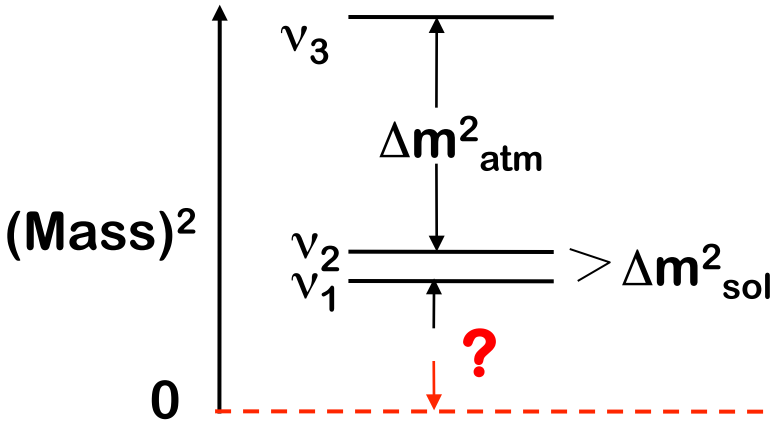
Sterile Neutrinos

Thierry Lasserre - Saclay

Asilomar, TAUP 2013

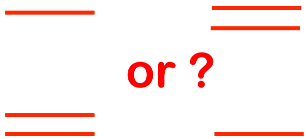
Open questions in ν physics

- 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?

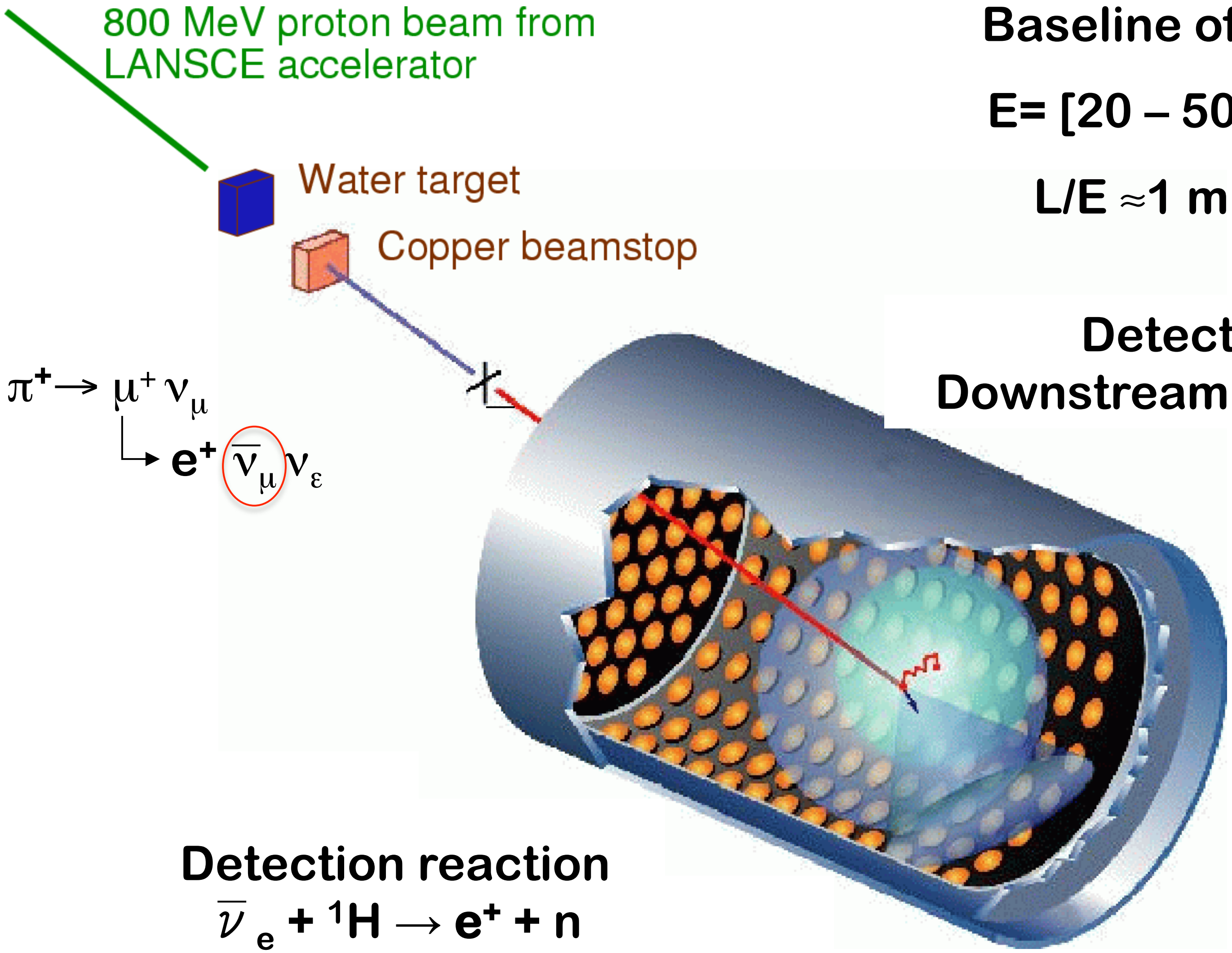
} ν flavor change

- **Are there additional (sterile) neutrino states** ν flavor, Astro/Cosmo

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

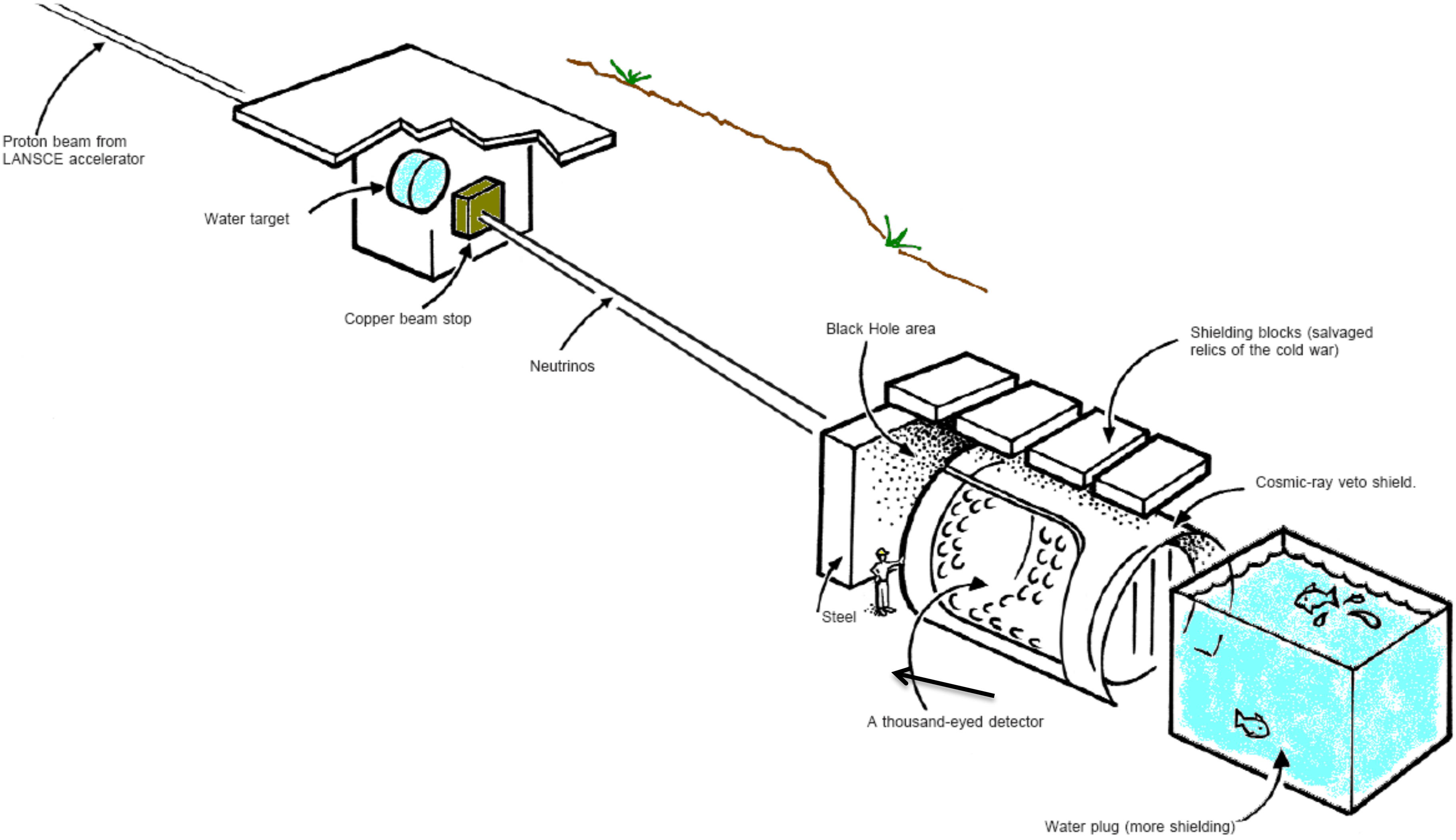
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \bar{\nu}_\mu \nu_\varepsilon$$

Detection reaction

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

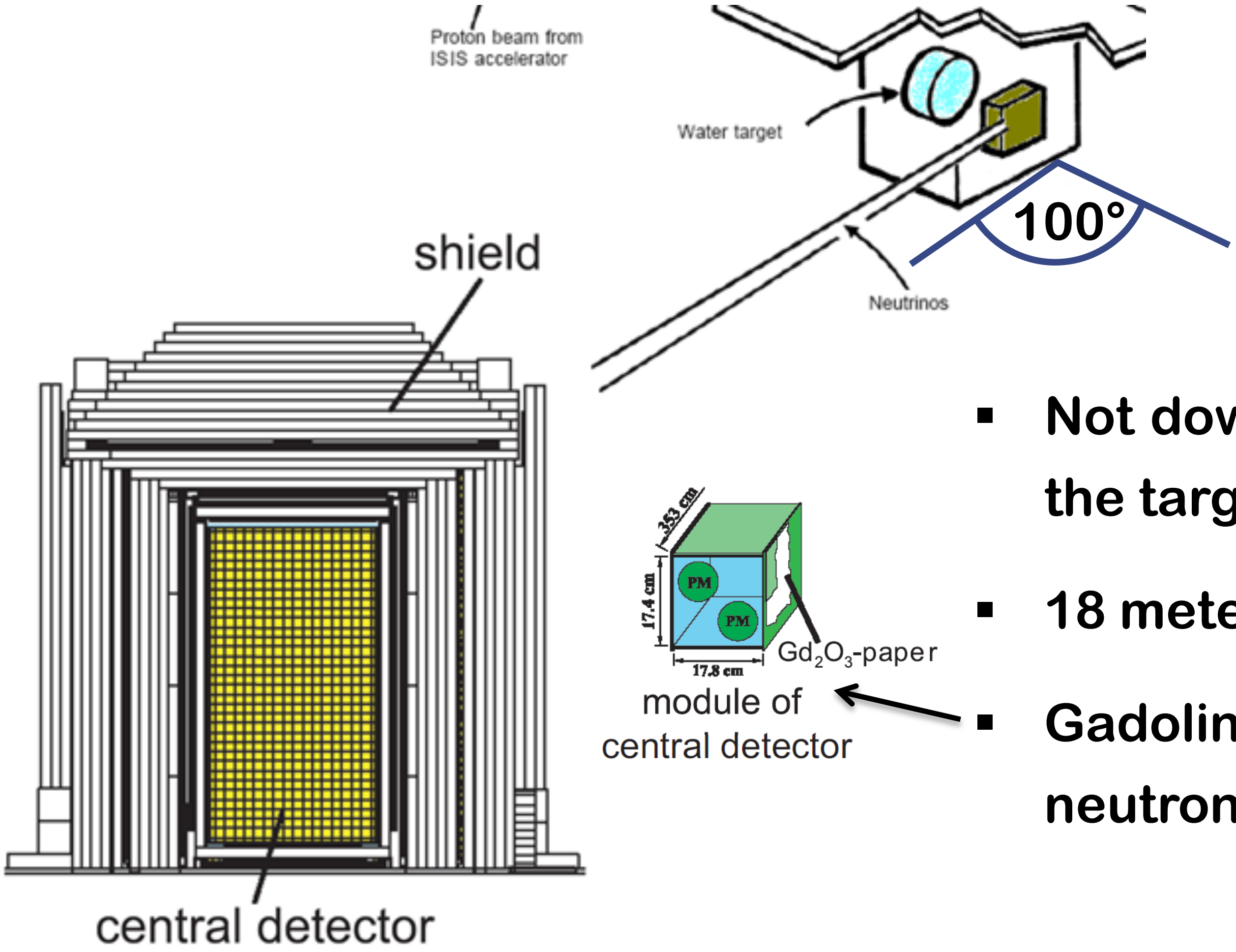
Karmen (stopped π^+ beam)

Oscillation not confirmed – exclude part of LSND



Karmen (stopped π^+ beam)

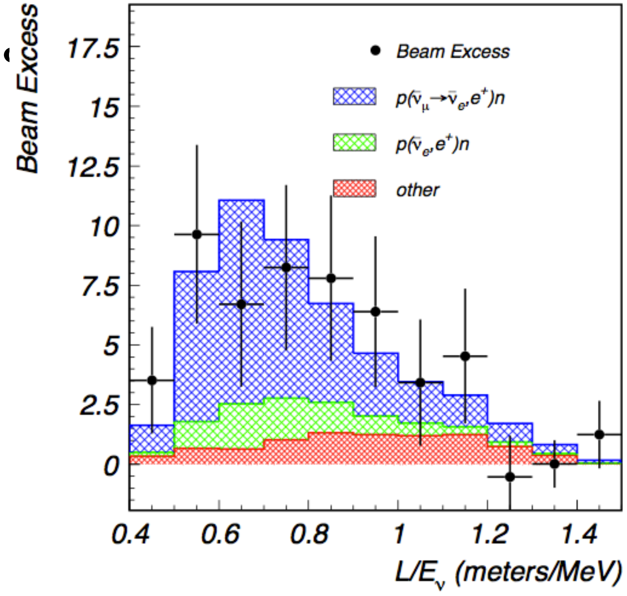
Oscillation not confirmed – exclude part of LSND

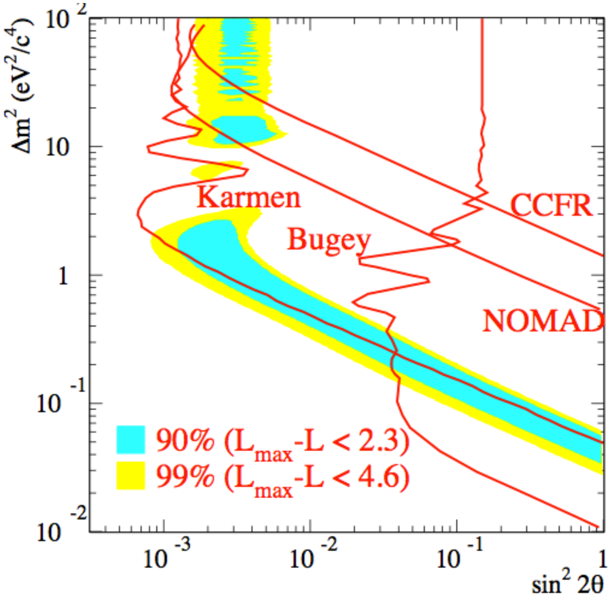


- **Not downstream of the target**
- **18 meters baseline**
- **Gadolinium for neutron capture**

LSND Results

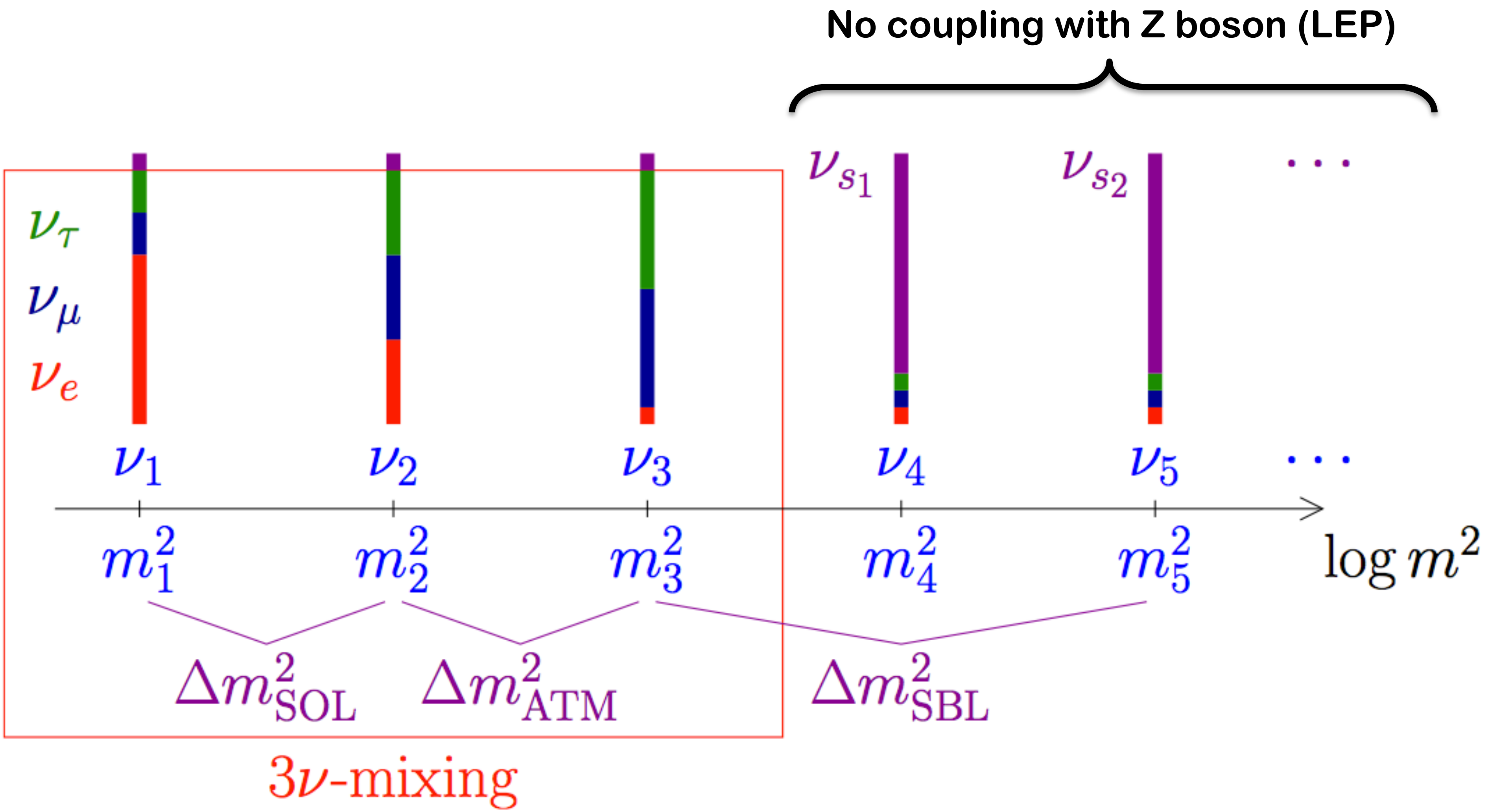
- 1^{st} results in 1995
- **Channel:** anti-ν_μ → anti-ν_e
- **Detection : anti-ν_e + ^1H → e^+ + n**
- **Baseline:** 30 m
- **Energy:** 20 < E (MeV) < 50
- **Status:**
  - anti-ν_e excess observed
    → 32.2 ± 9.4 ± 2.3 (3.8σ)
  - not confirmed nor ruled out by Karmen
- **ν-Oscillation interpretation:**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





