JUNO:

the Calibration Strategy

J. Pedro Ochoa-Ricoux*
University of California, Irvine
**On behalf of the JUNO collaboration*

Workshop on the evolution of advanced electronics and instrumentation for water Cherenkov detectors, April 2022

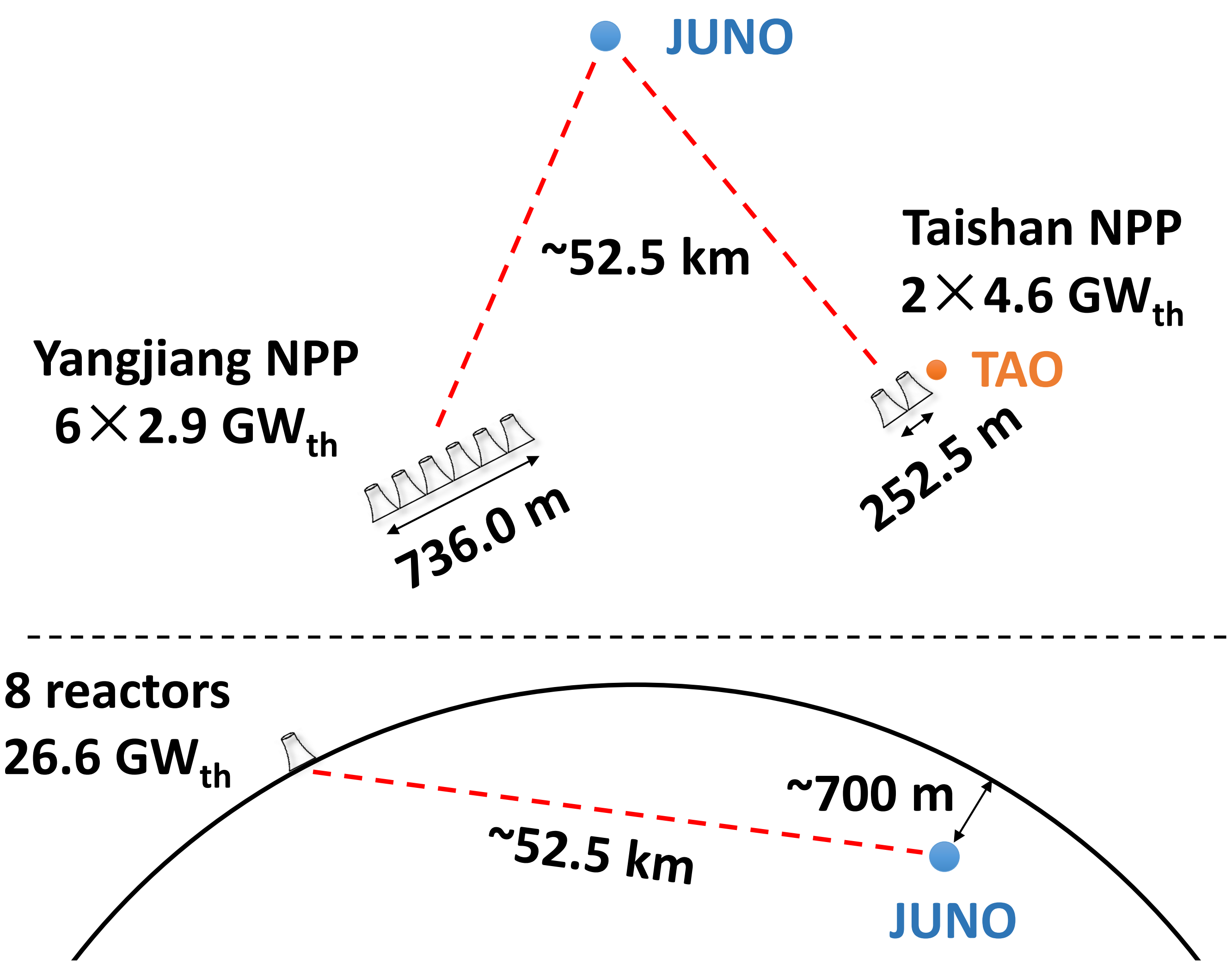
Outline

- JUNO Basics
- Calibration System
- 3-inch PMT System
- Performance Demonstration
- Summary & Conclusions

JUNO Basics

JUNO at a Glance

- The **J**iangmen **U**nderground **N**eutrino **O**bservatory (JUNO) is a large multi-purpose experiment under construction in China:
  - 53 km from two major nuclear power plants (8 reactors)
  - 35 m diameter sphere with 20 ktons of liquid scintillator (LS)
  - Unprecedented energy resolution of 3% at 1 MeV
  - Satellite detector (TAO) at one of the Taishan reactor cores

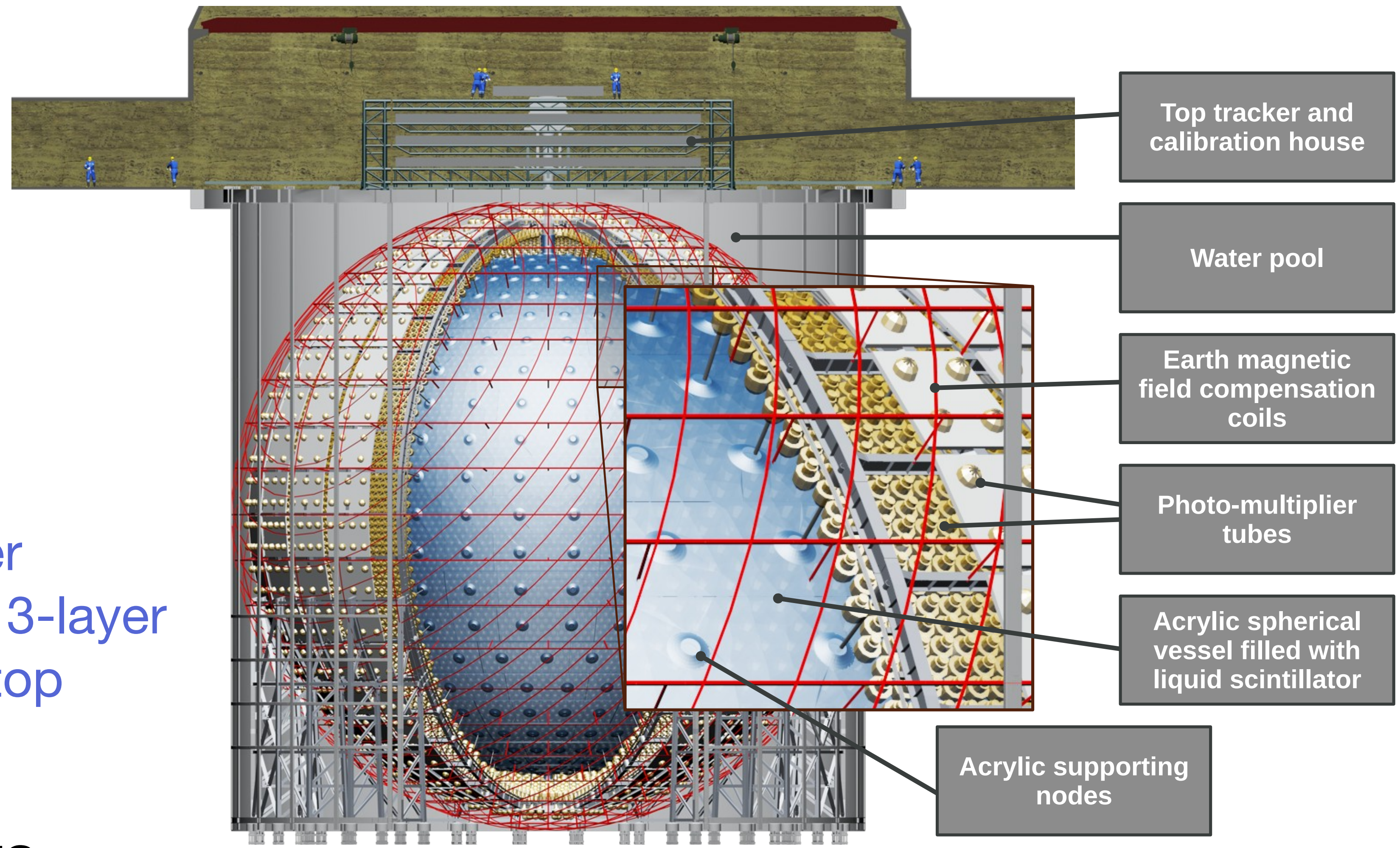


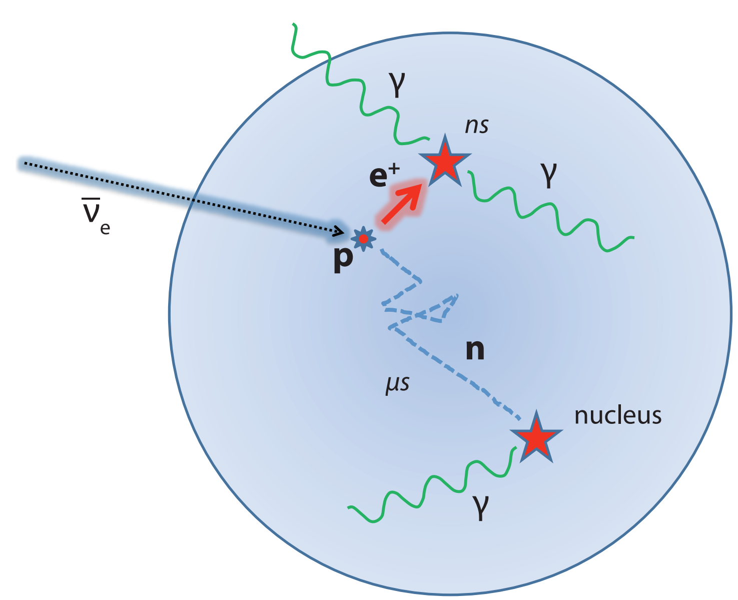
JUNO at a Glance

- 20 kton LS central detector (CD) surrounded by 17,612 large (20-inch) and 25,600 small (3-inch) PMTs
  - Optically decoupled from surrounding 35 kton water Cherenkov detector, with 3-layer scintillator tracker at the top
- The primary detection channel is the Inverse Beta Decay (IBD) reaction:

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

  - Energy of positron preserves information about energy of incoming $\bar{\nu}_e$

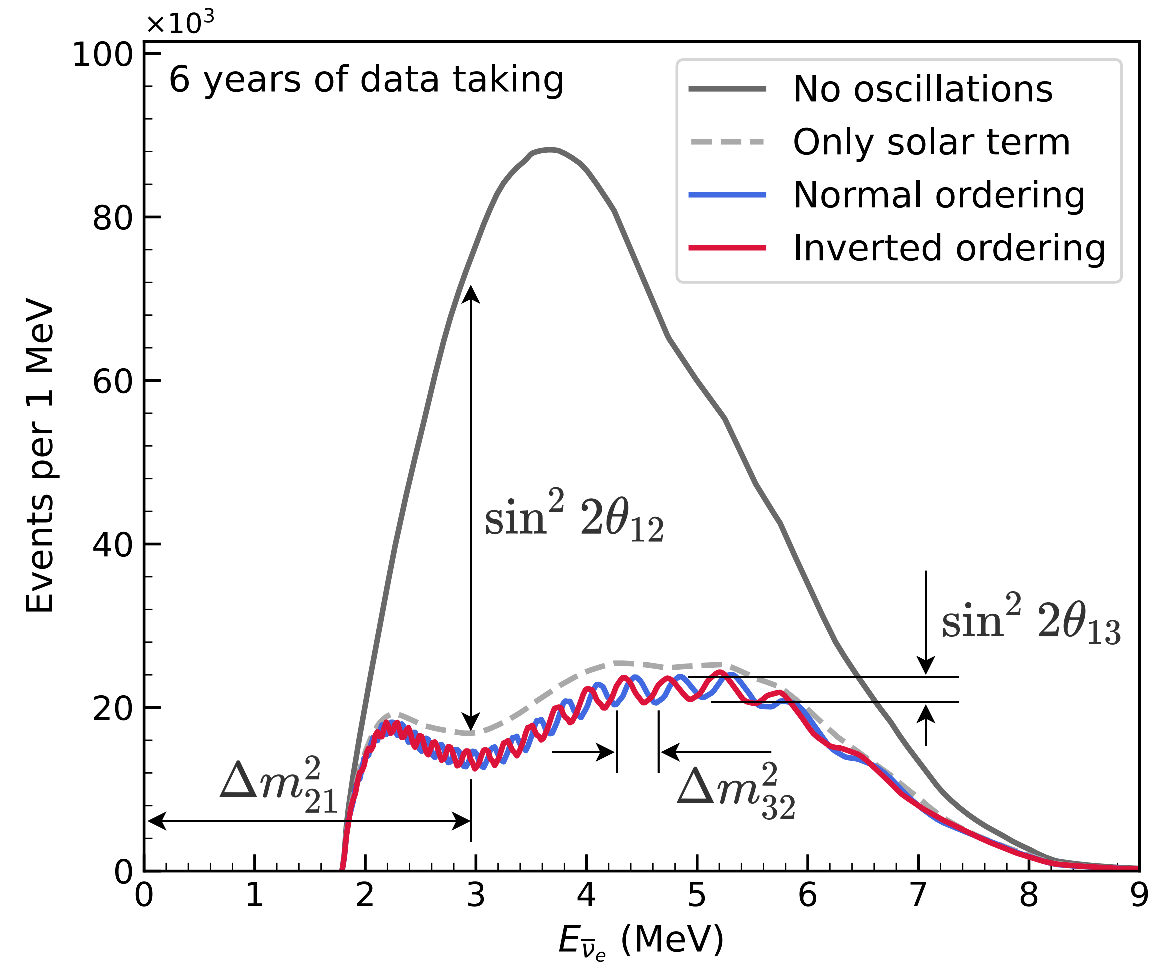




99% (1%) of n captures on H (C) with average delay time ~200 μs

Physics Goals

- Oscillation physics with reactor antineutrinos
  - Determination of the neutrino mass ordering
    - ~**3σ** sensitivity within 6 years
  - Measurement of $\sin^2 2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to ~0.5% or better in 6 years
- Rich program with neutrinos from natural sources
  - Solar neutrinos (^{8}B and perhaps ^{7}Be & pp)
  - Supernova neutrinos (burst & DSNB)
  - Atmospheric neutrinos
  - Geoneutrinos
- Great experiment to search for new physics
  - For example, proton decay with the $p \rightarrow \bar{\nu} + K^+$ channel



