Non-accelerator neutrino experiments

(selective) report of recent results and achievements

EPS HEP conference Grenoble, 26 July 2011

Stefan Schönert
Physik Department E15
Technische Universität München

Many thanks to:

T. Lasserre, A. Palazzo, K. Heeger, Inoue-san, M. Marino, G. Gratta, A. Giuliani, O. Cremonesi, F. Piquemal, G. Drexlin

for up-to-date information, discussions and slides – also for the many slides not used!

Outline

- Updates from solar & reactor ν-experiments on mixing
- θ_{13} search at nuclear reactors
- Reactor ν-anomaly & sterile ν's
- Kinematical ν-mass measurement
- $0\nu\beta\beta$ decay experiments

Outline

- Updates from solar & reactor ν-experiments on mixing
- θ_{13} search at nuclear reactors
- Reactor ν-anomaly & sterile ν's
- Kinematical ν-mass measurement
- $0\nu\beta\beta$ decay experiments

Non-accelerator experiments

PAST: 2-flavor analysis

small θ_{13}, favorable mass splitting & **limited precision**

Atmospheric — **Reactor:** Chooz, Palo Verde — **Solar & KamLAND**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha 2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Majorana phases not observable in oscillations but important for $0\nu\beta\beta$

Non-accelerator experiments

Recent years: 3-flavor analysis

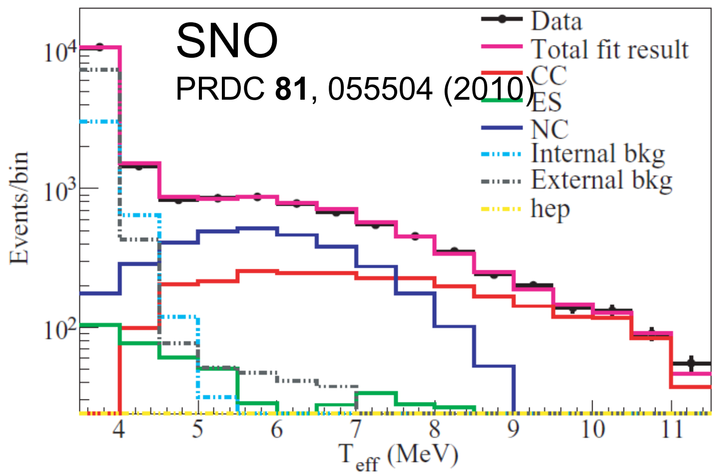
small θ_{13}, favorable mass splitting & **high precision**

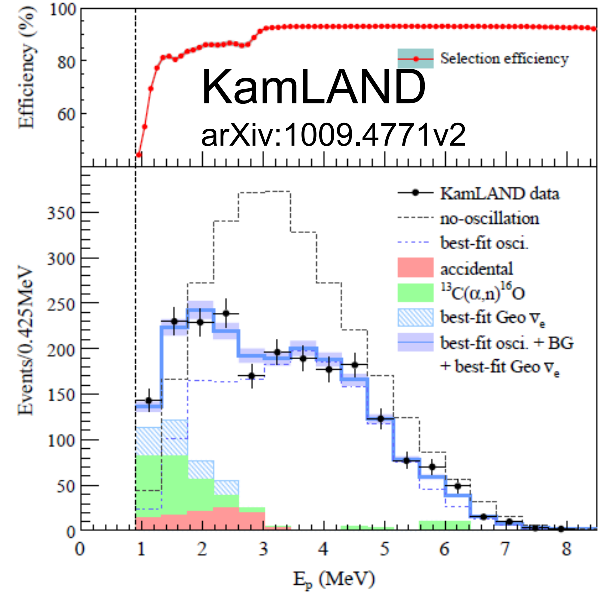
Atmospheric | **Reactor:** Chooz, Palo Verde | **Solar & KamLAND**

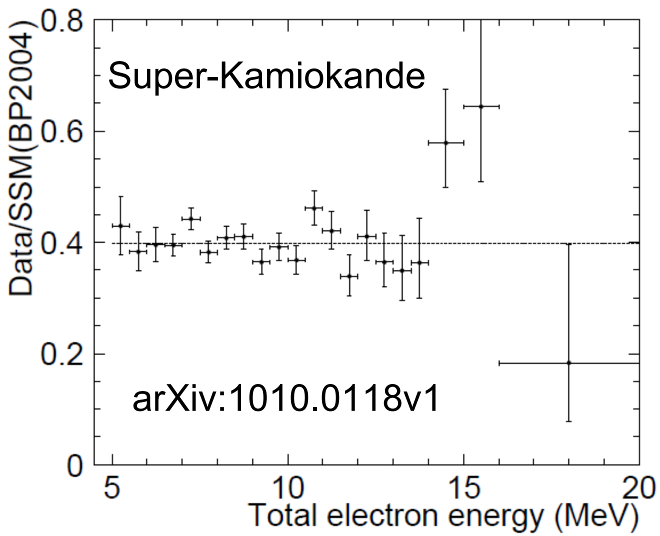
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha 2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

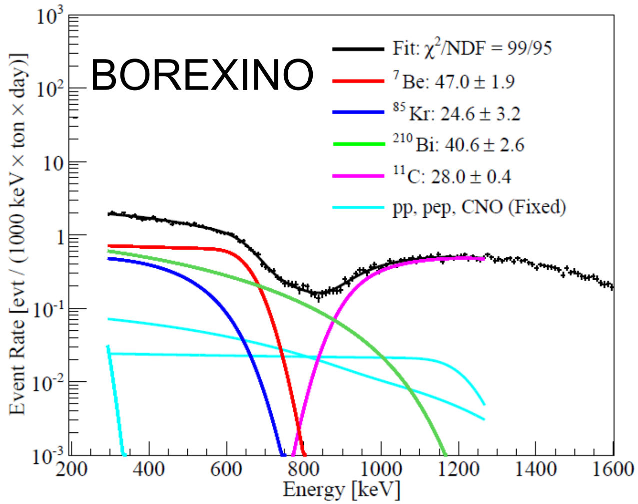
Majorana phases
not observable in
oscillations but
important for $0\nu\beta\beta$

Precision measurements of solar and reactor neutrinos with SNO, Super-K, KanLAND. Borexino

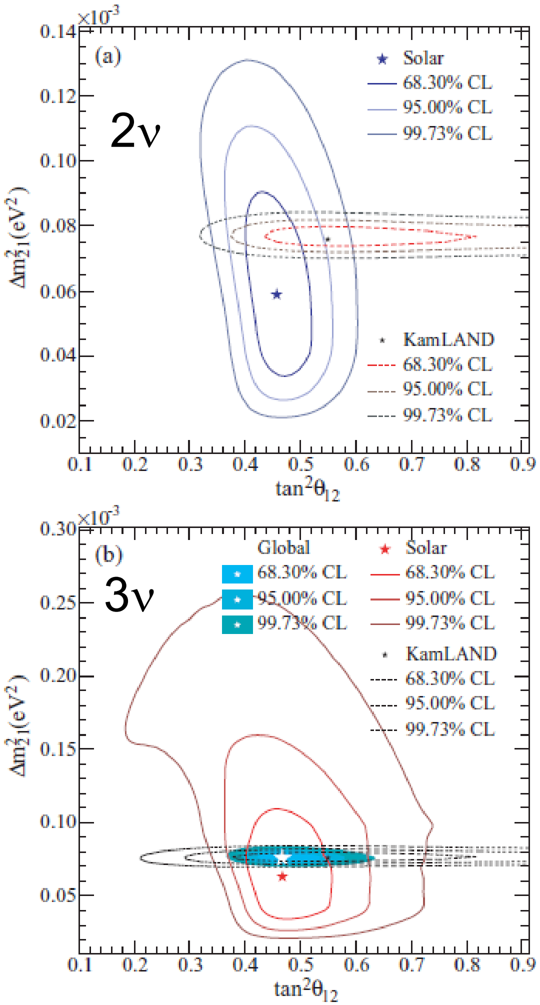




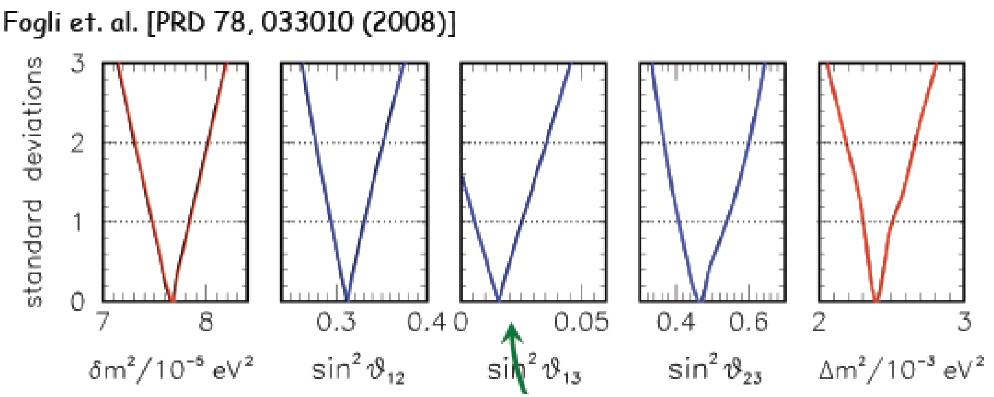




Tensions between solar & KL data in 2-flavor analysis



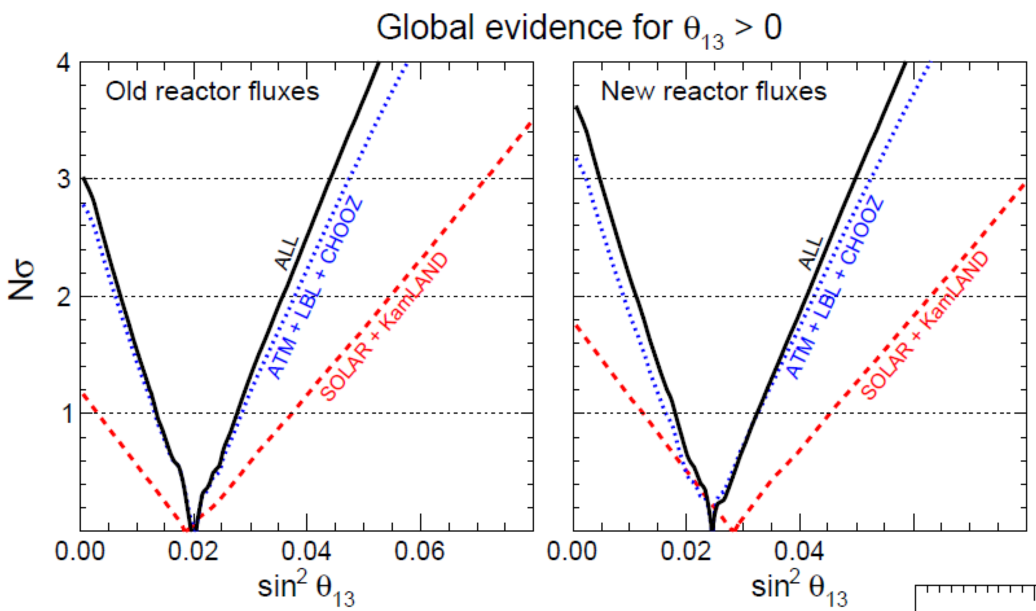
PRDC **81**, 055504 (2010)



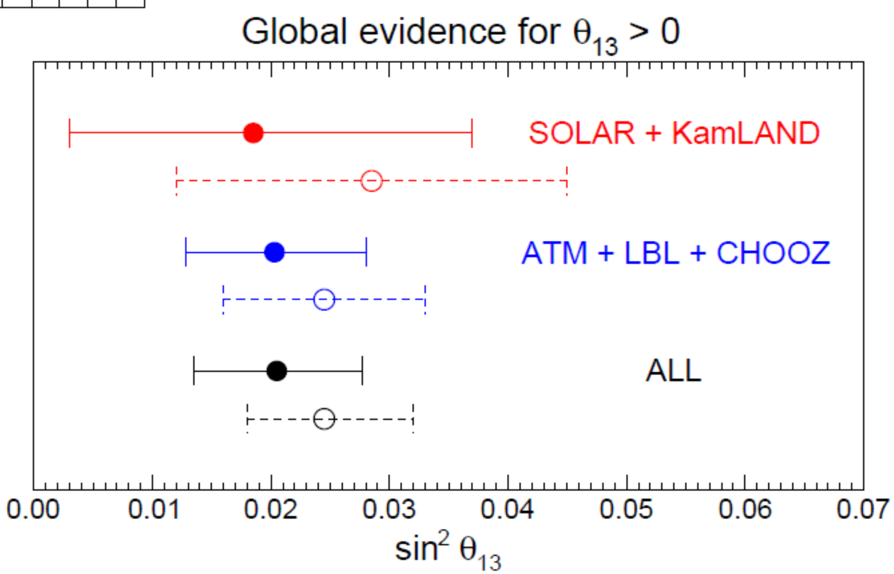
First pointed out in 2008: global analysis provided a preference for $\theta_{13} > 0$ at 90% C.L.

Fogli, Lisi, Marrone, A.P, Rotunnno,
PRL 101, 141801 (2008), [arXiv:0806.2649].

Global 3ν analysis inclusive T2K and Minos results

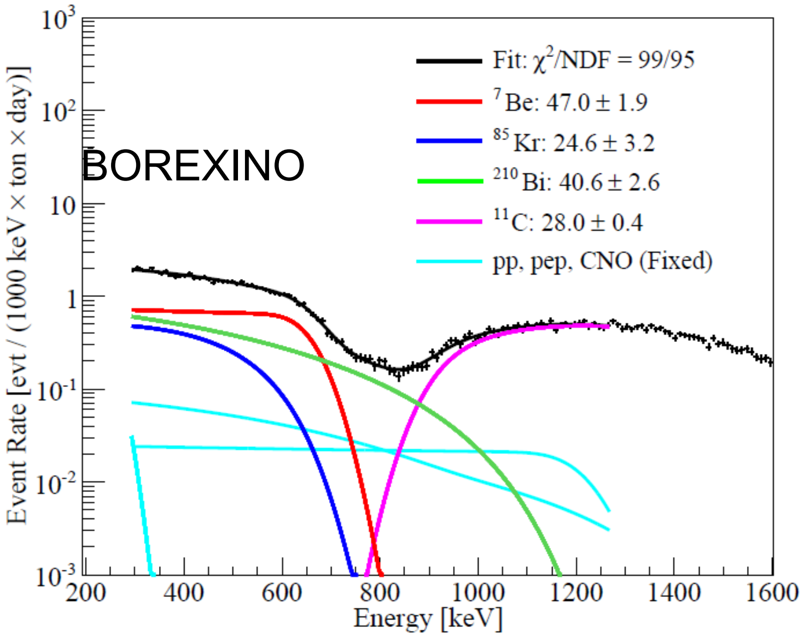


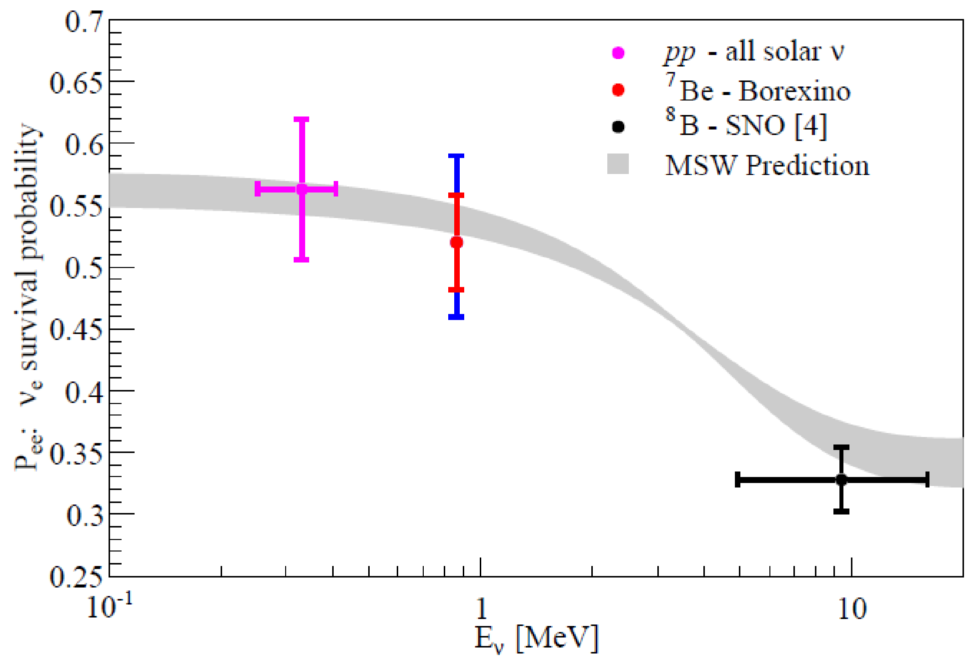
Fogli, Lisi, Marrone, Palazzo, Rotunno, arXiv:1106.6028 [hep-ph]

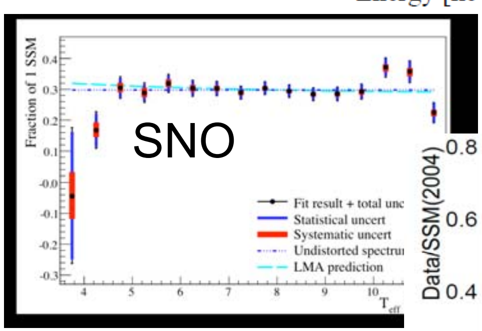


With old reactor fluxes: 3.0 sigma
(With new reactor fluxes: 3.6 sigma)

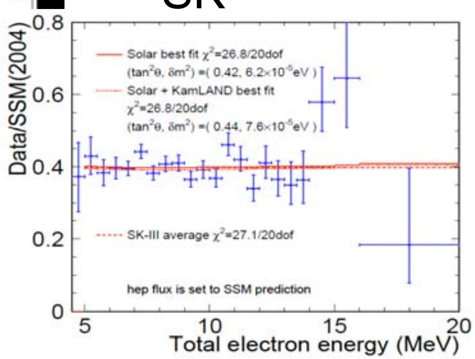
Precision measurement of solar ^{7}Be with Borexino







SK



Mapping the MSW suppression:

Transition region is sensitive to NSI:
Lower B threshold required to map
Expected up-turn

