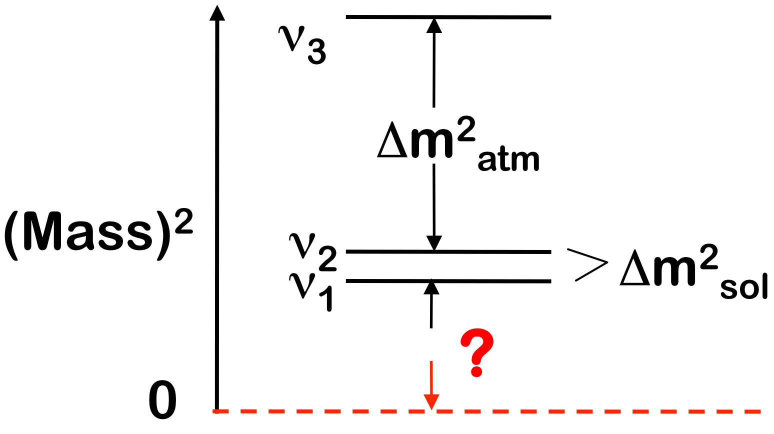
Some Issues In Neutrino Physics (At TAUP 2013)

Saclay, October 14th 2013

Th. Lasserre

Open questions in ν physics

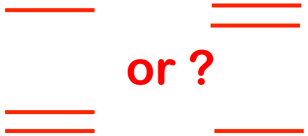
- What are the masses of the mass eigenstates ν_i?



} ν flavor change

} β decay, ββ0ν decay, cosmology

- Is the spectral pattern or ?



ν behavior in matter, ββ0ν, osc.

- Is there any conserved Lepton Number (Dirac or Majorana ν) ?

ββ0ν

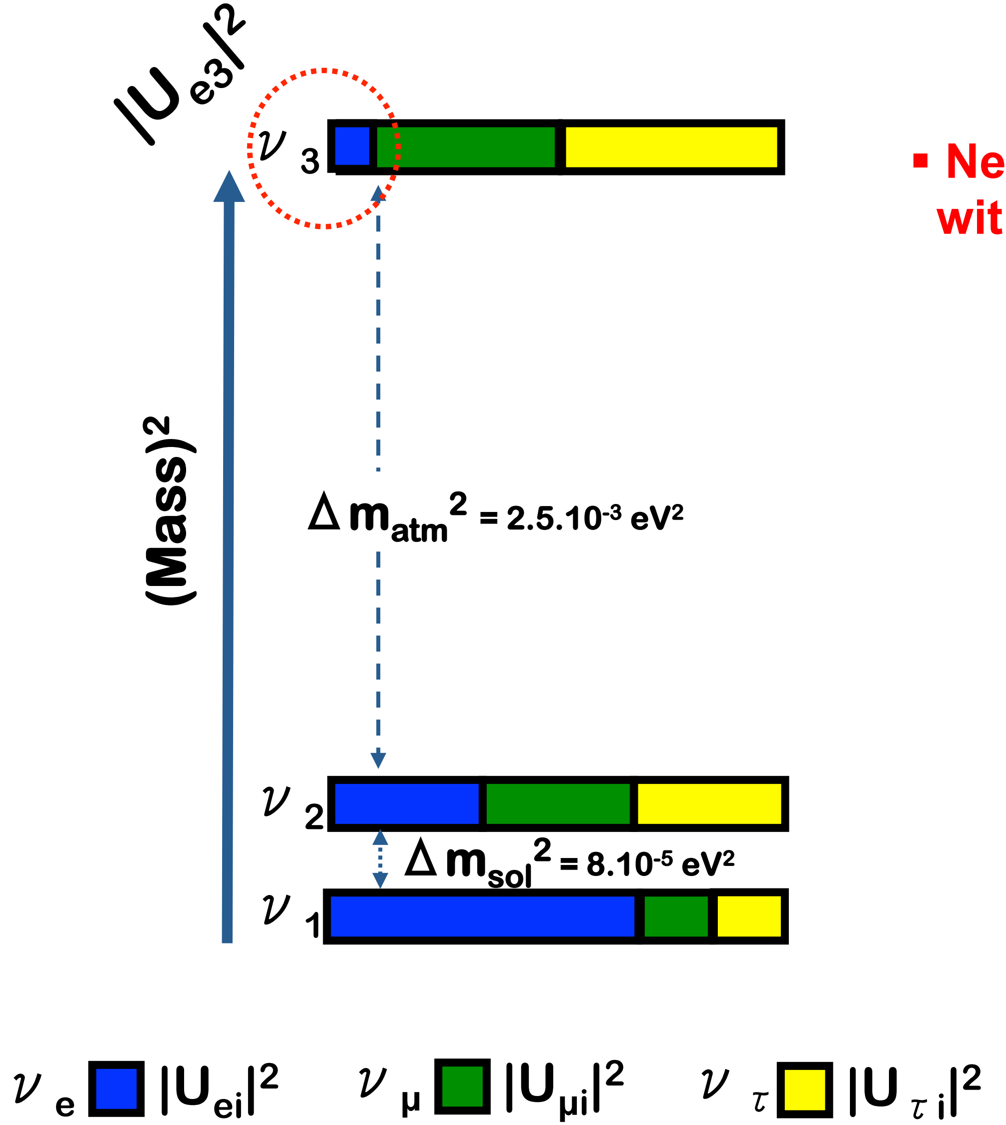
- Precise measurements of the leptonic mixing matrix?
- Do the behavior of ν violate CP?
- Is leptonic $\cancel{CP}$ responsible for the matter-antimatter asymmetry?

} ν flavor change

- Are there additional (sterile) neutrino states

ν flavor, Astro/Cosmo

θ_{13}



- **Need to connect the ν_e flavour with the isolated neutrino (Δm_{atm}^2)**

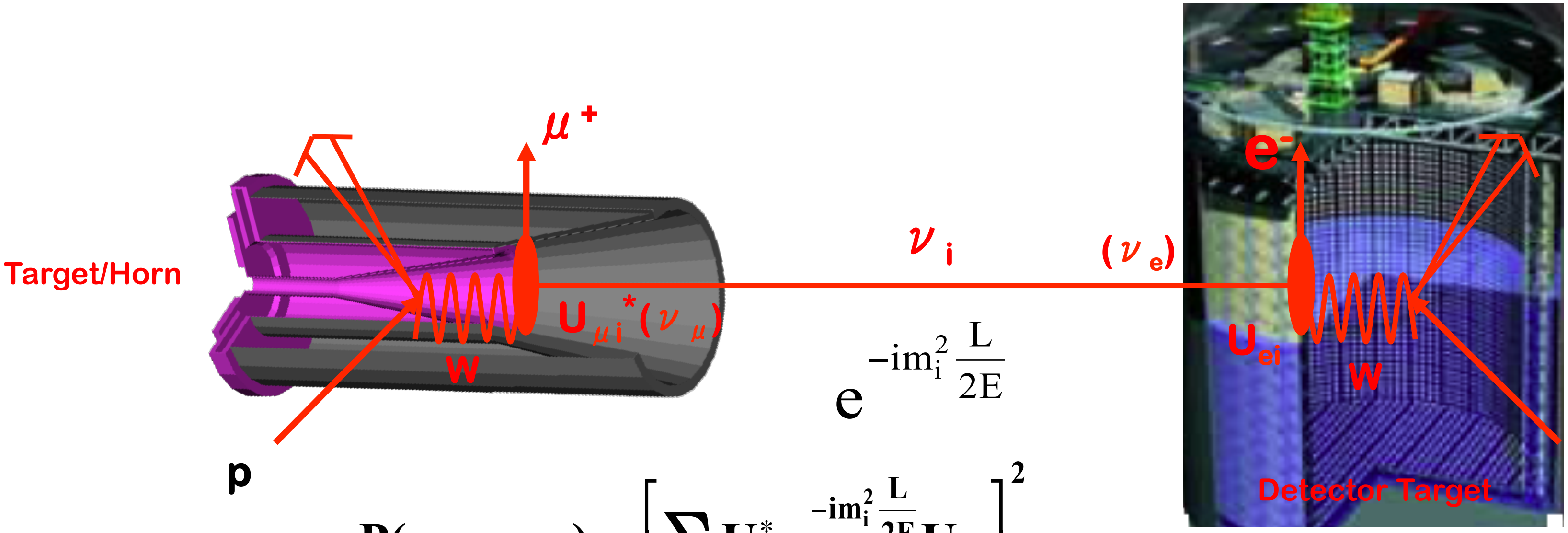
  - **L~1 km, E~MeV**
    - disappearance expt. @reactor
    - θ_{13} only → 'clean'

  - **L~1000 km, E~GeV**
    - accelerator experiments
    - appearance expt. @Beam
    - (θ_{13}, NH/IH, δ_{CP})
      → correlations & degeneracies

→ Complementary projects

Th. Lasserre – Neutrino Summary 2013

ν-Beam: Oscillation Physics



$$P(\nu_\mu \rightarrow \nu_e) = \left[\sum_i U_{\mu i}^* e^{-im_i^2 \frac{L}{2E}} U_{ei}\right]^2$$

- Complex oscillation formula

➔ depends on $\sin^2(2\theta_{13})$, Δm_{31}^2, sign(Δm_{31}^2), δ

- >> MeV muon antineutrinos ➔ appearance experiments

➔ $\sin^2(2\theta_{13})$ measurement depends on δ-CP

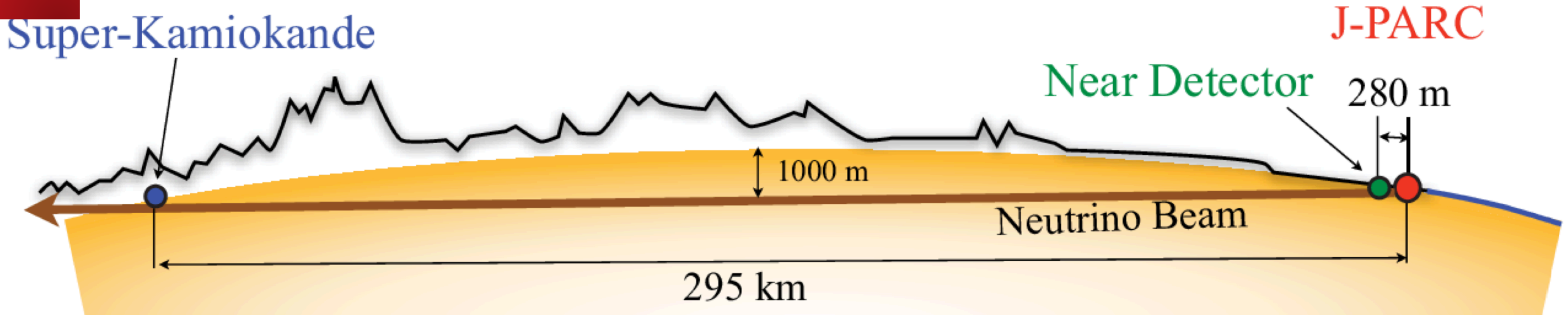
- >> MeV neutrinos + >>100 km baseline → matter effects

➔ $\sin^2(2\theta_{13})$ measurement independent of sign(Δm^2_{13})

Very sensitive to apparition

Correlation & degeneracies

T2K (Tokai to Kamioka) @JPARC

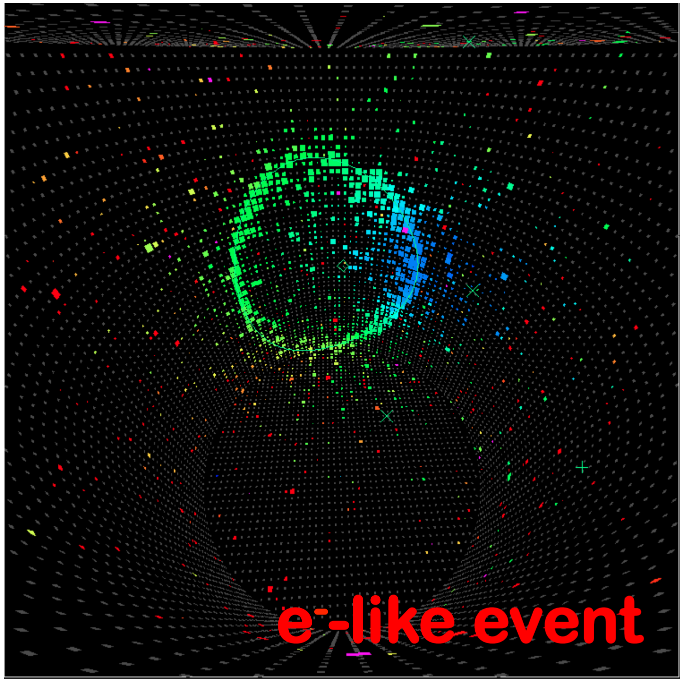


- **Channel:** $\nu_\mu \rightarrow \nu_e$ (1st goal: search for non-zero θ_{13}, beam contamination, NC-1π^0)
- Channel: $\nu_\mu \rightarrow \nu_\mu$ ($\sin^2 2\theta_{23}$ @ 1% & Δm^2_{23} @ 2%, single pion production)

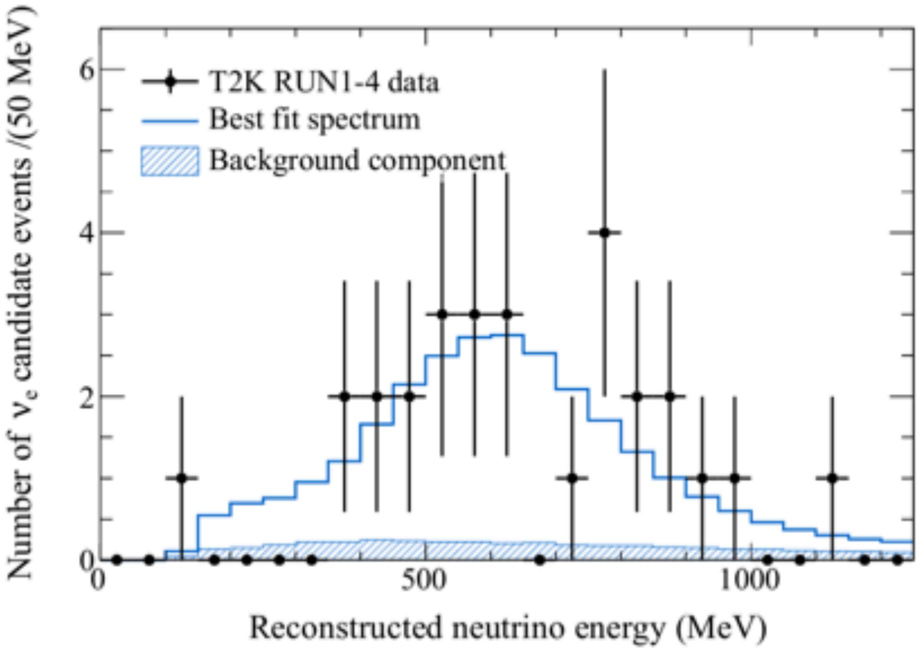
- Detection, **CCQE:** $\nu_l + n \rightarrow p + l^-$ ($l=e, \mu$)

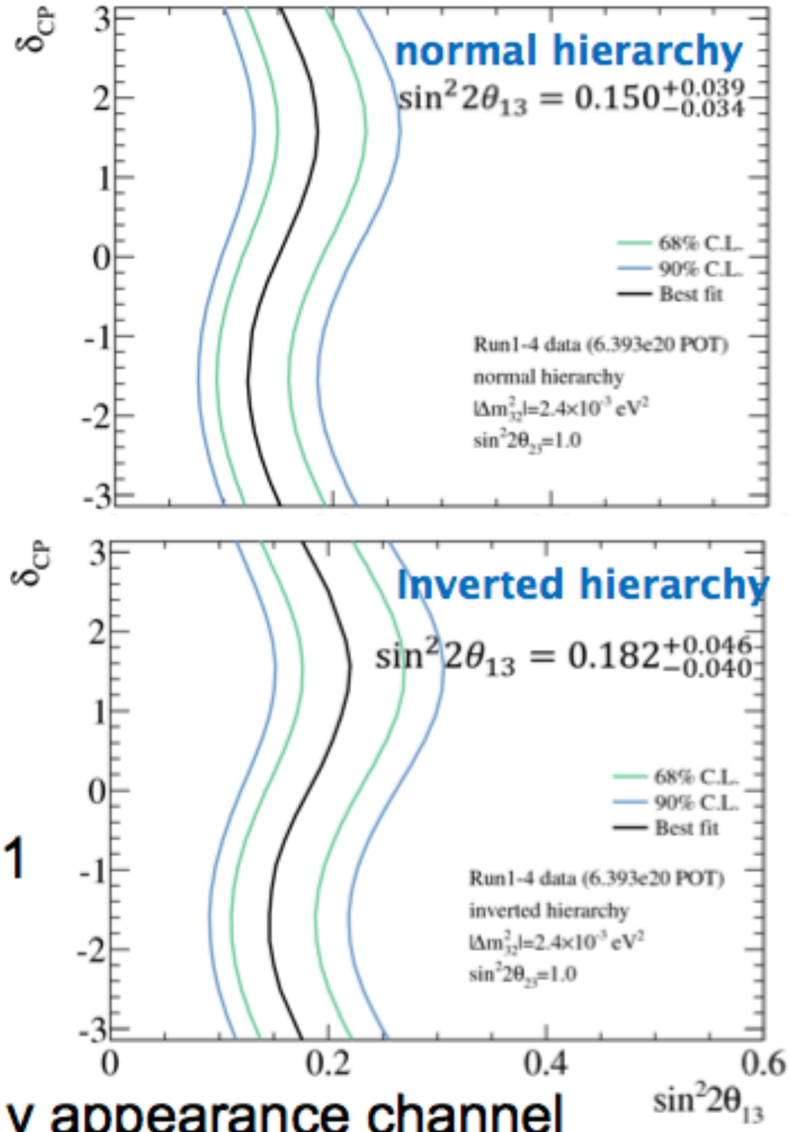
- **Beam Setup:**
  - Off-axis beam (2.5°), ramping to 750 kW…
  - Quasi-monochromatic ν_μ beam (400 MeV)
  - Small intrinsic ν_e contamination
  - Reduced high-E non-CCQE backgrounds

- **Far Detector at 295 km:**
  - Super Kamiokande (50 kt)
- **Near Detector at 280 m:**
  - On & Off-Axis detectors (Ingrid & ND280)



T2K (Tokai to Kamioka) @JPARC





4.6 events expected background

28 events observed

20.4 ± 0.8 events expected @ $\sin^2 2\theta = 0.1$

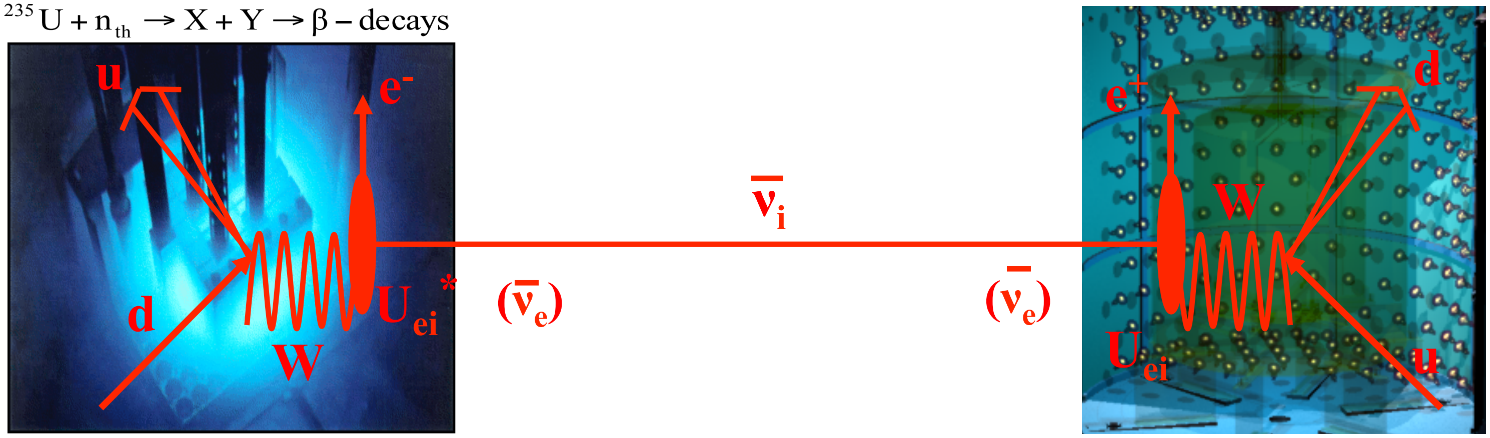
7.5σ significance for non-zero θ_{13}

First ever observation (>5σ) of an explicit ν appearance channel

Reactor: Oscillation Physics

$^{235}\mathrm{U} + \mathrm{n}_{\mathrm{th}} \rightarrow \mathrm{X} + \mathrm{Y} \rightarrow \beta - \mathrm{decays}$

