HIDDeν INVISIBLES' 22 SCHOOL

Sterile neutrinos:

Challenges and status of experimental searches

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1. Neutrino oscillations
2. Possible indications of a sterile neutrino
3. Let's confirm the sterile neutrino !
4. Do we really need a sterile neutrino ?
5. Conclusion

1. **Neutrino oscillations**

2. Possible indications of a sterile neutrino

3. Let's confirm the sterile neutrino !

4. Do we really need a sterile neutrino ?

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Neutrino oscillations : 3-flavour model

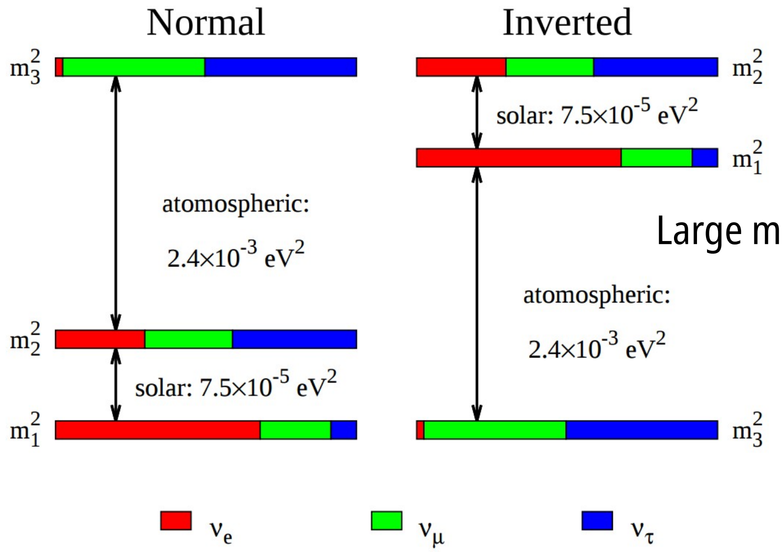
- **Neutrino Mixing**

Flavor eigenstates — Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Complex mixing matrix
(θ_{12}, θ_{13}, θ_{23}, δ_{CP})

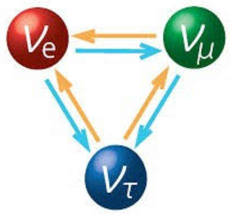
$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

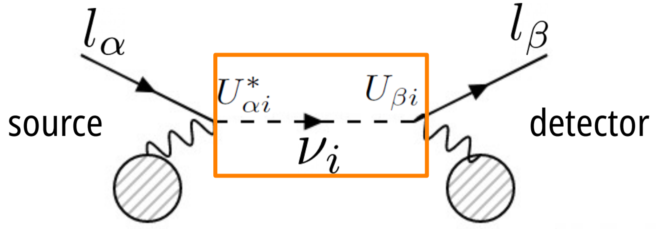


Large mixing !

- **Oscillations : ν_i interferences**

$$\mathbb{P}(\nu_\alpha \to \nu_\beta, L/E) = \sum_{i,j} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \exp\left(-i\frac{\Delta m^2_{ij} L}{2E}\right)$$

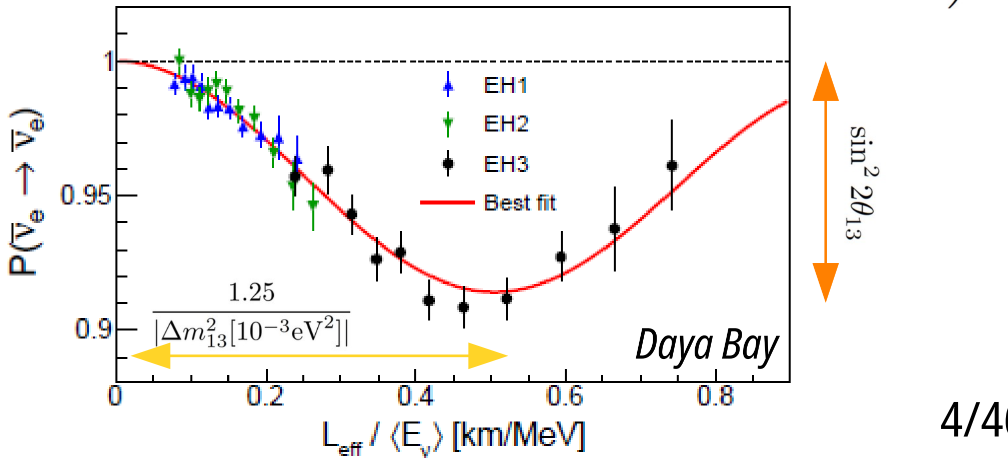




3 undistinguishable paths $\left|\sum_i \square\right|^2$

Develop as a function of L/E

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



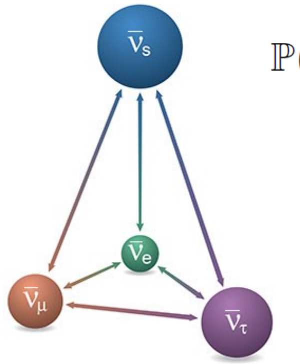
Neutrino oscillations : 3+1 model

- **4x4 mixing matrix**

Flavor eigenstates — Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U^{3+1}_{\rm PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

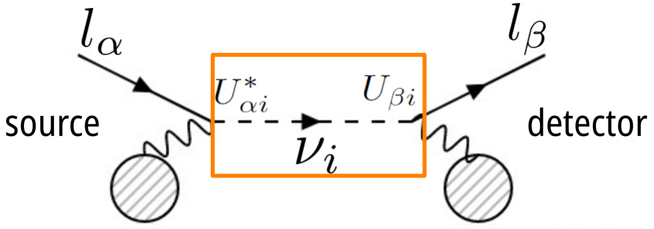
$$U^{3+1}_{\rm PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



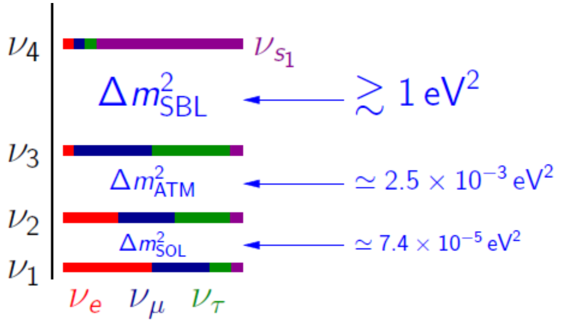
⚠ 'let's intoduce a sterile neutrino with mass ... (G)eV'
→ improper phrasing !

- **Oscillations : ν_i interferences**

$$\mathbb{P}(\nu_\alpha \to \nu_\beta, L/E) = \sum_{i,j} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{ij} L}{2E}\right)$$



4 undistinguishable paths $\left|\sum_i \square\right|^2$



Some neutrinos apparently missing (oscillations to ν_s)

Oscillations probabilities (P_{ee}, $P_{\mu e}$, etc) changed because of

1) 3x3 submatrix not unitary anymore → new amplitude for known Δm^2
2) 4th mass eigenstate → new frequency Δm^2_{41}

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31} + 2\sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31} - \sin^2 2\theta_{24} \sin^2 \Delta_{41}.$$

2 ways to find a sterile neutrino

Finding a sterile neutrino 1/2 : indications

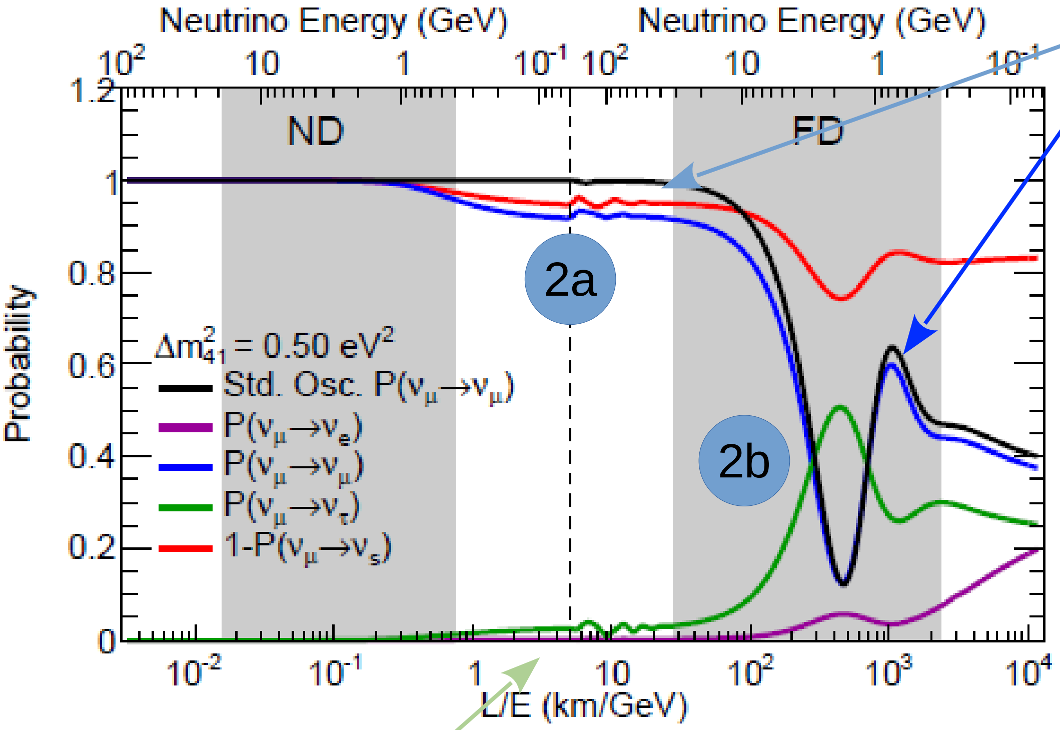
1. Anomalies in measurement of SM oscillations ($P_{\mu\mu}$, $P_{\mu e}$, etc)

from experiments studying SM neutrinos

Several anomalies were found 'by chance' over the last decades and could be explain by 3+1 model

See part 2 of the talk

illustration : DUNE



$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31}$$
$$+ 2\sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31}$$
$$- \sin^2 2\theta_{24} \sin^2 \Delta_{41}.$$

Alteration of oscillation around SM maximum

Additional disappearance at new L/E

$$\mathbb{P}(\nu_\mu \to \nu_e) \approx 2\sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31}$$
$$+ \sin 2\theta_{13} \sin \theta_{23} \sin 2\theta_{e\mu} \sin^2 \Delta_{31}$$
$$+ \sin^2 2\theta_{e\mu} \sin^2 \Delta_{41}$$

Alteration of oscillation around SM maximum

Additional appearance at new L/E

2 regions to look for a sterile :

- 2a New L/E
- 2b Existing L/E

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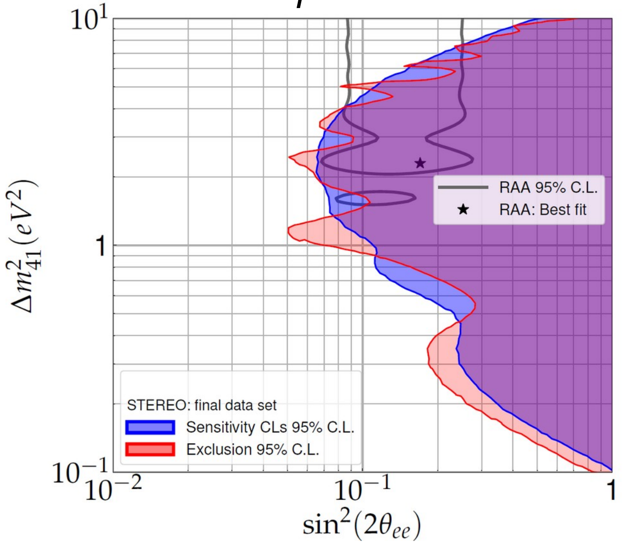
Finding a sterile neutrino 2/2 : confirmation ?

2a Are some neutrinos missing ?

> Investigate new L/E (small L/E ↔ high Δm^2)

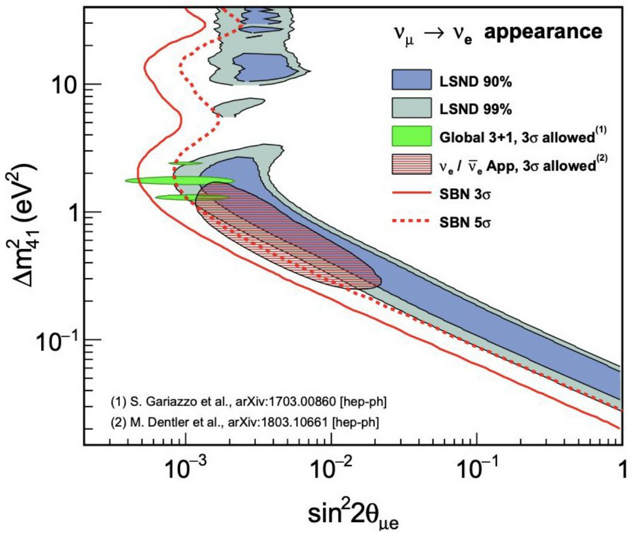
- Very close to reactors / source
- Using Near Detectors of accelerator experiments

example : STEREO



$P(\overline{\nu}_e \to \overline{\nu}_e)$

example : SNBD



$P(\nu_\mu \to \nu_e), P(\nu_\mu \to \nu_\mu)$

Dedicated experiments are optimized for new interesting Δm^2

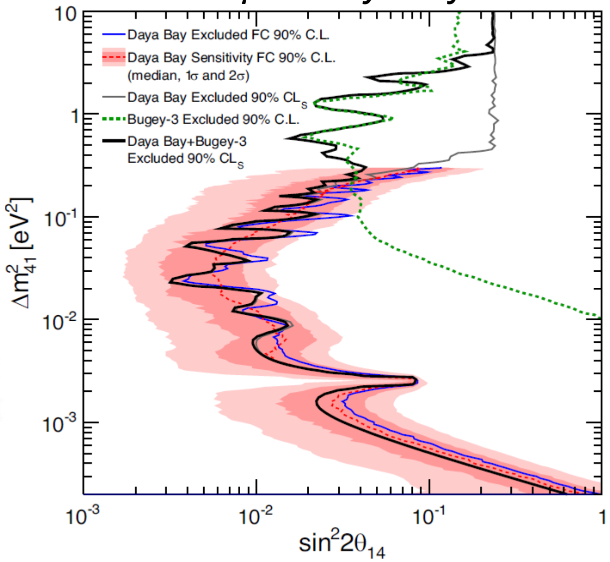
See part 3 of the talk

2b Perform high-precision measurements of the SM oscillations

> Measure precisely the oscillations at known L/E

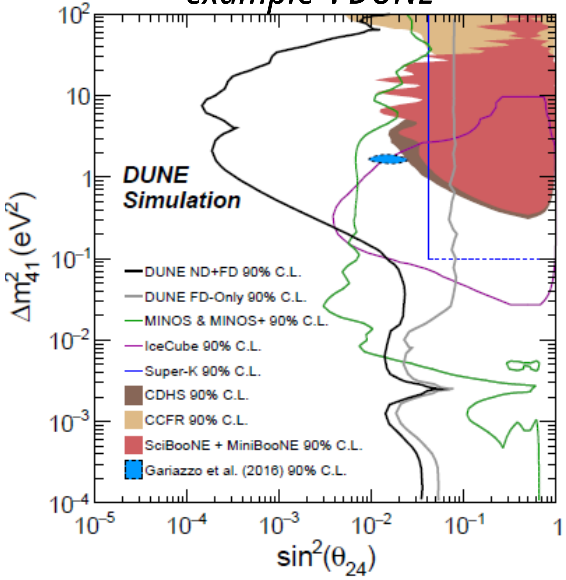
- Side-product of several experiments : reactor, accelerator, atmospheric, solar neutrinos

example : Daya Bay



$P(\overline{\nu}_e \to \overline{\nu}_e)$

example : DUNE



$P(\nu_\mu \to \nu_e), P(\nu_\mu \to \nu_\mu)$

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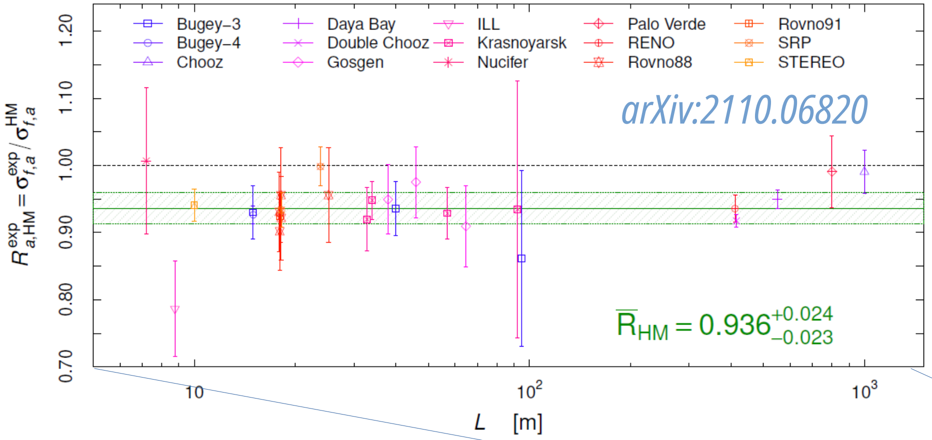
Reactor Antineutrino Anomaly

- **Discrepancy between measured and predicted neutrino rates** at nuclear reactors
  > Apparition in 2011 [PRD 83 (2011) 073006] after reevalutation of neutrino fluxes (Huber [PRC 84 (2011) 024617], Mueller [PRC 83 (2011) 054615])

Averaged oscillations :

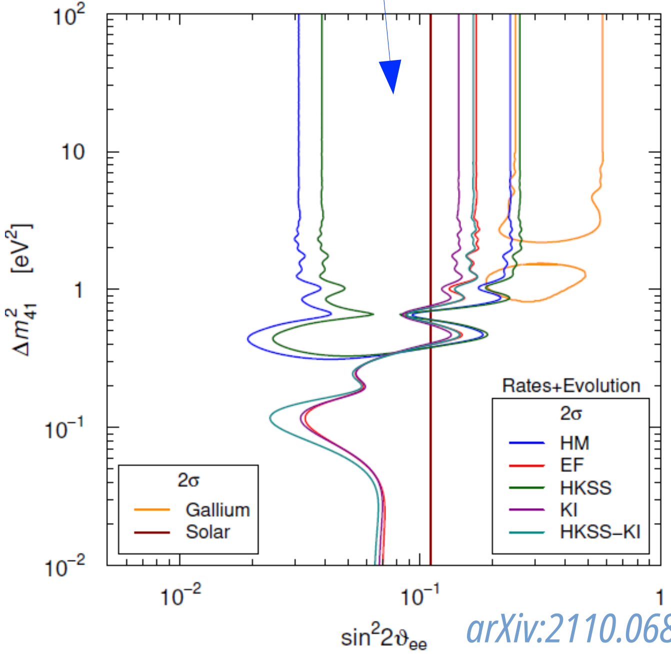
- High Δm^2
- $\sin^2(2\theta) \approx$ 2x deficit