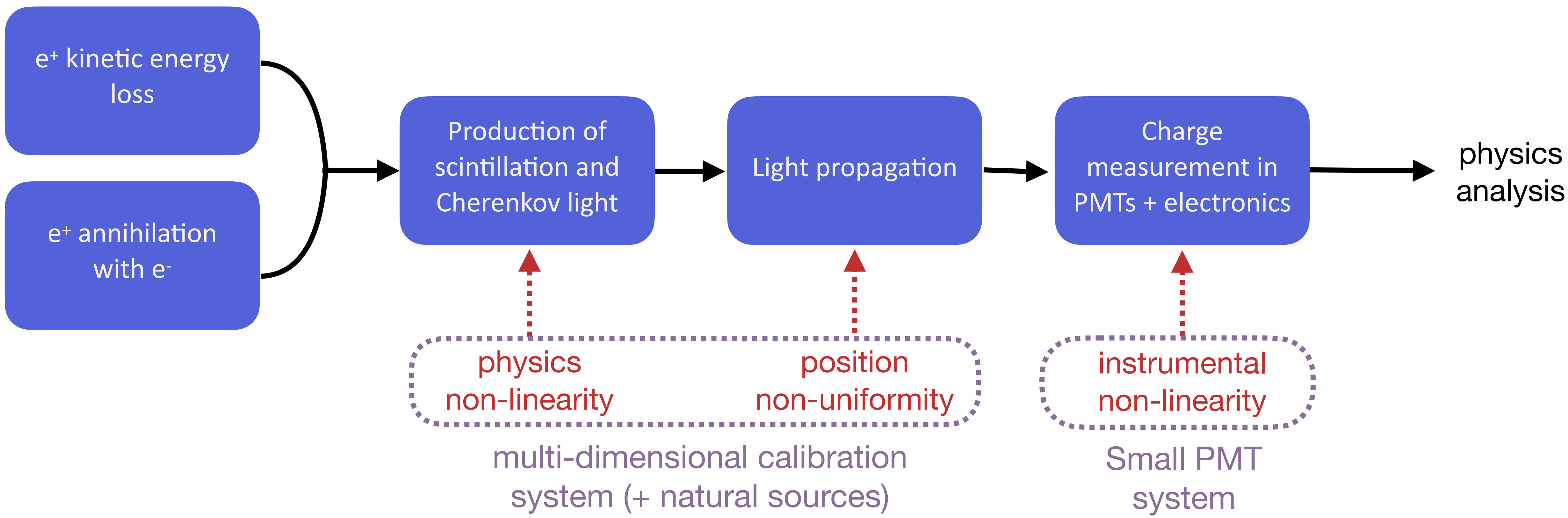
Parameter	Current precision (1σ)	JUNO Expected
$\sin^2\theta_{12}$	4.2%	~0.5%
Δm_{21}^2	2.4%	~0.3%
Δm_{31}^2	1.4% sign unknown	~0.2% sign determination

Key Calibration Requirements

- Physics goals impose extremely tight requirements on calorimetry systematics:
  - Energy resolution <3% between 1 and 8 MeV
  - <1% energy scale uncertainty

Calibration is essential to both of these goals! Of course, there are also detector-related requirements (PMT optical coverage, PMT detection efficiency, LS transparency, background mitigation… etc)

- Energy response chain:



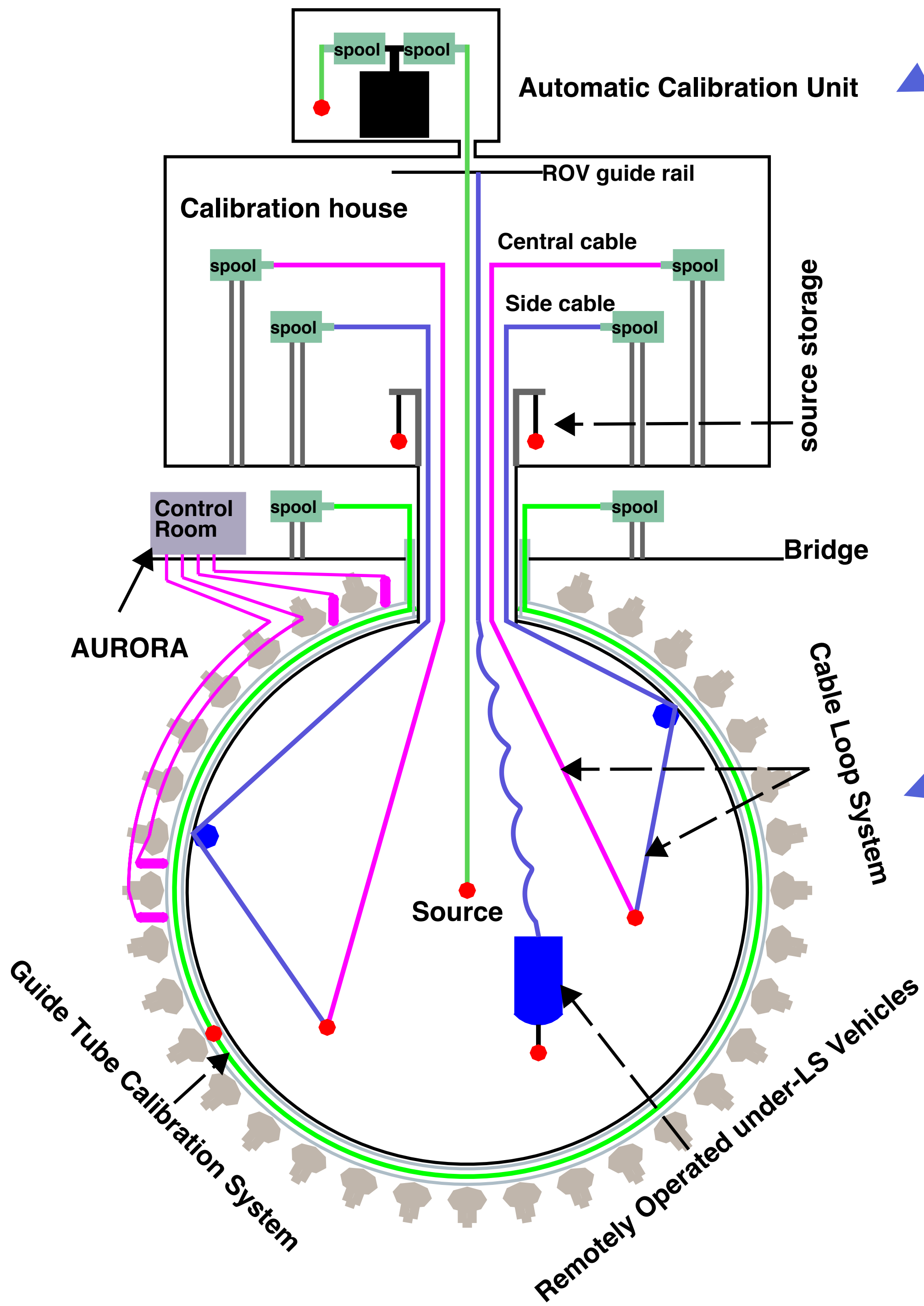
Effects in **red** must be properly calibrated for in order to satisfy these requirements

- Rest of this talk: calibration system, small PMT system, performance

Calibration System

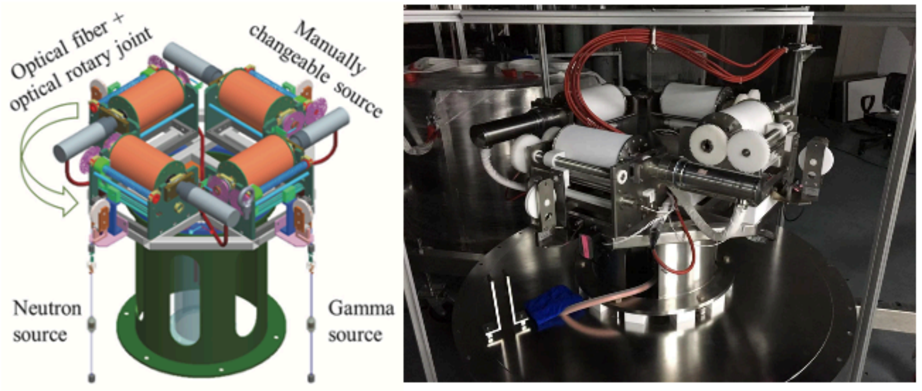
Overview of Calibration System

- Comprehensive calibration program with **four** complementary multi-dimensional scan systems:



Automated Calibration Unit (ACU)

1D Central Axis Scan with gamma sources, neutron sources and pulsed UV laser

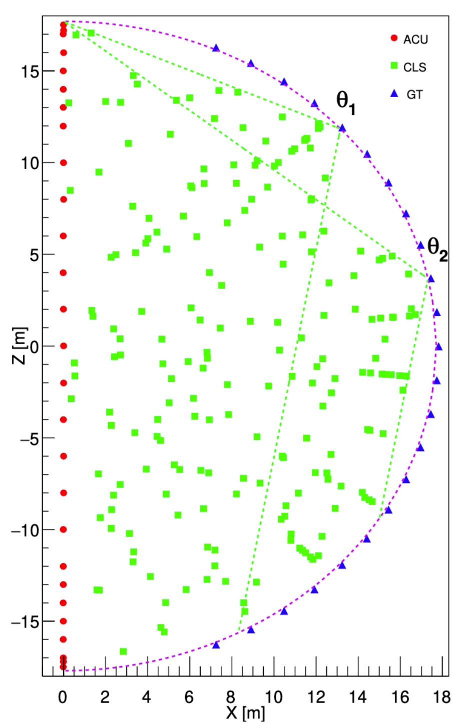


ACU diagram and prototype
1cm positioning precision

Cable Loop System (CLS)

2D source scan on two opposite half-planes

3cm positioning precision (with ultrasonic system)

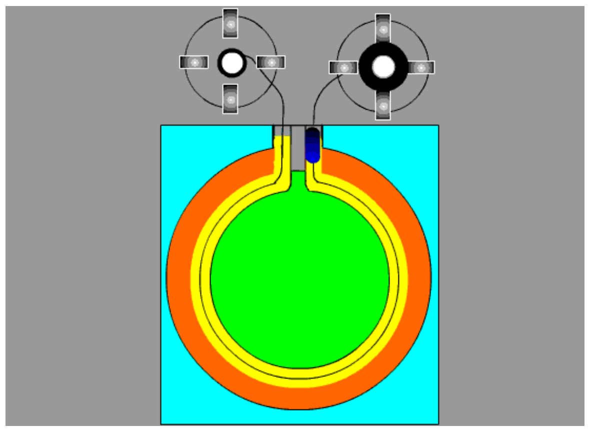


ACU: JINST 16 (2021) 08, T08008
CLS: NIMA 988 (2021) 164867

Overview of Calibration System

Guide Tube Calibration System (GTCS)

Deploy radioactive source along the periphery of the CD


Main concept

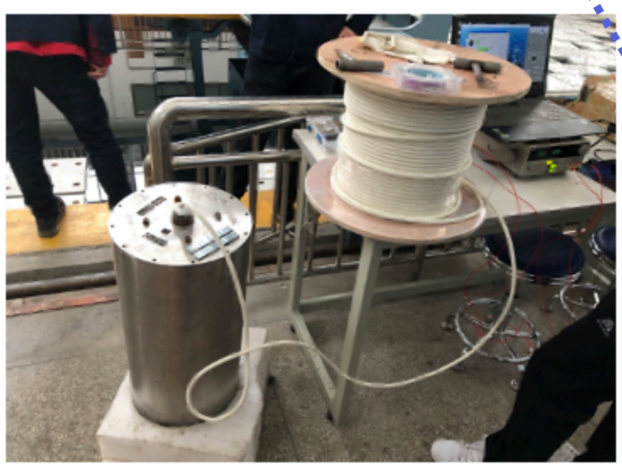

1:1 prototype

3cm positioning precision

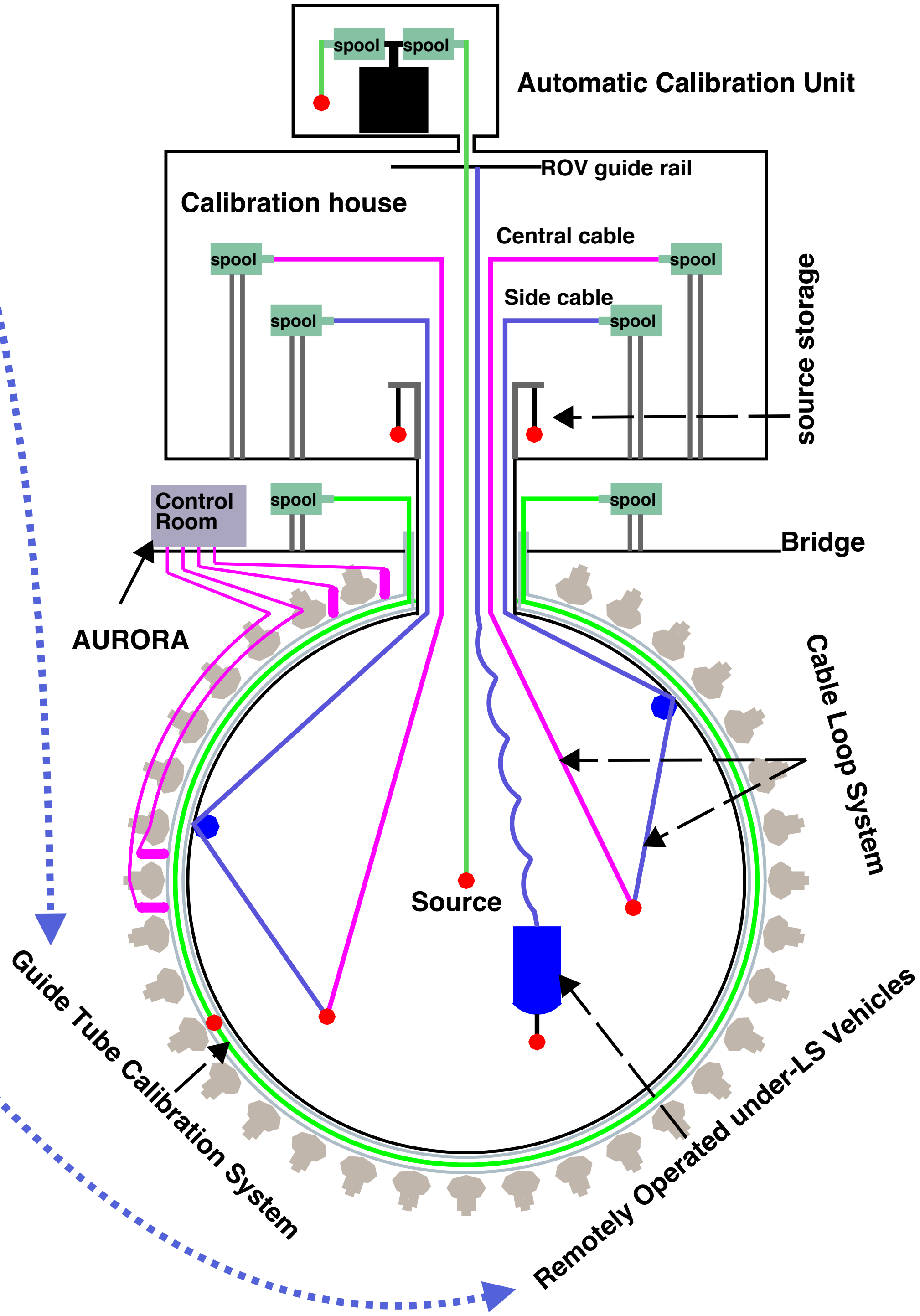
Remotely Operated Vehicle (ROV)

