Artificial neutrinos

- Reactor experiments (CHOOZ, PALOVERDE and th uture, KamLAND already covered)
- Neutrino beams based on medium energy accelerator
- I’ll not talk about high energy neutrino beams becaus here are no interesting results

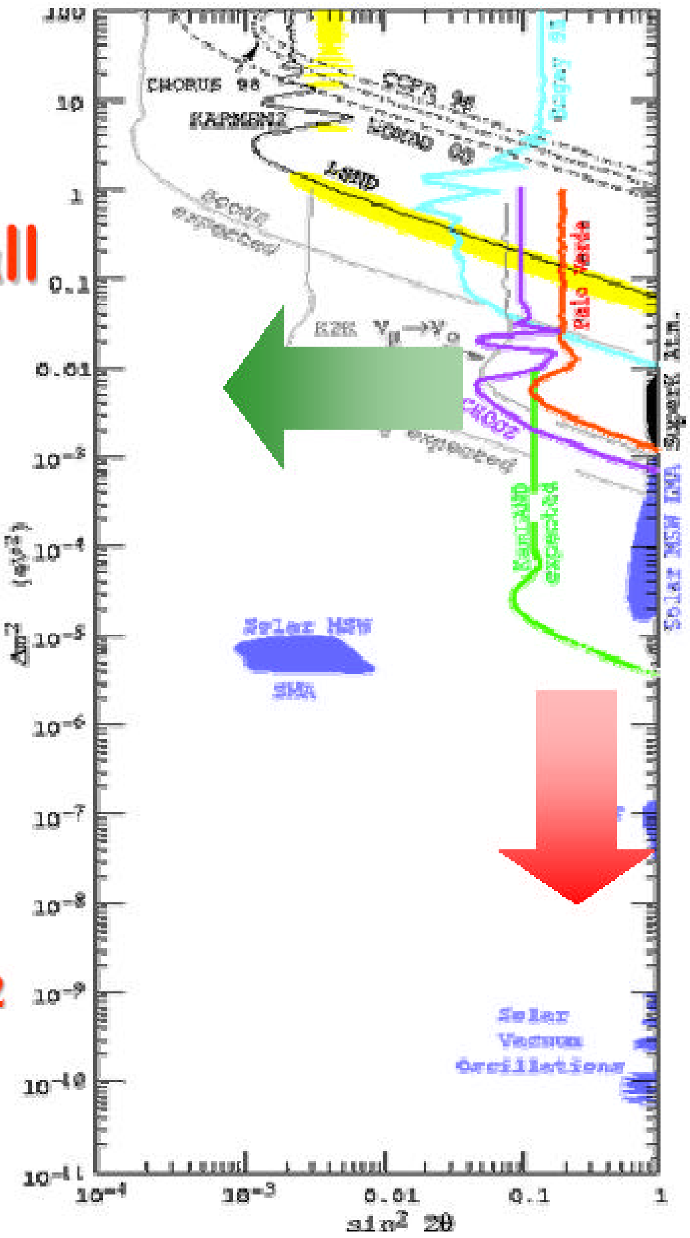
Complementary properties of
Reactors and Accelerators

E_ν~few MeV

an probe very small Δm^2

Disappearance only
→ fair $\sin^2 2\theta$ sensitivity

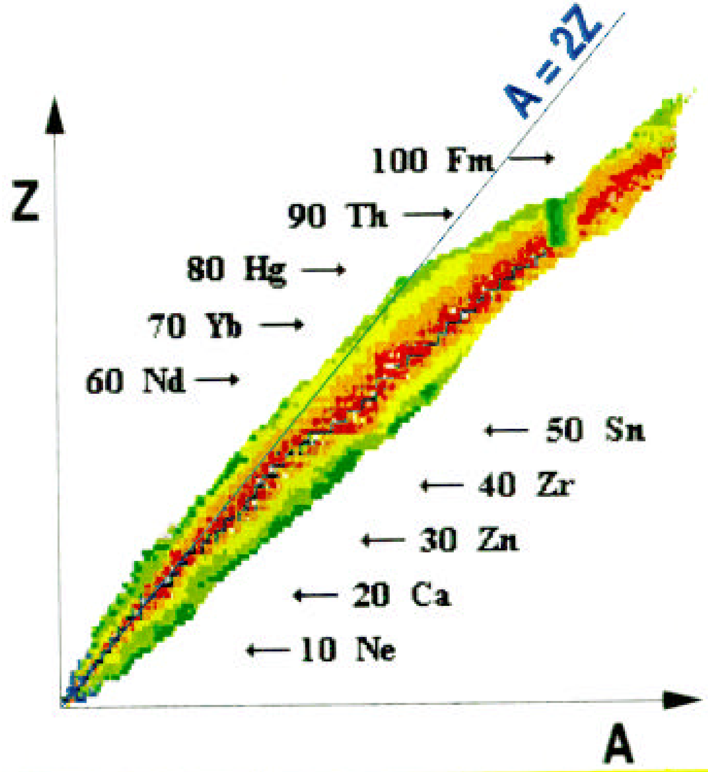
π source
→ detector mass grows with L^2



E_ν~few GeV

- Good mass sensitivity requires very large L
- Appearance possible (produce μ and
- "Collimated" beam

Fission fragments generally have excess neutrons and are β^- unstable



- Reactors are pure sources of ∇_e
- ∇_e "brilliance" $\propto$ Thermal Power
- Prediction of reactor ∇_e energy spectrum and "brilliance" requires careful bookkeeping
- ∇_e spectrum is in the MeV range typical of β decay

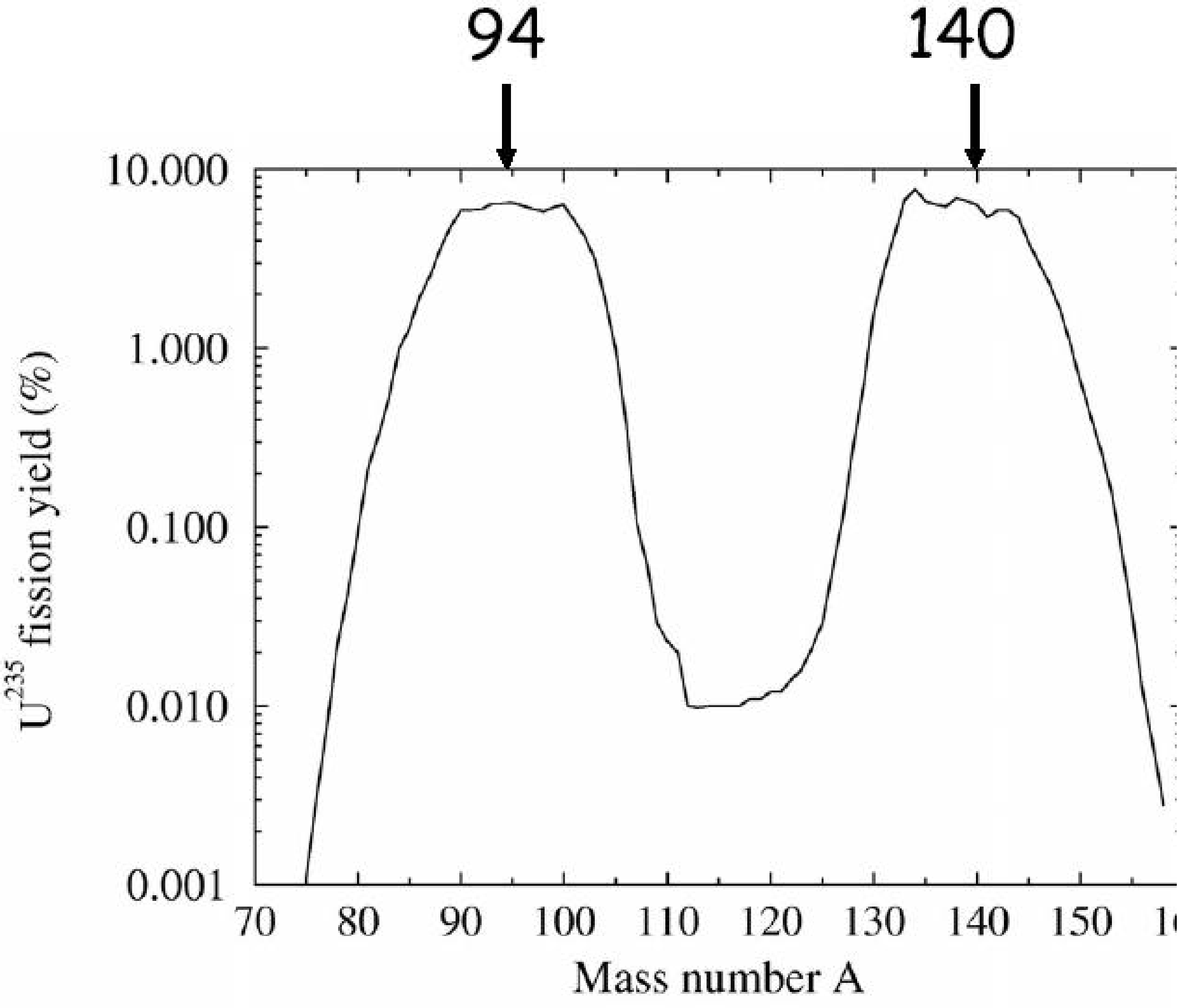
Example: ^{235}U fission

$${}^{35}_{2}U + n \rightarrow X_1 + X_2 + 2n$$

stable nuclei with A
most likely from fission

$${}^{94}_{40}Zr \qquad {}^{140}_{58}Ce$$

together these have
98 protons and
136 neutrons



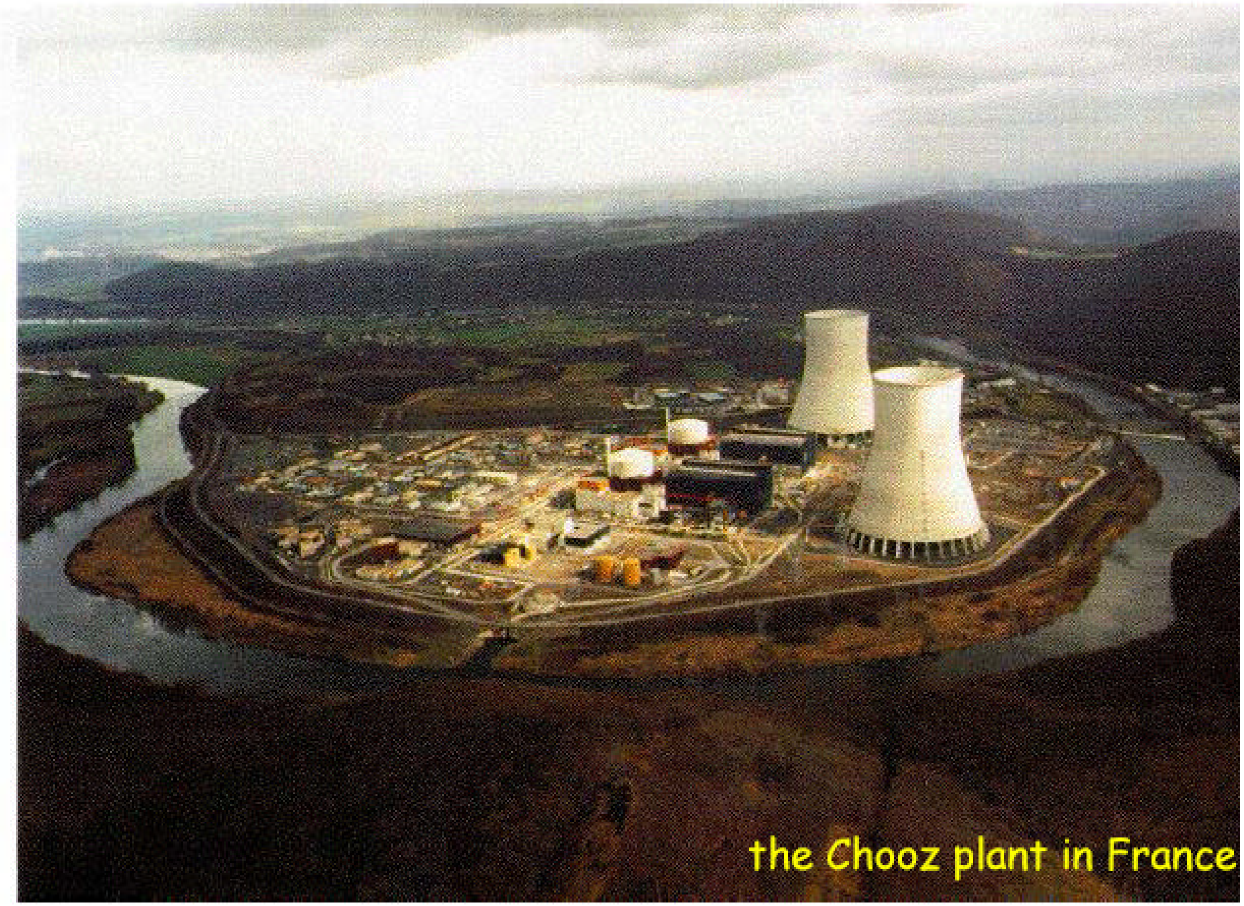
so, on average 6 n have to
decay to 6 p to reach stable matter

Power/commercial reactors are generally used since only requirement is to have large power

$$200\,MeV\,/\,fission$$

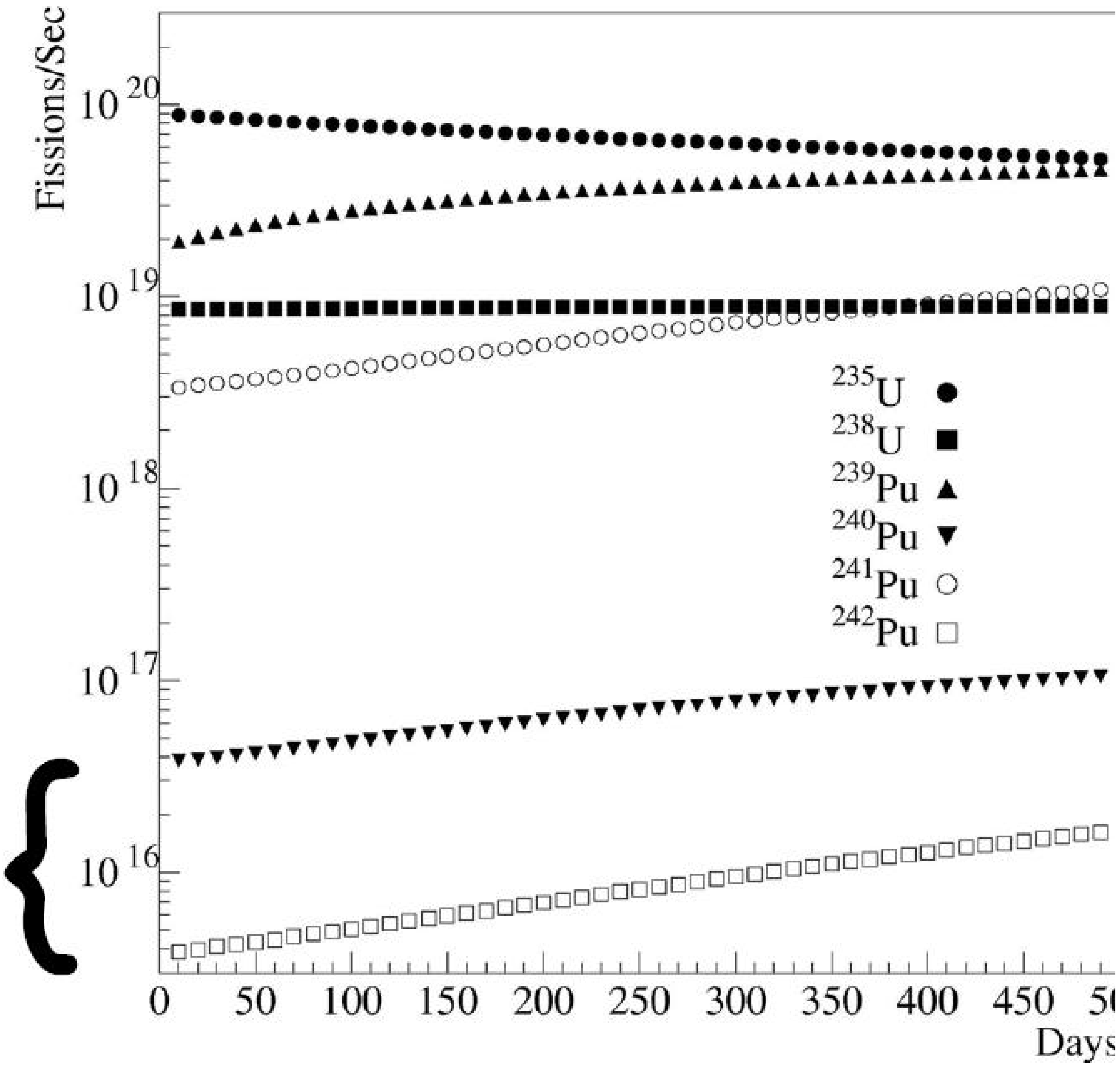
$$6\bar{\nu}_e\,/\,fission$$

A typical large power reactor produces 3 $GW_{thermal}$ and $6 \cdot 10^{20}$ antineutrinos/s



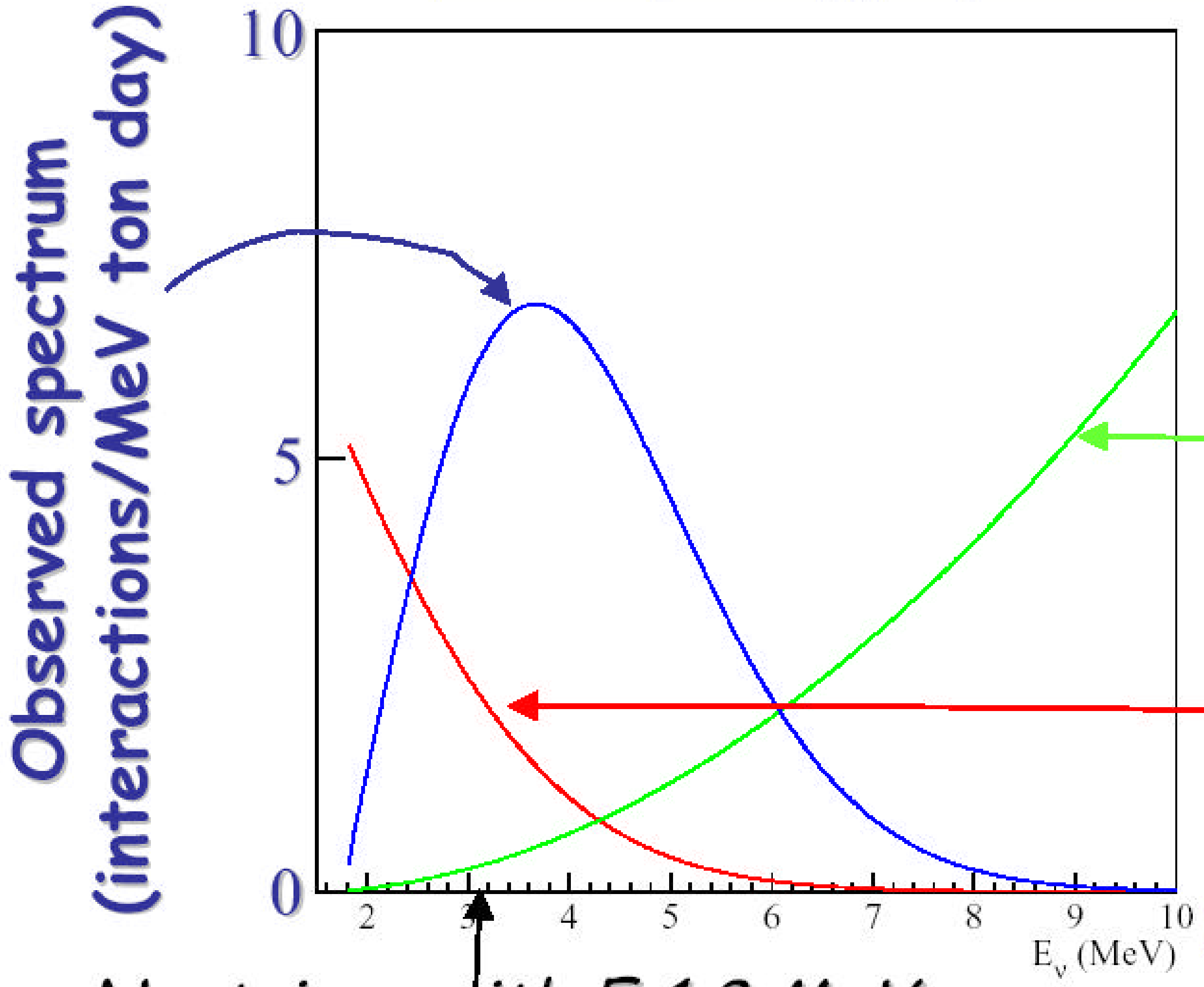
the Chooz plant in France

>99.9% of $\bar{\nu}$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu



contribution $<10^{-3}$ not taken into account for neutrino flux calculations

The $\bar{\nu}_e$ energy spectrum



$\nu_e + p \rightarrow n + e^+$

cross section

(~10^{-42} cm^2)

Calculated reacto

$\bar{\nu}_e$ spectrum

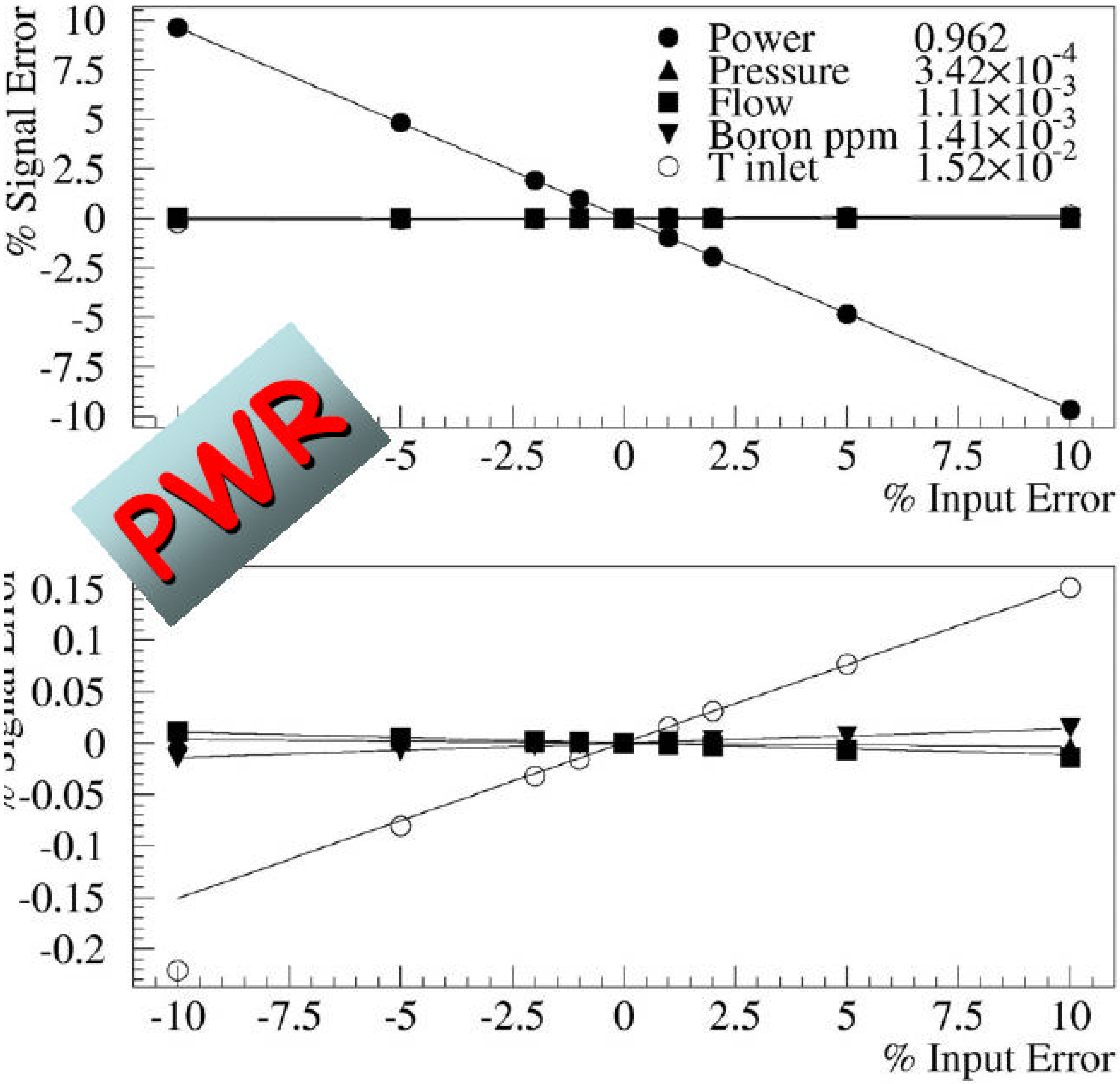
(10^{-8} /s MeV GW$_{th}$

Neutrinos with E<1.8 MeV
are not detected

So in practice only ~1.5 neutrinos/fission
can be detected above threshold

…disappearance experiments…
how well do we know the flux and spectrum ?

