Supernova Neutrinos in WbLS:

Promise and Requirements

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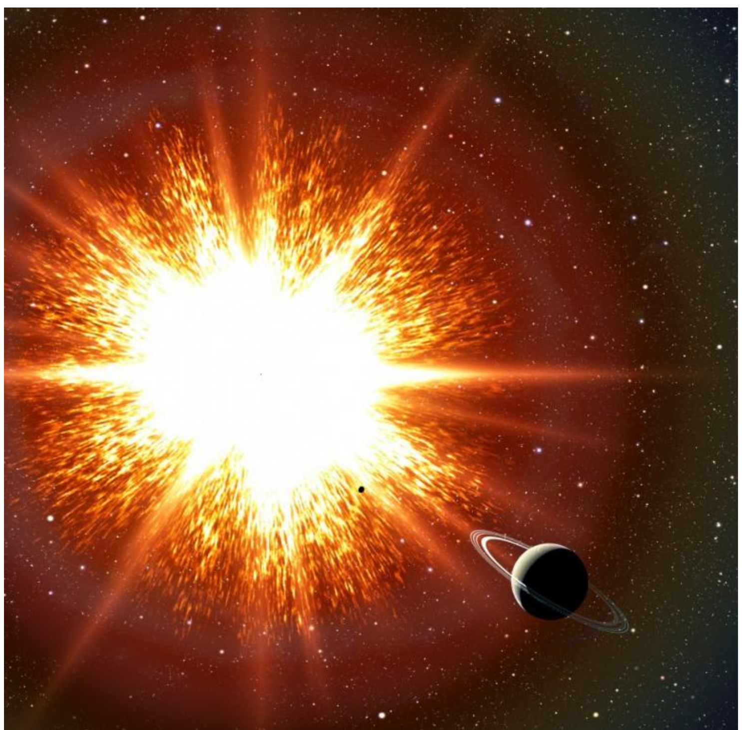
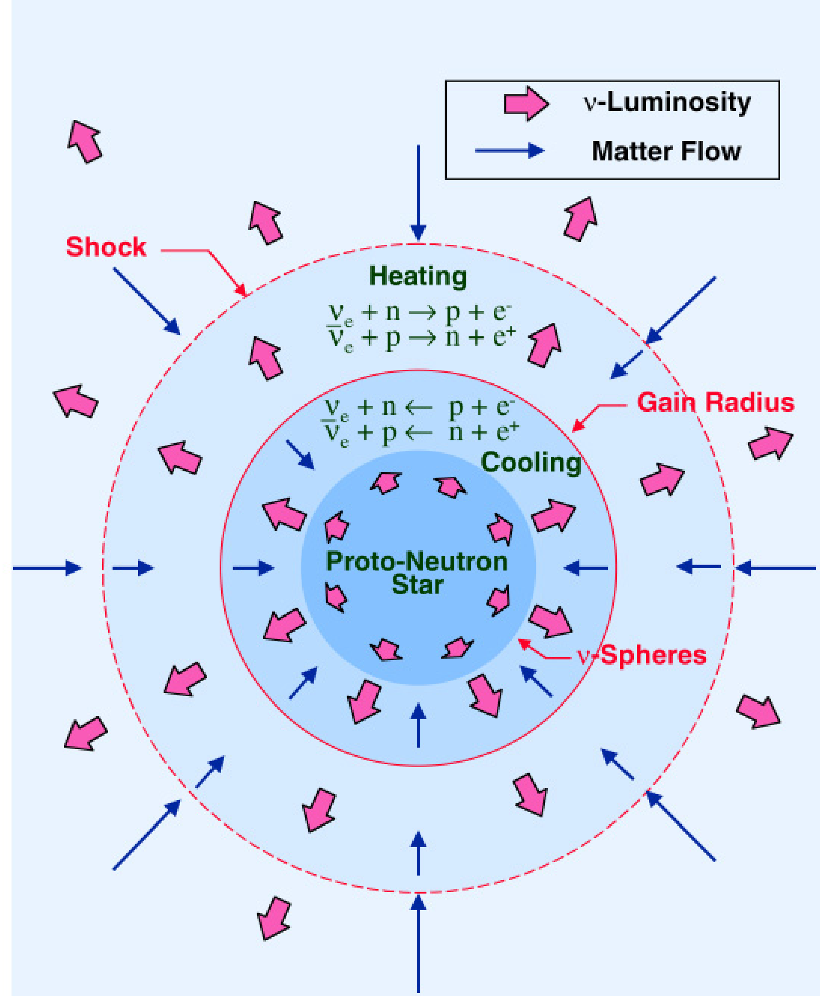
A core-collapse supernova is
a nearly perfect “neutrino bomb”.

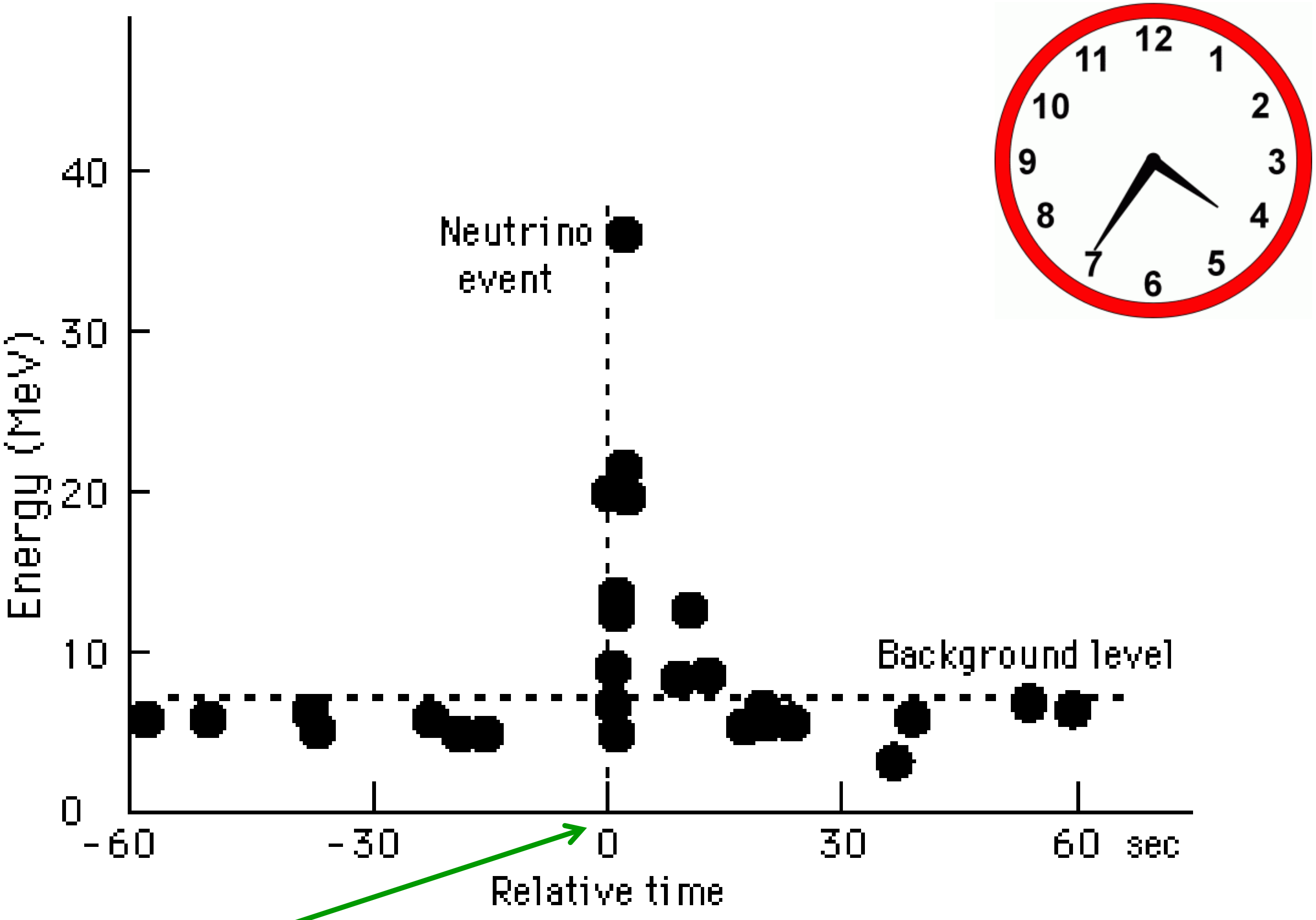
Within ten seconds of collapse it releases >98% of its huge energy (equal to 10^{12} hydrogen bombs exploding per second since the beginning of the universe!) as neutrinos.



