ECT Lecture 2

- Reactor Antineutrino Detection
- The Discovery of Neutrinos

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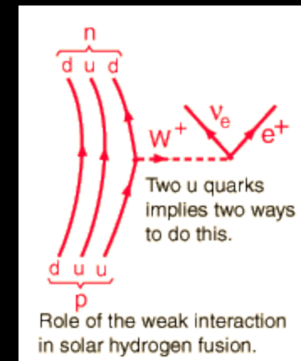
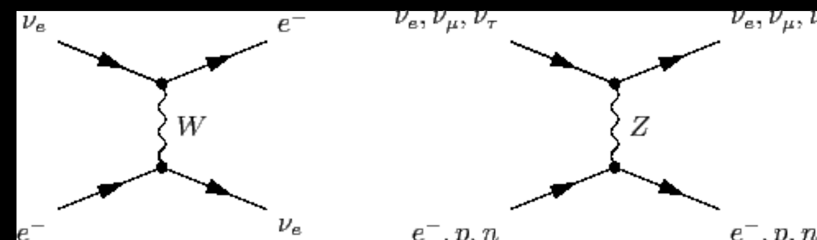
Reactor Neutrino Detection

- **Inverse Beta Decay**
  - p + anti-ν_e → e^+ + n
  - cross section @2 MeV : 5 10^{-43} cm^2
  - scale as E^2

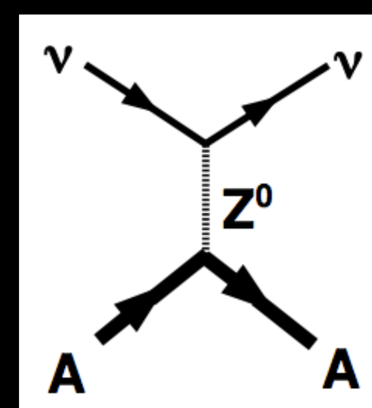


Role of the weak interaction in solar hydrogen fusion.

- **Neutrino-Electron Scattering**
  - e^- + anti-ν_e → e^- + anti-ν_e
  - cross section @0.8 MeV : 5 10^{-45} cm^2
  - scale as E



- **Neutrino-Nucleus Coherent Scattering**
  - A + anti-ν_e → A + anti-ν_e
  - cross section @2 MeV > 10^{-41} cm^2
  - scale as E^2
  - scale as N^2



IDB: Basics Kinematics

- Inverse beta-decay: $\overline{\nu}_e + p \rightarrow e^+ + n$
- Momentum conservation:

$$\overrightarrow{p_{\nu_e}} + \overrightarrow{p_p} = \overrightarrow{p_{e^+}} + \overrightarrow{p_n}$$

Most of the time $\overrightarrow{p_p} = \vec{0}$ (lab frame)

- Energy conservation:

$$E_{\nu_e} + E_p = E_{e^+} + E_n$$

neglecting neutron recoil

$$E_{\nu_e} + m_p c^2 = E_{e^+} + m_n c^2$$

$$E_{\nu_e} = E_{e^+} + (m_n - m_p)c^2 = E_{e^+} + \Delta$$

$$E_{e^+} = T_{e^+} + m_e c^2$$

$$E_{\nu_e} = T_{e^+} + m_e c^2 + \Delta$$

- Energy threshold:

$$\Delta \approx 1.293 \text{ MeV}$$

$$m_e c^2 \approx 0.5 \text{ MeV}$$

$$T_{e^+} = \Delta + m_e c^2 - E_{\nu_e}$$

$$T_{e^+} = 0 \rightarrow E_{\nu_e} = 1.804 \text{ MeV} = \mathrm{E}_{\mathrm{th,approx}}$$

But exact threshold given by:

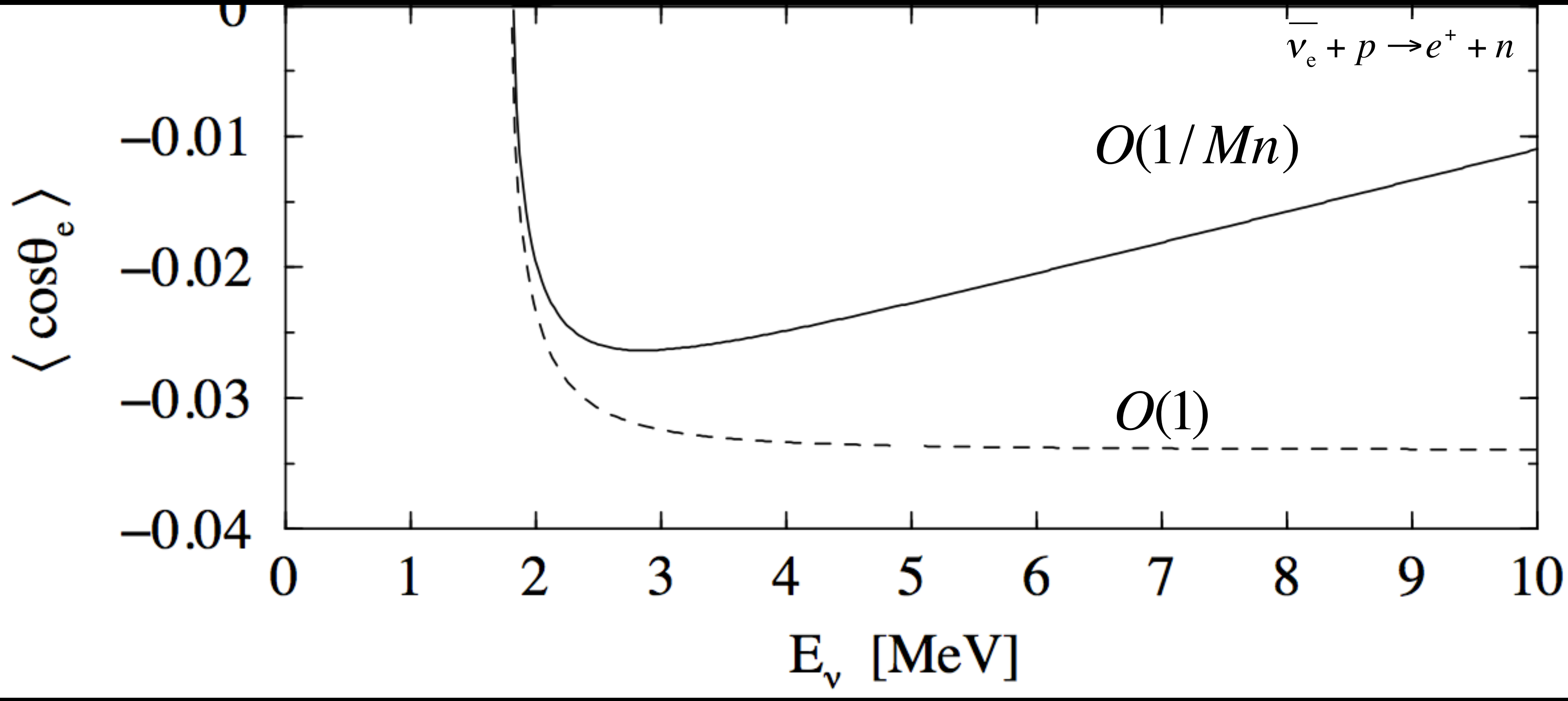
$$\mathrm{E}_{\mathrm{th,true}} = \frac{(m_n + m_e)^2 - m_p^2}{2m_p} = 1.806 \text{ MeV}$$

