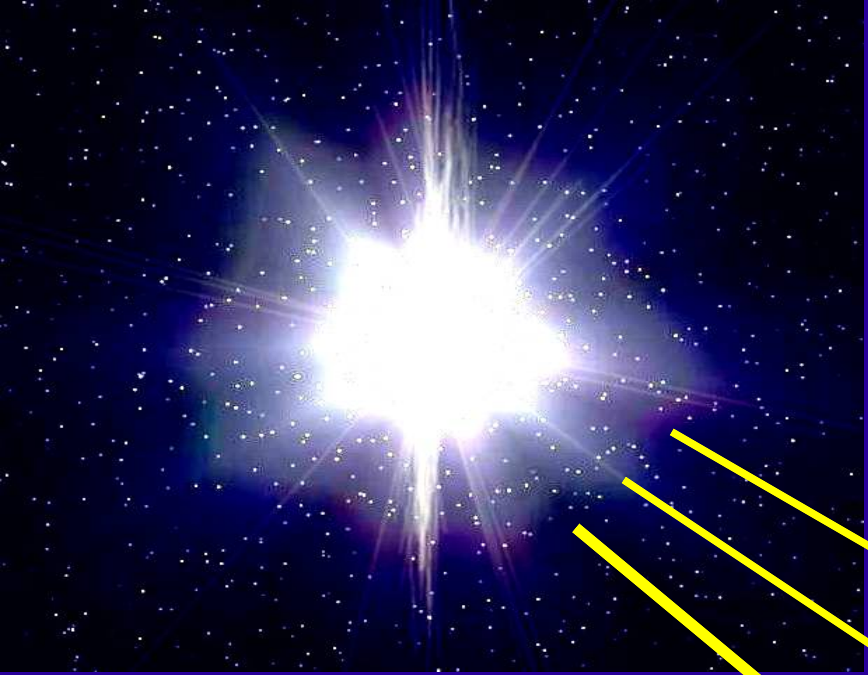
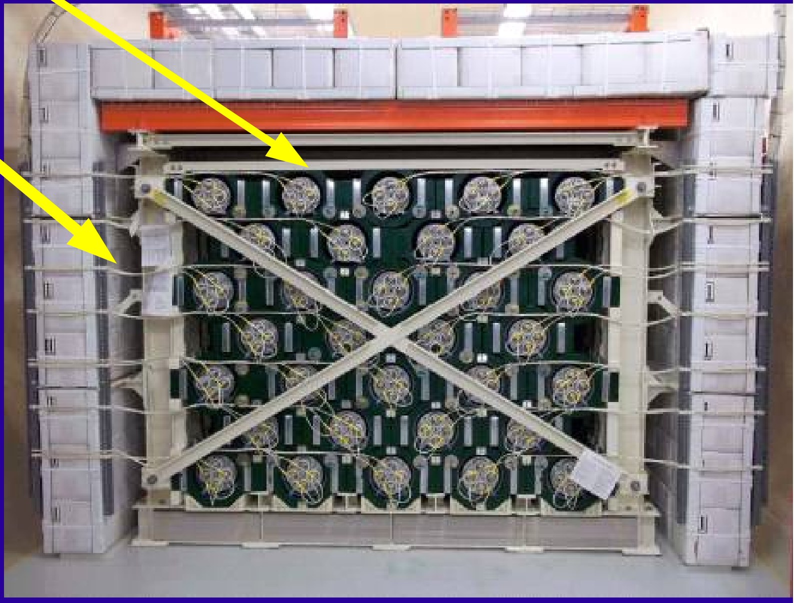
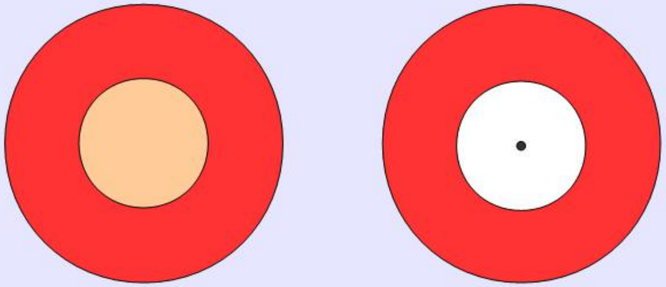


HALO / HALO-1kT Supernova Neutrino Detectors

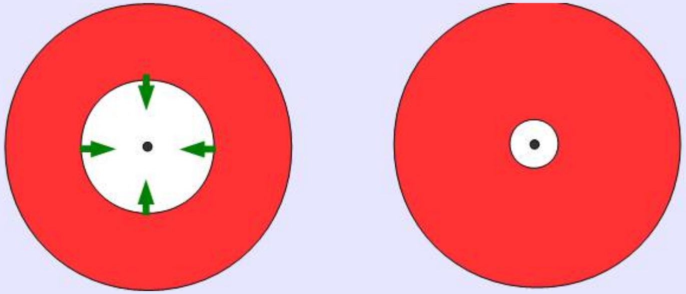
Stanley Yen, TRIUMF
Clarence Virtue, Laurentian U.



