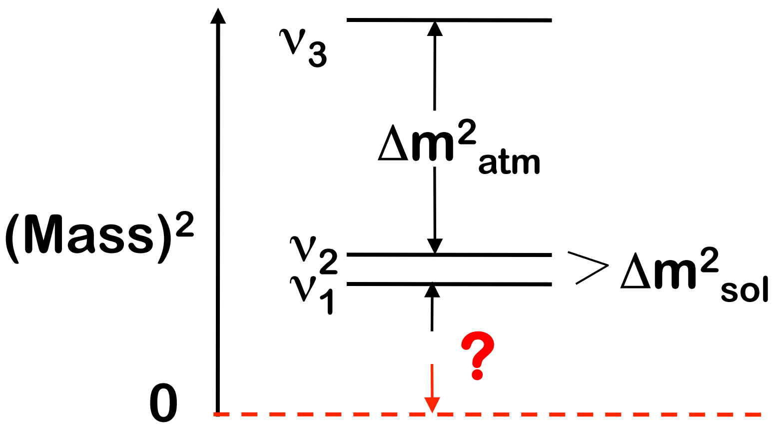
(Light) Sterile Neutrinos

Thierry Lasserre – Saclay & APC

APPEC Meeting
APC Paris, June 24th 2014

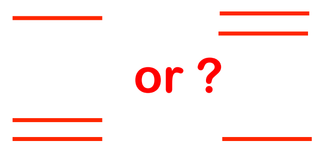
Open questions in ν physics

- What are the masses of the mass eigenstates ν_i?



} ν flavor change

} β decay, ββ0ν decay, cosmology

- Is the spectral pattern 

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 ~~CP~~ responsible for the matter-antimatter asymmetry?

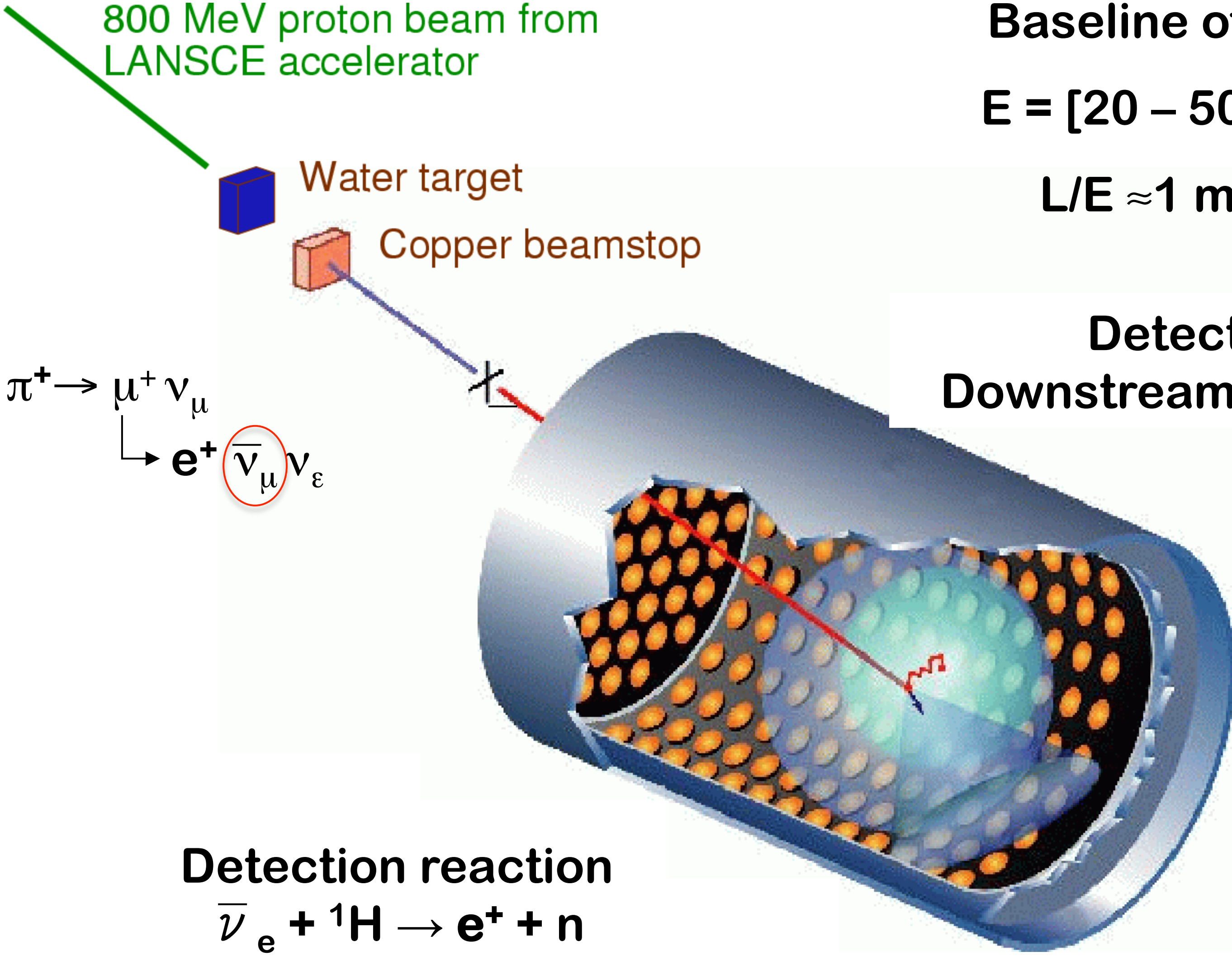
} ν flavor change

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

Anomalies or new ν-oscillation?

LSND (stopped π^+ beam)

Anomaly on the electron antineutrino interaction rate



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

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

Baseline of 30 m

E = [20 – 50] MeV

L/E ≈1 m / MeV

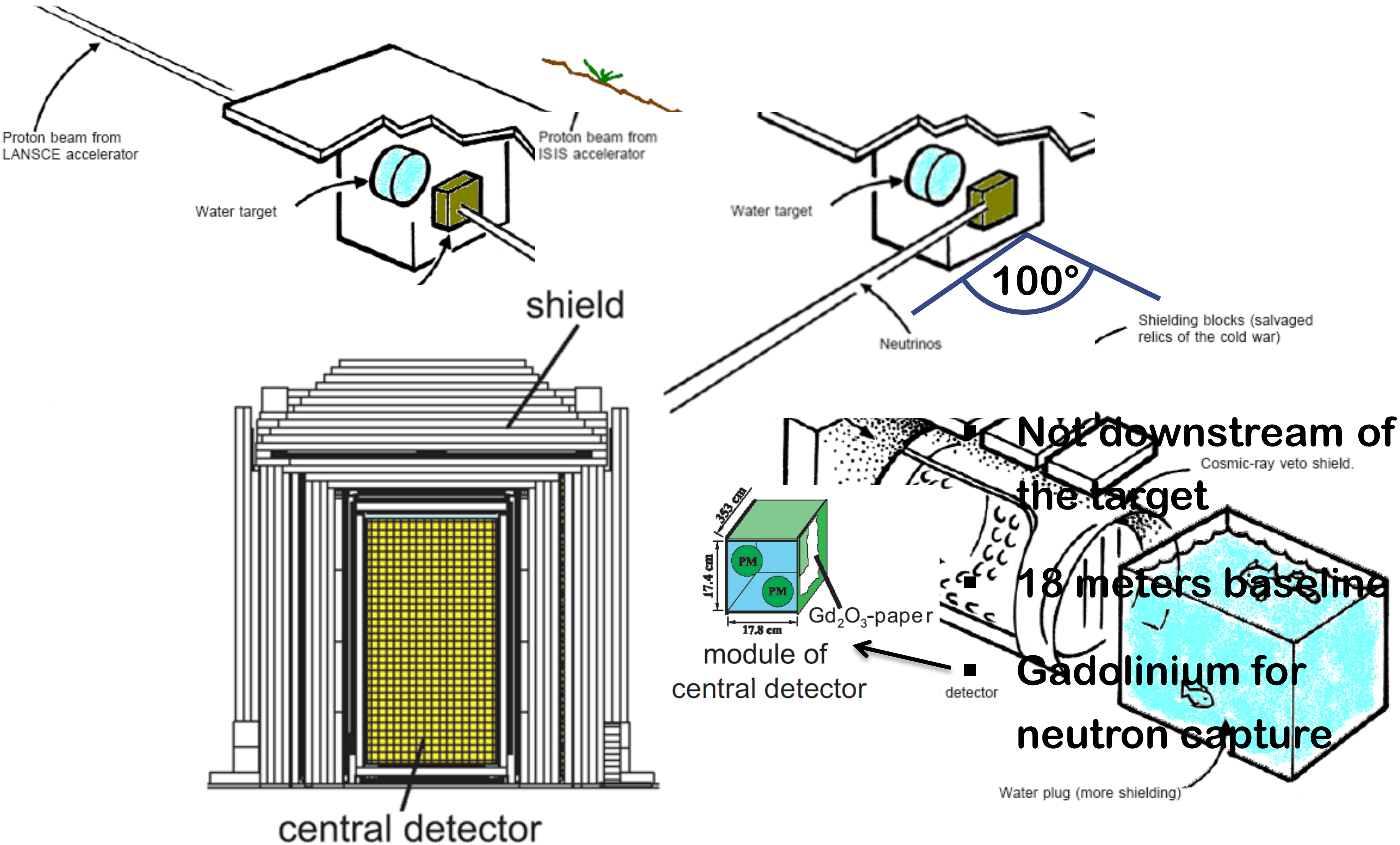
Detector
Downstream of target

Detection reaction

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

Karmen (stopped π^+ beam)

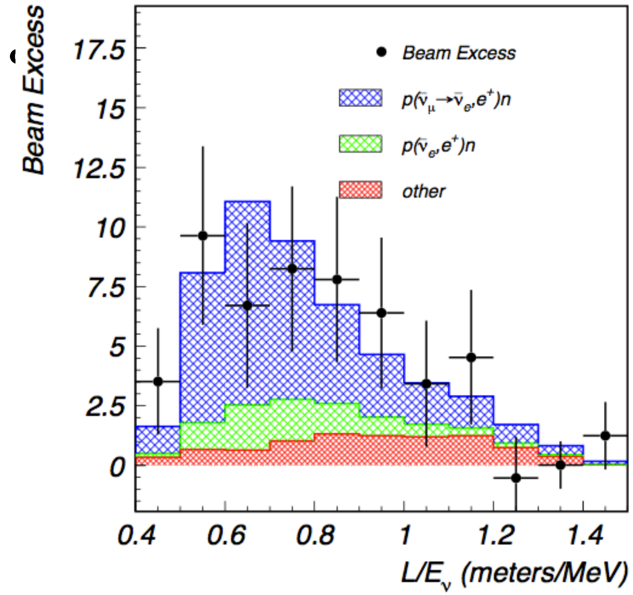
Oscillation not confirmed – exclude part of LSND

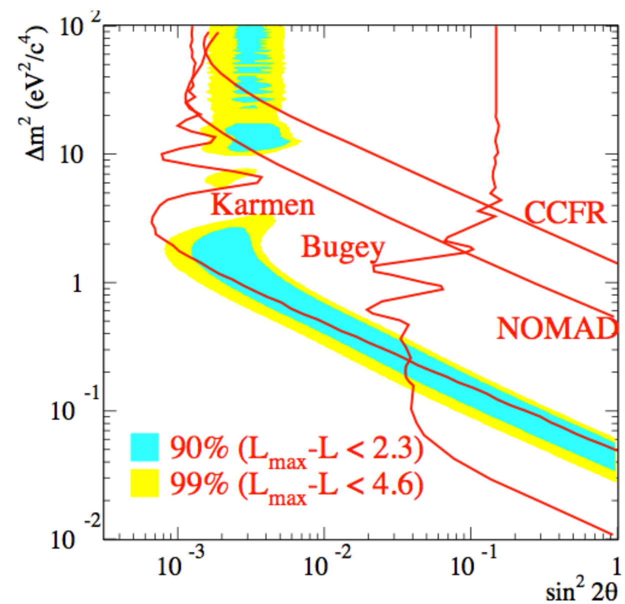


- Not downstream of the target
- 18 meters baseline
- Gadolinium for neutron capture

LSND Results

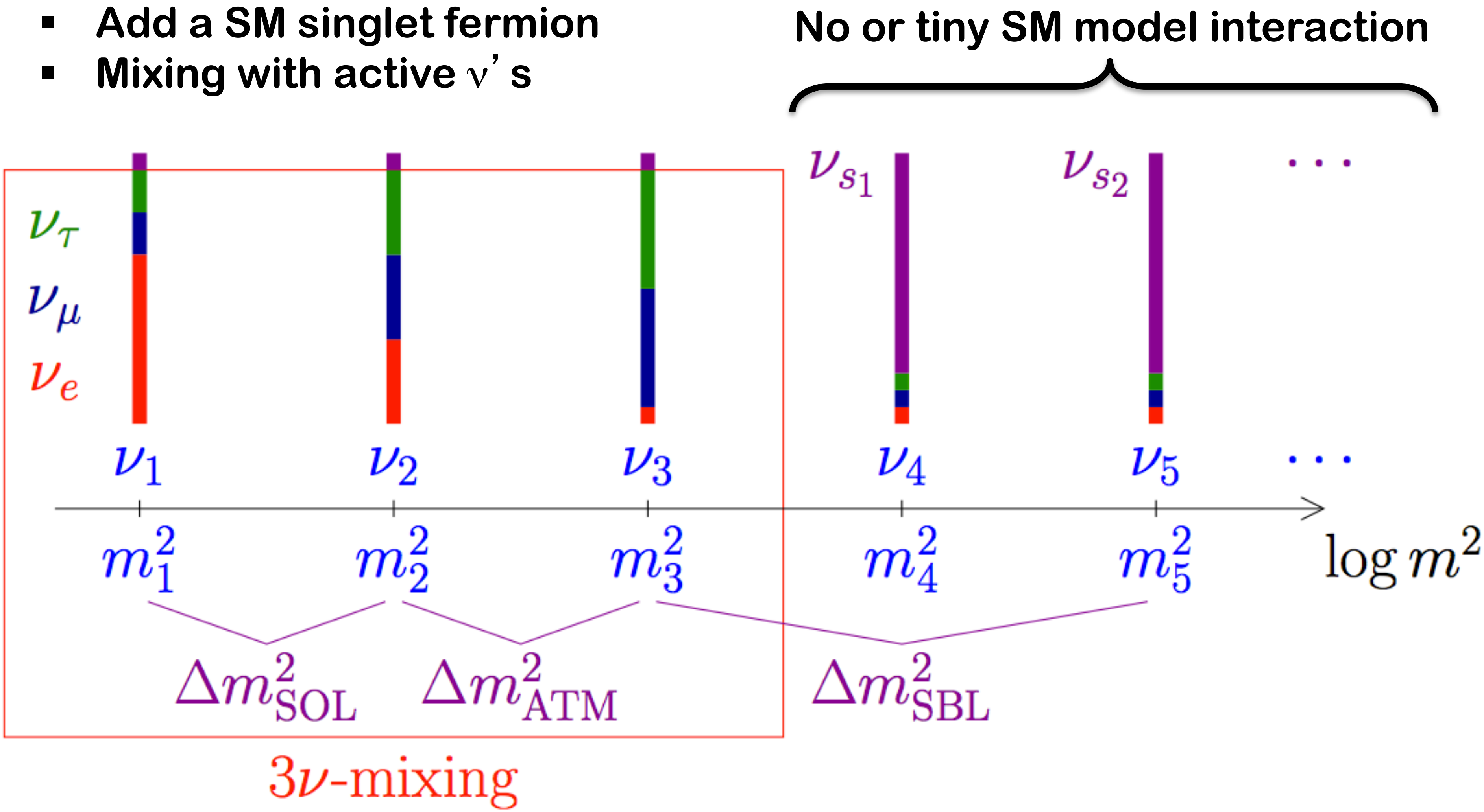
- 1^{st} results in 1995
- **Channel:** anti-$\nu_\mu \rightarrow$ anti-ν_e
- **Detection :** anti-ν_e + $^1H \rightarrow e^+ + n$
- **Baseline:** 30 m
- **Energy:** 20 < E (MeV) < 50
- **Status:**
  - anti-ν_e excess observed
    $\rightarrow$ 32.2 ± 9.4 ± 2.3 (3.8σ)
  - not confirmed nor ruled out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





The (light) sterile neutrino hypothesis

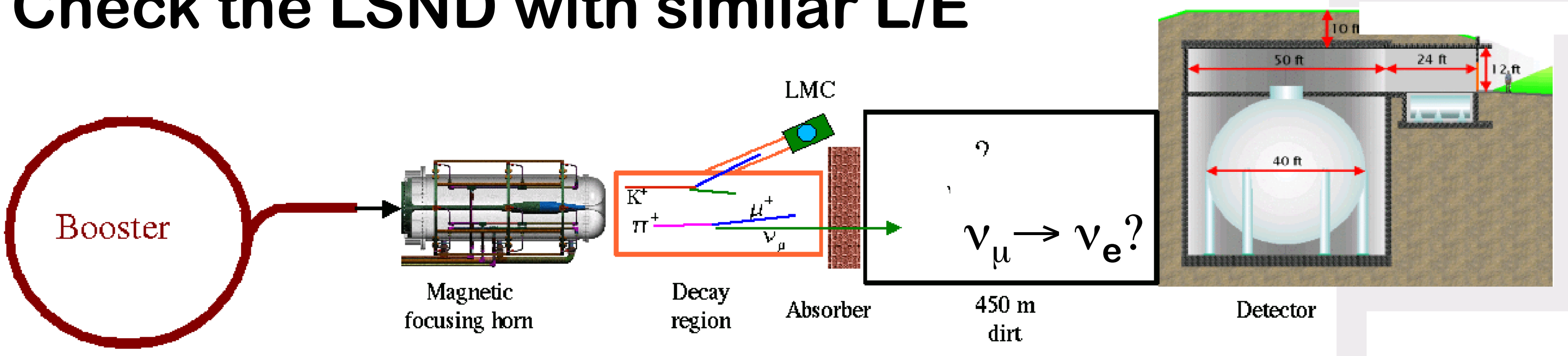
- Generic extension of SM model
- Add a SM singlet fermion
- Mixing with active ν' s

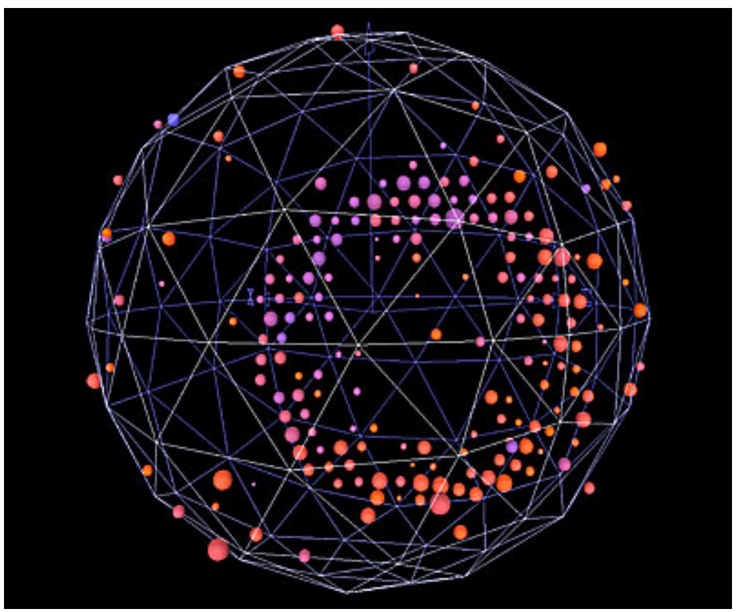


MiniBooNE (FNAL)

