21 Solar mixing

Solar neutrino experiments → θ_{12}

Naive expectation:

$$P_{ee}(E) = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \qquad L = 1\,\mathrm{AU}$$

$l_{osc} \sim 30\,\mathrm{km}$ for $E_\nu \sim 1\,\mathrm{MeV} \ll L$

→ very rapid change of P_{ee} with E_ν

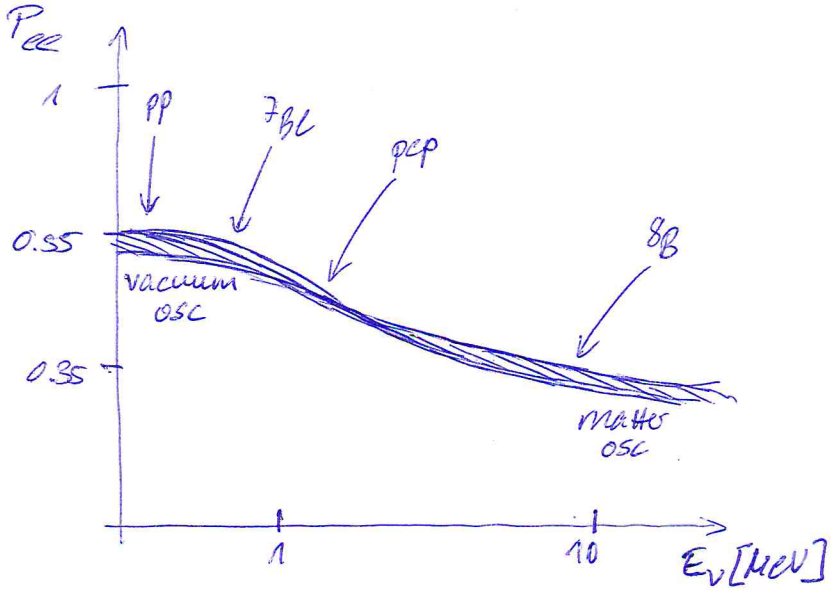
→ finite detector resolution: averaging effect

$$P_{ee} = 1 - \sin^2 2\theta_{12} \left\langle \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \right\rangle = 1 - \sin^2 2\theta_{12} \cdot \frac{1}{2}$$

Two additions:

- decoherence of neutrino mass states
  → oscillations stop on the way to Earth
- matter effects:
  ν_e are produced as ν_{2m}
  → ν_{2m} leaves the Sun as ν_2
  → $P_{e2} = |U_{e2}^2| = \sin^2\theta_{12}$ in vacuum

but: applies only to high values of E_ν



vacuum:

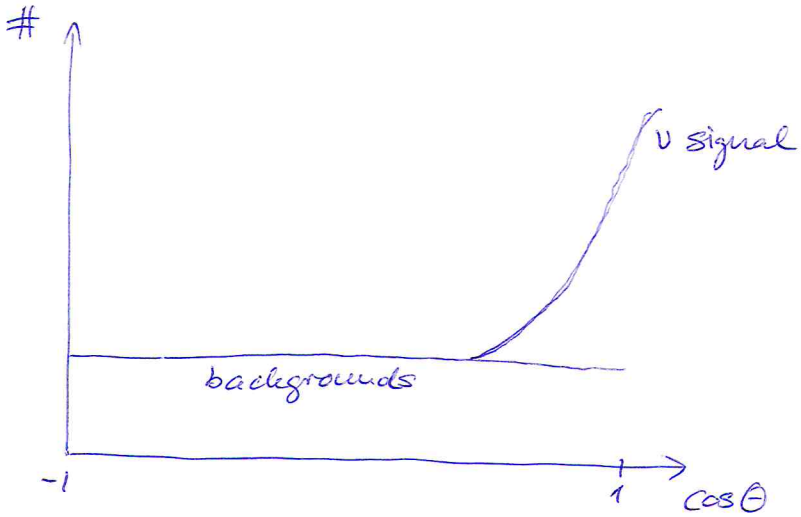
$$P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta_{12}$$

matter:

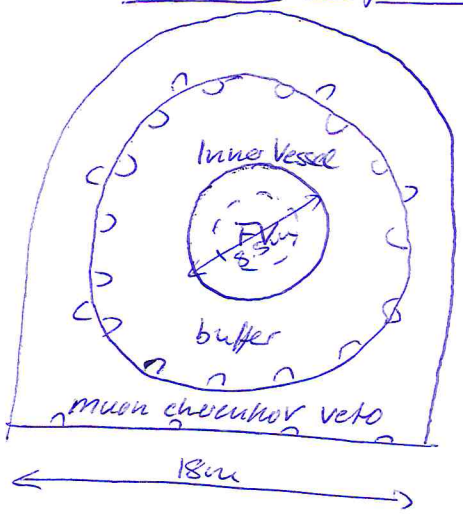
$$P_{ee} = \sin^2\theta_{12}$$

a) Wats-Cherenkov detectors → high-energy, ^8B only

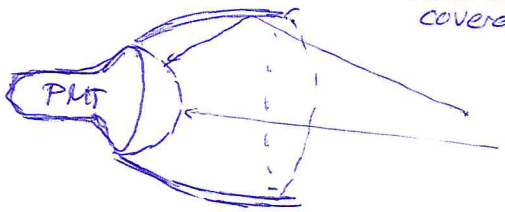
- SNO results prove that there is flavor conversion
- Super-Kamiokande:
  - much larger statistics for ν_e elastic scattering on e^- ($\gtrsim 10^4$ ev)
    → best measurement of θ_{12}: $\sin^2\theta_{12} = 0.305 \pm 0.013$ (2014 + other solar)
  - Analysis threshold: 5MeV (→ 3.5 MeV)
  - Main background:
    Radioactivity (Rn dissolved in water, cosmic spallation products)
    $\mu + {}^{16}O \rightarrow \mu + X^i$
  - Background suppression by
    - Fiducial volume cut → removes external γ-rays (spatial reco)
    - $\cos\theta$ distribution relative to the position of the Sun (directional reco of Cherenkov cones)
    - cosmic muons and spallation products
      ← time cut following muon signals (high μe number)



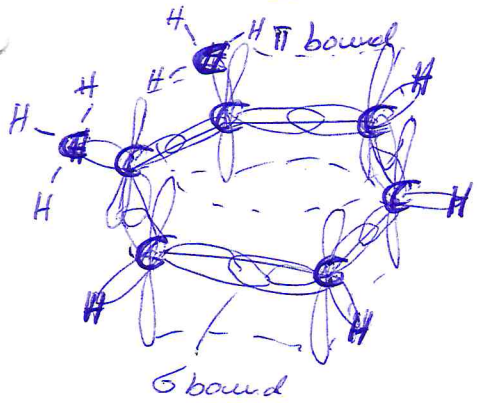
b) Borexino Experiment @ LNGS (Gran Sasso Lab)



- Liquid-scintillator detector:
  270t of pseudocumene (PC) in nylon balloon
  + 1.5g/l PPO (wavelengthshifter)
- 2200 PMTs (8") → 30% coverage
  + light concentrators: x2 increase in coverage

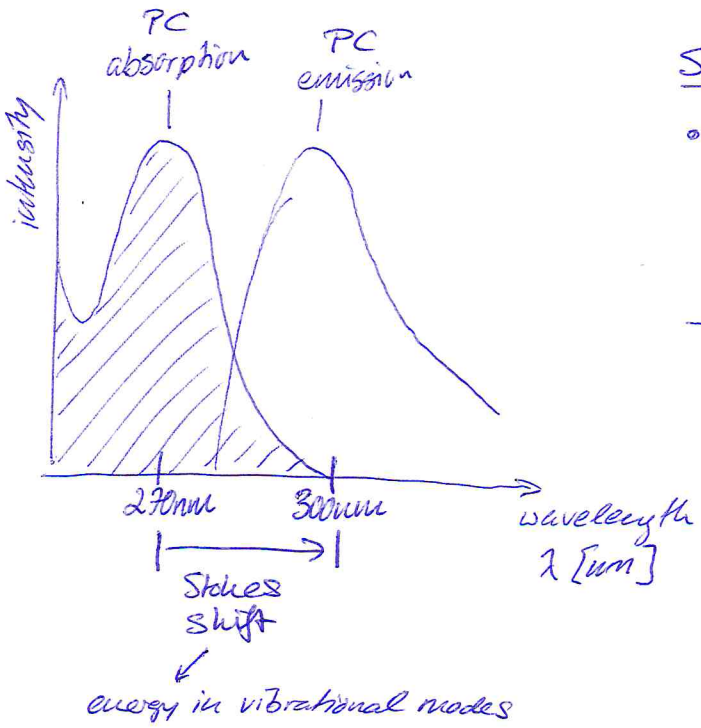


Scintillation mechanism



benzene ring

- 6 carbon atoms:
  4 electrons in outer shell (n=2)
  → 3 electrons bound to 2C, 1H (σ)
  → 1 electron loosely bound to whole benzene ring (π)
- excitation of π-electrons: ~4eV
  → deexcitation emits in UV (~300nm)
  (exact energy depends on ligands)



Scintillator

- Organic solvents (PC) are more transparent at longer wavelength
  → PPO added for further Stokes shift to ~390nm

- Light yield of scintillation: $\sim 10^4$ ph./MeV (cf. 300 ph./MeV for Č!)
- Little absorption in solvent

