Previous lecture

- Neutrino Oscillations, see handout lecture 8
  - Mass and weak eigenstates not the same
- Two-flavour mixing formala

$$\boxed{\text{Probability}(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)}$$

  - L (km), Δm^2 (eV^2), E (GeV)
  - Single mixing angle, θ (ensures matrix is unitary)
  - θ a parameter of nature, fixed, no relation to angular variable
  - θ defines size of mixing
  - Δm^2 (= $m_2^2 - m_1^2$) gives dependence of oscillations on L/E
  - ($E/1.27\Delta m^2$) defines an oscillation length scale

- Generalisation to 3 neutrino flavours
  - 3 mixing angles, θ_{12}, θ_{13}, θ_{23}
  - 3x3 "MNS" matrix
- Direct analogy with quarks ("CKM" mixing matrix)

Lecture Content

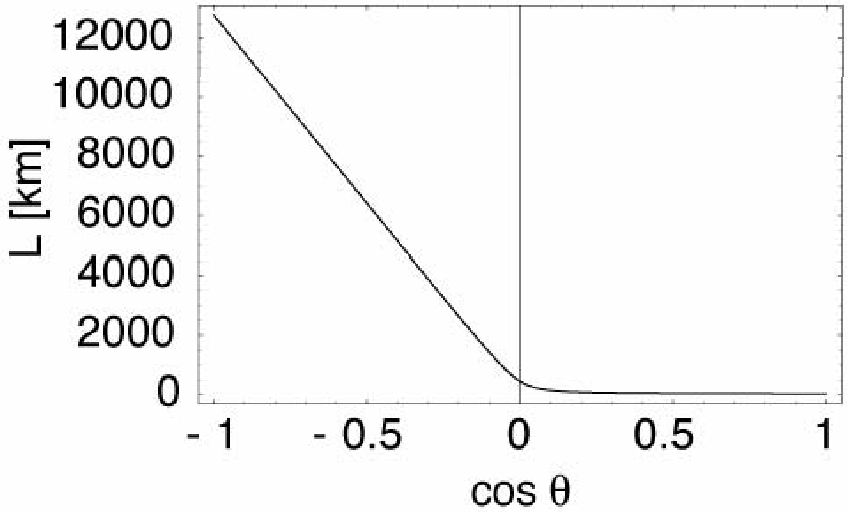
- Approx. lecture content
  1. PP intro
  2. PP intro.
  3. ν props 1: strong/e.m./weak, no. neutrino generations
  4. ν props 2: lepton no., ν existence
     - Examples of decay/production
  5. Neutrino mass
     - Fermi-Kurie plot
     - Phase space kinematics/4-momentum
  6. Parity and CP violation… (why so important in lepton sector?)
     - Wu et al., ^{60}Co experiment
  7. Detection & observation
     - Liquid, solid, bubble chamber
     - "Direct" methods (DONUT)
  8. Atmospheric neutrinos
     - Cerenkov detectors
     - SuperKamiokande experiment
  9. Atmopsheric neutrino data and oscillations
     - Interpretation of atmospheric ν data
     - Two-flavour neutrino oscillation formalism
  10. Solar neutrinos and SSM
      - SNO experiment and data
      - NDBD (NEMO, etc.)
  11. Implications for cosmology
      - Open vs. closed scenarios. various m_ν regions
      - ν as DM candidate?
      - Subject outlook (JPARC, MICE, Neutrino Factory, SK, SNO, KAMLAND, CHOOZ MINOS, miniBOONE, JPARC, νF,

