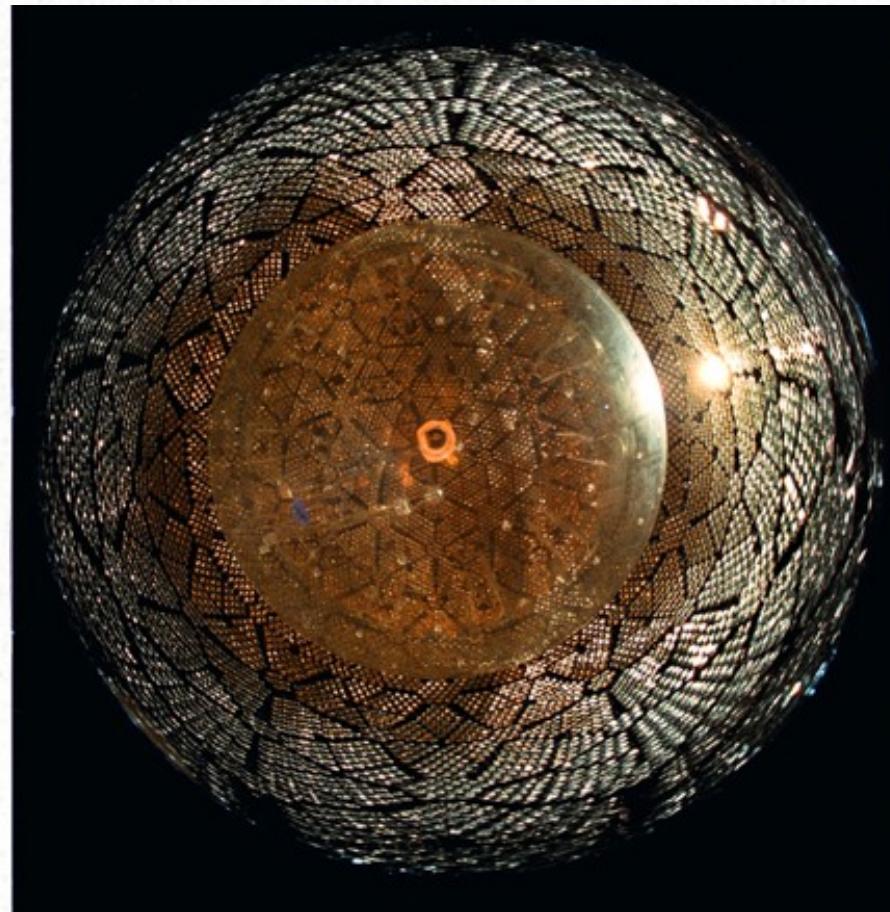


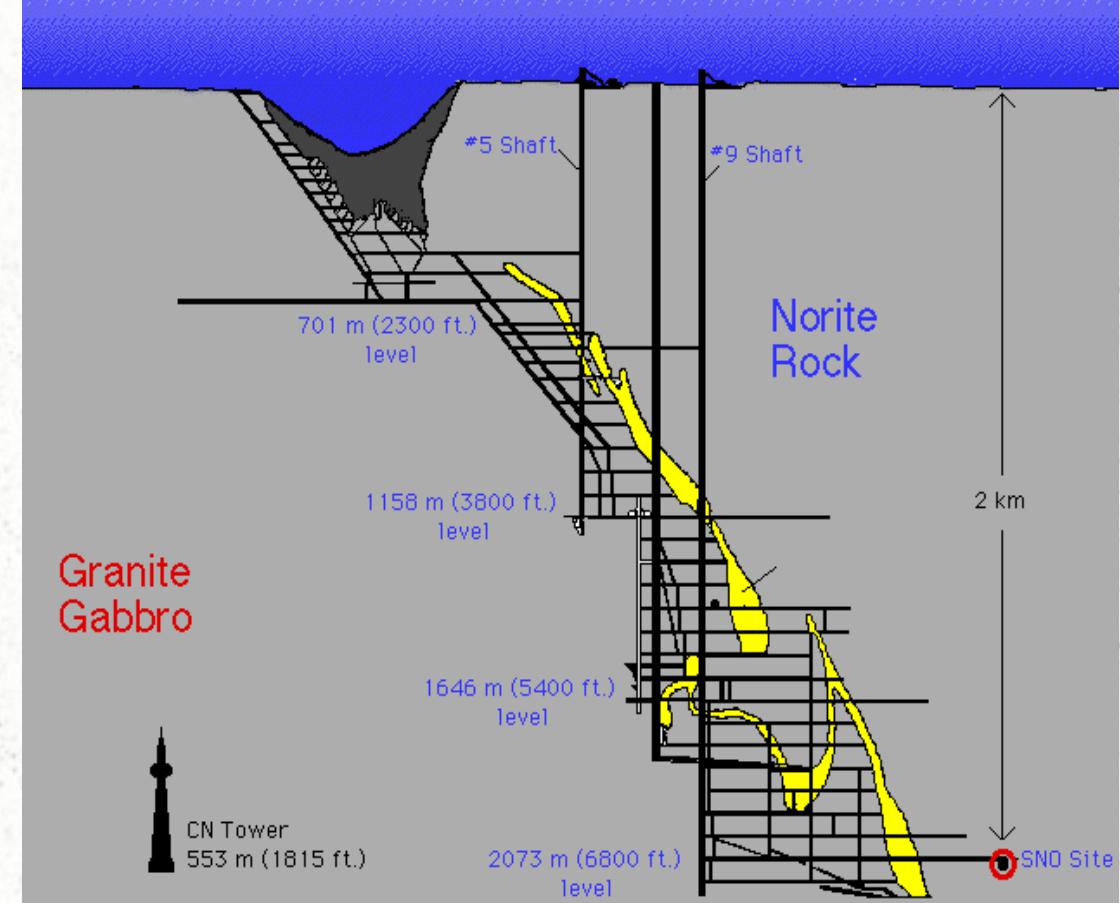
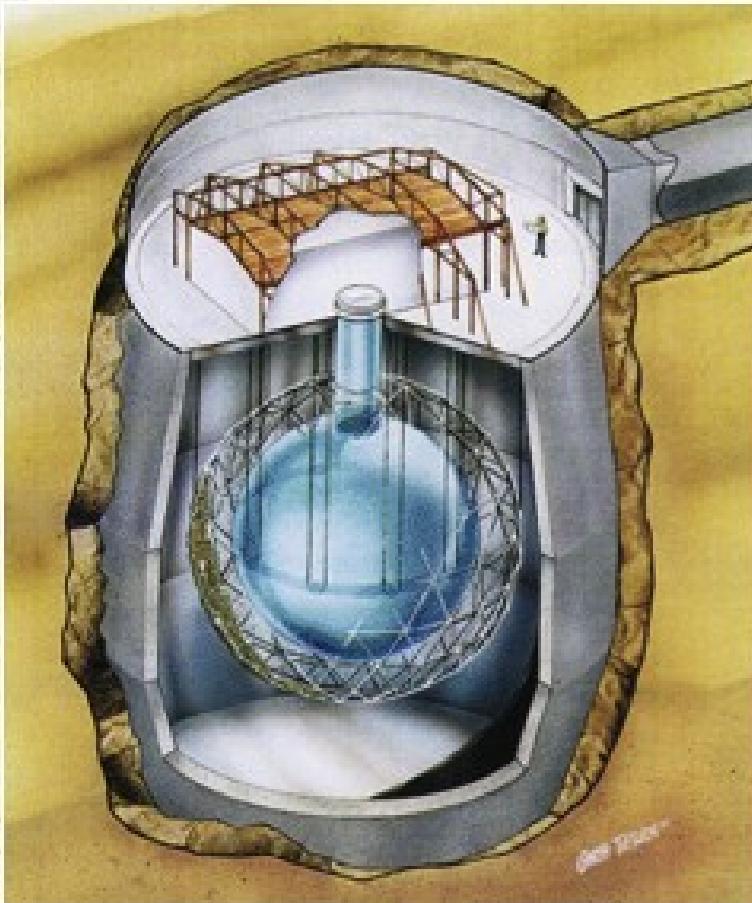
Neutrino oscillation studies in the upcoming SNO+ experiment



Overview

- The SNO+ detector at SNOLAB
- Survival probability of solar neutrinos
- Concept of the fit of the oscillation parameters
- Results of SNO+ alone studies