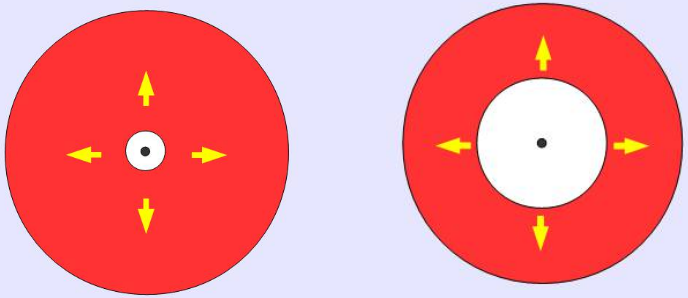
Stages of a core-collapse supernova:



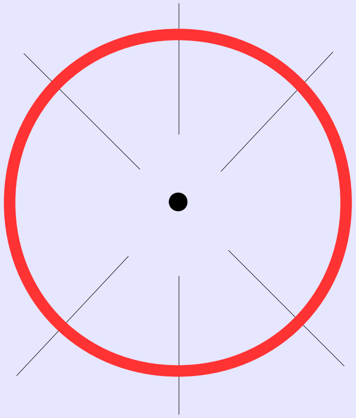
1. burst phase:
   iron core collapses
   $e^- + p \rightarrow \nu_e + n$



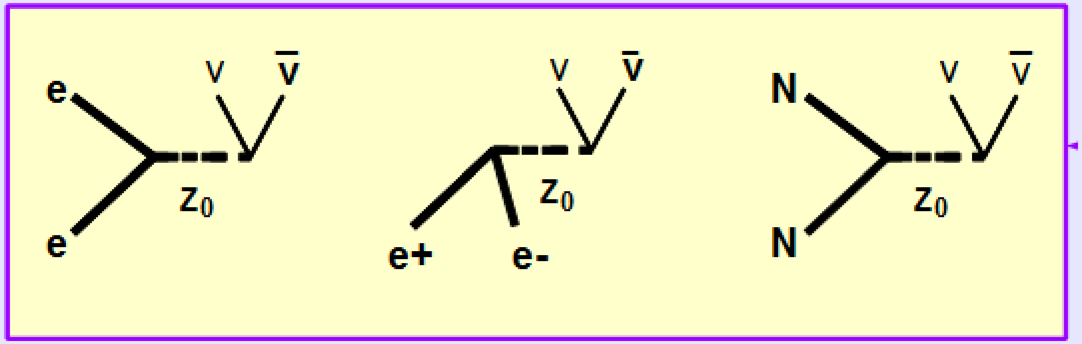
2. accretion stage:
   overlying layers fall inward
   onto proto-neutron star



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 lost in shock wave
0.01% as EM radiation
99% lost as neutrinos (≈10^{58} neutrinos of ~ 10 MeV energy)

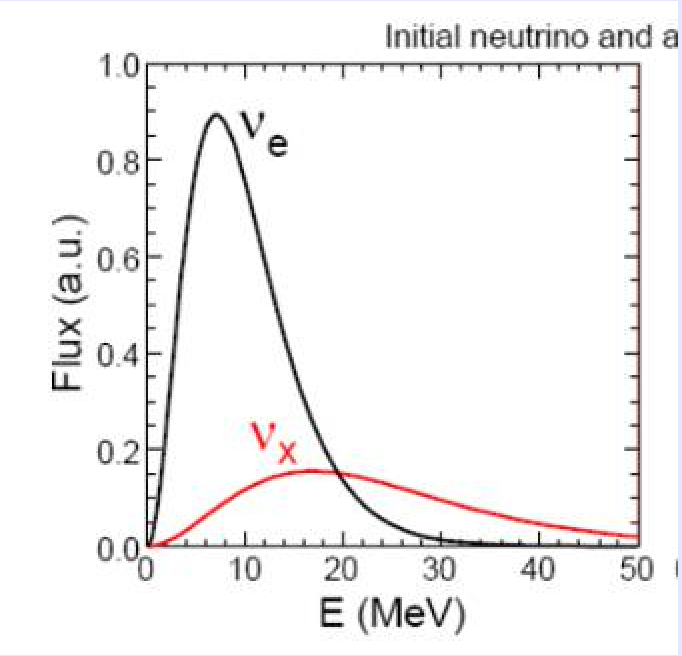
Neutrinos provide a prompt signal of the nuclear and particle processes in the core of the supernova, compared to the optical radiation which is emitted from the outer mantle and delayed by several hours.

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:

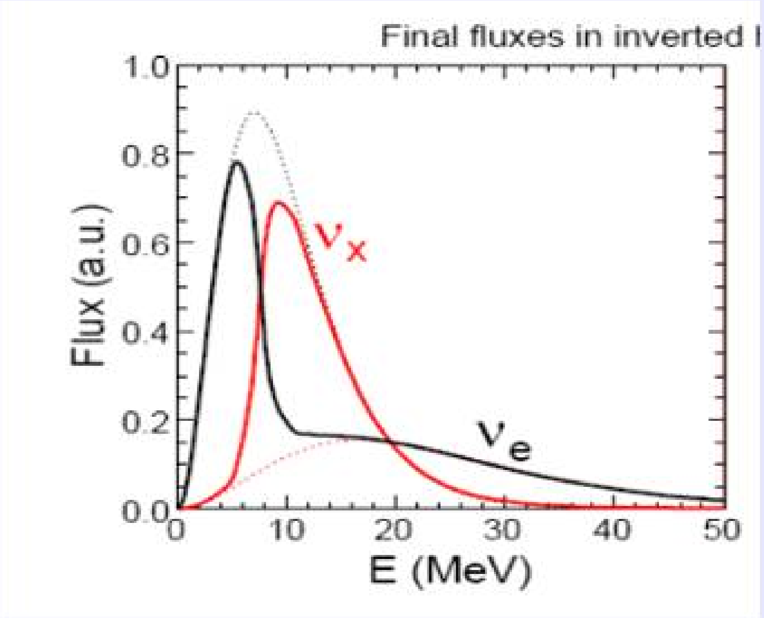
- the only place where the hadronic density is so large that the matter is opaque to neutrinos