The (light) sterile neutrino hypothesis

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

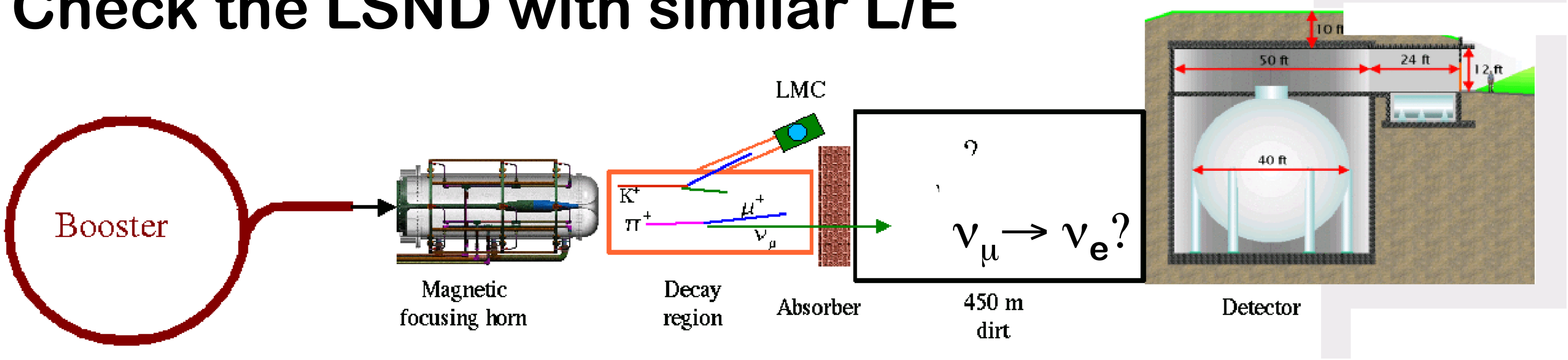


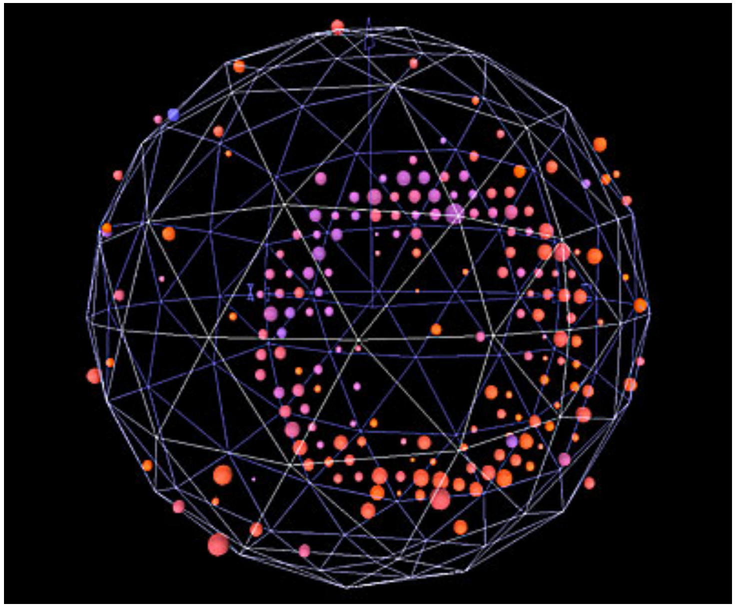
No coupling with Z boson (LEP)

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: Cherenkov + 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

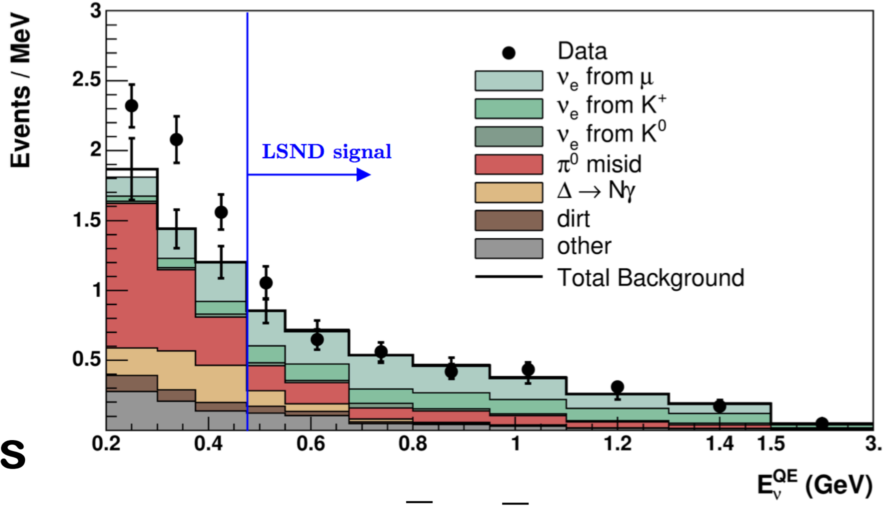
- **Detection:** ν_e (p)n → e p (CCQE)

- **Results:**
  - An overall 3.8 σ excess of events
  - Mostly at low energy

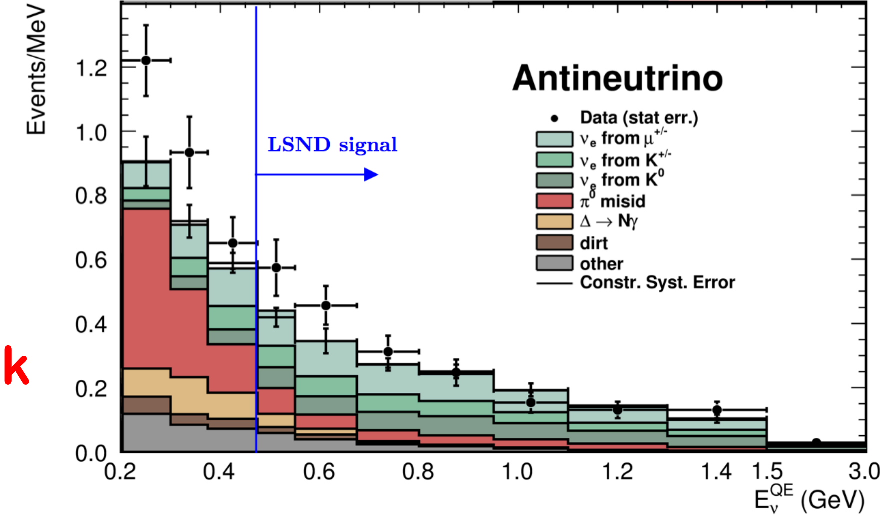
- **Interpretation:**
  - Backgrounds issue?
    (to be checked by MicroBooNE)
  - 4th neutrino? Or more….

- **MiniBooNE is not conclusive to check the LSND anomaly**

$\nu_\mu \rightarrow \nu_e$

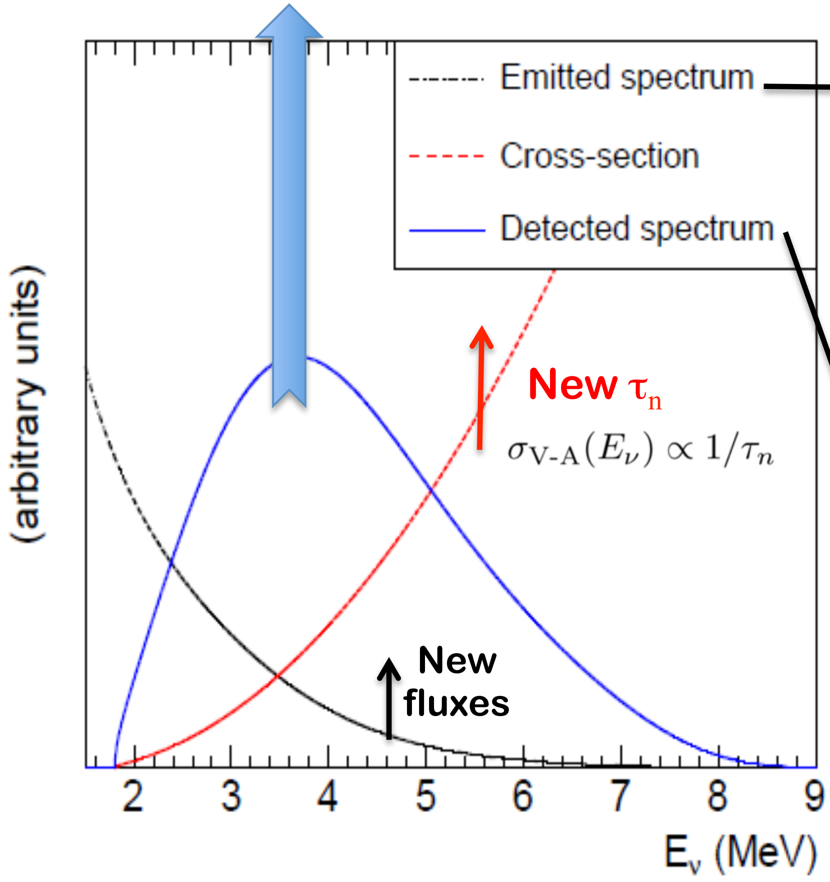


$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



New Reactor ν-Fluxes

Increased prediction of detected flux by 6.5%



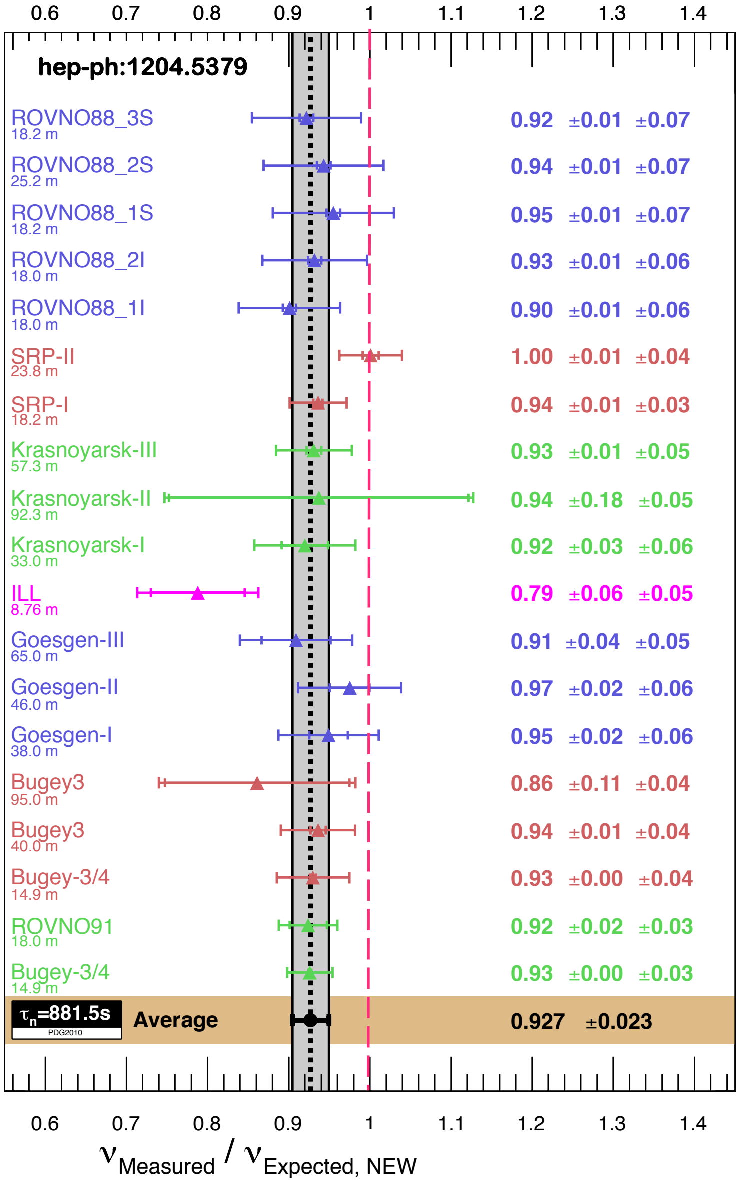
i) Neutrino Emission:

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

ii) Neutrino Detection:

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

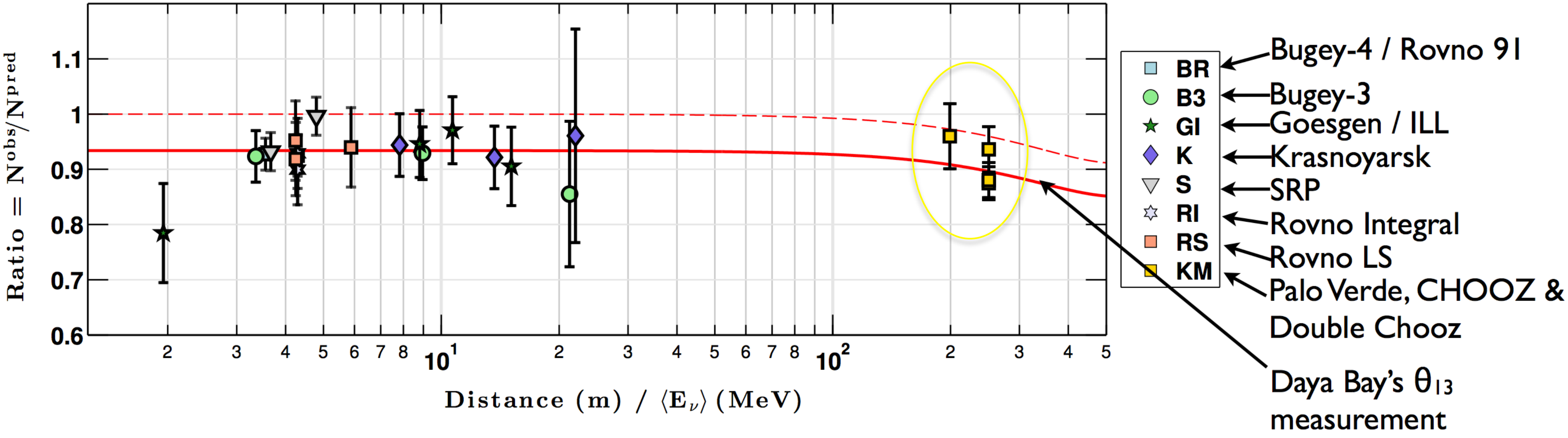
Reactor Antineutrino Anomaly



- 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

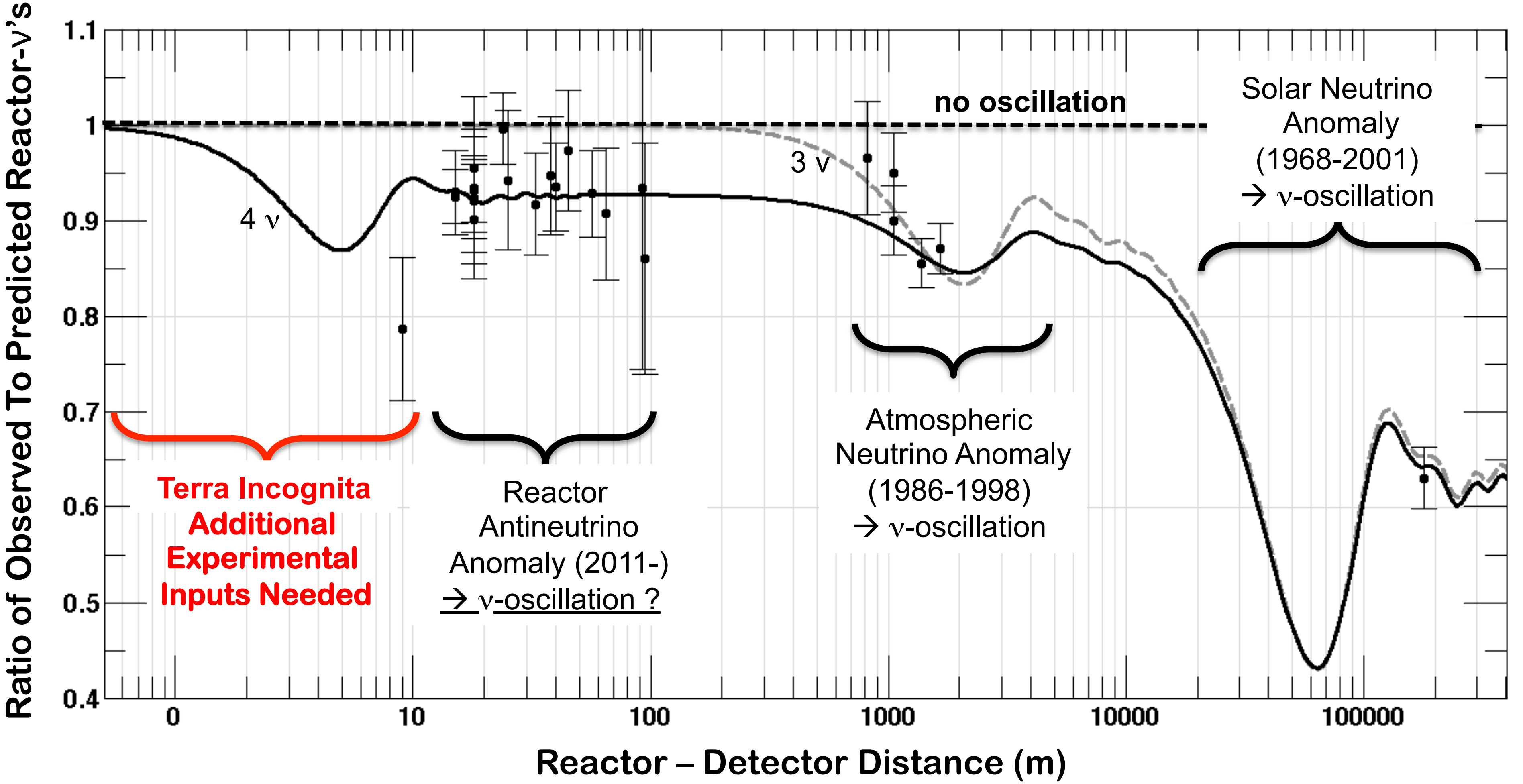
Including km-scale experiments

2013 Reactor Anomaly Update (new)



- 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?



