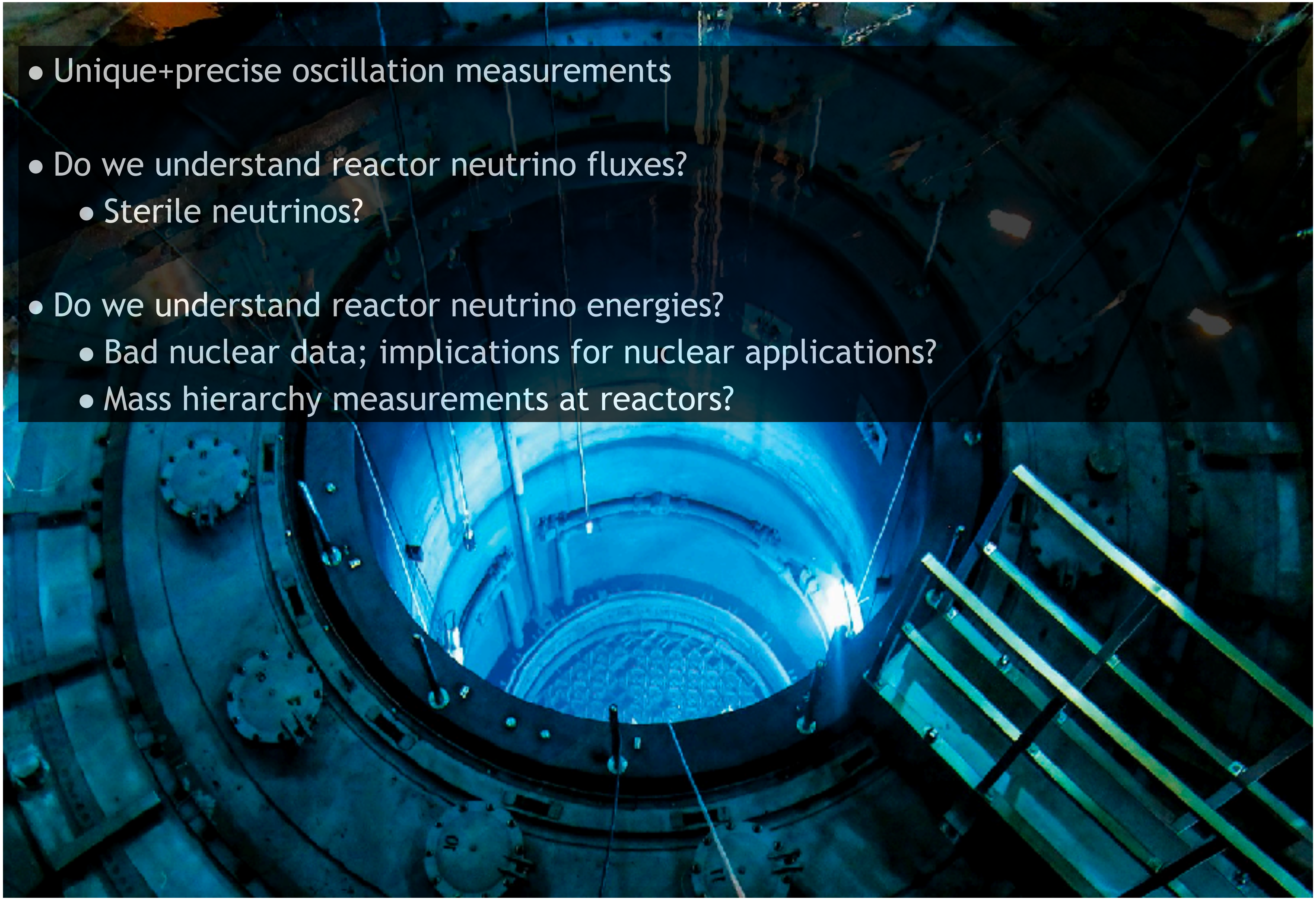
Reactor Neutrinos

Davide Franco, APC

Reactor Neutrinos

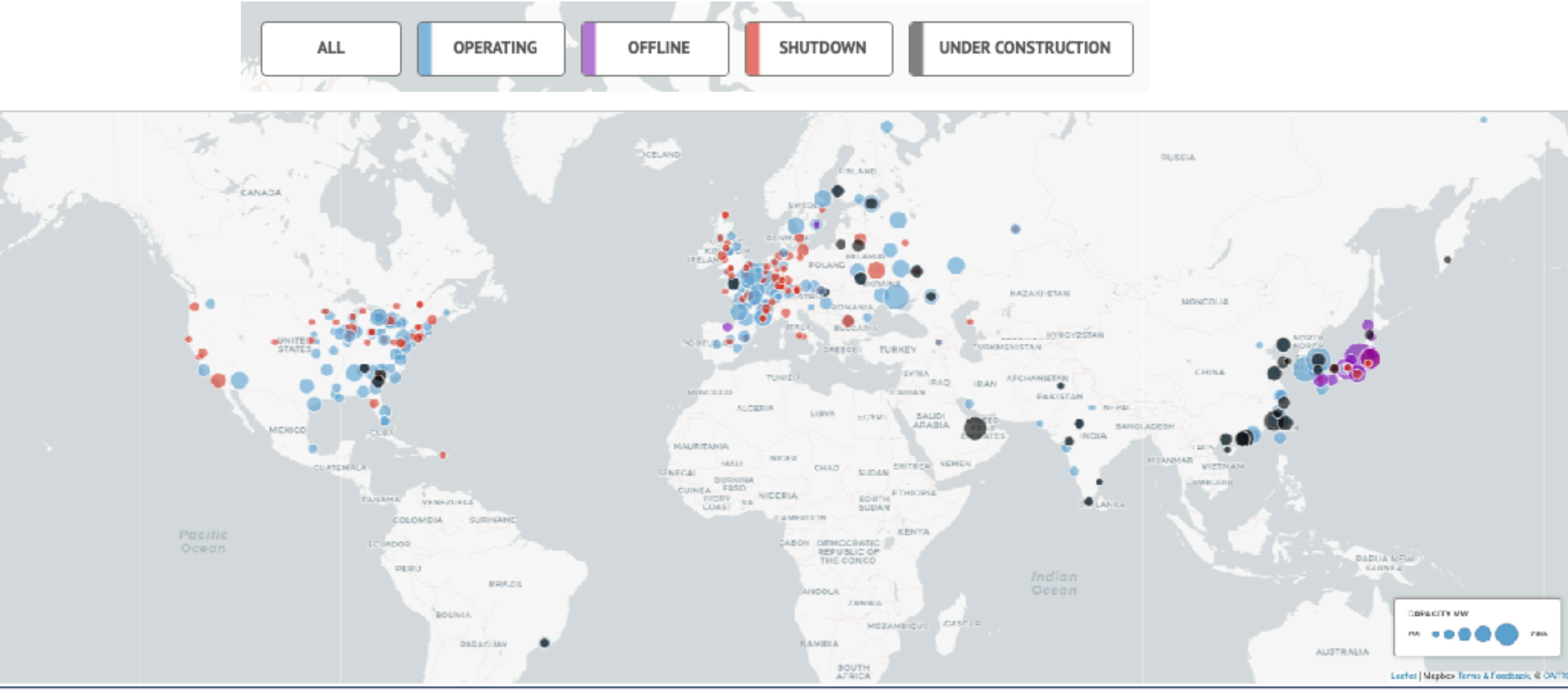


- Unique+precise oscillation measurements

- Do we understand reactor neutrino fluxes?
  - Sterile neutrinos?

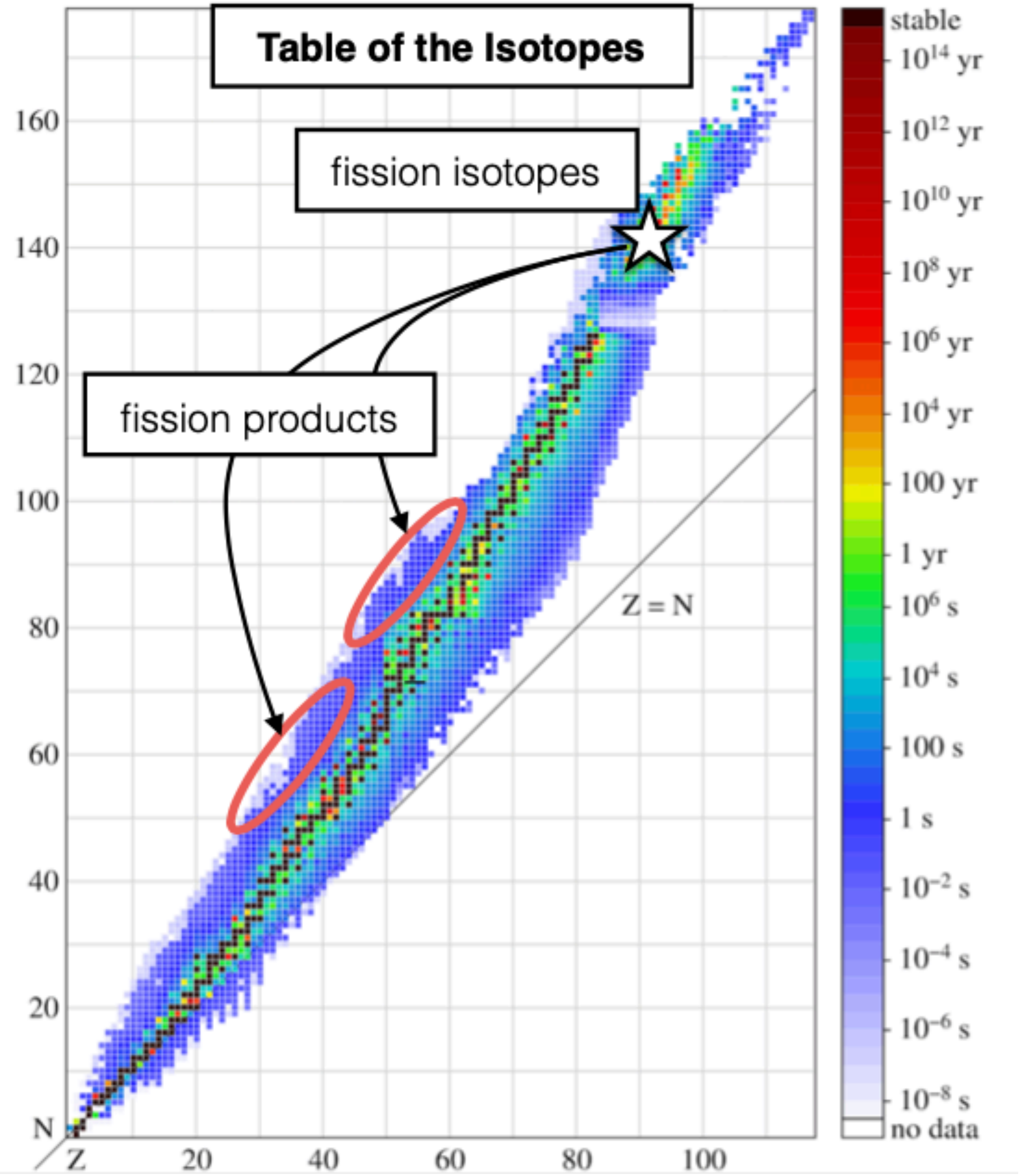
- Do we understand reactor neutrino energies?
  - Bad nuclear data; implications for nuclear applications?
  - Mass hierarchy measurements at reactors?

Reactor Neutrinos

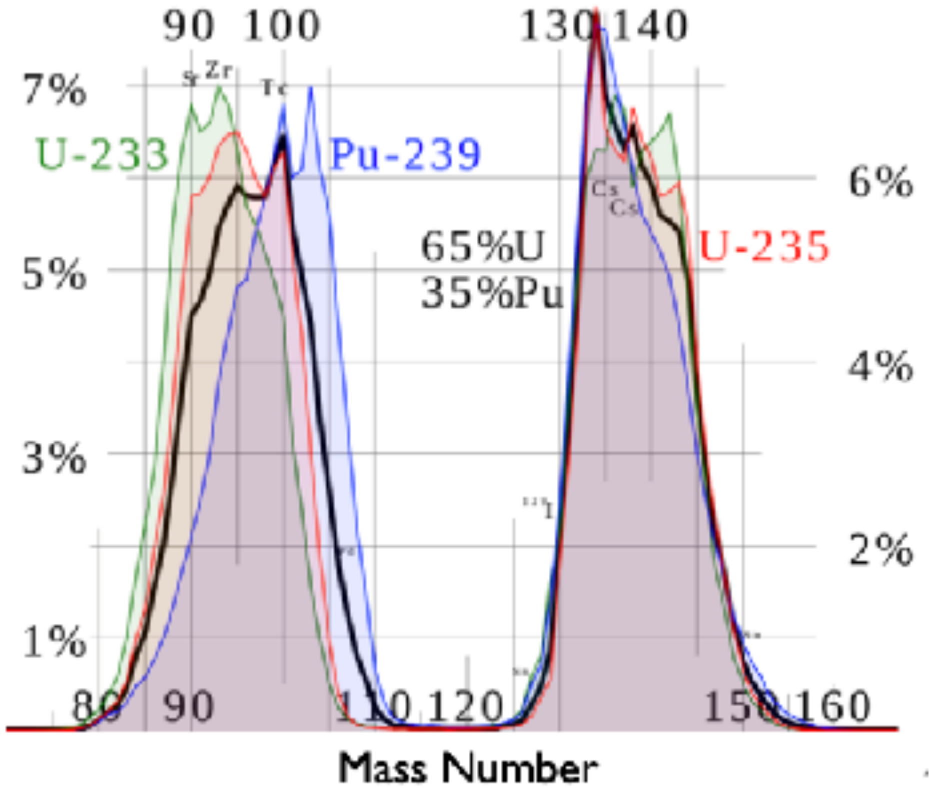


https://www.carbonbrief.org/mapped-the-worlds-nuclear-power-plants/

Nuclear Reactors



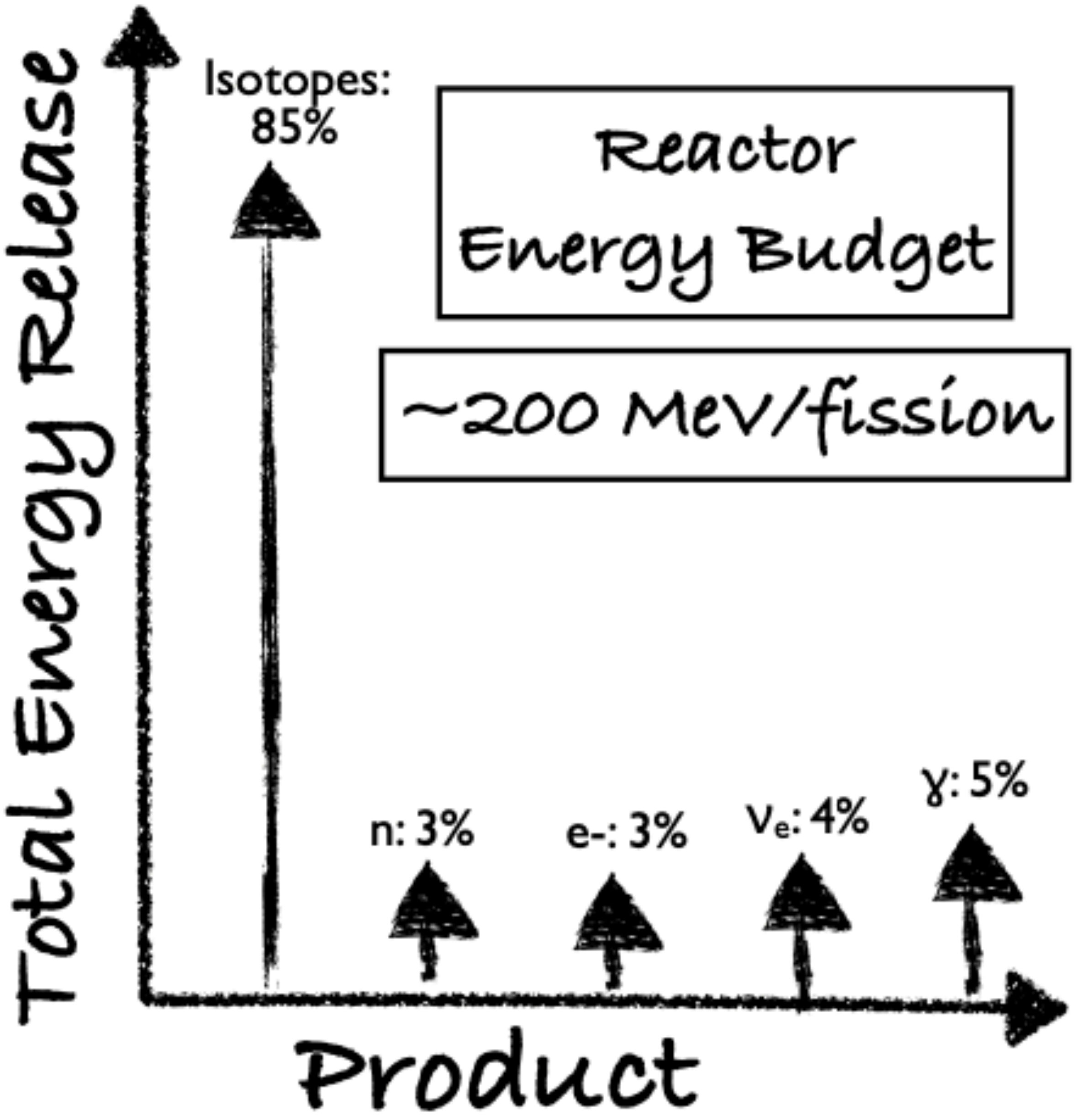
$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



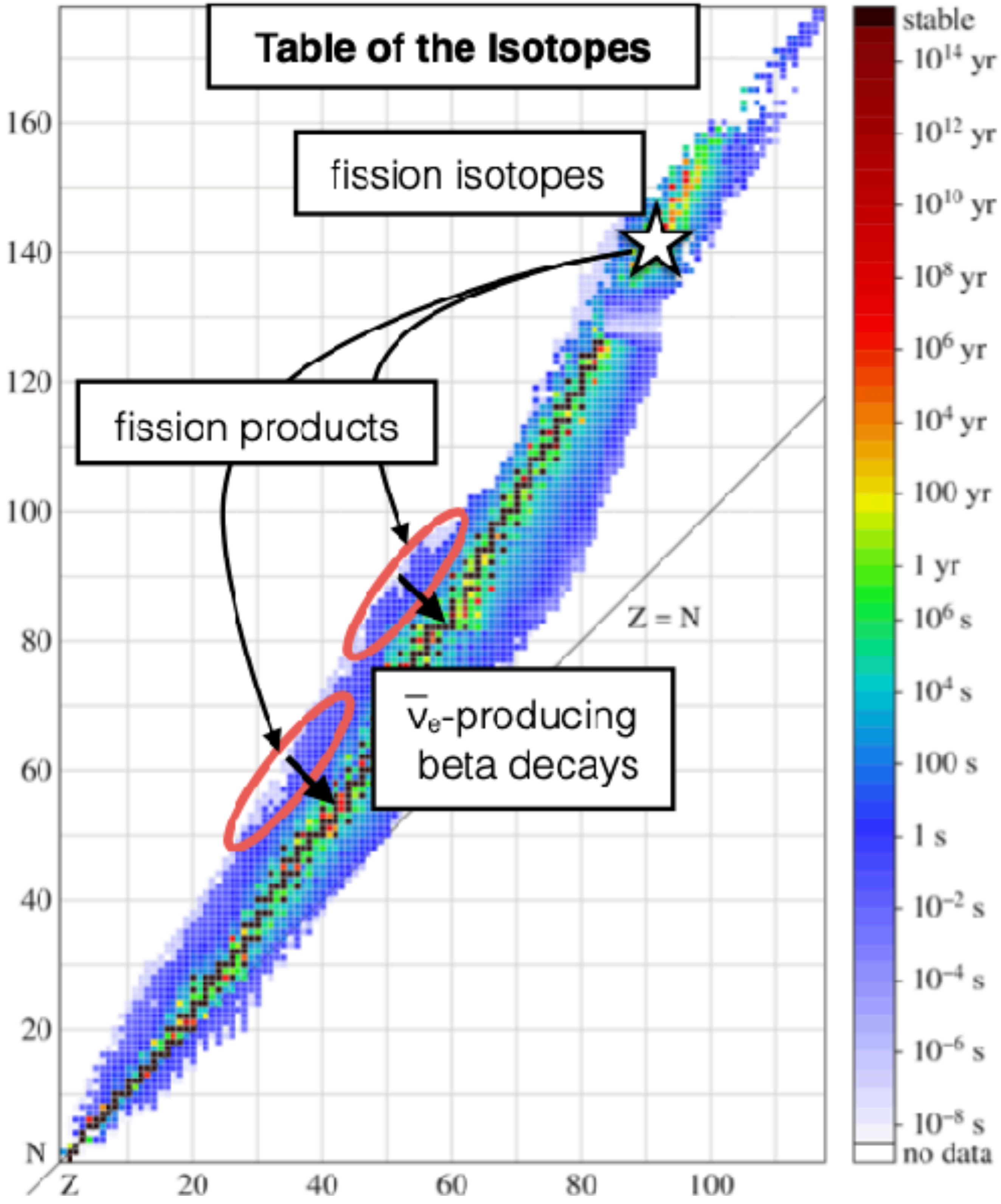
Nuclear Reactors

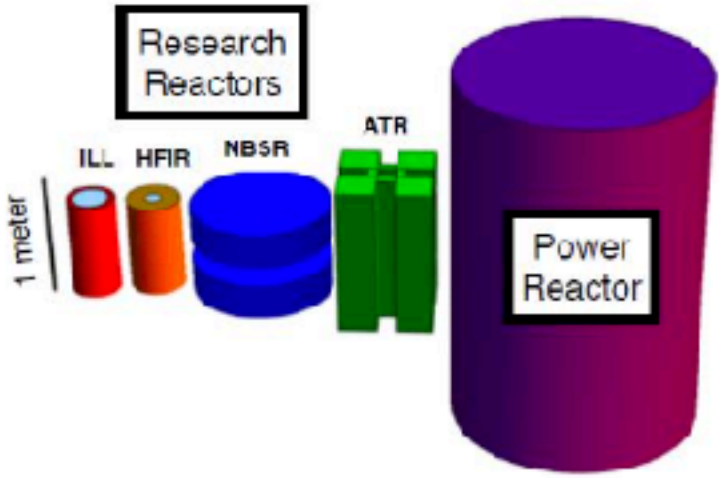
Heavy isotopes fission, making lighter isotopes, energy, neutrons, neutrinos, betas, and gammas

Different fission isotopes yield different products



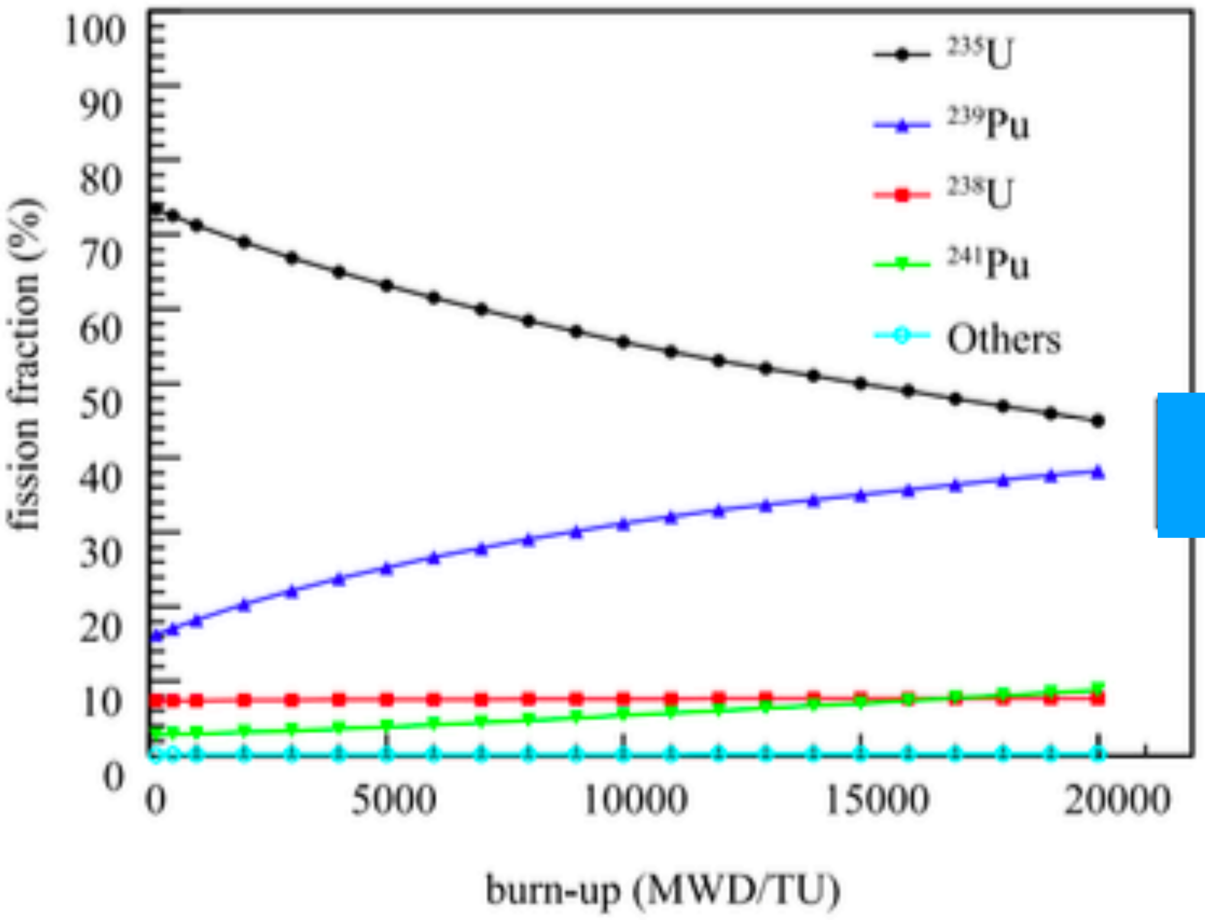
Nuclear Reactors

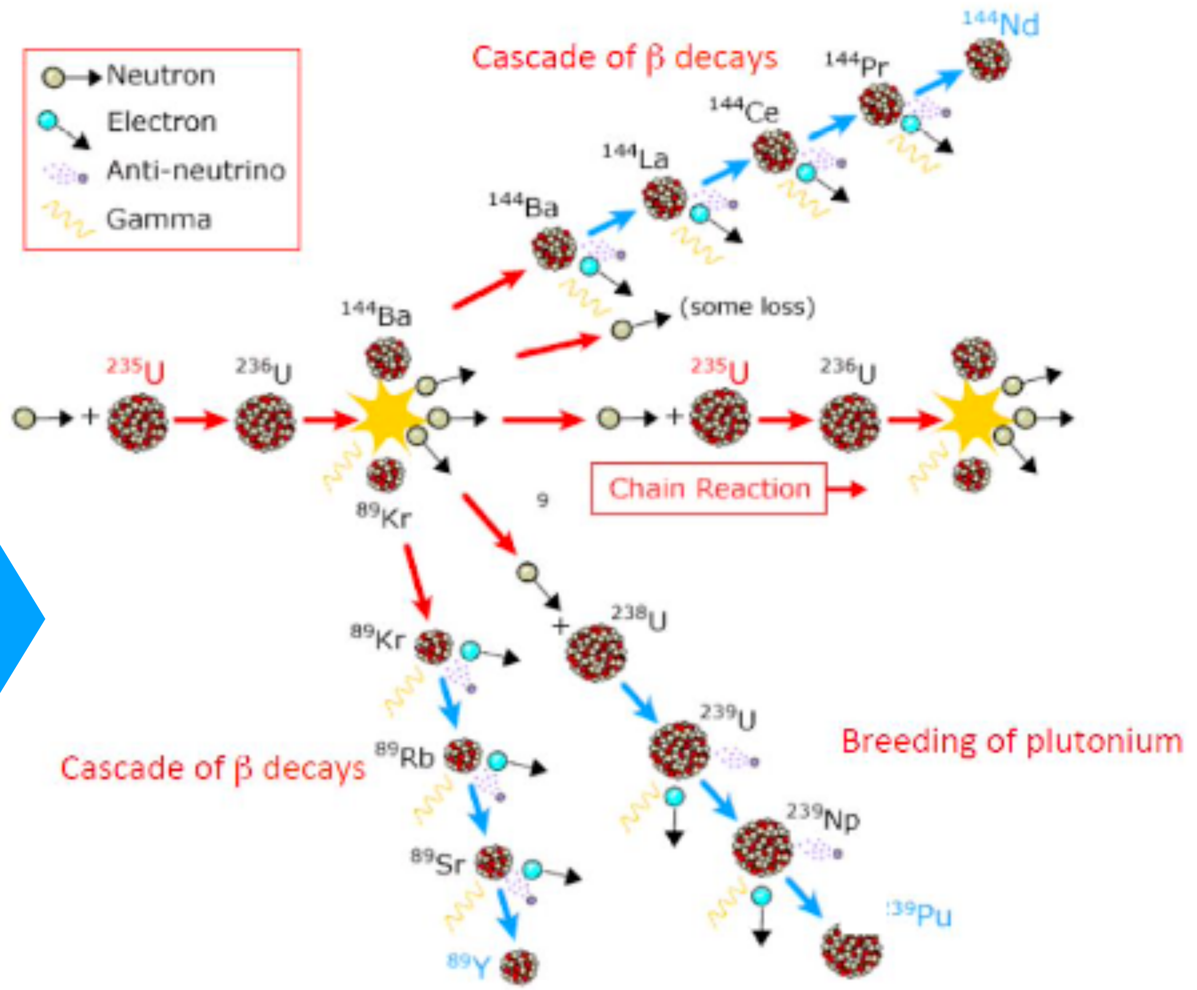




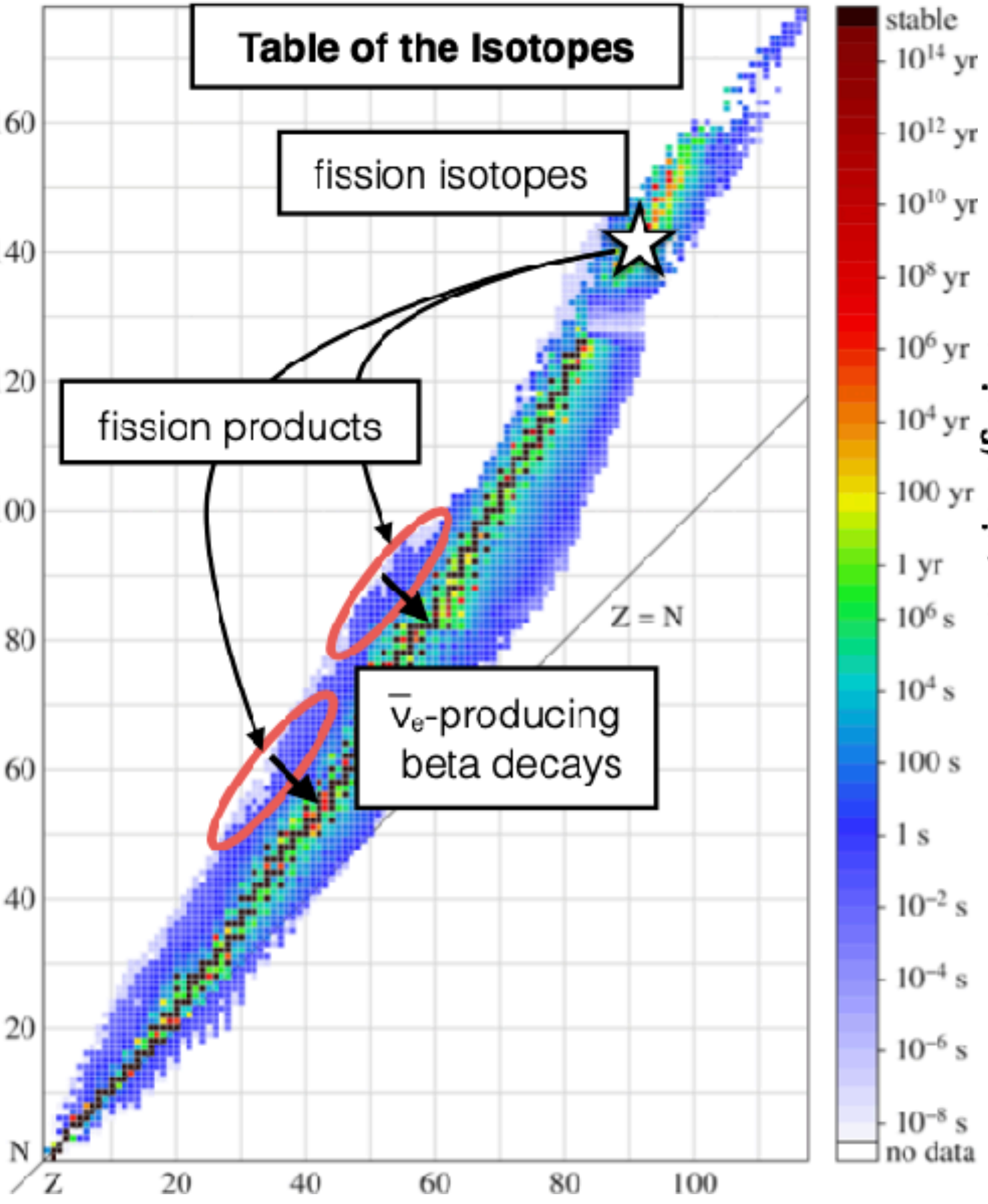
- ❑ Commercial reactors in Nuclear Power Plants have low-enriched uranium (LEU) cores
  - Mixture of fissions: ^{235}U (~55%), ^{239}Pu (~30%), ^{238}U (~10%), ^{241}Pu (~5%)
  - Large power: ~3 GW_{th}
- ❑ Research reactors have highly-enriched uranium (HEU) cores
  - ^{235}U fission fraction ~99%
  - Lower power, few tens of MW_{th}
  - compact size

