Detectors in Nuclear and Particle Physics

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July 16, 2015

10.1 Introduction

Electrically neutral particles do not interact via electromagnetic forces; for detection they are thus generally converted into charged particles.

Apart from the converting material, detectors for neutrals use essentially same techniques as those for charged particles.

Examples:

photons:	total energy deposited in electromagnetic shower use energy measurement, shower shape and information on neutrality (e.g. no track)
neutrons:	energy in calorimeter or scintillator (Li, B, ^{3}He) and information on neutrality (e.g. no track)
K_0, Λ, ...	reconstruction of invariant masses
neutrinos:	Identify products of charged and neutral current interactions

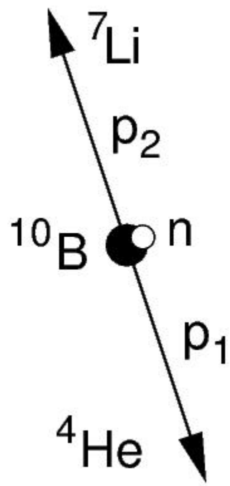
10.2 Detection of Neutrons

Neutron detection via nuclear interaction, interaction used varies with the neutron energy:

high energy	hadron calorimeter [see above] measure energy deposited in form of hadronic shower neutrality of incident particle has little effect on shower process
moderate energy	np-scattering detection of neutrons by scattering them from material containing appreciable amounts of hydrogen; recoiling proton is detected
low energy	exoergic nuclear processes use converter medium with large capture cross-section for slow neutrons; capture process results in unstable nuclei subsequent decay products give a detectable signal

Detection of Neutrons

Nuclear reactions used for neutron detectors:



$$
\begin{array}{llllll}
\text{Helium:} & n + {}^{3}\text{He} & \rightarrow & {}^{3}\text{H} + 1\text{H} & + 0.76\ \text{MeV} & \\
\text{Lithium:} & n + {}^{6}\text{Li} & \rightarrow & {}^{4}\text{He} + {}^{3}\text{H} & + 4.79\ \text{MeV} & \\
\text{Boron:} & n + {}^{10}\text{B} & \rightarrow & {}^{7}\text{Li}^{*} + {}^{4}\text{He} & + 2.31\ \text{MeV} + 0.48\ \text{MeV} & (93\%) \\
 & & \rightarrow & {}^{7}\text{Li} + {}^{4}\text{He} & + 2.78\ \text{MeV} & (7\%)
\end{array}
$$

charged nuclei Q-value

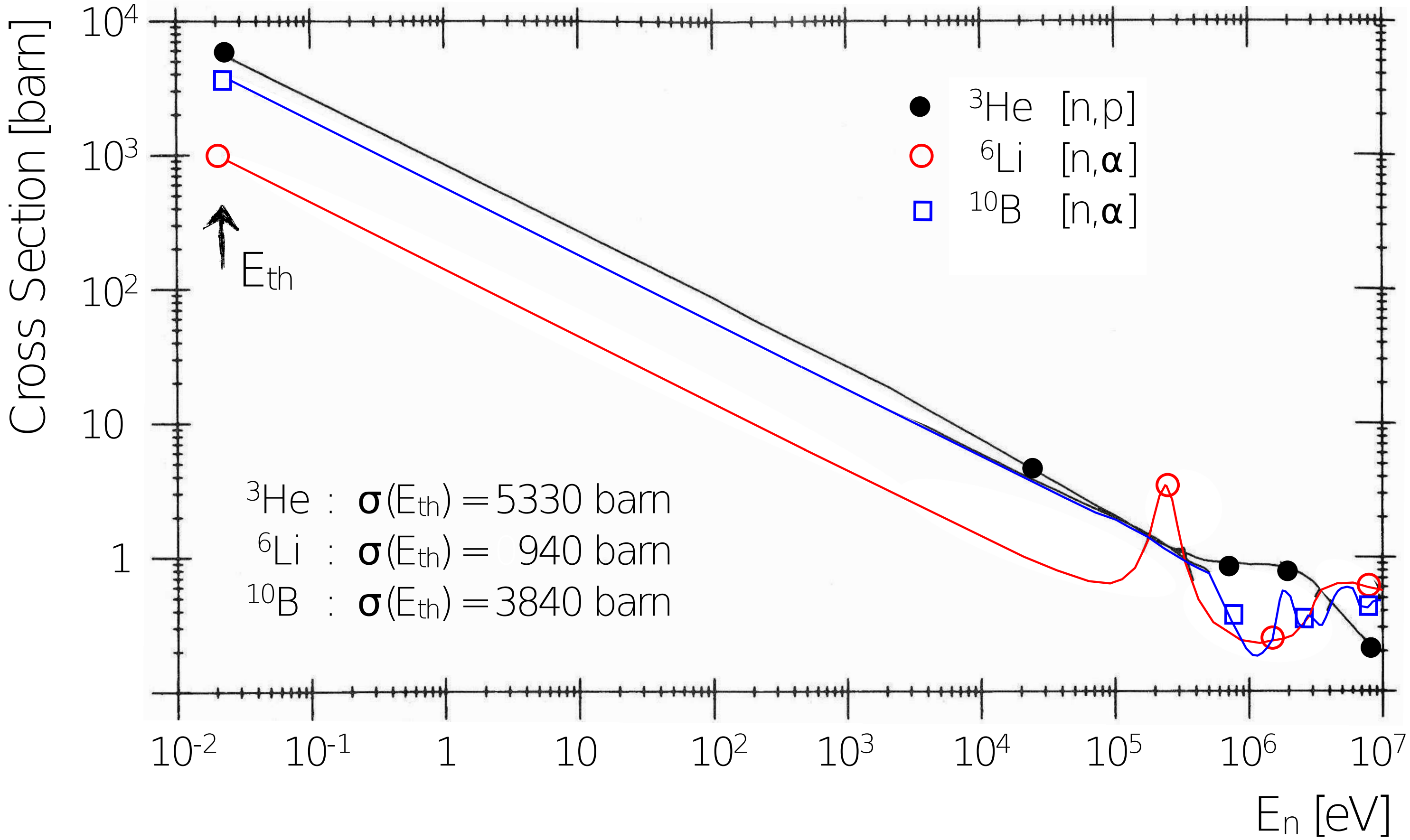
$$
\begin{aligned}
\vec{p}_1 &= -\vec{p}_2 \\
\frac{\vec{p}_1^{\,2}}{2m_1} + \frac{\vec{p}_2^{\,2}}{2m_2} &= \frac{-\vec{p}_1^{\,2}}{2m_1}\left(1 + \frac{m_1}{m_2}\right) = Q
\end{aligned}
\qquad
\begin{aligned}
E({}^{4}\text{He}) &= \frac{m_{\text{Li}}}{m_{\text{Li}} + m_{\text{He}}} \approx \frac{7}{11} Q = 1.77\ \text{MeV} \\
E({}^{7}\text{Li}) &= \frac{m_{\text{He}}}{m_{\text{Li}} + m_{\text{He}}} \approx \frac{4}{11} Q = 1.01\ \text{MeV}
\end{aligned}
$$

$$
\begin{array}{llll}
\text{Gadolinium:} & n + {}^{155}\text{Gd} & \rightarrow & \text{Gd}^{*} \rightarrow \gamma\text{-ray spectrum} \rightarrow \text{conversion electron spectrum} \\
 & n + {}^{157}\text{Gd} & \rightarrow & \text{Gd}^{*} \rightarrow \gamma\text{-ray spectrum} \rightarrow \text{conversion electron spectrum} \\
\text{Uranium:} & n + {}^{235}\text{U} & \rightarrow & \text{fission fragments (170 MeV)} + \text{neutrons} \\
\text{Plutonium:} & n + {}^{239}\text{Pu} & \rightarrow & \text{fission fragments (176 MeV)} + \text{neutrons}
\end{array}
$$

Detection of Neutrons

cross section for neutron capture process (apart from resonances)

$$\sigma(E) \approx \sigma(E_{\rm th}) \frac{v_{\rm th}}{v}$$



interpretation:

cross section increases with time neutron is close to absorbing nucleus

$\rightarrow v^{-1}$-dependence

Detection of Neutrons

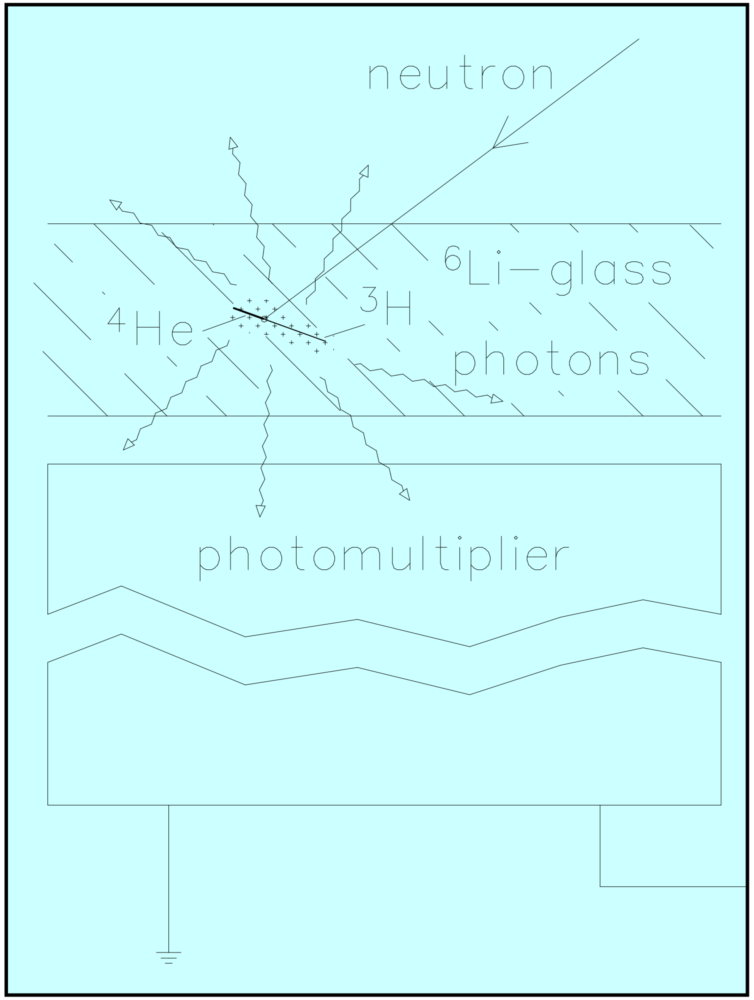
scintillation detectors: detect scintillation light produced in capture process

e.g. Lithium glass:

$n + {}^6Li \rightarrow {}^4He + {}^3H + 4.79\ MeV$

common scintillators used for neutron detection

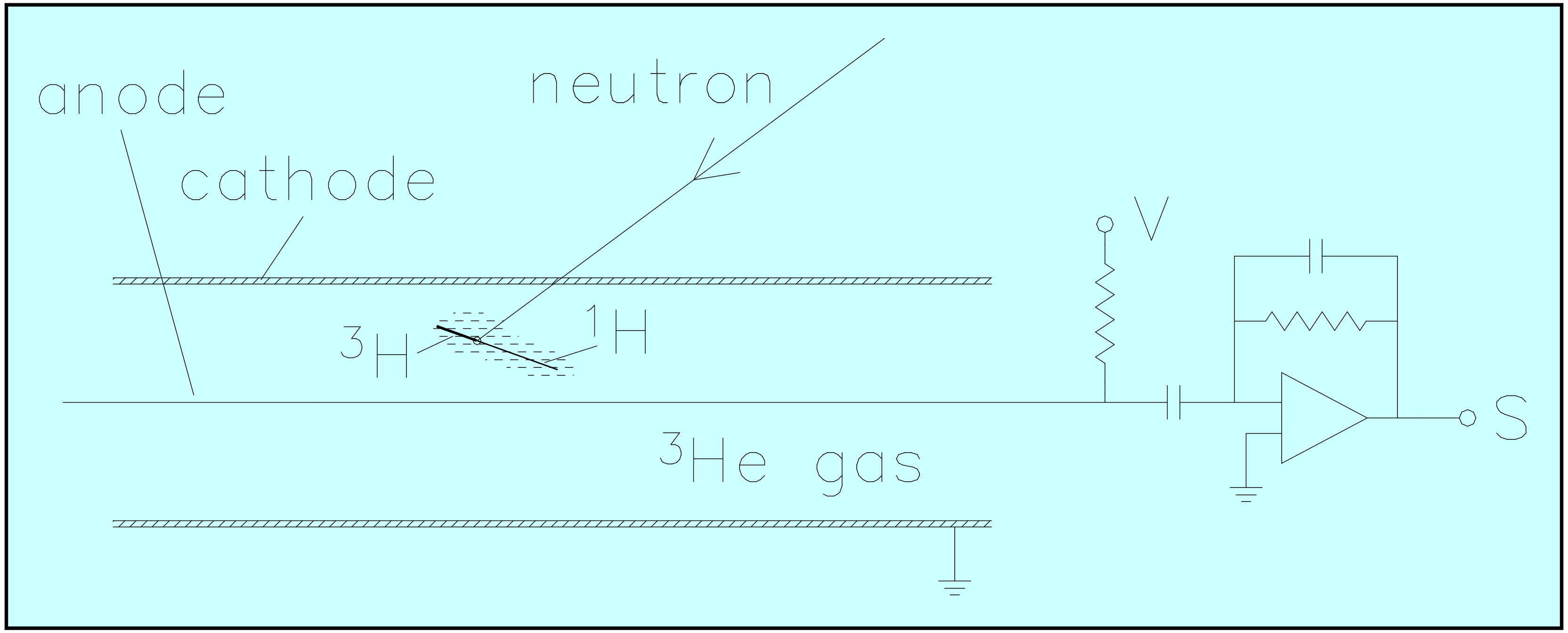
	density of ^{6}Li atoms [10^{22} cm^{-3}]	scintillation efficiency [in %]	photon wavelength [nm]	photons per neutron
Lithium glass (Ce)	1.75	0.45	395	7000
LiI(Eu)	1.83	2.8	470	51 000
ZnS(Ag)-LiF	1.18	9.2	450	160 000



Detection of Neutrons

gas detectors: standard Geiger counter with ^{3}He or BF$_3$ gas

e.g. Helium: $n + {}^3\text{He} \rightarrow {}^3\text{H} + {}^1\text{H} + 0.76\ \text{MeV}$
(about 25 000 ionizations produced per neutron, charge ≈ 4 fC)



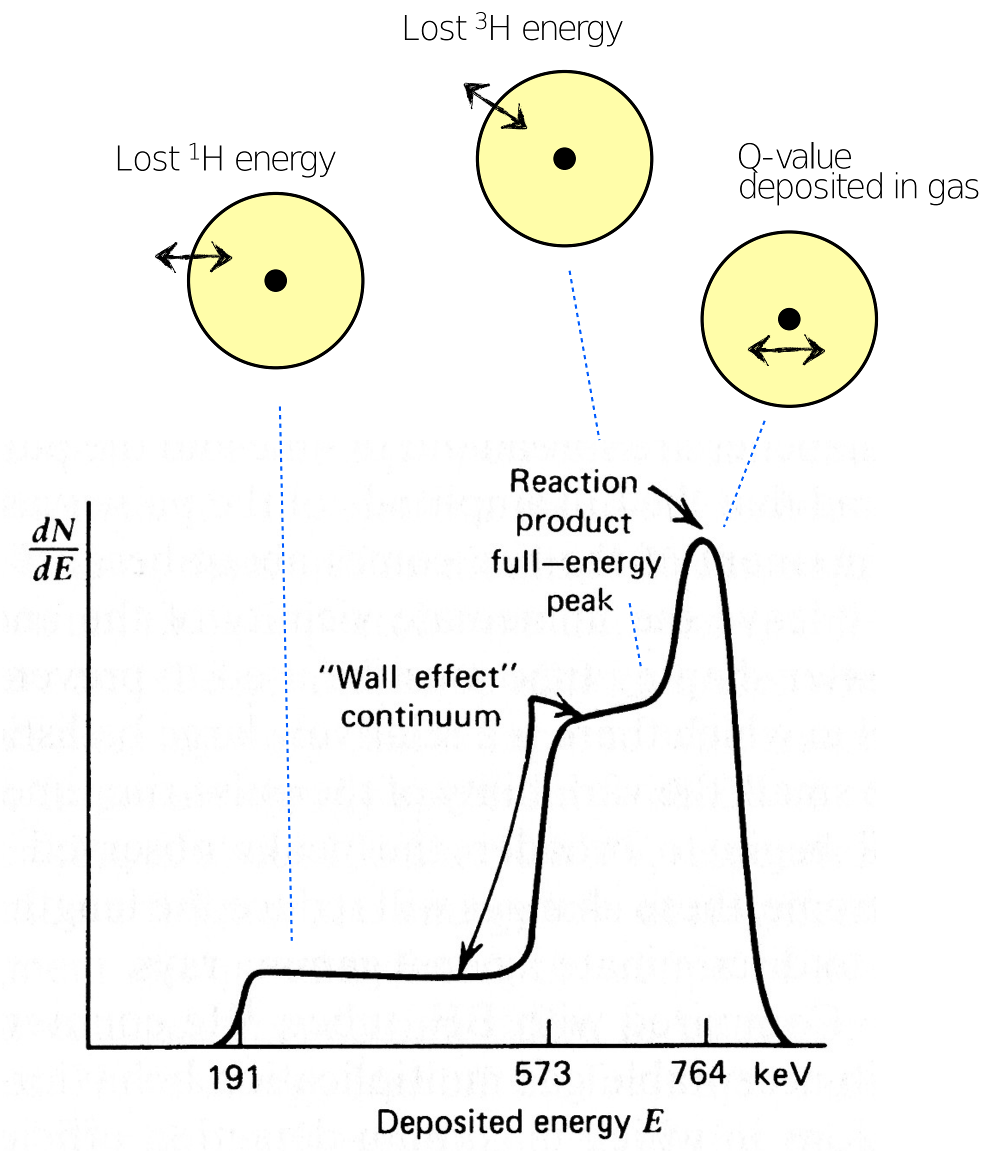
Detection of Neutrons

wall effect:
n + ^{3}He $\rightarrow$ ^{3}H + ^{1}H + 0.76 MeV

from mass ratio
E_p = 573 keV (p = ^{1}H)
E_t = 191 keV (t = ^{3}H)

ranges:
Si: $R_p \approx 6\mu$m, $R_t \approx 5\mu$m
gas: few mm ($\sim 1000 \times R_{\rm solid}$)

remark: energy spectrum reflects detector response, not neutron energy



Detection of Neutrons

Fast Neutrons

detection relies on observing neutron-induced nuclear reactions

capture cross sections for fast-neutron induced reactions are small compared to those at low energies; remember: $\sigma_{\text{cap}} \propto 1/v$

two approaches to detect fast neutrons:

- thermalize/moderate & capture as before, only providing count rates (i.e. neutron flux)
- elastic scattering from protons at high energy
  - protons are easy to detect in conventional detectors
  - observe recoils for time-of-flight (ToF), enables neutron energy measurements by measuring the velocity

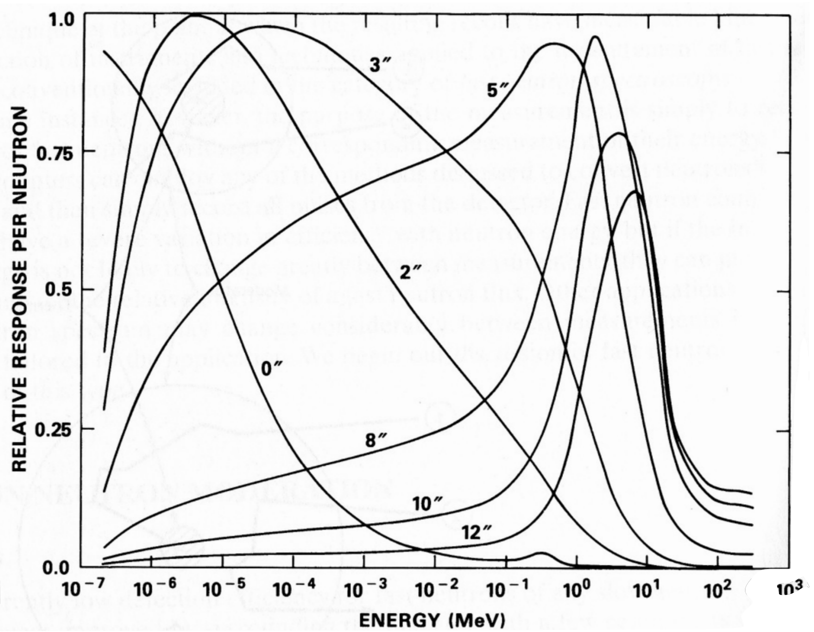
Detection of Neutrons

Neutron Moderation

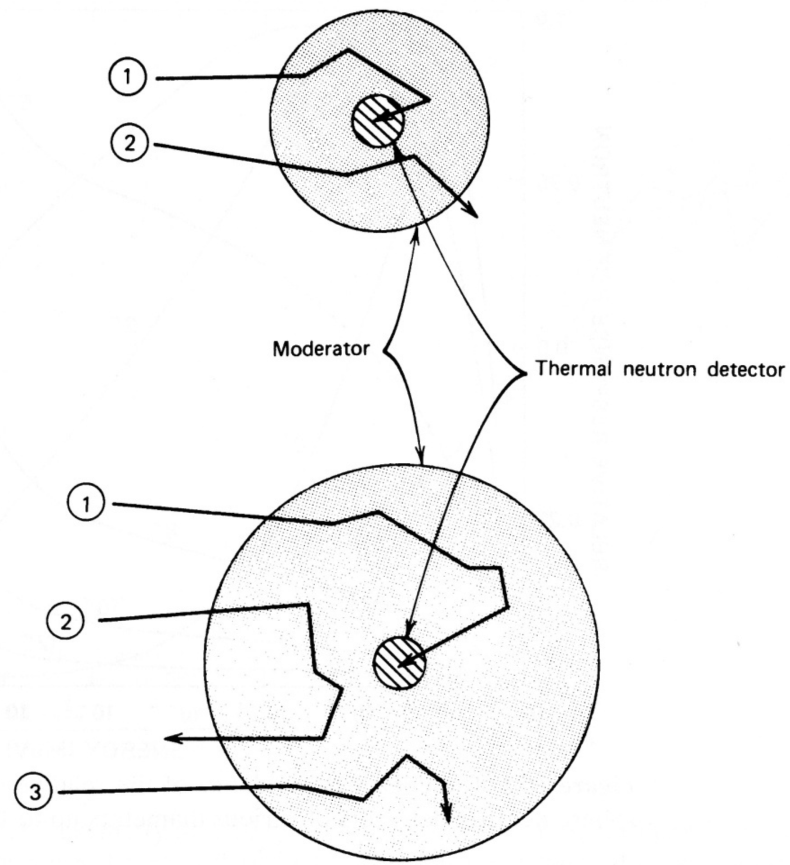
- moderate neutrons to increase efficiency in conventional slow-neutron detector
- hydrogen-rich materials: polyethylene or paraffin

optimum thickness between few cm to tens of cm for energies of keV to MeV

trade-off between sufficient slow down and detection cross section



Relative response vs. energy for various absorber thicknesses (in inch)



