Prospects for new eV-scale sterile neutrino searches

JUNO-TAO, PROSPECT-II, and IsoDAR

Josh Spitz (U. Michigan) and Daniel Winklehner (MIT), 5/31/2022

Outline

- The eV-scale sterile neutrino landscape
- Motivating electron-flavor disappearance searches
- Future experimental prospects
  - JUNO-TAO
  - PROSPECT-II
  - IsoDAR

I would like to start off with a 'Conclusions' slide (taken from my talk at Neutrino 2014; "Future short-baseline sterile neutrino searches with accelerators").

Taken from my talk at Neutrino 2014; "Future short-baseline sterile neutrino searches with accelerators".

Conclusions

- **The discovery of a light sterile neutrino would be a monumental result for particle physics and cosmology.**

- The light sterile neutrino issue needs to be resolved.

- A truly definitive resolution is difficult to achieve and will likely require multiple detectors/experiments.

- Regardless if there is a sterile neutrino or not, a lot of important physics and R&D can be provided by accelerator-based short-baseline experiments.

Taken from my talk at Neutrino 2014; “Future short-baseline sterile neutrino searches with accelerators”.

Conclusions

- **The discovery of a light sterile neutrino would be a monumental result for particle physics and cosmology.**

Unfortunately, (8 years later) the experimental situation is more complicated than ever, and a brief summary of the situation remains the same:

Anomalies remain, null results remain. The worldwide pursuit of understanding this physics is stronger than ever, but truly definitive experiments are extremely difficult to achieve.

physics and R&D can be provided by accelerator-based short-baseline experiments.

What have we learned in the past decade?

- Less than half of the MiniBooNE excess is due to electron neutrinos (MicroBooNE).
- Long baseline and atmospheric experiments see no muon-flavor disappearance (NOvA, MINOS, T2K, Super-K), except maybe IceCube.
- 3+1 sterile oscillations are effectively ruled out in consideration of global data.
  - But, there are some viable alternatives (e.g. 3+1+decay).
- Reactor flux modeling is hard (see: 5 MeV bump). An evolving situation!
  - No evidence of reactor anomaly (rate-only) with recent U235/Pu239 ratio.
  - No single reactor experiment sees spectral oscillations at $>3\sigma$.
- Less room for steriles in tritium and cosmology measurements.
- Gallium anomaly confirmed with a modern experiment (BEST, $4\text{-}5\sigma$).

The short-baseline anomalies represent one of the most important indications of new physics we have.

But, the situation is complicated and confusing.

Is this new physics or not?

Answering this question requires multiple experiments, including with muon and electron flavor and with appearance and disappearance!

Motivating electron-flavor disappearance searches

If **more than one** of the anomalies are due to some kind of **consistent underlying new physics**, it is likely that sterile oscillations are involved.

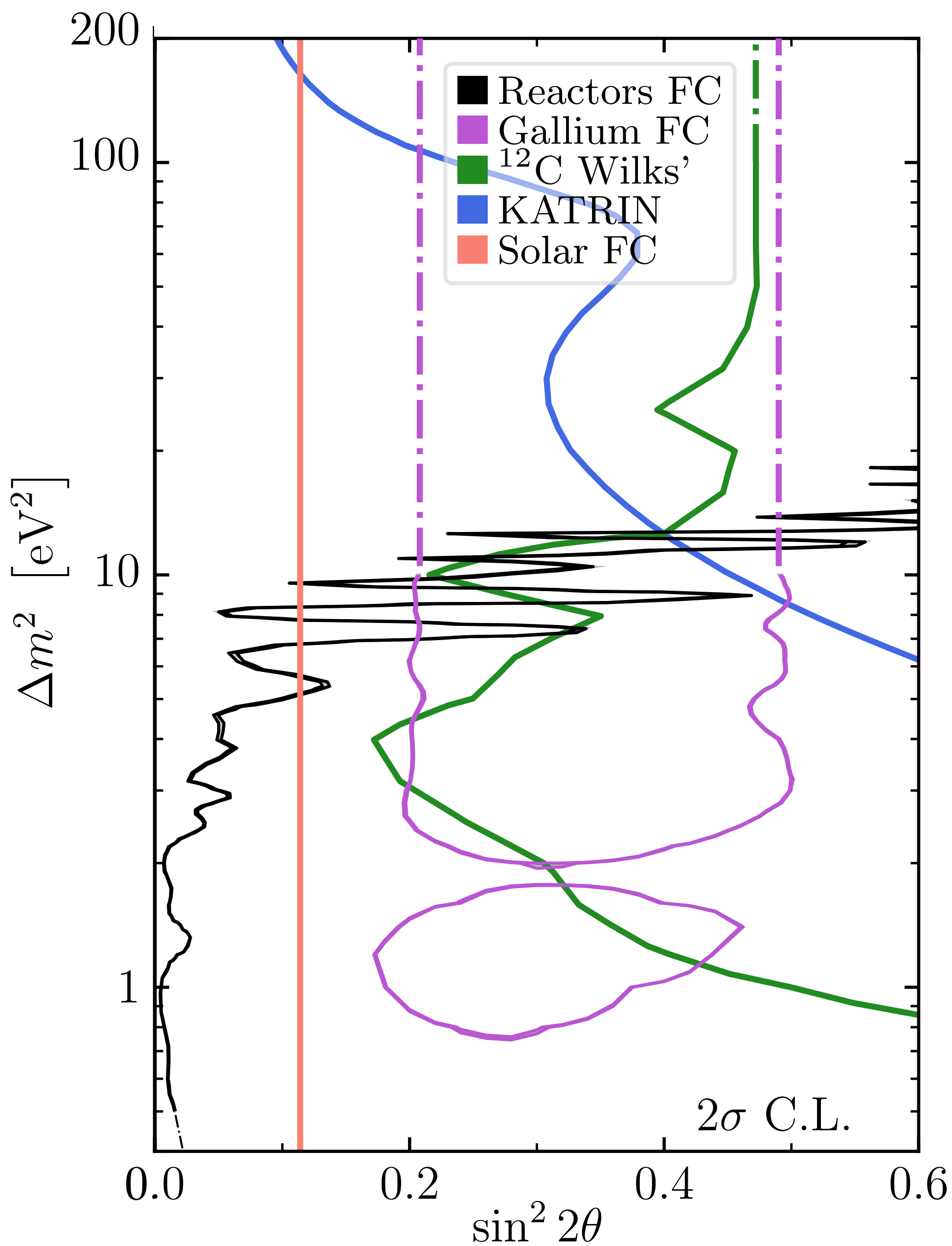
Reactor and source experiments are uniquely sensitive to the sterile hypothesis, without (many) complications from other new physics possibilities.

Category	Model	Signature	Anomalies: LSND	MiniBooNE	Reactor	Gallium
Flavor Conversion: Transitions	(3+1) oscillations	oscillations	✓	✓	✓	✓
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓
	(3+1) w/ sterile decay	$\nu_4 \to \phi \nu_e$	✓	✓	✓ (partial)	✓ (partial)
Flavor Conversion: Matter Effects	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓ (partial)	✓ (partial)
Flavor Conversion: Flavor Violation	lepton-flavor-violating μ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	✓	✗	✗	✗
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e \phi A$	✓	✓	✗	✗
Dark Sector: Decays in Flight	transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗
	dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗
Dark Sector: Neutrino Scattering	neutrino-induced up-scattering	$\nu A \to NA$, $N \to \nu e^+e^-$ or $N \to \nu\gamma\gamma$	✓ (partial)	✓	✗	✗
	neutrino dipole up-scattering	$\nu A \to NA$, $N \to \nu\gamma$	✓ (partial)	✓	✗	✗
Dark Sector: Dark Matter Scattering	dark particle-induced up-scattering	γ or e^+e^-	✗	✓	✗	✗
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗

✓– the model can naturally explain the anomaly, ✓– the model can partially explain the anomaly, ✗– the model cannot explain the anomaly.

"White Paper on Light Sterile Neutrino Searches", arXiv:2203.07323

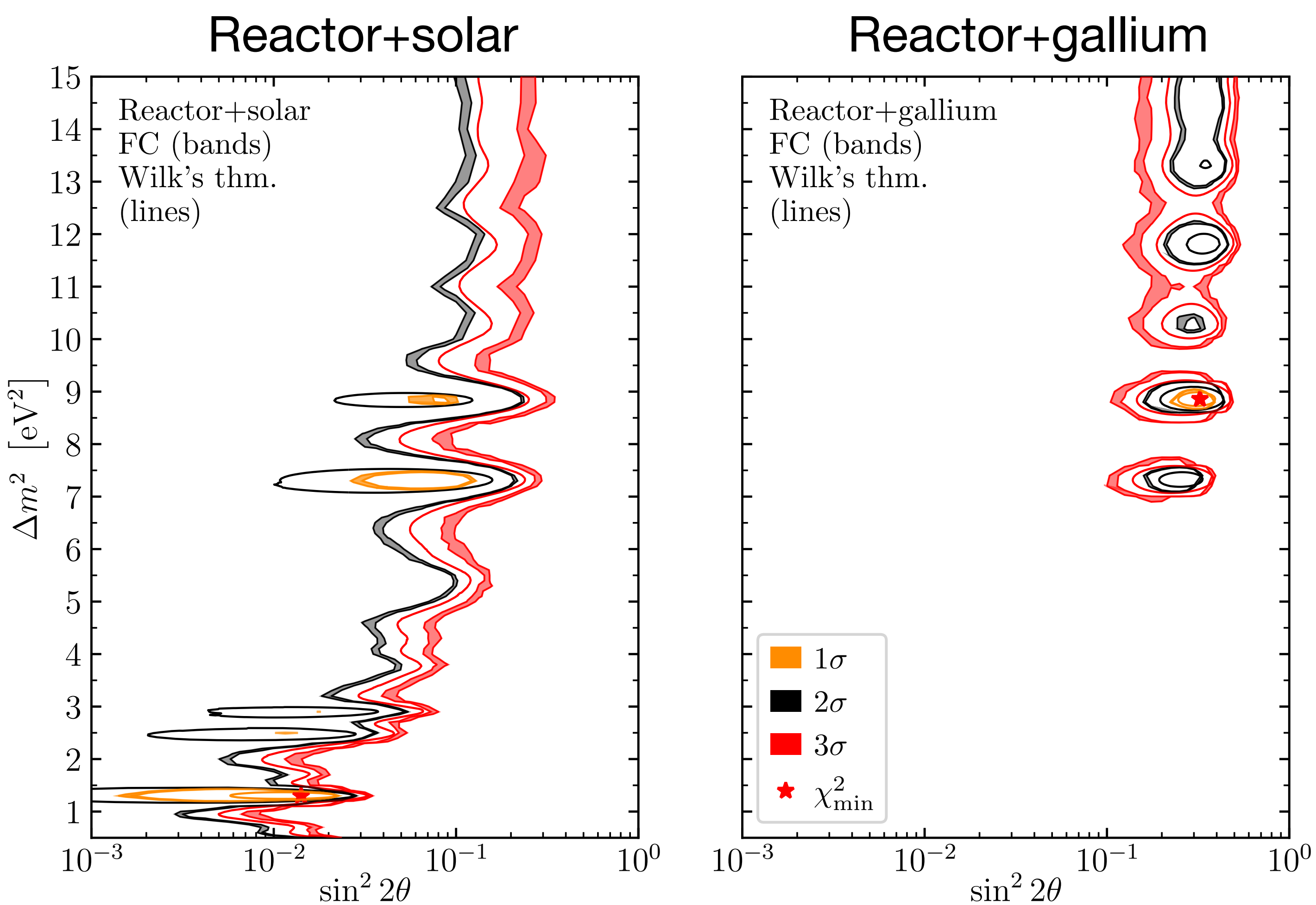
Latest electron-flavor global sterile results



For >2σ CL, the only closed contour is gallium.
But, it's ~5σ and not in conflict with reactors for some parameter space.

Berryman, Coloma, Huber, Schwetz, Zhou; arXiv:2111.12530

Latest electron-flavor global sterile results



Note: Solar and gallium not combined due to strong tension

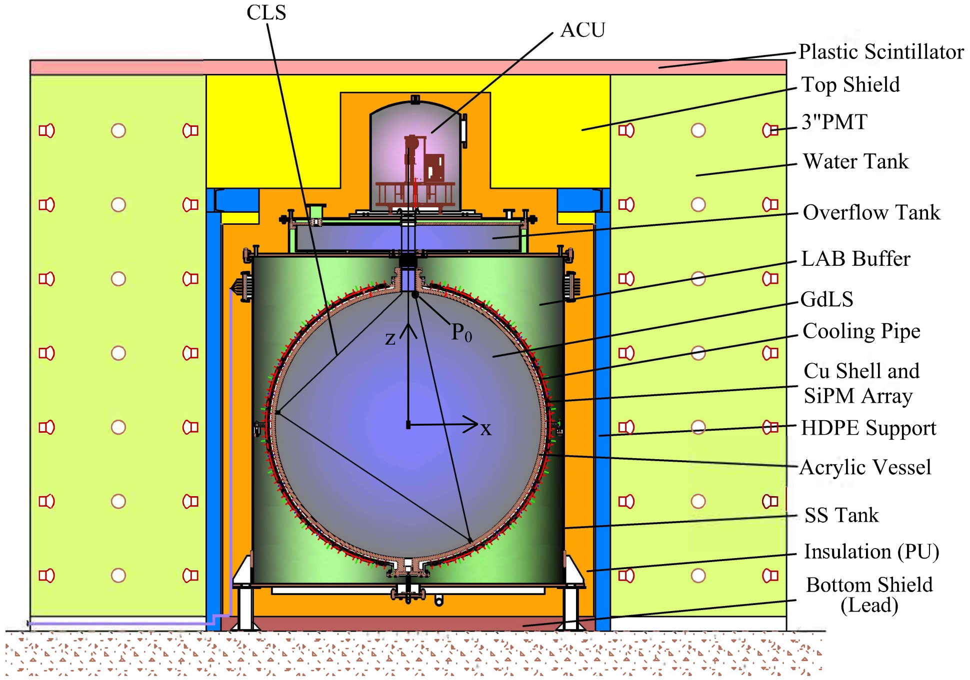
Overall conclusions:

-Electron-flavor anomaly is now driven by Gallium (~5σ BEST result).
-Large portions of parameter space are found to be in mutual agreement for Gallium+reactors.
-Reactor anomaly (rate) is gone and each individual reactor spectral analysis is <3σ, with strongest hint coming from Neutrino-4.
-Solar neutrino experiments are in tension at the ~3σ level.

