JUNO
(Jiangmen Underground Neutrino Observatory)
with a brief
Overview of the Neutrino Effort at ANL HEP

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ANL HEP-PHY Neutrino Meeting, April 13, 2015.

ANL Neutrino Effort within HEP

- ANL Neutrino program is aligned with HEP mission i.e. Intensity Frontier:

Intensity Frontier researchers use a combination of intense particle beams and highly sensitive detectors to make extremely precise measurements of particle properties, study some of the rarest particle interactions predicted by the Standard Model of particle physics, and search for new physics.

Measurements of the mass and other properties of neutrinos may have profound consequences for understanding the evolution of the universe.

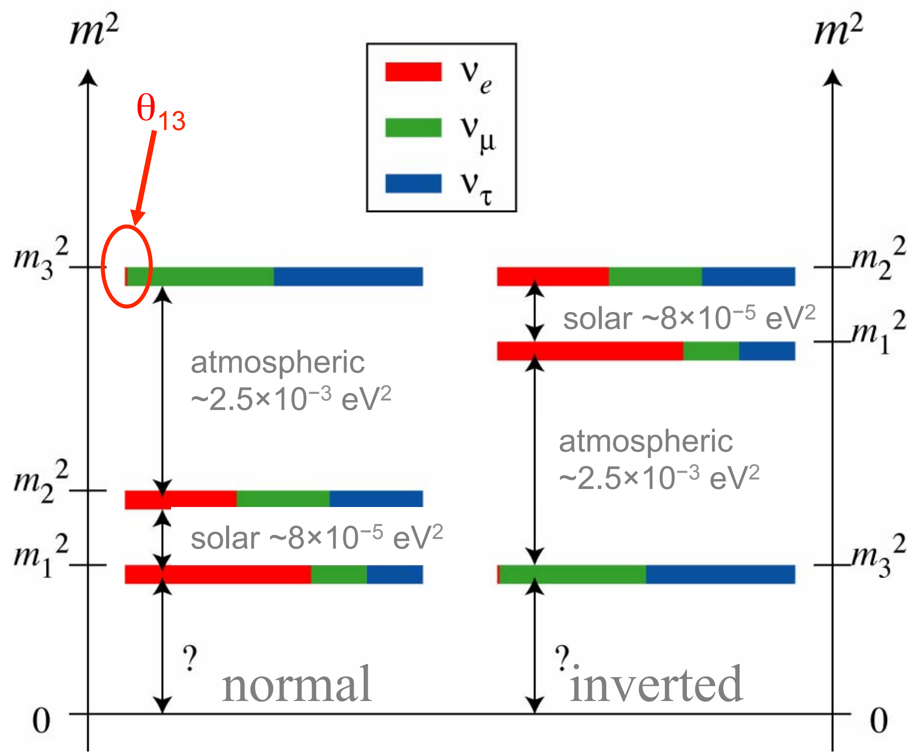
	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●		●
Cosmic Acceleration			●
Explore the Unknown	●	●	●

- Answer fundamental unanswered questions in neutrino physics, in particular:

1) What is the value of the third neutrino mixing angle, θ_{13}? => Done
2) Do neutrinos violate CP symmetry and if so by how much?
3) What is the hierarchy of neutrino masses?
4) Is neutrino its own anti-particle? Is there a sterile neutrino?

Neutrino Oscillation Questions

Recently measured what is ν_e component in the ν_3 mass eigenstate, i.e. θ_{13}.



Missing information in 3x3 mixing scheme:

1. Is the μ - τ mixing maximal?
   -Only know $\sin^2 2\theta_{23} > 0.90$.

2. What is the mass hierarchy?
   -Normal or inverted?

3. Do neutrinos exhibit CP violation, i.e. is $\delta_{CP} \neq 0$?

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

4. Why are quark and neutrino mixing matrices so different?

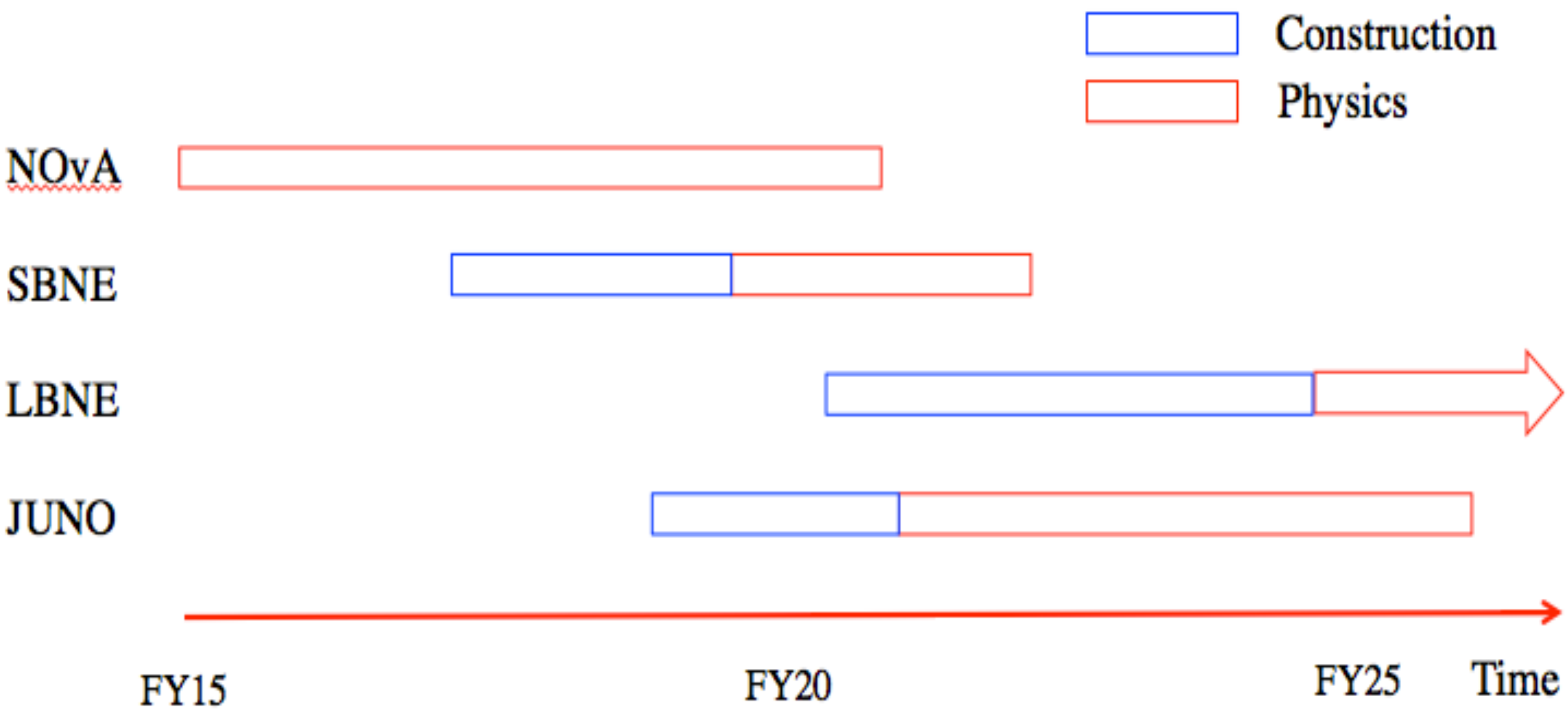
$$U_{MNSP} \sim \begin{pmatrix} Big & Big & Small \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix} \quad \text{vs.} \quad V_{CKM} \sim \begin{pmatrix} 1 & Small & Small \\ Small & 1 & Small \\ Small & Small & 1 \end{pmatrix}$$

ANL HEP Neutrino Projects

-MINOS
-Double Chooz } Concluded
-NOvA => Ongoing (data analysis)
-Liquid Argon Neutrino program
(SBND, DUNE)
-JUNO } Current/Future

ANL HEP Neutrino Projects

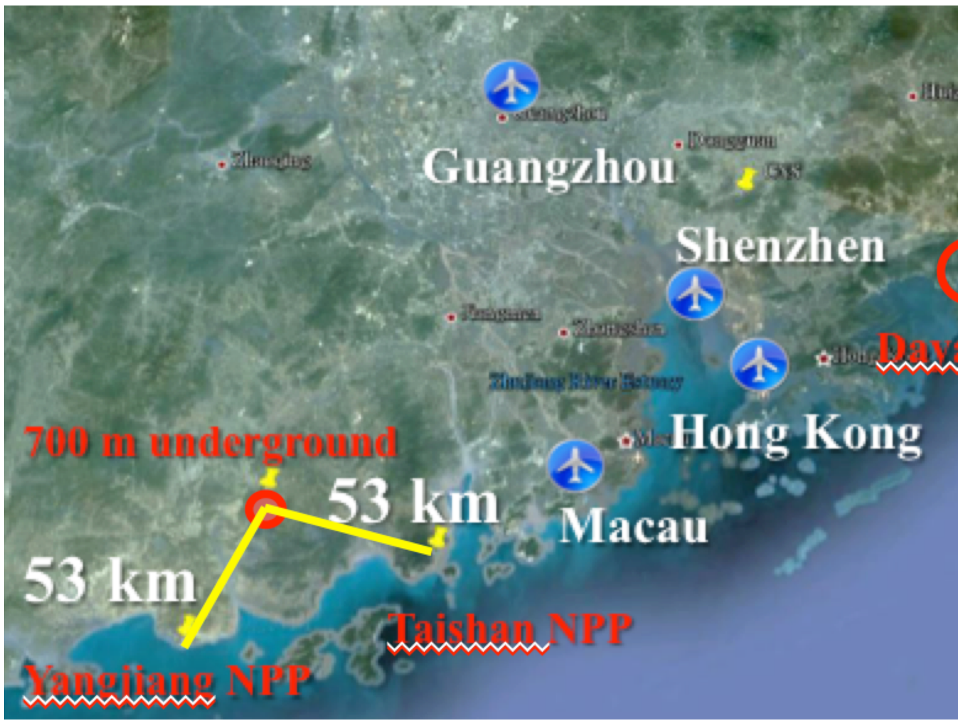
- Timescale is approximately correct, subject to change.

