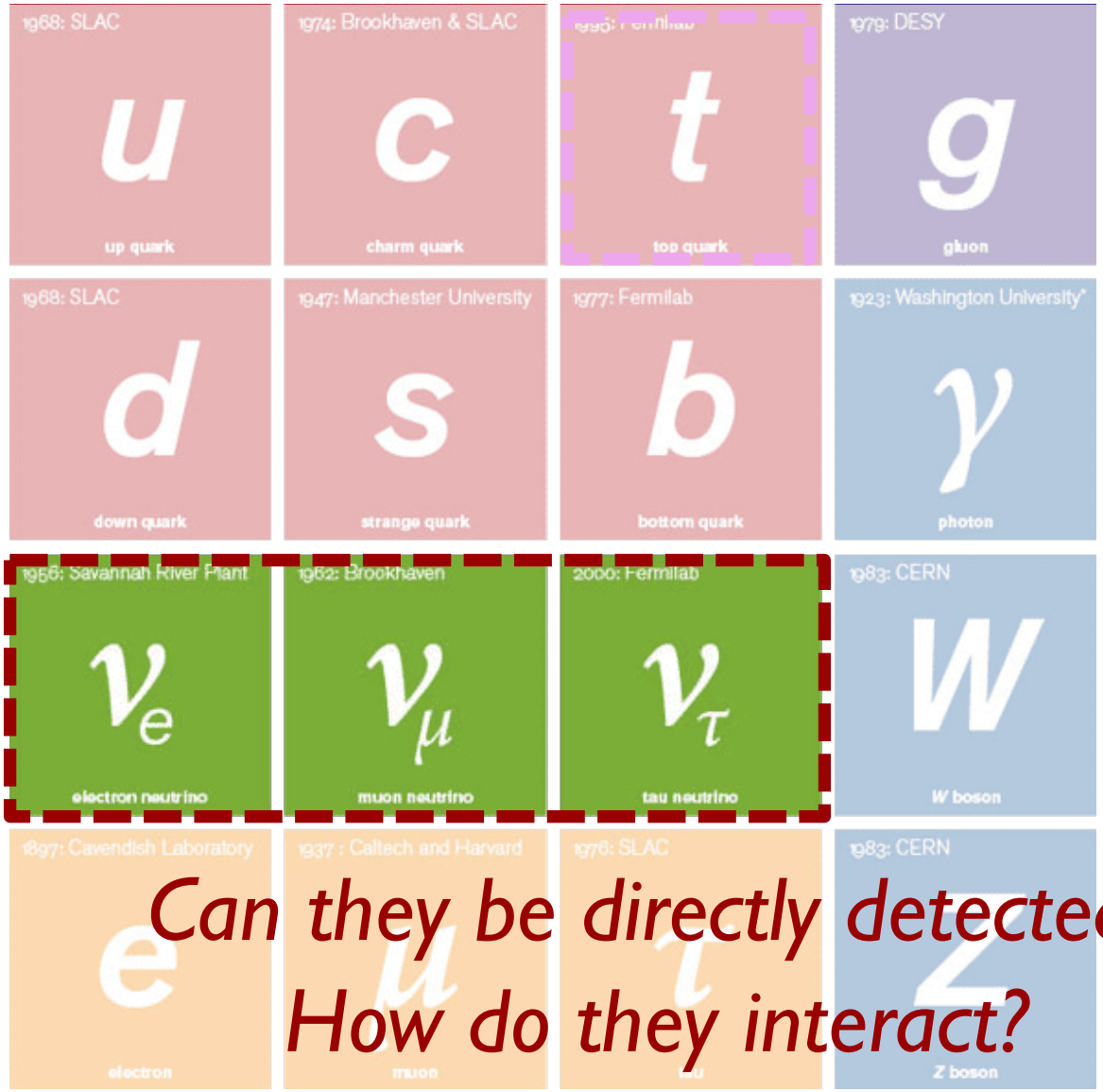
Experimental particle physics

esipap
European School of Instrumentation in Particle & Astroparticle Physics

5. experiments to detect "invisible" particles

“Invisible” particles?



invisible

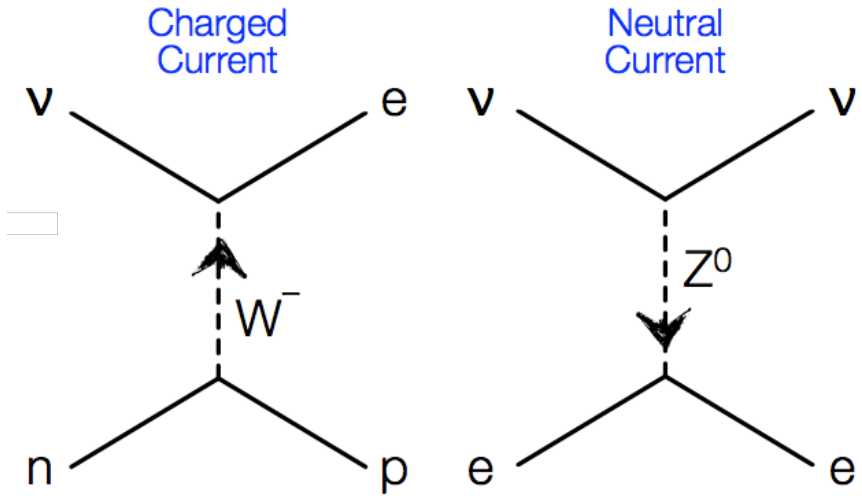
in particle detectors at accelerators

… but can “appear” in particle detectors at accelerators as missing transverse energy and momentum

Can they be directly detected?

How do they interact?

Neutrino interactions



Neutron detection only via weak interaction ...

Possible reactions:

Charged Current Reactions:

$$\nu_e + n \rightarrow e^- + p$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\nu_\mu + n \rightarrow \mu^- + p$$
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$
$$\nu_\tau + n \rightarrow \tau^- + p$$
$$\bar{\nu}_\tau + p \rightarrow \tau^+ + n$$
$$\dots$$
$$\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\bar{\nu}_e + e^- \rightarrow \tau^- + \bar{\nu}_\tau$$

Neutral Current Reactions:

$$\nu_e + e^- \rightarrow \nu_e + e^-$$
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$
$$\nu_\tau + e^- \rightarrow \nu_\tau + e^-$$

Remark:

Neutral Current νN-interactions not usable due to small energy transfer

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Neutrino nucleon x-Section:
[examples]

10 GeV neutrinos: $\sigma = 7 \cdot 10^{-38}$ cm^2/nucleon

Interaction probability for 10 m Fe-target: $R = \sigma \cdot N_A\ [\text{mol}^{-1}/\text{g}] \cdot d \cdot \rho = 3.2 \cdot 10^{-10}$
with $N_A = 6.023 \cdot 10^{23}$ g^{-1}; d = 10 m; $\rho = 7.6$ g/cm^3

Solar neutrinos [100 keV]: $\sigma = 7 \cdot 10^{-45}$ cm^2/nucleon

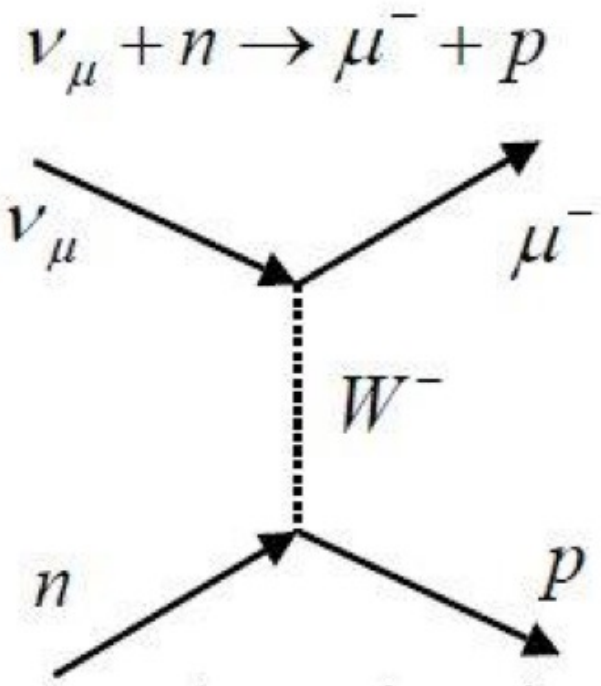
Interaction probability for earth: $R = \sigma \cdot N_A\ [\text{mol}^{-1}/\text{g}] \cdot d \cdot \rho \approx 4 \cdot 10^{-14}$
with $N_A = 6.023 \cdot 10^{23}$ g^{-1}; d = 12000 km; $\rho = 5.5$ g/cm^3

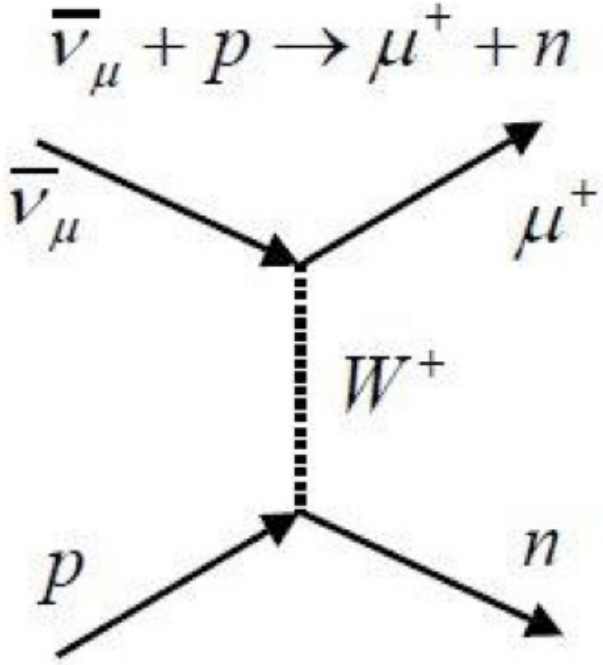
Neutrino interactions: ν-e

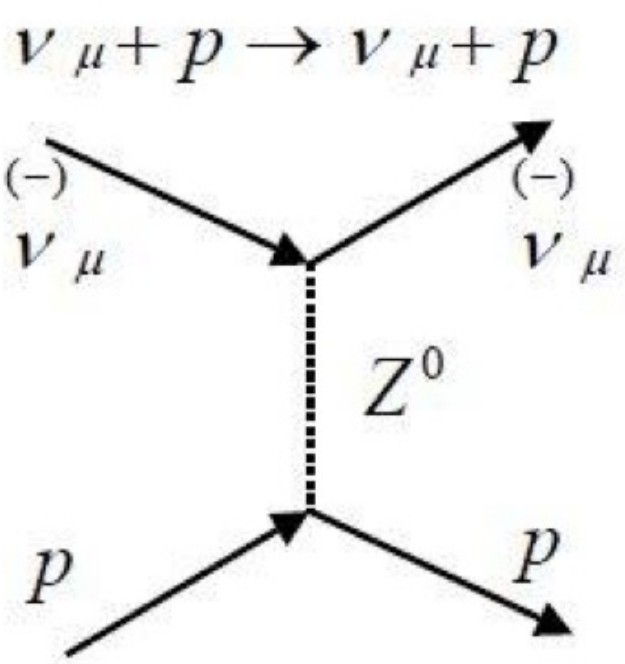
Process	Total Cross section
$\nu_\mu + e^- \to \mu^- + \nu_e$	$\frac{G_F^2 s}{\pi} \quad 1.7 \cdot 10^{-43} \left(\frac{E}{10\mathrm{MeV}}\right) \mathrm{cm}^2$
$\nu_e + e^- \to \nu_e + e^-$	$\frac{G_F^2 s}{4\pi}\left[\left(2\sin^2\theta_W - 1\right)^2 + \frac{4}{3}\sin^4\theta_W\right]$
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	$\frac{G_F^2 s}{4\pi}\left[\frac{1}{3}\left(2\sin^2\theta_W + 1\right)^2 + 4\sin^4\theta_W\right]$
$\nu_\mu + e^- \to \nu_\mu + e^-$	$\frac{G_F^2 s}{4\pi}\left[\left(2\sin^2\theta_W - 1\right)^2 + \frac{4}{3}\sin^4\theta_W\right]$
$\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$	$\frac{G_F^2 s}{4\pi}\left[\frac{1}{3}\left(2\sin^2\theta_W - 1\right)^2 + 4\sin^4\theta_W\right]$

Neutrino interactions: ν-nucleon

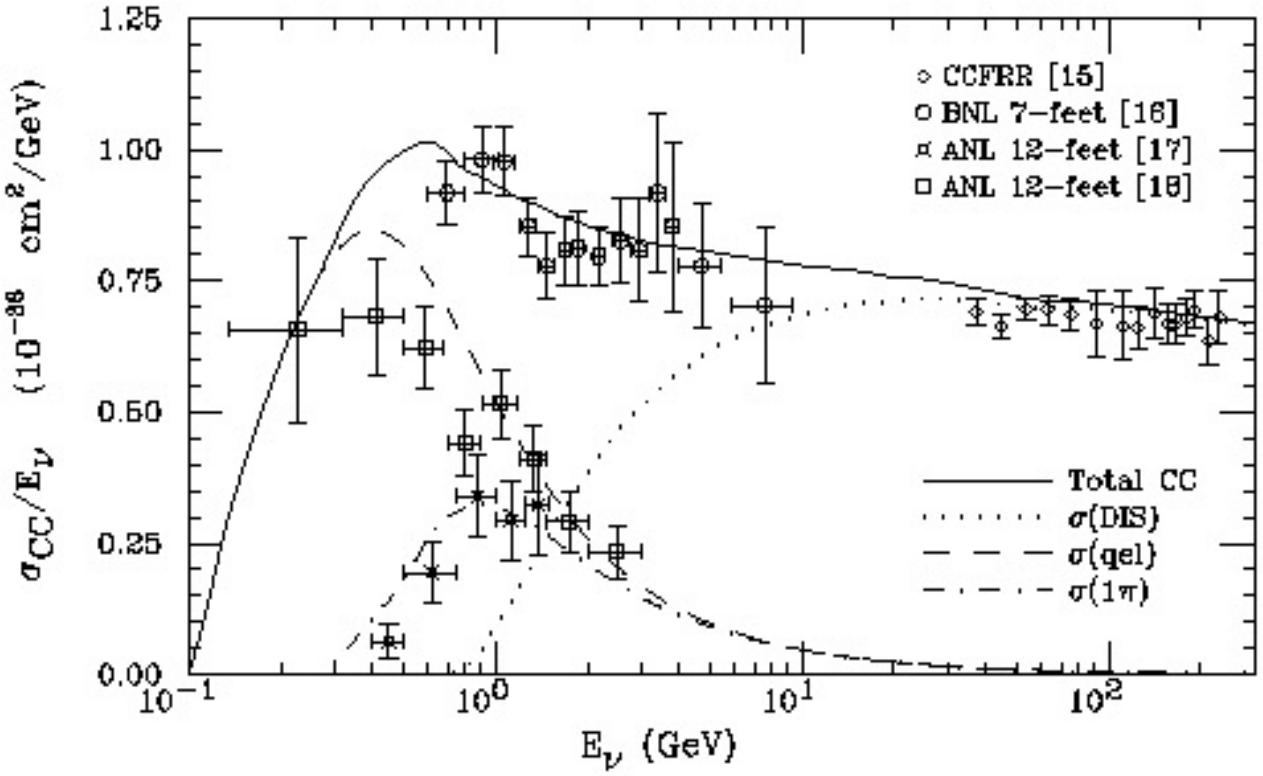
- Interaction happens with whole nucleon
  - ✓ Nucleon can at best undergo an *isospin* transition in case of charged current (quasi-elastic scattering)
  - ✓ In case of neutral current, scattering is perfectly elastic







Neutrino interactions: quasi-elastic ν-nucleon



Threshold is different for different neutrino flavors…

Paolo Lipari, Maurizio Lusignoli, Francesca Sartogo, "The neutrino cross section and upward going muons" http://arxiv.org/abs/hep-ph/9411341

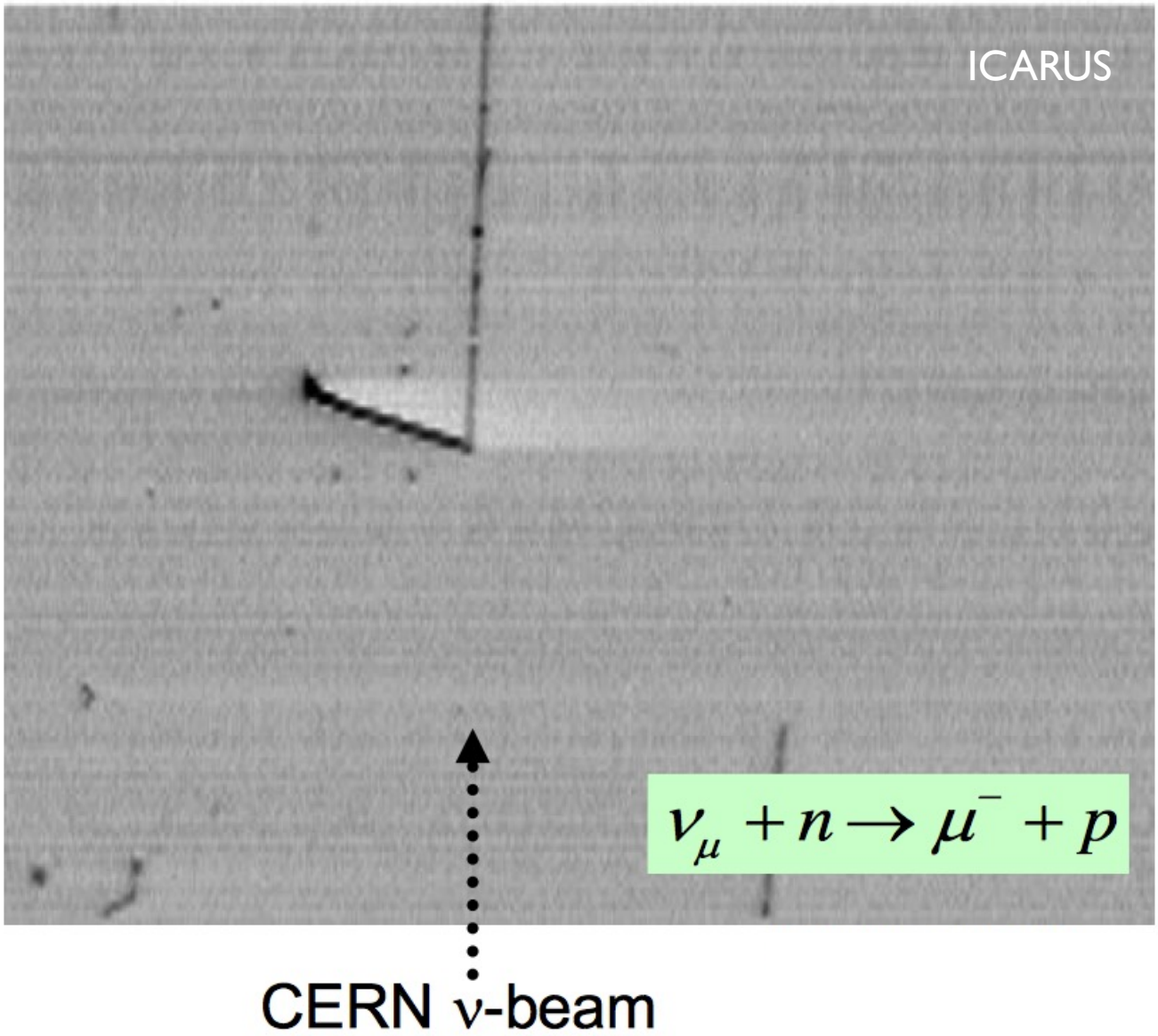
E << m_n $\quad \sigma(\nu n)=\sigma(\bar{\nu}p)\approx$