IDB: positron angular distribution

- Inverse beta-decay: $\overline{\nu}_e + p \rightarrow e^+ + n$
- Positron angular resolution given by (Vogel-Beacom 1999) $$\frac{d\sigma}{d\cos\theta} \approx 1 + velocity_{e^+} a(E_\nu)\cos\theta$$
- θ positron-neutrino angle
- Valid for reactor neutrino energies
- Average <cos θ > : $$\langle\cos\theta\rangle \approx \frac{velocity_{e^+} a(E_\nu)}{3} \approx -0.03$$
  - velocity = 1 (but near to the threshold)
  - Infinite nucleon mass approximation a(E)=a
  - Fermi/Gamow-Teller transitions competition → a=-0.1
- Angular distribution of the positron is slightly backward
- Rarely accessible…

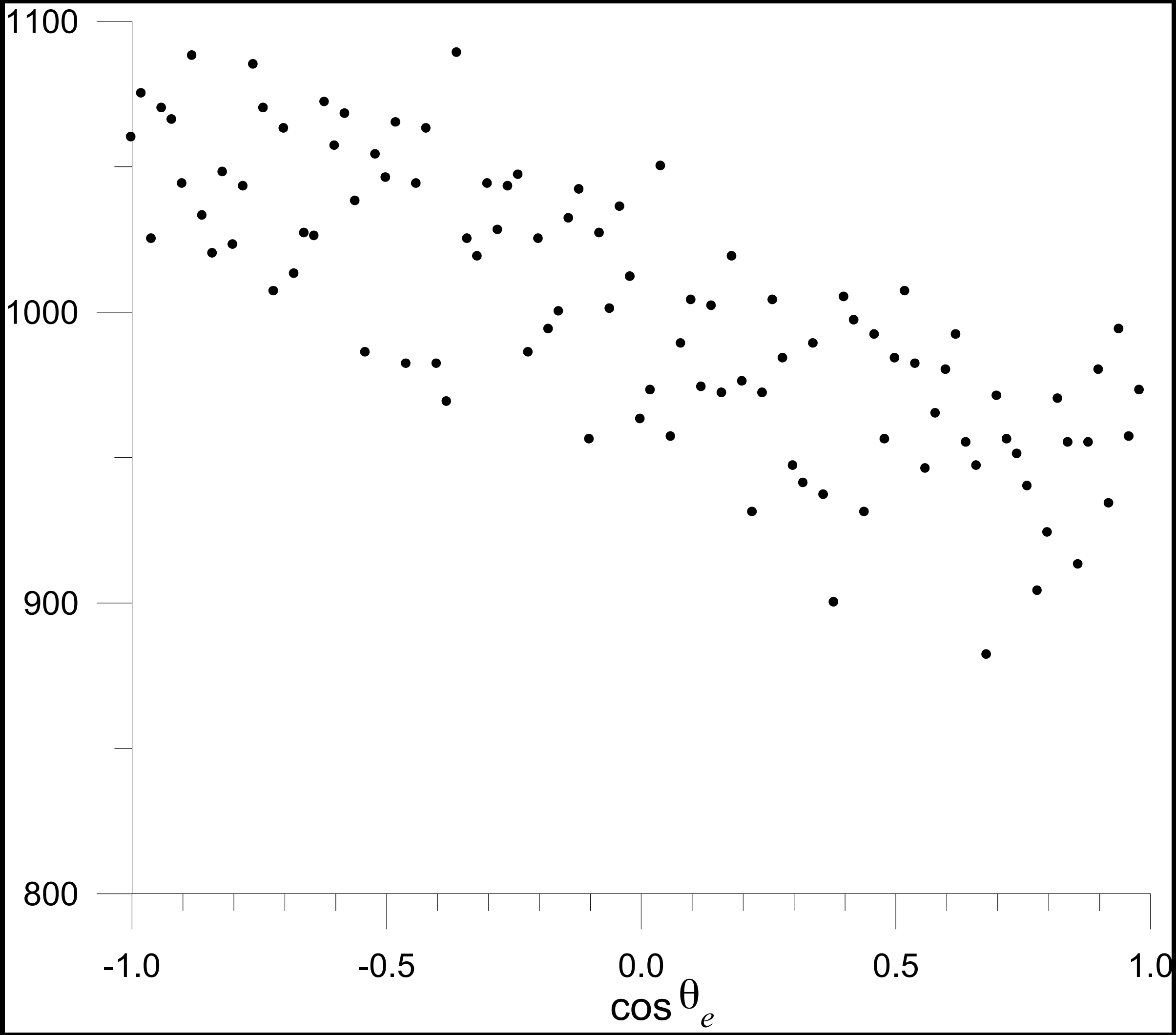
IDB: positron angular distribution

$$\langle \cos\theta \rangle \approx \frac{velocity_{e^+} \, a(E_\nu)}{3} \approx -0.03$$



IDB: positron angular distribution

IBD generated events: neutrino/positron angle (θ_e)



IDB: neutron kinetic energy

- Finite Neutron Mass → 1/M terms dev.