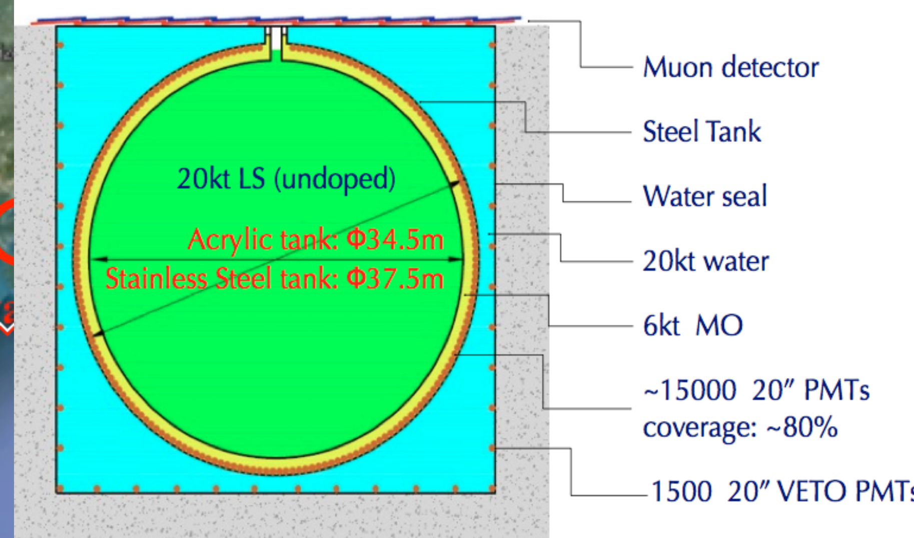


JUNO
(Jiangmen Underground Neutrino Observatory)

Physics Goals

-Neutrino Mass Hierarchy Determination, as primary goal.
-Precision measurement of mass-squared splittings and solar mixing angle.
-Underground science including supernova burst neutrinos, proton decay, geo-neutrinos, and solar neutrinos.

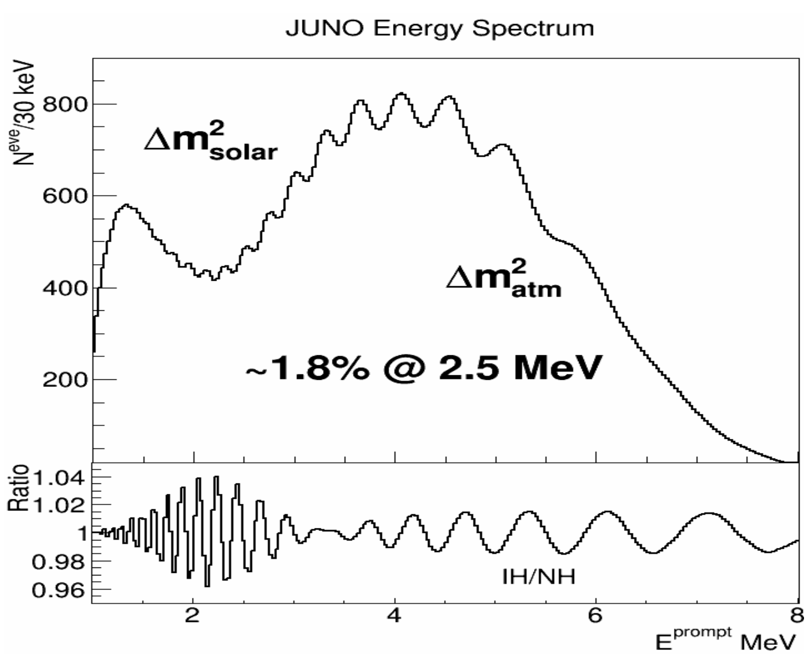


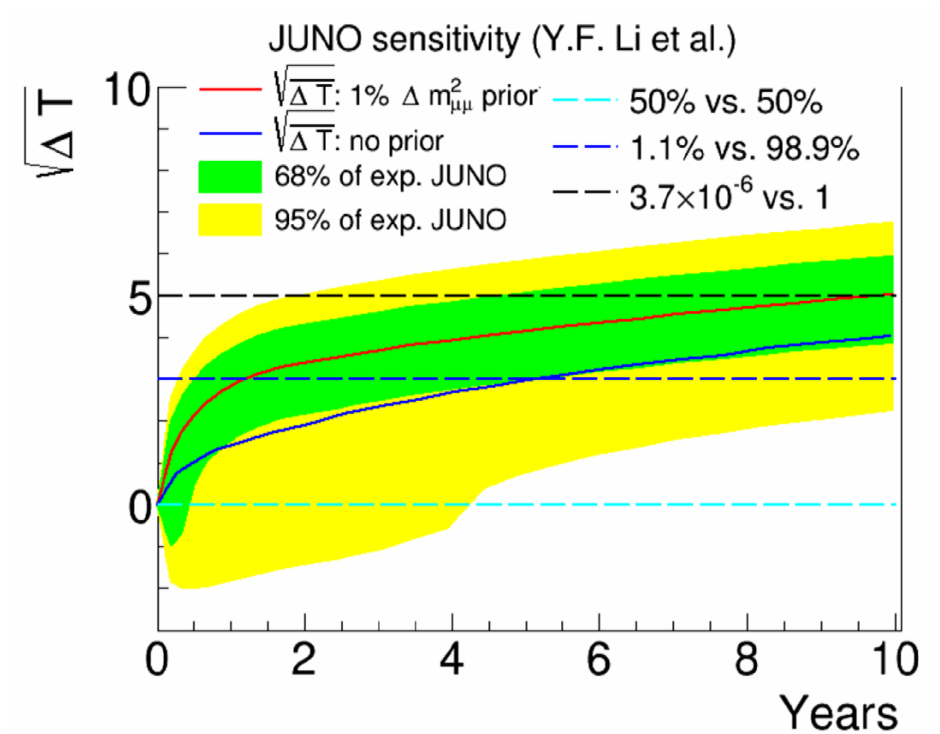


- Challenges: detector design and construction, photo-sensor production and performance, energy resolution, energy calibration.

