Low Energy
Neutrino Physics

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Low Energy Neutrino Physics

Introduction

- Neutrino masses and mixing
- Neutrino oscillations

Experimental determination of neutrino properties

Neutrino oscillation experiments

- Solar neutrinos
- Atmospheric neutrinos
- Reactor experiments (θ_{13})

Absolute mass determination

- Beta decay
- Neutrinoless double beta decay
- Cosmological limits

Low energy neutrino astronomy

Conclusions

2005: 75th anniversary of the neutrino!

1930 Pauli postulates the neutrino (at that time called neutron)

„Zürich, 4. Dezember 1930

Liebe radioaktive Damen und Herren,
wie der Überbringer dieser Zeilen ... Ihnen des näheren auseinandersetzen wird, bin ich ... auf einen verzweifelten Ausweg verfallen, um den Wechselsatz der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in dem Kern existieren, welche den Spin ½ haben..... Die Masse der Neutronen müßte von derselben Größenordnung wie die Elektronenmasse sein und jedenfalls nicht größer als 0,01 Protonenmasse. Das kontinuierliche β-Spektrum wäre dann verständlich unter der Annahme, daß beim β -Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, daß die Summe der Energien von Neutron und Elektron konstant ist. ... Ich ... wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal größeres Durchdringungsvermögen besitzen würde, wie ein γ-Strahl.“

Wolfgang Pauli
(1900 — 1958)

1956 first detection of electron(anti)neutrinos by Cowan and Reines

Neutrino masses and mixing

Standard Model: neutrinos are massless

Assumption: 3 massive neutrinos ν_1 ν_2 ν_3 with masses m_1, m_2, m_3

Flavour eigenstates ν_e ν_μ $\nu_\tau \neq \nu_1$ ν_2 ν_3

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

$s_{12} = \sin\theta_{12}$
$c_{12} = \cos\theta_{12}$

Unitary mixing matrix U:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}\,e^{-i\delta}\\0&1&0\\-s_{13}\,e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}1&0&0\\0&e^{i\phi_1}&0\\0&0&e^{i\phi_2}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

θ_{23}
atmos.

θ_{13}
cross-link
reactor?

θ_{12}
solar

Majorana ~~CP~~

9 parameter: 3 masses m_1, m_2, m_3 (or m_1, Δm_{21}^2, Δm_{32}^2)
3 mixing angles θ_{12}, θ_{23}, θ_{13}
1 CP-violating Dirac-phase δ (+ 2 Majorana-phases ϕ_1, ϕ_2)

Neutrino oscillations in vacuum

Time evolution:

$$|\nu_\alpha(t)\rangle = \sum_i e^{-E_i t} U_{\alpha i} |\nu_i\rangle$$

Mixing between two neutrinos:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

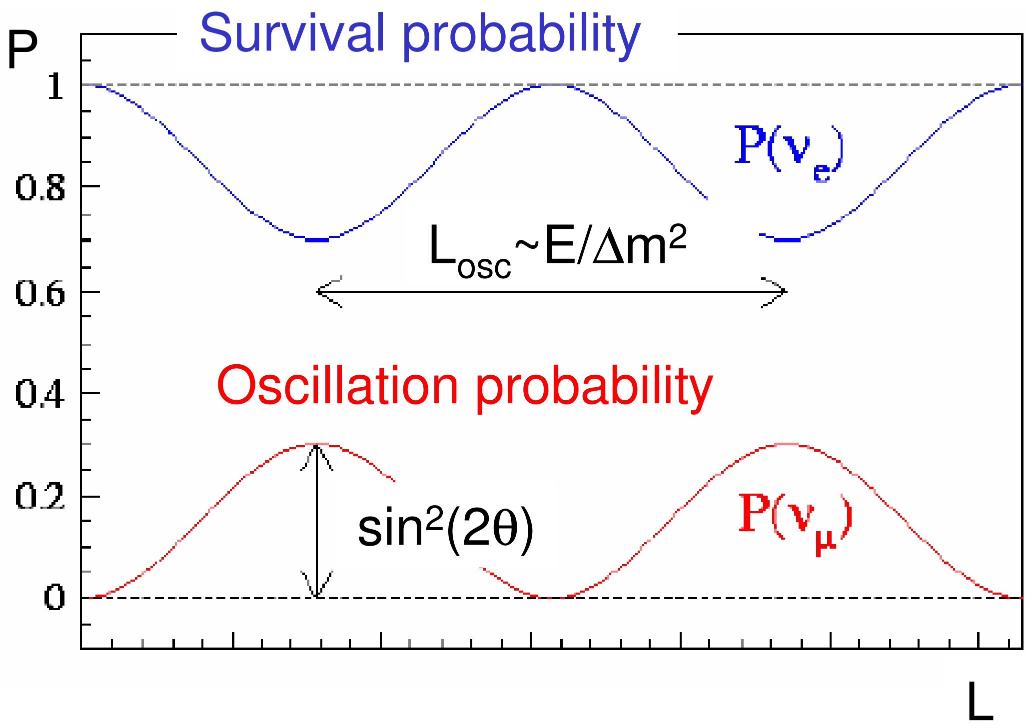
Oscillation probability:

$$\boxed{P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)}$$

Survival probability:

$$\boxed{P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta)\cdot\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)}$$

Mass difference: $\Delta m^2 = m_2^2 - m_1^2$



Oscillation length

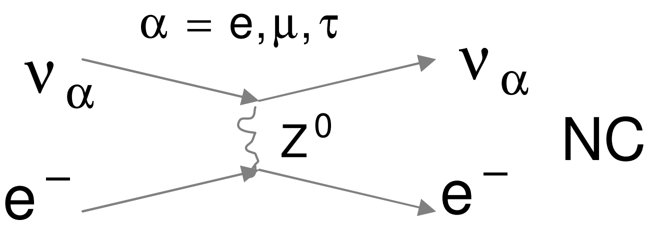
$$L_0 = \frac{4\pi E_\nu}{\Delta m^2} = 2.48\,\frac{E_\nu[\mathrm{MeV}]}{\Delta m^2[\mathrm{eV}^2]}\ \mathrm{m}$$

Sensitivity $\Delta m^2 \propto E/L$

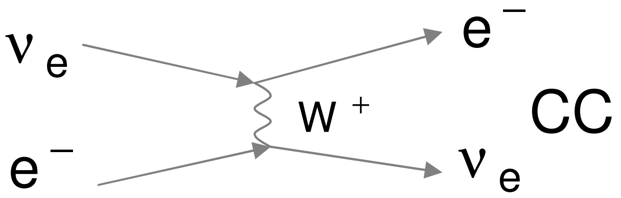
Note: no absolute mass determination with neutrino oscillation experiments!

Neutrino oscillations in matter – MSW-effect

ν - e^--scattering



all flavours



only ν_e

➔ modified mixing angle in matter (n_e= electron density)

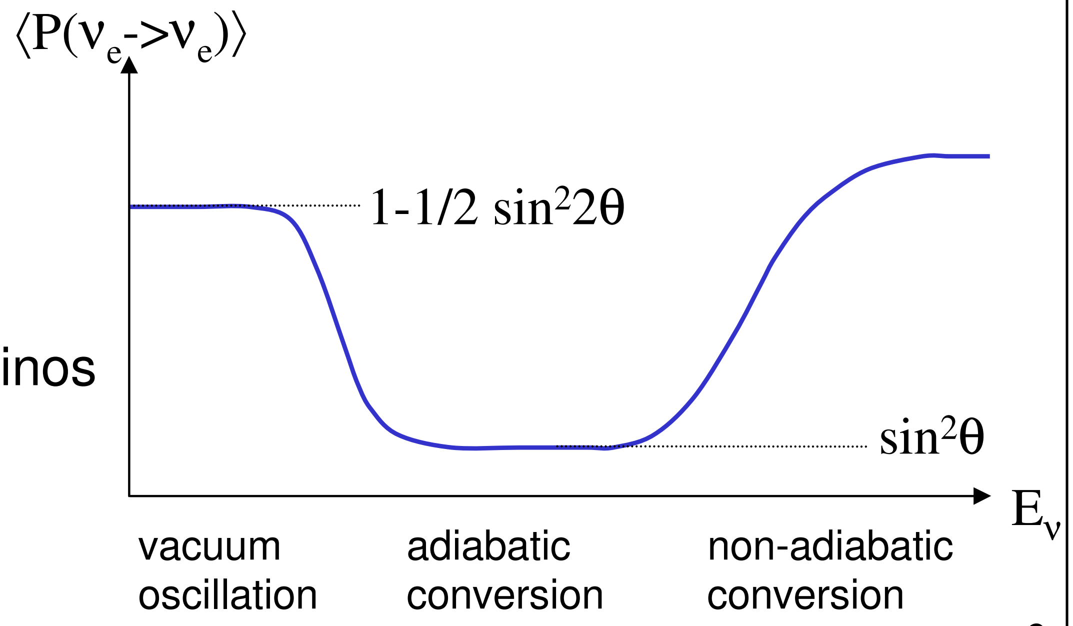
$$\sin^2(2\theta_m) = \frac{\sin^2(2\theta)}{(\cos(2\theta) - \underbrace{2\sqrt{2}G_F n_e E_\nu/\Delta m^2}_{= a})^2 + \sin^2(2\theta)}$$

$\Delta m^2 > 0$ Amplification
$\Delta m^2 < 0$ Attenuation

Resonance for

$a = \cos(2\theta) \;\; \Rightarrow \;\; \sin^2(2\theta_m) = 1$

In matter with slowly varying density,
e.g. Sun: adiabatic conversion for neutrinos
in a certain energy range



$P(\nu_e \to \nu_e) = |\langle \nu_e | \nu_2 \rangle|^2 = \sin^2\theta$

What do we know about neutrino masses and mixing?

- Number of light active neutrinos (Z^0-width, LEP): $N_\nu = 2.991 \pm 0.016$

- Upper limits from direct mass measurements,

  e.g. Tritium-decay: $m_\nu < 2.3$ eV

- solar and atmospheric neutrino oscillations detected

  ➔ neutrinos do have non-zero mass

  $m_{\text{heaviest } \nu} \geq (\Delta m_{atm}^2)^{1/2} \approx 0.05$ eV

  2 large mixing angles

  $\theta_{sol} \sim \theta_{12} \sim 33 \pm 2°$

  $\theta_{atm} \sim \theta_{23} \sim 45 \pm 3°$

  1 small (zero?) mixing angle $\theta_{13} < 10°$

  2 independent mass splittings

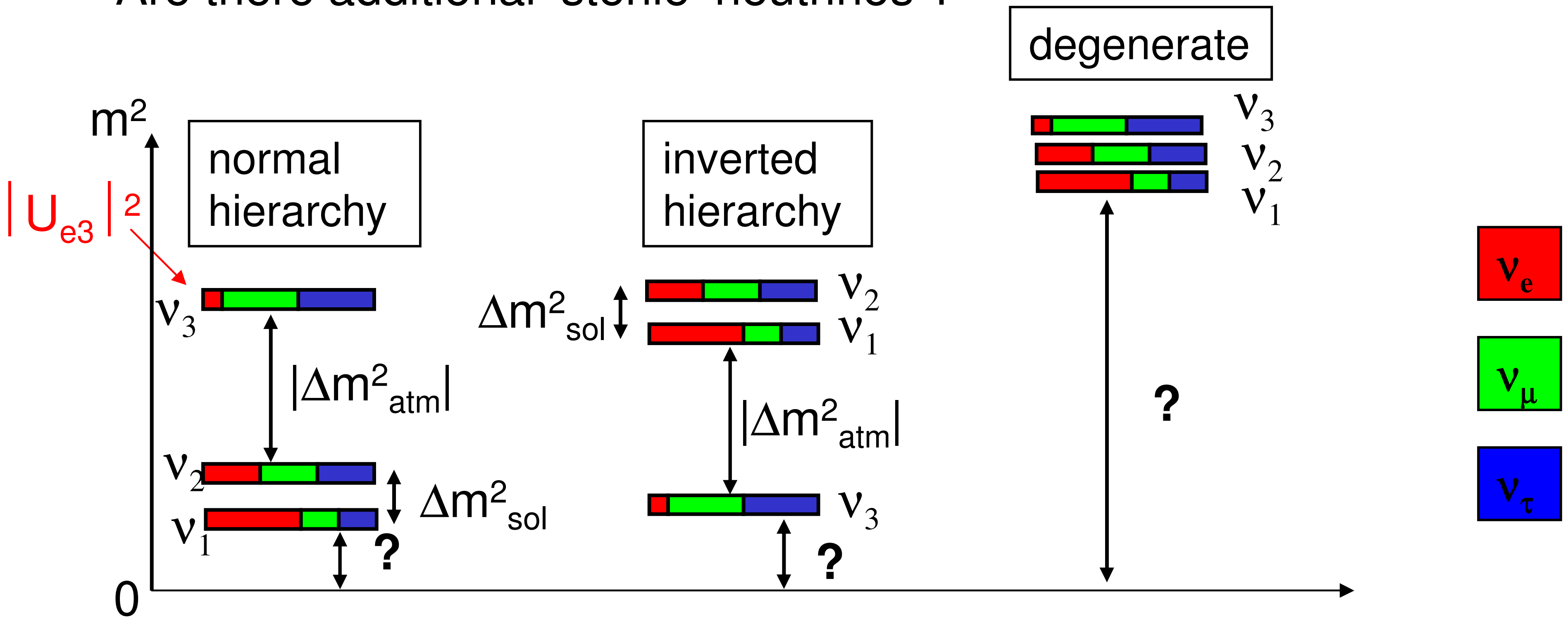
  $\Delta m_{sol}^2 \sim \Delta m_{21}^2 \sim 8 \cdot 10^{-5}$ eV^2,

  $|\Delta m_{atm}^2| \sim |\Delta m_{32}^2| \sim 2.5 \cdot 10^{-3}$ eV^2

- (LSND-evidence: $\theta_{LSND} \sim 0.5°$, $\Delta m_{LSND}^2 \sim 1$eV^2 => additional sterile neutrino?)

Open questions

- What is the absolute mass scale of the neutrinos ?
- What is the mass hierarchy: $m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$?
- How small is the mixing angle θ_{13} ? Is it equal to 0 ?
- Are neutrinos Dirac ($\nu_\alpha \neq \bar{\nu}_\alpha$) or Majorana particles ($\nu_\alpha = \bar{\nu}_\alpha$) ?
- Is there CP-violation in the leptonic sector ?
- Are there additional ‘sterile’ neutrinos ?



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- **Solar neutrinos**
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Absolute mass determination

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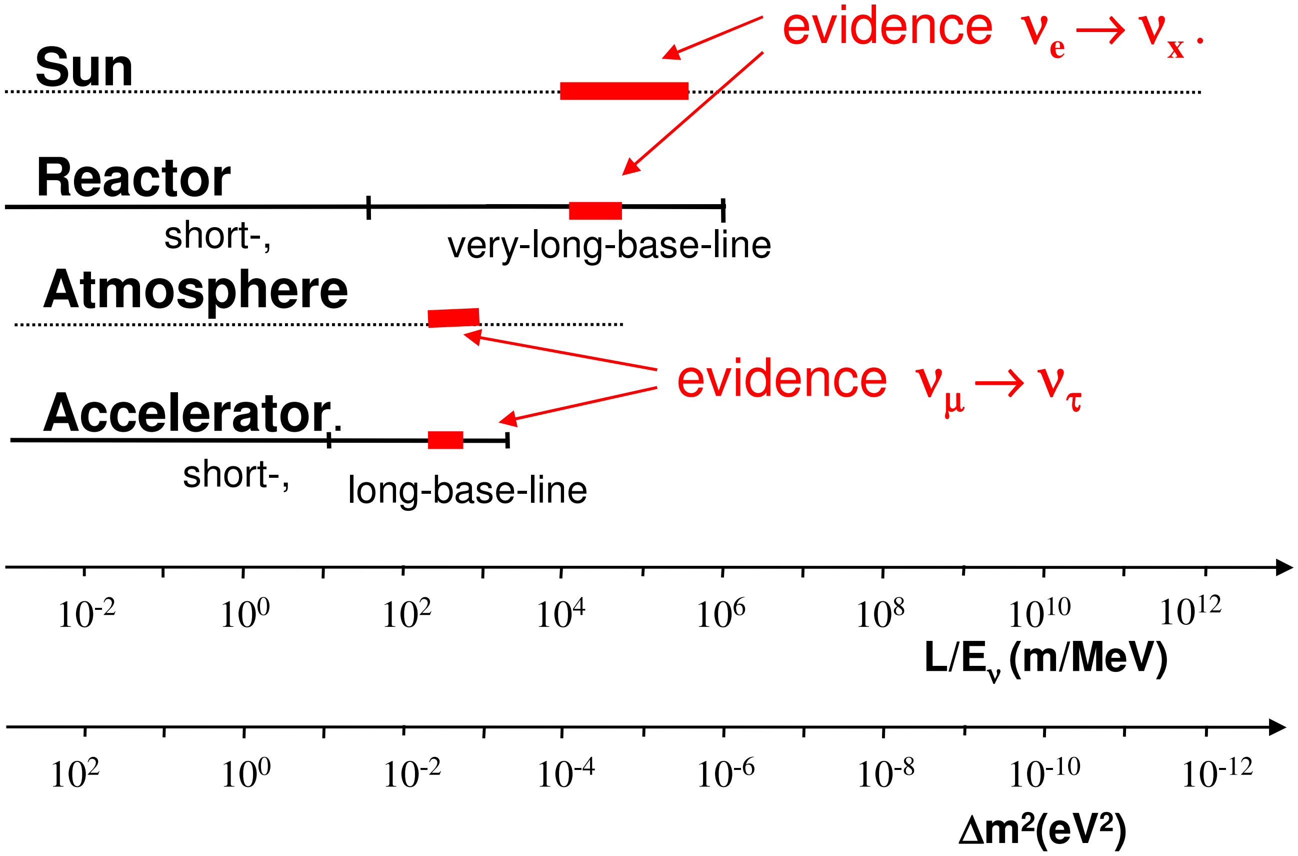
Sensitivity of neutrino oscillation experiments

$$\boxed{P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)}$$

choose L and E_ν for your experiment

ν-source:



Sun

Reactor

short-, very-long-base-line

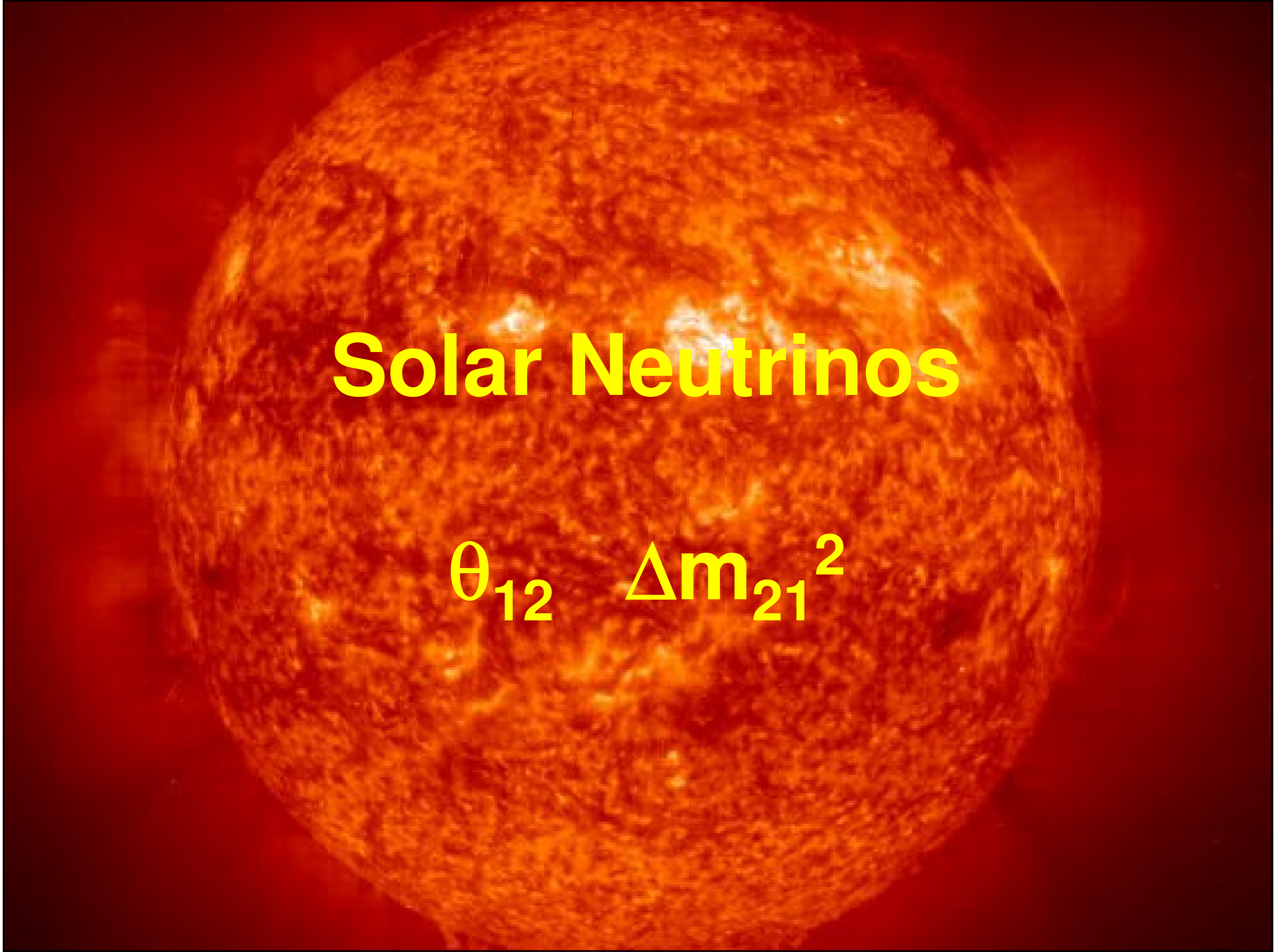
Atmosphere

Accelerator

short-, long-base-line

evidence $\nu_e \rightarrow \nu_x$.

evidence $\nu_\mu \rightarrow \nu_\tau$



Solar Neutrinos

$\theta_{12} \quad \Delta m_{21}{}^2$

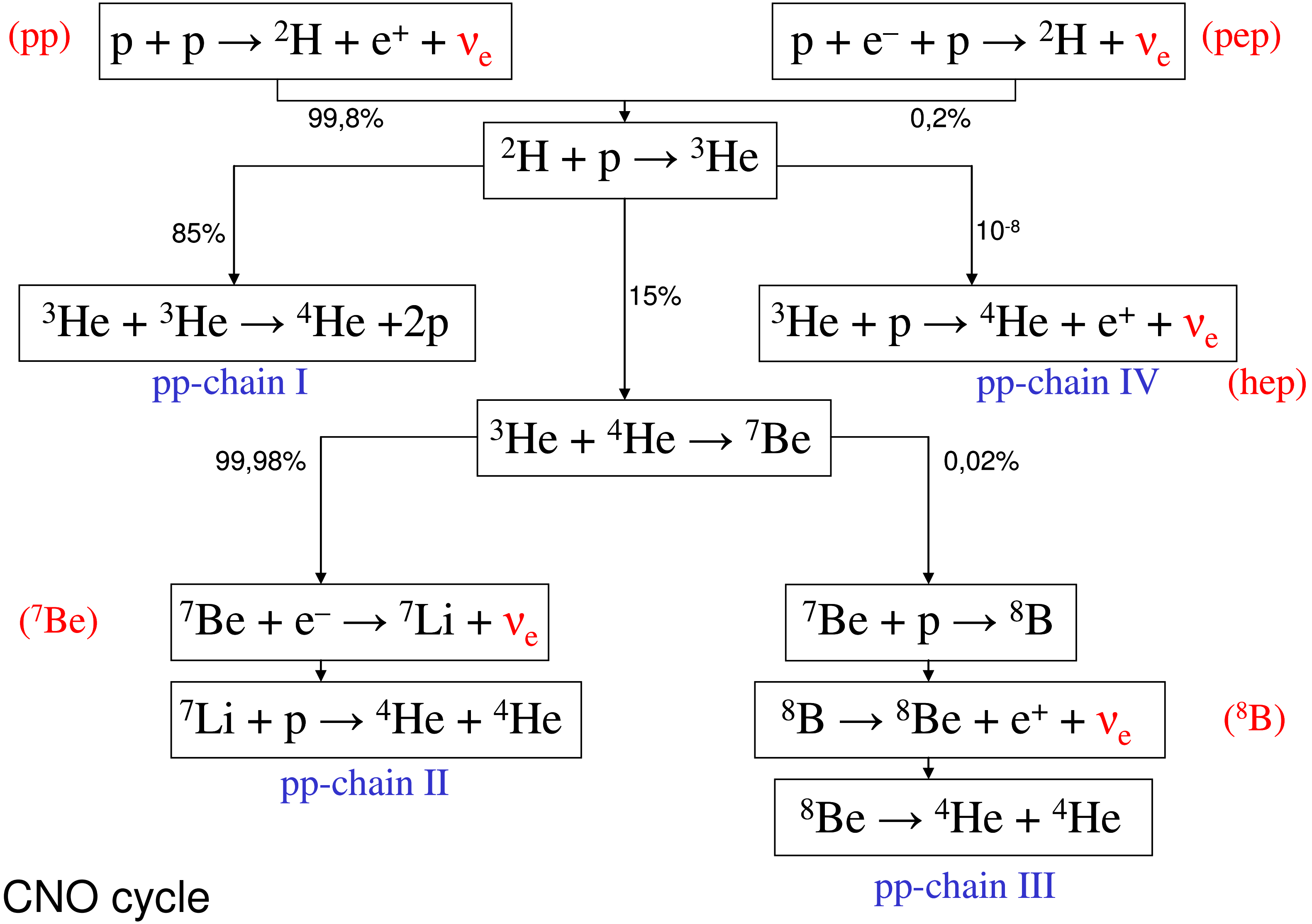
Solar Neutrinos

In the Sun:

$$\boxed{4p \rightarrow {}^4He + 2e^+ + 2\,\nu_e + 26.7\ \mathrm{MeV}}$$

(0.59 MeV in neutrinos)

98% pp-chain:



(pp) $p + p \rightarrow {}^2H + e^+ + \nu_e$

$p + e^- + p \rightarrow {}^2H + \nu_e$ (pep)

99,8%

0,2%

${}^2H + p \rightarrow {}^3He$

85%

15%

10^{-8}

${}^3He + {}^3He \rightarrow {}^4He + 2p$

pp-chain I

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

pp-chain IV (hep)

${}^3He + {}^4He \rightarrow {}^7Be$

99,98%

0,02%

(${}^7Be$) ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

${}^7Li + p \rightarrow {}^4He + {}^4He$

pp-chain II

${}^7Be + p \rightarrow {}^8B$

${}^8B \rightarrow {}^8Be + e^+ + \nu_e$ (${}^8B$)

${}^8Be \rightarrow {}^4He + {}^4He$

pp-chain III

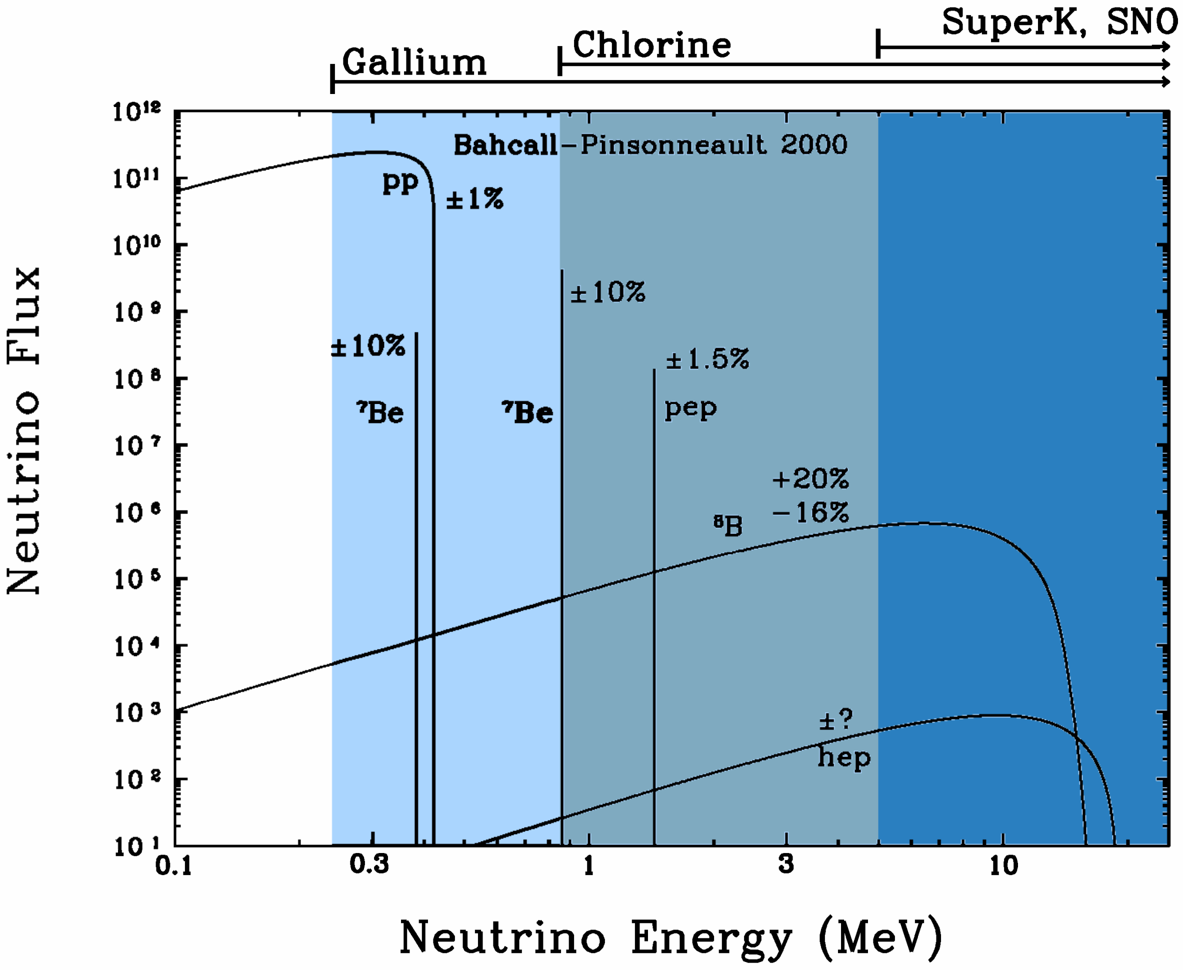
~2% CNO cycle

Solar Neutrinos

In the Sun:

$$\boxed{4p \rightarrow {}^4He + 2e^+ + 2\,\nu_e + 26.7\ \text{MeV}}$$ (0.59 MeV in neutrinos)

Energy spectrum:



neutrino flux on Earth $\Phi_\nu \sim 6.5\ 10^{10}\ \text{cm}^{-2}\ \text{s}^{-1}$ (ca. 90% pp, 7% ^{7}Be, 2% pep, 0.01 % ^{8}B)

$E_\nu < 20$ MeV => no appearance-experiment possible

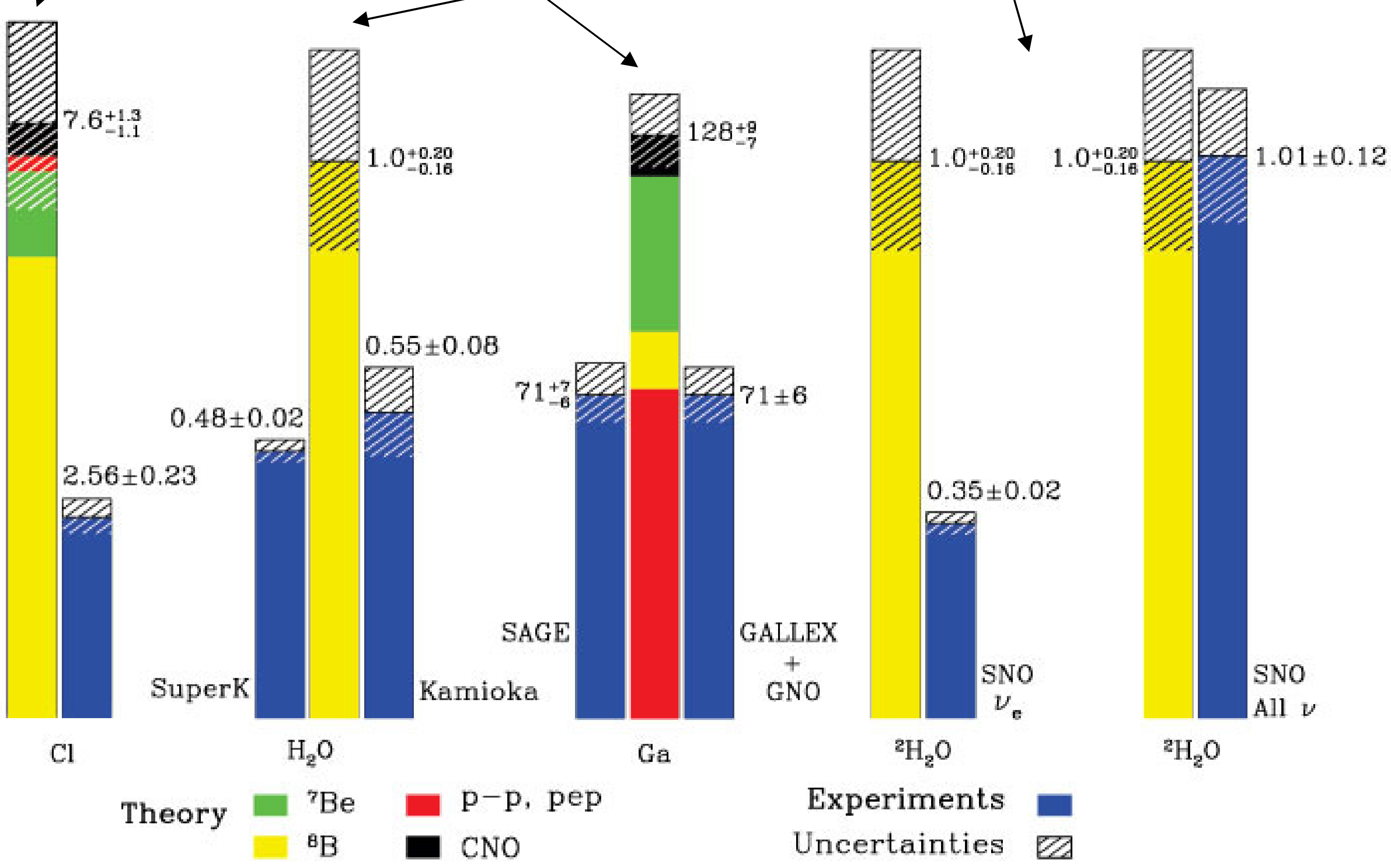
Solar Neutrino - Experiments

Radiochemical Experiments:

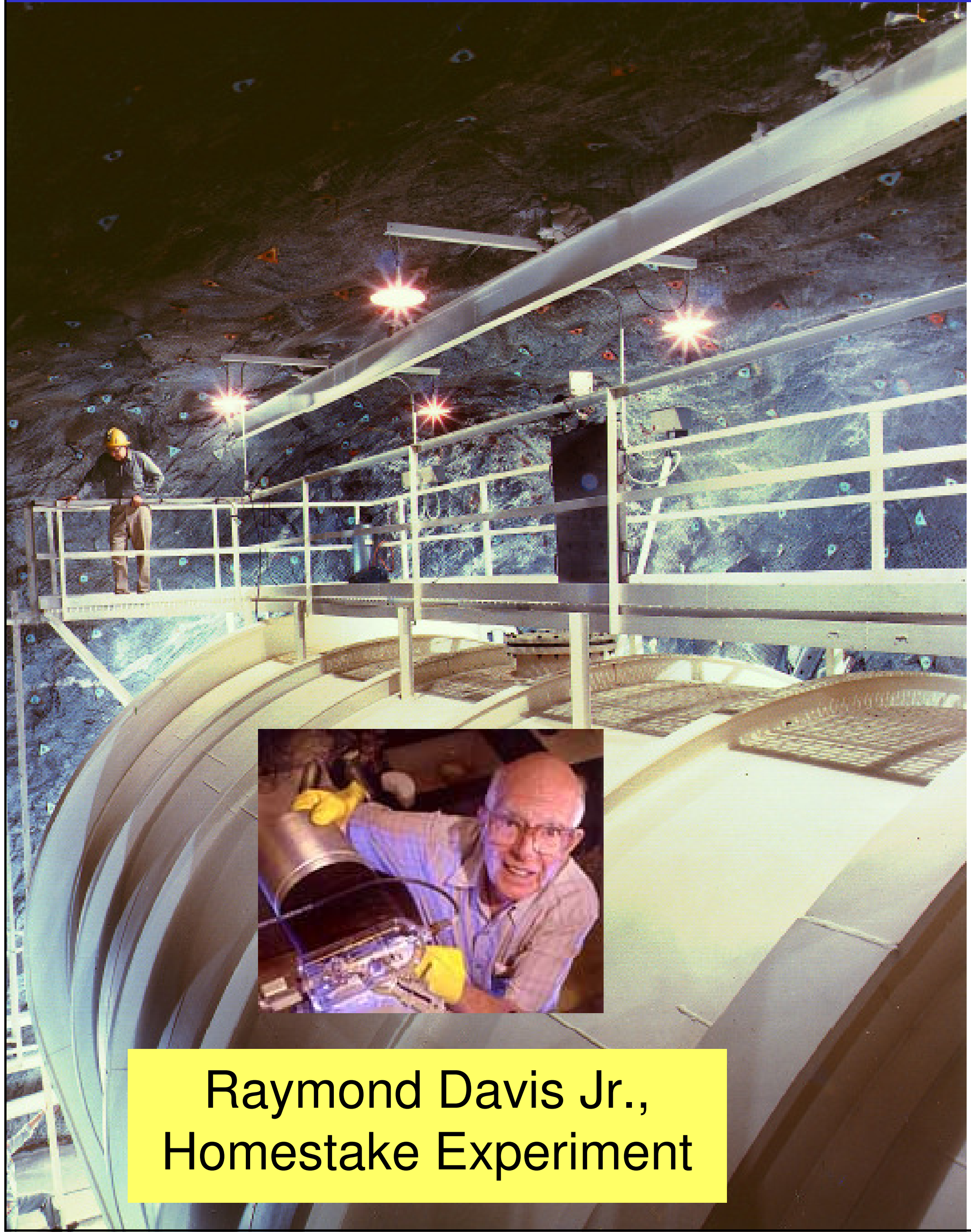
- sensitive only to ν_e
- low energy threshold
- integral flux measurement