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

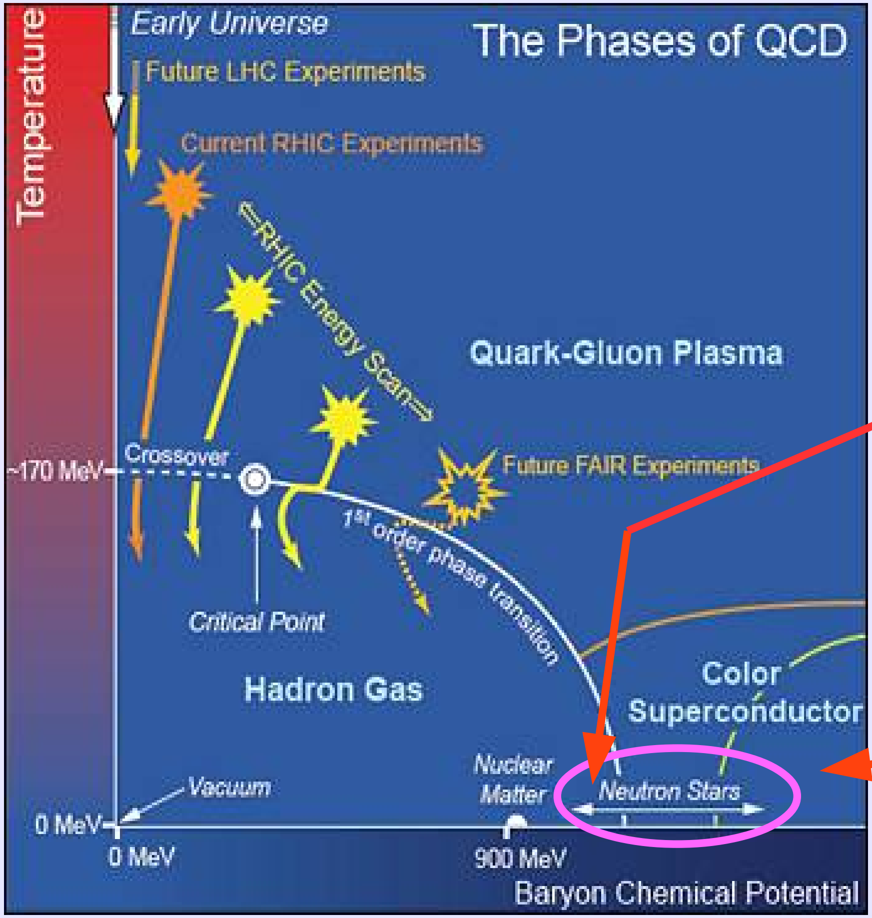
- the only place where the neutrino density is so large that neutrinos interact with each other, as a collective ensemble, and undergo collective neutrino flavor transitions



flavor swapping



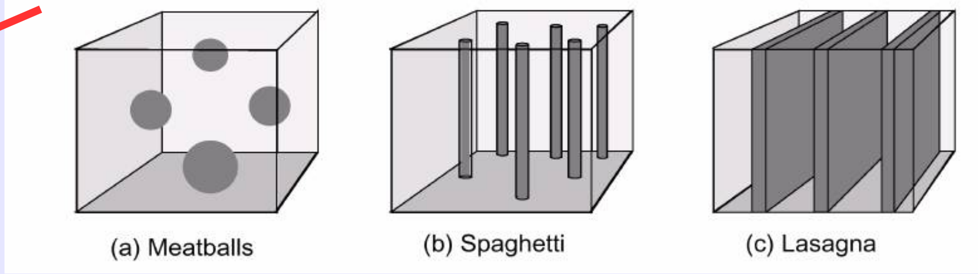
... and to study the state of hadronic matter at high density and low temperature
not accessible anywhere else in the universe

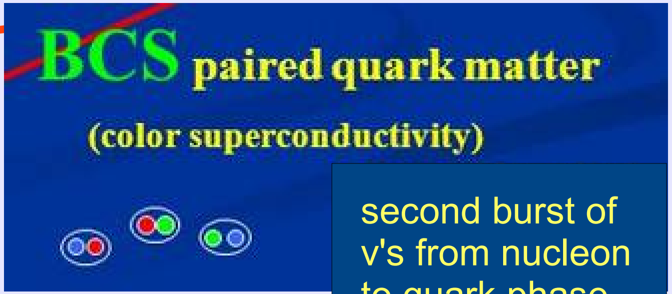


(density)