$$9.75\cdot 10^{-42}\left(\frac{E}{10\,MeV}\right)^2 \text{ cm}^2$$

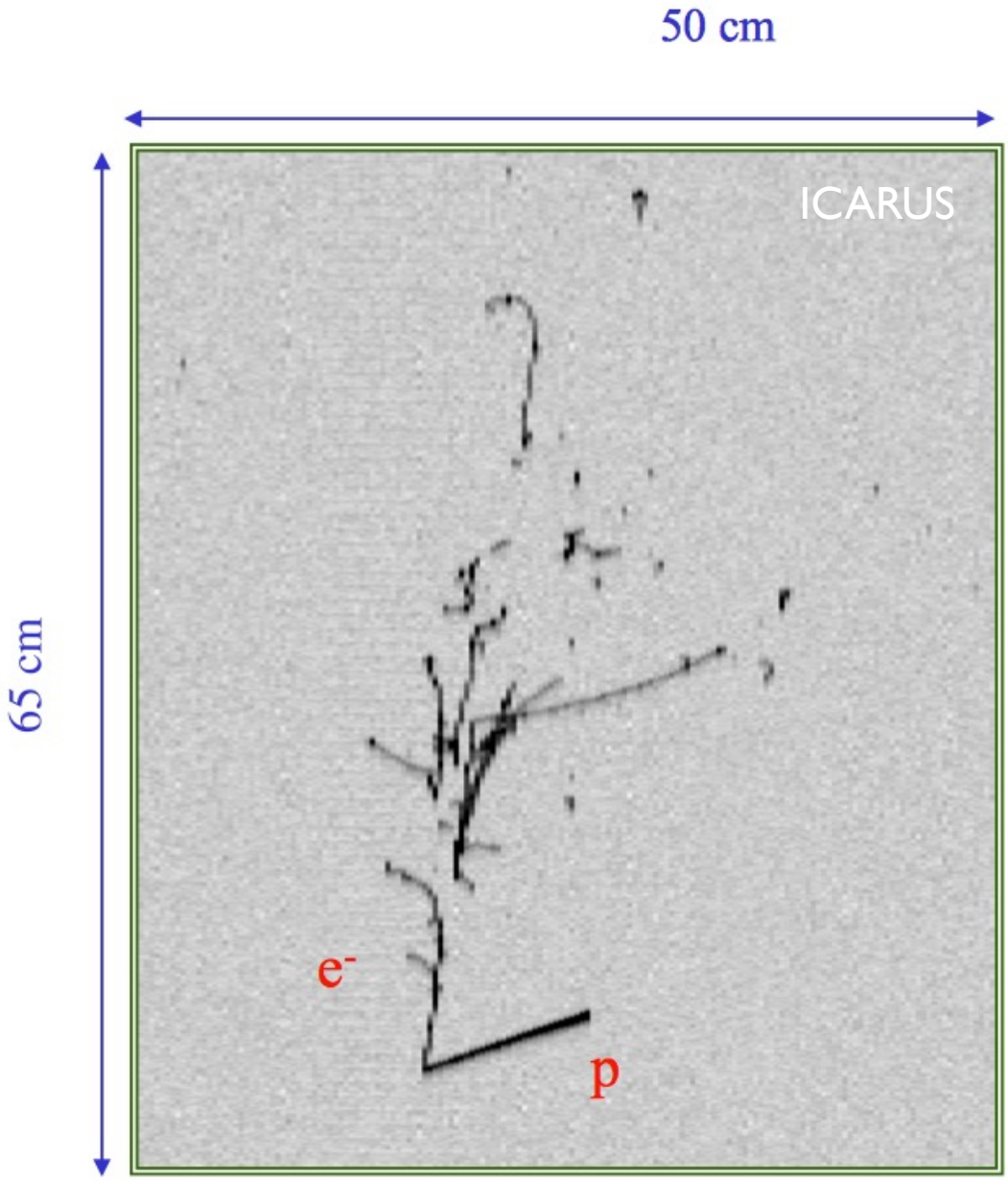
E > 1 GeV

σ/E ~ constant

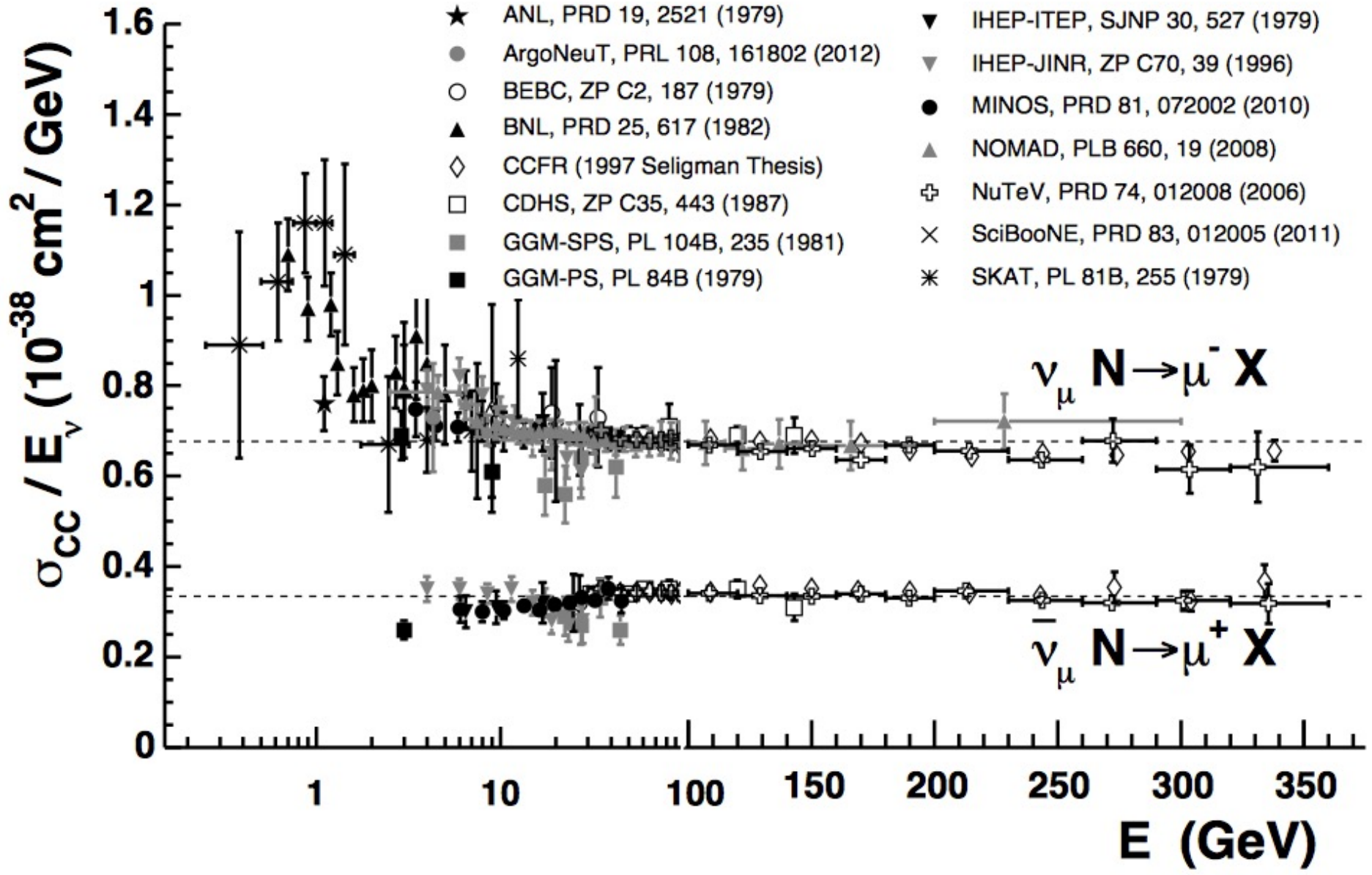
A neutrino interaction…



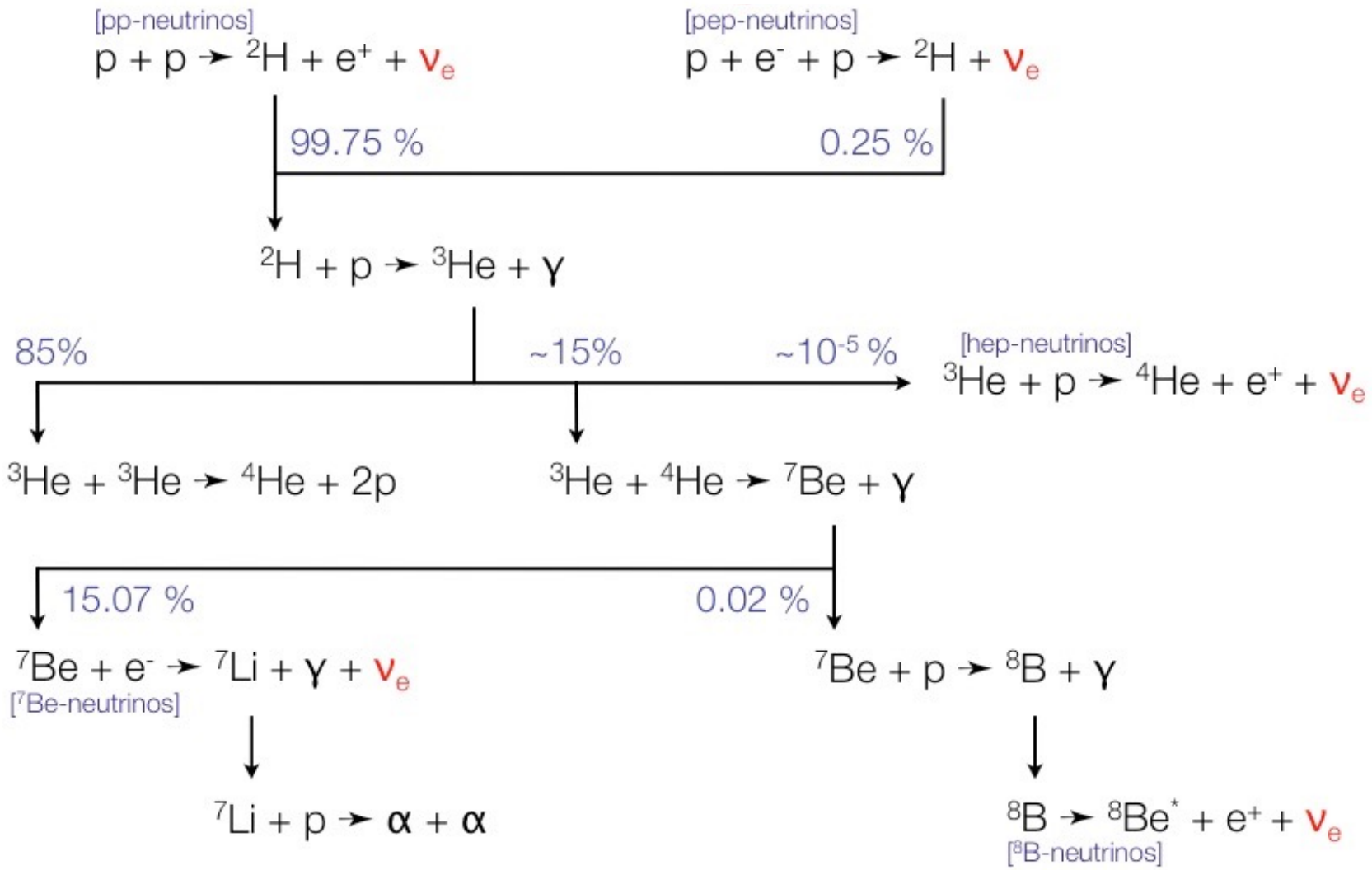
Another neutrino interaction…



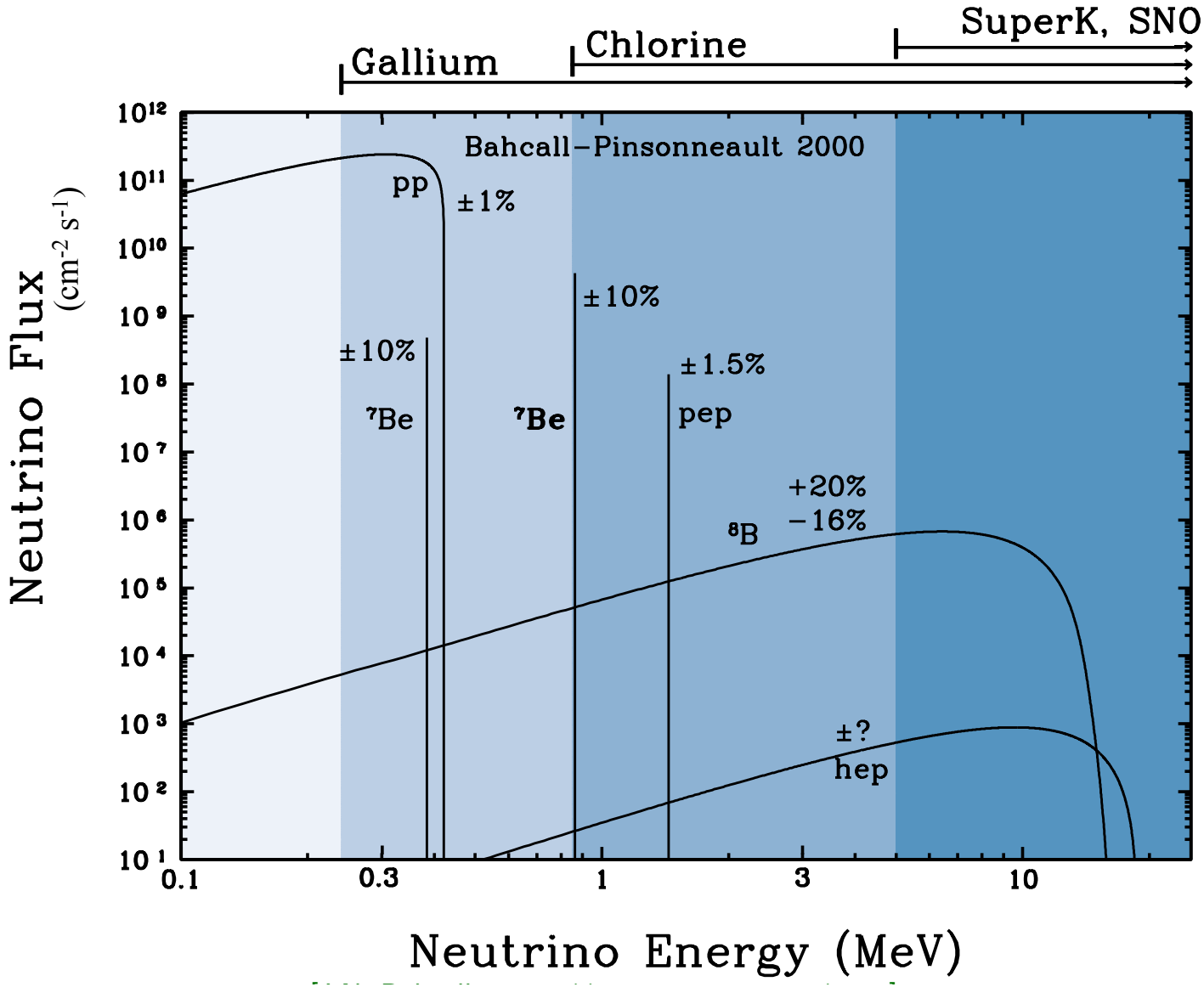
Neutrino interaction inclusive cross section



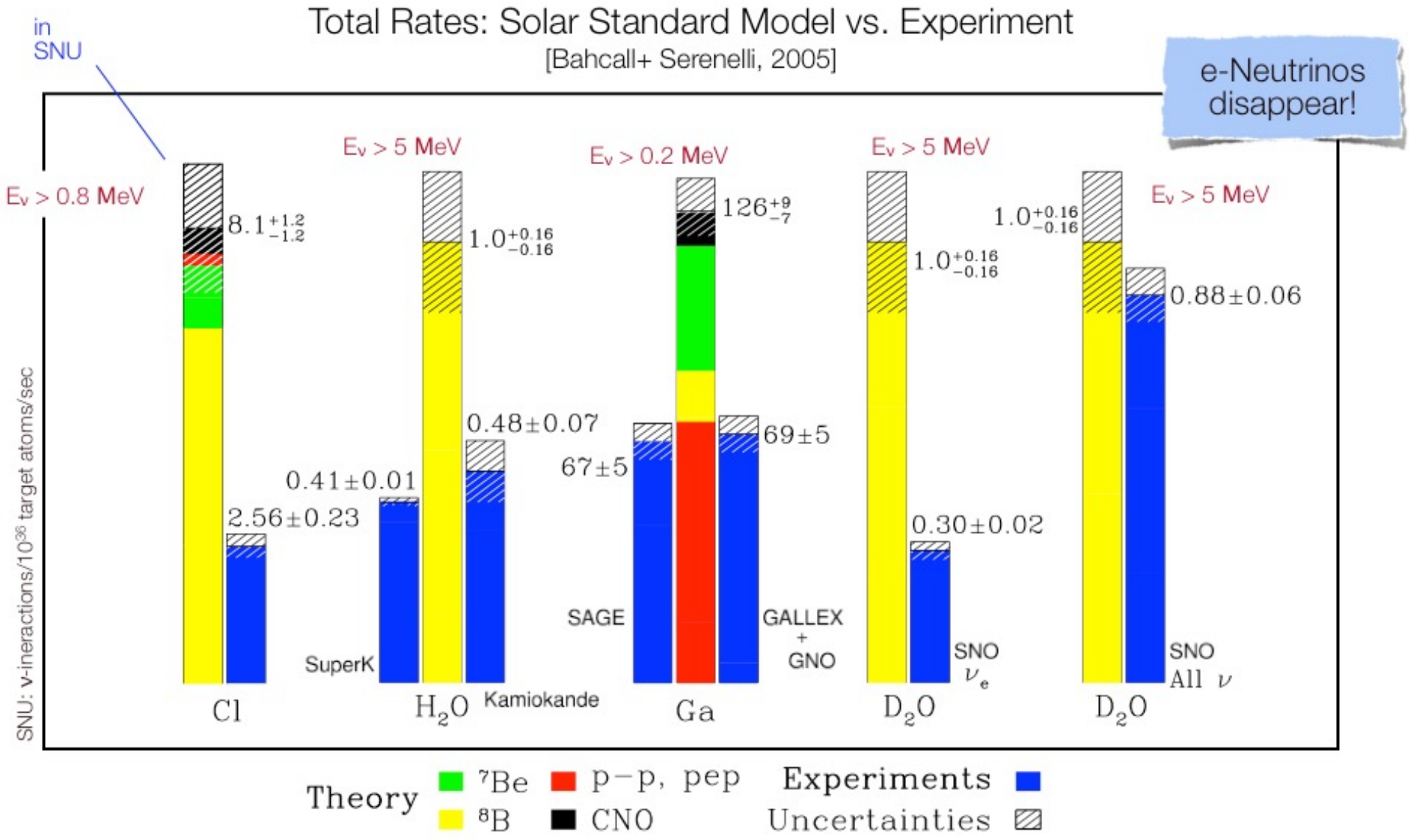
Neutrinos from the Sun



Neutrinos from the Sun



The "solar electron neutrino" problem



Neutrino oscillation

Imagine we send a neutrino on a *long* journey. Suppose neutrino is created in the pion decay

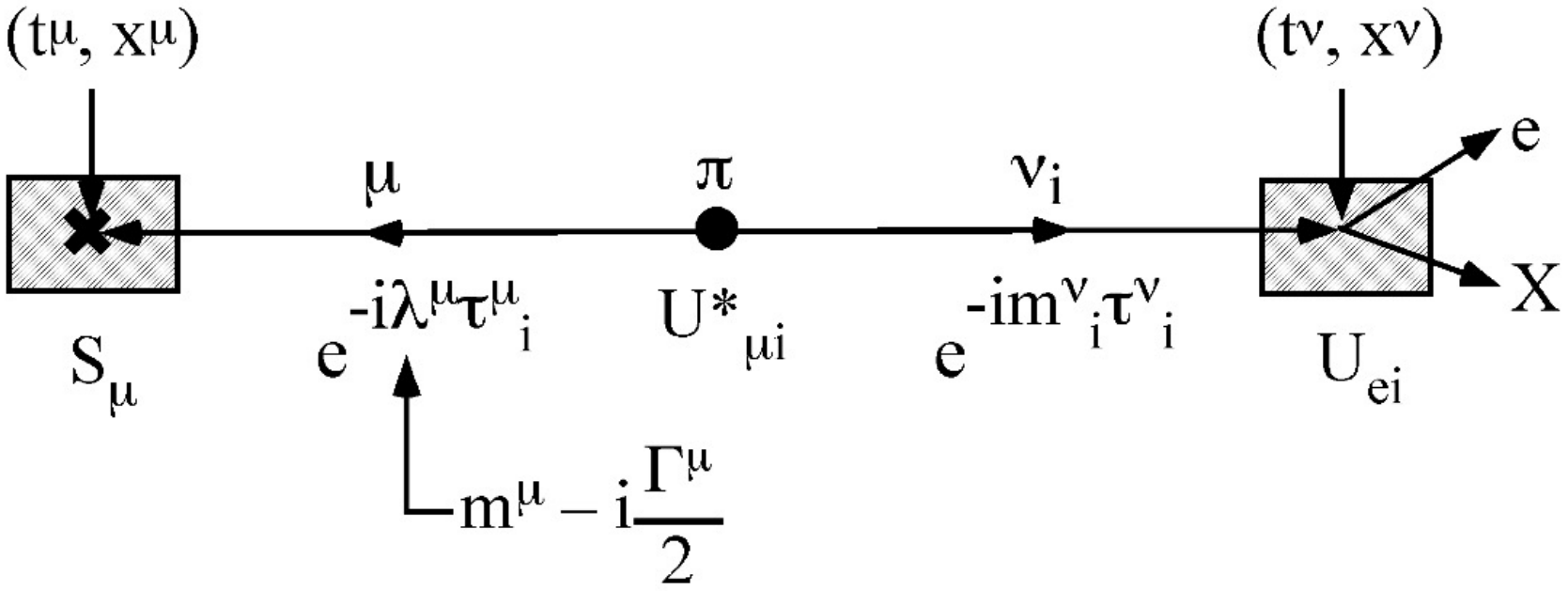
$$\pi \rightarrow \mu \nu_\mu$$

so that at birth it is a muon neutrino. Imagine that this neutrino interacts via *W* exchange in a distant detector, turning into a charged lepton. If neutrinos have masses and leptons mix, then this charged lepton need not be a muon, but could be, say, a tau.

- Neutrinos have masses → there is some spectrum of neutrino mass eigenstates ν_i w/ mass $m_{\nu i}$
- Leptons mix → neutrinos of definite flavor, ν_e, ν_μ, and ν_τ , are not mass eigenstates ν_i.

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \qquad U = \begin{array}{c} \\ e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \end{array}$$

Probability of neutrino oscillation



$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta;\, L, E) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re\mathrm{e}\,(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$\overset{+}{(-)}\,2\sum_{i>j} \Im\mathrm{m}\,(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin(\Delta m^2_{ij}\frac{L}{2E})$$

For full calculation see for instance Boris Kayser "Neutrino Oscillation Physics" http://arxiv.org/abs/1206.4325

(Simplified) probability of neutrino oscillation

Let's forget the imaginary part of U (assume neutrinos and antineutrinos behave the same) and suppose only 2 flavors…

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

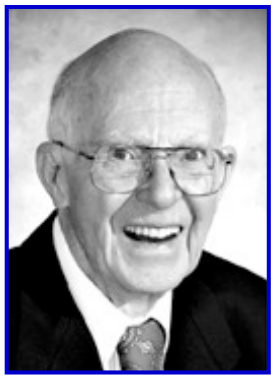
$$P(l \to l') = 2\cos^2\theta\sin^2\theta - 2\cos^2\theta\,\sin^2\theta\,\cos\frac{m_j^2 - m_k^2}{2E}L$$

$$= 2\cos^2\theta\,\sin^2\theta\left(1 - \cos\frac{m_j^2 - m_k^2}{2E}L\right) = 4\cos^2\theta\,\sin^2\theta\,\sin^2\left(\frac{m_j^2 - m_k^2}{4E}L\right)$$

$$= \sin^2 2\theta\,\sin^2\left(\frac{m_j^2 - m_k^2}{4E}L\right)$$

Nobel Prize 2002

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba "*for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos*" and the other half to Riccardo Giacconi "*for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources*".

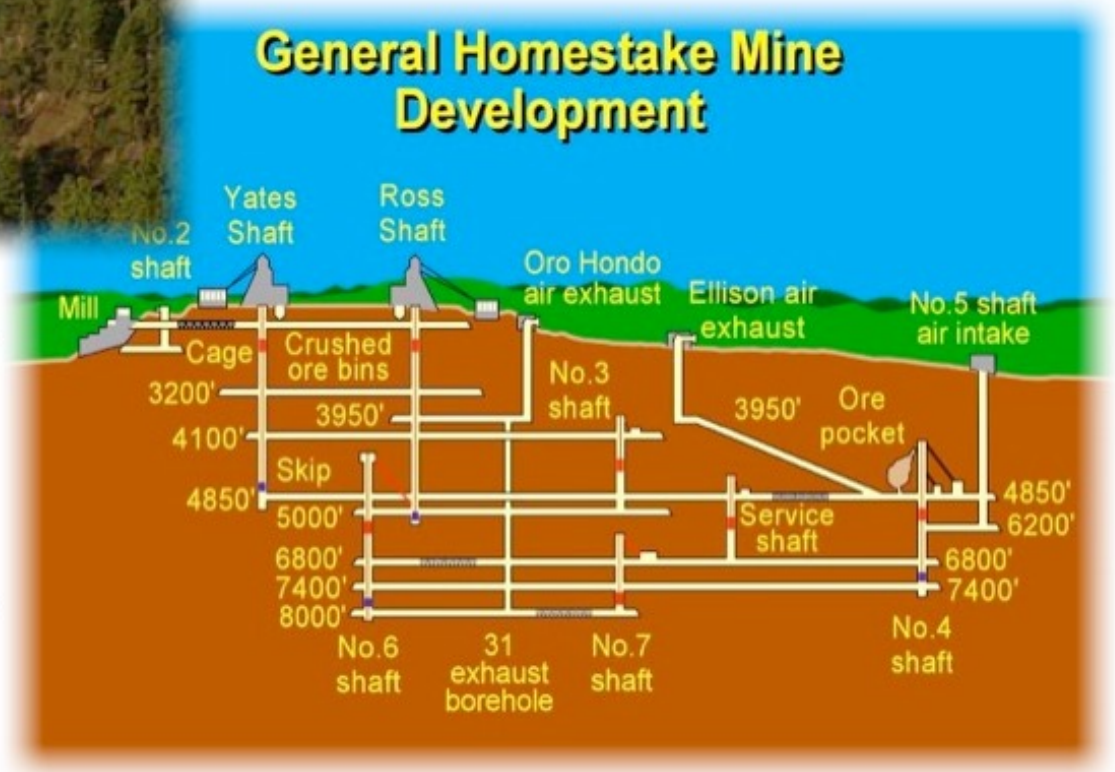


Raymond Davis Jr.
[Homestake]

Masatoshi Koshiba
[Kamiokande]

Riccardo Giacconi
[X-Ray Sources]