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



Reactor core

Target H

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

- Simple oscillation formula

➔ depends $\sin^2(2\theta_{13})$ & Δm_{atm}^2, weakly on Δm_{sol}^2

- MeV electron antineutrinos ➔ disappearance experiment

➔ $\sin^2(2\theta_{13})$ measurement independent of δ-CP

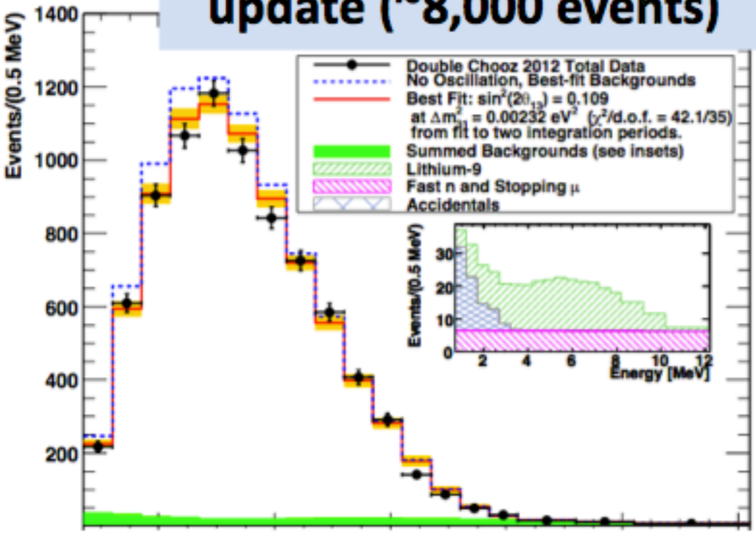
- MeV neutrinos + 1 km baseline → no matter effects O[10^{-4}]

➔ $\sin^2(2\theta_{13})$ measurement independent of sign(Δm^2_{13})

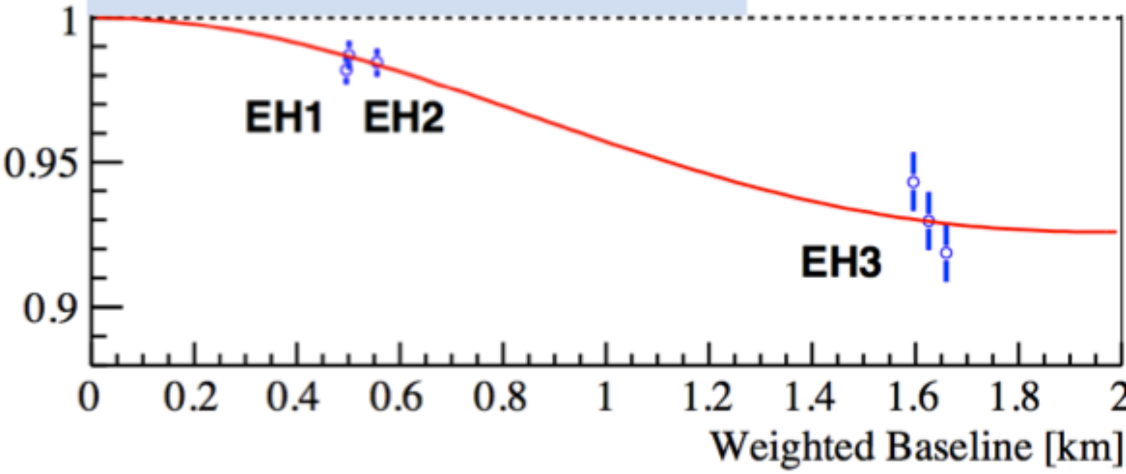
‘clean’ information on θ_{13}

Recent Progress

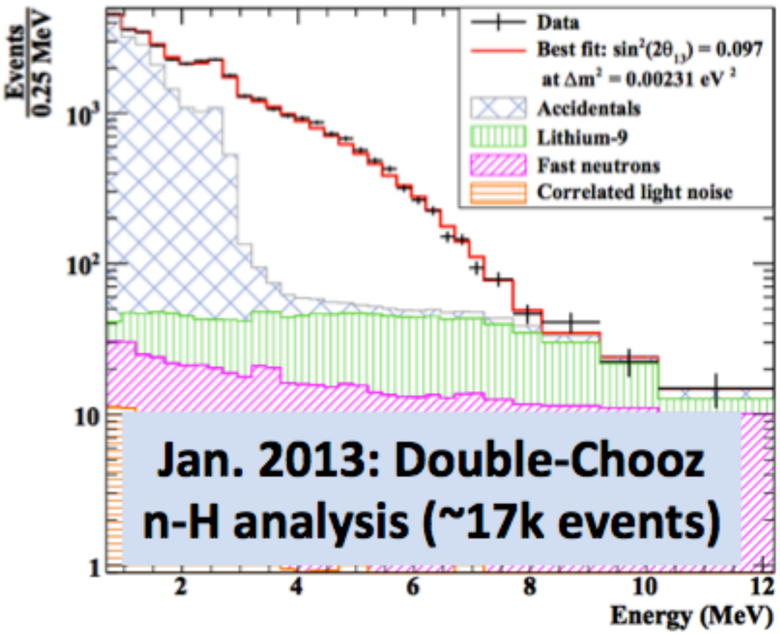
Jul. 2012: Double-Chooz update (~8,000 events)



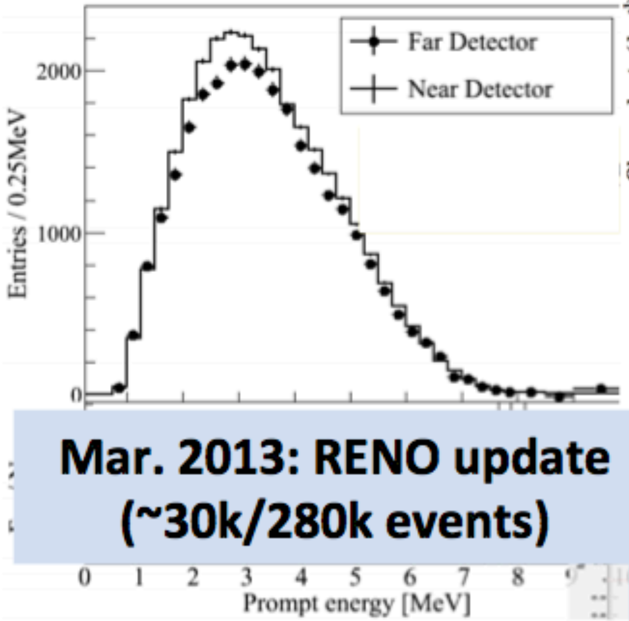
Nov. 2012: Daya Bay update (~29k/200k events)



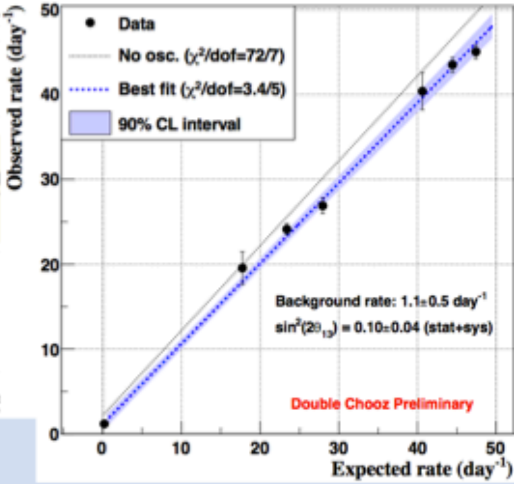
Jan. 2013: Double-Chooz n-H analysis (~17k events)



Mar. 2013: RENO update (~30k/280k events)

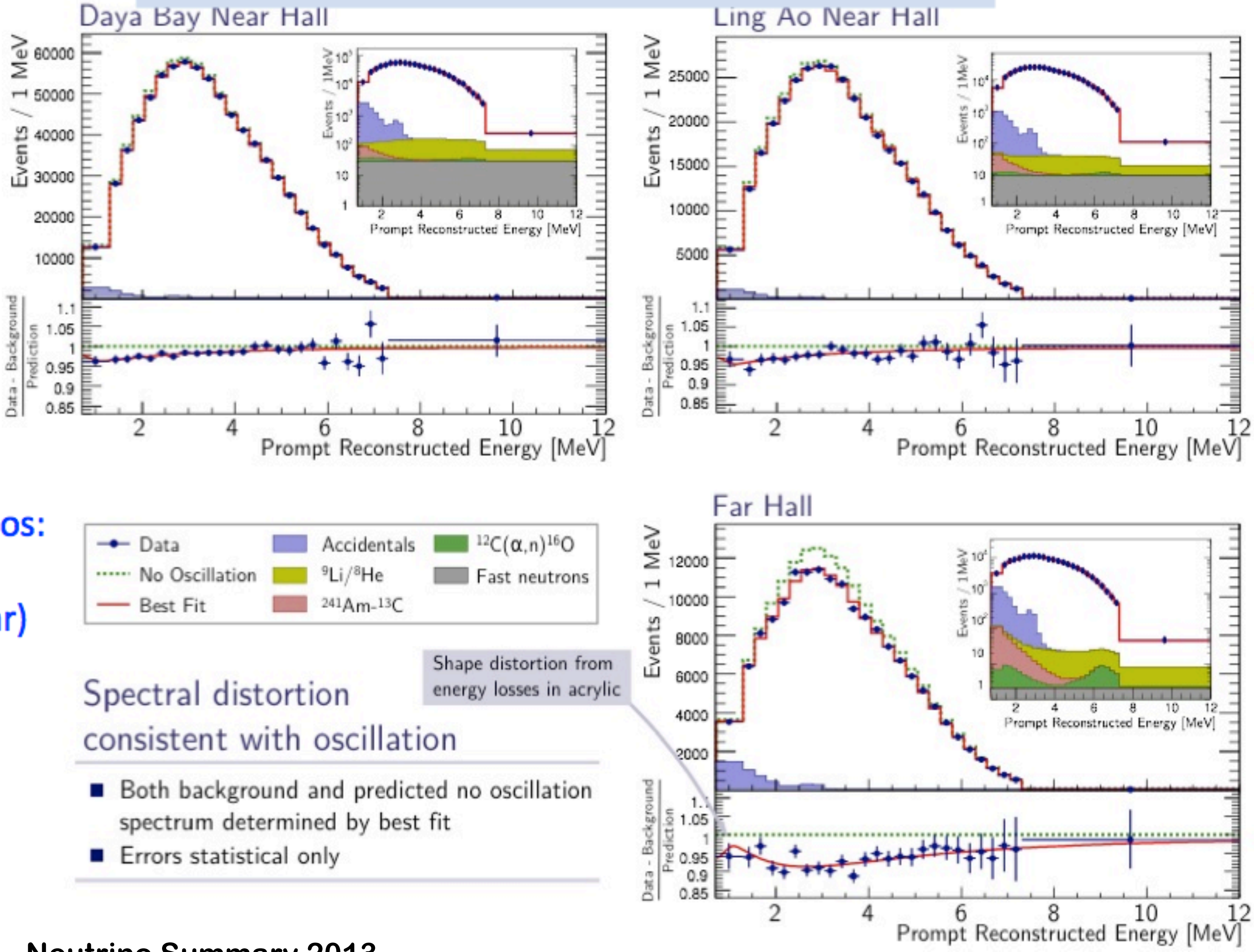


Aug. 2013: Double-Chooz reactor-on/off



Just Released

Aug. 2013: Daya Bay Spectral Analysis



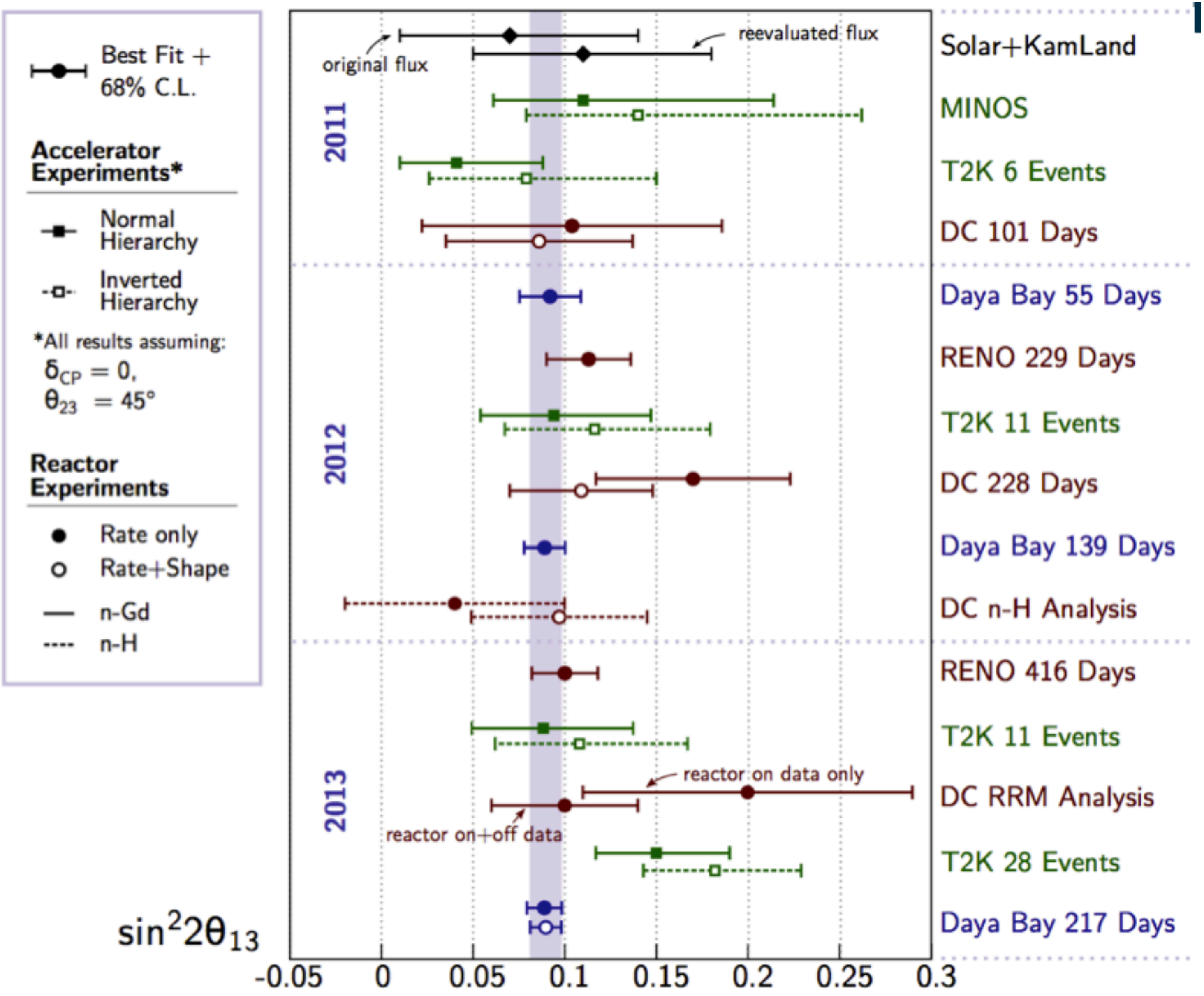
Shape distortion from energy losses in acrylic

Detected Antineutrinos:
~42k (far)
~297k (near)

Spectral distortion consistent with oscillation

- Both background and predicted no oscillation spectrum determined by best fit
- Errors statistical only

Summary of the θ_{13} Results

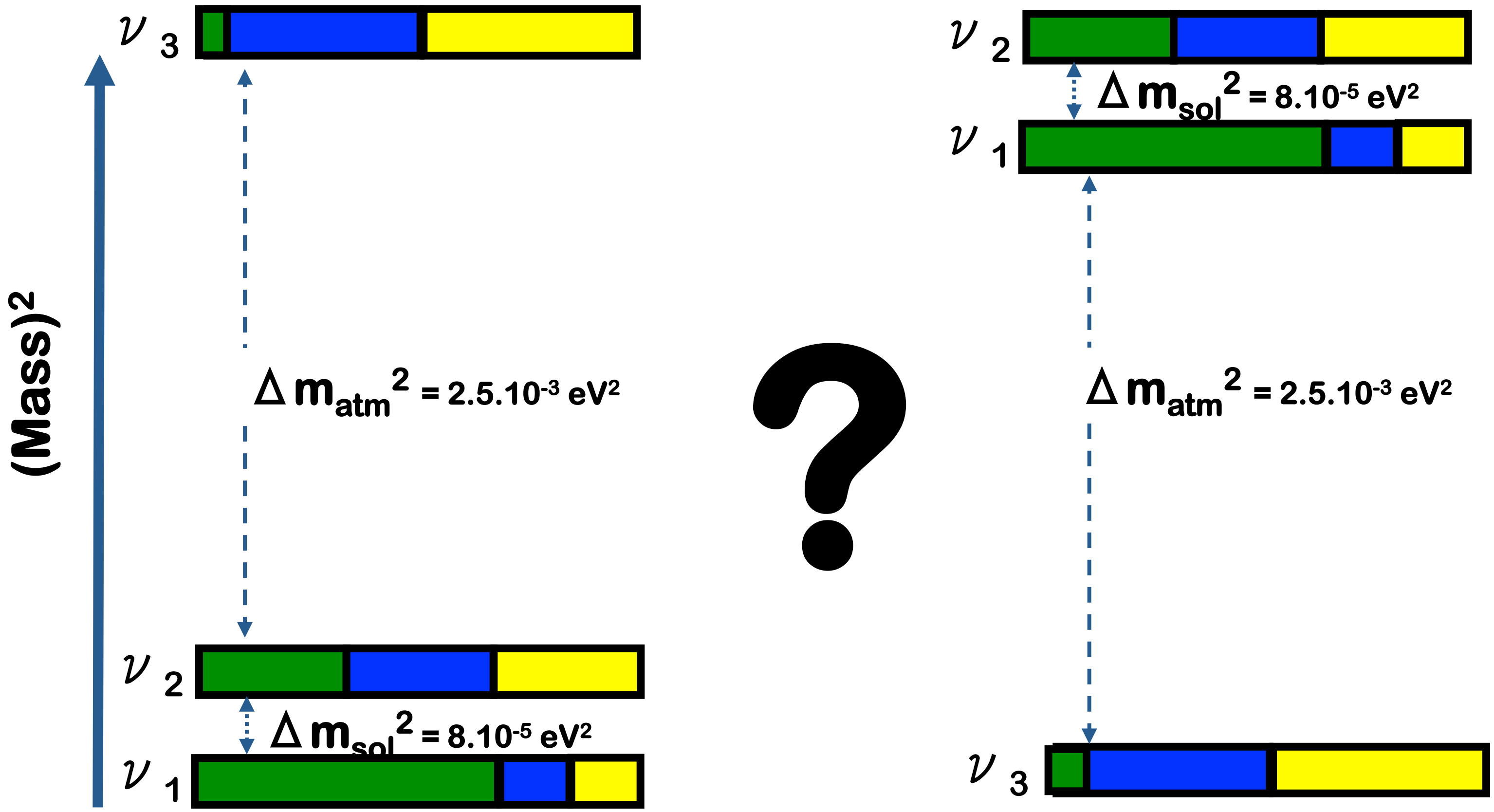


The Neutrino Mixing Angle θ_{13}: D. Dwyer

Question 2)

What is the spectral mass pattern ?

Sign of Δm^2_{31}



ν_3

$(\text{Mass})^2$

$\Delta m_{atm}^2 = 2.5.10^{-3}\ eV^2$

ν_2

$\Delta m_{sol}^2 = 8.10^{-5}\ eV^2$

ν_1

?

ν_2

$\Delta m_{sol}^2 = 8.10^{-5}\ eV^2$

ν_1

$\Delta m_{atm}^2 = 2.5.10^{-3}\ eV^2$

ν_3

ν_e 🟩 $|U_{ei}|^2$ ν_μ 🟦 $|U_{\mu i}|^2$ ν_τ 🟨 $|U_{\tau i}|^2$

MH: middle term projects

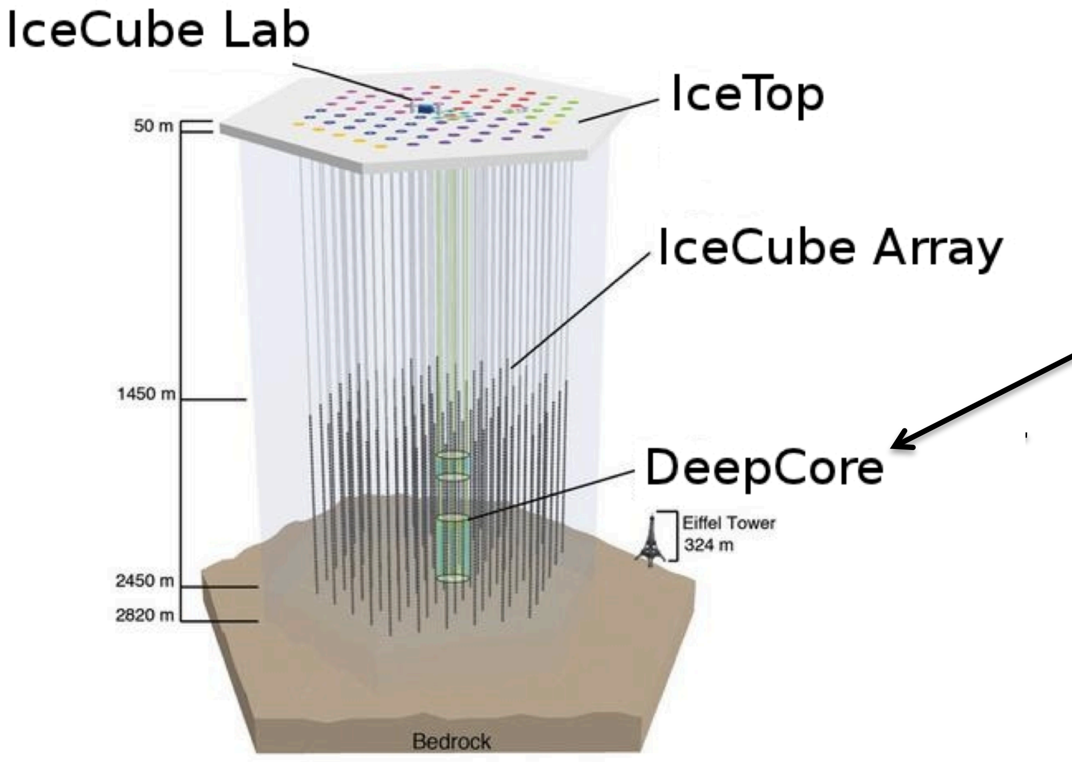
2012: Large θ_{13} open the door to new initiatives:

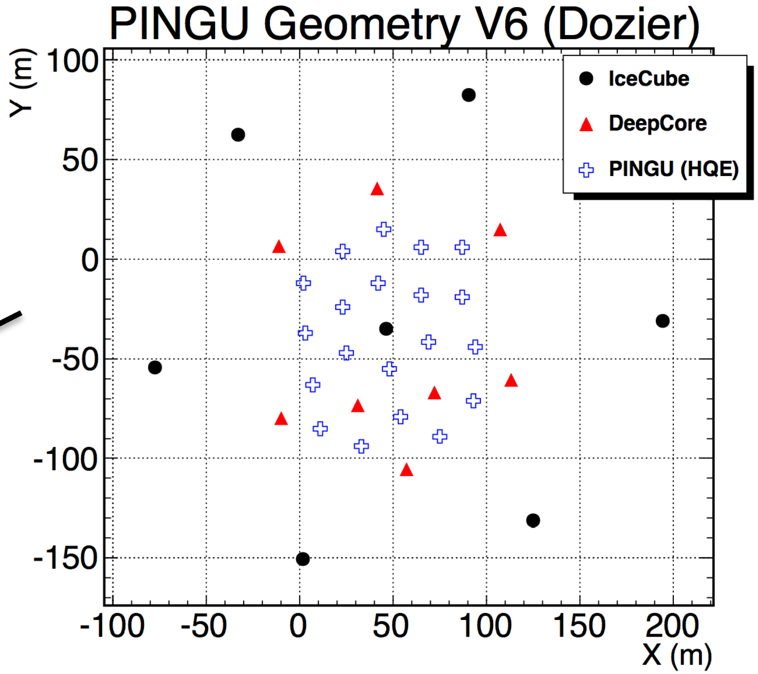
- Atmospheric neutrino L/E measurement
  - Pingu (Ice-Cube) & Orca (KM3net)
- 50 kt scale reactor experiment at 55 km
  - Daya-Bay II
- Atmospheric neutrino in magnetized detector
  - INO
- Beam of Neutrinos in Matter
  - LBNÖ
- **Prospects:** results before 2020 ?

