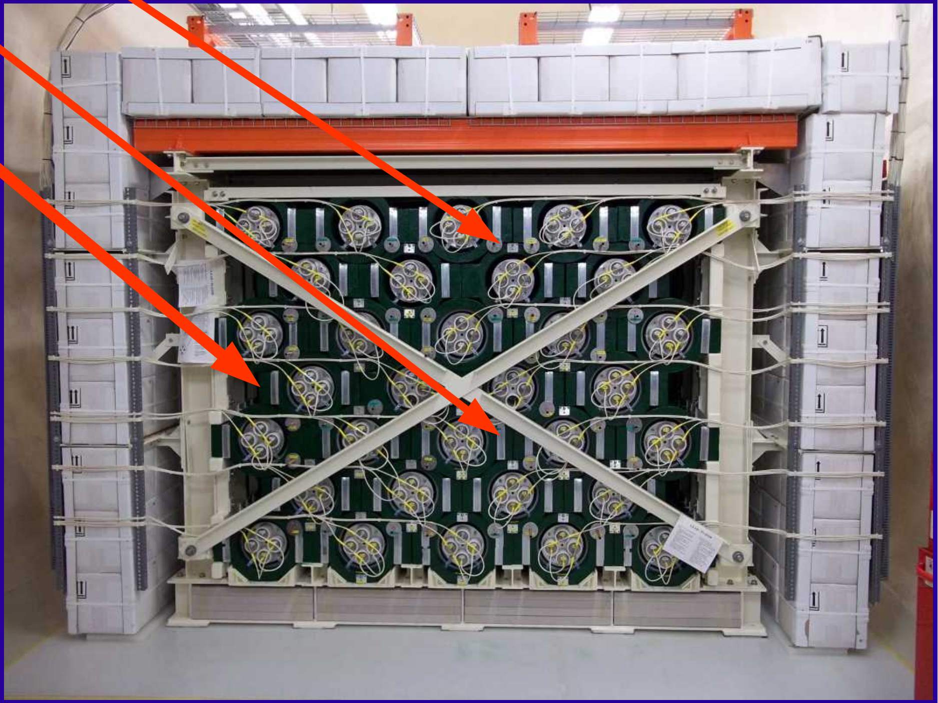
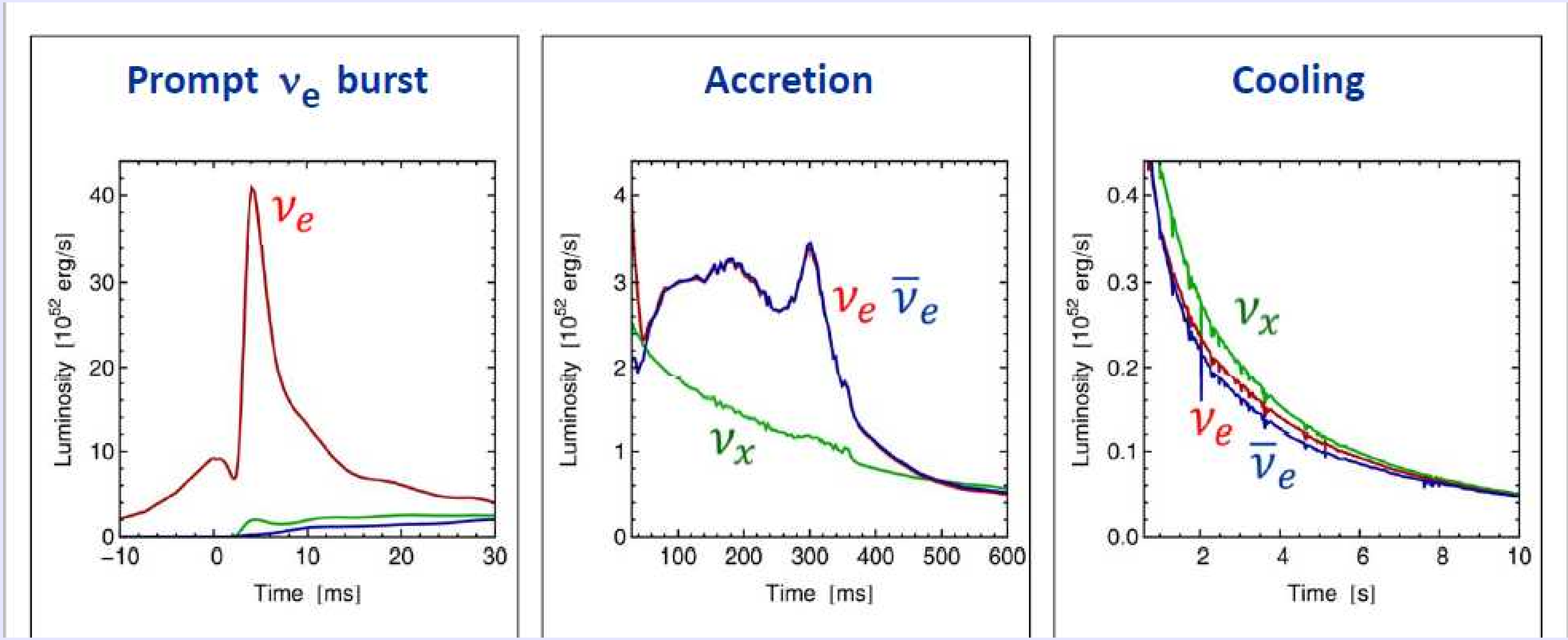
HALO / HALO-1kT Lead-based Supernova Neutrino Detectors