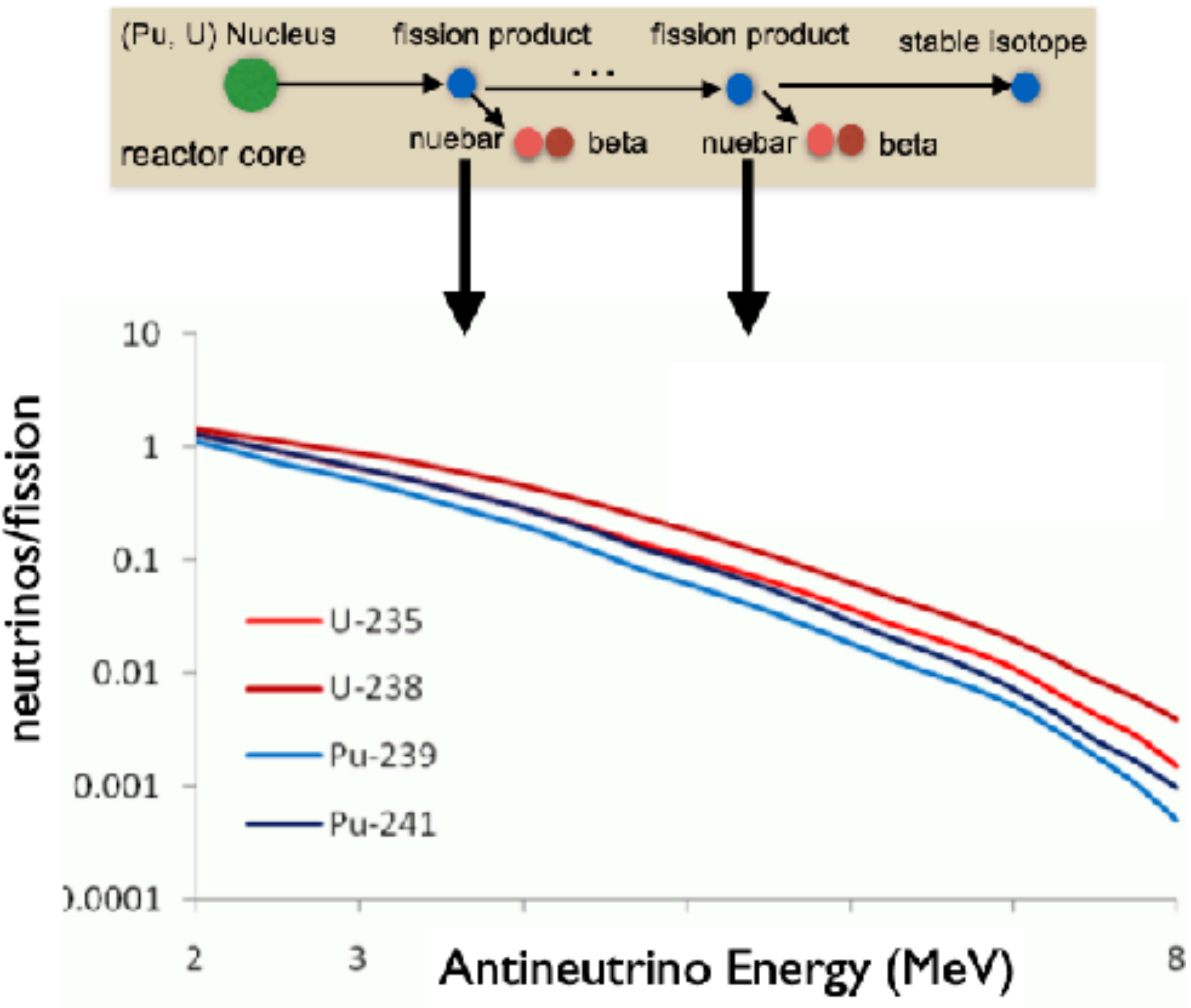
Nuclear Reactors





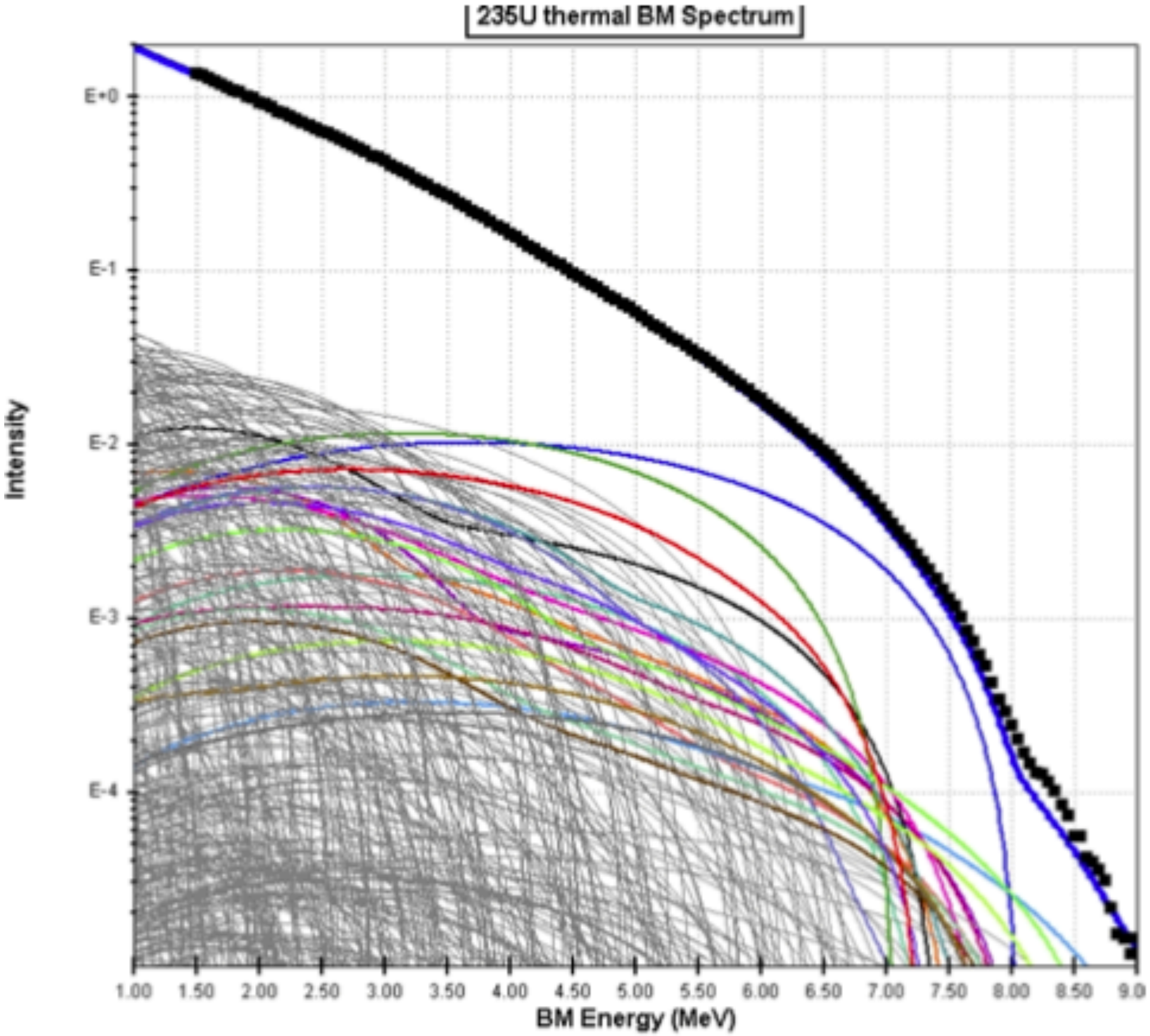
Nuclear Reactors





- ❑ Nuclear reactors produce pure $\overline{\nu}_e$ from beta decays of fission daughters
  - Low energy: < 10 MeV
- ❑ ~6 $\overline{\nu}_e$ / fission
- ❑ 2 x 10^{20} $\overline{\nu}_e$ / sec per GW_{th} (free for physicists)

Reactor Neutrinos

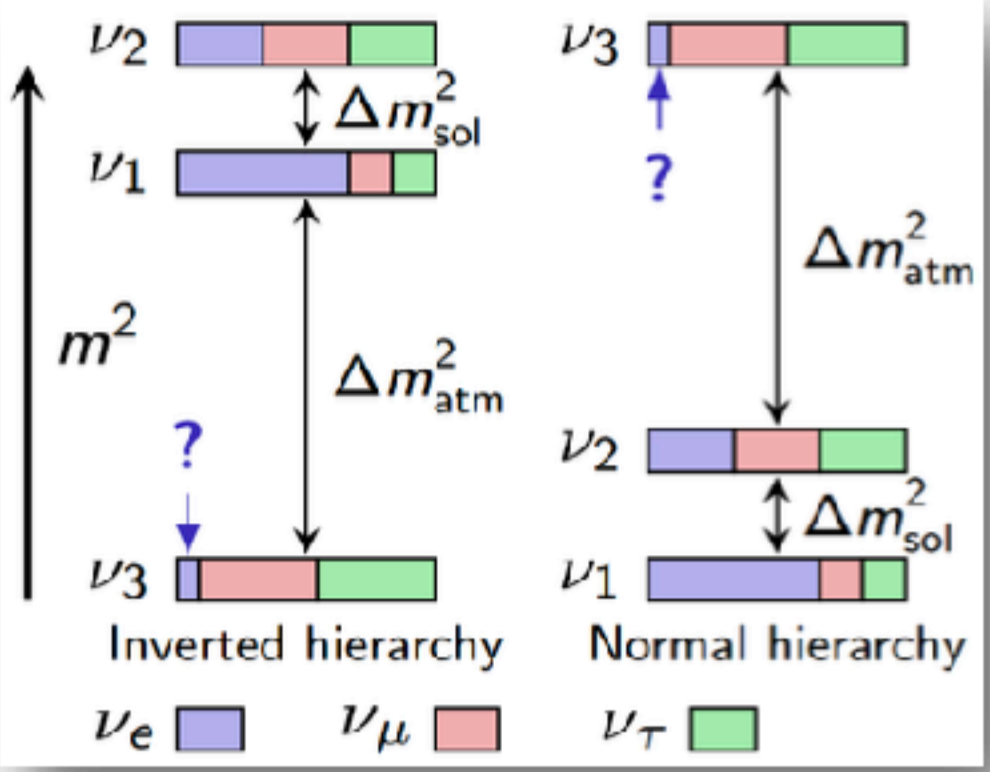


Calculated electron spectra of the 235U thermal neutron fission. The thin gray lines are from individual ß decays. The thick (color) lines highlight the 20 most important contributions to energies above 5.5 MeV. The squares are the sum of all decays and the thick blue line is the measures electron spectrum

Reactor Neutrinos

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha,i}\,|\nu_i\rangle$$

- PMNS matrix
- Mass eigenstates
- Weak eigenstates



- **Known**
  - $\theta_{12}, \theta_{23}, \boldsymbol{\theta_{13}}, \Delta m^2_{21}, |\Delta m^2_{32}|$
- **Unknown**
  - CP phase, mass hierarchy, $m_1/m_2/m_3$, δ_1/δ_2

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{-i\delta_1} & 0 & 0 \\ 0 & e^{-i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23}\sim 45^\circ$ by atmospheric neutrinos (1998)

$\theta_{13}\sim 9^\circ$ by reactor and accelerator neutrinos (2012)

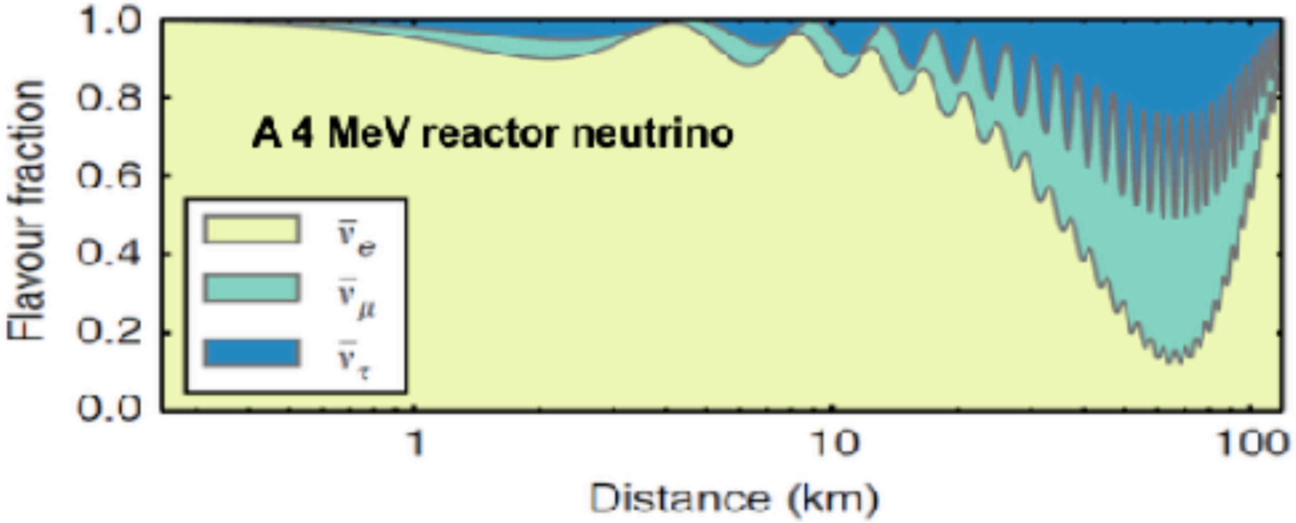
$\theta_{12}\sim 34^\circ$ by solar neutrinos (2001)

neutrino-less double beta decay

Reactor Neutrinos

Neutrino Oscillations

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - 4 s_{13}^2 c_{13}^2 \left(c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32} \right) - 4 c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \Delta_{21}$$



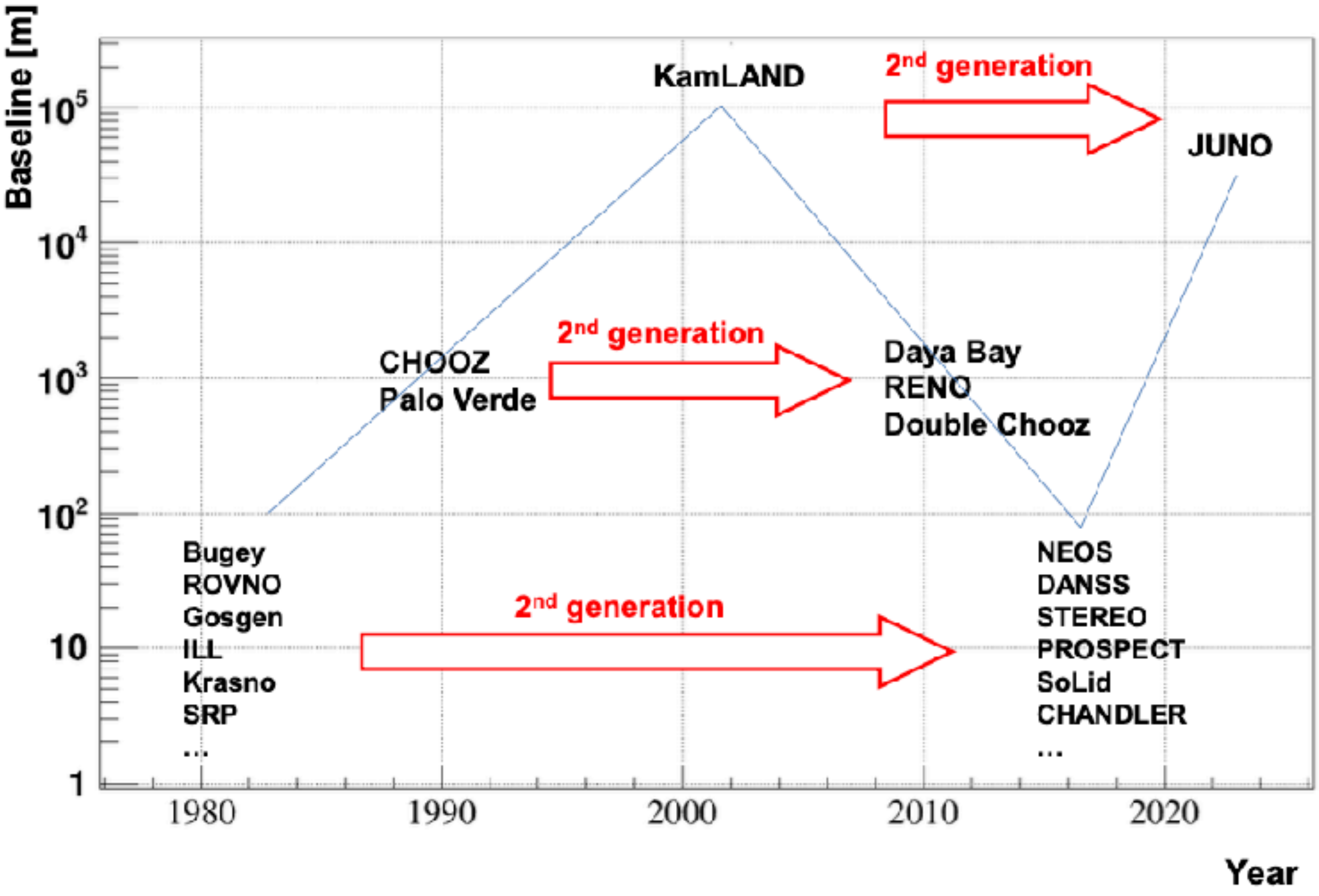
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\downarrow$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_1/2} & 0 \\ 0 & 0 & e^{-i\alpha_2/2} \end{pmatrix}$$

Atmospheric / Long baseline accelerator	Short baseline reactor / Long baseline accelerator	Solar / Long baseline reactor	Neutrinoless double beta decay

Reactor Neutrino Experiments



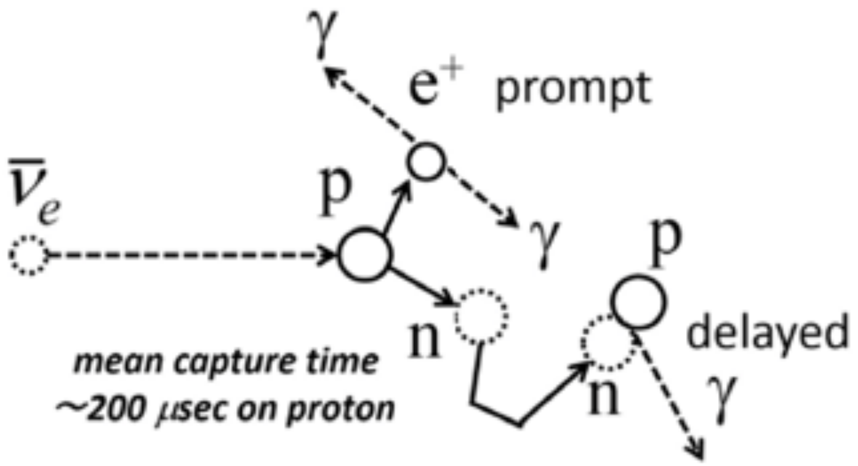
New generation of reactor neutrino experiments

- ❑ Precision measurement of neutrino oscillation parameters
- ❑ Search for new oscillation from sterile neutrinos
- ❑ Precision measurement of reactor neutrino flux and spectrum

Inverse beta decay

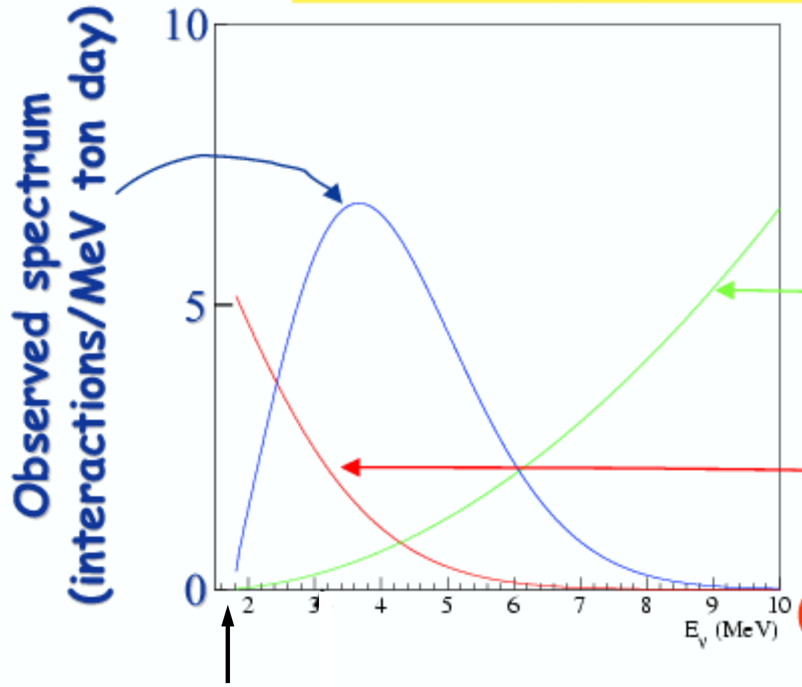
The energy threshold of inverse β-decay,

$$E_\nu^{thr} = [(M_n + m_e)^2 - M_p^2] / 2M_p = 1.806 \text{ MeV},$$



mean capture time ~200 μsec on proton

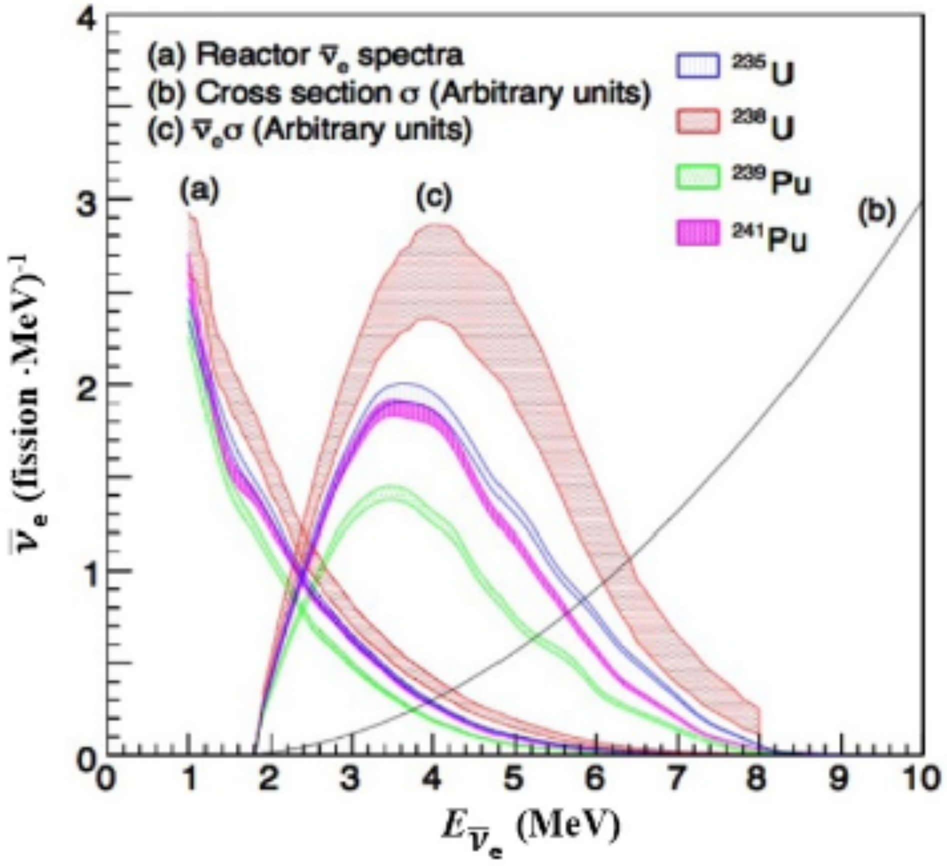
The $\bar{\nu}_e$ energy spectrum



ν_e+p→n+e^+ cross section (~10^{-42} cm^2)

Calculated reactor $\bar{\nu}_e$ spectrum (10^{-8} /s MeV GW$_{th}$)

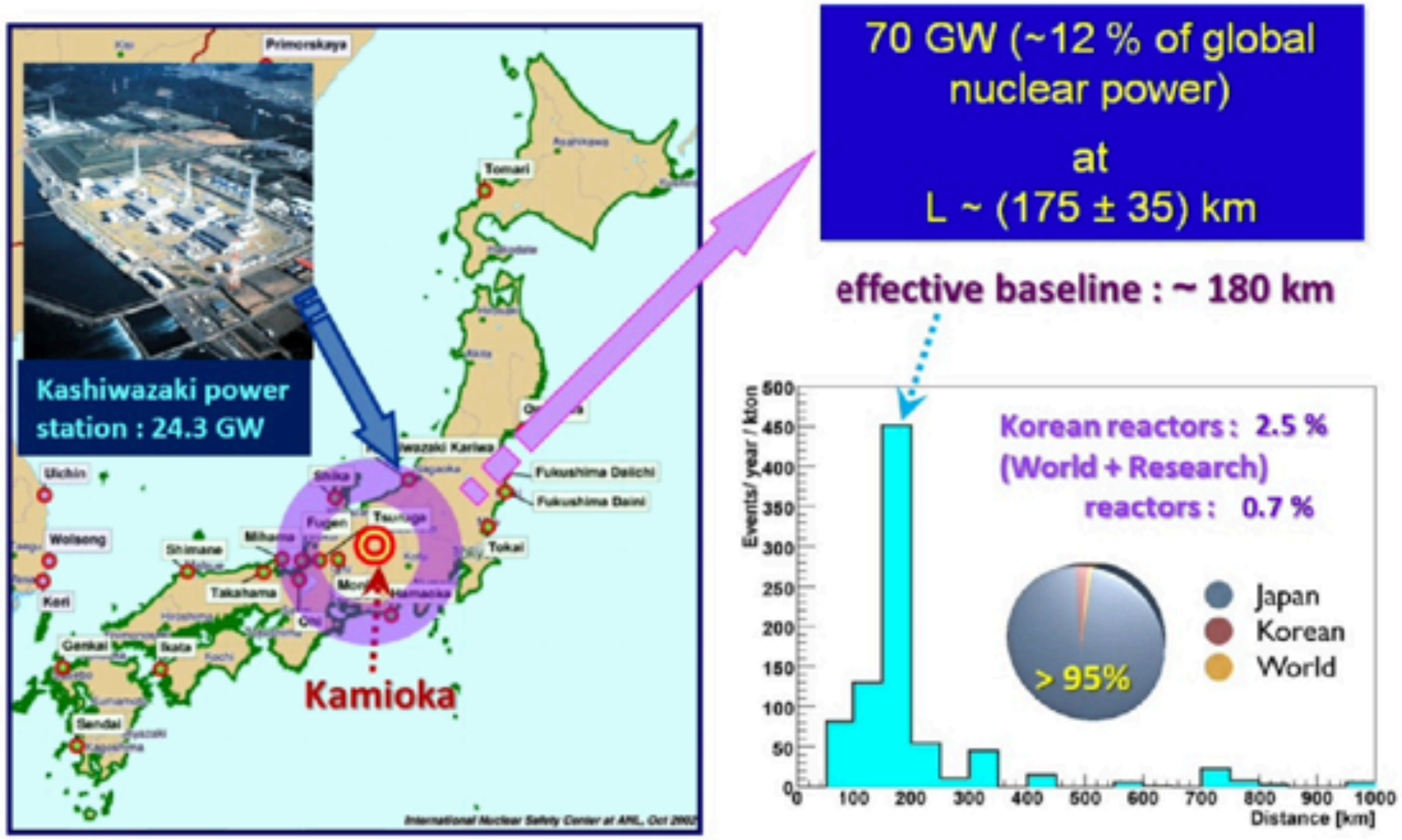
Neutrinos with E<1.8 MeV are not detected



KamLAND

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

$$1.27 \frac{GeV}{km} \frac{180\, km}{4\, 10^{-3}\, GeV} \Delta m^2 \sim 6\, 10^4\, \Delta m^2$$



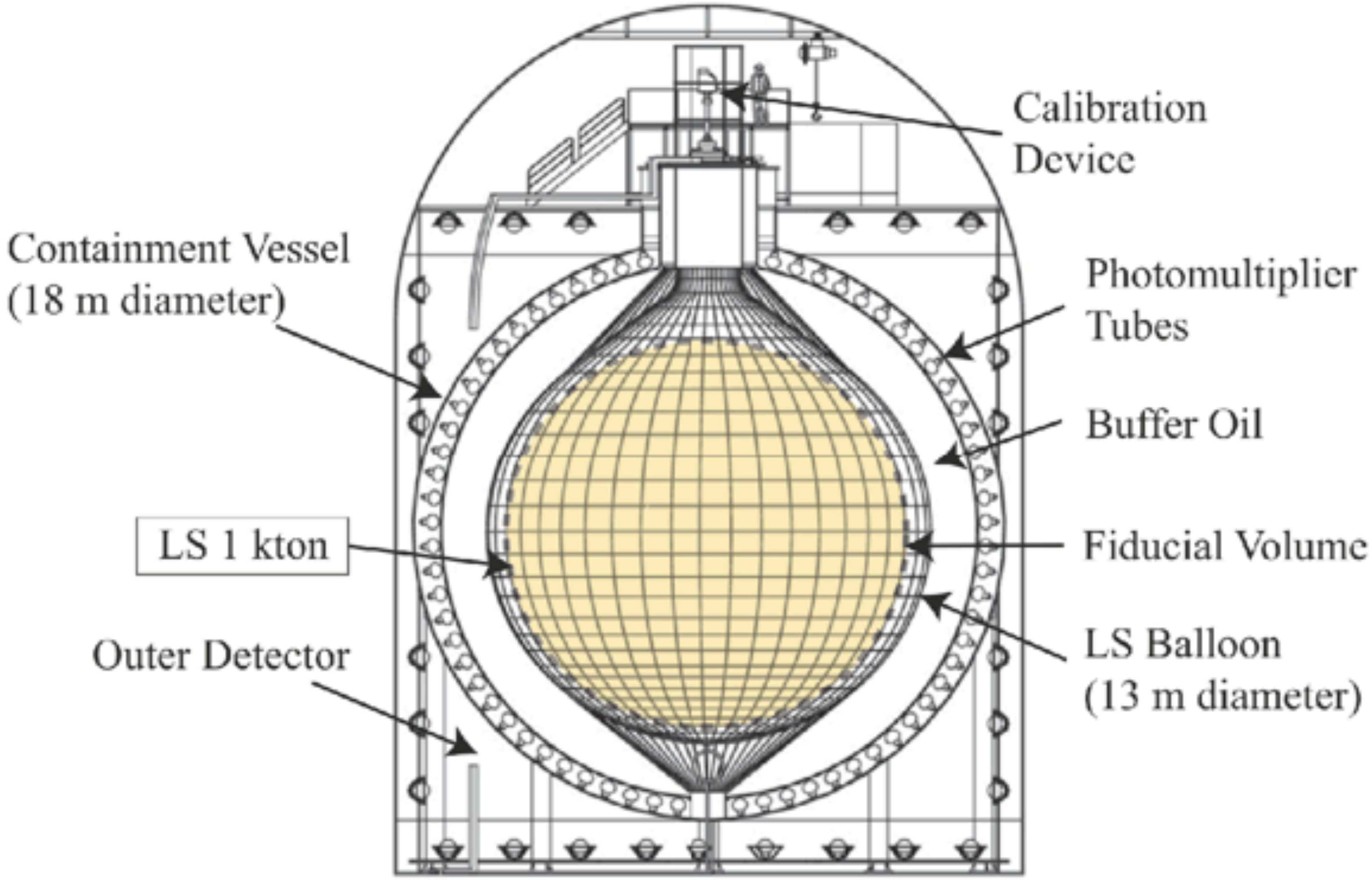
70 GW (~12 % of global nuclear power) at L ~ (175 ± 35) km

effective baseline : ~ 180 km

The experiment is surrounded by more than 50 nuclear reactors at various commercial Nuclear Power Plants. Most Nuclear Power Plants operate multiple reactors. The flux-weighted average distance of the reactors to KamLAND is ~180 km. Neutrino flux is approx. 6 × 10^6/cm^2/sec at site.

Sensitive to the neutrino oscillation solutions of the ‘solar neutrino problem’ for solar mass-splitting values of **Δm^2_{12} ~ 10^{-5} eV^2**

KamLAND



- Active volume: 1 kt of 20% pseudocumbne + 80% mineral oil + 1.36 g/liter of PPO
- 1800 m^3 buffer oil
- 1879 20” PMTs (photocoverage of 34%)
- Veto: ~3200 m3 of pure water equipped with 225 20-inch PMT’s
- Shielded by 2700 m.w.e. of rock at the Kamioka mine

KamLAND

Trigger: 200 PMT hits corresponding to about 0.7 MeV.