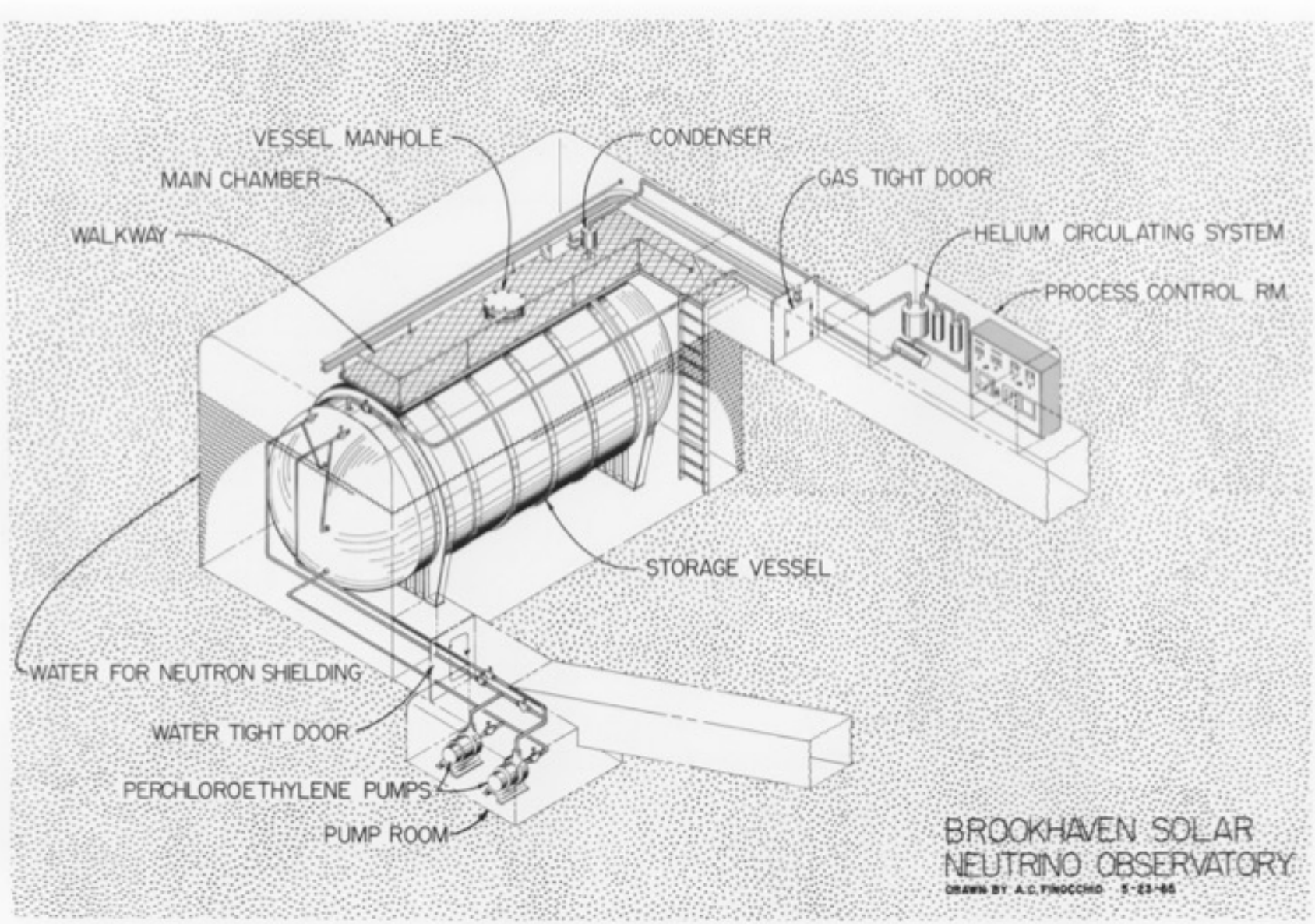
The Homestake experiment



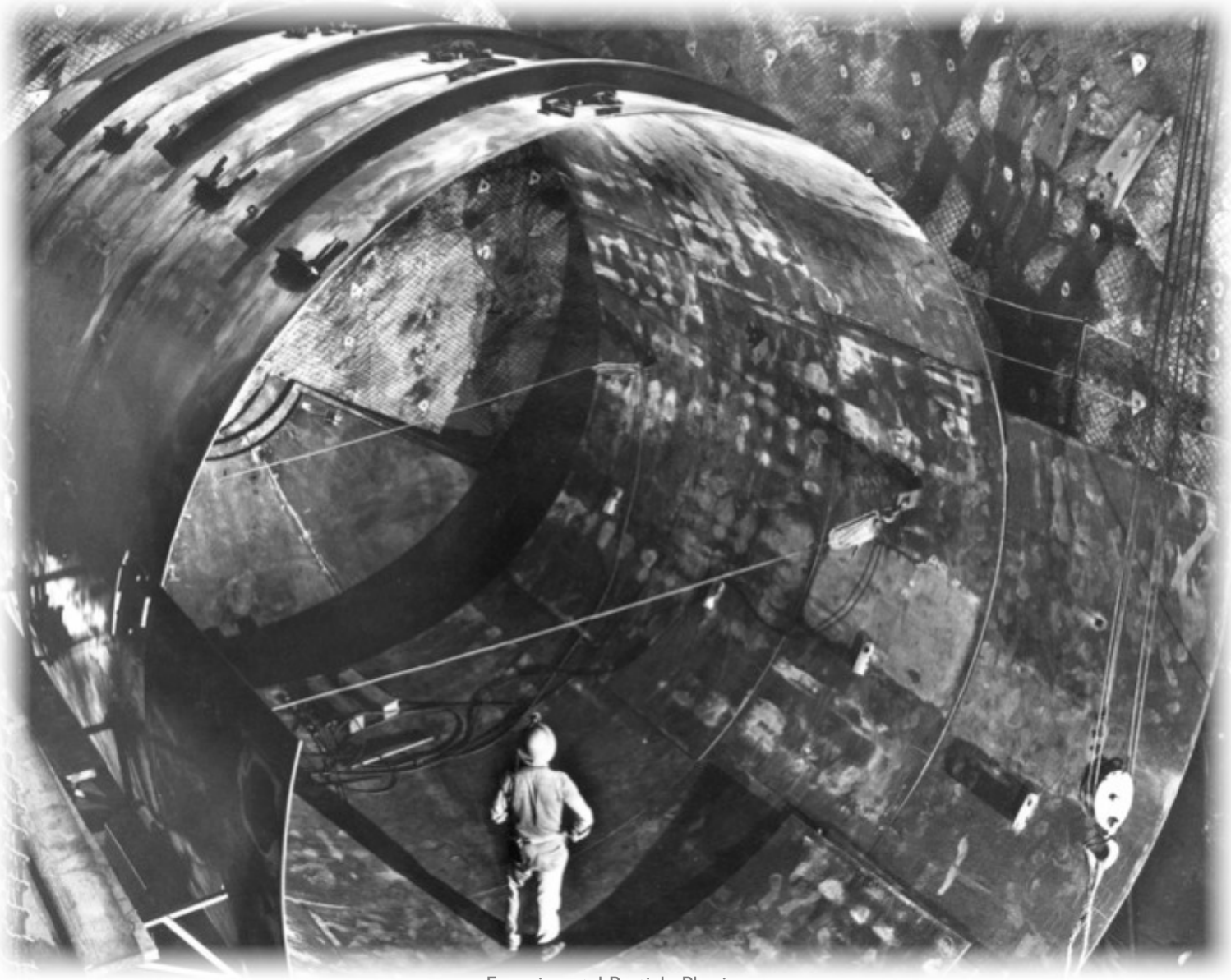
ca. 2500 m

The Homestake Mine

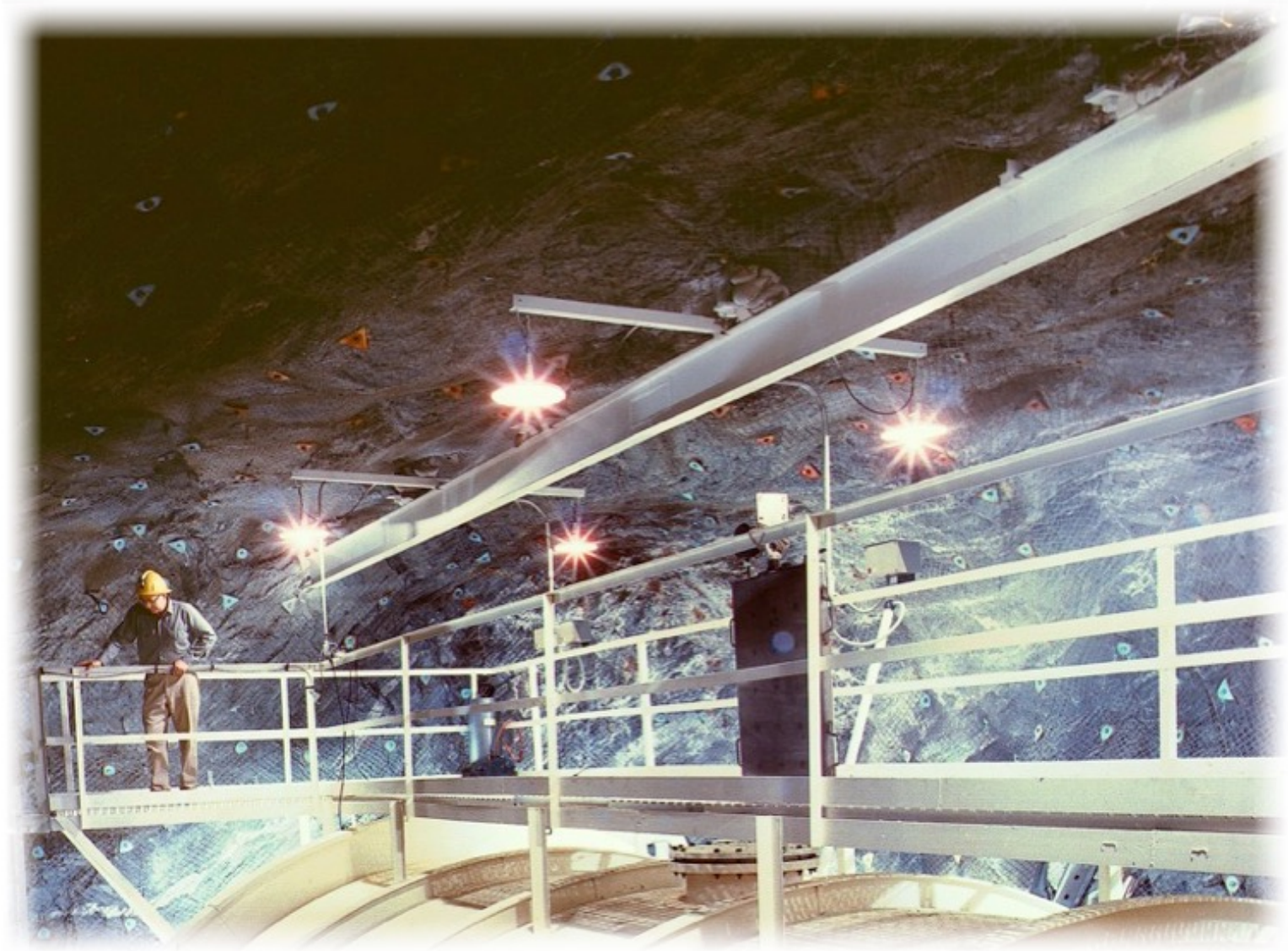
The Homestake experiment



The Homestake experiment



The Homestake experiment



The Homestake experiment

Neutrino capture:

Lifetime: 35 days

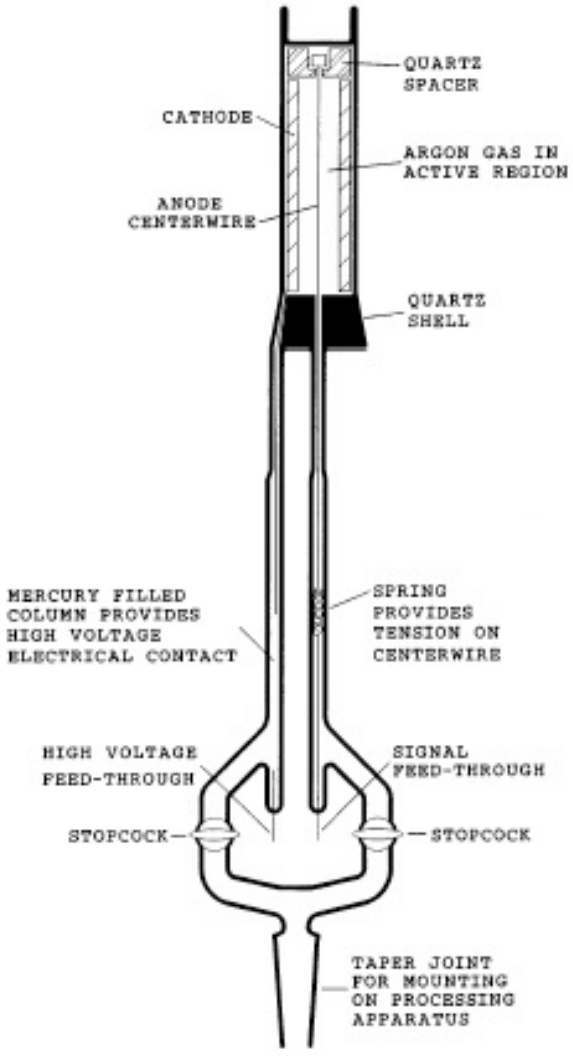
$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e$$

Detection of ^{37}Ar via e^--capture [$^{37}Ar(e,\nu_e)^{37}Cl$]; $\tau \approx 35$ days

results in Auger-electron @ 2.82 keV which after extraction is detected in proportional counter

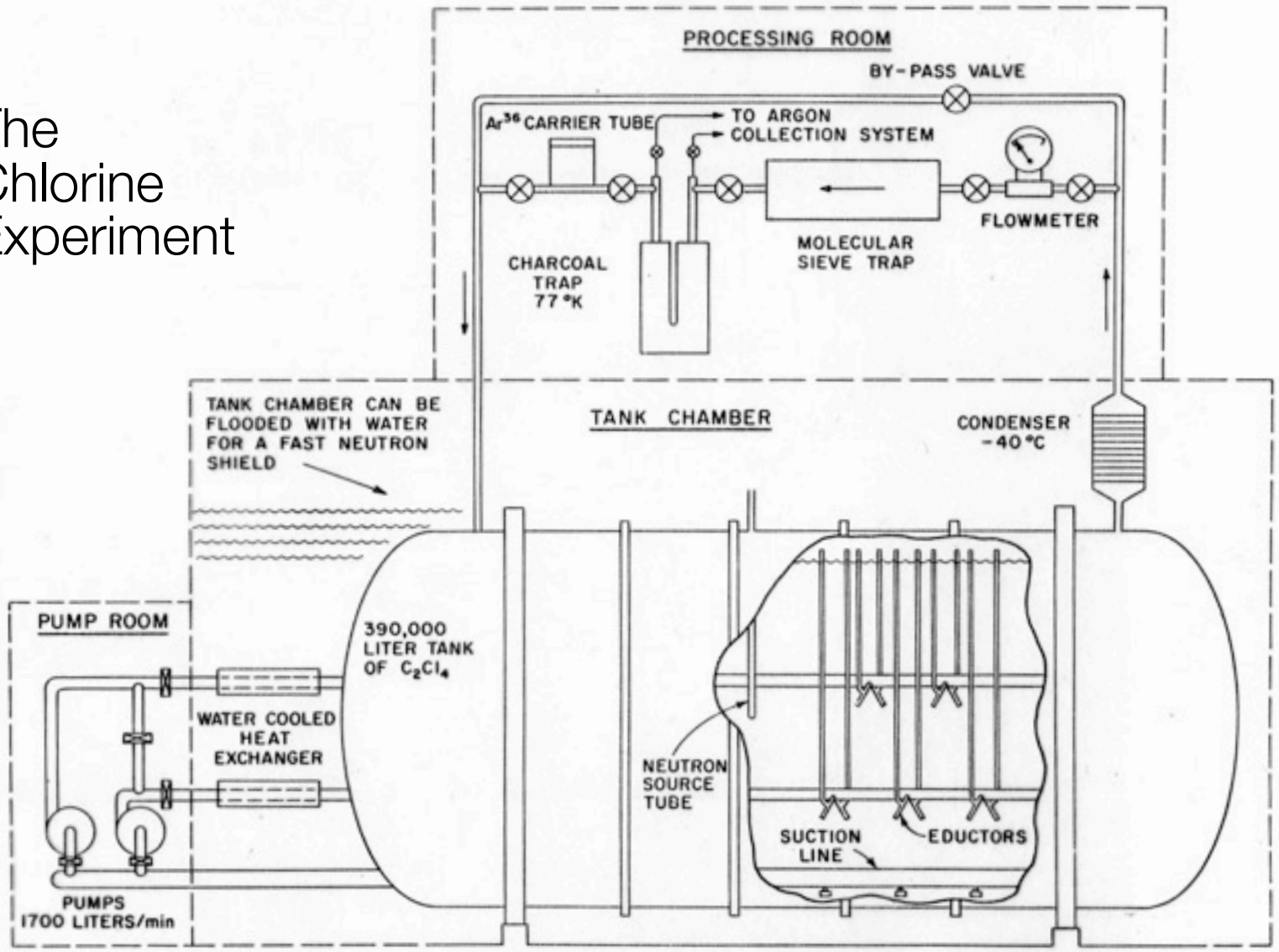
Experimental details:

- 615 tons of C_2Cl_4
- Threshold: 814-keV threshold
- Bubble He gas through to extract Ar [every 2-3 month]
- Ar trapped in cold trap
- Proportional Counter filled with Ar gas (7% methane)
- Important: ^{37}Cl is 24% abundant.



The Homestake experiment

The Chlorine Experiment



The Homestake experiment

Some very approximate numbers ...

- 615 tons C_2Cl_4 (Tetrachloroethelene)
- About 5 x 10^{29} Chlorine Atoms (^{37}Cl)

6 Atoms/Molecule

- Prediction: 8 x 10^{-36} ν-reactions/atom/sec
  i.e.: about 60 ^{37}Ar-atoms/month;
  but: half-life = 35 days ➛ 30 atoms/month

- Expect: 60 atoms every 2 month out of
  ca. 10^{30} Tetrachloroethelene molecules

- After 25 years:

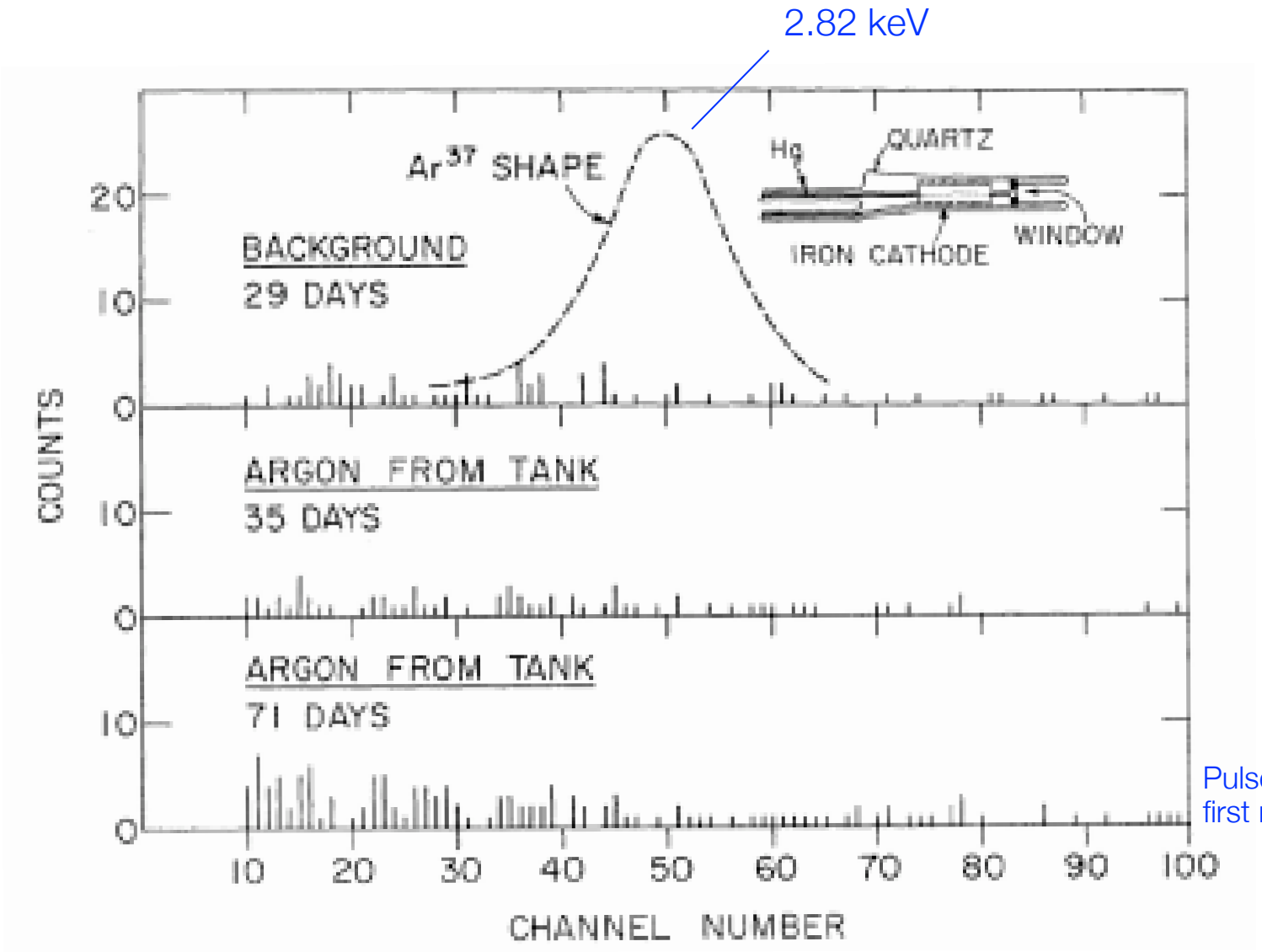
  Expectation: ~ 5000 ^{37}Ar-Atoms expected
  Observation: ~ 2200 ^{37}Ar-Atoms produced

  [875 counted; 776 after background subtraction]

^{37}Ar-Extraction Efficiency: ~ 95%

^{37}Ar-Detection Efficiency: ~ 45%

The Homestake experiment

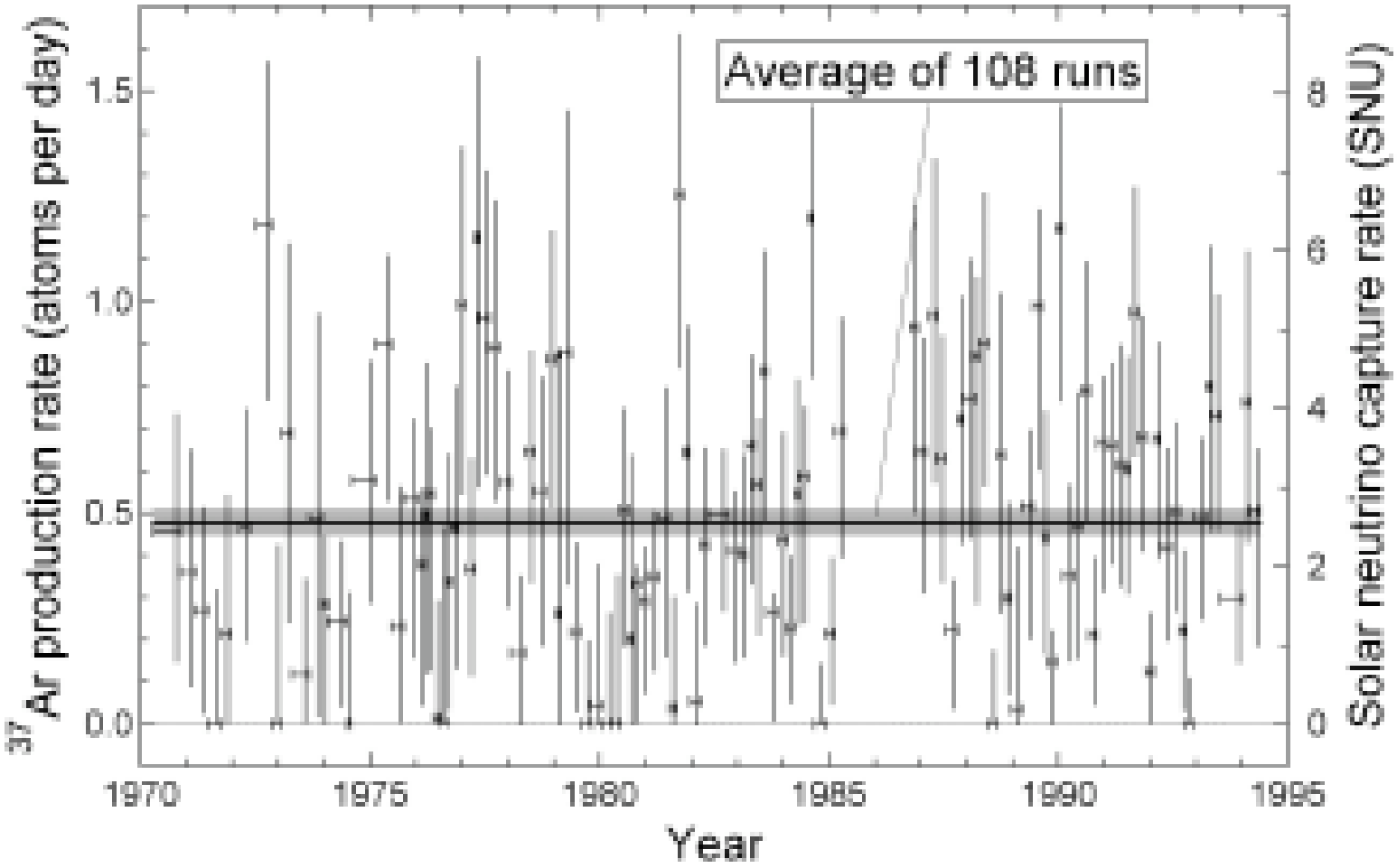


Pulse height Spectra from first runs [1968]

