(sub)eV Sterile Neutrinos: an experimental overview

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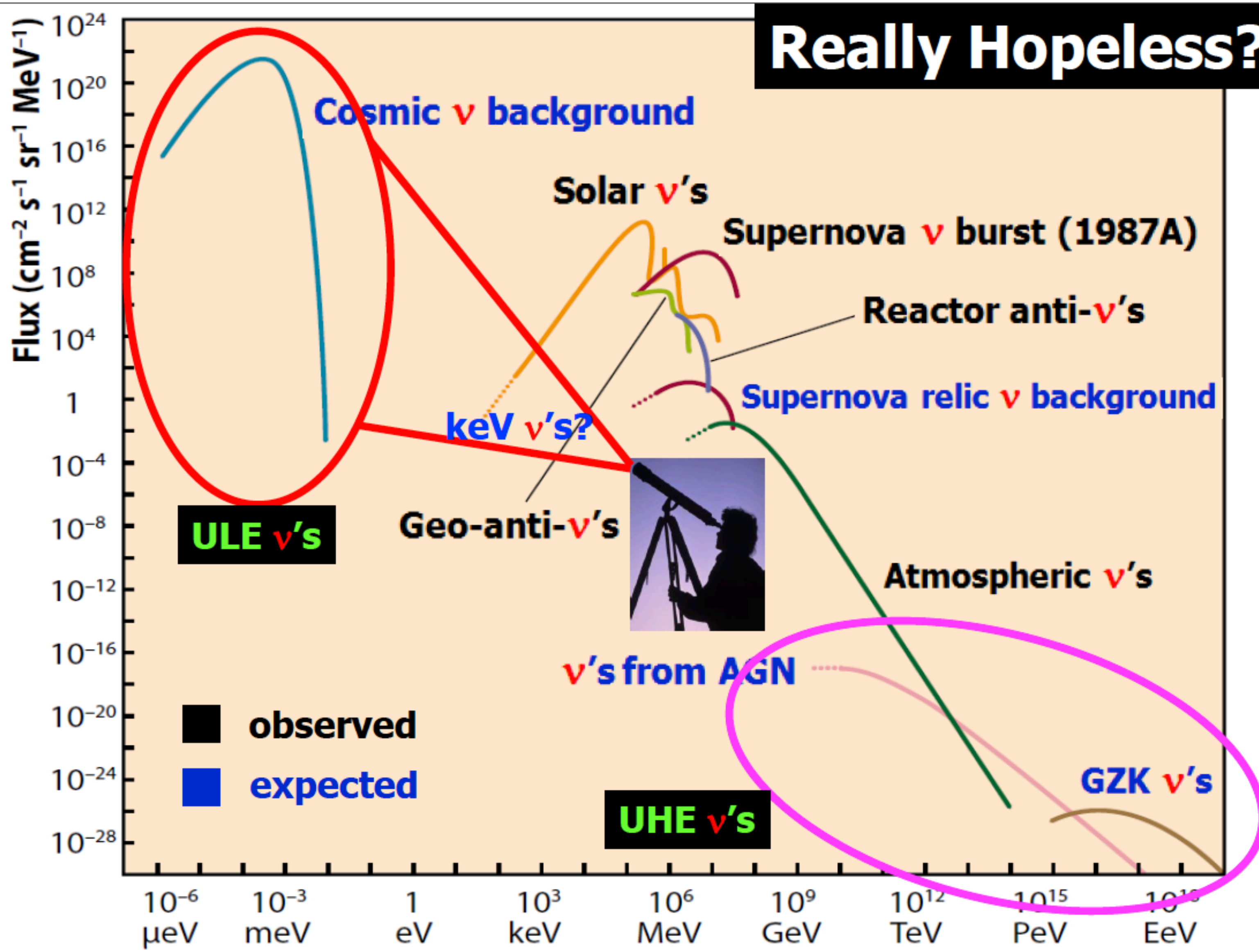
Established Neutrino Physics

- 3 types, spin ½, neutral, left handed, $\sigma(1\ \mathrm{MeV}) \approx 10^{-45\text{-}43}\ \mathrm{cm}^2$
- Neutrinos have tiny masses and mix: $0.04\ \mathrm{eV} < m_\nu < \approx 1\ \mathrm{eV}$
- PMNS matrix U relates mass & flavor:

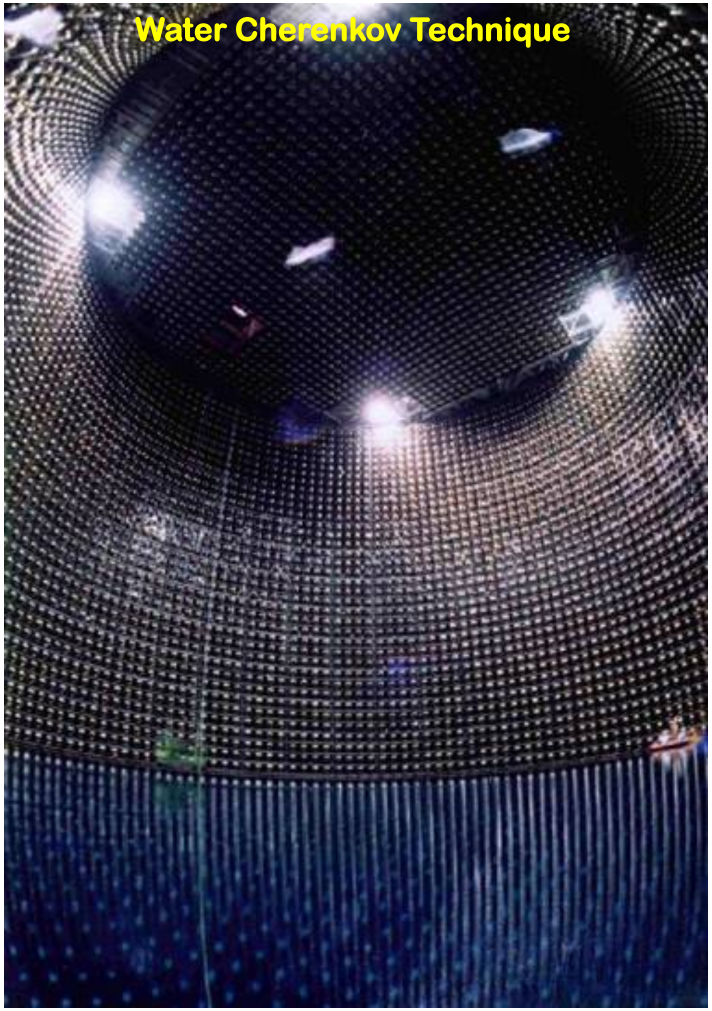
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Leftrightarrow |\nu_e(t)\rangle = \sum_i U_{ei} |\nu_i(t)\rangle$$

- A compelling evidence of physics Beyond the Standard Model

Neutrinos in the Universe

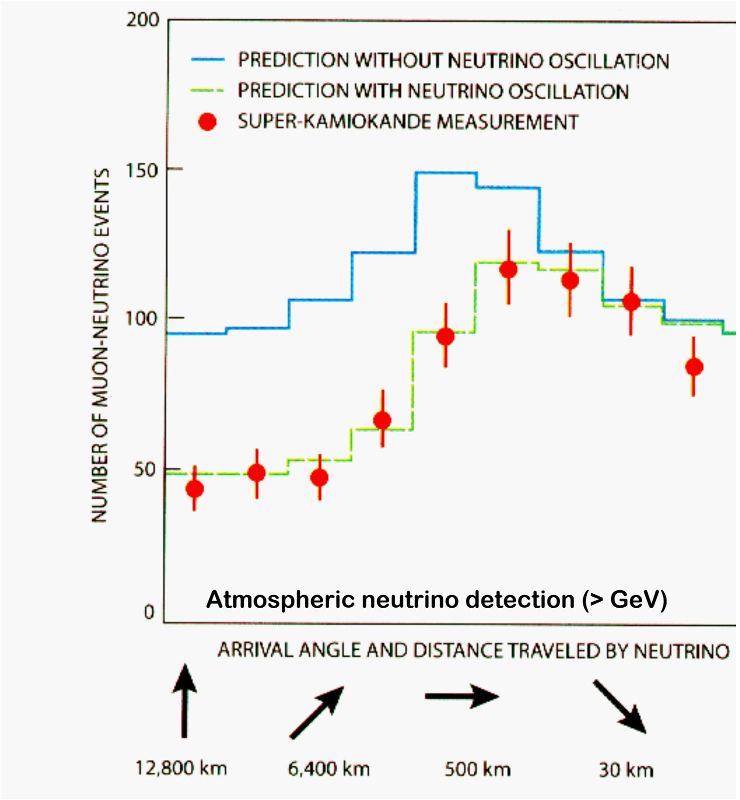


SuperKamiokande Breaktrough (1998)



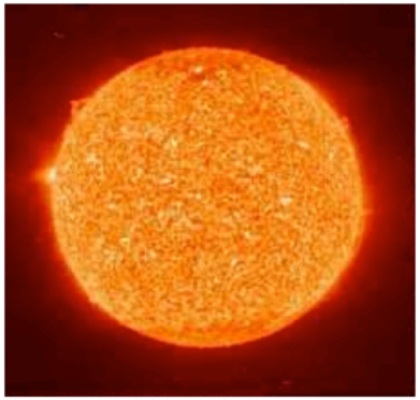
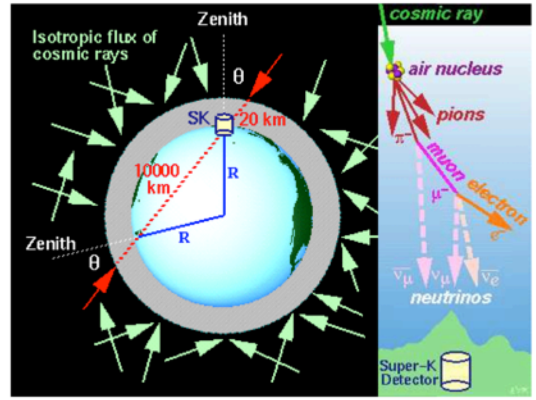
50 kt of pure water, 12 000 PMTs
Good E-resolution
e/ μ discrimination at low energy

$$\Phi^{Atm}{}_{\nu_\mu}(up) \Big/ \Phi^{Atm}{}_{\nu_\mu}(down) = 0.54 \pm 0.04$$



Neutrino do have mass and they mix (oscillation)

Neutrino Oscillation: Established

sun	reactors	atmosphere	accelerators
			
Homestake, SAGE, GALLEX SuperK, SNO, Borexino	KamLAND, CHOOZ	SuperKamiokande	K2K, MINOS, T2K

- $\nu_\mu \rightarrow \nu_{\tau,e}$ or anti-$\nu_\mu \rightarrow$ anti-$\nu_{\tau,e}$: **atmospheric & beam experiments**
- $\nu_e \rightarrow \nu_{\mu,\tau}$: **solar experiments**
- anti-$\nu_e \rightarrow$ anti-$\nu_{\mu,\tau}$: **reactor experiments**
- $\nu_\mu \rightarrow \nu_e$: **beam experiments**

$$P(\overline{\nu}_x \rightarrow \overline{\nu}_x) = 1 - \sin^2(2\theta_i)\sin\left(1.27\frac{\Delta m_i^2\ (\mathrm{eV}^2)\,L\ (\mathrm{m})}{E\ (\mathrm{MeV})}\right)$$

2-flavor oscillation formalism

3 ν Oscillation Formalism

PMNS mixing matrix

Atmospheric | Cross-Mixing | Solar | Majorana ~~CP~~ phases

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{23} : "atm." mixing angle | θ_{13} | θ_{12} : "solar" mixing angle

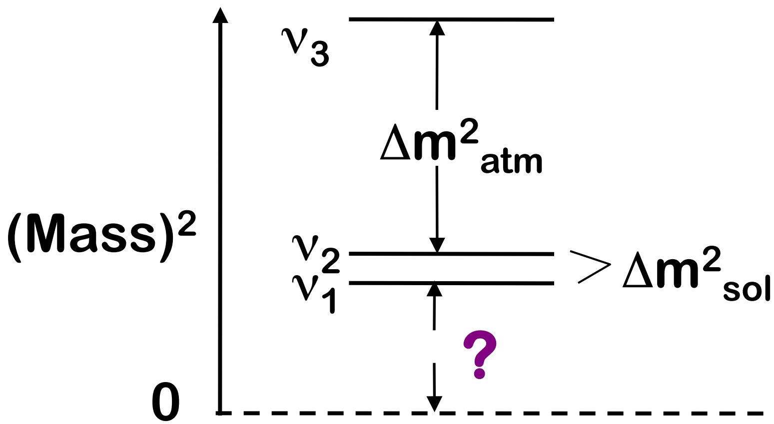
δ Dirac CP violating phase

2 Majorana phases (L violating processes)

- 3 masses m_1, m_2, m_3 : $\Delta m^2_{sol} = m_2^2 - m_1^2 \;\&\; \Delta m^2_{atm} = |m_3^2 - m_1^2|$
- 3-flavour effects are suppressed since: $\Delta m^2_{sol} << \Delta m^2_{atm}\ (1/30)\ \&\ \theta_{13} << 1$

Open questions

- What are the masses of the mass eigenstates ν_i?



ν flavor change

β decay, $\beta\beta0\nu$ decay, cosmology

- Is the spectral pattern (normal) or? (inverted) — $\overset{(-)}{\nu}$ behavior in matter, $\beta\beta0\nu$

- Is there any conserved Lepton Number (Dirac or Majorana neutrino) ? $\beta\beta0\nu$

- Precise measurements of the leptonic mixing matrix?
- Do the behavior of ν violate CP?
- Is leptonic ~~CP~~ responsible for the matter-antimatter asymmetry?

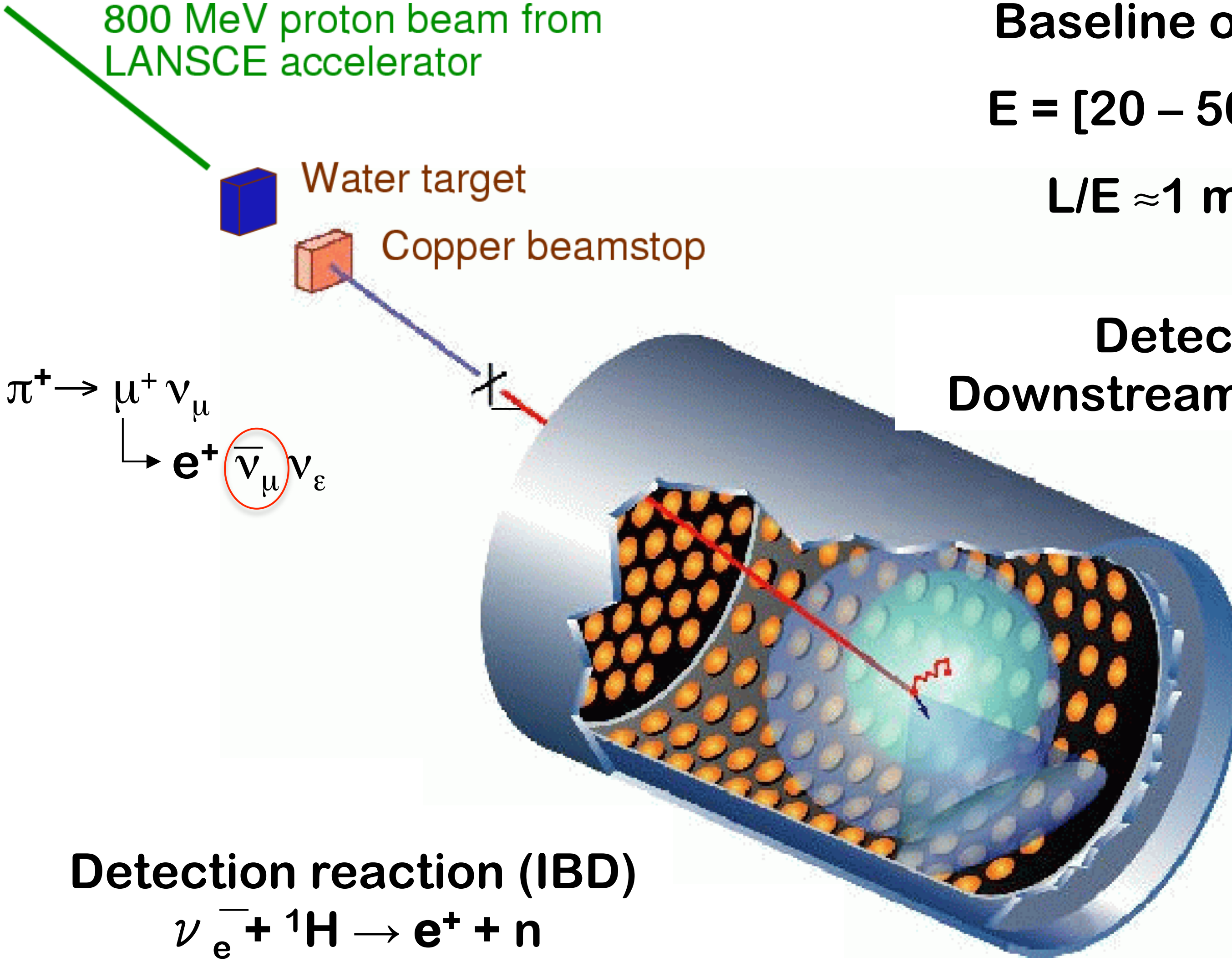
} ν flavor change

- Are there additional (sterile) neutrino states — ν flavor change, Cosmology

Anomalies or 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

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

Detection reaction (IBD)

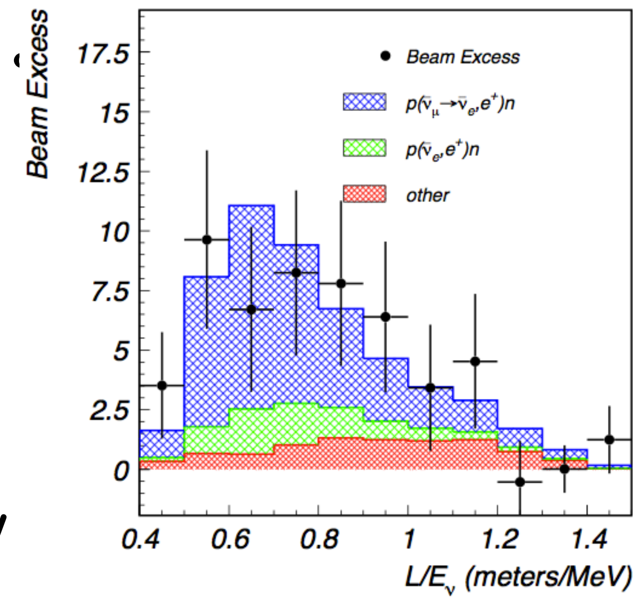
$\bar{\nu}_e + {}^1H \rightarrow e^+ + n$