Experimental Requirements

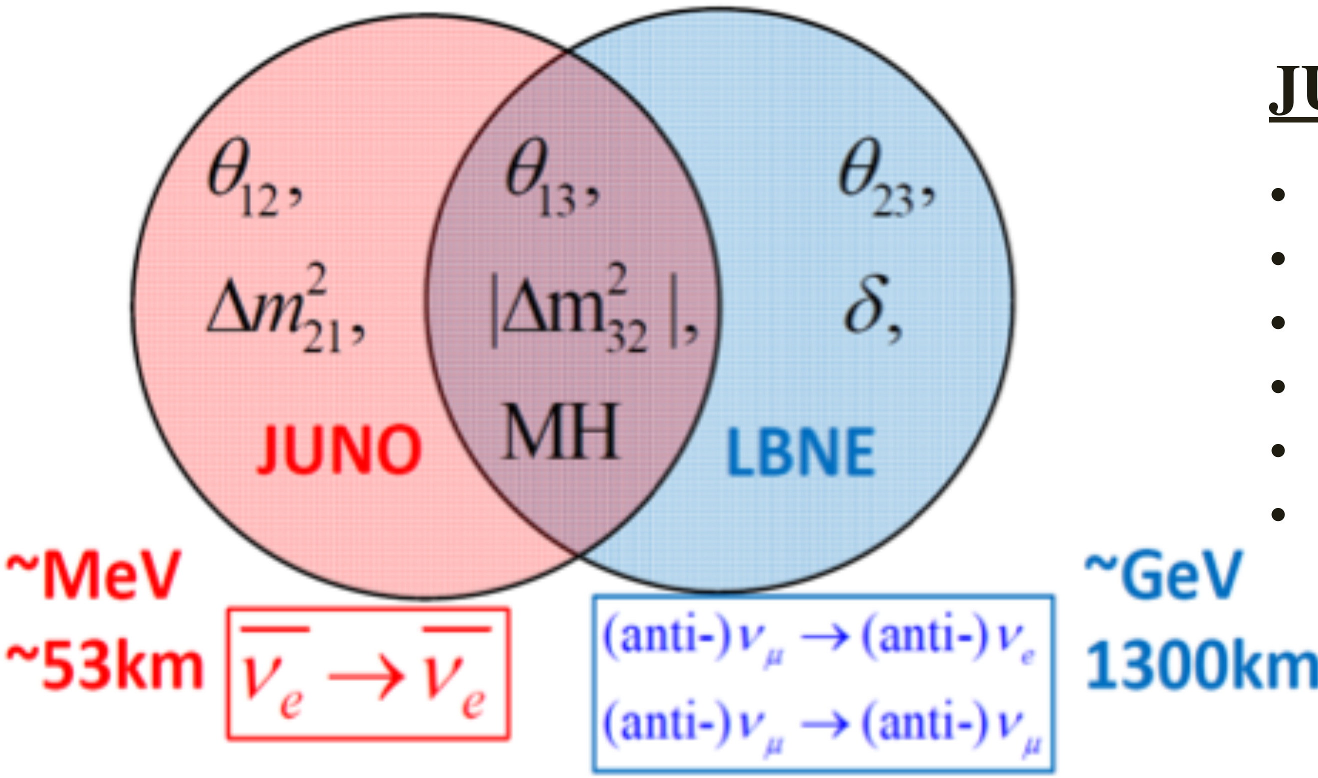
- JUNO central detector is a 20 kton liquid scintillator (LS) detector with a total overburden of 1850 meter water equivalent.
- Photo-cathode coverage is expected to reach ~75%.
- high performance LS (high photon yield with >14,000 photons per MeV, optical attenuation length of 30 m or better) .
- High quantum efficiency PMTs (~35%).
- JUNO aims to achieve energy resolution of better than 1.9% at 2.5 MeV





Synergies with Other Experiments

- Atmospheric (INO, PINGU, Hyper-K) and accelerator experiments (NOvA, LBNF) all utilize the matter effect to determine the neutrino mass hierarchy.
- JUNO uses a completely different method, from the frequency difference between Δm^2_{32} and Δm^2_{31} through precision measurement of the oscillation frequency.
- The JUNO measurement is independent of θ_{23}, δ_{CP} and the matter effect.



JUNO

- Reactor Power: 36 GW
- Baseline: 53 km
- Detector: 20 kton LS
- σ_E: 3% (2% at 2.5 MeV)
- ν rate: ~60/day
- Background:
  - Accidentals (10%)
  - ^{9}Li (<1%)
  - Fast neutrons (<1%)

ANL Interest in JUNO

- ANL is in a very good position to establish leadership roles, in areas of

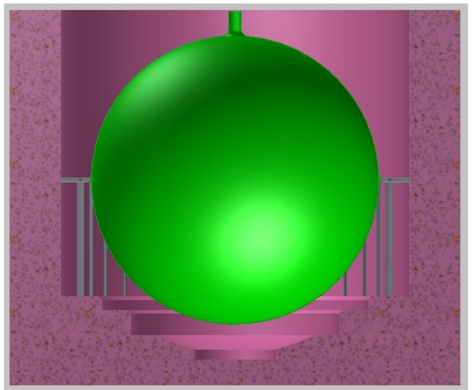
  -Mechanical Engineering of the central detector (design, construction).
  -Photo-detectors. LAPPD could be used at least partially if available early, or for a later upgrade.
  -Photo-detector characterization. Need requirements and a system to closely characterize a large number of photo-detectors. (Synergy with characterization of LAPPDs).
  -Guide tube calibration system design and construction (expertise from Double Chooz, ZEUS).
  -RPC (resistive plate chamber) system used for veto/muon-tagger.
  -Potential design, development, and operation of a positron accelerator.
  -Simulation and data analysis when the experiment is underway (roles from Double Chooz).
  -Opportunity to get physics results early (when compared to DUNE).

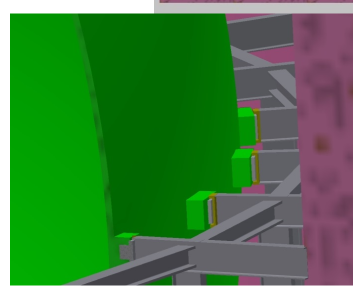
Mechanical Engineering of the central detector

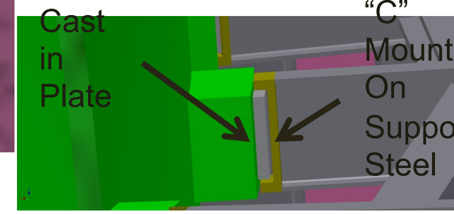
- Critical issues to be addressed within FY15 are development and analysis of the JUNO central detector design and calibration systems integration with the detector.
  -ANL is working closely with the Chinese collaborators on the design of the central detector.
  -ANL is performing detailed structural analysis of the detector and its supports.
  -ANL is investigating methods of fabrication and is developing a concept for assembling the detector, performing the required bonding on-site, and design the fixtures needed during assembly.

- Assembly Goals
  -Minimize the time of assembly
  -Minimize the number of acrylic pieces
  -Minimize the time for annealing/curing of the adhesive
  -Minimize the assembly fixtures
  -Eliminate the need for fixtures inside the sphere

- ANL will develop a concept for supporting the PMTs and perform a structural analysis of the structure that will support the PMTs.

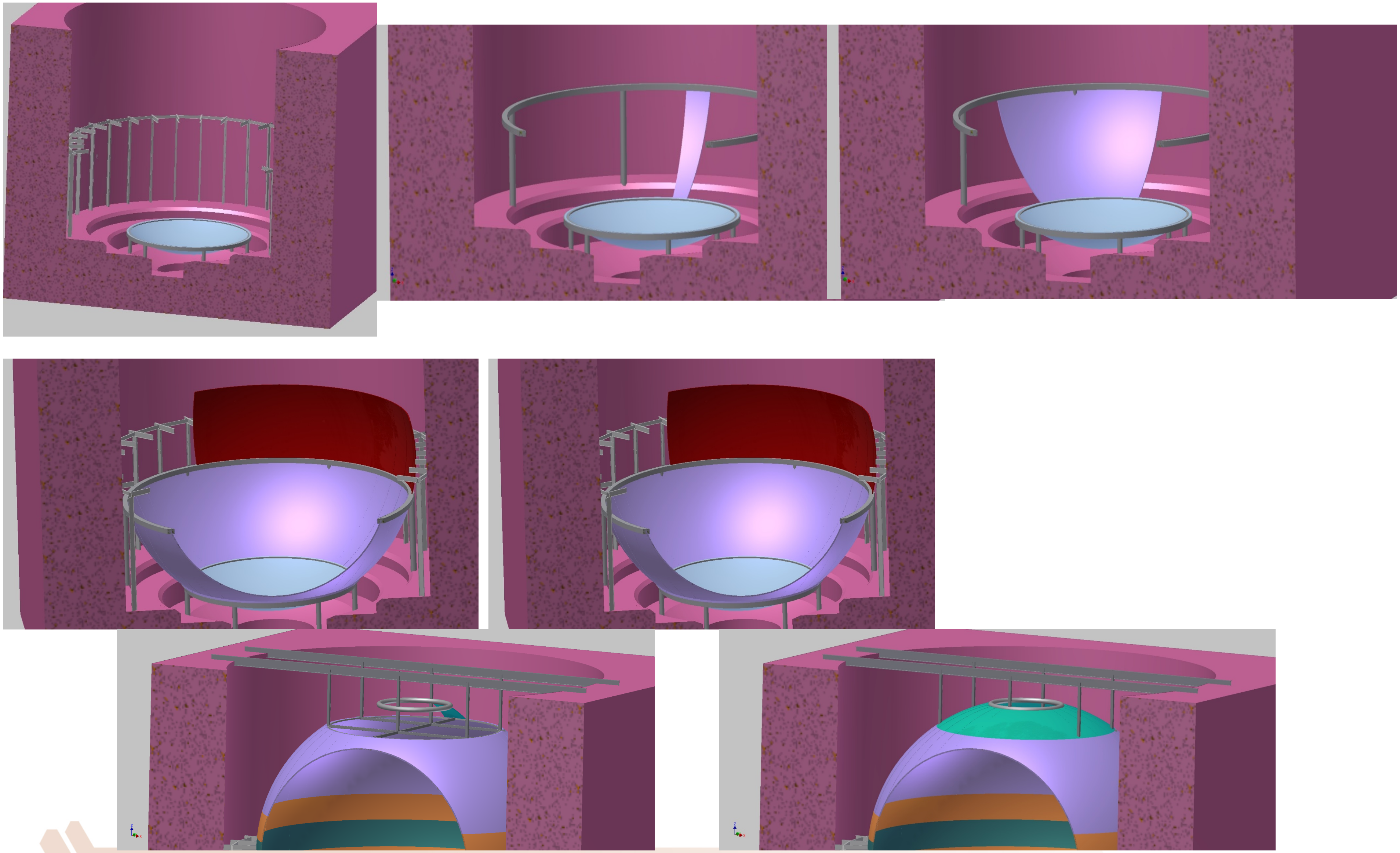






Mechanical Engineering of the central detector

- ANL proposal for the central detector design/assembly being developed:



JUNO Calibration Approach

- JUNO central detector energy resolution needs to be better than 3% at 1MeV, 1.9% at 2.5 MeV.