The Homestake experiment

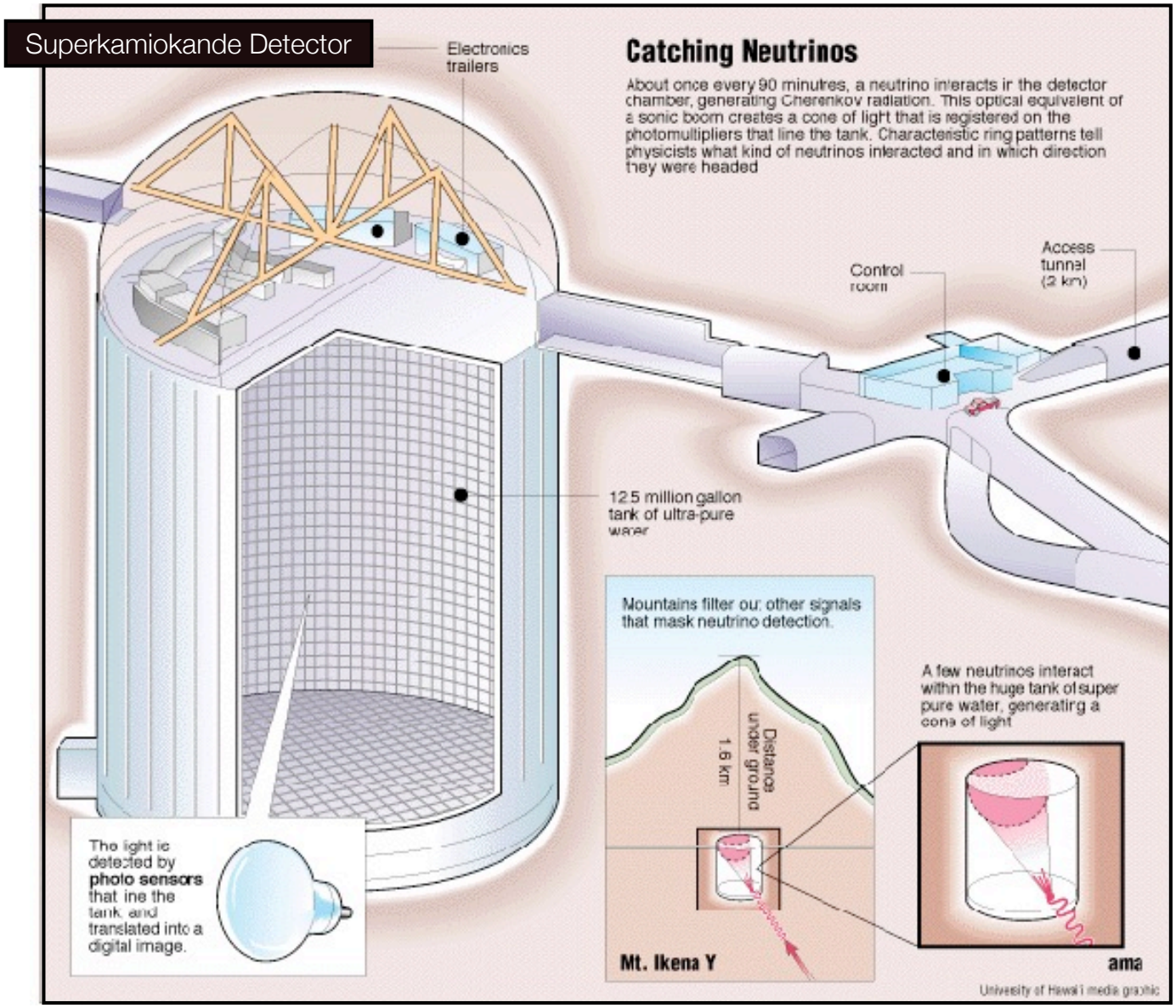
Result of 25 years of running

[after implementation of rise time counting]



2.56 SNU

Super-Kamiokande



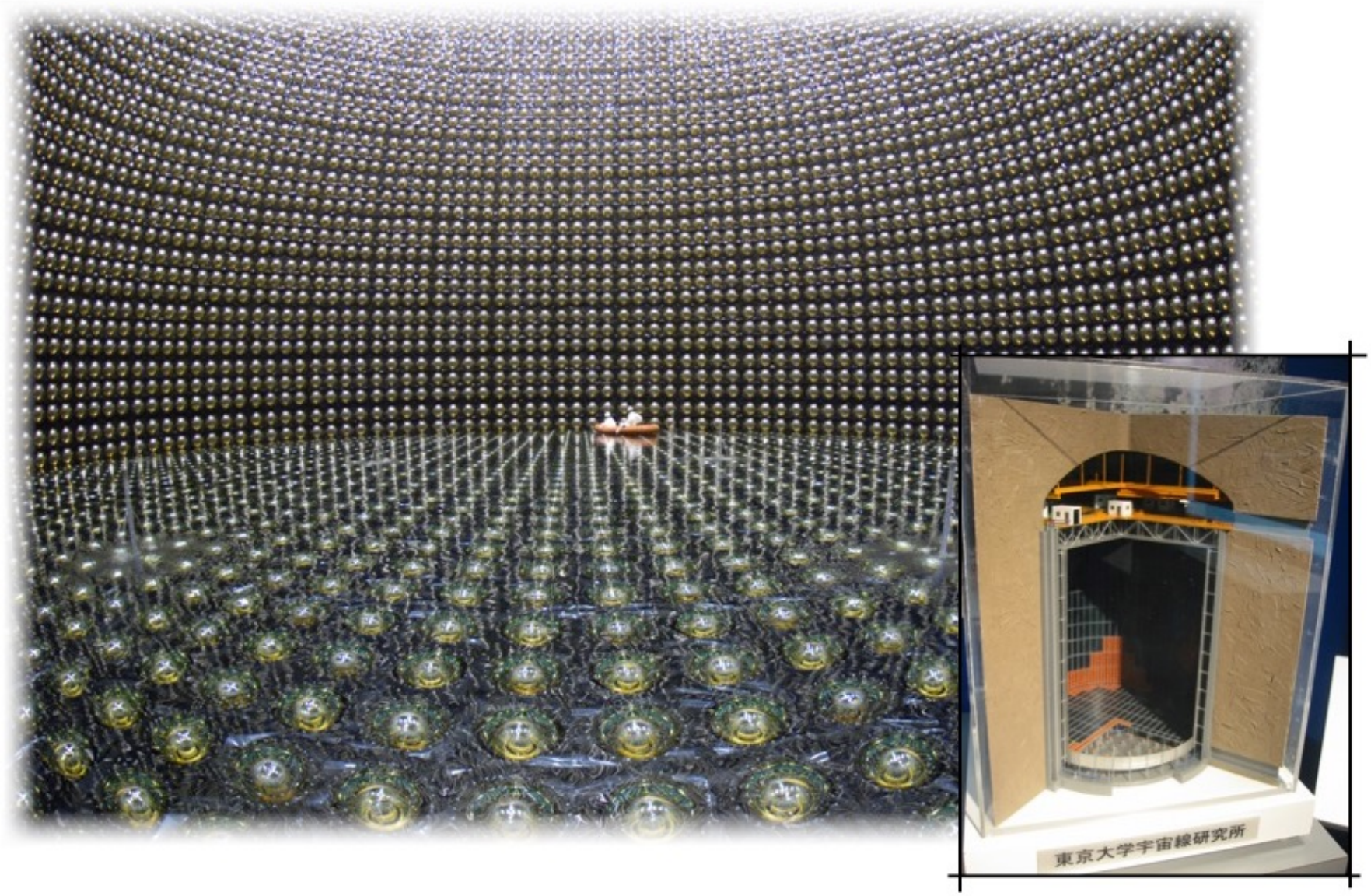
Water tank
1.6 km below ground

50 Million liter
ultra-pure water

1 Neutrino-interaction
every 1.5 hours

Neutrino detection
via Cherenkov light

Super-Kamiokande

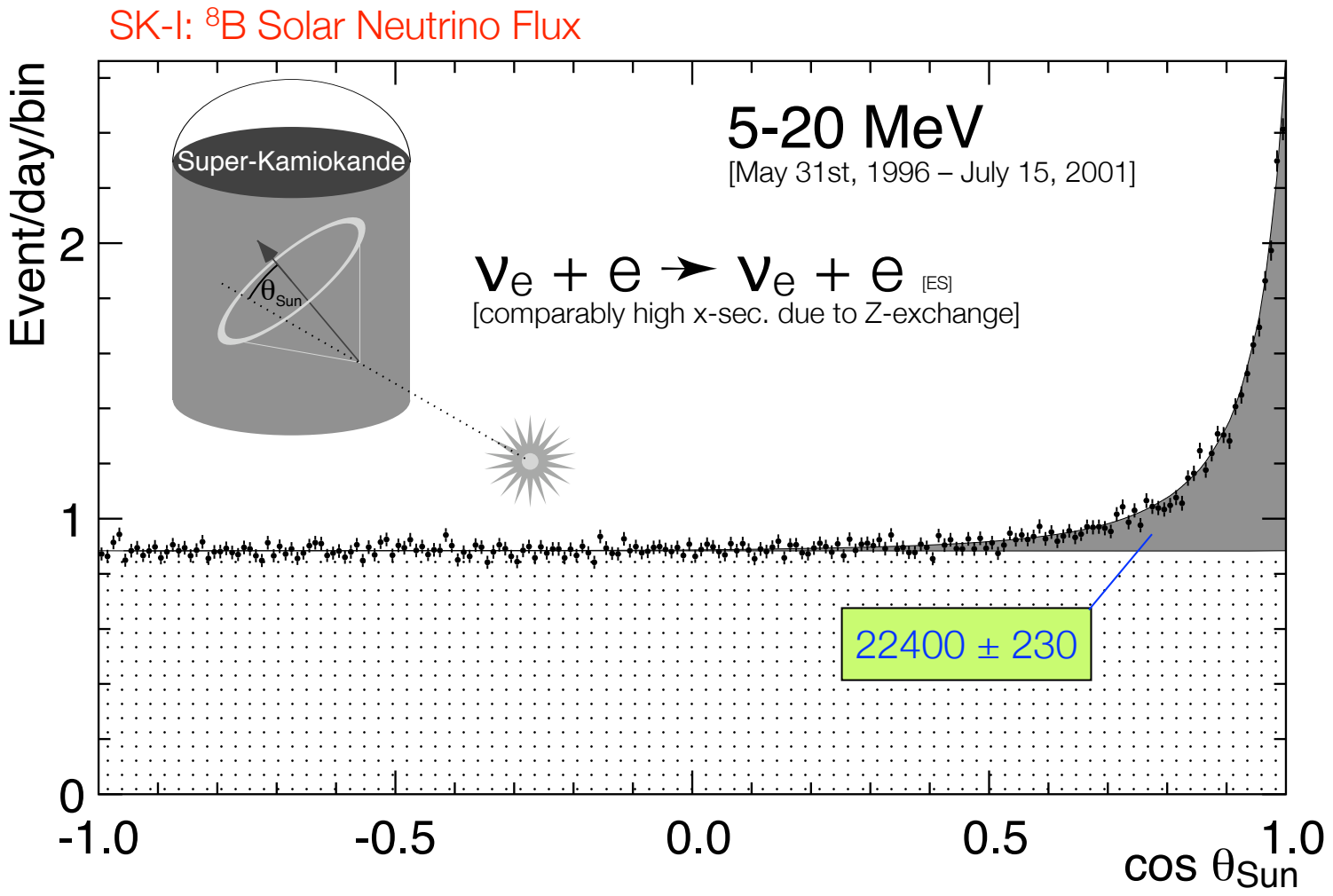


Super-Kamiokande

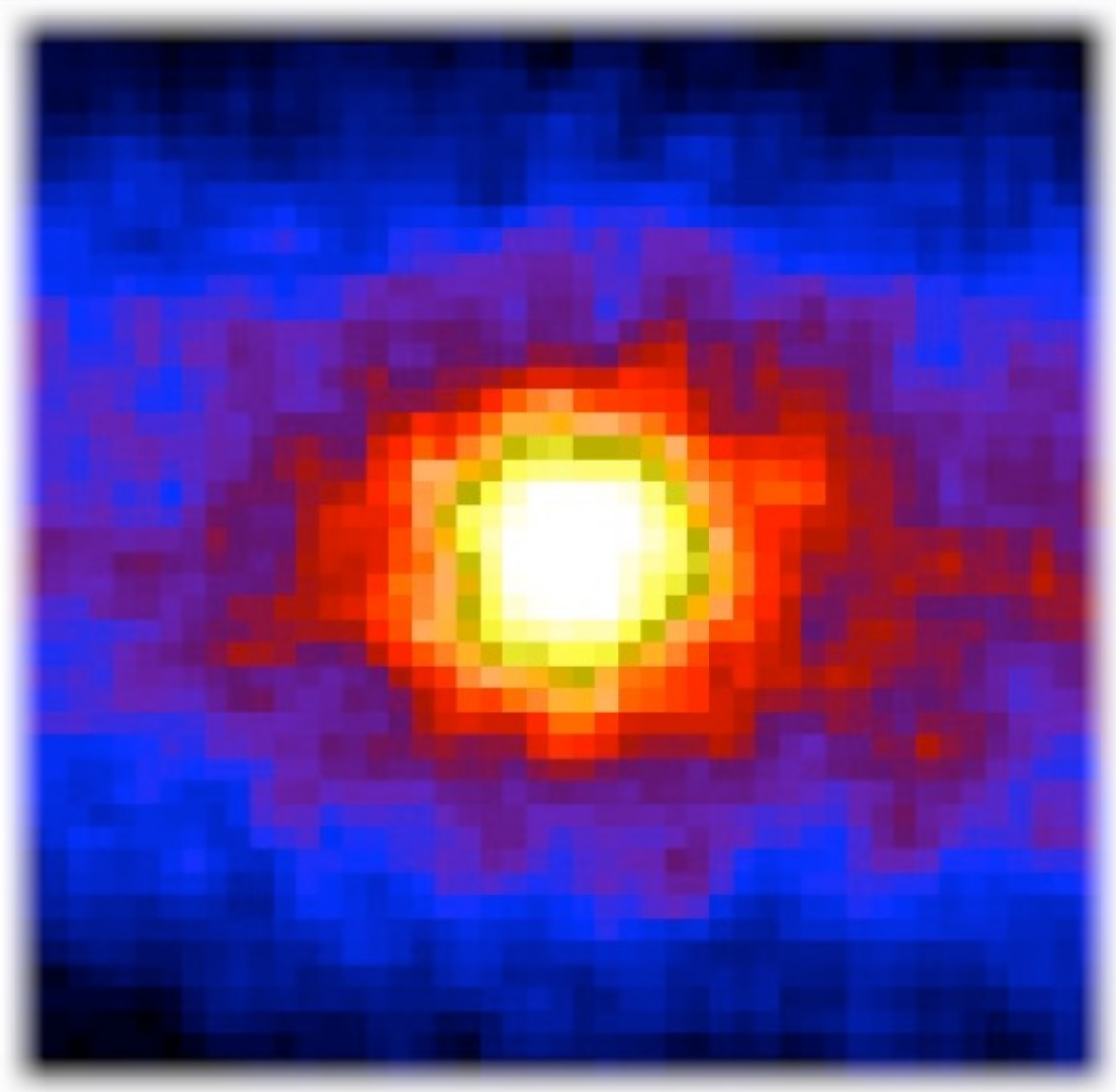
Mounting of
Photomultiplier Tubes

Total:	11,146	20″ pmts
	1,885	8″ pmts

Super-Kamiokande

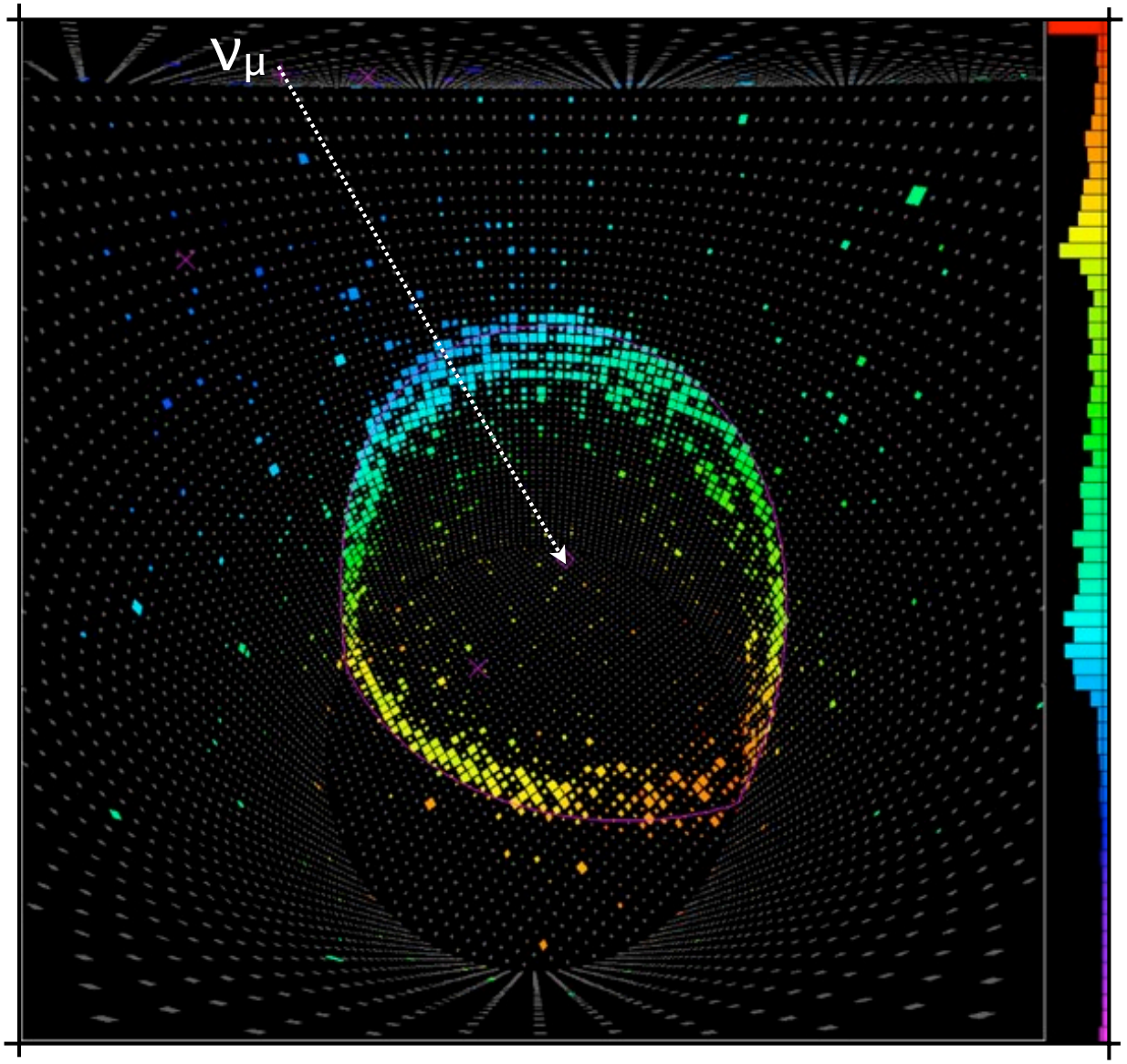


Super-Kamiokande



The sun seen
through the earth
in neutrino light

Super-Kamiokande



Muon event

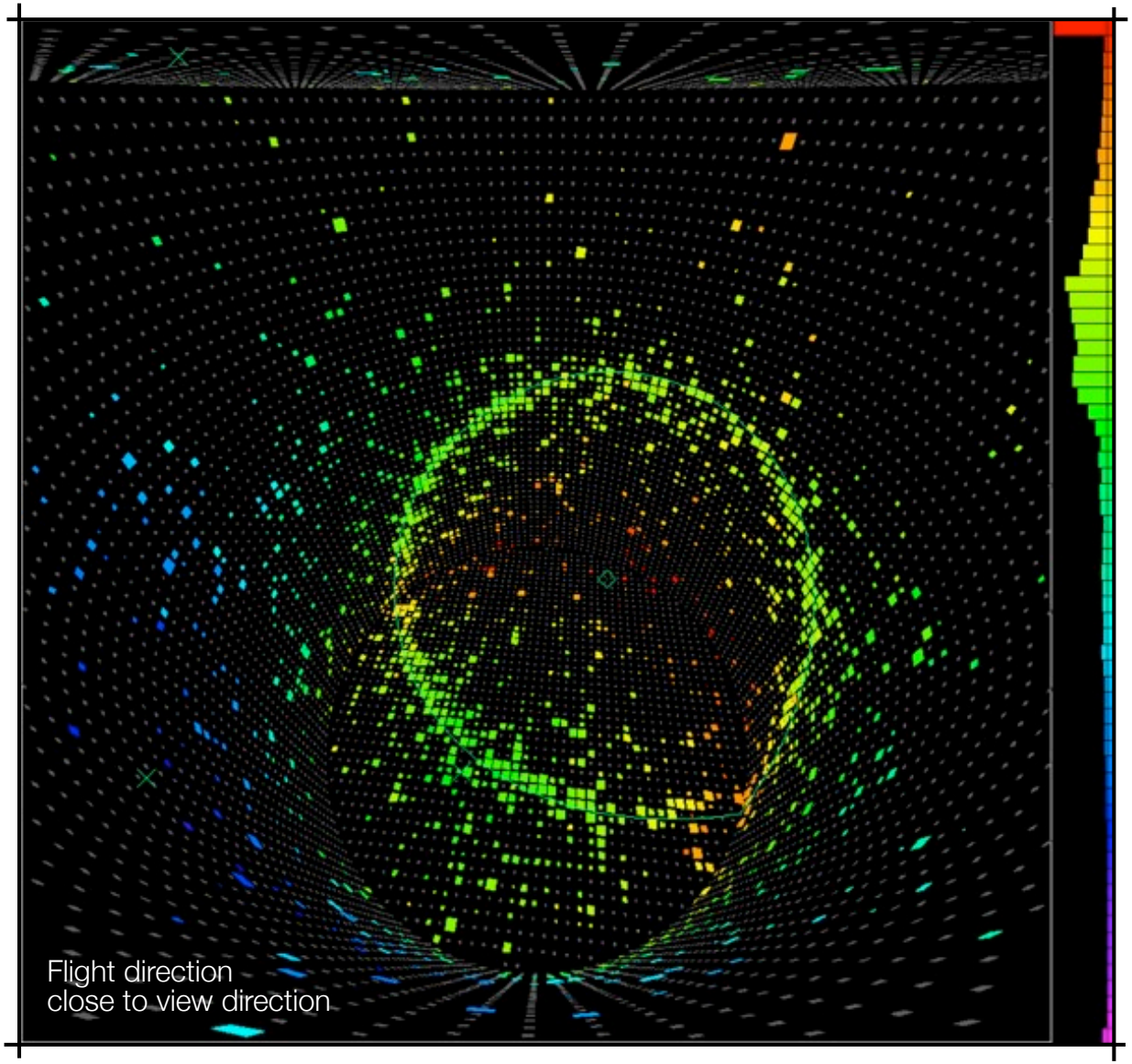
[603 MeV]

Observation of
clean Cherenkov ring
with sharp edges

Flight direction from
timing measurements
[blue: early; red: late]