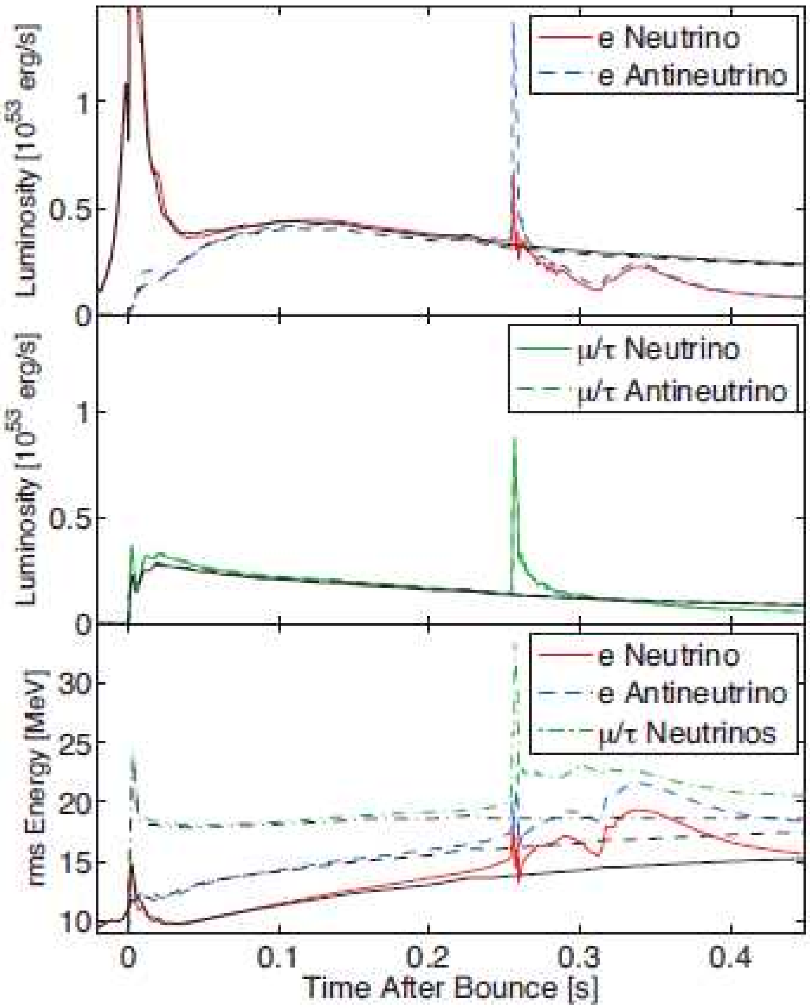


Stanley Yen, TRIUMF
stan@triumf.ca

In the standard picture of a core-collapse supernova,
each stage of the supernova has a different neutrino flavor mixture.



from G. Raffelt, Shanghai Conference, 2013.



QCD phase transition?
Quark supernova?

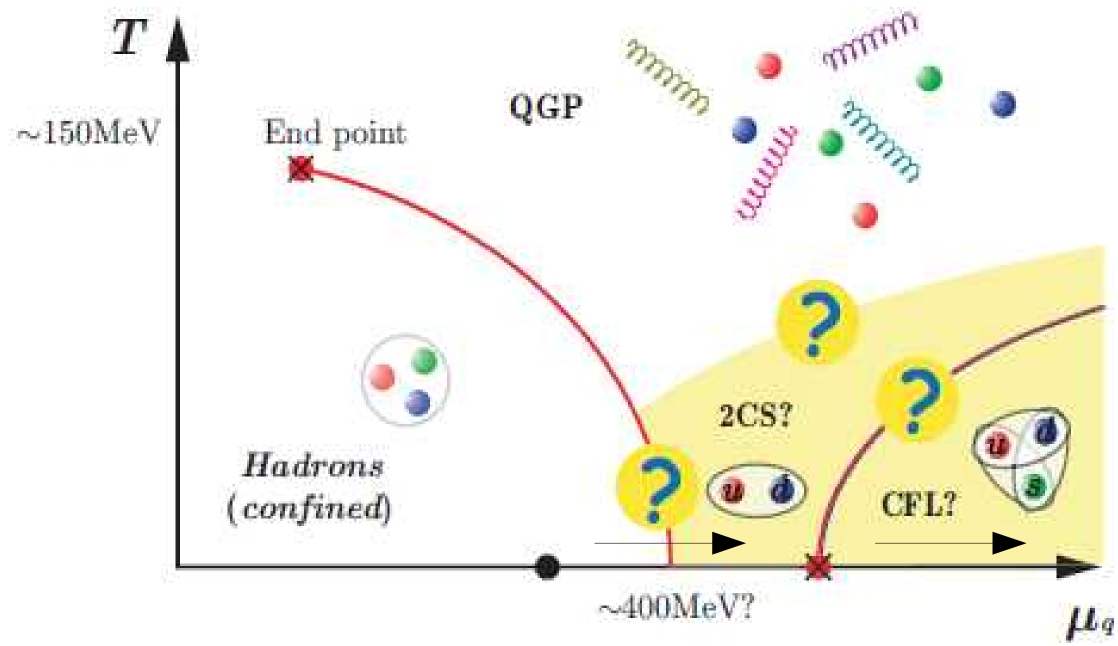


Figure adapted from Hiroaki. Abuki,
YITP International Workshop on “Multi-Quark Hadrons: four, five and more?”,
Kyoto, Japan, 17-19 Feb 2004

Sagert et al. arXiv:0902.2084v2 [astro-ph.HE] : transition from neutron matter to uds “color superconductor” quark matter would yield a delayed burst of anti-ν_e

It is evident that the different neutrino flavors behave differently!

All these are theoretical predictions and need to be tested against experimental data to see if the current picture of what causes a supernova to explode is really true!

Observing the neutrino flux from the next galactic supernova, in all its different neutrino flavors, would be a test of our picture of what's going in deep in the bowels of the supernova as it explodes.

We need a variety of neutrino detectors of different flavor sensitivities.

Recall the fundamental interactions of neutrinos with protons/neutrons:

$\nu_e + n \rightarrow e^- + p$ neutrinos turn neutrons into protons

$\bar{\nu}_e + p \rightarrow e^+ + n$ anti-neutrinos turn protons into neutrons

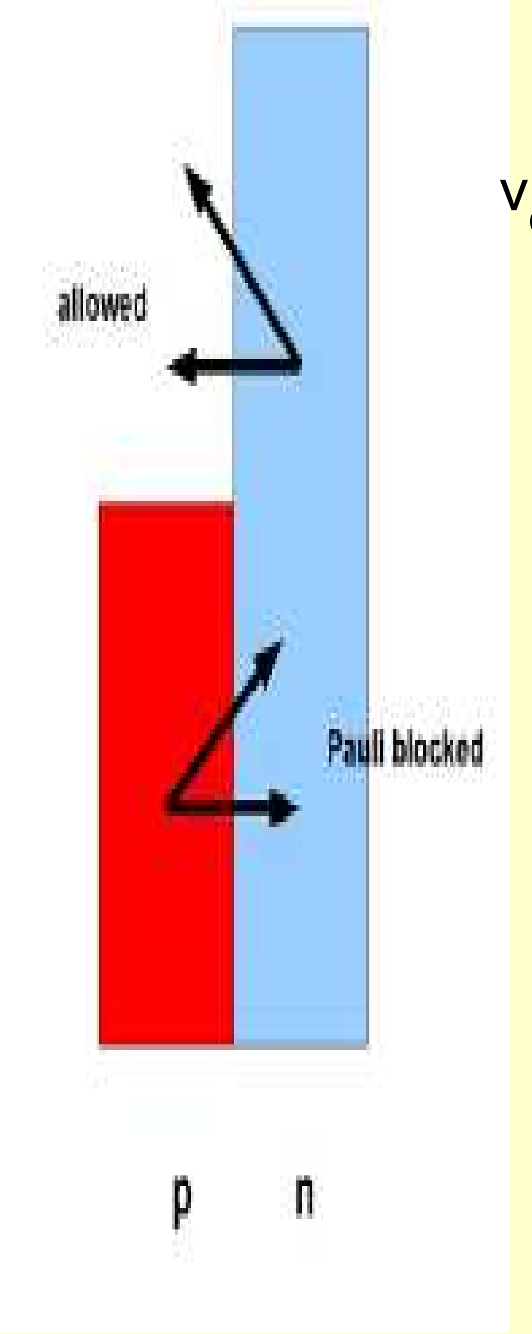
An organic scintillation detector
or a water Cerenkov detector
has lots of hydrogen (protons) so it is
mainly sensitive to **anti**-ν_e.