Terra Incognita Additional Experimental Inputs Needed

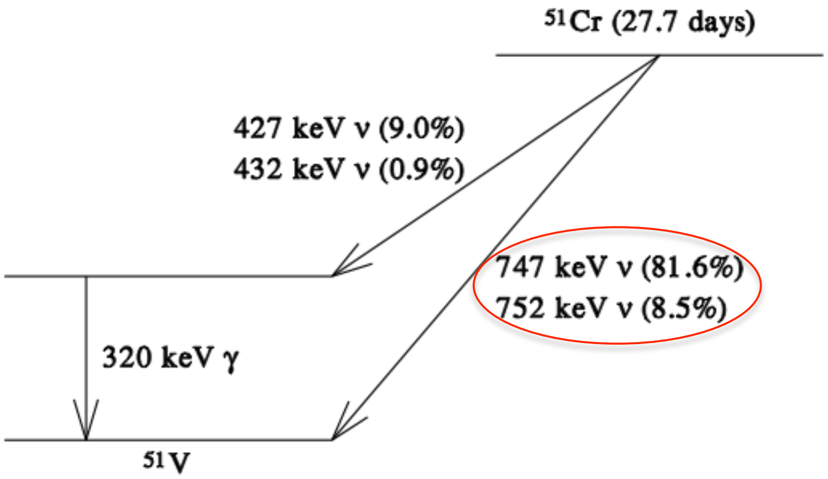
Reactor Antineutrino Anomaly (2011-) → ν-oscillation ?

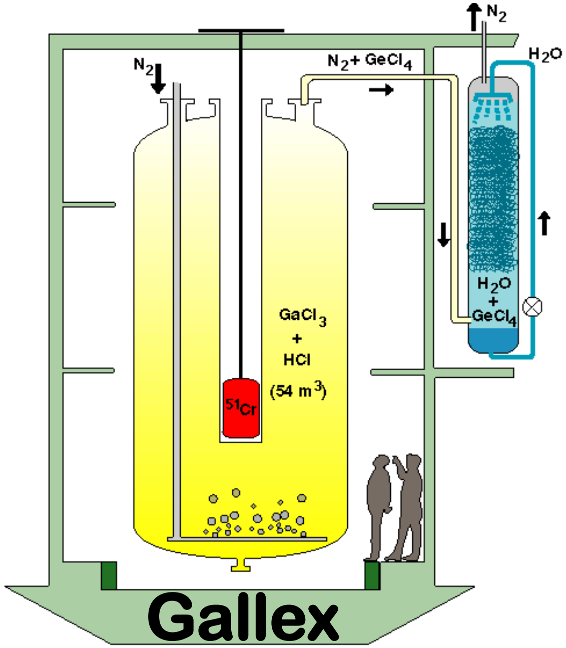
Atmospheric Neutrino Anomaly (1986-1998) → ν-oscillation

Solar Neutrino Anomaly (1968-2001) → ν-oscillation

The Gallium Neutrino Anomaly

- Test of solar neutrino radiochemical detectors GALLEX and SAGE
  - $^{71}\mathrm{Ga}/^{37}\mathrm{Ar} + \nu_e \rightarrow ^{71}\mathrm{Ge}/^{37}\mathrm{Cl} + e^-$
- 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 $^{71}\mathrm{Ga}(^3\mathrm{He}, ^3\mathrm{H})^{71}\mathrm{Ge}$ cross section meas.

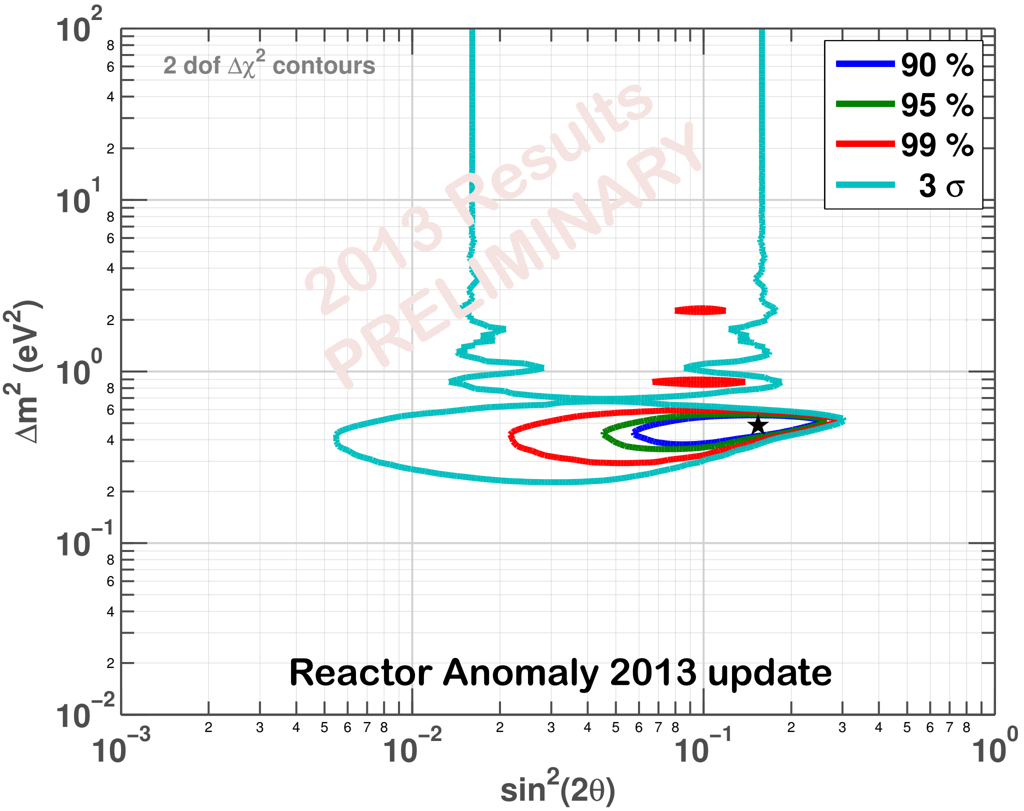




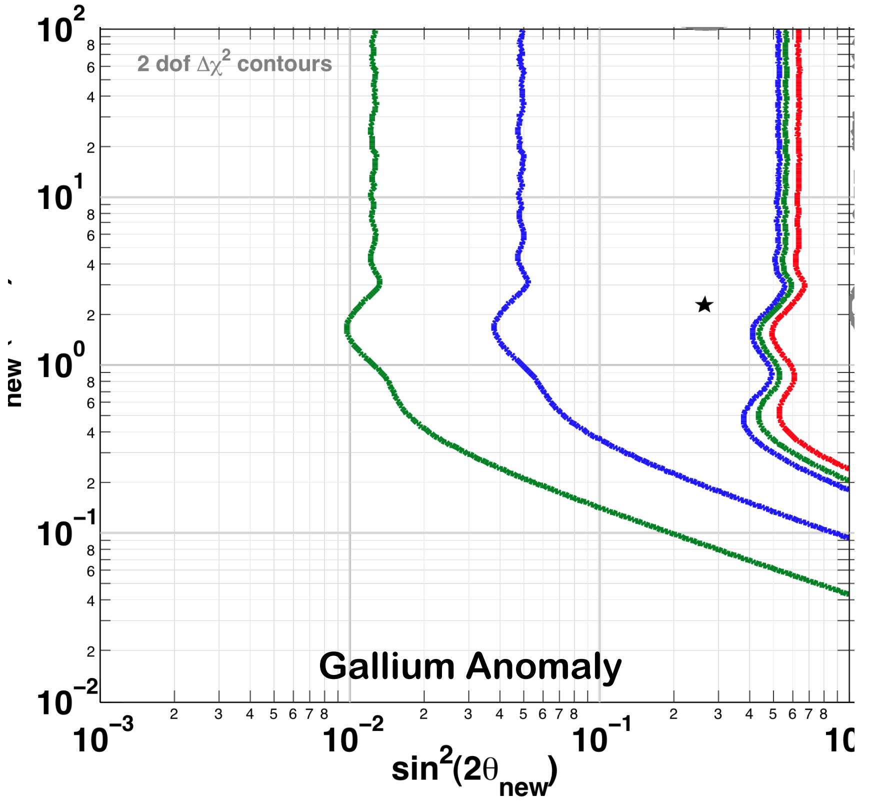
Sterile Neutrino Interpretation

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

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



Reactor Anomaly 2013 update



Gallium Anomaly

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

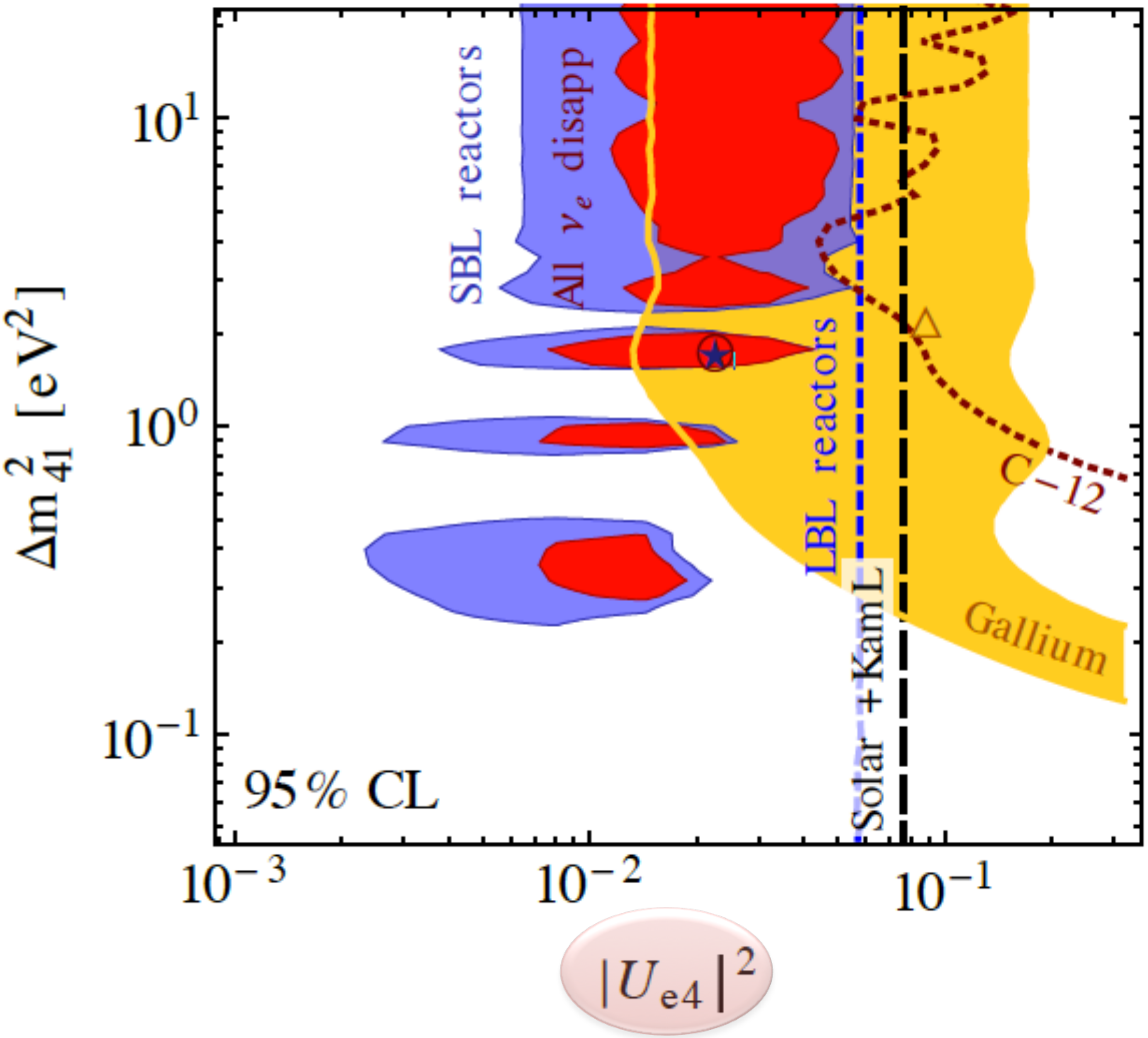
Sterile-ν Oscillation Phenomenology

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

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

$\overset{(-)}{\nu}_e$ disappearance (3+1 scenario)

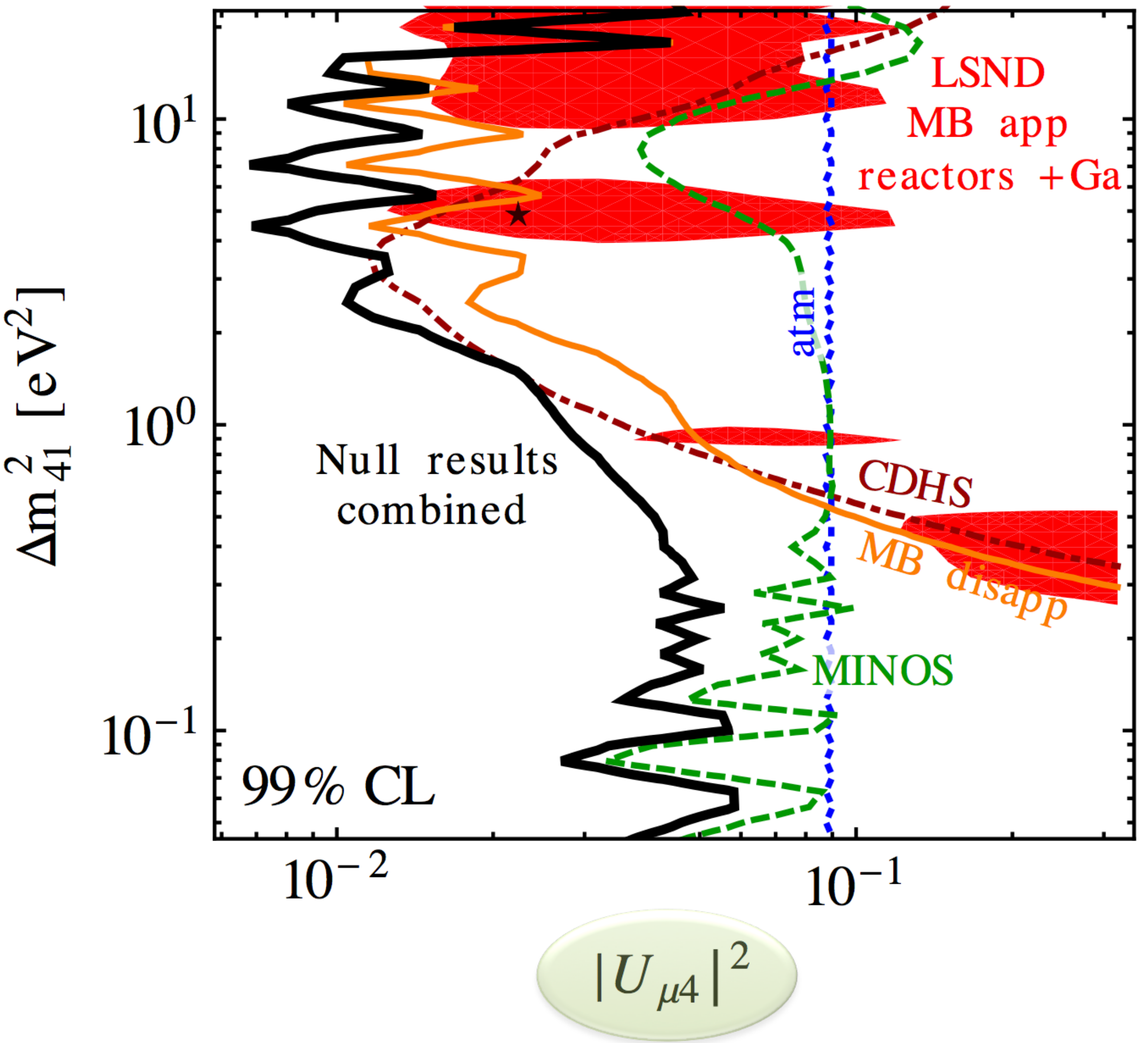
Data consistent with $\overset{(-)}{\nu}_e$ disappearance with L/E≈1 m/MeV



J. Kopp et al., arXiv:1303.3011

$\overset{(-)}{\nu}_\mu$ disappearance (3+1 scenario)

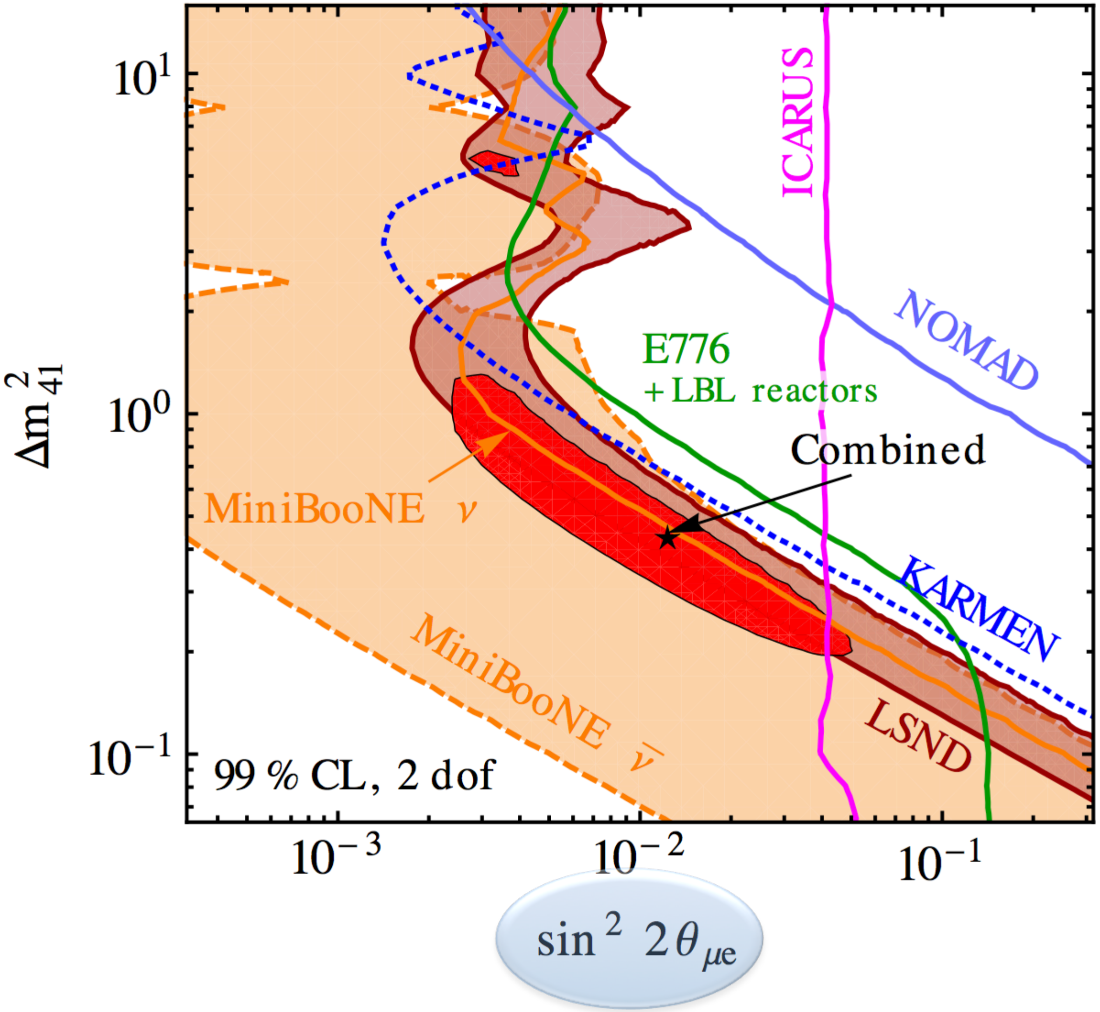
No hint for $\overset{(-)}{\nu}_\mu$ disappearance with L/E≈1 m/MeV



