Experimental particle physics

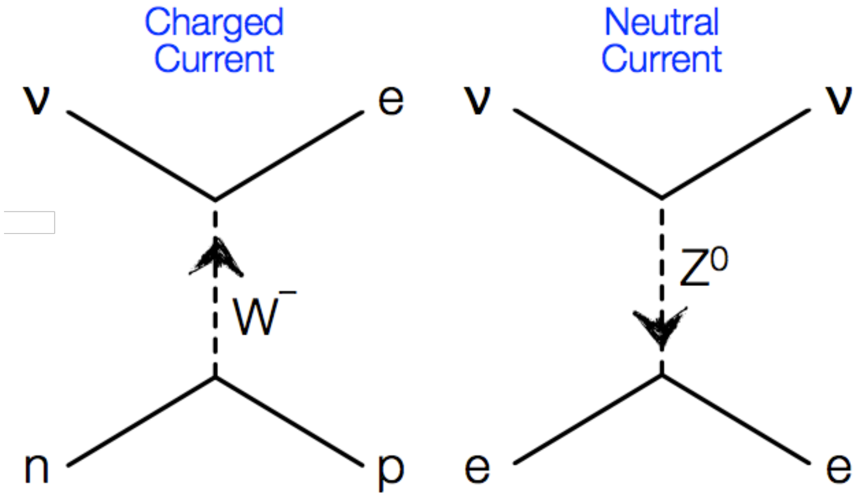
European School of Instrumentation in Particle & Astroparticle Physics

6. experiments to detect "invisible" particles

A bit of neutrino history…

1930 Neutrino postulated	***Pauli***
1934 Neutrino name and interaction theory	*Fermi*
1938 Solar neutrino flux calculation	*Bethe*
1946 Idea of neutrino chlorine detector	*Pontecorvo*
1956 Neutrino observation	***Reines & Cowan***
1957 Idea of neutrino oscillation	*Pontecorvo*
1958 Neutrino are Left-Handed	*Goldhaber*
1962 There are (at least) 2 neutrino species: n_{mu}, n_e	*Lederman, Schwartz & Steinberger*
1968 Solar neutrino deficit	***Davis***
1973 Neutral Current neutrino interactions observed	*Gargamelle*
1975 Tau lepton and the third neutrino	*Perl*
1986 Solar deficit again: maybe atmospheric?	*Kamiokande*
1987 Neutrino from SN1987A	***Kamiokande, IMB***
1989 There are only 3 light neutrino families	*LEP Collaborations*
1991 Still solar deficit	*Gallex, SAGE*
1998 Atmospheric neutrino oscillation	***Super-Kamiokande***
2002 Solar neutrino oscillation confirmed	***SNO, KamLand***
2004 Atmospheric oscillation confirmed at accelerator	*K2K*

Neutrino interactions



Neutron detection only via weak interaction ...

Possible reactions:

Charged Current Reactions:

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

...

$$\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\bar{\nu}_e + e^- \rightarrow \tau^- + \bar{\nu}_\tau$$

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: $\sigma = 7 \cdot 10^{-38}$ cm²/nucleon

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

Solar neutrinos [100 keV]: $\sigma = 7 \cdot 10^{-45}$ cm²/nucleon

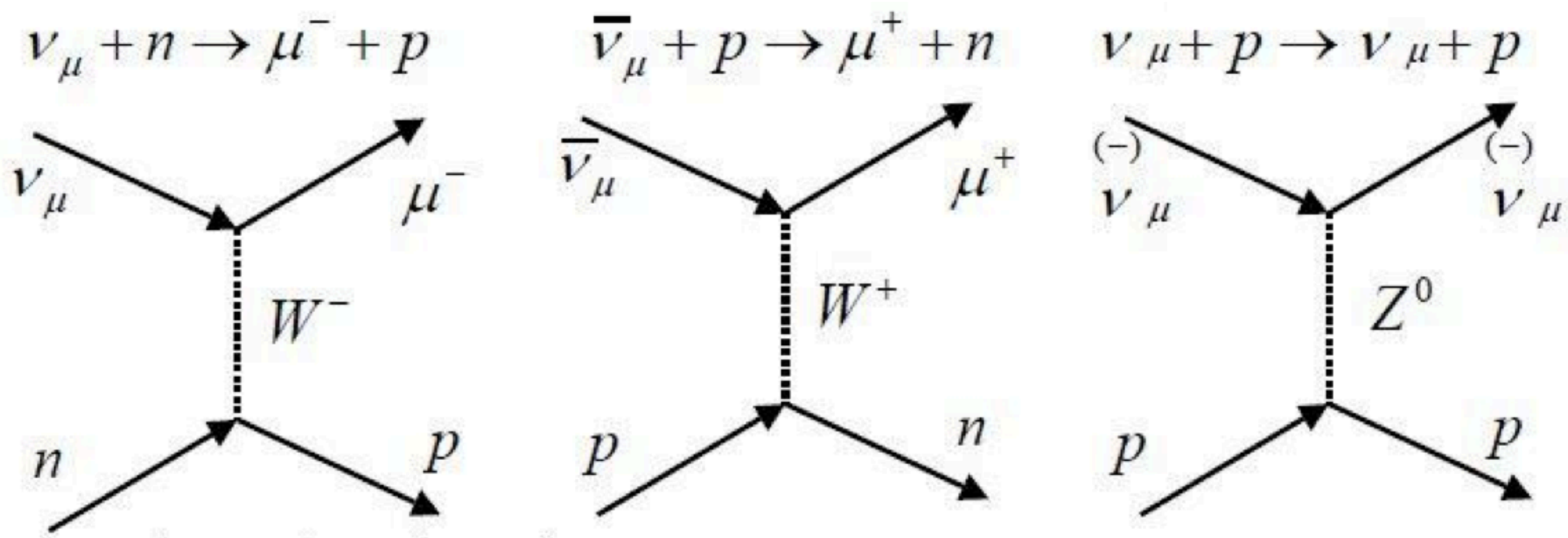
Interaction probability for earth: $R = \sigma \cdot N_A$ [mol^{-1}/g]$\cdot d \cdot \rho \approx 4 \cdot 10^{-14}$
with $N_A = 6.023 \cdot 10^{23}$ g^{-1}; d = 12000 km; ρ = 5.5 g/cm^3

Neutrino interactions: ν-e

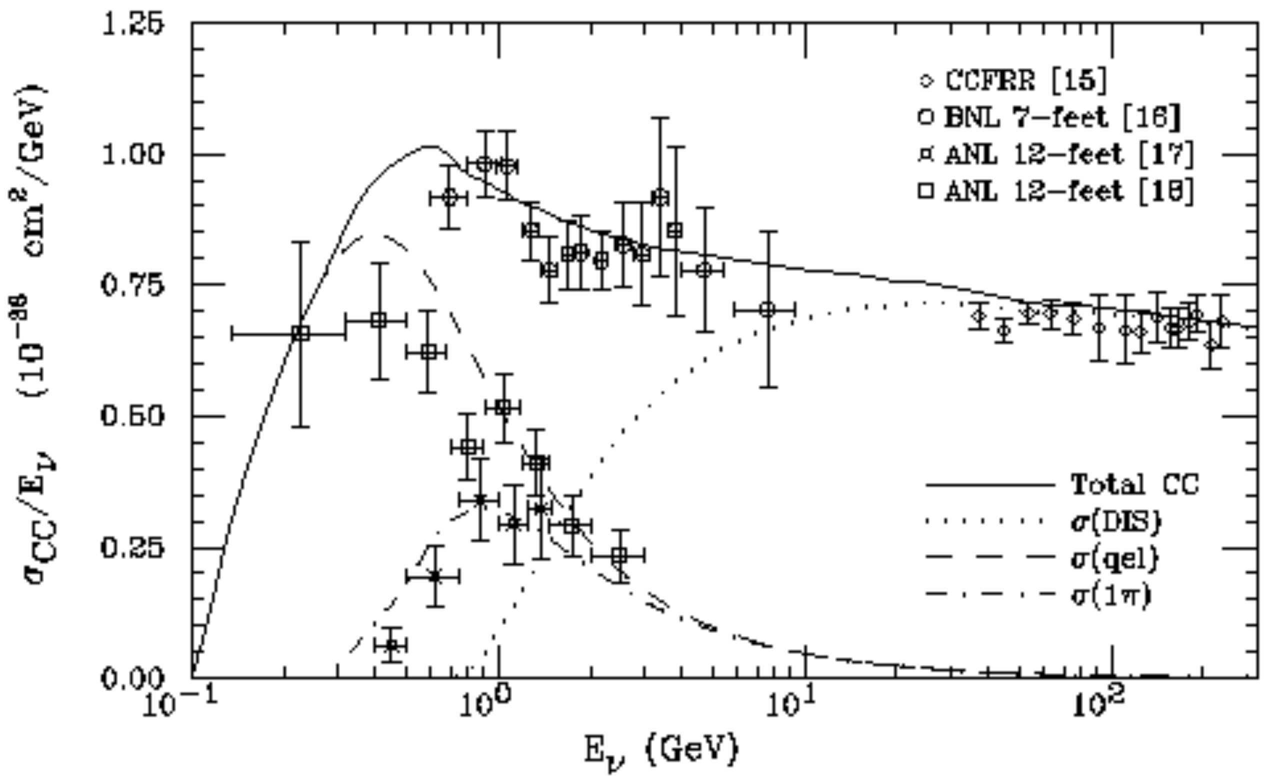
Process	Total Cross section
$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$	$\frac{G_F{}^2 s}{\pi}$ $\quad 1.7 \cdot 10^{-43} \left(\frac{E}{10\text{MeV}}\right) \text{cm}^2$
$\nu_e + e^- \rightarrow \nu_e + e^-$	$\frac{G_F{}^2 s}{4\pi}\left[\left(2\sin^2\theta_W - 1\right)^2 + \frac{4}{3}\sin^4\theta_W\right]$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

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

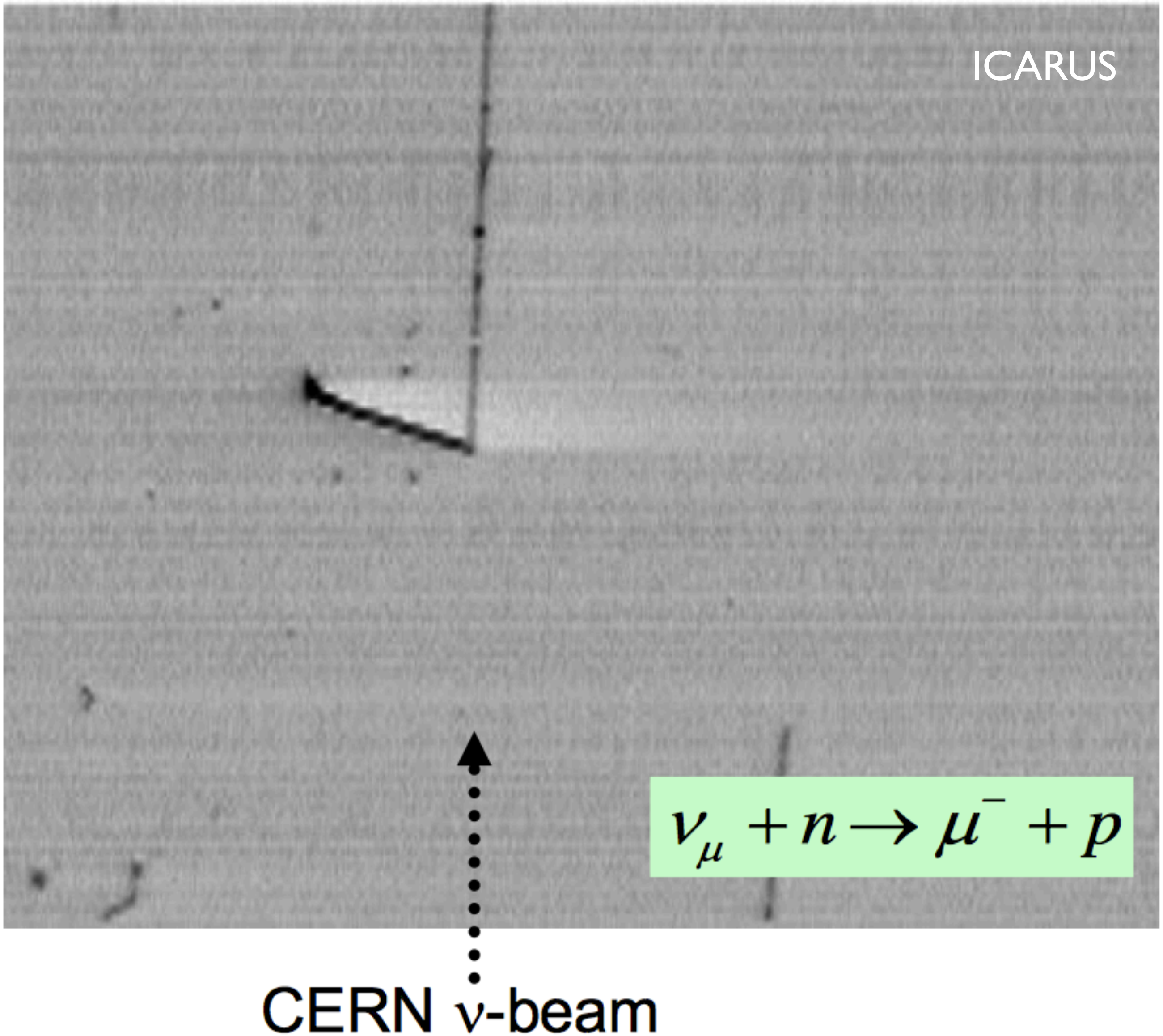
E << m_n

$$\sigma(\nu n) = \sigma(\bar{\nu} p) \approx 9.75 \cdot 10^{-42} \left(\frac{E}{10\,MeV} \right)^2 \ \mathrm{cm}^2$$

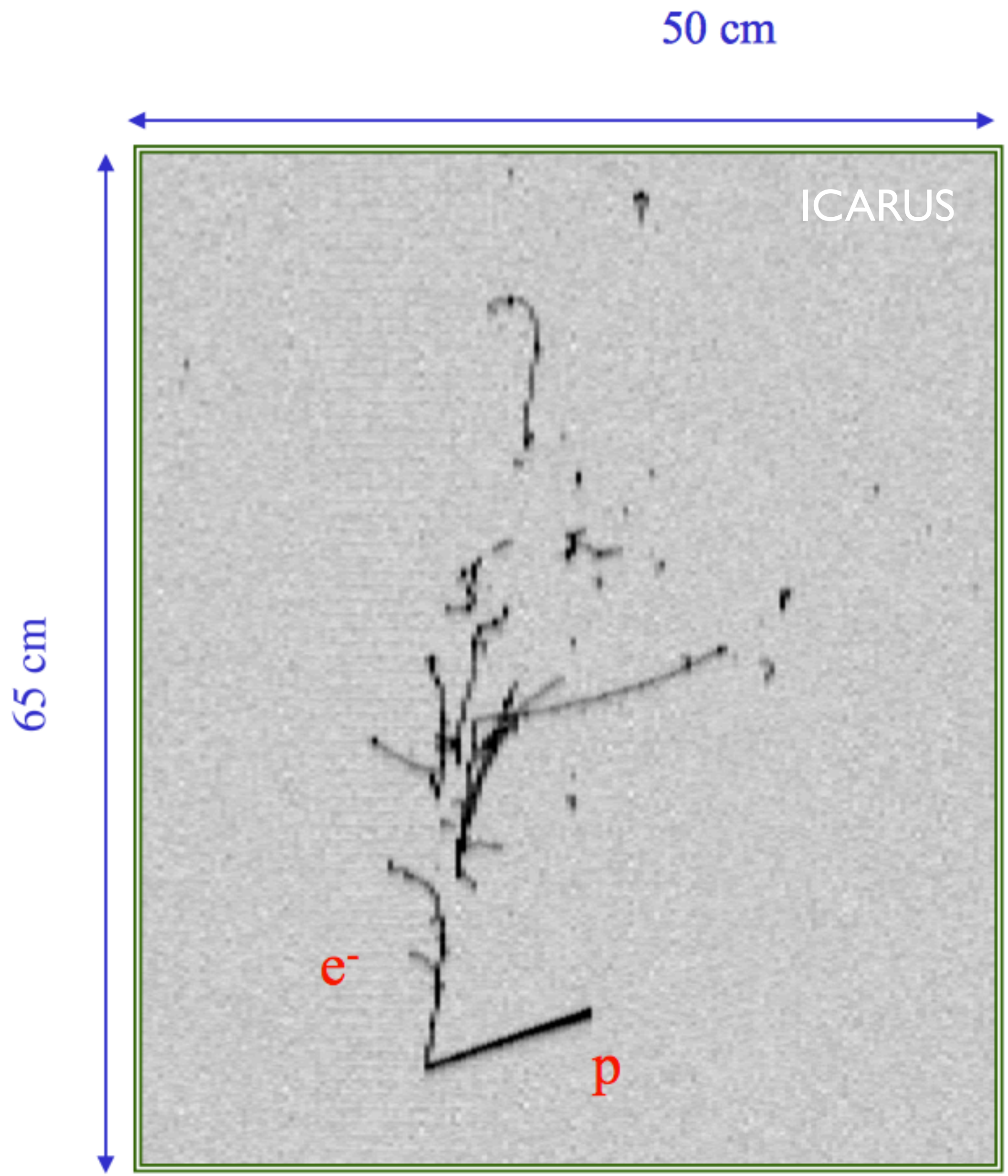
E > 1 GeV

σ/E ~ constant

A neutrino interaction…



Another neutrino interaction…



Neutrino interaction cross sections comparison

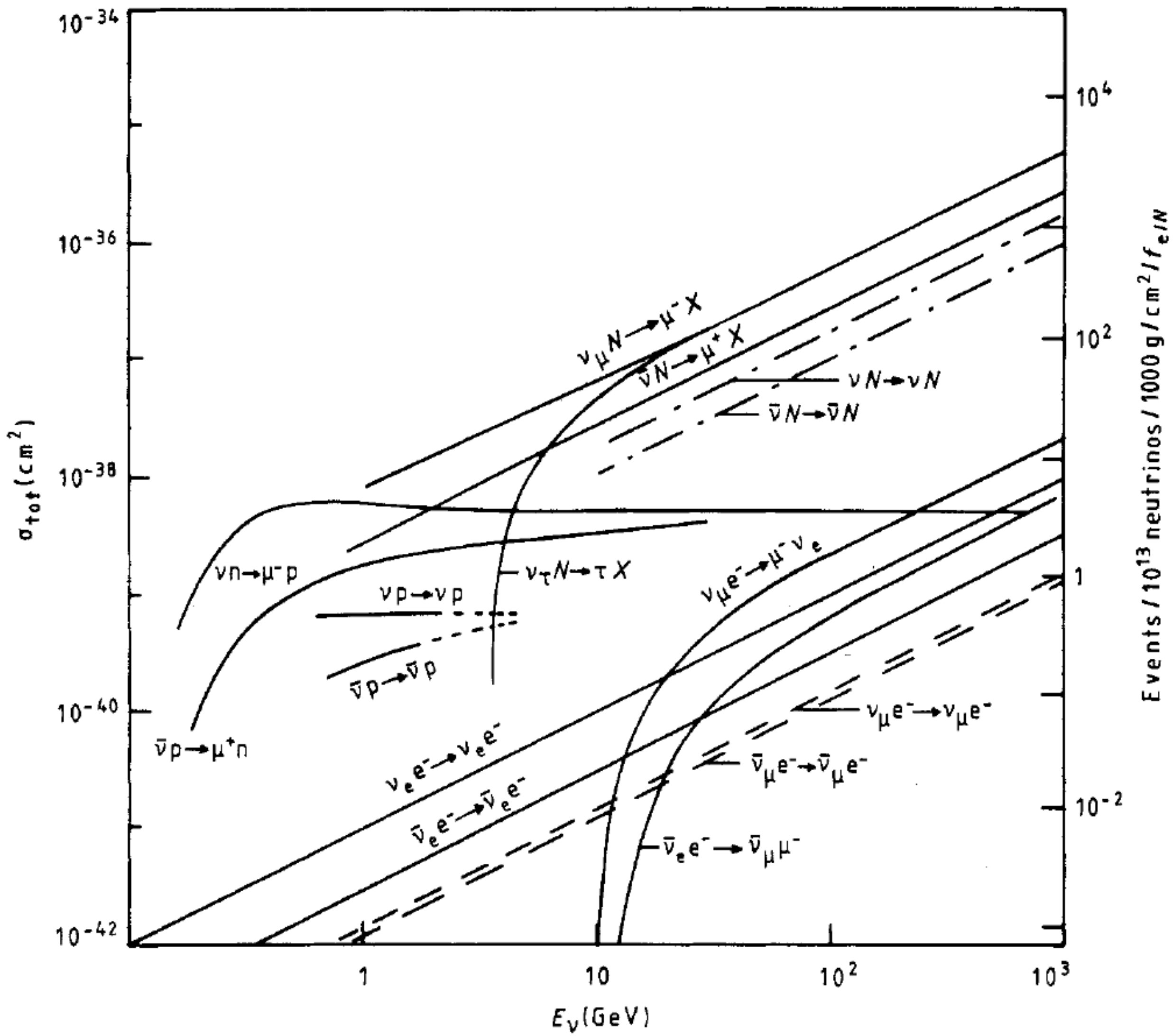


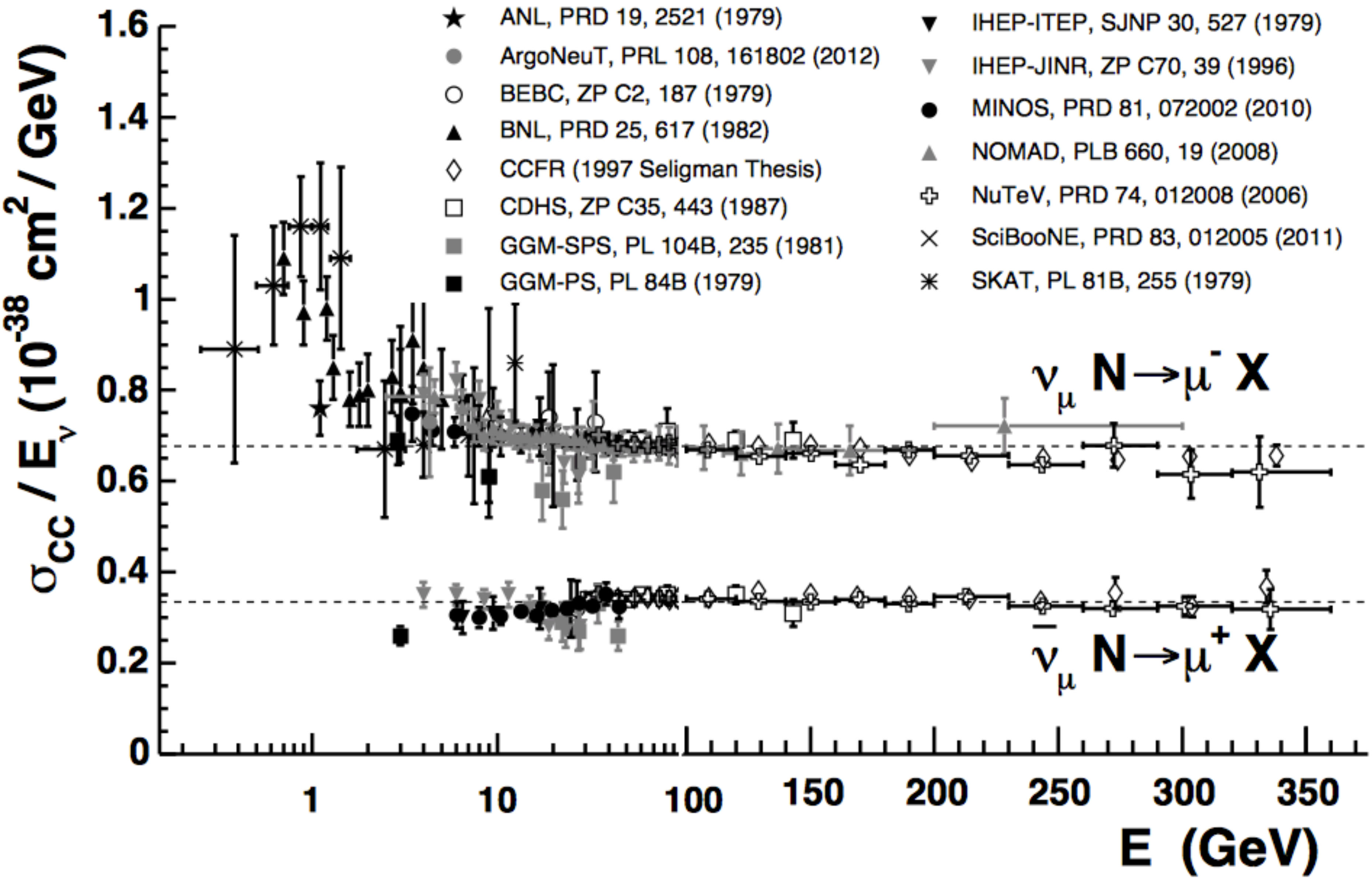
Figure 5. Energy dependence of various neutrino reactions and corresponding event rates. ($f_{e/N} = 1$ f reactions on nucleons, $f_{e/N} = A/Z$ for reactions on electrons.)

