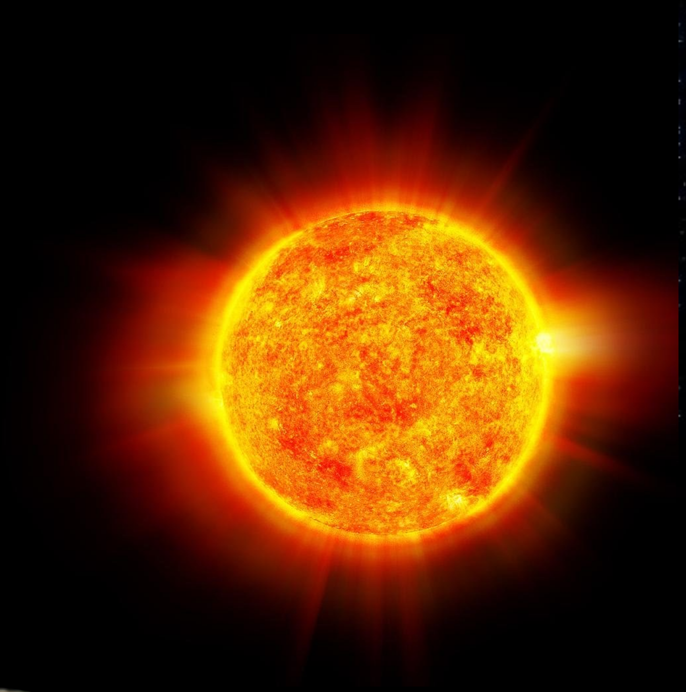
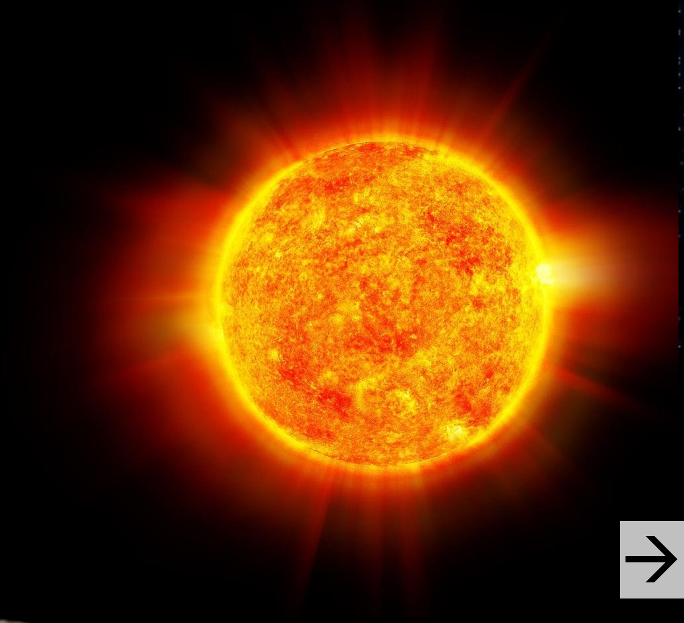
Low-Energy Astrophysical Neutrinos



++ Michael Wurm, Achim Stahl ++ Astroparticle Physics in Germany ++ KIT, 17.10.24 ++

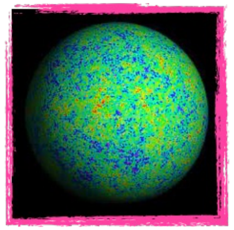
Low Energy Astrophysical Neutrinos



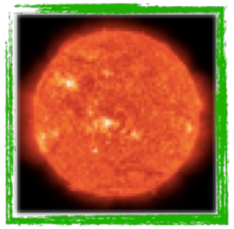
→ Astro-Neutrino-Properties Workshop in Mainz, 11.6.24

- How can neutrinos help to probe astrophysical sources?
- Can we combine observations with other messengers?
- What can we learn about neutrino properties?
- Which projects will contribute significantly?
- Where are new technological developments in the field?

Low Energy Neutrinos: Sources & Physics Goals



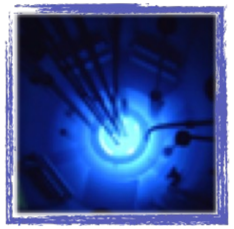
Cosmic Neutrino Background ← yet undetected



Solar neutrinos
from hydrogen burning

Supernova neutrinos
from neutron star cooling

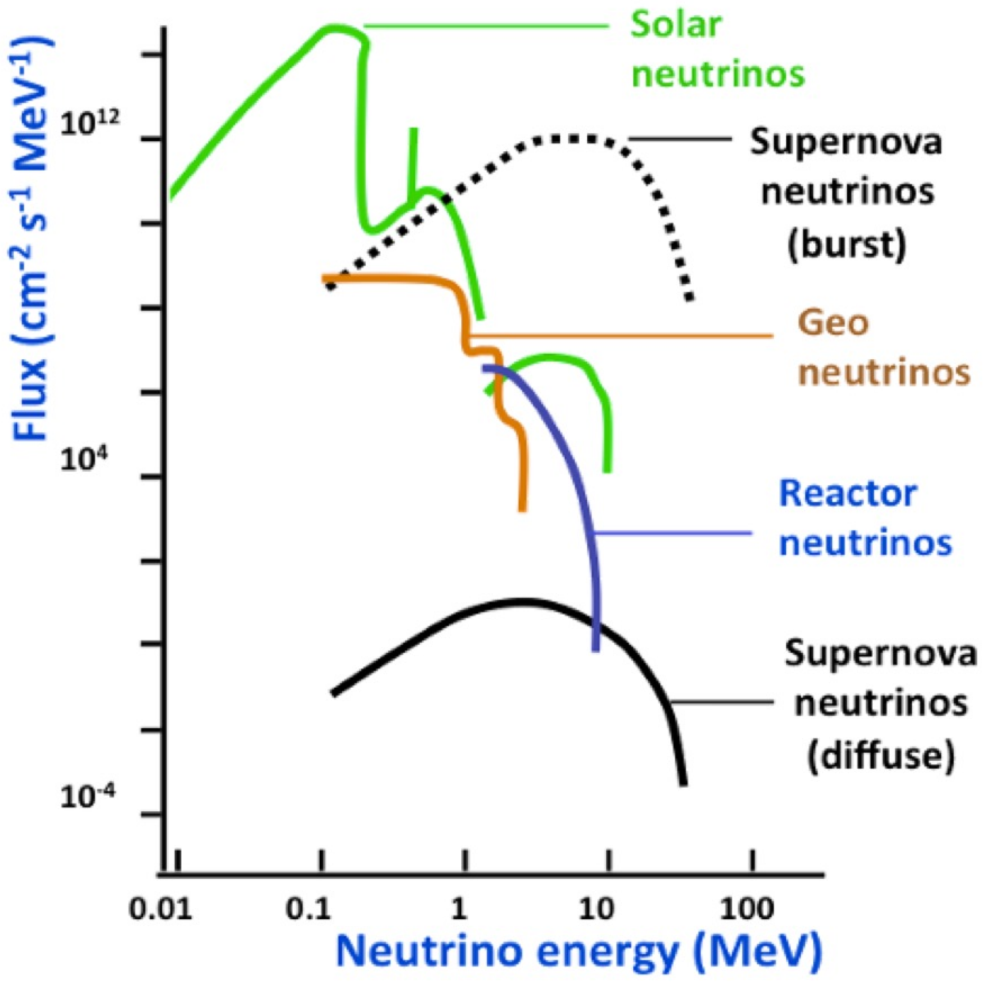
Geo-neutrinos
from Earth's radioactivity



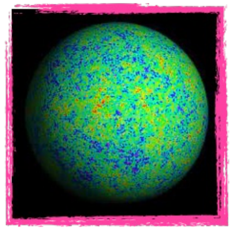
Reactor neutrinos
from nuclear fission

man-made but similar types of detectors →

Beam neutrinos
from pion decays



Low Energy Neutrinos: Sources & Physics Goals



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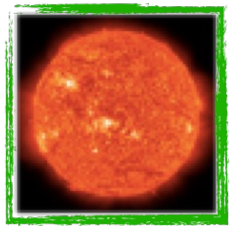

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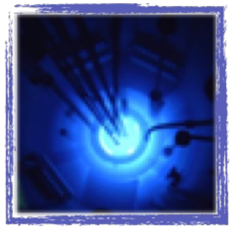


Reactor neutrinos
from nuclear fission

man-made but similar types of detectors →

Beam neutrinos
from pion decays

neutrinos as probes
to study interior of astrophysical objects

- solar fusion
- core-collapse and neutron star cooling
- Earth's heat budget

…

neutrino properties
from precision oscillation studies

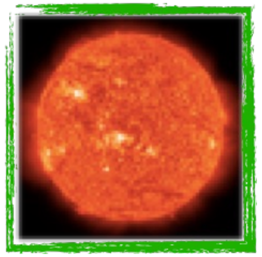
- mass ordering
- leptonic CP violation
- PMNS unitarity
- non-standard interactions …

Key science questions for astrophysics

Supernova Neutrinos: What can they tell us about core-collapse Supernovae?
- (proto) neutron star cooling and equation of state
- generation of heavy elements in the neutron-rich layers of the star
- cut-off of the neutrino signal due to black hole formation
- ‘trigger‘ for GW detection and observation of common signal features (SASI)

DSNB: What is the rate of supernovae throughout the Universe?
- discovery in SK-Gd and JUNO before the end of the decade
- with 10 years of data: what is the fraction of black-hole forming SNe?