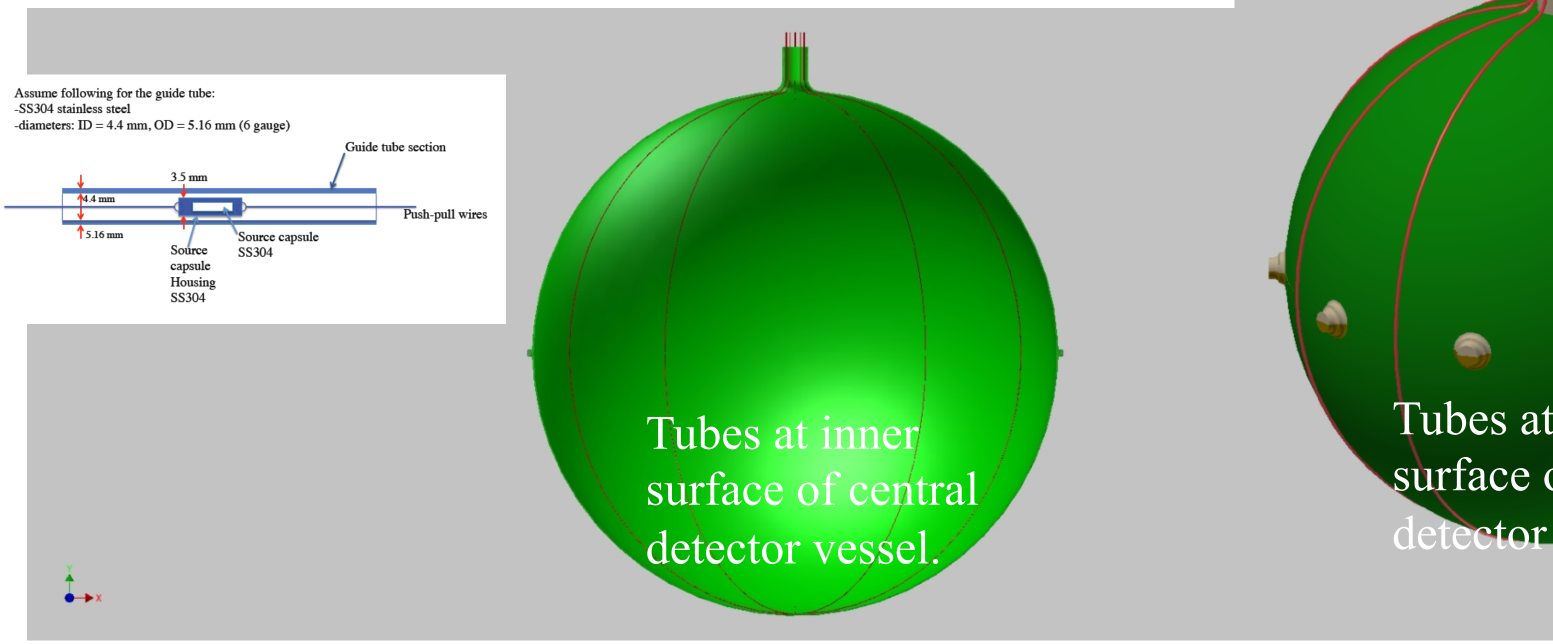
- Energy resolution of the detector has two major contributions
  -number of collected scintillation photons (LS light yield, att. length, PMT coverage, quantum eff., collection eff.)
  -non-uniformity of the detector response (detector geometry, optical properties).

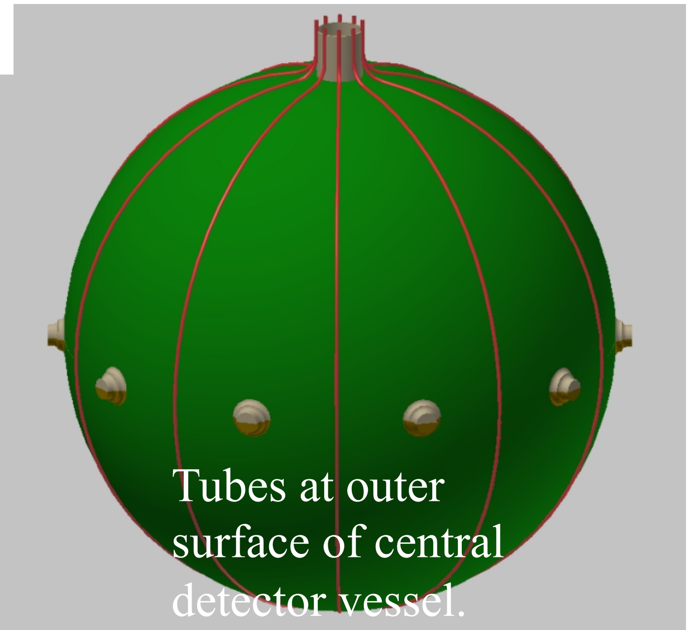
- The following calibration options are being investigated:
  -Central calibration unit for vertical source deployment along Z-axis
  -Pre-installed guide tubes to deploy sources at the central detector boundaries
  -Rope system for the off-center source deployment
  -Accelerator (pelletron) system to provide mono-energetic positron beam
  -System to diffuse short-lived radioactive isotopes within central detector
  -Remotely operated vehicle for "4π" radioactive source coverage

- Complementary to the options listed above will be use of the full volume cosmogenic data (spallation neutrons, B12)

Guide tube calibration system

- We expect changes in the detector energy scale response when going from the central part to the edges of the detector.
  -Such non-uniformity may be studied by deploying radioactive sources with known energies at off-center positions inside the detector.





-Acrylic or stainless steel tubes would be attached to the acrylic vessel and wires with radioactive sources would be driven through the tubes.

-We are considering two concepts for driving the wire over this long distance.

-In both cases wires exit up along chimney to drive system.

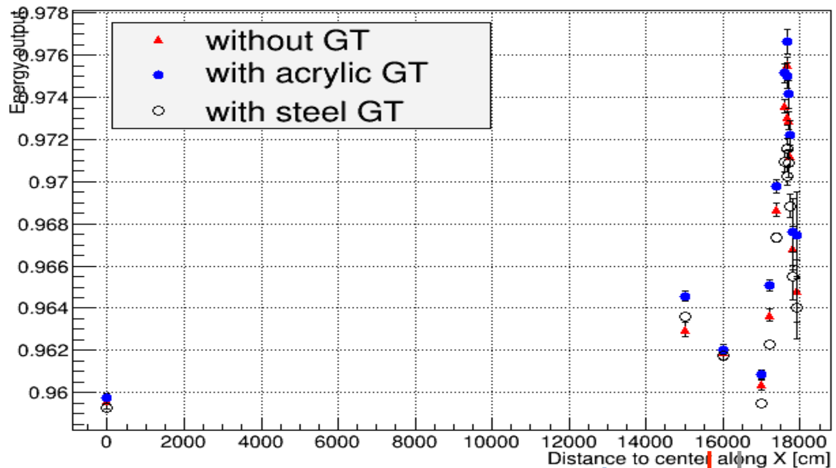
-Need to augment/optimize choices by doing simulation:

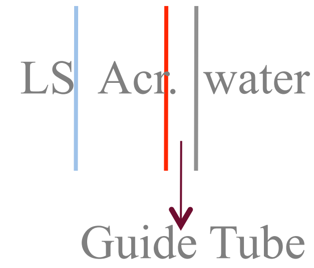
-guide tubes at inner vs outer surface of the central detector vessel?

-acrylic tube vs stainless-steel tube? Number and distribution of the tubes?