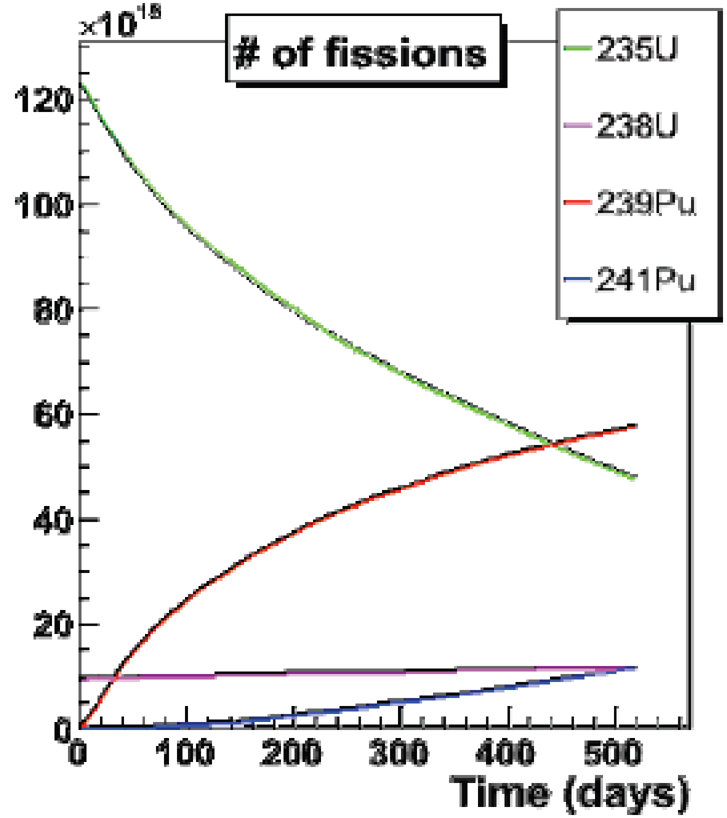
Outline

- Updates from solar & reactor ν-experiments on mixing
- **θ_{13} search at nuclear reactors**
- Reactor ν-anomaly & sterile ν's
- Kinematical ν-mass measurement
- **$0\nu\beta\beta$ decay experiments**

- **Electron antineutrinos emitted through Decays of Fission Products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu**
- **Nuclear reactors** : $1\ \mathrm{GW_{th}} \Leftrightarrow 2\ 10^{20}\ \bar{\nu}/\mathrm{s}$
- **Neutrino Luminosity** : $N_{\bar{\nu}} = \gamma(1+k)P_{\mathrm{th}}$

  γ: reactor constant

  k : fuel evolution correction up to 10%



- **Neutrino detection**
  - Inverse Beta-Decay reaction (xsec: $\sigma_{\text{V-A}}$)

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

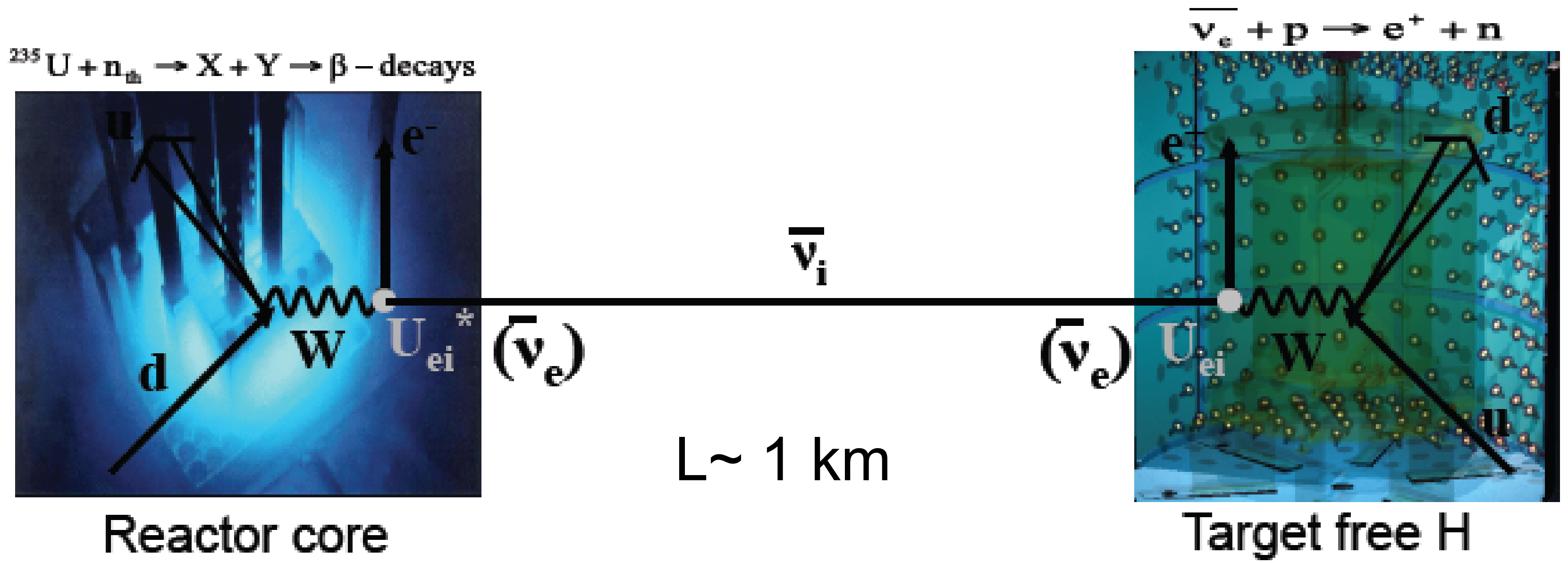
  - Threshold 1.8 MeV. E_ν extend to 10 MeV
  - Measure anti-ν_e of interaction rate

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

$$\updownarrow$$

  - Comparison of σ_f to prediction

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



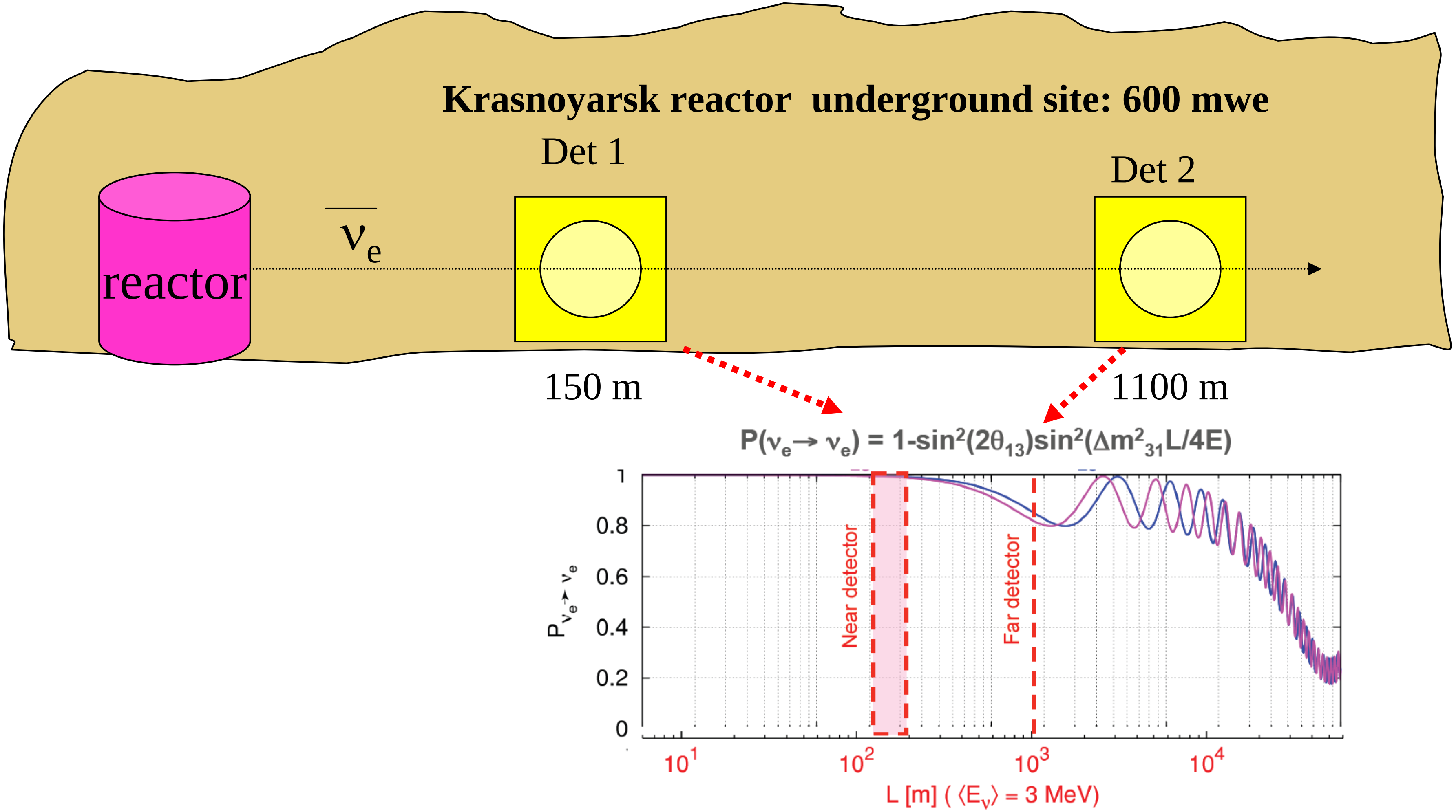
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \left[\sin\left(1.27 \frac{\Delta m^2_{atm}\,(eV^2)\,L\,(m)}{E\,(MeV)} \right) + O\left(\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}\right) \right]$$

- **Straightforward oscillation formula** : weak dependence on Δm_{sol}^2
- MeV electron antineutrinos : only **disappearance** experiments
- $\sin^2(2\theta_{13})$ measurement **independent of δ-CP**
- $\sin^2(2\theta_{13})$ measurement **independent of sign(Δm^2_{13})**

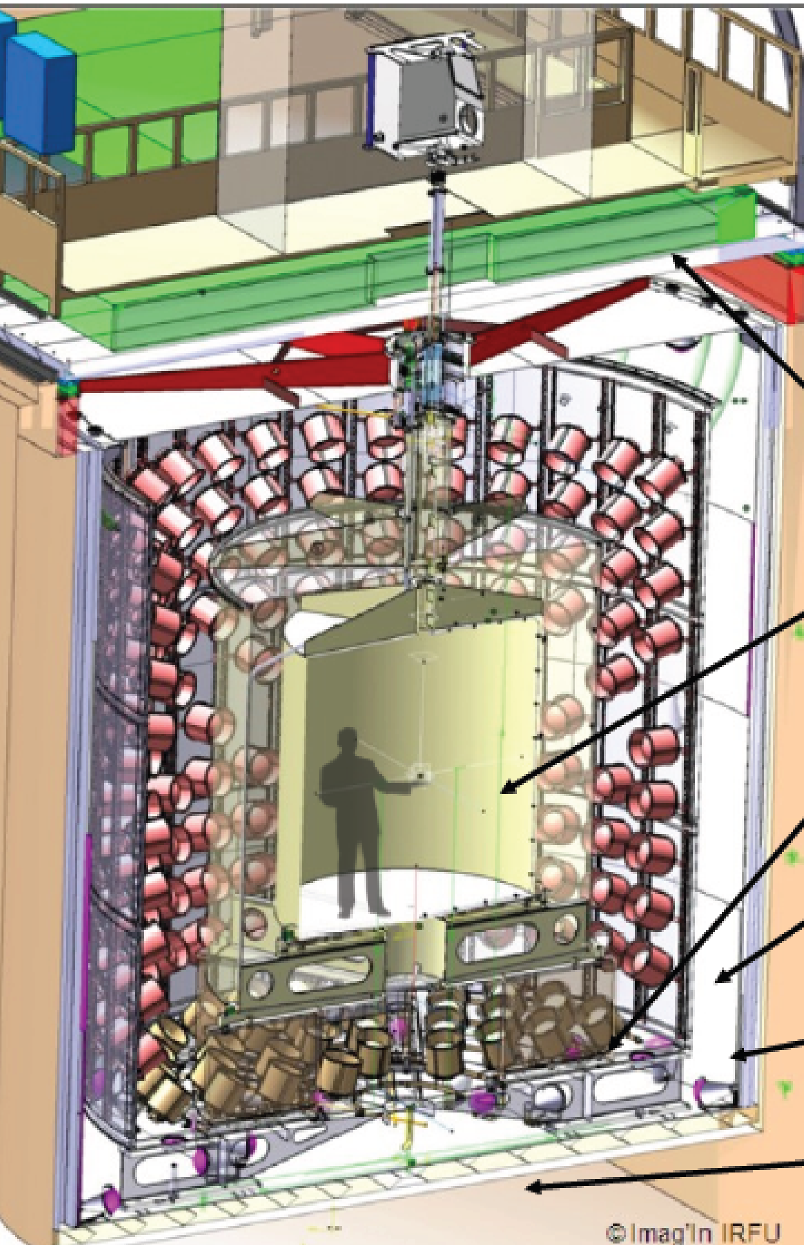
} **'clean'** information on θ_{13}

θ_{13} searches with reactors- $\bar{\nu}_e$'s

Kr2Det proposal (Mikaelyan et al. 2001):
(not realized) mother of Double Chooz, Daya Bay, Reno, …



Same concept….. but new 4-region detector design (developed by Double Chooz team 2002/2003)



CEA DSM Irfu

http://bama.ua.edu/~busenitz/nu2003_talks/lasserre1.doc
http://bama.ua.edu/~busenitz/nu2003_talks/suekane1.pdf

Outer Veto: plastic scintillator strips (400 mm)

ν-Target: 10,3 m^3 scintillator doped with 1g/l of Gd compound in an acryclic vessel (8 mm)

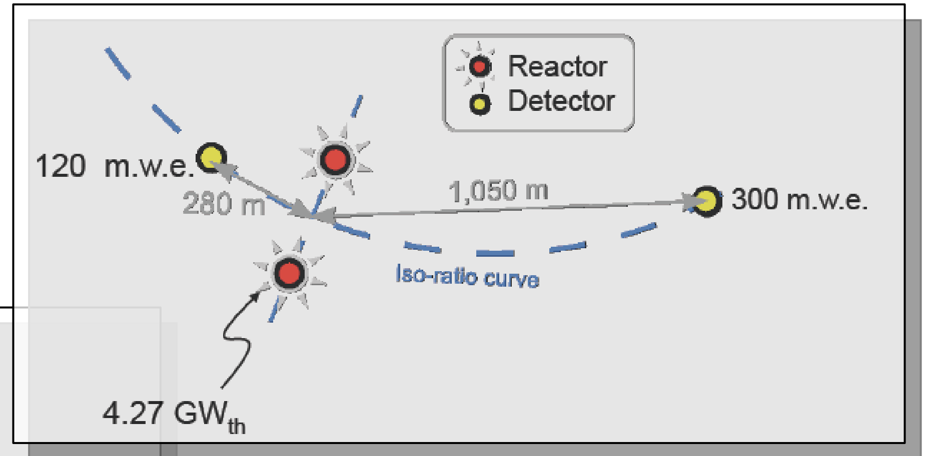
γ-Catcher: 22,3 m^3 scintillator in an acrylic vessel (12 mm)

Buffer: 110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs

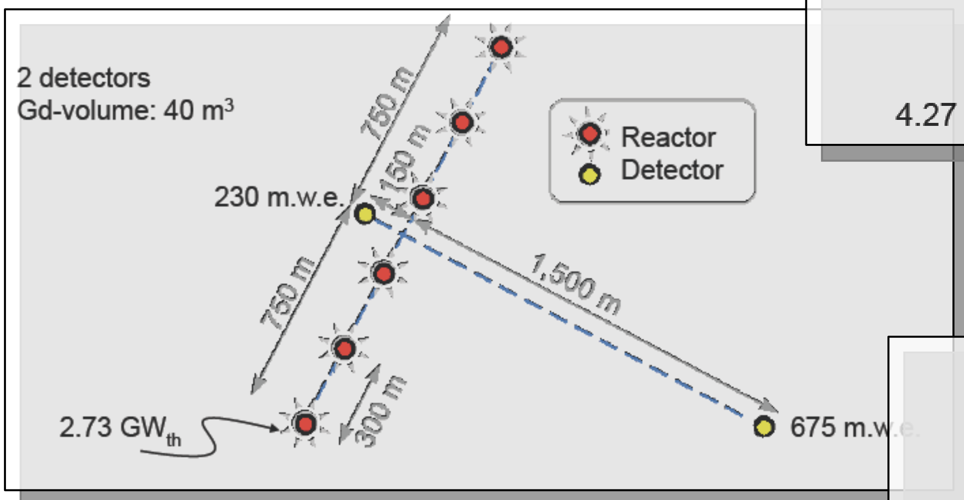
Inner Veto: 90m^3 of scintillator in a steel vessel equipped with 78 PMTs

Veto Vessel (10mm) & Steel Shielding (150 mm)

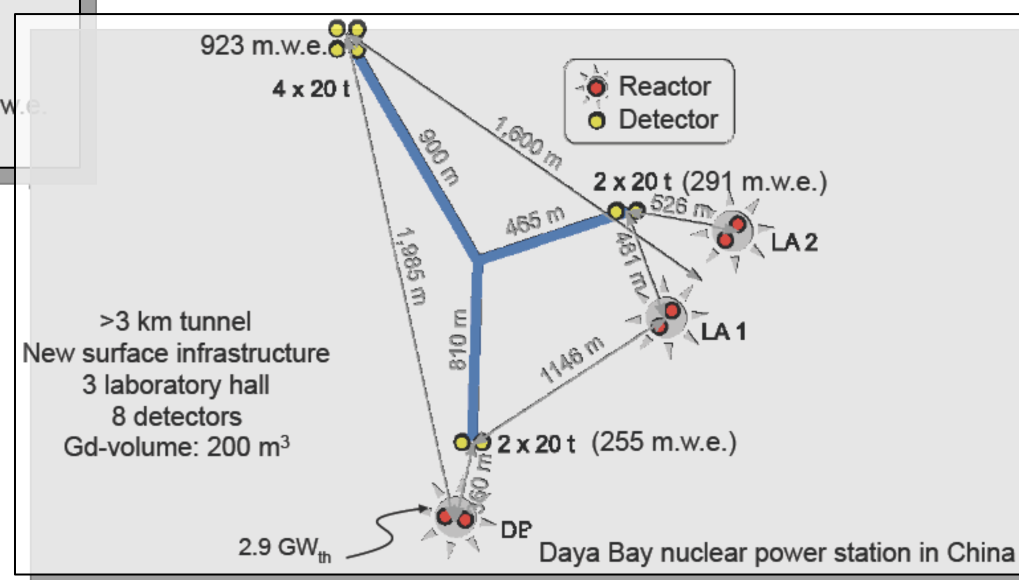
Double Chooz (France)