Primary goal: look for ν_e appearance in a ν_μ beam

Check the LSND with similar L/E

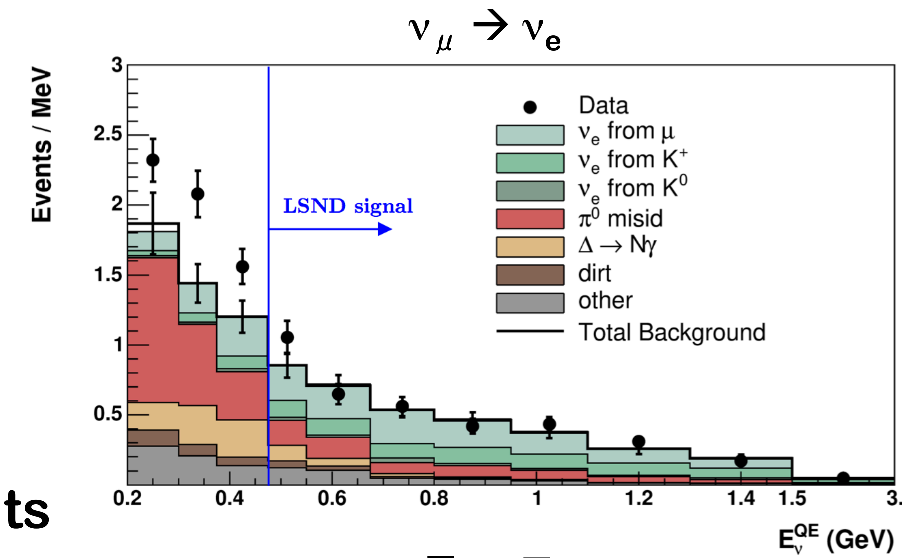


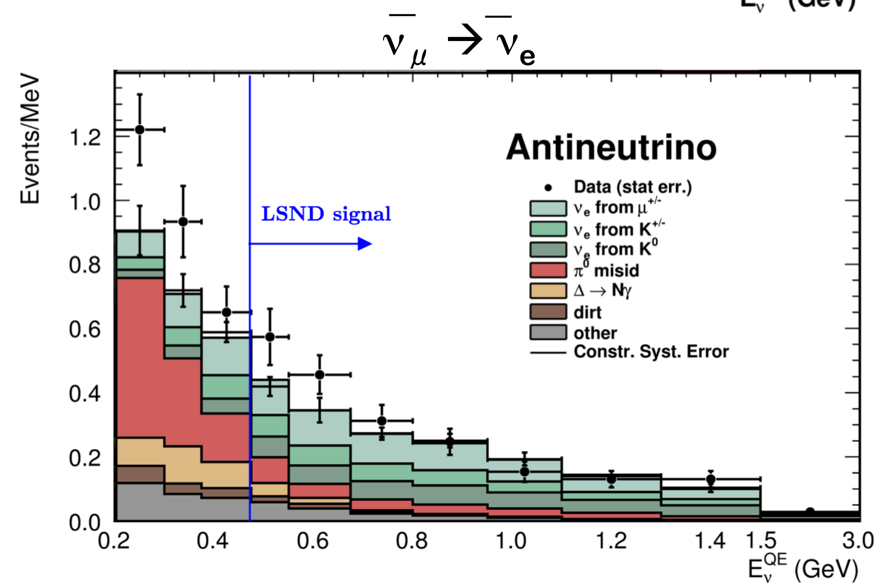


- **Beam: π^+ (π^-) decay in flight**
- **Detection: Cherenkov + scintillation**
- **L/E $\approx$1 m / MeV**
  - **Baseline: 541 m**
  - **<u>200</u> < E (MeV) < 3000**
- **Statistics:**
  - **ν : 6.46 × 10^{20} POT (2008)**
  - **$\bar{\nu}$:1.27 × 10^{20} POT (2012)**

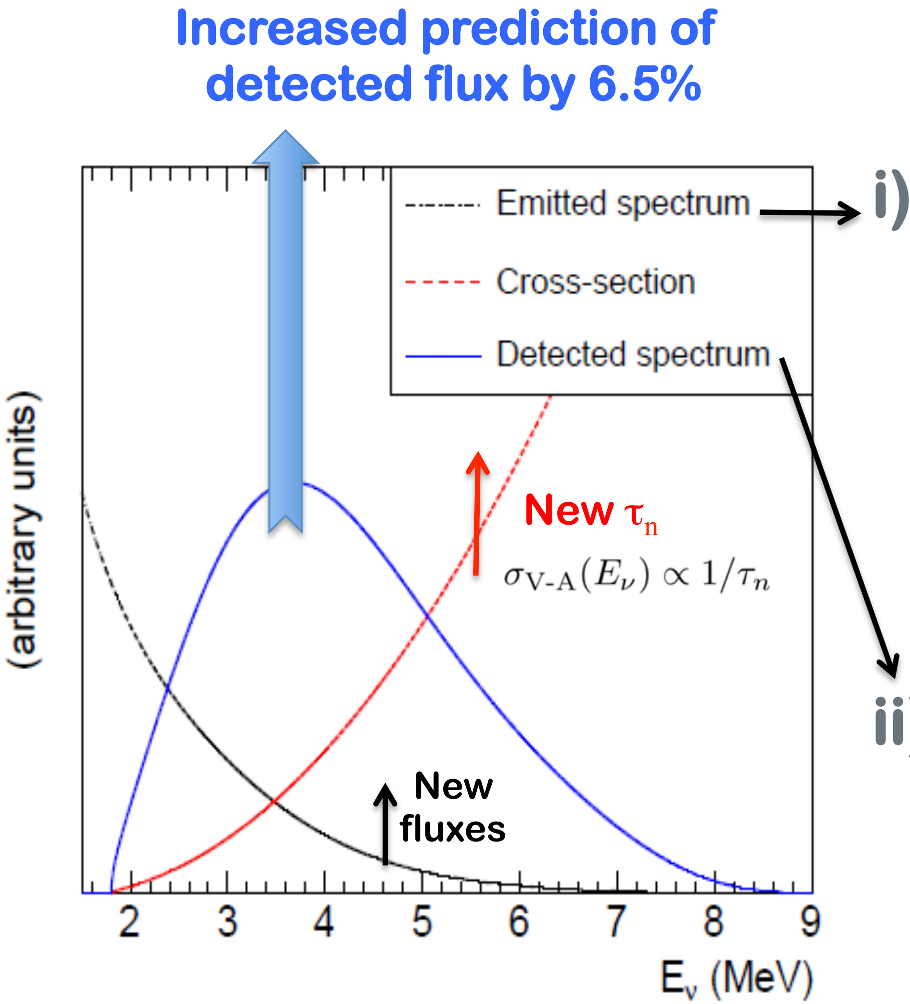
MiniBooNE Results

- 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 was not conclusive checking the LSND anomaly**





New Reactor ν-Fluxes



i) Neutrino Emission:

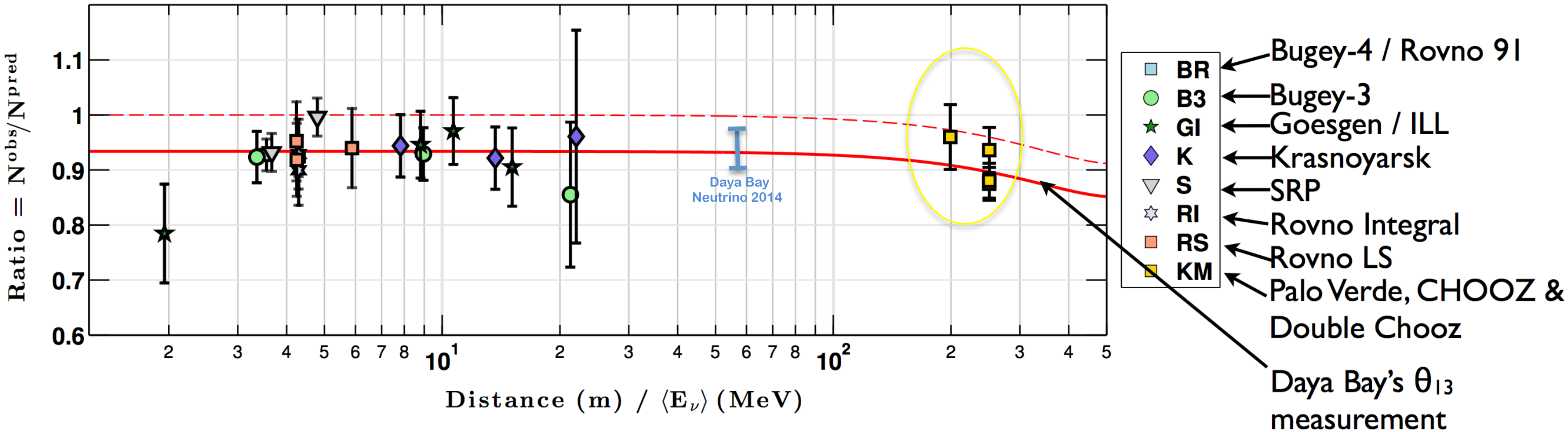
- Improved reactor neutrino spectra → **+3.5%**
- Accounting for long-lived isotopes in reactors → **+1%**

ii) Neutrino Detection:

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

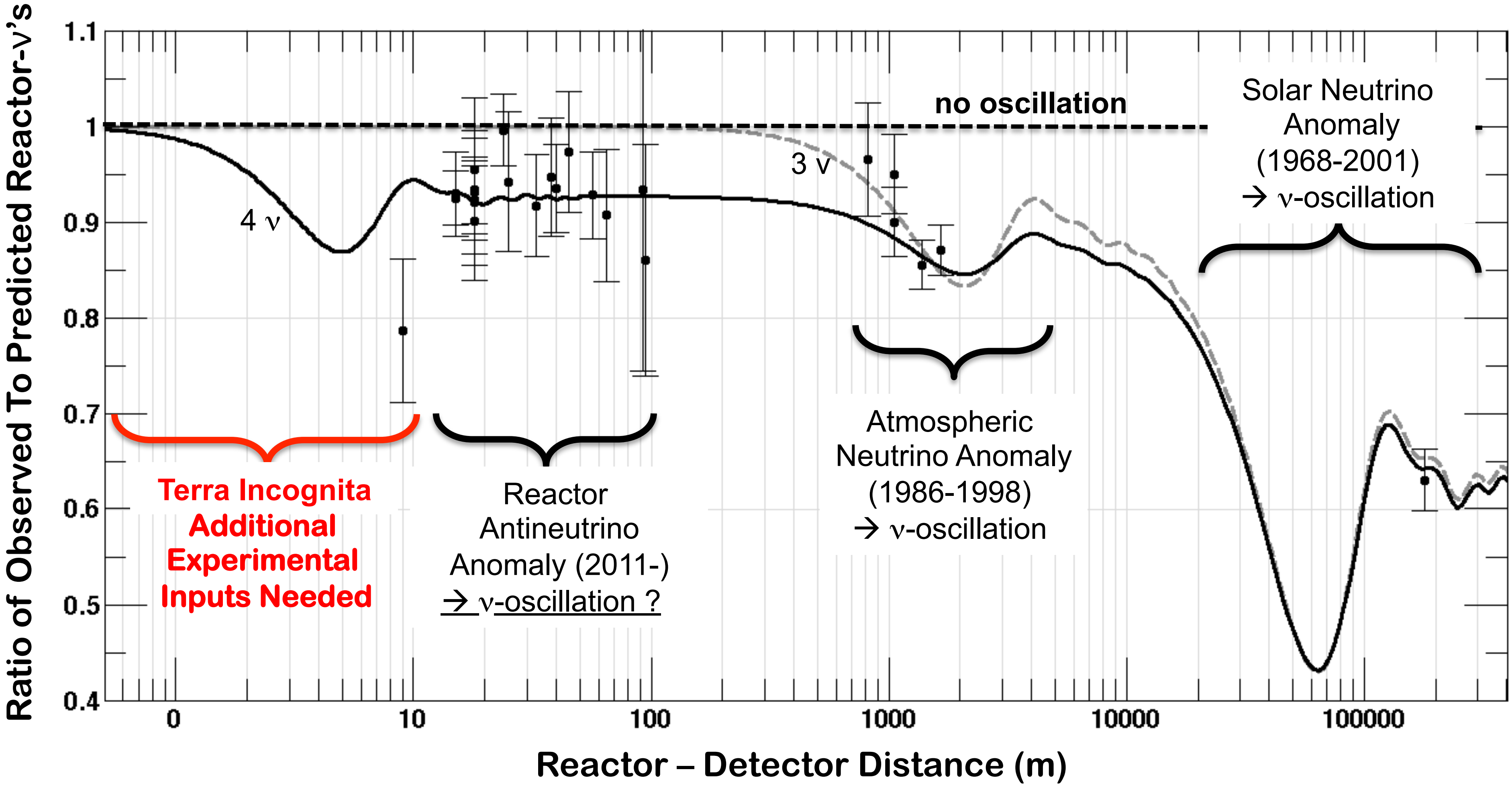
The Reactor Anomaly

2014 Reactor Anomaly Update (new)



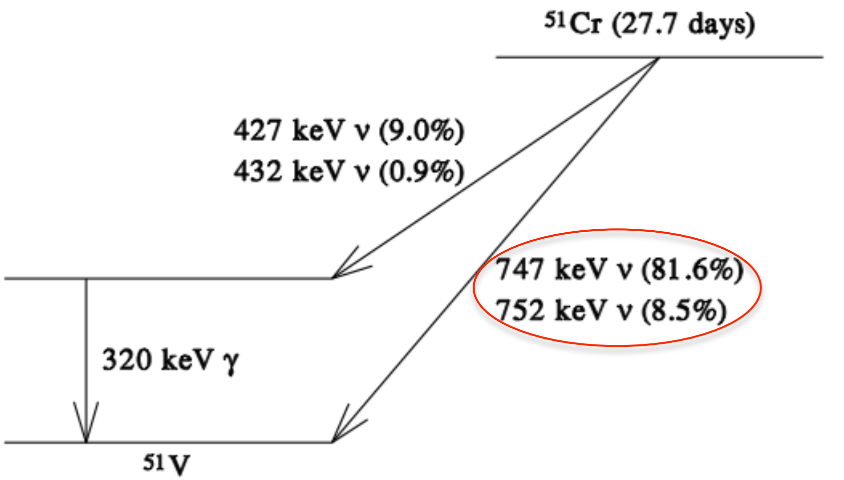
- All known nuclear corrections to β - ν spectra
- Refined treatment of experimental correlations
- Latest updated neutron mean life (τ_n = 881.5 s)
- Corrects for a statistical bias (1% shift)
- km-scale baselines (Chooz, DC, PV)
  - correcting for θ_{13} deficit from Daya Bay's measured value
- 2014 result: μ = 0.938 ± 0.023, 2.7σ deviation from unity

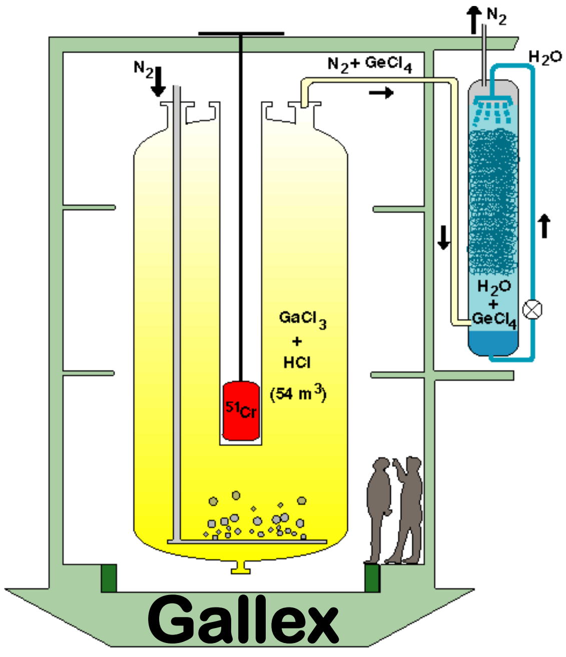
Experimental Artifact or New Physics?



The Gallium Neutrino Anomaly

- **Test of solar neutrino radiochemical detectors GALLEX and SAGE**
  - $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$
- **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 measurment

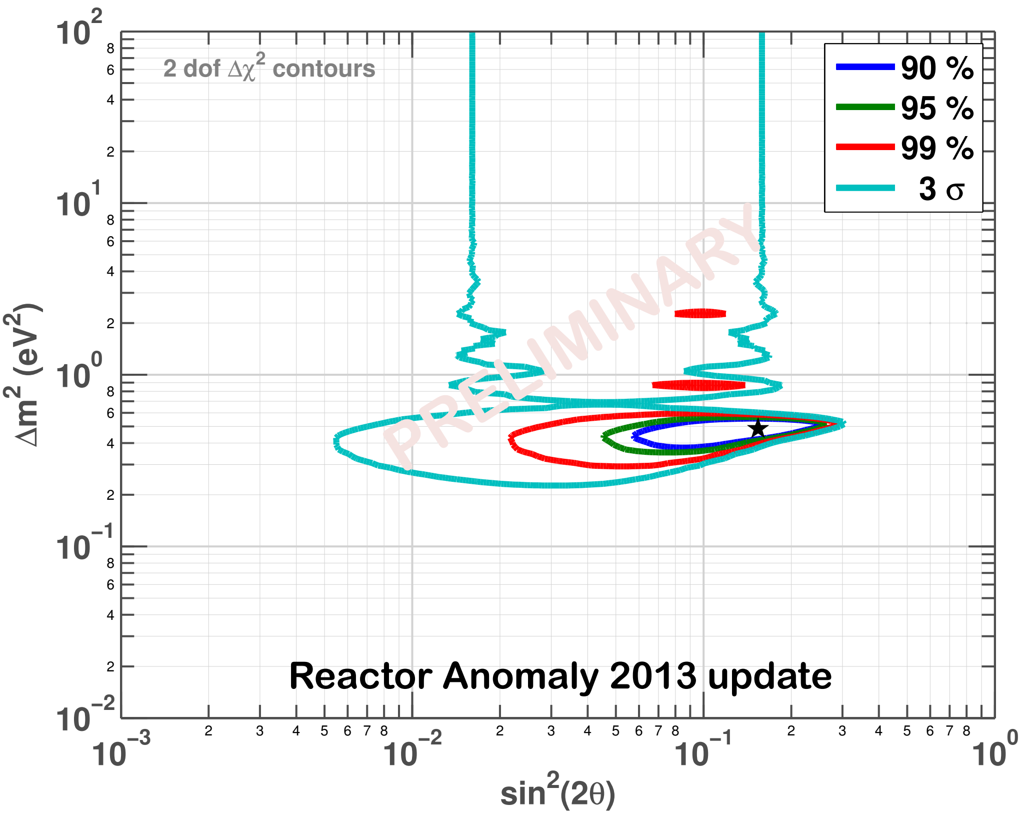


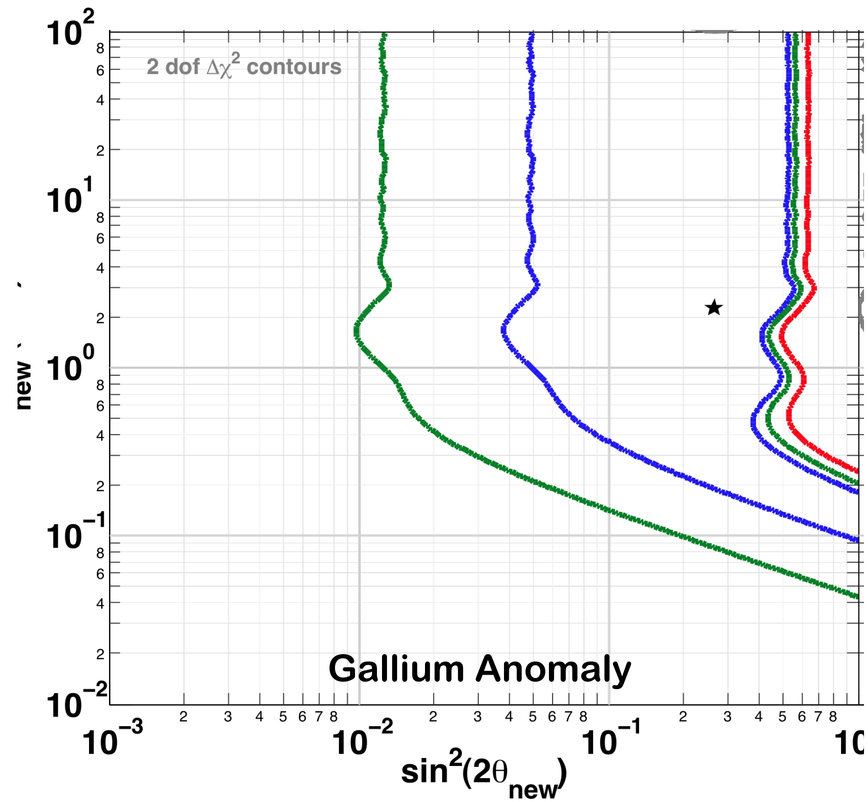


Sterile Neutrino Interpretation

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/Minos/ 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

