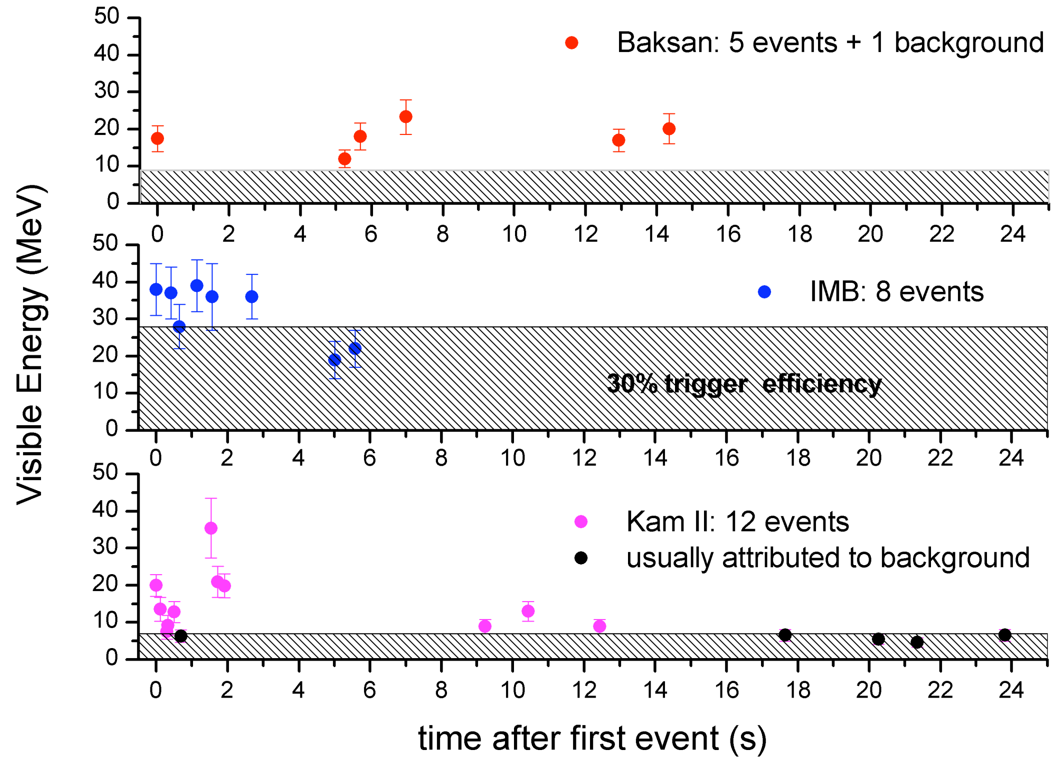
Cross-section in a liquid noble gases

- Use coherent ν-N scattering



SN1987A: 1° SN ν observation

- 23rd Feb 1987
- ~ 50 kpc
- Only 29 events
  - 16 Kamiokande (Cherenkov)
  - 8 IMB (Cherenkov)
  - 5 Baksan (LS)



After SN1987A

- A huge number of papers which confirm basic understanding of a core collapse
- Limit on neutrino mass (< 20 eV) from time-of-flight
- Limit on exotic particles and matter
- Hint of accretion+cooling phase (see Pagliaroli this meeting)

ONLY WITH 25 EVENTS!