Cuts:

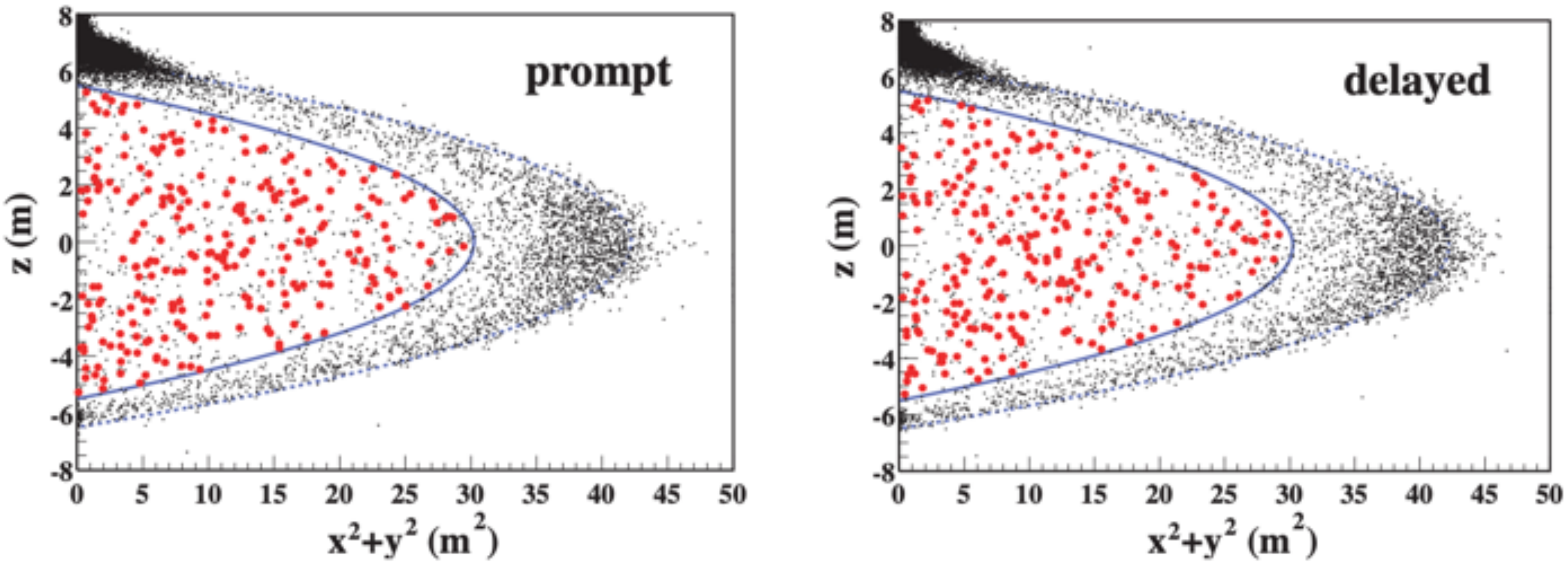
- fiducial volume: $R < 5.5\,\mathrm{m}$
- time correlation ($0.5\mu\mathrm{s} < \Delta t < 660\,\mu\mathrm{s}$)
- delayed energy ($1.8\,\mathrm{MeV} < E_{\mathrm{delay}} < 2.6\,\mathrm{MeV}$)

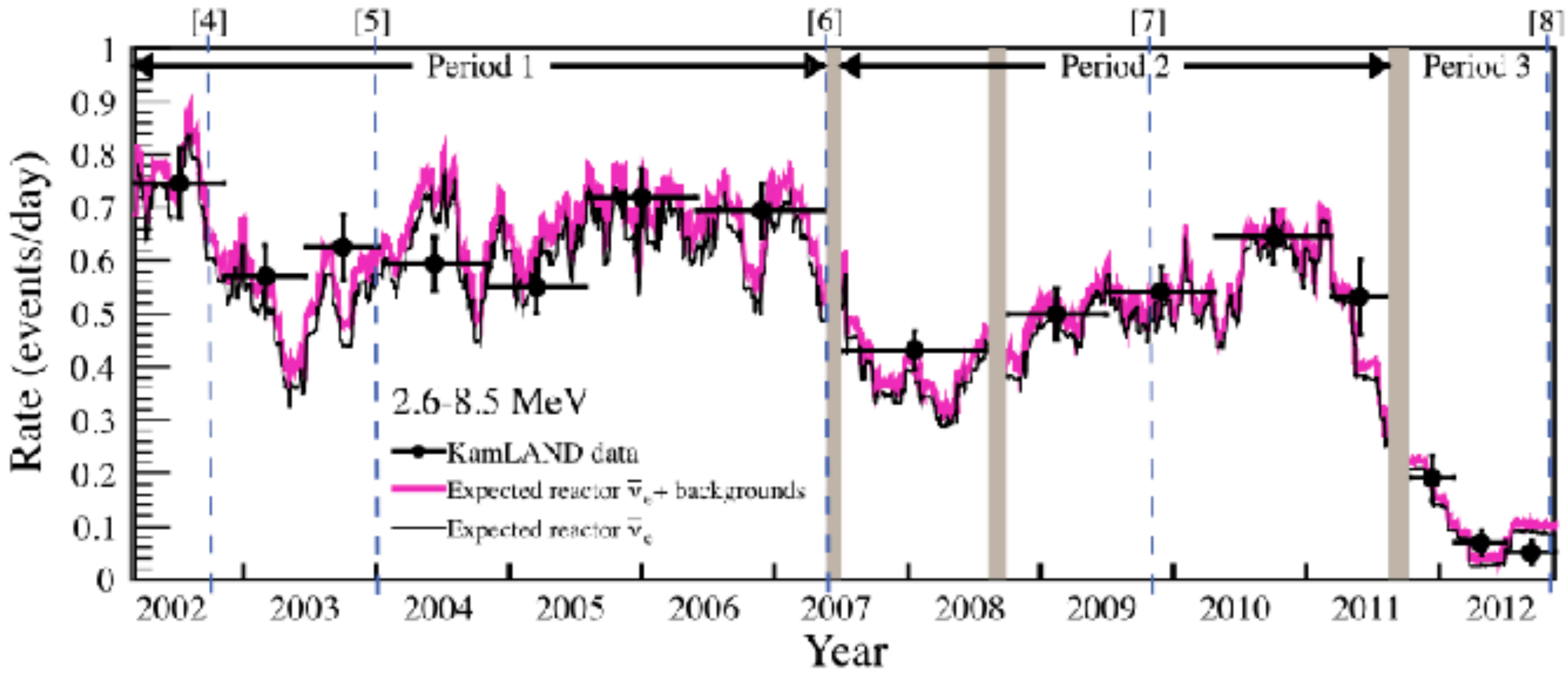
$\Rightarrow$ Fiducial Volume contains 4.61×10^{31} free protons

$\Rightarrow$ Spatial resolution of 25 cm (Reconstructed from the timing of PMT hits)

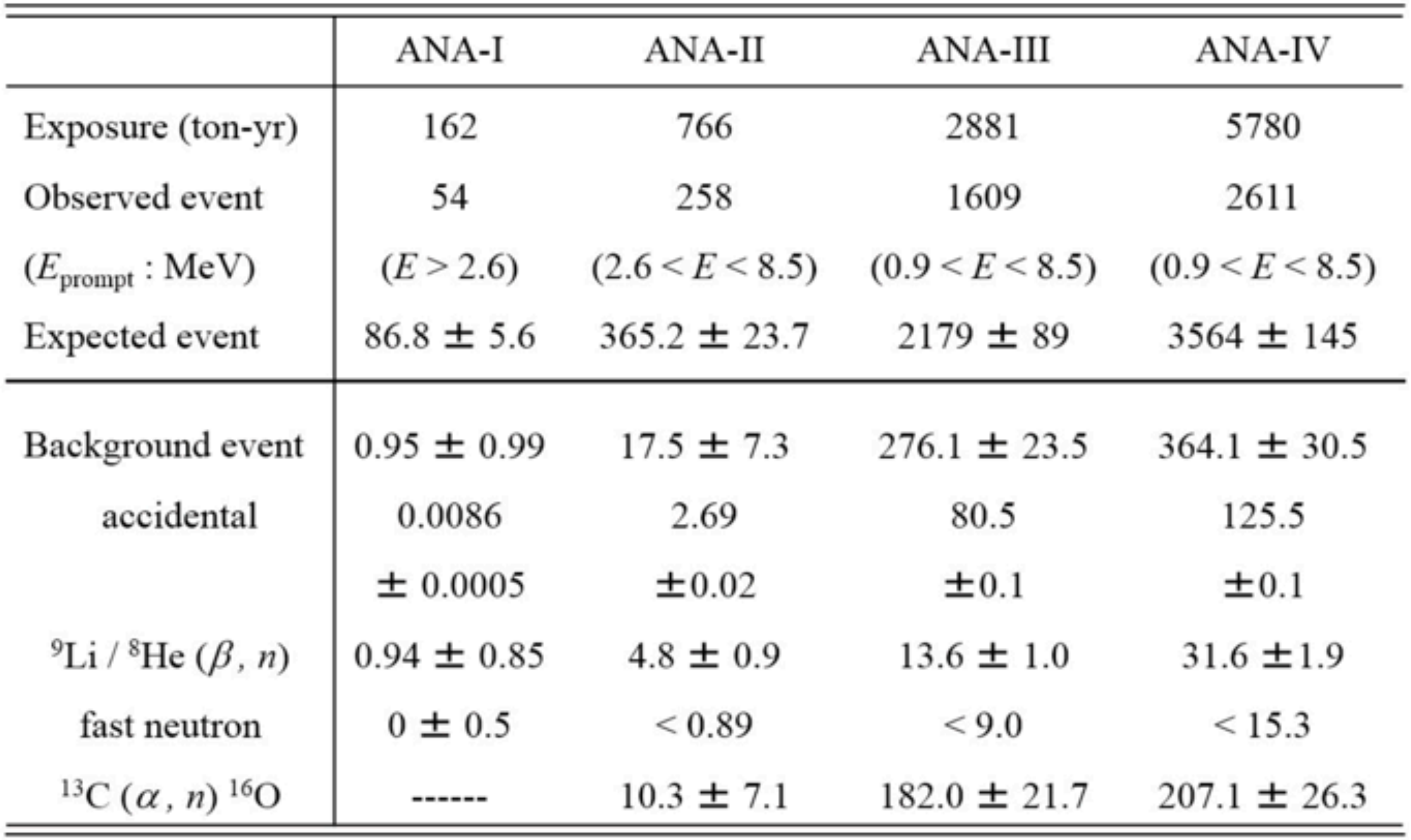
Events with less than 10000 p.e. (approx. 30 MeV) and no prompt tag from the outer detector are candidates for reactor $\bar{\nu}_e$, more energetic events are muon candidates.

KamLAND


prompt
delayed
z (m)
8
6
4
2
0
-2
-4
-6
-8
0
5
10
15
20
25
30
35
40
45
50
x^2+y^2 (m^2)

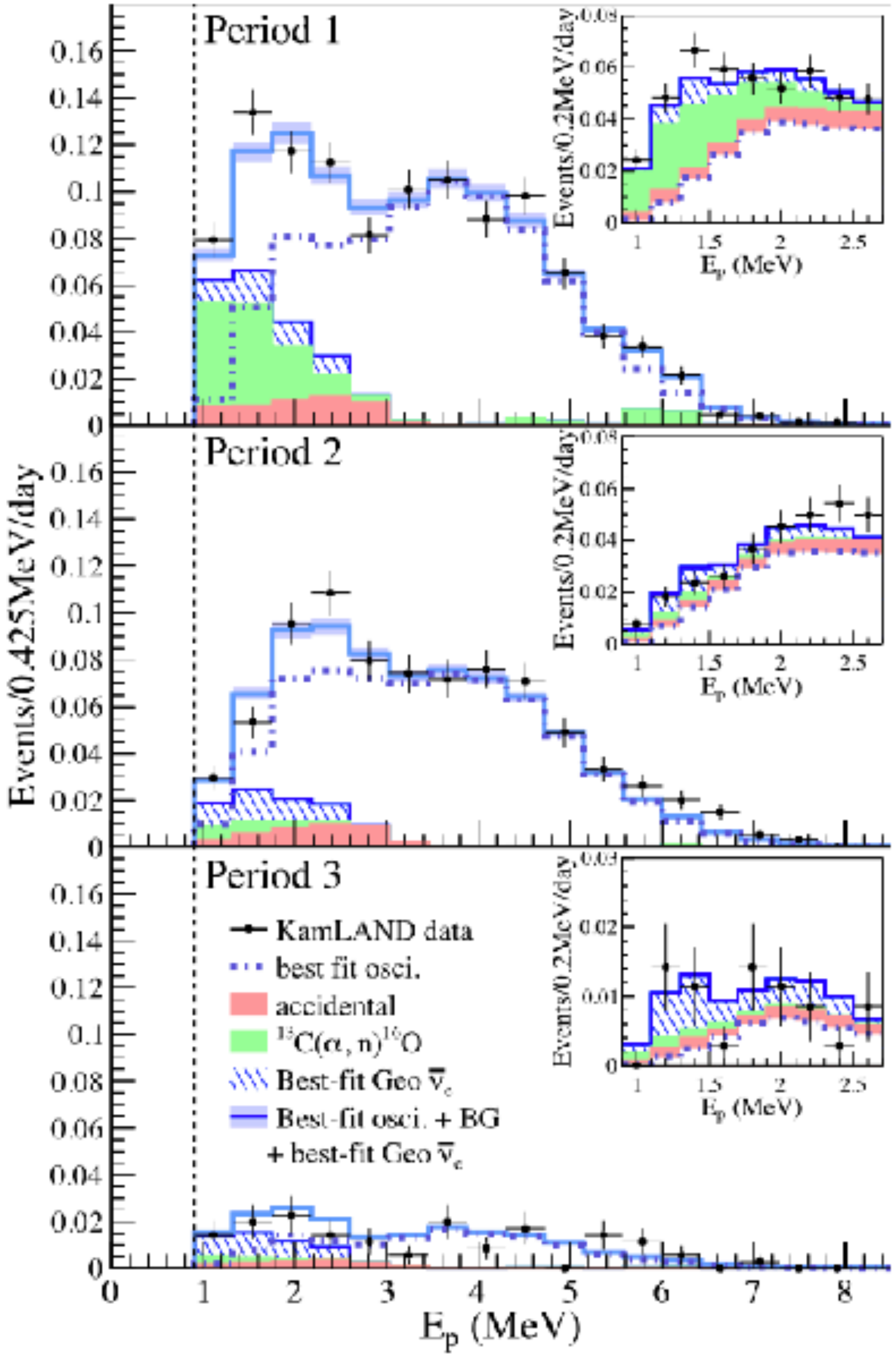

[4]
[5]
[6]
[7]
[8]
Period 1
Period 2
Period 3
Rate (events/day)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2.6-8.5 MeV
KamLAND data
Expected reactor $\bar{\nu}_e$ + backgrounds
Expected reactor $\bar{\nu}_e$
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Year

KamLAND

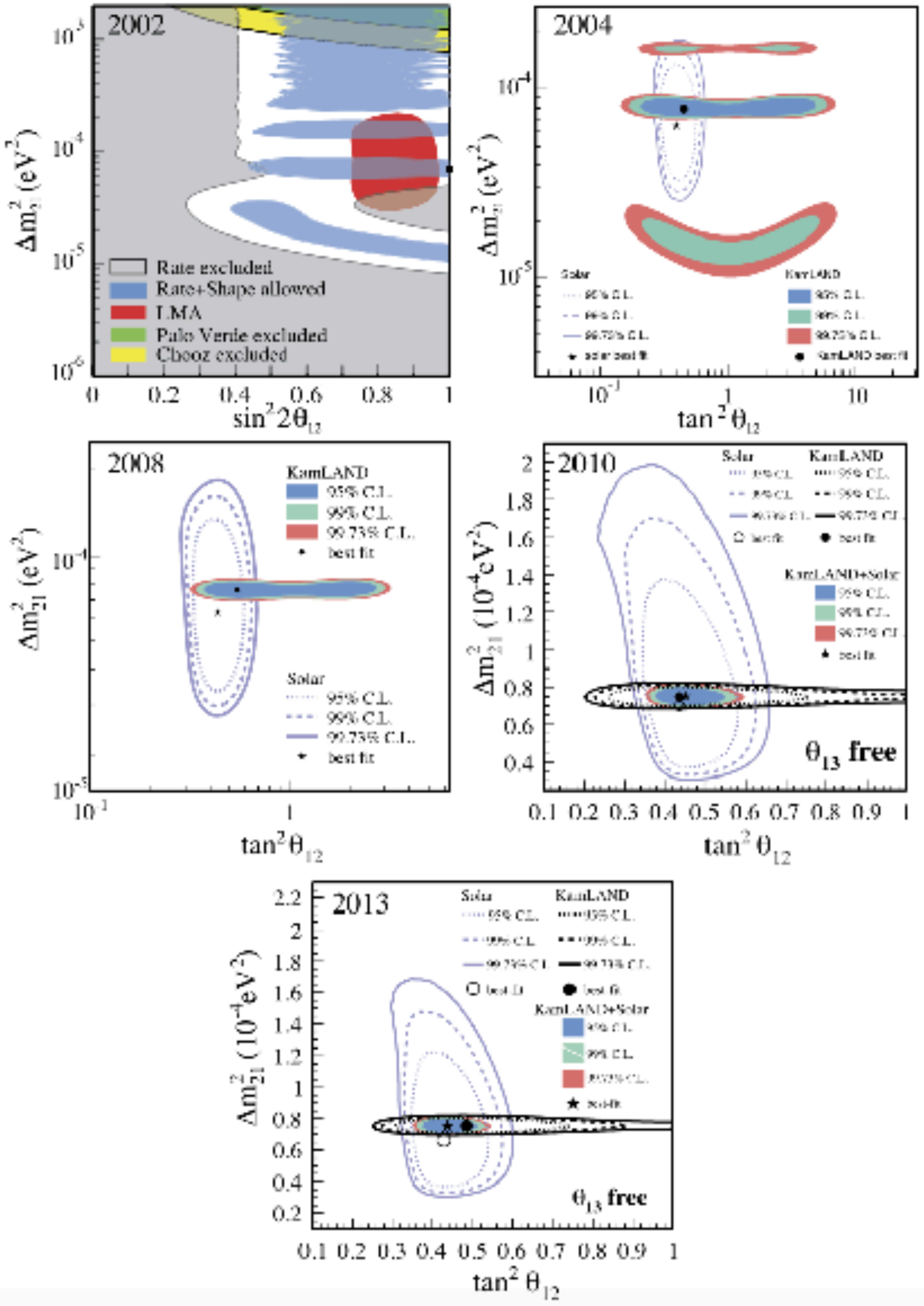


	ANA-I	ANA-II	ANA-III	ANA-IV
Exposure (ton-yr)	162	766	2881	5780
Observed event	54	258	1609	2611
(E_{prompt} : MeV)	($E > 2.6$)	($2.6 < E < 8.5$)	($0.9 < E < 8.5$)	($0.9 < E < 8.5$)
Expected event	86.8 ± 5.6	365.2 ± 23.7	2179 ± 89	3564 ± 145
Background event	0.95 ± 0.99	17.5 ± 7.3	276.1 ± 23.5	364.1 ± 30.5
accidental	0.0086 ± 0.0005	2.69 ±0.02	80.5 ±0.1	125.5 ±0.1
^{9}Li / ^{8}He (β, n)	0.94 ± 0.85	4.8 ± 0.9	13.6 ± 1.0	31.6 ±1.9
fast neutron	0 ± 0.5	< 0.89	< 9.0	< 15.3
^{13}C (α, n) ^{16}O	------	10.3 ± 7.1	182.0 ± 21.7	207.1 ± 26.3

KamLAND

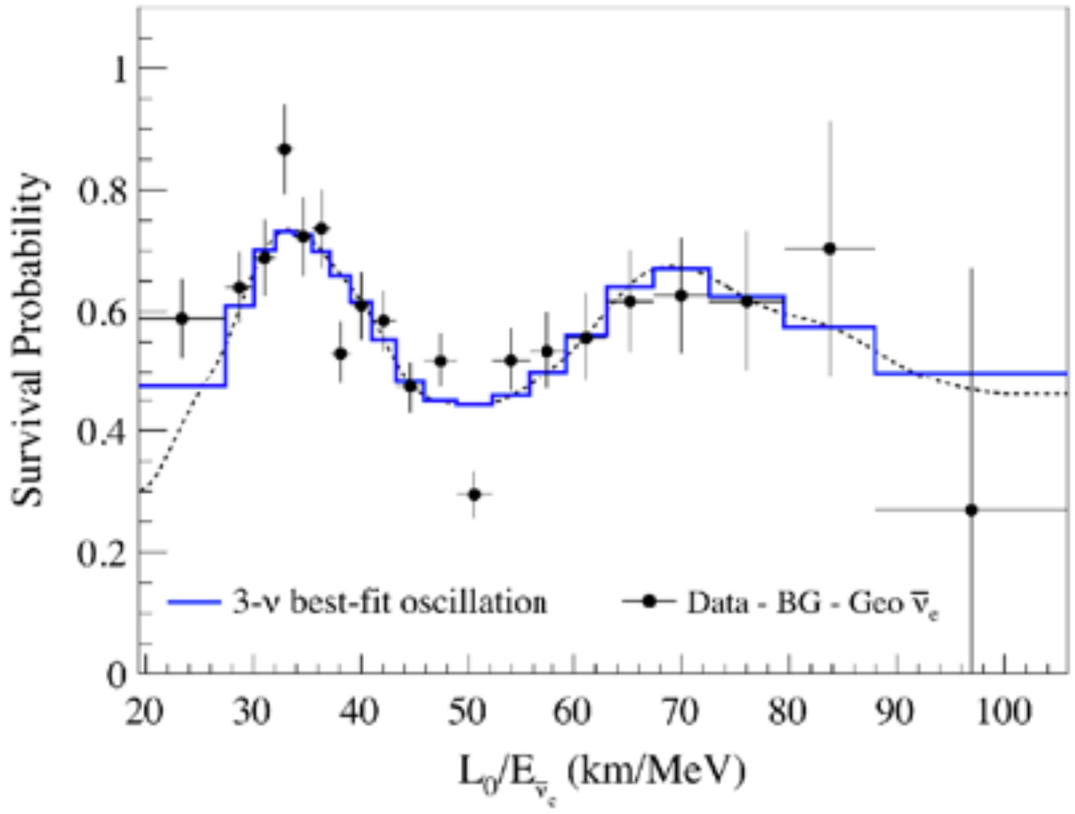


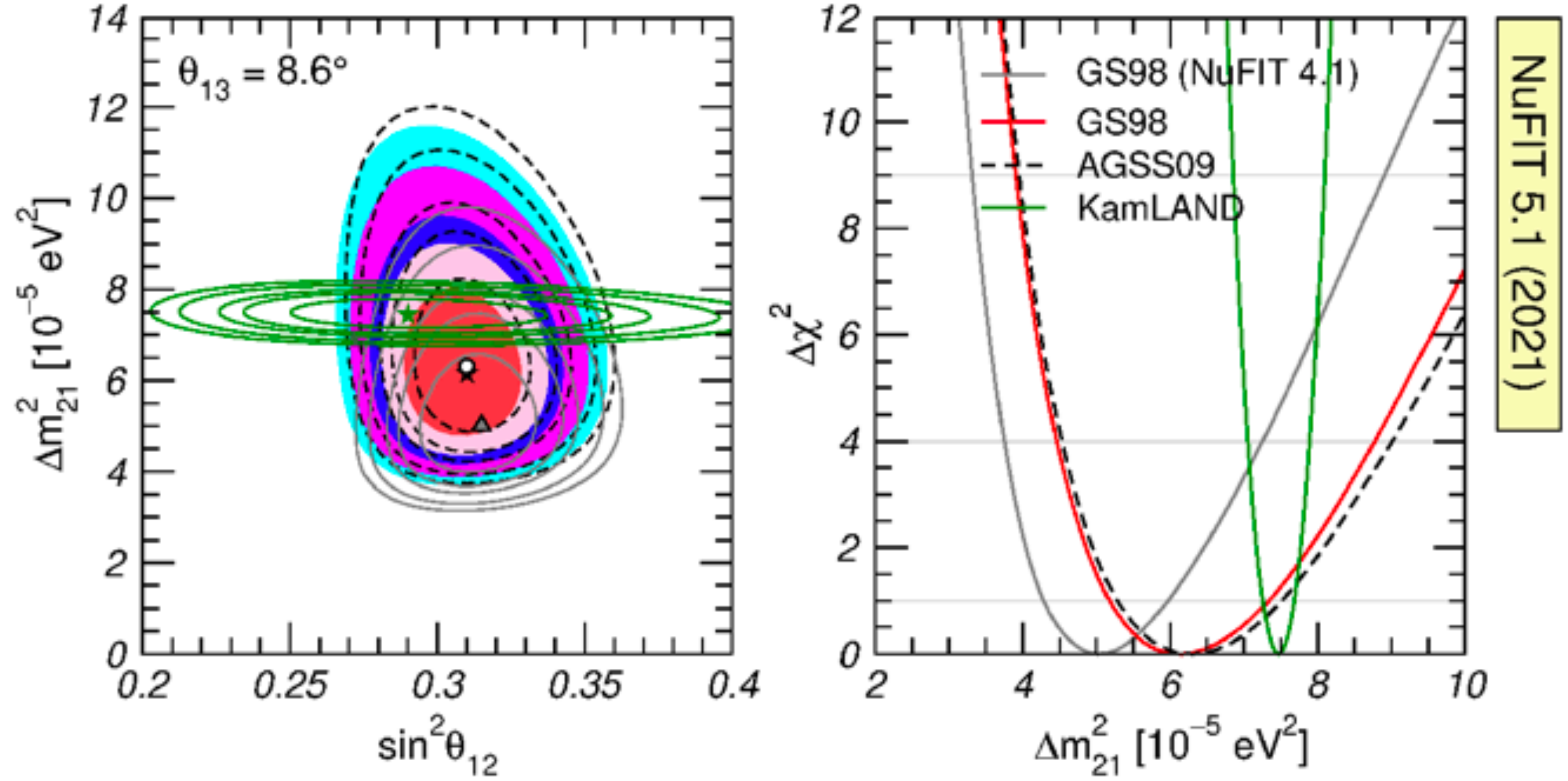
Period 1
Period 2
Period 3
Events/0.425MeV/day
Events/0.2MeV/day
E$_p$ (MeV)
KamLAND data
best fit osci.
accidental
^{13}C(α, n)^{16}O
Best-fit Geo $\bar{\nu}_e$
Best-fit osci. + BG + best-fit Geo $\bar{\nu}_e$



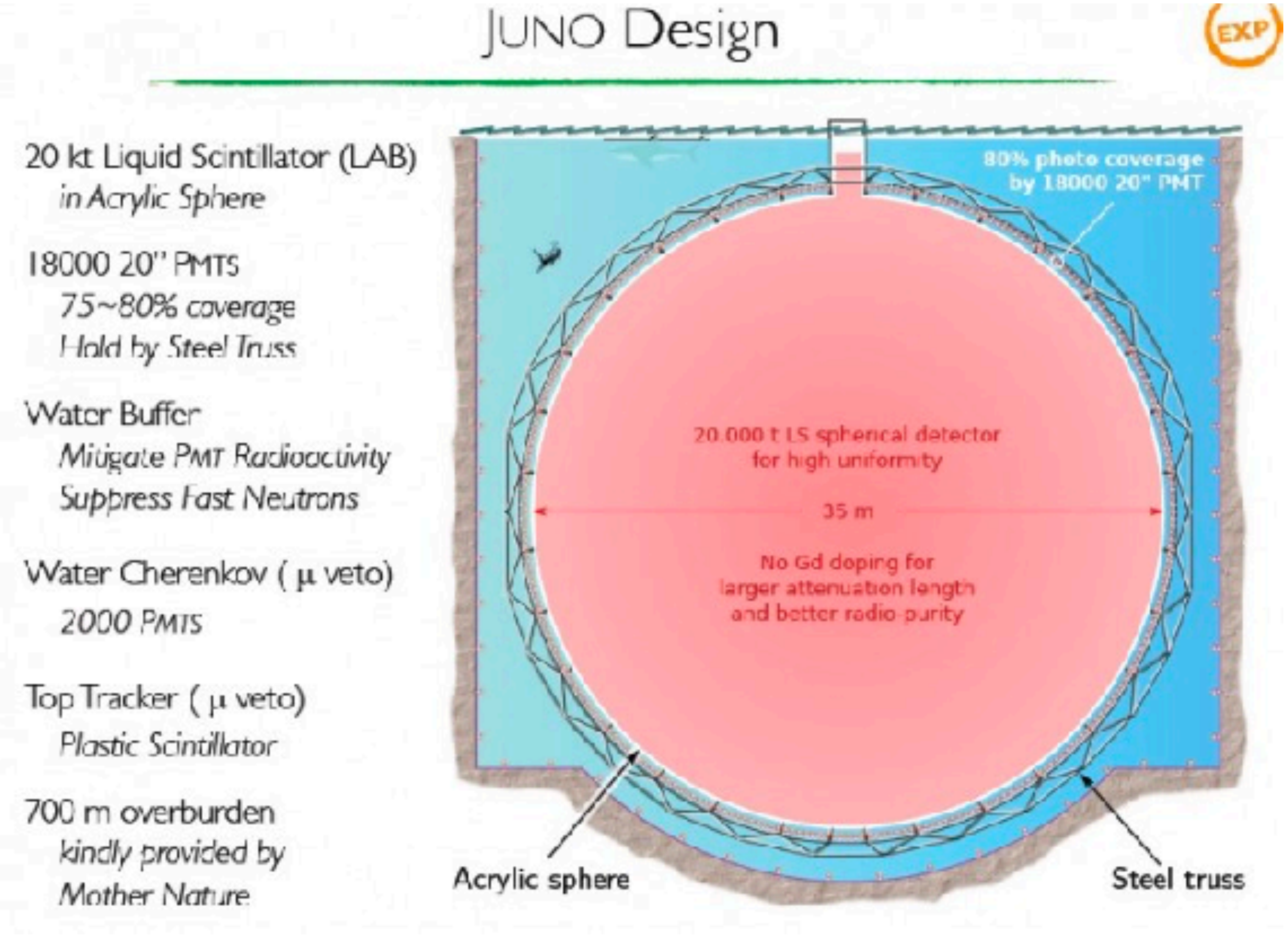
2002
2004
2008
2010
2013
Rate excluded
Rate+Shape allowed
LMA
Palo Verde excluded
Chooz excluded
Δm^2_{21} (eV^2)
Δm^2_{21} (10^{-4}eV^2)
$\sin^2 2\theta_{12}$
$\tan^2\theta_{12}$
KamLAND
Solar
KamLAND+Solar
95% C.L.
99% C.L.
99.73% C.L.
best fit
θ_{13} free

KamLAND


Survival Probability
0
0.2
0.4
0.6
0.8
1
20
30
40
50
60
70
80
90
100
$L_0/E_{\bar{\nu}_e}$ (km/MeV)
3-ν best-fit oscillation
Data - BG - Geo $\bar{\nu}_e$


$\theta_{13} = 8.6°$
Δm^2_{21} [10^{-5} eV^2]
0
2
4
6
8
10
12
14
0.2
0.25
0.3
0.35
0.4
$\sin^2\theta_{12}$
$\Delta\chi^2$
0
2
4
6
8
10
12
2
4
6
8
10
Δm^2_{21} [10^{-5} eV^2]
GS98 (NuFIT 4.1)
GS98
AGSS09
KamLAND
NuFIT 5.1 (2021)

JUNO



JUNO Design

20 kt Liquid Scintillator (LAB)
in Acrylic Sphere

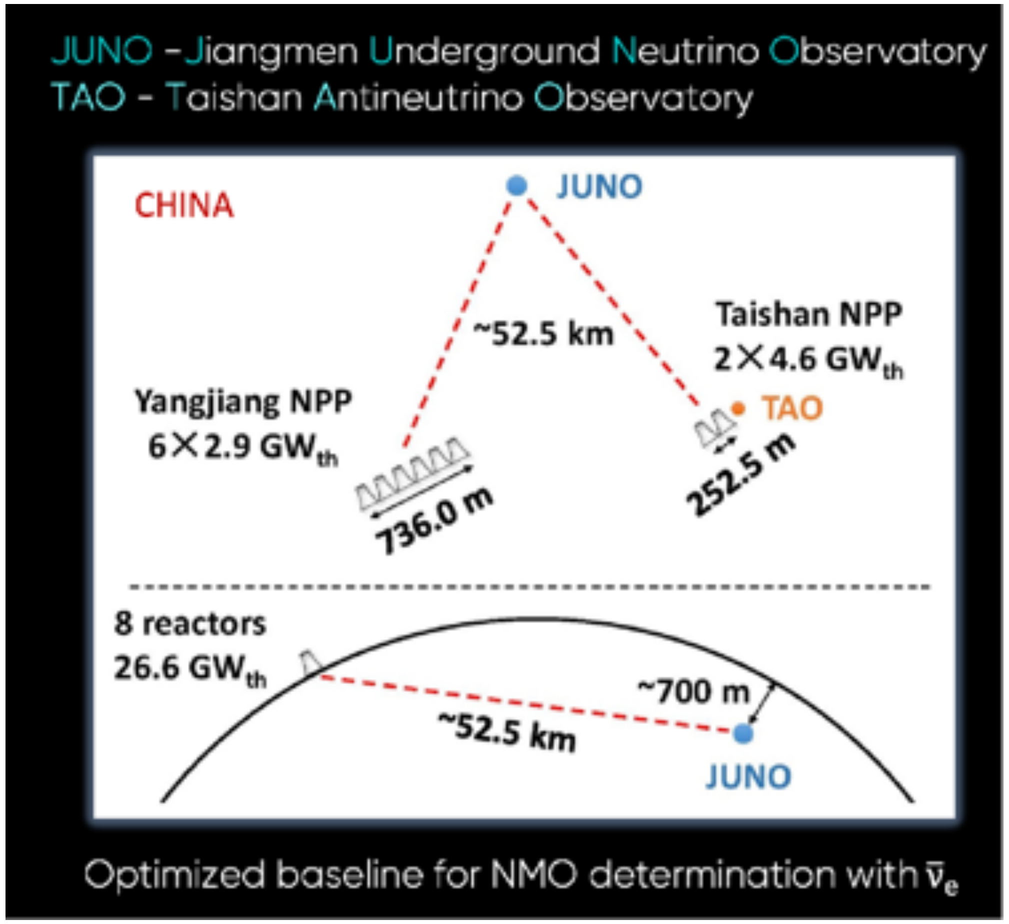
18000 20" PMTs
75~80% coverage
Hold by Steel Truss