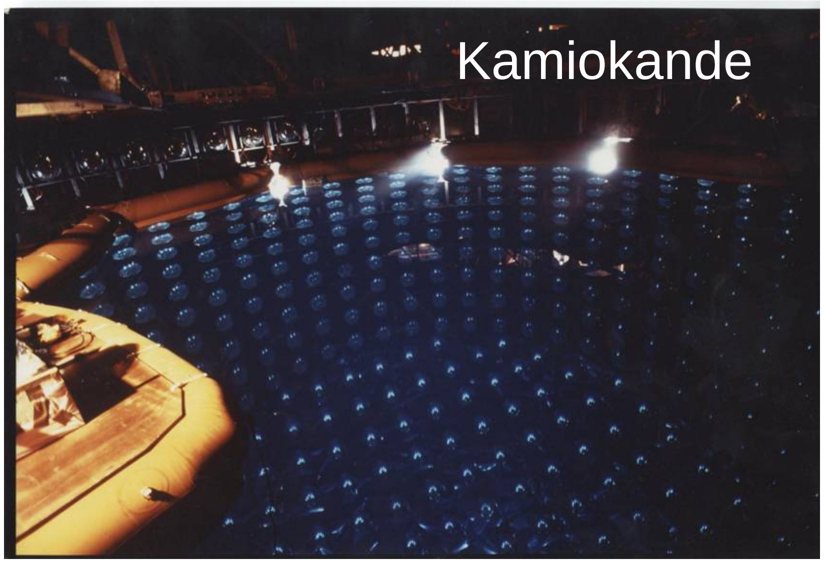


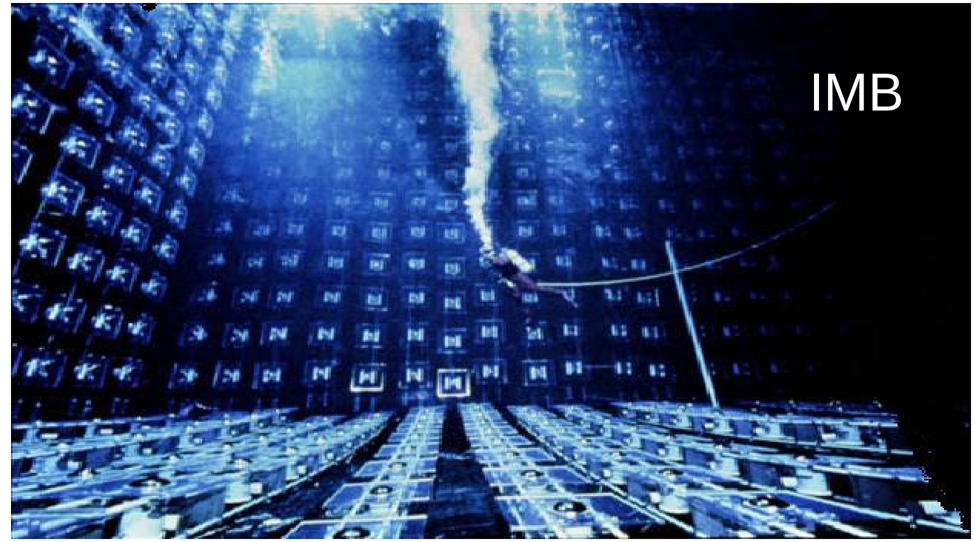
Neutrinos, along with gravitational waves, provide the only possible windows into core collapses’ inner dynamics.