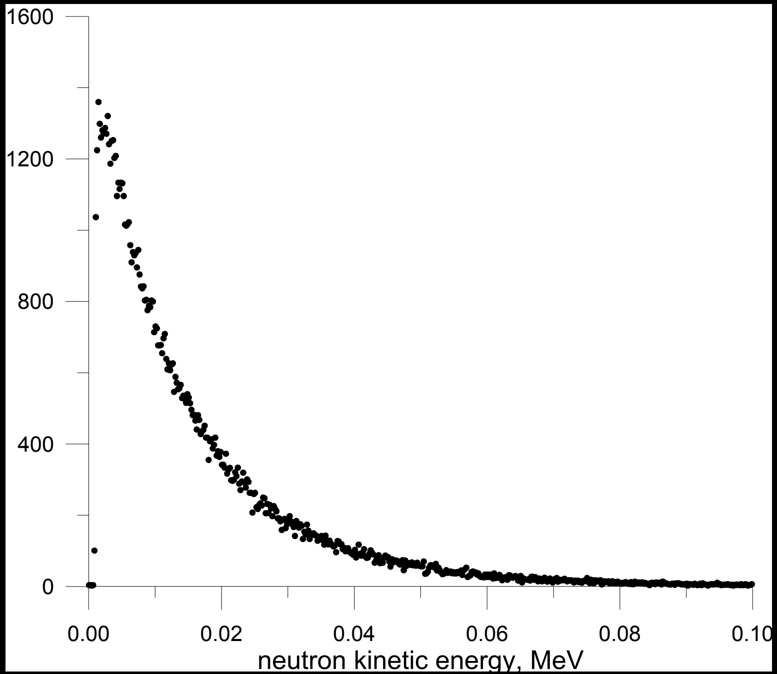
$$E_e^{(1)} = (E_\nu - \Delta)\left(1 - \frac{E_\nu}{M}(1 - \cos\theta)\right) - \frac{\Delta^2 - m_e^2}{2M}$$

$$T_n = \frac{E_\nu (E_\nu - \Delta)}{M}\left(1 - \cos\theta\right) + \frac{\Delta^2 - m_e^2}{2M}$$

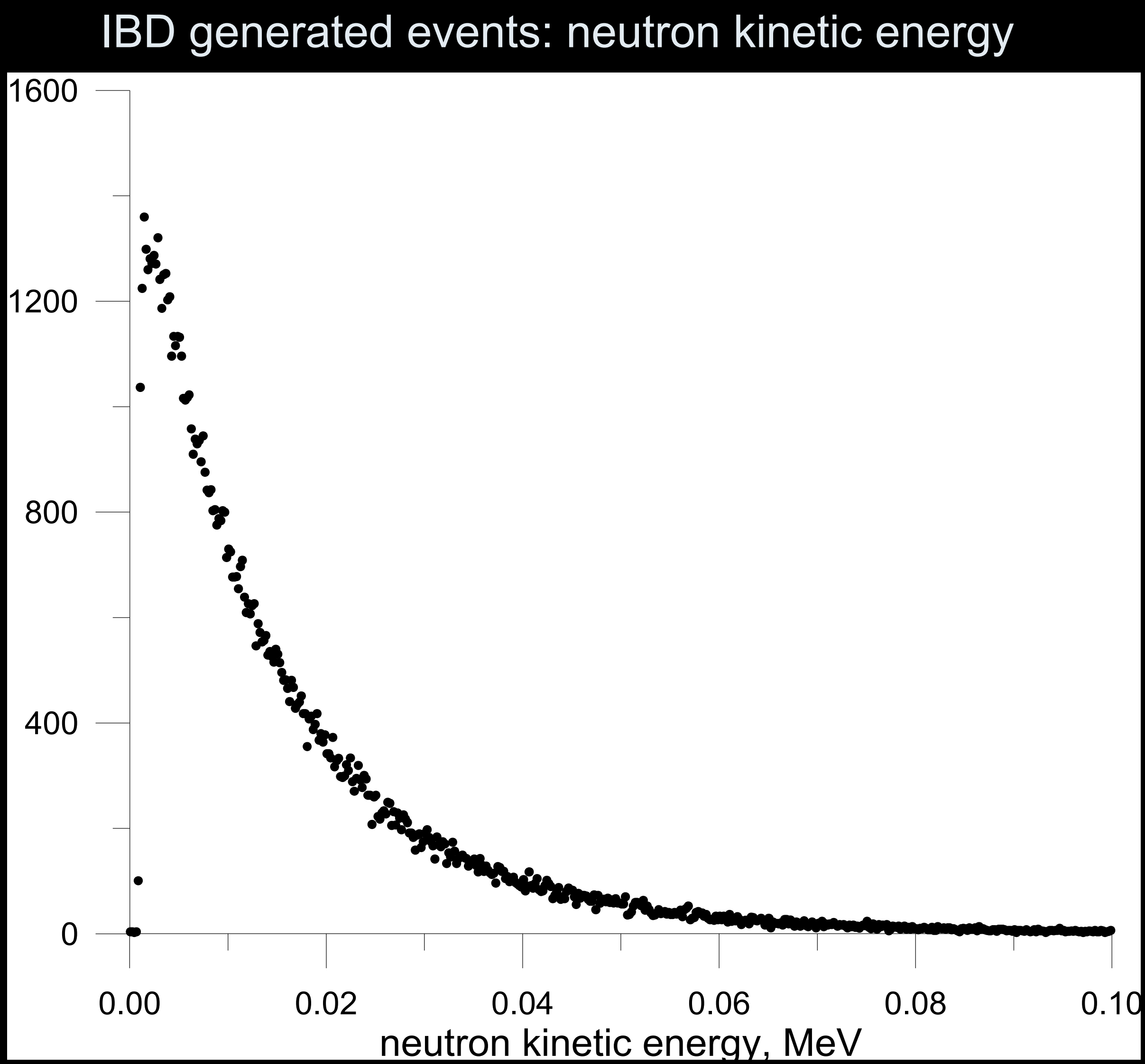
- E_ν = 3.5 MeV
- $E_e = E_\nu - \Delta$ = 3.5-1.3=2.2 MeV
- velocity=1
- assuming cos θ = 0
- M=938 MeV