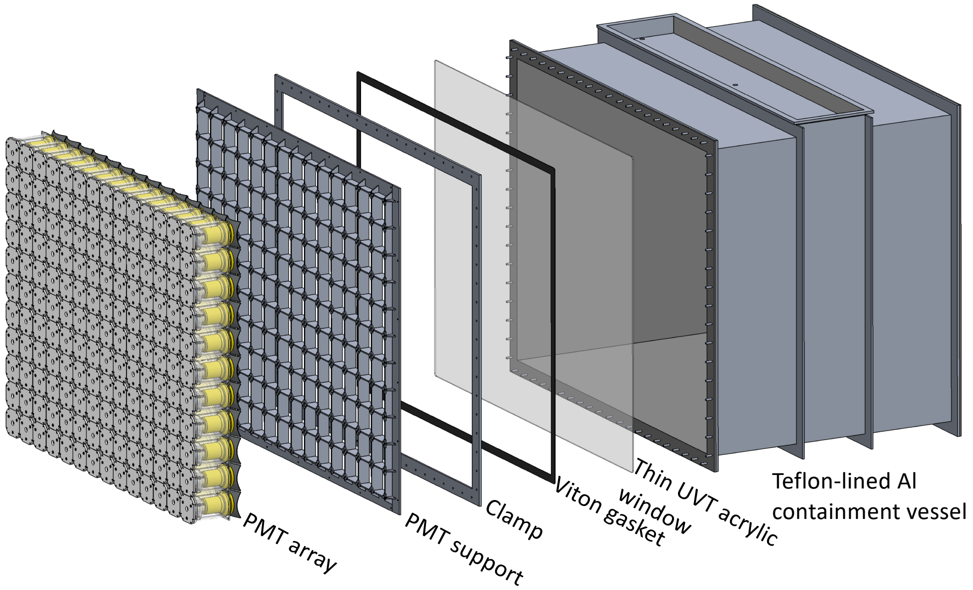
Berryman, Coloma, Huber, Schwetz, Zhou; arXiv:2111.12530

Experiments covered in this talk

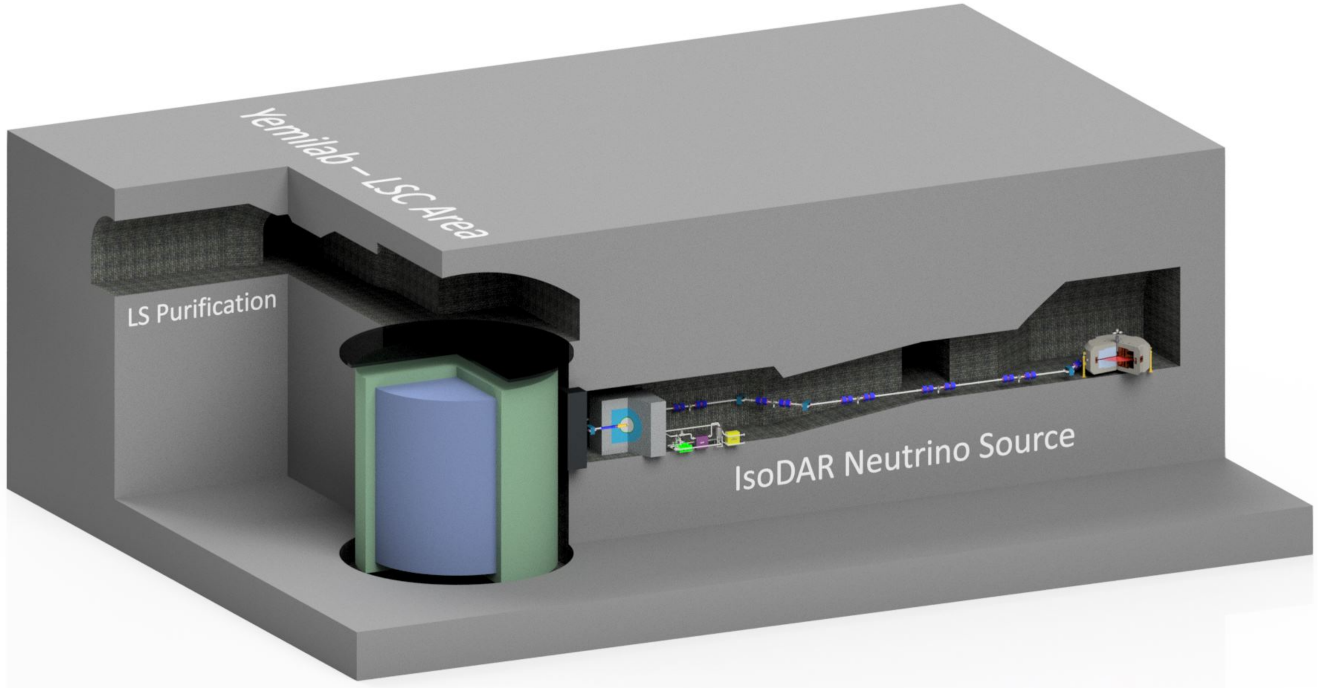
(electron-flavor disappearance at short-baseline)



JUNO-TAO (reactor)



PROSPECT-II (reactor)

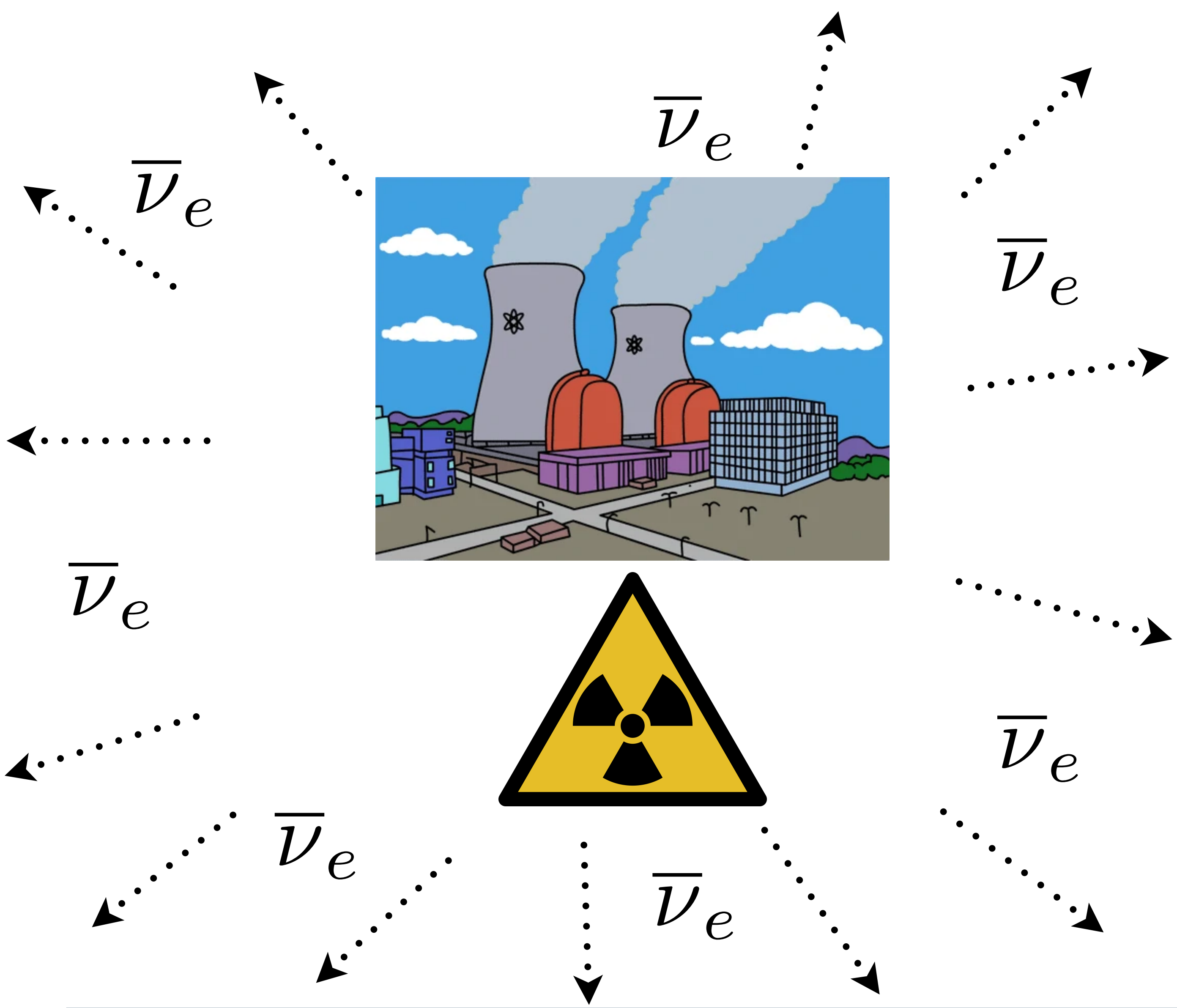


IsoDAR (accelerator-induced source)

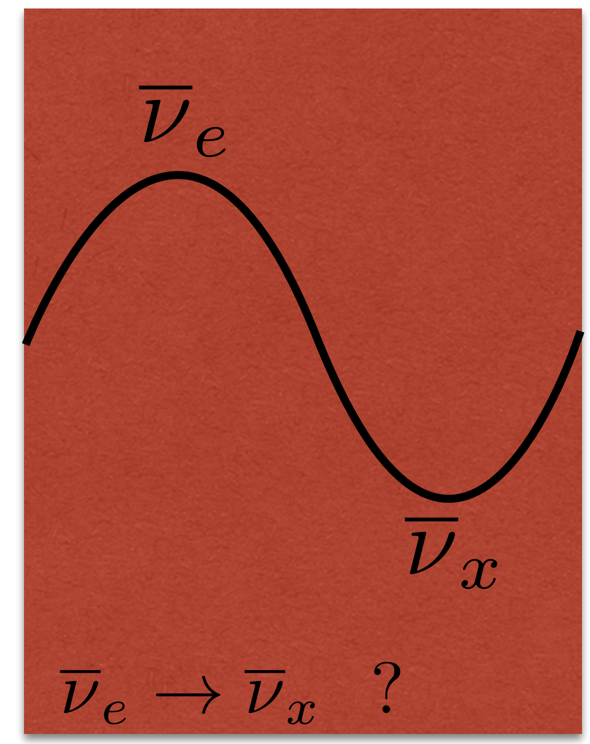
Overarching concept

Intense source of $\overline{\nu}_e$

(reactor or source)



Nearby detector ($\overline{\nu}_e p \to e^+ n$)



Big detector with free protons
(e.g. H_20, CH_2)

Important considerations:
knowledge of flux, energy and baseline resolution, signal rate, backgrounds

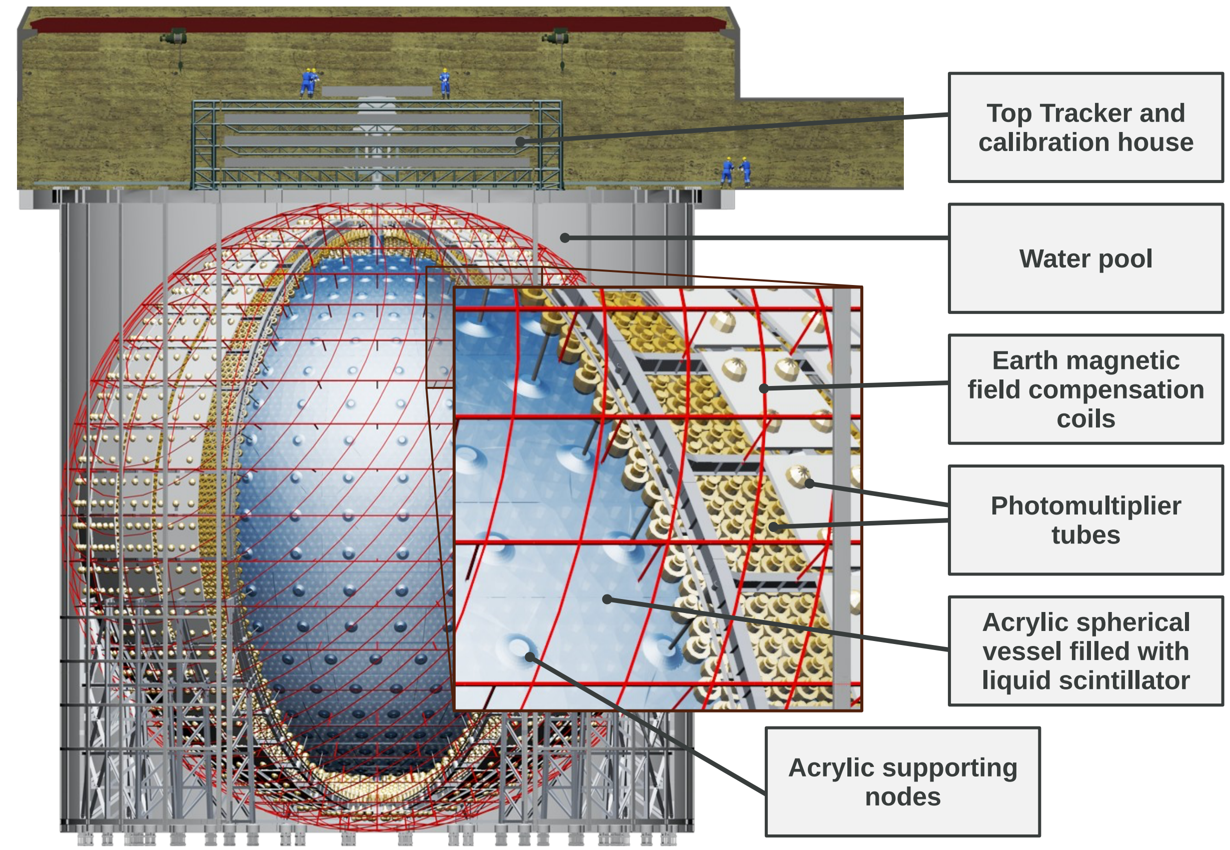
JUNO-TAO (reactor)

JUNO

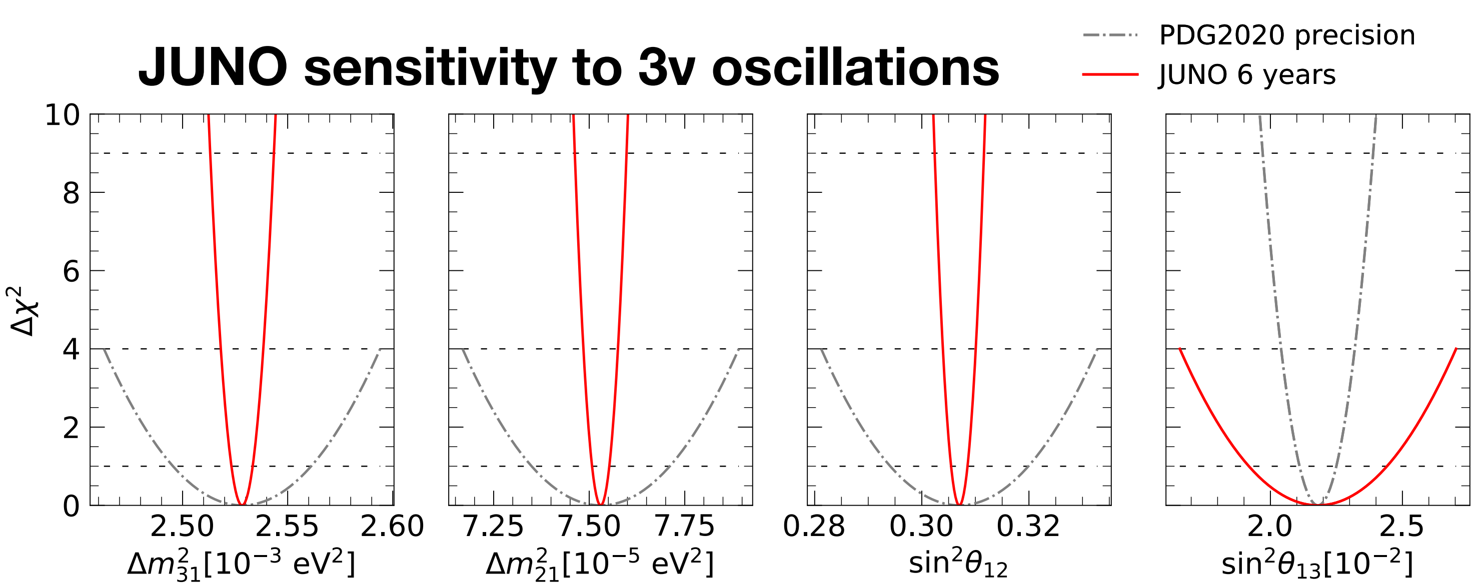
Reactor experiment

- JUNO: the most ambitious reactor experiment ever: 20 kton w/ 78% photocoverage @ 53 km from 26.6 GWth.
- Will utilize a near detector “JUNO-TAO” at 30 m with ultra-high-energy resolution to maximize its sensitivity to oscillations.
    - JUNO-TAO final on-site assembly/ installation in 2022.