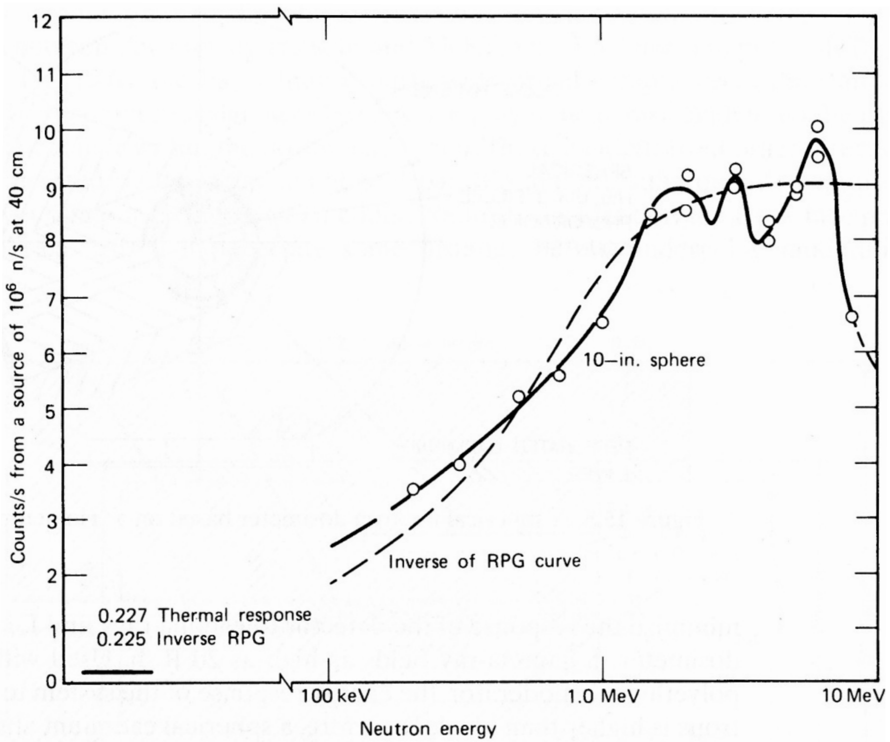
Detection of Neutrons

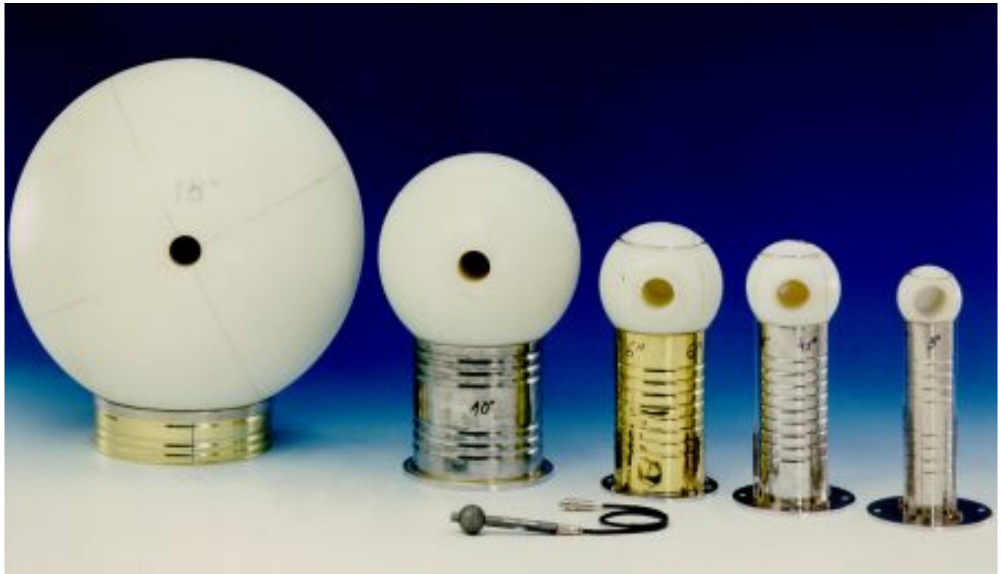
The Bonner Sphere

10-12" diameter moderator sphere has a similar response curve as the
neutron dose spectrum in tissue
e.g. with LiI(Eu) scintillator in center

application:

determination of dose equivalent due to neutrons with an unknown or variable neutron spectrum over a large range of neutron energies





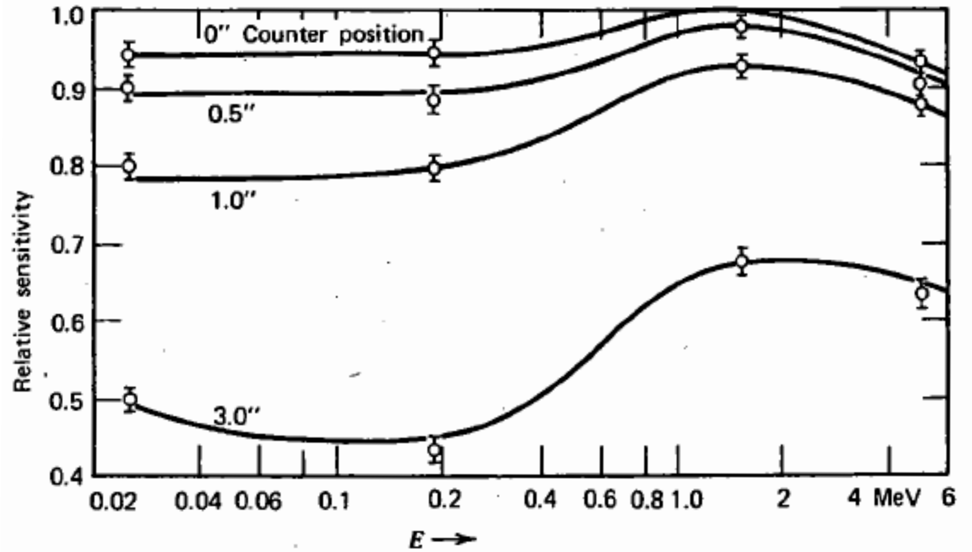
Detection of Neutrons

The Long Counter

neutron energy independent efficiency:
'flat response'

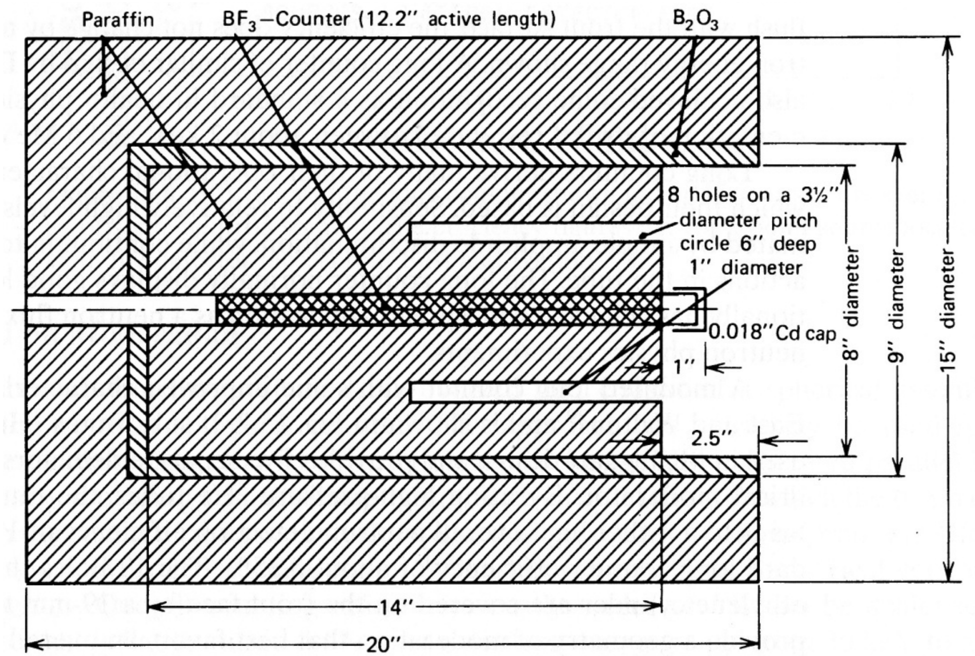
slow-neutron BF_3 detector in center of device
paraffin moderator, B_2O_3 absorber (shielding)

only sensitive to neutrons from one side



relative sensitivity of long counter

varied parameter is the distance of the end of the BF_3 tube if shifted in from the front of the moderator face



cross Section of Long counter

holes prevent efficiency reduction for neutrons with energies below 1 MeV

Detection of Neutrons

detector type	size	neutron active material	incident neutron energy	neutron detection efficiency[a] (%)	γ-ray sensitivity (R/h)[b]
plastic scintillator	5 cm thick	^{1}H	1 MeV	78	0.01
liquid scintillator	5 cm thick	^{1}H	1 MeV	78	0.1
loaded scintillator	1 mm thick	^{6}Li	thermal	50	1
Hornyak button	1 mm thick	^{1}H	1 MeV	1	1
CH_4 (7 bar)	5 cm Ø	^{1}H	1 MeV	1	1
^{4}He (18 bar)	5 cm Ø	^{4}He	1 MeV	1	1
^{3}He (4 bar), Ar (2 bar)	2.5 cm Ø	^{3}He	thermal	77	1
^{3}He (4 bar)m CO_2 (5%)	2.5 cm Ø	^{3}He	thermal	77	10
BF_3 (0.66 bar)	5 cm Ø	^{10}B	thermal	29	10
BF_3 (1.18 bar)	5 cm Ø	^{10}B	thermal	46	10
^{10}B-lined chamber	0.2 mg/cm^3	^{10}B	thermal	10	10^3
fission chamber	1.0 mg/cm^3	^{235}U	thermal	0.5	$10^6 - 10^7$

[a] interaction probability for neutrons of the specified energy, normal incidence angle
[b] approximate upper limit of γ-ray dose that can be present with the detector still providing usable neutron output signals

Detection of Neutrons

Cascade Detector

capture process:

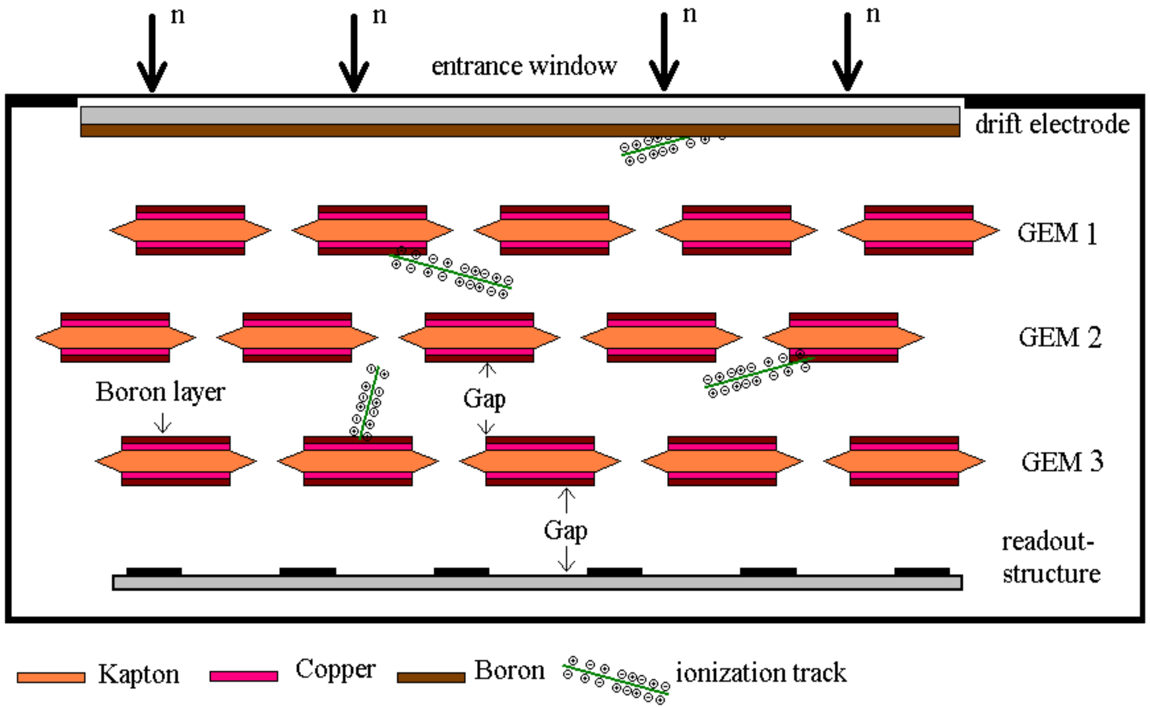
$$
\begin{aligned}
n + {}^{10}B &\rightarrow {}^{7}Li^{*} + {}^{4}He + 2.31\ \text{MeV} + 0.48\ \text{MeV} \quad (93\%) \\
&\rightarrow {}^{7}Li + {}^{4}He + 2.78\ \text{MeV} \quad (7\%)
\end{aligned}
$$

Setup:

Boron layers on multiple GEM foils

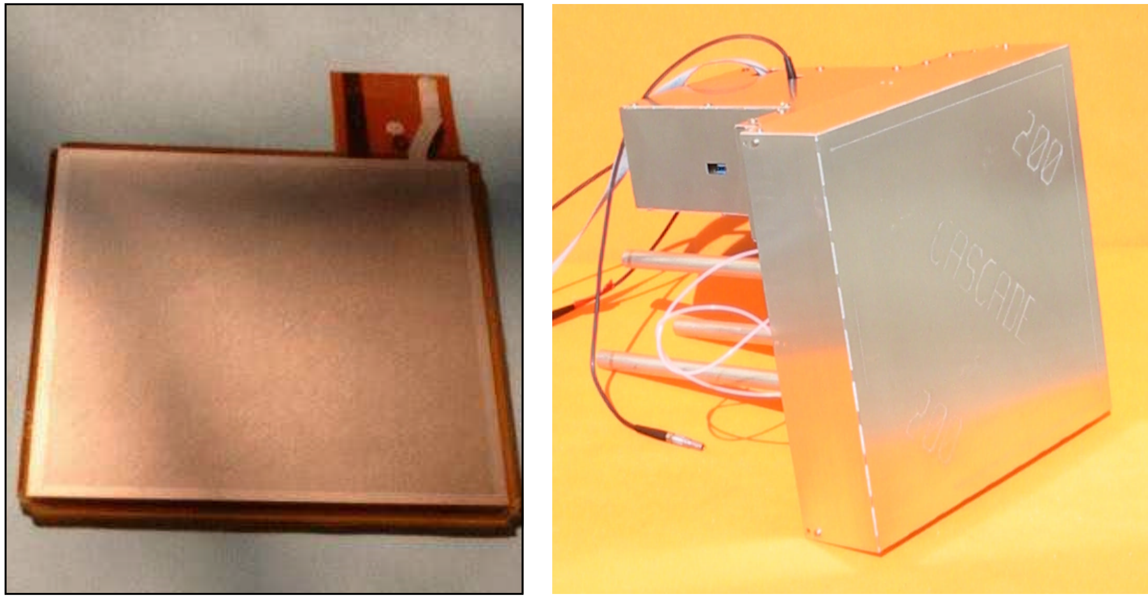
GEMs:

- operated to be transparent for produced charges
- can be cascaded
- two Boron layers each
- last one: amplification layer
- high rate capability [10^7 Hz/cm^2]

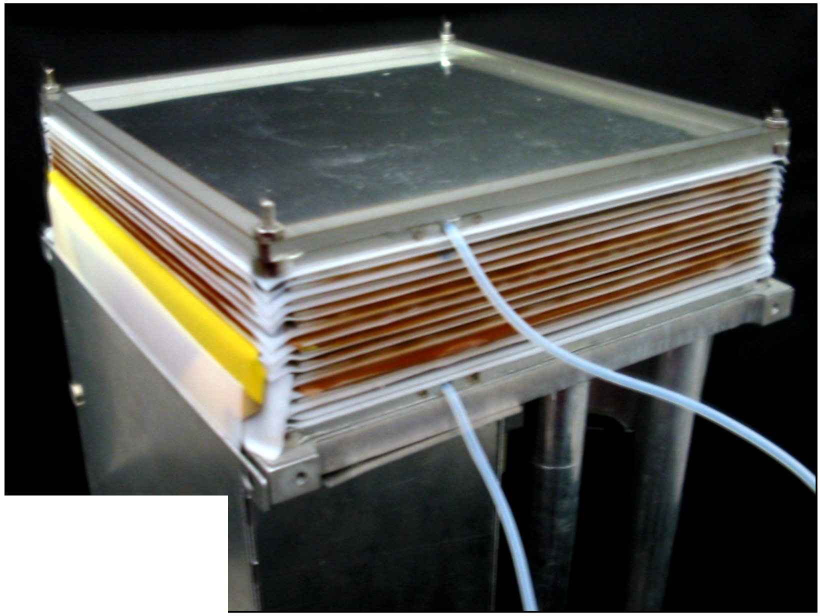


CASCADE neutron detector schematic

Detection of Neutrons
CASCADE Detector



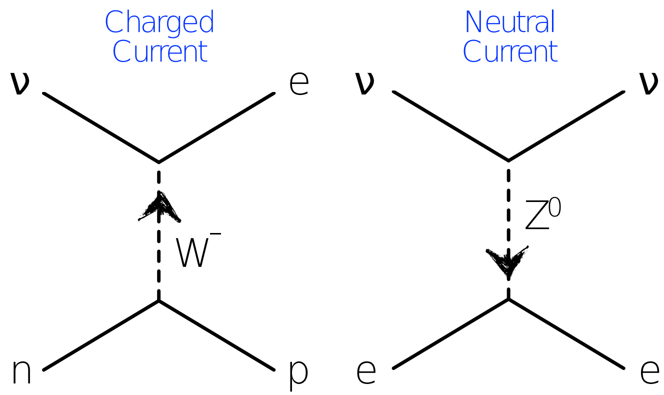
GEM foil glued to frame, complete CASCADE module



Cascade neutron detector: several GEM-modules stacked with drift electrodes and readout

10.3 Detection of Neutrinos

neutrino detection only via weak interaction



possible reactions:

charged current reactions:

$$
\begin{aligned}
\nu_e &+ \text{n} \rightarrow \text{e}^- + \text{p}\\
\nu_e &+ \text{p} \rightarrow \text{e}^+ + \text{n}\\
\nu_\mu &+ \text{n} \rightarrow \mu^- + \text{p}\\
\nu_\mu &+ \text{p} \rightarrow \mu^+ + \text{n}\\
\nu_\tau &+ \text{n} \rightarrow \tau^- + \text{p}\\
\nu_\tau &+ \text{p} \rightarrow \tau^+ + \text{n}
\end{aligned}
$$

...

$$
\begin{aligned}
\bar{\nu}_e &+ \text{e}^- \rightarrow \mu^- + \bar{\nu}_\mu\\
\bar{\nu}_e &+ \text{e}^- \rightarrow \tau^- + \bar{\nu}_\tau
\end{aligned}
$$

neutral current reactions:

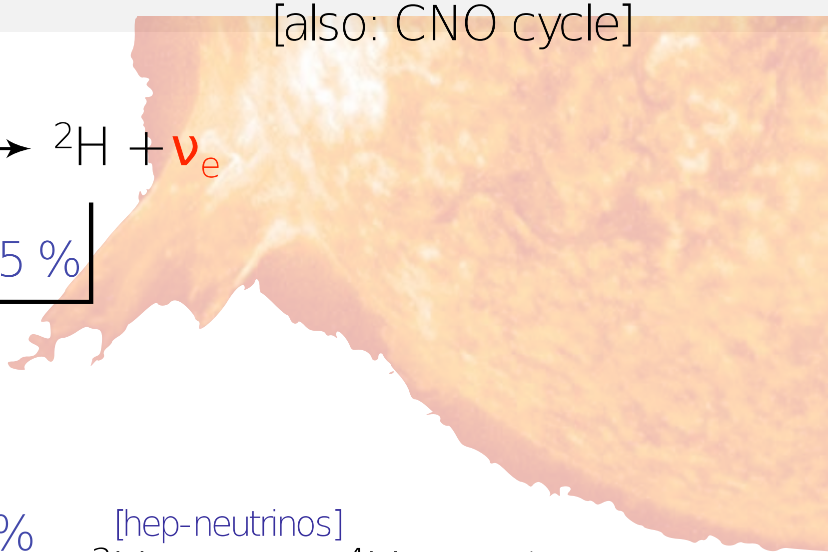
$$
\begin{aligned}
\nu_e &+ \text{e}^- \rightarrow \nu_e + \text{e}^-\\
\nu_\mu &+ \text{e}^- \rightarrow \nu_\mu + \text{e}^-\\
\nu_\tau &+ \text{e}^- \rightarrow \nu_\tau + \text{e}^-
\end{aligned}
$$

neutrino-nucleon cross section, examples:
10 GeV neutrinos: $\sigma = 7 \cdot 10^{-38}$ cm^2/nucleon
10 m Fe-target:
interaction probability $R = \sigma N_{\mathrm{A}} d\rho = 3.2 \cdot 10^{-10}$
with $d = 10$ m, $\rho = 7.6$ g/cm^3

solar neutrinos [100 keV]: $\sigma = 7 \cdot 10^{-45}$ cm^2/nucleon
interaction probability for earth: $R = \sigma N_{\mathrm{A}} d\rho \approx 4 \cdot 10^{-14}$
$d = 12000$ km, $\rho = 5.5$ g/cm^3

Neutrinos from the Sun (pp chain)

[also: CNO cycle]



[pp-neutrinos]
$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ (99.75 %)

[pep-neutrinos]
$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$ (0.25 %)

$^{2}H + p \rightarrow {}^{3}He + \gamma$

85%: $^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

~15%: $^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

~10^{-5} %: [hep-neutrinos]
$^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

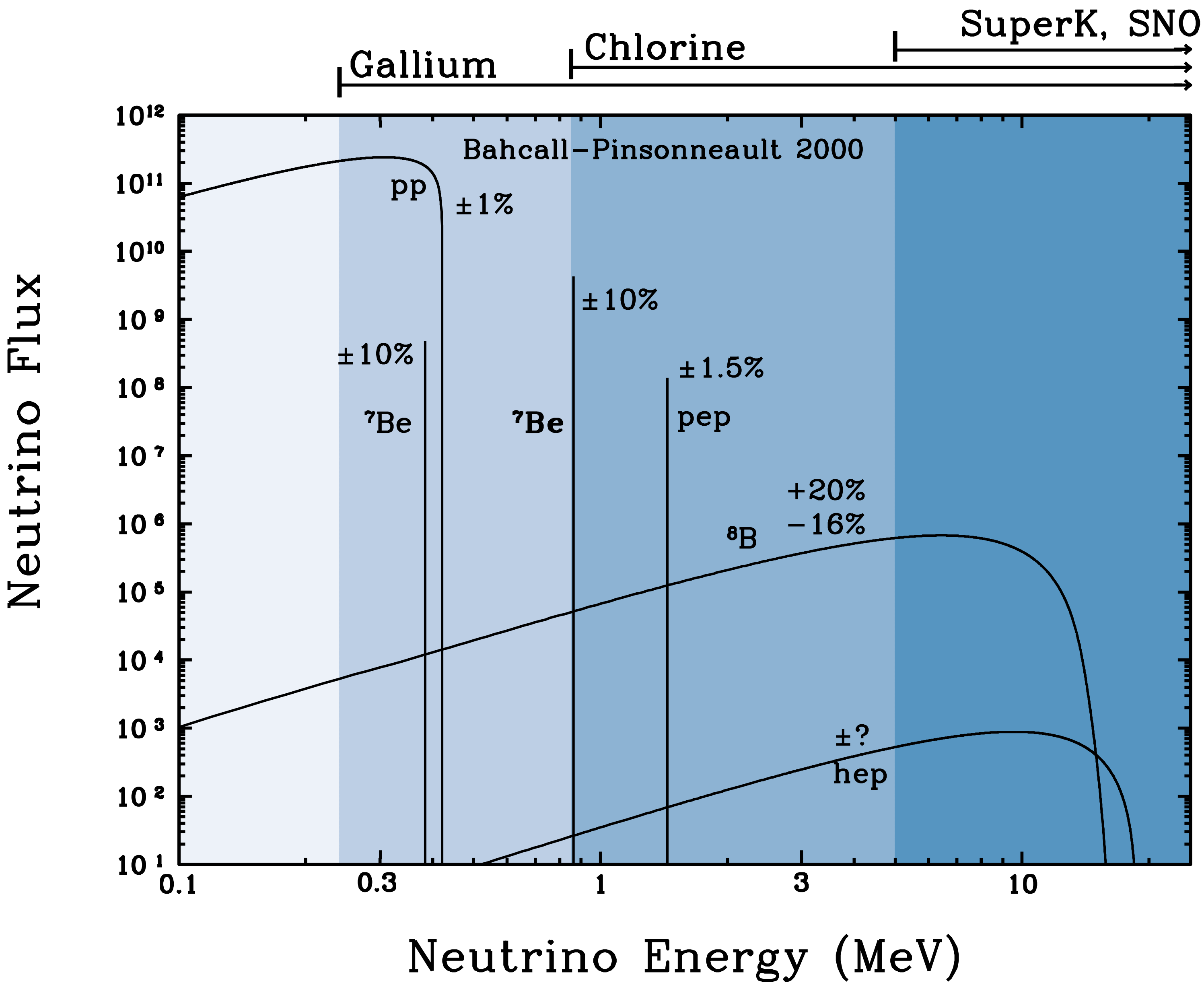
15.07 %: $^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$
[^{7}Be-neutrinos]

$^{7}Li + p \rightarrow \alpha + \alpha$

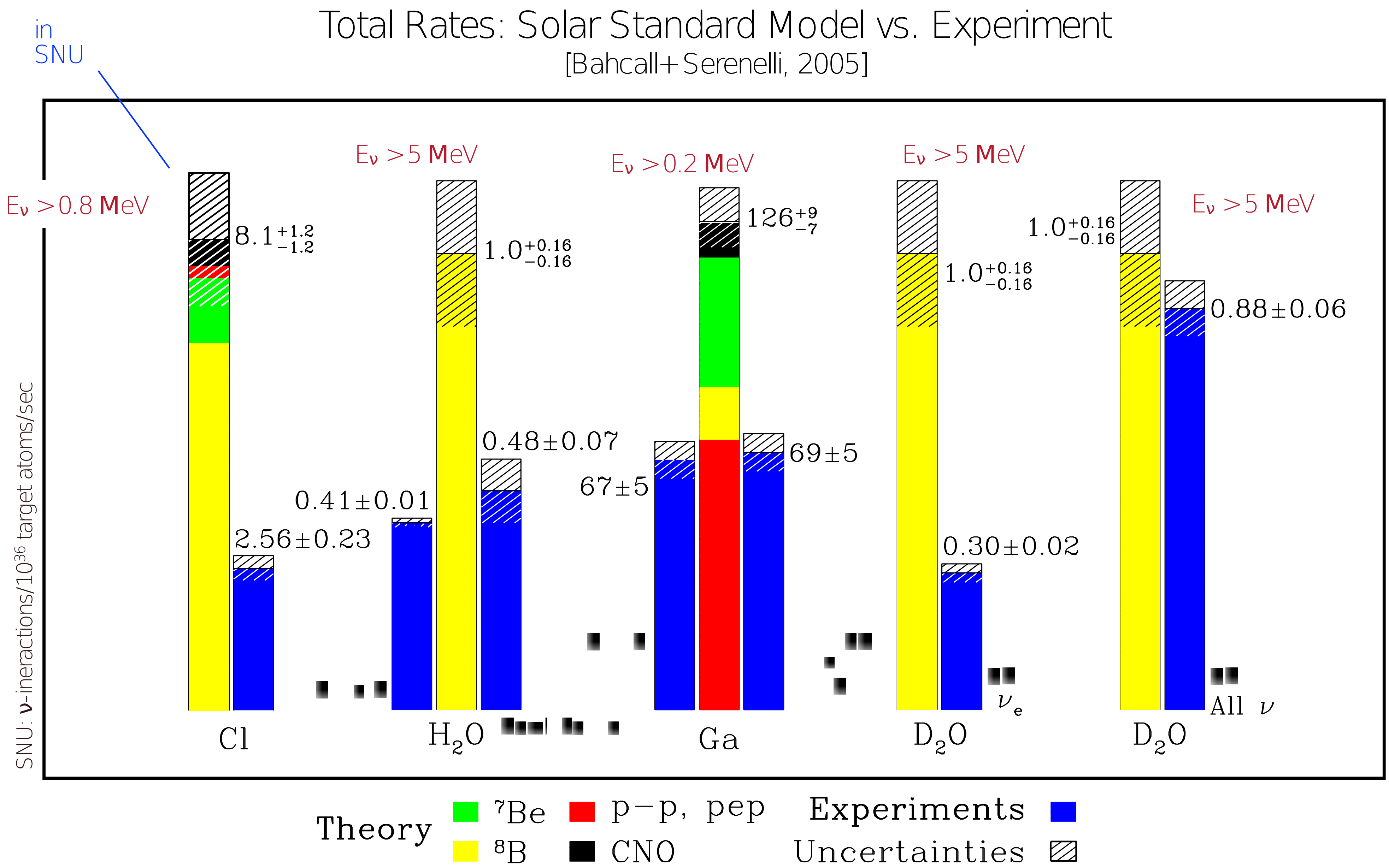
0.02 %: $^{7}Be + p \rightarrow {}^{8}B + \gamma$

$^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$
[^{8}B-neutrinos]