Geoneutrinos: What will we learn about the Earth with neutrinos?
- measurements in multiple locations helps understand crust and mantle contribution
  → explore radiogenic heat budget and formation history of the Earth
- Earth inner structure can be adressed as well with atmospheric neutrino tomography

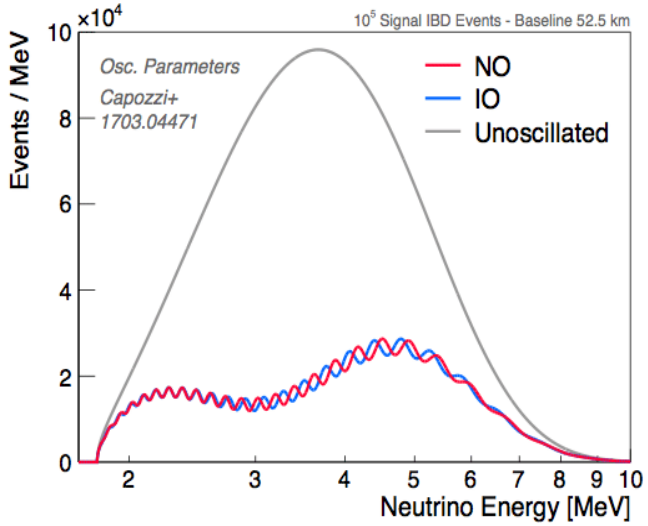


Solar neutrinos: What are the conditions in the core of the Sun?
- precision measurements of CNO/^{8}B/^{7}Be neutrinos to pin down solar metallicity
- precise pp-neutrino measurement to test solar luminosity constraint → new particles?

JUNO as an observatory for LE astro-neutrinos

OSIRIS

- 20kt Liquid Scintillator Detector in Southern China
- reactor neutrino oscillation experiment
  → sub-%-level precision on θ_{12}, Δm^2_{21}
  → neutrino mass ordering
- designed for broad astro-ν's program
  → solar and geo-neutrinos
  → galactic & diffuse SN neutrinos
  → neutrinos from DM annihilation



JUNO's signature of mass ordering in reactor ν oscillations

German contribution

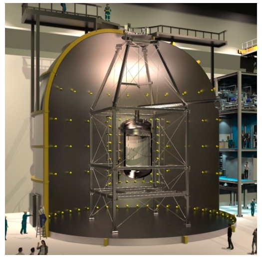
- six universities forming DFG Research Unit
- hardware work: scintillator radiopurity
  → pre-detector OSIRIS
- broad analysis contribution, based on experience from Borexino & Double-Chooz

Cross-relations with other experiments

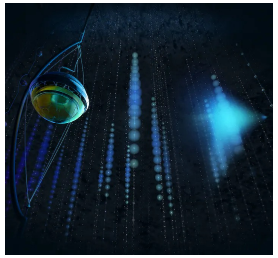
OSIRIS-Upgrade?
- precision pp-ν's, ββ

SNO+
(Kai Zuber, TU Dresden)
- ββ-experiment with Te-loaded LS
- currently: solar neutrinos

Common Topic
- SN neutrino burst
- different flavors, statistics, time & energy resolution
- multi-messenger, esp. GW signals



DARWIN
(many)
- SN neutrinos (ν_x)
- solar neutrinos, esp. pp



IceCube
(many)
- SN neutrinos flux (envelope)

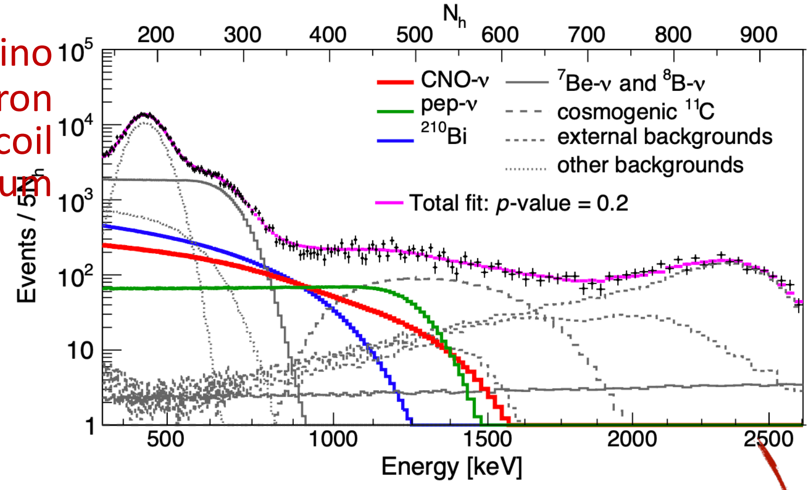
DUNE
(Alfons Weber, JGU Mainz)
- SN neutrinos (ν_e)

Precise CNO ν measurement with directionality

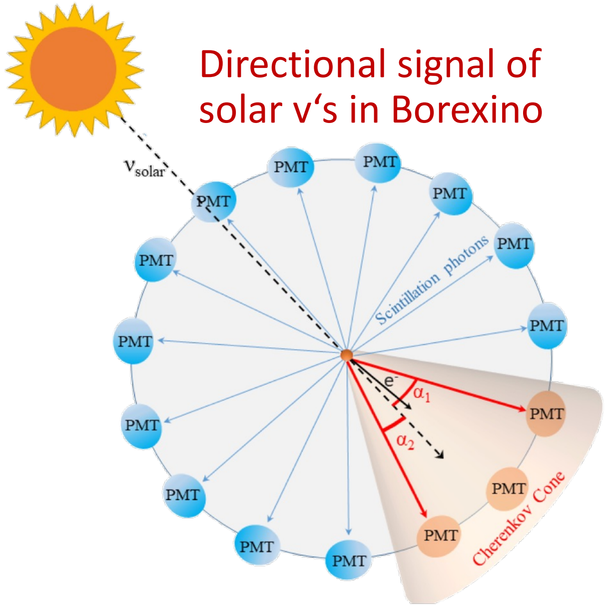
- final result from Borexino on CNO neutrinos: based on spectral fit (as before) and novel directional fit
- CID method: use limited amount of Cherenkov photons, integrated over all events collected, to separate directional CNO signal from flat BG