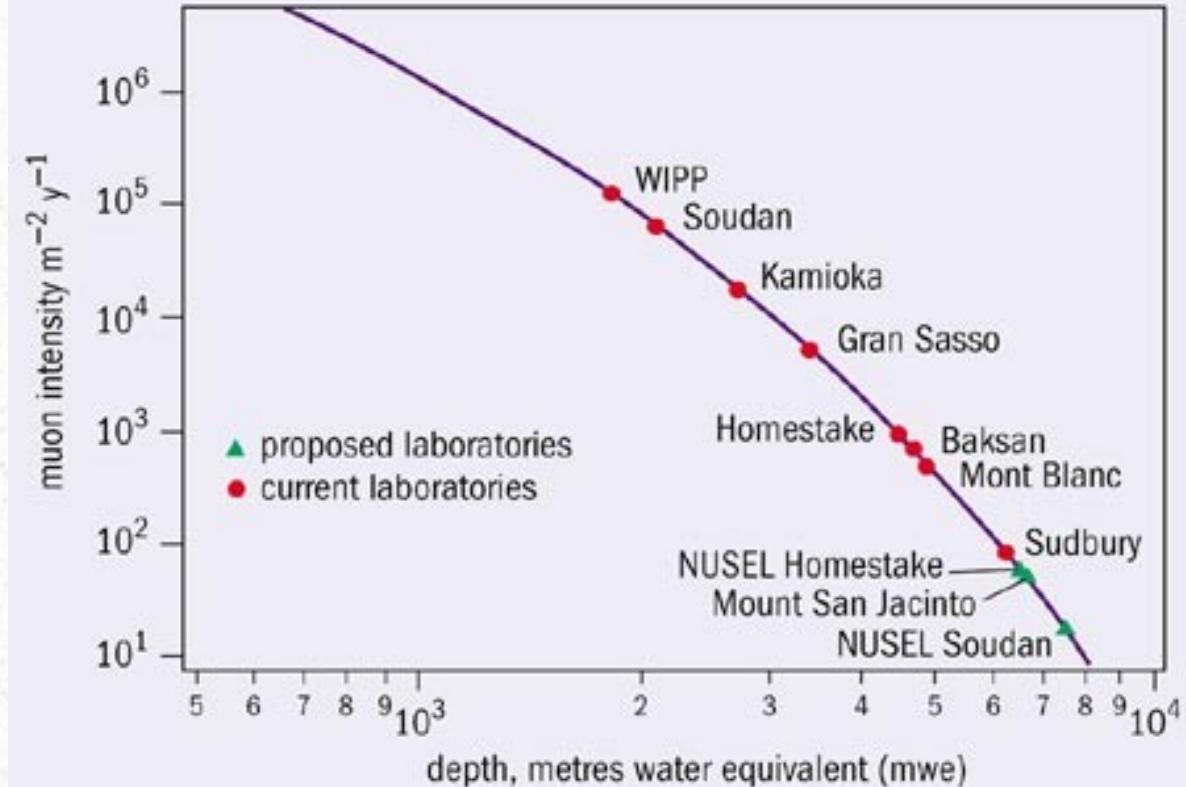
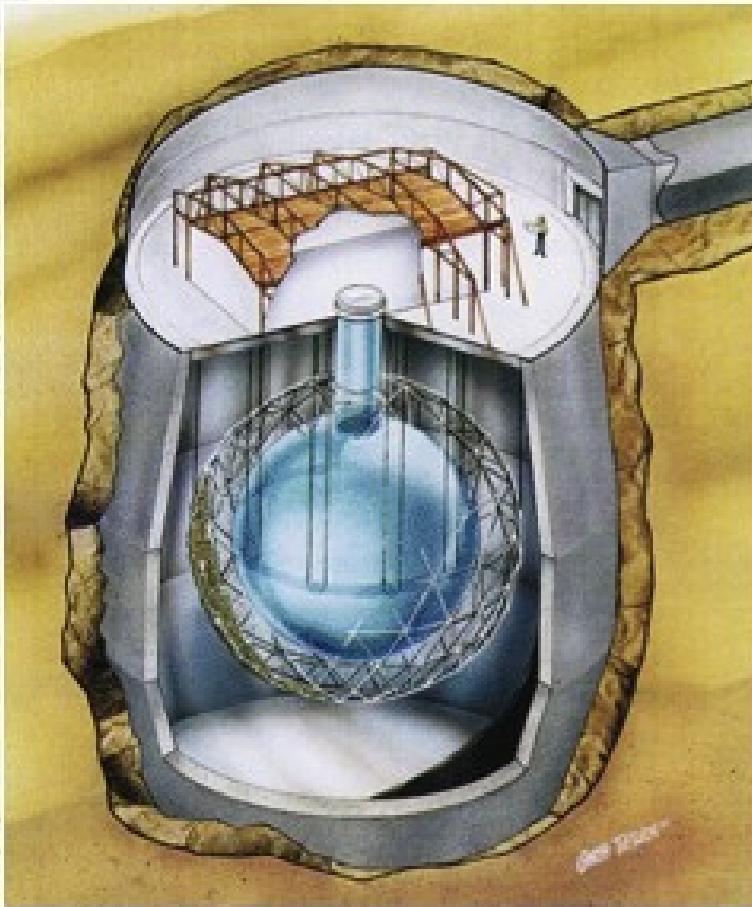
SNO+ Detector at SNOLAB



~ 2 km (6000 mwe) underground at „Vale INCO Ltd.“
Creighton Mine

Greater Sudbury, Ontario, Canada

SNO+ Detector at SNOLAB



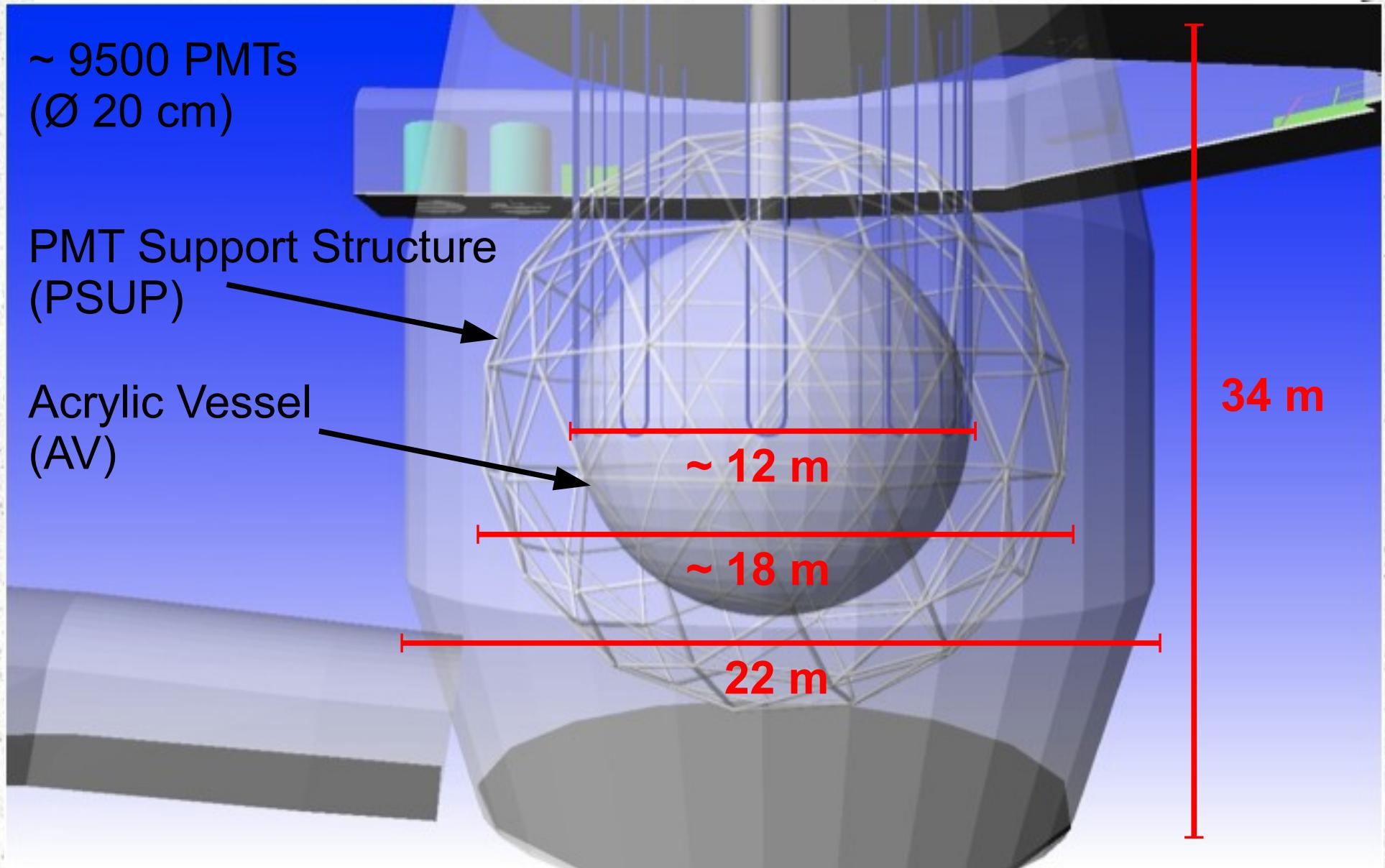
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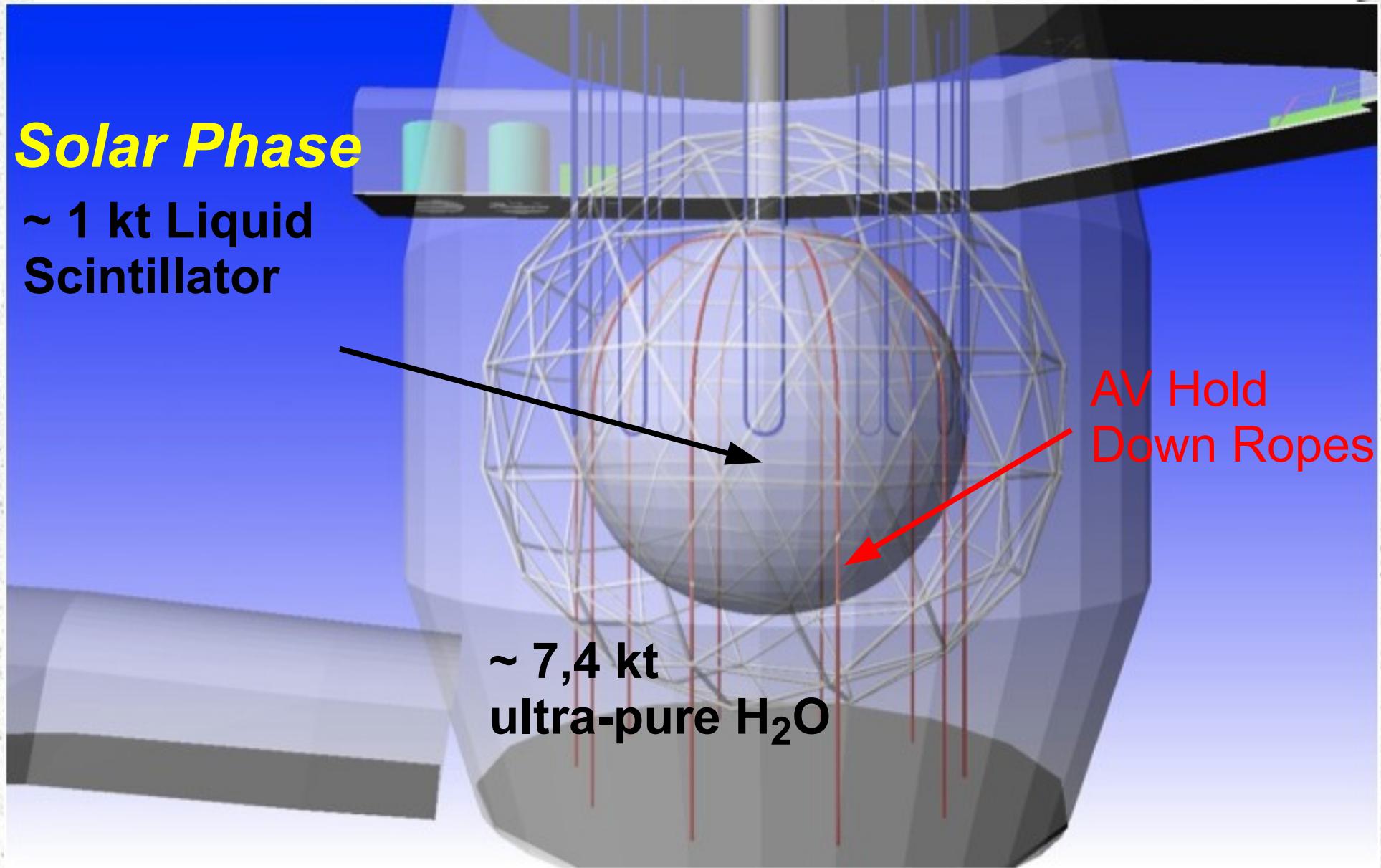
from the mine to the cleanroom (class < 2000)