Water Cherenkov Detectors:

- real time measurement
- sensitive to ν_e, (ν_μ, ν_τ)
- high energy threshold (only ^{8}B-ν)



The Chlorine Experiment



Raymond Davis Jr.,
Homestake Experiment

“pioneering experiment”

start: 1968

615 t perchloroethylene (C_2Cl_4)

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

$E_\nu > 814$ keV

$t_{1/2}(^{37}\mathrm{Ar}) = 35$ days

more than 25 years of data taking

$$\boxed{R_{exp} = 0.34 \times \mathrm{SSM}}$$

Nobel prize 2002

GNO – The Gallium Neutrino Observatory

Radiochemical Detection:

- Target: 103 t $GaCl_3$ solution
  (~30 t nat. Ga)
- $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

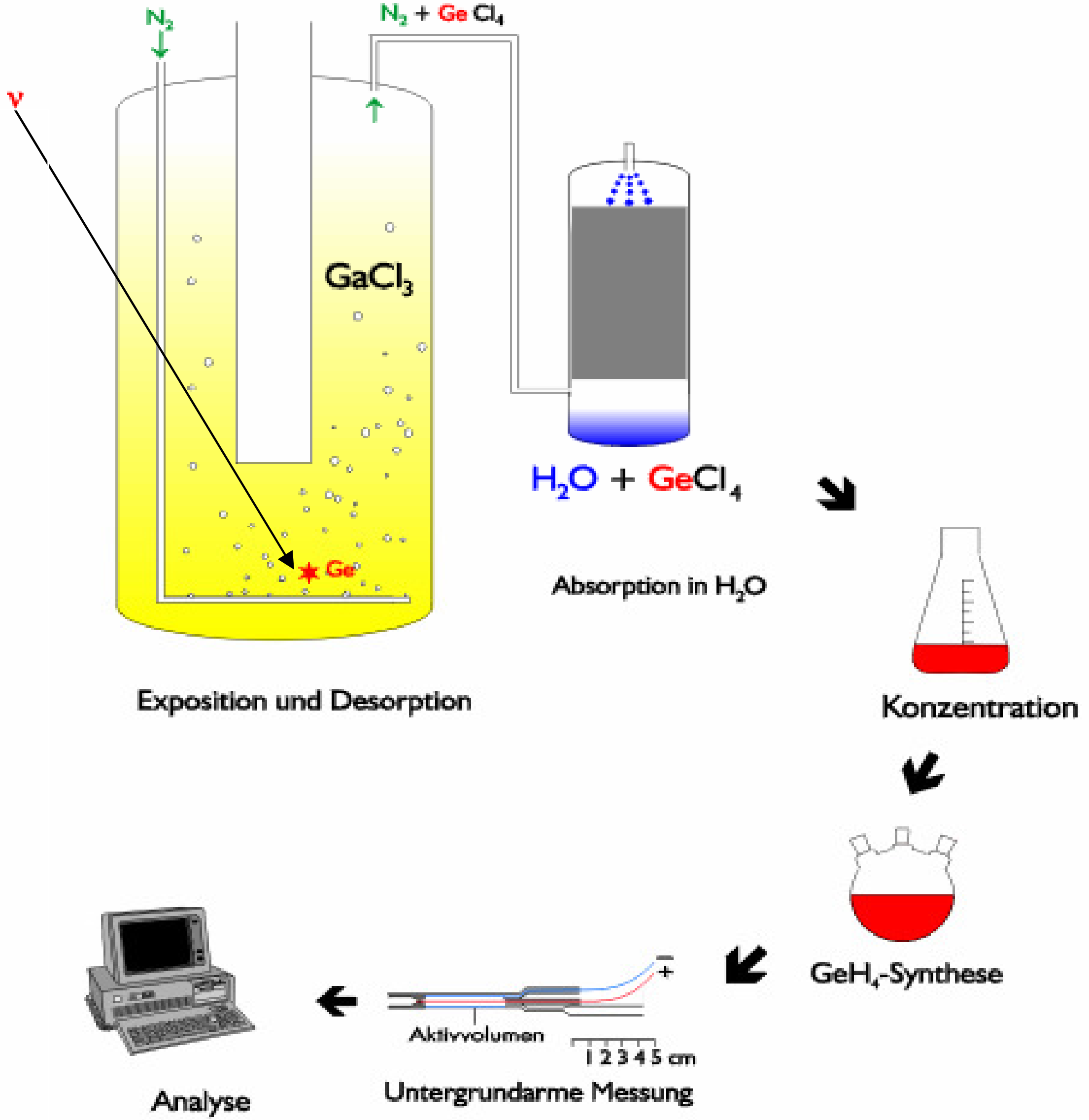
  $E_\nu > 233$ keV

  $T_{1/2}\,(^{71}Ge) = 11.43$ d
- Ge-extraction every ~ 4 weeks
- measure back decay

  $^{71}Ge + e^- \rightarrow {}^{71}Ga^* + \nu_e$

  $^{71}Ga^*$: X-Ray and Auger-e^-
  160 eV to 10 keV

‚A solar run'



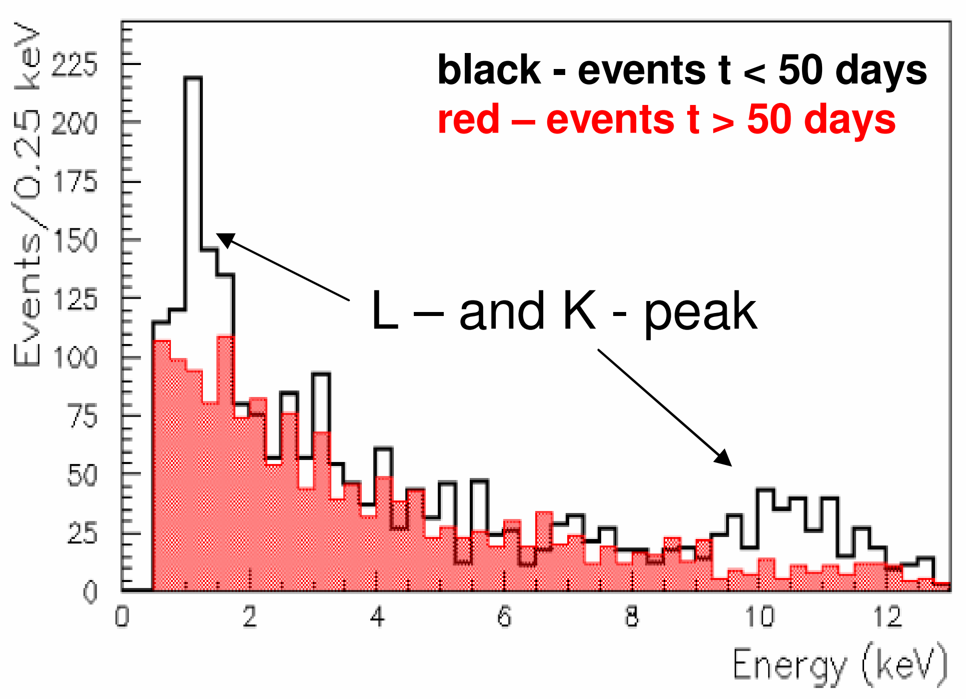
GNO – The Gallium Neutrino Observatory

^{71}Ge + e$^-$ → ^{71}Ga* + ν_e

^{71}Ga*: X-rays and Auger-e$^-$ 160 eV to 10 keV

measured in miniaturized proportional counters (~ 180 days counting time)

Energy spectrum

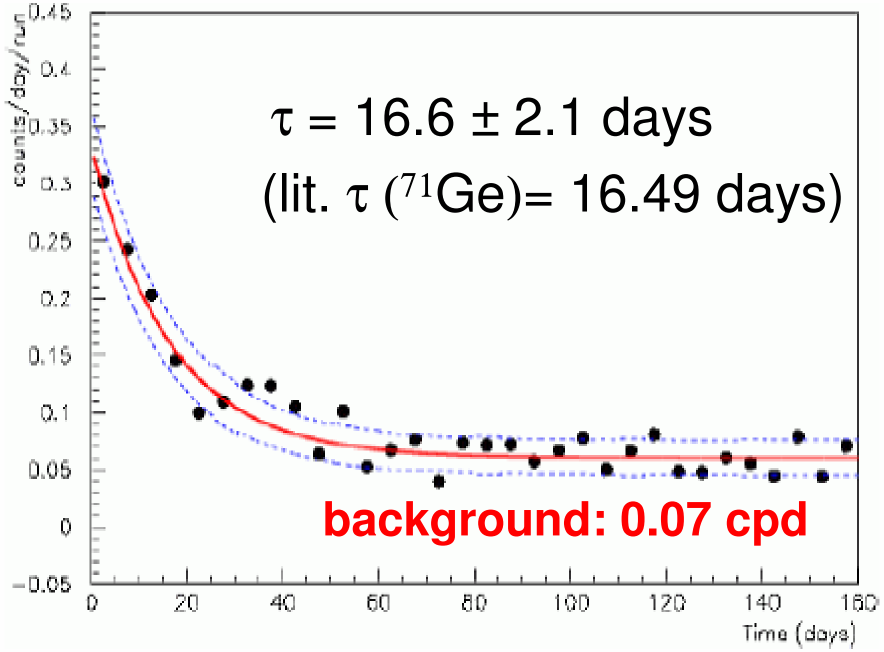


black - events t < 50 days

red – events t > 50 days

L – and K - peak

Time spectrum



τ = 16.6 ± 2.1 days

(lit. τ (^{71}Ge)= 16.49 days)

background: 0.07 cpd

~ 5 events per run

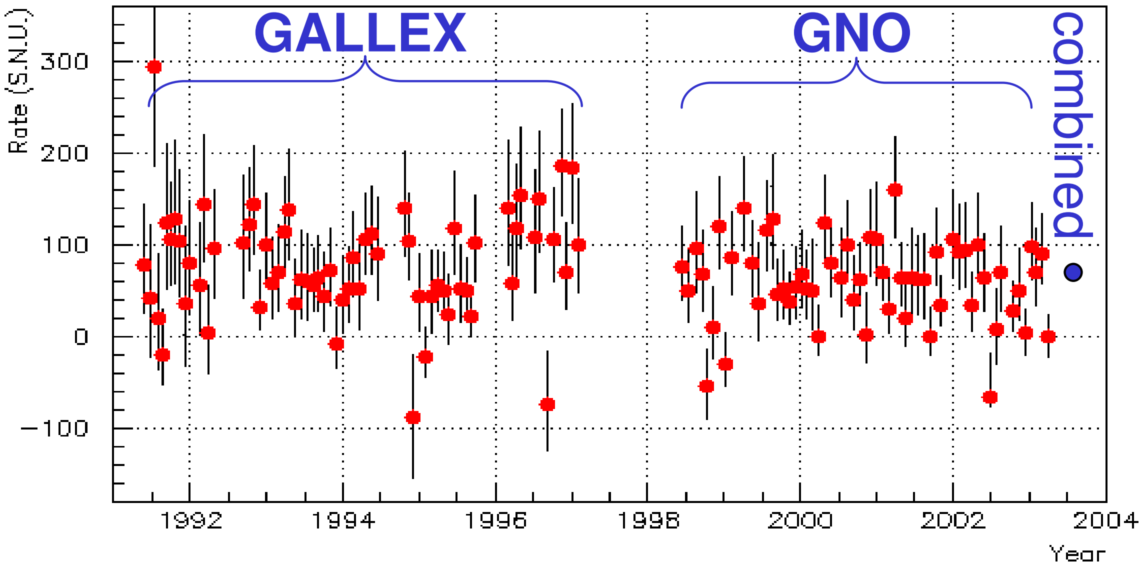
GNO total: 239 solar neutrino events in 1687 days

PL B 616 (2005) 174

GNO - Results

PL B 616 (2005) 174

1991 - 2003



GALLEX: (77.5 ± 6.2 ± 4.5) SNU
(65 runs, 1991-1997)

GNO: (62.9 ± 5.4 ± 2.5) SNU
(58 runs, 1998-2003)

GALLEX+GNO: (69.3 ± 4.1 ± 3.6) SNU
(123 runs)

SSM (BP04): (131± 12) SNU

⇒ overall suppression of the solar ν_e flux

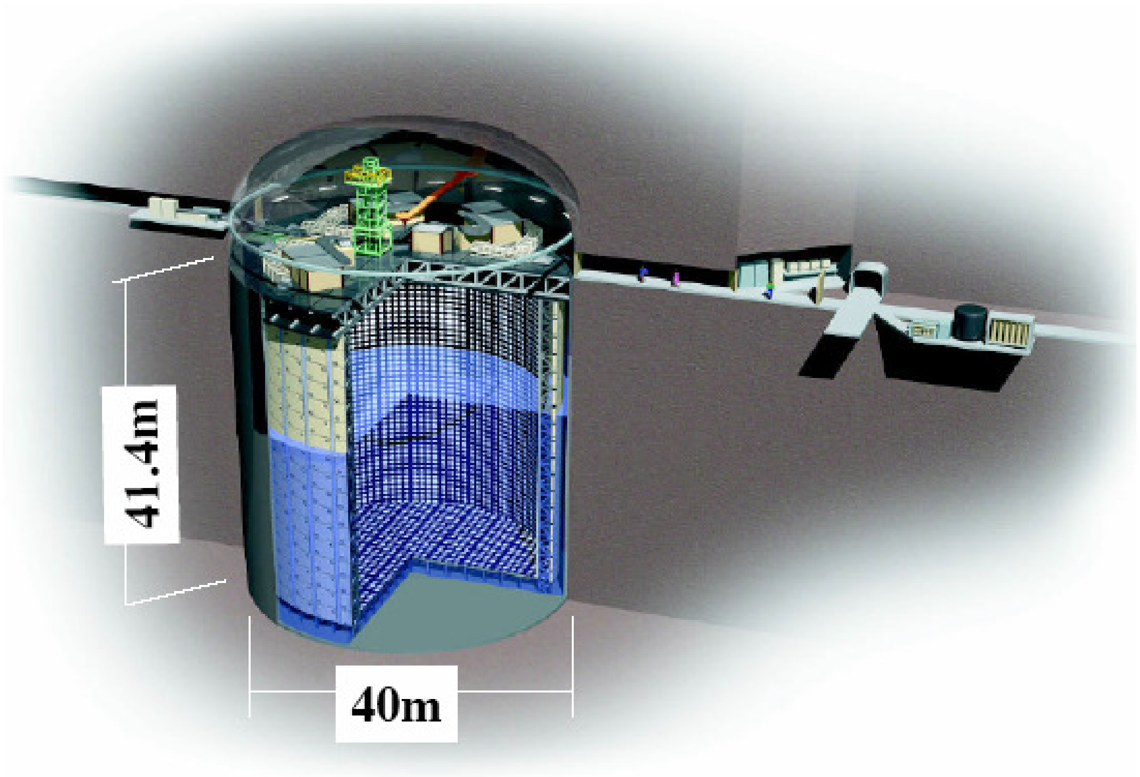
⇒ supression factor for low energy neutrinos (pp and ^{7}Be):
P = 0.556 ± 0.071

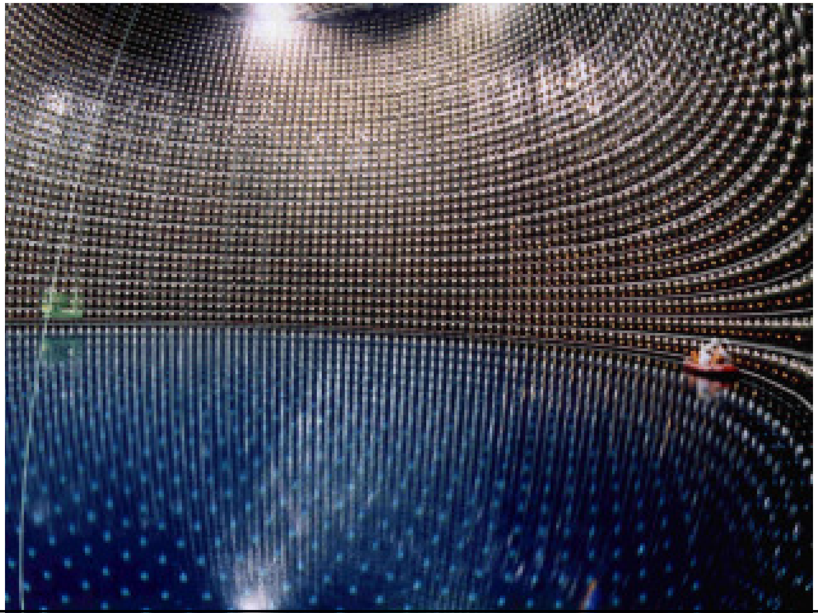
⇒ L(CNO) / L(sun) < 6.5 % (3 σ)
(SSM: 1.6% CNO)

⇒ no evidence for time variations after 1 full solar cycle (11 a)

(1 SNU = 1Solar Neutrino Unit
= 1 neutrino interaction per
10^{36} target atoms per second)

Super-Kamiokande





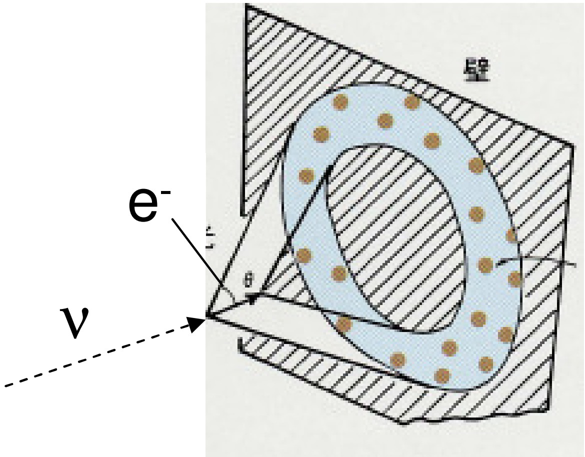
water Cherenkov detector

50000 t H_2O (22500 t fiducial)

11000 PMTs (50 cm diameter)

Location: Kamioka mine, 2700 mwe

neutrino-electron scattering
sensitive to ν_e, (ν_μ, ν_τ)



Cherenkov cone

- ⇒ energy (~7 pe per MeV)
- ⇒ vertex position and time
- ⇒ direction

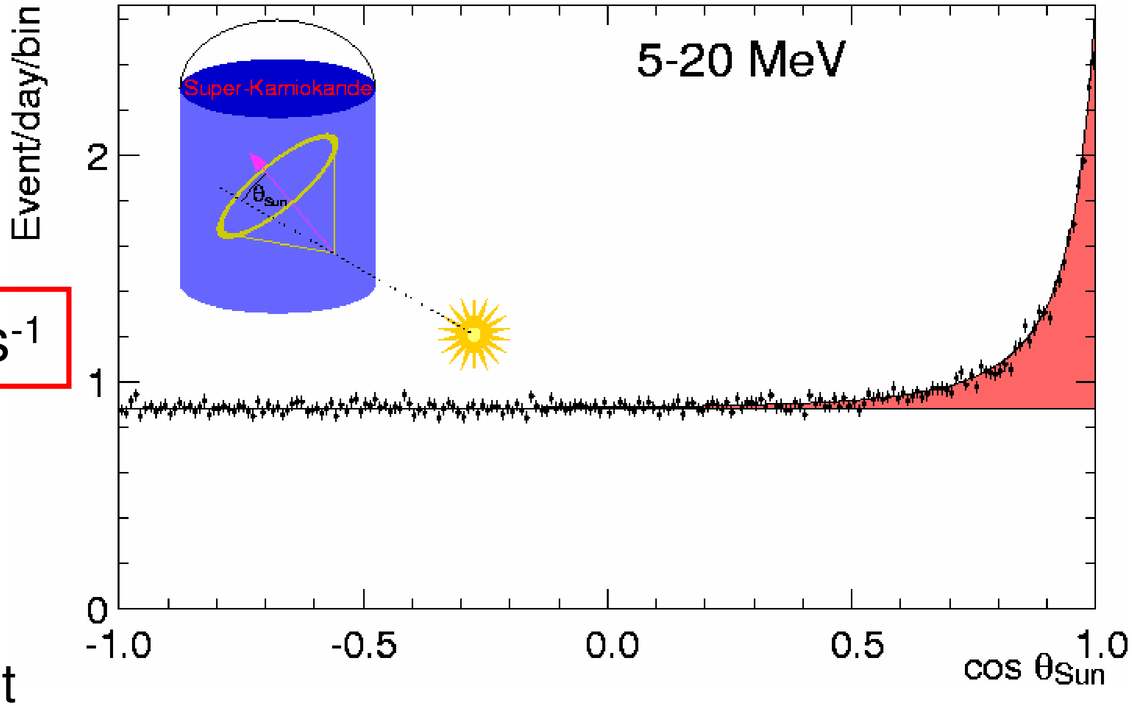
Super-Kamiokande - Results

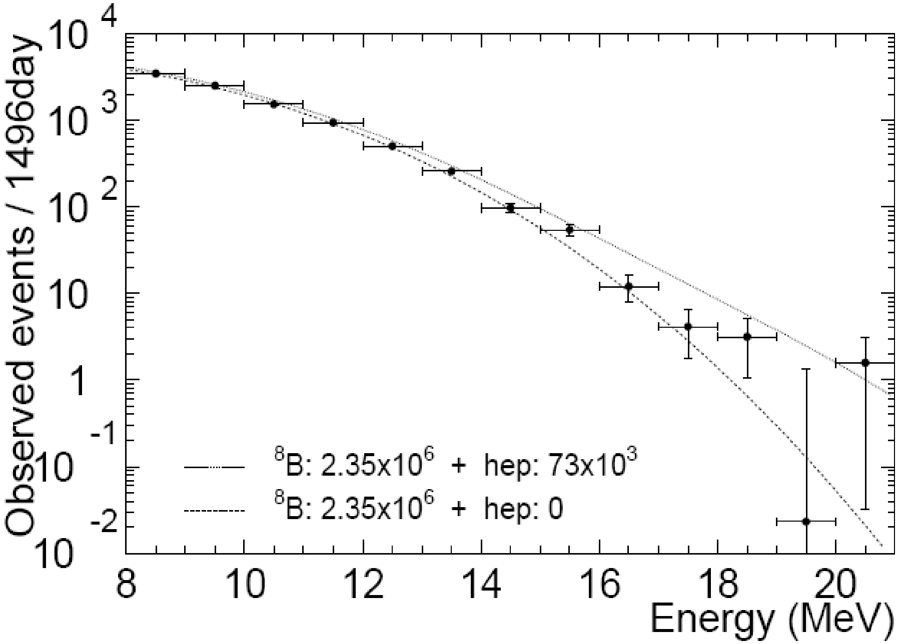
Super-Kamiokande I (1996-2001)
~ 22400 solar neutrino evts
in 1496 days (~ 15 evts per day)

$$\Phi_{8B} = (2.35 \pm 0.02 \pm 0.08)\ 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\Phi_{8B} / \Phi_{SSM} = 0.406$$

- no distortion of energy spectrum
- no significant time variations except seasonal variation
- first observation of the eccentricity of the earth‘s orbit made with neutrinos
- small day/night asymmetry:
  $A_{D/N} = (2.1 \pm 2.0 \pm 1.3)$ %
  consistent with LMA
- limit on hep-ν flux: < 7.3 x $10^4 \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  (SSM: ~ 9 x 10^3 $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)





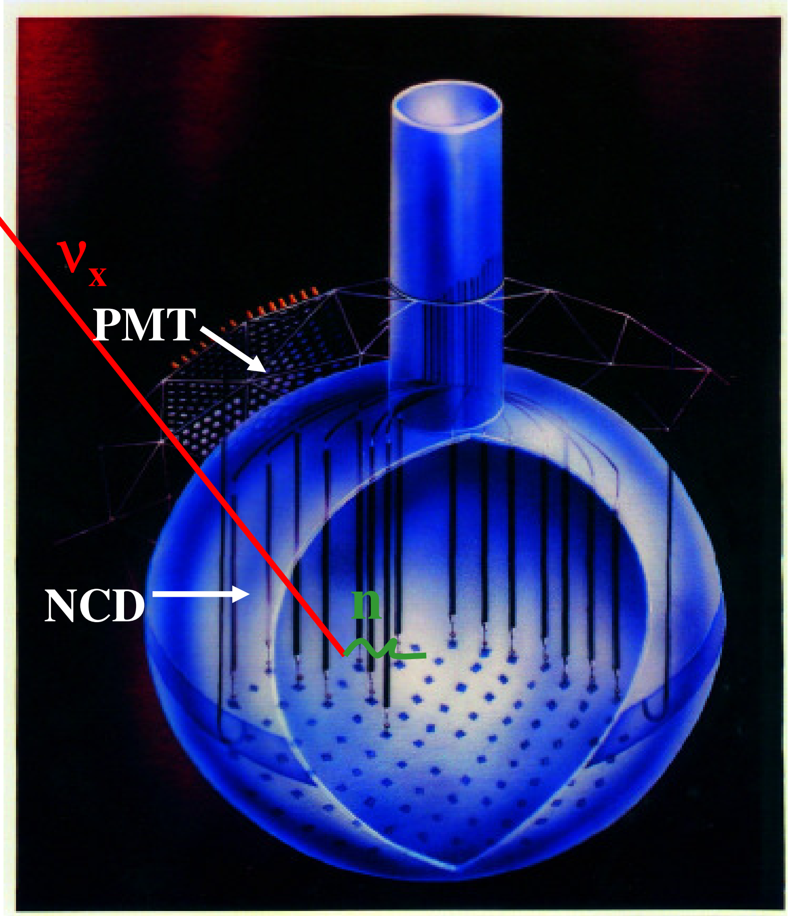
SNO – The Sudbury Neutrino Observatory

Heavy Water-Cherenkov detector (1000 t D_2O, 9500 PMTs, 6000 mwe)

Independent measurement of ν_e and ν_μ, ν_τ

➔ ‚Appearance‘ experiment

CC	$\nu_e + d \rightarrow p + p + e^-$	ν_e
NC	$\nu_x + d \rightarrow p + n + \nu_x$	ν_e, ν_μ, ν_τ
ES	$\nu_x + e^- \rightarrow \nu_x + e^-$	$\nu_e, (\nu_\mu, \nu_\tau)$



Energy threshold ~ 5 MeV => only ^8B neutrinos

Neutron detection for NC reaction:

Phase1: 11/99 - 05/01	$n + d \rightarrow {}^3H + \gamma$ (6.25 MeV)	
Phase2: 07/01 – 09/03	$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma$ (8.6 MeV)	0.25% $MgCl_2$ (2.5 t) higher efficiency
Phase3: 11/04 – 12/06	$n + {}^3He \rightarrow p + {}^3H$	40 He- counters (total of 398 m) event-by-event separation

SNO - Results

Result of 391 days salt-phase (nucl-ex 0502021):

~2500 solar ν detected (~6/day)

$\Phi_{CC} = (1.68 \pm 0.06^{stat} \pm 0.09^{syst})$

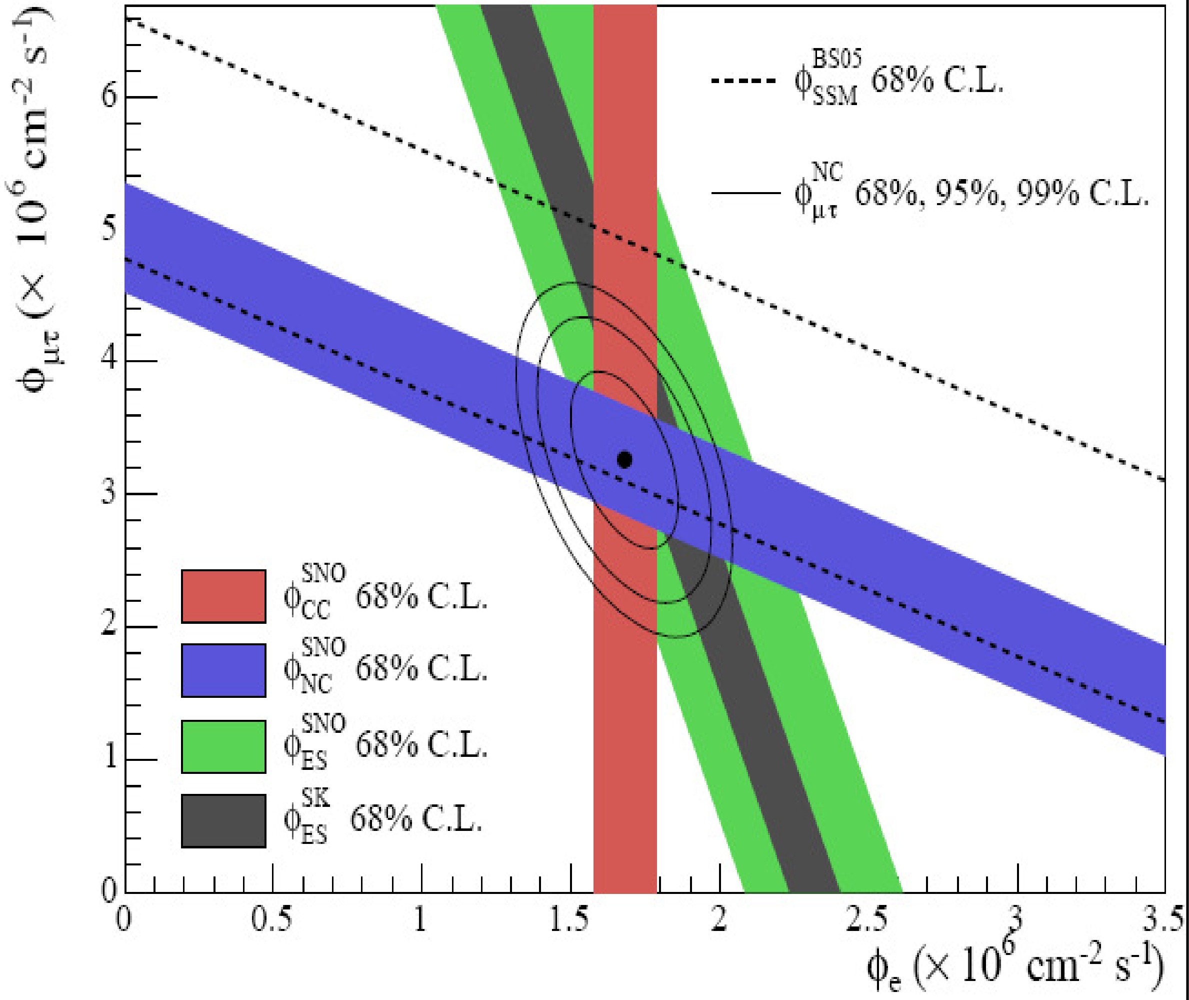
$\Phi_{NC} = (4.94 \pm 0.21 \pm 0.38)$

$\Phi_{ES} = (2.35 \pm 0.22 \pm 0.15)$

in units of $10^6\ cm^{-2}\ s^{-1}$

➔ 2/3 of ^8B neutrinos have changed into μ-/τ neutrinos

➔ neutrino oscillations



best fit: $\Delta m^2 = (8.0 \pm 0.06) \cdot 10^{-5} eV^2$

$\tan^2\theta_{12} = 0.45 \pm 0.09$

LMA (MSW effect)

$$\frac{\Phi_{CC}}{\Phi_{NC}} = 0.34 \pm 0.023^{+0.029}_{-0.031} = cos^4 \Theta_{13}\, sin^2 \Theta_{12}$$

flavour transition proven by more than 7σ

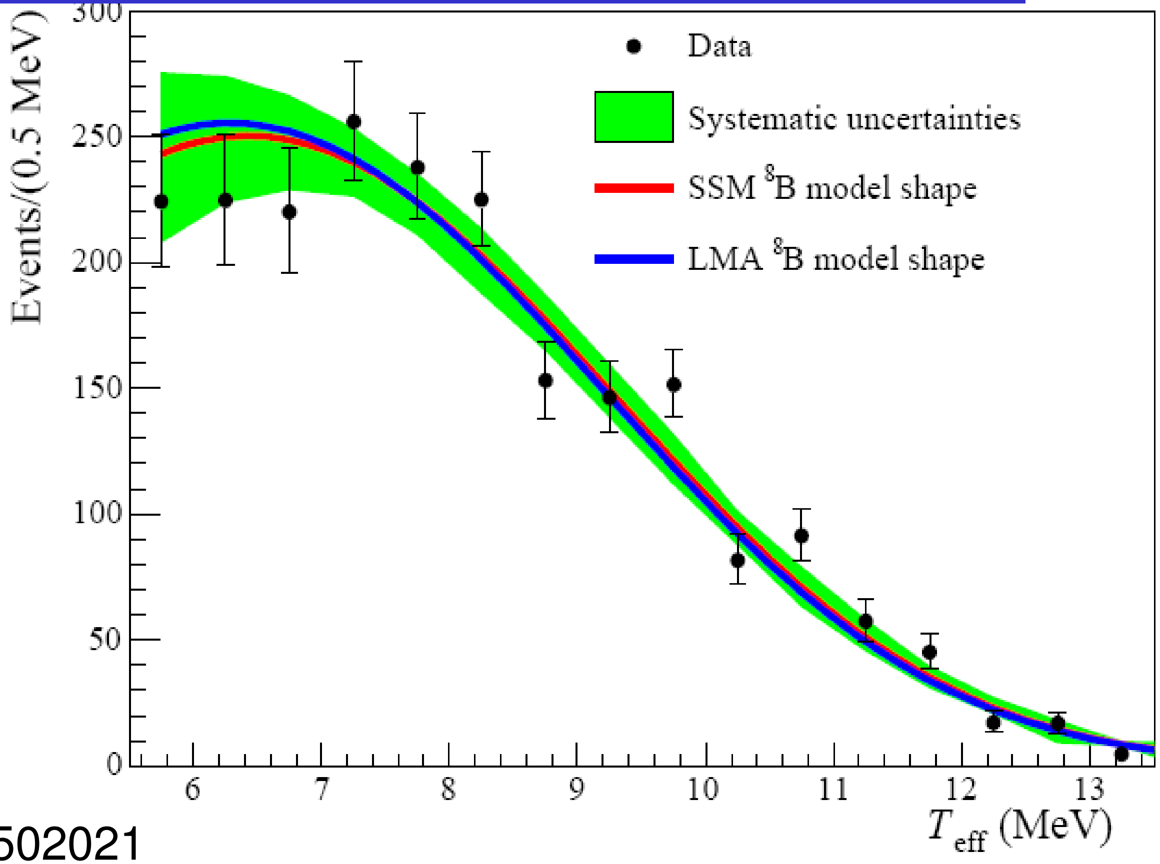
SNO – Results (2)