The 200 MeV/fission part:



Thermal power is routinely measurec by the reactor operator in order to adjust the reactor to the highest licensed power

Economics push the error on this to 0.6-0.7%

…disappearance experiments…
how well do we know the flux and spectrum ?
The 6 $\bar{\nu}$/fission part:

Anti-neutrino spectra from ^{235}U, ^{239}Pu and ^{241}Pu fission can be derived from β^- spectroscopy

This is not entirely trivial as there are very many fission branches and then many possible β decays for each branc

Schreckenbach et al. Phys. Lett. B160 (1985) 325
Hahn et al. Phys. Lett. B218 (1989) 365

From number of fissions to neutrinos...

β^- spectra from ^{235}U, ^{239}Pu, ^{241}Pu fission were measured directly at ILL

Hahn et al. Phys. Lett. B218 (1989) 365
Schreckenbach et al. Phys. Lett. B160 (1985) 325

An empirical parametrization:

$$\frac{dN_\nu}{dE_\nu} = e^{(a_0 + a_1 E_\nu + a_2 E_\nu^2)}$$

can be used to reproduce the spectra from each of the 3 isotopes

^{238}U spectrum was not measured as it requires neutrons of higher energy than available (more later)

Approximately

200 MeV/fission
6 $\bar{\nu}$ /fission

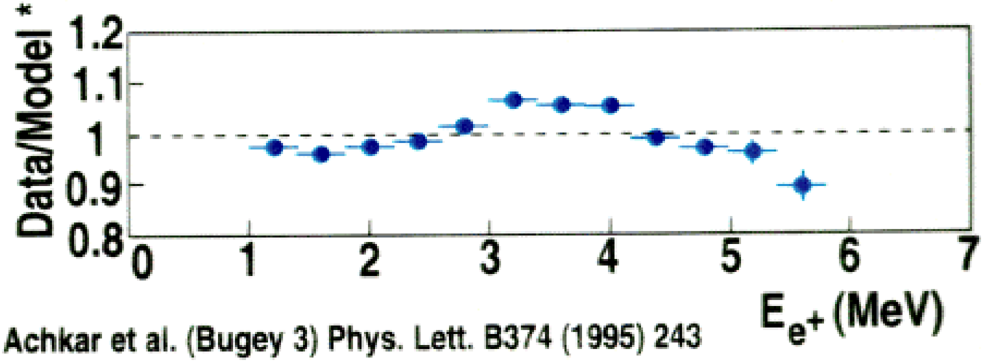
$1\ \mathrm{GW}_{\mathrm{Thermal}} = 1.9 \times 10^{20}\ \bar{\nu}$

2000

Reactor spectra can also be calculated as weighted sums of β spectra for all the fission products.

Typically ~750 decays have been considered of which ~270 have experimentally complete decay schemes.

There is generally good agreement between models and high statistics experiments (with detectors near reactor cores)



* Data: Achkar et al. (Bugey 3) Phys. Lett. B374 (1995) 243

Model: H.V. Klapdor and J.Metzinger Phys. Lett. B112 (1982) 22,
Phys. Rev. Lett. 48 (1982) 127

(Other models: Davis et al. Phys. Rev. C 19 (1979) 2259
Vogel et al. Phys. Rev. C 24 (1981) 1543
Tengblad et al. Nucl. Phys. A503 (1989) 136)

These calculations are used for cross-checks and for the spectrum from ^{238}U

The $\bar{\nu}$ yield from ^{238}U derives from fast-neutron fission and could not be measured in the papers above

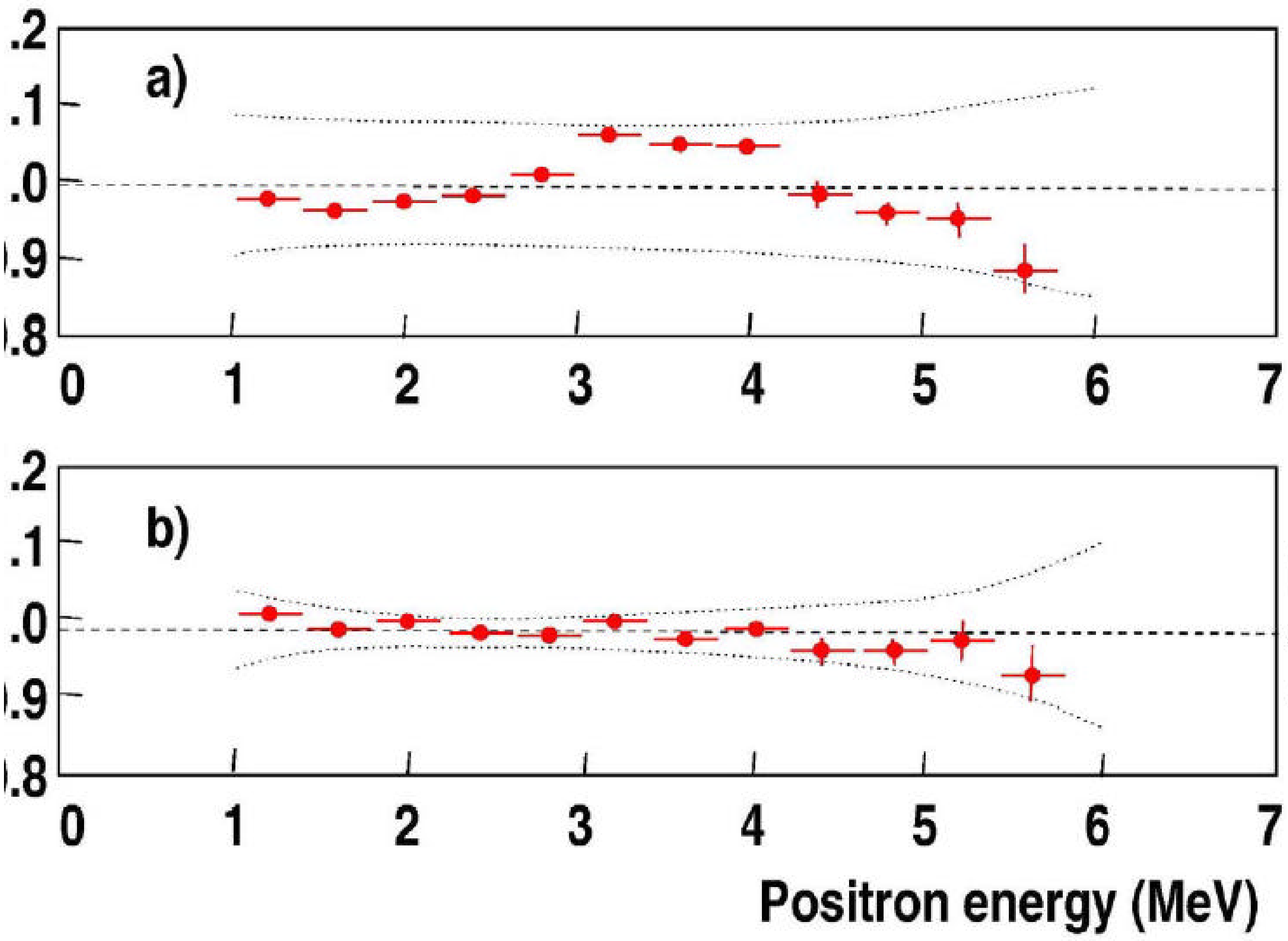
…but one can also calculate the $\bar{\nu}$ yield from first principles

Errors of about 10% are typical in these calculations tha have to include ~1000 channels

So, ^{238}U that contributes about 11% to the total yield, introduces a total error of about 1%

All these techniques can be cross-checked using precise $\bar{\nu}$ spectra measured at short baseline reactor experiments

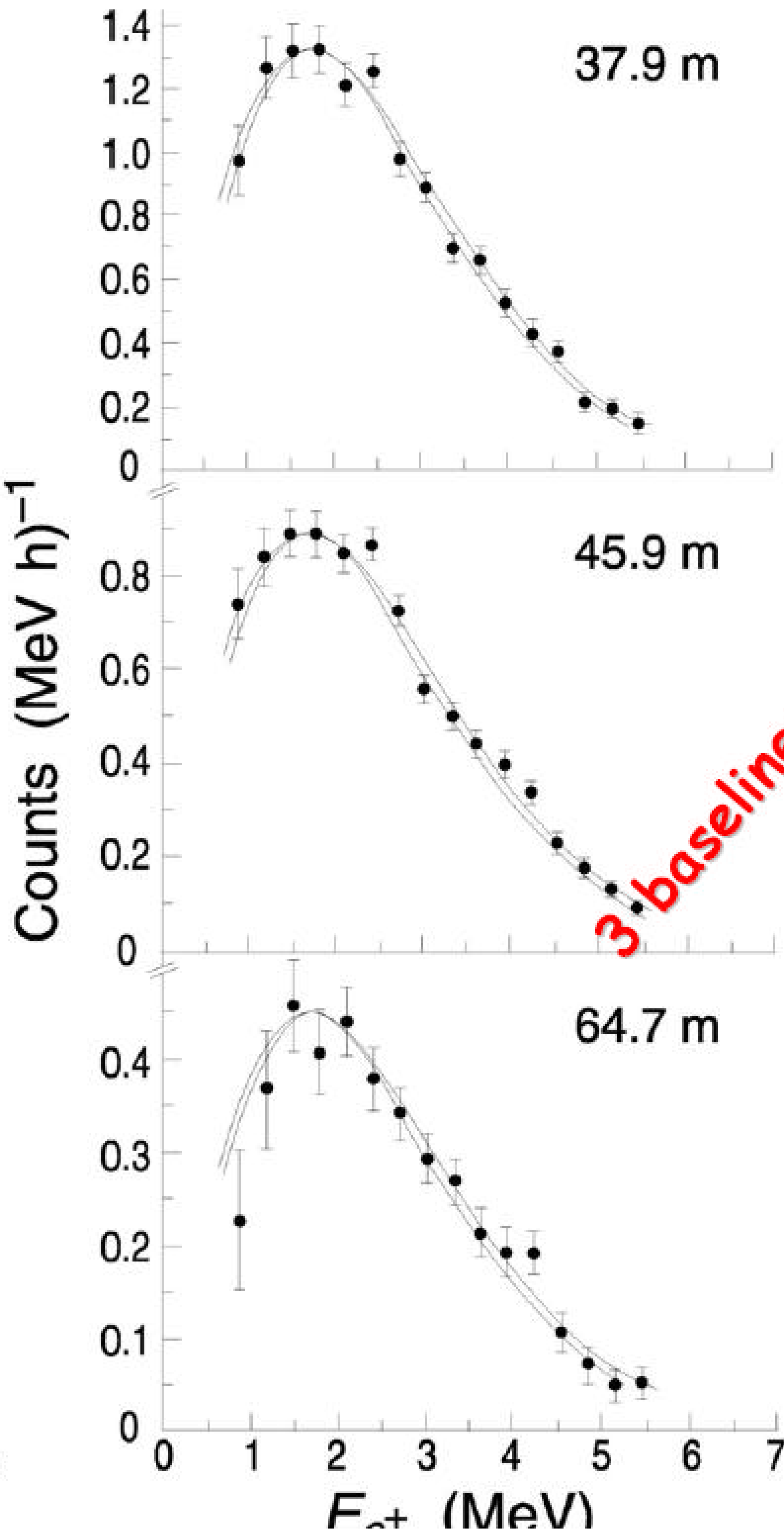
From Bugey3 exp (short baseline, 1.5*10^5 events)



Bugey3/"first principle calculatior

Bugey3/"best prediction" *(uses β-spectra where possible and calculation for ^{238}U)*

Of course the use of
short baseline experiments
to check normalization
implies no oscillations,
as it can be directly
checked in cases where the
baseline was varied



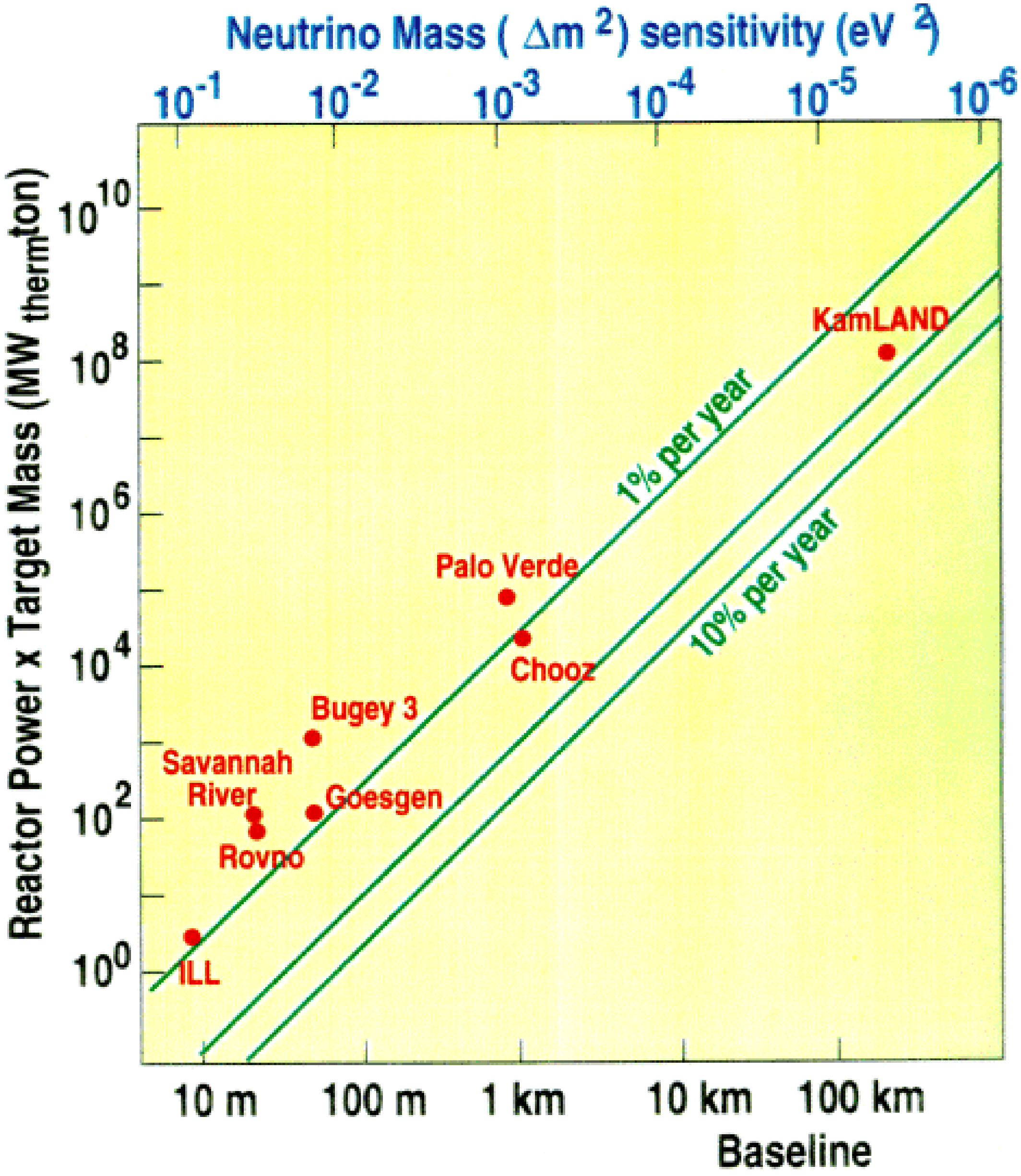
3 baselines at Goesgen

Conclusion:

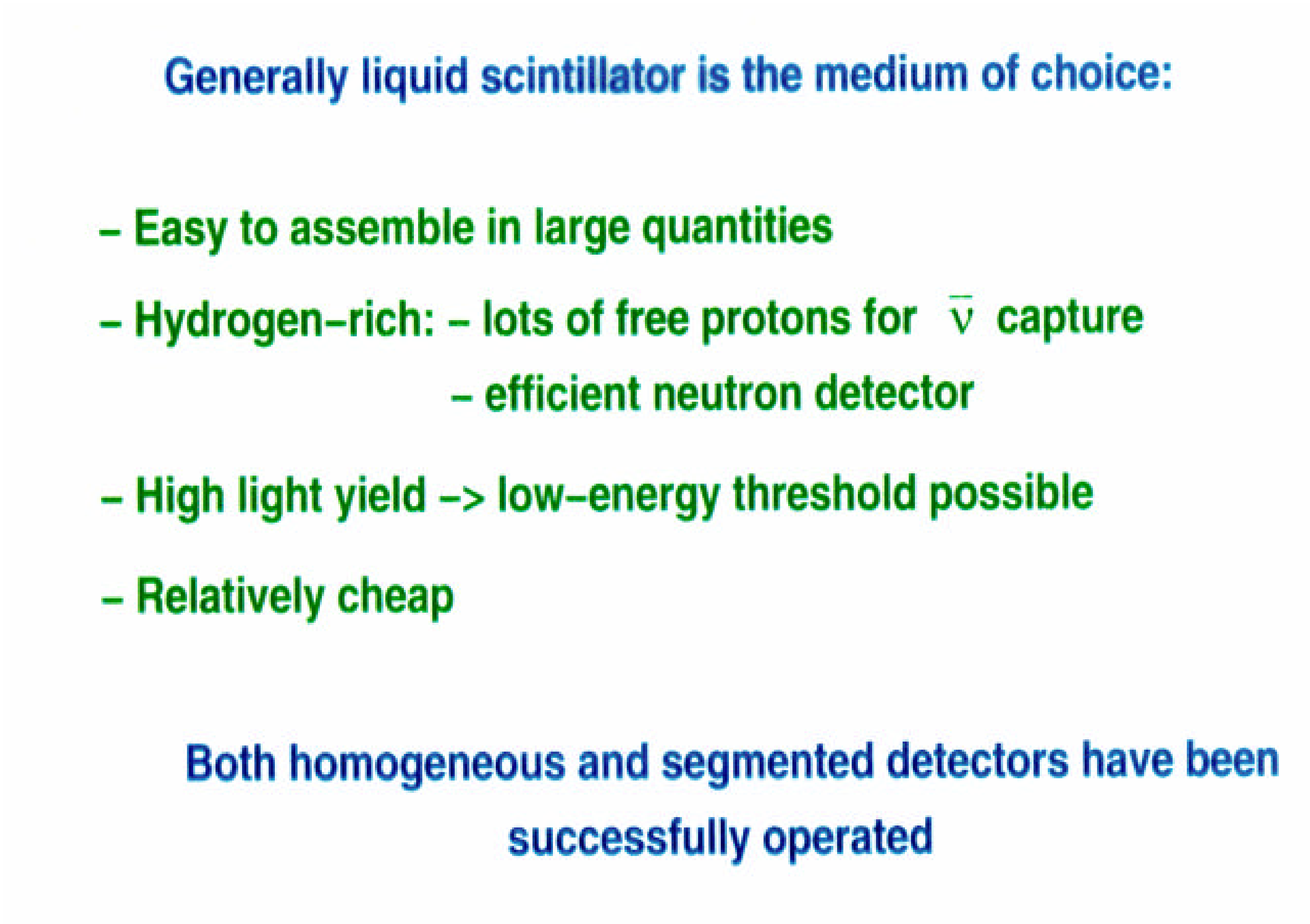
there is no need for an "explicit" near detector

Or:

(old) short baseline experiments can be used
as "implicit near detectors"



Long baseline experiments require many tons of active target



Generally liquid scintillator is the medium of choice:

- Easy to assemble in large quantities
- Hydrogen–rich: – lots of free protons for $\bar{\nu}$ capture
  - efficient neutron detector
- High light yield –> low–energy threshold possible
- Relatively cheap

Both homogeneous and segmented detectors have been successfully operated

Both Chooz and Palo Verde used Gd loaded scintillator

- ^{157}Gd (15.6% of natural Gd) has a thermal neutron capture cross section of 2.5 x 10 ^{5} barn !

  -> at 0.1% loading (natural Gd) neutron capture time reduces from ~170 μs (capture on p only) to ~27 μs

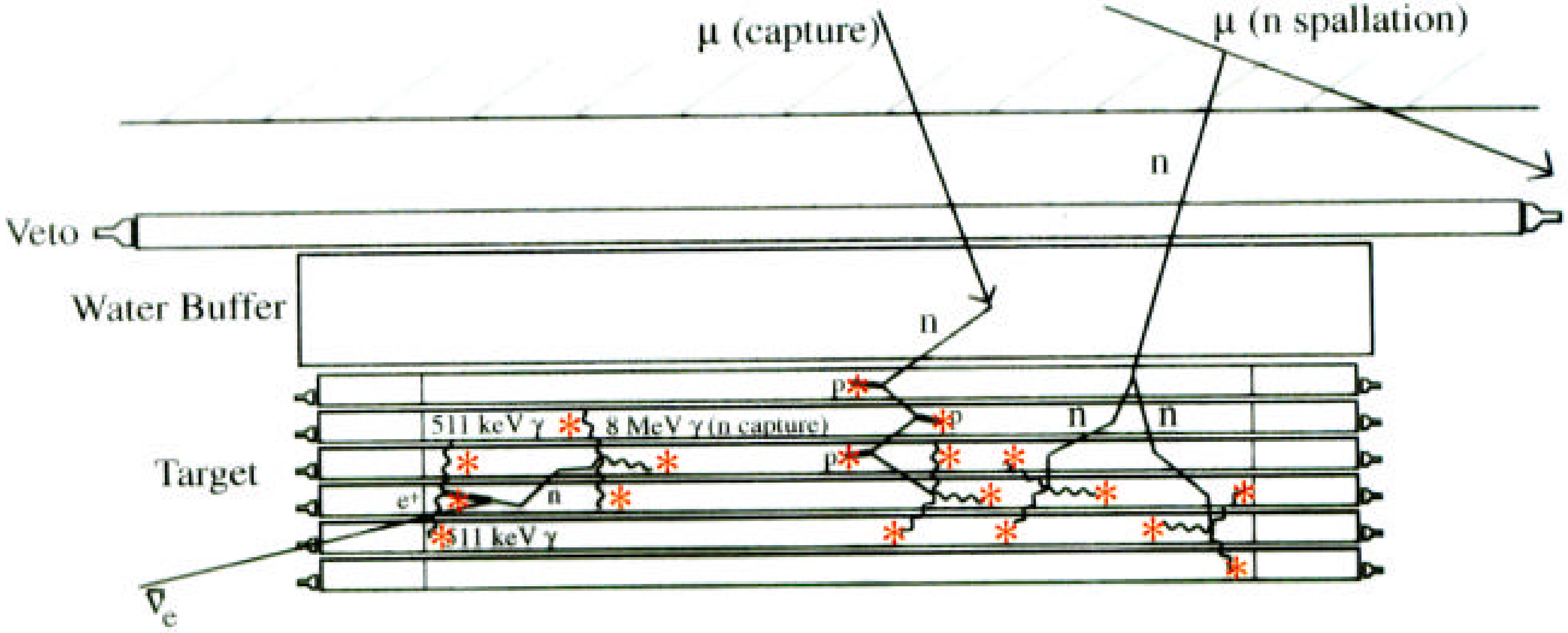
- The n–capture process in Gd is followed by a nuclear de–excitation γ –cascade with (complicated details and) total energy of 8 MeV, as opposed to a single 2.2 MeV γ for capture on protons

Gd provides substantial uncorrelated background reduction !