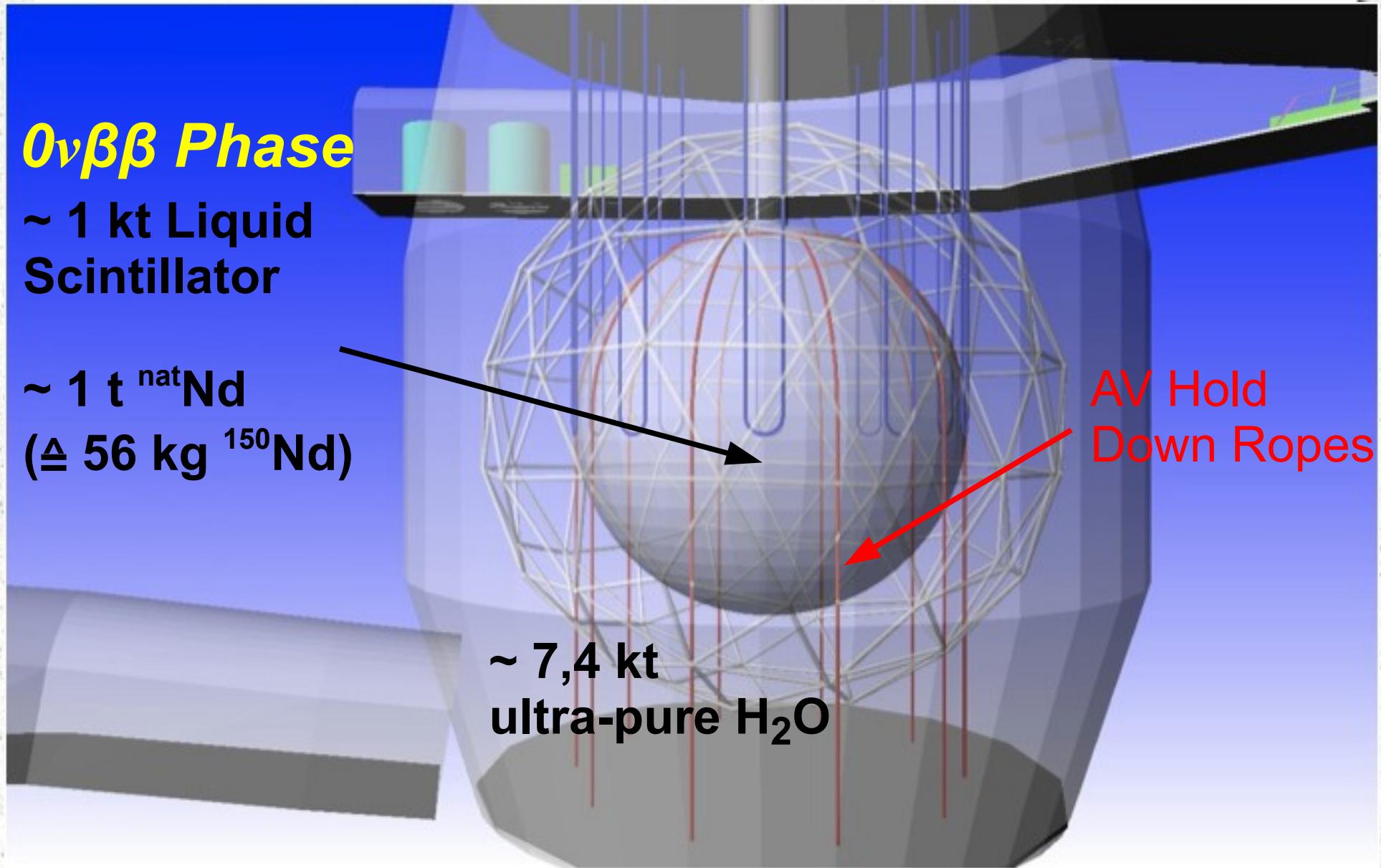
Using existing SNO Detector



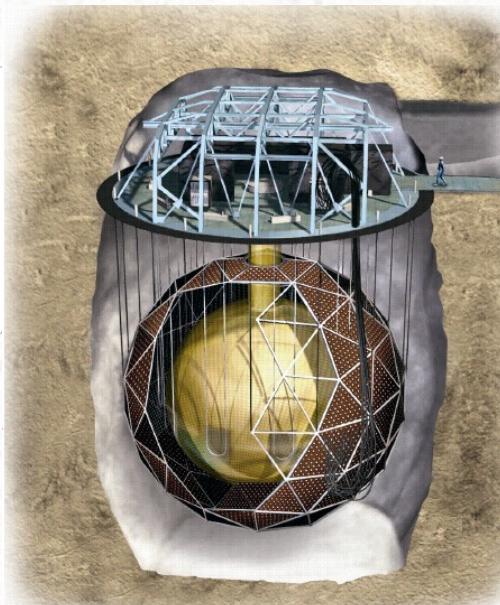
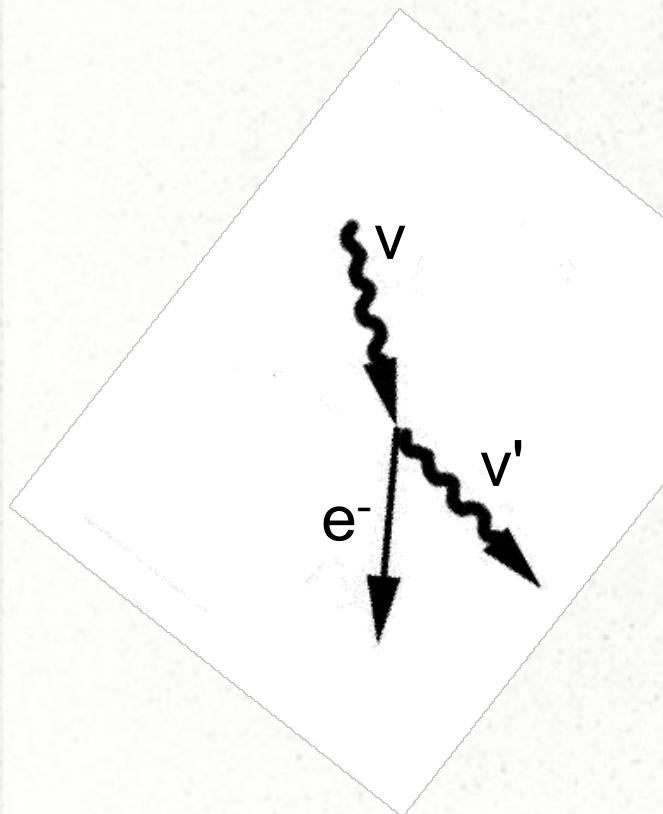
Changing into SNO+ Detector