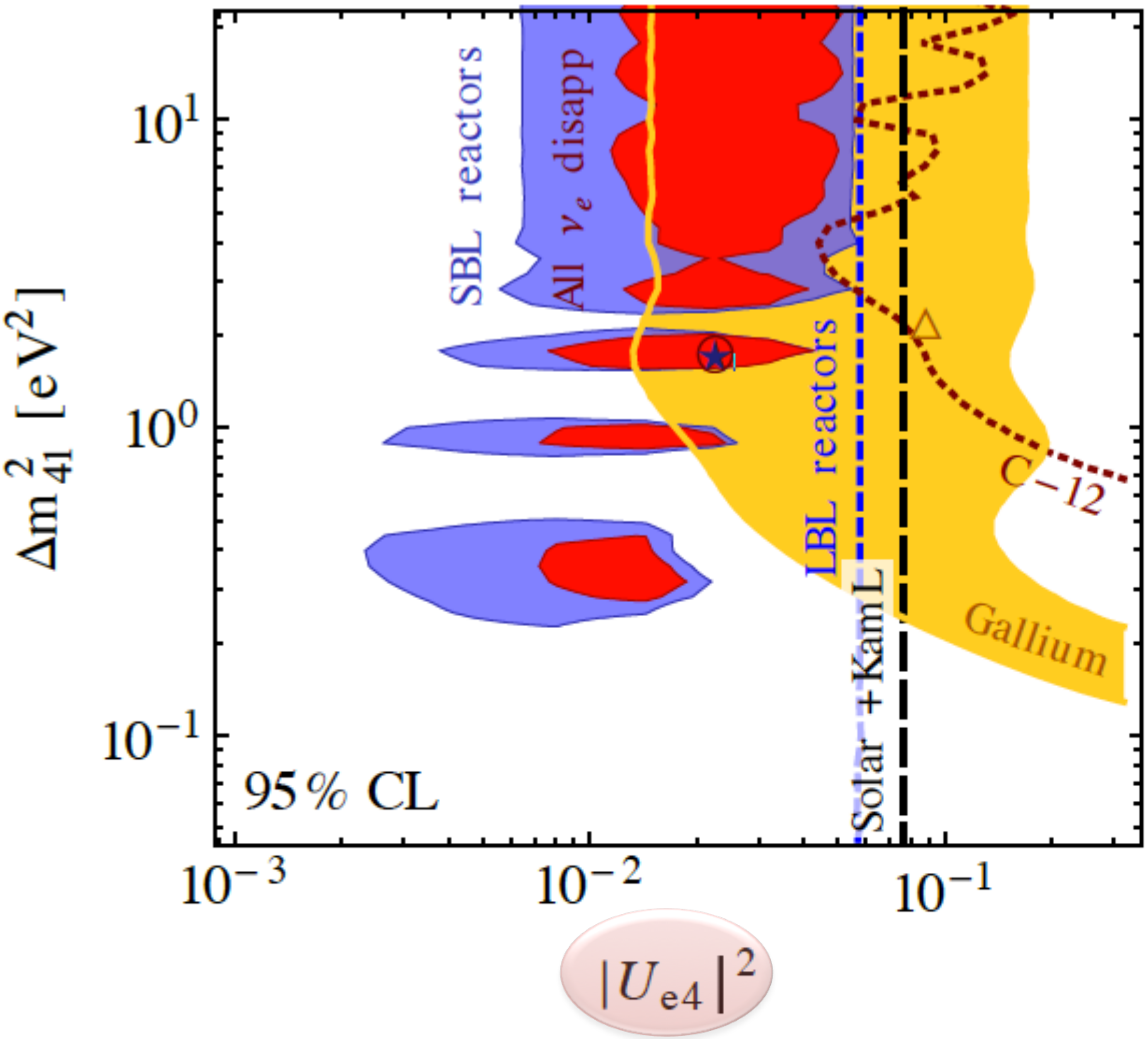
Sterile-ν Phenomenology (3+1)

- $\overset{(-)}{\nu}_e$ **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, Opera, Icarus...)
  - $$P_{\mu e} = 4\sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

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

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

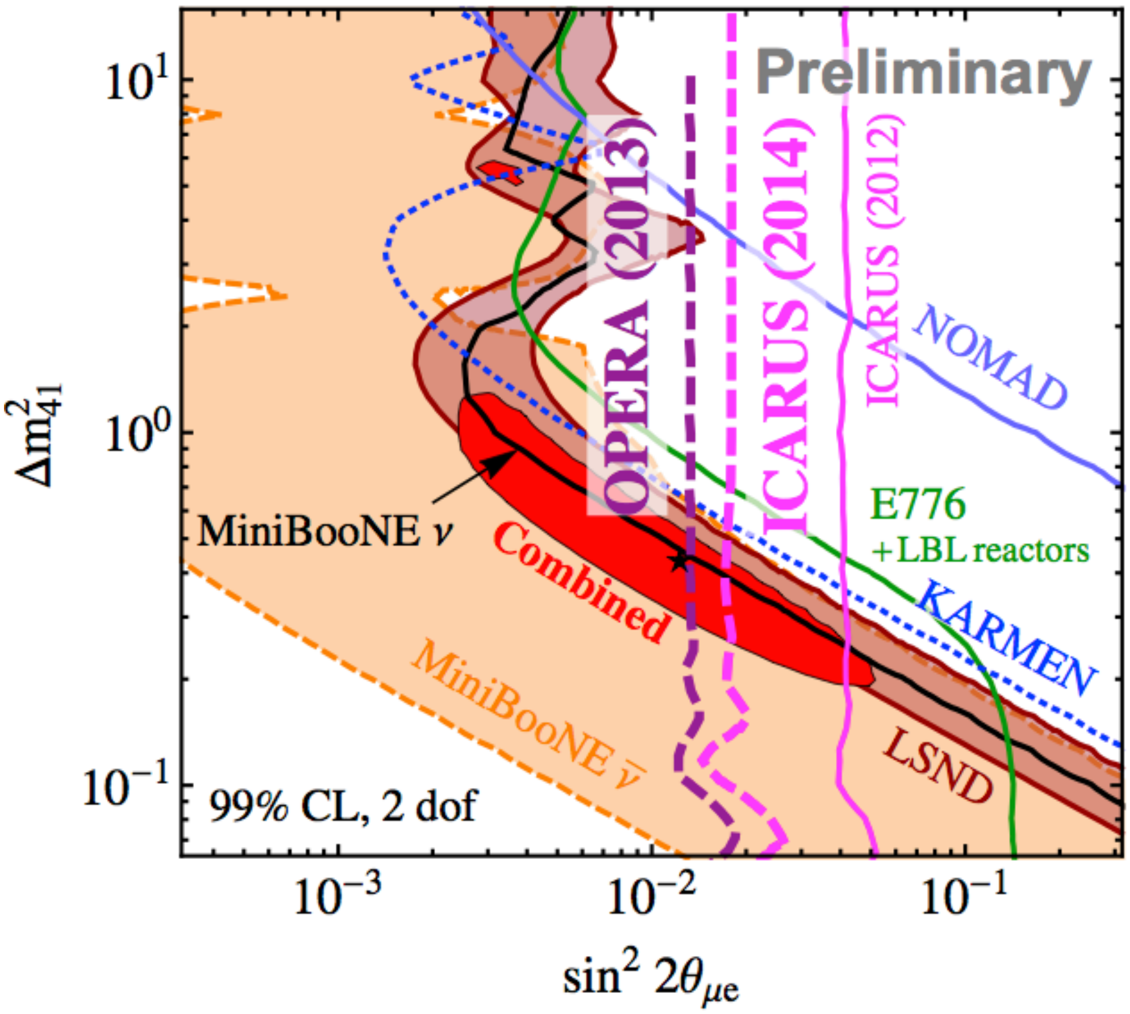
Data consistent with $\overset{(-)}{\nu}_e$ disappearance with L/E≈1 m/MeV



J. Kopp et al., arXiv:1303.3011

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

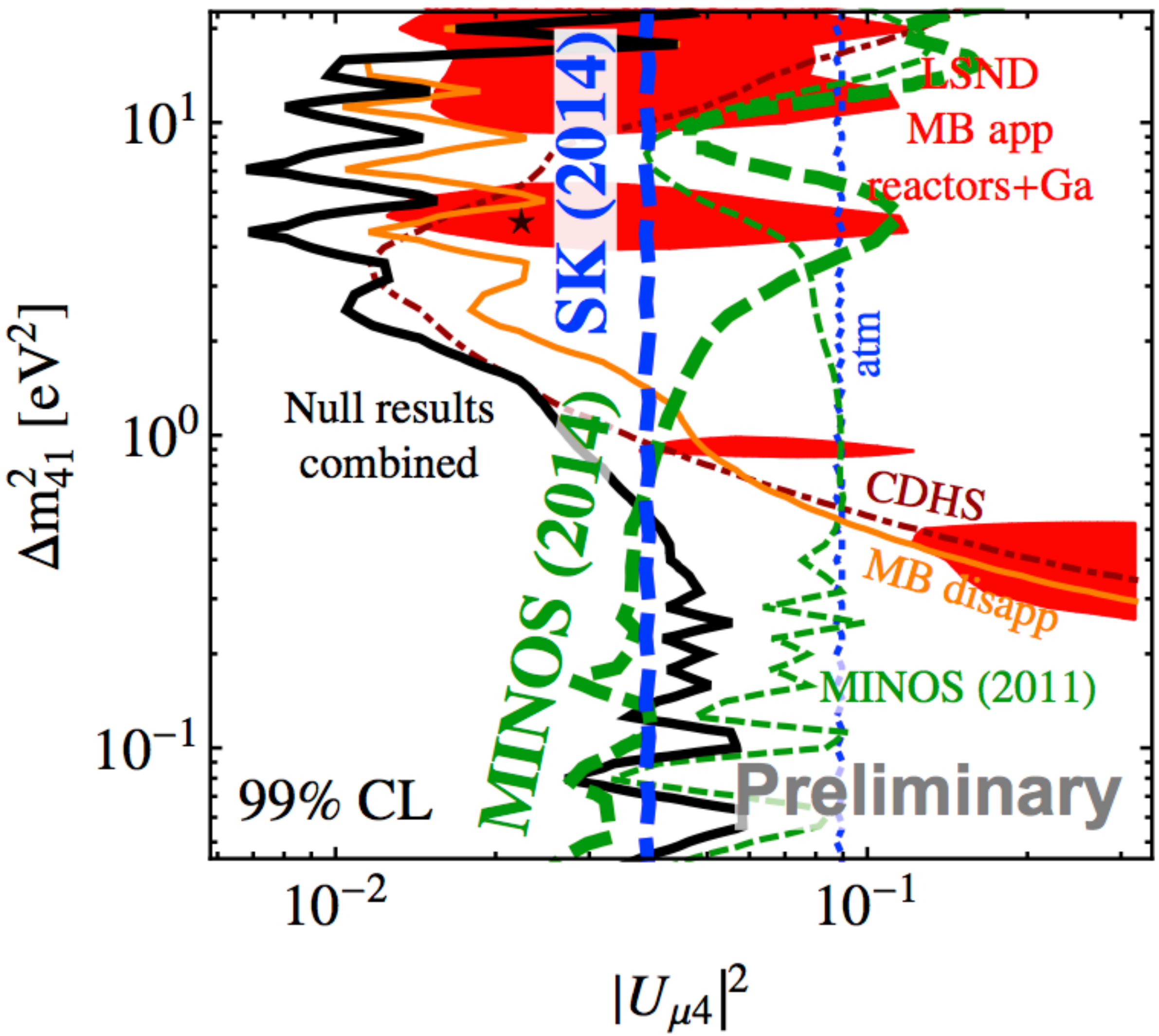
Consistent solution for $\overset{(-)}{\nu}_e$ appearance with L/E≈1 m/MeV



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

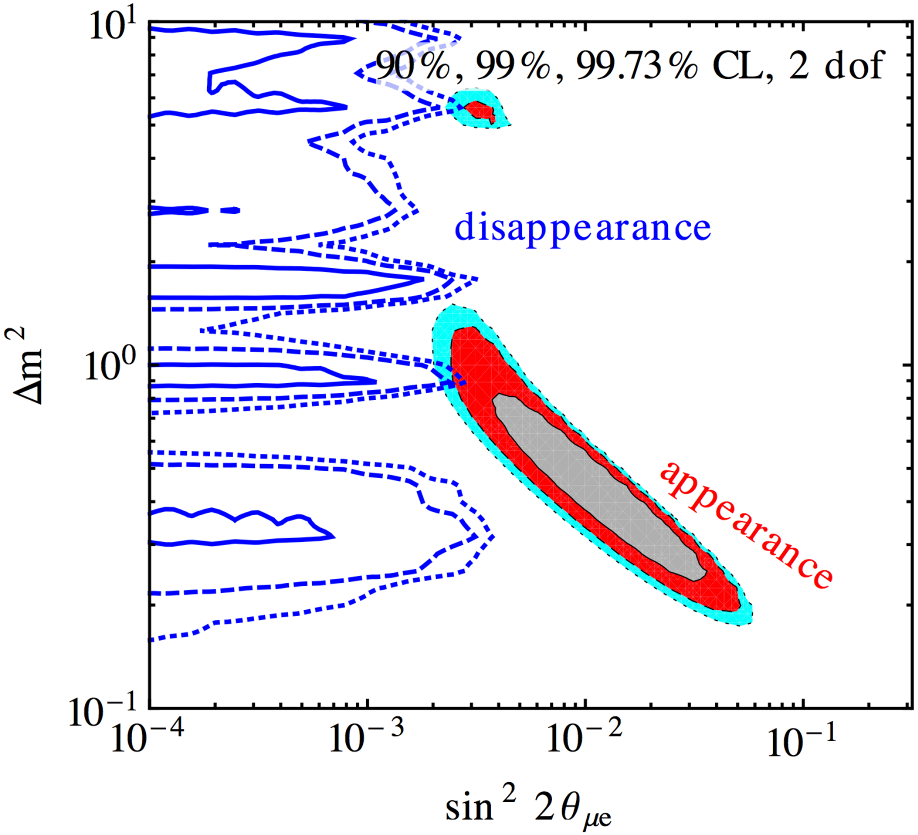


J. Kopp et al., arXiv:1303.3011

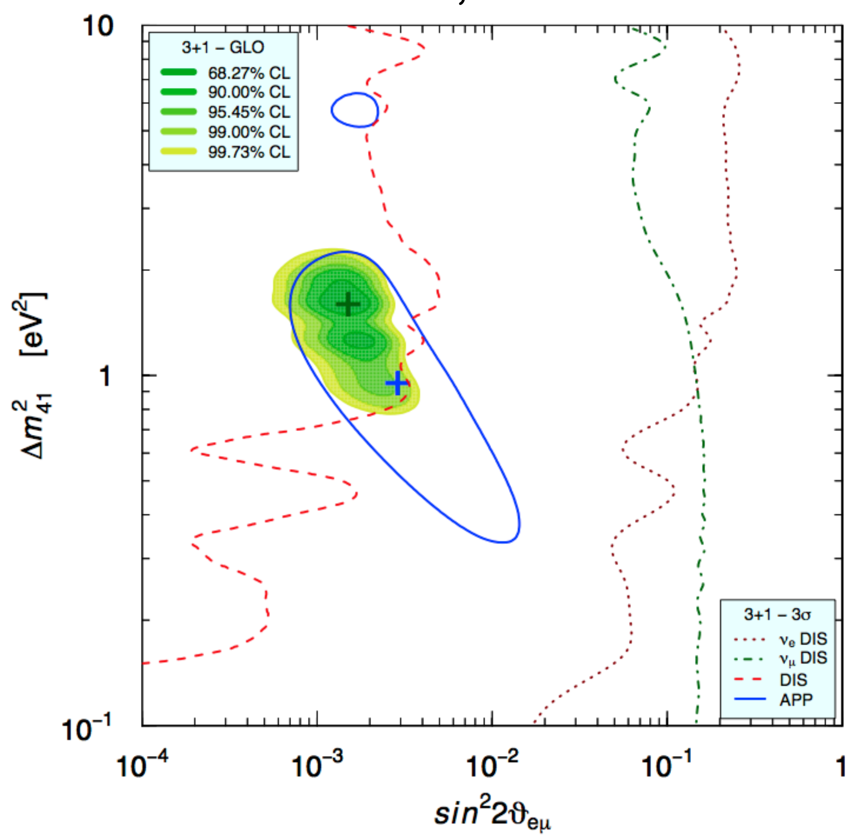
New result MINOS 2014

Appearance VS Disappearance

J. Kopp et al., **arXiv:1303.3011**



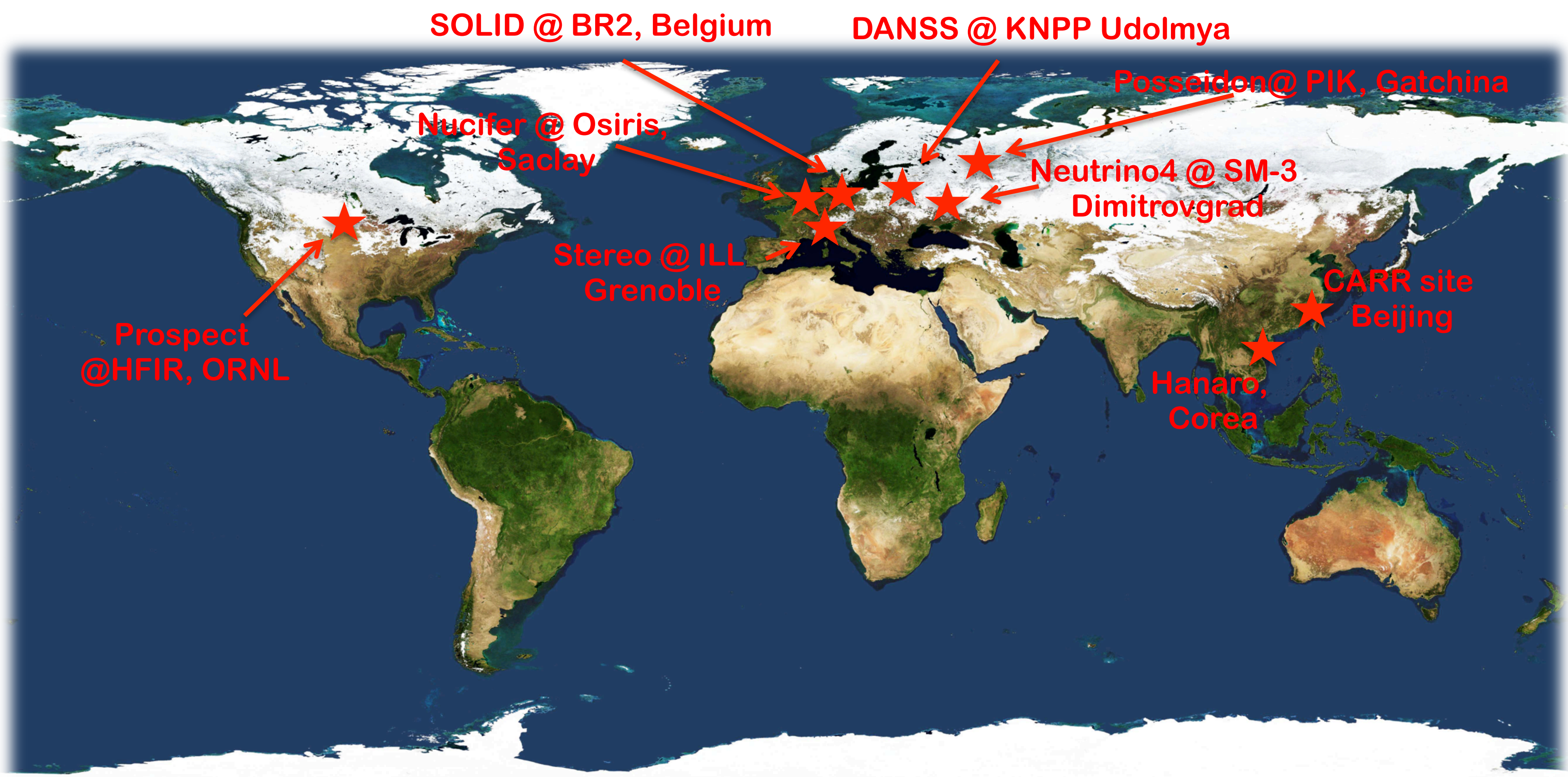
C. Giunti et al., **arXiv:1308.5288**



Tension between $\bar{\nu}_e / \nu_e$ appearance/disappearance and $\bar{\nu}_\mu / \nu_\mu$ disappearance (3+1 & 3+2 models)