If we want to detect ν_e, we would need a target of neutrons.

No bulk quantities of free neutrons exist for us to build a detector with, so the next best thing is
a heavy nucleus like lead, which has an excess of neutrons
(Pb-208 = 82 protons, 126 neutrons).

^{208}Pb:

82 p
126 n

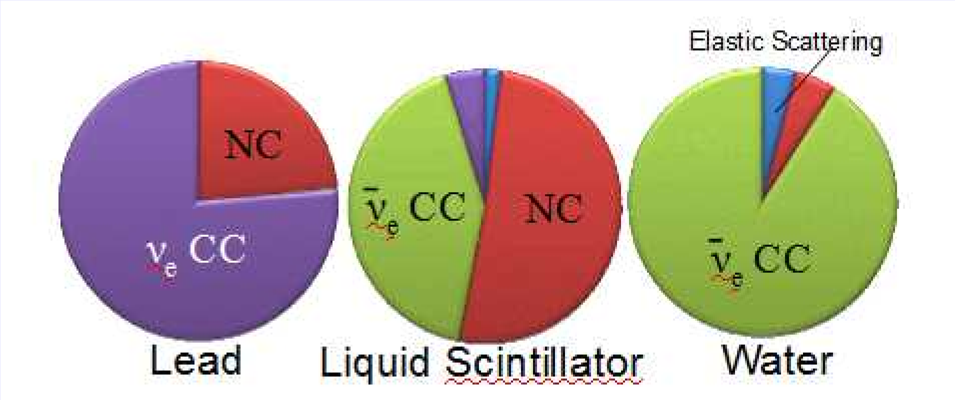


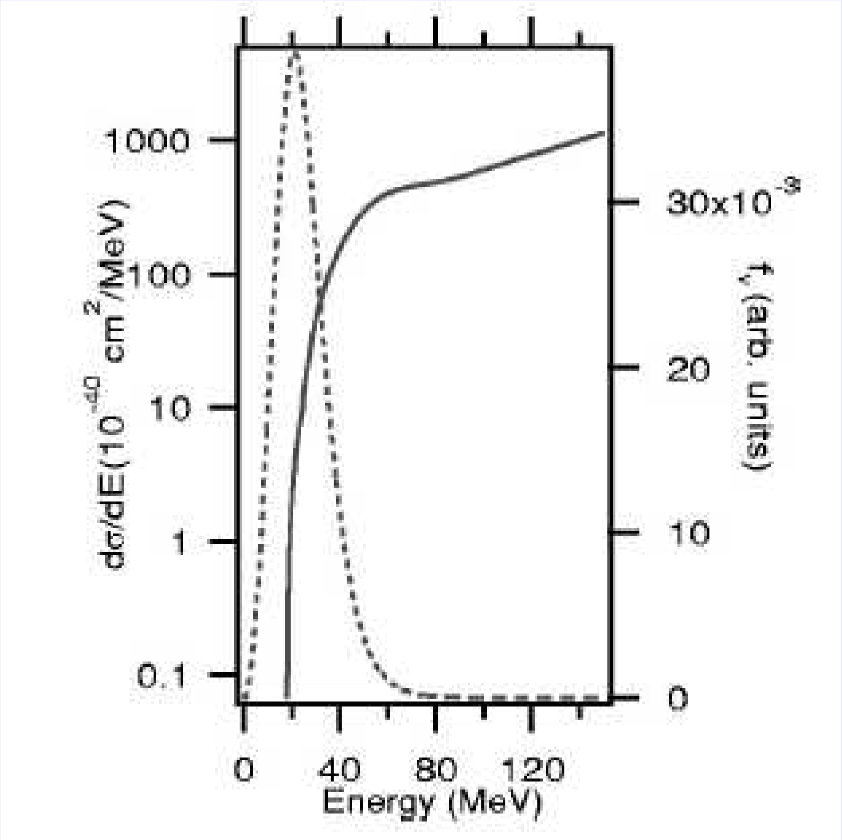
$\nu_e + n \rightarrow e^- + p$ allowed, lots of neutrons available

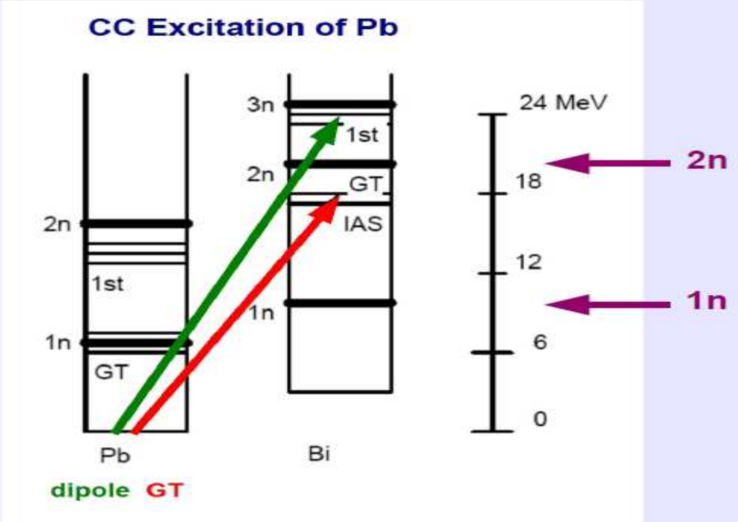
$\bar{\nu}_e + p \rightarrow e^+ + n$ **not** allowed, blocked by Pauli excl. principle

