Sterile neutrino search projects and European activities: Accelerators, Reactors and Source

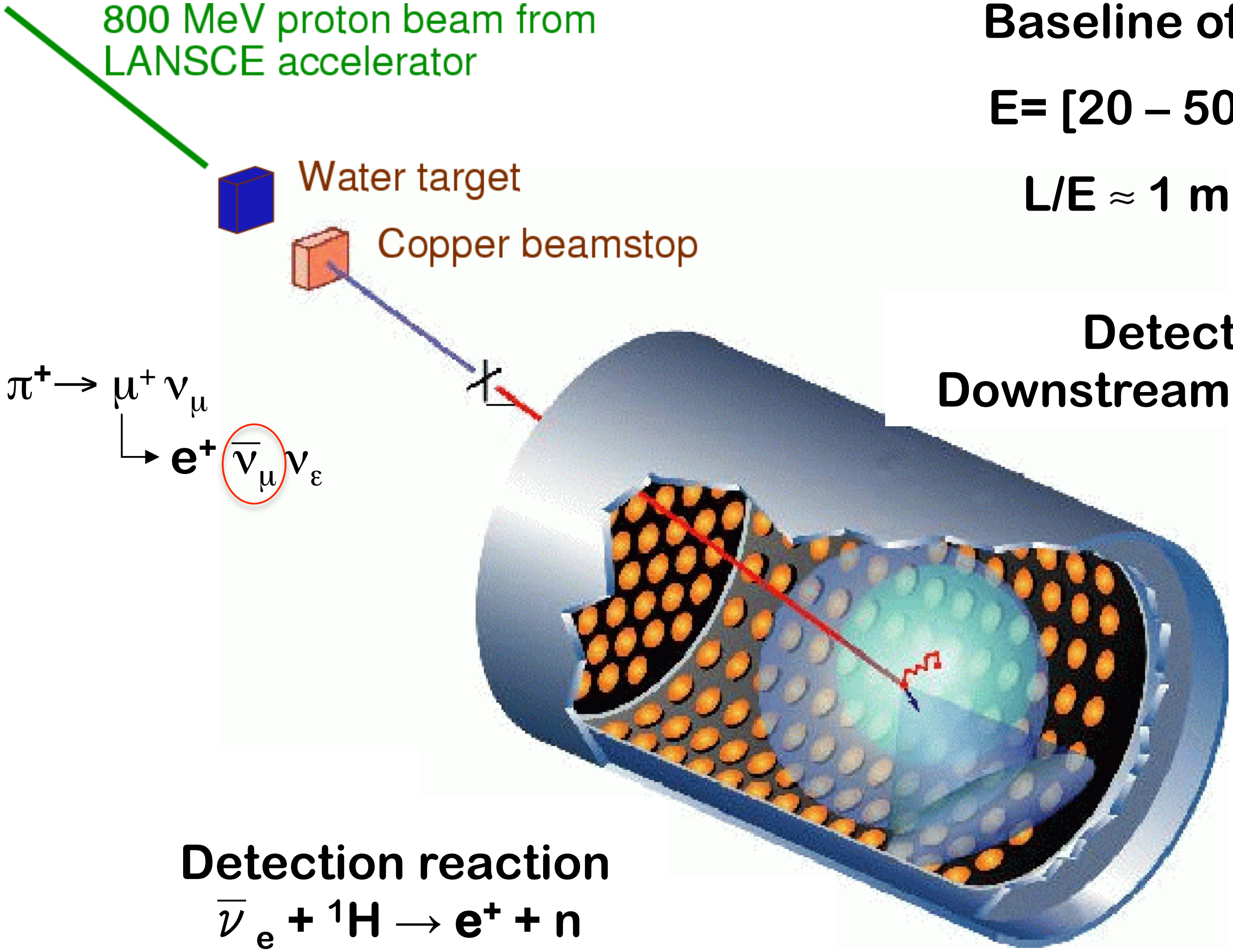
ICFA Neutrino European Meeting
January 8-10, 2014, APC Laboratory

Thierry Lasserre – CEA & APC

Anomalies: New ν-Oscillation?

LSND (stopped π^+ beam)

Anomaly on the electron antineutrino interaction rate



Baseline of 30 m

E= [20 – 50] MeV

L/E ≈ 1 m / MeV

Detector Downstream of target

$\pi^+ \rightarrow \mu^+ \nu_\mu$

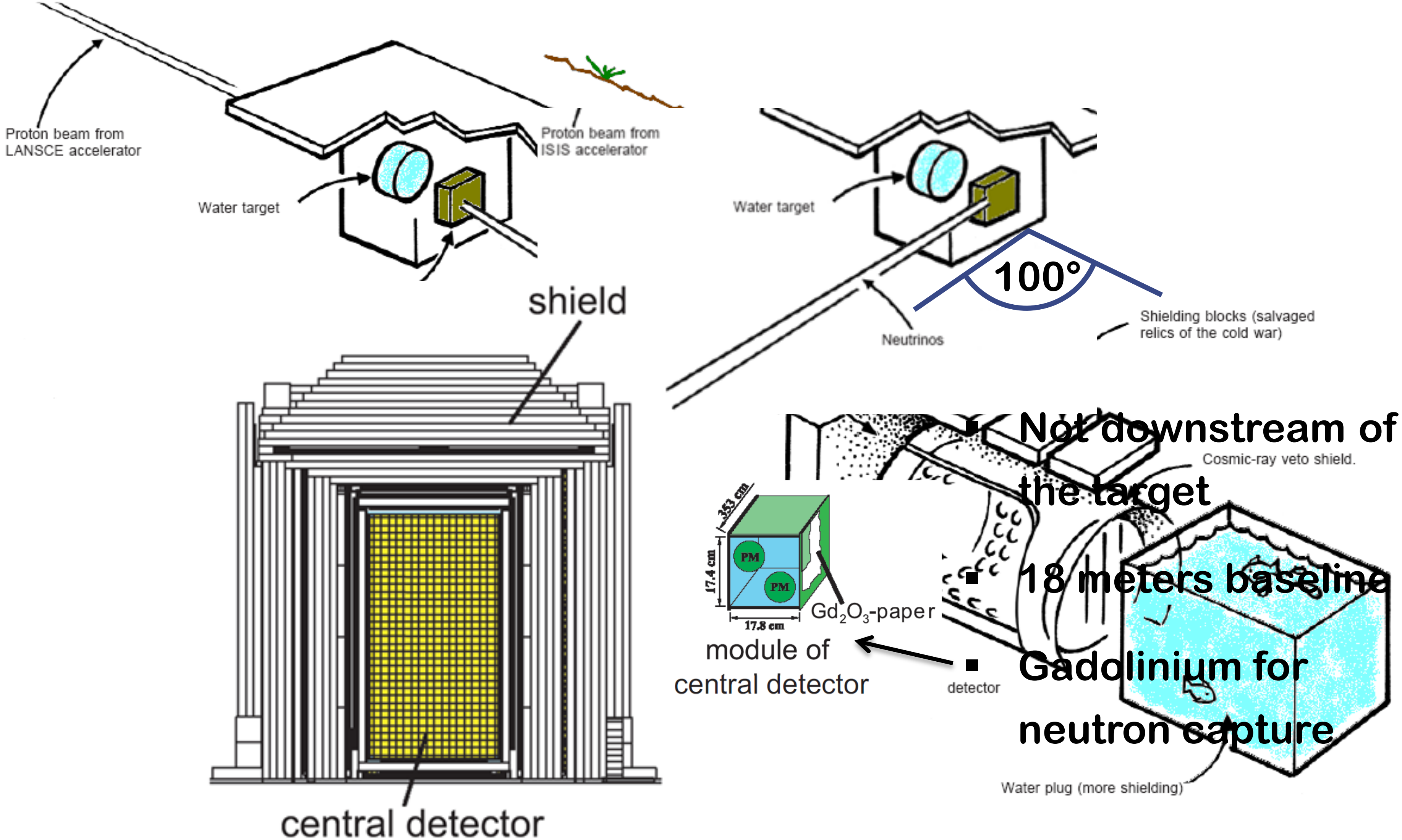
$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$

Detection reaction

$\bar{\nu}_e + {}^1H \rightarrow e^+ + n$

Karmen (stopped π^+ beam)

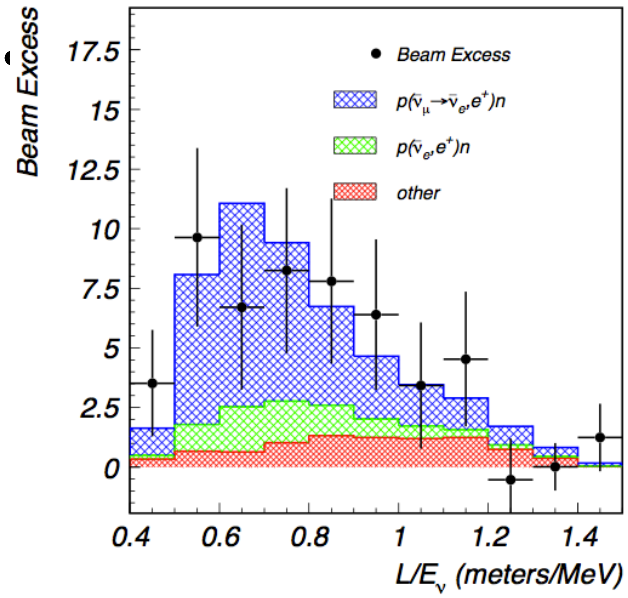
Oscillation not confirmed – exclude part of LSND

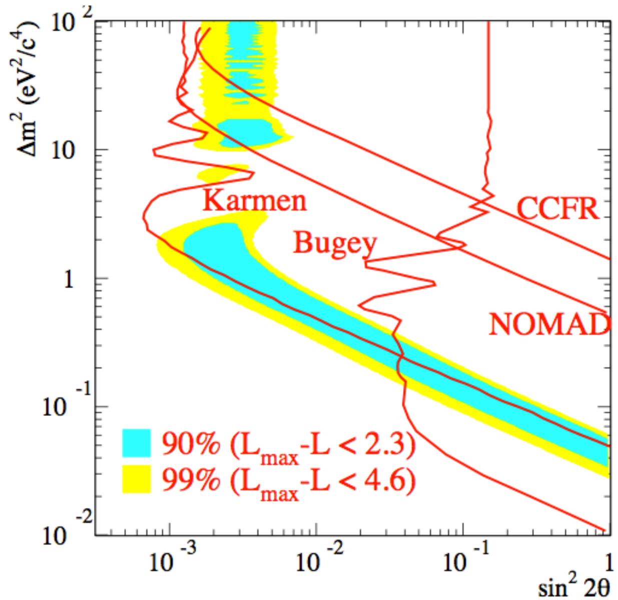


- Not downstream of the target
- 18 meters baseline
- Gadolinium for neutron capture

LSND Results

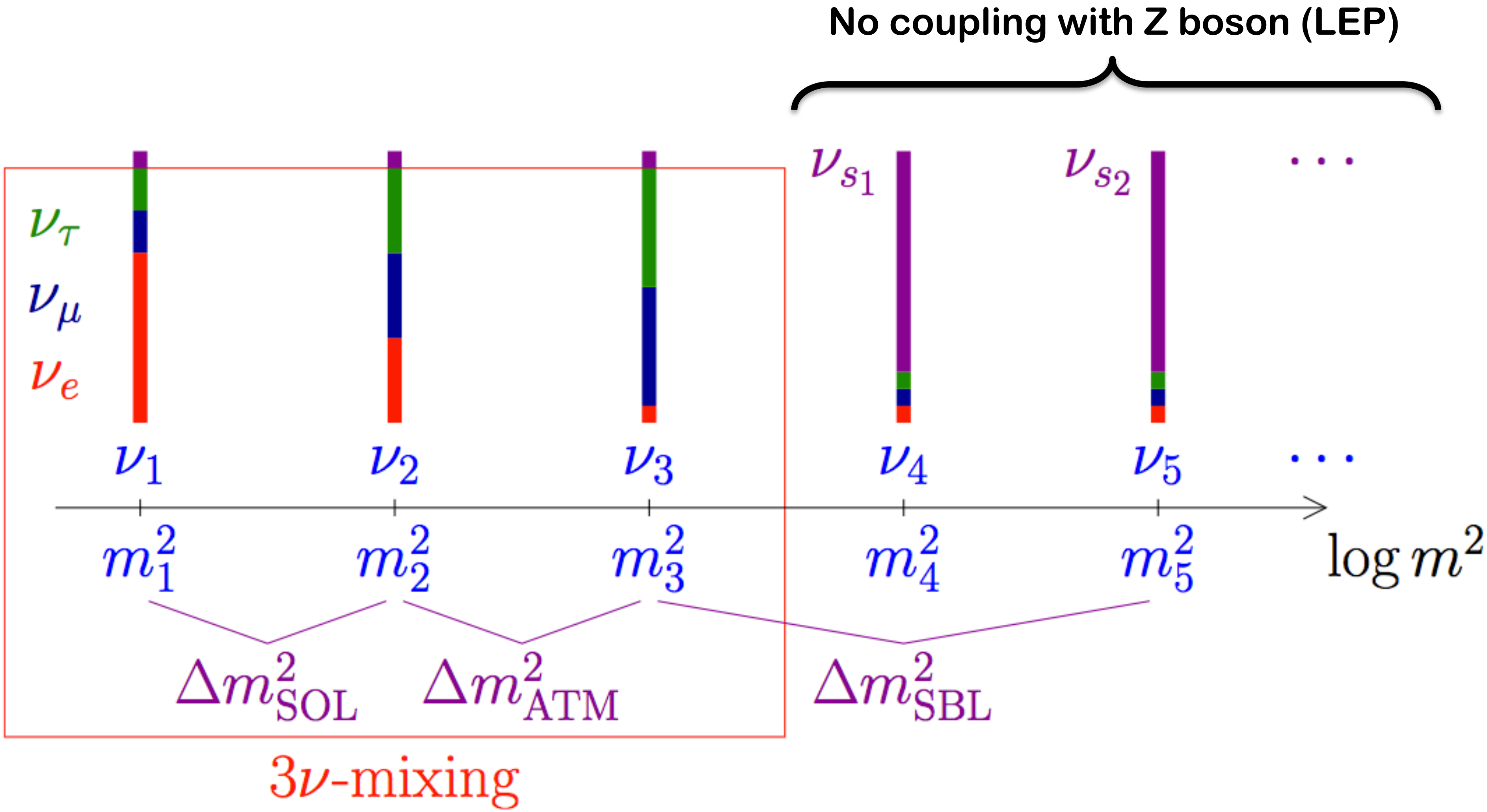
- 1^{st} results in 1995
- **Channel:** anti-$\nu_\mu \rightarrow$ anti-ν_e
- **Detection :** anti-ν_e + ^{1}H → e^+ + n
- **Baseline:** 30 m
- **Energy:** 20 < E (MeV) < 50
- **Status:**
  - anti-ν_e excess observed
    → 32.2 ± 9.4 ± 2.3 (3.8σ)
  - not confirmed nor ruled out by Karmen
- **ν-Oscillation interpretation:**
  - $\Delta m^2 > 0.1$ eV^2 >> Δm_{atm}^2
  - Require a 4^{th} neutrino state