IceCube Neutrino Telescope

Existing: 1 km^3 antarctic ice instrumented with 5160 PMTs
+ Deep Core 20 strings to reduce threshold

Next: PinGU → Add 20 strings within DeepCore

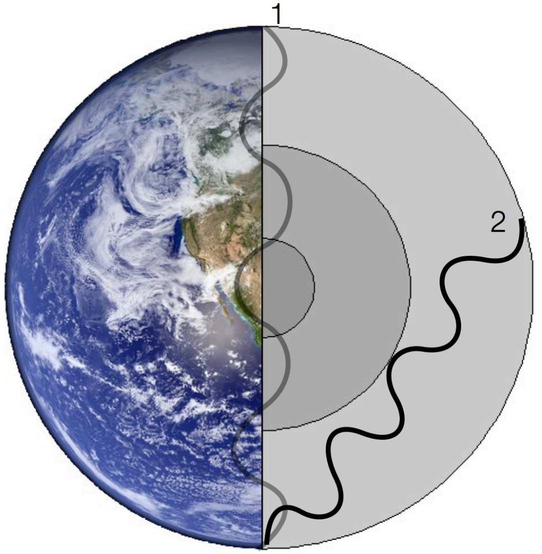




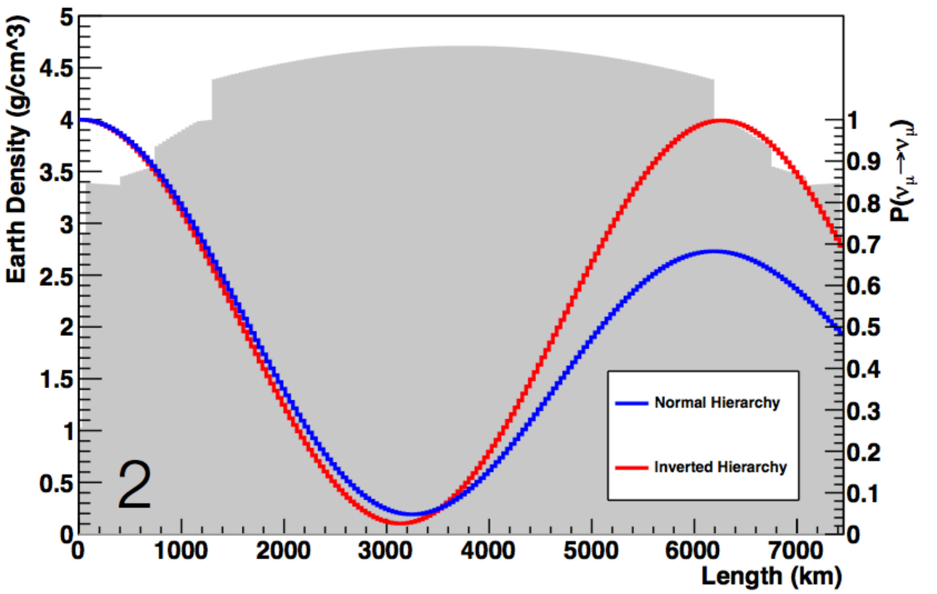
MH with PINGU (& ORCA)

- Lower Threshold to few GeV
  - Fine mesh string array
- Keep Megaton volume
- Matter Effects:

  IH/NH has up to a 20% difference in oscillation probability for specific energies and zenith angles
- Promising but sensitivity under study…
- Deployment by 2018
- Similar project in the Mediterranean see (Orca)

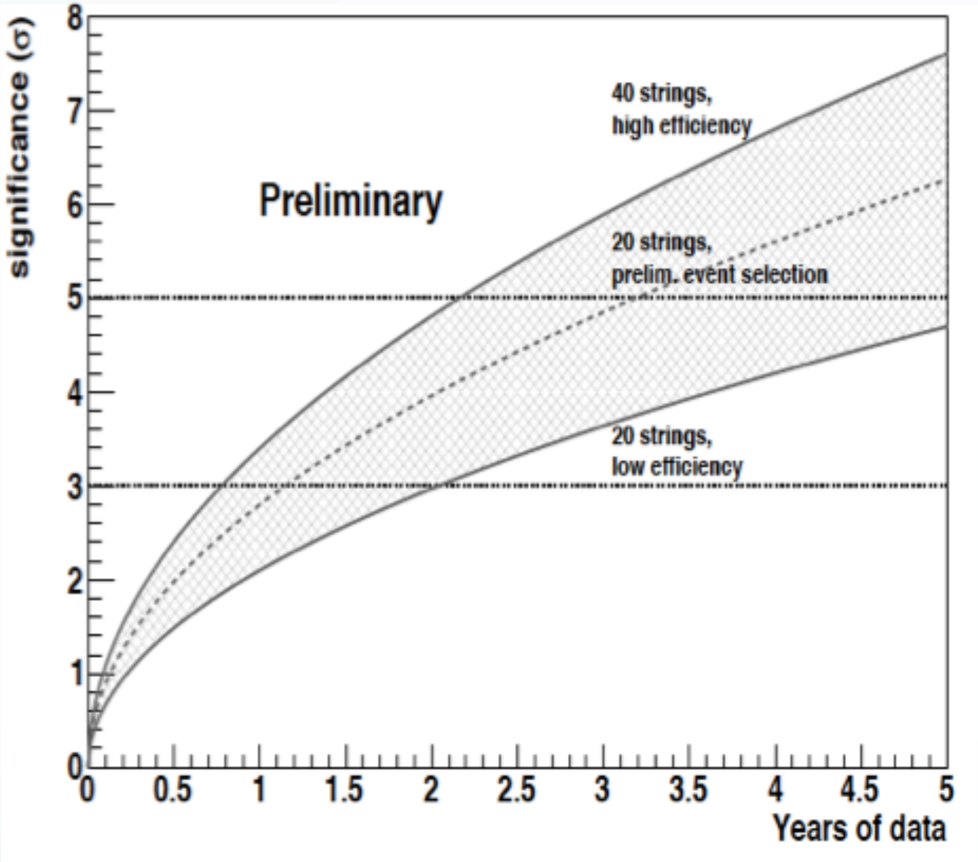


$P(\nu_\mu \rightarrow \nu_\mu)$ with Travel Through the Earth - 6 GeV, 126



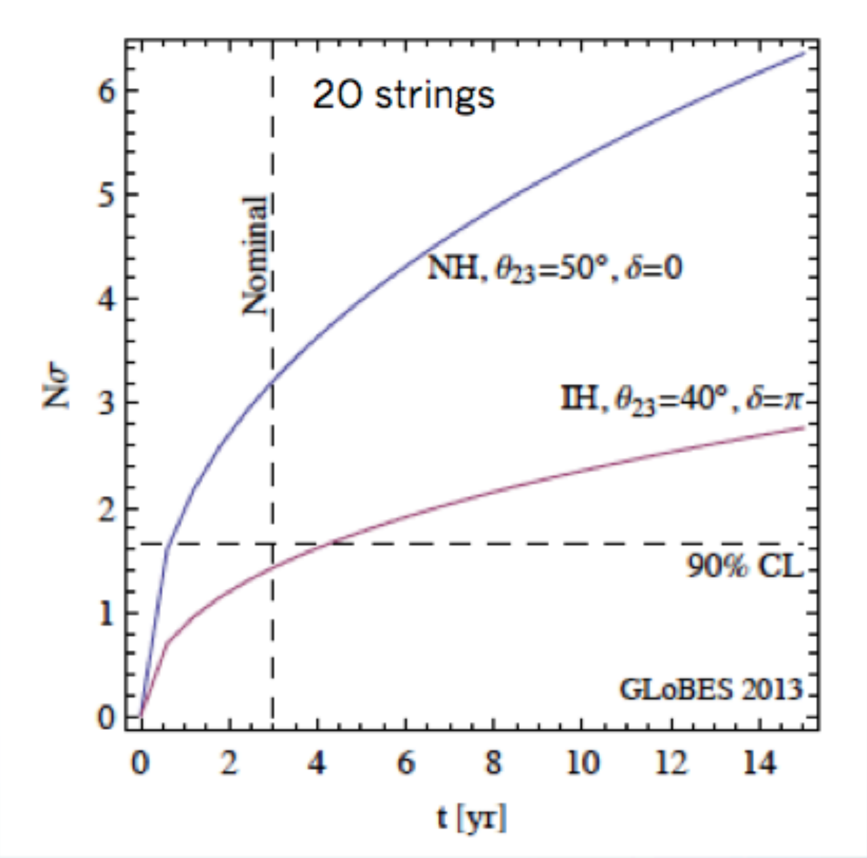
PINGU Sensitivity

📖 PINGU collaboration, arXiv:1306.5846



3 different studies performed.
Sys uncertainties include norm (30%), spectral index (±0.05), energy scale (10%), zenith bias (10%)
Realistic energy and direction resolutions

📖 W. Winter, arXiv:1305.5539v1



2 extreme cases of true param values.
$\Delta E/E = 25\%$ and $\Delta\theta/\theta = 0.6\sqrt{(m_p/E)}$
5% Flavor mis-id
Method : $\Delta\chi^2$
(optimistic 📖 E. Cuifolli et al 1305.5150)

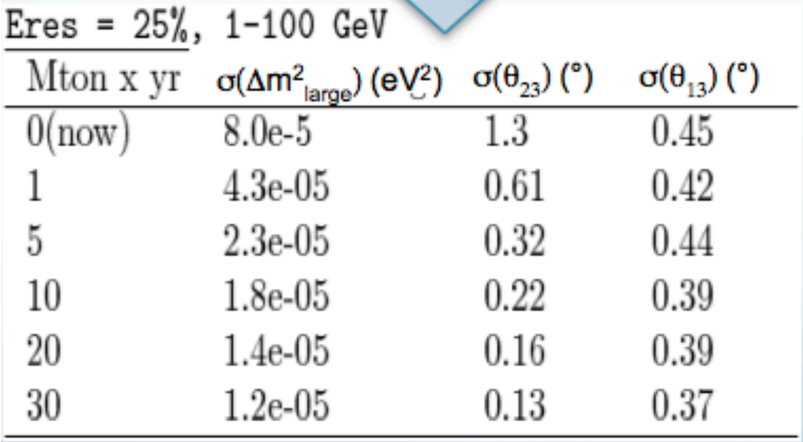
ORCA Sensitivity

To optimally distinguish between IH and NH: likelihood ratio test with nuisance parameters
→ *deal with degeneracies by fitting!*

$$\Delta \log(L^{\max}) = \sum_{\text{bins}} \log P(\text{data}|\hat{\theta}^{\text{NH}}, \text{NH}) - \log P(\text{data}|\hat{\theta}^{\text{IH}}, \text{IH})$$

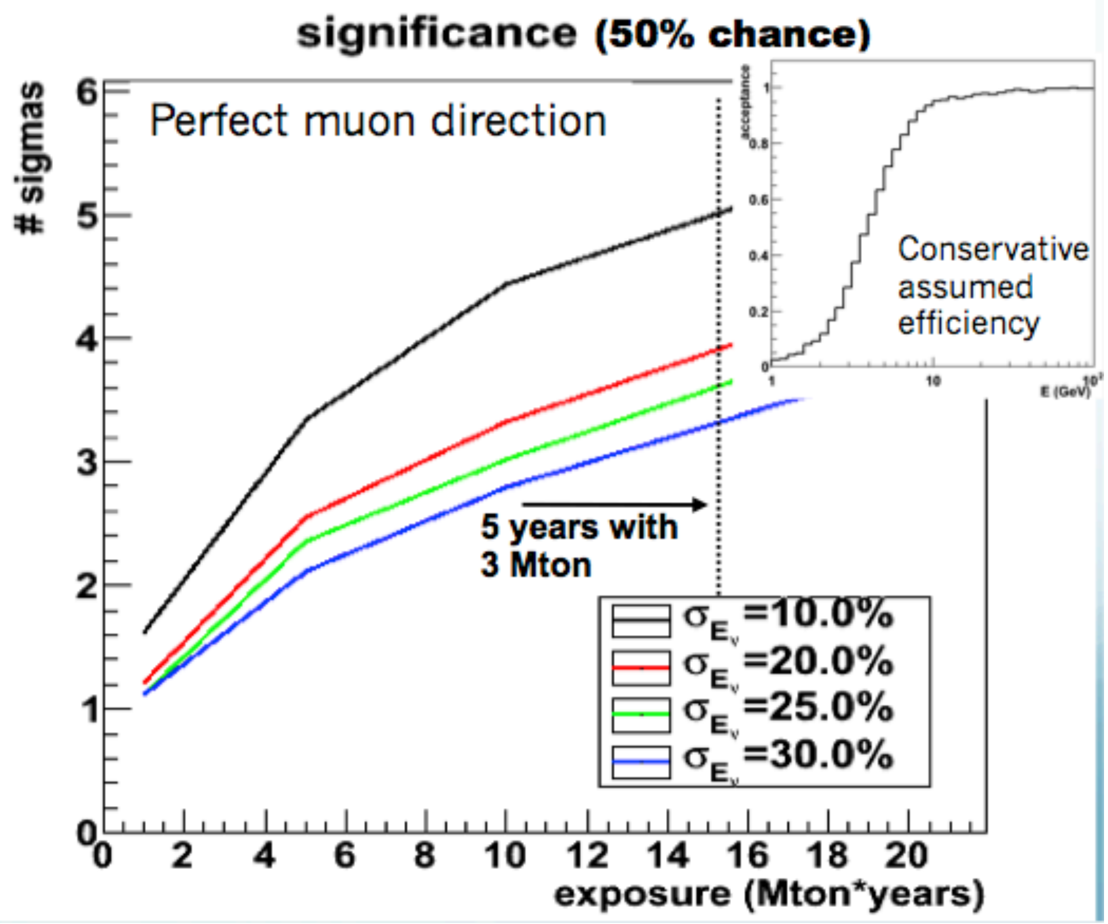
$\hat{\theta}^{\text{H}} =$ maximum-likelihood estimates for the Δm^2's and angles using both data and constraints from global fit.
nb: constraints are different for H=IH and H=NH

Uncertainty on the mixing parameters as a function of the exposure



Eres = 25%, 1-100 GeV

Mton x yr	$\sigma(\Delta m^2_{\text{large}})$ (eV^2)	$\sigma(\theta_{23})$ (°)	$\sigma(\theta_{13})$ (°)
0(now)	8.0e-5	1.3	0.45
1	4.3e-05	0.61	0.42
5	2.3e-05	0.32	0.44
10	1.8e-05	0.22	0.39
20	1.4e-05	0.16	0.39
30	1.2e-05	0.13	0.37



significance (50% chance)

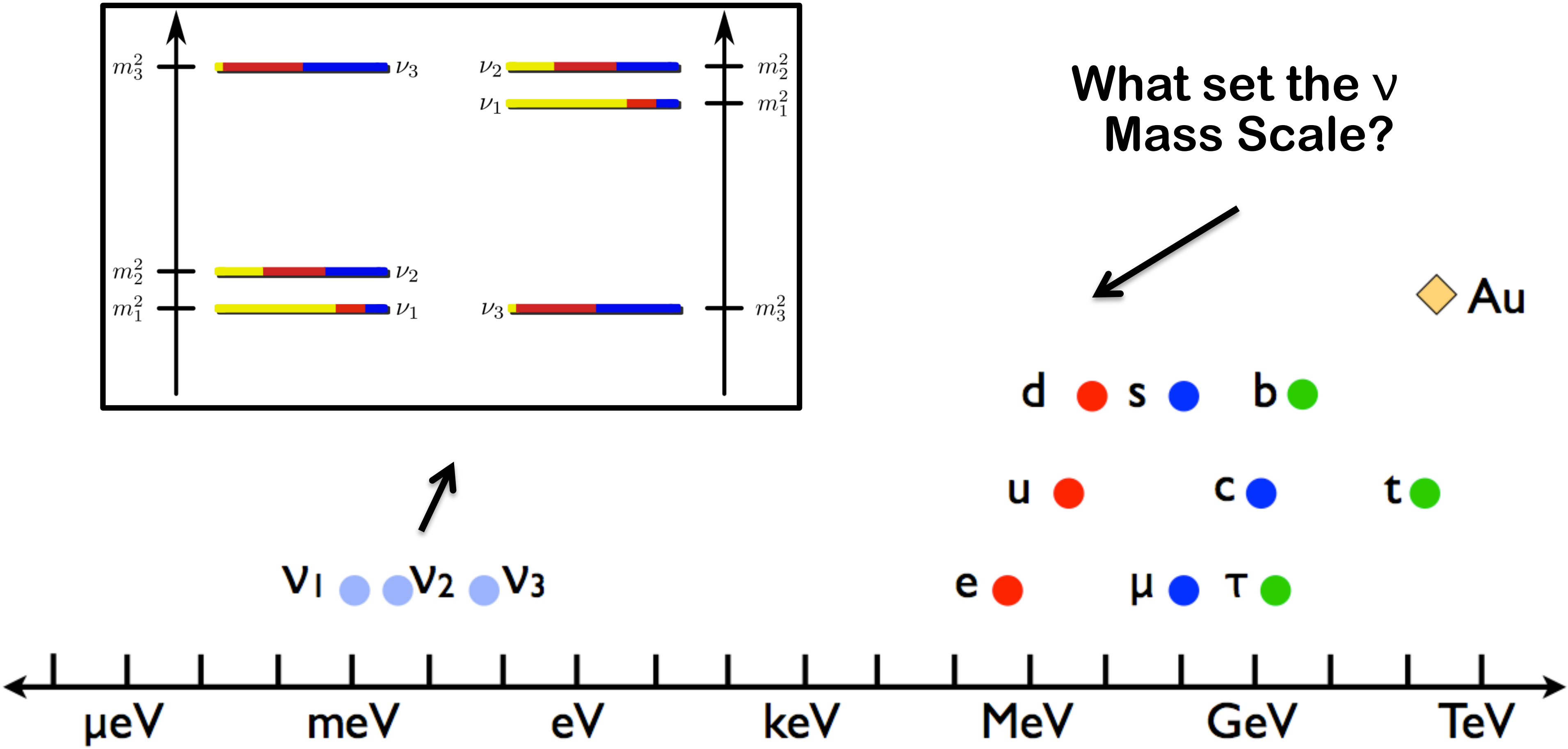
Conservative assumed efficiency

Question 4)

What are the masses of the mass eigenstates ?

Neutrino Mass Scale

What is the ν Mass Hierarchy?



What set the ν Mass Scale?