so lead detector strongly favours detecting neutrinos, over anti-neutrinos

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





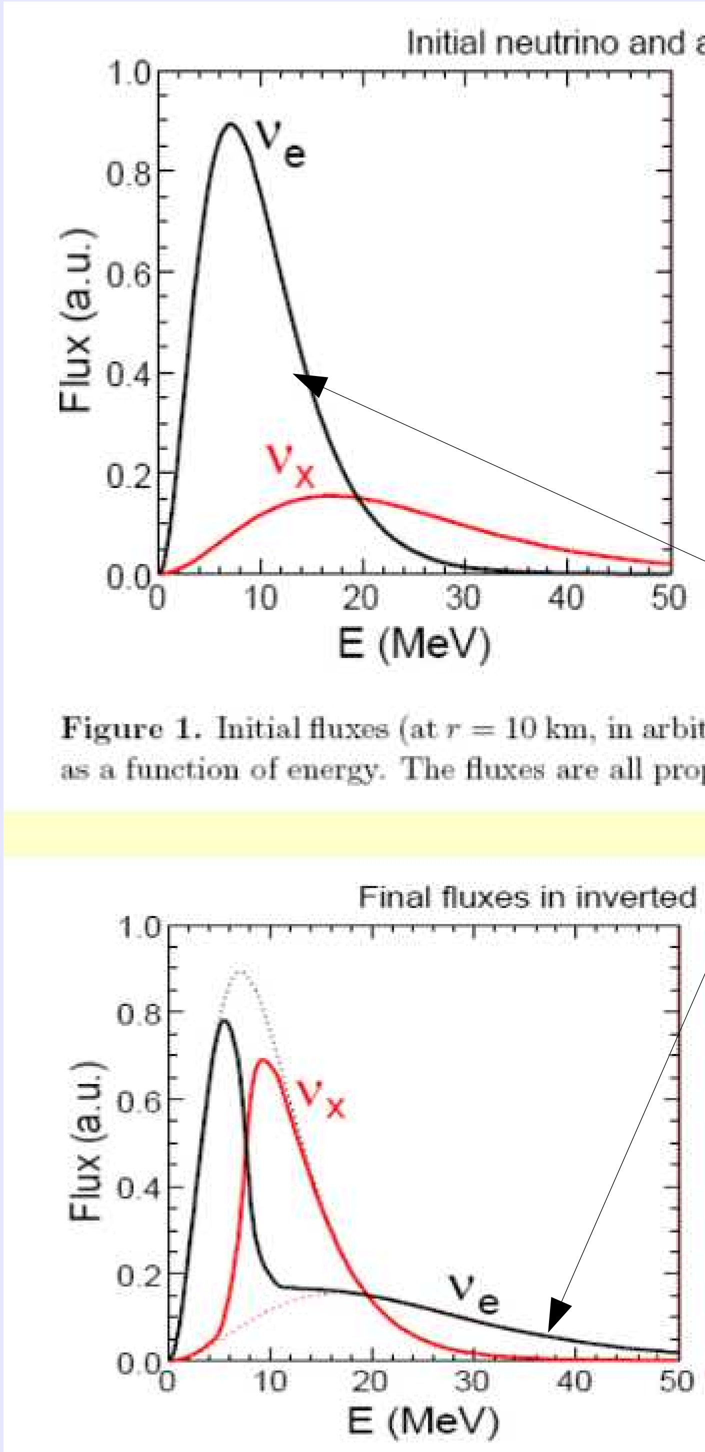


ratio of 2-n to 1-n emission events gives a measure of the average neutrino energy

σ a rapid function of E, sensitive to enhancement of high E tail of ν_e

Before

After



Collective neutrino effects

Neutrino density so high that they scatter off each other and induce collective flavor changes

Flavor swapping - the initial cold v_e spectrum swaps places with the initial hot v_x spectrum.

→ greatly increased rate in a v_e - sensitive detector like HALO

In 3rd phase of SNO, ^{3}He proportional neutron detectors deployed in the D_2O to detect neutrons from the neutral current distintegration of the deuteron, which detects all neutrino flavors:

$$\nu + d \rightarrow \nu + p + n$$

very low radioactivity chemical vapor deposited nickel bodies, filled with 2.5 atm of 85% ^{3}He, 15% CF_4

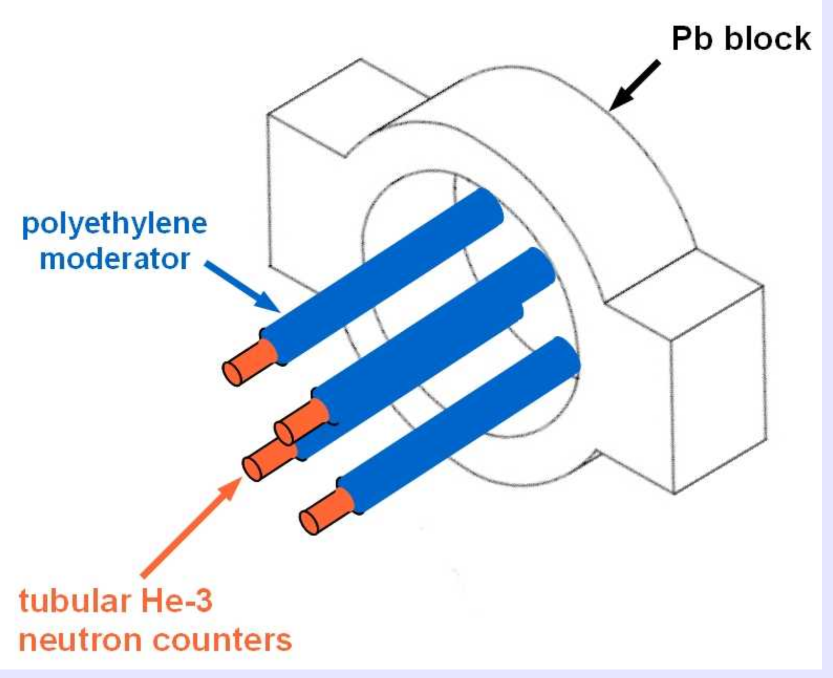
When the SNO experiment ended, these ^{3}He neutron counters were removed from the acrylic vessel, and became available to build a supernova neutrino detector!