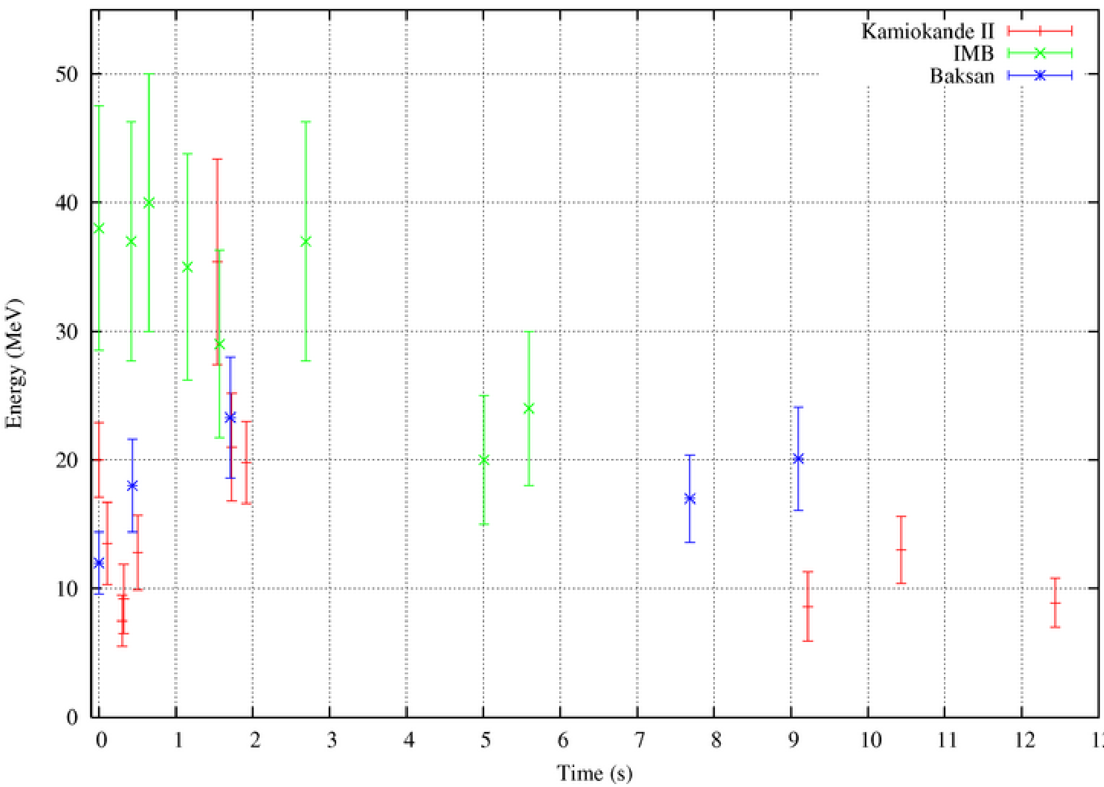
Kamiokande's Burst Time Structure

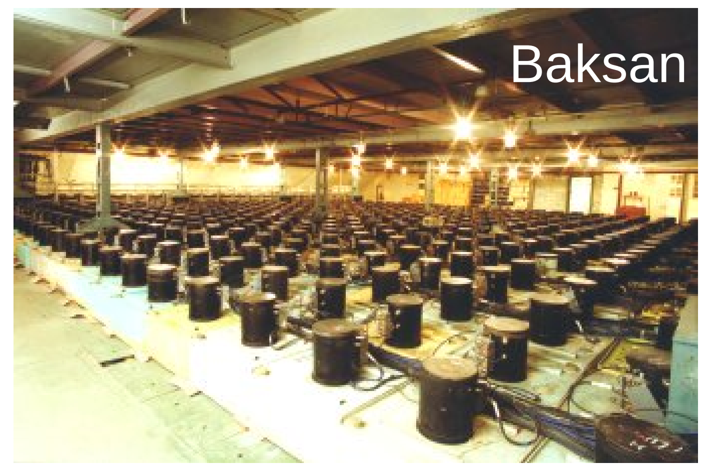


16:35:41 JST on February 24th, 1987


Kamiokande

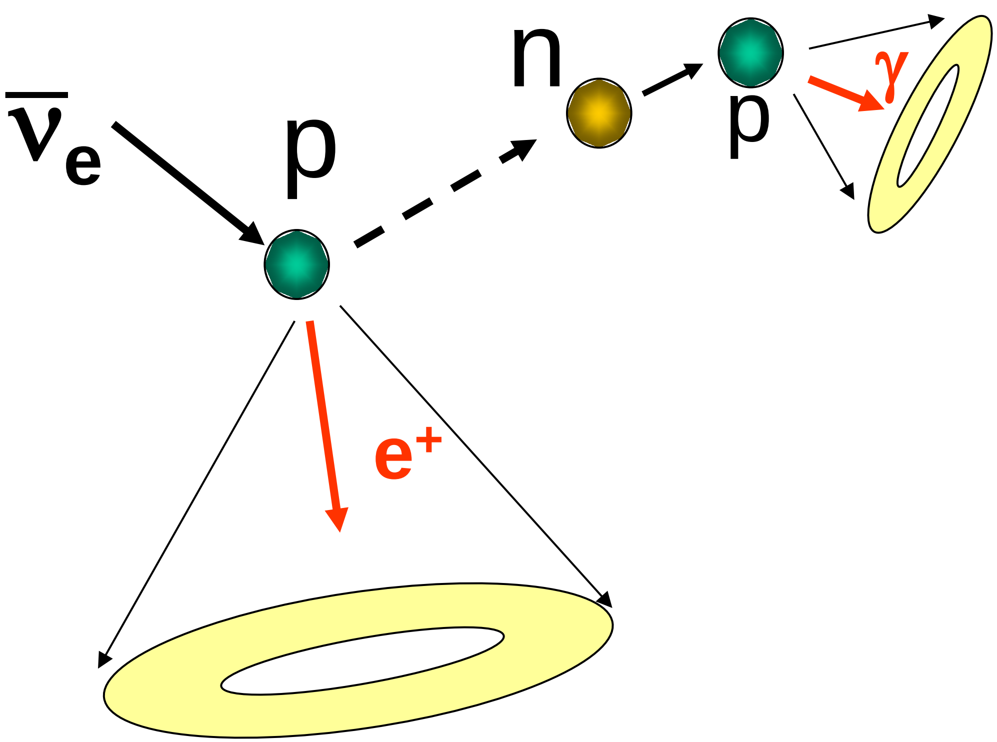

IMB


Kamiokande II
IMB
Baksan
Energy (MeV)
Time (s)
0
10
20
30
40
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13