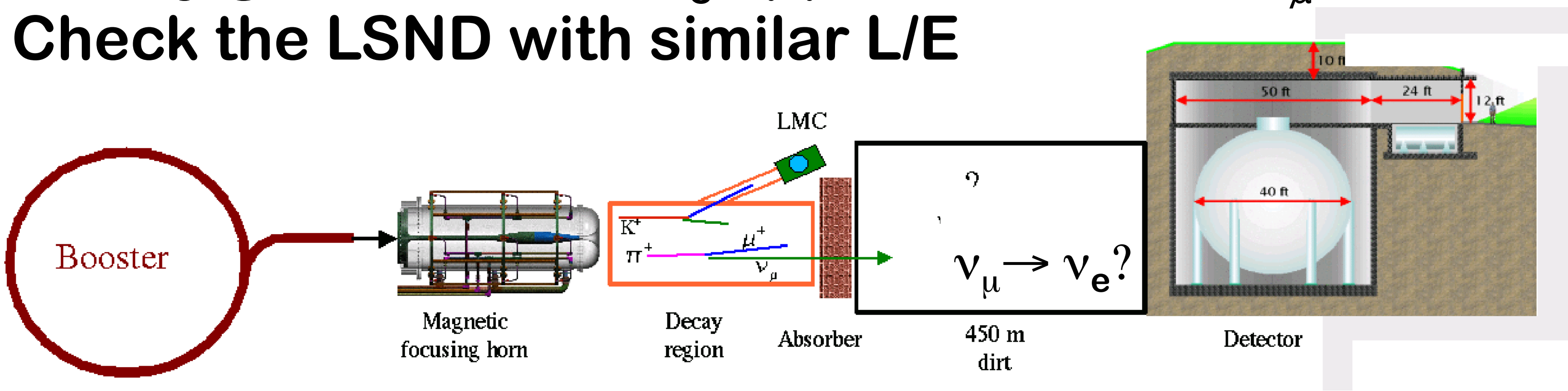
The (light) sterile neutrino hypothesis

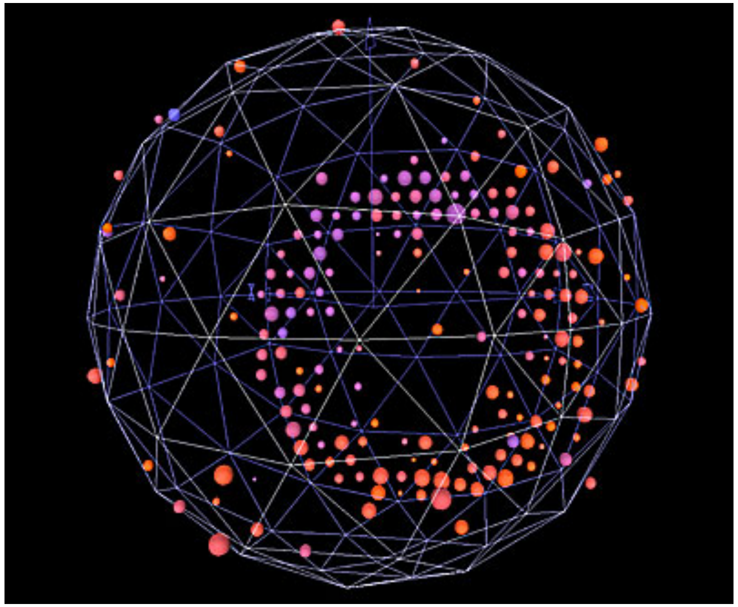
Add a light ν_R to SM, no SM interaction but mixing with active ν' s



MiniBooNE

Primary goal: look for ν_e appearance in a ν_μ beam
Check the LSND with similar L/E

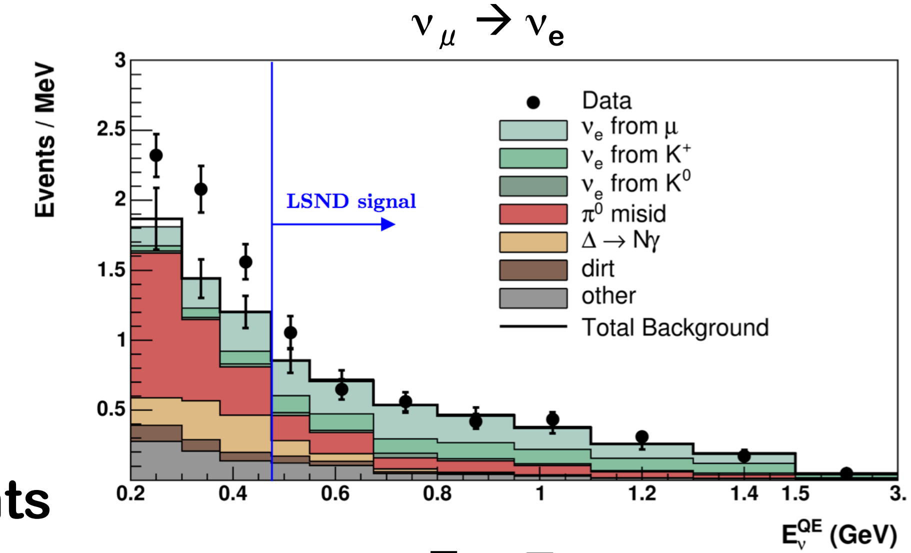


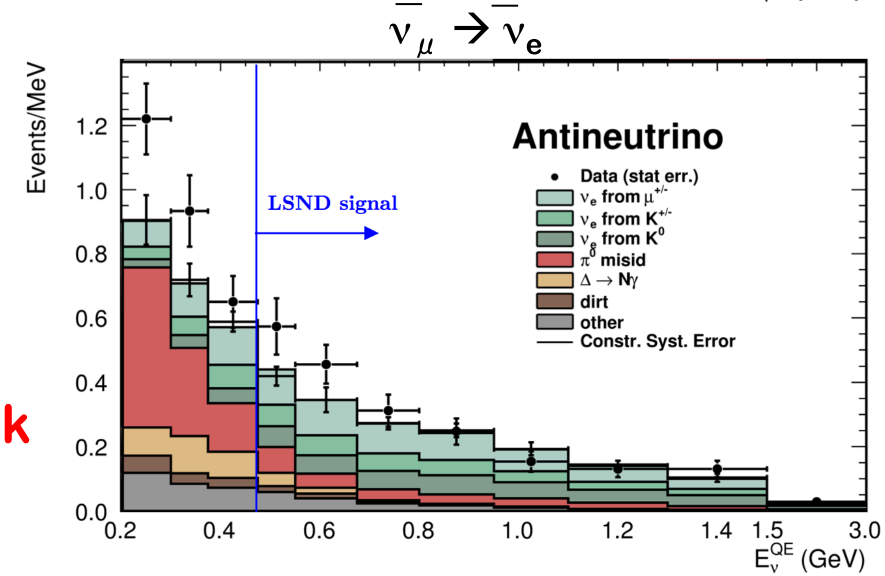


- **Beam: π^+ (π^-) decay in flight**
- **Detection: Cerenkov + scintillation**
- **L/E ≈ 1 m / MeV**
  - **Baseline: 541 m**
  - **200 < E (MeV) < 3000**
- **Statistics:**
  - **ν : 6.46 × 10^{20} POT (2008)**
  - **$\bar{\nu}$:1.27 × 10^{20} POT (2012)**

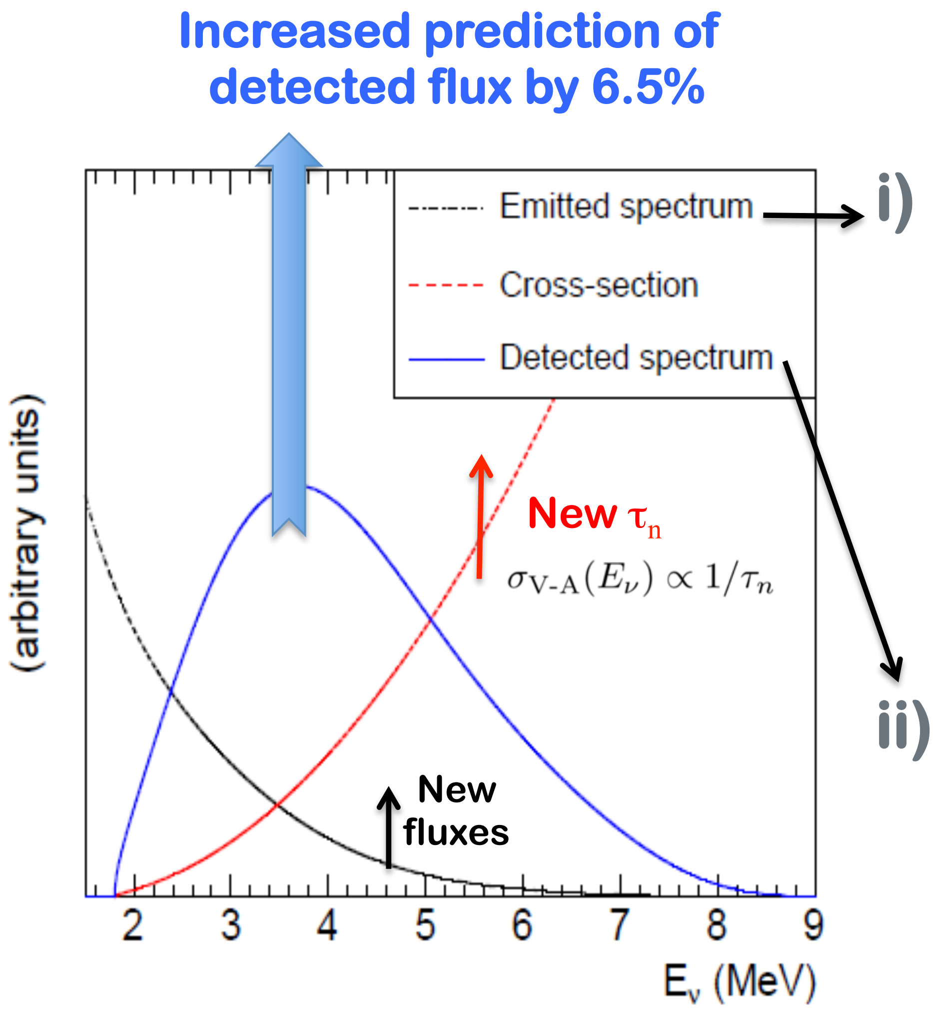
MiniBooNE Results

- Results published from 2007-12
- **Channel:** (anti-)$\nu_\mu \rightarrow$ (anti-)ν_e
- **Detection:** ν_e (p)n → e p (CCQE)
- **Results:**
  - An overall 3.8 σ excess of events
  - Mostly at low energy
- **Interpretation:**
  - Backgrounds issue?
    (to be checked by MicroBooNE)
  - 4th neutrino? Or more….
- **MiniBooNE is not conclusive to check the LSND anomaly**





New Reactor ν-Fluxes



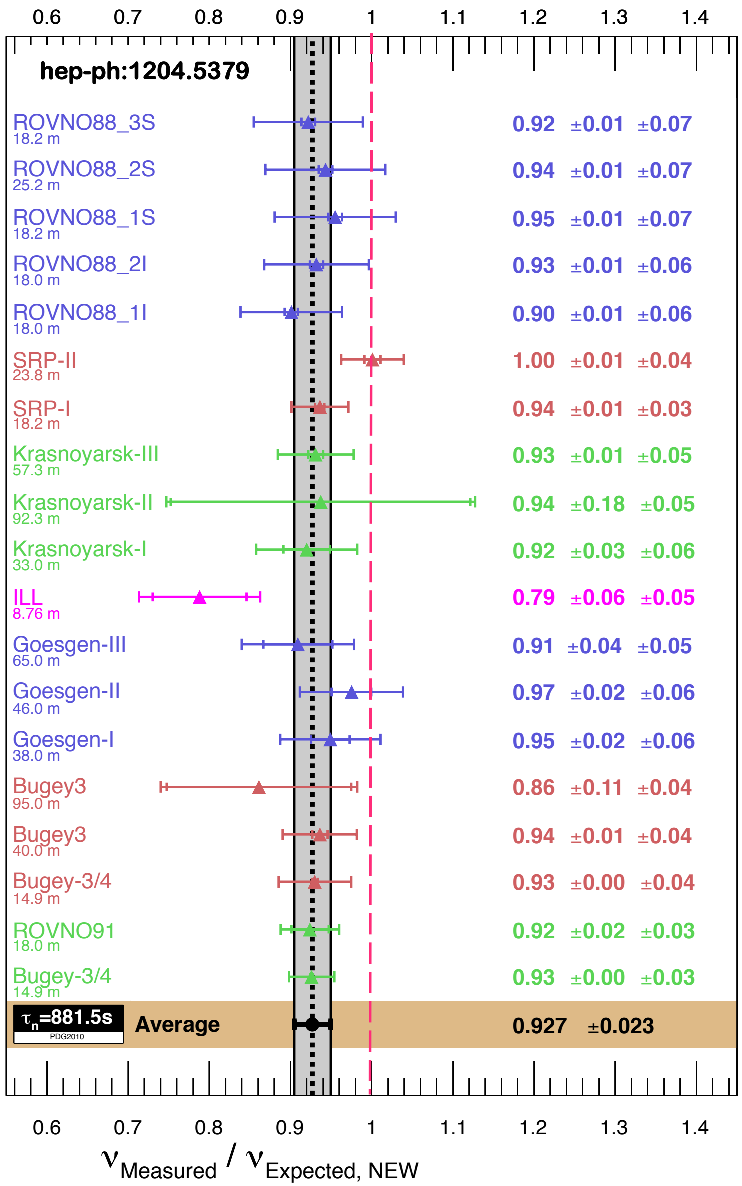
i) **Neutrino Emission:**

- **Improved reactor neutrino spectra → <u>+3.5%</u>**
- **Accounting for long-lived isotopes in reactors → <u>+1%</u>**

ii) **Neutrino Detection:**

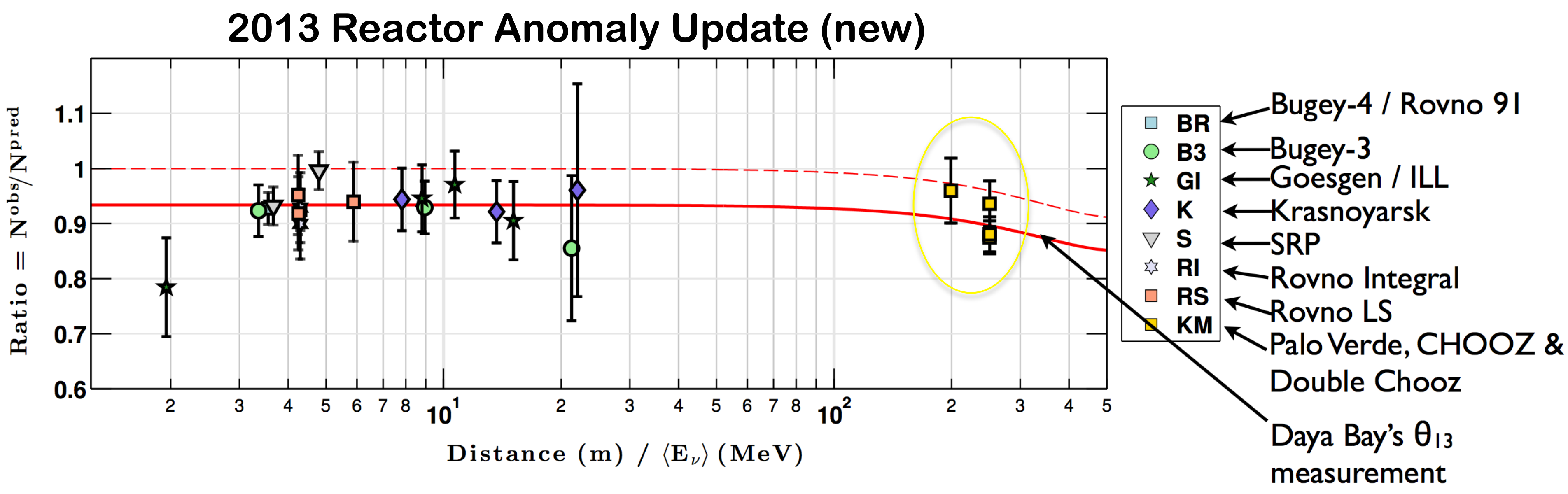
- **Reevaluation of σ_{IBD} → <u>+1.5%</u> (evolution of the neutron life time)**
- **Reanalysis of all SBL experiments**