Experimental Prospect

Experimental Prospect:
@ Nuclear Reactor



Test of both reactor & gallium anomalies

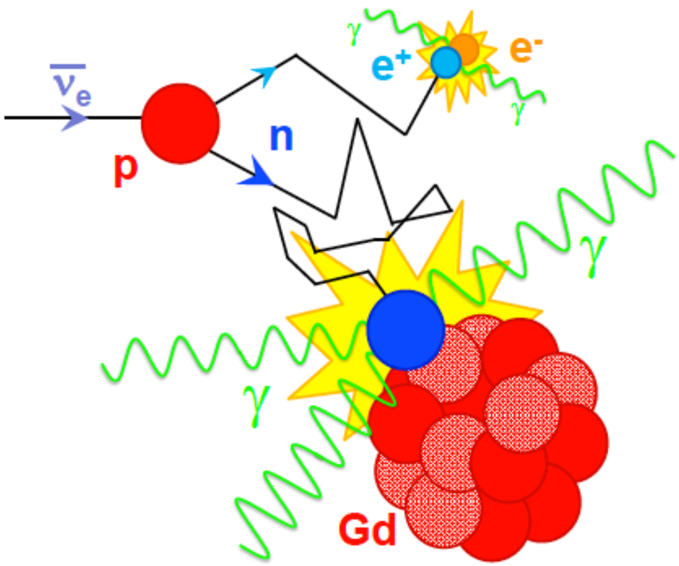
Testing $\overset{(-)}{\nu}_e$ disappearance anomalies

- Need robust test, beyond the current mean deviation from reactor predicted rate
- Input from sterile neutrino fits
  - $\Delta m^2 \approx$ 0.1-10 eV² $\rightarrow L_{osc}(m) = 2.5 \dfrac{E(MeV)}{\Delta m^2 (eV^2)} \approx 2-10\ m$
  - $\sin^2(2\theta_{ee}) \approx$ 0.01-0.15
- Experimental specifications
  - Compact source, <1 meter scale
  - 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: a killer!
    - <u>must be negligible</u>

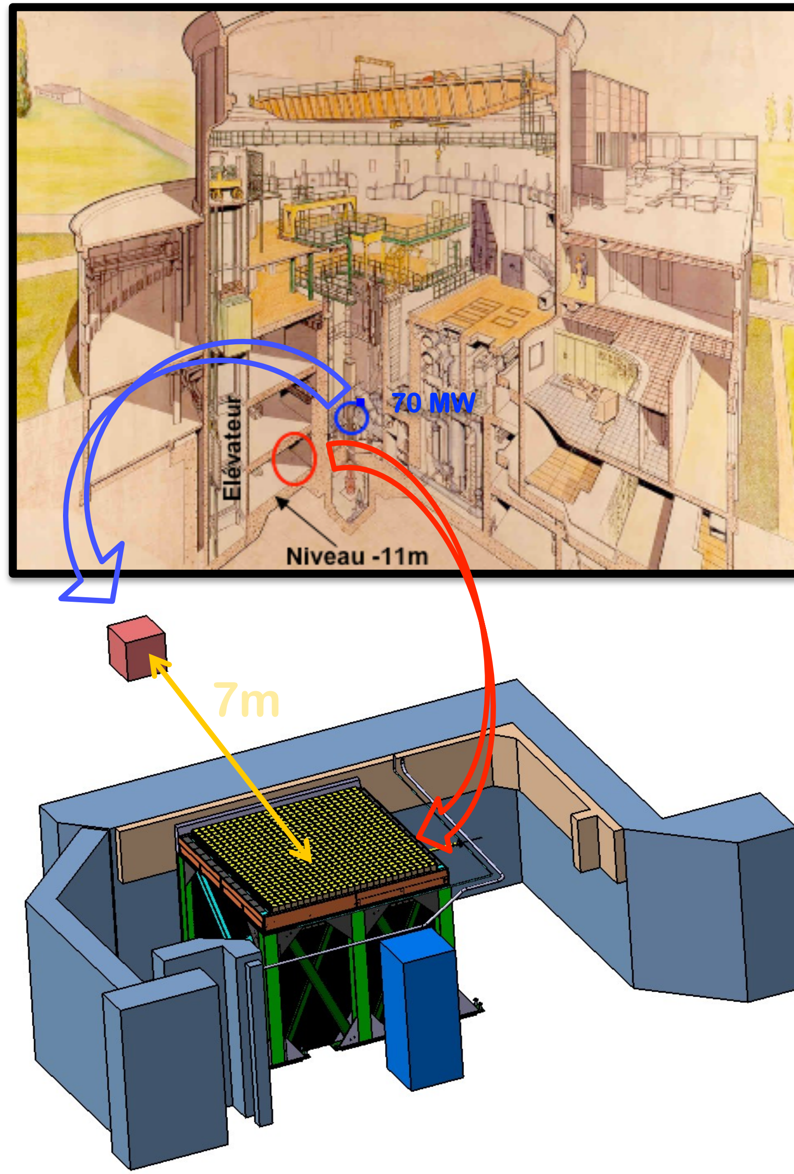
Reactor ν Proposals

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	Prospect	85 MW	-	7m & 18m	Surf.
	China project	-			
	DANSS/Neutrino4	Movable detector			

Nucifer @ OSIRIS *(Gd-LS)*

Originally Dedicated for non proliferation

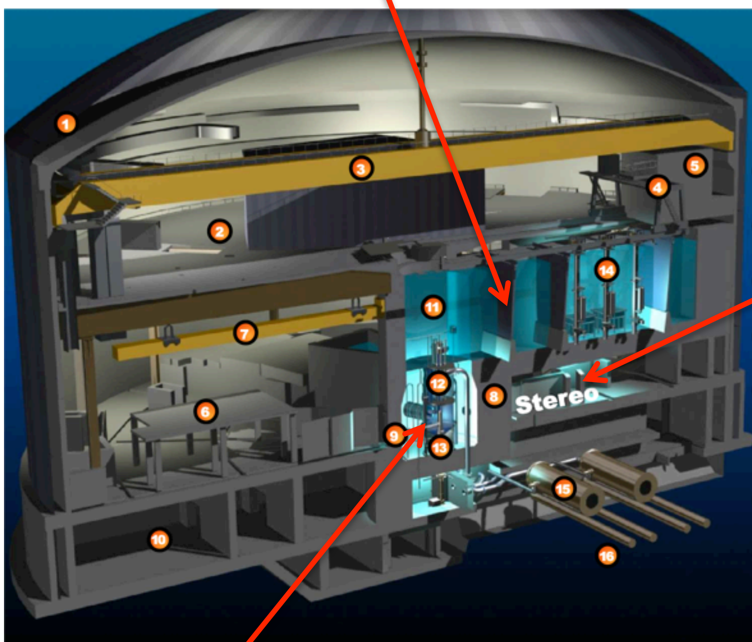
- **Osiris research reactor**
  - At Saclay, France
  - 70 MW, 20% ^{235}U
- **Detector designed for reactor monitoring studies**
  - 850 kg Gd-loaded LS
  - 350 int. expected / day
  - Shallow depth (few mwe)
- **Modest sensitivity to Sterile-v:**
  - Compact core: 60x60x60 cm^3
  - Short baseline: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



Stéréo @ ILL *(Gd-LS)*

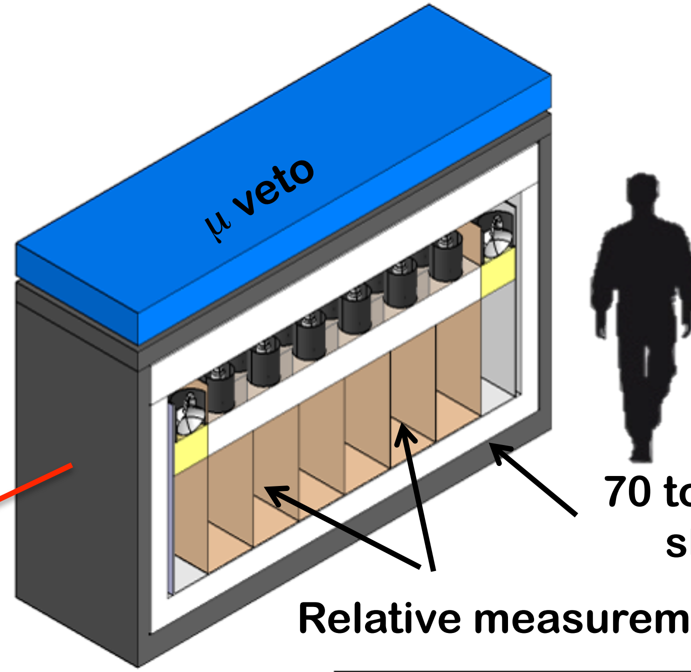
Start Data Taking in 2015

factor 4 attenuation of vertical flux from water pool



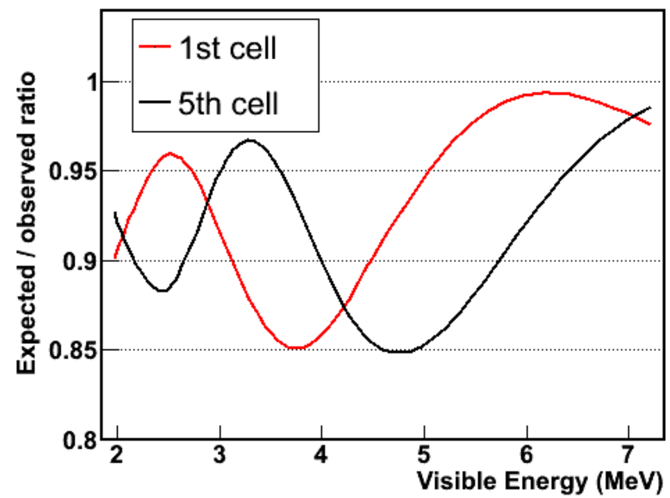
50 MW core
h=80cm, Φ=40cm

[8.5-11] m
baseline range



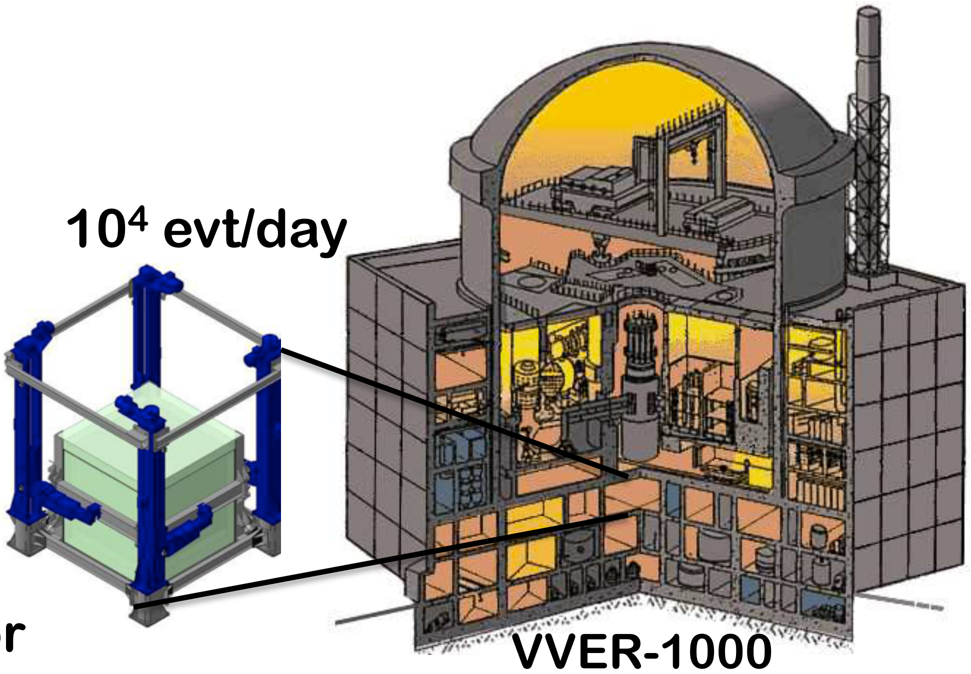
70 tons γ and n shielding

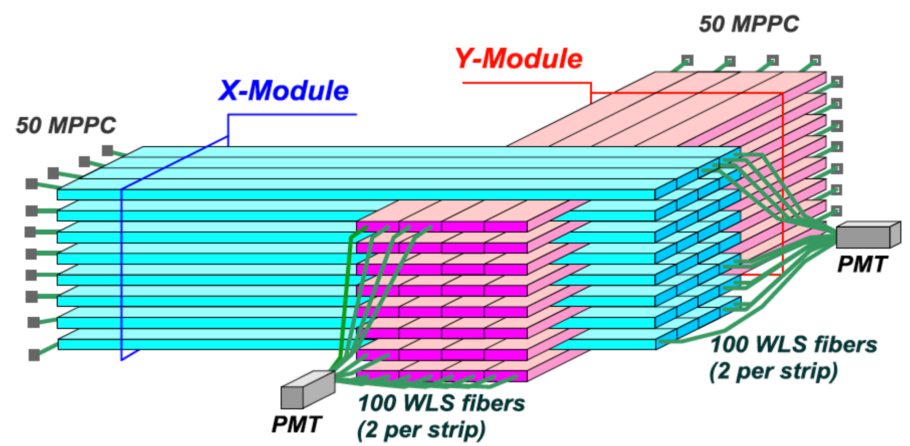
Relative measurement in 6 cells



DANSS @ KNPP *(High-Seg)*

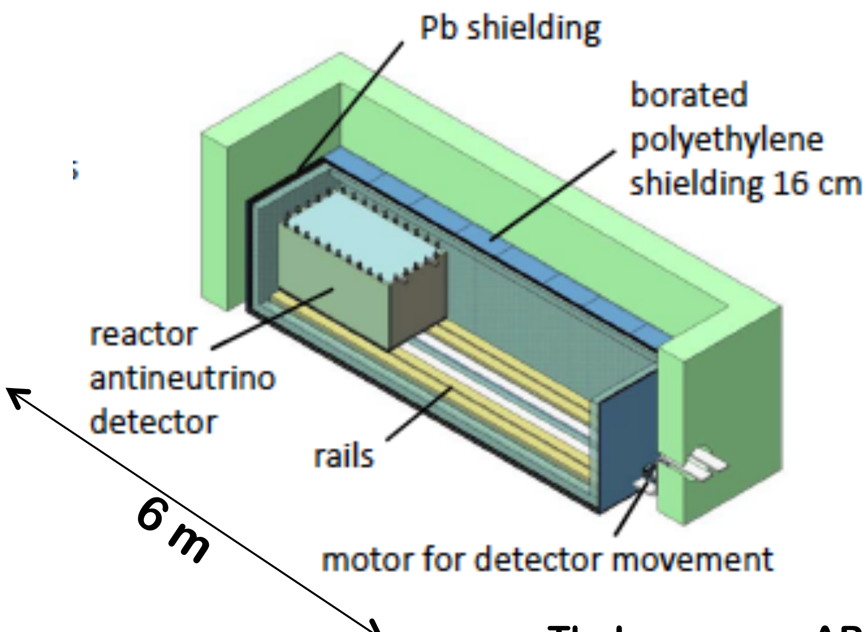
- 1 GW extended core
- Good overburden
- Vertical motion of the detector (9.7-12.2 m)
- Highly segmented detector → background rejection
- Plastic strips with Gd-loaded interlayer, WLS fibers readout
- Start in 2014/15?





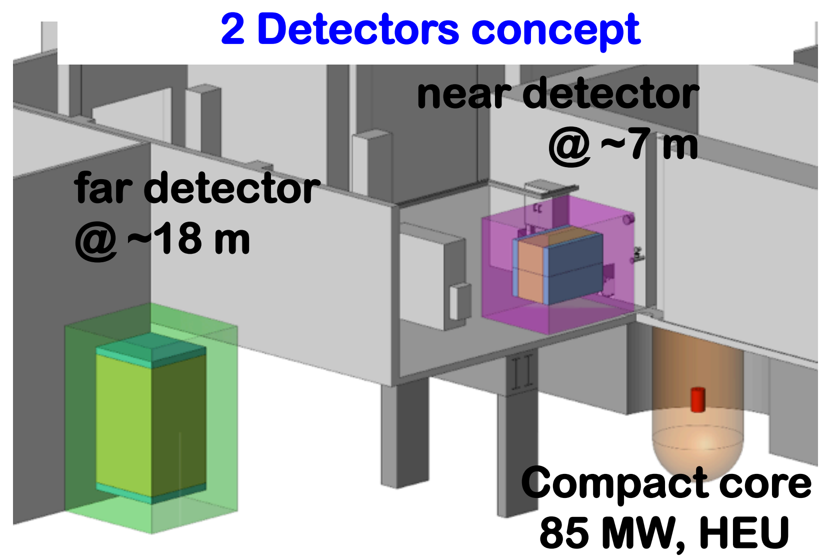
Neutrino-4 @ SM3 *(Gd-LS)*

- $2.5\ m^3$ LS target, 5 section movable detector [6-12] m
- 100 MW compact core
- Detector at Surface
- Status:
  - Proto: On/Off ν-data
  - Shielding integrated
  - Start in 2015

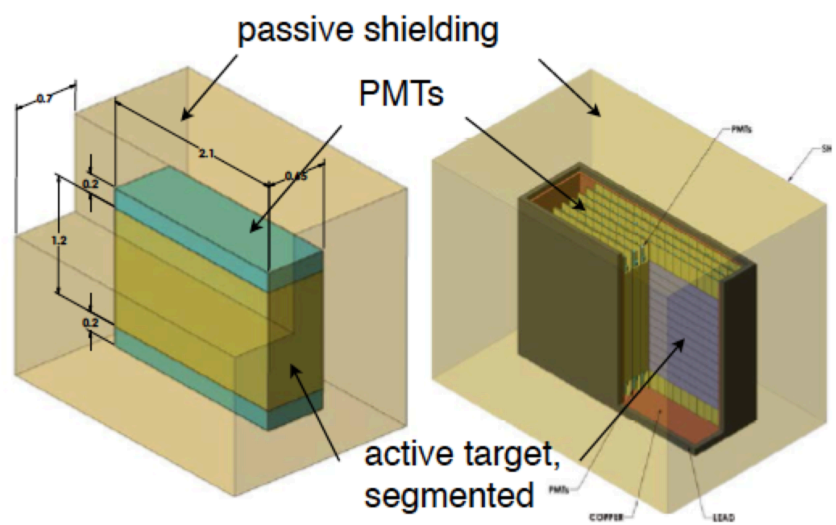


Prospect @HFIR

- 3 reactor sites
  - HFIR – 85 MW
- 7-18 m baselines
- Surface location
- Detector
  - Segmented
  - ^{6}Li-doped for n-tagging or Gd-loaded?
- Status:
  - Site characterization
  - R&D
  - Start 2016?