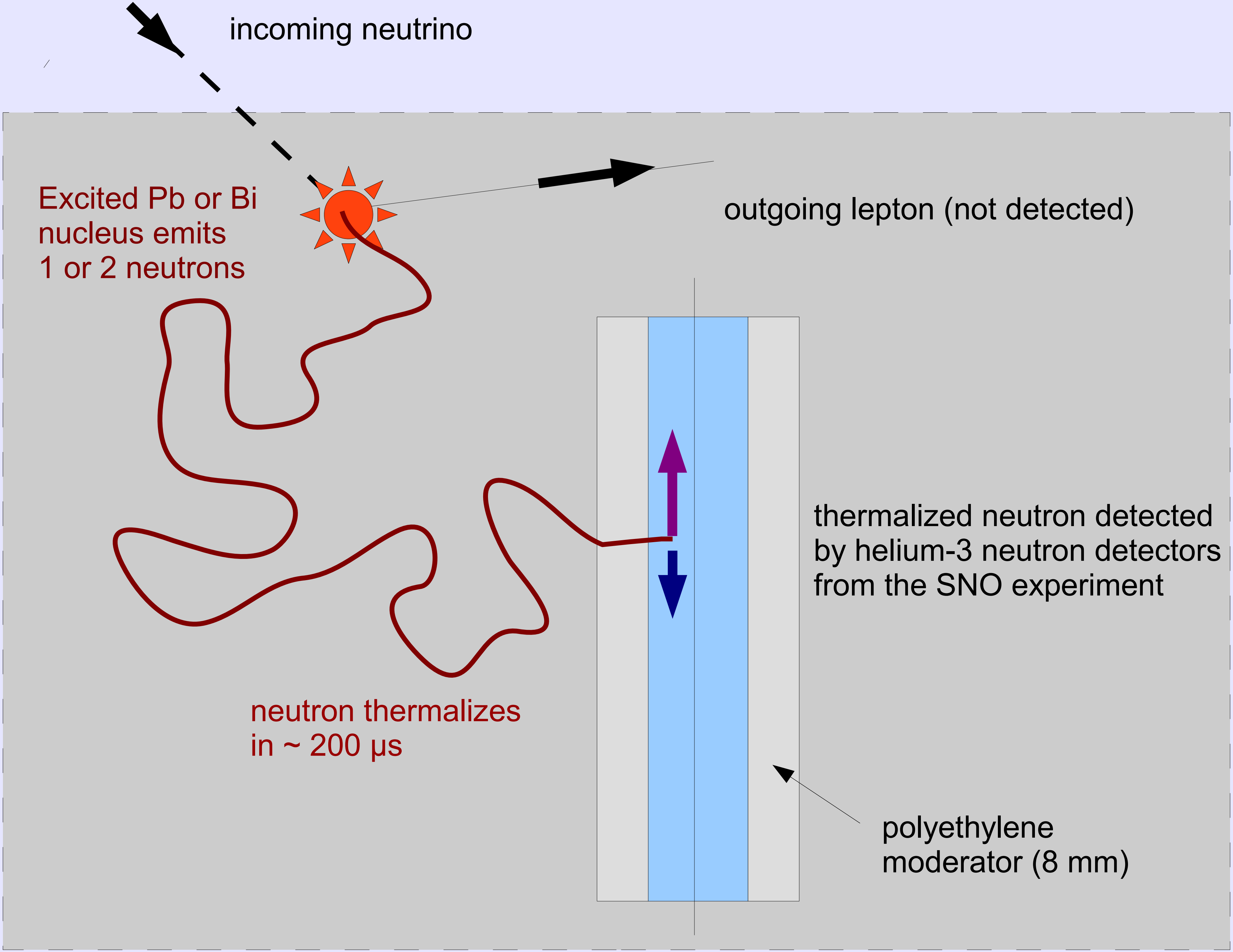
HALO (Helium And Lead Observatory)

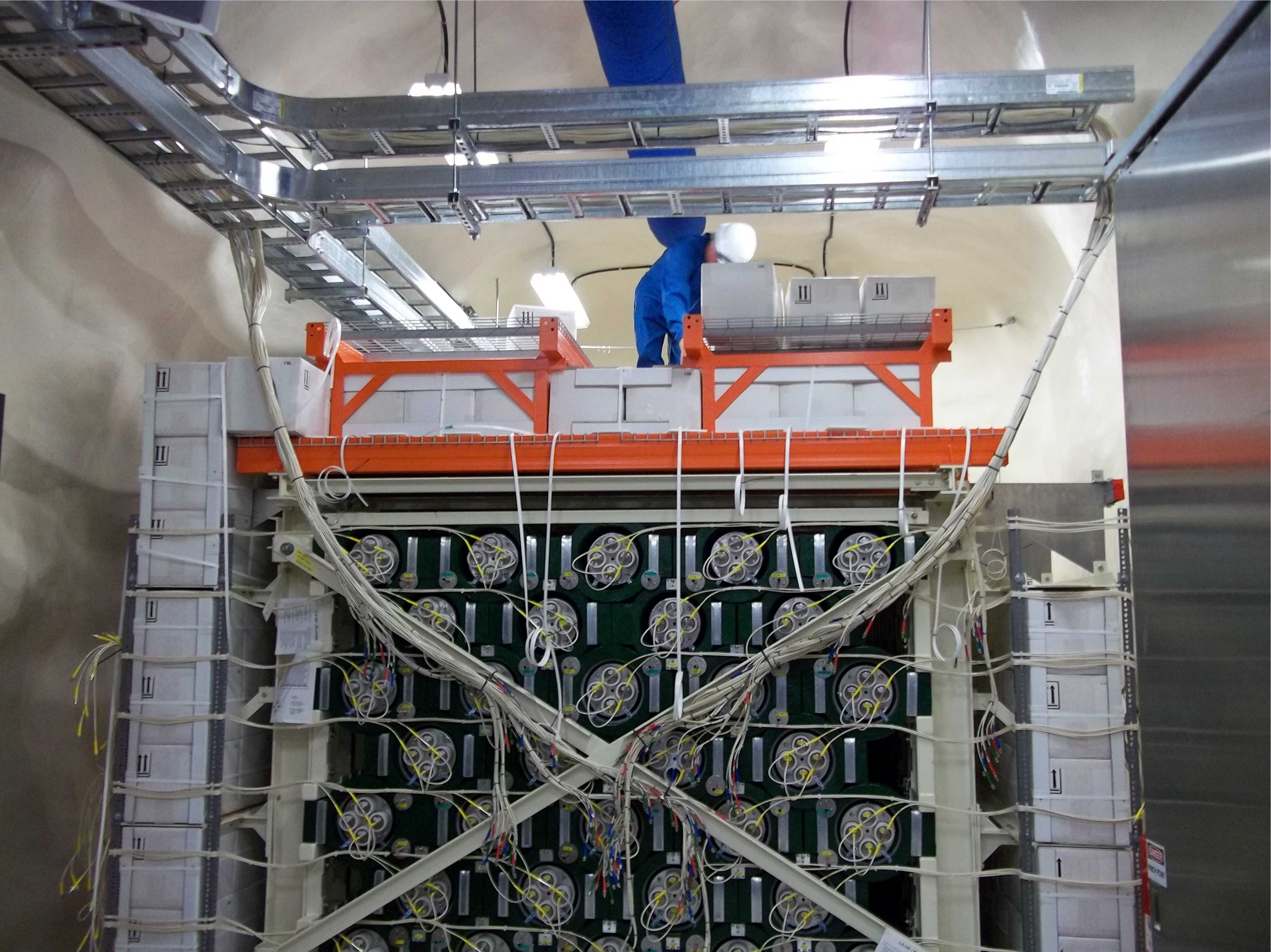
A detector of opportunity in SNOLAB assembled from surplus equipment