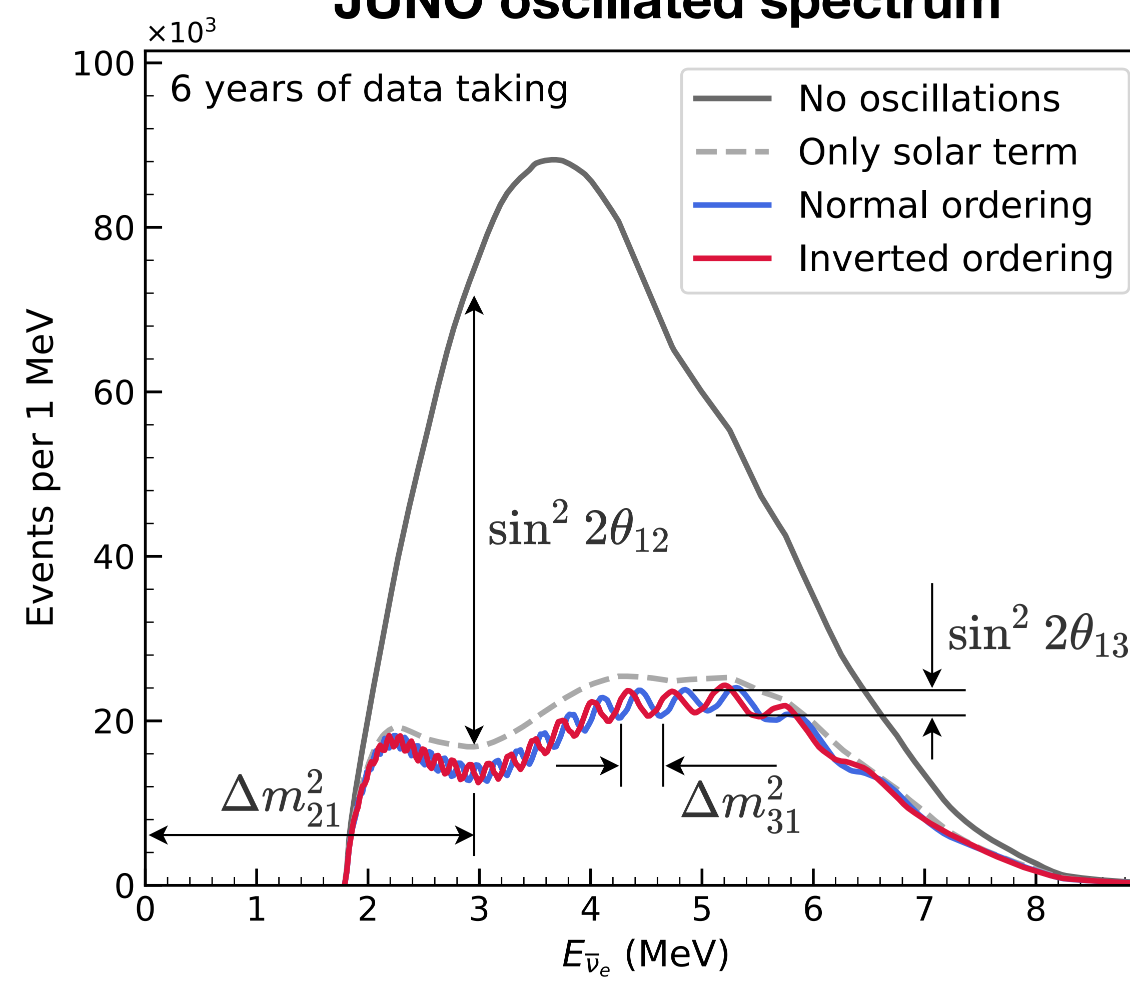
JUNO detector



JUNO sensitivity to 3ν oscillations



JUNO oscillated spectrum

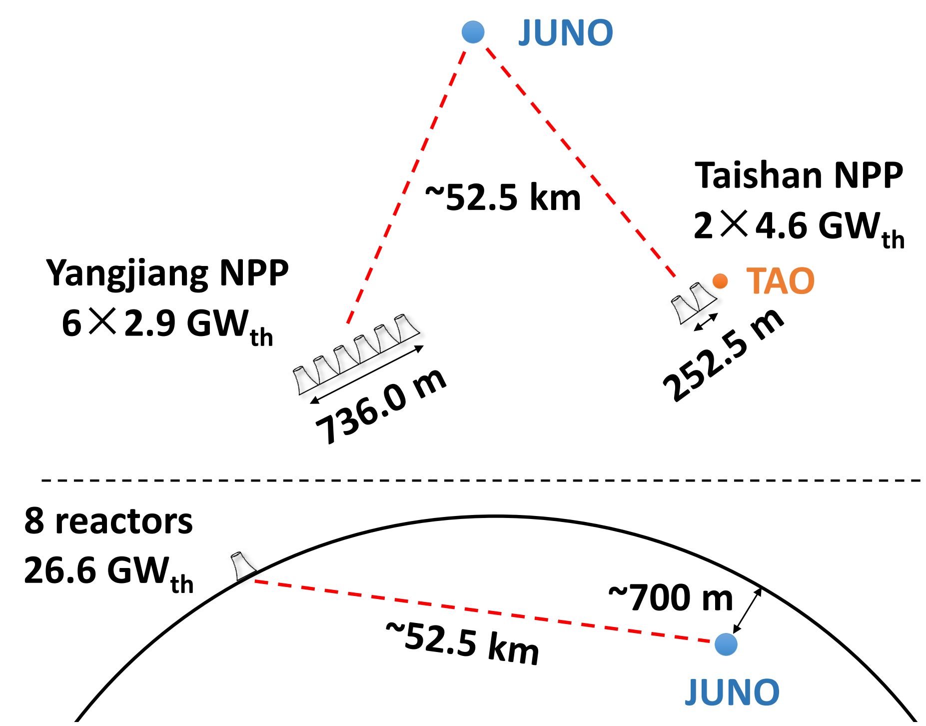


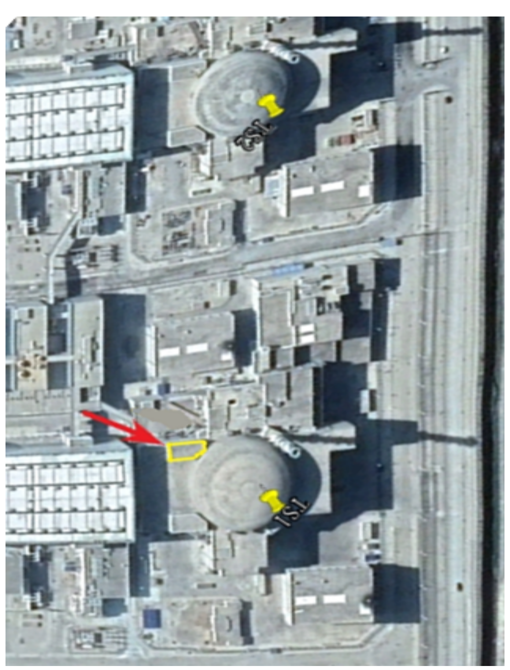
JUNO, arXiv:2204.13249

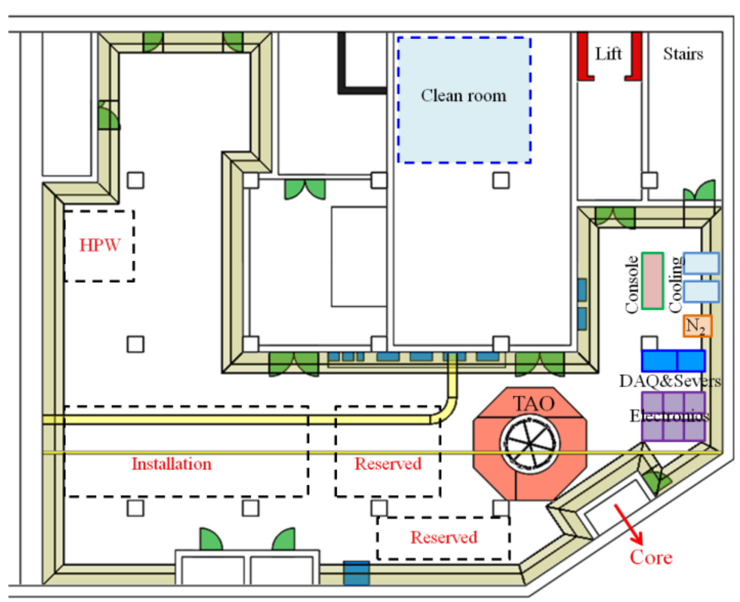
JUNO-TAO

A near detector for JUNO

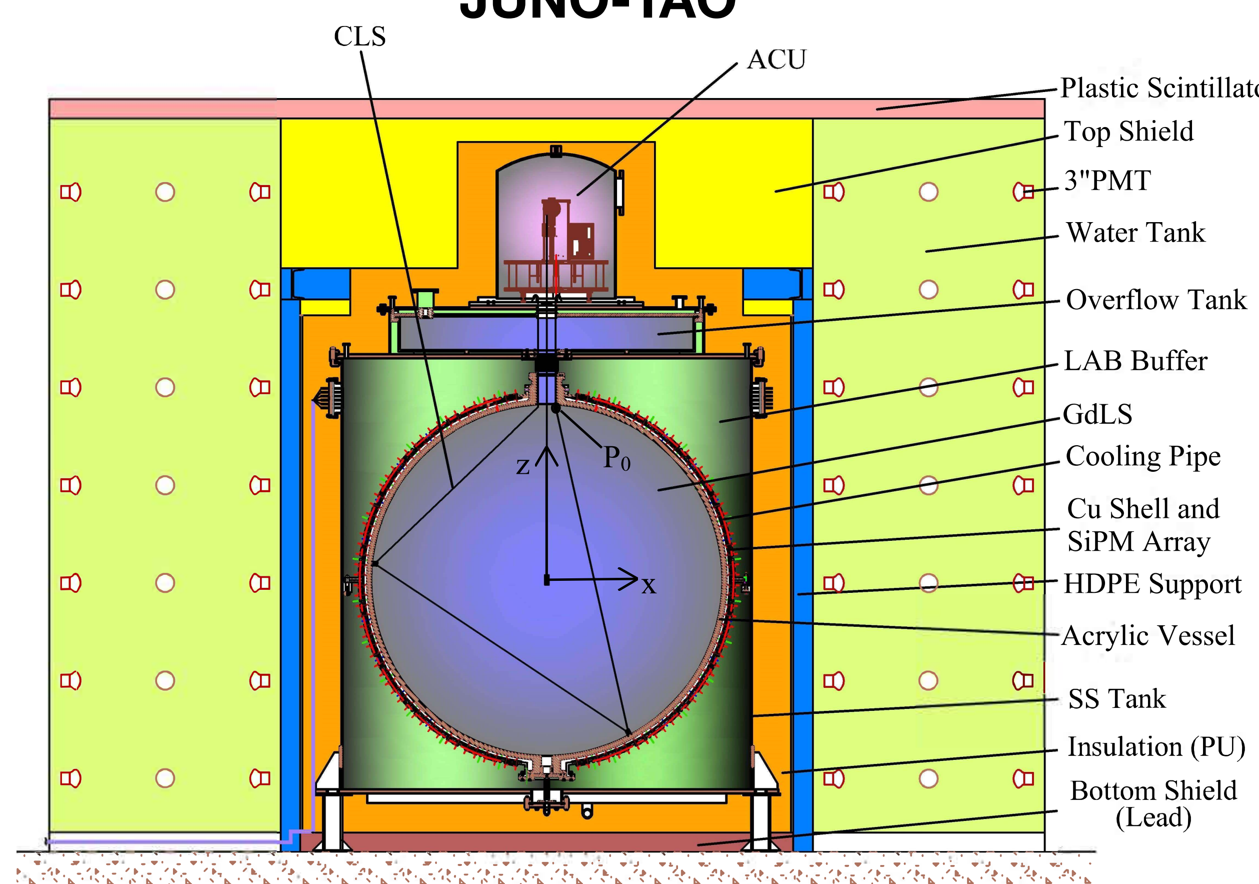
- JUNO-TAO: 2.8 ton (1 ton fiducial volume) GdLS @ 30 m baseline from one core (4.6 GWth) of the Taishan NPP.
- Detector is in a basement, 9.6 m underground.
- Will provide:
    - Reference spectrum for JUNO.
    - Sensitivity to nuclear reactor spectrum fine structure.
    - Sterile oscillation sensitivity.