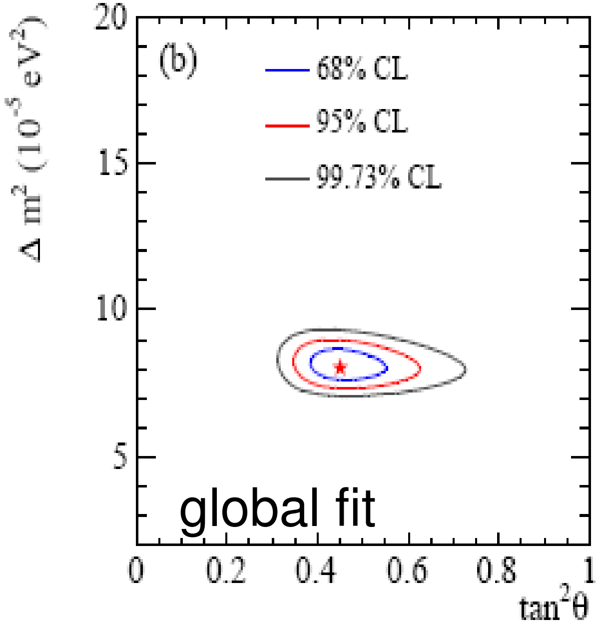
LMA-solution:
very small spectral deformation

no significant day/night asymmetry (~3%)

improved accuracy on Θ_{12}

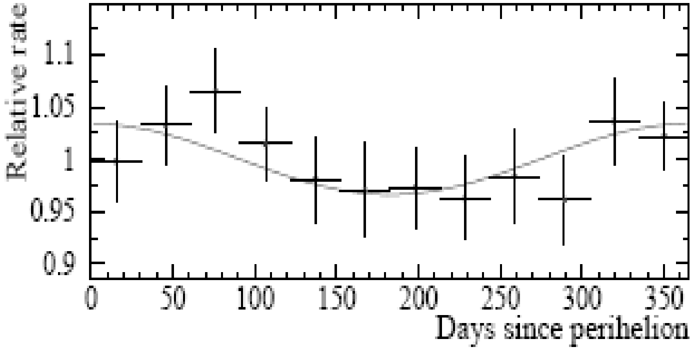
non maximum mixing by 5 σ





nucl-ex 0502021
hep-ex 0507079

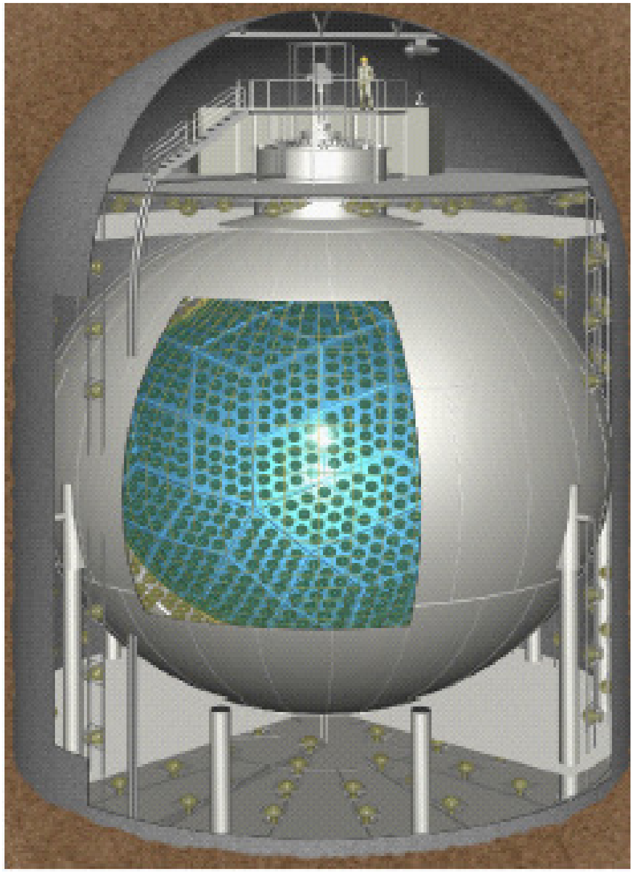
no significant periodicity in the signal found except seasonal variation due to eccentricity of earth's orbit



best fit: $\Delta m^2 = (8.0\pm0.06)\cdot10^{-5}\,\text{eV}^2$
$\tan^2\theta_{12} = 0.45\pm0.09$

KamLAND

Verify LMA solution for solar neutrino oscillations with reactor antineutrinos



Reactor: $\overline{\nu}_e$ source, $\langle E_\nu \rangle \approx 4$ MeV

Solar LMA solution: $\Delta m^2 \sim 7 \cdot 10^{-5}$ eV^2 ➔ $L_{osc}/2 \approx 70$ km

KamLAND:

average distance to reactors $L_0 \sim 180$ km

1000 t liquid scintillator

inverse beta decay (threshold 1.8 MeV)

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$$\hookrightarrow n + p \rightarrow d + \gamma\,(2.2\,\text{MeV})$$

Complementarity:

Solar neutrino experiments

- electron neutrinos
- matter effects dominant (for ^{8}B neutrinos)
- adiabatic conversion

KamLAND

- electron antineutrinos
- vacuum oscillations
- matter effects negligible
- oscillation phase crucial for detected effect

$\Delta m_{21}{}^2$, θ_{12}

Kamland - Results

258 events detected (03/2002 – 01/2004: 766 t y)

365 ± 24 events expected (w/o oscillation)

hep-ex 0406035

18 ± 7 background events

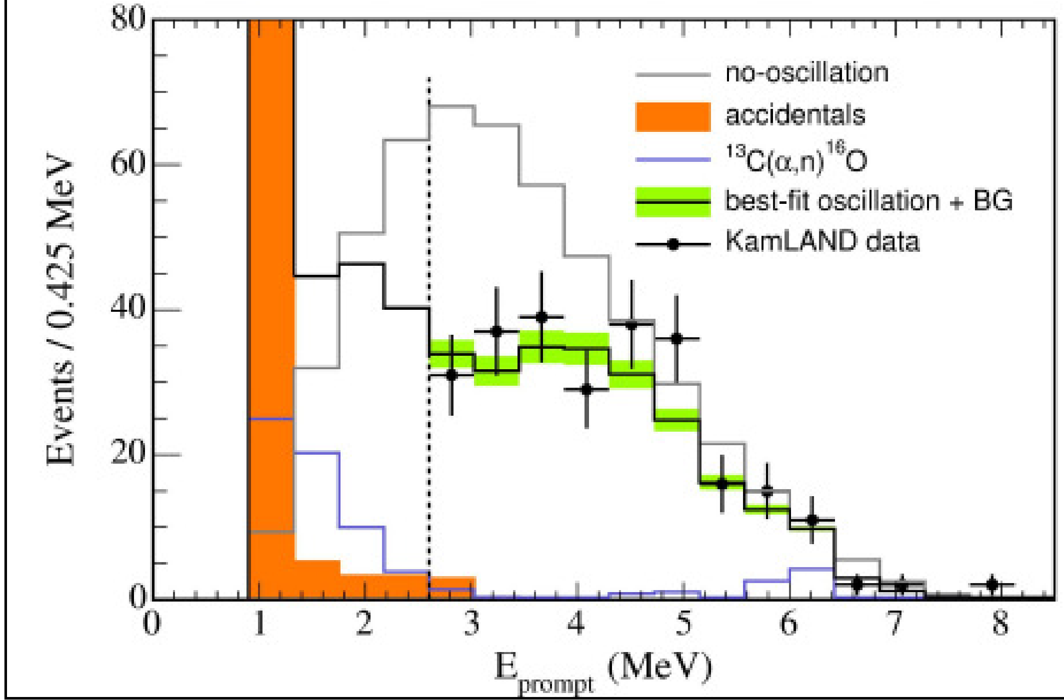
➔ disappearance confirmed @ 99.998% C.L.

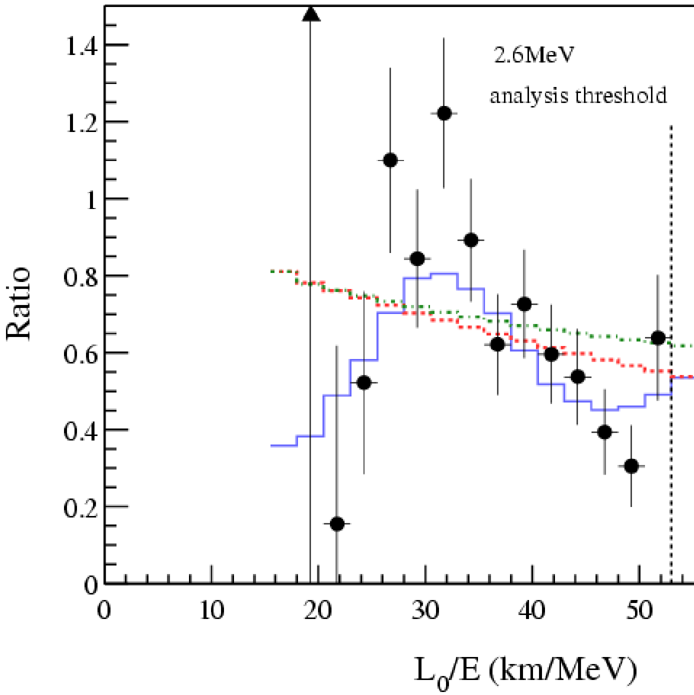
energy spectrum shows deformation

➔ neutrino decay, decoherence excluded (95% C.L. resp. 94% C.L.)

Best Fit KamLAND + solar ν: $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\,\mathrm{eV}^2,\ \tan^2\theta = 0.40^{+0.10}_{-0.07}$

LMA solution confirmed!

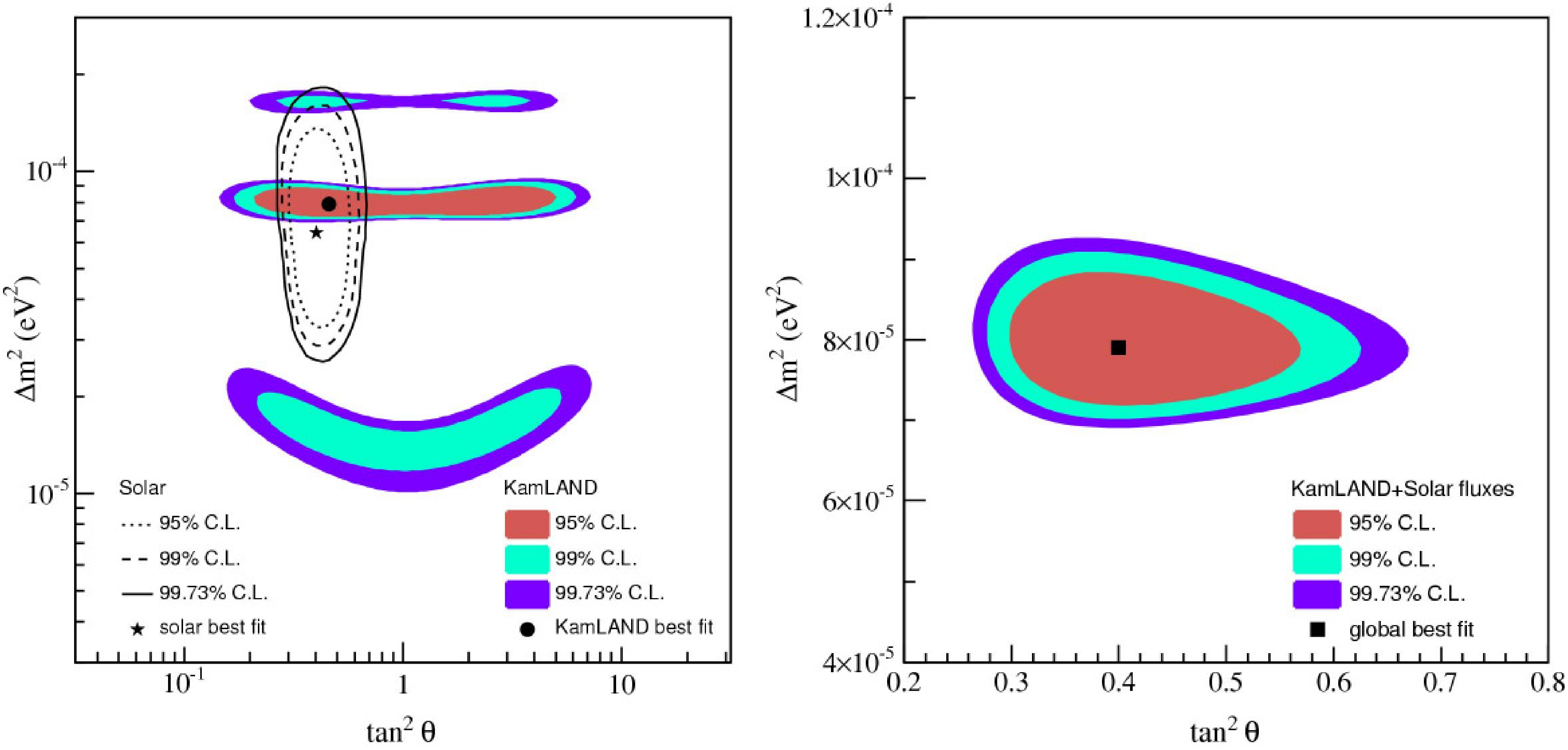




L_0 =180 km

Global Fit: Kamland + Solar Neutrino Experiments

hep-ex 0406035

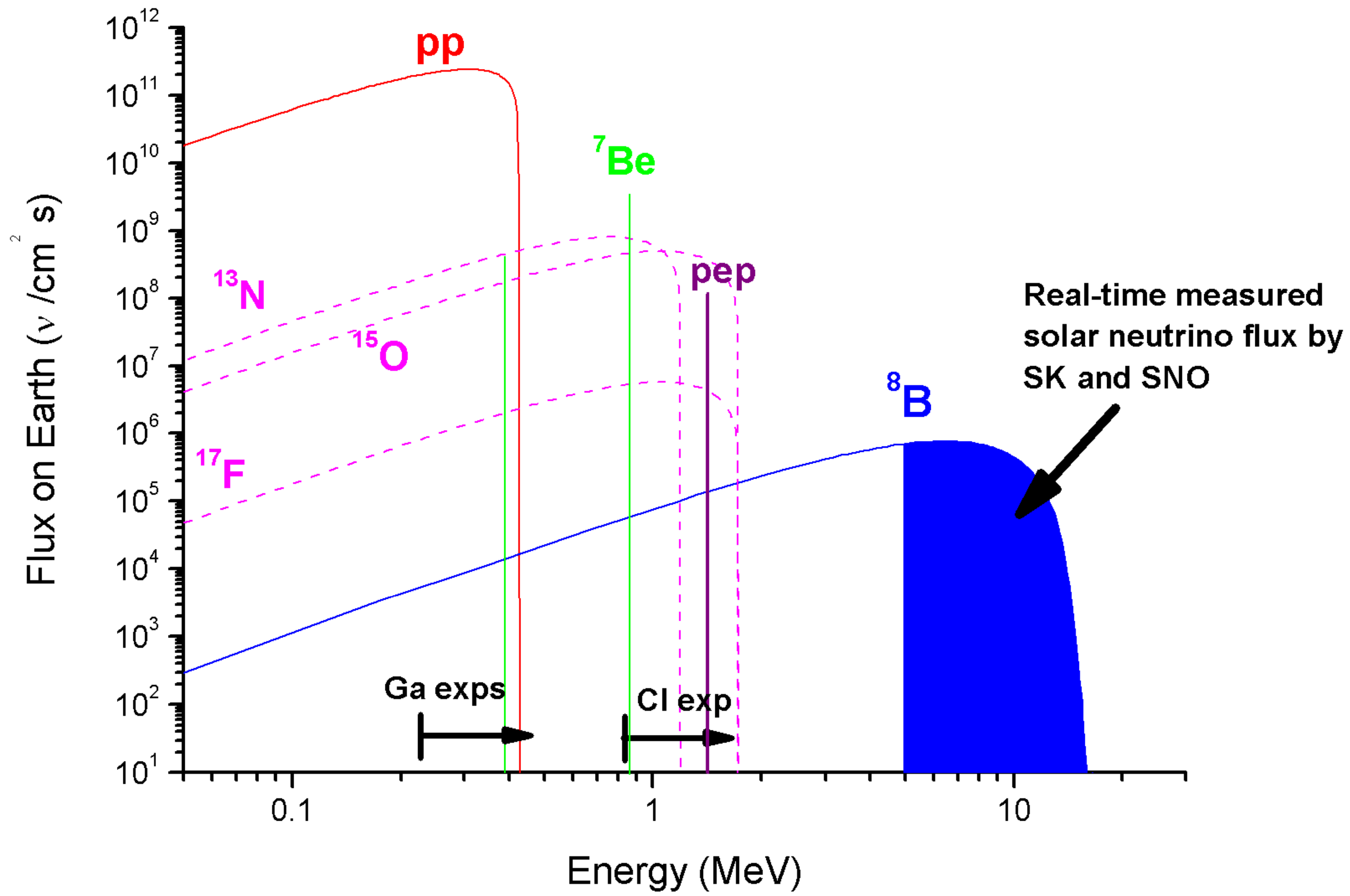


Best Fit KamLAND: $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\,\mathrm{eV}^2$

Best Fit KamLAND + solar ν: $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\,\mathrm{eV}^2, \quad \tan^2\theta = 0.40^{+0.10}_{-0.07}$

Solar neutrinos - Future

99.994% of solar neutrino spectrum is NOT measured yet in real-time mode



SSM: Bahcall Serenelli 2005

Solar Neutrinos: Future

Goal: low energy neutrino spectroscopy: ^{7}Be, pep, CNO, pp

- test transition MSW- to vacuum oscillations
- precision measurement θ_{12}, Δm_{21}^2
- test solar models:

$\Phi_B/\Phi_{SSM} = 0.87\,(1.0 \pm 0.05^{exp} \pm 0.23^{theo})$

$\Phi_{pp}/\Phi_{SSM} = 1.01\,(1.0 \pm 0.02 \pm 0.01)$

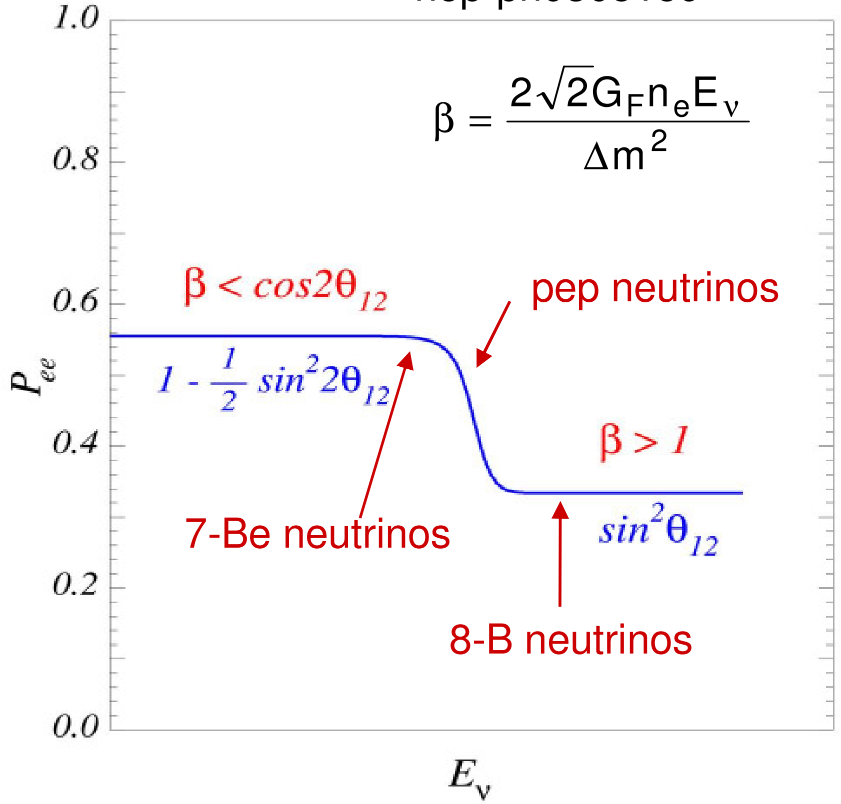
$\Phi_{Be}/\Phi_{SSM} = 1.03\,(1.0^{+0.23}_{-1.0} \pm 0.12)$

$L_{CNO} = (0.0^{+2.7}_{-0.0})\% \quad (L_{SSM} = 1.6\%)$

$L_\nu / L_\gamma = 1.4^{+0.2}_{-0.3}$

(hep-ph 0406294)

Bahcall, Pena-Garay
hep-ph0305159



- a 10% measurement of ^{7}Be yields pp-flux with <1% uncertainty
- determination of pp, pep gives solar luminosity (in neutrinos)
- CNO: important for heavy stars

Future Experiments

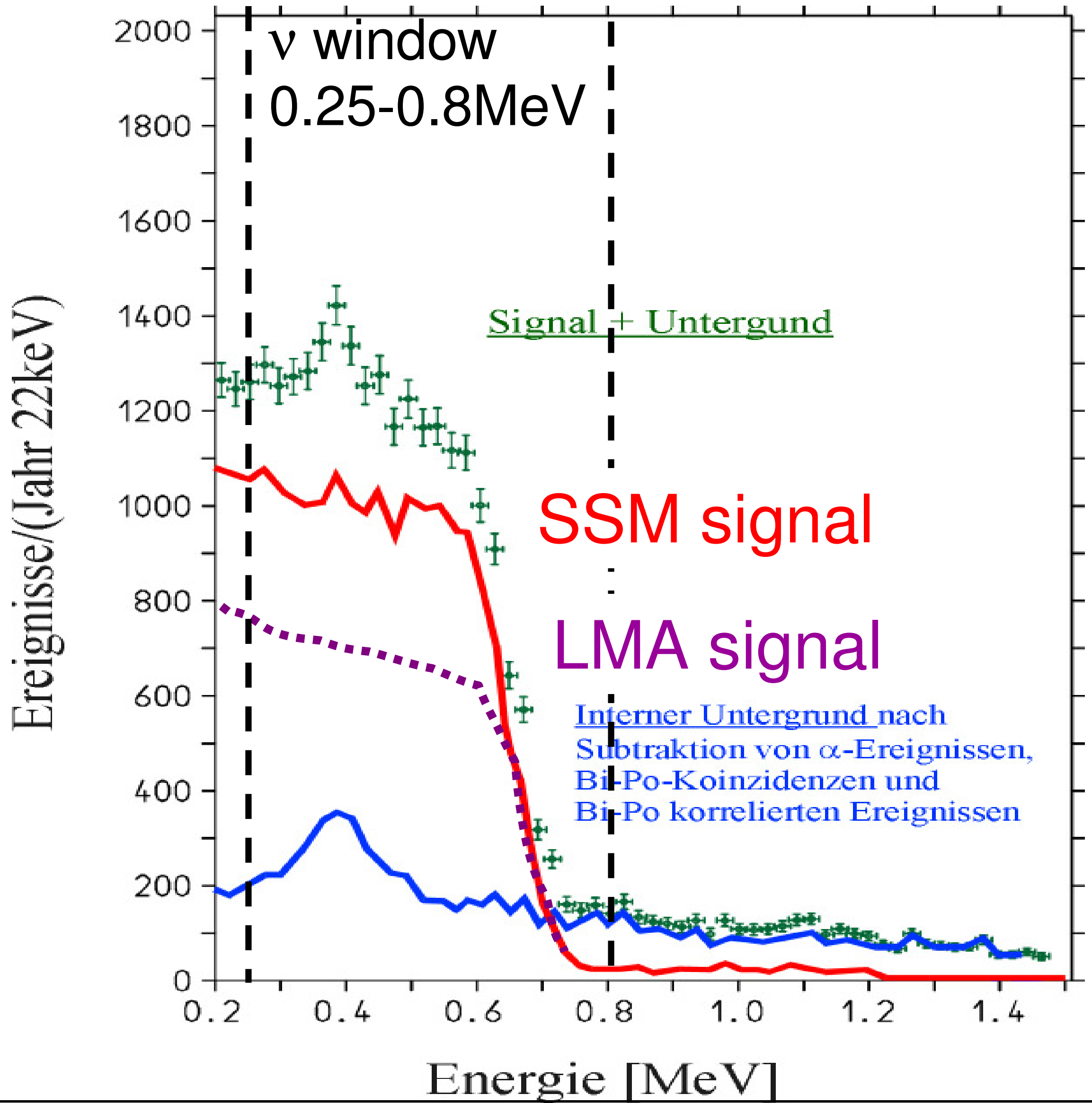
experiment	reaction	detector
LENS	$\nu_e\,{}^{115}\mathrm{In} \rightarrow e^{-}\,{}^{115}\mathrm{Sn}, e, \gamma$	60 tons In-loaded scintillator
MOON	$\nu_e\,{}^{100}\mathrm{Mo} \rightarrow e^{-}\,{}^{100}\mathrm{Tc}(\beta)$	3.3 ton ^{100}Mo foil + plastic scintillator
Lithium	$\nu_e\,{}^{7}\mathrm{Li} \rightarrow e^{-}\,{}^{7}\mathrm{Be}$	Radiochemical, 10 ton lithium
BOREXINO*	$\nu e^{-} \rightarrow \nu e^{-}$	100 ton Liquid scintillator (^{7}Be only)
KAMLAND *	$\nu e^{-} \rightarrow \nu e^{-}$	1000 ton Liquid scintillator (^{7}Be only)
XMASS	$\nu e^{-} \rightarrow \nu e^{-}$	10 ton Liquid Xe (pp, ^{7}Be)
HERON	$\nu e^{-} \rightarrow \nu e^{-}$	10 ton super-fluid He (pp, ^{7}Be)
CLEAN	$\nu e^{-} \rightarrow \nu e^{-}$	10 ton Liquid Ne (pp, ^{7}Be)
TPC type	$\nu e^{-} \rightarrow \nu e^{-}$	Tracking electron in gas target (pp, ^{7}Be)
SNO+ (Liq.scint.)	$\nu e^{-} \rightarrow \nu e^{-}$	1000 ton Liquid scintillator (pep, CNO)

🟨 CC exp. (ν_e only) 🟩 νe scattering exp. ($\nu_e + \alpha(\nu_\mu + \nu_\tau)$)

Borexino @ Gran Sasso

Goals:

- ^{7}Be solar neutrino measurement ~ 35 ev/day



Borexino @ Gran Sasso

Goals:

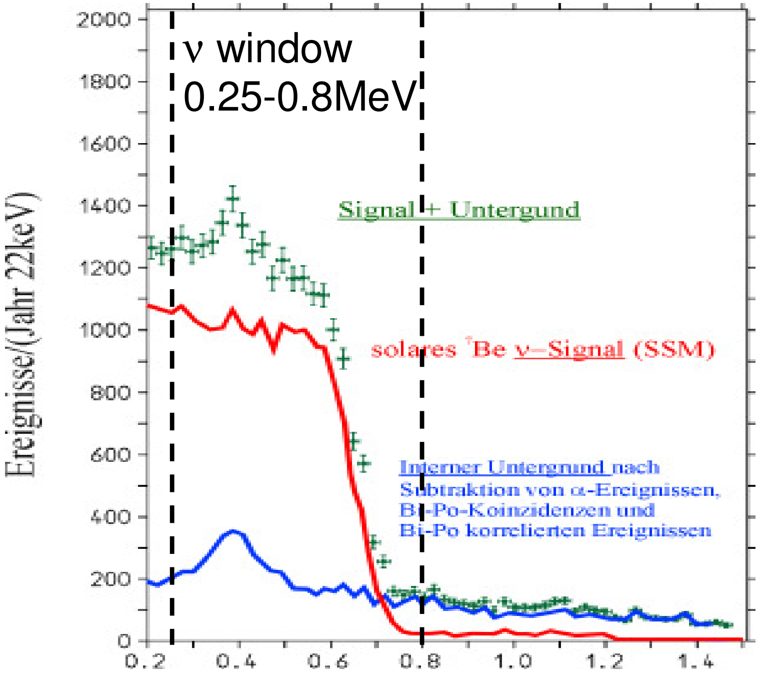
- ^{7}Be solar neutrino measurement — 35 ev/day
- CNO and pep neutrinos — 1-2 ev/day

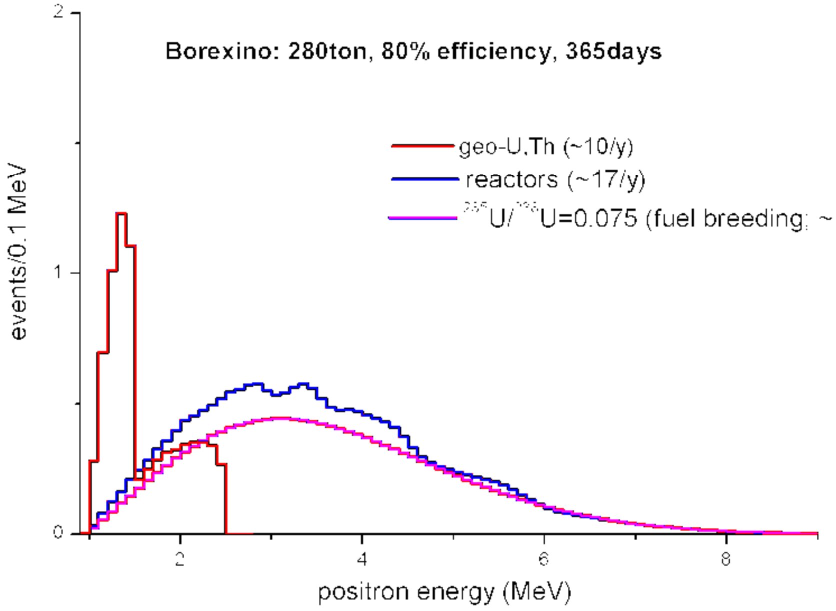
}ν-e$^-$ scattering

- Long baseline reactor neutrinos — 20 ev/year
- Terrestrial neutrinos — 10-30 ev/y

}inverse beta decay

- Supernova neutrinos — ~ 100 ev for SN in 10kpc
- Search for neutrino magnetic moment with an artificial ν source

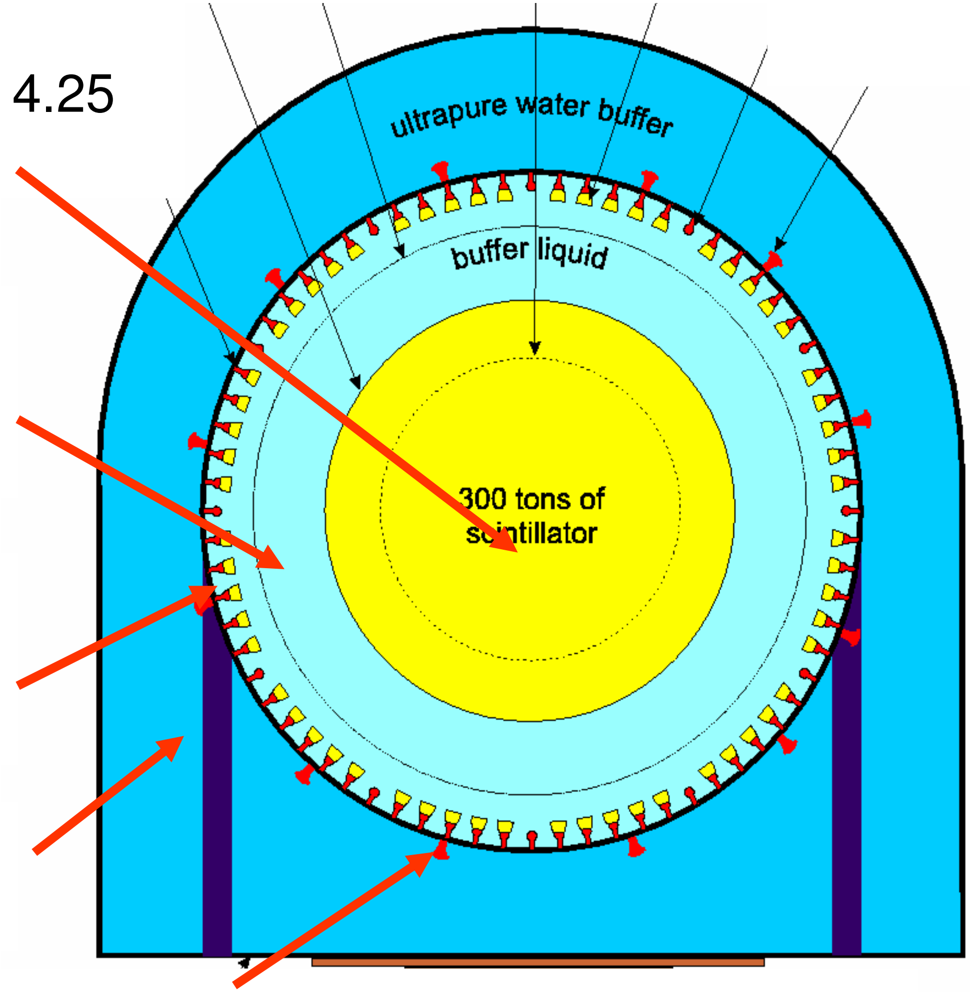




The Borexino Detector

Location: Gran Sasso Underground Laboratory, Italy

3600 mwe (residual muon flux = 1 μ /m² hour)



Core of the detector: 300 tons of liquid scintillator contained in a nylon vessel of 4.25 m radius (PC+PPO)

1st shield: 1000 tons of ultra-pure buffer liquid (pure PC) contained in a stainless steel sphere of 7 m radius

2214 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator

2nd shield: 2000 tons of ultra-pure water contained in a 18 m Ø cylindrical dome

200 PMTs mounted on the SSS pointing outwards to detect light emitted in the water by muons crossing the detector

Radiopurity constraints

- Neutrino-electron-scattering of ^{7}Be-neutrinos in liquid scintillator:

  continuous recoil energy spectrum up to ~ 700 keV, no special event signature

  => high radiopurity levels required

- Intrinsic contamination of the scintillator:

  U and Th $< 10^{-16}$ g/g; ^{40}K $< 10^{-14}$ g/g; $^{14}C\,/^{12}C < 10^{-18}$

- Contamination of the nylon vessel: U and Th $< 10^{-12}$ g/g;

- Constraints on N_2 used to sparge scintillator:

  Kr <0.14 ppt (0.2 μBq $^{85}Kr/m^3\ N_2$)

  Ar < 0.36 ppm (0.5 mBq $^{39}Ar/m^3\ N_2$)

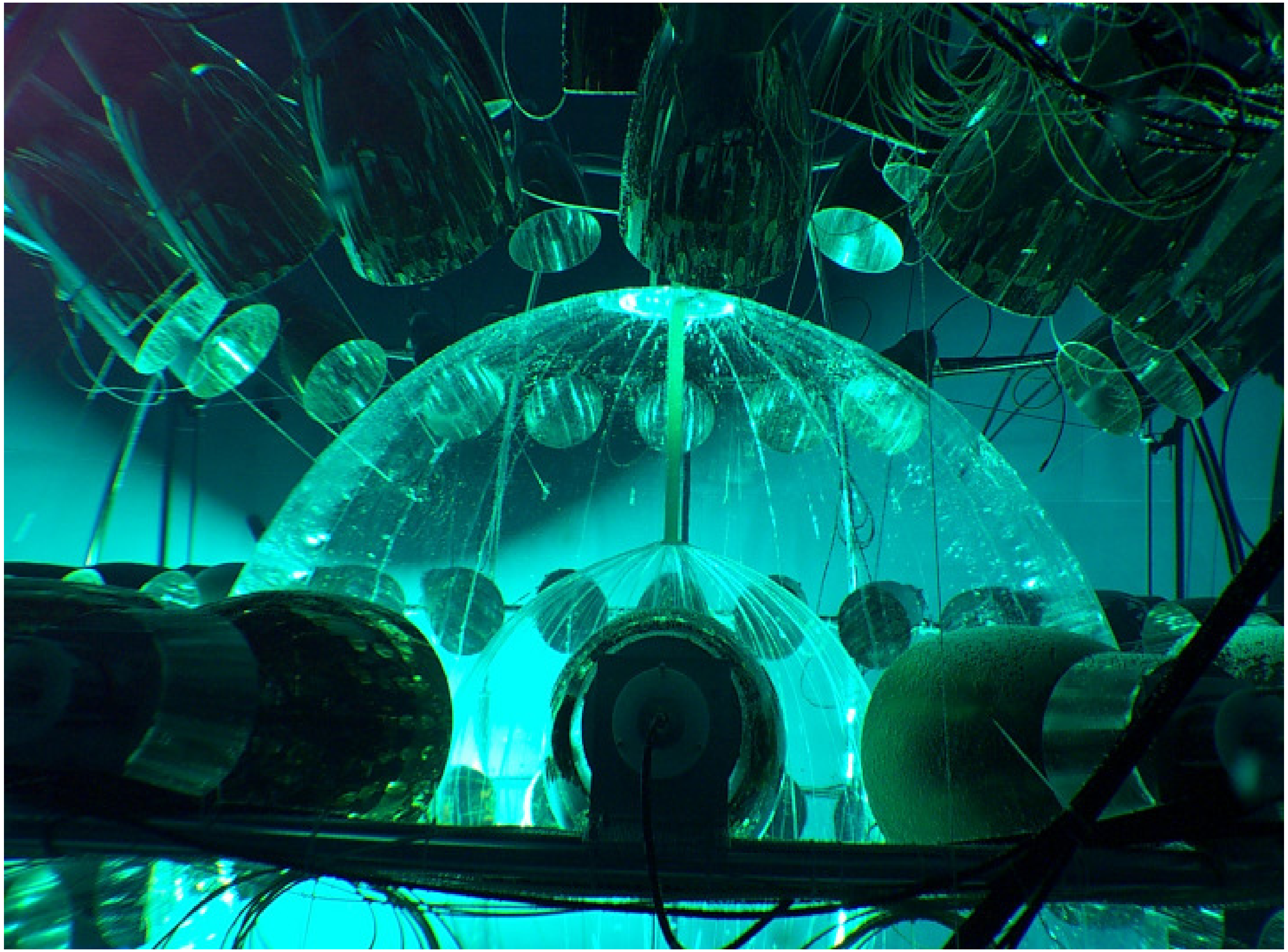
- Contamination of the buffer liquid: U and Th $< 10^{-14}$ g/g