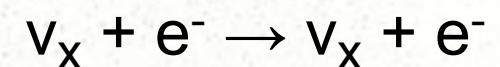
Changing into SNO+ Detector



SNO+ - Solar Phase



ES:



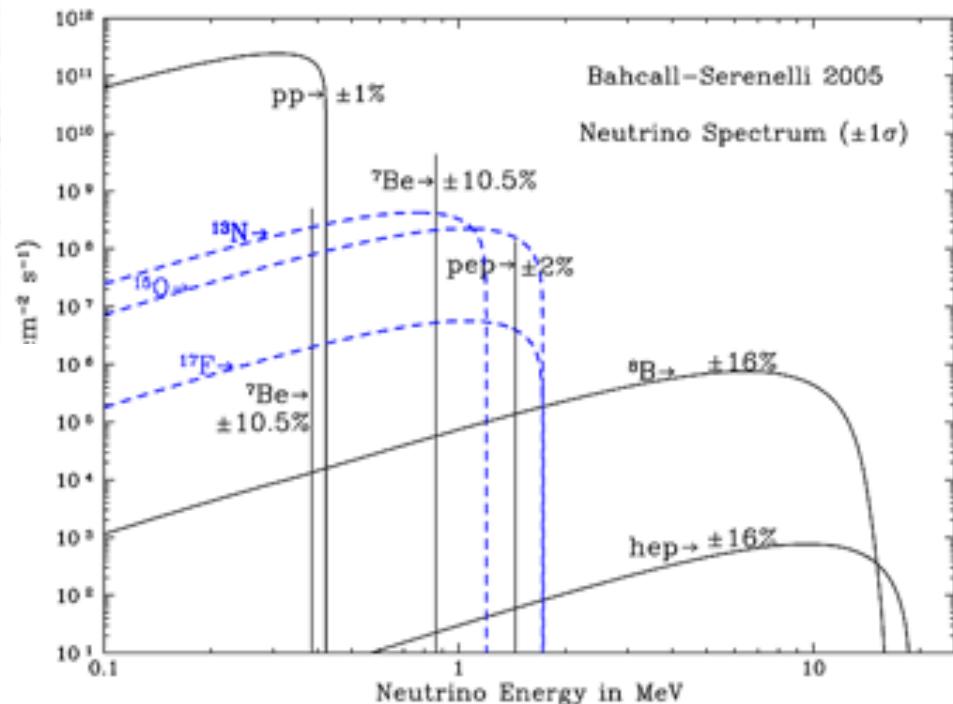
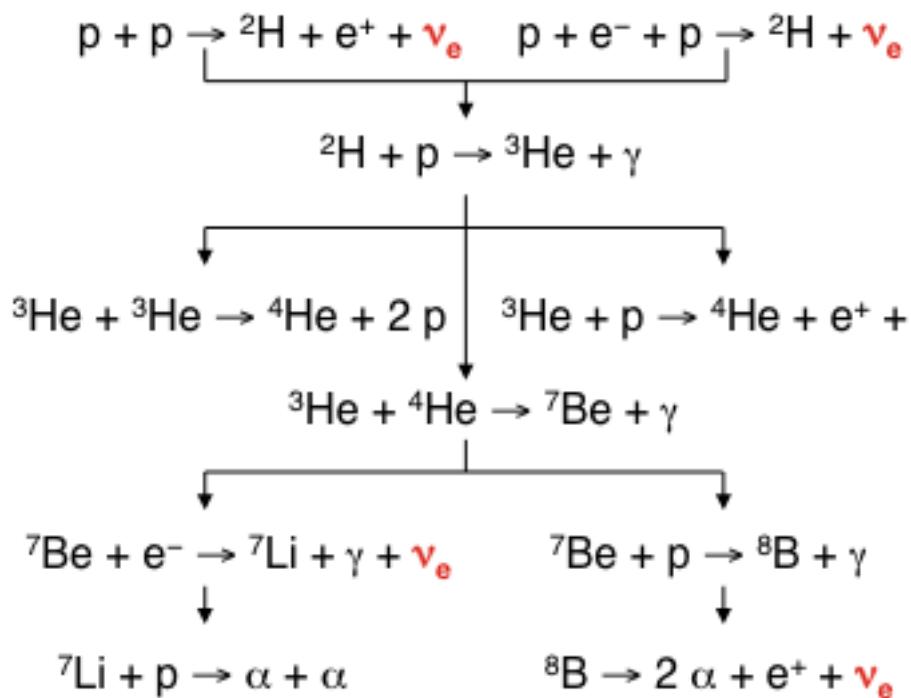
E_{vis} :

e^- recoil energy

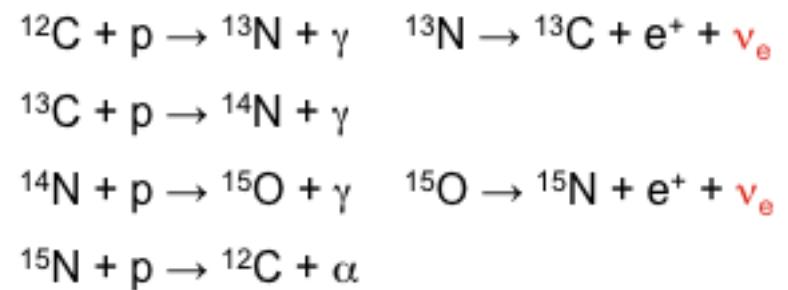
Solar Neutrinos

Sun as ν_e source

p-p Solar Fusion Chain



CNO Cycle



Neutrino Oscillations

simplest framework:

3 active flavor eigenstates (ν_α , $\alpha = e; \mu; \tau$) being superpositions of **3 light mass eigenstates** (ν_i , $i = 1; 2; 3$) via a **3 x 3 unitary mixing matrix U**

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i} |\nu_i\rangle$$

$$i \frac{d}{dt} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} = H_M \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\epsilon_1/2} & 0 & 0 \\ 0 & e^{i\epsilon_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

transition amplitude:

$$\Psi_{\alpha\beta} = \langle \nu_\beta(T, L) | \nu_\alpha \rangle$$

oscillation probability:

$$P_{\alpha\beta}(L, E_\nu) = |\Psi_{\alpha\beta}|^2$$

Neutrino Oscillations

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transition amplitude:

$$\Psi_{\alpha\beta} = \langle \nu_\beta(T, L) | \nu_\alpha \rangle$$

survival probability:

$$P_{\alpha\alpha}(L, E_v) = 1 - P_{\alpha\beta}(L, E_v)$$

Survival Probability P_{ee}

vacuum:

$$P_{ee}^{2\nu}(L, E_\nu) = 1 - \sin^2 2\theta_{12} \cdot \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$

$$P_{ee}^{3\nu}(L, E_\nu) \approx \cos^4 \theta_{13} \cdot P_{ee}^{2\nu} + \sin^4 \theta_{13}$$

with $|\Delta m_{31}^2| \approx |\Delta m_{32}^2| \gg \frac{2E_\nu}{L}$

matter:

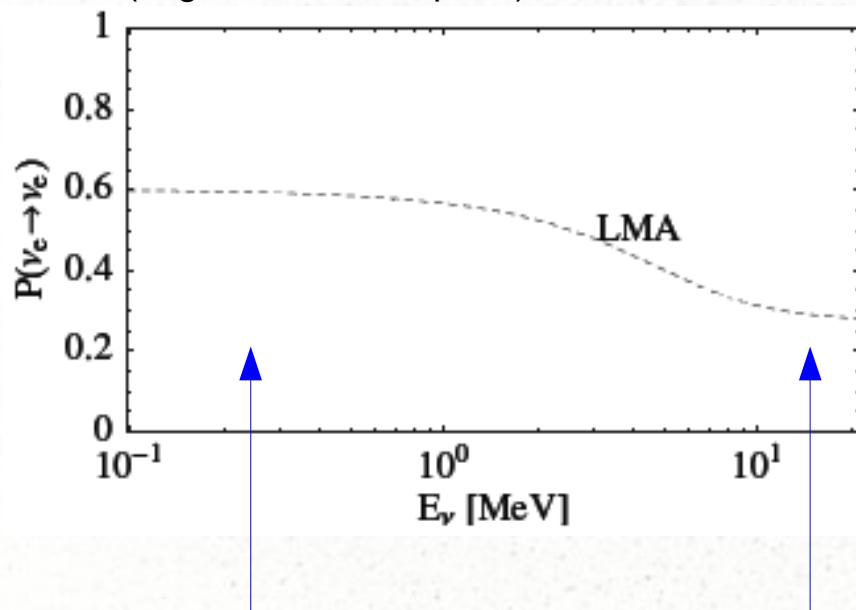
- additional CC (NC) potential enters H through W (Z) exchange of ν_e (ν_x) with e^-
 - NC potential only adds common phase \Rightarrow negligible
 - only forward coherent elastic scattering relevant
- amplitude of oscillation prob. (2ν) becomes dependent on N_e (e^- density) and E_ν
- resonance at $\cos 2\theta_{12} = \omega$, i.e. oscillation amplitude = 1 even for small θ_{12} **(MSW effect)**