close to thresholds…

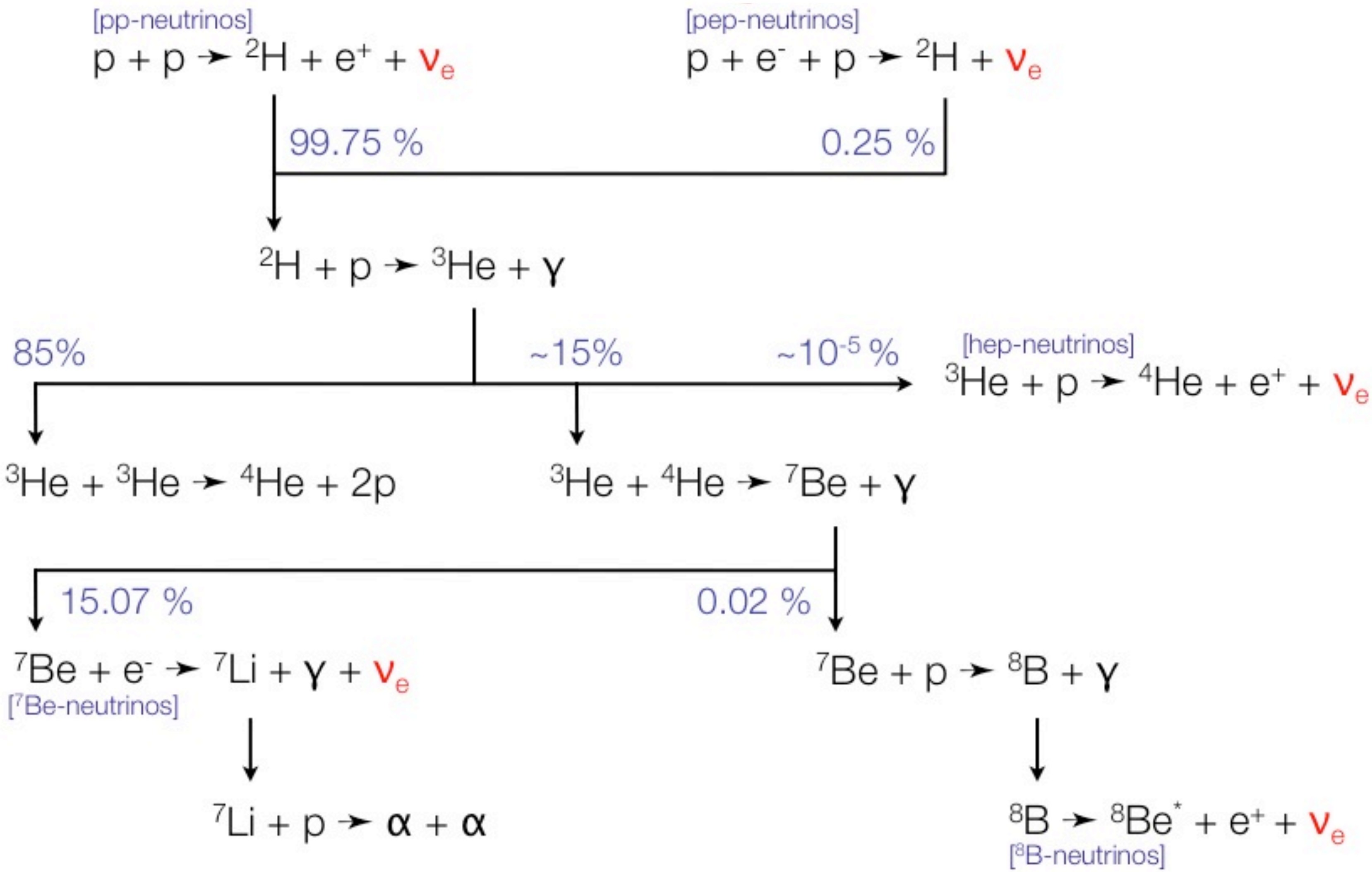
$$\sigma \sim \frac{\left(s - m_\mu^2\right)^2}{s}$$

$$s_{lab} = 2 m_e E + m_e^2$$

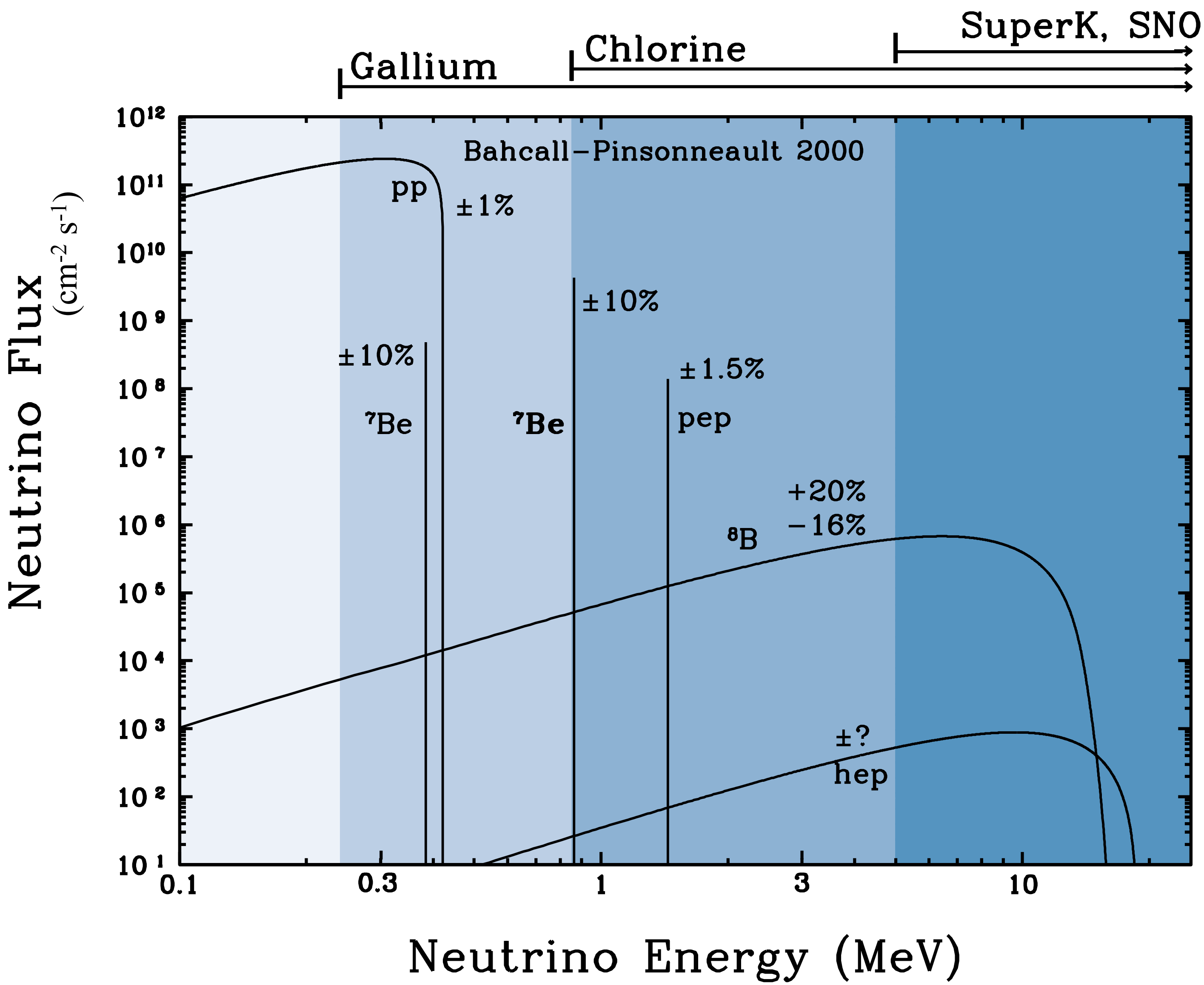
Neutrino interaction inclusive cross section



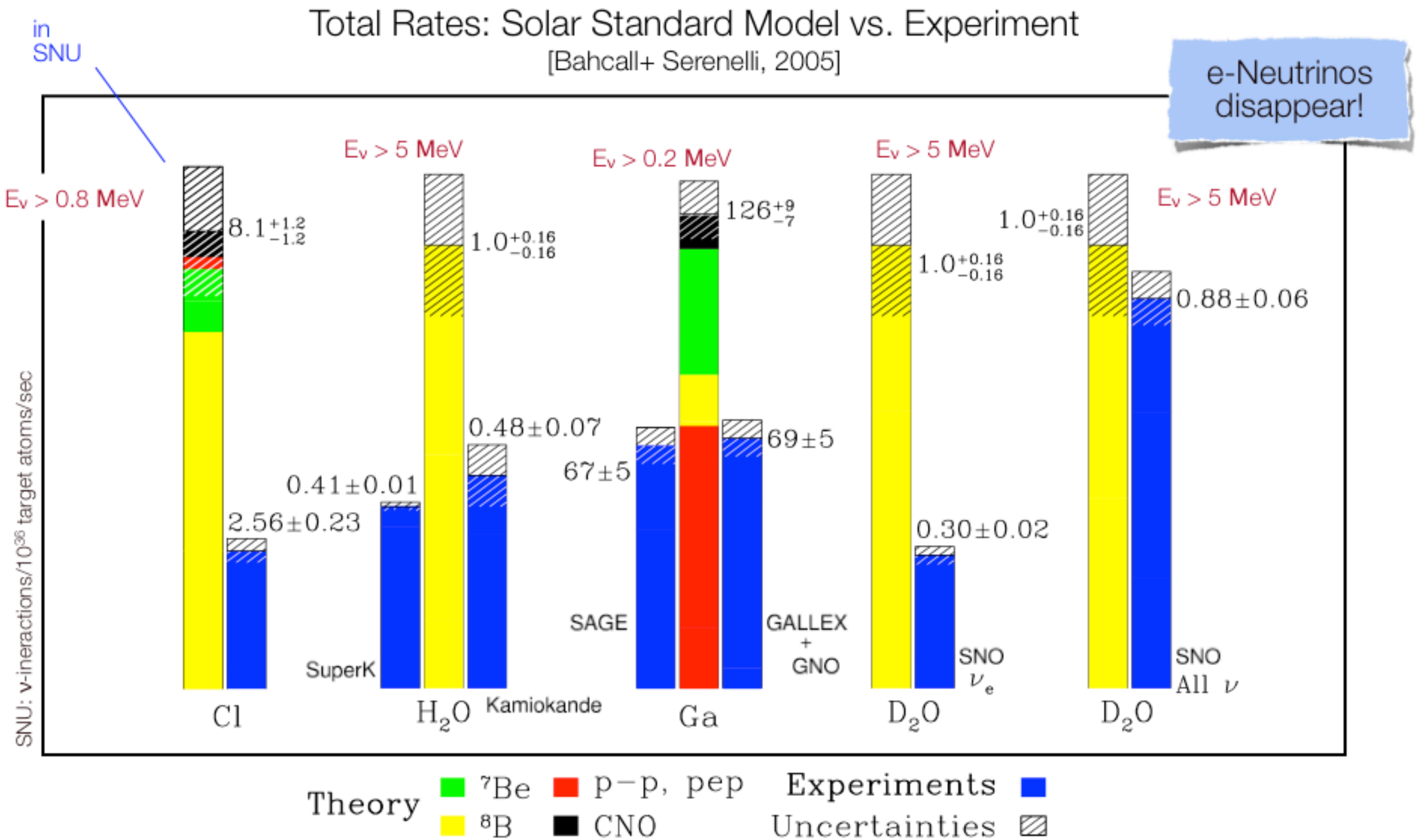
Neutrinos from the Sun



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

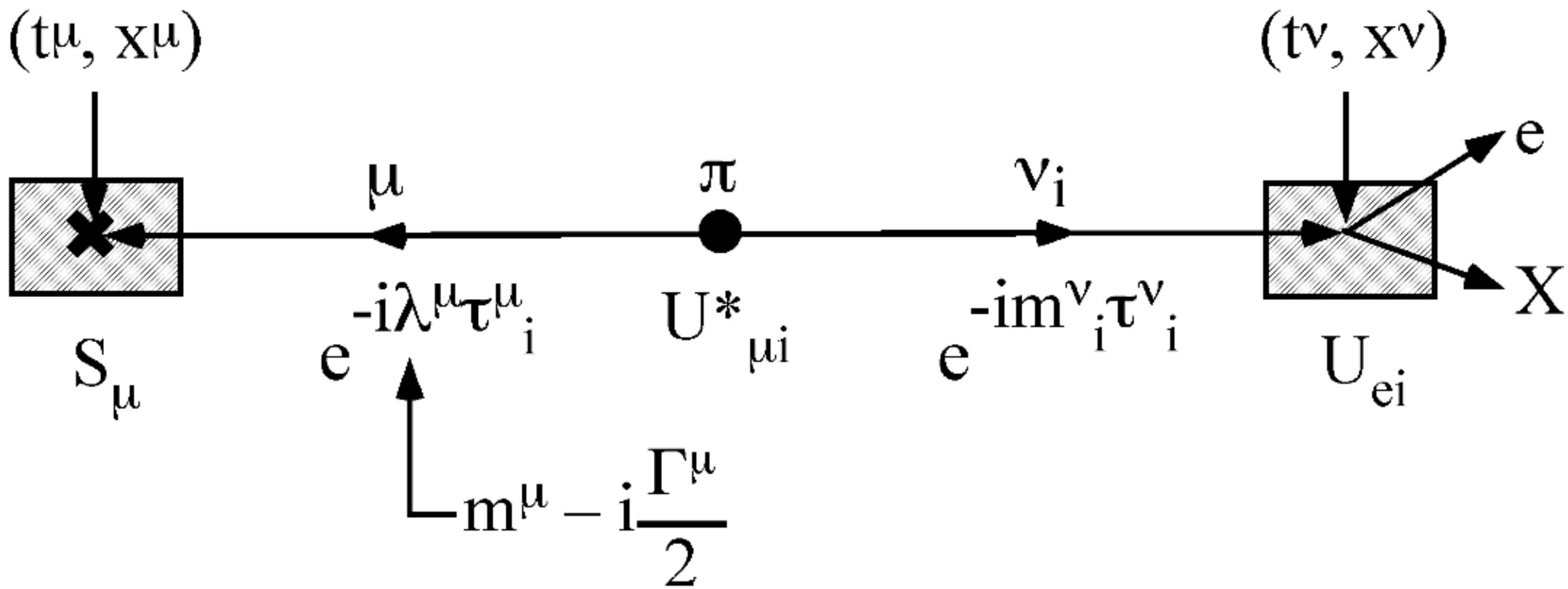
$$\pi \to \mu\nu_\mu$$

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



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

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

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…

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

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

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

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

(Simplified) probability of neutrino oscillation

… and calculate!

$$\frac{m_j^2 - m_k^2}{4E} L = \frac{\Delta m^2\,[\mathrm{eV}^2]}{4\times 10^6\, E\,[\mathrm{MeV}]}\frac{L}{\hbar c} = \frac{\Delta m^2\,[\mathrm{eV}^2]}{4\times 10^6\, E\,[\mathrm{MeV}]}\frac{L\,[\mathrm{m}]}{197\times 10^6 [\mathrm{eV}]\times 10^{-15} [\mathrm{m}]}$$

$$= 1.27\frac{\Delta m^2\,[\mathrm{eV}^2] L\,[\mathrm{m}]}{E\,[\mathrm{MeV}]} = 1.27\frac{\Delta m^2\,[\mathrm{eV}^2] L\,[\mathrm{km}]}{E\,[\mathrm{GeV}]}$$

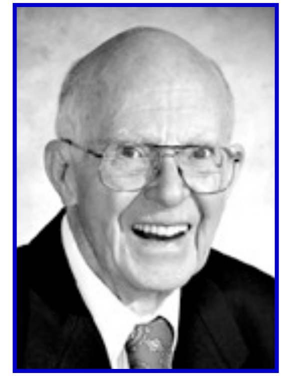
Being able to observe oscillations implies phase variation ~ 1.

Given L and E, accessible range is thus Δm^2 [eV^2] > E[GeV] / L[km]

Sorgente	E	L	Δm^2 [eV^2]
Reattori	1 - 10 MeV	10 m - 100 km	
Acceleratori	0.1 - 10 GeV	10 m - 100 km	
Atmosferici	1-10 GeV	10 - 10000 km	
Solari	0.1 - 10 MeV	1.5×10^{11} m	

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*".