Finding the Neutrino Mass Scale

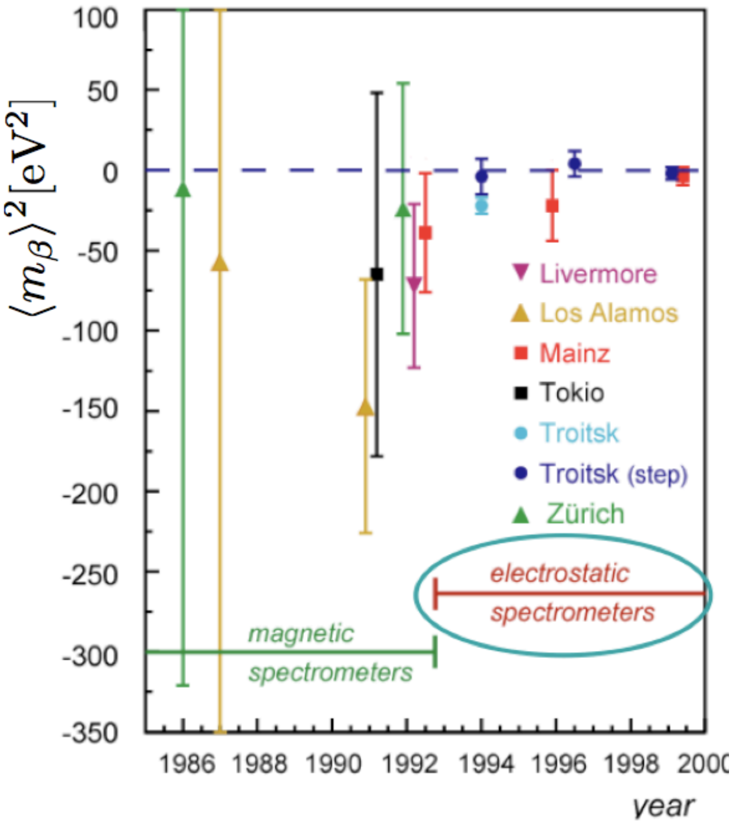
- Astrophysics
  - Supernovae, from 1987A m < 23eV
- Cosmology
  - CMB+ Large Scale Structures +… - $\sum m_i < 1$ eV
- Fermion Decays
  - μ , τ decays - relatively poor sensitivity
  - β decay
  - β β decay
- Neutrino Oscillations
  - No absolute scale but only square of mass differences

Beta Decay

- **β^- Decay:** $^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + e^- + \bar{\nu}_e$
- **Energy spectrum shape depends on ν mass**
  - **Based on kinematics and energy conservation**
  - **Weak dependence on theory**
  - **Sensitive to incoherent sum:**

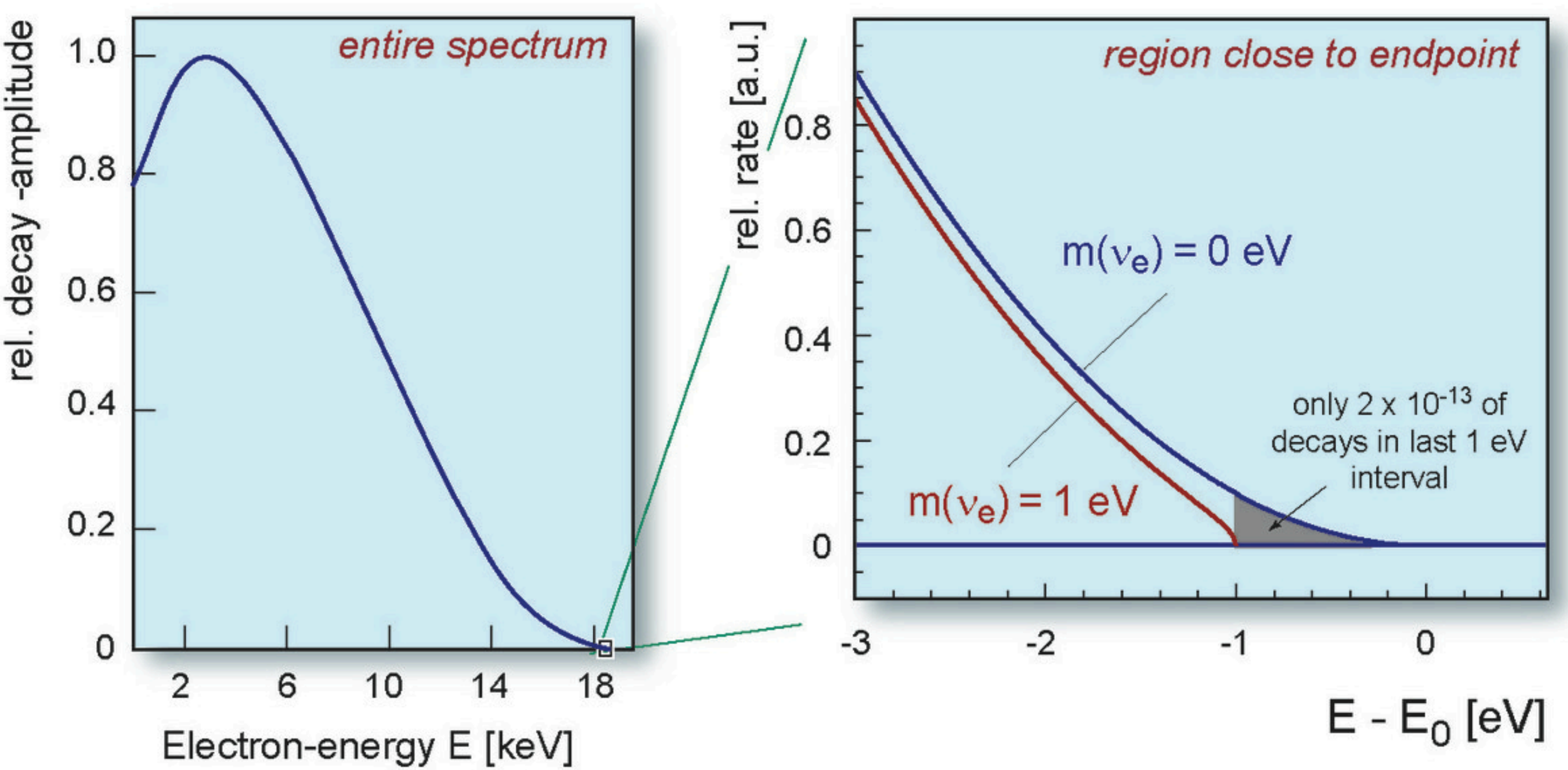
$$\langle m_\beta \rangle = \sqrt{\sum_{1,2,3,..} |U_{ei}|^2 m_i^2}$$

- **Best constraint by Mainz & Troitsk Experiments** →
  - **$<m_\beta> < 2.2$ eV**



Absolute Mass From Beta decay

Tritium beta decay $^3_1H \rightarrow ^3_2He + e^- + \overline{\nu}_e$



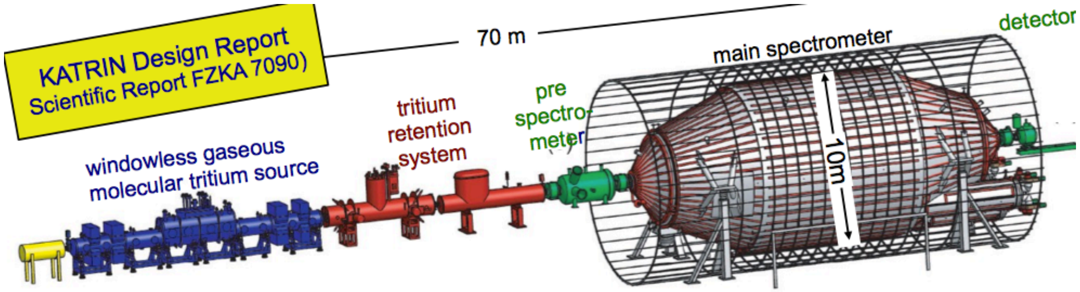
Beta Decay: KATRIN

- Measure both energy of e^- in the last few eV's below the Tritium beta decay endpoint energy

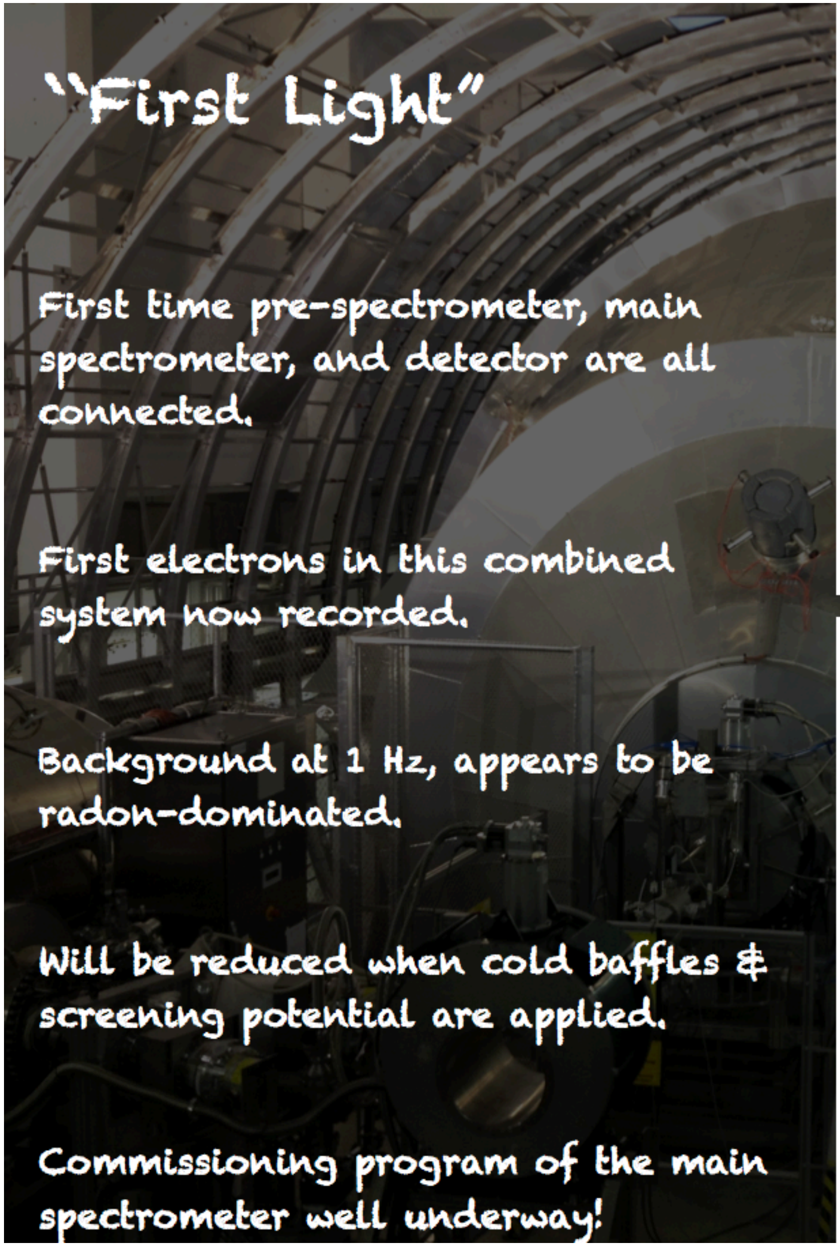
- Detector:
  - Gaseous Tritium Source (^3H decay, $t_{1/2}$=12.3 y, Q=18.57 keV)
  - 10 m diameter Magnetic Spectrometer (MAC-E Filter)

- Status: commissioning detector components. Data in 2015

- 90% C.L sensitivity : 0.2 eV



KATRIN First Light



"First Light"

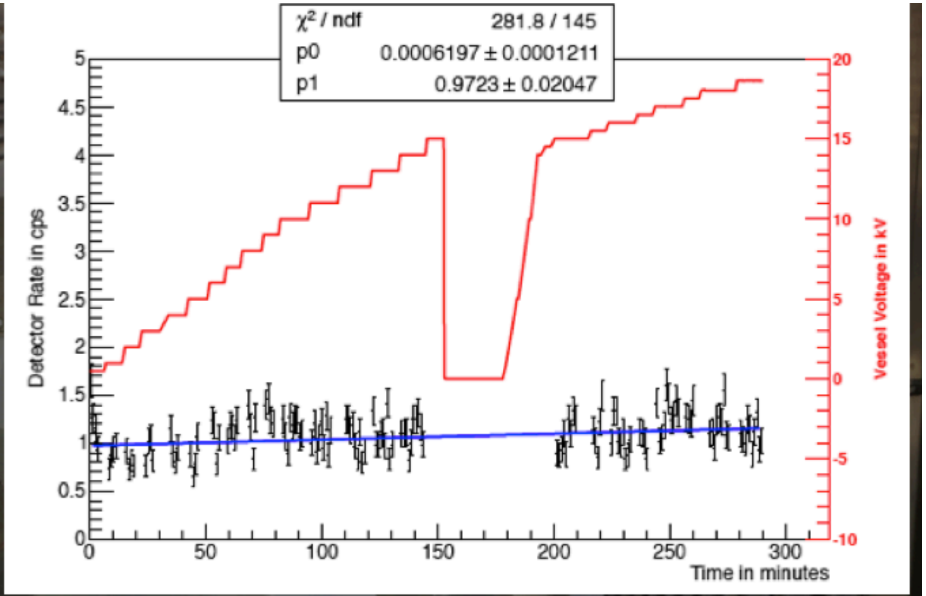
First time pre-spectrometer, main spectrometer, and detector are all connected.

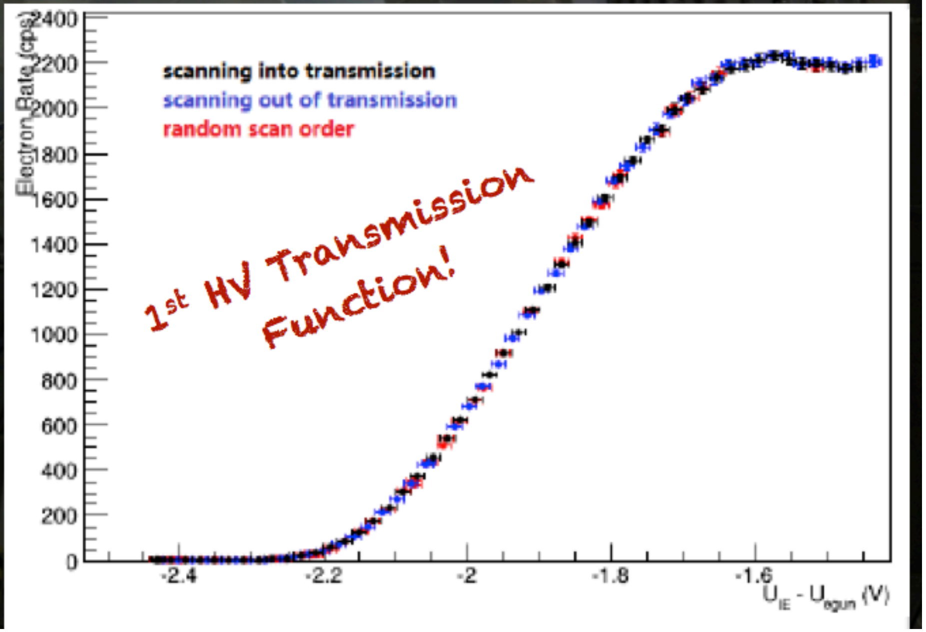
First electrons in this combined system now recorded.

Background at 1 Hz, appears to be radon-dominated.

Will be reduced when cold baffles & screening potential are applied.

Commissioning program of the main spectrometer well underway!

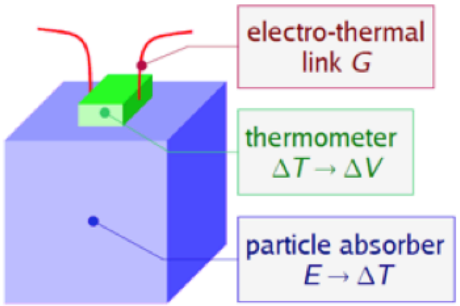


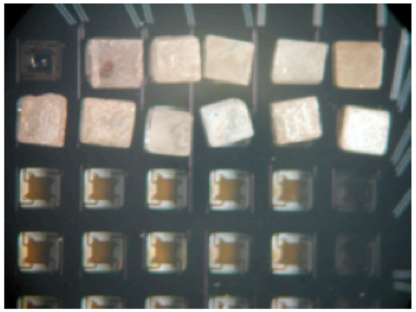


1st HV Transmission Function!

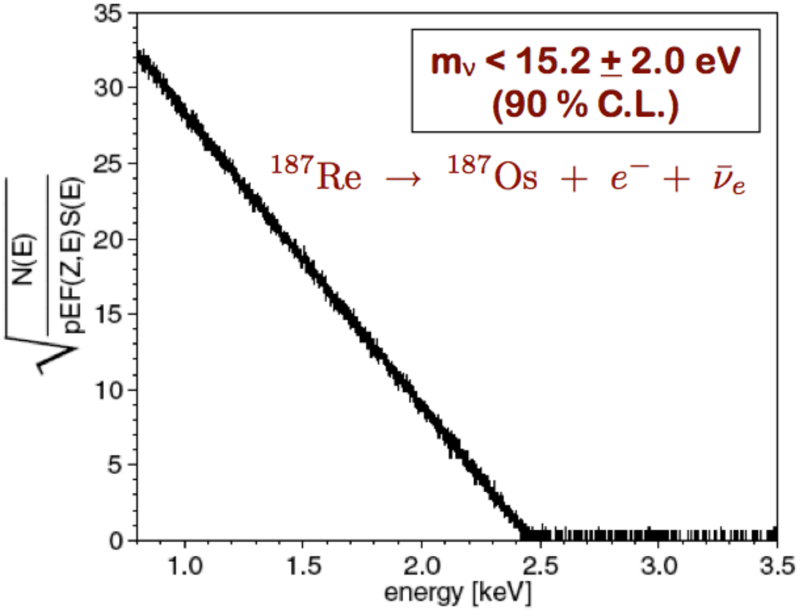
Calorimetric Thechniques

Calorimetry





$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^- + \bar{\nu}_e$$



$m_\nu < 15.2 \pm 2.0$ eV (90 % C.L.)

$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^- + \bar{\nu}_e$$

Phys. Rev. Lett. 91 161802 (2003)

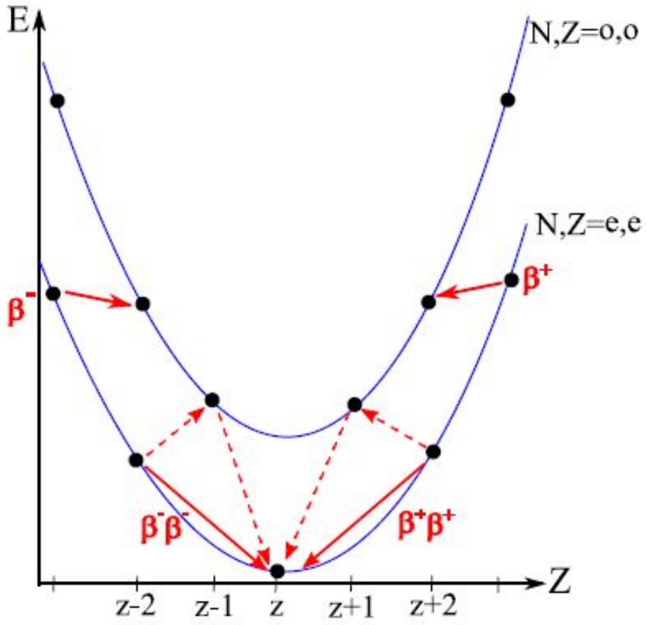
- The use of low temperature calorimetry for beta decay has focused on isotopes with the lowest endpoint energy.
- Particularly, ^{187}Re as beta source (one of the lowest endpoints, 2.3 keV).
- More recently, ^{163}Ho electron capture (De Rujula and Lusignoli, 1982) has been the subject of R&D over the past several years.

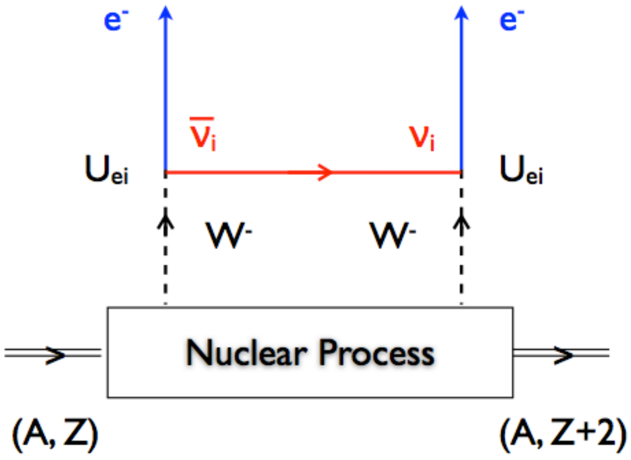
Question 5)

Is there a conserved Lepton Number? Eq. Dirac or Majorana ν ?