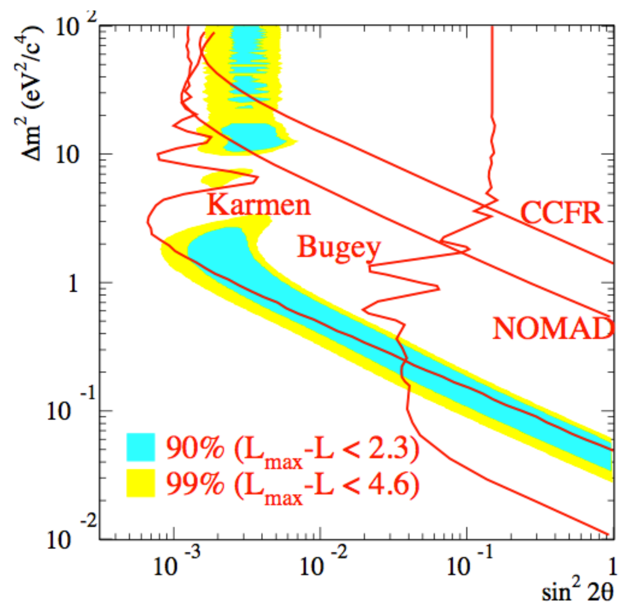
LSND Results

- 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

L/E ≈ 1m/MeV

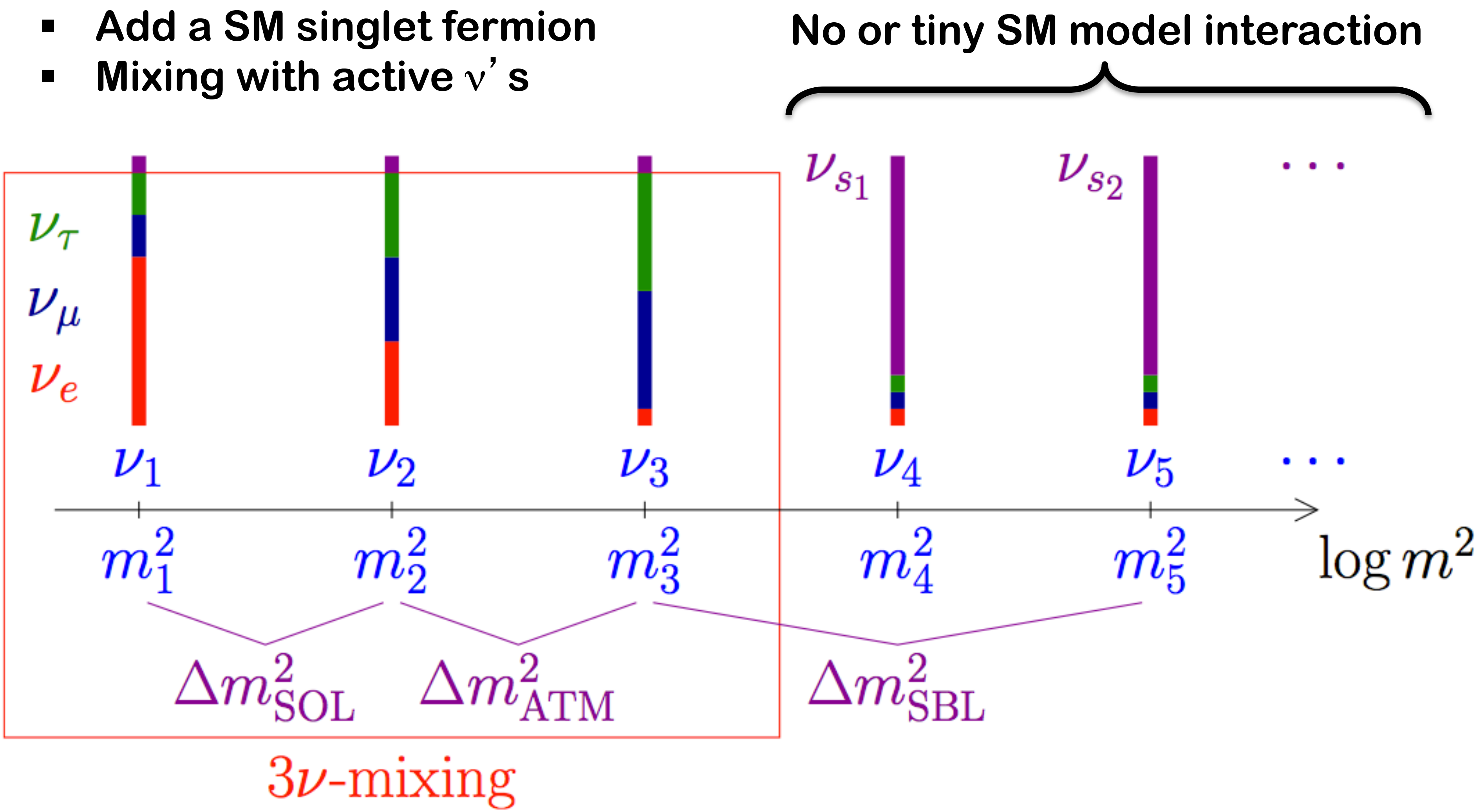
- **Status:**
  - anti-ν_e excess observed → 32.2 ± 9.4 ± 2.3 (3.8σ)
  - not confirmed nor ruled out by Karmen
- **ν-Oscillation interpretation:**
  - $\Delta m^2 > 0.1\ eV^2 >> \Delta m_{atm}^2$
  - Require a 4^{th} neutrino state





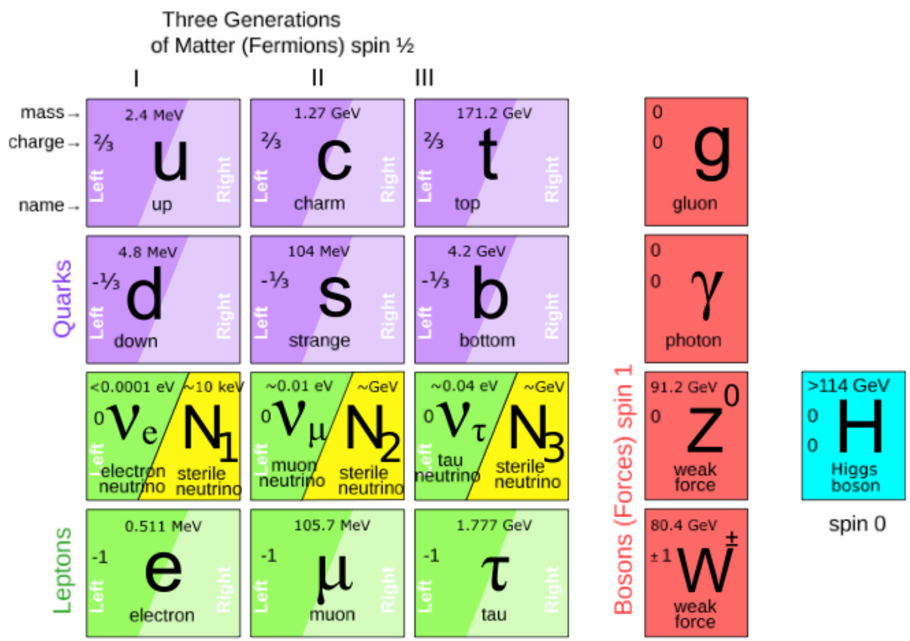
The (light) sterile neutrino hypothesis

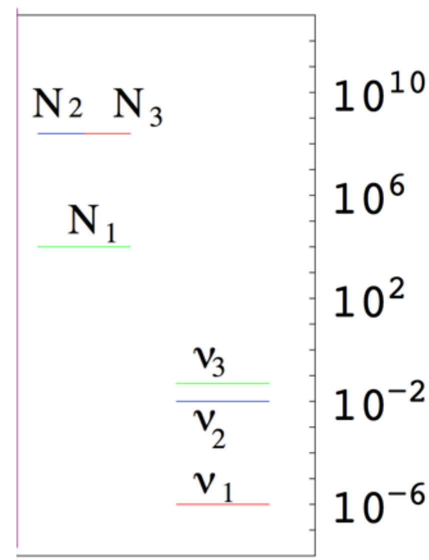
- Generic extension of SM model
- Add a SM singlet fermion
- Mixing with active ν's



νMSM: a comprehensive model

Shaposhnikov, PLB 620, 17 (2005)





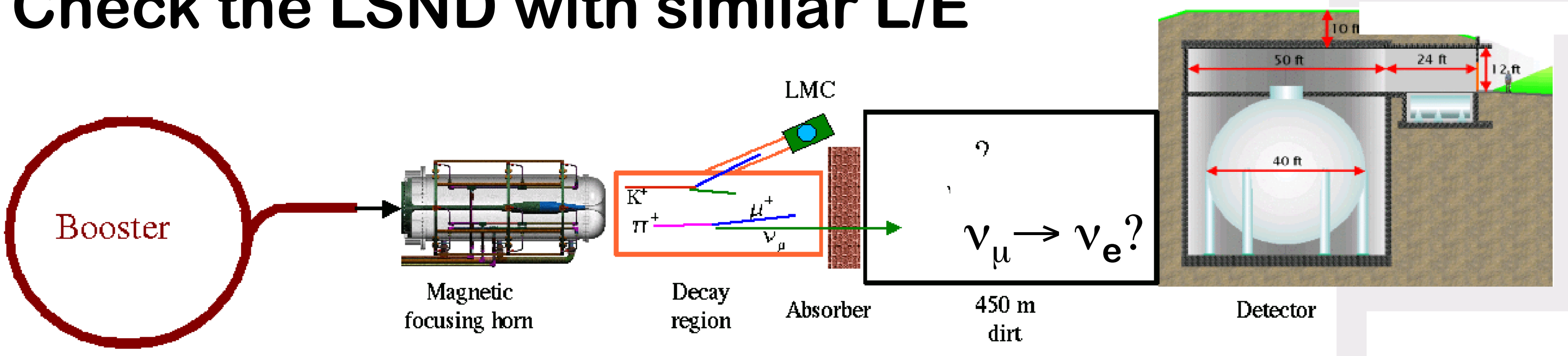
Majorana masses

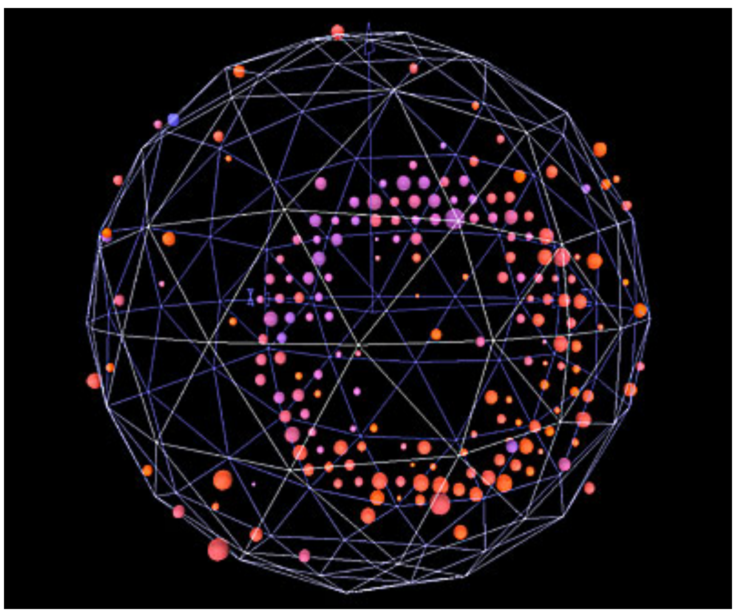
- SM + 3 MJ masses, 3 Dirac masses, 6 mixing angles and 6 CP-phases
- Role of N_1 with mass in keV region: Dark Matter
- Role of N_2, N_3 with mass in 100 MeV – GeV region: “give” masses to ν’s and produce baryon asymmetry of the Universe
- No eV scale neutrino…

MiniBooNE (FNAL)

Primary goal: look for ν_e appearance in a ν_μ beam

Check the LSND with similar L/E

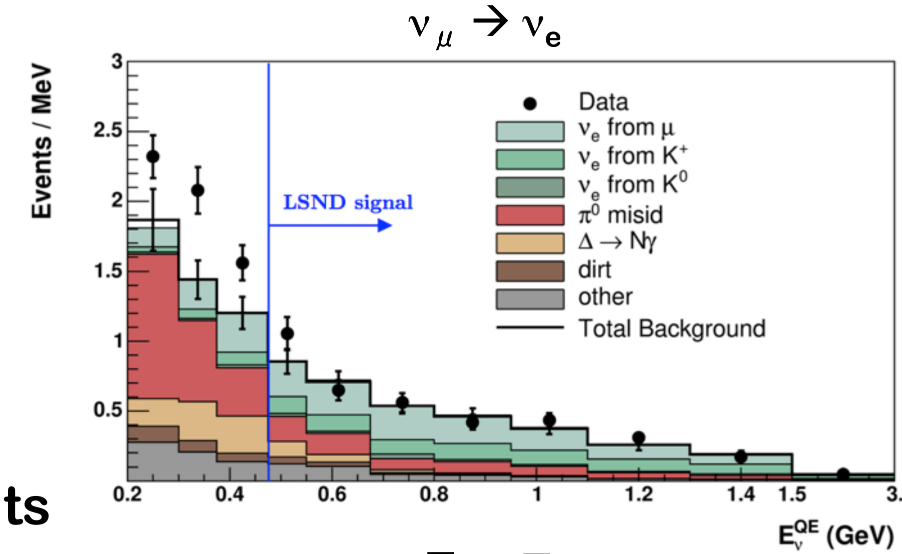


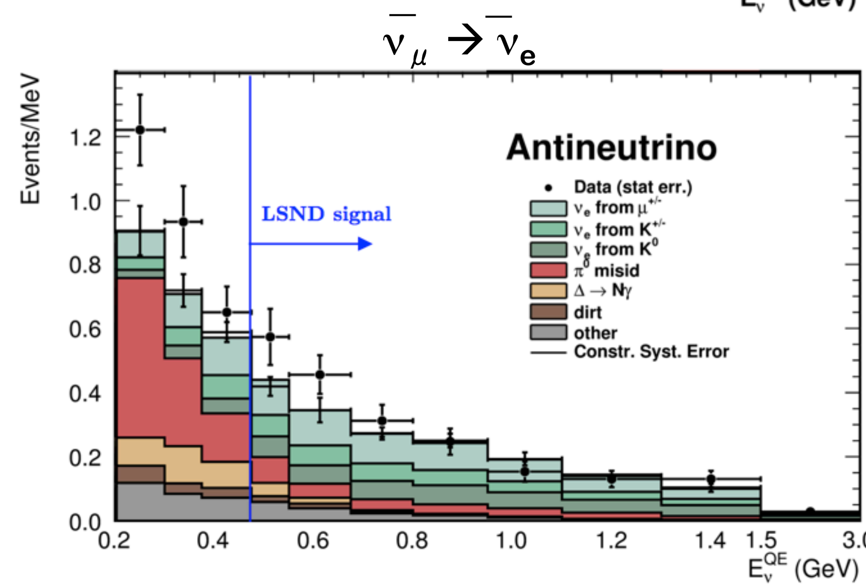


- **Beam: π^+ (π^-) decay in flight**
- **Detection: Cherenkov + scintillation**
- **L/E ≈1 m / MeV**
  - **Baseline: 541 m**
  - **<u>200 </u>< E (MeV) < 3000**
- **Statistics:**
  - **ν : 6.46 × 10^{20} POT (2008)**
  - **$\bar{\nu}$:1.27 × 10^{20} POT (2012)**

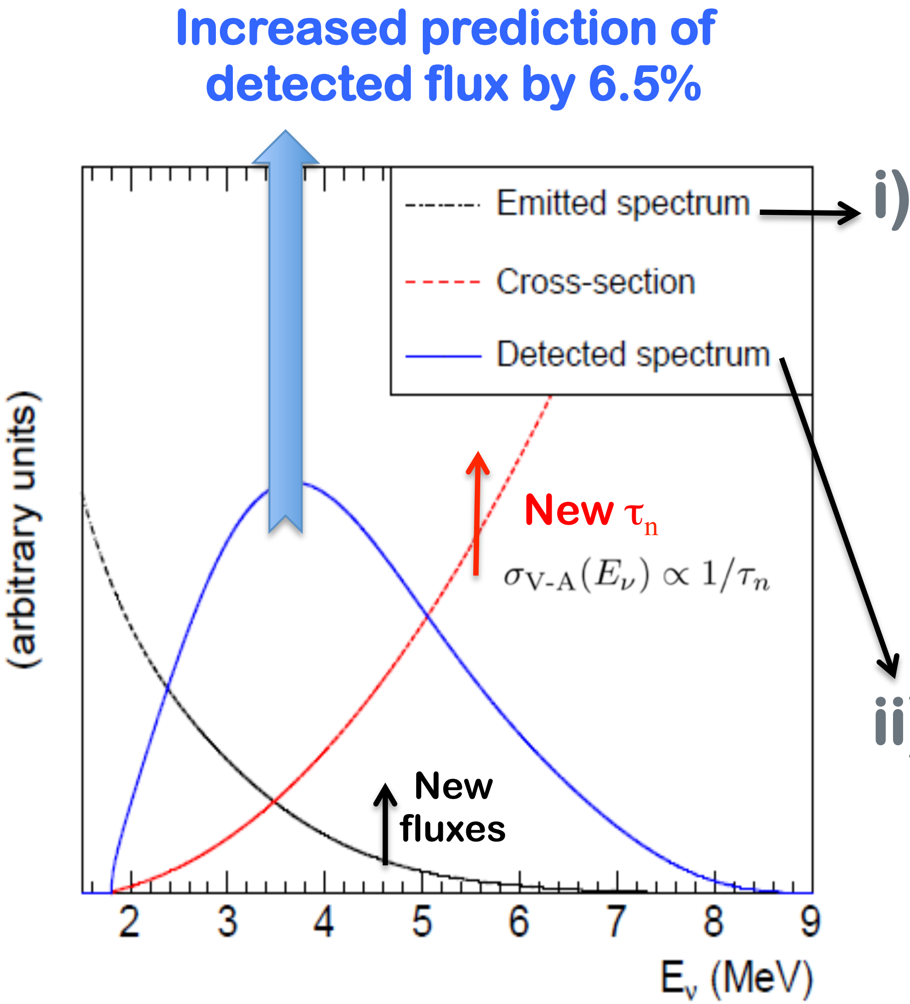
MiniBooNE Results

- 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:**

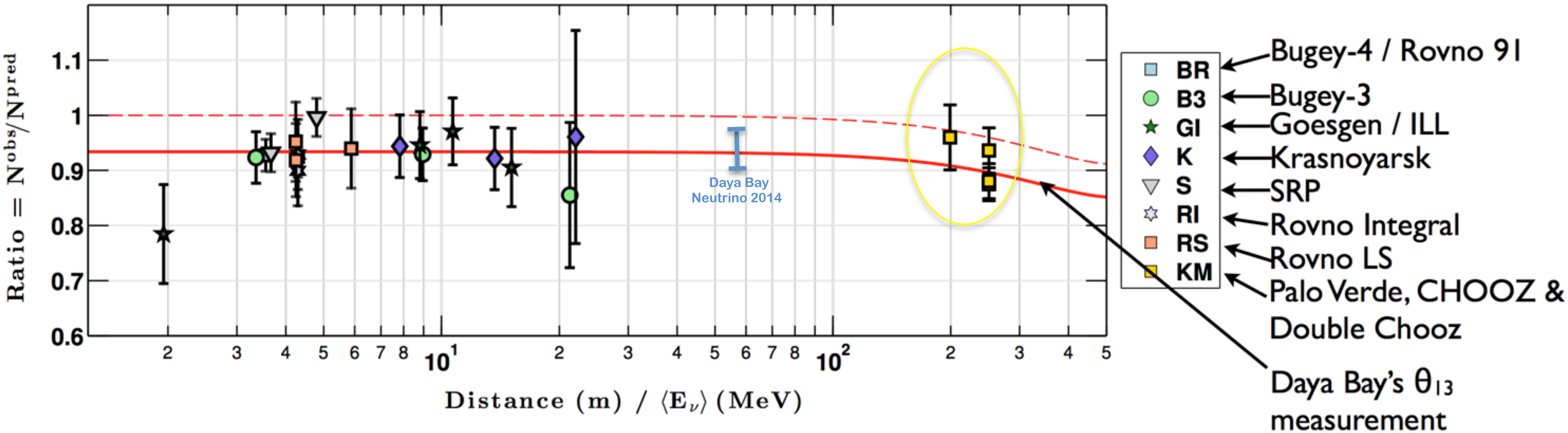
- **Improved reactor neutrino spectra → +3.5%**
- **Accounting for long-lived isotopes in reactors → +1%**

ii) **Neutrino Detection:**

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

The Reactor Anomaly

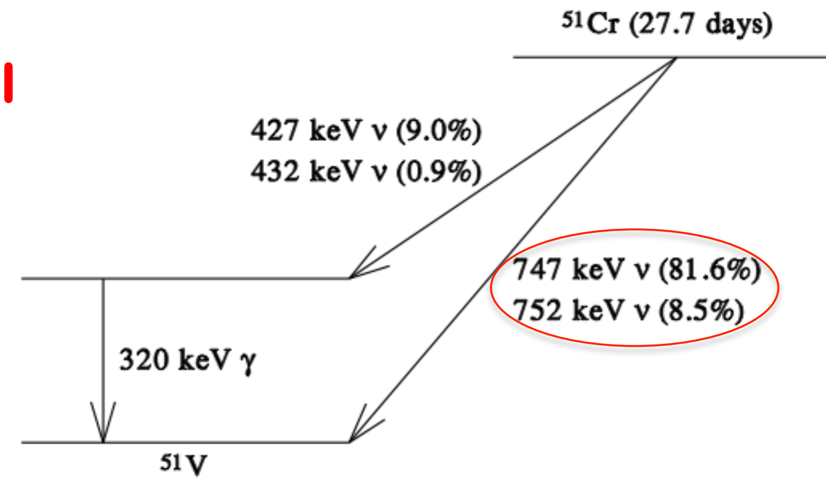
2014 Reactor Anomaly Update (new)