3D source scan with self-driven vehicle


ROV test in water


ROV

3cm positioning precision (with ultrasonic system)



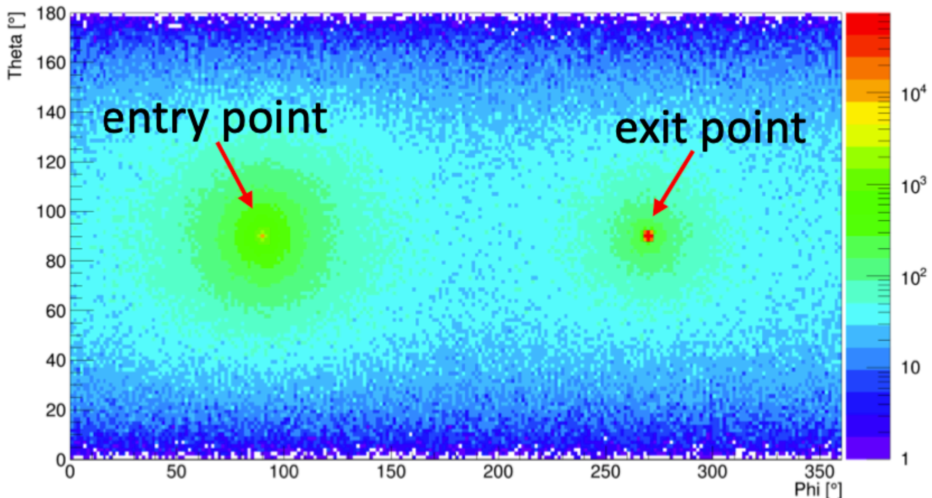
GTCS: JINST 14 (2019) 09, T09005

Auxiliary Systems

A Unit for Researching Online the LSc tRAnsparency (AURORA)

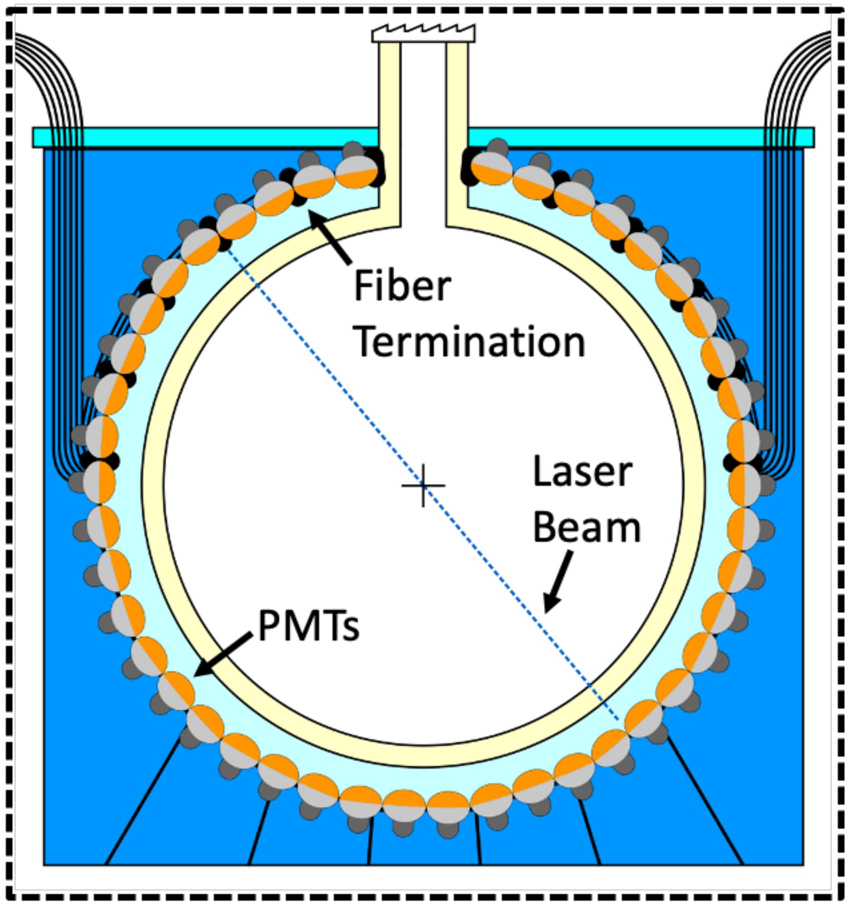
Monitor LS attenuation, scattering, and absorption lengths with laser beams

Anticipated absolute precision of 1m

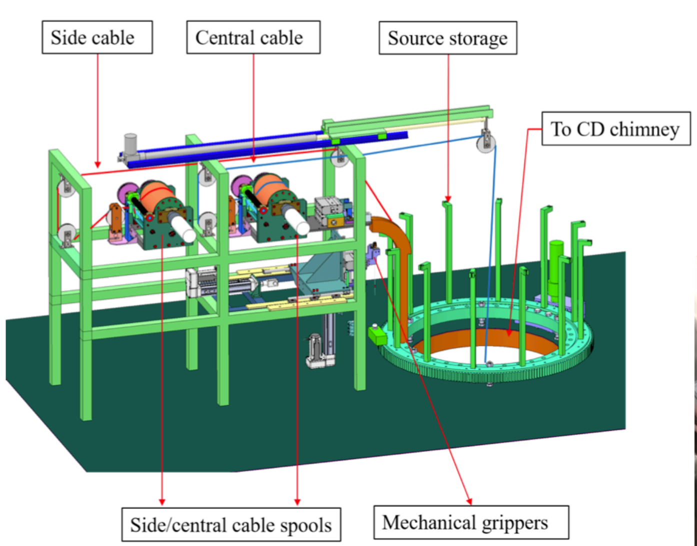


Simulated hit map

Central Detector (CD)

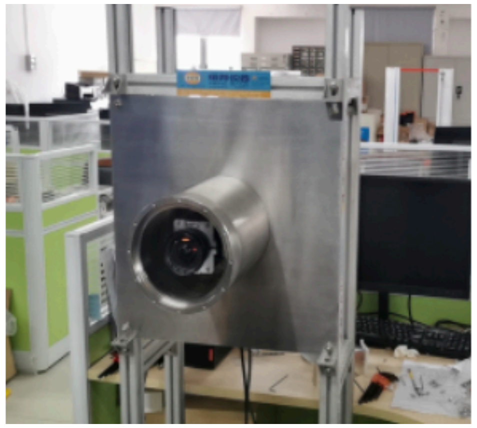


Calibration House



Positioning Systems

Ultrasonic receiver (8 in total)

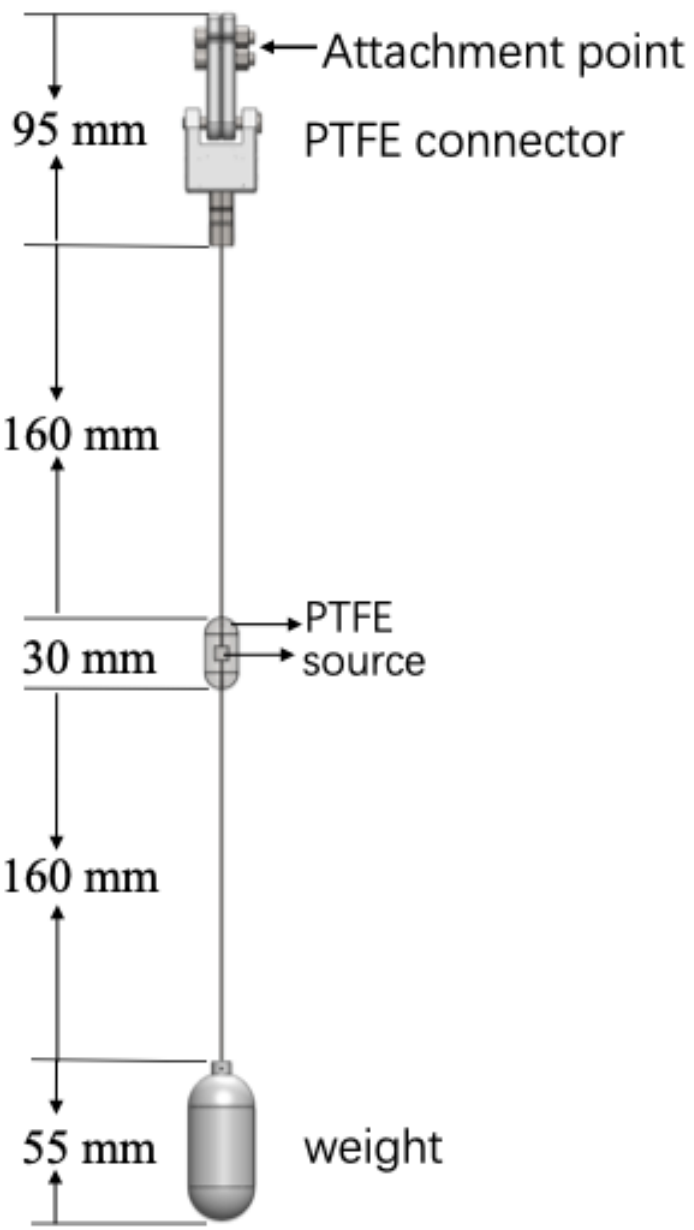


CCD prototype

Calibration Sources

- Use a wide range of calibration sources spanning the energy range of interest
  - Source assemblies designed to minimize optical shadowing and energy loss effects

Design of Typical Source Assembly



List of Calibration Sources

Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV

JHEP 03 (2021) 004

The Small PMT System

Motivation

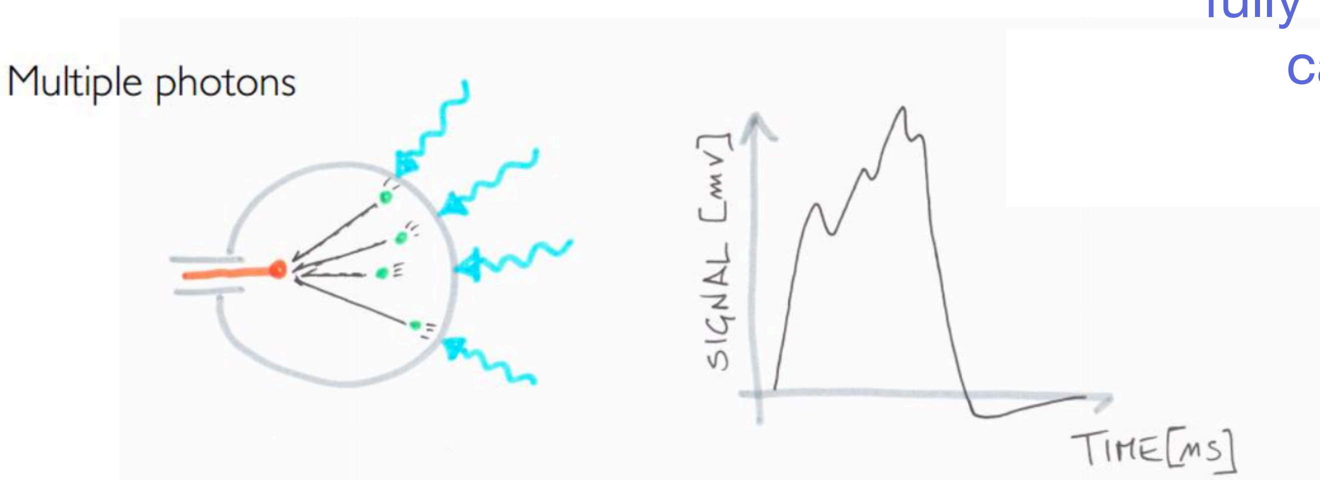
- JUNO will have to control the non-stochastic term of the resolution at an unprecedented level (≲1%)

$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{STOCH}}{E} + \sigma^2_{NON-STOCH}}$$

< 1% never achieved before!

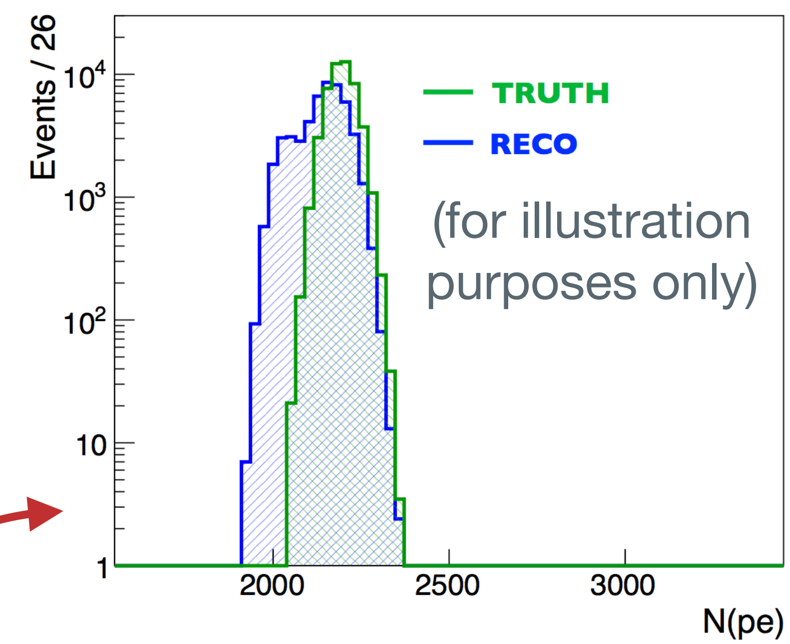
Example of how residual systematics could affect JUNO:

1) Charge extraction with the large PMTs + electronics is non-trivial (0-100 PE) and can lead to systematics (e.g. non-linearity)



2) Non-linearities in the charge reconstruction would introduce an artificial non-uniformity

3) This effect is <u>energy dependent</u> and thus cannot be fully taken out with calibrations.