- Contamination of the external water: U and Th $< 10^{-10}$ g/g

Each of these points required careful selection and clean handling of materials, + implementation of sophisticated purification techniques

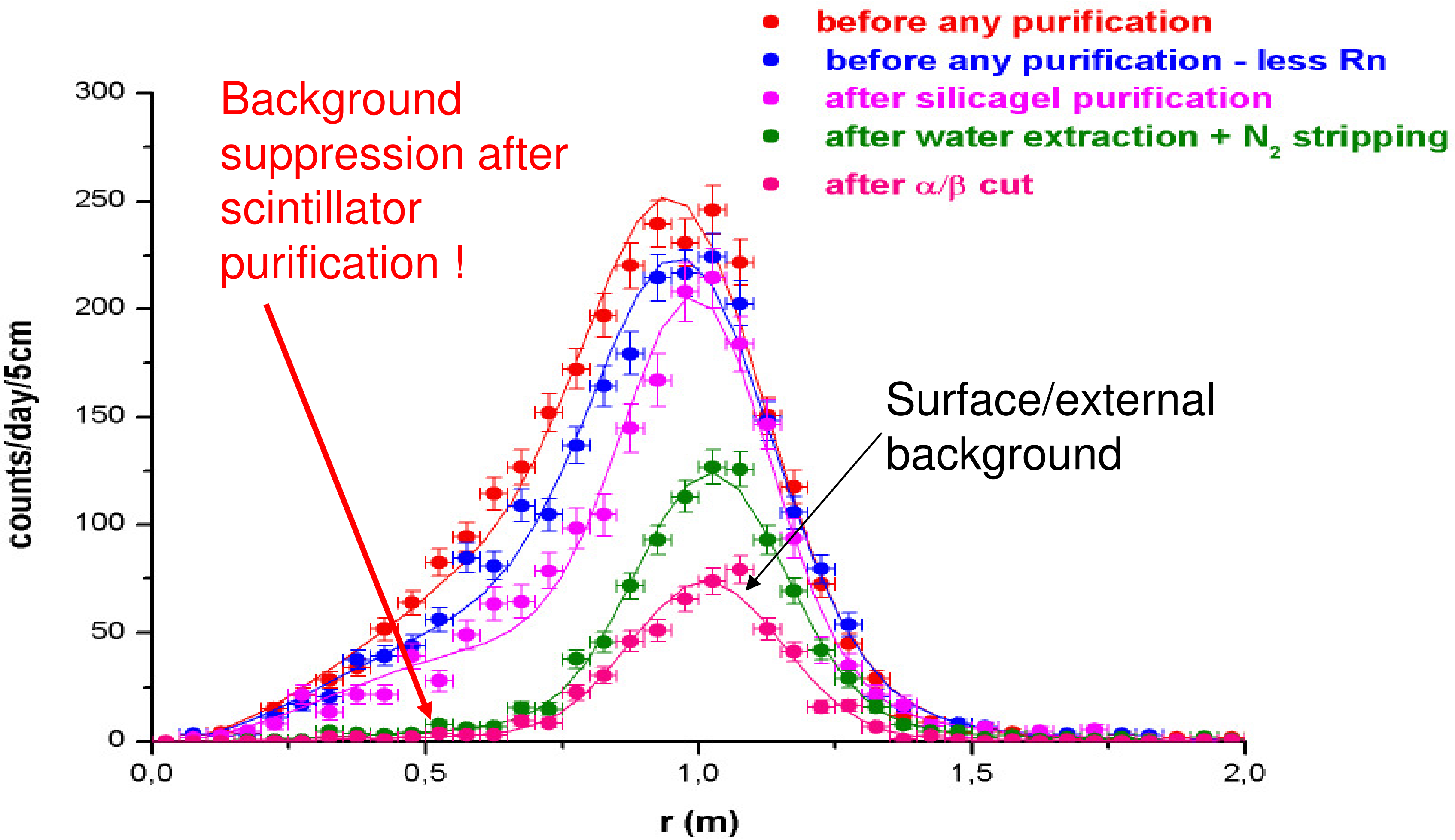
Borexino

Tests of scintillator purification (Si-gel, H_2O extraction, distillation) with the CTF (prototype of Borexino: 4 t scint., 100 PMTs, 1000 t H_2O)



CTF - Result on Background

Radial distribution CTF events (0.2 < E / MeV < 0.8) :



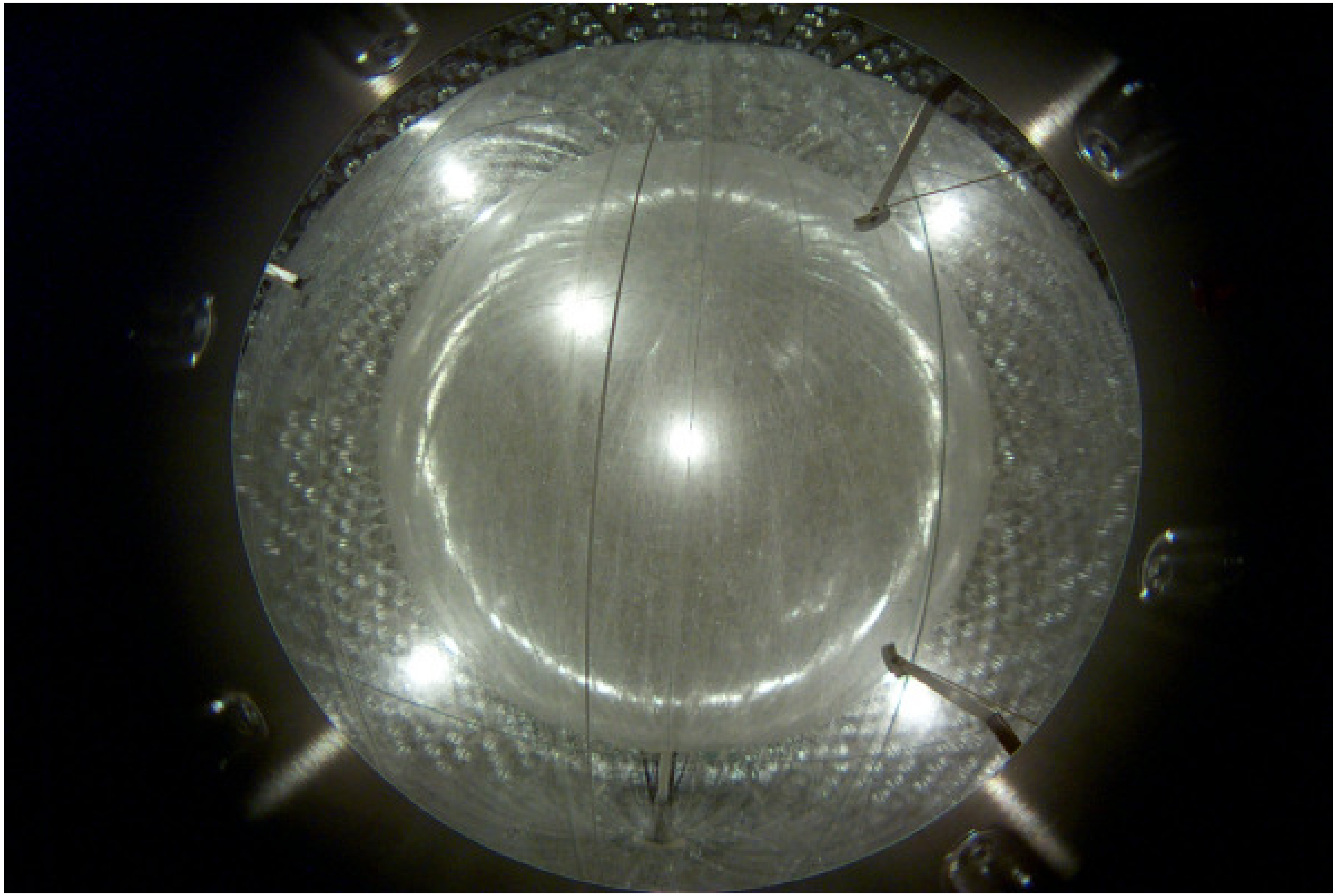
Background suppression after scintillator purification !

Surface/external background

Remaining problem: ^{210}Pb, reduction factor to achieve ~ 10

Borexino - Schedule

Inner Vessel installation completed in 2004



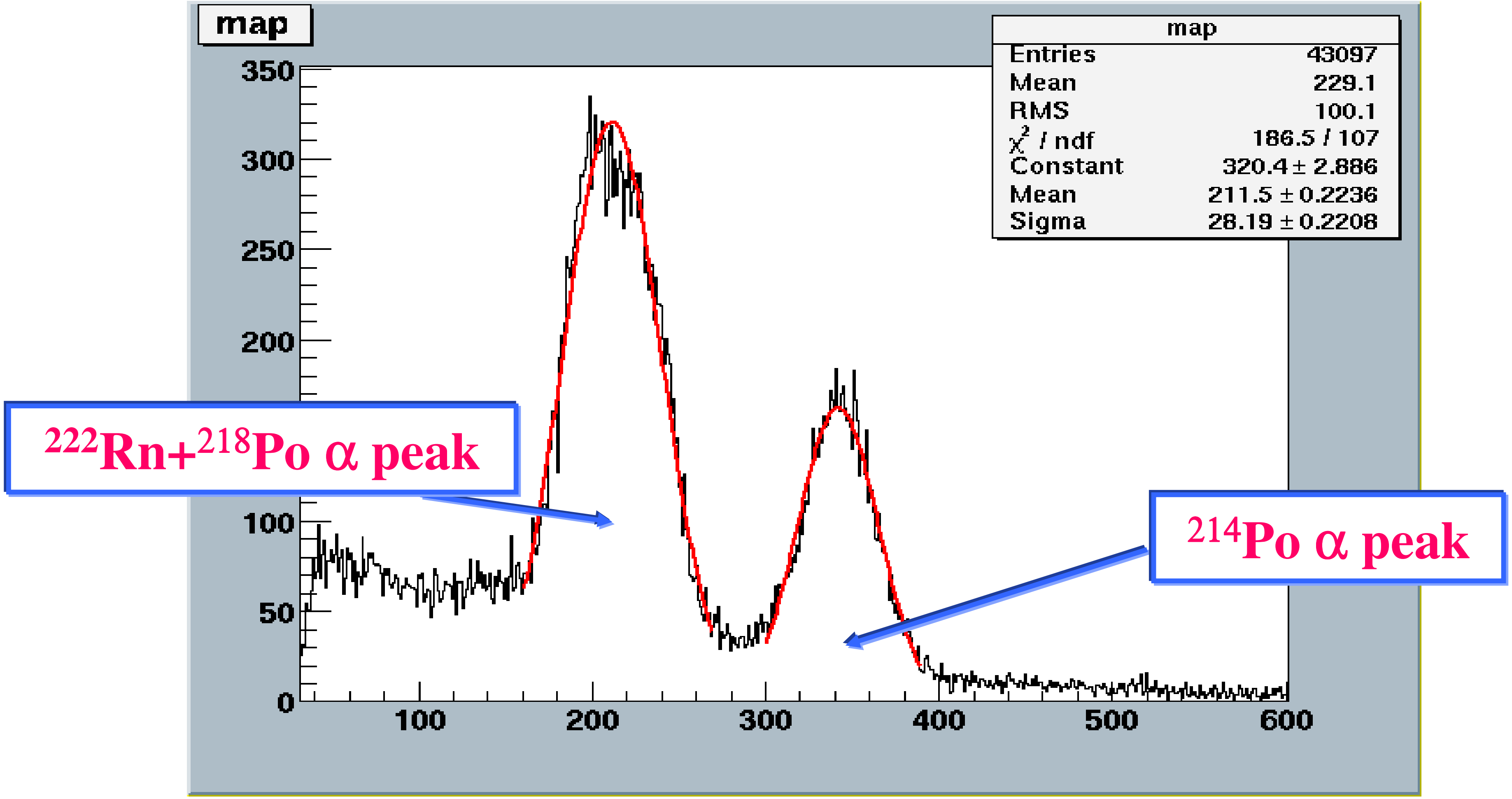
Water filling: beginning 2006

Scintillator filling: summer 2006

Start data taking: 2007

First signals in Borexino

Source test: radon loaded scintillator in a quartz cylindrical cell (4x4 cm) moved in different positions on the z-axis



^{222}Rn+^{218}Po α peak

^{214}Po α peak

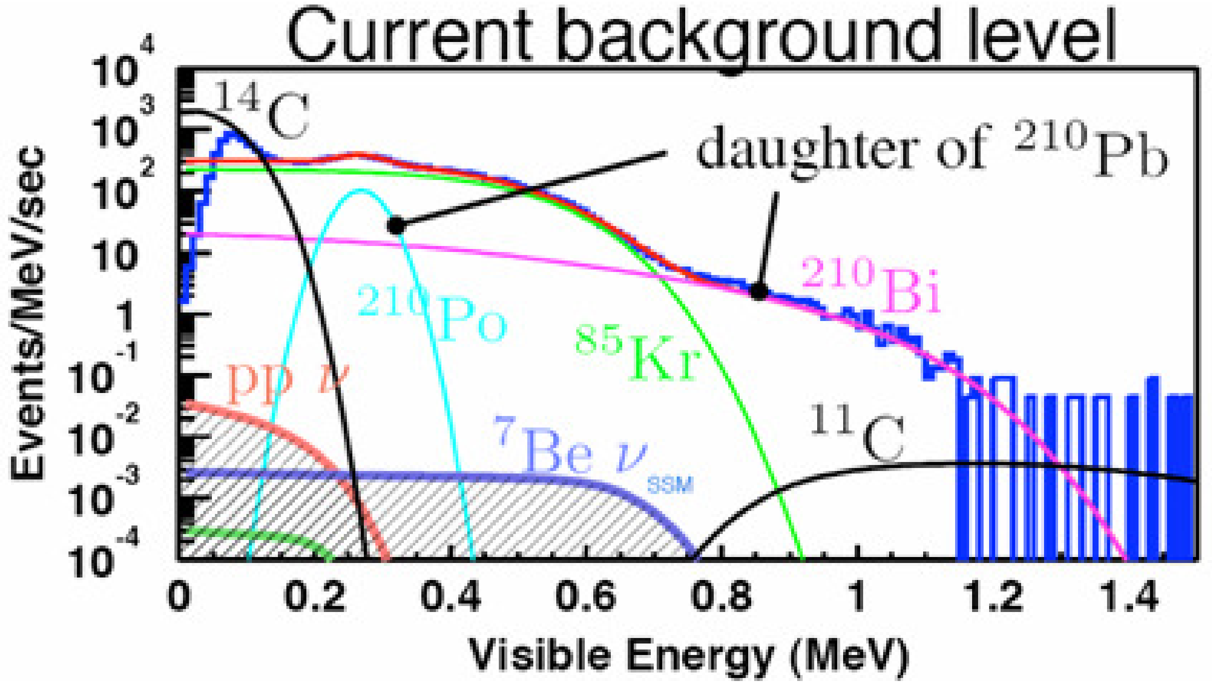
Result: ~ 460 pe / MeV

(energy resolution 4.7 % @ 1 MeV)

Kamland solar

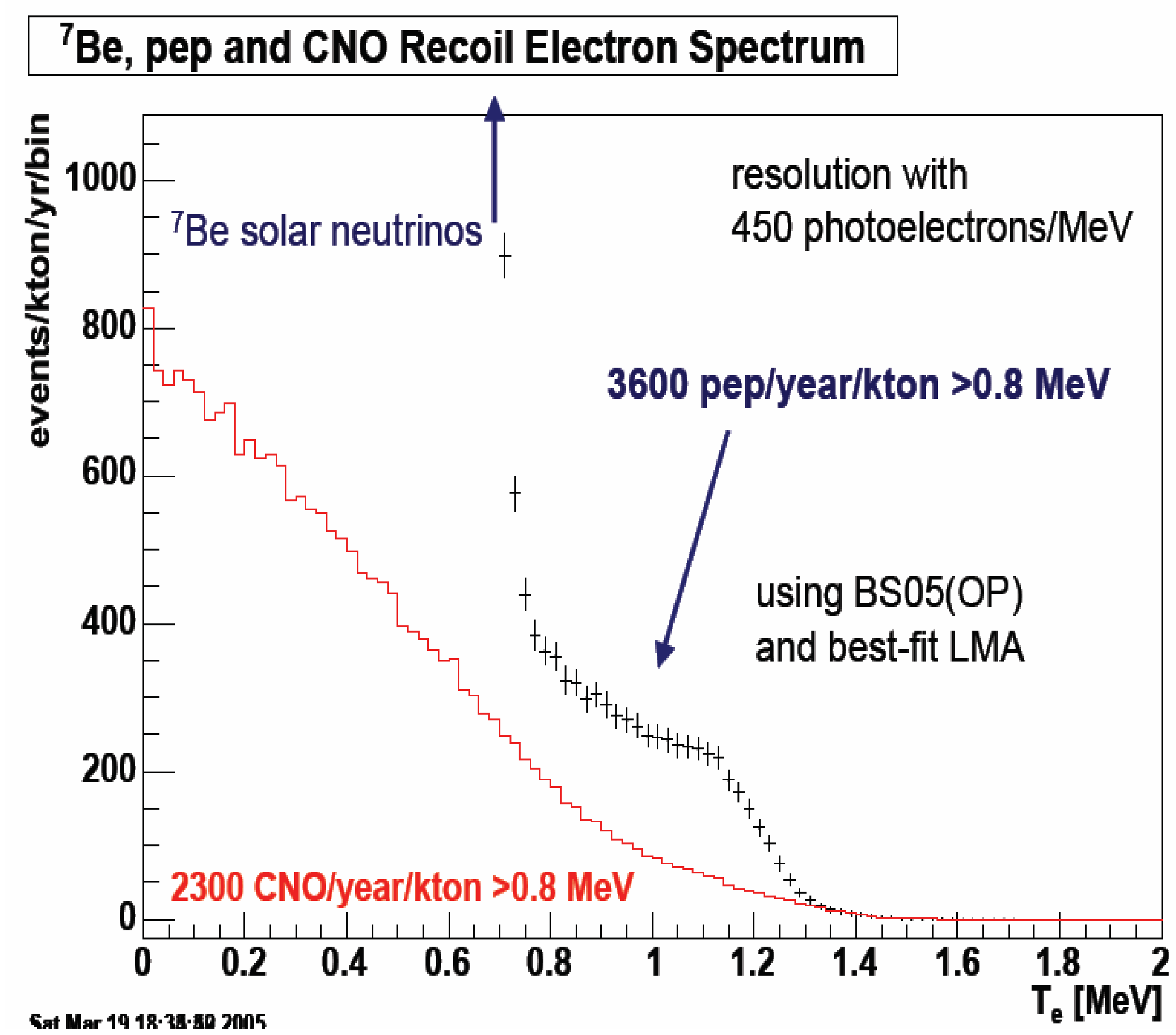
<u>Background problem:</u>

- Kr: 10^6 too high
- ^{210}Pb and daughters (from Radon): 10^5 too high
- Cosmogenic background x 7 compared to Borexino
- R&D phase (distillation)
- 6 M$ invest. System installation summer 2006

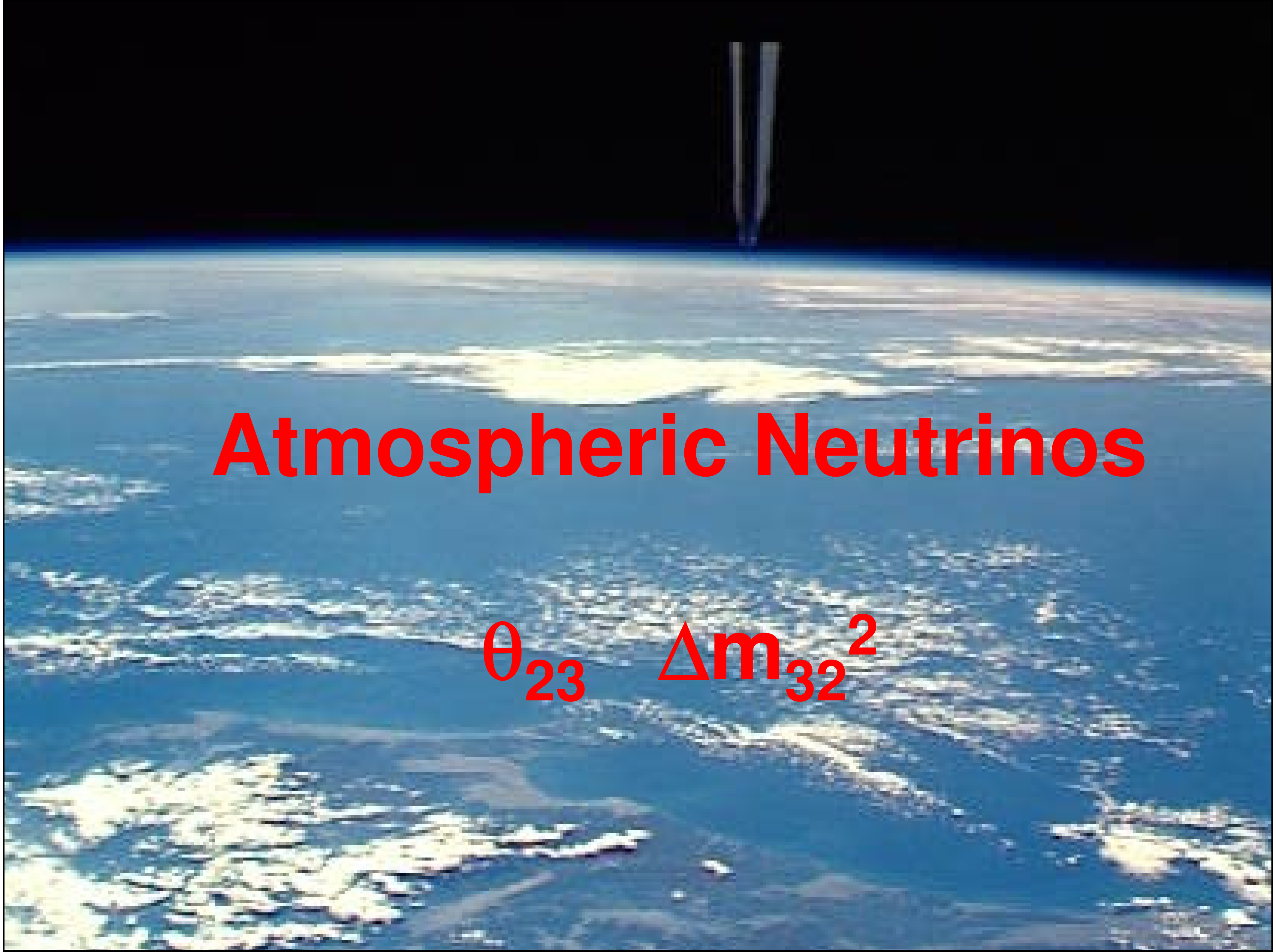


distillation test system

SNO+



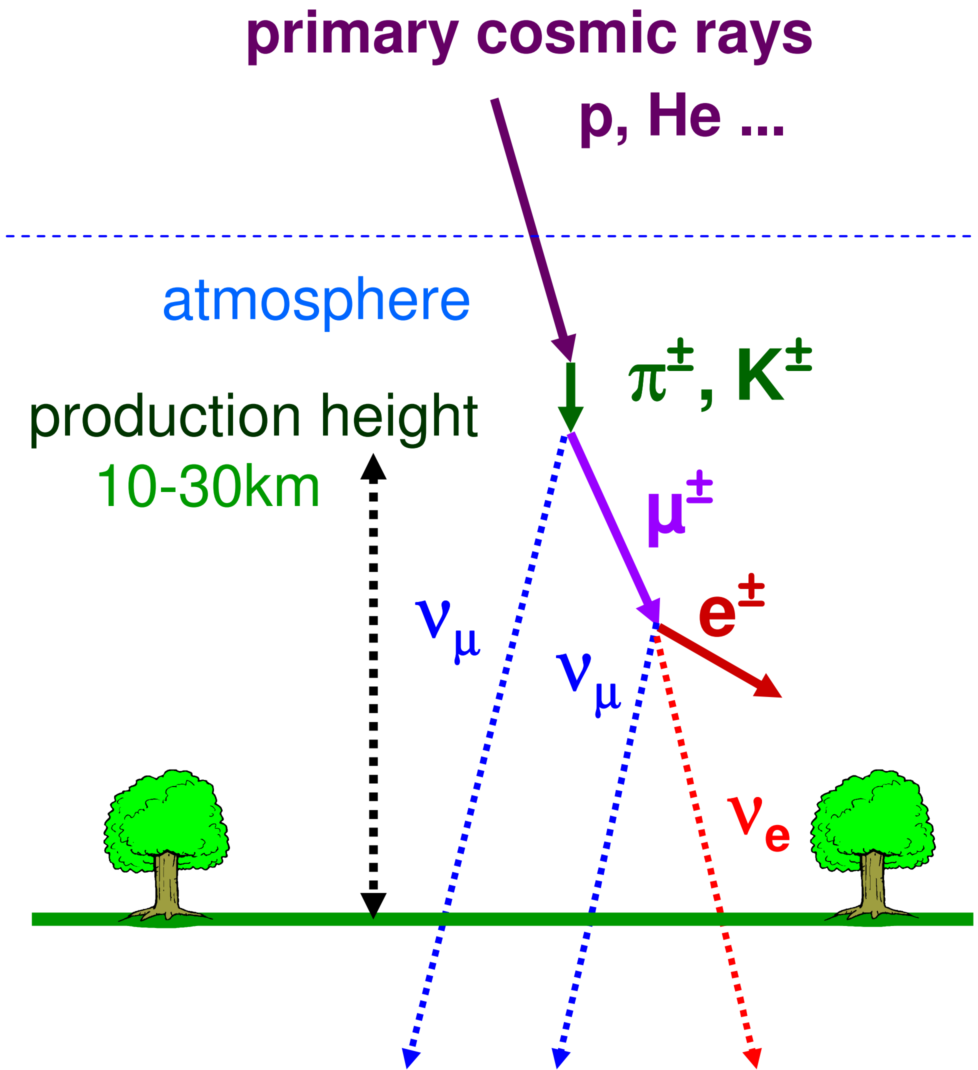
- Liquid scintillator 1kt (after heavy water period)
- Muon rate ~ 70 / d (KamLAND 26 x 10^3 /d) => low ^{11}C background
- pep + CNO solar neutrinos
- geoneutrinos
- maybe also $0\nu\beta\beta$ with Nd-loaded scintillator

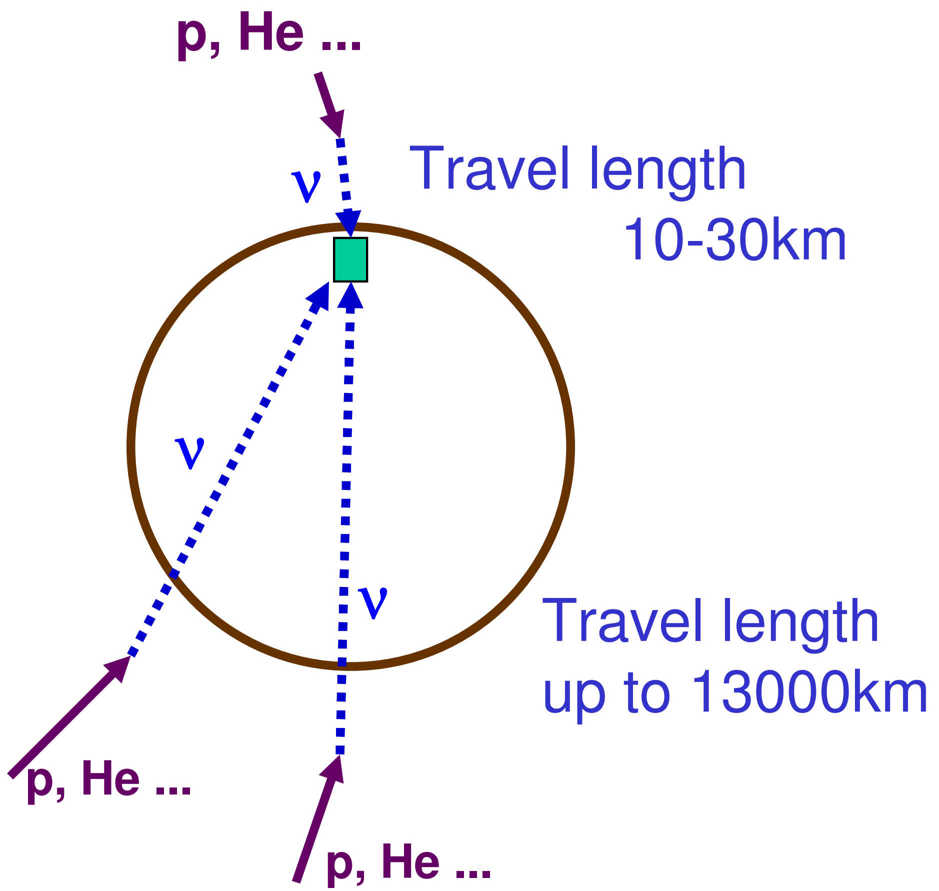


Atmospheric Neutrinos

θ_{23} Δm_{32}^2

Atmospheric neutrinos

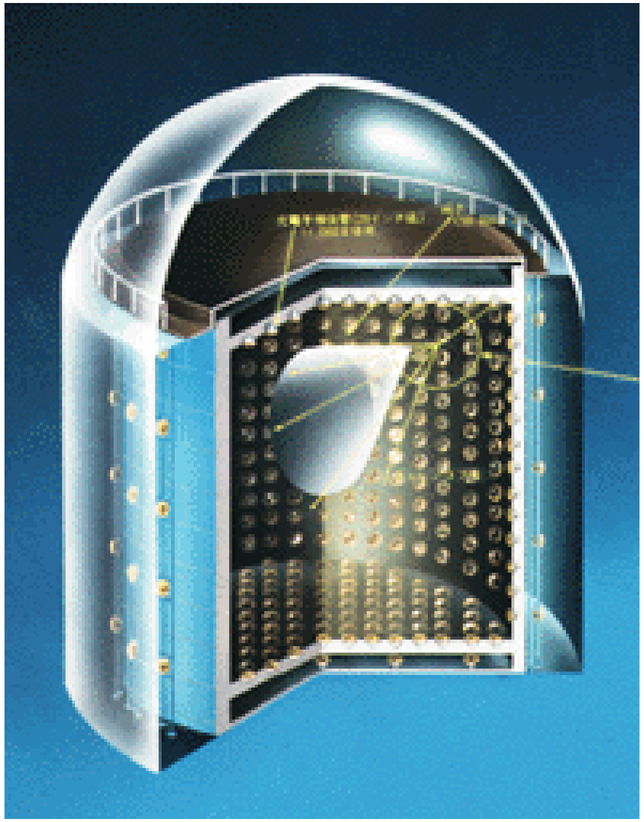




$$\frac{\phi(\nu_\mu + \bar{\nu}_\mu)}{\phi(\nu_e + \bar{\nu}_e)} \begin{cases} \sim 2 (\text{for } E_\nu < 1\text{GeV}) \\ > 2 (\text{for } E_\nu > 1\text{GeV}) \end{cases}$$

For E_ν > a few GeV,
Up-going / down-going ~ 1

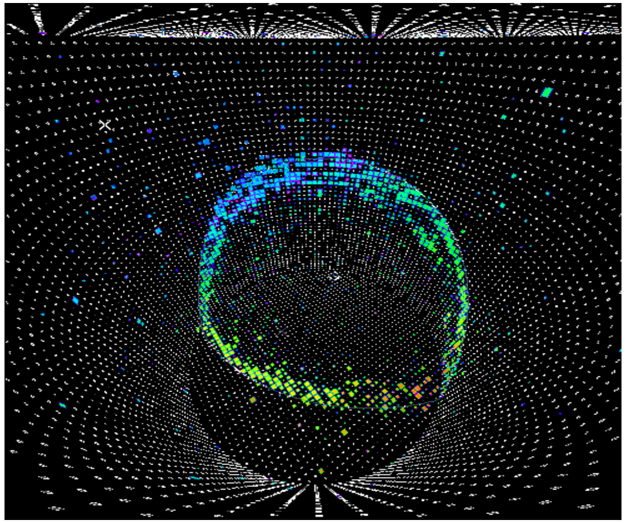
Super-Kamiokande



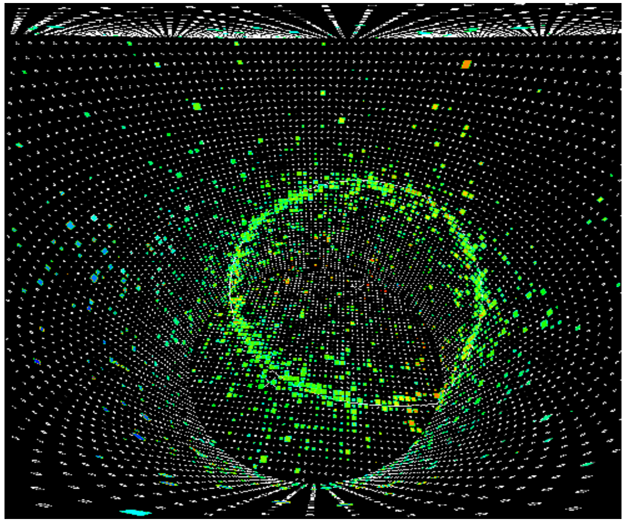
water Cherenkov detector
50000 t H_2O, 11000 PMTs
2700 mwe

detect neutrinos from
100 MeV – 10 TeV
via ν-N CC-interactions

μ-like events:
ν_μ produces a μ,
which gives a
sharp ring

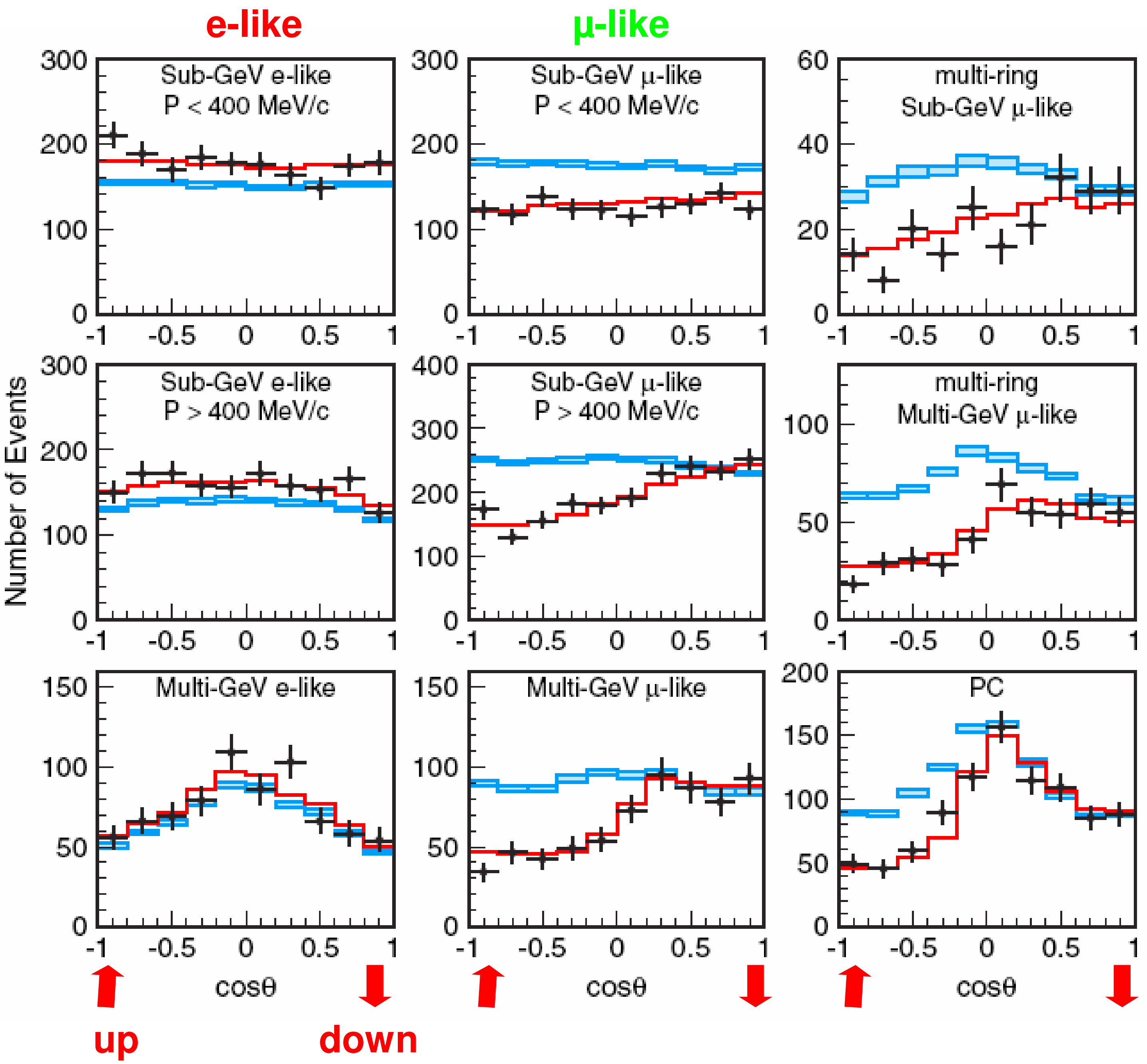


e-like events:
ν_e produces
an electron,
which produces
a “fuzzy” ring
(em shower)



Super-Kamiokande - Results

hep-ex0501064



05/96 – 07/01: 1489 days

in total ~ 15000 events

~ 10 atm. ν per day

+ Data

▨ MC w/o osc.