3ν model

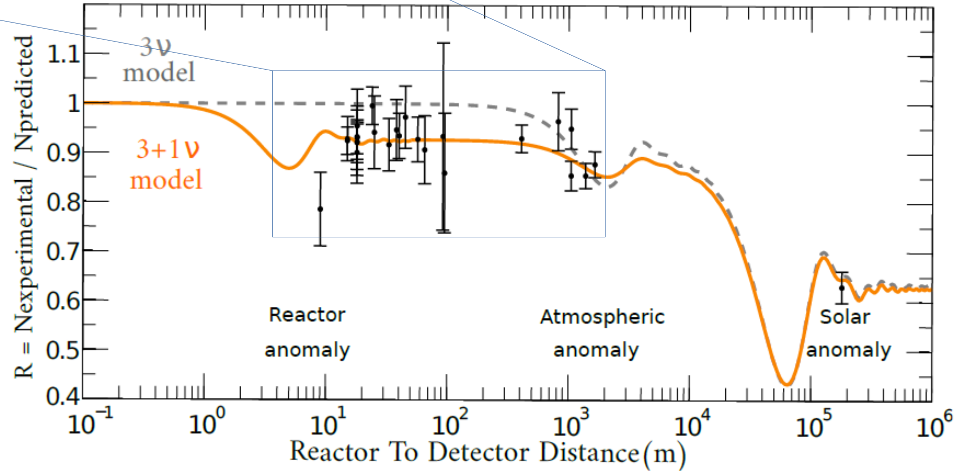
$$P_{ee} = 1 - \cos^4\theta_{41}\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E_{\bar{\nu}_e}}\right) - \sin^2(2\theta_{41})\sin^2\left(\frac{\Delta m^2_{41} L}{4E_{\bar{\nu}_e}}\right)$$

3+1ν model



arXiv:2110.06820

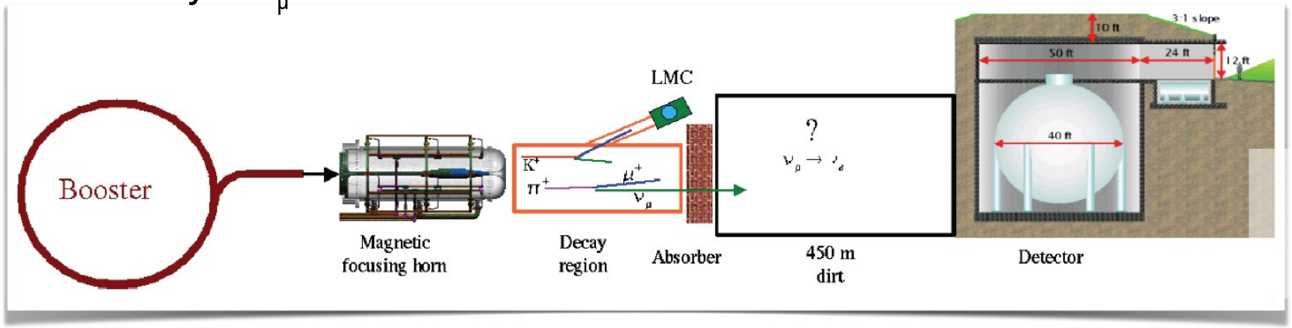
Could be explained by additionnal short-distance oscillation to a sterile state



NB : contour depends on what model is used

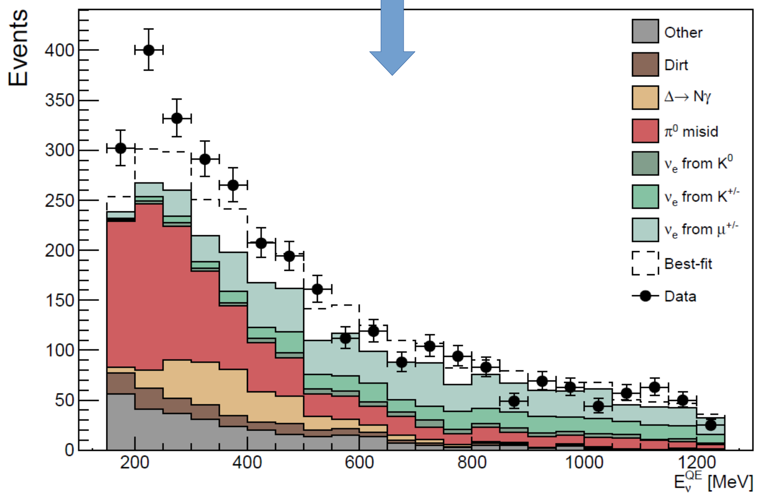
LSND and MiniBooNE anomalies

The MiniBooNE experiment (2000's) @ FermiLab
> study of ν_μ interactions

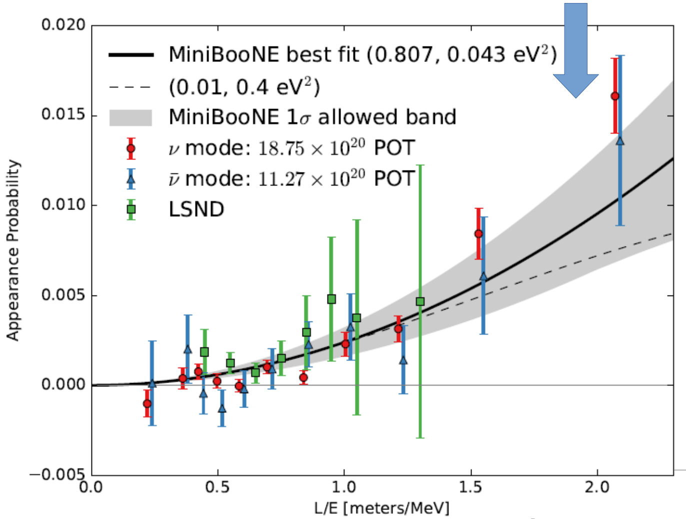


LSND : L ~30m
MiniBooNE : L~450m

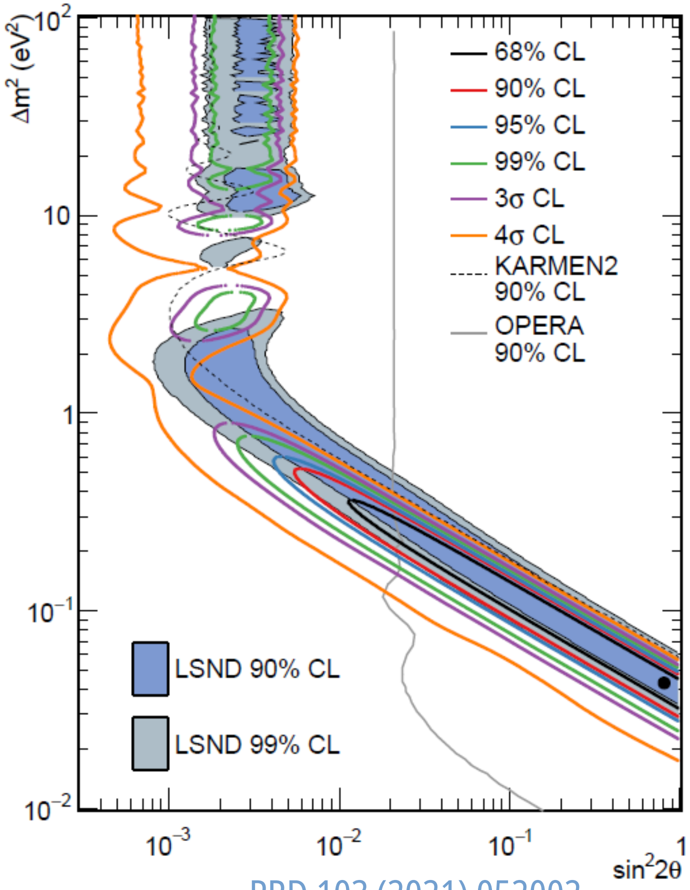
Excess of ν_e events in ν_μ beam



$\nu_\mu \to \nu_e$ at short L due to heavy ν_4



ν_e appearance in 3ν model @ L/E = 500m/MeV



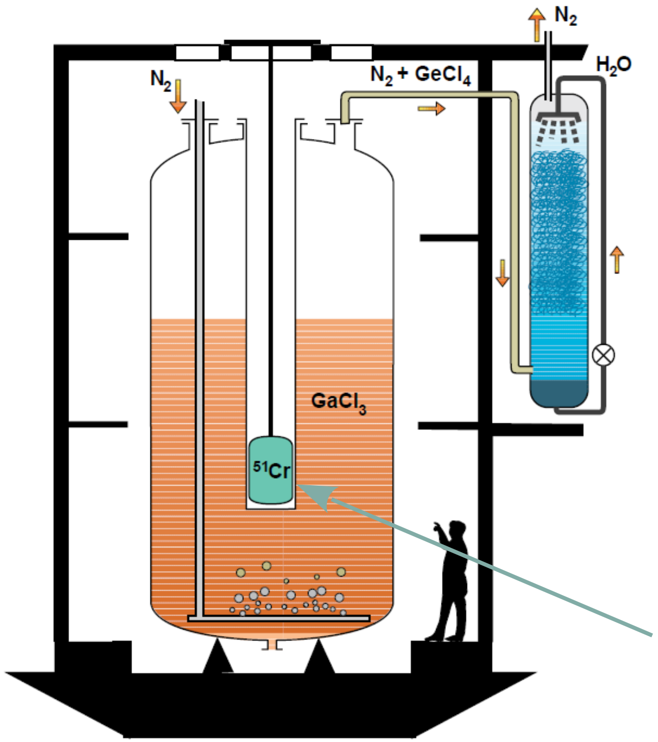
PRD 103 (2021) 052002

$$\mathbb{P}(\nu_\mu \to \nu_e) \approx 2\sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\Delta_{31} + \sin 2\theta_{13}\sin\theta_{23}\sin 2\theta_{e\mu}\sin^2\Delta_{31} + \sin^2 2\theta_{e\mu}\sin^2\Delta_{41}$$

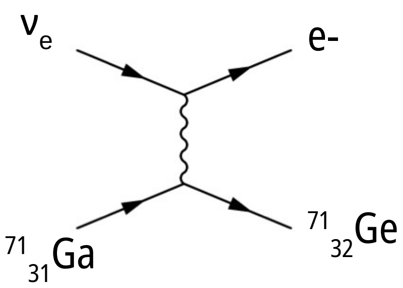
Gallium anomaly (GALLEX, SAGE)

arXiv:2110.06820

The GALLEX experiment (1990's) @ Gran Sasso
> observation of solar neutrinos



1) Neutrino capture on Ga

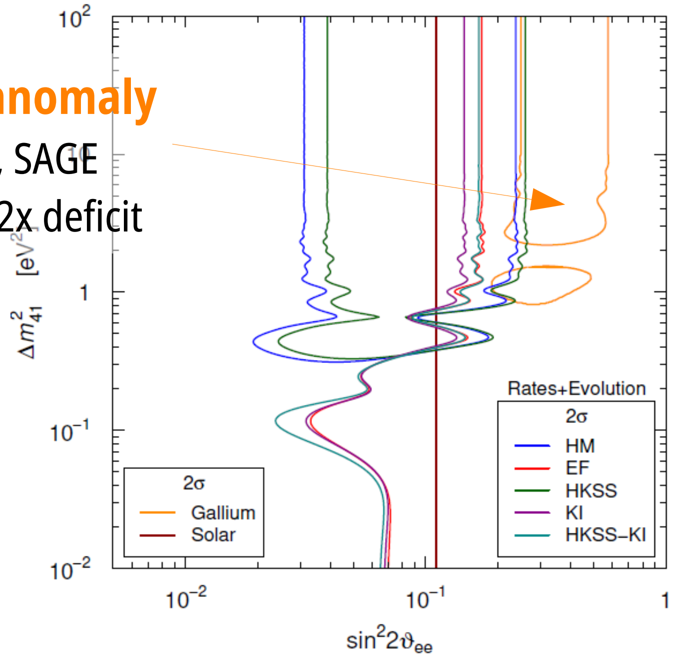


2) Circulate liquid to mesure the Ge activity

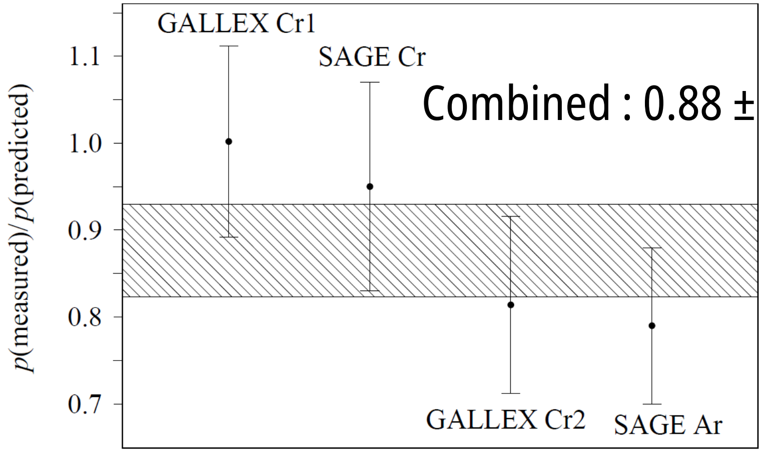
2 **Cr sources** for calibration

Activity directly measured (PBq)	$63.4^{+1.1}_{-1.6}$	$69.1^{+3.3}_{-2.1}$
Activity deduced from ^{71}Ge (PBq)	$64.0^{+7.3}_{-6.9}$	$57.9^{+7.6}_{-7.2}$
Ratio R	$1.01^{+0.12}_{-0.11}$	$0.84^{+0.12}_{-0.11}$

Gallium anomaly
GALLEX, SAGE
$\sin^2(2\theta) \approx 2$x deficit



Combined : 0.88 ± 0.05



How to solve these anomalies ?

The optimistic way

« There is certainly a sterile neutrino, let's find it ! »

See part 3 of the talk

The pessimistic way

« I don't think there is a sterile neutrino, let's cross check the so-called anomalies ! »

See part 4 of the talk

1. Neutrino oscillations

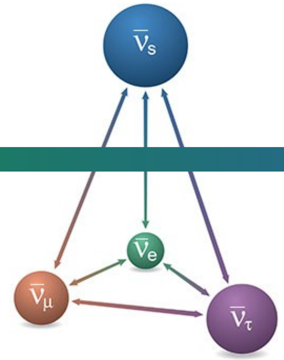
2. Possible indications of a sterile neutrino

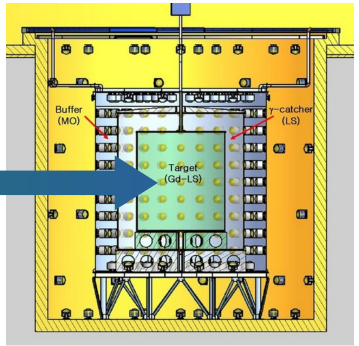
3. Let’s confirm the sterile neutrino ! 😄

4. Do we really need a sterile neutrino ?

5. Conclusion

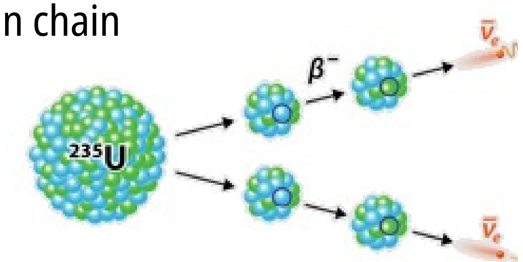
Sterile neutrino searches with nuclear reactors





Antineutrino flux

1) Fuel elements (U and Pu isotopes) are fissionned
2) Fission fragments undergo β-decays in chain



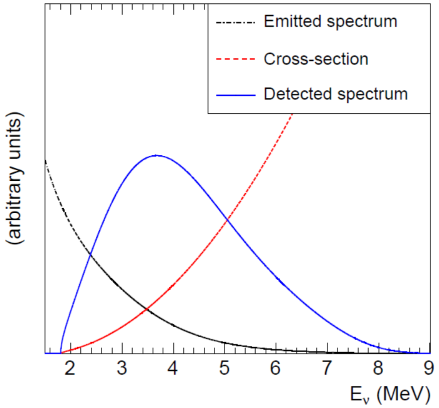
Total $\bar{\nu}_e$ flux is combination of all decays of all fission fragments

Survival probability

$$P_{ee} = 1 - \cos^4\theta_{41}\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E_{\bar{\nu}_e}}\right)$$
$$-\sin^2(2\theta_{41})\sin^2\left(\frac{\Delta m^2_{41}\,L}{4E_{\bar{\nu}_e}}\right)$$

Extra term we are looking for

– Oscillation peak for L/E ≈ 500m/MeV
– Negligible for L ≈ 10m

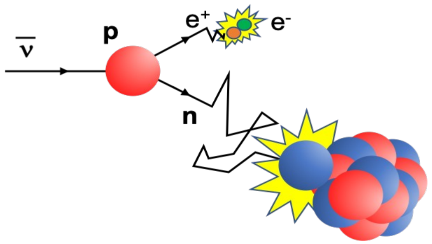


Useful energy range is E_ν ~ 2-8 MeV

Detection

Inverse β-decay : $\bar{\nu}_e$ p → e^+ n

1) e+e- annihilation
2) n capture
→ coincidence in space and time



A world-wide effort with reactors

$$P_{ee} = 1 - \sin^2(2\theta_{41})\sin^2\left(\frac{\Delta m^2_{41}\,L}{4E_{\bar{\nu}_e}}\right)$$

Δm^2_{41} unknown ; oscillation peak at

$$\Delta m^2_{41} \simeq 2 - 10\ \text{eV}^2 \times \left(\frac{1\text{m}}{L}\right)$$

← Complementary coverage →

$$P_{ee} = 1 - \cos^4\theta_{41}\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E_{\bar{\nu}_e}}\right) - \sin^2(2\theta_{41})\sin^2\left(\frac{\Delta m^2_{41}\,L}{4E_{\bar{\nu}_e}}\right)$$

Very short baseline (VSBL)

- L ~ O(10 m)
- access to large Δm^2
- restricted space available, high background environnement

Short baseline (SBL)

- L ~ O(1 km)
- restricted to smaller Δm^2
- larger detectors possible
- no reactor background

Research reactors

- lower power, lower stat
- compact core (Ø ≈ 0.5m)
- *pure ^{235}U (irrelevant)*

Commercial reactors

- high power, high stat
- extended core (Ø ≈ few m)
- *mixed isotopes (irrelevant)*