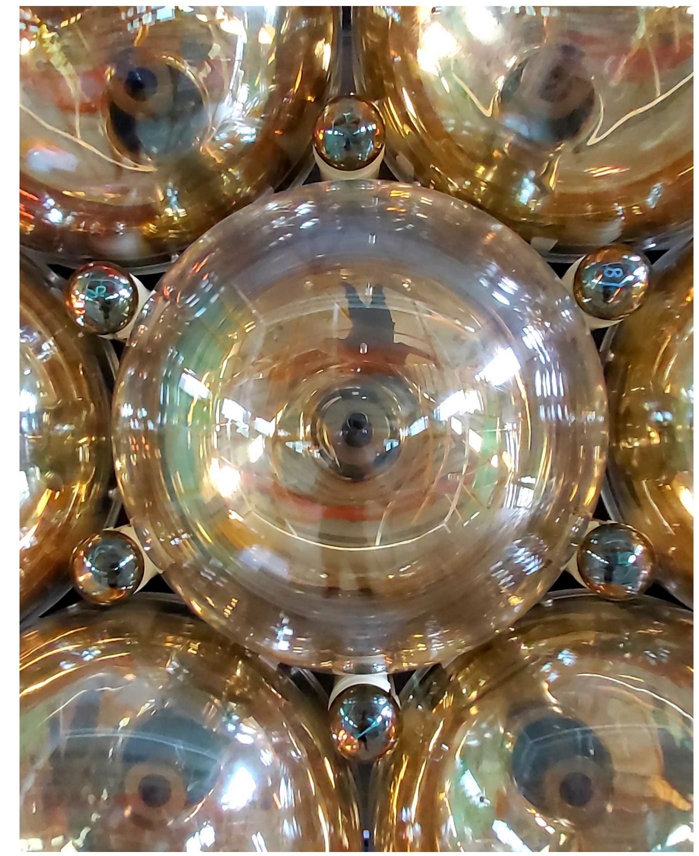
Example: trying to reconstruct 2.2 MeV events with a non-uniformity map derived with 1 MeV events (assuming hypothetical 1% charge non-linearity)

(Plots from M. Grassi's talk on double-calorimetry at WIN 2017)

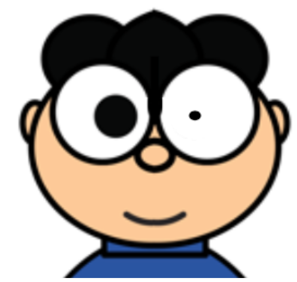
- Different calibration terms can become (hopelessly?) entangled, degrading the resolution

The Small PMT System

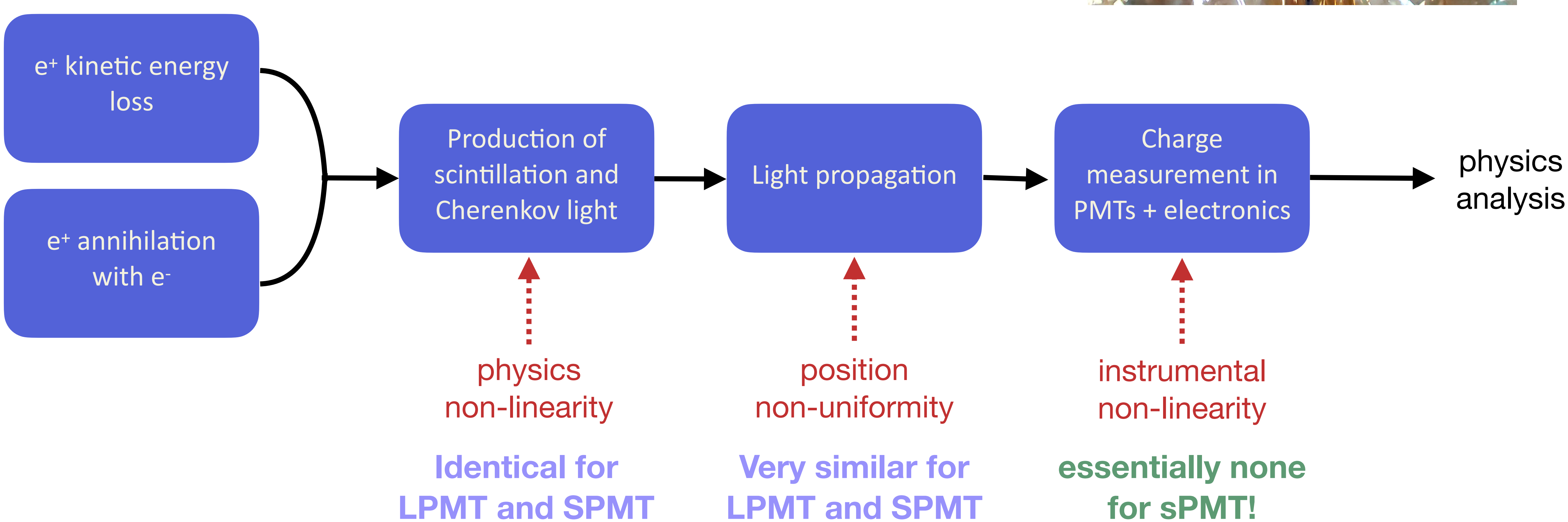
- Solution: JUNO will have 25,600 small PMTs (sPMTs) in the space between the large ones (LPMTs)



Basic principle: look at the same events with two sets of "eyes" that have different systematics



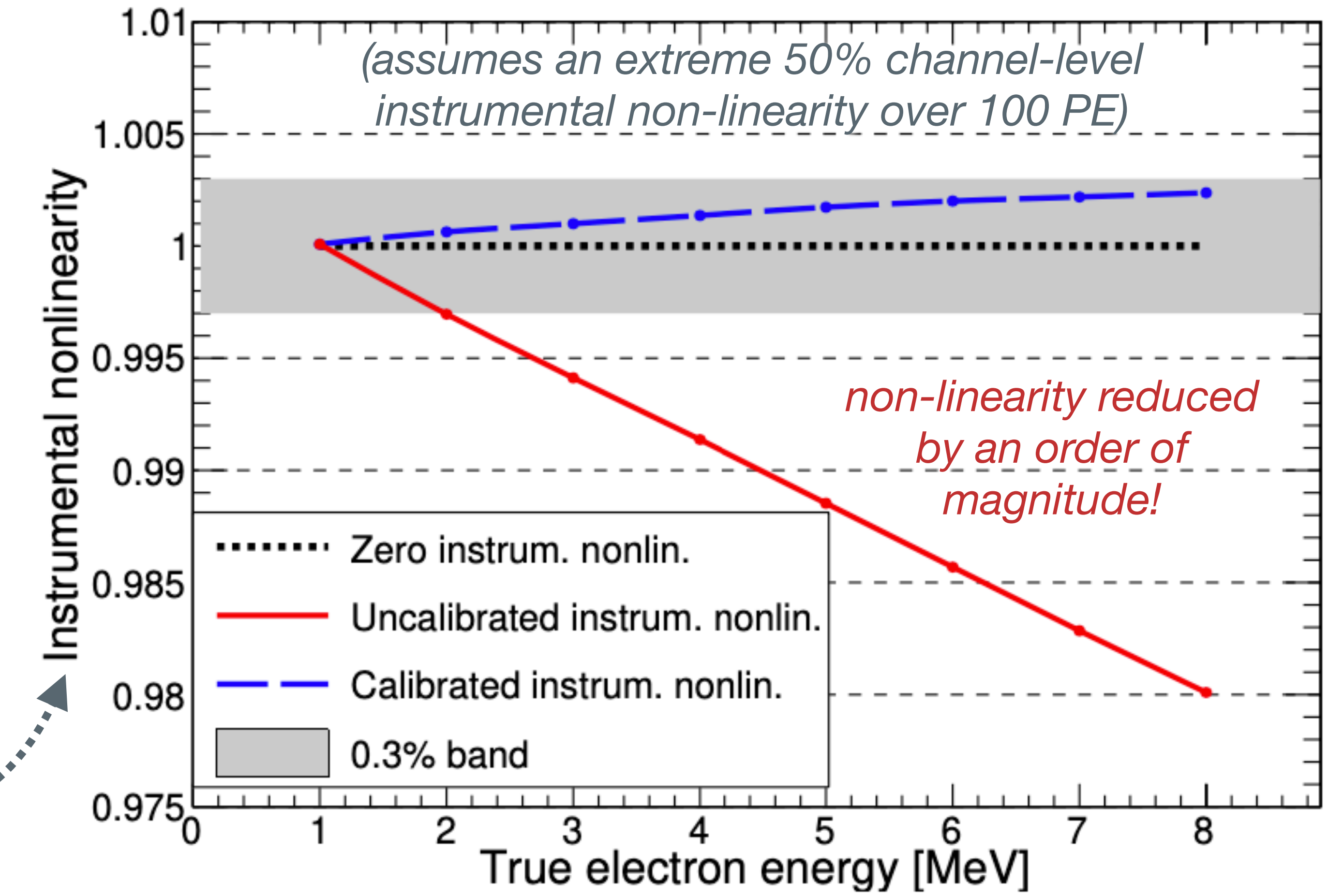
In particular, the sPMTs will operate predominantly in photon-counting mode for 0-10 MeV and will thus **serve as a linear reference**



Double Calorimetry Calibration

- Can directly disentangle the instrumental LPMT+electronics non-linearity with the sPMT system
- Comparison between LPMT and sPMT systems can be implemented in many ways
  - Possibly the most straightforward: **each channel LPMT calibrated to full sPMT response using UV laser at the detector center**
  - Procedure immune to physics non-linearity and non-uniformity
  - Other implementations (with gamma sources and/or physics events) under investigation

event-level instrumental non-linearity (total measured charge / true charge)



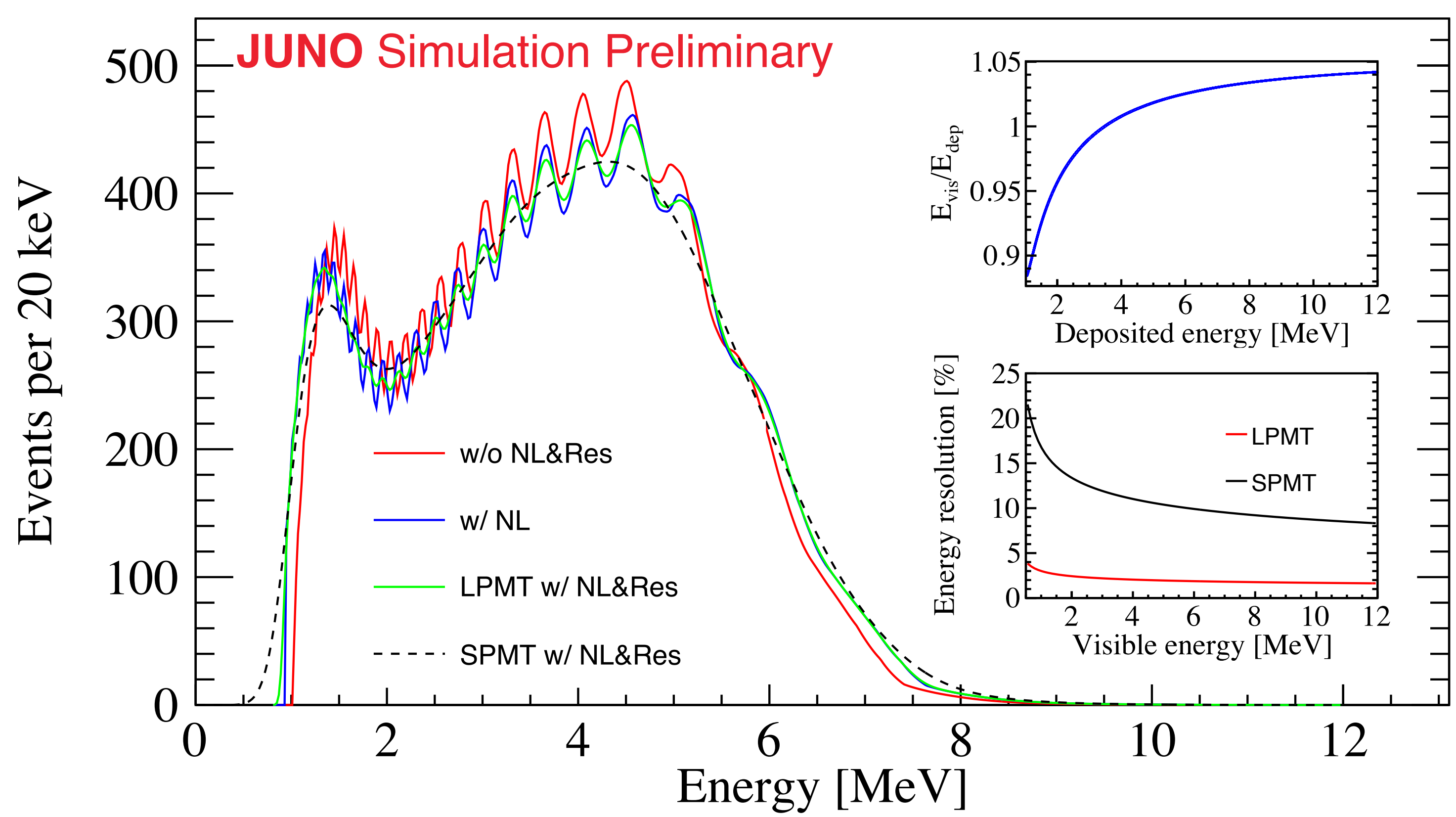
- Provides resiliency even against extreme charge non-linearity scenarios

JHEP 03 (2021) 004

Additional Benefits

- The small PMTs also bring other nice benefits to the table:
  - Aid to position reconstruction and muon reconstruction due to the better timing resolution compared to the Microchannel Plate 20-inch PMTs
  - Aid to supernova burst neutrino measurement
  - Larger dynamic range
  - Semi-independent physics (e.g. measurement of solar parameters)

