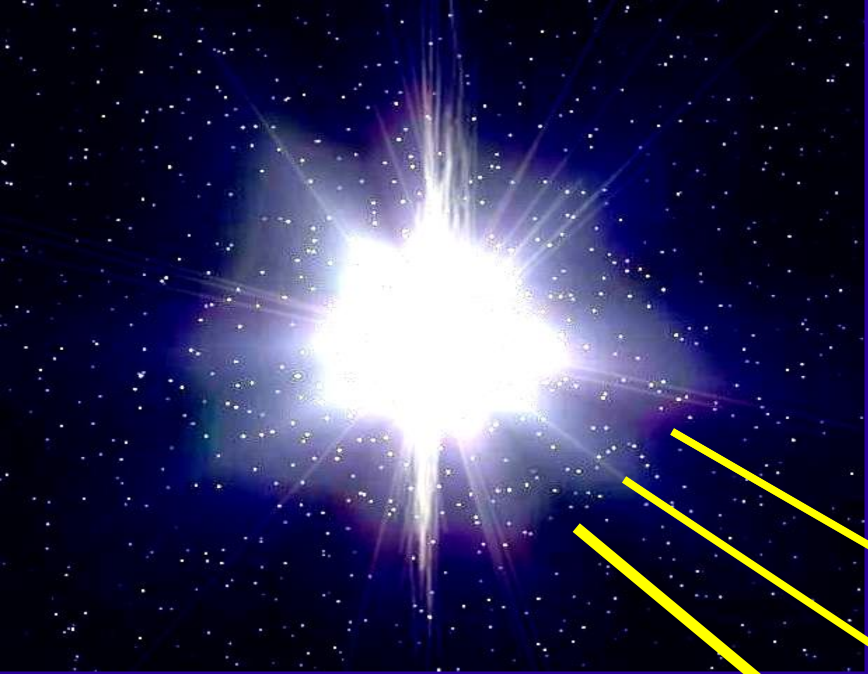
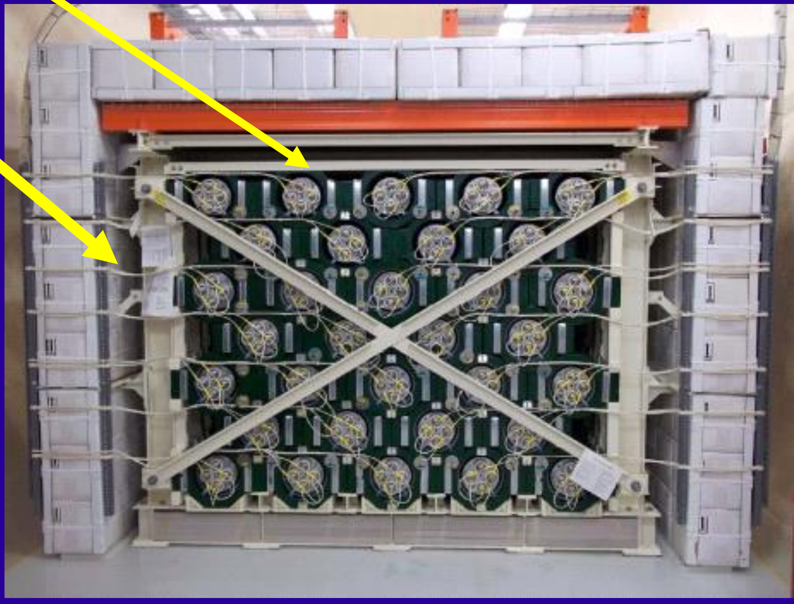
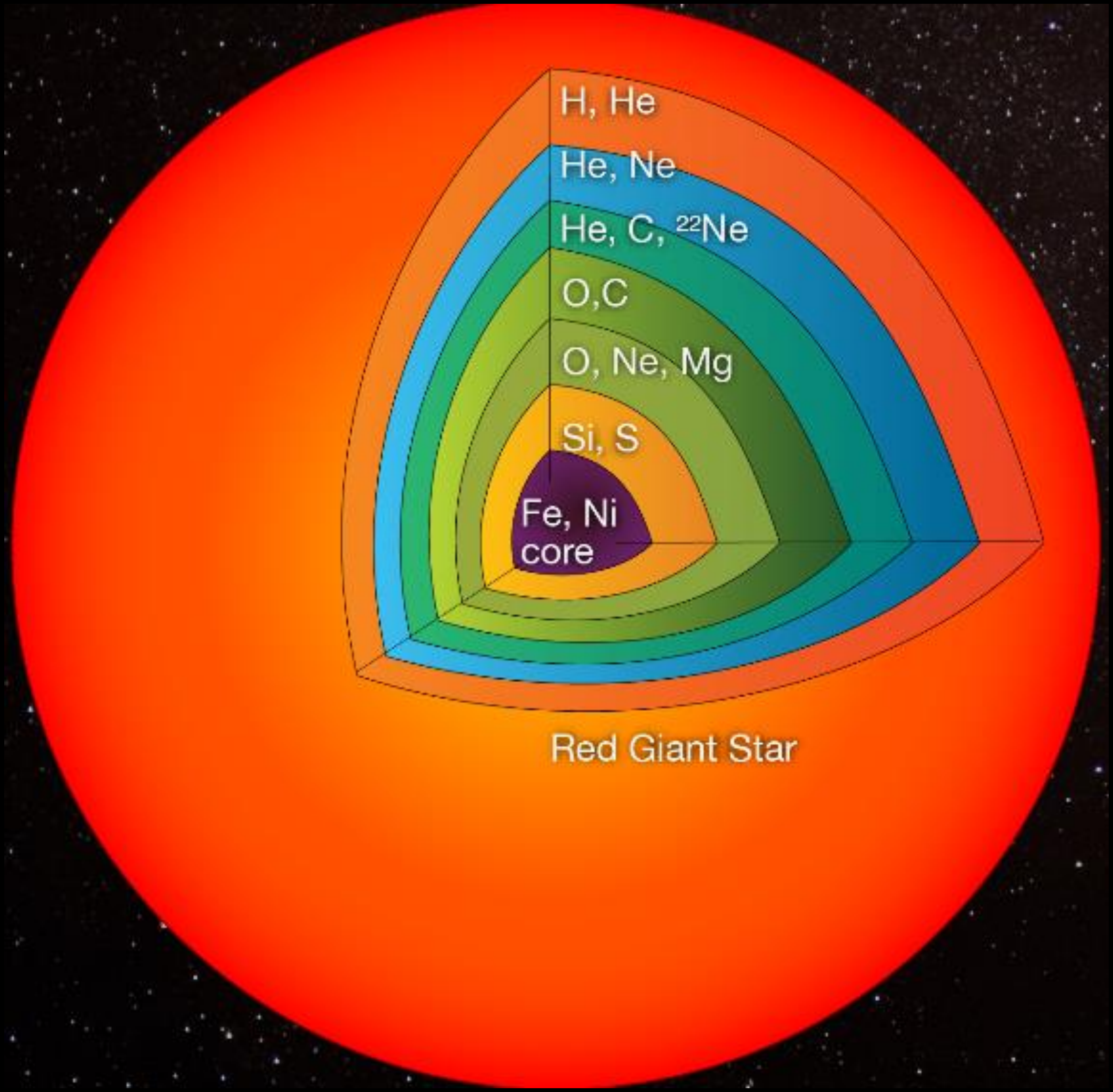


Supernova Neutrinos and the HALO Detector

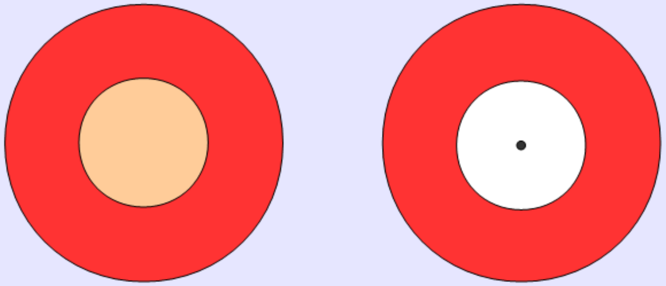


Stanley Yen, TRIUMF
for the HALO collaboration

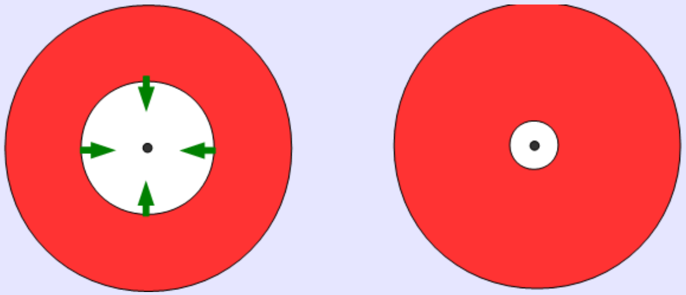
Last stage in the life of a massive star:



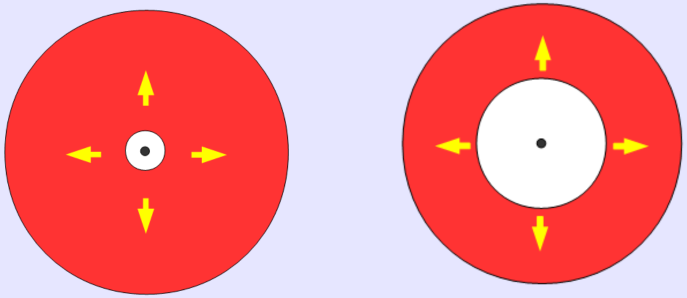
Stages of a core-collapse supernova:



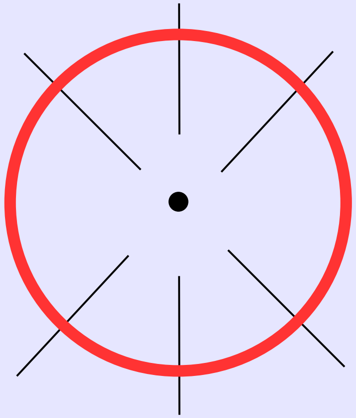
1. burst phase:
   iron core collapses
   e- + p → v_e + n



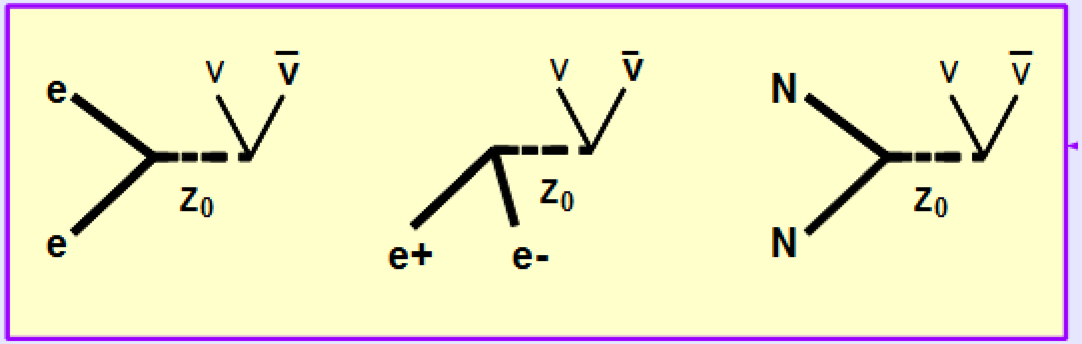
2. accretion stage:
   overlying layers fall inward
   onto proto-neutron star



3. rebound:
   outward shock wave stalls,
   neutrino heating revives the
   shock and blows the star up



4. cooling phase:
   hot neutron star cools over ~20 sec by emitting
   neutrinos pairs of all flavors



≈ 3 x 10^{46} Joule of energy emitted in SN
1% of energy in shock wave
0.01% as EM radiation
99% as neutrinos (≈10^{58} neutrinos of ~ 10 MeV energy)

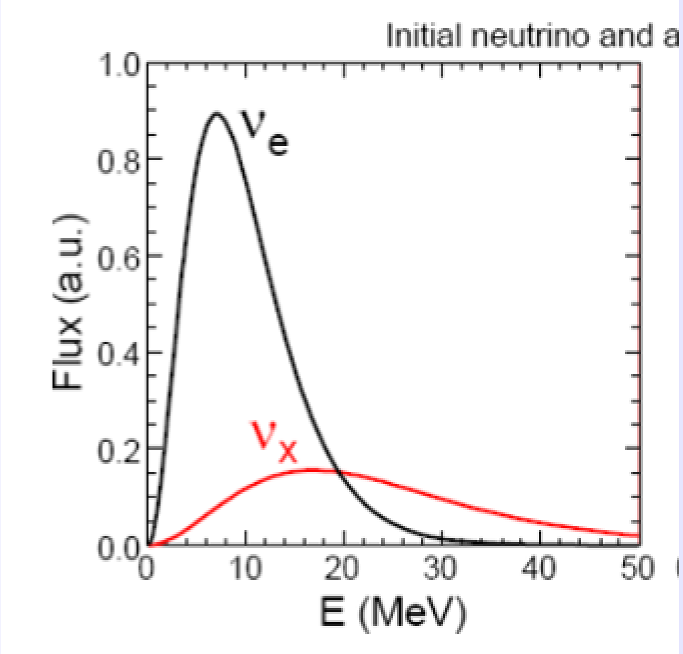
Neutrinos provide a prompt signal of the nuclear and particle processes in the core of the supernova, compared to the optical radiation which is emitted from the outer mantle and delayed by several hours.

A core-collapse supernova presents the opportunity to study neutrino interactions in a system of high density which is not present elsewhere in the universe:

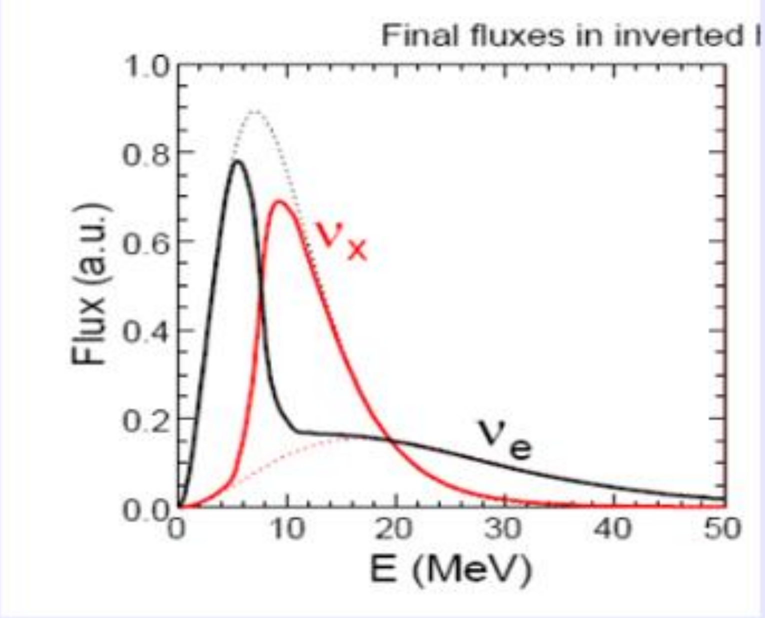
- the only place where the hadronic density is so large that the matter is opaque to neutrinos

- hence, neutrinos are trapped for several seconds and thermalize to a Fermi-Dirac energy spectrum

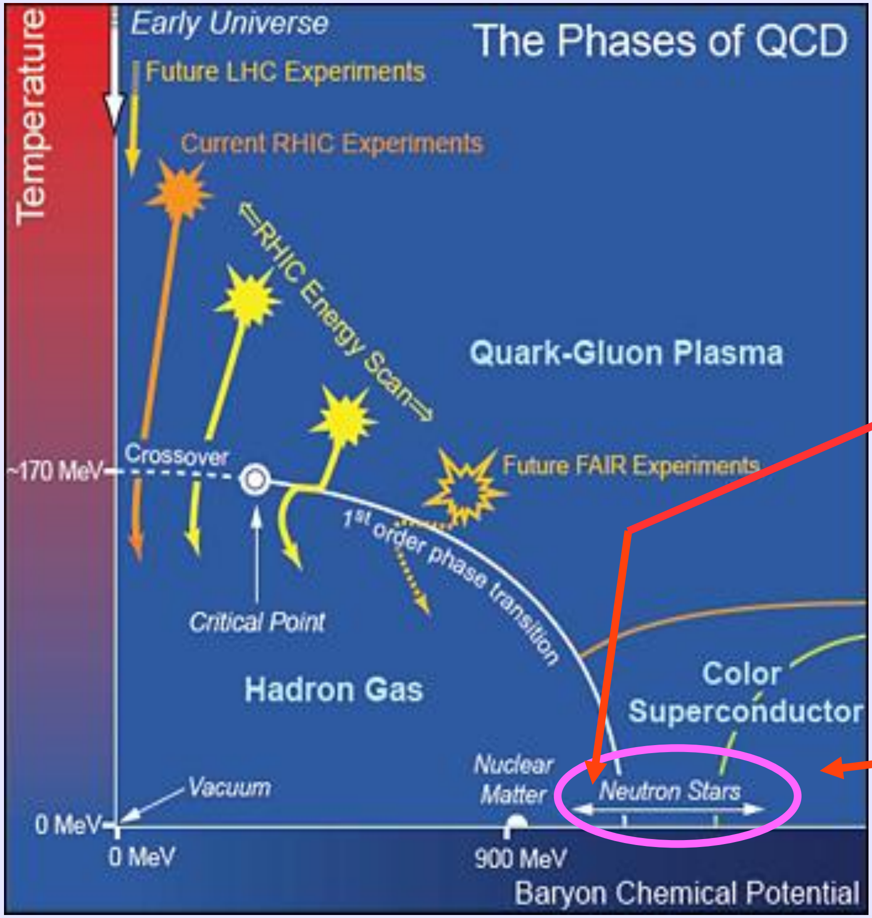
- the only place where the neutrino density is so large that neutrinos interact with each other, as a collective ensemble, and undergo collective neutrino flavor transitions