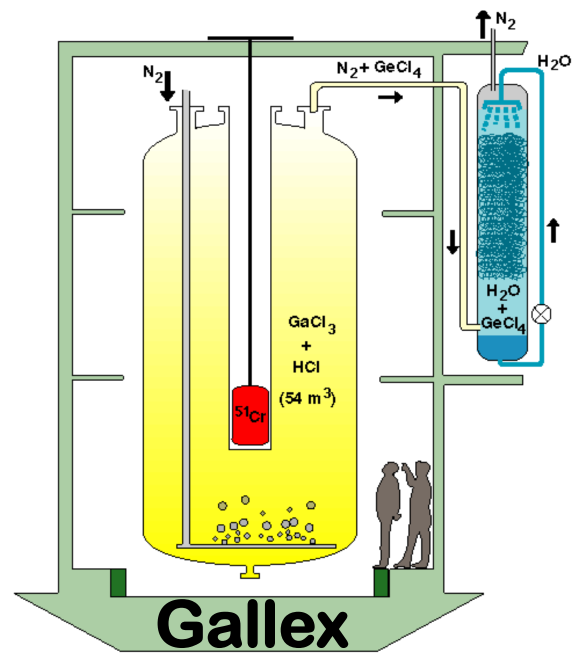


- All known nuclear corrections to β - ν spectra
- Refined treatment of experimental correlations
- Updated neutron mean life (τ_n = 881.5 s)
- km-scale baselines (Chooz, DC, PV)
  - correcting for θ_{13} deficit from Daya Bay's measured value
- **2014 result: μ = 0.938 ± 0.023, 2.7σ deviation from unity**

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 19 – 62 PBq 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 measurement

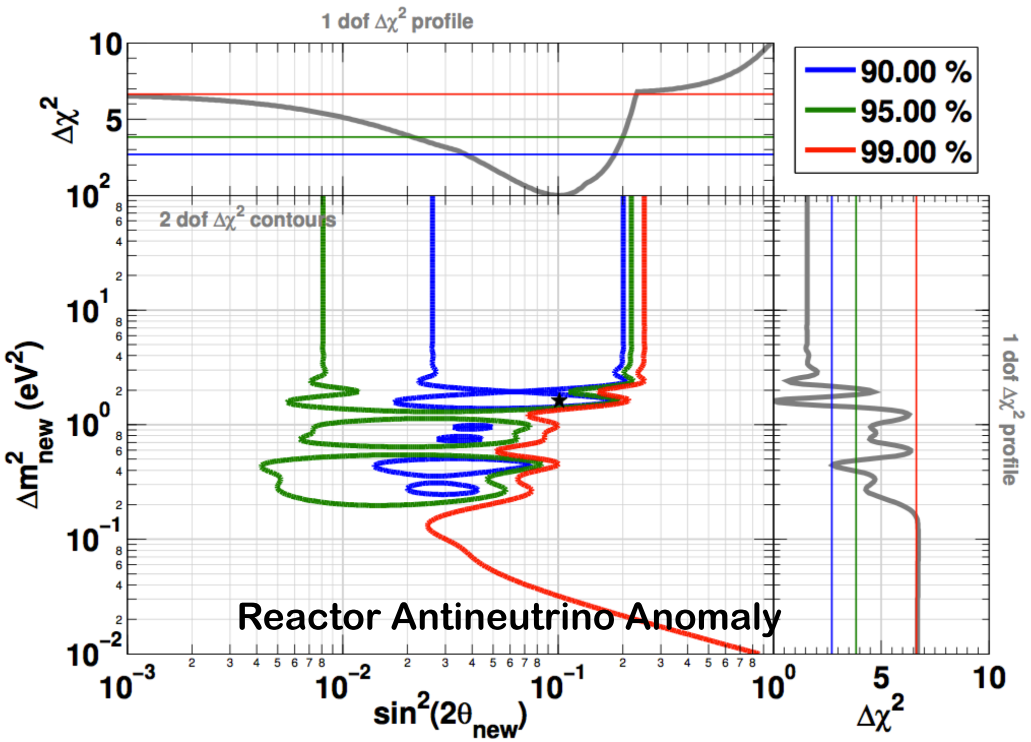


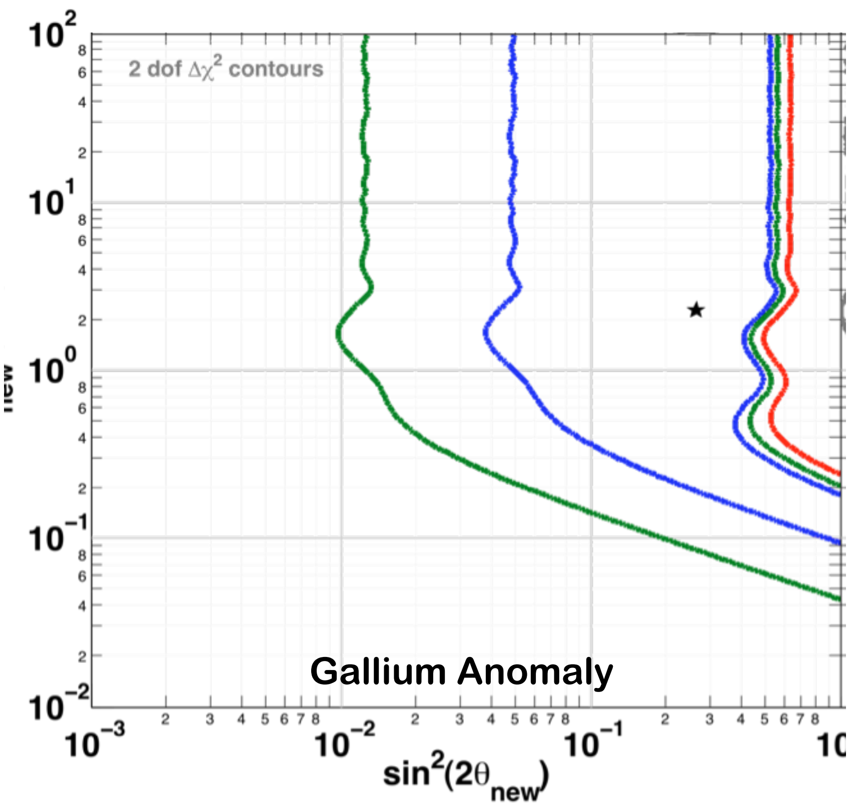


Sterile Neutrinos

Fit to ν_e and $\bar{\nu}_e$ disappearance hypothesis (3+1 model)

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





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	$\bar{\nu}_\mu \to \bar{\nu}_e$	Total Rate, Energy	CC	3.8 σ
MiniBooNE	Meson Decay-in-Flight	$\nu_\mu \to \nu_e$	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	$\nu_\mu \to \nu_e$	Total Rate, Energy	CC
CDHS/Minos/ MiniBooNE	Meson Decay-in-Flight	$\nu_\mu \to \nu_\mu$	Total Rate, Energy	CC
Minos	Meson Decay-in-Flight	$\nu_\mu \to \nu_s$	Total Rate	CC
T2K	Meson Decay-in-Flight	$\nu_e \to \nu_s$	Total Rate, Energy	CC

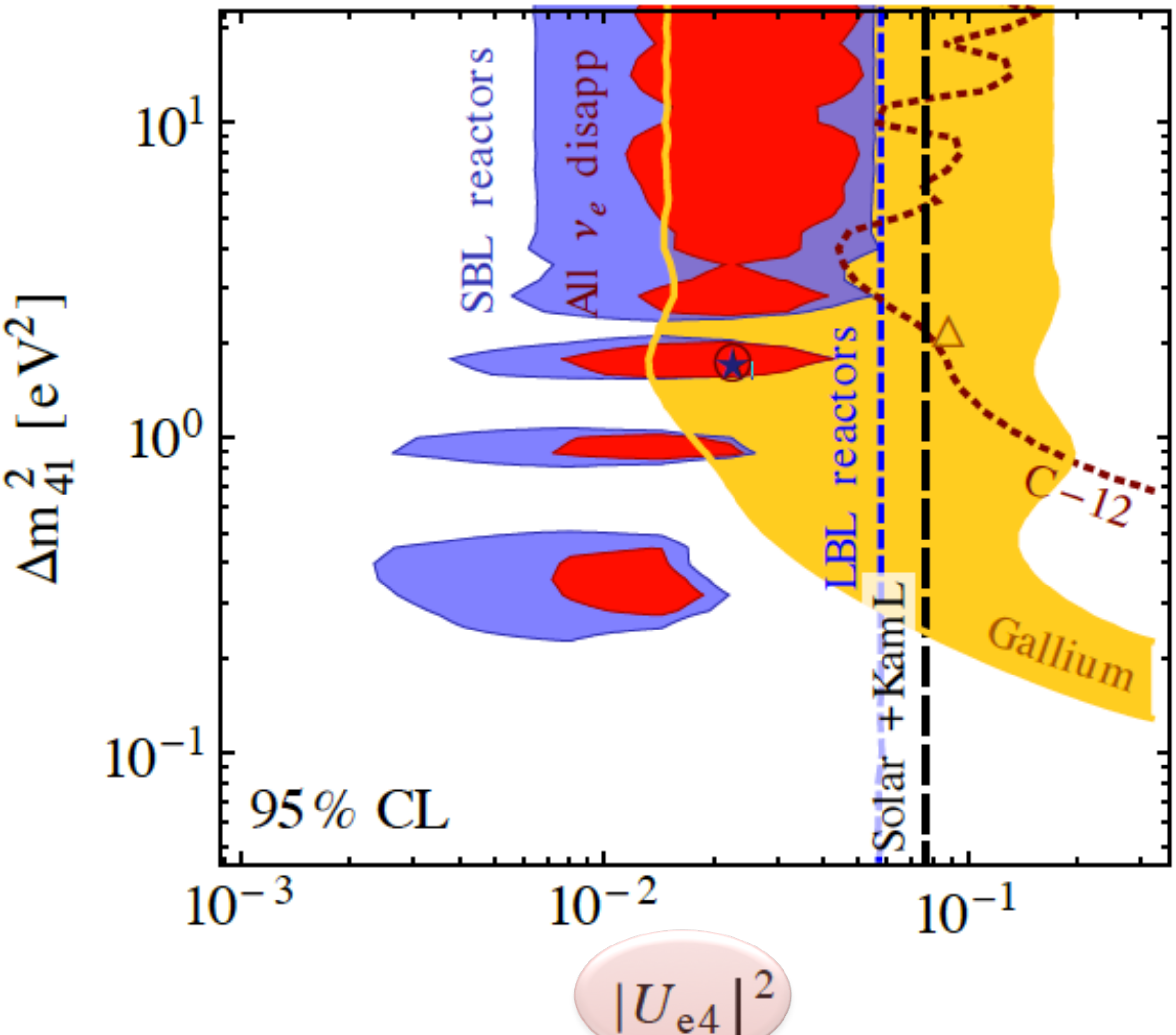
Sterile-ν Phenomenology (3+1)

- $\overset{(-)}{\nu}_e$ **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)

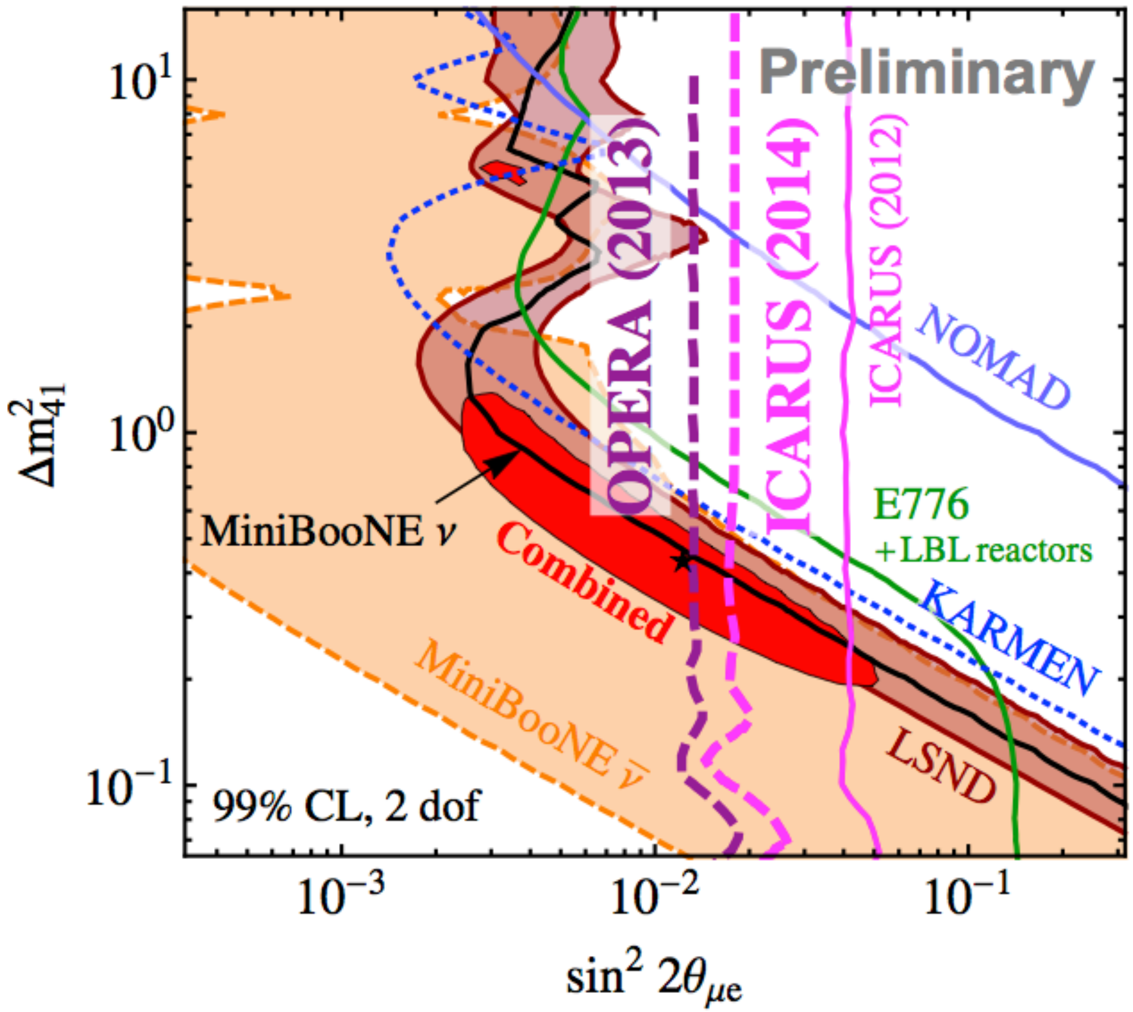
Data consistent with $\overset{(-)}{\nu}_e$ disappearance with L/E≈1 m/MeV



J. Kopp et al., arXiv:1303.3011

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

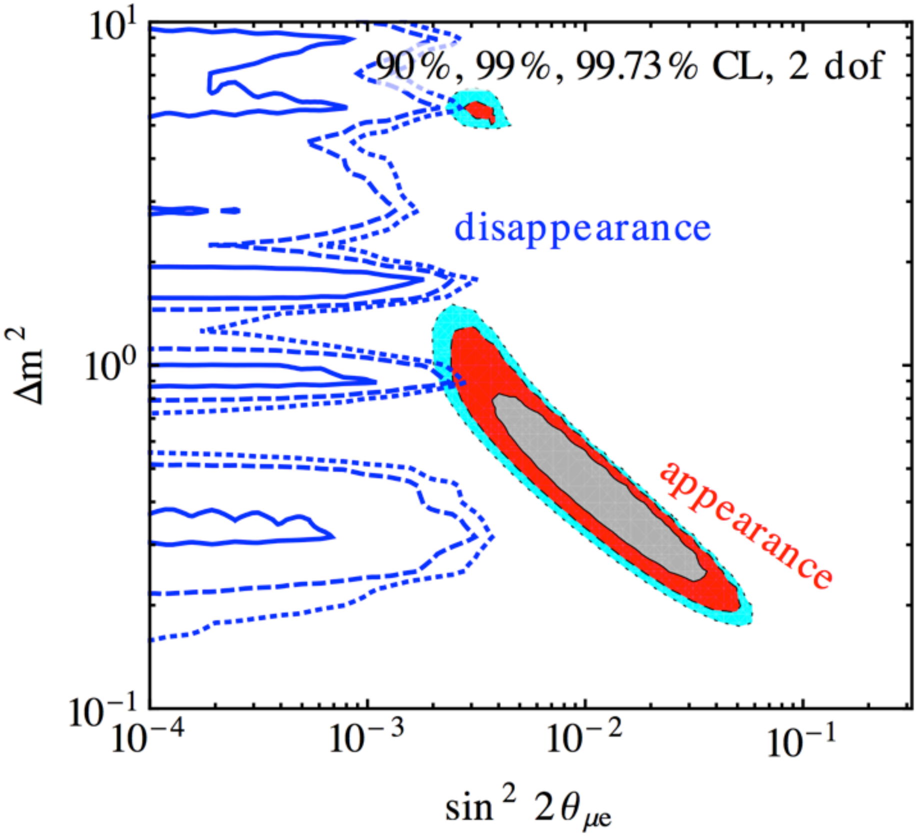
Consistent solution for $\overset{(-)}{\nu}_e$ appearance with L/E≈1 m/MeV