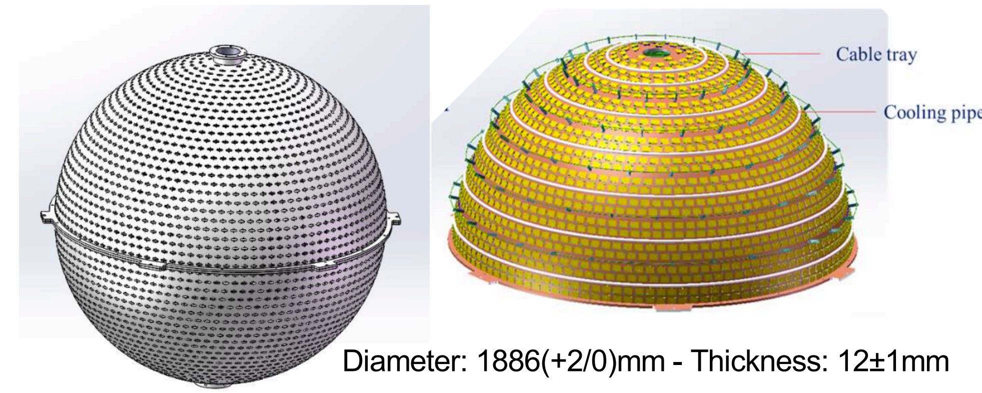
JUNO-TAO



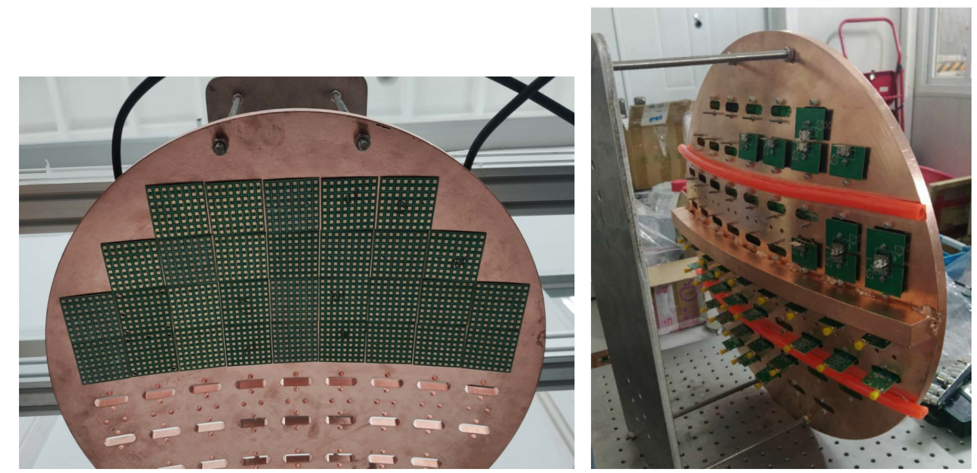
JUNO-TAO CDR, arXiv:2005.08745

JUNO-TAO

Energy resolution



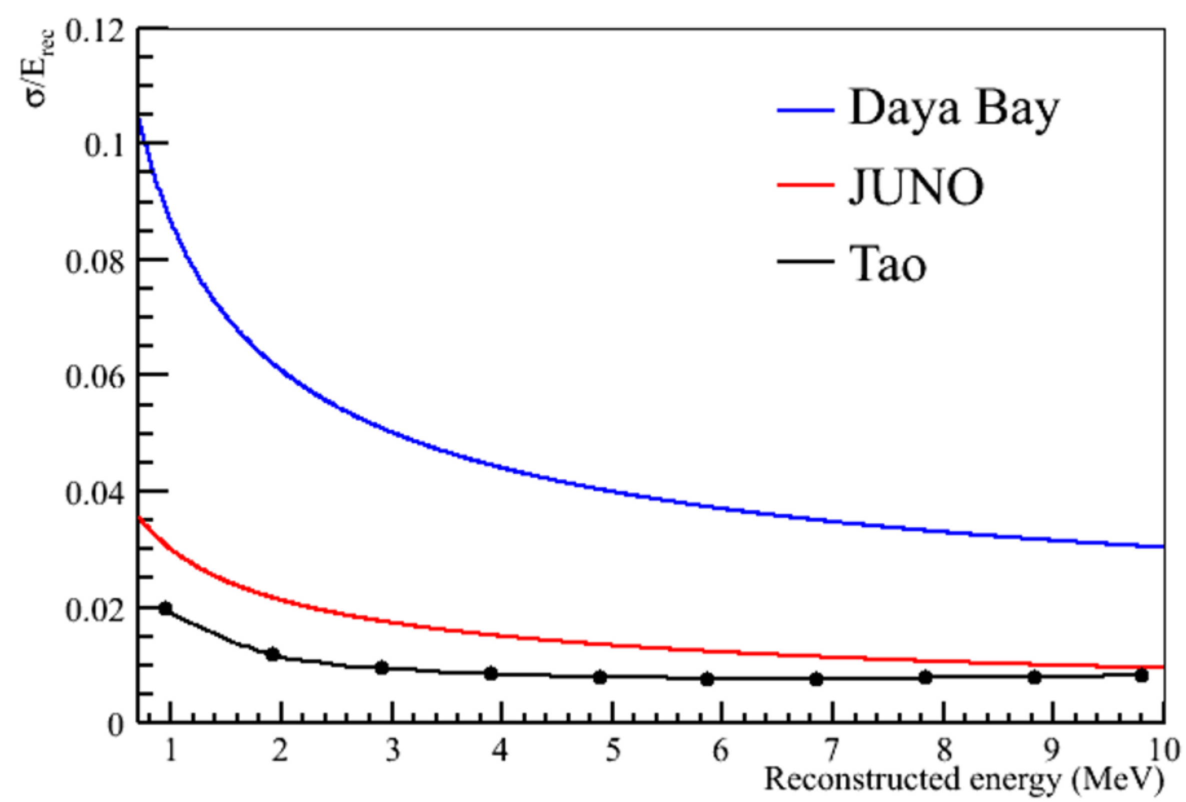
Diameter: 1886(+2/0)mm - Thickness: 12±1mm



~5x5 cm^2 SiPM tiles arrangement optimized → 4024 tiles, ~94% coverage

F. Petrucci, NeuTel 2021

- Sub-2% energy resolution at all energies!
  - LS light yield: 4500 p.e./MeV.
  - 10 m^2 SiPMs (94% coverage) with 50% photon detection efficiency, operated at -50^o C to reduce dark noise.



JUNO-TAO CDR, arXiv:2005.08745

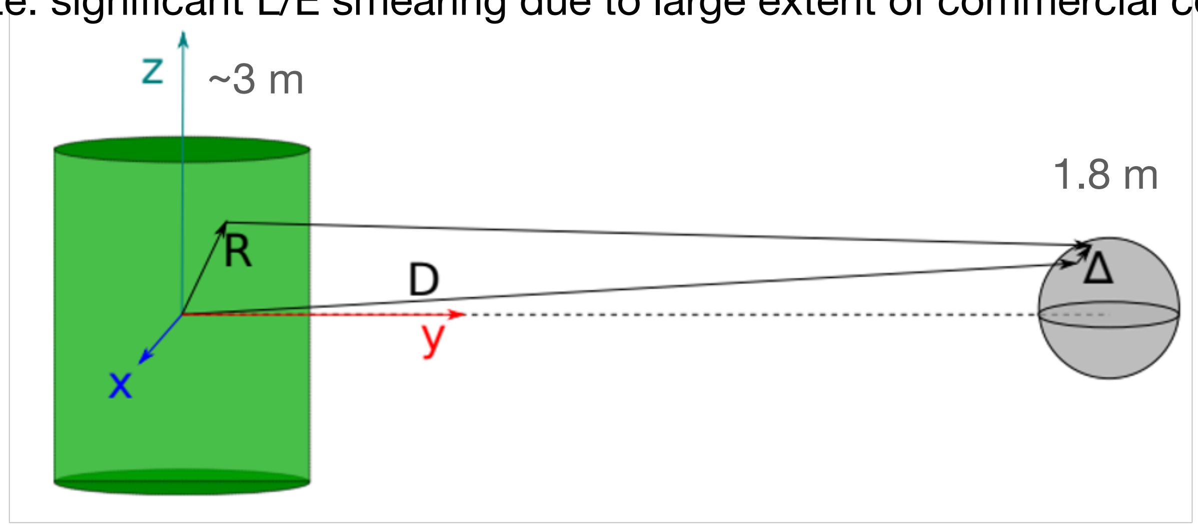
JUNO-TAO

Sterile oscillation sensitivity

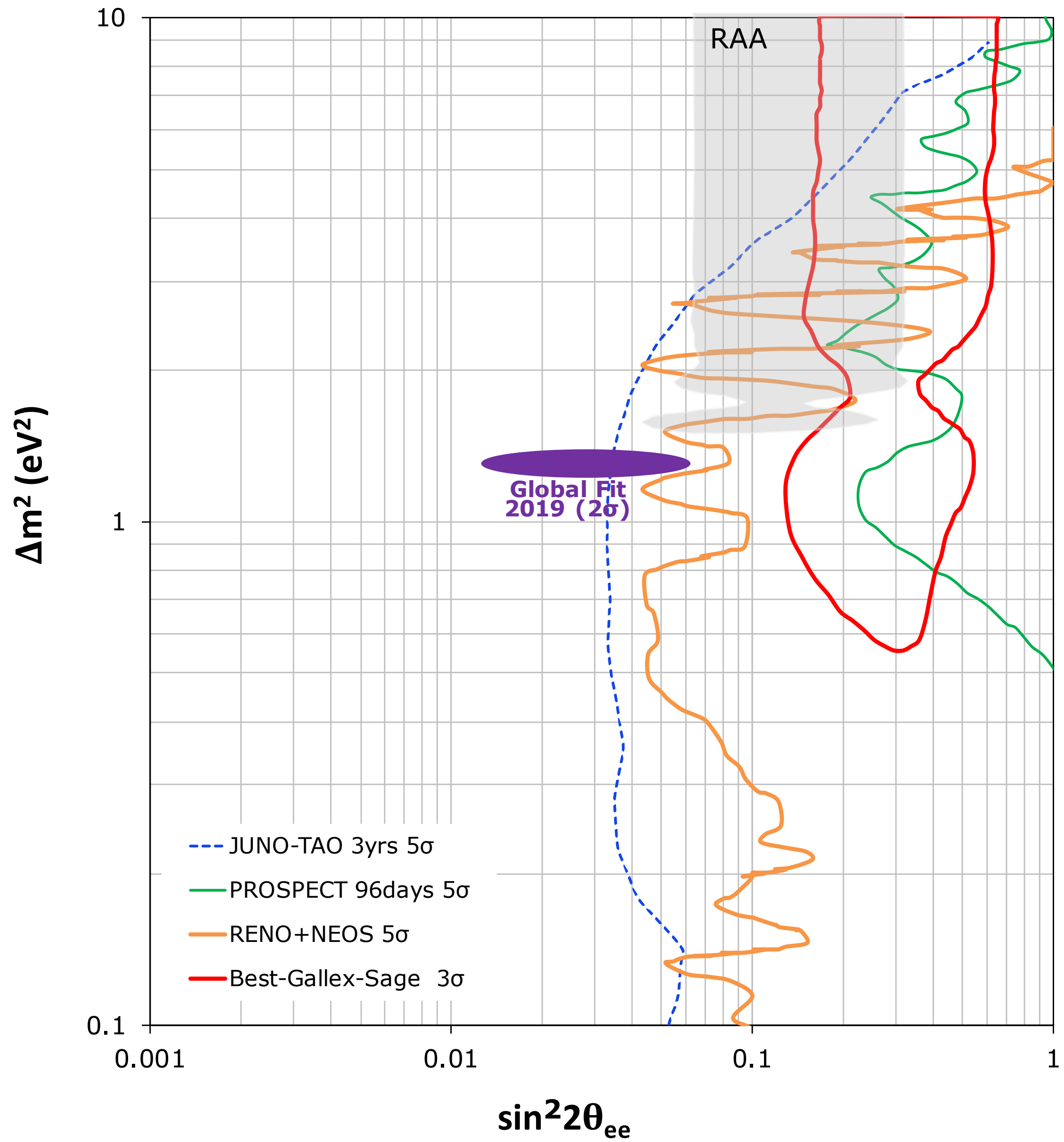
- JUNO-TAO will provide world leading reactor-based sterile oscillation sensitivity.

IBD signal	2000 events/day
Muon rate	70 Hz/m^2
Fast neutron background before veto	1880 events/day
Fast neutron background after veto	$<$ 200 events/day
Singles from radioactivity	$<$ 100 Hz
Accidental background rate	$<$ 190 events/day
$^{8}He/^{9}Li$ background rate	$\sim$ 54 events/day

Note: significant L/E smearing due to large extent of commercial core.



3+1 sterile oscillation sensitivity (3 years of JUNO-TAO)



3+1 oscillations assumed:

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L,E) = 1 - 4\sum_{i=1}^{3} |U_{ei}|^2 |U_{e4}|^2 \sin^2 \frac{\Delta m^2_{4i} L}{4E}$$

Next up: Dr. Daniel Winklehner (MIT)

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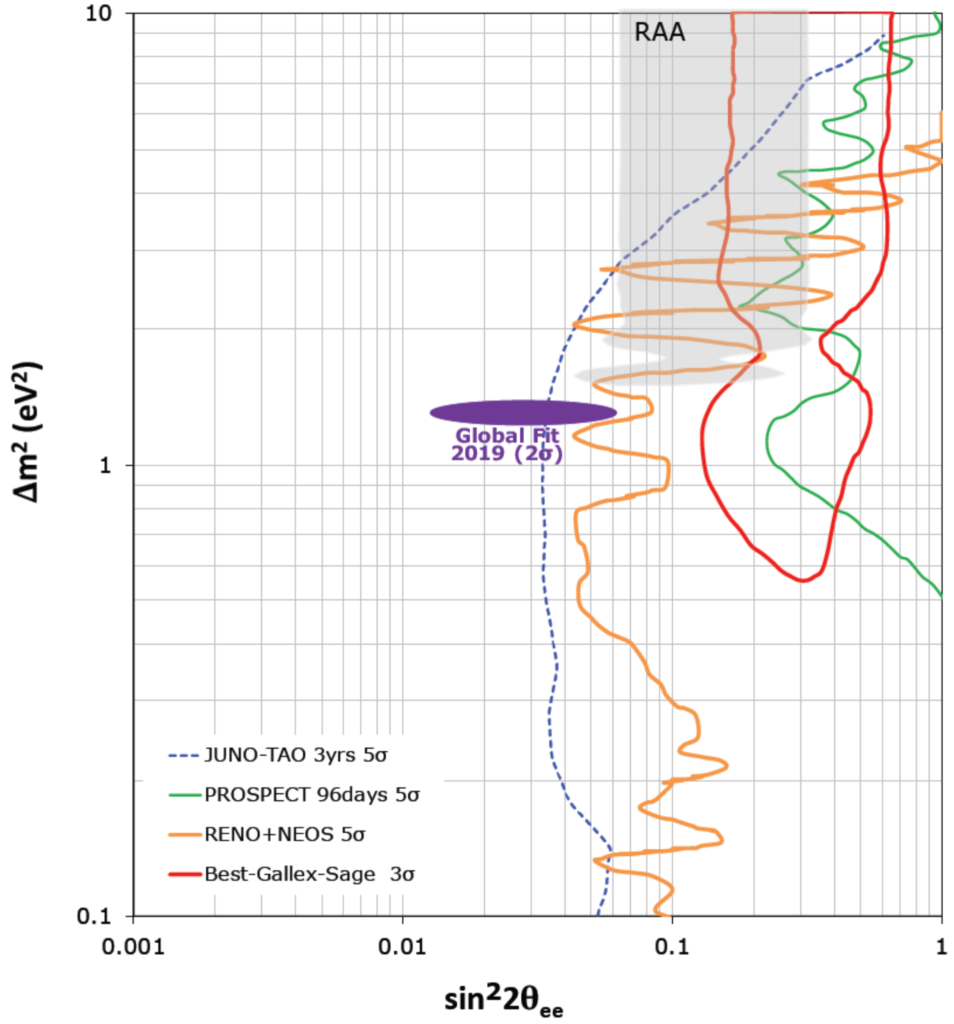
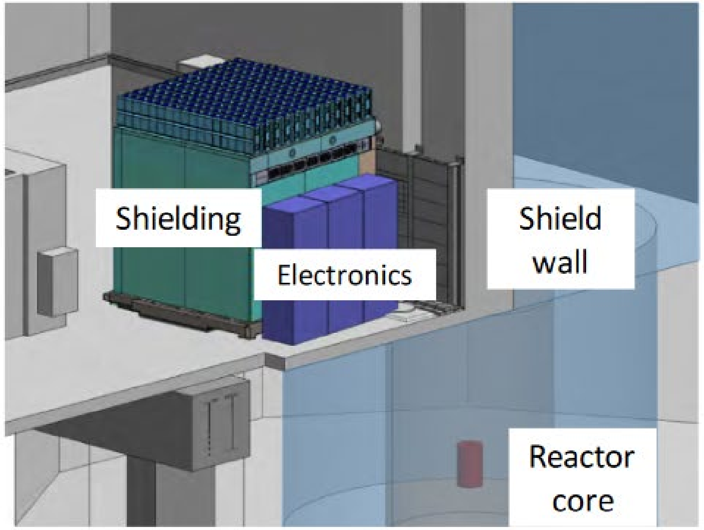
Motivation for PROSPECT-II