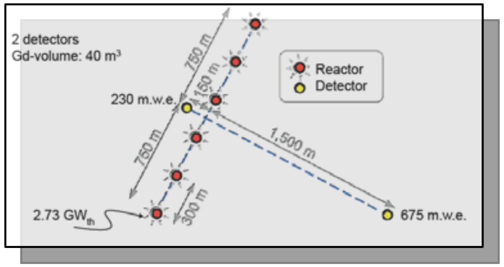
Reno (South Korea)



Daya Bay (China)



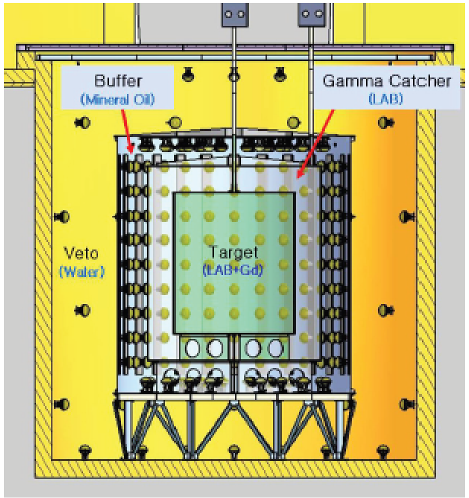
Status of RENO



Site: Youngwang, Korea

Tunnel + halls ready

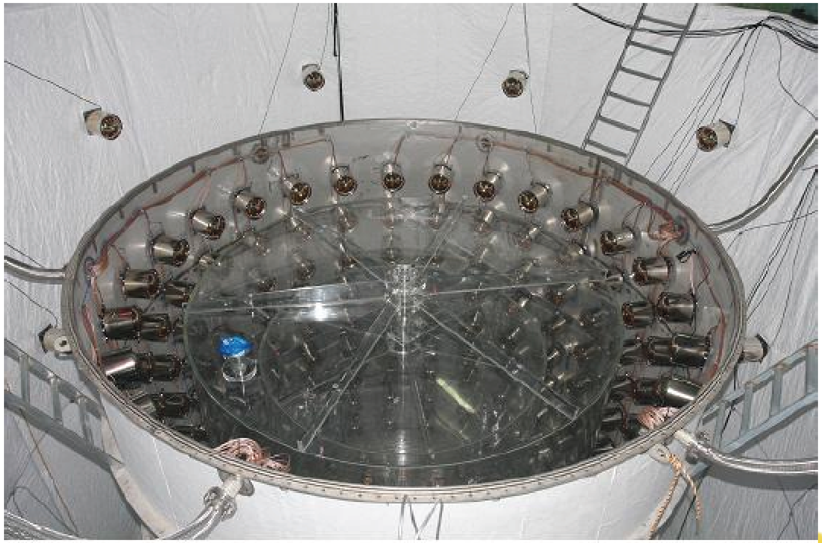
6 cores, 16 GW



Two 20 tons detectors

Near: 20 tons - 350 m – 200 mwe

Far: 20 tons - 1.4 km - 700 mwe



Sensitivity

0.5% systematic error

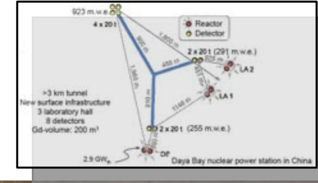
$\sin^2(2\theta_{13}) < 0.02$ (90% C.L.), 3 y

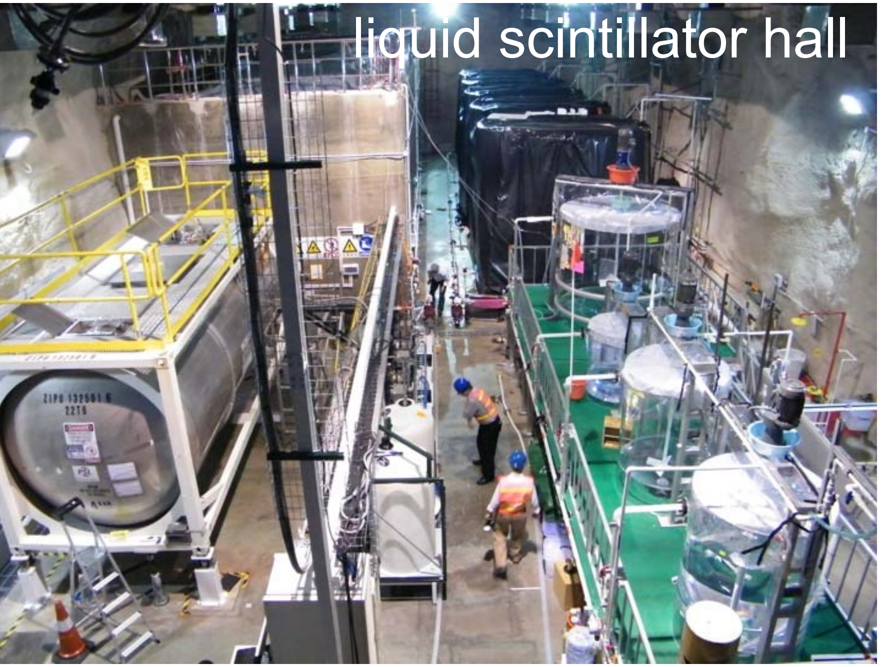
Status

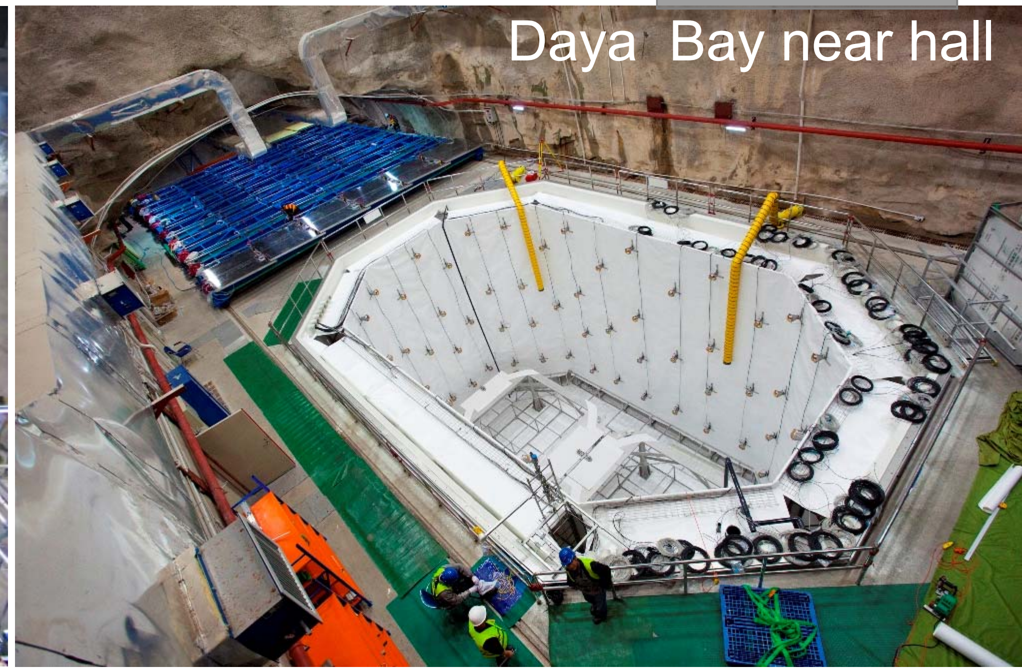
Two detector filled

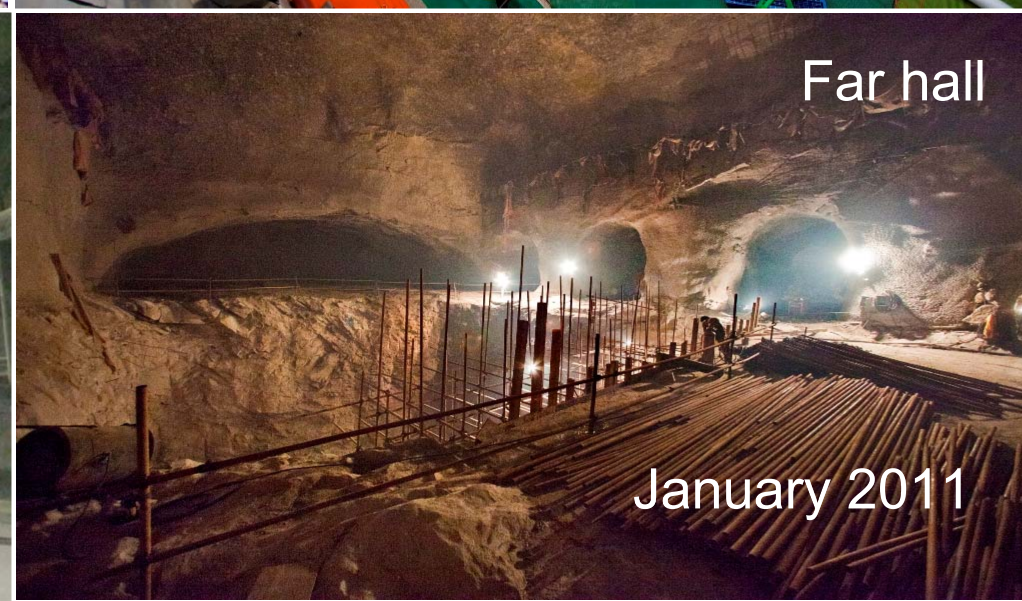
Data taking by August 2011

Daya Bay Underground Laboratory

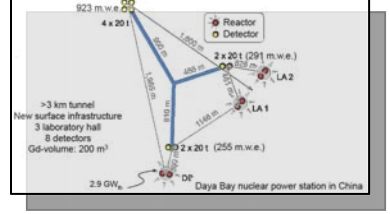


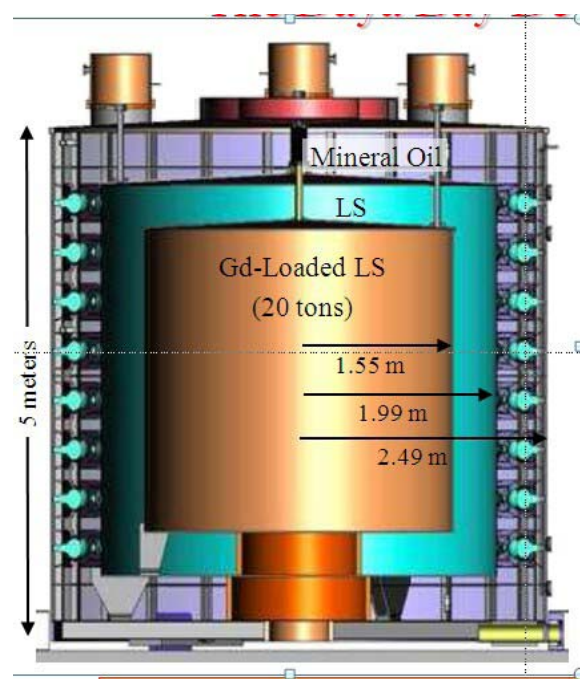






Status of Daya Bay





Site: Daya Bay Plant (11.6+6 GWth), China

Near: 1 km tunnel + laboratory

Far: 2 km tunnel + laboratory

8x20 tons detector modules (fiducial)

Near: 4x20 tons – 360-500 m – 200 mwe

Far: 4x20 tons - 1.6-1.9 km – 1000 mwe

Expected Sensitivity

0.36% systematic error (relative)

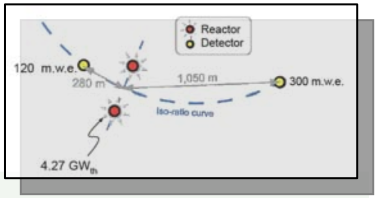
5 years, $\sin^2(2\theta_{13}) < 0.01$ (90% C.L.)

Status

2 near det. running by Summer 2011

4 far detectors deployment in 2012

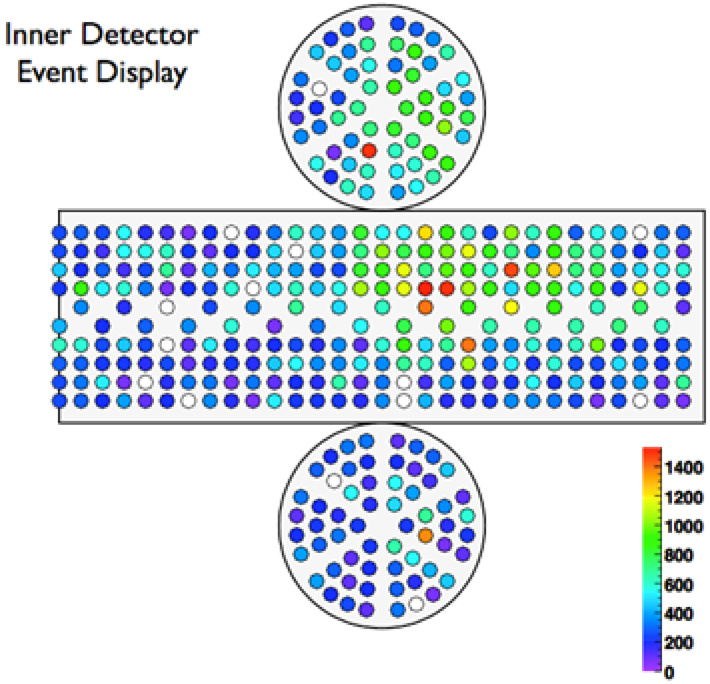
Double Chooz

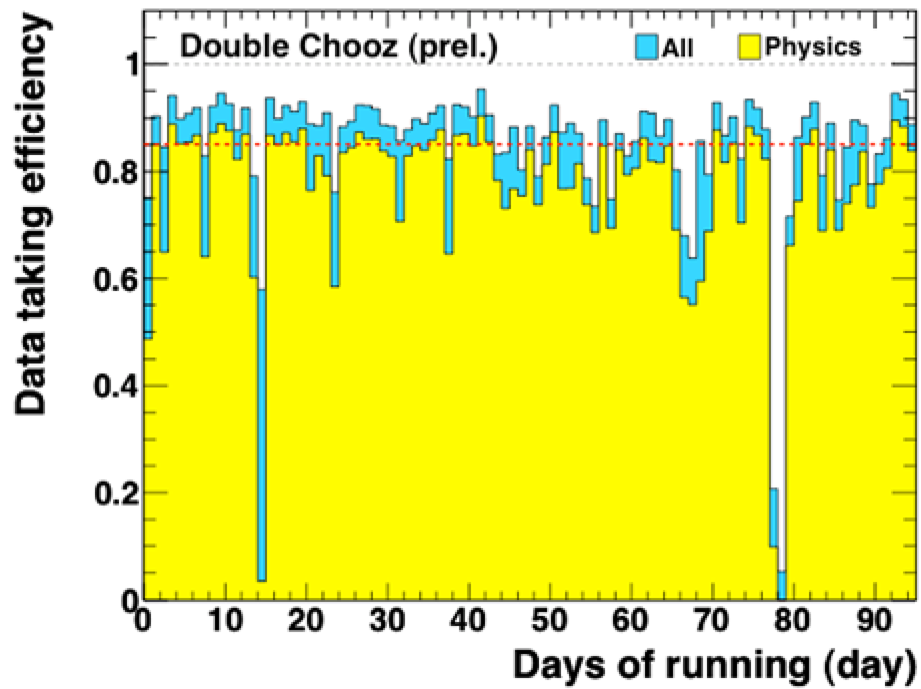


Detector integration and filling: 2008-2010

- Dec. 2010: filling of liquids completed.
- Jan. – March 2011:
  detector Commissioning
- Since Apr. 2011:
  stable data taking for physics

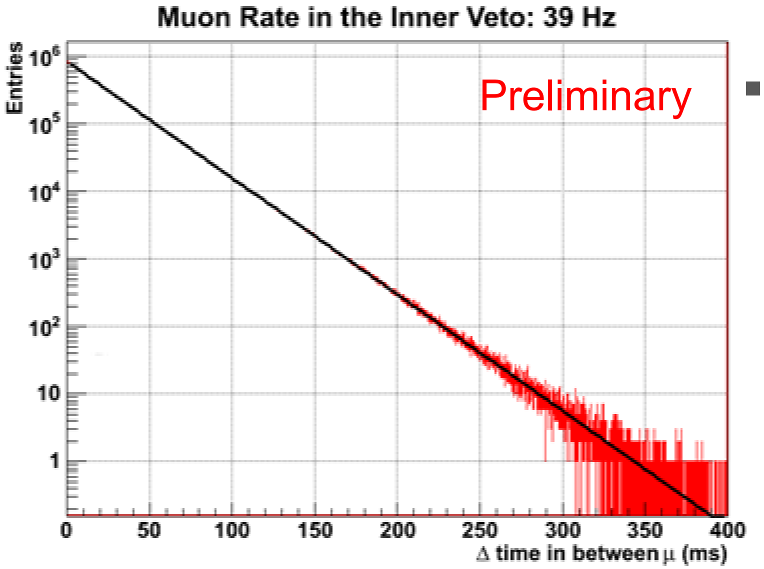
Stable Data Taking since April 13th 2011



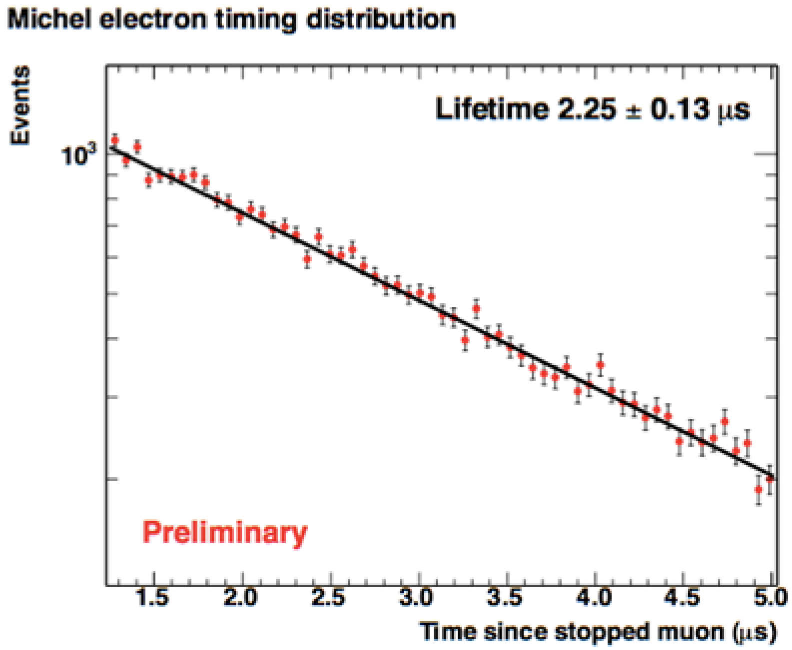


- >70 full days of physics before any data-quality flags (Physics run eff. 75%)
- Trigger rate ~120 Hz - Trigger threshold < 0.6 MeV
- Calibration runs 10% of the time (light injection by embedded fiber)
- Outer Veto Muon & Glove Box ready. Source Calibration Deployment soon