JUNO 6 years data taking



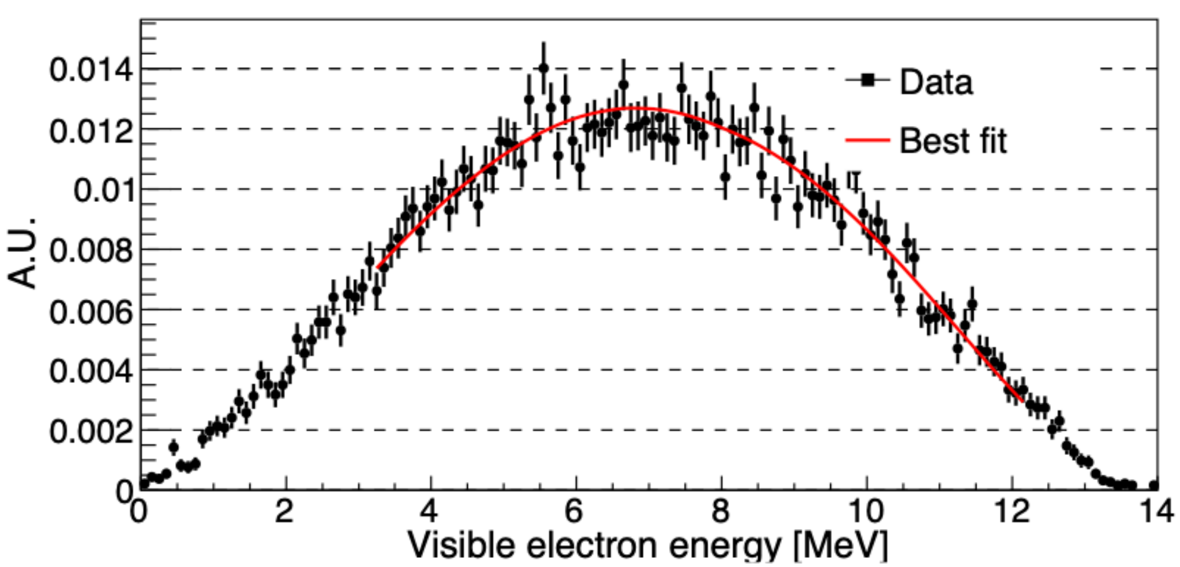
See backup for more technical information on the sPMT system

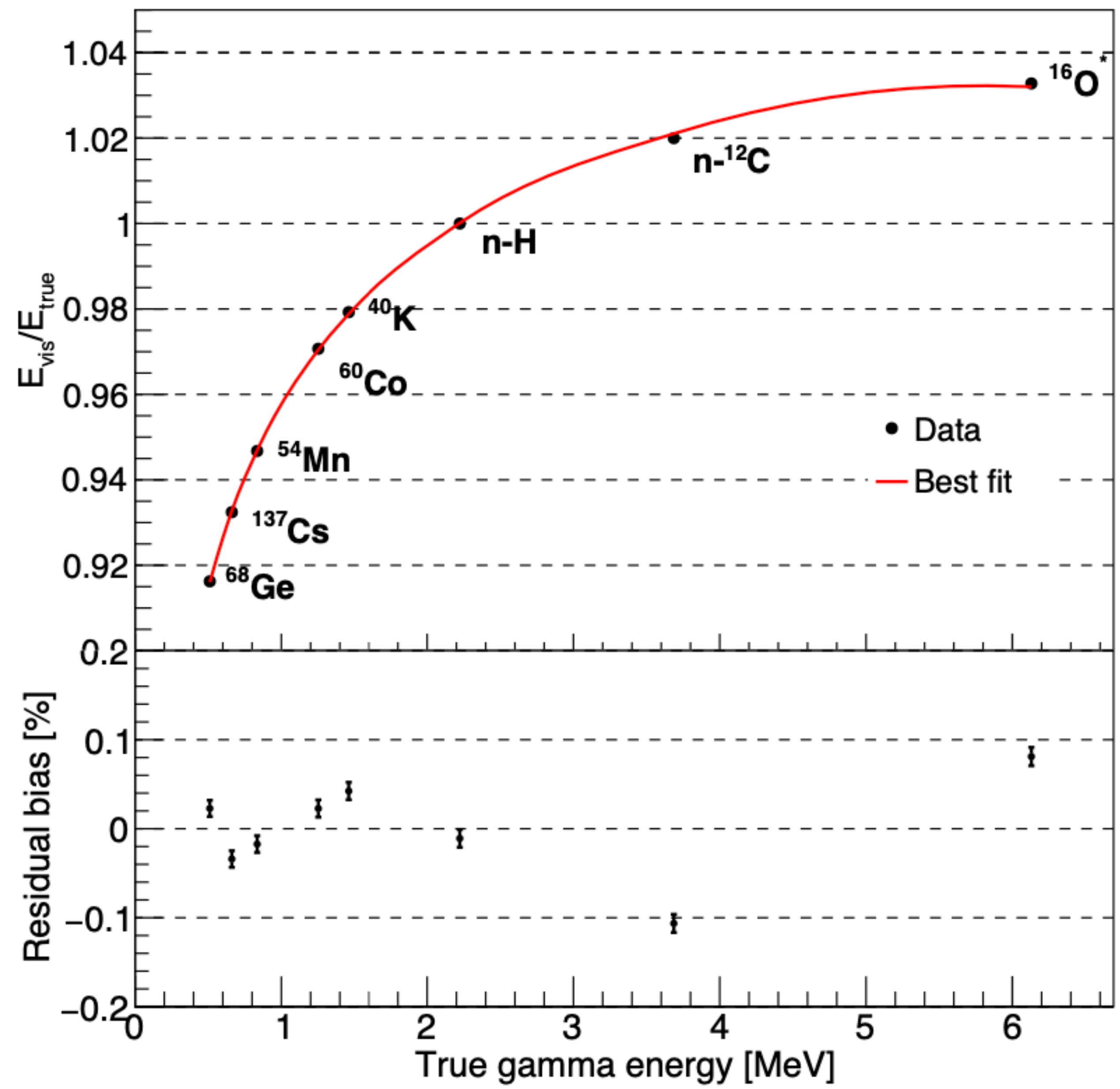
  - A little extra light (~45 photoelectrons per MeV)

Calibration Performance

Physics Non-Linearity

- Have performed a comprehensive study with simulated data to demonstrate the ability to calibrate the detector
    - Use gamma sources and ^{12}B cosmogenic background to calibrate the physics non-linearity

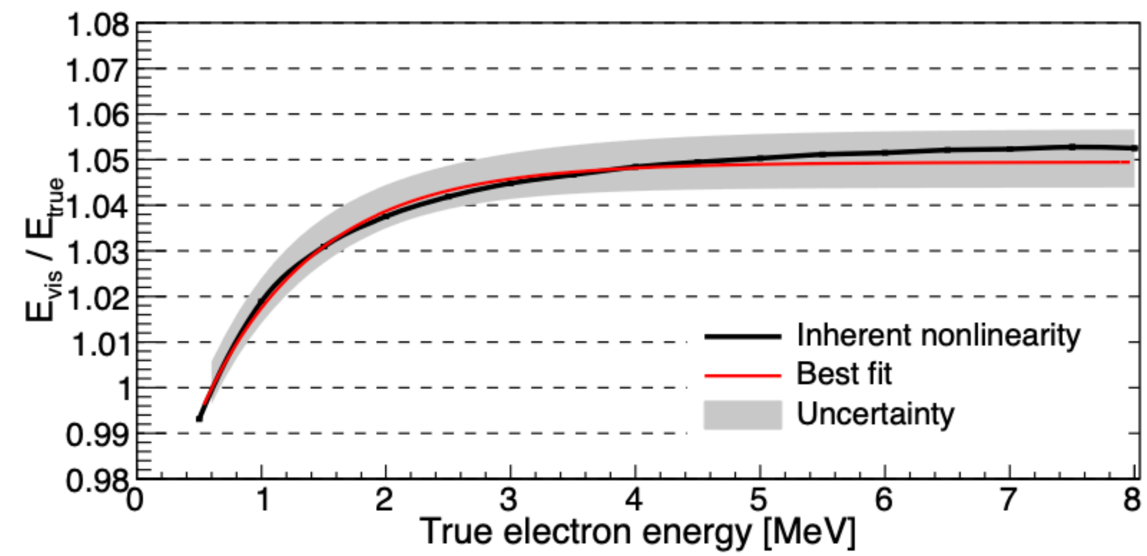


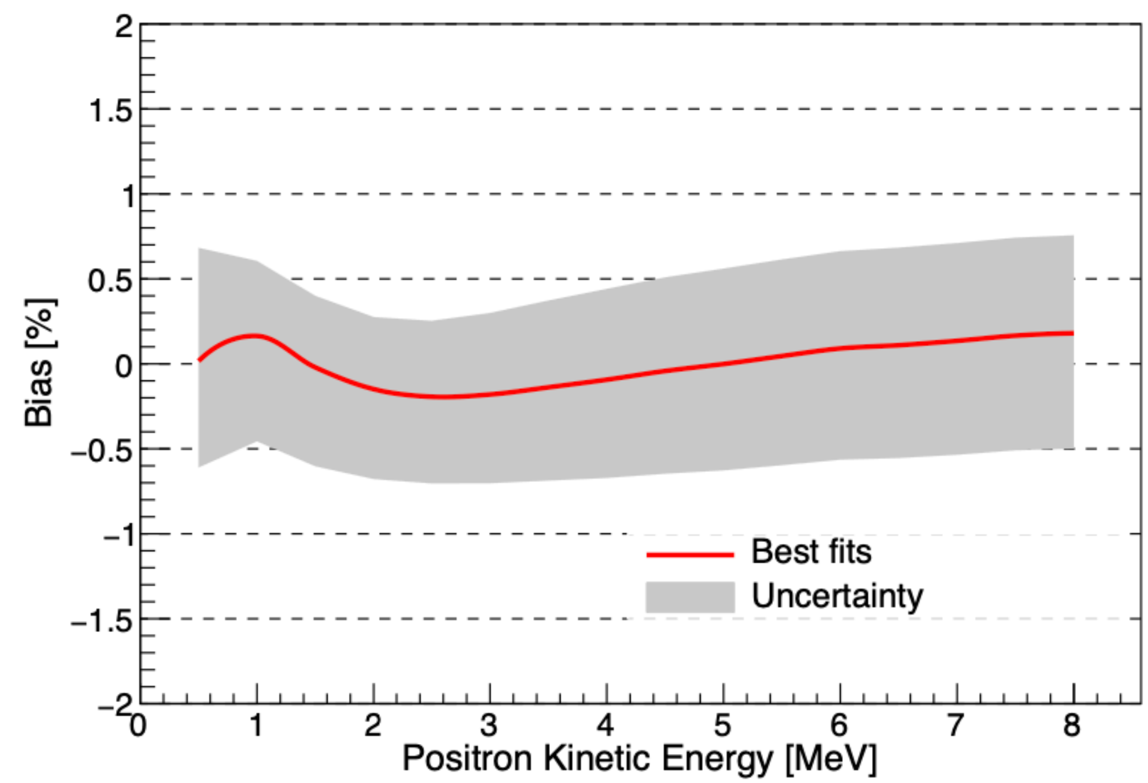


JHEP 03 (2021) 004

Performance

- Randomly bias the fake data sets with the following systematic uncertainties:
  - Shadowing effect: < 0.15%
  - Energy losses: < 0.1%
  - High-energy gamma uncertainty: <0.4%
  - Instrumental non-linearity: < 0.3%
  - Position dependent effects: < 0.3%
  - Statistics: 0.01%
- Uncertainty band is ~0.7%, in agreement with the requirement
- This study also yields an energy resolution of 3.02% at 1 MeV





- Currently envision weekly calibrations lasting ~2.5 hours and occasional comprehensive calibration campaigns lasting ~2 days

JHEP 03 (2021) 004

Summary & Conclusions

Summary & Conclusions

- JUNO is a multipurpose neutrino observatory with a rich program in neutrino physics and astrophysics
  - Neutrino mass ordering, oscillation parameters, supernova ν's, solar ν's, atmospheric ν's, geo-ν's, proton decay, and others.
- The physics goals place stringent requirements on the energy calibration
- Our current strategy involves two systems working synergistically:
  - A comprehensive calibration system including four complementary multi-dimensional scan systems
  - A small PMT system serving as a reference for the primary 20-inch PMT system and bringing additional benefits
- Progress is well underway, and expect to complete the construction of the detector by 2023
- Anticipate some exciting results (and maybe some surprises?)

Stay tuned!

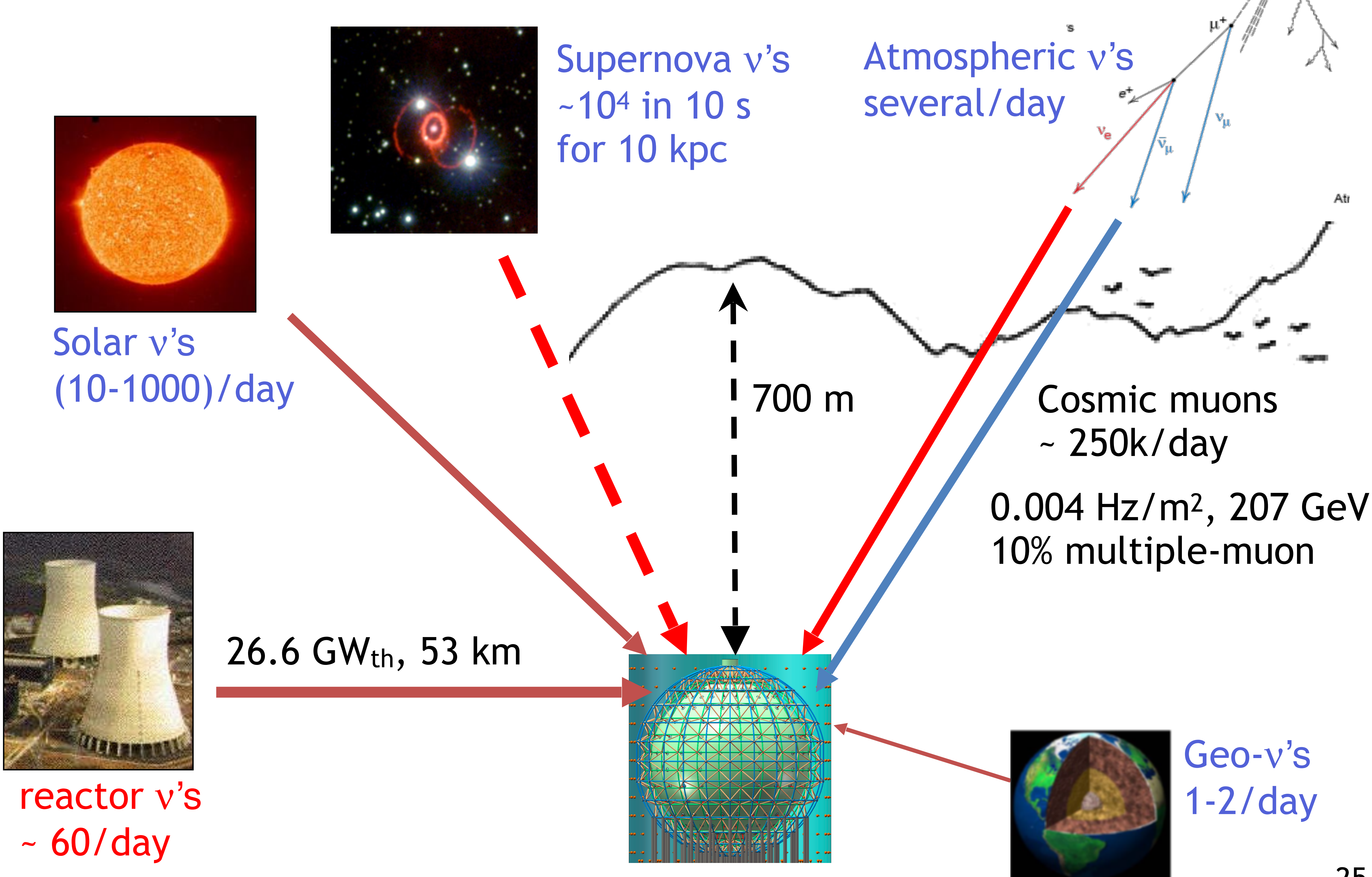
JUNO

The JUNO Collaboration: 76 institutions from over 17 countries

Thank you for your attention!