A two component model for SN1987A

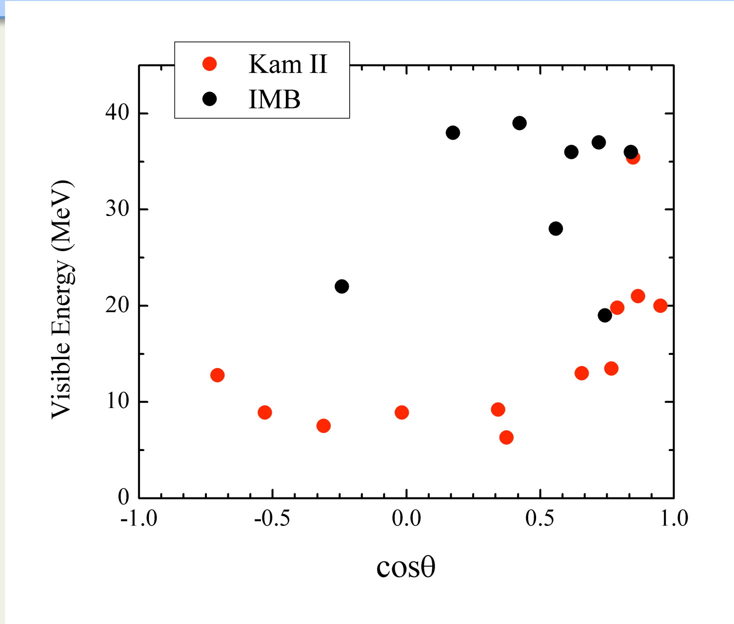
Emission of $\bar{\nu}_e$ from a ν - sphere :

Cooling	Accretion
$R_\nu = 16^{+9}_{-5}$ km	$M_a = 0.22^{+0.68}_{-0.15} M_{Sun}$
$T_c = 4.6^{+0.7}_{-0.6}$ MeV	$T_a = 2.4^{+0.6}_{-0.4}$ MeV
$\tau_c = 4.7^{+1.7}_{-1.2}$ s	$\tau_a = 0.55^{+0.58}_{-0.17}$ s
$E_c \sim 2 \cdot 10^{53}$ erg	$E_a \sim 0.6 \cdot 10^{53}$ erg

G.Pagliaroli et al.

SN1987A: anomalies

- General scenario confirmed with some obscure points
  - Mean energy too low: <E^{exp}>8MeV, <E^{th}>~13MeV
  - Angular distribution: expected uniform



Next SN for a high statistic data sample …

Water Cherenkov

Golden channel: inverse beta decay

Experiment	Location	Mass	Status	Threshold	Events for 10kpc and golden channel
Super-Kamiokande	Kamioka lab	22.5kton	operational	5 MeV	~8000 [~2000 at 20kpc]
SNO	SNOlab	1kton	stopped	5 MeV	-

SNO had: $\nu_e + d \rightarrow e^- + p + p$

In SK

~300 from ES

~360 NC on ^{16}O

~100 CC on ^{16}O

Liquid Scintillators

Golden channel: inverse beta decay

1. prompt signal: E_{prompt}> 1MeV
2. delayed signal: Δt~250 μs from np->dγ(2.2MeV)

Exp.	Location	Mass	Status	Threshold	Events for 10kpc and golden channel
LVD	Gran Sasso	1kton	operational since 1992	5 MeV	400
Borexino	Gran Sasso	300ton	Operational since 2007	0.2 MeV	80
KamLAND	Kamioka	1kton	Operational since 2002	1 MeV	330
MiniBooNE	USA	0.7kton	operational	0.2 MeV	190
SNO+	SNOlab	1kton	>2010	0.2MeV (goal)	800
Baksan	Russia	330t	Operational since 1980	7MeV	100

LVD

Thanks to Walter Fulgione

LVD

- LVD consists of an array of 840 counters 1.5 m^3 each, for a total target:

  1000 t of C_nH_{2n}

  900 t of Fe

- It is divided in three "towers" independent for power supply, trigger and DAQ.

LVD has been designed with the main purpose of detecting neutrinos from core collapse SN in our Galaxy.