Muon & Michel Electron Data

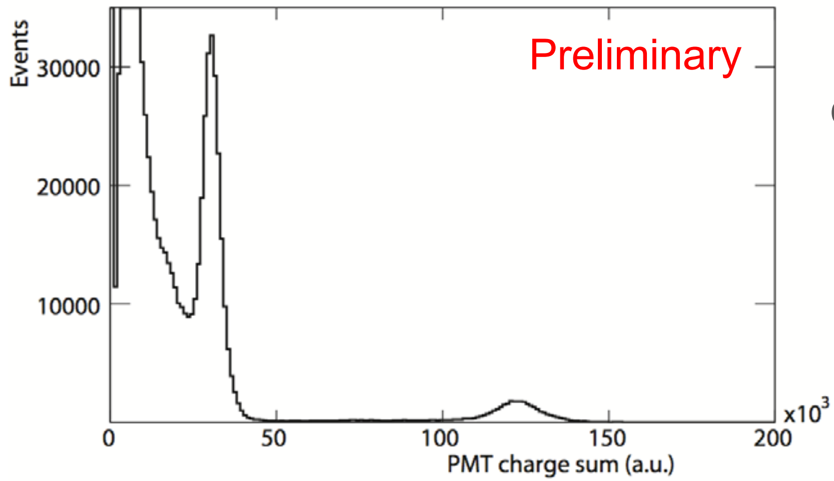


- **Muons**
  - Δt time between two events (ms)
  - ~40Hz of muons tagged by Inner Veto
  - ~10Hz by Inner Detector



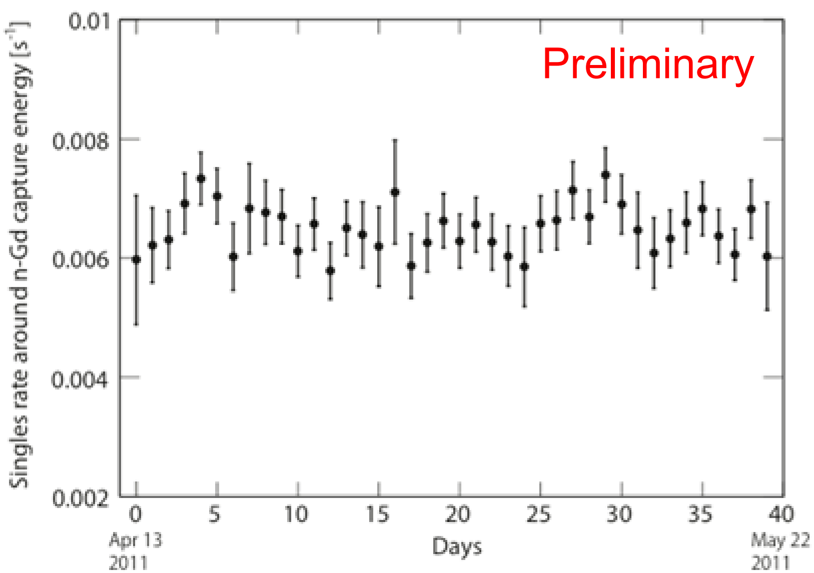
- **Michel Electrons**
  - Time since stopped muon (μs) + Energy Selection Criteria
  - Stat. error only
  - Delayed coincidence works well

Neutron Data



- **Charge spectrum for muon-correlated events in delayed time window**

- Peaks of neutron capture
  - on Hydrogen (2.2MeV)
  - on Gadolinium (~8MeV).



- **Stability of singles rate in delayed energy window**
  - **A**fter vetoing muon-correlated events

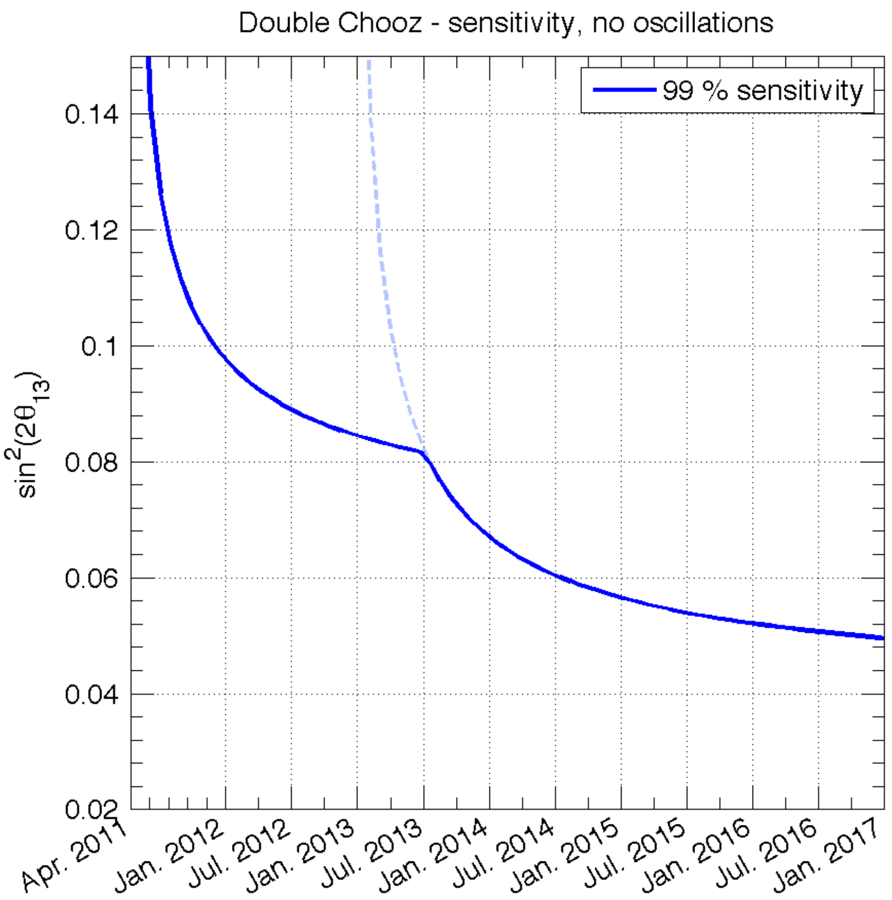
- **Caveat:**
  - RAW data, no gain calibration, no energy calibration, no vertex correction

Detector Performances & Sensitivity

- **Singles rates**
  - after vetoing muon-correlated events
  - ~10 Hz in [0.7, 12] MeV → ~DC proposal
  - <0.01 Hz in [6, 12] MeV <0.01 Hz
  → < 1/2 better w.r.t DC proposal
  - Promising sign for low accidental rates
- **Neutron-capture as expected**
  - on Gd (Target) & H (T+GC)

→ data indicates that DC has 'clean' neutrino candidates

- **Correlated backgrounds under study**
- **T2K's central values can be addressed at 99% CL with 2011 data**
- **Neutrino analysis on-going**

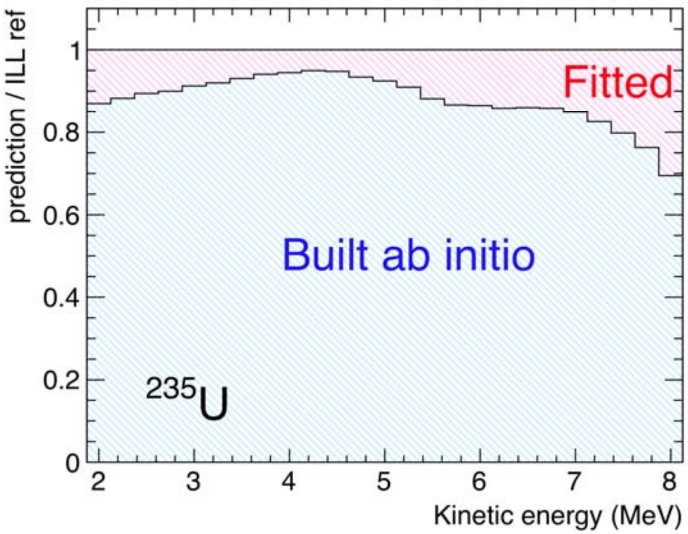


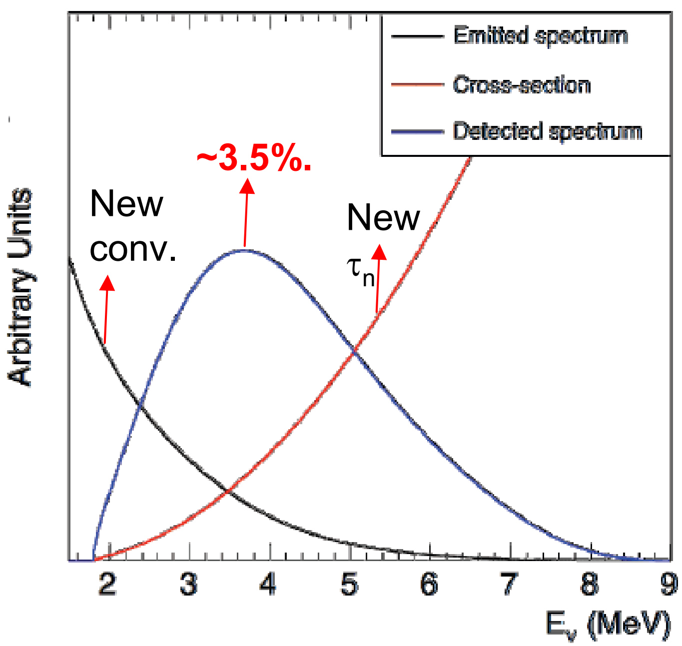
Outline

- Updates from solar & reactor ν-experiments on mixing
- θ_{13} search at nuclear reactors
- Reactor ν-anomaly & sterile ν's
- Kinematical ν-mass measurement
- $0\nu\beta\beta$ decay experiments

Revised reactor neutrino spectra & VSBL reactor ν-anomaly

T. Mueller et al. Phys. Rev. D83, 073006, 2011





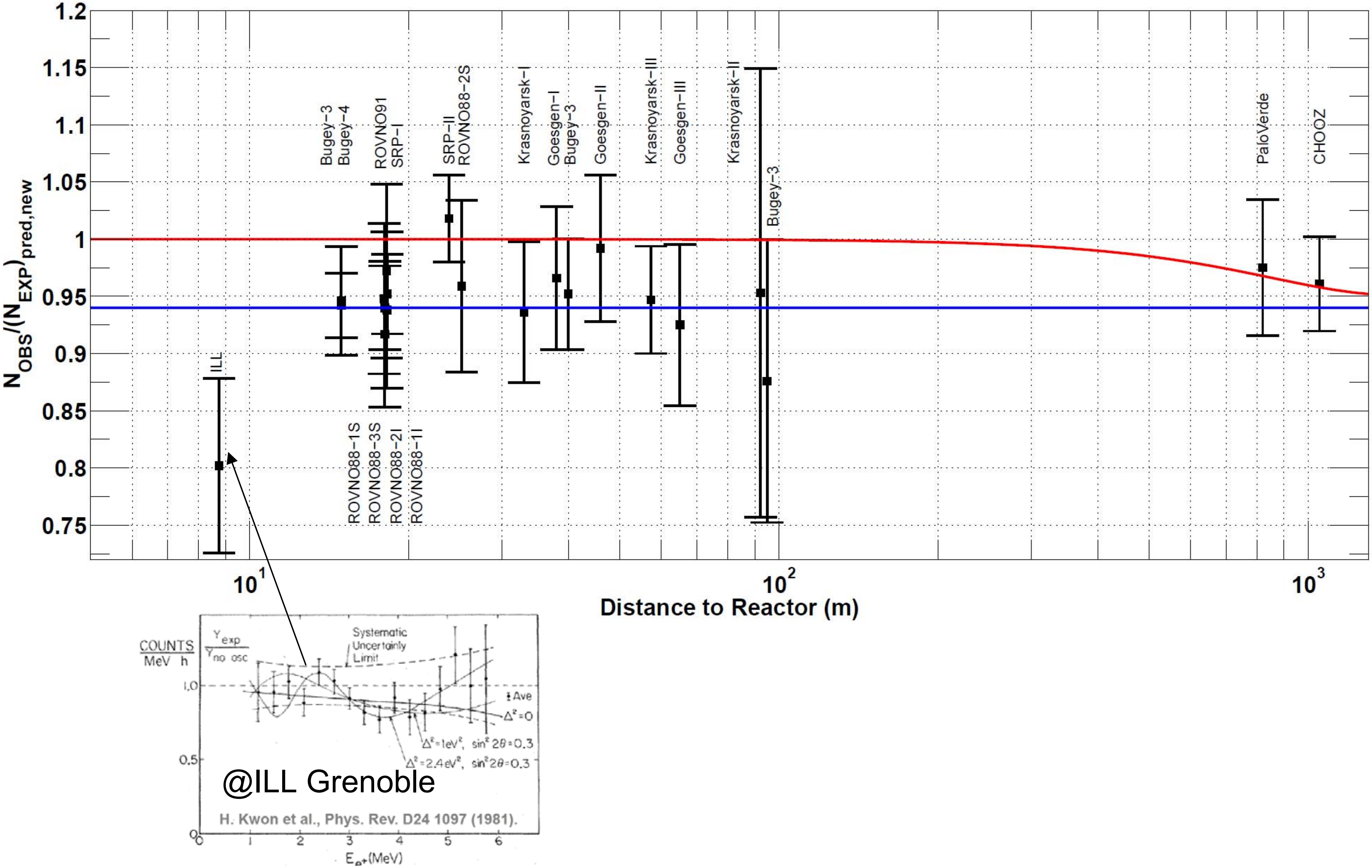
- Triggered by evaluation for DC far-detector phase
- Improved conversion from β to $\bar{\nu}_e$ spectra:
  - Anchored to experimentall ILL BILL-spectra of fission products
  - Conversion at individual β-branch level; residuals fitted as in original ILL conversion
  - Off-equilibrium effects included
- Improved (& increased) neutron life time measurement; also improved weak magnetism and radiative corrections

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

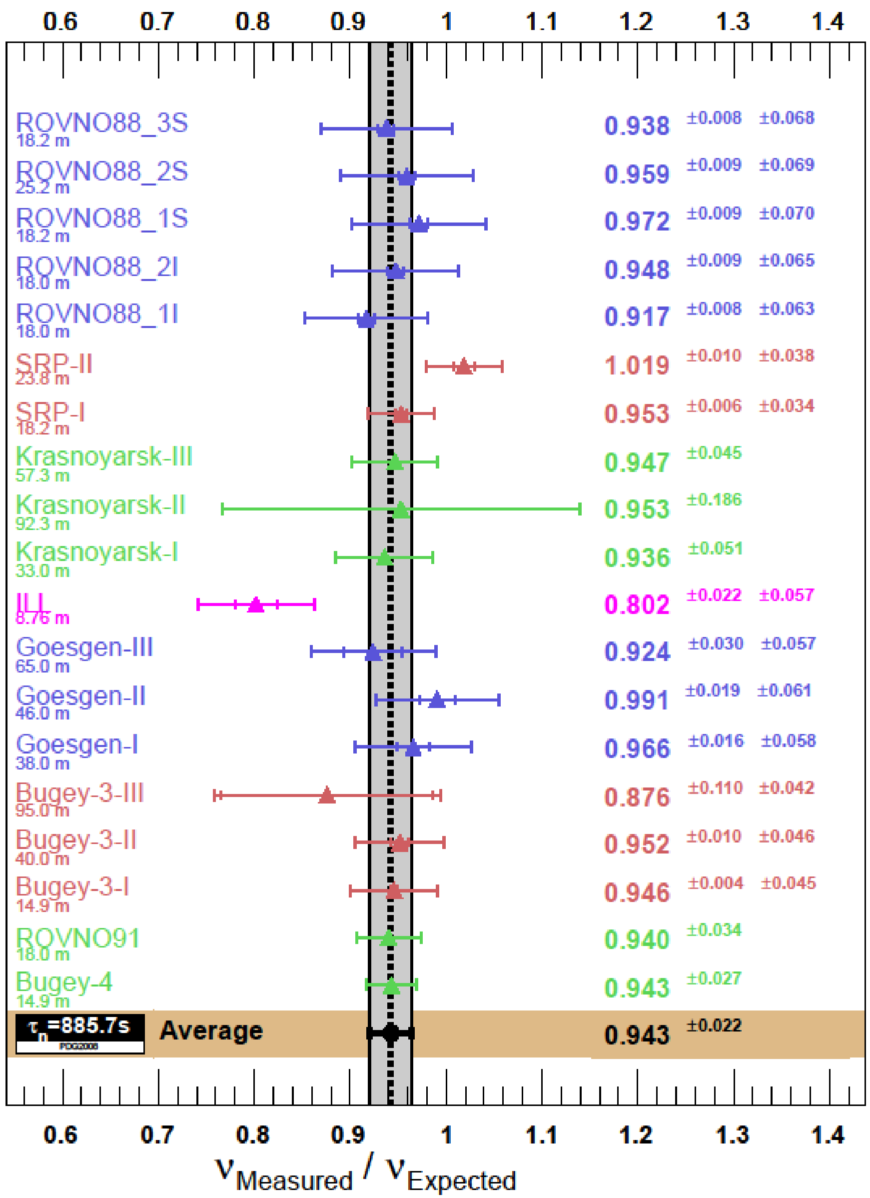
	old [3]	new	new/old
$\sigma^{pred}_{f,^{235}U}$	6.39±1.9%	6.61±2.11%	+3.4%
$\sigma^{pred}_{f,^{239}Pu}$	4.19±2.4%	4.34±2.45%	+3.6%
$\sigma^{pred}_{f,^{238}U}$	9.21±10%	10.10±8.15%	+9.6%
$\sigma^{pred}_{f,^{241}Pu}$	5.73±2.1%	5.97±2.15%	+4.2%