arXiv:1309.7647



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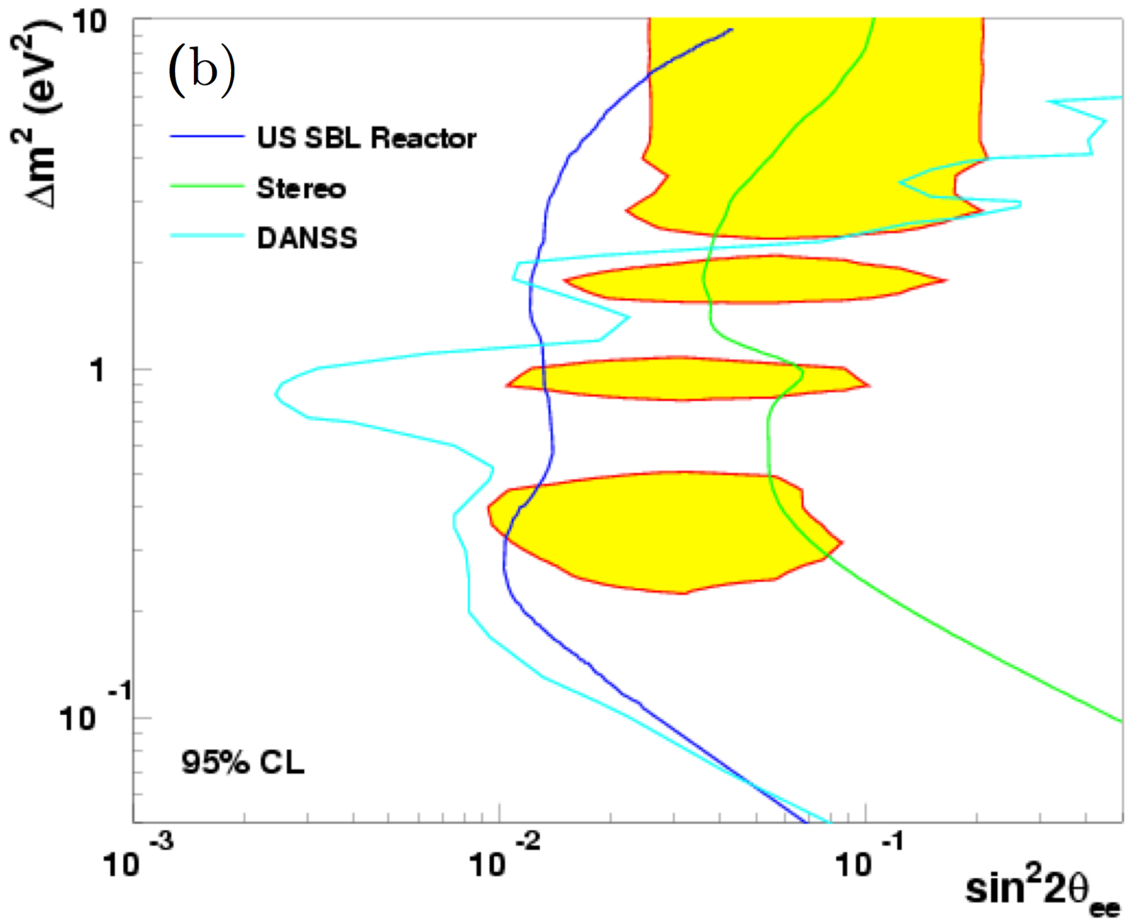
Reactor Experiment Sensitivity

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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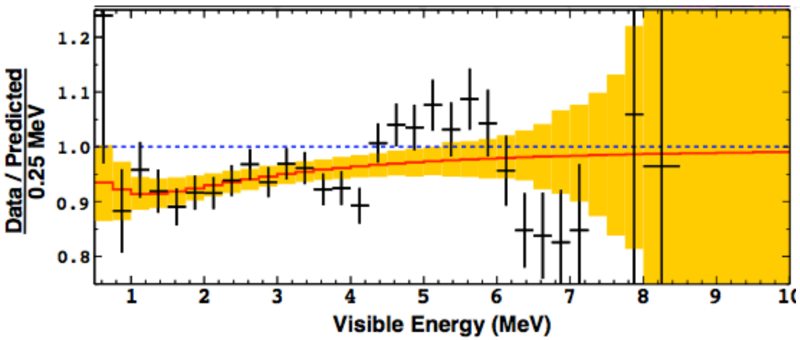
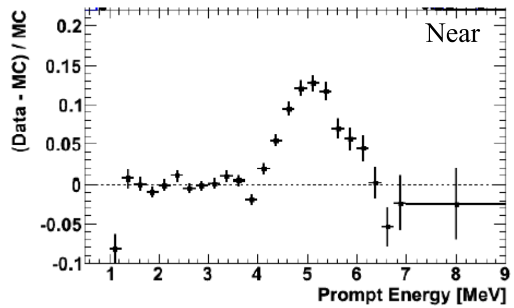
A ‘new’ 1-2% n Excess at 5 MeV

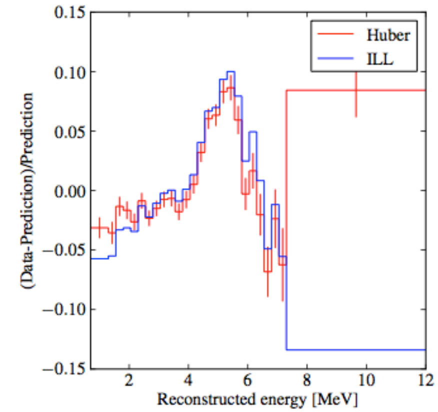
Double Chooz, May 22nd 2014



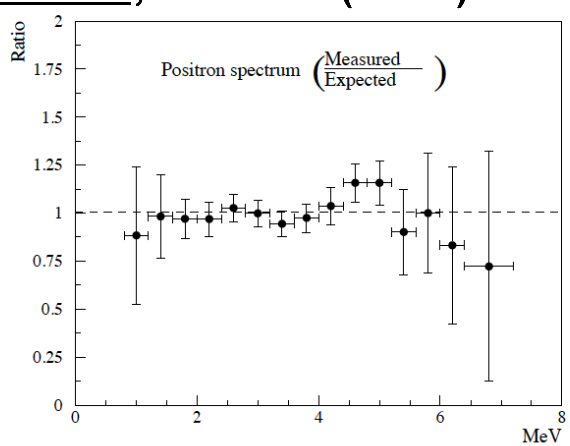
RENO, Neutrino 2014



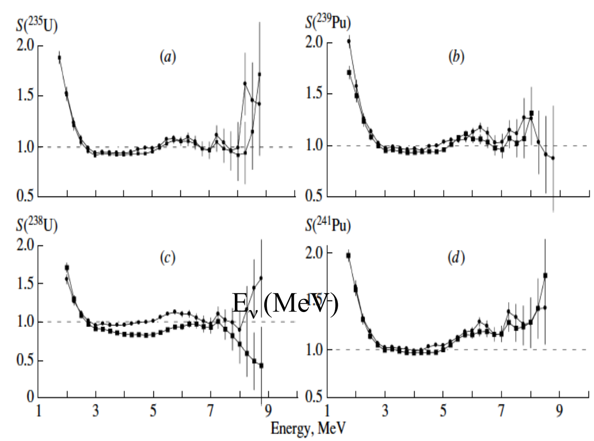
DB, PhD, now



CHOOZ, PLB466 (1999) 415-430



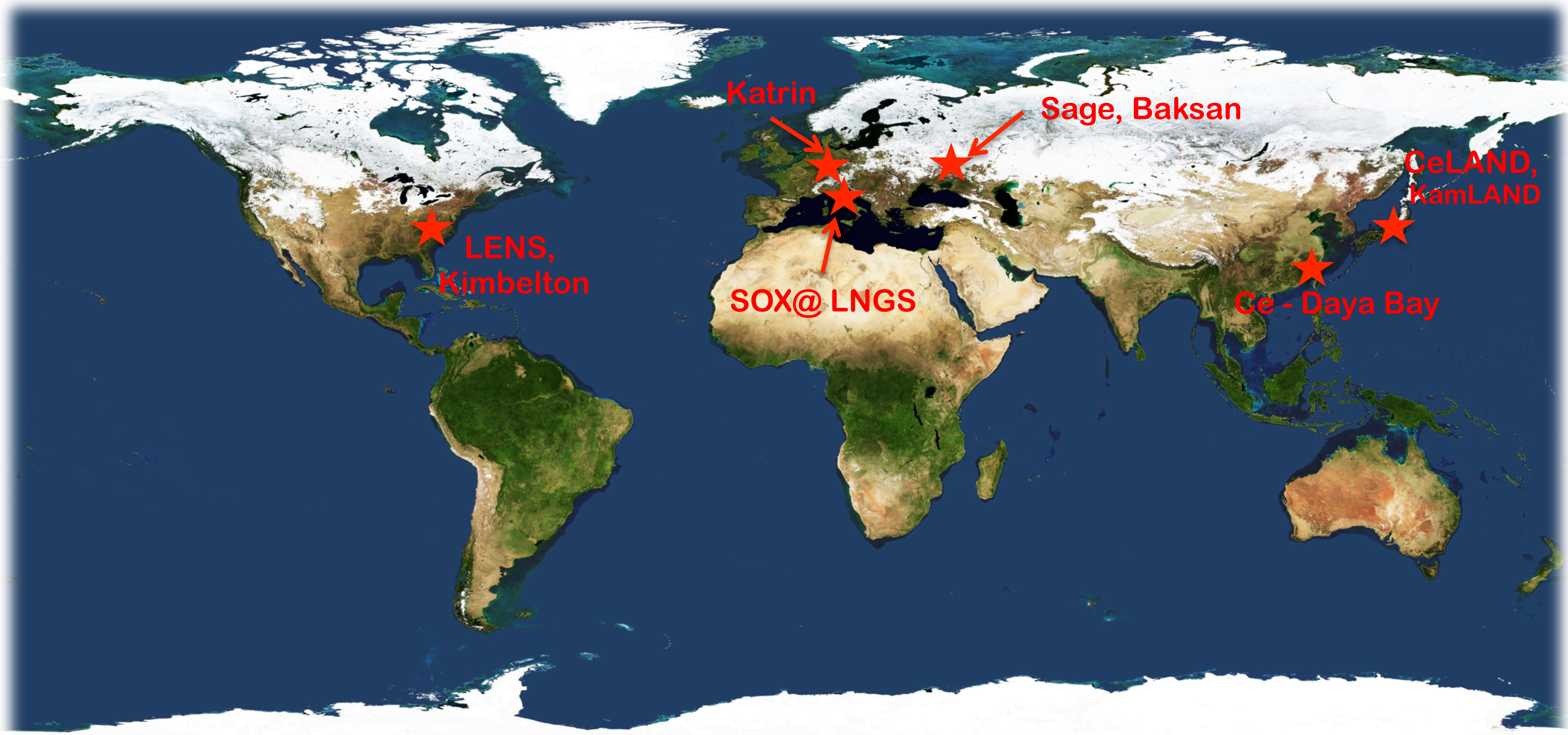
Rovno, arXiv:1207.6956



Origin to be understood (fluxes or e-ν conversion, new interaction?)

Relative measurements: modest impact on sterile-ν search

Experimental Program: @ Neutrino Generator



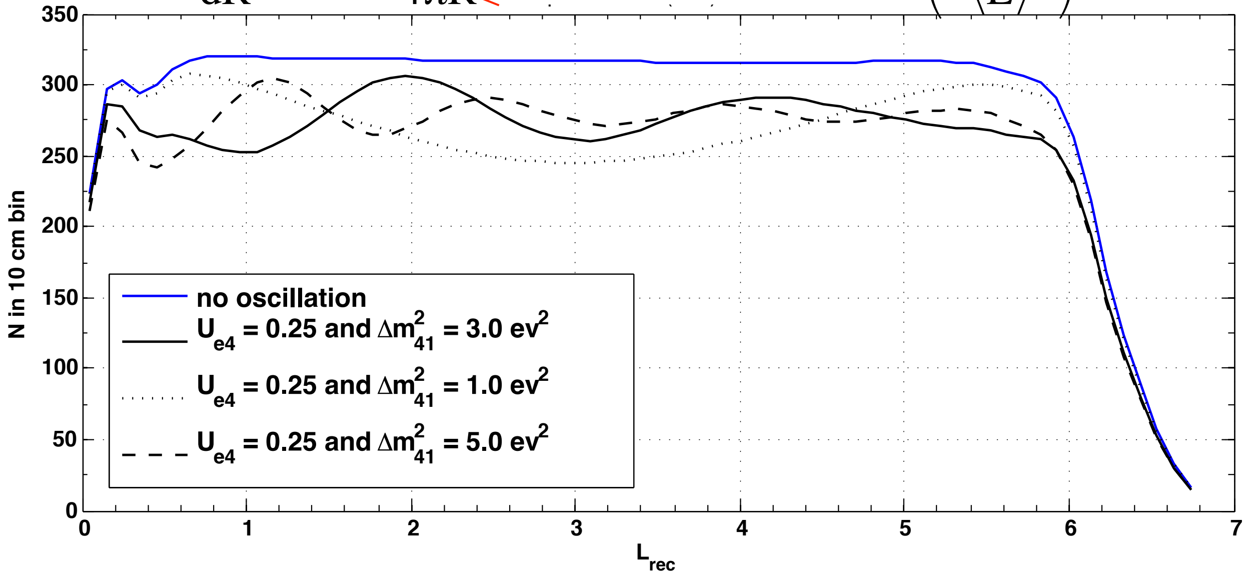
Test of both reactor & gallium anomalies

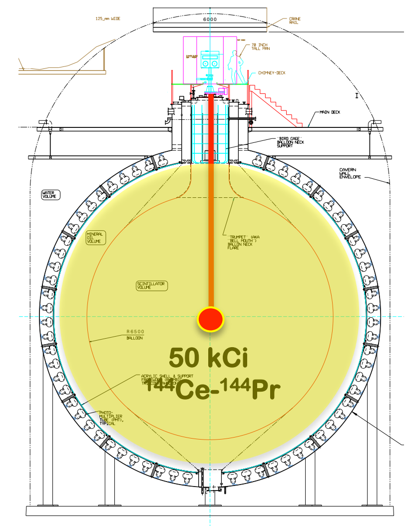
ν Generator Proposals

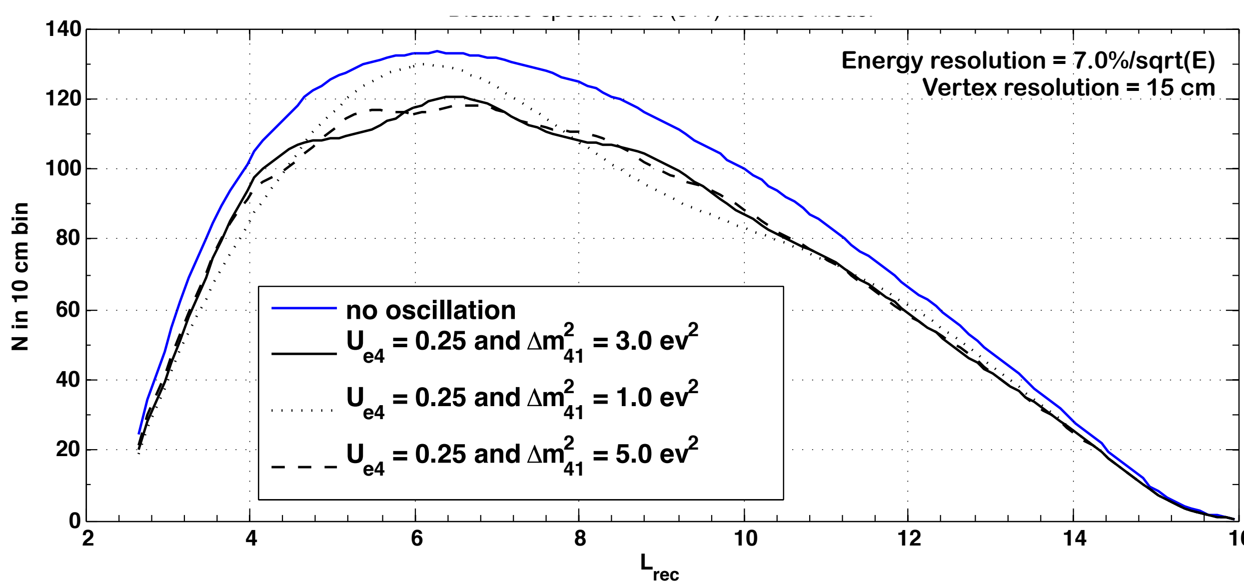
Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	$\nu_e e \rightarrow \nu_e e$ 5% E_{res} 15cm R_{res} or Radio-chemical	Detector Radioactivity Solar ν (irreducible) ν generator impurities	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	>3 MCi	Sage LENS
					>10 MCi	SOX-Cr (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 Ce-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)

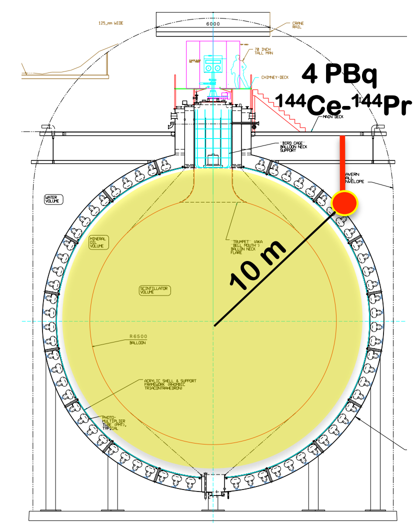
Search for $\bar{\nu}_e \to \bar{\nu}_s$ with $^{51}Cr/^{144}Ce$

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









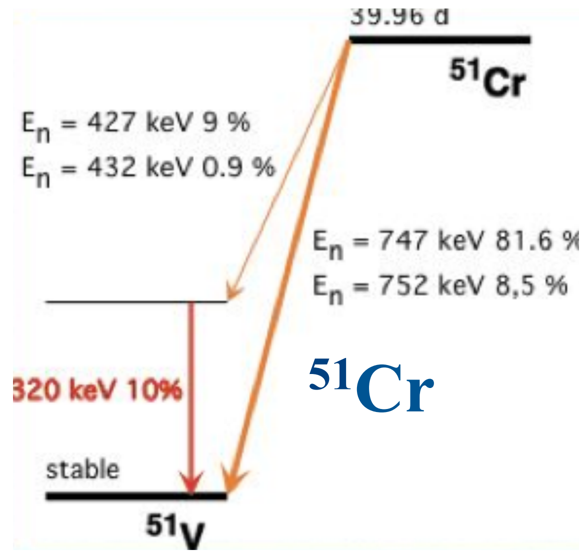
^{51}Cr neutrino generator

- ^{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 (SOX)



Gallex source & shield in Saclay

^{51}Cr: SOX (Borexino)

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

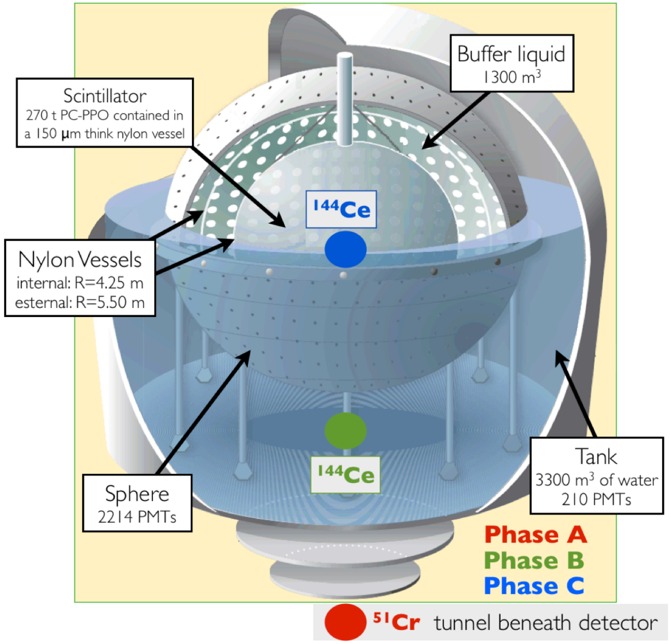
- Production reactors
  - Oak Ridge (US) ?
  - Ludmila (Ru) ?