Reactor Antineutrino Anomaly



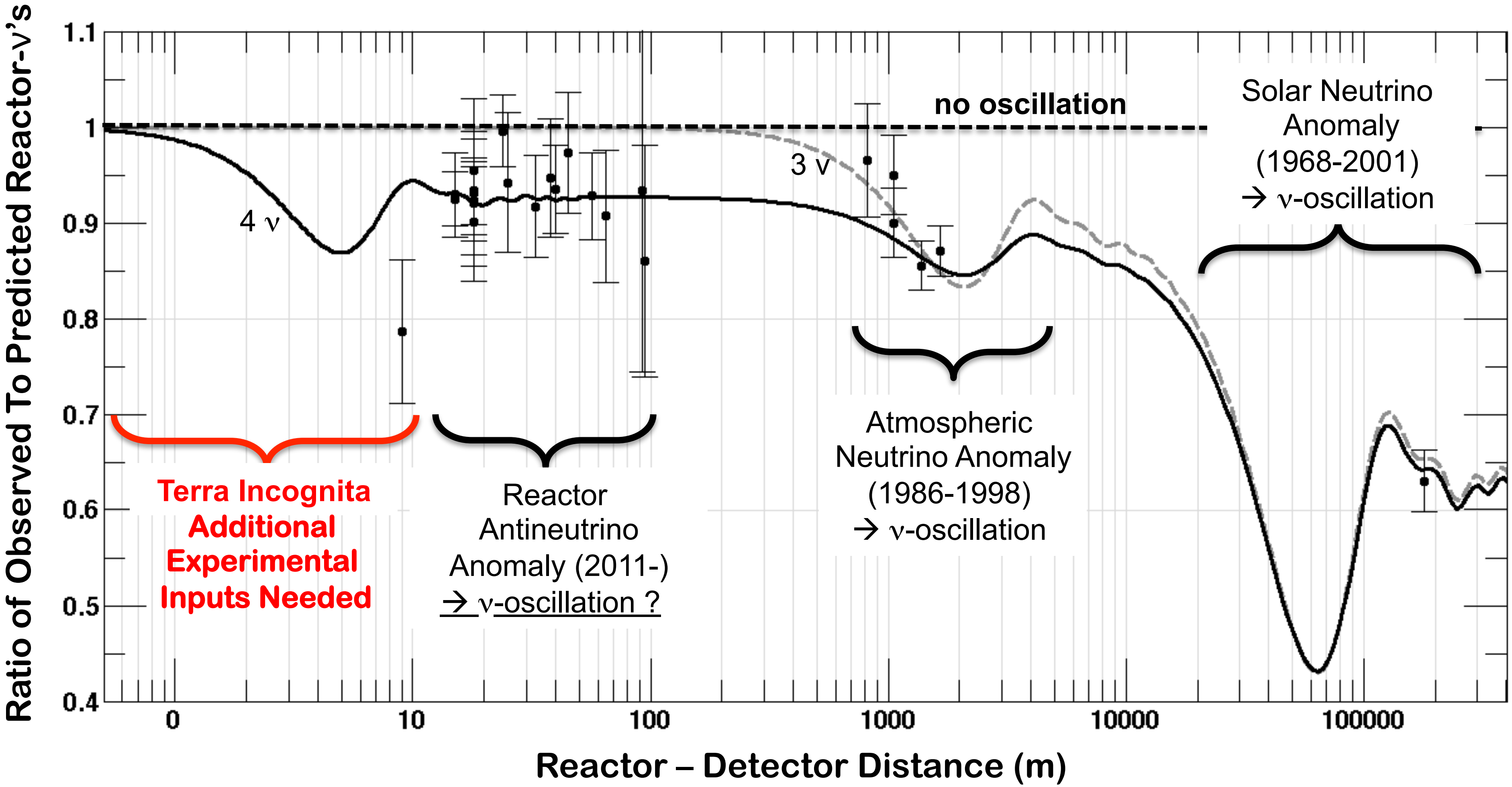
- 19 Short Baseline Experiments (L<100m)
- Observables: ratios of observed event rate to predicted rate of events
- 2011 results
  - Average: μ = 0.943 ± 0.023
  - 98.6 % C.L. deviation from μ = 1
- 2012 results
  - Average μ = 0.927 ± 0.023
  - 99.7 % C.L. deviation from μ = 1
- 2013: update: refined analysis

Including km-scale experiments



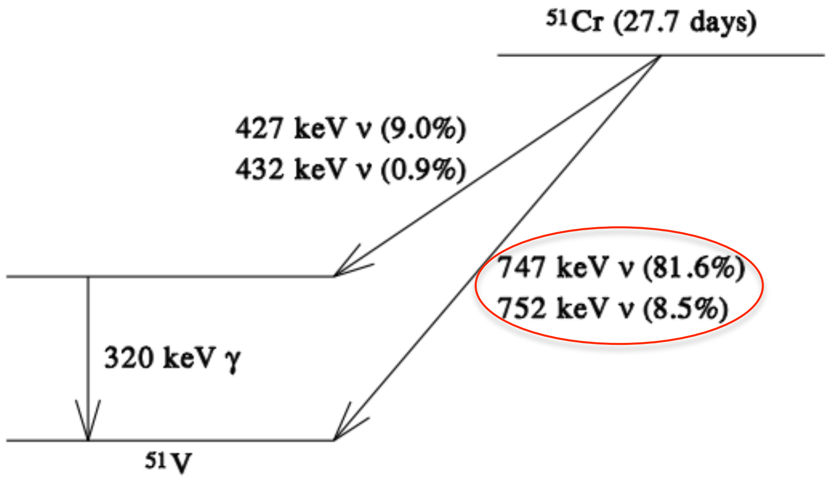
- All known nuclear corrections to β - ν spectra.
- Refined treatment of experimental correlations
- Latest updated neutron mean life (τ_n = 881.5 s).
- Corrects for a statistical bias (1% shift)
- km-scale baselines (Chooz, DC, PV)
  - correcting for θ_{13} deficit from Daya Bay's measured value
- 2013 result: μ = 0.936 ± 0.024, 2.7σ deviation from unity

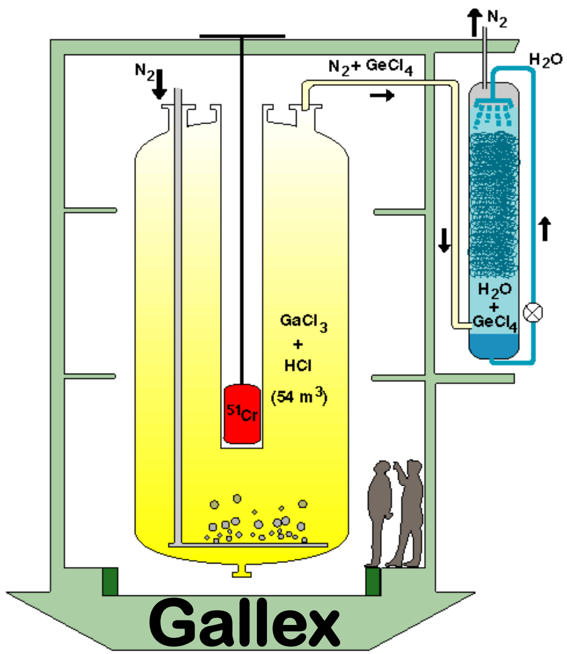
Experimental Artifact or New Physics?



The Gallium Neutrino Anomaly

- **Test of solar neutrino radiochemical detectors GALLEX and SAGE**
    - $^{71}Ga/^{37}Ar + \nu_e \rightarrow {}^{71}Ge/^{37}Cl + e^-$
- **4 calibration runs with 0.6 - 2 MCi Electron Capture ν_e emitters**
    - Gallex, <L>=1.9 m
        - ^{51}Cr, 750 keV
    - Sage, <L>=0.6 m
        - ^{51}Cr & ^{37}Ar (810 keV)
- **Deficit observed**
    - 3σ anomaly
    - Supported by new $^{71}Ga(^3He, {}^3H)^{71}Ge$ cross section meas.

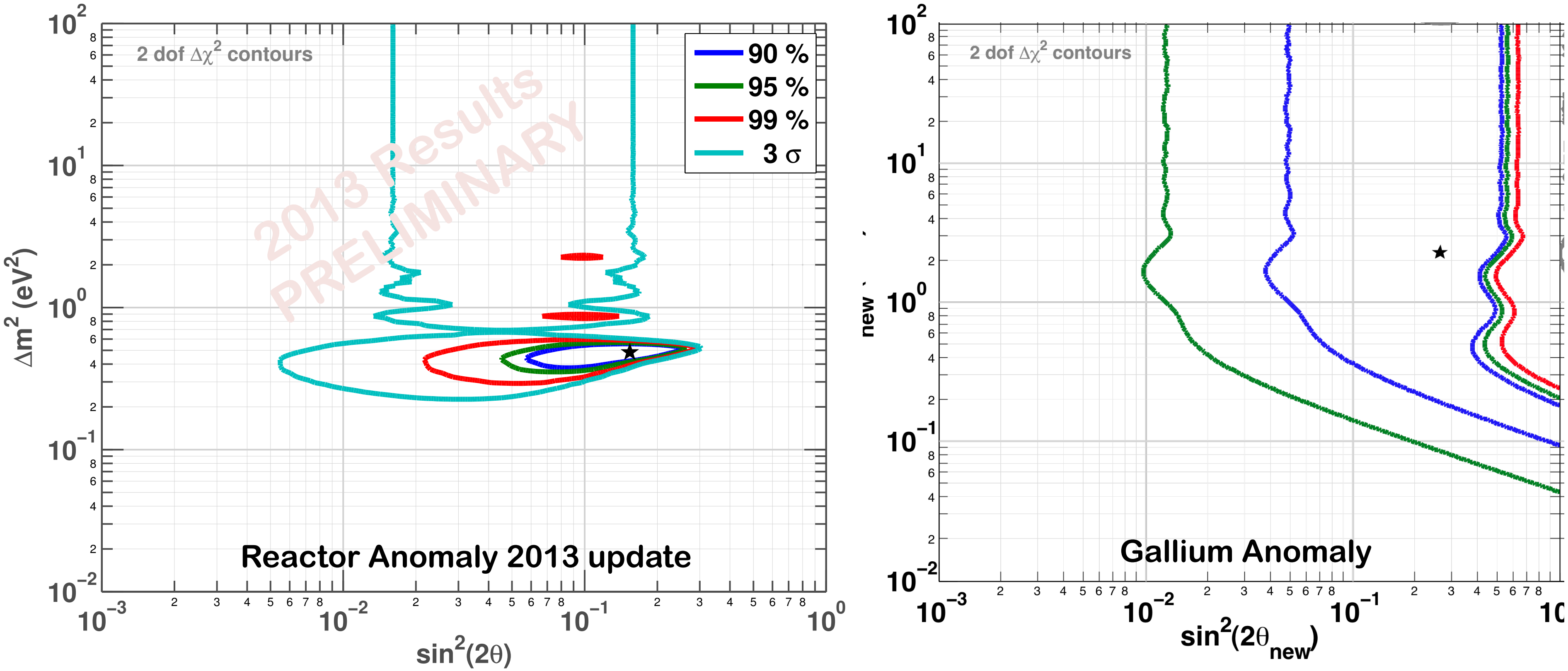




Sterile Neutrino Interpretation

Fit to ν_e and $\overline{\nu}_e$ disappearance hypothesis (3+1, Okkam razor)

$$\begin{pmatrix}\nu_e\\ \nu_s\end{pmatrix} = \begin{pmatrix}\cos\theta_{new} & \sin\theta_{new}\\ -\sin\theta_{new} & \cos\theta_{new}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_{new}\end{pmatrix}, P_{ee} = 1-\sin^2(2\theta_{new})\sin^2\left(\frac{\Delta m^2_{new}L}{E}\right)$$



No-oscillation hypothesis disfavored at >99.9% C.L.

Interpreting Data As ν-Oscillation

Anomalous & Regular Results

Anomalous	Source	Type	Signal	Channel	Significance
LSND	Meson Decay-at-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	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

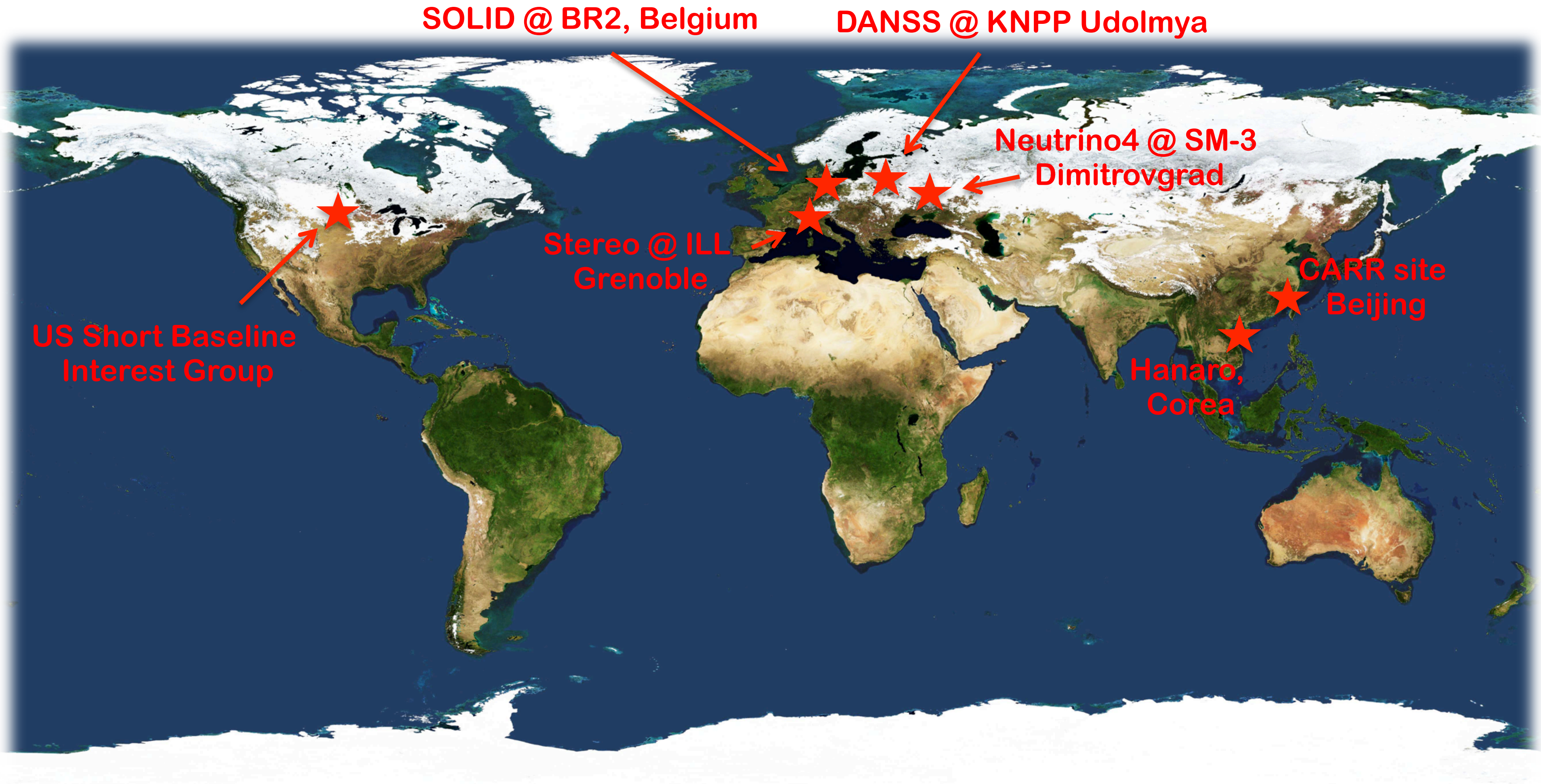
Sterile-ν Oscillation Phenomenology

- $\overset{(-)}{\nu}_e$ **disappearance** (Reactor, Gallium, ...)
  - $$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$
- $\overset{(-)}{\nu}_\mu$ **disappearance** (CDHS, MiniBOONE, Minos,...)
  - $$P_{\mu\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{\mu\mu} = |U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right)$$
- $\overset{(-)}{\nu}_e$ **appearance** (LSND, Karmen, MiniBooNE, ...)
  - $$P_{\mu e} = 4 \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

$\nu_\mu \rightarrow \nu_e$ appearance requires ν_μ & ν_e disappearance

Experimental Prospects

Experimental Prospect:
@ Nuclear Reactor



Test of both reactor & gallium anomalies

Testing $\overset{(-)}{\nu}_e$ disappearance anomalies

- Need direct test, beyond the current mean deviation from predicted rate

- Input from sterile neutrino fits
  - $\Delta m^2 \approx 0.1\text{-}10\ eV^2 \rightarrow L_{osc}(m) = 2.5 \frac{E(MeV)}{\Delta m^2 (eV^2)} \approx 2 - 10\ m$
  - $\sin^2(2\theta_{ee}) \approx 0.01\text{-}0.15$