Implications for SBL reactor experiments: reactor neutrino anomaly

G. Mention et al. arXiv:1101.2755v4



Implications for SBL reactor experiments: reactor neutrino anomaly



T. Lasserre, this conference

- **Best fit : 0.943±0.023** (χ^2 = 19.6/19)
  Deviation from unity (2.5 σ)
  (Full treatment of correlations)

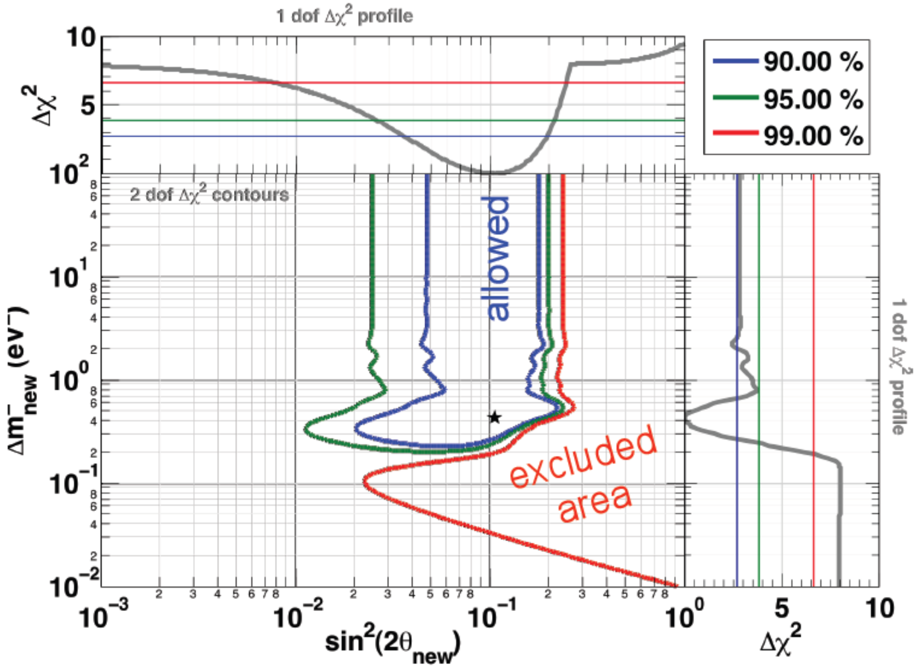
- **Wrong preditions of ν-spectra?**

- **Bias in all SBL reactor experiments?**

- **Hint for new physics at VSBL?**
  Mixing with 4th sterile ν:
  θ_{new} and Δm^2_{new}

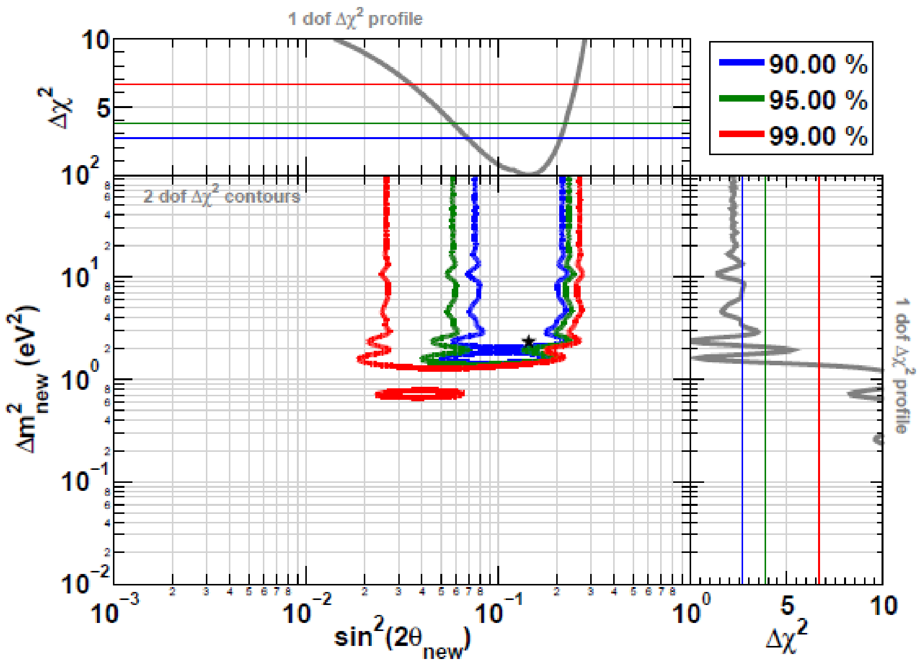
(N.B.: also corroborated by Gallium source measurements)

Combine all reactor rate measurements, no spectral-shape information



no-oscillations disfavored at 98.6% C.L.

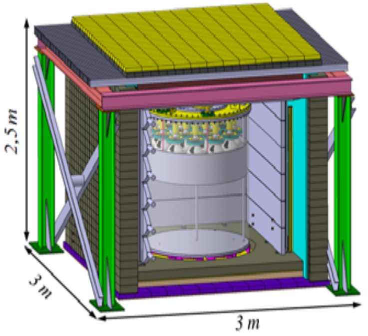
Combining reactor rates + shape + Gallium Anomaly



no-oscillation disfavored at 99.8% CL

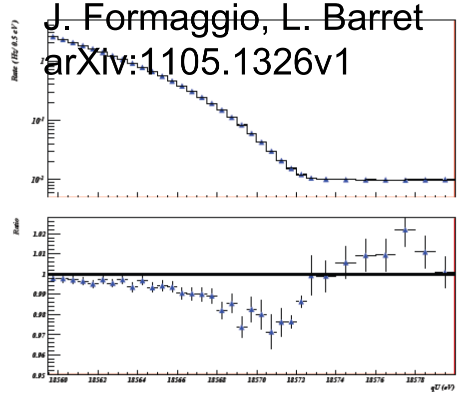
G. Mention et al. arXiv:1101.2755v4

How to scrutinize VSBL oscillation signal with non-accelerator ν-experiments?

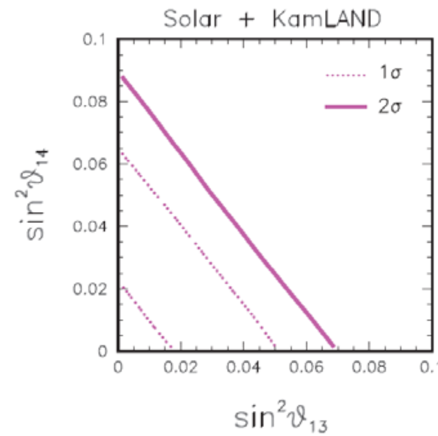


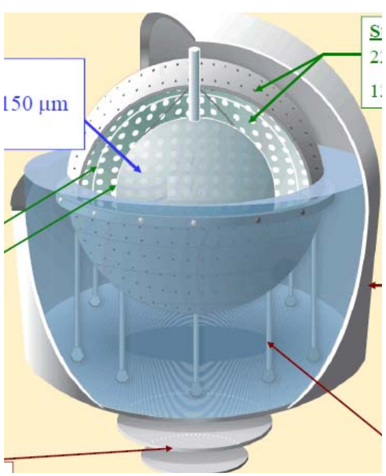
ILL-type experiment:
Short distance / compact core
- Nucifer @ 7m from Orsiris (CEA)
- New exp. at ILL

Kink search with KATRIN
J. Formaggio, L. Barret
arXiv:1105.1326v1



From Solar and KL data with fixed θ_{13}
A.Palazzo, PRD 83 113013 (2011)





ν-source: Borexino (KamLAND, SNO+)
A. Ianni et al.,
M. Cribier et al.
arXiv:1107.2335

Resonant matter effects with TeV atmospheric ν's in IceCube (Choubey, Smirnov, & IceCube collab.)

N.B. reactor neutrino anomaly has no implications for θ_{13} searches in upcoming reacor oscillation experiments:

- For data taking with single-detector (far): use experimental cross section per fission measured in Bugey-4 and apply burn-up corrections, as done in the CHOOZ experiment (Eur.Phys.J. C27:331 374 (2003))

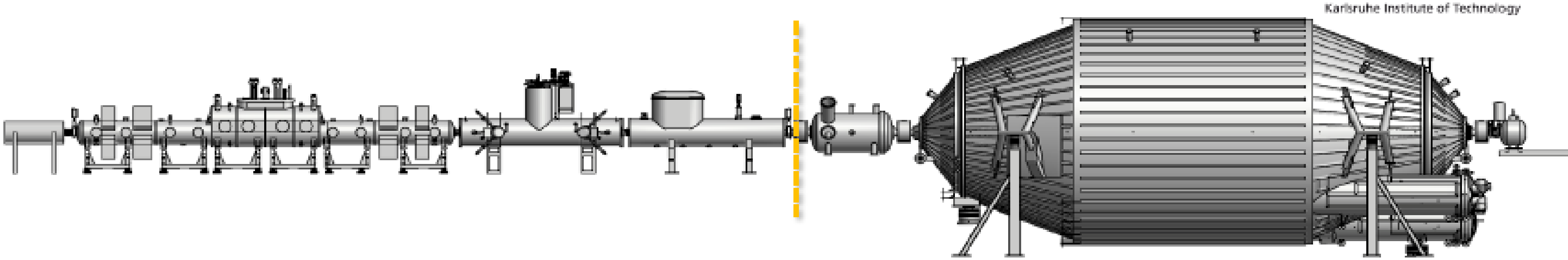
- Results are then independent of new physics at short base line or erroneous predictions of reactor neutrino fluxes

- Two-detector phase: relative measurement is independent of VSBL oscillations or reactor ν-flux uncertainties

Outline

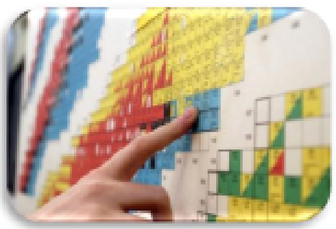
- Updates from solar & reactor ν-experiments on mixing
- θ_{13} search at nuclear reactors
- Reactor ν-anomaly & sterile ν's
- Kinematical ν-mass measurement
- $0\nu\beta\beta$ decay experiments

KATRIN experiment – overview



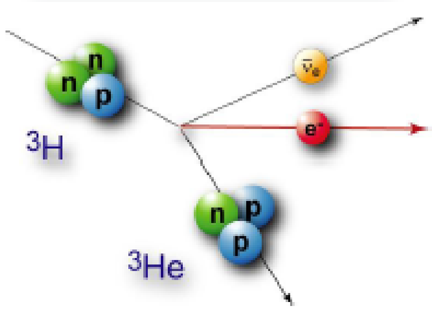
tritium-bearing components

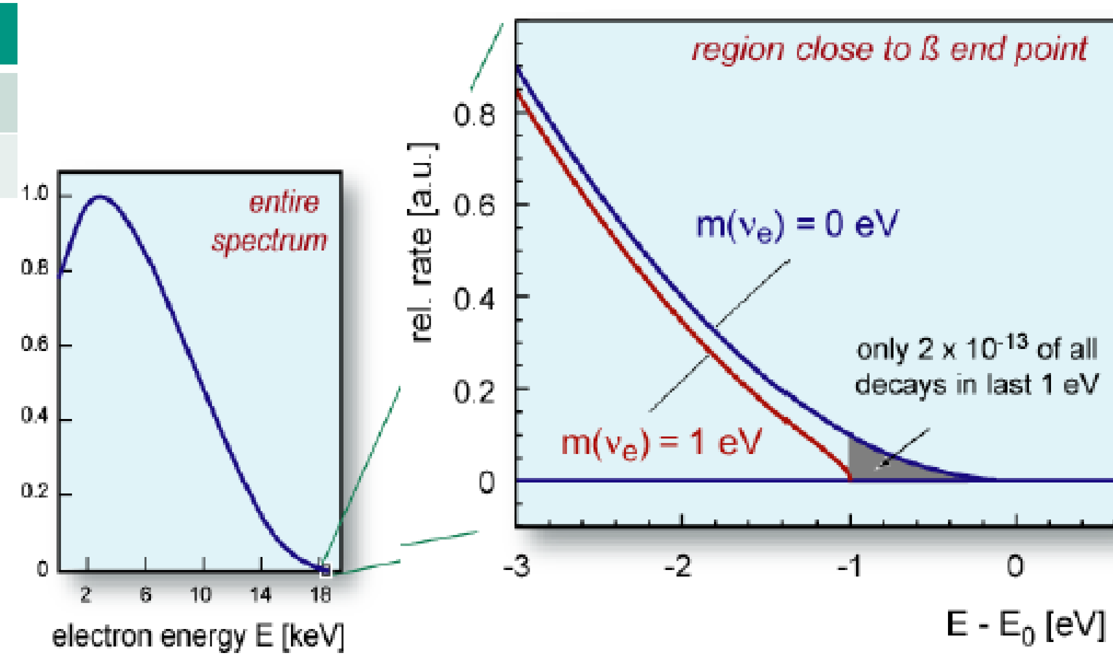
electrostatic spectrometers & detector



^3H: super-allowed	
E_0	18.6 keV
$t_{1/2}$	12.3 y

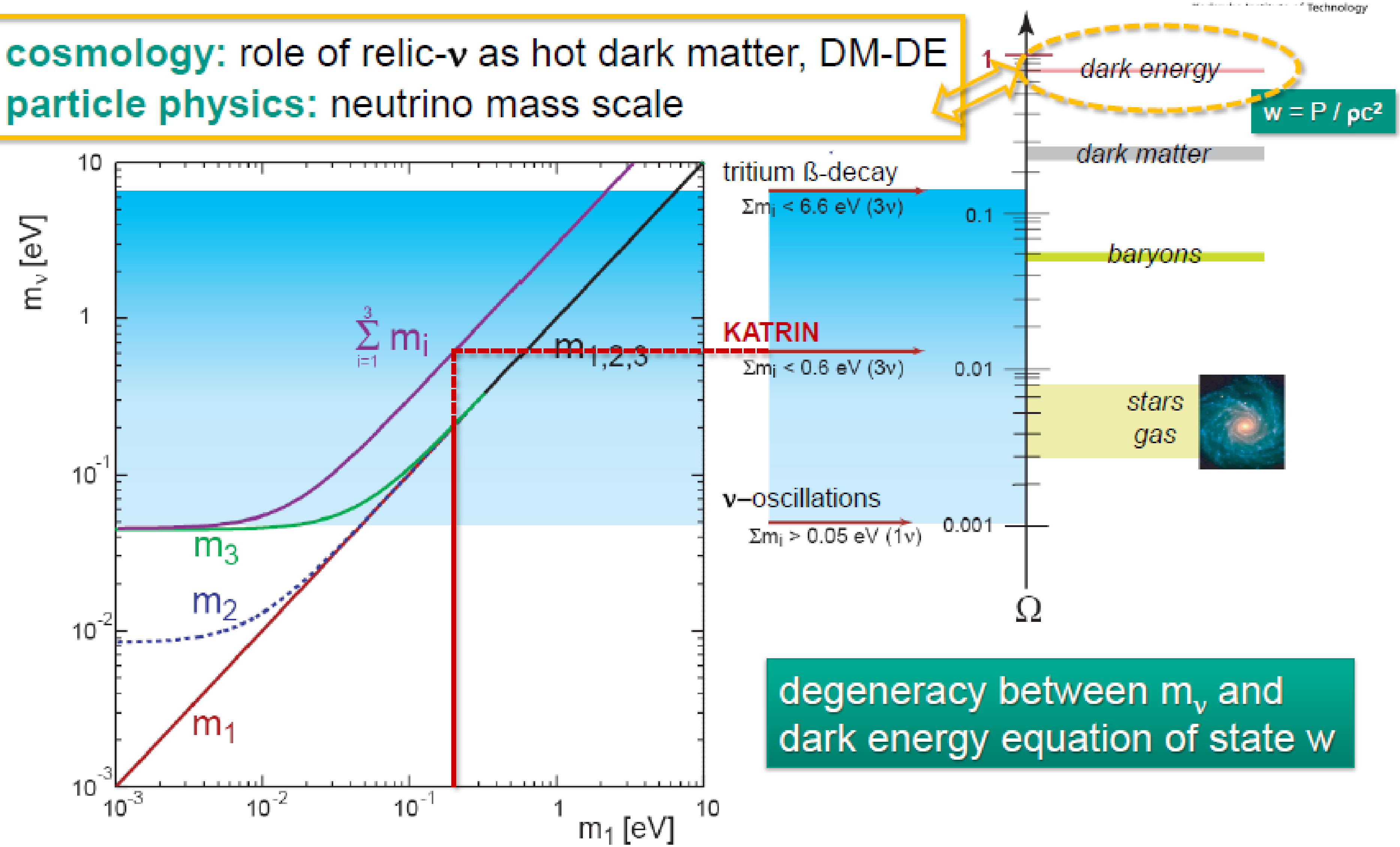
$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$





KATRIN experiment – scientific objectives

cosmology: role of relic-ν as hot dark matter, DM-DE
particle physics: neutrino mass scale



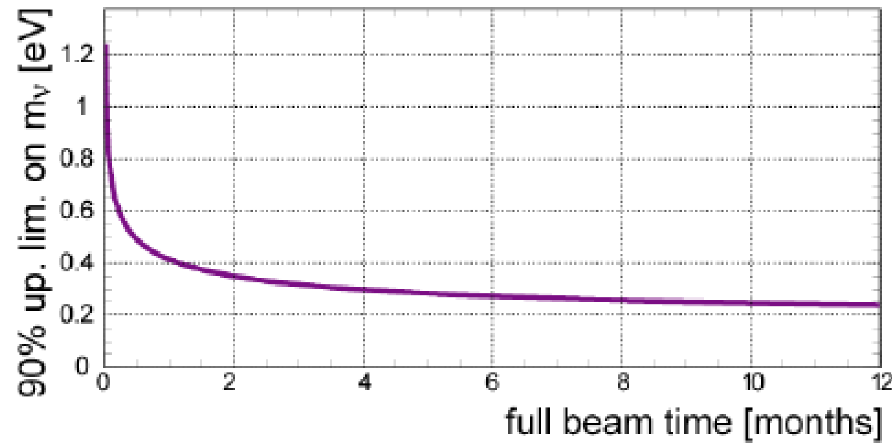
degeneracy between m_ν and dark energy equation of state w