— MC with best fit osc.

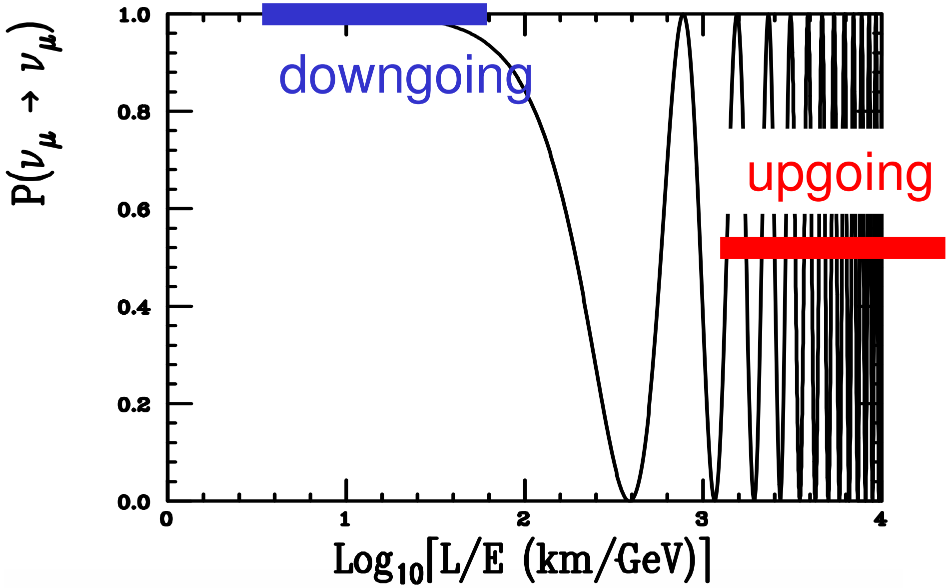
Best Fit:

ν_μ-ν_τ oscillations:

$\Delta m^2_{atm} = 2.1 \times 10^{-3}$ eV^2

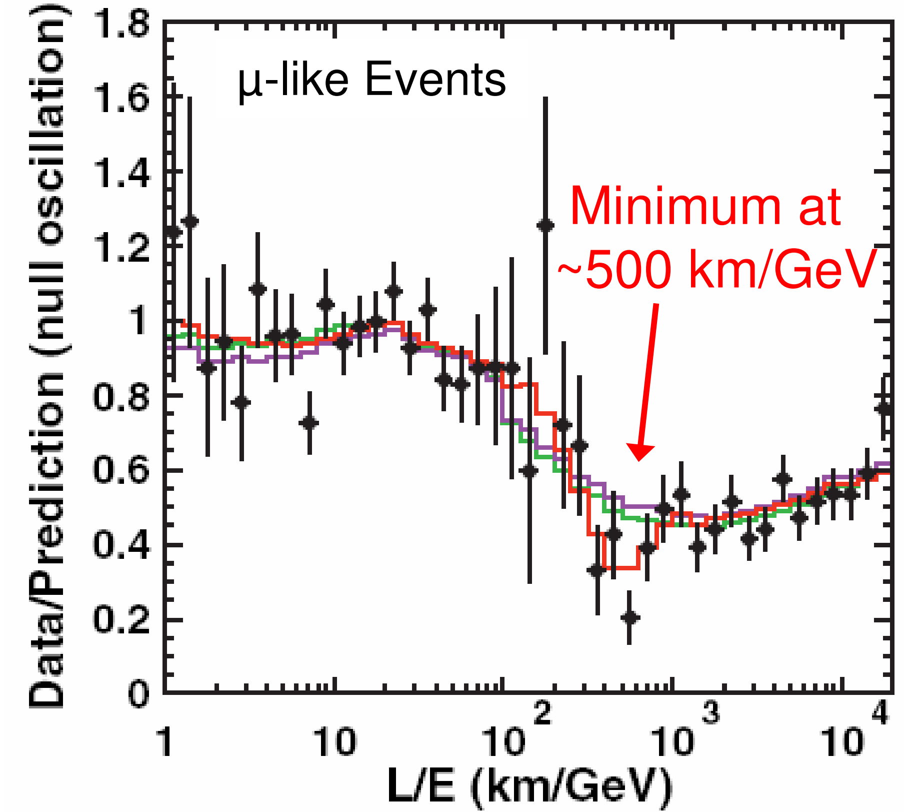
$\sin^2 2\theta_{atm} = 1.0$

Super-Kamiokande – L/E Analysis



downgoing

upgoing

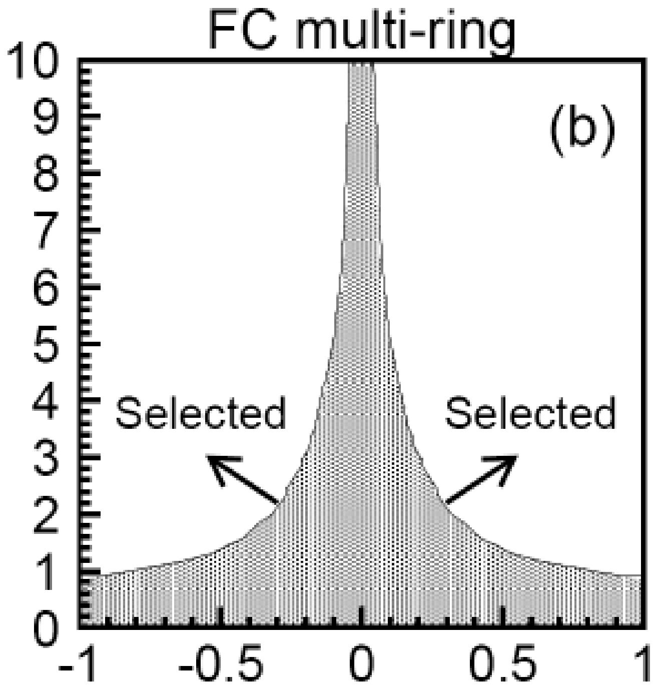


μ-like Events

Minimum at ~500 km/GeV

PRL 93, 101801 (2004)

select events with good L/E resolution (not horizontal events, low energy events)



Best fit:

$\Delta m^2_{atm} = 2.4\times10^{-3}\ \mathrm{eV}^2$

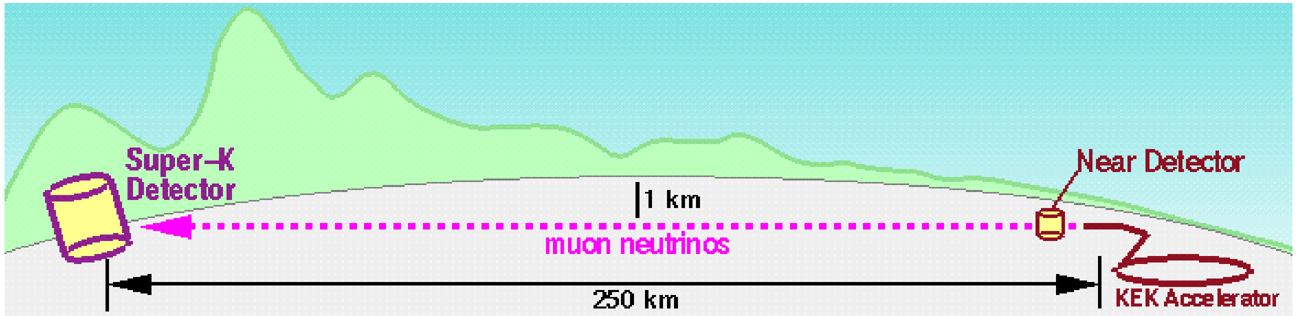
$\sin^2 2\theta_{atm} = 1.0$

Decay rejected at 3.4σ

Decoherence rejected at 3.8σ

KEK to Kamioka: K2K-Experiment

Long-Baseline- accelerator experiment to test atmospheric neutrino oscillations



L = 250 km

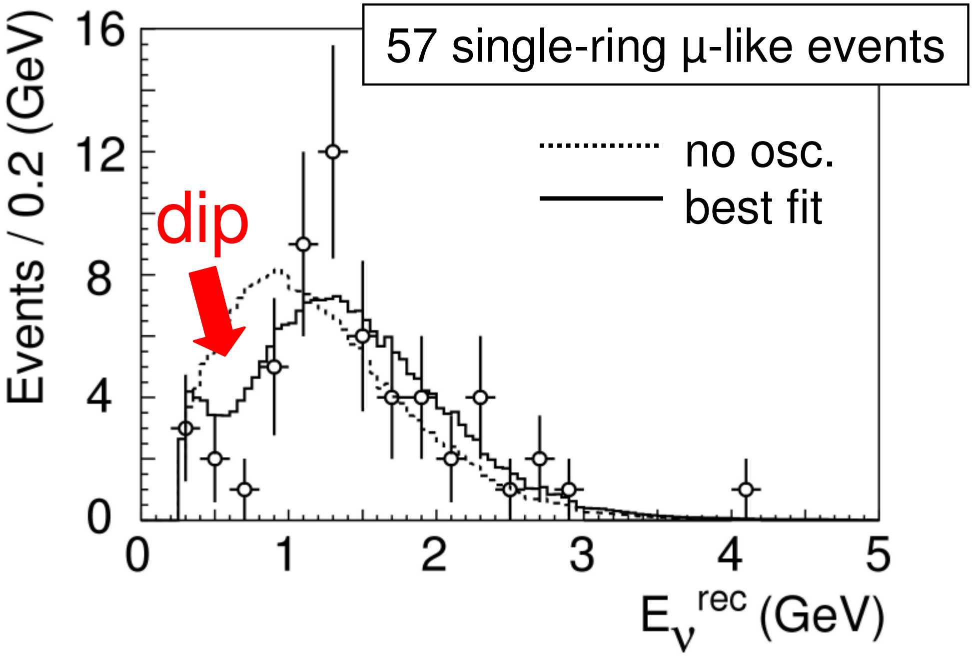
$E_\nu \sim 1.3$ GeV, Δm_{atm}^2

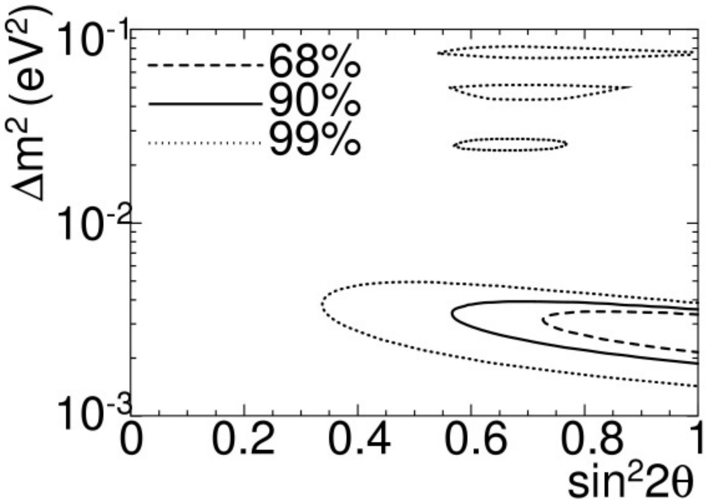
➔ $L_0/2 \sim 650$ km

<u>Result:</u> $(8.9 \cdot 10^{19}$ pot)

107 $\nu_\mu \rightarrow \nu_\mu$ events detected

151 ±12 expected





oscillations confirmed @ 3.9σ

> Best Fit: $\sin^2 2\theta = 1.0$
>
> $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2

hep-ex/0411038

θ_{13}

CHOOZ - limit for θ_{13}

Goal: test of $\bar{\nu}_e \to \bar{\nu}_x$ oscillations for atmos. Δm^2

M. Apollonio et. al.,
Eur.Phys.J. C27 (2003) 331

$$\boxed{P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2_{atm} L}{4E_{\bar{\nu}}}}$$

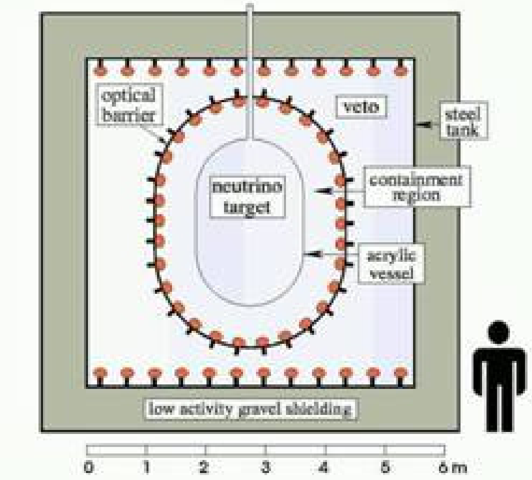
E_ν ~ 4 MeV, Δm_{atm}^2 ➔ $L_{osc}/2$ ~ 1.5 km

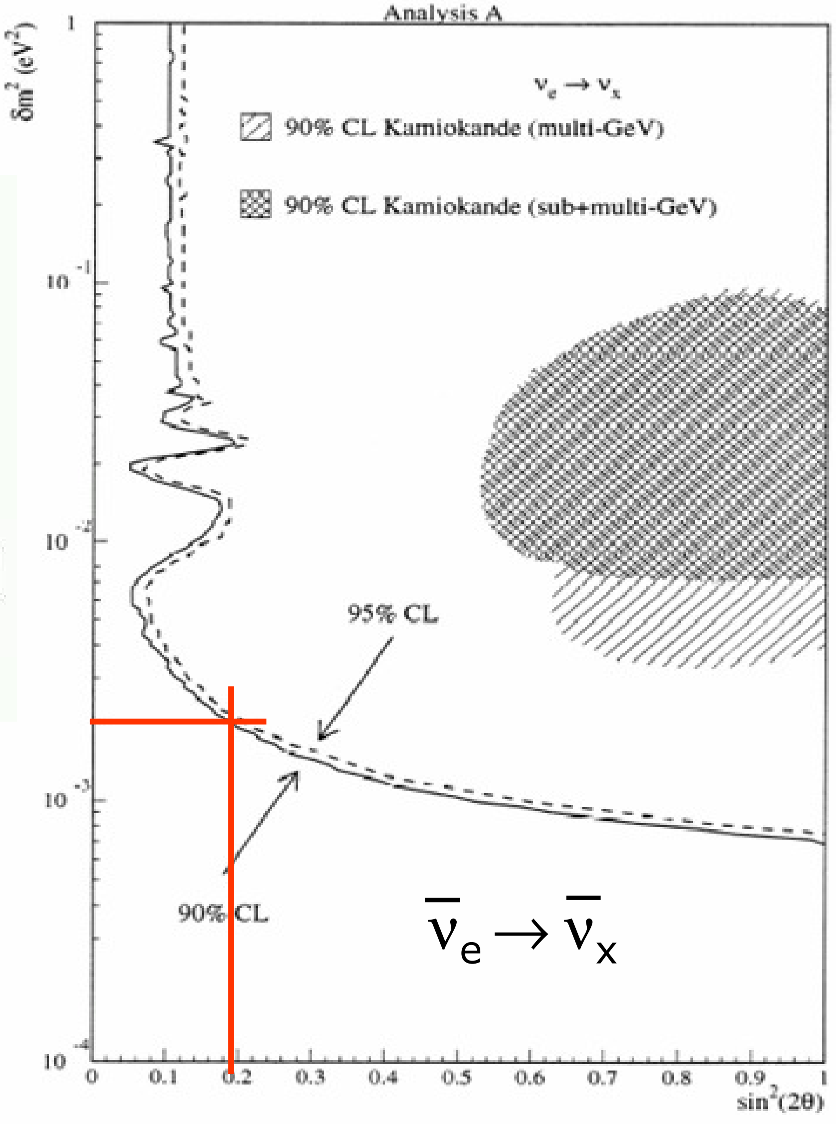
reactor experiment @ 1km

P_{th}= 8.4 GW_{th}

5 t Gd loaded scintillator

overburden: 300 mwe





$\bar{\nu}_e \to \bar{\nu}_x$

Result:

R(data/MC)=1.01 ± 0.028^{stat} ± 0.027^{syst}

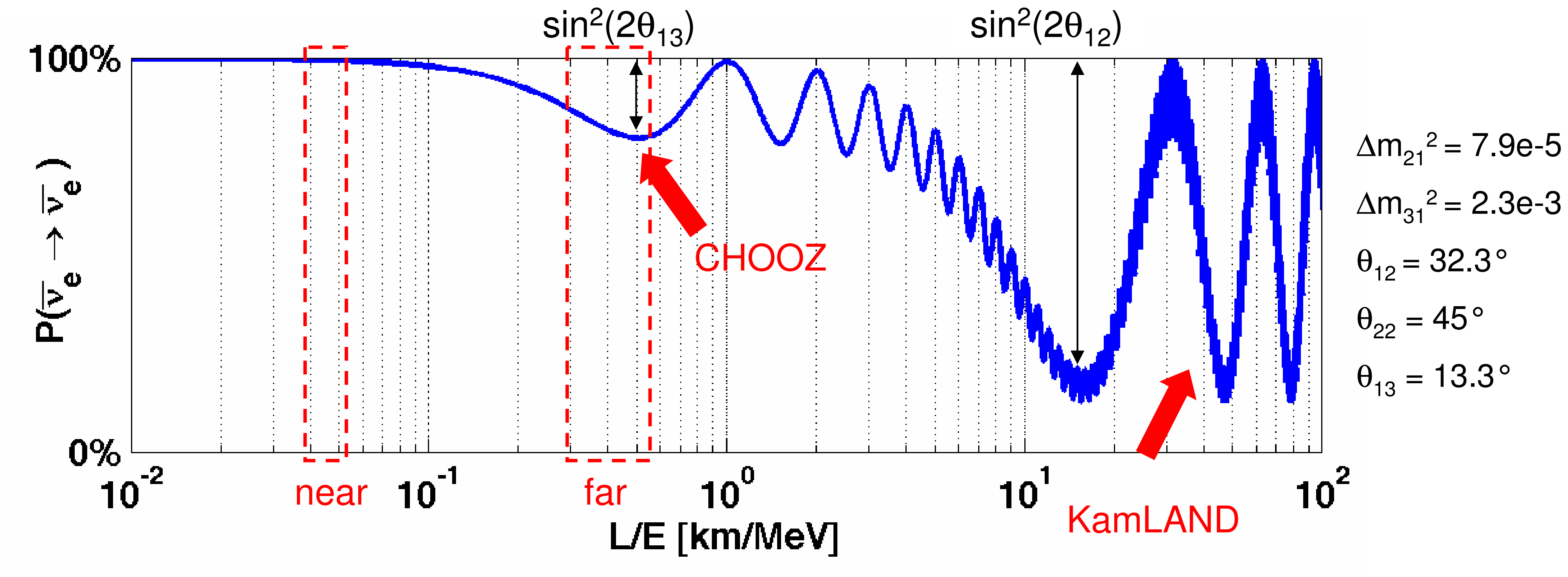
➔ atm. oscillations are $\nu_\mu \to \nu_\tau$

➔ limit for θ_{13}: $\sin^2(2\theta_{13}) < 0.20$ (90%CL)

for $\Delta m^2 = 2 \cdot 10^{-3}$ eV²

Searching for θ_{13} with reactor neutrinos

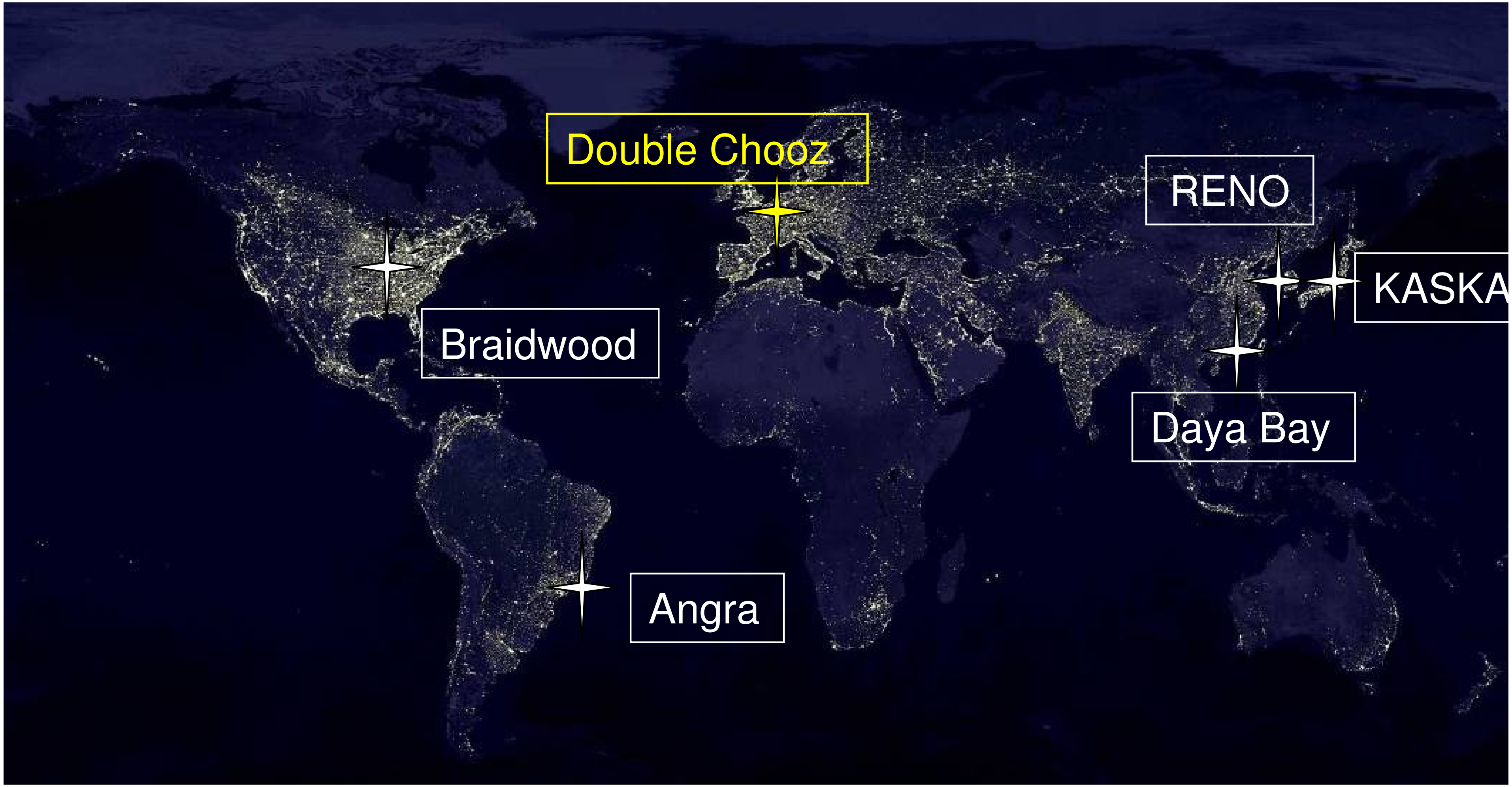
$$\boxed{P(\overline{\nu_e} \rightarrow \overline{\nu_e}) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_{\bar{\nu}}} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E_{\bar{\nu}}}}$$



- max. sensitivity for θ_{13}: $E_\nu \sim 4$ MeV, $\Delta m_{atm}{}^2$ ➔ $L_{osc}/2 \sim 1.5$ km
- disappearance experiment: look for rate deviating from $1/r^2$
  maybe additionally spectral distortion
- reduce systematic errors: monitor absolute neutrino flux with near detector

Proposed Sites for an Experiment

Ingredients: - strong nuclear power plant as ν source
- near detector (< 200m) to monitor the absolute ν flux
- far detector @ 1-2 km, well shielded against cosmic rays



Double-Chooz

Goal: $\sin^2(2\theta_{13}) > 0.02 - 0.03$

→ higher statistics ($N_{far} \sim 5 \cdot 10^4$ in 3a)

10 t Gd-loaded scintillator

$\sigma_{stat} < 0.5\%$

→ 2 identical detectors:

‚near' ~ 150 m (60 mwe)

‚far' ~ 1050 m (300 mwe)

➔ reactor related errors –> 0

➔ relative normalization $\sigma_{rel} < 1\%$

→ background suppression:

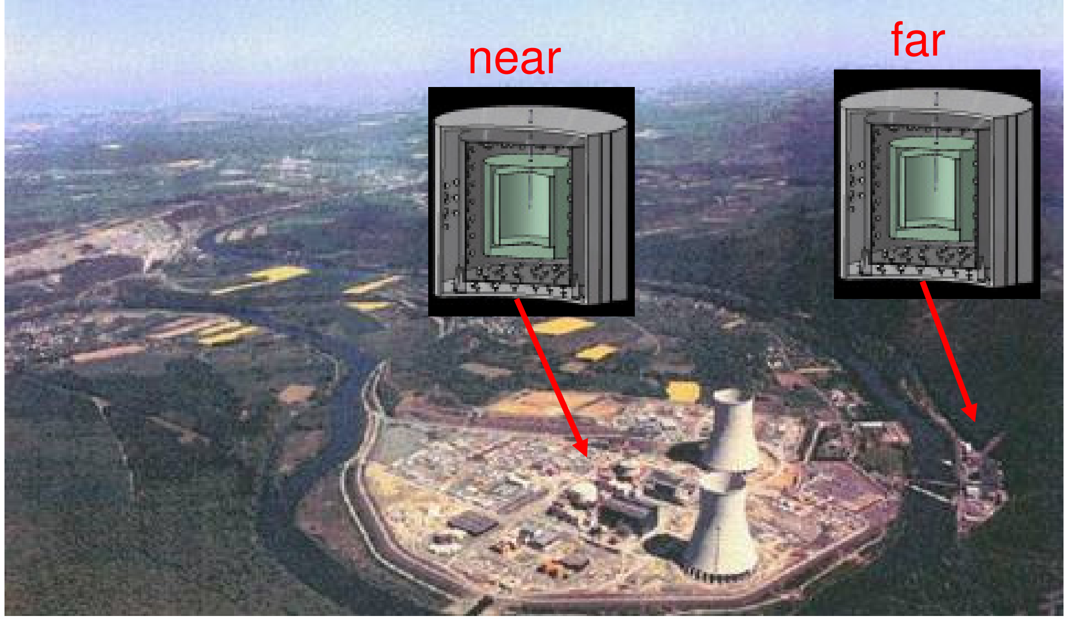
S/N ~ 25 in Chooz

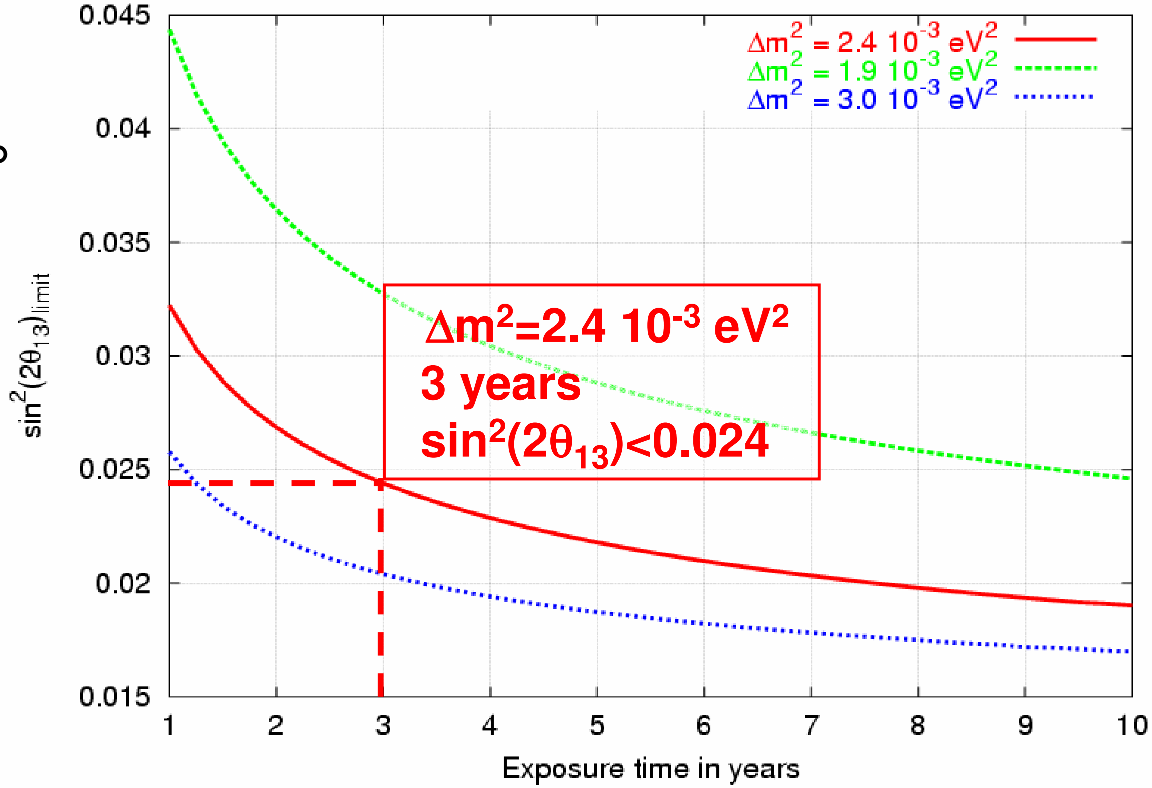
S/N > 100 in Double-Chooz

start data taking 2007 (far)

2008 (near)

Letter of Intent:
hep-ex 0405032





$\Delta m^2 = 2.4\ 10^{-3}\ eV^2$
3 years
$\sin^2(2\theta_{13}) < 0.024$

Expected Sensitivity 2007-2012

- Far Detector starts in 2007
- Near detector follows ~18 months later

- after 3 years:

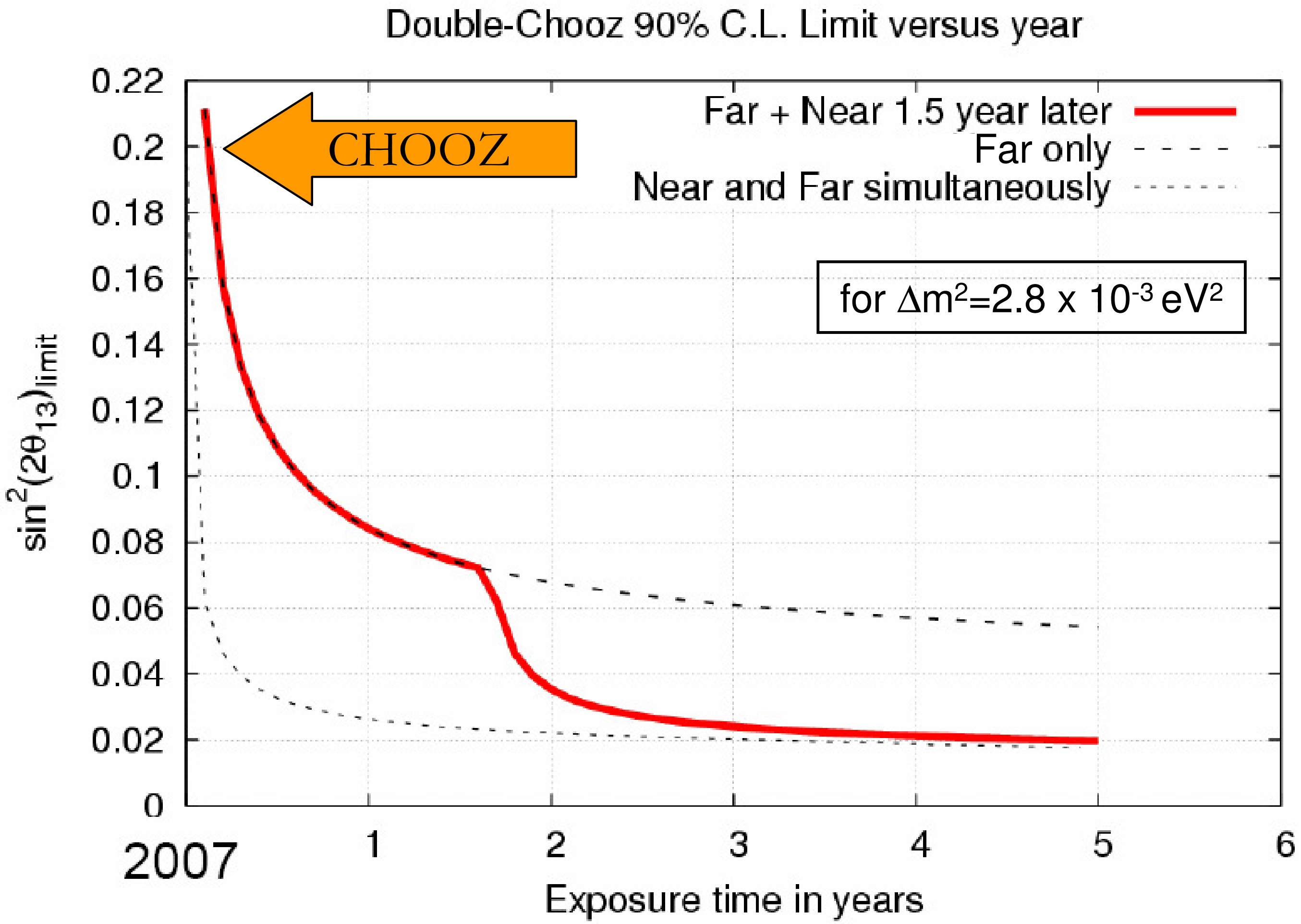
  60000 evts in far det.

  3 mio evts in near det.