- **79 tons of hollow lead blocks from a decommissioned cosmic ray station**

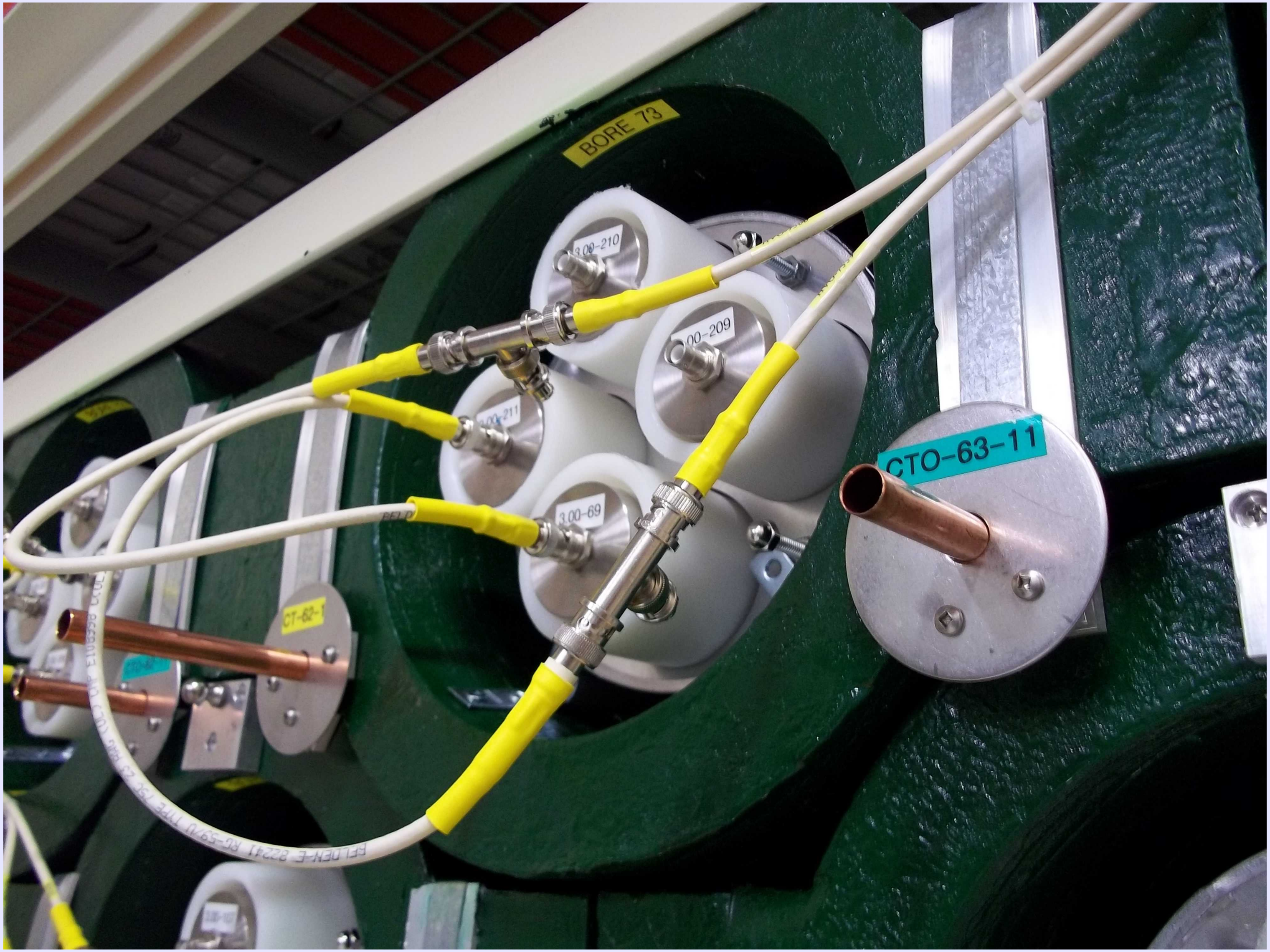
- **the ^{3}He neutron detectors from the 3rd phase of the SNO experiment**




incoming neutrino
Excited Pb or Bi
nucleus emits
1 or 2 neutrons
outgoing lepton (not detected)
thermalized neutron detected
by helium-3 neutron detectors
from the SNO experiment
neutron thermalizes
in ~ 200 μs
polyethylene
moderator (8 mm)



Closeup of lead annuli with white polyethylene moderator tubes surrounding the ^{3}He neutron counters

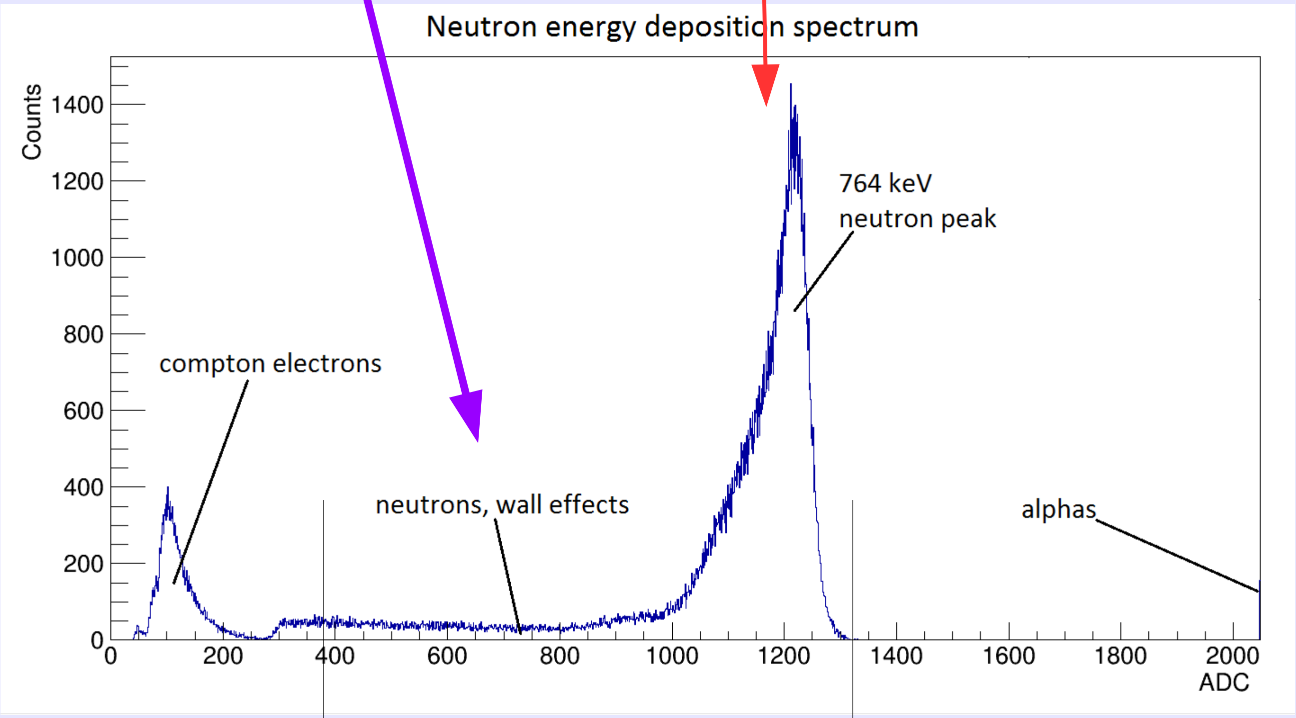


^{252}Cf neutron source inserted into lead matrix to calibrate neutron detection efficiency, rate ~20 Hz