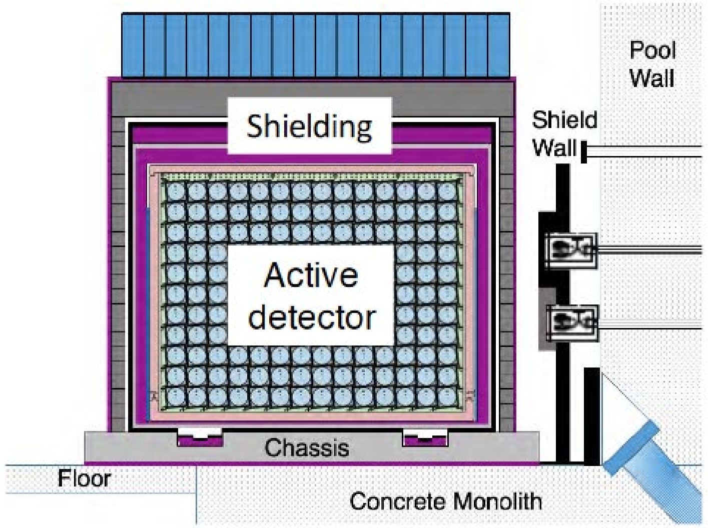
- Probe $\bar{\nu}_e$ disappearance from high Δm^2 sterile neutrinos
- Tests of Gallium Anomaly (GA) with high sensitivity
- Test Reactor Antineutrino Anomaly (RAA)
- PROSPECT provided important results, but suffered from technical issues
  - Loss of active volume due to LiLS entering PMT housings – electronics failures
  - Light yield degradation over time (likely due to LiLS contamination)

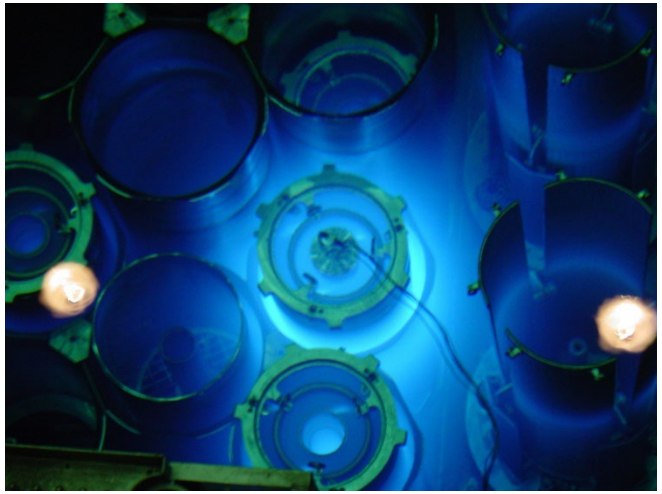


Prospects for new eV-scale sterile neutrino searches

Original PROSPECT Design







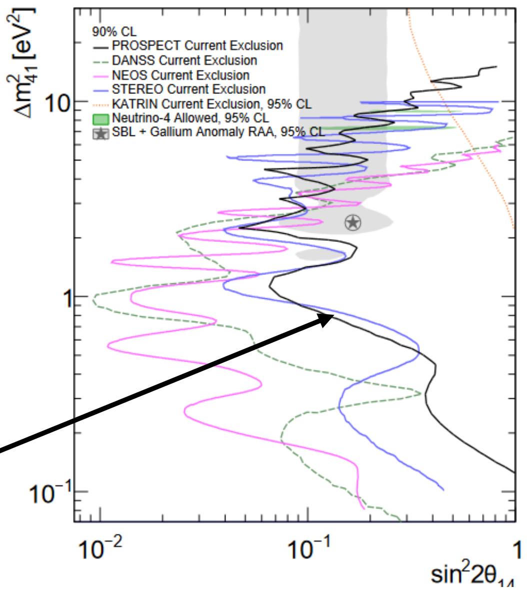
https://arxiv.org/abs/2107.03934

HFIR@ORNL – www.wikipedia.org

- Deployment at High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory – 7.84 m center-to-center
- 4-ton ^{6}Li-doped (0.08% by mass) liquid scintillator (LiLS) – 14 x 11 segments (118 cm long, 14.4 cm x 14.4 cm)
- IBD detection of protons on LiLS – 1.8 MeV threshold
- Prompt (positron annihilation, 1-8 MeV) + delayed (n + ^{6}Li→ α + t + 4.8 MeV)
- excellent PSD provides a distinctive antineutrino signature, greatly suppressing backgrounds

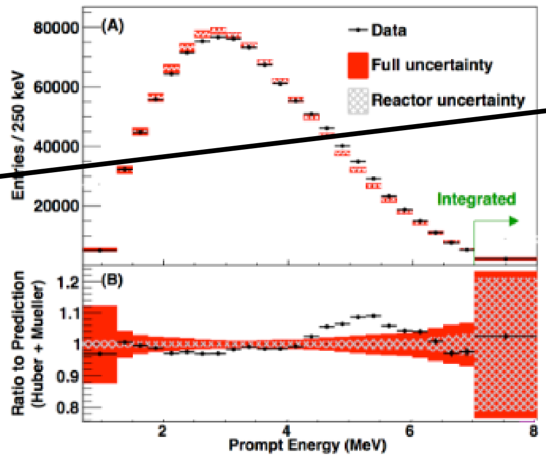
Original PROSPECT Results

- Demonstrated observation of reactor antineutrinos in an aboveground detector
- Good energy resolution and well-controlled backgrounds
- Limits on eV scale sterile neutrinos

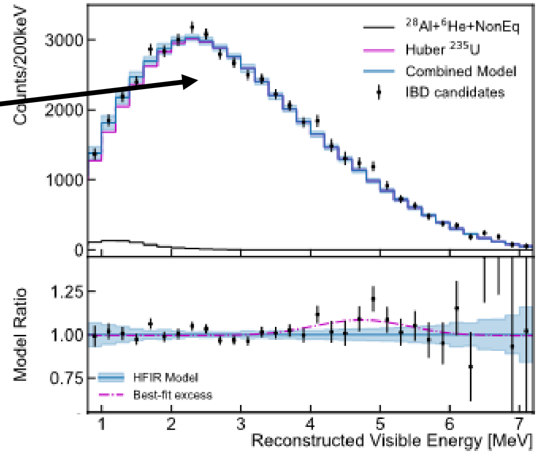


https://arxiv.org/abs/2107.03934

- Precision measurement of the reactor antineutrino spectrum from ^{235}U
- Uranium at least partially responsible for ”bump”?



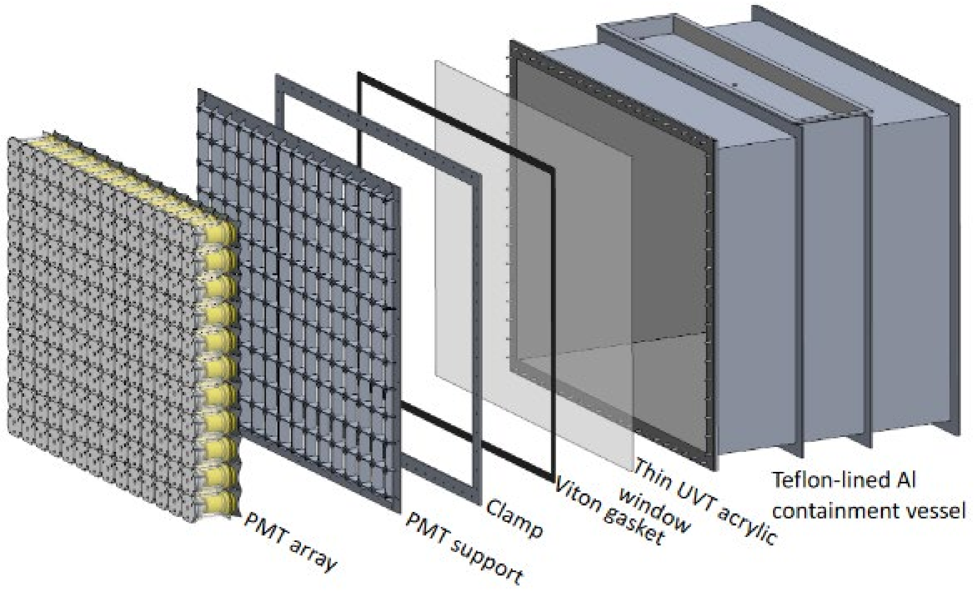
Daya Bay



PROSPECT@HIFR

PROSPECT-II Detector Design

- PROSPECT-II is an upgrade from PROSPECT addressing the challenges
- Unchanged:
  - Background rejection through
    - detector segmentation
    - pulse shape discrimination
  - Segmented ^{6}Li-doped liquid scintillator volume
  - Inverse Beta Decay (IBD) detection
  - Minimal cosmic ray shielding (not needed)



https://arxiv.org/abs/2107.03934

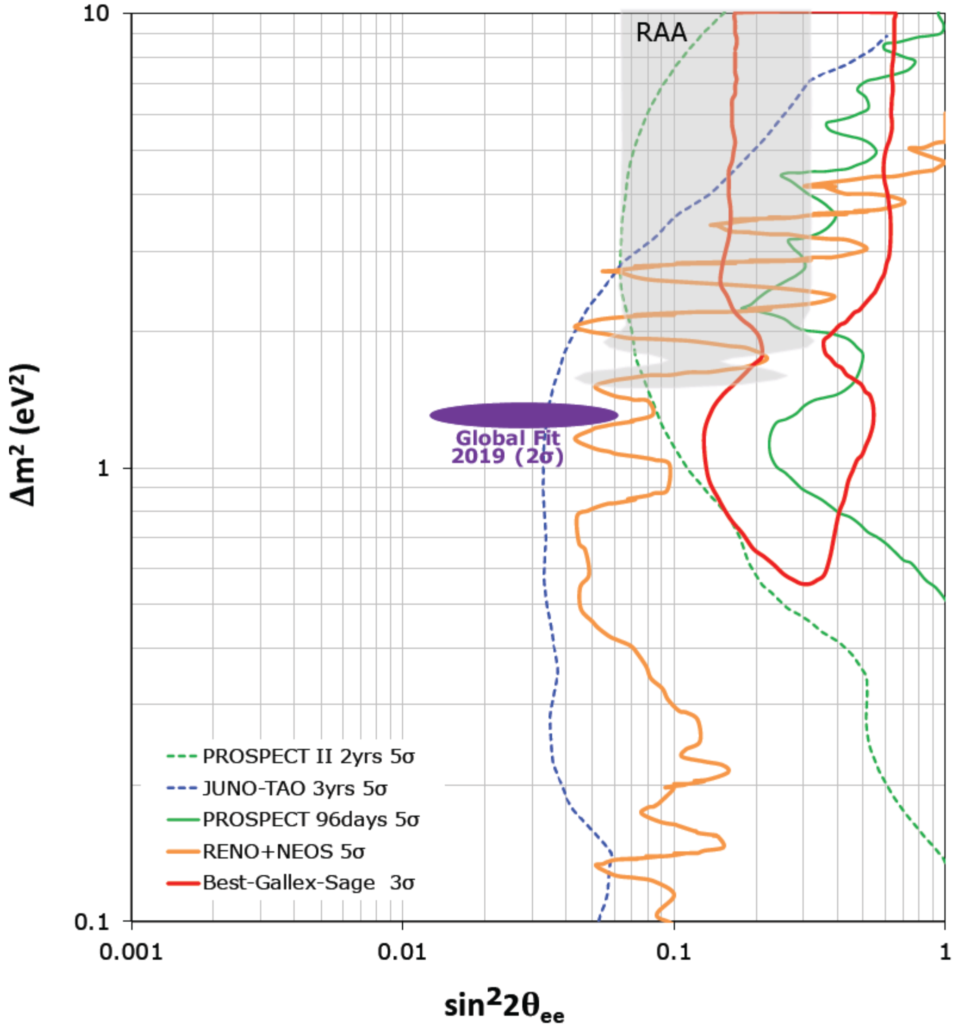
- Principal design change moves the PMTs outside the liquid scintillator volume
- Slightly higher ^{6}Li loading (0.1% by mass)
- Larger segment length of 145 cm → IBD rate increases to roughly 1150/day
- Signal-to-background ratio of 4.3:1

PROSPECT-II Physics

- Two-year deployment at High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory
- Probe Reactor Antineutrino Anomaly (RAA)
- Probe Gallium Anomaly
- Precise measurement of ^{235}U antineutrino spectrum
- Measure the absolute flux of antineutrinos from ^{235}U

PROSPECT-II Sensitivity

- Great reach to high Δm^2
- Covers much of RAA in 2 years of running
- Covers GA up to 10 eV^2



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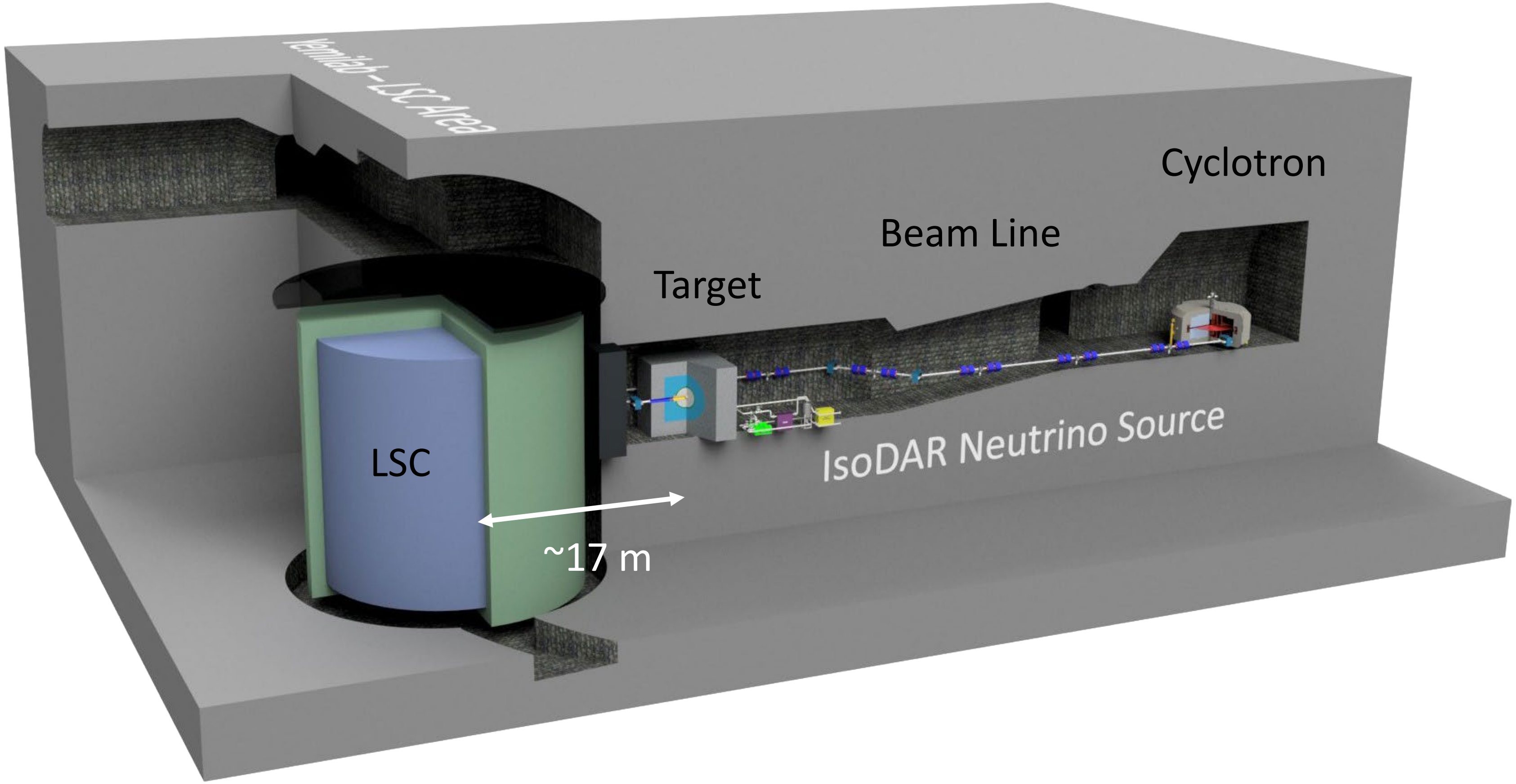
Wishlist for Sterile Neutrino Experiments