Guide tube calibration system

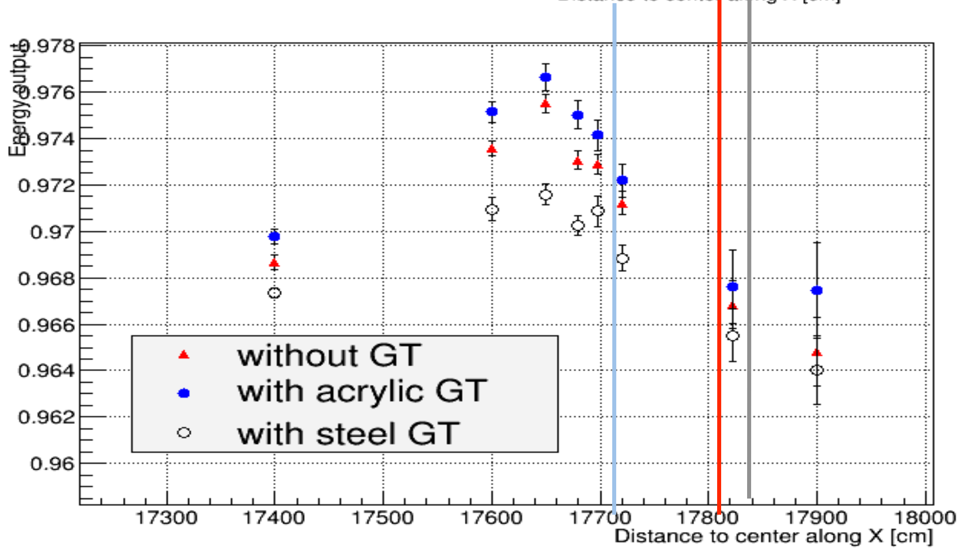
- Simulation is underway here at ANL to inform design choices
- Simulation example with 1 MeV gammas in inner GT, acrylic vessel wall, outer GT

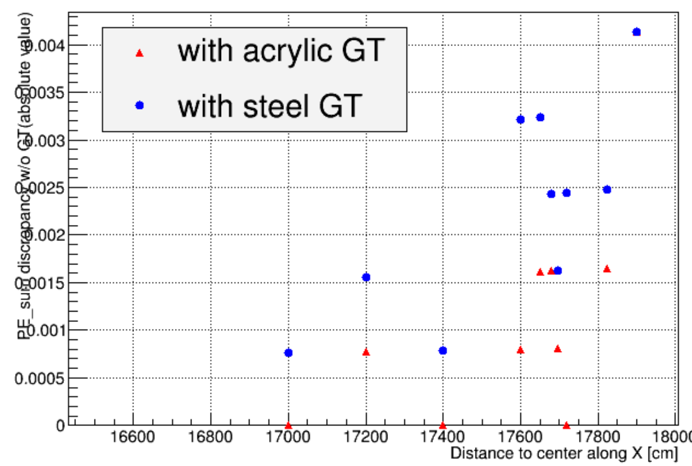




Total PE at each position:

$$\frac{PE_{with} - PE_{without}}{PE_{without}}$$





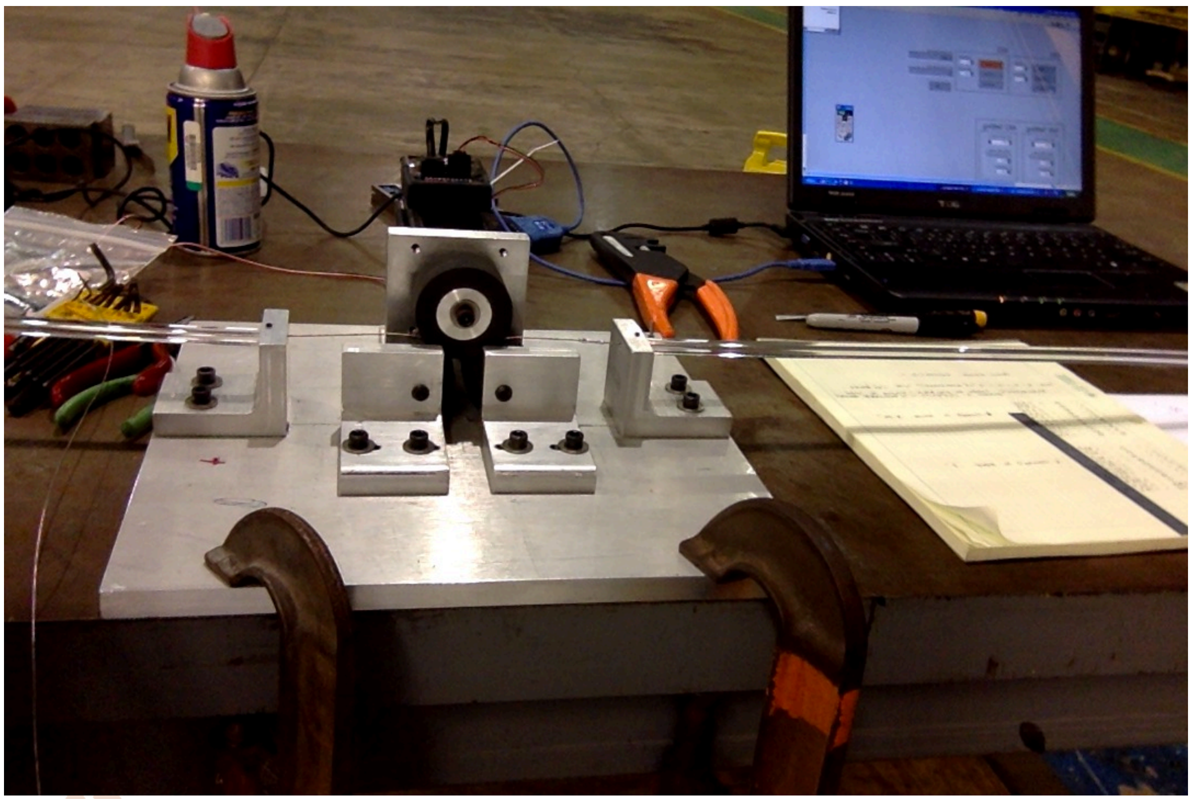
Guide tube calibration system

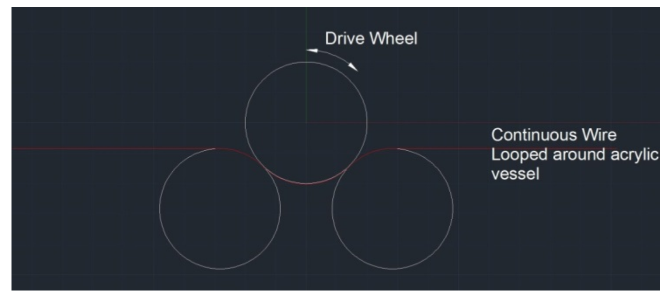
- Wire-driving concept with continuous wire

-A continuous wire would run in a closed loop through the source tubes.

-Wire driven using a wheel that would push/pull the wire.

-A proof of concept prototype has been constructed.

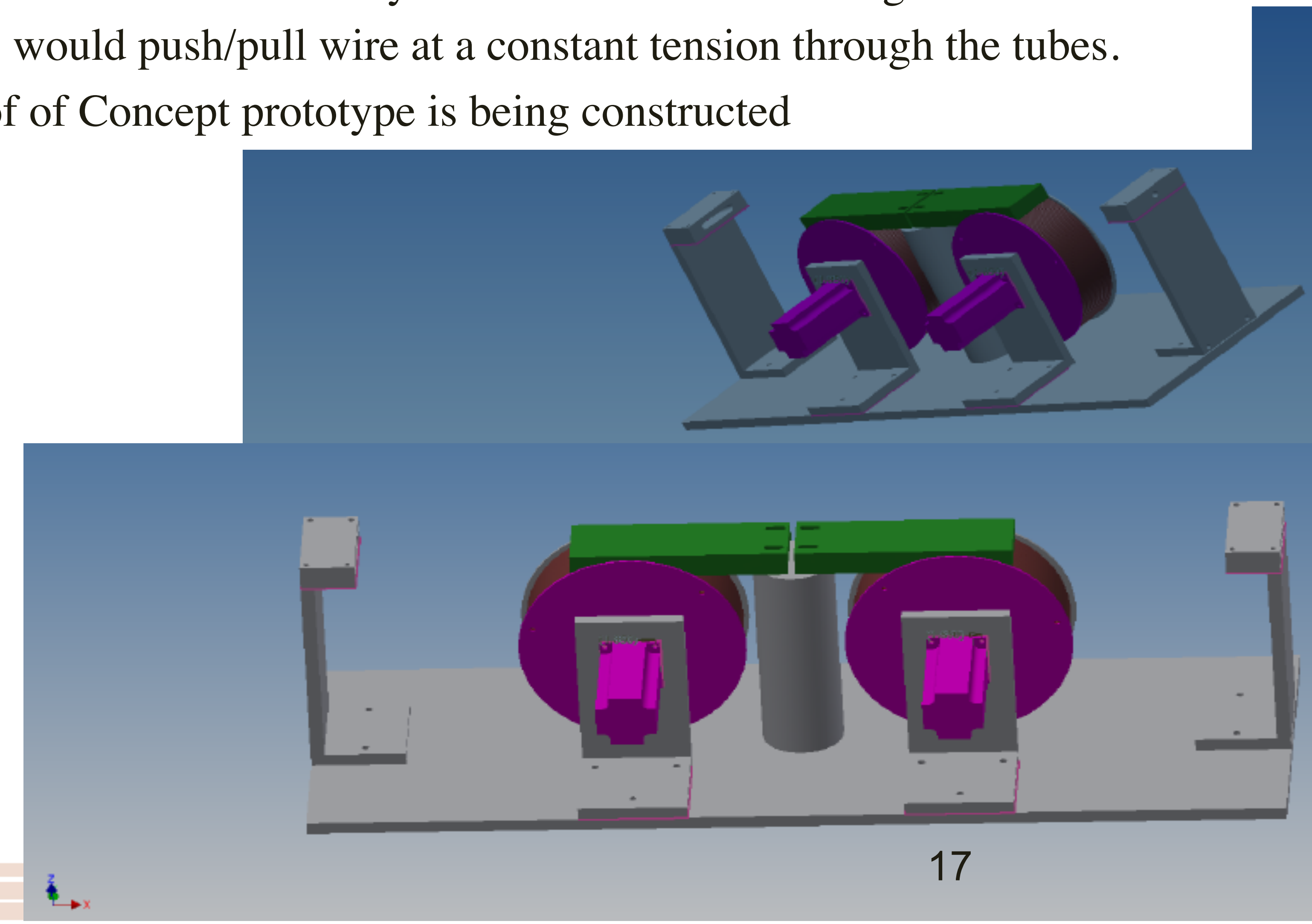




Test with the acrylic/lexan tube as the driver for stranded SS wire.