→ pe yield: $Y_{pe} = 10^4/\text{MeV} \times 0.3 \times 0.2 \hat{=} 600\ \text{pe/MeV}$

(0.3: optical coverage; 0.2: PMT efficiency)

→ much lower instrumental threshold: ~ 50 keV

→ much better energy resolution:

$$\frac{\Delta E}{E} \cong \frac{\sqrt{N_{pe}}}{N_{pe}} = \frac{1}{\sqrt{N_{pe}}} \hat{=} 5\% \text{ @ } 1\text{MeV}$$

Prerequisite: Low background levels

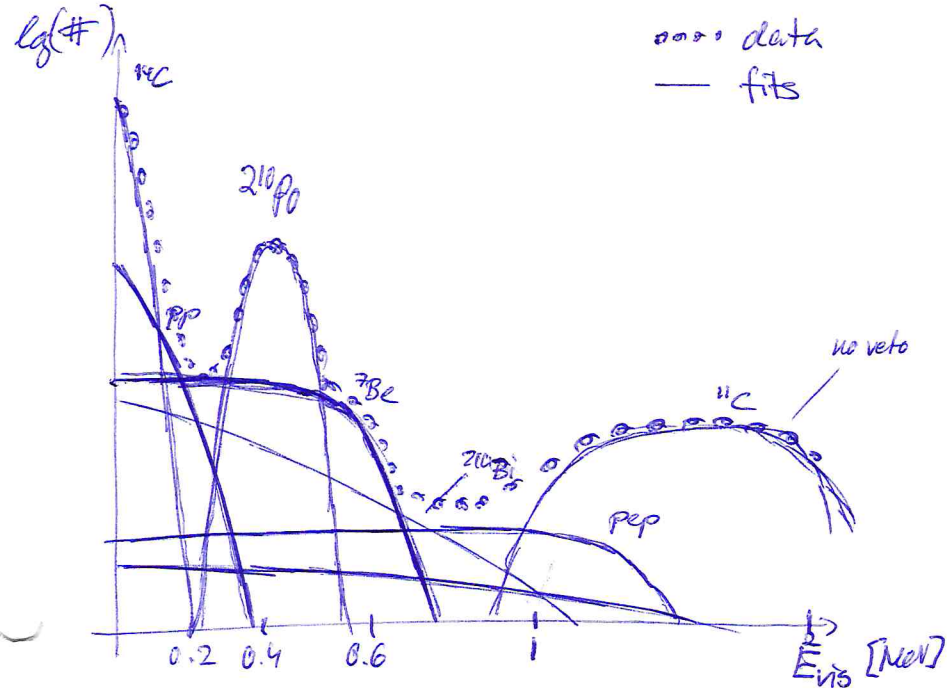
- intrinsic $^{14}C \rightarrow {}^{14}N + e^- + \bar{\nu}_e$, $E_\beta < 156$ keV, $\dot{N}(^{14}C) \sim 10^{-2}\,s^{-1}$
  → effective detection threshold at $\lesssim 200$ keV

- radioactive metalls dissolved in scintillator:
  ^{238}U, ^{232}Th and decay products
  energy range: $0 \sim 2.6$ MeV
  expected neutrino rate: ~ 1 ES event per day and ton
  → corresponds to $U/Th \hat{=} 10^{-17}$ g/g of LS
  → LS purification: distillation, water & N_2 purging

- gamma rays from detector materials,
  e.g. ^{40}K, ^{208}Tl in PMT glass
  → shielding by buffer
  → pre-selection of components (low-K glass)
  → fiducial volume cut (spatial reco, $R < 3$m)

- cosmogenic isotopes, e.g. $^{12}C \xrightarrow{\mu} {}^{11}C + n$
  ↳ $^{11}C \xrightarrow{20\,\text{min}} {}^{11}B + e^+ + \nu_e$ (↳ visible energy: 1–2 MeV)
  → veto based on parent muon and neutron capture signals
  → rock shielding (3,500 mwe)

Data analysis



Fit of selected data (volume cut, μ rejection etc.) with spectral shapes expected for signal and background

Results & uncertainties

- ^{7}Be rate at 5%
- pep-ν 20%
- pp-ν 11%
- ⊕ low-threshold ^{8}B analysis (2.8 MeV)

$\Rightarrow$ measurement of P_{ee} in vacuum oscillation regime

Overall solar results:

- best measurement of θ_{12}
- occurrence of matter resonance
  → positive sign of Δm^2_{21}
- some sensitivity to value of $|\Delta m^2_{21}|$ from position of the transition
- open: solar vacuum-matter transition
  → P_{ee} not well known
  ↳ non-standard effects ?
  ↳ new couplings to matter ?
  ↳ effect of light sterile ν's ?