Pulse height spectrum from n + ^{3}He → p + ^{3}H Q=764 keV

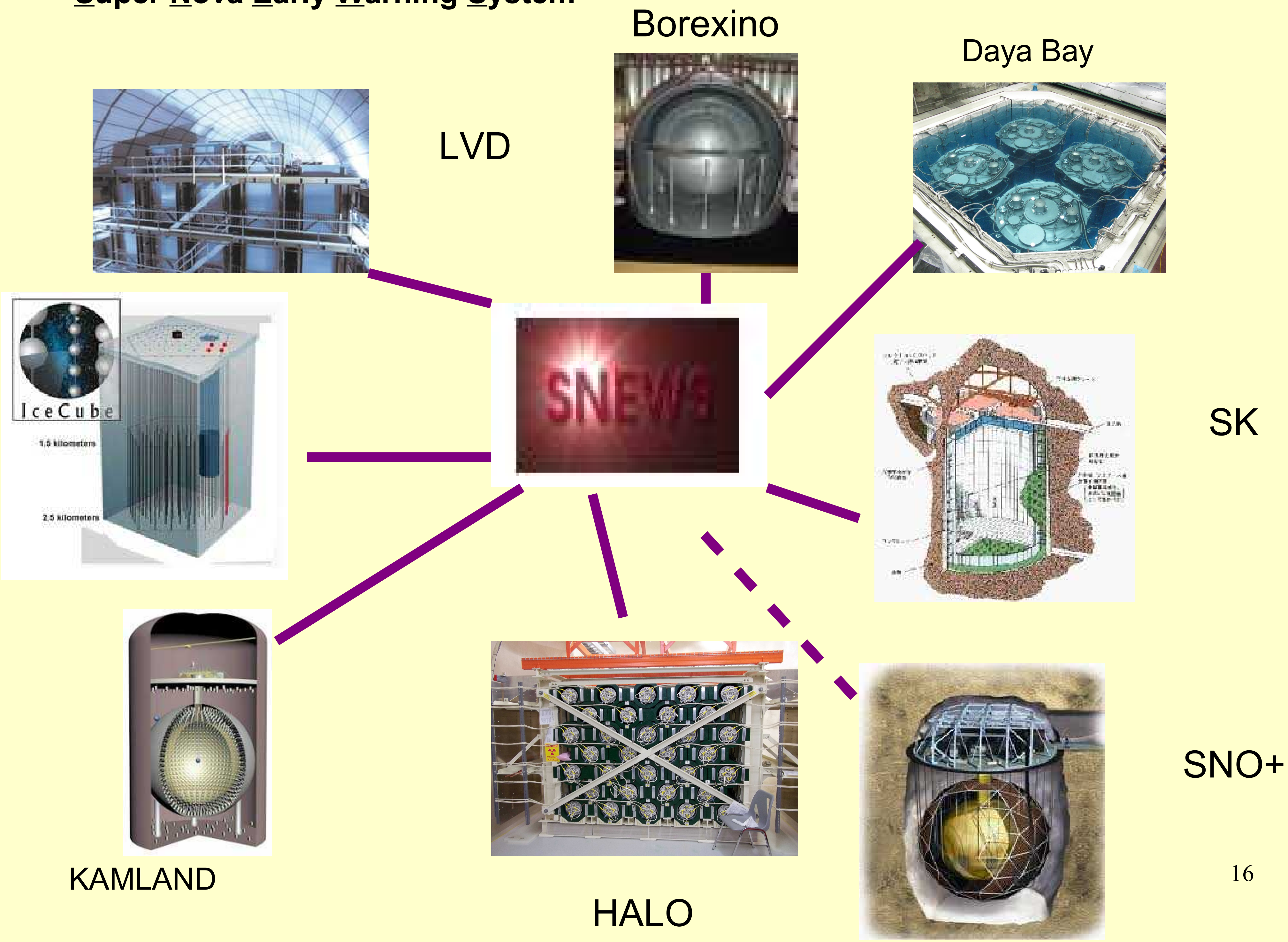
wall effects:
one of the final particles
hit the wall and hence
leave less ionization
in the gas

full energy peak:
both p and ^{3}H
range out in gas



region of interest
for real neutrons

Super Nova Early Warning System



HALO singles neutron rate 1300/day

HALO SNEWS trigger -- 4 or more neutrons in 2 second window, with a burst length of > 10 ms to exclude muon spallation and spontaneous fission

false supernova trigger rate sent to SNEWS: 4.3 per year

HALO in SNOLAB is complete, has been taking data since 2012,
a member of SNEWS since fall 2015.

But at only 79 tons, it is expected to detect only ~20 events for a galactic supernova

The decommissioning of the OPERA experiment at the Gran Sasso lab in Italy has made available 1300 tons of low-radioactivity lead.

We hope to use this to build another “detector of opportunity” with an order-of-magnitude greater sensitivity than HALO.

The anticipated rate of SN in our galaxy is 2 or 3 per century, and the neutrino signal lasts only ~ 20 seconds.