- High flux → High statistics
- Continuous operation → High statistics
- Well understood (anti)neutrino spectrum (e.g. from single isotope decay)
- Shape analysis → Distinguish models (3+1, 3+2, decay, wave packet, …)
- Overburden → Background reduction
- Good detector resolution

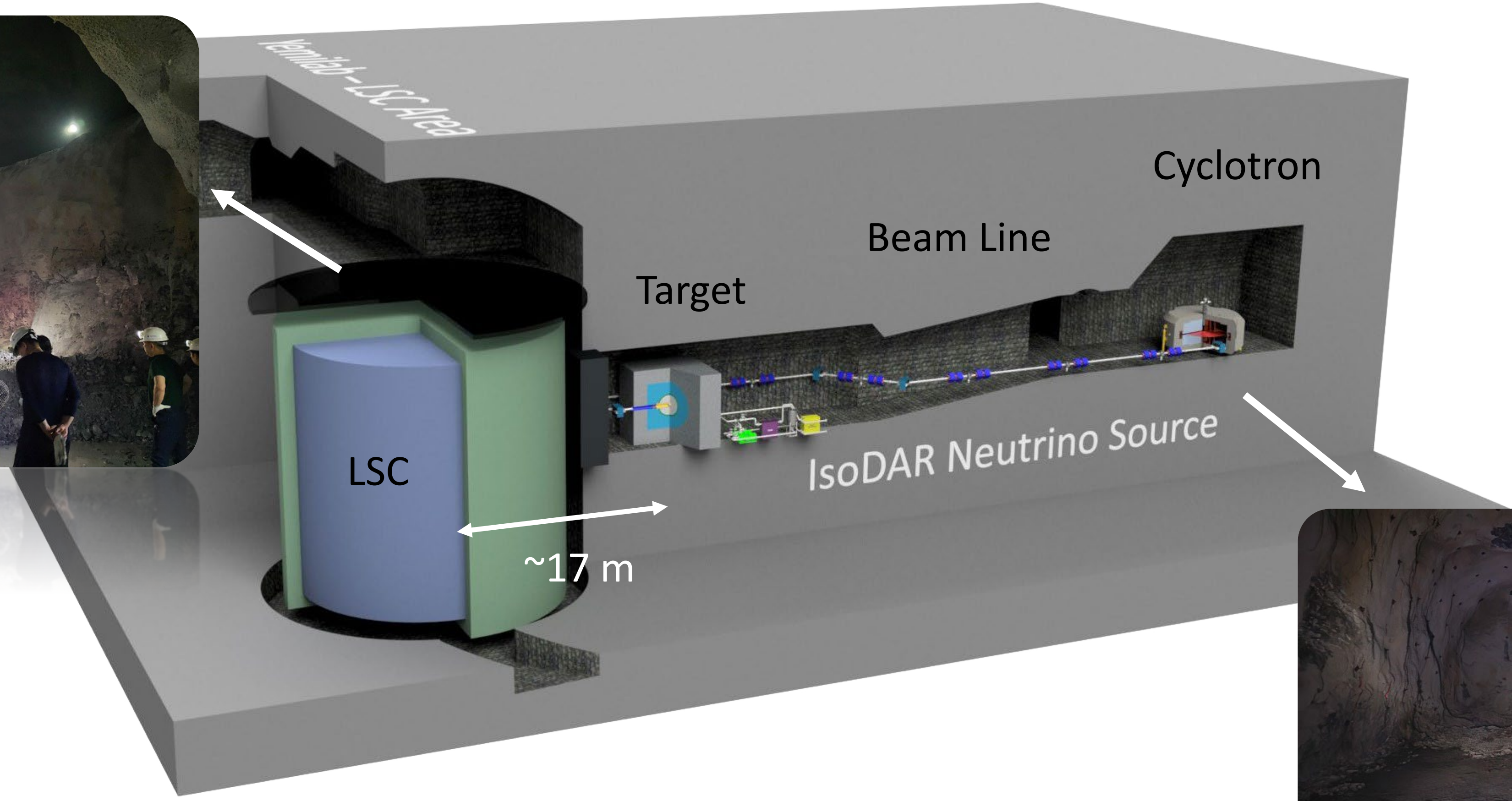
→ Definitive Experiment!

In IsoDAR@Yemilab the source is brought to the detector



- Compact Cyclotron → 10 mA protons @ 60 MeV (10x more current than existing)
- Target → 600 kW power deposited → ~1 mole $\bar{\nu}_e$ produced in 5 years from pure ^{8}Li DAR
- Liquid Scintillator Counter → ~2M Inverse Beta Decay ev., ~7000 $\bar{\nu}_e - e^-$ ES ev.

Pre-approved to run at Yemilab in Korea

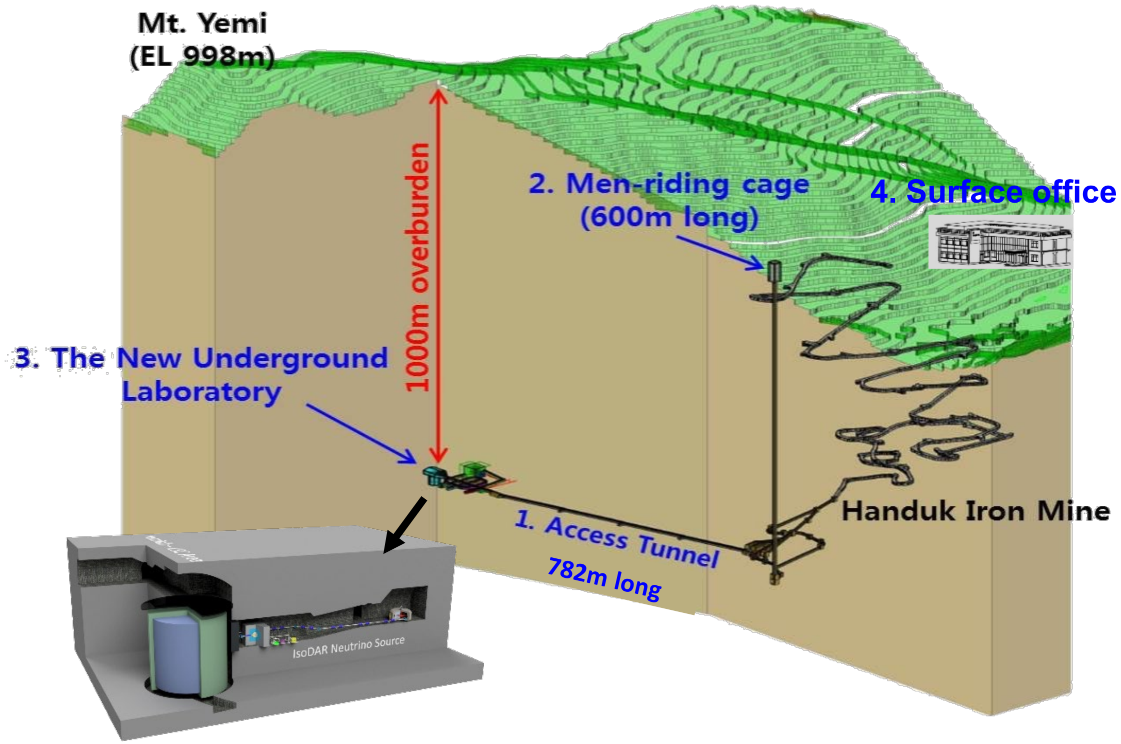


Caverns are already constructed

Physics Paper: http://arxiv.org/abs/2111.09480, PRD 2022
IsoDAR@Yemilab – CDR: http://arxiv.org/abs/2110.10635 arXiv 2021

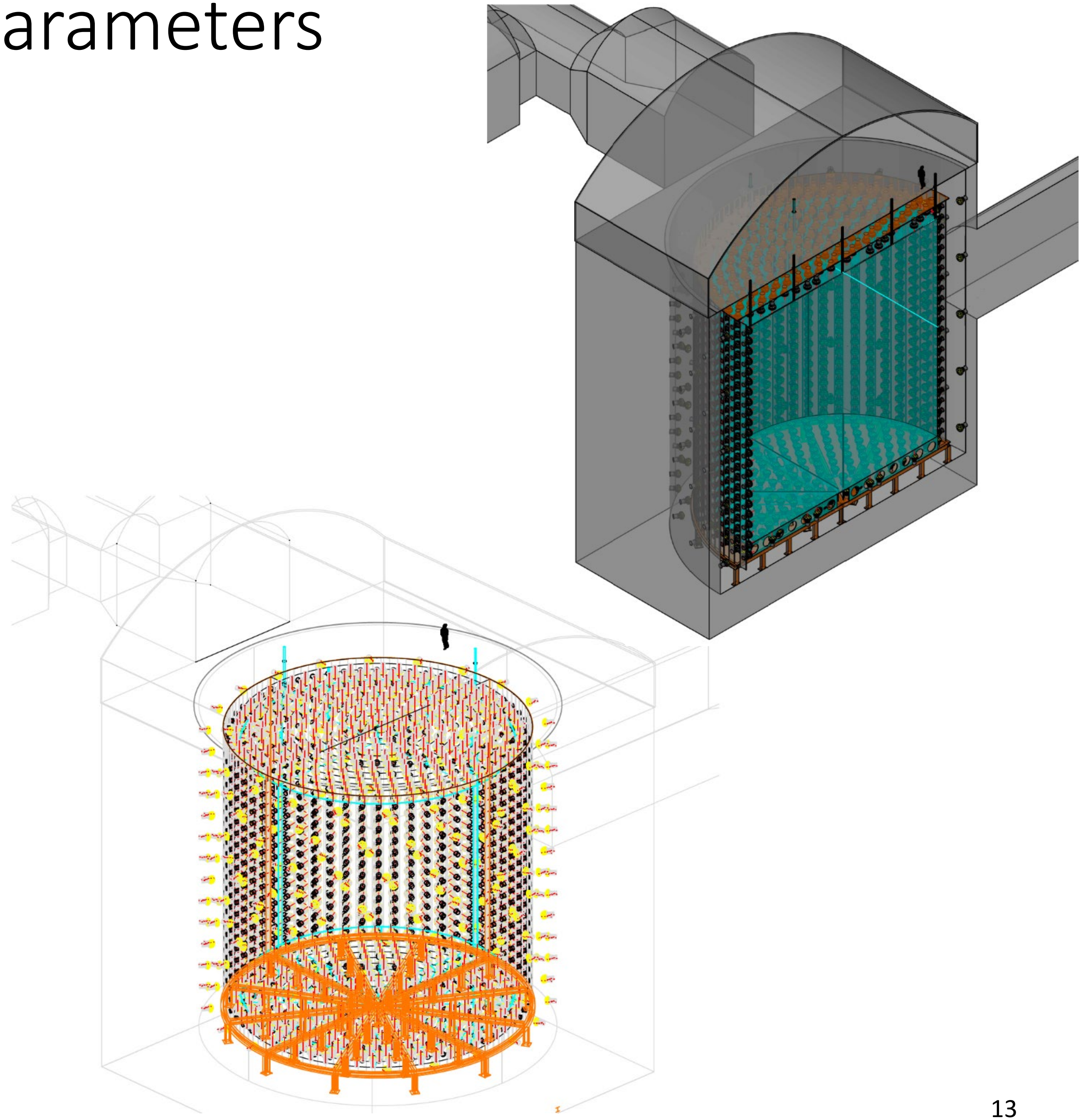
Yemilab

- Underground facility at Mt. Yemi in Korea
- Operated by Institute of Basic Science (IBS)
- > 1000 m overburden (cosmic ray shielding)
- Excavation finished, LSC proposal underway
- Drive-in access



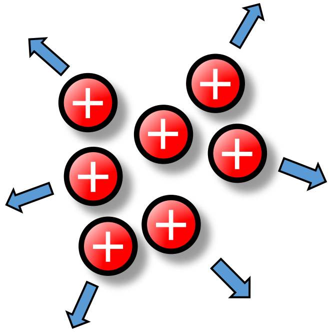
LSC - Parameters

- Target:
  2.26 kton liquid scintillator
  15 m x 15 m cylinder
- Buffer: 1.14 kton
- Veto 2.41 kton
- Prompt (e^+) energy resolution:
  $\sigma(E) = 6.4\,\%/\sqrt{E}$ (MeV)
- Prompt (e^+) vertex resolution:
  $\sigma(vertex\ [cm]) = 12/\sqrt{E}$ (MeV)
- Total $\bar{\nu}_e$ IBD efficiency: 92%



Accelerator Requirements/Challenges

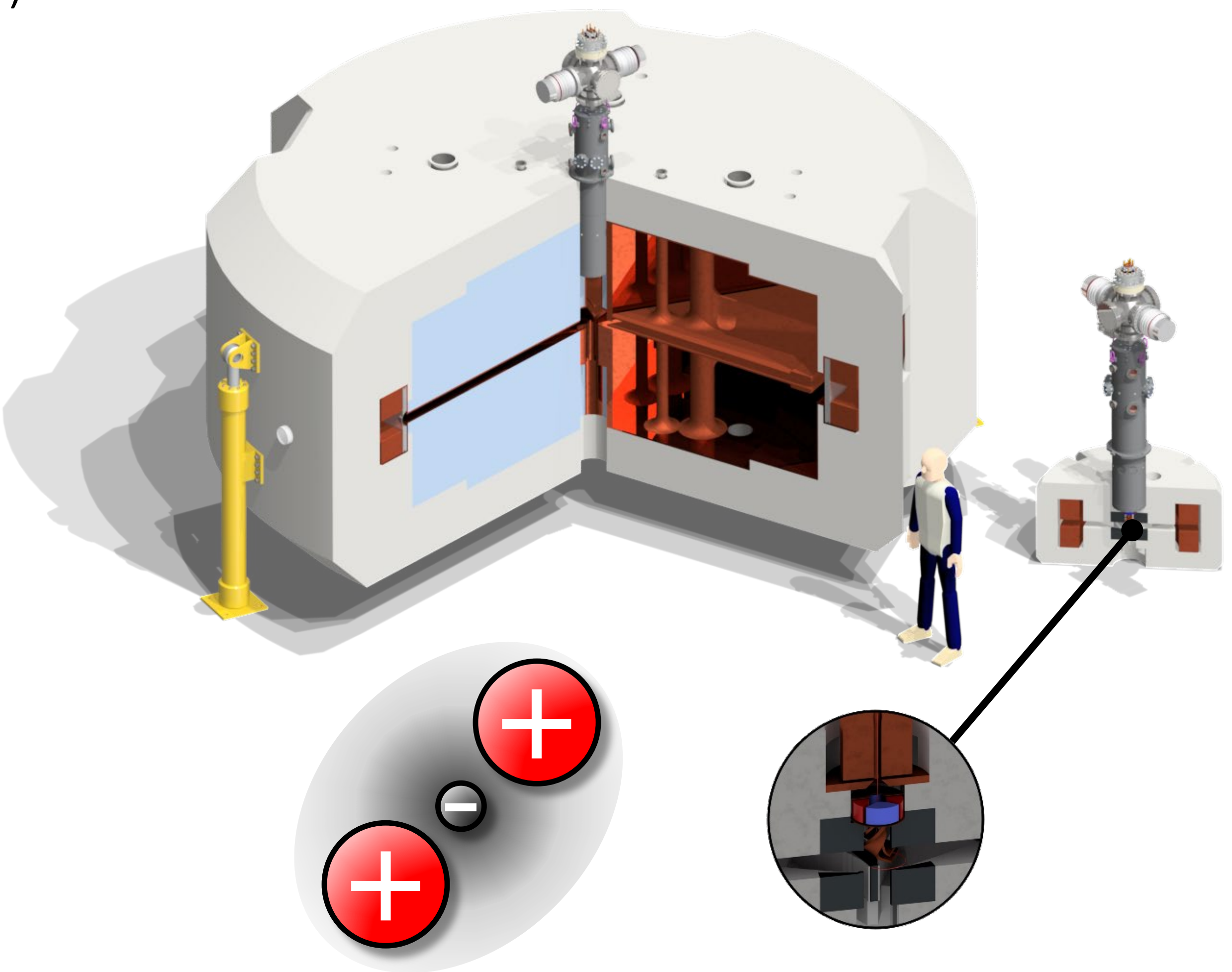
- Requirements:
  - Compact, robust, cost-effective
  - Continuous Wave (CW) operation, 80% duty factor (for maintenance)
  - 10 mA, 60 MeV protons on target
- Challenges:
  - Related to space-charge (Coulomb-repulsion of particles in bunch)
  - Leads to beam spread
  - Leads to non-linear behavior
  - Leads to controlled and uncontrolled beam losses
  - Leads to activation of the machine
    (limit is 200 W in extraction region – PSI experience)



