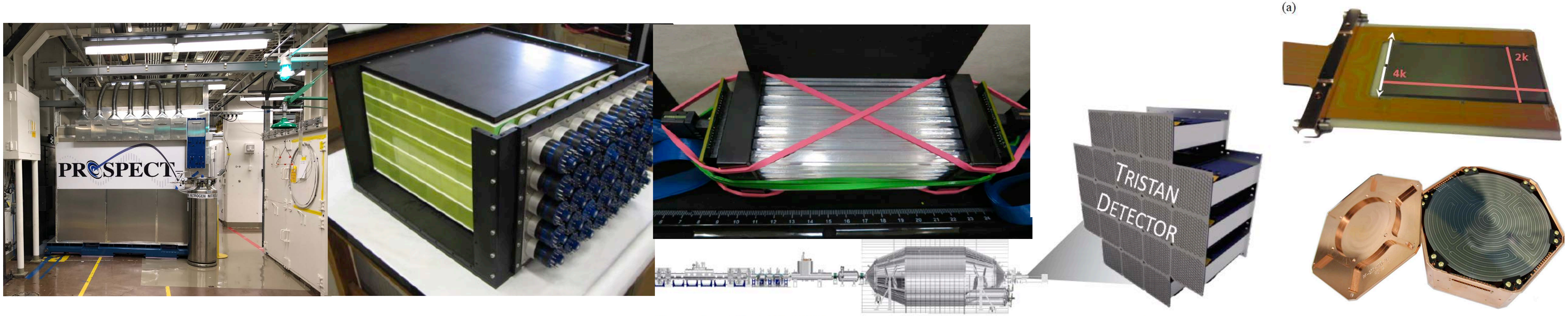
Reactor and Radioactive Source Experiments

Snowmass NF02 - Sterile Neutrinos



19 LOIs, a range of technologies at different stages of developments
opportunities for training, various physics goals, potential for discovery science

Karsten Heeger
Yale University

LOIs

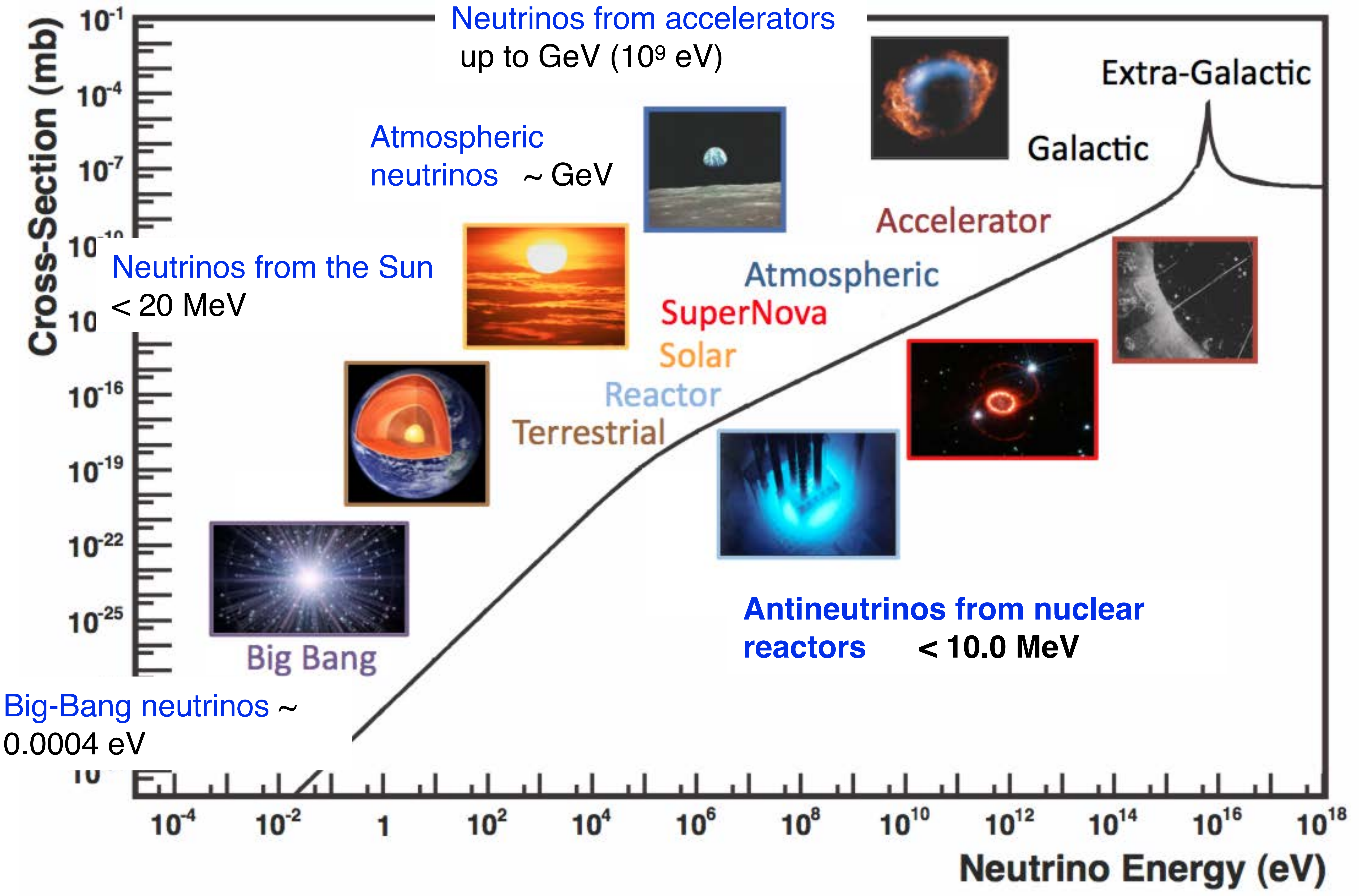
include current and proposed experiments, R&D efforts

1. HUNTER: A Facility for a Trapped Atom Sterile Neutrino Search and Other Studies
2. Physics with Electron Capture Neutrino Sources
3. Laboratory searches for KeV sterile neutrinos
4. Laboratory-Based keV-Scale Sterile Neutrino Searches and the BeEST Experiment
5. Secondary Physics Potential of the Project 8 Experiment
6. Prospects for keV Sterile Neutrino Searches with KATRIN
7. COherent Neutrino-Nucleus Interaction Experiment (CONNIE): Status and Plans
8. Reactor neutrino detection experiment using Skipper CCDs
9. NuLat: A Compact Anti-Neutrino Detector
10. Joint Experimental Oscillation Analyses in Search of Sterile Neutrinos
11. An Application of Pulse Shape Sensitive Plastic Scintillator - Segmented AntiNeutrino Directional Detector (SANDD)
12. CHANDLER: A Technology for Surface-level Reactor Neutrino Detection
13. Forthcoming Science from the PROSPECT-I Data Set

14 The Expanded Physics Reach of PROSPECT-II

15. MIvER CEvNS Experiment - A Tool for Discovery of New Physics and Applied Reactor Monitoring
16. Measuring Inelastic Charged- and Neutral-Current Antineutrino-Nucleus Interactions with Reactor Neutrinos
17. Prediction and Measurement of the Reactor Neutrino Flux and Spectrum
18. The JUNO-TAO Experiment
19. ROADSTR: a Mobile Antineutrino Detector Platform for enablingMulti-Reactor Spectrum, Oscillation, and ApplicationMeasurements

Neutrino Sources



Neutrinos from accelerators up to GeV (10^9 eV)

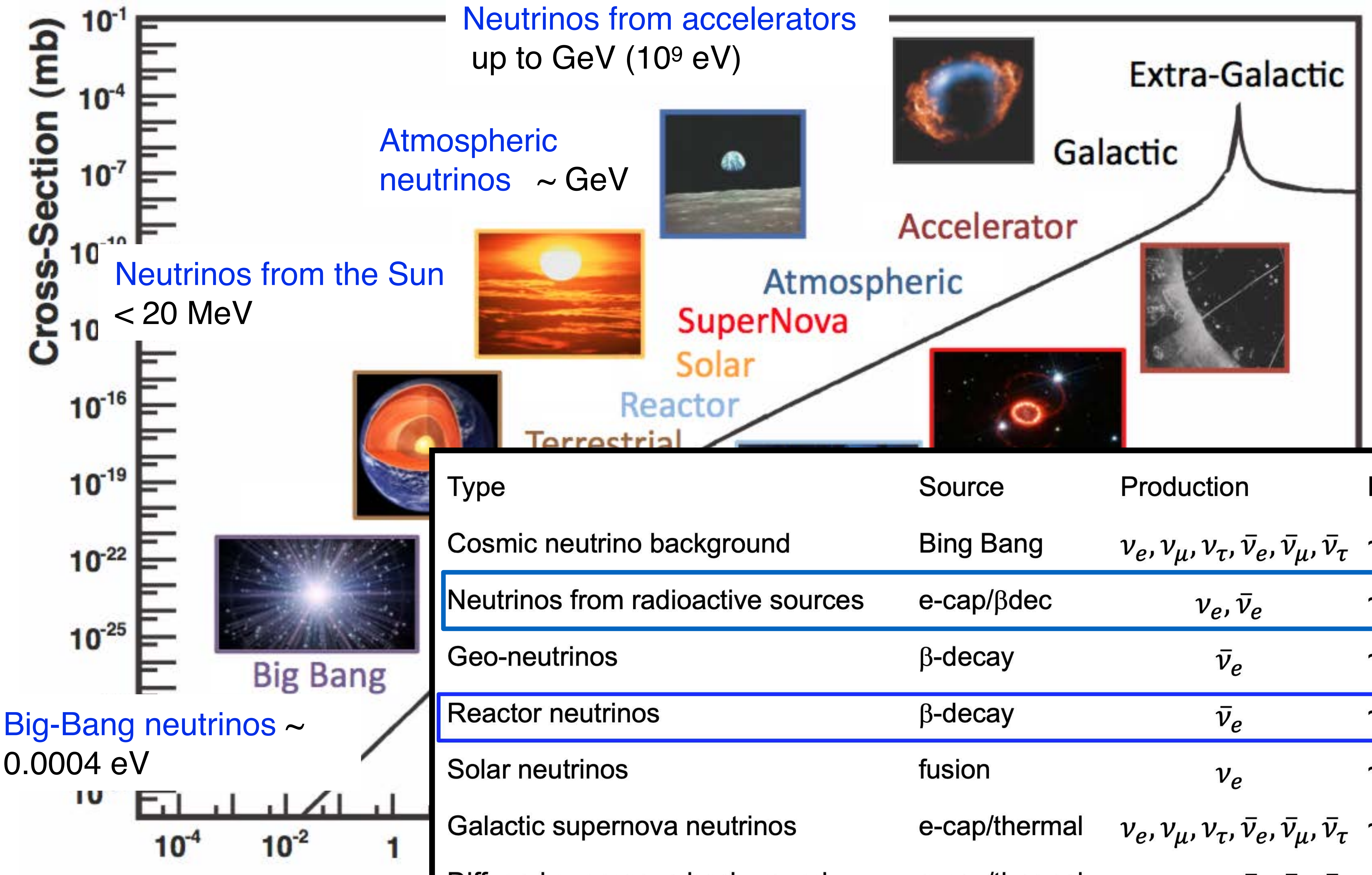
Atmospheric neutrinos ~ GeV

Neutrinos from the Sun < 20 MeV

Antineutrinos from nuclear reactors < 10.0 MeV

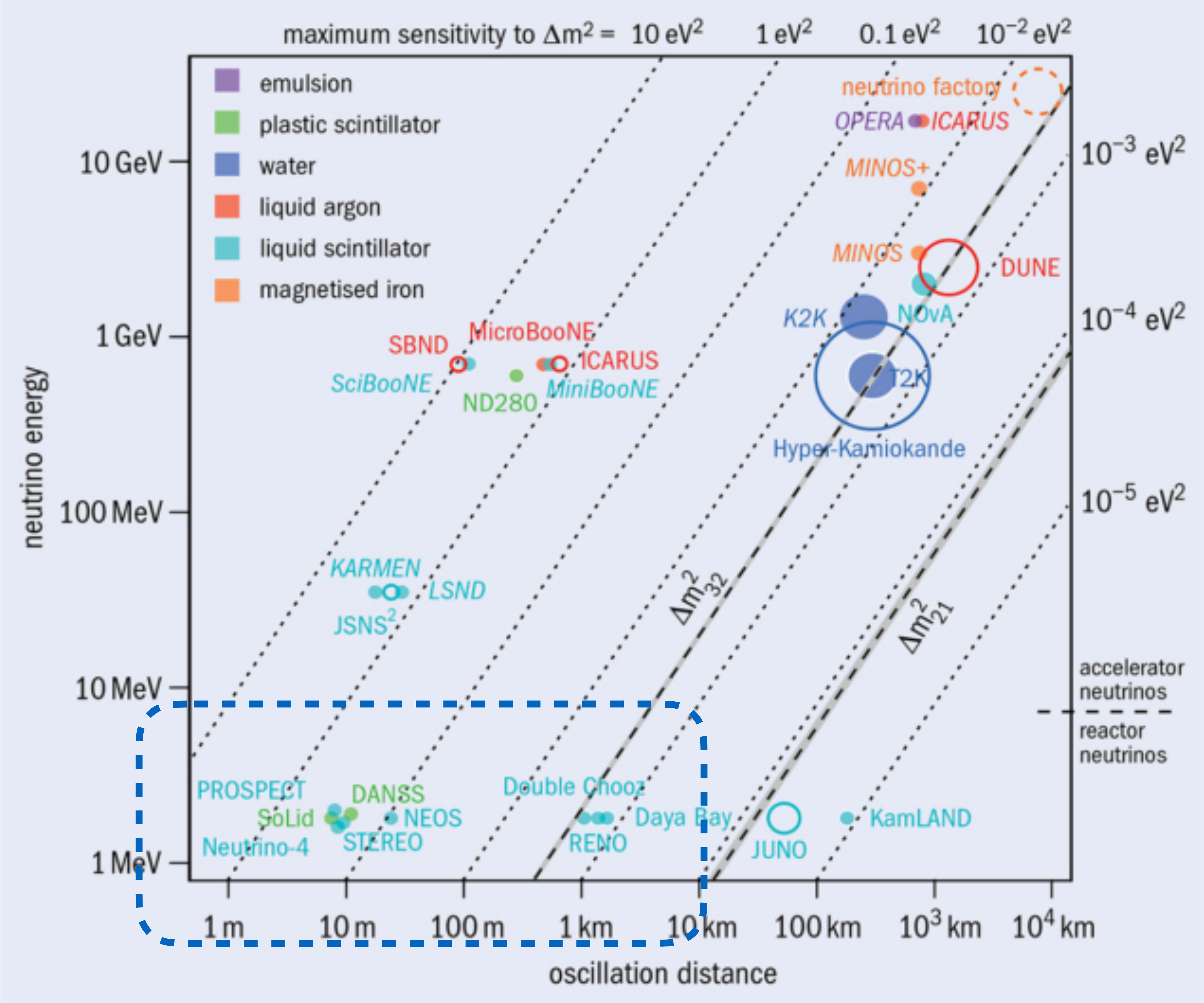
Big-Bang neutrinos ~ 0.0004 eV

Neutrino Sources



Type	Source	Production	Energy
Cosmic neutrino background	Bing Bang	$\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$	~0.1 meV
Neutrinos from radioactive sources	e-cap/βdec	$\nu_e, \bar{\nu}_e$	~0.7 - 0.8 MeV
Geo-neutrinos	β-decay	$\bar{\nu}_e$	~ 2 MeV
Reactor neutrinos	β-decay	$\bar{\nu}_e$	~4 MeV
Solar neutrinos	fusion	ν_e	~0.4-10 MeV
Galactic supernova neutrinos	e-cap/thermal	$\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$	~10-30 MeV
Diffused supernova background	e-cap/thermal	$\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$	~10 MeV

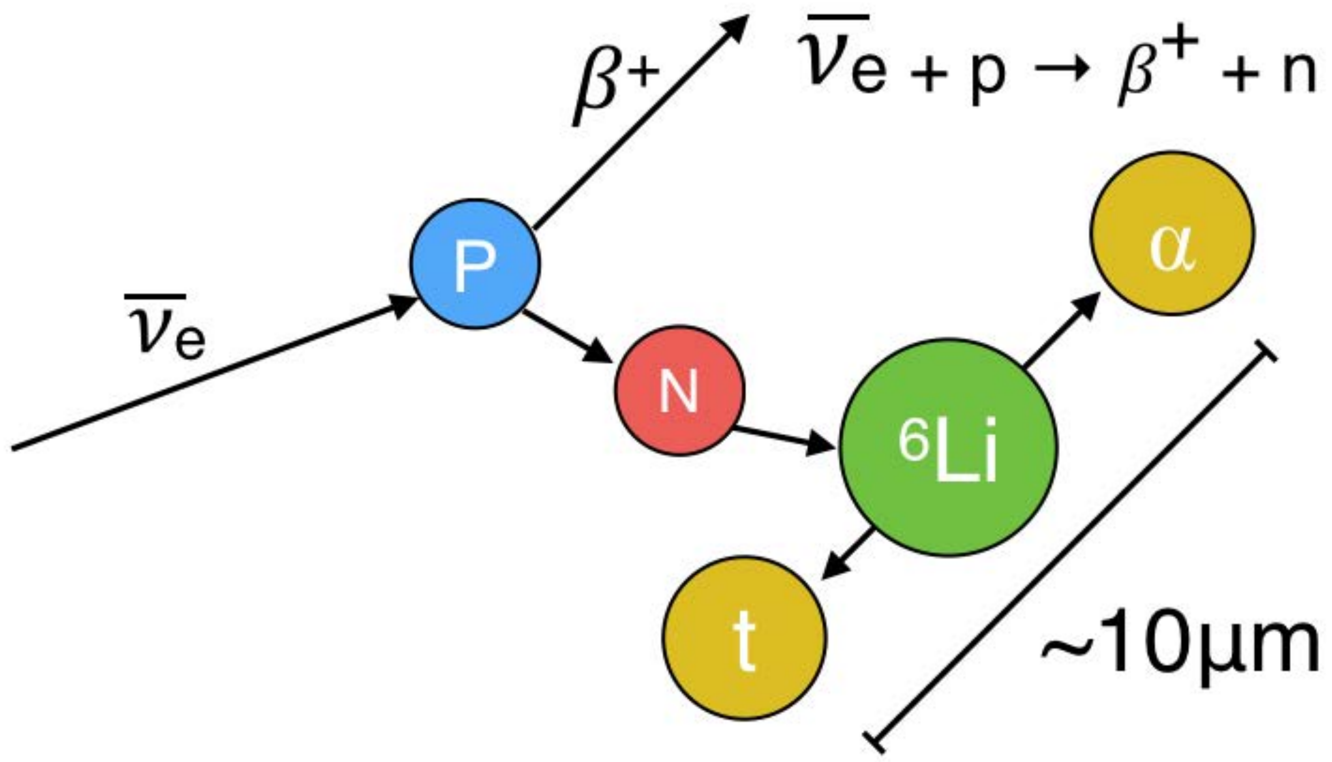
Precision Oscillation Physics

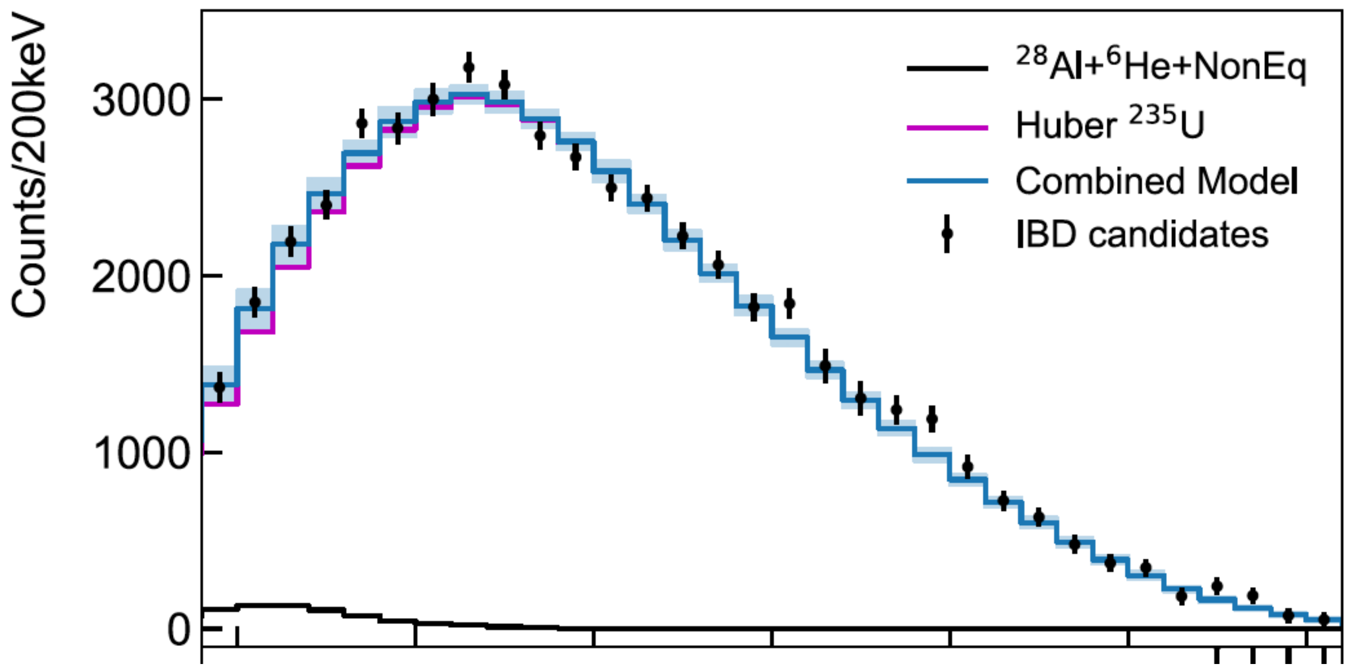


https://cerncourier.com/a/tuning-in-to-neutrinos/

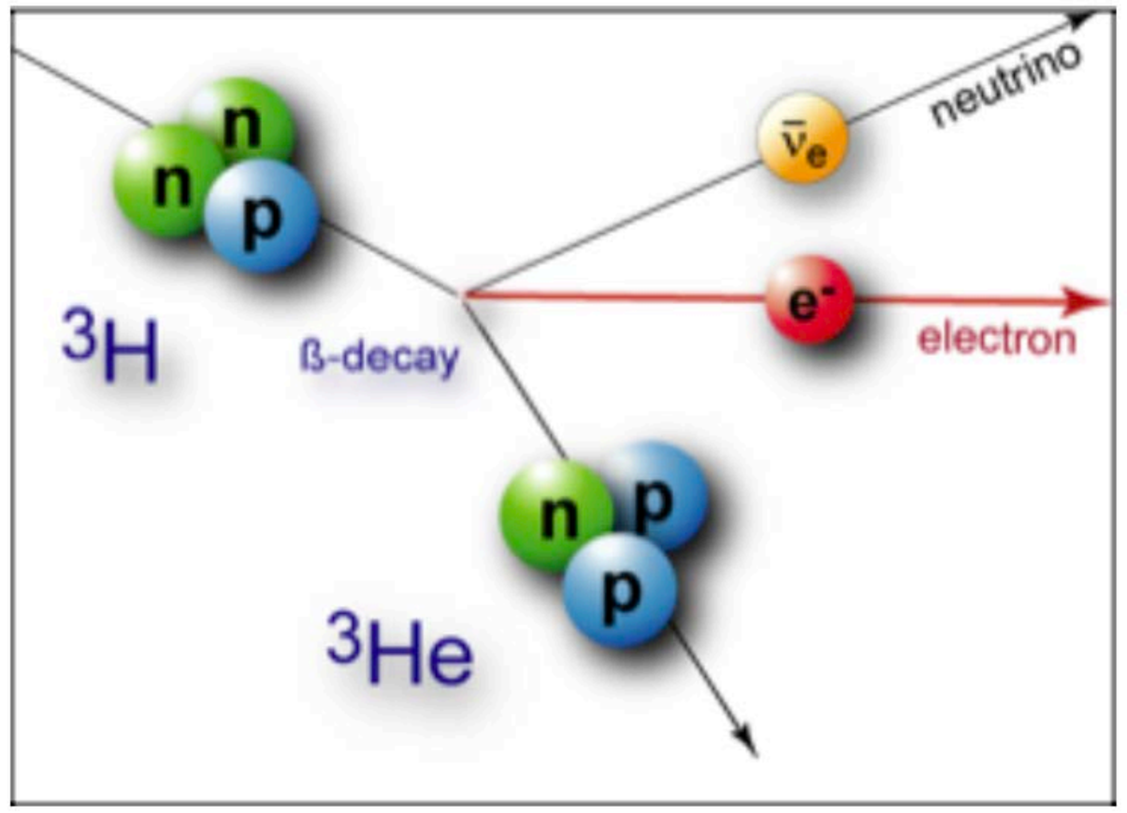
Detection Channels of (Anti)neutrinos from Reactors and Sources

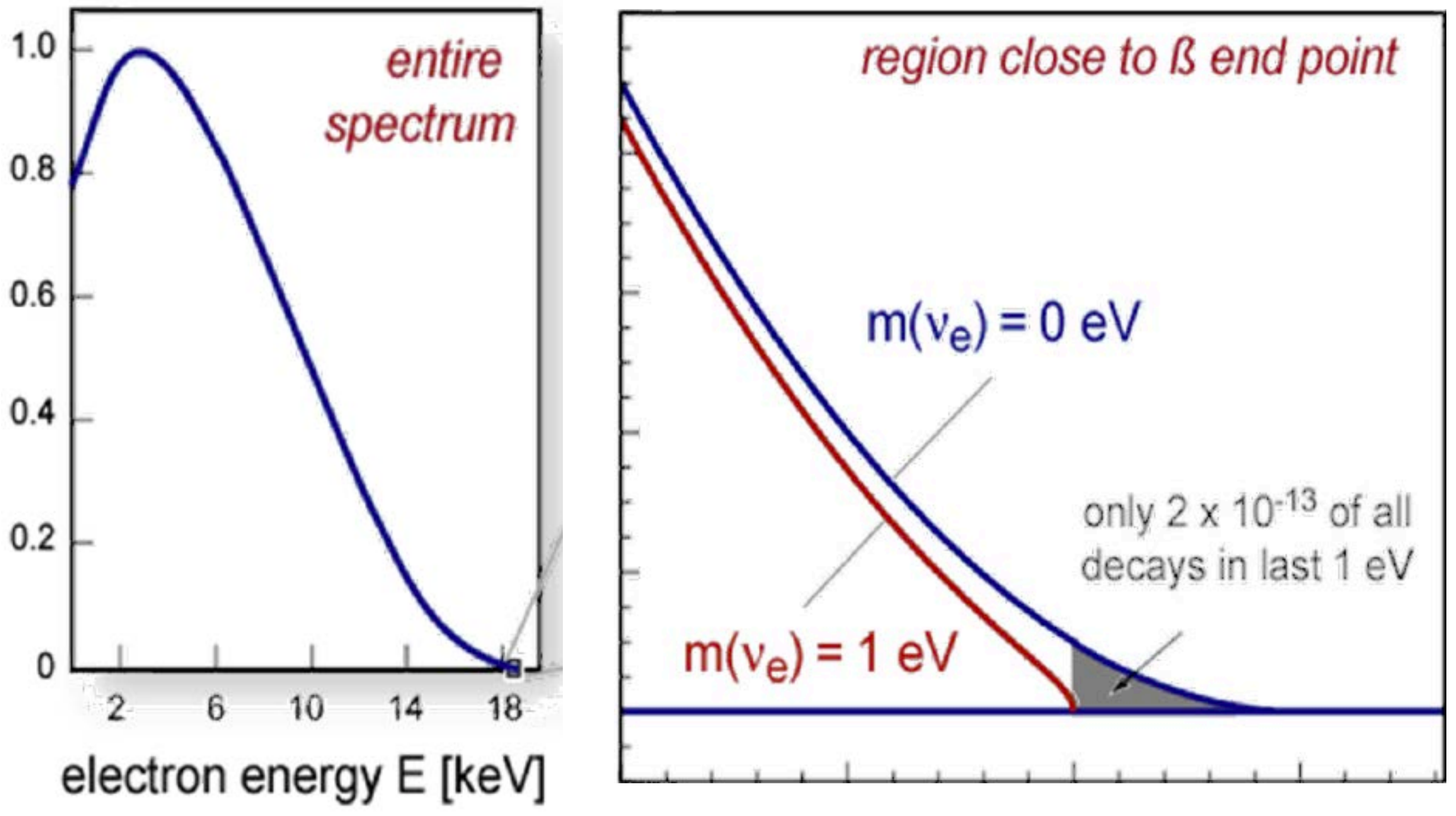
Inverse Beta-Decay



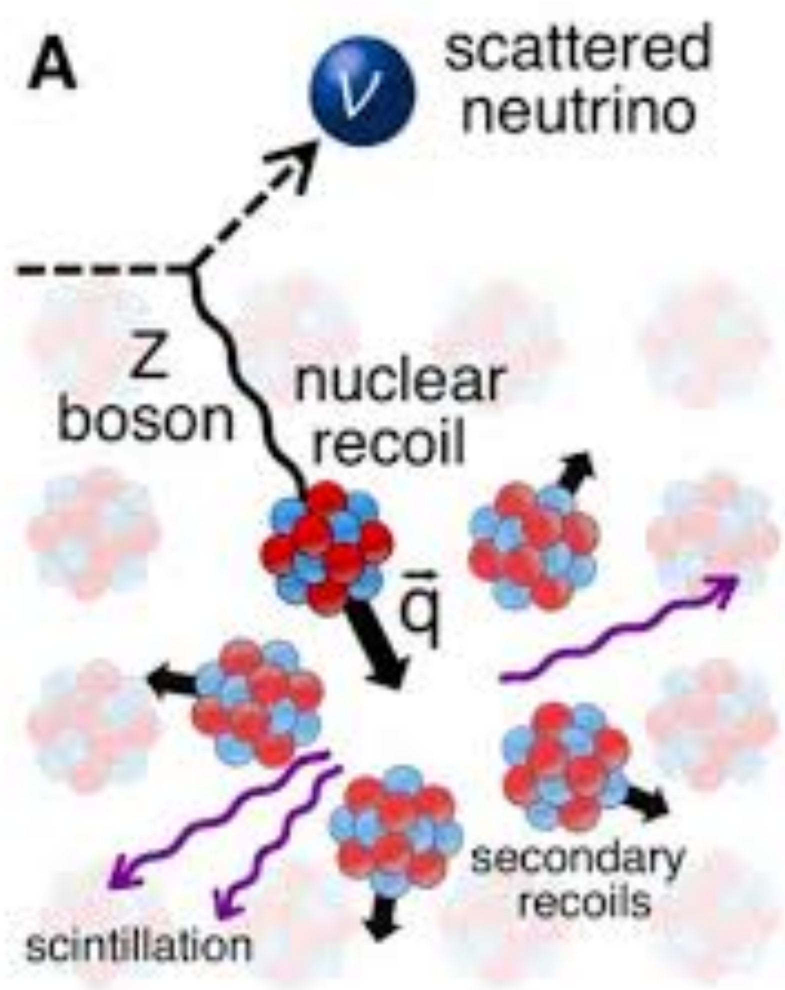


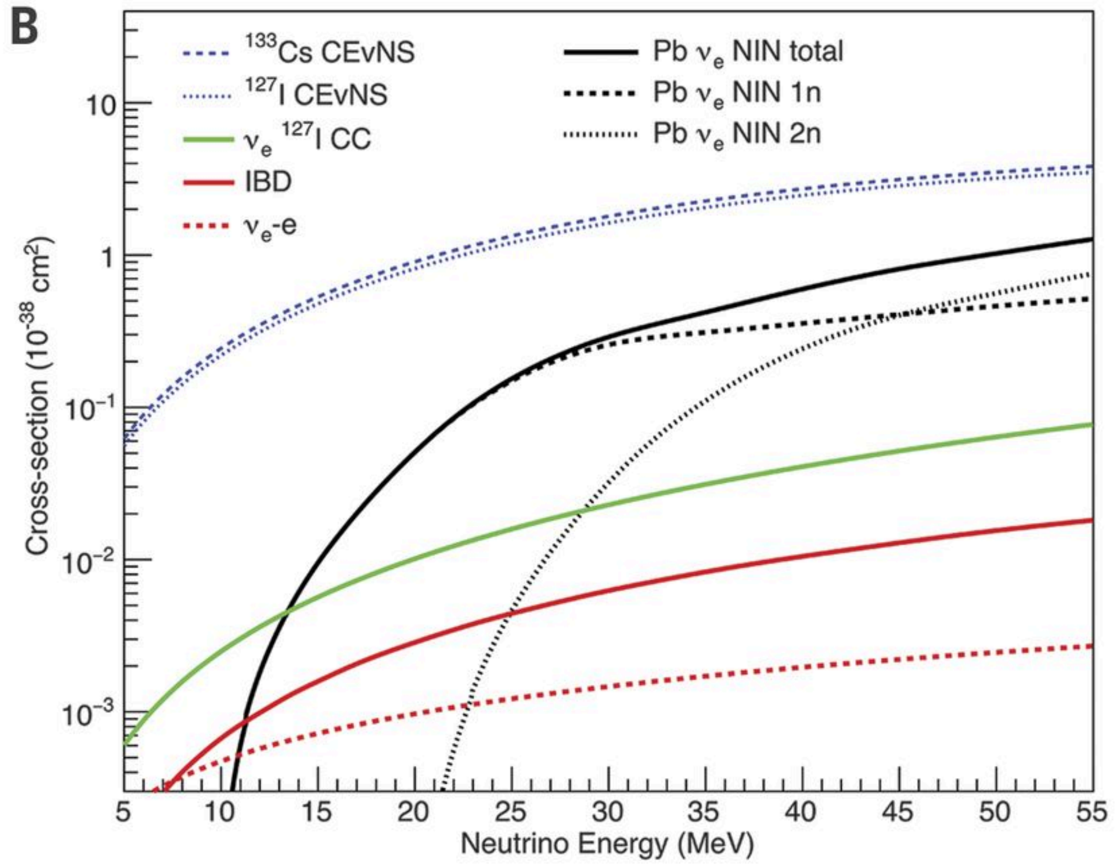
Direct Kinematics





Coherent Elastic Neutrino scattering



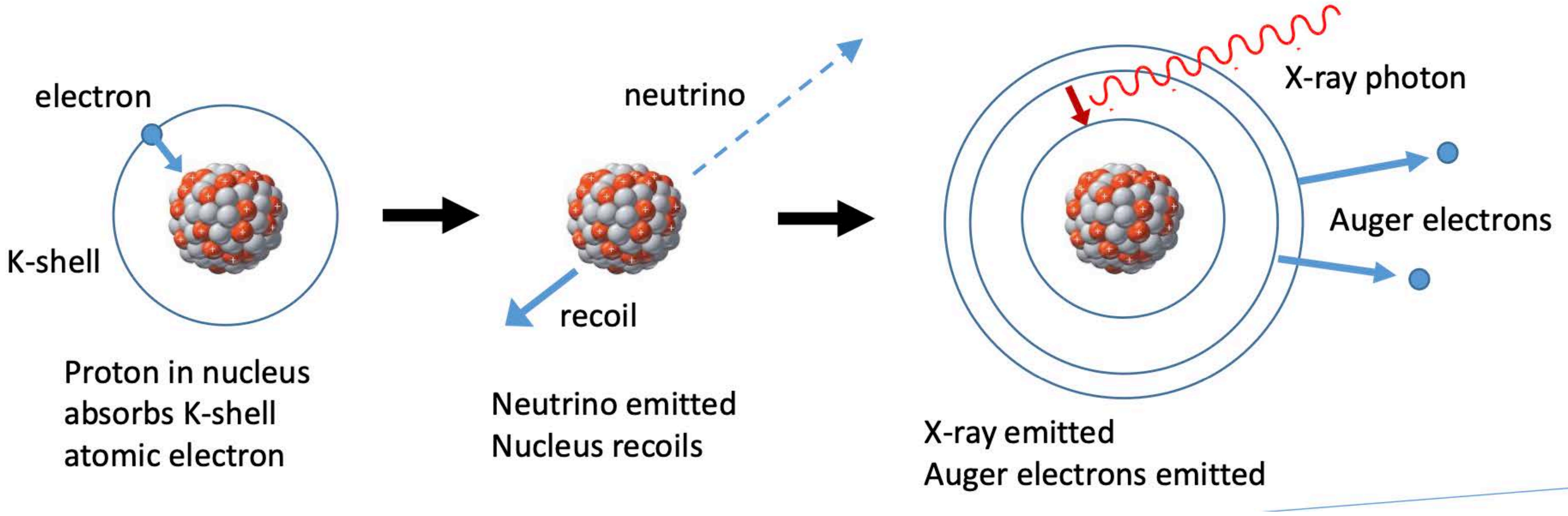


LOIs

Detection Channels of (Anti)neutrinos from Reactors and Sources

Electron Capture

Proposed K-capture experiment: measuring the mass of an unseen neutrino



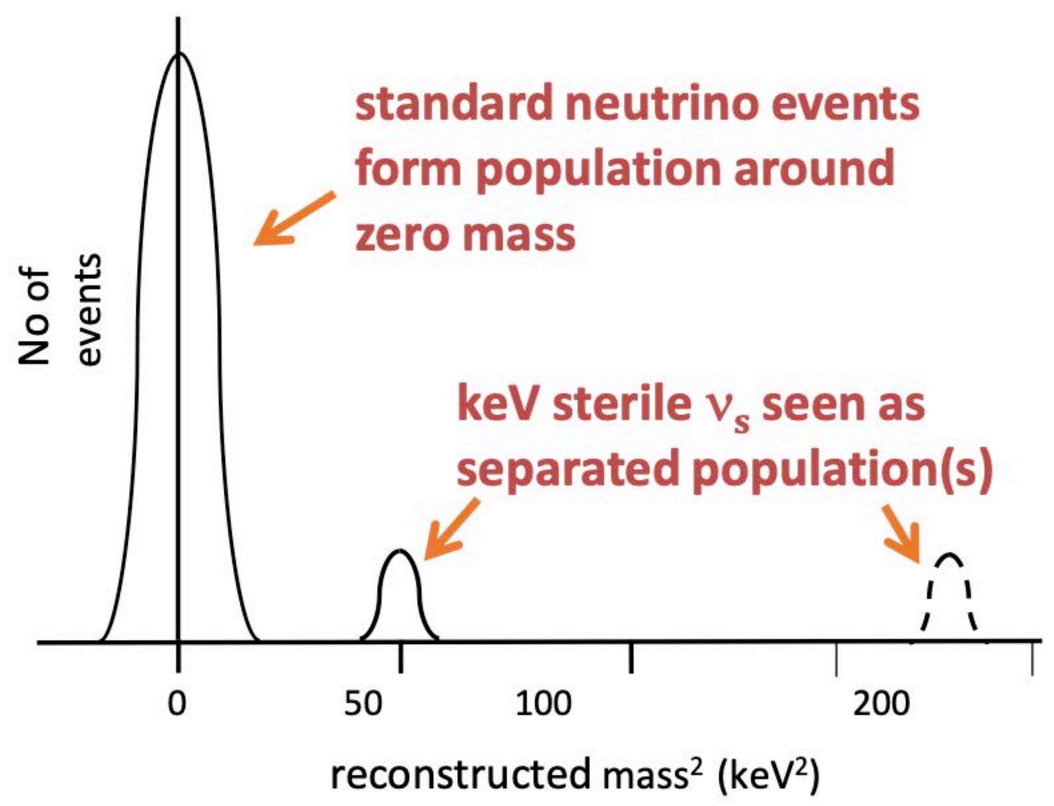
make precision momentum measurements of:

- recoil ion
- X-ray photon
- Auger electrons

↓

calculate missing ν momentum

Reconstructed mass spectra:

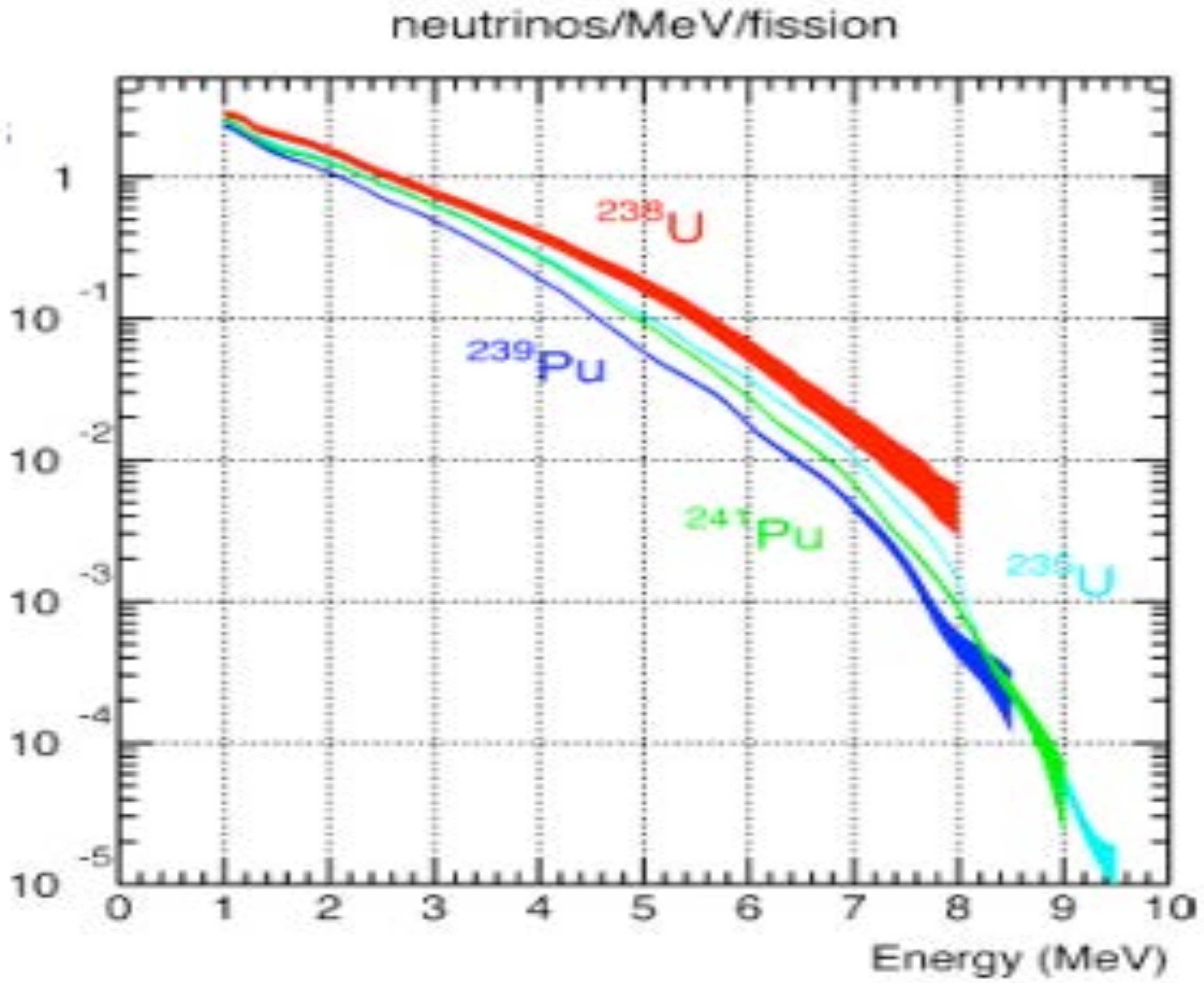


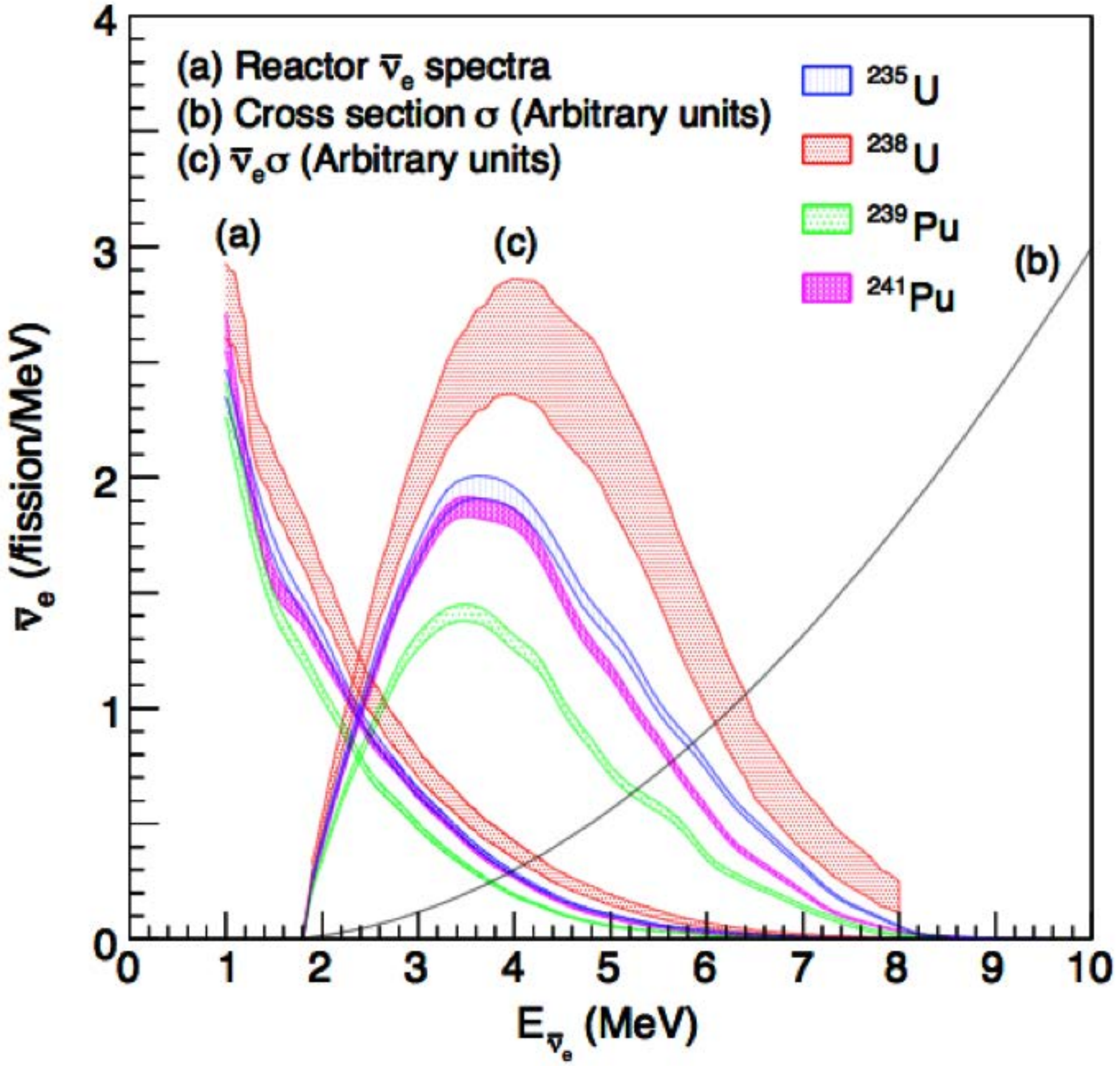
Experiment	Isotope	Strength	Production Process
GALLEX [3]	^{51}Cr	1.69 MCi	Thermal neutron capture on ^{50}Cr
SAGE [2]	^{51}Cr	0.517 MCi	Epithermal neutron capture on ^{50}Cr
GALLEX [1]	^{51}Cr	1.87 MCi	Thermal neutron capture on ^{50}Cr
SAGE [4]	^{37}Ar	0.409 MCi	Fast neutron $^{40}\mathrm{Ca}(n,\alpha)^{37}\mathrm{Ar}$
BEST [5]	^{51}Cr	3.4 MCi	Thermal neutron capture on ^{50}Cr

LOIs

Reactor Antineutrinos

$\bar{\nu}_e$ from β-decays, pure $\bar{\nu}_e$ source
of n-rich fission products
on average ~6 beta decays until stable



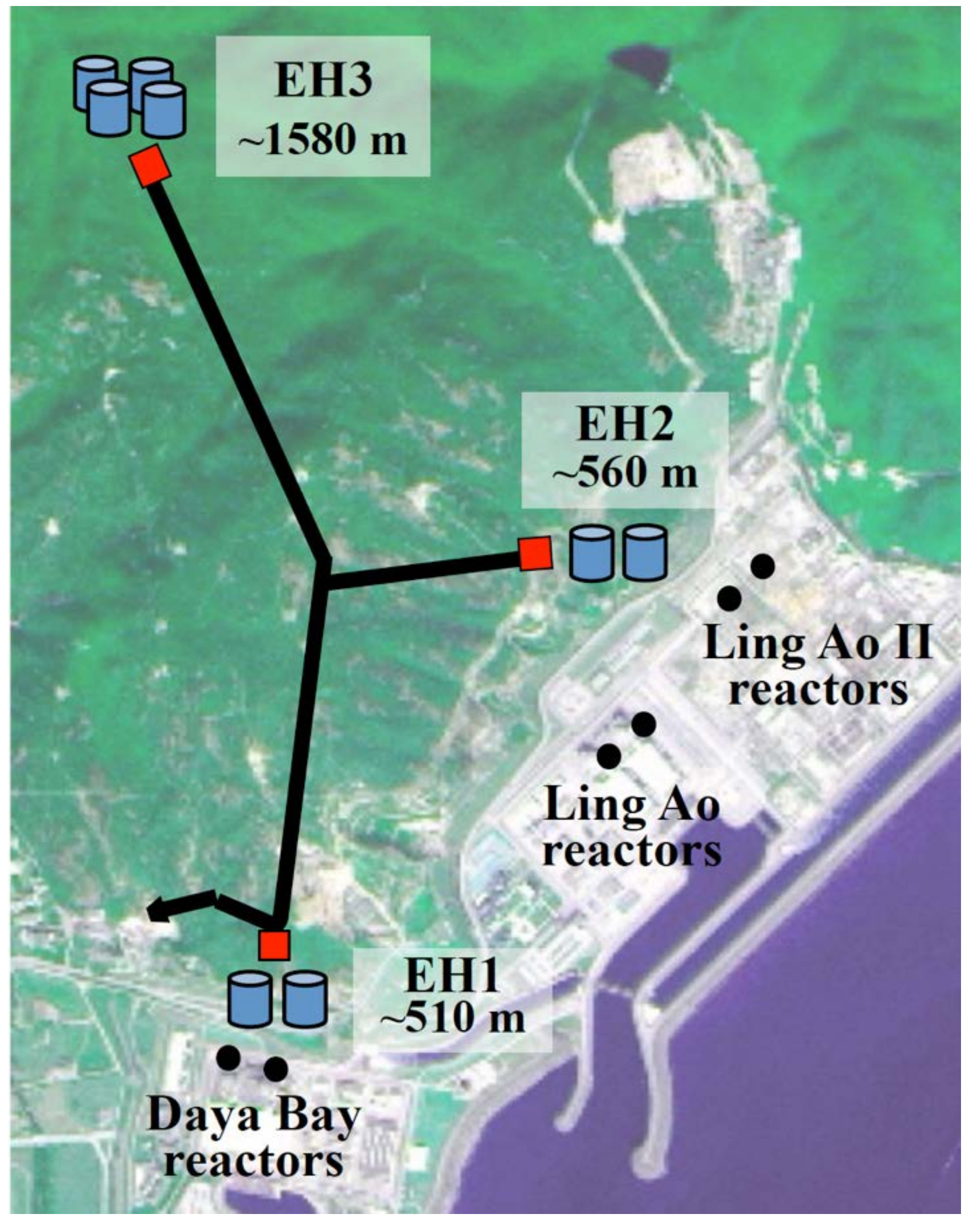


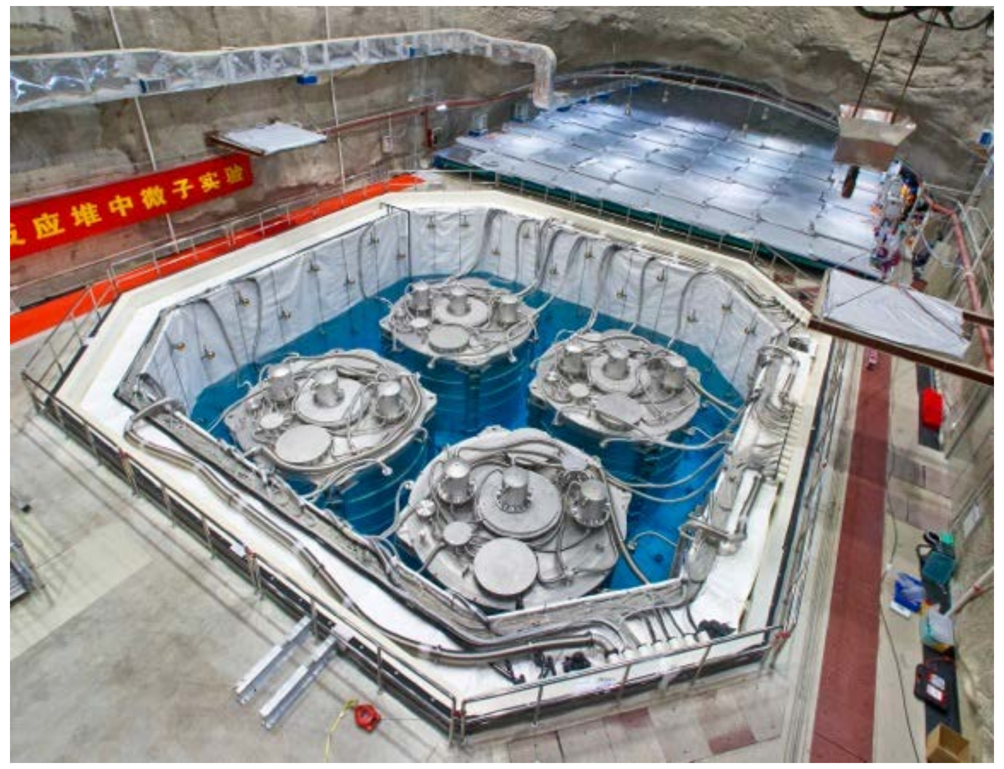
> 99.9% of $\bar{\nu}_e$ are produced by fissions in
^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

mean energy of $\bar{\nu}_e$: 3.6 MeV

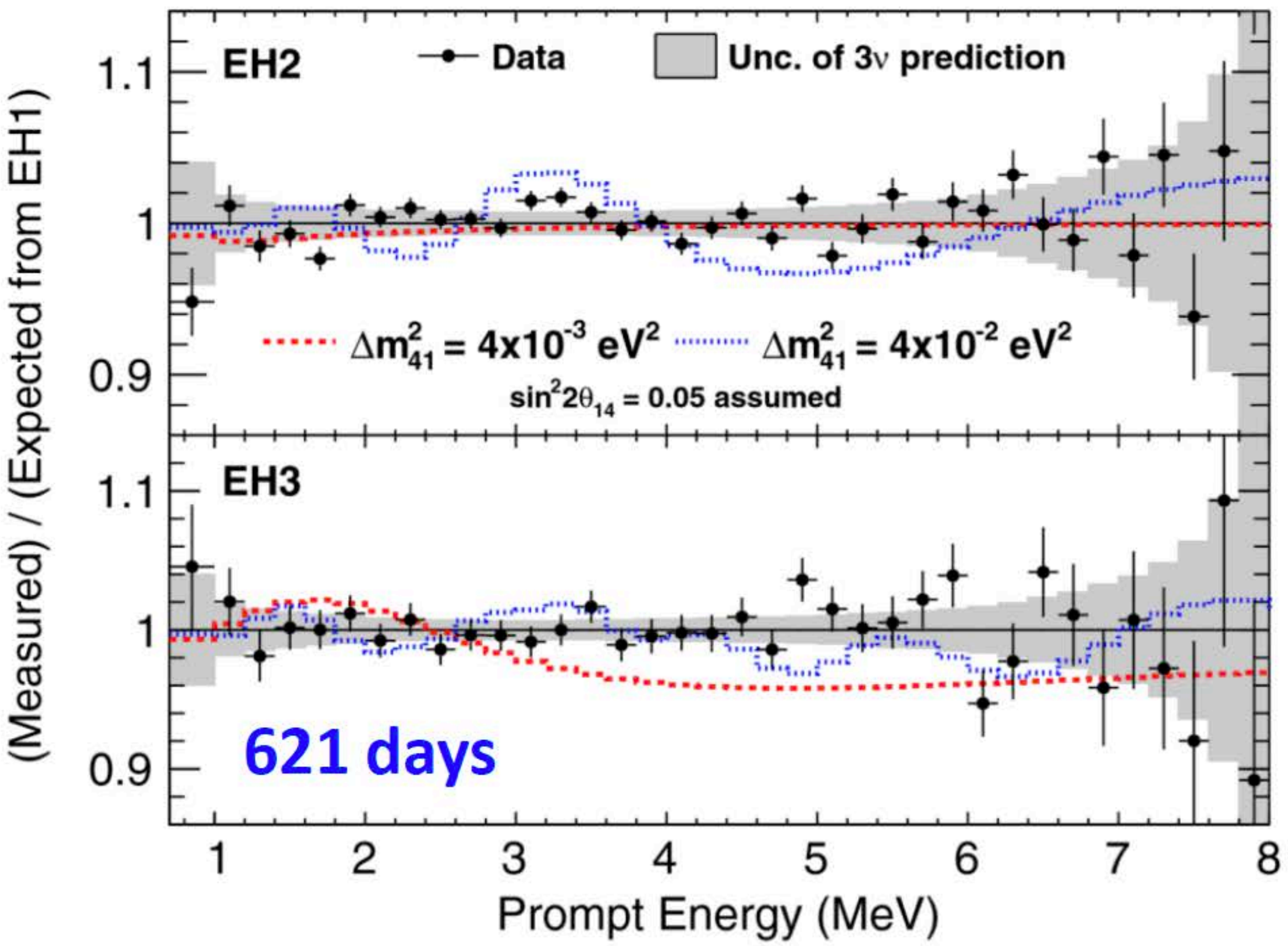
only disappearance
experiments possible

Precision Measurements with Daya Bay

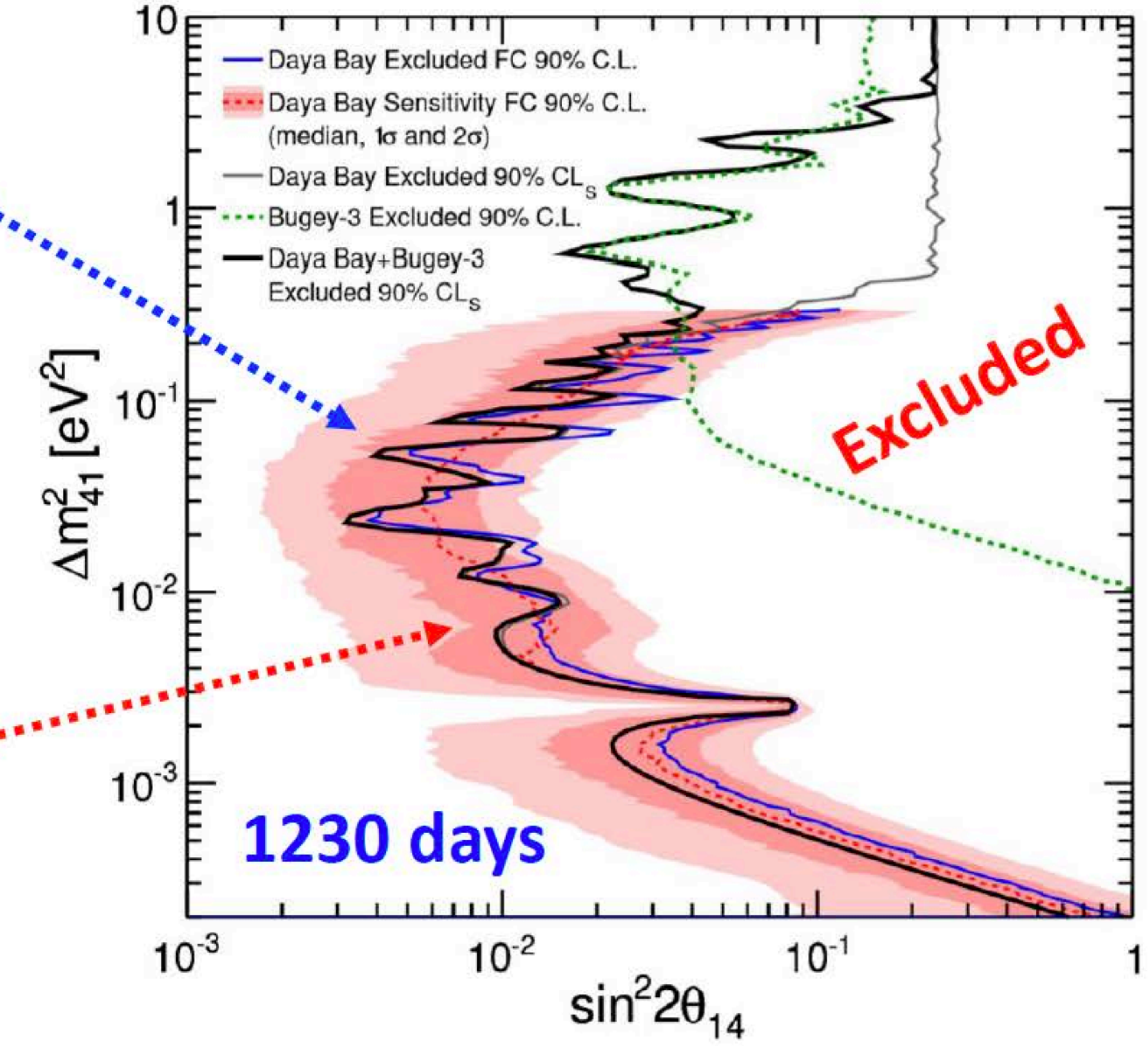




PRL **117** 151802 (2016)



arXiv:2002.00301, accepted by PRL



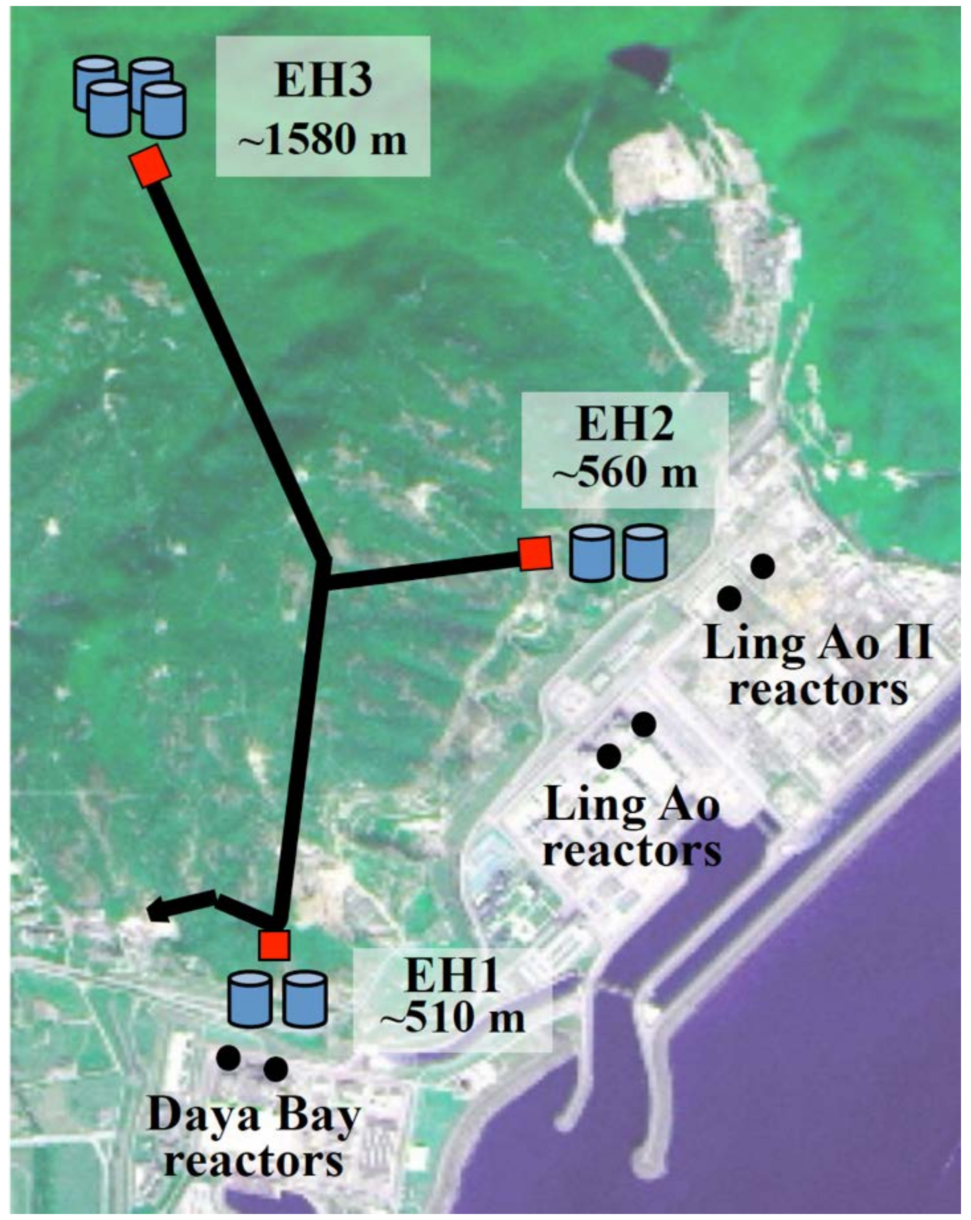
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - cos^4\theta_{14} sin^2 2\theta_{13} sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) - sin^2 2\theta_{14} sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

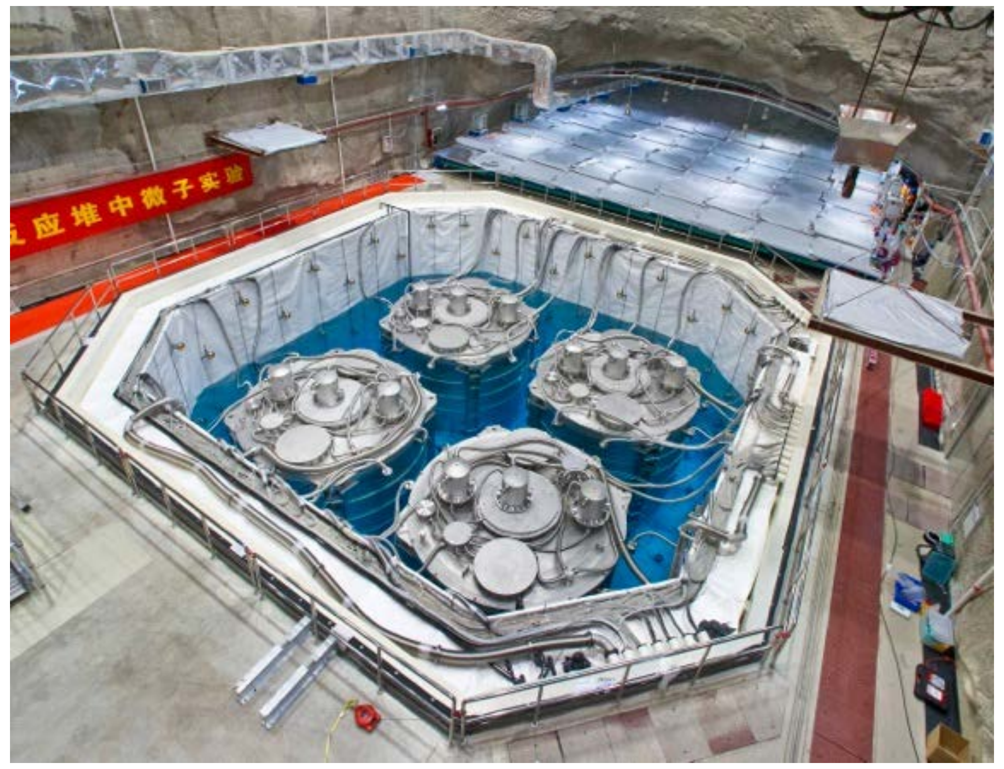
- Search for an additional oscillation frequency besides Δm^2_{31} and Δm^2_{32}
- Data is consistent with 3-ν model; No light sterile neutrino signal observed
- Consistent results from Feldman-Cousins and CLs methods

The most stringent upper limit for light sterile neutrinos ($\Delta m^2 < 0.2$ eV²)