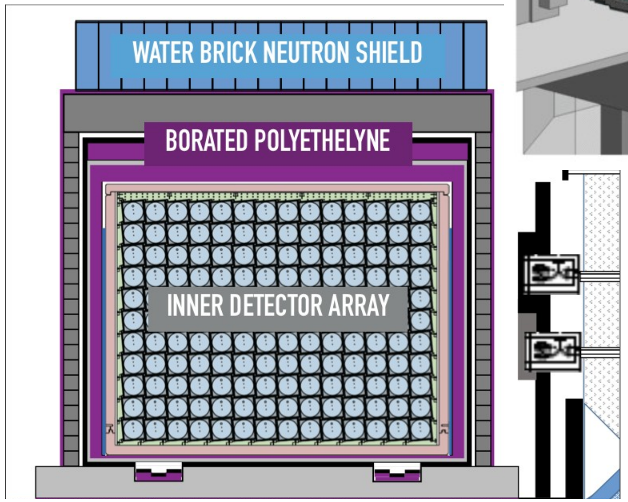
Challenge #1 : environnement

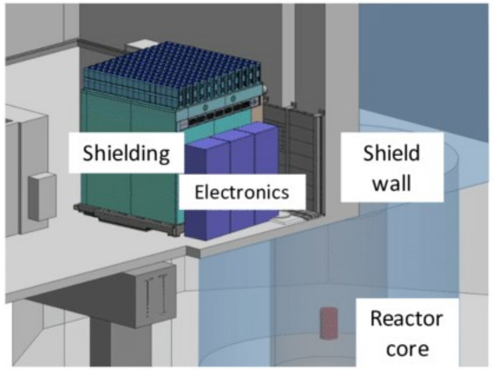
L~10m → **vicinity of reactor core**

- **Design constraints**
  Limited space, limited floor load in the reactor building
  → Constraints : size of detector, amount of shielding

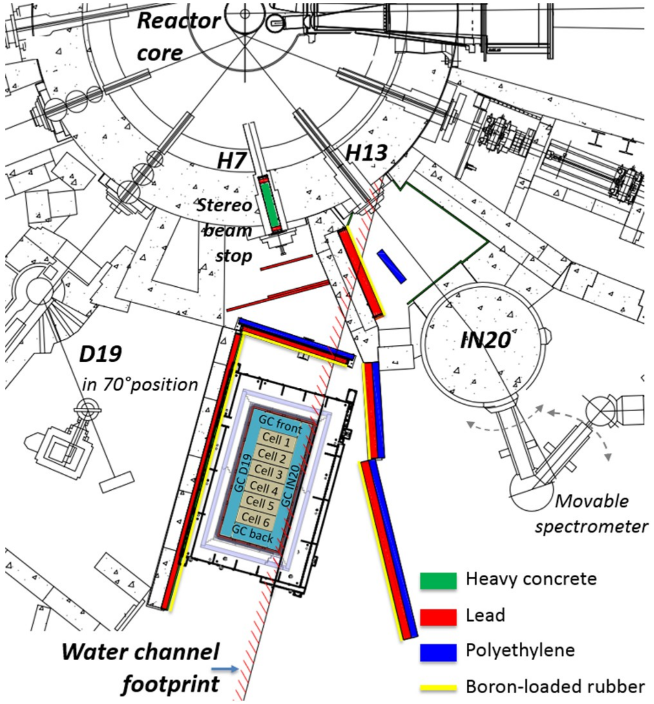
- **Large backgrounds**
  - Cosmogenic : surface level → low overburden (building + muon veto, max ~10 m.w.e.)
  - Ambient fast neutron flux
  - Noise from surrounding experiments (γ, n, B field)

Example : PROSPECT





Good S/B is challenging !

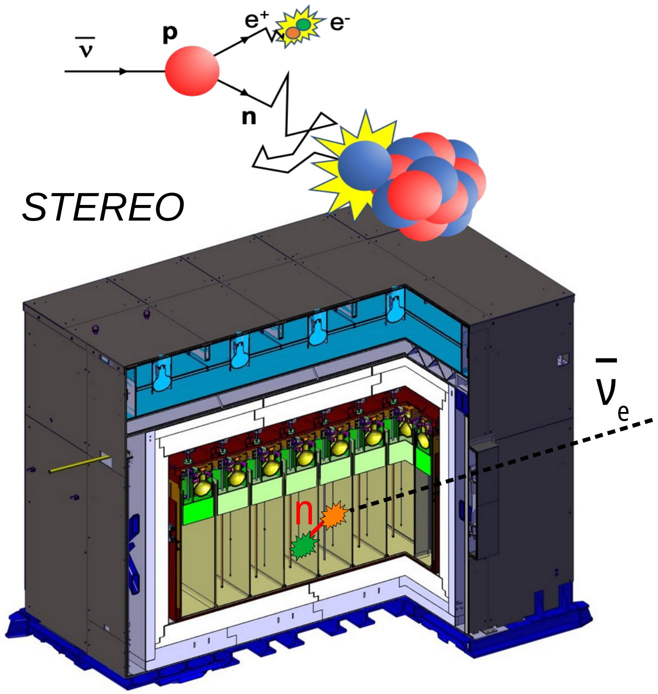


Example : STEREO

Answer #1 : signal selection

How to get to S/B ~ 1 ?

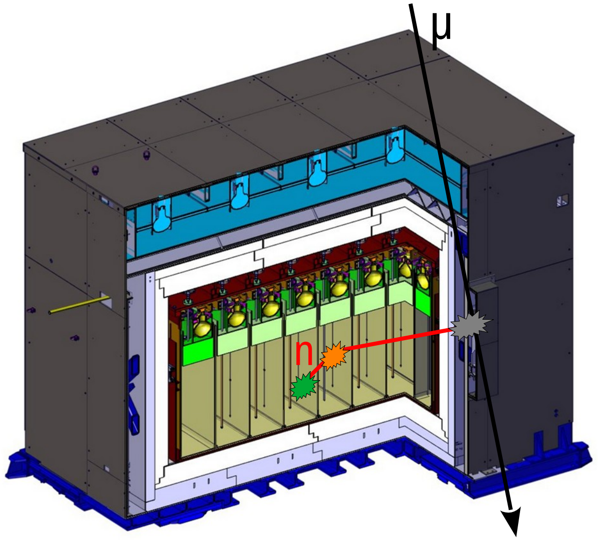
- **Signal topology : IBD**

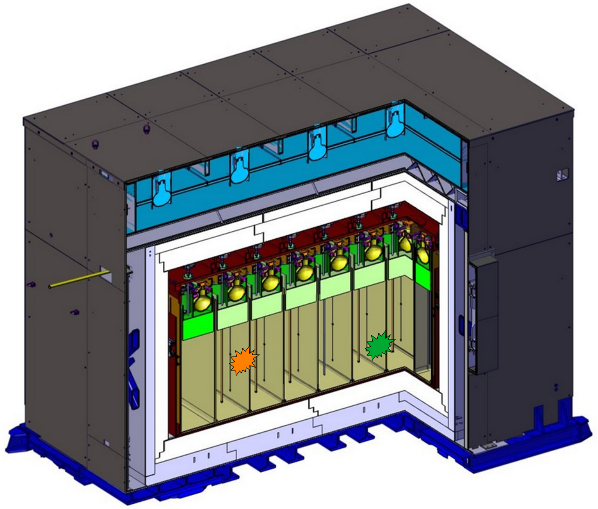


$\Delta t < 70\ \mu s \quad \Delta X < 600\ \mathrm{mm}$

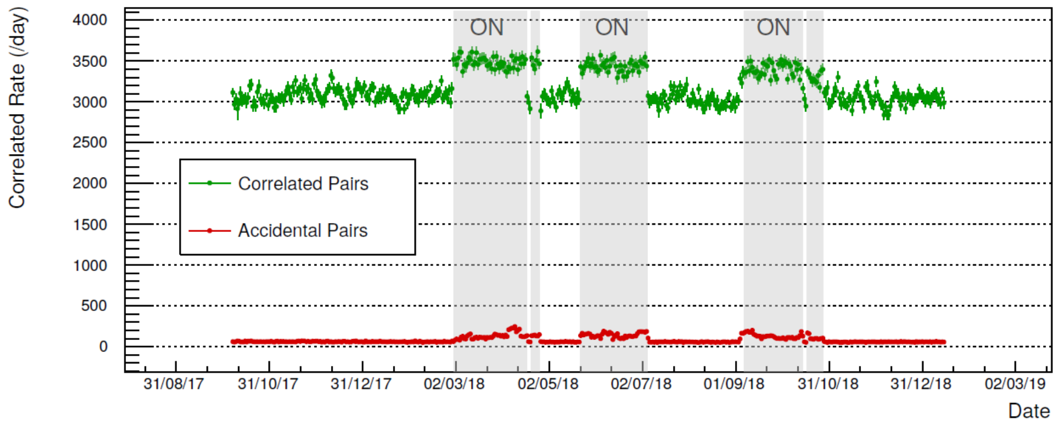
Prompt signal

Delayed signal





- **Cosmogenic background :** spallation neutron in the shielding
  > Reduced by muon veto
  > Remainder: measured when the reactor is off



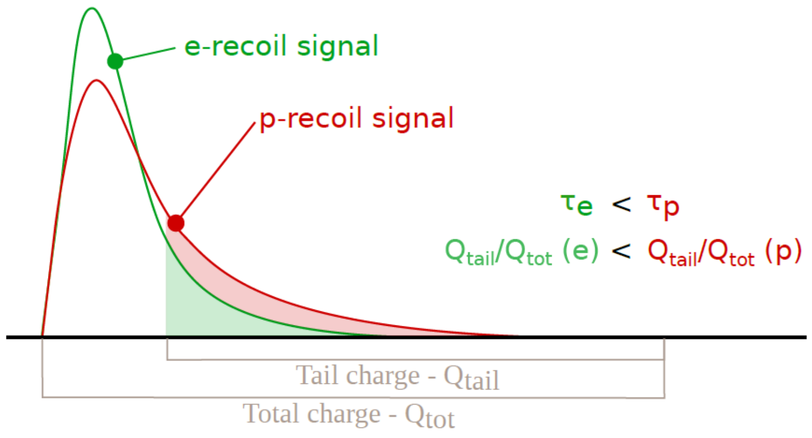
- **Accidental background :** random coincidence of two events
  > Reduced by coincidence cuts
  > Measured in a control region with large Δt

Answer #1 : signal selection

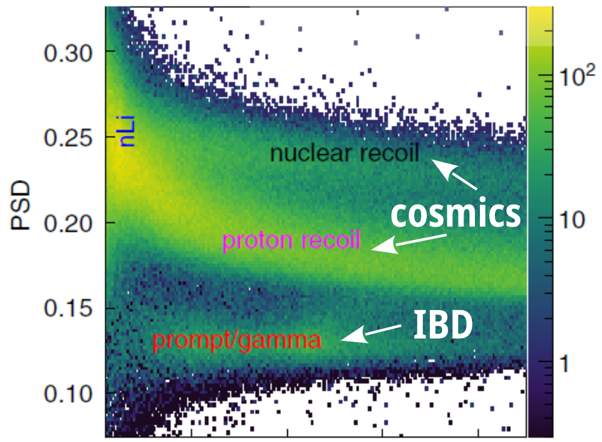
How to get to S/B ~ 1 ?

- **Pulse Shape Discrimination**
  > separation e-like and p-like recoils

Similar approach for all experiments at research reactors



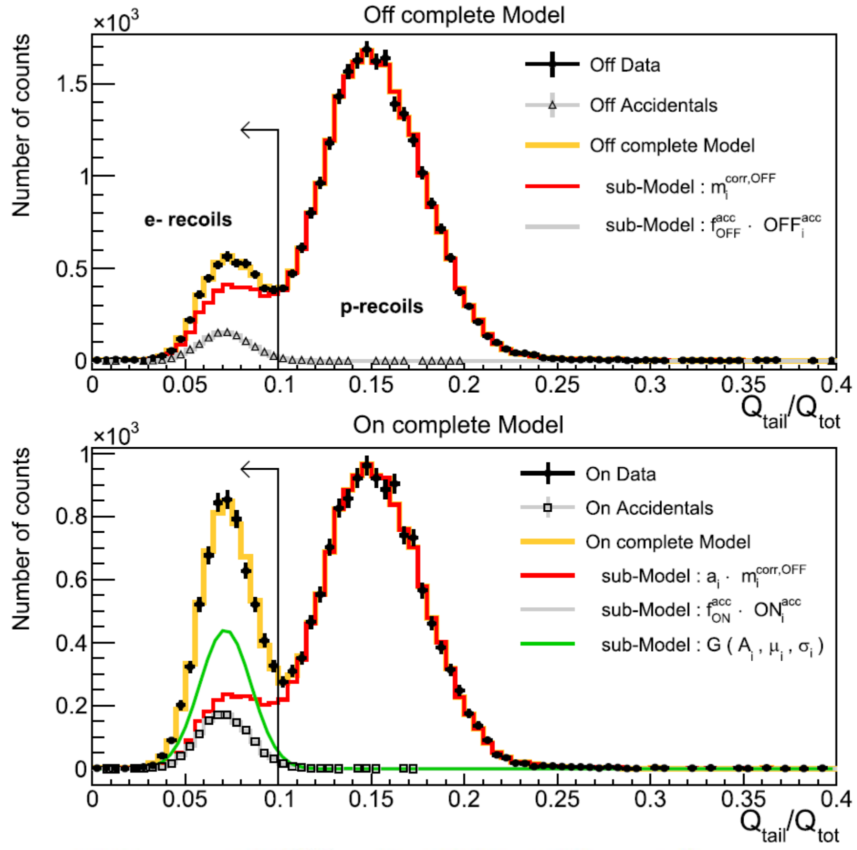
PRD 103:032001 (2021)



Excitation of liquid scintillator molecules :

- low dE/dx (e,γ) → singlet states → faster de-excitation
- high dE/dx (p,n) → triplet states → slower de-excitation

On-Off joint fit in PSD space



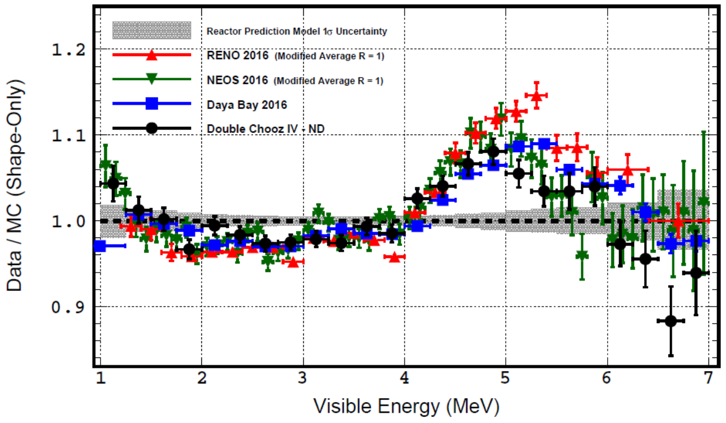
$$\mathrm{ON}_{i,p} = a_i\, m_{i,p}^{\mathrm{corr,OFF}} + f_{\mathrm{ON}}^{\mathrm{acc}}\, \mathrm{ON}_{i,p}^{\mathrm{acc}} + G_\nu(A_i, \mu_i, \sigma_i^2),$$

$$\mathrm{OFF}_{i,p} = m_{i,p}^{\mathrm{corr,OFF}} + f_{\mathrm{OFF}}^{\mathrm{acc}}\, \mathrm{OFF}_{i,p}^{\mathrm{acc}},$$

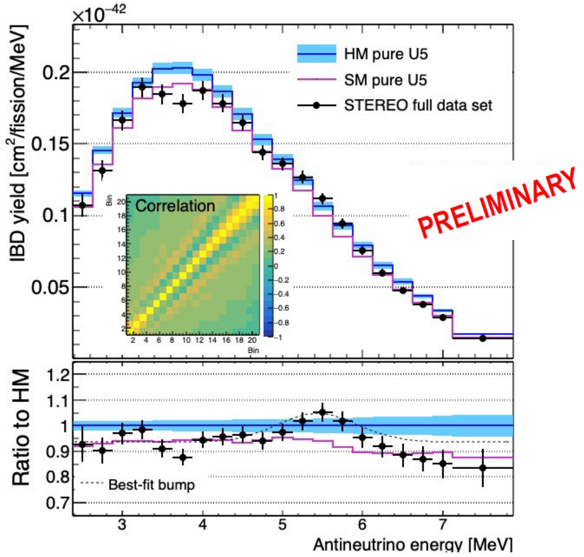
Challenge #2 : dependence on flux models

- Reactor flux predictions do not match measurements
  - Notably the « 5 MeV bump », first seen by Daya Bay, RENO, Double Chooz (commercial reactors)

Nature Physics 16, 558-564 (2020)



STEREO final measurement

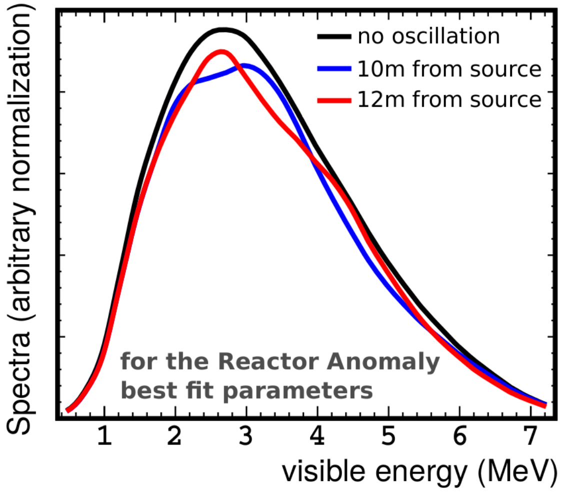


... and several flux models are available

- Oscillations induce spectral distortions between baselines

$$P_{ee} = P_{ee}(L/E)$$

→ Energy regions do not oscillate at the same frequency



- Comparing **data(L)** to **no-oscillation** prediction depends on flux models
- Comparing **data(L)** to **data(L')** is independent of flux models

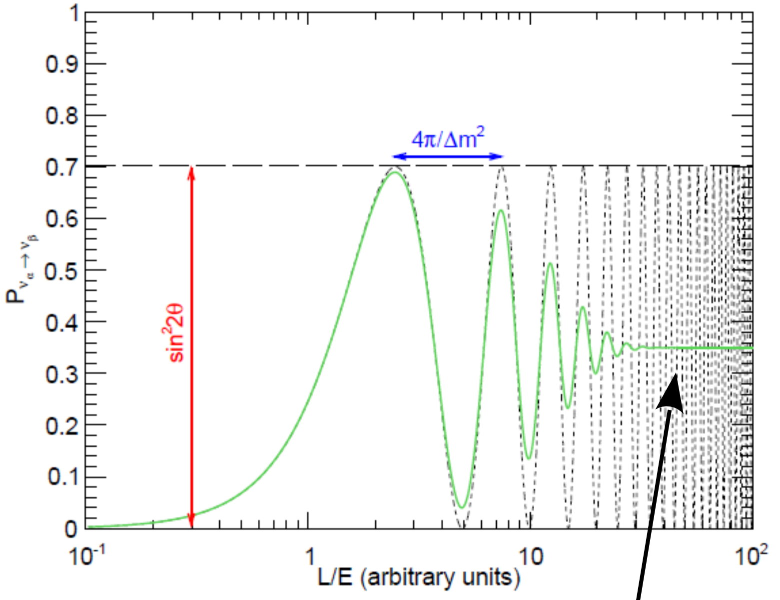
→ Comparison of baselines gives model- independent results