J. Kopp et al., arXiv:1303.3011

$\overset{(-)}{\nu}_e$ appearance (3+1scenario)

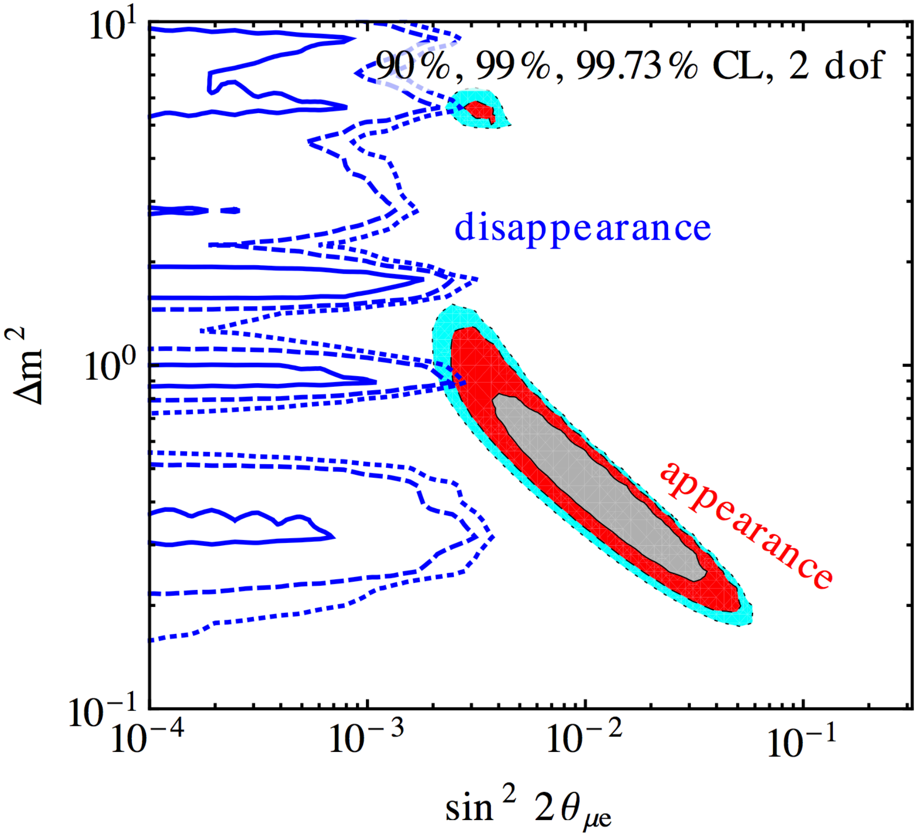
Consistent solution for $\overset{(-)}{\nu}_e$ appearance with L/E≈1 m/MeV



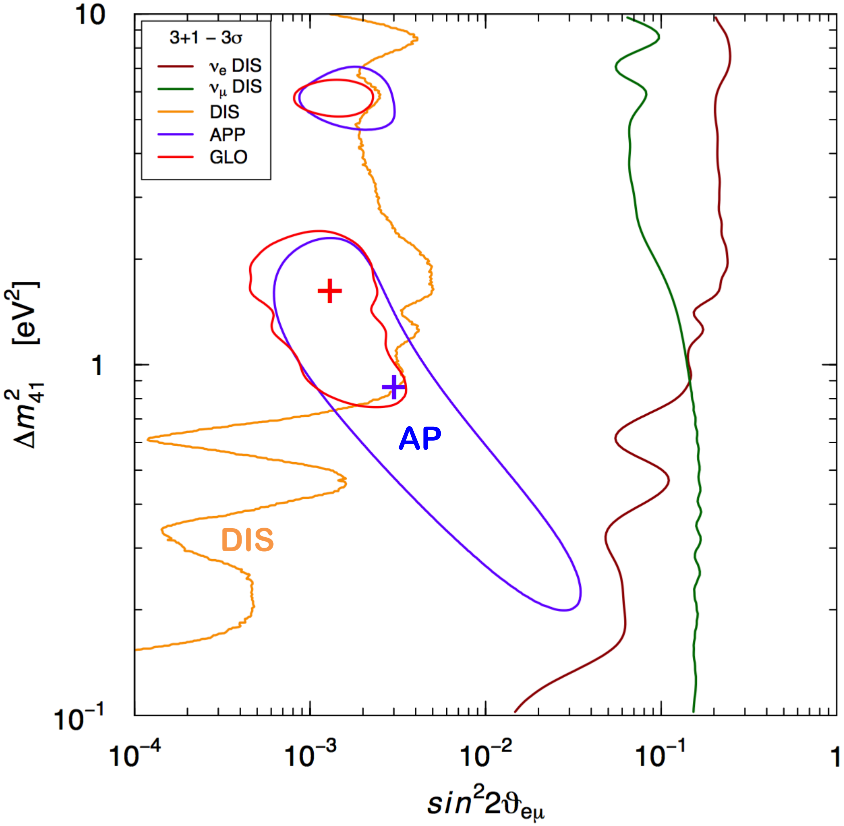
J. Kopp et al., arXiv:1303.3011

Appearance VS Disappearance

J. Kopp et al., arXiv:1303.3011



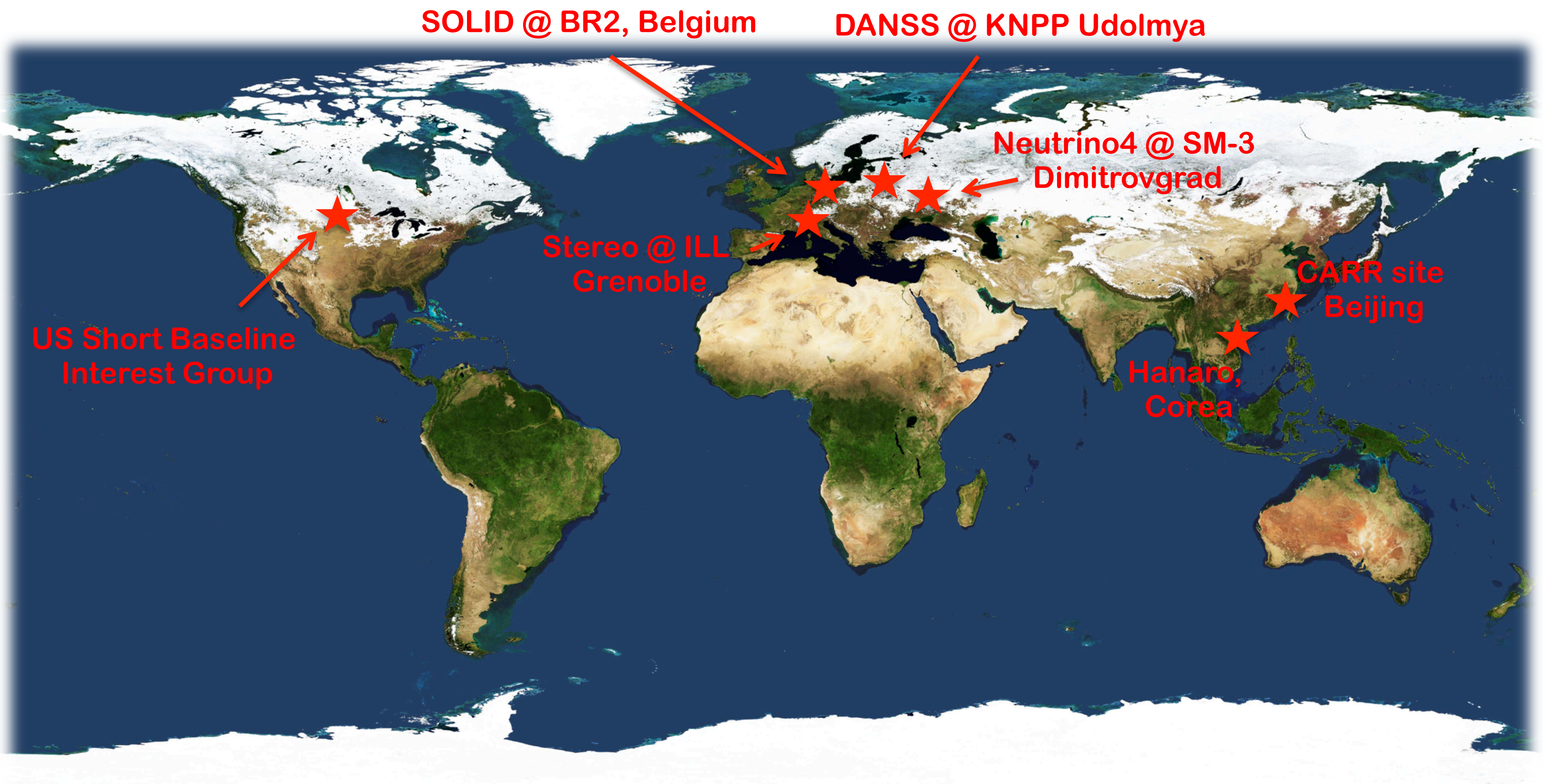
C. Giunti et al., arXiv:1302.6720



Hard to reconcile $\bar{\nu}_e / \nu_e$ appearance/disappearance with $\bar{\nu}_\mu / \nu_\mu$ disappearance (3+1 & 3+2 models)

Experimental Prospect

Experimental Prospect: @ Nuclear Reactor



Test of both reactor & gallium anomalies

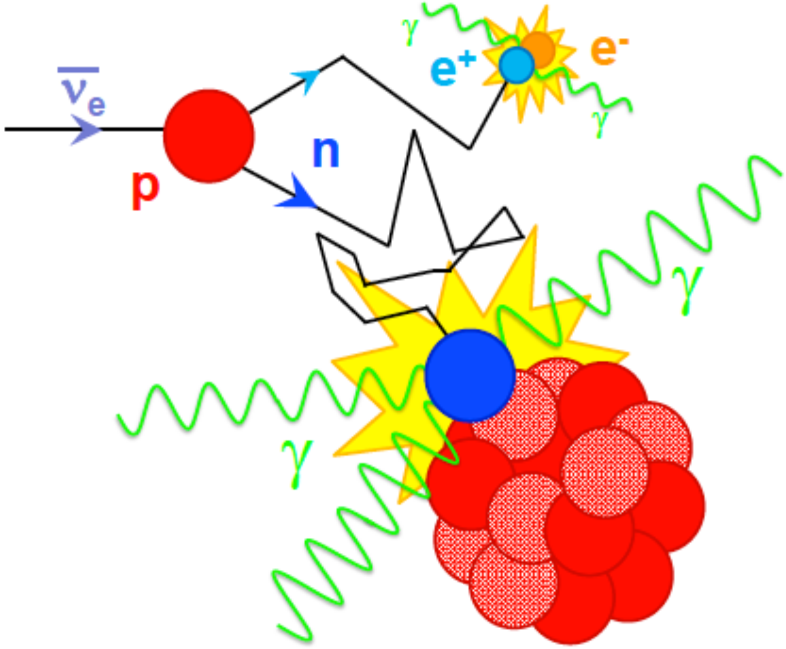
Testing $\overset{(-)}{\nu}_e$ disappearance anomalies

- **Need direct test, beyond the current mean deviation from predicted rate**
- **Input from sterile neutrino fits**
  - **$\Delta m^2 \approx 0.1\text{-}10\ \mathrm{eV}^2 \rightarrow L_{osc}(m)=2.5\dfrac{E(MeV)}{\Delta m^2(eV^2)} \approx 2-10\ m$**
  - **$\sin^2(2\theta_{ee}) \approx 0.01\text{-}0.15$**
- **Experimental specifications**
  - **Compact source**
  - **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

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



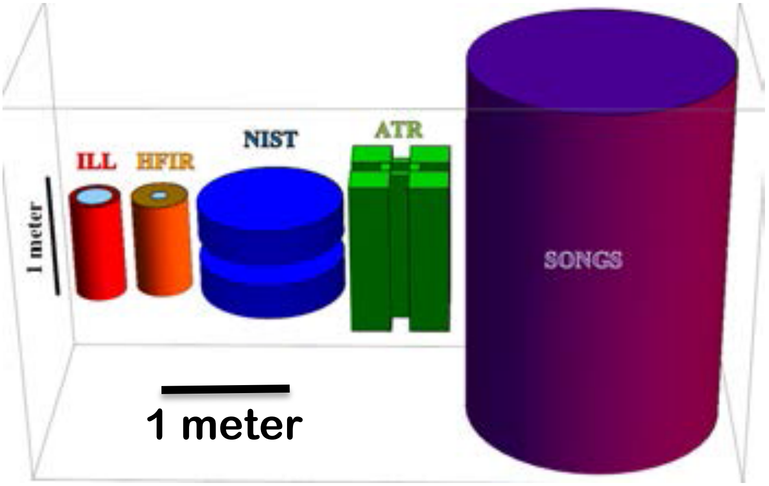
Selective coincidence
e^+ prompt signal & n-capture

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:
    - <u>must be negligible</u>

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 <u>challenging</u> 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

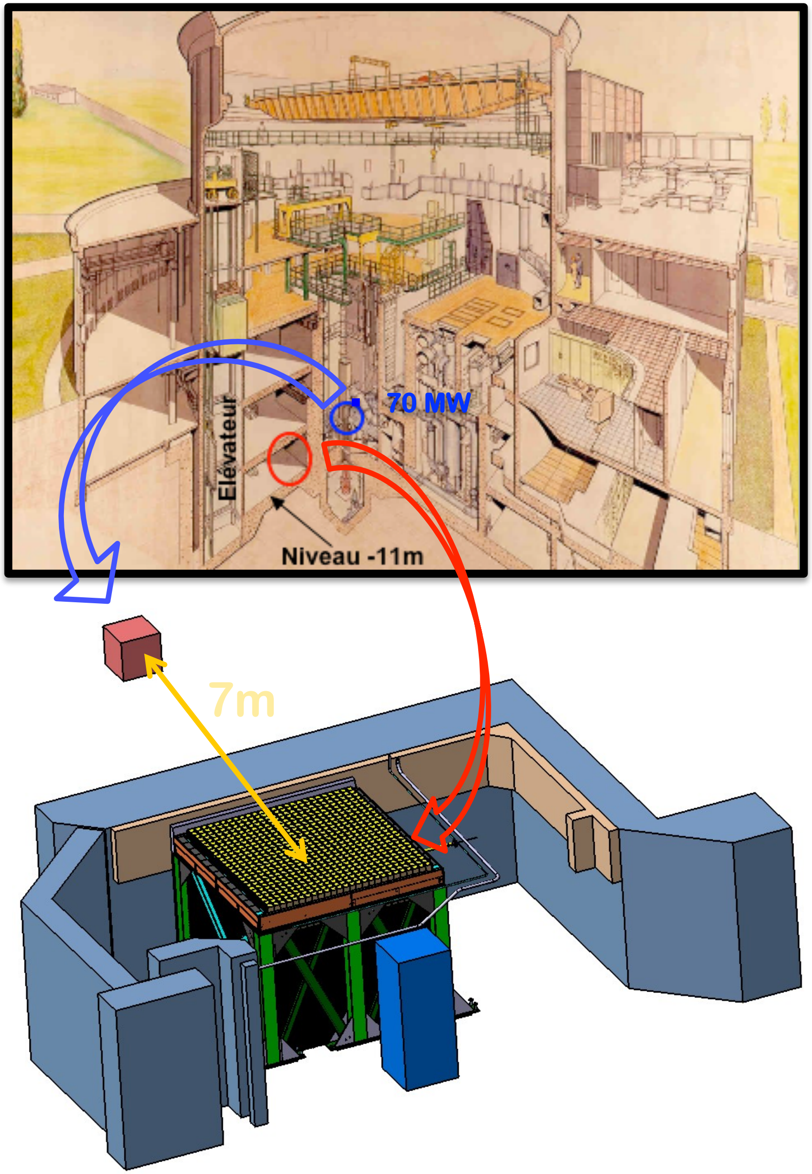
Reactor ν Proposals

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			

Nucifer @ OSIRIS *(Gd-LS)*

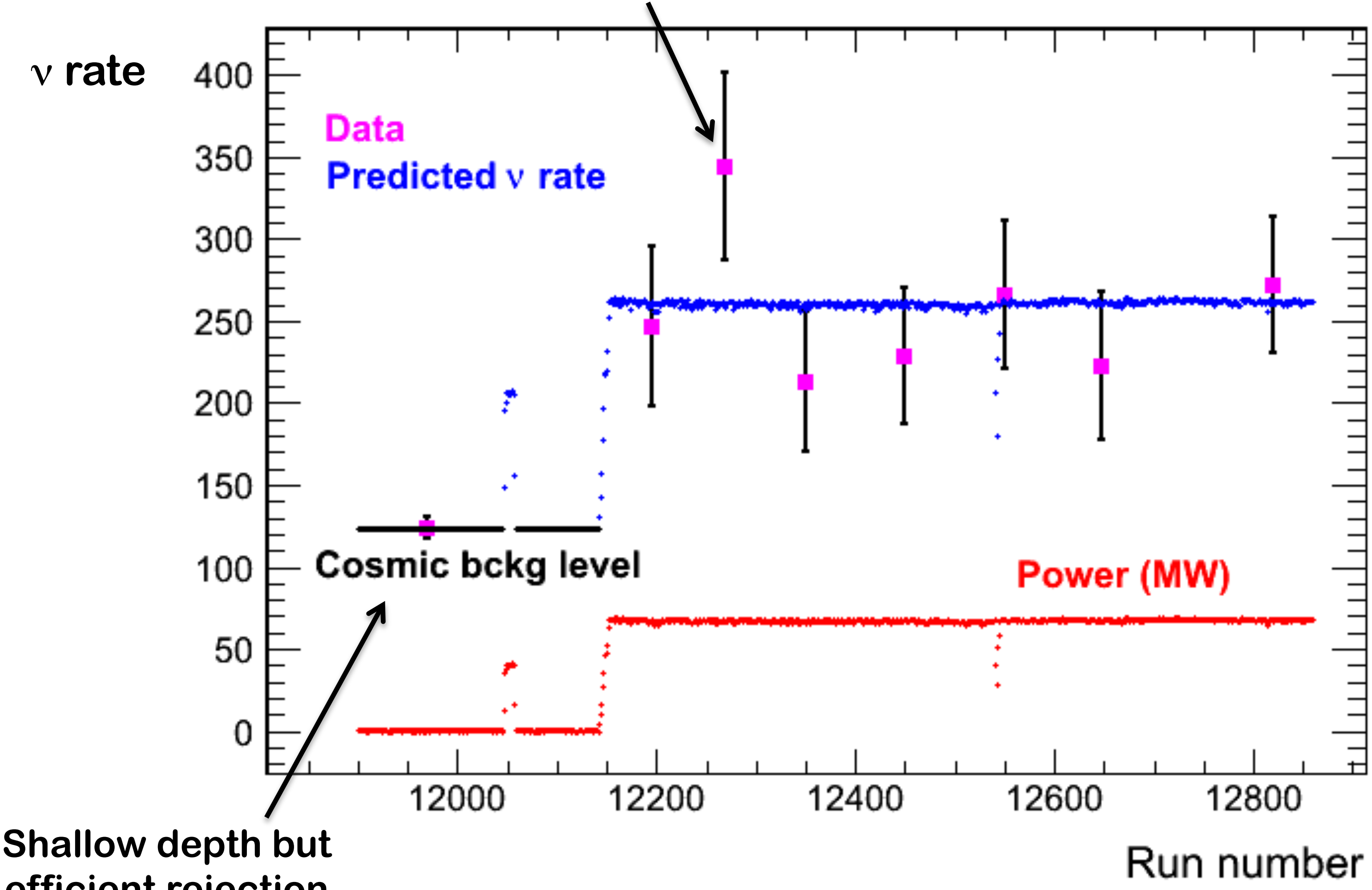
Originally Dedicated for non proliferation