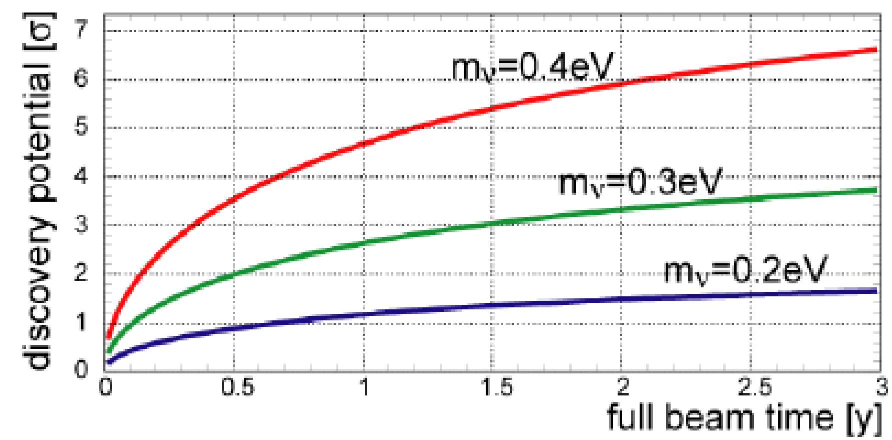
KATRIN sensitivity

- **neutrino mass sensitivity:** detailed investigations of of reference design, requirements: highest luminosity, high energy resolution, low background, control/monitoring of fluctuations near on-line MC of experim. data
- **statistical & systematic errors** are expected to contribute equally
  - statistical error $\sigma_{stat} = 0.018\ eV^2$
  - systematic error $\sigma_{syst} < 0.017\ eV^2$
- **reference sensitivity (3 fb years)**

sensitivity (90% CL)
$m(\nu) < 200$ meV

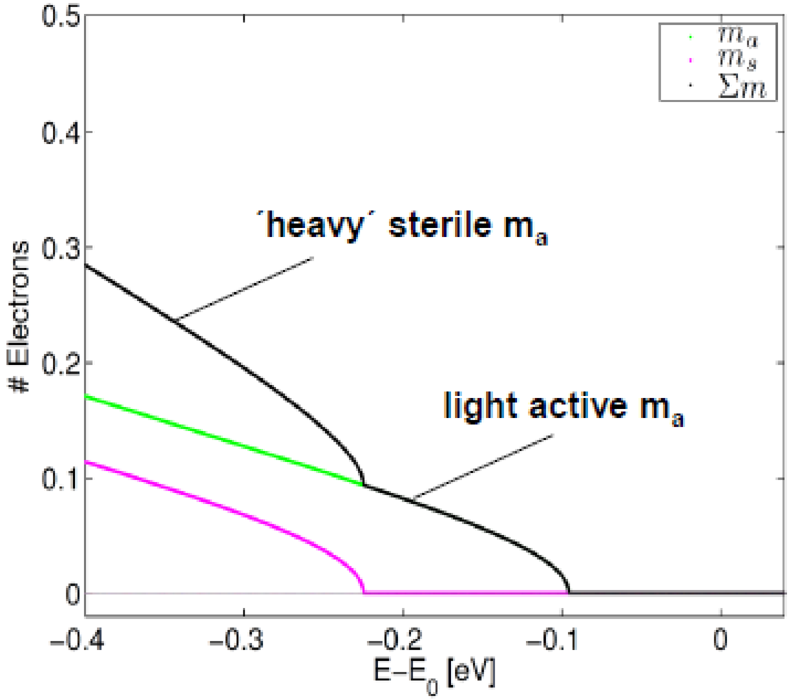
discovery potential
$m(\nu) = 350$ meV (5σ)





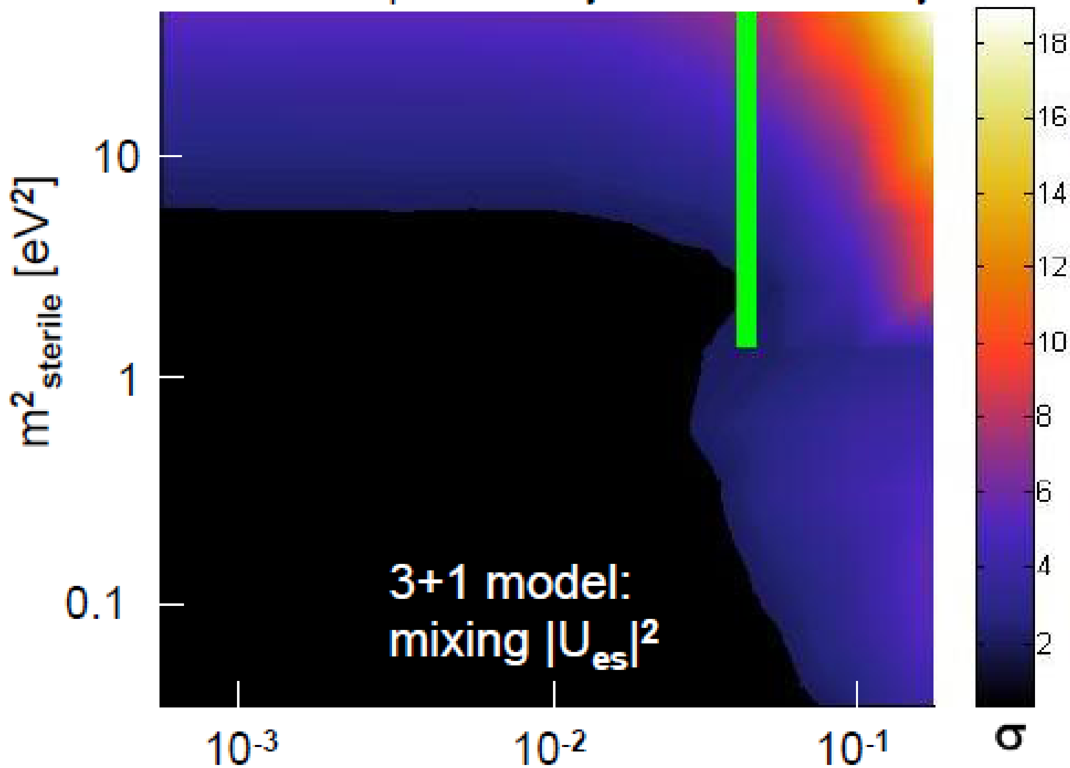
KATRIN sensitivity for sterile neutrinos

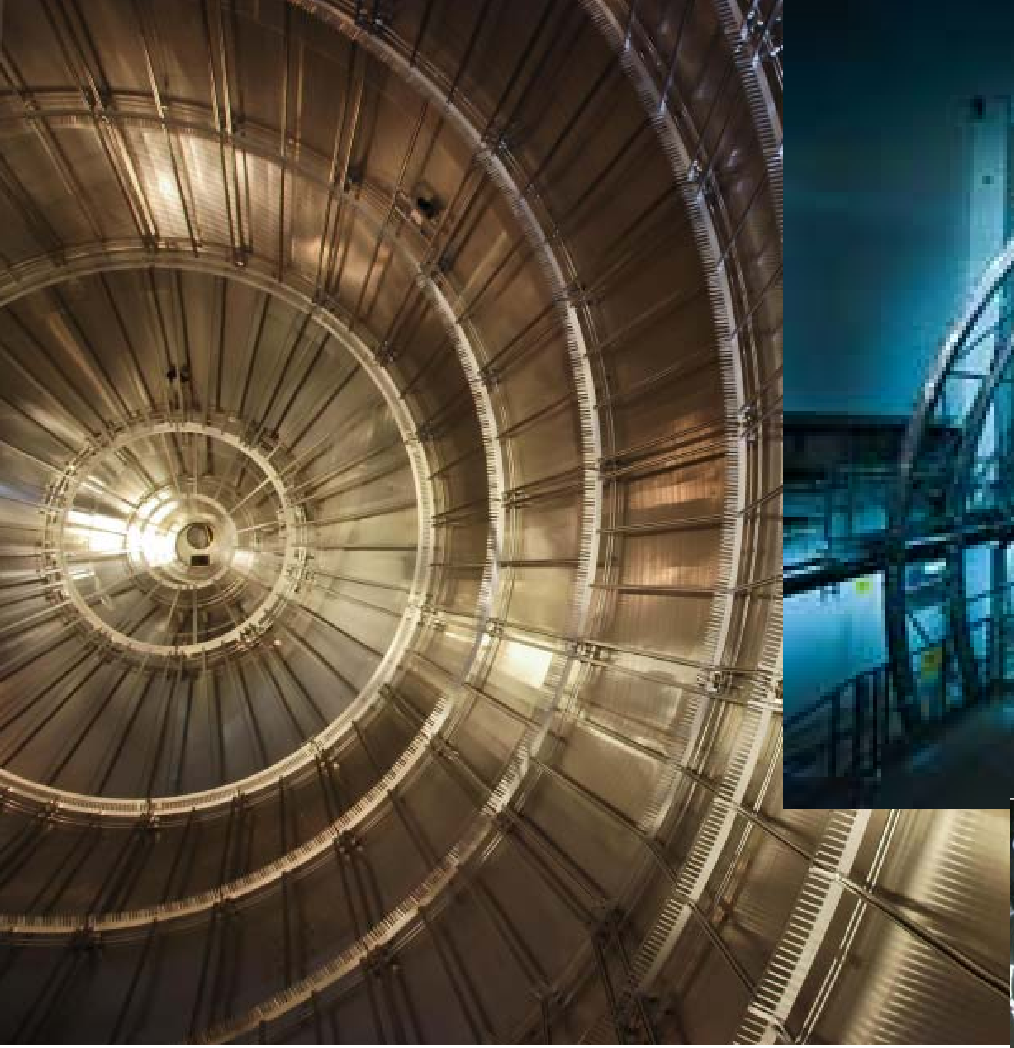
- Hannestad et al: initial estimates of KATRIN sensitivity for sterile ν´s assume very light active neutrinos $m_a(\nu) \sim 0$ eV, mixed with sterile $m_s(\nu)$
- 3 σ detection of ´kink´ by $m_{sterile}$ if active-sterile mixing **$|U_{es}|^2 \geq 0.055$**
  3+2 scenarios can also be disentangled



A.S. Riis, S. Hannestad,
arXiv: 1008.1495v2, JCAP02(2011)011

preferred by reactor ν anomaly



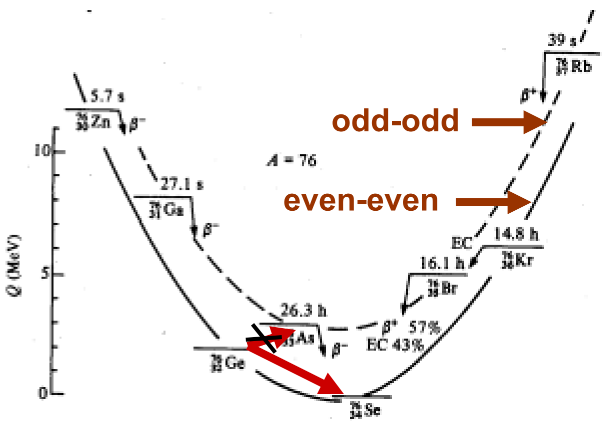


Status:
-commissioning of sub-components ongoing
- Start of physics 2013

Outline

- Updates from solar & reactor ν-experiments on mixing
- θ_{13} search at nuclear reactors
- Reactor ν-anomaly & sterile ν's
- Kinematical ν-mass measurement
- $0\nu\beta\beta$ decay experiments

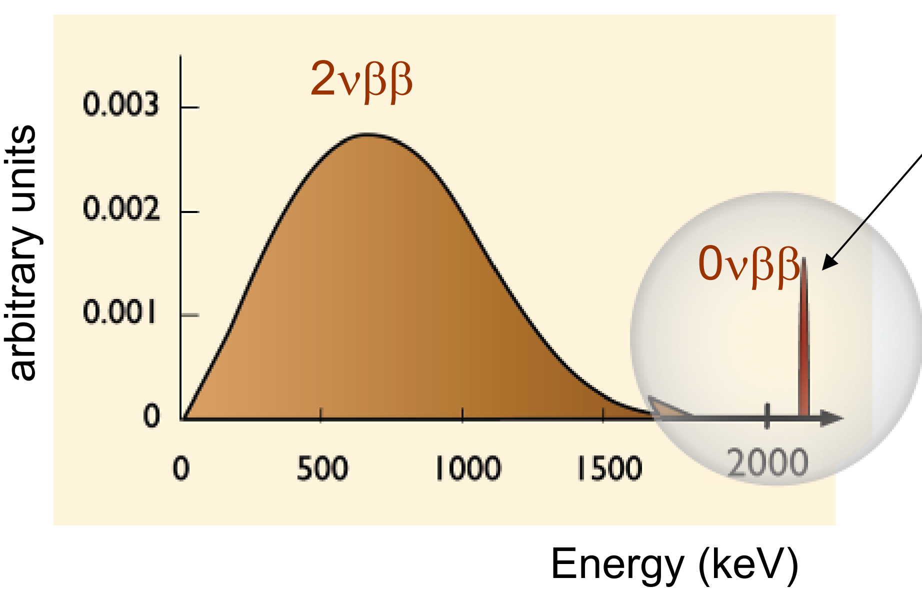
Double beta decay



$2\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\ \bar{\nu}_e$ **$\Delta L=0$**

$$T_{1/2}^{2\nu} = (10^{18} - 10^{21})y$$

$0\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^-$ **$\Delta L=2$**



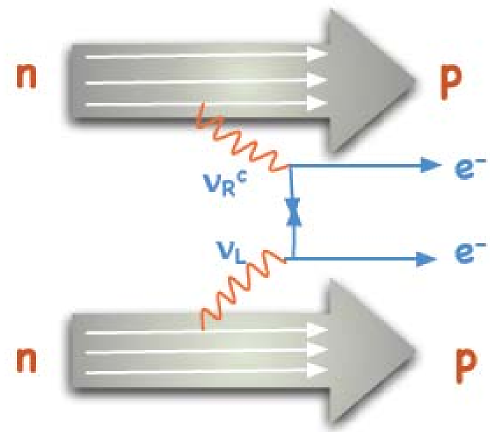
Experimental signatures:

- peak at $Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e$
- two electrons from vertex
- production of grand-daughter isotope

Discovery would imply:

- neutrino is its own anti-particle, (Majorana particle)
- absolute neutrino mass scale
- lepton number violation $\Delta L = 2$
- further new physics beyond the standard model

Neutrinoless double beta decay



Assume leading term is exchange of light Majorana neutrinos

Expected decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \left\langle m_{ee} \right\rangle^2$$

Phase space integral

Nuclear matrix element

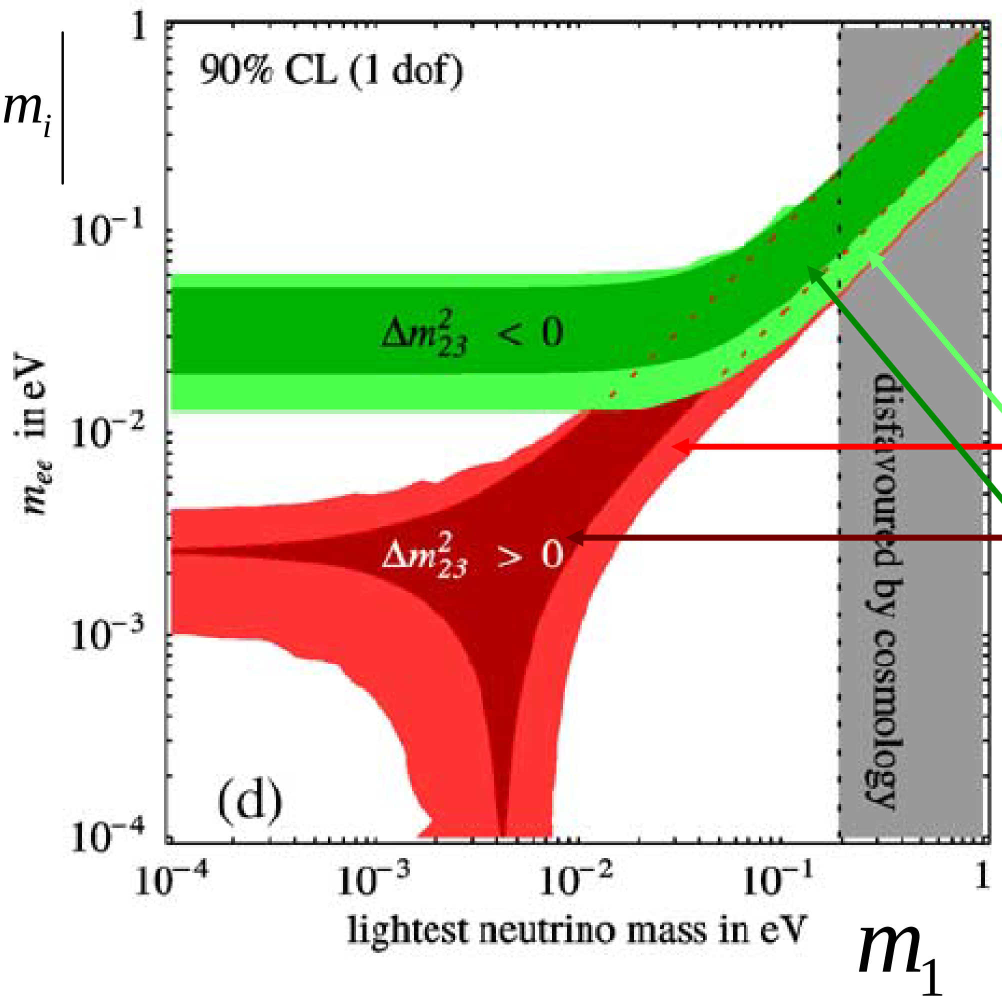
$$Q = E_{e1} + E_{e2} - 2m_e$$ Q-value of decay

$$\left\langle m_{ee} \right\rangle = \left| \sum_i U_{ei}^2\, m_i \right|$$ Effective neutrino mass