→ T_n=1/938 (3.5 x 2.2 + 0.7) = 10 keV

IBD generated events



IDB: neutron kinetic energy



IDB: neutron angular distribution

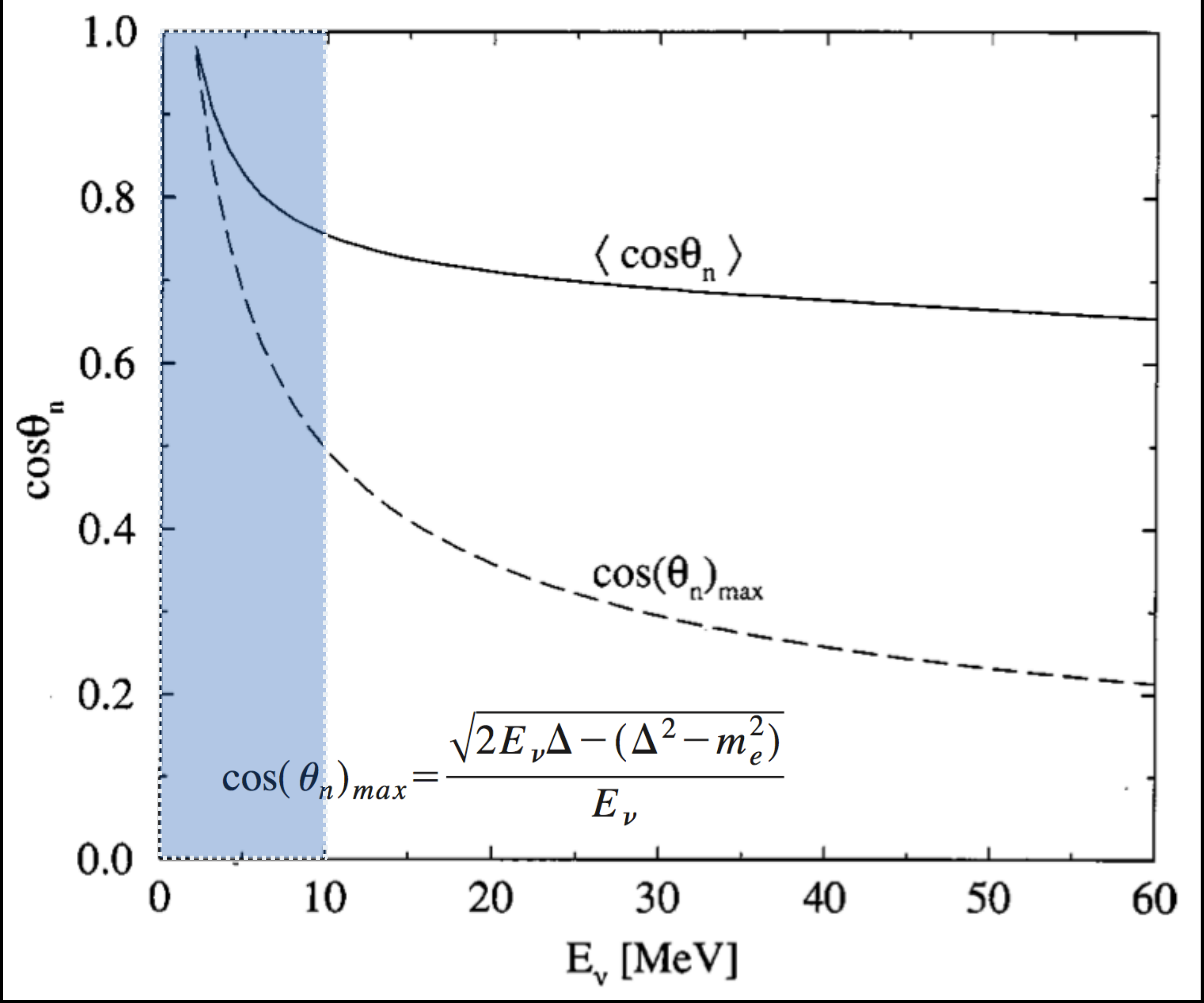
- **IDB reaction**
  - Positron emission (no position information): vertex reconstruction
  - First neutron step in the forward direction → directionality information
  - Then neutron thermalization → random walk → loose directionality
  - Finally neutron capture → vertex localization possible

- After vertex reconstruction: (e^+,n) vertex vector reconstructed for all events and statistically studied → 1.5-2 cm displacement in the antineutrino direction

- **Experimentally**
  - Observed in the Goesgen experiment (10 sigmas)
    - Segmented detector
  - Observed in the Bugey-3 experiment
    - Segmented detector
  - Observed in the CHOOZ experiment
    - Unsegmented detector