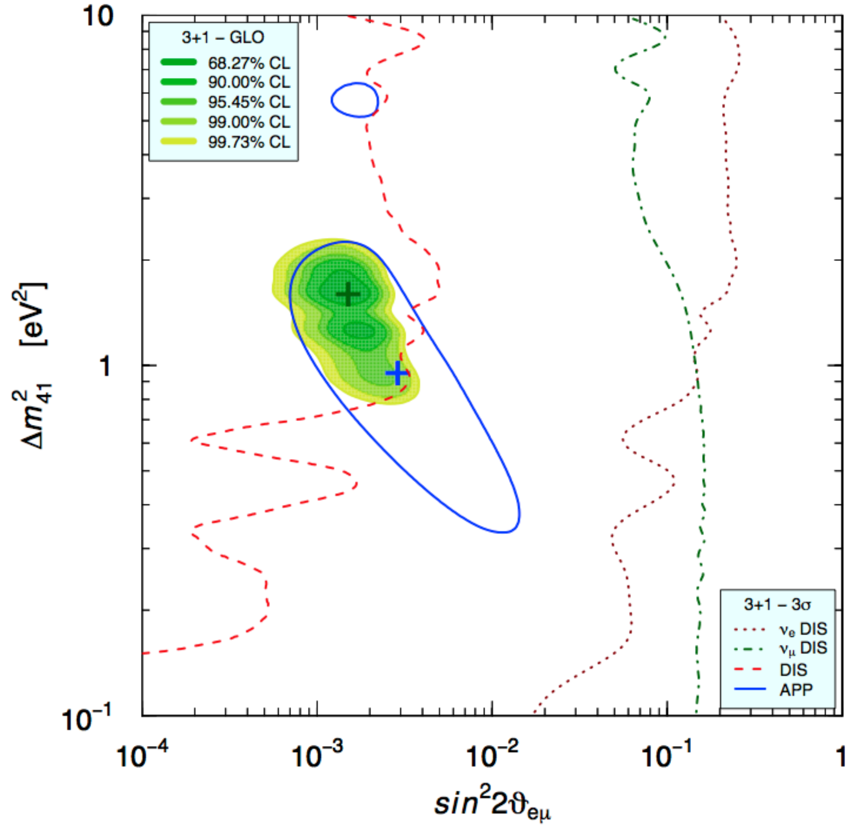
J. Kopp et al., arXiv:1303.3011

Appearance VS Disappearance

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



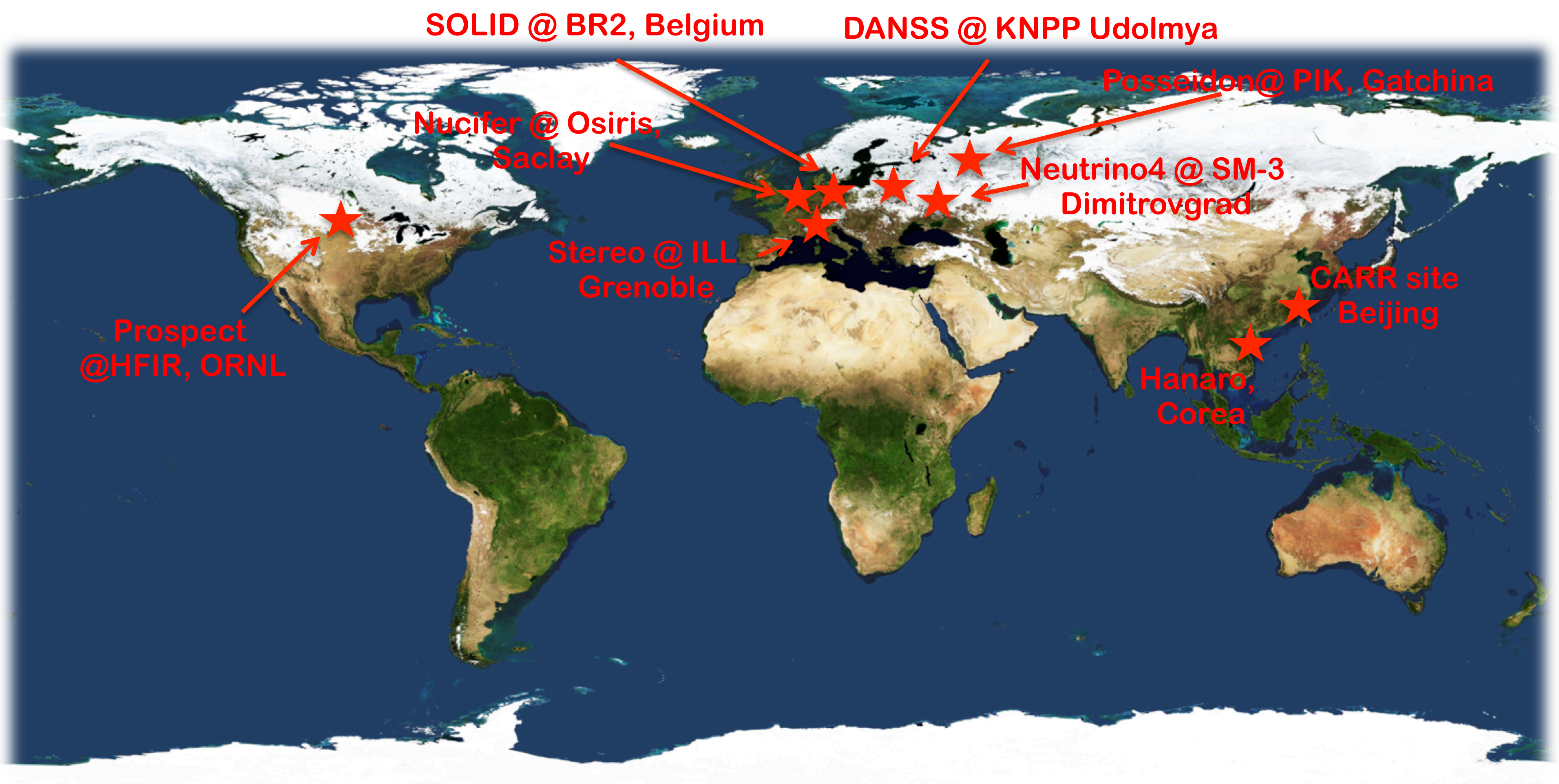
C. Giunti et al., **arXiv:1308.5288**



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

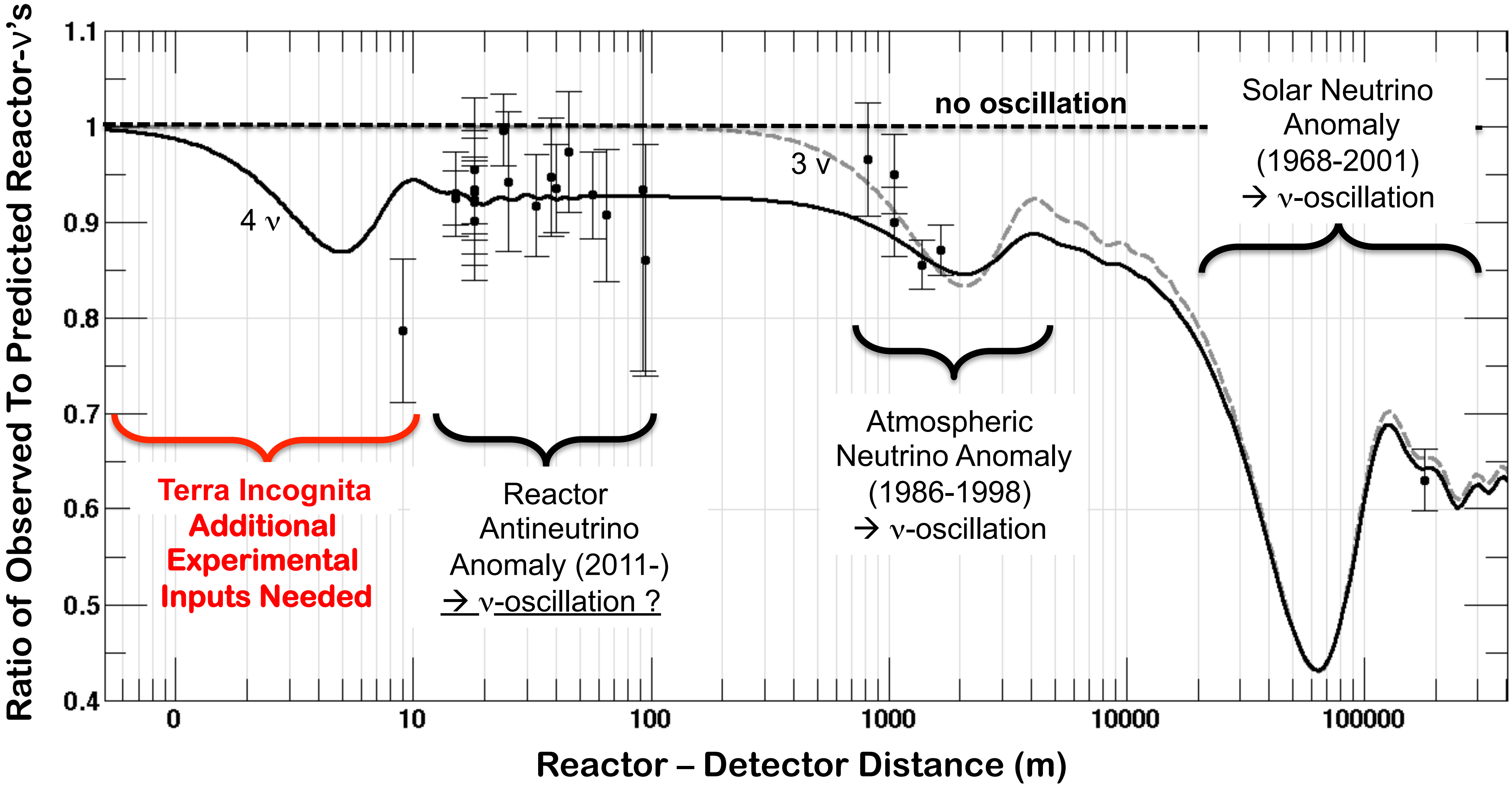
Experimental Prospects

Experimental Prospect: @ Nuclear Reactor



Test of both reactor & gallium anomalies

Experimental Artifact or New Physics?



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

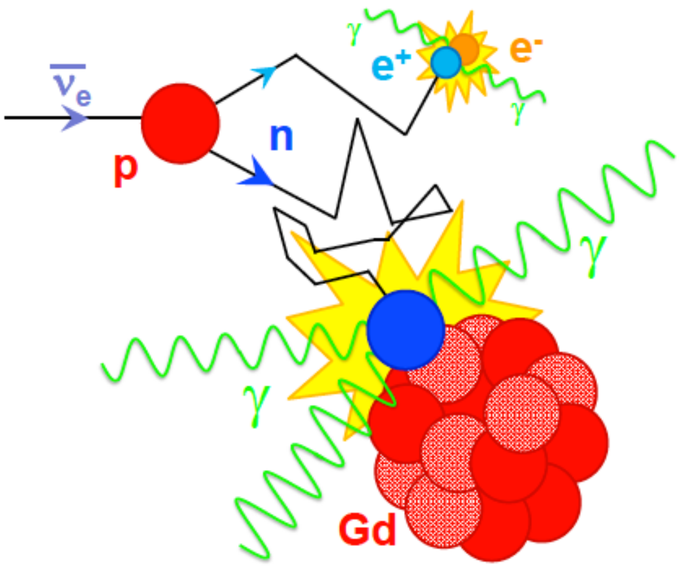
- Experimental specifications
  - Compact source, <1 meter scale
  - Good vertex and energy resolutions
  - High statistics (few % stat. uncertainty)
  - Few % syst. uncertainty → low backgrounds

- 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

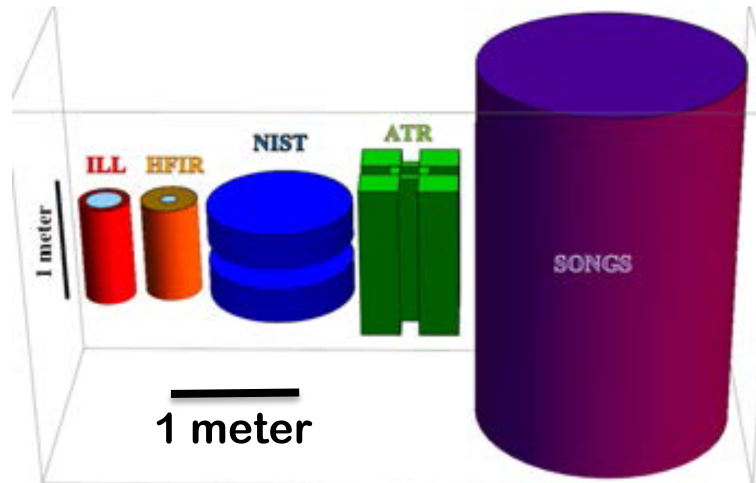
Background rejection

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

- **Fast-n correlated background**
  - Rejection of recoil protons with PSD
  - Cosmic rays induced:
    - Reactor OFF data
    - Overburden > few m.w.e.
  - Reactor induced neutrons: a killer!
    - <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)
- Fuel
  → Highly enriched ^{235}U preferable (^{235}U fission spectrum)
- Reactor ON/OFF periods
  → Moderate overburden compensated by accurate measurement of the cosmogenic background
- But challenging reactor-induced backgrounds (γ and n)
  → Need site characterization & specific shieldings

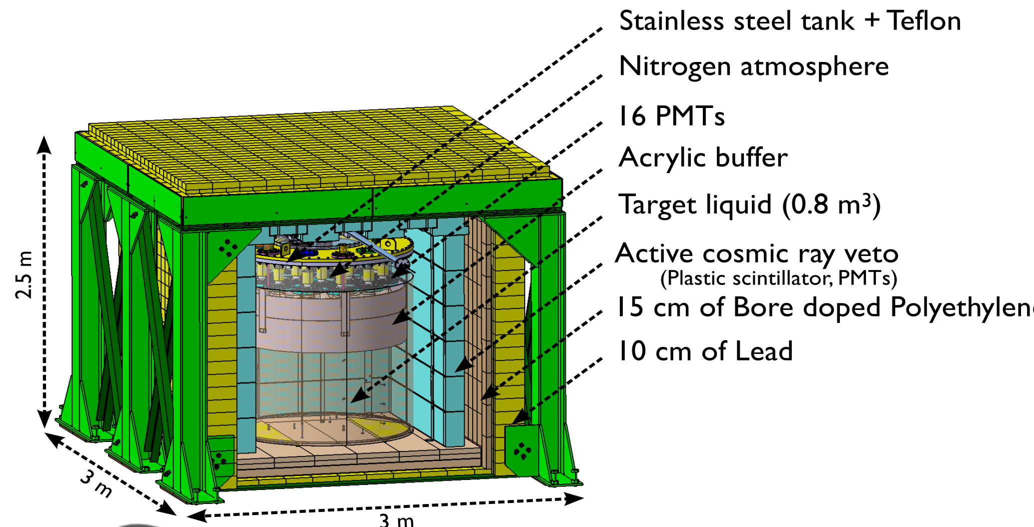
Reactor ν Proposals

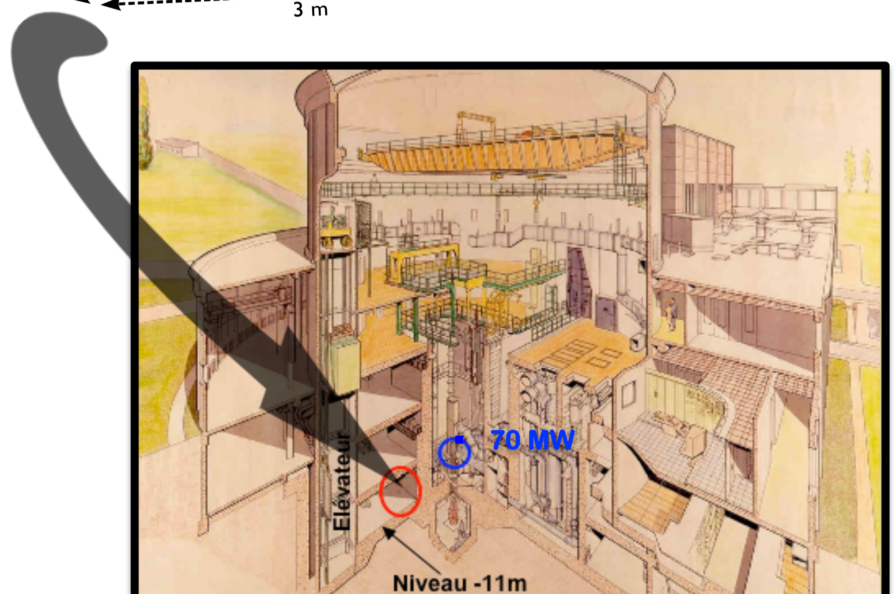
Experiment Type	Projects	P_{Th}	M_{det}	L	Depth
Mature Gd-doped LS detector Technology	Nucifer (FRA)	70 MW	0.7 tons	7 m	Few mwe
	Stéréo (FRA)	50 MW	2 tons	[8-11] m	10 mwe
	Neutrino 4 (RU)	100 MW	2 tons	[6-12] m	Surf.
Highly segmented detector for background reduction	DANSS (RU)	1 GW	1 ton	[10-12] m	50 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)*

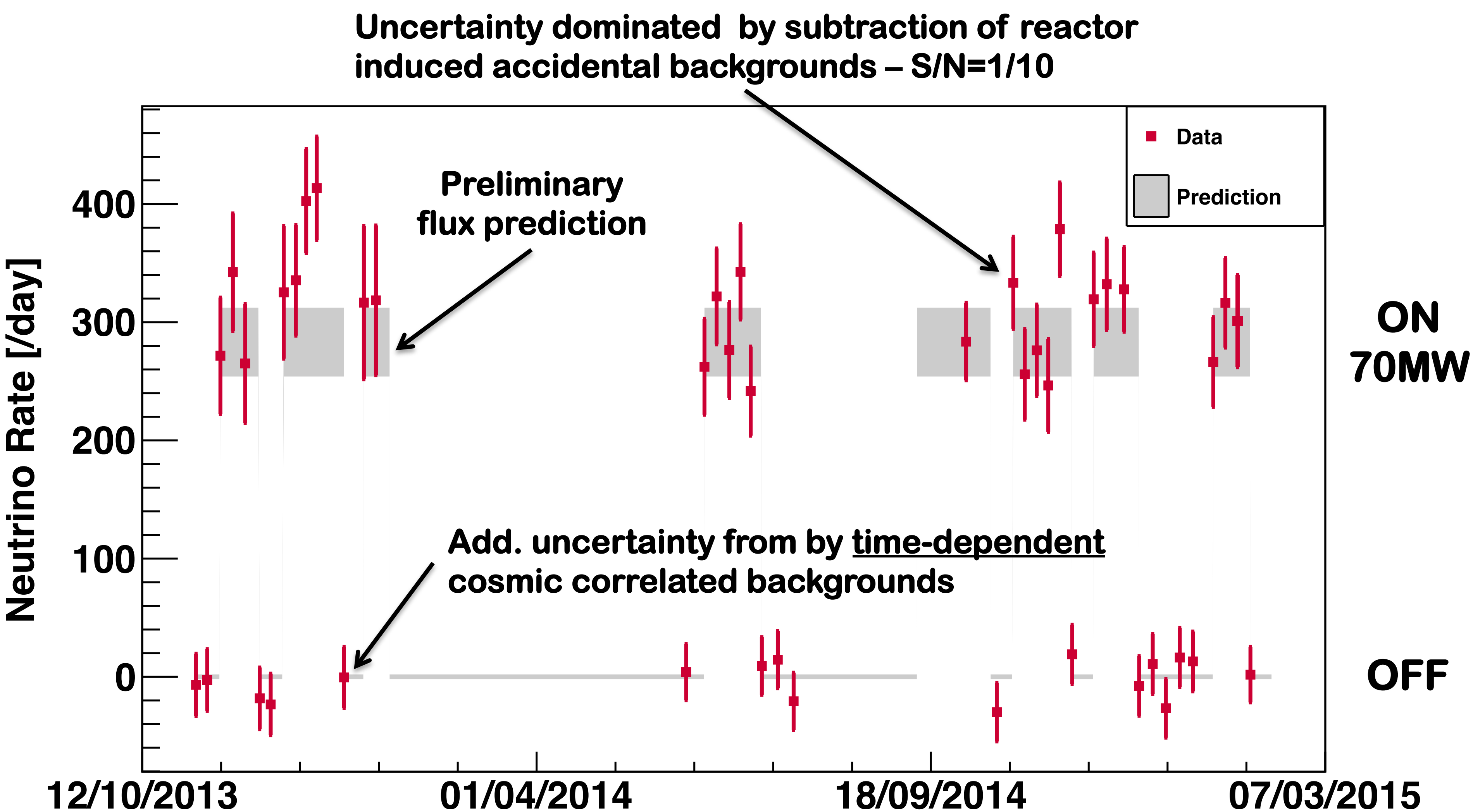
Designed for non proliferation studies

- **Osiris research reactor**
  - Saclay
  - 70 MW, 20% ^{235}U
- **Detector**
  - 850 kg Gd-loaded LS
  - Shallow depth (few mwe)
- **Sensitivity to Sterile-ν:**
  - Compact core: 60x60x60 cm³
  - Short baseline: 7 m
  - Simple design (counting exp.)
  - Challenging reactor acc. Bkgs
- **Data taking ongoing**
  - ≈300 ν/day
  - Until end of 2015

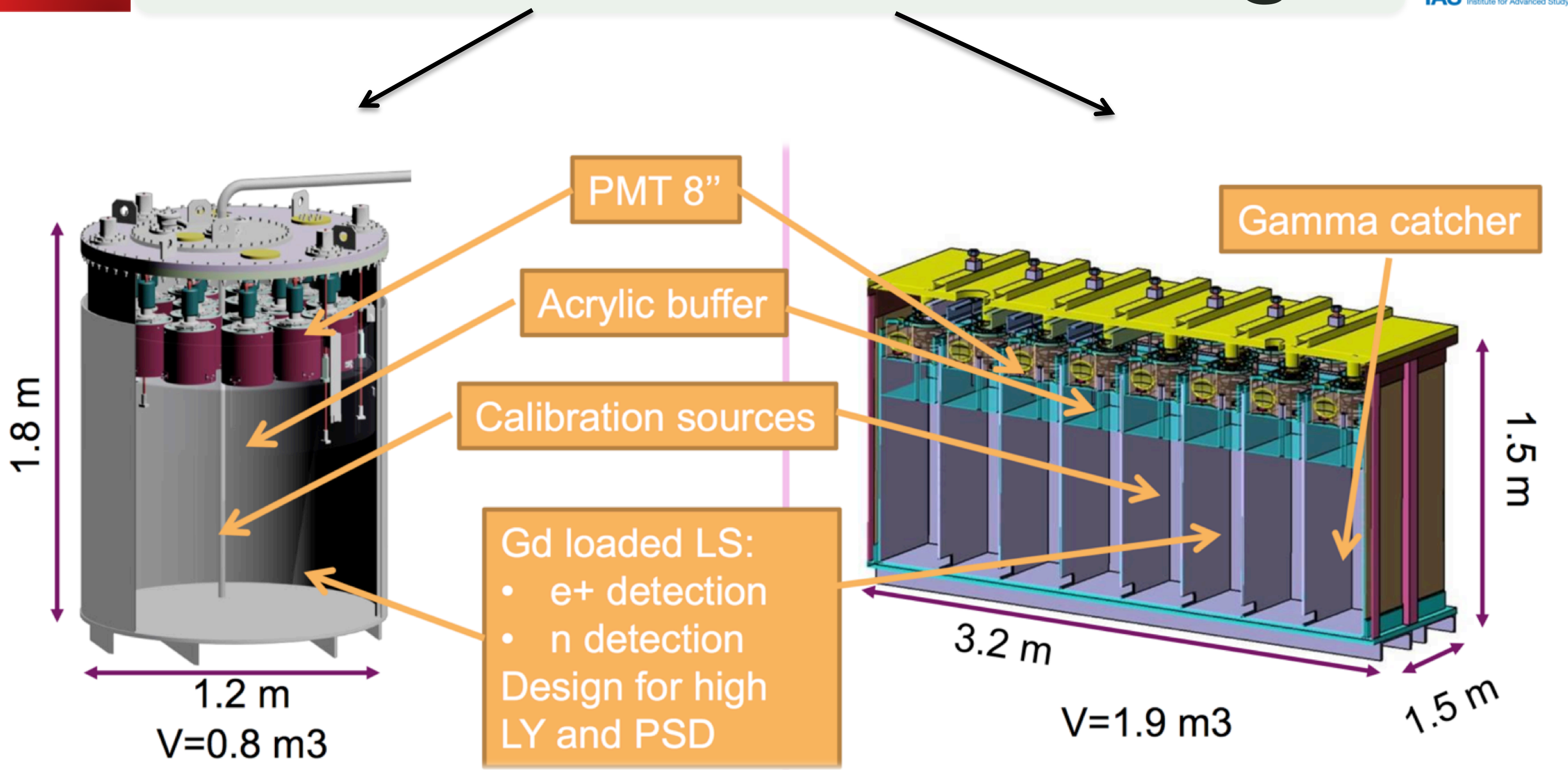




First Nucifer Results



Nucifer / Stéréo Design



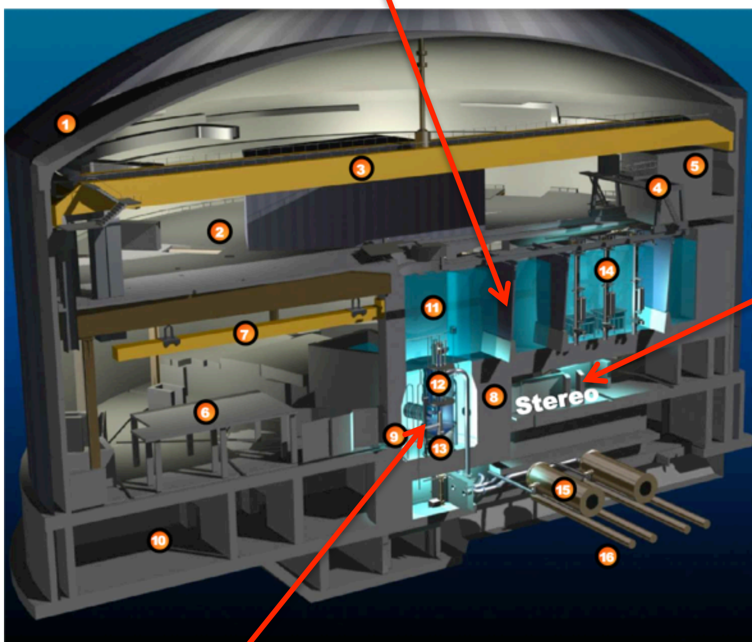
- Rate only analysis
- RMS/peak = 30% for 2 MeV e^+