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

$\nu_e + {}^{12}C \to {}^{12}N + e^-$

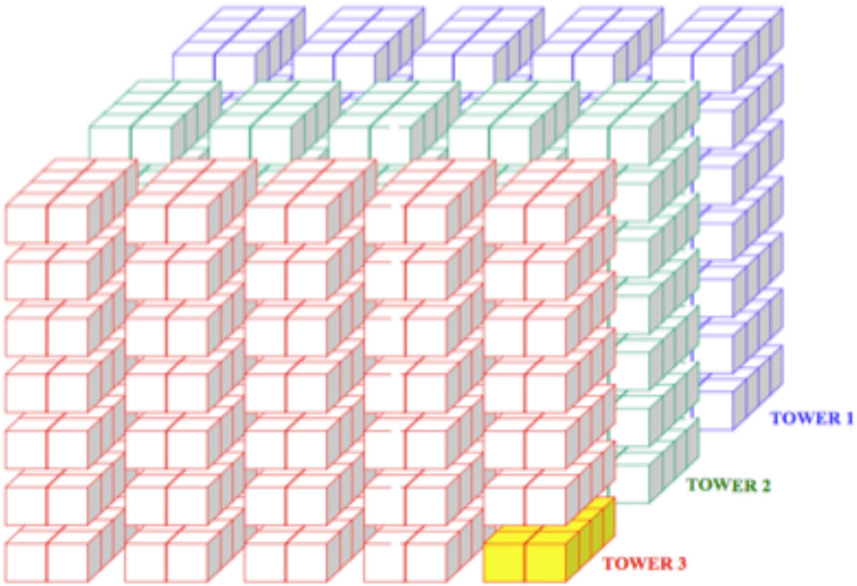
$\bar{\nu}_e + {}^{12}C \to {}^{12}B + e^+$

$\nu_i + {}^{12}C \to \nu_i + {}^{12}C^*$

$\nu_e + {}^{56}Fe \to {}^{56}Co + e^-$

$\bar{\nu}_e + {}^{56}Fe \to {}^{56}Mn + e^+$

$\nu_i + Fe \to \nu_i + Fe$



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Expected events in LVD

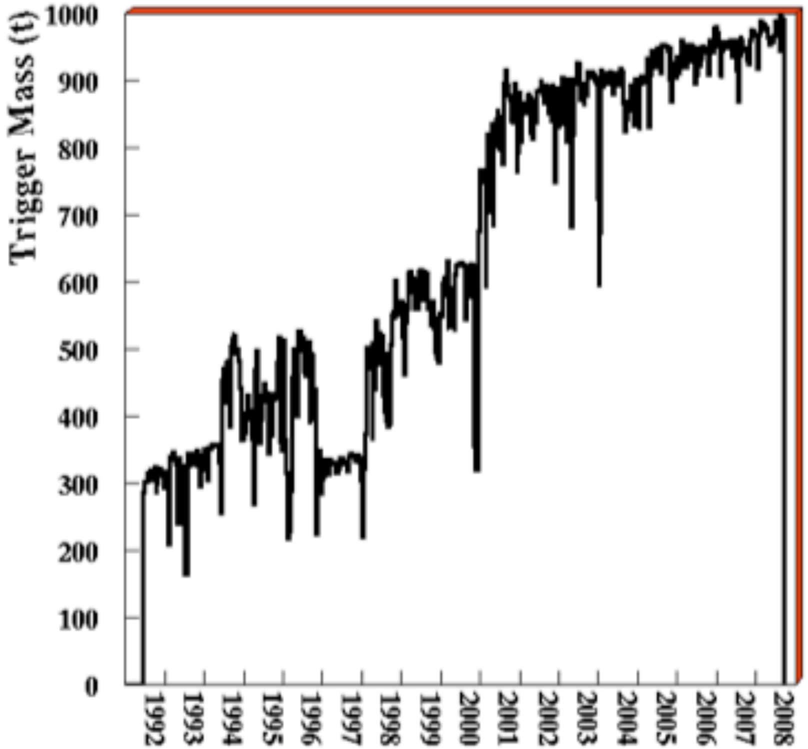
	No oscillations	Oscillations NH	Oscillations IH
Golden ch.	346	391	494
<E> for golden ch. [MeV]	25	30	37
CC on ^{12}C	8	29	27
CC on ^{56}Fe	22	95	92
NC on ^{12}C	22	27	27