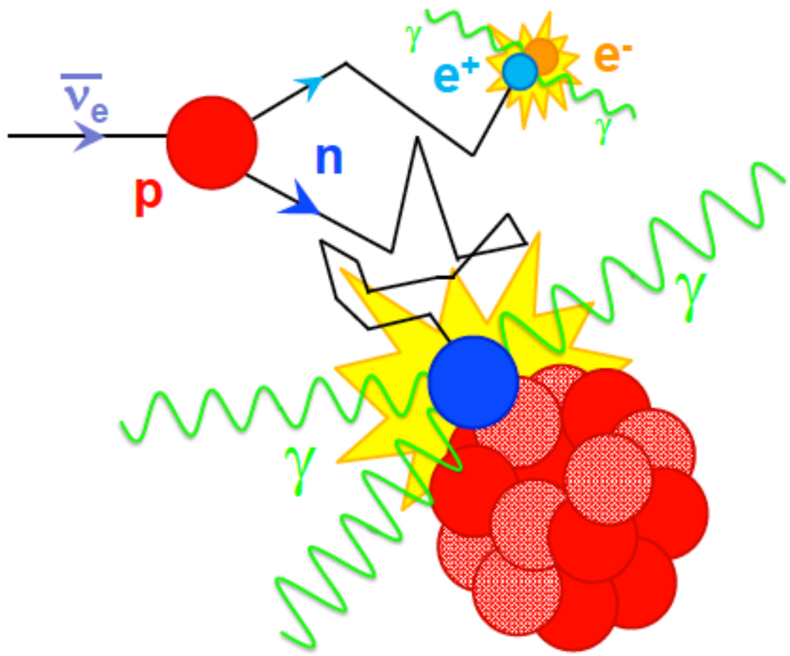
- Experimental specifications
  - Compact neutrino source (with respect to L_{osc})
  - Good vertex and energy resolutions
  - High statistics (few % stat. uncertainty)
  - Few % syst. uncertainty → Low Backgrounds

- Search for a new oscillation pattern in E & L completed by normalization information

IBD Signal & Backgrounds

Inverse Beta Decay

$$\overline{\nu_e} + p \rightarrow e^+ + n$$



Selective coincidence
e^+ prompt signal & n-capture

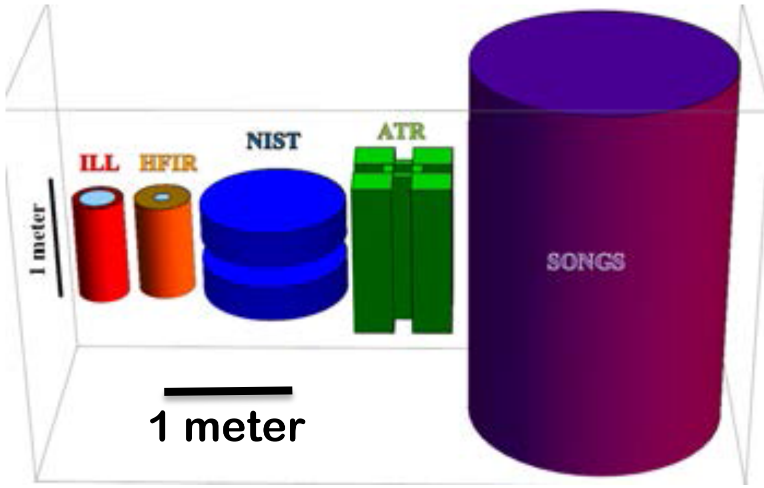
Background rejection

- **Accidental γ-neutron coincidence**
  - Shielding
  - Segmentation
  - Neutron discrimination

- **Fast-n correlated background**
  - Rejection of recoil protons with PSD
  - Cosmic rays induced:
    Reactor OFF
    Overburden
  - Reactor induced:
    - must be negligible

New SBL reactor experiments

Typical reactor core sizes



- Compact reactor core
  - No oscillation smearing
- High statistics (few 100 evts/day/t)
  → High Power (10-3000 MW)
  → Short baselines (5-50 m)
- Highly enriched fuel
  → Well known ^{235}U fission spectrum
- Reactor ON/OFF periods
  → Moderate overburden compensated by accurate measurement of the cosmogenic bkg component
- But challenging reactor-induced backgrounds (γ and n)
  → Need comprehensive site characterization

Reactor ν Proposals

Experiment Type	Experimental Strategy
Mature Gd-doped LS detector Technology	- Clear signature of n-capture (8 MeV γ-cascade) - High light yield → fast n background rejection by PSD - But sensitive to high-E γ' s → need large passive shielding
Highly segmented detector for background reduction	- Vertex correlation between prompt and delayed - Topology of E depositions: e → compact track γ → longer interaction length
Enhanced neutron Tagging	- Unique signature of neutron capture with Li-doped LS/PS $^{6}Li + n \rightarrow \alpha + t$
2 detector complex or Moving detector	- Better sensitivity to lower Δm^2 - But Need larger volume and/or longer running time

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			

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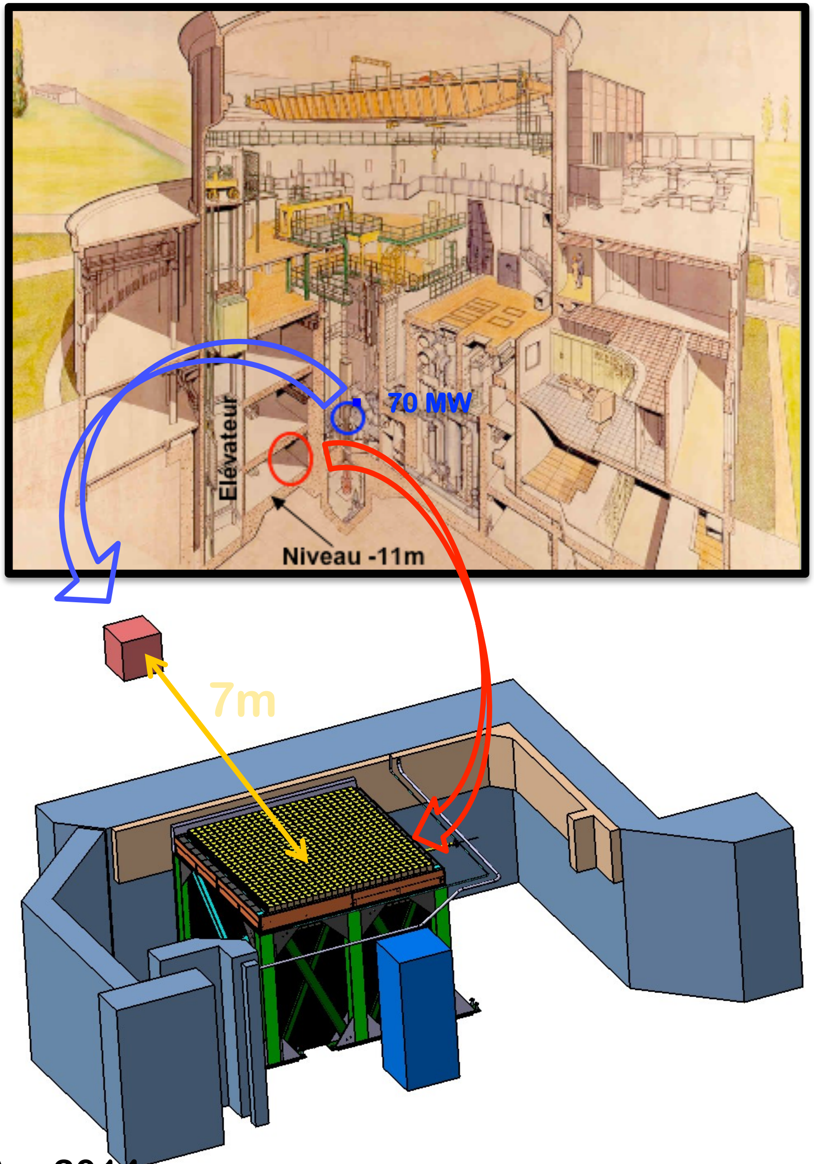
Nucifer @ OSIRIS *(Gd-LS)*

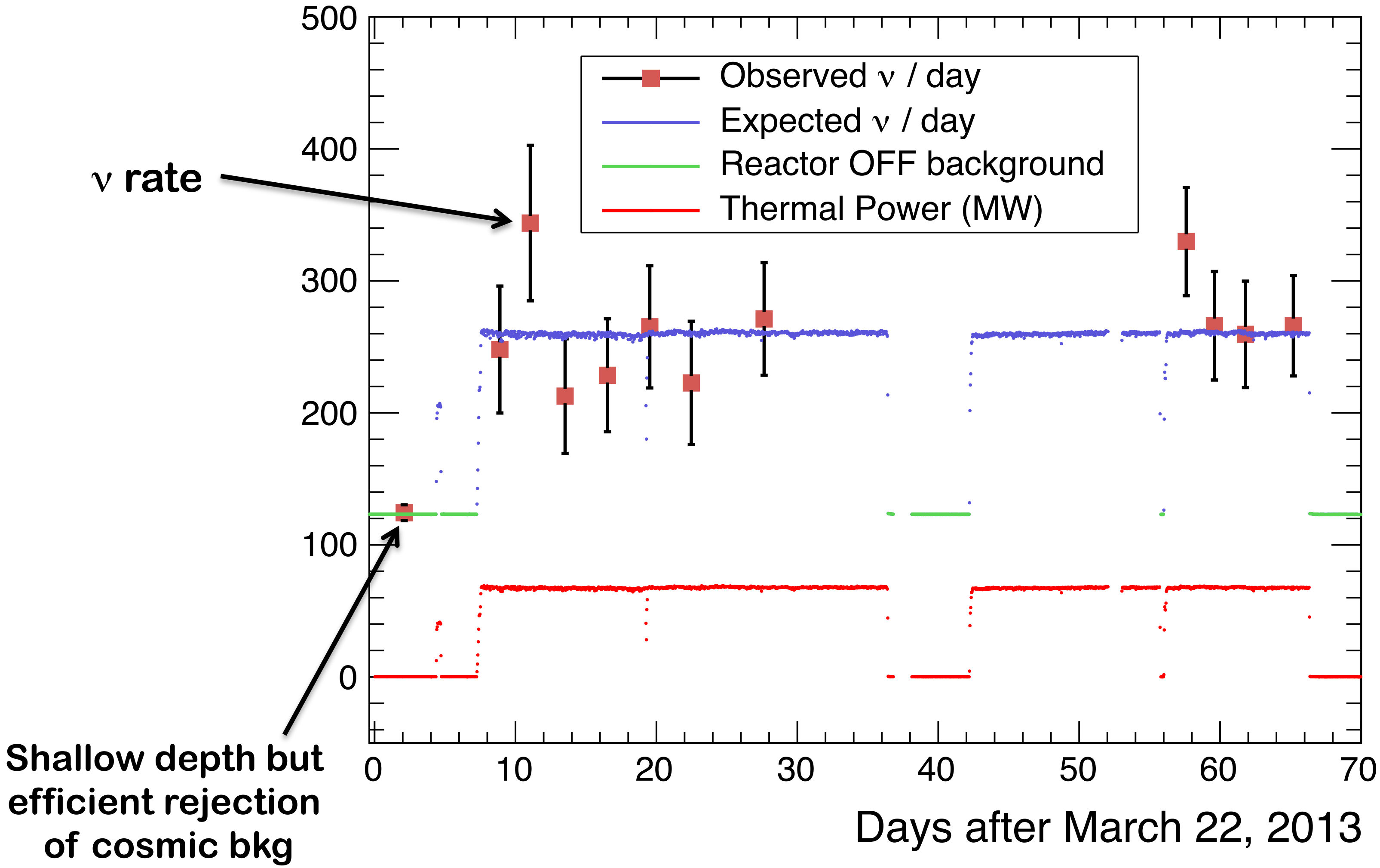
Originally Dedicated for non proliferation

- Osiris research reactor
  - At Saclay, France
  - 70 MW, 20% ^{235}U
- Detector designed for reactor monitoring studies
  - 850 kg Gd-loaded LS
  - Currently 250 / day
  - Shallow depth (few mwe)
- Modest sensitivity to sterile-ν:
  - Compact core: 60x60x60 cm^3
  - Short baseline: only 7 m
  - But Simple design
  & Challenging Reactor bkg
- Data taking started 04/2013
  Shielding Upgrade Feb. 2014



Nucifer: First Neutrino Run

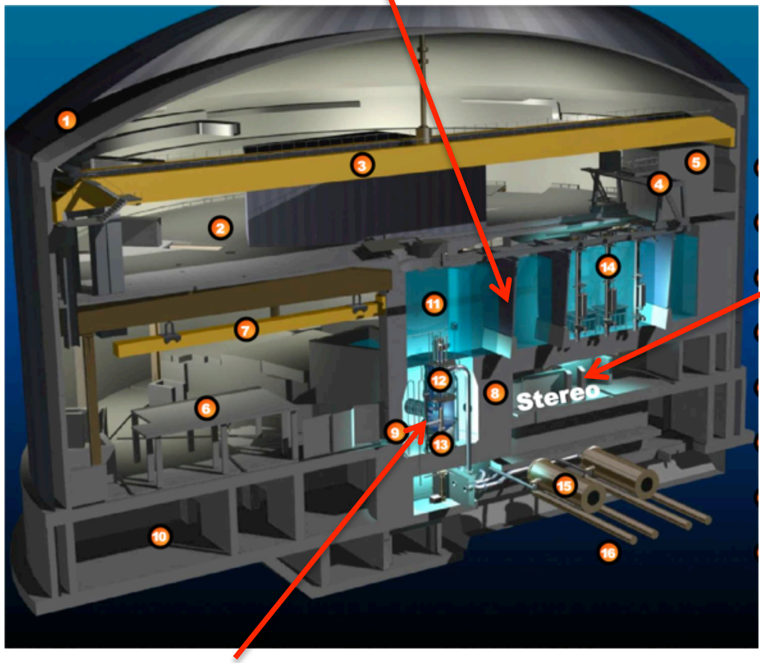
- **No reactor induced fast neutrons**
- **but need further γ attenuation (lead, 4 cm) for sterile ν search**