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



Nucifer: First Neutrino Run

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

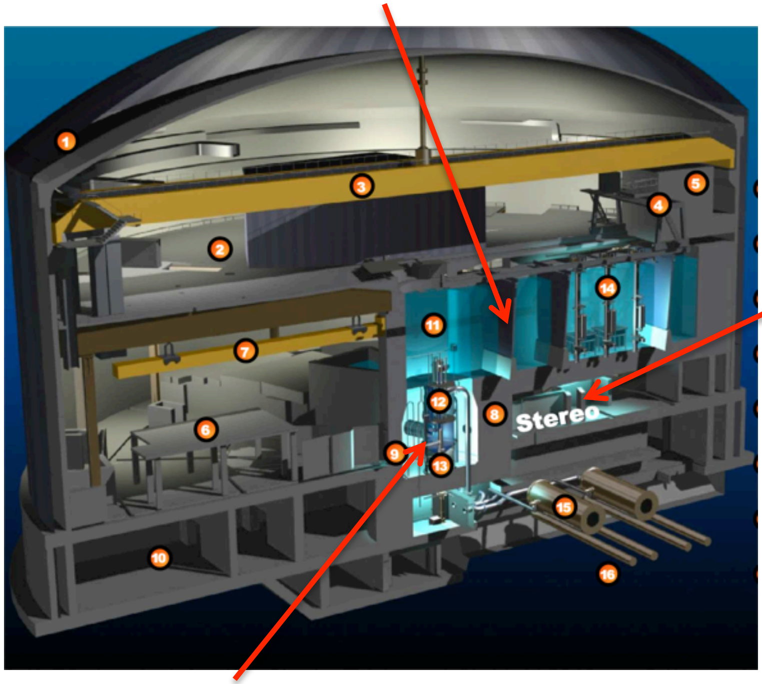


Shallow depth but efficient rejection of cosmic bkg

Stéréo @ ILL *(Gd-LS)*

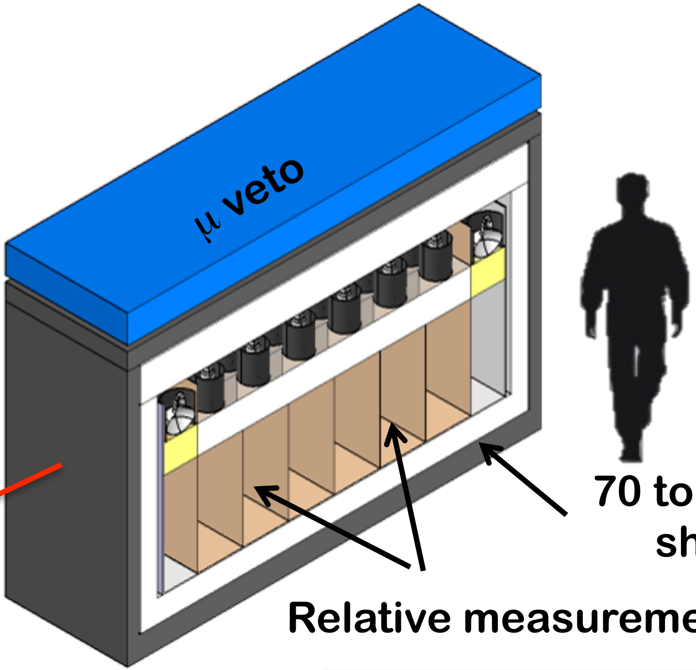
Start Data Taking in 2015

factor 4 attenuation of vertical flux from water pool



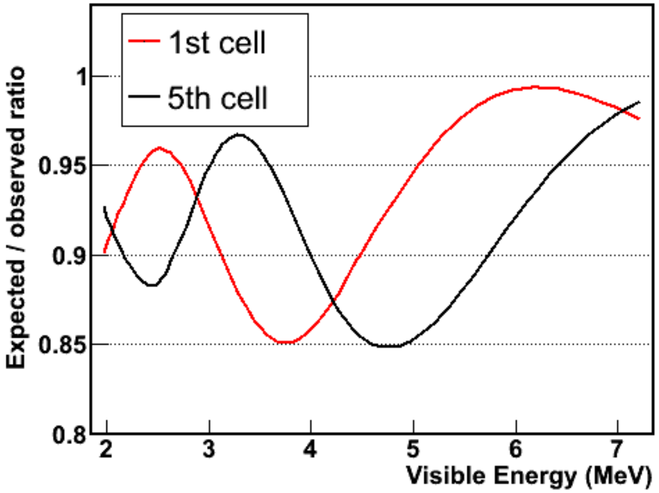
50 MW core
h=80cm, Φ=40cm

[8.5-11] m baseline range



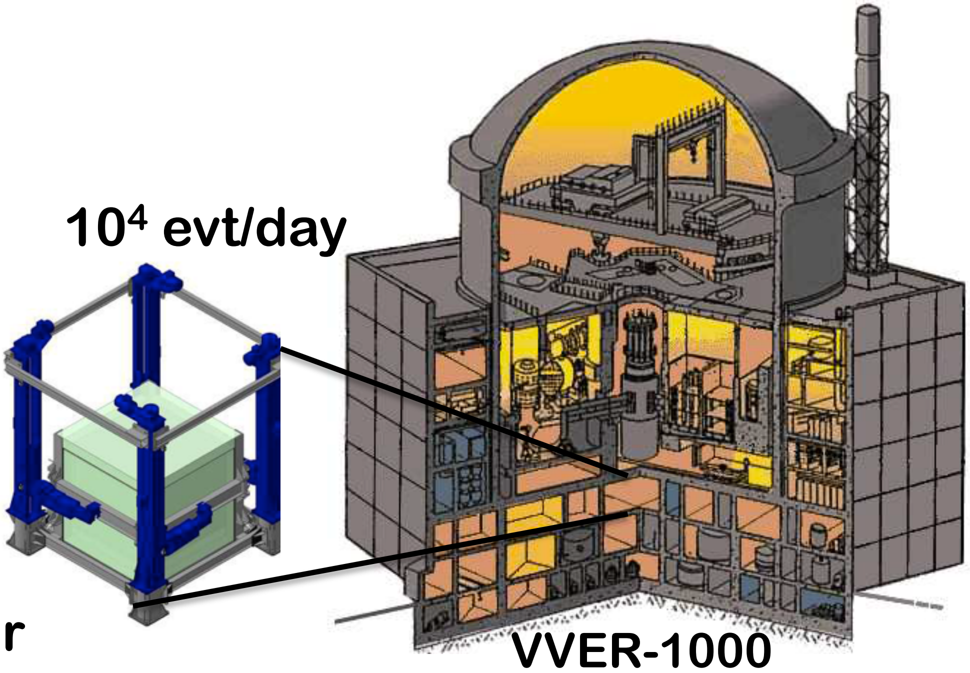
70 tons γ and n shielding

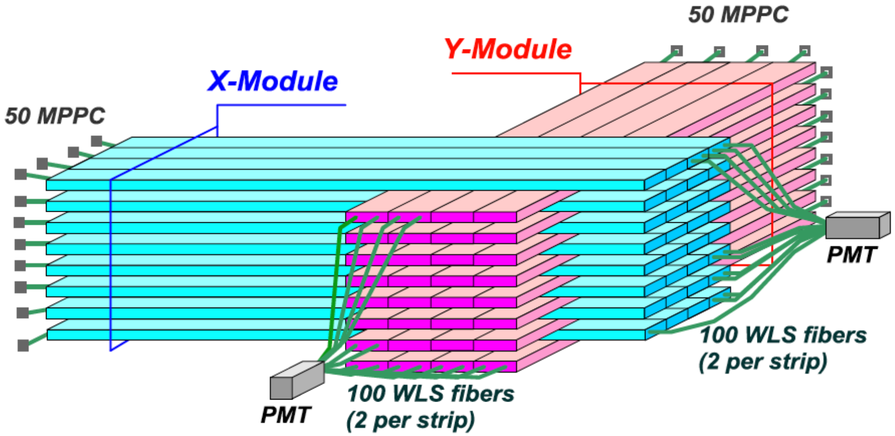
Relative measurement in 6 cells



DANSS @ KNPP *(High-Seg)*

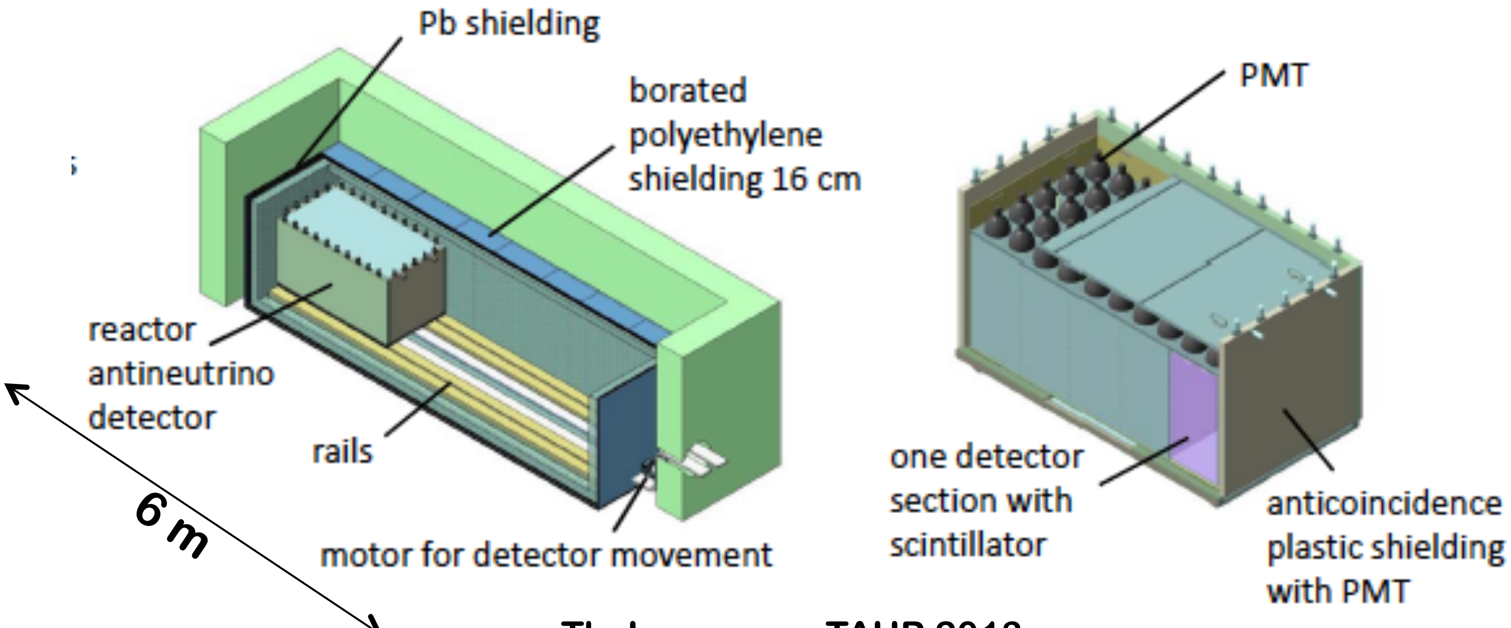
- 1 GW <u>extended</u> core
- Good overburden
- Vertical motion of the detector (9.7-12.2 m)
- Highly segmented detector → background rejection
- Plastic strips with Gd-loaded interlayer, WLS fibers readout
- Start in 2014/15





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

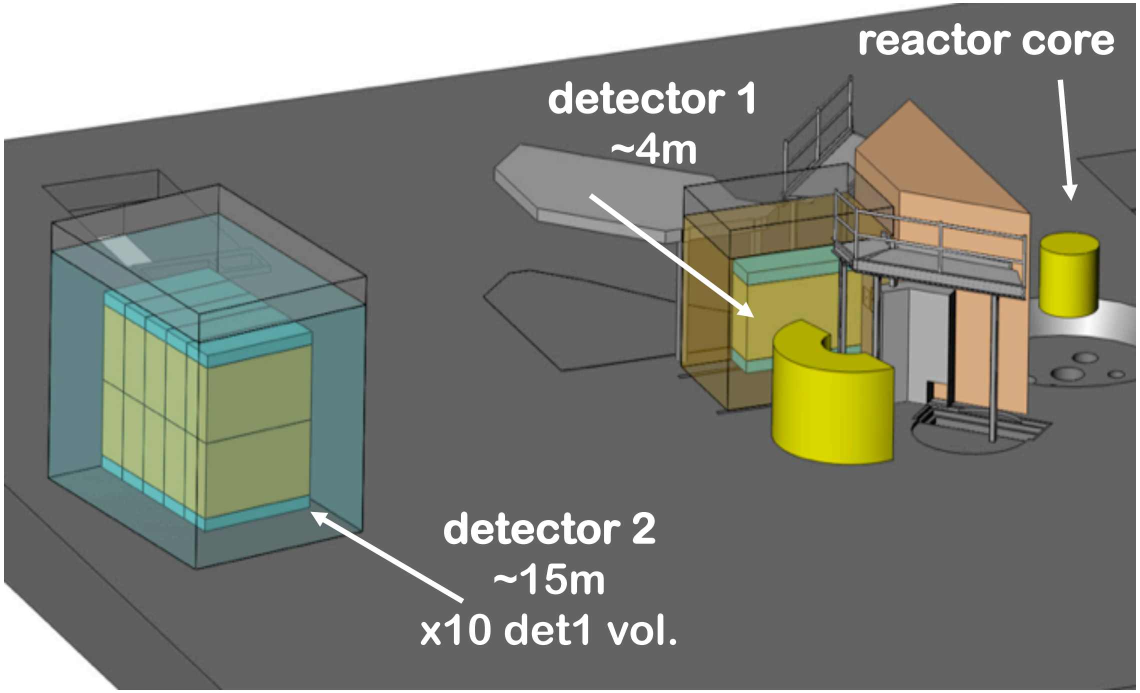
- 2.5 m^3 LS target, 5 section movable detector [6-12] m
- 100 MW compact core
- Detector at Surface
- Status:
  - Shielding integrated
  - Start in 2015

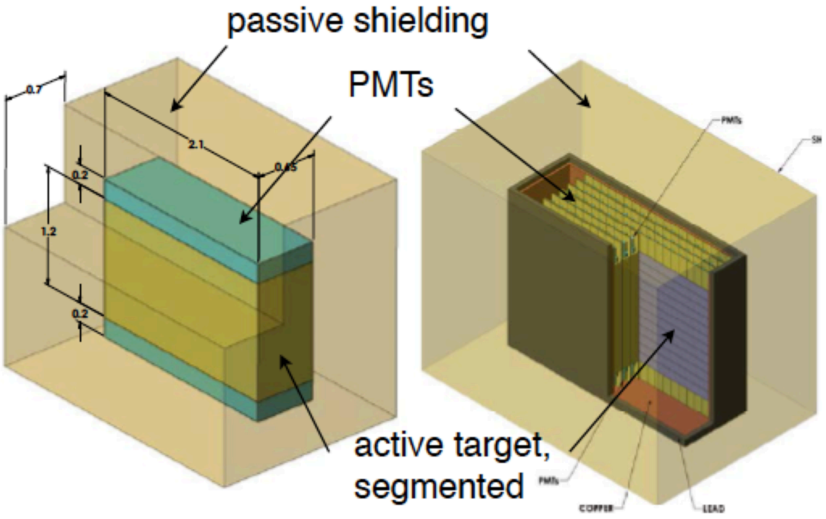


Th. Lasserre – TAUP 2013

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?