Baksan

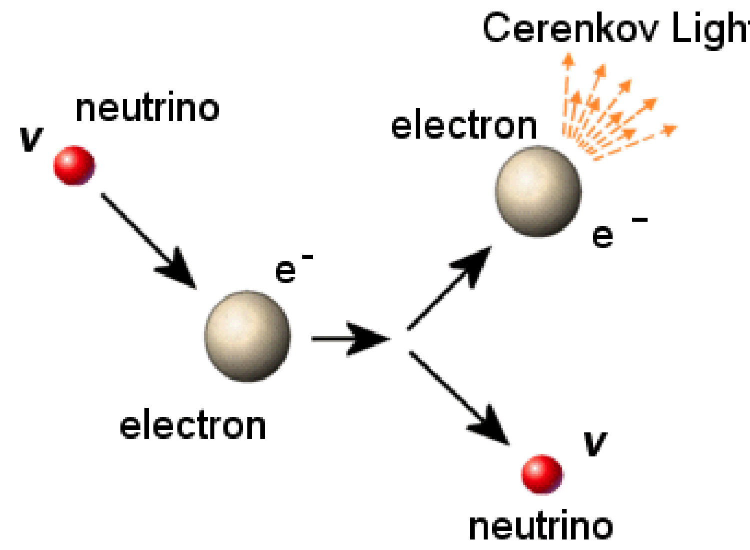
Inverse Beta Decay

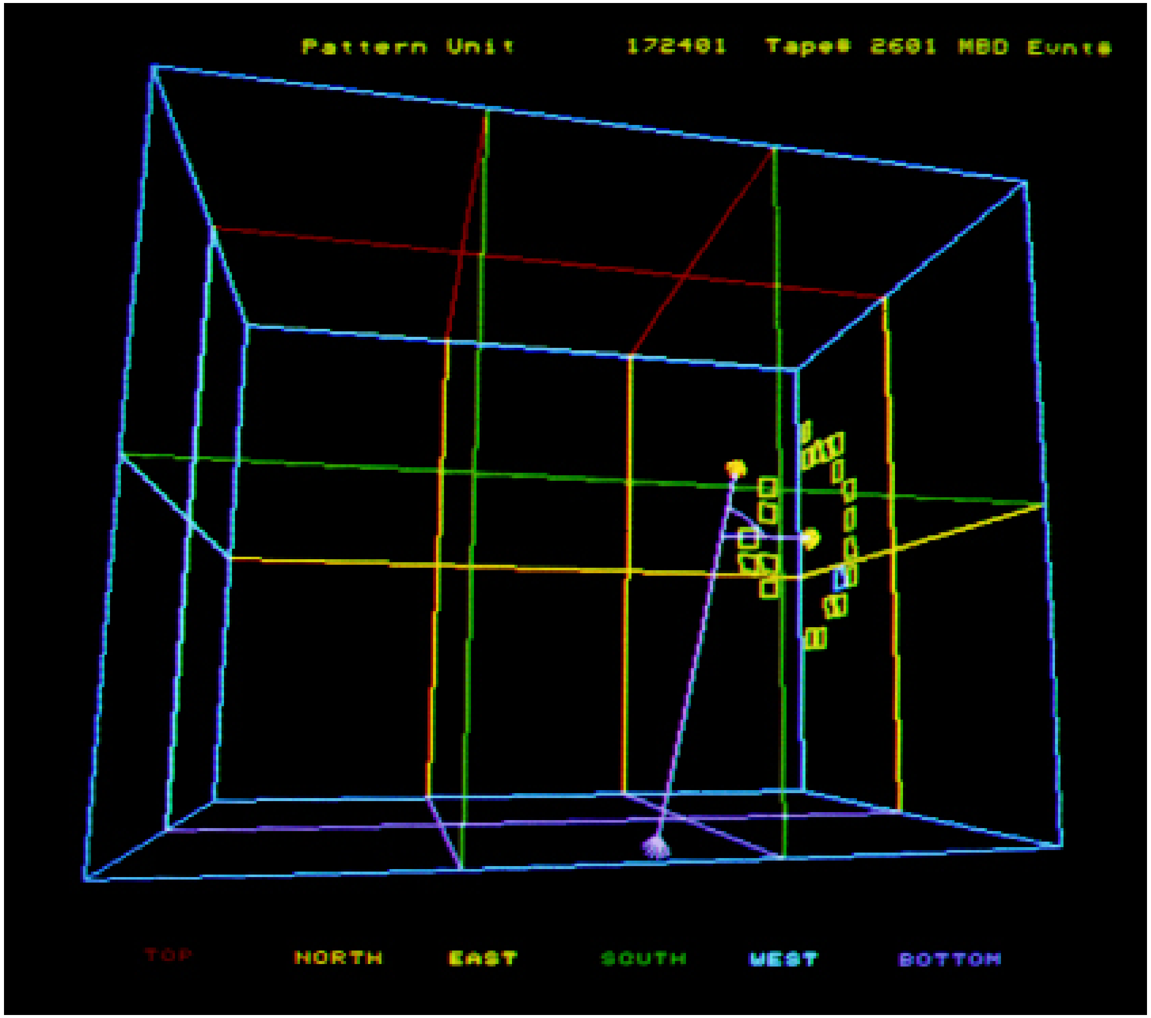
(~88% of events)



Elastic Scattering

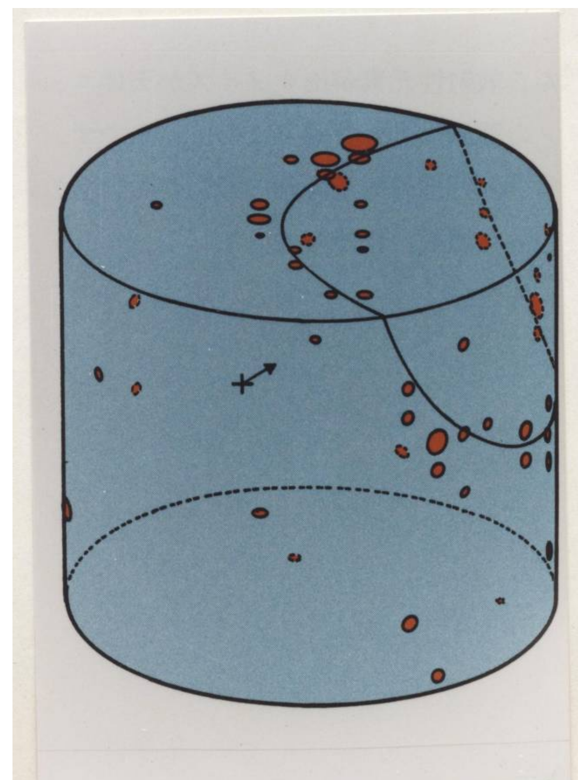
(~3% → directional)





IMB
(in USA)

Kamiokande
(in Japan)

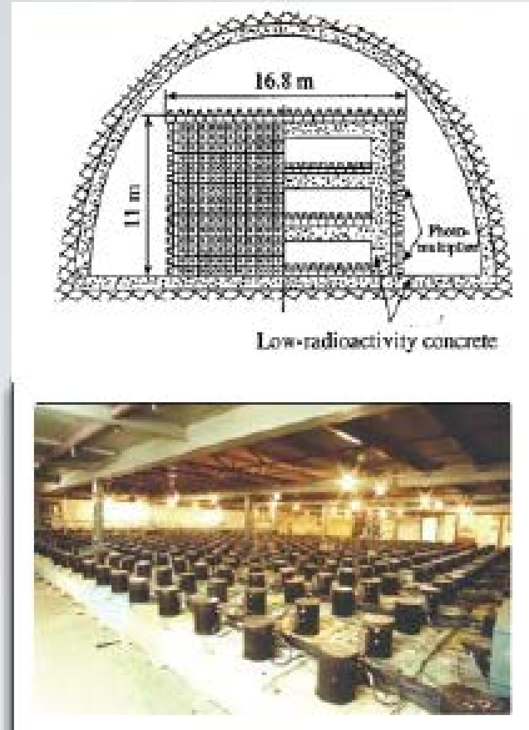


Event Displays of Actual Neutrinos from SN1987A

Masatoshi Koshiba ultimately received the Nobel Prize in physics for observing the neutrinos from SN1987A.