Energy from amount
of light observed in PMTs

Super-Kamiokande



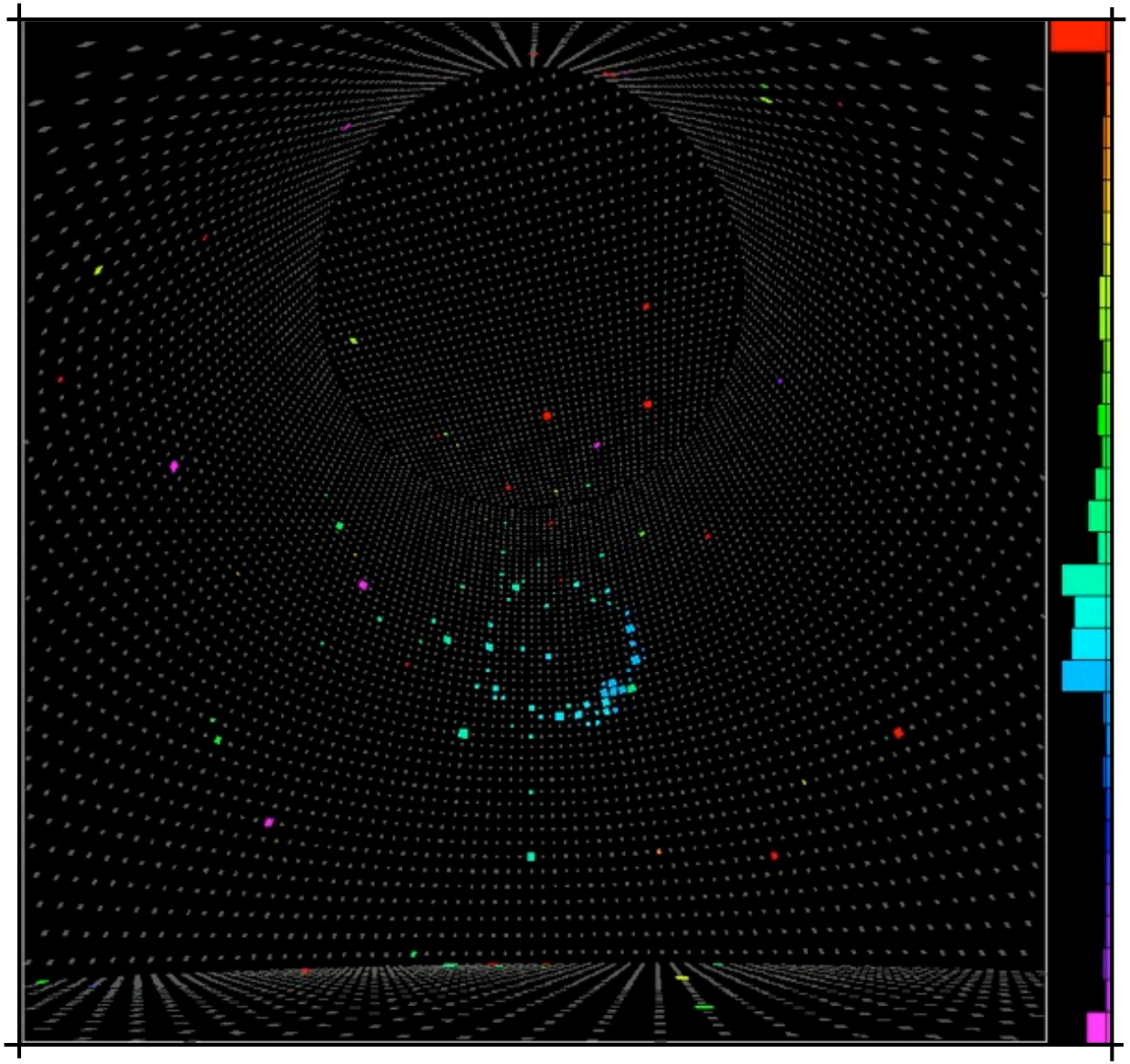
Electron event
[492 MeV]

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 PMTs

Super-Kamiokande



Solar neutrino
[12.5 MeV]

Unusually nice,
well-defined

Flight direction from
timing measurements
[blue: early; red: late]

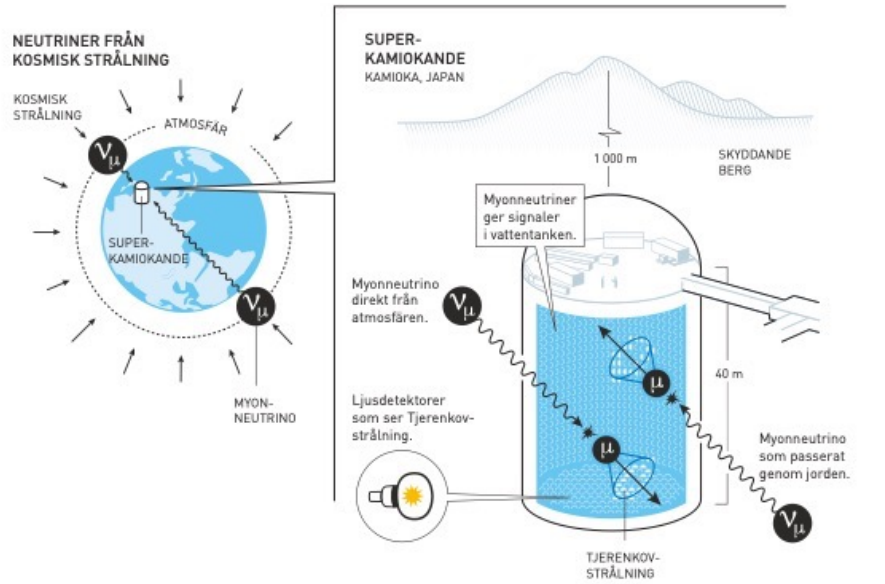
Energy from amount
of light observed in PMTs

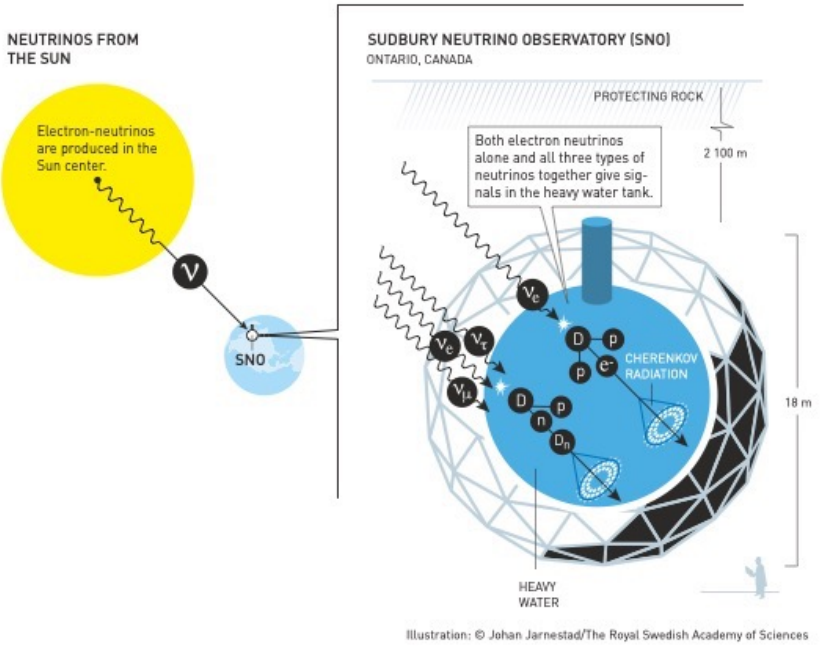
Nobel Prize 2015

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "*for the discovery of neutrino oscillations, which shows that neutrinos have mass*."

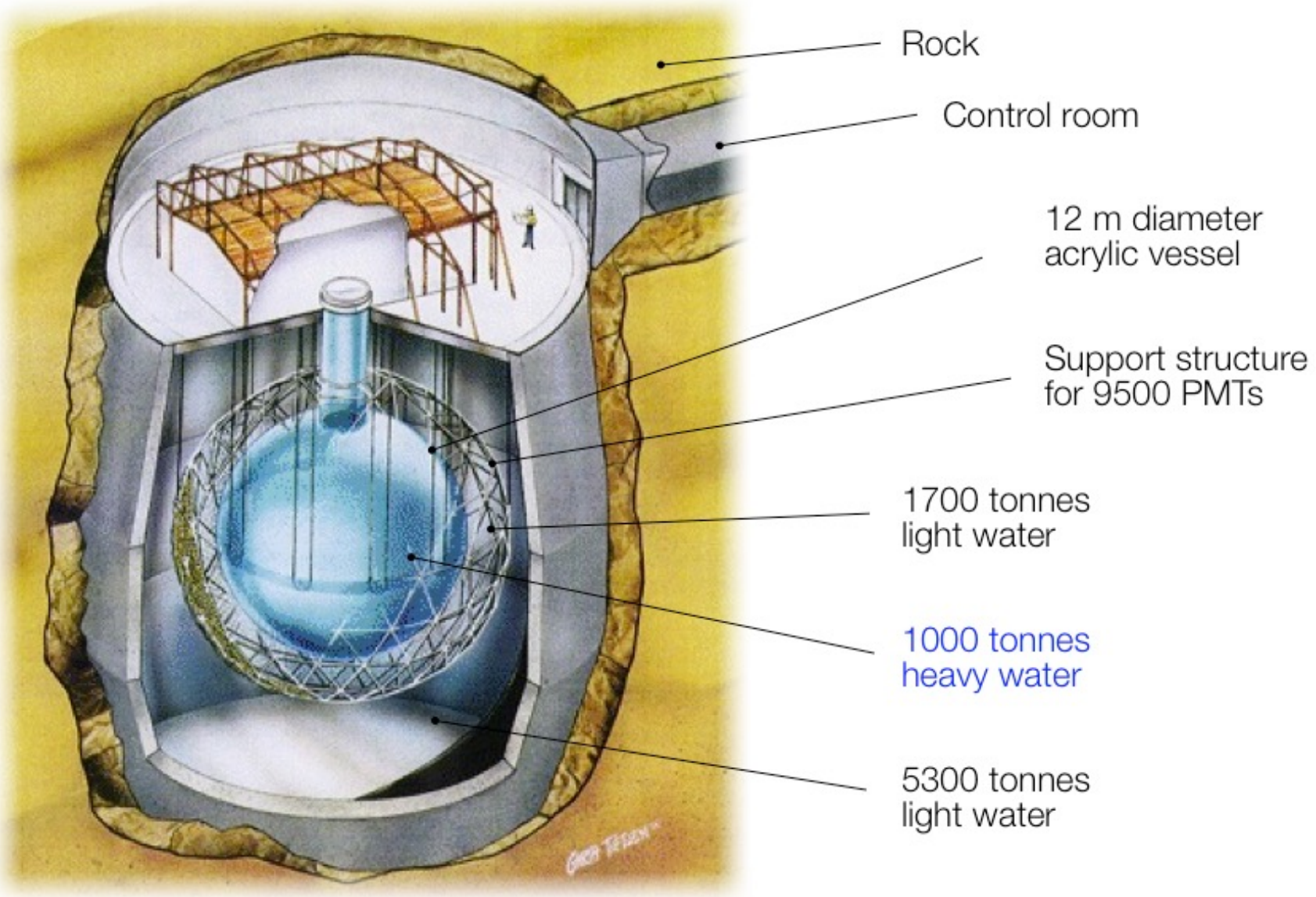
Takaaki Kajita

Arthur B. McDonald

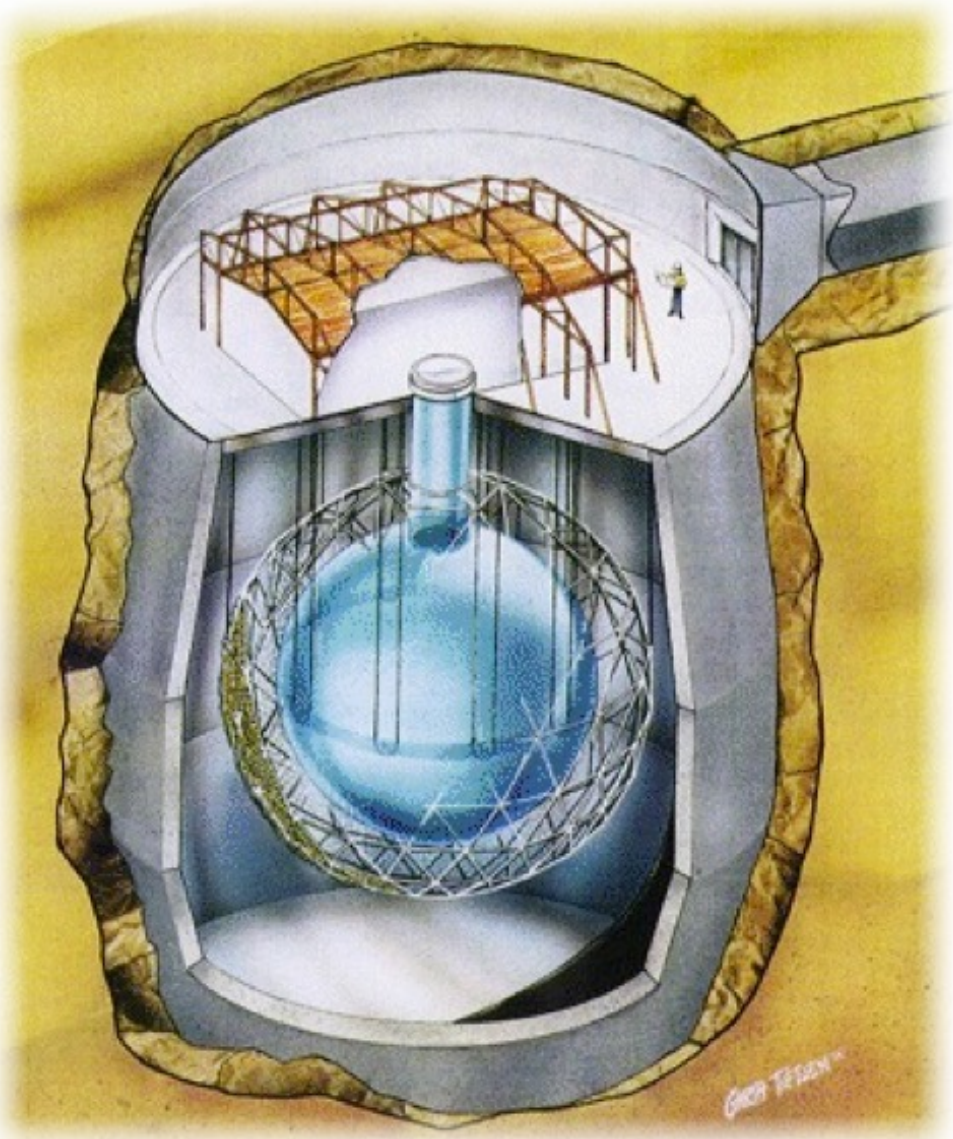




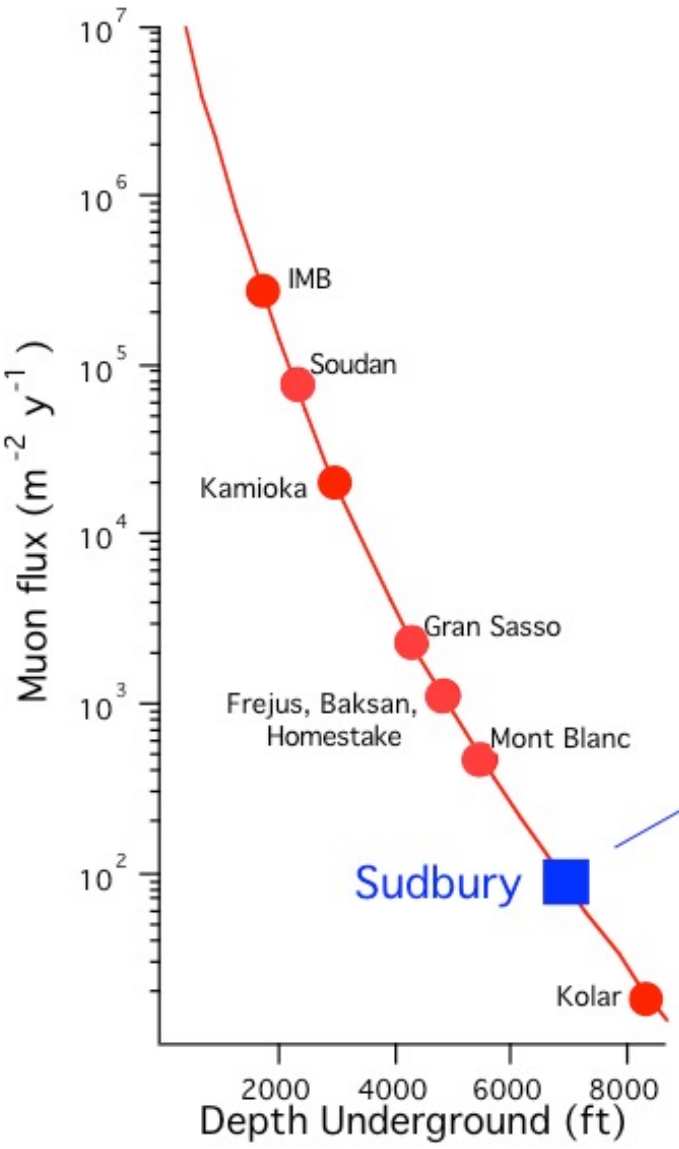
The SNO experiment



The SNO experiment



The SNO experiment



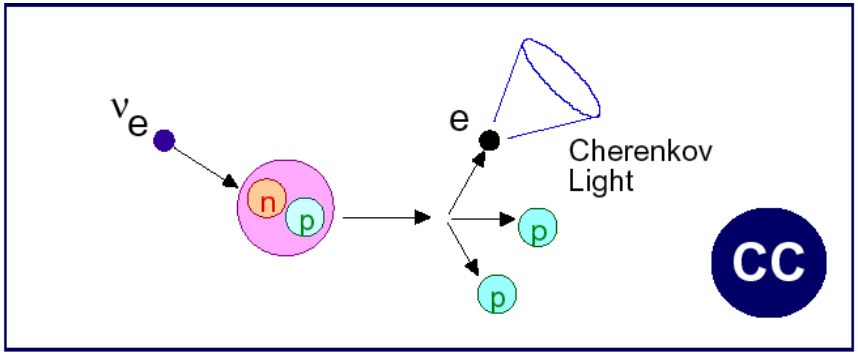
More than 2 km below ground

Background: < 100 μ/day

The SNO experiment

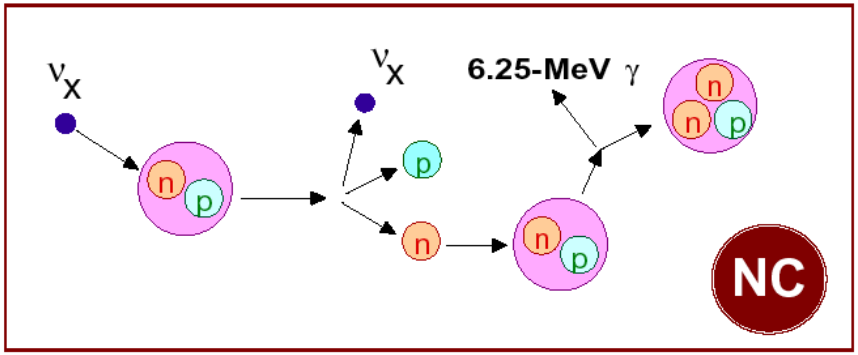
CC $\nu_e + d \rightarrow p + p + e^-$

- Measurement of ν_e energy spectrum
- Weak directionality: $1 - 0.340\cos\theta$



NC $\nu_x + d \rightarrow p + n + \nu_x$

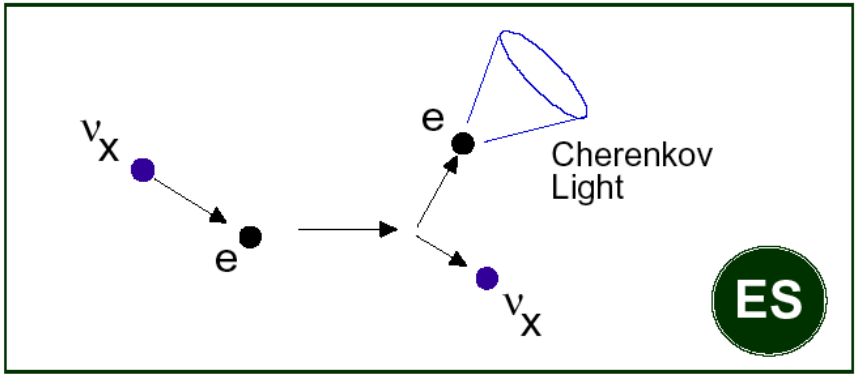
- Measure total ^{8}B ν flux from the sun
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$



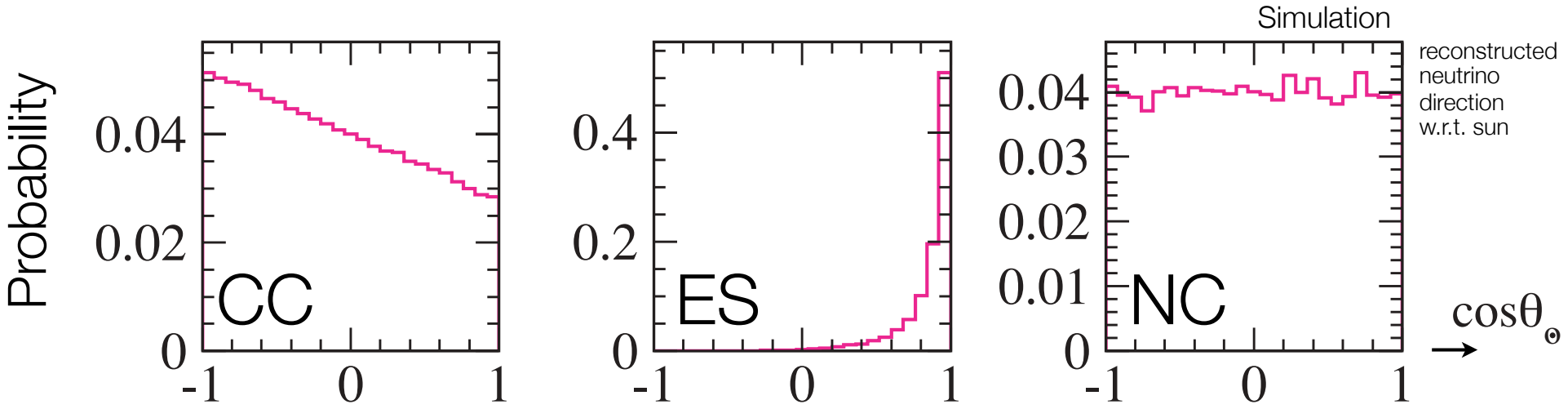
ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- Low Statistics
- $\Sigma\phi = \phi(\nu_e) + 0.154\ \phi(\nu_\mu + \nu_\tau)$
- Strong directionality:

$\theta_e \leq 18^o$ (T_e = 10 MeV)