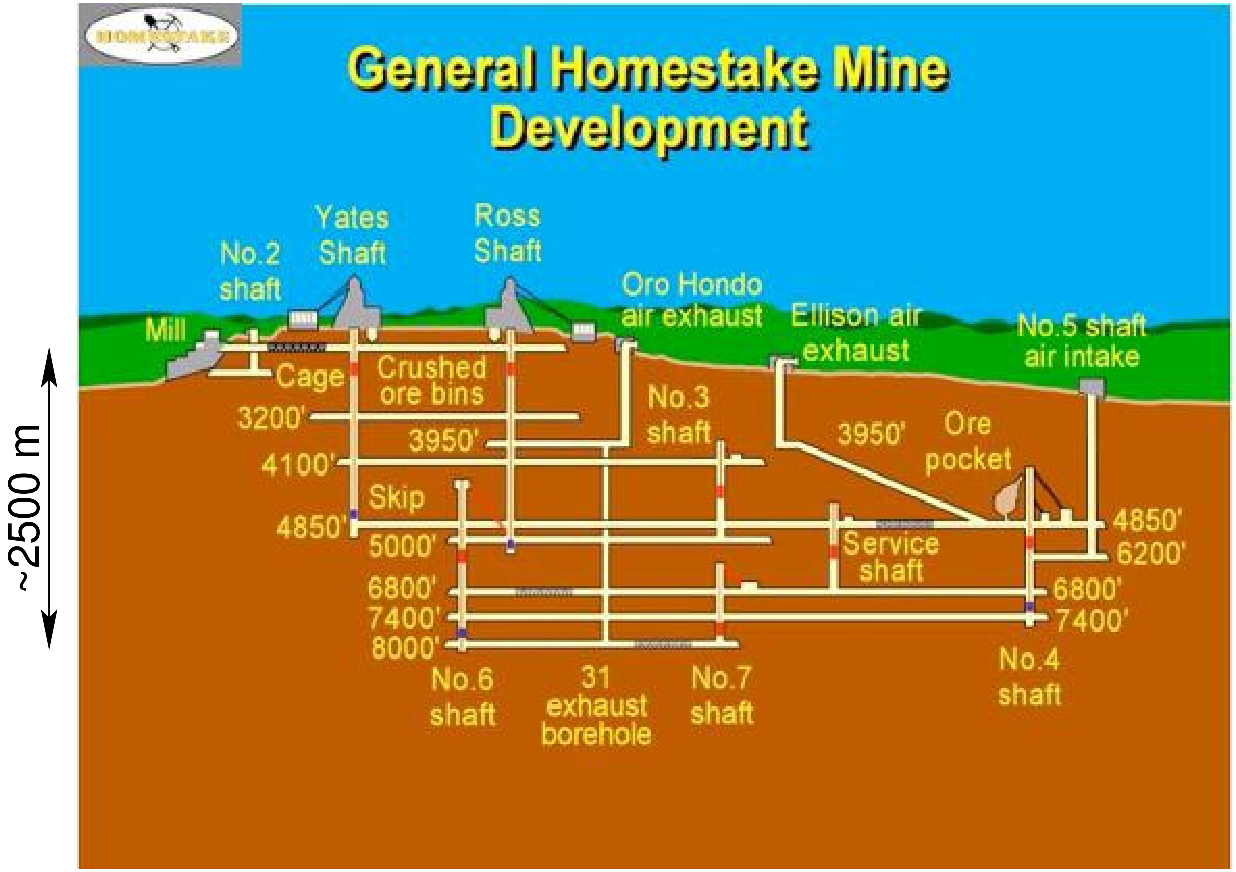
Neutrinos from the Sun



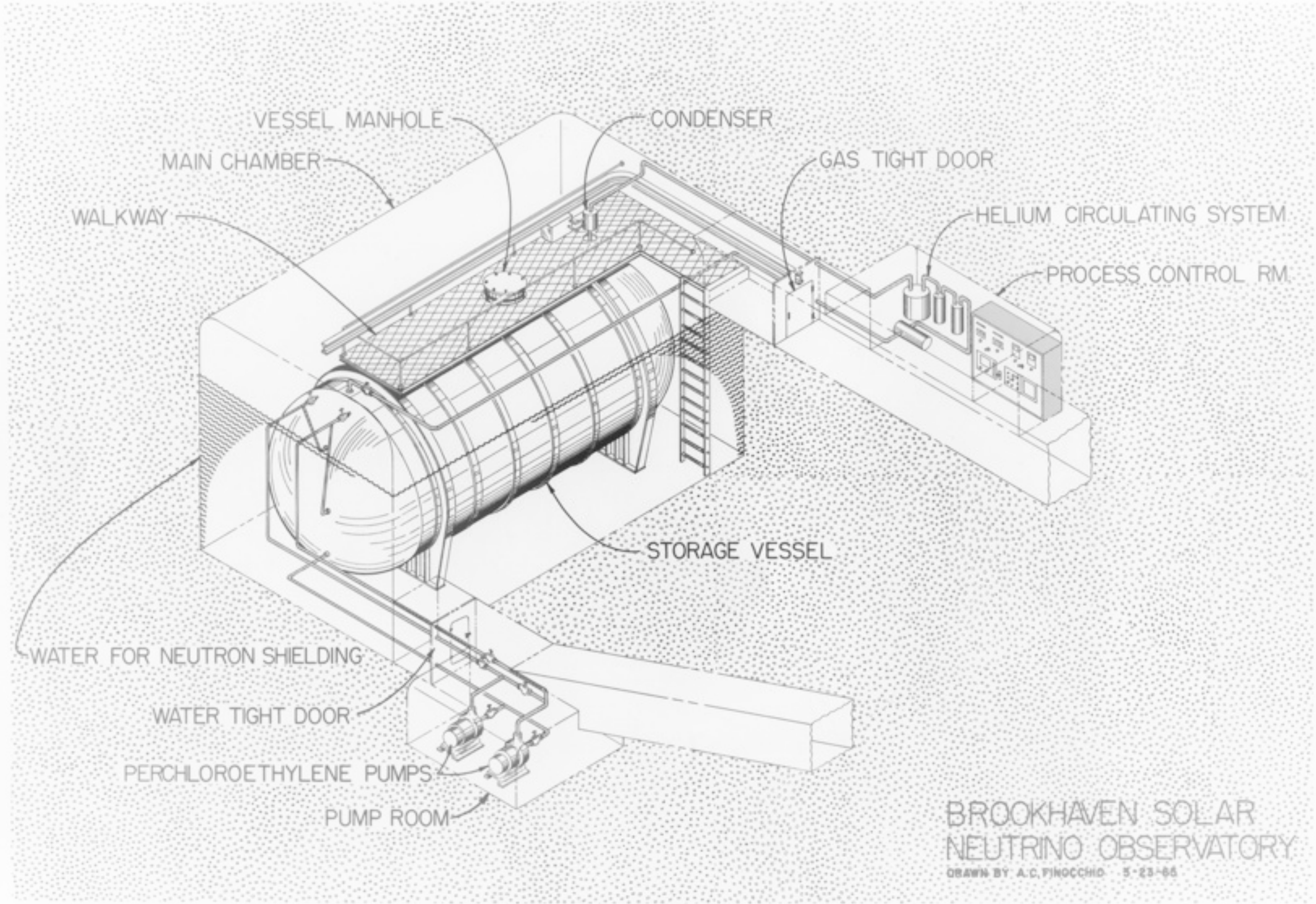
Solar Electron-Neutrino Problem



The Homestake Experiment: the Homestake Mine

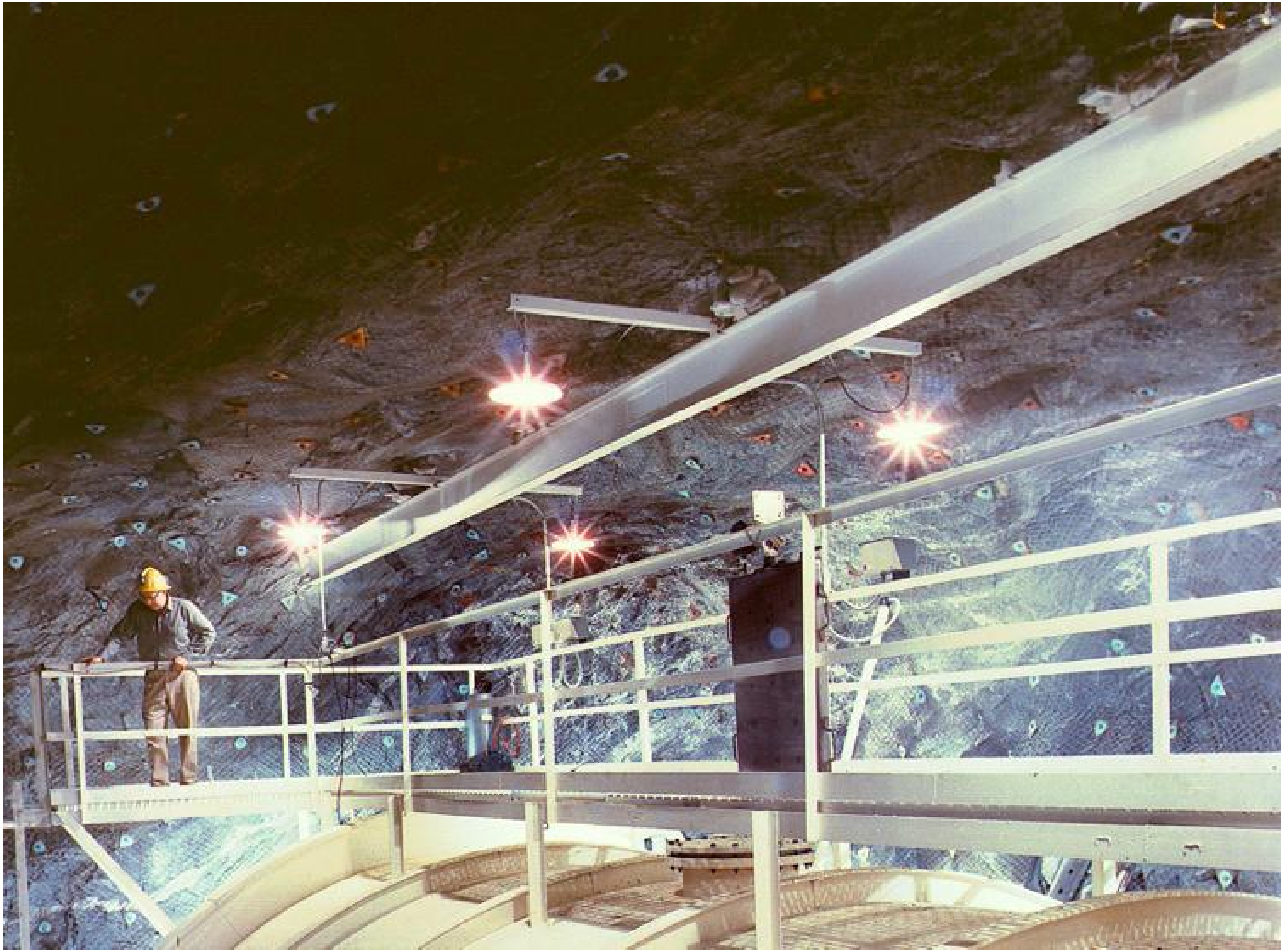


The Homestake Experiment

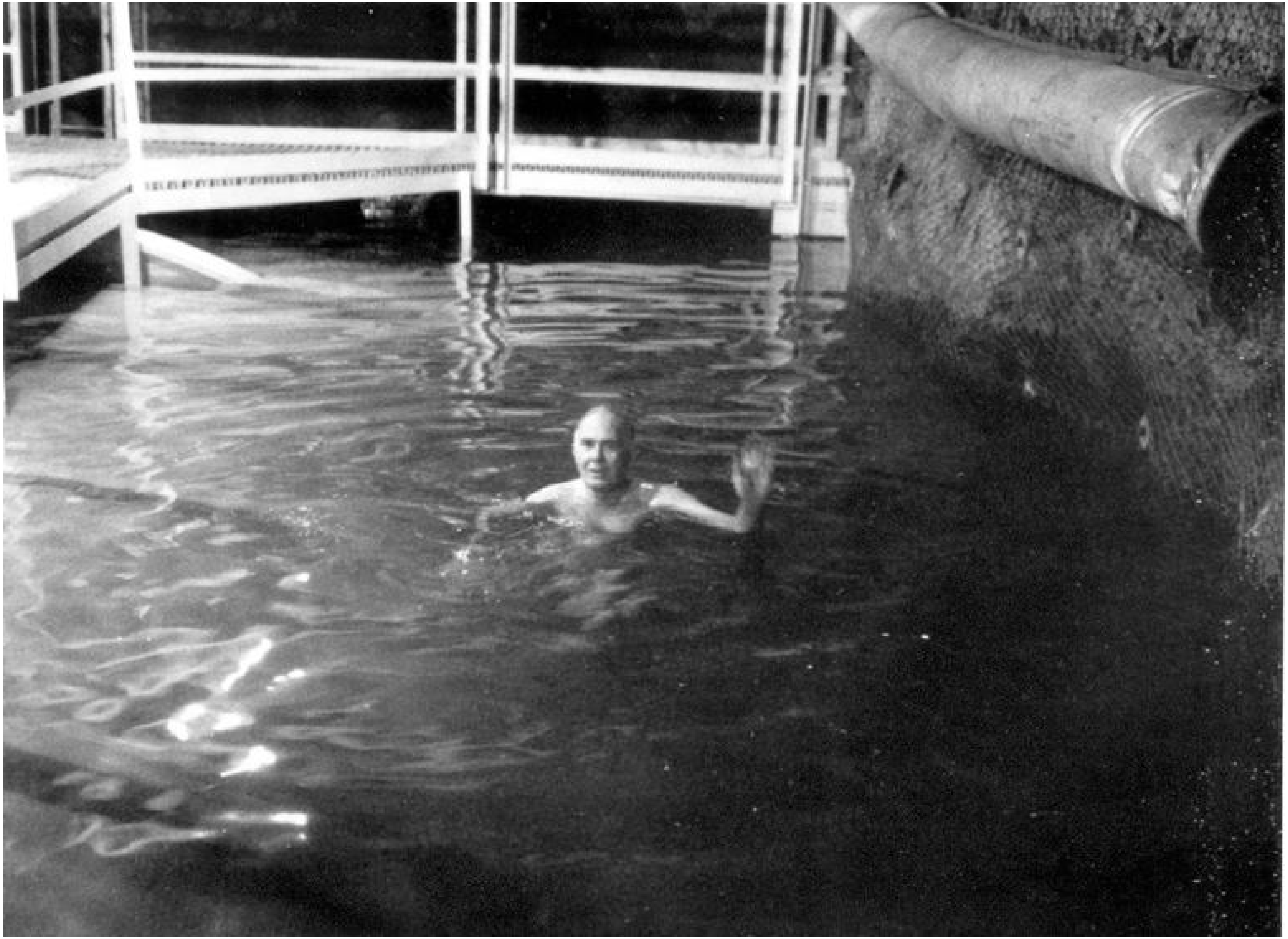


The Homestake Experiment

The Homestake Experiment



The Homestake Experiment



The Homestake Experiment

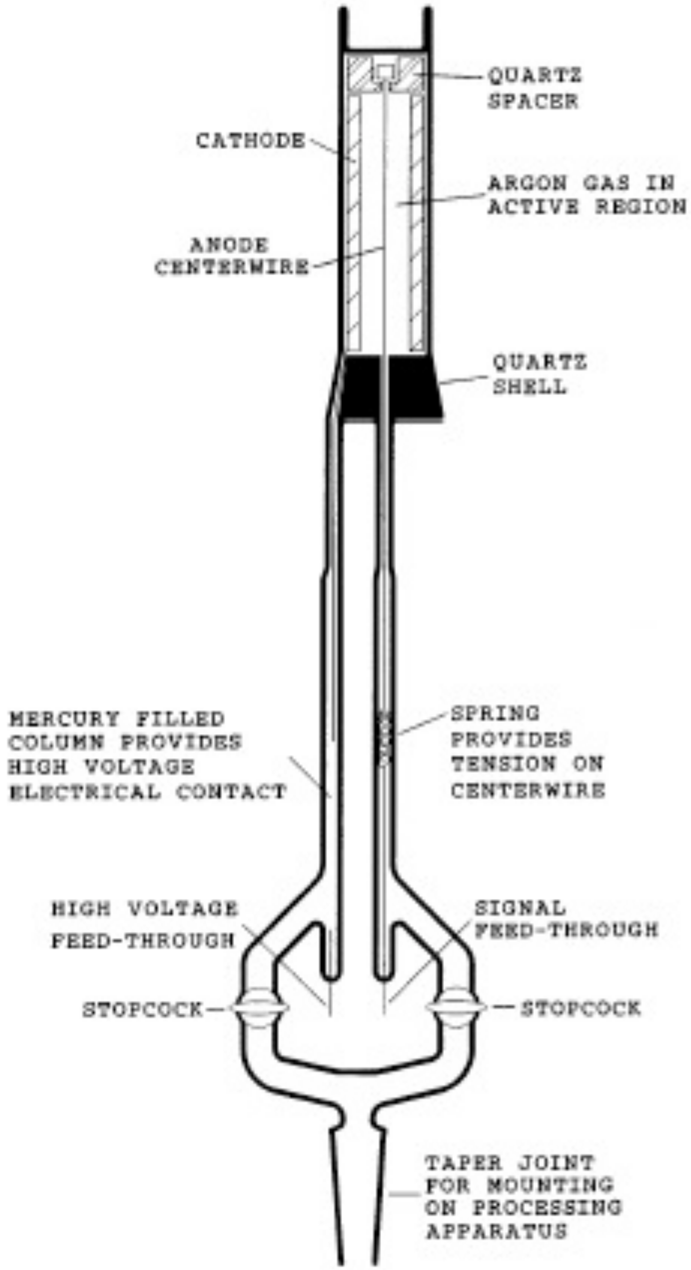
neutrino capture:

^{37}Cl $+ \nu_e \rightarrow ^{37}$Ar $+$ e

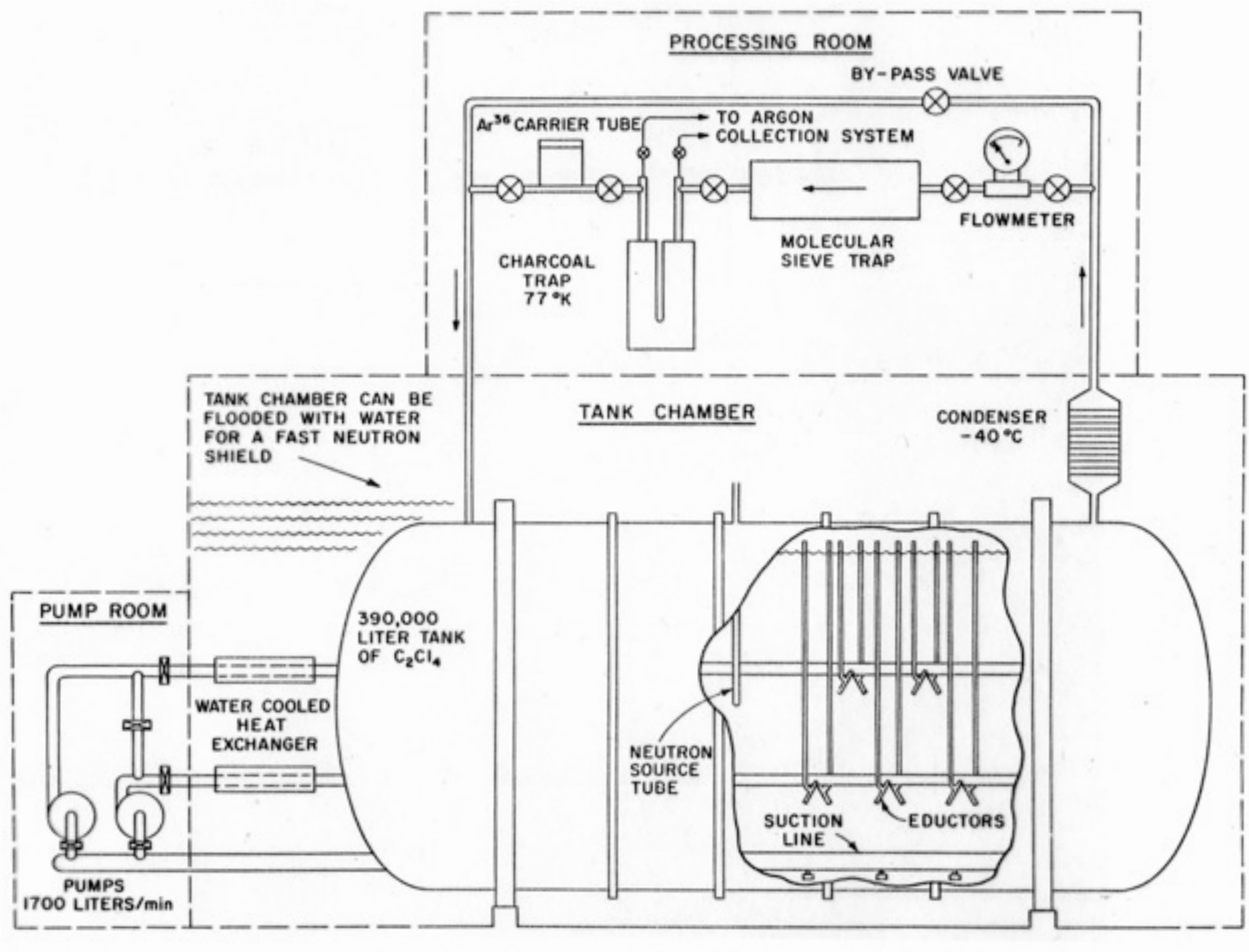
detection of ^{37}Ar via e$^-$-capture

[^{37}Ar(e,ν_{e})^{37}Cl] $\tau \approx 35$ d

results in 2.82 keV Auger electron
detection after extraction in proportional counter



The Homestake Experiment



The Homestake Experiment

some very approximate numbers

- 615 tons C_2Cl_4 (tetrachlor-ethylene)
- about $5 \cdot 10^{29}$ chlorine atoms (^{37}Cl)
- prediction: $8 \cdot 10^{-36}$ neutrino reactions/atom/s
  i.e.: about 60 ^{37}Ar atoms/month
  but: half-life = 35 days $\rightarrow$ 30 atoms/m
- expect: 60 atoms every 2 month out of ca. 1030 tetrachlor-ethylene molecules
- After 25 years: expectation: $\approx$ 5000 ^{37}Ar atoms expected
  observation: $\approx$ 2200 ^{37}Ar atoms produced

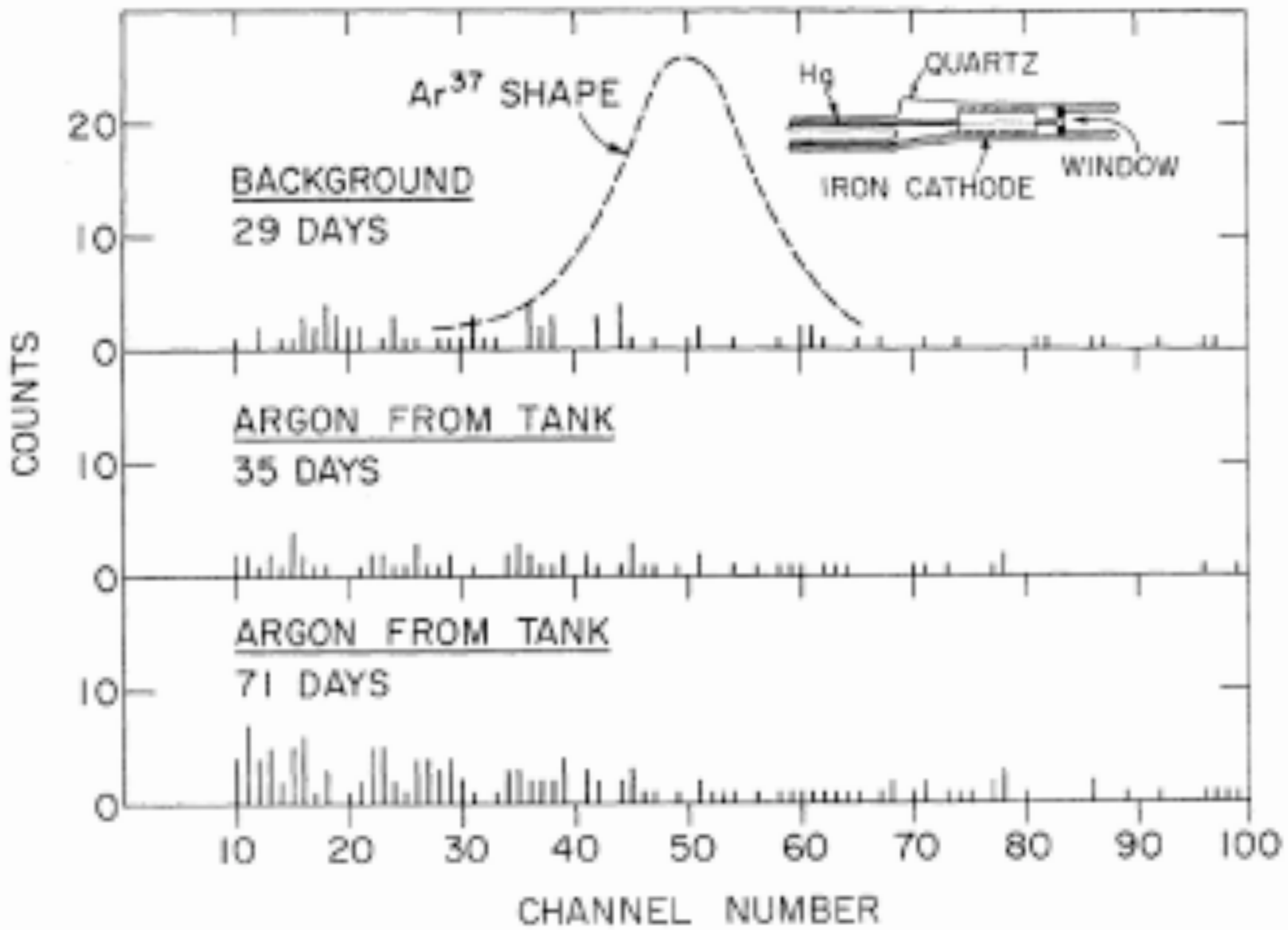
  [875 counted, 776 after background subtraction]

  ^{37}Ar extraction efficiency: $\approx$ 95%
  ^{37}Ar detection efficiency: $\approx$ 45%

The Homestake Experiment

Pulse height Spectra from first runs [1968]

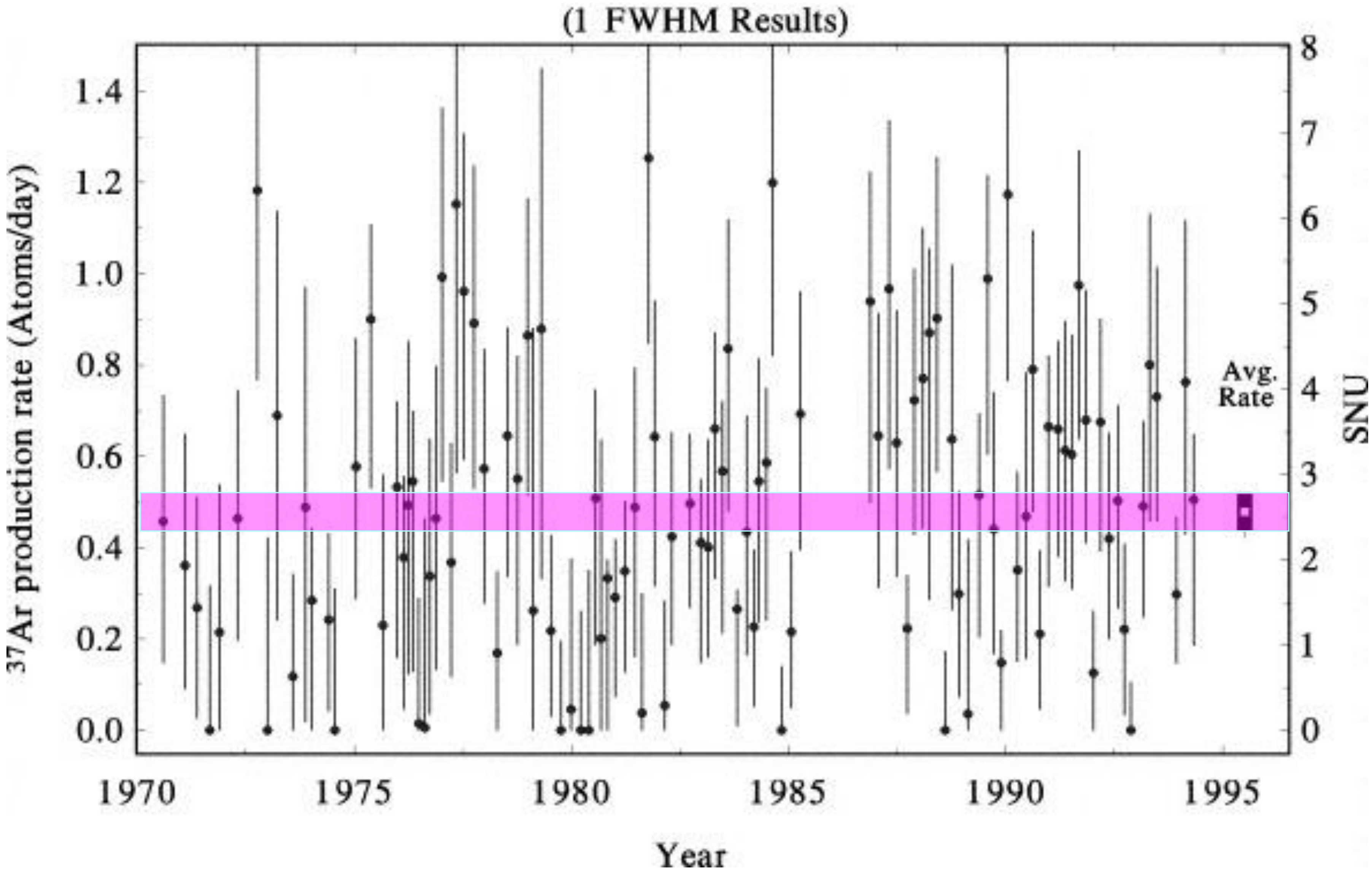
2.82 keV



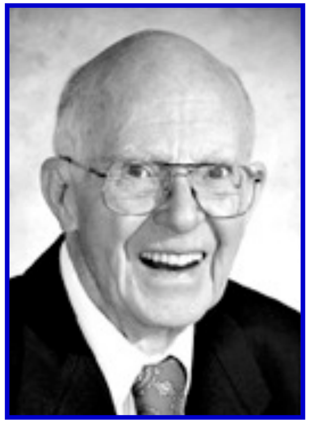
The Homestake Experiment

Result of 25 years of running

(after implementation of rise time counting)