Ling, Neutrino 2020

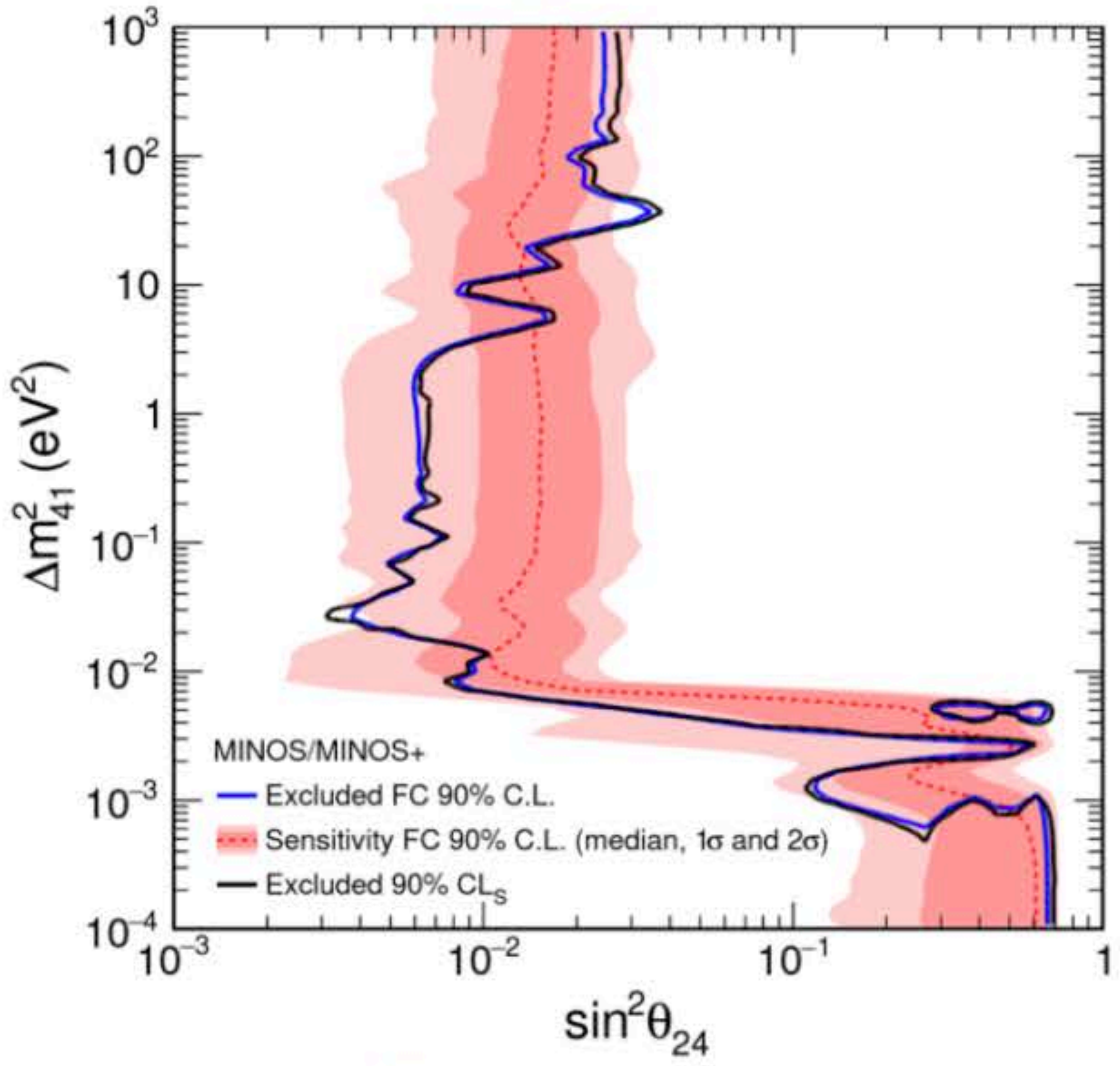
Precision Measurements with Daya Bay





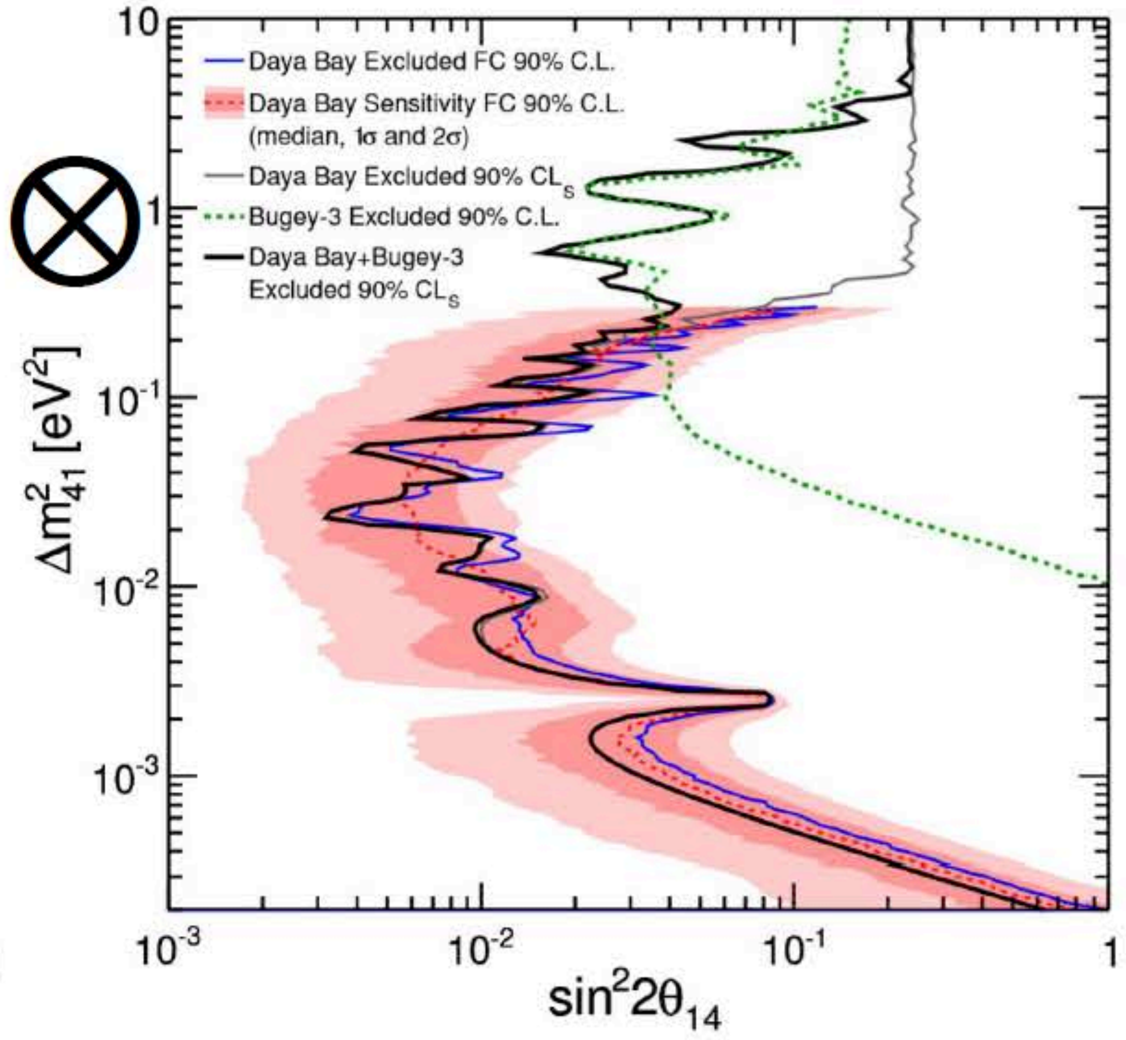
PRL ***122*** *091803 (2019)*

MINOS/MINOS+



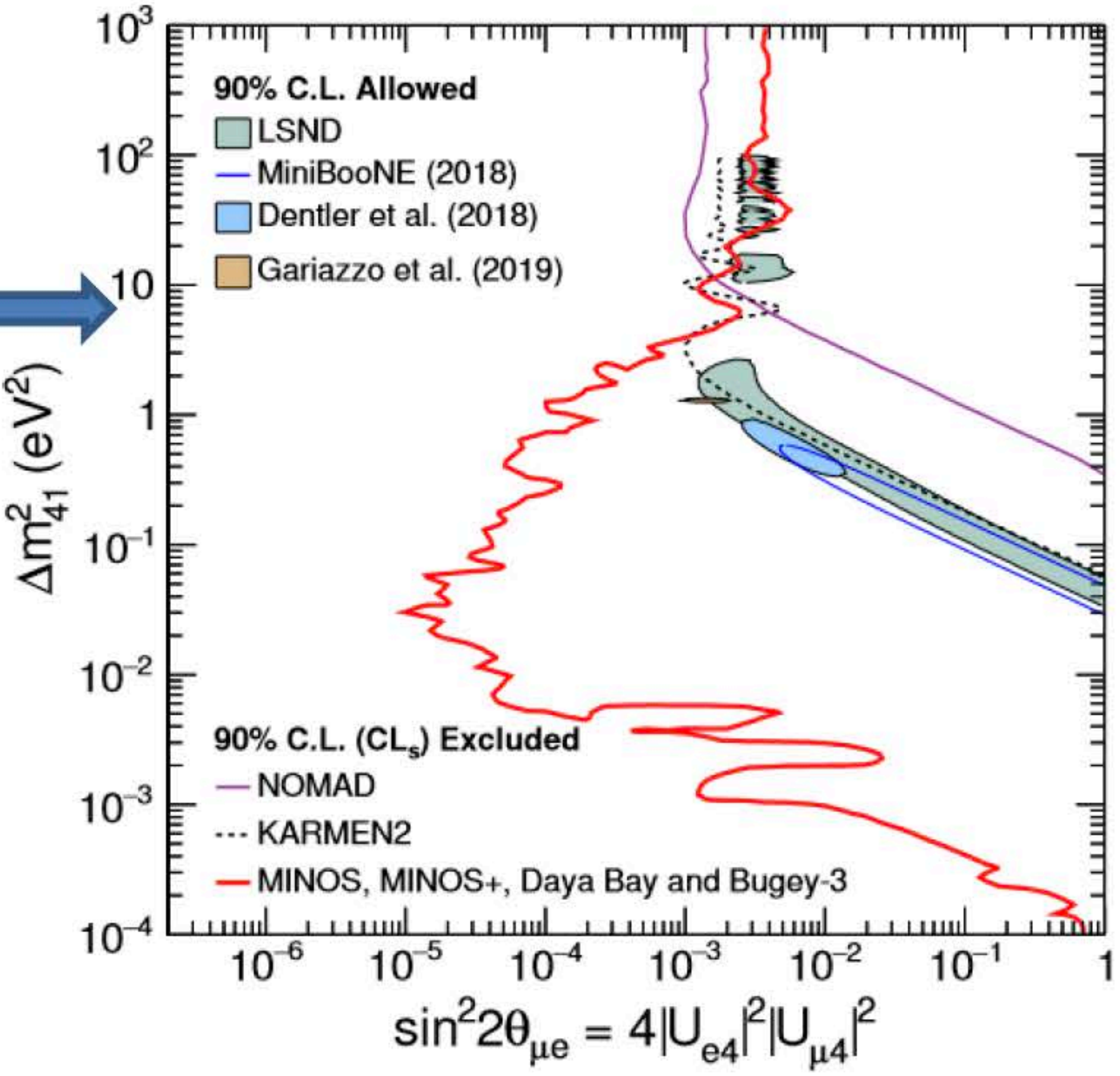
$$|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$$

Daya Bay + Bugey-3



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

arXiv:2002.00301, accepted by PRL



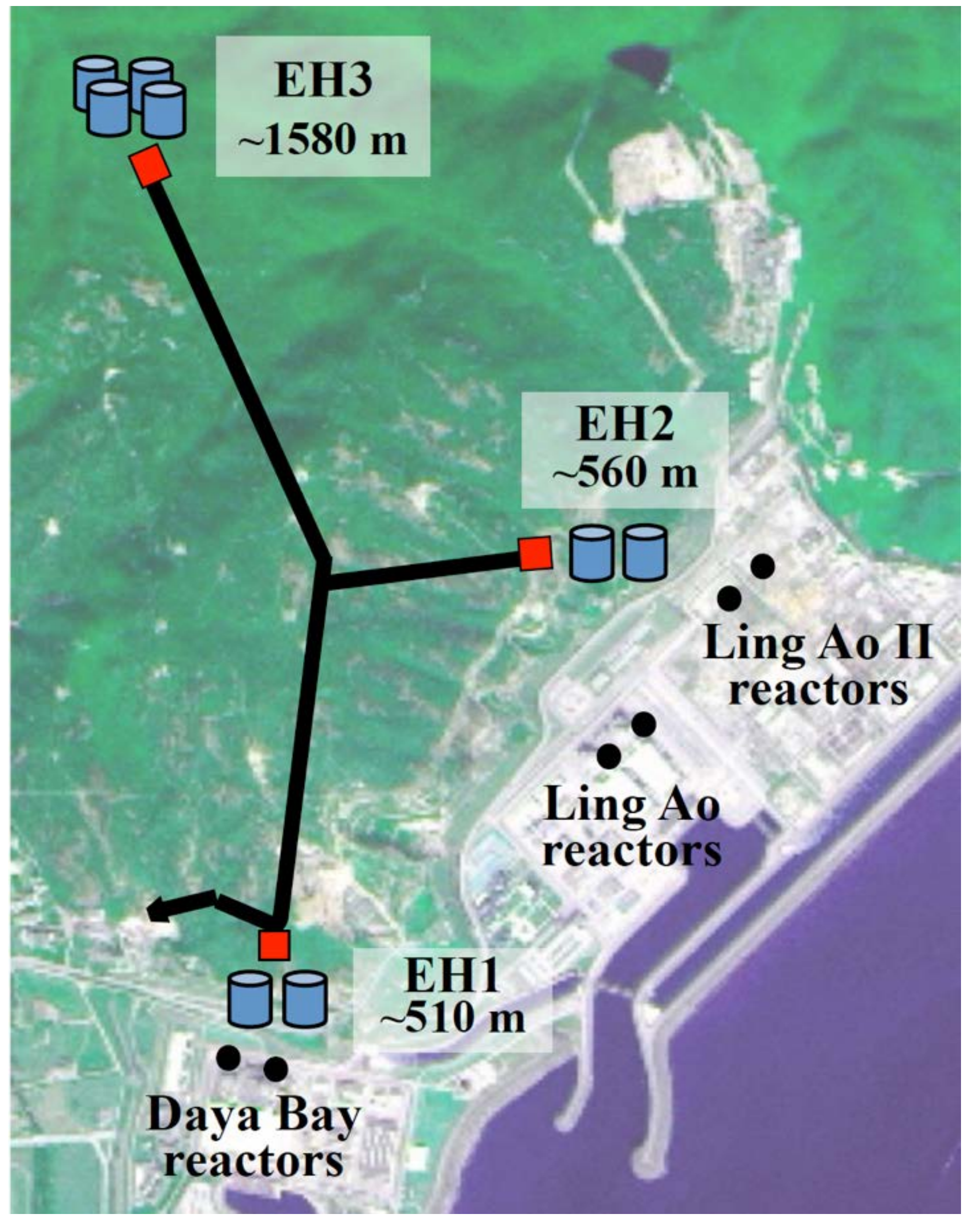
- The combined results can exclude the LSND and MiniBooNE signal region at $\Delta m^2_{41} < 5$ eV² at 90% C.L.

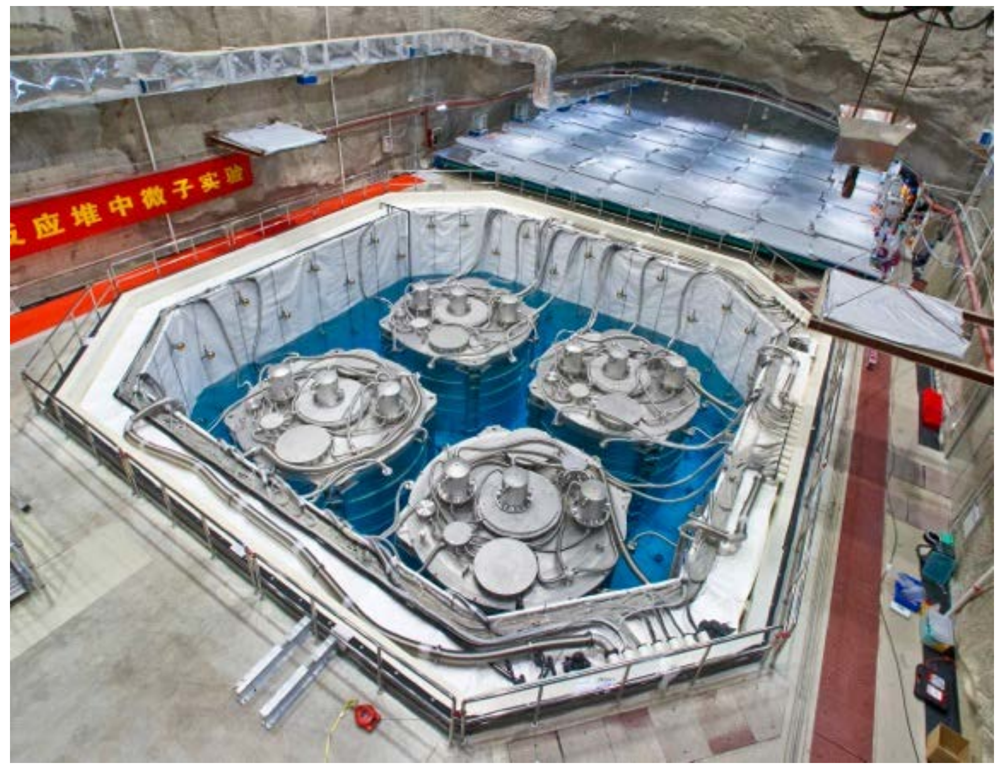
Ling, Neutrino 2020

joint analysis provides some of the most stringent oscillation limits

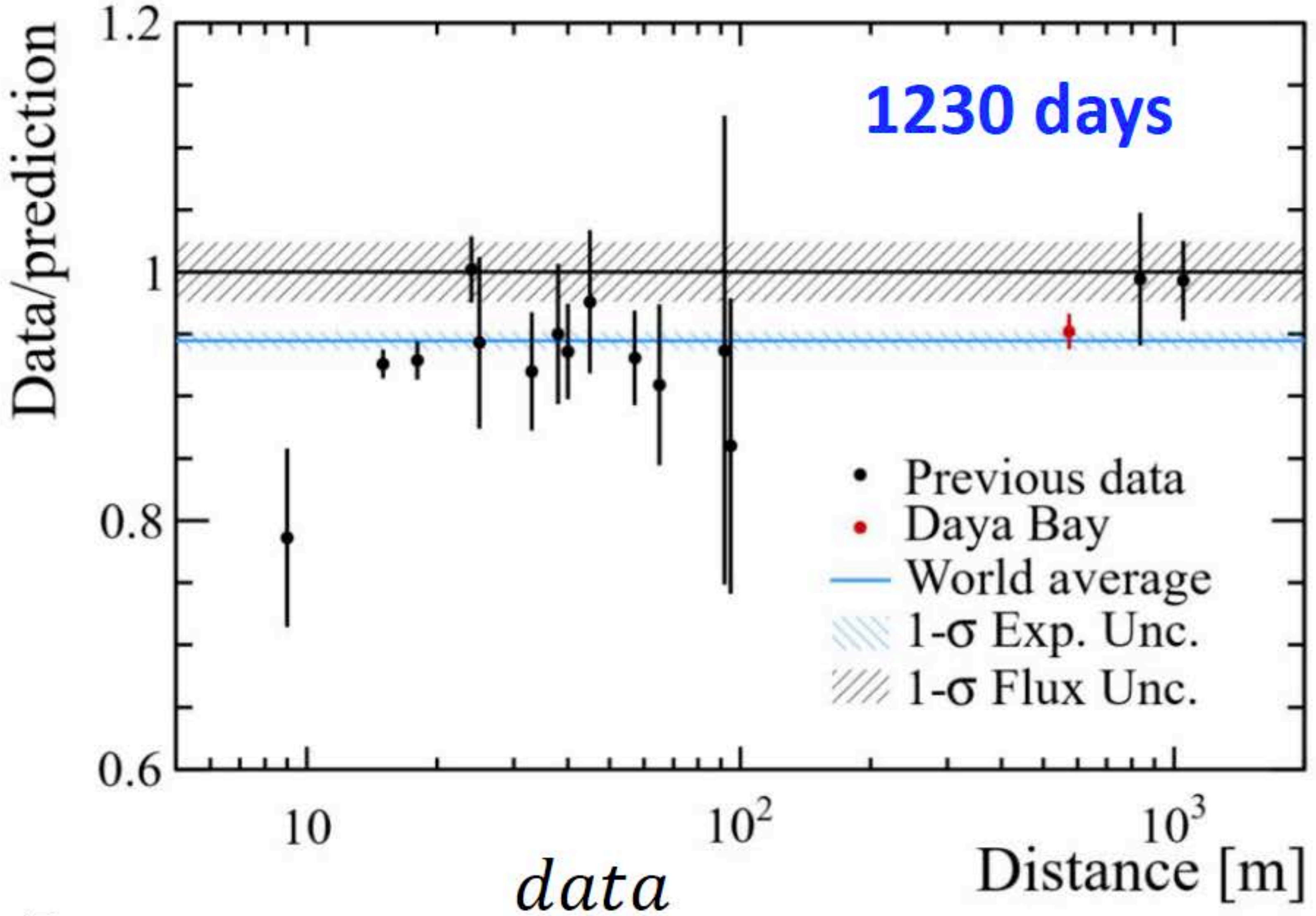
LOIs

Reactor Antineutrino Anomaly (RAA) and Spectrum Anomaly





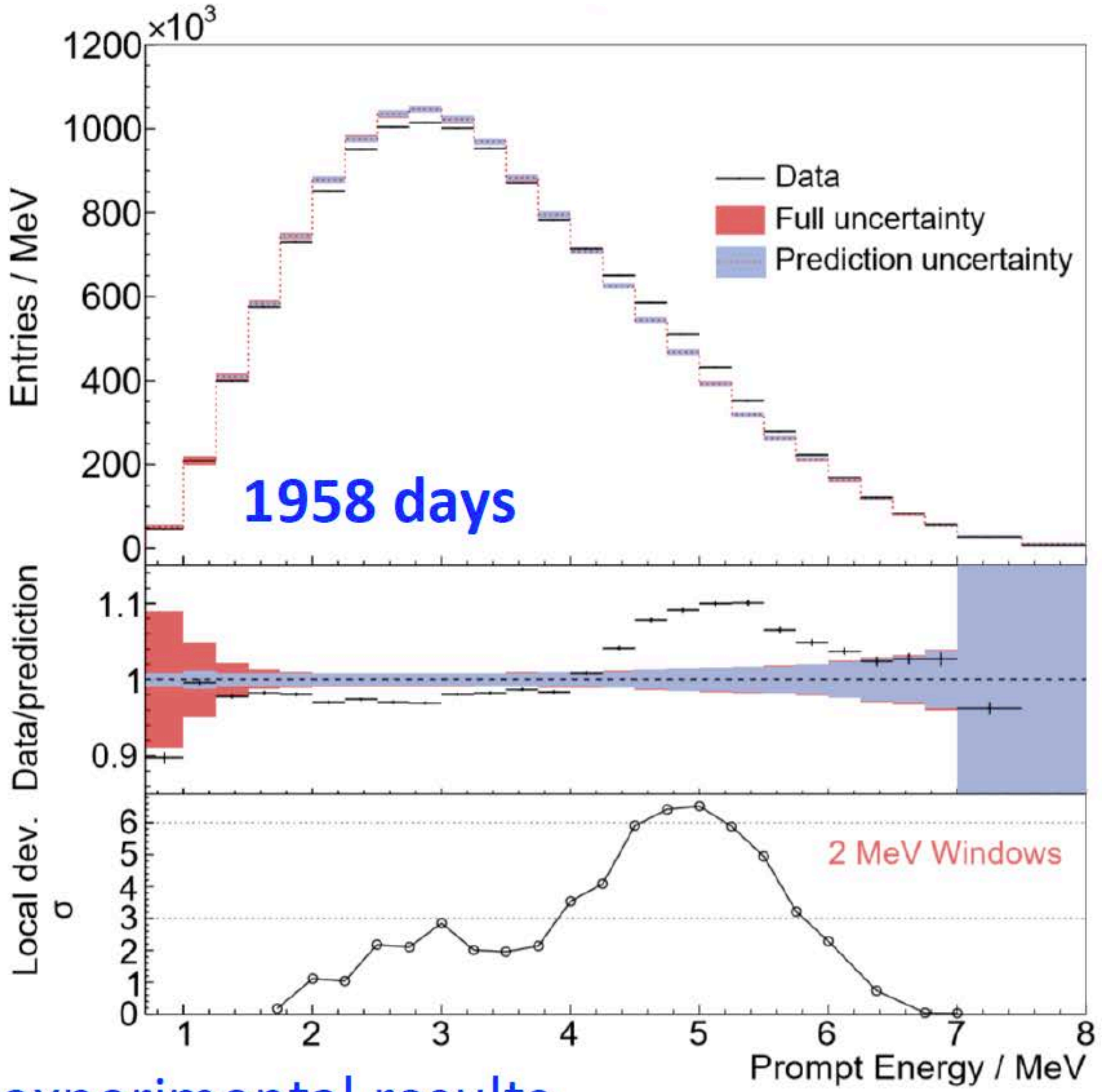
PRD **100** 052004 (2019)



$$R = \frac{data}{Model\ (Huber + Mueller)}$$

$$= 0.952 \pm 0.014(exp) \pm 0.023(model)$$

PRL **123** 111801 (2019)

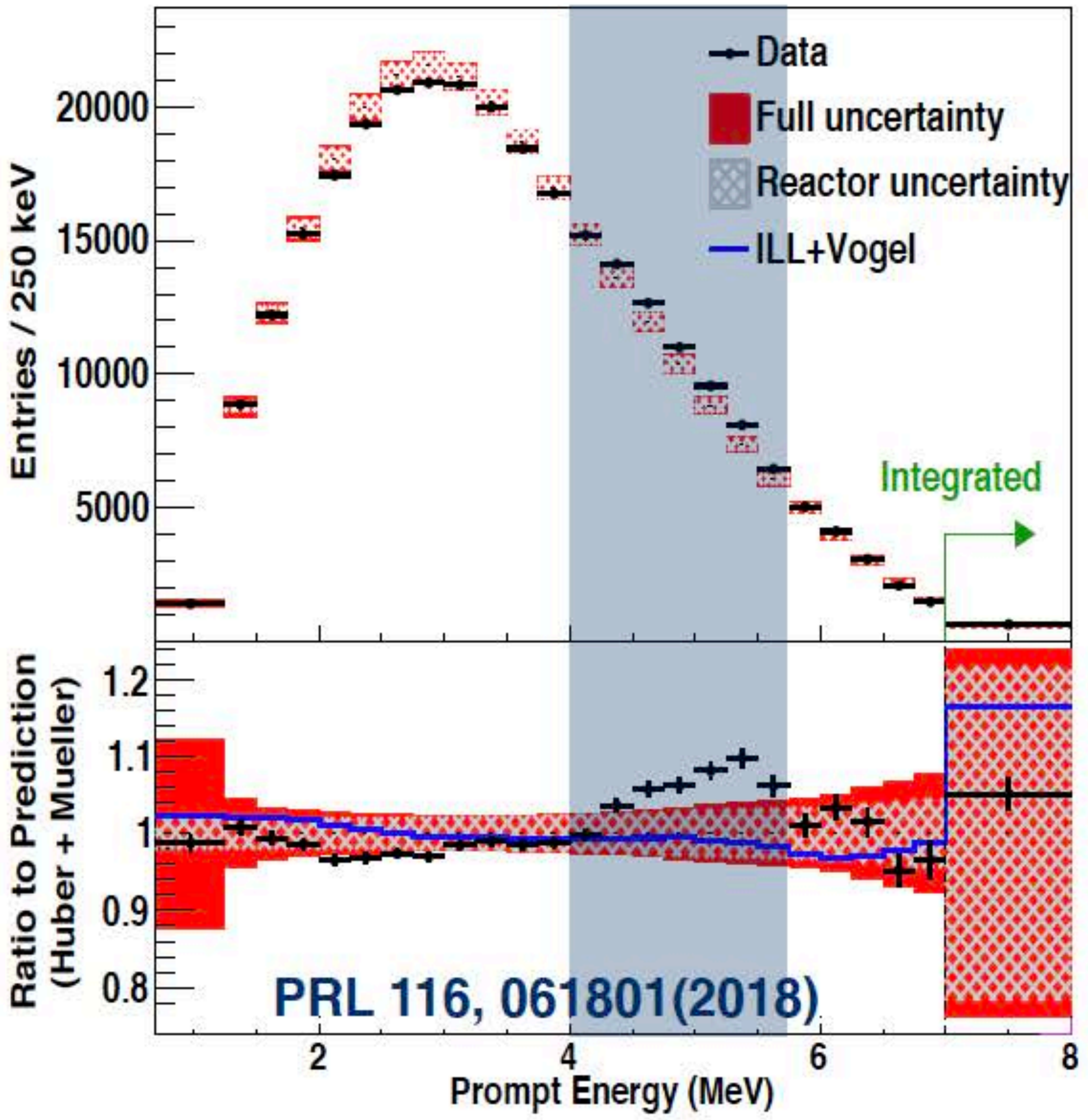


- Daya Bay result is consistent with the previous experimental results
- Data/prediction spectrum shows a total >5σ deviation, especially significant deviation at 4-6 MeV region of the prompt energy (>6σ)
- No effect on far/near relative measurement for θ_{13} and Δm^2_{ee}