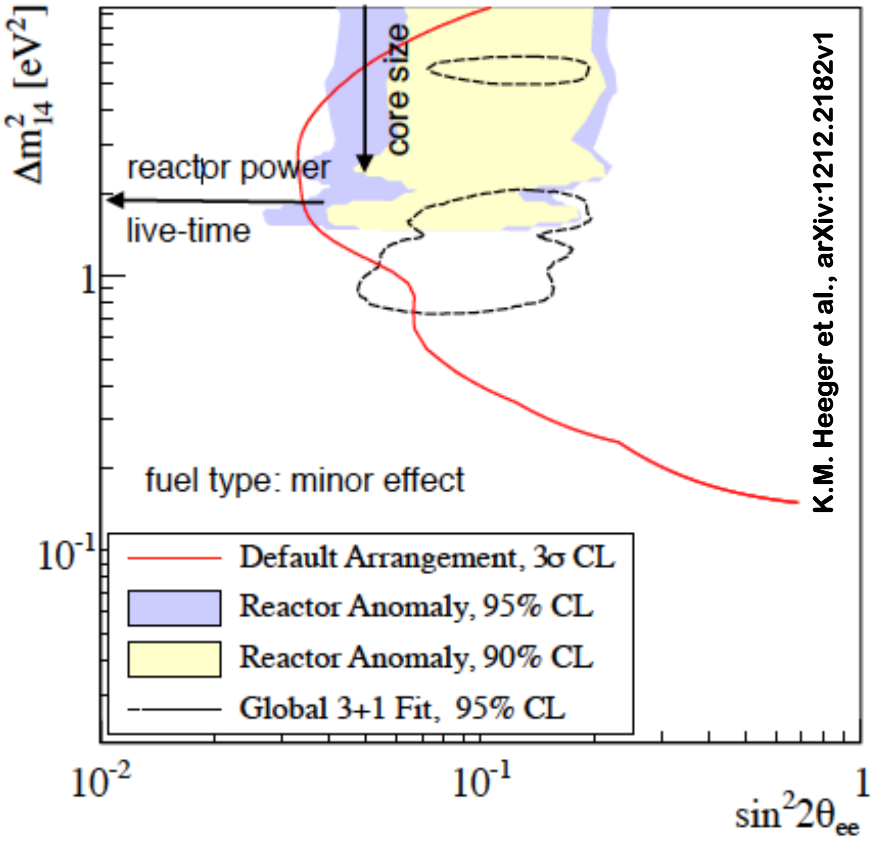




Influence of Source/Detector Parameters

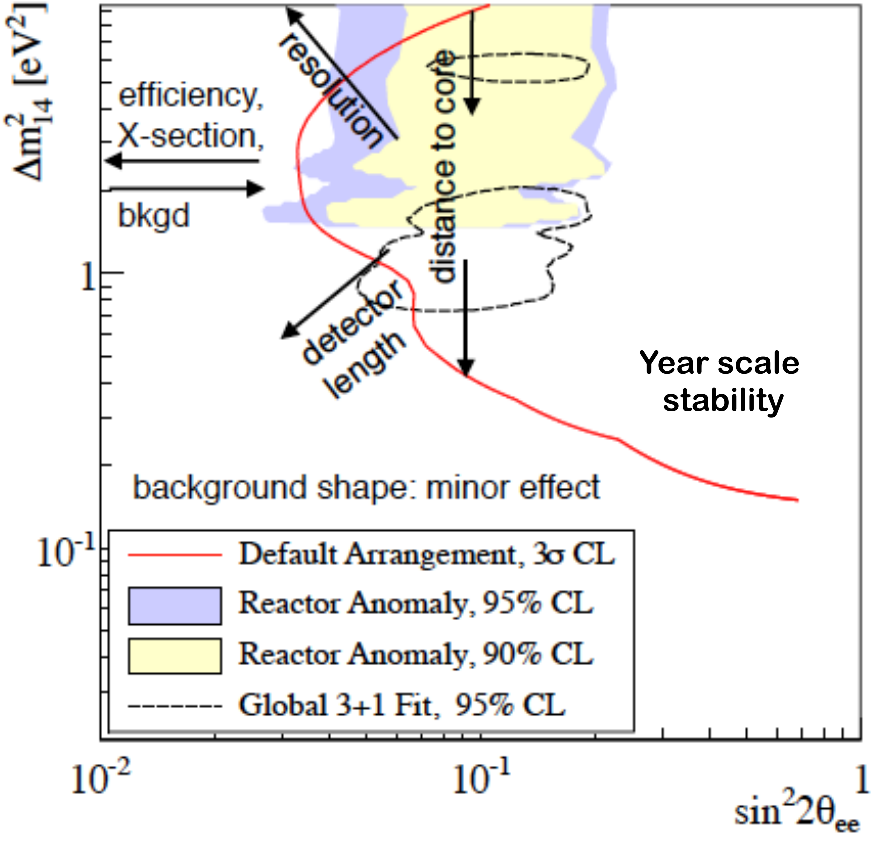
All current project have the sensitivity to test the reactor anomaly space of parameters, Δm²>0.1, sin²2θ>0.05

Source



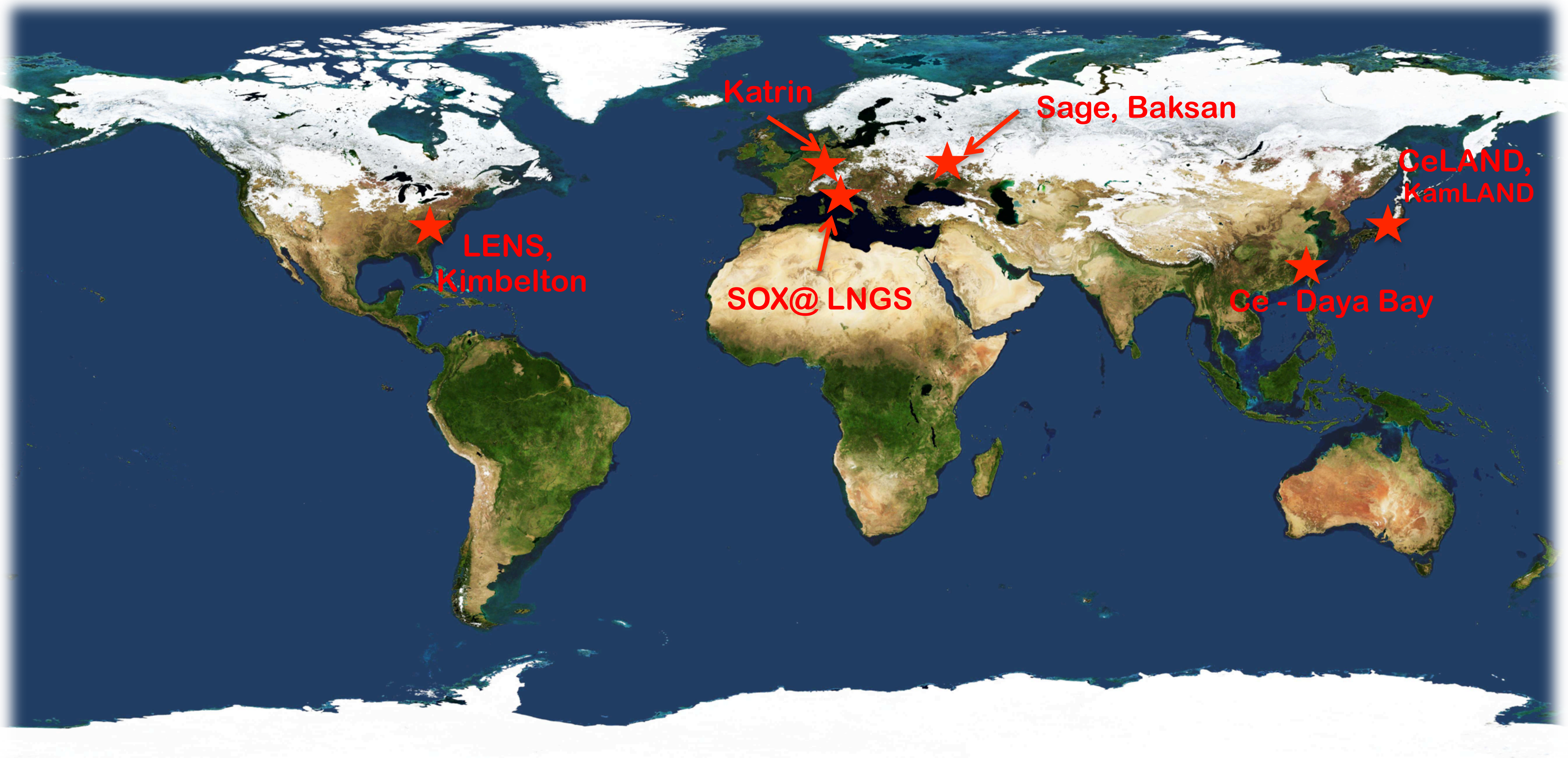
K.M. Heeger et al., arXiv:1212.2182v1

Detector



Year scale stability

Experimental Program: @ Neutrino Generator



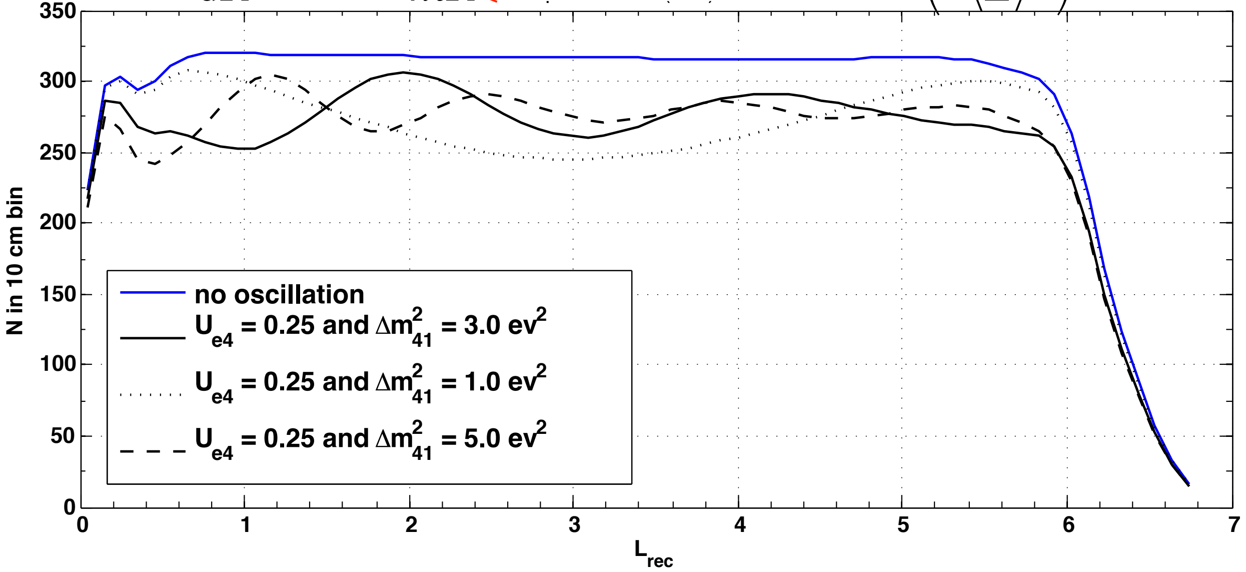
Test of both reactor & gallium anomalies

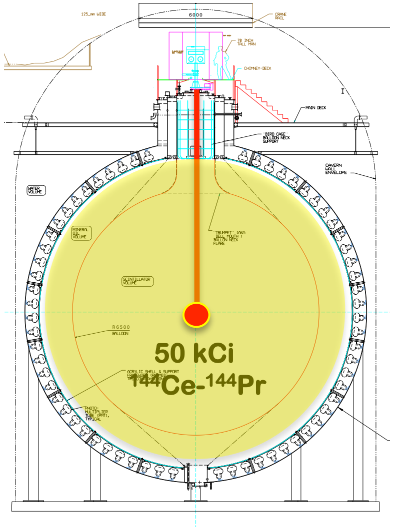
ν Generator Proposals

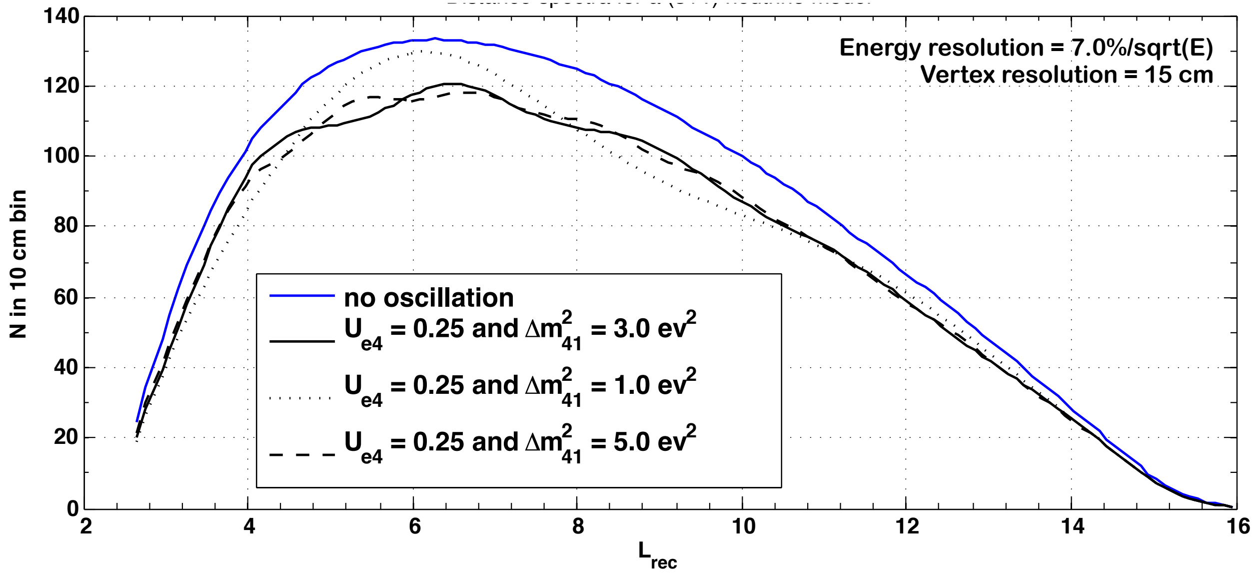
Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	$\nu_e e \rightarrow \nu_e e$ 5% E_{res} 15cm R_{res} or Radio-chemical	Detector Radioactivity Solar ν (irreducible) ν generator impurities	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	>3 MCi	Sage LENS
					>10 MCi	SOX (SNO+)
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	>1 MCi	-
					5 MCi	Ricochet
$\bar{\nu}_e$	$\bar{\nu}_e p \rightarrow e^+ n$ 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		-	-
	$^3H \rightarrow He\ e^-\ \bar{\nu}_e$ EC/β-decay	Kink search	^3H E<18 keV	Irradiation in reactors	3 Ci	KATRIN (Mare/Echo)

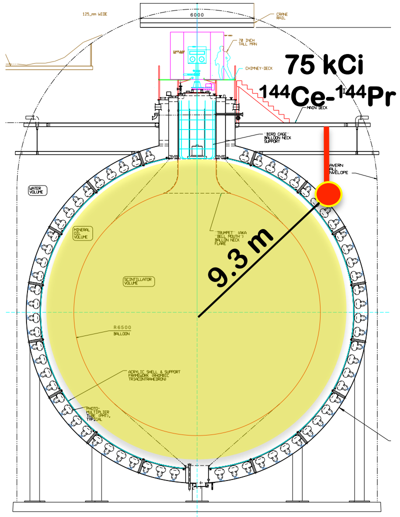
Search for $\bar{\nu}_e \rightarrow \bar{\nu}_s$ with ^{51}Cr/^{144}Ce

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



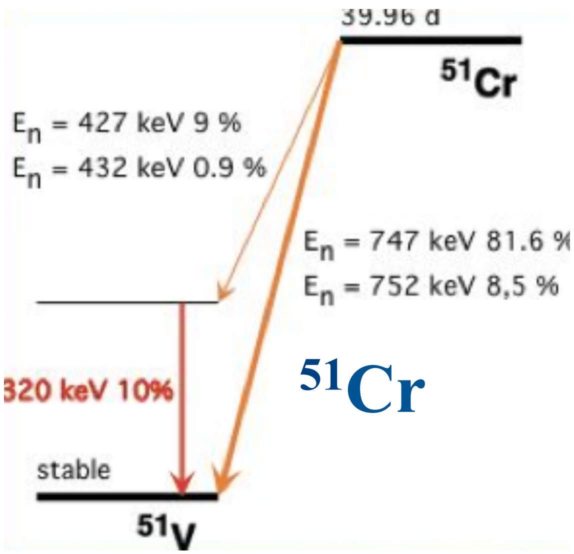


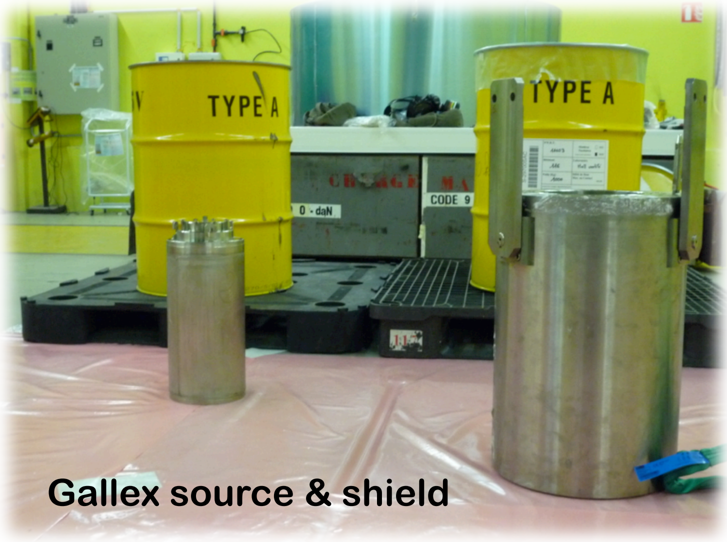




^{51}Cr neutrino generator

- ^{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

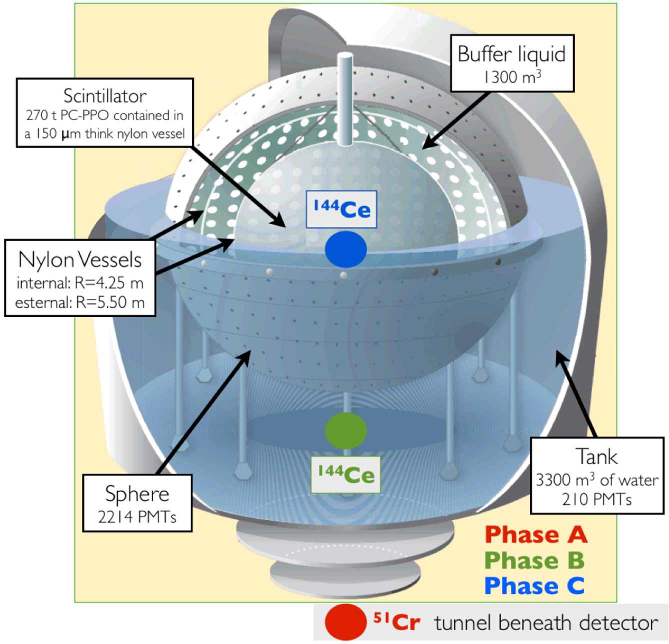


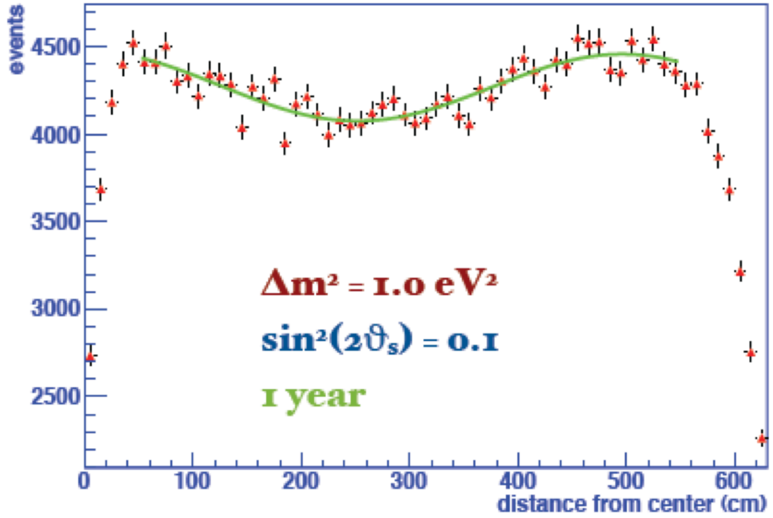


Gallex source & shield

^{51}Cr: SOX (Borexino)