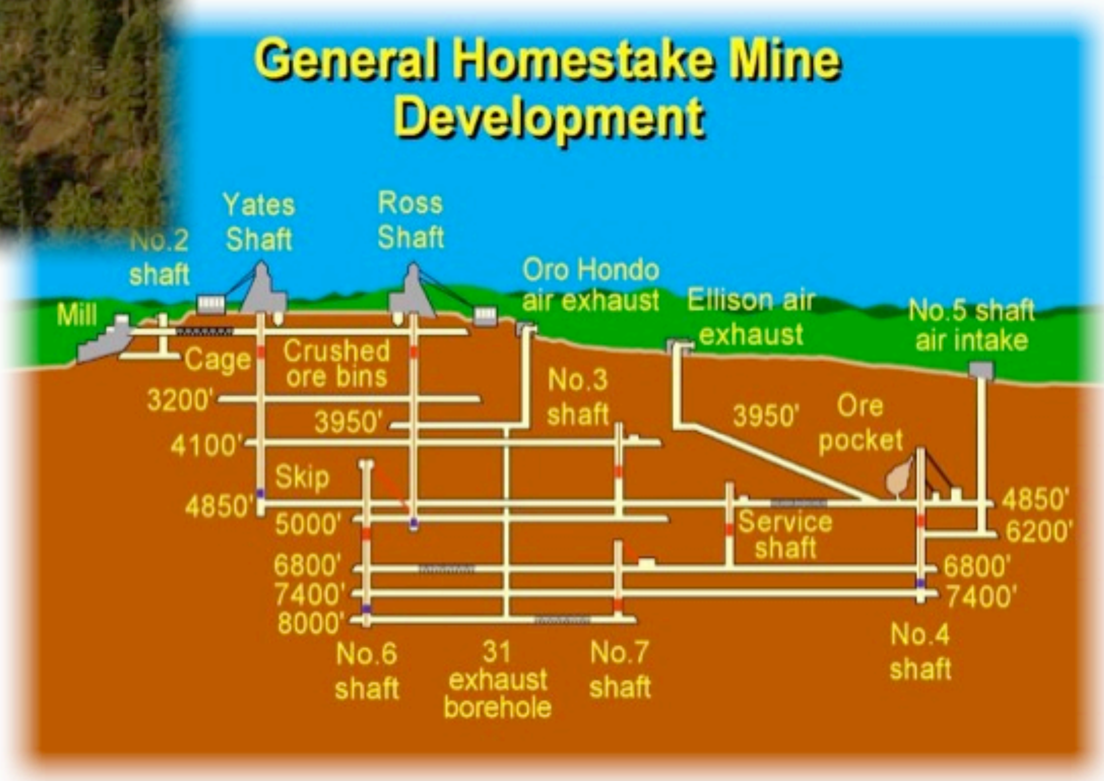
Raymond Davis Jr.
[Homestake]

Masatoshi Koshiba
[Kamiokande]

Riccardo Giacconi
[X-Ray Sources]

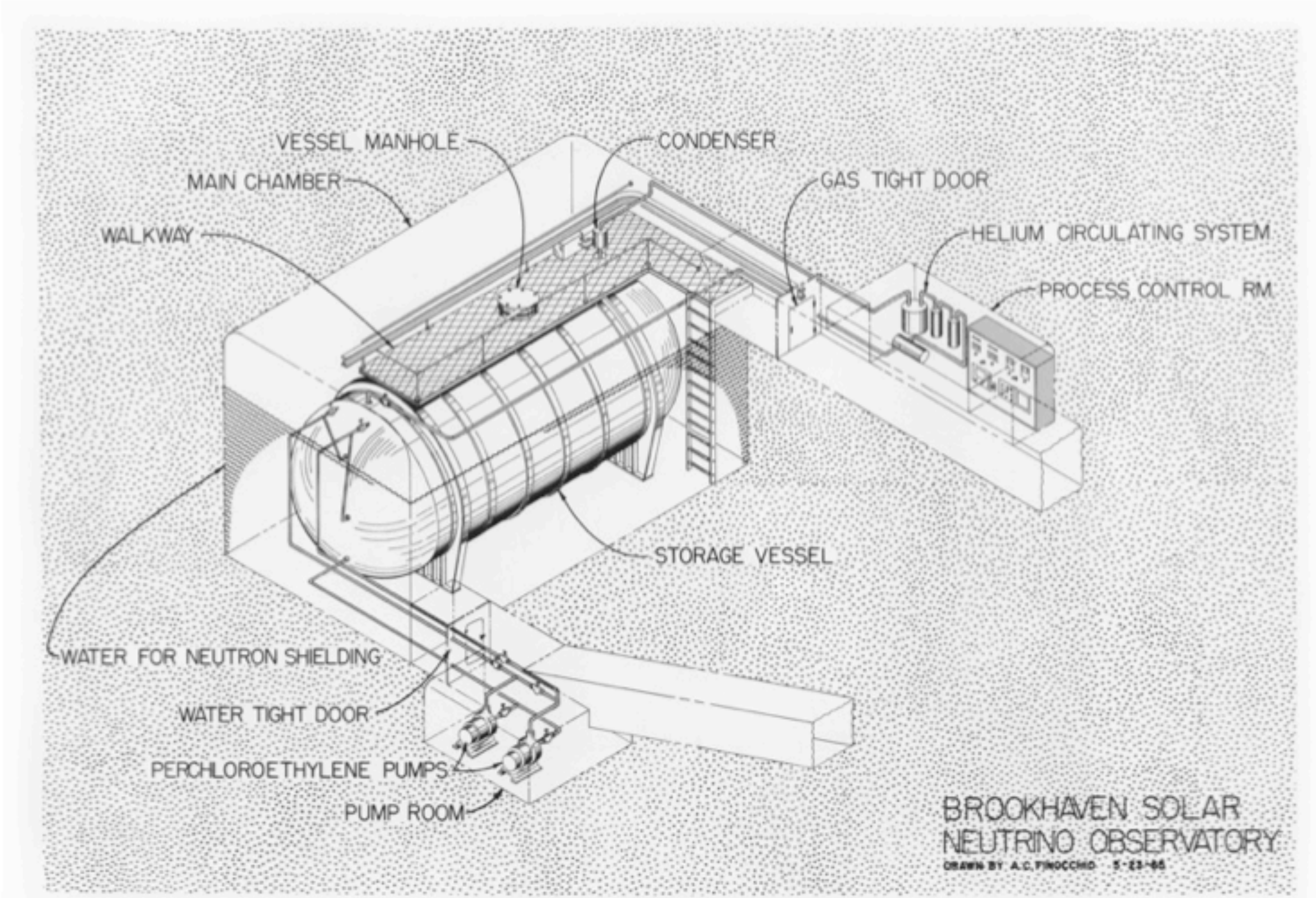
The Homestake experiment

ca.
2500 m



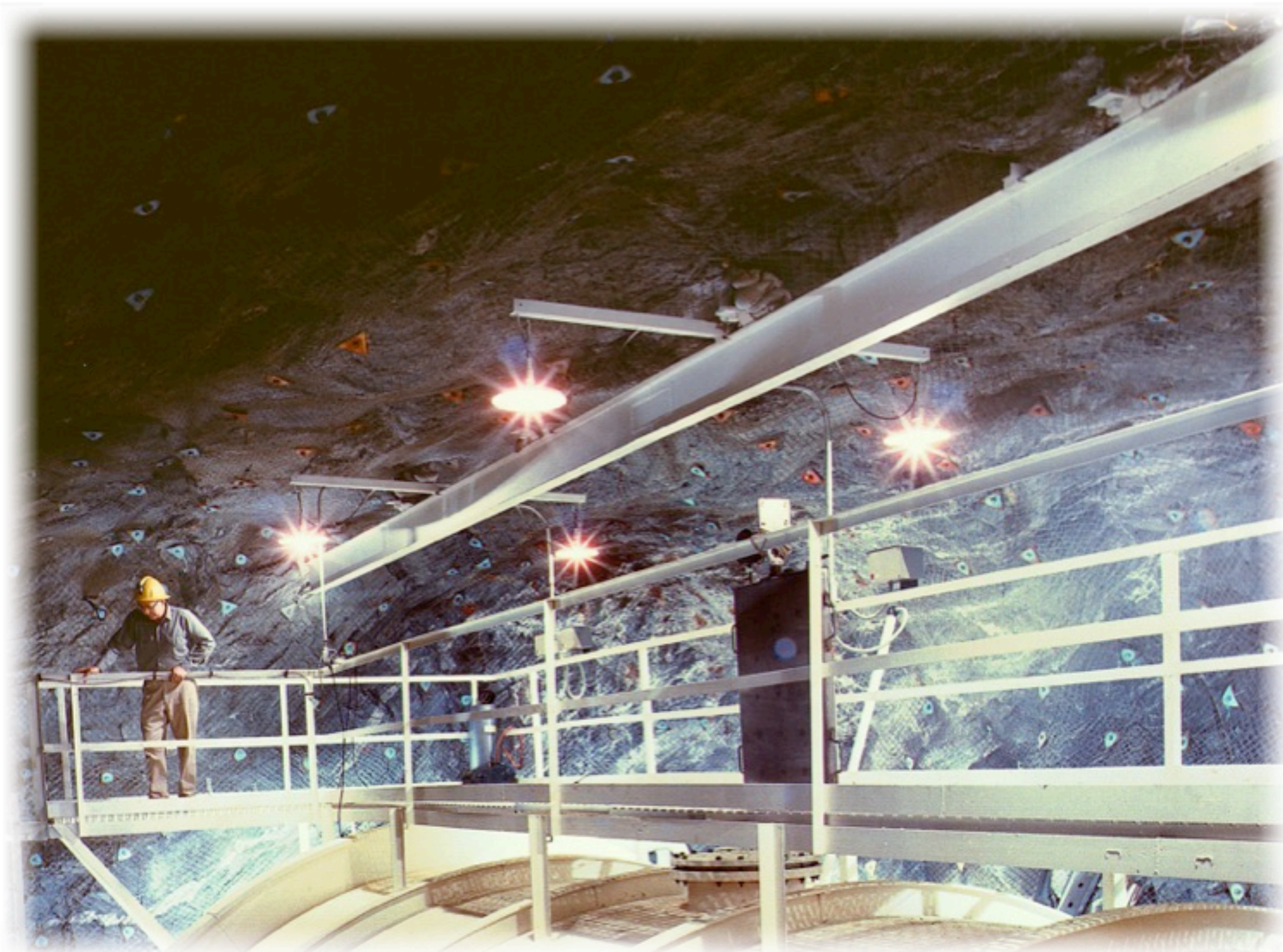
The
Homestake Mine

The Homestake experiment



The Homestake experiment

The Homestake experiment



The Homestake experiment

Neutrino capture:

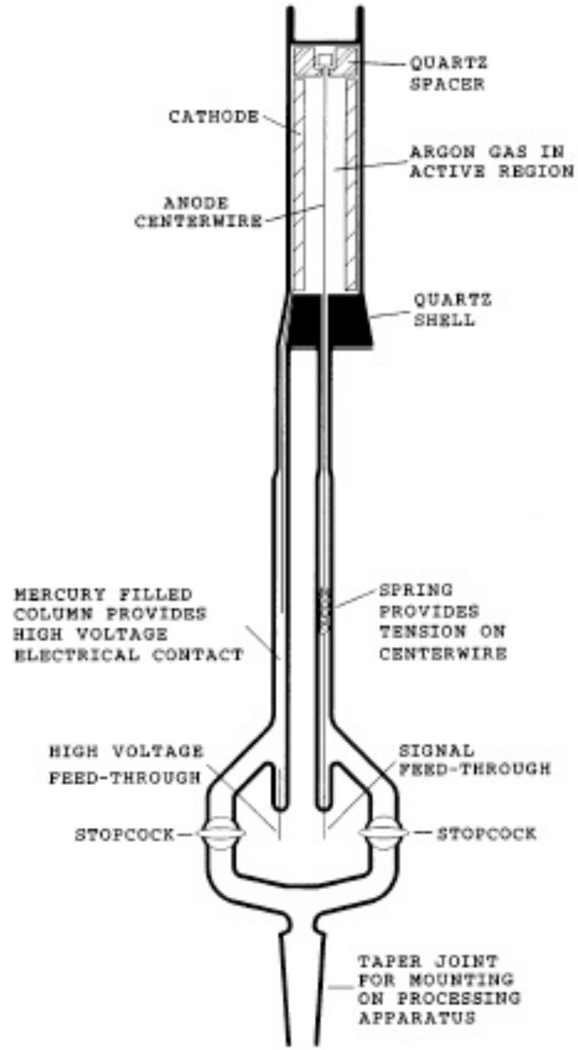
Lifetime: 35 days

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

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

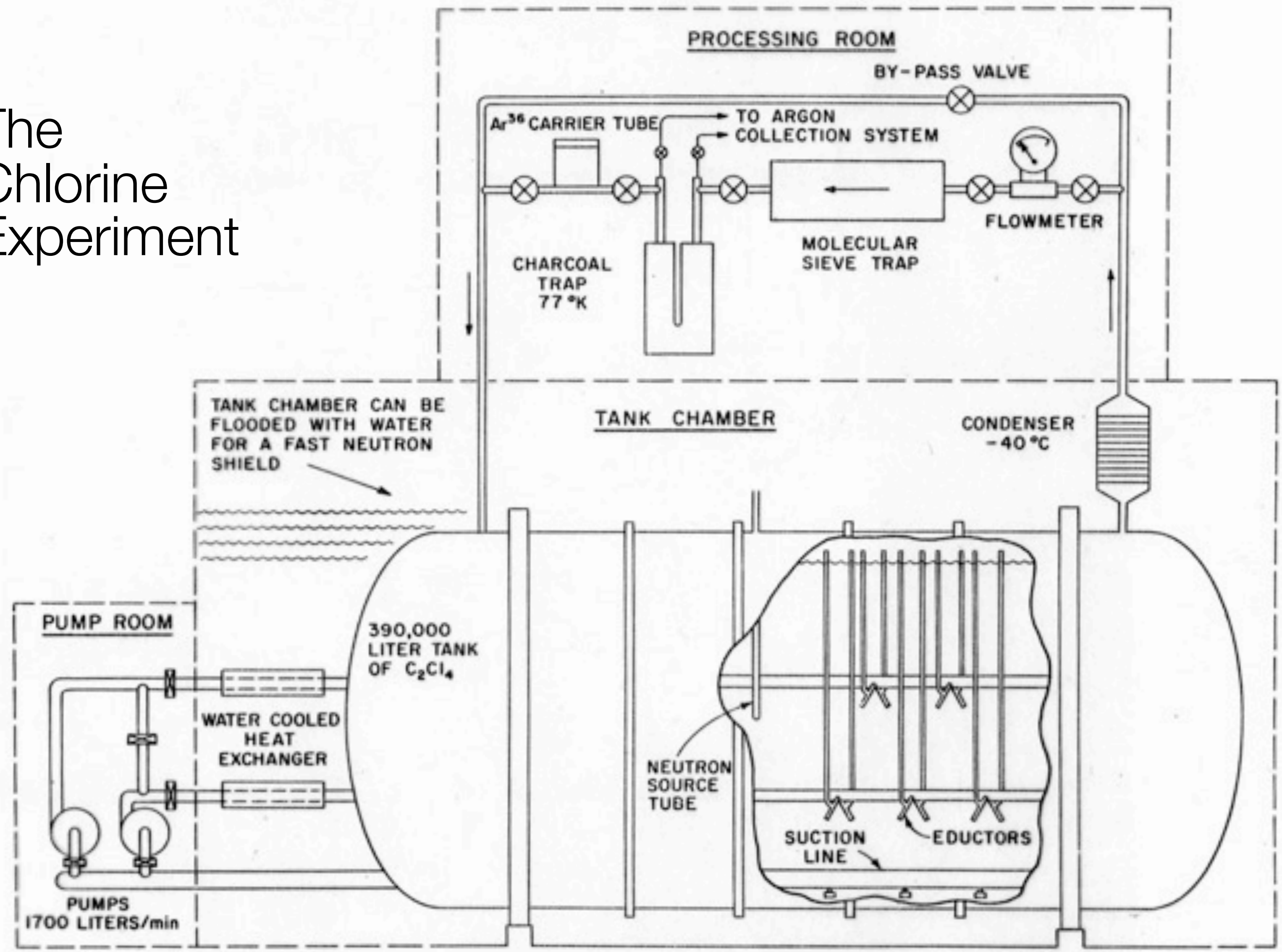
Experimental details:

- 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:

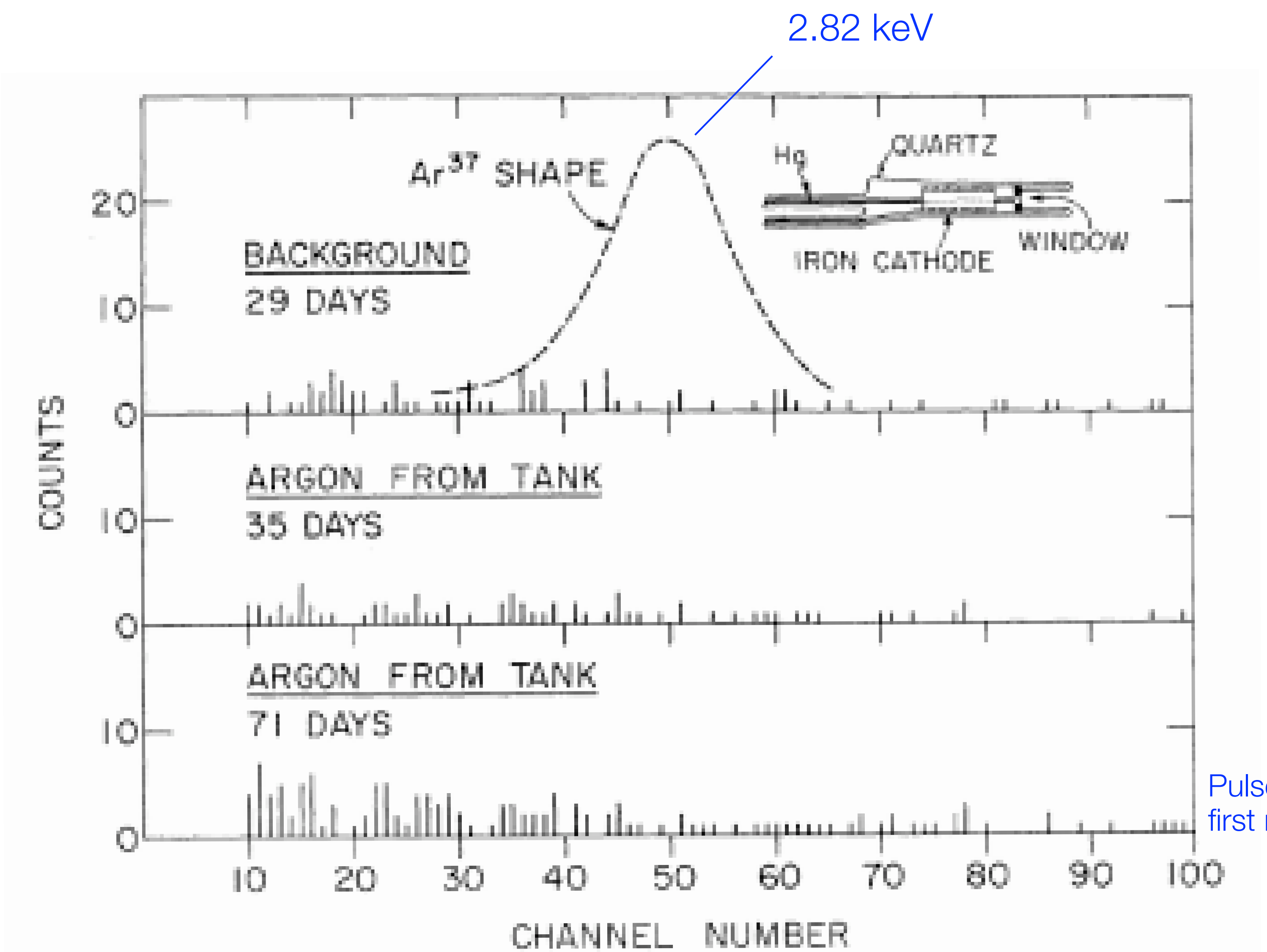
  Expectation: ~ 5000 ^{37}Ar-Atoms expected
  Observation: ~ 2200 ^{37}Ar-Atoms produced

  [875 counted; 776 after background subtraction]

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

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

The Homestake experiment

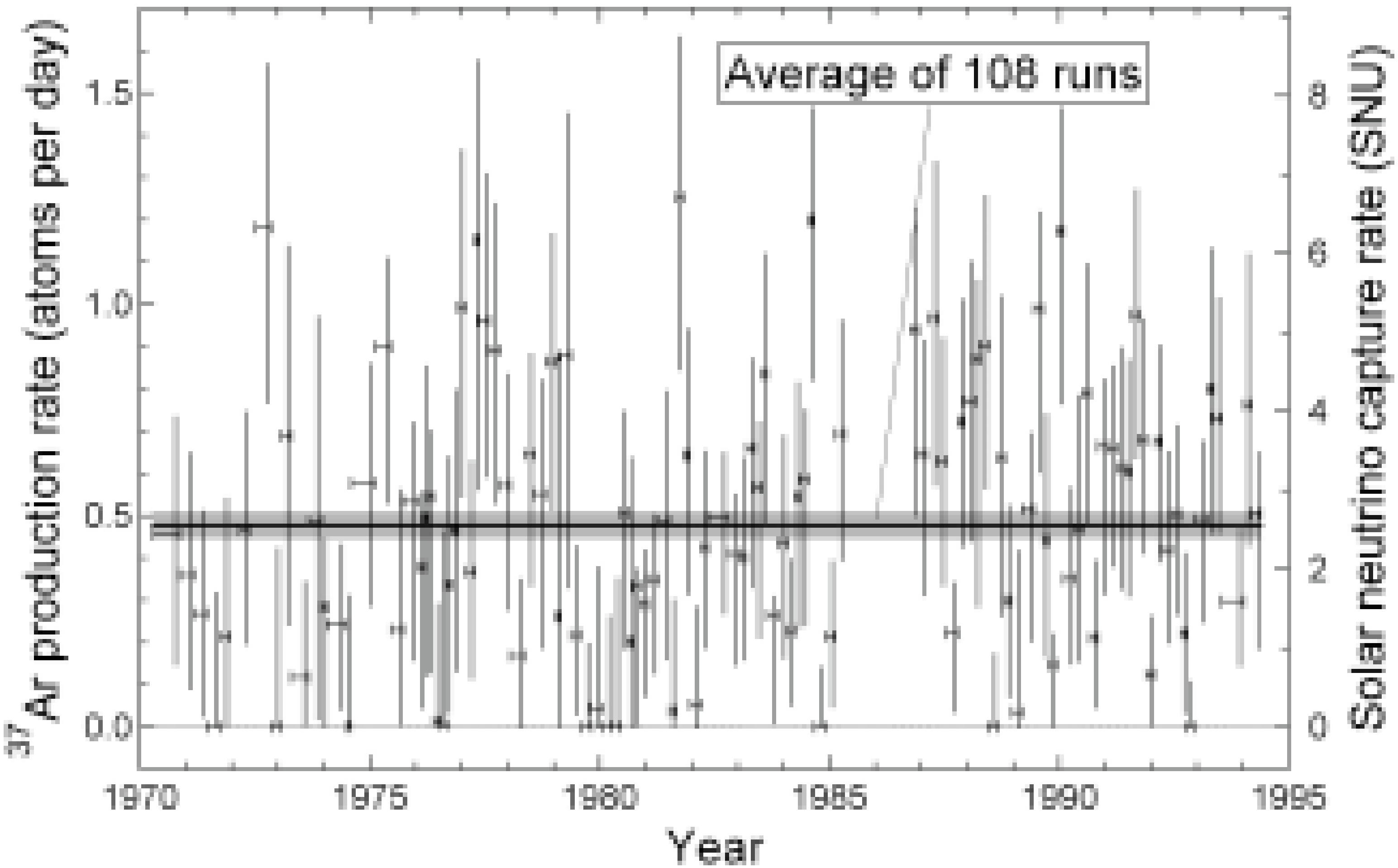


Pulse height Spectra from first runs [1968]