Nobel Prize 2002

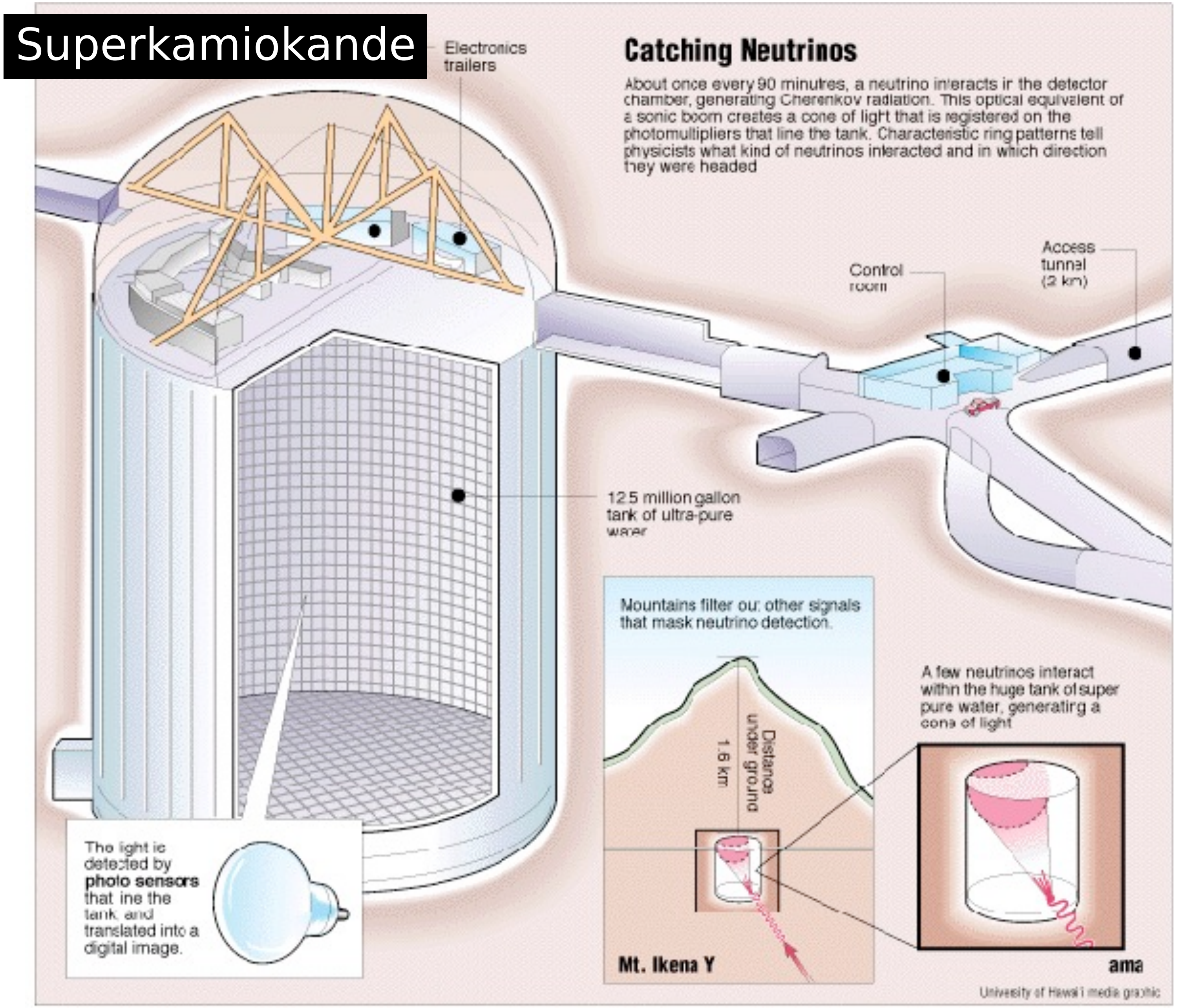


Raymond Davis Jr.
[Homestake]

Masatoshi Koshiba
[Kamiokande]

Riccardo Giacconi
[X-Ray Sources]

Super-Kamiokande



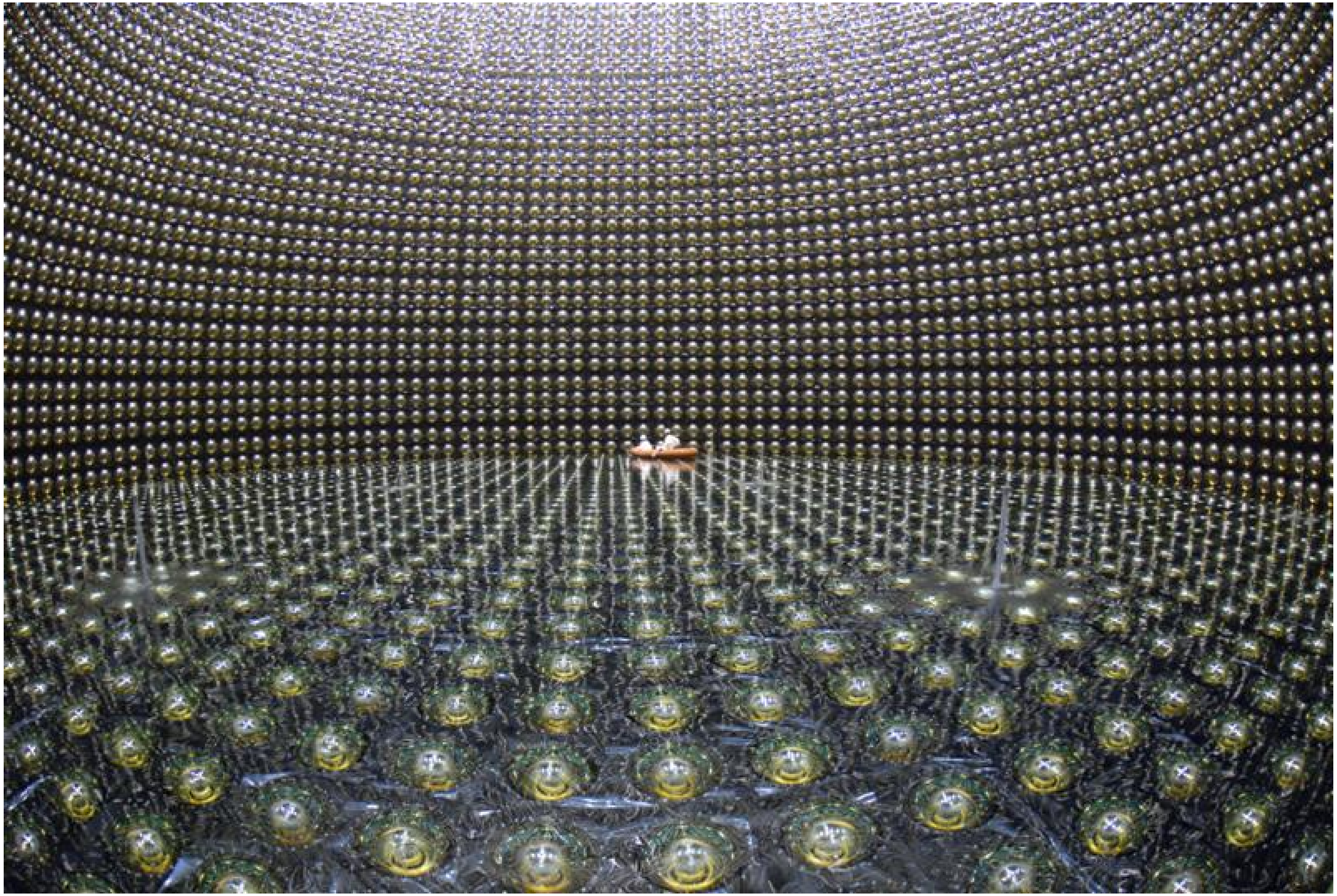
water tank
1.6 km below ground

50 million liter
ultra-pure water

1 neutrino interaction
every 1.5 hours

neutrino detection
via Cherenkov light

Super-Kamiokande



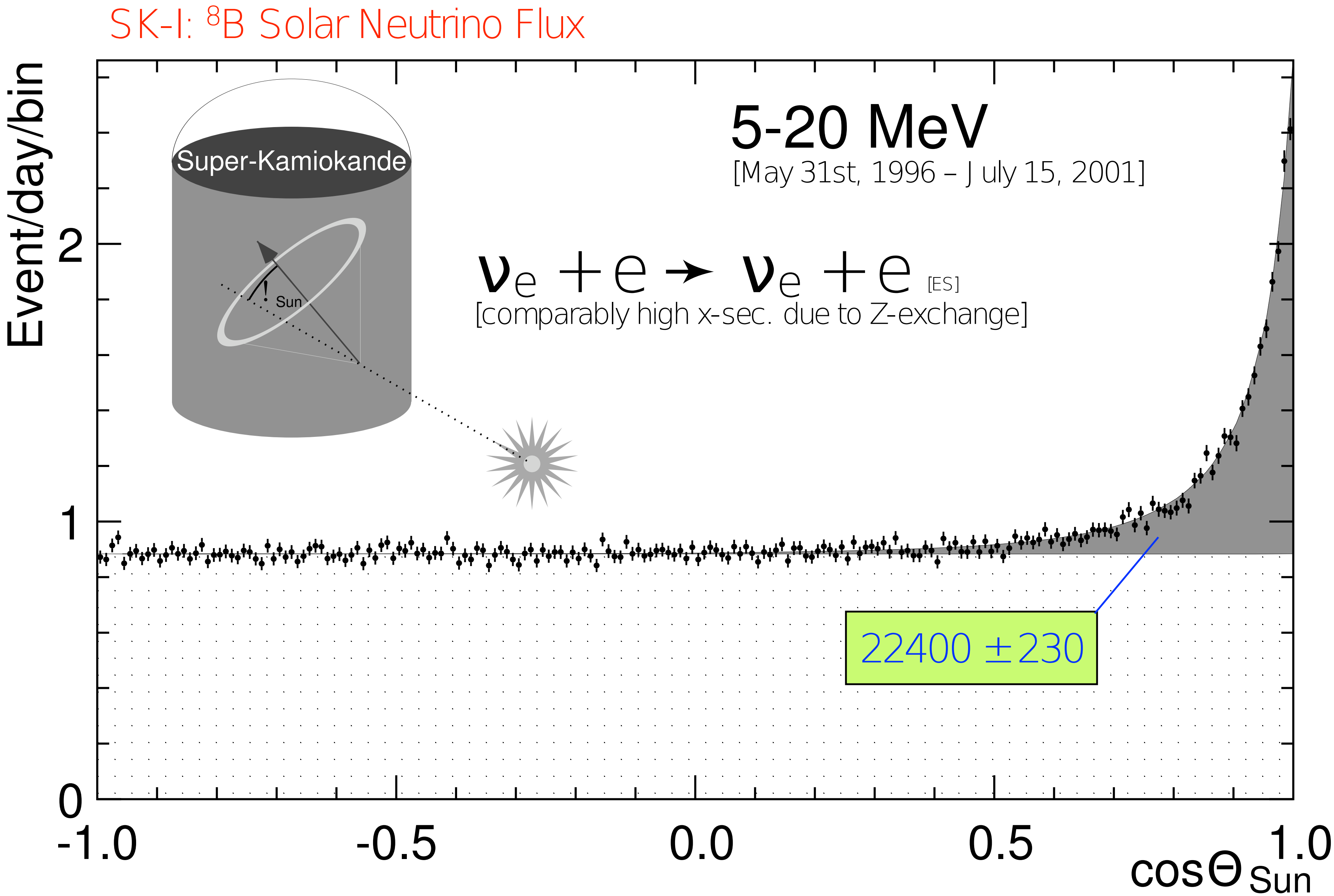
Super-Kamiokande

Mounting of Photomultiplier Tubes

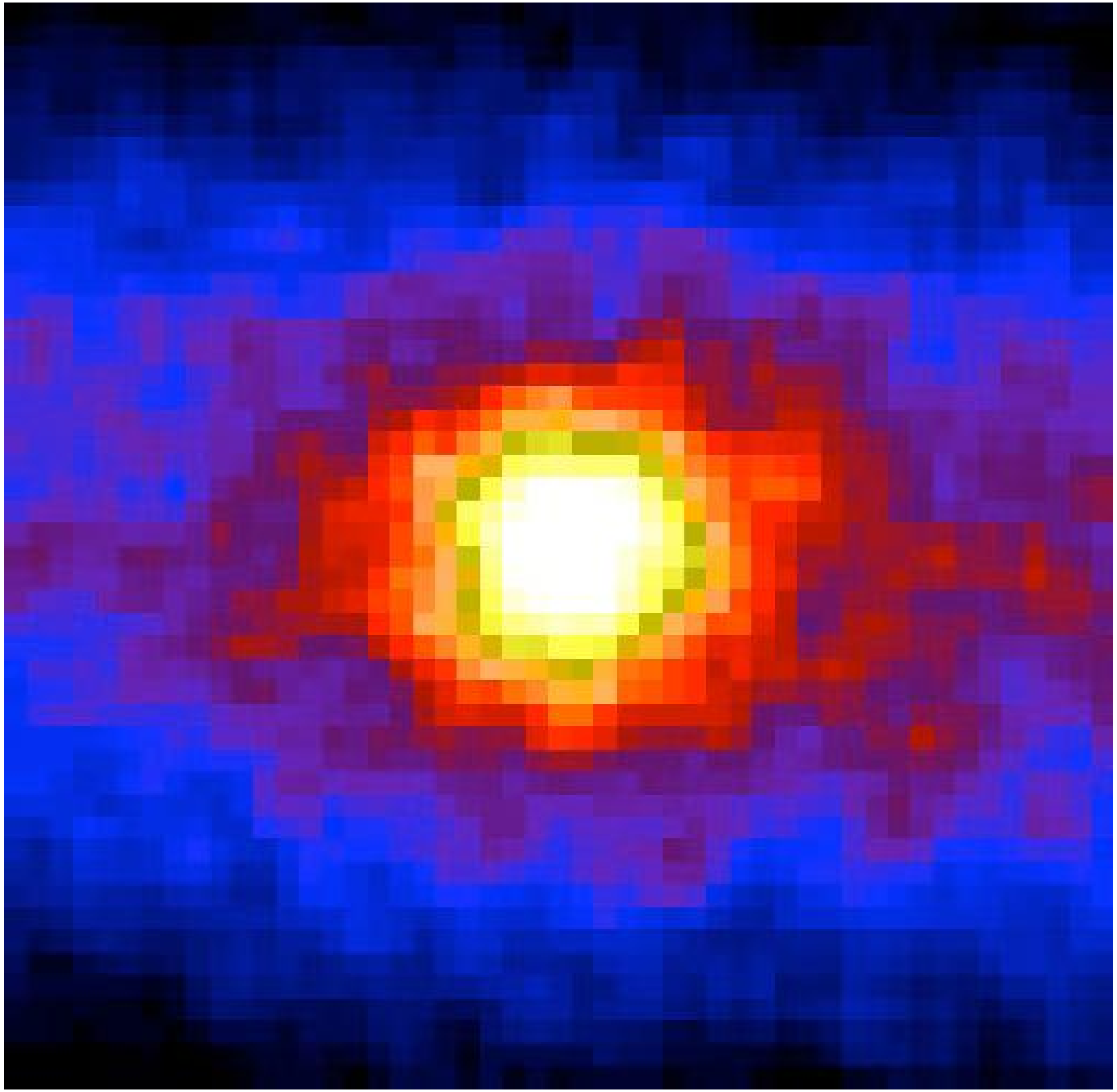
total number of photomultipliers:

20 inch Ø	11,146
8 inch Ø	1,885

Super-Kamiokande

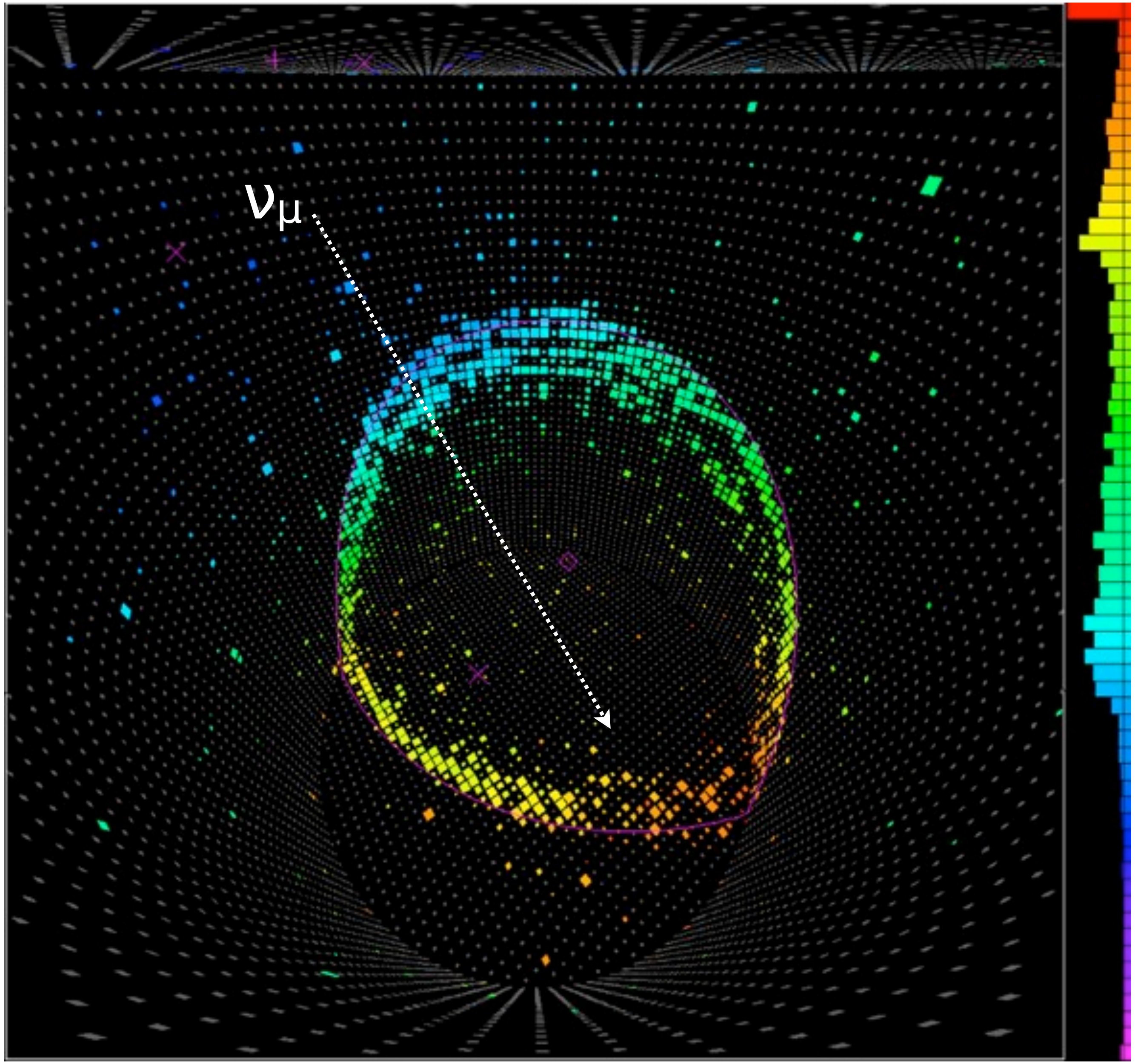


Super-Kamiokande



the sun seen through the earth in neutrino light

Super-Kamiokande



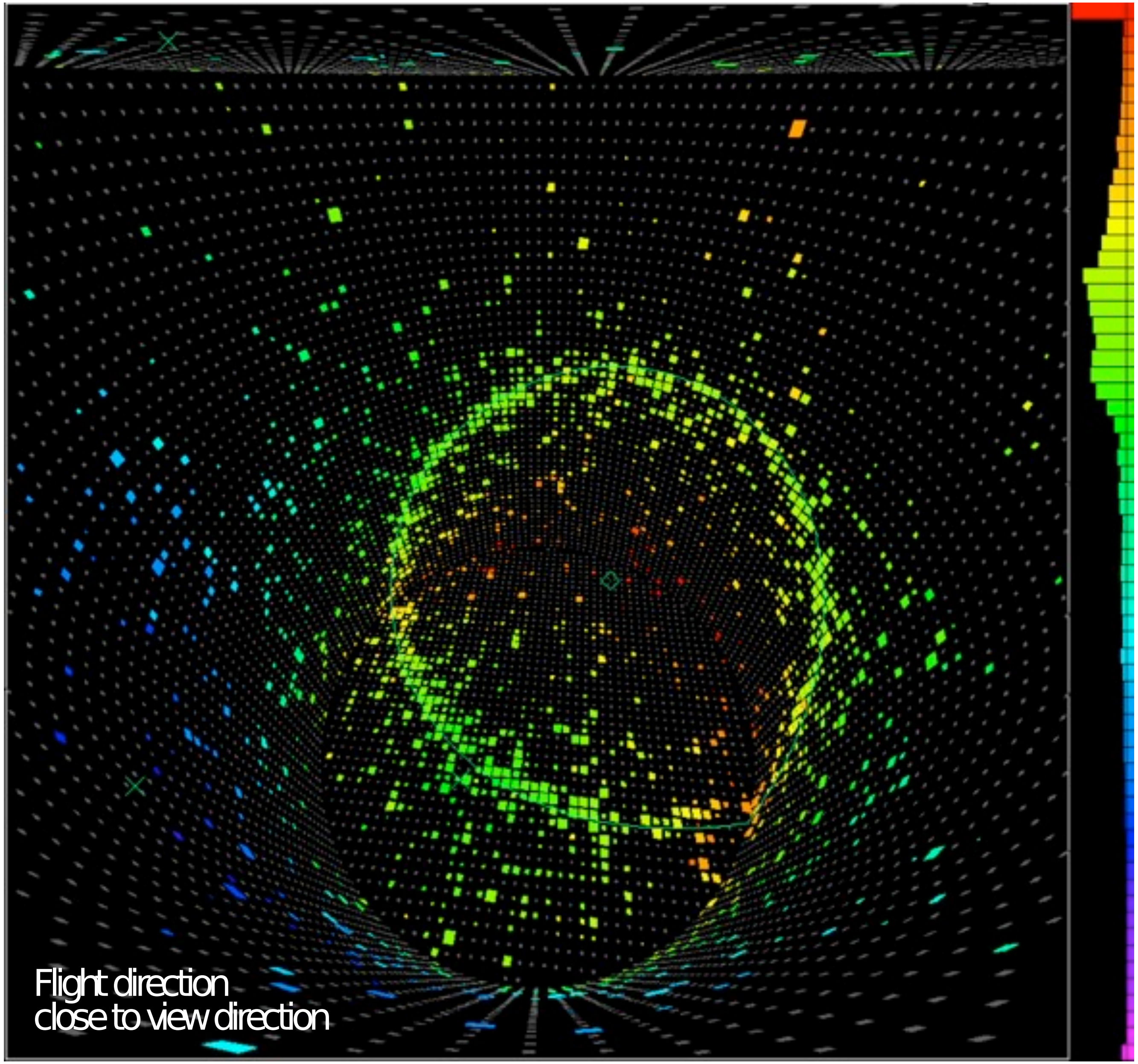
muon event (603 MeV)