Backup

A Multipurpose Neutrino Observatory



Oscillation Physics with Reactor $\bar{\nu}_e$'s

- Determination of the neutrino mass ordering (NMO)
  - Exploit interference effects in the fine structure of the oscillated spectrum
  - **~3σ** sensitivity within 6 years
  - Independent of θ_{23} and δ_{CP}
    - Complementary information to that of other experiments
- Measurement of $\sin^2 2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to ~0.5% or better in 6 years

Parameter	Current precision (1σ)	JUNO Expected
$\sin^2\theta_{12}$	4.2%	~0.5%
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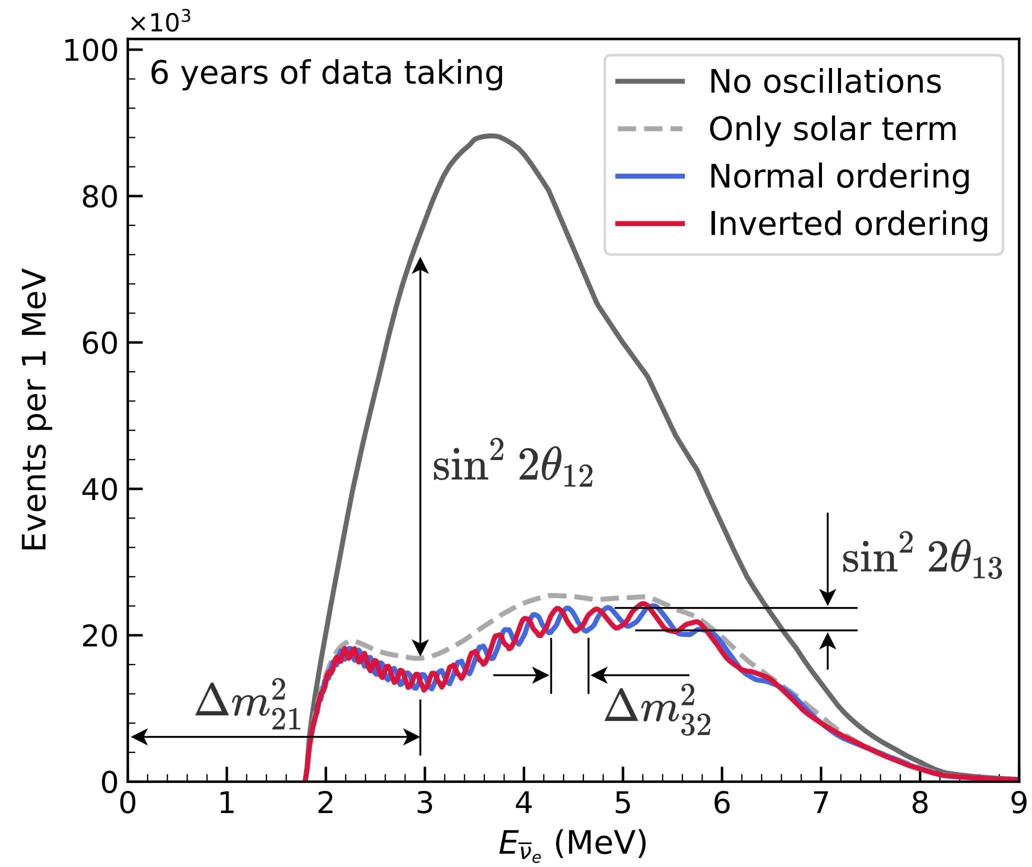
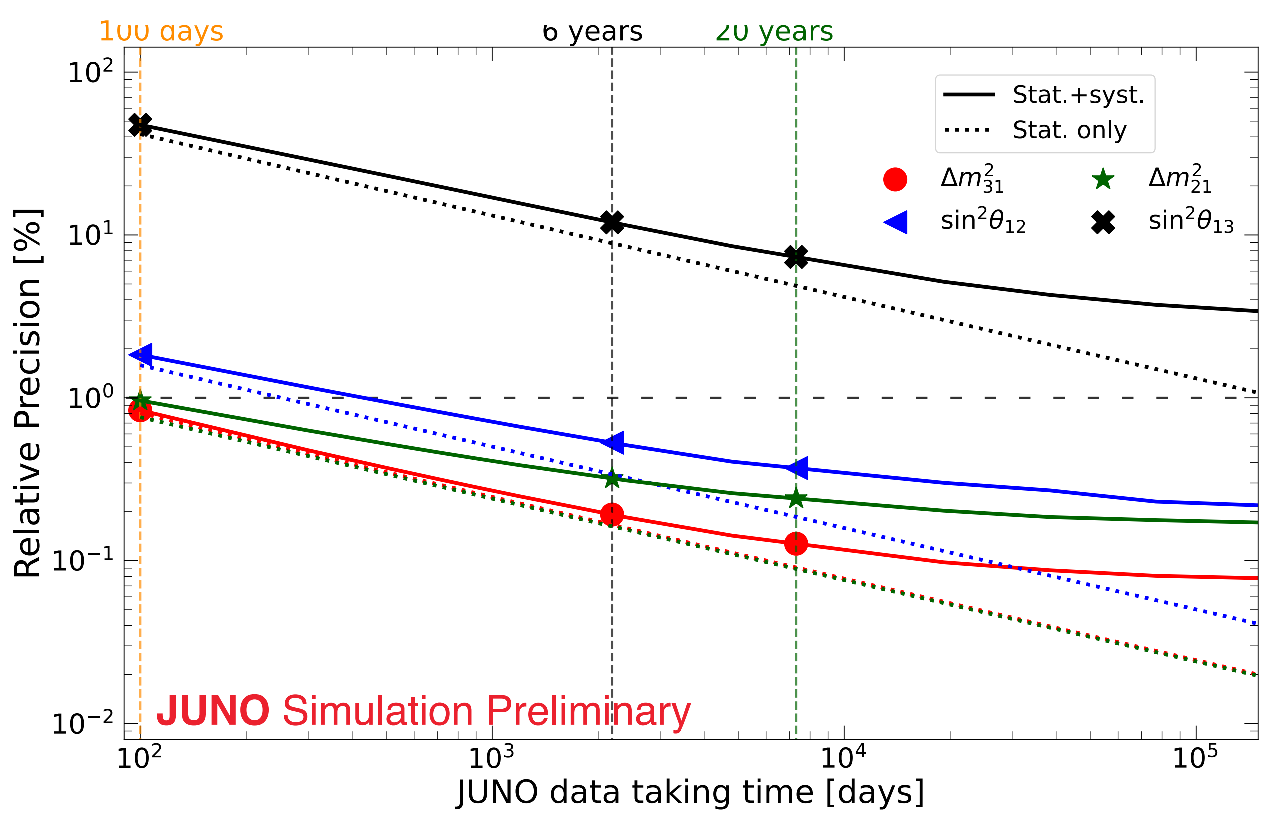
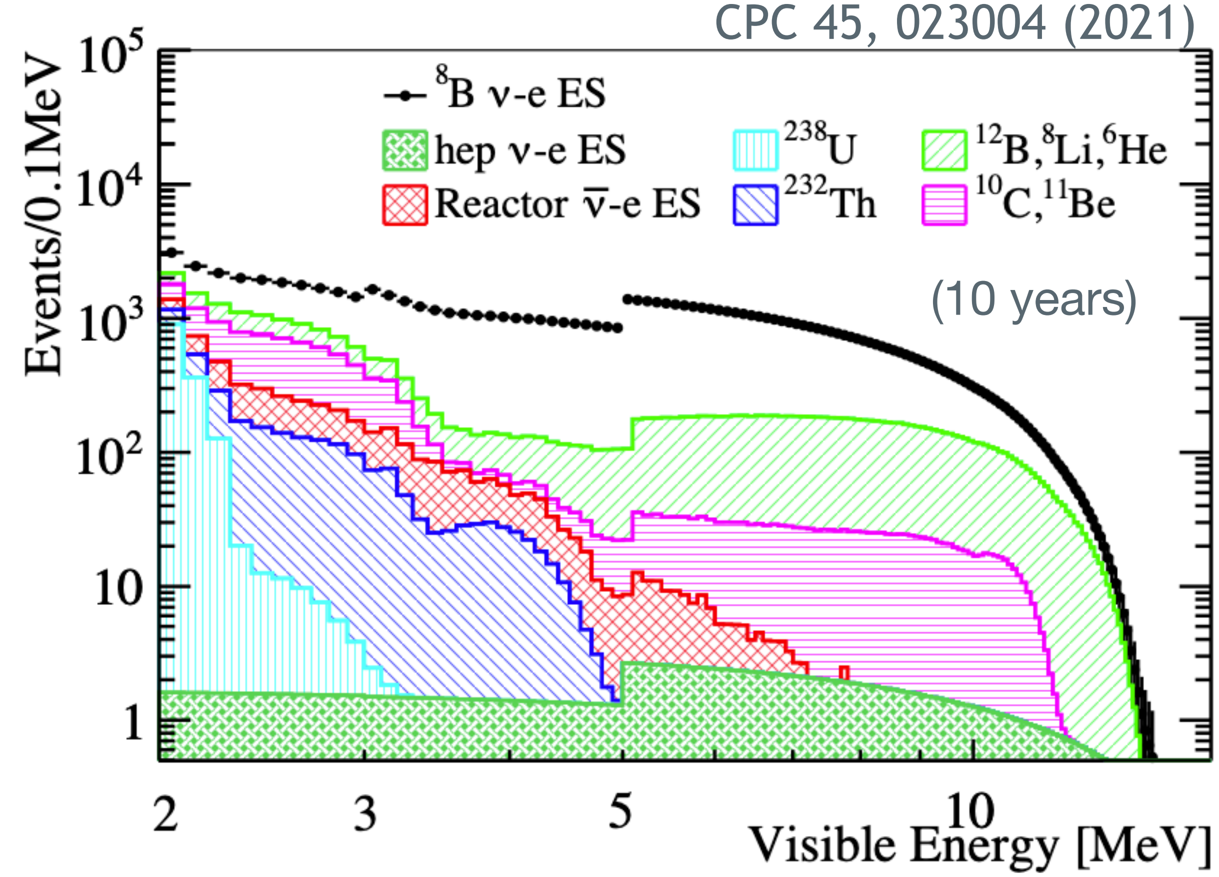
Δm^2_{31}	1.4% sign unknown	~0.2% sign determination

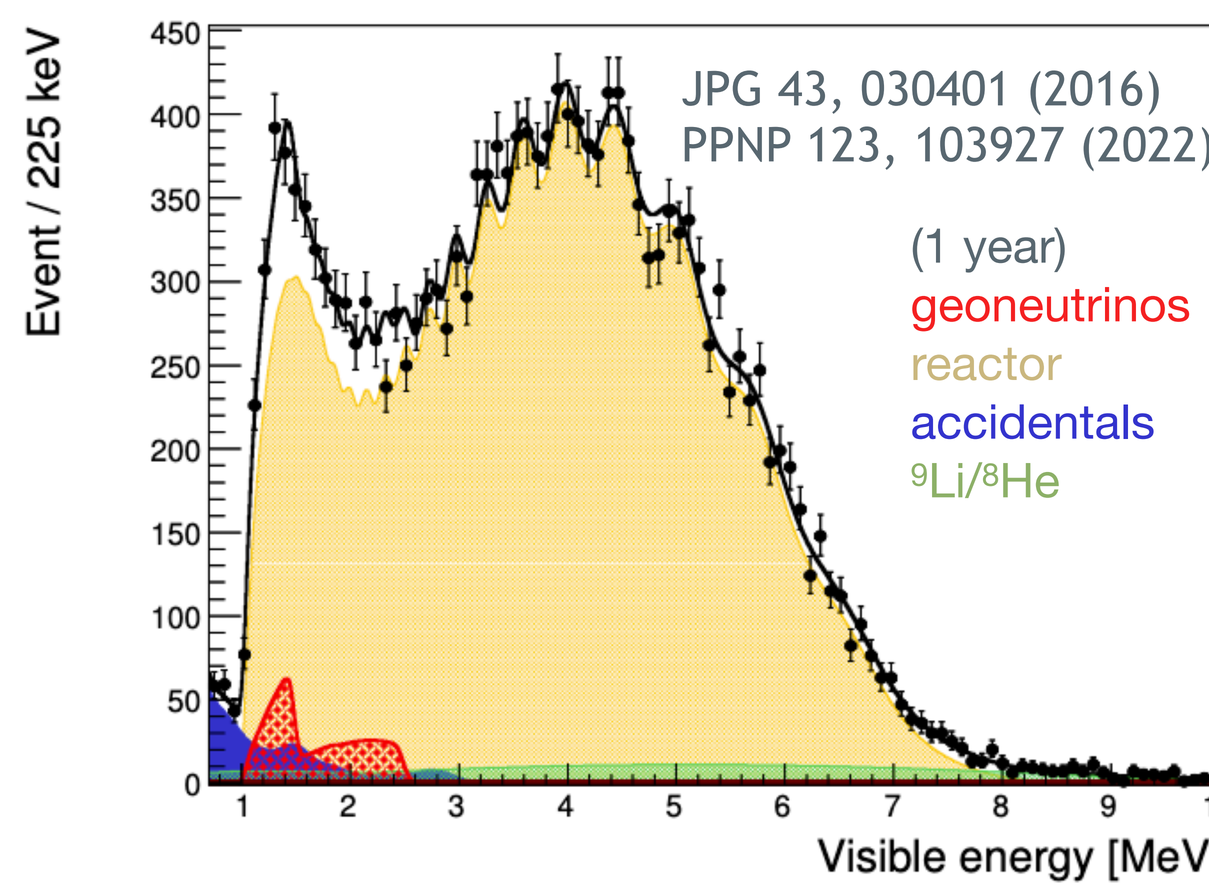




Solar, Atmospheric and Geoneutrinos

- Solar neutrinos:
  - Will collect a very large sample of ^{8}B neutrinos (60,000 events in 10 years)
  - May see solar neutrinos below 1 MeV (^{7}Be & pp)
- Atmospheric neutrinos:
  - Independent measurement of NMO via matter effect
  - Sensitivity to θ_{23}
  - Reconstruction of atmospheric neutrino spectrum
- Geoneutrinos:
  - Precision of ~13% in 1 year and ~5% in 10 years