flavor swapping



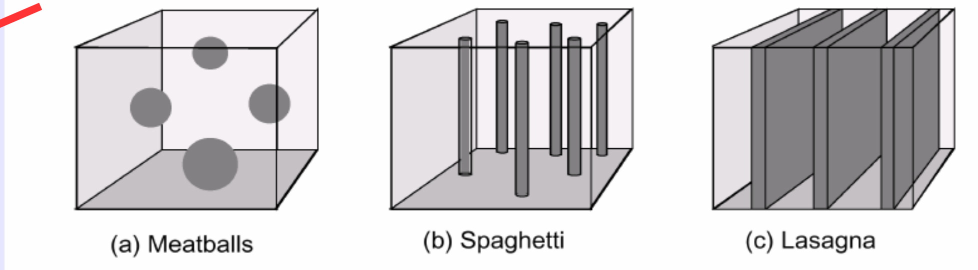
... and to study the state of hadronic matter at high density and low temperature
not accessible anywhere else in the universe

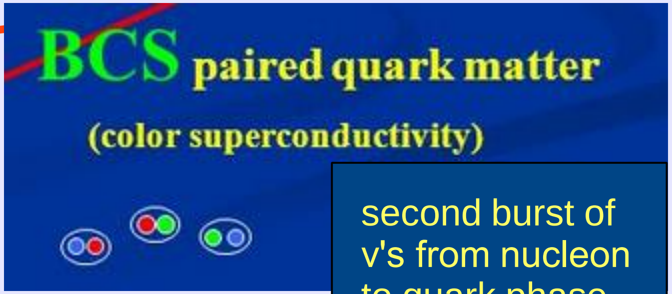


(density)

Possible exotic states of nuclear/hadronic matter in a neutron star:

Nuclear pasta phase increases ν opacity → ν spectral distortions

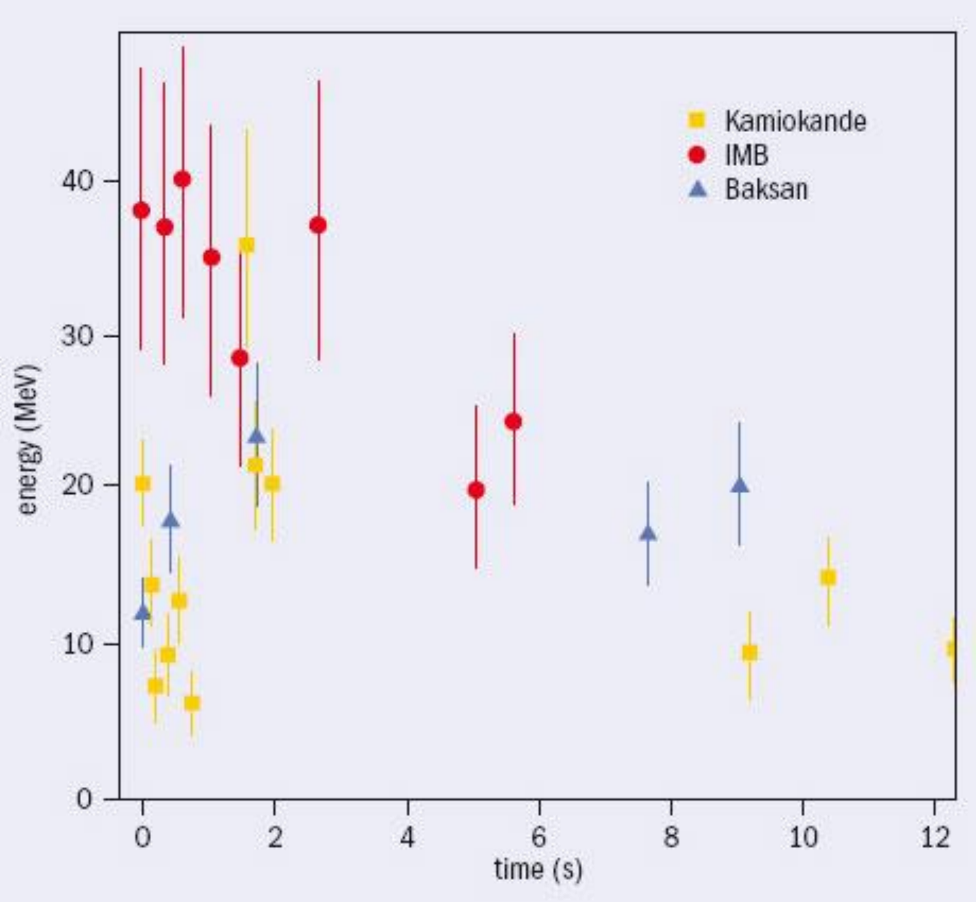




second burst of ν's from nucleon to quark phase transition

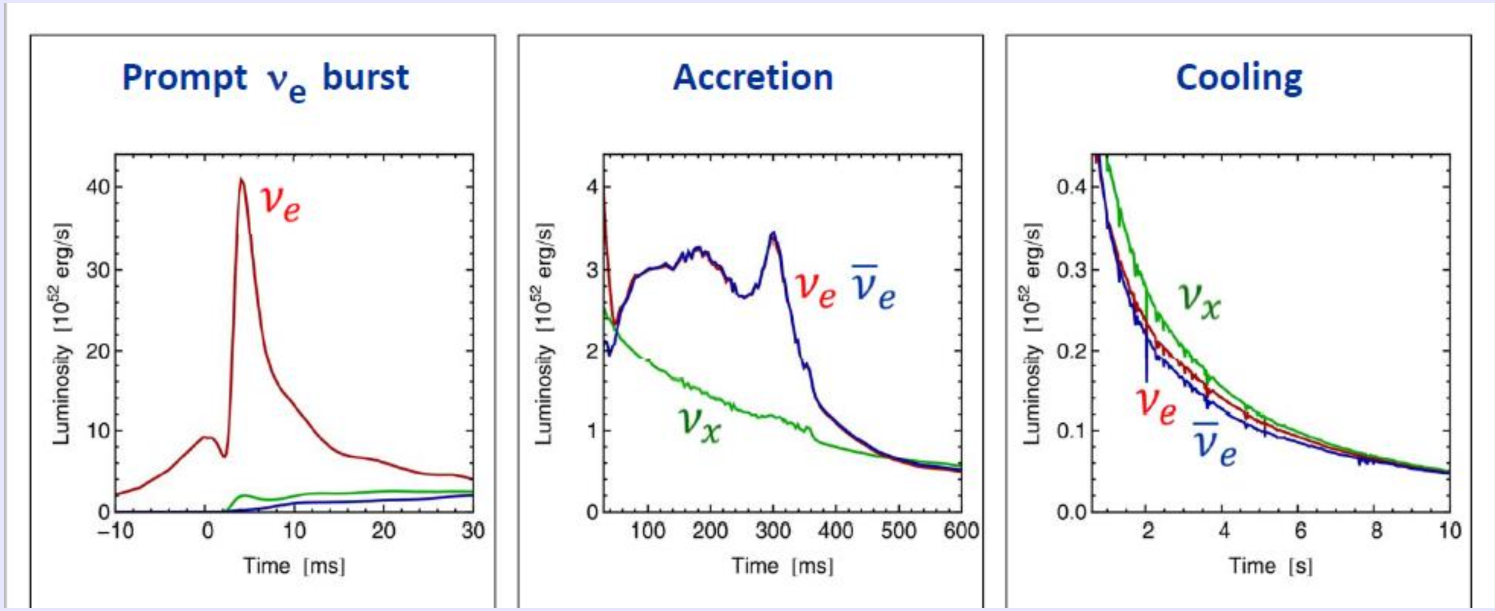
These could all leave imprints on the time / energy development of the neutrino emission from a core collapse supernova.