observation of clean Cherenkov ring with sharp edges

flight direction from timing measurements
blue: early, red: late

energy from amount of light observed in PMs

Super-Kamiokande



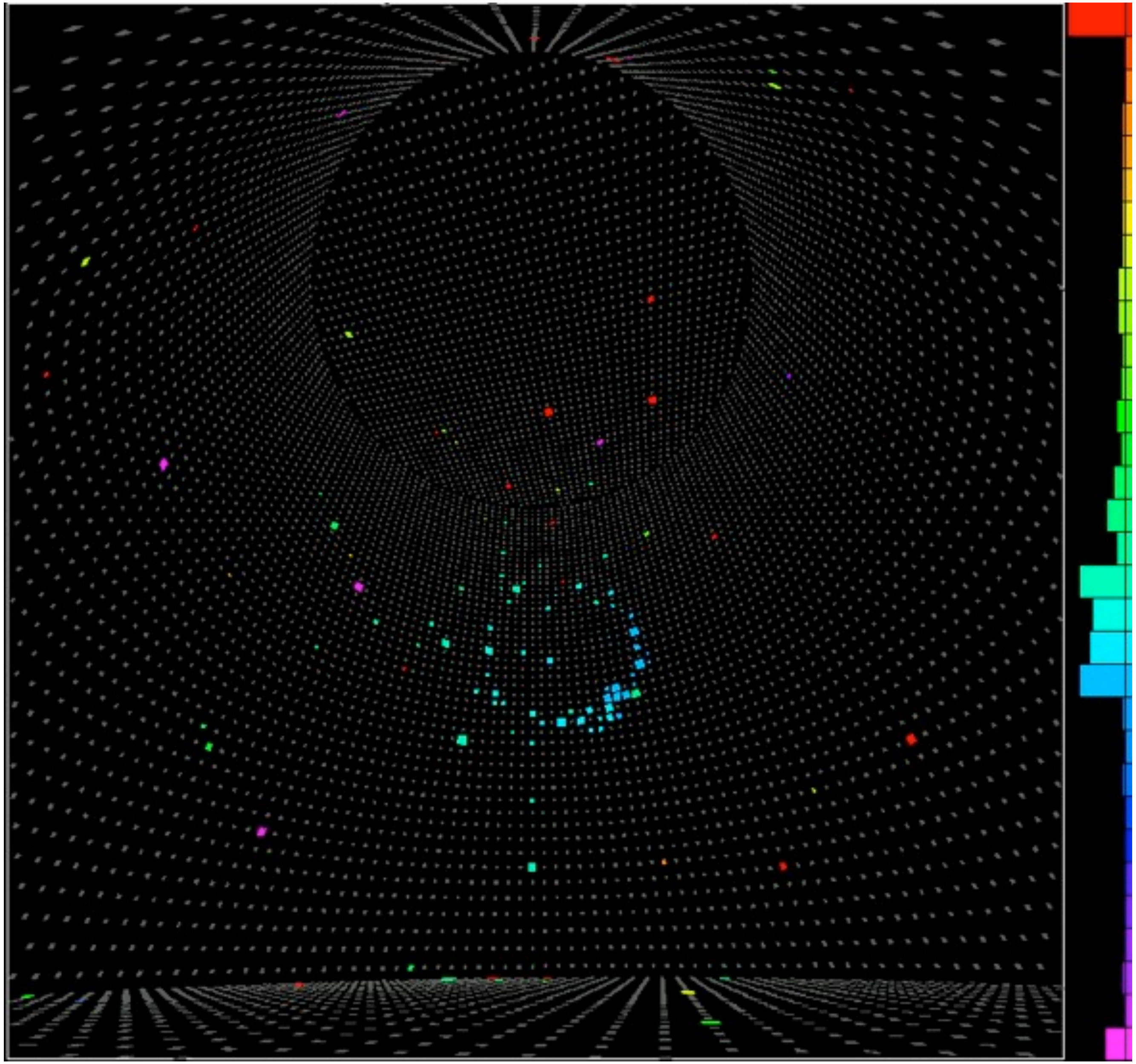
electron event (492 MeV)

observation of Cherenkov ring with fuzzy edge (from e.m. shower)

flight direction from timing measurements
blue: early; red: late

energy from amount of light observed in PMs

Super-Kamiokande



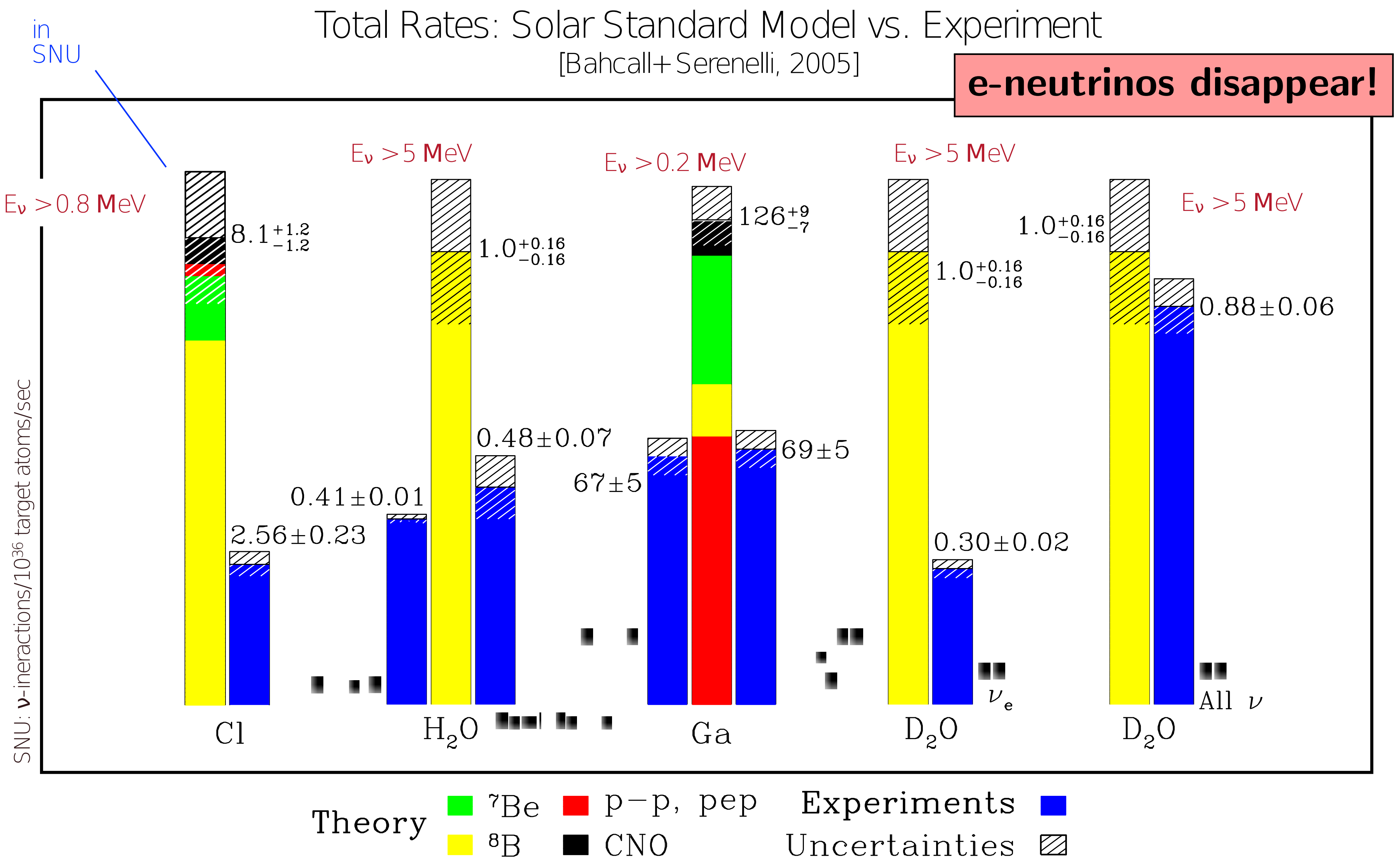
solar neutrino (12.5 MeV)

unusually nice, well-defined

flight direction from timing measurements
blue: early; red: late

energy from amount of light observed in PMs

Solar Electron-Neutrino Problem



Other Solar Neutrino Experiments

- ^{37}Cl $\rightarrow ^{37}$Ar (Homestake)

  Exp: 2.6 SNU
  BS05: 8.1 SNU

- ^{37}Ga $\rightarrow ^{37}$Ge (Gallex, GNO, Sage)

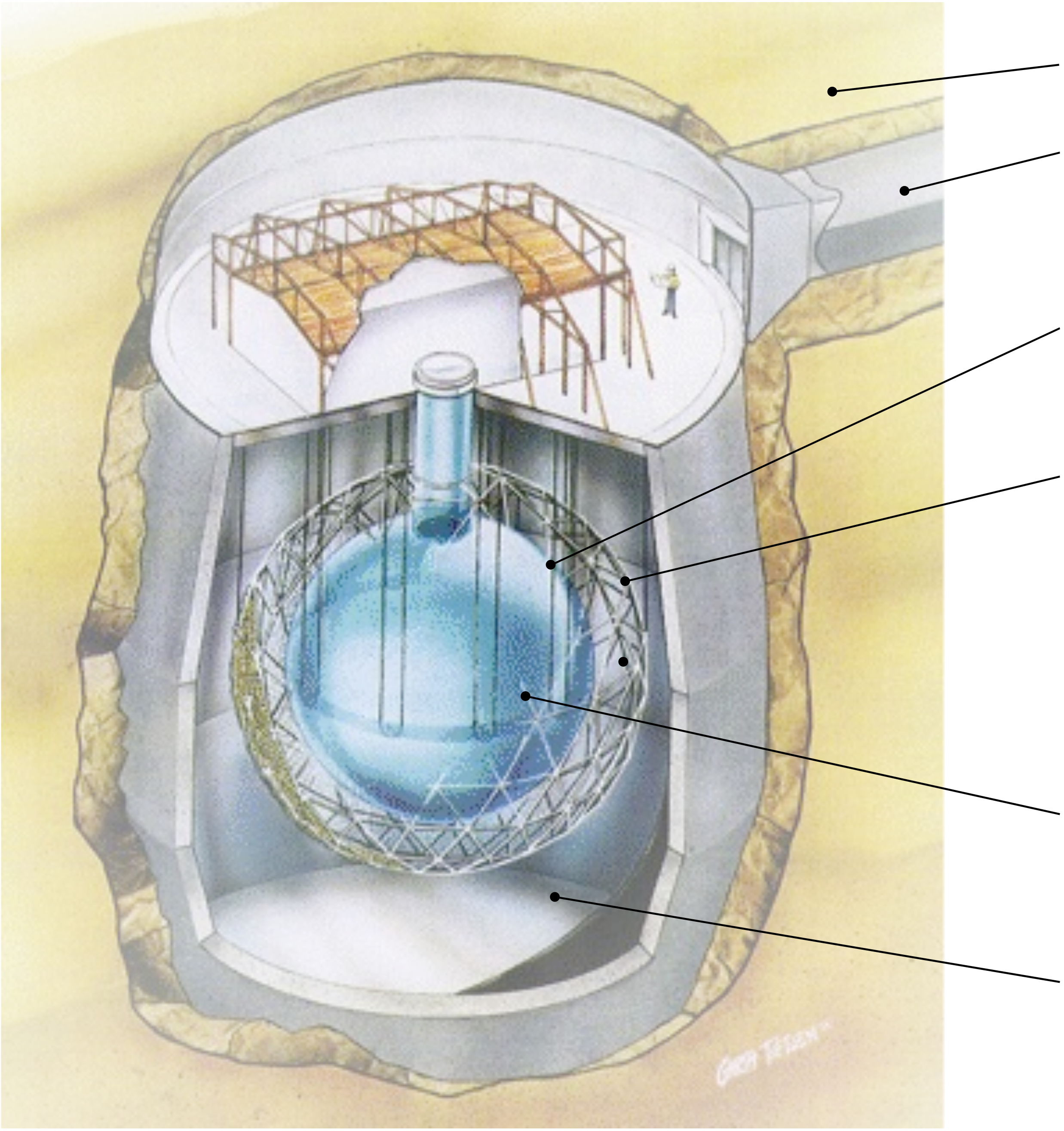
  Exp: 70 SNU
  BS05: 126 SNU

- ^{8}B ν_e-flux (Kamikande, SNO)

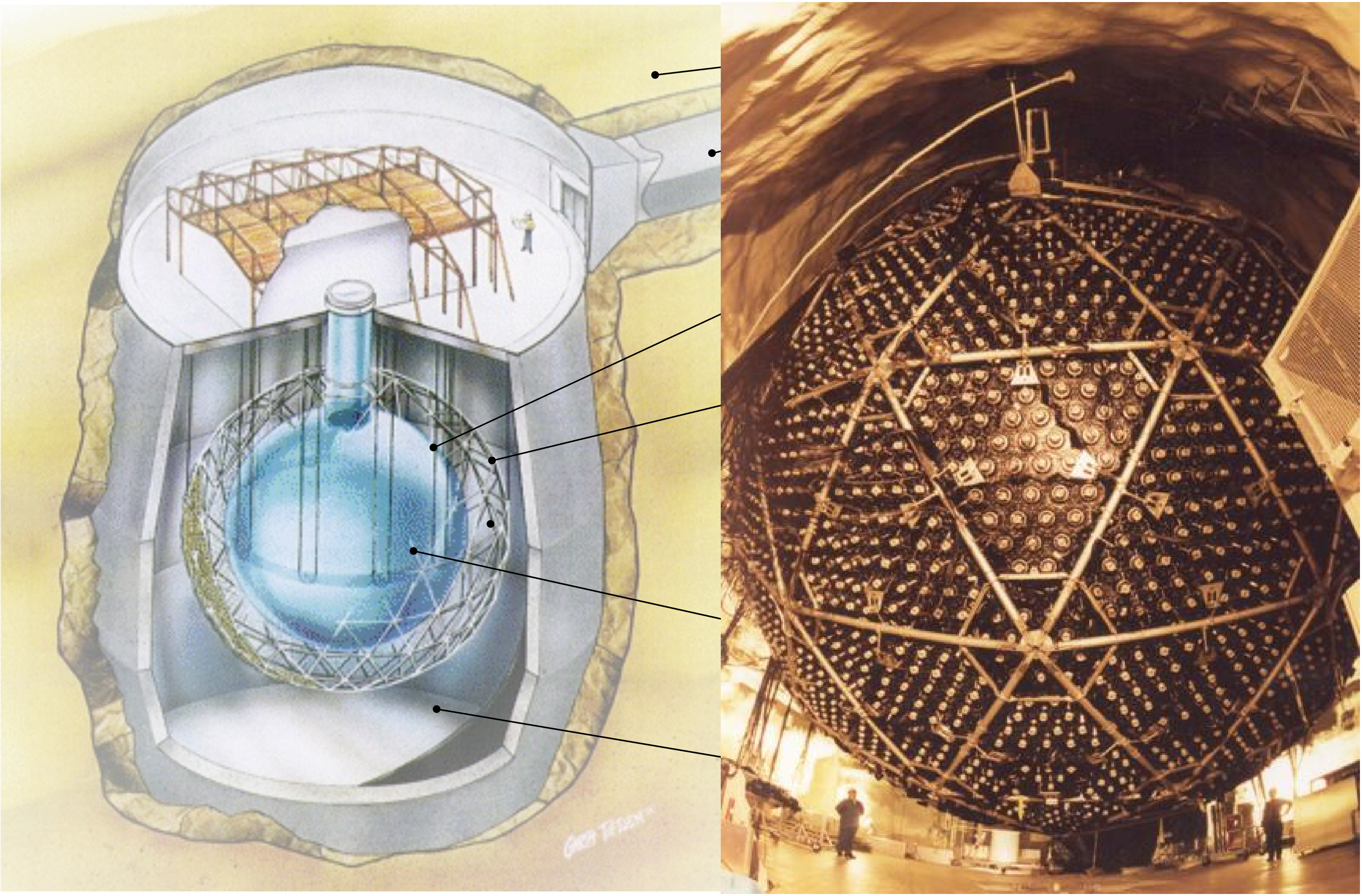
  Exp: 2.4 SNU
  BS05: 5.7 SNU

	^{37}Cl→ ^{37}Ar (SNU)	^{71}Ga→ ^{71}Ge (SNU)	^{8}B ν flux (10^6cm^{-2}s^{-1})
Homestake			
(CLEVELAND 98)[20]	2▹56 ∘ 0▹16 ∘ 0▹16	—	—
GALLEX			
(HAMPEL 99)[21]	—	77▹5 ∘ 6▹2$^{+4.3}_{-4.7}$	—
GNO			
(ALTMANN 05)[22]	—	62▹9$^{+5.5}_{-5.3}$ ∘ 2▹5	—
GNO+GALLEX			
(ALTMANN 05)[22]	—	69▹3 ∘ 4▹1 ∘ 3▹6	—
SAGE			
(ABDURASHI▹▹▹02)[23]	—	70▹8$^{+5.3+3.7}_{-5.2-3.2}$	—
Kamiokande			
(FUKUDA 96)[24]	—	—	2▹80 ∘ 0▹19 ∘ 0▹33†
Super-Kamiokande			
(HOSAKA 05)[25]	—	—	2▹35 ∘ 0▹02 ∘ 0▹08†
SNO (pure D$_2$O)			
(AHMAD 02)[4]	—	—	1▹76$^{+0.06}_{-0.05}$ ∘ 0▹09‡
	—	—	2▹39$^{+0.24}_{-0.23}$ ∘ 0▹12†
	—	—	5▹09$^{+0.44+0.46}_{-0.43-0.43}$*
SNO (NaCl in D$_2$O)			
(AHARMIM 05)[11]	—	—	1▹68 ∘ 0▹06$^{+0.08}_{-0.09}$‡
	—	—	2▹35 ∘ 0▹22 ∘ 0▹15†
	—	—	4▹94 ∘ 0▹21$^{+0.38}_{-0.34}$*
BS05(OP) SSM [13]	8▹1 ∘ 1▹3	126 ∘ 10	5▹69(1▹00 ∘ 0▹16)
Seismic model [18]	7▹64 ∘ 1▹1	123▹4 ∘ 8▹2	5▹31 ∘ 0▹6

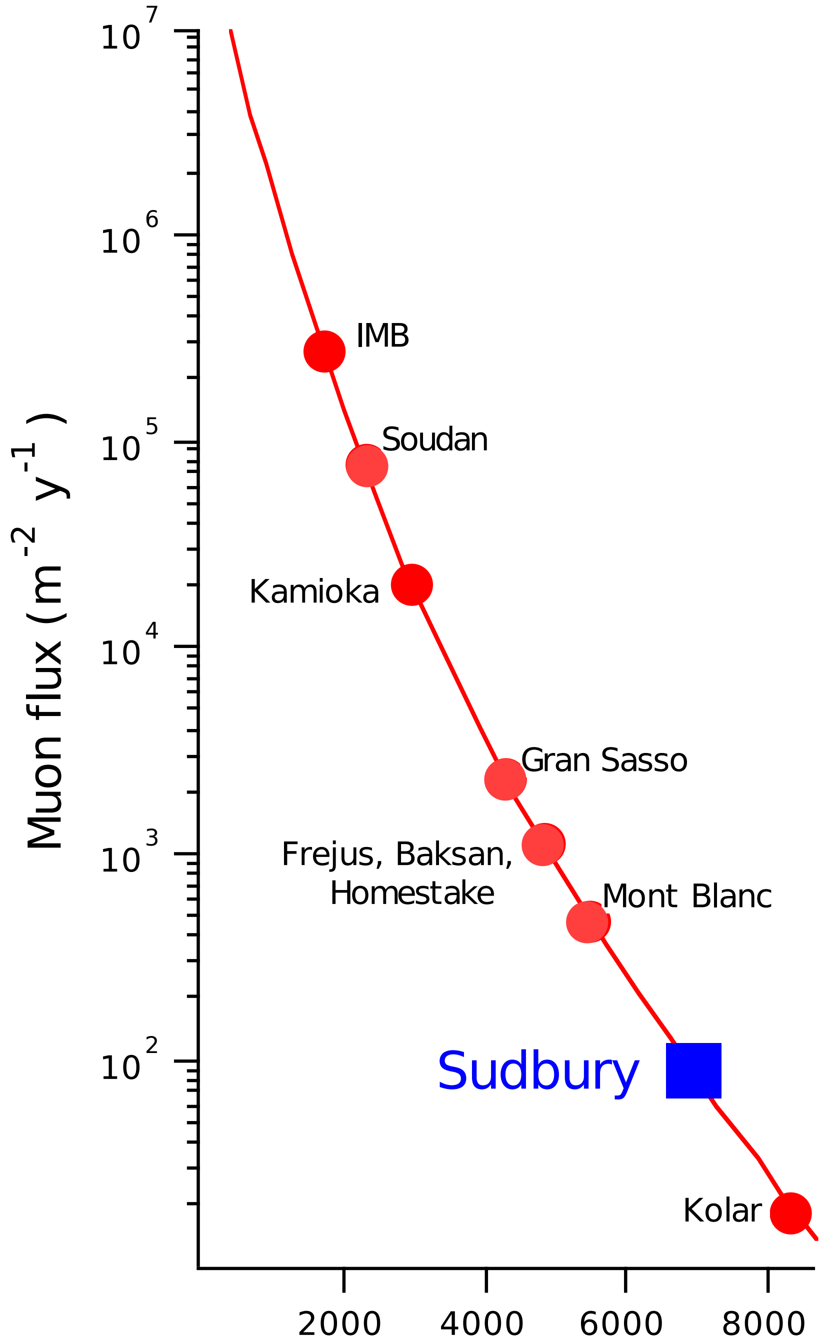
The SNO Experiment



The SNO Experiment



The SNO Experiment



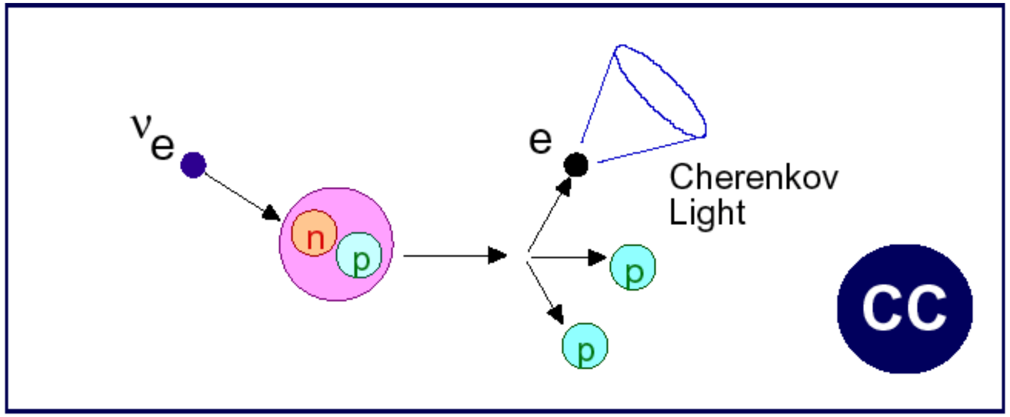
more than 3 km below ground
background < 100 muons/d