Two classes of background are important:

1) Time–uncorrelated: coincidences of random hits from γ and n

2) Time–correlated: fast n from cosmic–ray spallation
(time correlation same as in neutrino events)



Relative importance of 1) and 2) depends upon the depth, natural activity and shielding configuration

Chooz and Palo Verde where optimized in rather different ways:

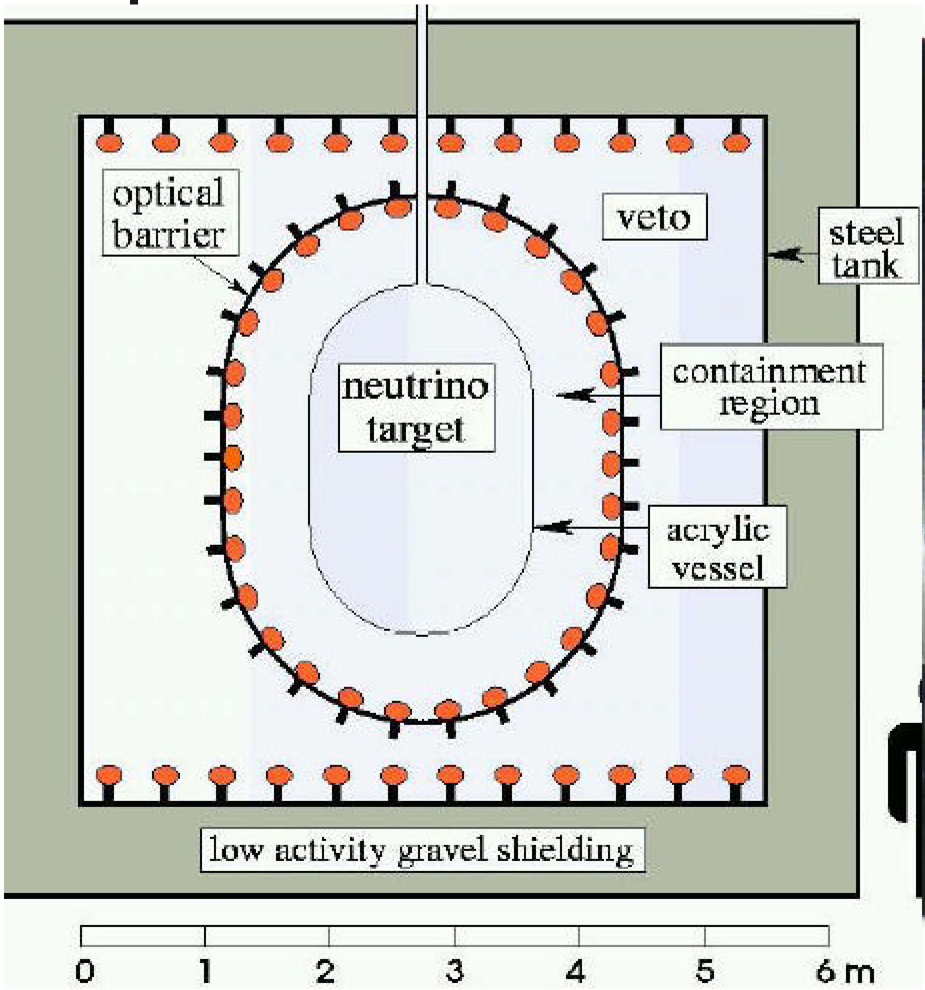
Chooz

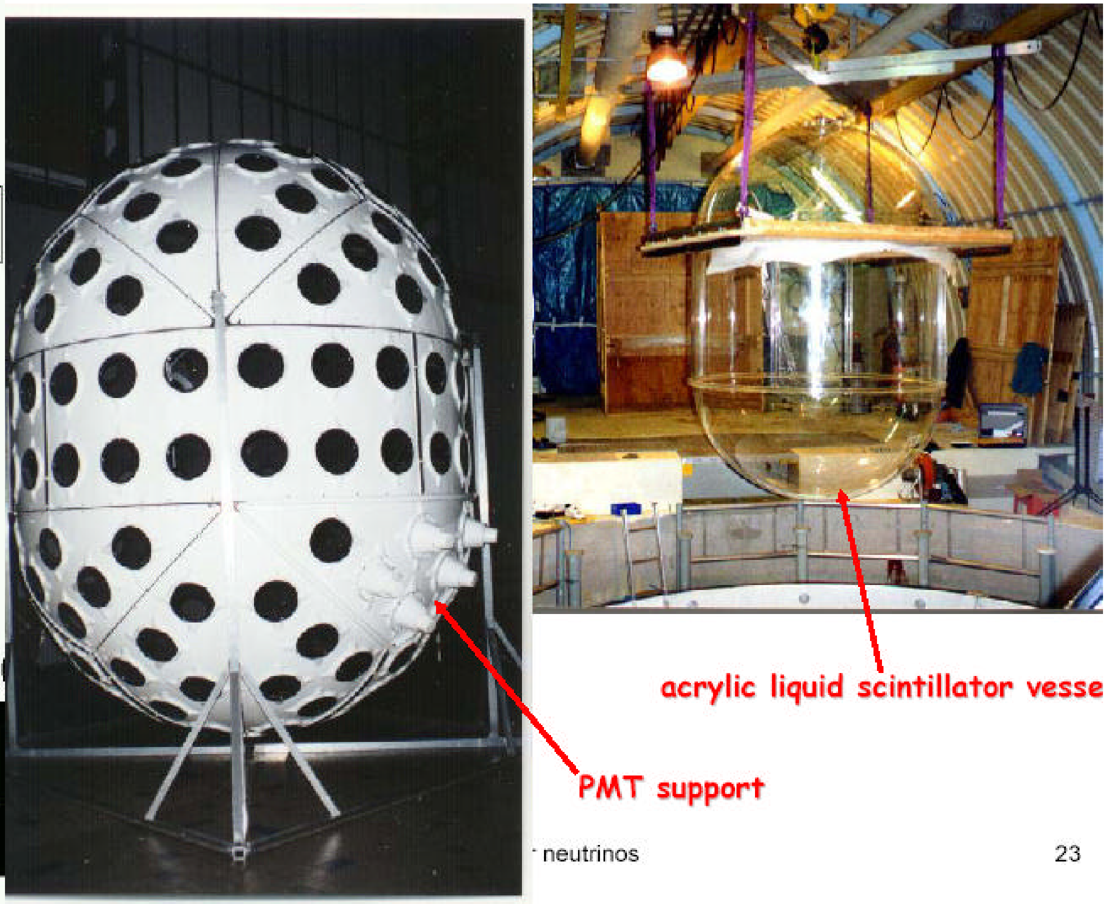
- At an existing deep site (300 mwe)
- Homogeneous detector: antineutrinos are double coincidences
- Smaller detector (5 ton) but high effic. (~100%)
- 2 reactors: 8.5 GW_{th}
- New reactors: zero power data (but worry they would not come up)
- Baselines 1115 m and 998 m
- Expect ~25 evts/day (no osc)

Palo Verde

- At an artificial shallow site (32 mwe)
- Segmented detector: antineutrinos are 4-fold coincidences
- Larger detector (12 ton) but lower efficiency (~10%)
- 3 reactors: 11.6 GW_{th}
- Well established reactors: can only turn off one at the time for background studies
- Baselines 890m and 750 m
- Expect ~50 evts/day (no osc)

The CHOOZ detector

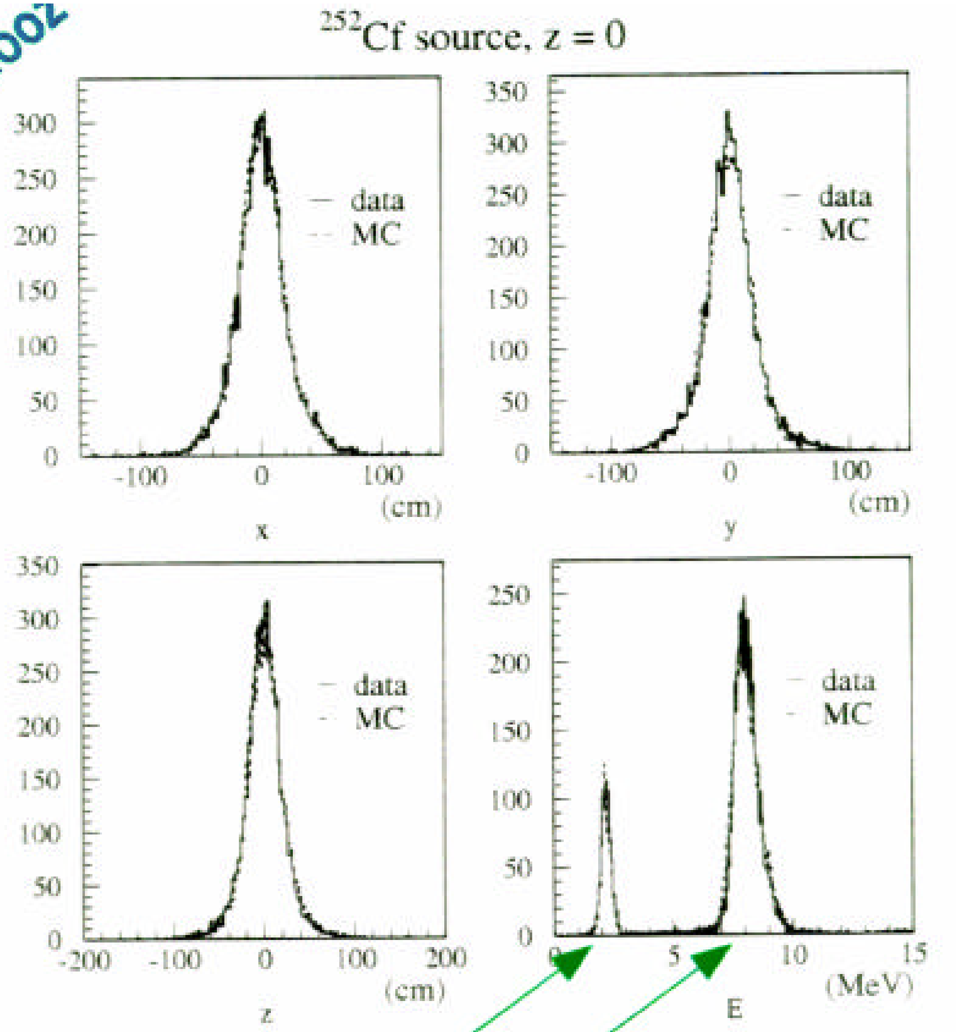




acrylic liquid scintillator vesse

PMT support

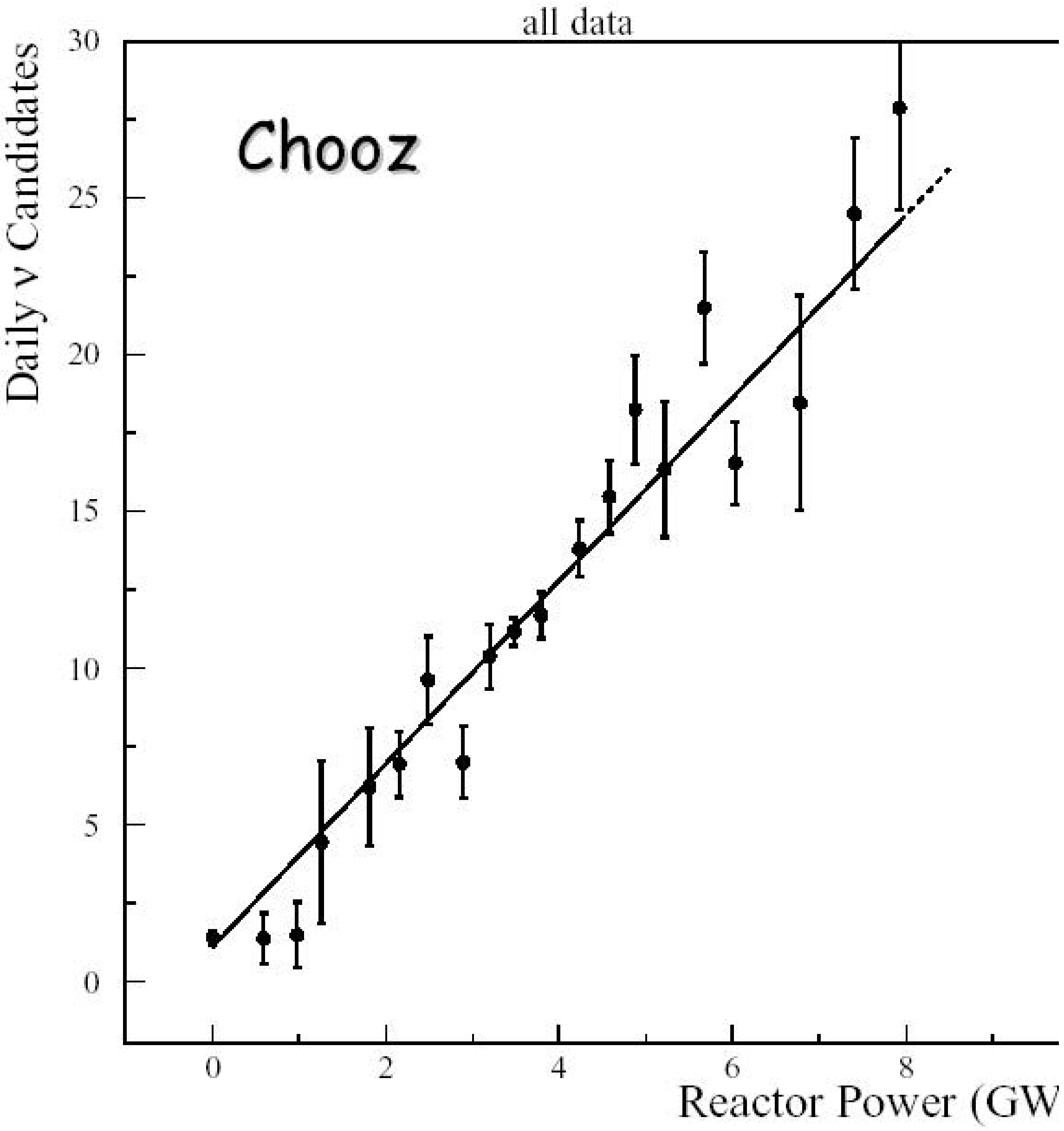
Chooz



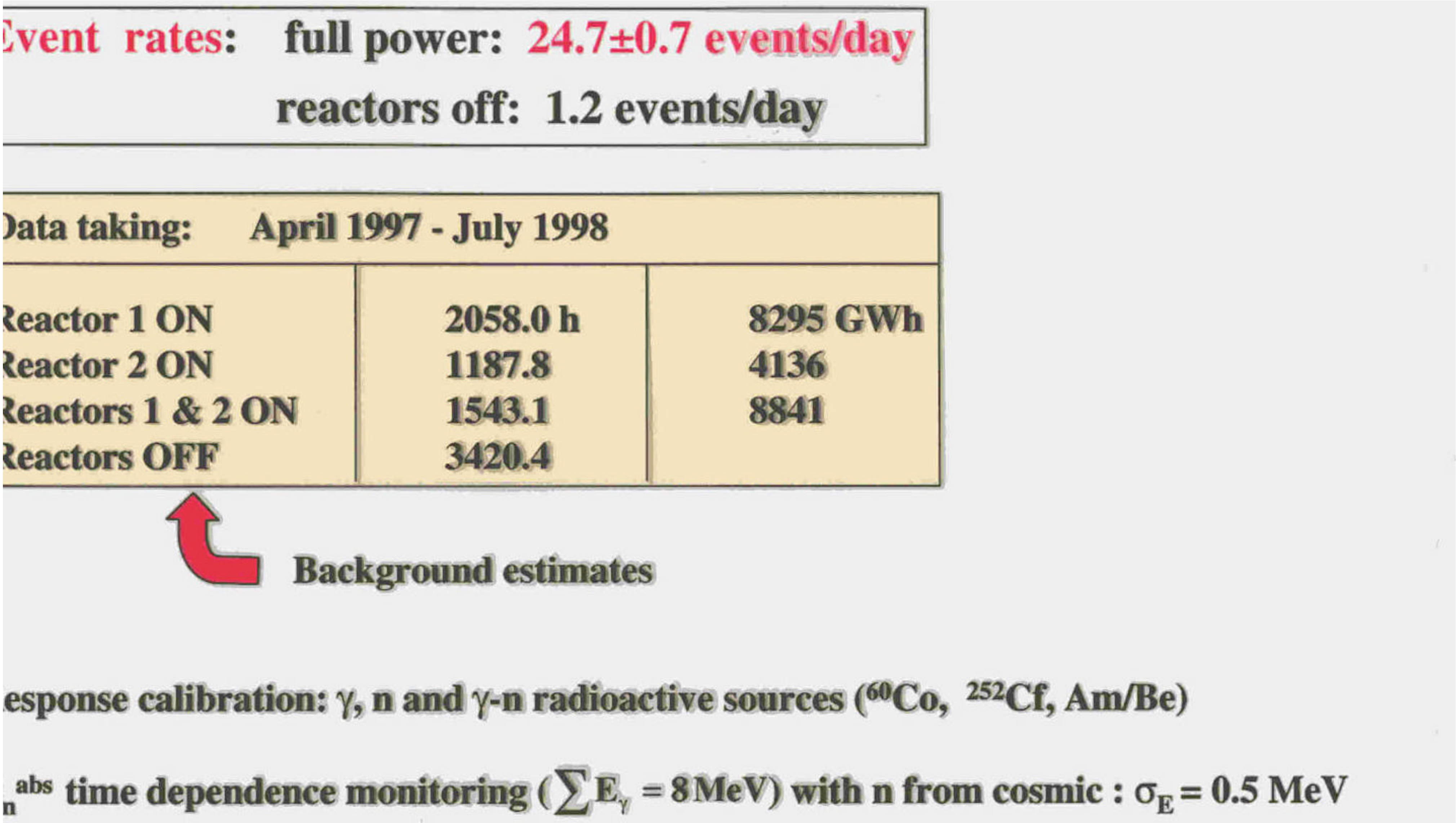
n–capture on p and Gd

Best fit obtained for
2 gaussians
7.77 MeV (^{157}Gd, 77%)
8.31 MeV (^{155}Gd, 23%)

Chooz managed to start data taking before the reactors were fully commissioned,
this provided zero power measurements and the demonstration that the detected neutrino rate is proportional to the reactor's thermal power



VERY IMPORTANT FOR BACKGROUND MEASUREMENT



vent rates: full power: 24.7±0.7 events/day

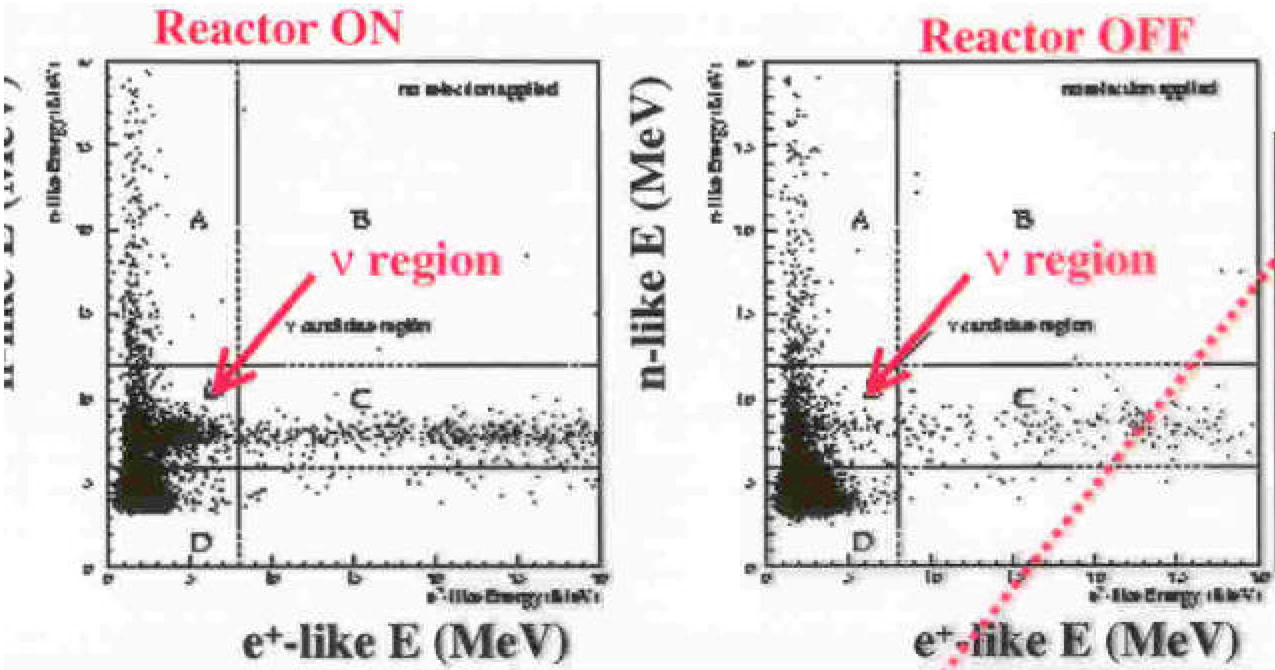
reactors off: 1.2 events/day

ata taking:	April 1997 - July 1998	
eactor 1 ON	2058.0 h	8295 GWh
eactor 2 ON	1187.8	4136
eactors 1 & 2 ON	1543.1	8841
eactors OFF	3420.4	

Background estimates

esponse calibration: γ, n and γ-n radioactive sources (^{60}Co, ^{252}Cf, Am/Be)

${}_n^{abs}$ time dependence monitoring ($\sum E_\gamma = 8$ MeV) with n from cosmic : $\sigma_E = 0.5$ MeV



No event selection

Main background

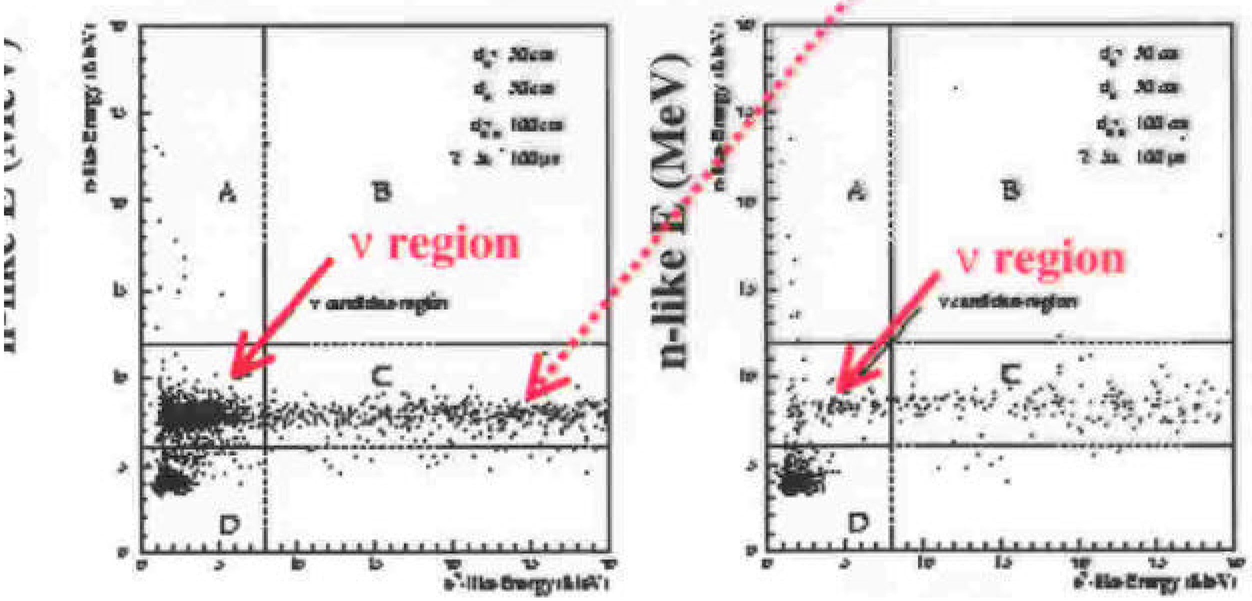
fast spallation n in rock

+

p from n scattering (e^+ like)

+

n capture



ν selection

@ > 30 cm from wall,

n - e^+ distance < 100 cm

n - e^+ delay in (2-100) μs

E(e^+-like) in (1.3 - 8) MeV

E(n-like) in (6-12) MeV

2991 candidates
(287 reactors off)

Efficiency: 69.8%

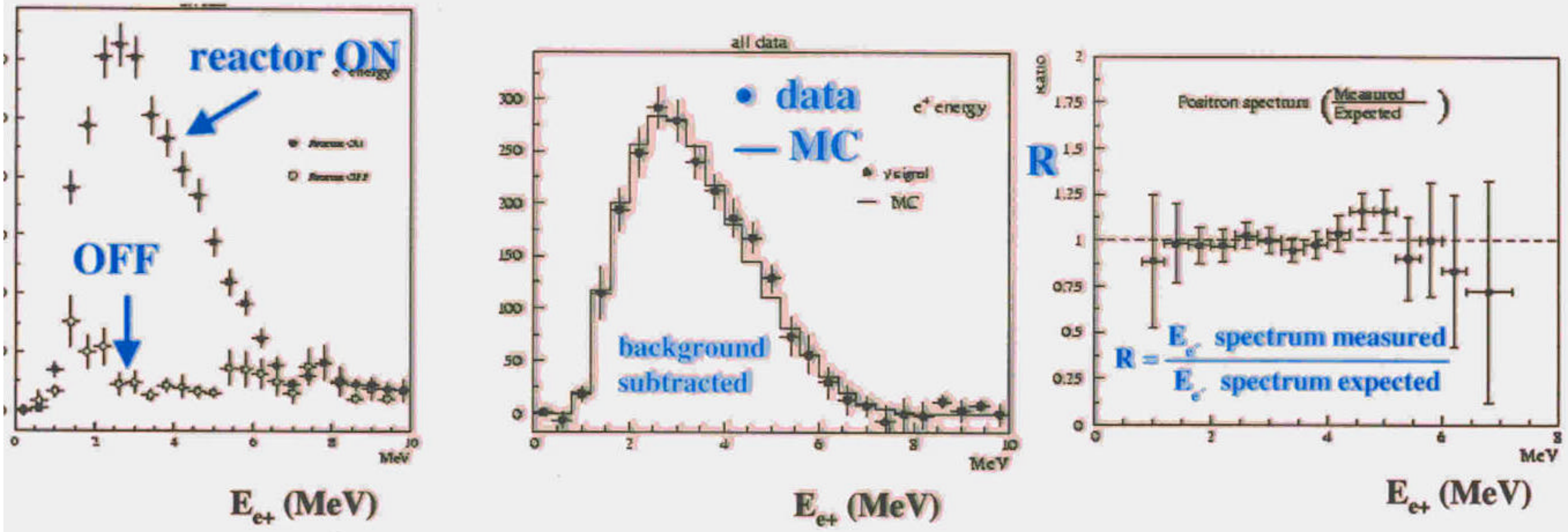
$\bar{\nu}_e$ flux known to 1.4%

- daily evolution of core isotopic evolution
- instantaneous fission rate from thermal power
- ν yield from measured β spectra of main isotopes