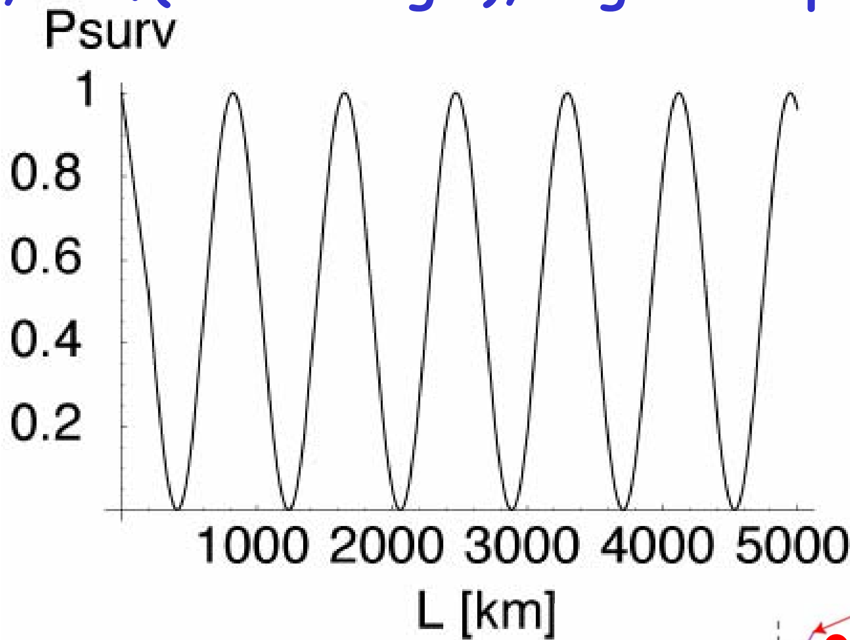
Today

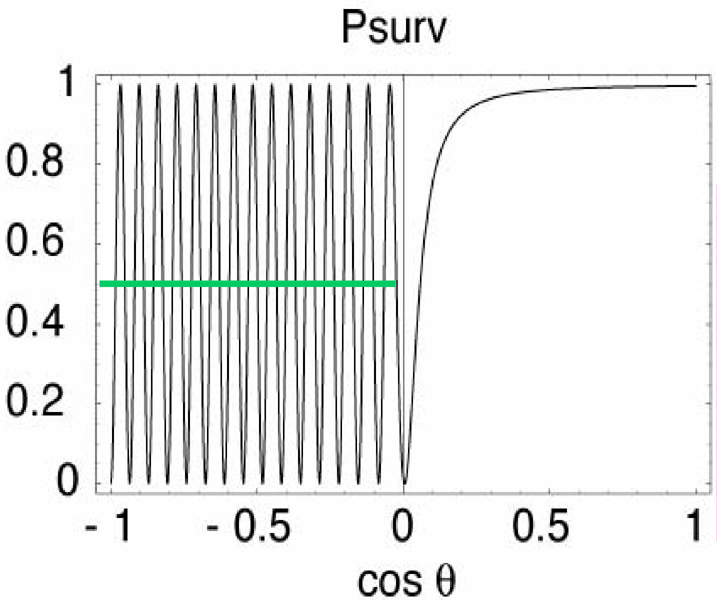
- Discussion of neutrino oscillations – See Winter 2.4.6
- "Solar neutrino problem" – See Winter, Sec. 6.1.x
- SNO
  - What it measures

“Survival” Probability

Distance from production, L, as f(zenith angle), e.g. in Super-K

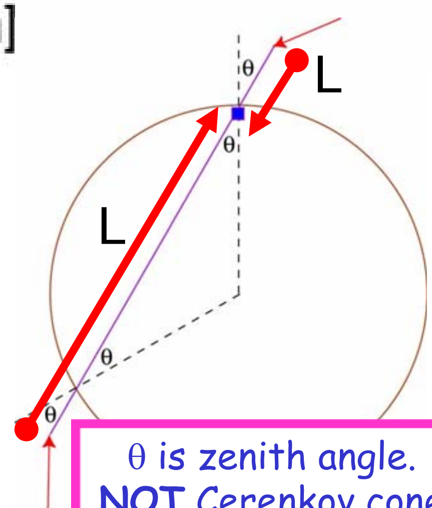






Finite angular resolution may effectively average over several oscillation cycles, net result is see P_{surv}~0.5

[Figs. from H.Murayama]



θ is zenith angle.
NOT Cerenkov cone
or mixing angle!