Double Beta Decay (ββ)

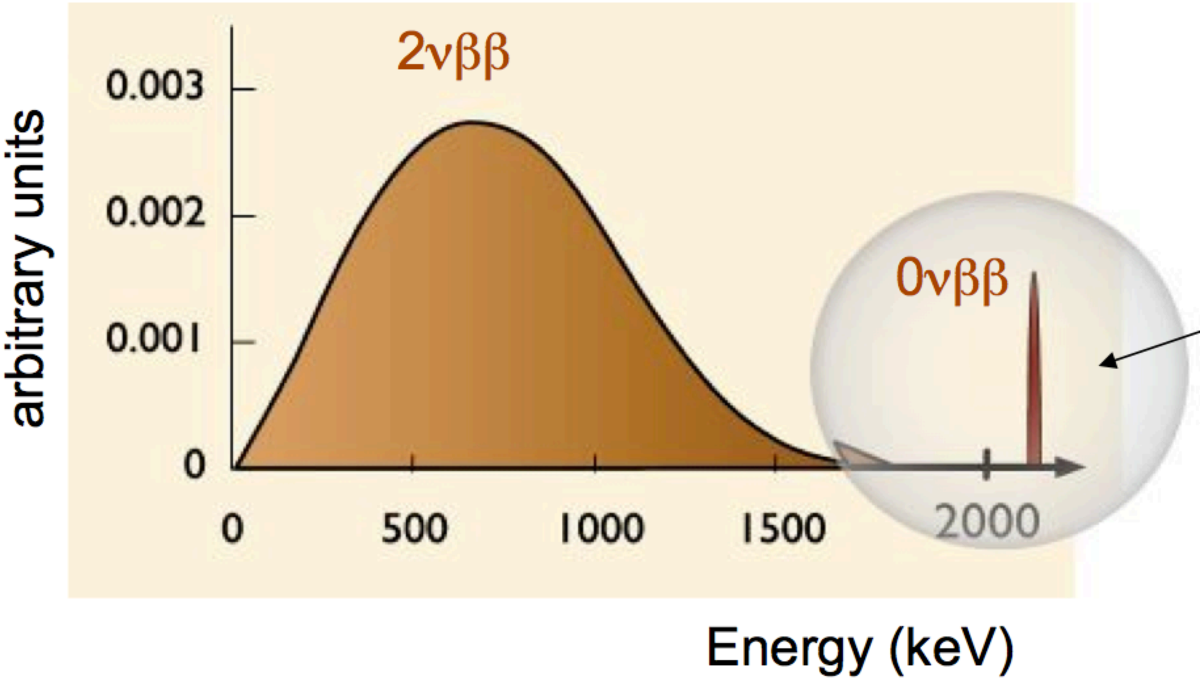
- Second-order process only detectable if first-order β decay is energetically forbidden
- **2ν:** ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-} + 2\overline{\nu}_{e}$ **(detected)**
  - ΔL=0
  - $\left(T^{2\nu}_{1/2}\right)^{-1} = G_{2\nu}\left|M_{2\nu}\right|^{2} \approx 10^{18-21}\mathrm{y}$
- **0ν:** ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-}$ **(not yet seen)**
  - ΔL=2 – Majorana Neutrino
  - $\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu}\left|M_{0\nu}\right|^{2}\left|m_{\beta\beta}\right|^{2}$
- **ββ mass:** $\left\langle m_{\beta\beta}\right\rangle = \left|\sum_{1,2,3,..} U_{ei}^{2} m_{i}\right|$





2v0β: experimental signature

- Peak at $Q = E_{e1} + E_{e2} - 2m_e$ → Calo (Gerda, KamLAND-Zen)
- Two electrons from same vertex → Tracking (Super Nemo)
- Production of grand-daughter isotope → EXO



[Candidates with Q>2 MeV]

Candidate	Q[MeV]	%Abund
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.530	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

Detector Efficiency
Isotopic Fraction
Detector Mass
Running Time

$$T_{1/2}^{0\nu} \propto \epsilon \frac{a}{A} \sqrt{\frac{Mt}{b\Delta E}}$$

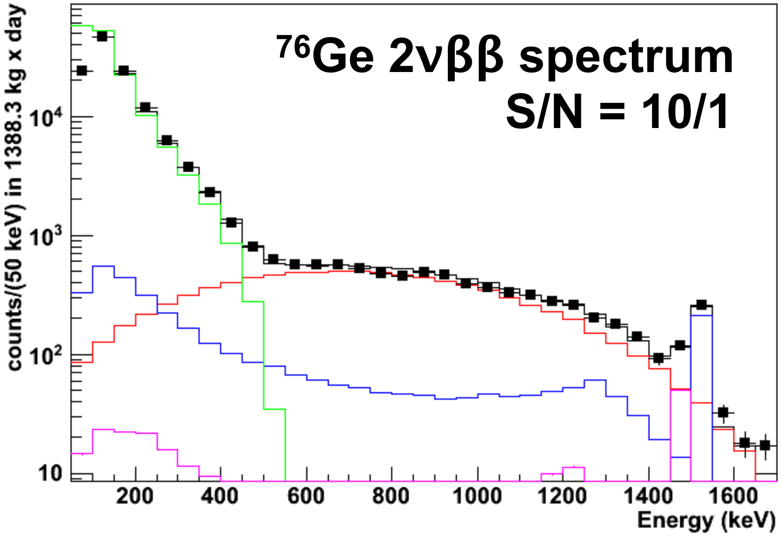
Atomic Mass
Background Rate
Detector Resolution

GERDA at LNGS

- Target: ^{76}Ge
  - Low $2\nu\beta\beta$ rate ($T_{1/2}=1.4\times10^{21}$ y)
  - High $Q_{\beta\beta}$ value (2039 keV)

- Detector: high purity ^{76}Ge-diodes (source & detector) in Lar as shielding and coolant

- Status (Phase 1):
  - 21.6 kg·yr of exposure since 2011
  - Bkg 10^{-2} counts/(keV·kg·yr)
  - → Factor 10 bkg reduction wrt HDM
  - Blind analysis, no positive signal



- Future (Phase 2):
  - Factor 10 bkg reduction by LAr scintillation and novel HP-Ge detectors

GERDA & Klapdor Claim

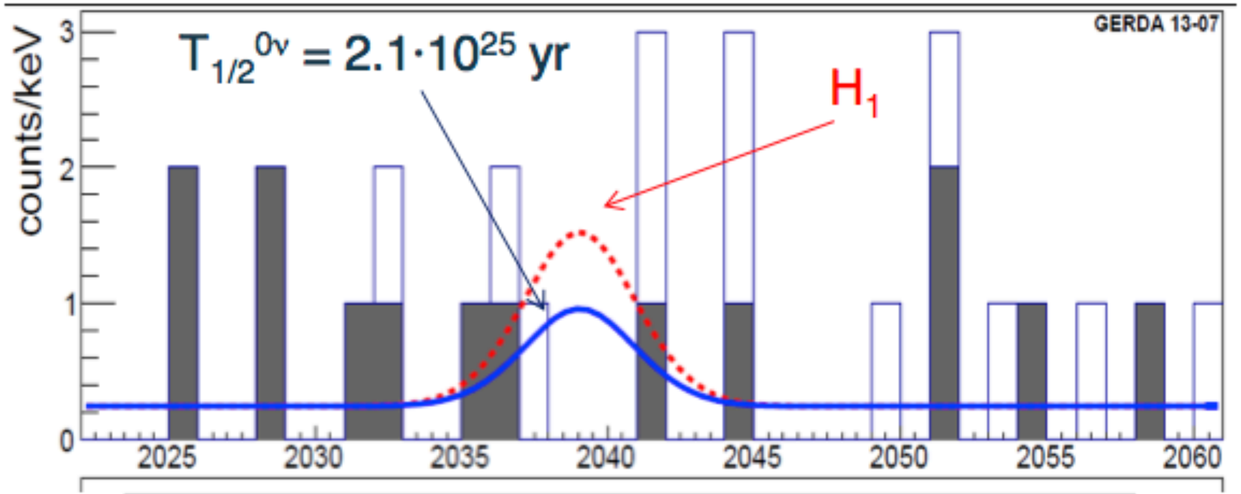
Comparison with Phys. Lett. B 586 198 (2004) claim

- Compare **two hypotheses**
  - **H**$_1$: $T_{1/2}^{0\nu} = 1.19^{+0.37}_{-0.23}\cdot 10^{25}$ yr (*) vs. **H**$_0$: background only

Expected Signal (w/ PSD): (5.9 ± 1.4) cts in ±2σ

Expected Bckgd (w/ PSD): (2.0 ± 0.3) cts in ±2σ

Observed: **3.0** in ±2σ (0 in ±1σ)



Claim strongly disfavoured

GERDA only:

Profile likelihood:

P (N$^{0\nu}$=0|H$_1$)=0.01

Bayes factor

P(H$_1$)/P(H$_0$)=0.024

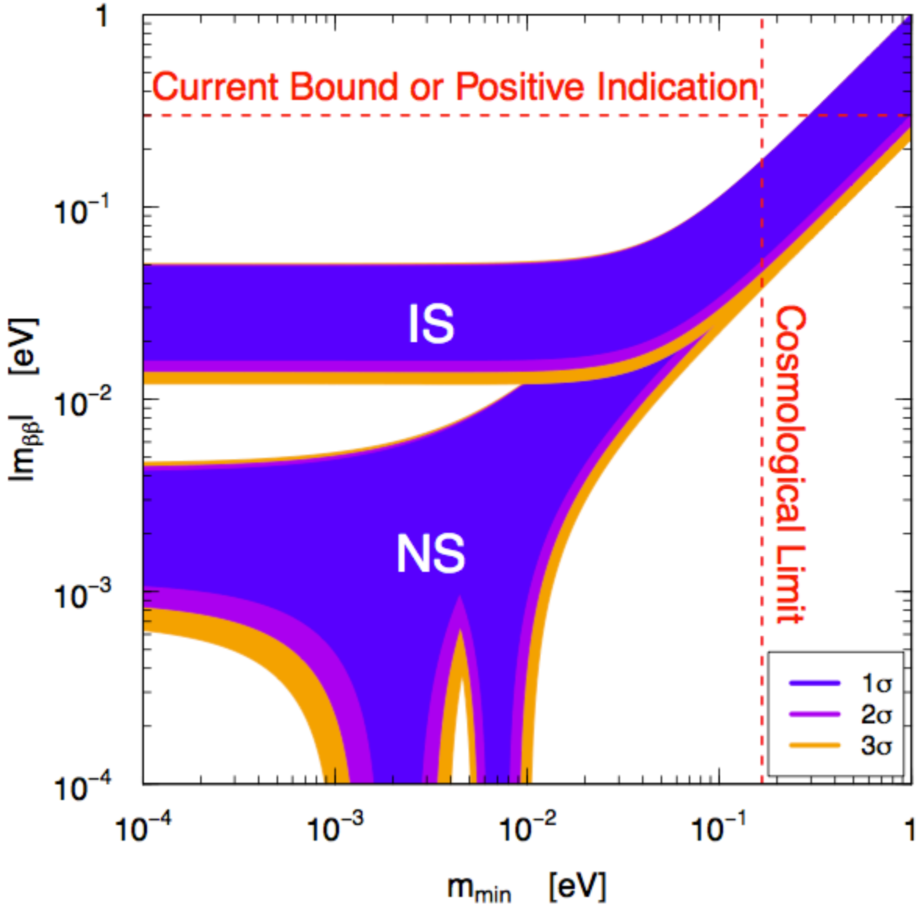
GERDA+HdM+IGEX:

Bayes factor

P(H$_1$)/P(H$_0$)=0.0002

Prospect of ββ0ν

- 1- Test the ^{76}Ge Claim – $m_{\beta\beta} \approx 100$ meV → ongoing
  2- Test the IH scheme - $m_{\beta\beta} \approx 10$ meV
  3- Need new ideas / technology - $m_{\beta\beta} \approx 1$ meV ?



- ββ0ν implications
  - ν = Majorana
  - L number violation
  - Credit to See-Saw mass generation mechanisms

Th. Lasserre – Neutrino Summary 2013

Question 5)

Are there additional (sterile) ν states?

Anomalous & Regular Results

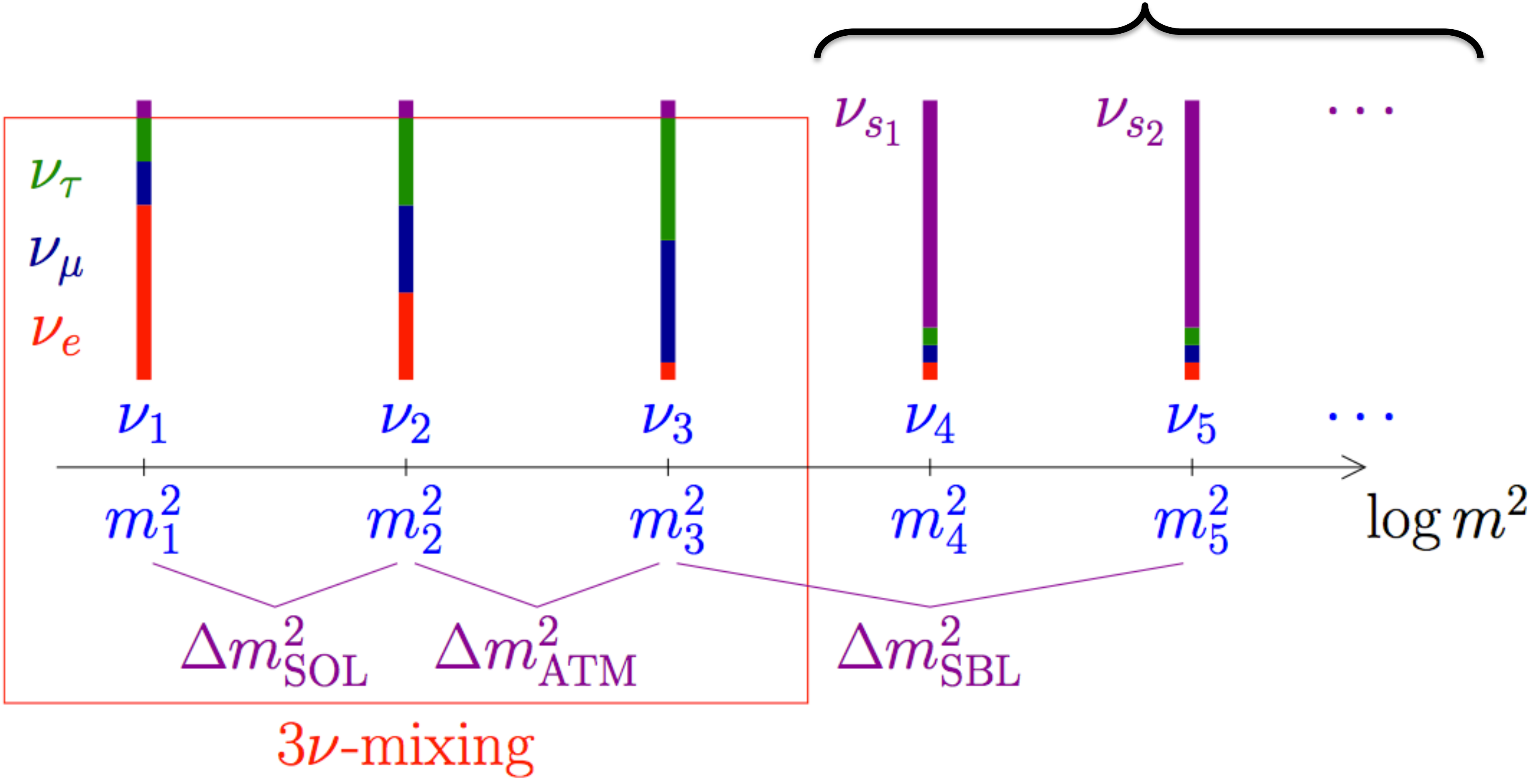
Anomalous	Source	Type	Signal	Channel	Significance
LSND	Meson Decay-at-Rest	$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	Total Rate, Energy	CC	3.8 σ
MiniBooNE	Meson Decay-in-Flight	$\nu_\mu \rightarrow \nu_e$	Total Rate, Energy	CC	3.8 σ
Gallium	Electron Capture	ν_e dis.	Total Rate	CC	2.7-3.0 σ
Reactor	Beta-decay	ν_e dis.	Total Rate, Energy	CC	2.7 σ

Regular	Source	Type	Signal	Channel
KARMEN Icarus/Opera	Meson Decay - at-Rest & Flight	$\nu_\mu \rightarrow \nu_e$	Total Rate, Energy	CC
CDHS/ MiniBooNE	Meson Decay-in-Flight	$\nu_\mu \rightarrow \nu_\mu$	Total Rate, Energy	CC
Minos	Meson Decay-in-Flight	$\nu_\mu \rightarrow \nu_s$	Total Rate	CC

The (light) sterile neutrino hypothesis

Add a light ν_R to SM, no SM interaction but mixing with active ν' s

No coupling with Z boson (LEP)



Th. Lasserre – TAUP 2013

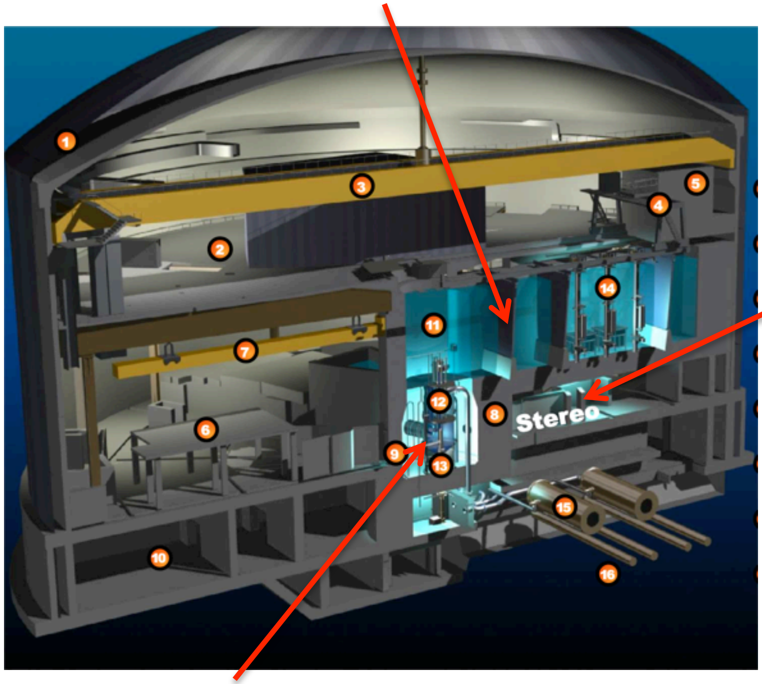
Reactor ν Proposals

Experiment Type	Projects	P_{Th}	M_{det}	L	Depth
Mature Gd-doped LS detector Technology	Nucifer (FRA)	70 MW	0.7 tons	7 m	Few mwe
	Stéréo (FRA)	50 MW	2 tons	[8-11] m	10 mwe
	Neutrino 4 (RU)	100 MW	2 tons	[6-12] m	Surf.
Highly segmented detector for background reduction	DANSS (RU)	1 GW	1 ton	[10-12] m	50 mwe
	SoLid (UK)	45-80 MW	3 tons	8 m	10 m
Enhanced neutron Tagging					
	Hanaro (KO)	30 MW	0.5 t	6 m	Few mwe
2 detector complex or Moving detector	US project	20-120 MW	-	4m & 15m	Surf.
	China project	-			
	DANSS/Neutrino4	Movable detector			

Stéréo @ ILL *(Gd-LS)*

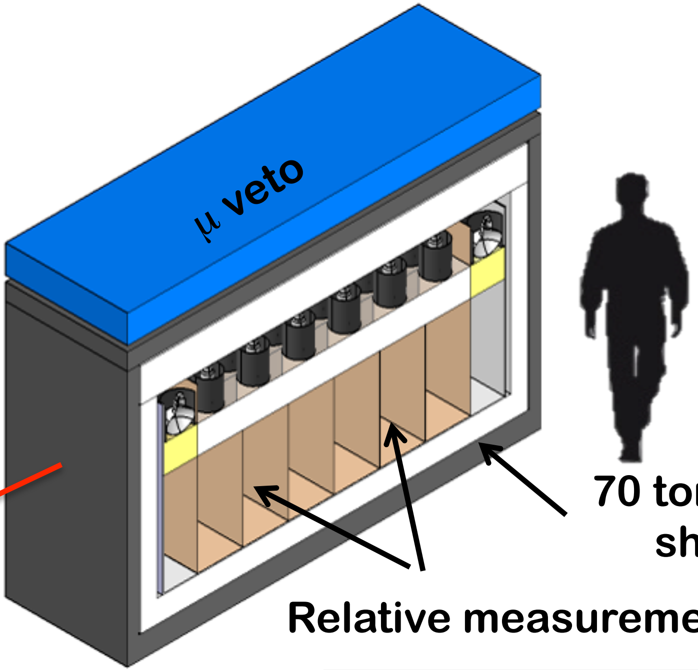
Start Data Taking in 2015

factor 4 attenuation of vertical flux
from water pool



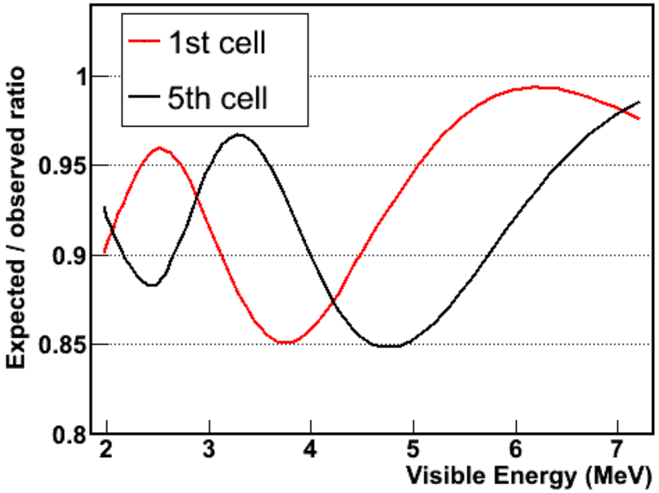
50 MW core
h=80cm, Φ=40cm

[8.5-11] m
baseline range



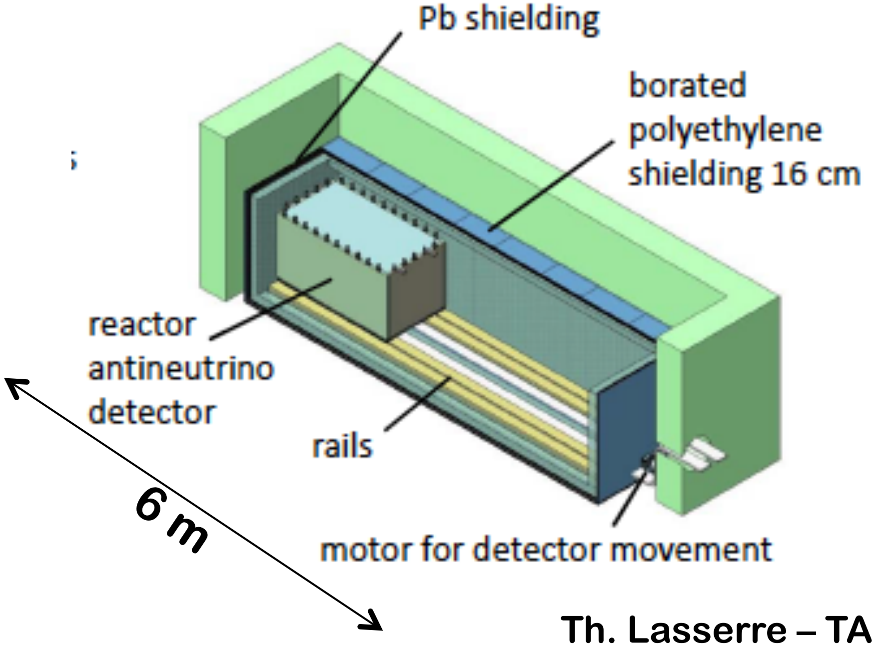
70 tons γ and n
shielding

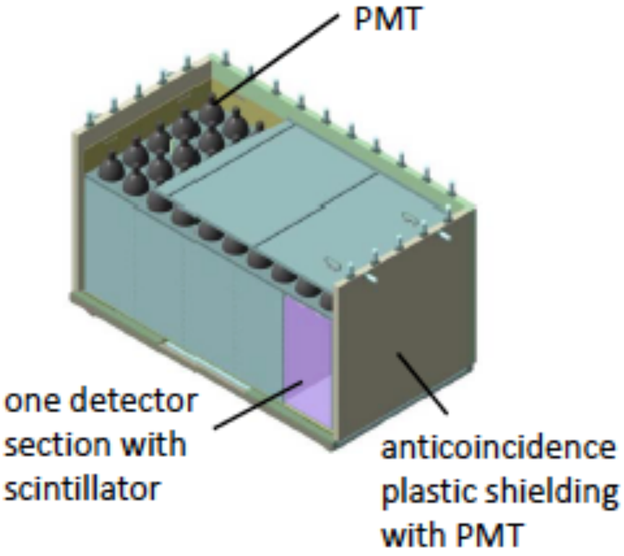
Relative measurement in 6 cells



Neutrino-4 @ SM3 *(Gd-LS)*

- 2.5 m^3 LS target, 5 section movable detector [6-12] m
- 100 MW compact core
- Detector at Surface
- Status:
  - Shielding integrated
  - Start in 2015