Stéréo @ ILL *(Gd-LS)*

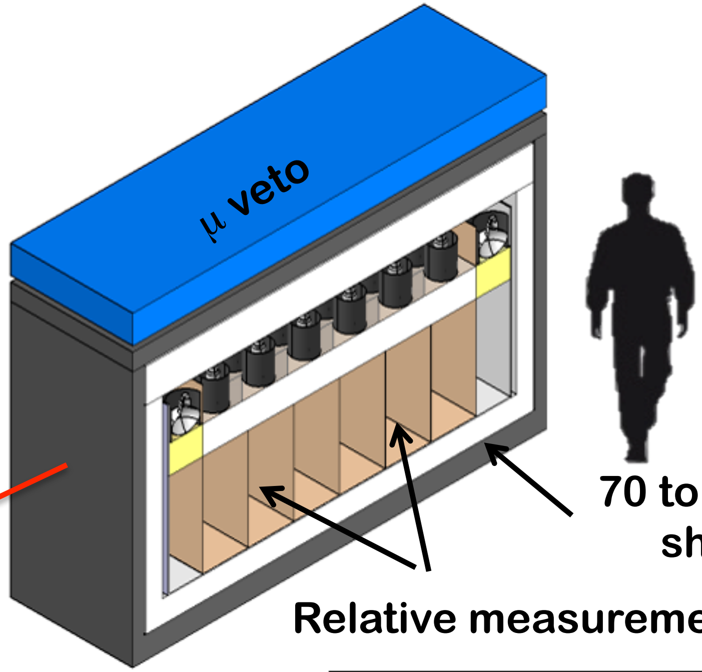
Start Data Taking in 2015

factor 4 attenuation of vertical flux
from water pool



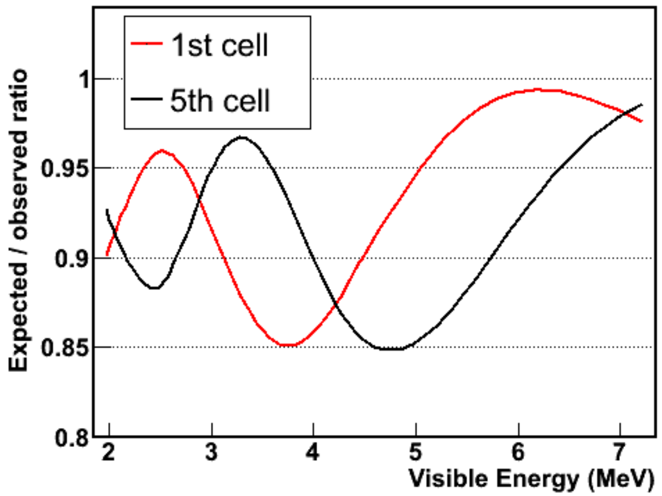
50 MW core
h=80cm, Φ=40cm

[8.5-11] m
baseline range



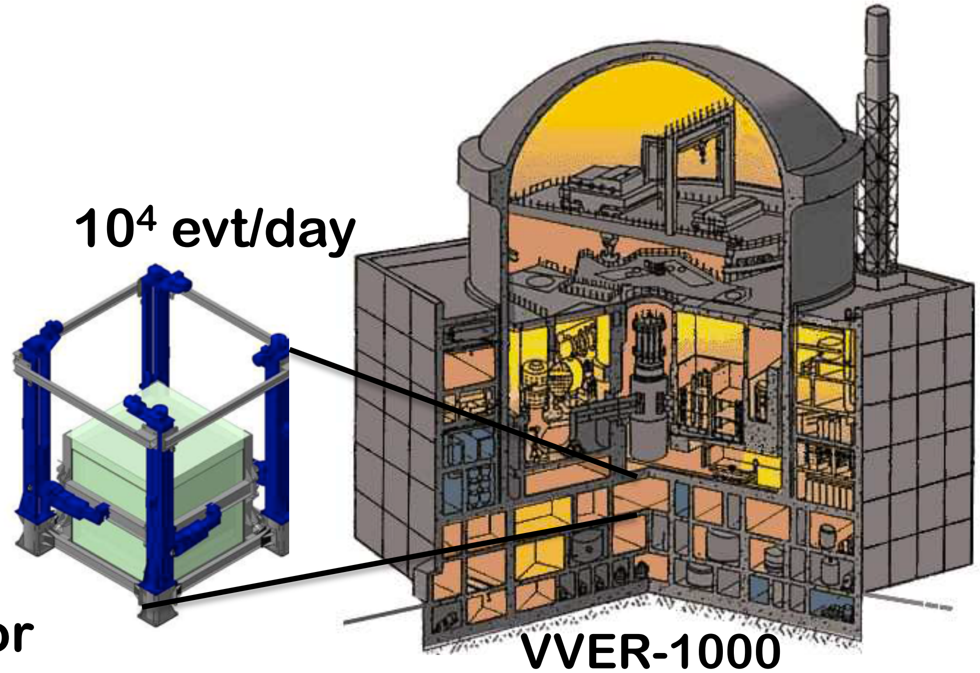
70 tons γ and n
shielding

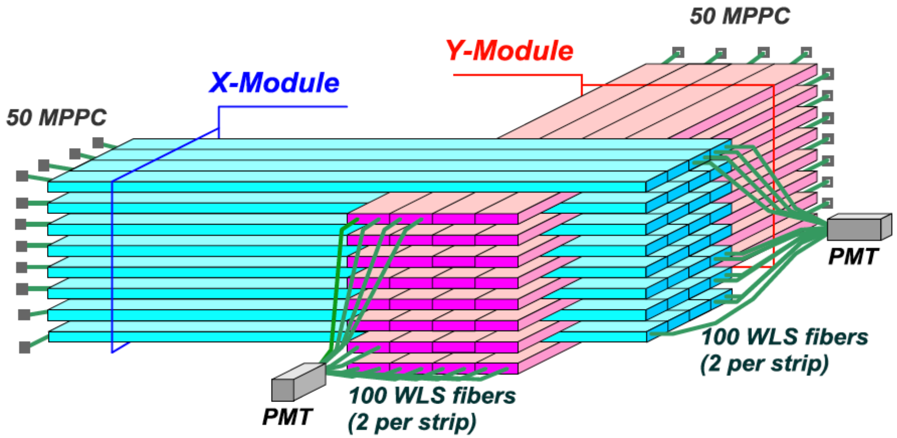
Relative measurement in 6 cells



DANSS @ KNPP *(High-Seg)*

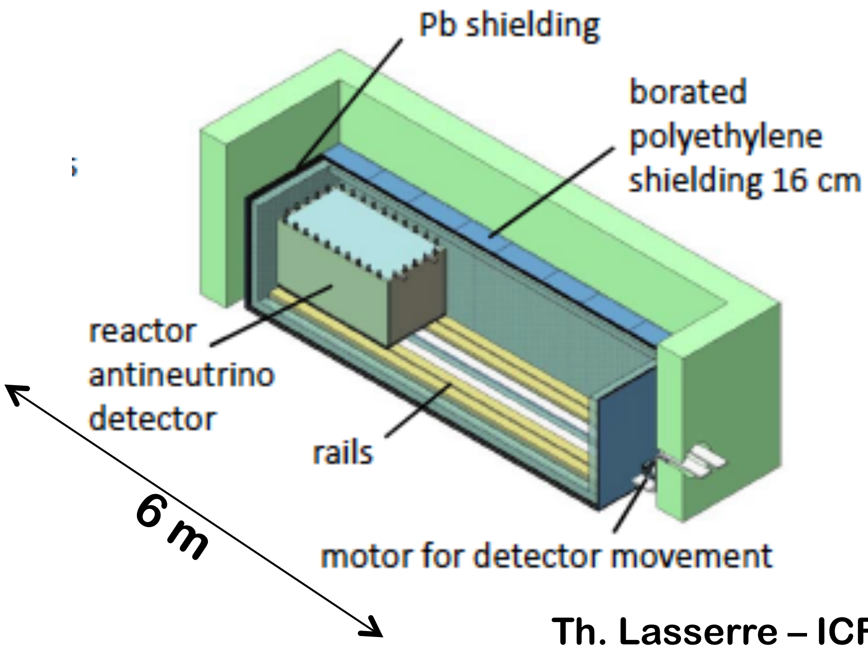
- 1 GW extended core
- Good overburden
- Vertical motion of the detector (9.7-12.2 m)
- Highly segmented detector → background rejection
- Plastic strips with Gd-loaded interlayer, WLS fibers readout
- Start in 2014/15?

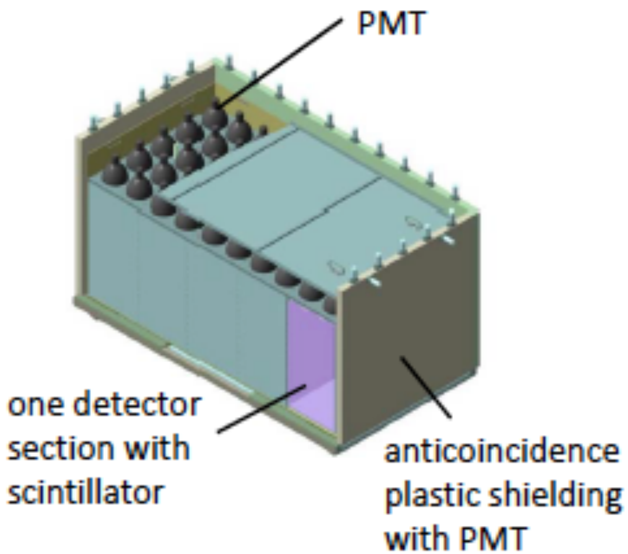




Neutrino-4 @ SM3 *(Gd-LS)*

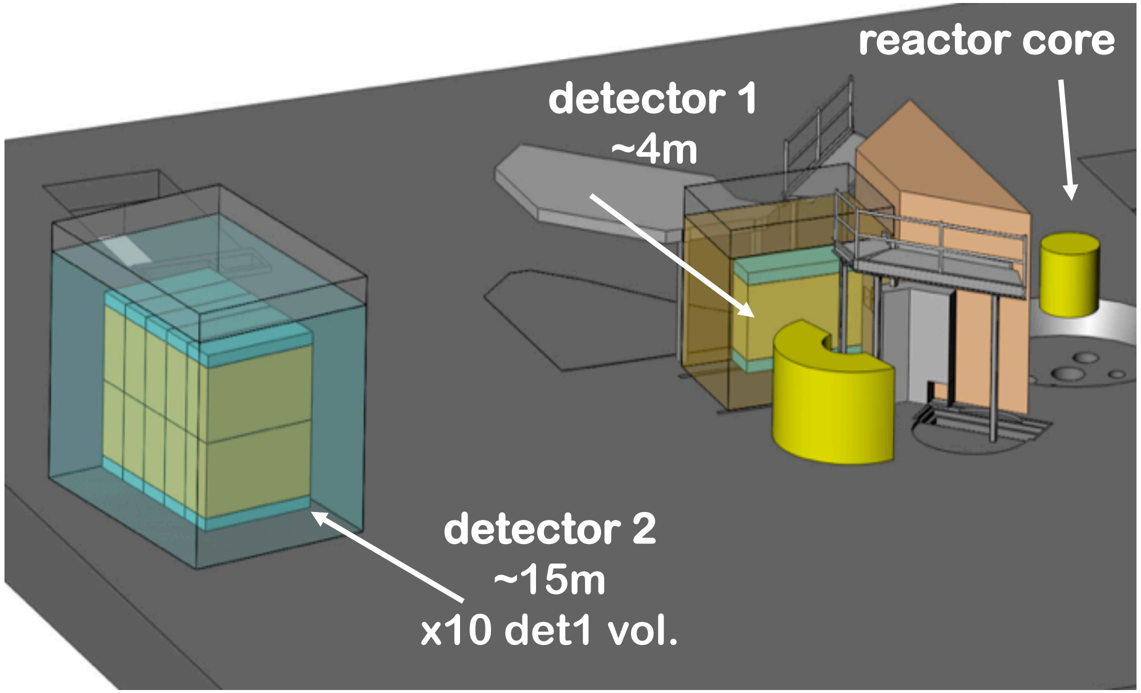
- 2.5 m^3 LS target, 5 section movable detector [6-12] m
- 100 MW compact core
- Detector at Surface
- Status:
  - Shielding integrated
  - Start in 2015

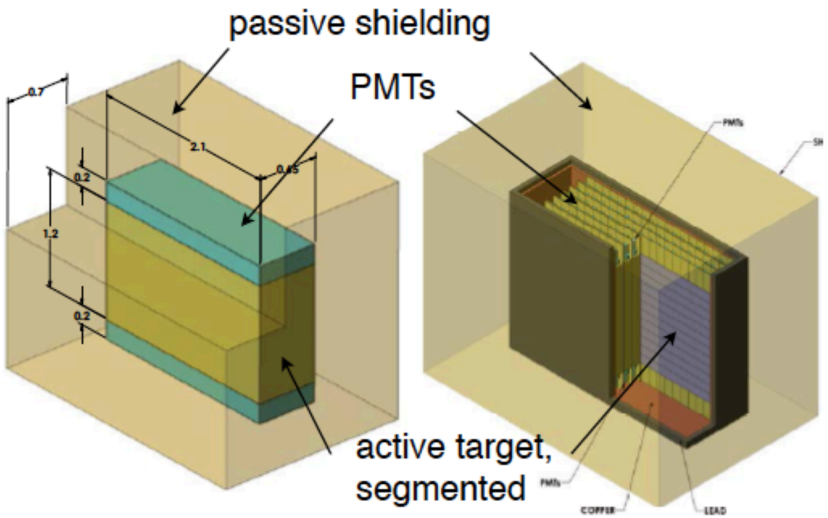




US effort: 2-Detector Oscillation

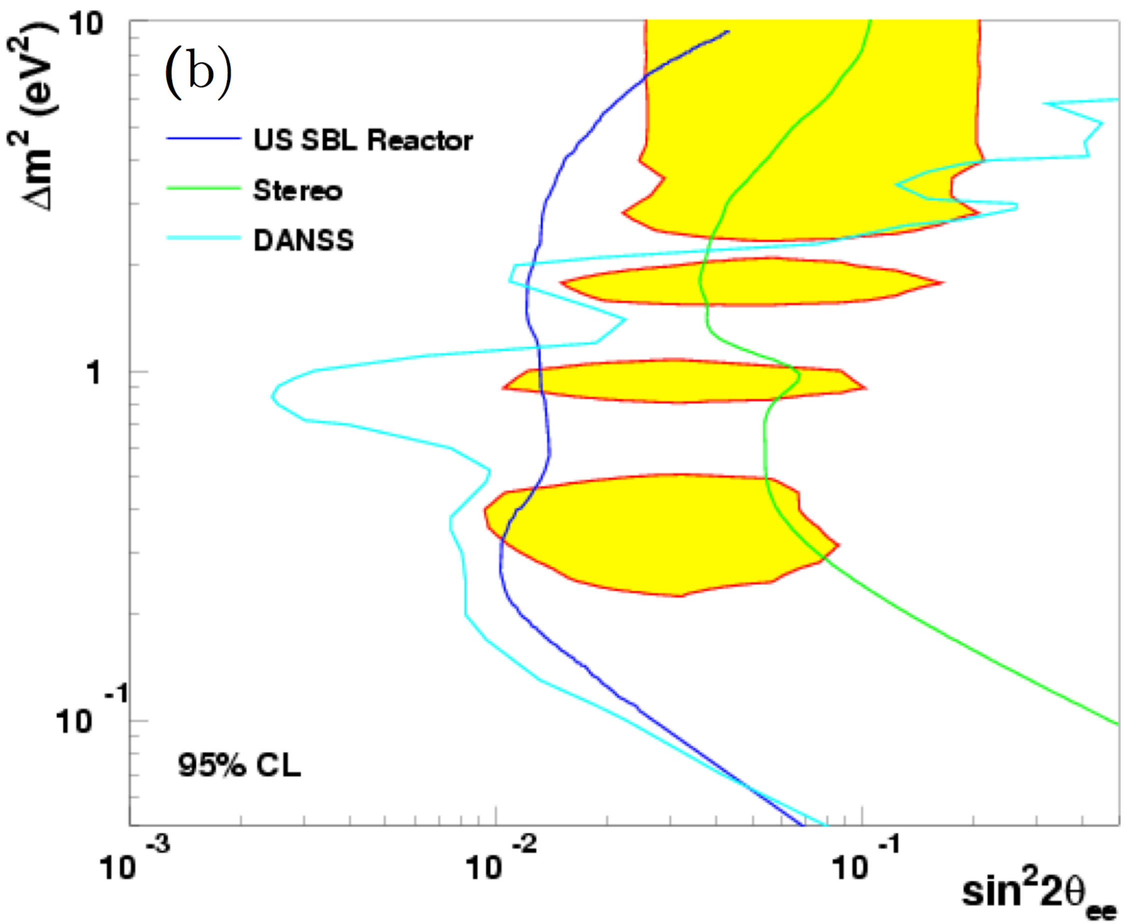
- LS target based technology
- 3 reactor sites
  - NIST – 20 MW
  - ATR – 85 MW
  - HFIR – 120 MW
- Surface location
- 2-detector concept
- Status:
  - Site characterization ongoing
  - Start 2016?