- Different detectors
- Different detector parts
- Movable detector

Challenge #3 : resolution on L/E

$$\Delta m^2 \sim E/L$$
$$L \simeq 10\text{m}$$
$$E \simeq 2-8 \text{ MeV}$$

Effect on a 20 % resolution on L/E



Averaged oscillations
→ no sensitivity to Δm^2

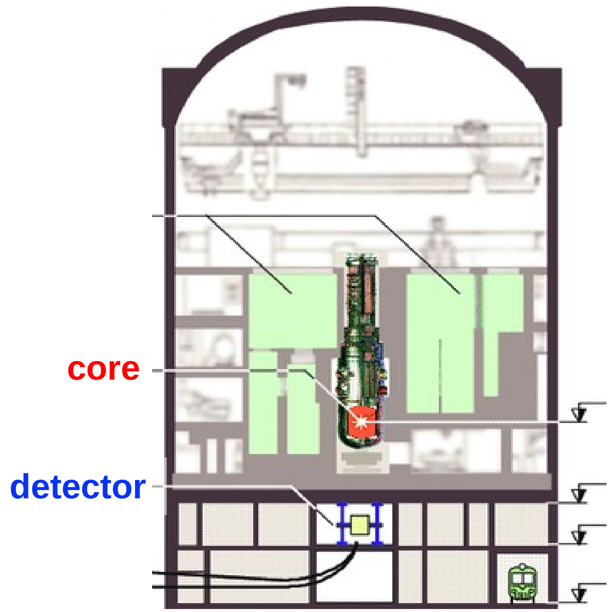
Resolution on L/E : several physical effects

- Energy resolution of the detector
- Width of energy bins
- Uncertainty on baseline L
- Resolution on vertex position

Extended cores (commercial reactors)

size ~3m

→ σ_L/L up to 15%



Example : DANSS

Small cores (research reactors)

size ~0.5m

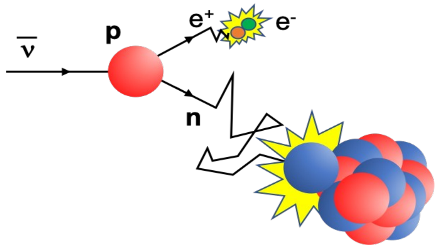
→ σ_L/L down to 3%

→ resolution on E is dominant

Sensitivity region of experiments at commercial reactors is smaller in Δm^2 (but larger in $\sin^2 2\theta$ due to statistics)

Answer #3 : reconstruction / calibration of E_ν

Determination of E_ν is key for oscillation studies



Target *p* at rest → *ν*-kinematics carried by positron

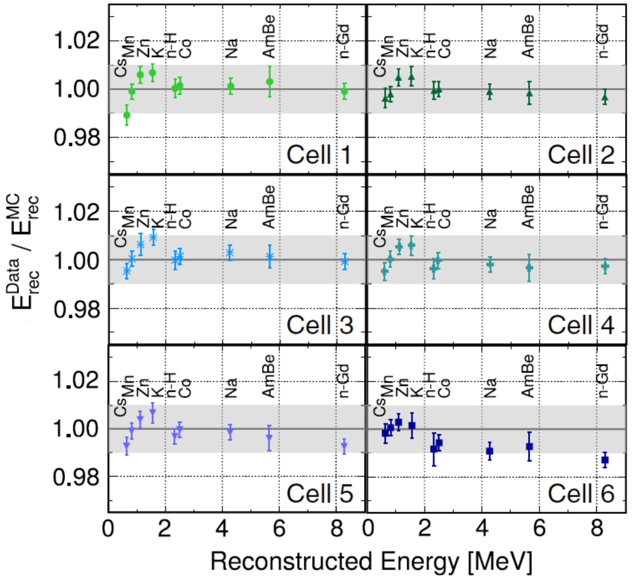
Energy of prompt signal (e^+e^-) :

$$E_{\rm pr} \simeq E_\nu - \Delta M + m_e = E_\nu - 0.782\ {\rm MeV}$$

> Goal = produce a detailled detector response in simulation

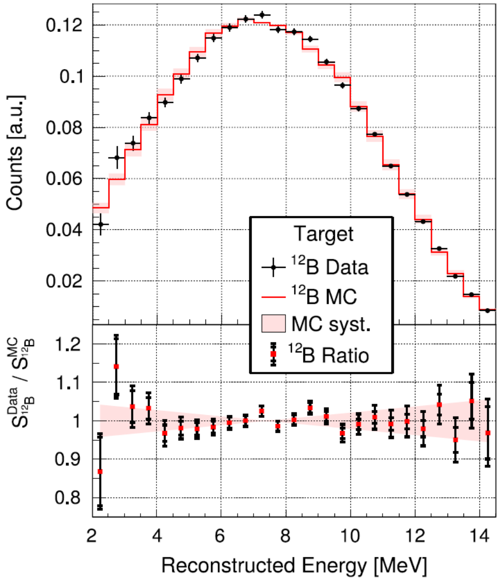
1. Sources (known γ-lines)

1% accuracy



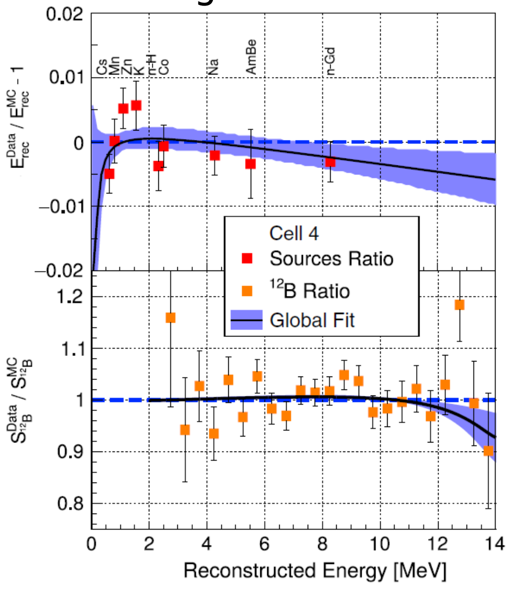
2. ^{12}B β-decays (continuous)

Produced by μ capture on ^{12}C



3. Joint fit source + ^{12}B

Excellent agreement data/MC



PRD 102 (2020) 052002

HIDDeν INVISIBLES' 22 SCHOOL

Very short baseline experiments

$$P_{ee} = 1 - \sin^2(2\theta_{41}) \sin^2\left(\frac{\Delta m^2_{41}\, L}{4E_{\bar{\nu}_e}}\right)$$

Very short baseline (VSBL)

- L ~ O(10 m)
- access to large Δm^2
- restricted space available, high background environnement

Research reactors

- lower power, lower stat
- compact core (Ø ≈ 0.5m)
- *pure ^{235}U (irrelevant)*

Commercial reactors

- high power, high stat
- extended core (Ø ≈ few m)
- *mixed isotopes (irrelevant)*

The PROSPECT experiment

NIM A922 (2019) 287-309
https://prospect.yale.edu

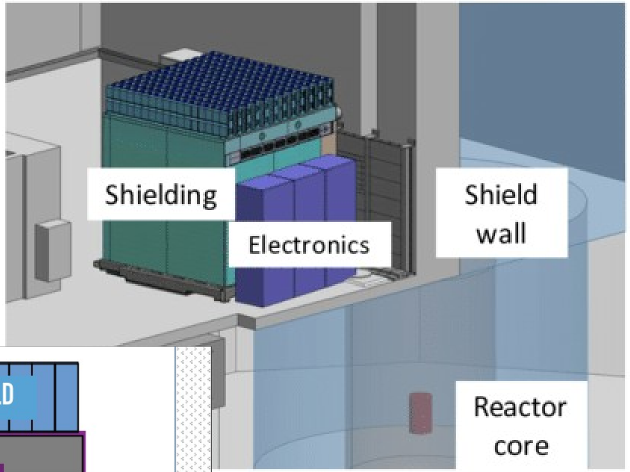
High Flux Isotope Reactor

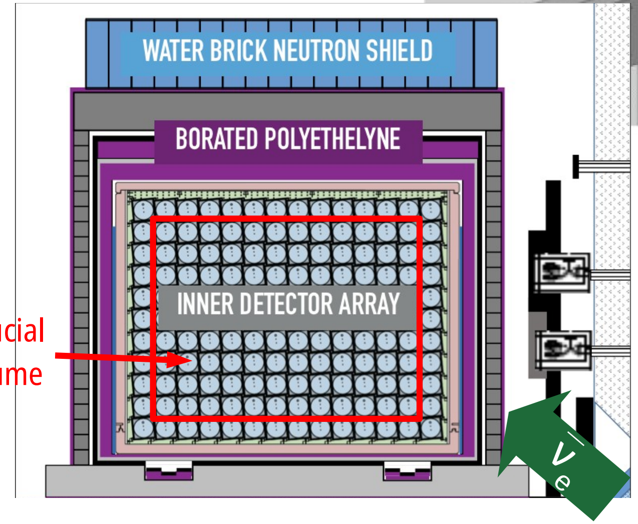
Oak Ridge, USA

85 MW HEU reactor core with

46% duty cycle

Compact core Ø 44cm, h=51cm





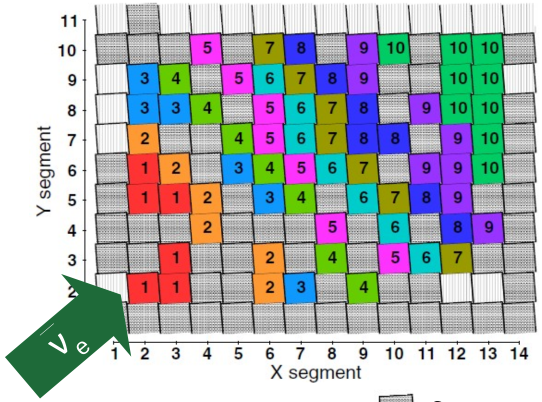
Segmented detector

L ≈ 6.7 – 9.2m

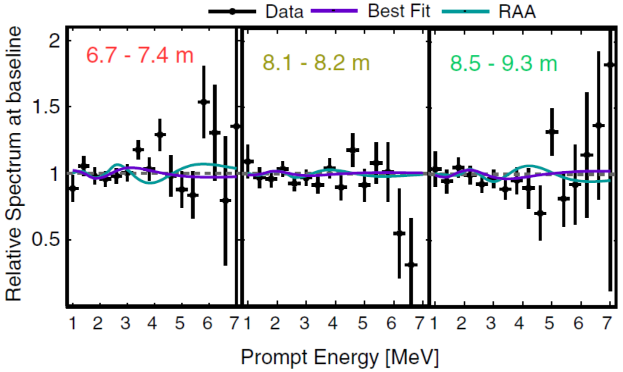
- 4t liquid scintillator + ^{6}Li
- 2D array of segments for fiducialization and bkgd suppression (no overburden)
- 500 $\bar{\nu}_e$/day, S/B = 1.4
- 5 % resolution at 1 MeV

Analysis method

- Group segments with similar baseline



- Relative measurement using ratio to baseline-averaged spectrum → independent of flux models



The STEREO experiment

JINST 13 (2019) 07, P07009
www.stereo-experiment.org

Segmented detector

6 cells: **L ≈ 9.4 – 11.2 m** with 37cm step

- 1.6t liq. scintillator + Gd
- 9% resolution @ 1 MeV
- About 380 $\bar{\nu}_e$/day, S/B ≈ 1.1

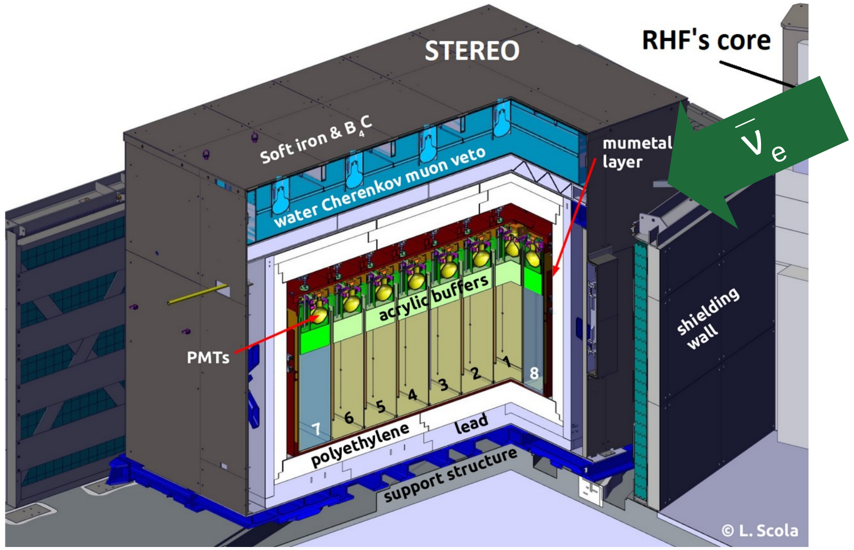
Réacteur Haut Flux (RHF)

ILL, Grenoble, France

58 MW HEU reactor

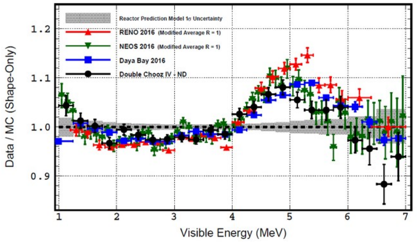
Compact core Ø 40cm, h=80cm

Noise from nearby instruments



Analysis method

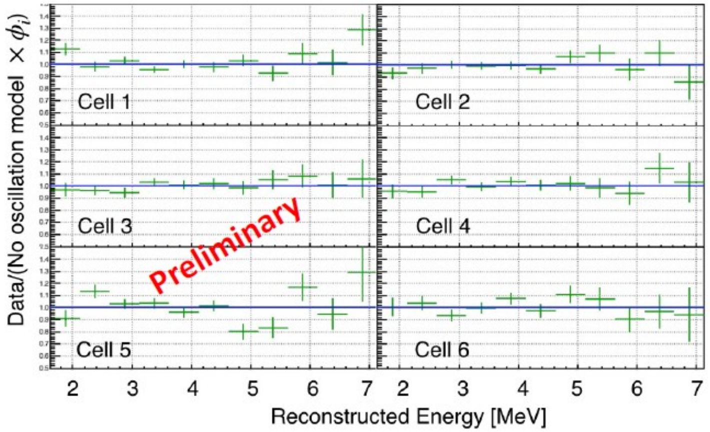
- Look for relative distortions between cells
- Free params ϕ_i absorb model dependence



$$\chi^2 = \sum_{l=1}^{N_{\text{cells}}} \sum_{i=1}^{N_{\text{Ebins}}} \left(\frac{A_{l,i} - \phi_i M_{l,i}}{\sigma_{l,i}} \right)^2 \text{ + pull terms}$$

$$M_{l,i} = M_{l,i}\left(\sin^2 2\theta_{14}, \Delta m^2_{14}; \vec{\alpha}\right)$$

Data over no-oscillation adjusted model $\phi_i M_{l,i}$

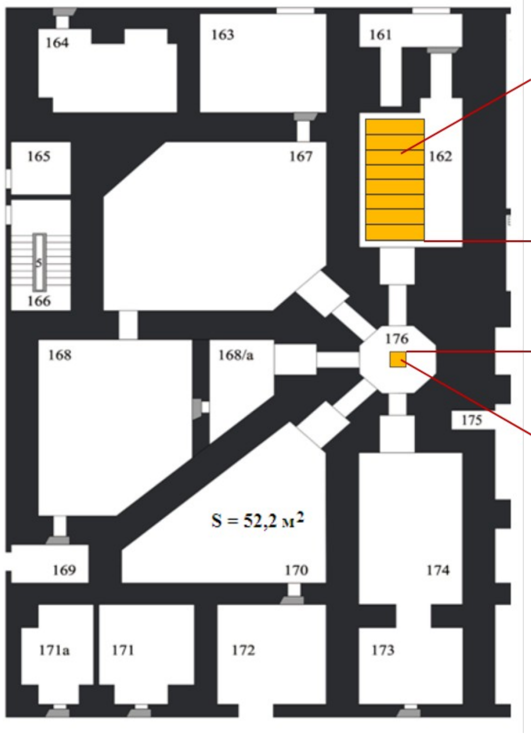


No sign of significant oscillations

The Neutrino-4 experiment

PRD 104 (2021) 032003

Reactor SM-3 Dimitrovgrad, Russia



90 MW HEU reactor
Compact core 42x42x35cm
Highly enriched ^{235}U fuel

Movable segmented detector

L ≈ 6.4 – 11.9m with 23 cm steps (24 positions)

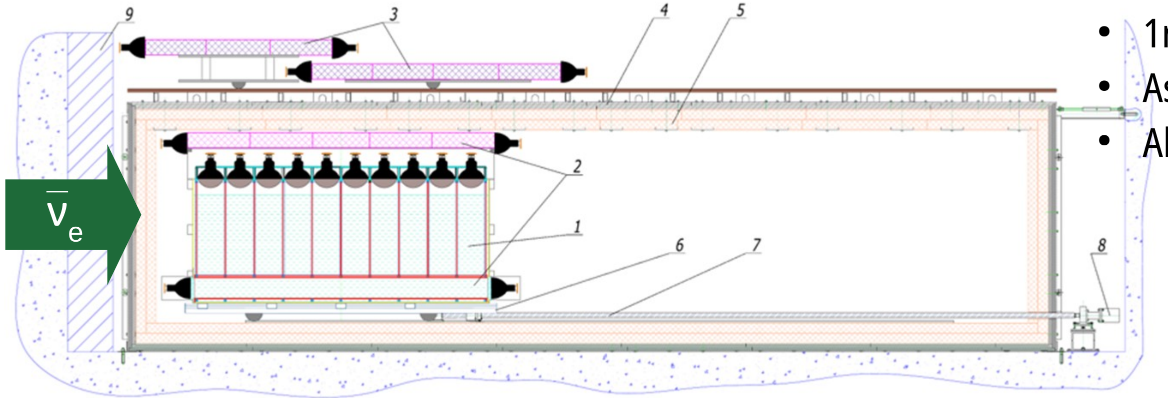
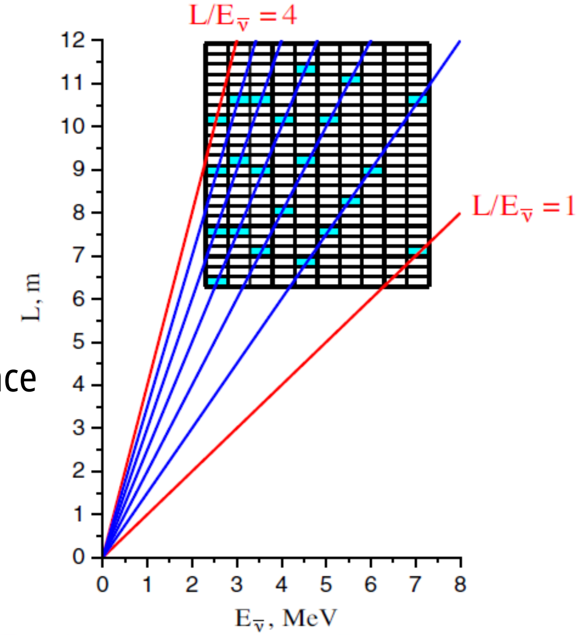


FIG. 18. General scheme of an experimental setup. 1—detector of reactor antineutrino, 2—internal active shielding, 3—external active shielding (umbrella), 4—steel and lead passive shielding, 5—borated polyethylene passive shielding, 6—moveable platform, 7—feed screw, 8—step motor, 9—shielding against fast neutrons made of iron shot.