- Shape and rate analysis
- RMS/peak = 11.5% for 2 MeV e^+

Stéréo @ ILL *(Gd-LS)*

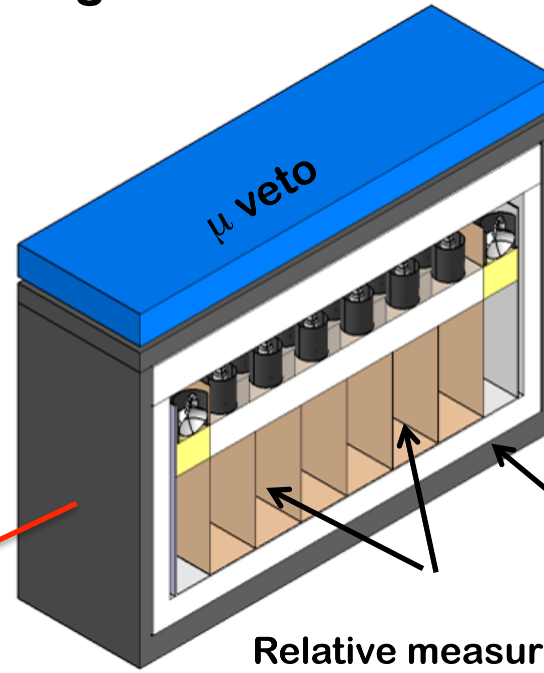
Start Data Taking in June 2016

factor 4 attenuation of μ vertical flux
from water pool (15 m.w.e)

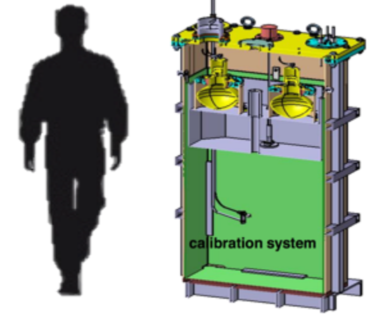


50 MW core
h=80cm, Φ=40cm

[9-11] m
baseline range

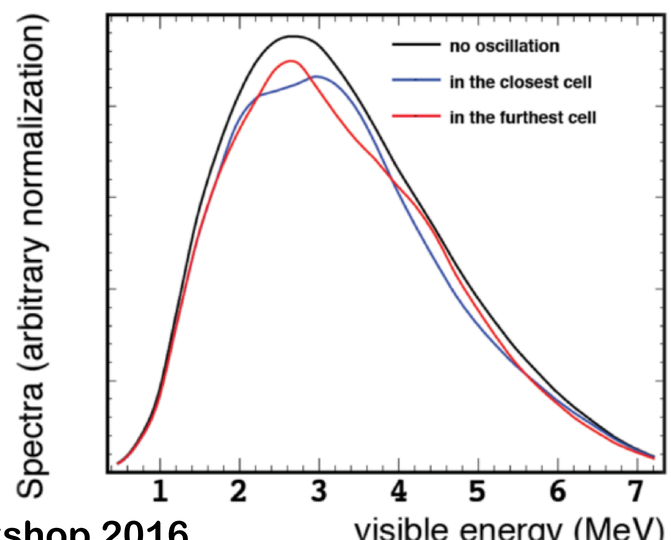


proto



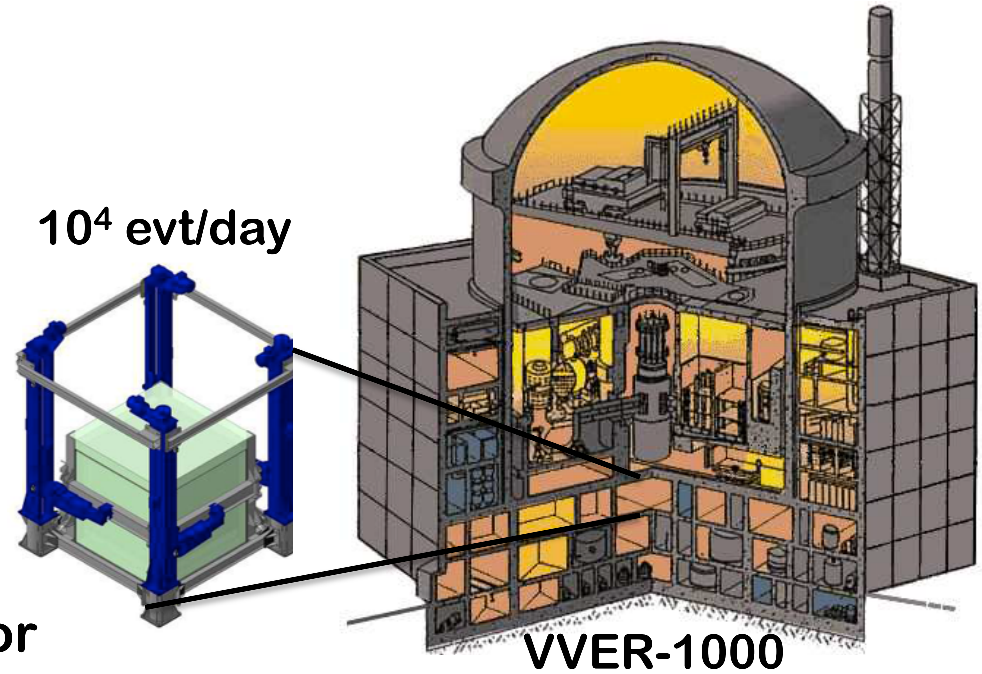
70 tons γ and n
shielding

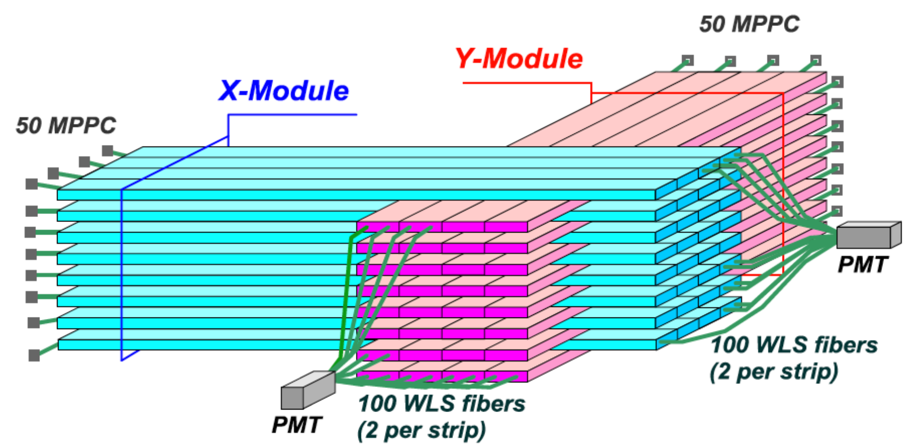
Relative measurement in 6 cells



DANSS @ KNPP *(High-Seg)*

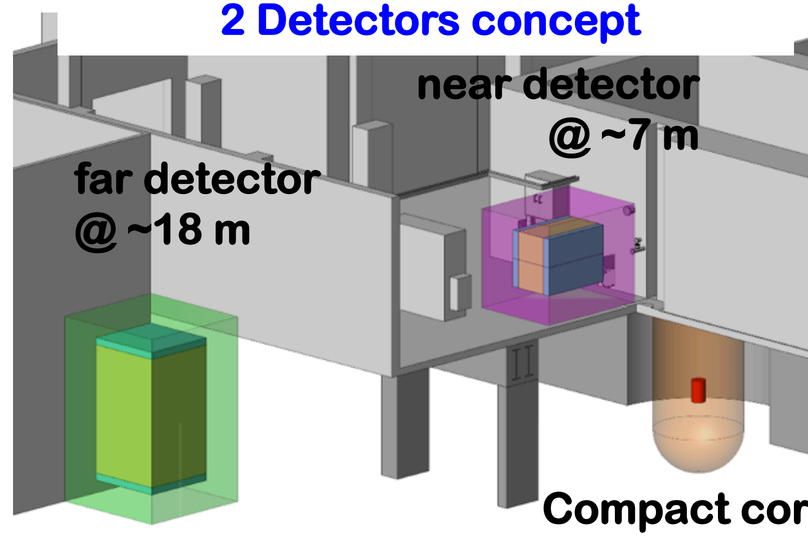
- 1 GW extended core
- Good overburden
- Vertical motion of the detector (9.7-12.2 m)
- Highly segmented detector → background rejection
- Plastic strips with Gd-loaded interlayer, WLS fibers readout
- Started in 2015

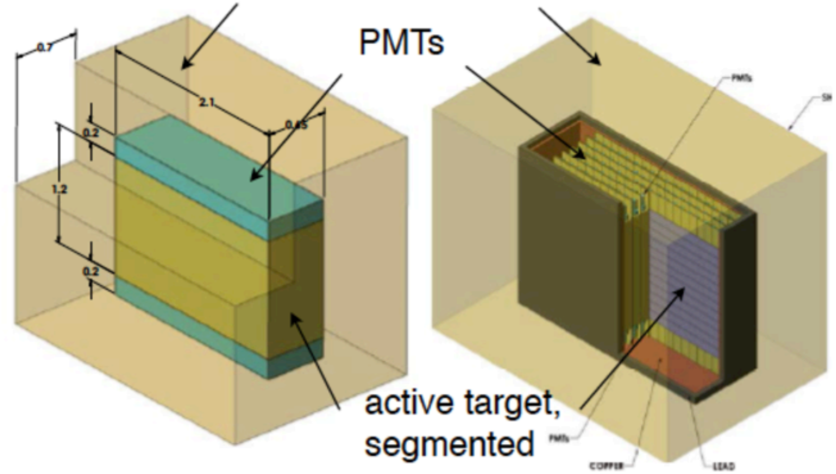




Prospect @HFIR

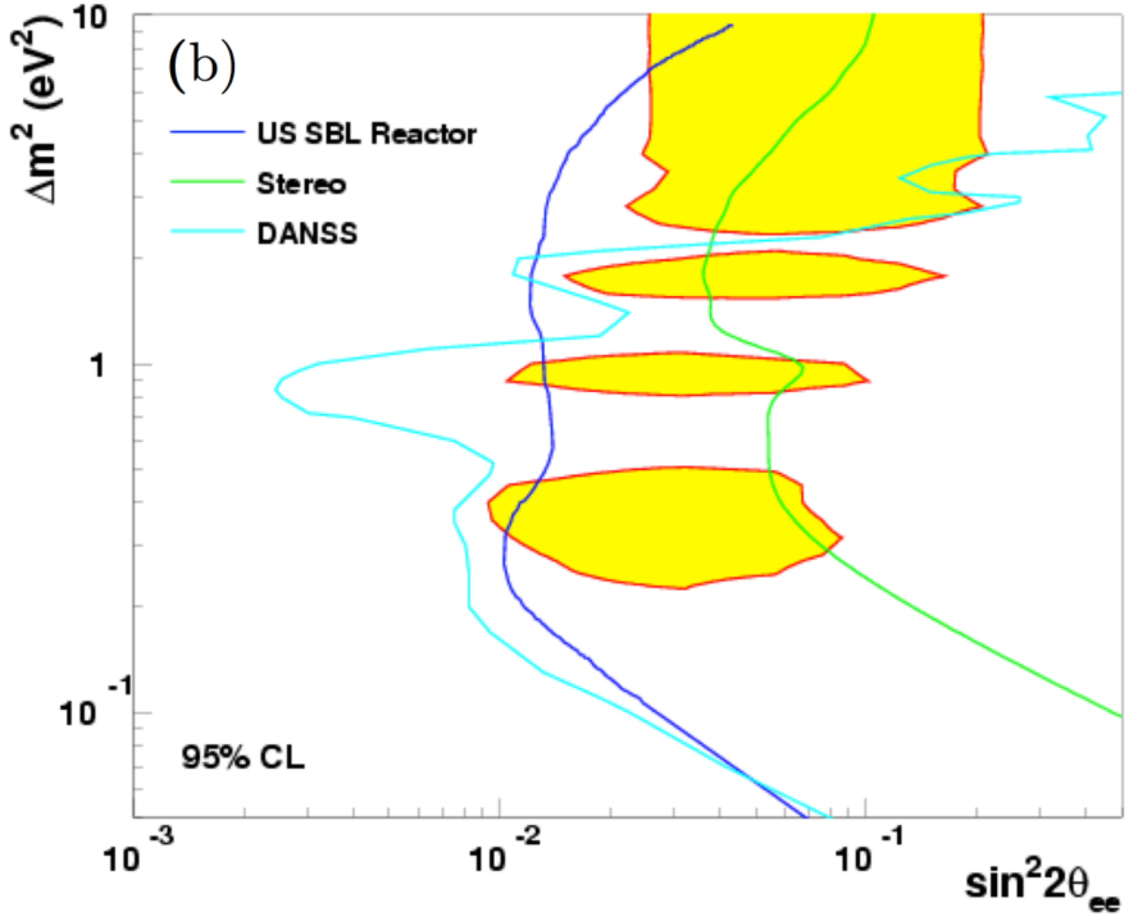
- Reactor sites
  - HFIR @ ORNL – 85 MW
- 7-18 m baselines
- Surface location
- Detector
  - Segmented
  - ^{6}Li-doped (+PSD)
- Status:
  - Site characterization
  - R&D ongoing
  - Construction start in 2015





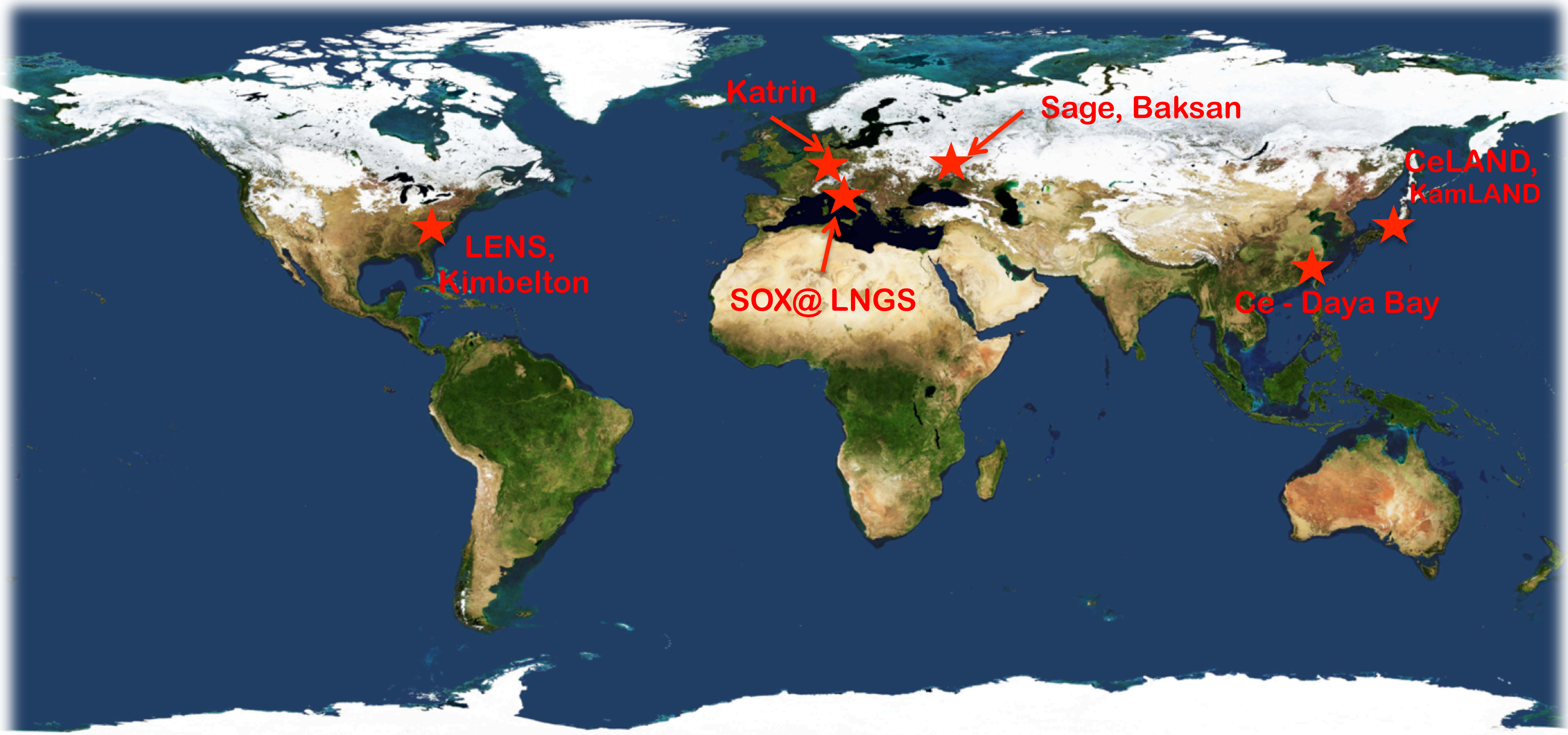
Reactor Experiment Sensitivity

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



arXiv:1310.4340

Experimental Program:
@ Neutrino Generator



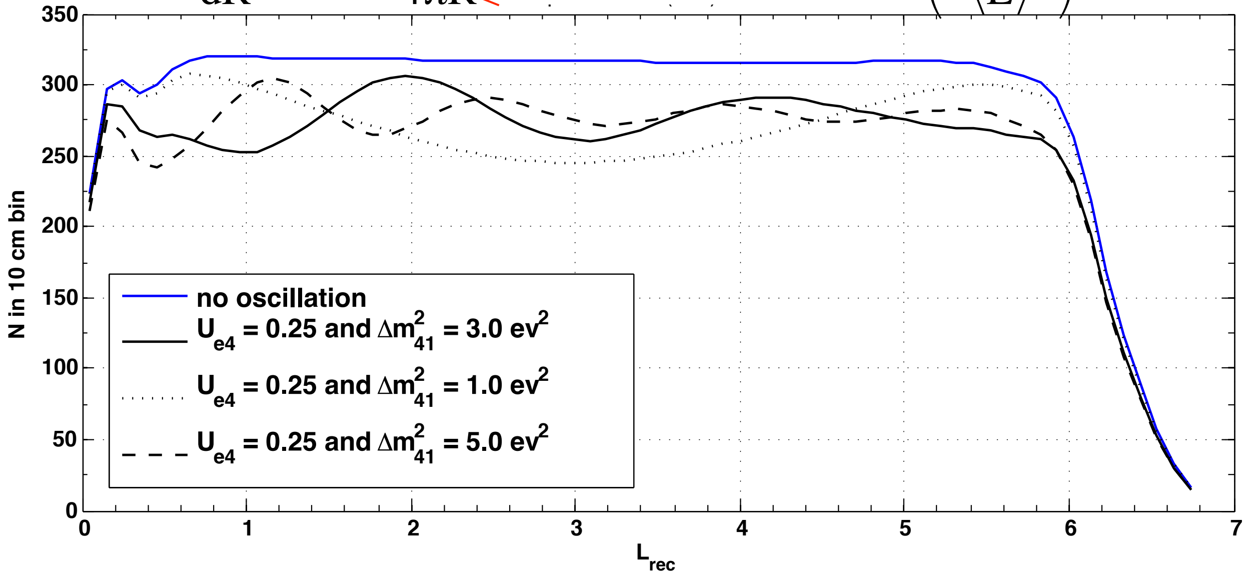
Test of both reactor & gallium anomalies