Guide tube calibration system

- Wire-driving concept with drum drive system
  - -Two drums would have wire wound on them.
  - -Wire would run continuously between drums and through source tubes.
  - -Drums would push/pull wire at a constant tension through the tubes.
  - -A proof of Concept prototype is being constructed

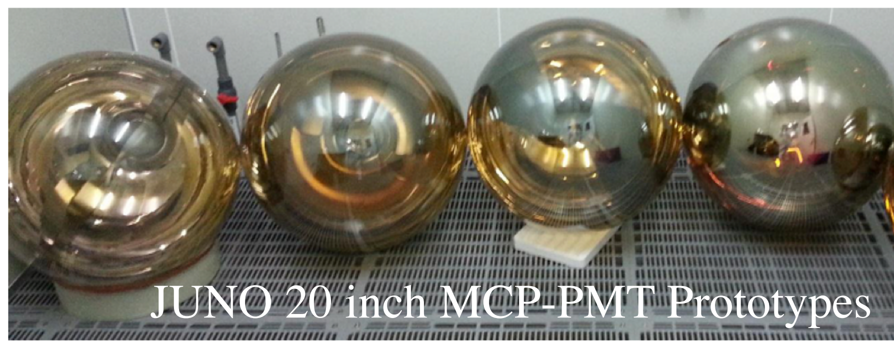


JUNO PMTs

- The US groups could have critical impact on JUNO in the area of the photo-detectors to be deployed in JUNO.
- Based on expertise in photo-sensor development at ANL, the quality control standards and test systems for about 20000 PMTs to be used in the experiment could be established and the physics implications of improvements in detector performance studied.
- Argonne is producing Micro-channel based photo-detectors with atomic layer deposition, the same kind of photo-detectors that are the baseline for JUNO.

PMT Requirements

Parameters	Specs	Comments
Diameter (mm)	508	20 inches
Photocathode diameter (mm)	500	Glass thickness 4 mm
Peak quantum efficiency (QE)	≥ 38%	Prefer at wavelength ~420 nm
Photoelectron Collection efficiency (PCE)	≥ 93%	Average over entire photocathode
Photon detection efficiency (PDE)	≥ 35%	PDE ≅ QE ×PCE
Spectral response (nm)	300 - 650	Scintillation 380 – 550 nm
Transition time spread (ns)	5 ns	FWHM
Gain	$> 10^7$	
Single pe peak/valley (P/V)	> 2	
Dark noise pulse rate (kHz)	30	Based on Hamamatsu R3600-2 (25°C, >0.25 pe)
Linear range (pe)	0.1 - 1000	
Dynamic range (pe)	0.1 - 4000	
Pre-pulse	< 1%	
Fast after pulse	< 1%	< 1 μs
Slow after pulse	< 5%	< 200 μs
Maximum hydraulic pressure (atm)	9	4.2 atm in JUNO
^{238}U content (g/g)	1×10^{-8}	PMT weight ~ 10 kg
^{232}TH content (g/g)	2×10^{-8}	PMT weight ~ 10 kg
^{40}K content (g/g)	10^{-5}	PMT weight ~ 10 kg
Lifetime (year)	> 20	


JUNO 20 inch MCP-PMT Prototypes

PMT schedule of the mass production

Year	Tasks	Parameters
2013	8inch prototype	QE ≥ 25%, P/V ≥ 1.5
2014	20 inch prototype	QE ≥ 30%, P/V ≥ 2.0, other parameters meet specs
2015	Engineering design	QE ≥ 30%, P/V ≥ 2.0, other parameters meet specs and Yield ≥ 80%
2016	Preproduction	1000 20inch PMTs
2017	Mass production	5000 20inch PMTs
2018	Mass production	5000 20 inch PMTs
2019	Mass production	5000 20inch PMTs

PMT Scanning System

- The large number of PMTs to be deployed by the experiment makes the full characterization of each photodetector a crucial requirement to extract the physics.

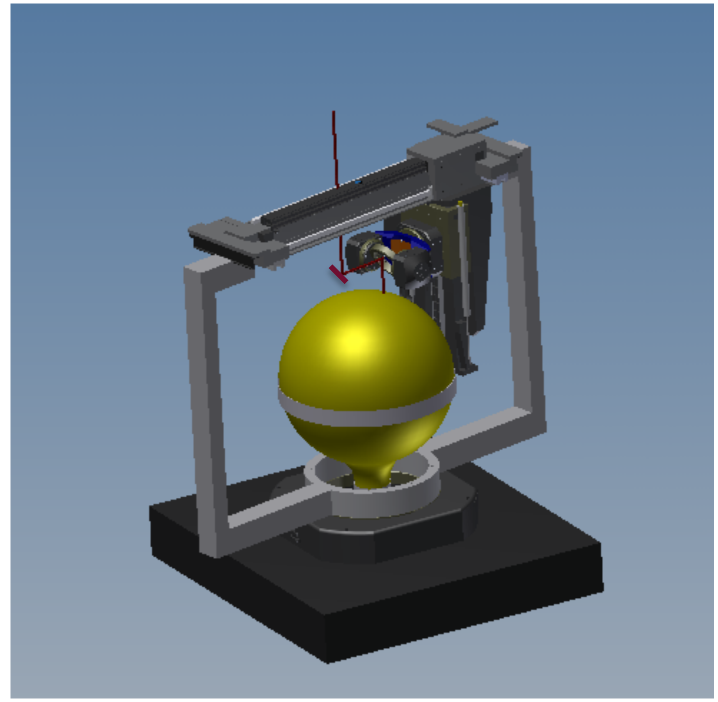
- Careful consideration has to be given to the development of a fast and efficient automated testing procedure for each tube.
  -controlling the detector's absolute energy calibration and energy resolution is of utmost importance for reaching the experimental goals.
  -main parameter in controlling the energy resolution of the liquid scintillator detector is knowledge of the response of each photo-detector.

- An automated 4-axis calibration system is proposed to characterize each photo-detector, which will be replicated at multiple institutions in China.

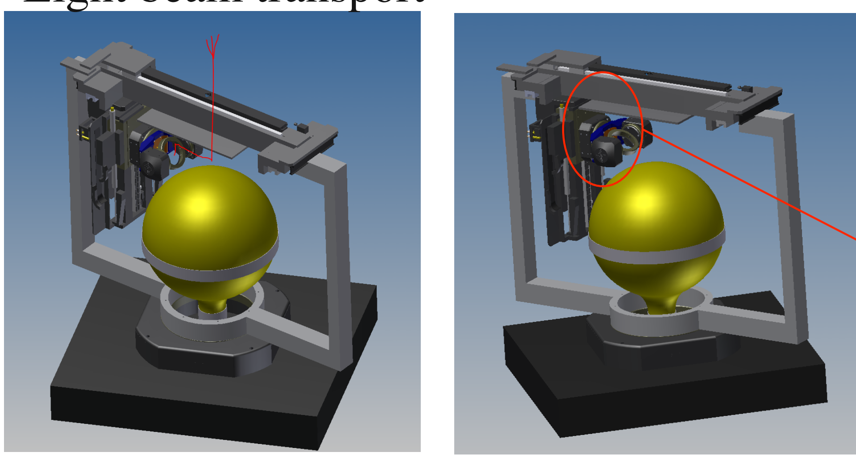
- Each on-site optical station is a fully automated optical and electrical measurement system.
  -It is proposed that the system be designed and built at Argonne National Laboratory and replicas built for the various testing institutions.

PMT Scanning System

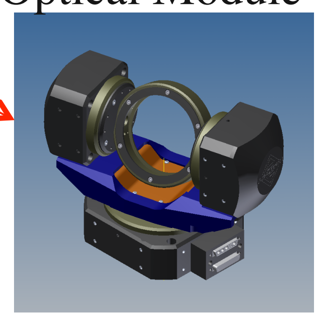
- Conceptual design of the PMT QA machine for JUNO.
- This machine have 5 degree of freedom: rotation around PMT axis, vertical and horizontal slide, plus two rotation of the optical mounts.
- A light beam comes on the PMT axis direction and deflected to center of the optical mount.