- 1m^3 liquid scintillator + Gd
- Assumed flat 250 keV resolution
- About 300 $\bar{\nu}$ / day (**S/B ≈ 0.54**)

Analysis method

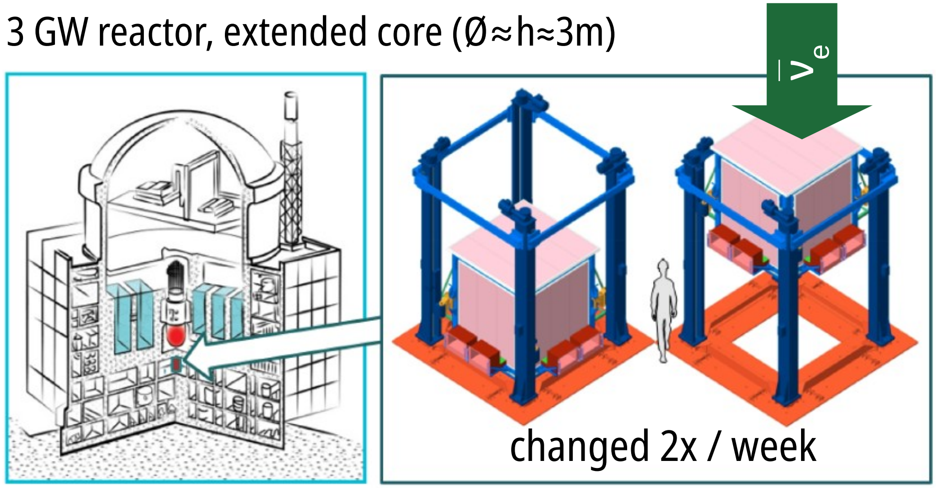
- Relative measurement using ratio to baseline-averaged spectrum
- Summation of these ratios in L/E space



The DANSS experiment

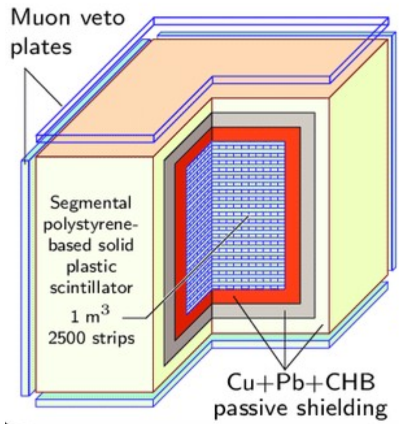
Kalininskaya NPP Dimitrovgrad, Russia

3 GW reactor, extended core (Ø≈h≈3m)

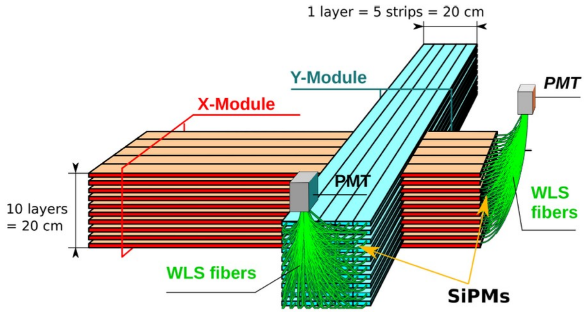


Movable detector

L ≈ 10 – 12m (3 positions : top, middle, bottom)

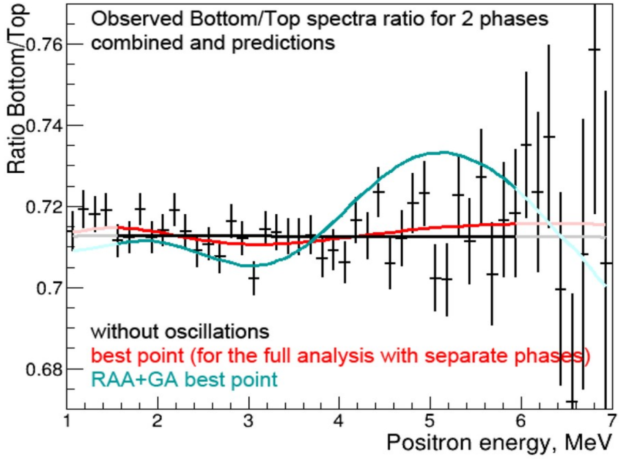


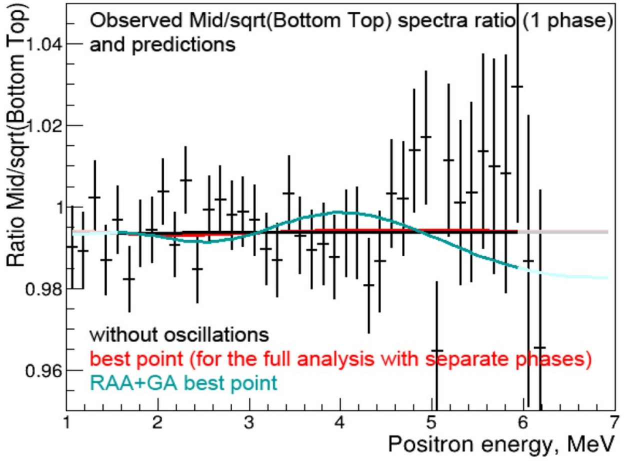
- 1m^3 plastic scintillator, Gd coating
- Resolution of 34%/√E
- **5000 $\bar{\nu}_e$/day, 1.7% background**



Analysis method

Ratio of spectra at ≠ positions





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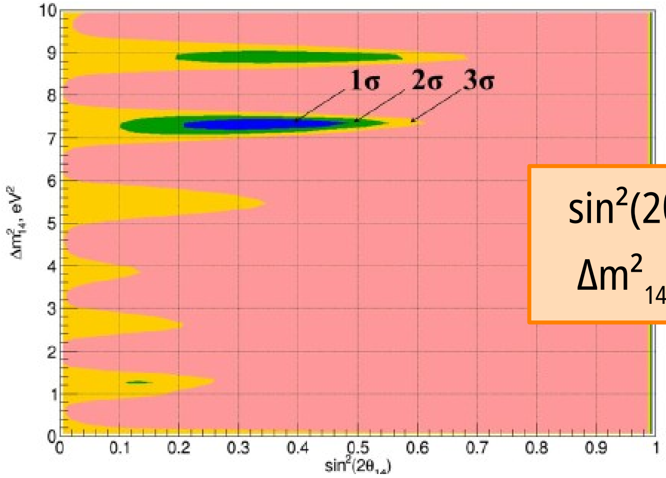
1 controversial observation ...

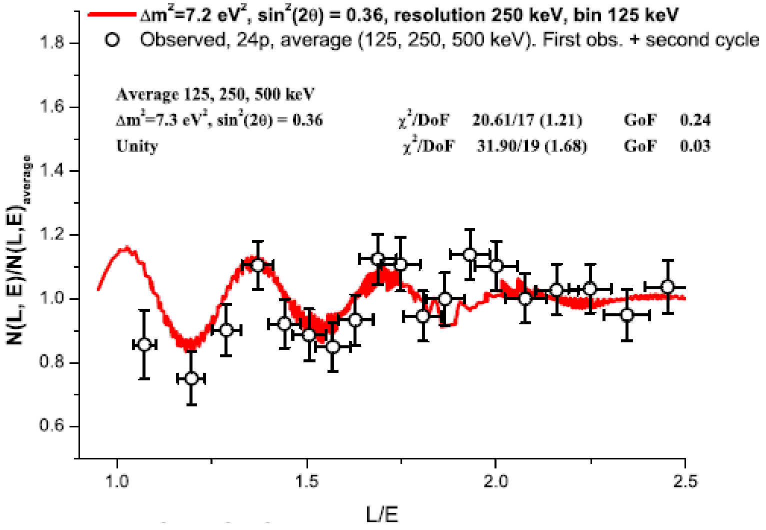
Neutrino-4



$\sin^2(2\theta_{14}) \approx 0.36$

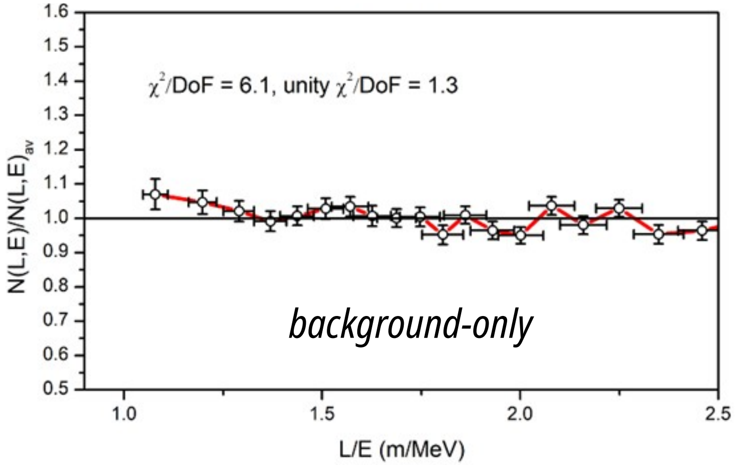
$\Delta m^2_{14} \approx 7.3$ eV^2

(2.7σ)



Some concerns however

- Low S/B (0.54)
  Oscillatory pattern of cosmic background amplified x2

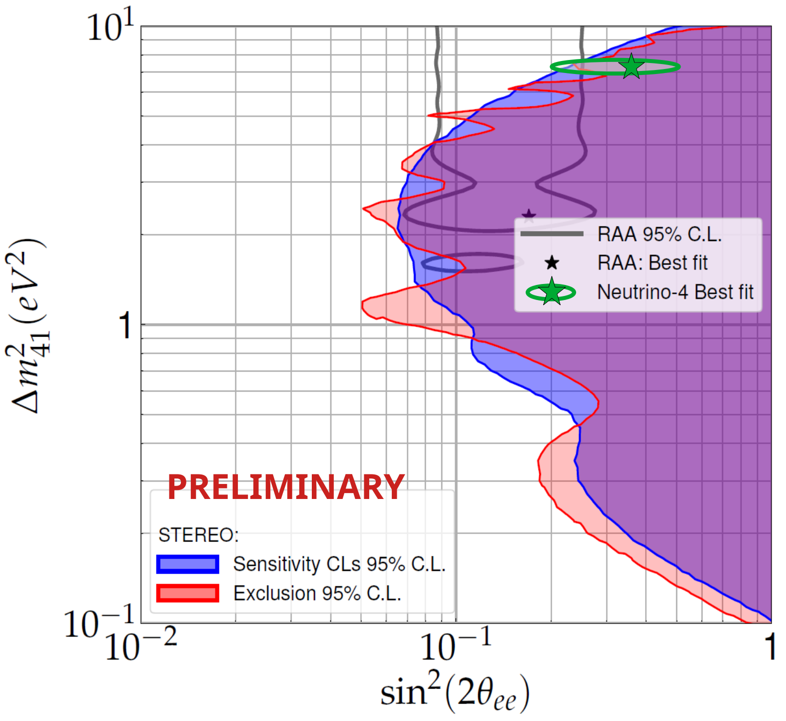


- No systematics included in statistical analysis
- Analysis performed with average of 3 times the same data (different E binning)
  Artificial increase of the dataset

... but no clear sign of a sterile neutrino

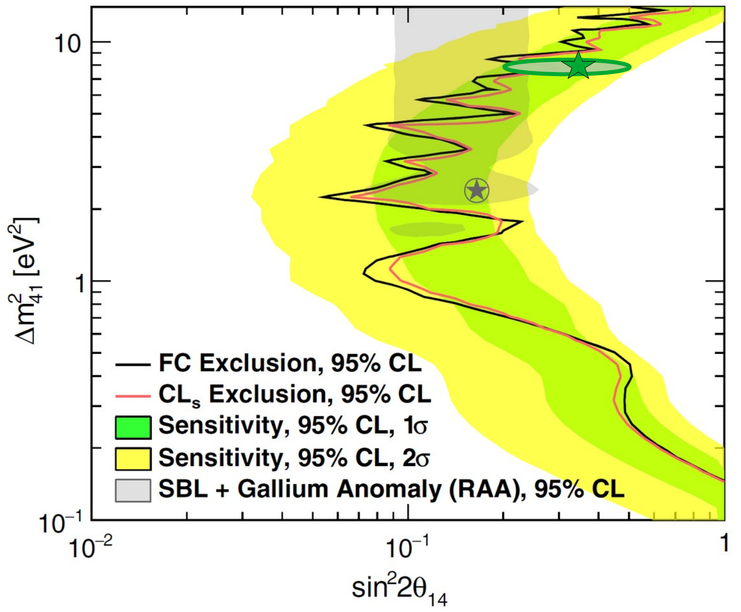
Neutrino-4 best fit + 1σ contour

STEREO
107k neutrinos



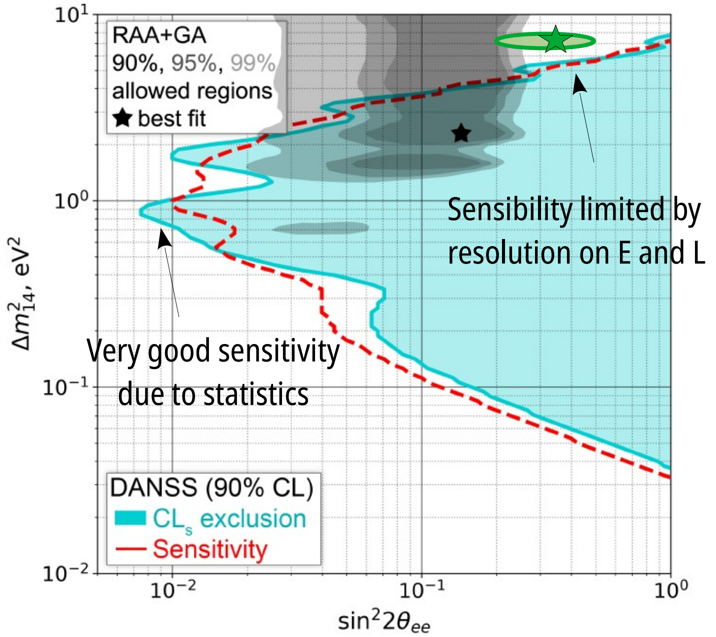
- RAA best-fit point : **>4σ**
- Neutrino-4 best fit : **3.1σ**

PROSPECT
51k neutrinos



- RAA+Gallium best-fit point : **2.5σ**
- Neutrino-4 best fit : **>95%CL**

DANSS
5M neutrinos



- RAA+Gallium best-fit point : **>5σ**

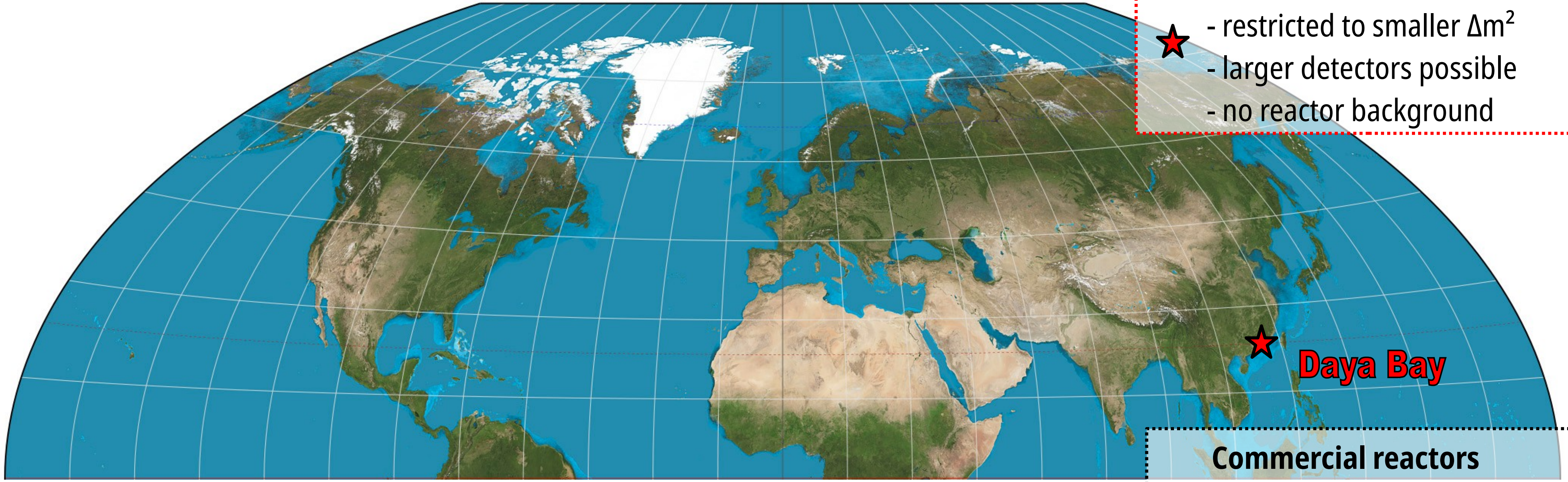
No conclusive sign of a sterile neutrino corresponding to Reactor or Gallium Anomaly

Short baseline experiments : Daya Bay

$$P_{ee} = 1 - \cos^4\theta_{41}\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E_{\bar{\nu}_e}}\right) - \sin^2(2\theta_{41})\sin^2\left(\frac{\Delta m^2_{41}\,L}{4E_{\bar{\nu}_e}}\right)$$

Short baseline (SBL)

- L ~ O(1 km)
- restricted to smaller Δm^2
- larger detectors possible
- no reactor background



Commercial reactors

- high power, high stat
- extended core (Ø ≈ few m)
- *mixed isotopes (irrelevant)*