→ demonstrates potential of hybrid Cherenkov/scintillation detection technique

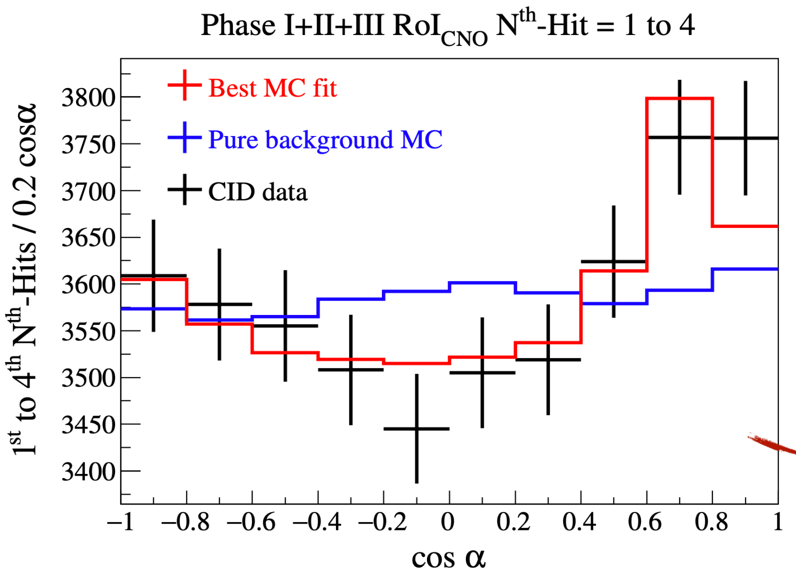
Borexino electron recoil spectrum



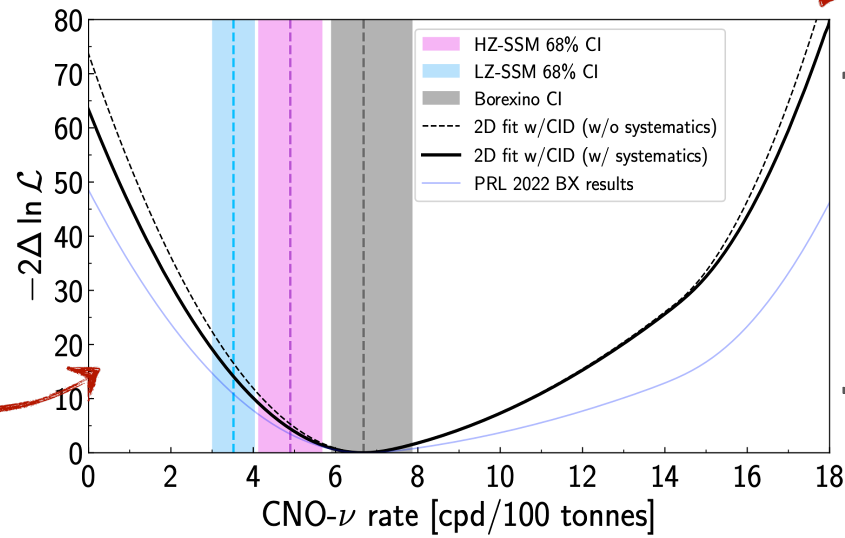
Directional signal of solar ν's in Borexino



Borexino directional distribution of PMT hits

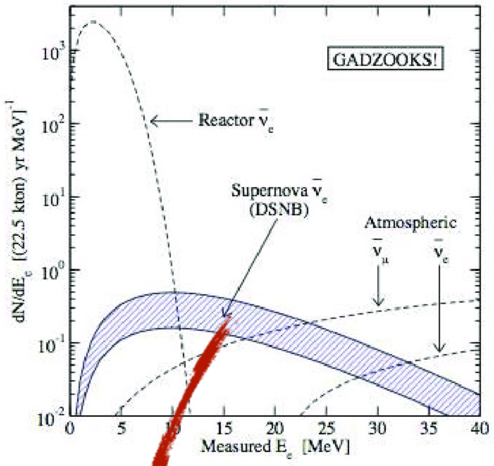


Final Borexino result on CNO neutrinos



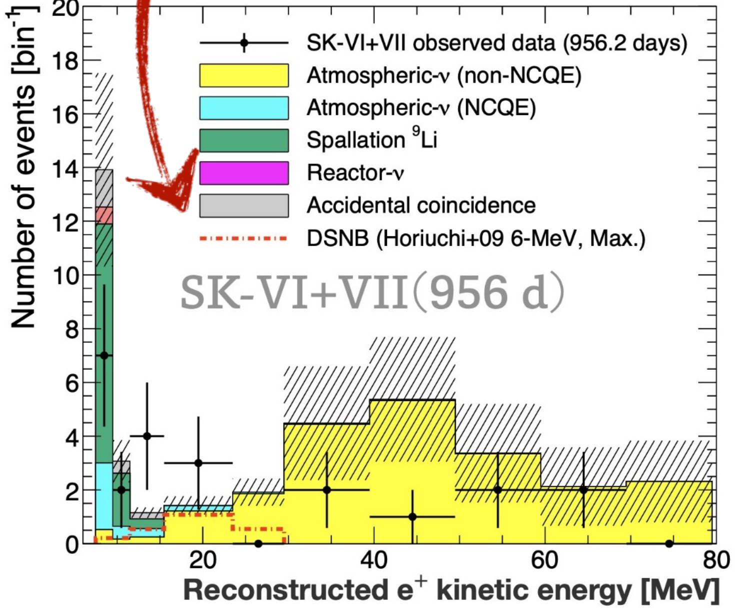
[arXiv:2307.14636]

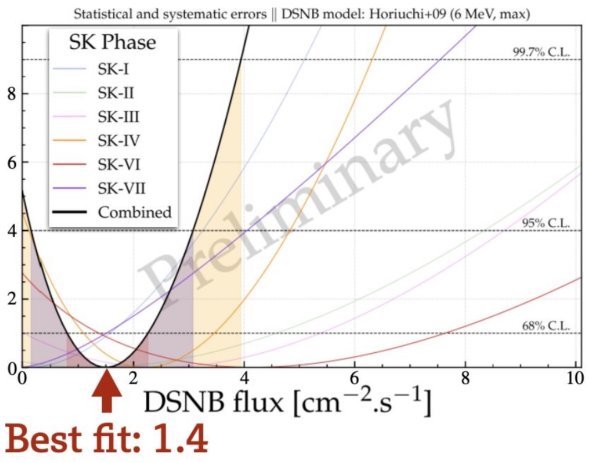
Are we on the verge to detect Diffuse SN Neutrinos?



- Nu24: update from **SK-Gd** → tension with BG-only but no clear signal yet
- major background by atmospheric neutrinos (NC+CC)
- similar background is expected for JUNO
  → pulse shape discrimination essential!
- most recent **JUNO** sensitivity study suggests excellent performance
  → first observation within few years running?