- look for rate deviation from $1/r^2$

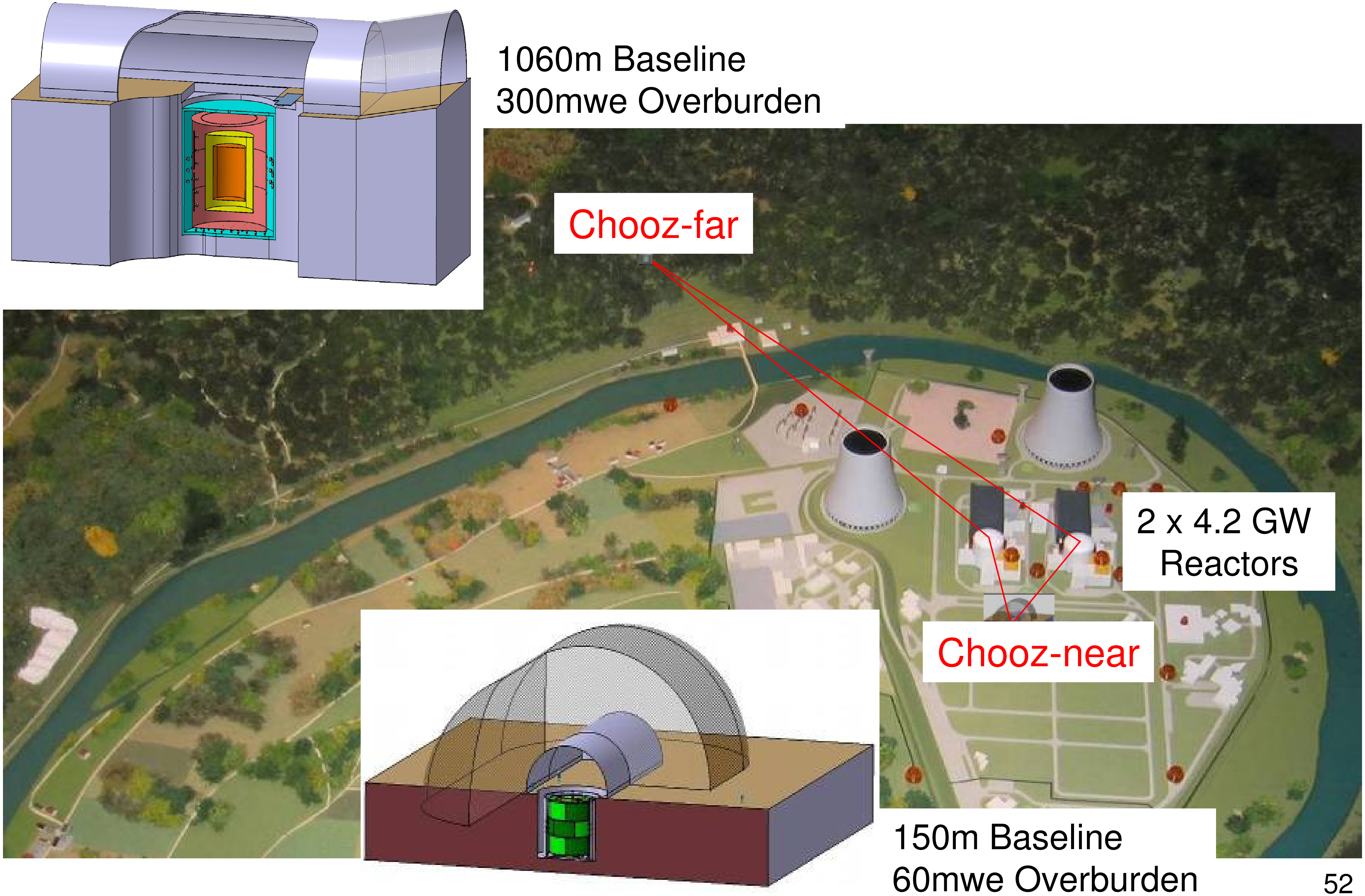
  &

- look for spectral distortion



- Double Chooz can surpass the original Chooz bound in 6 months

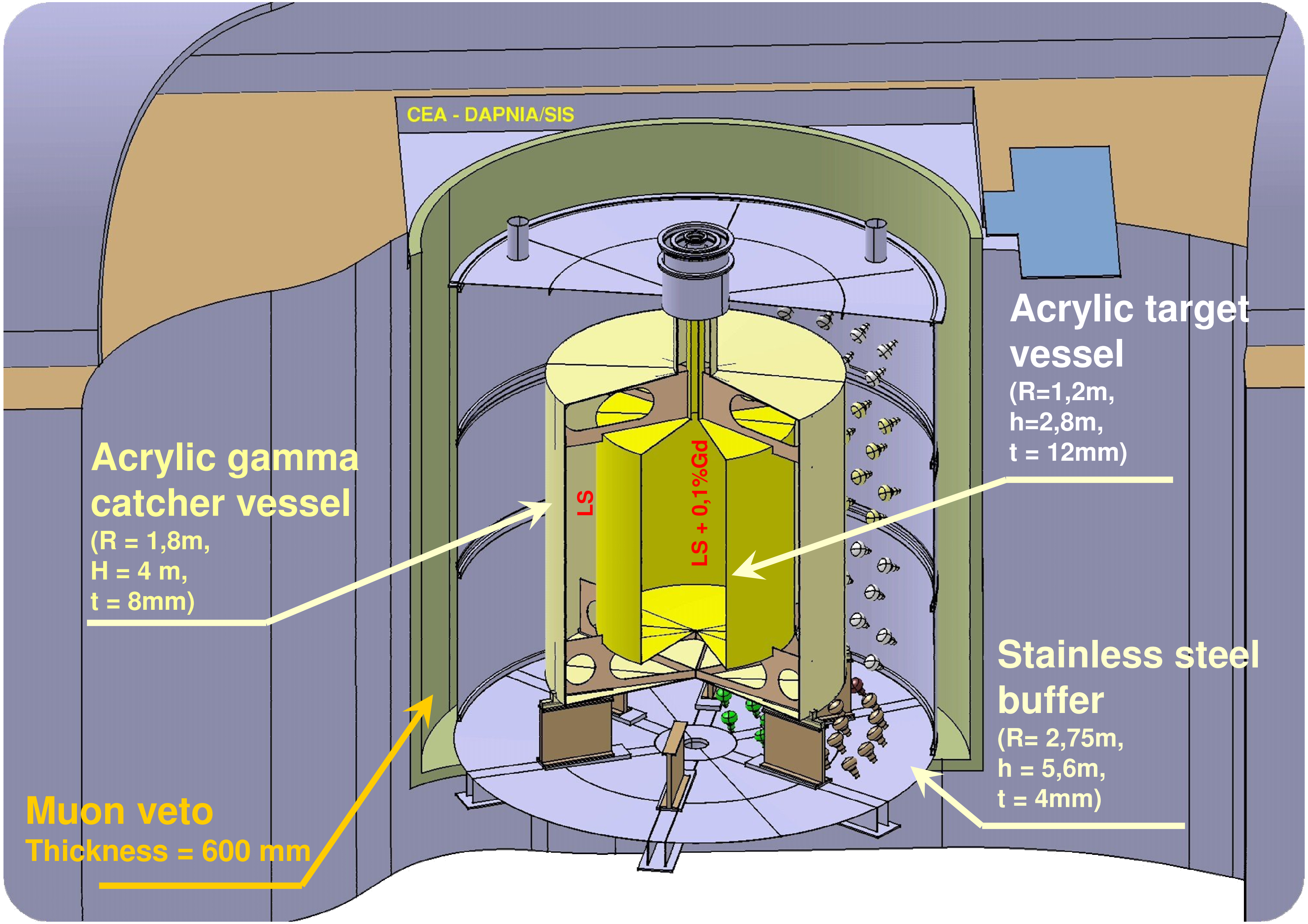
Double-Chooz - Site



1060m Baseline
300mwe Overburden

150m Baseline
60mwe Overburden

Double Chooz - Detector



Acrylic target vessel
(R=1,2m,
h=2,8m,
t = 12mm)

Acrylic gamma catcher vessel
(R = 1,8m,
H = 4 m,
t = 8mm)

Stainless steel buffer
(R= 2,75m,
h = 5,6m,
t = 4mm)

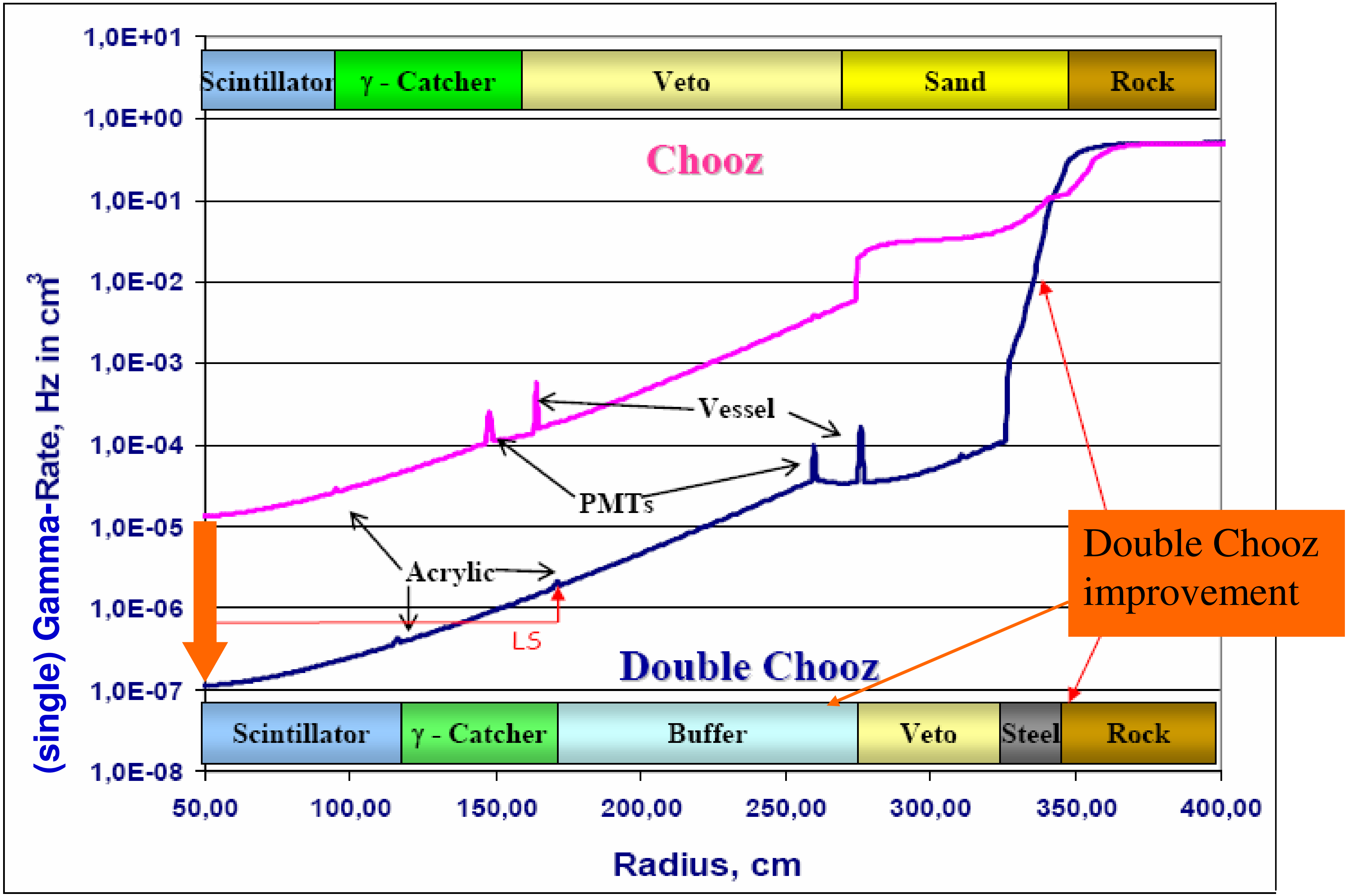
Muon veto
Thickness = 600 mm

Double Chooz - Systematics

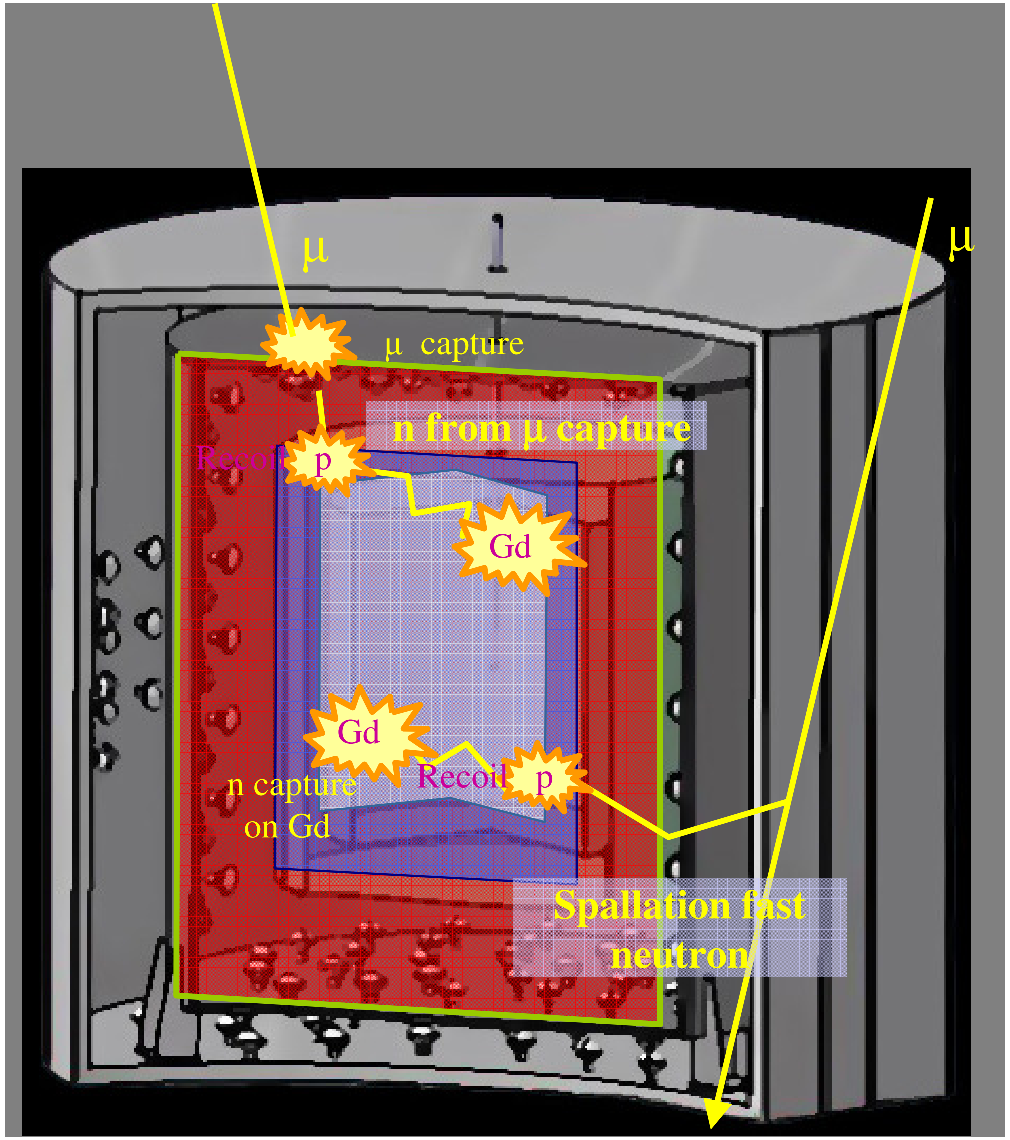
	CHOOZ	Double-Chooz Goal
• Reactor systematics:		
– reactor power	0.7%	-
– energy per fission	0.6%	-
– reaction cross section	1.9%	-
• Detector systematics:		
– number of protons	0.8%	0.2%
– detection efficiency	1.5%	0.5%
• relative normalization of the 2 detectors < 1% is crucial!		
– solid angle (different for near and far)		0.2%
– dead time (near)		<1%

- long term stability of the liquid scintillator is crucial!

Accidental Background



Correlated Background



Background from fast neutrons from muon capture and spallation evaluated in simulations:

Rate of $\bar{\nu}_e$-mimicking events

- between 1 and 8 MeV
- without veto signal

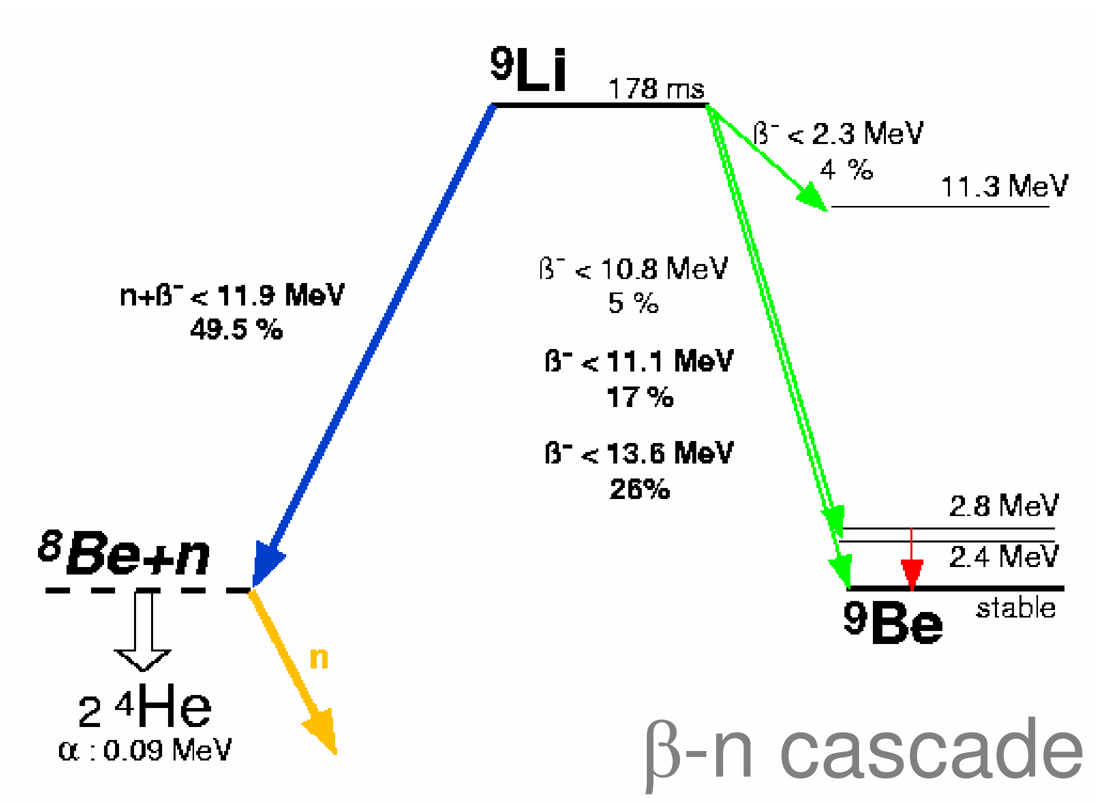
in far detector (300m.w.e):

N_{bck}< 0.5 evts/day (90% C.L.)
Signal (no osc) ≈ 85 evts/day

in near detector (60m.w.e):

N_{bck}< 3.2 evts/day (90%C.L.)
Signal ≈ 4000 evts/day

Muon induced radio nuclides



- produced by muon reactions on ^{12}C (^{9}Li, ^{8}He, ^{11}Li)
- „long" life times (0.1 – 1 s)
- spectral shape is known
- measurement of σ_{prod} at SPS CERN with $\langle E_\mu \rangle$=190 GeV (T. Hagner et al., AstroparticlePhys. 14, 33 (2000))

	Near detector		Far detector	
Isotopes	R_μ ($E^{0.75}$ scaling)	R_μ ($E > 500$ GeV)	R_μ ($E^{0.75}$ scaling)	R_μ ($E > 500$ GeV)
	per day			
^{9}Li	17 ± 3	3.6	1.7 ± 0.3	0.36
^{8}He	^{8}He & ^{9}Li measured together			

- data from CHOOZ, CTF and KamLAND

S/B: > 100:1 > 50:1

1/5 scale prototype

- Test for material compatibility and various procedures
- completed Summer 2005
- will be filled soon

Low Energy Neutrino Physics

Introduction

- Neutrino masses and mixing
- Neutrino oscillations

Experimental Determination of neutrino properties

Neutrino oscillation experiments

- Solar neutrinos
- Atmospheric neutrinos
- Reactor experiments (θ_{13})

Absolute mass determination

- **Beta Decay**
- **Neutrinoless Double Beta Decay**
- **Cosmological limits**

Low Energy Neutrino Astronomy

Conclusions

Absolute Neutrino Mass Determination

- Supernovae:

  SN produce many neutrinos in a short time, and measuring time shifts can in principle measure neutrino masses, $m_\nu < \sim 30$ eV

- Weak decays:

  from neutrino oscillation results, all $\Delta m^2 < 0.1$ eV^2, therefore only ν_e measurements have useful sensitivity => current best is Tritium beta decay, $m_\nu < 2.2$ eV

- Neutrinoless double beta decay:

  If neutrinos are Majorana particles, then $0\nu\beta\beta$ is allowed => observation of $0\nu\beta\beta$ would be direct evidence for neutrino mass, $\langle m_\nu \rangle < \sim 1.1$ eV

- Comological limits:

  Neutrinos are the second most numerous particle in the Universe => even a tiny neutrino mass could have astrophysical implications, $\Sigma m_\nu < 0.23$ eV(?)

Beta-Decay- Experiments

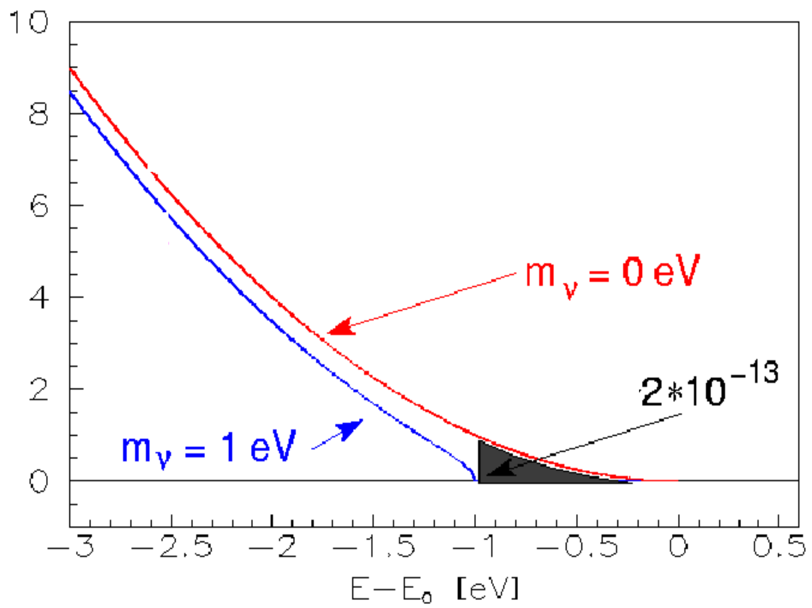
- β-spectrum close to the end point:

  $dN/dE \propto (E_0-E_e) \cdot [\,(E_0-E_e)^2 - m_\nu^2\,]^{1/2}$

  $$\boxed{m_\nu{}^2 = \sum |U_{ei}|^2 m_i^2}$$

- Tritium decay $^3H \rightarrow {}^3He + e^- + \overline{\nu}_e$

  $E_0 = 18.57$ keV, $t_{1/2} = 12.3$ a



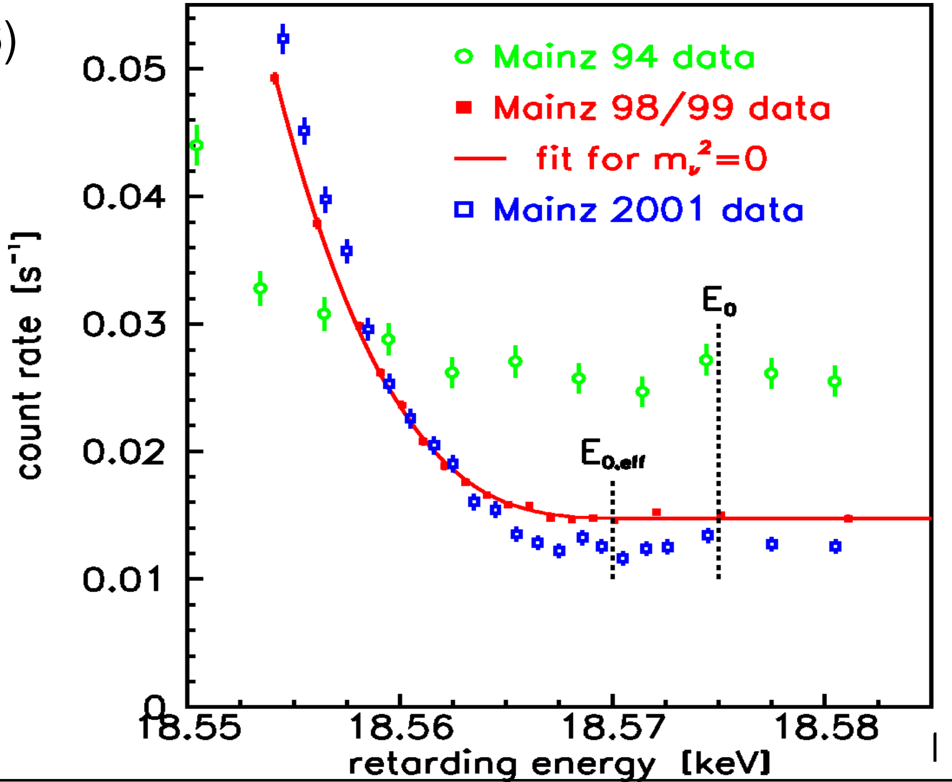
Mainz experiment (hep-ex 0412056)

condensed T_2 film

MAC-E filter, $\Delta E = 4.8$ eV

$$\boxed{\begin{array}{l} m_\nu{}^2 = (-0.6 \pm 2.2 \pm 2.1)\,eV^2 \\ \Rightarrow \;\; m_\nu < 2.3\,eV\;(95\%CL) \end{array}}$$

(Troitsk experiment: $m_\nu < 2.2$ eV)



- ^{187}Re with cryo bolometers (MIBETA)

  $E_0 = 2.5$ keV, $t_{1/2} = 5 \cdot 10^{10}$ a

The Karlsruhe Tritium Neutrino Experiment

(hep-ex/0109033)

Goal: Sensitivity for neutrino masses << 1eV

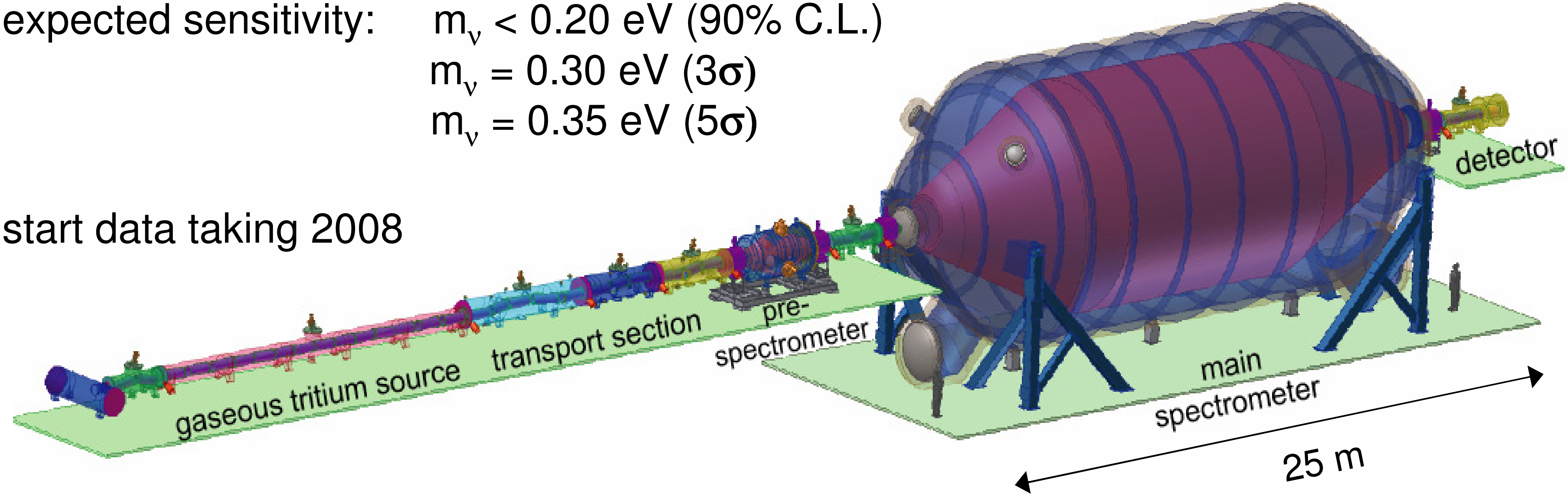
➔ very good energy resolution
high luminosity
low background

➔larger spectrometer
(Ø =10 m)

gaseous Tritium source (alternatively Tritium film)
dual spectrometer ($\Delta E_{pre} \approx$ 50eV, $\Delta E_{main} \approx$ 1eV)

expected sensitivity: m_ν < 0.20 eV (90% C.L.)
m_ν = 0.30 eV (3σ)
m_ν = 0.35 eV (5σ)

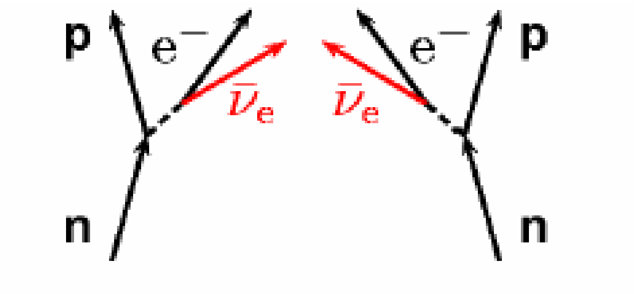
start data taking 2008



Neutrinoless Double Beta Decay

ββ(2ν): $(A,Z) \rightarrow (A,Z+2) + e_1^- + e_2^- + \bar{\nu}_{e1} + \bar{\nu}_{e2}$

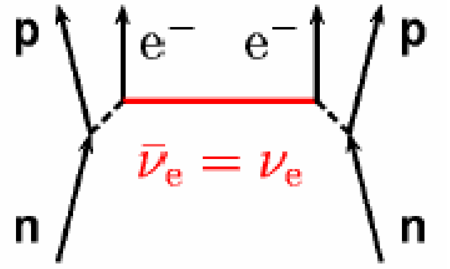
allowed in SM, observed on several isotopes



ββ(0ν): $(A,Z) \rightarrow (A,Z+2) + e_1^- + e_2^-$

in SM not allowed, ΔL =2

if observed => $m_\nu \neq 0, \quad \nu_e^C = \nu_e$



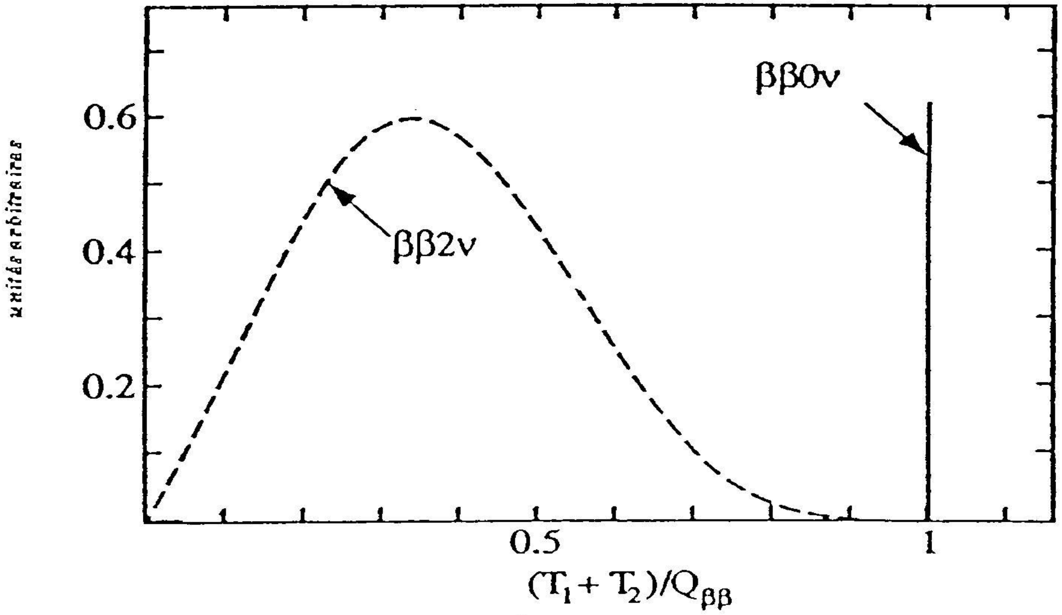
$$\boxed{\frac{1}{T_{1/2}^{0\nu}} = G(Q,Z)\,|M_{nucl}|^2\, m_{ee}^{\;2}}$$

Effective Majorana mass

$$\boxed{m_{ee} = \left|\sum U_{ei}^{\;2} m_i\right|}$$

(cf. beta decay:

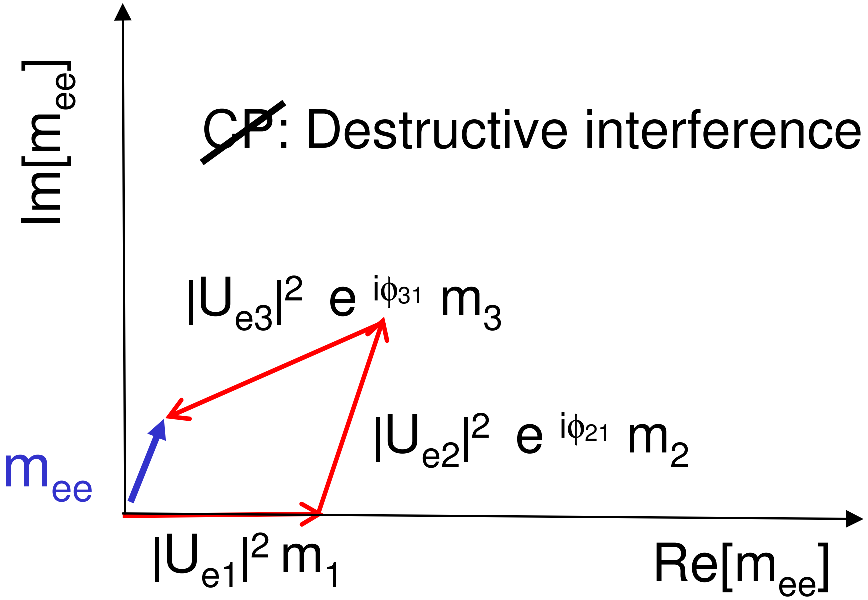
$$m_\nu^{\;2} = \sum_i |U_{ei}|^2 m_i^2 \quad)$$



Neutrinoless Double Beta Decay

$$\boxed{m_{ee} = m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\phi_1} + m_3|U_{e3}|^2 e^{i\phi_2}}$$

- sensitive to CP phases
- cancellations possible



~~CP~~: Destructive interference possible

Sensitivity

without background: $\langle m_{ee}\rangle \geq \text{const.}\left(\frac{1}{M\,T}\right)^{1/2}$

with background: $\langle m_{ee}\rangle \geq \text{const.}\left(\frac{b\,\Delta E}{M\,T}\right)^{1/4}$

b = background level [1/(kg · year · keV)]

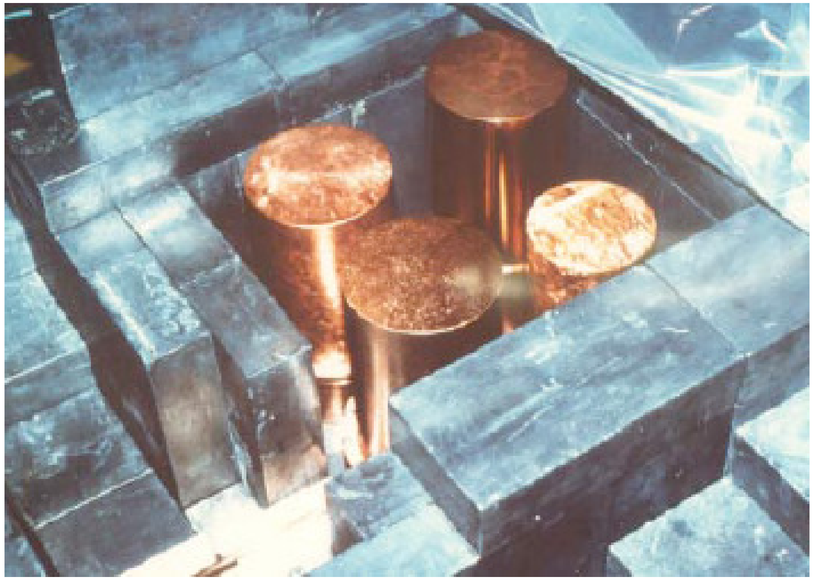
Evidence for 0νββ in ^{76}Ge?

Heidelberg-Moscow-Experiment:

5 detectors with 10.96 kg enriched Ge (86% ^{76}Ge)

Data taking 1990 – 2003: 71.7 kg yr

Endpoint ^{76}Ge: 2039 keV

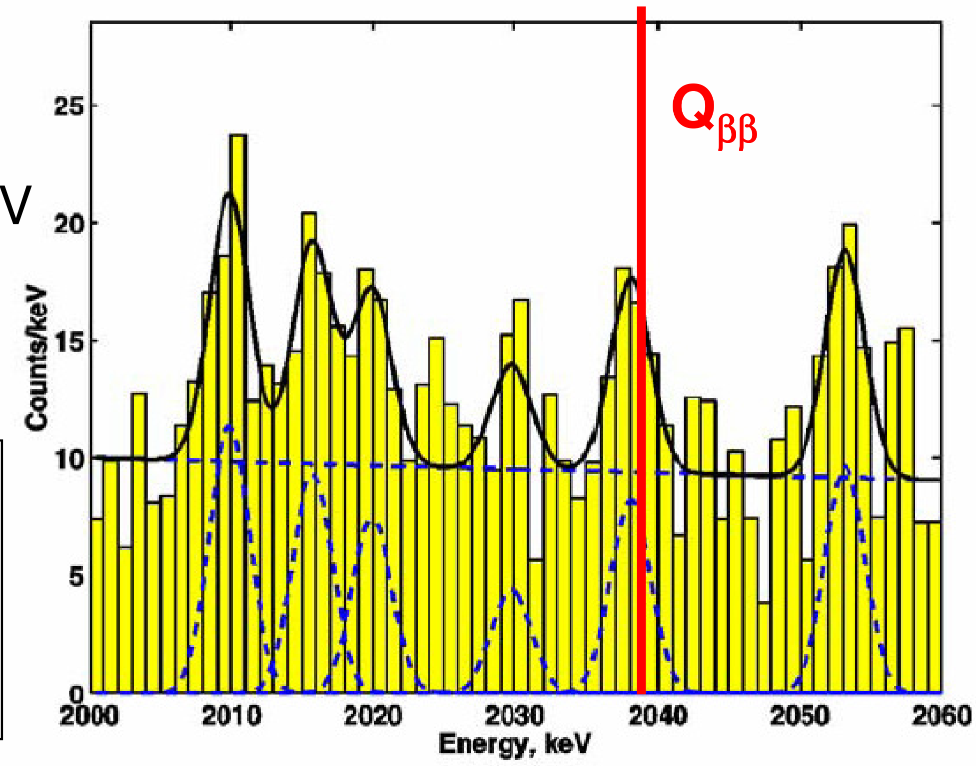


Analysis by subgroup yields peak at 2038.1 keV with 28.75 ± 6.86 events (4.2 σ)

➔ $T_{1/2}$ = (0.69 – 4.18) 10^{25} a (3 σ)
m_{ee} = (0.24 – 0.58) eV (3 σ)

50% error assumed on M_{nuc}: m_{ee} = 0.1 – 0.9 eV

Klapdor-Kleingrothaus et al., PLB 586 (2004) 198



until 2001 (53.9 kg yr): 0νββ not observed
$t_{1/2}^{0\nu} > 1.9 \times 10^{25}$ y
$m_{ee} < 0.35$ eV (90% c.l.)