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

Nuclear pasta phase increases v opacity → v spectral distortions


(a) Meatballs (b) Spaghetti (c) Lasagna


BCS paired quark matter

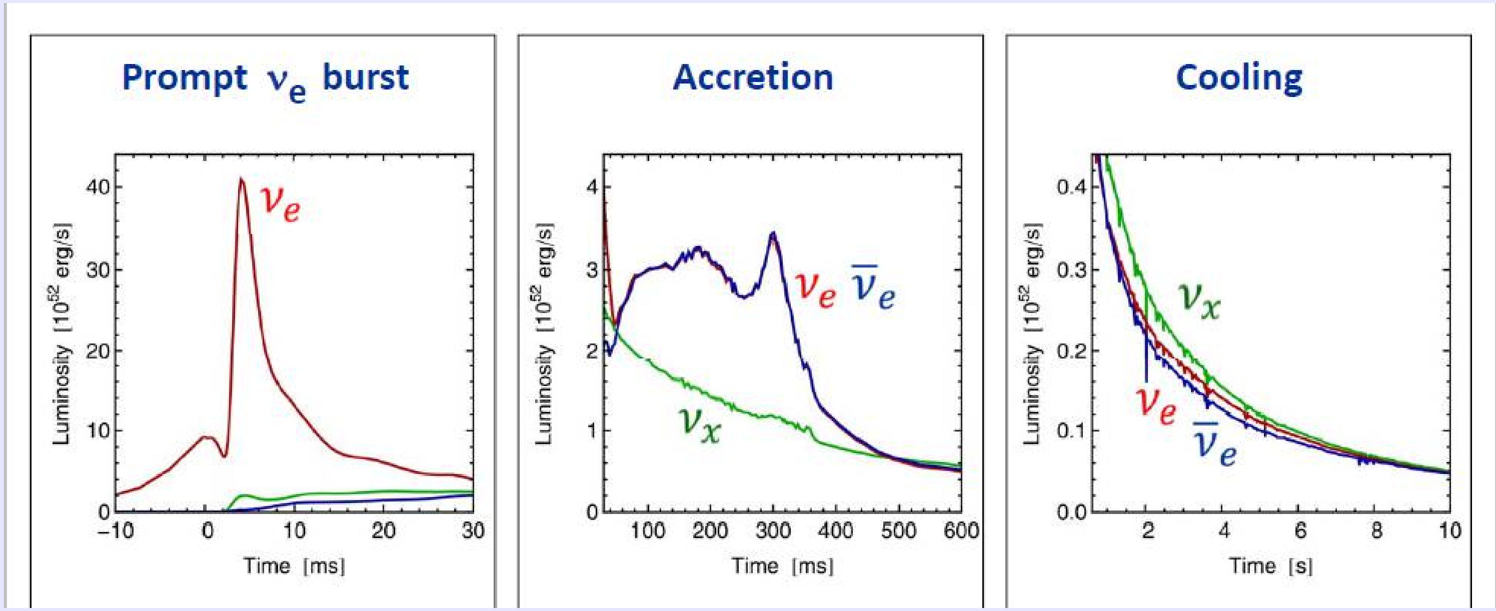
(color superconductivity)

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

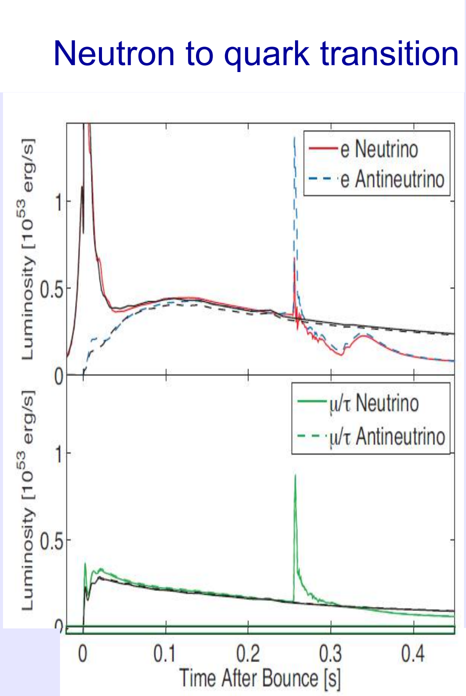
These could all leave imprints
on the time / energy development
of the neutrino emission from
a core collapse supernova.

Questions:
- are the models correct (time evolution, flavor partition)?
- 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
- second burst of neutrinos due to quark nova formation?
- role of matter-induced and neutrino-induced flavor oscillations?

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



from G. Raffelt, Shanghai Conference, 2013.



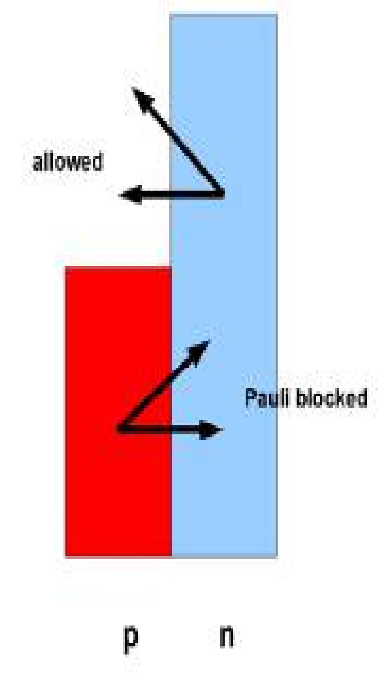
adapted from Sagert et al. arXiv:0902.2084 [astro-ph.HE]

Essential to observe each flavor separately, but Water Cerenkov and organic scintillation detectors are sensitive mostly to anti-ν_e .