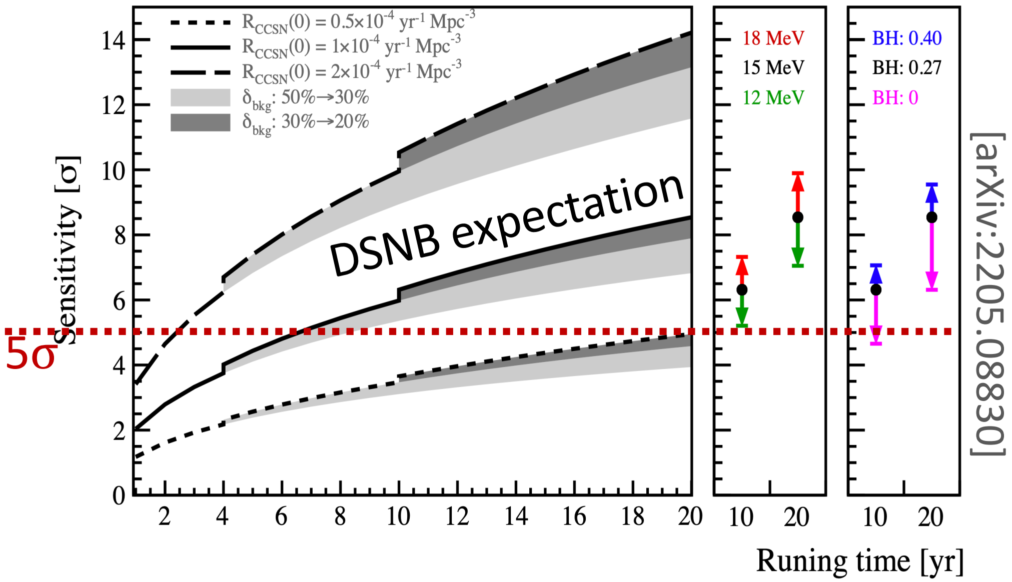
SK-Gd Neutrino24 result



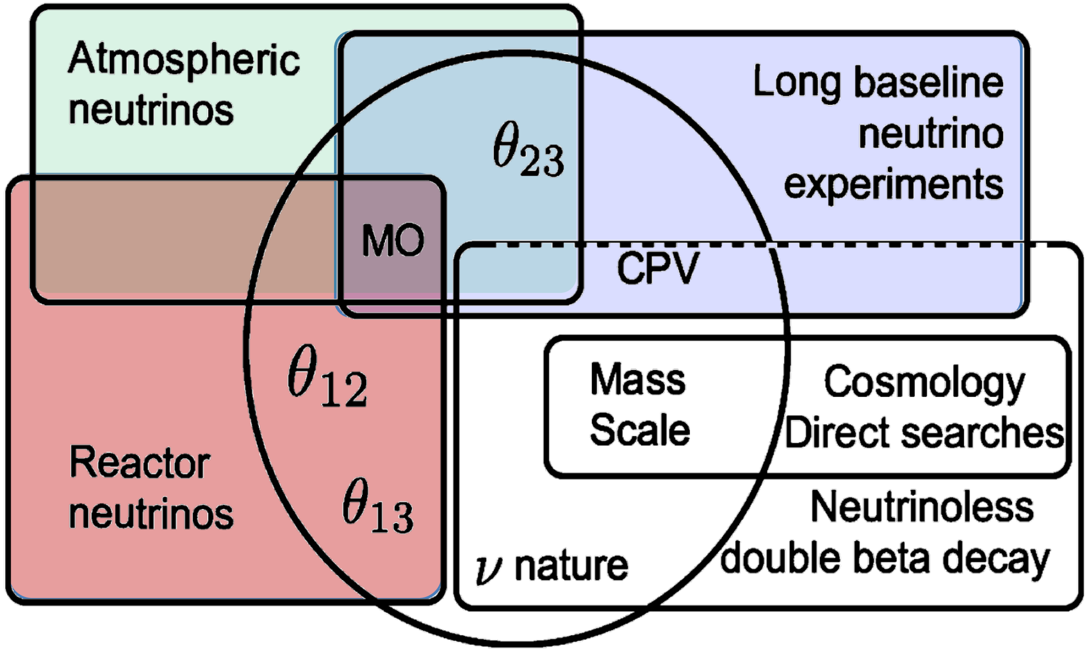


2.3σ tension with background only

expected sensitivity of JUNO



Key science questions for neutrino properties



Low energy neutrinos
→ **mostly regards neutrino mixing/oscillations**

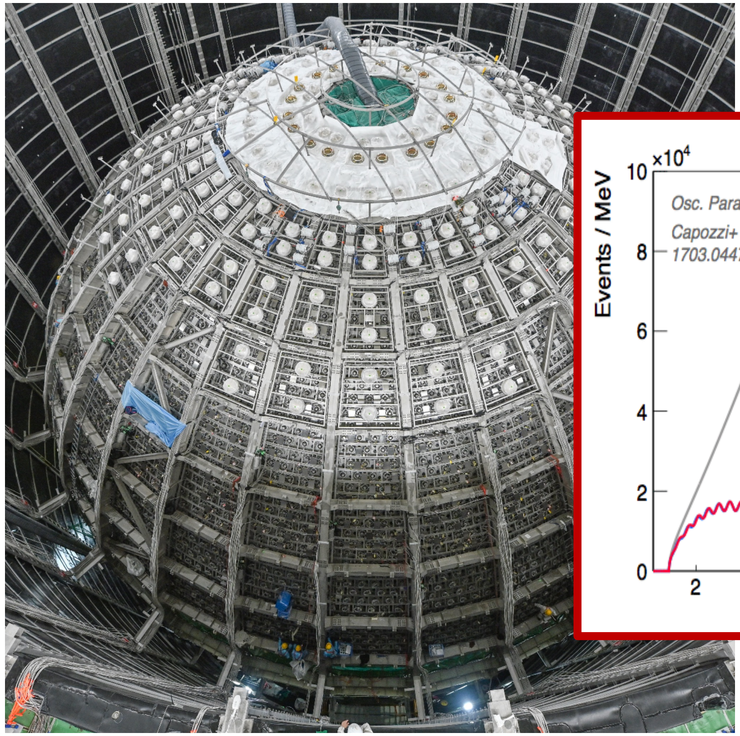
Key questions:

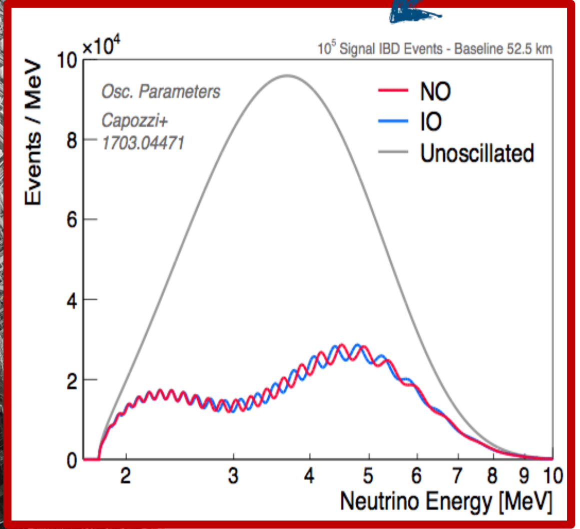
- what is the neutrino mass ordering?
- how large is leptonic CP violation?
- what is the octant of θ_{23}?
- can we test PMNS unitarity?

Large thematical and technological overlap with adjacent fields of (astro-)particle physics:

- neutrino properties
- HE astrophysical neutrinos
- long baseline accelerator experiments → KET

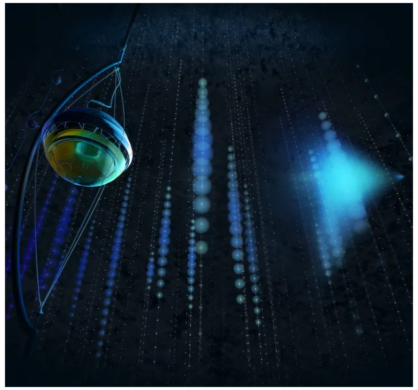
What are the relevant experiments?

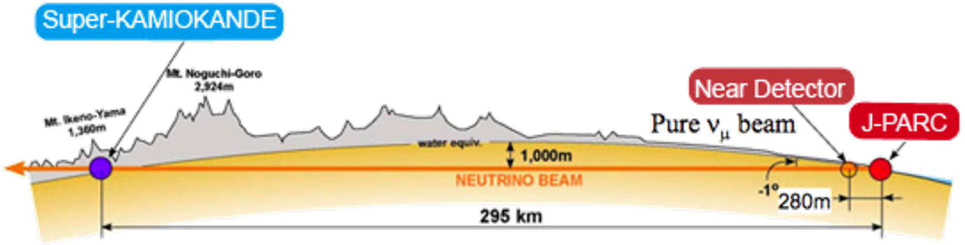




Low-energy upgrades of neutrino telescopes

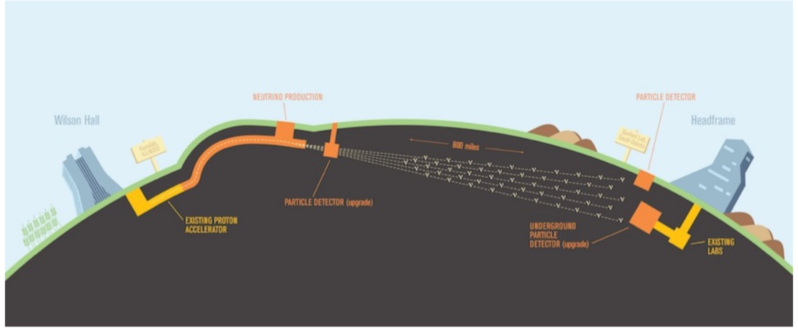
- IceCube-Upgrade, ORCA
- sensitive to mass ordering via matter effects of atmospheric neutrinos





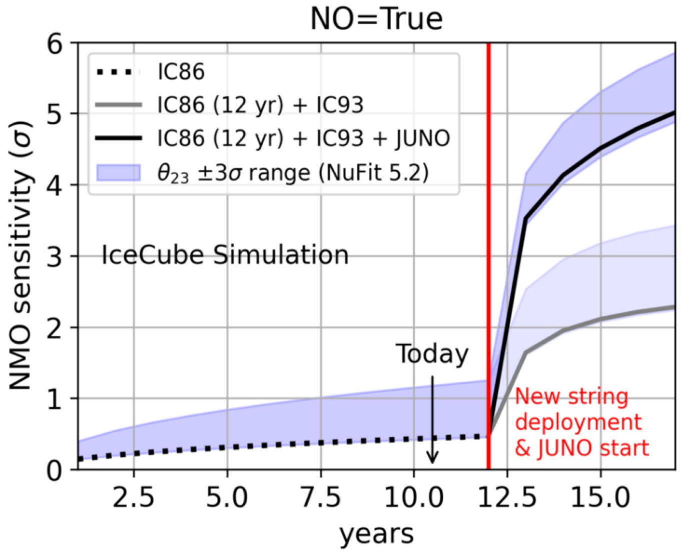
Current & future long baseline experiments