HM collaboration, Klapdor–K. et al., Eur.Phys. J. A12 (2001) 147

CUORICINO

low temperature detectors @ Gran Sasso

40.7 kg of TeO_2 (18 crystals 3x3x6 cm^3 + 44 crystals 5x5x5 cm^3)

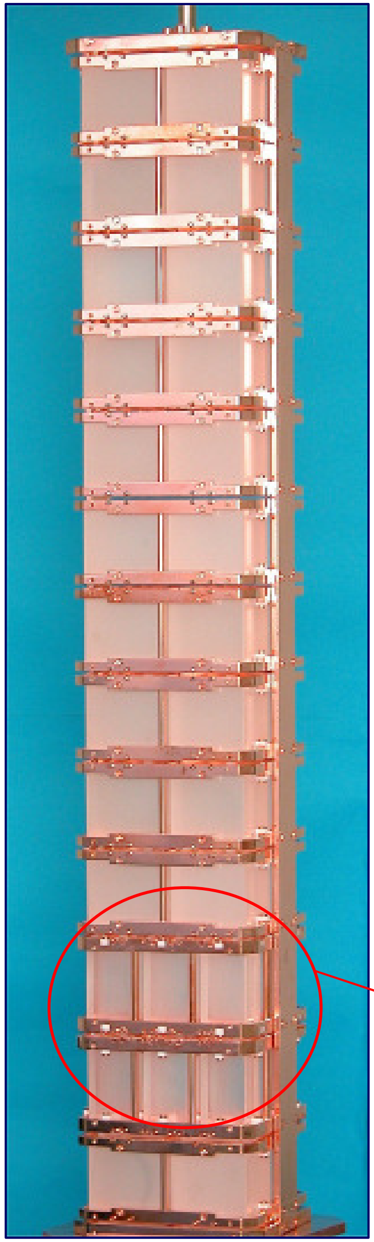
^{130}Te (Q=2529 keV, nat. abundancce 34 %)

Start in 2003

source = detector

Search for $0\nu\beta\beta$:

$T_{1/2}^{0\nu}(^{130}Te) > 1.8 \times 10^{24}$ a
$<m_\nu> < 0.2 - 1.1$ eV (hep-ph0501034)



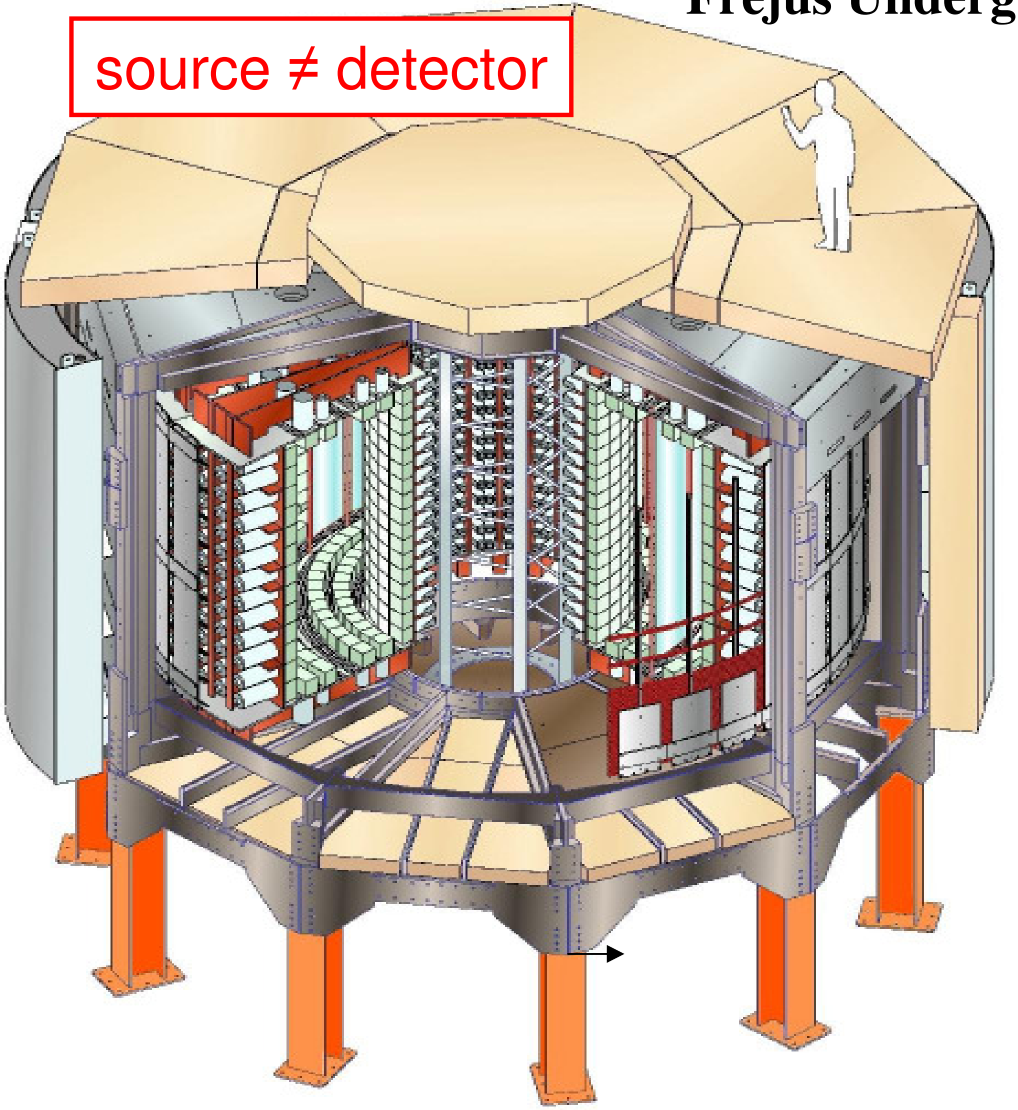
Future: CUORE
Array of 988 crystals:
19 towers of 52 crystals/tower
total mass: 0.78 ton of TeO_2

sensitivity after 10 years:
$m_{ee} < 11 – 62$ meV

NEMO 3

Fréjus Underground Laboratory : 4800 m.w.e.

source ≠ detector



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m^2, e ~ 60 mg/cm^2

Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

ββ0ν search

^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

^{100}Mo: m_{ee} < 0.7 – 1.2 eV
^{82}Se: m_{ee} < 1.3 – 3.6 eV

Double Beta Decay – Future

<u>Tasks:</u>

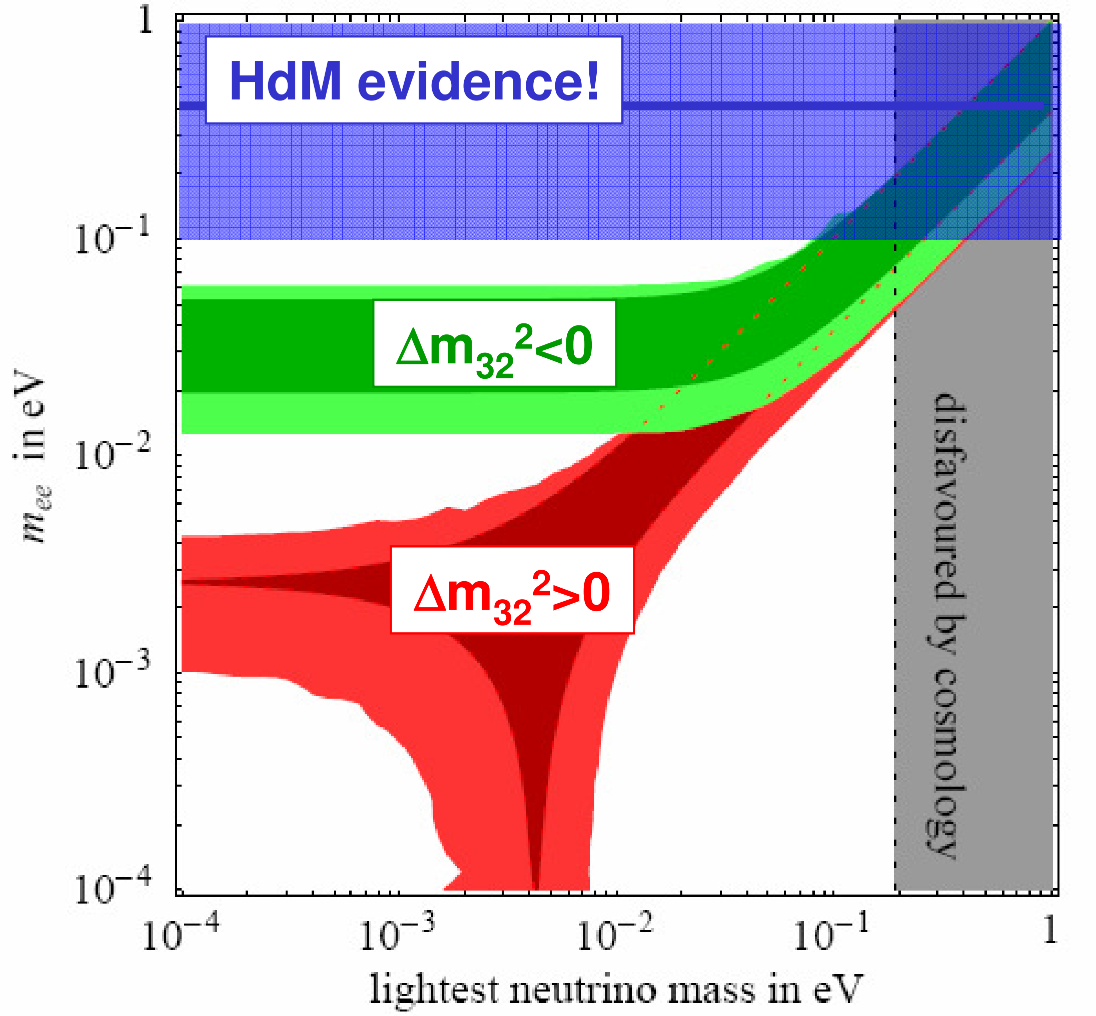
confirm HdM evidence $m_{ee}<0.1$eV

test inverted hierarchy $m_{ee}<0.01$eV

<u>various projects, isotopes:</u>

- GERDA,Majorana ^{76}Ge
- MOON, NEMO-Next ^{100}Mo
- CUORE, COBRA ^{130}Te
- EXO, XMASS ^{136}Xe
- SNO++ ^{150}Nd

hep-ph/0201291



improved nuclear matrix elements calculations needed

GERDA @ Gran Sasso

Experimental Concept:

- HP Ge-diodes (86%^{76}Ge): **point-like** energy deposition at $Q_{\beta\beta}$ = 2039 keV
- Operation of bare Ge diodes in **high-purity LN_2** or **LAr shield**
- **Baseline: LN_2:** ρ=0.8 g/cm^3
- possible **upgrade LAr:** ρ=1.4 g/cm^3, active anti-coincidence with scintillation light from LAr
- Reduction of backgrounds key to sensitivity :
  - Half-life limit
    - w/o backgrounds: $t_{1/2} \propto (MT)$
    - with backgrounds: $t_{1/2} \propto (MT)^{1/2}$
- Only method to scrutinize 0ν-DBD claim on short time scale: test $T_{1/2}$, not m_{ee} !
- Phased approach: increment of target mass

Phases and Physics reach of GERDA

Phase I :
15 kg, 15 kg y

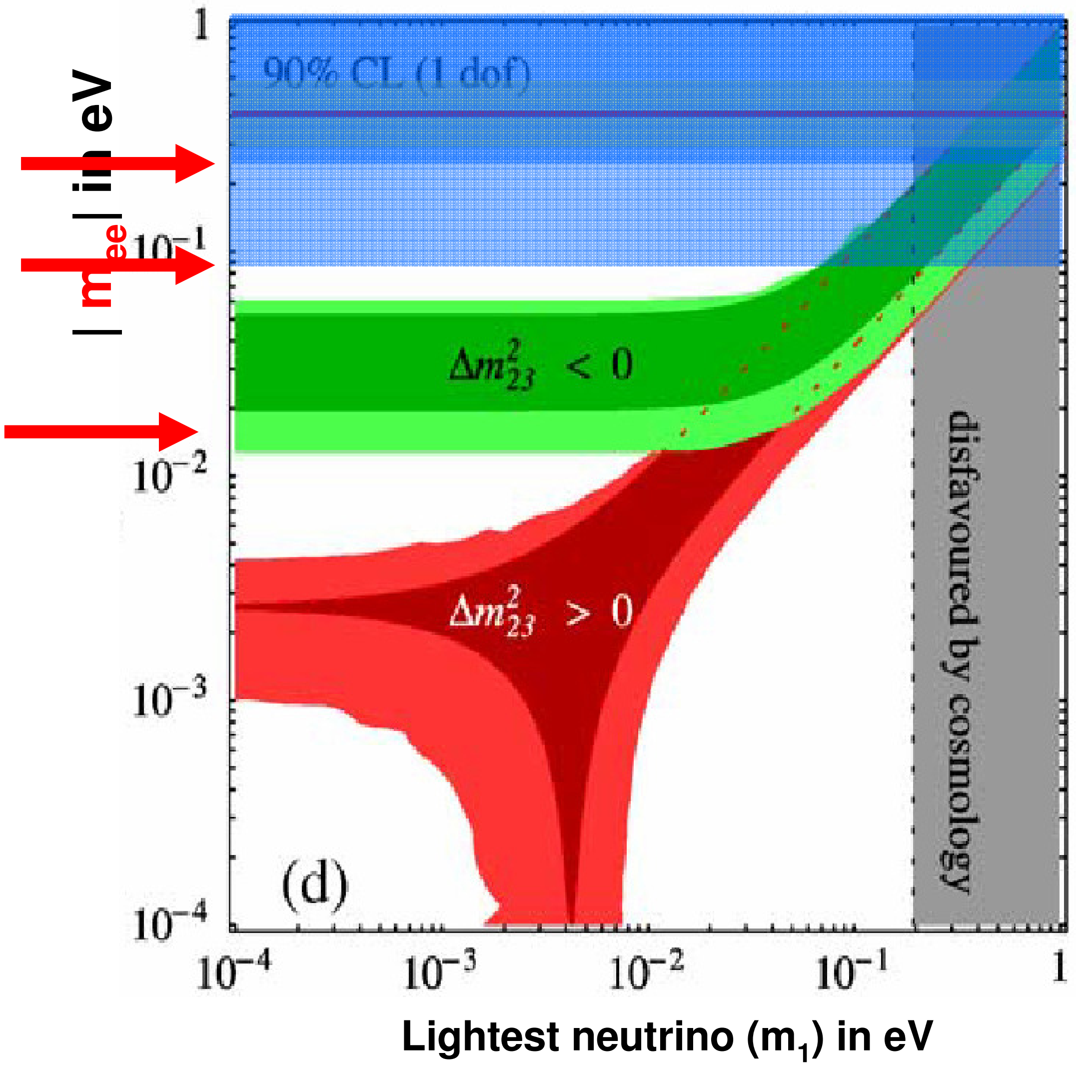
Phase II :
35 kg, 100 kg y

Phase III:
~ 500 kg?

Phase I:

Phase II:

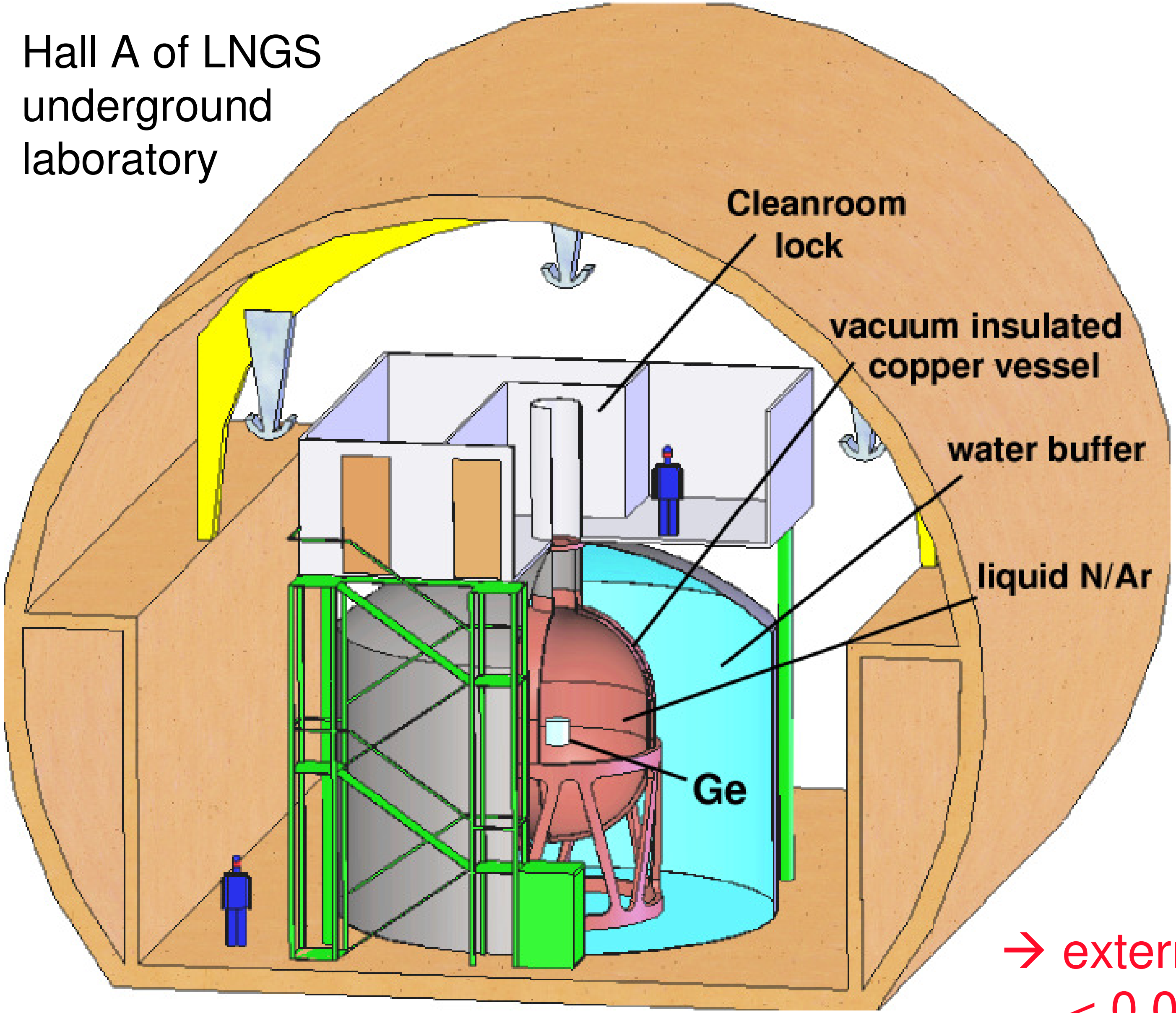
Phase III:



F.Feruglio, A. Strumia, F. Vissani, NPB 659

GERDA - Setup

Hall A of LNGS
underground
laboratory



4m Ø Cu cryostat
50 m^3 of liquid nitrogen
10 m Ø water tank
700 m^3 of water

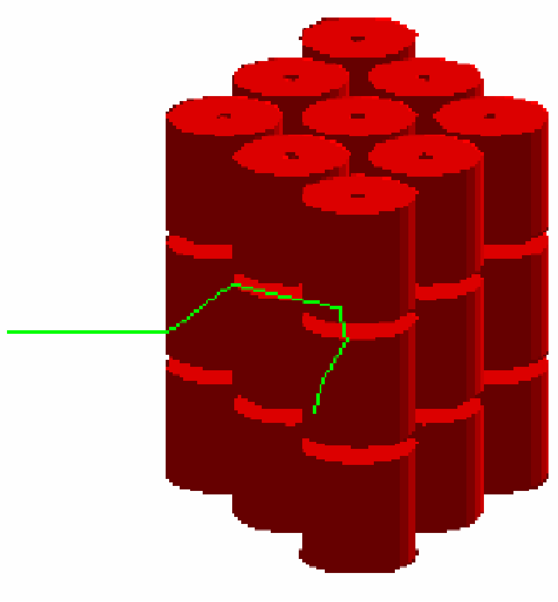
Graded shielding

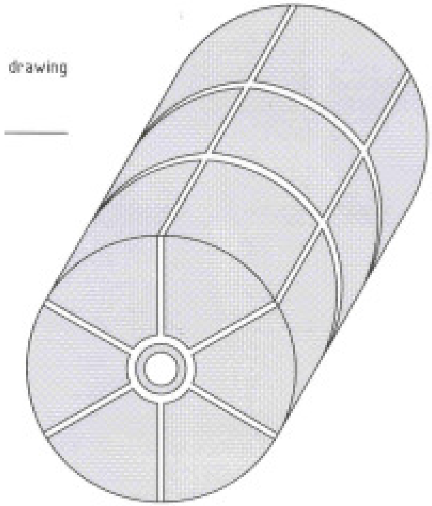
Advantages of water:

- shielding > than LN,
- cheaper,
- safer,
- neutron moderator,
- Cherenkov medium for muon veto

→ external γ/n/m background
< 0.001 cnt/(keV kg y) for LN
~ factor 10 smaller for LAr

Background





Background Contributions :

- internal ^{68}Ge, ^{60}Co
- surface contamination
- external gammas ^{208}Tl
- ^{222}Rn in liq. N_2, Ar
- U, Th in holder
- ext. muons, neutrons

Background Reduction:

- Muon Veto
- Anti-coincidence between detectors
- Segmentation of readout electrodes (Phase II)
- Pulse shape analysis (Phase I+II)
- Coincidence in decay chain (Ge-68)
- Scintillation light detection (LAr)

Total Background:

Phase I:	$< 10^{-2}$ / (keV kg y)
Phase II:	$< 10^{-3}$ / (keV kg y)
(HDM	~ 0.11/(keV kg y)
CTF	~ 0.002 /(keV kg y))

GERDA - Schedule

- approved by LNGS with location in Hall A,
- substantially funded by BMBF, INFN, MPG, and Russia in kind
- construction to start in LNGS Hall A in summer 2006
- parallel and fast R&D for phase II
- start of data taking in 2007

goal: **phase I :** background 0.01 cts / (kg·keV·y)

► scrutinize KKDC result within 1 year

phase II : background 0.001 cts / (kg·keV·y)

► $T_{1/2} > 2 \cdot 10^{26}$ y , $<m_{ee}> < 0.09 – 0.29$ eV

phase III : world wide collaboration

► $T_{1/2} > \sim 10^{28}$ y , $<m_{ee}> \sim 10$ meV

GERDA- Schedule

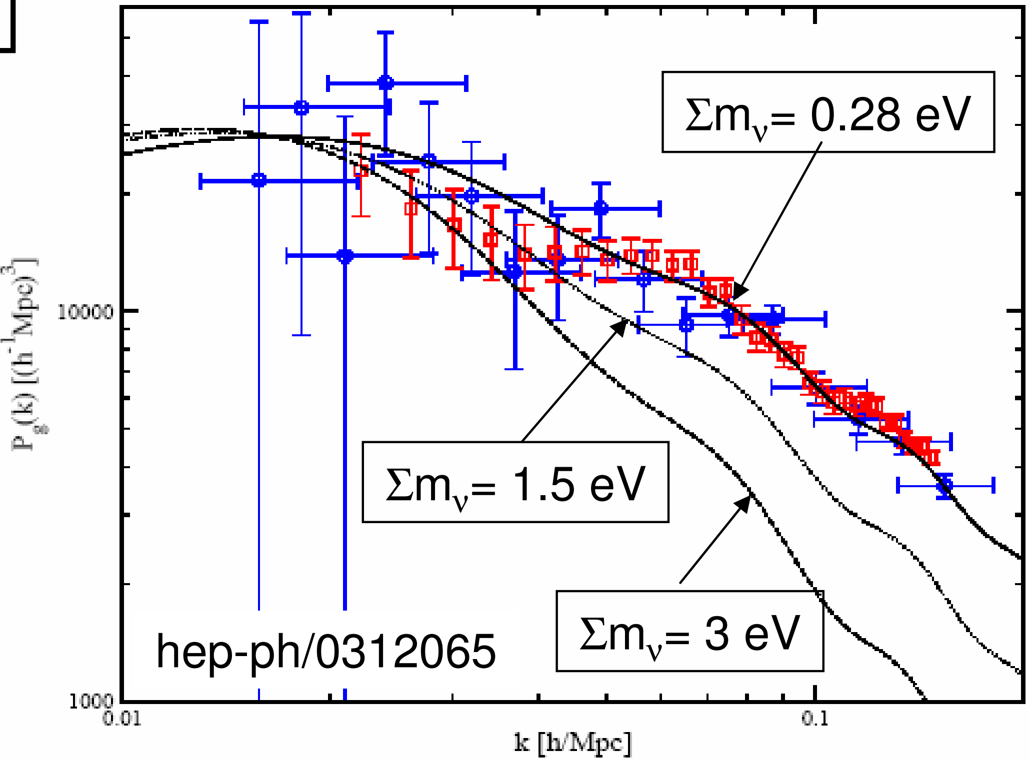
Cosmological limits on neutrino masses

neutrinos are Hot Dark Matter (HDM) => structure formation suppressed on small scales (large k)

neutrino mass is one parameter in LSS and CMB determination

$$\boxed{\frac{\Delta P_m}{P_m} \approx -8\,\frac{\Omega_\nu}{\Omega_m} \approx -0.8\left(\frac{\Sigma m_\nu}{1\mathrm{eV}}\right)\left(\frac{0.1}{\Omega_m h^2}\right)}$$

Galaxy power spectrum



hep-ph/0312065

Results e.g.

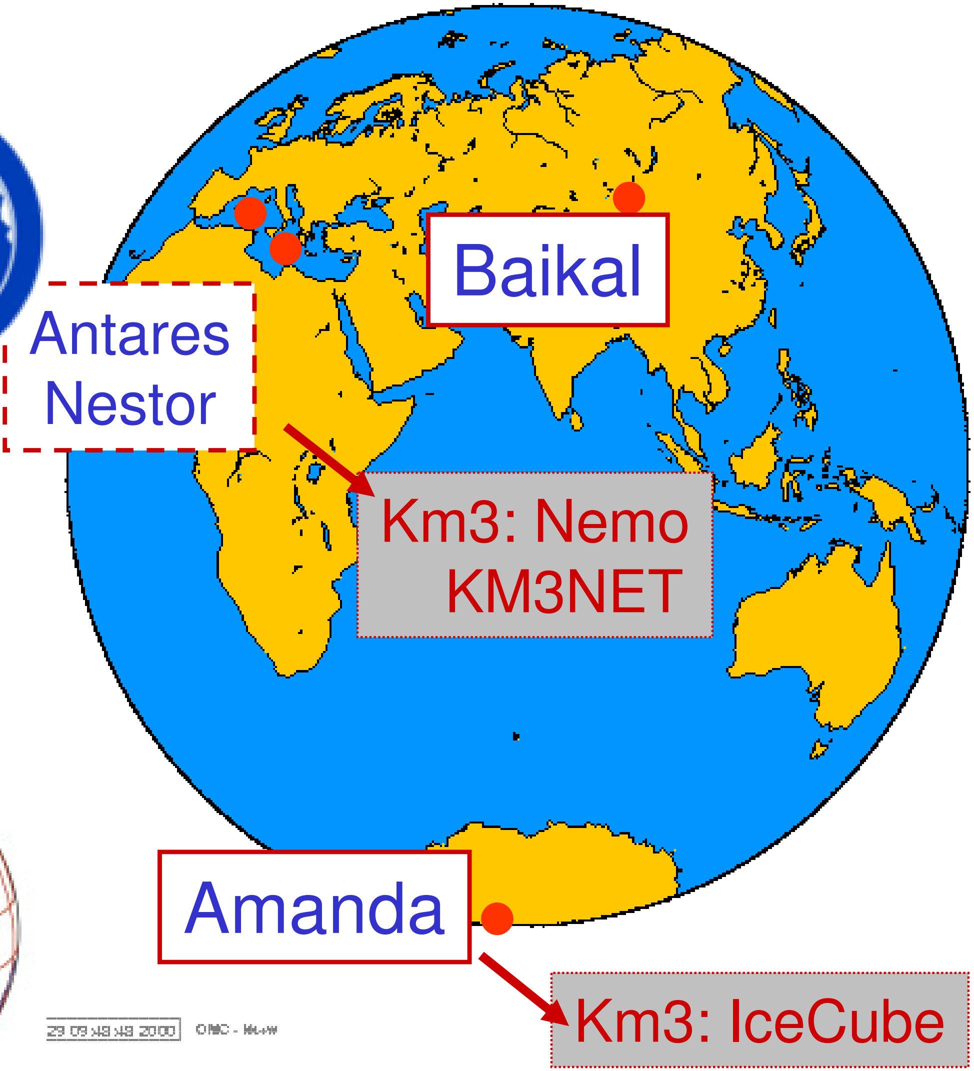
- WMAP + 2dFGRS + Lyα
  => $\Sigma m_\nu < 0.71$ eV (95%CL)
  (Spergel et al., astro-ph 0302209)
- WMAP + SDSS
  => $\Sigma m_\nu < 1.7$ eV (95%CL)
  (Tegmark et al., astro-ph 0310723)

Similar sensitivity as laboratory measurements

Caveat: Results are model dependent!

Future: astronomy with neutrinos

Neutrino telescopes:
large water (or ice) Cherenkov detectors (km^3) for the detection of UHE neutrinos



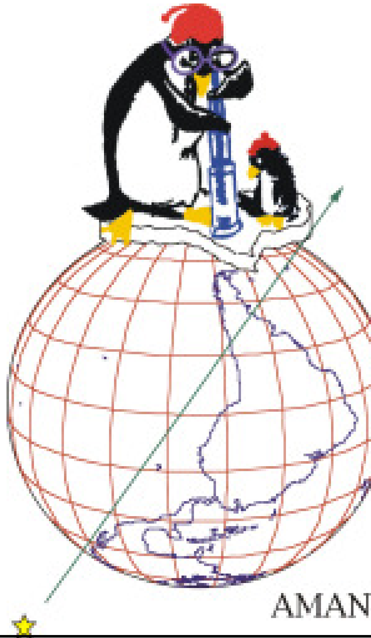
Antares
Nestor

Baikal

Km3: Nemo
KM3NET

Amanda

Km3: IceCube



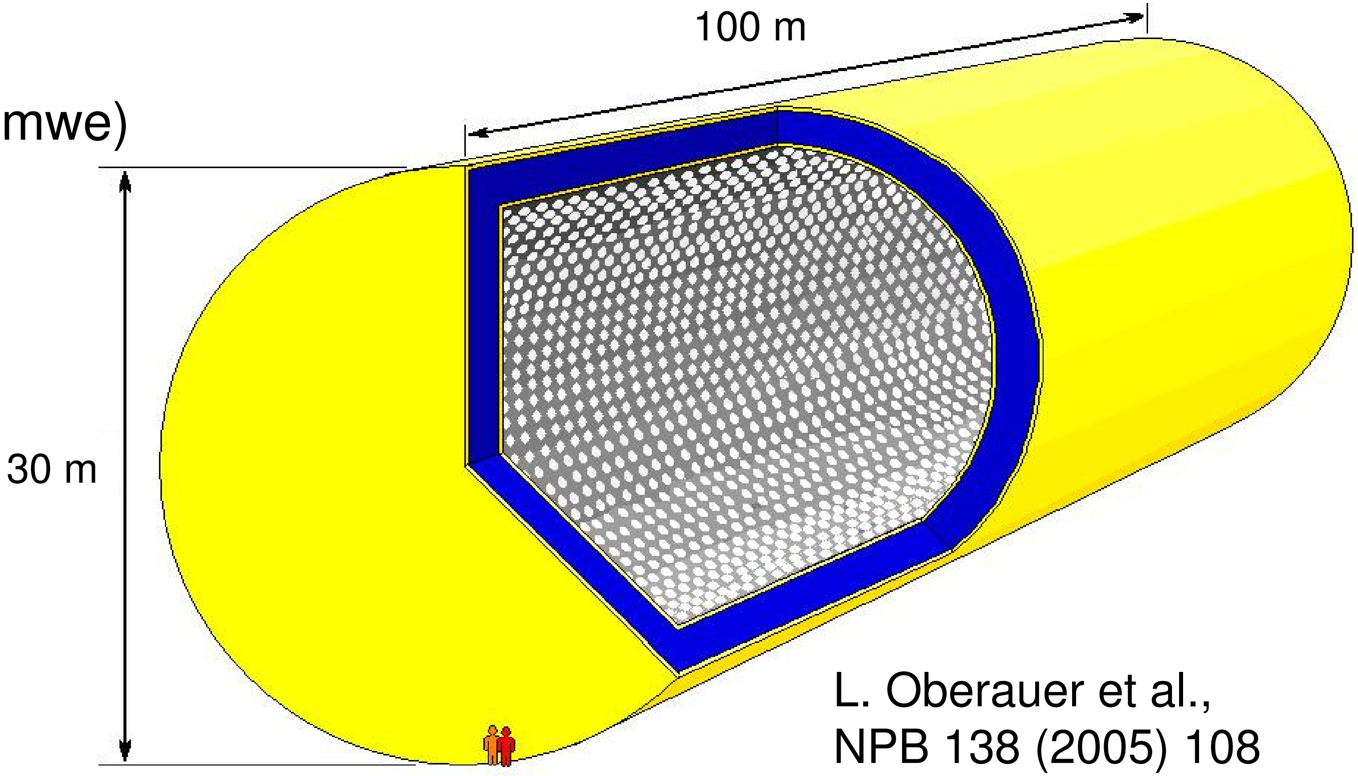
LENA (Low Energy Neutrino Astrophysics)

Low background detector with ~ 50 kt liquid scintillator , ~ 10000 PMTs

- detection of galactic Supernova neutrinos
- detection of Supernova relic neutrinos
- search for proton decay $p \to K^+ \bar{\nu}$
- spectroscopy of solar neutrinos (pep, CNO)
- detection of geo neutrinos (georeactor?)
- detection of low energy atmospheric neutrinos
- detector for very long baseline accelerator experiments

possible locations (~4000 mwe)

CENTRE FOR UNDERGROUND
PHYSICS IN PYHÄSALMI MINE



L. Oberauer et al.,
NPB 138 (2005) 108

LENA – Supernova neutrinos

possible neutrino reactions
in liquid scintillator:

Event rates for a SN IIa in
the galactic centre (~10 kpc)

(1)	$\bar{\nu}_e + p \rightarrow e^+ + n$	$(\mathrm{Q} = 1.8\ \mathrm{MeV})$	~ 7800
(2)	$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	$(\mathrm{Q} = 13.4\ \mathrm{MeV})$	
(3)	$\nu_\mathrm{e} + {}^{12}C \rightarrow e^- + {}^{12}N$	$(\mathrm{Q} = 17.3\ \mathrm{MeV})$	~ 65
(4)	$\nu_\mathrm{x} + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$	with ${}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma$ $(\mathrm{Q} = \mathrm{E}_\gamma = 15.1\ \mathrm{MeV})$	~ 4000
(5)	$\nu_\mathrm{x} + e^- \rightarrow \nu_\mathrm{x} + e^-$	(elastic scattering off electrons)	~ 480
(6)	$\nu_\mathrm{x} + p \rightarrow \nu_x + p$	(elastic scattering off protons).	~2200

- electron antineutrino spectroscopy with (1), (2)
- electron neutrino spectroscopy with (3) (use (1) to disentangle (2), (3))
- (4) gives information on total neutrino flux (monoenergetic γ)
- low energy neutrino spectroscopy with (5), (6)

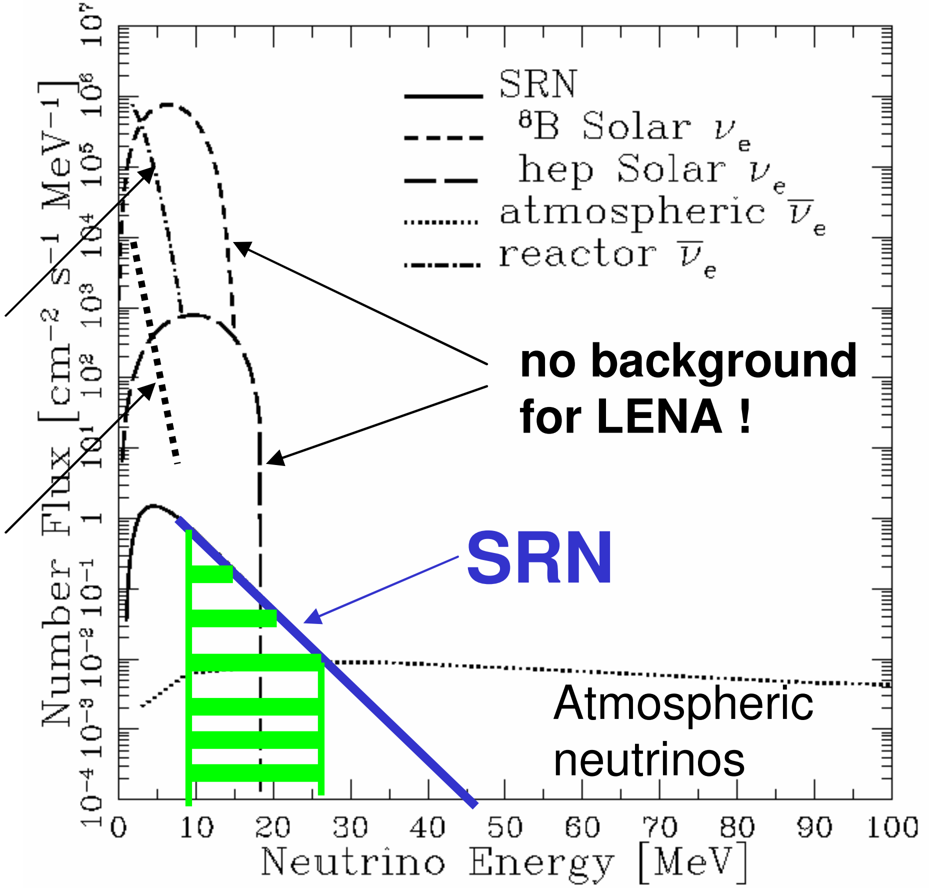
LENA - Supernovae Relic Neutrino Detection

- SRN flux gives information about star formation in the early universe
- Super-Kamiokande limit (< 1.2 cm^{-2} s^{-1} for E > 19 MeV) close to theoretical expectations
- use delayed coincidence $\bar{\nu}_e$ p -> e$^+$ n
- advantage of LENA:

  low reactor neutrino background

  → threshold ~ 9 MeV (SK 19 MeV)
- predicted SRN rate in LENA

  ~ 6 counts per year



Reactor bg SuperK

Reactor bg LENA

no background for LENA !