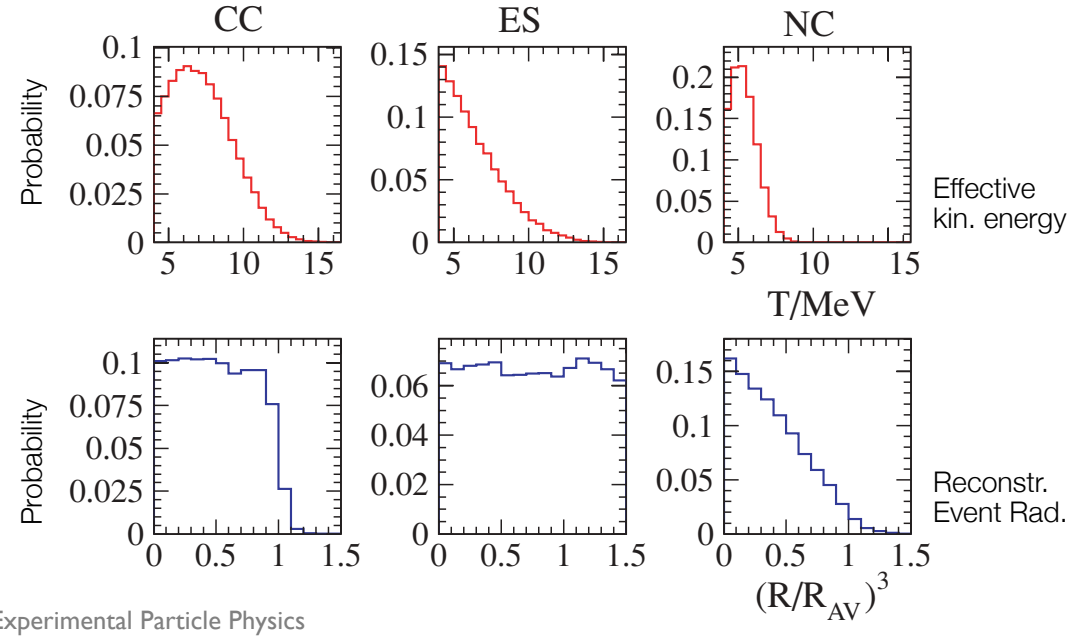


The SNO experiment

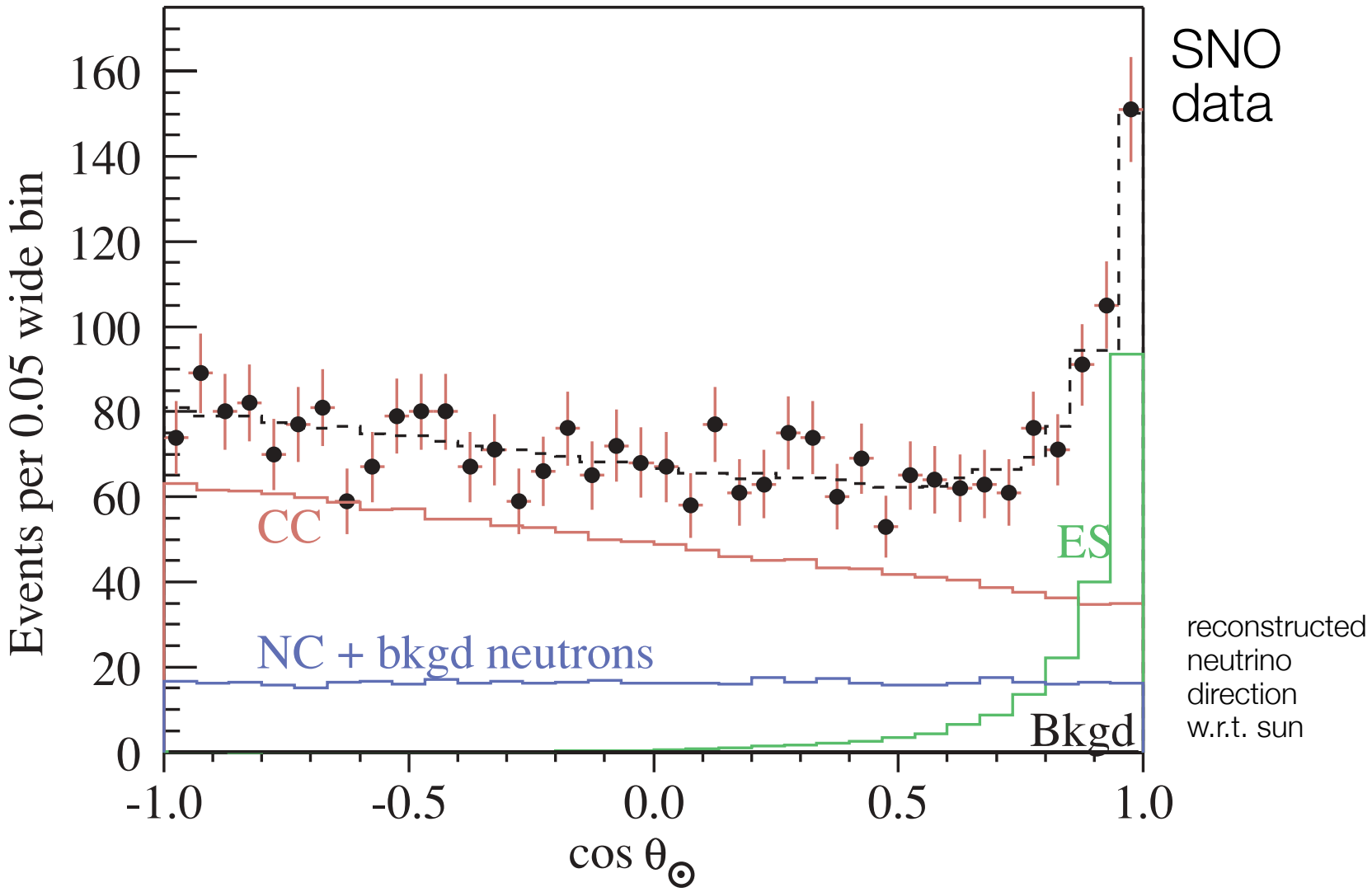


Analysis strategy:

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



The SNO experiment

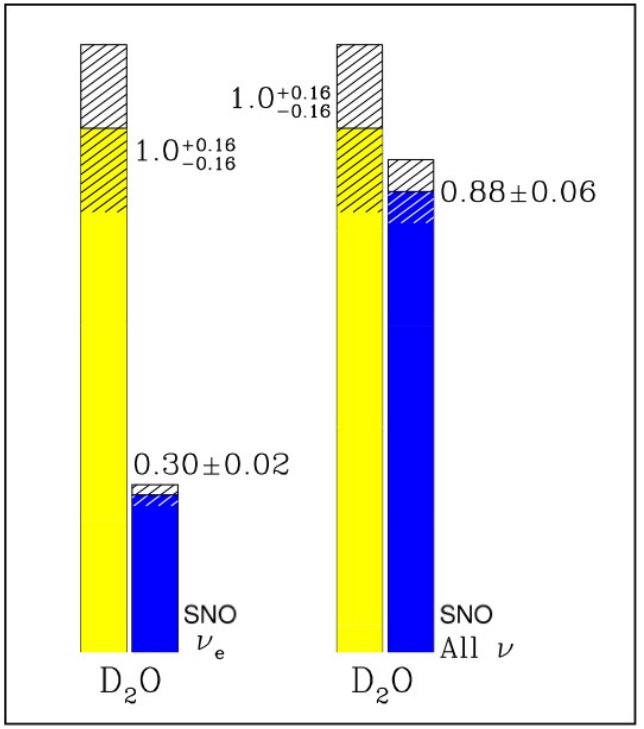


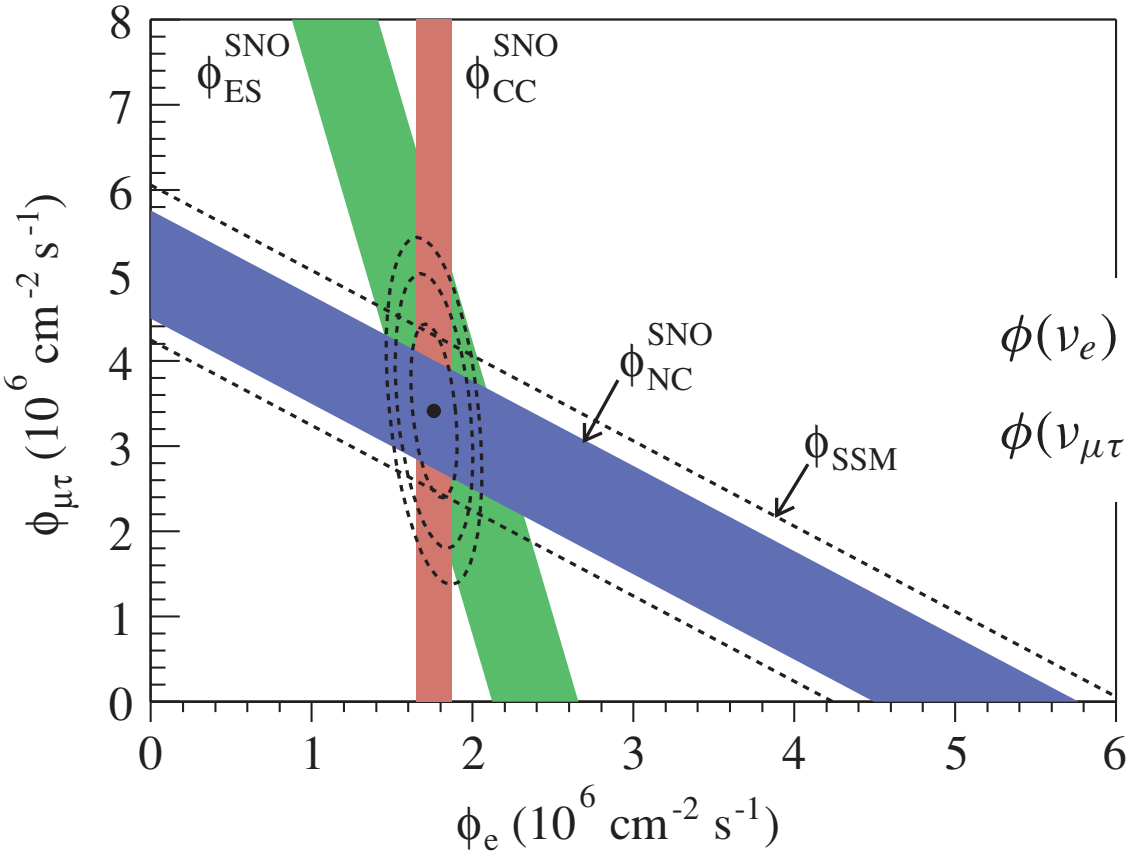
The SNO experiment

$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.}) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\,(\text{stat.})^{+0.12}_{-0.12}\,(\text{syst.}) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{syst.}) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$





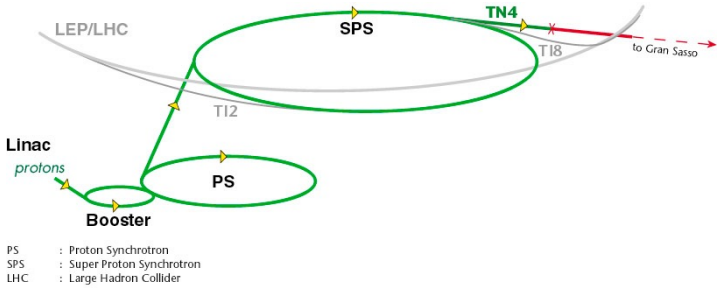
$$\phi(\nu_e) = 1.76^{+0.05}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.})$$

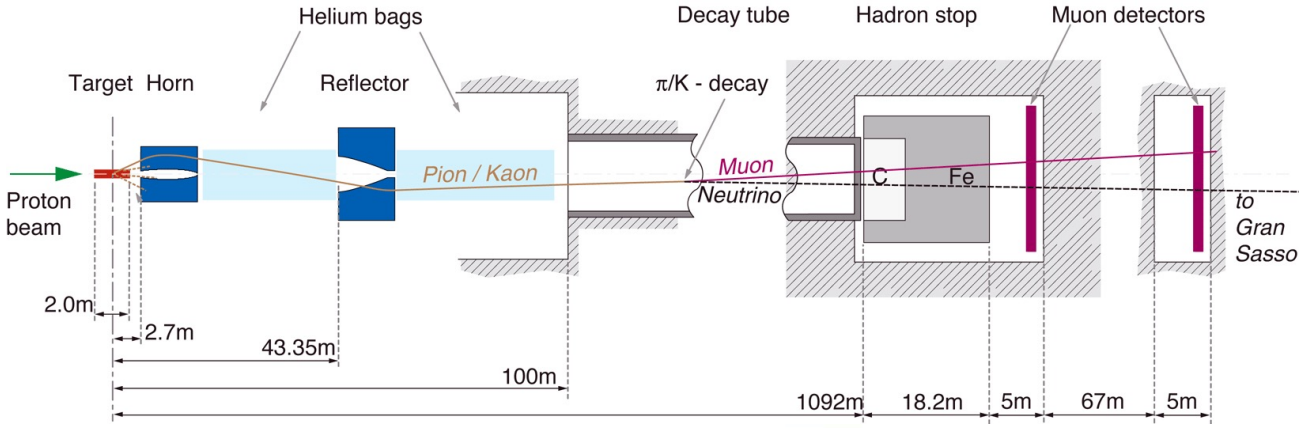
$$\phi(\nu_{\mu\tau}) = 3.41^{+0.45}_{-0.45}\,(\text{stat.})^{+0.48}_{-0.45}\,(\text{syst.})$$

$$\times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

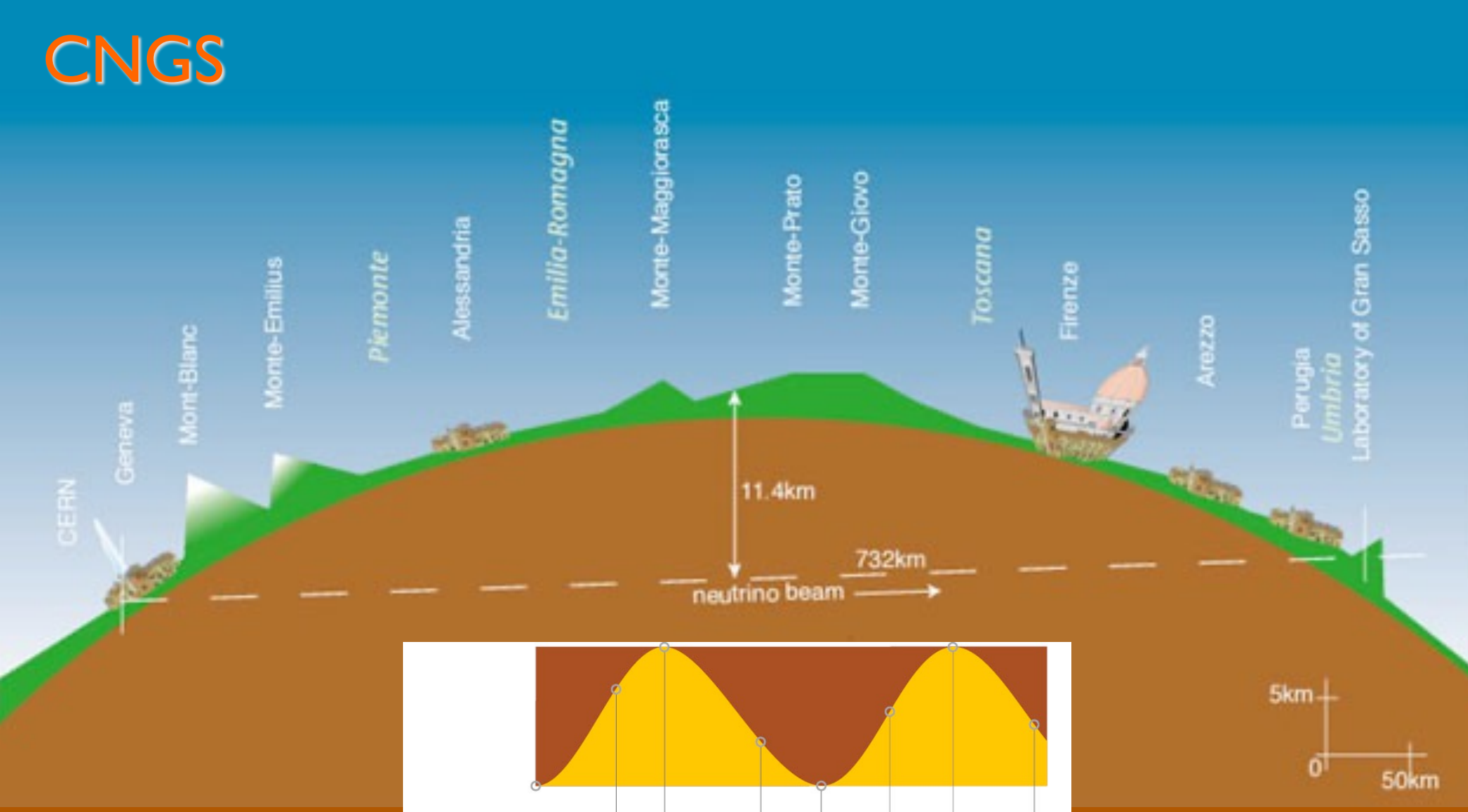
ν_e-flux too low!
Oscillations!

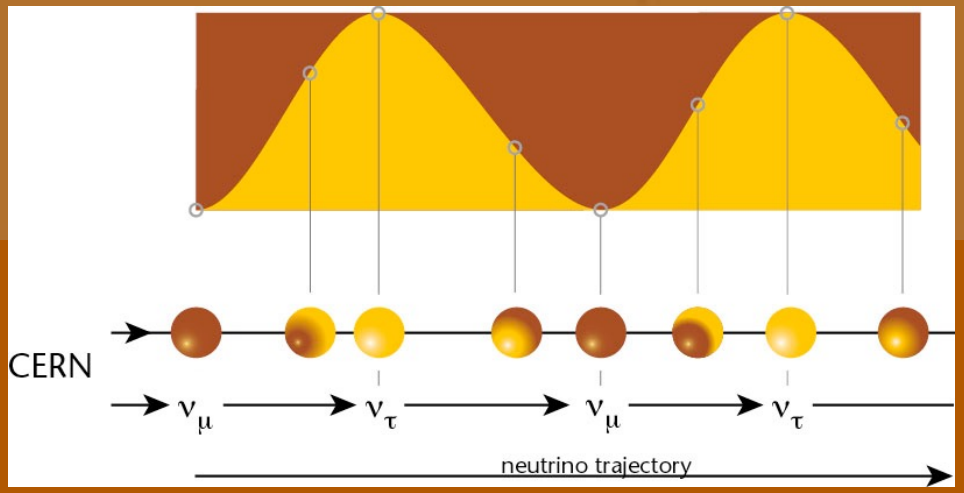
CNGS


LEP/LHC
SPS
TN4
TI8
to Gran Sasso
TI2
Linac
protons
PS
Booster
PS : Proton Synchrotron
SPS : Super Proton Synchrotron
LHC : Large Hadron Collider

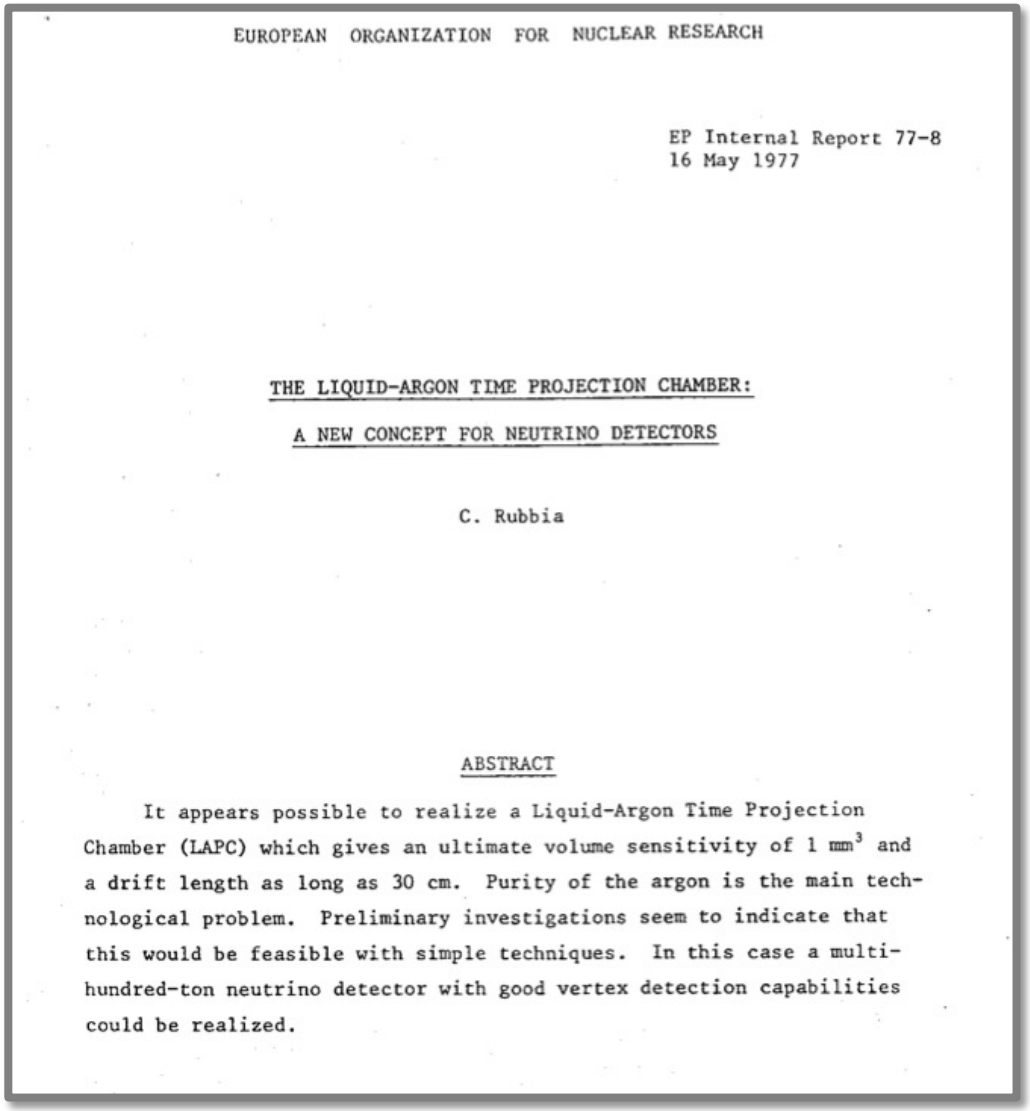

Helium bags
Decay tube
Hadron stop
Muon detectors
Target
Horn
Reflector
π/K - decay
Pion / Kaon
Muon
Neutrino
C
Fe
Proton beam
to Gran Sasso
2.0m
2.7m
43.35m
100m
1092m
18.2m
5m
67m
5m

CNGS


CERN
Geneva
Mont-Blanc
Monte-Emilius
Piemonte
Alessandria
Emilia-Romagna
Monte-Maggiorasca
Monte-Prato
Monte-Giovo
Toscana
Firenze
Arezzo
Perugia
Umbria
Laboratory of Gran Sasso
11.4km
732km
neutrino beam
5km
0
50km


CERN
ν_μ
ν_τ
ν_μ
ν_τ
neutrino trajectory

TPC as neutrino detectors



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

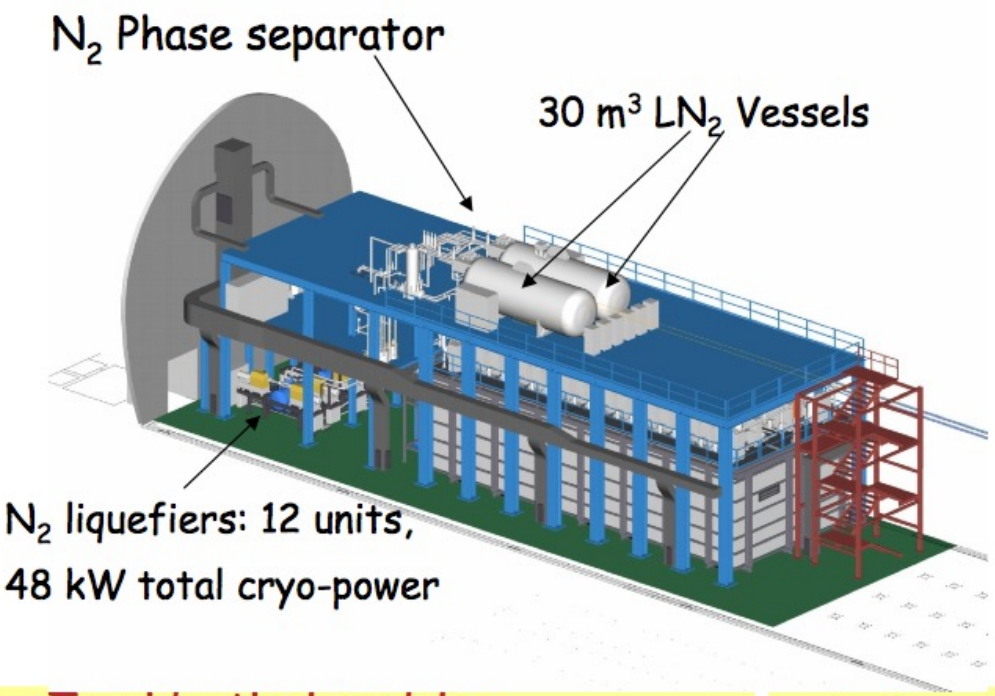
http://cds.cern.ch/record/117852/files/CERN-EP-INT-77-8.pdf

Why LAr for neutrino detectors?