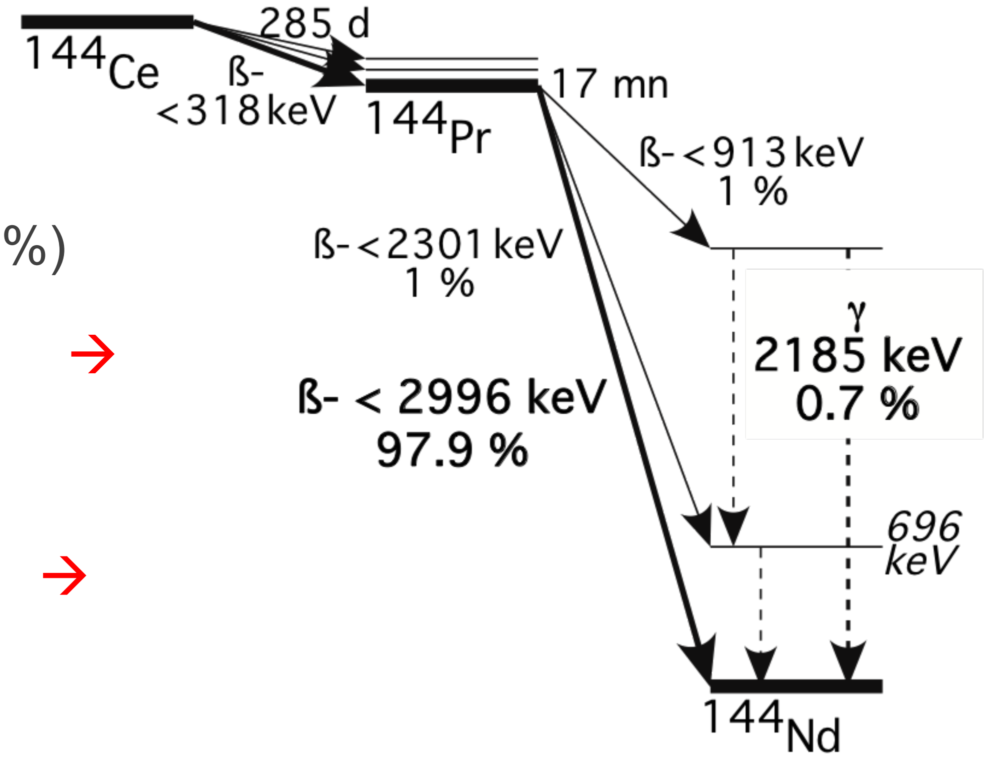
- Re-use **Gallex 36 kg** of enriched chromium
- Production reactors
  - Oak Ridge (US)
  - Ludmila (Ru)
- Source **8.25 m** from center
- **Detection as for ^{7}Be solar ν**
  - Well known background
- Status:
  - Preparation for irradiation and transportation (10 MCi)
- Staged approach: ^{51}Cr & ^{144}Ce





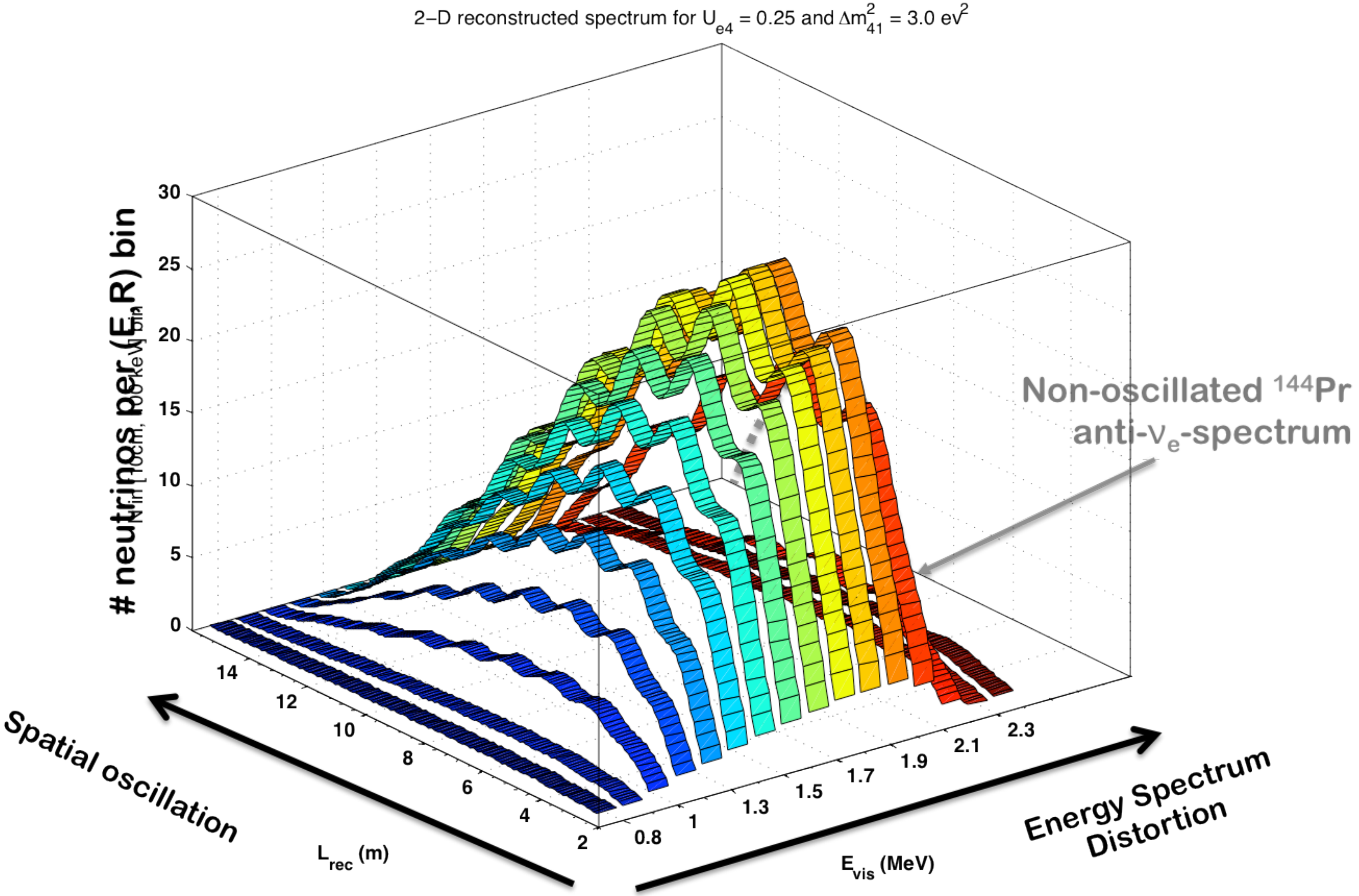
^{144}Ce-^{144}Pr $\bar{\nu}$ generator

- 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



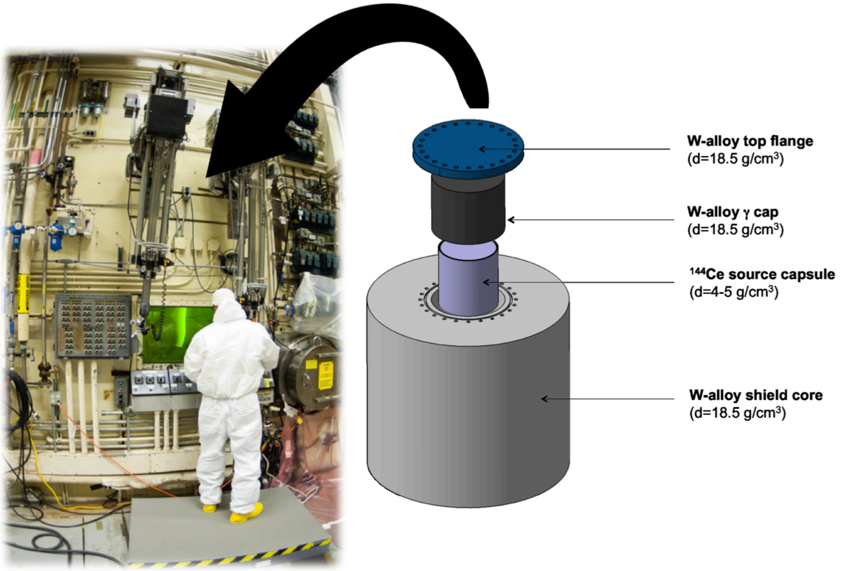
Non-oscillated ^{144}Pr anti-ν_e-spectrum

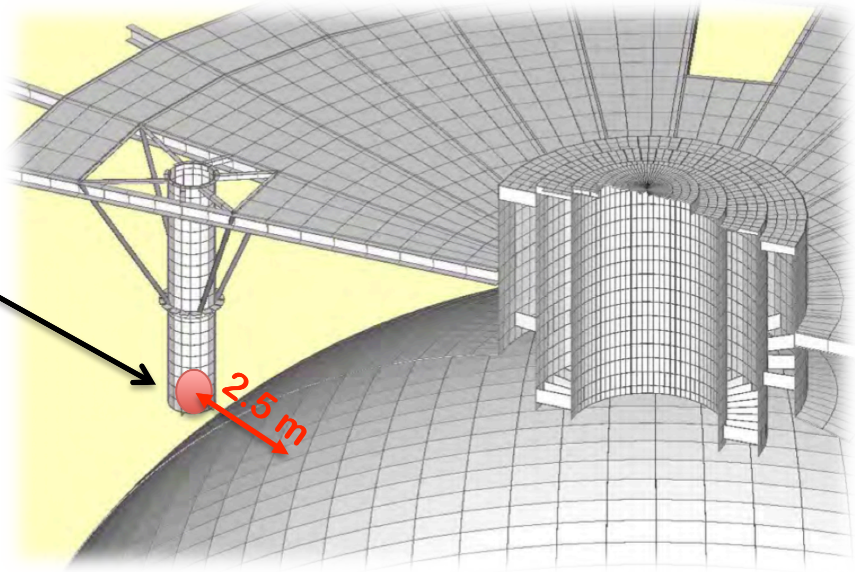
Spatial oscillation

Energy Spectrum Distortion

^{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



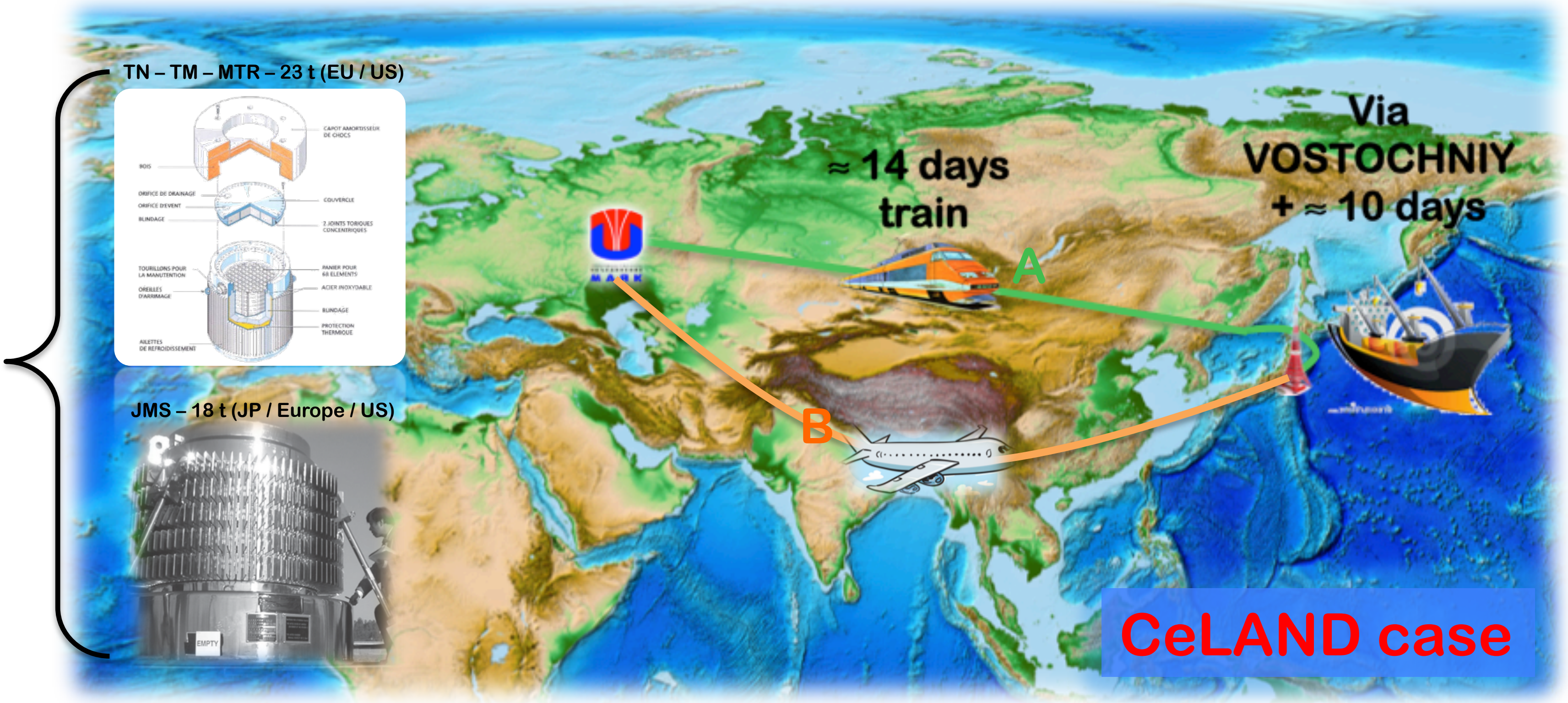


^{144}Ce & ^{51}Cr: a Challenging Logistic

IAEA rules on Safe Transportation of Radioactive Material

A) Find a suitable certified transport container

suitable B(U) casks identified



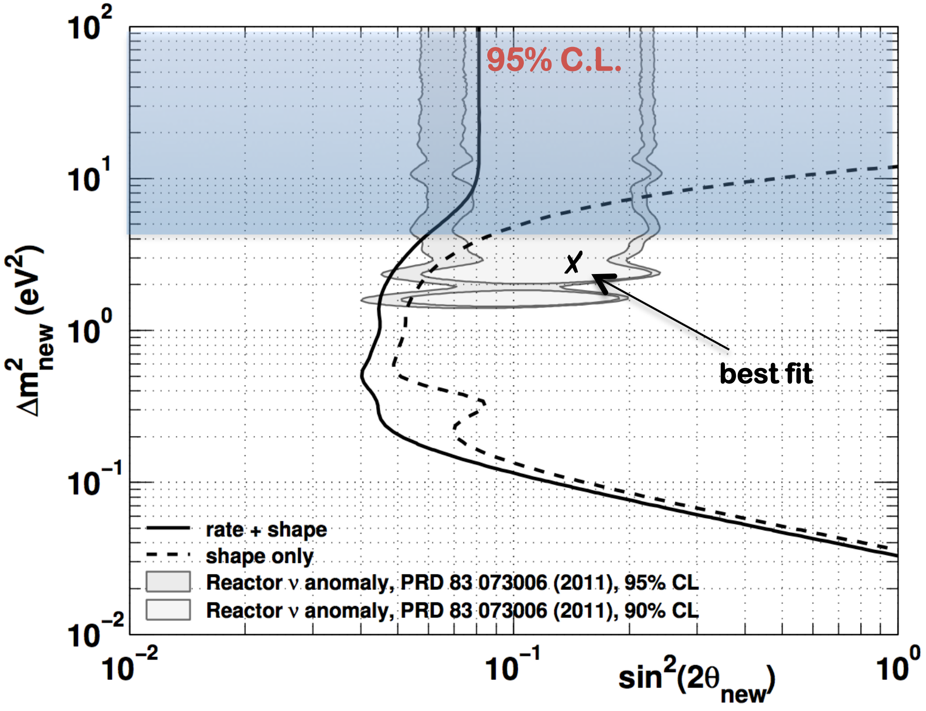
B) Find a suitable route (4 weeks journey for CeLAND)

Th. Lasserre – TAUP 2013

ν-Generator sensitivities

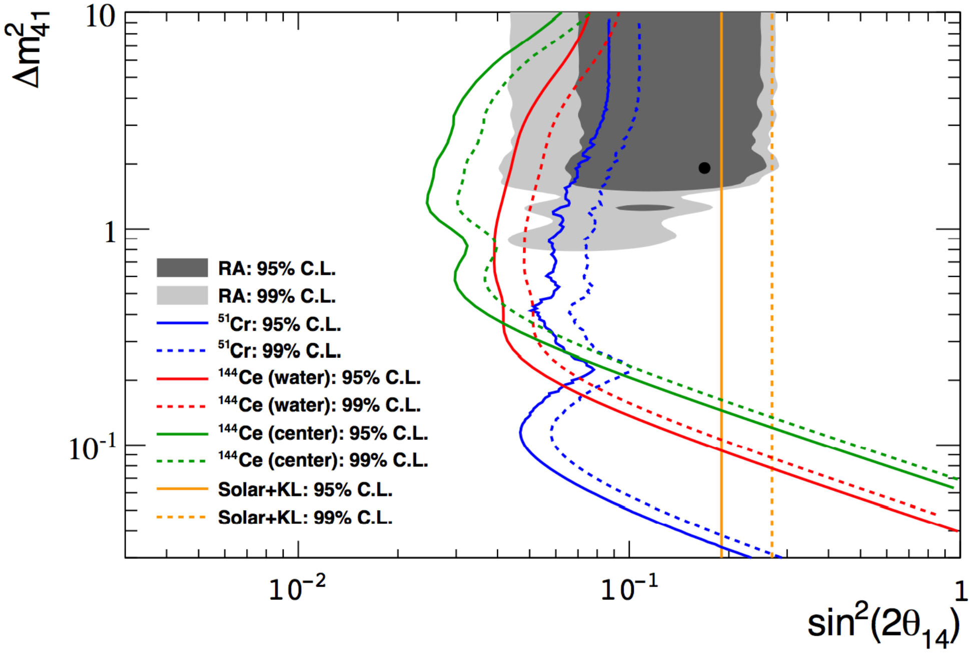
CeLAND (KamLAND)

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



SOX (Borexino)

^{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

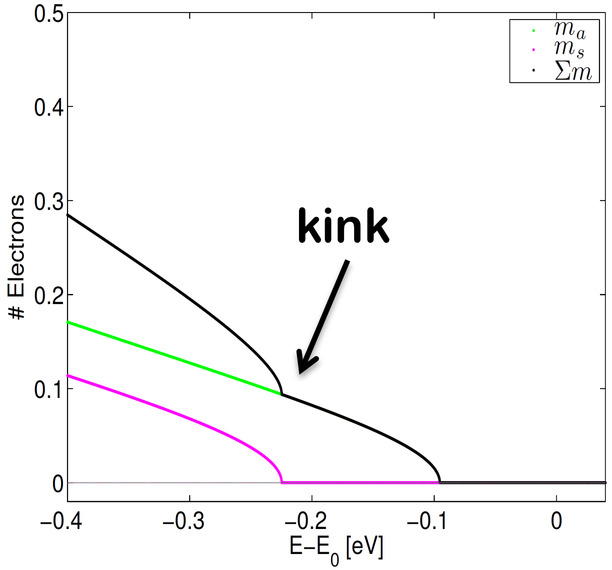
^{51}Cr in 2015
^{144}Ce-^{144}Pr in 2016/7