- T2K→H2K
- DUNE
- sensitive to δ_{CP} (and mass ordering)

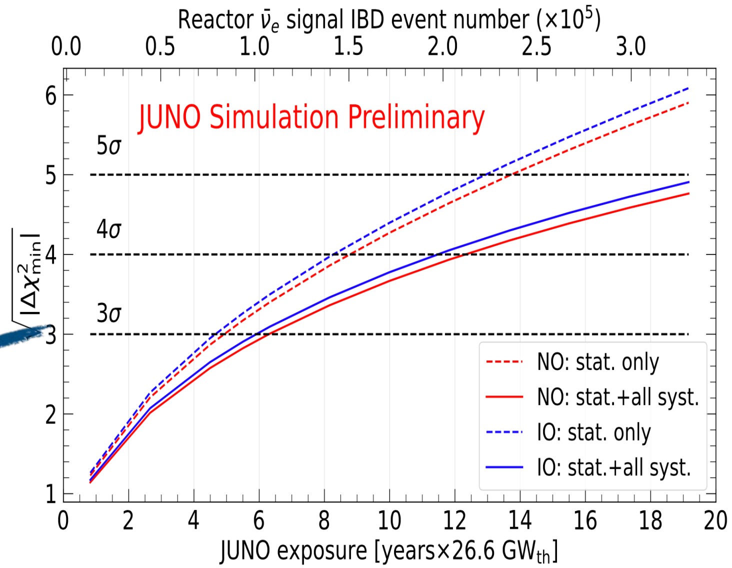


PMNS matrix parameters and unitarity

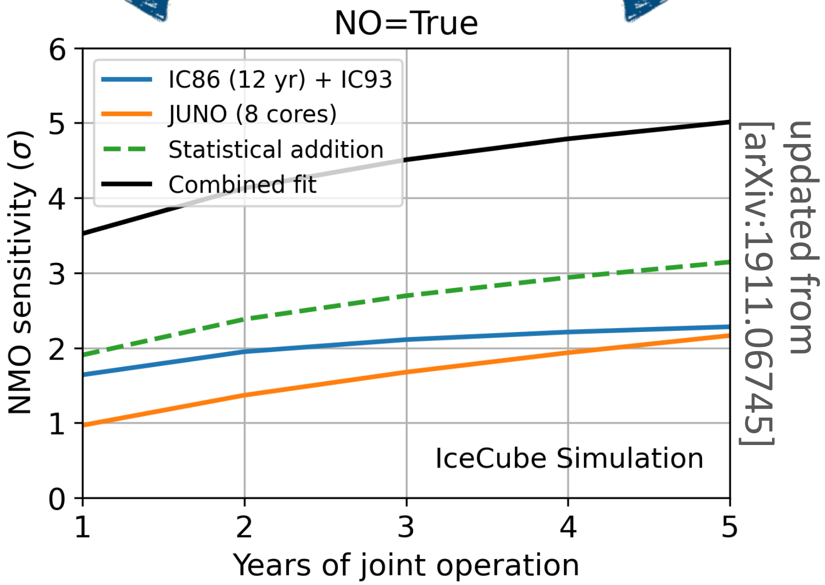
Neutrino Mass Ordering: Combined Analyses



- combined oscillation analysis of the data produces tension in best-fit values of $\Delta m^2_{31/32}$
- synergetic effect on mass ordering sensitivity



IceCube Upgrade
- LE atmospheric ν's
- sensitivity arises from Earth matter effects

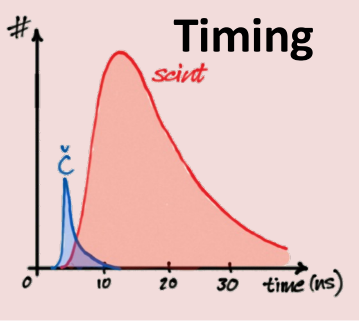


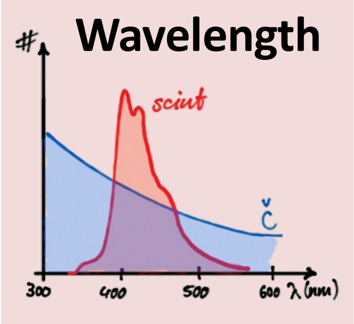
JUNO
- medium BL reactor ν's
- sensitivity from 2nd order vacuum oscillations

→ originally proposed by Blennow+Schwetz [arXiv:1306.3988]

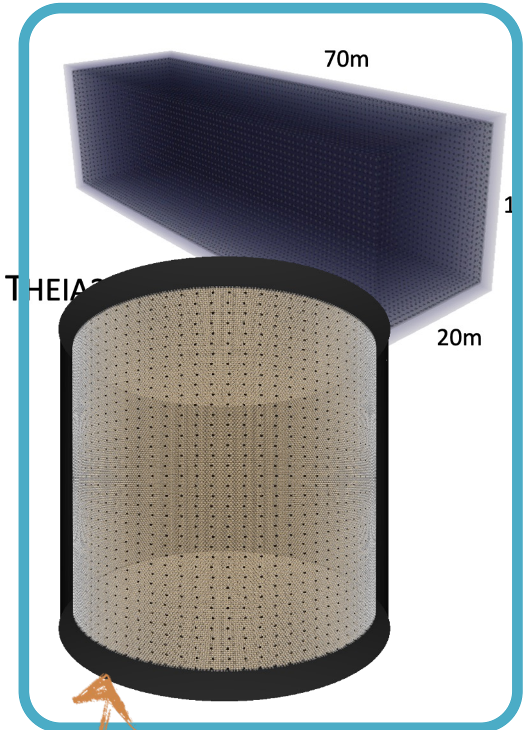
→ a similar study has been performed for JUNO+ORCA [arXiv:2108.06293]

New R&D: Hybrid Cherenkov/Scintillator Detectors

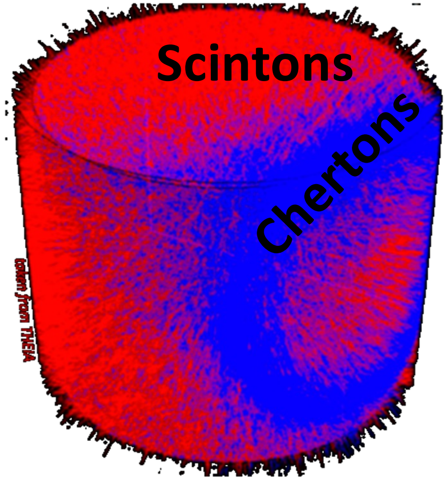


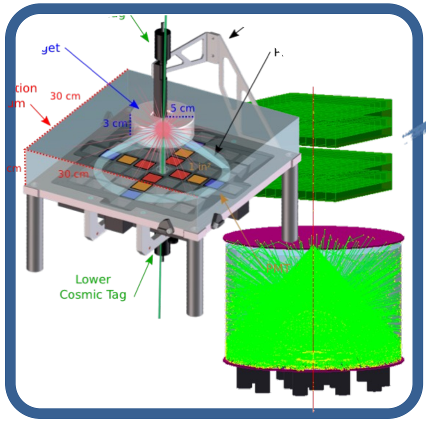


- co-detect intrinsic Cherenkov and scintillation signals using novel target media, light sensors & reconstruction techniques
- new types of water-based and slow (bi-solvent) scintillators
  → R&D at German universities [arXiv:2405.05743] [arXiv:2405.01100]
- promise: excellent event reco & background suppression for
  - astrophysical & accelerator neutrinos: MeV→GeV
  - 0νββ searches with loaded scintillators (50t scale)
- coordinated development effort with US/UK groups
  → currently ton-scale demonstrators: **ANNIE**, EOS, BNL-1T
- long-term goals: Theia-25 (DUNE-WbLS module?), JUNO-ββ