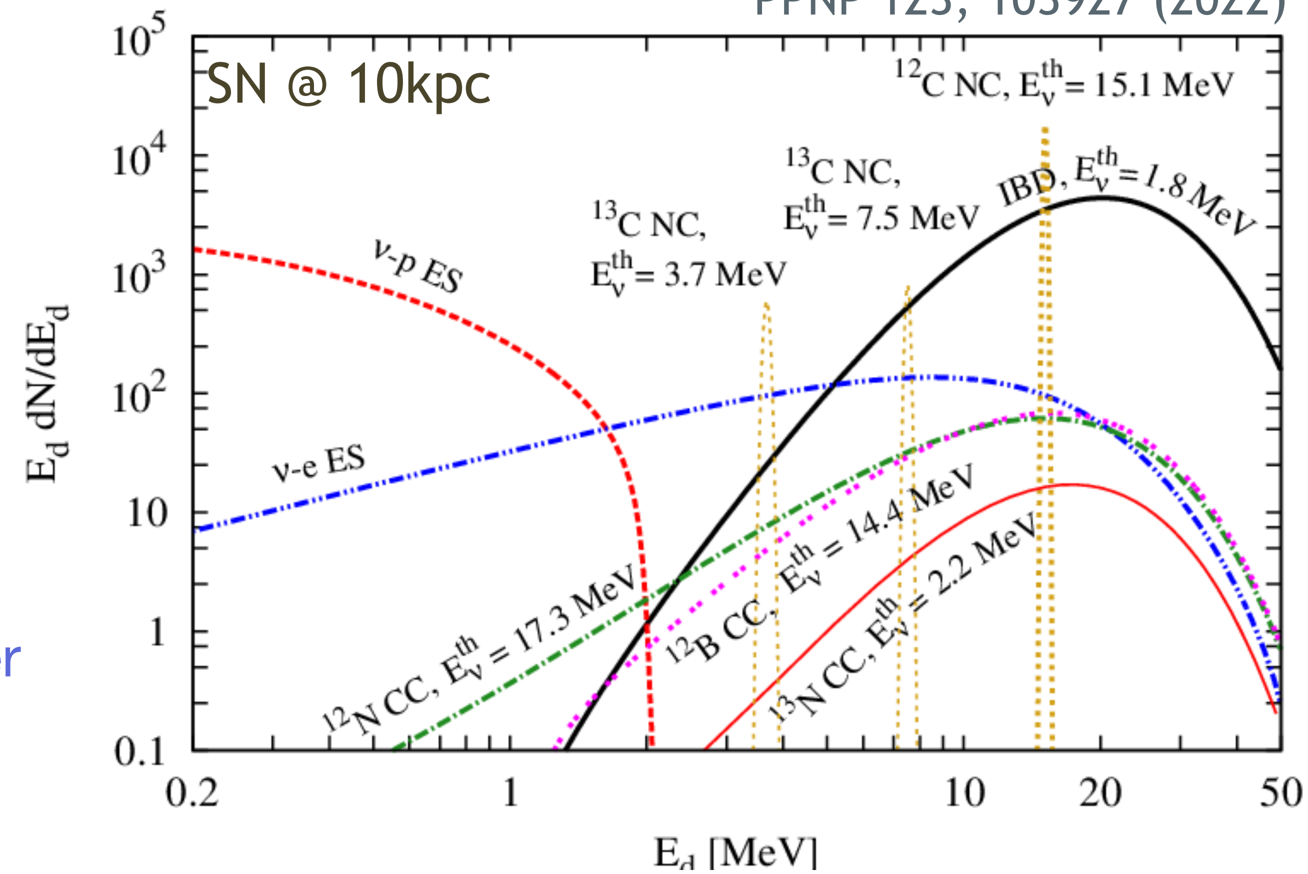


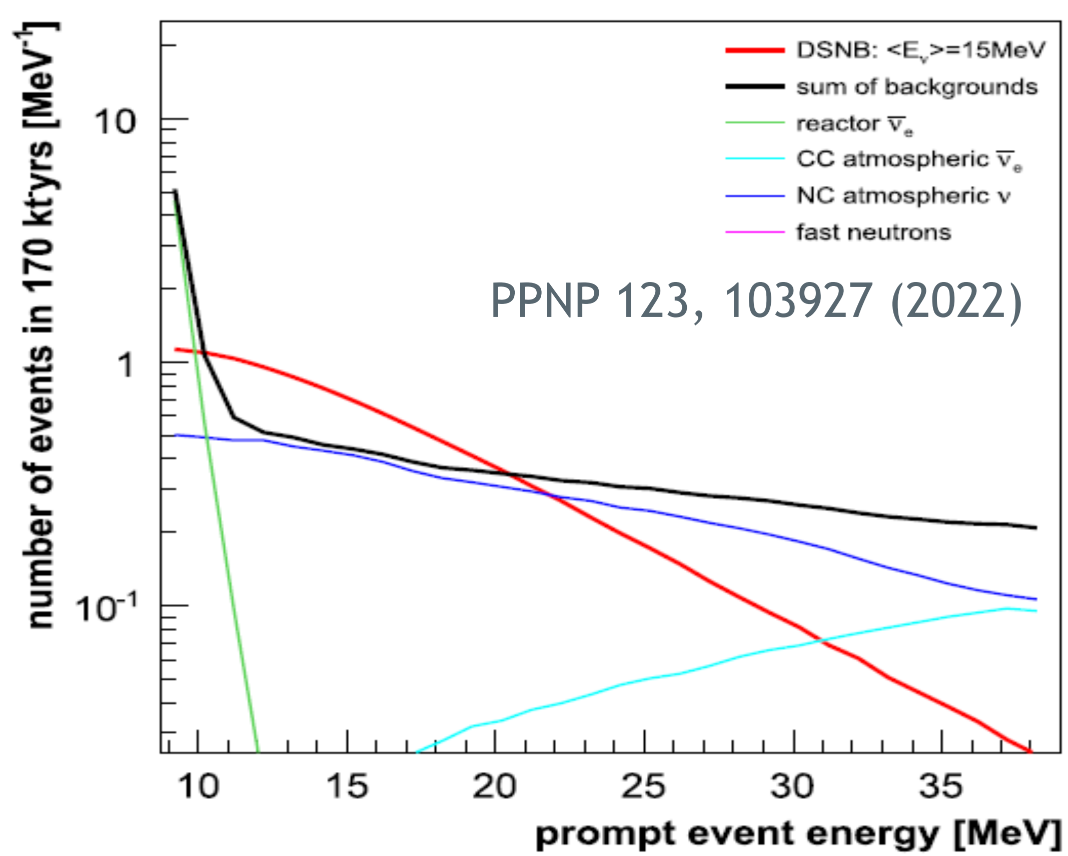


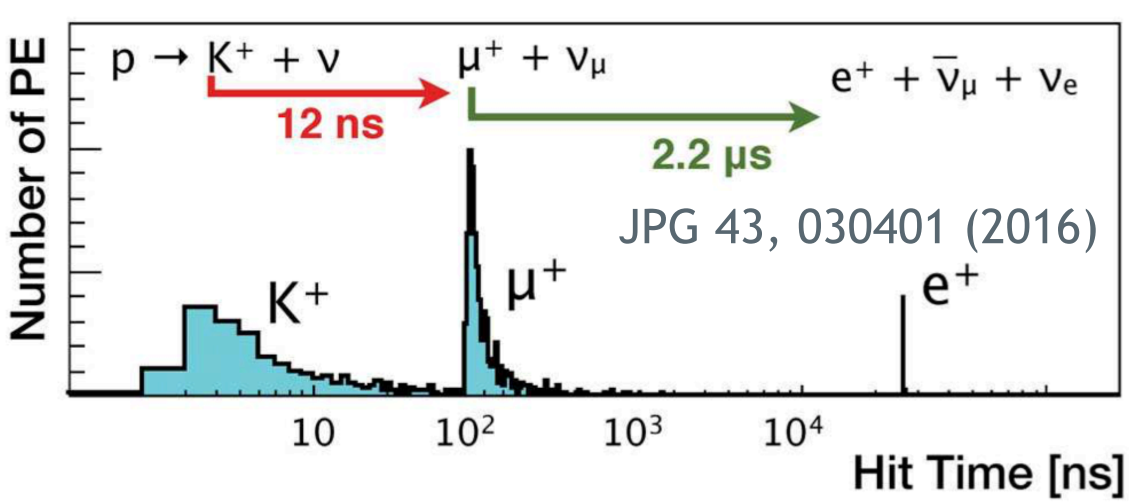
Supernova Neutrinos and Nucleon Decay

- Able to determine flavor content, energy spectrum and time evolution of supernova (SN) burst neutrinos
  - 10^4 detected events (5000 IBDs) for SN @ 10 kpc
- Leading sensitivity to diffuse SN neutrino background (DSNB)
  - Expected detection significance of ~3σ after 10 years of data
- Competitive sensitivity to proton decay searches, particularly in the $p \rightarrow \bar{\nu} + K^{+}$ channel (SUSY favored)
  - Sensitivity of 8.34×10^{33} years @ 90% C.L. with 10 years of data

PPNP 123, 103927 (2022)







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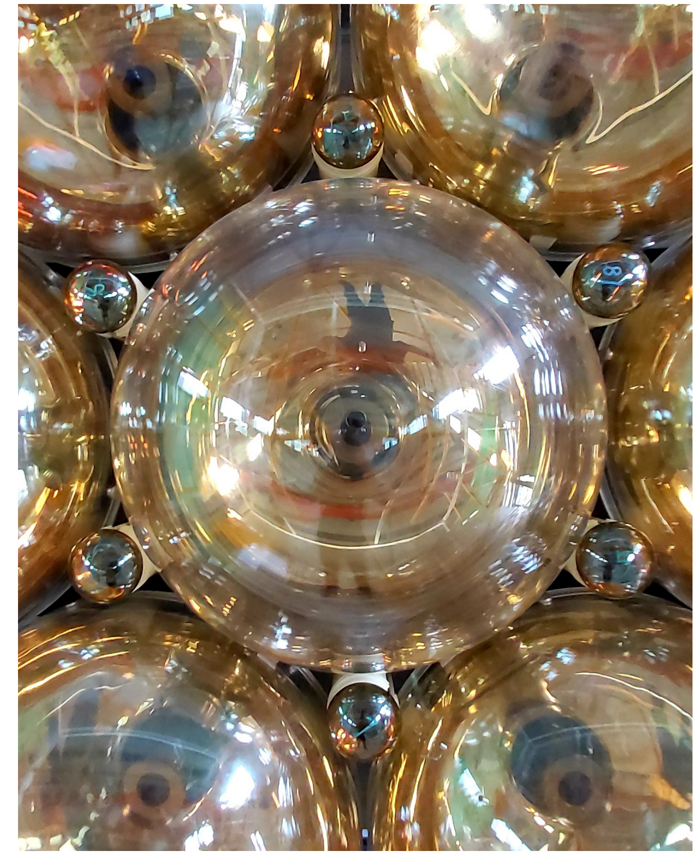

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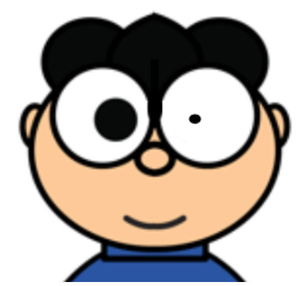

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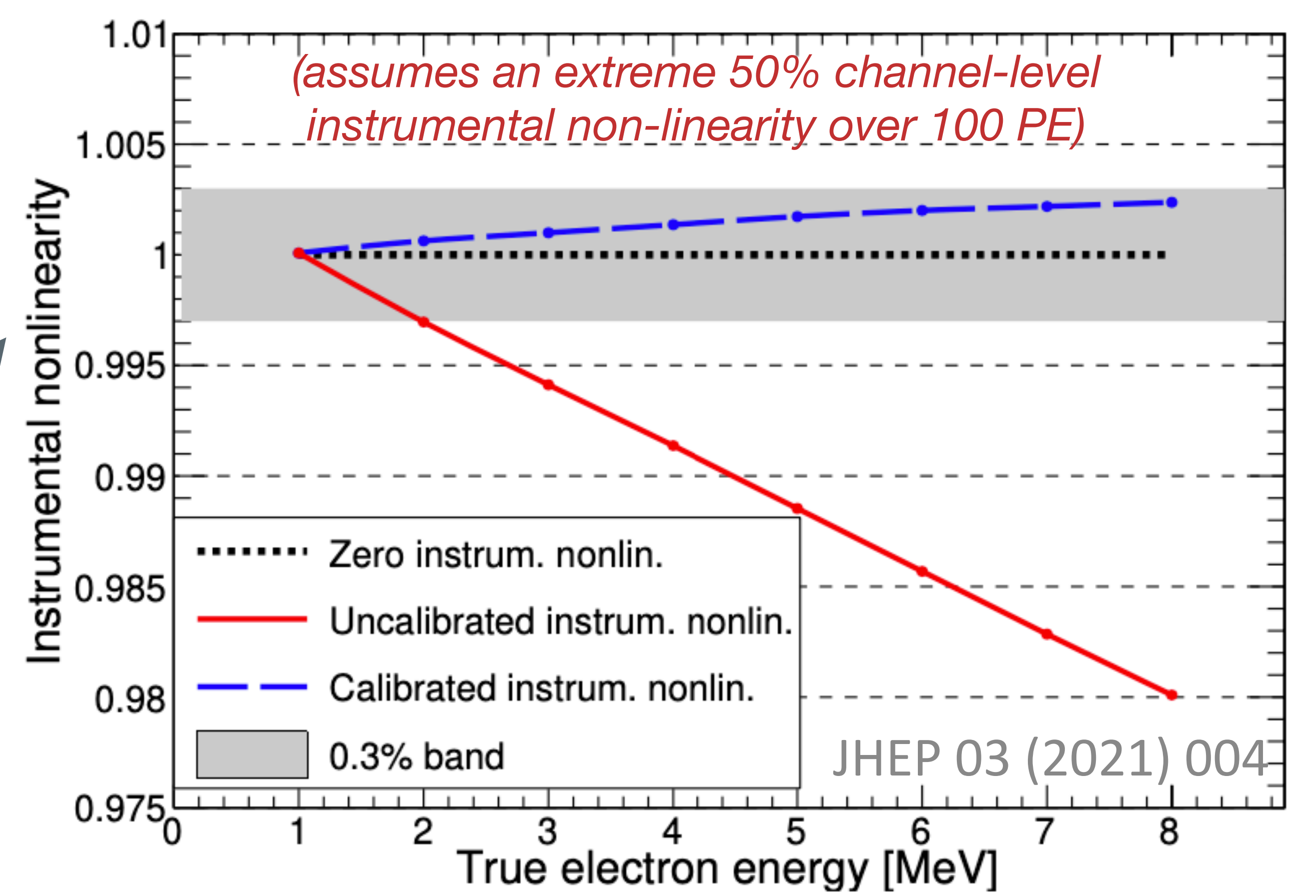
- Provides resiliency even against extreme charge non-linearity scenarios

event-level instrumental non-linearity (total measured charge / true charge)