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta_{12}}{(\cos 2\theta_{12} - \omega)^2 + \sin^2 2\theta_{12}}$$

with $\omega = \frac{2\sqrt{2}G_F N_e E_\nu}{\Delta m_{12}^2}$

Survival Probability P_{ee}

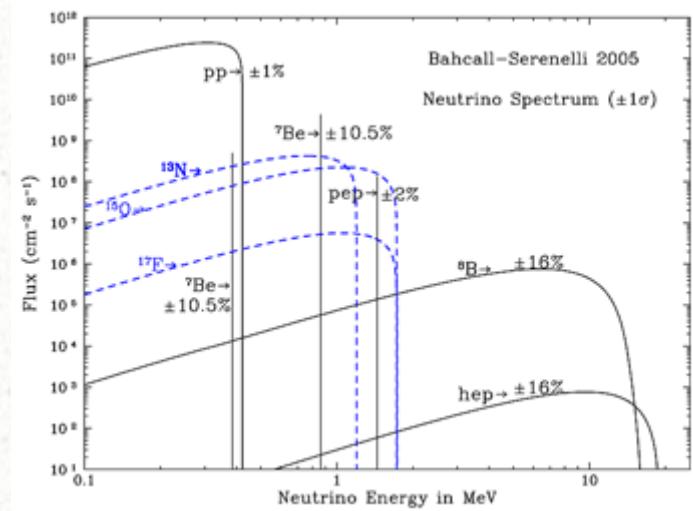
P_{ee} for fixed Δm^2_{21} , $\tan^2\theta_{12}$, $\sin^2\theta_{13}$
(in general best fit point):



vacuum dominated
region

matter dominated
region

E spectra of solar ν :



χ^2 -Fit

covariance approach (O : observable, σ : covariance matrix):

$$\chi^2 = \sum_{n,m=1}^N (O_n^{\text{exp}} - O_n^{\text{theo}}) [\sigma_{nm}^2(tot)]^{-1} (O_m^{\text{exp}} - O_m^{\text{theo}})$$

if only uncorrelated errors: off-diag. elements of σ are 0:

$$\chi^2 = \sum_{n=1}^N \frac{(O_n^{\text{exp}} - O_n^{\text{theo}})^2}{\sigma_n^2(tot)}$$

with $\sigma^2(tot) = \sigma_{\text{stat.}}^2 + \sigma_{\text{sys.}}^2$

χ^2 - Fit

$$\chi^2 = \sum_{n=1}^N \frac{(O_n^{\text{exp}} - O_n^{\text{theo}})^2}{\sigma_n^2(\text{tot})}$$

for solar analysis in general:

$$\chi^2 = \chi^2(\tan^2 \theta_{12}, \Delta m_{21}^2, \sin^2 \theta_{13})$$

$$\vec{O}^T = [R_{\text{Galex}}, R_{\text{Sage}}, \dots] \quad \text{R: sum of rates of all resp. } \nu \text{ types}$$

for analysis on SNO+ alone (each ν type adds one observable):

$$\chi^2(\tan^2 \theta_{12}, \Delta m_{21}^2, \sin^2 \theta_{13}) = \sum_{n=1}^N \frac{(R_n^{\text{exp}} - R_n^{\text{theo}})^2}{\sigma_n^2(\text{tot})}$$

χ^2 -Fit

$$\chi^2(\tan^2 \theta_{12}, \Delta m_{21}^2, \sin^2 \theta_{13}) = \sum_{n=1}^N \frac{(R_n^{\text{exp}} - R_n^{\text{theo}})^2}{\sigma_n^2(tot)}$$

rate (at fixed energy): $R \sim \Phi_{tot} \cdot P_{ee} \cdot \sigma_{ES}$

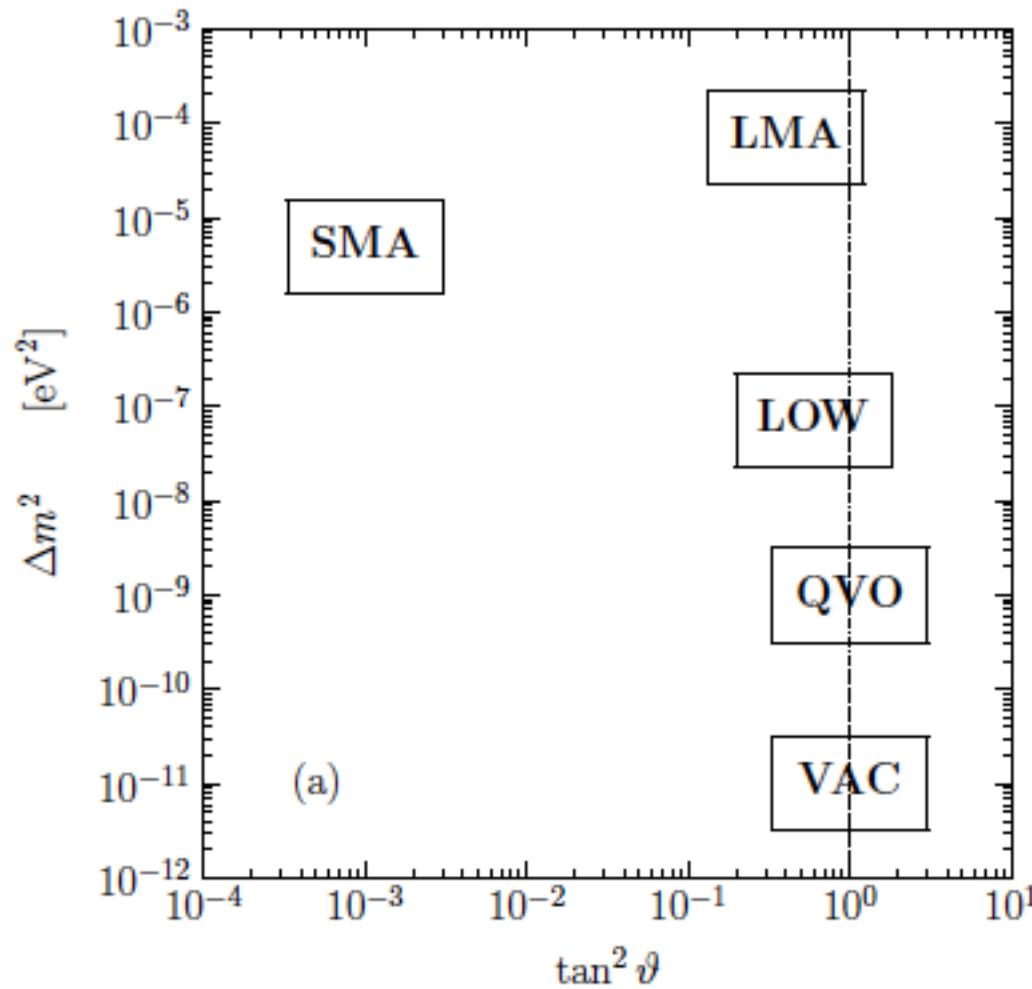
R^{exp} (no SNO+ measurement so far):

- use (bin with) latest solar best fit point
- calculate P_{ee} for best fit point
- apply P_{ee} to SSM flux ϕ (here: BS05(OP))
- consider both ES cross-sections (σ_e , $\sigma_{\mu,\tau}$)
- only integrated rates at present

R^{theo}: • grid scan over MSW parameter space

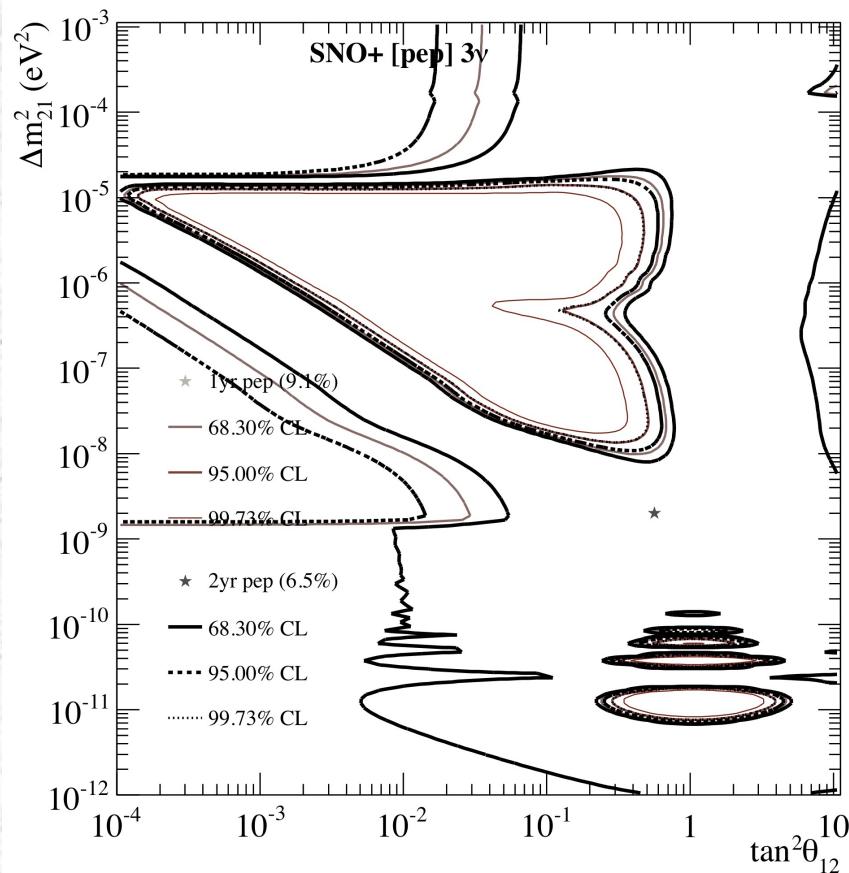
σ^2 : • only „statistical“ uncertainties at present
• including uncertainties from backgrounds (e.g. U, Th)
• 8B shape