Solar fusion: the p-p mechanism

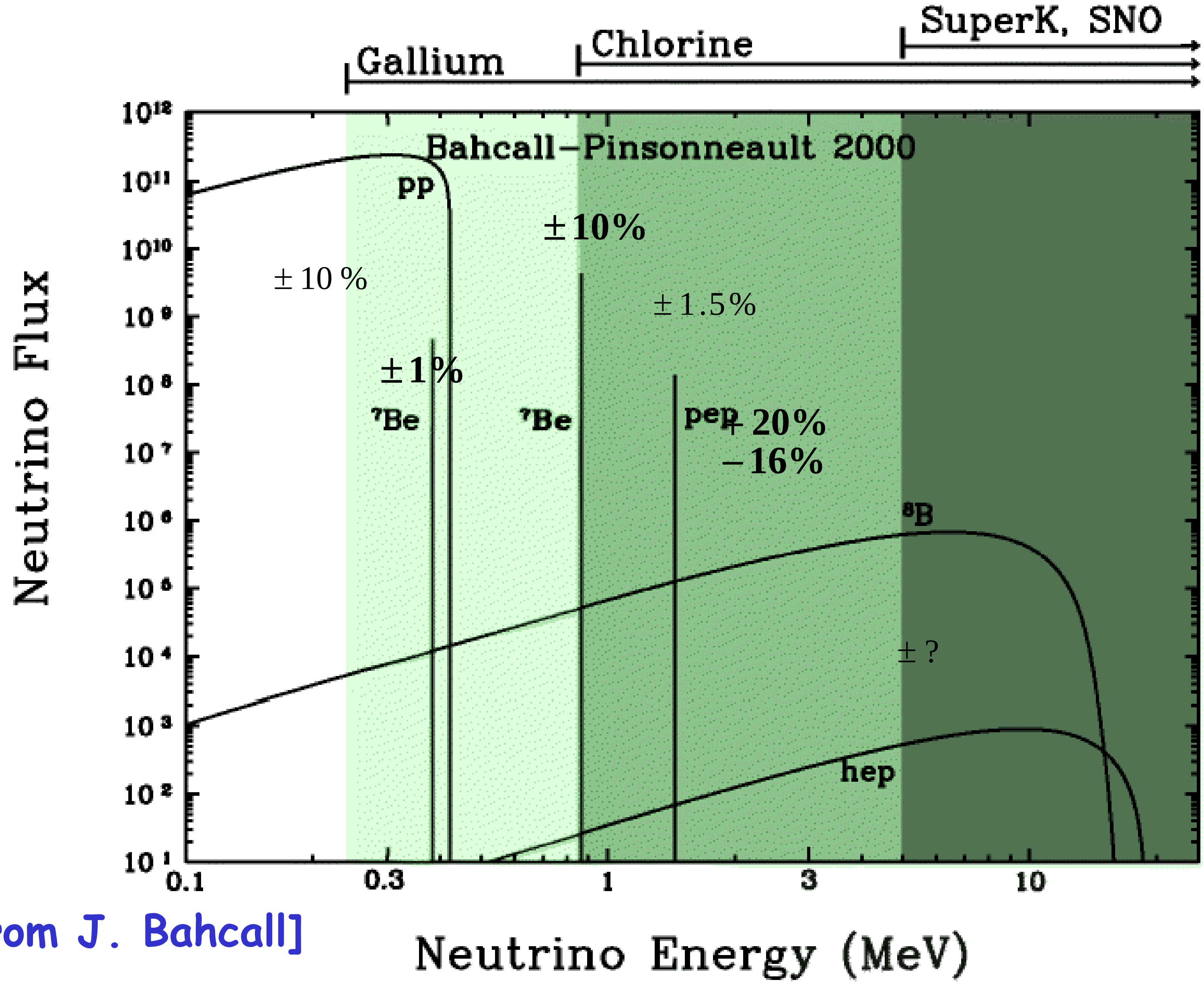
$$\left.\begin{array}{l} p + p \rightarrow D + e^{+} + \nu_e \\ e^{+} + e^{-} \rightarrow \gamma + \gamma \end{array}\right\} \times 2$$