Questions:
- are the models correct ?
- what fraction of core collapses are duds ? (neutrinos but no explosion)
- do the neutrinos get trapped and thermalize as expected?
- neutrino opacity in stellar matter - nuclear pasta could increase opacity
- etc etc

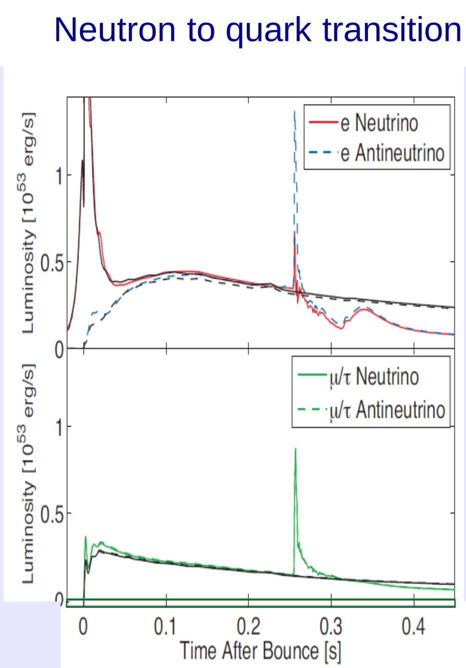


Many questions, many models, but the 23 events observed for SN1987A is all the data that currently exists!

Each stage of a supernova emits a different neutrino flavor mixture, according to current models.



from G. Raffelt, Shanghai Conference, 2013.


Neutron to quark transition

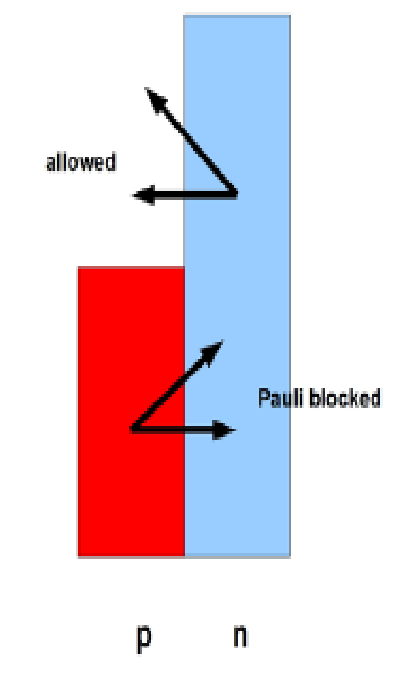
adapted from Sagert et al.
arXiv:0902.2084 [astro-ph.HE]

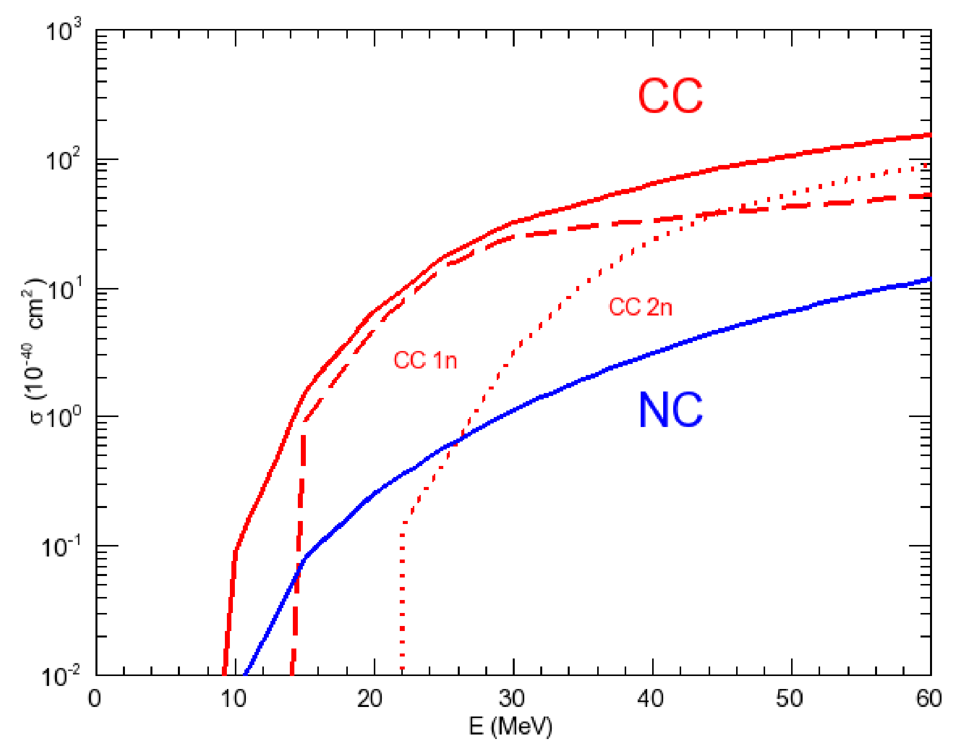
Essential to observe each flavor separately, but Water Cerenkov and organic scintillation detectors are sensitive mostly to anti-v_e .
A lead detector is primarily sensitive to v_e , flavor-complementary to other types.

Features of Pb as neutrino detector:

1. Neutron excess blocks p → n nuclear transitions, favors $v_e + n \rightarrow e^- + p$

2. Large Z of Pb nucleus pulls in wavefunction of outgoing electron, enhances CC cross sec.



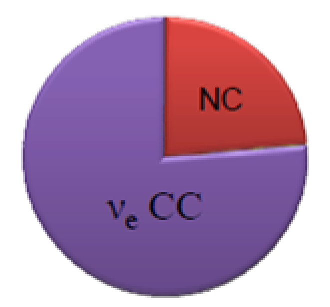


3. σ a rapid function of E, sensitive to enhancement of high E tail of v_e

4. Ratio of 2-n to 1-n emission gives a measure of average neutrino energy

Flavour Sensitivities

Water Cerenkov

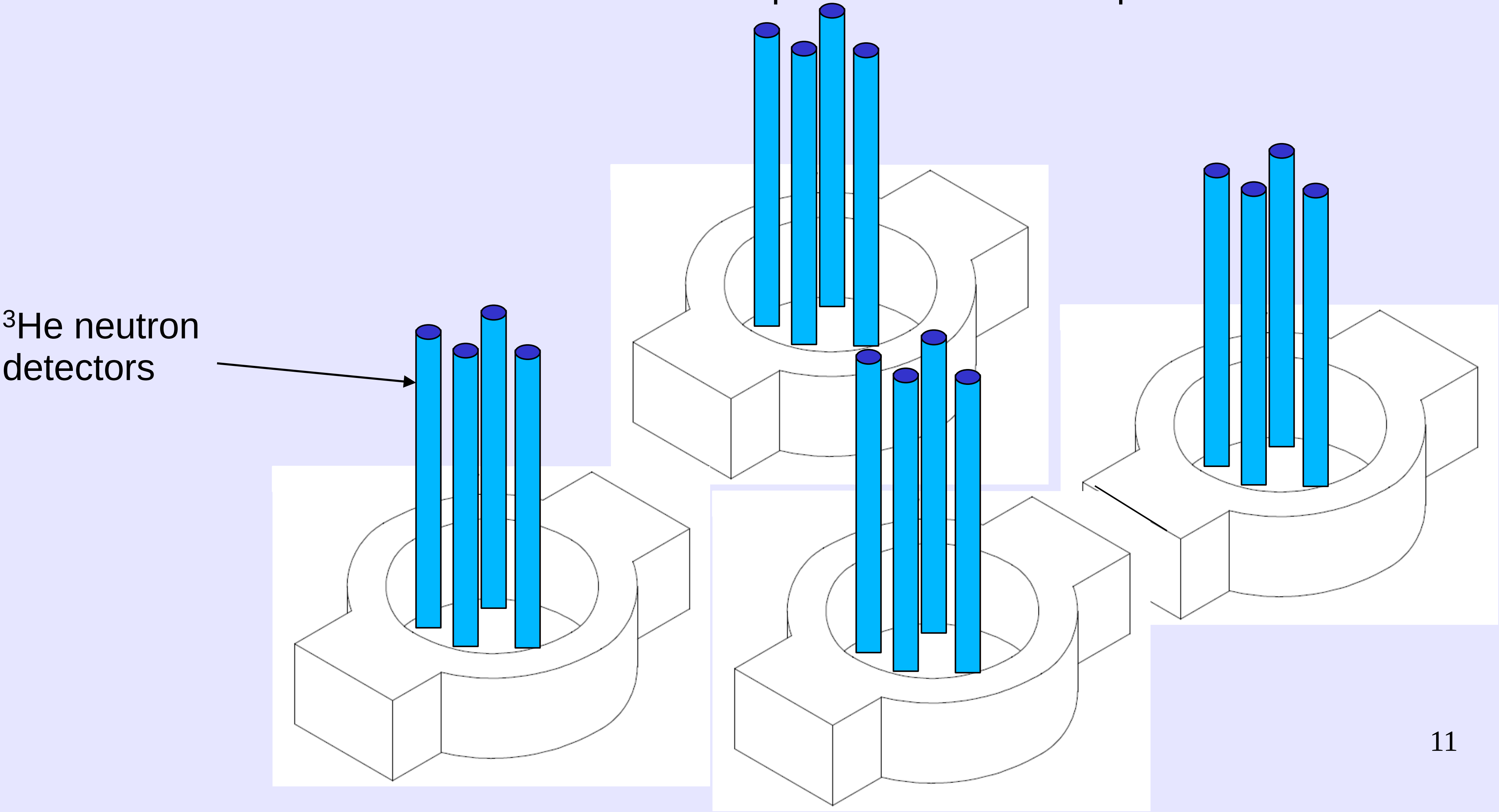


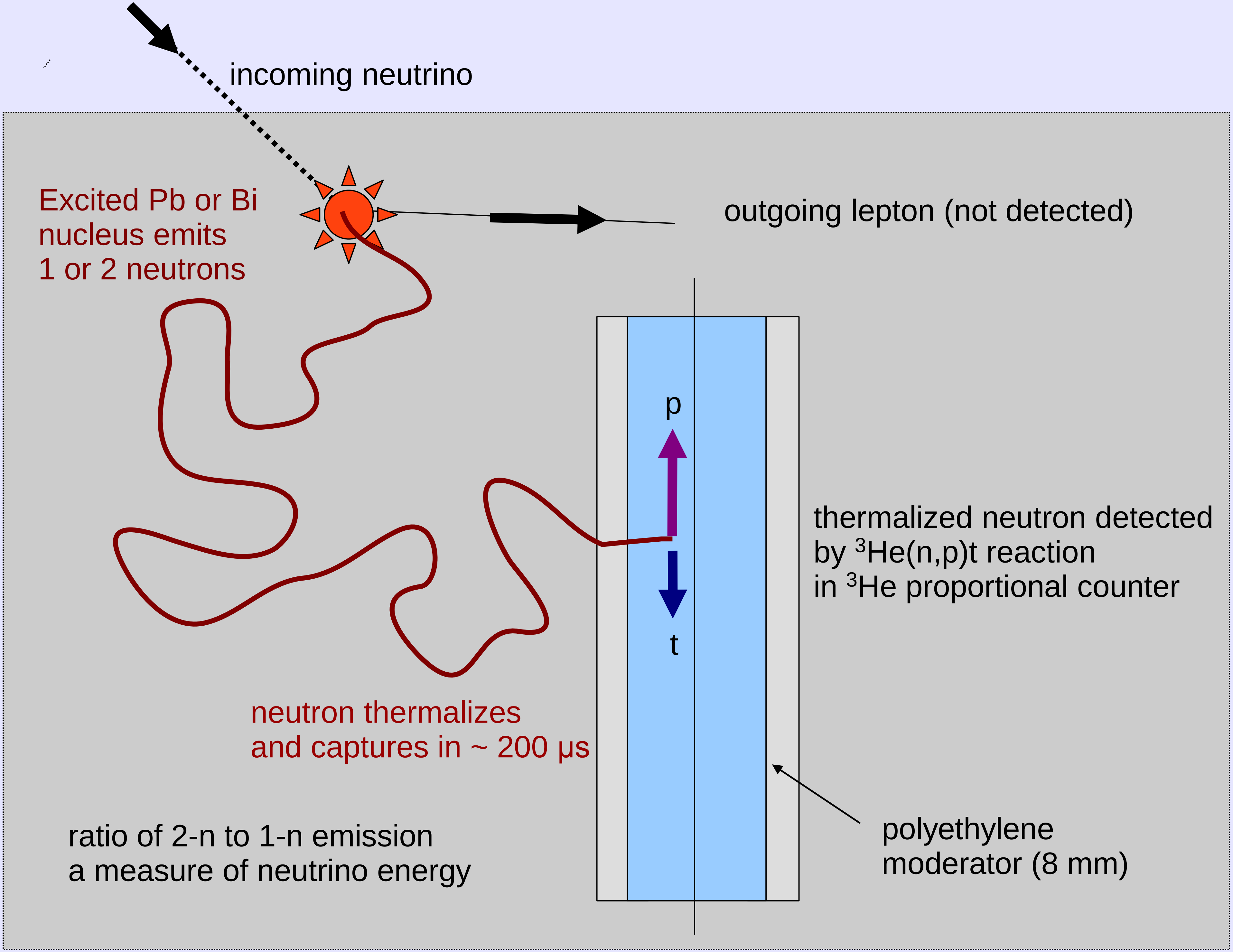
Lead

HALO **H**elium **A**nd **L**ead **O**bservatory

A “detector of opportunity” assembled from surplus materials:

- 79 tons of discarded lead blocks from a decommissioned cosmic ray station
- The ^{3}He neutron counters from the 3rd phase of the SNO experiment





incoming neutrino

Excited Pb or Bi
nucleus emits
1 or 2 neutrons

outgoing lepton (not detected)

thermalized neutron detected
by ^{3}He(n,p)t reaction
in ^{3}He proportional counter

neutron thermalizes
and captures in ~ 200 μs

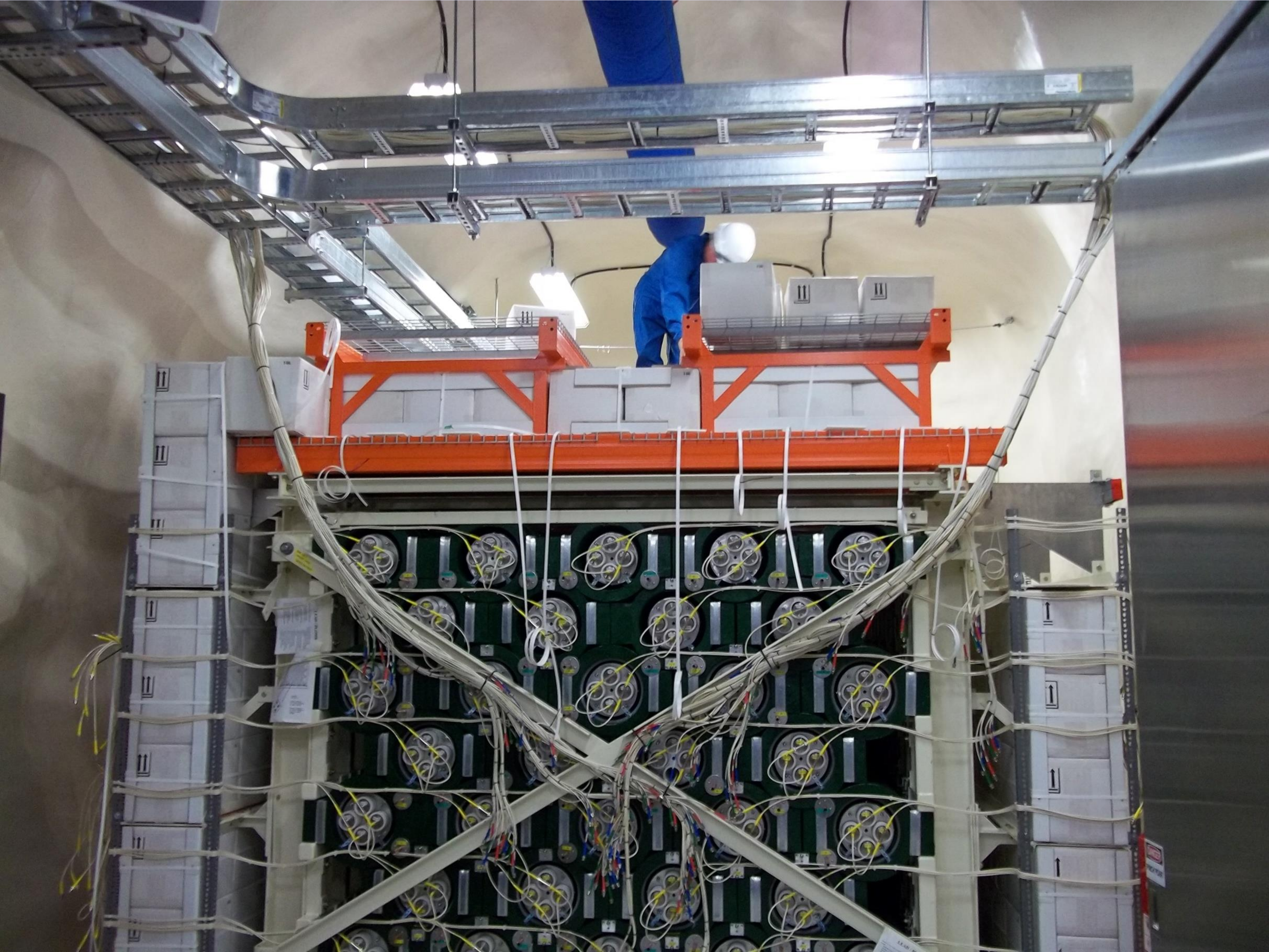
polyethylene
moderator (8 mm)