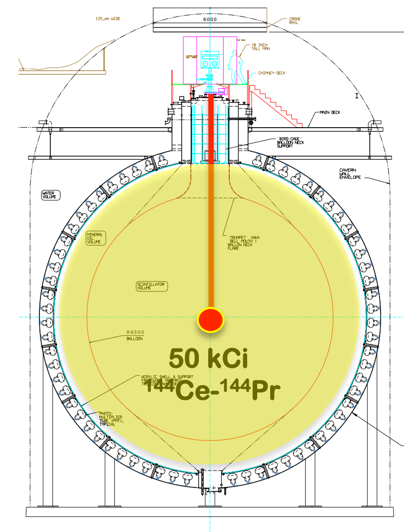
ν Generator Proposals

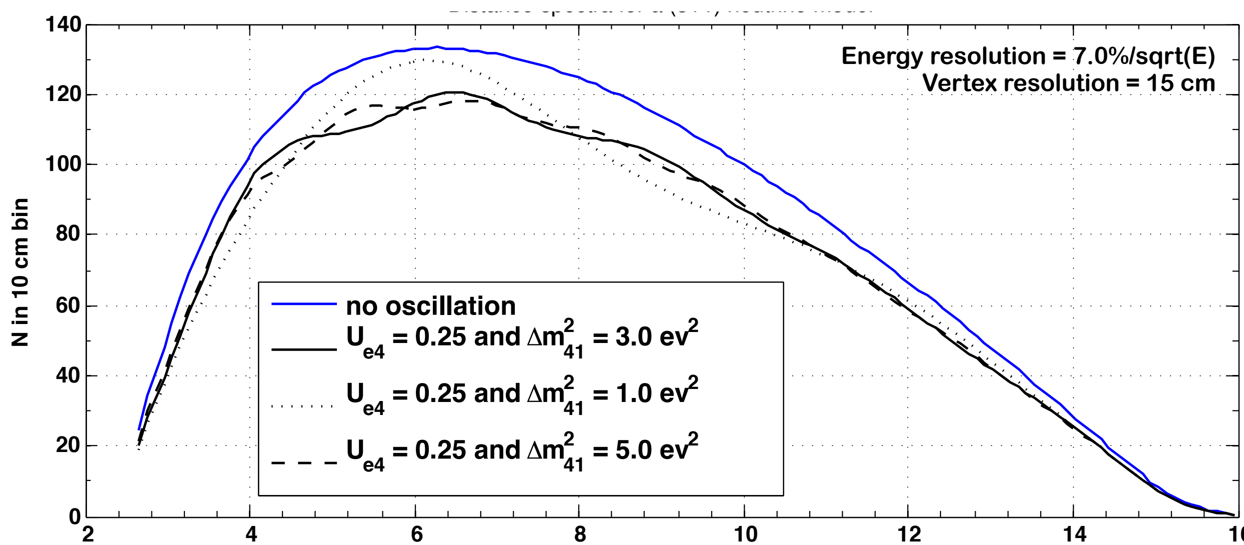
Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	$\nu_e e \rightarrow \nu_e e$ 5% E_{res} 15cm R_{res} or Radio-chemical	Detector Radioactivity Solar ν (irreducible) ν generator impurities	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	>110 PBq	Sage LENS
					>370 PBq	SOX-Cr (SNO+)
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	>37 PBq	-
					185 PBq	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	3.7 PBq	CeLAND Ce-SOX
					18.5 PBq	Daya-Bay
			^{90}Sr ^{106}Rh		-	-
	$^{3}H \rightarrow He\ e^- \bar{\nu}_e$ EC/β-decay	Kink search	^{3}H E<18 keV	Irradiation in reactors	110 GBq	KATRIN (Mare/Echo)

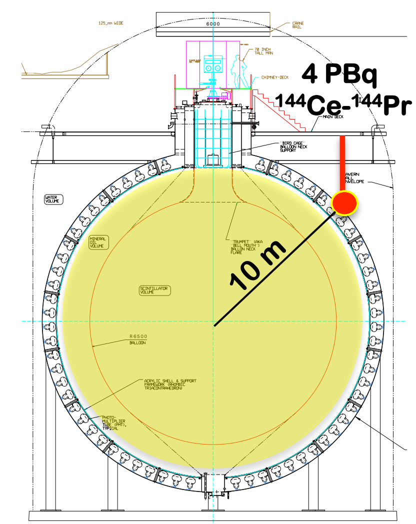
Search for $\overline{\nu}_e \rightarrow \overline{\nu}_s$ with ^{51}Cr/^{144}Ce

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



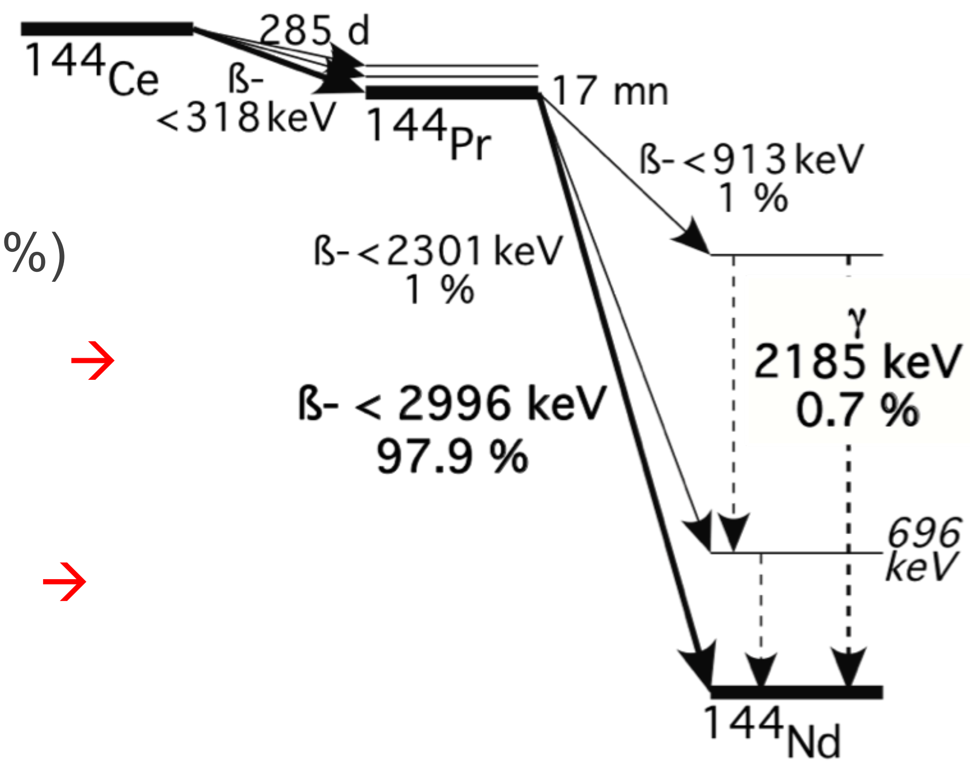






^{144}Ce-^{144}Pr $\bar{\nu}$ generator

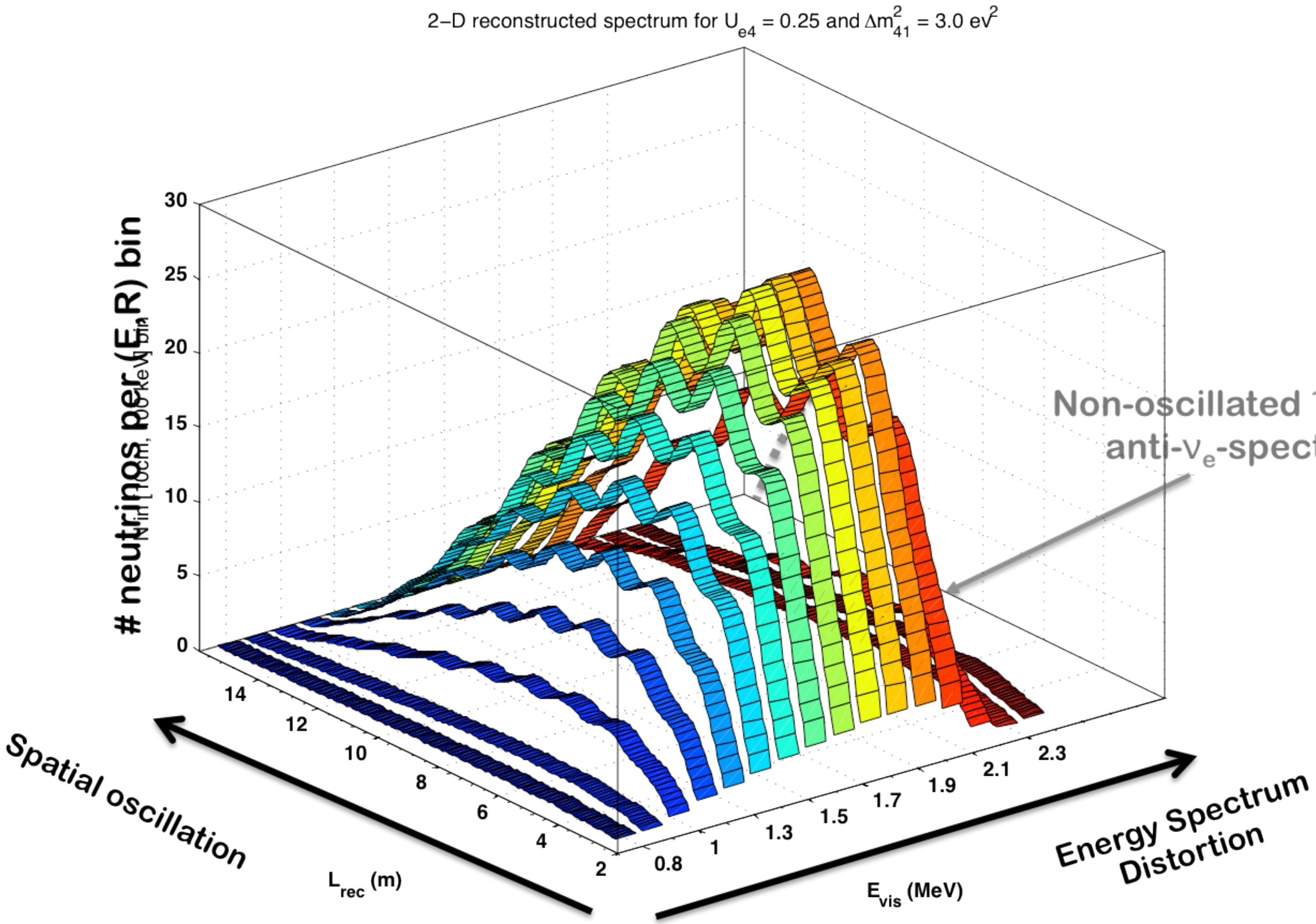
- **1st Trick: $\bar{\nu}_e$ source detected via $\bar{\nu}_e + p \rightarrow e^+ + n$ (Thr=1.8 MeV)**
  - **High IBD cross section → few PBq activity (3-5 PBq)**
  - **(e$^+$,n) detected in coincidence → Strong background reduction**



- 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

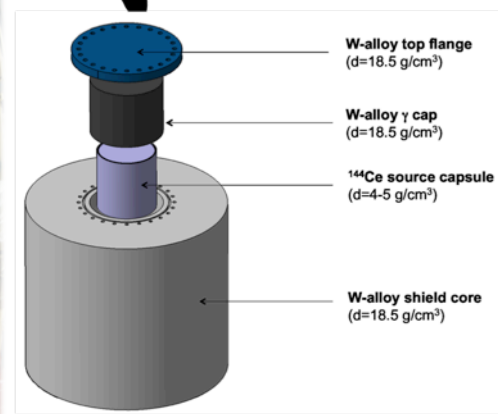
100 kCi ^{144}Ce-^{144}Pr – 8.3 m from detector center – 1.5 year

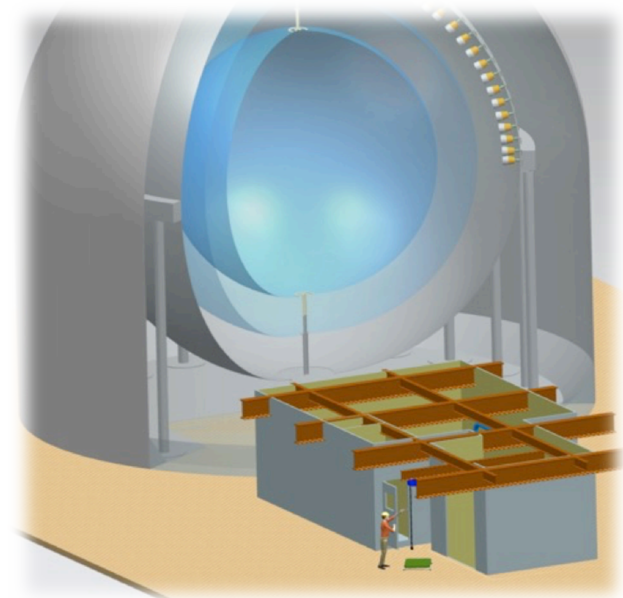


M. Vivier – Chalonge Workshop 2016

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

- 4 PBq of ^{144}Ce-^{144}Pr (CeO_2)
- Production at Mayak Facility (RU) in 2015/16 (1 y)
  - Standard SNF reprocessing
  - Ce extraction through displacement chromatography
- Need 19 cm tungsten-shield
  - Manufacturing ongoing
- Borexino getting ready
  - Tunnel below the detector
  - 8.25 m from center
- Deployment in 9/2016
  - 1.5 y data taking
  - 10000/1.5 y interactions expected





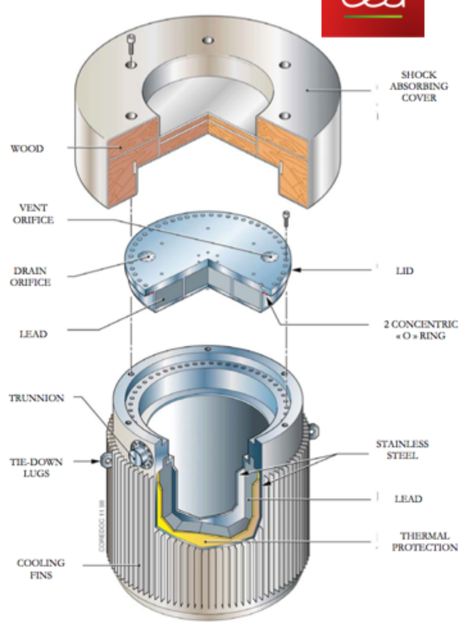
CeSOX: a Challenging Logistic

IAEA rules on Safe Transportation of Radioactive Material

A) Suitable certified transport container: licensing ongoing

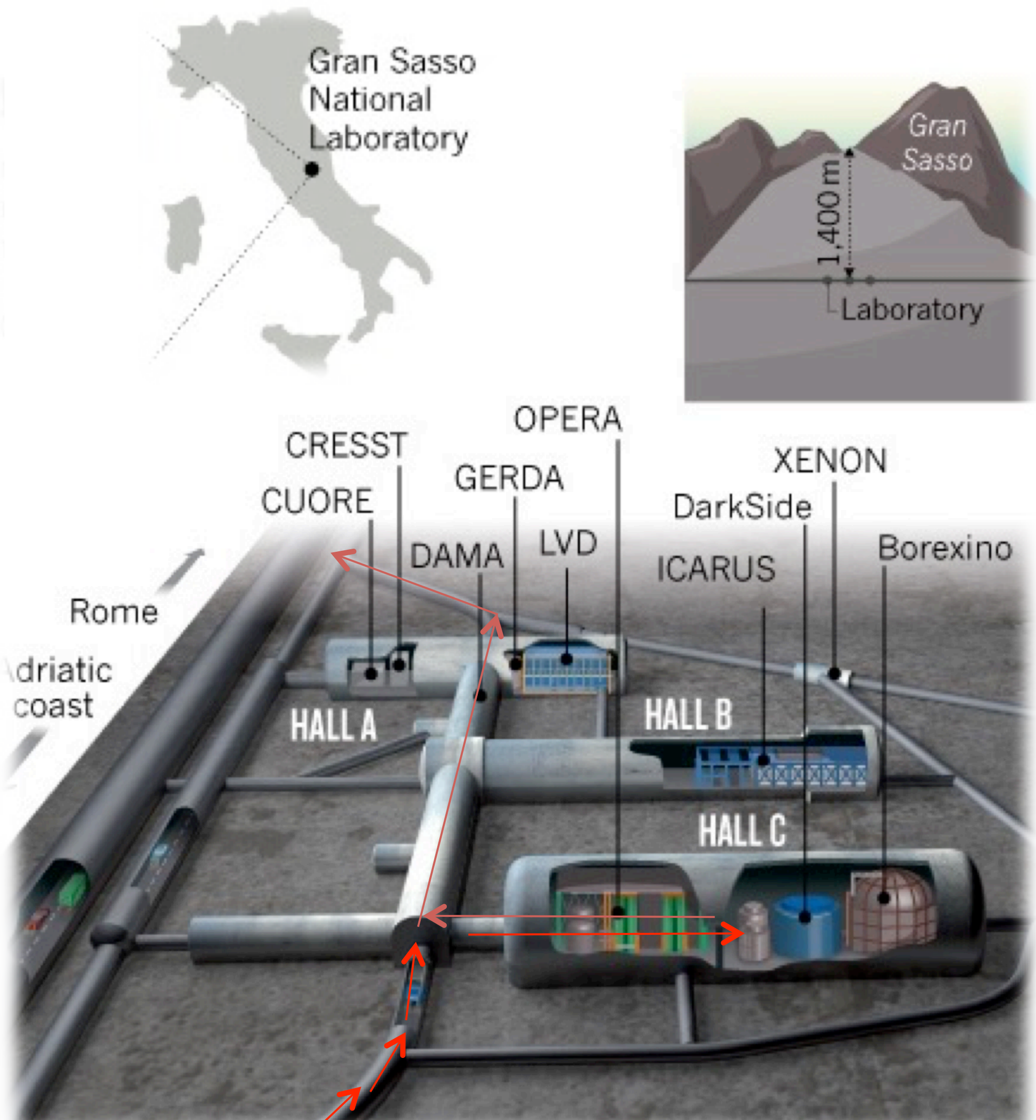
suitable B(U) casks identified

TN – TM – MTR – 23 t

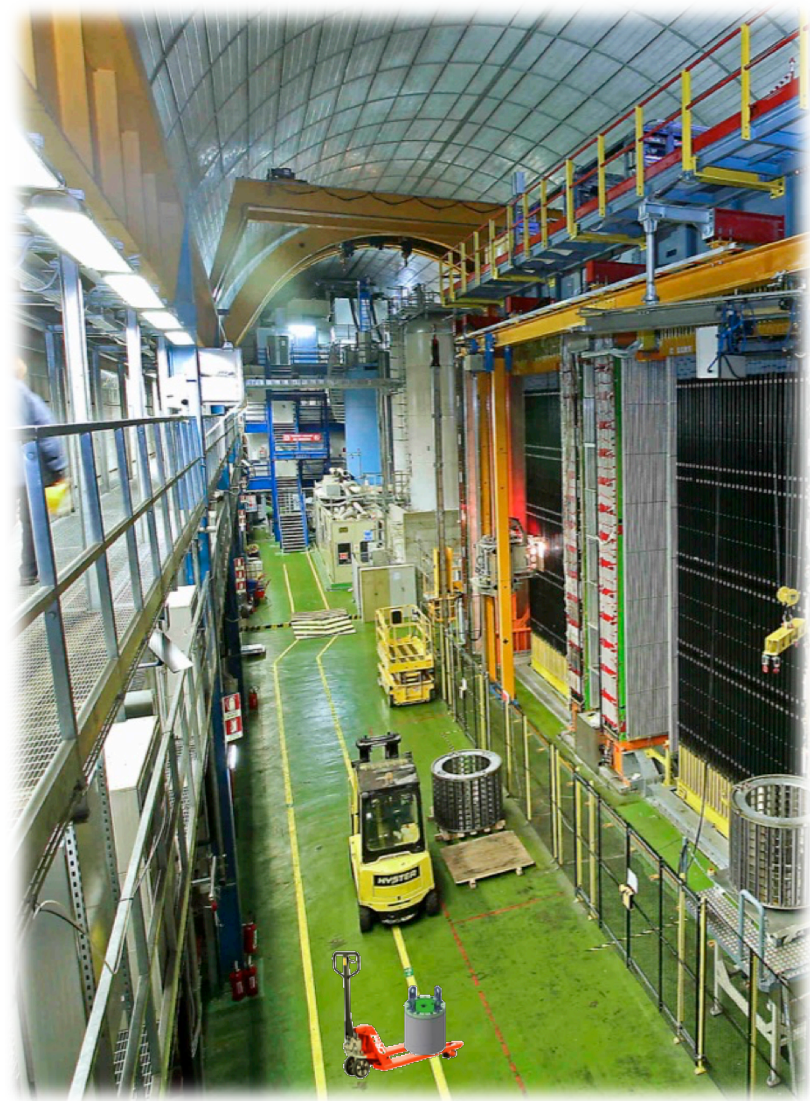


B) Route: Mayak – St Petersburg – Le Havre – Gran Sasso (duration of the trip: ≈3 weeks)