The Homestake experiment

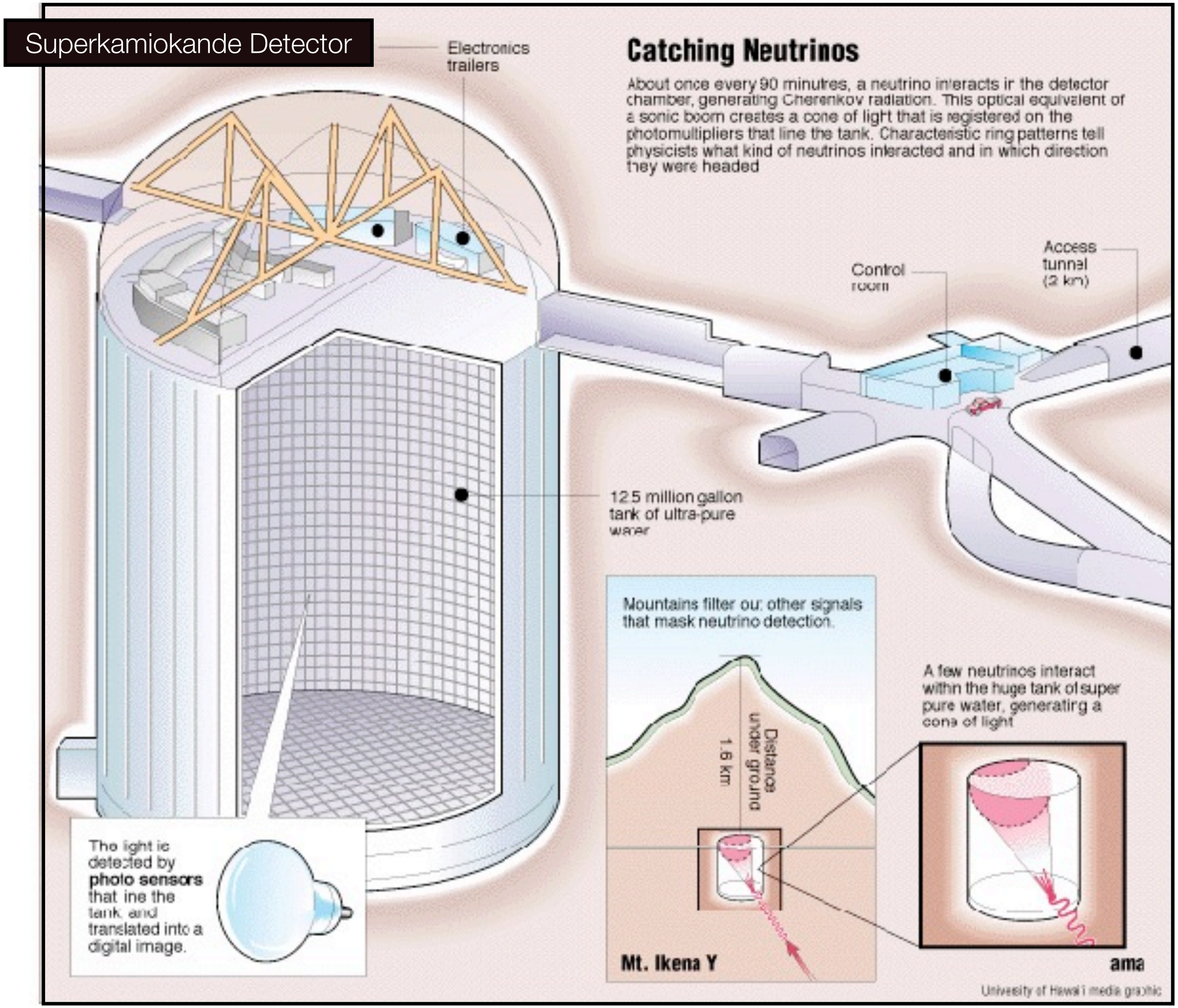
Result of 25 years of running

[after implementation of rise time counting]



2.56 SNU

Super-Kamiokande



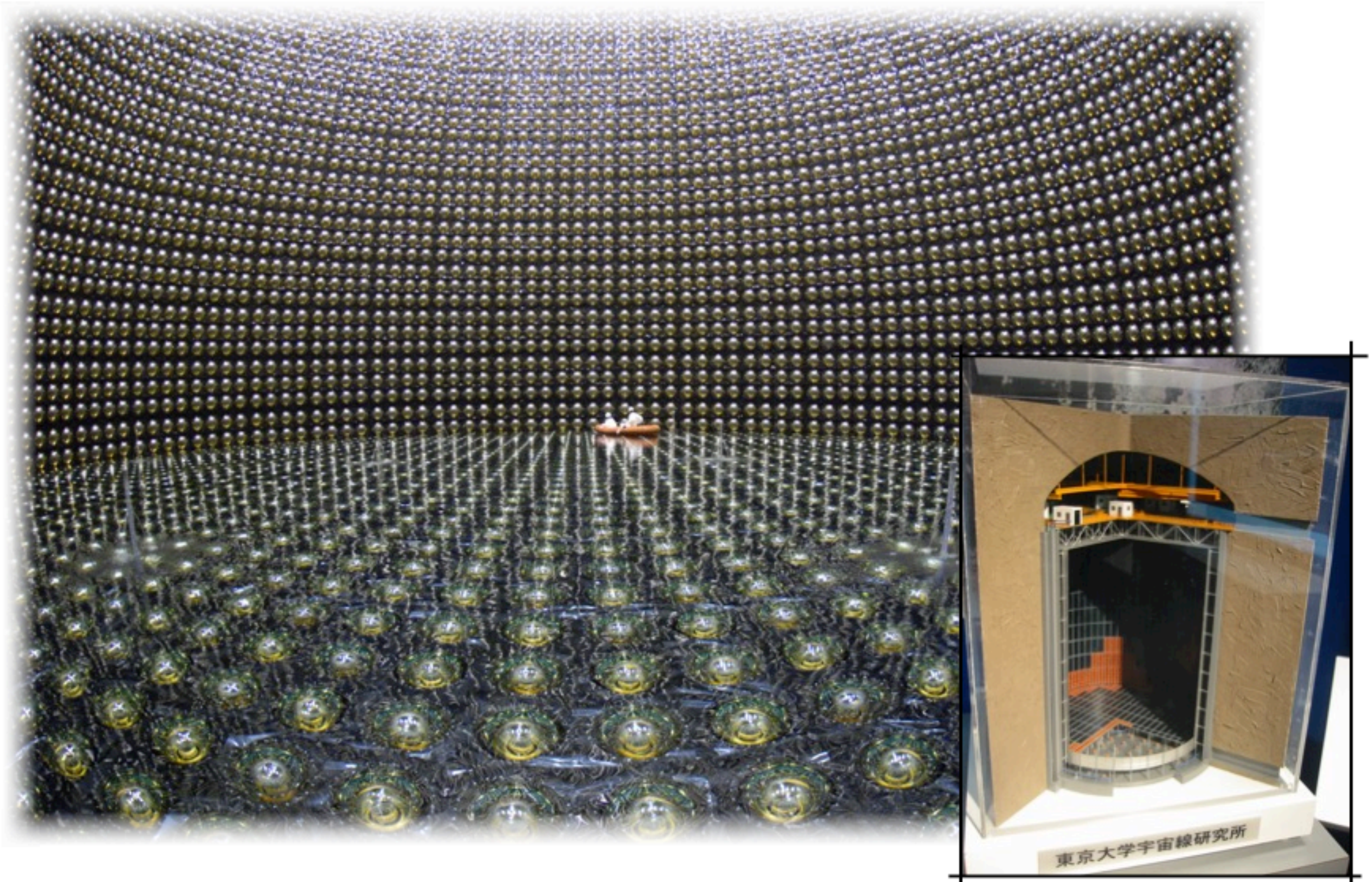
Water tank
1.6 km below ground

50 Million liter
ultra-pure water

1 Neutrino-interaction
every 1.5 hours

Neutrino detection
via Cherenkov light

Super-Kamiokande

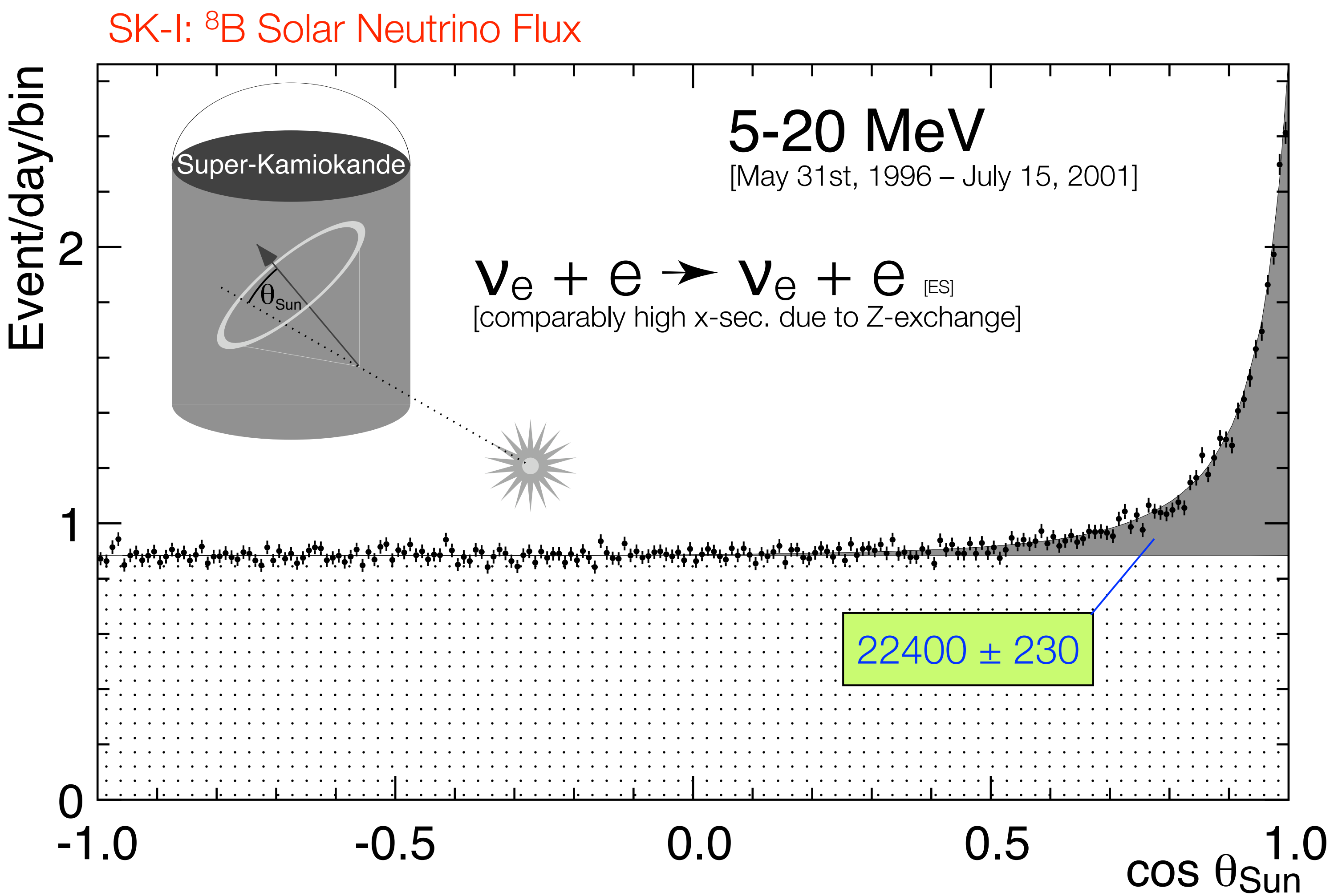


Super-Kamiokande

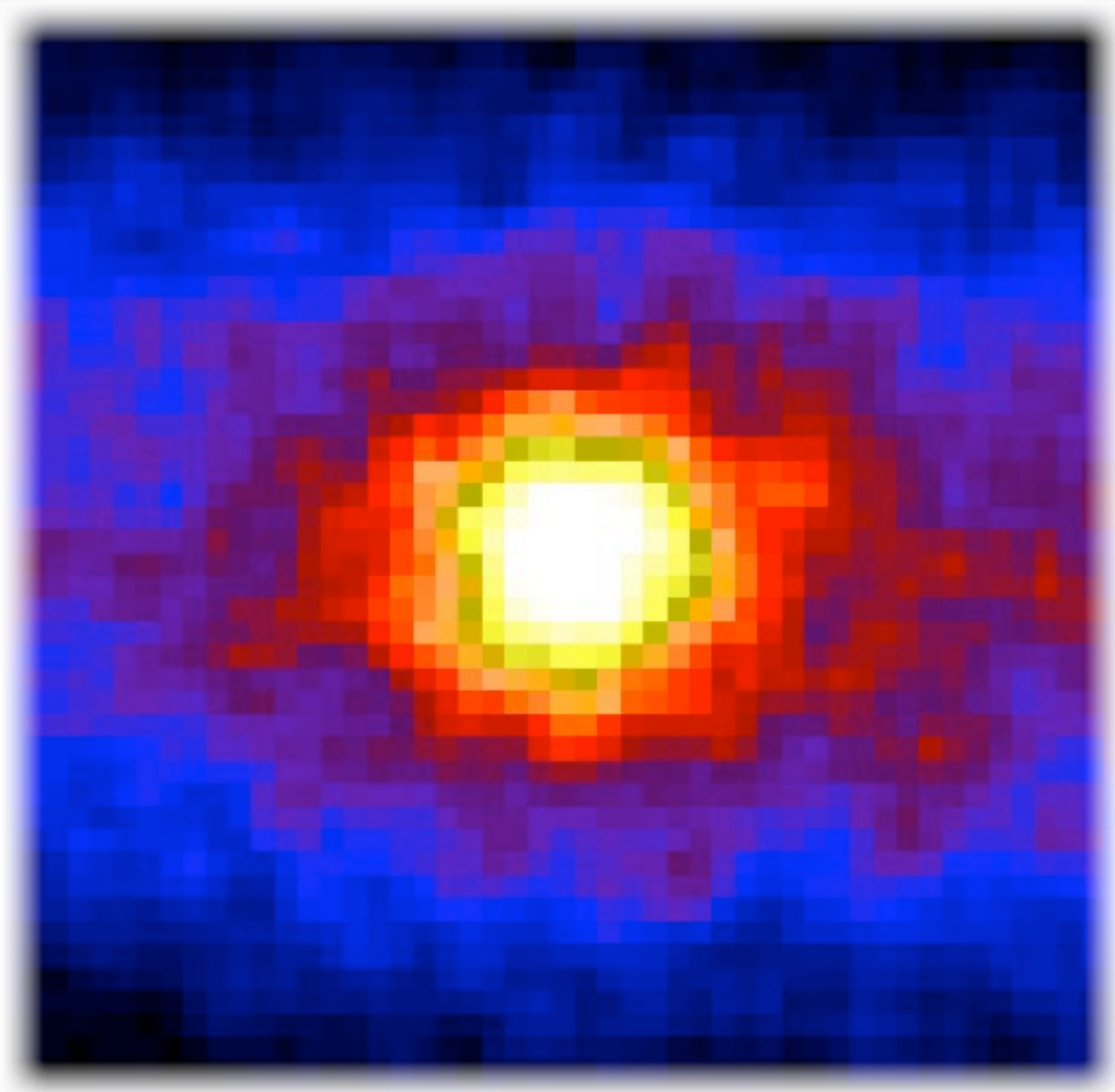
Mounting of
Photomultiplier Tubes

Total:	11,146	20″ pmts
	1,885	8″ pmts

Super-Kamiokande

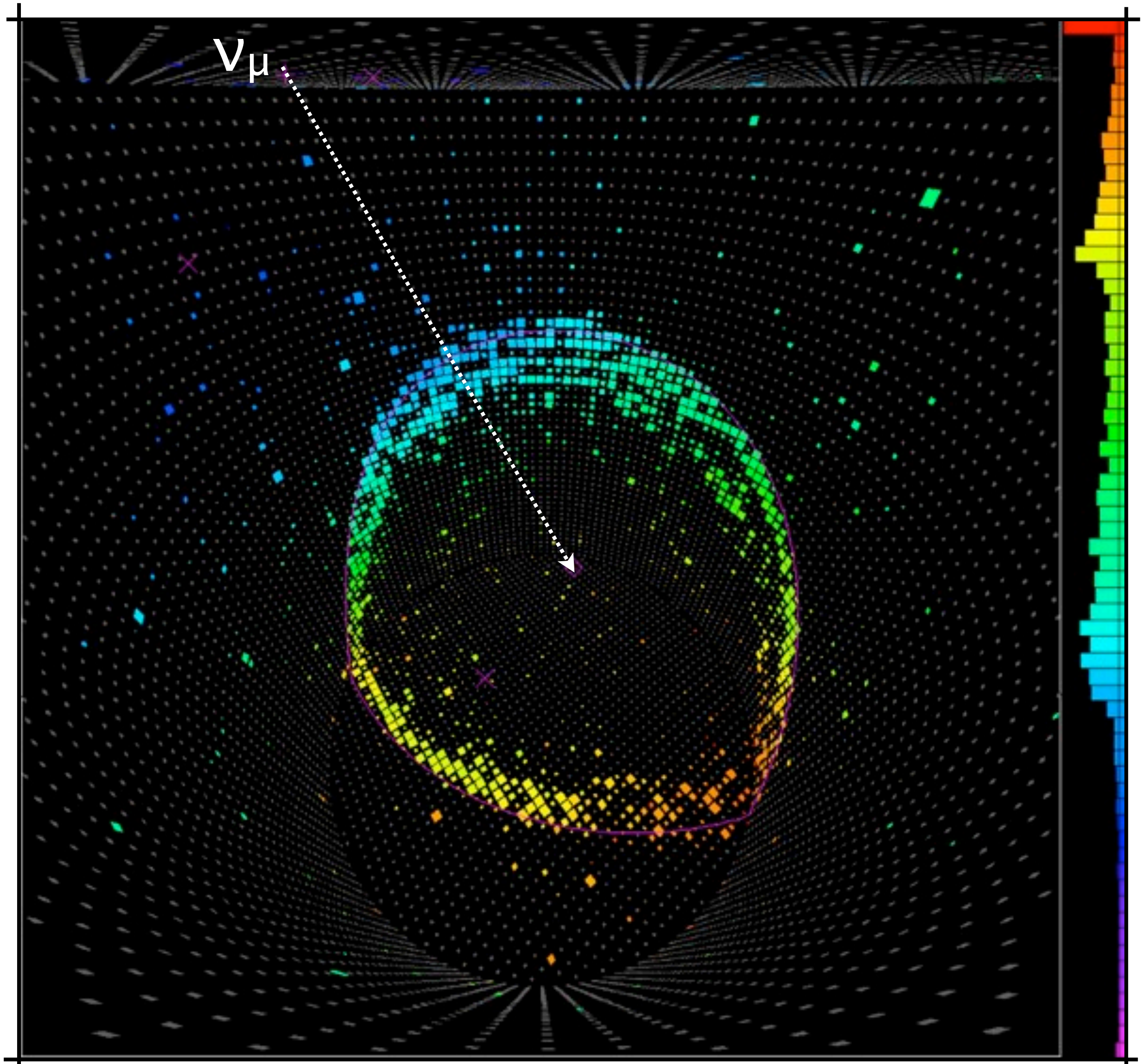


Super-Kamiokande



The sun seen through the earth in neutrino light

Super-Kamiokande



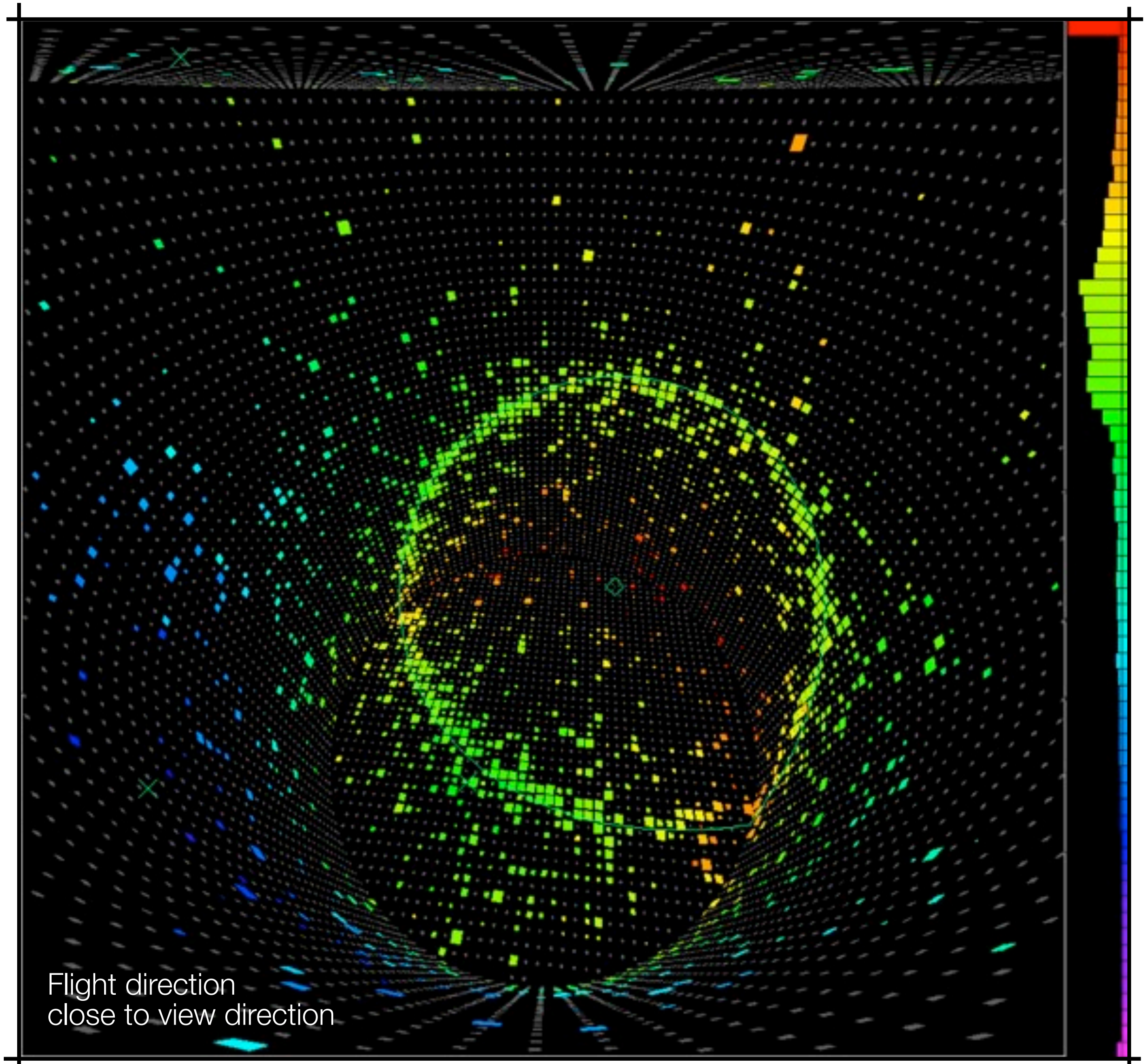
Muon event
[603 MeV]