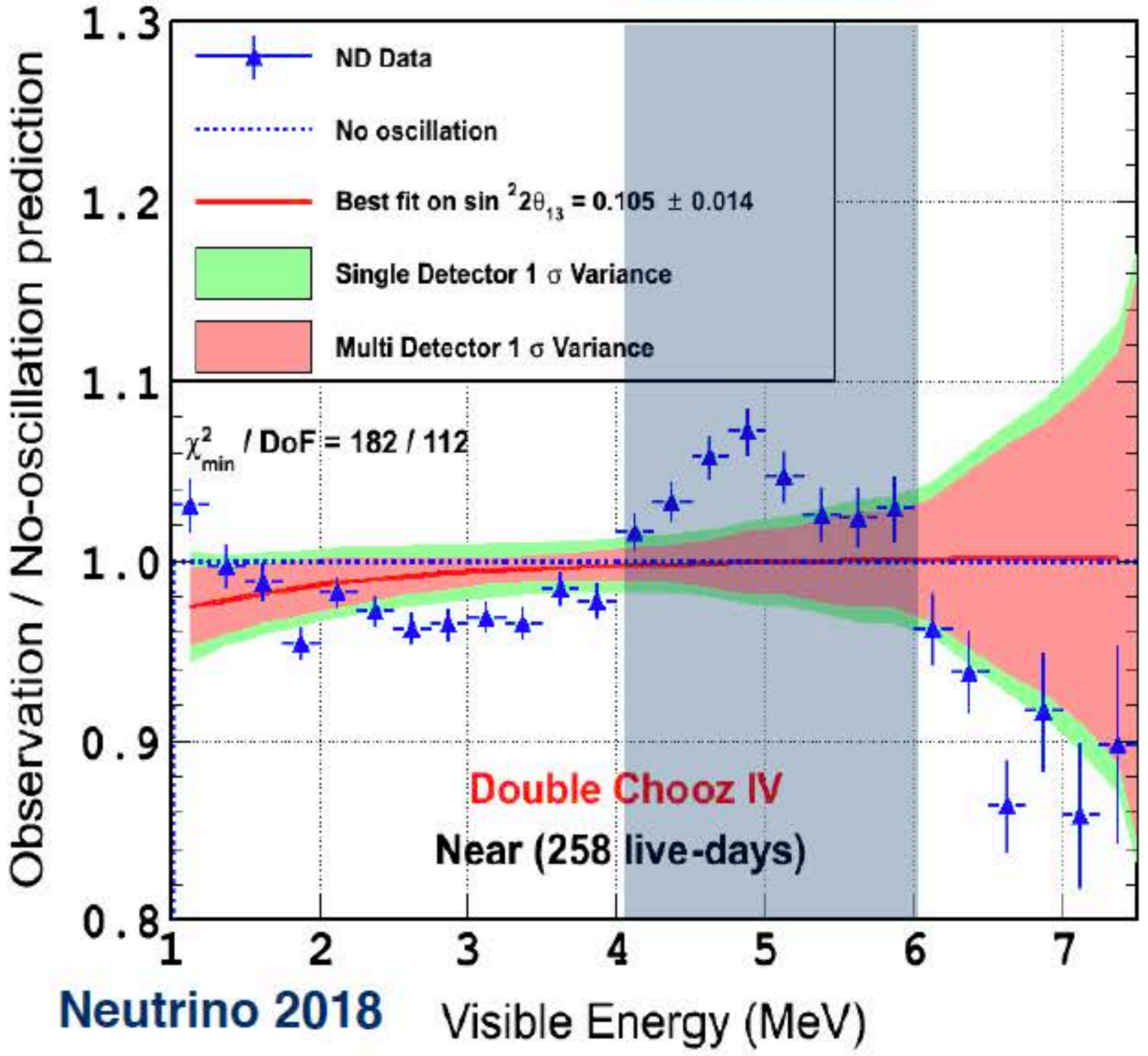
Ling, Neutrino 2020

Understanding the Reactor Spectrum

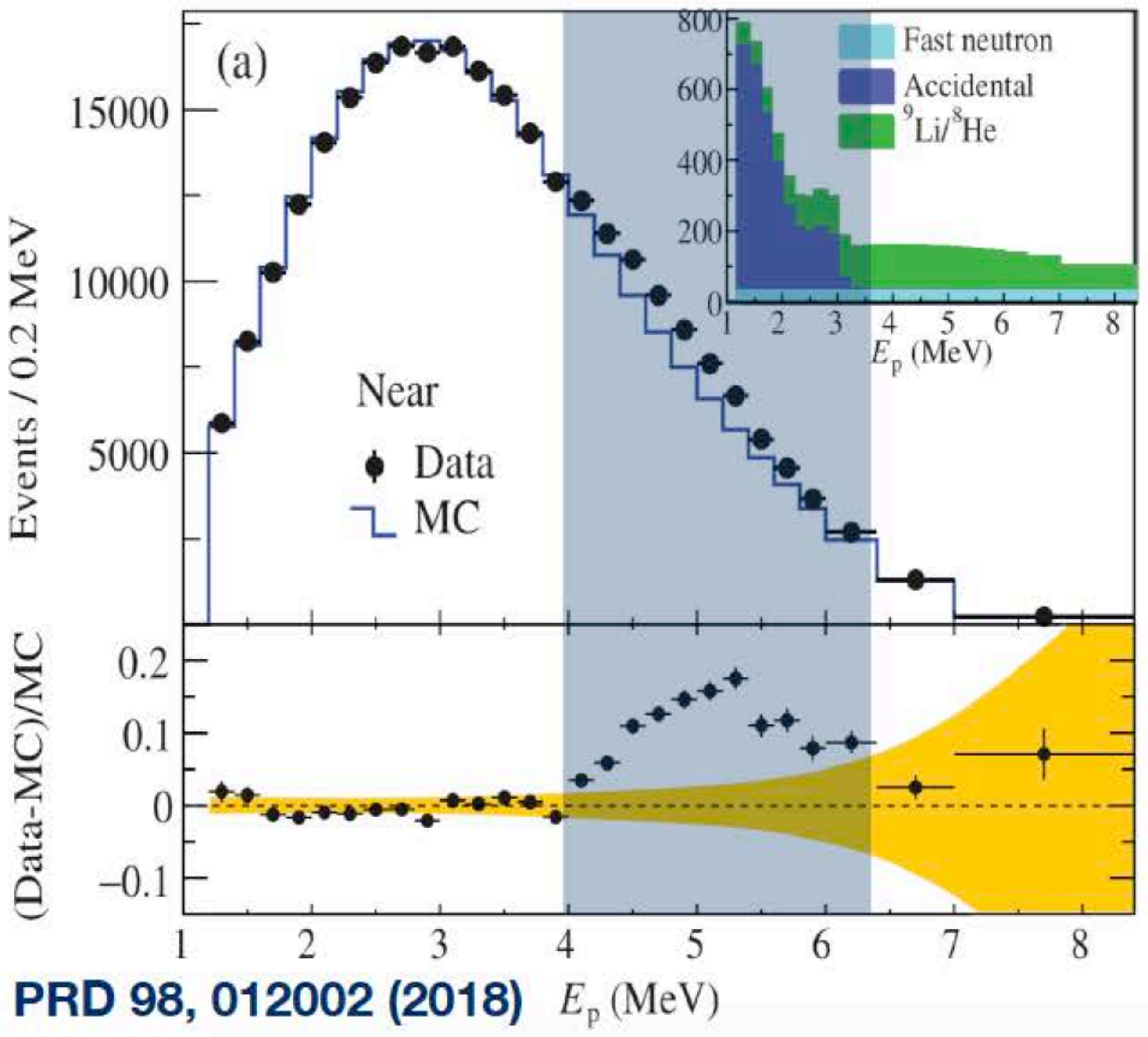
Daya Bay



Double Chooz



RENO

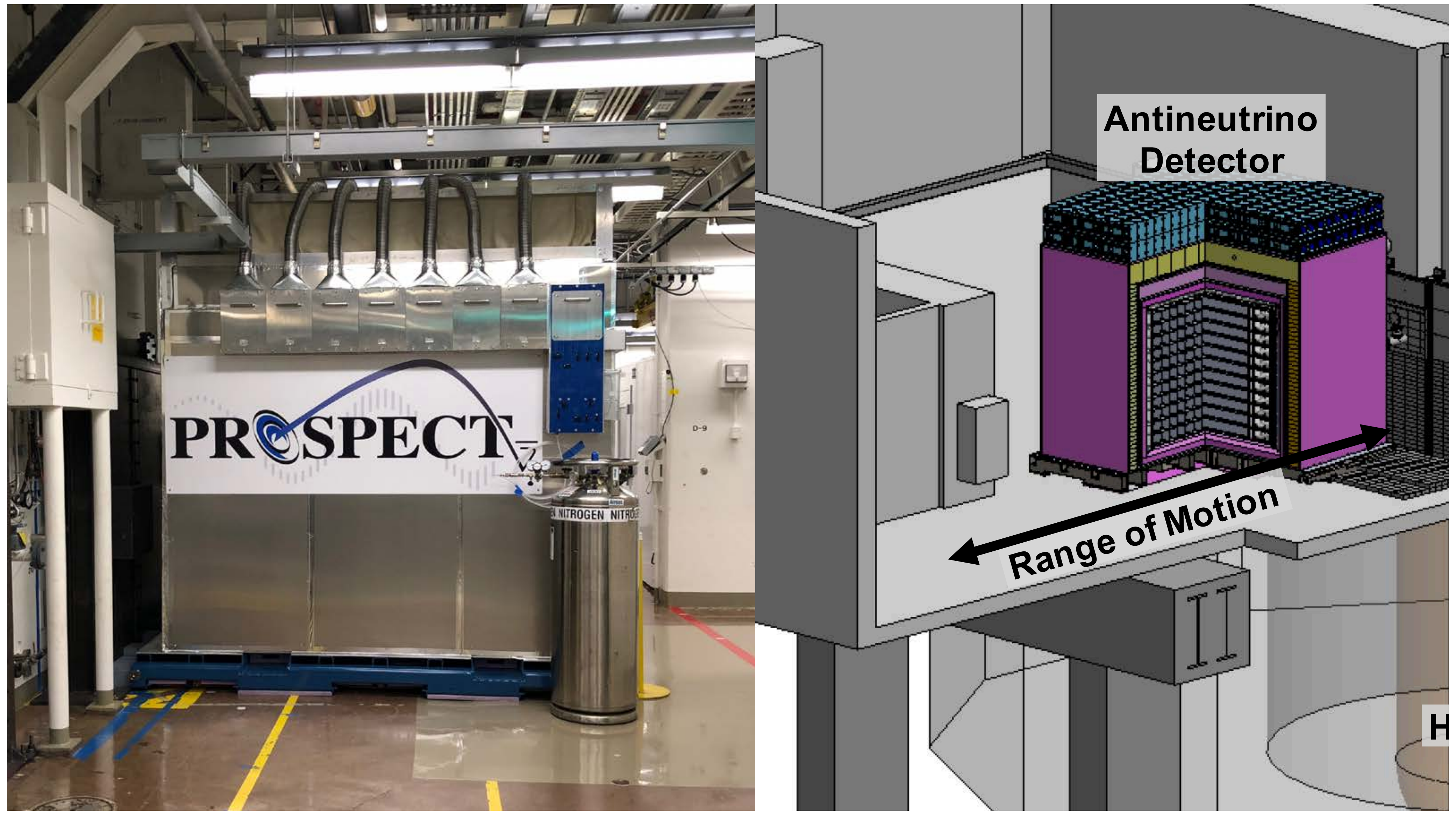


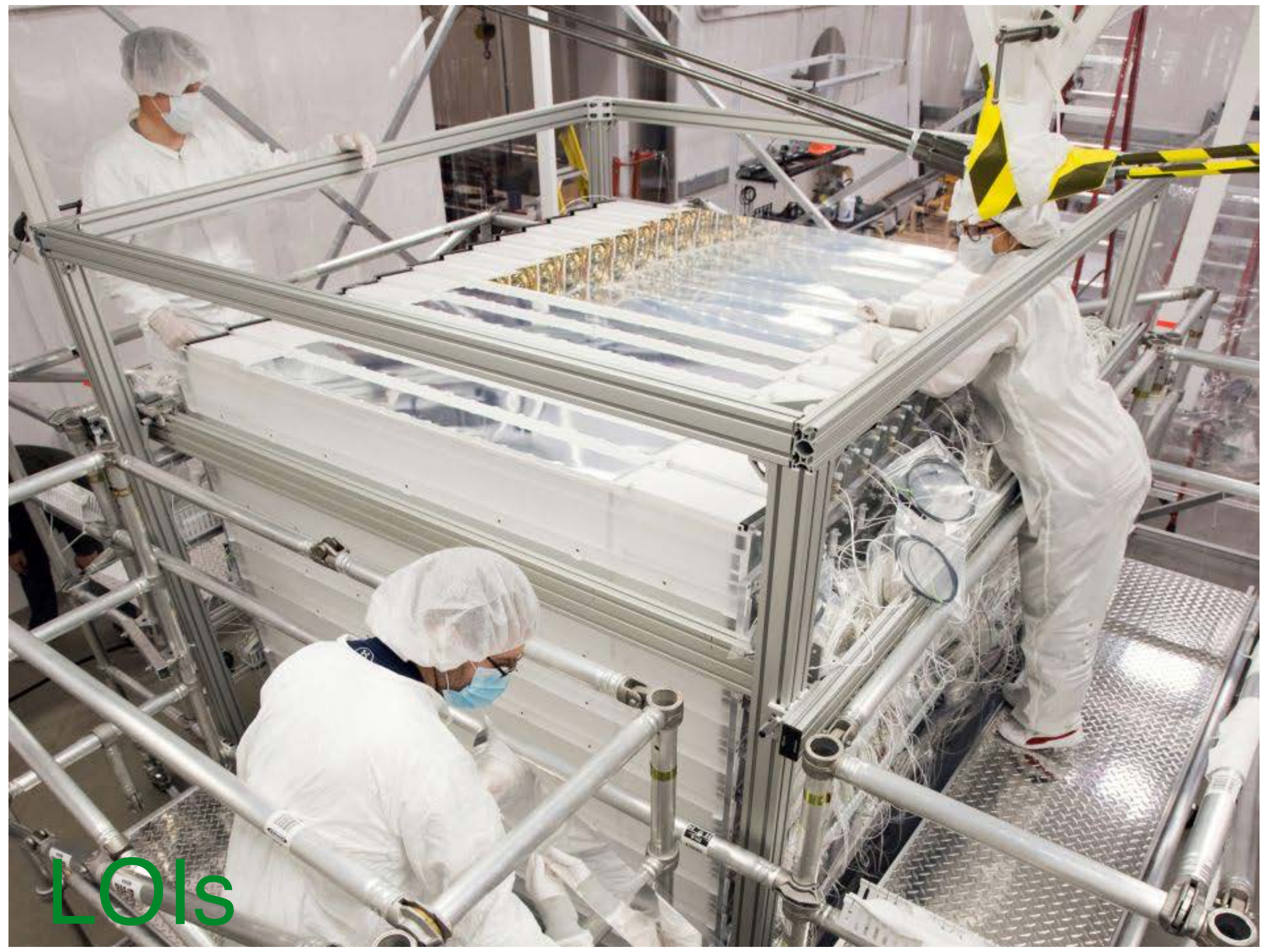
- θ_{13} experiments show disagreement with spectrum models
- Could be a contribution from a single isotope or multiple isotopes
- Inconsistent with neutrino oscillation scenarios
- Reactor models wrong? Need data

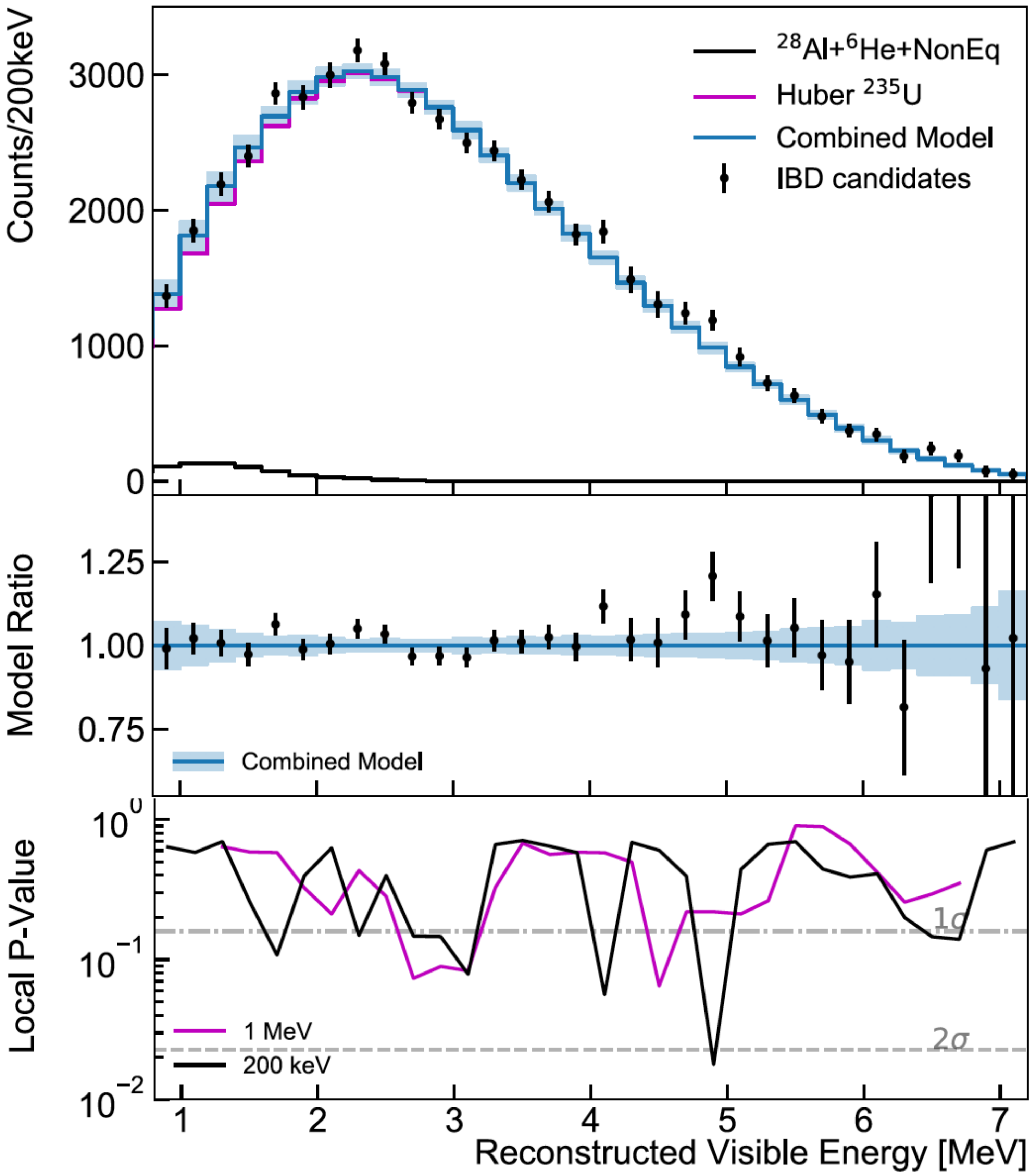
LEU Reactors:
^{235}U ~ 45-65%
^{239}Pu ~ 25-35%
^{238}U,^{241}Pu < 10% each

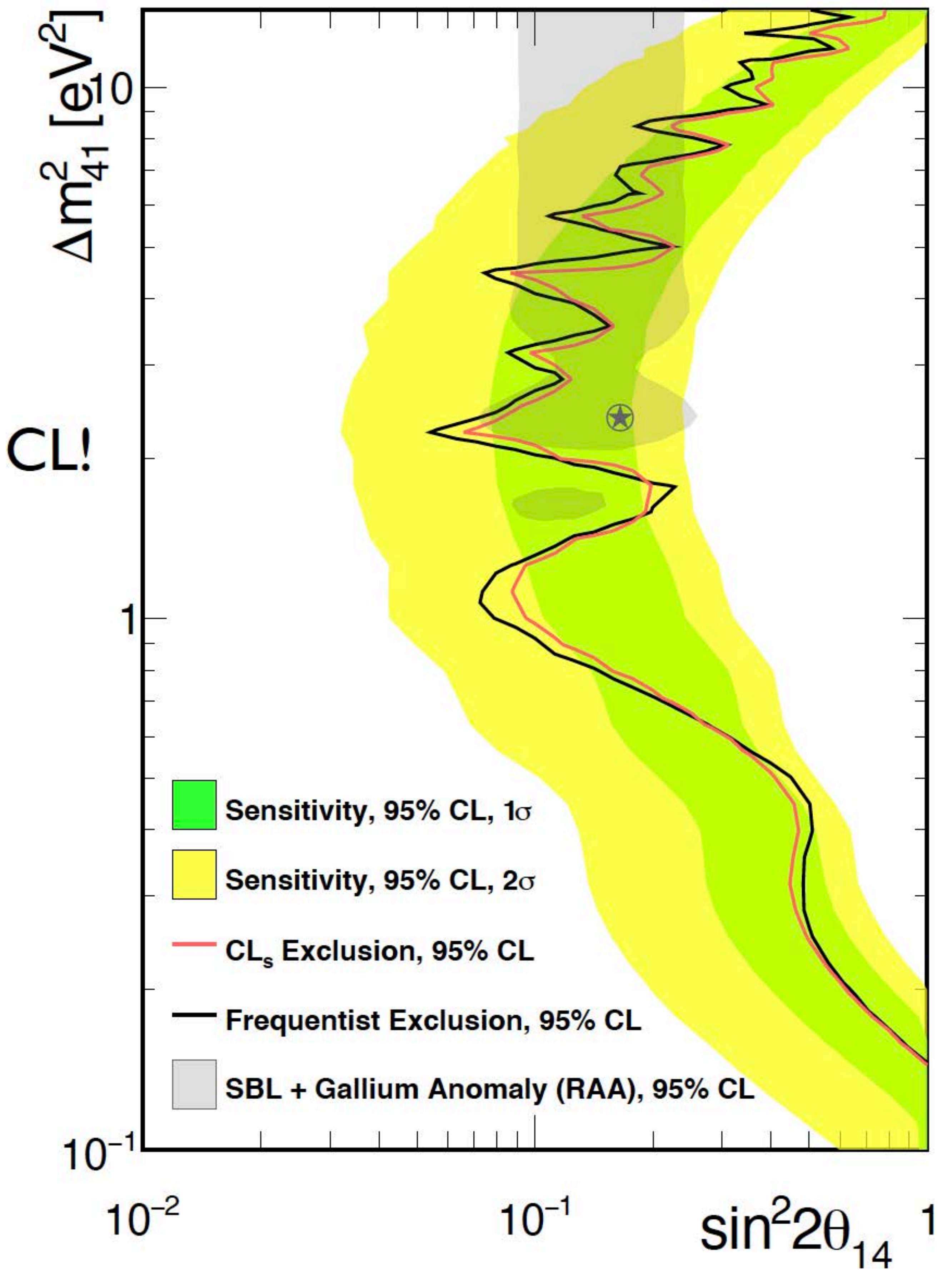
Ref: Mumm

Precision Oscillation and Spectrum Experiment









CL!

LOIs

PROSPECT and Daya Bay are consistent with all isotopes playing equal roles in the 5-7 MeV data disagreement

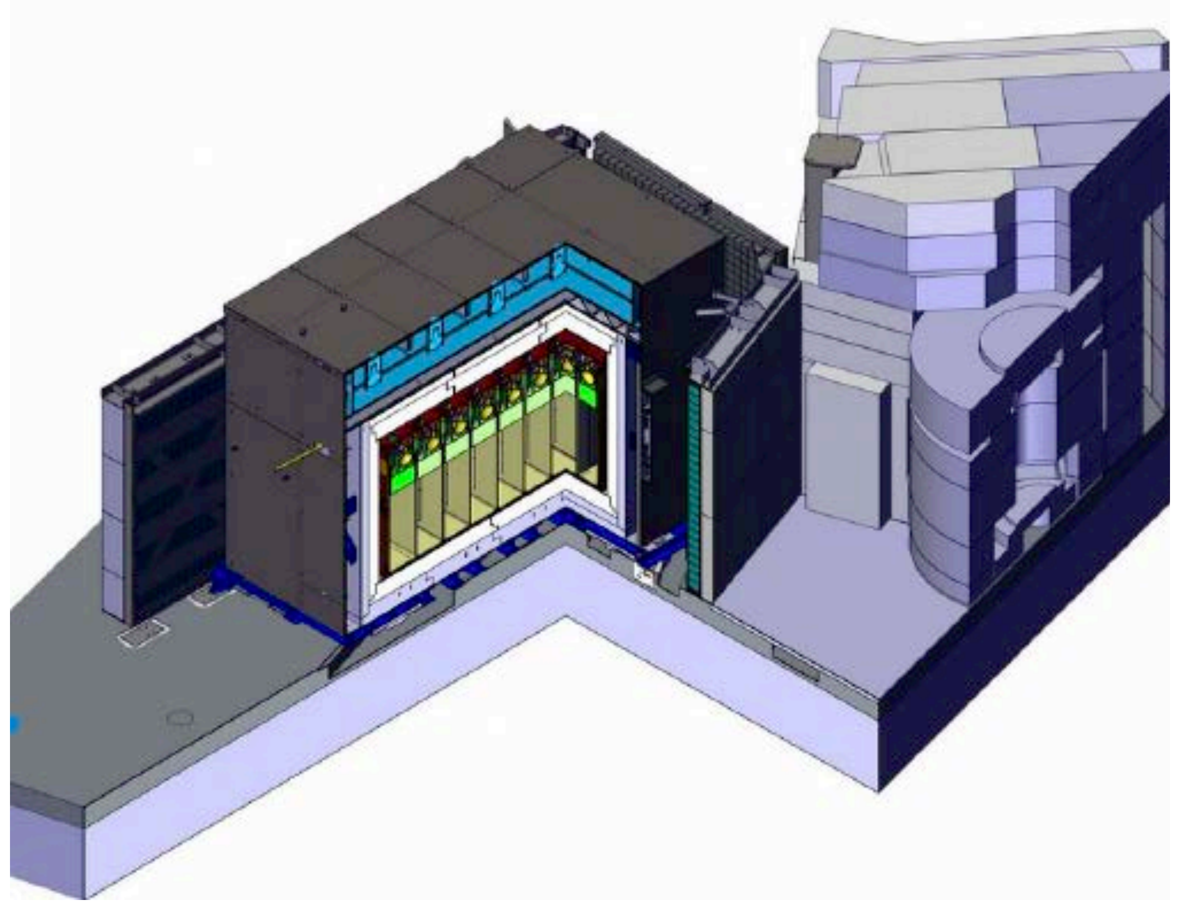
RAA best-fit exclude: 98.5% CL.