- Excellent insulator, very weakly electronegative: free electrons produced by ionization drift long distances
- Produces many electron-ion pairs: measurement of energy deposited in liquid;
- Good scintillator: measurement of energy of luminous flash produced by event, event localization
- Available in sufficient quantity

	Argon	CF_3Br
Nuclear collision length	53.2	49.5 cm
Absorption length	80.9	73.5 cm
dE/dx, minimum	2.11	2.3 MeV/cm
Radiation length	14	11 cm
Density	1.40	1.50 g/cm^3

ICARUS (Imaging Cosmic And Rare Underground Signals)

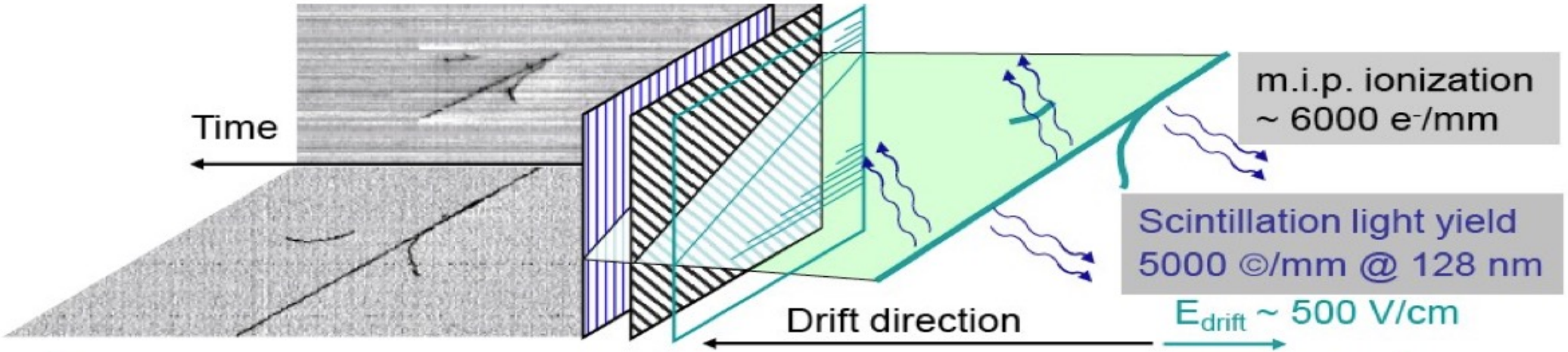


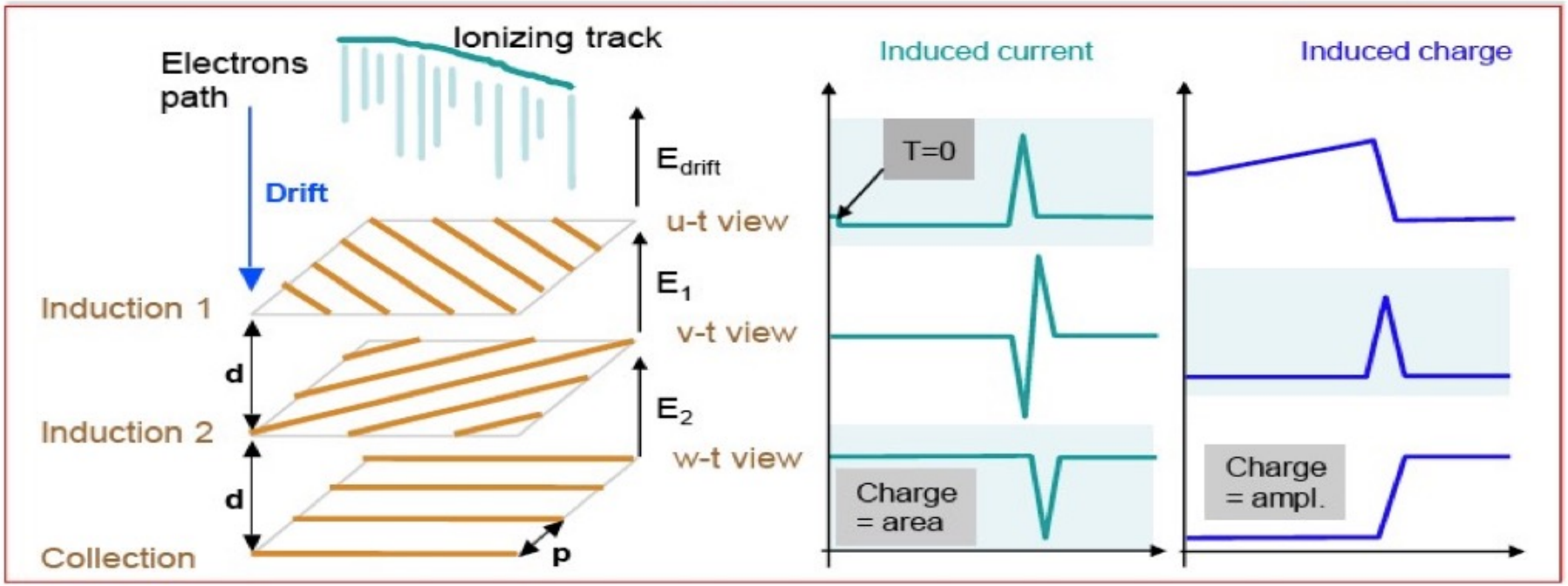
Hall B @ LNGS

- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m³ each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs

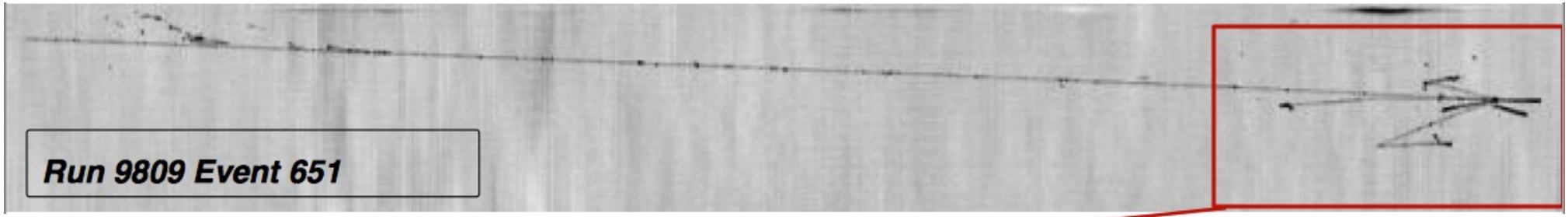
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0,±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light detection:
  - VUV sensitive (128nm) with wave shifter (TPB)

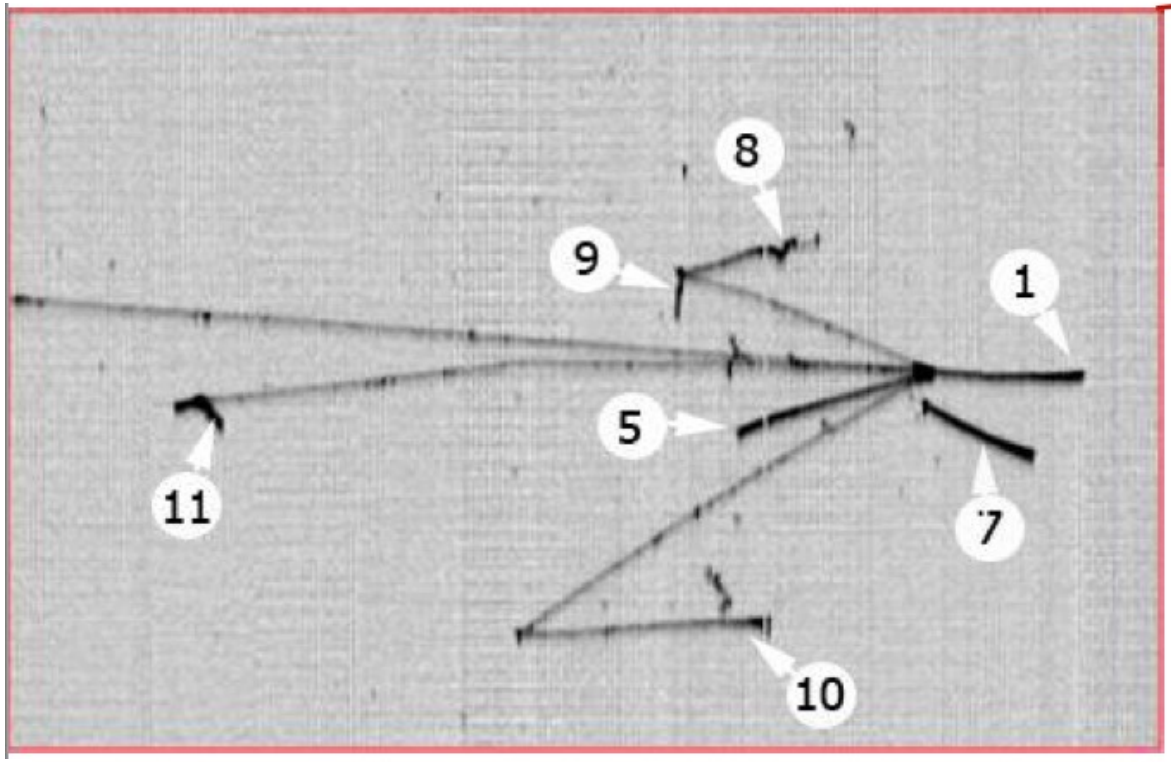
ICARUS


Time
m.i.p. ionization
~ 6000 e-/mm
Scintillation light yield
5000 ©/mm @ 128 nm
Drift direction
Edrift ~ 500 V/cm


Ionizing track
Electrons path
Drift
Induction 1
Induction 2
Collection
d
d
p
Edrift
u-t view
E1
v-t view
E2
w-t view
Induced current
Induced charge
T=0
Charge = area
Charge = ampl.

ICARUS





6 protons and 1 pion which decays at rest
muon: 7.1 ± 1.3 [GeV/c]

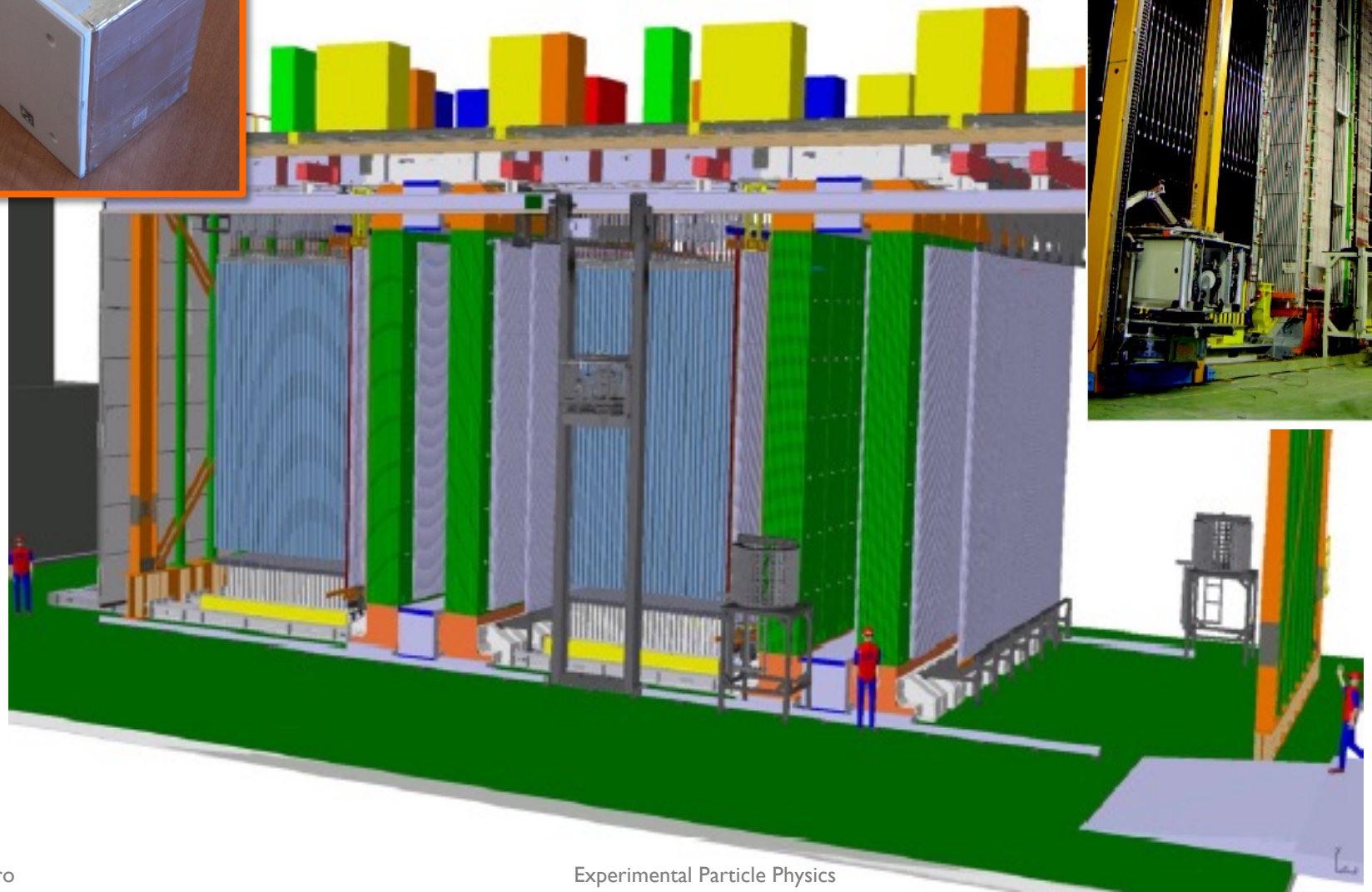
http://icarus.lngs.infn.it/photos/NeutrinoEventsGallery/

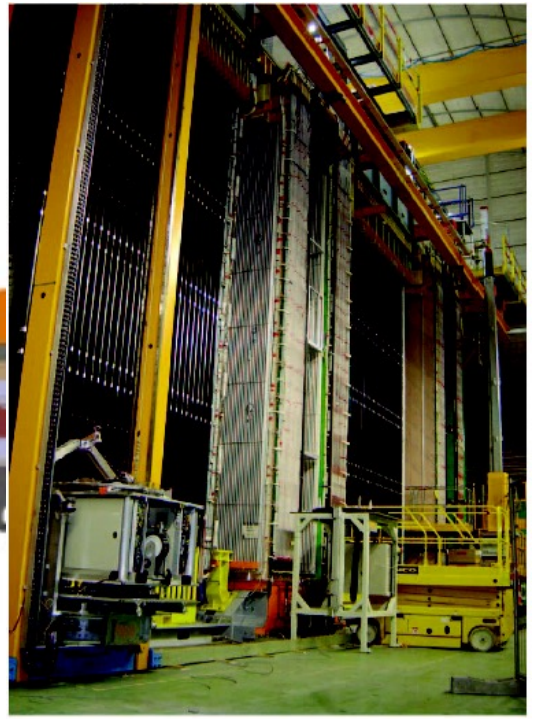
Particle identification based on dE/dx dependence:

- Reconstr. 3D track segments: d*x*
- charge dep. on track segment: d*E*

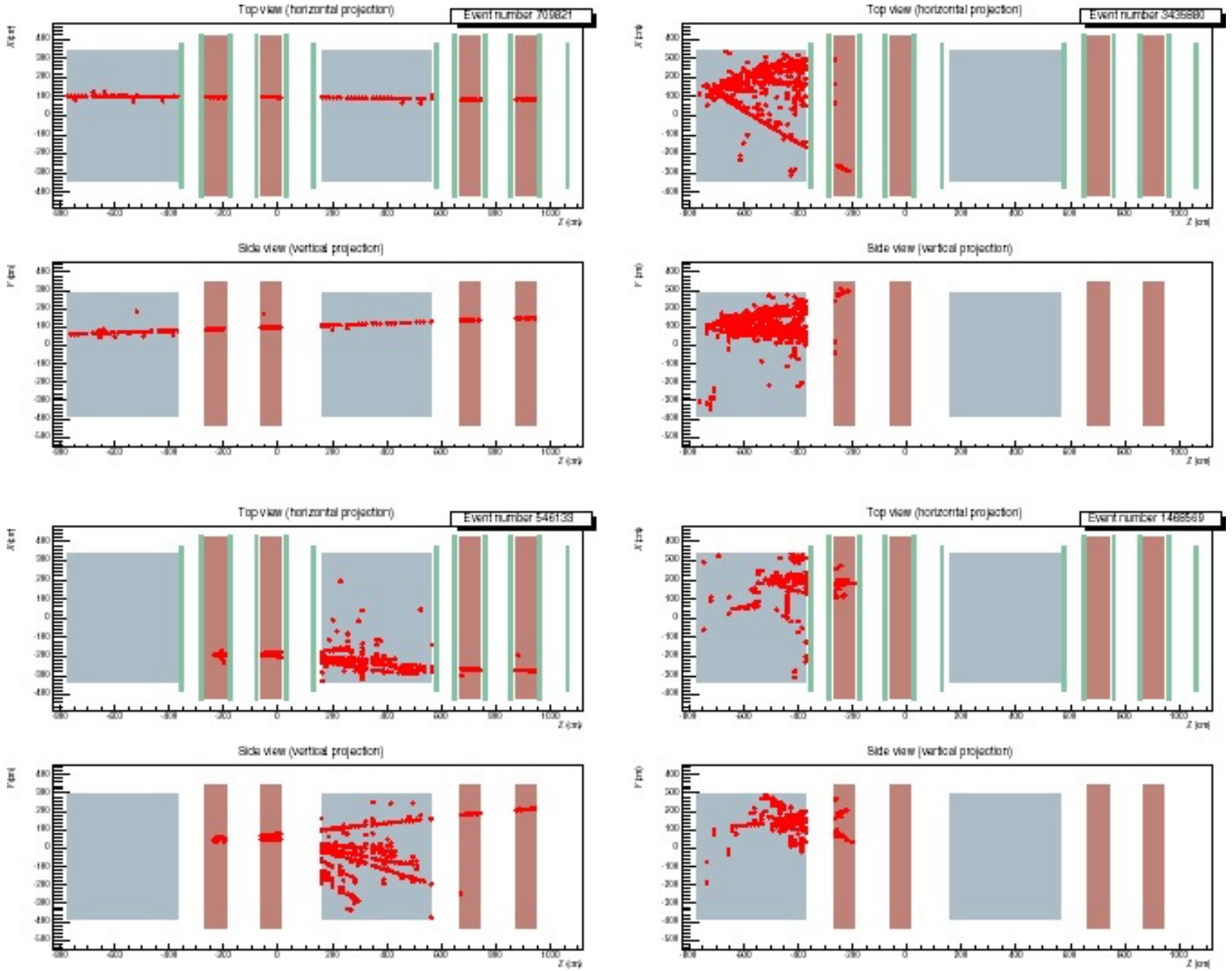
Track	E_{dep} [MeV]	range [cm]
1(p)	185±16	15
5(p)	192±16	20
7(p)	142±12	17
8(π)	94±8	12
9(p)	26±2	4
10(p)	141±12	23
11(p)	123±10	6

OPERA (Oscillation Project with Emulsion-tRacking Apparatus)

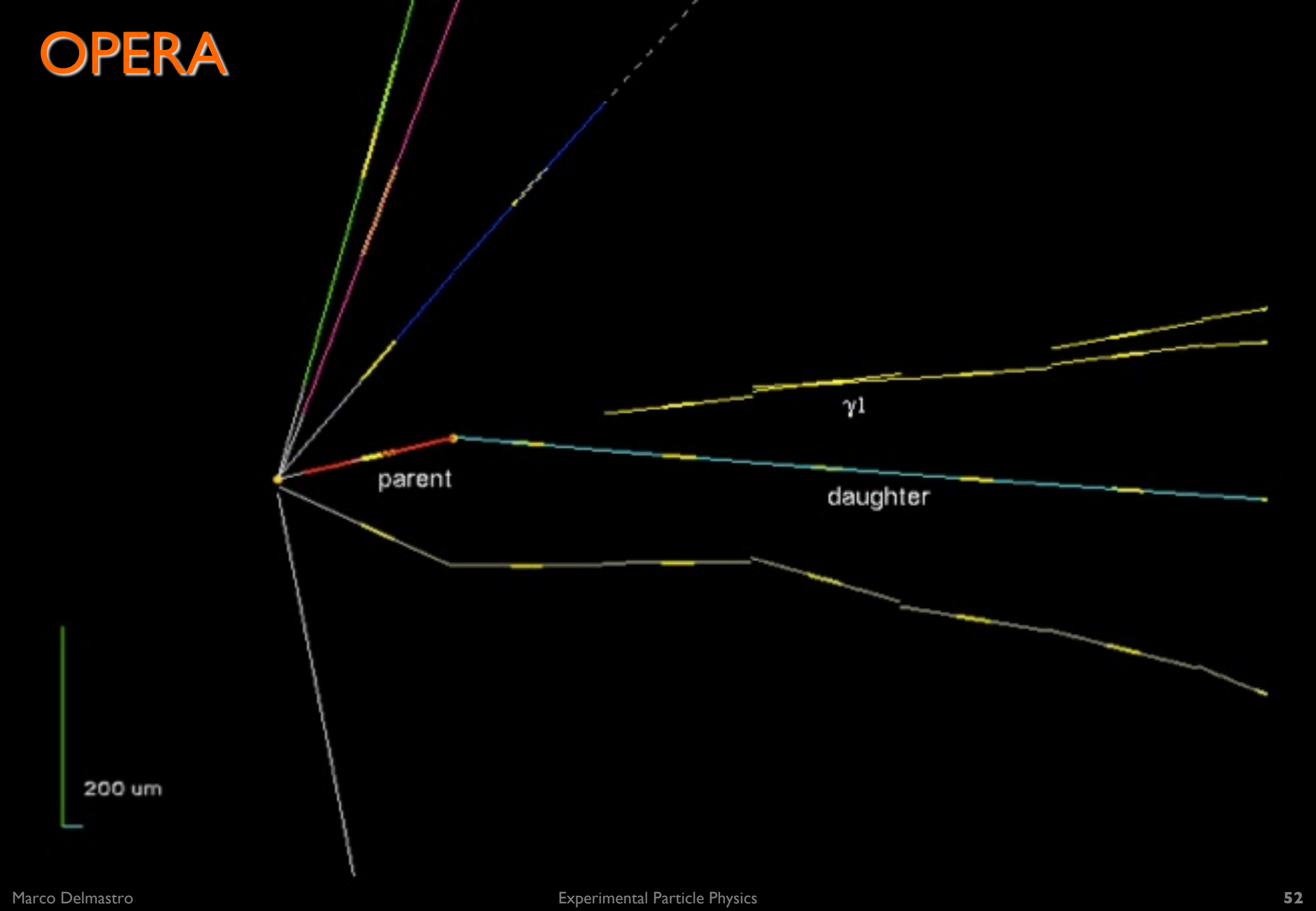




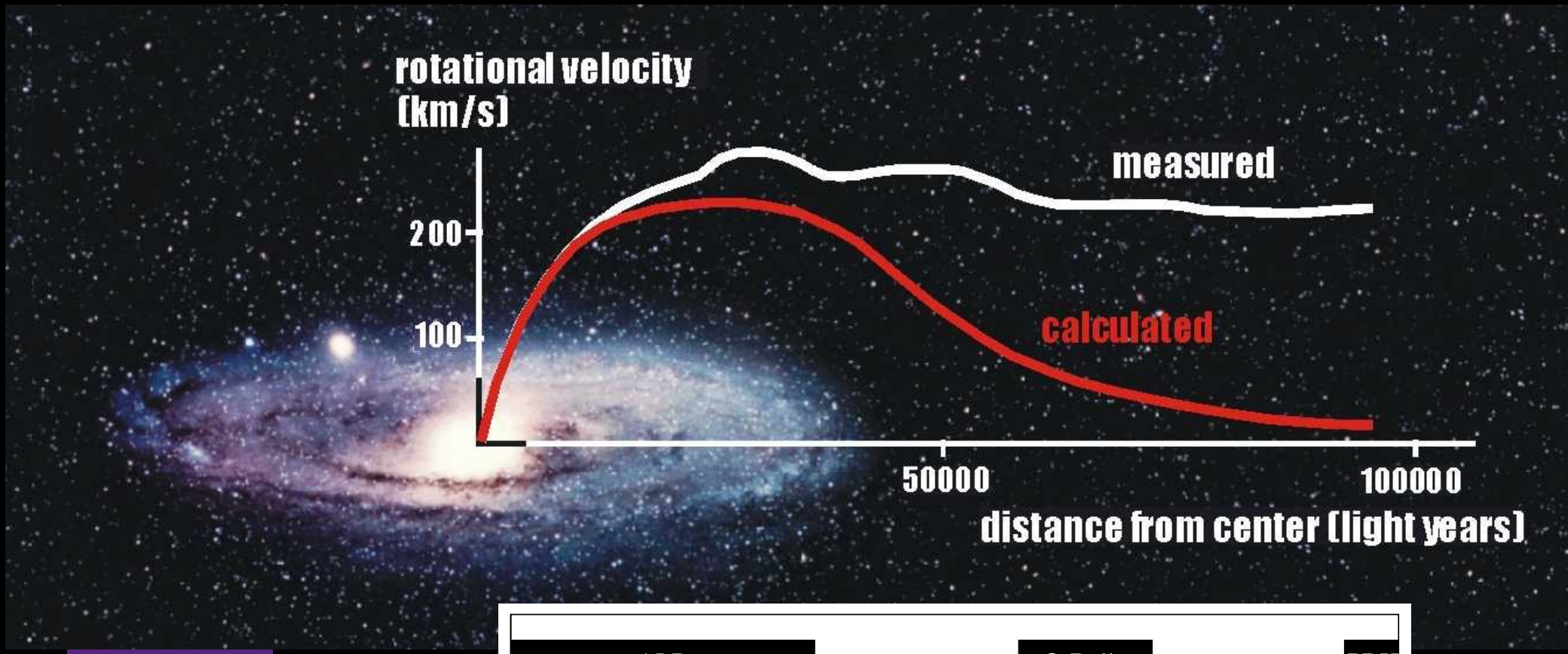
OPERA

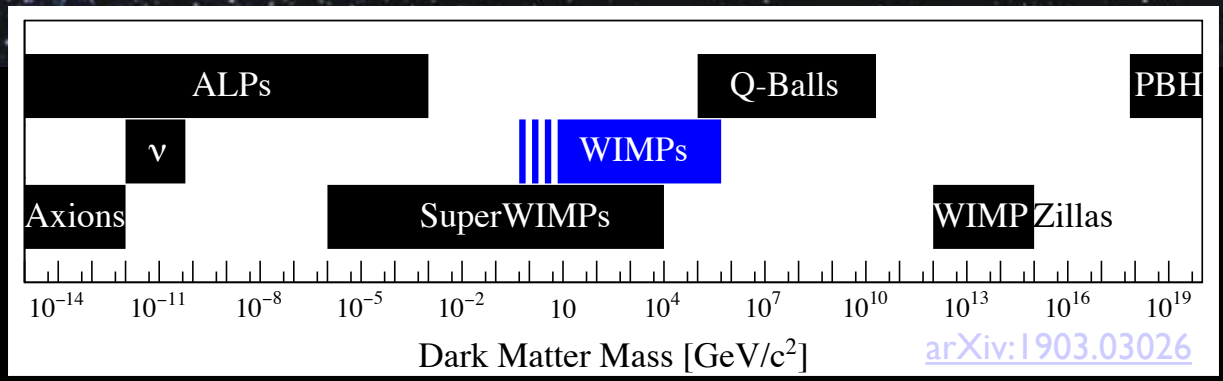

Top view (horizontal projection)
Event number 703821
Side view (vertical projection)
Top view (horizontal projection)
Event number 3435880
Side view (vertical projection)
Top view (horizontal projection)
Event number 546133
Side view (vertical projection)
Top view (horizontal projection)
Event number 1488569
Side view (vertical projection)

OPERA



Dark Matter: astronomical evidence and candidates





WIMP detection: cryogenic experiments

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) in order to allow for galaxy formation ...