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



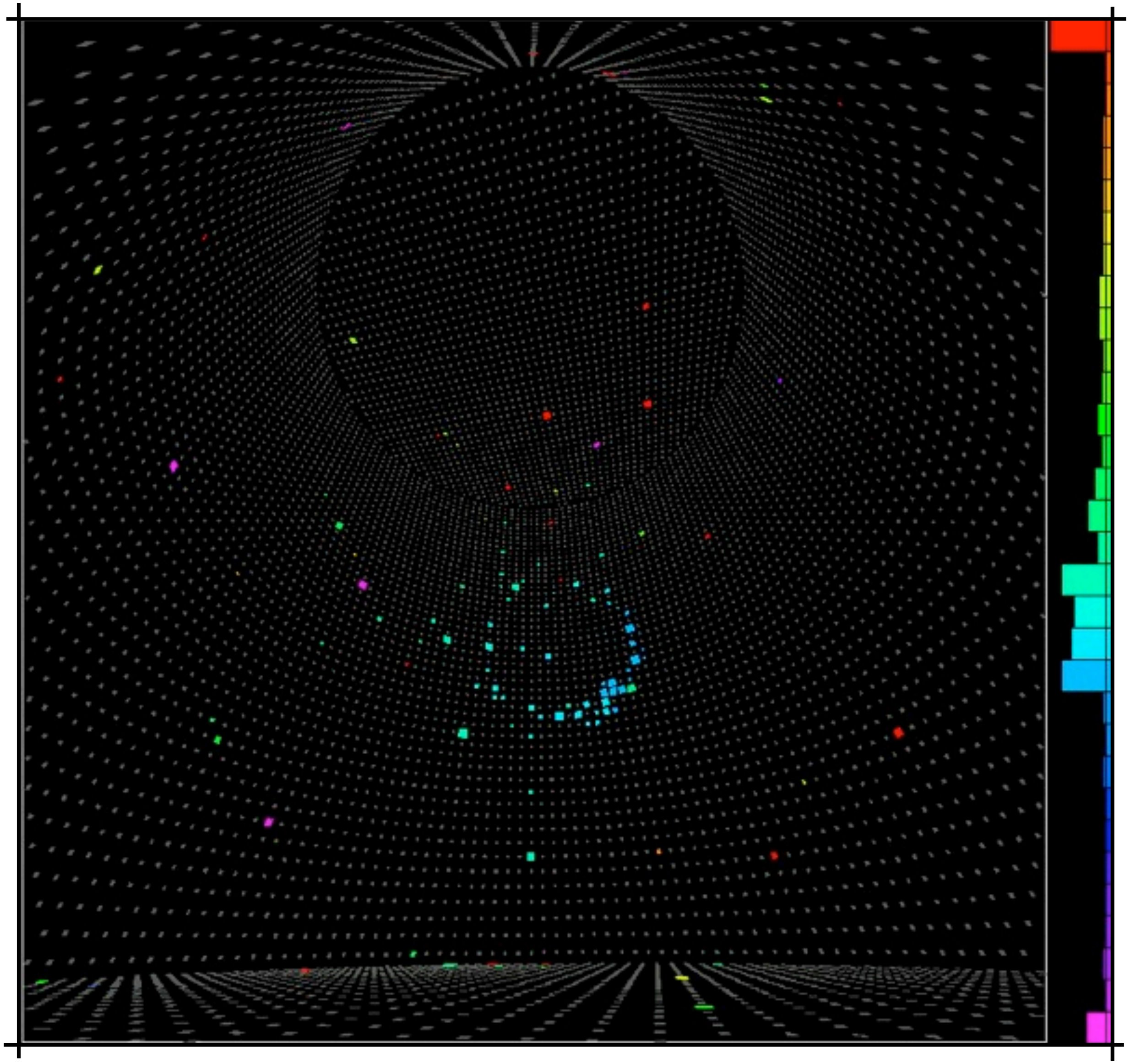
Electron event
[492 MeV]

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

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-flux

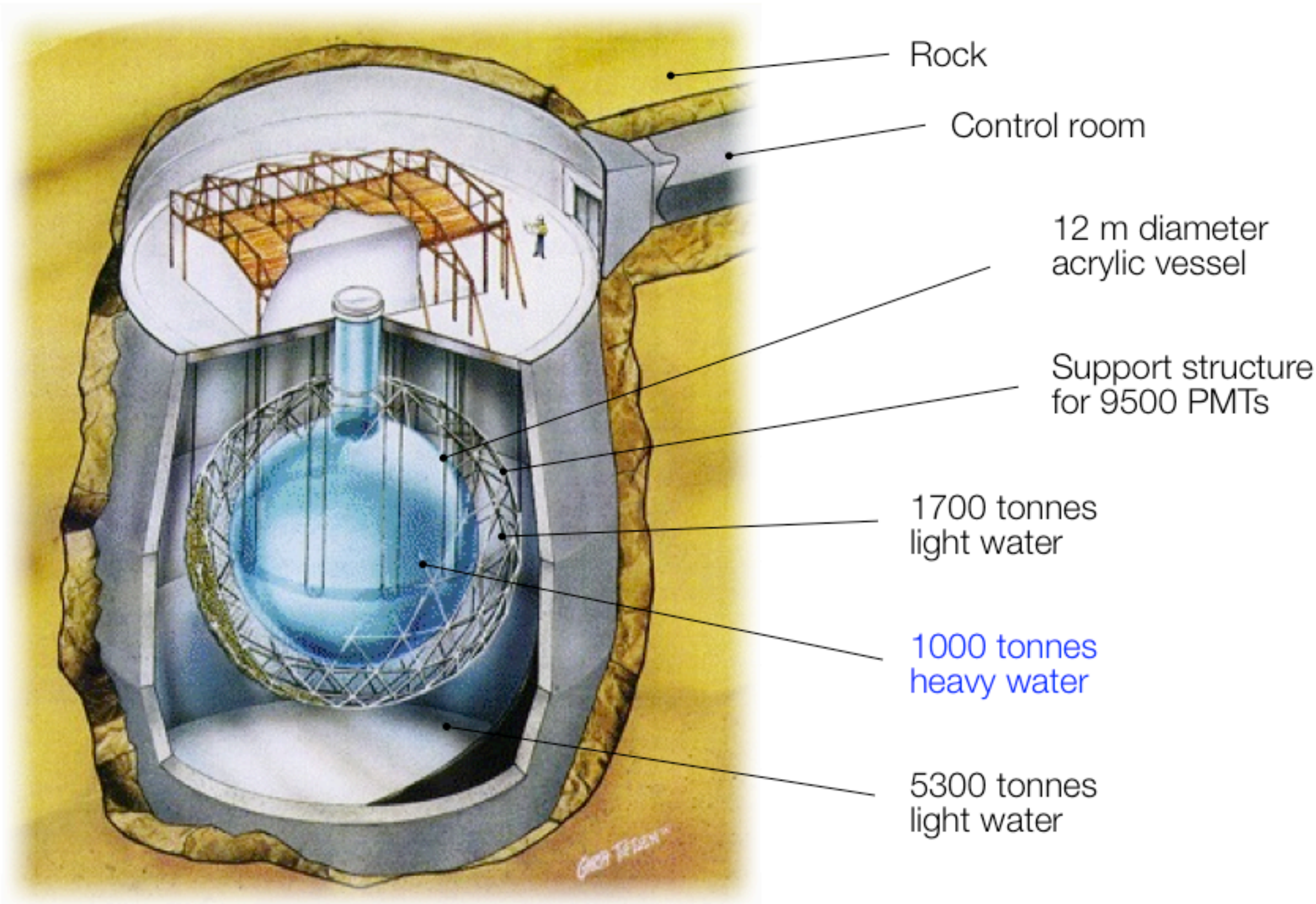
[Kamikande, SNO]

Exp: ~ 2.4 SNU (ν_e only)
BS05: ~ 5.7 SNU

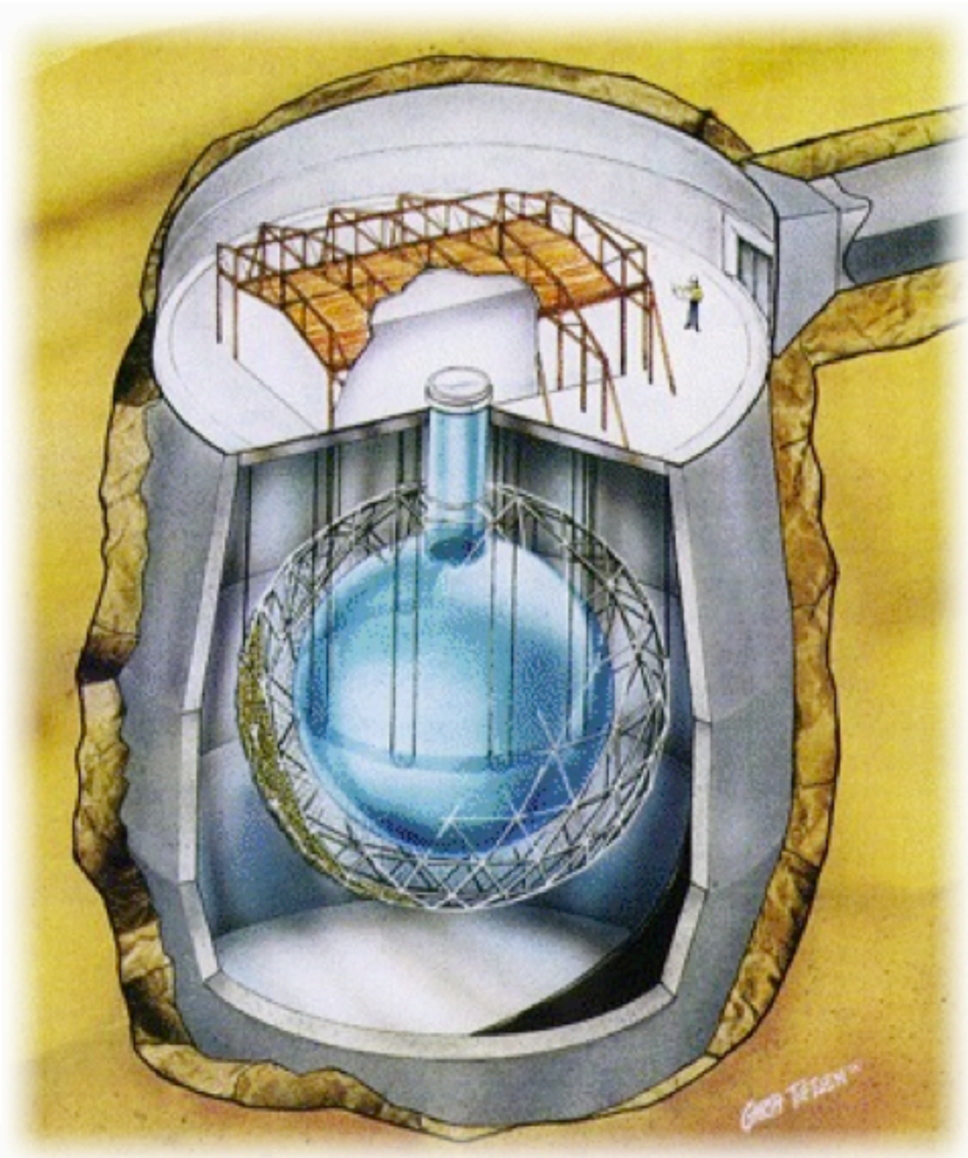
	$^{37}Cl \rightarrow {}^{37}Ar$ (SNU)	$^{71}Ga \rightarrow {}^{71}Ge$ (SNU)	^{8}B ν flux ($10^6 cm^{-2}s^{-1}$)
Homestake			
(CLEVELAND 98)[20]	$2.56 \pm 0.16 \pm 0.16$	—	—
GALLEX			
(HAMPEL 99)[21]	—	$77.5 \pm 6.2^{+4.3}_{-4.7}$	—
GNO			
(ALTMANN 05)[22]	—	$62.9^{+5.5}_{-5.3} \pm 2.5$	—
GNO+GALLEX			
(ALTMANN 05)[22]	—	$69.3 \pm 4.1 \pm 3.6$	—
SAGE			
(ABDURASHI...02)[23]	—	$70.8^{+5.3+3.7}_{-5.2-3.2}$	—
Kamiokande			
(FUKUDA 96)[24]	—	—	$2.80 \pm 0.19 \pm 0.33^{\dagger}$
Super-Kamiokande			
(HOSAKA 05)[25]	—	—	$2.35 \pm 0.02 \pm 0.08^{\dagger}$
SNO (pure D_2O)			
(AHMAD 02)[4]	—	—	$1.76^{+0.06}_{-0.05} \pm 0.09^{\ddagger}$
	—	—	$2.39^{+0.24}_{-0.23} \pm 0.12^{\dagger}$
	—	—	$5.09^{+0.44+0.46}_{-0.43-0.43}{}^{*}$
SNO (NaCl in D_2O)			
(AHARMIM 05)[11]	—	—	$1.68 \pm 0.06^{+0.08}_{-0.09}{}^{\ddagger}$
	—	—	$2.35 \pm 0.22 \pm 0.15^{\dagger}$
	—	—	$4.94 \pm 0.21^{+0.38}_{-0.34}{}^{*}$
BS05(OP) SSM [13]	8.1 ± 1.3	126 ± 10	$5.69(1.00 \pm 0.16)$
Seismic model [18]	7.64 ± 1.1	123.4 ± 8.2	5.31 ± 0.6

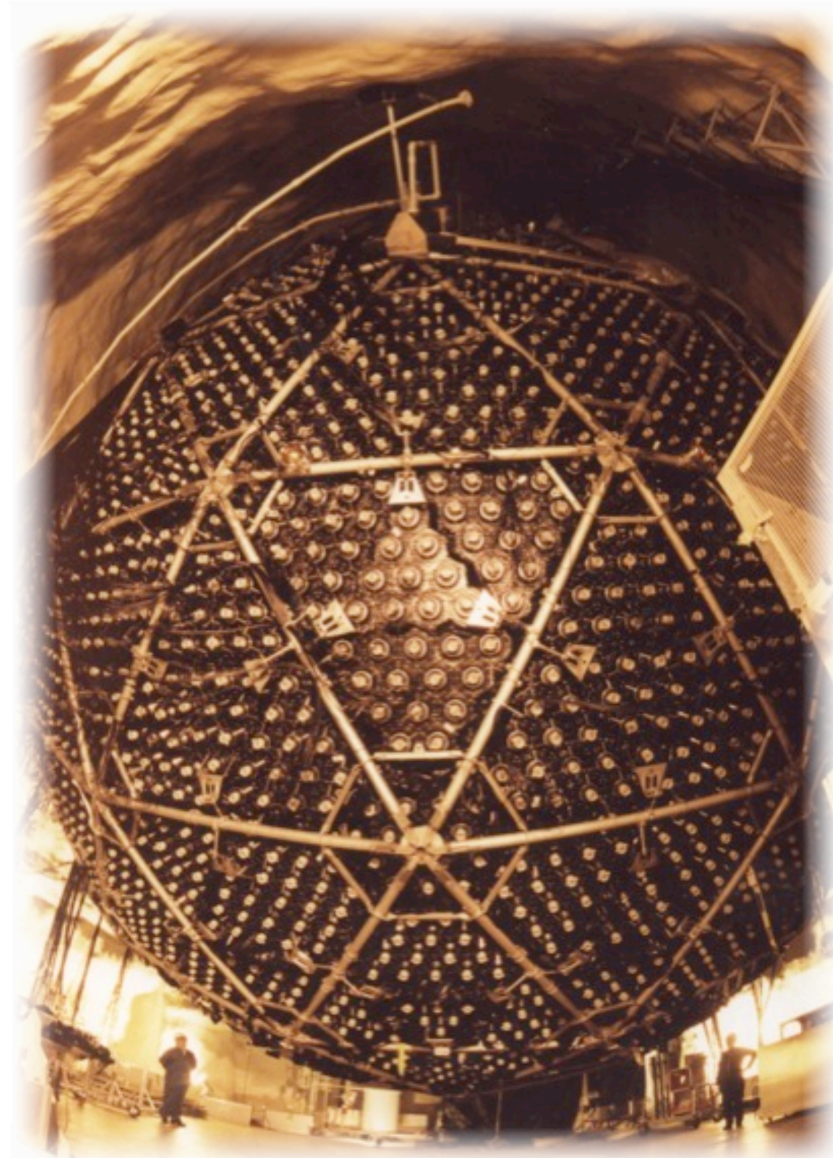
[PDG 2008]

The SNO experiment

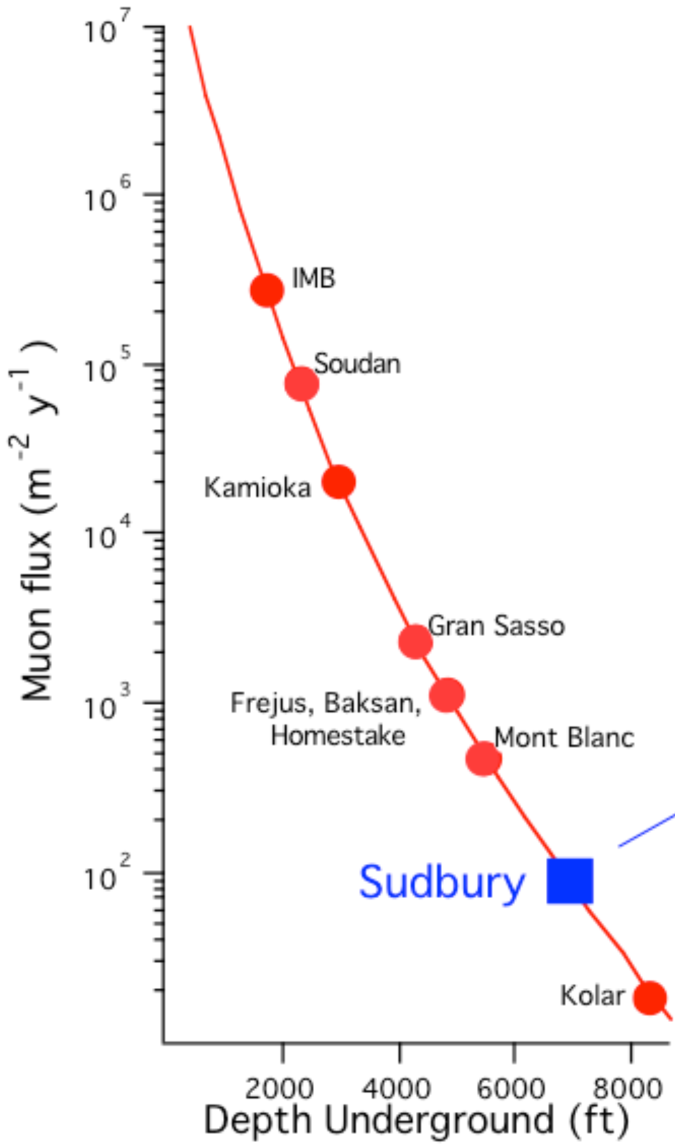


The SNO experiment





The SNO experiment



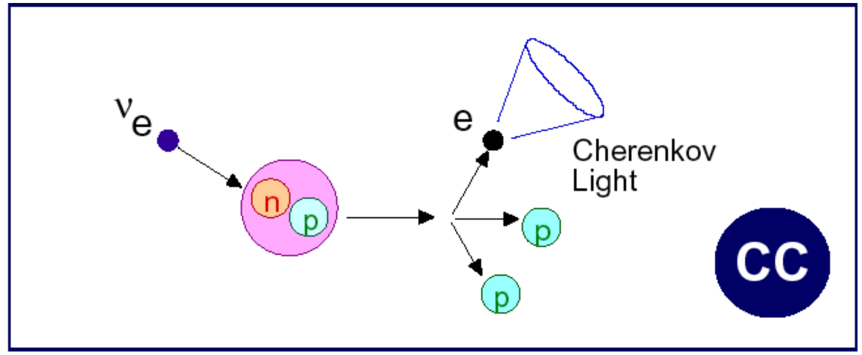
More than 2 km below ground

Background: < 100 μ/day

The SNO experiment

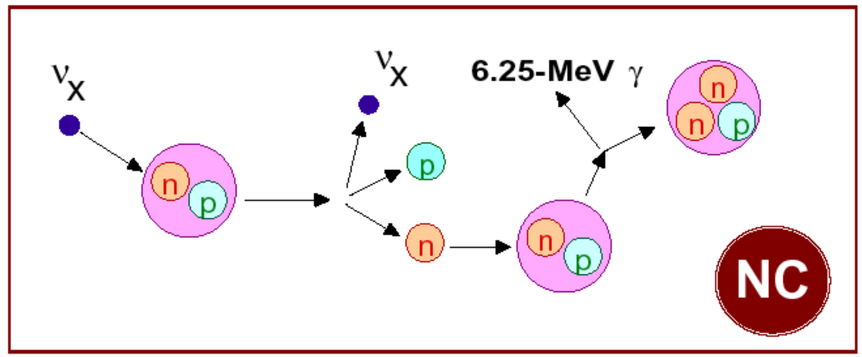
CC $\nu_e + d \rightarrow p + p + e^-$

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



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

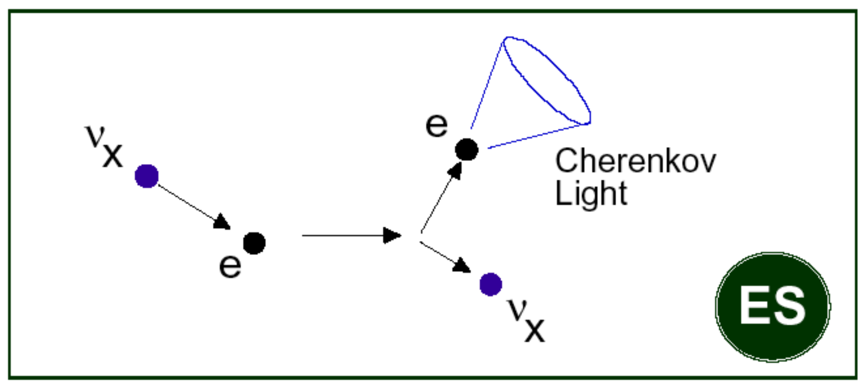
- Measure total ^8B ν flux from the sun
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$