$$D + p \rightarrow {}^{3}He + \gamma \qquad \} \times 2$$

$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p$$

Protons fuse, ultimately form an alpha particle, net release of 26.7 MeV/event

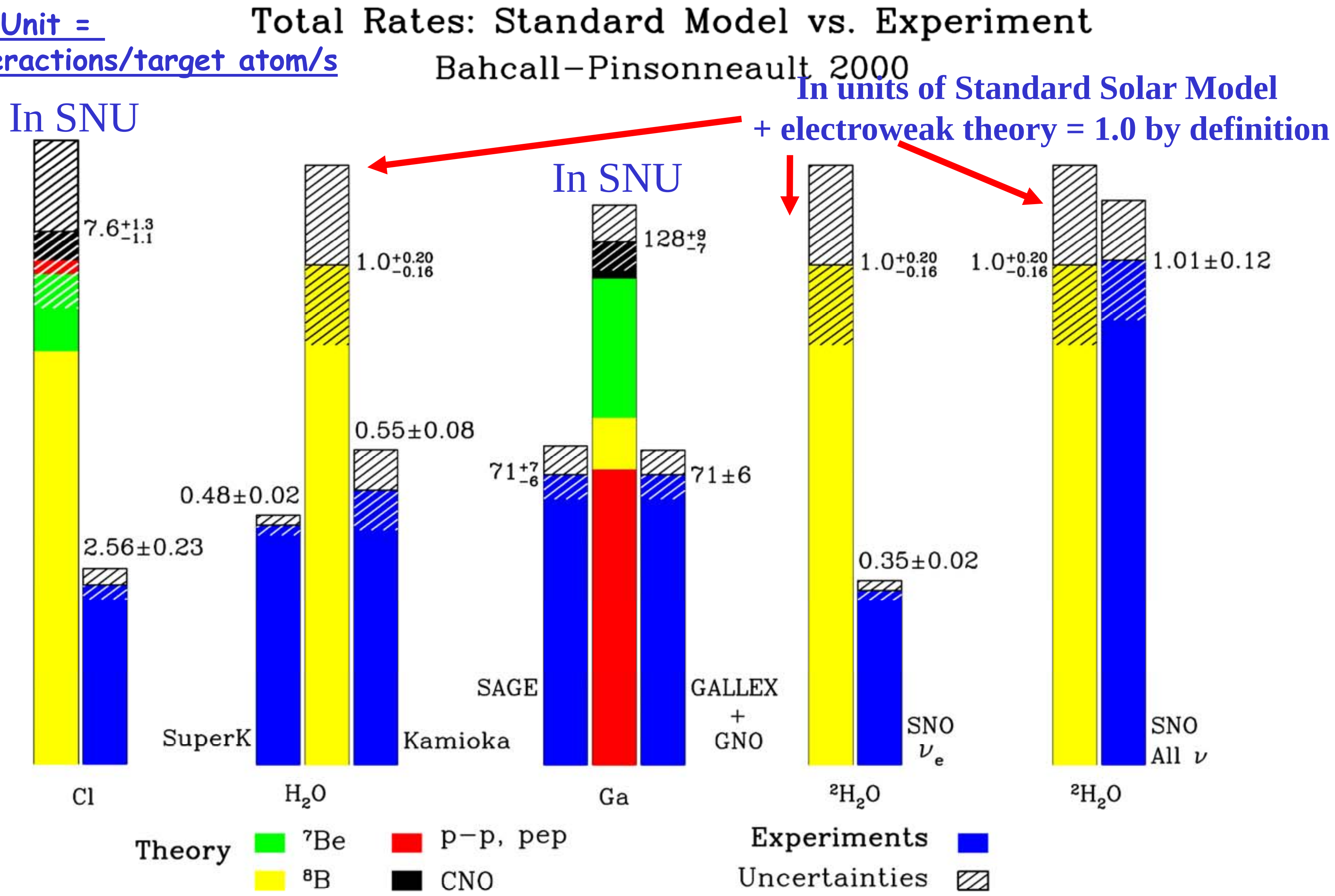
ν_e Solar Neutrino Spectrum



[Fig. from J. Bahcall]