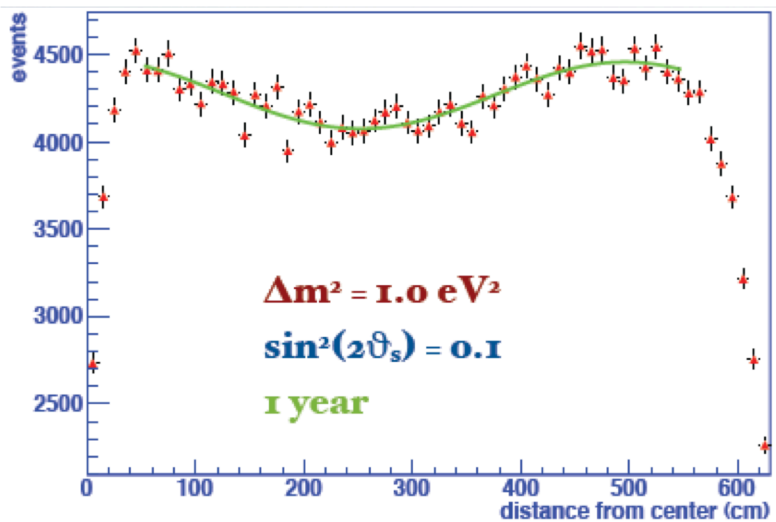
- Source **8.25 m** from center

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

- Status:
  - R&D for irradiation (need 2 x 5 MCi)

- Staged approach: after ^{144}Ce

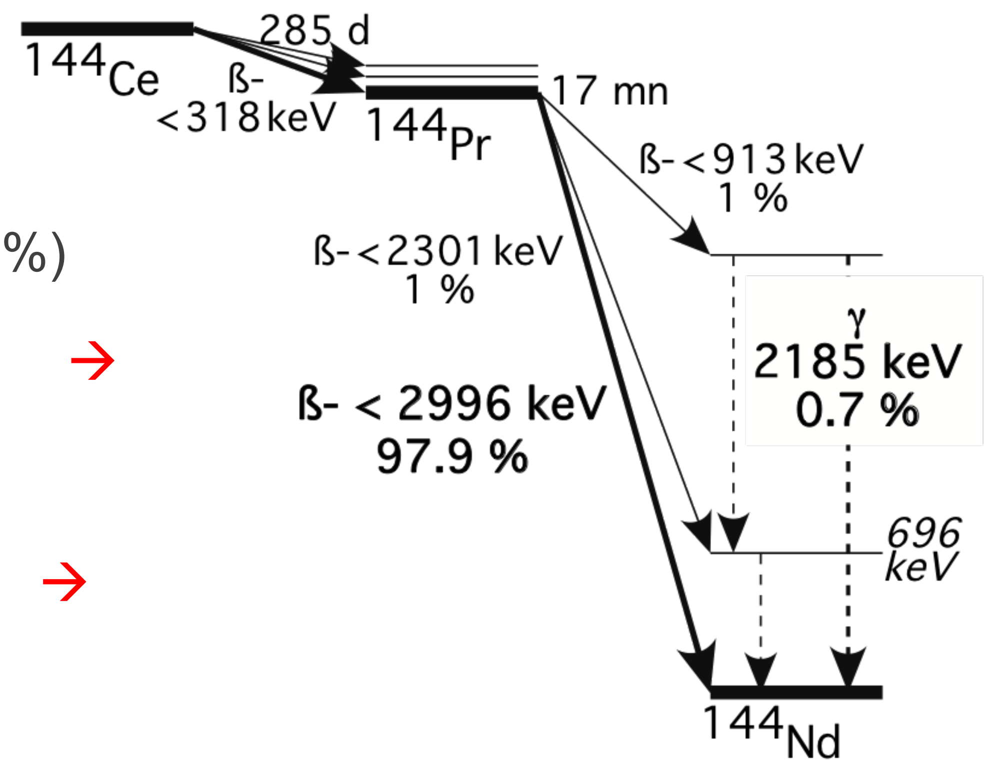




^{144}Ce-^{144}Pr $\bar{\nu}$ generator

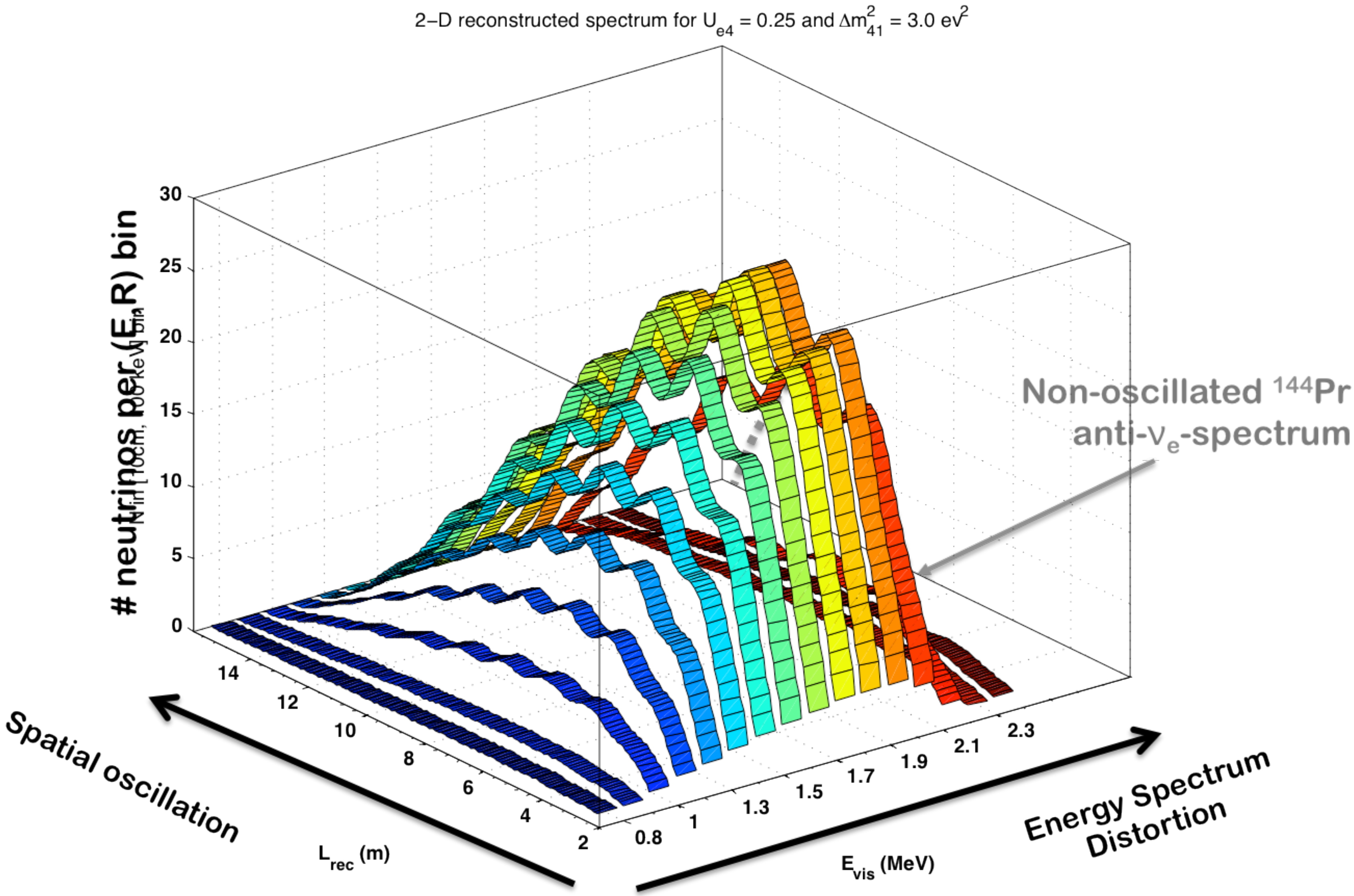
- 1^{st} Trick: $\bar{\nu}_e$ source detected via $\bar{\nu}_e + p \rightarrow e^+ + n$ (Thr=1.8 MeV)
  - High IBD cross section → few PBq activity (100 kCi)
  - (e^+,n) detected in coincidence → Strong background reduction

- 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



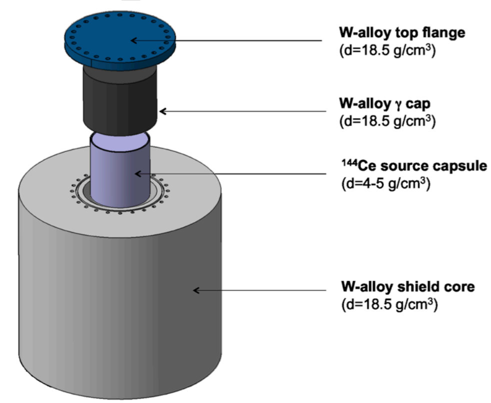
^{144}Ce-^{144}Pr Signal

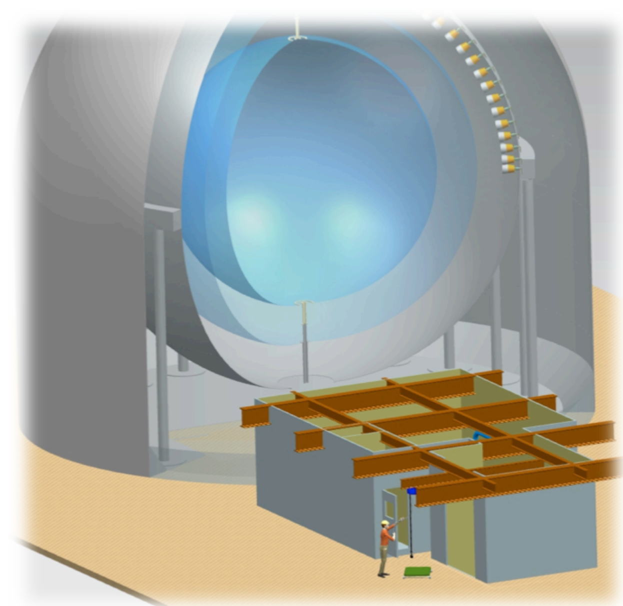
75 kCi ^{144}Ce-^{144}Pr – 9.3 m from detector center – 1.5 year



^{144}Ce-^{144}Pr: CeSOX in BX

- 4 PBq of ^{144}Ce-^{144}Pr (CeO_2)
- **Production feasible at Mayak Facility (RU) in 2014/5 (1 y)**
  - Standard SNF reprocessing
  - Ce extraction through displacement chromatography
- **Need 19 cm tungsten-shield**
- **Borexino being prepared**
  - Tunnel below the detector
  - 8.25 m from center
- **Deployment in 11/2015**
  - 1.5 y data taking
  - 10 000 interactions expected





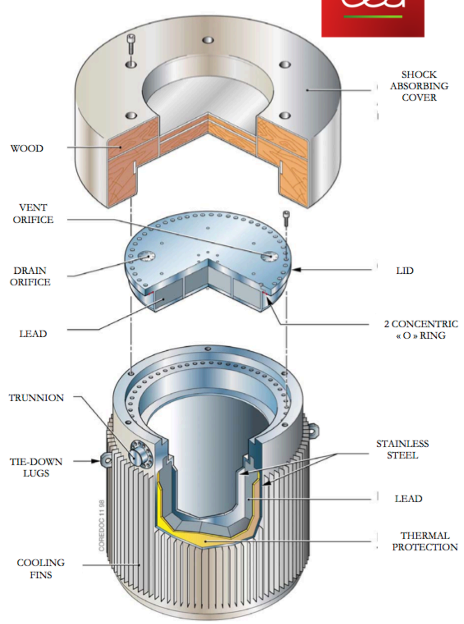
CeSOX: a Challenging Logistic

IAEA rules on Safe Transportation of Radioactive Material

A) Suitable certified transport container: licensing ongoing

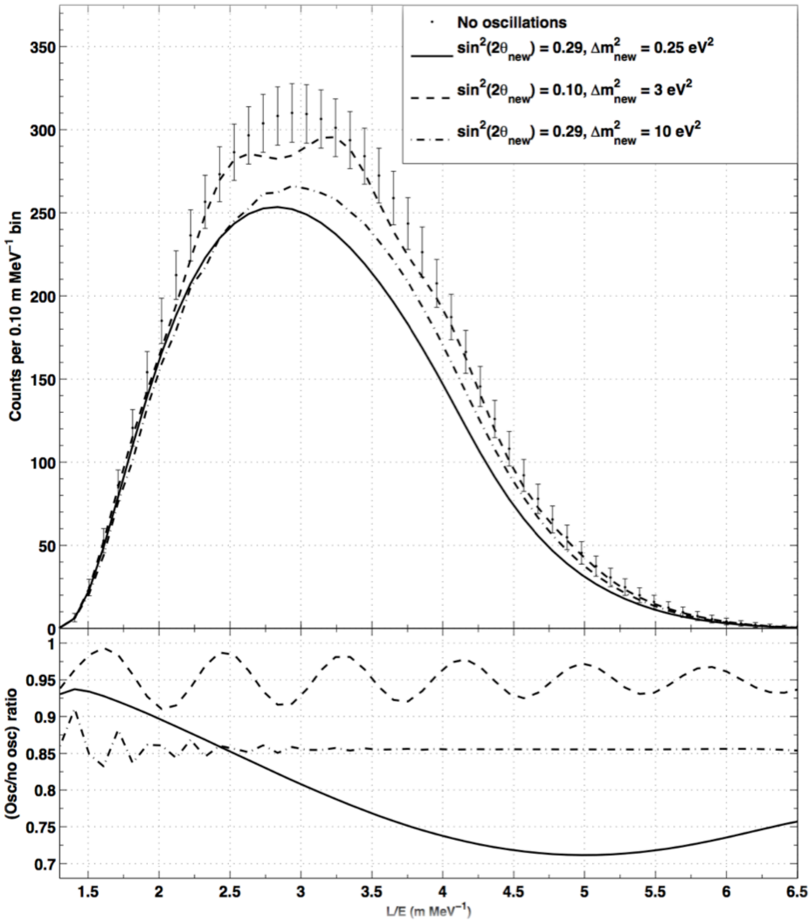
suitable B(U) casks identified

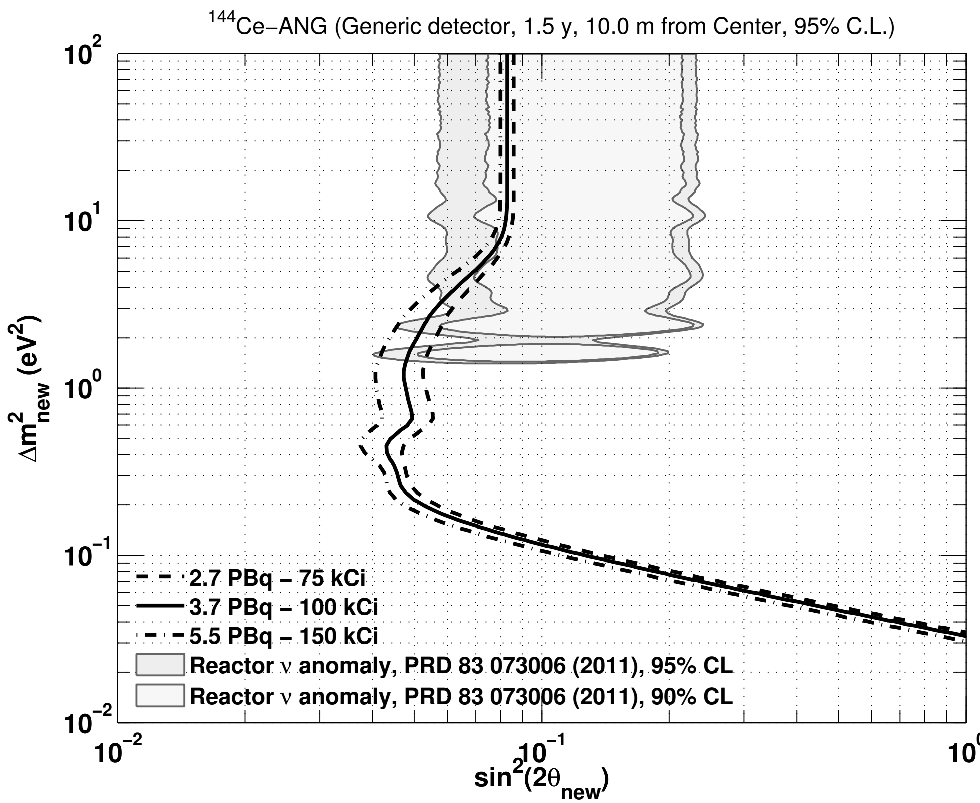
TN – TM – MTR – 23 t



B) Route: Mayak – St Petersburg – Le Havre – Gran Sasso

CeSOX sensitivity



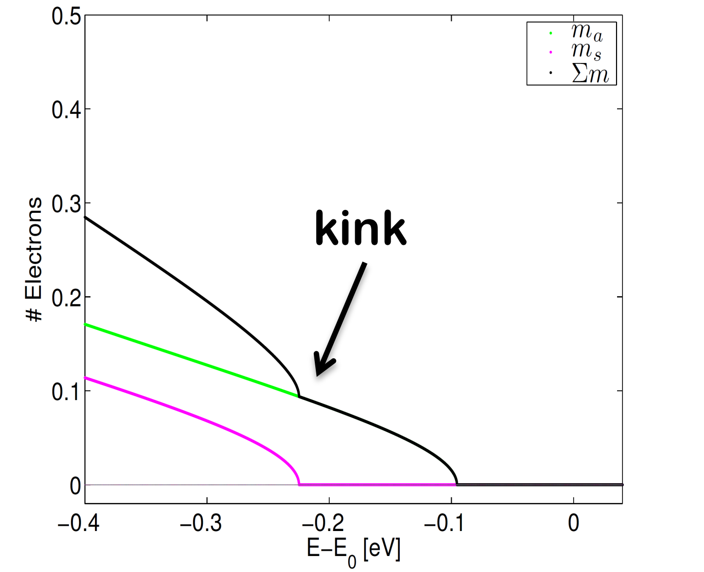


Search for ν_s with ^3H β decay

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

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

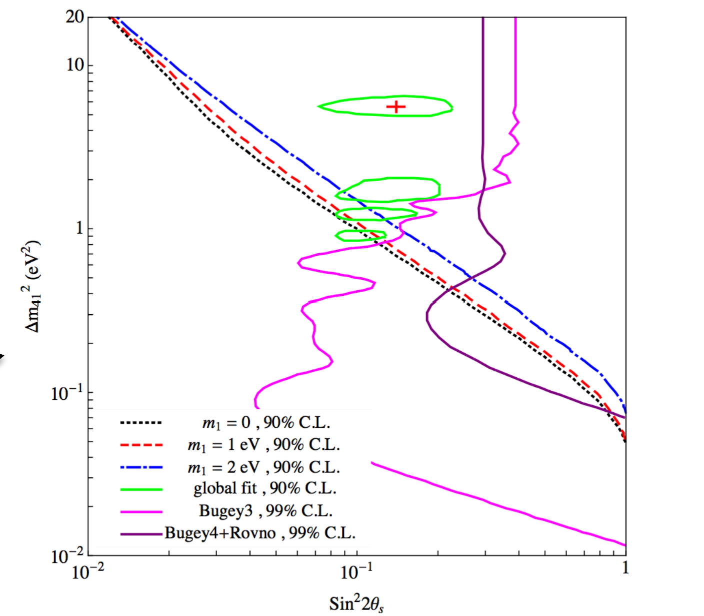
- **Hypothetical 4th ν contribution**



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

→Search for a kink few eV below end point

- **KATRIN –as designed – can test the ν_e disappearance anomalies (sensitivity to be assessed with syst.)**



Experimental Program: @ Neutrino Beam

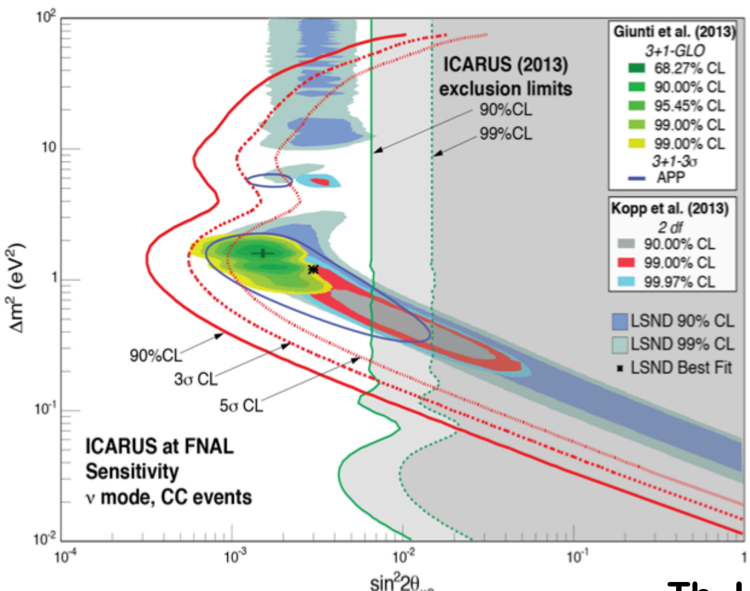
Test of LSND/MinibooNE/reactor/gallium anomalies
If positive signal, detailed study of sterile-ν phenomenology