Light beam transport



Optical Module



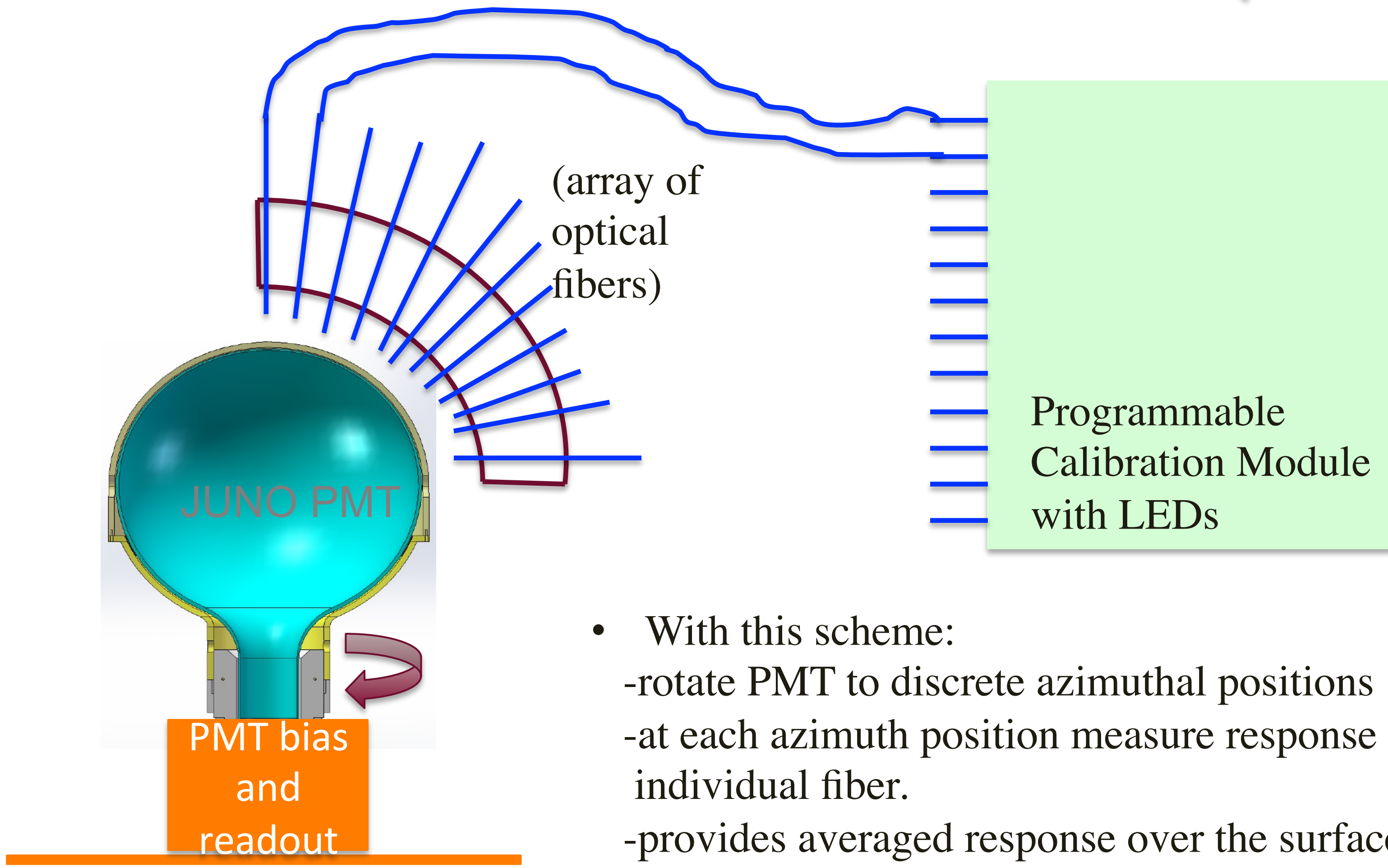
- PMT quantities to be measured:

  -absolute quantum efficiency, collection efficiency, gain, dark current, time resolution.

  -uniformity of quantum efficiency (a map) over the PMT surface.

PMT Scanning System

- The PMT machine discussed above could be used for detailed characterization of limited number of PMTs.
- Alternative solutions may be required for a faster test of larger number of PMTs.



Similar Calibration module designed and build at ANL for liquid argon detectors (LBNE)

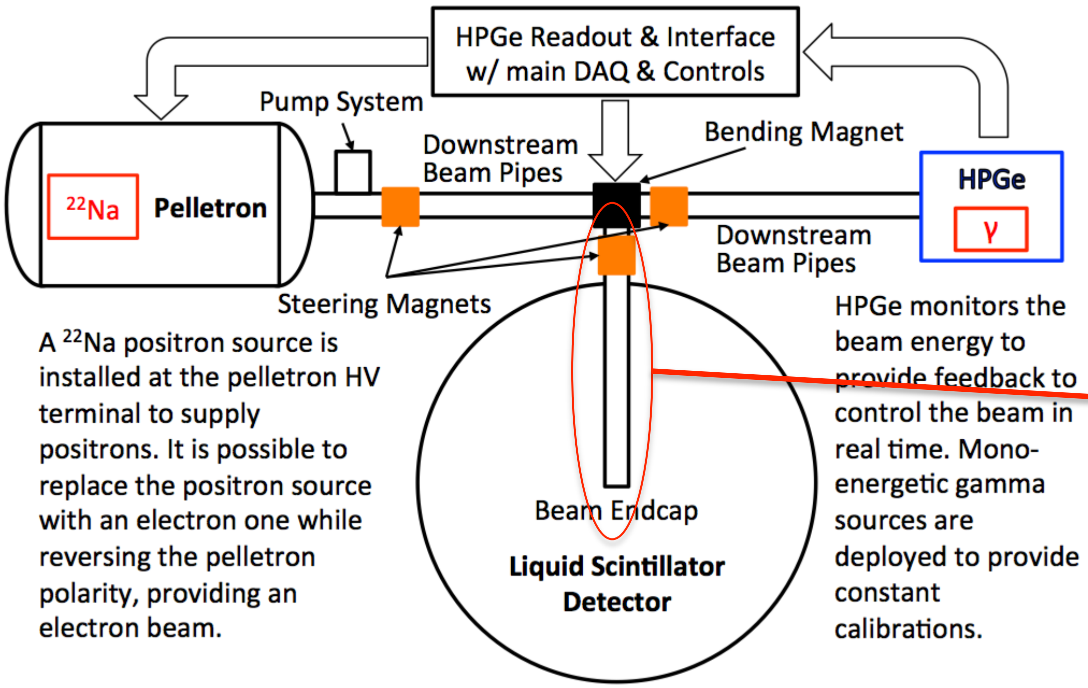
- With this scheme:
  -rotate PMT to discrete azimuthal positions
  -at each azimuth position measure response to each individual fiber.
  -provides averaged response over the surface.
- Variation of this approach would be a simultaneous test of a large number of PMTs, each with a single fiber at center.

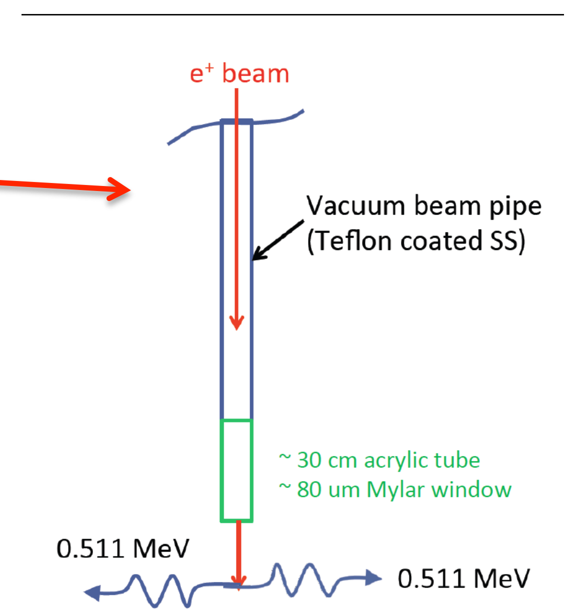
Existing Collaboration with IHEP

- In the framework of an exchange program between the Beijing Center of the University of Chicago and Argonne, we have an existing collaboration with IHEP on photodetector development.
  - Dr. Qian Sen visited Argonne for two weeks last year
  - Dr. Xing Wang visited Argonne for six months to work on photodetector development
- Recently (december 2014) we had a workshop on MCP-based photodetectors at Argonne with important participation from IHEP.
- Had very constructive visit of the vice president of CAS (Wenlong Zhan) in December 2014 at Argonne and discussed further collaboration on Photodetector development.
- Universities could do the PMT tests; we could provide quality control standards and test systems.