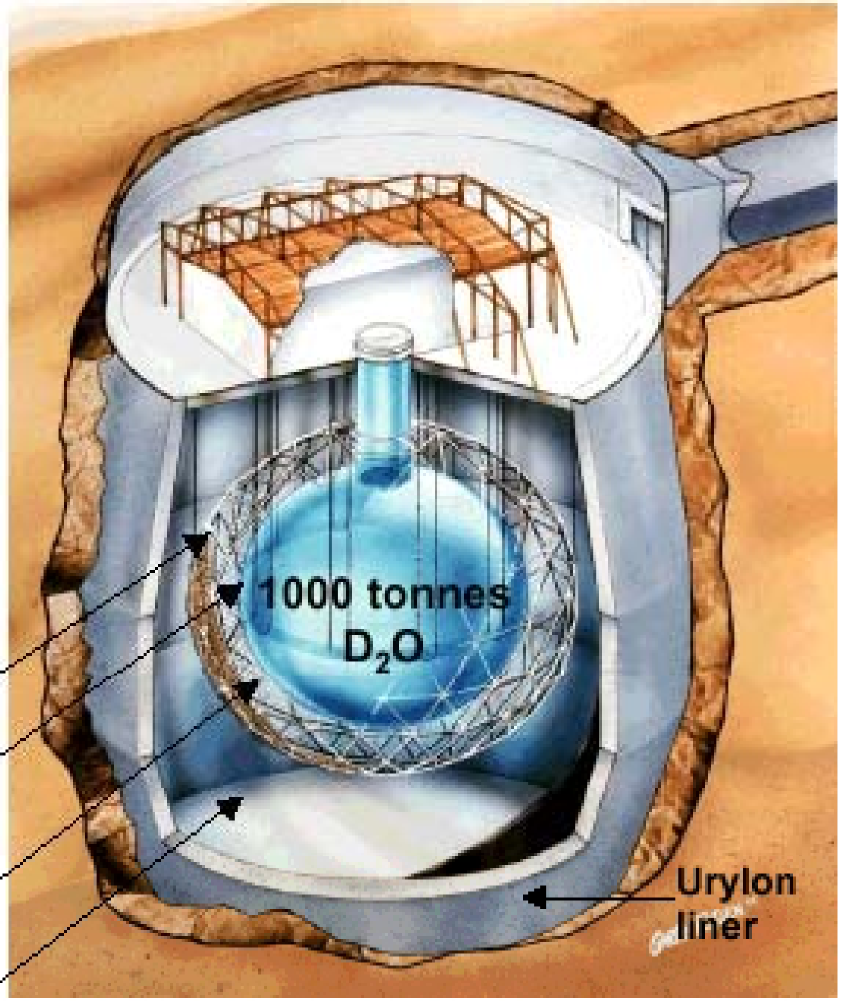
Solar ν: Data vs. Theory

1 Solar ν Unit = 10^{-36} interactions/target atom/s



[Fig. from J. Bahcall]

SNO (Sudbury Neutrino Observatory)