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, JPARC-MLF
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

Pion Decay in Flight ν-sources

- Move T600 from LNGS to CERN for rehauling and then to FNAL
- Build new near detector
- Add magnetic spectrometers (Nessie)



Pion Decay at Rest ν-sources

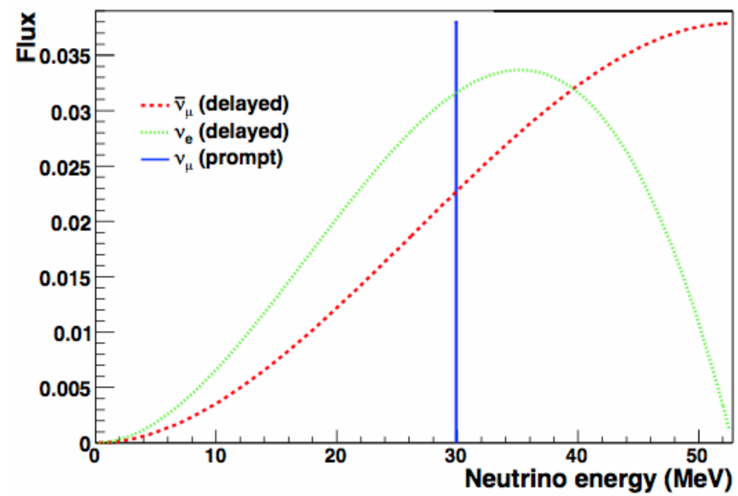
- **High Energy Proton source**
  - Each π^+ decay
    - $\nu_\mu, \nu_e, \bar{\nu}_\mu$
    - known E spectrum

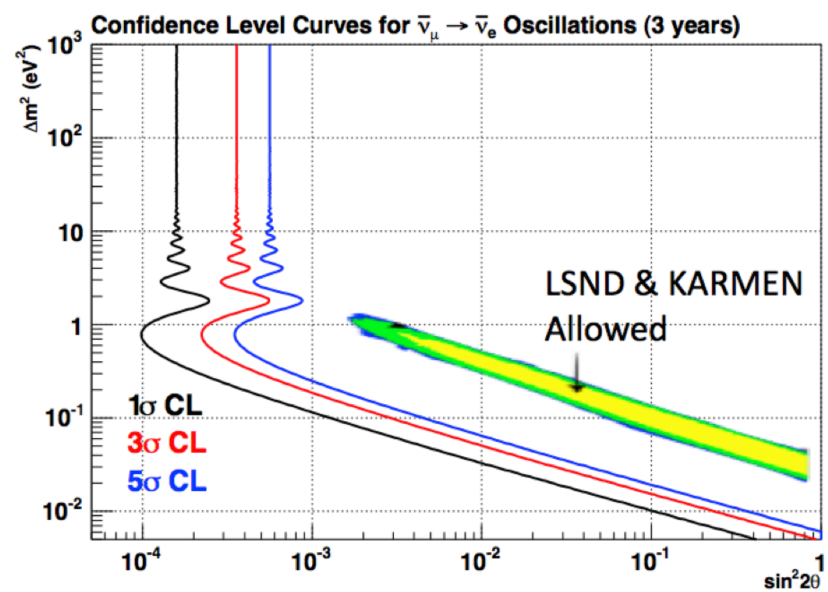
- **Detection channels**
  - $\nu_e \rightarrow \nu_e$ Disappearance
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance

- Direct Test of LSND

- **OscSNS (ORNL, 1.4 MW)**
  - 800t LS-det @ 60 m

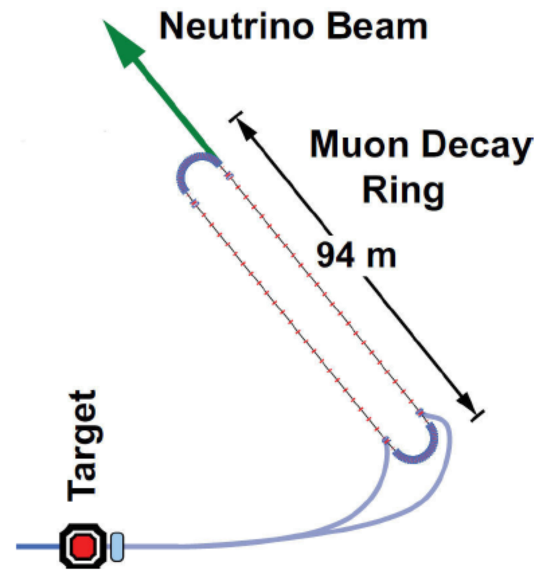
- **JPARC-MLF**
  - 2x25ton Gd-LS-det @17 m

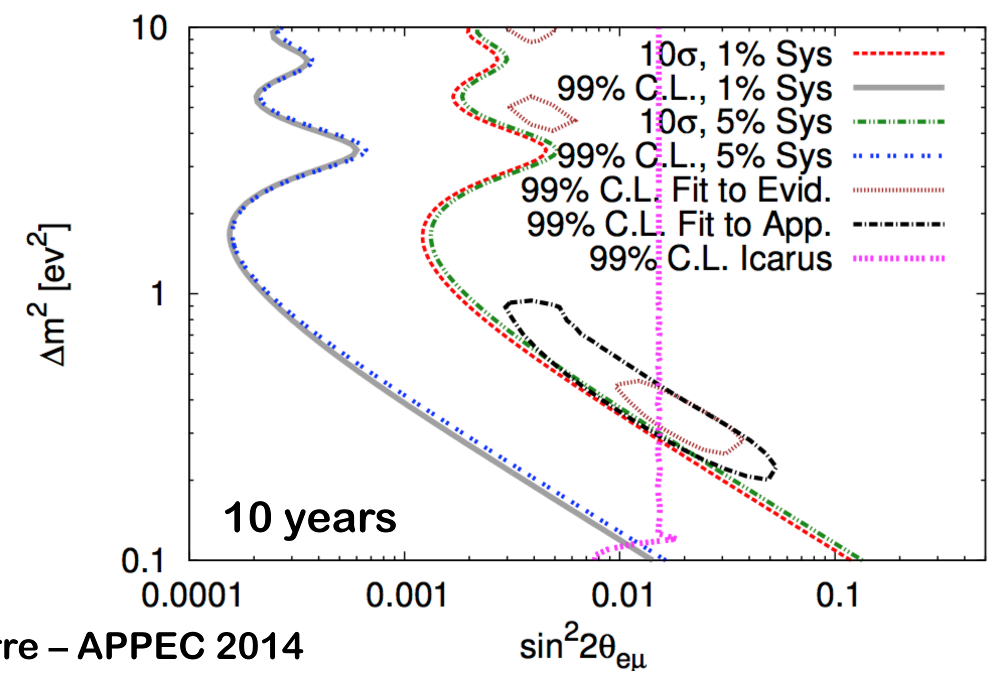




Muon Decay Rings: ν-STORM

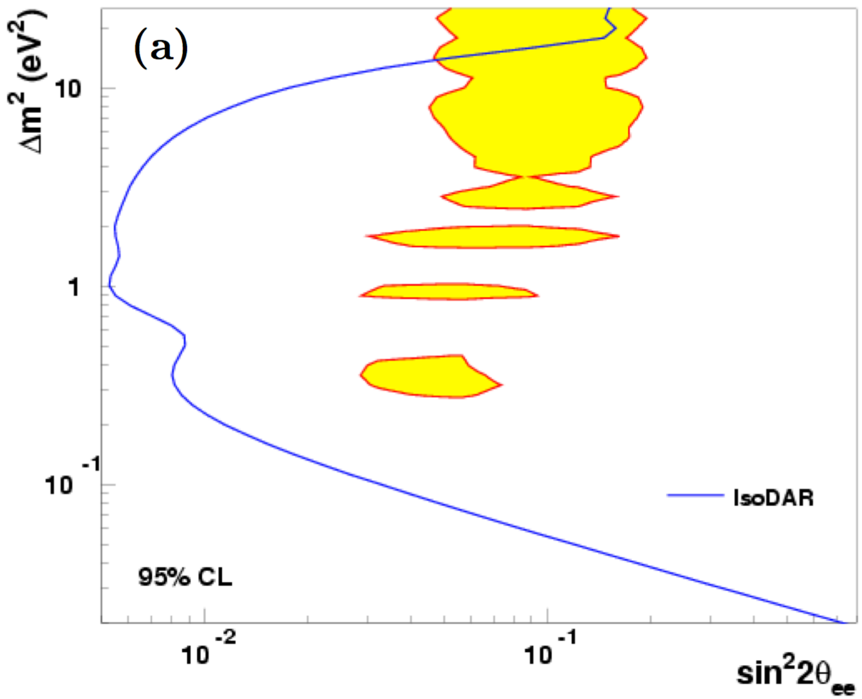
- **Neutrino Factory Concept**
  - 60 GeV protons on solid target
  - Horn capture and π transfer
  - Muon Decay ring
- **APP and DIS channels with:**
  - $\overset{(-)}{\nu}_{\mu}$, $\overset{(-)}{\nu}_{e}$
- **1.3 kT-scale Minos-like**
  - 2 km baseline
  - Near detector
- **Golden Mode**
  - $\overset{(-)}{\nu}_{\mu}$ APP in a $\overset{(-)}{\nu}_{e}$ beam
- Definitive sterile ν search



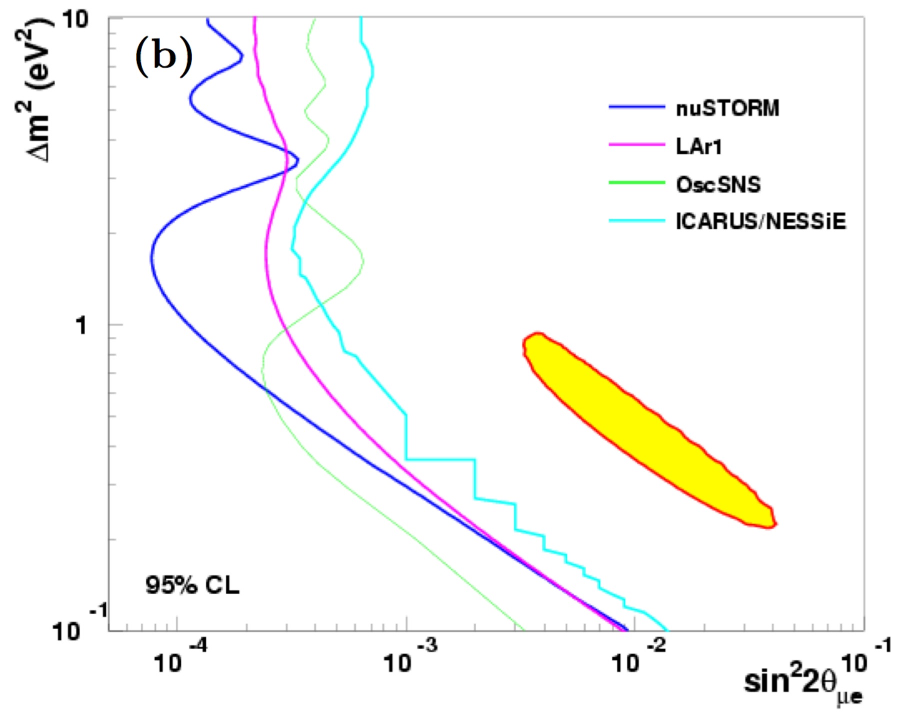


Beam Experiment Sensitivities

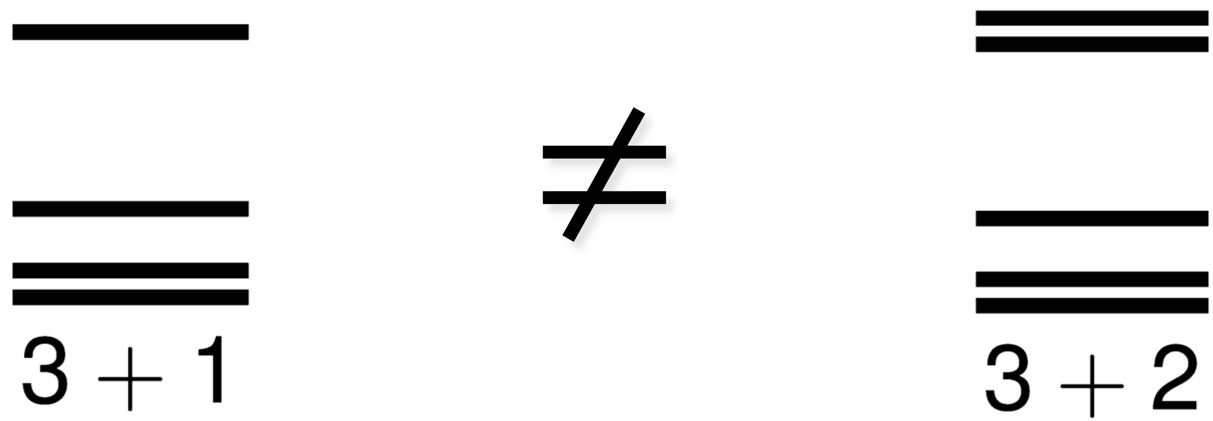
Disappearance



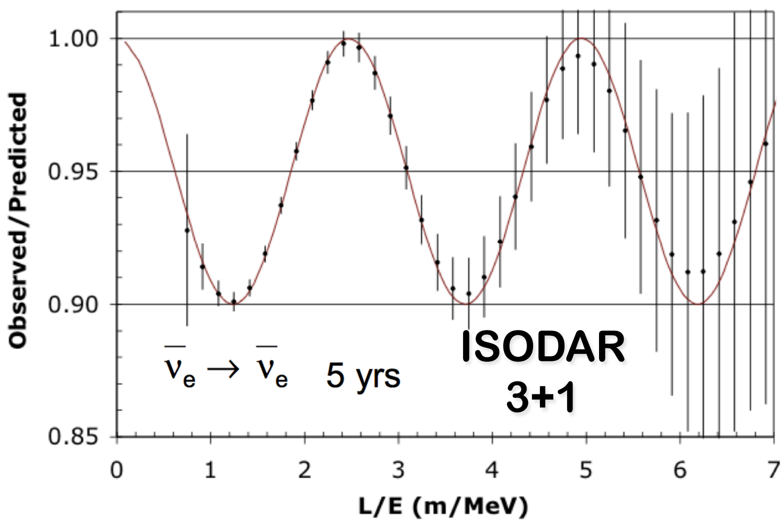
Appearance

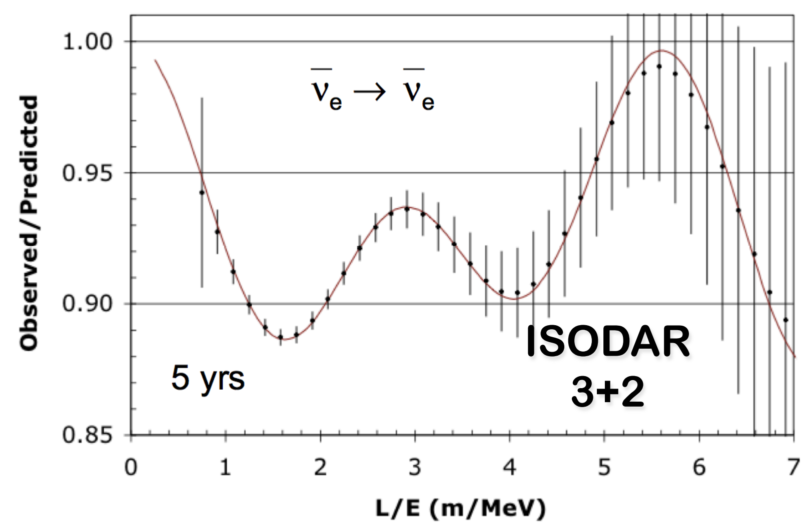


Isotope Decay at Rest ν-sources



Oscillation L/E Waves with High Statistics





Number of ν's From Cosmology

- Constraint sum of neutrino masses < 0.5 – 1 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
    - $H_{0,planck}$ in tension with $H_{0,HST}$
    - Planck + BAO + H0: $N_{eff} = 3.52 \pm 0.46$ (95% C.L.)
    - Depends on BICEP2 results
- N_{eff} = 4 mildly disfavored & bound model dependent

- Neutrino laboratory experiments should be used as an input for cosmology

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)

- A definitive probe of this parameter space is necessary → need several experiments

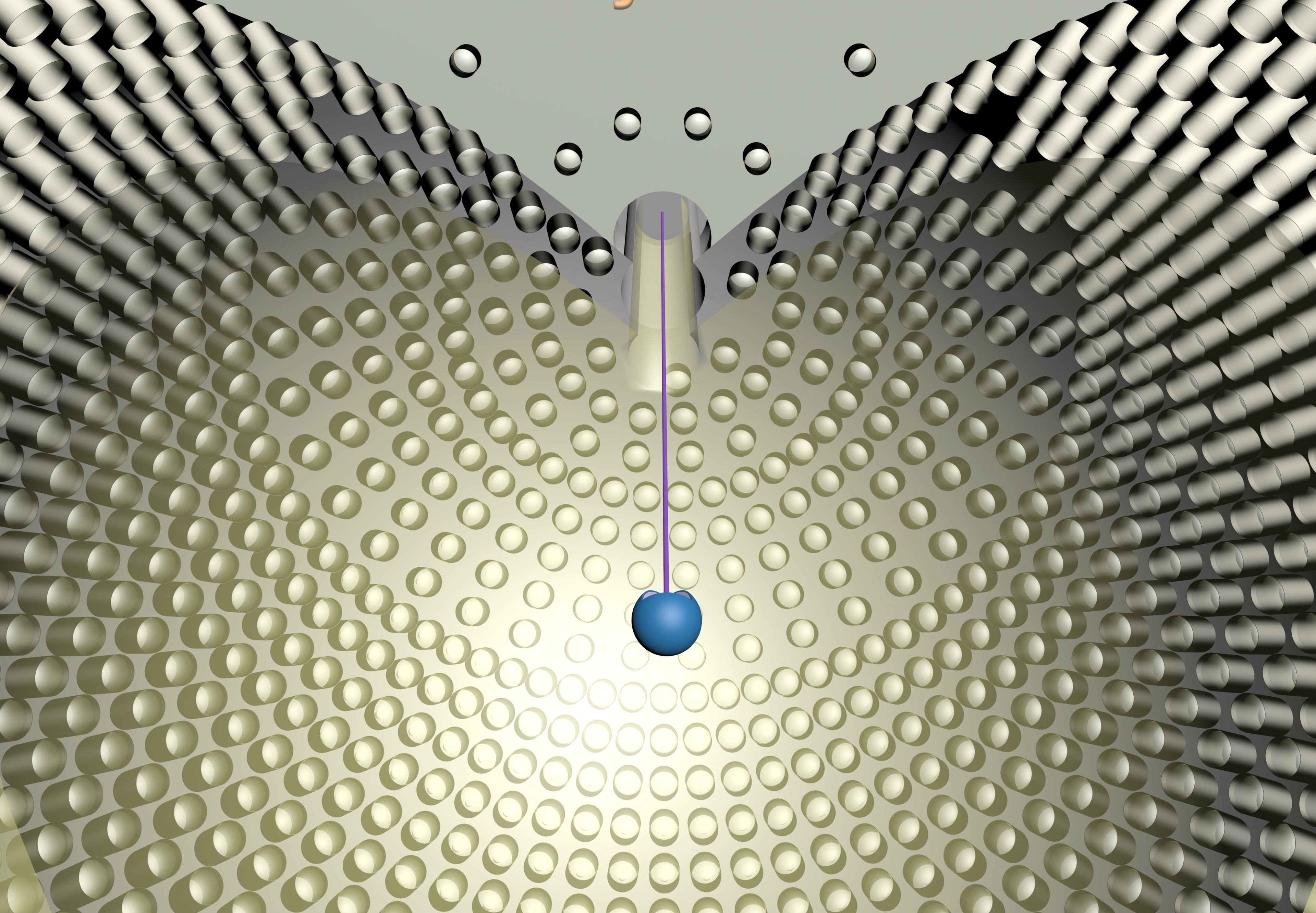
Conclusion (2)

- Many proposals with capabilities to unambiguously test L/E≈1 m/MeV oscillatory behavior with low backgrounds
- Reactor Neutrinos
  - Results within 5 years, Cost :1-10 M$
  - Background mitigation is challenging
- Neutrino Generator
  - Results within 5 years, cost ≈5 M$
  - Challenge for the source production and transportation
- Neutrino 'Beam'
  - Longer term, cost 10-300 M$
  - Would allow studying sterile neutrino phenomenology
  - Relevant for Xsection study and R&D for next generation projects
- Other tests through β-decay and $(\beta\beta)0\nu$-decay, Cosmo

	Primary Channel	Other osc channels	Definitive sterile?	Other physics	Tech R&D?	Cost	Why worry?	Comment
MicroBooNE (π DIF)	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\mu$		GeV-scale xsec	Yes	\$20M	tech, cosmics	Exists!
LAr1-ND (π DIF)	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\mu$		GeV-scale xsec	Yes	\$13M	tech, cosmics	
ICARUS@FNAL (π DIF)	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\mu$		GeV-scale xsec	Yes	Under study	tech, cosmics	
TripleLAr@FNAL (π DIF)	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	Probably	GeV-scale xsec	Yes	Under study	tech, cosmics	Work in progress. Anti-nu?
OscSNS (π,μ DAR)	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_e \rightarrow \nu_e$	Yes	Supernova xsec	No	\$20M	intrinsic $\bar{\nu}_e$	
JPARC MLF (π,μ,K DAR)	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_e \rightarrow \nu_e$ $\nu_\mu \rightarrow \nu_e$	Not in phase 1	Supernova and 235 MeV ν_μ xsec	No	\$5M	intrinsic $\bar{\nu}_e$	Phase 1
IsoDAR-KamLAND (Isotope DAR)	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	-	Yes	$\bar{\nu}_e e^-$ (electroweak)	Yes	\$30M	timeline, tech	
nuSTORM (μ DIF)	$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ $\nu_e \rightarrow \nu_e$	Yes	GeV-scale xsec	Yes	\$300M	timeline, tech, cost	P5 says no

J. Spitz, Neutrino 2014

Thanks for your attention !