MSW Parameter Space

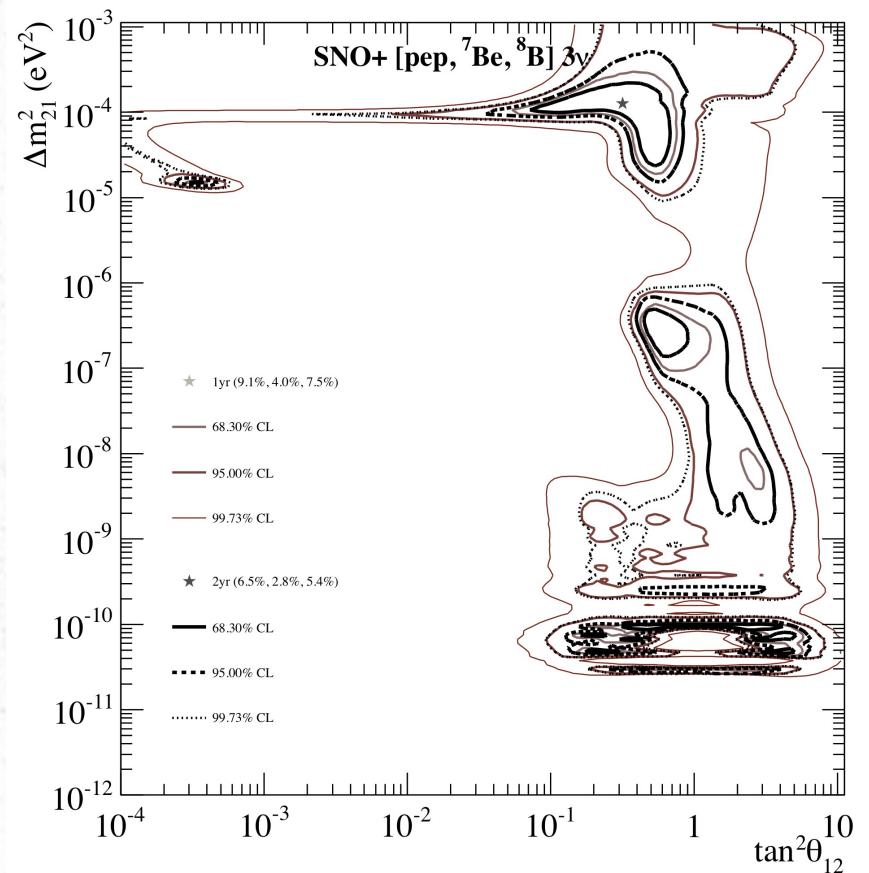


SNO+ alone

pep

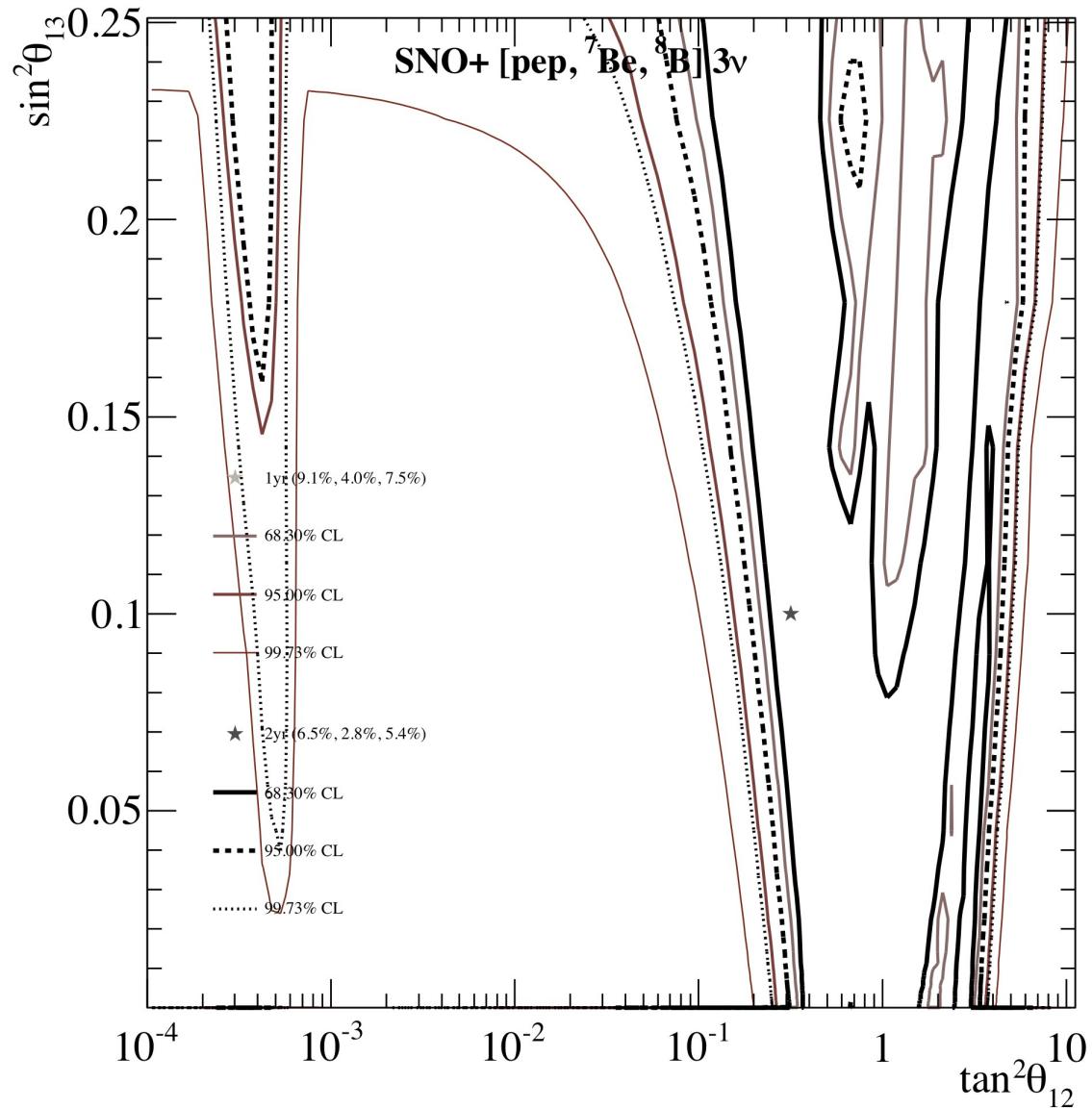


pep, ${}^7\text{Be}$, ${}^8\text{B}$



	1 year	2 years
pep	9.1%	6.5%
${}^7\text{Be}$	4.0%	2.8%
${}^8\text{B}$	7.5%	5.4%

SNO+ alone



Does the Earth has an effect on Pee?

Does the Earth has an effect on Pee?

depends...

Survival Probability P_{ee}

vacuum:

$$P_{ee}^{2\nu}(L, E_\nu) = 1 - \sin^2 2\theta_{12} \cdot \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$

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with $|\Delta m_{31}^2| \approx |\Delta m_{32}^2| \gg \frac{2E_\nu}{L}$

oscillation amplitude in matter:

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta_{12}}{(\cos 2\theta_{12} - \omega)^2 + \sin^2 2\theta_{12}}$$