Assumed mass range: 10 GeV - 10 TeV

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

$$T_K^{\max} = 2\,\frac{m_\chi^2\, M_K\, c^2}{(m_\chi + M_K)^2}\,\beta^2 \;\overset{m_\chi \gg M_K}{\approx}\; 2 M_K v_\chi^2$$

M_K = 100 GeV
➔ $T_K^{max} \approx$ 100 keV

How to detect WIMP?

Transferred energy of recoiling nuclei generally much smaller (< 10 %) ...
Need detector that allows nuclei detection below keV range ...

Energy resolution requires: $N_{excite} \gg 1$
i.e. $E_{excite} \ll 1$ 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 > 2Δ (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:

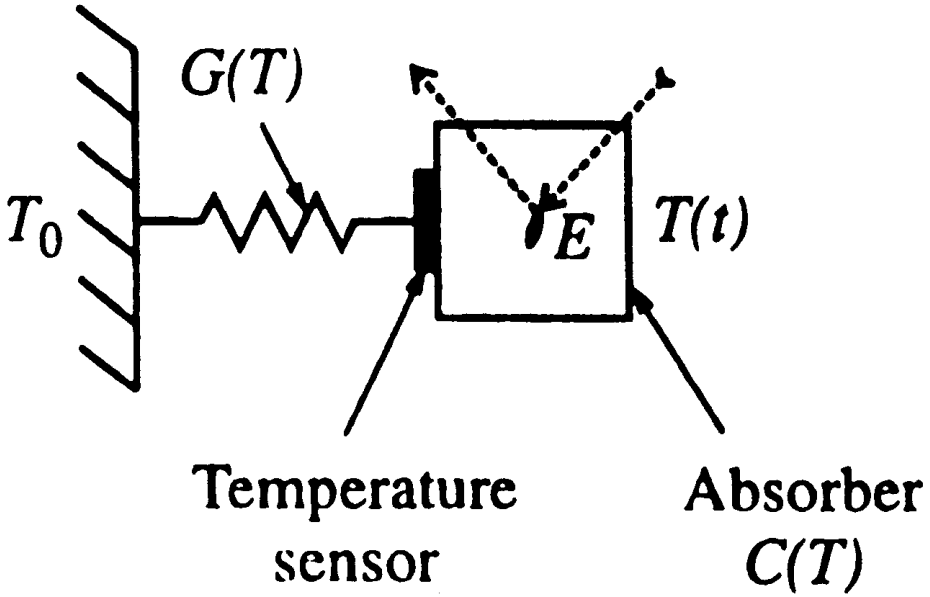
$$\Delta T = E/C$$

C: heat capacity of the sample [specific heat × mass]

E: deposited energy

Optimal detector: low heat capacity

Basic configuration of cryogenic calorimeter



Example 1: Si-detector at room temperature ...
C_{spec} = 0.7 J/gK; E = 1 keV; m = 1 g ➛ $\Delta T = 2 \cdot 10^{-16}$ K

Not very practical ...
Need lower specific heat and mass ...

Example 2: Si-detector at low temperature ...
$C_{spec} \propto (T/\Theta)^3$; $C_{spec} = 2 \cdot 10^{-15}$ K; T = 0.1 K;
E = 1 keV; m = 15 μg
➛ ΔT = 0.04 K [possible!]

Resolution:

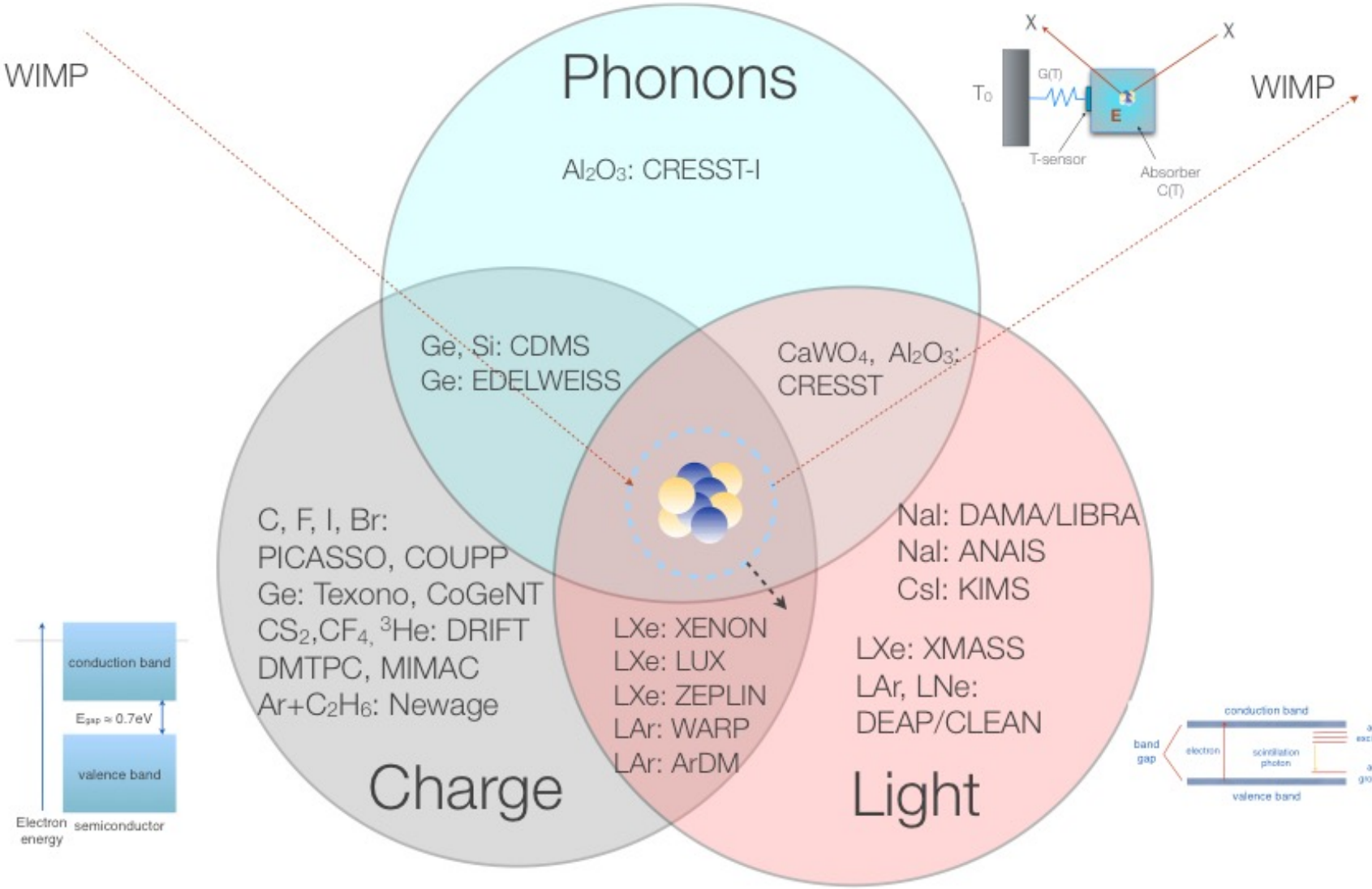
$n = CT/kT = C/k$

$\sigma_0 = kT\sqrt{n} = \sqrt{(CkT^2)}$
$\sigma_E = \varepsilon_{Ph}\sqrt{(E/\varepsilon_{Ph})} = \sqrt{(kTE)}$

$\sigma = \sigma_0 + \sigma_E$

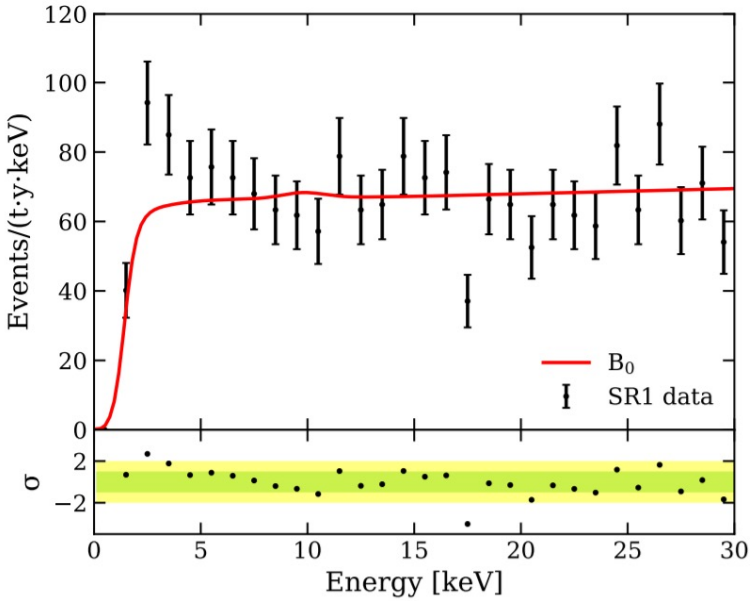
Yields: $\sigma < 0.2$ eV
[Si Semiconductor detector: σ = 20 eV]

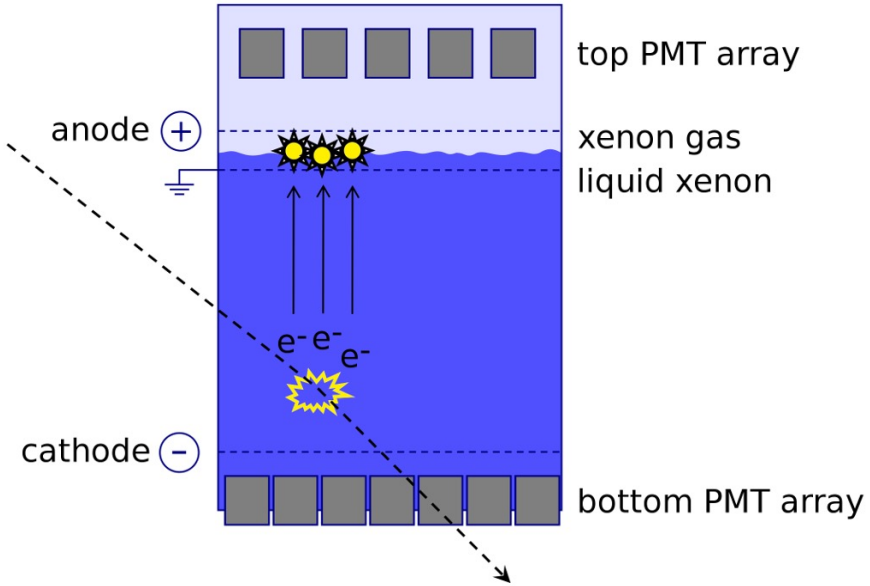
Dark matter detection overview



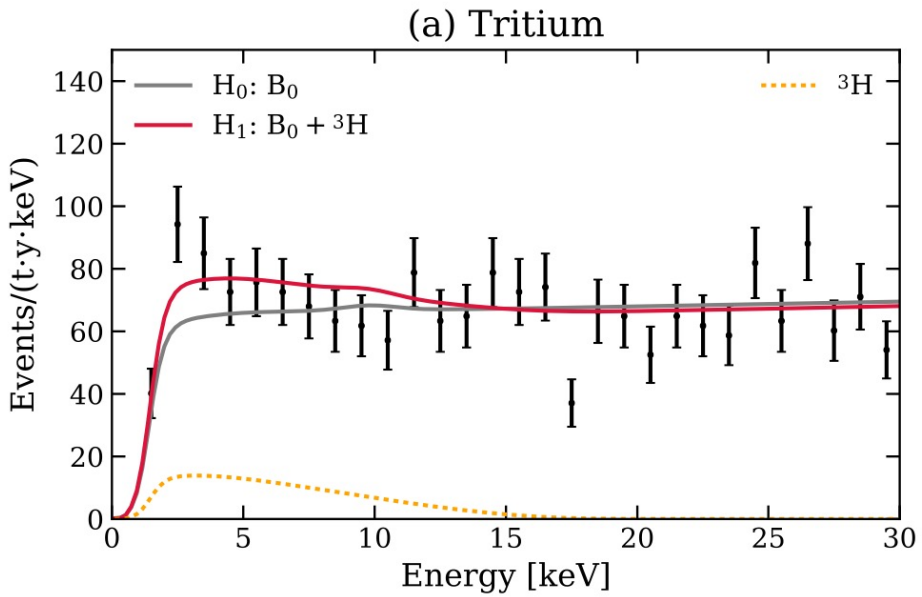
A Dark Matter detection example: XENON 1T

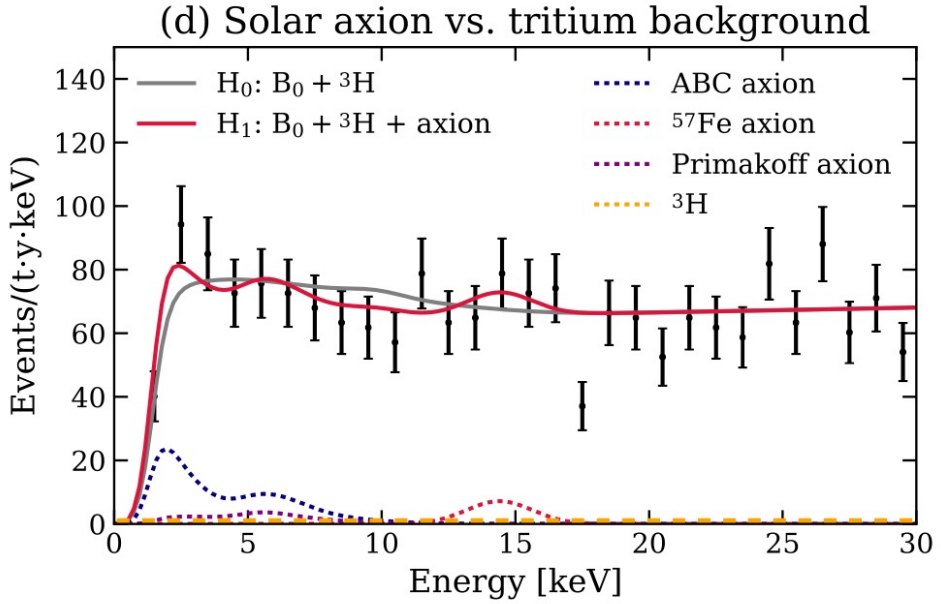
- XENON1T
  - ✓ Gran Sasso (Italy) underground lab
  - ✓ 3.2 tonnes of ultra-pure liquefied xenon, 2.0 t of which serve as a target for particle interaction
  - ✓ Signal = light + ionisation free electrons from a Xe
  - ✓ Detector = Photomultipliers + TPC
  - ✓ Possible fake = β-decays from Tritium contamination in Xe
- 2020 excess…
  - ✓ Excess of 53 events over 232 expected observed…
    - https://arxiv.org/abs/2006.09721

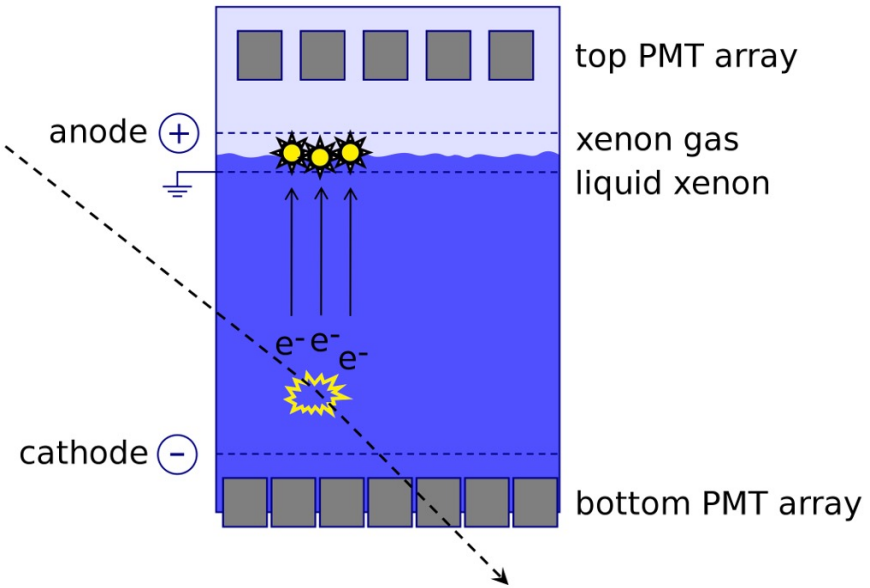




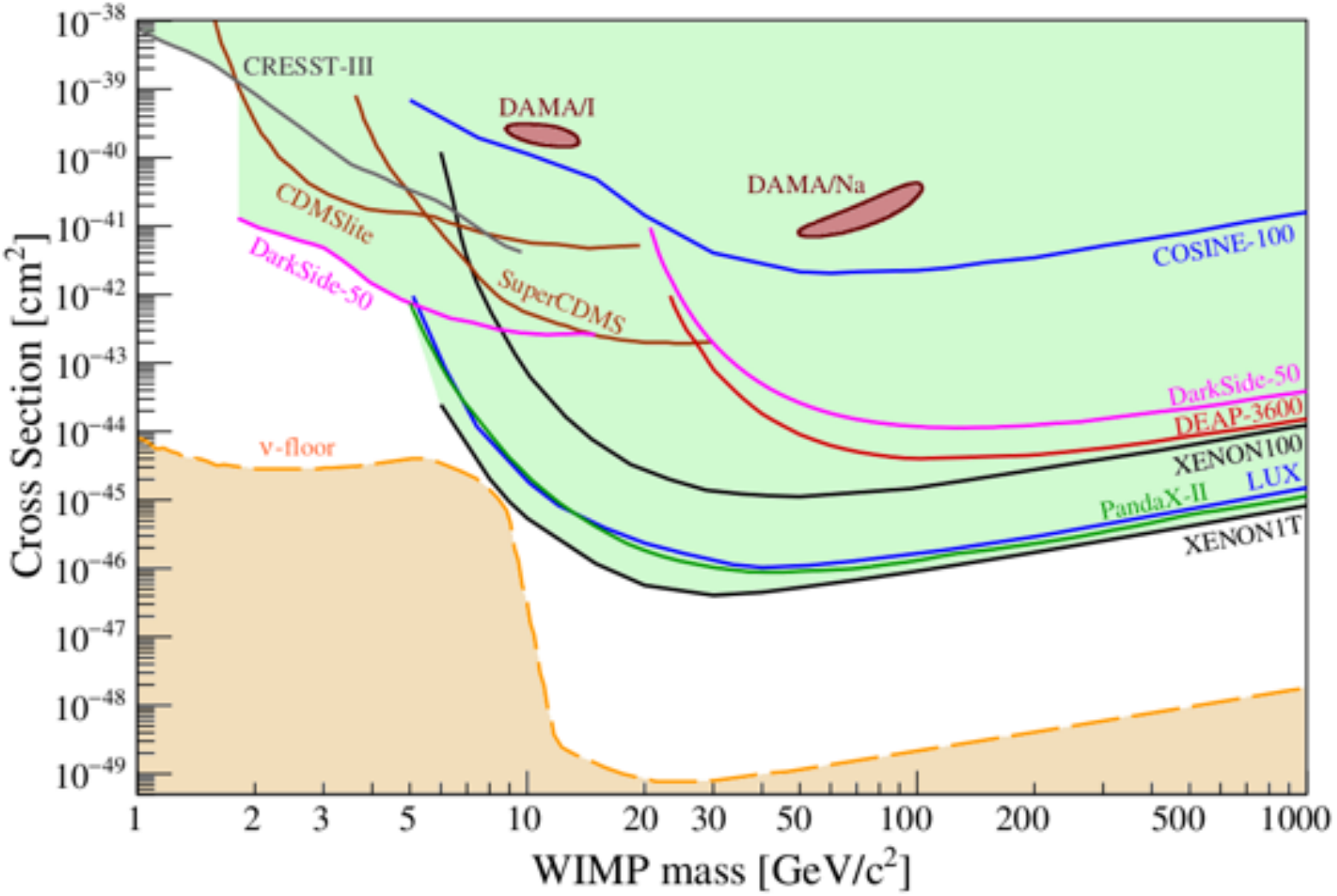
A Dark Matter detection example: XENON 1T







Limits and projected sensitivities



Spin-Independent limits and sensitivities, from "Direct Detection of WIMP Dark Matter: Concepts and Status" by Marc Schumann (arXiv:1903.03026v2). For Spin-Dependent sensitivities see full review paper.

Finding new particles that constitute dark matter would be a major breakthrough in physics. As extraordinary new findings require extraordinary evidence, the hurdles are high. Various unusual experimental results of the last decade have been interpreted in terms of dark matter, but all of them could also be the result of a misunderstood background or other effects.

M. Klasen, M. Pohl, G. Sigl

Indirect and direct search for dark matter

https://arxiv.org/abs/1507.03800