+

E_{e+} spectrum

- inverse β-decay cross-section
- simulation of detector response



$R = 1.010 \pm 0.028$ (stat) ± 0.027 (syst) → **No oscillation signal**

Analysis Methods

A - Compare unfolded E_{e+} absolute spectra of both reactors to expectation

Systematic uncertainty on absolute normalisation: ~2%

Two “independent” measurements

B - Ratio of spectra

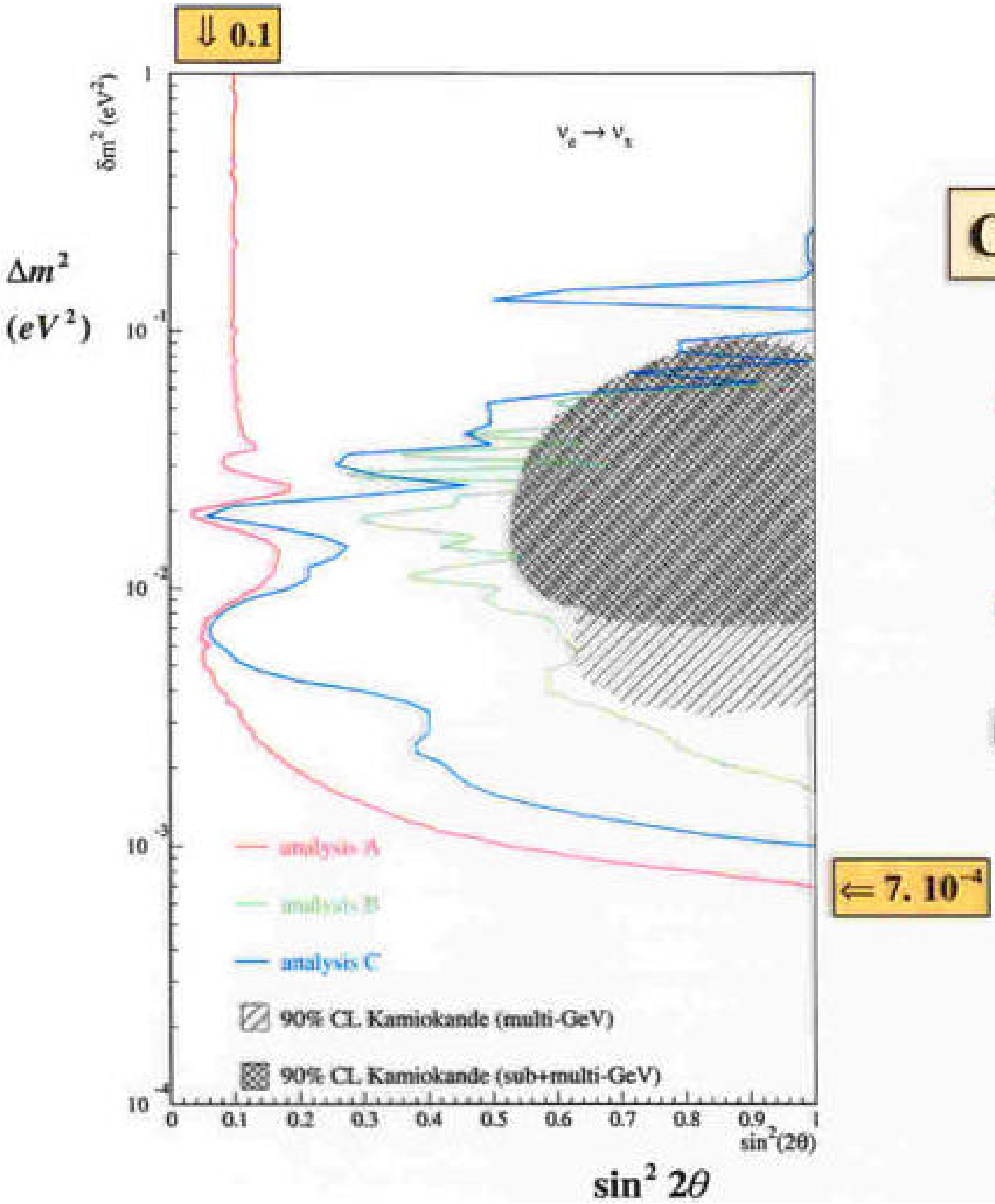
Most systematic cancel

No sensitivity at large Δm^2

C - Compare unfolded E_{e+} spectra shapes of both reactors to expectation

Intermediate sensitivity

Chooz exclusion plo



A — absolute spectra

B — spectra ratio

C — spectra shape

▨ **Kamiokande 90%**

Back to reactors…
is there a future ?
or: is KamLAND really the *ultimate* experiment ?

From the point of view of "long" baseline probably
we can't go beyond KamLAND:
to cover the "LOW" region one would need
~3 orders of magnitude longer baseline, or ~10^5 km
larger than the diameter of the Earth !
Anyway even for 2 orders of magnitude increase the
detector mass would escalate to 10 Mton !

Allright, and what about pushing the $\sin^2 2\theta$ sensitivity ?

Errors in recent experiments

Systematic	Chooz (%)		Palo Verde (%)		Absolute best possible
x section	1.9		-		
number of p in target	0.8		-		
thermal power	0.7		-		
"200MeV/fission"	0.6		-		
Total rate prediction		2.3		3.0	
positron det eff	-		4.0		
n det eff	-		3.0		
neutrino selection	-		4.0		
background estimate	-		4.0		
Total neutrino measurement		1.5		7.5	
Total syst		2.7		8.0	1
Stat		2.4		2.8	0
Grand total		3.6		8.5	1

So, pushing everything to the limit, one may be able to achieve a sensitivity of $\sin^2 2\theta \sim 1\text{-}2*10^{-2}$.

This requires:

- Infinite statistic
- Cancellation of all reactor AND detector efficiency syst
- Perfect knowledge of background

Very challenging !

A number of basic ideas have been put forward:

1. Use 2 detectors of 50 ton at ~1 km and ~100 m with the underground (600 mwe) reactors and facilities at Kransnoyarsk to measure $\sin^2 2\theta_{13}$ to 2% for $\Delta m^2 \sim 10^{-3}$ eV^2 (it may be possible to alternate the role of the 2 detectors using existing underground rail)

   L.Mikaelyan Nucl. Phys. B Proc. Suppl. 91 120

2. Locate a ~200 ton detector in the Heilbronn salt mine complex (Germany). Possible to be 19.5 km from each of Neckarwertheim (6.4 GW_{th}) and Obringheim (1.1 GW_{th}) reactors. But other baseline combinations possible. The idea is to zero in onto the LMA solution if KamLAND confirms it but has too-long a baseline for an accurate measurement.

   S.Schoenert et al. hep-ex/0203013 (Apr 2002)

3. Use a naval (mobile) reactor and hence obtain a variable baseline with a single detector.

   J.Detwiler et al. hep-ex/0207001 (Jun 2002)

Naval reactors and anti-neutrinos

Some numbers:

Largest nuclear subs:
  the Russian “Typhoon” class.
  They have 2 reactors with
  total power 380 MW_{th}
The USS Enterprise:
  8 (!) reactors but apparently
  only 2 of them run for
  propulsion
  each reactor is 420 MW_{th}
There are essentially no civilian ships
  except for Russian icebreakers

Should we worry about backgrounds ?

…but if large detectors are not easy to move a reactor on a ship is !

Russian icebreakers have been chartered to take (wealthy) tourists to the Arctic, so they can, in principle, be hired to just sit somewhere and just run their reactors

Arktica class" vessels have 2 reactors, for 200 MW_{th} total power. So they are rather small compared to fixed power plants: a large detector is needed and the baseline cannot be very large.

But systematics should, in principle, be much smaller:

background is measured *without* reactor

reactor yield, x-sections, detector efficiencies are all cancelled by normalizing any measurement to a short baseline one.

Only remaining syst.: *relative* reactor power

n addition baseline can be fine tuned to map the oscillation pattern

…and what about a **much larger** reactor ?

Is there a natural reactor in the middle of the Earth ?
(D.F.Hollenbach and J.M.Herndon Proc. Natl. Acad. Sci. 98 (2001) 11085)

Such reactor would power the Earth's magnetic field and explain how it can flip polarity rather frequently (on geological scale)

The reactor would spontaneously turn on and off as it is know the Oklo reactor in Gabon did ~one billion years ago

The existence of this reactor is controversial and anti-neutrinos could be the ideal (and only conclusive) probe for could be a truly remarkable geophysical phenomenon

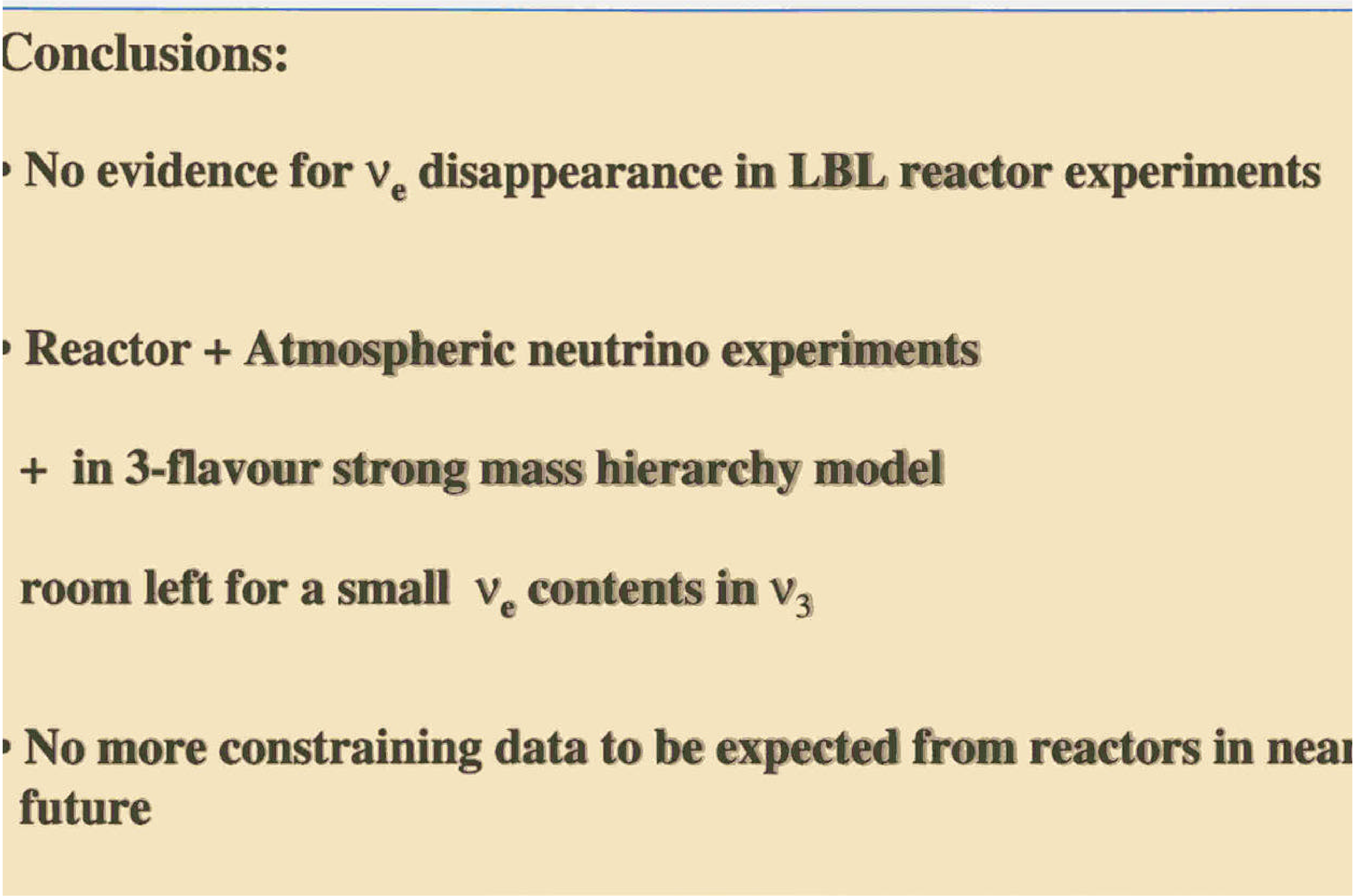
Such a “terrestrial” reactor would have a power of 4 TW (10% of the Earth’s total power)

This would produce a signal in KamLAND of ~40 ν/yr, a 5% excess, difficult to detect under the “artificial” reactors background

But a 20 kton “SuperKamLAND” located in a place away from artificial fixed nuclear installations would see 800 ν/yr with essentially no background !

(In fact this would be the obvious “ultimate” oscillation experiment at a reactor !)

Maybe there is a really rich program covering particle physics, geophysics and astrophysics for a very large, low energy, anti-neutrino detector in the future !!



Conclusions:

- No evidence for ν_e disappearance in LBL reactor experiments

- Reactor + Atmospheric neutrino experiments

+ in 3-flavour strong mass hierarchy model

room left for a small ν_e contents in ν_3

- No more constraining data to be expected from reactors in near future

Medium baseline neutrino oscillation searches

LSND: $\bar{n}_m \to \bar{n}_e \quad 20 < E_n < 60$ MeV $\quad m^+$ decay at rest

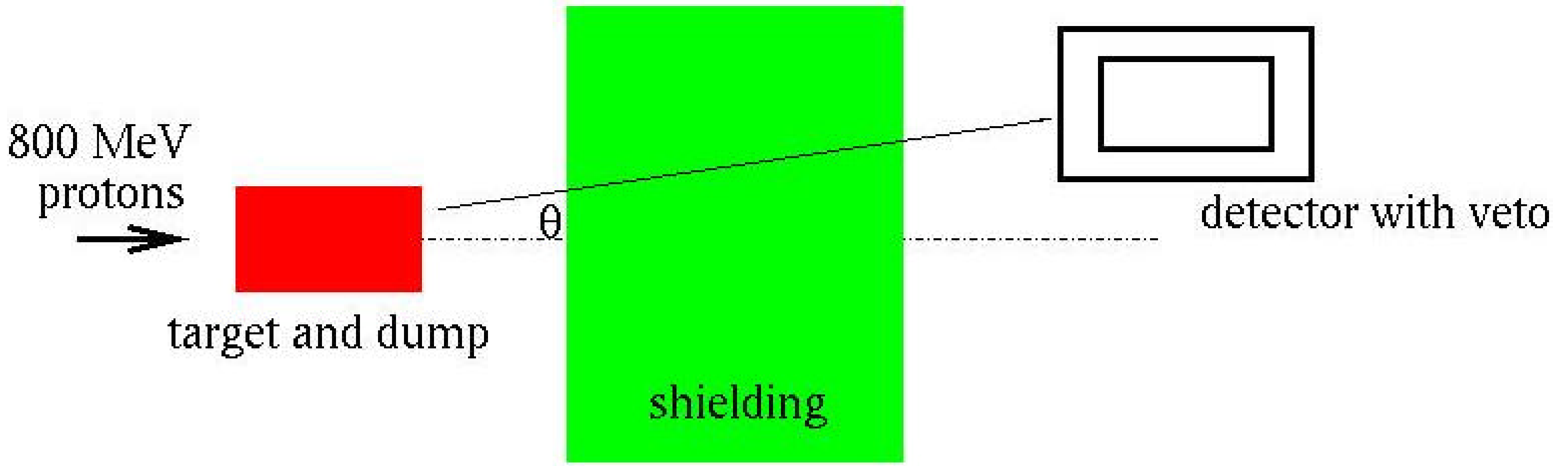
$n_m \to n_e \quad 20 < E_n < 200$ MeV $\quad p^+$ decay in flight

Final results, 1993-98 data
event excess, evidence for oscillations

KARMEN: $\bar{n}_m \to \bar{n}_e \quad 20 < E_n < 60$ MeV $\quad m^+$ decay at rest

Results based on 75% of expected data, Feb 97 - Mar (Nov) 00
experiment ended March 2001
no excess, does not confirm LSND, but does not rule it out either

LSND and KARMEN experimental scheme



$^{+} \rightarrow m^{+} n_{m}$ muon decay at rest

$\hookrightarrow e^{+} n_{e} \bar{n}_{m}$

$\hookrightarrow \bar{n}_{e}$

$\bar{n}_{e} p \rightarrow e^{+} n$

detect prompt *e* track, 20<E_e<60 MeV

neutron capture $np \rightarrow dg$ 2.2 MeV, $Gd(n,g)$ 8 Me

correlated in position and in time with *e*

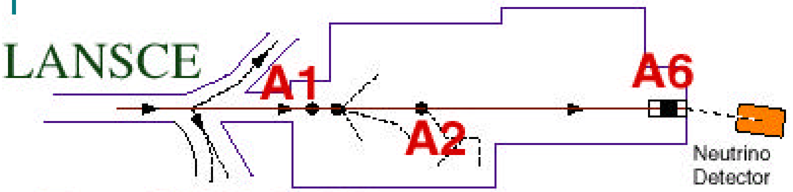
o B-field, *e* and γ sequence distinguishes e^+ from e^-

arameters of the LSND and KARMEN experiment

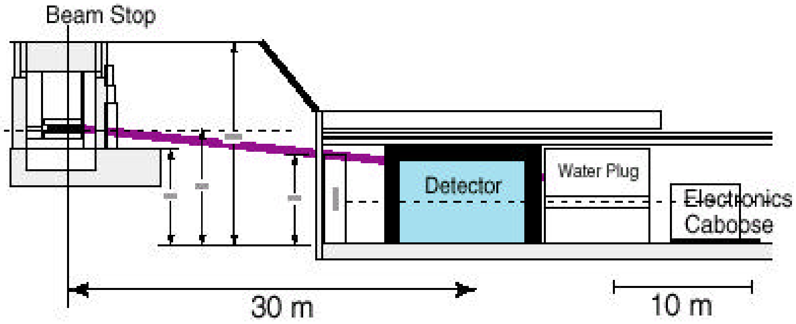
	LSND	KARMEN
Accelerator	**Los Alamos Neutron Science Centre**	**Neutron Spallation Facility ISIS ar R.A.L. (U.K.)**
Proton kin. energy	**800 MeV**	**800 MeV**
Proton current	**1000 mA**	**200 mA**
Detector	**Single cylindrical tank filled with liquid scintillator Collect both scintillating and Cerenkov light**	**512 independent cells filled with liquid scintillato**
Detector mass	**167 tons**	**56 tons**
Event localisation	**PMT timing**	**cell size**
Distance from n source	**29 m**	**17 m**
Angle q between proton and n direction	**11°**	**90°**
Data taking period	**1993 – 98**	**1997 – 2001**
Protons on target	**4.6 x 10^{23}**	**1.5 x 10^{23}**

LSND experimental layout

$L \approx 29.7\text{m} @ 7°$

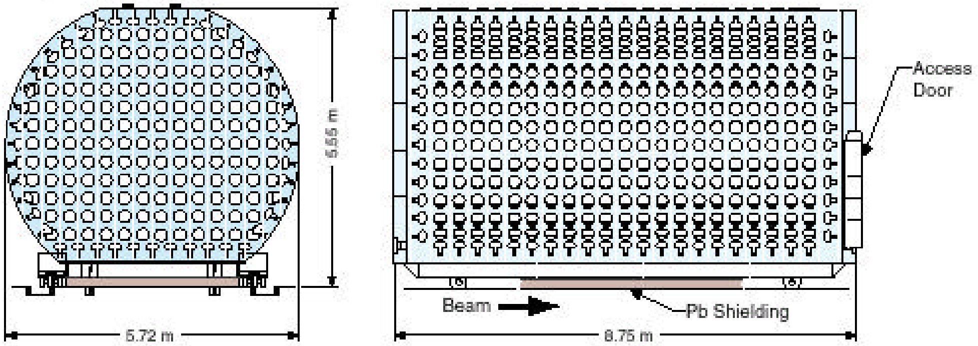


E_p=800MeV



C_nH_{2n+2}

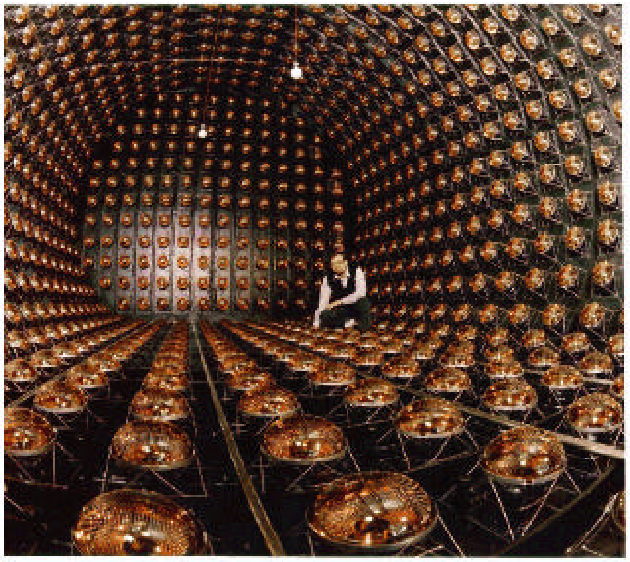
8.75m



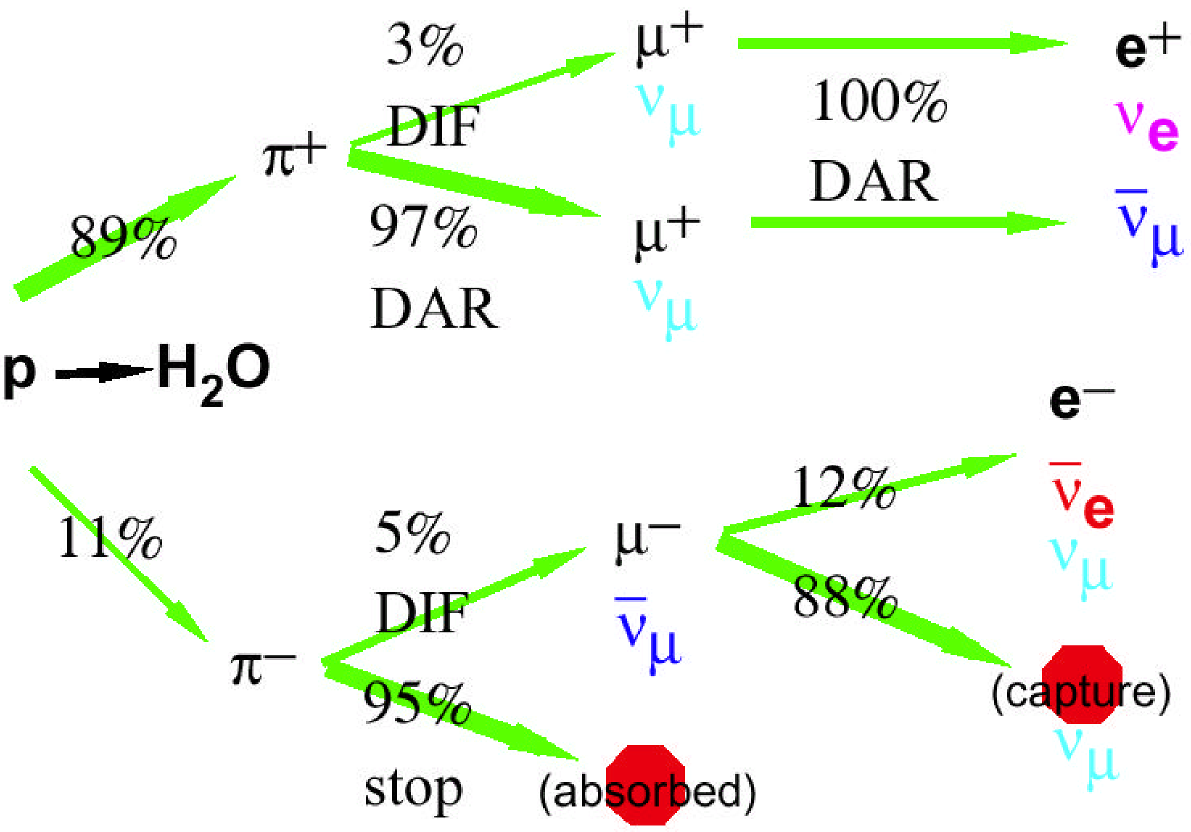
167t

1220 8" PMT's

5.7m



LSND
neutrino fluxes



$p \rightarrow H_2O$

89% π^+

3% DIF μ^+ ν_μ

97% DAR μ^+ ν_μ

100% DAR e^+ ν_e $\bar{\nu}_\mu$

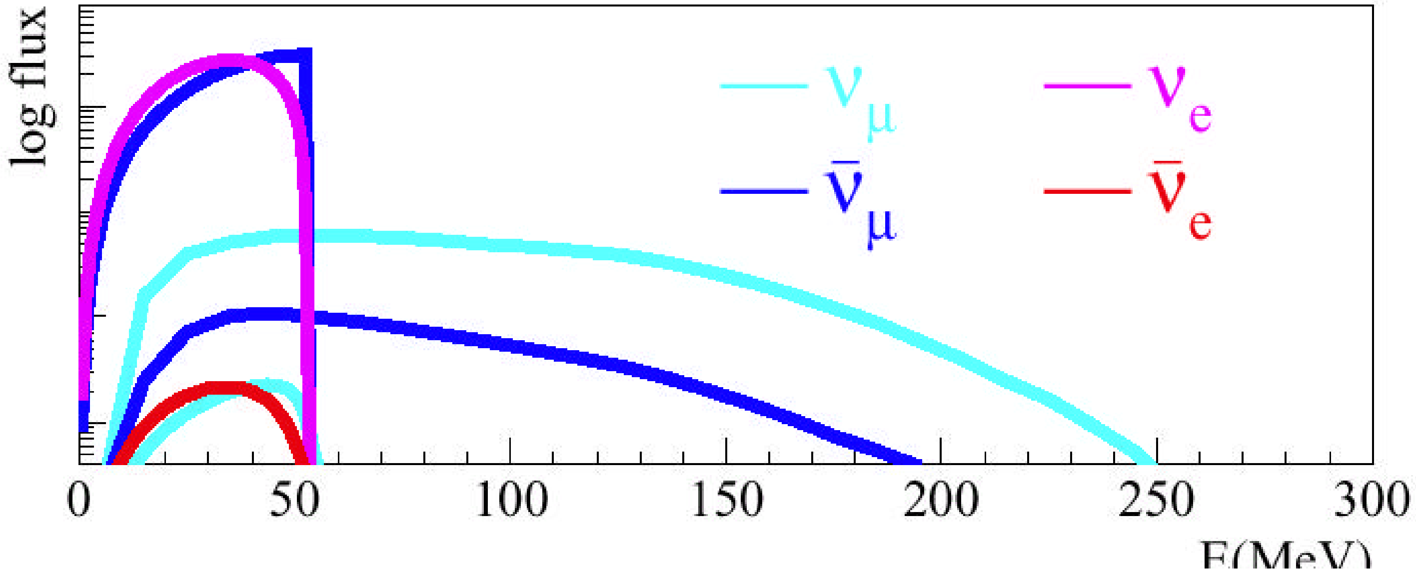
11% π^-

5% DIF μ^- $\bar{\nu}_\mu$

95% stop (absorbed)