with $\omega = \frac{2\sqrt{2}G_F N_e E_\nu}{\Delta m_{12}^2}$

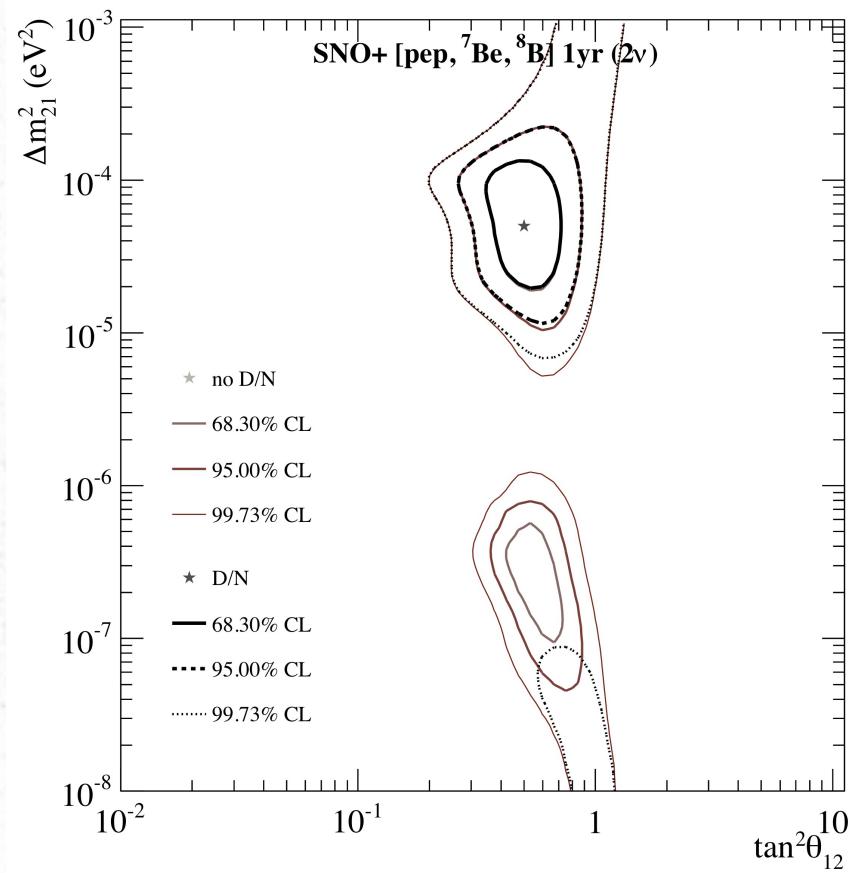
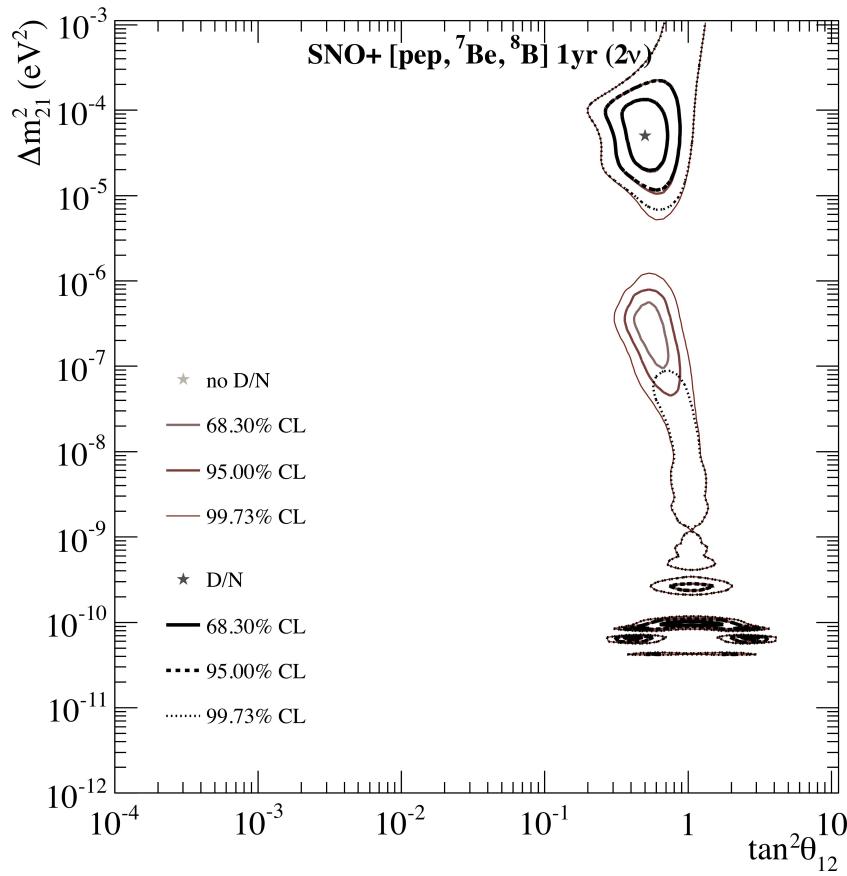
... also on Δm_{12}^2

Adding D/N to SNO+ alone

- D/N asymmetry at low E_ν enhanced outside LMA
- separation into two observables with larger uncertainties (\sim factor $\sqrt{2}$)
- Borexino favors LMA region at 90% CL in 2ν analysis due to non-observation of D/N asymmetry (arXiv:1104.2150v1)
- testing same effect with SNO+

Adding D/N to SNO+ alone

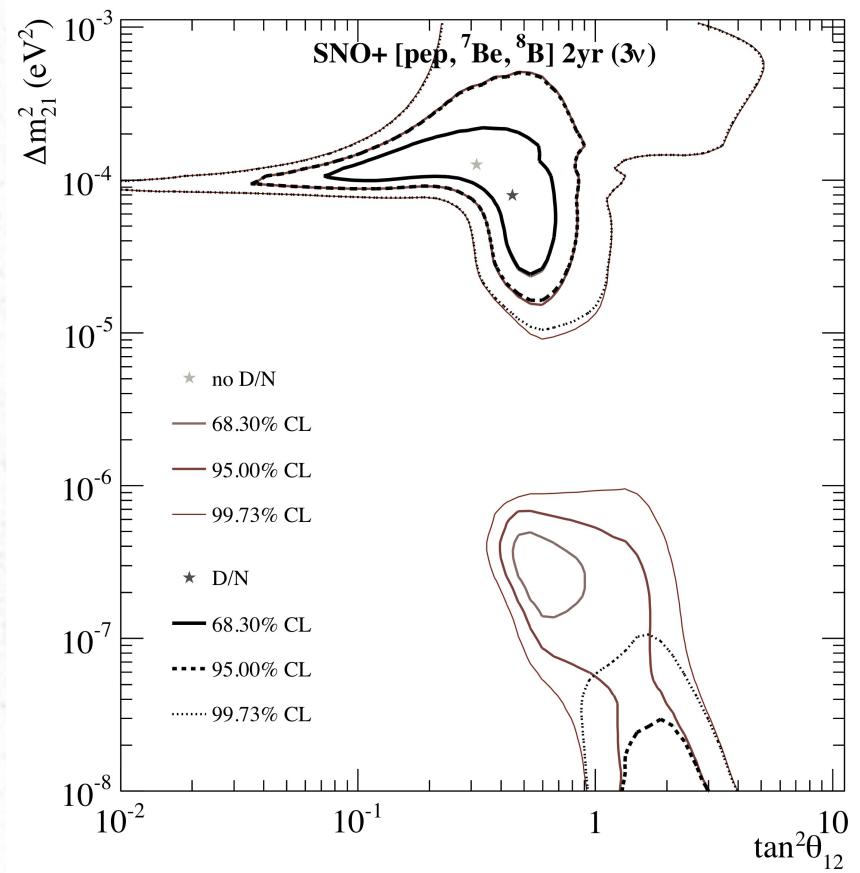
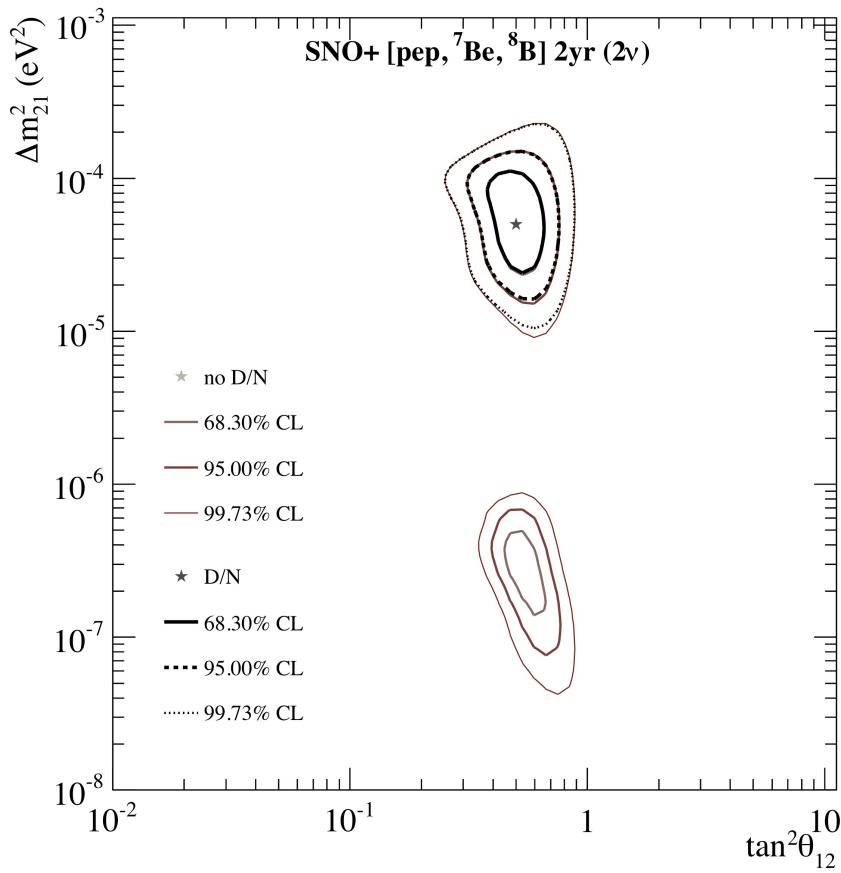
2ν -1yr



- after 1yr (2yr), SNO+ excludes LOW region at 95% CL (99.73% CL)
- doesn't change LMA region significantly

Adding D/N to SNO+ alone

- 2yr -



- after 2yr, SNO+ excludes LOW region at 99.73% CL (2v)
- doesn't change LMA region significantly

Summary

- SNO+ is a deep underground large scale LS experiment with two major physics goals
 - $0\nu\beta\beta$
 - solar neutrino precision measurement
- Oscillation studies done for SNO+ alone (and for SNO+ combined with all other solar experiments)

Outlook

- Updates/improvements on code in progress
- Sensitivity studies on oscillation parameters ongoing



Thanks for your Attention!