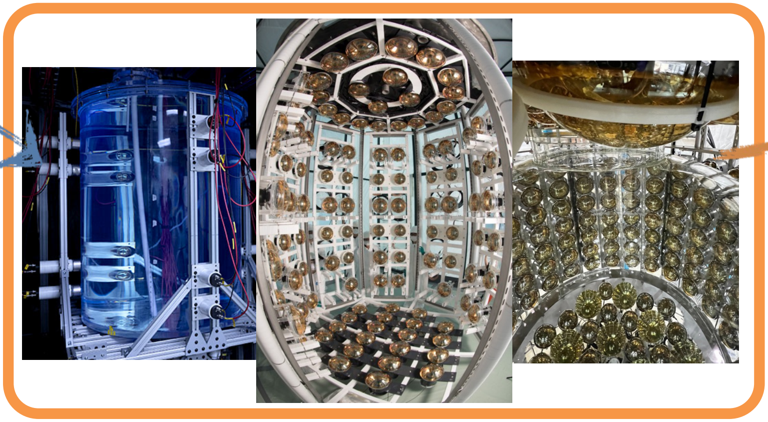


Future full-scale hybrid detectors
Theia 25/100
[arXiv:1911.03501]





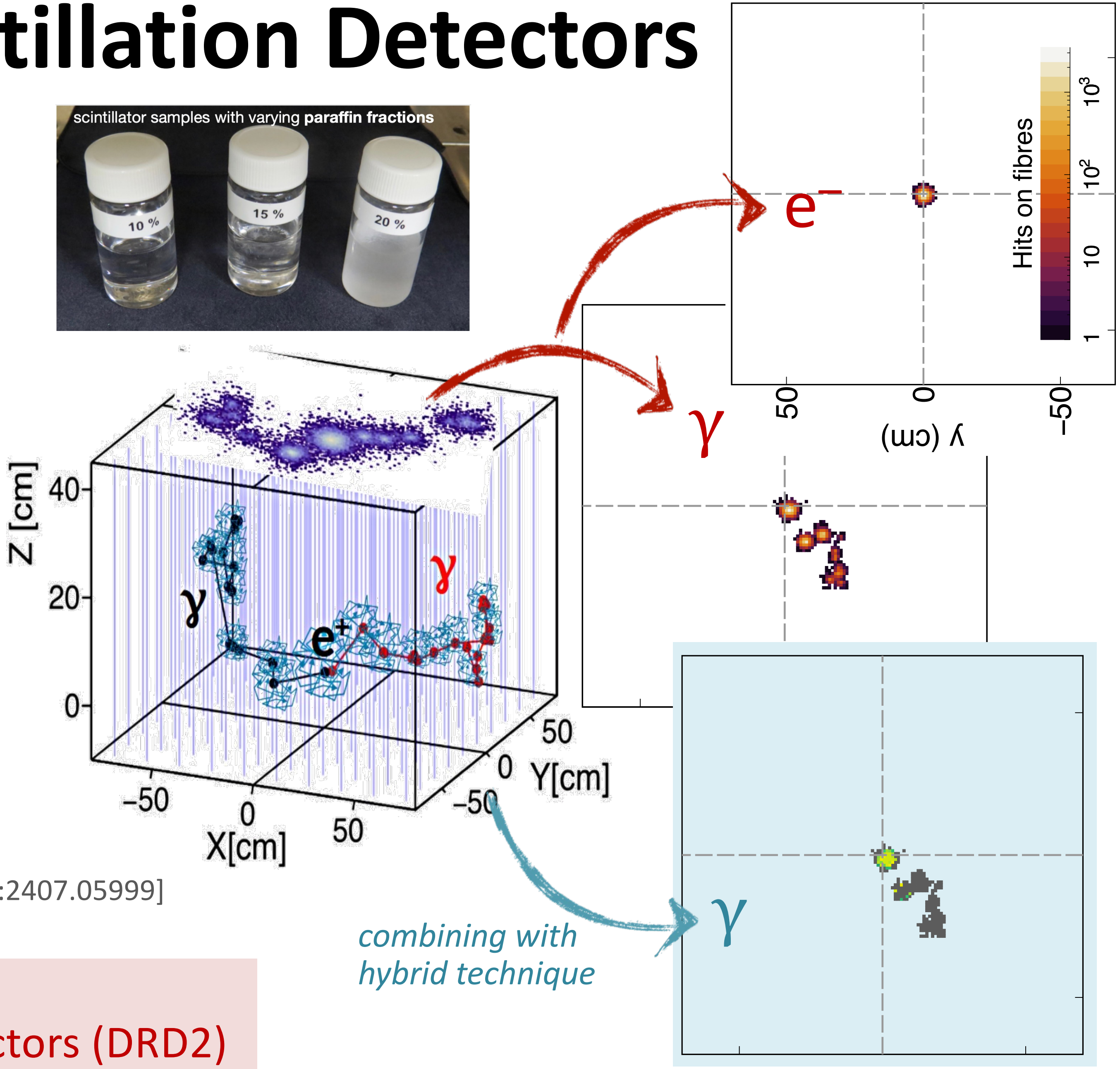
Lab-Scale Setups
CHESS
DISCO
....



Ton-Scale Setups
BNL Prototype
ANNIE [arXiv:2312.09335]
EOS

New R&D: Opaque Scintillation Detectors

- highly scattering scintillators with regular grid of WLS fibers for signal extraction
- promise: cm-scale spatial reconstruction
  → excellent particle ID based on topology
- areas of application
  - reactor and solar neutrinos
  - 0ν2β searches with very high isotope-loading factors (transparency not crucial)
- currently 10-100 liter scale prototypes
- next years:
  - LiquidO cons. for generic R&D [arXiv:1908.02859]
  - reactor monitoring with few-ton detector at Chooz (Amotech/CLOUD)
  - Mainz: ββ-demonstrator → NuDoubt^{++} [arXiv:2407.05999]



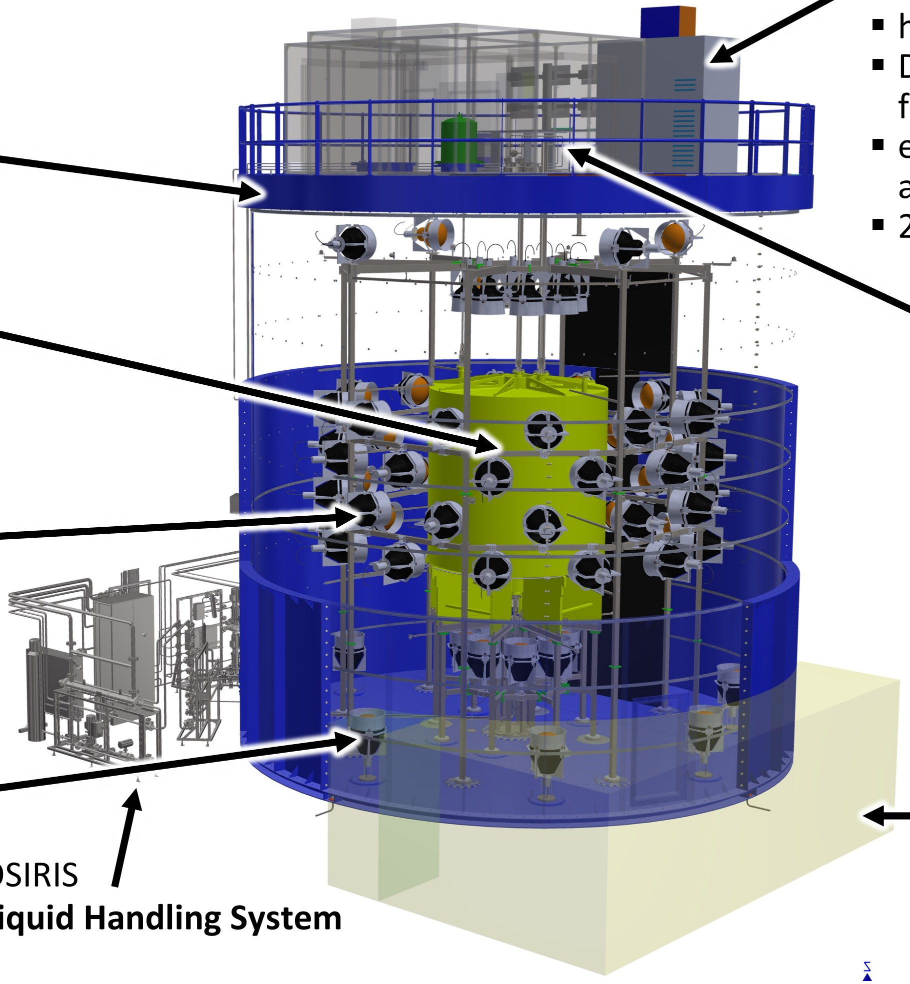
→ both for hybrid and opaque scintillators: new **European R&D Collaboration** for Liquid Detectors (DRD2)

Conclusions

- JUNO the main experiment in the field with substantial German participation
- unique sensitivity for astrophysical neutrinos (solar, SN ν's, DSNB) and neutrino properties (mass ordering from sub-dom vacuum oscillations)
- important synergy effects with experiments in neighboring fields, e.g.
  - neutrino properties: high-energy neutrino telescopes for mass ordering, long baseline experiments on PMNS parameters
  - SN neutrinos: sensitivity for all neutrino flavors when combining large-scale detectors (also IceCube), added information from GW interferometers
- two novel efforts on detector R&D for hybrid and opaque scintillator detectors
  → currently in the ton-scale demonstrator stage
  → basis for the next generation of large-scale LE neutrino observatories

Thank you!