ratio of 2-n to 1-n emission
a measure of neutrino energy

5 cm diameter x 3 metre long neutron detectors filled with ^{3}He gas

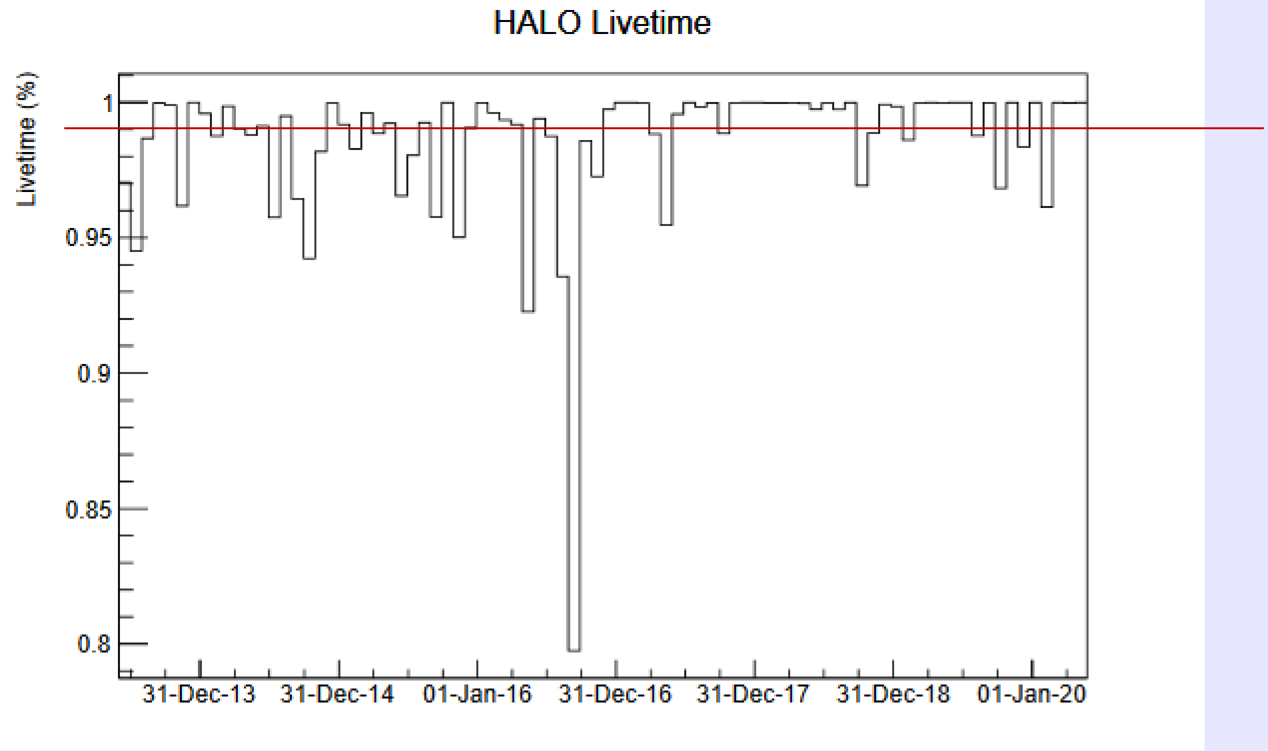
128 of these are deployed in HALO

stacking lead blocks 2km underground in Sudbury during HALO construction



A galactic supernova is expected about once every 40 years on average … the signal lasts about 10 seconds … so high livetime is a must!

- UPS good for ~ 3 hours of operation
- Detector divided into two independent halves, with separate HV and electronics
- Two DAQ computers, either one of which can read both halves of the detector