- **Future Goal: Could directionaly being used for background rejection?**

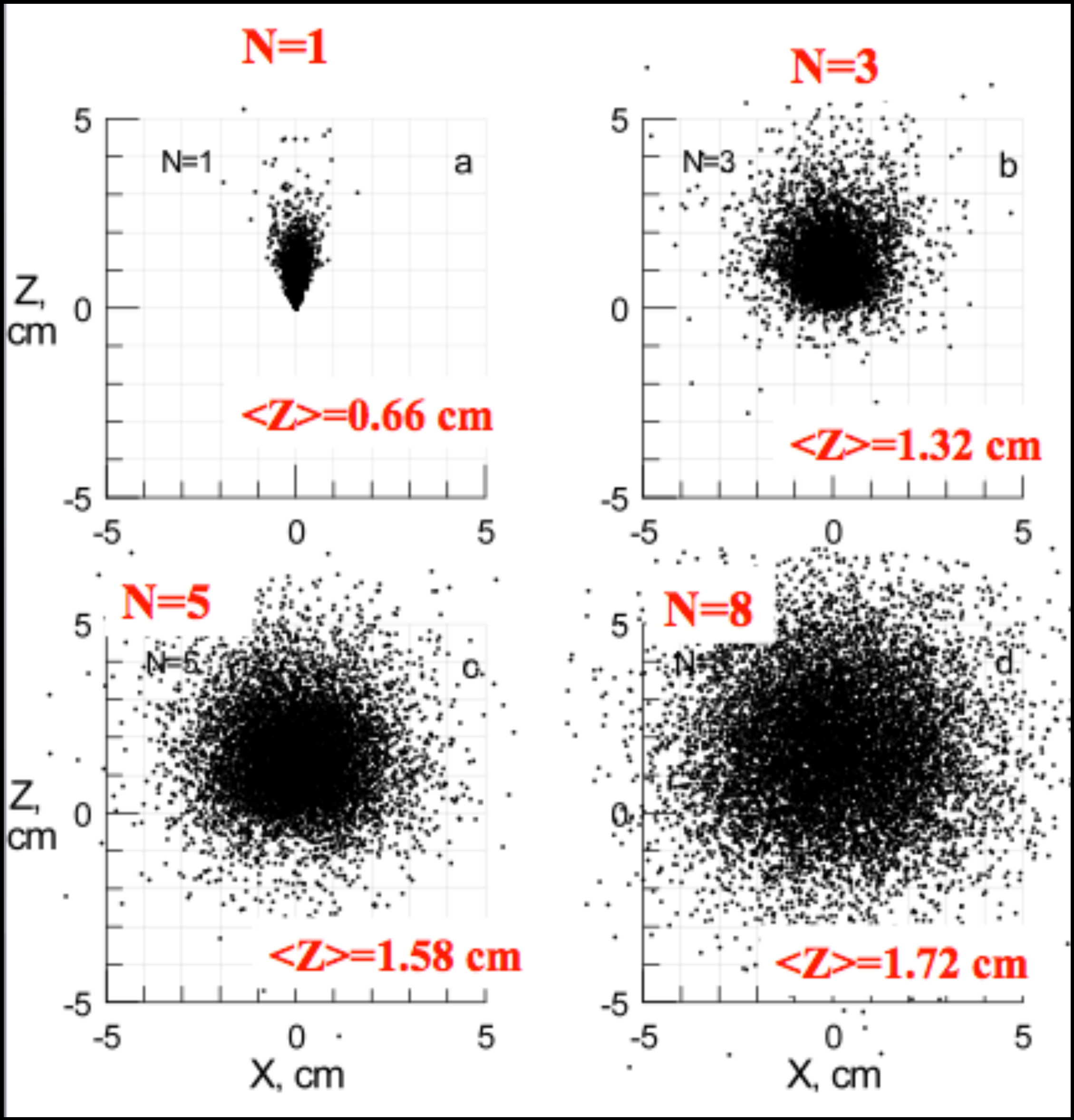
IDB: neutron angular distribution



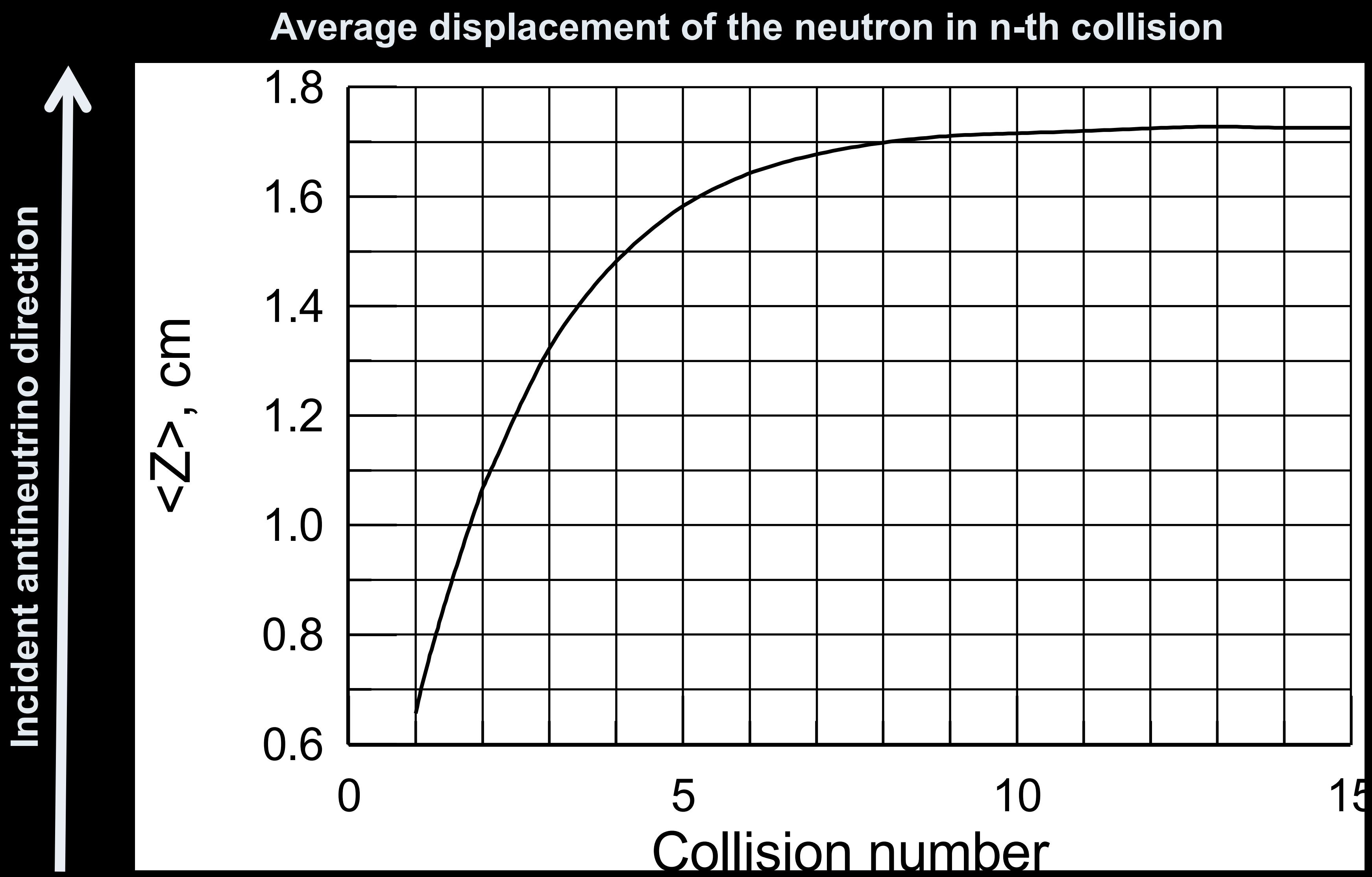
$$\cos(\theta_n)_{max} = \frac{\sqrt{2E_\nu \Delta - (\Delta^2 - m_e^2)}}{E_\nu}$$