Water Buffer
Mitigate PMT Radioactivity
Suppress Fast Neutrons

Water Cherenkov (μ veto)
2000 PMTs

Top Tracker (μ veto)
Plastic Scintillator

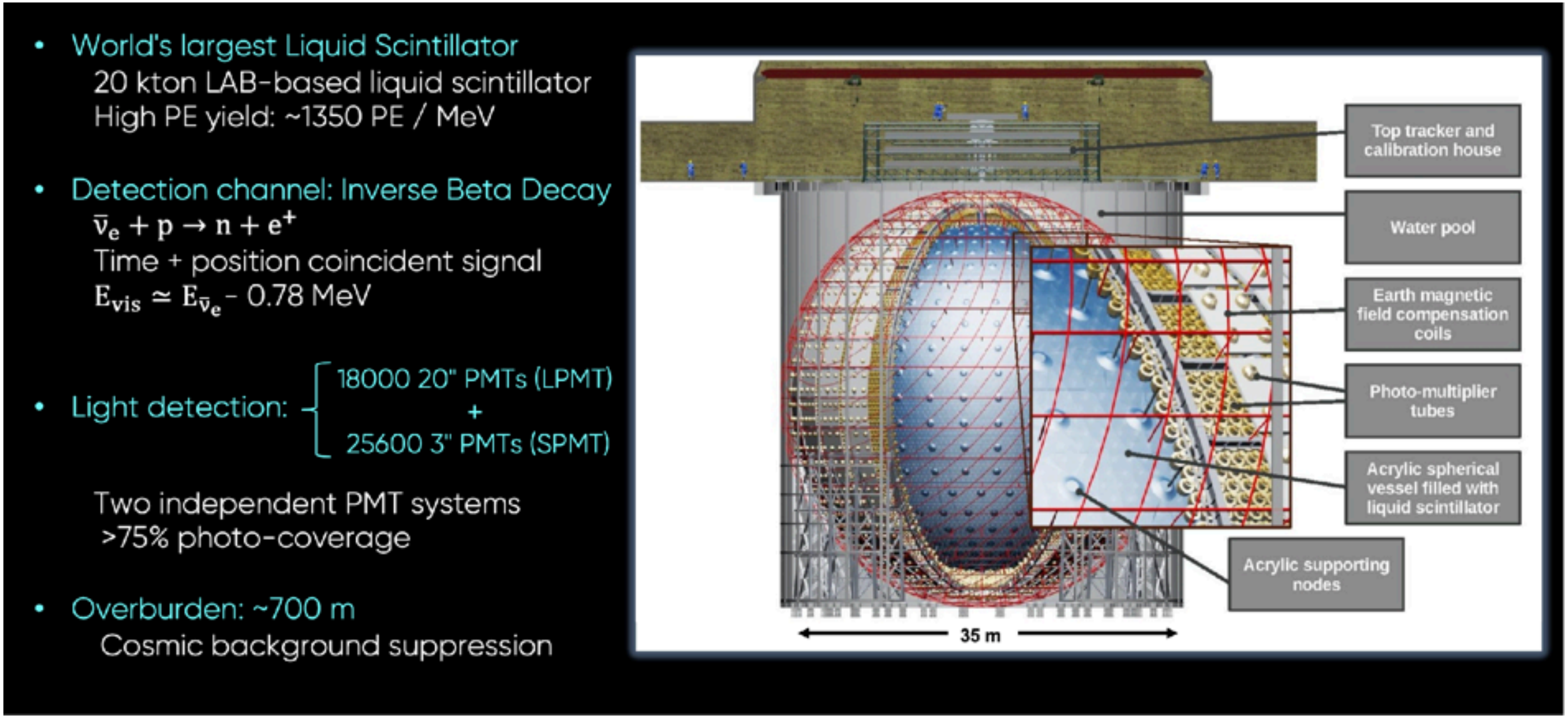
700 m overburden
kindly provided by
Mother Nature



JUNO - Jiangmen Underground Neutrino Observatory
TAO - Taishan Antineutrino Observatory

Optimized baseline for NMO determination with $\bar{\nu}_e$

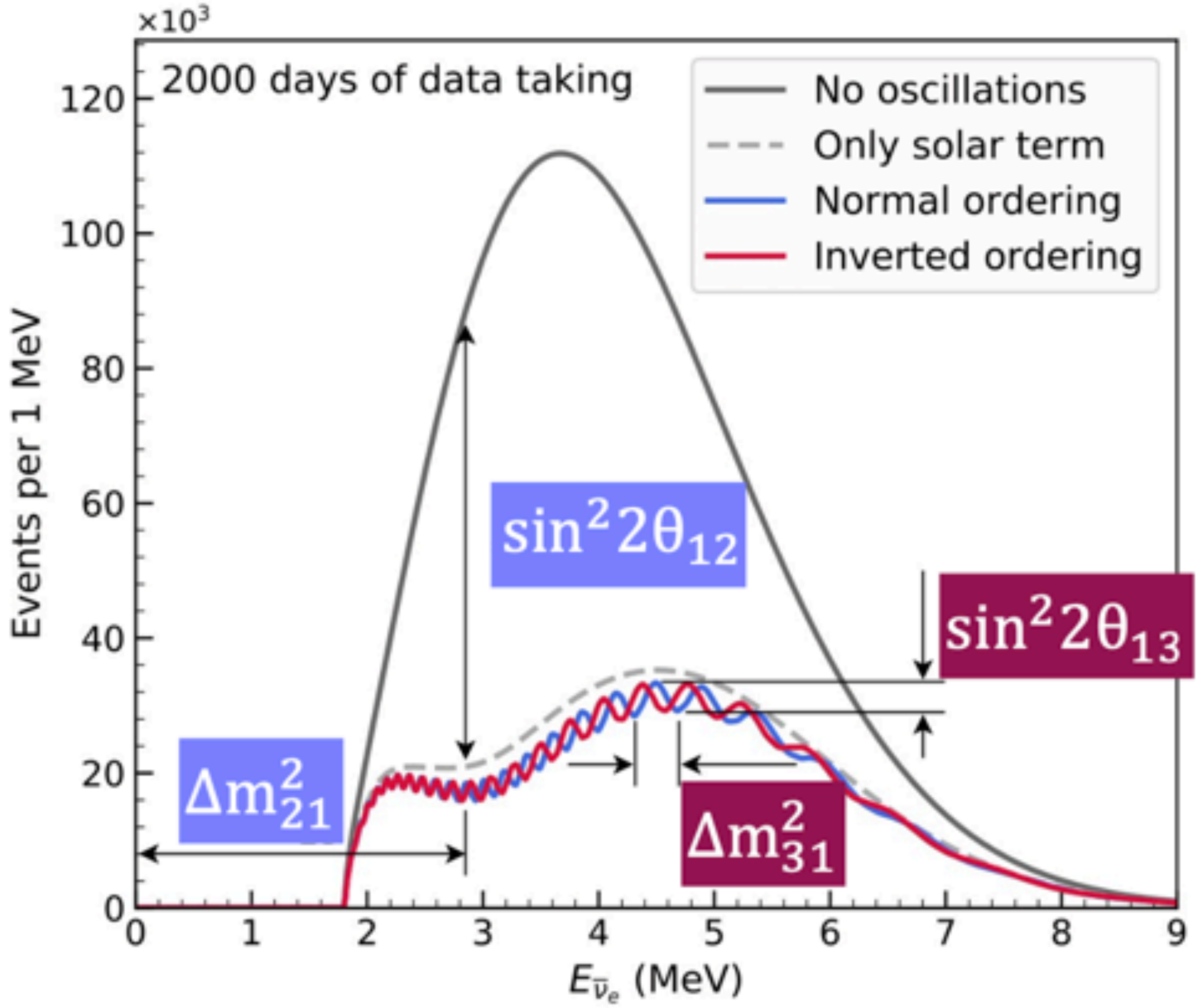
JUNO



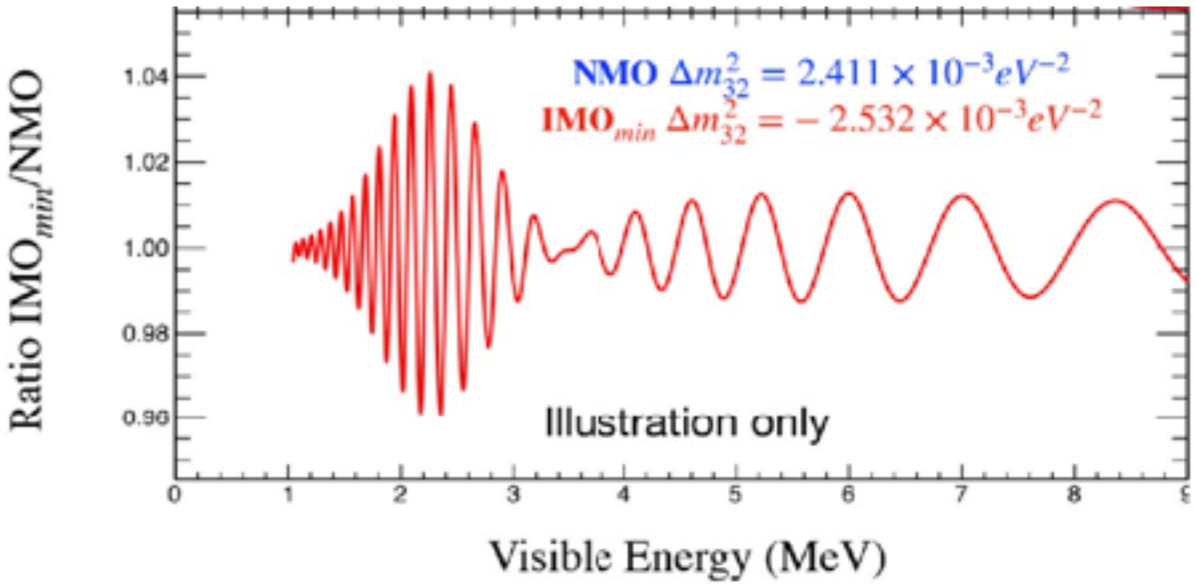
- World's largest Liquid Scintillator
  20 kton LAB-based liquid scintillator
  High PE yield: ~1350 PE / MeV
- Detection channel: Inverse Beta Decay
  $\bar{\nu}_e + p \rightarrow n + e^+$
  Time + position coincident signal
  $E_{vis} \simeq E_{\bar{\nu}_e}$ - 0.78 MeV
- Light detection: 18000 20" PMTs (LPMT) + 25600 3" PMTs (SPMT)

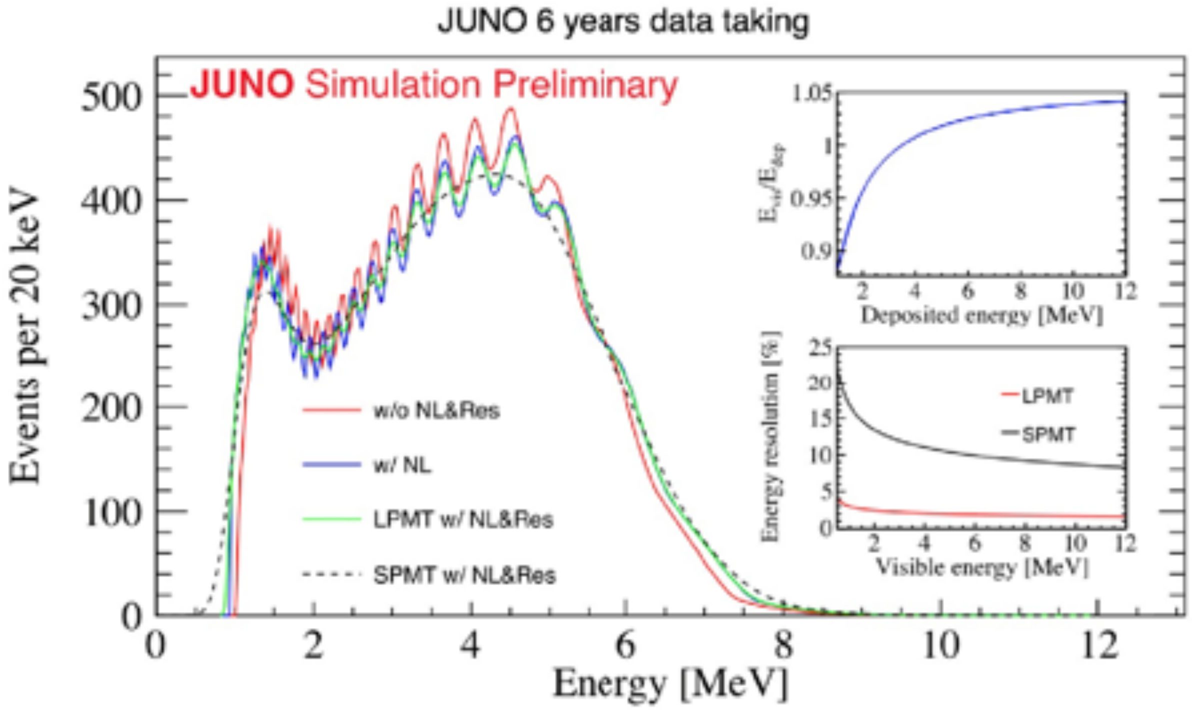
  Two independent PMT systems
  >75% photo-coverage
- Overburden: ~700 m
  Cosmic background suppression

JUNO

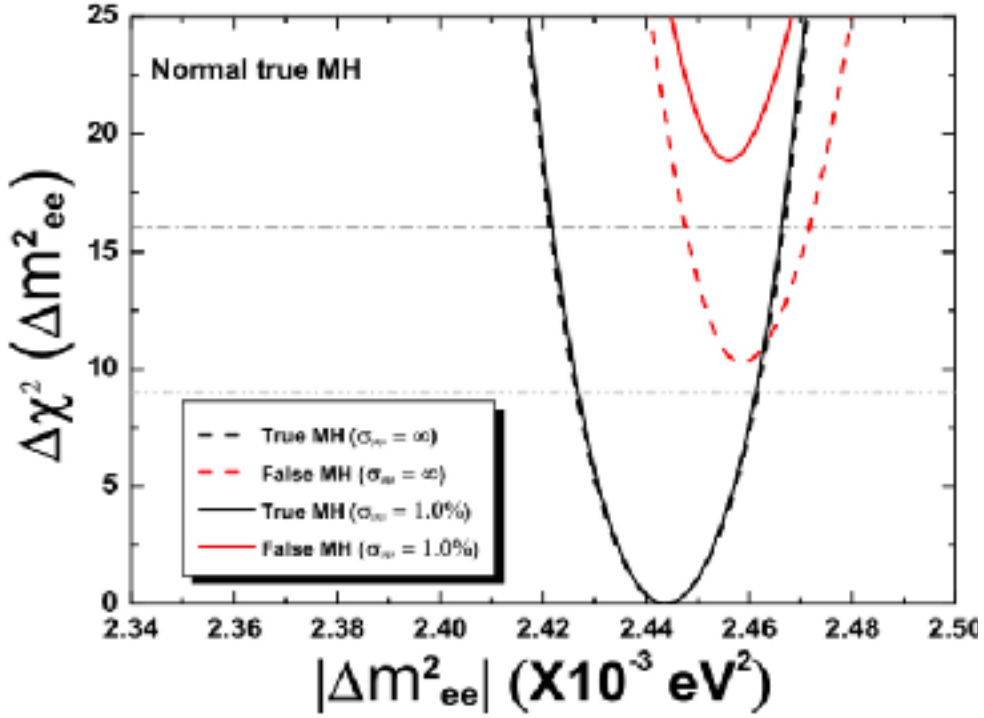


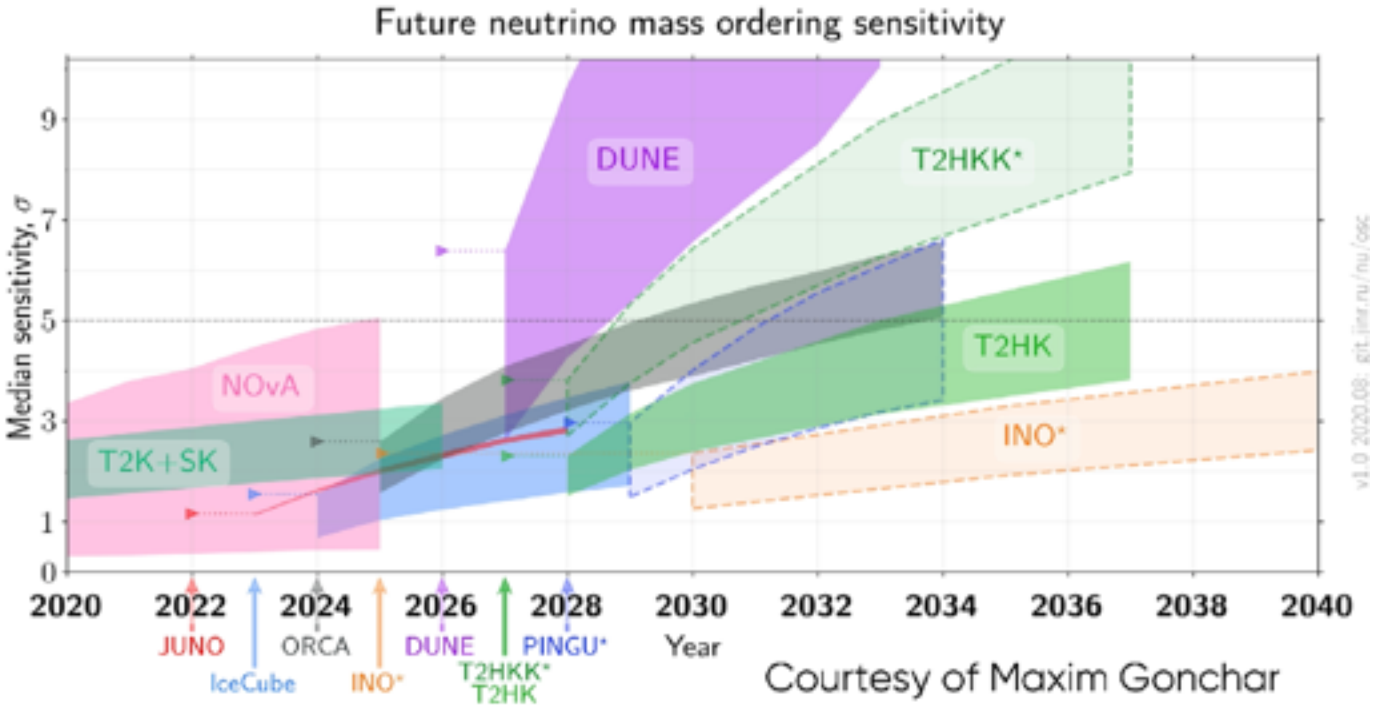
- **Energy non-linearity**
  - Scale uncertainty < 1%
  - Ensure the oscillation peak positions
- **Energy resolution**
  - σ_E< 3% at 1 MeV
  - Resolve the fast component oscillation peaks





JUNO





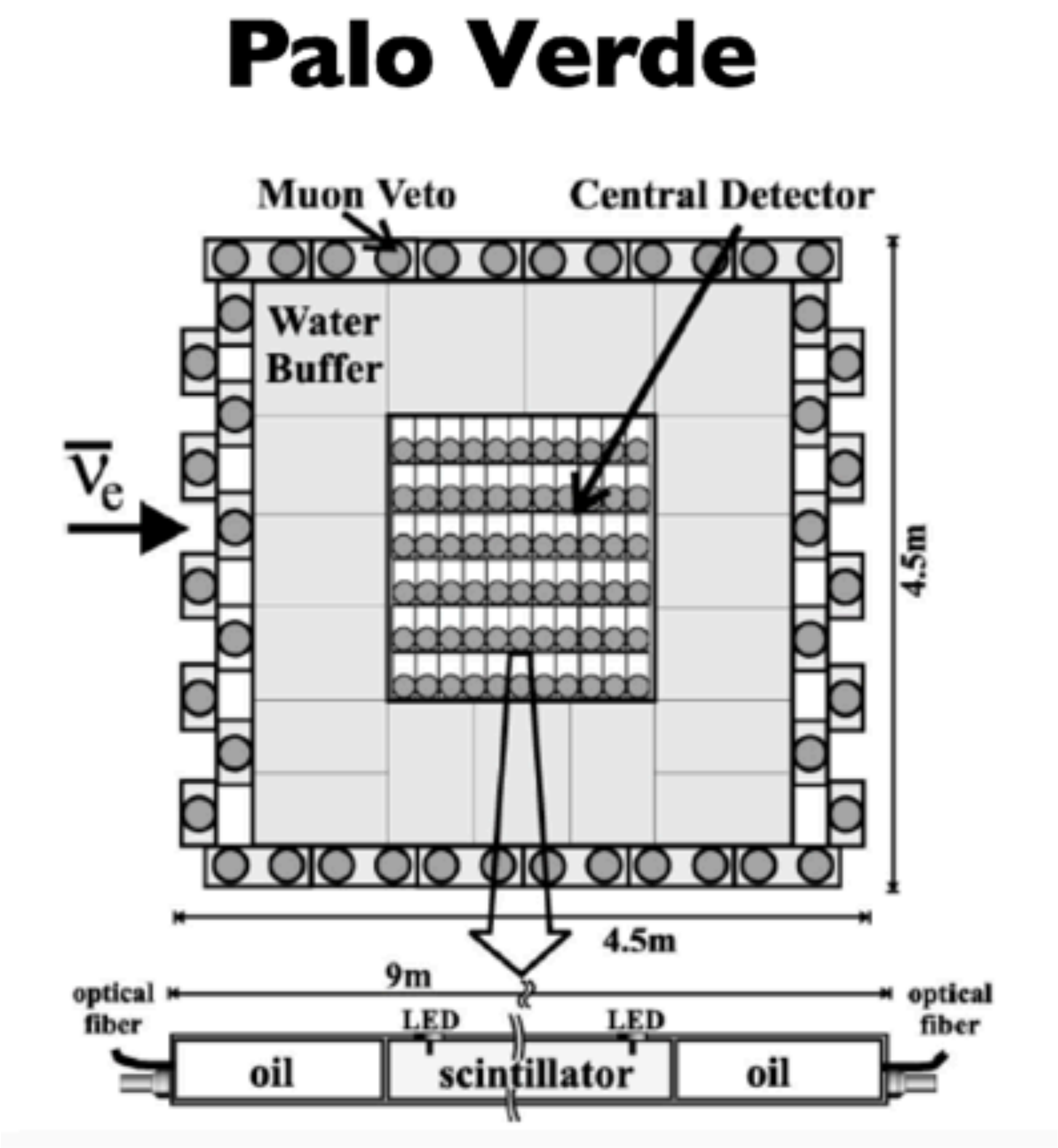
Courtesy of Maxim Gonchar

~1 km baselines: θ_{13}

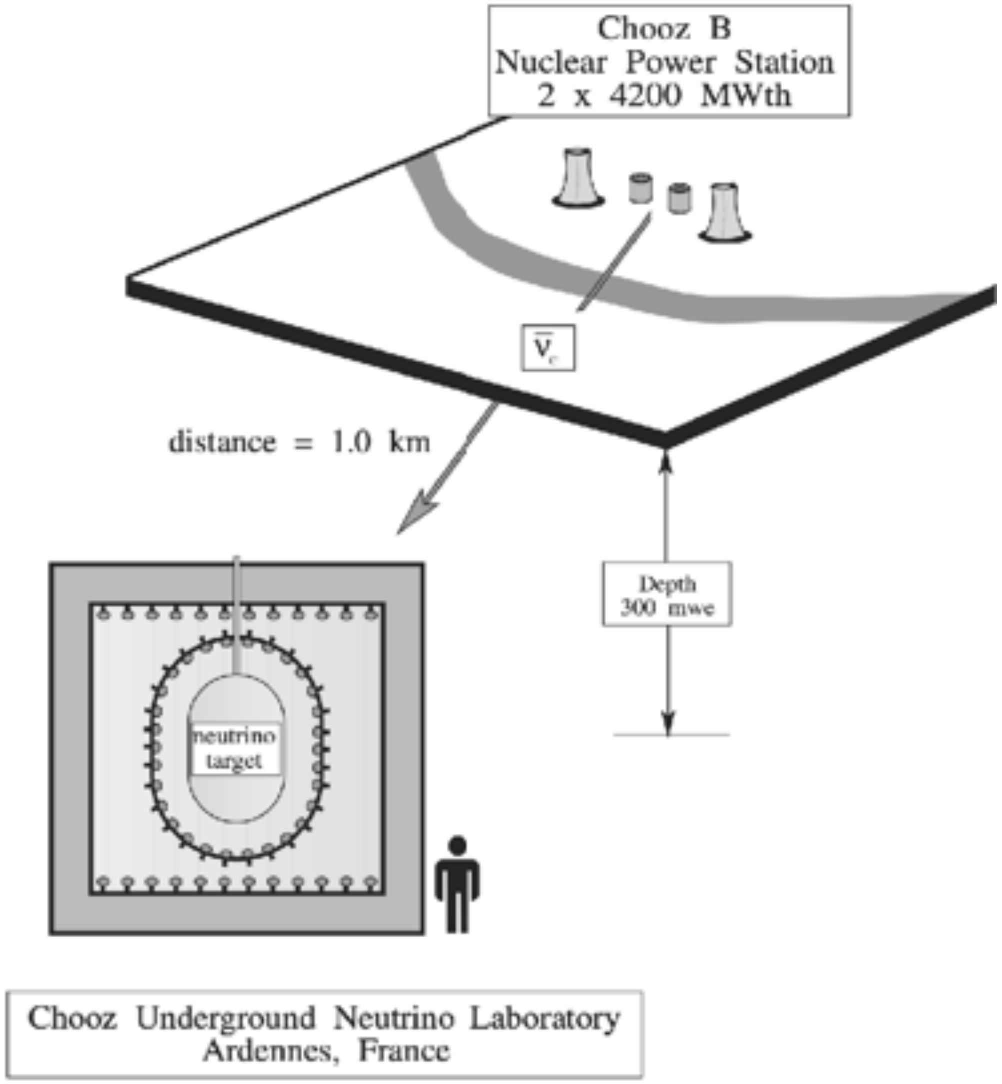
Bugey, Palo Verde, Chooz

	Bugey	Palo Verde	Chooz
Location	south-east France	Arizona (near Phoenix)	northern France
Operating period	1991 - 1992	10/1998 – 07/2000	04/1997 – 06/1998
Life-time data	132 d, 205 d, 33 d	350 d	342 d
Distance to core	15 m, 40 m, 95 m	750 m, 2 x 890 m	998 m, 1115 m
Thermal power	4 x 2800 MW	3 x 3900 MW	2 x 4250 MW
Shielding of lab (m)	23 mwe, 9.5 mwe	32 mwe	300 mwe
Detector	3 x 600 ℓ (98 cells each)	11.4 t (66 cells)	5 t homogen. detector

~1 km baselines: θ_{13}



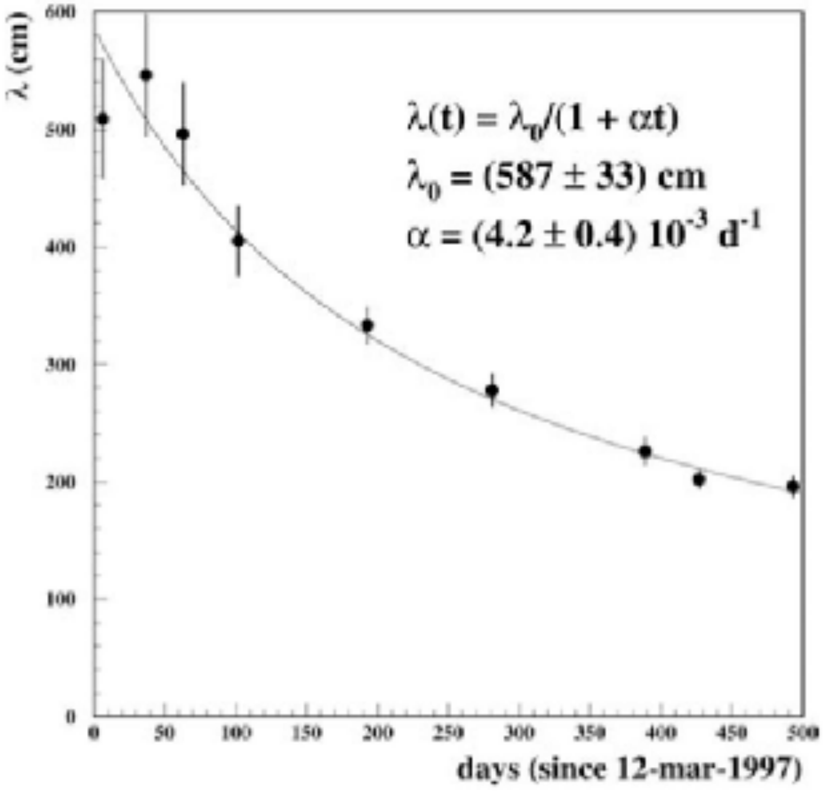
~11 tons gadolinium 2-ethylhexanoate in PC + MO + compounds for wavelength shifting.

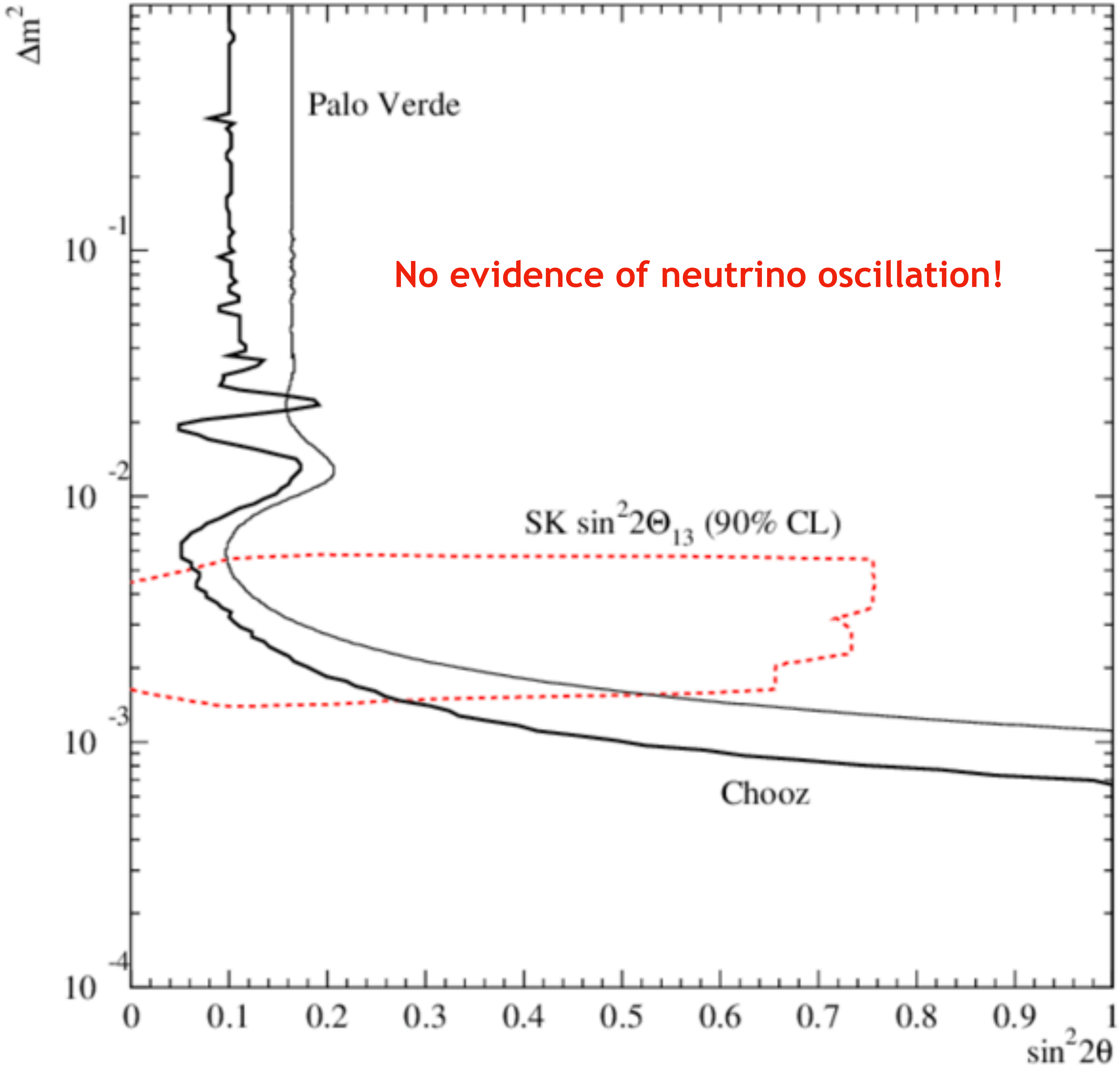


~5 tons gadolinium salt ($Gd(NO_3)_3$) in hexanol + MO + compounds for wavelength shifting

~1 km baselines: θ_{13}

Scintillator instability





No evidence of neutrino oscillation!