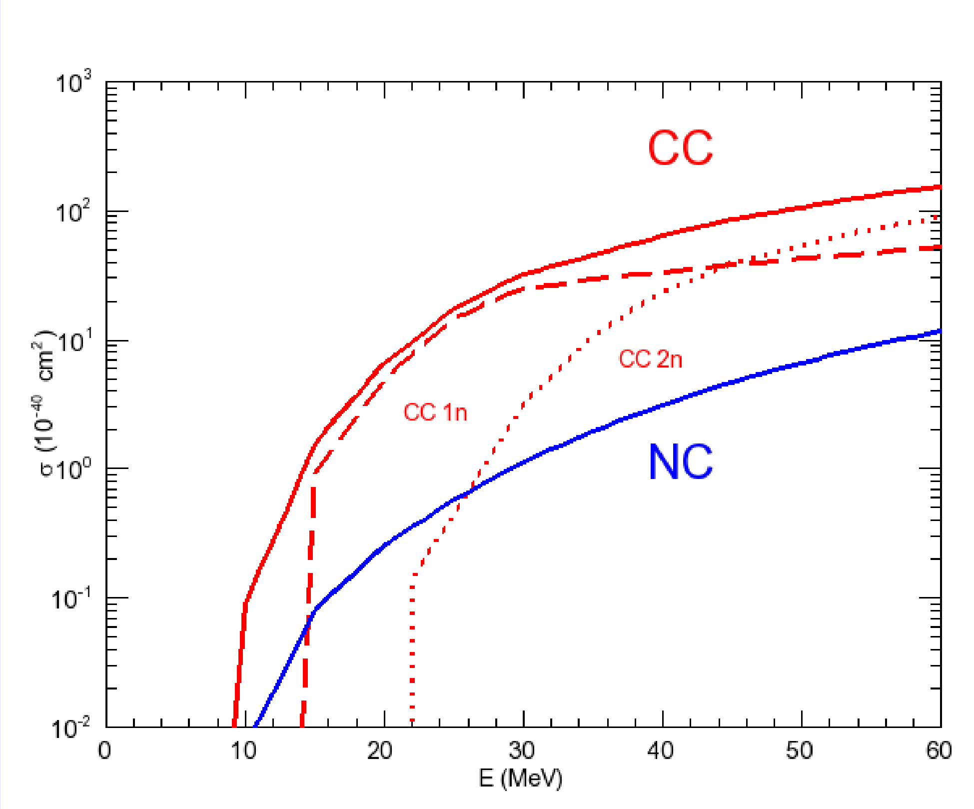
A lead detector is primarily sensitive to ν_e , flavor-complementary to other types.

Features of Pb as neutrino detector:

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

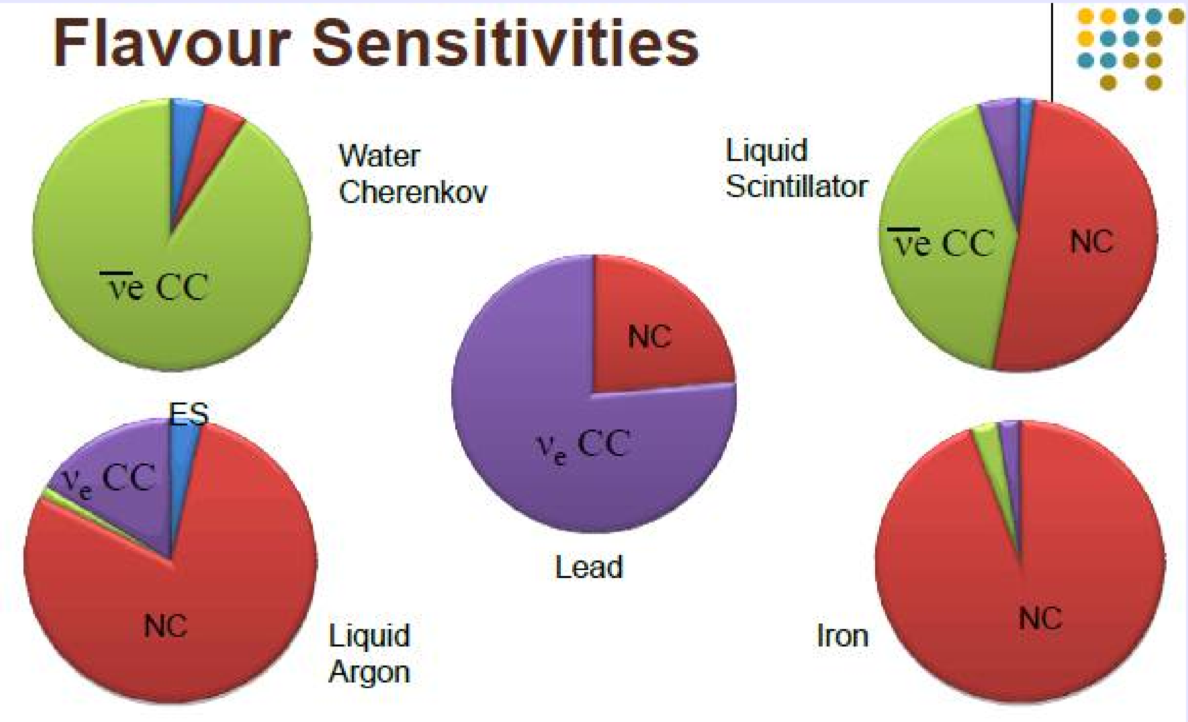


2. Large Z of Pb nucleus pulls in wavefunction of outgoing electron, enhances CC cross sec.



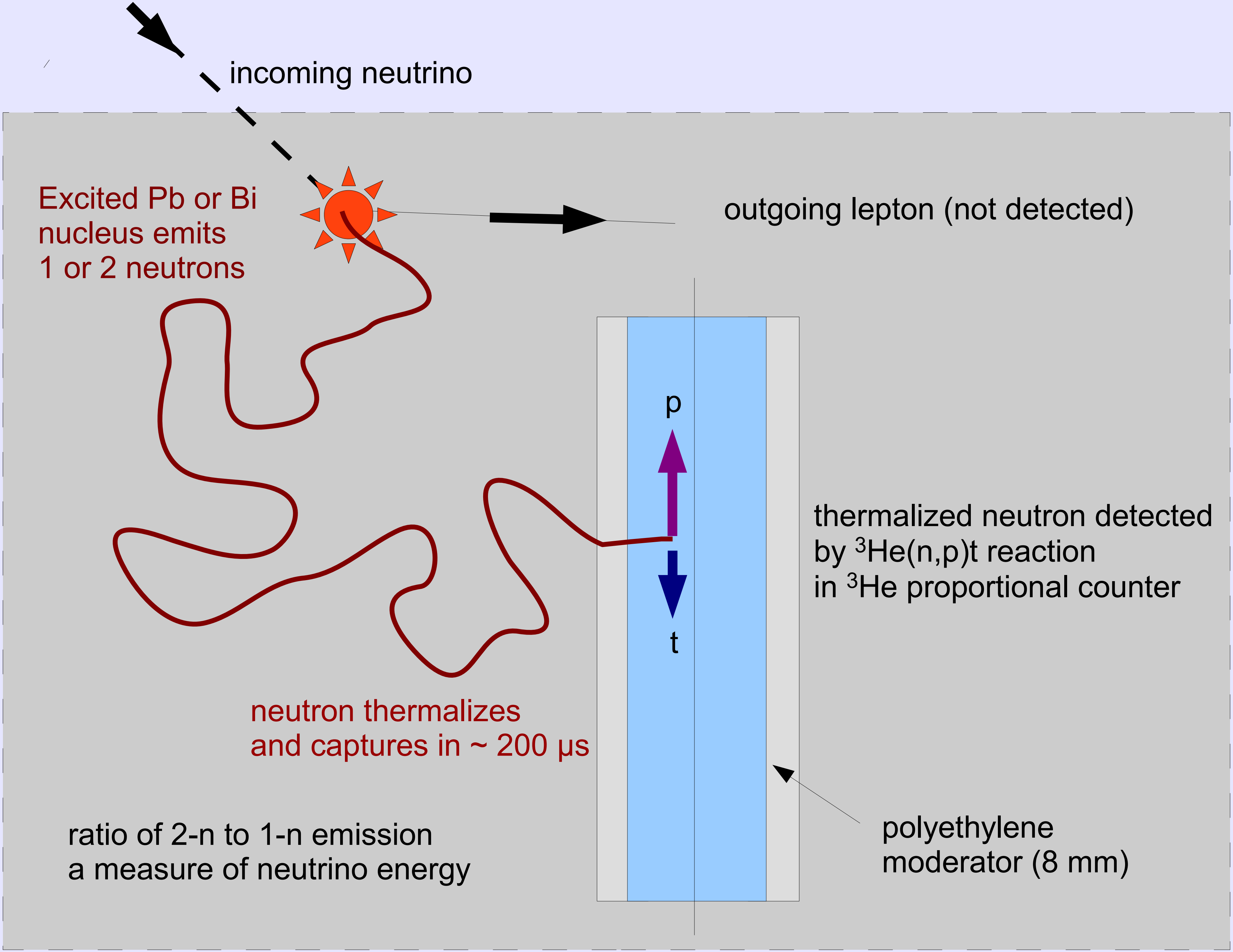
3. σ a rapid function of E, sensitive to enhancement of high E tail of v_e

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



Flavour Sensitivities

Helium **A**nd **L**ead **O**bservatory
HALO-1 in SNOLAB was a “detector of opportunity” built using 79 tonnes of surplus lead blocks from a decommissioned cosmic ray station, and the ^{3}He neutron detectors from the decommissioned SNO experiment.