17.8m dia. PMT Support Structure
9456 PMTs, 56% coverage

12.01m dia. acrylic vessel

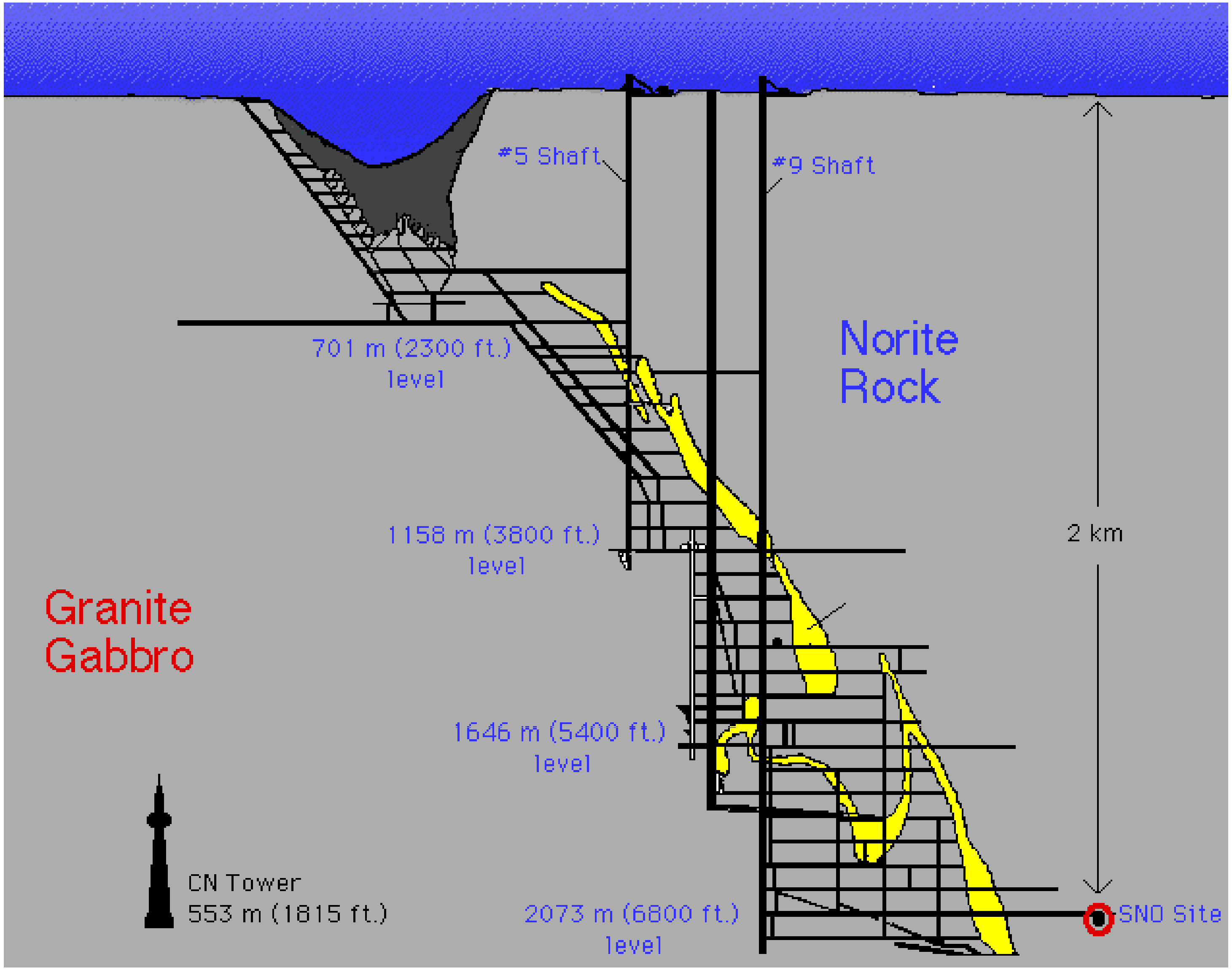
1700 tonnes of inner shielding H_2O

5300 tonnes of outer shielding H_2O

Host: INCO Ltd., Creighton #9 mine
Coordinates: 46°28'30"N 81°12'04"W
Depth: 2092 m (~6010 m.w.e., ~70 μ day^{-1})

[D_2O on loan from Atomic Energy of Canada Ltd, value $300M (Cnd)!]

SNO lab



#5 Shaft
#9 Shaft
Norite Rock
701 m (2300 ft.) level
1158 m (3800 ft.) level
Granite Gabbro
2 km
1646 m (5400 ft.) level
CN Tower 553 m (1815 ft.)
2073 m (6800 ft.) level
SNO Site