The IsoDAR design solves all the challenges

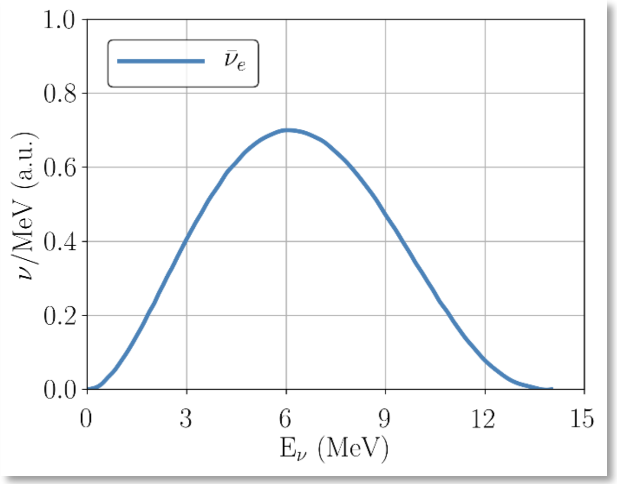
See also P0659

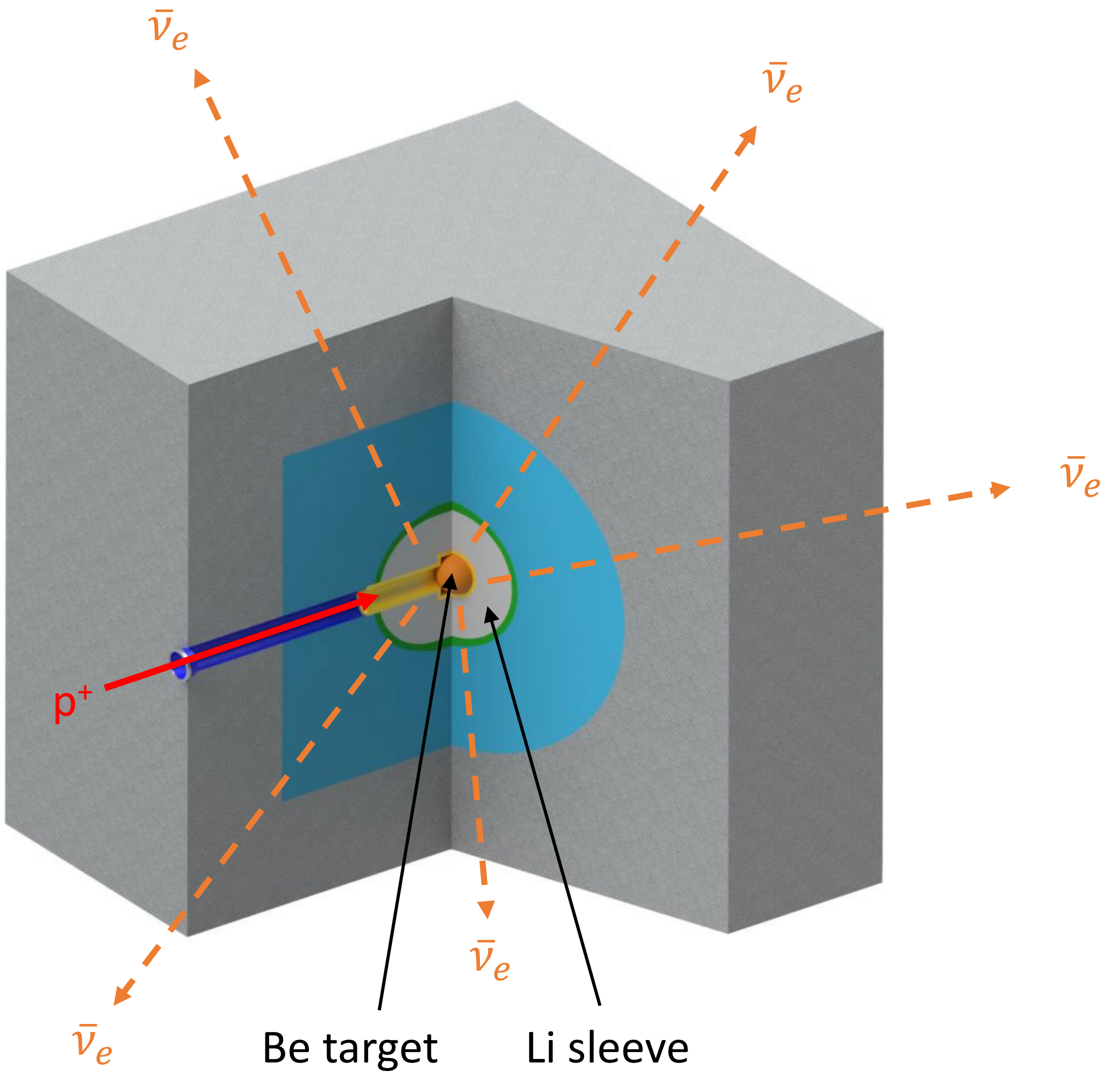
- Room-temperature coils (no cryogenics needed)
- Isochronous, cw, 80% duty factor
- Operates at 32.8 MHz (4th harmonic)
- 4 double-gap cavities
  → high energy gain/turn
- Accelerates H_2^+ ions instead of protons
- Direct axial injection through a
  Radiofrequency Quadrupole (RFQ)
  - Efficient bunching
  - Moderate pre-acceleration
- Utilizes vortex motion
  (a beam dynamics effect during acceleration)



The IsoDAR high power neutrino target

- The 10 mA proton beam is spread out transversally and “painted” across the ~20 cm Be target.
- 99.99% pure ^{7}Li sleeve around target
- p^{+} + Be → spallation neutrons
- n + ^{7}Li → ^{8}Li* → ^{8}Be + e^{-} + $\bar{\nu}_e$

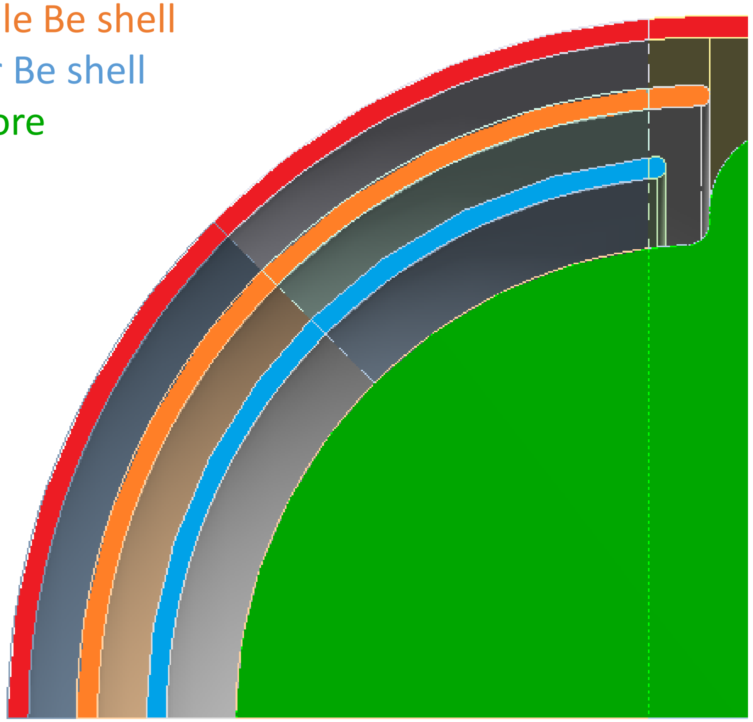


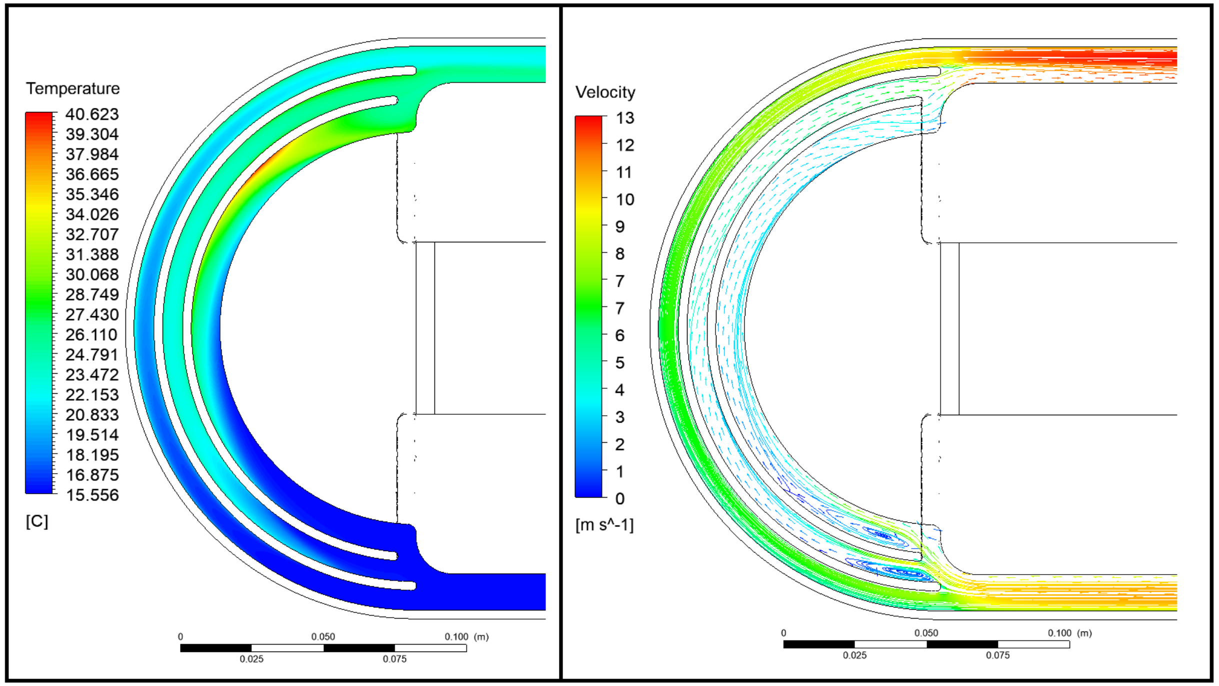


Target cooling with heavy water

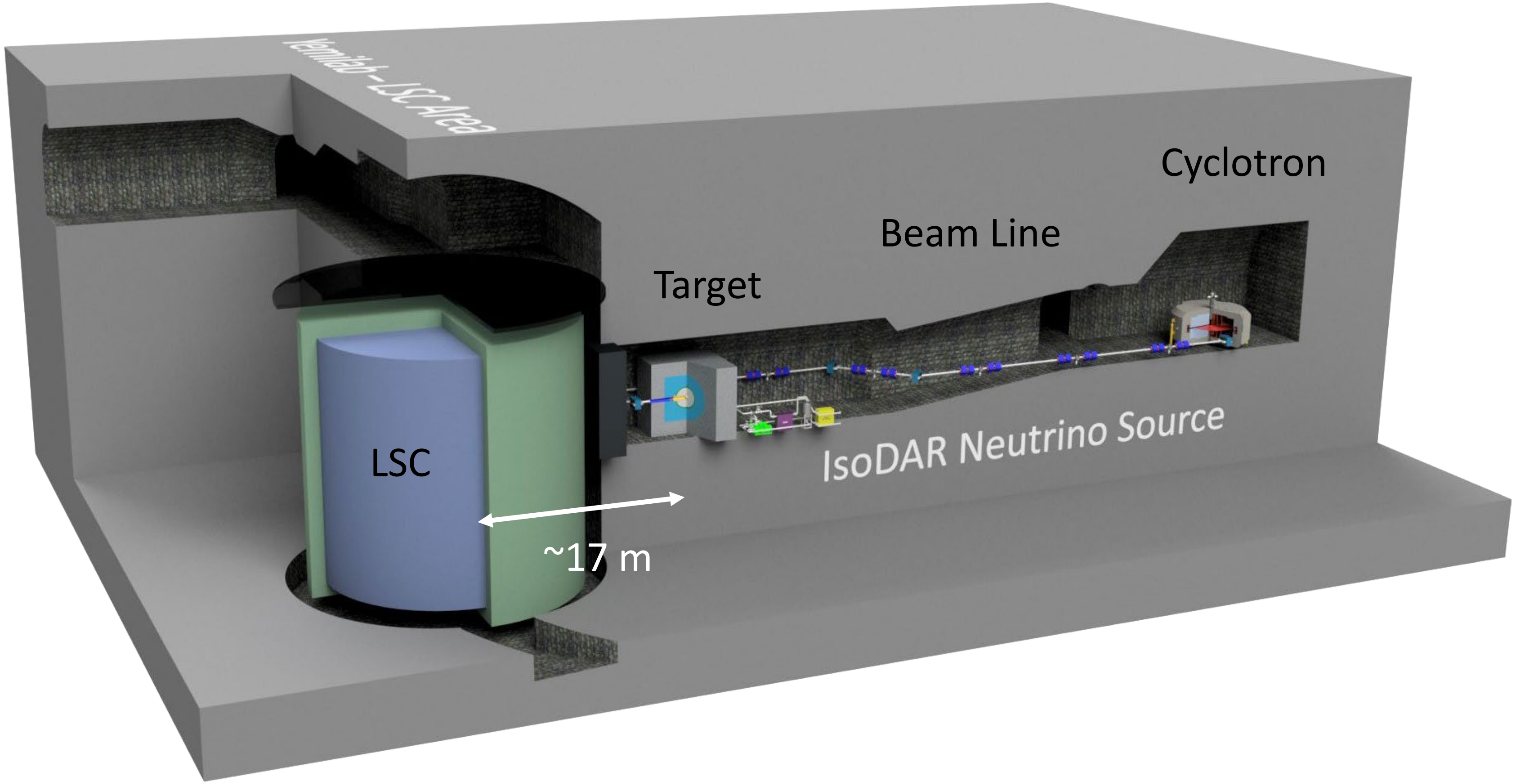
- Heavy water is pumped through a nested-shell beryllium structure
- CFD/FEA calculations show adequate cooling, stresses, and deformation