Positron Accelerator Option

- Potential in development of a positron accelerator for JUNO calibration is under discussion within US groups.
- A commercial pelletron could be adapted.





- Issues to address: beam pipe and transport, beam calibration and monitoring, interface to central detector, positron energy losses, shadowing effects.

Positron Accelerator Option

- Extensive expertise at ANL on accelerator side: PHYSICS (ATLAS/TANDEM,…), AWA at HEP, APS.

- There is existing infrastructure at PHY that could be explored in connection with JUNO accelerator needs (initial discussion with R. Padro)
  -Opportunities include use of the existing beam line magnets:
  at least one bending dipole magnet, and few quadrupole (focussing) magnets.
  -Expertise with beam line development and instrumentation.
  -Perhaps the whole existing TANDEM could be shipped to China.

Contribution to Top Veto

- JUNO plans to use Opera Target Tracker (plastic scintillator) as the top muon veto.
- ANL RCPs could be used as a muon veto

  -The available system consists of ~50 x 1m^2 flat RPC detectors panels, each with 96 x 96 readout channels, each of 1 cm^2. More modules would be required.
- Initially developed as Digital Hadron Calorimeter (DHCAL).

Active element

Thin Resistive Plate Chambers (RPCs)

Glass as resistive plates

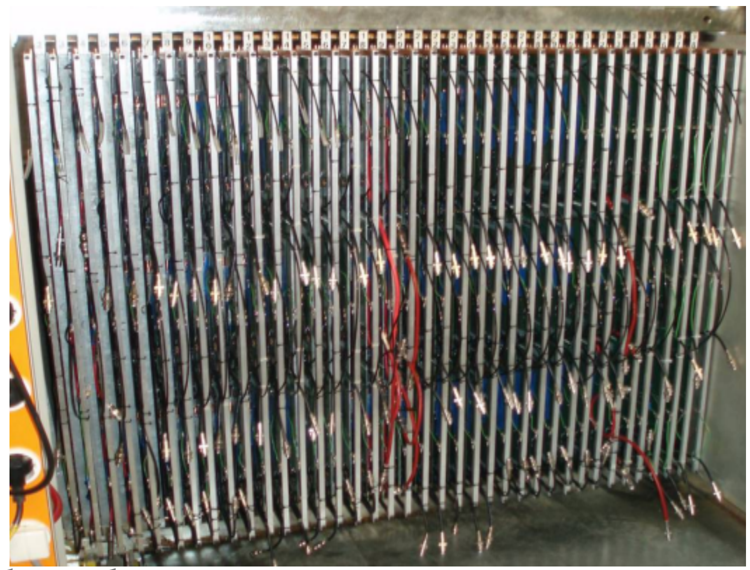
Single 1.15 mm thick gas gap

Readout

1 x 1 cm^2 pads

1-bit per pad/channel → digital readout

100-ns level time-stamping



Calorimeter

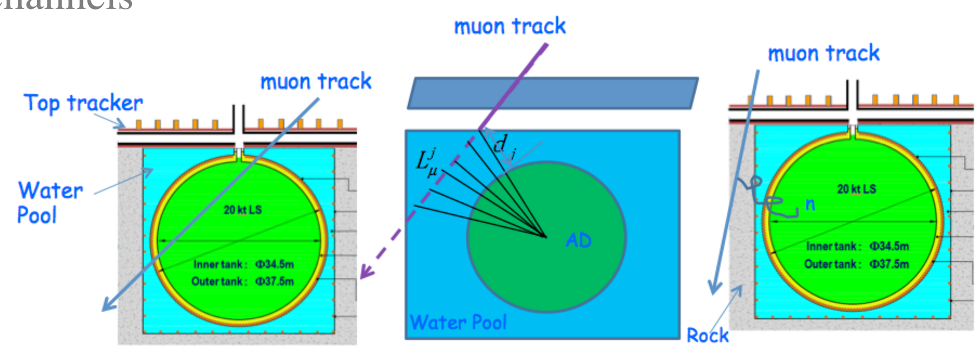
54 active layers

1 x 1 m^2 planes with each 9,216 readout channels

3 RPCs (32 x 96 cm^2) per plane

Absorber

Either Steel, Tungsten or none



Schedule

- JUNO Schedule as of January 15, 2015: the goal is to be the first experiment to measure the mass hierarchy at 3-5 σ level, by ~2024.
  -R&D FY15-16, project development FY16-18, Construction FY18-20, Operations FY20-24

		Start	end	condition
1	Underground lab construction	2015.1.1	2017.12.31	
2	Water pool cleaning and CD construction preparation	2018.1.1	2018.3.31	1
3	CD & water poll equipment installation	2018.4.1	2018.11.30	2
4	PMT base(& to be sealed electronics) design finalized	2016.1.1	2016.9.30	
5	PMT base production and aging test	2016.10.1	2017.5.30	4
6	PMT bidding	2015.7.1	2015.12.31	
7	PMT mass production	2016.1.1	2018.11.30	6
8	PMT testing	2017.1.1	2018.12.31	
9	PMT water-proof sealing and testing	2017.7.1	2019.1.30	5
10	CD & VETO PMT installation	2018.12.1	2019.2.28	
11	Readout electronics design finalized	2017.1.1	2017.5.30	
12	Readout electronics mass production	2017.6.1	2018.5.30	11
13	Readout electronics testing and aging	2018.4.1	2018.11.30	12
14	Readout electronics installation	2018.10.1	2019.2.28	
15	CD & water pool cleaning	2019.3.1	2019.3.31	
16	Water pool cover is placed	2019.4.1	2019.4.10	15
17	TTS supporting structure installation	2019.4.10	2019.4.30	16
18	TTS installation	2019.5.1	2019.7.30	17
19	AD & VETO water filling	2019.4.1	2019.4.30	18
20	LS filling	2019.5.1	2019.7.30	19
21	Test run	2019.8.1	2019.10.30	20

JUNO Status

- DOE is currently not supporting the US participation in JUNO.
  - -However in December 2014 we did receive a financial support for ANL engineering to help design of the JUNO central detector, perform analysis of existing designs, and start developing calibration subsystems.
  - -Had a US-JUNO phone briefing with DOE in January 2015.
  - -Further support to JUNO most likely conditioned by Chinese support to US programs.

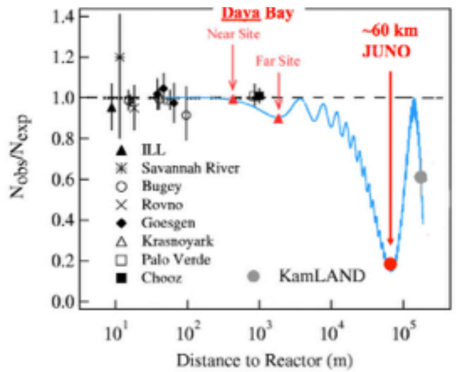
- JUNO was presented as an option for ANL HEP involvement at DOE budget briefing for FY16.

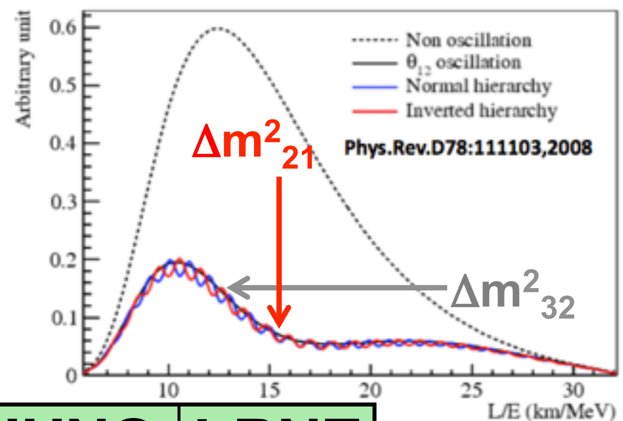
Summary

- JUNO is a new generation reactor anti-neutrino experiment with major goal to determine neutrino mass hierarchy in a way orthogonal to long-baseline accelerator neutrino oscillation searches.

- ANL is in a very good position to establish leadership roles, in areas of
  -Mechanical Engineering of the central detector (design and construction)
  -Photo-detectors. LAPPD could be used at least partially if available early, or for a later upgrade.
  -Photo-detector characterization (Q&A). Need requirements and a system to closely characterize a large number of photo-detectors.
  -Guide tube calibration system design and construction.
  -RPC (resistive plate chamber) system used for veto/muon-tagger).
  -Potential design, development, and operation of a positron accelerator.
  -Simulation and data analysis when the experiment is underway.

- HEP/PHY collaboration would make ANL participation stronger in existing areas of interest
  -there may exist additional areas of contribution.





	JUNO	LBNE
$\sin^2 2\theta_{12}$	0.7%	
Δm^2_{21}	0.6%	
$\lvert\Delta m^2_{32}\rvert$	0.5%	0.3%
MH	3–4σ	>5σ
$\sin^2 2\theta_{13}$	14%	3%
$\sin^2 2\theta_{23}$		3%
δ_{CP}		10°