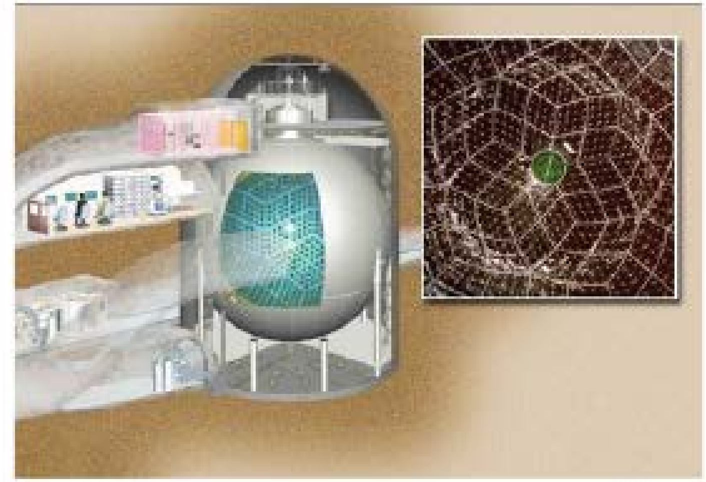
December 10, 2002

(running) Liquid Scintillator Detectors



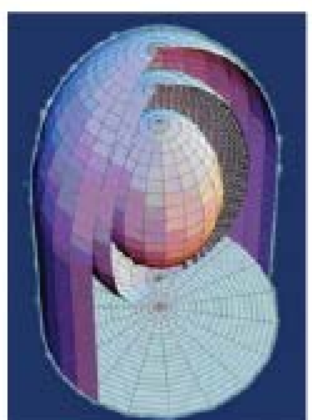
BNO
Baksan Neutrino Observatory
(INR - Russia)
[0.33 kT]

LVD
Large Volume Detector
(INFN - GranSasso - Italy)
[1 kT]



KAMLAND
Kamioka Liquid-scintillator Antineutrino Detector
(Japan)
[1 kT]

BOREXINO
(INFN - GranSasso - Italy)
[0.3 kT]



[Flavio Cavanna]

Liquid scinitillator detectors

Expected number of events(for 10kpc SN)

Events/1000 tons

- Inverse beta($\bar{\nu}_e$+p→e^++n) : ~300 events

  Spectrum measurement with good energy resolution, e.g. for spectrum distortion of earth matter effect.
- CC on ^{12}C (ν_e+^{12}C→e+^{12}N(^{12}B)) : ~30 events

  Tagged by ^{12}N(^{12}B) beta decay
- Electron scattering (ν+e^-→ ν+e^-) : ~20 events
- NC γ from ^{12}C (ν+^{12}C→ν+^{12}C+γ): ~60 events

  Total neutrino flux, 15.11MeV mono-energetic gamma
- ν+p scattering(ν+p→ ν+p): ~300 events

  Sensitive to all types of neutrinos.
  (Independent from neutrino oscillation)
  Spectrum measurement of higher energy component.

From K.Inoue, G.Bellini, M.Chen

SN Neutrino Signals in Water Cherenkov Detectors

Neutrino Reaction	Percentage of Total Events	Type of Interaction	Events/1000 tons @ 10 kpc
$\bar{\nu}_e + p \rightarrow n + e^+$	88%	Inverse Beta	~300 events
$\nu_e + e^- \rightarrow \nu_e + e^-$	1.5%	Elastic Scattering	~5 events
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	<1%	Elastic Scattering	~2 events
$\nu_x + e^- \rightarrow \nu_x + e^-$	1%	Elastic Scattering	~2 events
$\nu_e + ^{16}O \rightarrow e^- + ^{16}F$	2.5%	Charged Current	~10 events
$\bar{\nu}_e + ^{16}O \rightarrow e^+ + ^{16}N$	1.5%	Charged Current	~5 events
$\nu_x + ^{16}O \rightarrow \nu_x + O^*/N^* + \gamma$	5%	Neutral Current	~15 events

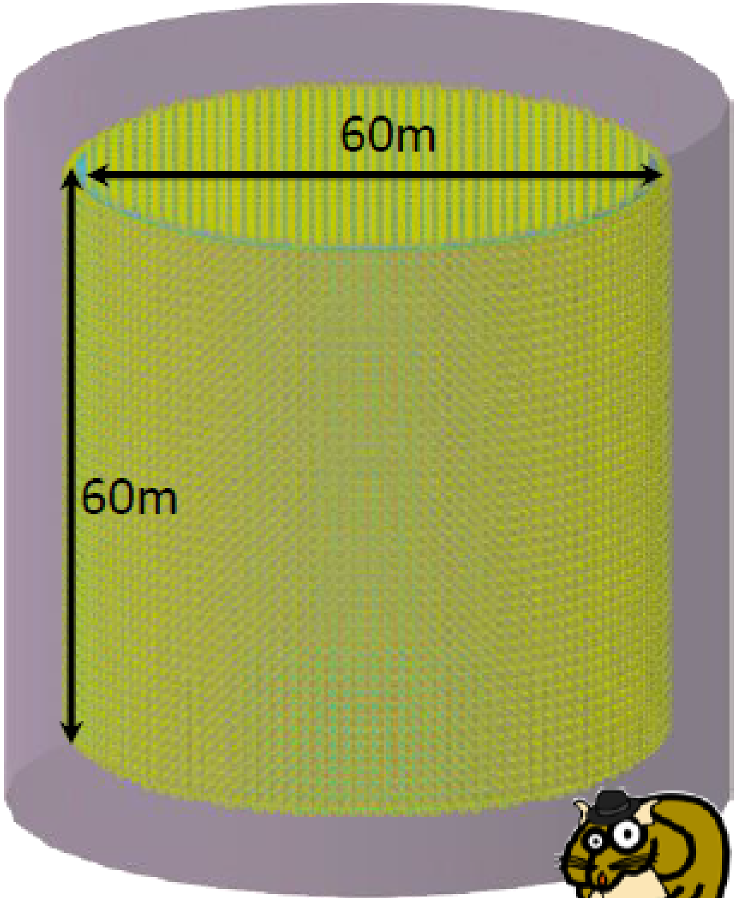
THEIA:

A realisation of the Advanced Scintillation Detector Concept (ASDC)

[Bob Svoboda]

Concept paper - arXiv:1409.5864

- 50-100 kton WbLS target
- High coverage with ultra-fast, high efficiency photon sensors
- 4800 m.w.e. underground (Homestake).
- Is Kamioka a possibilty?
- Comprehensive low-energy program: solar neutrinos, supernova, DSNB, proton decay, geo-neutrinos, DBD
- In the LBNF beam: long-baseline program complementary to proposed LAr detector