SRN

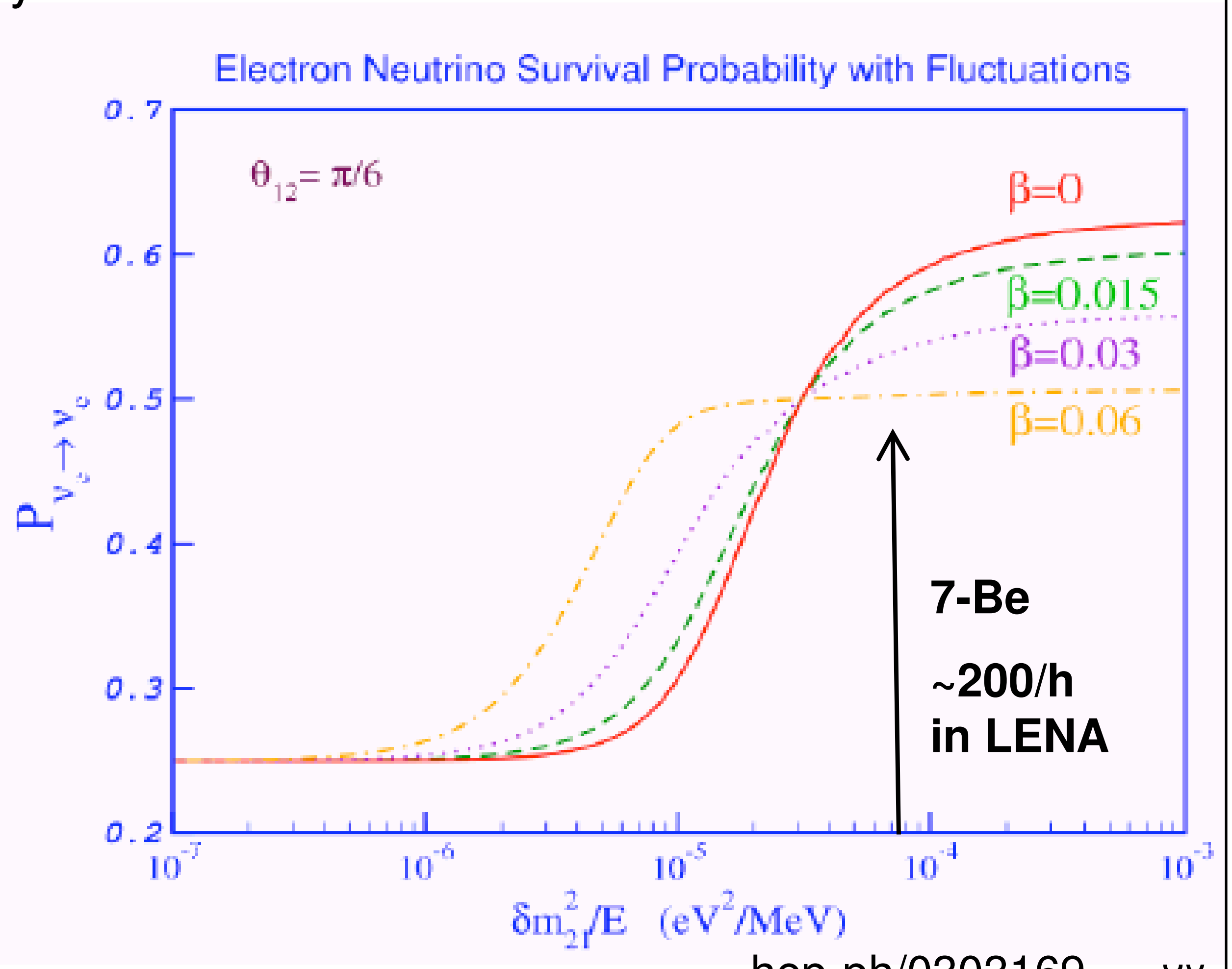
Atmospheric neutrinos

LENA - solar neutrinos

high statistics solar neutrino spectroscopy:

- ^{7}Be ~ 5400 events per day
  - ⇒ test of even small flux variations, e.g. due to density profile fluctuations look for coincidences with helioseismological data !
  - ⇒ test of day/night asymmetry (MSW effect in the earth)
- pep ~ 300 events per day
  - ⇒ solar luminosity
- CNO ~ 300 events per day
- ^{8}B-ν_e ~ 3 events per day from CC reactions on ^{13}C

⇒ precise determination of solar fusion processes



7-Be

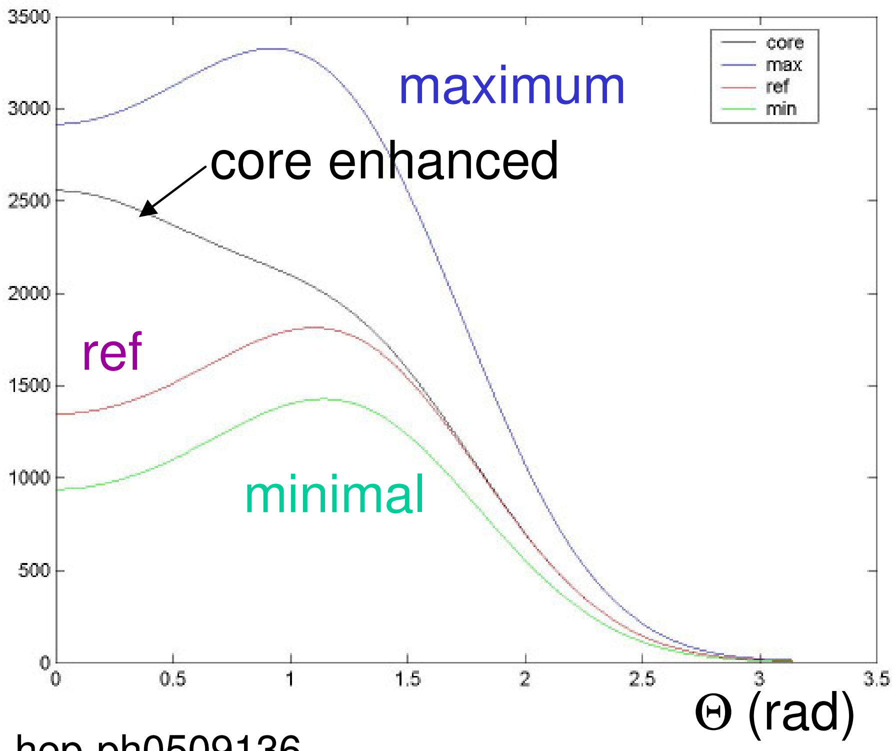
~200/h in LENA

hep-ph/0303169

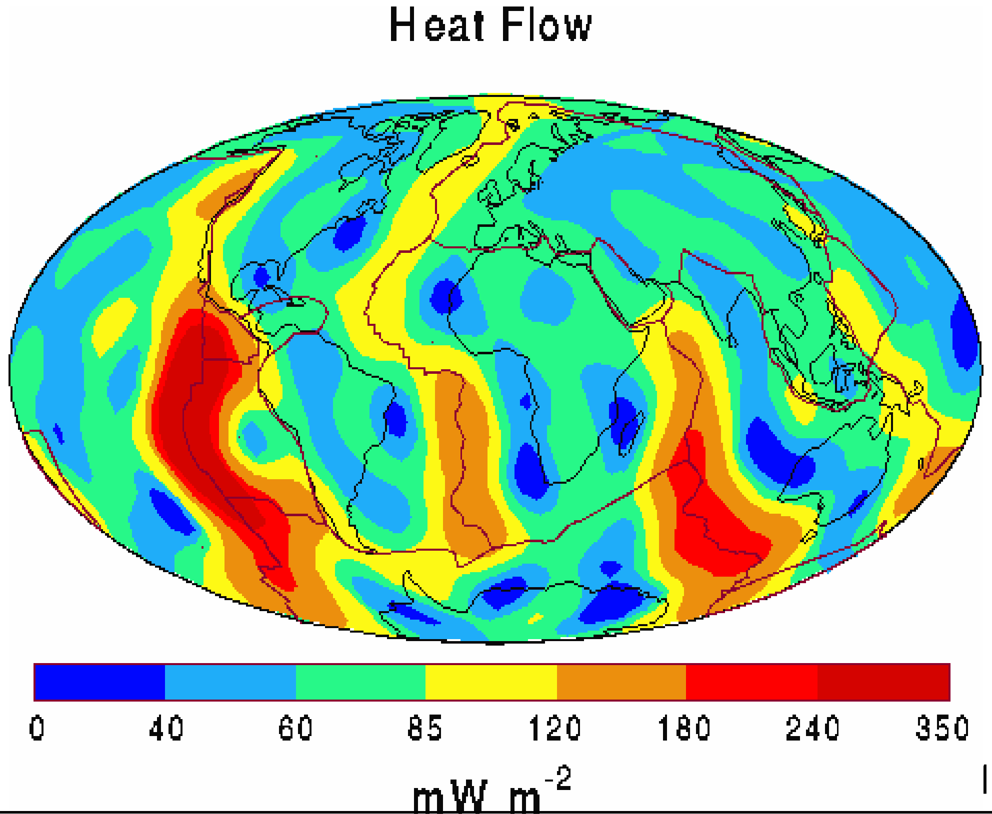
LENA - geoneutrinos

Detection via $p + \overline{\nu}_e \rightarrow n + e^+$

- source of the terrestrial heat flow
- contribution of natural radioactivity
- distribution of U, Th, K in crust, mantle and core
- hypothetical natural reactor at the Earth's center?



hep-ph0509136



LENA - atmospheric neutrinos

- LENA can measure the low energy part of atmospheric neutrinos, esp. $\overline{\nu}_e$
- for 30 MeV - 200 MeV ν_e :

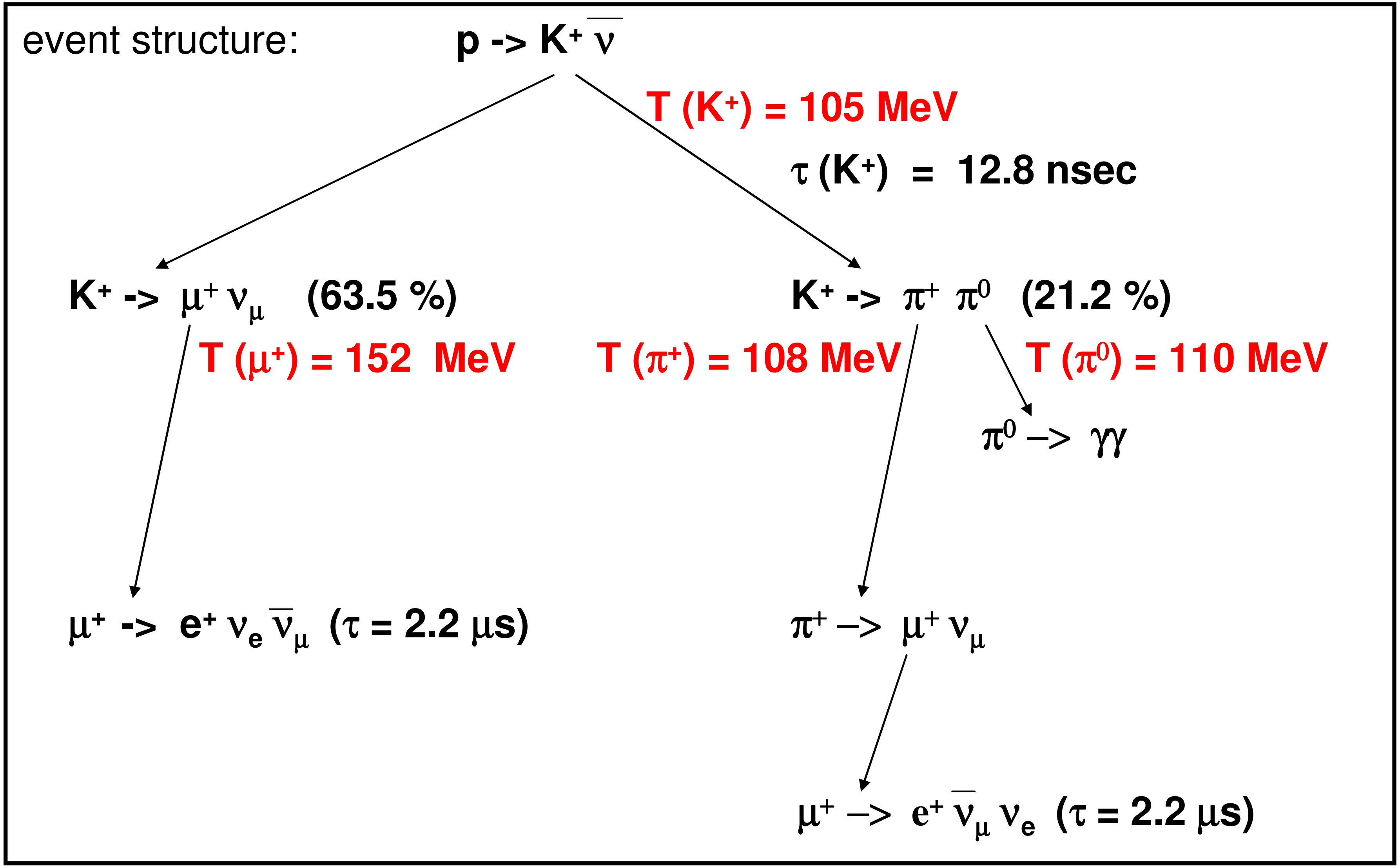
  L_{osc} ~ 10^3 km to 7 x 10^3 km (Δm^2 solar neutrinos!)

  $\overline{\nu}_e$ <–> $\overline{\nu}_\mu$ atmospheric oscillations, but based on Δm^2_{solar}
- observable ?

  ...difficult (low statistics), needs further investigations

LENA – proton decay

- proton decay predicted by GUT, SUSY theories
- decay mode p -> $K^+\bar{\nu}$ is invisible in water Cherenkov detectors



event structure: **p -> $K^+ \bar{\nu}$**

T (K^+) = 105 MeV

τ (K^+) = 12.8 nsec

K^+ -> $\mu^+ \nu_\mu$ (63.5 %)

T (μ^+) = 152 MeV

μ^+ -> $e^+ \nu_e \bar{\nu}_\mu$ (τ = 2.2 μs)

K^+ -> $\pi^+ \pi^0$ (21.2 %)

T (π^+) = 108 MeV

T (π^0) = 110 MeV

π^0 –> $\gamma\gamma$

π^+ –> $\mu^+ \nu_\mu$

μ^+ –> $e^+ \bar{\nu}_\mu \nu_e$ (τ = 2.2 μs)

- 3-fold coincidence, use time and position correlation, pulse shape analysis

Summary

Great progress in neutrino physics during last decade:

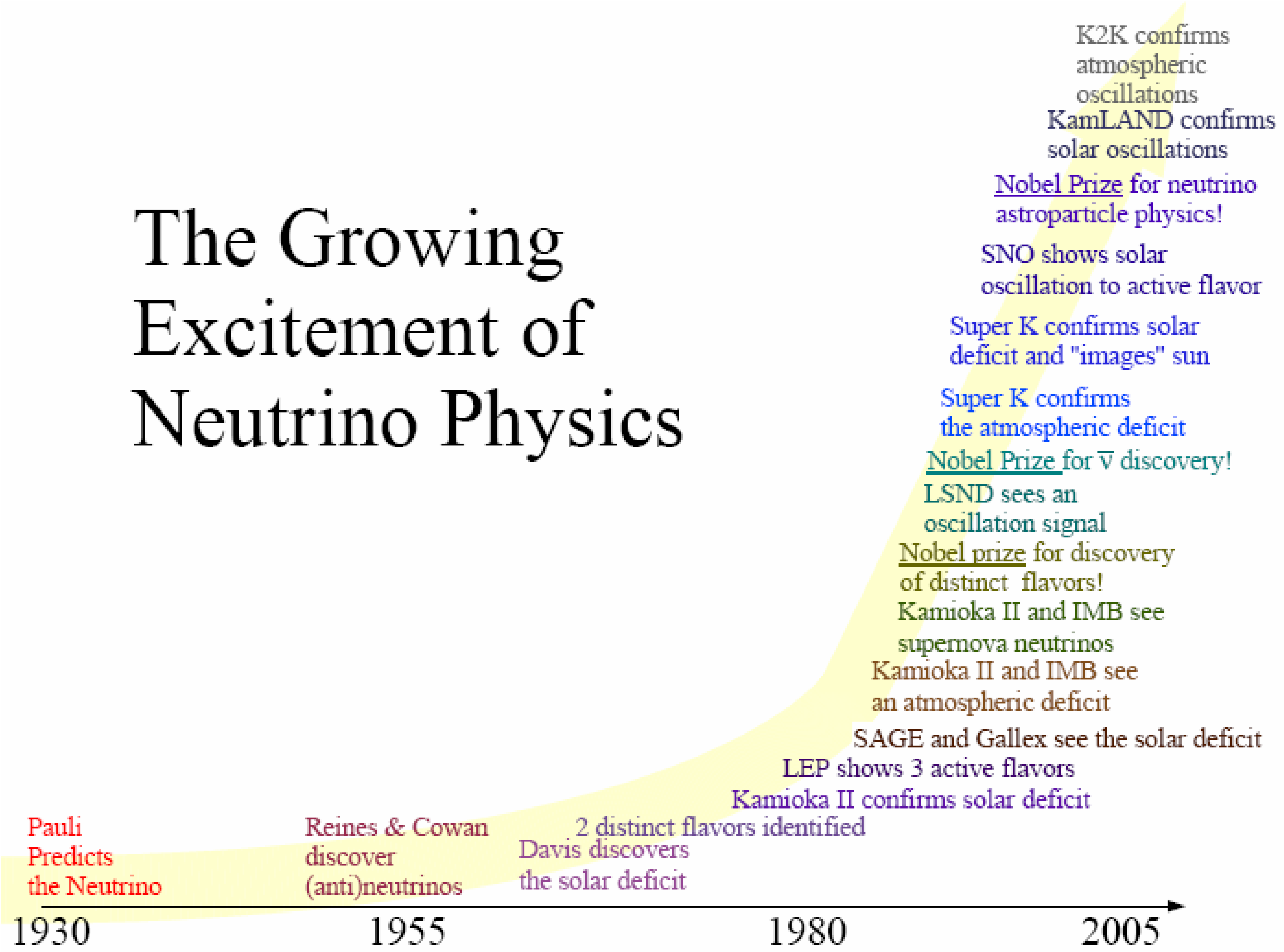
- solar and atmospheric neutrino oscillations detected
  => $m_\nu \neq 0$ physics outside SM
- upper limits from direct mass measurements (beta decay, $0\nu\beta\beta$, cosmological limits)
- all solar experiments so far have confirmed the Standard Solar Model

---

Program for the future:

- determine absolute neutrino mass (beta decay, $0\nu\beta\beta$, cosmological limits)
- determine θ_{13}, improve accuracy on θ_{12}, θ_{23} , Δm_{21}^2, Δm_{32}^2 (reactor, solar, atm oscillation experiments)
- establish Majorana nature of neutrino ($0\nu\beta\beta$)
- use neutrinos as messengers from the Sun, the Earth, the Universe...

???



The Growing Excitement of Neutrino Physics

Pauli Predicts the Neutrino

Reines & Cowan discover (anti)neutrinos

Davis discovers the solar deficit

2 distinct flavors identified

Kamioka II confirms solar deficit

LEP shows 3 active flavors

SAGE and Gallex see the solar deficit

Kamioka II and IMB see an atmospheric deficit

Kamioka II and IMB see supernova neutrinos

Nobel prize for discovery of distinct flavors!

LSND sees an oscillation signal

Nobel Prize for $\overline{\nu}$ discovery!

Super K confirms the atmospheric deficit

Super K confirms solar deficit and "images" sun

SNO shows solar oscillation to active flavor

Nobel Prize for neutrino astroparticle physics!

KamLAND confirms solar oscillations

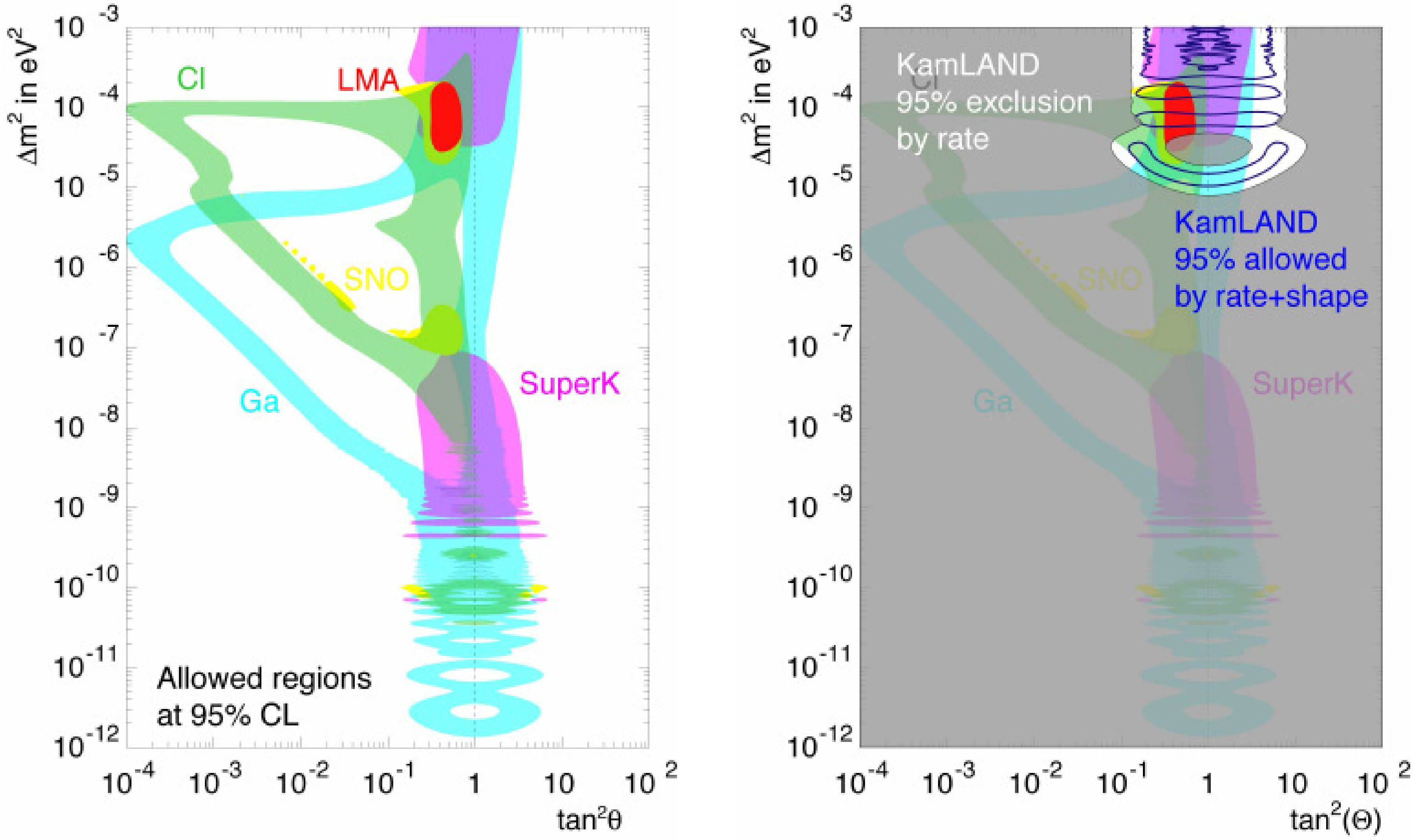
K2K confirms atmospheric oscillations

‚The neutrino matrix'/ physics 0411216

The End

Global Fit: Kamland + Solar Neutrino Experiments

http://hitoshi.berkeley.edu



LSND, MiniBoone

Goal: Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

LSND: E_ν~ 30 MeV, L ~ 30 m
3.8σ excess of ν_e
$\Delta m^2 = 0.3 - 3\ eV^2$
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$

Problem: third Δm^2 at ~ 1eV ➔
4 light ν? <–> Z^0 resonance (LEP): N_ν=3
➔ sterile neutrino ?!

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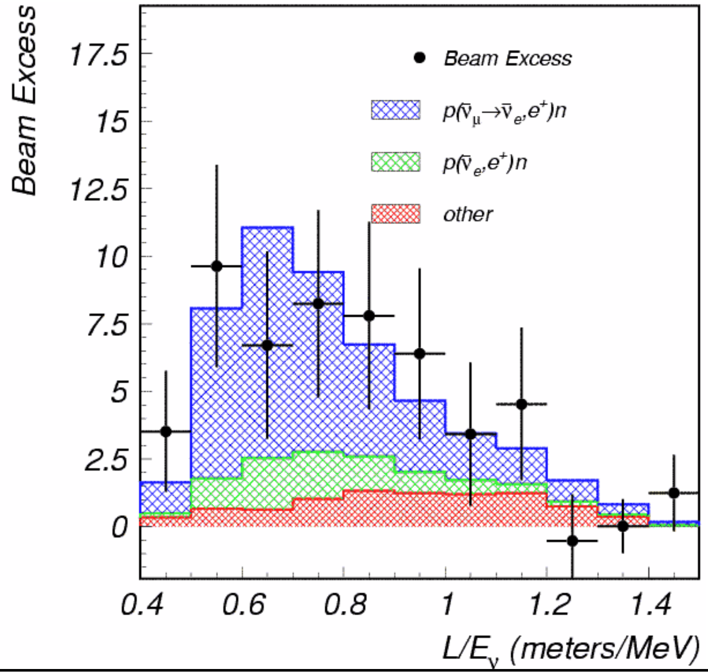
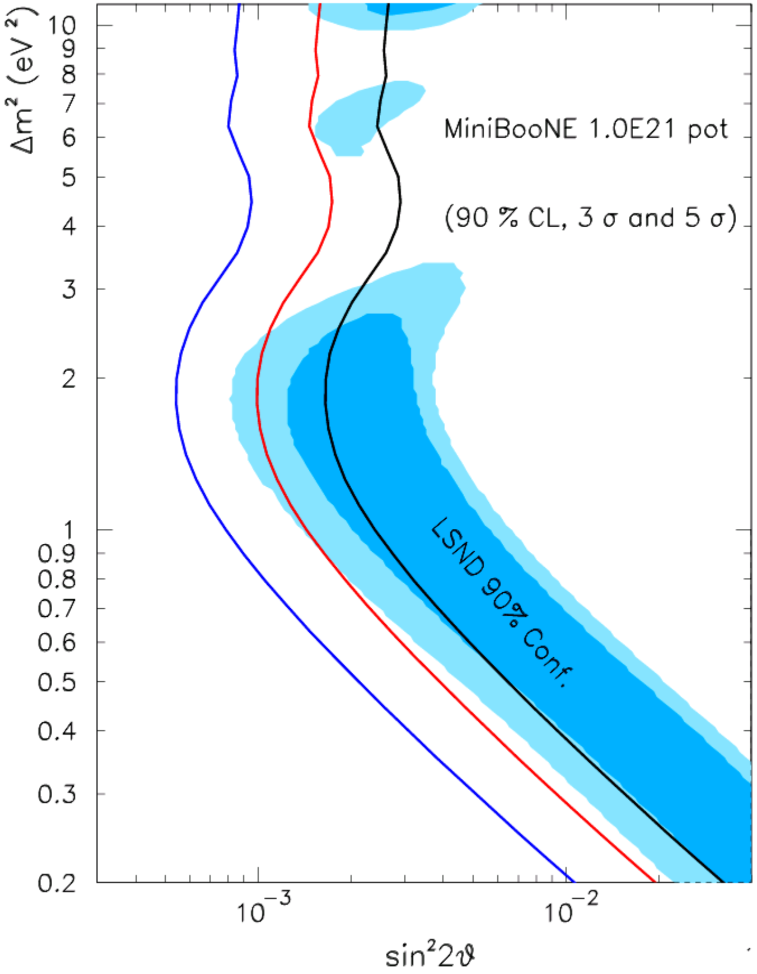


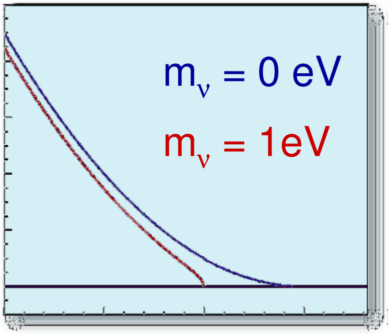


MiniBoone:
verify LSND result
E_ν~ 1 GeV, L ~ 500 m
data taking since end of 2002
Results expected soon !

Experimental Methods for the Determination of neutrino parameters

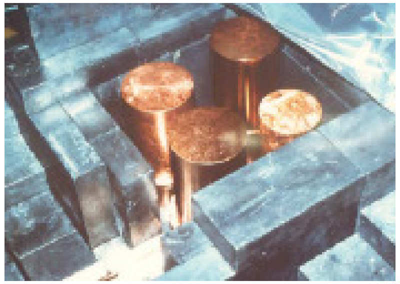
– meutrino oscillations

➔ mass differences Δm^2, mixing angles θ, maybe CP-violating phase δ



– kinematics of weak decays (e.g. beta decay)

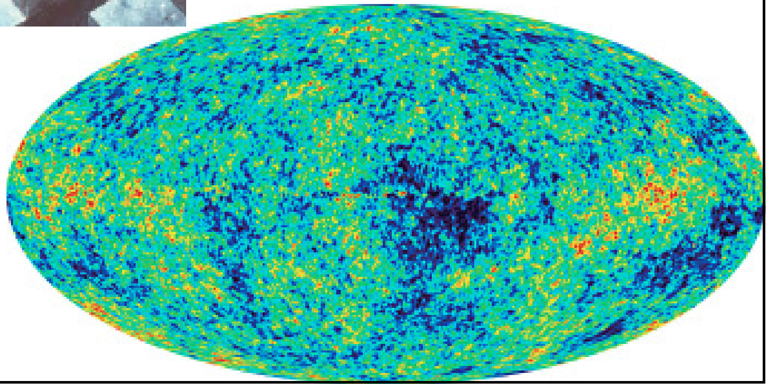
➔ neutrino mass



– neutrinoless double beta decay

➔ Majorana-neutrinos, neutrino mass

(maybe Majorana-phases ϕ_i)

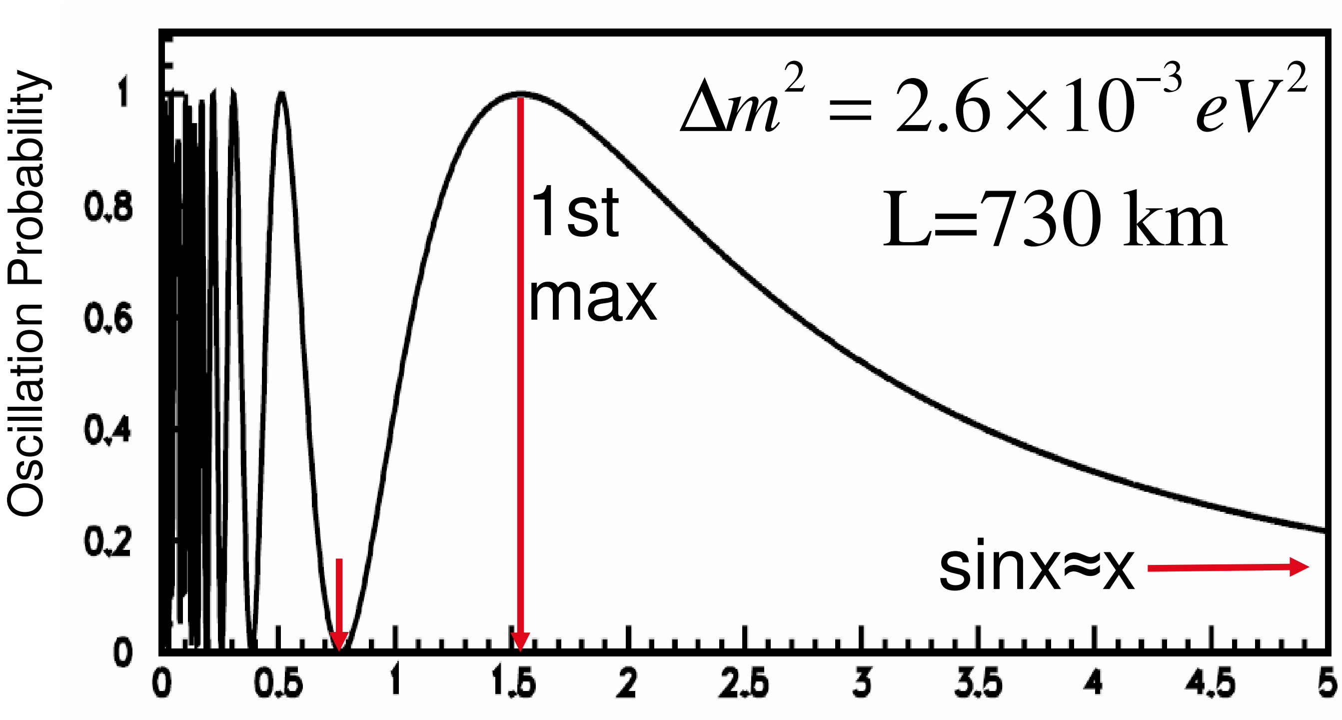


– cosmological limits

➔ neutrino masses, number of neutrinos

First Maximum and Minimum of the oscillation probability

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E_\nu(GeV)}\right)$$



$\Delta m^2 = 2.6\times10^{-3} eV^2$

L=730 km

1st max

sinx≈x

$\boxed{P \propto E_\nu^{-2}}$

E_{min} E_{max}

"On" peak

"Off" peak

$$\boxed{1.27\frac{L\ (\mathrm{km})}{E_{min}\ (\mathrm{GeV})}\Delta m^2\ (\mathrm{eV}^2) \simeq \pi.}$$

$$\boxed{1.27\frac{L\ (\mathrm{km})}{E_{max}\ (\mathrm{GeV})}\Delta m^2\ (\mathrm{eV}^2) \simeq \frac{\pi}{2}.}$$

Principle of the MAC-E-filter

- Two supercond. solenoids compose magnetic guiding field
- Electron source (T_2) in left solenoid
- e^- in forward direction: magnetically guided
- adiabatic transformation: $\mu = E_\perp/B = \text{const.}$

  $\Rightarrow$ parallel e^- beam
- Energy analysis by electrostat. retarding field

  $\Delta E = E \cdot B_{min}/B_{max}$

  $= E \cdot A_{s,eff}/A_{analyse}$

  ≈ 4.8 eV (Mainz)