Current Status of OSIRIS Installation



Water Tank
- CR class ISO6-7

Acrylic Vessel (AV)
- pipes connected
- flushed with N2
- LS thermometer rod feedthrough (seal)

Stainless steel frame
- 64x LPMTs + 26x GCUs
- optical diffusers for laser calibration
- thermometer array
- IR cameras

Muon veto
- optical separation
- 12x LPMTs
- cold-water loop

OSIRIS
Liquid Handling System

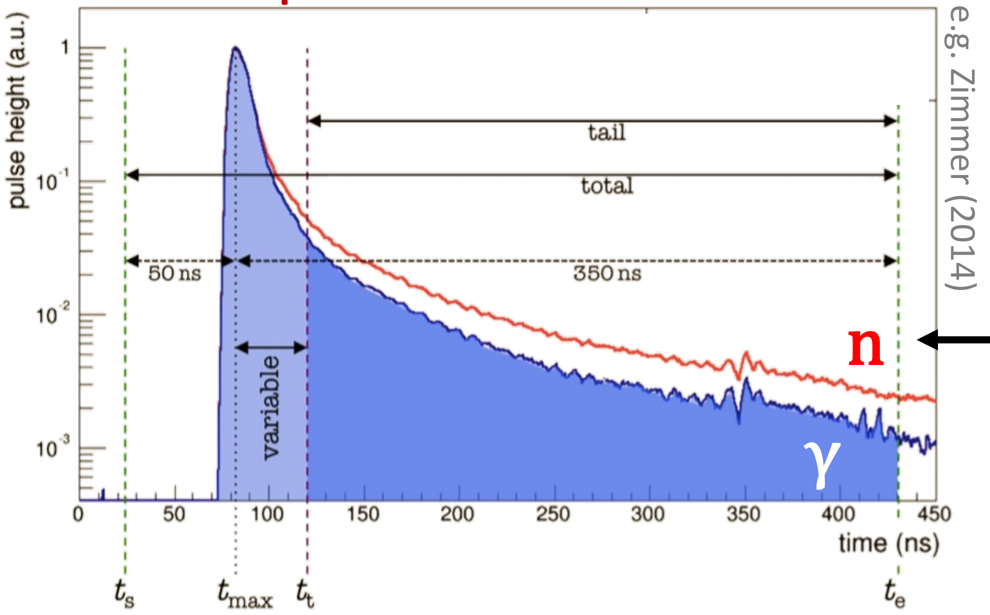
Electronics Cabinet
- humidity control now OK
- DCS&DAQ PCs installed, first versions running
- electronics for calibration and LHS sensors
- 2nd cabinet for LPMT electronics

Top Clean Room
- head tank for filling & hydrostatic pressure
- LS heater to maintain AV temperature gradient
- Automatic Calibration Unit (ACU) for radioactive source insertion

Ground Clean Room
(during installation)
main access for personnel and material

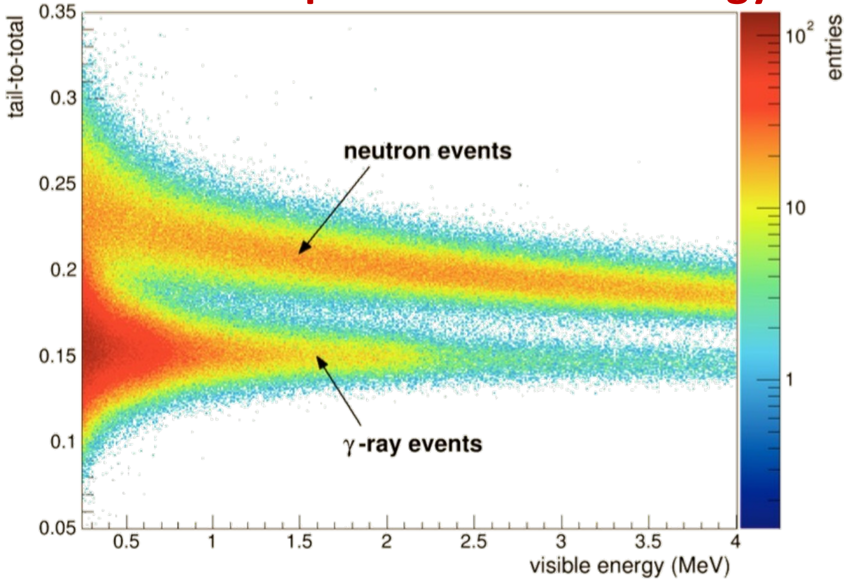
Pulse Shape Discrimination (PSD) in LS

Pulse Shapes of Gammas and Neutrons



- in liquid scintillators, pulse shapes (and light yield) of highly ionizing particles (n,p,α's) differs from light particles (e,γ's)
- can be exploited for discrimination, e.g. by **tail-to-total ratio** of time-of-flight corrected pulses

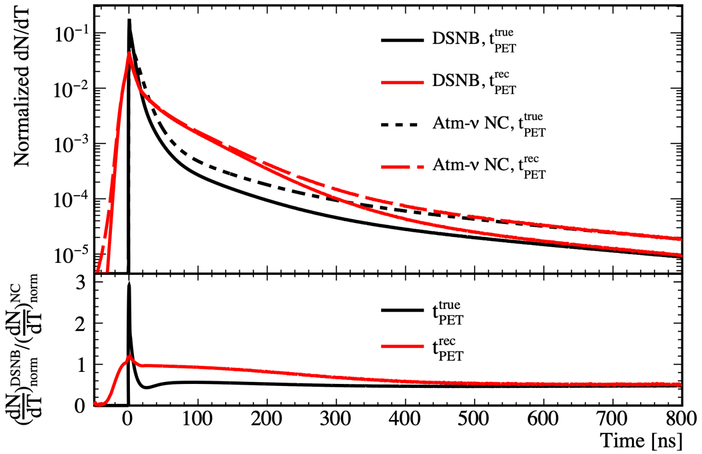
PSD performance vs. energy



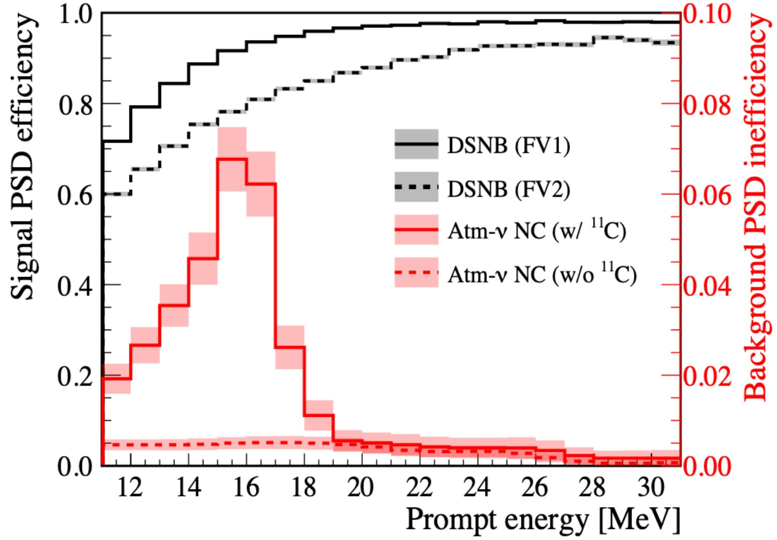
- example shown here for 11 MeV neutrons vs. 4 MeV gammas
- efficiency rises with energy/number of photons detected
- JUNO is a high light yield experiment! → expect ~1300 pe/MeV