12% e^- $\bar{\nu}_e$ ν_μ

88% (capture) ν_μ



$\frac{\bar{n}_e}{n_e}$ £ 10^{-3}

LSND analysis strategy

Particle detection and identification via Cherenkov and scintillation light

Search for $\bar{n}_m \rightarrow \bar{n}_e$ DAR osc. events in energy range 20-60 MeV

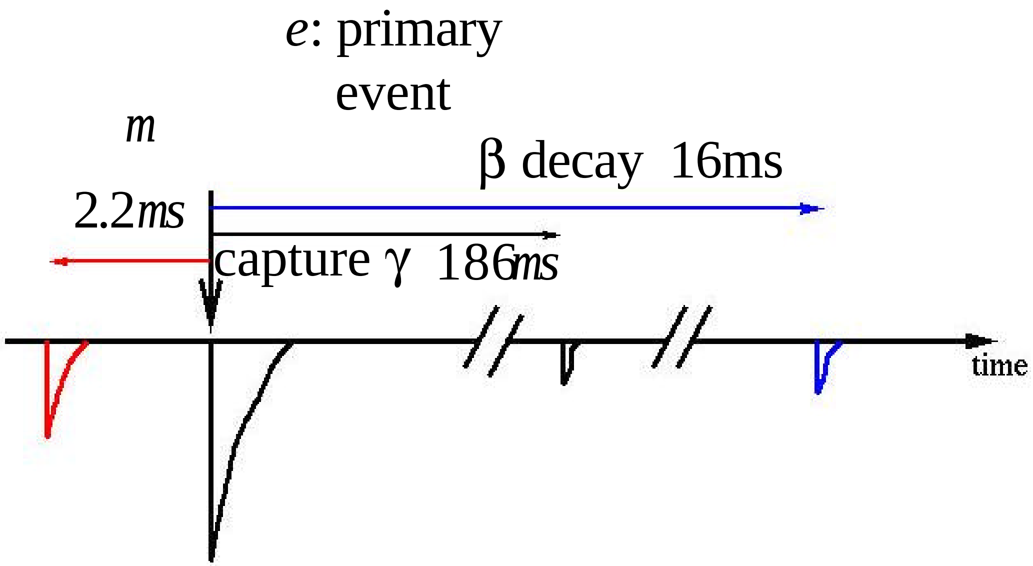
Search for $n_m \rightarrow n_e$ DIF osc. events in energy range 20-200 MeV

Use common primary event electron selection across all neutrino processes.

Simultaneously fit all neutrino processes to constrain fluxes and backgrounds.

Identify 20-60 MeV electron events with a correlated neutron capture γ

Fit 20-200 MeV oscillation candidate events in (E, R, z, $cosq$) to determine best oscillation parameter values.



ata acquisition: PMT time and pulse height

rimary trigger: >150 hit PMTs (~4 MeV electron equiv.)
ith <4 veto PMTs hit and no event with >5 veto hits
ithin previous 15.2 ms

past” event: any activity with >17 PMT hits or >5 veto hits
uring the preceding 51.2 ms

future” event: any activity with >21 PMT hits during the
ollowing 1 ms

e.g. μ+*e* events: the μ is the past event, its decay *e* is the primary even

μ+β events: $n_e C \rightarrow e^- N_{g.s.}$ β decay electron is future event

Conventional neutrino processes

Measurements used to constrain fluxes, efficiencies, cross-sections and backgrounds

Events with muons

μ+e: $n_m C \rightarrow m^- N^*$

μ+e+β: $n_m C \rightarrow m^- N_{g.s.}$

μ+e+γ: $\bar{n}_m p \rightarrow m^+ n$

Events without muons

e: $ne \rightarrow ne, \quad n_e C \rightarrow e^- N^* \quad (n_m \rightarrow n_e)$

e+β: $n_e C \rightarrow e^- N_{g.s.}$

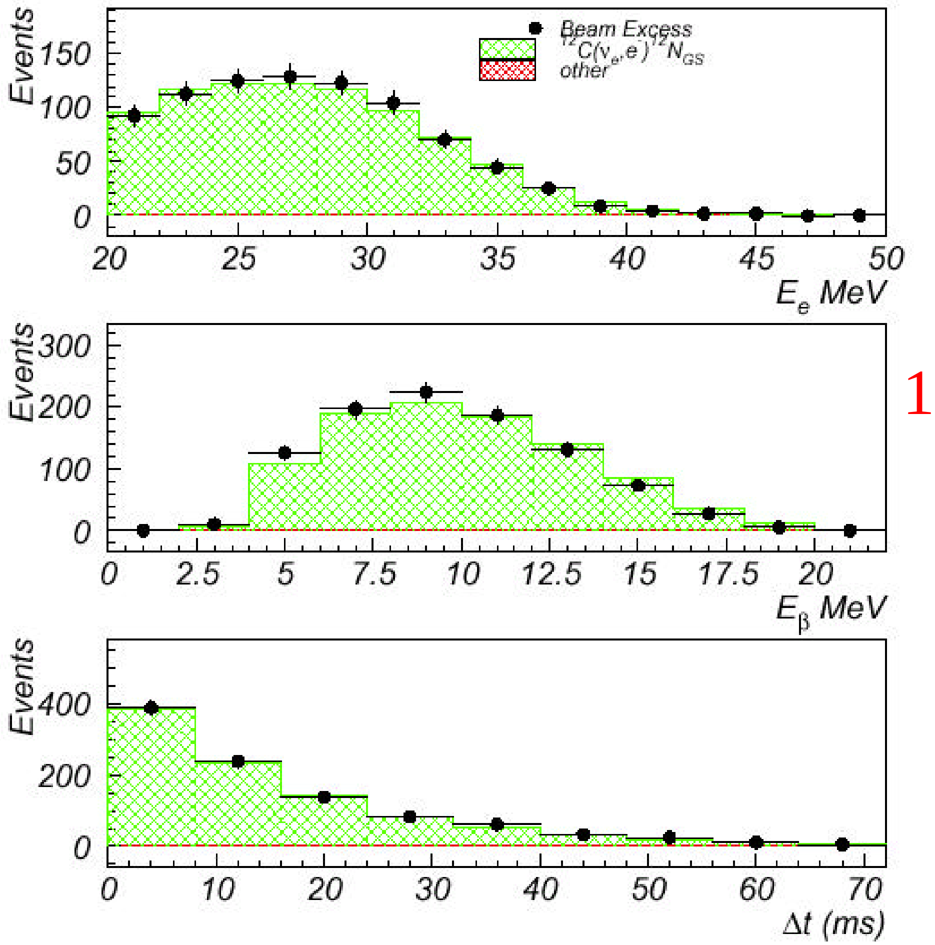
e+γ: $\bar{n}_e p \rightarrow e^+ n \quad (\bar{n}_m \rightarrow \bar{n}_e)$

e+b events

e energy

β energy

time between
the *e* and β

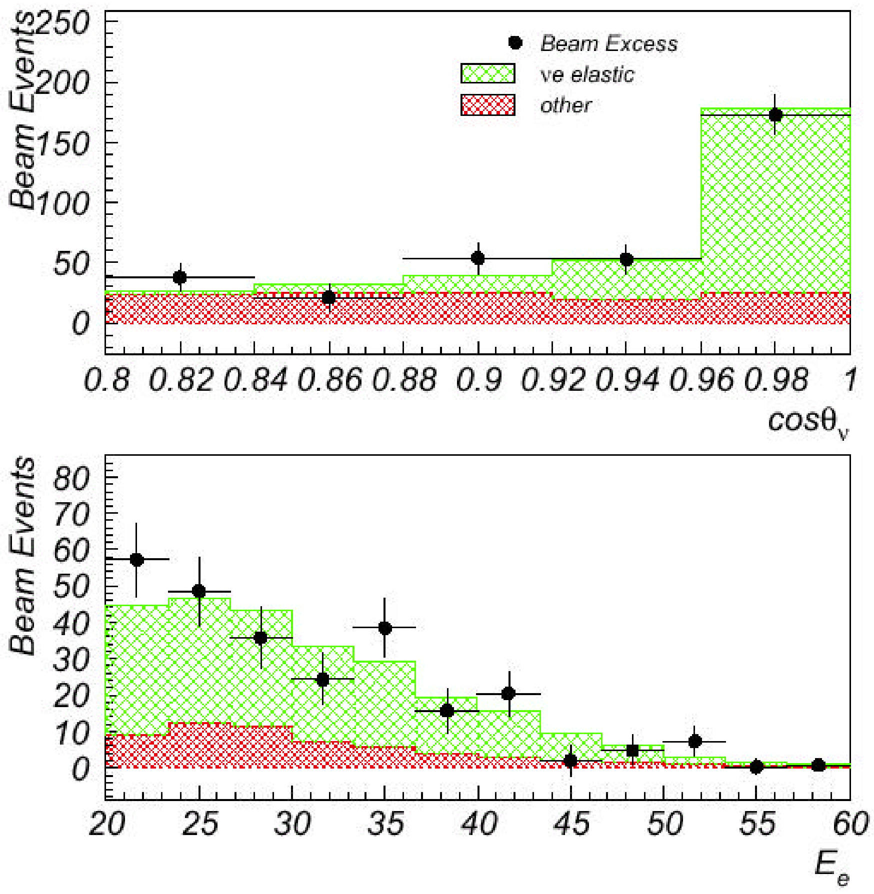


$$^{12}C(n_e,e^-)^{12}N_{g.s}$$

e events

os θ : angle between
 and ν

energy



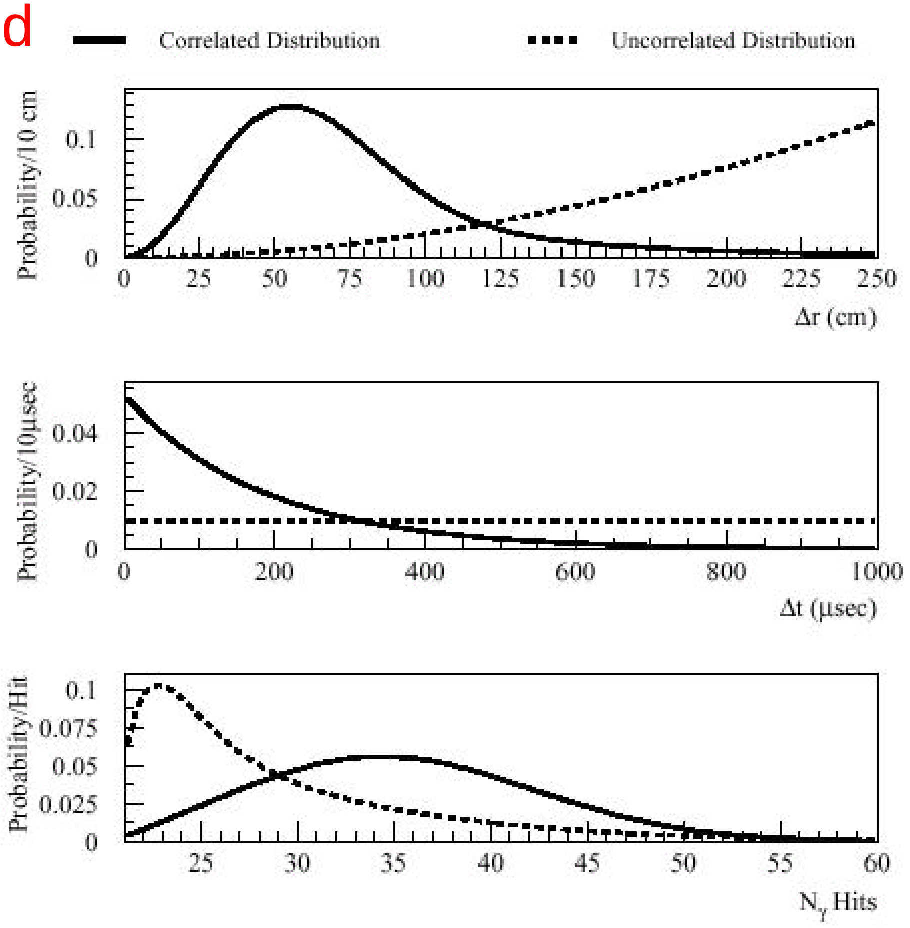
$ne \rightarrow ne$

The correlated 2.2 MeV g: R_g

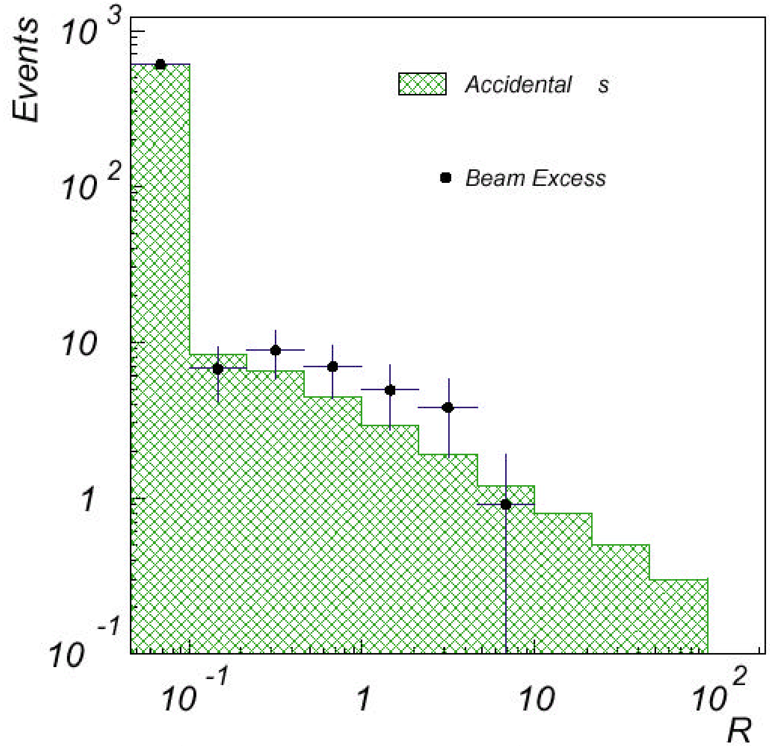
$$R_g = \frac{\text{likelihood that } \gamma \text{ is correlated}}{\text{likelihood that } \gamma \text{ is uncorrelated}}$$

depends on:

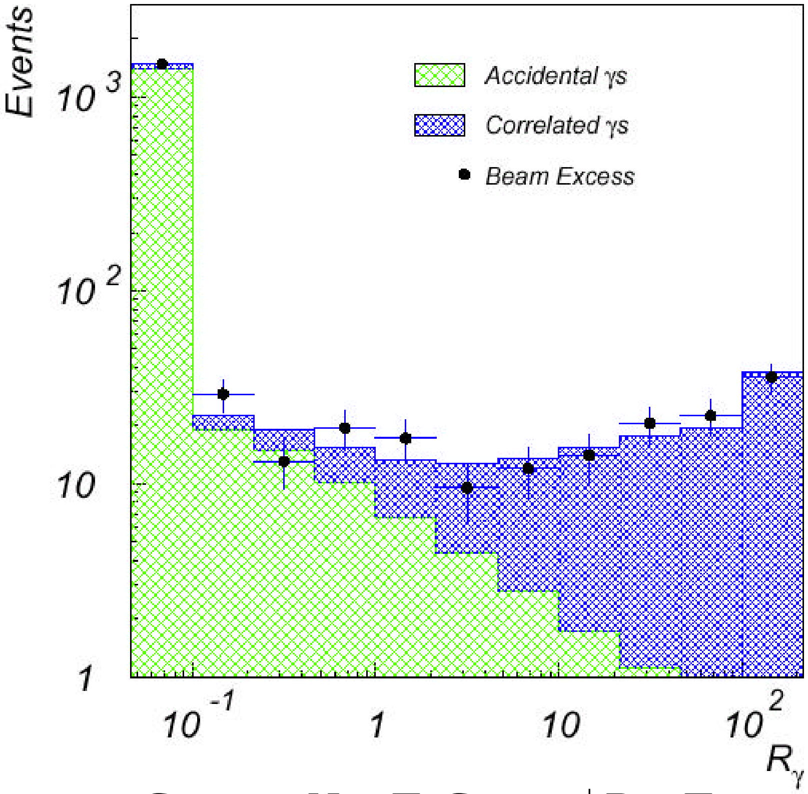
- distance between e and γ
- time interval between e and γ
- number of PMT hits for the γ



Checks of the R_g likelihood distributions



$$^{12}C(n_e, e^-)^{12}N_{g.s.}$$



$$n_m C \to m^- N,\ \bar{n}_m C \to m^+ B,\ \bar{n}_m p \to m^+ n$$

expected: $f_c = 0.0$

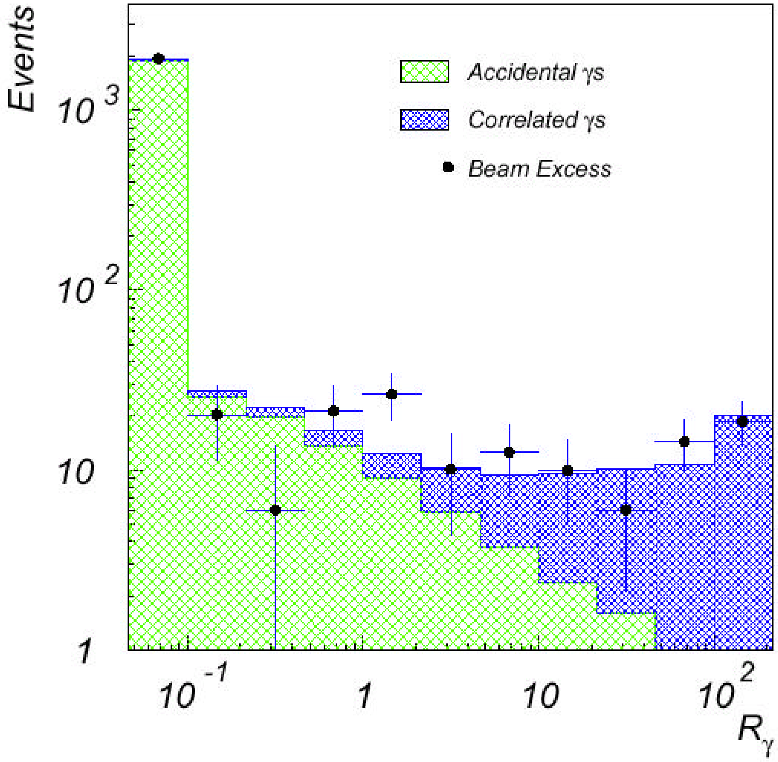
measured: $f_c = -0.004 \pm 0.007$

expected: $f_c \approx 0.14$

measured: $f_c = 0.129 \pm 0.013$

Oscillation results

$20 < E_e < 60$ MeV



eam on-off excess

117.9 ± 22.4 events

kgd : m^- DAR 19.5 ± 3.9 events

p^- DIF 10.5 ± 4.6 events

$87.9 \pm 22.4 \pm 6.0$ events

otal excess:

Excess for 100% transmutation: 33300 ± 3330 events

Oscillation probability $(0.264 \pm 0.067 \pm 0.045)\%$

$R_g > 10$ and $20 < E_e < 60$ MeV

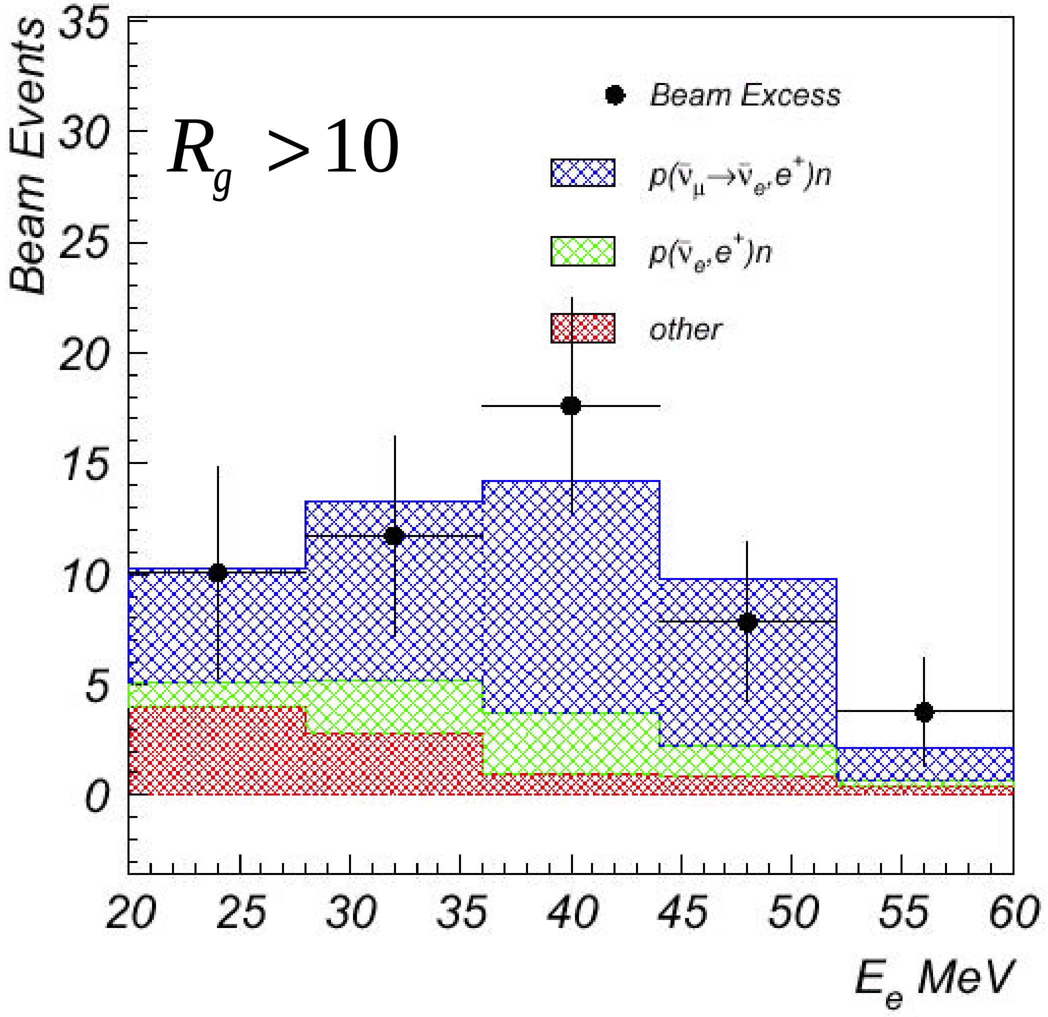
beam on : 86 events

beam off : 36.9 ± 1.5

n bkgd : 16.9 ± 2.3

---

otal excess $32.2 \pm 9.4 \pm 2.3$

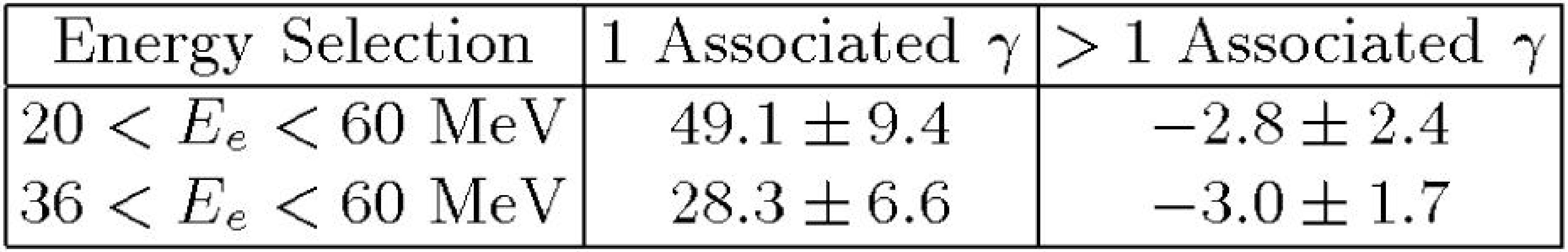


Tests of the DAR oscillation hypothesis

Is there an excess of events with >1 correlated γ?