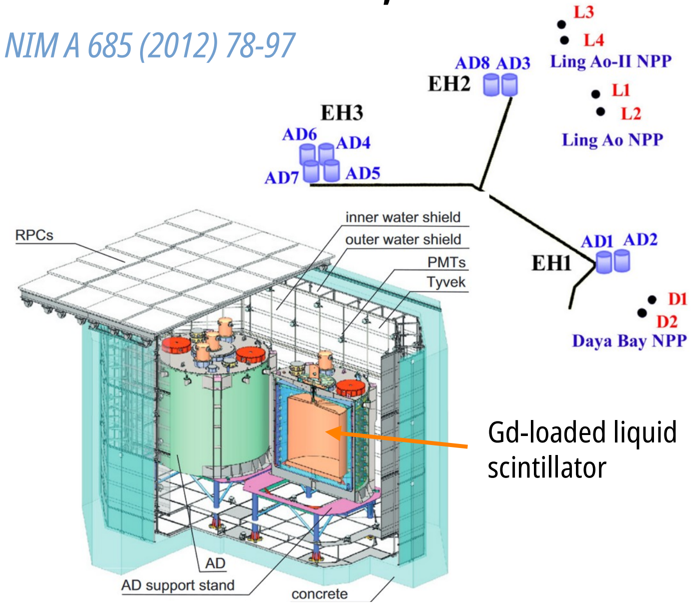
The Daya Bay experiment

Daya Bay

Daya Bay and Ling Ao (II) NPPs

L = 550m, 1600m

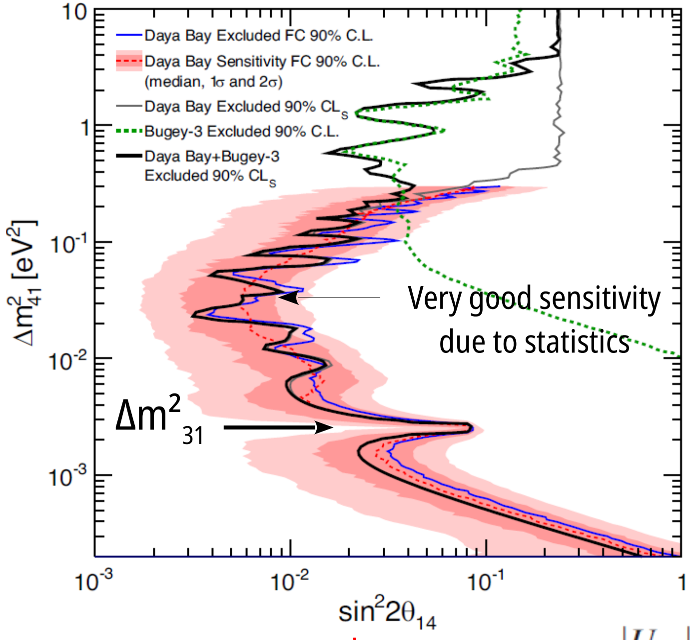
NIM A 685 (2012) 78-97

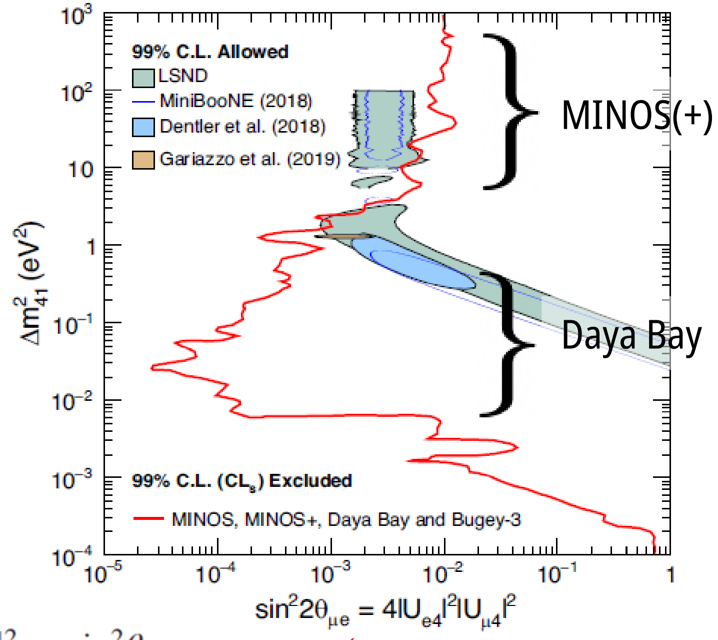


- 8 identical detectors (4 NDs + 4 FDs)
- Each 20t of Gd-loaded liquid scintillator
- Energy resolution 8% @1MeV

Analysis results

PRL 125 (2021) 071801

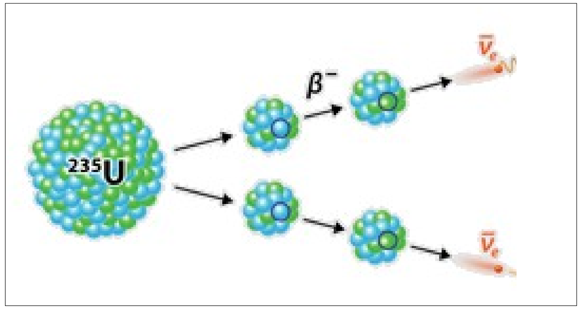


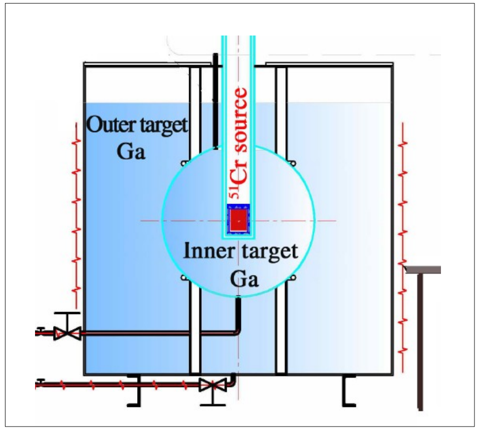


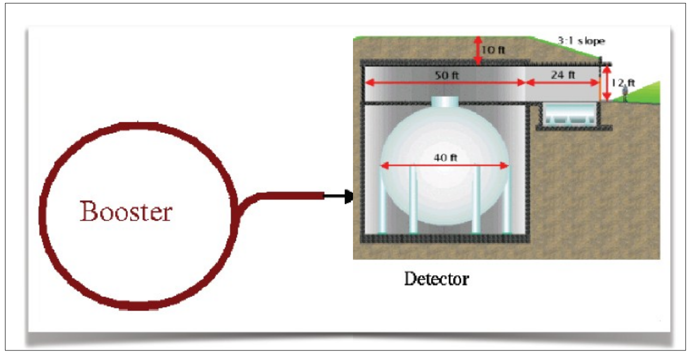
$|U_{e4}|^2 = \sin^2\theta_{14}$

- Sterile search in $\bar{\nu}_e$ disappearance transfered to ν_e disappearance
- LSND/MiniBooNE global fit : excluded **>99%CL**

Let's confirm the sterile neutrino ! 😄







Reactor anomaly :
no sterile

✗

Gallium anomaly :
no sterile

✗

ν_e appearance anomaly :
no sterile

✗

Remaining region at $\Delta m^2 > 10$ eV^2 can't be covered by oscillation experiments

1. Neutrino oscillations

2. Possible indications of a sterile neutrino

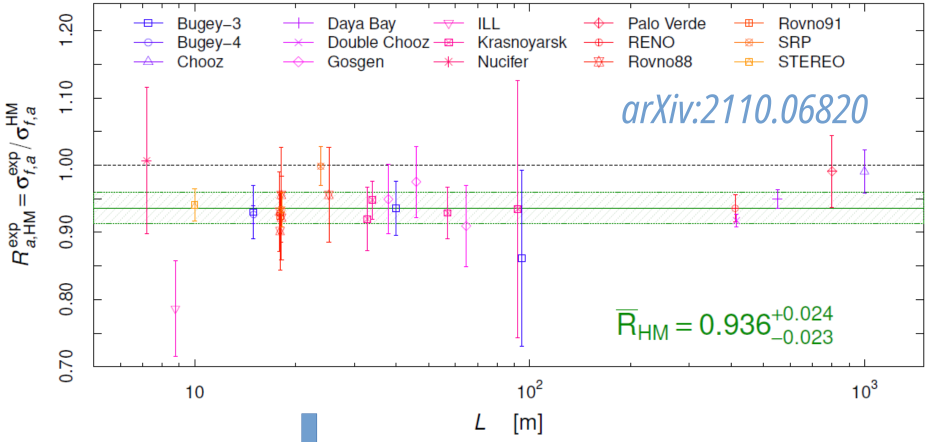
3. Let’s confirm the sterile neutrino !

4. Do we really need a sterile neutrino ? 🤔

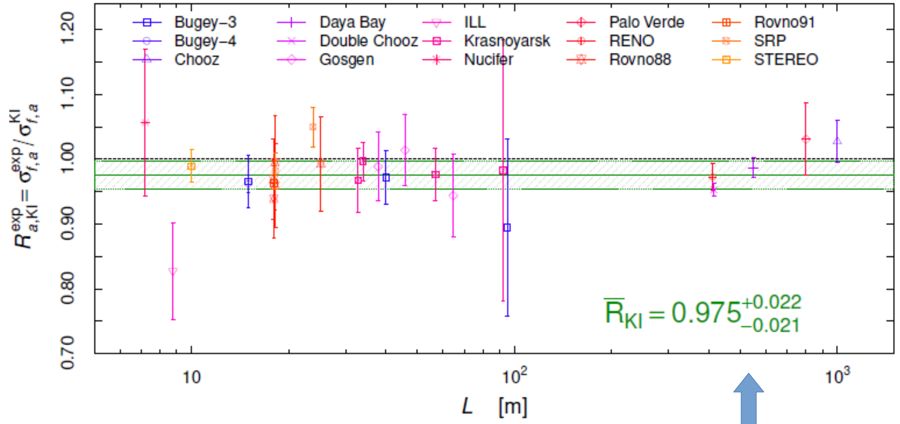
5. Conclusion

Kopeykin *et al.* : reactor anomaly revisited

- **RAA = deficit w.r.t. Huber-Mueller model**



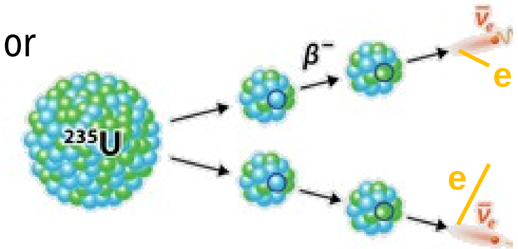
No more anomaly !



- **Huber-Mueller : conversion model**

  β decays produce e^- along with $\bar{\nu}_e$

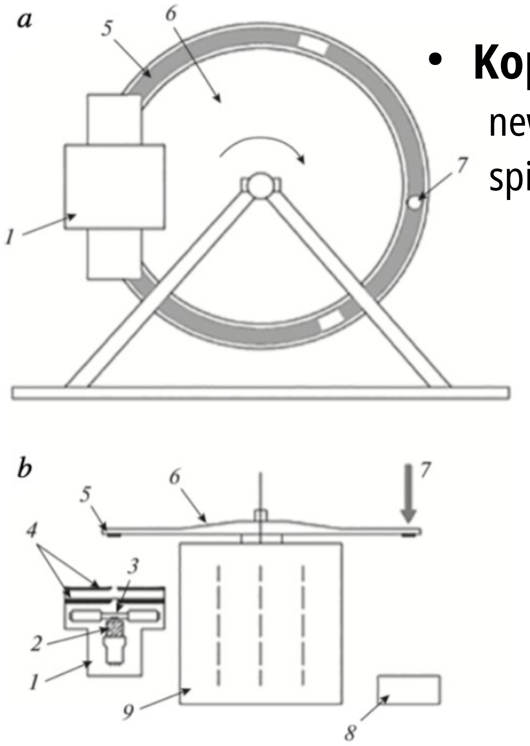
  → measure the total e^- spectrum from U or Pu and convert it to $\bar{\nu}_e$

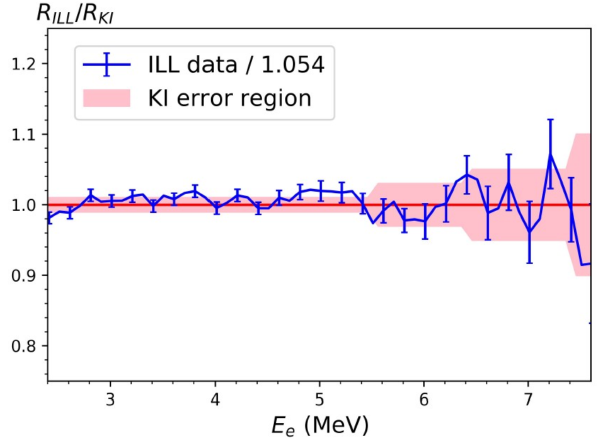


- **Kopeykin :** arXiv:2103.01684

  new measurement of β spectra $^{235}U/^{239}Pu$

  spinning wheel to ensure same irradiation level of the two isotopes





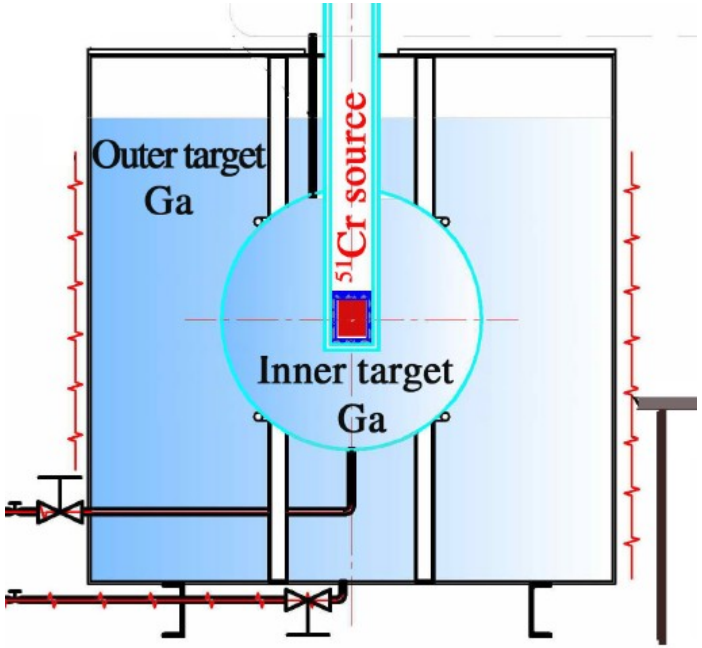
- β spectrum measured in the 1980's at ILL
  - Irradiate $^{235}UO_2$ foils during ~2 days with neutrons to initiate fission *Phys. Lett.* B **160** 325–30
  - Measure electron spectrum

1: spectrometer 5: $^{235}U/^{239}Pu$/empty foils

6: spinning wheel (10turns/min) 7: n beam

BEST : gallium anomaly revisited

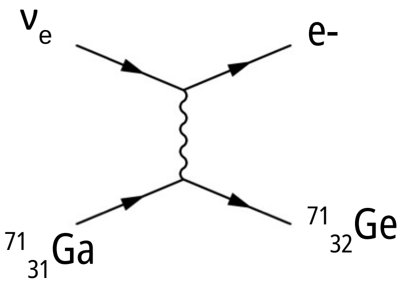
PRC 105 (2022) 065502



- Size 2m x 2m
- 2 volumes for relative measurement

- **Same principle than GALLEX, SAGE**

1) Neutrino capture on Ga

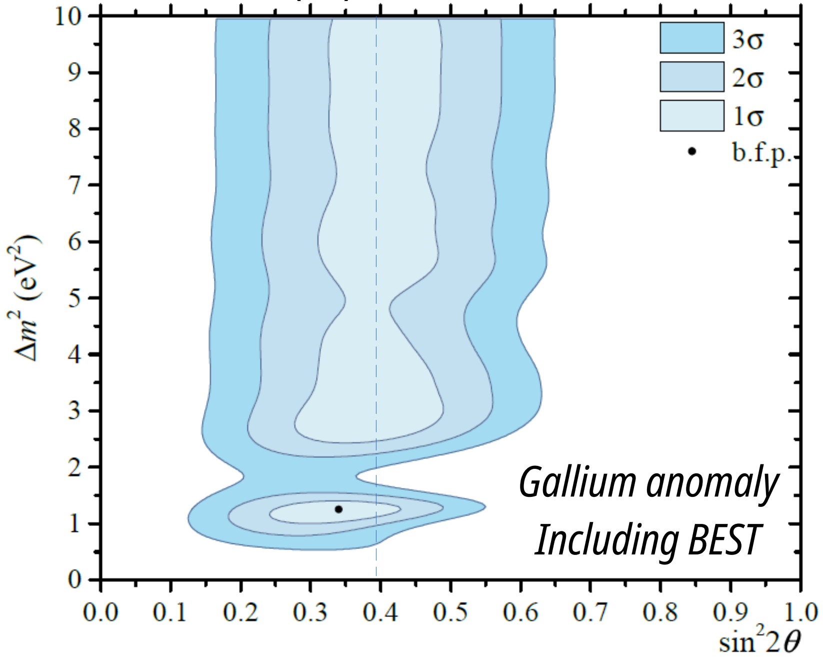


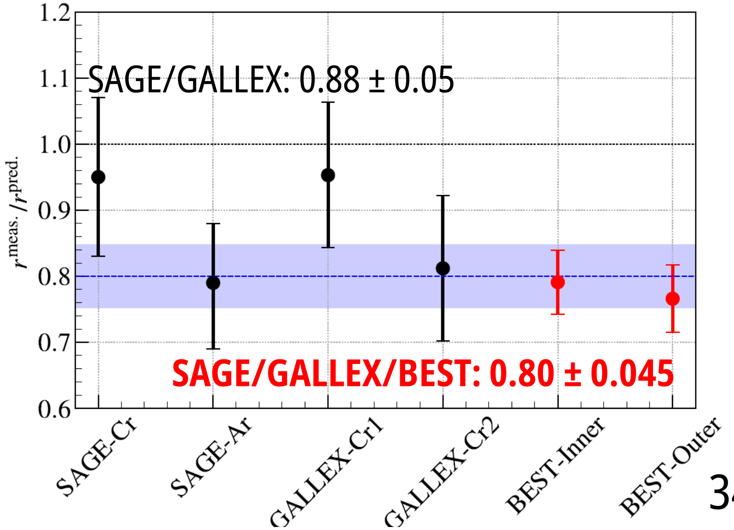
2) Circulate liquid to mesure the Ge activity
3) **Cr** source gives monoenergetic neutrino beam