Solare Neutrinos (pep, CNO)

Materie- oder MSW-Effekt

$$i \frac{d}{dt} \begin{bmatrix} \nu_e \\ \nu_x \end{bmatrix} = H \begin{bmatrix} \nu_e \\ \nu_x \end{bmatrix}$$

(Mikheyev, Smirnov, Wolfenstein)

Hamiltonian für ν_e -Ausbreitung in Materie:

$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \boxed{\sqrt{2} G_F N_e} & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{bmatrix}$$

extra Term wegen zusätzlicher Wechselwirkung der ν_e über W mit den e- in Sonne und Erde

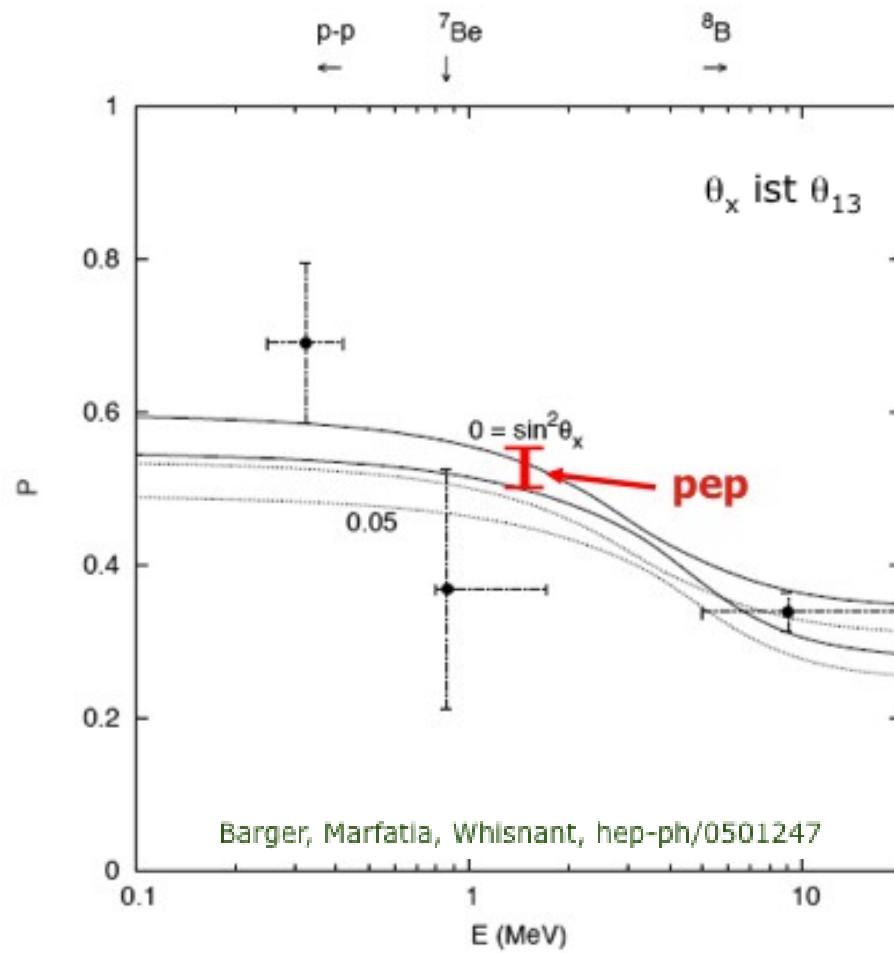
=> in Oszillations-Wahrscheinlichkeit P:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\omega = -\sqrt{2} G_F N_e E / \Delta m^2$$

pep Neutrinos...

... und θ_{13}

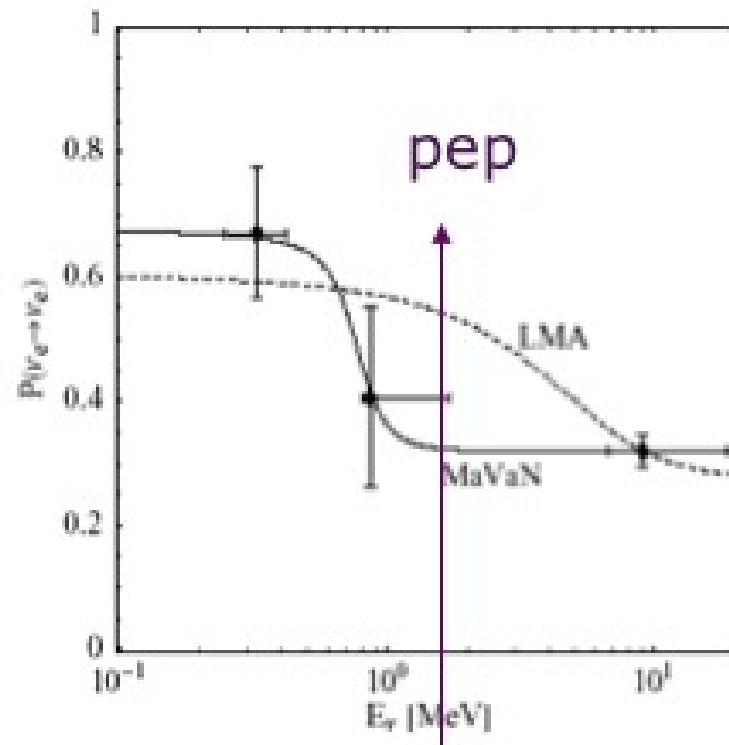


pep Neutrinos... Neue Physik?

„Mass-Varying Neutrinos“

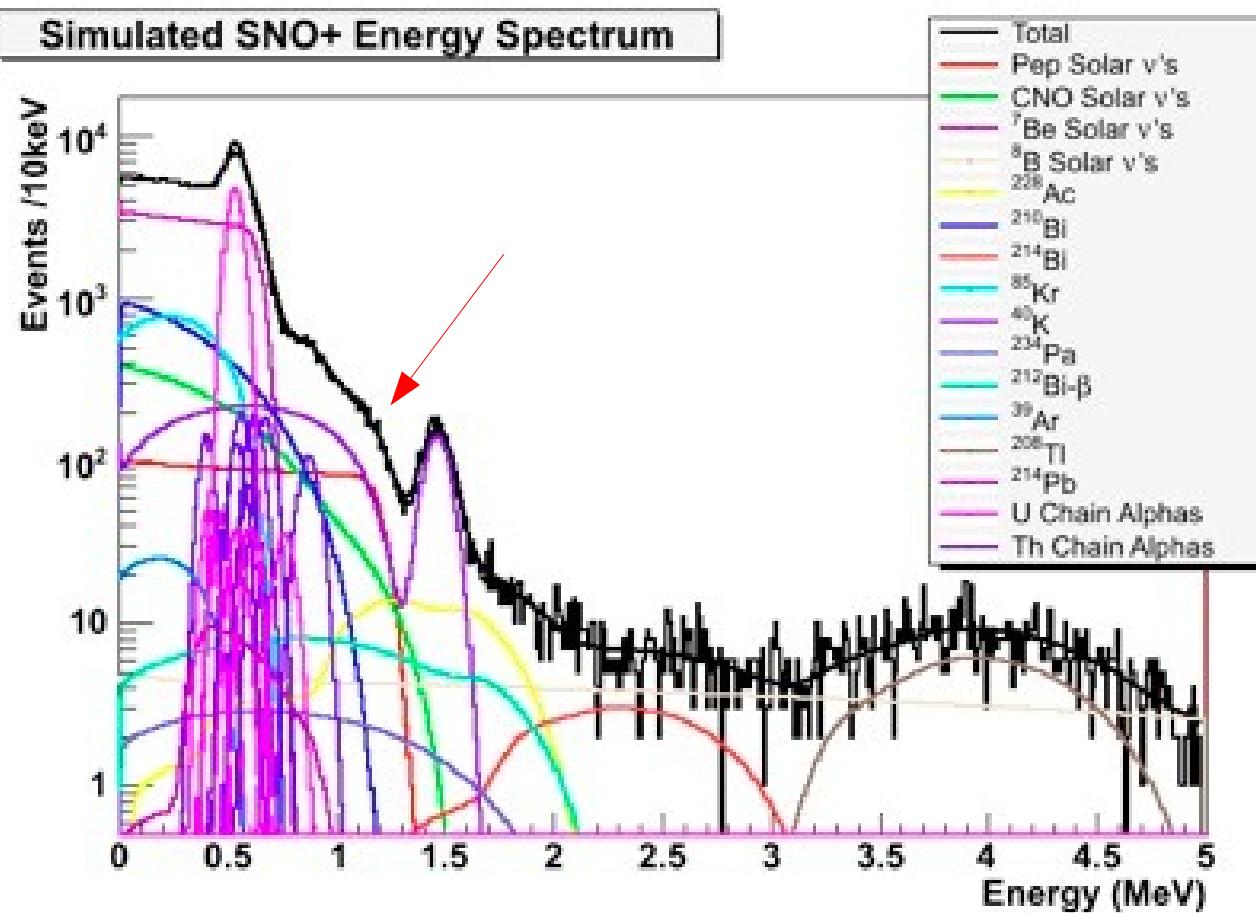
Fardon, Nelson, Weiner
(hep-ph/0309800):

Kopplung von ν mit skalarem
Feld führt zu ν deren Masse
mit dem Hintergrund-Feld
variiert (z.B. von anderen ν)



Solare Neutrinos (pep, CNO)

- Solares Neutrino Ereignis: $\nu_e + e^- \rightarrow \nu_e + e^-$



bei 3 Jahren Datennahme

Expected rates for SNO+

$$R_{^{11}\text{C}} = 1090.1 / \text{kt} \cdot \text{yr}$$