Recoil n from anti-ν_e $p \rightarrow e^+ n$ is too low in energy (<5 MeV) to knock out additional neutrons

If excess involves higher energy neutrons from cosmic rays or the beam (>20 MeV) then would expect large excess with >1 correlated γ, as observed in the beam-off data



Energy Selection	1 Associated γ	> 1 Associated γ
$20 < E_e < 60$ MeV	49.1 ± 9.4	-2.8 ± 2.4
$36 < E_e < 60$ MeV	28.3 ± 6.6	-3.0 ± 1.7

DIF analysis

Analysis extended up to 200 MeV. However, event selection was optimized for the DAR analysis therefore, beam-off backgrounds above 60 MeV are large

Applying the above analysis to the data (except no correlated γ): $60 < E_e < 200\ \text{MeV}$

$$\text{Beam on–off excess:}\quad 14.7 \pm 12.2\ \text{events}$$

$$\underline{\text{bkgd:}\quad 6.6 \pm 1.7\ \text{events}}$$

$$\text{Total excess:}\quad 8.1 \pm 12.2 \pm 1.7\ \text{events}$$

$$\text{Osc. prob:}\quad (0.10 \pm 0.16 \pm 0.04)\%$$

Less precise than previous analysis of 1993-95 data, where the tota excess was $18.1 \pm 6.6 \pm 4.0$ events

Osc. prob: $(0.26 \pm 0.10 \pm 0.05)\%$

Neutrino oscillation fit

Likelihood in the $\sin^2 2q - \Delta m^2$ plane is formed over each of the 5697 beam-on events that pass the oscillation cuts.

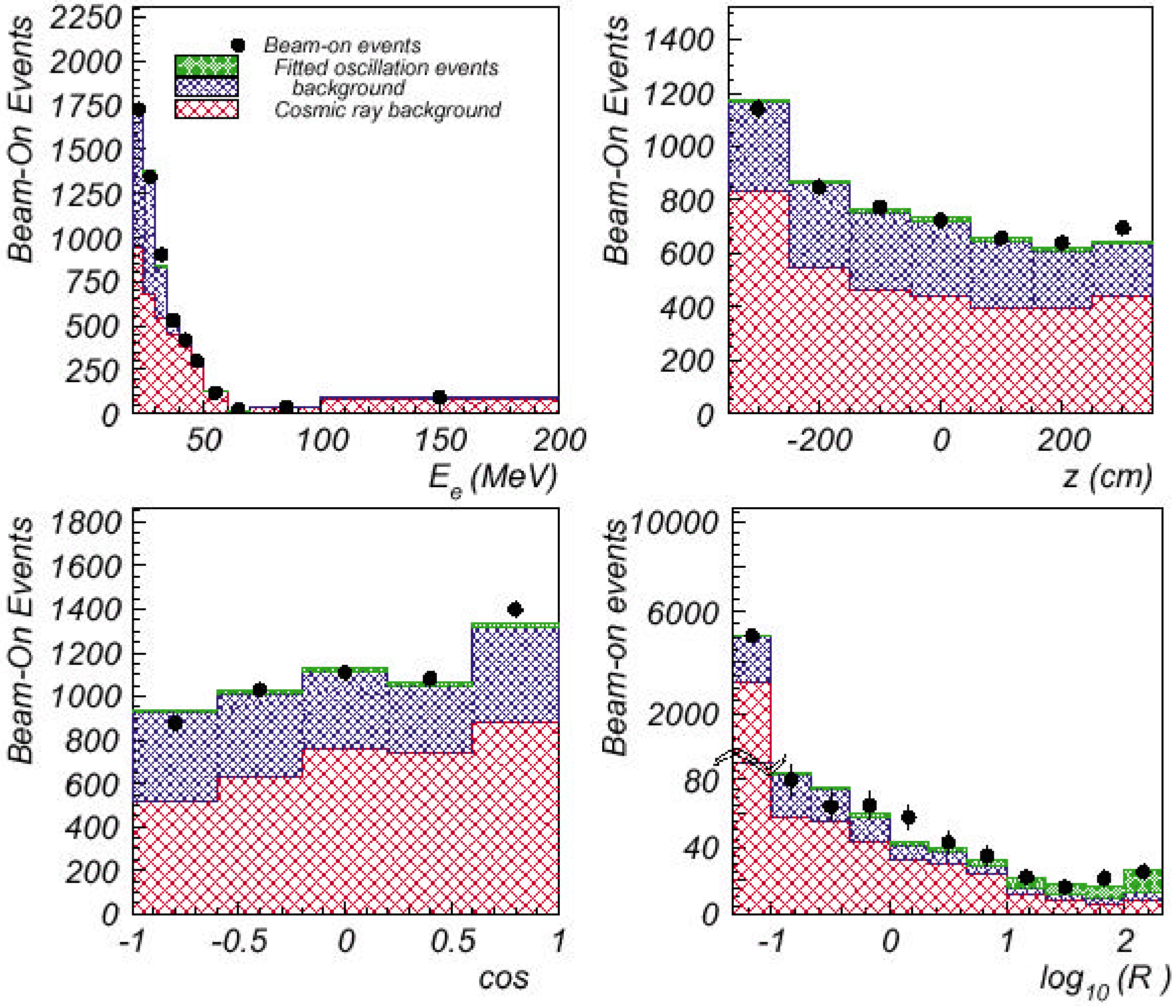
Beam related backgrounds are determined from MC.

Fit over $20 < E_e < 200$ MeV — both DAR and DIF

Each beam-on event characterized by four variables:

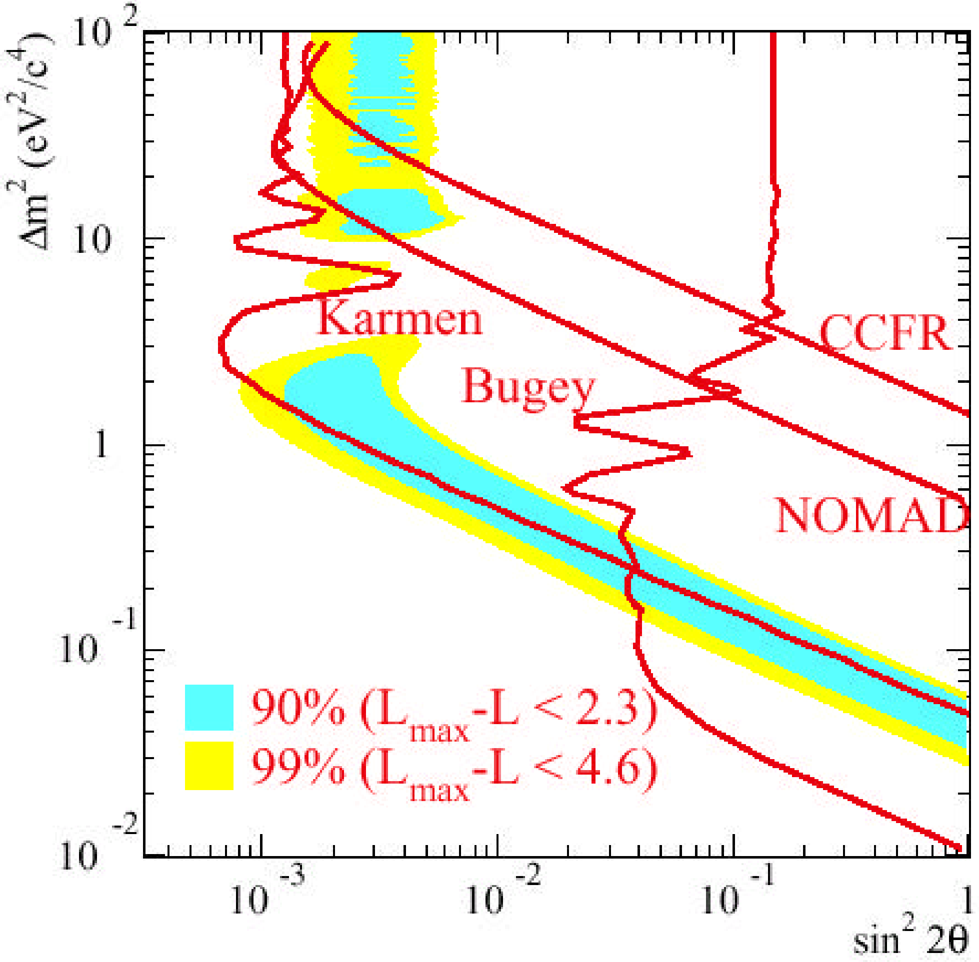
- electron energy E_e
- electron reconstructed distance along the tank z
- direction the electron makes with the ν $\cos q_n$
- correlated γ likelihood ratio R_g

Neutrino oscillation fit



LSND oscillation parameter fit results

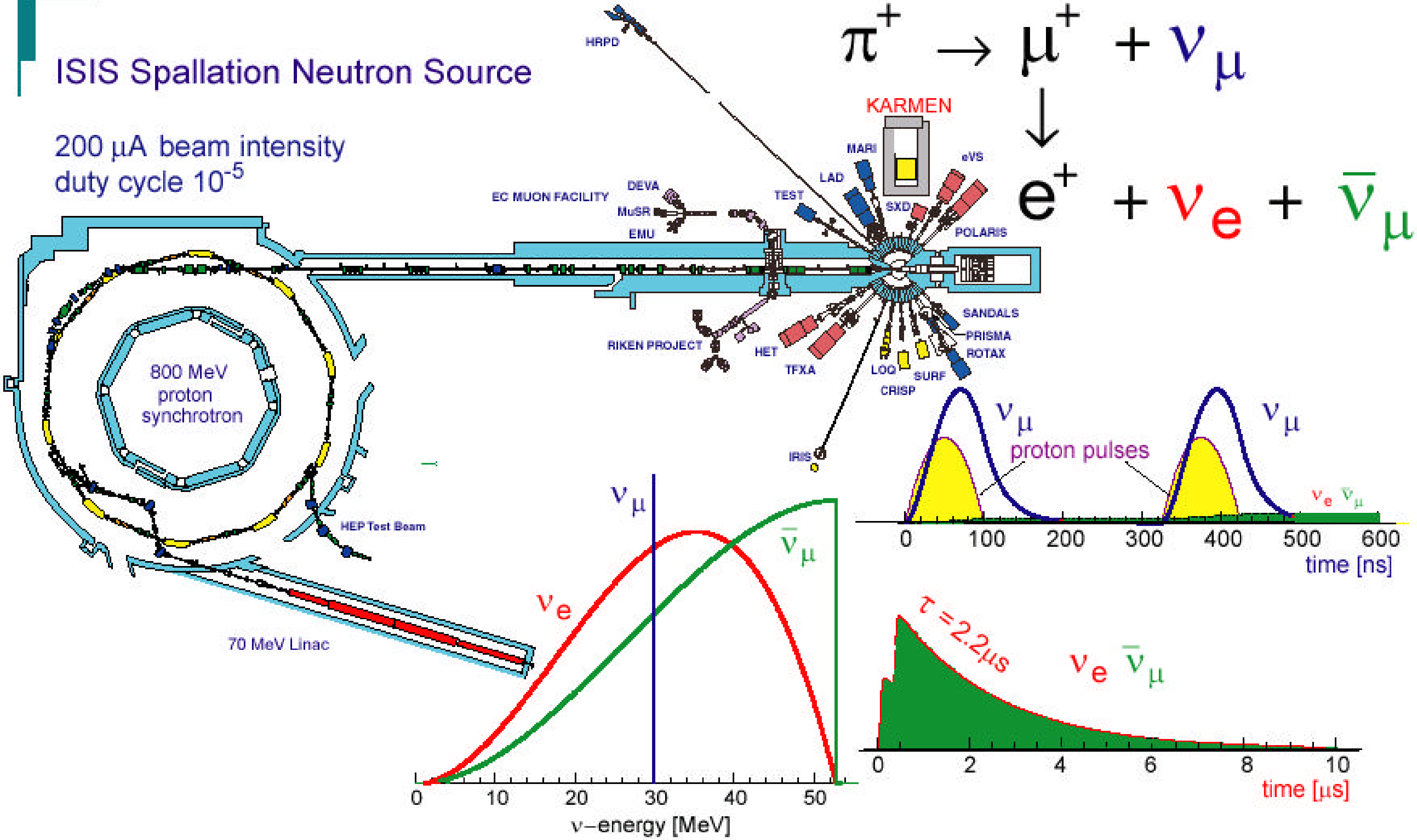
90% CL limits from other experiments



KARMEN

ISIS Spallation Neutron Source

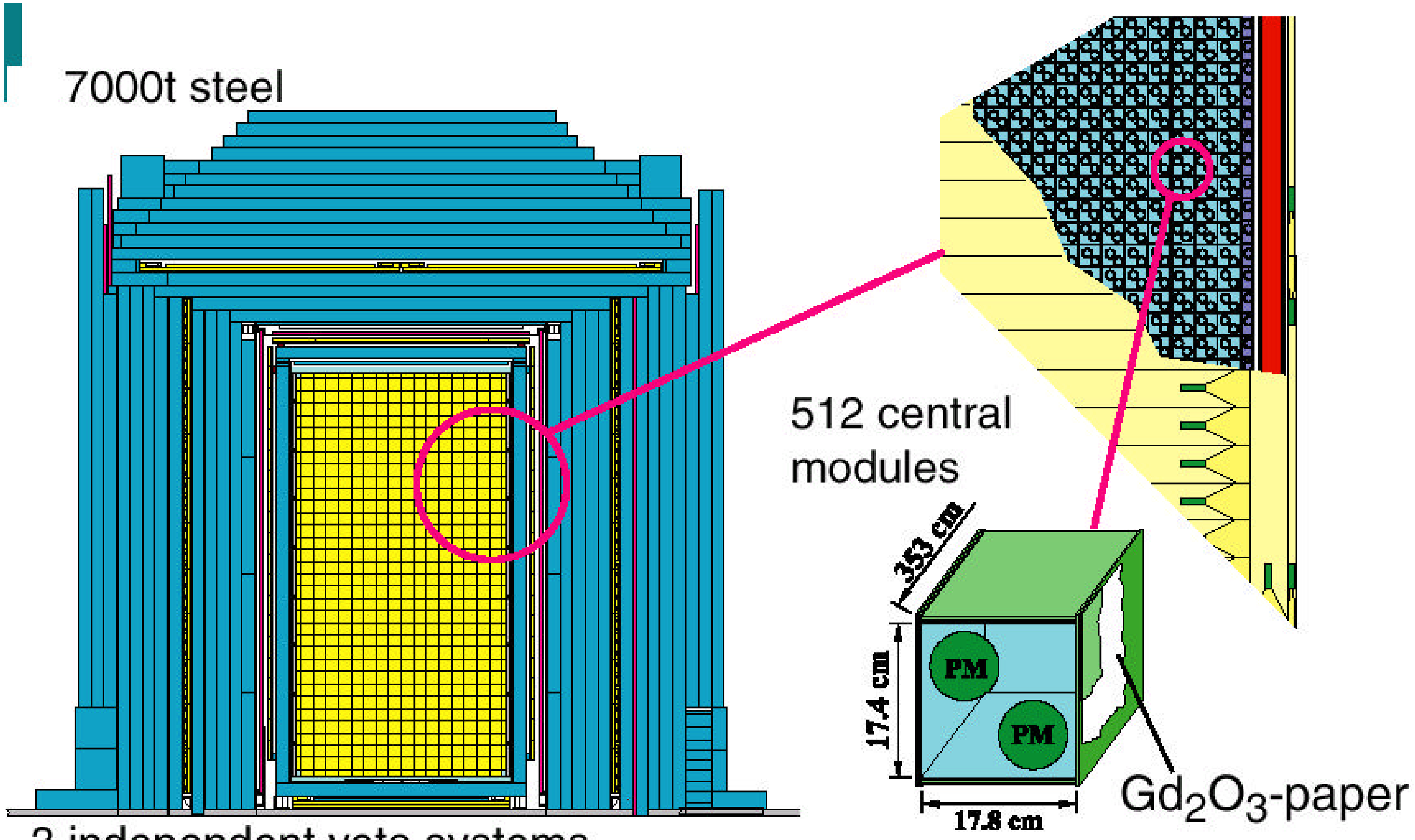
200 μA beam intensity
duty cycle 10^{-5}



$$\begin{array}{l} \pi^+ \to \mu^+ + \nu_\mu \\ \qquad\quad\; \downarrow \\ \qquad\quad\; e^+ + \nu_e + \bar{\nu}_\mu \end{array}$$

KARMEN detector

Position from struck module and PMT signals from each end.



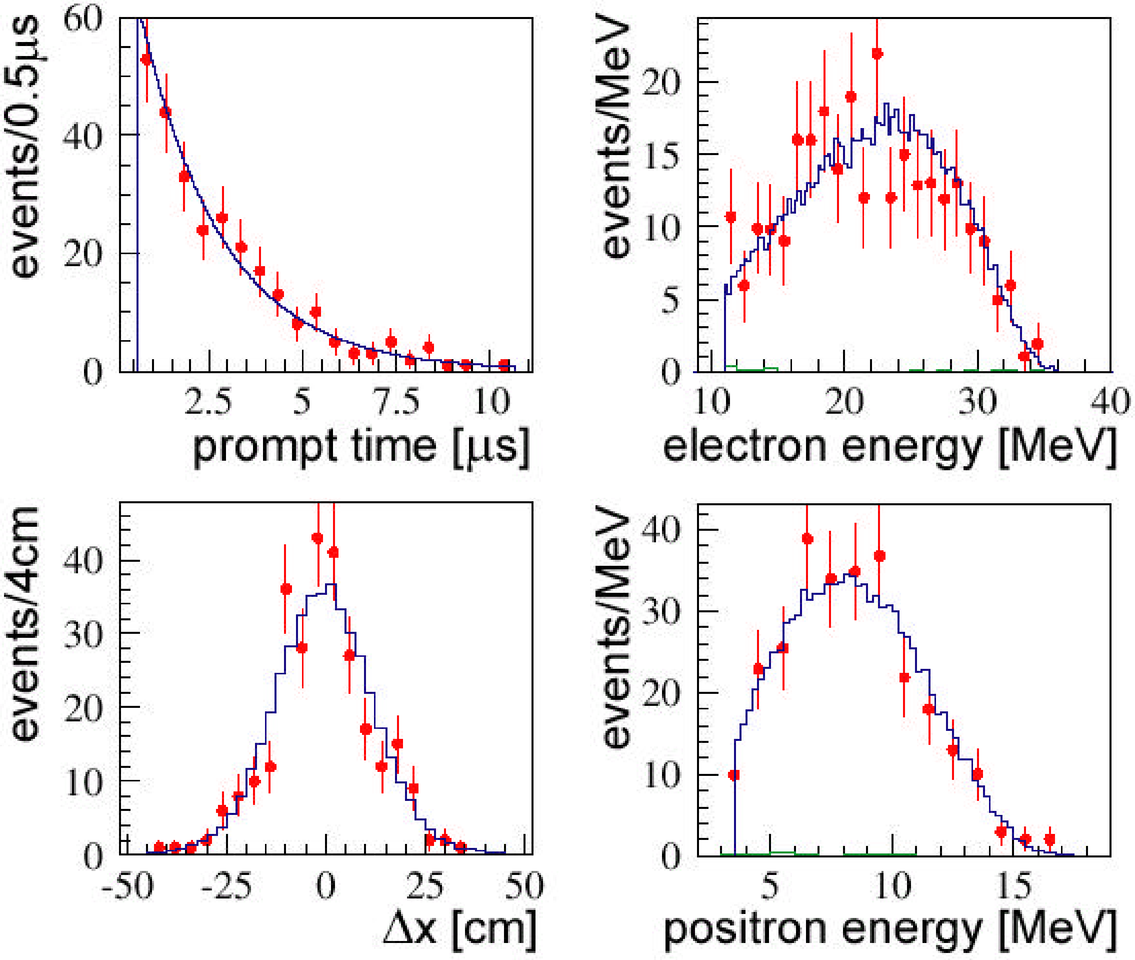
7000t steel

512 central modules

Gd_2O_3-paper

3 independent veto systems

e+b events



$$^{12}C(n_e, e^-)^{12}N_{g.s.}$$

274 sequences,
1.3 cosmic bg

281 sequences
expected
from KARMEN1

Oscillation signature at KARMEN

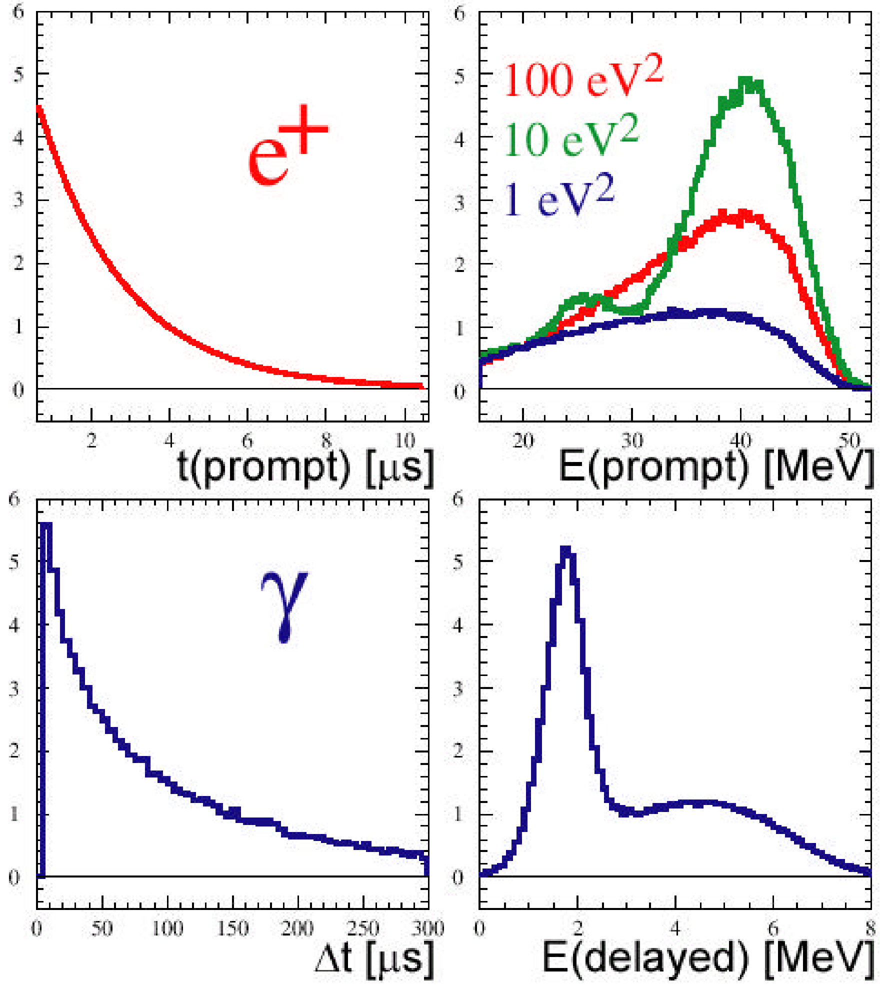
$\bar{n}_e p \to e^+ n$

$\to Gd(n,g)$

$\Sigma E_g = 8\,\mathrm{MeV}$

$\to p(n,g)$

$\Sigma E_g = 2.2\,\mathrm{MeV}$



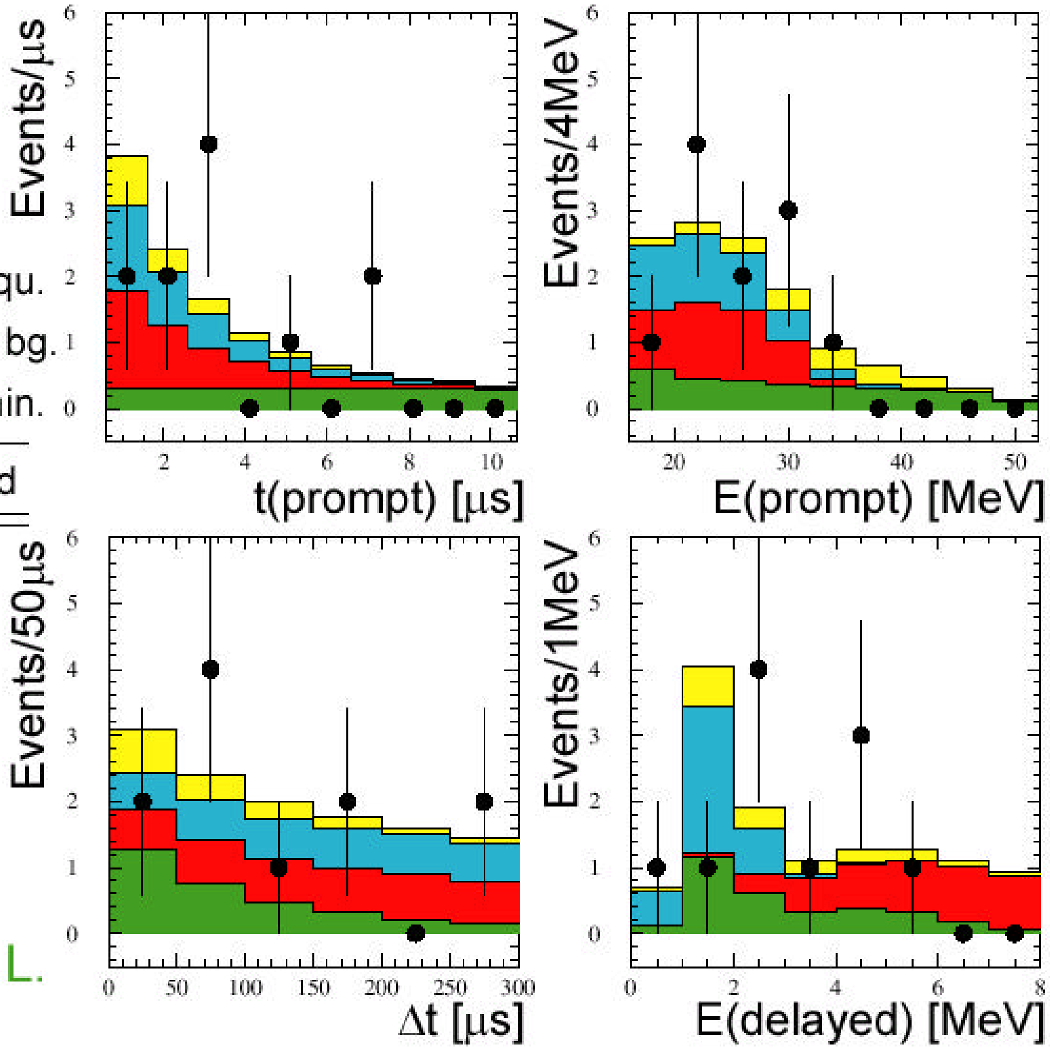
KARMEN oscillation results

11 candidates

3.9 +- 0.5	🟥	ν_e-induced CC sequ.
3.5 +- 0.3	🟦	ν-induced random bg.
1.7 +- 0.2	🟨	$\bar{\nu}_e$ intrinsic contamin.
3.2 +- 0.2	🟩	cosmic background
12.3 +- 0.6		total background