Anomaly confirmed ! 2.5σ → 4σ

... but no difference between volumes ?! 🤔

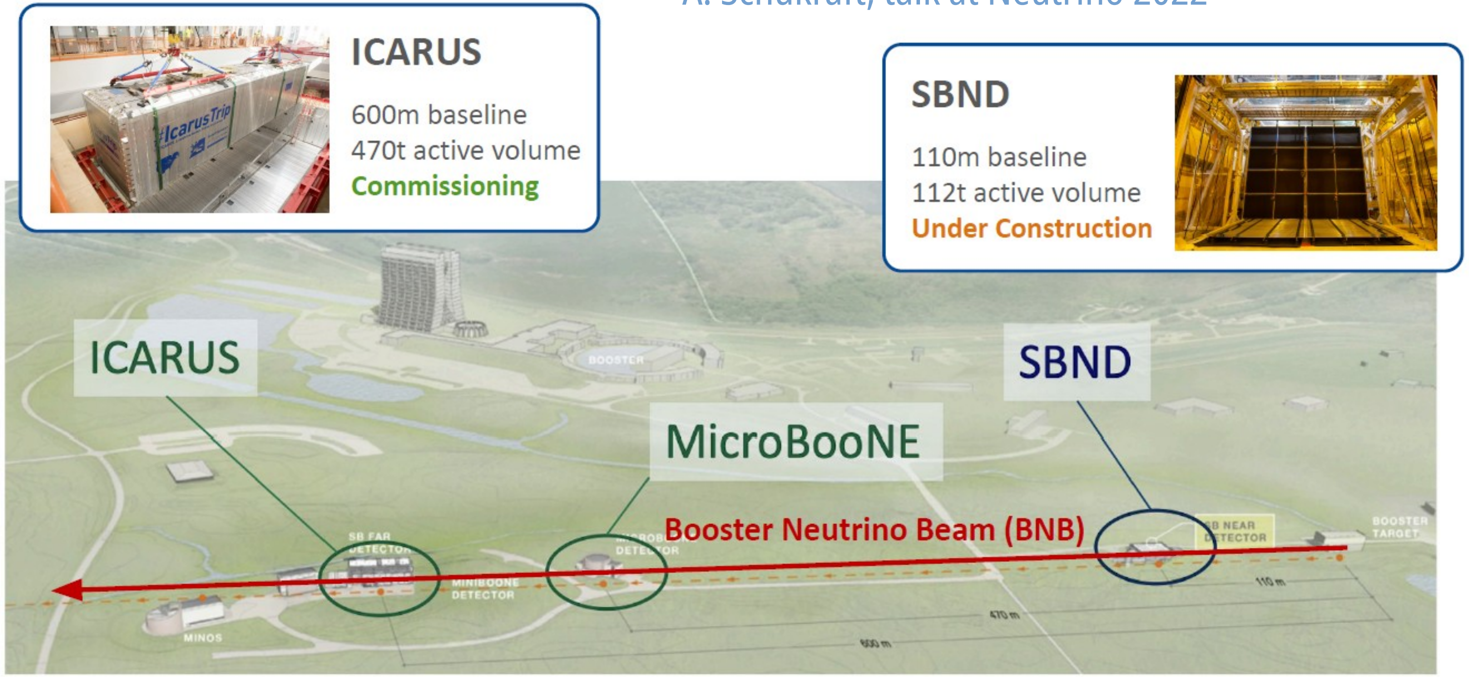
$\sin^2(2\theta) \approx$ 2x deficit



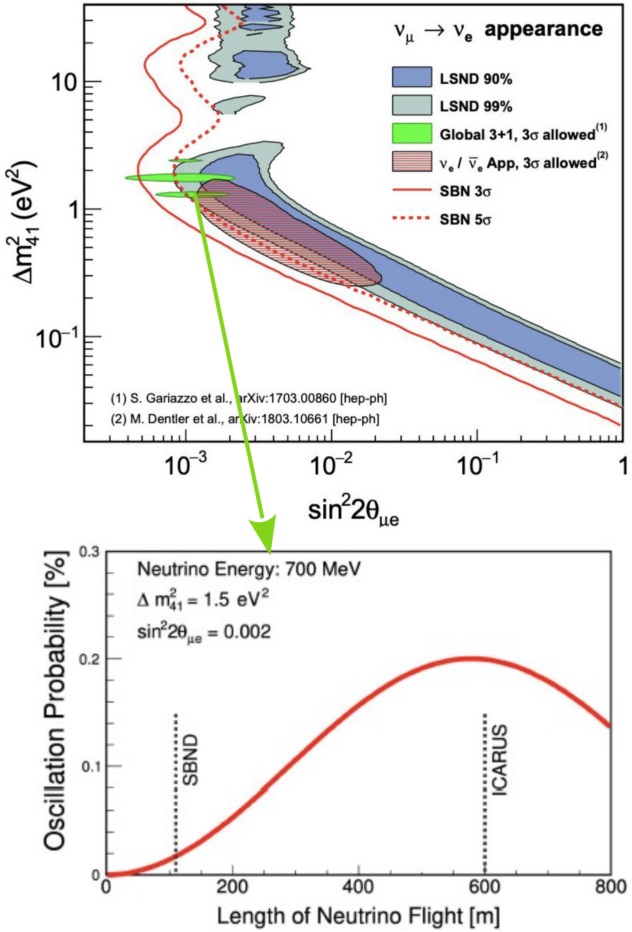


SBND-ICARUS : MiniBooNE anomaly revisited

A. Schukraft, talk at Neutrino 2022



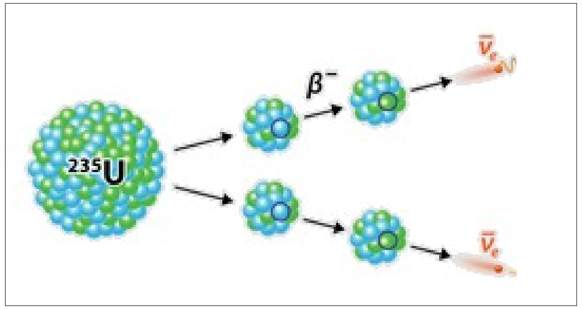
- Three detectors sampling the *same neutrino beam* at different distances
- *Same nuclear target* (Ar) and *detector technology* (LArTPC)
- reduces systematic uncertainties to the %-level

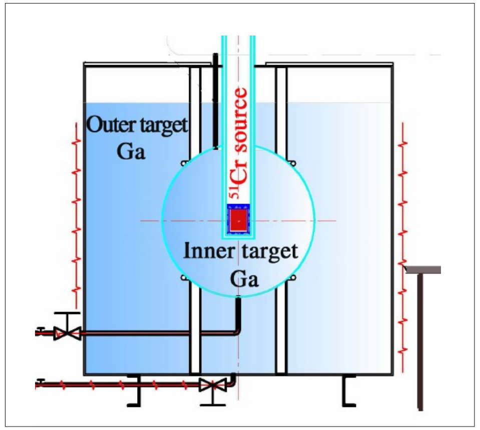


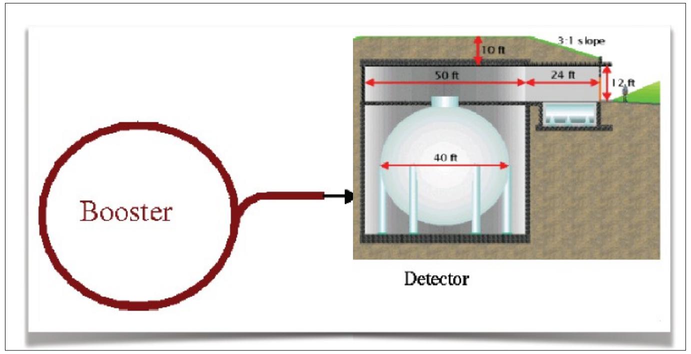
P. Machado et al, arXiv:1903.04608V11

Results coming in 1-2 years

Do we really need a sterile neutrino ?







Reactor anomaly solved ✓

Gallium anomaly confirmed ✗

ν_e appearance anomaly ?

1. Neutrino oscillations

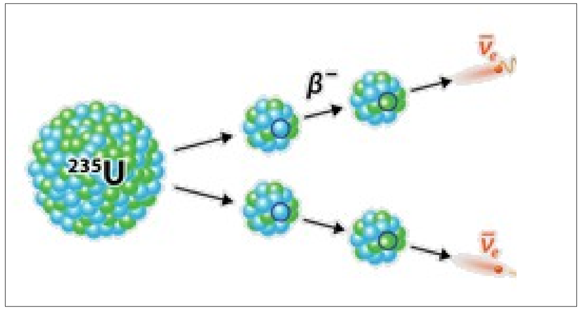
2. Possible indications of a sterile neutrino

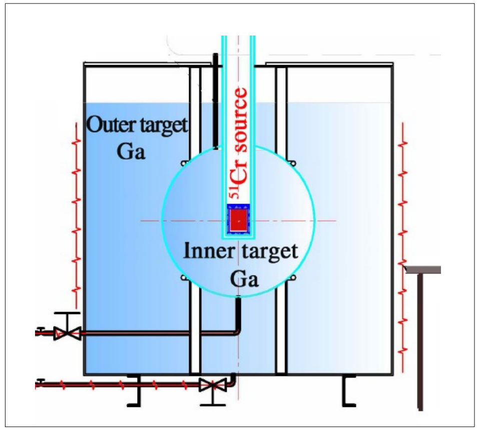
3. Let's confirm the sterile neutrino !

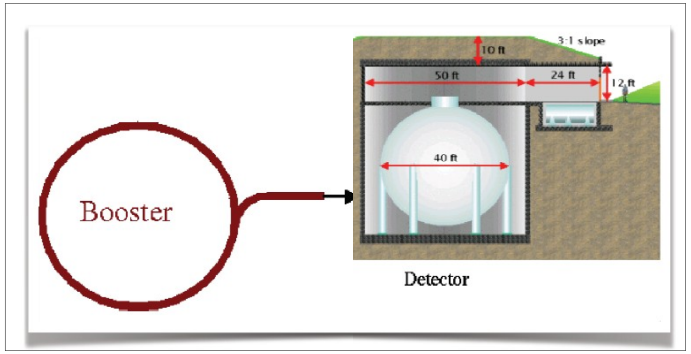
4. Do we really need a sterile neutrino ?

5. Conclusion

Overview







Reactor anomaly

- Possible steriles rejected
- No sterile needed anymore

Gallium anomaly

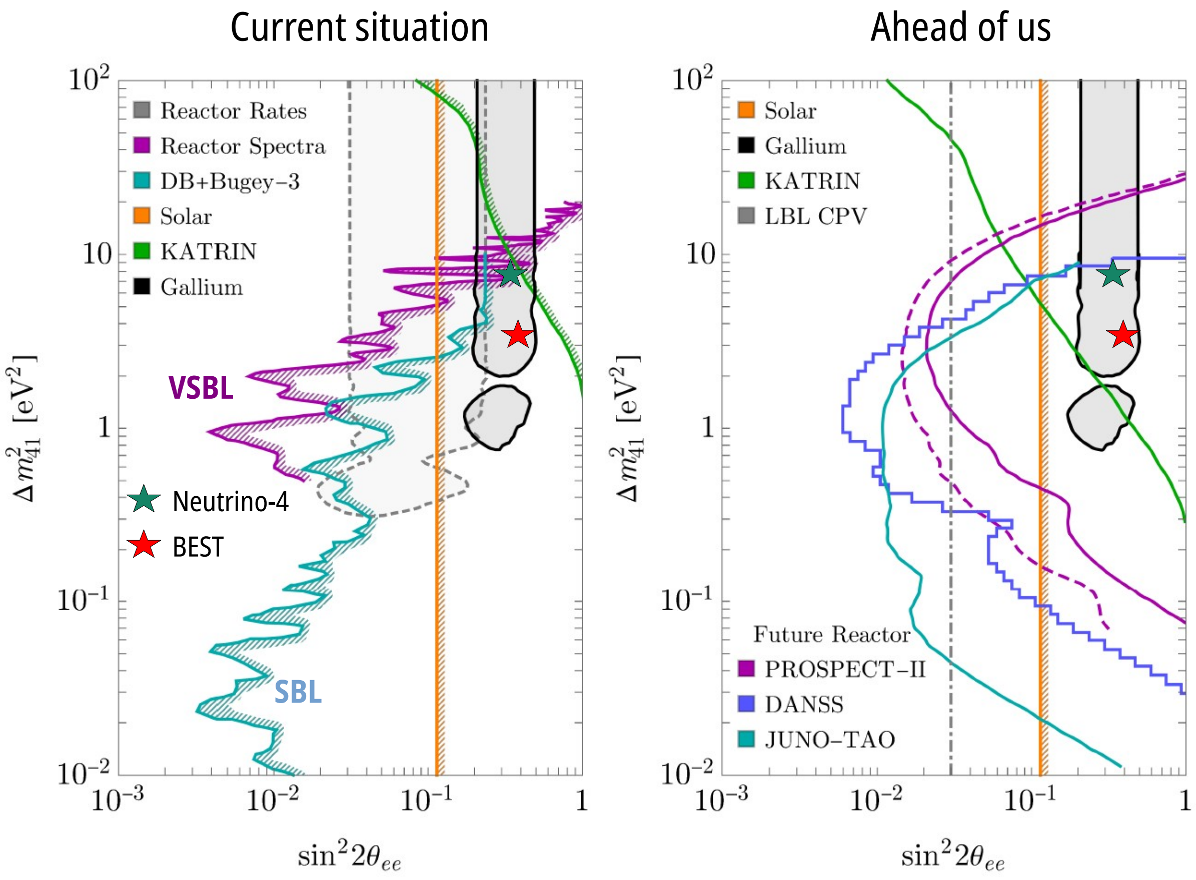
- Possible steriles rejected
- Anomaly was confirmed…

ν_e appearance anomaly

- Possible steriles rejected
- Anomaly to be checked

Easy and appealing to explain a data/theory discrepancy by a sterile neutrino…
but is it really relevant ?

Global picture and perspectives



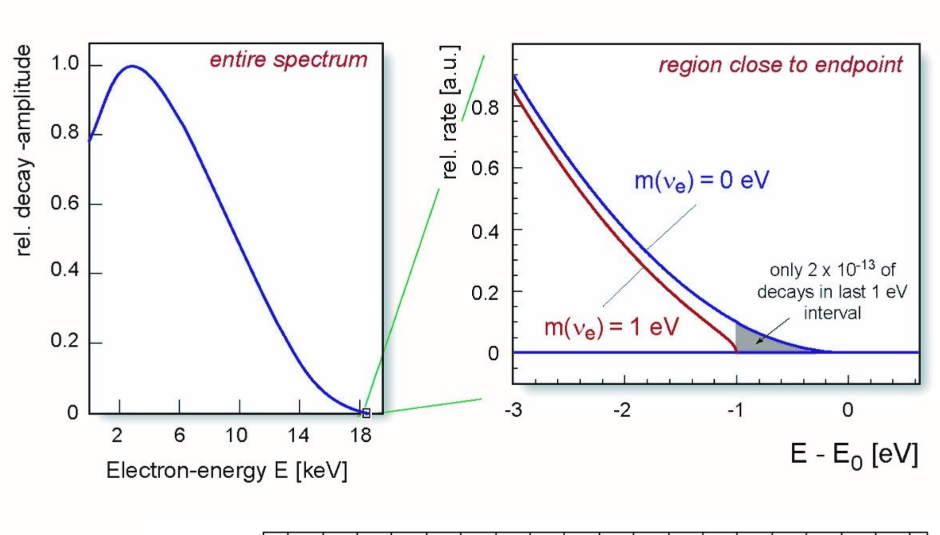
Snowmass 2021 white paper 2203.07214

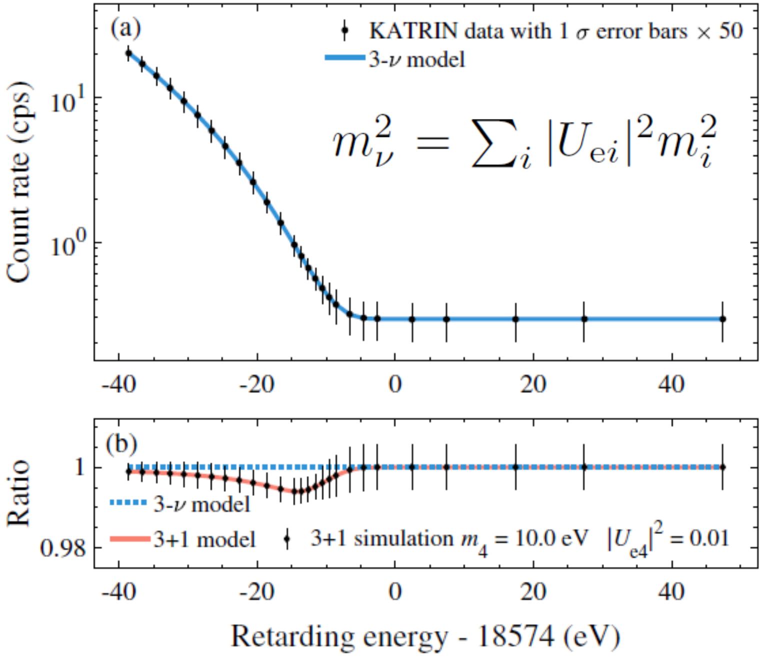
- The **experimental challenges** of very short baseline reactor experiments have been met !
- **Complementary constraints** from short- and very-short-baseline experiments
- **KATRIN** (neutrino mass measurement) excludes the high-Δm^2 solutions
- Several **upgrades are planned** (PROSPECT, DANSS, Neutrino-4)
- Positive observations (BEST, Neutrino-4) **in (strong) tension** with other experiments, to be confirmed in the next few years

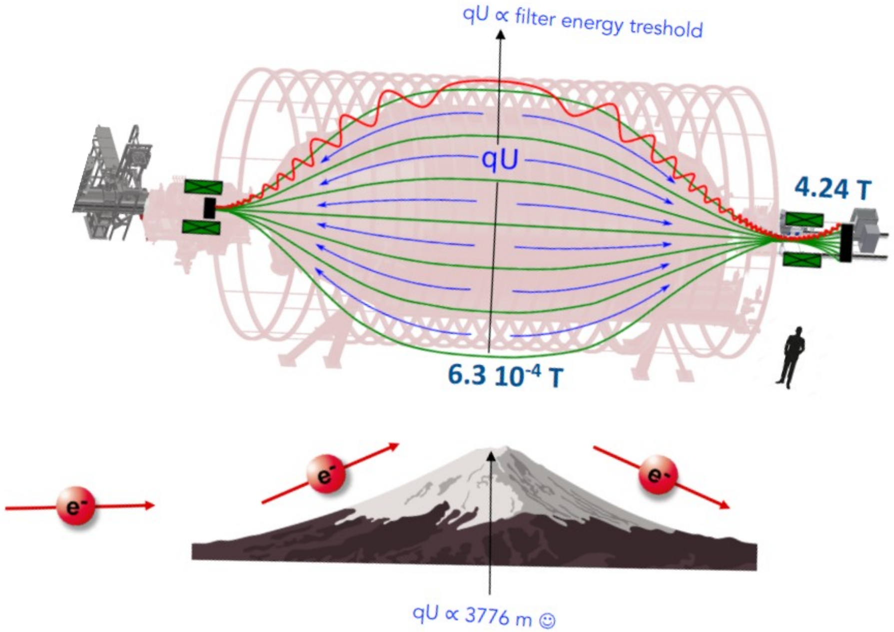
Thank you !