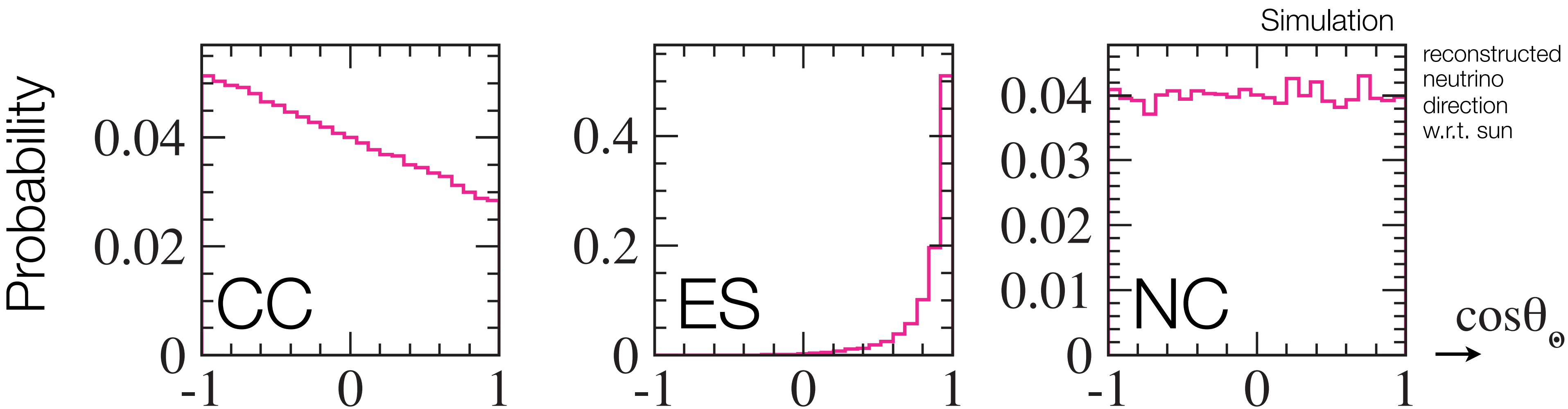
ES $\nu_x + e^- \rightarrow \nu_x + e^-$

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

$$\theta_e \leq 18^o \quad (T_e = 10 \text{ MeV})$$

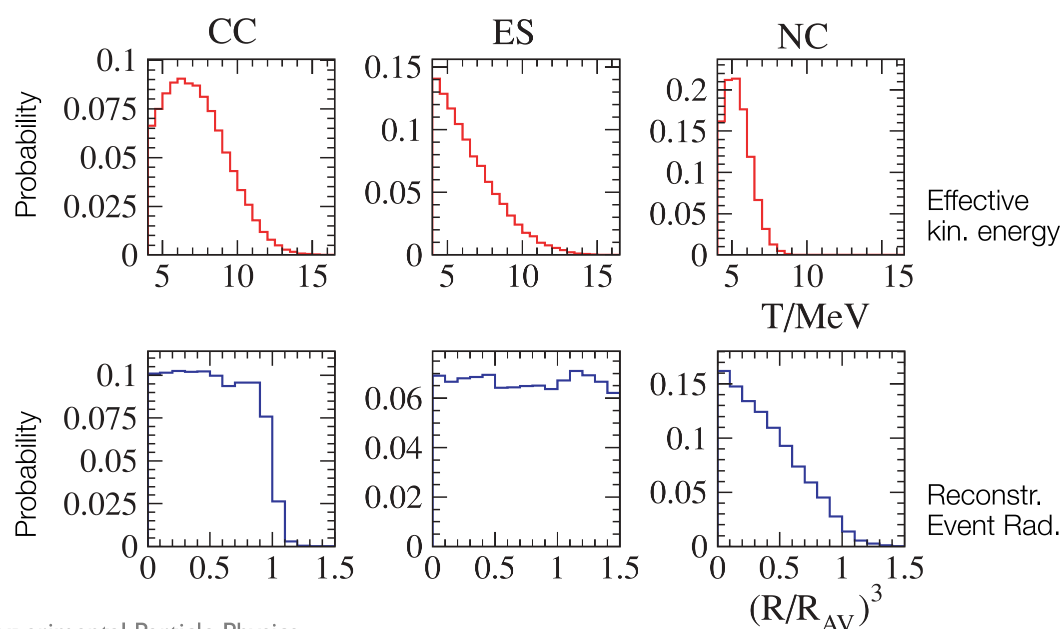


The SNO experiment

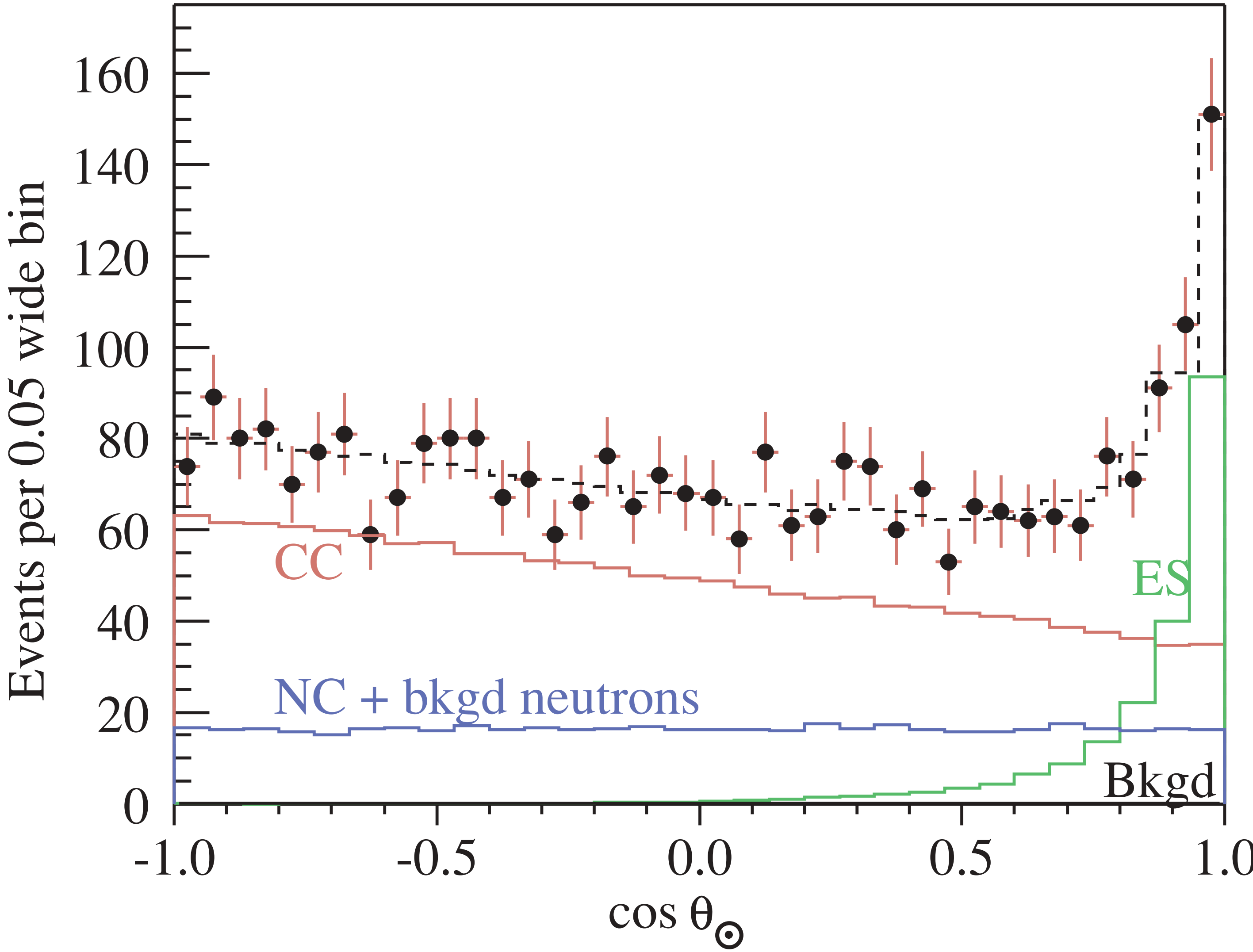


Analysis strategy:

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



The SNO experiment

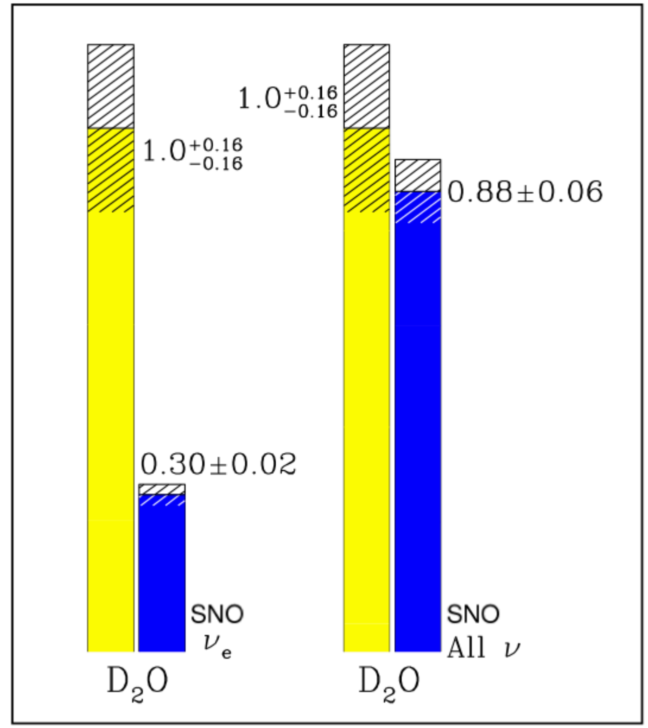


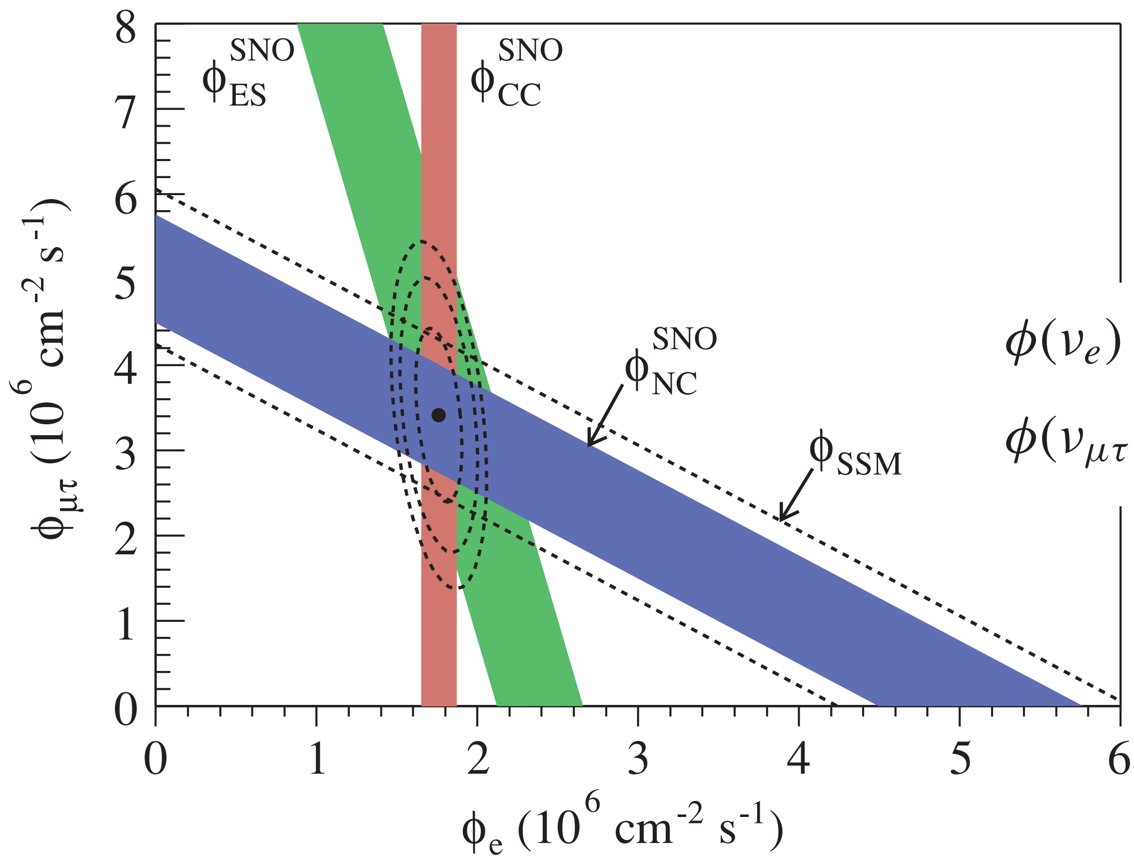
SNO data

reconstructed neutrino direction w.r.t. sun

The SNO experiment

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

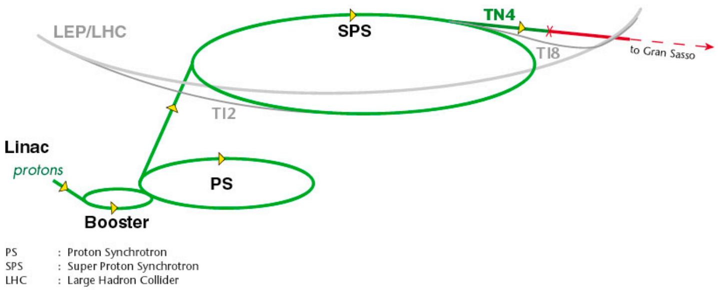


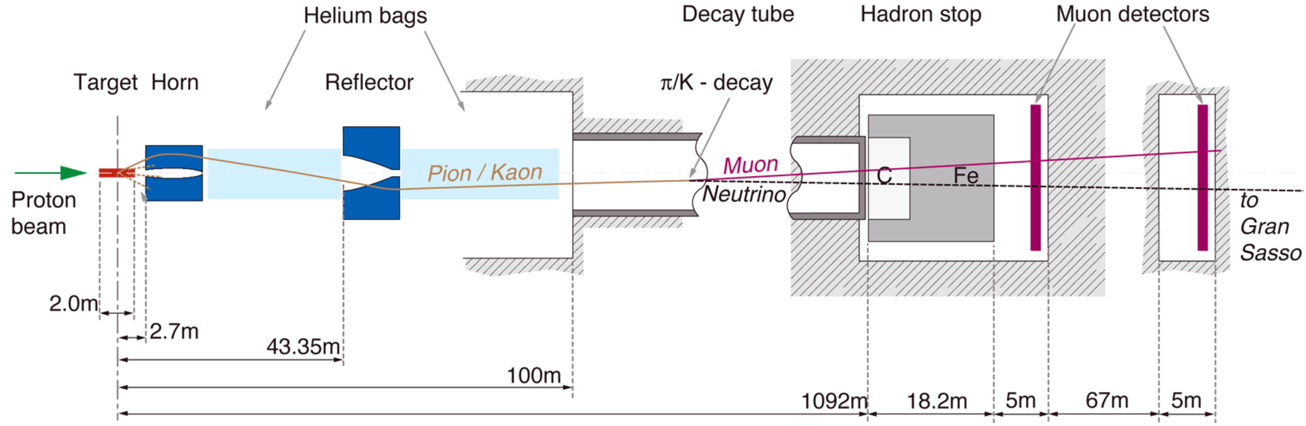


$$\phi(\nu_e) = 1.76^{+0.05}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.})$$
$$\phi(\nu_{\mu\tau}) = 3.41^{+0.45}_{-0.45}\,(\text{stat.})^{+0.48}_{-0.45}\,(\text{syst.})$$
$$\times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

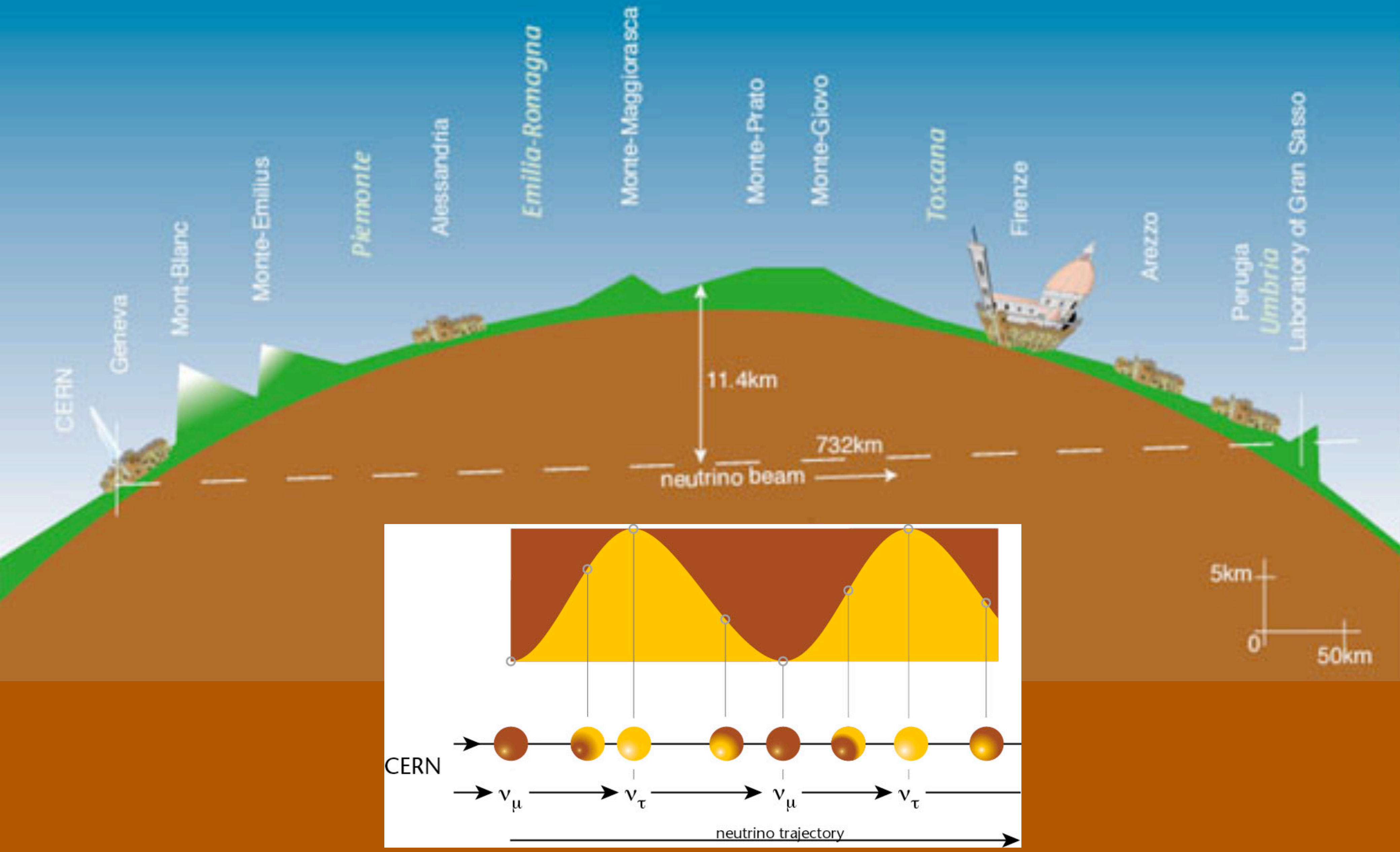
ν_e-flux too low!
Oscillations!

CNGS


LEP/LHC
SPS
TN4
T18
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
Proton beam
Pion / Kaon
Muon
Neutrino
C
Fe
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.