Outer Be shell
Middle Be shell
Inner Be shell
Be Core





All of it together makes IsoDAR@Yemilab a unique experiment

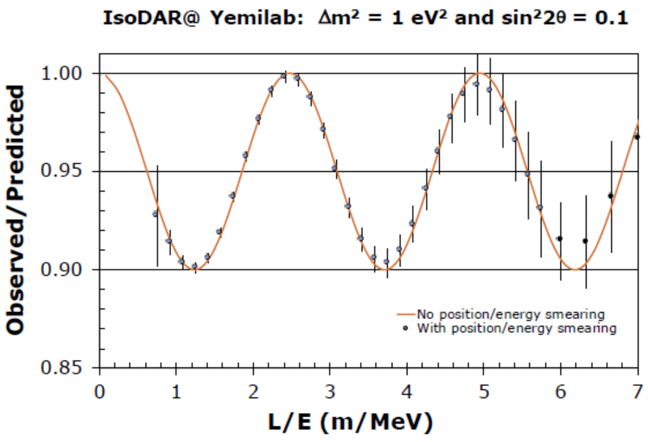


- High statistics
- High resolution
- Low backgrounds
- Well known $\bar{\nu}_e$ energy spectrum
- Very compact $\bar{\nu}_e$ source

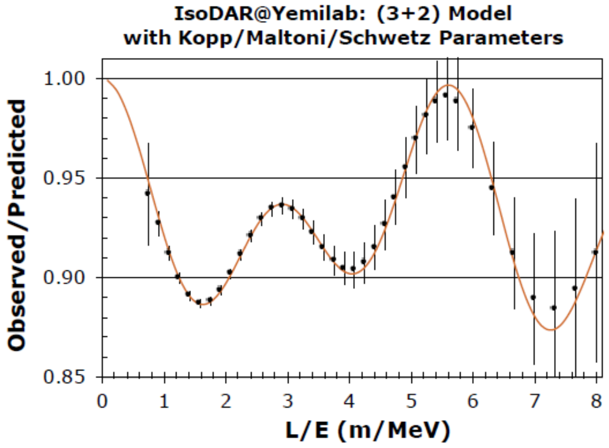
} Great L/E resolution and statistical precision → robust L/E shape analysis http://arxiv.org/abs/2111.09480

Physics 1: World-leading search for exotic (sterile) neutrinos through precision L/E measurements

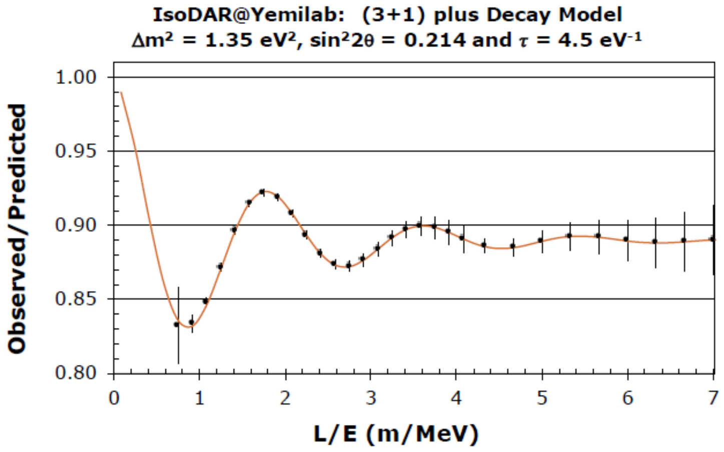
one exotic neutrino



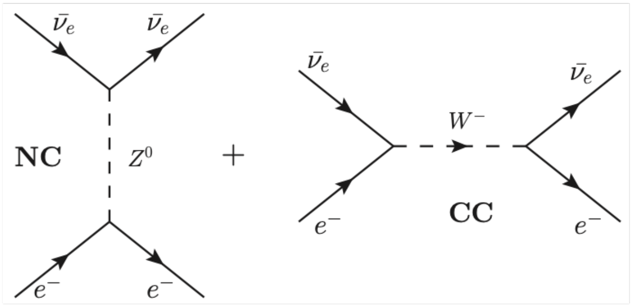
two exotic neutrinos

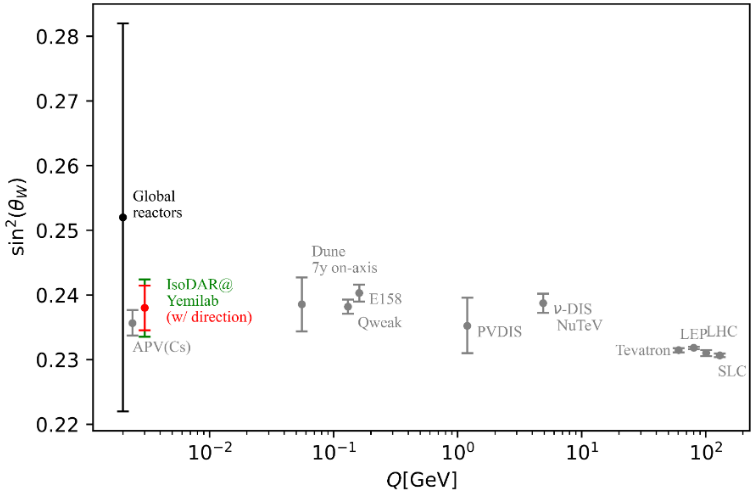


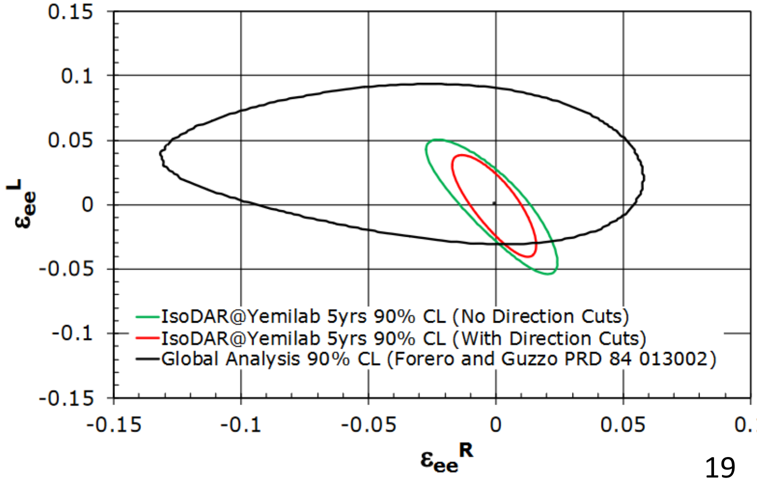
one that decays...



Physics 2: Unprecedented $\bar{\nu}_e - e^-$ elastic scatter sample (>7000 events) at low Q

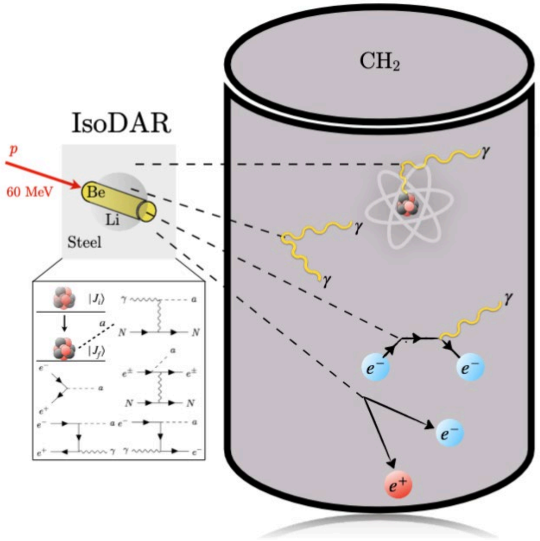


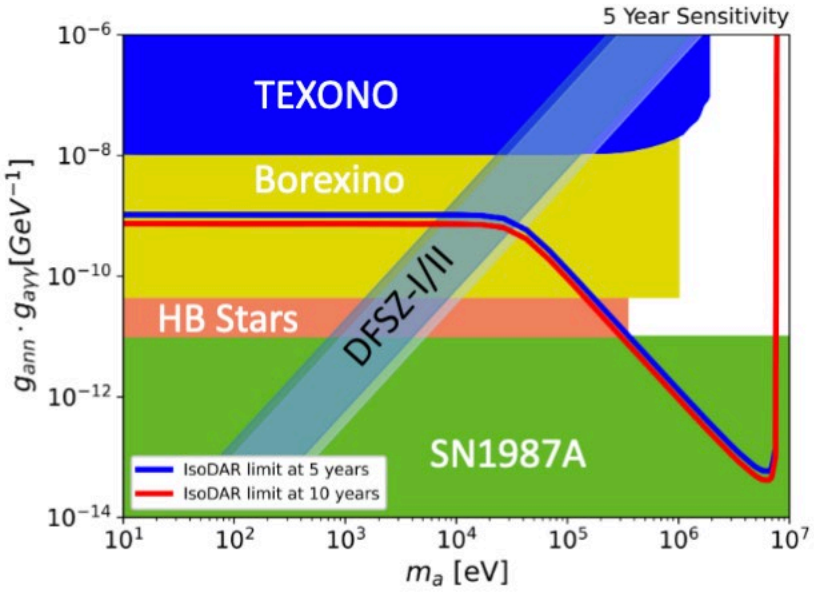




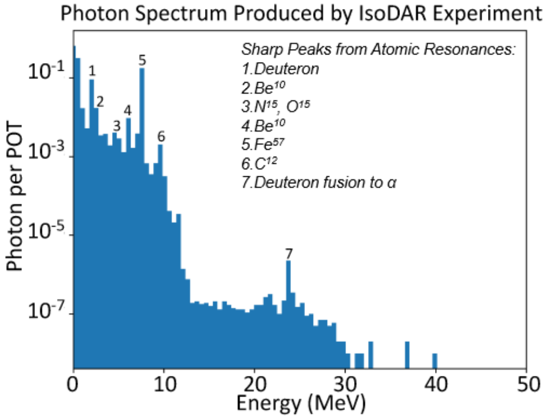
http://arxiv.org/abs/2111.09480

Physics 3: Search for Axion-Like Particles (ALPs)

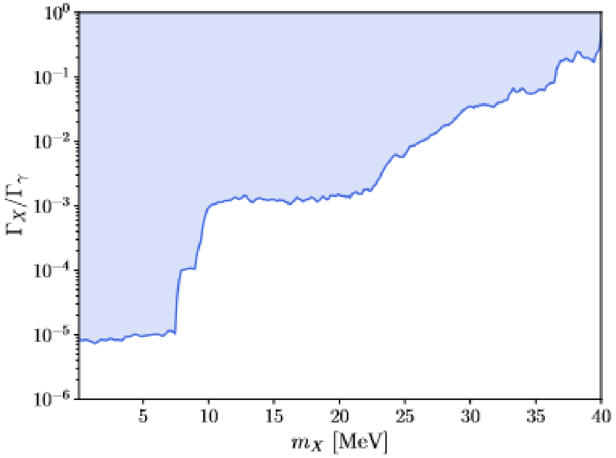




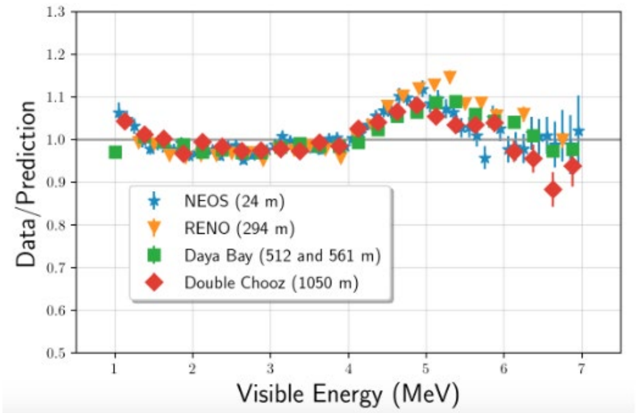
Physics 4: Bump hunt in the neutrino spectrum, *light X particles* produced in the target → $\nu_e\bar{\nu}_e$



Produced by mixing w/ photons in target



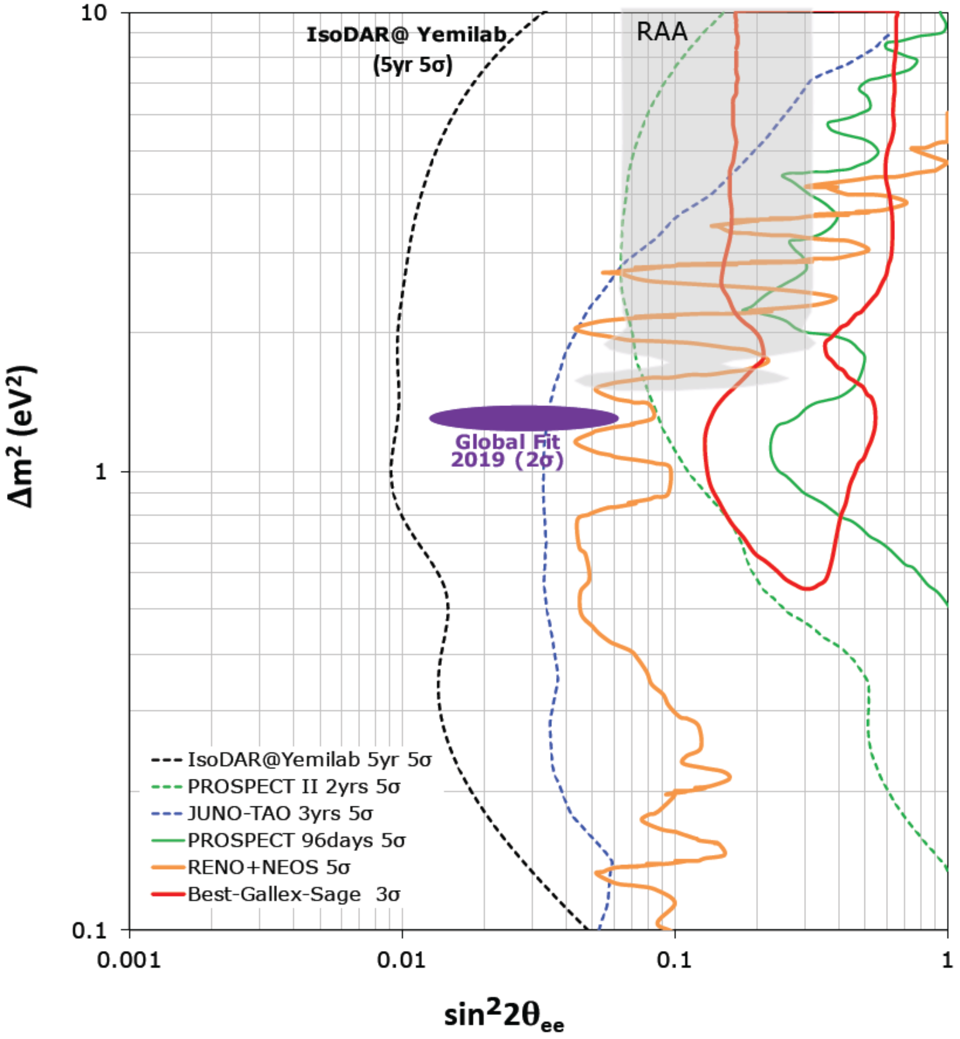
Sensitivity



Help explain 5 MeV bump in reactors?

Conclusion

- SBL Experiments (Accel, Reactor, Source) hint at BSM physics → sterile neutrinos?
- Need for definitive experiments!
- On timescales from 2-5 years there are good prospects to cover the most important regions in parameter space
- 2y: PROSPECT-II → high Δm^2
- 3y: JUNO-TAO → low Δm^2
- 5y: IsoDAR@Yemilab → full coverage



Prospects for new eV-scale sterile neutrino searches