Projects Overview

Experiment Type	Appearance / Disappearance	Oscillation Channel	Projects
Reactor	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	Nucifer, Stéréo, Scraam, Neutrino-4, DANSS, Poséidon, Solid, …
Radioactive Source	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	CeLAND, SOX (Cr & Ce), Sage2, SNO+, LENS-s
Cyclotron	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest	Apparition & Disappearance	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Pion Decay-in-Flight (Beam)	Appearance & Disappearance	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_\mu$ $\nu_e \rightarrow \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, Icarus/Nessie@CERN
Low-E Neutrino Factory	Appearance & Disappearance	$\nu_e \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_e$	νSTORM@Fermilab

Reactor ν Proposals

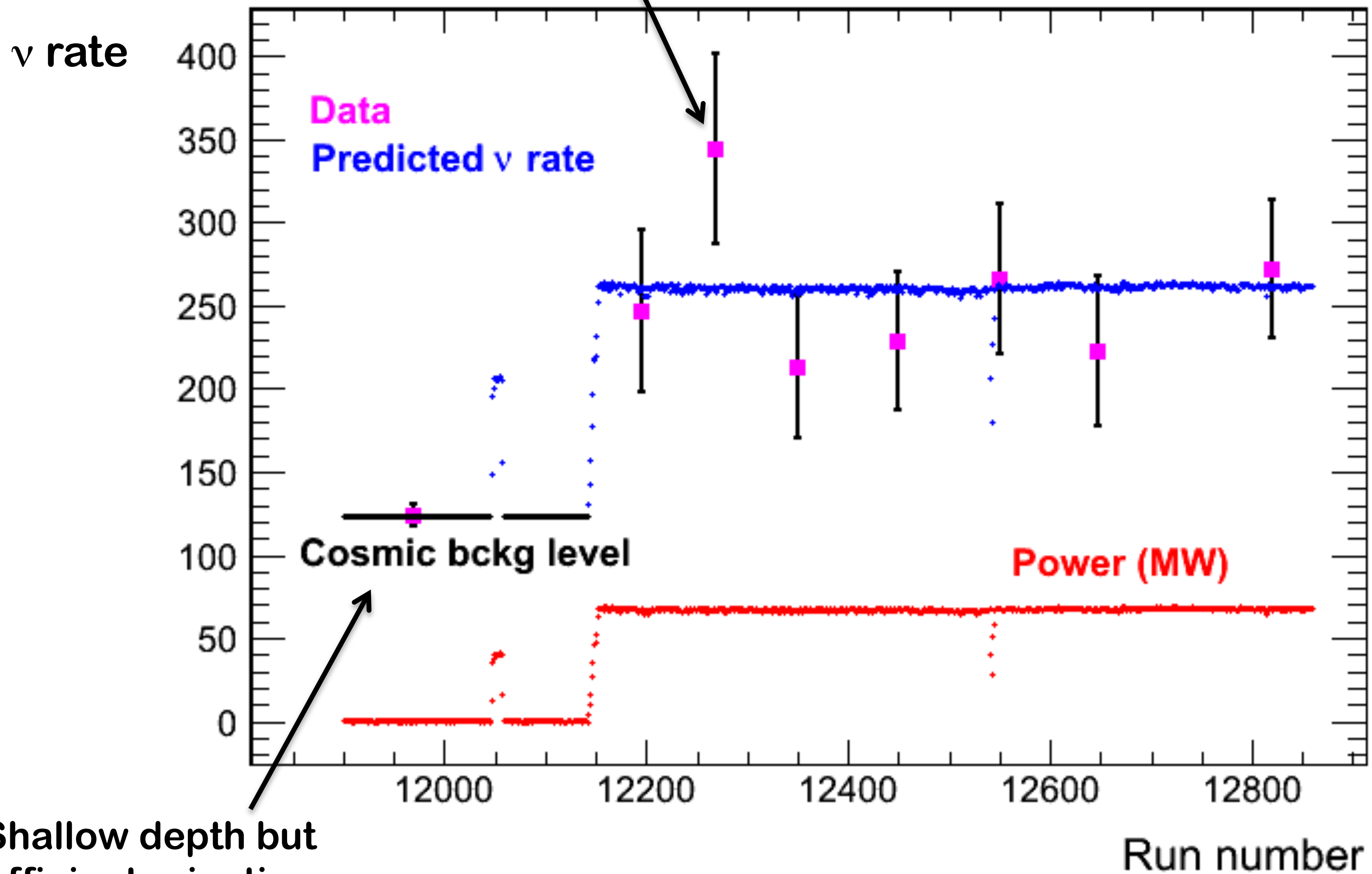
Experiment Type	Experimental Strategy	Projects	Features
Gd-doped LS detector	-Clear signature of n-capture by an 8 MeV γ-cascade - Mature -High light yield → fast n background rejected by PSD -Sensitive to high-E γ's → large passive shielding	Nucifer (FRA)	70 MW / 0.7 t / 7 m / few mwe
		Stéréo (FRA)	50 MW / 2 t / [8-11] m / 10 mwe
		Neutrino 4 (RU)	100 MW / 2 t / [6-12] m / surf.
Highly segmented detector	Improved bkg rejection: - Vertex correlation between prompt and delayed - Topology of E depositions: e = compact track γ = longer interaction length	DANSS (RU)	1 GW / 1 t / [10-12] m / 50 mwe
		SoLid (UK)	45-80 MW / 3 t / 8 m / 10 mwe
Enhanced neutron Tagging	-Unique signature of neutron capture with Li-doped LS/PS $^6Li + n \rightarrow \alpha + t$	Hanaro (KO)	30 MW / 0.5 t / 6 m / few mwe
Extended Baseline Complex	-Better sensitivity to lower Δm^2 -Larger volume and/or Longer running time	US project	20-120 MW / 4m-15m / surf.
		China project	
		DANSS/Neutrino4	Movable detector

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

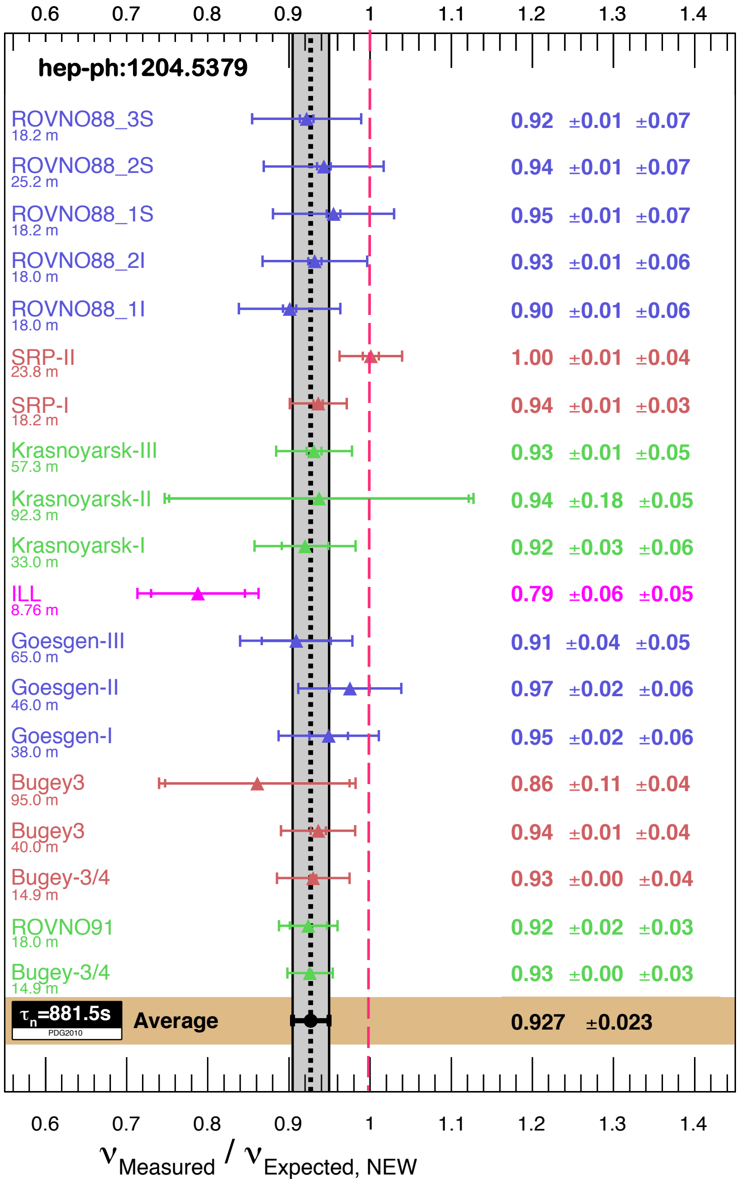
Nucifer: First Neutrino Run

- 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

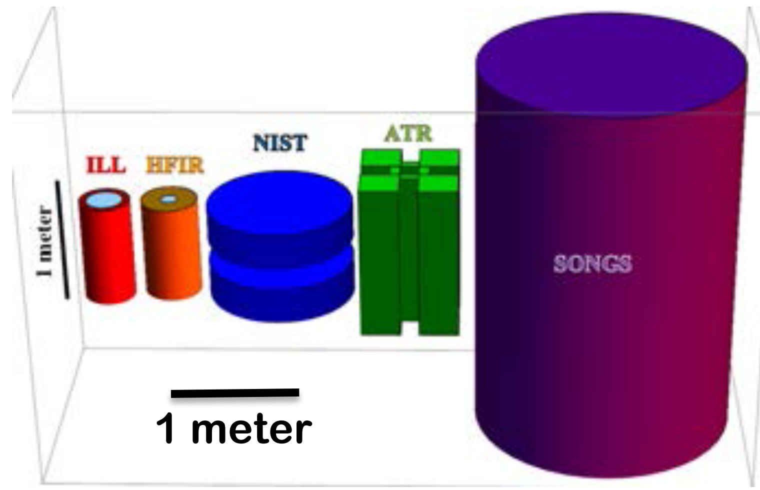
Reactor Antineutrino Anomaly



- 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

New SBL reactor experiments

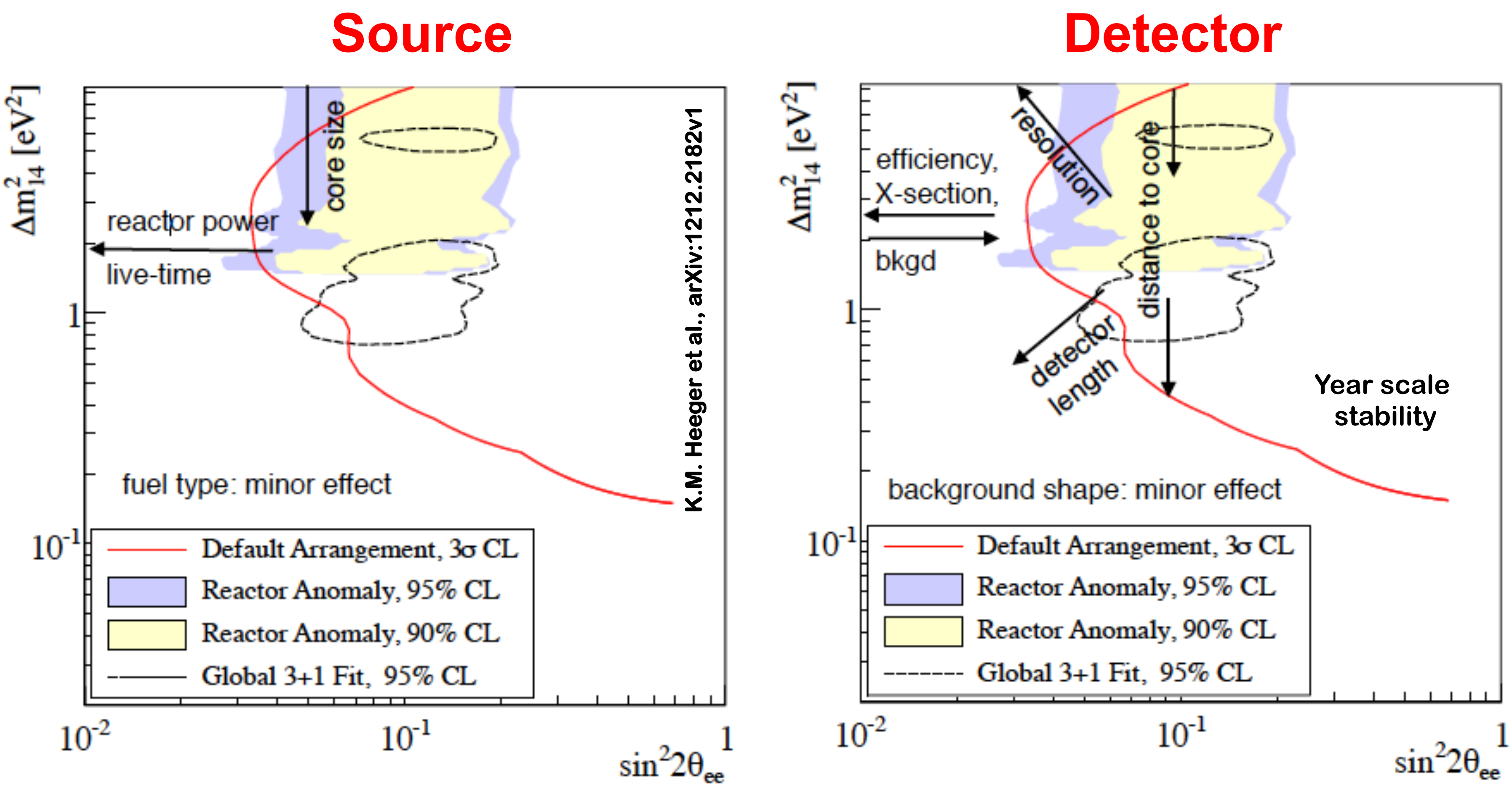
Typical reactor core sizes



- 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
  → A singly ^{235}U fission spectrum component
- Reactor ON/OFF periods
  → Moderate overburden compensated by accurate measurement of the cosmogenic bkg
- But challenging reactor-induced backgrounds (γ and n)
  → Need comprehensive site characterization

Influence of Source/Detector Parameters

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



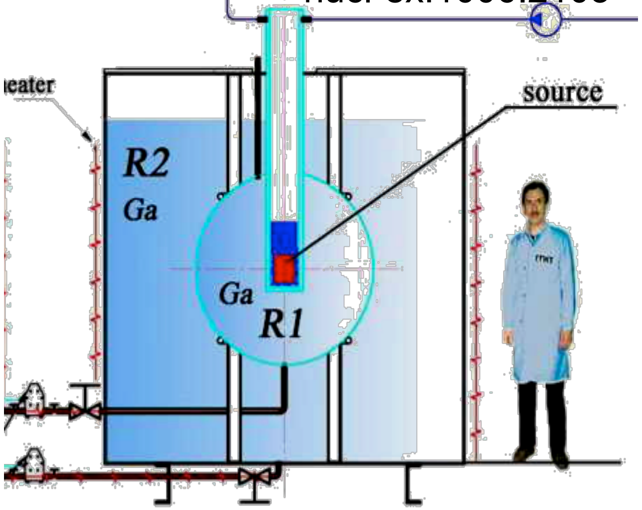
^{51}Cr: SAGE 2-Zone (Sage)

- **^{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

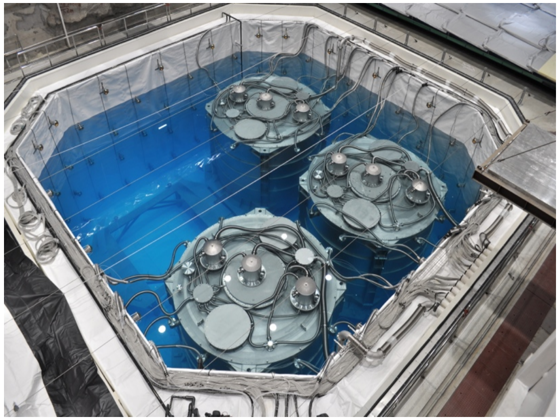
nucl-ex:1006.2103

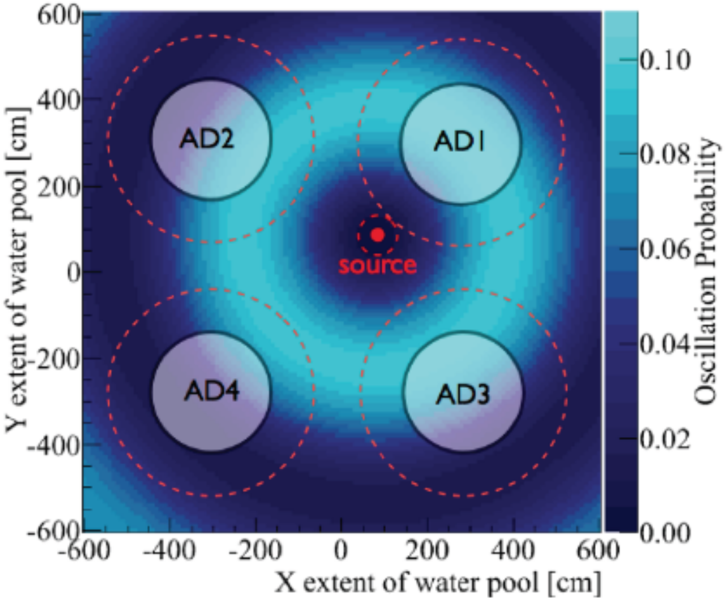


65 Ge atoms/day expected

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





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