Detector image product of RAT-PAC

[Please see Gabriel's, Minfang's, Zhe's, and Lindsey's talks tomorrow]

Why seeing galactic SN ν's in Theia would be great:

→ Fine-grained, high statistics SN neutrino data are a unique probe of many important particle physics topics
(neutrino ocsillations, mass hierarchy, sterile neutrinos, extra dimensions, Lorentz violation, neutrino-neutrino self-interactions)

→ They would also provide valuable insight into key astrophysical subjects
(supernova explosion mechanism, neutron star/black hole formation, nucleosynthesis, stellar evolution)

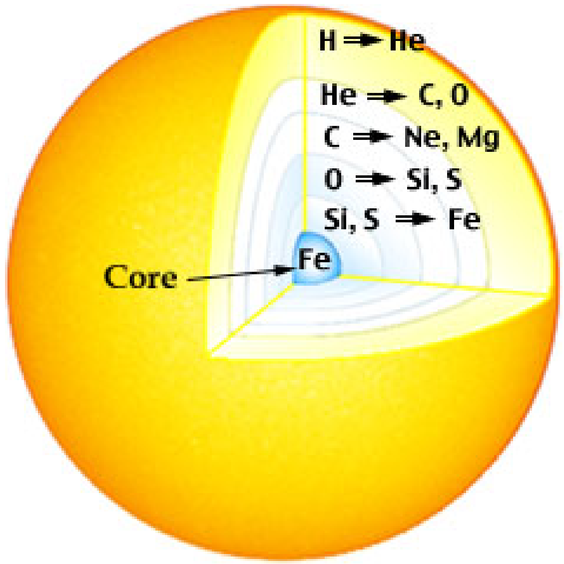
→ Theia data in concert with that from Super-K and IceCube detectors would allow instant triangulation based on first event arrival times
(though ~10X less accurate than eventual elastic scattering analysis)

→ Theia's ES would provide the world's most accurate pre-optical direction
(if the analysis and announcement can be automated, guide astronomers)

→ Serve as an accurate time-zero for gravitational wave observations
(gravitational wave signal is less certain compared to neutrino signal)

→ Very good public relations value, especially if SN is a naked-eye object

Odrzywodek *et al.* have calculated that late-stage Si burning in very large, very close stars could provide a useful early warning of a core collapse supernova if neutron detection is possible.



$e^+ + e^- \rightarrow \bar{\nu}_e + \nu_e$ (just above inverse beta threshold)

$\bar{\nu}_e + p \rightarrow e^+ + n$ (e^+ non-relativistic)

[Odrzywodek, Misiaszek, and Kutschera, *Astropart.Phys.* 21:303-313, 2004]

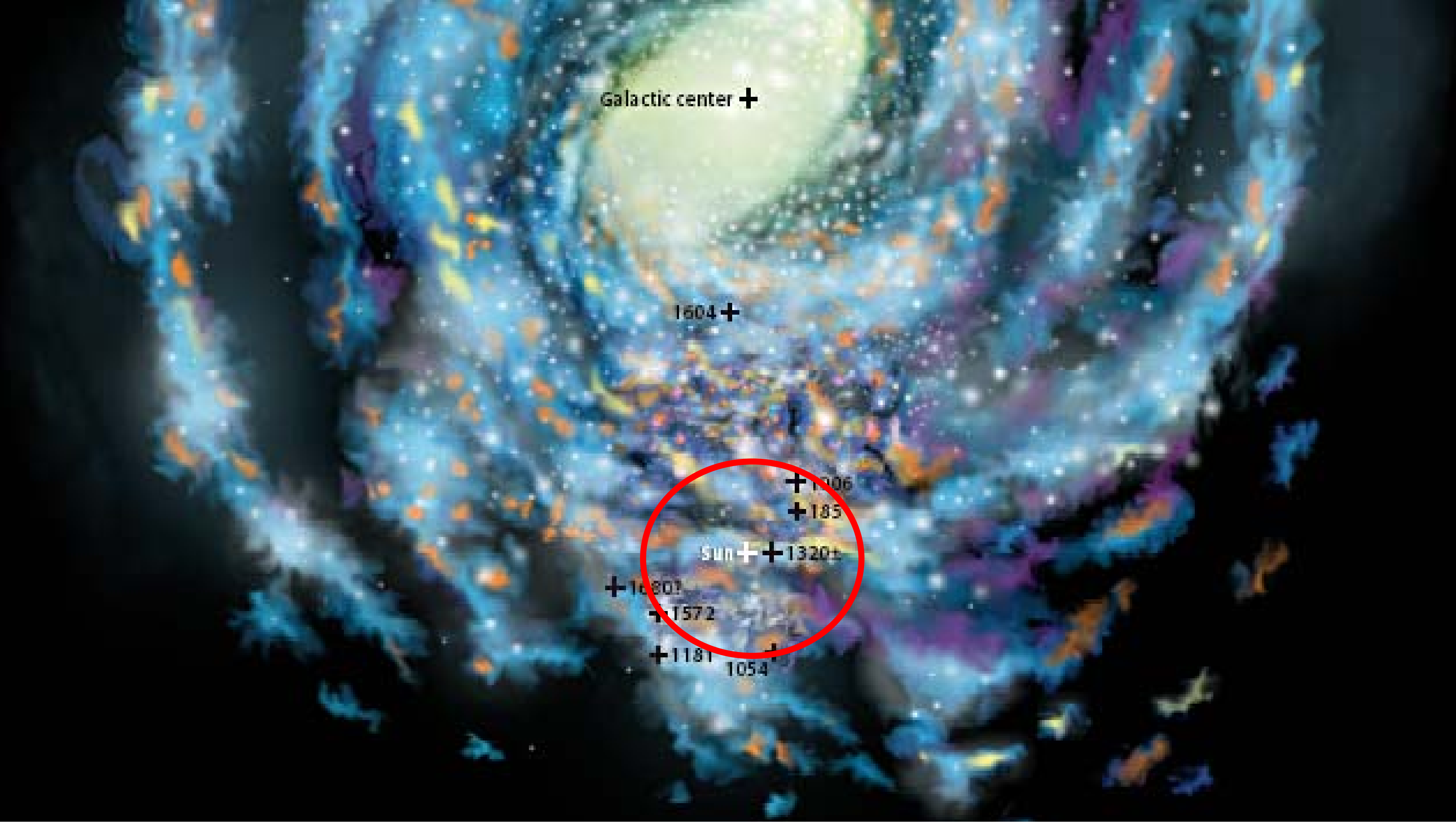
Okay, so who’s on the stellar deathwatch in our galactic neighborhood?