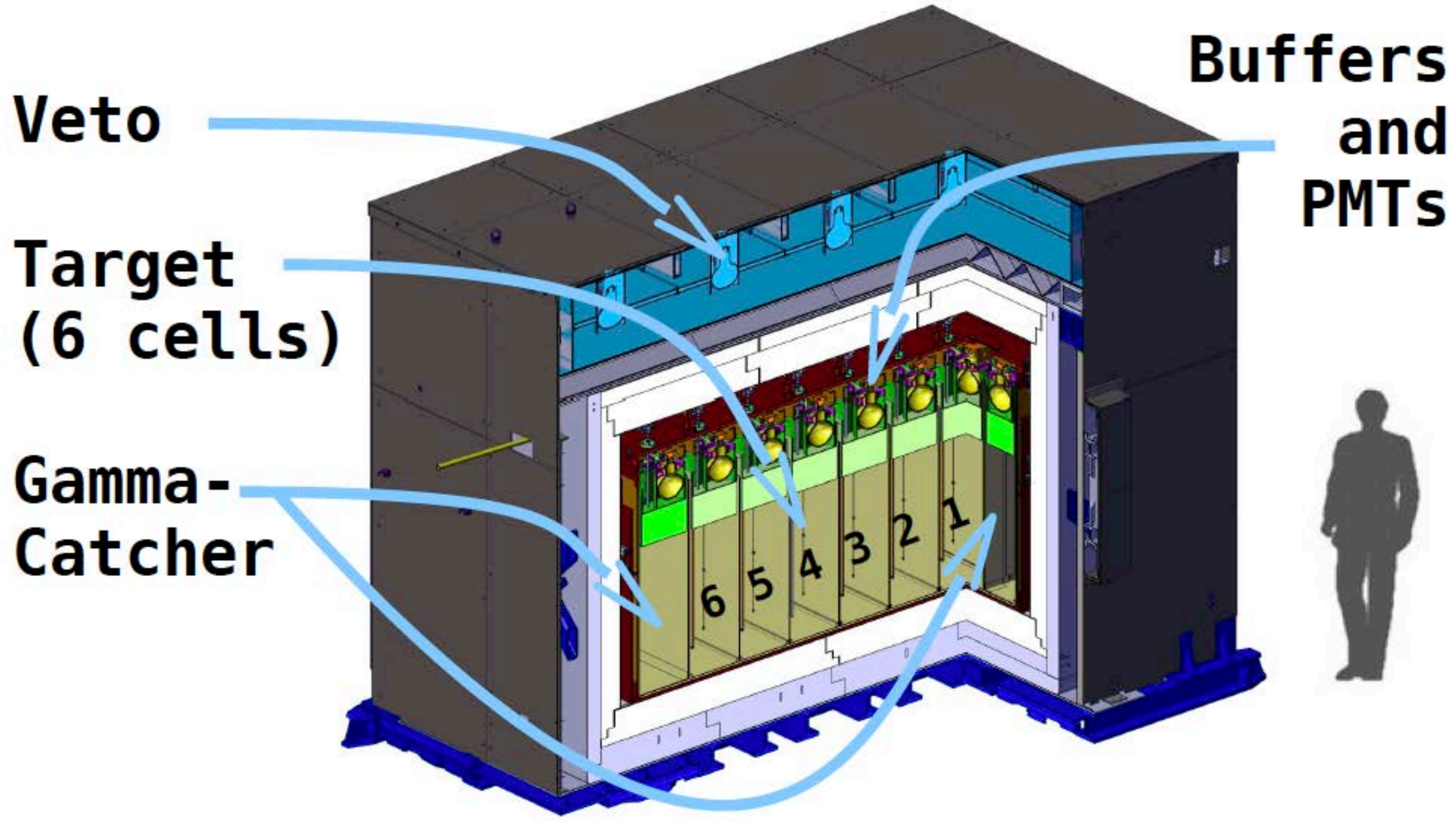
no indications of sterile yet

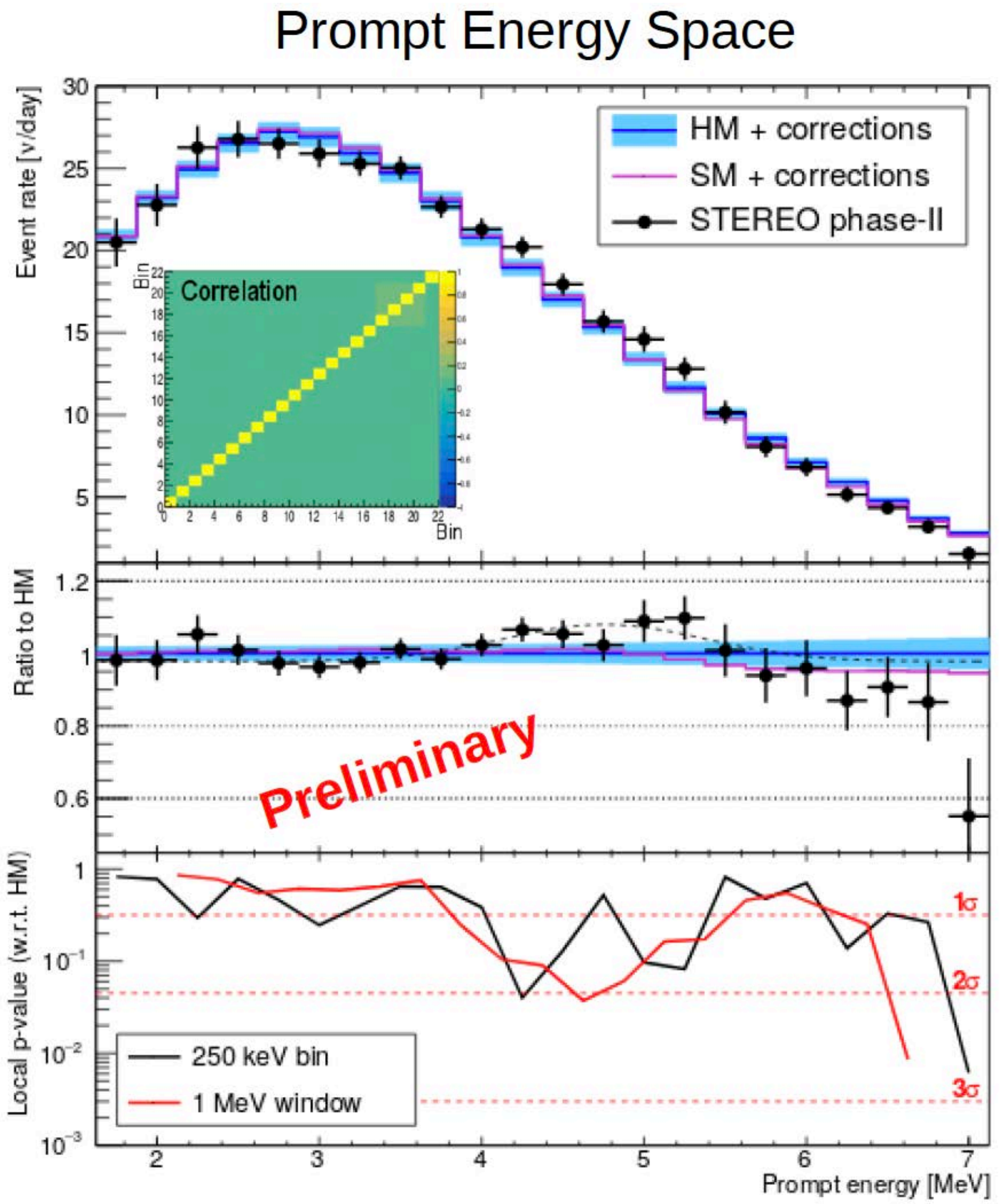
LOIs

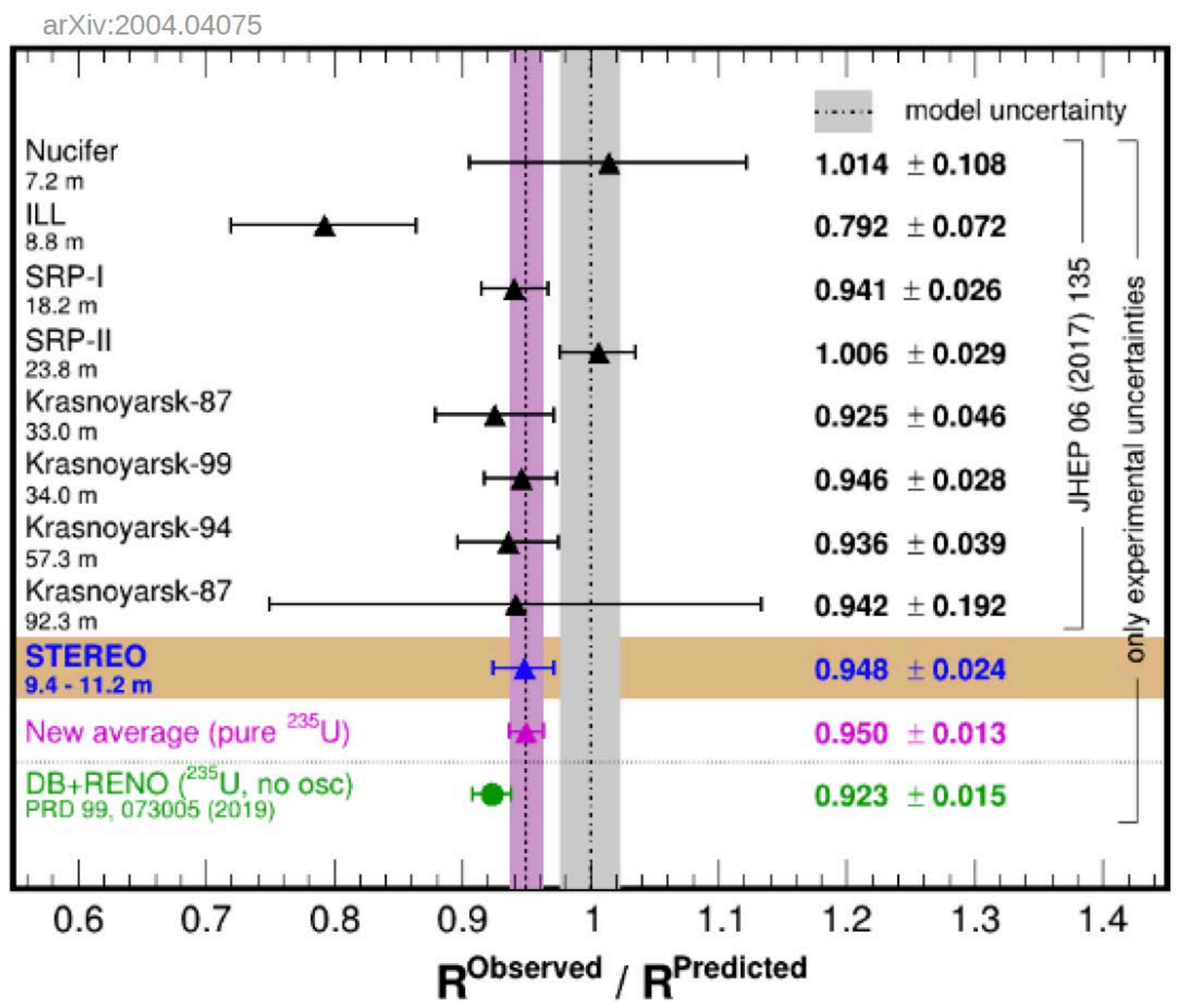
Littlejohn, Neutrino 2020

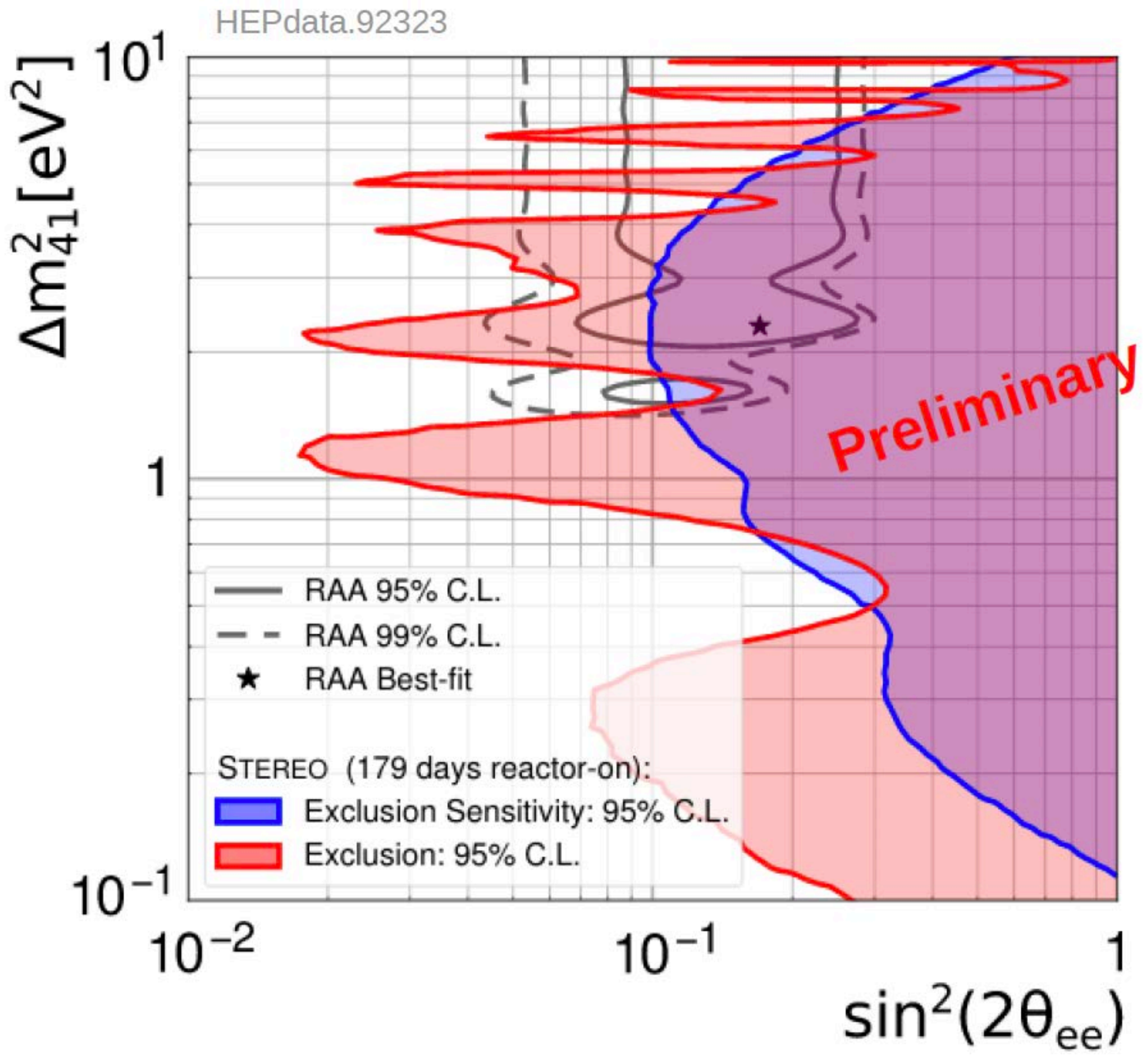
Recent Results from STEREO











Joint analysis with PROSPECT in progress

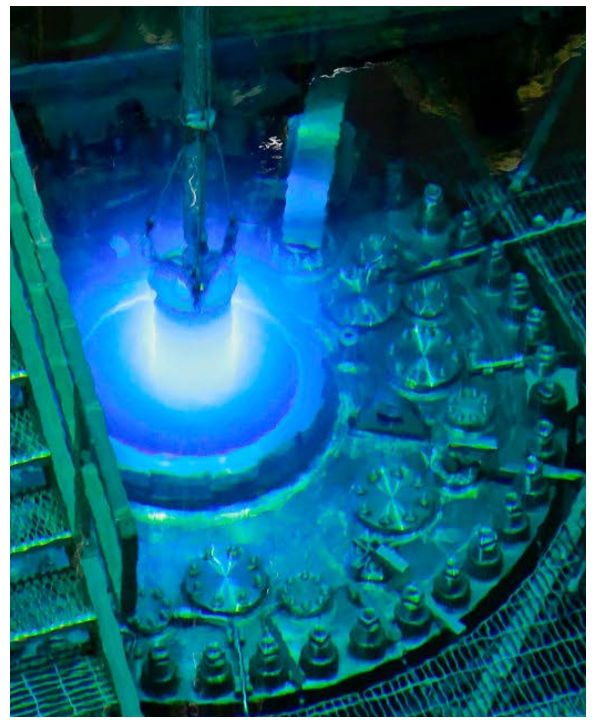
LOIs

Schoppmann, Neutrino 2020

Antineutrinos from Research and Power Reactors

High-powered research reactors

HFIR, ORNL

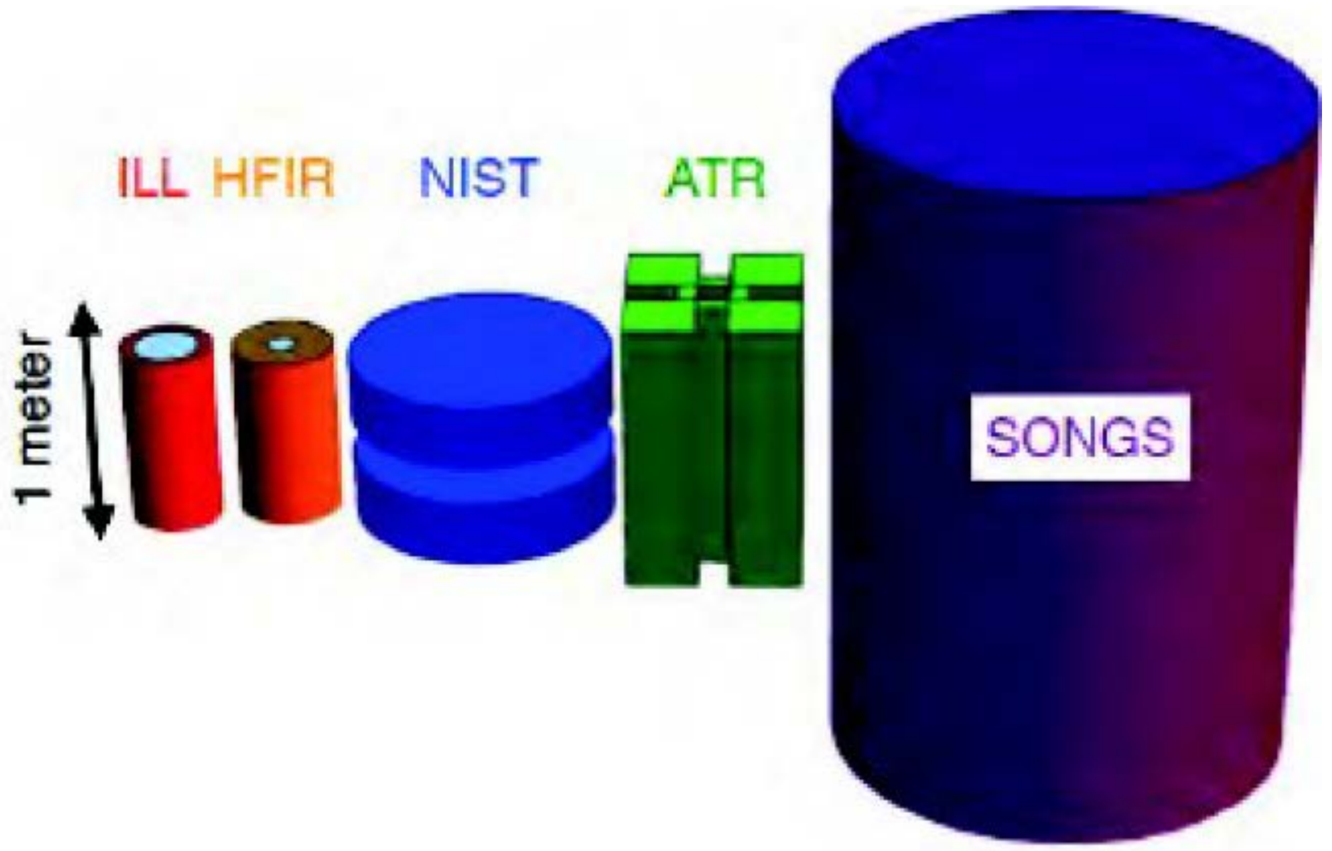


highly-enriched (HEU):
mainly ^{235}U, ~10-100 MW$_{th}$,

Commercial power reactors

low-enriched (LEU):
many fission isotopes, ~GW$_{th}$

"Point Source" vs Extended Core

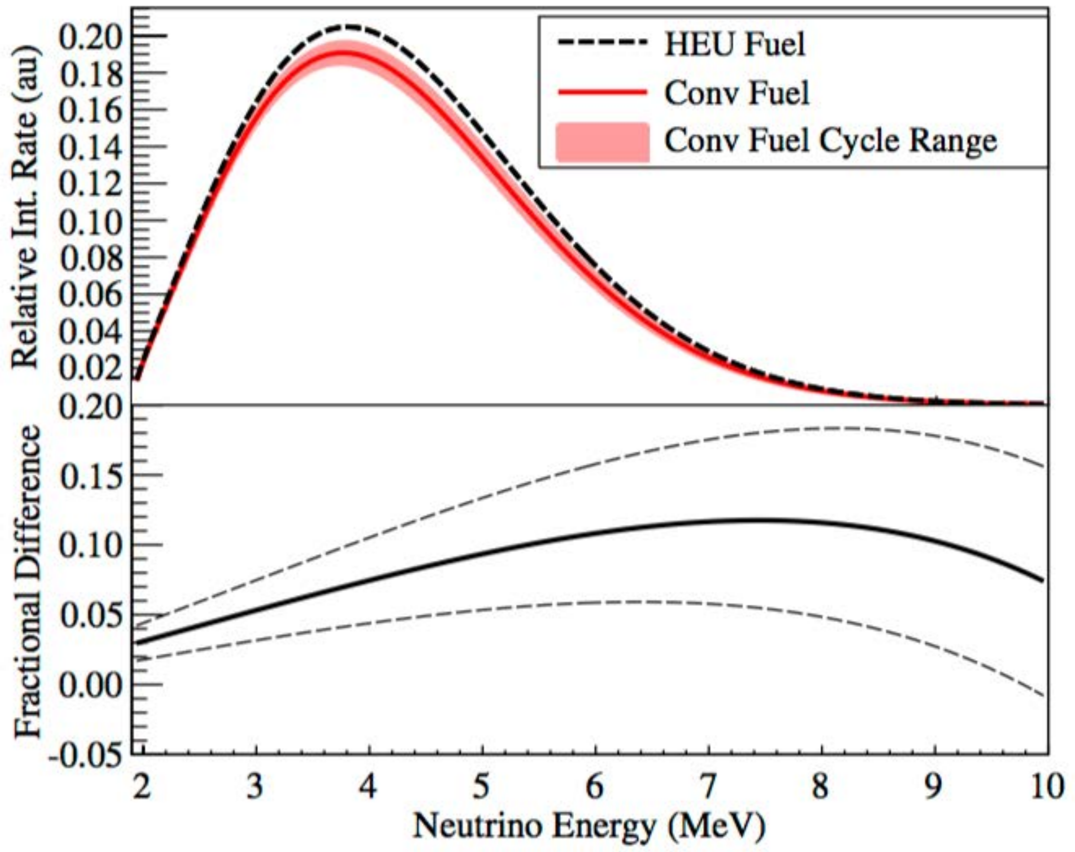


research and power reactors offer complementary information

both facilities exist in the US

LOIs

HEU core provides static spectrum of ^{235}U



~93 % ^{235}U enrichment
(>99% ν_e from ^{235}U)

reactor cycles: ~25 days,
low ^{239}P buildup (< 0.5%)

JUNO-TAO *(design and construction)*

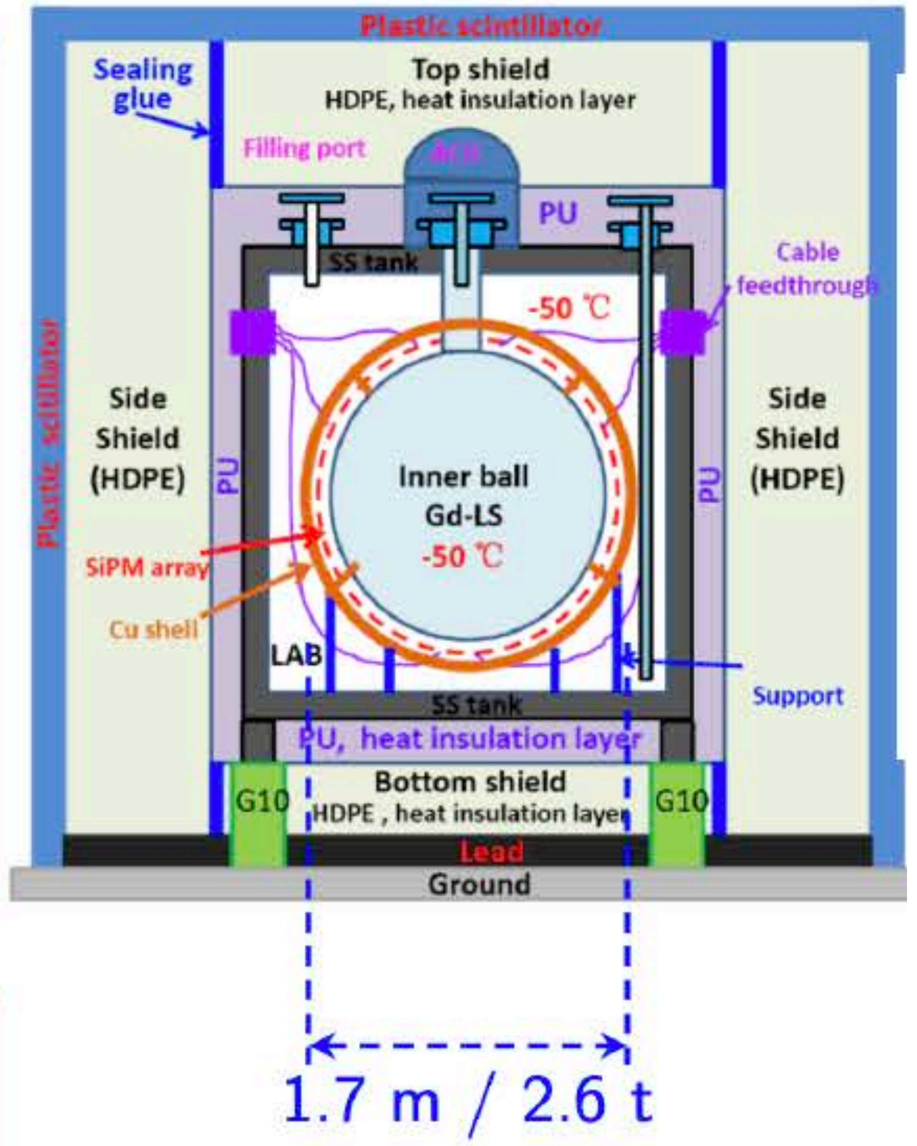
Taishan Antineutrino Observatory (TAO) is a satellite detector of JUNO

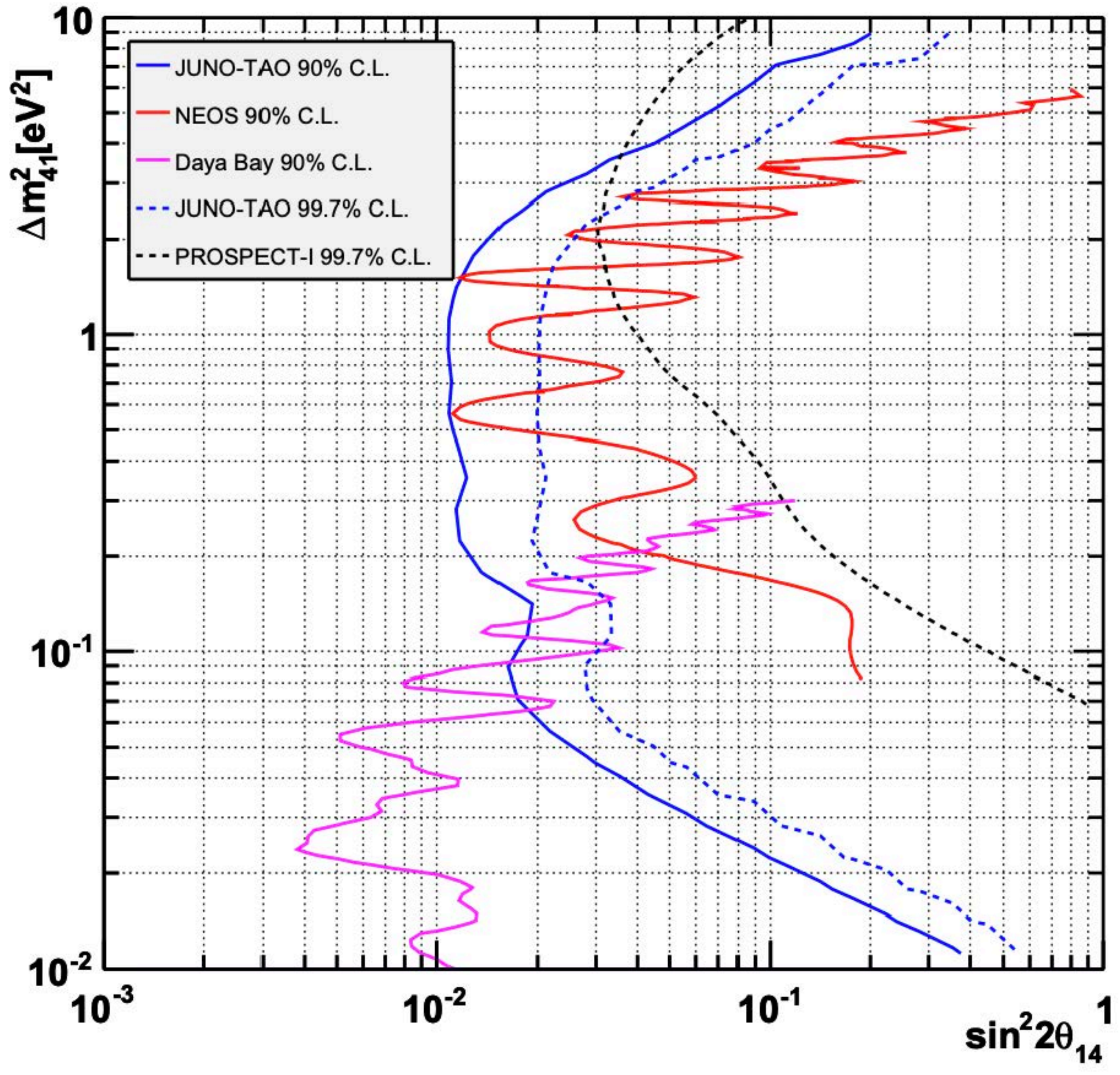
Purposes
- Precisely measure the reactor antineutrino spectrum
- Provide a model independent reference spectrum for JUNO
- Provide isotopic yields and spectra
- Reactor monitoring and safeguard
- Search for sterile neutrino

Detector design
- 30-35 m from a Taishan reactor core (4.6 GWth)
- Ton-level Gadolinium-doped LS at -50 °C
- 10 m^2 SiPM with PDE>50% and >90% coverage
- Sub-percent energy resolution