Influence of Source/Detector Parameters

All current projects have the sensitivity to test the reactor anomaly space of parameters, $\Delta m^2 > 0.1\ eV^2$, $\sin^2 2\theta > 0.05$



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Experimental Program: @ Neutrino Generator

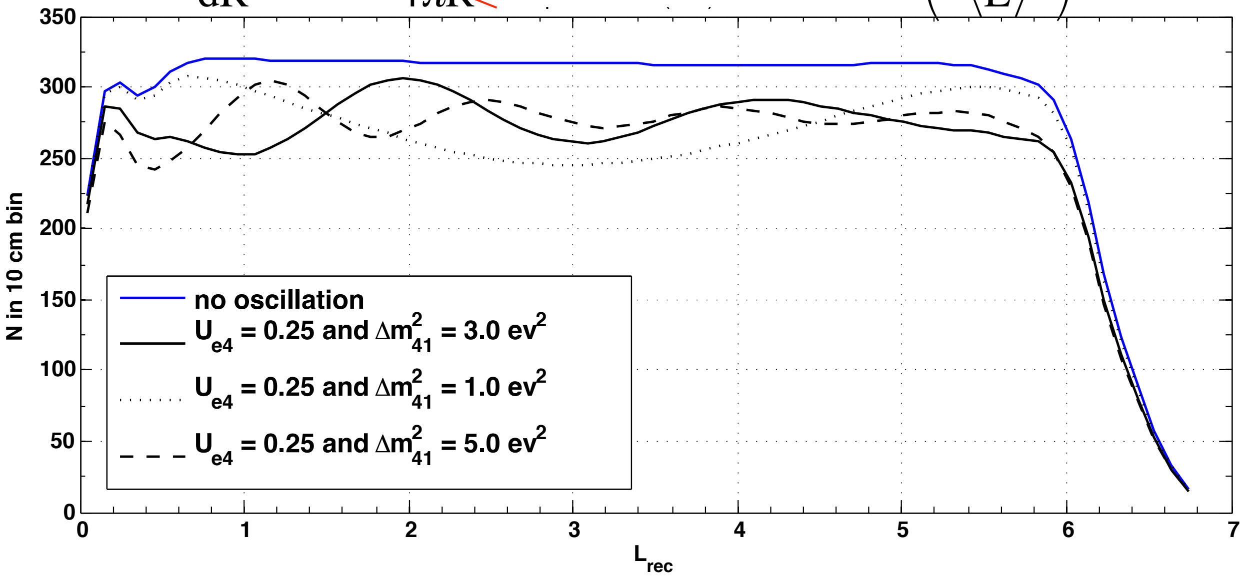
Test of both reactor & gallium anomalies

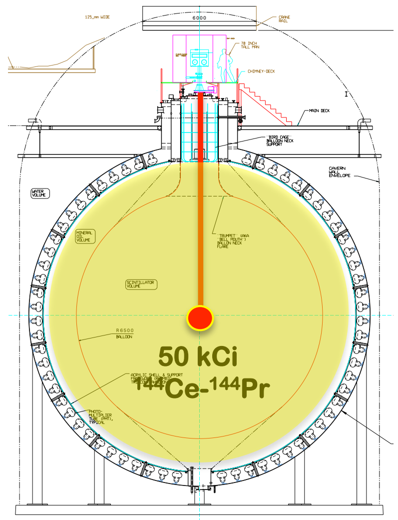
ν Generator Proposals

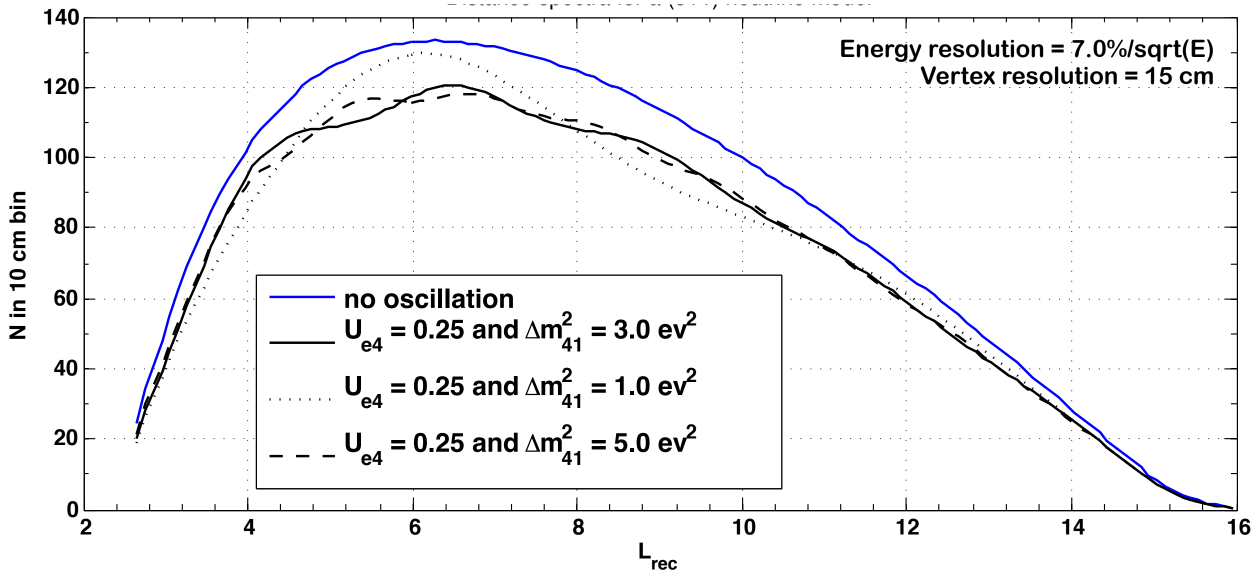
Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	$\nu_e e \to \nu_e e$ 5% E_{res} 15cm R_{res} or Radio-chemical	Detector Radioactivity Solar ν (irreducible) ν generator impurities	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	>3 MCi	Sage LENS
					>10 MCi	SOX (SNO+)
			^{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		-	-
	$^{3}H \to He\ \underline{e^-}\ \bar{\nu}_e$ EC/β-decay	Kink search	^{3}H E<18 keV	Irradiation in reactors	3 Ci	KATRIN (Mare/Echo)

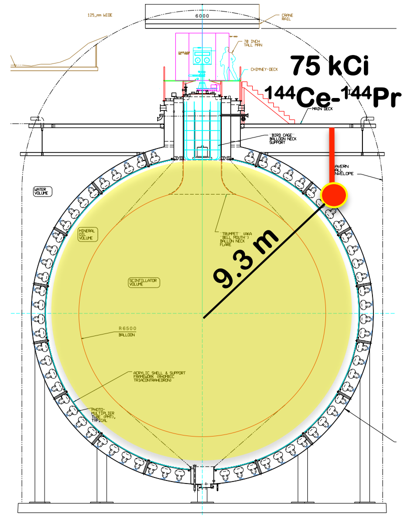
Search for $\bar{\nu}_e \rightarrow \bar{\nu}_s$ with $^{51}Cr/^{144}Ce$

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









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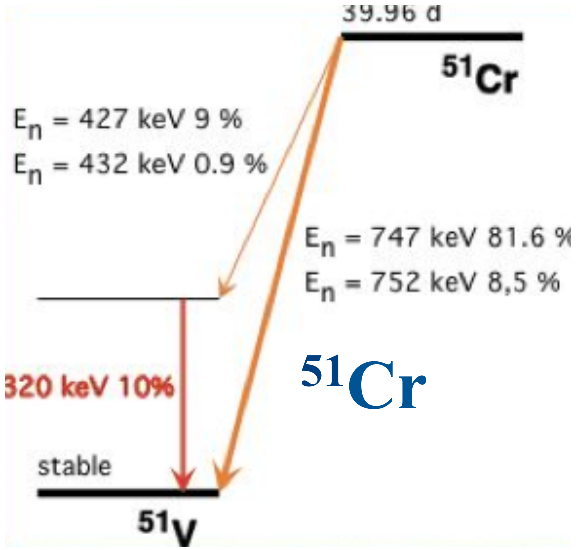
^{51}Cr neutrino generator

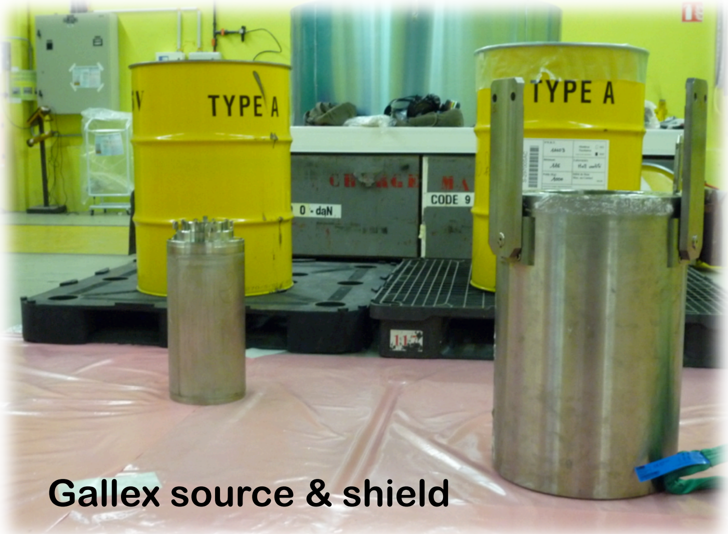
- **^{51}Cr EC**
  - E = 0.75 MeV
  - $t_{1/2}$ = 26 days

- **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

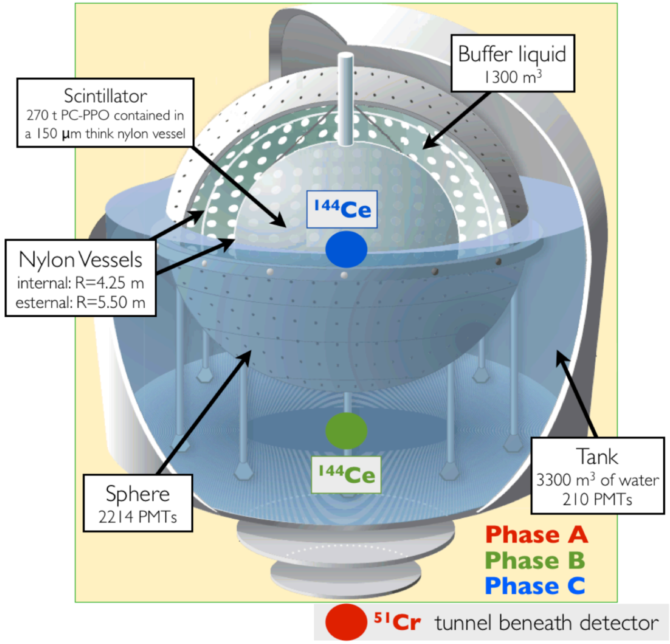


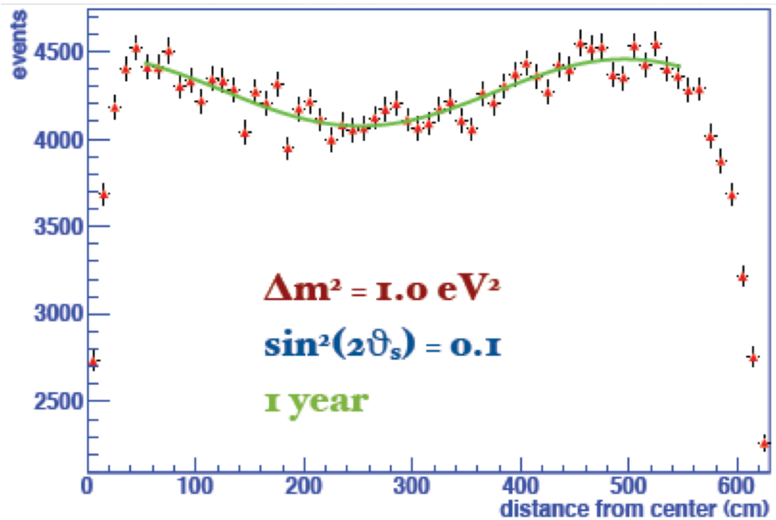


Gallex source & shield

^{51}Cr: SOX (Borexino)

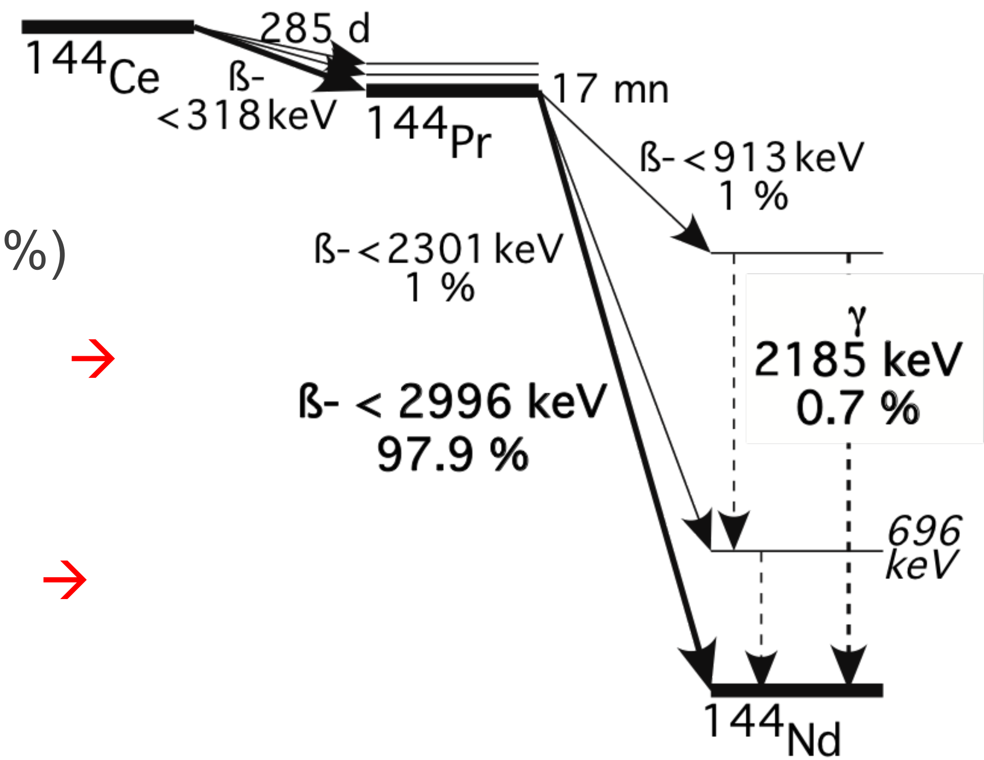
- Re-use **Gallex 36 kg** of enriched chromium
- Production reactors
  - Oak Ridge (US)
  - Ludmila (Ru)
- Source **8.25 m** from center
- **Detection as for ^{7}Be solar ν**
  - Well known background
- Status:
  - Preparation for irradiation and transportation (10 MCi)
- Staged approach: ^{51}Cr & ^{144}Ce





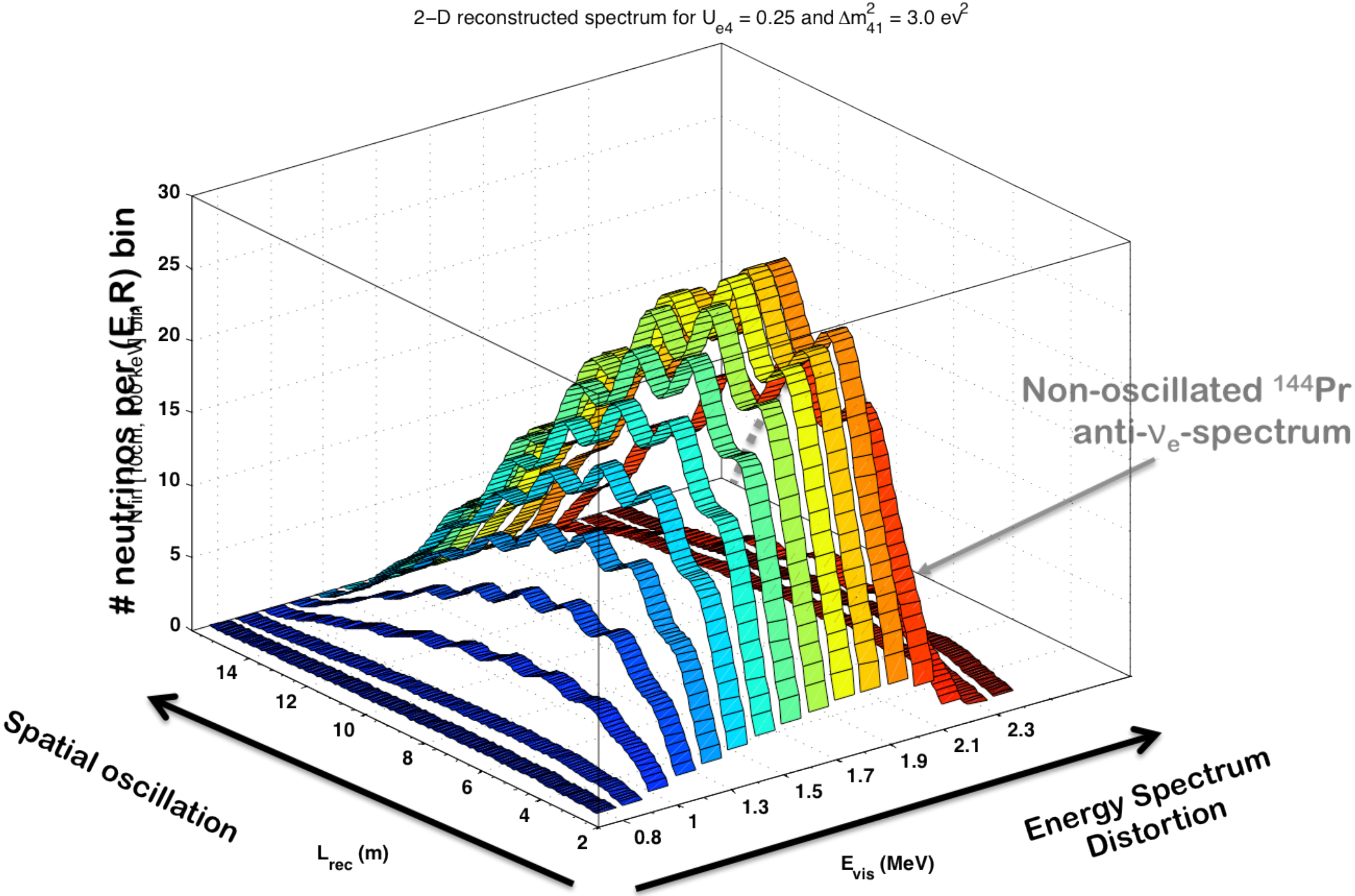
^{144}Ce-^{144}Pr $\bar{\nu}$ generator

- 1st 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**
- 2nd 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 Signal