The Neighborhood (Death)watch

Theia could give an early warning
out to about 7000 lightyears.

Rasalgethi	**380 +/- 120 light-years**	**~8 solar masses**
Antares	**600 +/- 150 ly**	**~12 solar masses**
Betelgeuse	**640 +/- 150 ly**	**~12 solar masses**
Rigel	**780 +/- 150 ly**	**~18 solar masses**
Deneb	**2600 +/- 220 ly**	**~19 solar masses**

These stars could explode tomorrow… or >100,000 years from now.



Let’s not dismiss the importance of having early warning out to two kiloparsecs… a look at the historical record shows that these are explosions we *really* cannot afford to miss!

→ If trigger rate steadily increases, do NOT turn off detector! ←

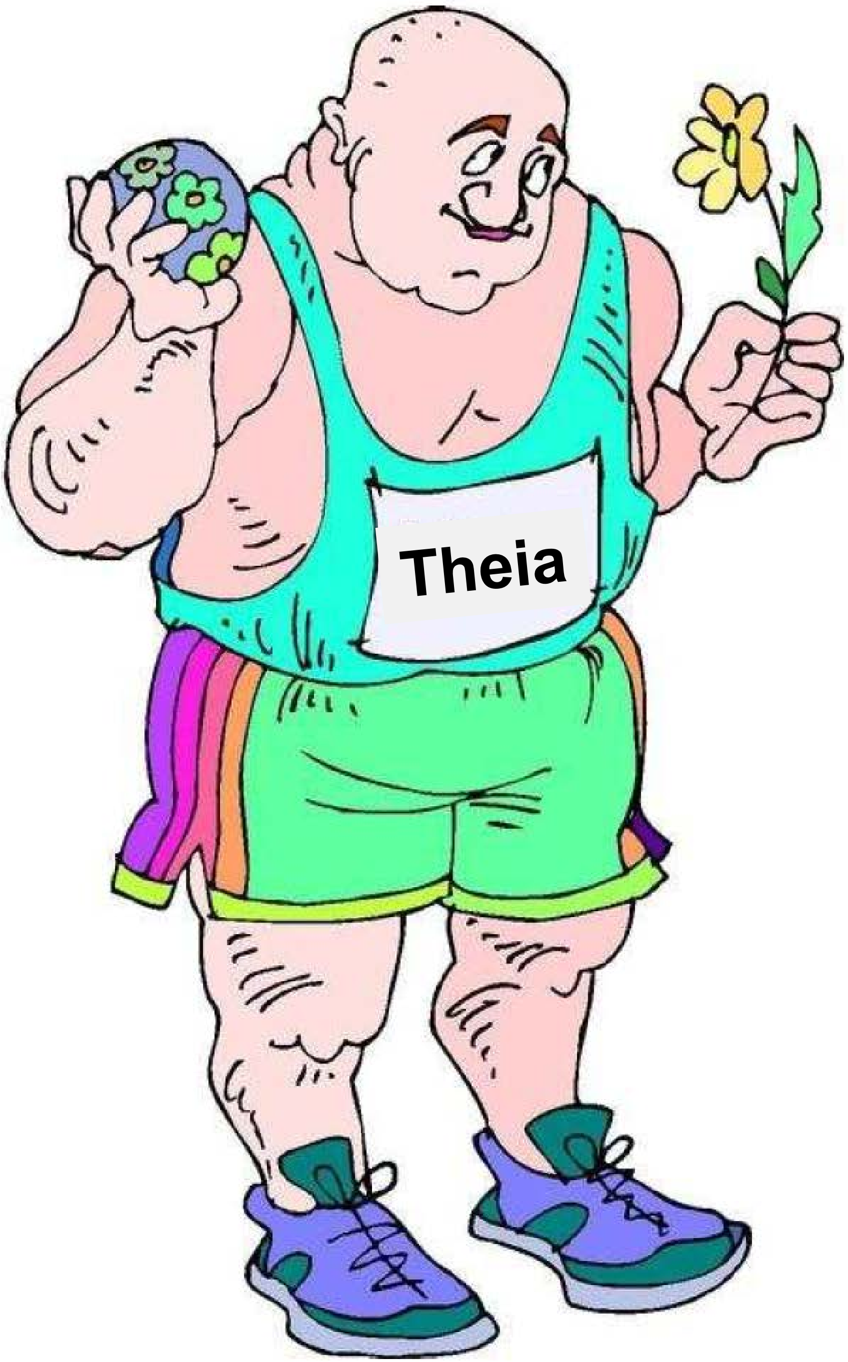
To get good quality SN burst data we need:

→ As low a threshold as possible since spectrum falls rapidly with rising energy
(SN1897A example: Kamiokande-II vs. IMB 3)

→ Low cosmic ray muon rate to minimize contamination of the precious burst data
(avoids losing fine-grained features due to vetoing)

→ DAQ system must be able to handle very high data rates (10's of MHz) over a period of ten seconds or so; Gd-loading reduces overlap of delayed signals with subsequent prompts
(Betelgeuse will generate about 100 million neutrino events in 50 ktons in ten seconds, about half in the first second)