incoming neutrino

Excited Pb or Bi
nucleus emits
1 or 2 neutrons

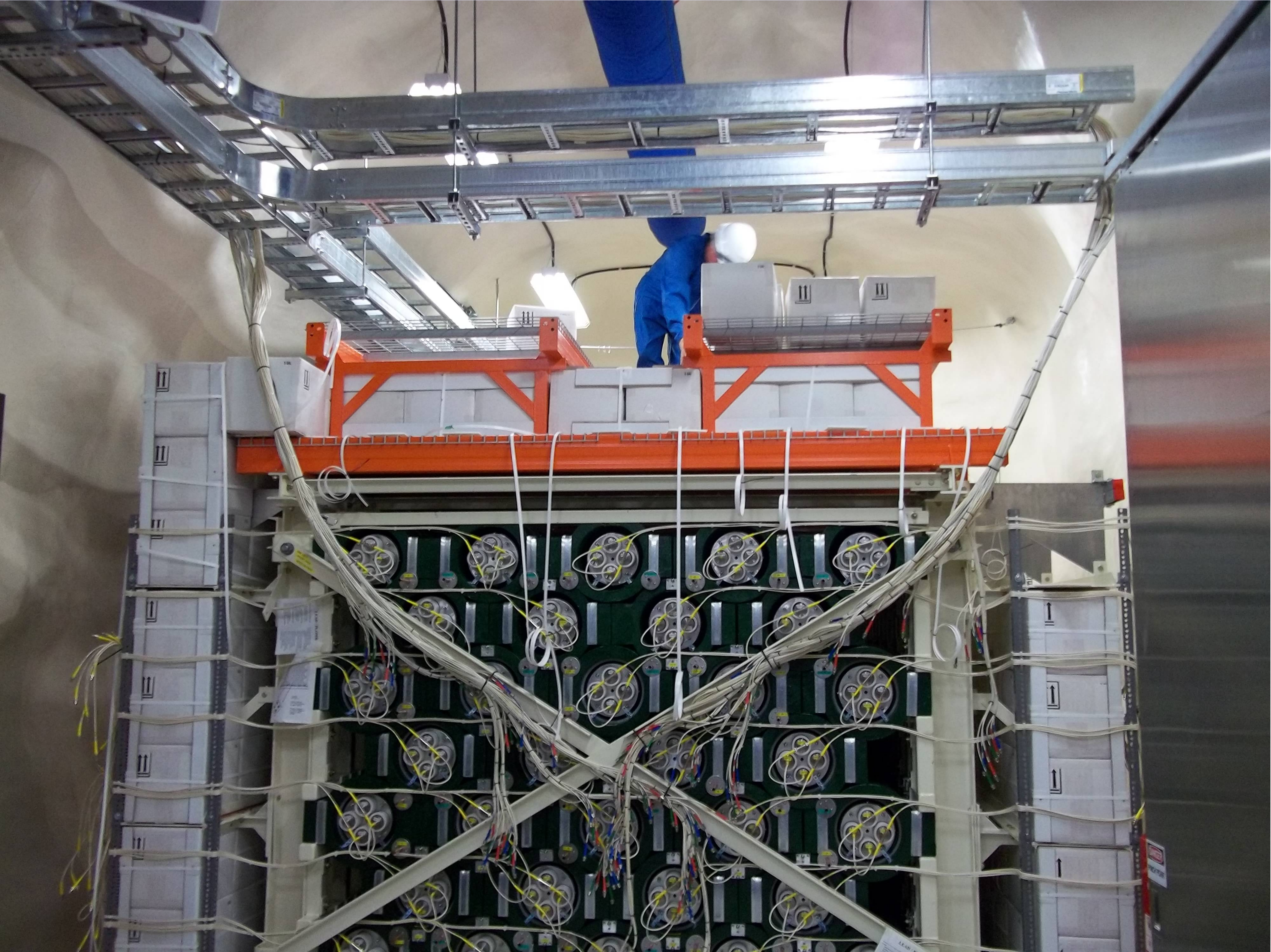
outgoing lepton (not detected)

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

neutron thermalizes
and captures in ~ 200 μs

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

polyethylene
moderator (8 mm)



HALO-1 in SNOLAB is complete, has been taking data since 2012,
a member of SNEWS since fall 2015.

- a well-understood detector, calibrated with neutron sources inserted into the lead matrix, efficiency of ~29% matches expectations of Monte-Carlo