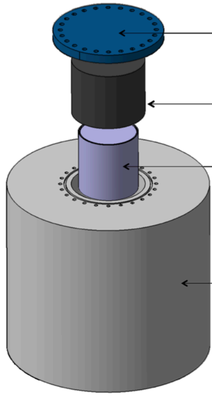
75 kCi ^{144}Ce-^{144}Pr – 9.3 m from detector center – 1.5 year

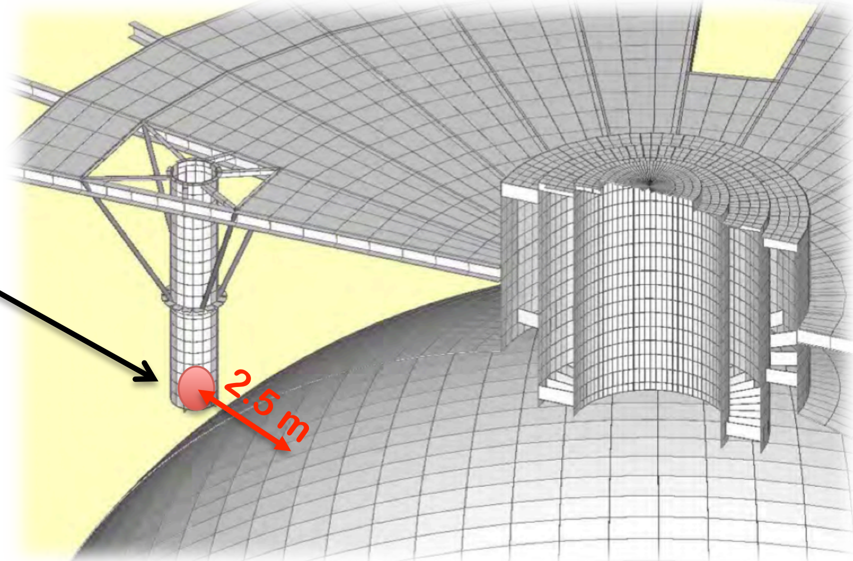


Th. Lasserre – ICFA-ν 2014

^{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 2015/16

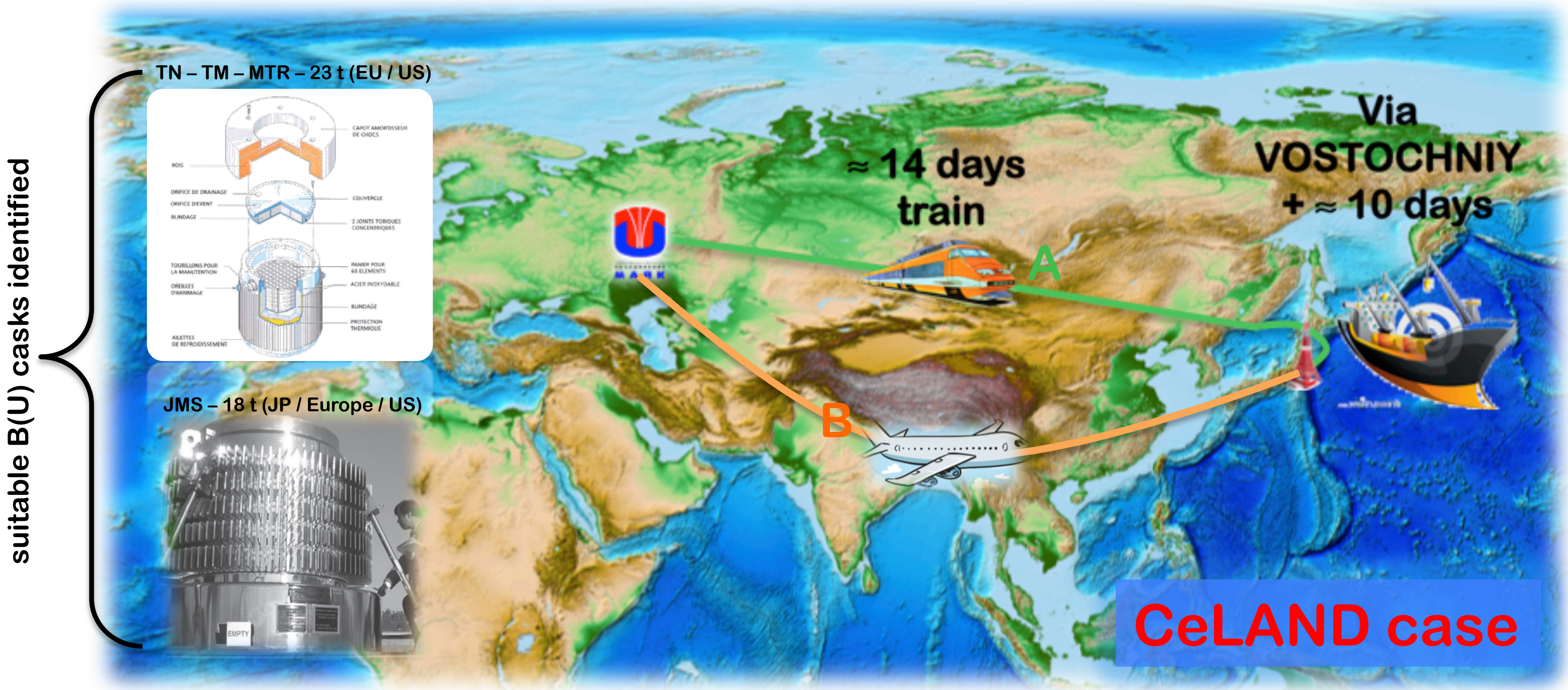




^{144}Ce & ^{51}Cr: a Challenging Logistic

IAEA rules on Safe Transportation of Radioactive Material

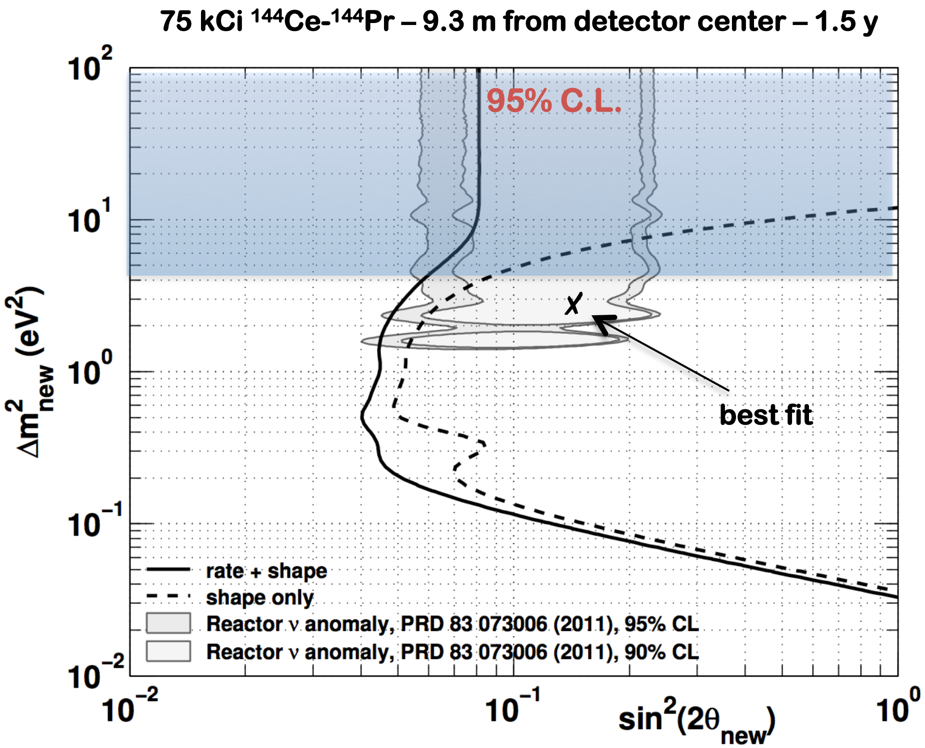
A) Need suitable certified transport container



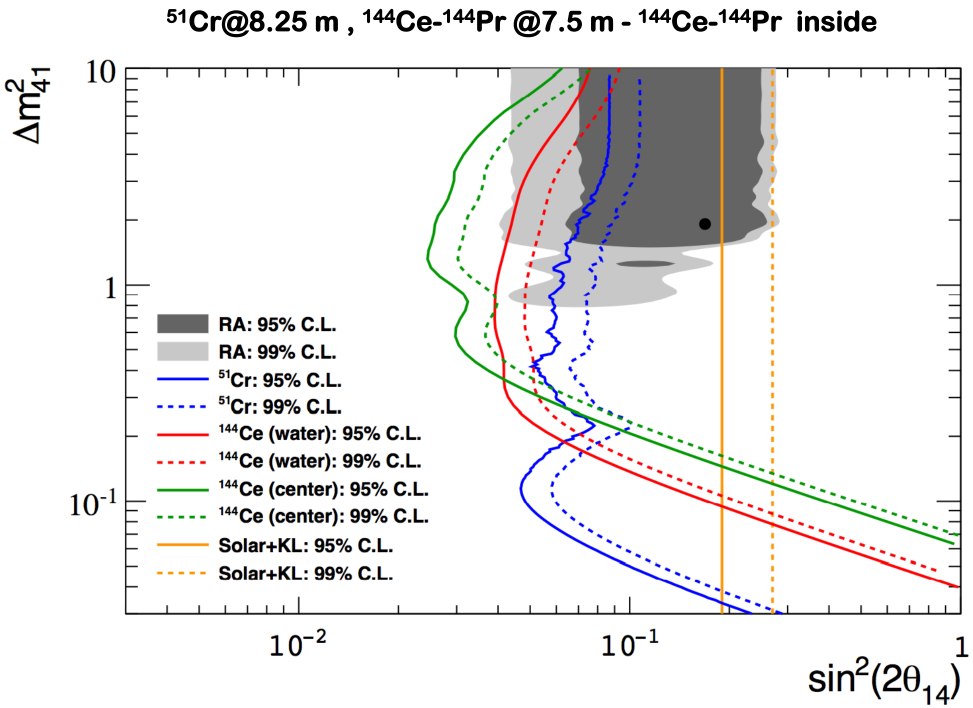
B) Route identified (4 weeks journey for CeLAND)

ν-Generator sensitivities

CeLAND (KamLAND)



SOX (Borexino)



Data Taking Goals

^{144}Ce-^{144}Pr in 2015/6

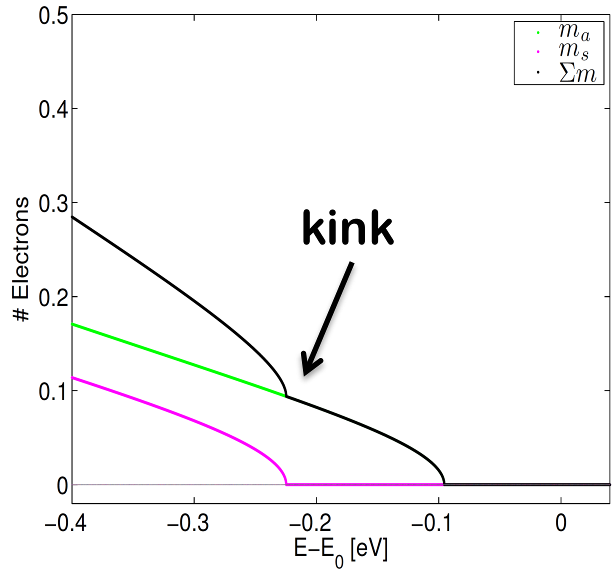
^{51}Cr in 2015/6
^{144}Ce-^{144}Pr in 2016/7

Search for ν_s with ^{3}H β decay

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

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

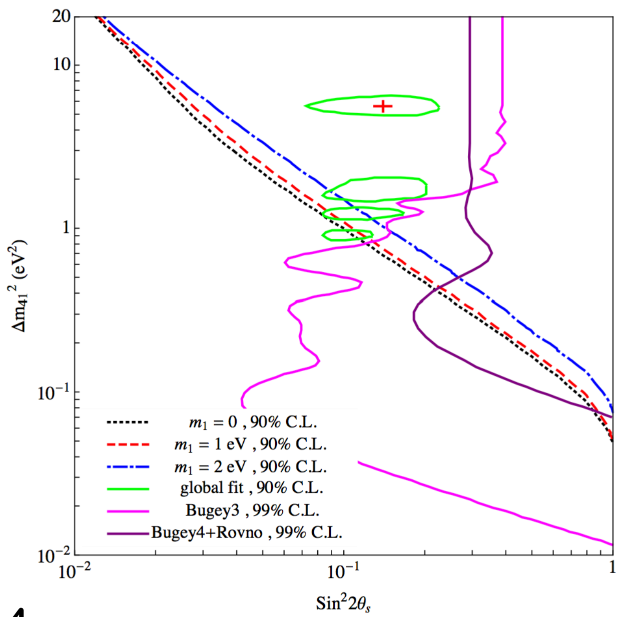
- **Hypothetical 4th ν contribution**



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

→Search for a kink few eV below end point

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



Experimental Program:
@ Neutrino Beam

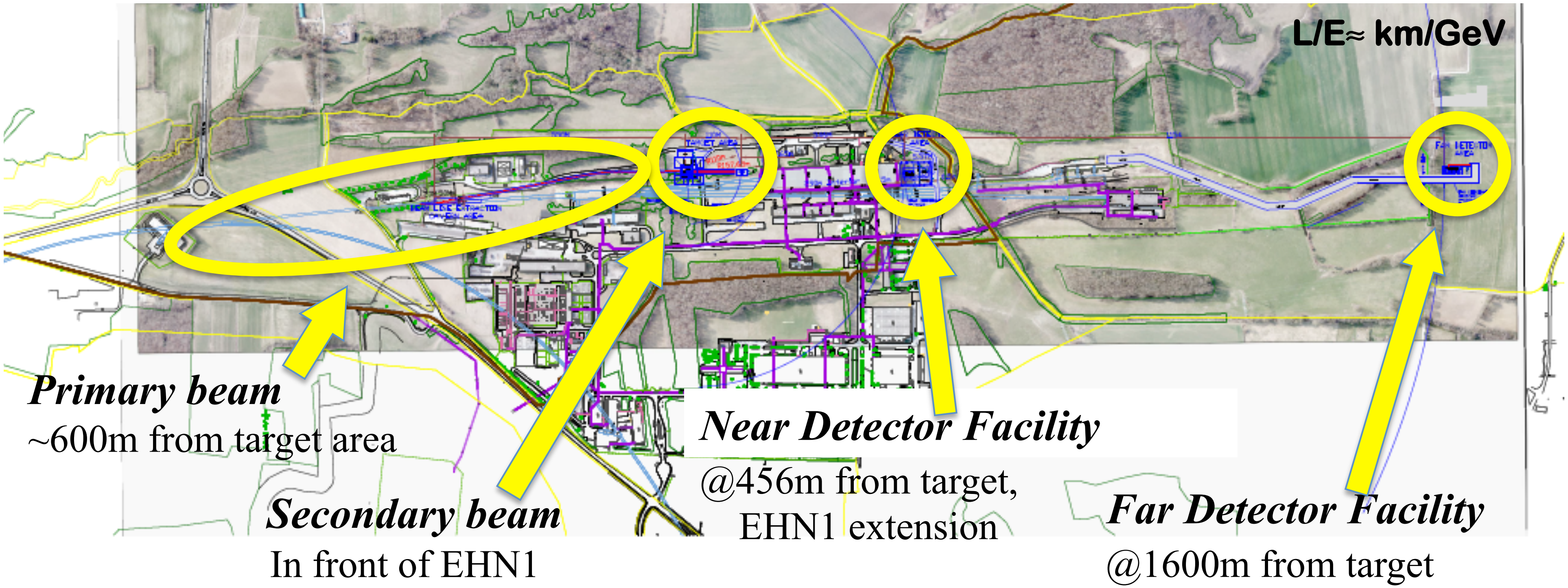
Test of LSND/MinibooNE/reactor/gallium anomalies
If positive signal, detailed study of sterile-ν phenomenology