The SNO Experiment

charged current

$\nu_\mathrm{e} + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$

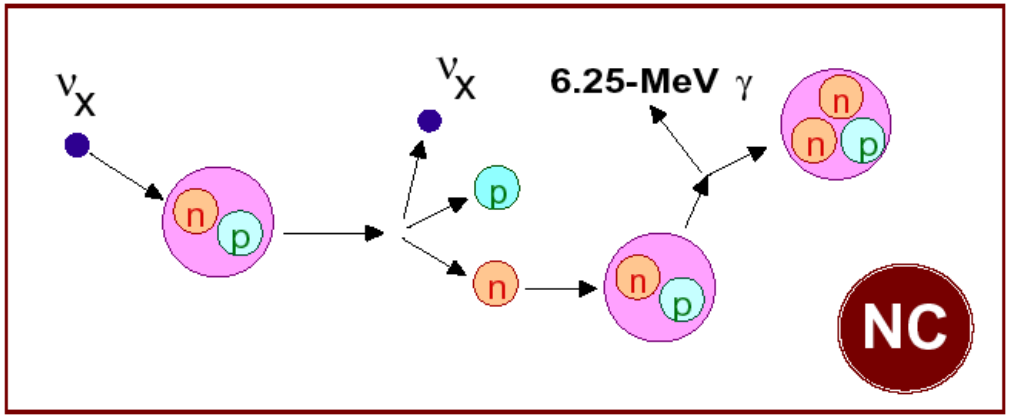
measurement of ν_e energy spectrum
weak directionality: $0.34 < \cos\theta < 1$



neutral currents

$\nu_\mathrm{x} + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{n} + \nu_\mathrm{x}$

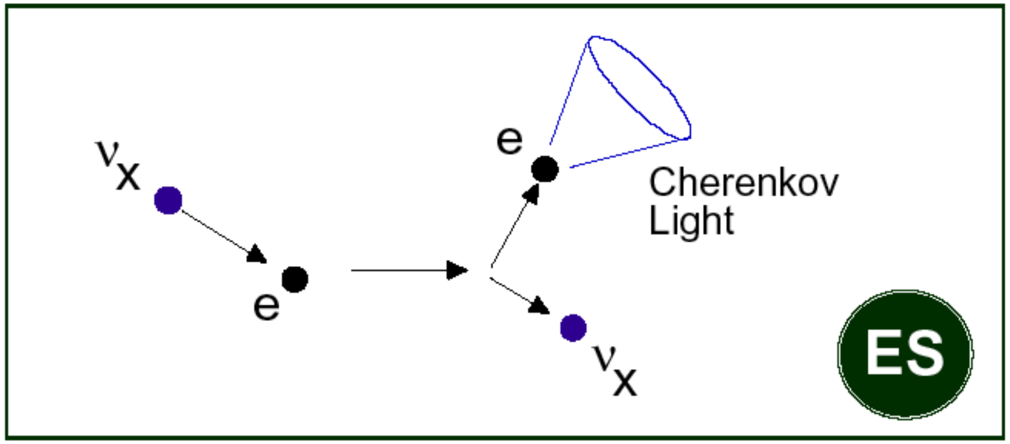
measure total ^{8}B neutrino flux from the sun
$\sigma(\nu_\mathrm{e}) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$



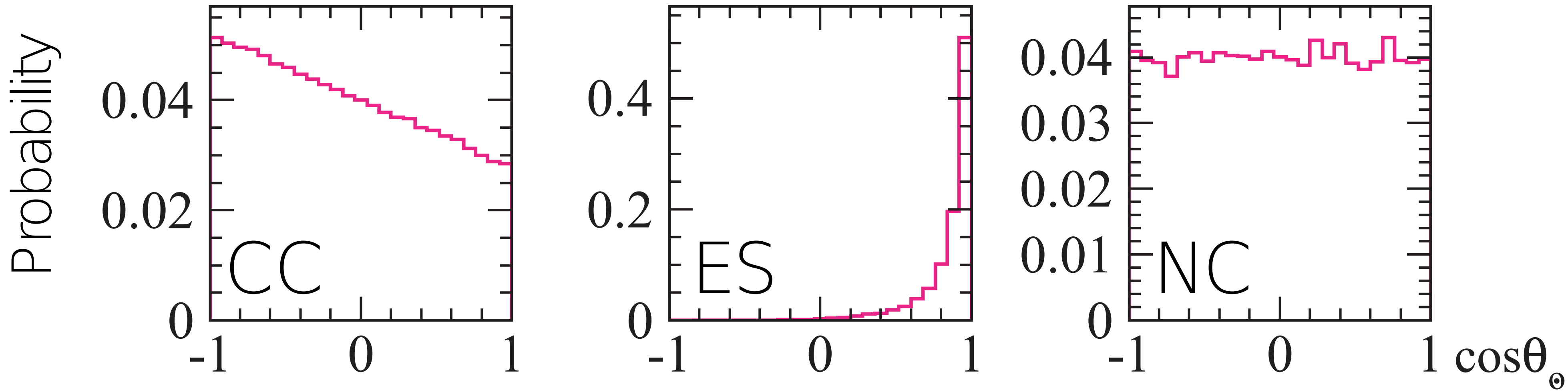
electron scattering

$\nu_\mathrm{x} + \mathrm{e}^- \rightarrow \nu_\mathrm{x} + \mathrm{e}^-$

low statistics
strong directionality: $\theta \leq 18^\circ$ ($T_\mathrm{e} = 10$ MeV)

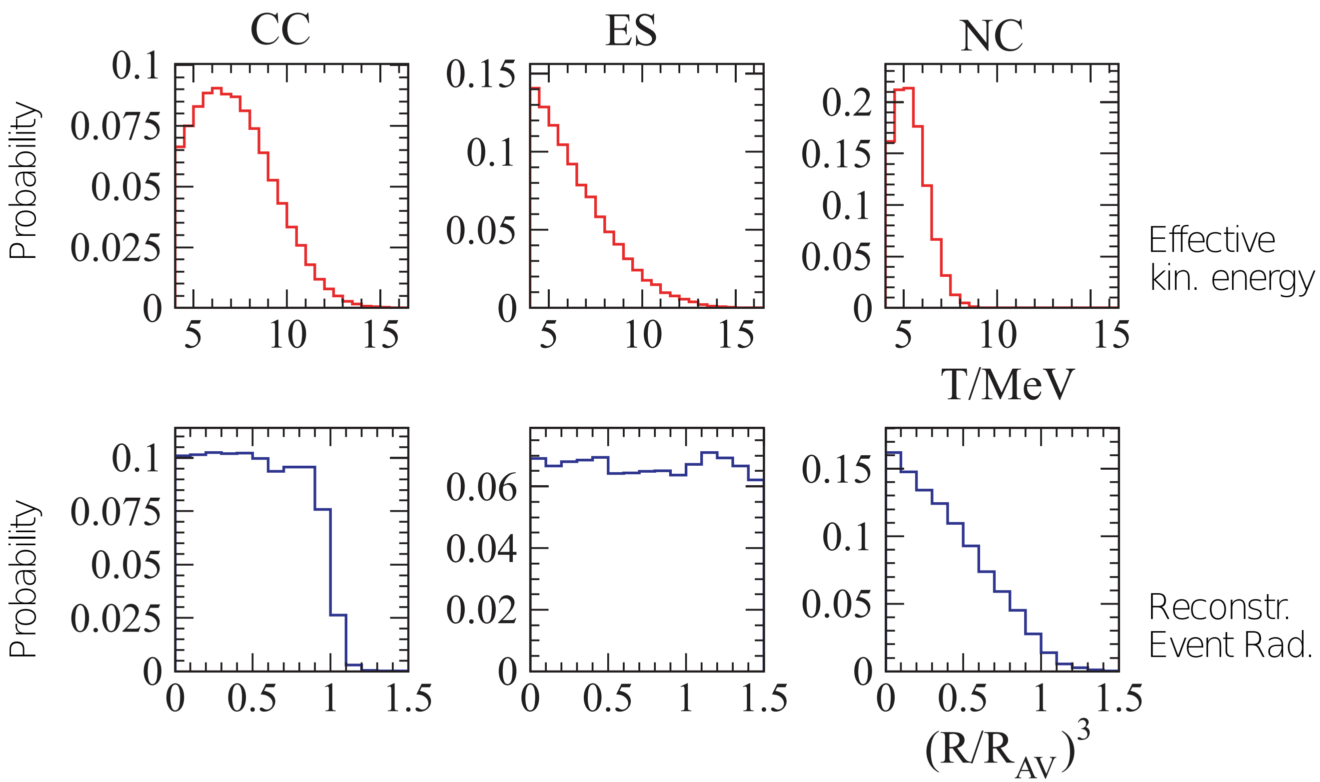


The SNO Experiment

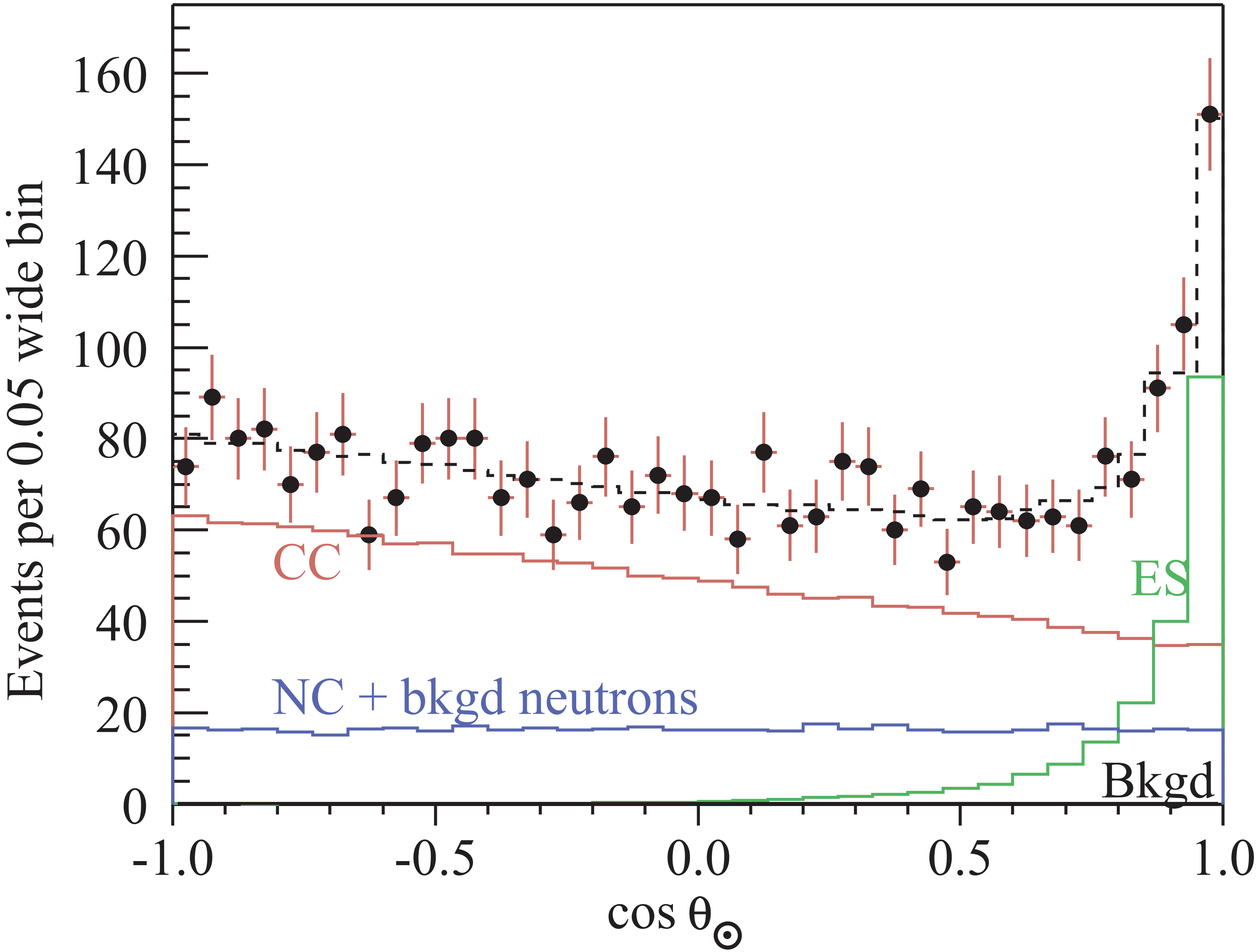


analysis strategy:

determine size of
CC, ES, and NC signals
via fit of the data
to probability distributions

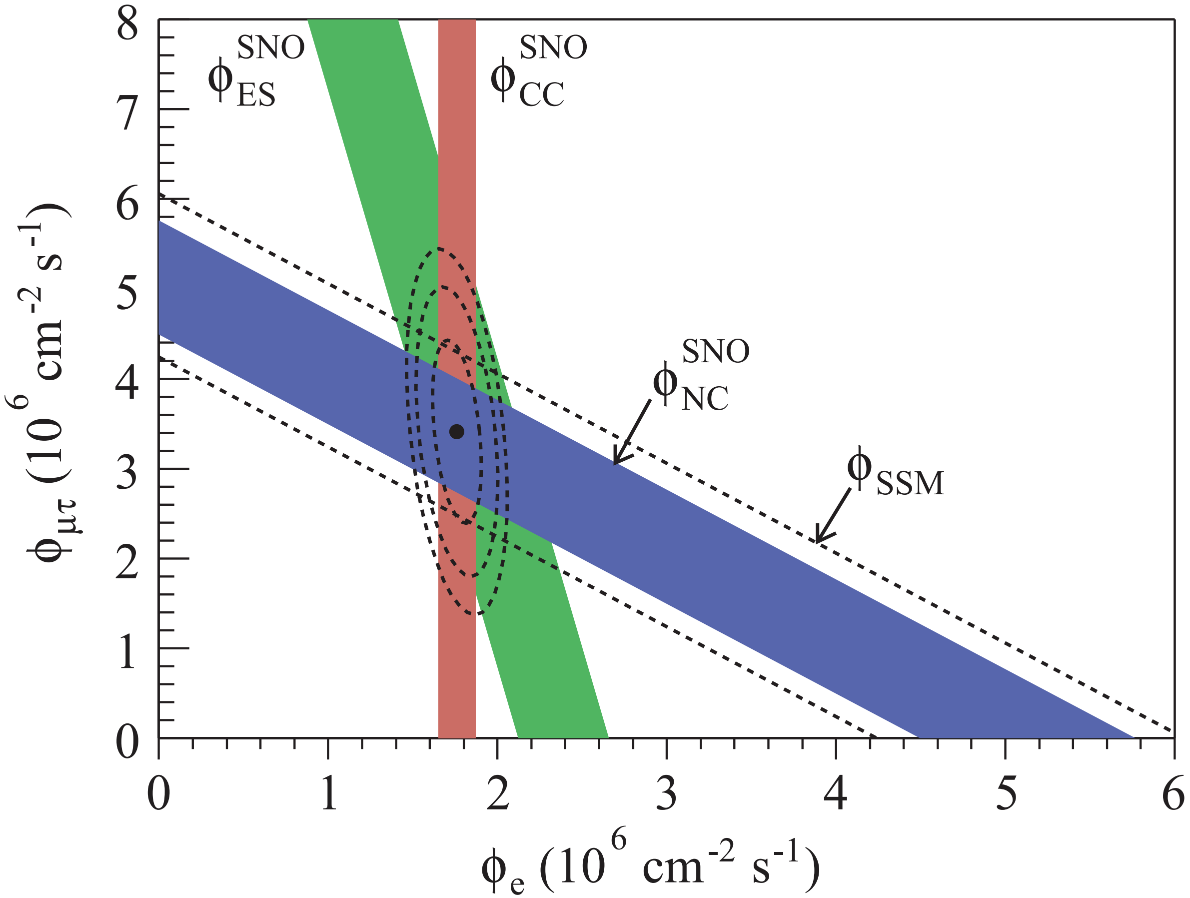


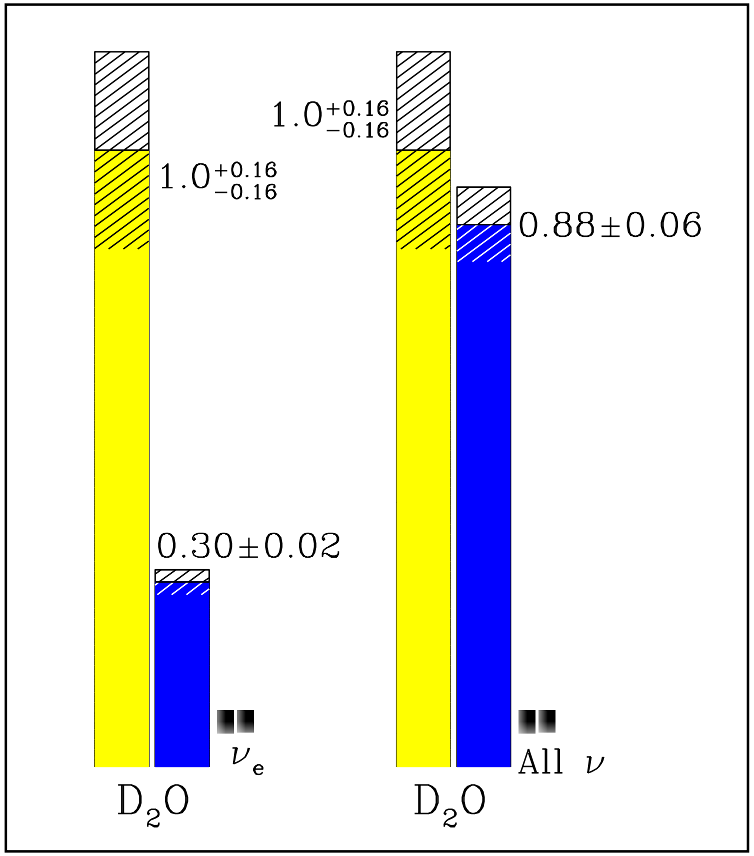
The SNO Experiment



The SNO Experiment

$$\Phi_{CC} = 1.76\ ^{+0.06}_{-0.05}(\text{stat.})\ ^{+0.09}_{-0.09}(\text{syst.}) \cdot 10^6\ \text{cm}^{-2}\text{s}^{-1}$$
$$\Phi_{ES} = 2.39\ ^{+0.24}_{-0.23}(\text{stat.})\ ^{+0.12}_{-0.12}(\text{syst.}) \cdot 10^6\ \text{cm}^{-2}\text{s}^{-1}$$
$$\Phi_{NC} = 5.09\ ^{+0.44}_{-0.43}(\text{stat.})\ ^{+0.46}_{-0.43}(\text{syst.}) \cdot 10^6\ \text{cm}^{-2}\text{s}^{-1}$$





$$\Phi(\nu_e) = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}(\text{syst.})$$
$$\Phi(\nu_{\mu\tau}) = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}(\text{syst.})$$
$$\cdot 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

Cryogenic Detectors

motivation: **WIMP detection**

WIMPs = weakly interacting massive particles

dark matter particles:

must be neutral, i.e. must neither interact via electromagnetic nor strong interactions