IDB: Toy MC Simulation

- First neutron step before collision: very clear forward emission
- First few collisions with scintillator atoms the memory is partially conserved and neutron is displaced from the reaction point in +Z direction
- After 8 collisions the memory is lost and neutrons slow down and diffuse symmetrically around the displaced center.
- After 20 collisions the neutron is thermalized (0.025 eV) and captured



IDB: Toy MC Simulation



IDB: Cross Section

- Vogel: cross-section with corrections (Phys Rev D29 p1918, 1984)
- Fayans 1985: very close to Vogel 84 (Sov J Nucl Phys 42, Oct 85)

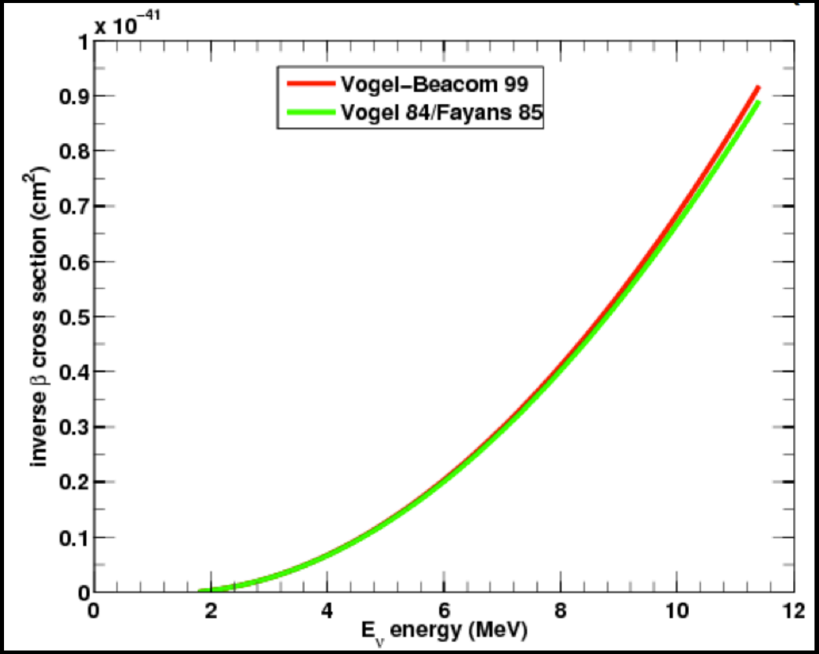
- Order 0 cross-section: $\sigma_0 = K\, p_e E_e$

- K = prefactor

- Need extra corrections:

$$\sigma_1 = \sigma_0 (1 + \delta_{rec} + \delta_{wm} + \delta_{rad})$$

  - neutron recoil,
  - weak-magnetism,
  - outer radiative corrections:

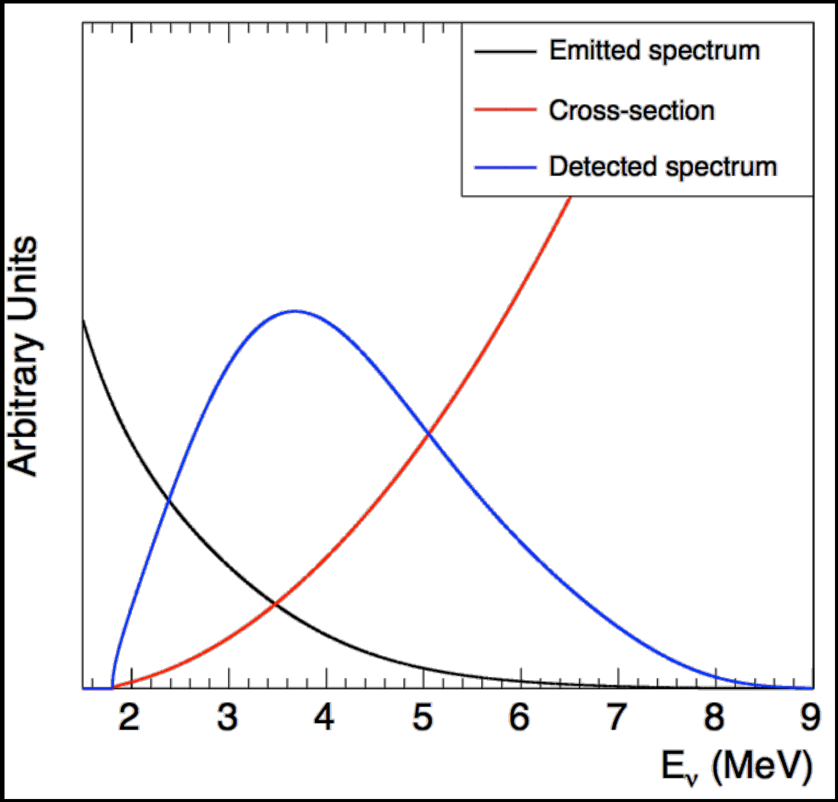


- Vogel-Beacom 99: "supersedes" Vogel 84 (Phys Prev D60 053003)
  Full development to order 1/M, only outer radiative corrections needed
  Complicated formula, numerical integration