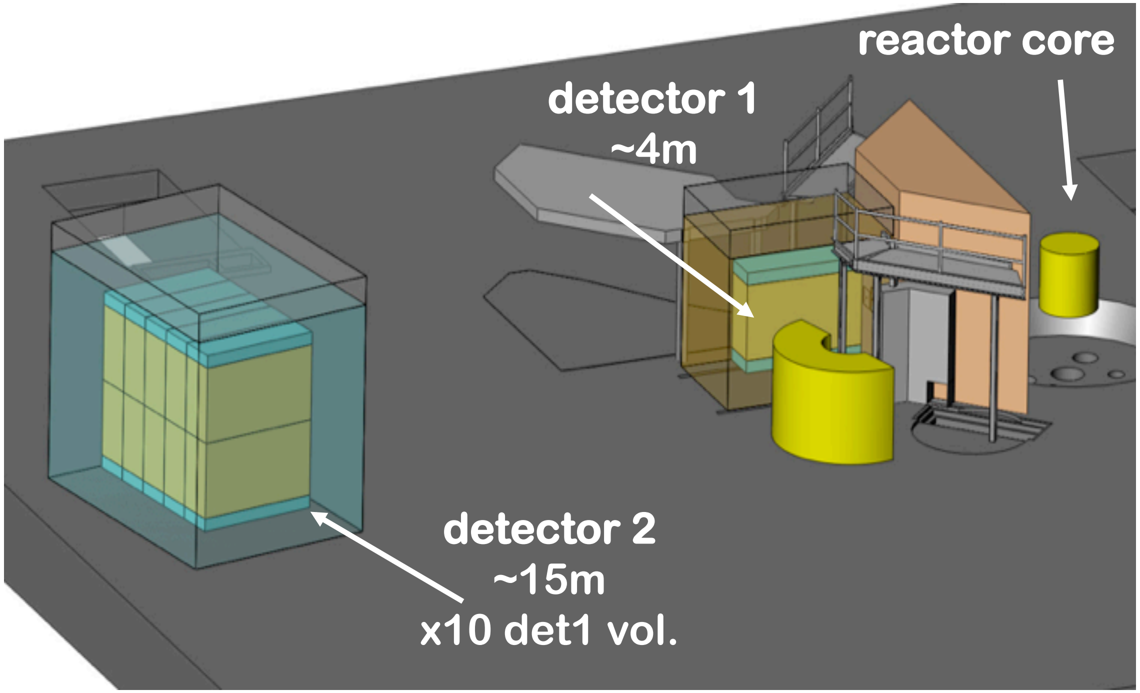


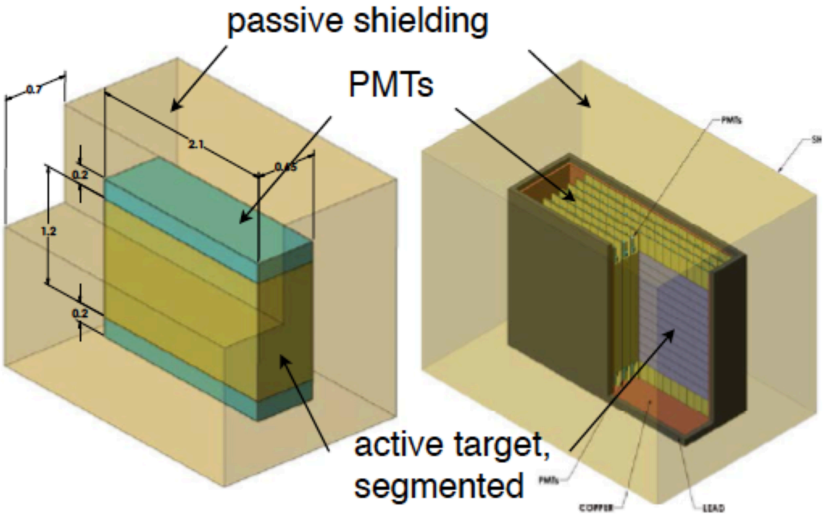


Th. Lasserre – TAUP 2013

US effort: 2-Detector Oscillation

- LS target based technology
- 3 reactor sites
  - NIST – 20 MW
  - ATR – 85 MW
  - HFIR – 120 MW
- Surface location
- 2-detector concept
- Status:
  - Site characterization ongoing
  - Start 2016?

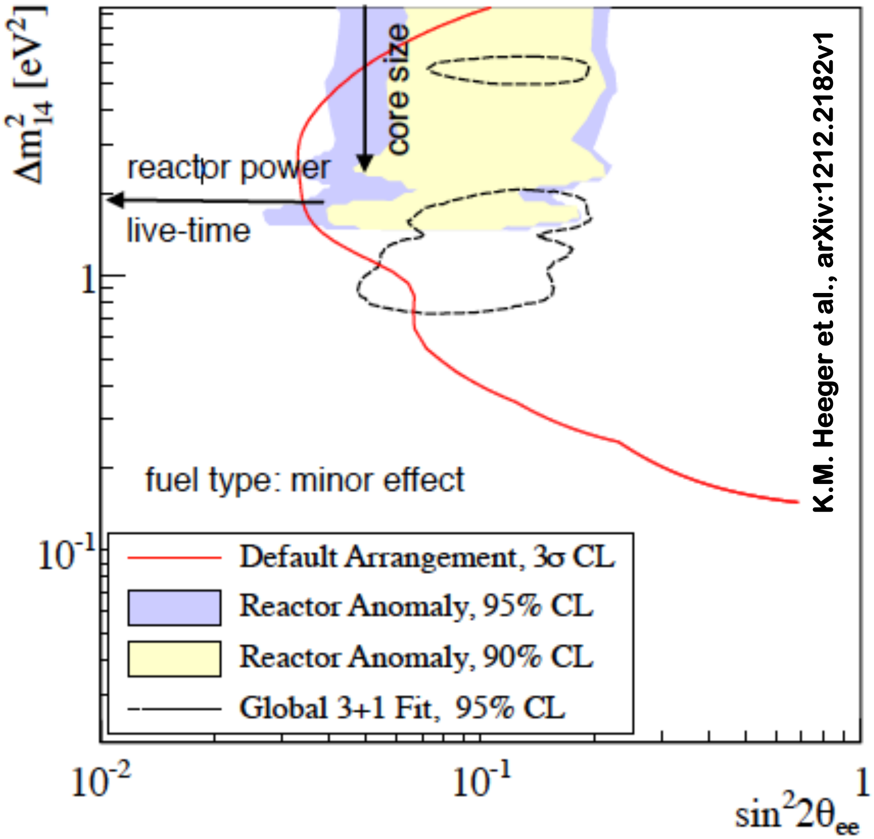




Influence of Source/Detector Parameters

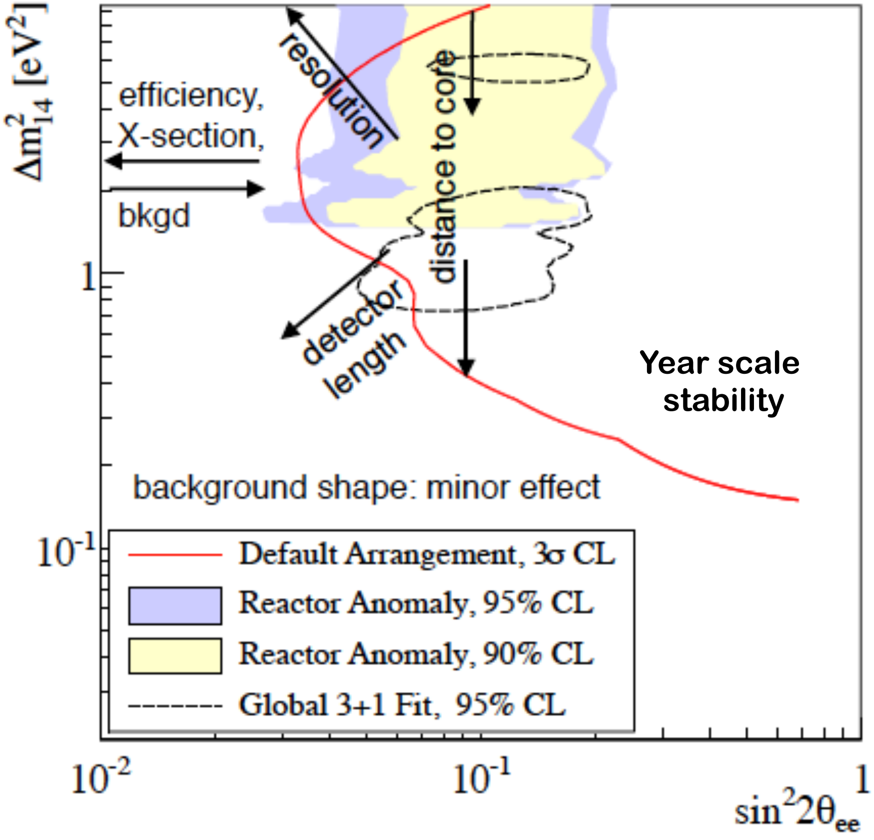
All current project have the sensitivity to test the reactor anomaly space of parameters, Δm²>0.1, sin²2θ>0.05

Source



K.M. Heeger et al., arXiv:1212.2182v1

Detector

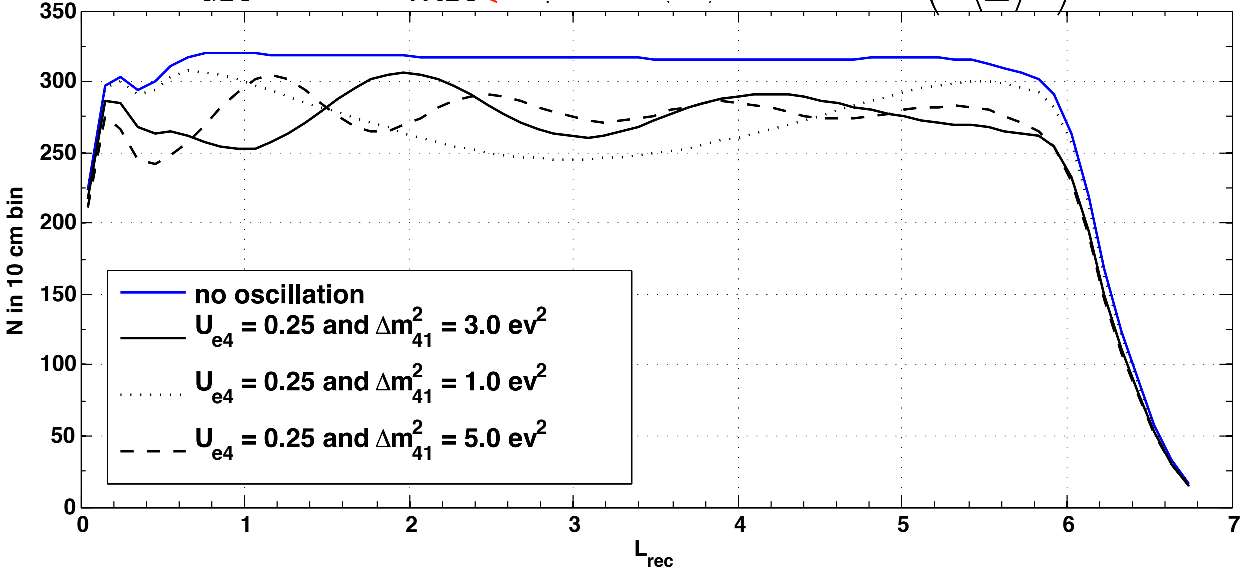


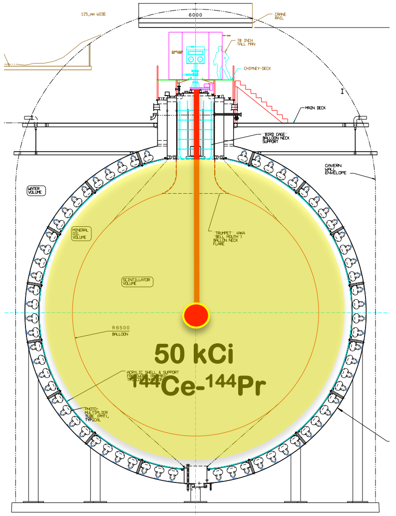
ν Generator Proposals

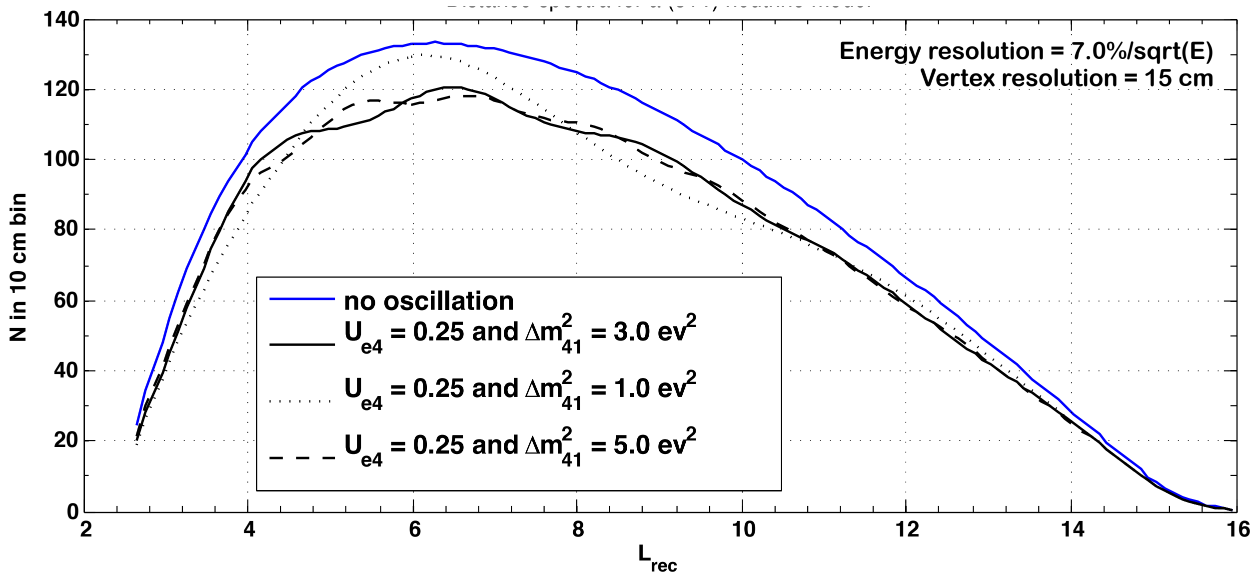
Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	$\nu_e e \to \nu_e e$ 5% E_{res} 15cm R_{res} or Radio-chemical	Detector Radioactivity Solar ν (irreducible) ν generator impurities	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	>3 MCi	Sage LENS
					>10 MCi	SOX (SNO+)
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	>1 MCi	-
					5 MCi	Ricochet
$\bar{\nu}_e$	$\bar{\nu}_e p \to e^+ n$ E_{th}=1.8 MeV (e^+,n) 5% E_{res} 15cm R_{res}	reactor ν, geo ν, ν generator impurities	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing + REE extraction	75 kCi	CeLAND SOX
					500 kCi	Daya-Bay
			^{90}Sr ^{106}Rh		-	-
	$^3H \to He\ \underline{e^-}\ \bar{\nu}_e$ EC/β-decay	Kink search	^3H E<18 keV	Irradiation in reactors	3 Ci	KATRIN (Mare/Echo)

Search for $\bar{\nu}_e \rightarrow \bar{\nu}_s$ with ^{51}Cr/^{144}Ce

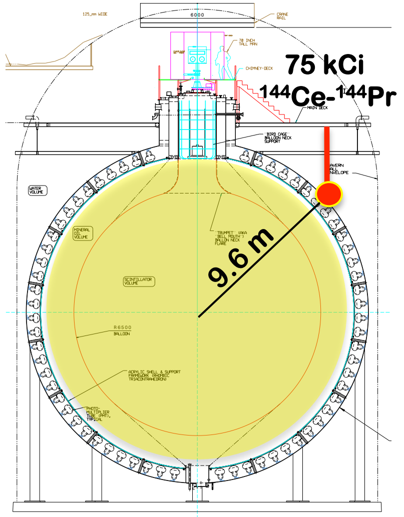
$$\frac{dN}{dR}(R,t) \propto \frac{A(t)}{\cancel{4\pi R^2}} \times \langle\sigma\rangle \times N_p \times \cancel{4\pi R^2} \times P_{ee}\left(\frac{\Delta m^2 R}{\langle E\rangle}\right)$$







Energy resolution = 7.0%/sqrt(E)
Vertex resolution = 15 cm



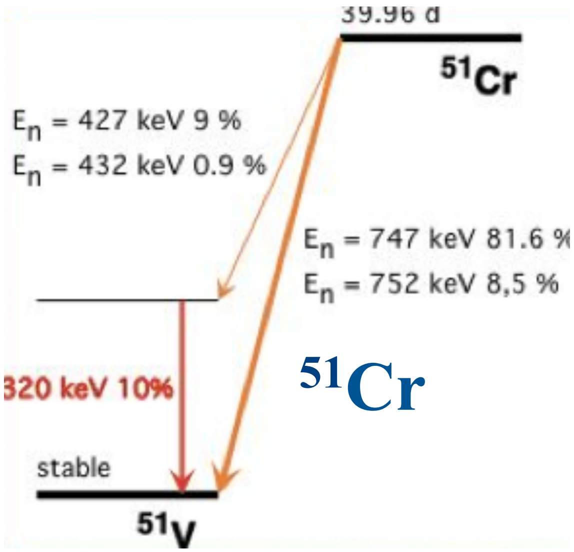
^{51}Cr neutrino generator

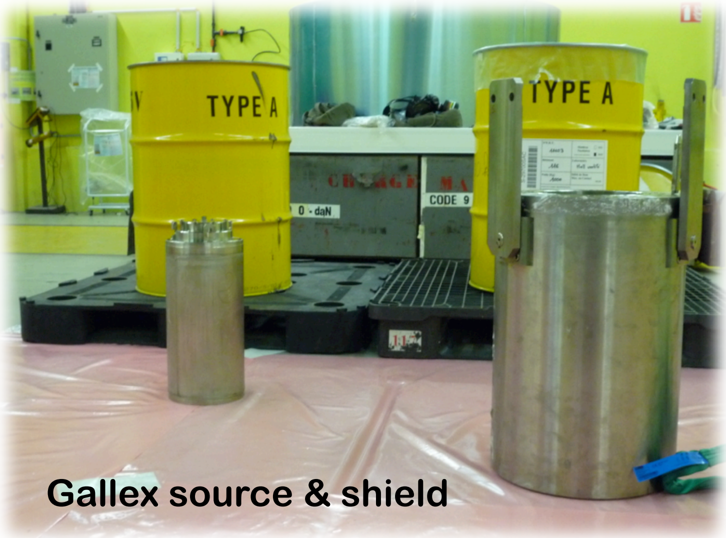
- **^{51}Cr EC**
  - E = 0.75 MeV
  - $t_{1/2}$ = 26 days