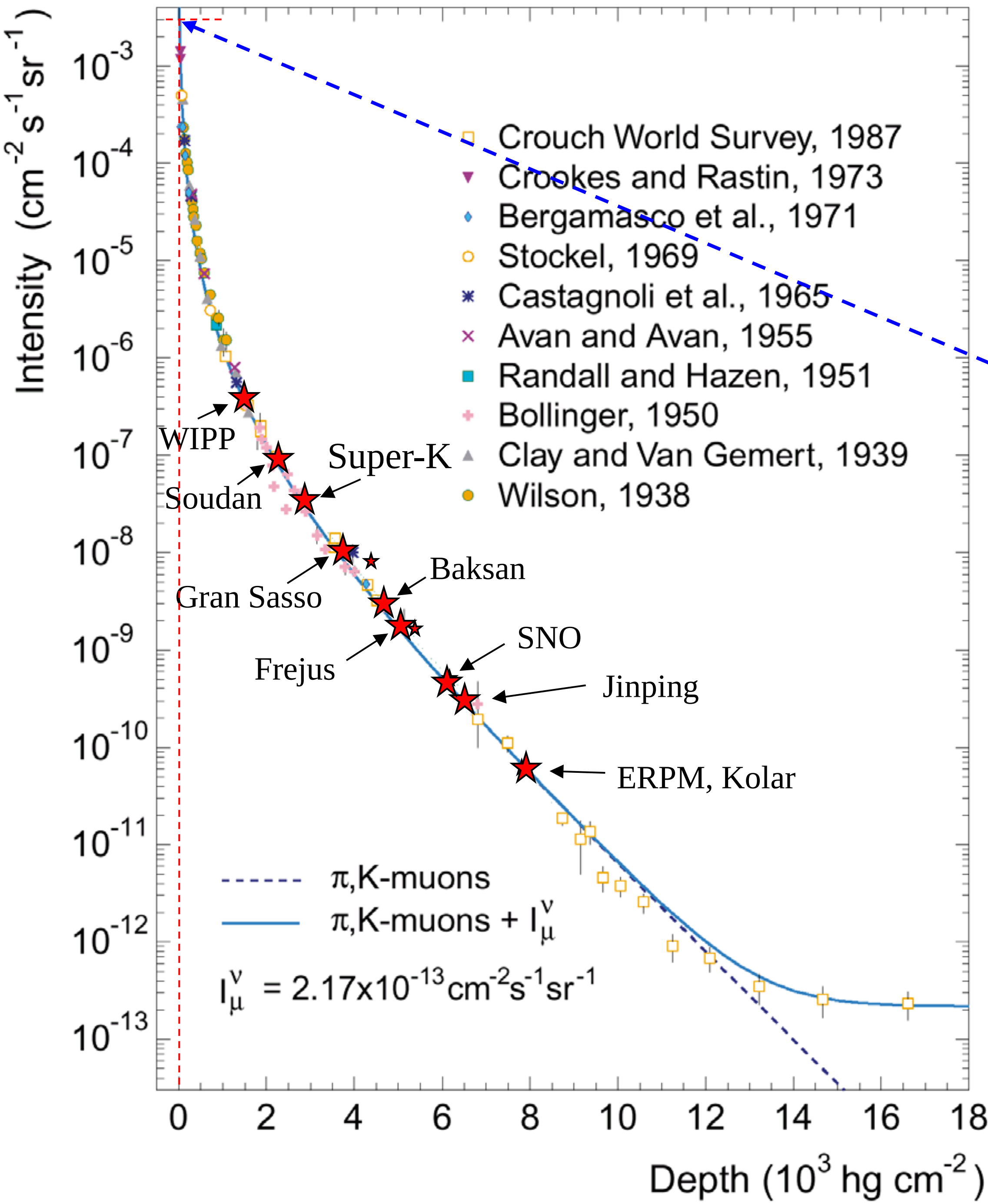
→ High uptime fraction to not miss a burst
(detector must be live essentially all the time)



We would like our new water-based liquid scintillator detector to be, at the same time, both BIG and SENSITIVE.

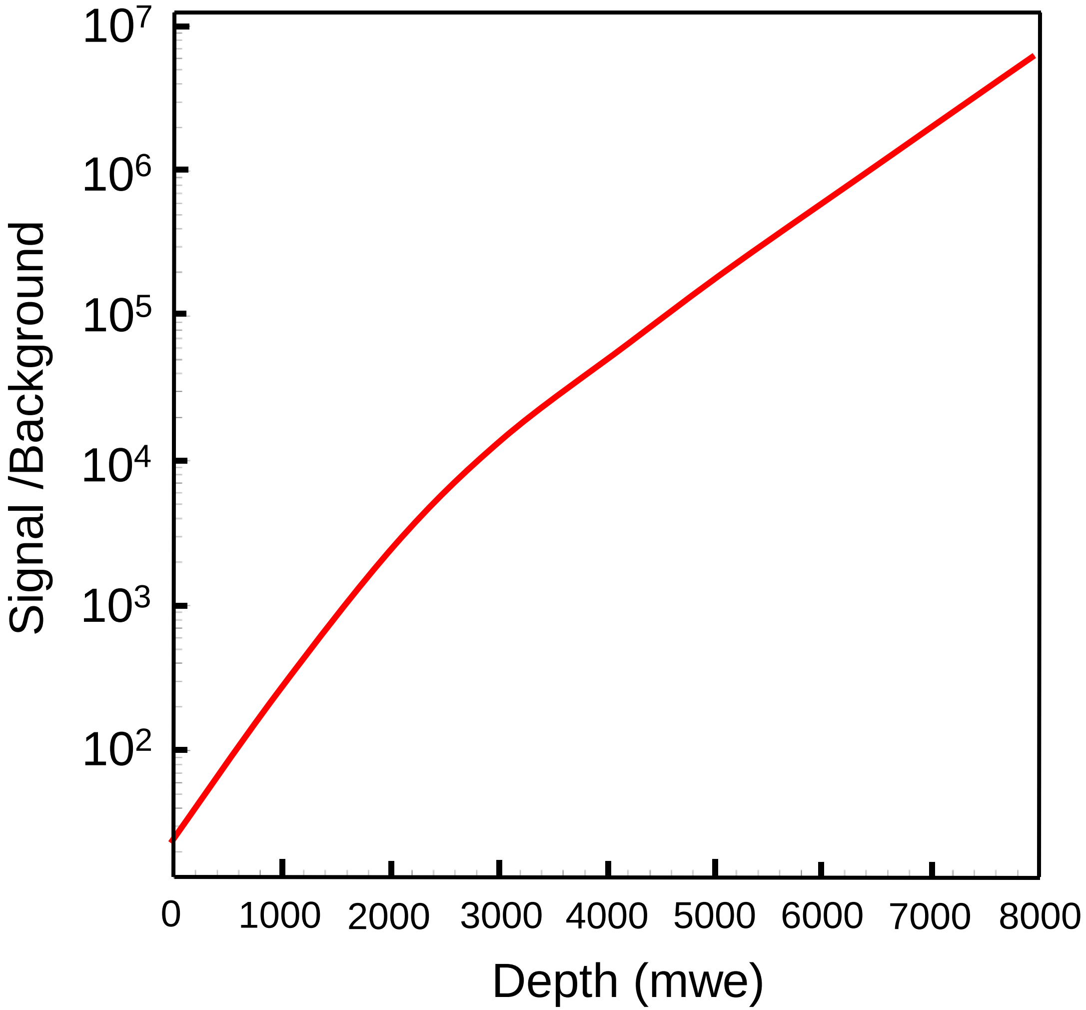
How deep will we have to go for the galactic supernova neutrino signal?

Depth-Intensity Data



ϕ_μ < 1.6 x 10^{-3} cm^{-2} sr^{-1} s^{-1}

SN Signal/Background vs. Depth (assuming SN at 10 kpc – rate analysis only)



Still usable for SN detection at very shallow depths

It would be wonderful to have a large WbLS detector in operation when the next galactic supernova neutrino wave sweeps across the planet.

If such a detector can be built at all - even with a very modest overburden - it will intrinsically have extremely good capabilities for this kind of physics… but only if the electronics and data pipeline is designed from the outset to handle a wide dynamic range of event rates.

The simplest solution is just to buffer the data and finish reading out after the burst.