Positron Yield Calculation

- For fixed positron energy E_e only a narrow interval of neutrino energies contribute to the yield, centered around :

$$\overline{E_\nu} = E_e + \Delta + \frac{2E_e(E_e+\Delta)+\Delta^2-m_e^2}{2M_p}$$

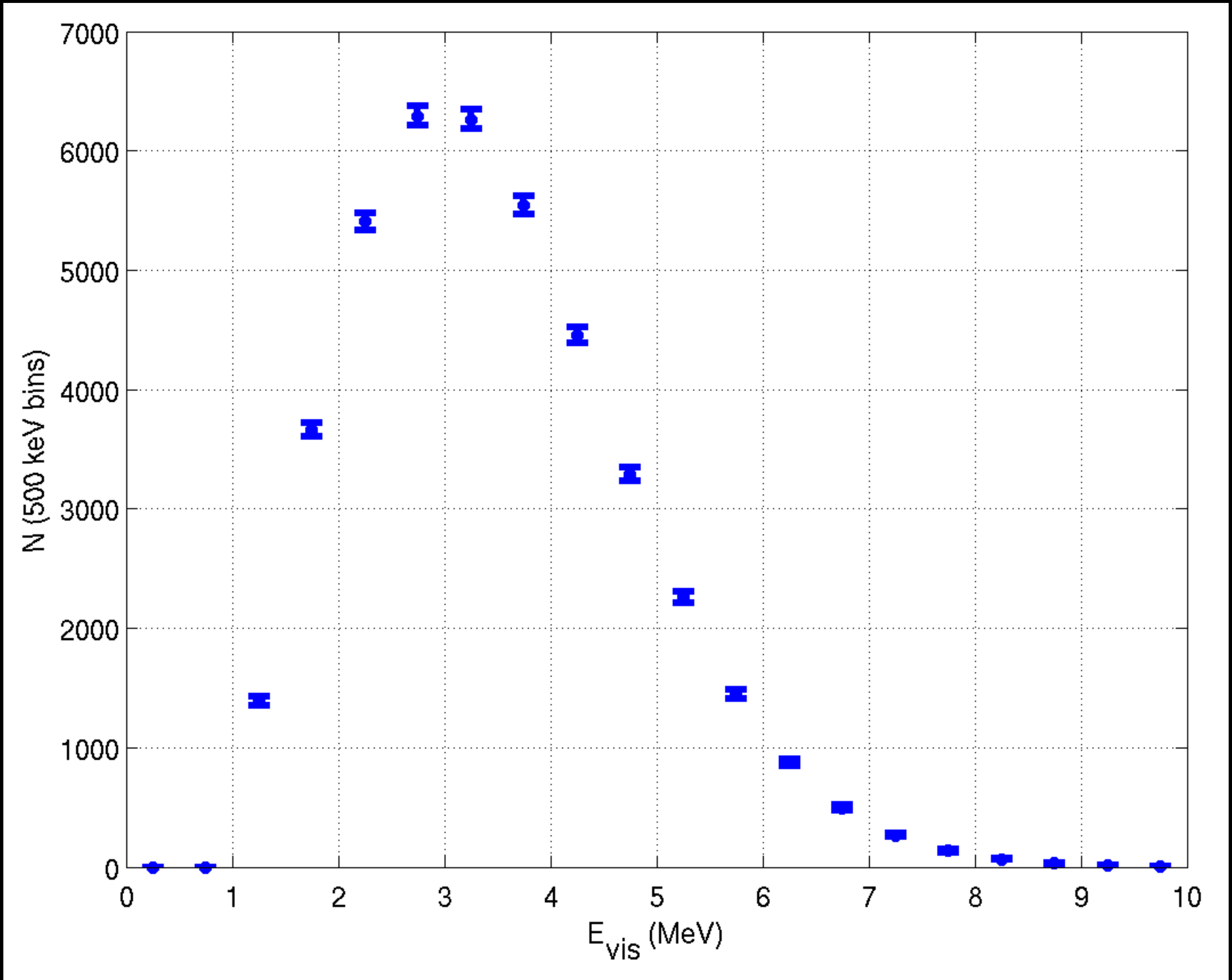


- Therefore : $n(E_e) \approx \phi(\overline{E_\nu})\sigma_1(E_e)$

- For σ_1 Vogel-Beacom99 should be used

- cross-section accurate to +/-0.2%

Visible Energy Spectrum



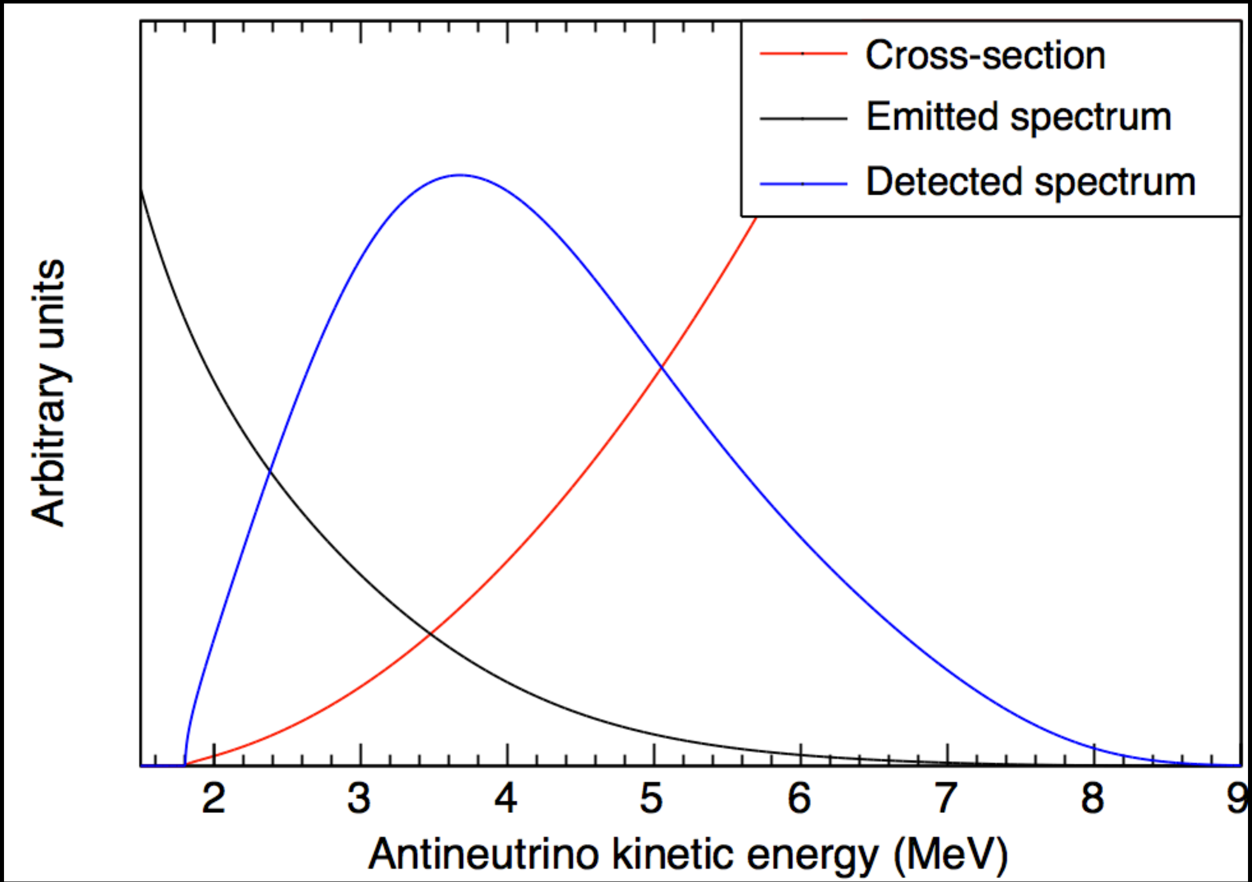
IBD Prefactor

- $$\kappa = \frac{G_F^2 \cos^2\theta_C}{\pi}(1+\Delta_{\text{inner}}^R)(1+3\lambda^2) = \frac{2\pi^2}{m_e^5 f^R \tau_n} \qquad \lambda = |\frac{g_A}{g_V}|$$
- **The "prefactor" requires experimental inputs (dominant errors):**
  - Either the neutron lifetime
  - Or the axial-to-vector coupling ratio $\lambda = |\frac{g_A}{g_V}|$
- According to Vogel & Beacom, K = 9.52 10^{-44} cm^2/MeV^2
- Based on PDG 2010: K = 9.56 10^{-44} cm^2/MeV^2
- **τ and λ are accessible through different kinds of experiments**
  - τ = 885.7 s (PDG 2010)
  - BUT: recent measurements (Serebrov, confirmed by MAMBO-II) will have the average fall to 881.4 s (Schreckenbach, private com)
  - λ=1.2694 (PDG2010) or even ~1.275 (more recent measurements)
  - All point to a forthcoming revision of K = 9.61 10^{-44} cm^2/MeV^2

Cross Section Per Fission

$$\sigma_f^{\text{pred}} = \int_0^{+\infty} S_{\text{tot}}(E_\nu)\sigma_{\text{V-A}}(E_\nu)dE_\nu = \sum_k f_k \sigma_{f,k}^{\text{pred}}$$

Ex: $^{235}U \rightarrow 6.6(1)10^{-43}\ cm^2$