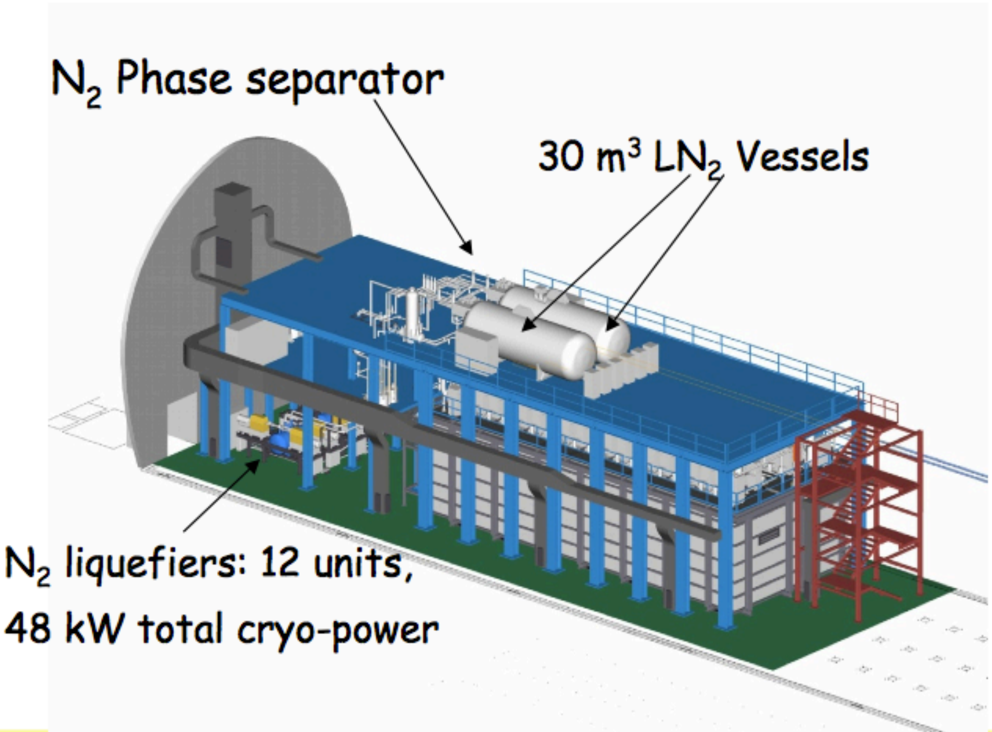
http://cds.cern.ch/record/117852/files/CERN-EP-INT-77-8.pdf

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

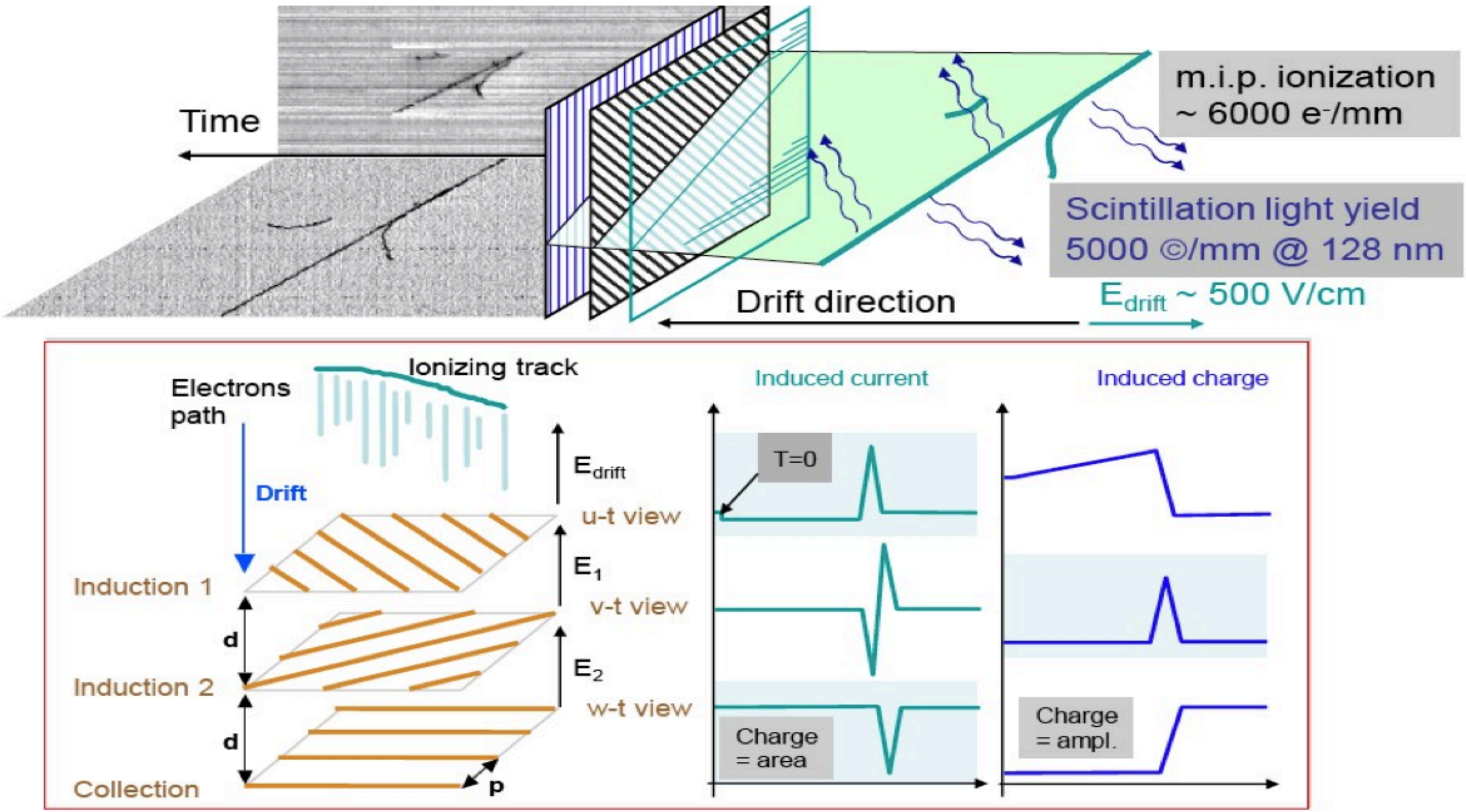
ICARUS (Imaging Cosmic And Rare Underground Signals)



Hall B @ LNGS

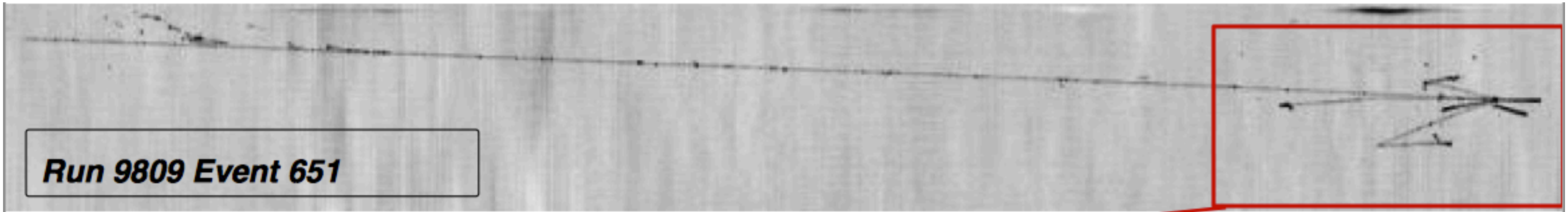
- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0,±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light detection:
  - VUV sensitive (128nm) with wave shifter (TPB)

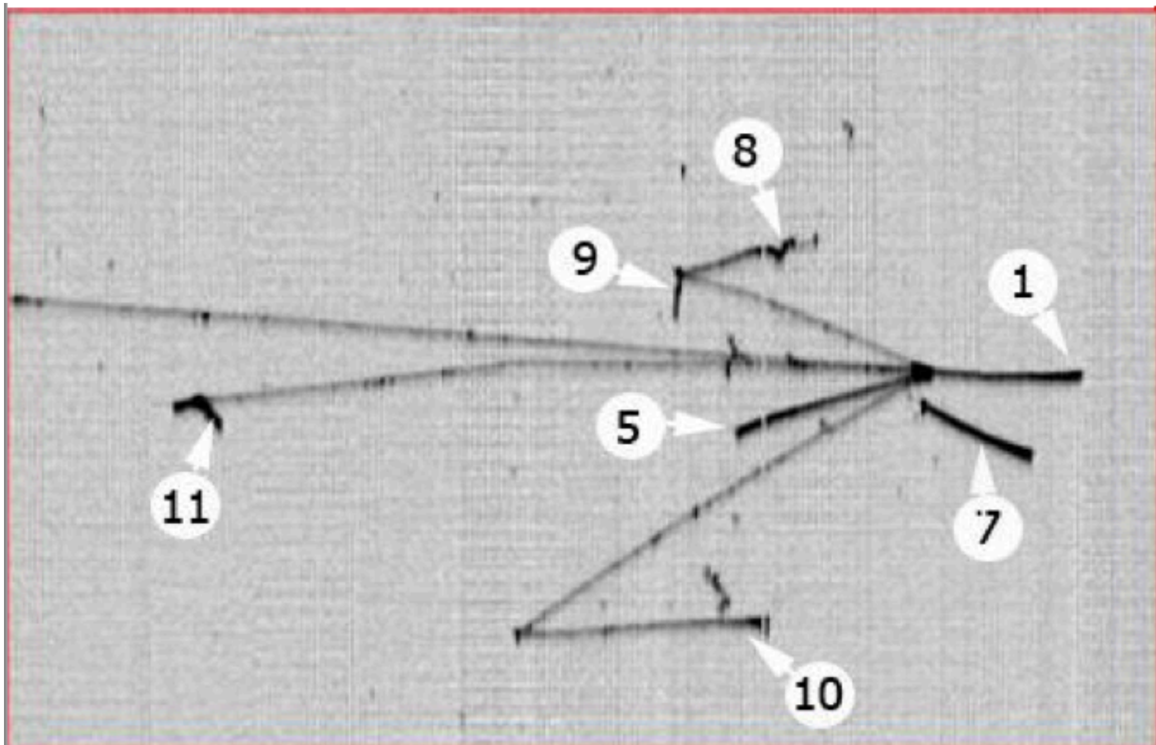
ICARUS



Time
m.i.p. ionization
~ 6000 e-/mm
Scintillation light yield
5000 ©/mm @ 128 nm
Drift direction
E_{drift} ~ 500 V/cm
Electrons path
Ionizing track
Drift
E_{drift}
u-t view
E_1
v-t view
E_2
w-t view
Induction 1
Induction 2
Collection
d
d
p
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]

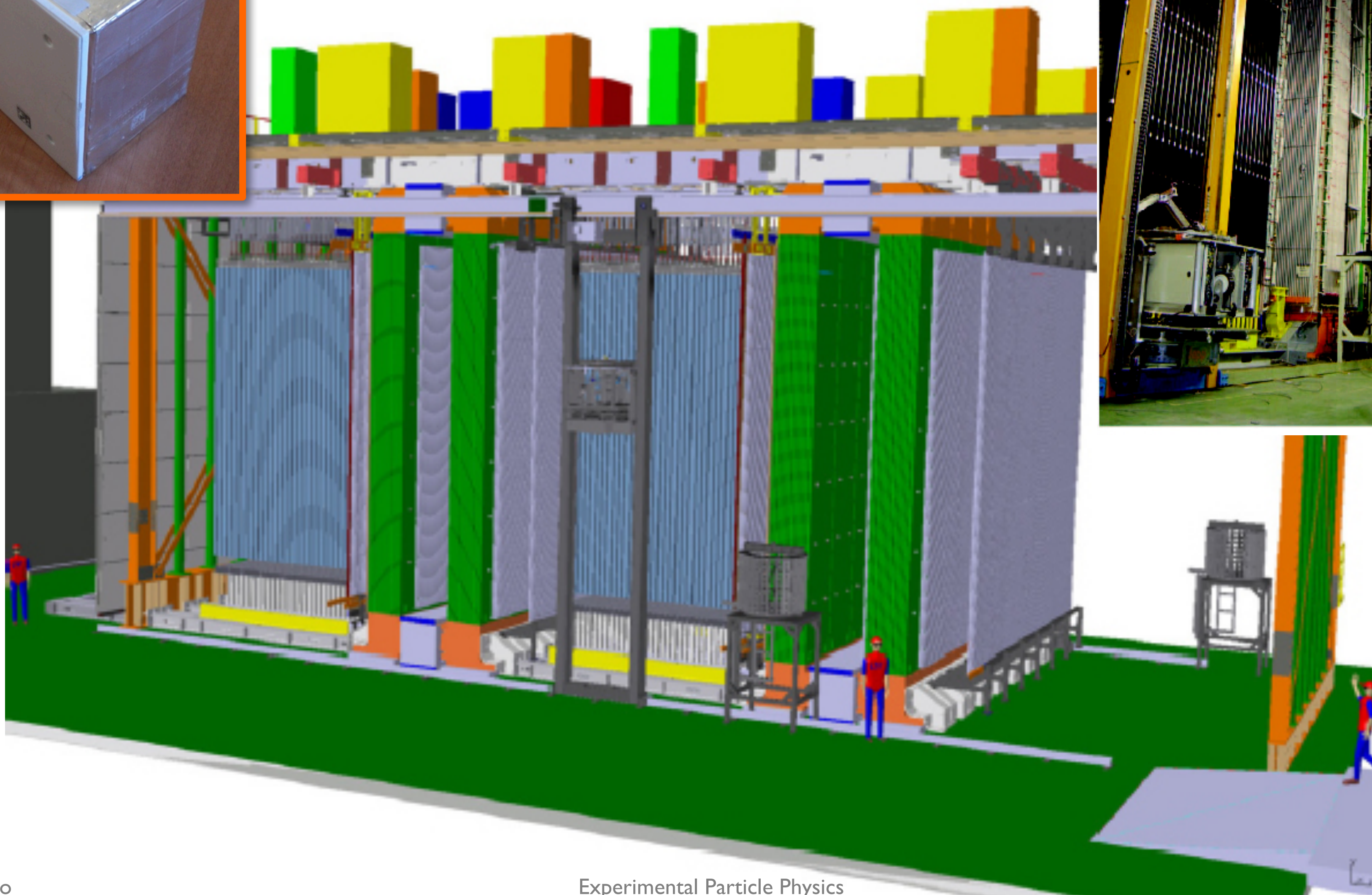
http://icarus.lngs.infn.it/photos/NeutrinoEventsGallery/

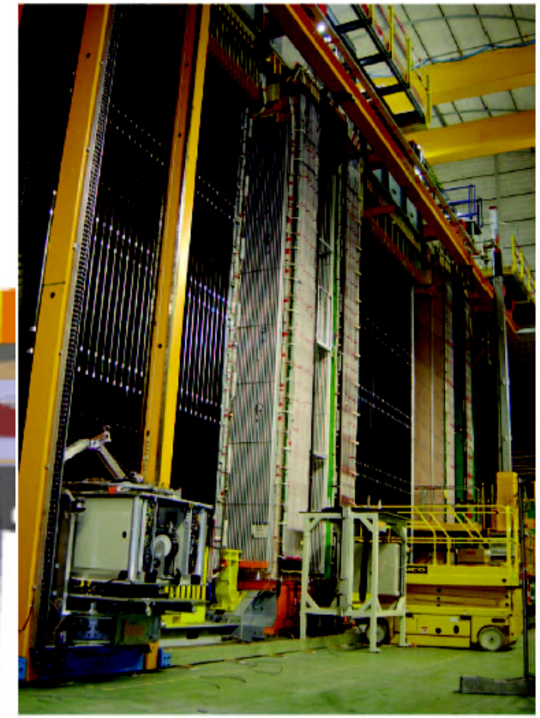
Particle identification based on dE/dx dependence:

- Reconstr. 3D track segments: dx
- charge dep. on track segment: dE

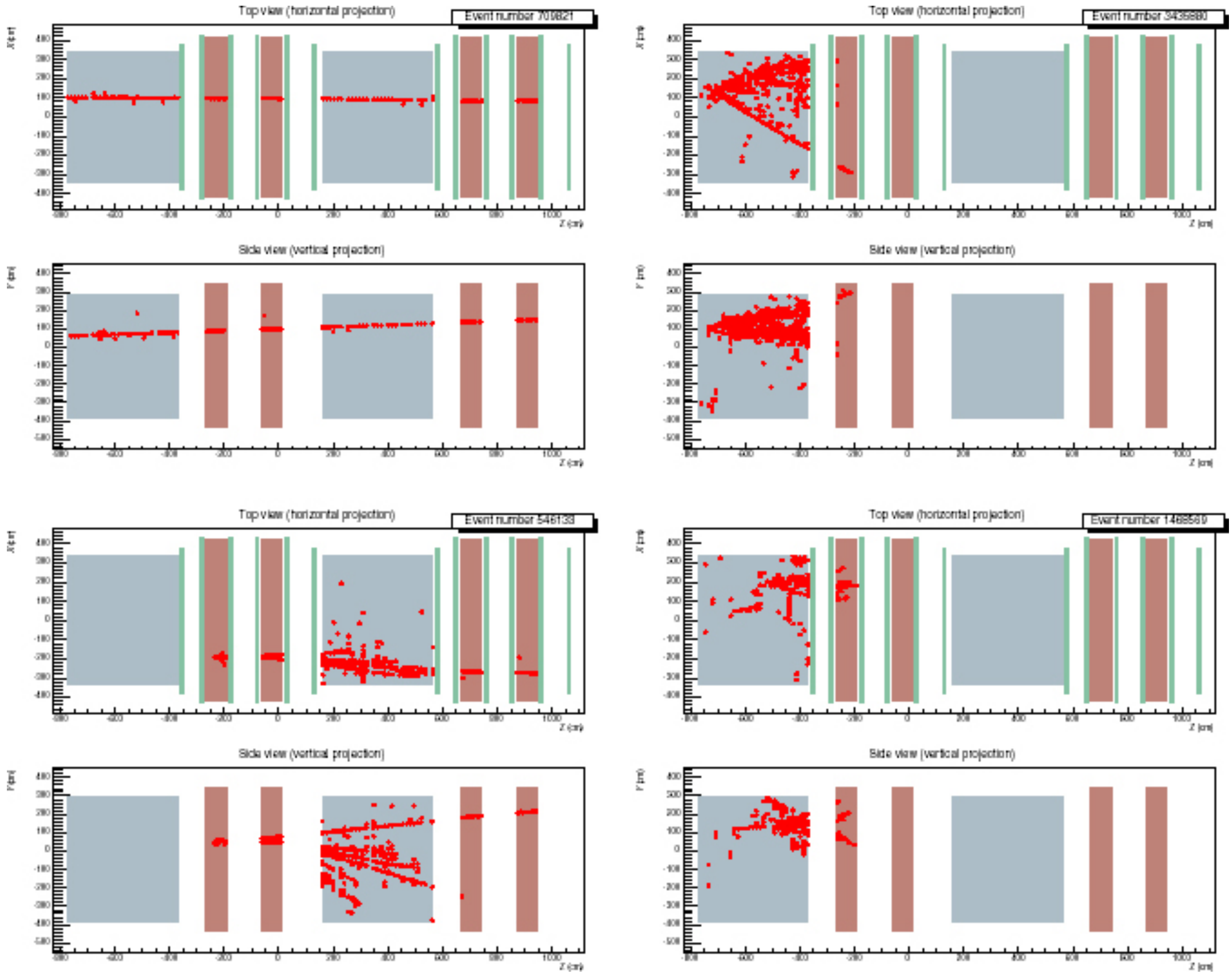
Track	E_{dep} [MeV]	range [cm]
1(p)	185±16	15
5(p)	192±16	20
7(p)	142±12	17
8(π)	94±8	12
9(p)	26±2	4
10(p)	141±12	23
11(p)	123±10	6

OPERA (Oscillation Project with Emulsion-tRacking Apparatus)

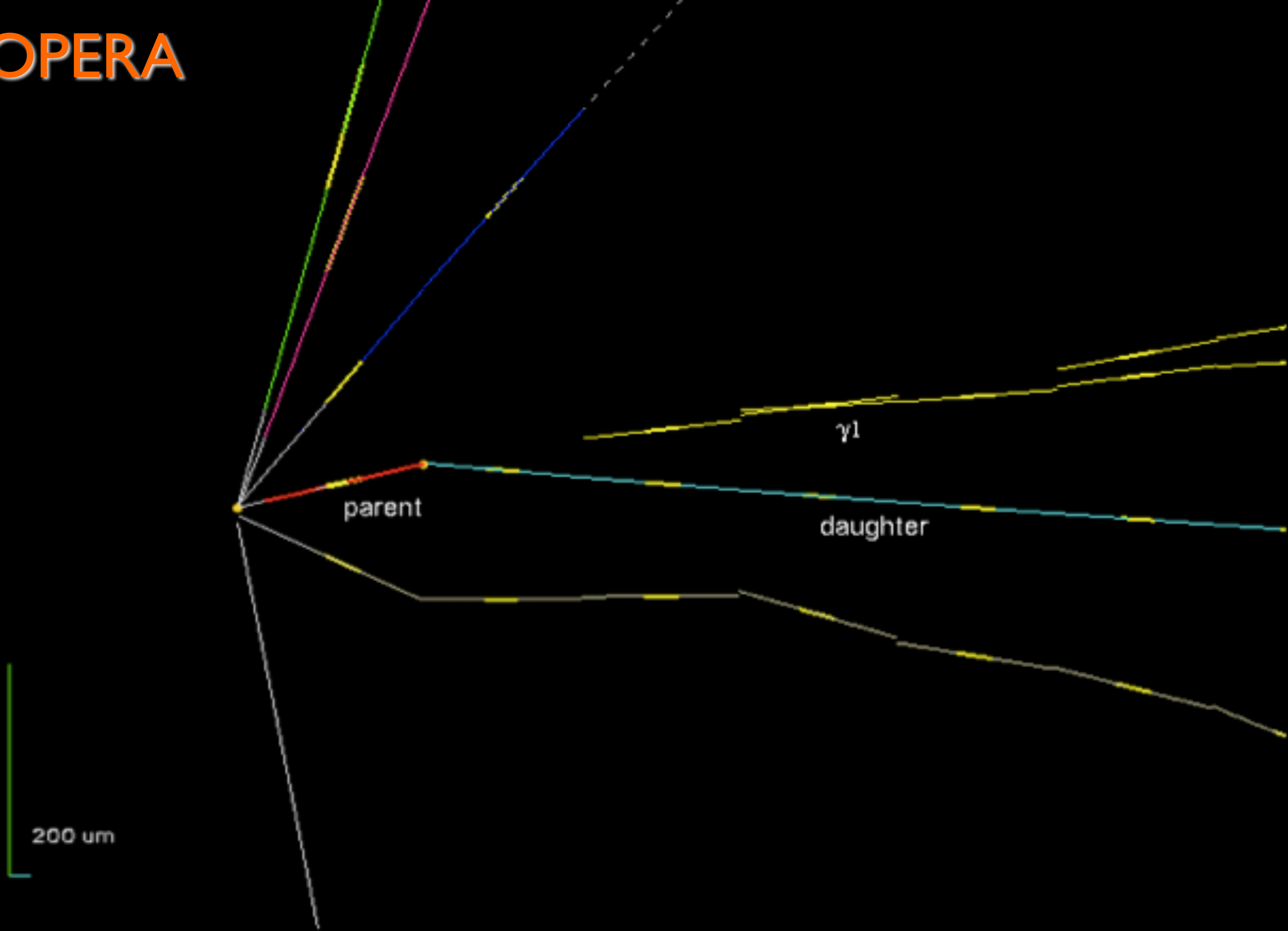




OPERA

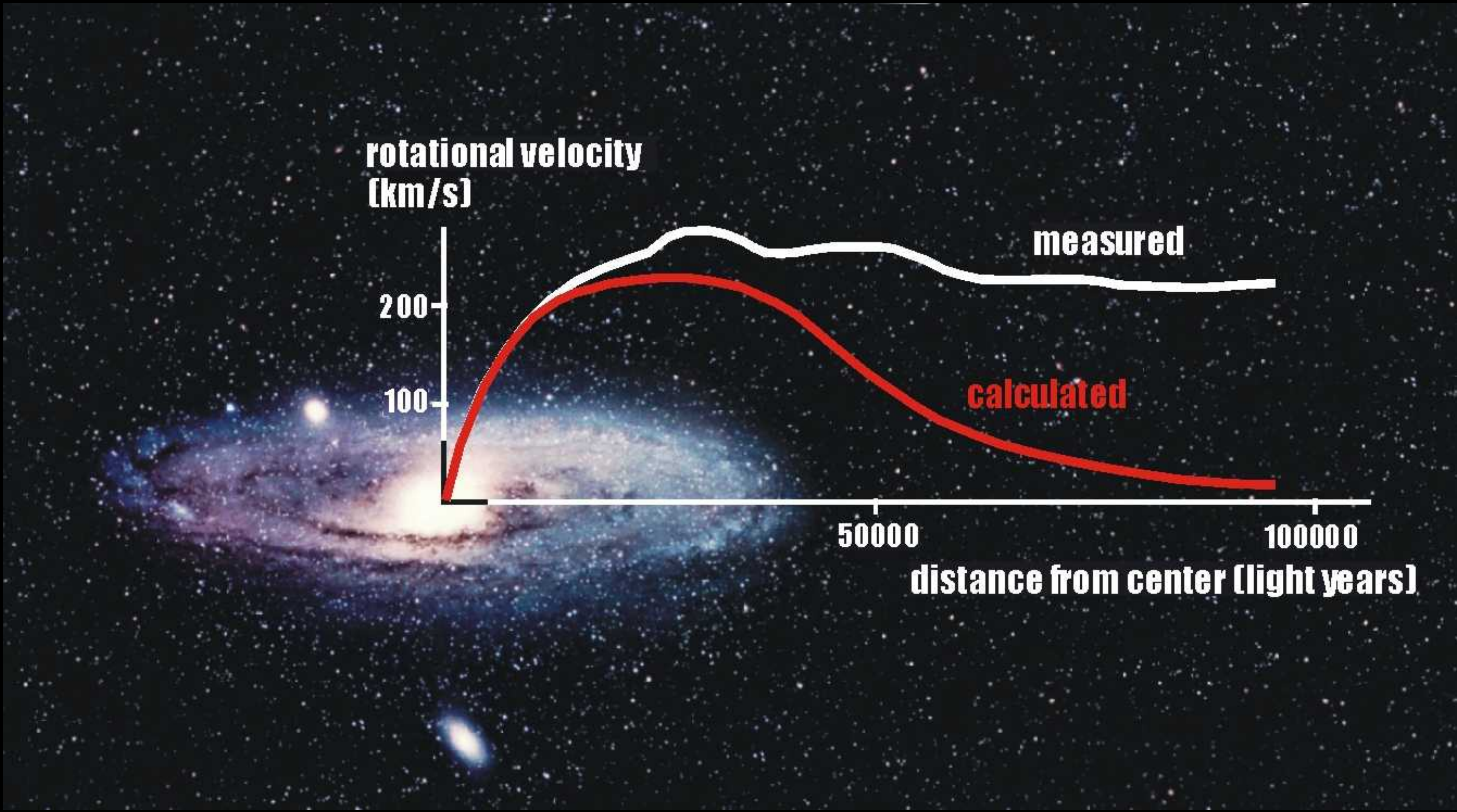

Top view (horizontal projection)
Side view (vertical projection)
Top view (horizontal projection)
Side view (vertical projection)
Top view (horizontal projection)
Side view (vertical projection)
Top view (horizontal projection)
Side view (vertical projection)

OPERA




300 000
KM/S
LUMIÈRE

Dark matter astronomical evidence



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:

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

$M_K = 100$ 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 ...