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:**

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

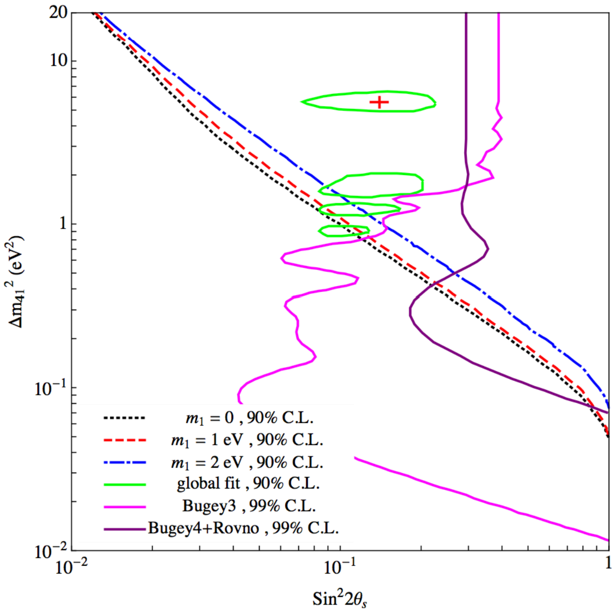
- **Hypothetical 4th ν contribution**



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

→Search for a kink few eV below end point

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



Experimental Program:
@ Neutrino Beam

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

ν Beam Proposals

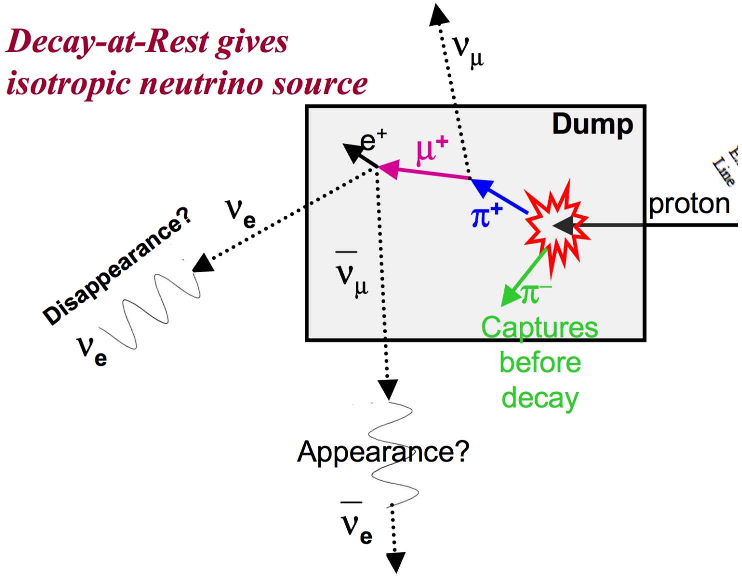
Type	Source	App. /Dis.	Oscillation Channels	Projects
Isotope Decay at Rest	$p + {}^{9}Be \rightarrow {}^{8}Li + 2p$ $n + {}^{7}Li \rightarrow {}^{8}Li$ ${}^{8}Li \rightarrow {}^{9}Be + e^{-} + \bar{\nu}_e$	Dis.	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	IsoDAR
Pion (Kaon) Decay at Rest	$\pi^{+} \rightarrow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

Pion Decay at Rest ν-sources

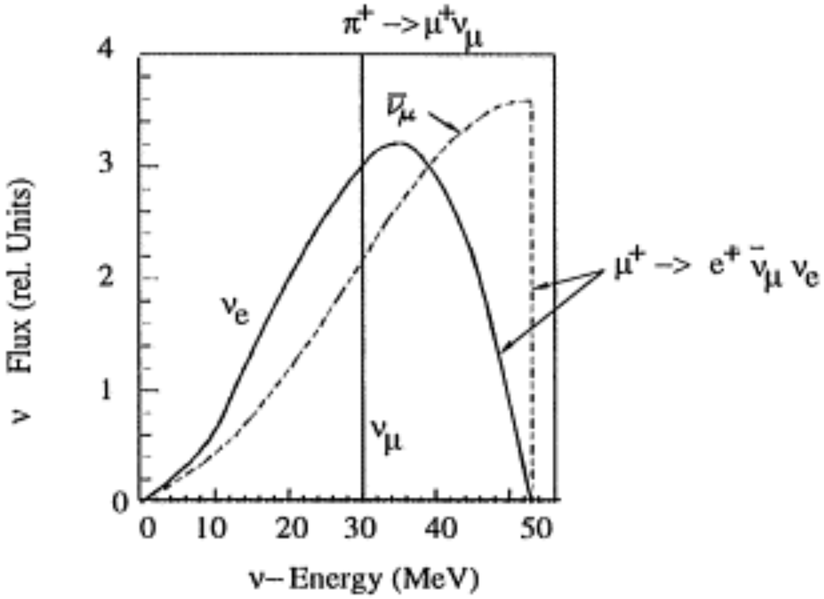
- High Energy Proton source
  - Each π+ decay
    - $\nu_\mu, \nu_e, \bar{\nu}_\mu$
    - known E spectrum
  - Near a large detector
    - Cherenkov (water or oil)
    - Liquid argon
    - Liquid scintillator

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

- Look for oscillation wave in L/E
  - > 5σ coverage of LSND



Decay-at-Rest gives isotropic neutrino source



Muon Decay Rings: ν-STORM

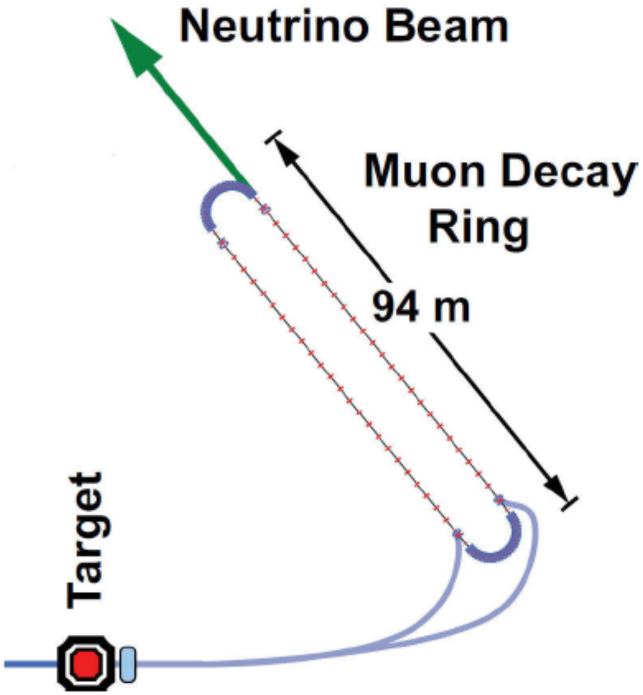
- **Neutrino Factory Concept**
  - 60 GeV protons on solid target
  - Horn capture and π transfer
  - Muon Decay ring

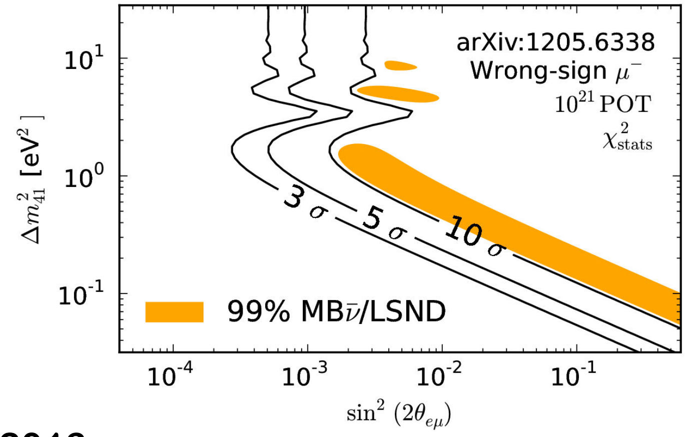
- **APP and DIS channels with:**
  - $\overset{(-)}{\nu}_{\mu}, \overset{(-)}{\nu}_{e}$

- **kT-scale Minos-like**
  - 2 km baseline

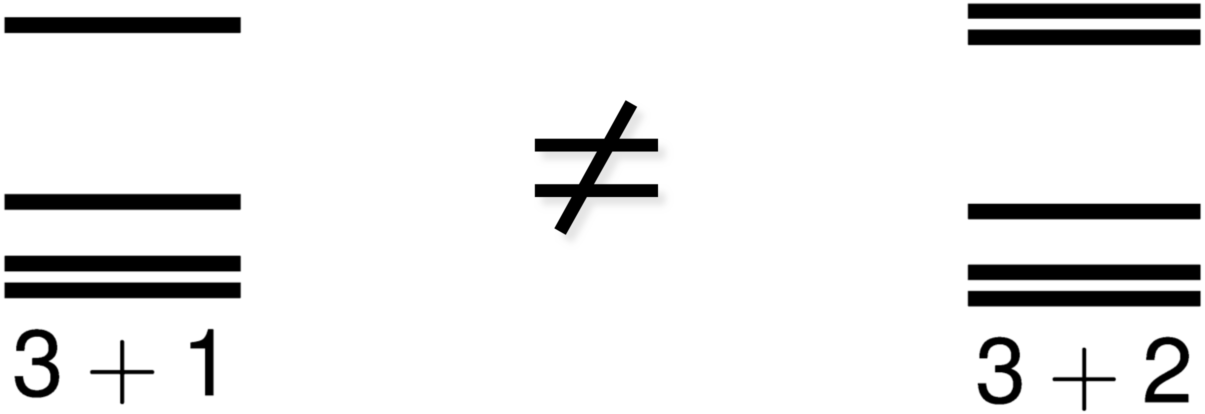
- **Golden Mode**
  - $\overset{(-)}{\nu}_{\mu}$ APP in a $\overset{(-)}{\nu}_{e}$ beam

- Definitive sterile ν search

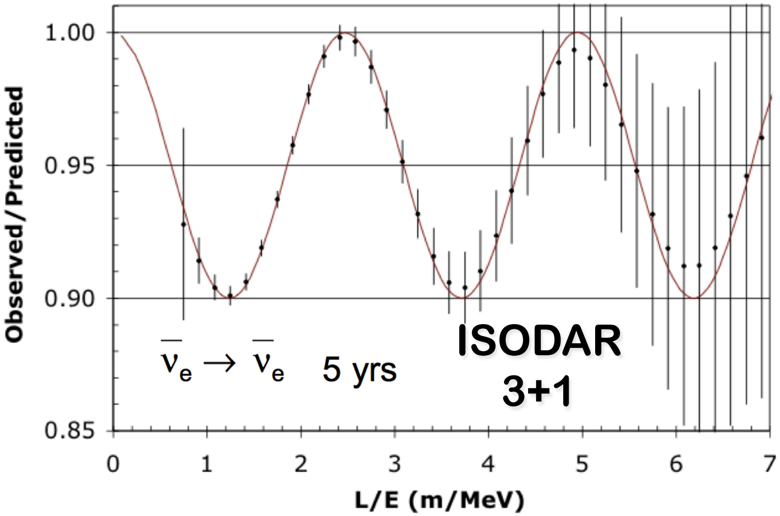


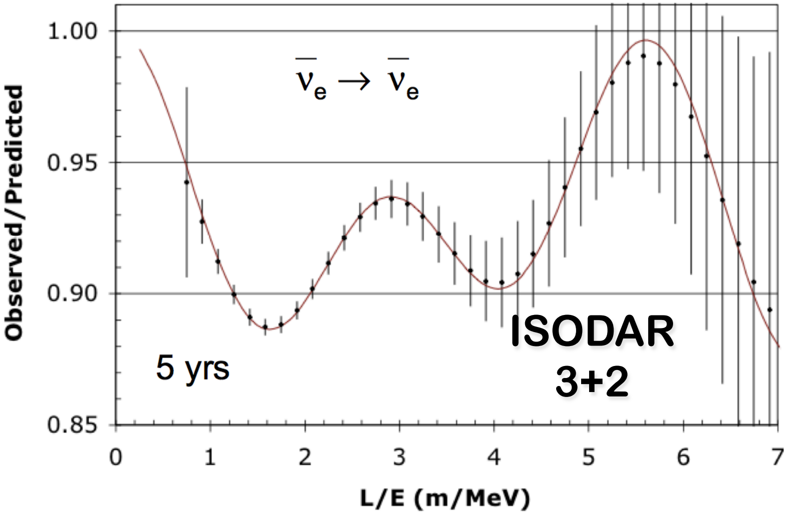


Isotope Decay at Rest ν-sources



Oscillation L/E Waves with High Statistics





Number of ν's From Cosmology

- Constraint sum of neutrino masses < 0.5 eV
- An excess of non-interacting relativistic energy density → can be interpreted as "extra ν"
- **WMAP** 2013 + other observables → $N_{eff} = 3 - 4$
- **Planck:**
  - Planck alone: $N_{eff} = 3.36 \pm 0.66$ (95% C.L.)
  - But
    - The Planck-inferred Hubble parameter is incompatible with HST measurement
    - Planck + BAO + H0: $N_{eff} = 3.52 \pm 0.46$ (95% C.L.)
- **$N_{eff} = 4$ mildly disfavored & bound model dependent**

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 (1-10 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 studying sterile neutrino phenomenology**
- **Independent tests through β-decay and $(\beta\beta)0\nu$-decay**

Munich Institute for Astro- and Particle Physics

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Submission of proposals for 2015 is open!

MIAPP Workshops 2014

The Extragalactic Distance Scale
26 May – 20 June 2014
L. Macri, W. Gieren, W. Hillebrandt, R. Kudritzki

Neutrinos in Astro- and Particle Physics
30 June – 25 July 2014
S. Schönert, G. Raffelt, A. Smirnov, T. Lasserre

Challenges, Innovations and Developments in Precision Calculations for the LHC
28 July – 22 Aug. 2014
M. Krämer, S. Dittmaier, N. Glover, G. Heinrich

Cosmology after Planck
25 Aug . – 19 Sept. 2014
N. Aghanim, E. Komatsu, B. Wandelt, J. Weller

Submission of proposals/application for workshop participation:
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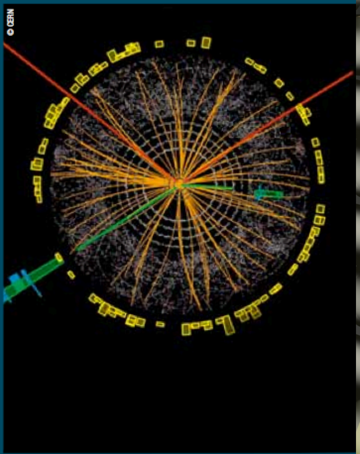

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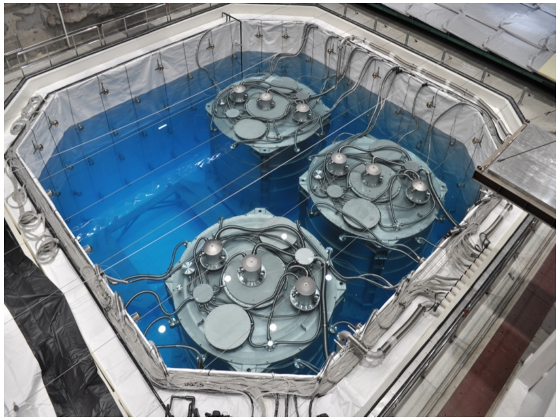
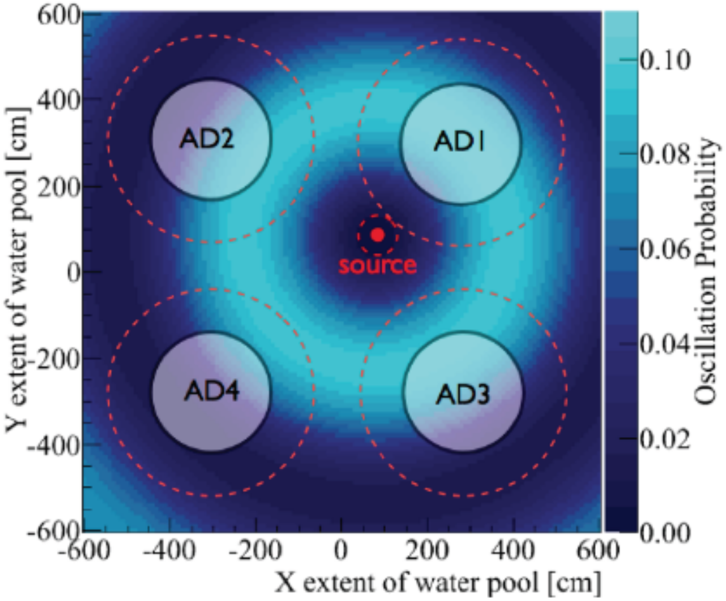
500 kCi ^{144}Ce-^{144}Pr in Daya Bay

- 500 kCi of ^{144}Ce in the water pool of the Daya Bay far hall
  - Baseline range: 1.5 - 8 m
  - Energy range: 1.8 - 3 MeV
  - 35 000 IBD events/per year
  - ‘Easy’ to deploy

- Ongoing discussion for ^{144}Ce recovery with LLNL

- Multiple source location to probe sterile oscillations





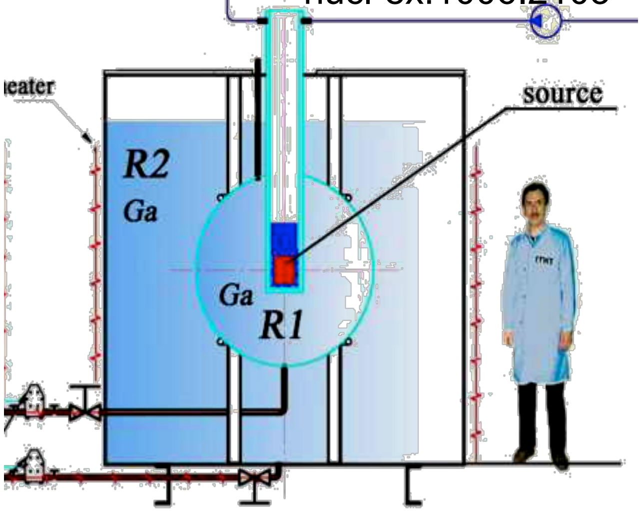
^{51}Cr: SAGE 2-Zone (Sage)

- **^{51}Cr Source:**
  - Enrichment of 3.5 kg ^{50}Cr (97%, 2014)
  - Irradiation to reach 3 MCi (2015?) at research reactor SM-3

- **2-layer detector in Baksan**
  - Inside a new dual Metallic Ga Target
  - Zone 1: 8t - Zone 2: 42 t metal Ga
  - SAGE procedures well understood
  - Not sensitive to γ-ray background

- **Observable**
  - Ratio of ν_e capture rates to predicted rate in inner (R1) and outer zone (R2)
  - Ratio R_2/R_1

nucl-ex:1006.2103



65 Ge atoms/day expected

From Gavrin 20.08.2013

500 kCi ^{144}Ce-^{144}Pr in Daya Bay

- Specific oscillation pattern through simulation

- Water + 50 cm W-shielding
  - γ's attenuation

- Must subtract reactor neutrino 'background'
  - well-known to <1% from near detectors

- Sterile neutrino oscillations with mass >1eV can be tested