Detected Spectrum

- Threshold : 1.8 MeV (neutrino energy)
- Mean Energy : 3.6 MeV
- Disappearance experiment
- No matter effect to be considered for < 1000 km baseline experiments c

Cross Section Measurement

- **Inverse Beta Decay:** $\bar{\nu}_e + p \to e^+ + n$

- **Anti-ν_e interaction rate** $n_\nu = \frac{1}{4\pi R^2} \frac{P_{\mathrm{th}}}{\langle E_f \rangle} N_p \varepsilon \sigma_f$

- **Experimental cross section per fission:** σ_f

$$\sigma_f^{\mathrm{meas.}} = \frac{4\pi R^2 n_\nu^{\mathrm{meas.}}}{N_p \varepsilon} \frac{\langle E_f \rangle}{P_{\mathrm{th}}}$$

- **Predicted cross section per fission:** σ_{pred}

$$\sigma_f^{\mathrm{pred.}} = \int_0^\infty \phi_f^{\mathrm{pred.}}(E_\nu) \sigma_{\mathrm{V\text{-}A}}(E_\nu) \mathrm{d}E_\nu$$

Expected Event Rate

- **Inverse Beta Decay – No oscillation**

- **Anti-ν_e interaction rate:**

$$n_\nu = \frac{1}{4\pi R^2}\frac{P_{\rm th}}{\langle E_f\rangle}N_p\varepsilon\sigma_f$$

  - P = 2 x 4.3 GW_{th}
  - R = 1000 meters
  - E_f = 204 MeV
  - N_p= 10 m^3 x 6.6 10^{28} H/m^3 = 6.6 10^{29} H
  - σ_f = 6 10^{-43} cm^2 $fission^{-1}$
  - ε = 0.8
  - 1 day = 86400 s

  → **2*4.3*1e9 / (204*1e6*1.6e-19)*6.6e29*6e-43/4/pi/(1e5)^2*86400*0.8**

  → **57 interactions detected per day**

- **Anti-ν_e flux (above 1.8 MeV):**
  - Fission number x 1.5 neutrinos/sec
  - 4 10^{20} neutrinos/sec emitted by the plant & 3 10^9 neutrinos/cm^2/sec at 1 km
  - @1 km, for a detector section of 6,25 m^2 (target) : 1.7 10^{19} neutrinos crossing the target of the detector each day