Arrival at LNGS

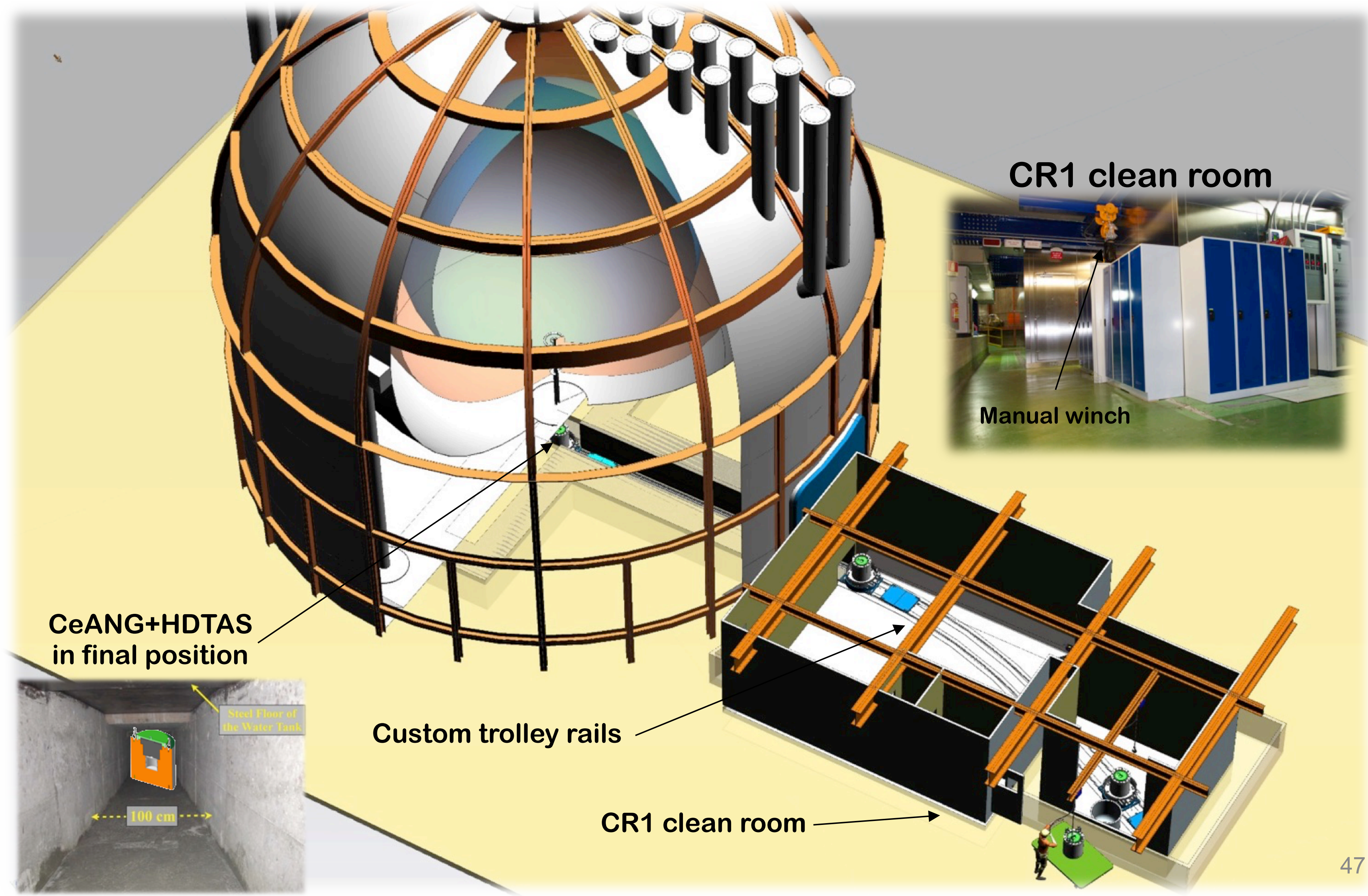


Gran Sasso National Laboratory

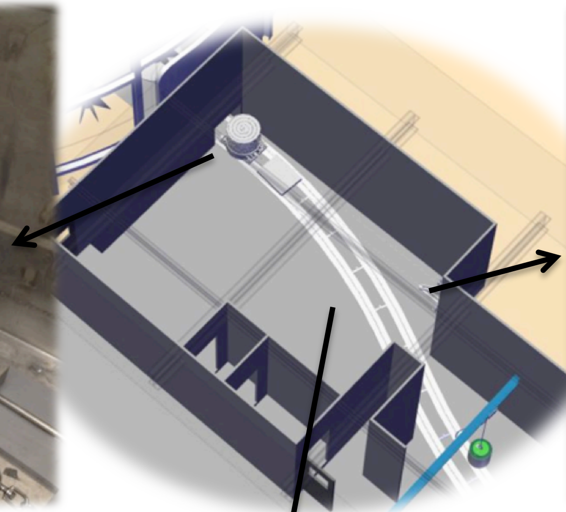


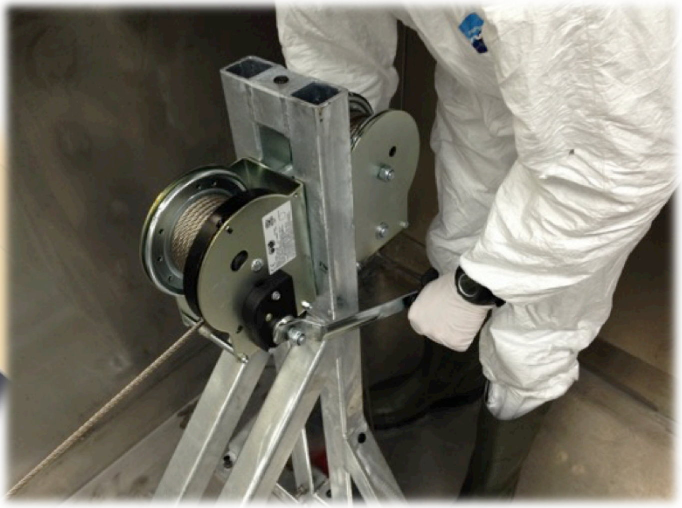
Hall C (Opera / Borexino)

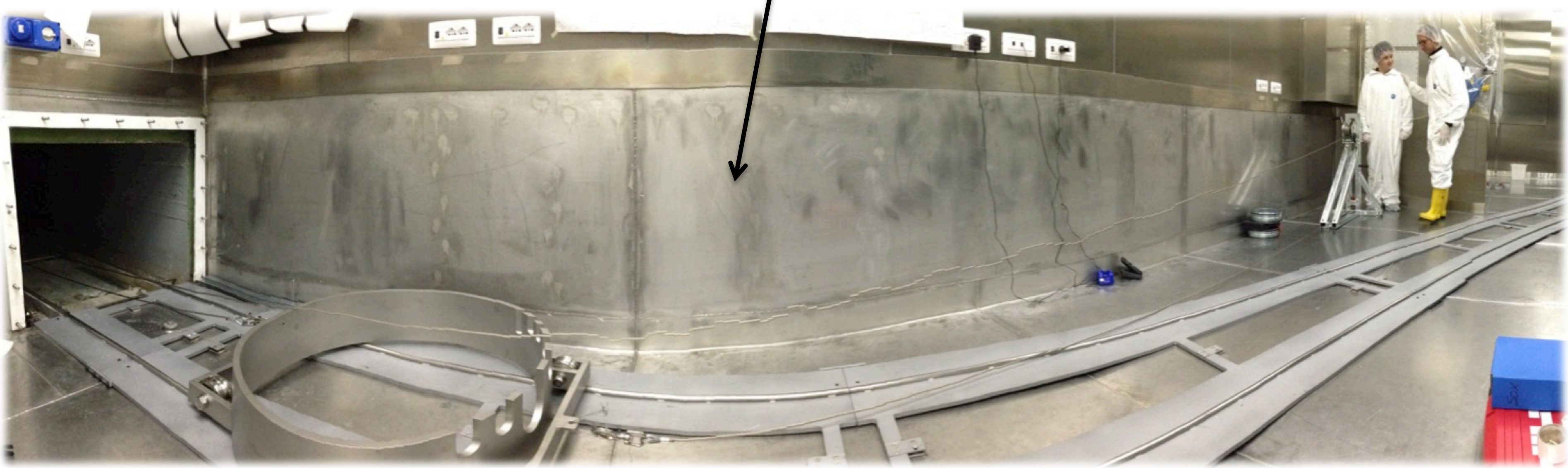
Place CeANG next to BX



Installation Status at LNGS



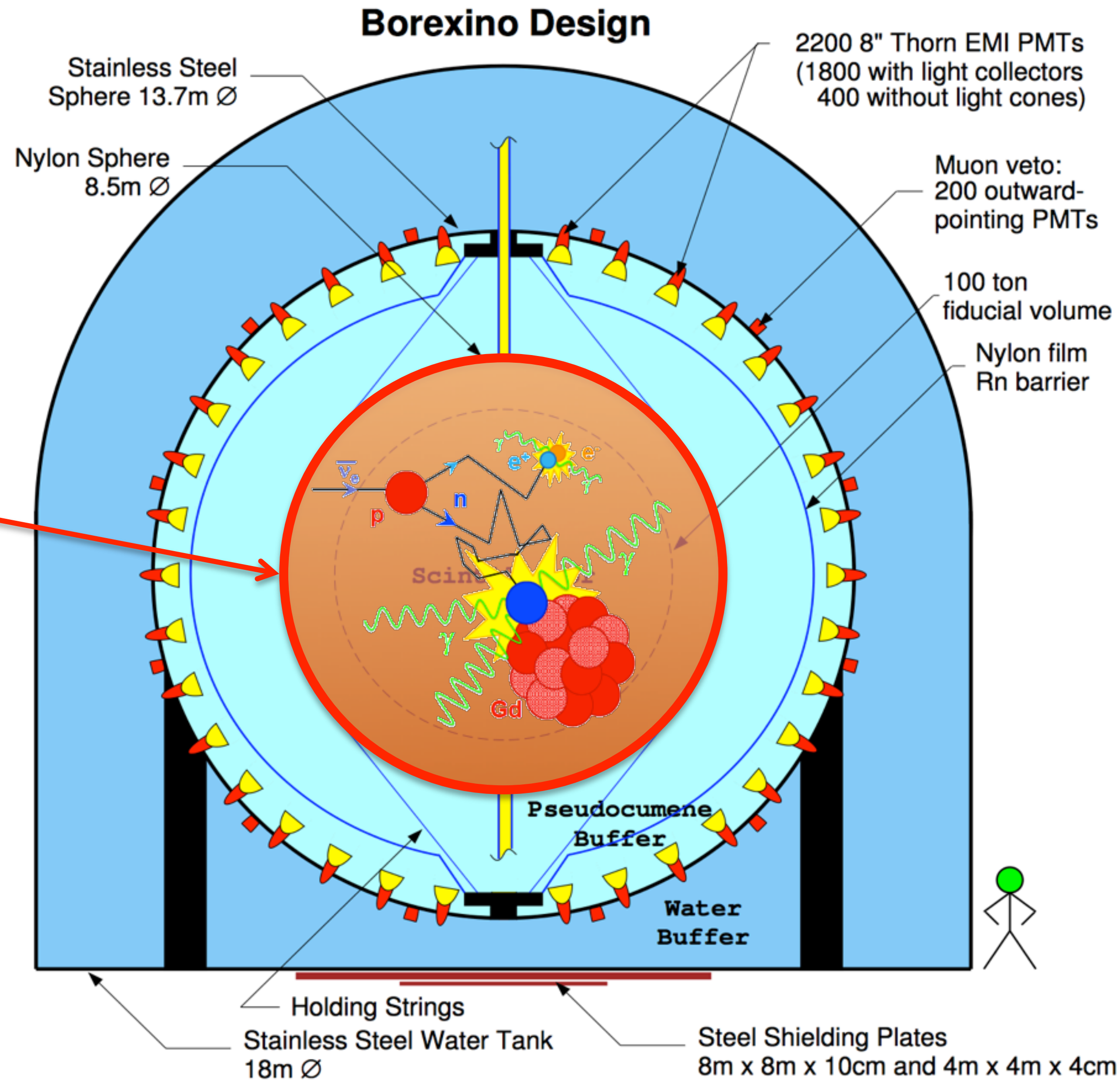




Minimal Configuration

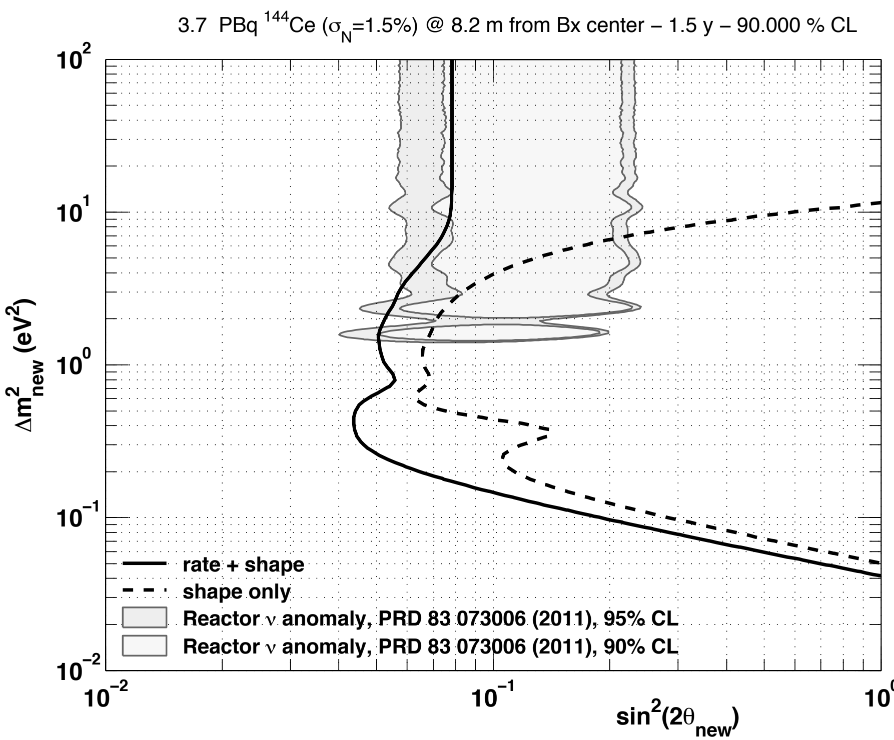
CeSOX target

- R < 4.25 m
- 280 tons
- C_6H_{12}
- #H: $1.7\ 10^{31}$

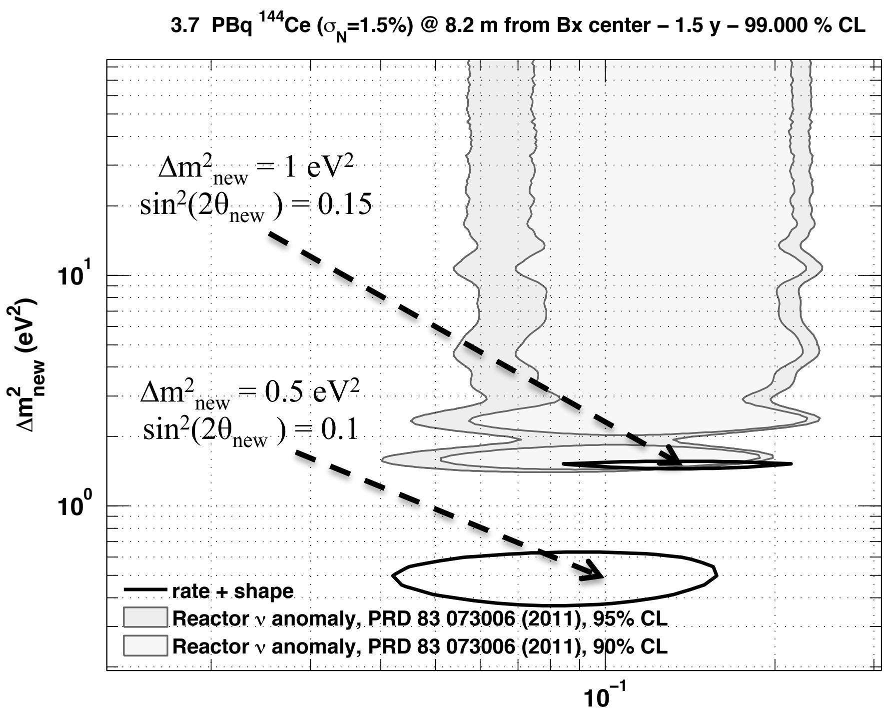


Expected Sensitivity

3.7 PBq (100 kCi) - 1.5 year of data taking
Activity measurement uncertainty: 1.5%
Shape only analysis (- - -) & Rate + Shape analysis (---)



Exclusion contour (90% CL)



Discovery potential (99% CL)

Search for ν_s with ^{3}H β-decay

- **Source:** $^3_1H \rightarrow \; ^3_2He + e^- + \overline{\nu}_e$
- **A new branch in the β-spectrum :**

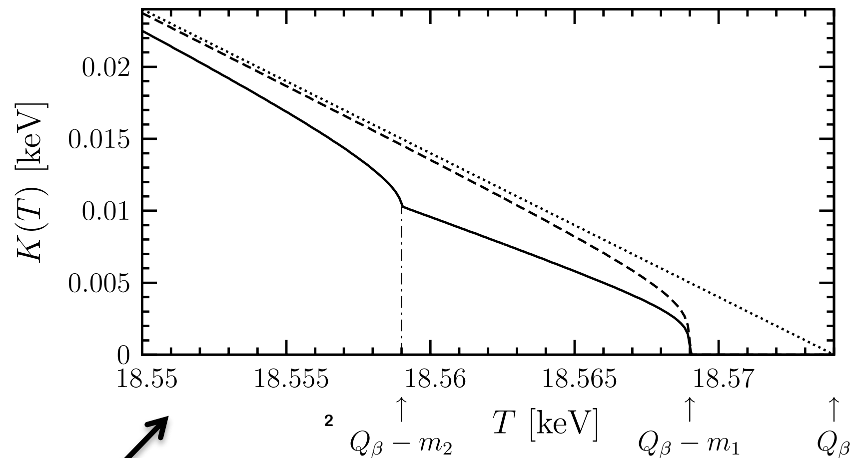
$$\langle m_\beta \rangle_4 = |U_{e4}| \sqrt{\Delta m^2_{41}}$$