TAO installation and commissioning in 2022

TAO detector design



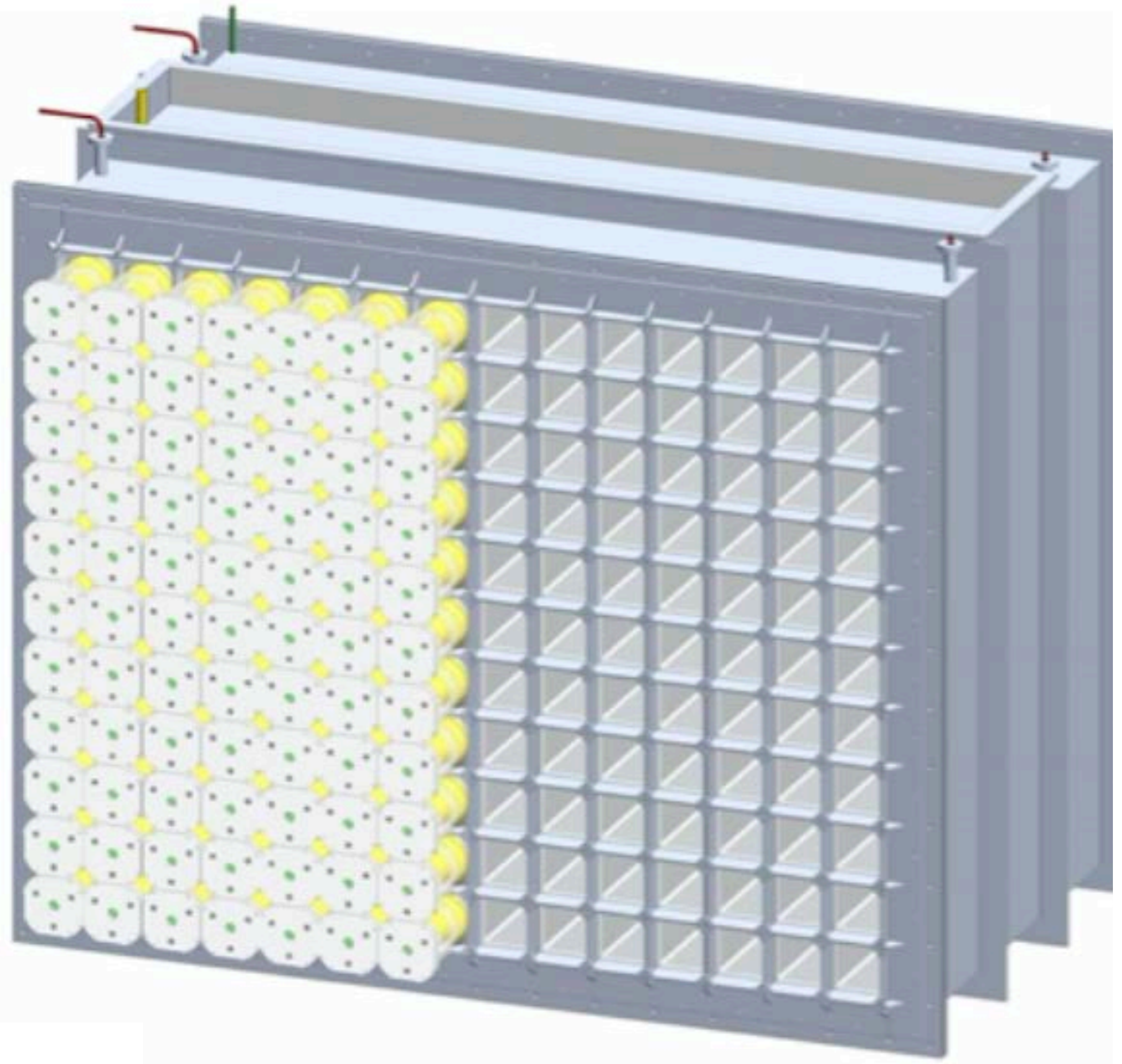


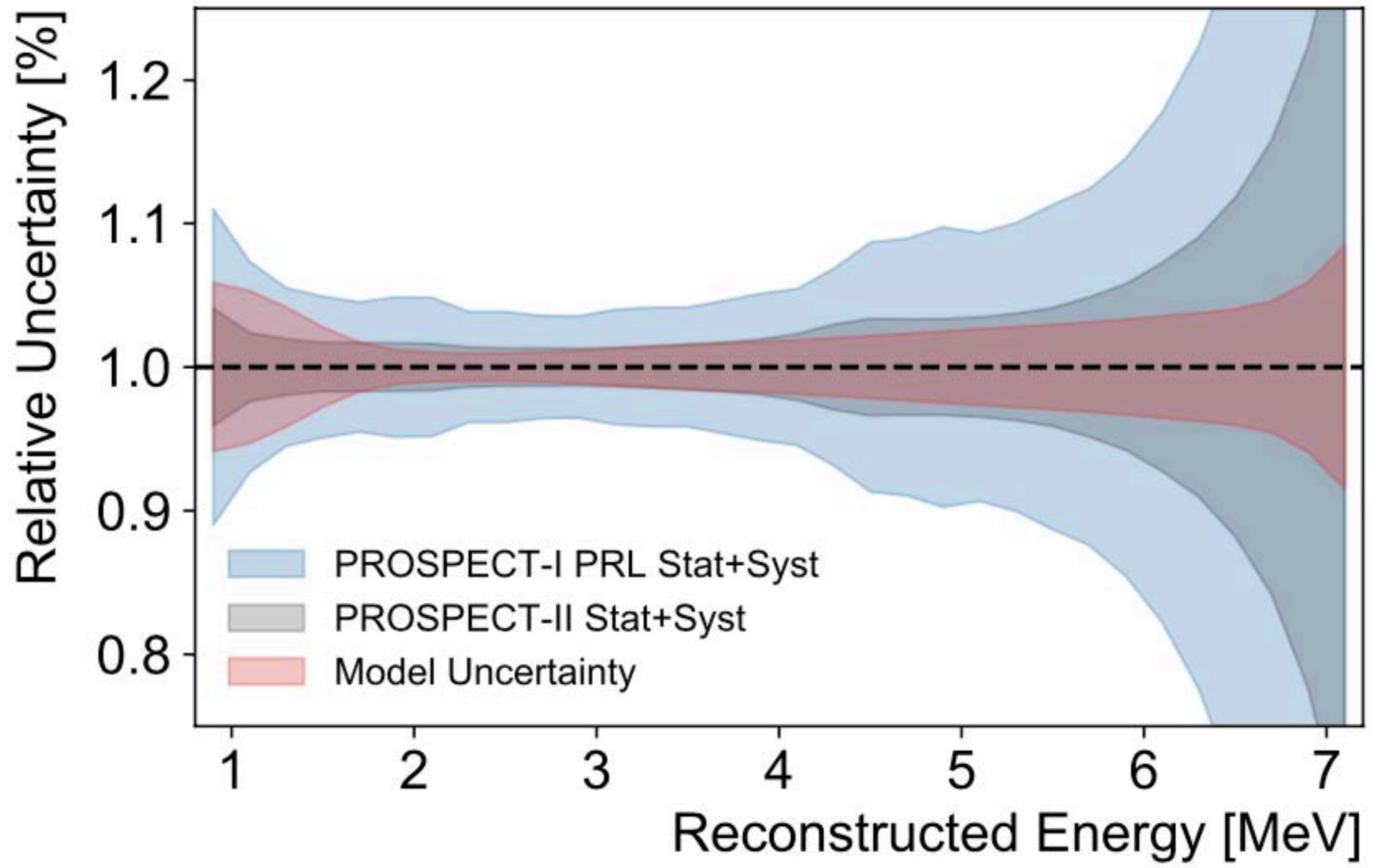
TAO prototype under construction

Meng, Neutrino 2020

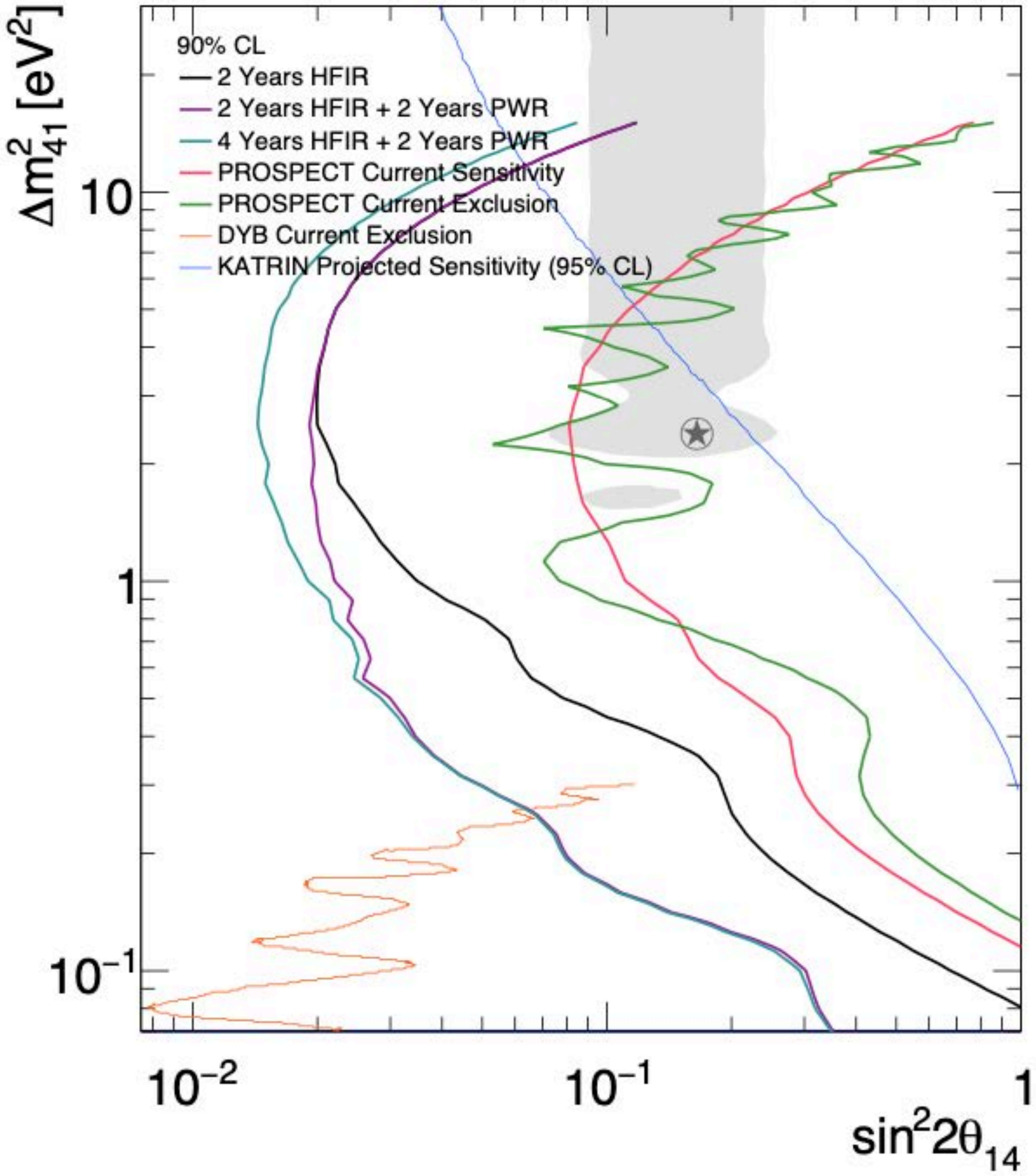
LOI

PROSPECT-II *(proposed)*





^{235}U spectrum uncertainties

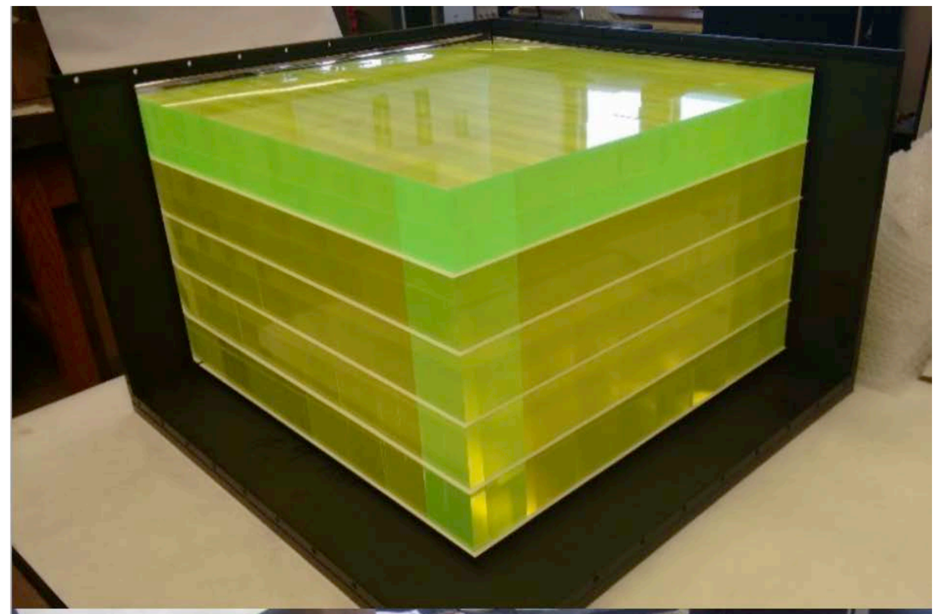


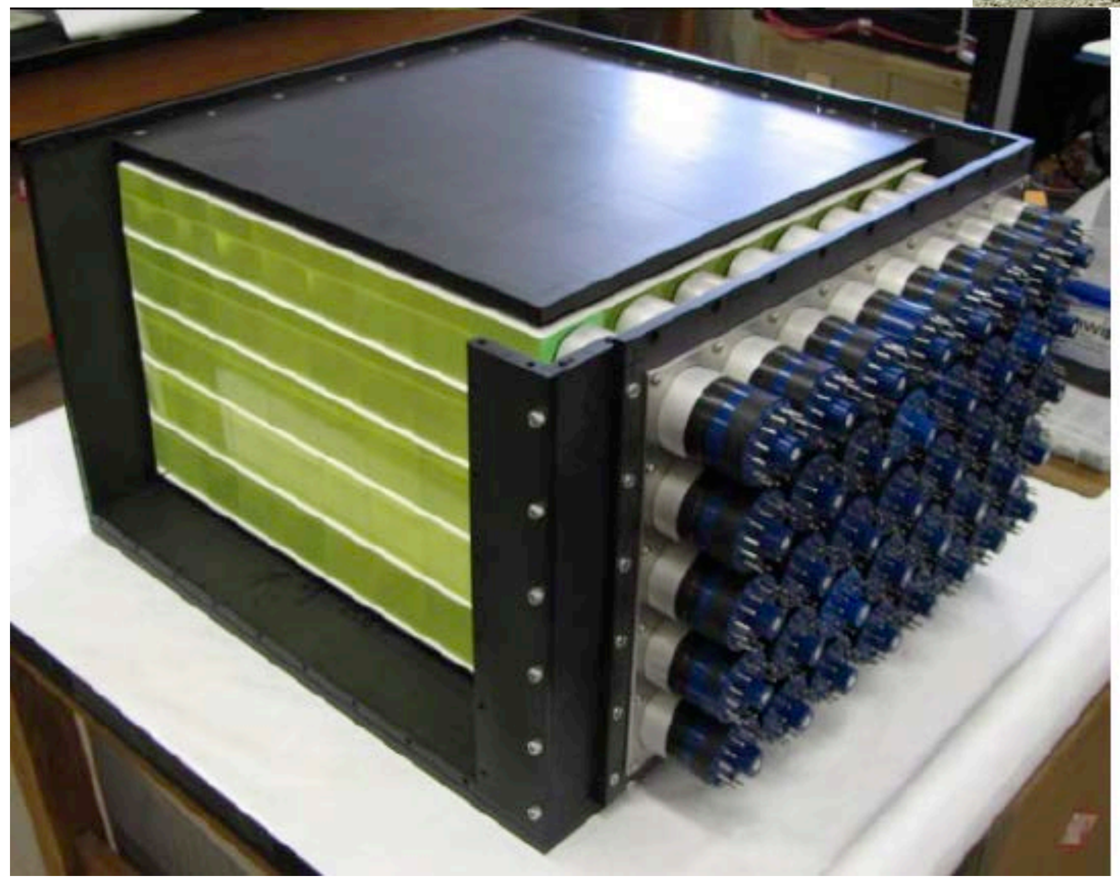
increased sensitivity

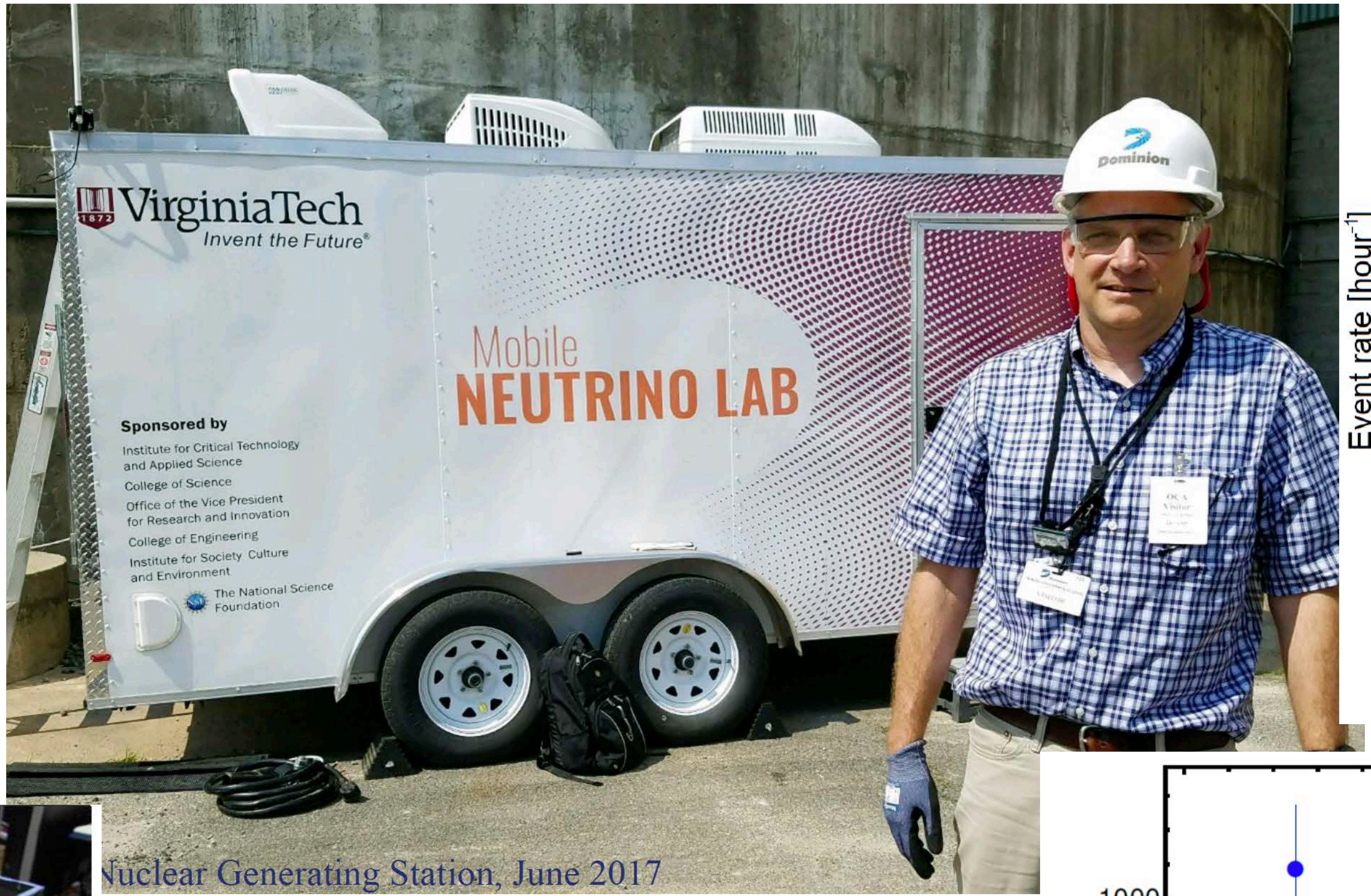
complementary to DYB and KATRIN

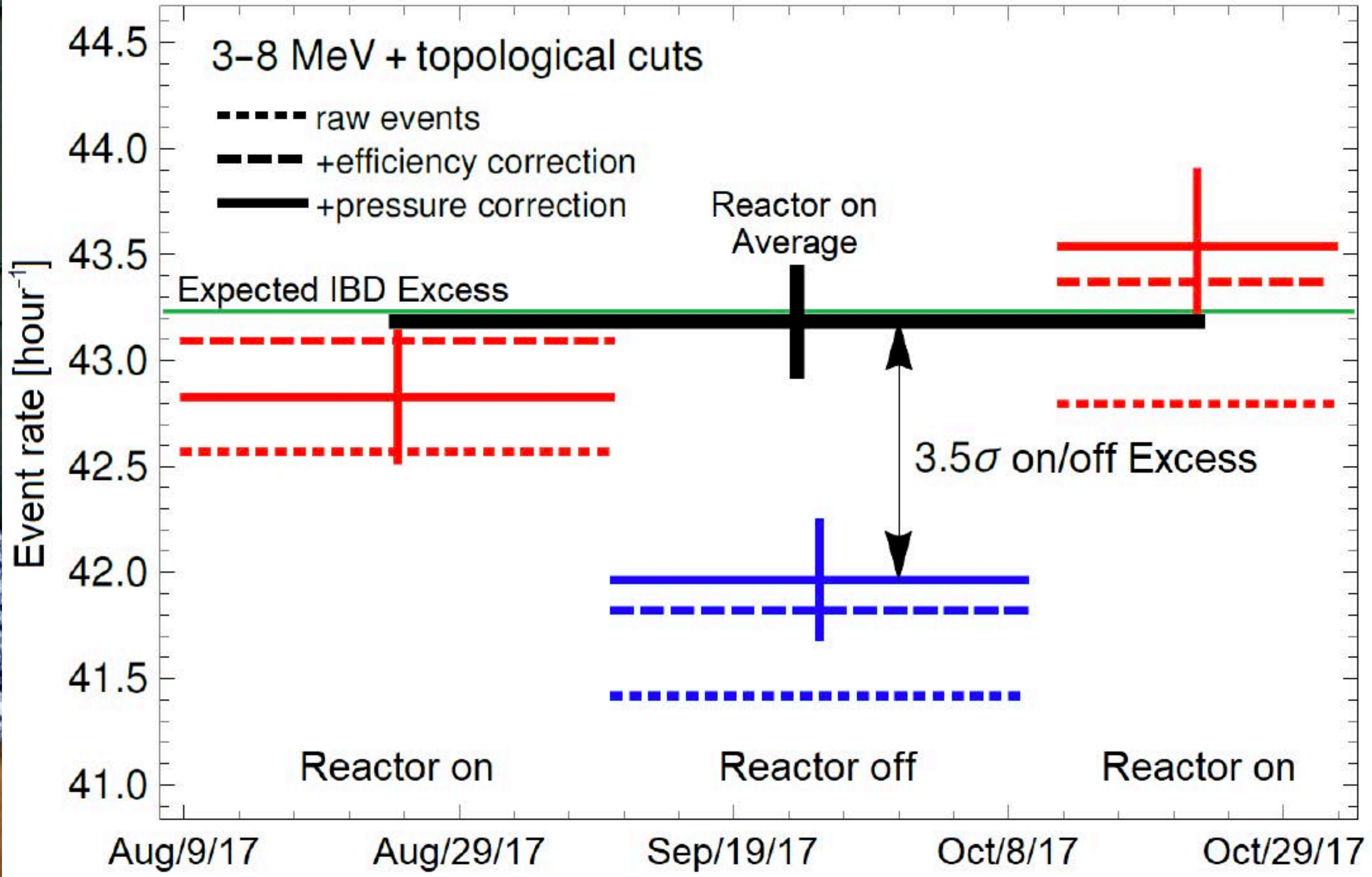
Ref: PROSPECT collaboration LOI

Reactor Neutrino Detector Development - CHANDLER

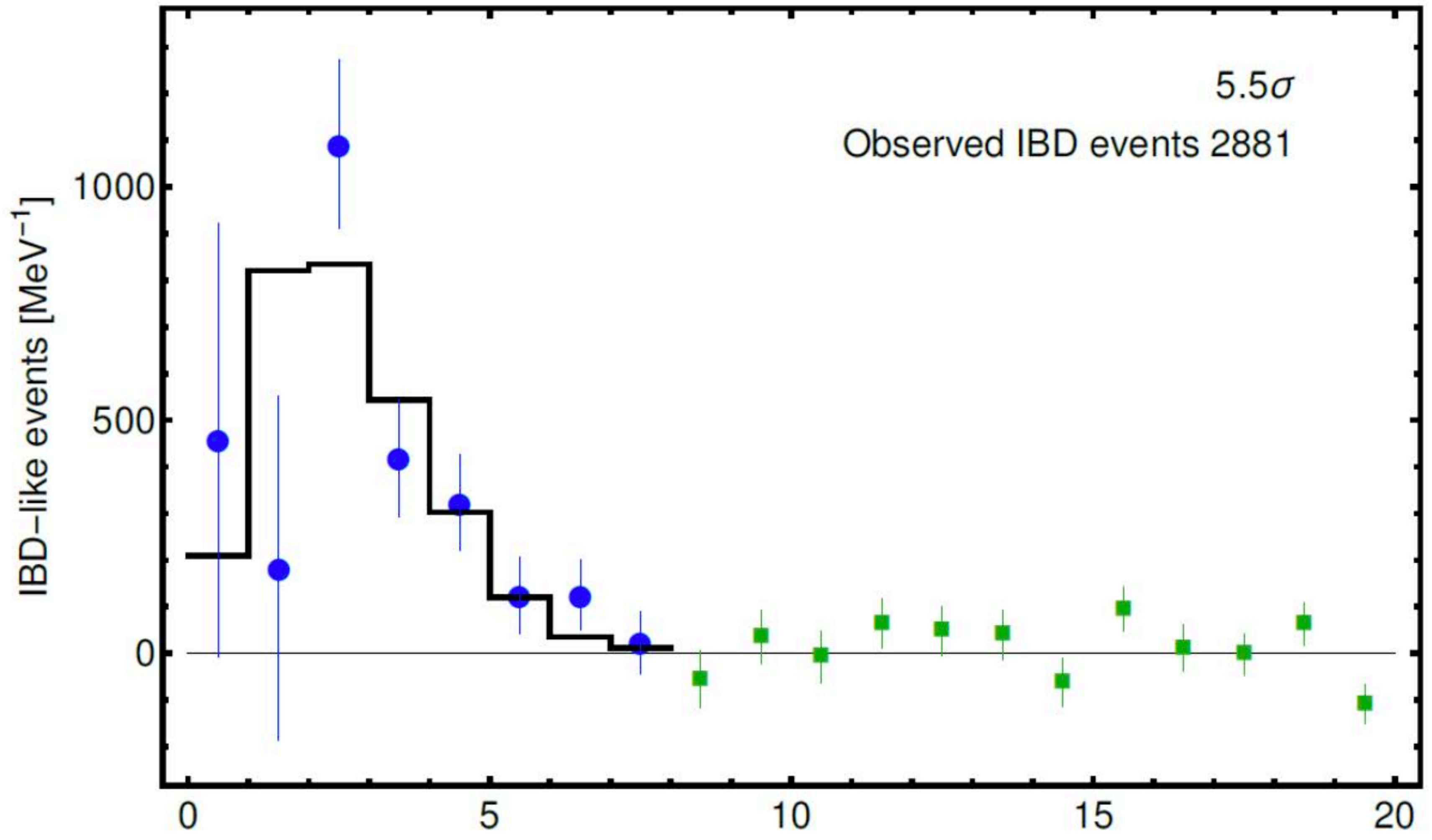






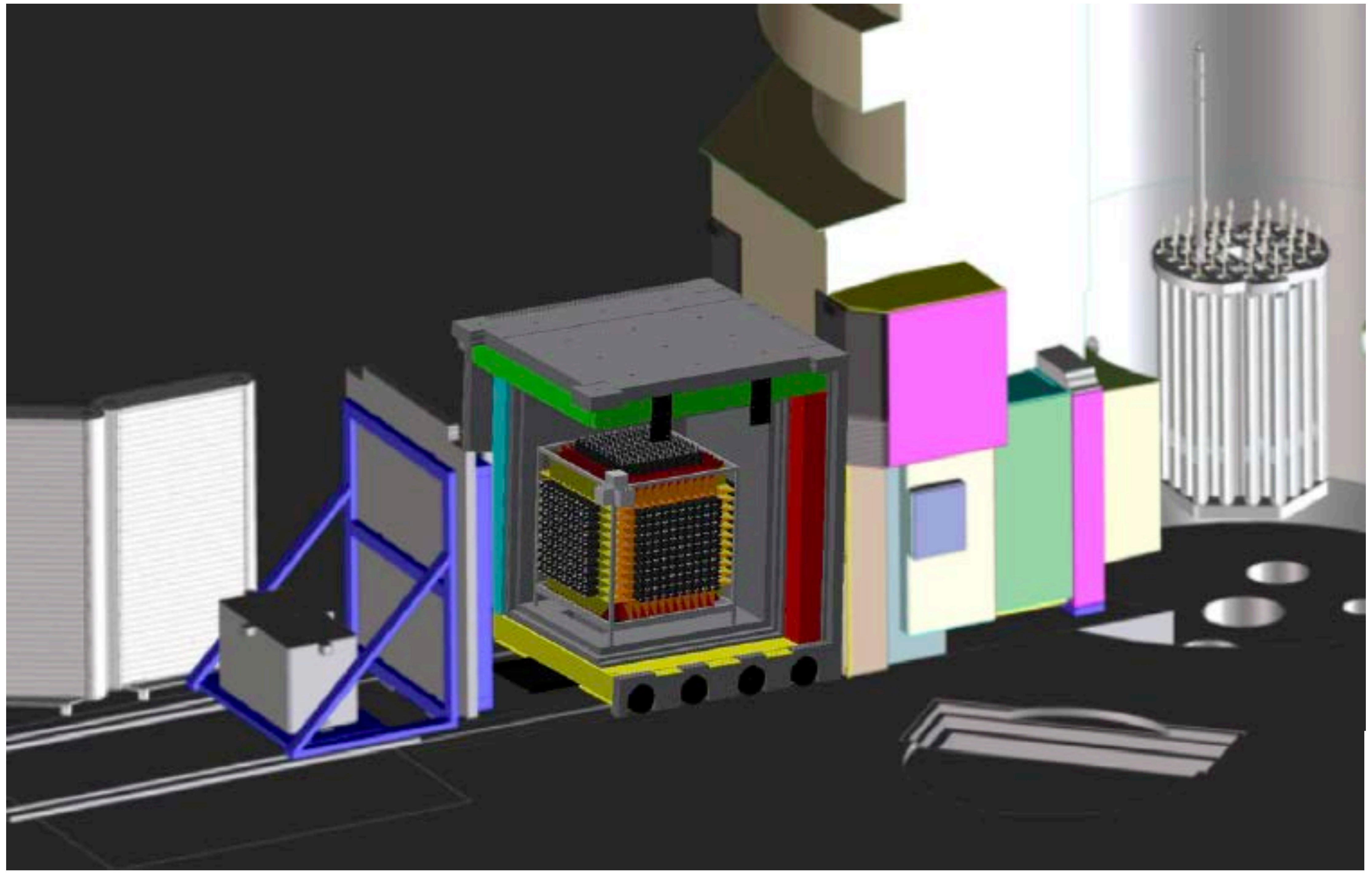


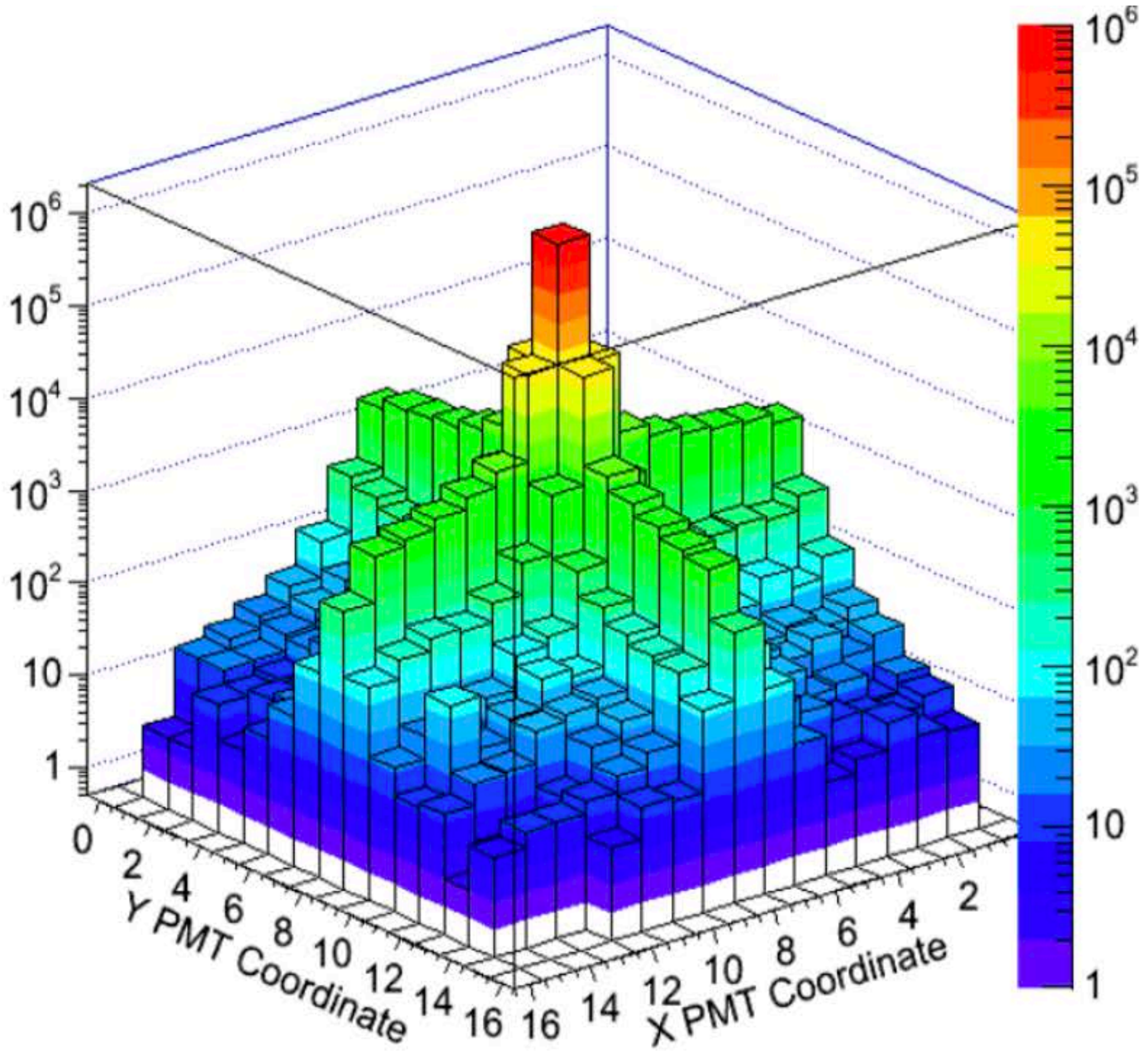
a mobile neutrino lab



LOI

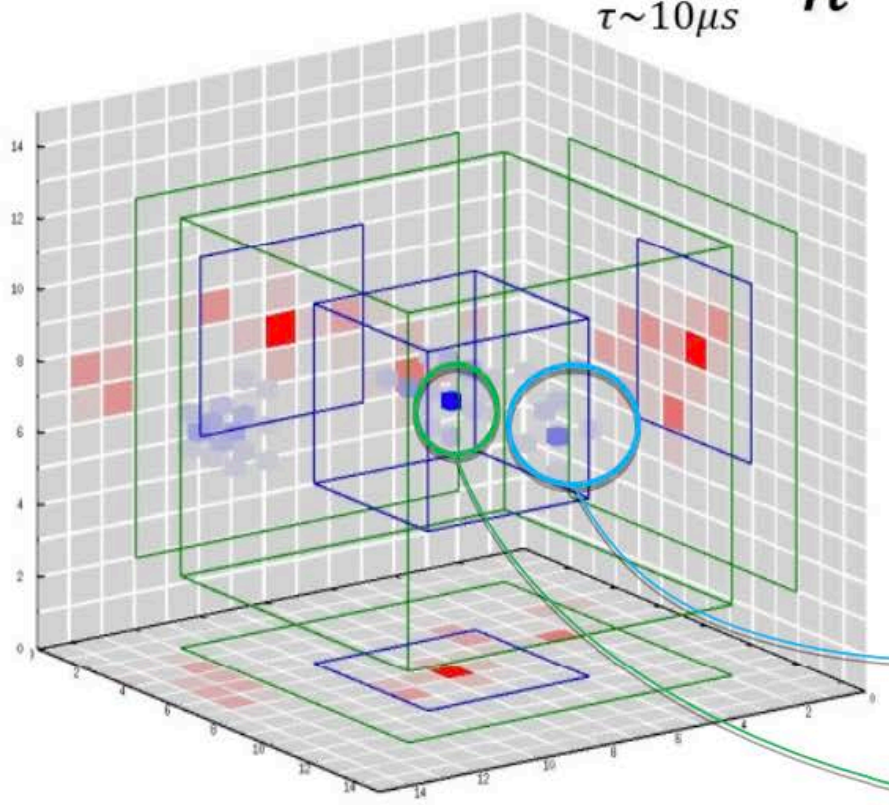
Reactor Neutrino Detector Development - NuLAT

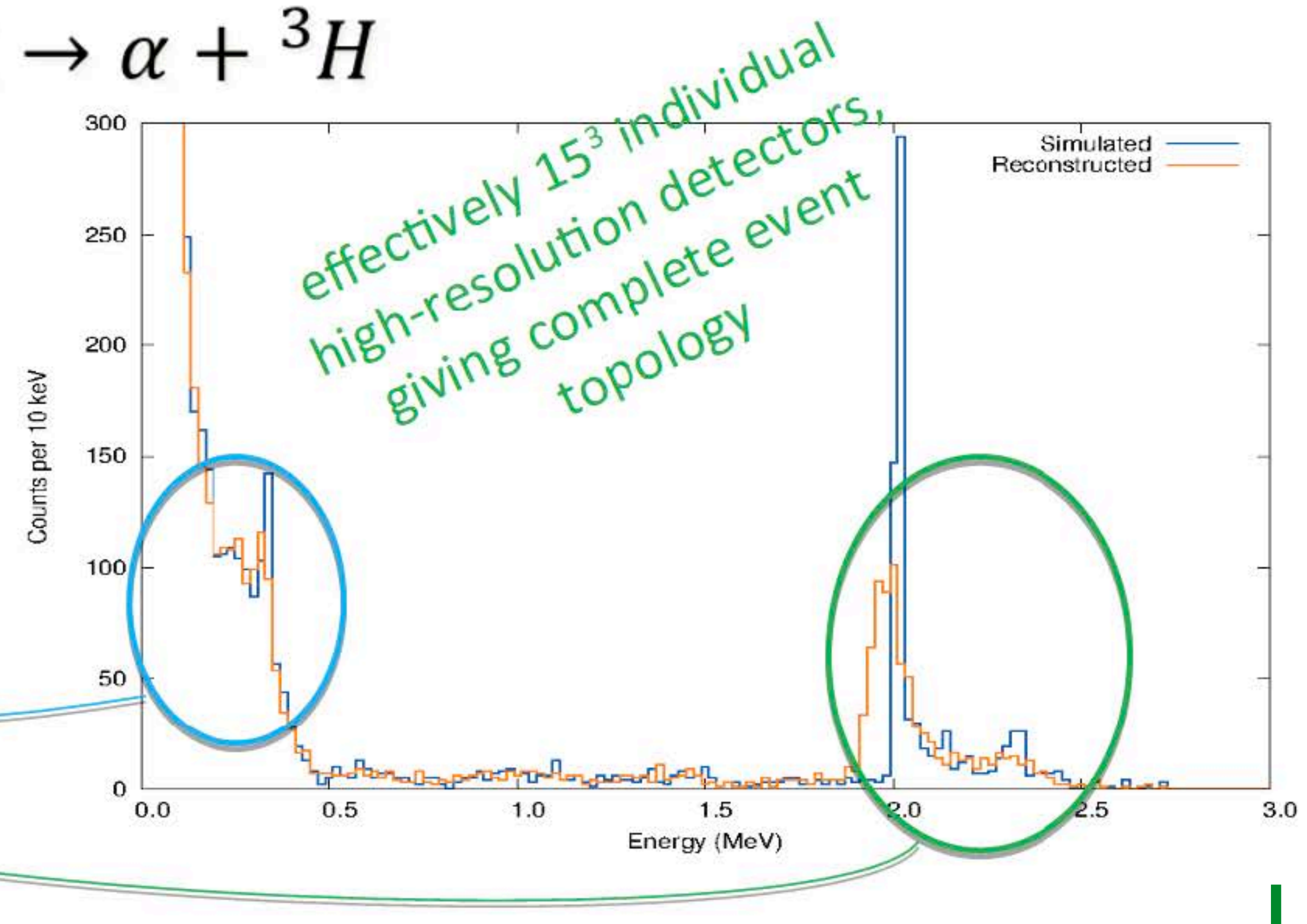




$$\overline{\nu}_e + \mathrm{p} \rightarrow e^+ + n$$

$$\xrightarrow{\tau \sim 10\mu s} n + {}^6Li \rightarrow \alpha + {}^3H$$



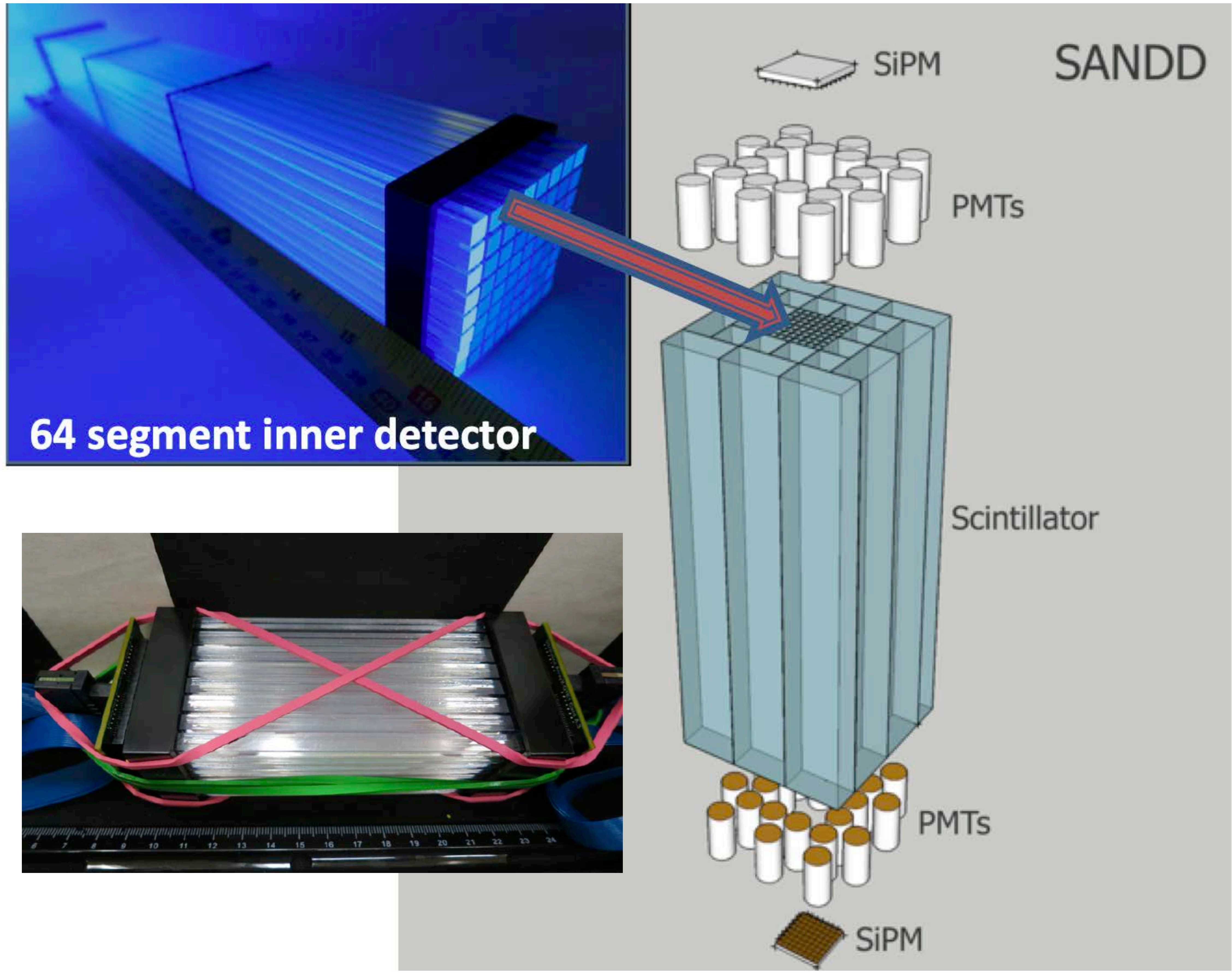


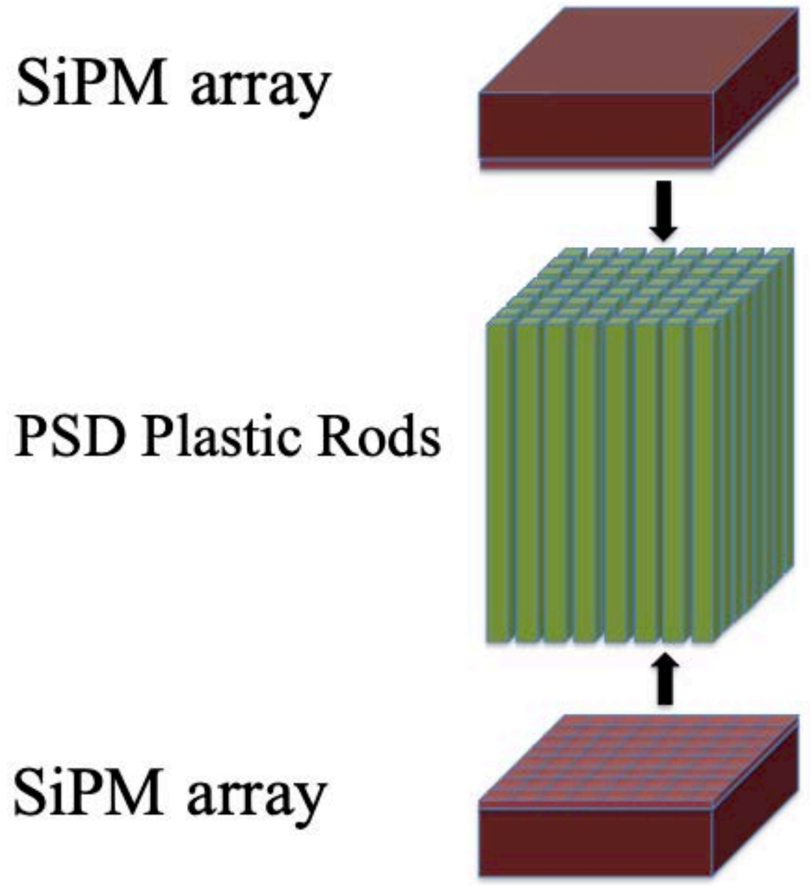
Ref: Dorrill, Neutrino 2020

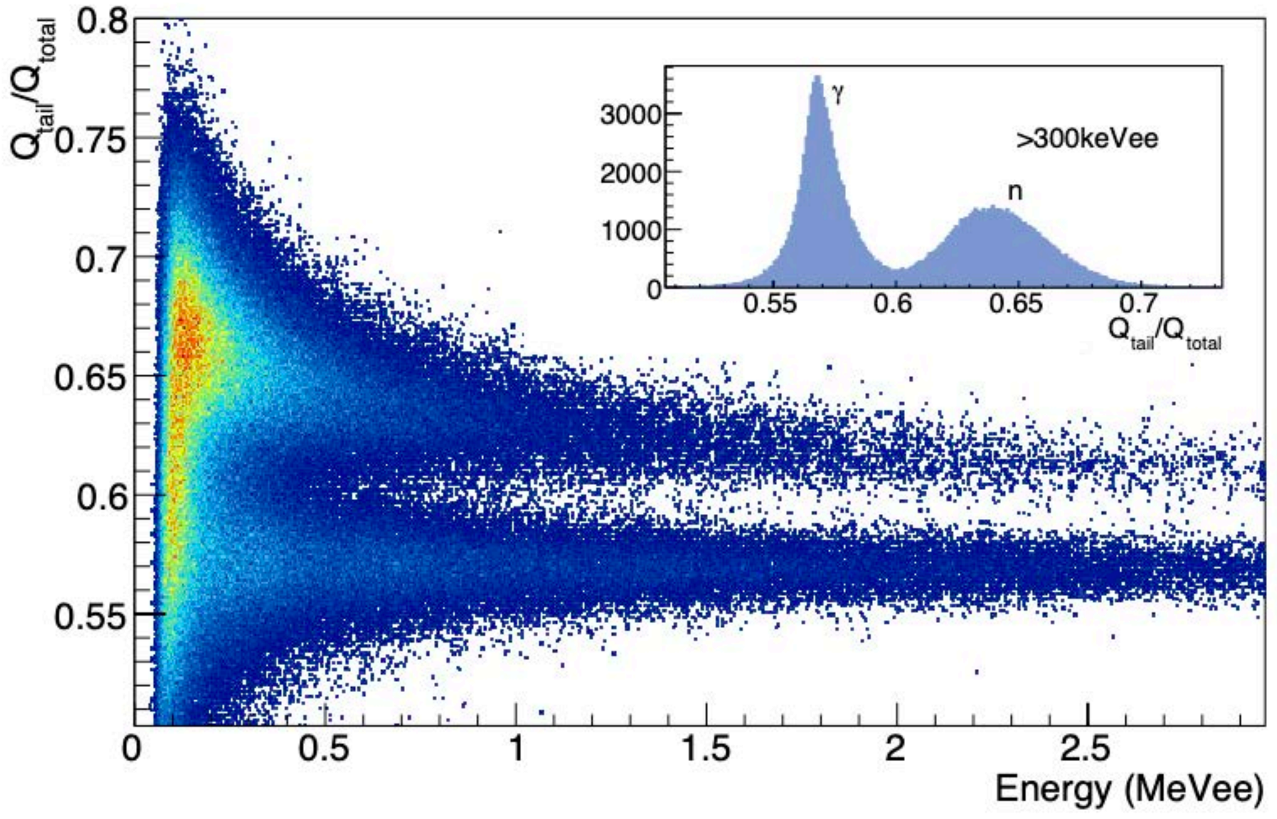
LOI

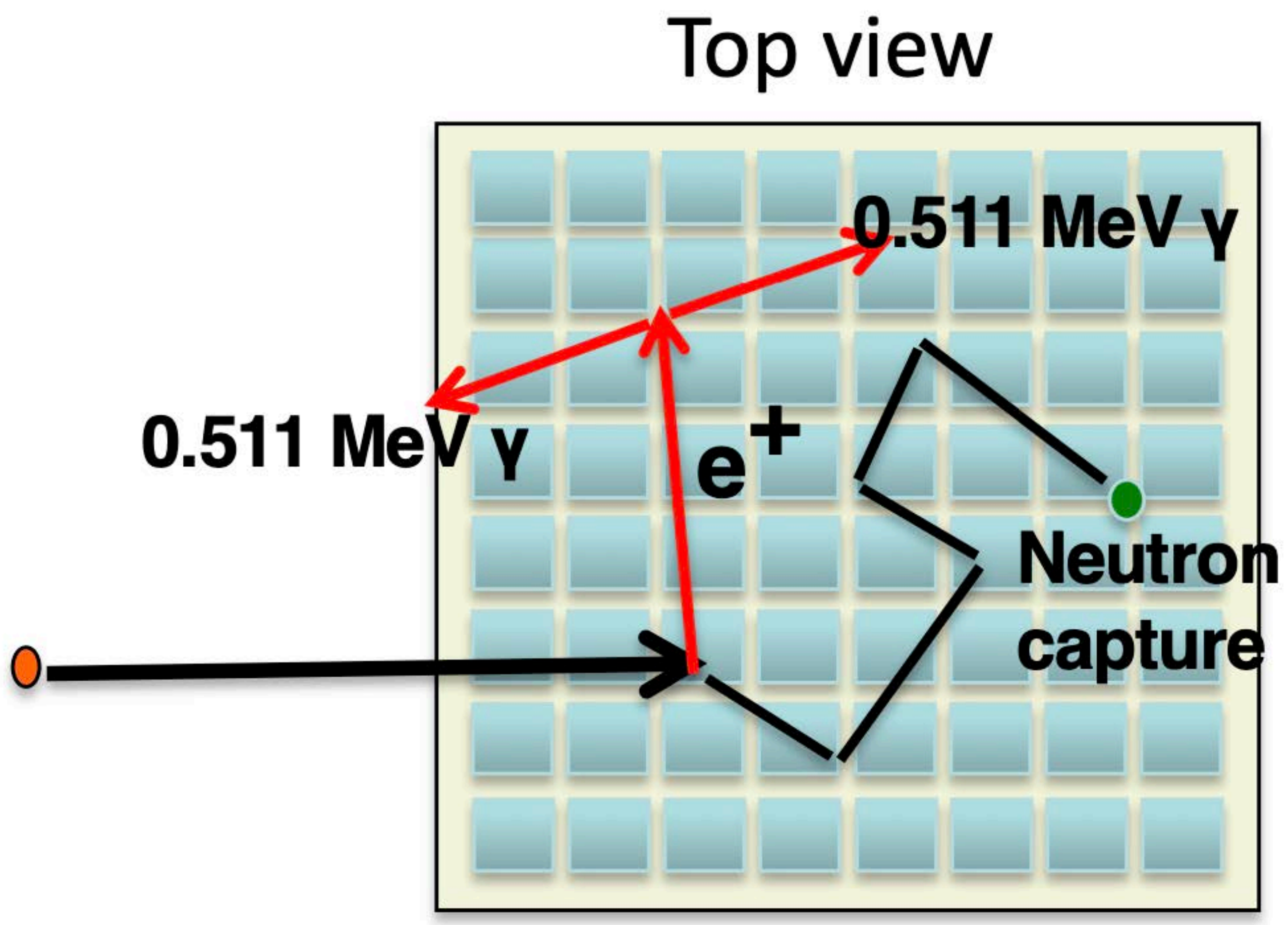
Reactor Neutrino Detector Development - SANDD

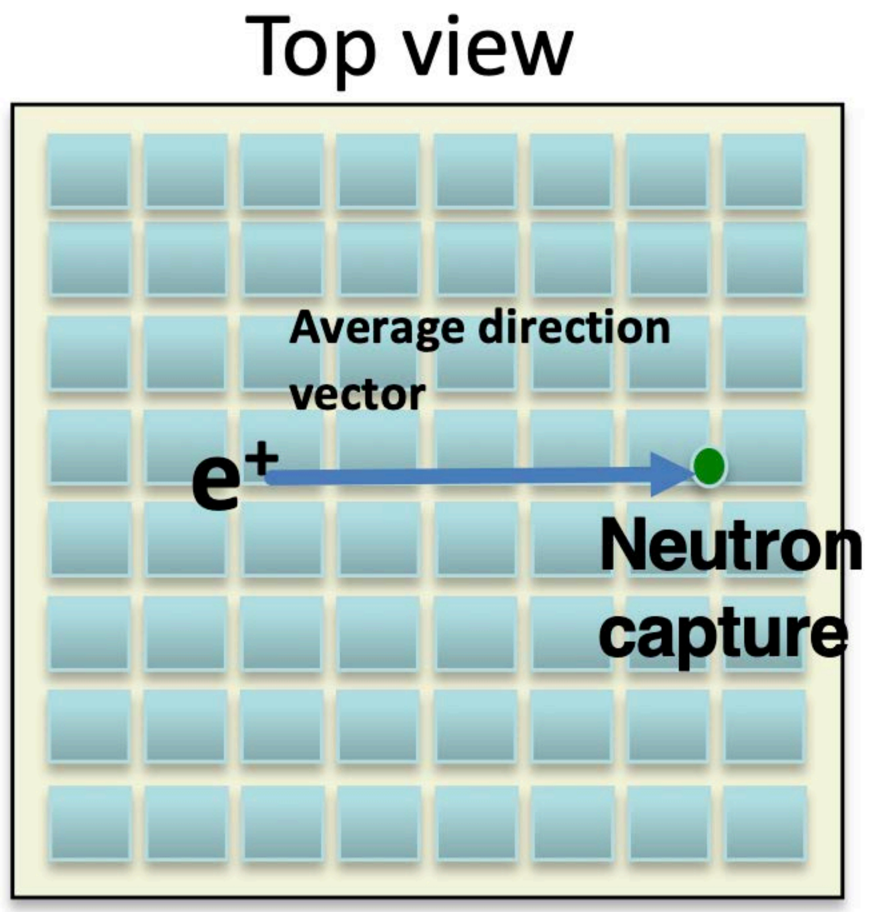
SANDD: A small directionally sensitive detector prototype