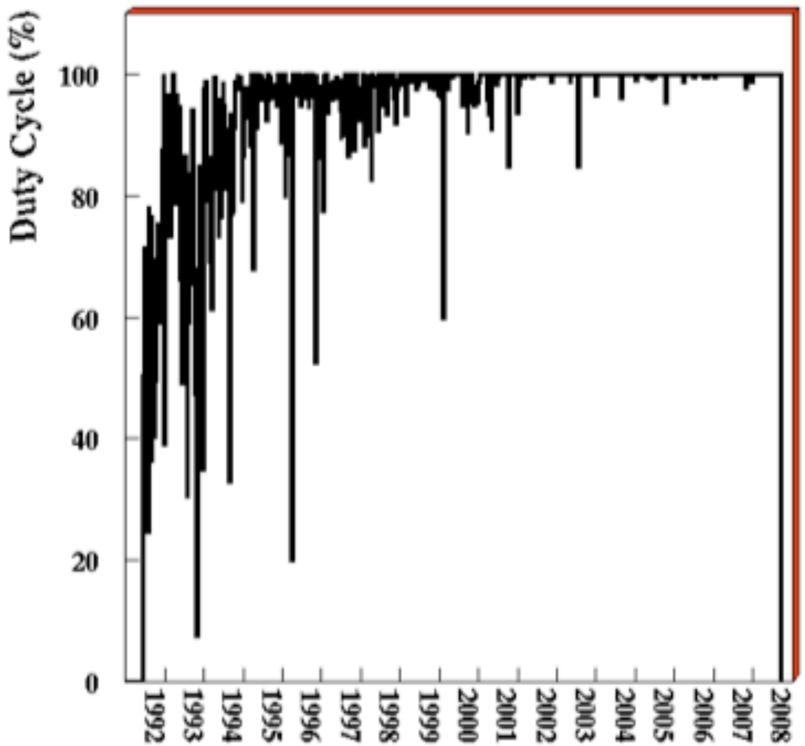
M. Selvi, hp-ex/0608061

Active Mass and Duty Cycle

LVD modularity helps preventing problems with failures of subsets of the detector

LVD active mass and duty-cycle during more than 15 years of data taking.





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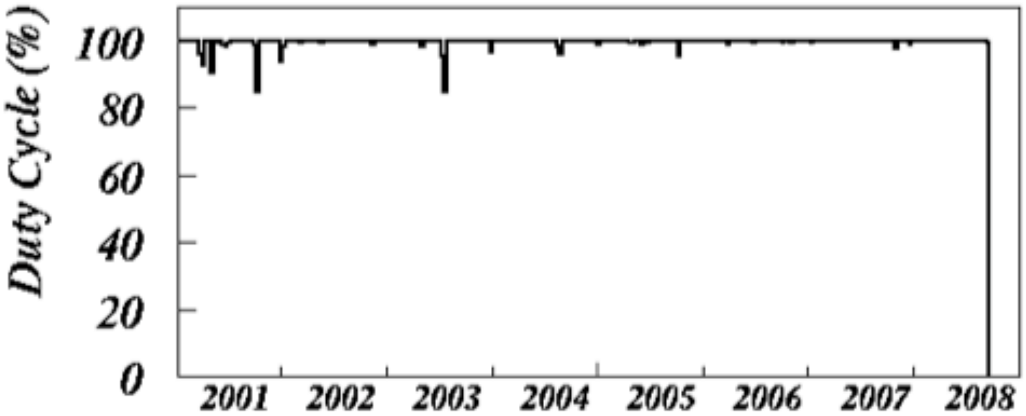
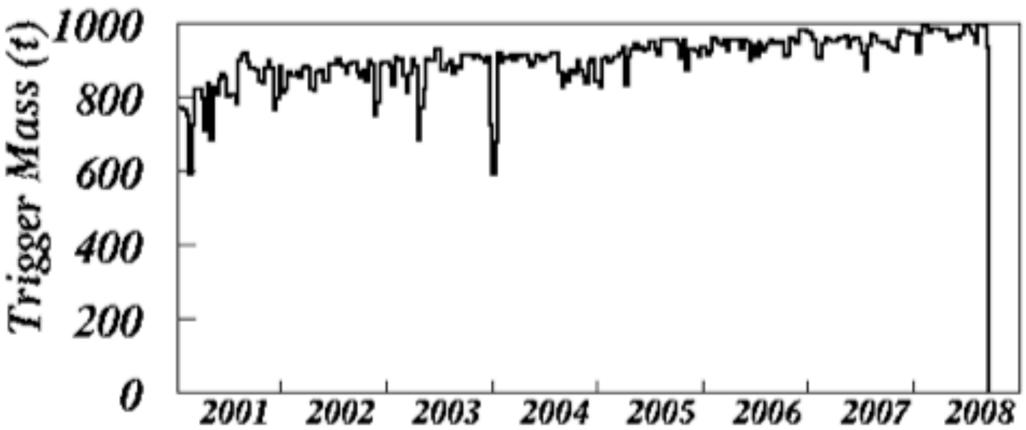
Active Mass and Duty Cycle