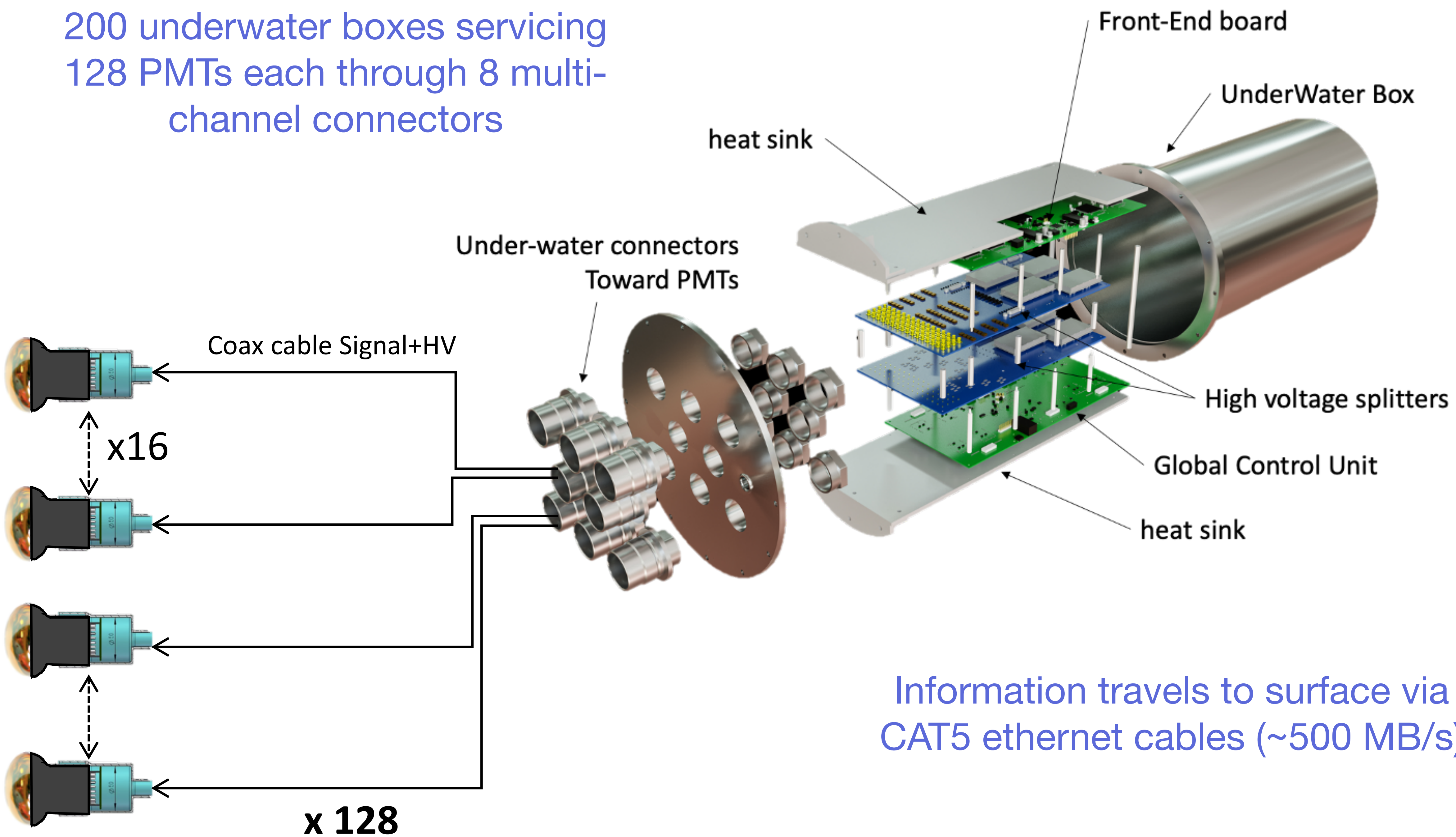
- Can work with UV laser, gamma sources, and even physics events
- Procedure immune to physics non-linearity and non-uniformity (with laser)



sPMT System Architecture

- The sPMT frontend electronics will be underwater

200 underwater boxes servicing 128 PMTs each through 8 multi-channel connectors



Information travels to surface via CAT5 ethernet cables (~500 MB/s)

Some Hardware Highlights

sPMTs

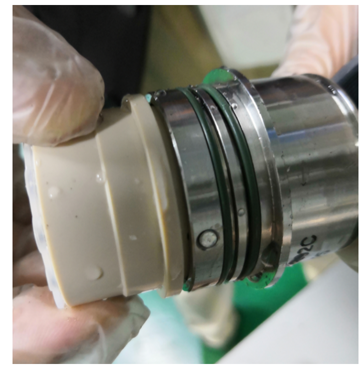
HZC PHOTONICS

XP72B22

- Custom designed for JUNO
- ~1,000 / month

All 25,600 sPMTs have been produced and tested at the factory

Connectors and Cables



16-channel connectors developed in partnership with Axon-cable company

Cable equipped with longitudinal waterproofing (high-density polyethylene jacket)

Potting

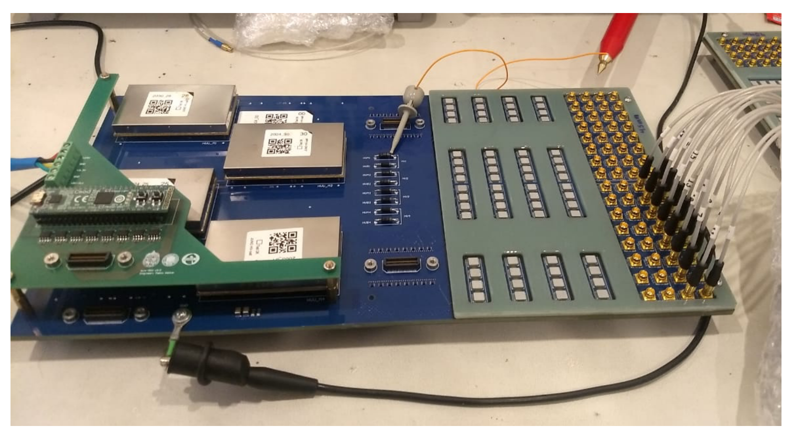
Polyurethane in ABS plastic shell, surrounded by butyl tape

epoxy + low-pressure injection molding

Underwater Boxes

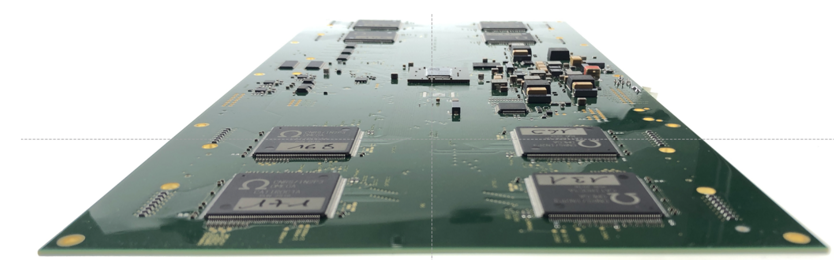
- Passivated stainless steel
- Carefully machined removable lid and flange coupled via 3 o-rings

HV Splitter Boards



- 64 channels per board
- Connects to individual channels via MCX
- HV produced in boards via independent & redundant units

ABC Frontend Board



- 128 channels per board
- Readout and digitization of Q,T information by 8 CATIROC chips controlled by Kyntex-7 FPGA
- Operates in trigger-less mode

arXiv:2012.01565

NIMA 1005 165347 (2021) & PPNP 123, 103927 (2022)

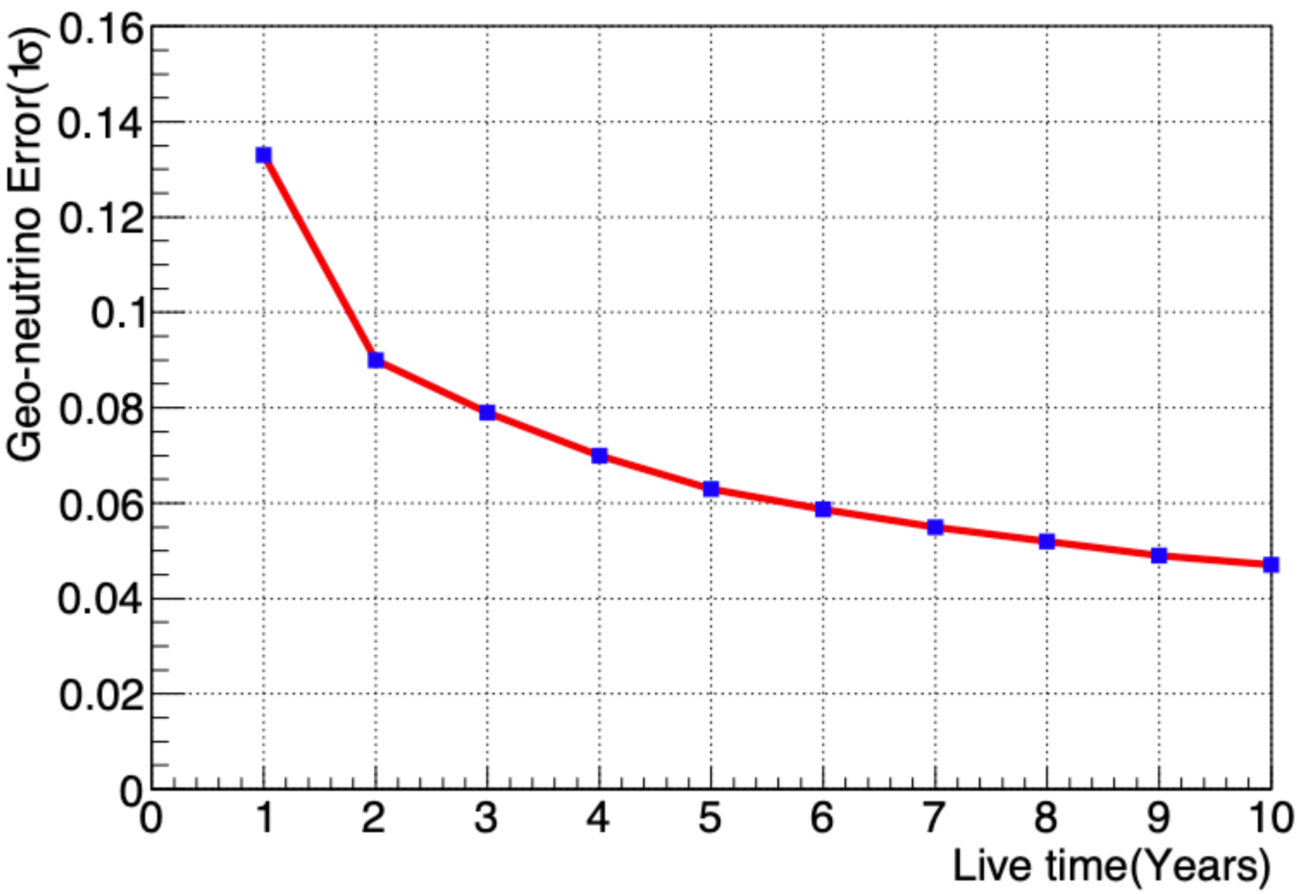
Summary & Conclusions

Assumptions	a	b	c	$\tilde{a} = \sqrt{a^2 + (1.6b)^2 + (\frac{c}{1.6})^2}$	energy bias (%)
Central IBDs	2.62(2)	0.73(1)	1.38(4)	2.99(1)	-
Ideal correction	2.57(2)	0.73(1)	1.25(4)	2.93(1)	-
Azimuthal symmetry	2.57(2)	0.78(1)	1.26(4)	2.96(1)	-
Single gamma source	2.57(2)	0.80(1)	1.24(4)	2.98(1)	-
Finite calibration points	2.57(2)	0.81(1)	1.23(4)	2.98(1)	-
Vertex smearing($8\,\text{cm}/\sqrt{E(\text{MeV})}$)	2.60(2)	0.82(1)	1.27(4)	3.01(1)	-
PMT QE random variations	2.61(2)	0.82(1)	1.23(4)	3.02(1)	0.03(1)
1% PMT death (random)	2.62(2)	0.84(1)	1.23(5)	3.04(1)	0.09(1)
1% PMT death (asymmetric)	2.63(2)	0.86(1)	1.20(4)	3.06(1)	0.23(1)
Y_0 reduced by 1%	2.62(2)	0.85(1)	1.25(4)	3.05(1)	0.09(1)
Y_0 reduced by 5%	2.68(2)	0.85(1)	1.28(5)	3.11(1)	0.09(1)
Absorption length reduced by 4%	2.62(2)	0.82(1)	1.27(4)	3.03(1)	0.07(1)
PMT single photon charge resolution (30%)	2.72(2)	0.83(1)	1.23(5)	3.12(1)	0.08(1)

Table 3. Energy resolution after sequential downgrade from the ideal to realistic calibration, considering all assumptions from section 3.1 to section 3.9. Values in parentheses indicate fitting uncertainties, and the uncertainty of $\tilde{a}$ has taken into account the correlations in a, b and c. Each row from "Azimuthal symmetry" to "PMT QE random variations" indicates cumulative effects down to this row. This gives an $\tilde{a}$ of 3.02% for nominal JUNO situation. Each line starting from "1% PMT death (random)" represents an individual imperfection of the CD, which also includes effects up to the double-line (nominal $\tilde{a}$).

Other Sensitivities

Geoneutrinos



DSNB