WIMPs must be heavy, i.e. non-relativistic (cold dark matter) to allow for galaxy formation

assumed mass range: 10 GeV - 10 TeV

mass limits dependent on cross section, e.g.: $\sigma_{\chi\mathrm{p}} = 1.6 \cdot 10^{-7}$ pb yields $m_{\mathrm{WIMP}} > 60$ GeV

detection via elastic χp-scattering

assume WIMP velocity: $v_\chi \approx 300$ km/s, i.e. $\beta = 10^{-3}$

solar system speed w.r.t. to milky way: $v = 250$ km/s
velocity of earth moving w.r.t solar system: $v = 30$ km/s

maximum energy transfer for collision with nucleus N:

$$T_{\mathrm{N}}^{\mathrm{max}} = 2\frac{m_\chi^2 M_{\mathrm{N}} c^2}{(m_\chi + M_{\mathrm{N}})^2}\beta^2 \quad (\approx 2 M_{\mathrm{N}} v_\chi^2 \text{ for } m_\chi \ll M_{\mathrm{N}})$$

for e.g. $M_{\mathrm{N}} = 100$ GeV: $\quad T_{\mathrm{N}}^{\mathrm{max}} \approx 100$ keV

Cryogenic Detectors

How to detect WIMPs

transferred energy of recoiling nuclei generally much smaller ($< 10\%$)

need detector that allows detection of recoil nuclei below keV range
energy resolution requires: $n_{\mathrm{excitation}} \gg 1$, i.e. $E_{\mathrm{excitation}} \ll 1$ eV

remember:	gases	–	ionzation energy ≈ 30 eV
	silicon	–	electron/hole pair creation ≈ 3 eV

better possibilities:

- phonon excitation:

  maximum phonon energy in Si is 60 meV,
  roughly 2/3 of the energy required for electron-hole formation goes into phonon excitation

- superconducting detectors:

  in superconductors the energy gap 2Δ is equivalent to the band gap in semiconductors
  absorption of energy $> 2\Delta$ (typically 1 meV) can break up a Cooper pair

Cryogenic detectors:

detect low energies with very good resolution

Cryogenic Detectors

Phonon Detectors

assume thermal equilibrium:

convert absorbed energy into phonons:

$$\Delta T = E/C$$

C: heat capacity of the sample
(specific heat $\times$ mass)
E: deposited energy

optimal detector: low heat capacity

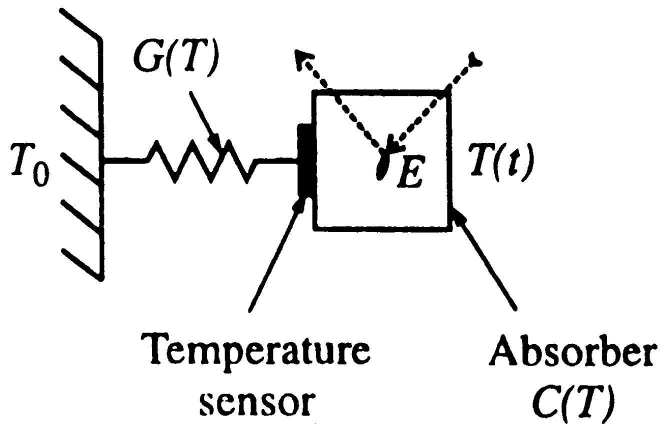
example 1: Si-detector at room temperature

$C_{\rm spec} = 0.7$ J/gK
$E = 1$ keV, $m = 1$ g $\rightarrow \Delta T = 2 \cdot 10^{-16}$ K
not very practical, need lower specific heat and mass

example 2: Si-detector at low temperature

$C_{\rm spec} \propto (T/\Theta)^3$
$C_{\rm spec} = 2 \cdot 10^{-15}$ J/gK at $T = 0.1$ K
$E = 1$ keV, $m = 15$ μg $\rightarrow \Delta T = 0.04$ K (possible!)

basic configuration of cryogenic calorimeter

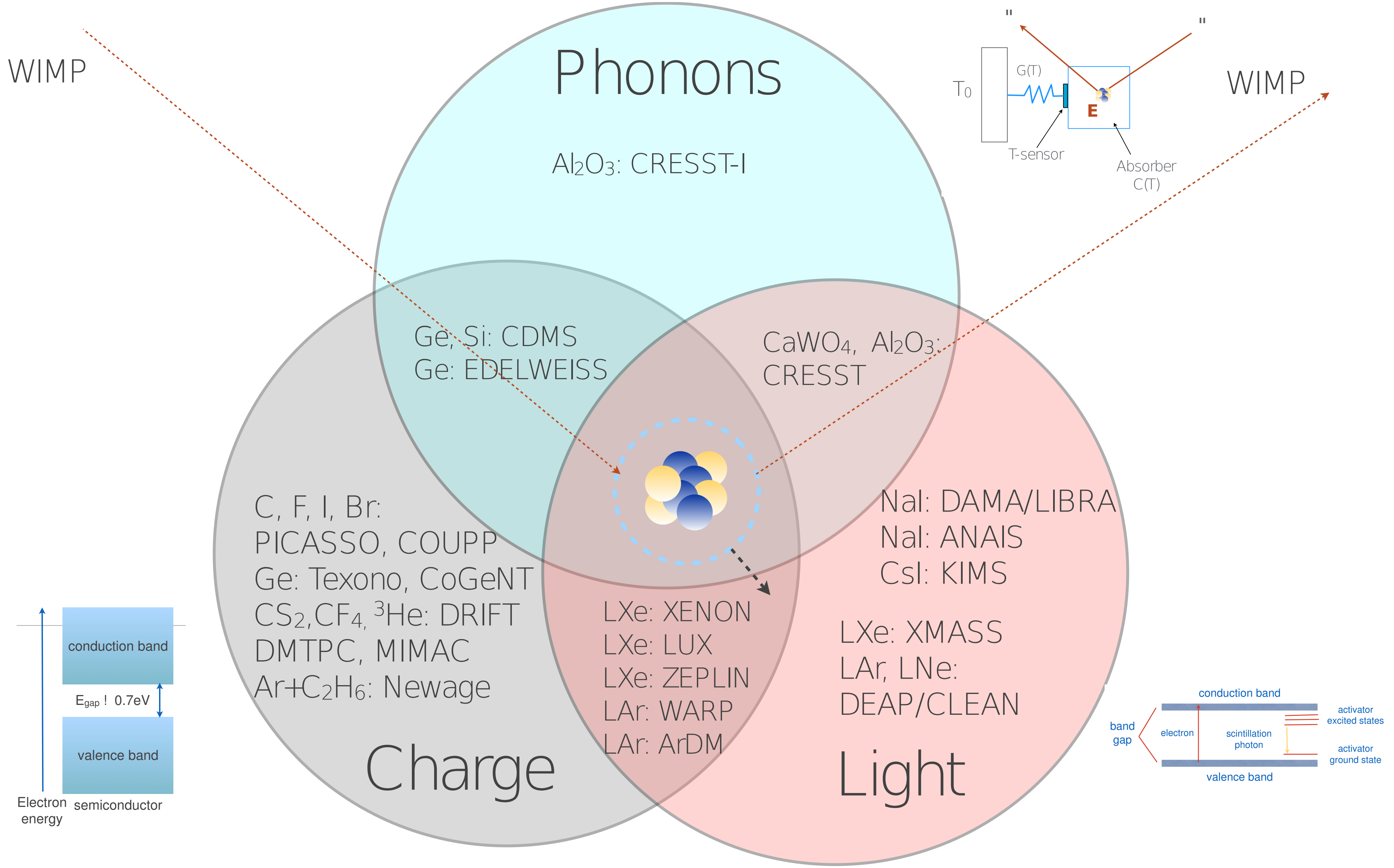


resolution:

$$\begin{aligned} n &= CT/kT = C/k \\ \sigma_0 &= kT\sqrt{n} = \sqrt{CkT^2} \\ \sigma_E &= \varepsilon\mathrm{Ph}\sqrt{E/\varepsilon Ph} = \sqrt{kTE} \\ \sigma^2 &= \sigma_0^2 + \sigma_E^2 \end{aligned}$$

yields: $\sigma < 0.2$ eV
(cf. Si semiconductor detector: $\sigma = 20$ eV)

Dark Matter Detection



Dark Matter Detection

Example: CDMS

Soudan Underground Lab

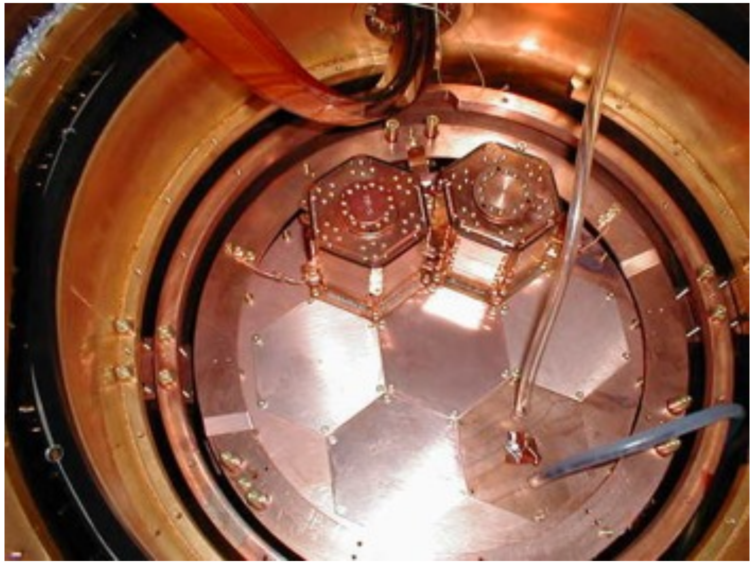
5 towers with 6 Ge/Si detectors each
operated at $T \approx 20$ mK

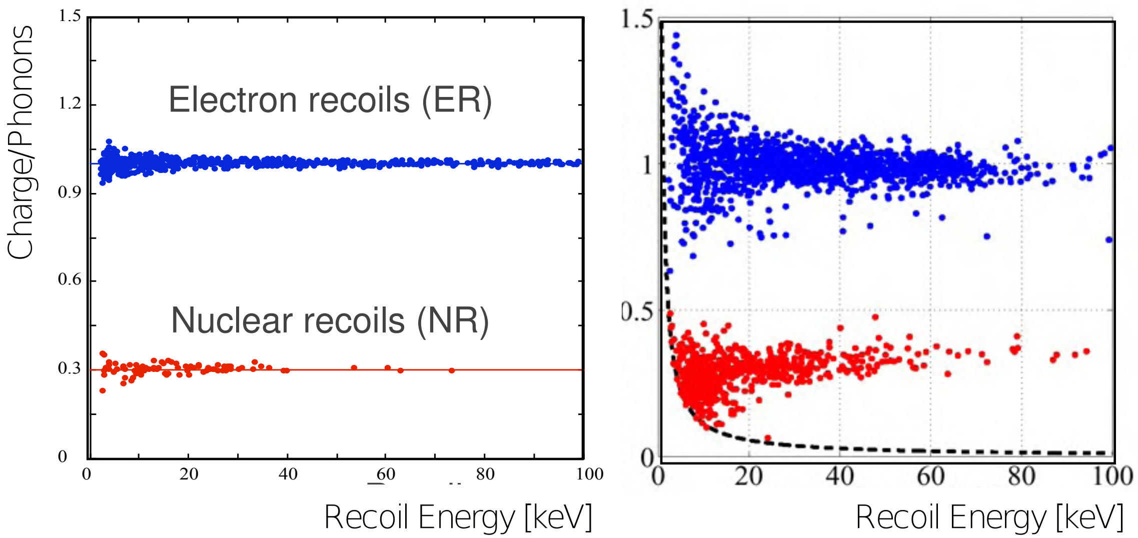
Idea:

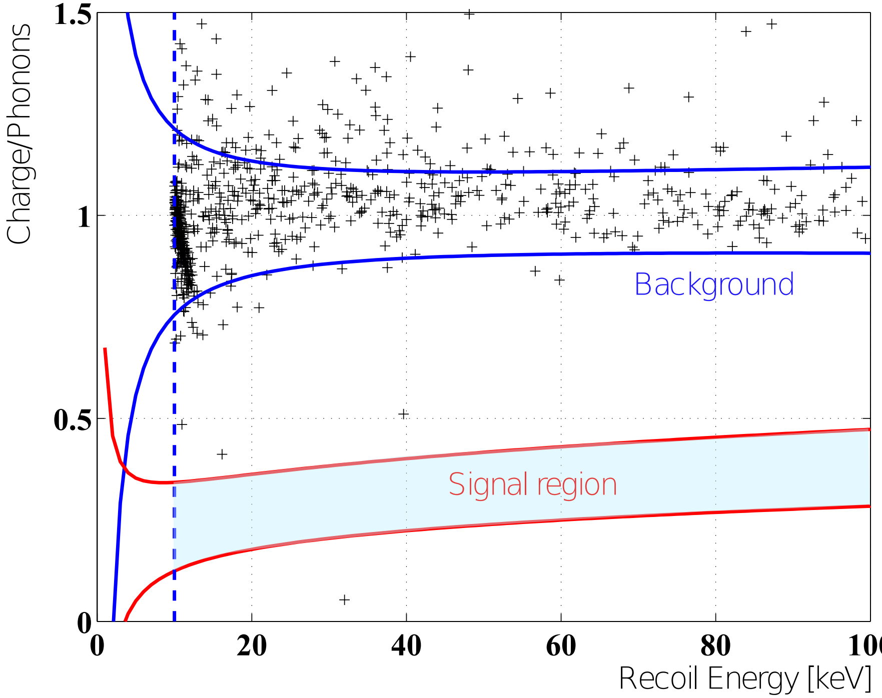
WIMPs (and neutrons) scatter off nuclei

most background noise sources (γ,e) scatter off electrons

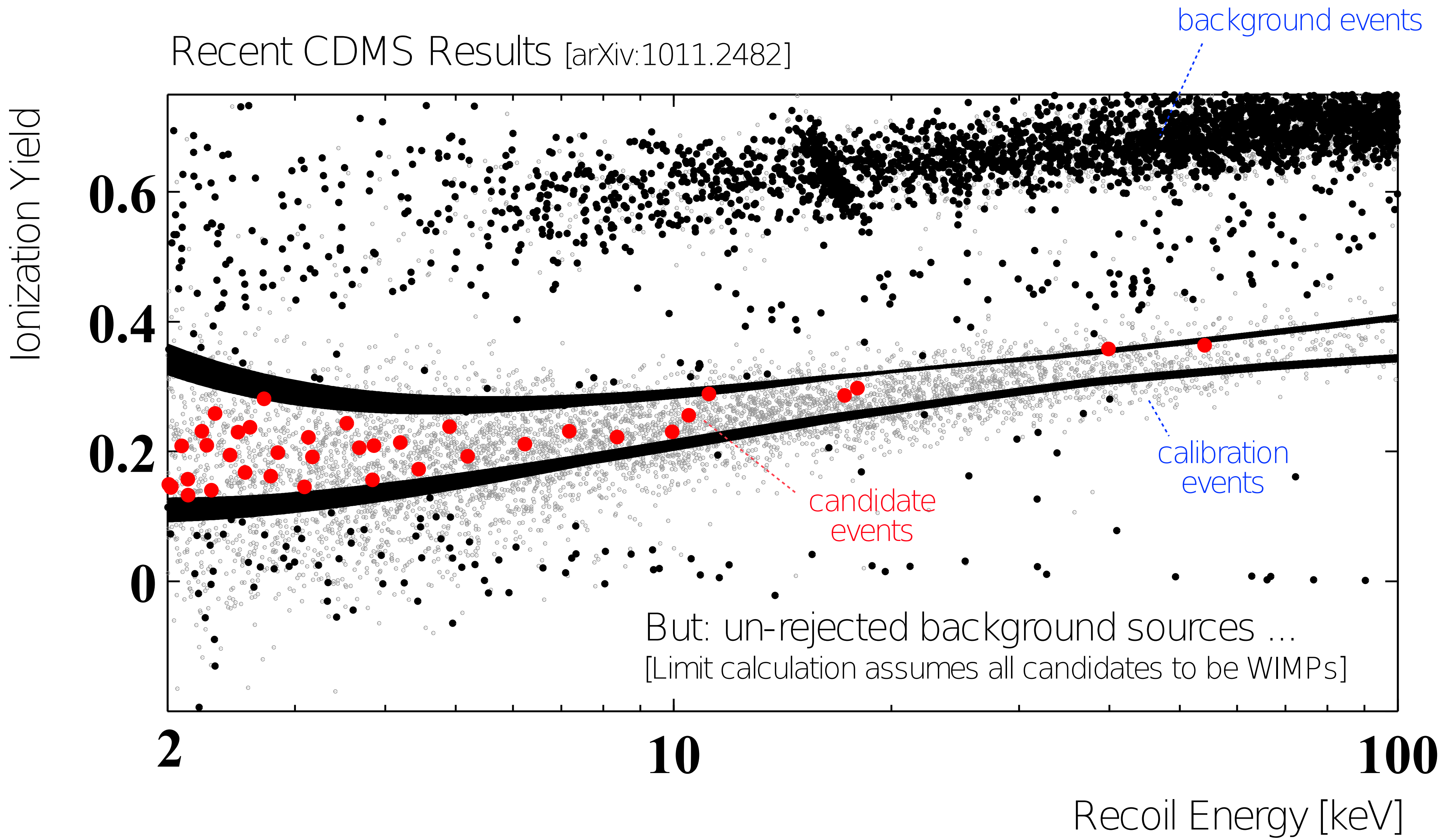
ratio ionization/phonons differs for nuclear and electron recoils





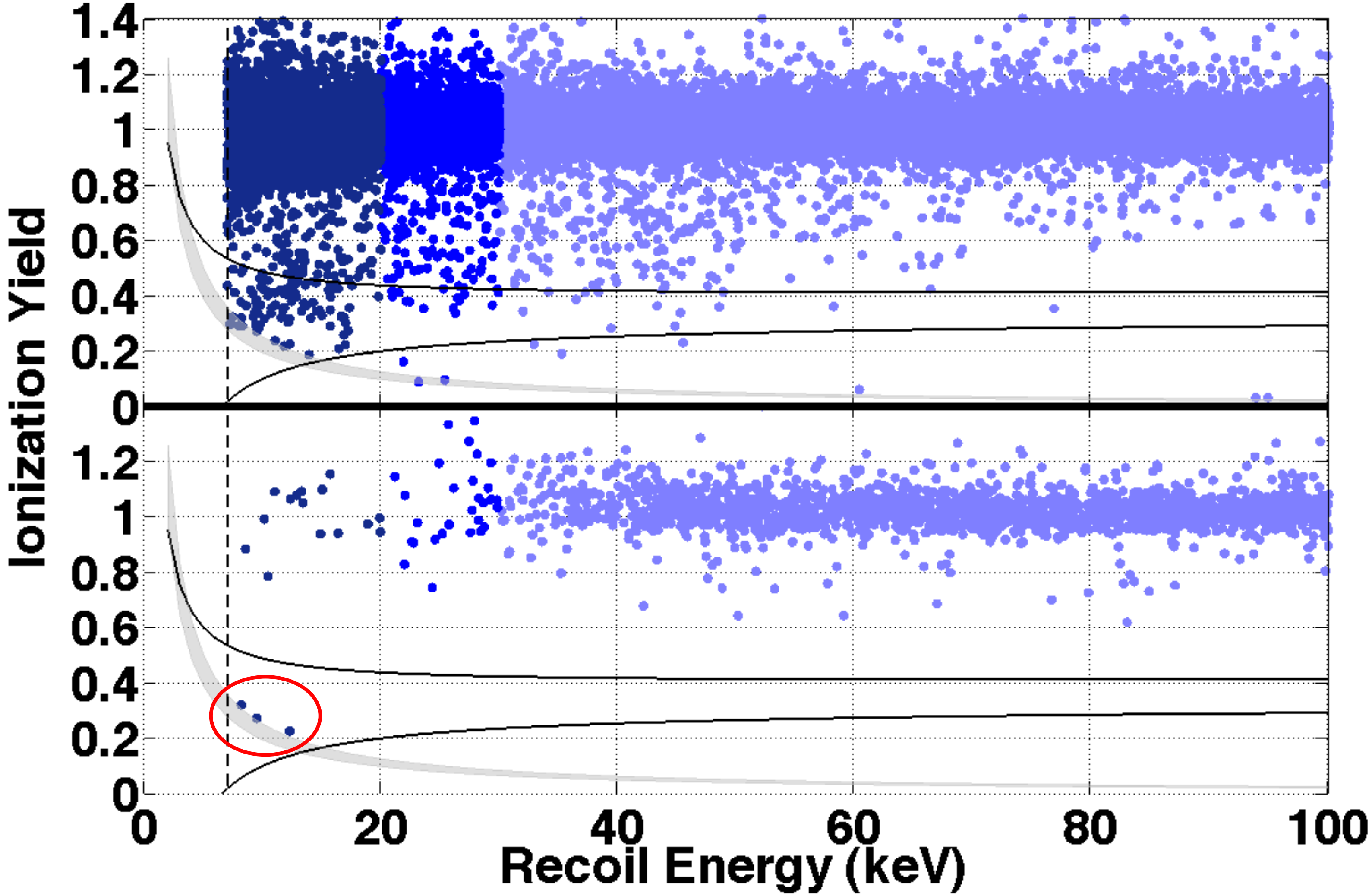


Dark Matter Detection



Dark Matter Detection

CDMS II Si 2013 Result



3 candidate WIMPs, 'not yet a discovery'

Dark Matter Detection

Summary Dark Matter WIMP Searches