The ν observatory reached its final configuration in the end of 2000.





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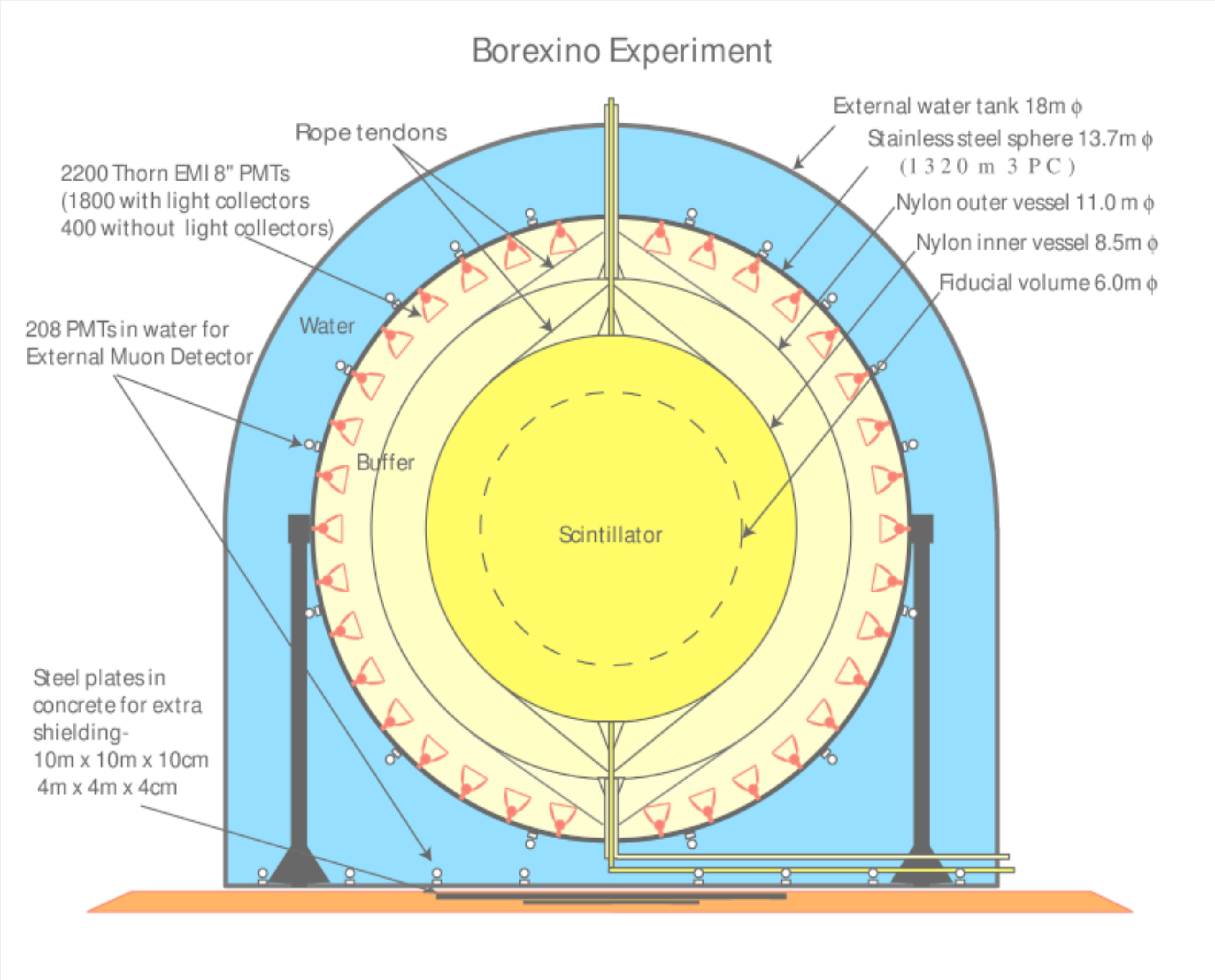
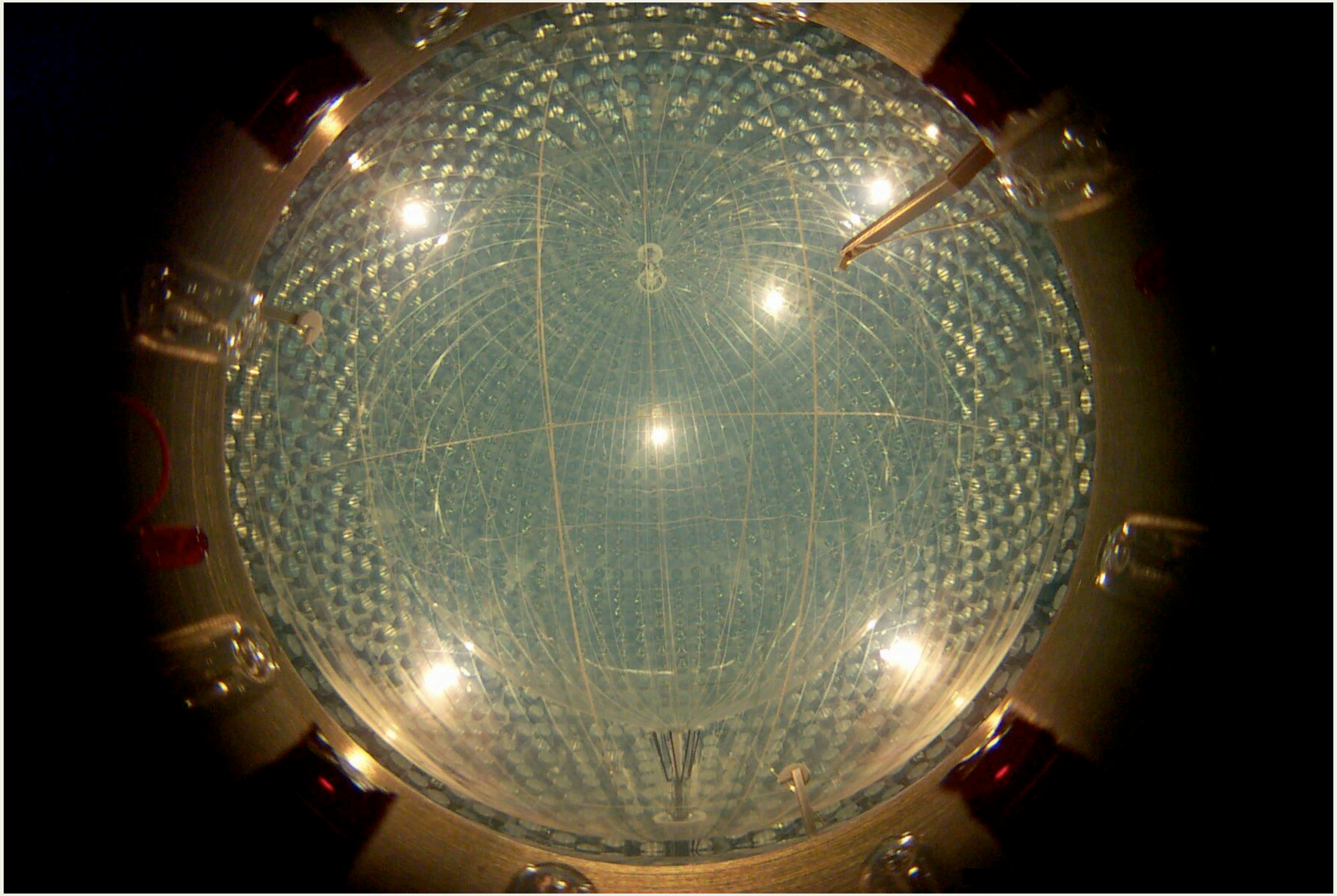
Borexino detector