~1 km baselines: θ_{13}

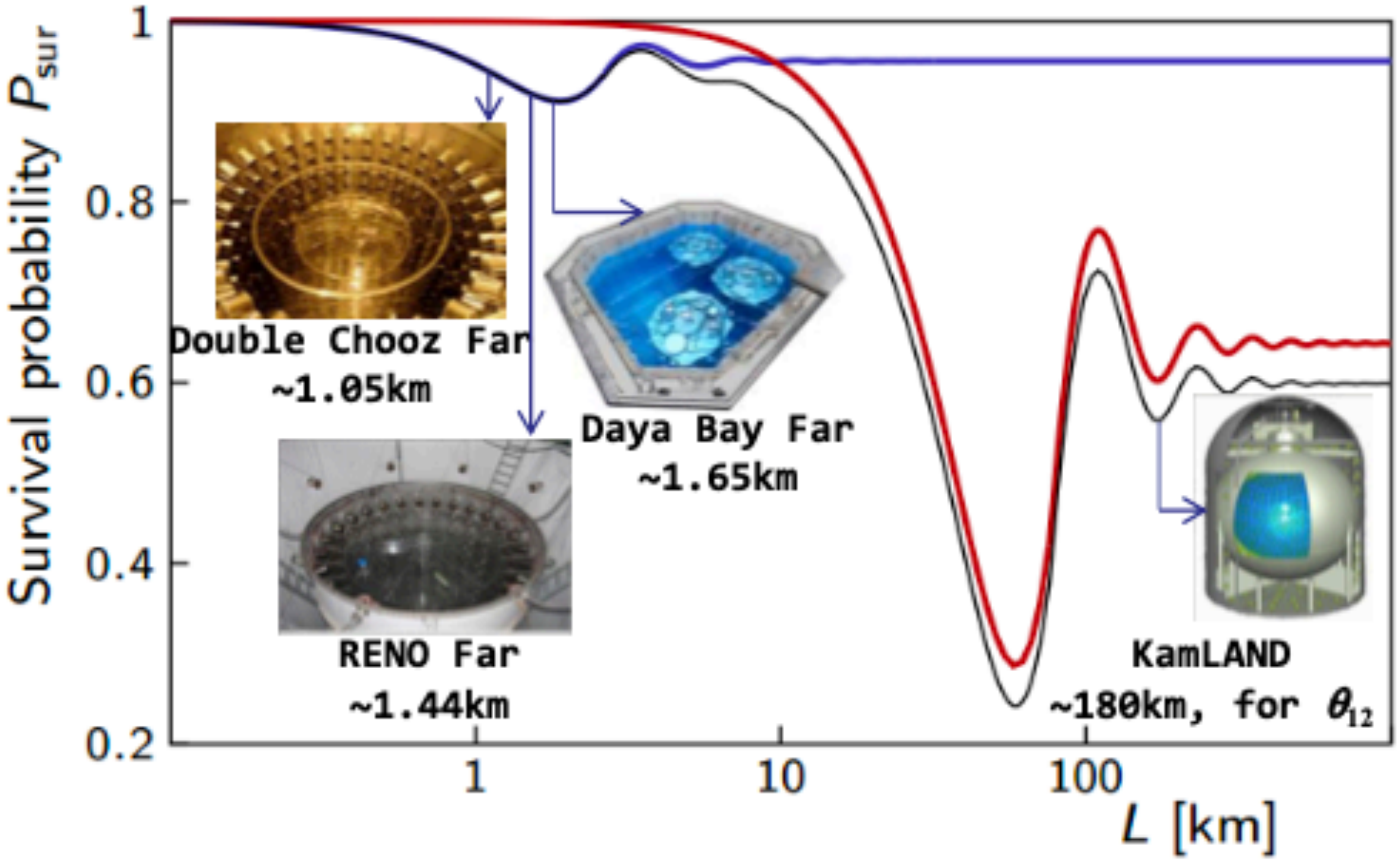
"Disappearance" experiments: $\bar{\nu}_e \rightarrow \bar{\nu}_e$

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

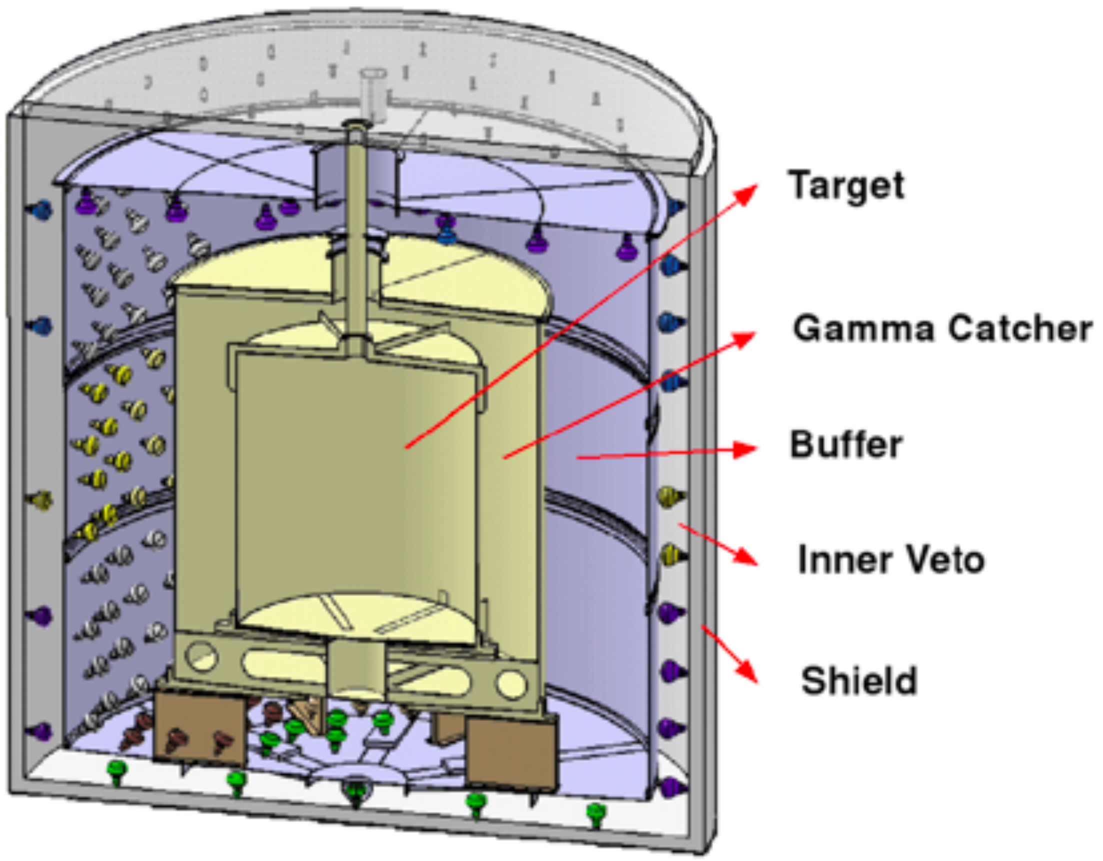
An unambiguous measurement of θ_{13}, no interference with CP violation phase or matter effects.

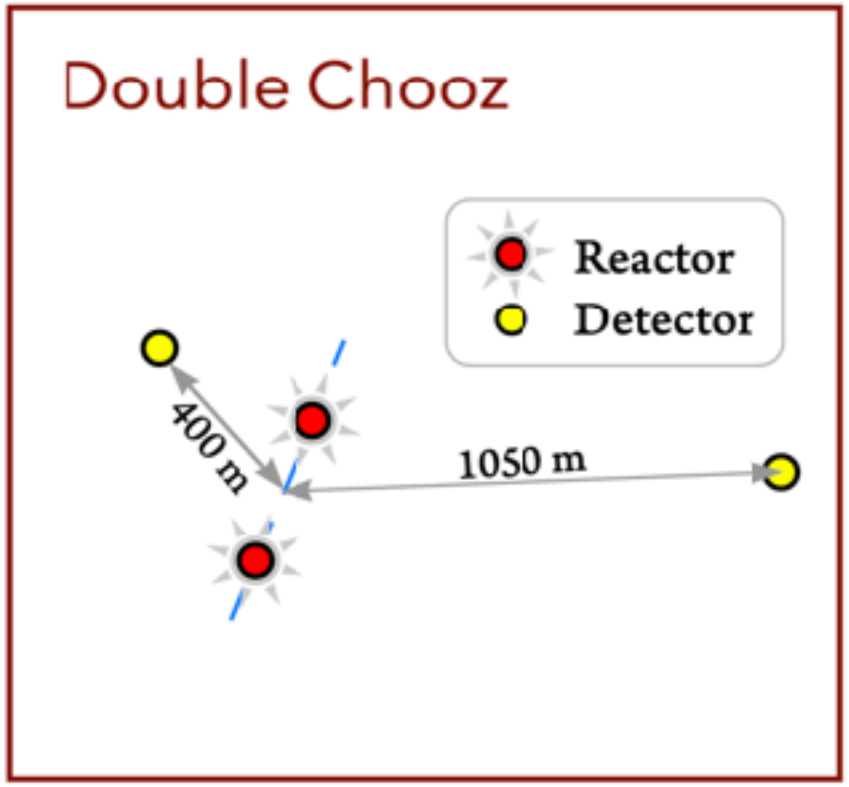
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left(\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right)$$

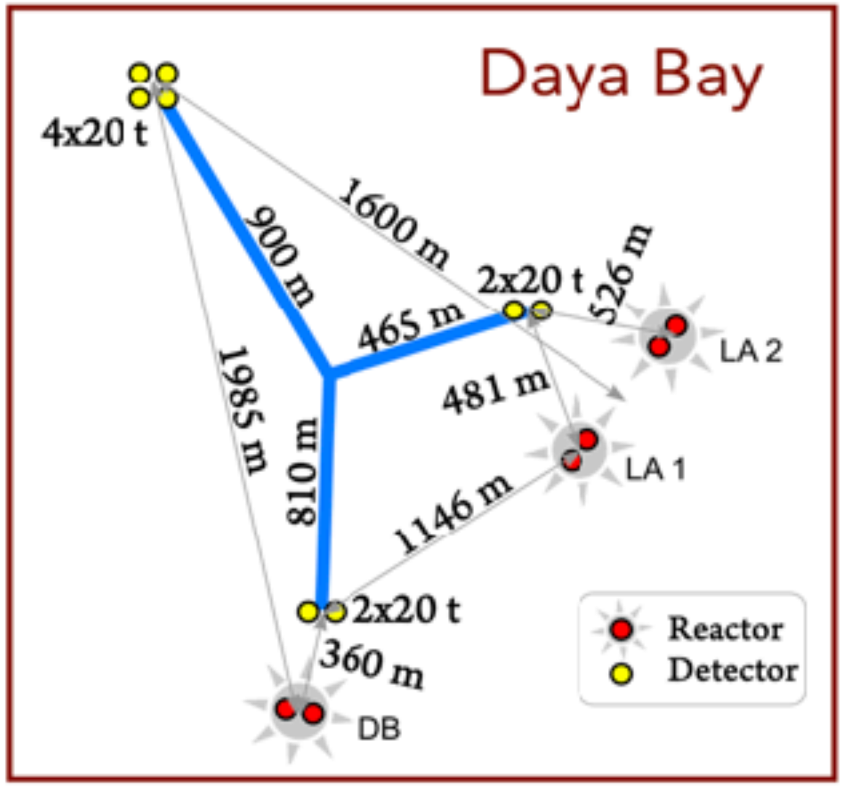
Far-near relative measurement reduces systematics of reactor flux, target mass and detection efficiency from percent to sub-percent level.

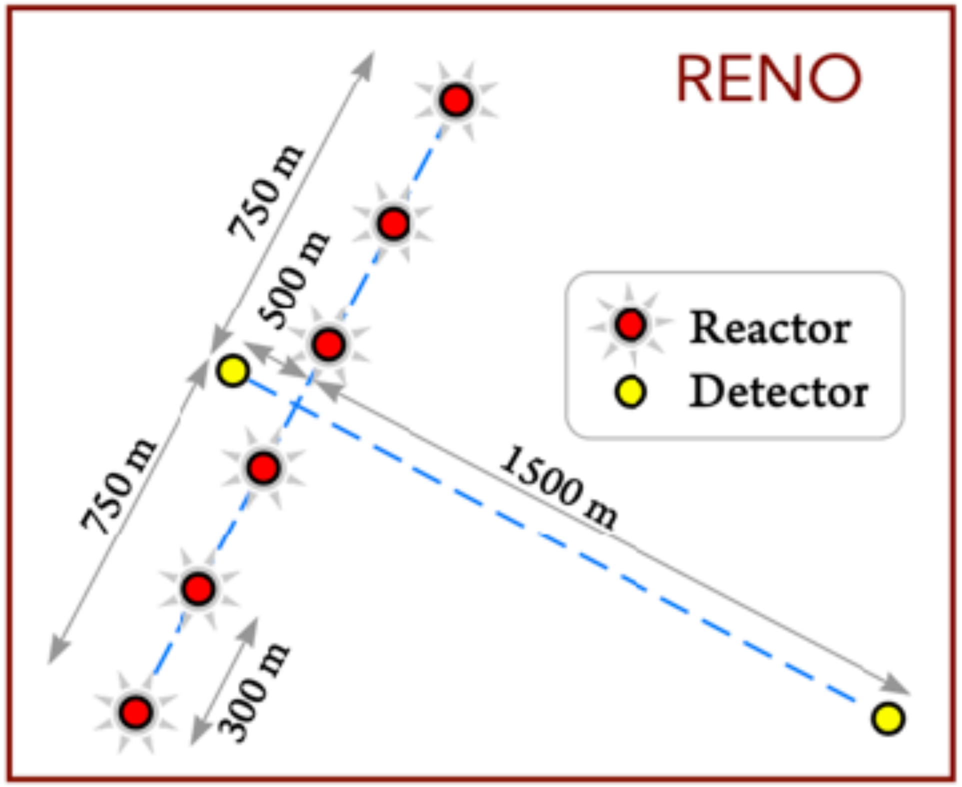


~1 km baselines: θ_{13}



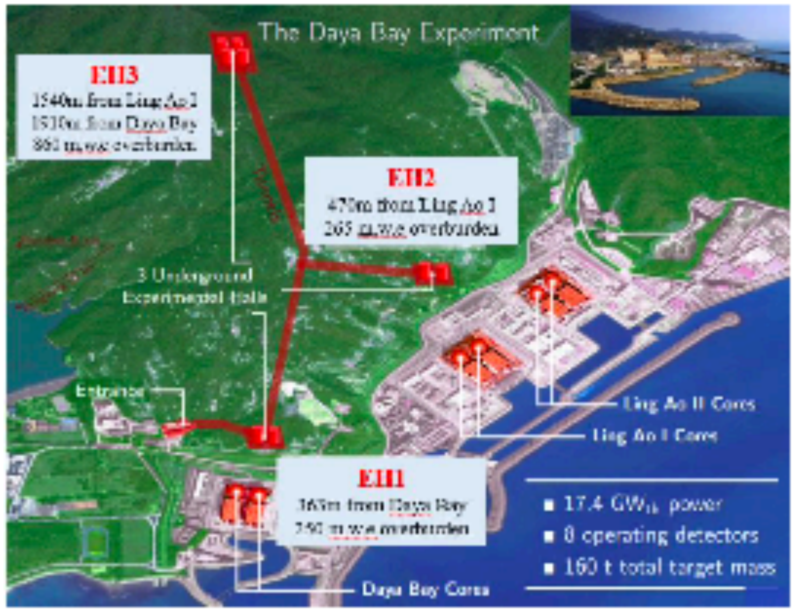






~1 km baselines: θ_{13}

Daya Bay (China)



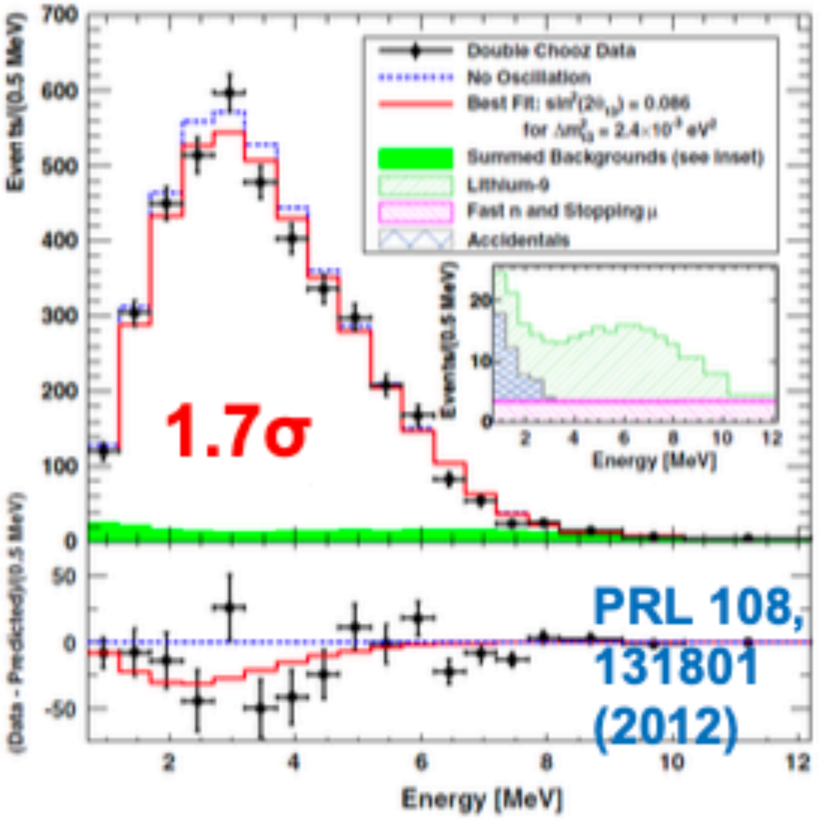
Double Chooz (France)

RENO (South Korea)

	Reactor power (GW_{th})	Overburden near/far (m.w.e.)	nGd target mass at far site (tons)	Status of data taking
Daya Bay	17.4	270/950	80	2011-2020
Double Chooz	8.6	80/300	8.3	2011-2017
RENO	16.4	90/440	15.4	2011-2021 (?)

Discovery of non-zero θ_{13}

Double Chooz
with only a far detector
(Nov. 2011)



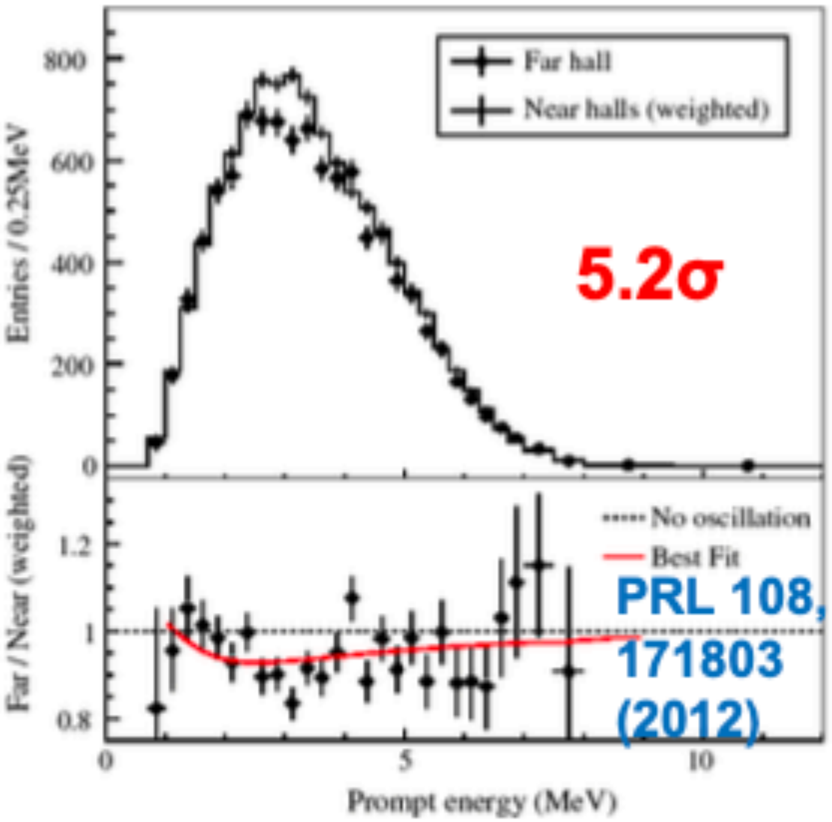
1.7σ

PRL 108, 131801 (2012)

Rate+shape

$$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\mathrm{stat}) \pm 0.030(\mathrm{syst})$$

Daya Bay
(March 2012)



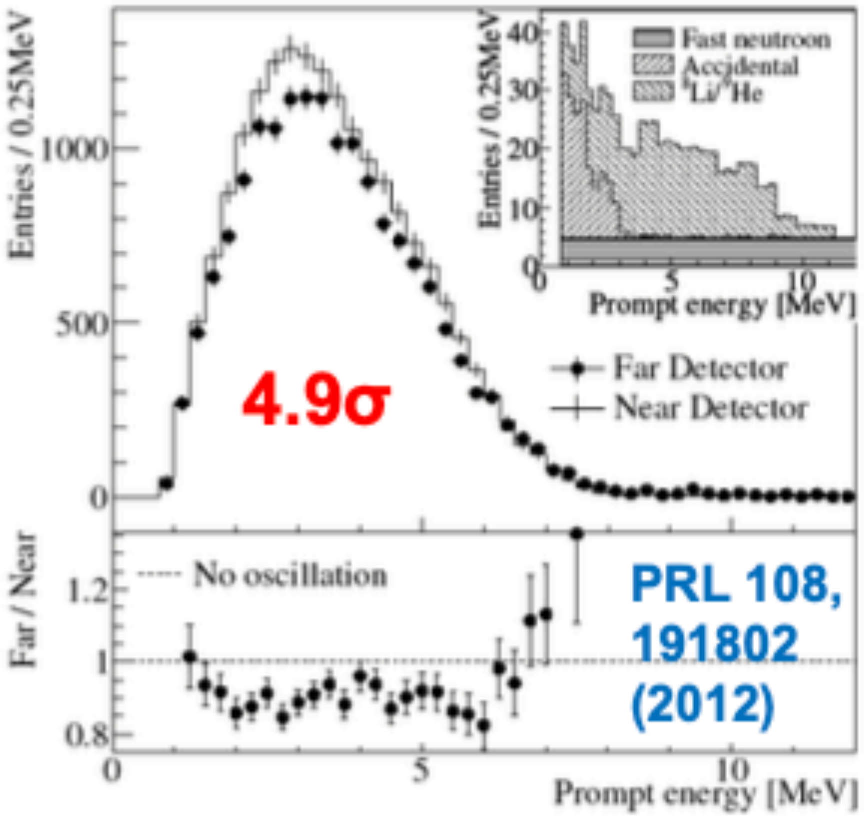
5.2σ

PRL 108, 171803 (2012)

Rate only

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat.}) \pm 0.005(\mathrm{syst.})$$

RENO
(April 2012)



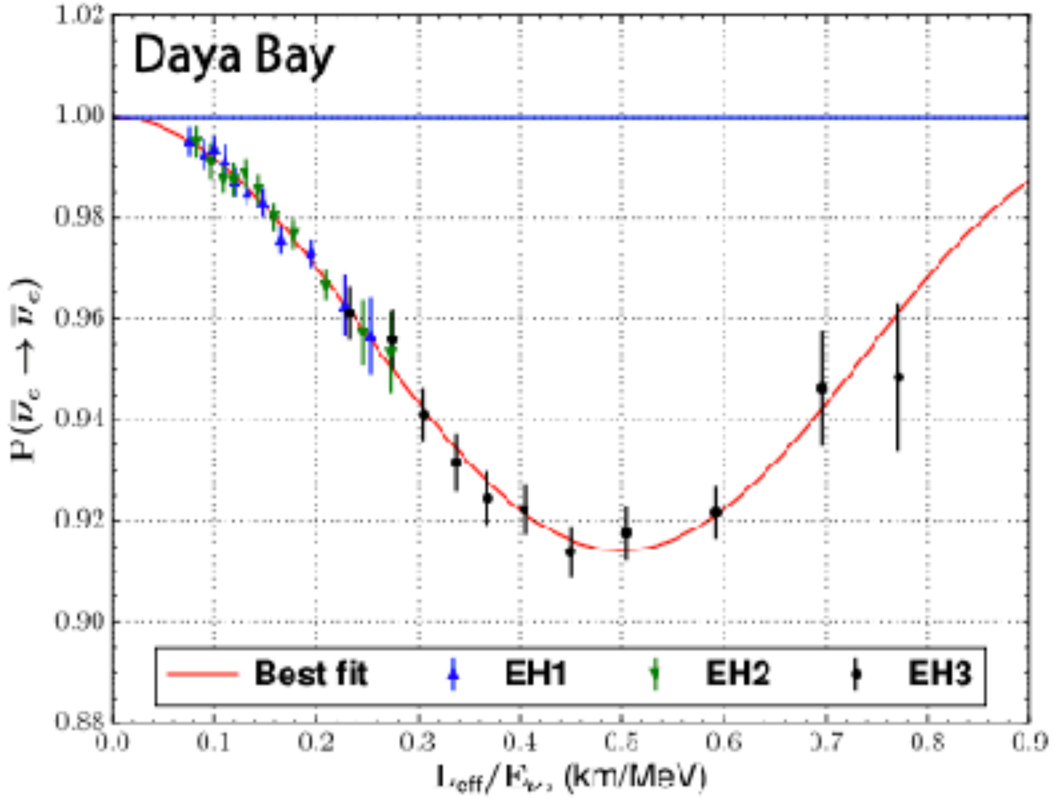
4.9σ

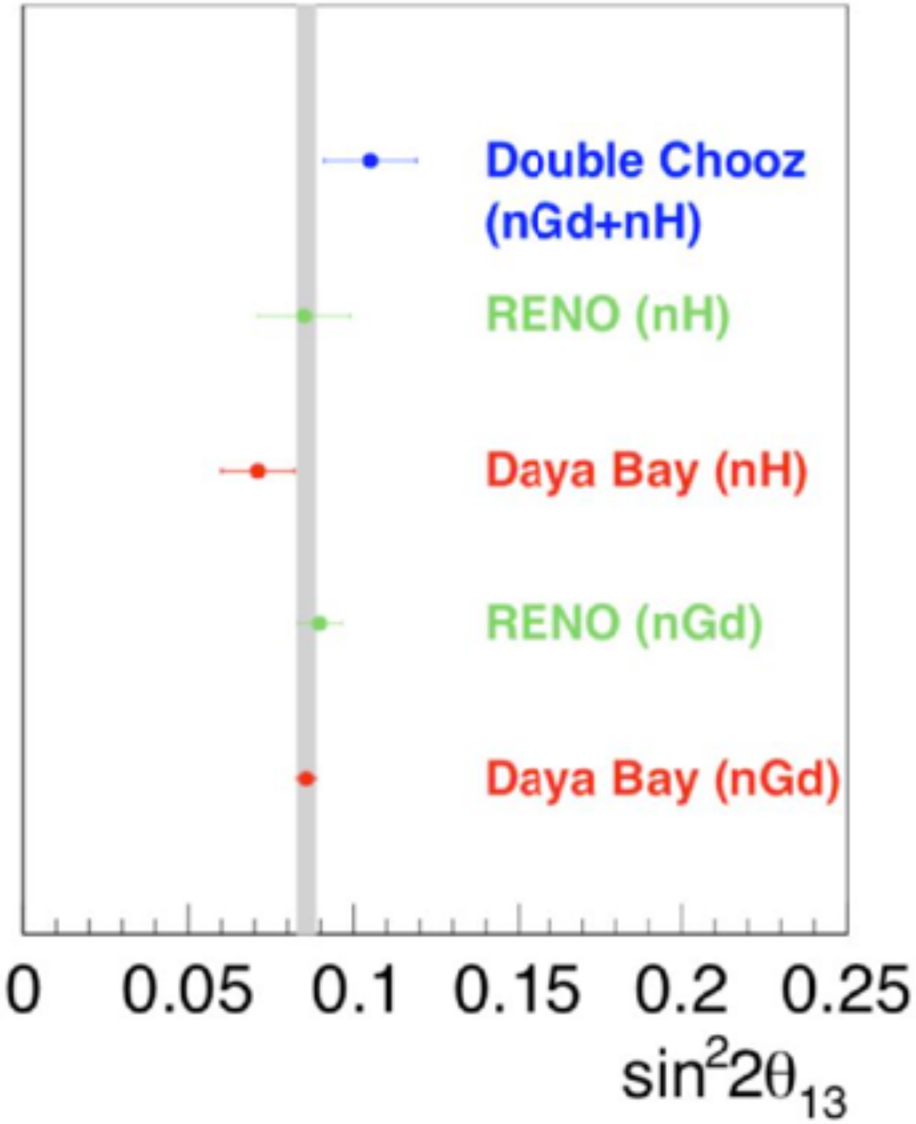
PRL 108, 191802 (2012)

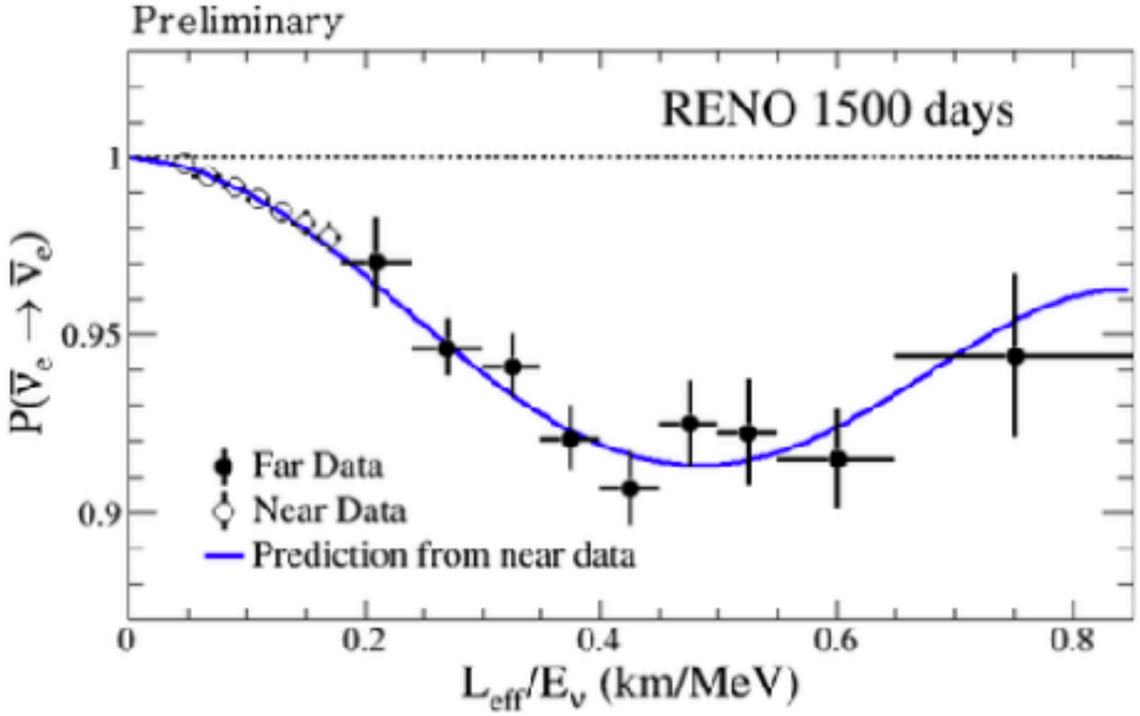
Rate only

$$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\mathrm{stat.}) \pm 0.011(\mathrm{syst.})$$

~1 km baselines: θ_{13}

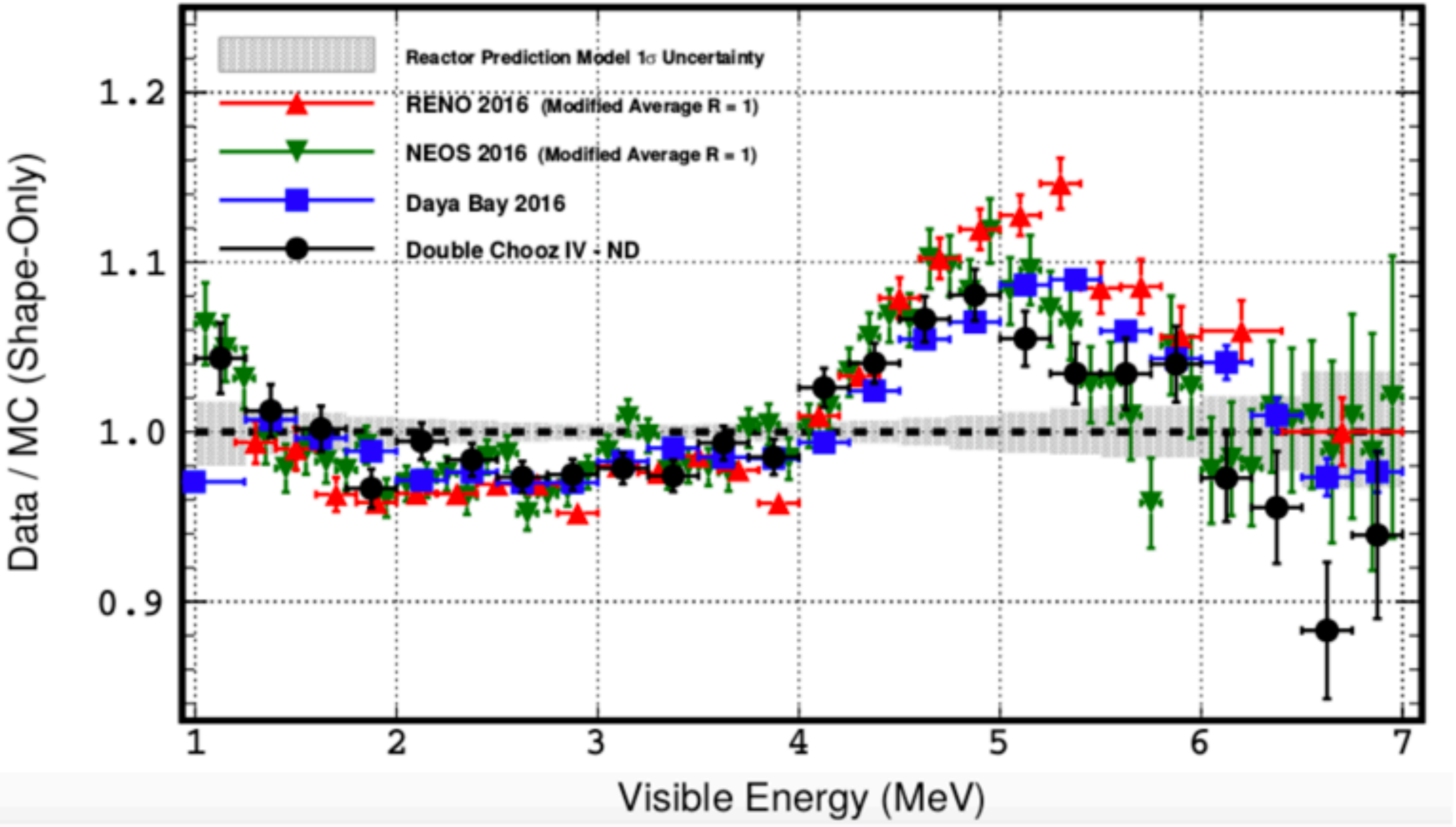






~1 km baselines: θ_{13}

Spectral distortion



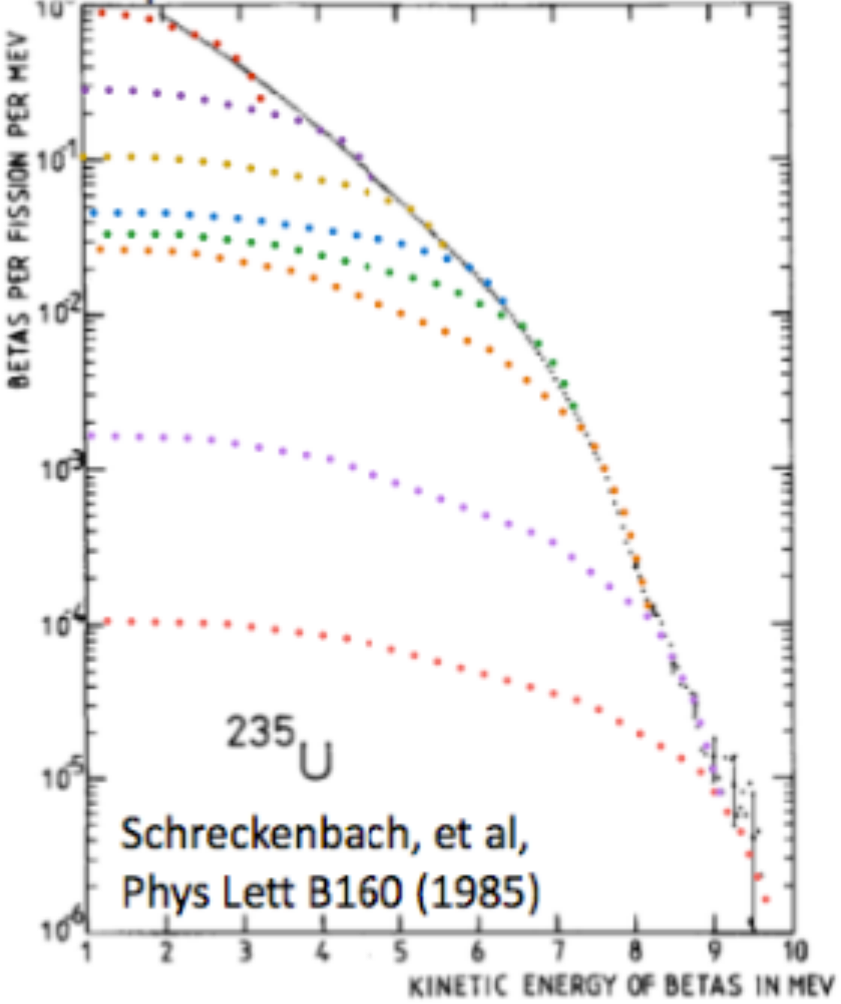
Reactor Neutrino Models

Summation (ab initio) method

- Calculate the spectrum of each beta-decay branch using nuclear databases: fission yields, decay schemes
- ~10% uncertainty