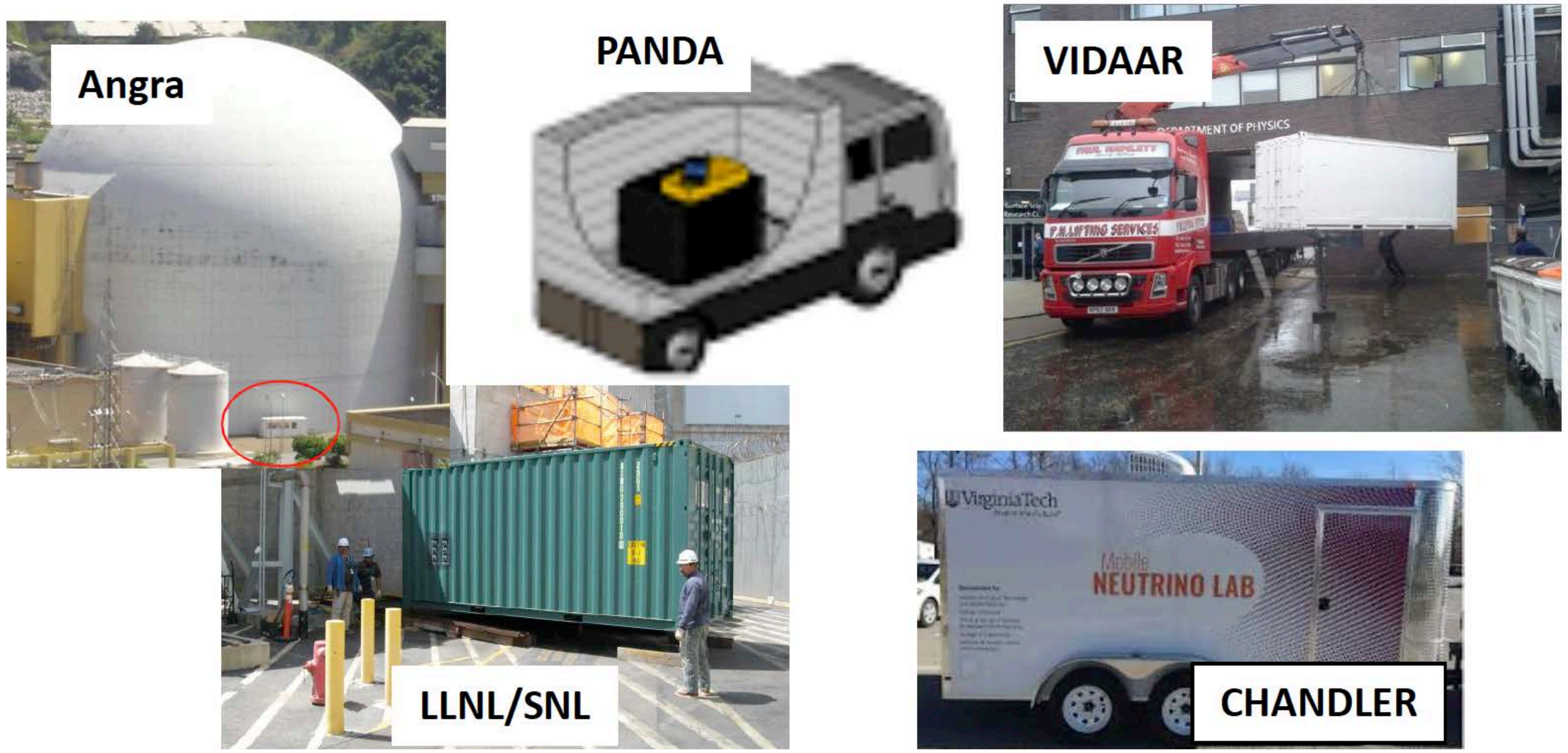


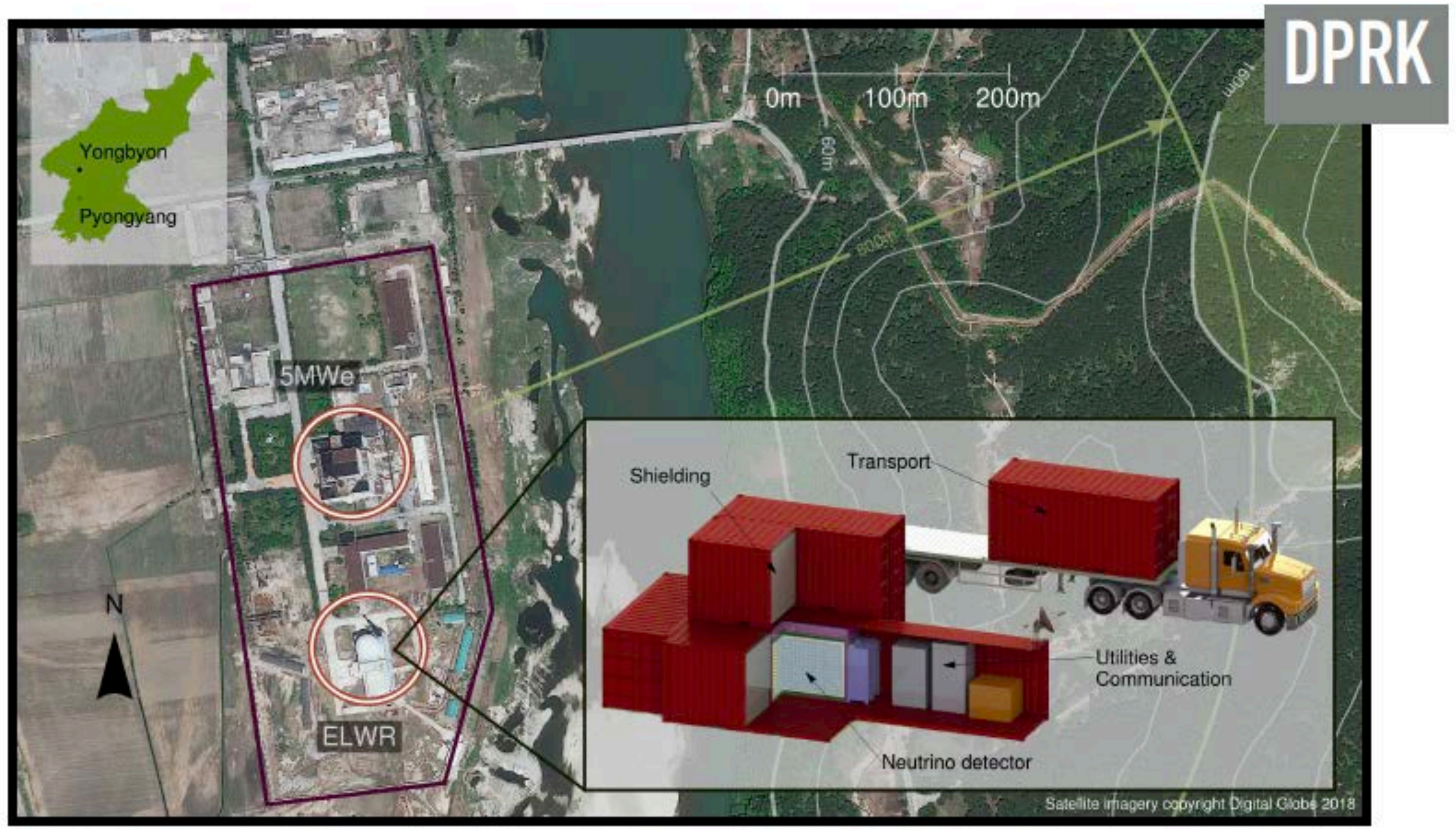
Plastic form of 6Li PSD scintillator enables a highly segmented, position sensitive readout with no dead material.

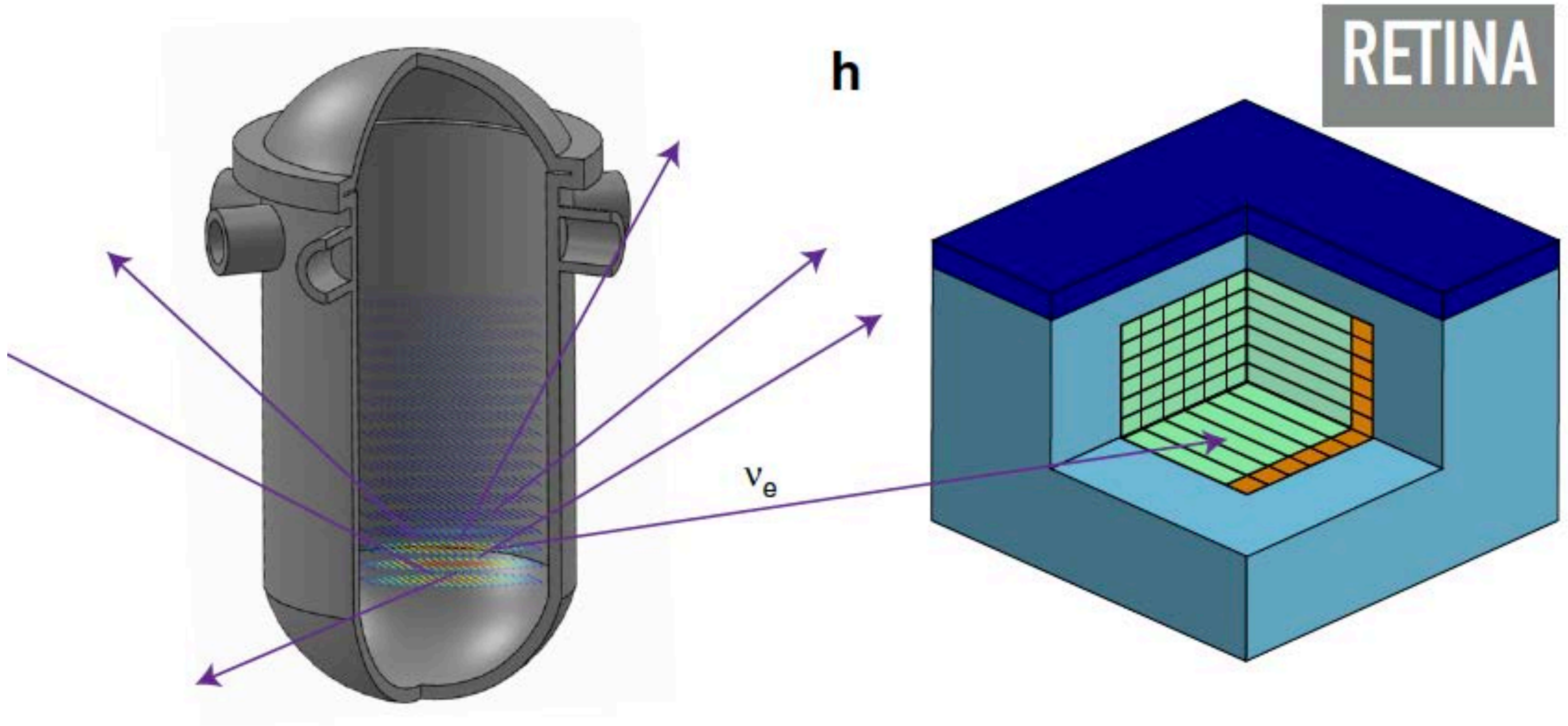
LOI

Ref: Bowden, Dazeley et al

Reactor Monitoring Using Antineutrinos



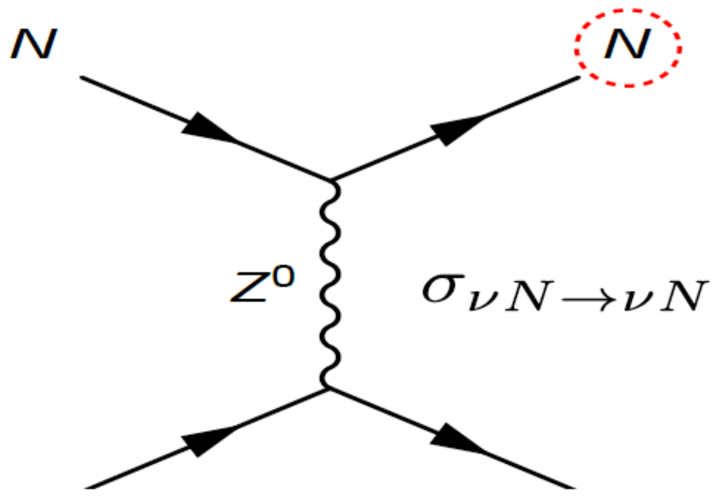




development of mobile, above-ground detection systems

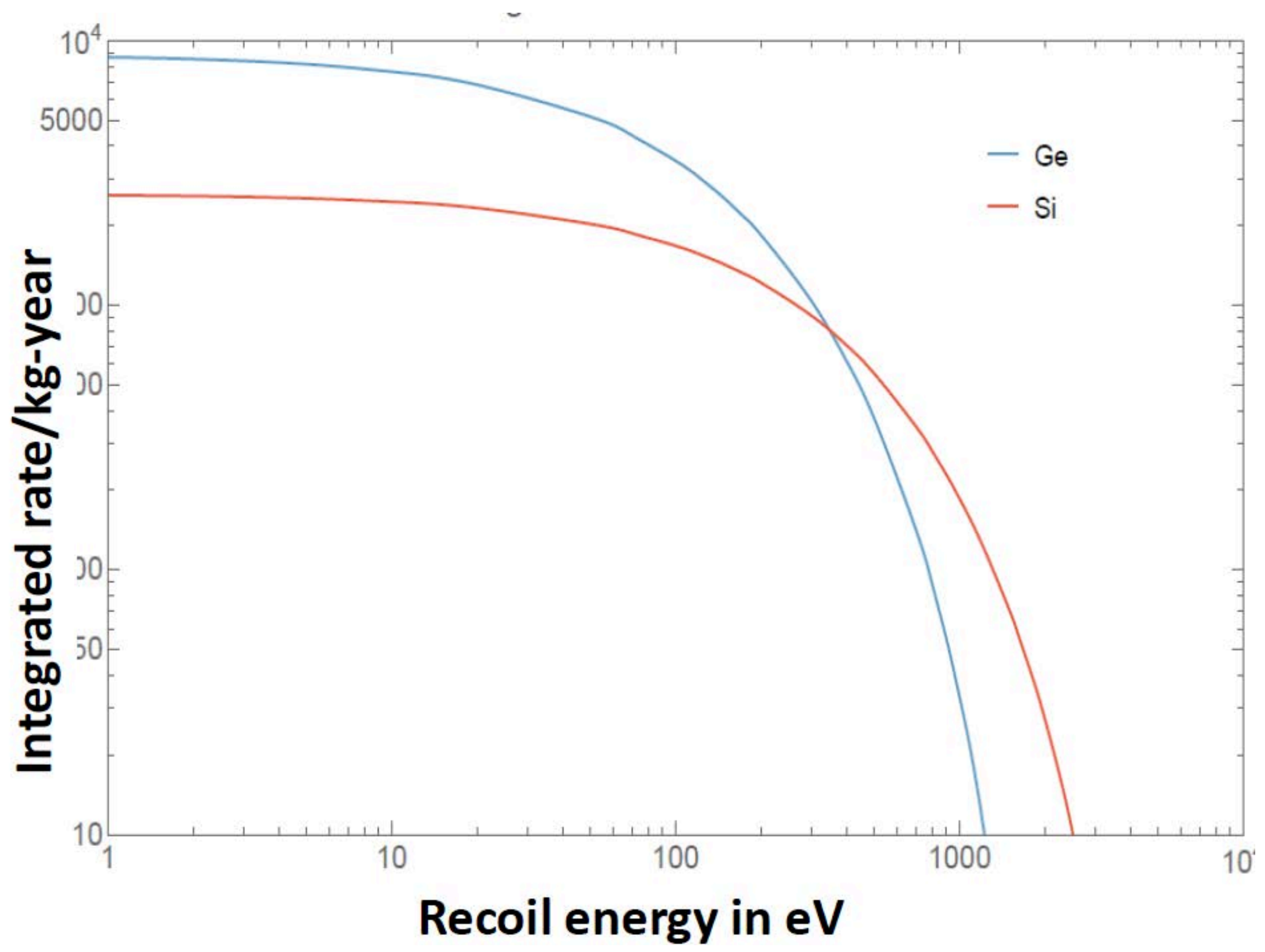
LOI

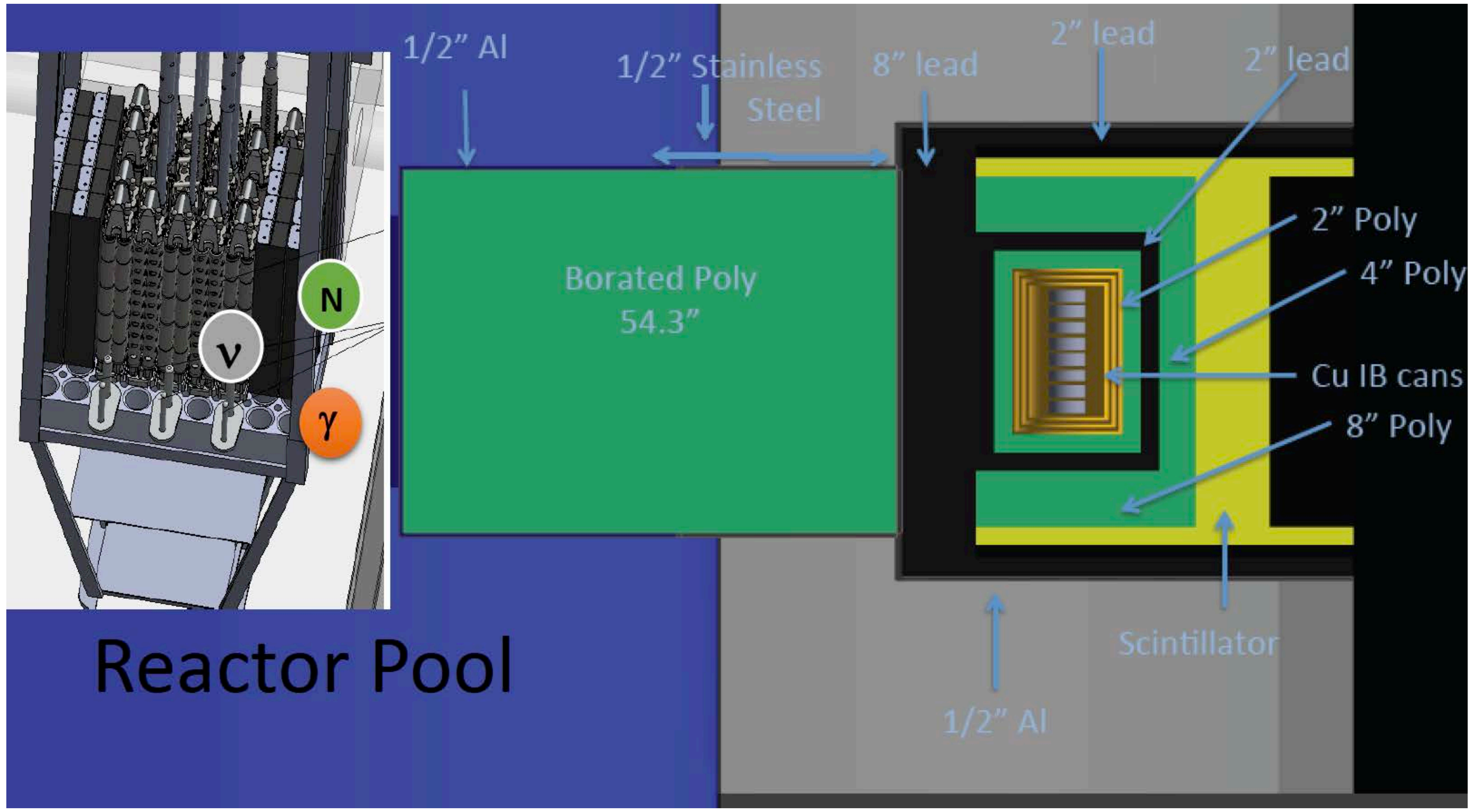
Reactor Neutrino Detector Development - MINER

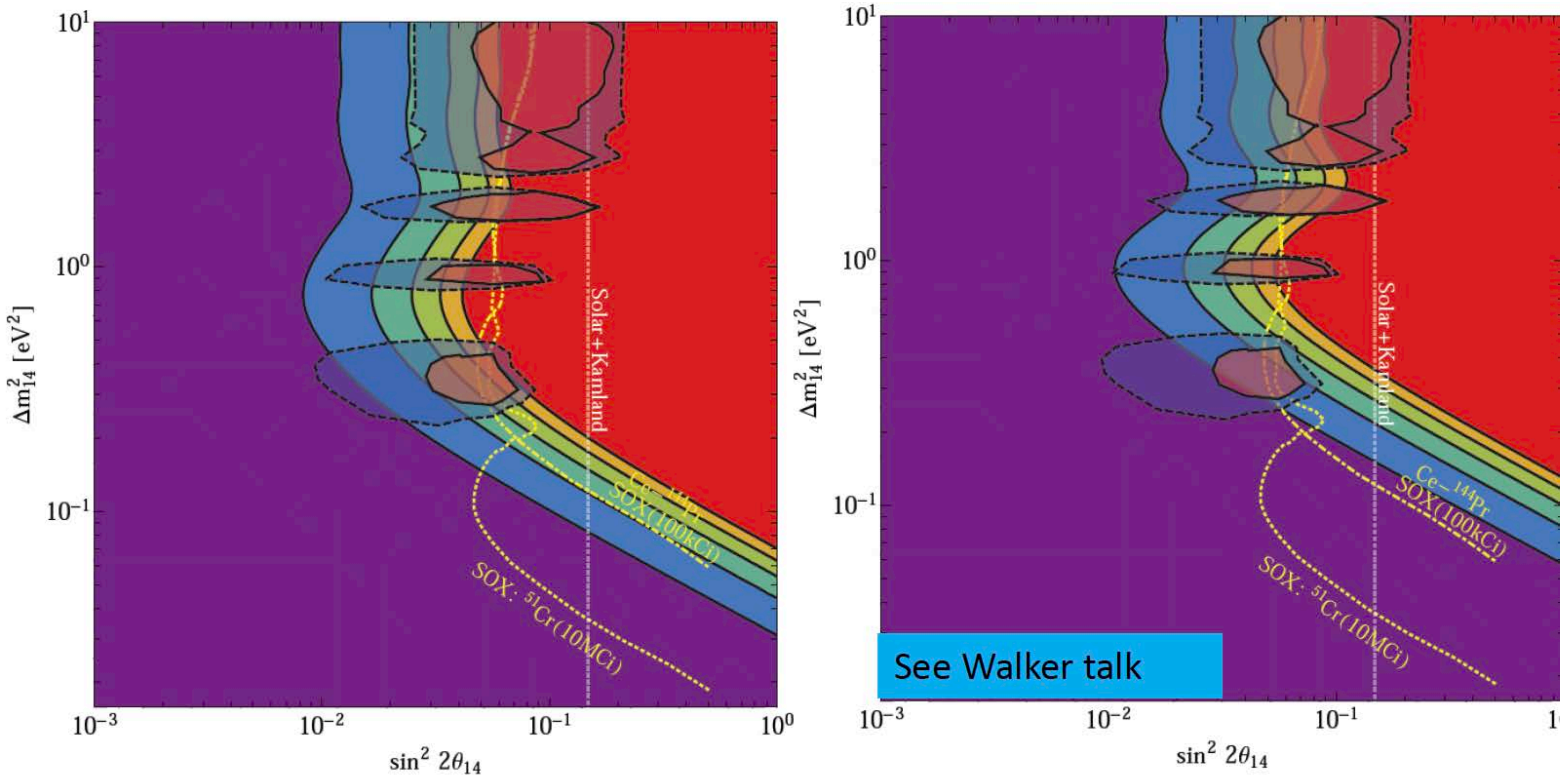


Flavor-blind

$$\sigma_{\nu N \to \nu N} \simeq \frac{G_F^2}{4\pi} N^2 E_\nu^2$$







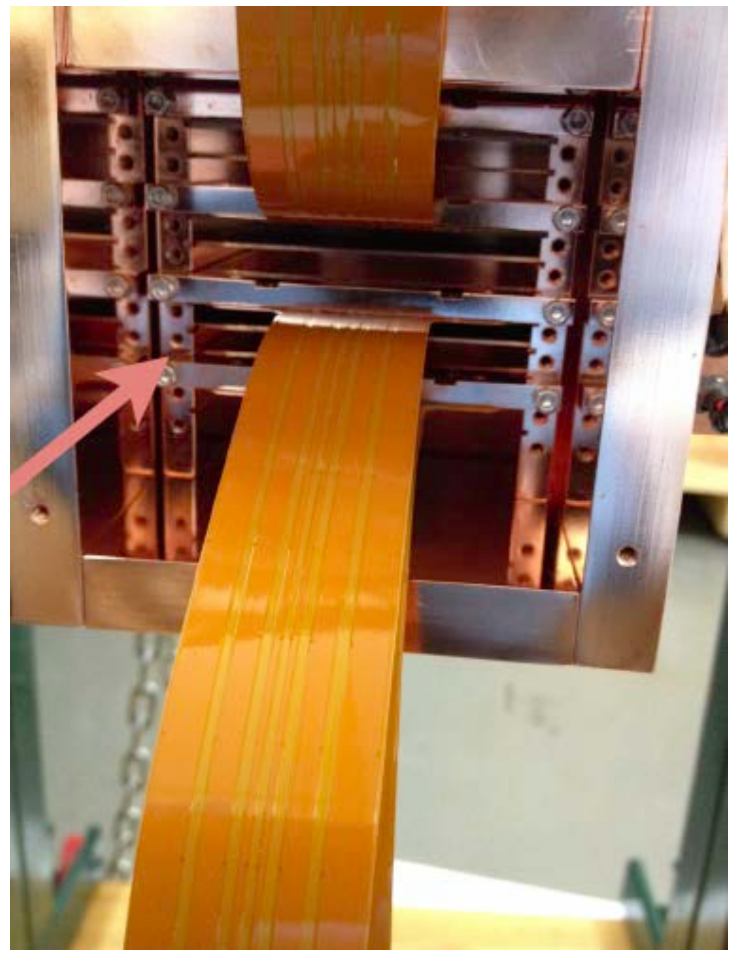
Excellent scientific potential in 3 years of running, before SNOLAB science starts flowing

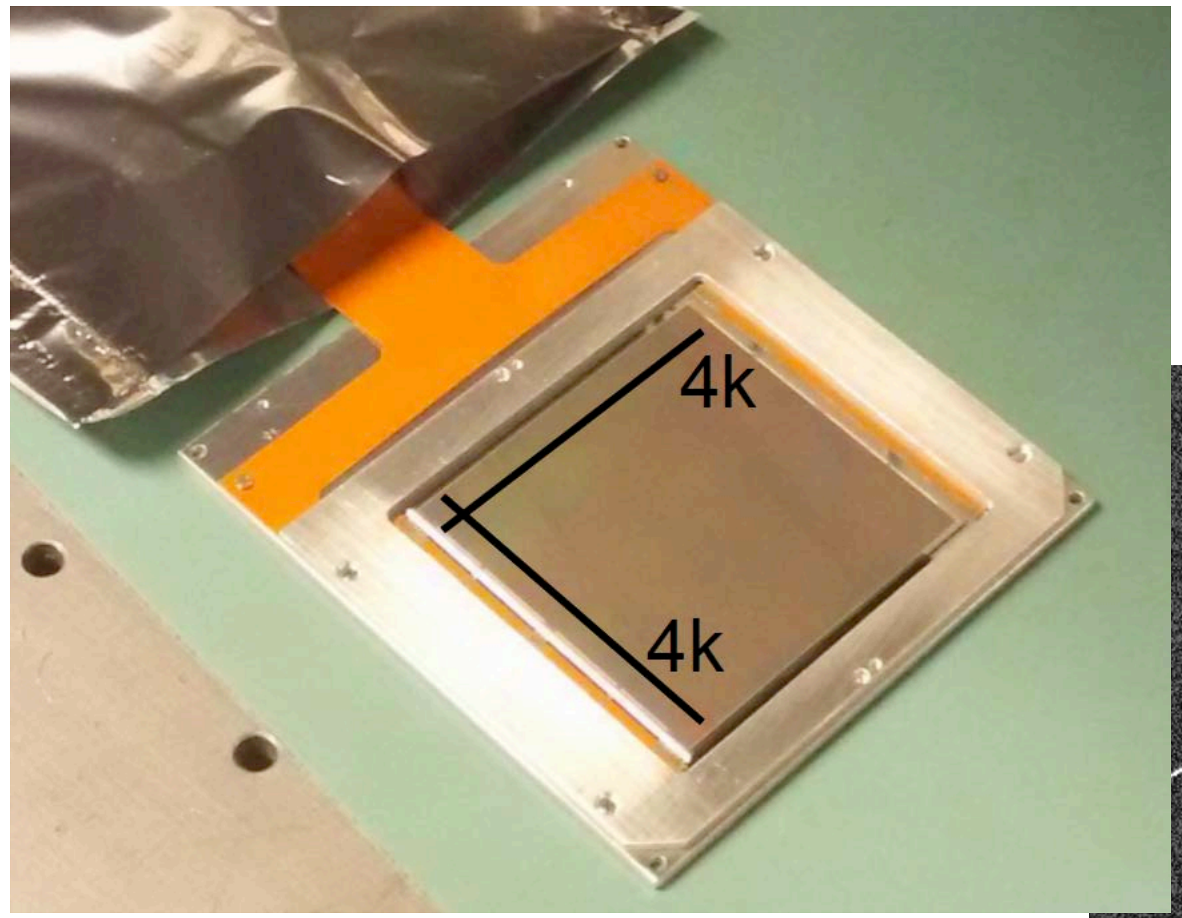
Ref: Mohapatra

LOI

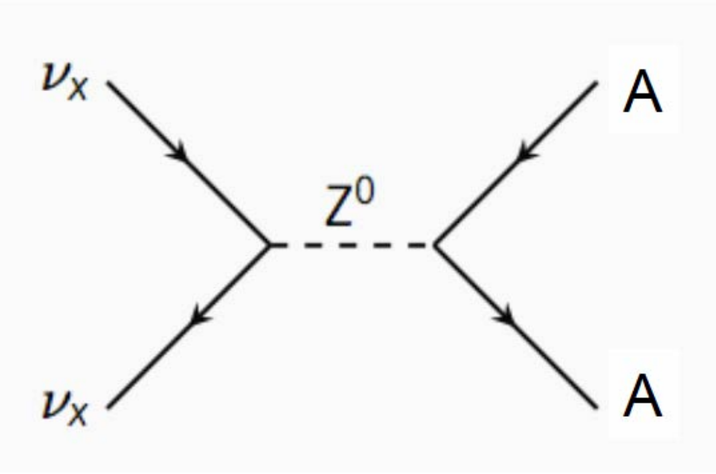
Reactor Neutrino Detector Development - CONNIE

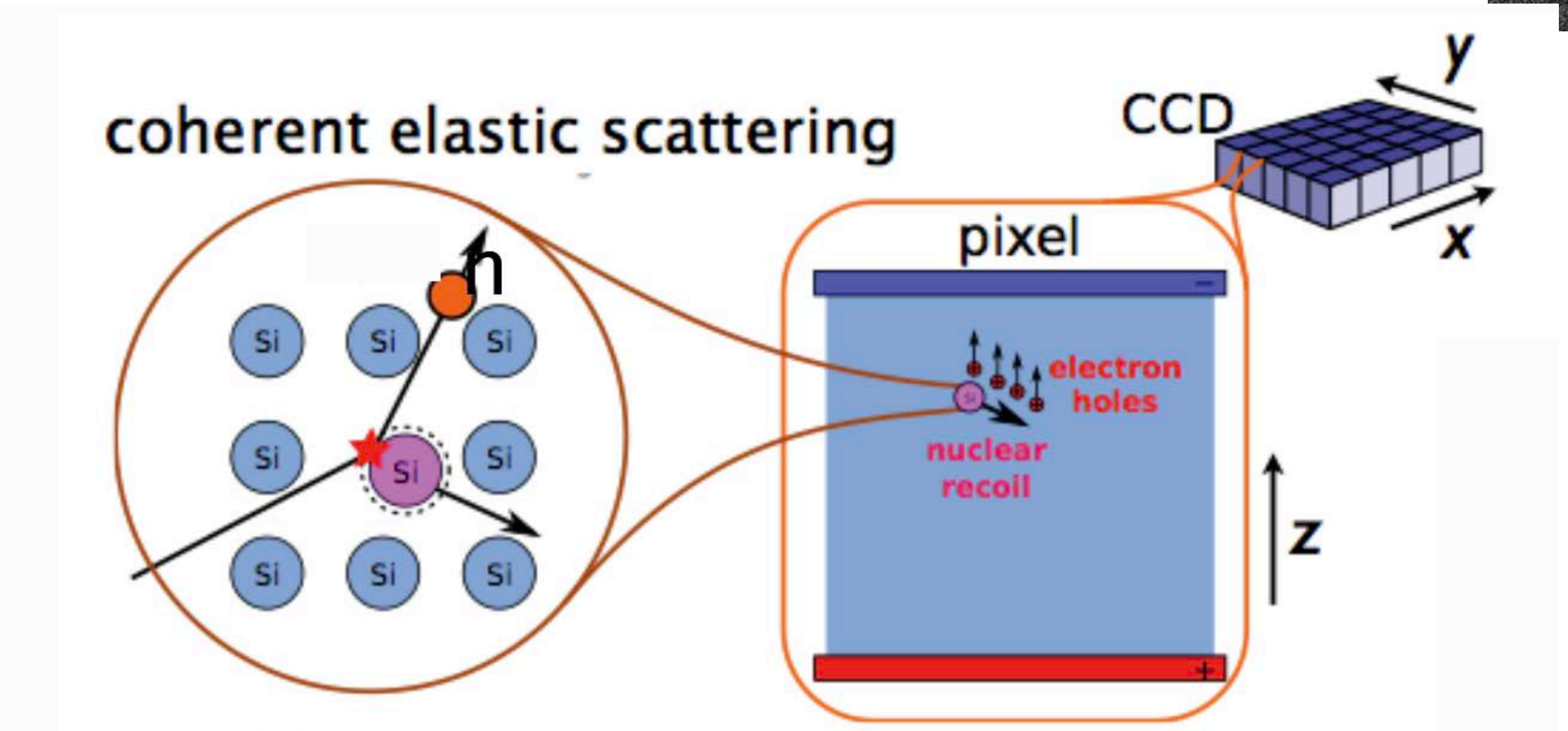
A reactor experiment using CCDs

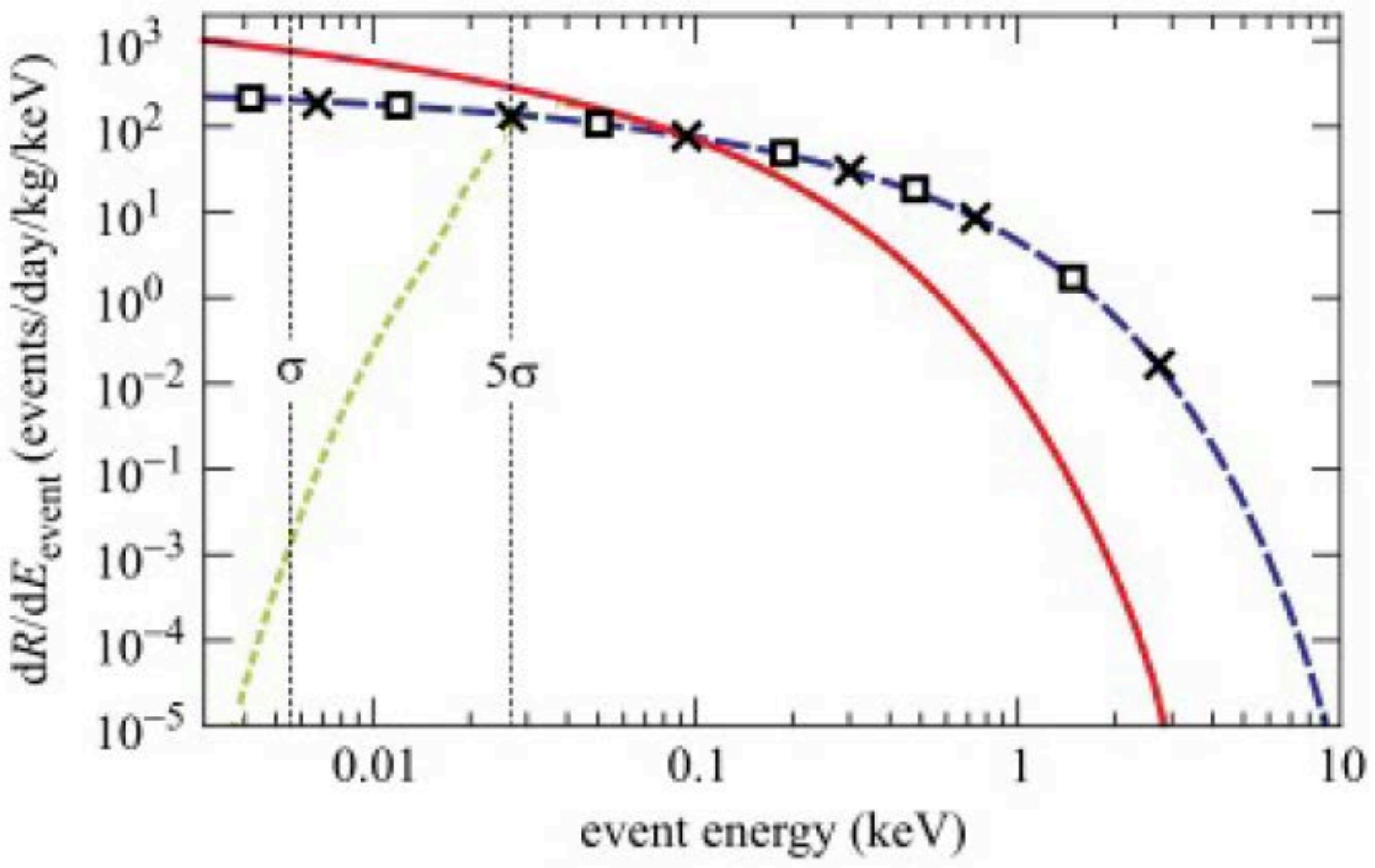




$$\frac{d\sigma}{d(\cos\theta)} = \frac{G^2}{8\pi}\left[Z(4\sin^2\theta_W - 1) + N\right]^2 E_\nu^2(1+\cos\theta)$$