U_{ei} (complex) neutrino mixing matrix

Predictions from oscillation experiments

$$\langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$



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

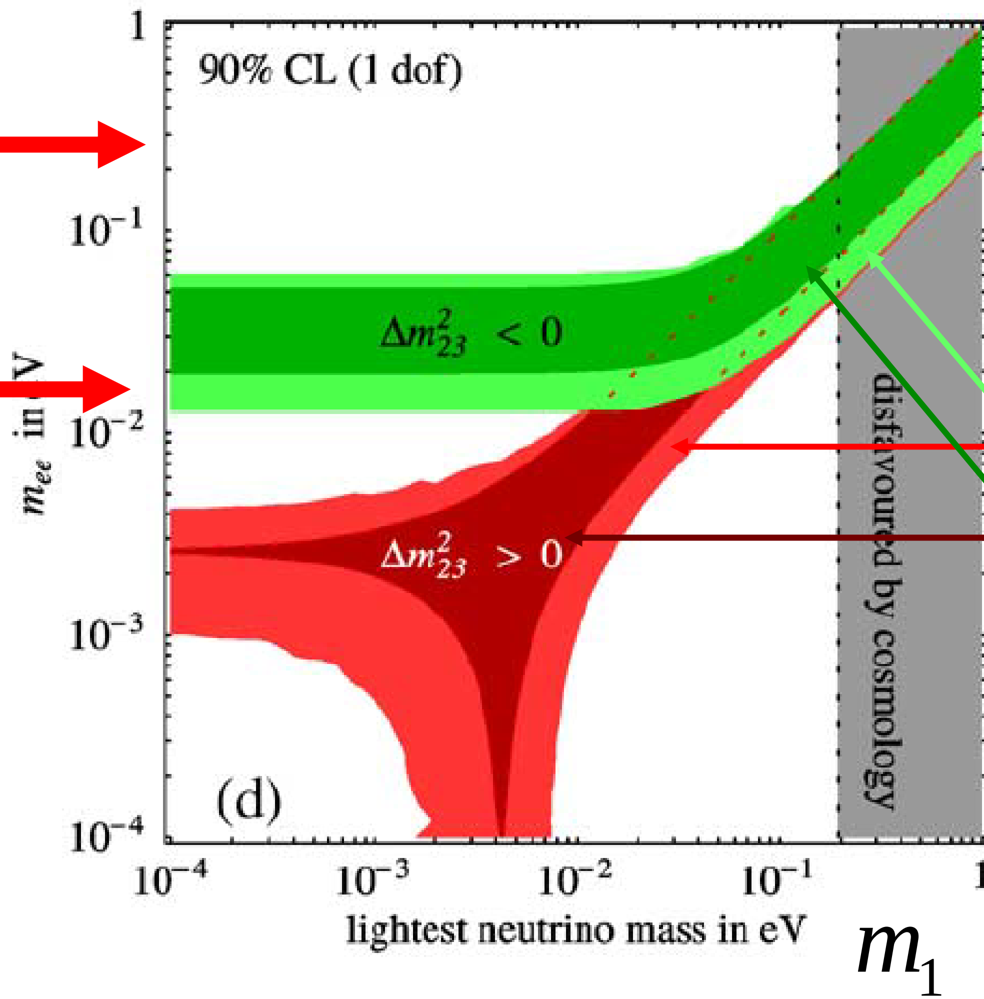
90% CL

Negligible errors from oscillations; width due to CP phases

Predictions from oscillation experiments

KDKC claim:
[0.17-0.45] eV
(PRD79)

Goal of next generation experiments: ~10 meV



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

90% CL

Negligible errors from oscillations; width due to CP phases

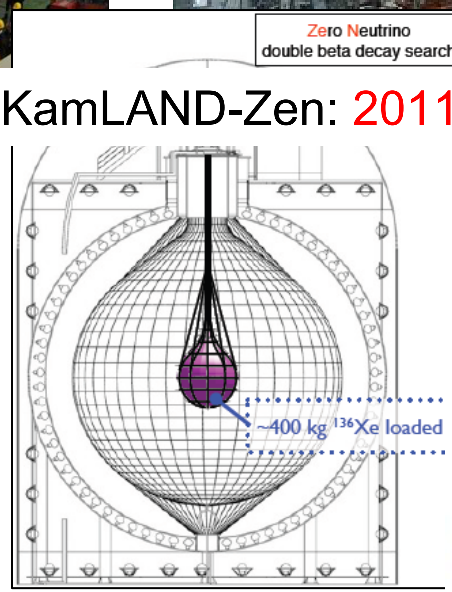
Next generation experiments

GERDA: 2011

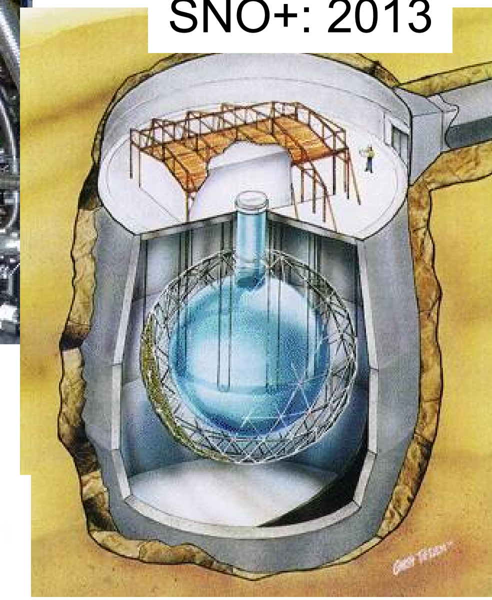
LNGS

CUORE-0: 2011
CUORE: 2014

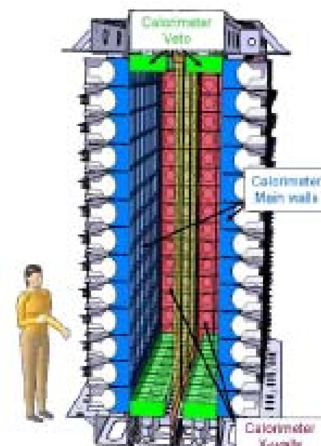
EXO @ WIPP: 2011



KamLAND-Zen: 2011



SNO+: 2013



Super-Nemo @ LSM:
Demonstrator2014

Majorana: 2013
NEXT: 2013
Lucifer
EXO-gas
XMASS

GERDA & EXO in commissioning phase, KamLAND-zen will start in August

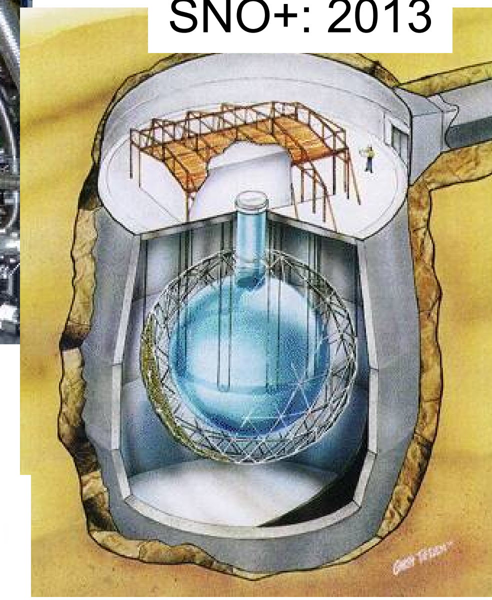
Next generation experiments

Yet, only data available from

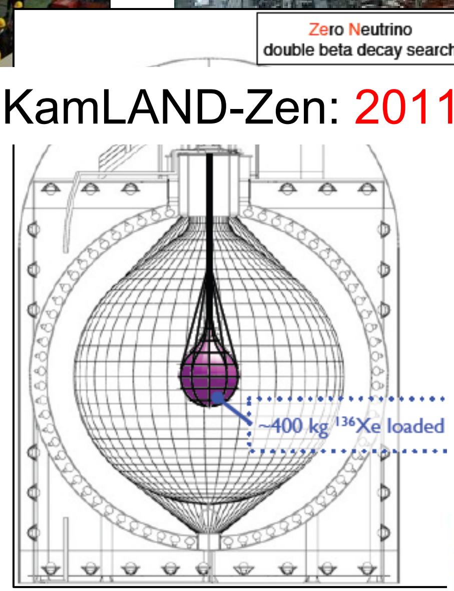
GERDA @ LNGS: 2011

EXO @ WIPP: 2011

SNO+: 2013

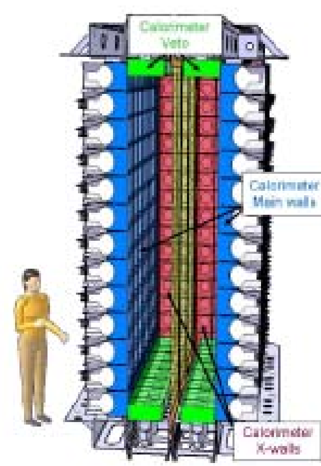


LNGS



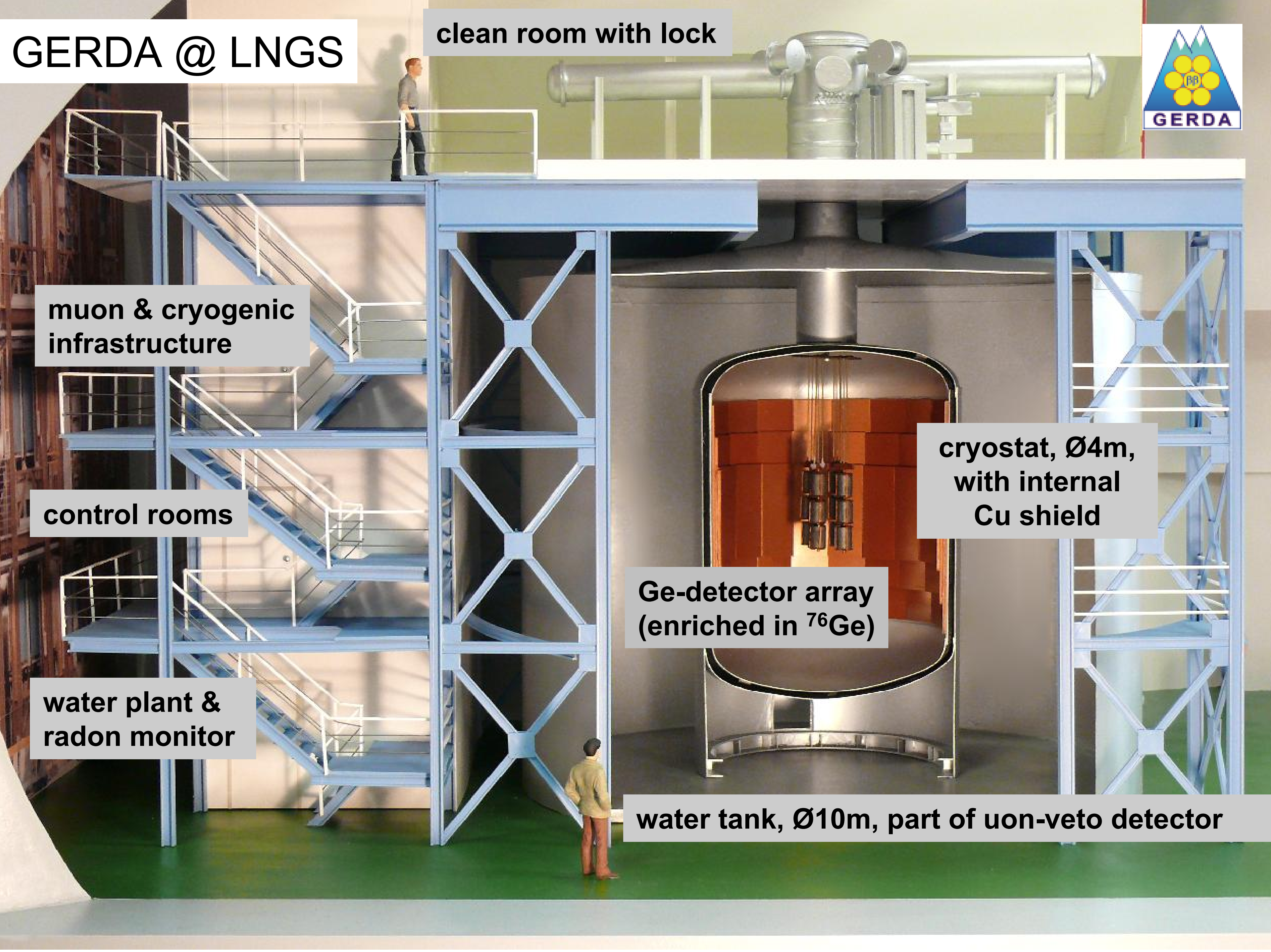
KamLAND-Zen: 2011

CUORE-0: 2011
CUORE: 2014

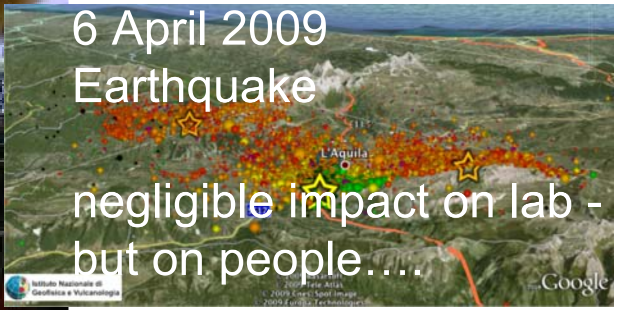


Super-Nemo
@ LSM: Demonstrator 2014

Majorana: 2013
NEXT: 2013
Lucifer
EXO-gas
XMASS

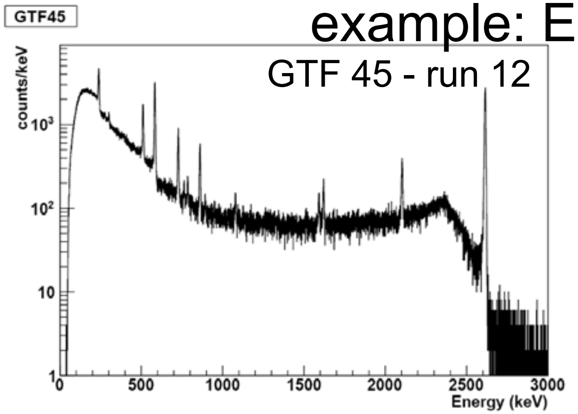

GERDA @ LNGS
clean room with lock
GERDA
muon & cryogenic infrastructure
control rooms
water plant & radon monitor
cryostat, Ø4m, with internal Cu shield
Ge-detector array (enriched in ^{76}Ge)
water tank, Ø10m, part of uon-veto detector

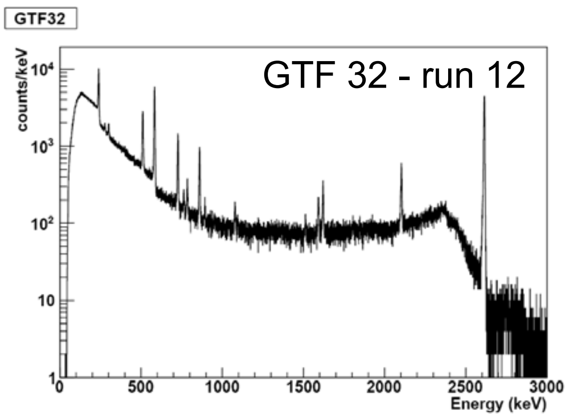
GERDA construction: 2008-2010

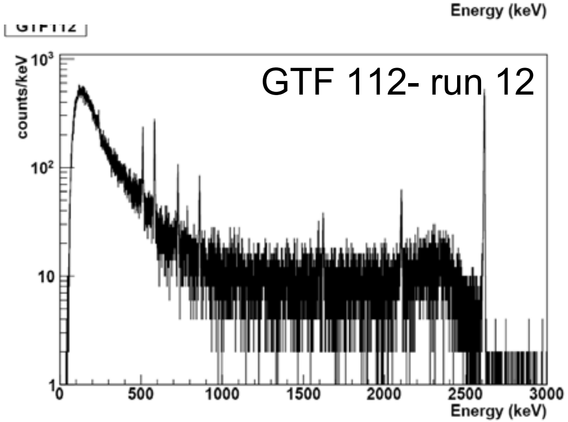


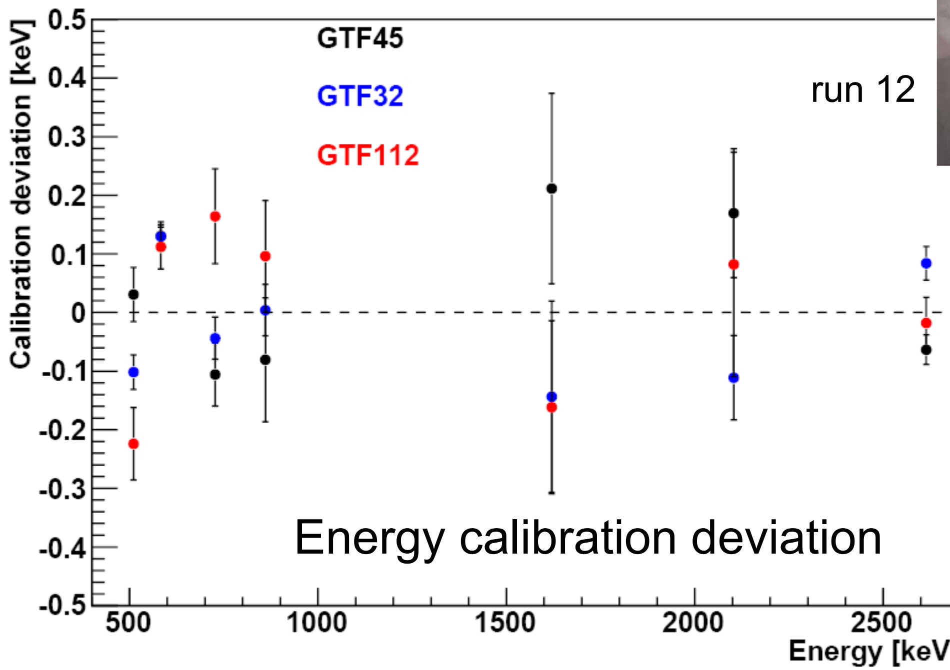
GERDA Inauguration @ LNGS: Nov 2010

Commissioning runs with **non-enriched** low-background detectors to study performance and backgrounds example: Energy calibration with ^{228}Th γ-source