What we need is a dedicated detector with

- long lifetime of 50+ years
- zero maintenance and upkeep costs
- 100% livetime
- uncompromised by other physics objectives

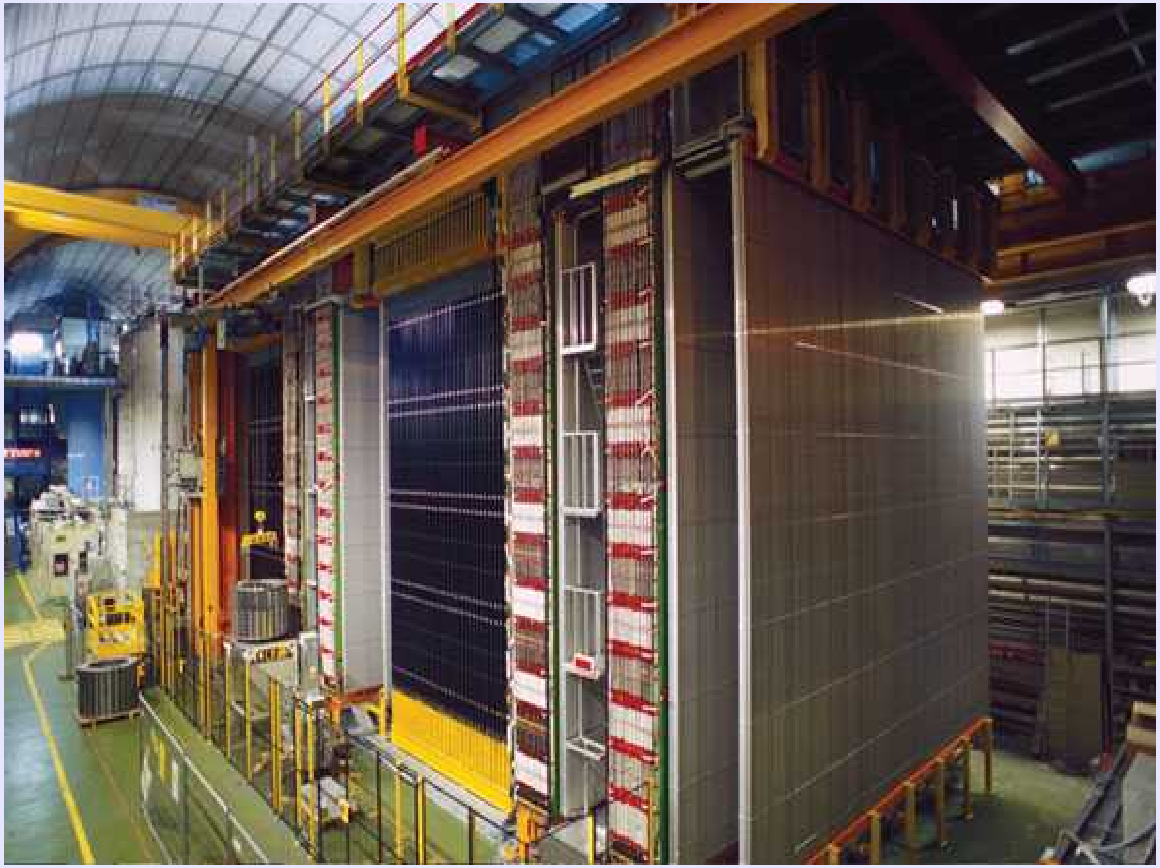
HALO and the future HALO-1kT fulfill these requirements!

HALO-1kT at Gran Sasso

- 1 kiloton of Pb (maybe 1.3 kT) available from decommissioning of OPERA experiment, in the form of 6.7 million sheets, measuring 10.3 cm x 12.8 cm x 1 mm thick

- if stacked, would form a “cube” 4 m x 4 m x 5.5 m

- this is 12.7 times more Pb than HALO-1
- a supernova at 10 kpc (centre of our galaxy) would have ~300 interactions, rather than a couple dozen



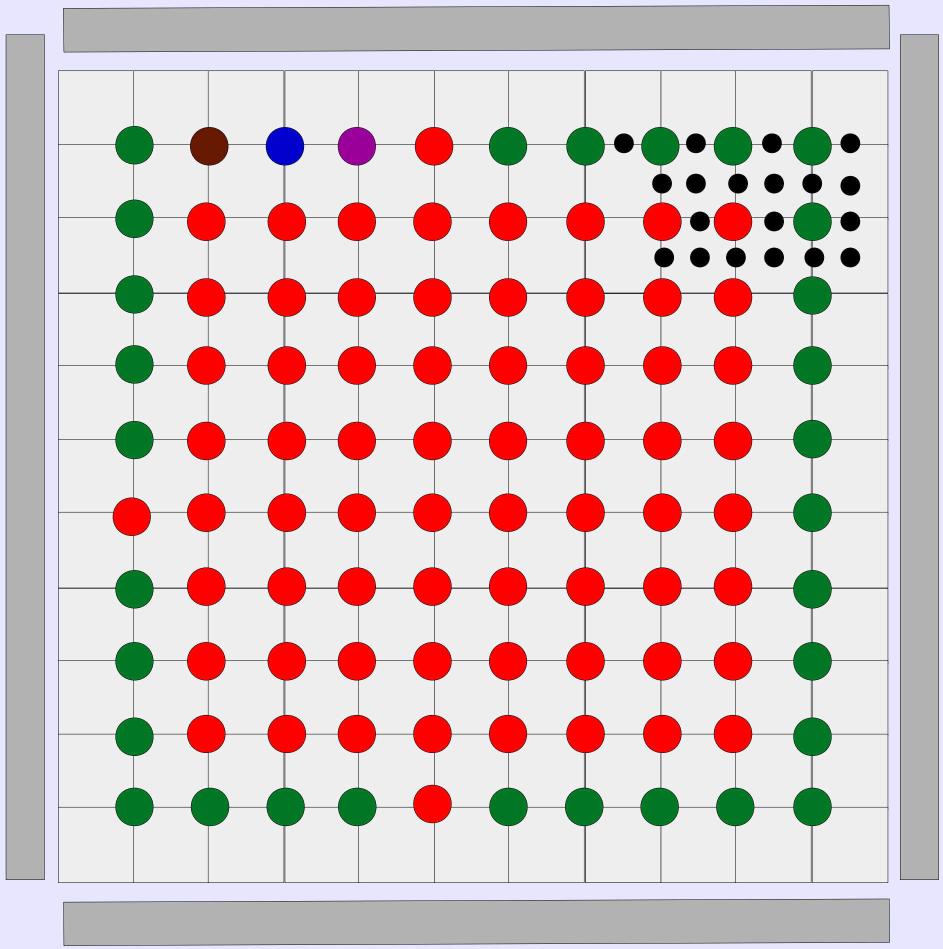
OPERA detector
at Gran Sasso,
now being decommissioned

Need more neutron counters!

^{3}He was prohibitively expensive in the decade after 9/11
and practically unobtainable

In summer 2016, US DOE declared ^{3}He shortage to be over

Jan 2017 - initial consultation with DOE about procuring ~10,000 litre-atm
of ^{3}He from its repository for HALO-1kT (research sale value $800 per litre-atm)



Baseline design:
20x20 array of neutron detectors
10,000 litre-atm of ^{3}He
Efficiency = 48.7%

SNO 3He detectors (ultra low background)

commercial detectors filled with DOE ^{3}He (not all shown)

15 cm graphite reflector

Possible timeline

April 2017 Canadian grant request for R&D money for low-background neutron detectors

April 2017 Scientific case presented to Gran Sasso program committee

summer 2017 discussion with US DOE about ^{3}He procurement

...

construction 2019+ ?

New collaborators welcome!