Borexino Filled: May 2007



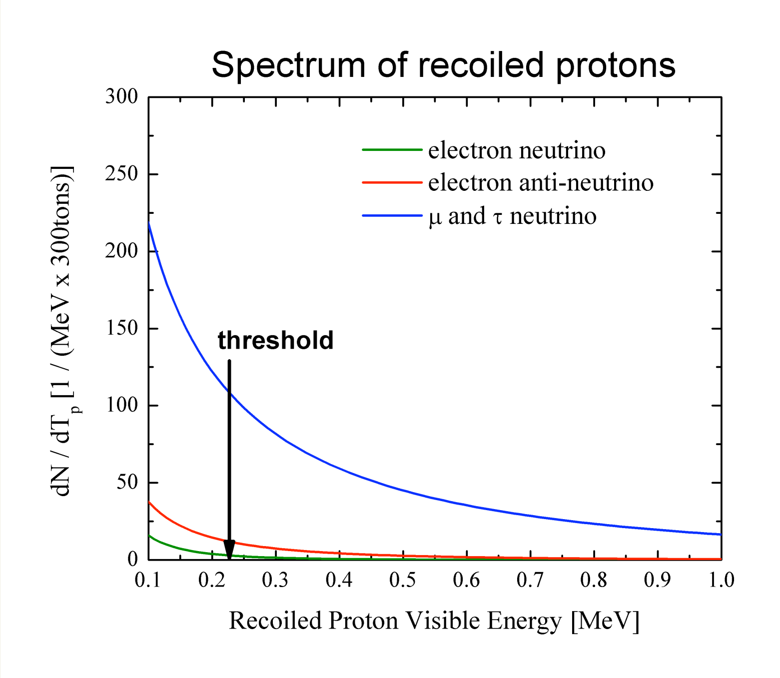
Expected events in Borexino

	No oscillations	Oscillations NH	Oscillations IH
Golden ch.	67	78	101
<E> for golden ch. [MeV]	25	30.5	39
CC on ^{12}C->^{12}B CC on ^{12}C->^{12}N	2 0.5	3 9	6 6
ES	5	5	5
NC on ^{12}C	9 + 8(anti-ν)		
νp	64		

The ν+p channel: measurement of T_x

- The golden ch. gives the temperature of anti-ν_e
- This NC ch. Can give the temerature of ν_x
- Due to quenching only the contribution from ν_x can be measured
- Other NC detection channels cannot break the degeneracy

$$\text{Events} \propto \left(4\frac{E_B}{6}\right)\frac{\langle\sigma\rangle}{T_x}$$



J. Beacom et al., PRD66:033001, 2002

Detectors based on liquid noble gases

- T600 Icarus at Gran Sasso:
  - Liquid Ar: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K$
- CLEAN: 10ton liquid Ne + νN NC ES
  - C. Horowitz et al., PRD68:023005, 2003
- Detectors based on liquid Ar and Xe for dark matter search
- Same information as from νp for LS detectors

Amanda/IceCube

- Long strings (~km) of PMT in ice
- Observation based on burst at low energy (nominally threshold at multi-GeV)

SuperNova Early Neutrino Warning System

- Network of SN sensitive detectors
- Alert if coincidence within 10s
- At present: Super-Kamiokande, LVD, Amanda in the network

Next SN …

- High statistic
- Sensitivity to details of emission (early burst, accretion)
- Neutrino mass sensitivity at 1eV level with GW to set time zero
- New particles and new phase of matter
- Neutrino oscillations
- …

Thank you !