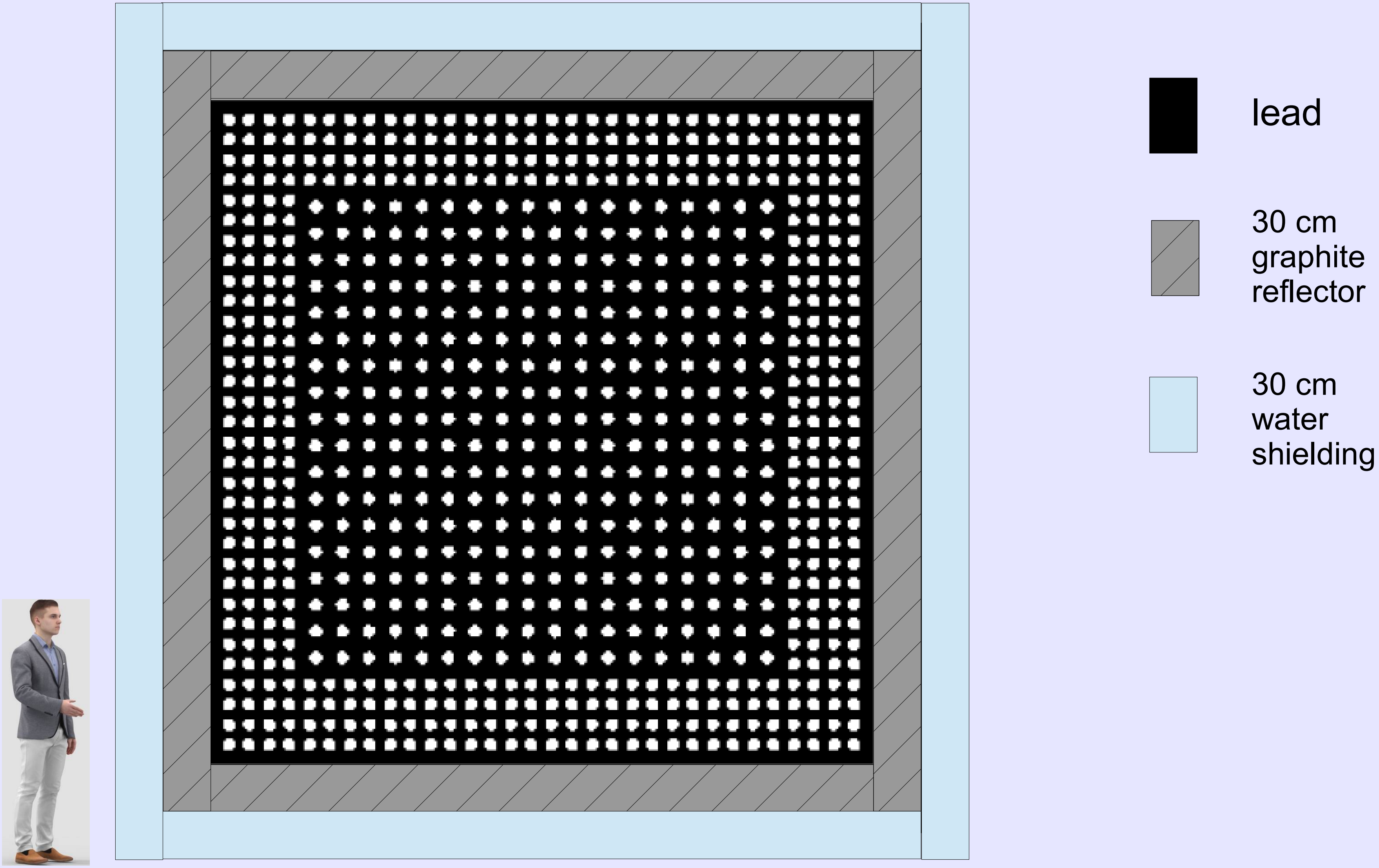
But at only 79 tonnes, it is expected to detect only ~20 events for a galactic supernova

The decommissioning of the OPERA experiment at the Gran Sasso lab in Italy has made available 1000+ tonnes of low-radioactivity lead

We hope to use this to build another “detector of opportunity” with ~25x greater sensitivity than HALO-1.

The anticipated rate of core-collapse supernovae in our galaxy is 3 ± 1 per century. The appropriate instrument is a long-lifetime, low-maintenance, robust detector that can be built and then left to run by itself for 50+ years .

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



Neutron detection efficiency ~ 53%

HALO-1kT Collaboration:

Currently 27 members Canada (10) Italy (8) USA (8) Mexico (1)

Marco Aglietta[1,2], Mauricio Barbi[3], Jake Bobowski[4], Gianmarco Bruno[5], Erica Caden[6], Alan Chen[7], Jacques Farine[8], Walter Fulgione[2,5], Alfredo Galindo-Uribarri[9], Andrea Gallo Rosso[5], Alec Habig[10], Mark Howe[11], Christine Kraus[8], Andrea Molinario[5], Giulia Pagliaroli[5], Barry Pointon[12], Diane Reitzner[13], Kate Scholberg[14], Jeff Secrest[15], Krzysztof Starosta[16], Gian Carlo Trinchero[1,2], Eric Vazquez Jauregui[17], Carlo Vigorito[1,18], Clarence Virtue[8,*], Paul Voytas[19], John Wilkerson[11], Stanley Yen[20]

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[7] McMaster University, Hamilton, ON L8S 4L8, Canada
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[18] Torino University, Torino, Italy
[19] Wittenberg University, Springfield, OH 45504, USA
[20] TRIUMF, Vancouver, BC V6T 2A3, Canada

- bi-weekly meetings since fall 2015, doing Monte-Carlo simulations, discussions about detector technologies, astrophysics, ...

- posssible locations in Gran Sasso lab identified (Oct 2016)

- NSERC project grant awarded April 2017 to continue HALO-1 and develop technical design for HALO-1kT

- initiate request for ^{3}He from US DOE (July 2017)

- prototype neutron counters filled with ^{4}He to be made by commercial vendors and tested for sufficiently low radioactivity (summer 2017); R&D on cleaning and electroplating if needed

- submission of physics case to Gran Sasso Lab (Oct 2, 2017)

- use spare ^{3}He neutron counters for measurement of v-Pb cross section at SNS (background tests in progress; cross section measurements 2018 onwards)

- aiming for technical design report by summer 2018, ready for next round of CFI

New collaborators welcome - from Canada, USA, other countries!
e-mail stan@triumf.ca cjv@snolab.ca