~99% uptime

Super Nova Early Warning System

Borexino

Daya Bay

LVD

Super Kamiokande

SNO+

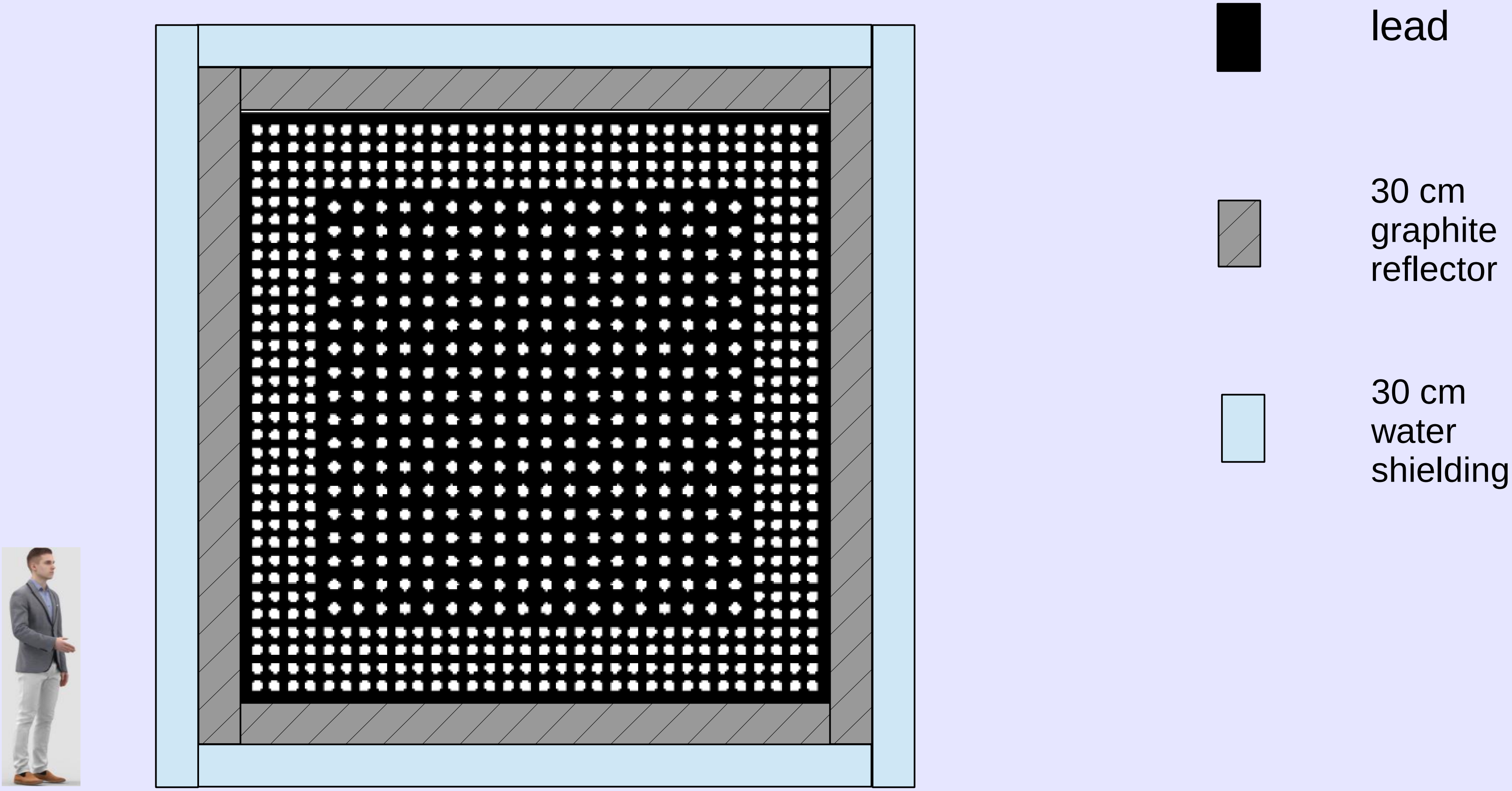
KAMLAND

HALO

The decommissioning of the OPERA experiment at the Gran Sasso lab
in Italy has made available 1000+ tonnes of lead.
An effort is under way to use this to build another “detector of opportunity” with
~20x greater sensitivity than HALO@SNOLAB.

current conceptual design:
4.3 x 4.3 x 5.5 metre volume of lead, with 772 cylindrical proportional
counters each 5 cm diam x 5.5 m long, containing in total
10,000 litre-atm of ^{3}He gas

See Clarence Virtue cjv@snolab.ca for more details.

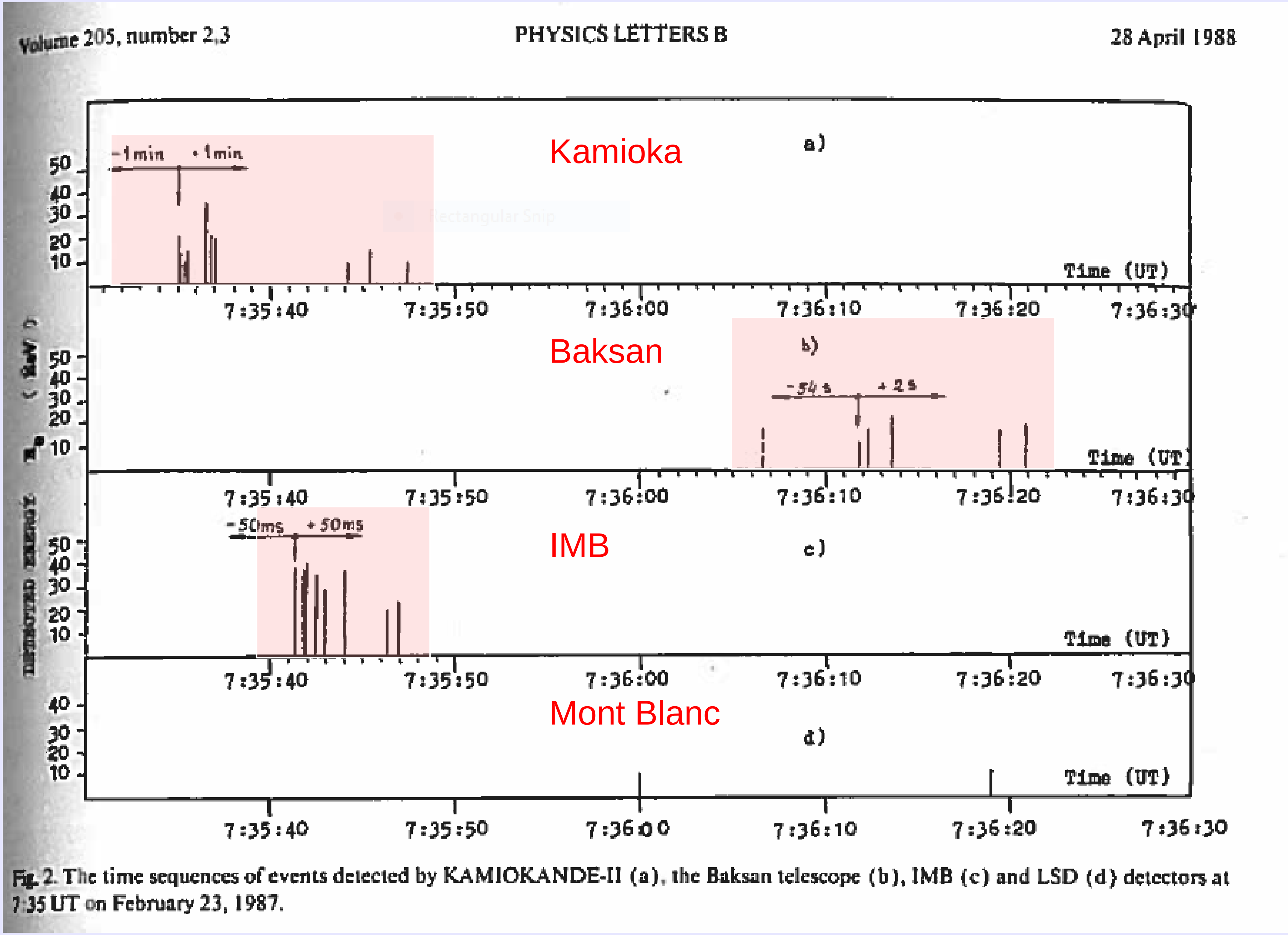


And be ready for surprises!

In the case of SN1987A, in addition to the 23 neutrinos observed
by IMB, Kamioka and Baksan,

4.7 hours earlier, the Mont Blanc detector observed a burst of 5 neutrinos
This does not accord with the standard model of core-collapse supernovae
and is still unexplained.

Kamioka, Baksan, IMB observe clusters of events on Feb 23, 1987 about 7:35 UT
NOTE LARGE TIMING UNCERTAINTIELS ~1 min. IN KAMIOKA, BAKSAN



Volume 205, number 2,3 PHYSICS LETTERS B 28 April 1988

Fig. 2. The time sequences of events detected by KAMIOKANDE-II (a), the Baksan telescope (b), IMB (c) and LSD (d) detectors at 7:35 UT on February 23, 1987.

From Alexeyev et al., Phys. Letters B 205, 1988

Mount Blanc alone observes a cluster of 5 events about 4.7 hours earlier;
no clusters observed in the other detectors.