Conversion Method

- Measure total outgoing beta-decay electron energy spectra. (Experiments done for 235U, 239Pu, 241Pu at ILL in the 1980s)
- Predict corresponding anti-neutrino spectra with >30 virtual branches
- Default model by most reactor neutrino experiments
- Considered to be more precise: ~2.5% uncertainty


Example: Fit virtual beta branches

Schreckenbach, et al,
Phys Lett B160 (1985)

Recent re-analyses in 2011 increased prediction by ~5%

- Conversion +3%
- Neutron lifetime +1%
- Non-equilibrium isotopes +1%

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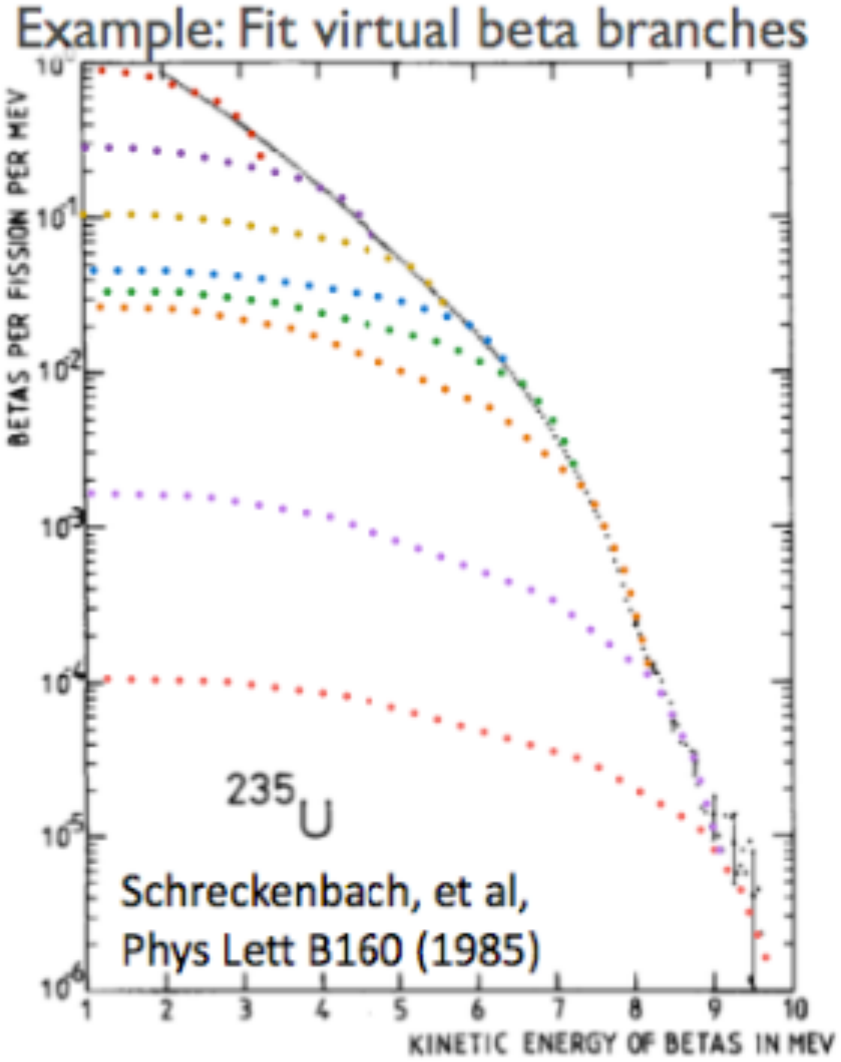

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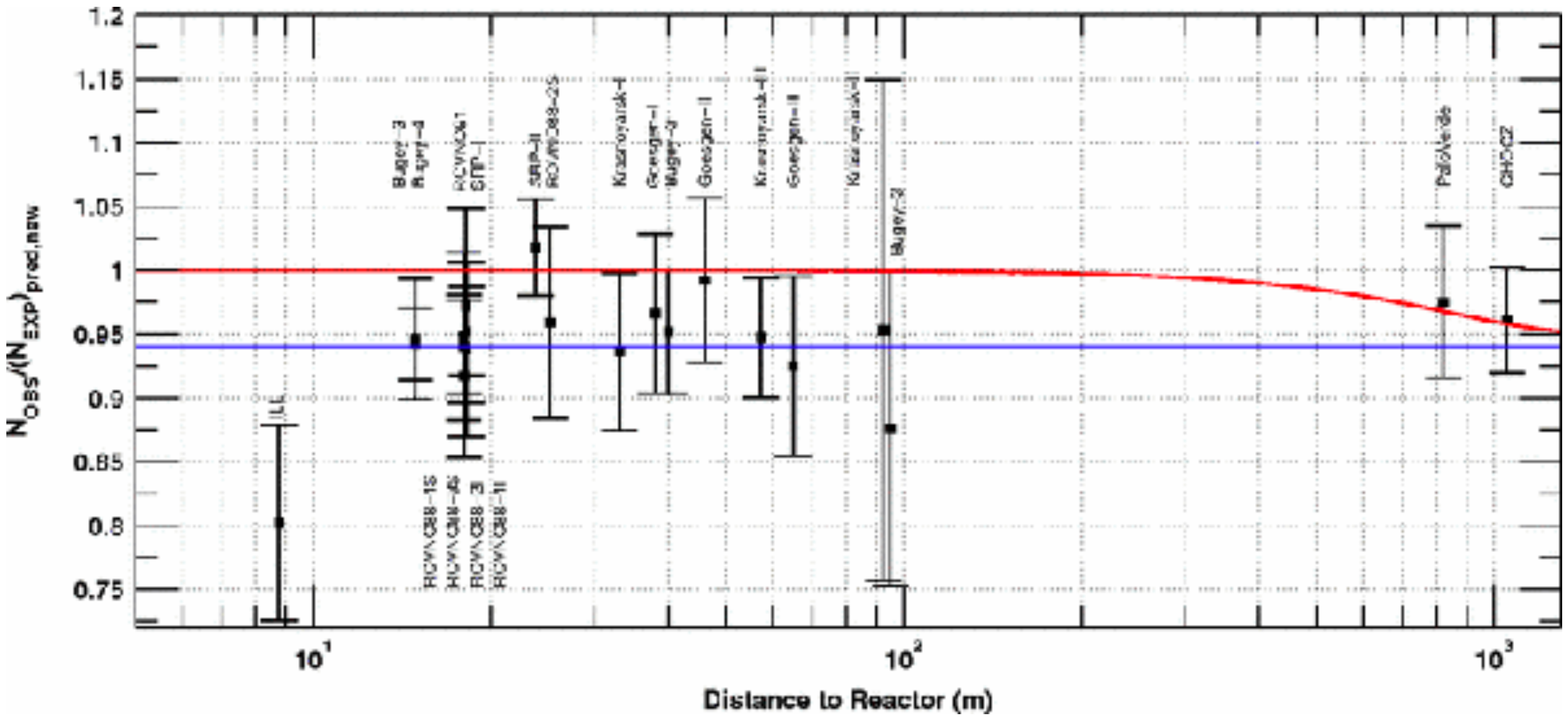
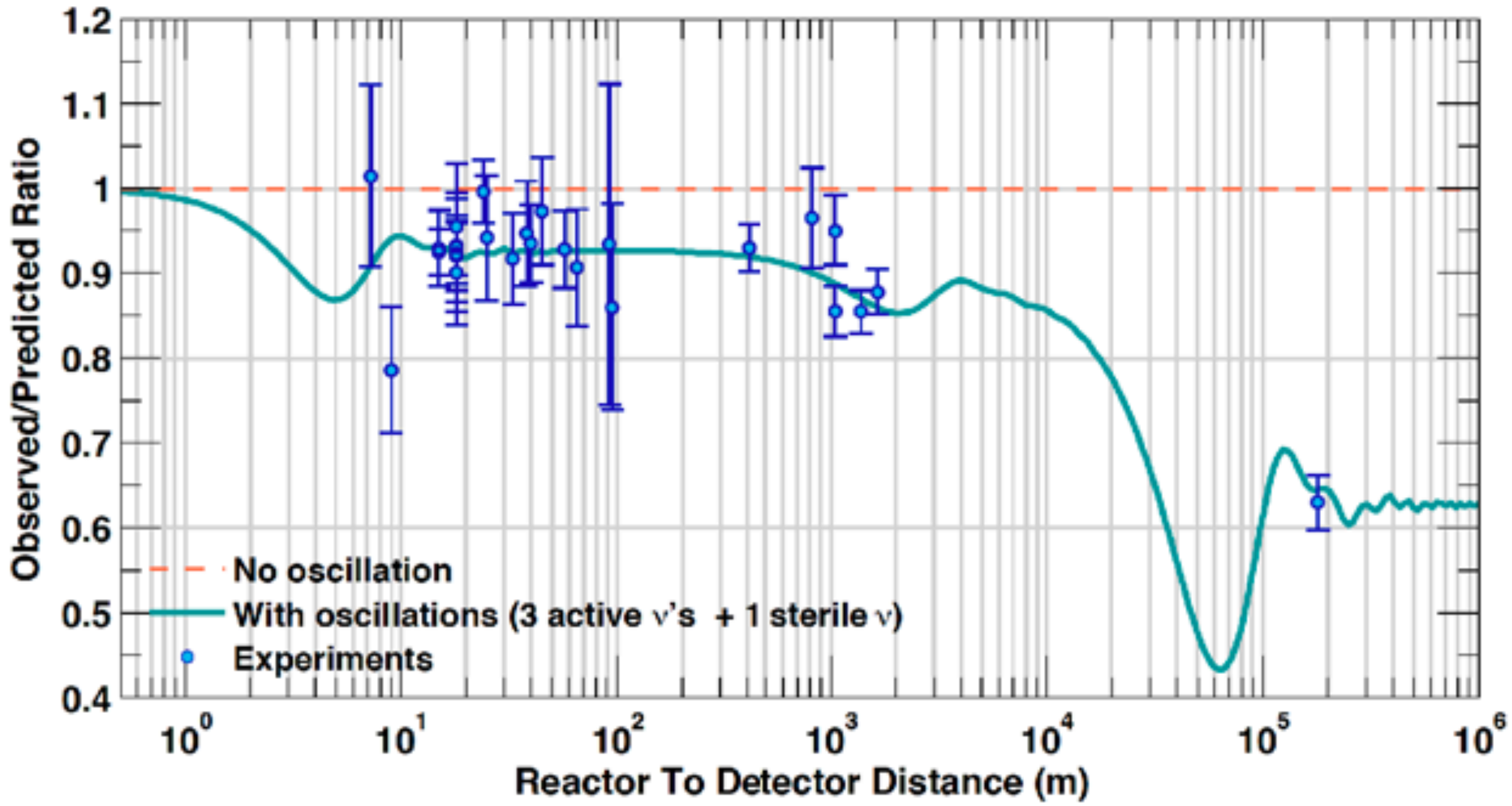
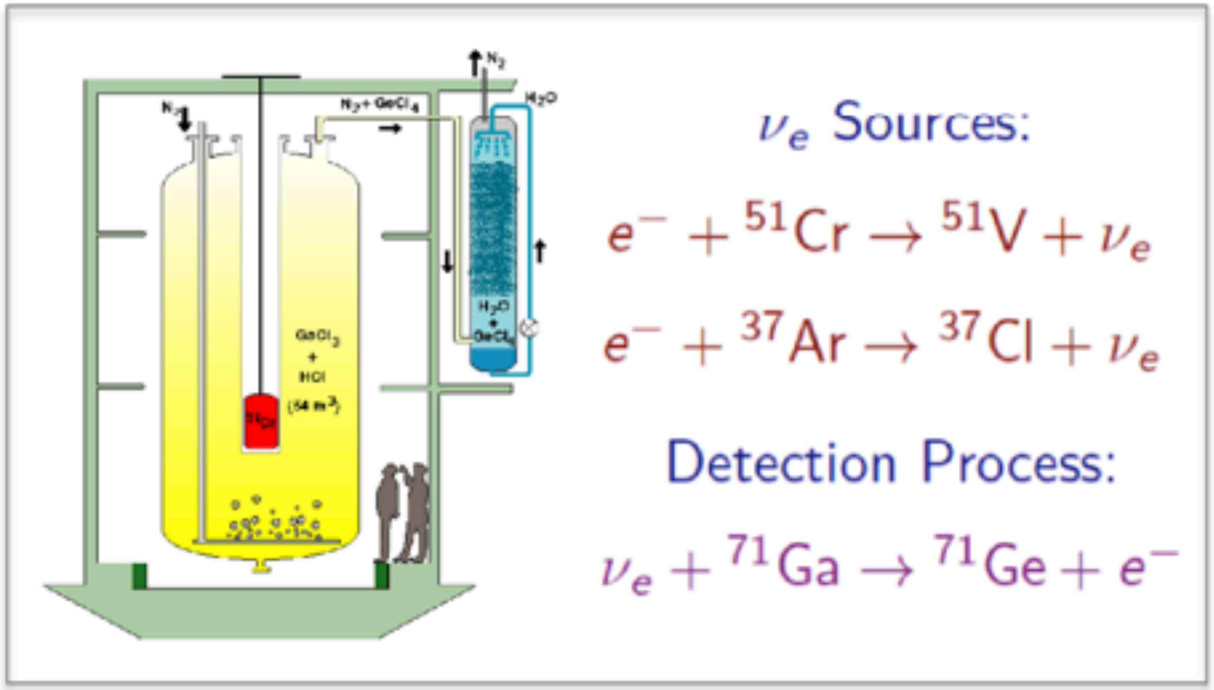
Reactor Anomaly





Gallium Anomaly

- The GALLEX and SAGE experiments were designed for the radiochemical detection of solar neutrinos.
- The detectors were calibrated using the radioactive sources ^{51}Cr and ^{37}Ar, which emit neutrinos via electron capture.
- The neutrino interaction rates were found to be 2.7σ lower than expected.



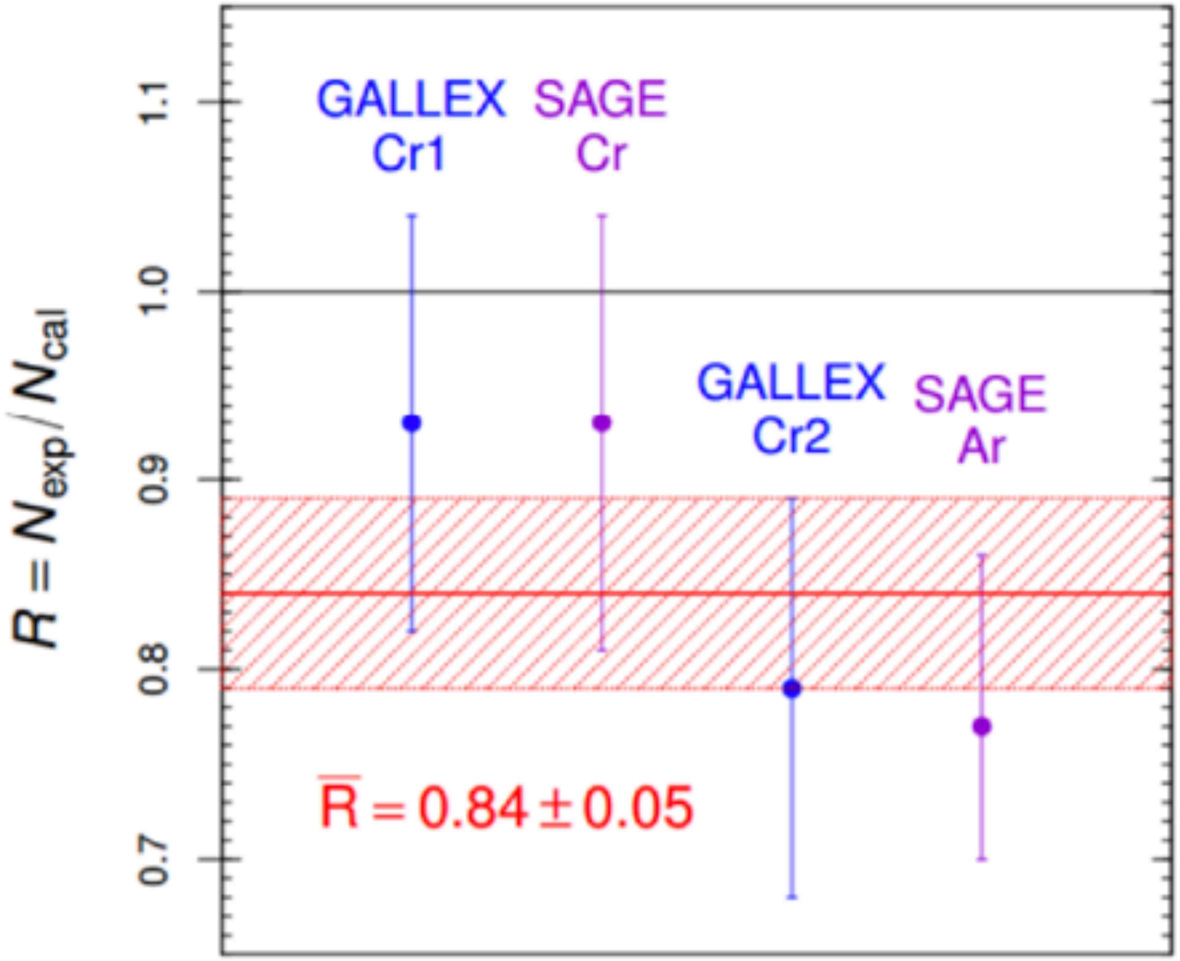
ν_e Sources:

$$e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$$

$$e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$$

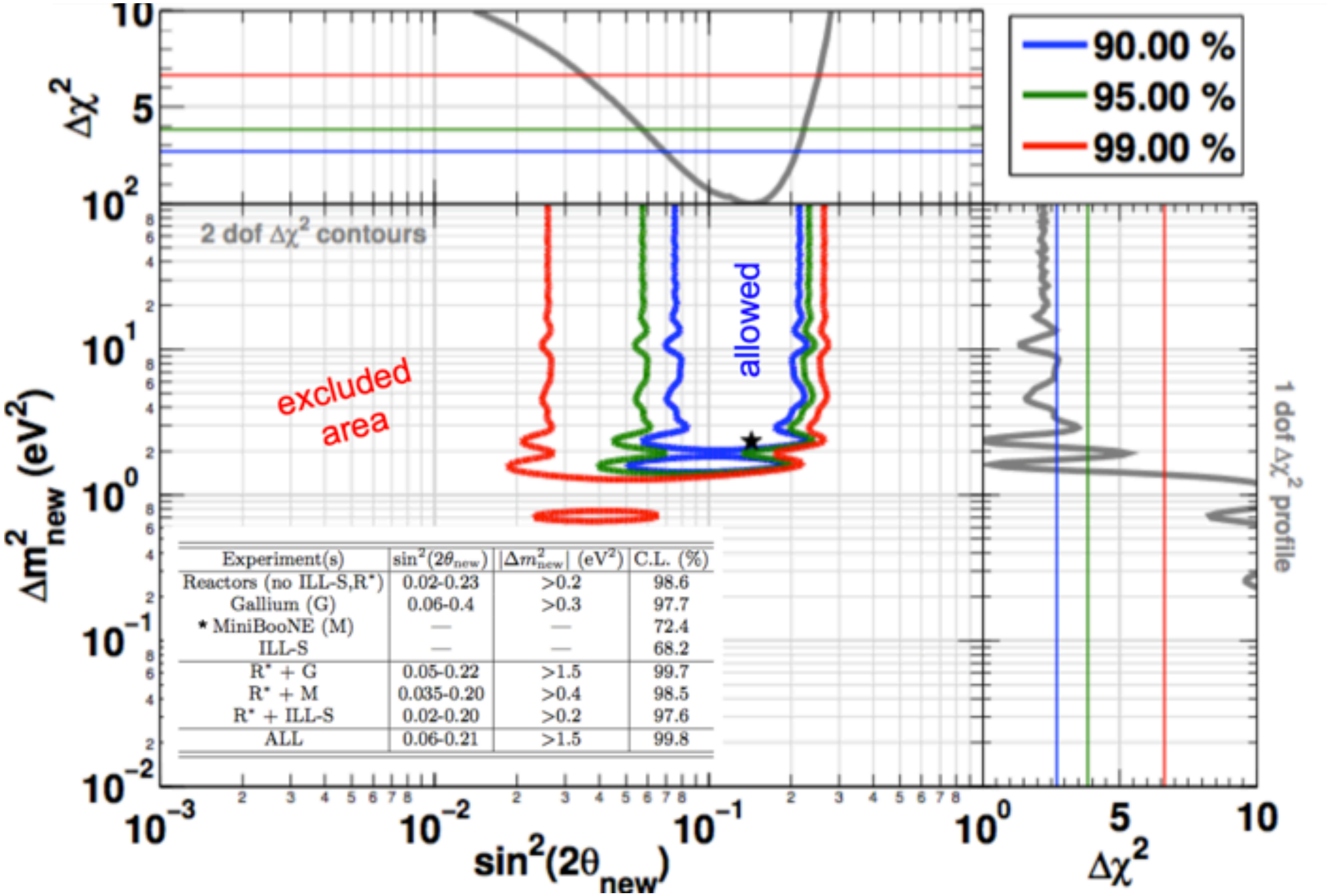
Detection Process:

$$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$$



Gariazzo et al. J.Phys. G43, 033001 (2016)

Reactor + Gallium Anomaly



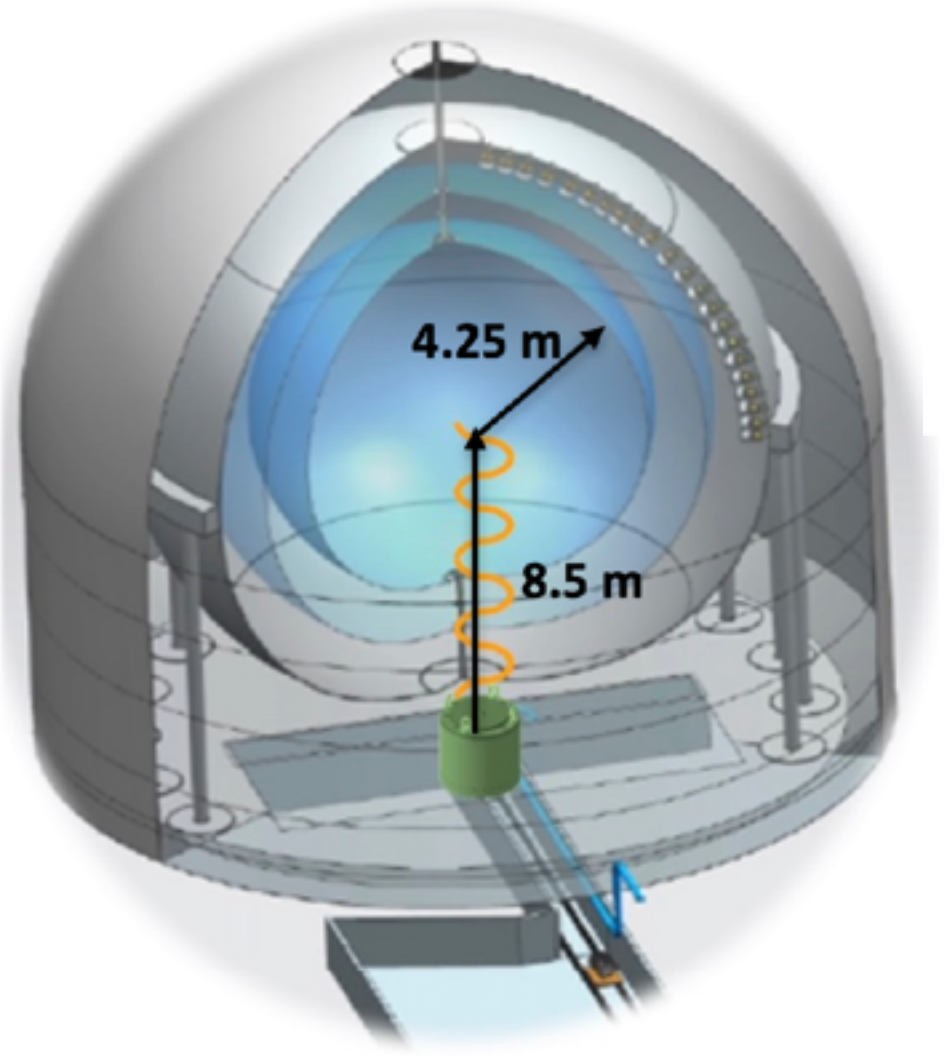
Experiment(s)	$\sin^2(2\theta_{new})$	$\lvert\Delta m^2_{new}\rvert$ (eV^2)	C.L. (%)
Reactors (no ILL-S,R*)	0.02-0.23	>0.2	98.6
Gallium (G)	0.06-0.4	>0.3	97.7
★ MiniBooNE (M)	—	—	72.4
ILL-S	—	—	68.2
R* + G	0.05-0.22	>1.5	99.7
R* + M	0.035-0.20	>0.4	98.5
R* + ILL-S	0.02-0.20	>0.2	97.6
ALL	0.06-0.21	>1.5	99.8

The no-oscillation hypothesis WAS disfavored at 99.8% CL (in 2011)

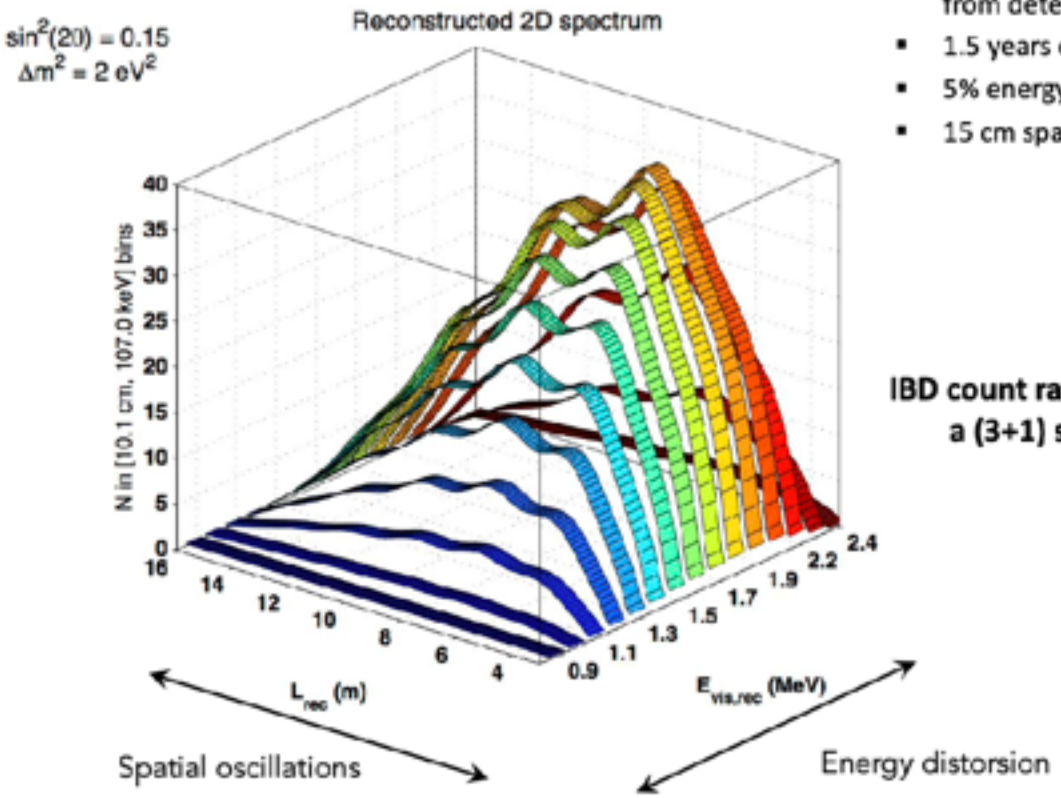
Sterile Neutrinos

SOX

Borexino



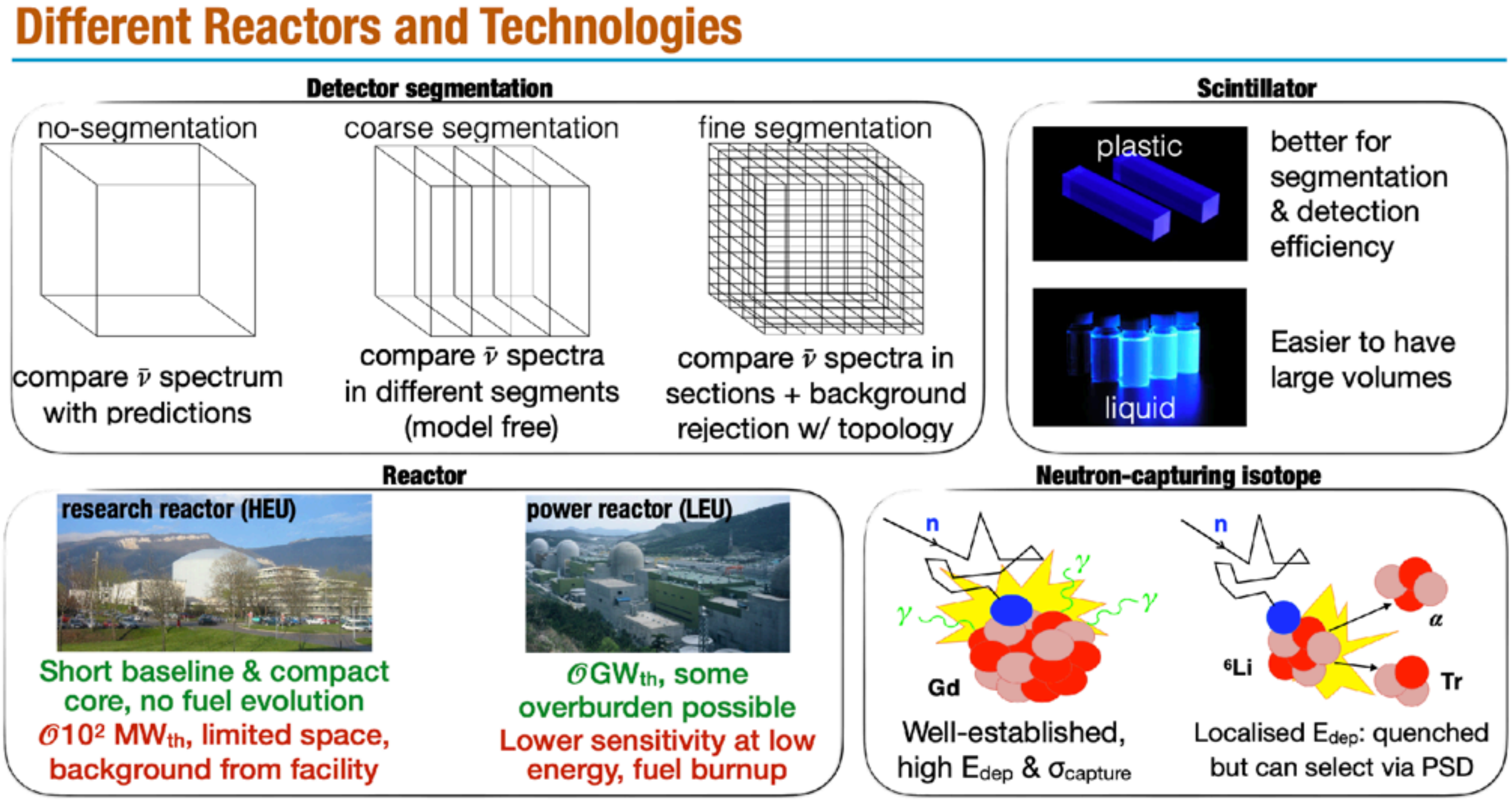
$$\mathcal{P}(\theta, \Delta m^2, L, E) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 \frac{L}{E})$$



- 100 kCi ^{144}Ce source in pit @ 8.5 m from detector center
- 1.5 years of data taking: ≈ 10^4 events
- 5% energy resolution @ 1 MeV
- 15 cm spatial resolution

IBD count rate as a function of L & E in a (3+1) sterile neutrino model

Sterile Neutrinos



Different Reactors and Technologies

Detector segmentation

no-segmentation

compare $\bar{\nu}$ spectrum with predictions

coarse segmentation

compare $\bar{\nu}$ spectra in different segments (model free)

fine segmentation

compare $\bar{\nu}$ spectra in sections + background rejection w/ topology

Scintillator

better for segmentation & detection efficiency

Easier to have large volumes

Reactor

research reactor (HEU)

Short baseline & compact core, no fuel evolution

$\mathcal{O}10^2$ MW$_{th}$, limited space, background from facility

power reactor (LEU)