- **Production** through n_{th} irradiation of enriched ^{50}Cr in a nuclear reactor

- **Need 10 MCi ^{51}Cr**
  - 2 MCi in Gallex/Sage

- **Detection:**
  - $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$
  - ν scattering off electrons





Gallex source & shield

^{51}Cr: SOX (Borexino)

- Re-use **Gallex 36 kg** of enriched chromium

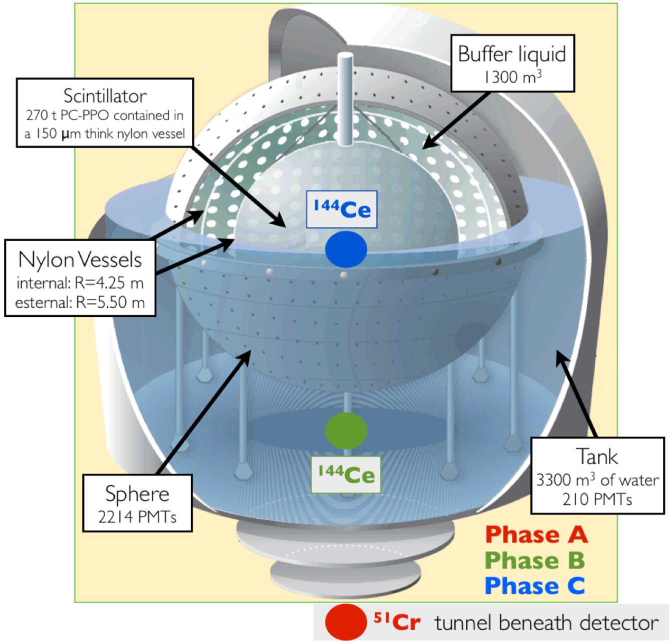
- Production reactors
  - Oak Ridge (US)
  - Ludmila (Ru)

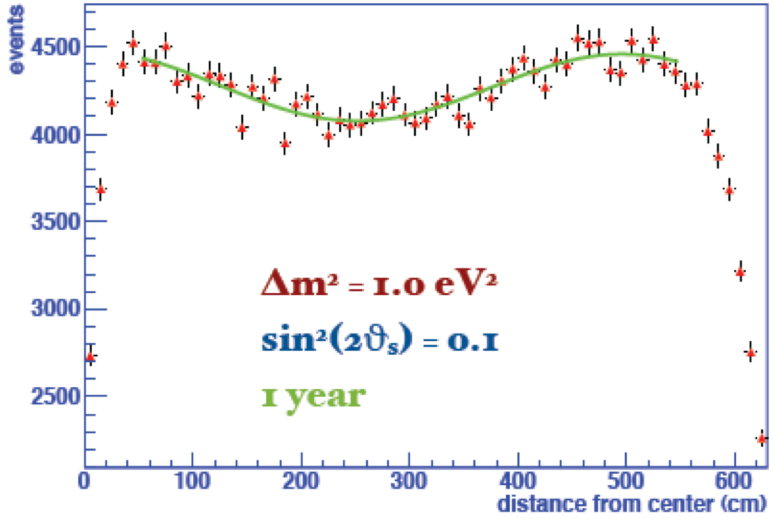
- Source **8.25 m** from center

- **Detection as for ^{7}Be solar ν**
  - Well known background

- Status:
  - Preparation for irradiation and transportation (10 MCi)

- Staged approach: ^{51}Cr & ^{144}Ce

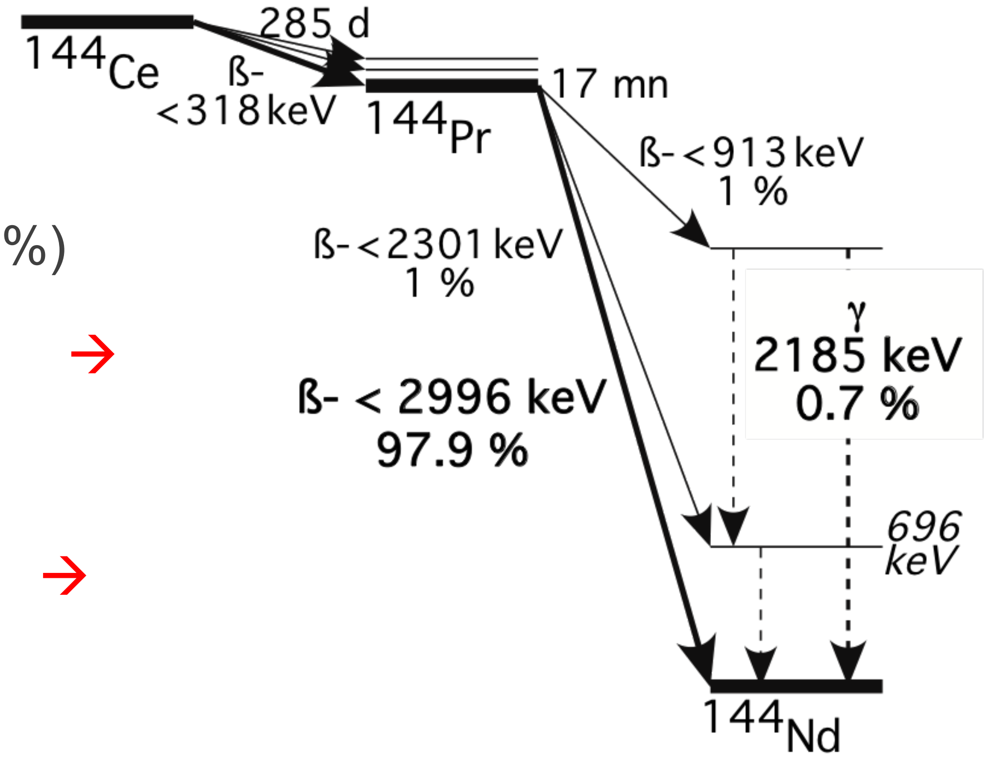




^{144}Ce-^{144}Pr $\bar{\nu}$ generator

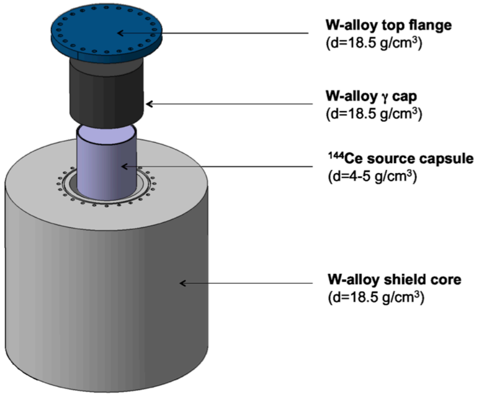
- 1^{st} **Trick: $\bar{\nu}_e$ source detected via $\bar{\nu}_e + p \rightarrow e^+ + n$ (Thr=1.8 MeV)**
  - **High IBD cross section → 75 kCi activity**
  - **(e^+,n) detected in coincidence → Strong background reduction**

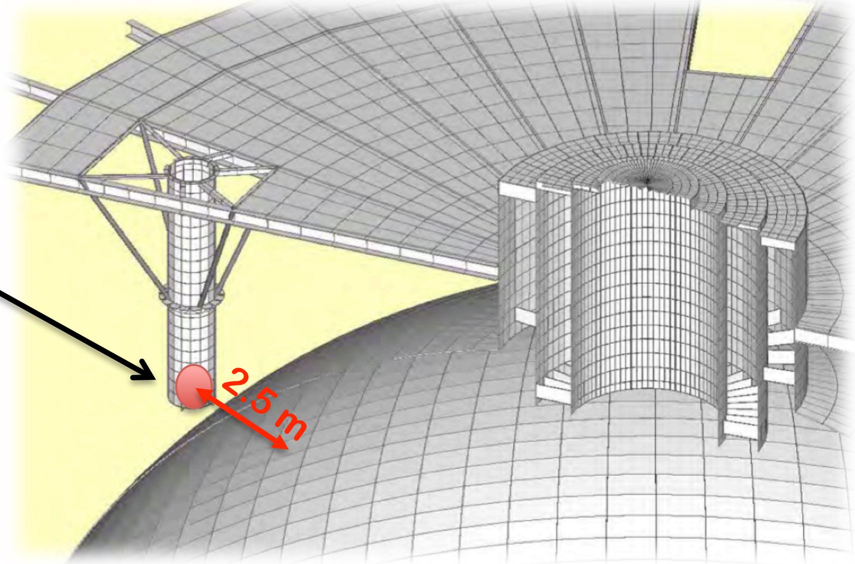
- 2^{nd} Trick: **^{144}Ce-^{144}Pr**
  - Abundant fission product (5%)
  - ^{144}Ce: long-lived & low-Q_β → Enough time to produce, transport, use
  - ^{144}Pr: short-lived & high-Q_β → $\bar{\nu}_e$-emitter above threshold



^{144}Ce-^{144}Pr: CeLAND (KamLAND)

- 75 kCi of ^{144}Ce-^{144}Pr (CeO_2)
- Production feasible at Mayak Facility (RU) in 2014 (1 y)
    - Standard SNF reprocessing
    - Ce extraction through displacement chromatography
- Need 16 cm tungsten-shield
- KamLAND being prepared
    - Deployment
        - in water veto (3-16 m)
        - In Xenon Room (5-18 m)
    - Run in // with KamLAND-zen
- Deployment in 2015



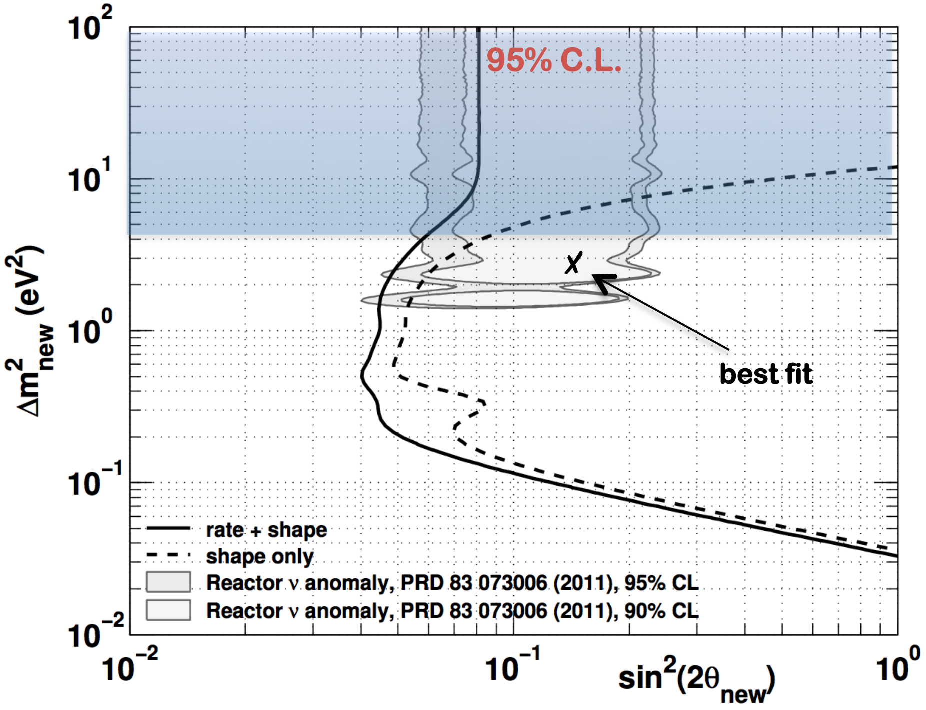


ν-Generator sensitivities

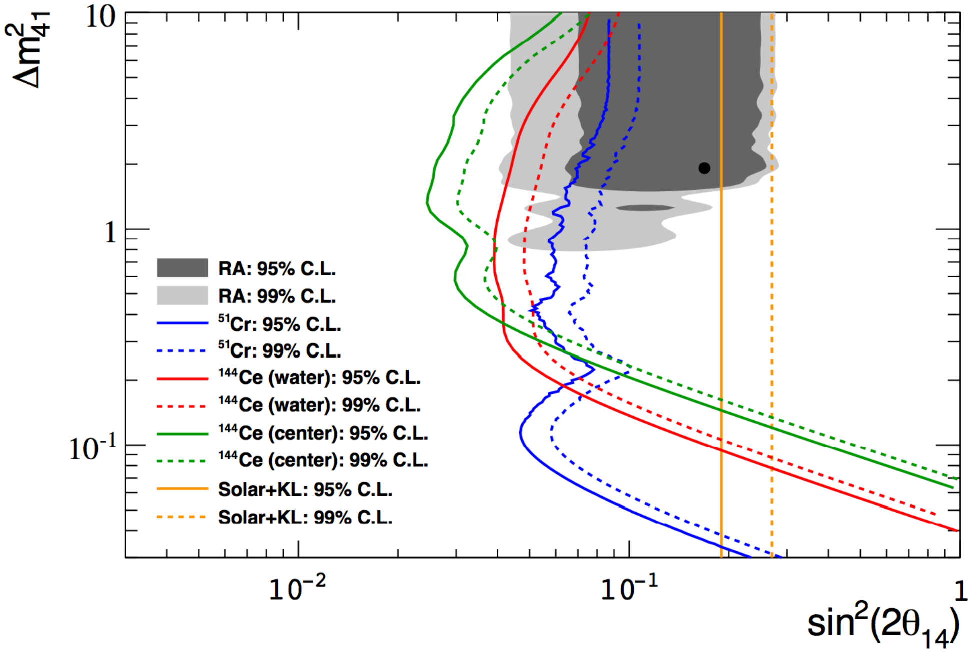
CeLAND (KamLAND)

SOX (Borexino)

75 kCi ^{144}Ce-^{144}Pr – 9.3 m from detector center – 1.5 y



^{51}Cr@8.25 m , ^{144}Ce-^{144}Pr @7.5 m - ^{144}Ce-^{144}Pr inside



Data Taking Goals

^{144}Ce-^{144}Pr in 2015

^{51}Cr in 2015
^{144}Ce-^{144}Pr in 2016/7

Search for ν_s with ^{3}H β decay

- **Source:** $^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + e^{-} + \overline{\nu}_{e}$
- β spectrum shape depends on:

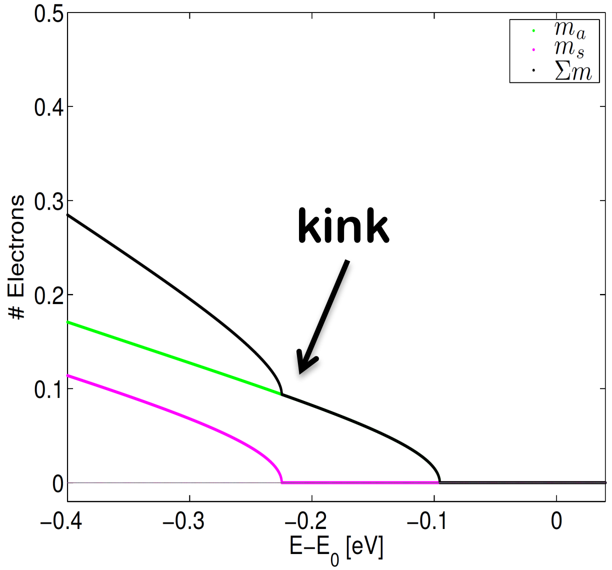
$$\langle m_\beta \rangle = \sqrt{\sum_{1,2,3,..} |U_{ei}|^2 m_i^2}$$

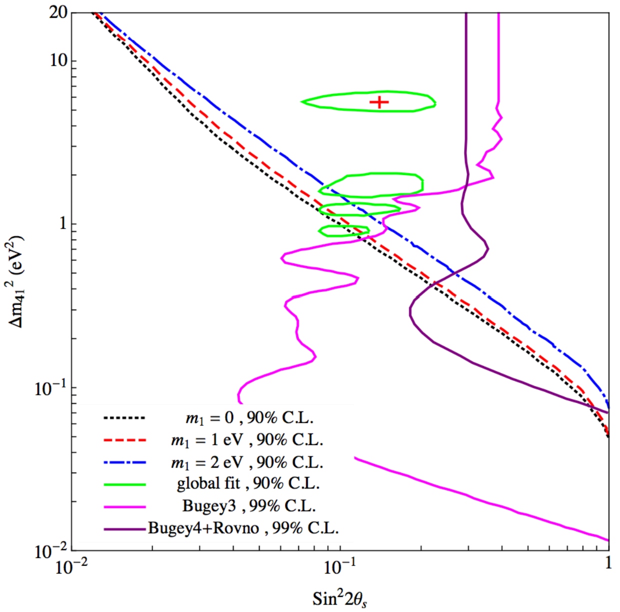
- Hypothetical 4th ν contribution

$$\langle m_\beta \rangle_4 = |U_{e4}| \sqrt{\Delta m^2_{41}}$$

→Search for a kink few eV below end point

- KATRIN –as designed- can test the ν_e disappearance anomalies





ν Beam Proposals

Type	Source	App. /Dis.	Oscillation Channels	Projects
Isotope Decay at Rest	$p + {}^{9}Be \rightarrow {}^{8}Li + 2p$ $n + {}^{7}Li \rightarrow {}^{8}Li$ ${}^{8}Li \rightarrow {}^{9}Be + e^{-} + \bar{\nu}_e$	Dis.	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	IsoDAR
Pion (Kaon) Decay at Rest	$\pi^+ \rightarrow \mu^+ \nu_\mu$ $\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$	App. & Dis.	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	OscSNS, DAEδALUS, KDAR
Pion Decay in Flight	$\pi^+ \rightarrow \mu^+ \nu_\mu$ $\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$	App. & Dis.	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_\mu$ $\nu_e \rightarrow \nu_e$	MINOS+, MicroBooNE, LAr1kton Icarus/Nessie
Low-E Neutrino Factory	$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$	App. & Dis.	$\nu_e \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_e$	ν STORM

Question 6)

Do the behavior of ν violate CP?

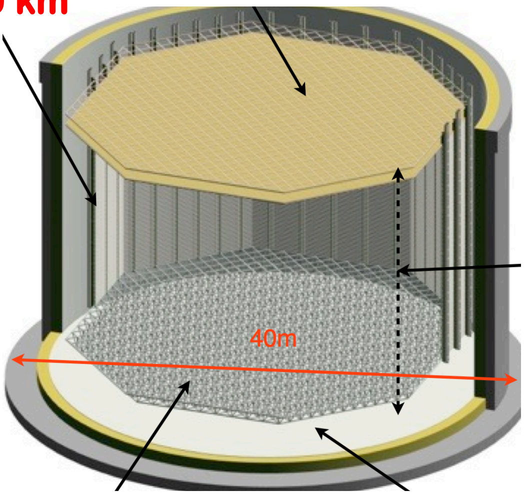
Towards CP-violation Search

$$\left.\begin{aligned} P(\nu_e \rightarrow \nu_\mu) &= |A|^2 + |S|^2 + 2\,A\,S\,\sin\delta \\ P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) &= |A|^2 + |S|^2 - 2\,A\,S\,\sin\delta \end{aligned}\right\} \quad A_{CP}\ \alpha\ \frac{P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}{P(\nu_e \rightarrow \nu_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}$$

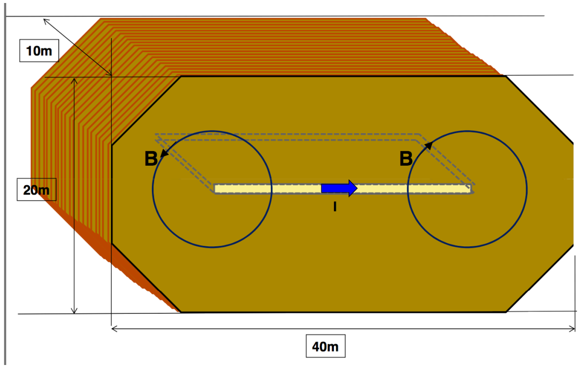
$$A_{CP} = \frac{2\,AS\,\sin\delta}{|A|^2 + |S|^2} = \frac{\sin(\Delta m^2_{12}\,L/4E)\,\sin\theta_{12}\,\sin\theta_{13}\,\sin\delta}{\sin^2 2\theta_{13} + \text{solar term...}}$$