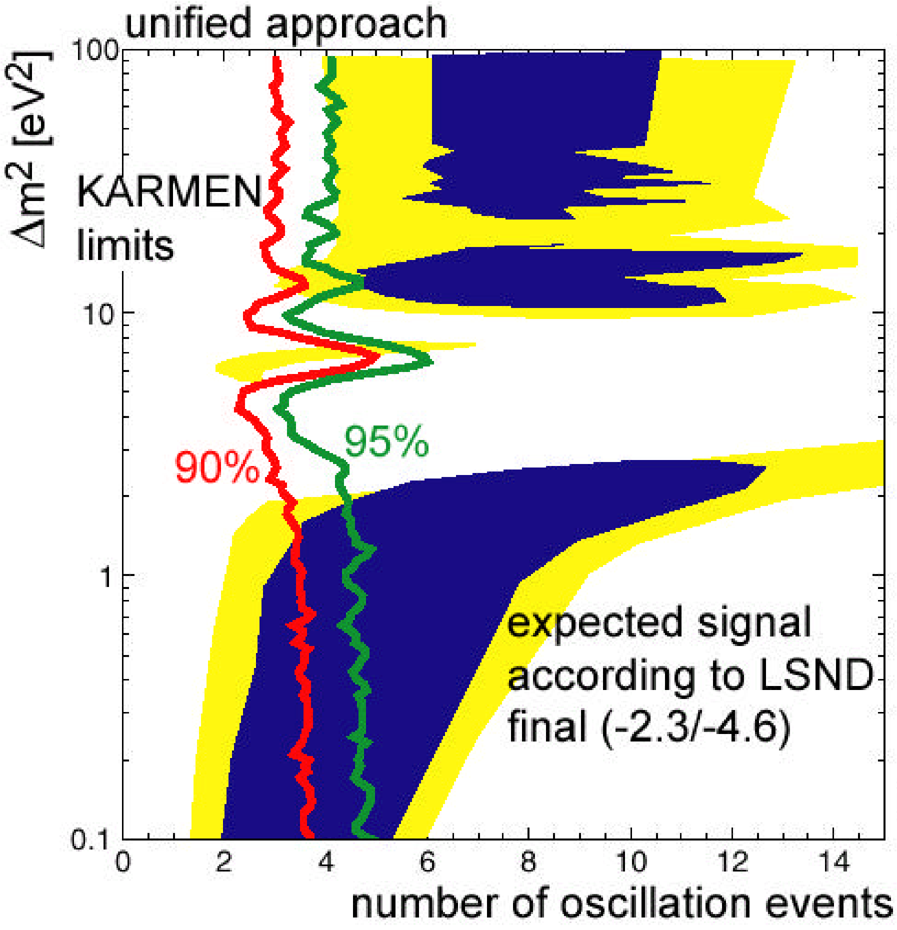
⟹ **no osci signal**

Bayes:
signal > 6.3 evts
excluded @ 90% C.L.



KARMEN: expected excess for LSND hypothesis

excess for 100% transmutation



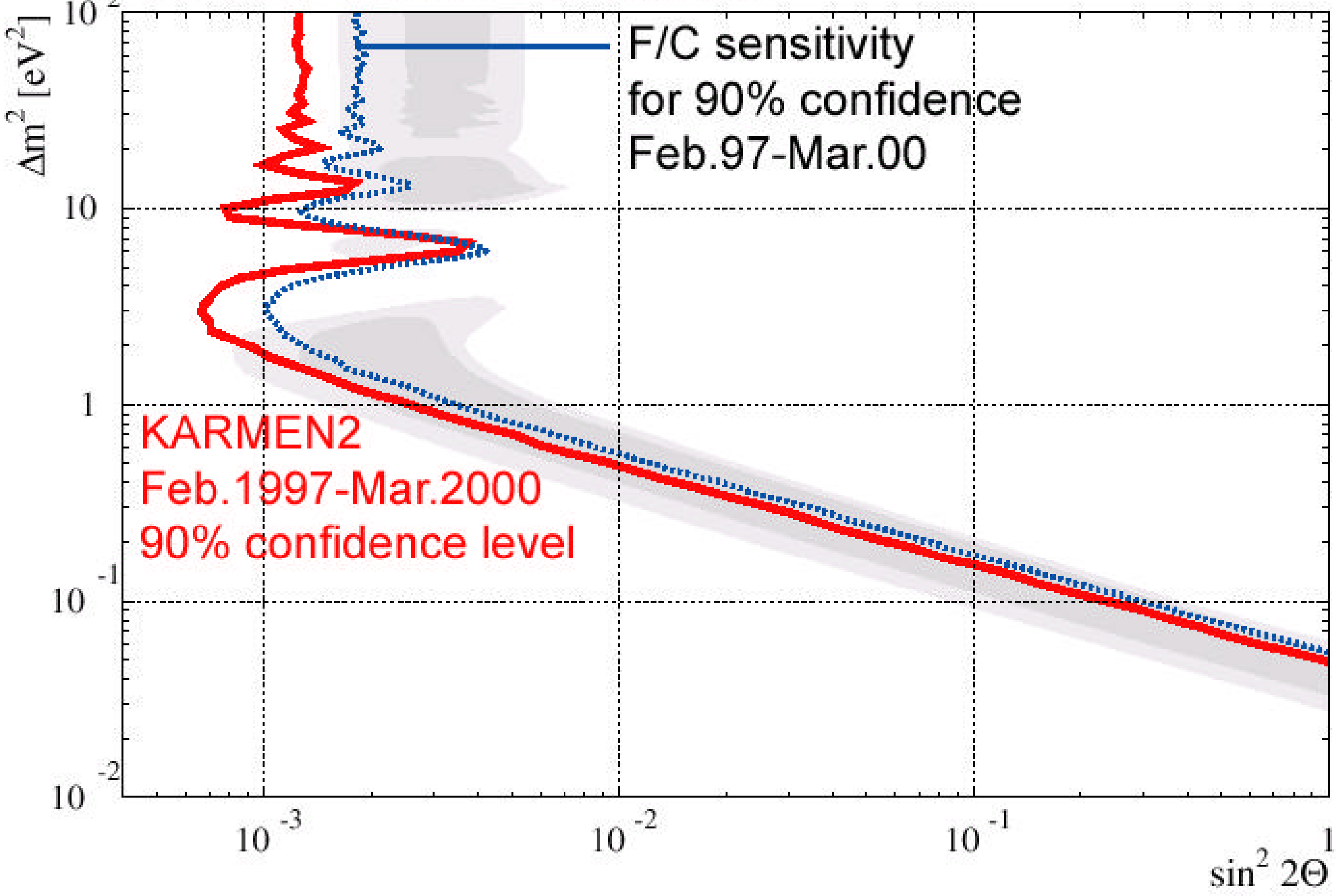
N(expected)=2442 for $\sin^2(2\Theta)=1$

N(osc)<**3.1** (90% CL)
$\Delta m^2=100\text{eV}^2$

N(osc)<**3.8** (90% CL)
$\Delta m^2=0.1\text{eV}^2$

KARMEN sensitivity plot

$\sin^2(2\Theta) < 1.3\times10^{-3}$ for large Δm^2



KARMEN November 2000 status report

data Feb.´97-March 2000
(7160C prot.-on-target):

11 candidates

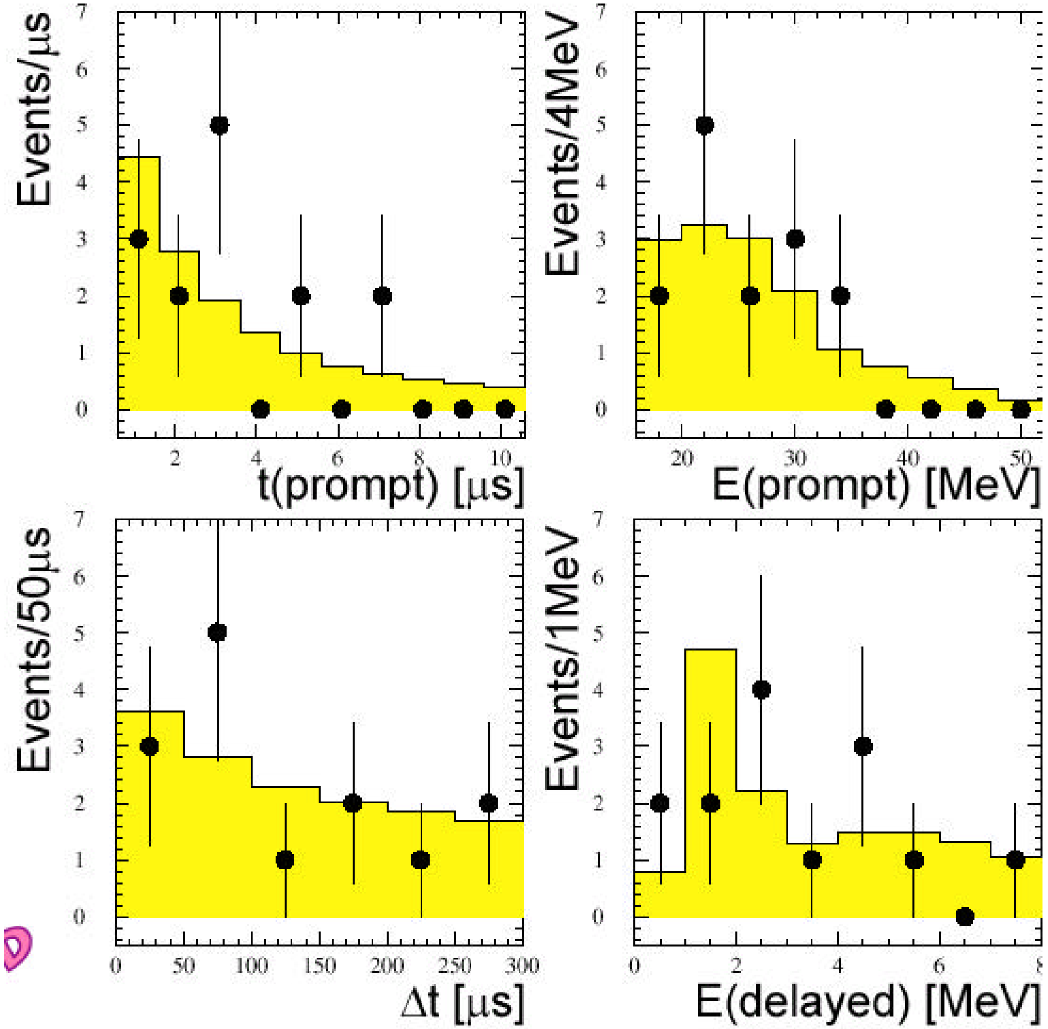
12.3 bg events
sensitivity: $\sin^2 2\Theta < 1.7 \times 10^{-3}$

data Feb.´97-Nov. 2000
(8300C prot.-on-target):

14 candidates

14.3 bg events

KARMEN ended March 2001



SND evidence for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations: a very serious problem

efine: $\Delta m_{ik}^2 = m_k^2 - m_i^2$ (i,k = 1, 2, 3)

$$\Longrightarrow \quad \Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

vidence for neutrino oscillations:

Solar neutrinos: $\Delta m_{12}^2 \approx 6.9 \times 10^{-5}\ \mathrm{eV}^2$

Atmospheric neutrinos: $\Delta m_{23}^2 \approx 2.5 \times 10^{-3}\ \mathrm{eV}^2$

LSND: ⟹ $|\Delta m_{31}^2| = 0.2 — 2\ \mathrm{eV}^2$

⇓

$$| \Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 | = 0.2 — 2\ \mathrm{eV}^2$$

If all three results are correct, at least one additional neutrino is needed.

To be consistent with LEP results (only three neutrinos), any additional neutrino, if it exists, must be "sterile" (no coupling to W and Z bosons → no interaction with matter)

LSND result needs confirmation

How Can We Explain Solar, Atmospheric, & LSND?

Problem:

3 separate Δm^2 observed, which cannot be explained by 3 $m_{\nu i}$!?!

Possible Solutions:

(1) Non-Standard Interactions (e.g. Lepton # Violating Muon Decay for LSND: $\mu^+ \to e^+ \bar{\nu}_e \bar{\nu}_i$, tested by TWIST)

(2) Sterile neutrinos (2+2 or 3+1 or 3+2)

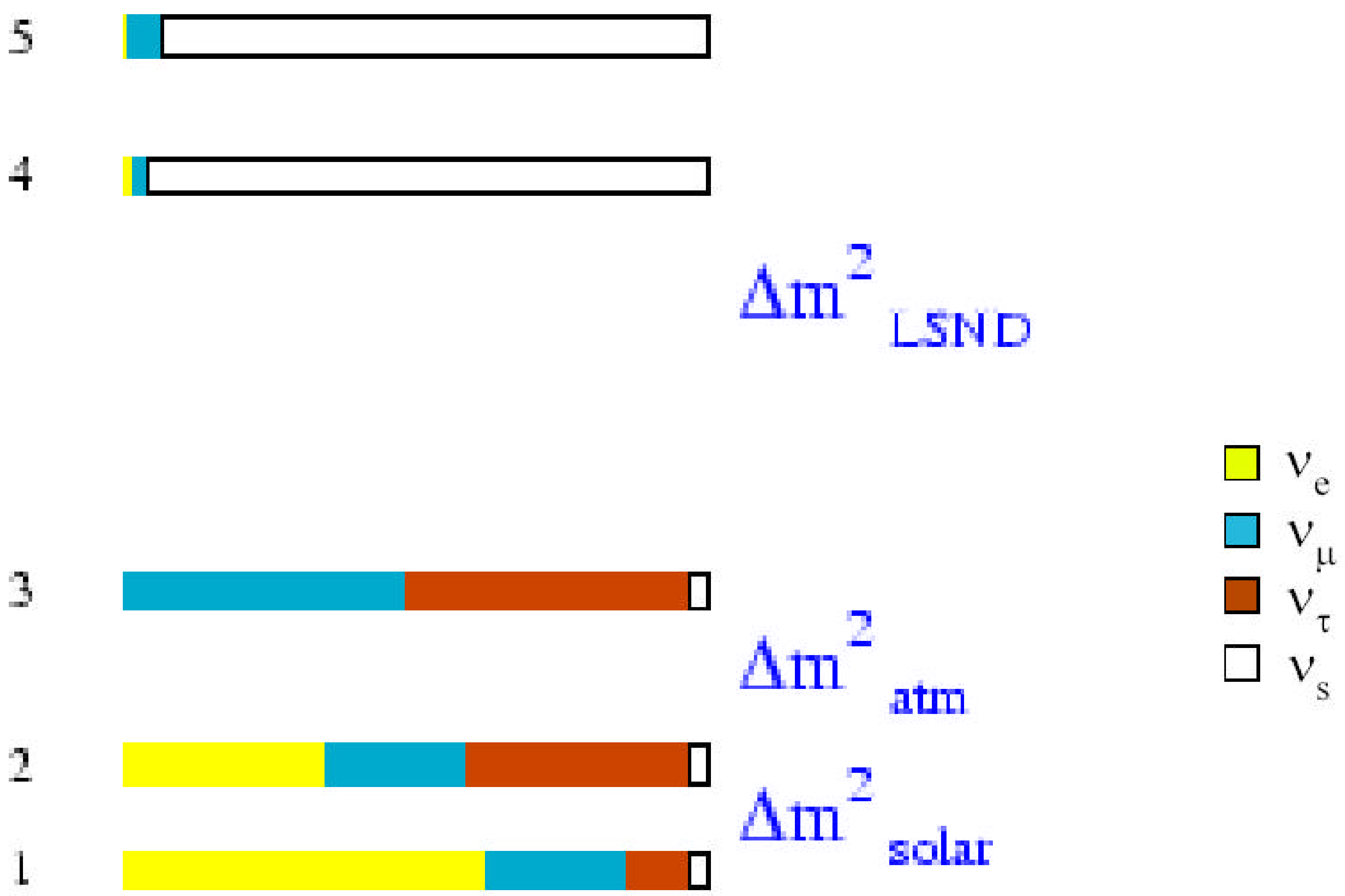
(3) CPT Violation ($m_\nu = m_{\bar{\nu}}$?)

Light Sterile Neutrinos?

- In (2+2) models, solar and atmospheric can be explained by a combination of active & sterile oscillations.
- In (3+1) & (3+2) models, LSND can be explained by heavier sterile neutrinos.
- There is tension with sterile neutrino models explaining all of the data, but the (3+2) model is not too unreasonable.
- Light, sterile neutrinos could have a big impact on BBN, the R-process in Supernovae, and the mass of the universe (cold, warm, or hot).

3+2 Model

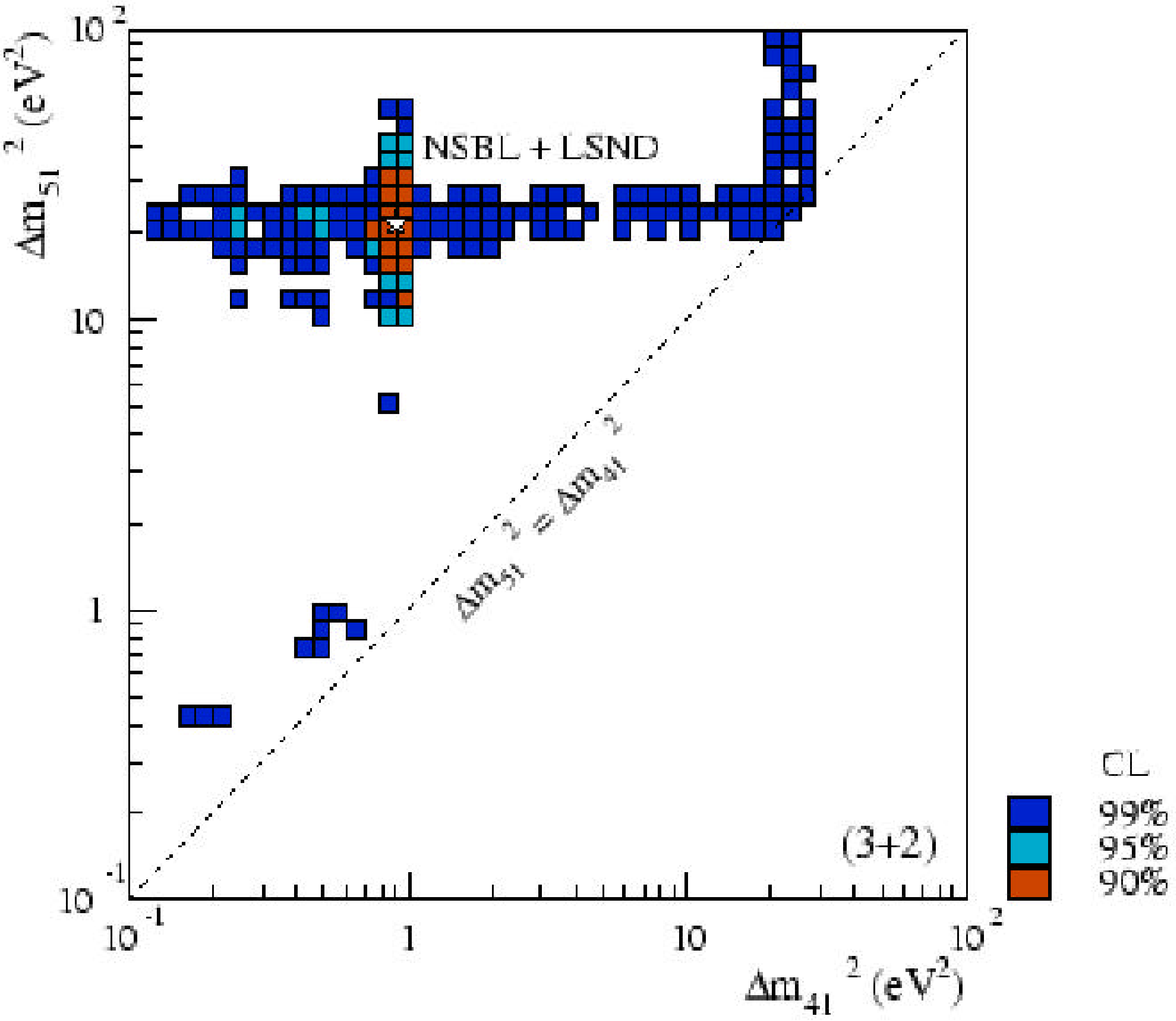
Sorel, Conrad, & Shaevitz
hep-ph/0305255