KATRIN

Goal : measure max E(e-) with $T_2 \rightarrow {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e$







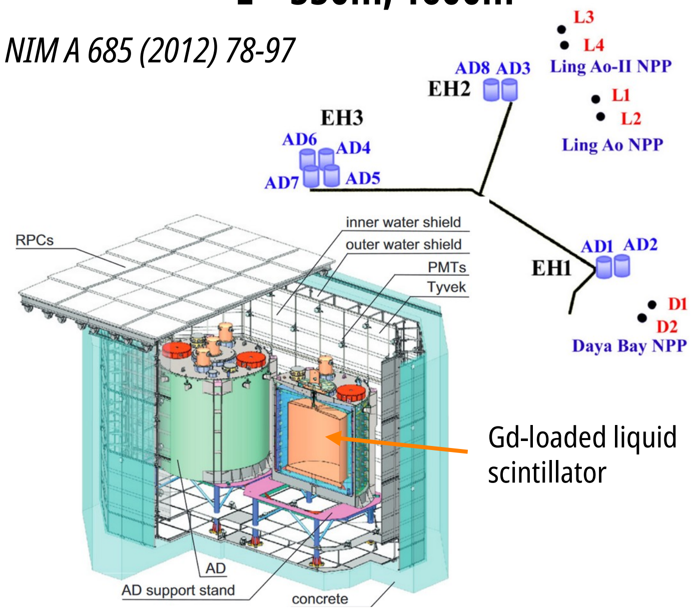
Short-baseline experiments

Daya Bay

Daya Bay and Ling Ao (II) NPPs

L = 550m, 1600m

NIM A 685 (2012) 78-97



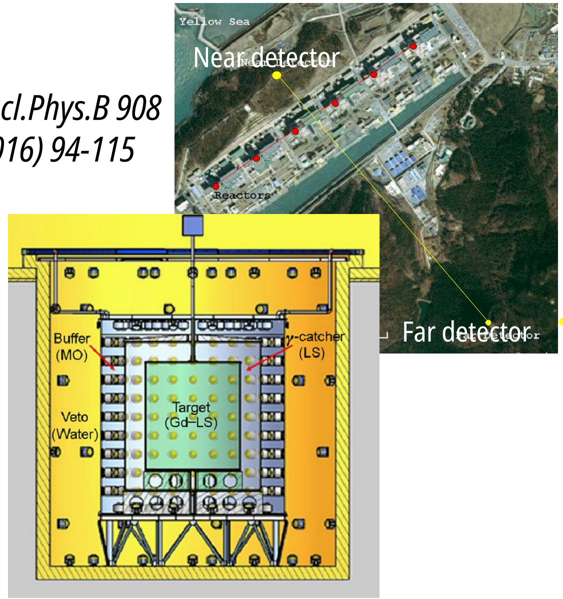
- 8 identical detectors (4 NDs + 4 FDs)
- Each 20t of Gd-loaded liquid scintillator
- Energy resolution 8% @1MeV

RENO

Hanbit NPP, Korea

L ≈ 300m, 1380m

Nucl.Phys.B 908 (2016) 94-115

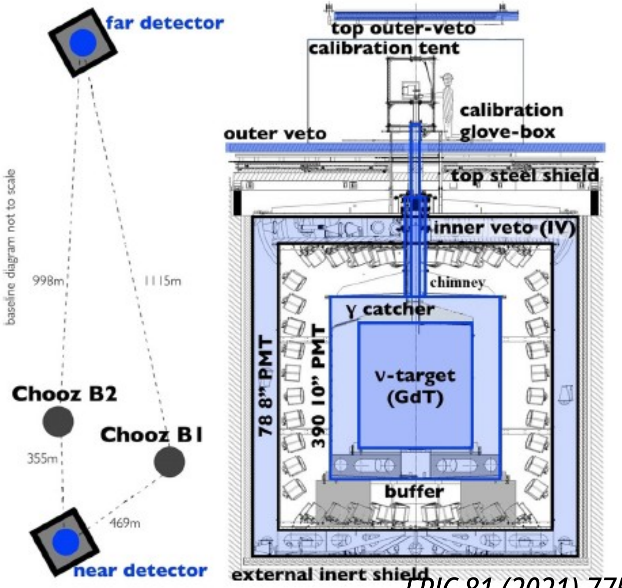


- Identical ND and FD
- 16t Gd-loaded liquid scintillator
- Energy resolution 8% @1MeV

Double Chooz

Chooz-B NPP, France

L = 400m, 1050m



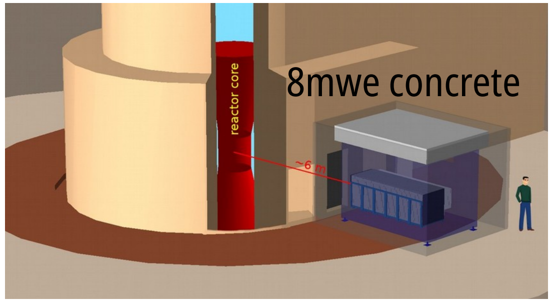
EPJC 81 (2021) 775

- Identical ND and FD
- Gd-loaded liquid scintillator (GdT, 10m^3)
- Energy resolution 7% @1MeV

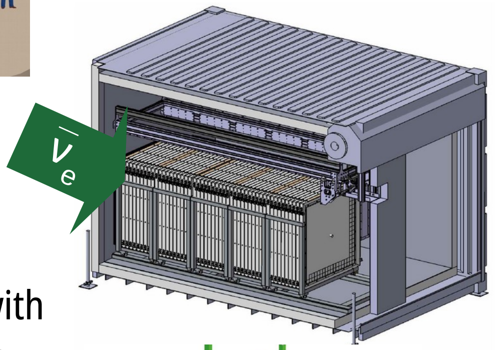
The Solid experiment

JINST 16 (2021) P02025;
D.Gabinski's talk at Nufact21

Reactor BR2 Mol, Belgium



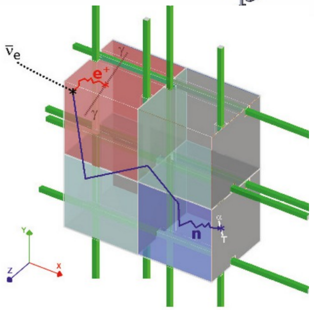
40-80 MW HEU reactor
Compact core Ø<50cm, h=90cm



Segmented detector

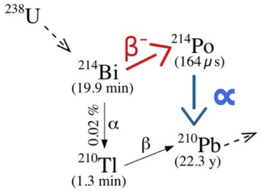
L ≈ 6.3 – 8.9m

- 12.8k scintillator cubes $(5cm)^3$ with ^{6}LiF:ZnS foils → double scintillation
- Pulse shape discrimination on LiF:ZnS
- 1.6t fiducial volume
- 12% resolution @1MeV
- Selection based on event topology



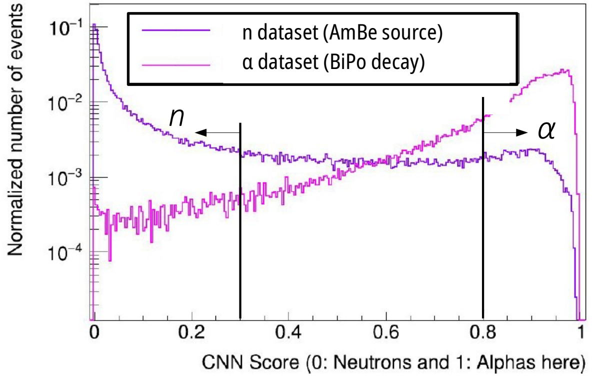
Bi-Po background rejection

Unexpectedly high contamination of ^{6}LiF:ZnS
(2 orders of magnitude above IBD)



→ BiPonator

Machine Learning PSD method to separate α/n



94 % α rejection for
80 % neutron efficiency

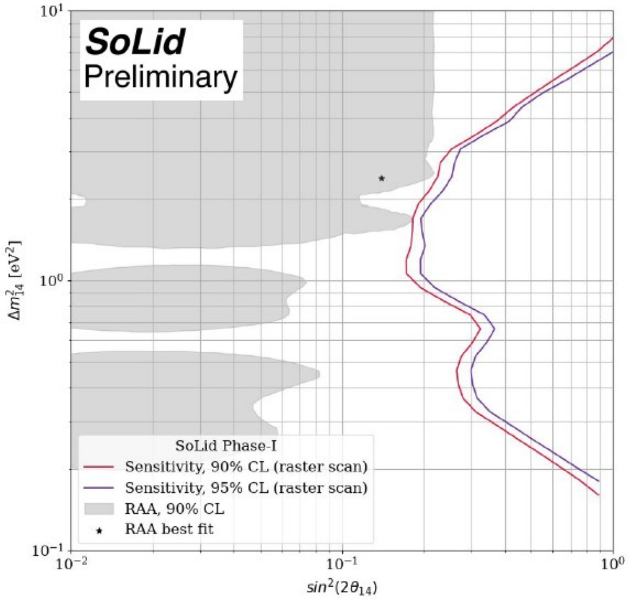
≈90 $\bar{\nu}_e$/day with S/B = 1/3

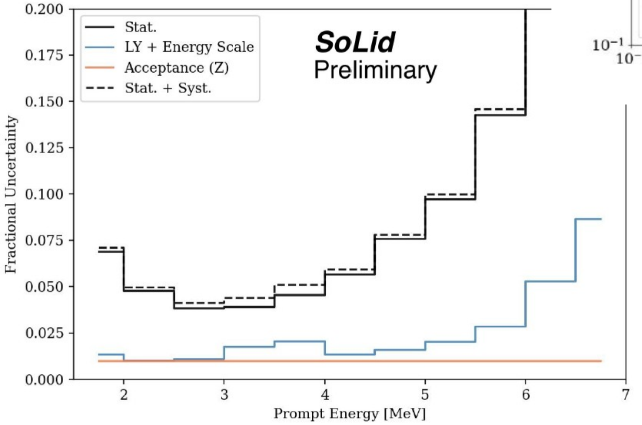
Solid results

D.Gabinski's talk at Nufact21

Analysis status

- Currently working on phase-I data (2 yrs of data)
- Analysis will be stat. limited

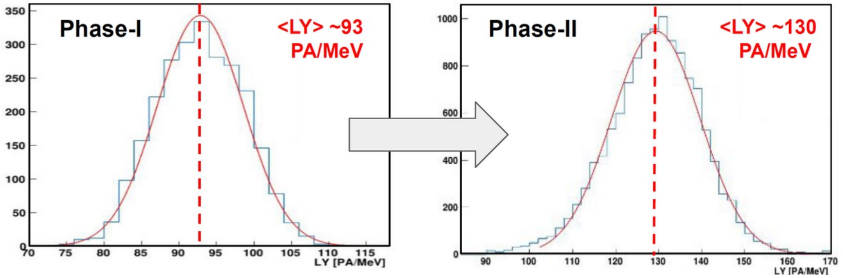




First exclusion contour coming soon !

Solid Upgrade

- Detector upgrade with improved MPPCs
  - 40 % more light yield
  - Better energy resolution
  - Improved reconstruction of annihilation gammas → event topology



- Phase-II detector taking data since late 2020

Neutrino-4 results

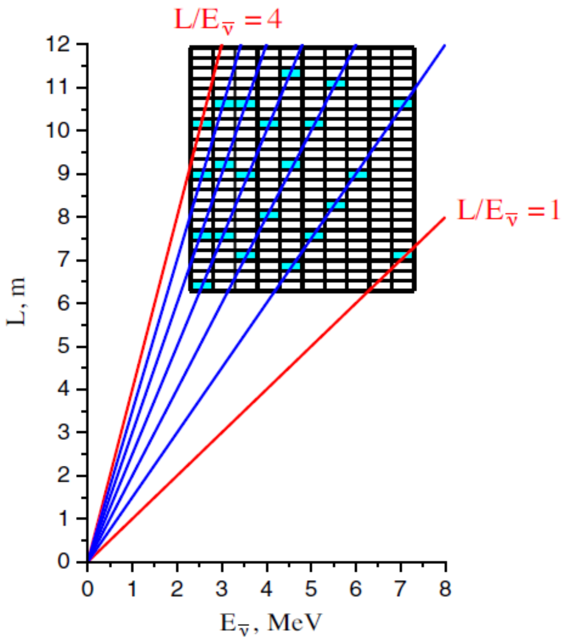
PRD 104 (2021) 032003

Analysis method

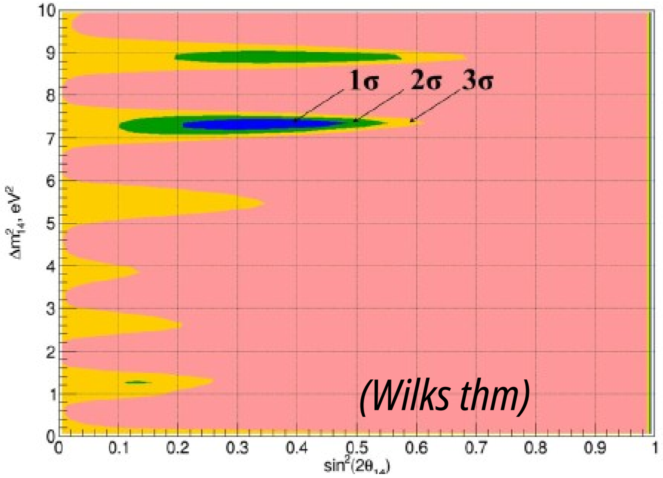
- Relative measurement using ratio to baseline-averaged spectrum

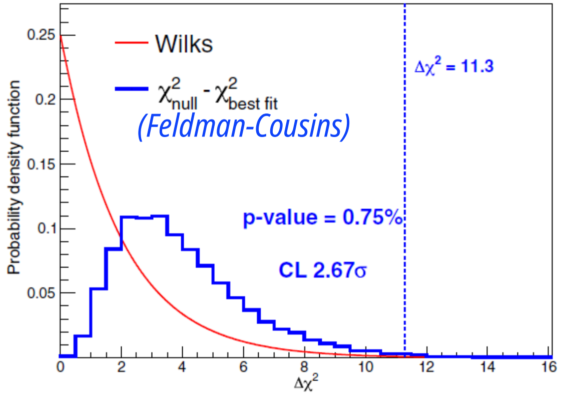
$$R_{ik}^{\mathrm{exp}} = (N_{ik} \pm \Delta N_{ik}) L_k^2 / K^{-1} \sum_{k}^{K} (N_{ik} \pm \Delta N_{ik}) L_k^2$$

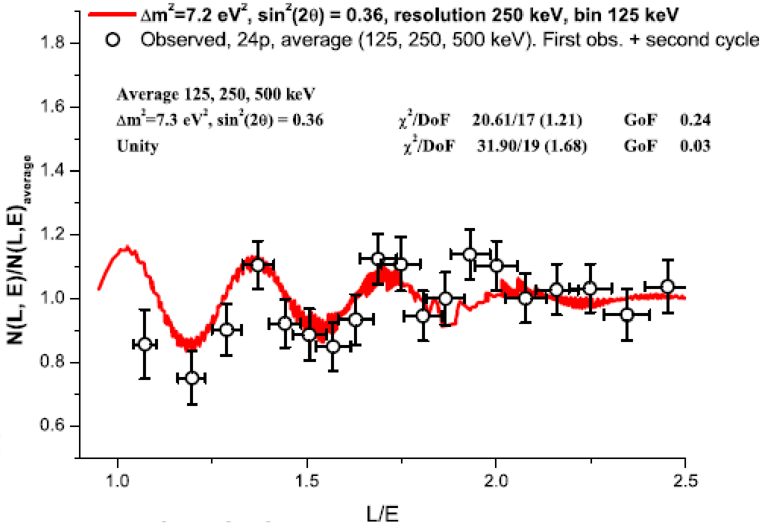
- Summation of R_{ik} in L/E space



Analysis results







$\sin^2(2\theta_{14}) \approx 0.36$

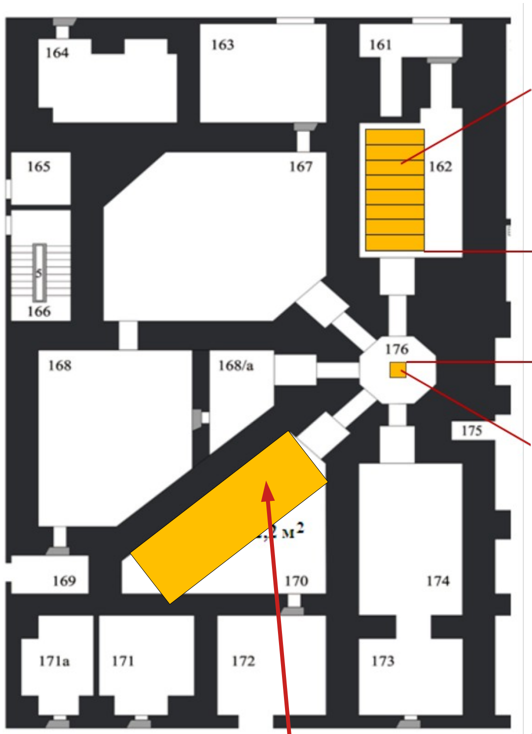
$\Delta m^2_{14} \approx 7.3$ eV^2

***2.9σ** with Wilks thm*

***2.7σ** with F-C*

Neutrino-4 future plans

R.M. Samoilov, talk at Nucleus 2020



antineutrino detector

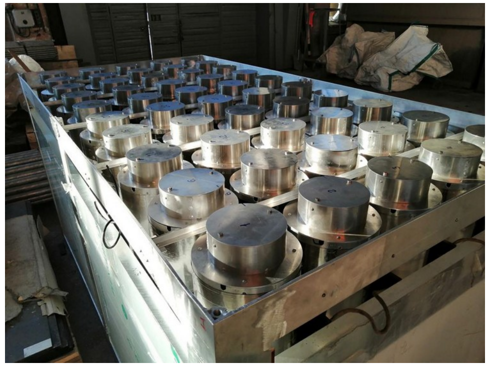
5 m

Reactor core

New antineutrino detector

Current

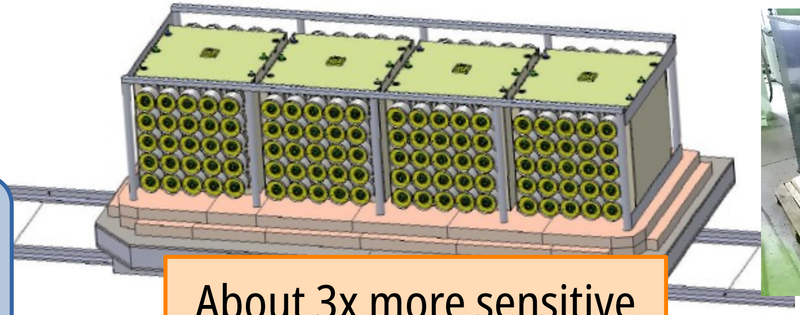
10x5 cells, single-PMT readout



Upgrade

4 sub-detectors with 5x5 cells, double-PMT readout

- New scintillator → PSD capability, reduce correlated bkg
- More Gd → reduce accidental background



Installation 2022
Data taking 2023-24

About 3x more sensitive