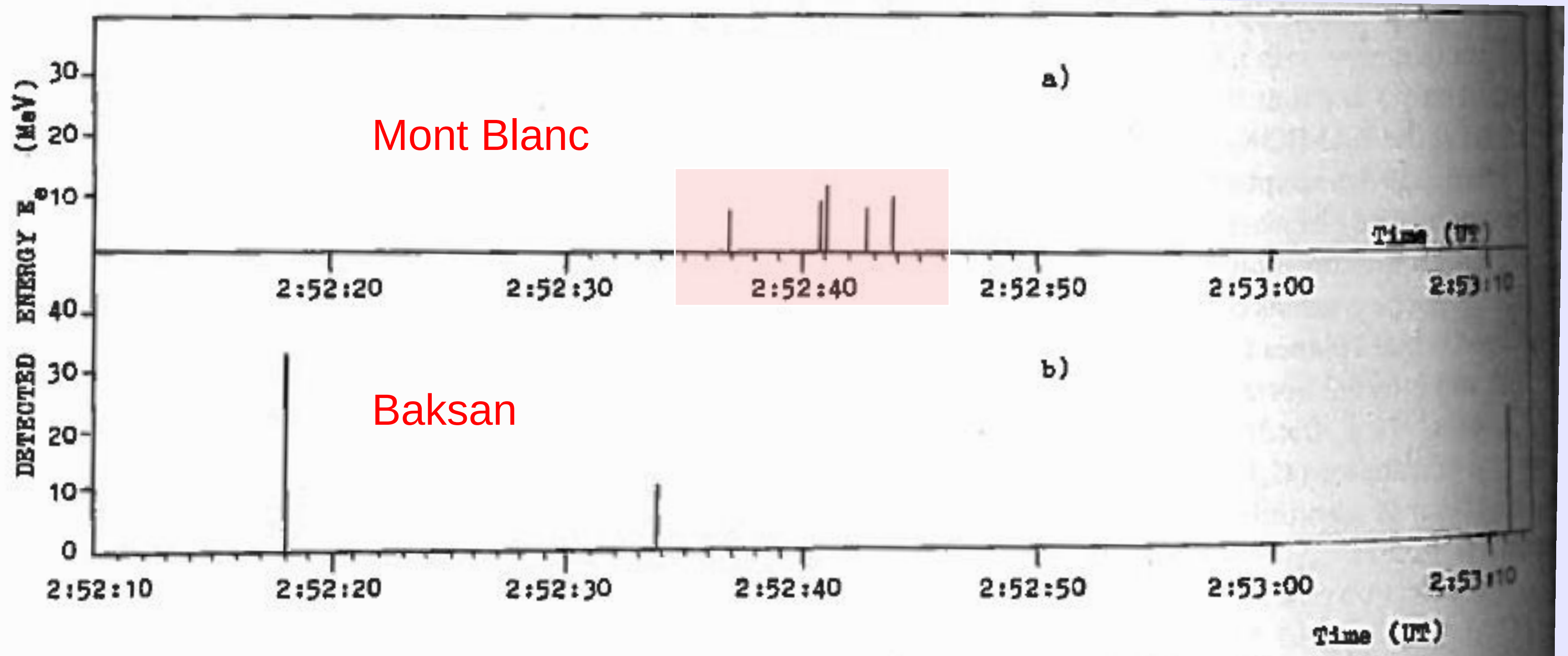
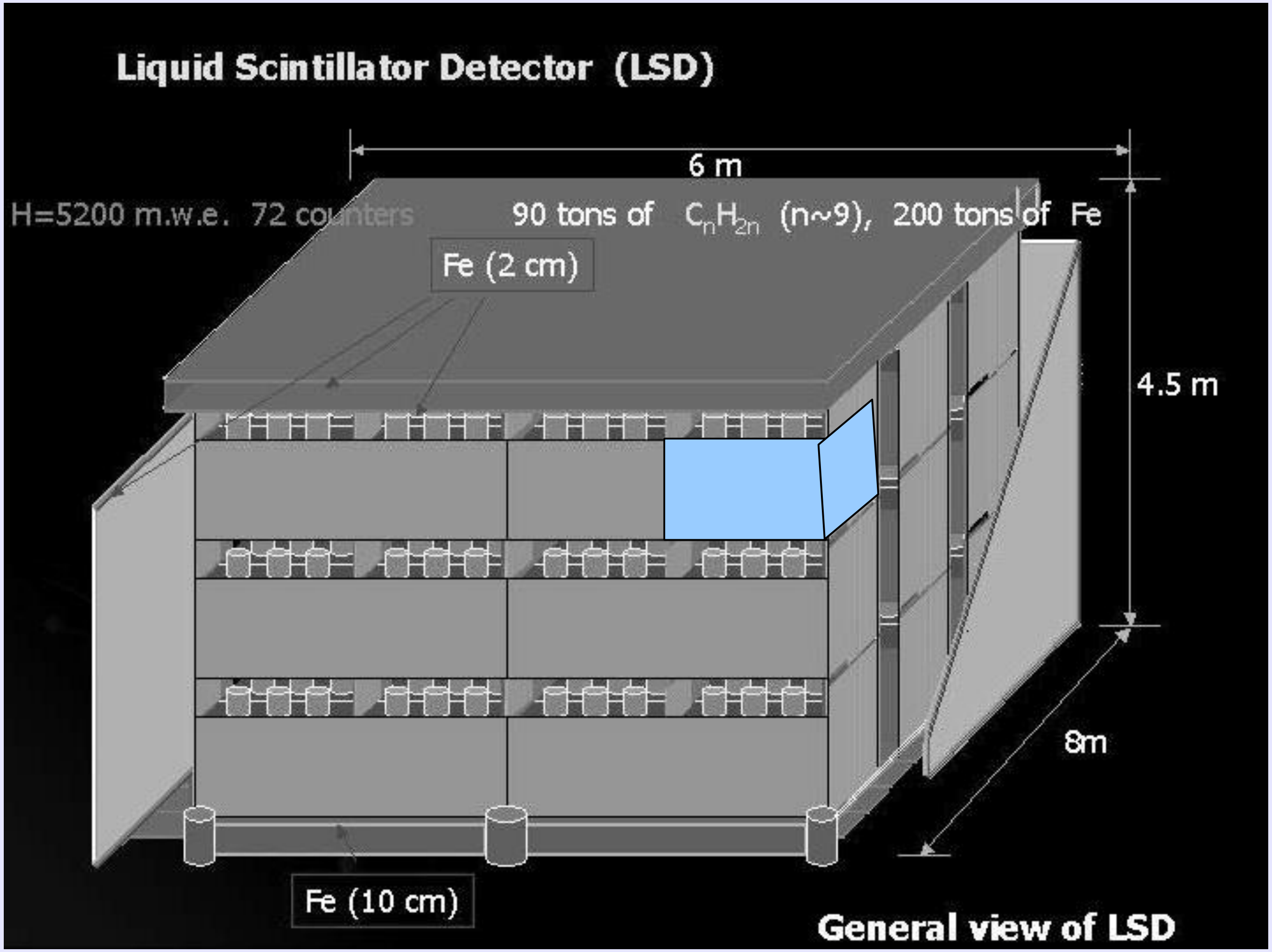
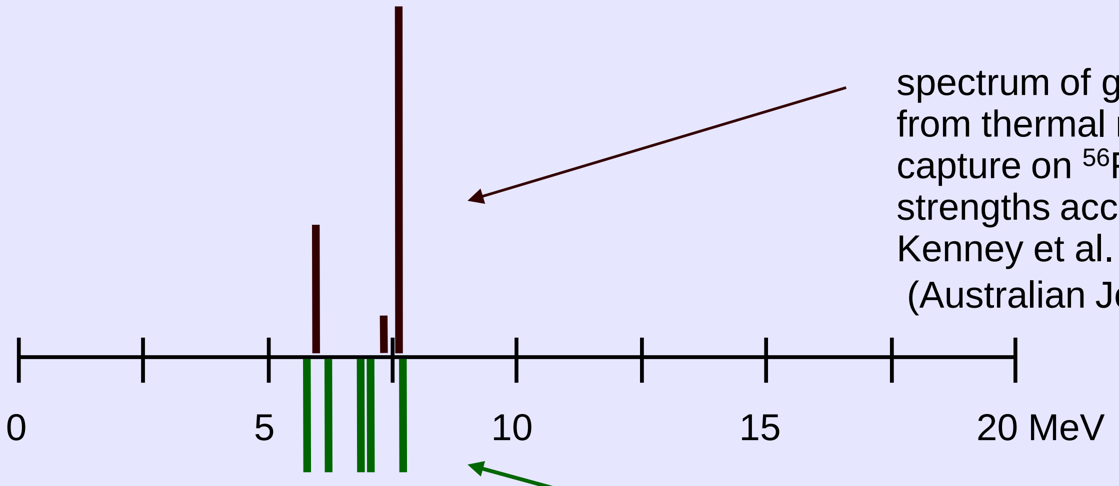


Fig. 1. The time sequences of events detected by the LSD (a) and the Baksan telescope (b) at 2:52 UT on February 23, 1987.

Mont Blanc Detector: 90 tons liquid scintillator (= 4% of Kamioka)
200 tons of iron



Neutron capture on ^{56}Fe ?



spectrum of gamma rays from thermal neutron capture on ^{56}Fe, with strengths according to Kenney et al.
(Australian Journal of Physics 24, 805 (1971)

visible energy of neutrino burst in Mont Blanc

Voilà ! **It fits like a hand in a glove !**

It seems highly plausible that the signal in the Mont Blanc detector was due to capture of thermal neutrons on the iron slabs surrounding the liquid scintillator.

My hypothesis:

Early burst of low energy $\bar{\nu}_e$ $(1.8 < E < 6$ MeV$)$ which make low energy neutrons via inverse beta decay on protons in the liquid scintillator

$\bar{\nu}_e + p \rightarrow e^+ + n$ (energy threshold = 1.8 MeV)

These neutrons then capture on the iron slabs and make the
5-7 MeV of visible energy in the Mt Blanc detector,

These low energy $\bar{\nu}_e$ would be invisible to IMB, Kamioka, Baksan (thresholds > 6 MeV) , and are made visible to Mt Blanc by the nuclear binding energy liberated by neutron capture on Fe.

What was the astrophysical cause of this early burst?
Nobody knows!

Be prepared for surprises at the next galactic core collapse supernova!

The End

Thank you!