3+2 Model

Sorel, Conrad, & Shaevitz

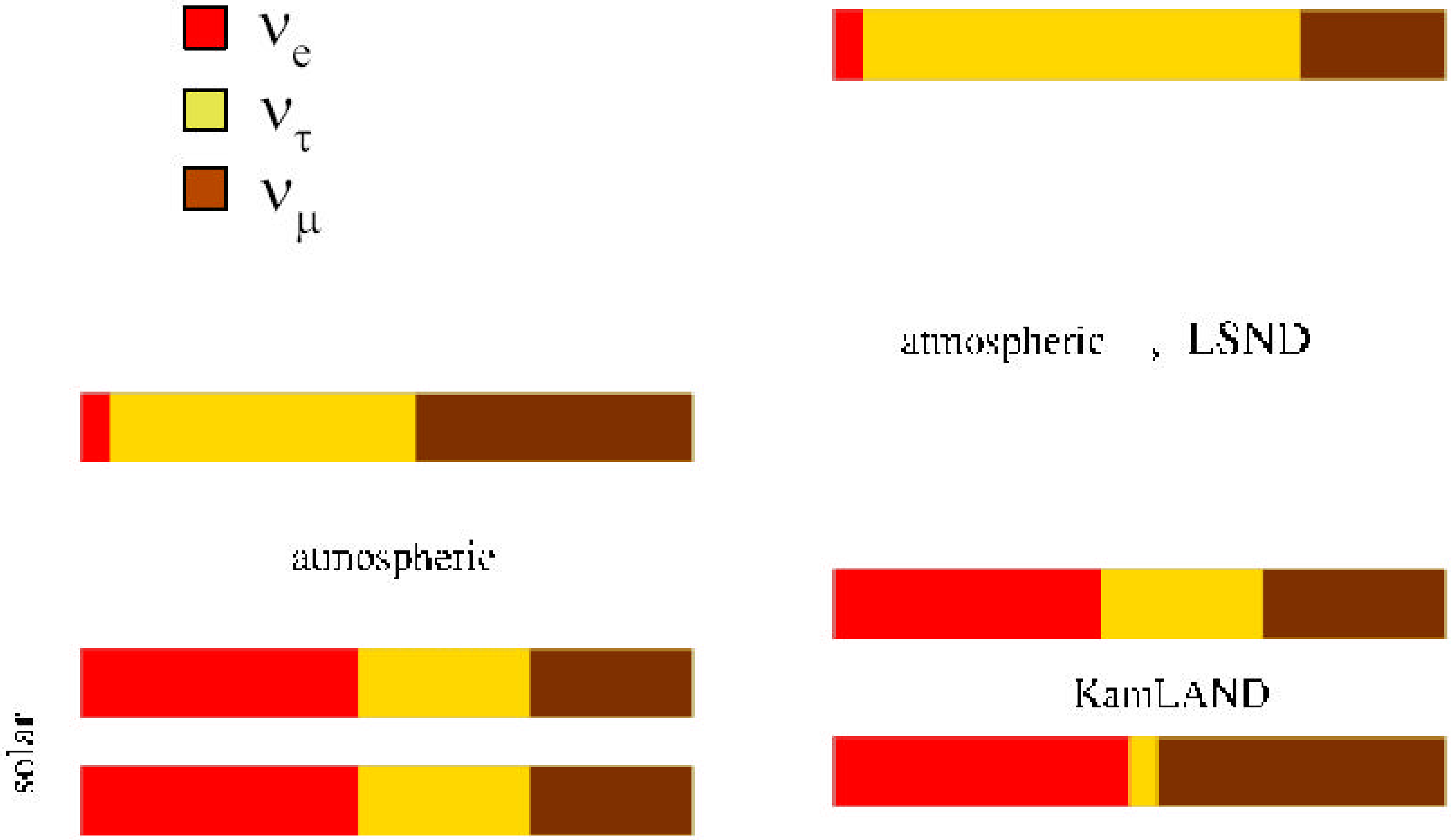
hep-ph/0305255



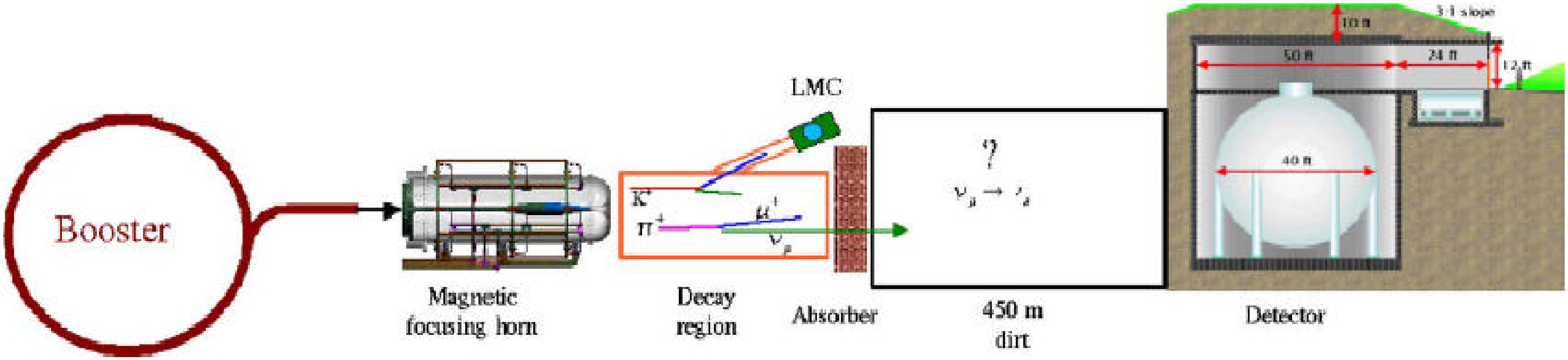
CPT Violation Model

Barenboim, Borissov, & Lykken

hep-ph/0212116



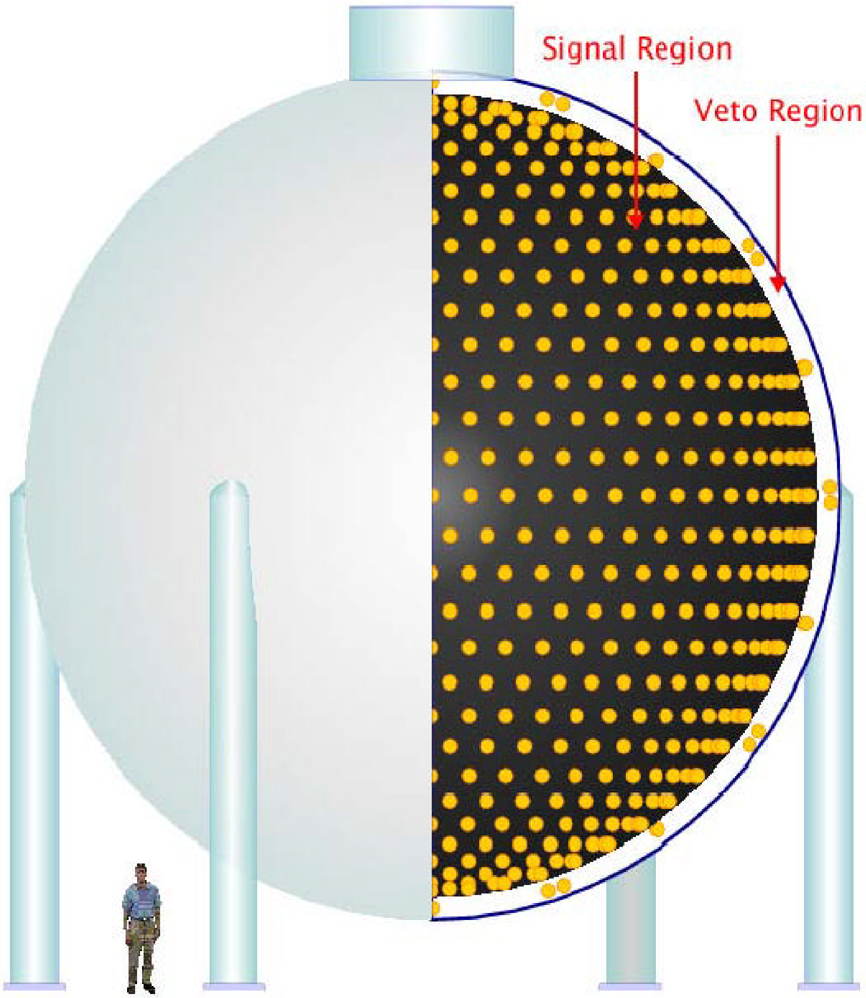
MiniBooNE - A Definitive Test of the LSND Evidence for ν Oscillations



- Booster - 8 GeV proton beam (5 x 10^{20} POT/y)
- Target - 71 cm Be
- Horn - 5 Hz, 170 kA, 143 μs, 2.5 kV, 10^8 pulses/y
- Decay Pipe - 50 m (adjustable to 25 m)
- Neutrino Distance - ~ 0.5 km
- $<E_\nu>$ ~ 1 GeV
- $(\nu_e / \nu_\mu) \sim 3 \times 10^{-3}$
- Detector - 40' diameter spherical tank
- Mass - 800 (450) tons of mineral oil
- PMTs - 1280 detector + 240 veto, 8" diameter

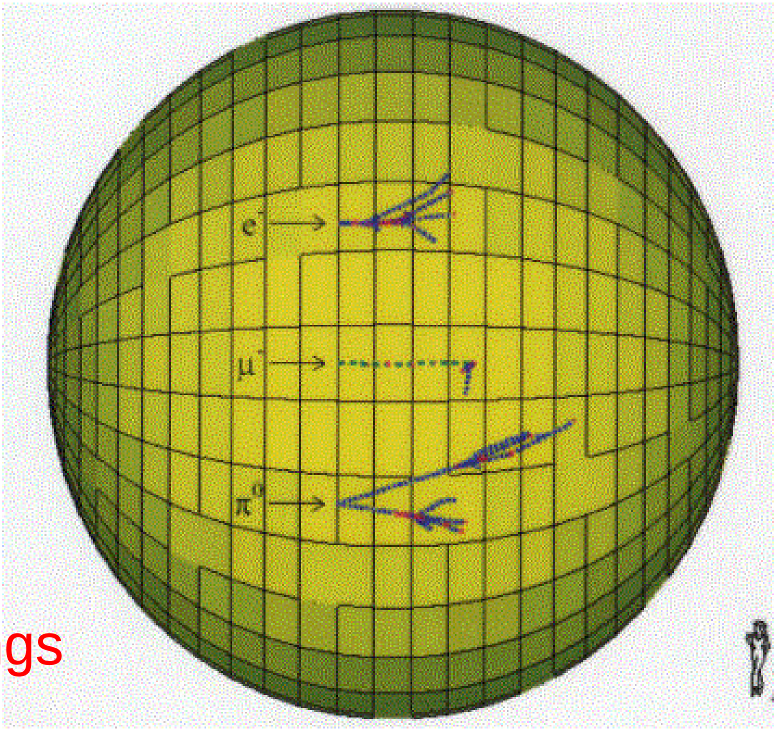
MiniBooNE detector

- 12 m diameter spherical tank
- 807 tons mineral oil used as Cerenkov radiator
- fiducial mass 445 tons
- optically isolated inner region with 1280 20 cm diam. PM tubes
- external anticoincidence region with 240 PM tubes

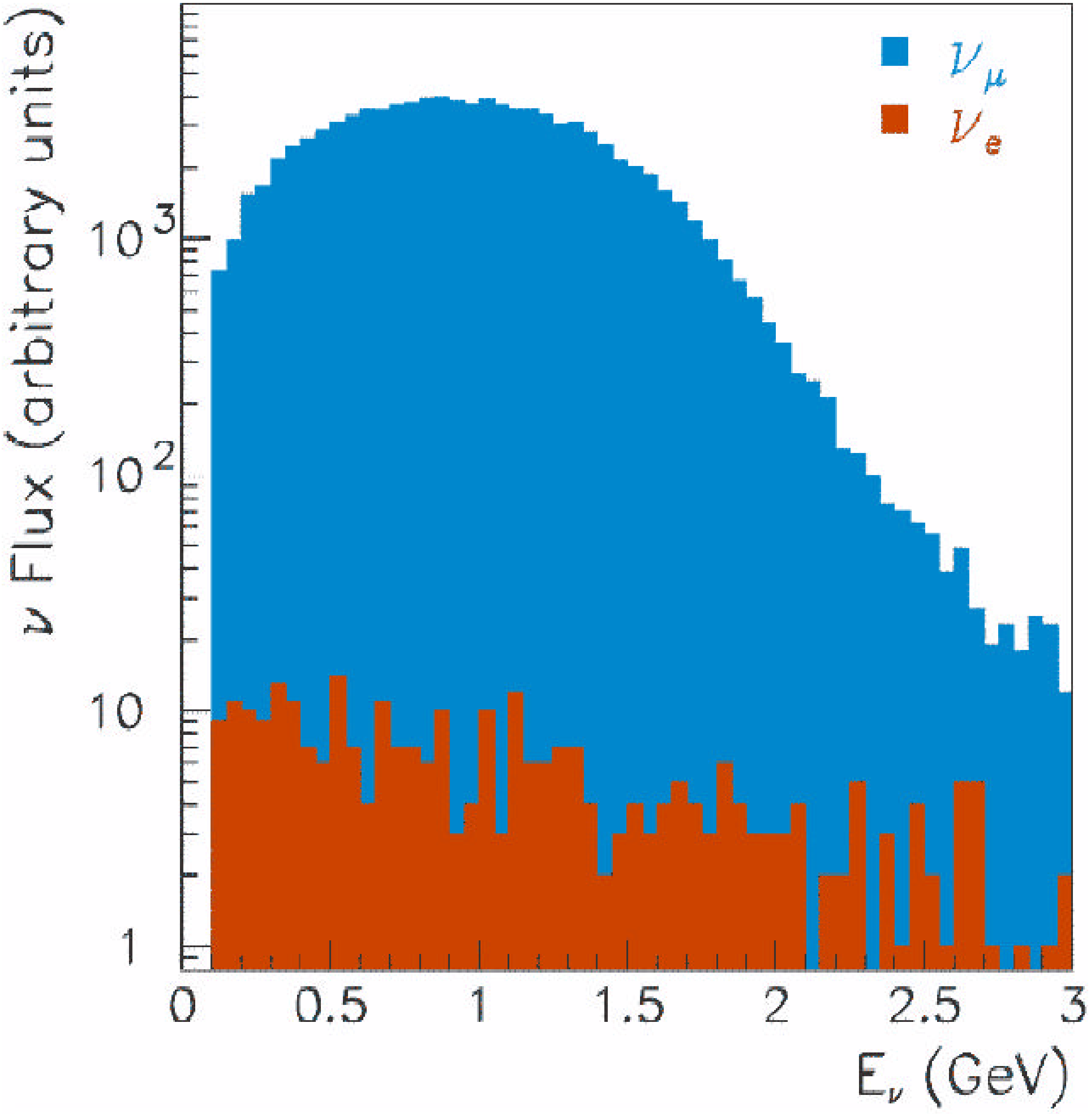


article identification:

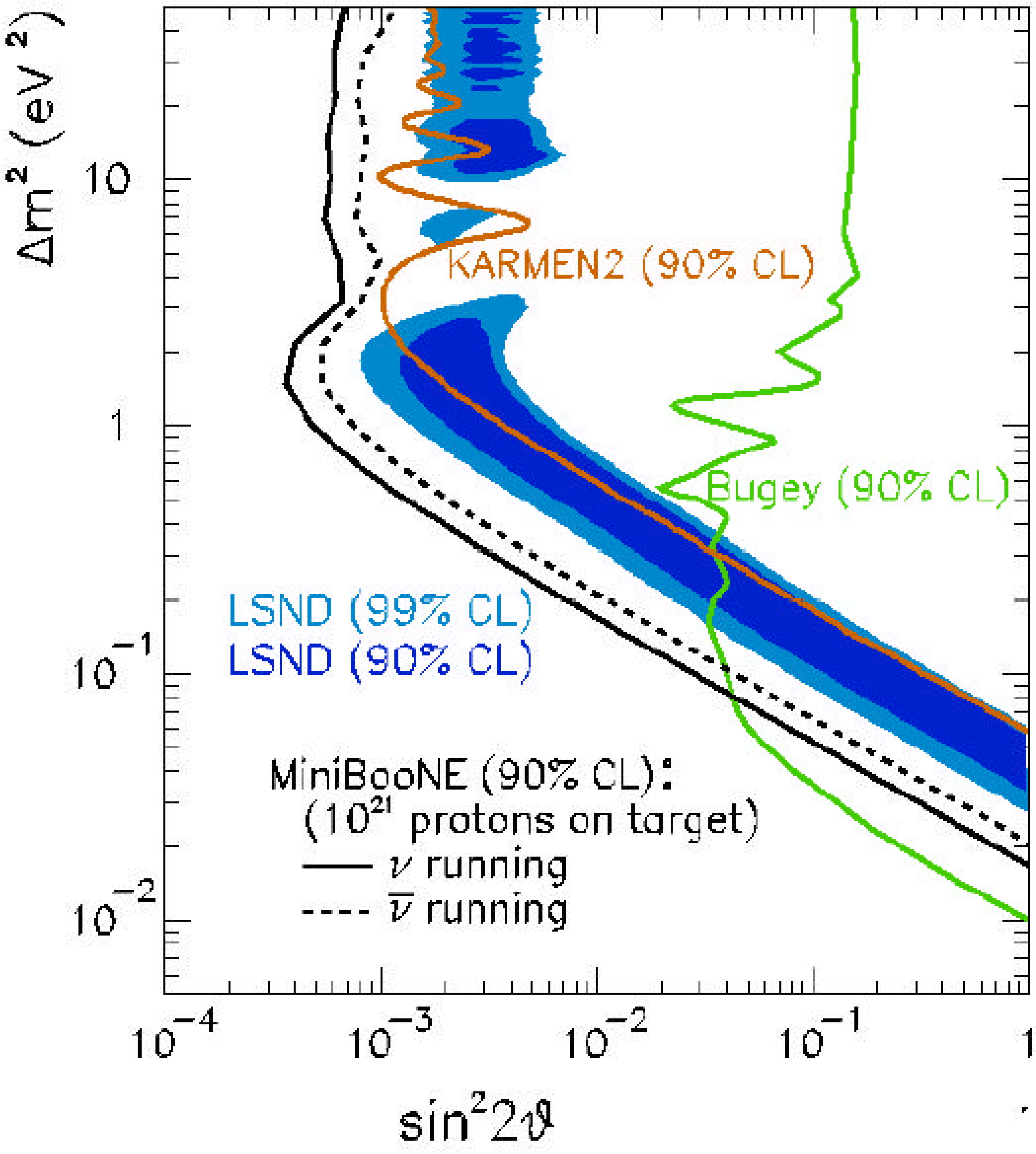
ased on different behaviour of electrons, uons, pions and pattern of Cerenkov light rings



MiniBooNE Estimated Neutrino Flux



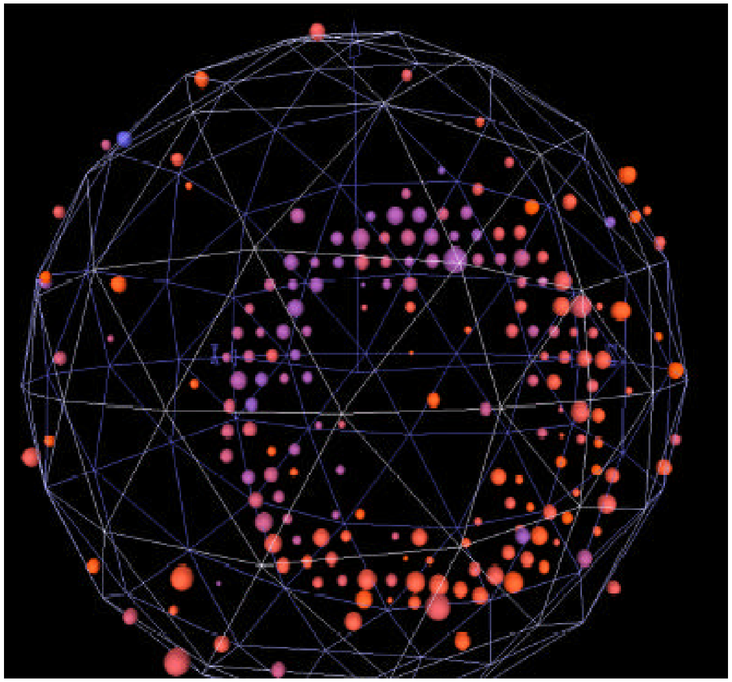
Expected MiniBoone sensitivity

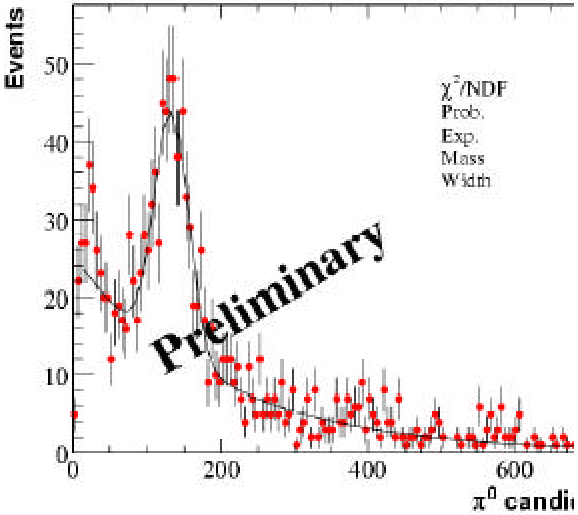


MiniBoone detector status

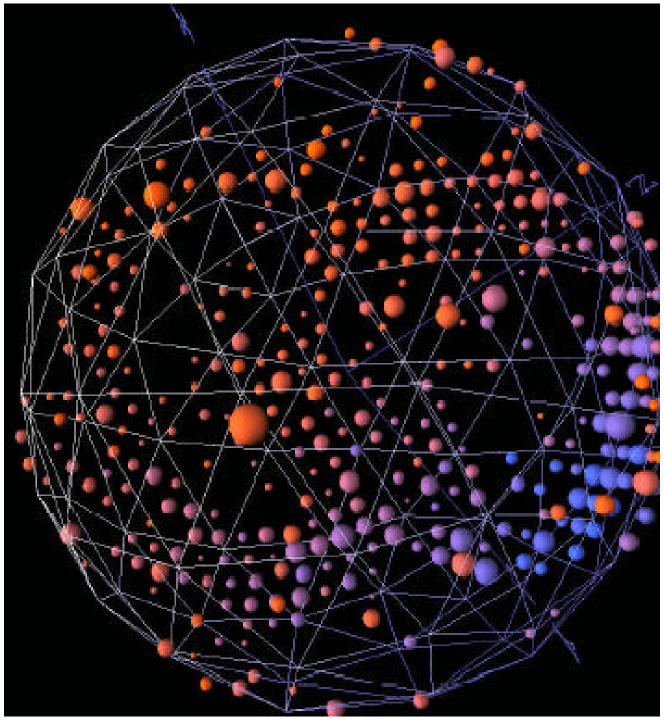
- Beamline & Detector Working Beautifully!
- Booster Proton Intensity Within Factor 2 of Goal
- ~99% of all PMT channels working well
- DAQ Livetime is ~99%
- Time, Energy, Position, & Angular Resolutions Consistent with Expectations
- ν Event Rate Consistent with Expectations
- Clearly Reconstructing CC μ & NC π^0 Events

Typical ν_μ CC Event

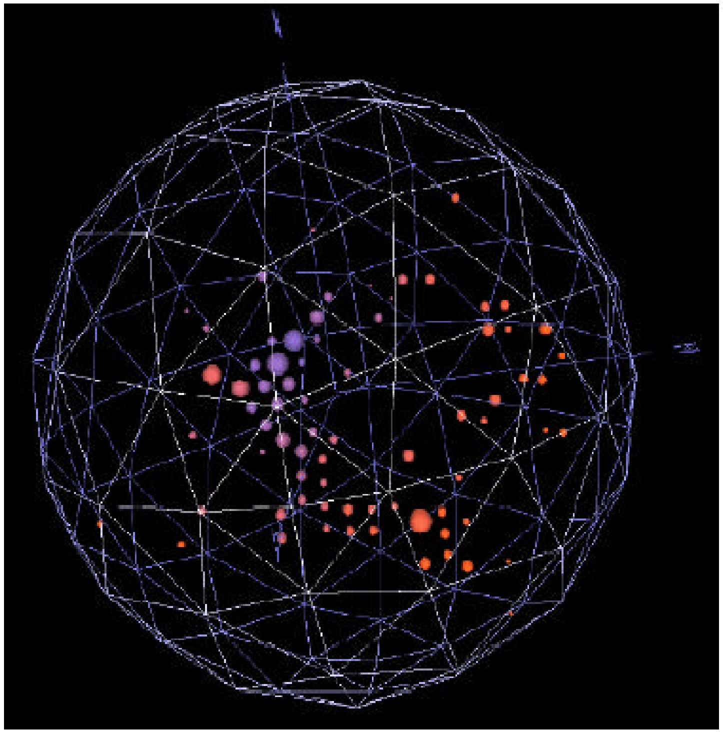


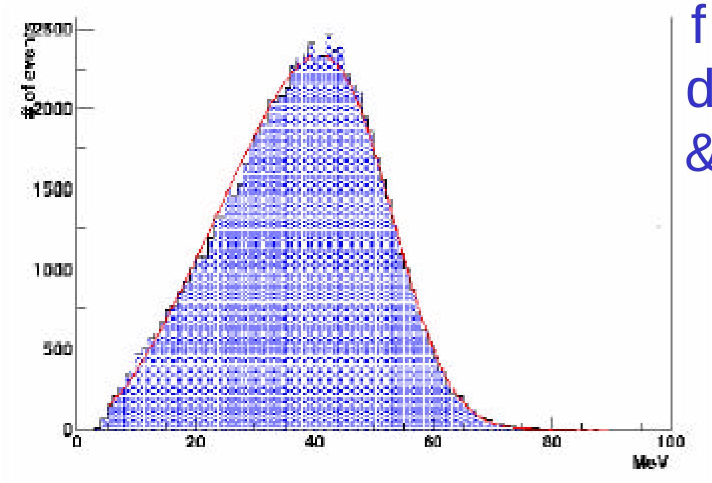


π^0 Candidate Event



Typical Michel Electron Event





Use Michel electrons from μ decay to determine energy scale & resolution

MiniBoone conclusion

- MiniBooNE Beamline & Detector Are Working Beautifully!
- Have Collected ~100K ν Events (~20% of $5\text{x}10^{20}$ POT Yearly Goal)
- Booster Intensity Is Steadily Increasing (Proton Intensity Now Within 2 of Goal)
- First σ & $\nu_\mu \rightarrow \nu_x$ Results in ~2003
- First $\nu_\mu \rightarrow \nu_e$ Results in ~2005
- If MiniBooNE Confirms LSND, Then Build a 2nd Detector at a Different Distance (BooNE!)