$\mathcal{O}$GW$_{th}$, some overburden possible

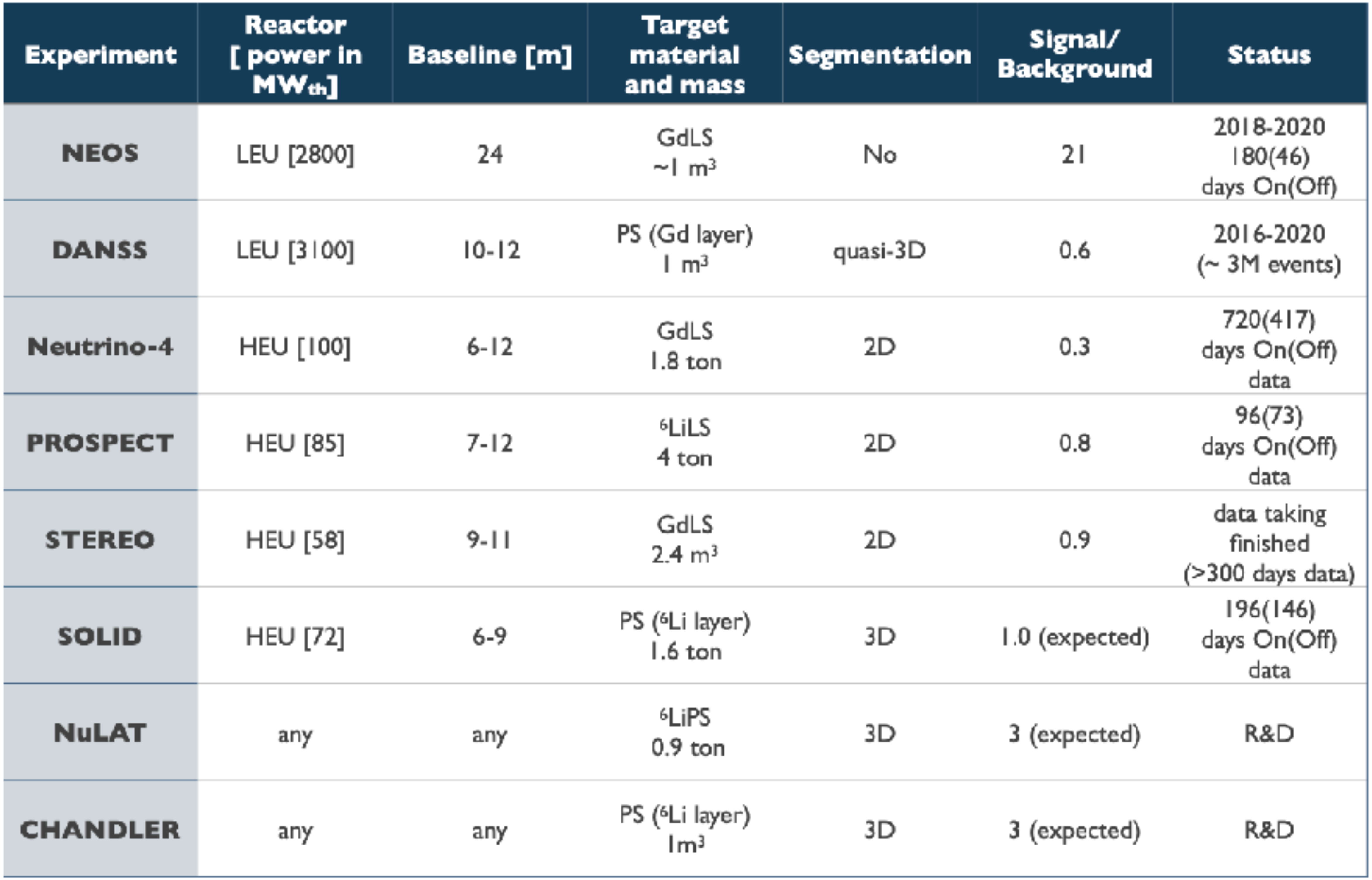
Lower sensitivity at low energy, fuel burnup

Neutron-capturing isotope

Well-established, high E$_{dep}$ & $\sigma_{capture}$

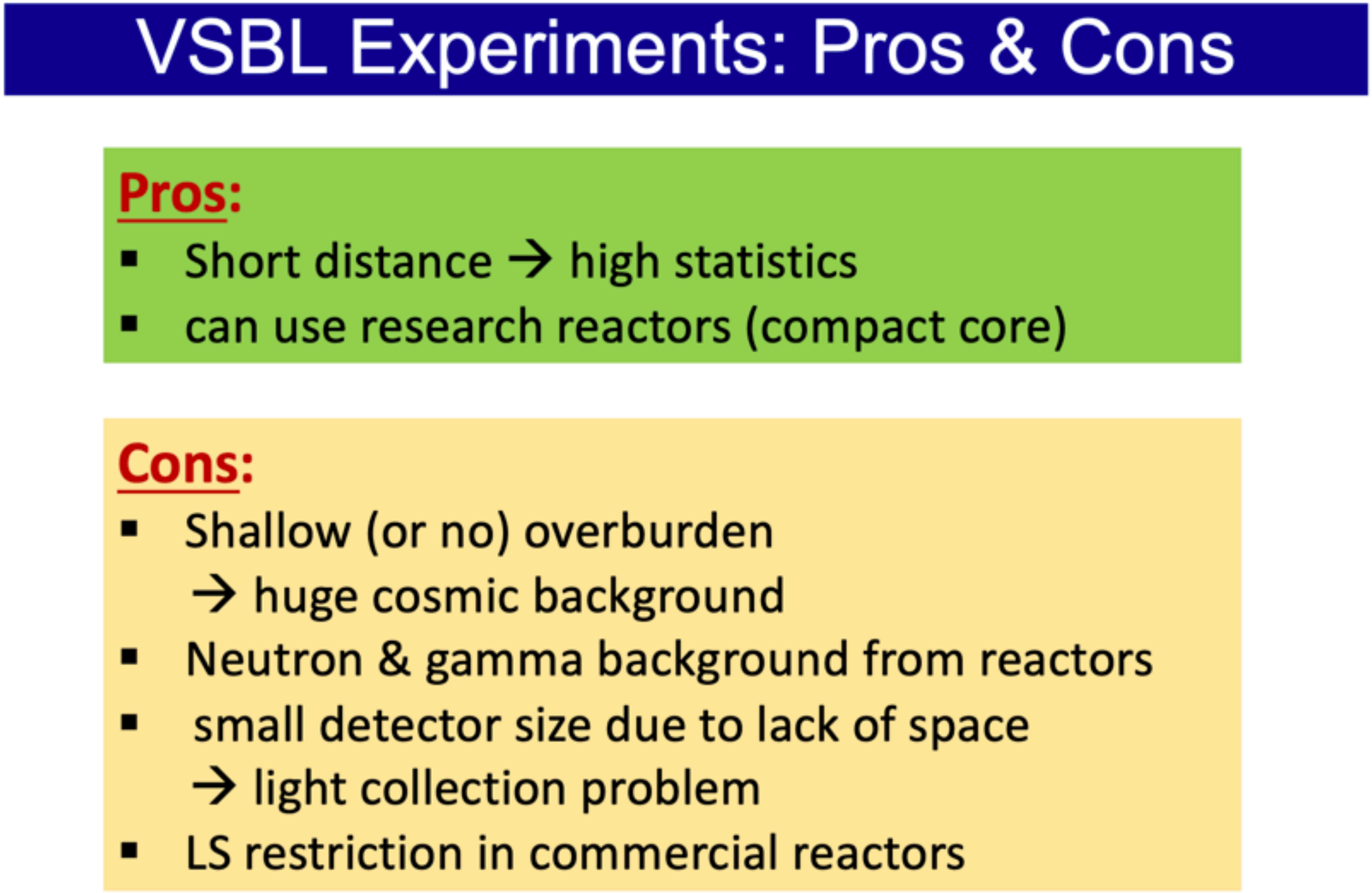
Localised E$_{dep}$: quenched but can select via PSD

Sterile Neutrinos



Experiment	Reactor [power in MW_{th}]	Baseline [m]	Target material and mass	Segmentation	Signal/ Background	Status
NEOS	LEU [2800]	24	GdLS ~1 m^3	No	21	2018-2020 180(46) days On(Off)
DANSS	LEU [3100]	10-12	PS (Gd layer) 1 m^3	quasi-3D	0.6	2016-2020 (~ 3M events)
Neutrino-4	HEU [100]	6-12	GdLS 1.8 ton	2D	0.3	720(417) days On(Off) data
PROSPECT	HEU [85]	7-12	^{6}LiLS 4 ton	2D	0.8	96(73) days On(Off) data
STEREO	HEU [58]	9-11	GdLS 2.4 m^3	2D	0.9	data taking finished (>300 days data)
SOLID	HEU [72]	6-9	PS (^{6}Li layer) 1.6 ton	3D	1.0 (expected)	196(146) days On(Off) data
NuLAT	any	any	^{6}LiPS 0.9 ton	3D	3 (expected)	R&D
CHANDLER	any	any	PS (^{6}Li layer) 1m^3	3D	3 (expected)	R&D

Sterile Neutrinos



VSBL Experiments: Pros & Cons

Pros:

- Short distance → high statistics
- can use research reactors (compact core)

Cons:

- Shallow (or no) overburden
  → huge cosmic background
- Neutron & gamma background from reactors
- small detector size due to lack of space
  → light collection problem
- LS restriction in commercial reactors

Sterile Neutrinos: STEREO

☐ **Reactor: ILL, France**

58 MW_{th} ^{235}U Reactor

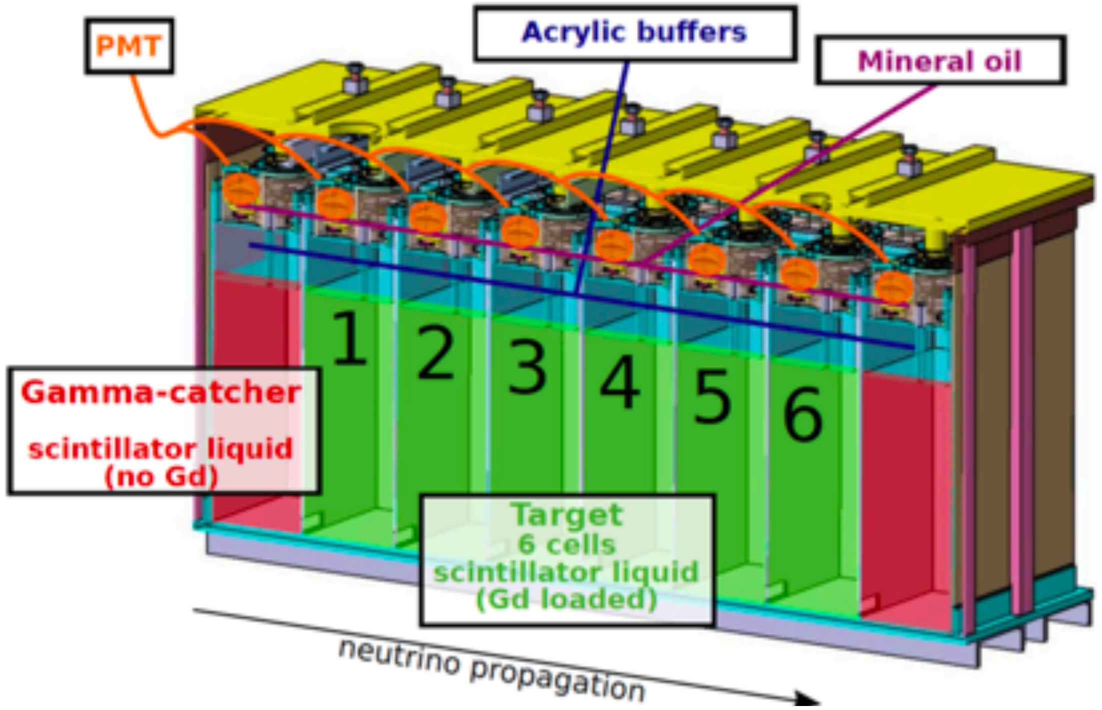
(D40xH80cm^3)

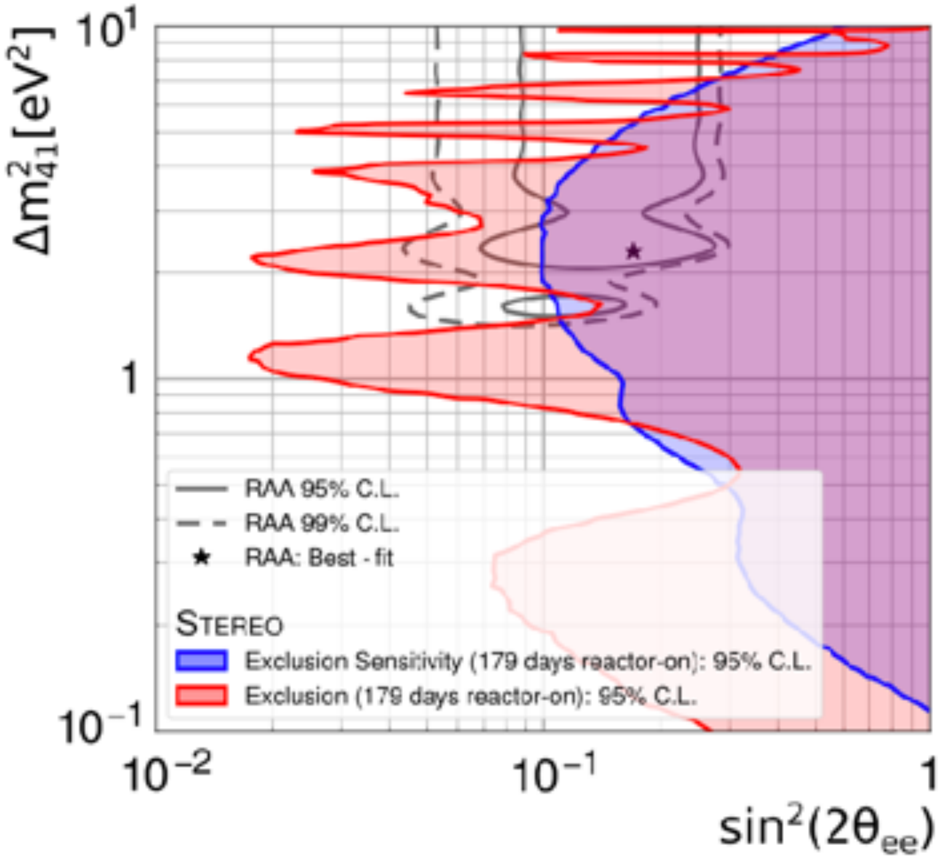
☐ **Detector: GdLS** 0.2% Gd

- 2.4 m^3 (6x1 cells)
- L = 9~11 m
- 15 m.w.e.

- ~400 IBDs/day
- E resolution: ~ 9% @1MeV
- PSD (moderate)

→ S/B ~ 0.9





Sterile Neutrinos: PROSPECT

☐ Reactor: HFIR, USA

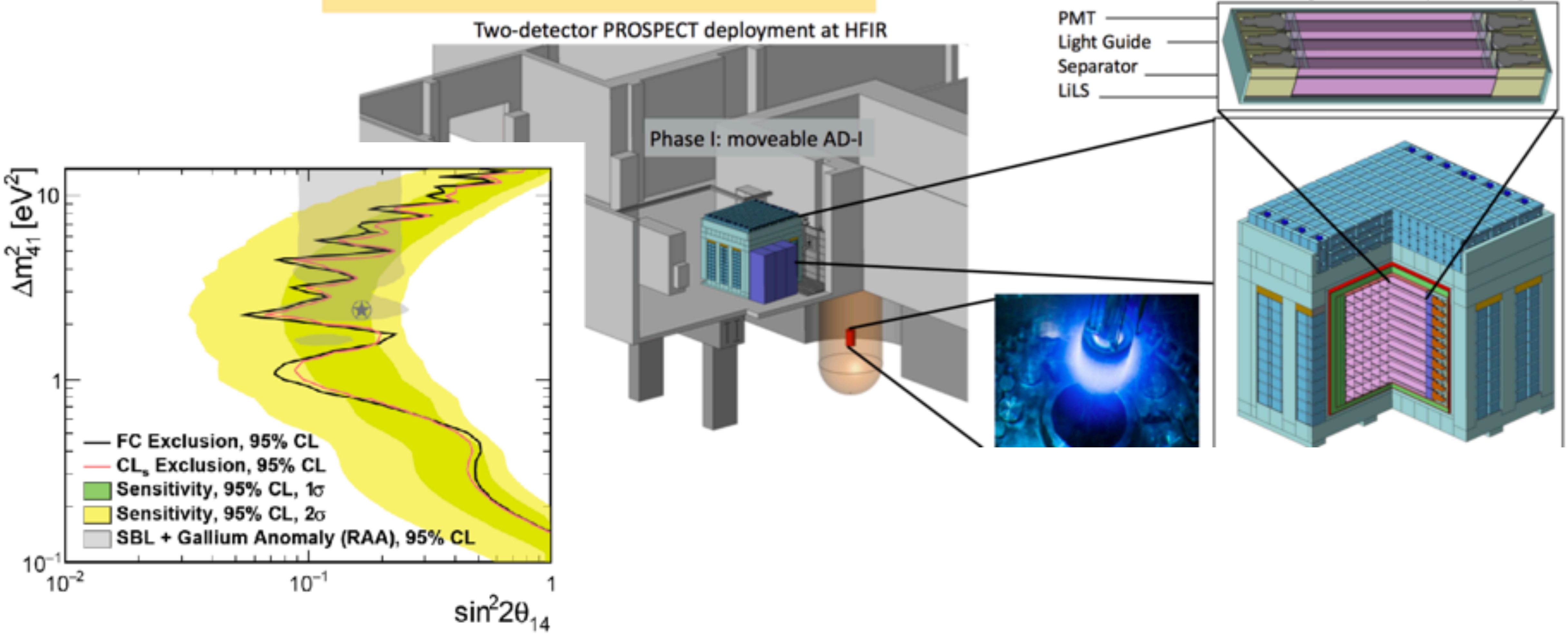
80 MW$_{th}$ ^{235}U Reactor

☐ Detector: ^{6}LiLS **0.1% ^{6}Li**

- 4 ton (154 cells)
- L = 7~9 m
- < 1 m.w.e.

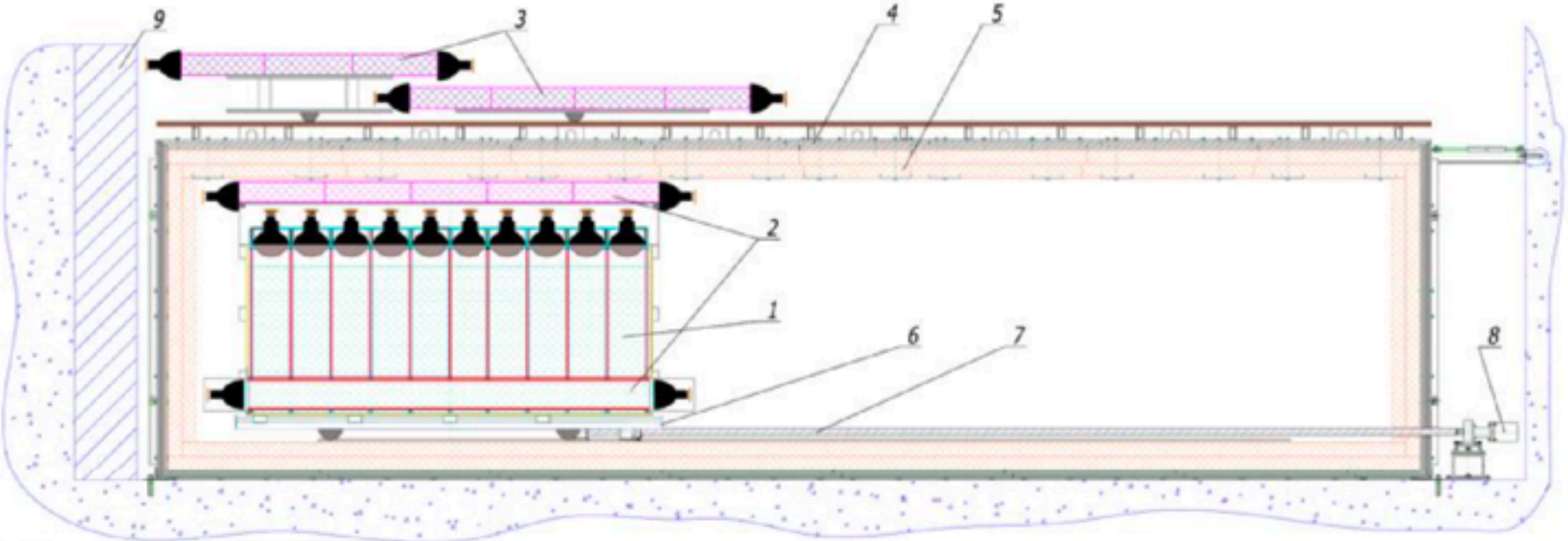
- 771 IBDs/day
- E resolution: 4.5%@1MeV
- Good PSD

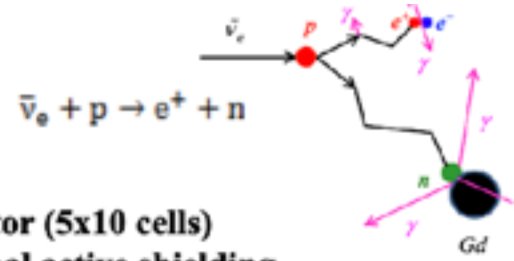
→ S/B ~ 2.2 (acci. bkg)
~1.32 (corr. bkg)



Sterile Neutrinos: Neutrino-4

Movable and spectrum sensitive antineutrino detector at SM-3 reactor





$\bar{\nu}_e + p \to e^+ + n$

1. detector (5x10 cells)
2. internal active shielding
3. external active shielding
4. steel and lead
5. borated polyethylene
6. moveable platform
7. feed screw
8. step motor
9. shielding

Passive shielding - 60 tons

← Neutrino channel outside and inside →

Detector prototype ←

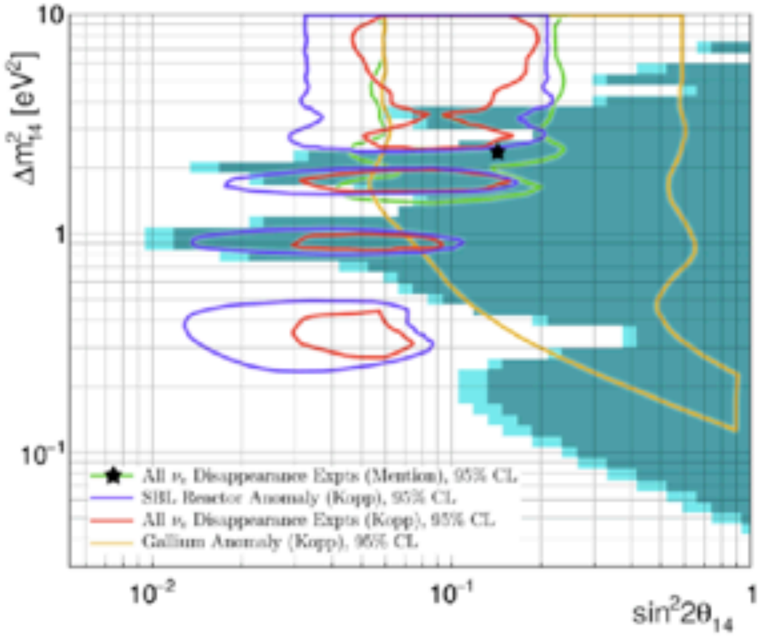
Full-scale detector →

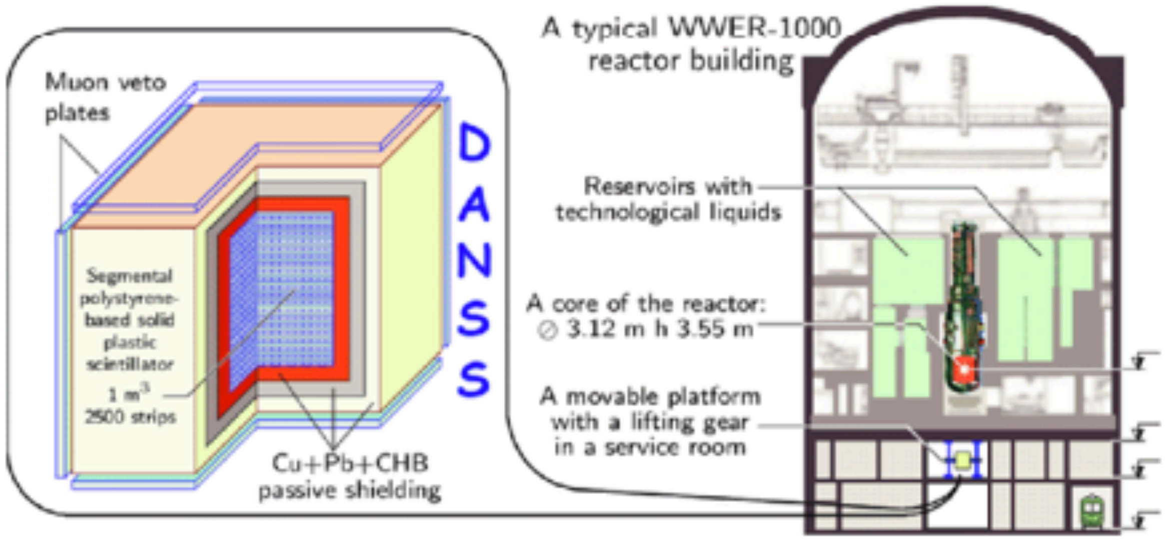
Range of measurements is 6 – 12 meters

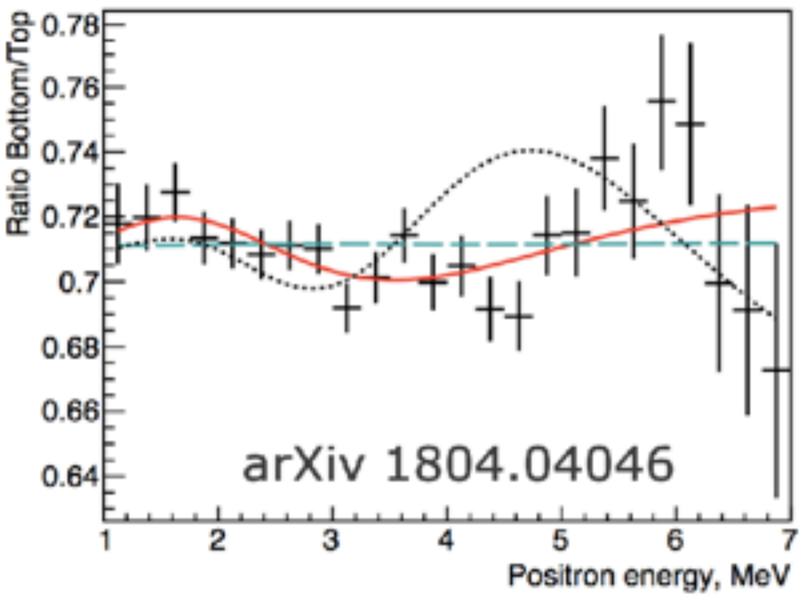
Liquid scintillator detector 50 sections 0.235x0.235x0.85м³

Sterile Neutrinos: DANSS

- DANSS operates at the Kalinin reactor (Russia) using a 1m³ highly-segmented plastic scintillator detector.
- Detector is moveable! Distance to core can be varied from 10.7m to 12.7m.
- Oscillation analysis based on ratio of “top” and “bottom” energy spectra.
- No evidence for oscillations.



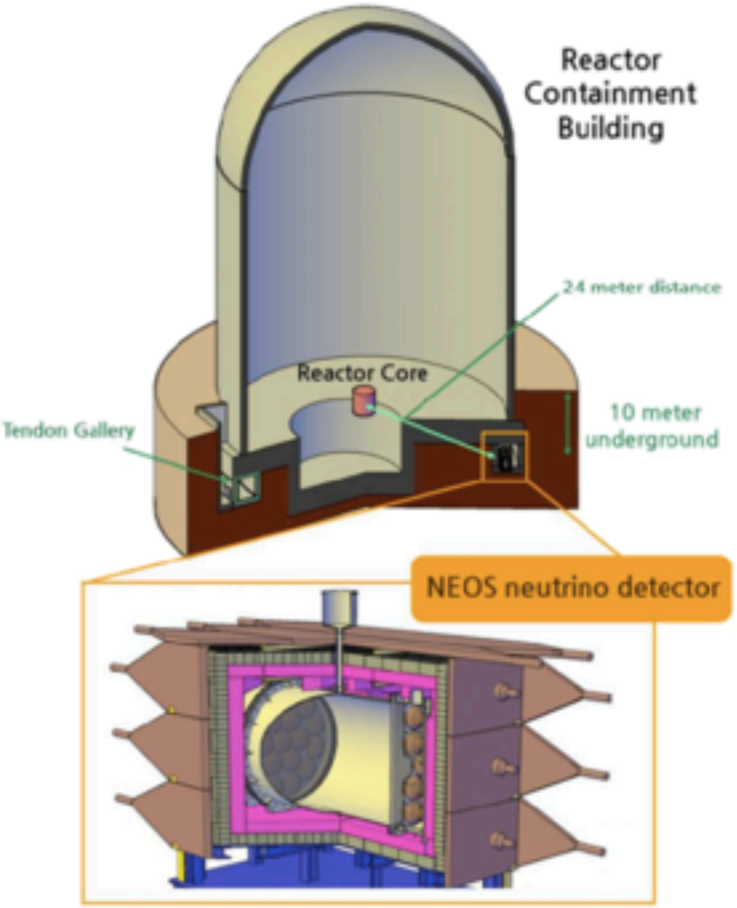


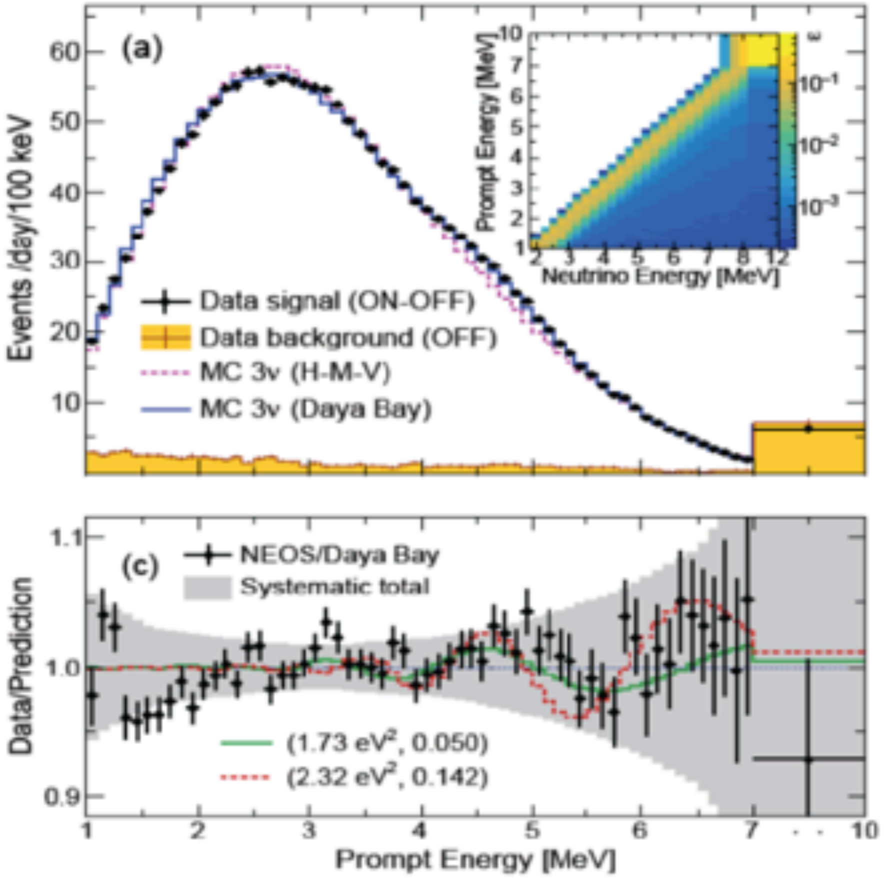


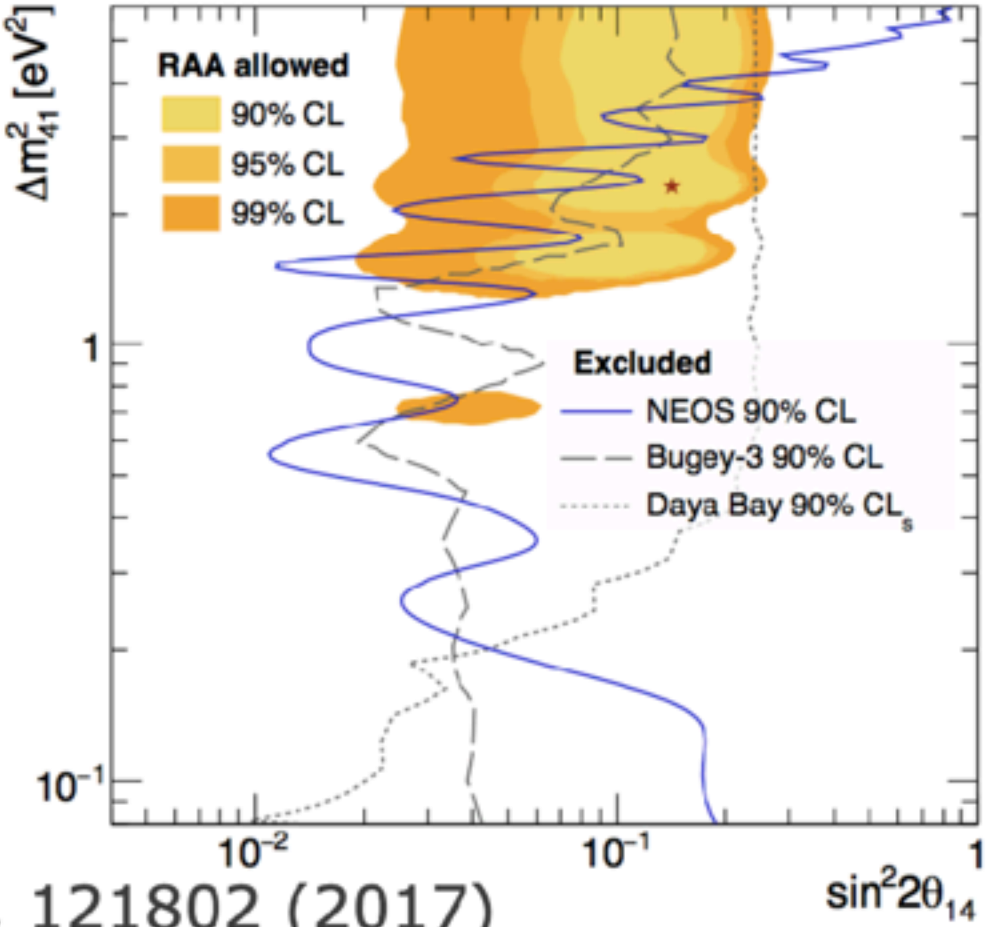
- ► Exciting 2018 model-independent indication of light sterile neutrinos at the eV scale from the NEOS and DANSS experiments in approximate agreement with the reactor and Gallium anomalies.
- ► 2019 DANSS data do not confirm the 2018 indication and the reactor indications in favor of SBL oscillations seem to be fadind away.