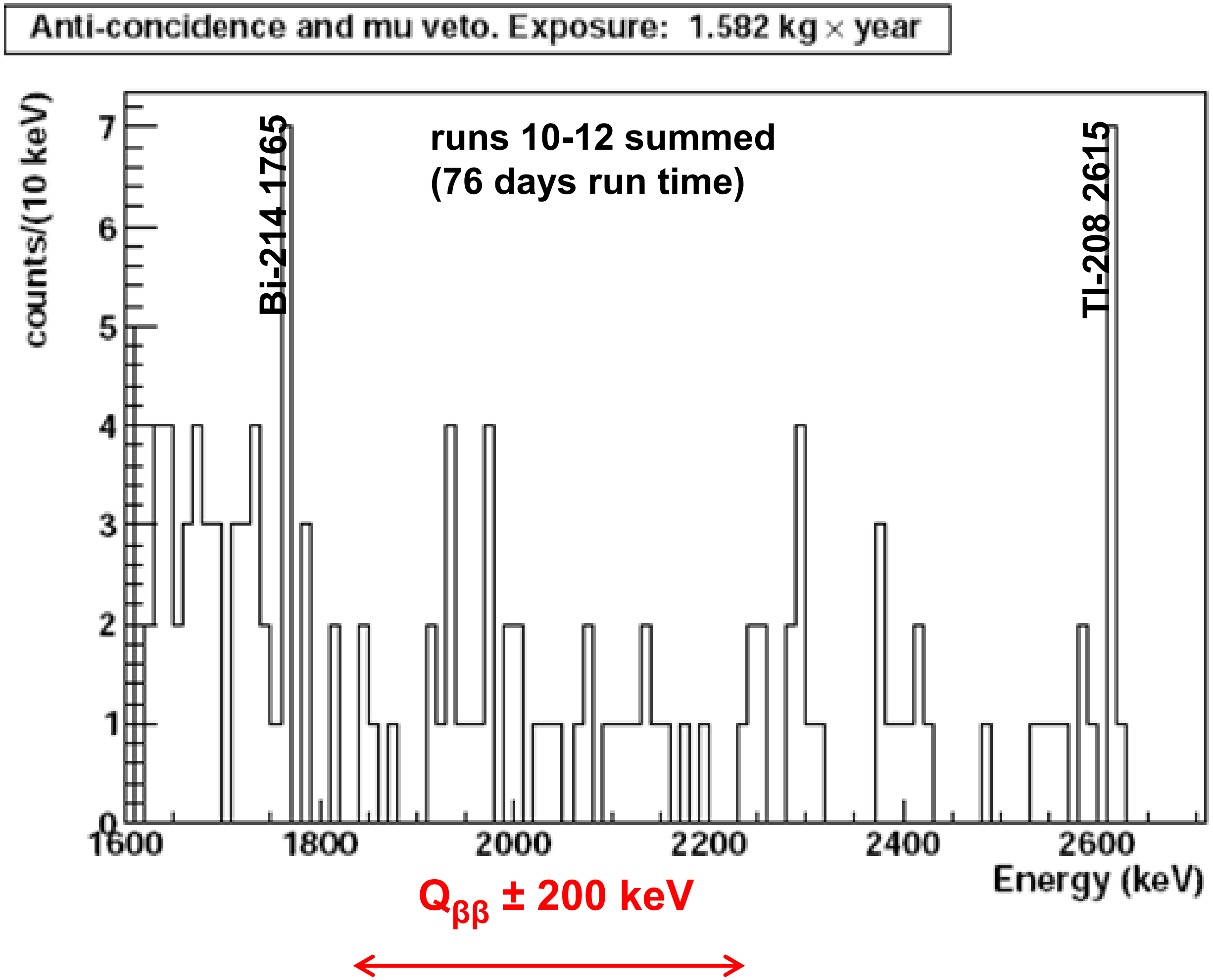




Measured energy resolution in GERDA during commissioning phase: dependent on chosen detector configuration (e.g.: p+ or n+ read-out, mini-shroud,..):

- Coaxial detectors (Phase I): best: 3.6 keV (FWHM) at 2.6 MeV
- BEGe (Phase II): 2.8 keV (FWHM) at 2.6 MeV

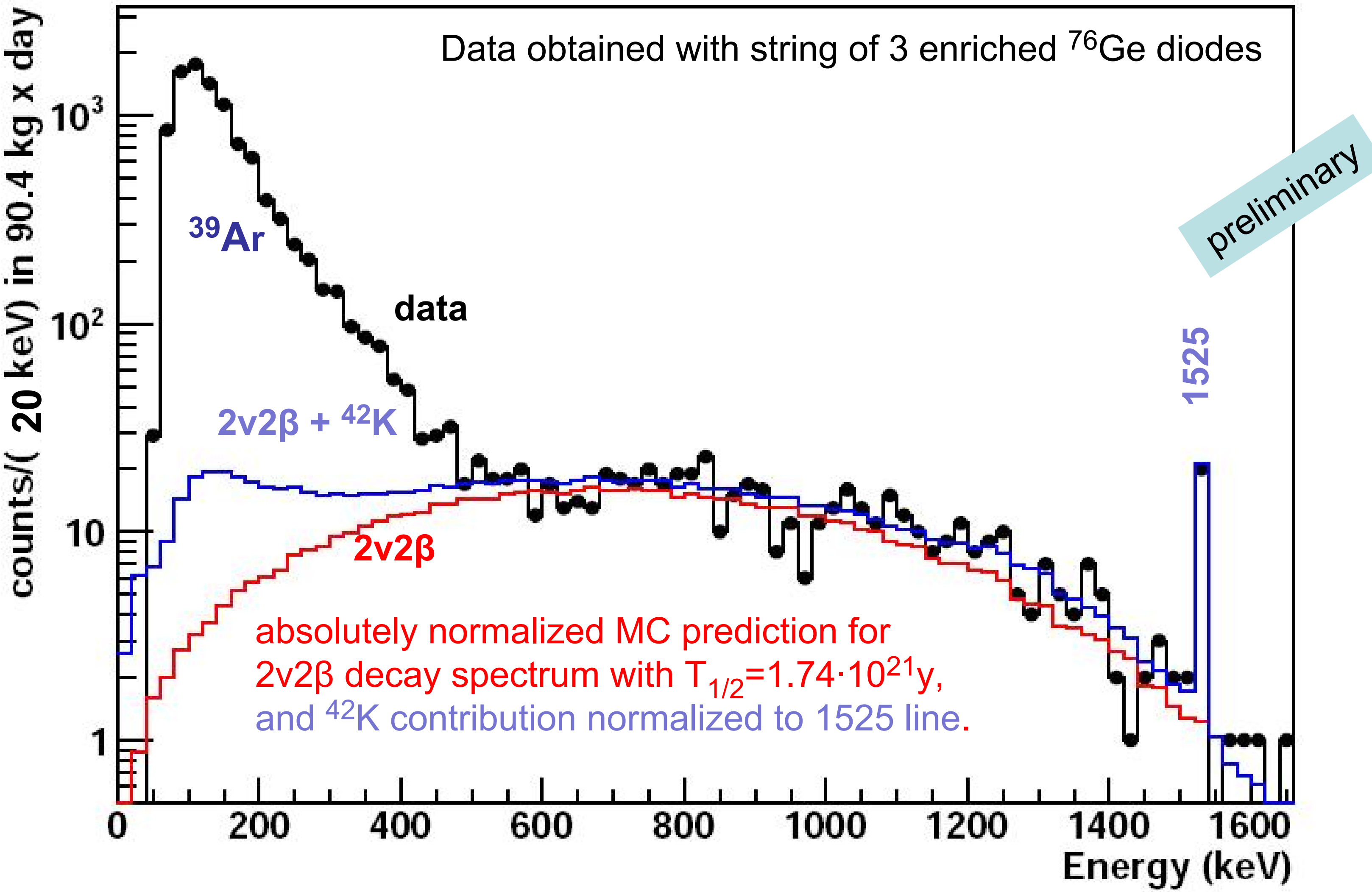
Commissioning with **non-enriched Ge diodes**: bgd in $Q_{\beta\beta}$-region



- Deduced background index in interval ($Q_{\beta\beta}$ ± 200) keV: 0.06 ± 0.01 cts/(keV·kg·y)

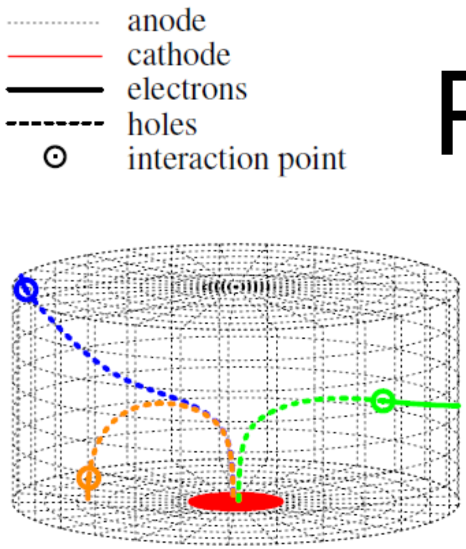
- Background rate significantly lower than in previous experiments (HdM, IGEX) - but still higher than Phase I goal of 0.01.

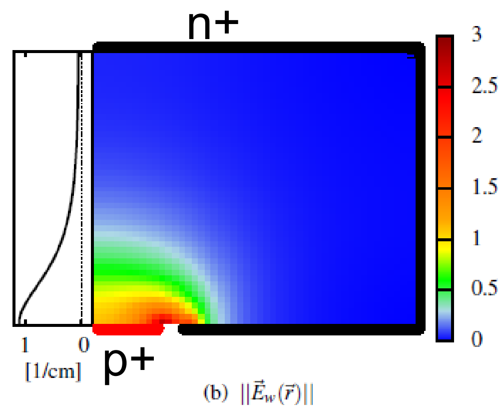
Commissioning: spectrum of **enriched ^{76}Ge** diodes and MC $2\nu\beta\beta$ & ^{42}K



Most events between ^{39}Ar endpoint & 1525 keV line accounted for by 2v2β decays.

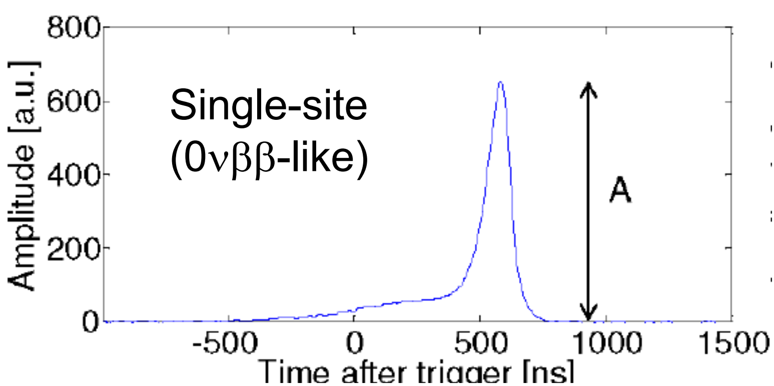
Phase II detectors

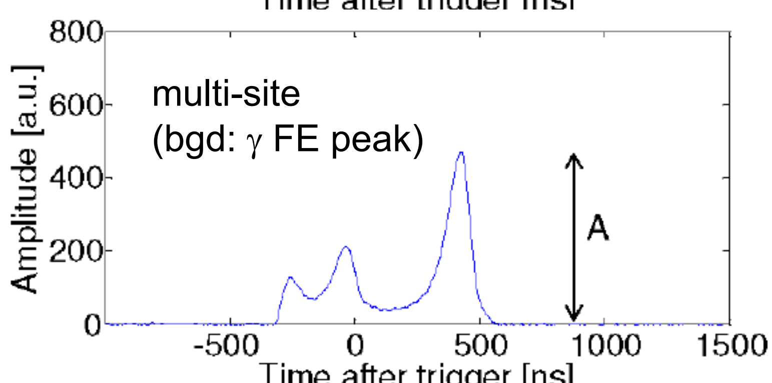


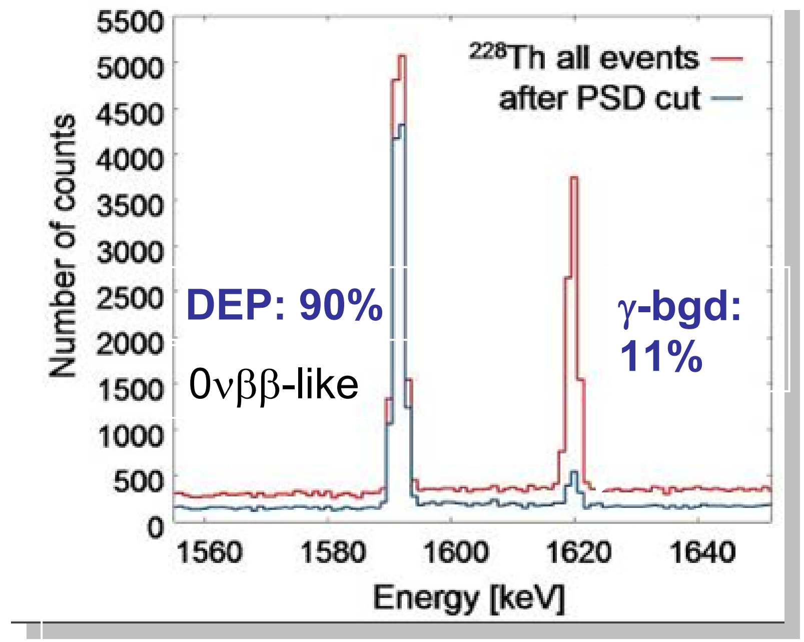


Signal shape provides clear topology for event-by-event signal ID / bgd discrimination:

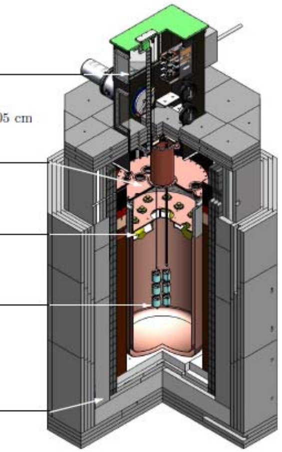
- SSE/MSE discrimination
- Surface events:
  - n+ slow pulses
  - p+: 'amplified' current pulses

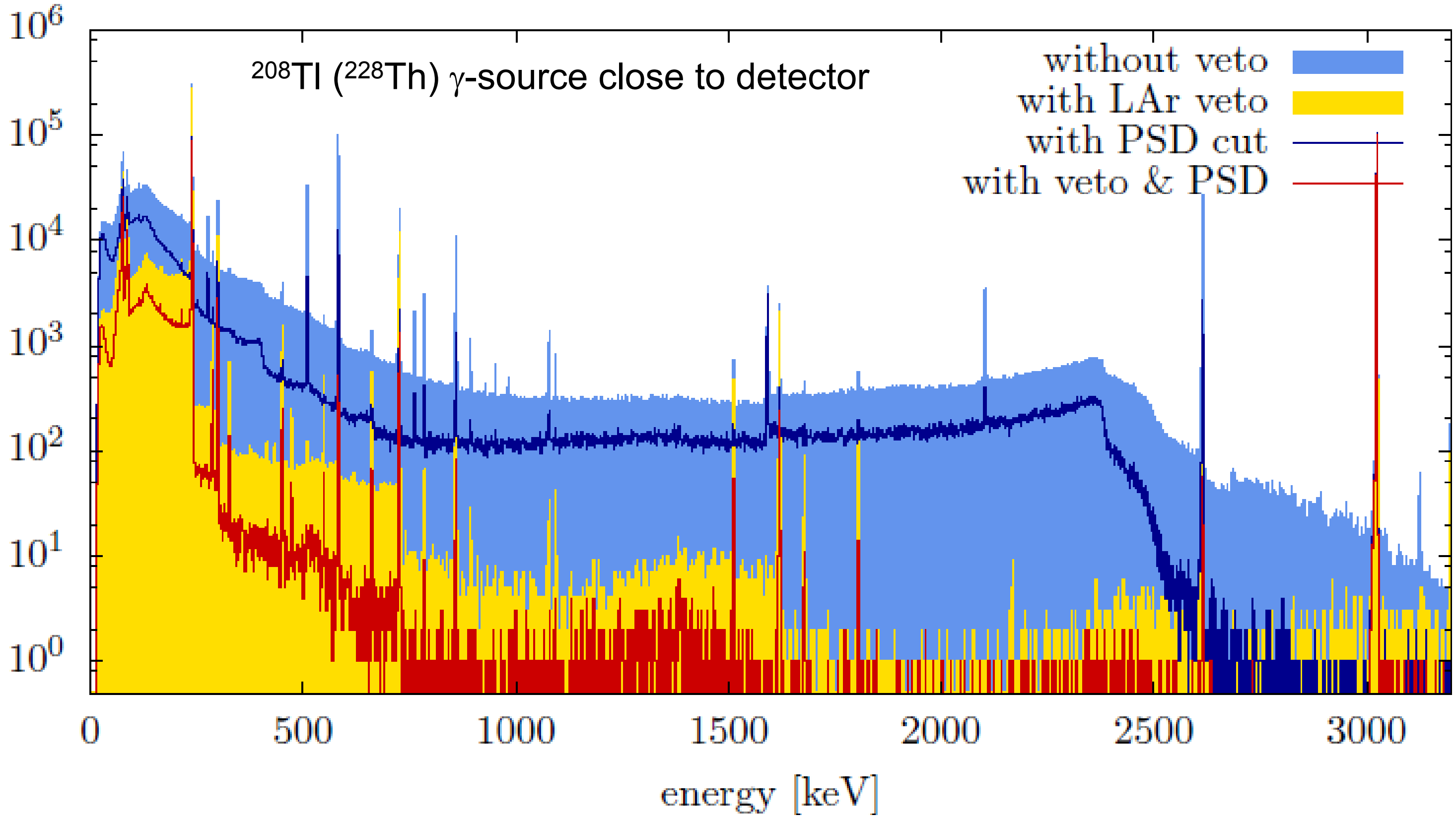






R&D liquid argon instrumentation





Operation of Phase II detector prototype in LArGe:

Measured suppression factor at $Q_{\beta\beta}$: **~0.5·10^4** for a near ^{228}Th calibration source

Also: successful read out of scintillation light with fibers coupled to SiPMs

Summary & Outlook

- **Non-accelerator neutrino experiments** (atmospheric, solar, reactor) are now doing **precision measurements**: test of sub-leading terms θ_{13}, θ_{14}, NSI,…

- **Hint for θ_{13}>0** from non-accelerator experiments together with recent results from T2K & Minos are now at **3σ C.L**.

- **θ_{13} search** with **Double Chooz** started in April 2011, statistics in 2011 expected to be sufficient to verify central value of T2K; Reno, Daya Bay coming soon online.

- Does the **reactor anomaly** (together with other 2.5 σ anomalies) point to **sterile neutrino(s)?** Experimental tests required!

- **2011: GERDA & EXO-200 started, soon KL-Zen, Cuore-0** will start search for **0$\nu\beta\beta$ decay**

- **2012:** expect a plethora of interesting results on θ_{13} **and 0$\nu\beta\beta$, and more!**