MH & CPV: long term projects

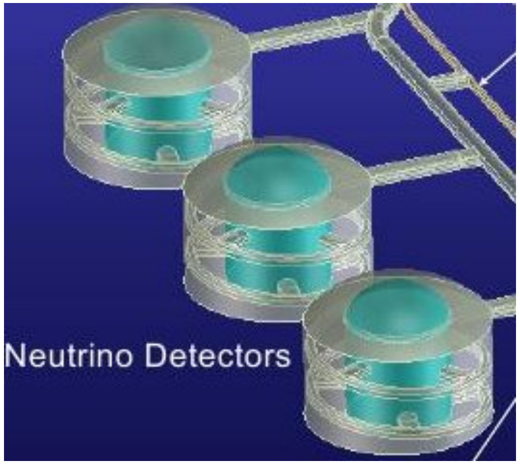
L=2300 km



LBNO (Europe, underground)
20-100 kt LAr +
Magnetic Spectrometer

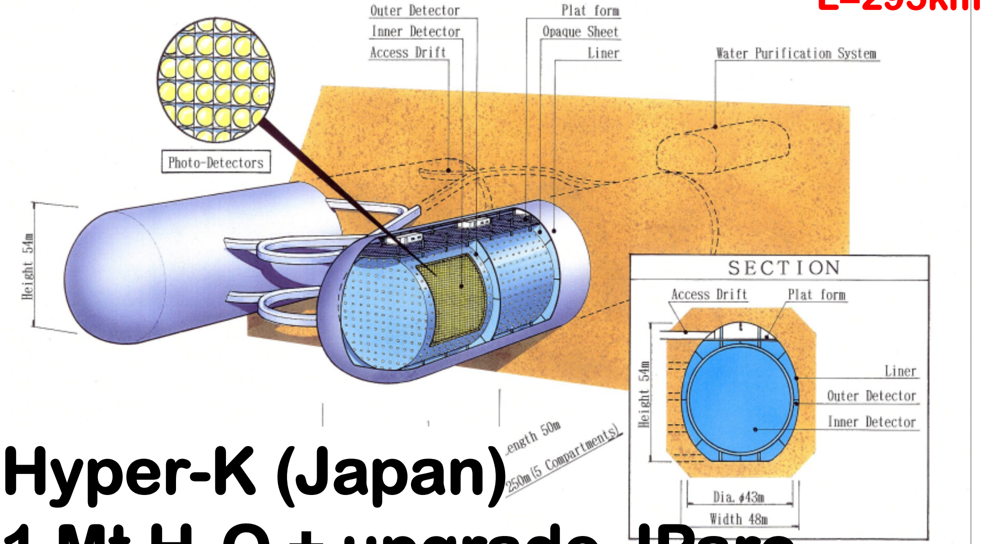


L=1300 km



LBNE (US)
10 kt LAr
(surface)
To be Upgraded

L=295km



Hyper-K (Japan)
1 Mt H_2O + upgrade JParc

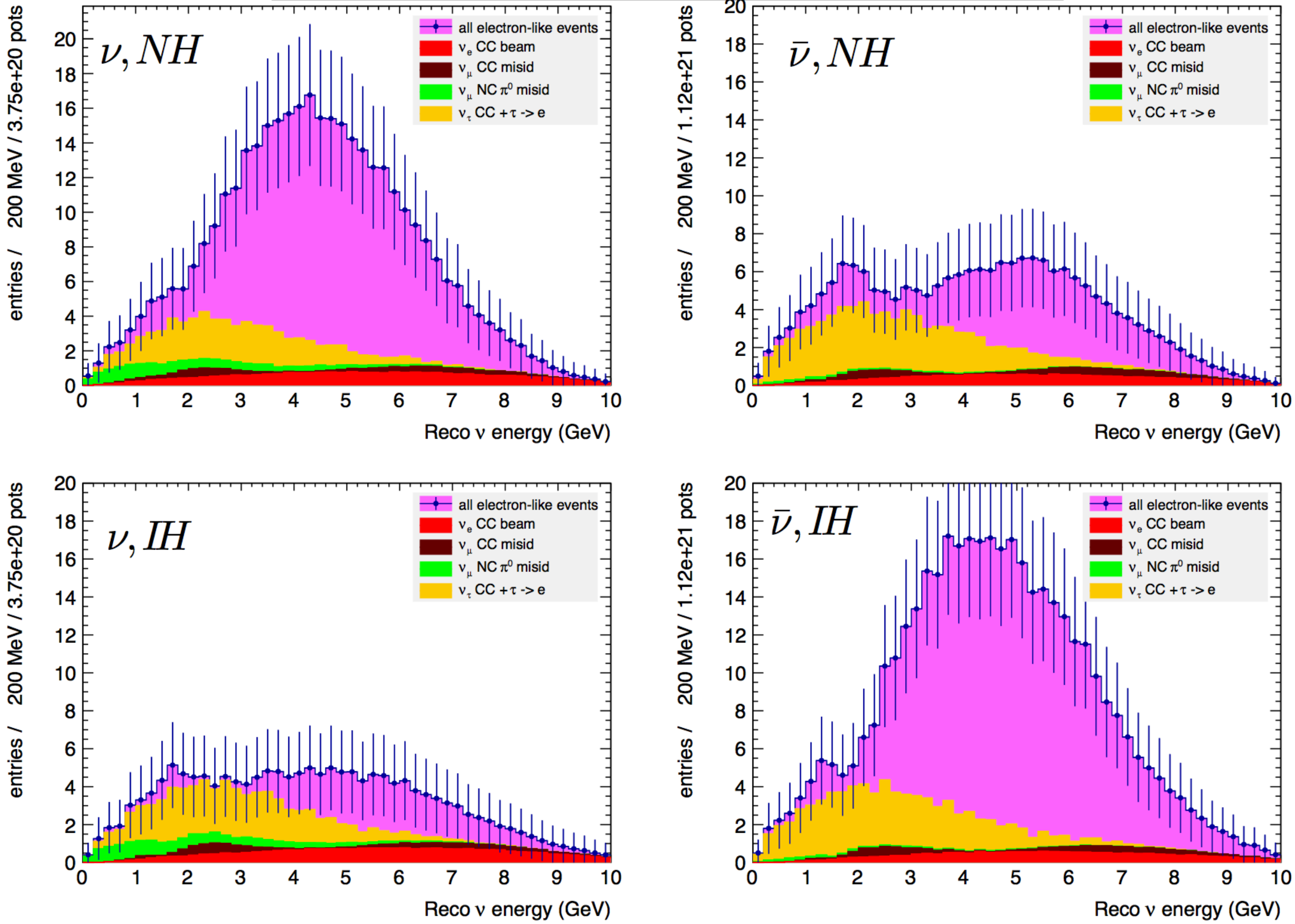
LBNO: Mass Hierarchy ($\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$)

Excellent prospect – Earliest schedule for 5σ : 2026 (start + 3 years)

Detector response and resolution included

Running m

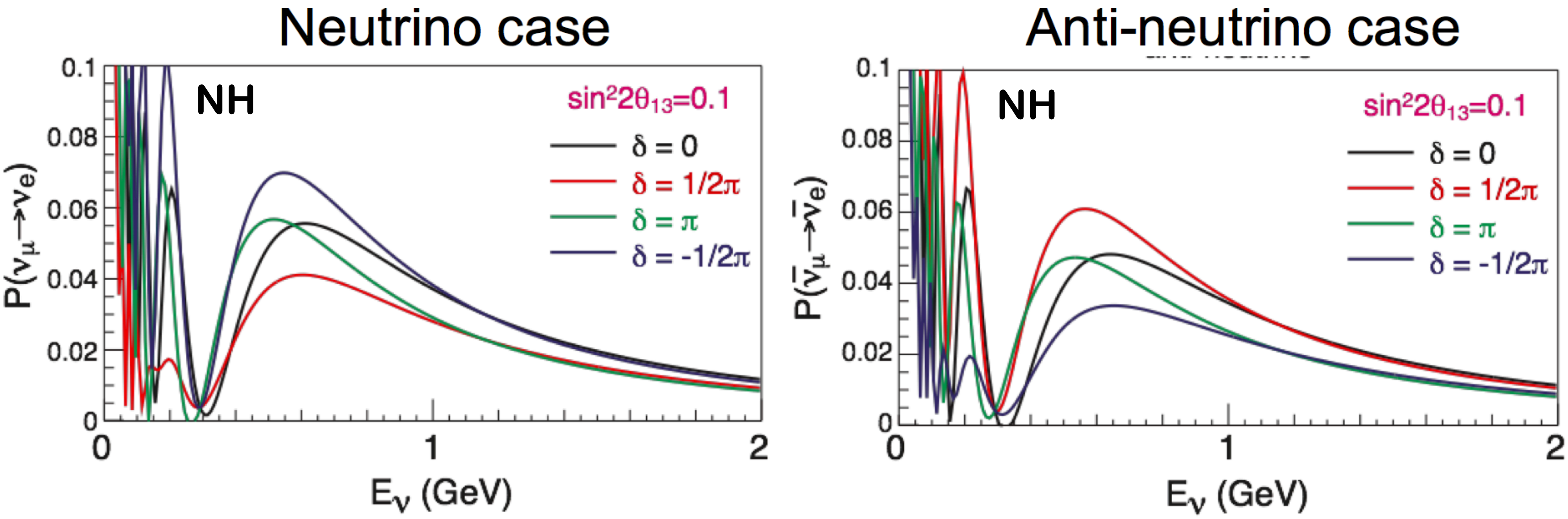
ν/anti-ν:25



Th. Lasserre – Neutrino Summary 2013

HK: CPV signal ($\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$)

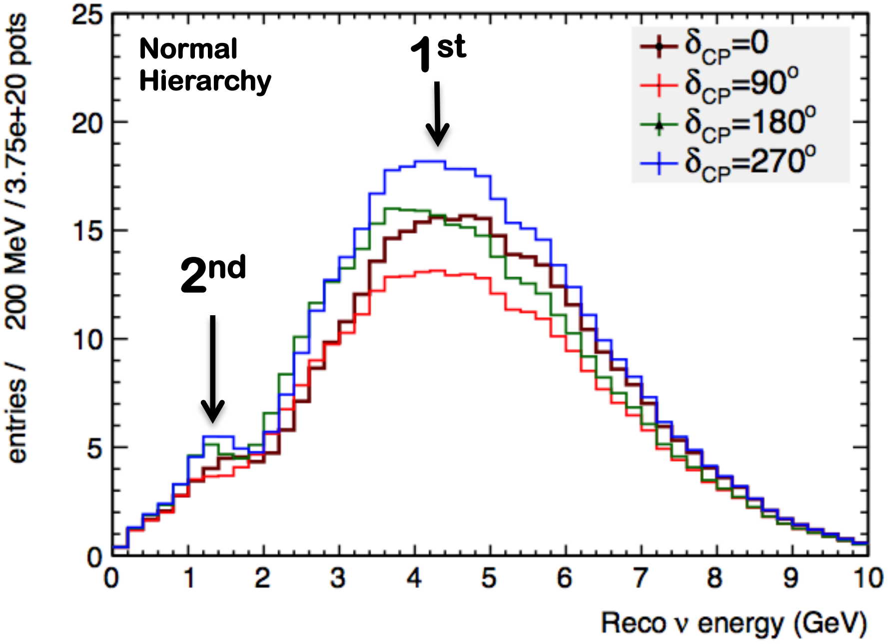
- **Identity CC ν_e events**
- **Comparison between P($\nu_\mu \rightarrow \nu_e$) & P(anti-$\nu_\mu \rightarrow$ anti-ν_e)**
  - **Up to 25% difference expected**
- **Need statistics → 1 Mt H_2O for HK (x25 SK)**



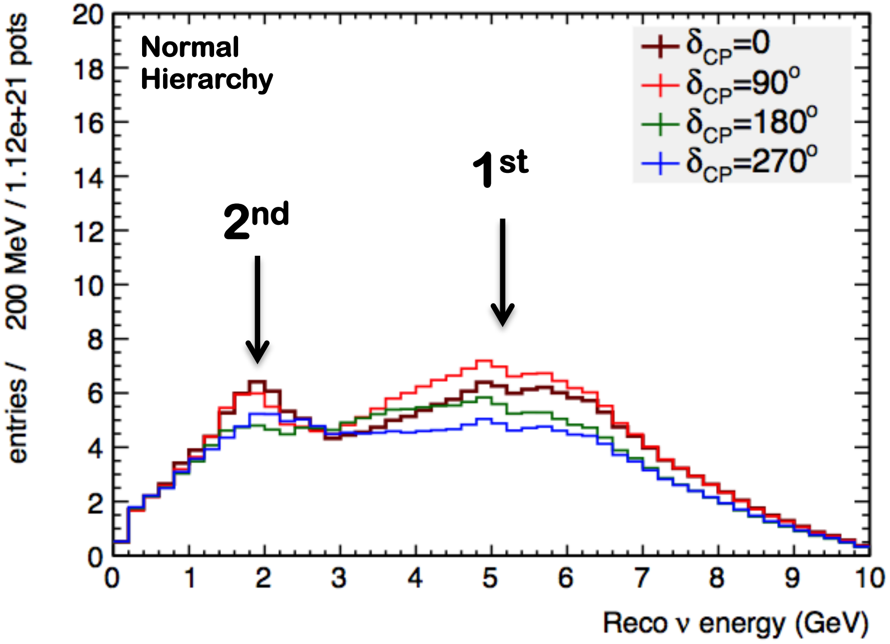
CPV Signal in LBNO (1.5e21 pot)

- Search for a P($\nu_\mu \rightarrow \nu_e$) / P(anti-$\nu_\mu \rightarrow$ anti-ν_e) asymmetry
- LBNO: 20 kt, 12 years of data → limited by statistics
  - Maximize #events at 1st max osc. peak
  - While enhancing 1st / 2nd oscillation peak ratio

Neutrino Running (25%)

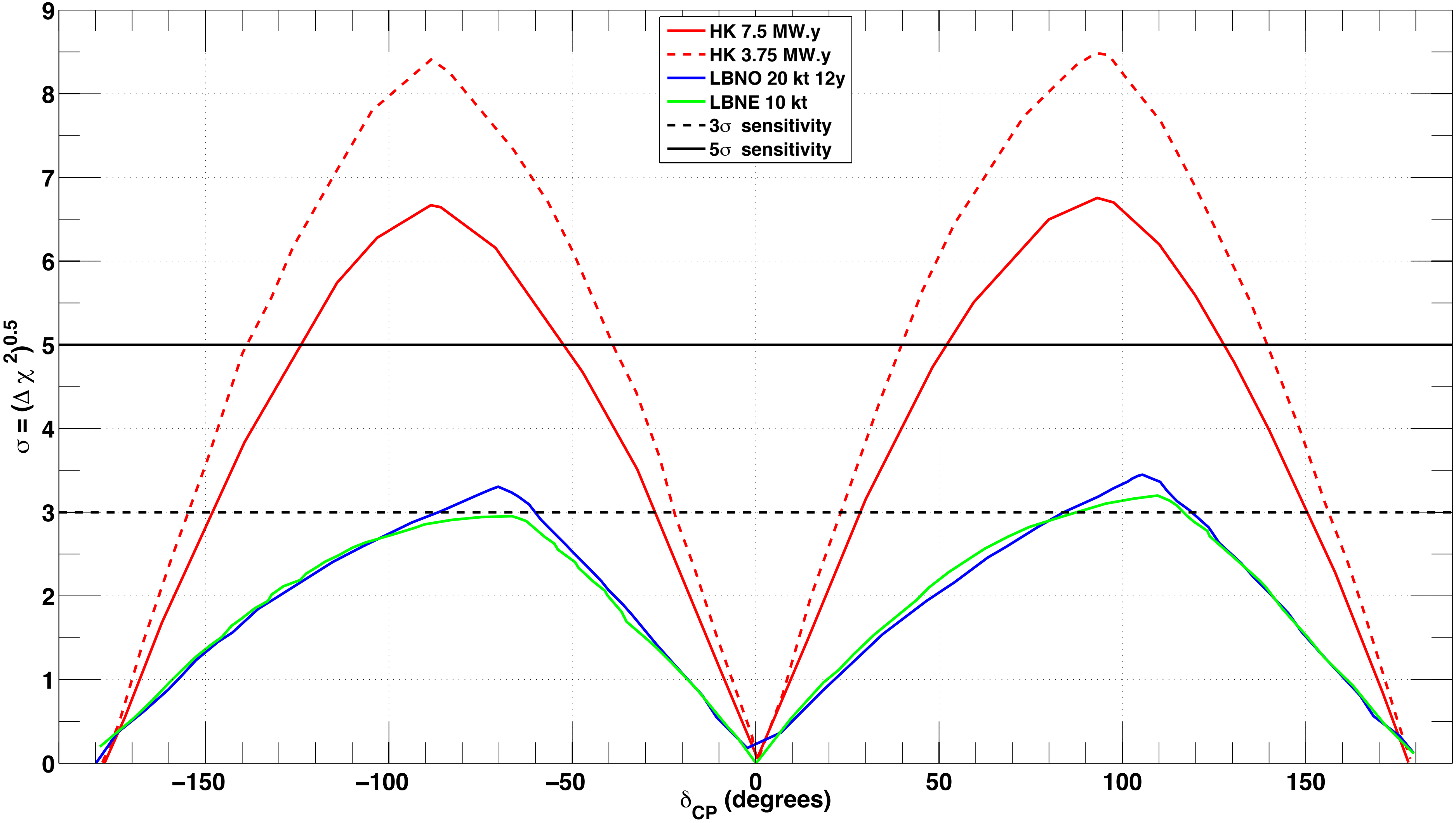


Anti-neutrino Running (75%)



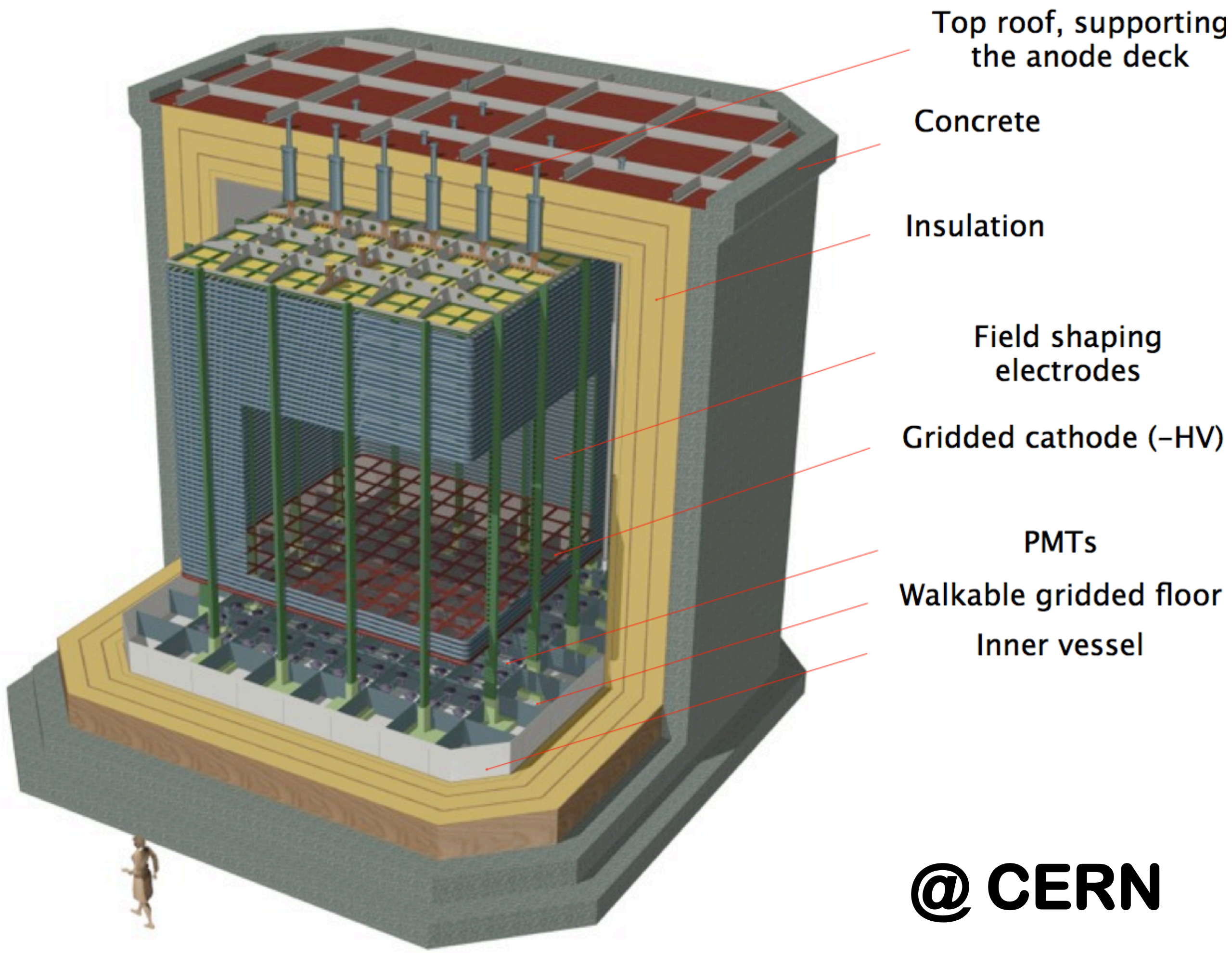
LBNO(E), HK: CPV Sensitivity

Rejection of the null hypothesis for different CP values



Th. Lasserre – Neutrino Summary 2013

LBNO Technological Prototype



@ CERN

Conclusion (1/2)

- Neutrinos mix and oscillate. A lot's of momentum to understand the neutrino mixing properties ! Neutrino $\neq$ Quark mixing

$$U_{CKM} = \begin{bmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{bmatrix} \qquad U_{PMNS} = \begin{bmatrix} 0.8 & 0.5 & 0.16 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{bmatrix}$$

- Large undergoing program towards the measurement of neutrino masses (Katrin, Gerda, EXO/KamLAND-Zen…)
- Two mixing angles and mass splitting measured
- NEW: θ_{13} measured (T2K/DC/DB/RENO)

→ Lot's of prospects for Mass Hierarchy determination

→ Open the way for CP violation measurements (LBNÖ, HK)

Conclusion (2/2)

- A bunch of anomalies calling for clarification:
  - LSND (ν_s, $\Delta m^2 \approx eV^2$?) & Miniboone ?
  - Gallium Anomaly (ν_s, $\Delta m^2 \approx eV^2$?)
  - Reactor Anomaly (ν_s, $\Delta m^2 \approx eV^2$?)
- Hint in favor of sterile neutrinos not in contradiction with cosmological data, if <1 eV-scale mass
- Bunch of 2 to 3 σ effects but cannot be ignored…
- Need for new conclusive short baseline experiments, more than 15 projects, a few already being funded