Sterile Neutrinos: NEOS

- NEOS operates 24m from the Hanbit-5 reactor (Yeong-gwong, Korea) using a 1-ton Gd-loaded scintillator detector.
  - ➢ Phase 1: Sep’2015 – May’2016
    - – No evidence for sterile neutrinos (disfavour RAA best fit at 90% CL)
  - ➢ Phase 2: Ongoing since 2018
    - – Plan to operate over a full fuel cycle.





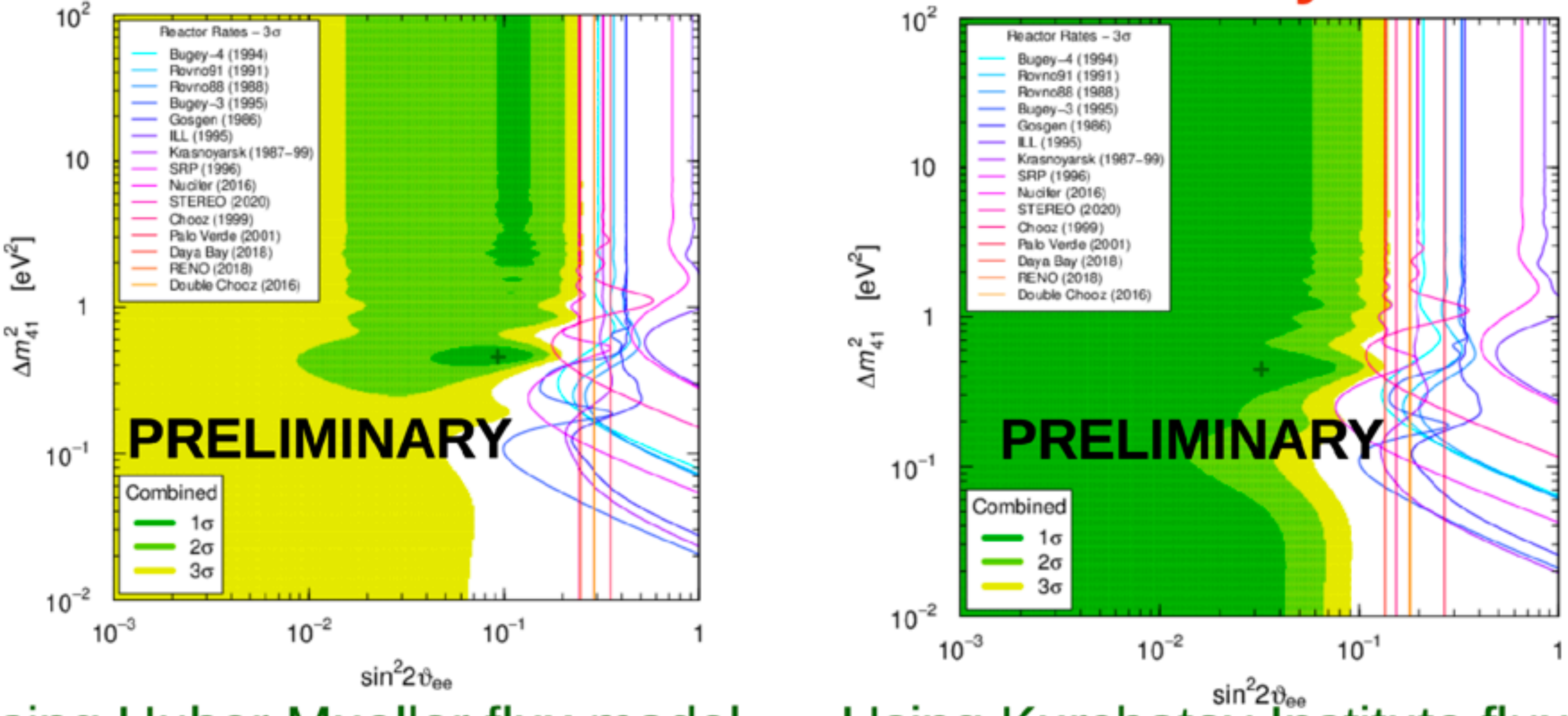


PRL 118, 121802 (2017)

Sterile Neutrinos: Evolution

2011

The reactor antineutrino anomaly



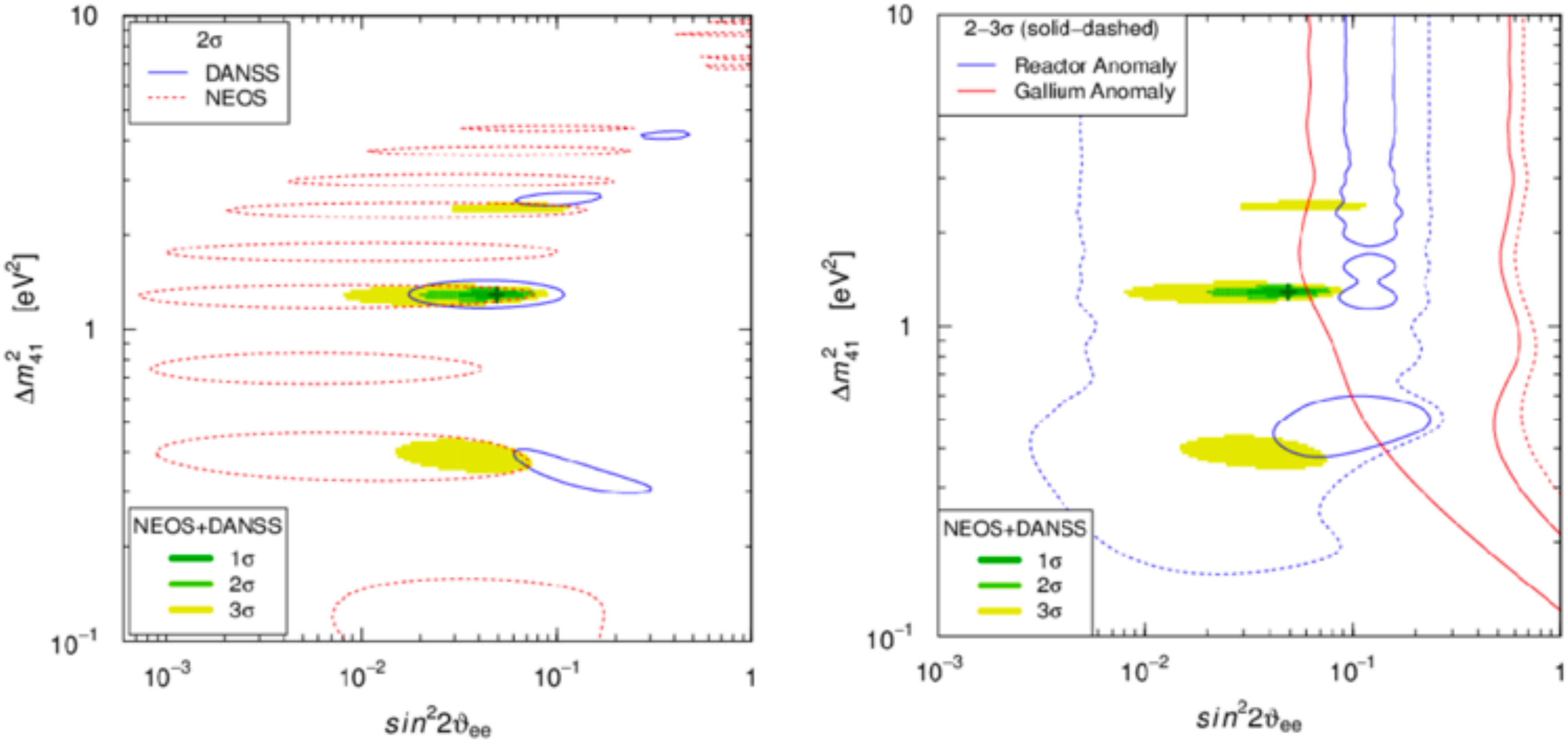
Using Huber Mueller flux model

Using Kurchatov Institute flux model

Sterile Neutrinos: Evolution

Ratio analysis 2018

Gariazzo, Giunti, Laveder, Li, 1801.06467, PLB 2018



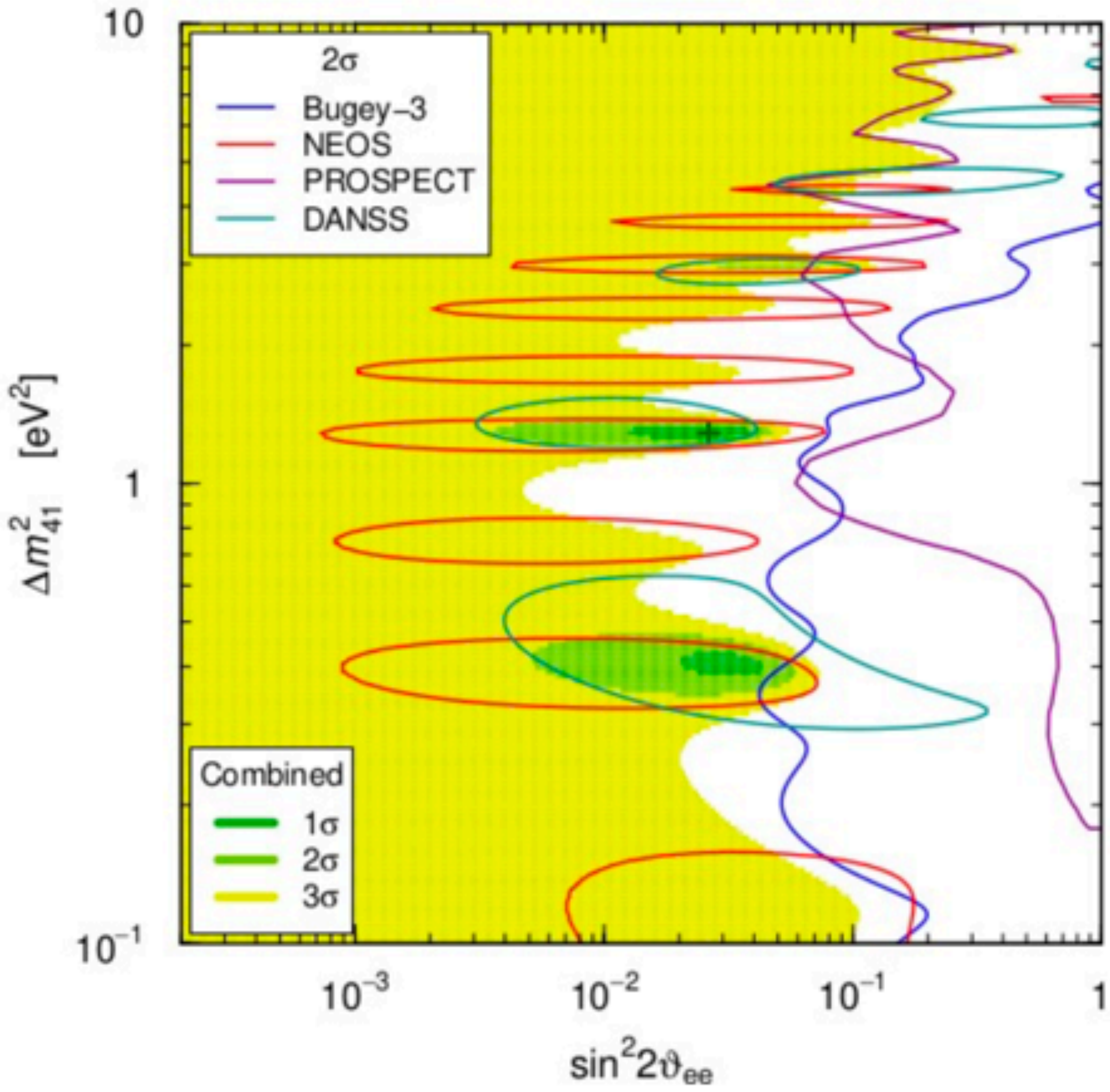
~2σ individual preference from DANSS and NEOS

>3σ combined preference

Sterile Neutrinos: Evolution

Ratio analysis 2019/2020

Giunti, Li, Zhang, 1912.12956, JHEP 2020

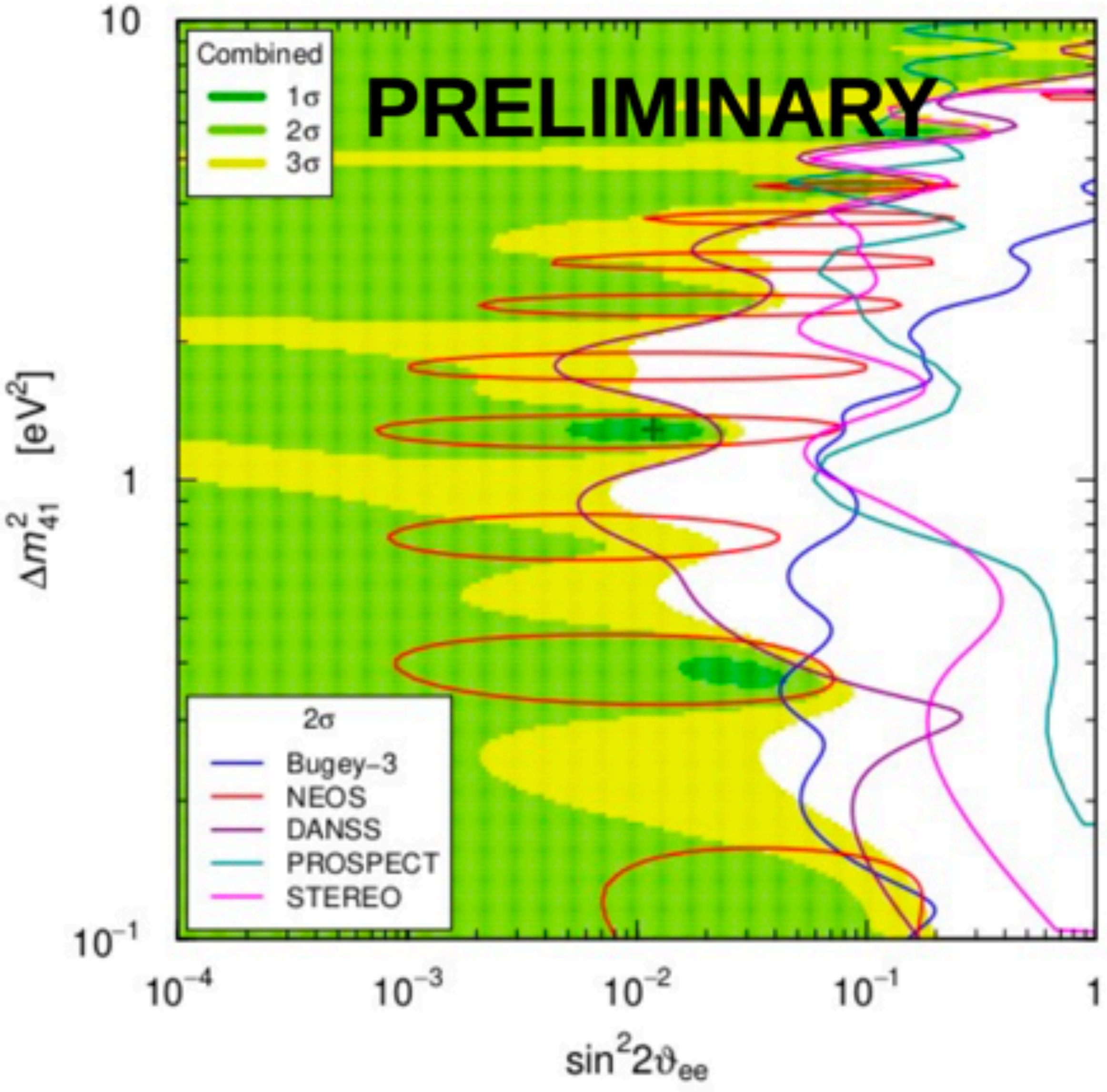


Less agreement between DANSS and NEOS

still >2σ combined preference

Sterile Neutrinos: Evolution

Ratio analysis 2021



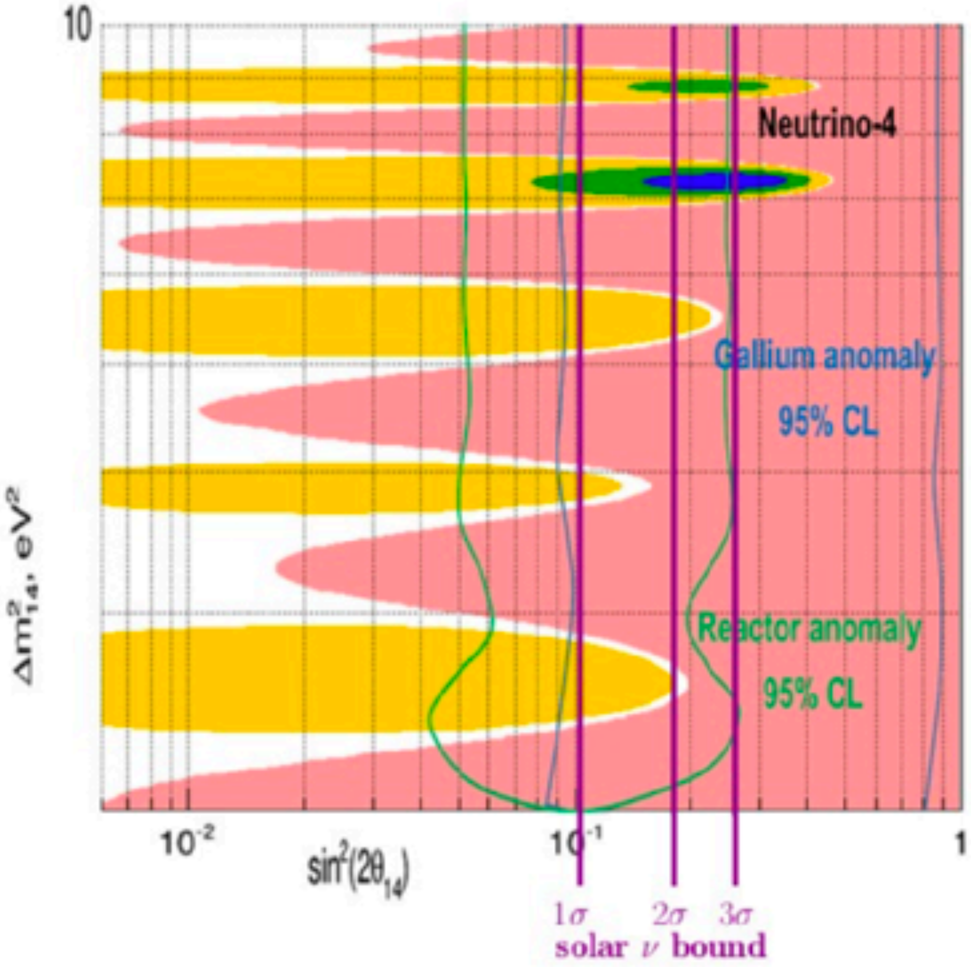
No preference at all for oscillations in DANSS data

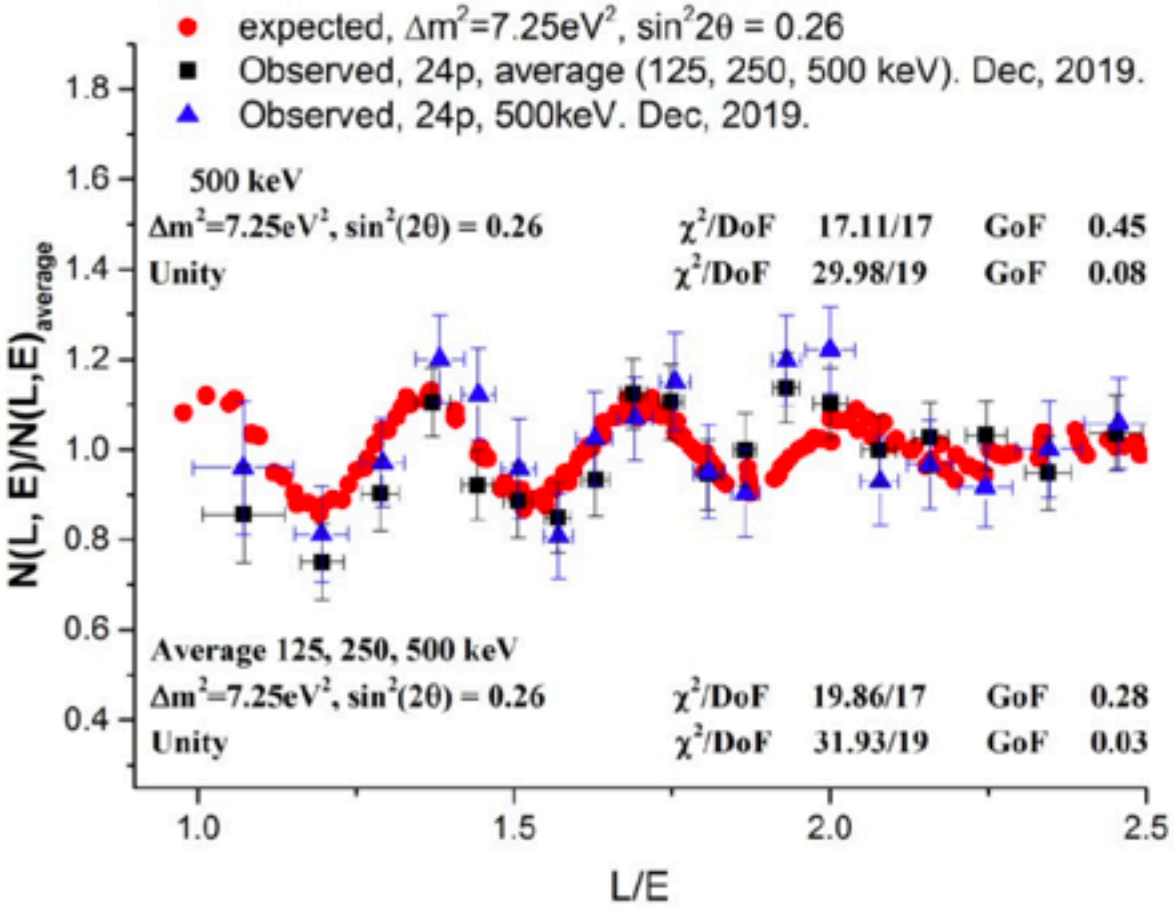
no closed contours at 2σ

we can only set upper limits on $|U_{e4}|^2 = \sin^2\theta_{14}$

Sterile Neutrinos: Neutrino-4

Neutrino-4



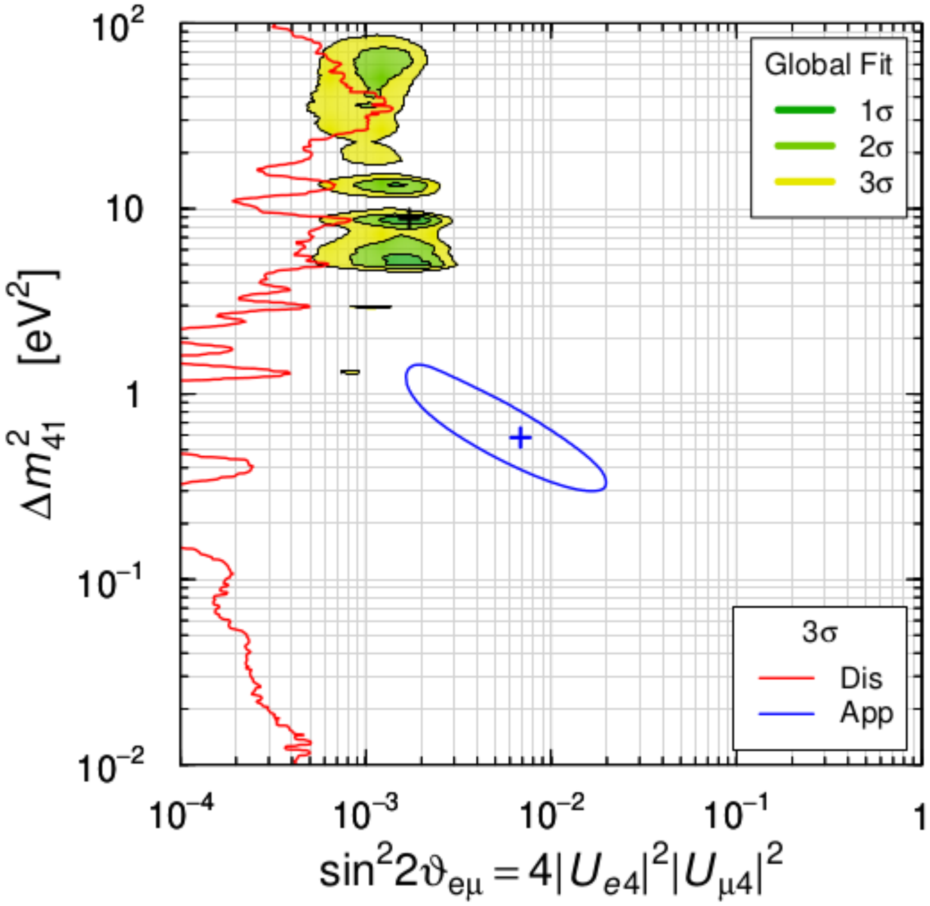


Neutrino-4 observes sterile oscillations at ~3σ

Very large mixing In tension with solar data

Sterile Neutrinos: Global Fit

Global fit?



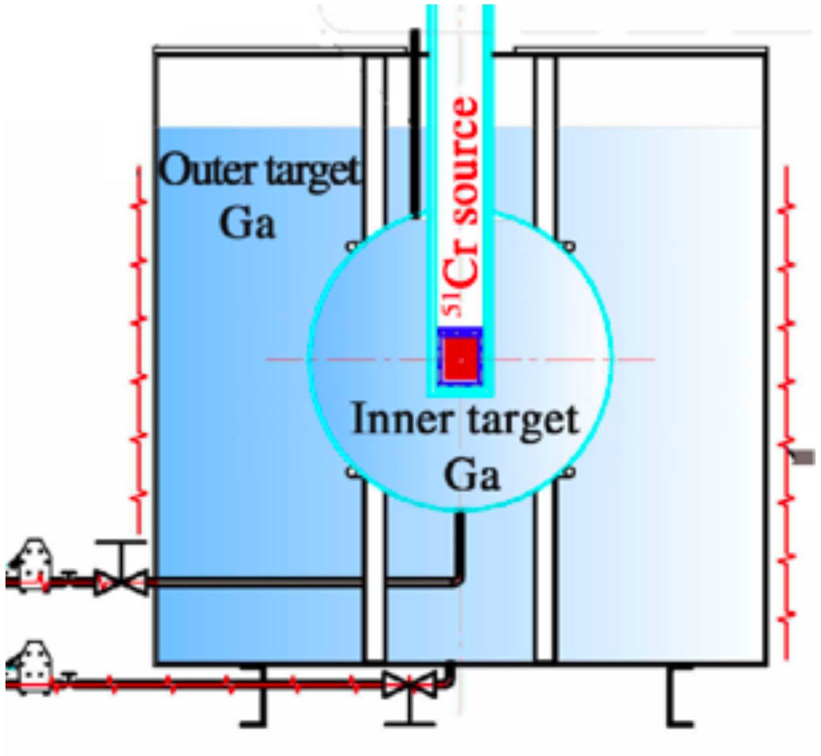
NOT most up-to-date data included in this figure!

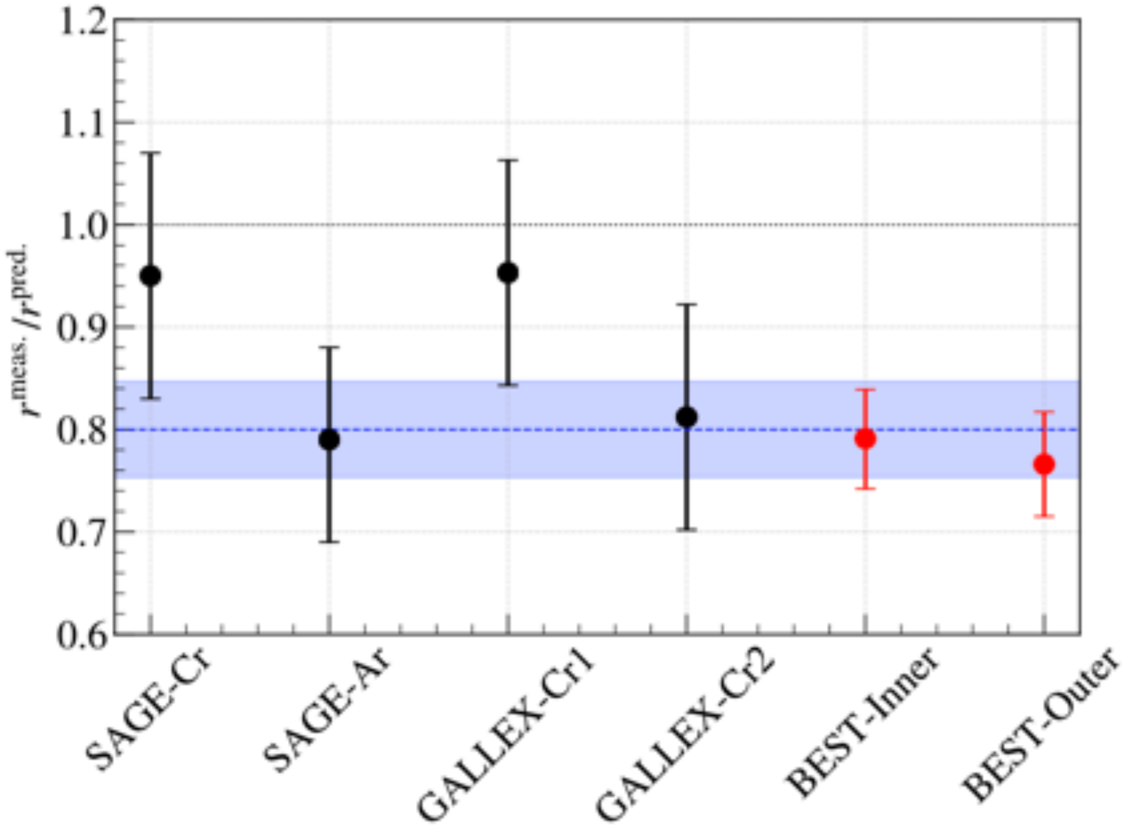
No overlap anymore!

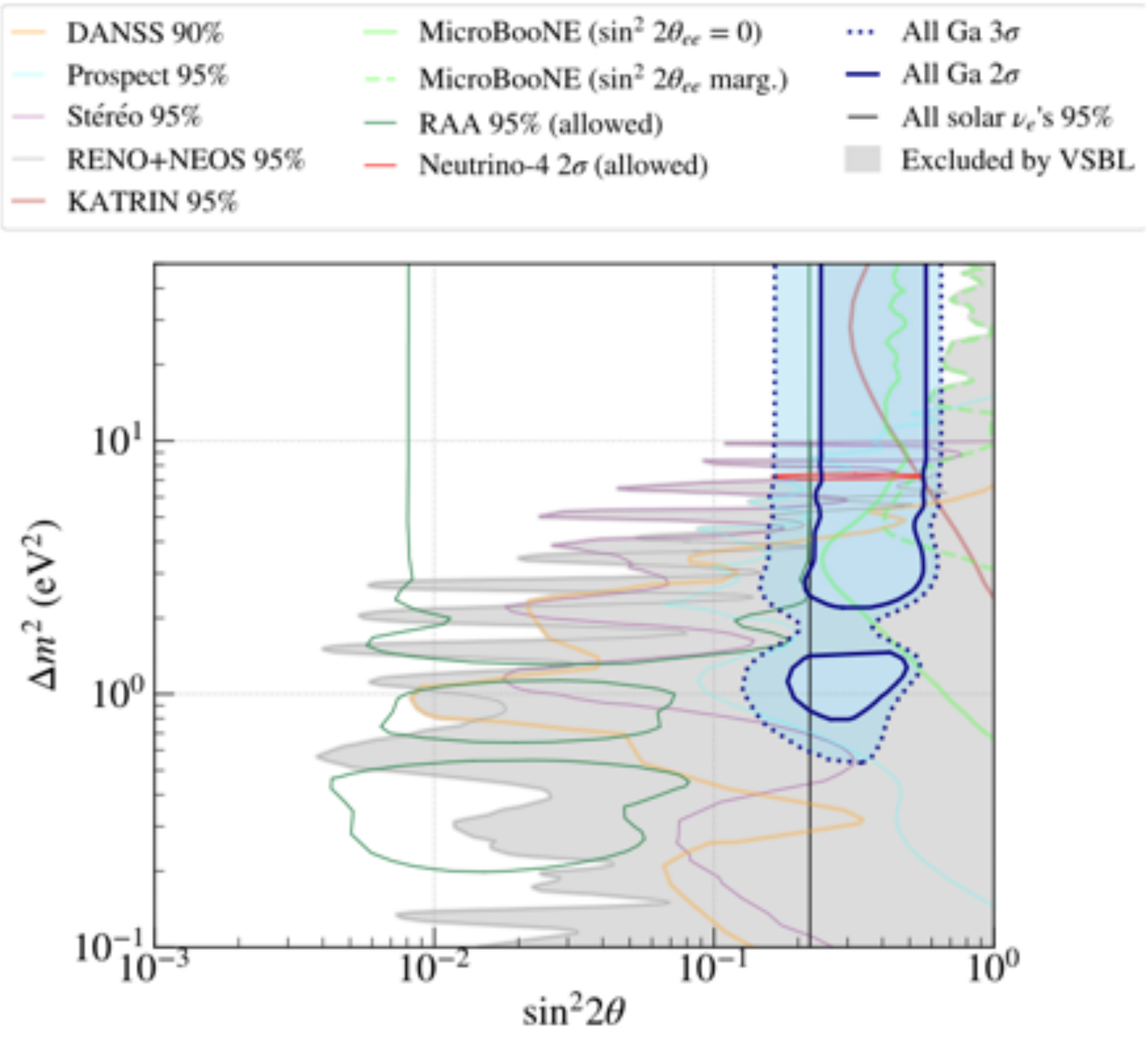
$GoF_{PG} = 7 \times 10^{-11}$

Global 3+1 fit is unacceptable!

Sterile Neutrinos: BEST







Sterile Neutrinos?