ν Beam Proposals

Type	Source	App. /Dis.	Oscillation Channels	Projects
Isotope Decay at Rest	$p + {}^{9}Be \rightarrow {}^{8}Li + 2p$ $n + {}^{7}Li \rightarrow \underline{{}^{8}Li}$ $\underline{{}^{8}Li} \rightarrow {}^{9}Be + e^{-} + \bar{\nu}_e$	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.	$\nu_e \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_e$	νSTORM

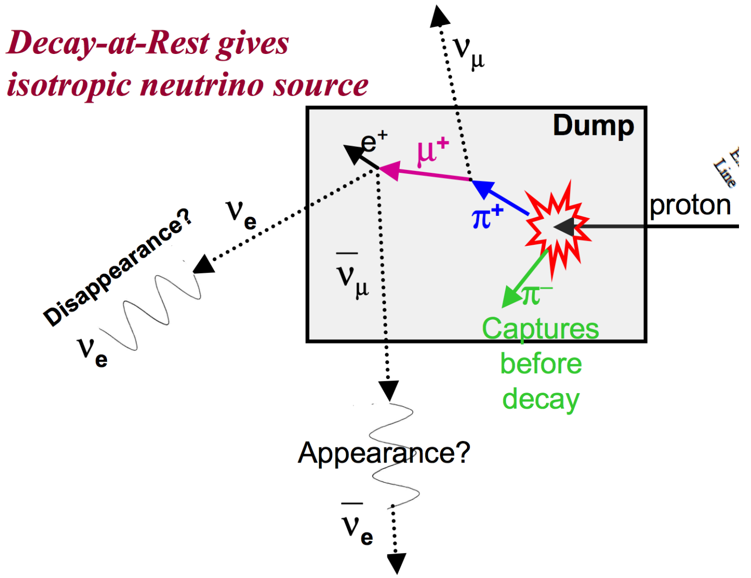
Pion Decay in Flight ν-sources

- **Icarus/Nessie at CERN (also proposed at FNAL)**
  - **Move T600 (2 x 300 tons) from LNGS to CERN new T150 (150 tons)**
  - **New magnetized muon spectrometers**
  - **New neutrino beam extracted from SPS (on-axis, few GeV, fast extraction, 4.5 10^{19} pot/y, neutrinos & antineutrino runs)**



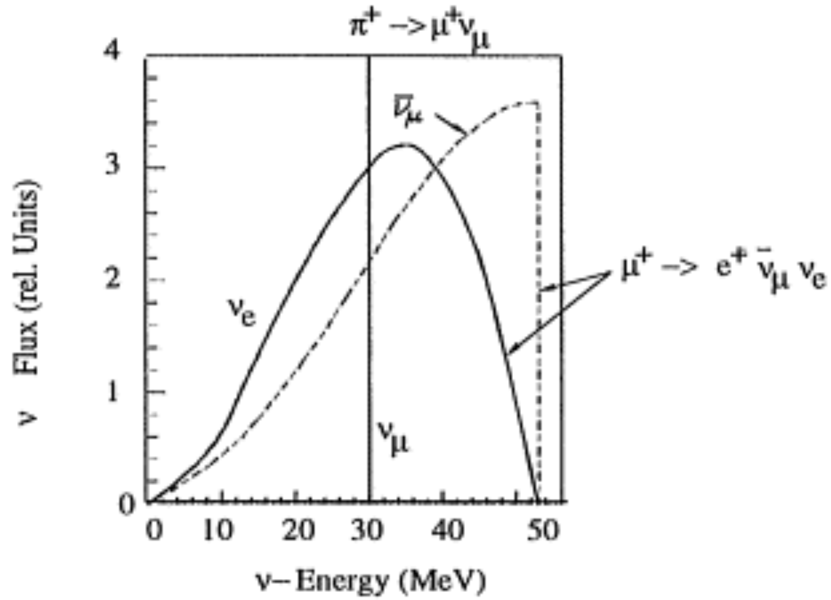
Pion Decay at Rest ν-sources

- **High Energy Proton source**
  - Each π^+ decay
    - $\nu_\mu, \nu_e, \bar{\nu}_\mu$
    - known E spectrum
  - Near a large detector
    - Cherenkov (water or oil)
    - Liquid argon
    - Liquid scintillator



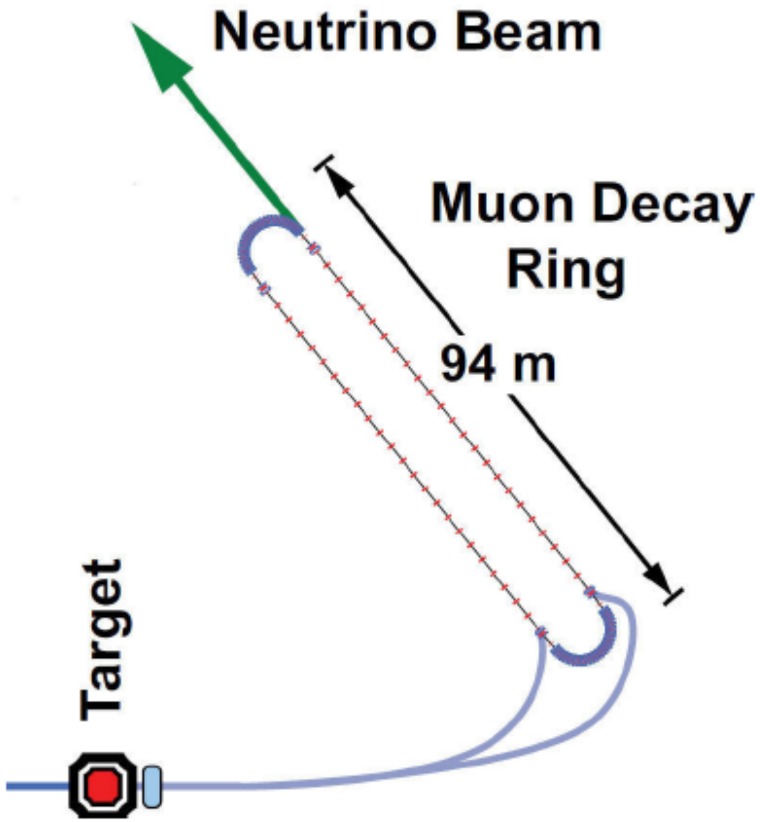
- **Detection channels**
  - $\nu_e \rightarrow \nu_e$ Disappearance
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance

- **OscSNS**
  - Direct Test of LSND
  - 800t detector @ 60 meters



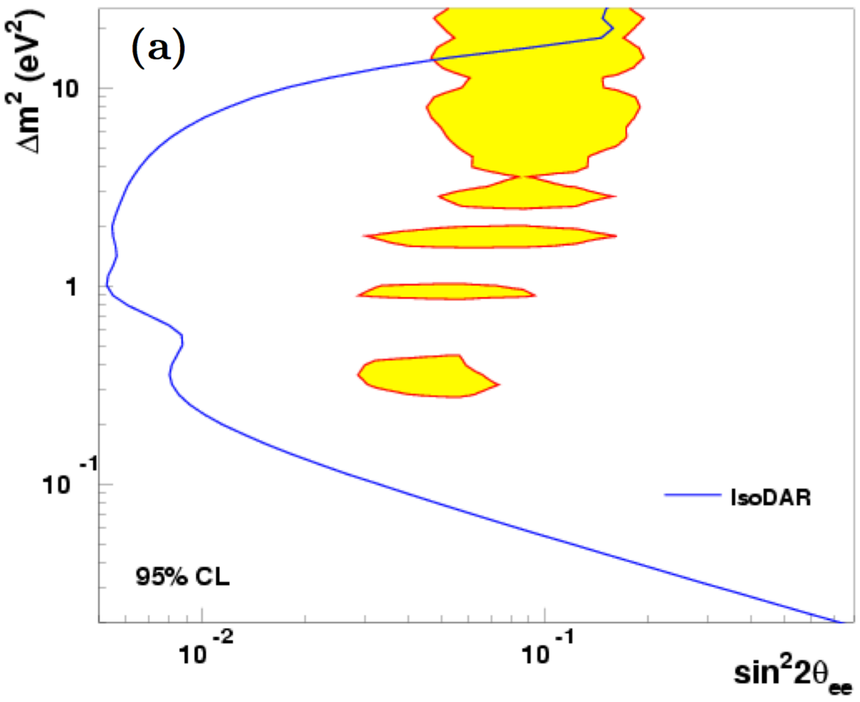
Muon Decay Rings: ν-STORM

- Neutrino Factory Concept
  - 60 GeV protons on solid target
  - Horn capture and π transfer
  - Muon storage ring
- APP and DIS channels with:
  - Well known beam of $\overset{(-)}{\nu}_\mu$, ν_e
- kT-scale Minos-like
  - 2 km baseline
  - Magnetized (tag muon charge)
- Golden Mode (μ^+ stored)
  - ν_μ APP in a ν_e beam
- Definitive sterile ν search

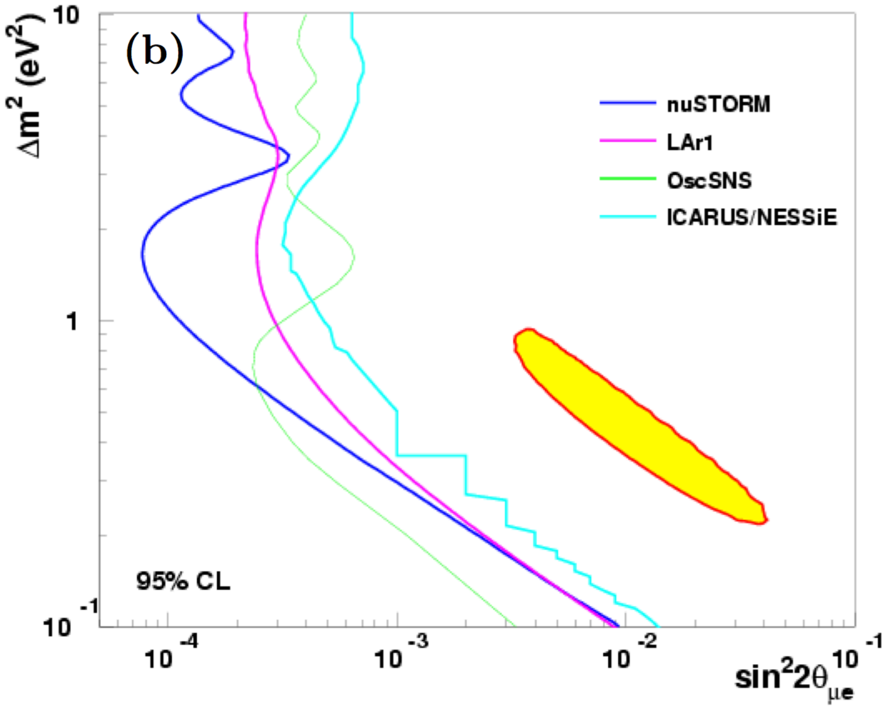


Beam Experiment Sensitivities

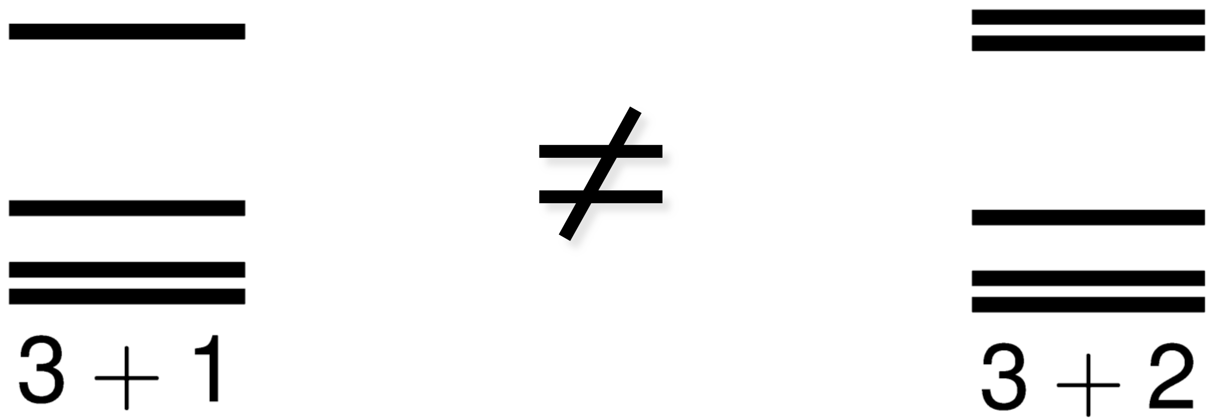
Disappearance



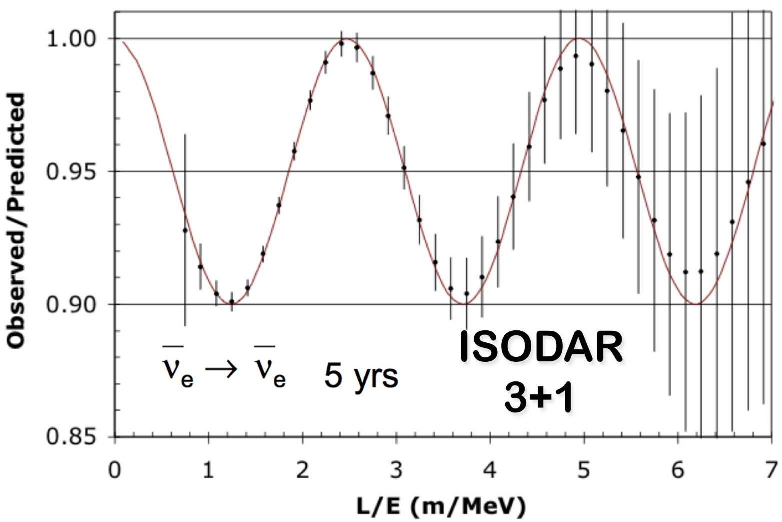
Appearance

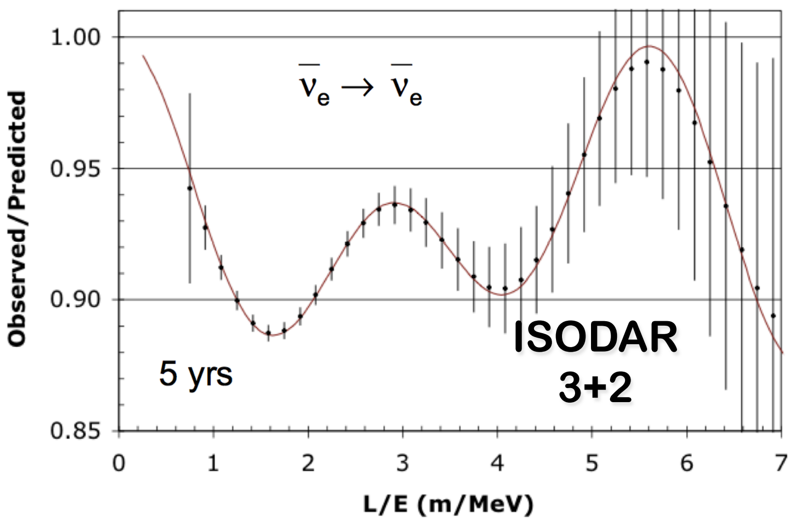


Isotope Decay at Rest ν-sources



Oscillation L/E Waves with High Statistics





Conclusion (1)

- 2.7 – 3.8 σ anomalies (each) calling for clarification
  - LSND & MiniBooNE?
  - Gallium Anomaly
  - Reactor Anomaly
  - → $\Delta m^2 \approx eV^2$ Sterile Neutrino? Or Experimental Artifacts?
- But also negative indications:
  - No deficit in $\Delta m^2 \approx eV^2$ muon disappearance
  - Tensions in global fits (APP vs DIS)
- Establishing the existence of sterile neutrinos would be a major result for physics

Conclusion (2)

- Many proposals with capabilities to unambiguously test L/E≈1 m/MeV oscillatory behavior with low backgrounds
- **Reactor Neutrinos**
  - Results within 5 years, Modest Cost (2-10 M$)
  - Background mitigation is challenging
- **Neutrino Generator**
  - Results within 5 years, Modest Cost (<5 M$)
  - Challenge for the source production and transportation
- **Neutrino 'Beam'**
  - Longer Term, Higher Cost
  - Would allow a complete study sterile neutrino phenomenology
- **Independent tests through β-decay and $(\beta\beta)0\nu$-decay**