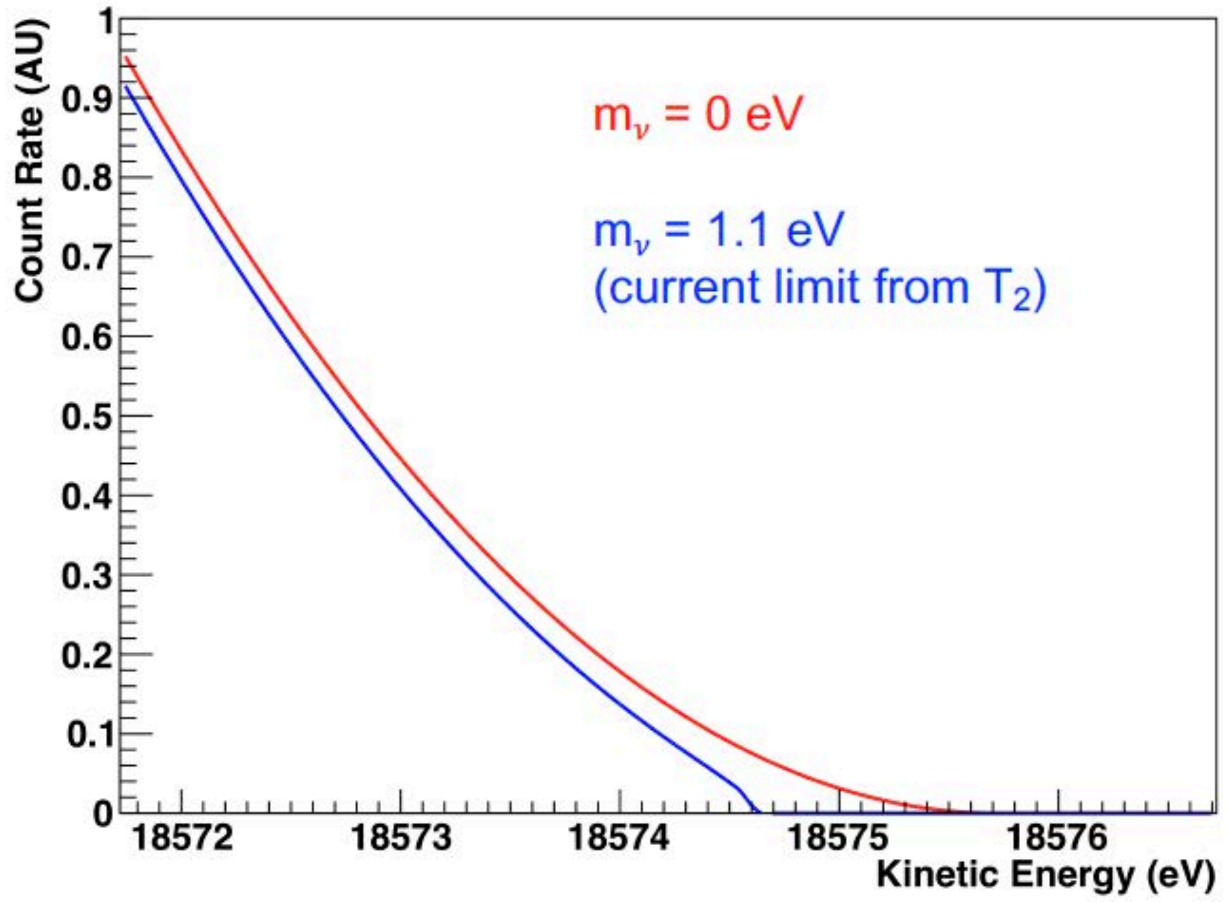
expected recoil energy spectrum

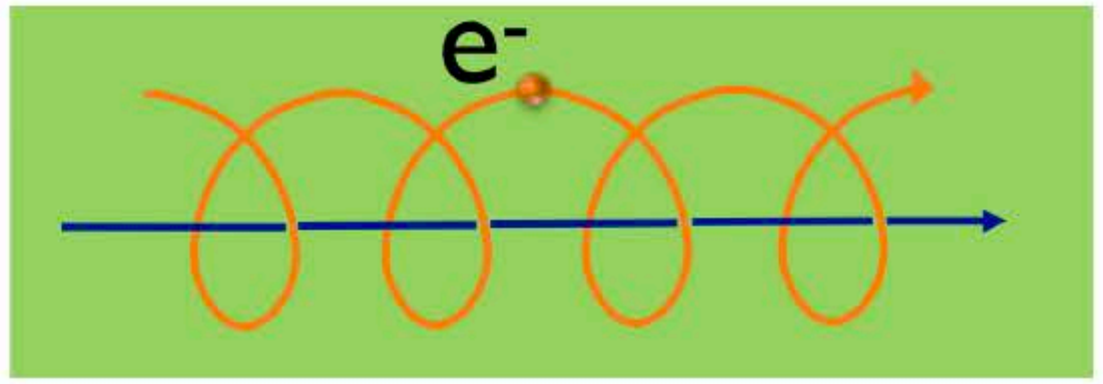
LOI

Secondary Physics Potential of Project 8

- An electron traveling in a magnetic field emits cyclotron radiation
- The frequency of the emitted radiation depends on the relativistic boost

Zoom in on the endpoint…

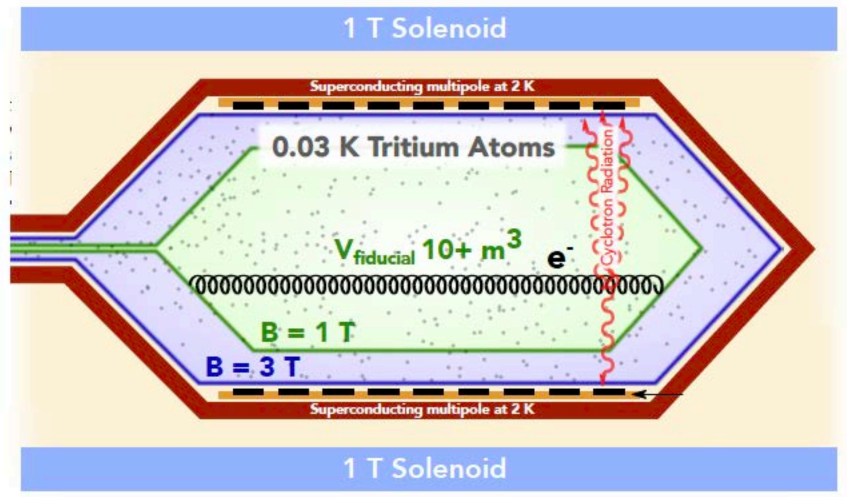




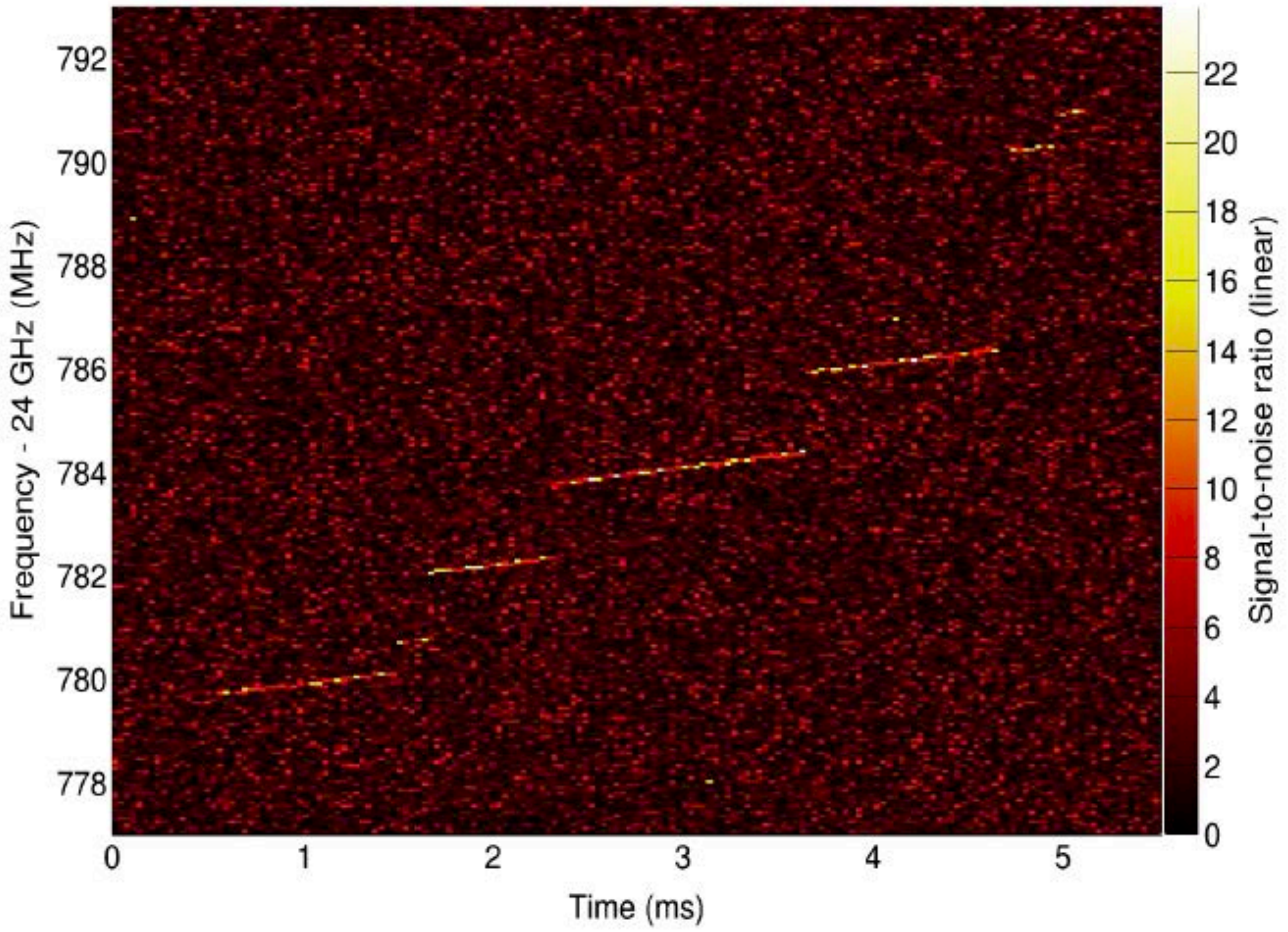
$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$$

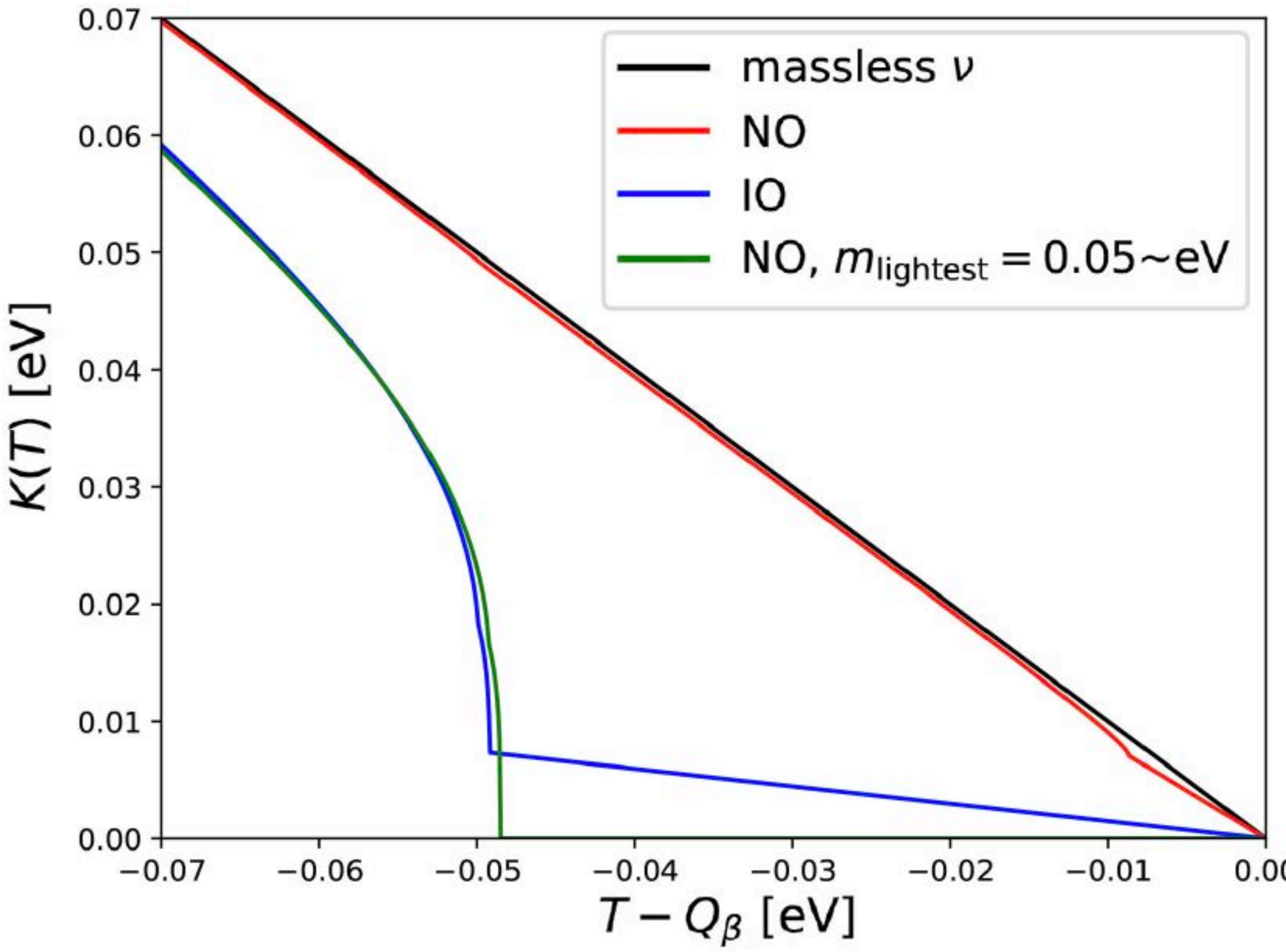
$$\frac{dN}{dE} = CF(Z,E)p(E + m_e c^2)(E_0 - E)\sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}$$

Large Volume



First CRES Event





$$\frac{dN}{dE} = \cos^2\theta \frac{dN}{dE}(m_\beta) + \sin^2\theta \frac{dN}{dE}(m_s),$$

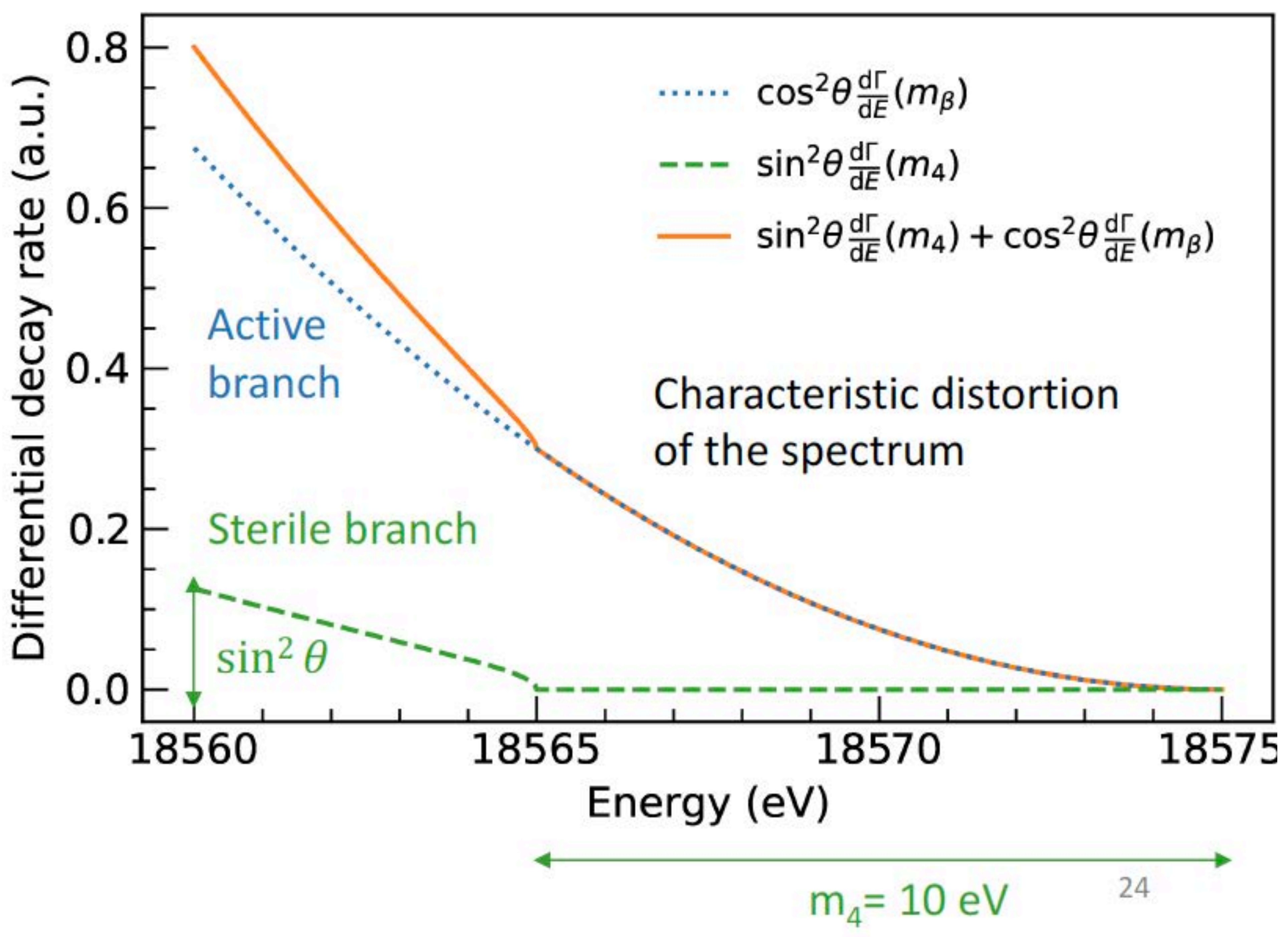
sterile neutrinos would create a distortion in the beta spectrum

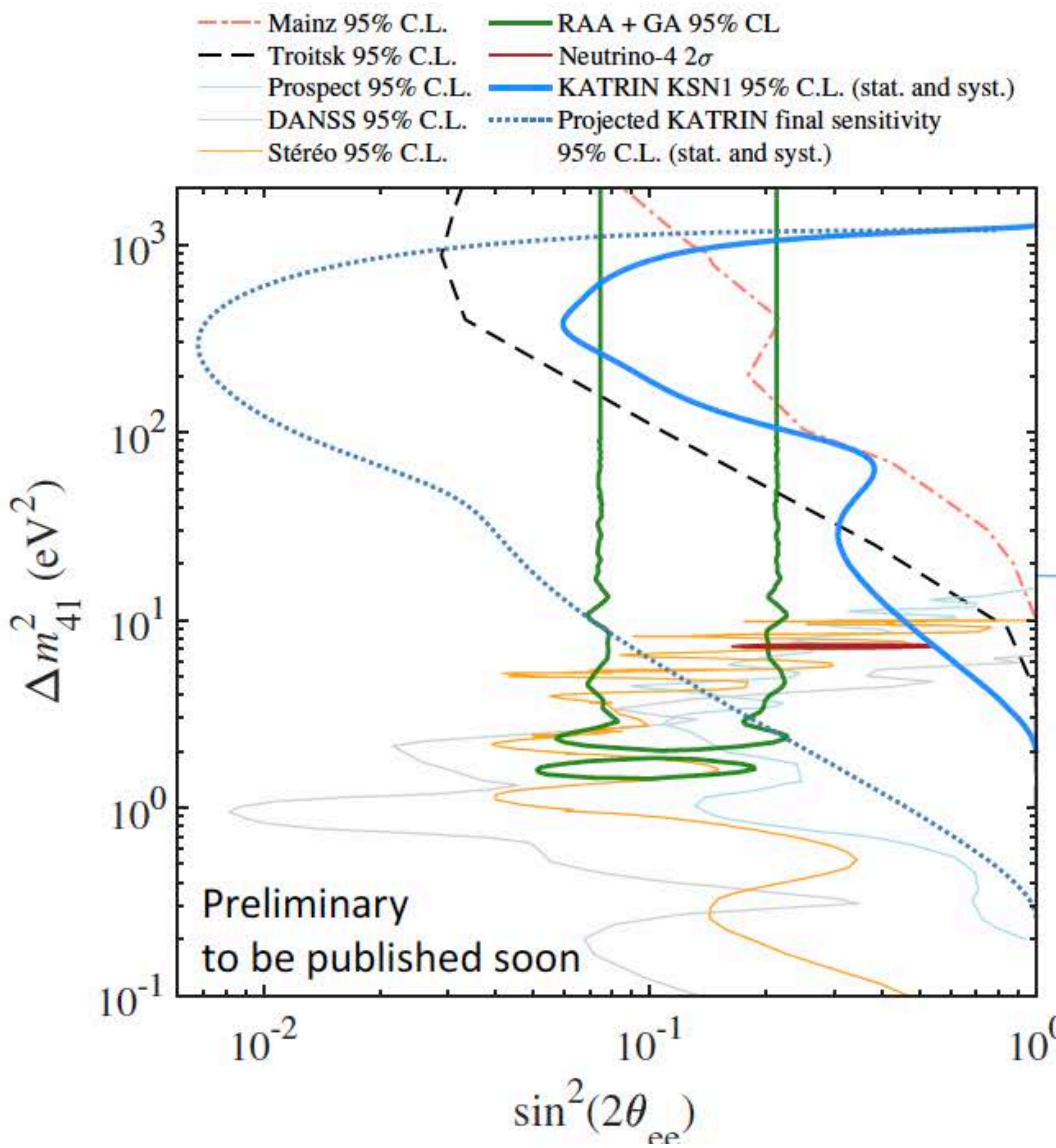
Oblath, Neutrino 2020
Project 8 Collaboration

LOI

KATRIN and Sterile Neutrinos

Light sterile neutrinos





High Δm_{41} region:

- ✓ Improve exclusion with respect to DANSS, PROSPECT, and STEREO
- ✓ Exclude parameter space of Reactor Anomaly (RAA)

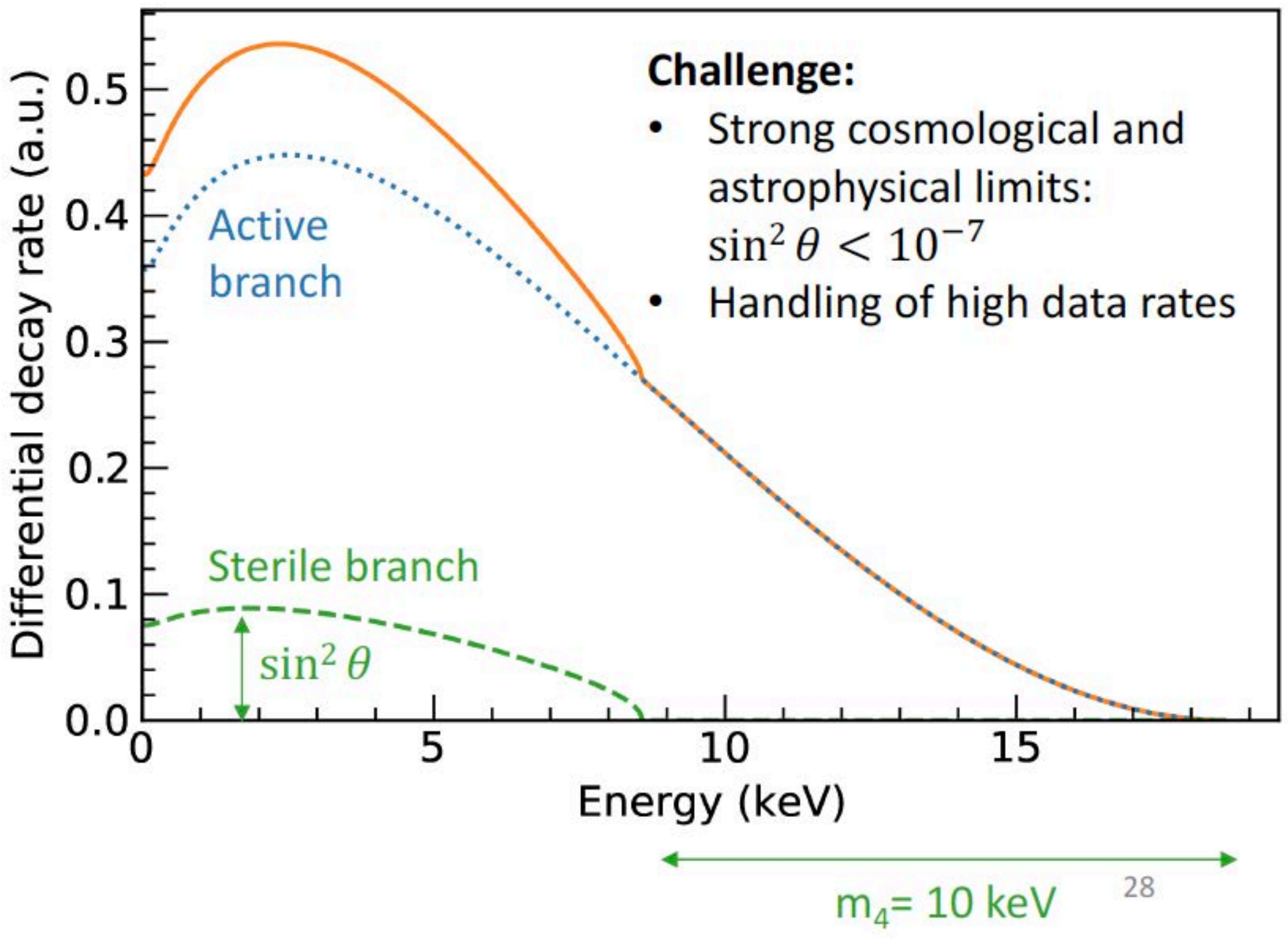
Low Δm_{41} region:

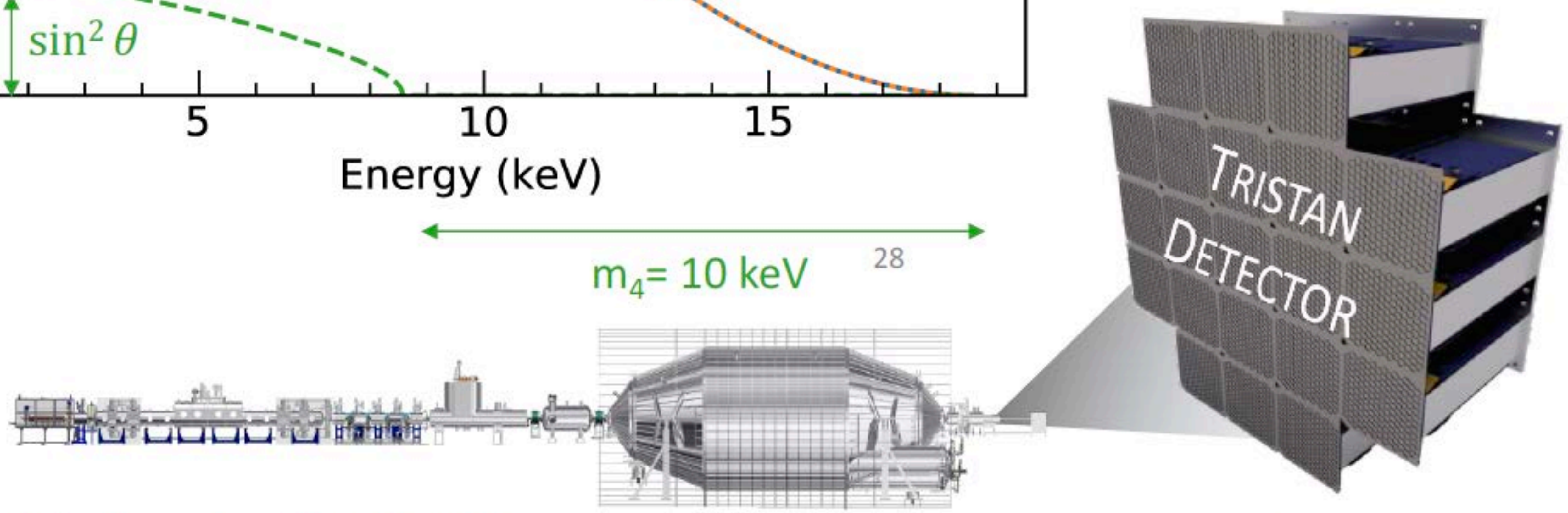
- ✓ Improve MAINZ and TROITSK limit
- ✓ The NEUTRINO-4 hint at the edge of exclusion limit

Mertens, Neutrino 2020 LOI

KATRIN and Sterile Neutrinos

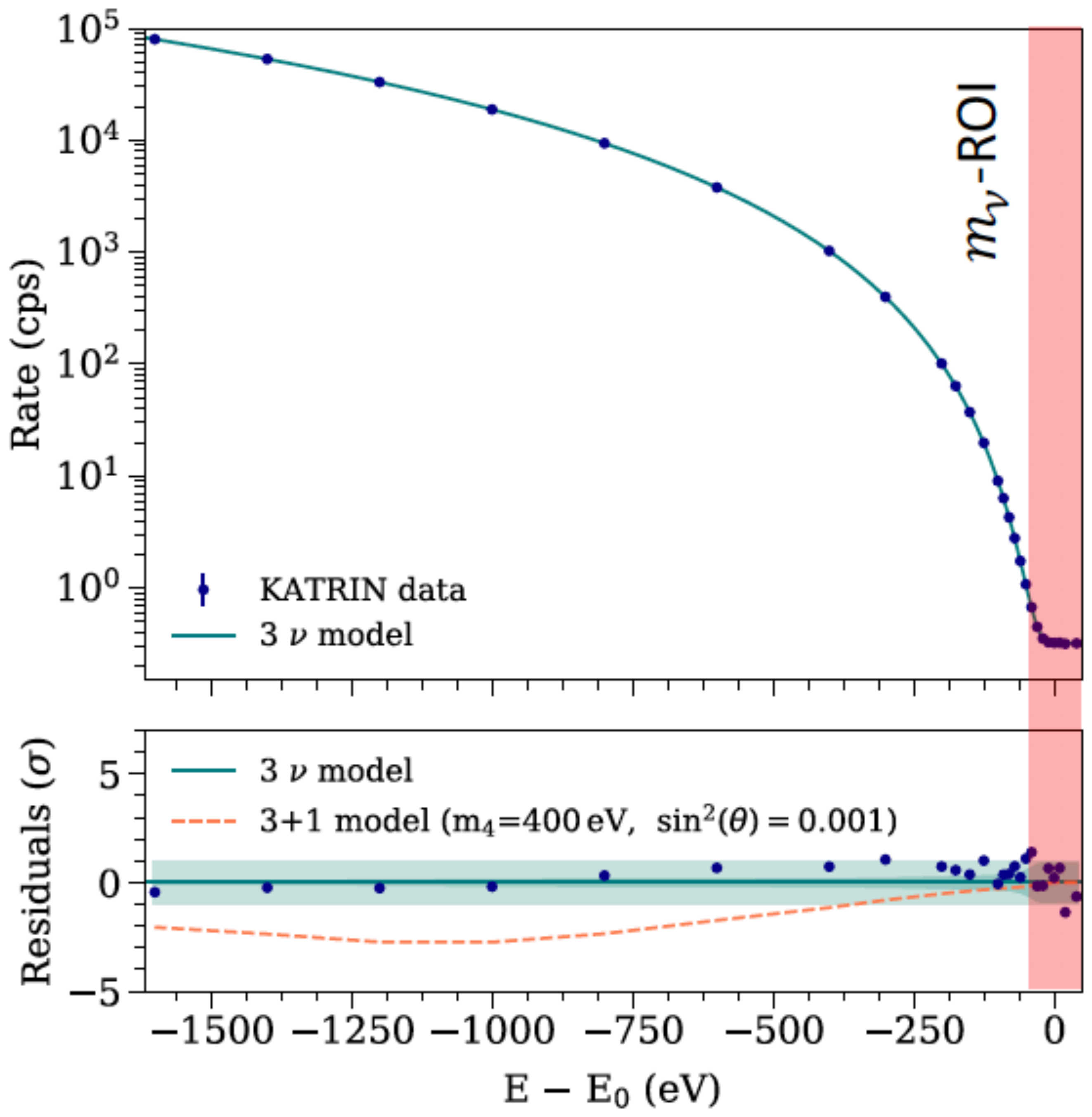
keV sterile neutrinos





Mertens et al, JCAP 1502 (2015)
Mertens et al, J. Phys. G46 (2019)

T. Houdy et al



Proof of principle: Deep scan (1.6 keV below E_0) with low-activity commissioning data

✓excellent agreement of model and data (p-value = 0.6)

✓sensitivity to $\sin^2\theta < 10^{-3}$ @ m_4 = 0.4 keV

Future: Novel multi-pixel Silicon Drift Detector array (TRISTAN)

✓high-statistics search

✓target sensitivity of $\sin^2\theta < 10^{-6}$

Mertens, Neutrino 2020 LOI

Outlook

- 19 LOIs, a vibrant field of small and medium-scale experiments
- complementary to other sterile searches, potential to address open questions about reactor anomaly and spectrum
- **potential for discovery science**
- range of technologies at different stages of developments, **running and proposed experiments in next 5-8 years, opportunities for R&D and training**
- capitalize on existing investments and leverage unique US facilities
- fundamental and applied physics goals, cross-disciplinary opportunities between HEP and other DOE offices