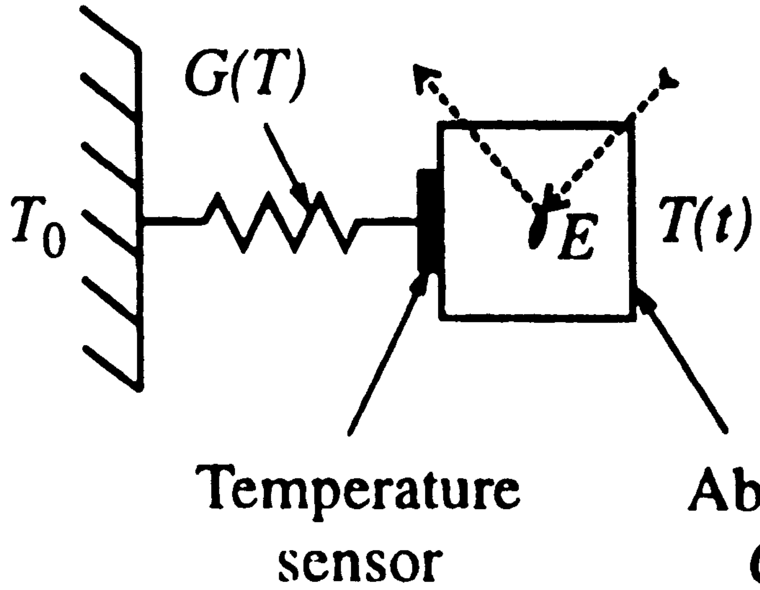
Cryogenic detectors:

Detect low energies
with very good resolution ...

Cryogenic detectors

Phonon Detectors ...

Basic configuration
of cryogenic calorimeter



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

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 ➛ $\Delta T = 0.04$ K [possible!]

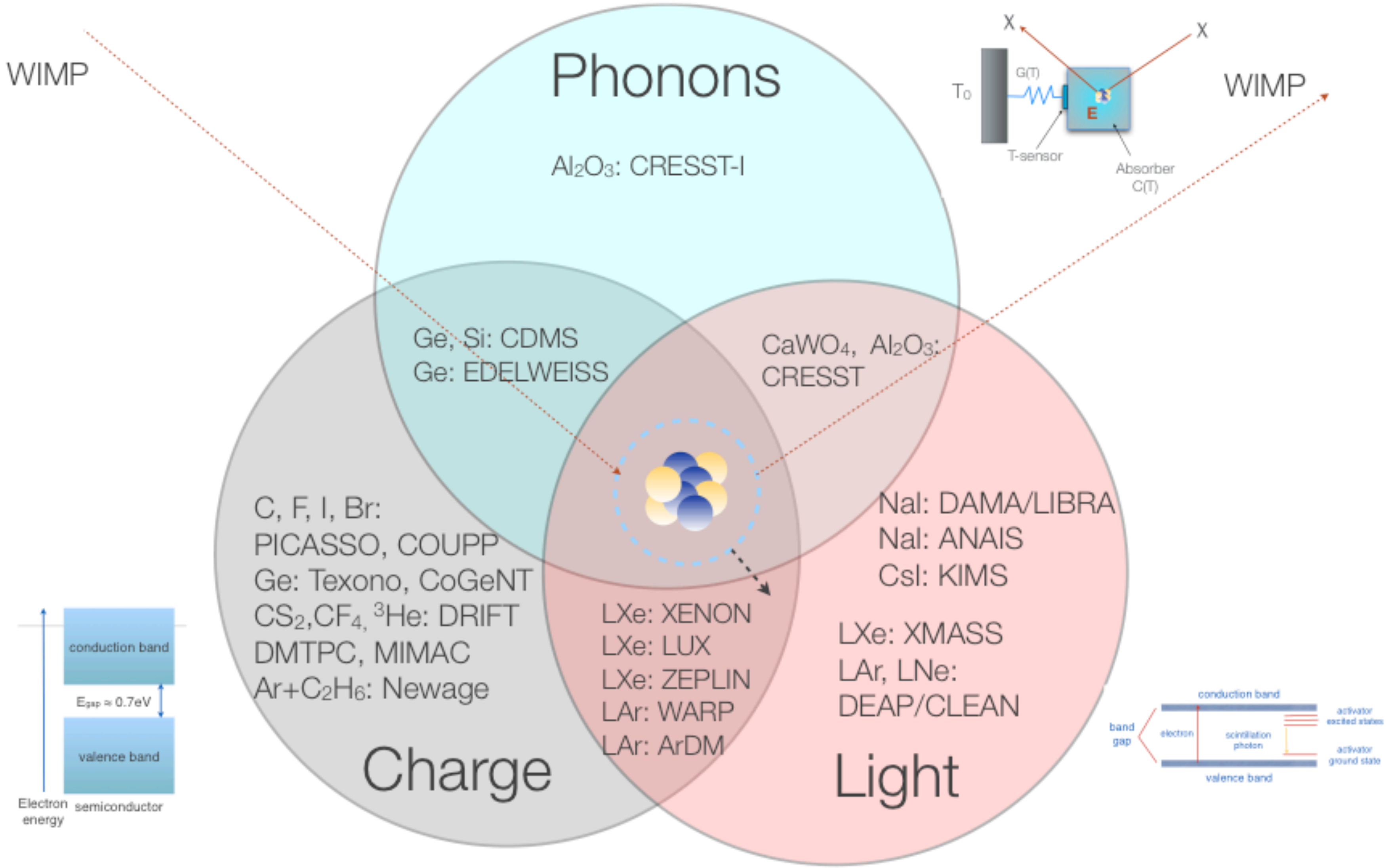
Resolution:

$n = CT/kT = C/k$

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

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

Dark matter detection overview



Dark matter detection

Example: CDMS

[Soudan Underground Lab]

5 towers each with 6 Ge/Si detectors
operated at T ≈ 20 mK ...

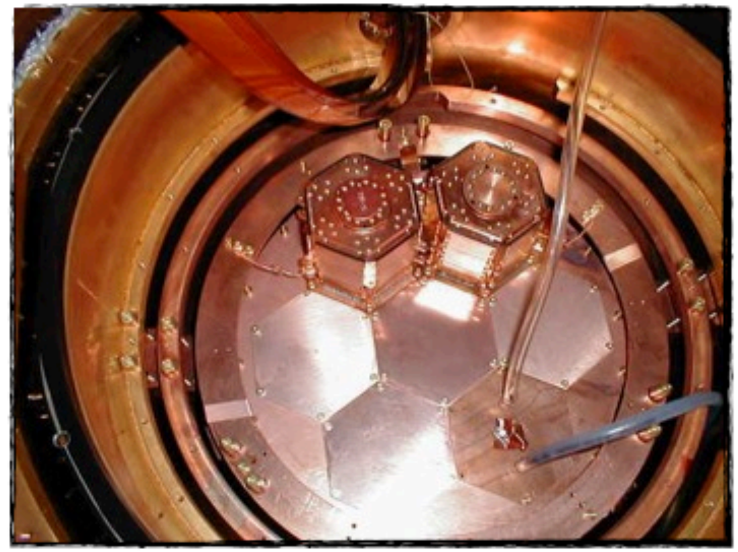
Double readout:

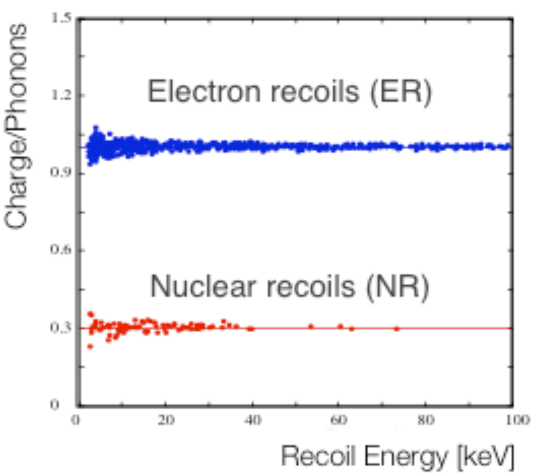
- Temperature change (Phonons)
- Charge readout (Ionization)

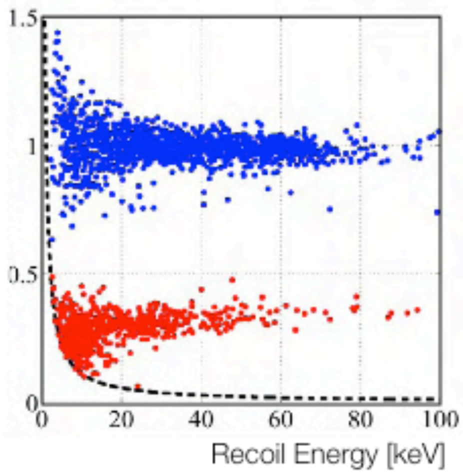
Idea:

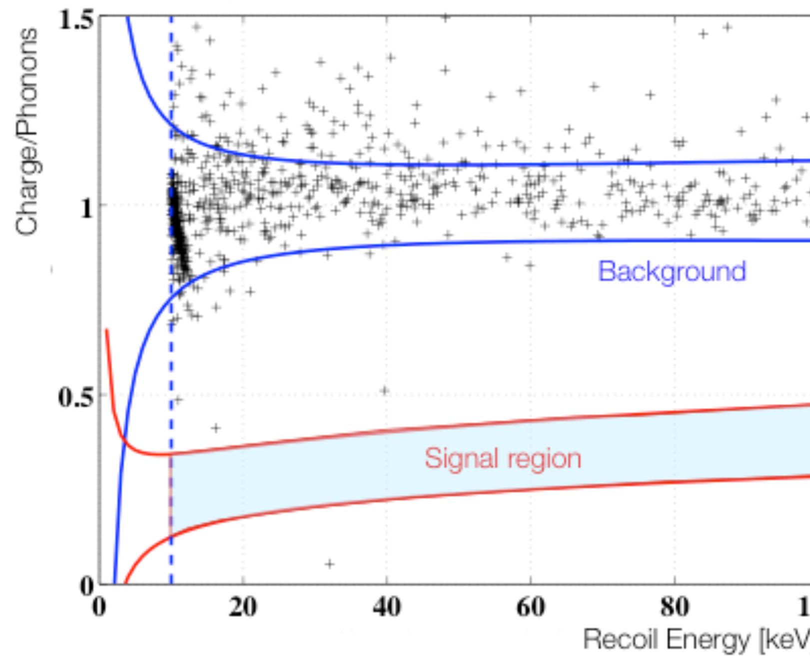
- WIMPs (and neutrons) scatter off nuclei
- Most background noise sources (γ,e) scatter off electrons
- Different response to nuclear recoils than to electron recoils

View into
CDMS Experiment







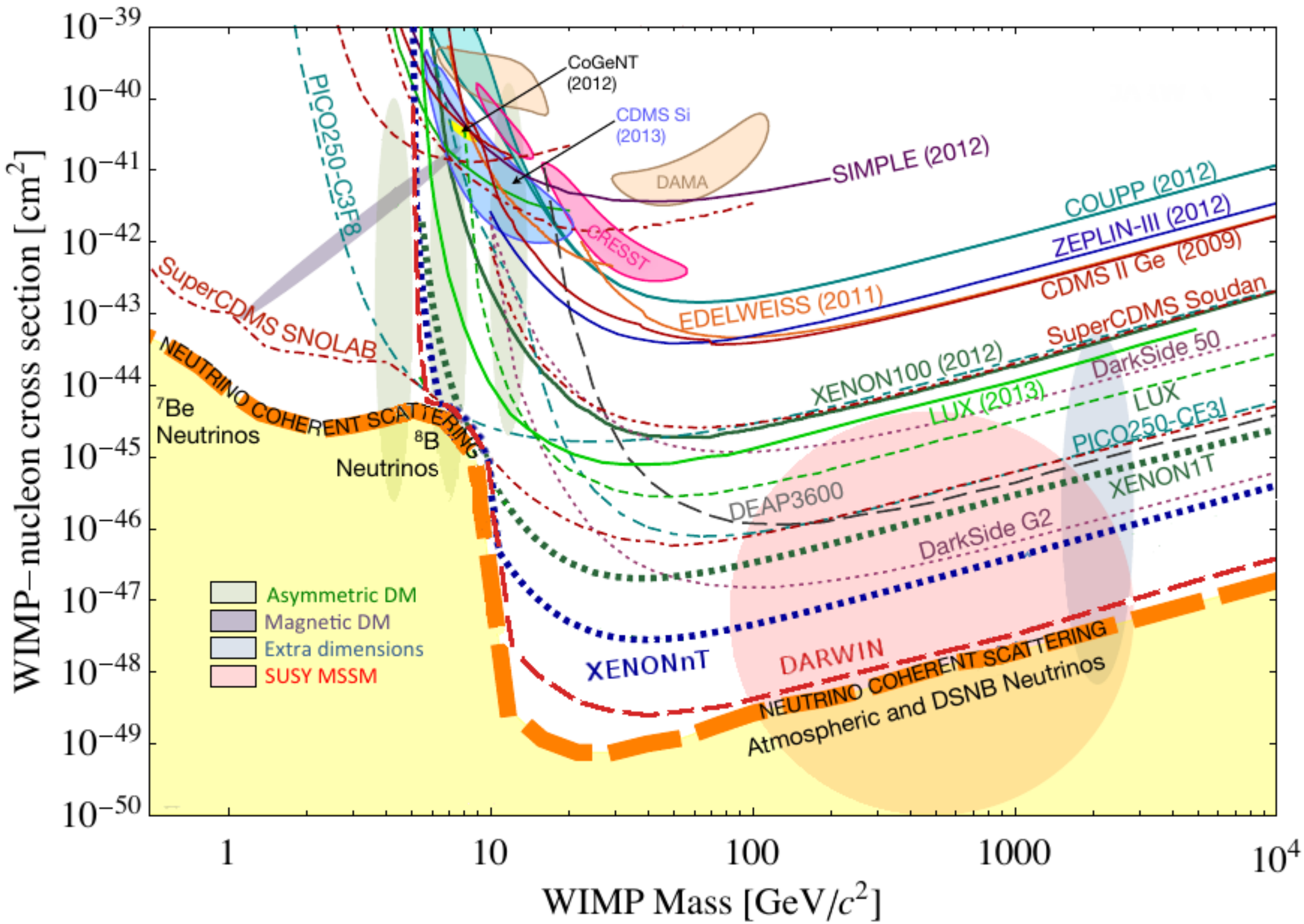


Did anyone observe signs of dark matter?

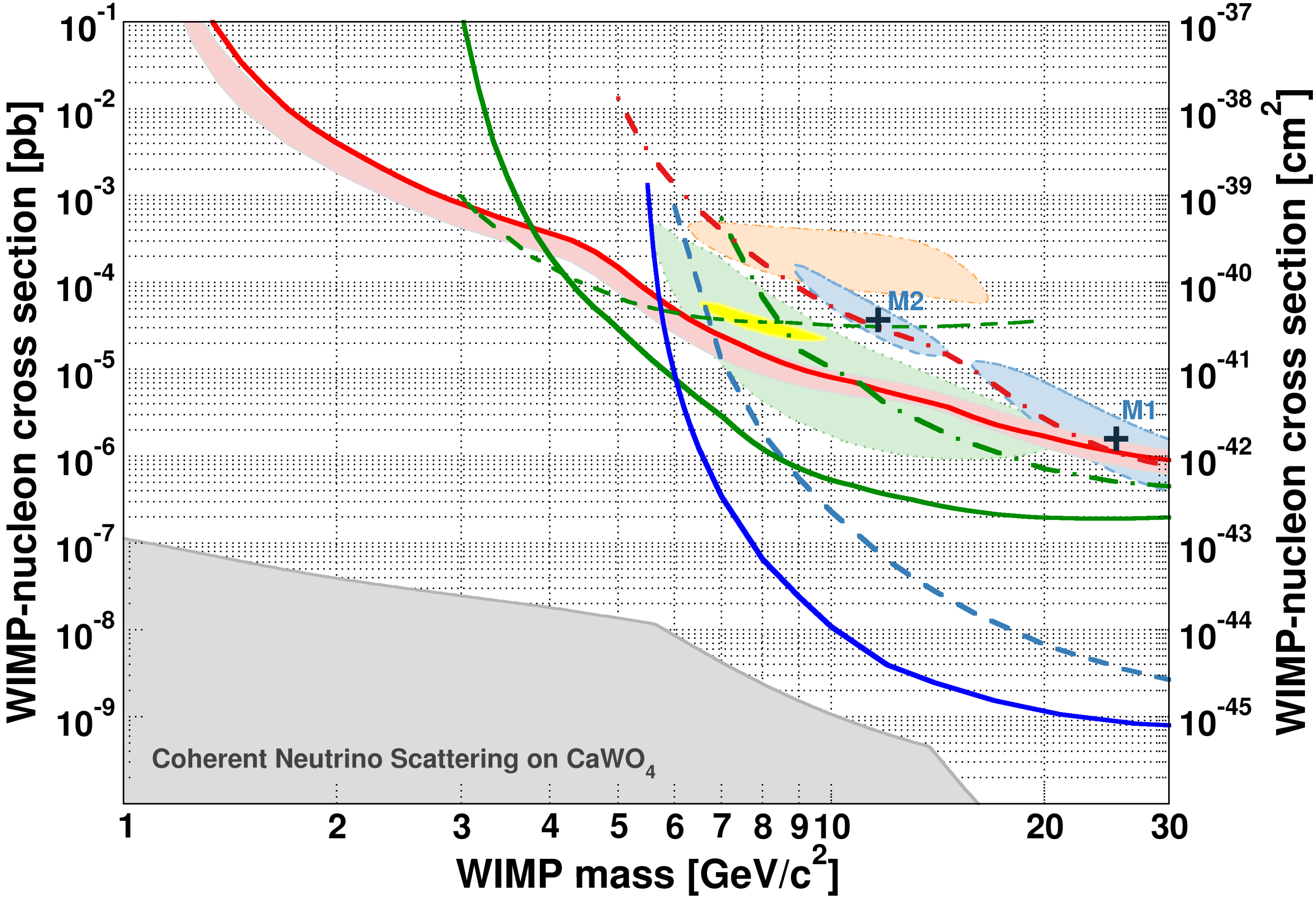
- Currently (2015) 3 experiments claim evidence for potential DM signals
  - ✓ DAMA/LIBRA (Gran Sasso)
    - 9.3σ for annual modulation of single-hit events
      - 2-6 keV energy, (0.0112 ± 0.0012) counts/kg/keV/day amplitude; (144 ± 7) days phase; (0.998 ± 0.002) years period
  - ✓ CoGeNT (Soudan Underground Lab)
    - $\sim 2\sigma$ DM excess, annual modulation
  - ✓ CDMS-II (SNOLAB)
    - 3 unexplained low-energy events in Si-detector sample
  - ✓ After detector upgrade, CRESST-II no longer finds previously claimed excess
- All claimed excesses cluster in mass region of tens of GeV with cross sections between 10^{-42} and 10^{-39} cm^2

- All other direct detection searches have set exclusion limits on the dark matter-nucleus cross section that contradict the claims listed above

Did anyone observe signs of dark matter?



Did anyone observe signs of dark matter?



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