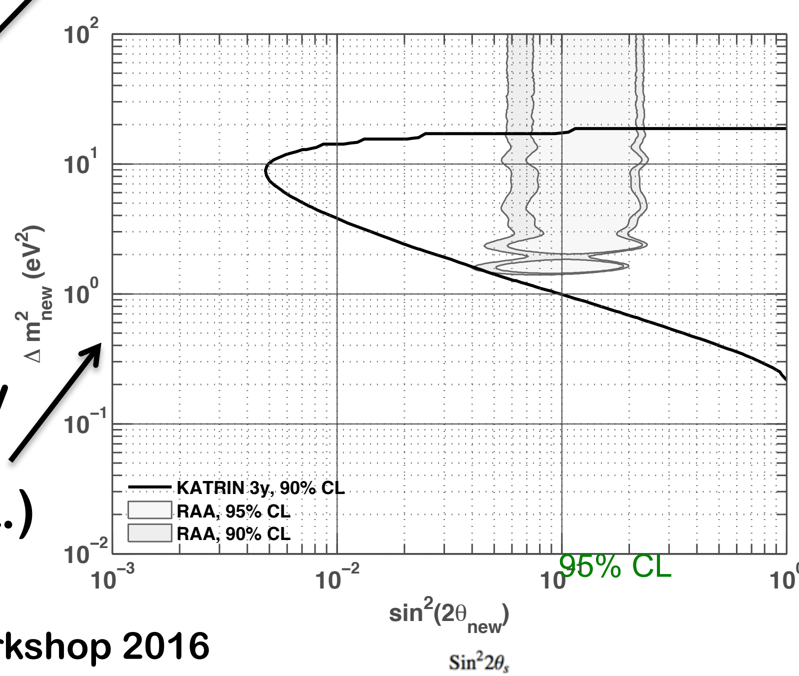
- **Modification of the effective mass**

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

→Search for a –kink-
a few eV below end point

- **KATRIN –as designed – can partially 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

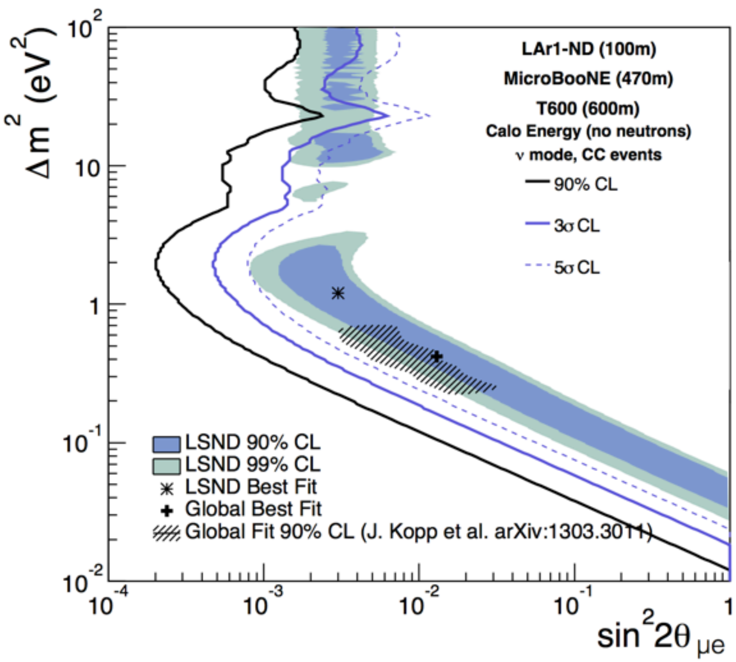
Type	Source	App. /Dis.	Oscillation Channels	Projects
Isotope Decay at Rest	$p + {}^{9}Be \to {}^{8}Li + 2p$ $n + {}^{7}Li \to {}^{8}Li$ ${}^{8}Li \to {}^{9}Be + e^{-} + \bar{\nu}_e$	Dis.	$\bar{\nu}_e \to \bar{\nu}_e$	IsoDAR
Pion (Kaon) Decay at Rest	$\pi^{+} \to \mu^{+} \nu_\mu$ $\mu^{+} \to e^{+} \bar{\nu}_\mu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

Pion Decay in Flight ν-sources

- ICARUS (770t LAr, 600 m)
  - rebuilt @CERN (WA104)
  - Data taking at FNAL

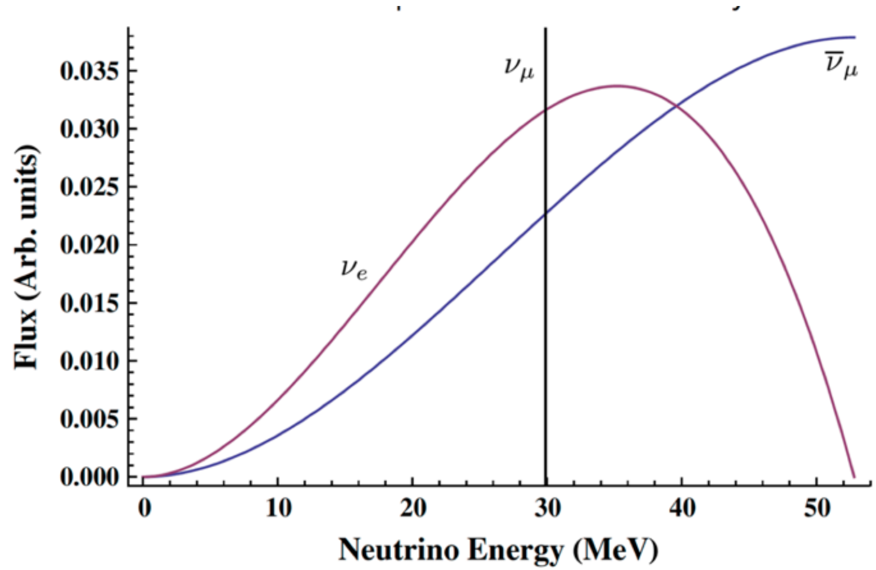
- New near detector (82t, 100m)
- LAr1-ND → T-1053 R&D

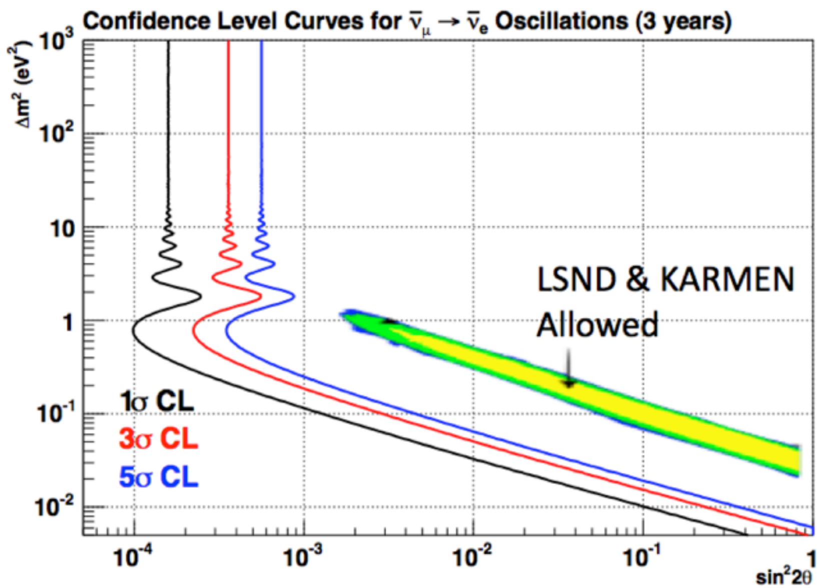
- MicroBooNE (470 m)



Pion Decay at Rest ν-sources

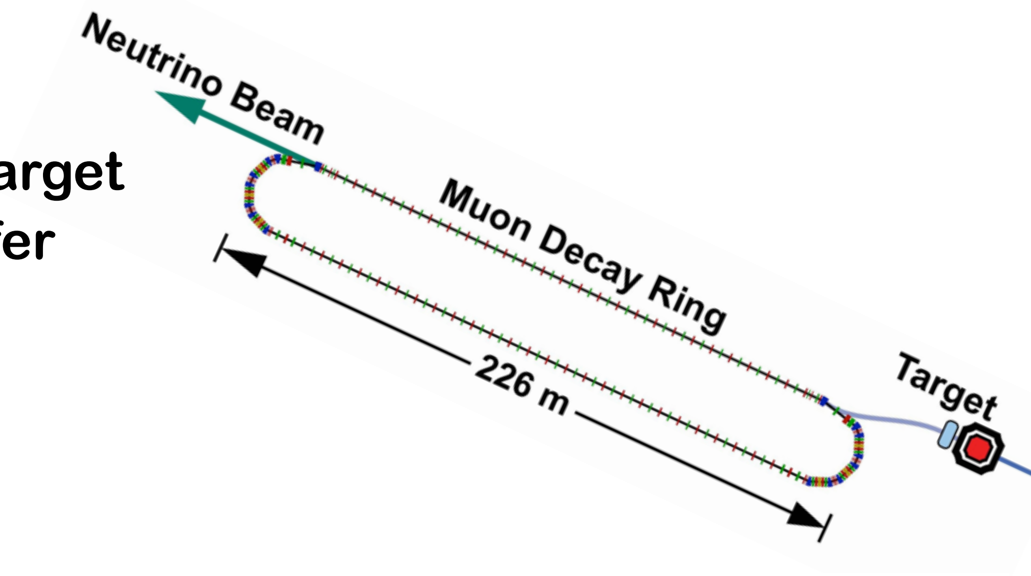
- **High Energy Proton source**
  - Each π^+ decay
    - $\nu_\mu, \nu_e, \bar{\nu}_\mu$
    - well known E spectrum
- **Detection channels**
  - $\nu_e \rightarrow \nu_e$ Disappearance
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance
- Direct Test of LSND
- **OscSNS (ORNL, 1.4 MW)**
  - 800 t 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
  - Low-E muon Decay ring

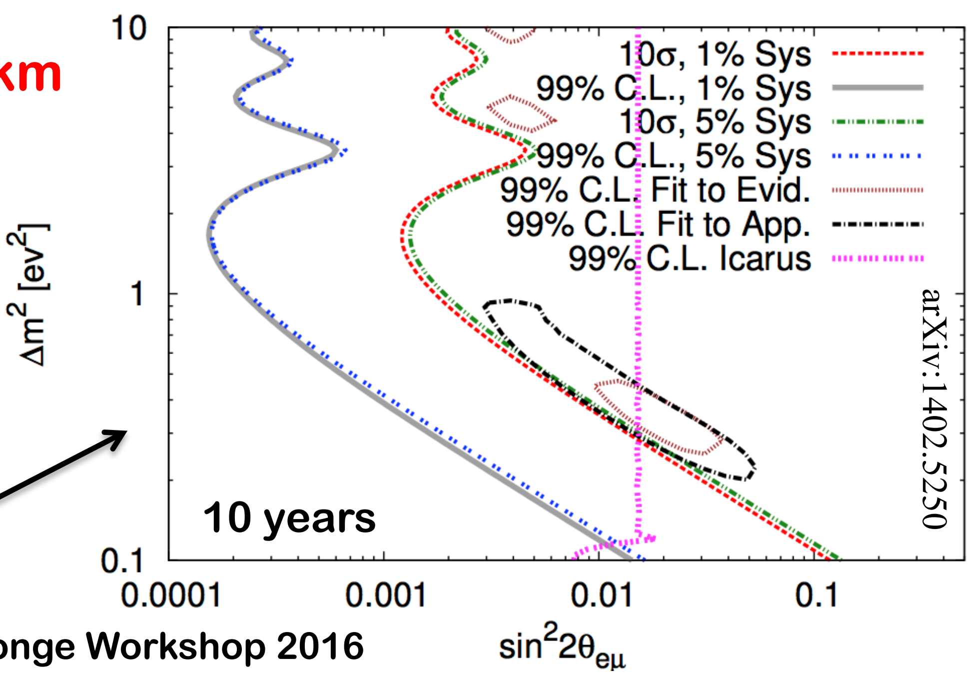


- **APP and DIS channels with:**
  - $\overset{(-)}{\nu}_\mu, \overset{(-)}{\nu}_e$

- **kT-scale Fe+PS detector @ 2km**
  - Magnetized to tag wrong charged muons

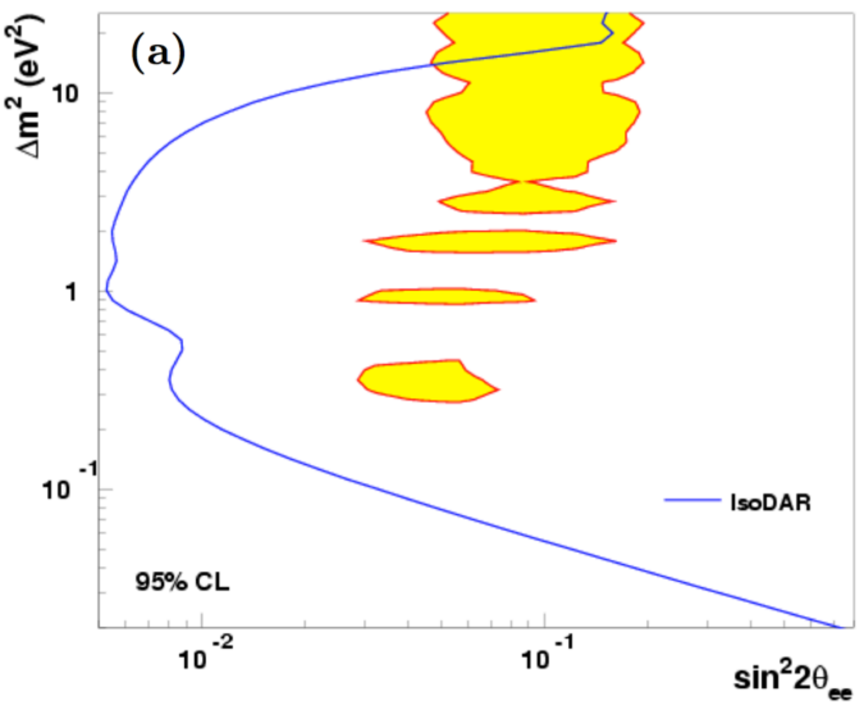
- **Golden Mode**
  - $\overset{(-)}{\nu}_\mu$ APP in a $\overset{(-)}{\nu}_e$ beam

- **Ultimate sterile ν search**



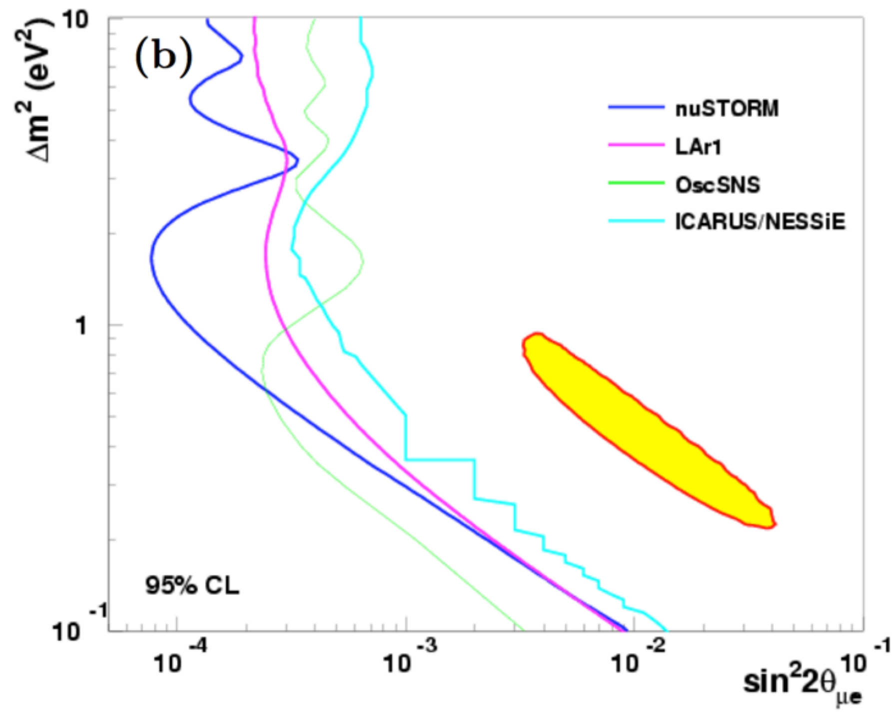
Beam Experiment Sensitivities

Disappearance

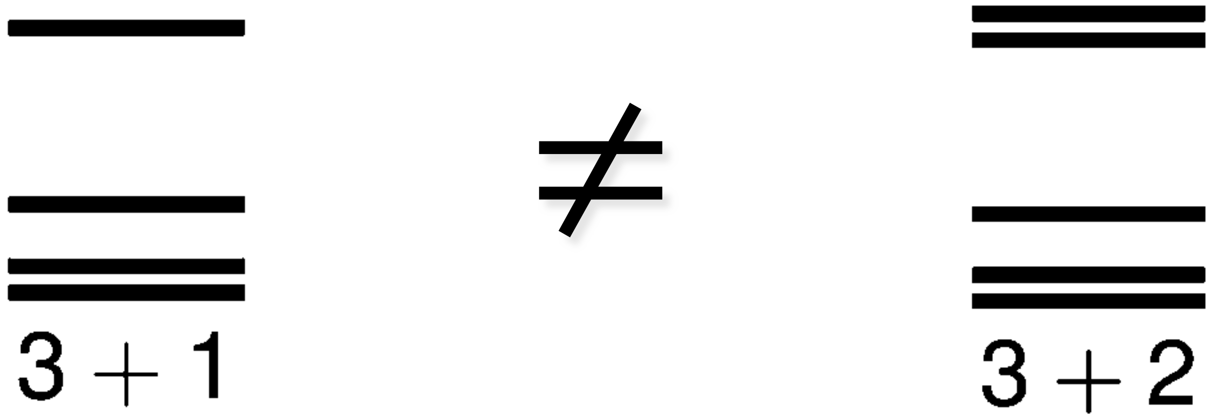


arXiv:1310.4340

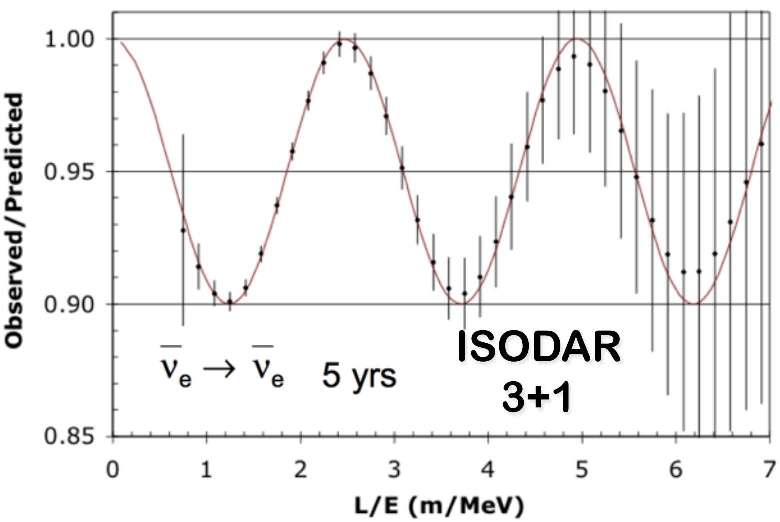
Appearance

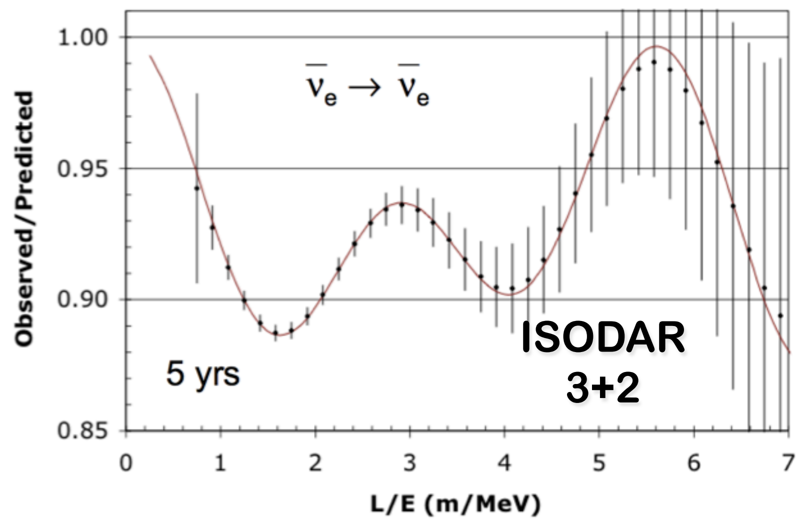


Isotope Decay at Rest ν-sources



ν_e disappearance: L/E Waves with 1e6 ν / 5y @16m





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 exp.
  - 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 systematics**
- **Reactor Neutrinos**
  - Results within 5 years, Cost :1-10 M$
  - Challenge: Background mitigation
- **Neutrino Generator**
  - Results within 5 years, cost ≈5 M$
  - Challenge: the isotope production and transportation
- **Neutrino 'Beam'**
  - Middle or long terms, cost 10-300 M$
  - Would allow studying sterile neutrino phenomenology
  - Relevant for X-section study and R&D for next generation projects
- **Other tests through β-decay and $(\beta\beta)0\nu$-decay, Cosmo**