Updated JUNO study with better PSD

Improved knowledge of pulse shapes

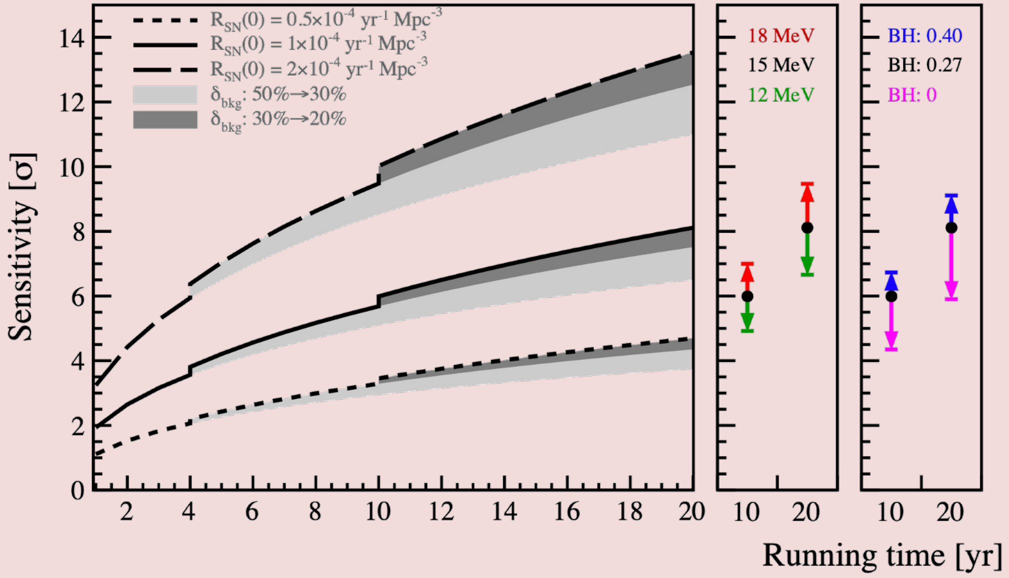


Improved PSD performance



- **2022:** state-of-the art modeling of NC final states and LS fluorescence parameters
- improved PSD techniques (radius-dep. Tail-to-Total, machine learning TMVA) promises excellent BG suppression
- atm.NC reactions with ^{11}C in final state are harder to discriminate by PSD but can be tagged based on delayed β^+-decay

→ substantially improved sensitivity!



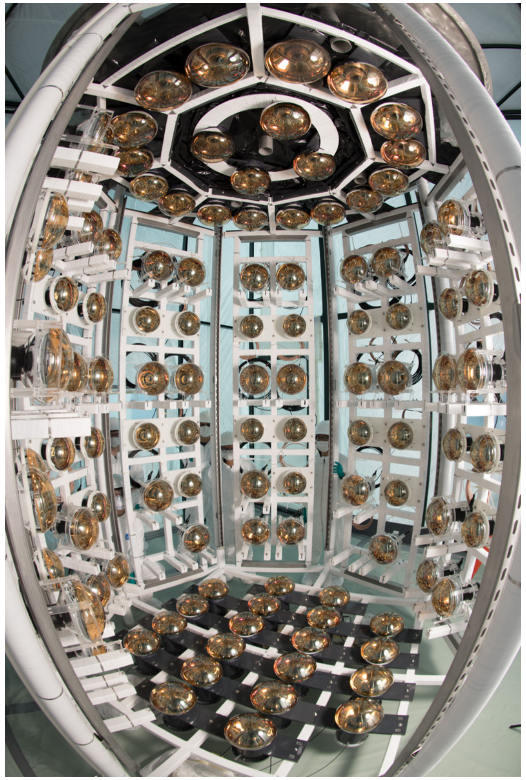
JUNO (2022)

ANNIE Experiment

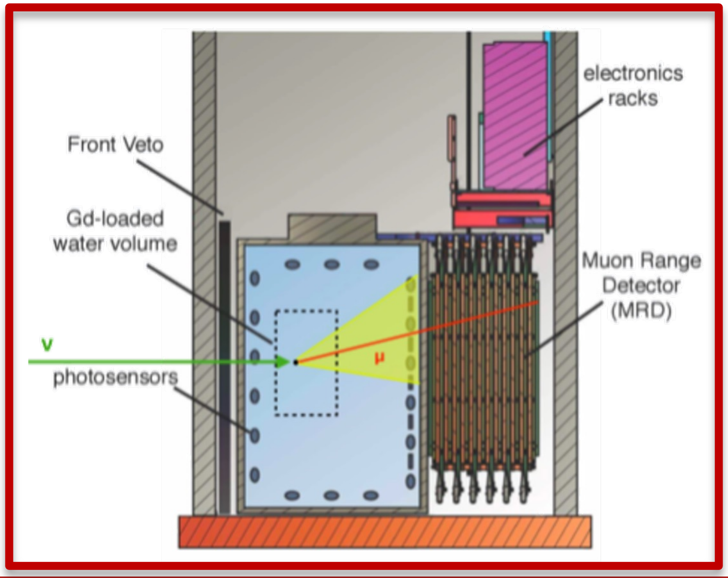
Accelerator Neutrino Nucleus Interaction Experiment

27-ton (Gd-loaded) Water Cherenkov Detector running in the **Fermilab BNB neutrino beam**

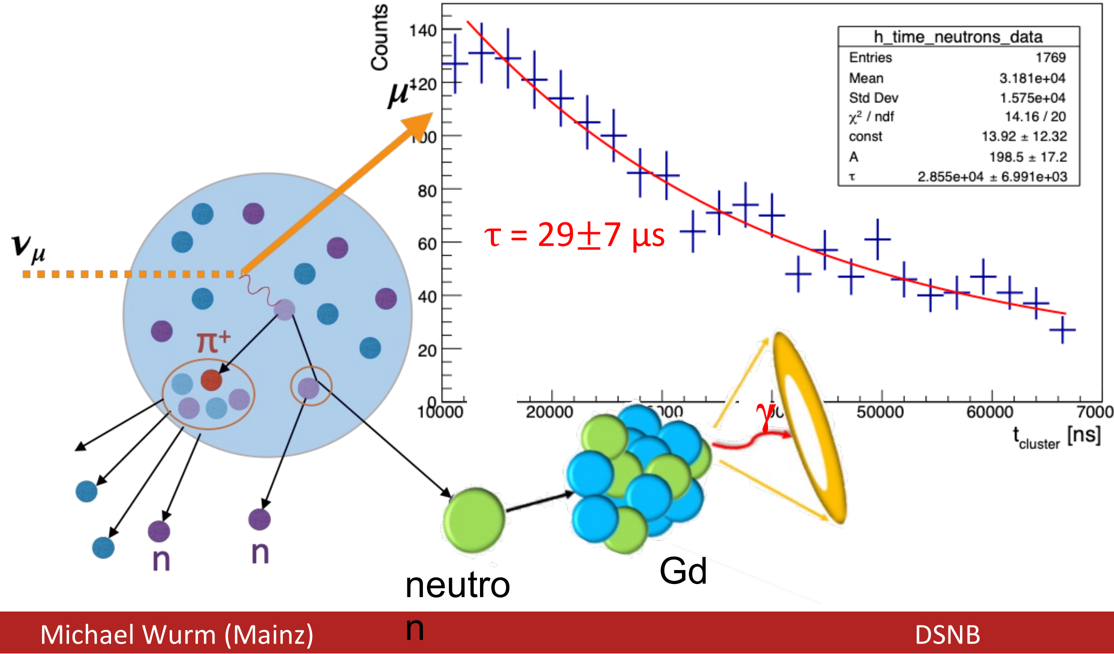
- measurement of GeV neutrino differential cross-sections and neutron multiplicity
  → *predict NC background rates for DSNB*
- physics data taking started in early 2021
- R&D program for new technologies
  → Gd-water → LAPPDs → WbLS



ANNIE Detector Layout



neutron capture time following beam events

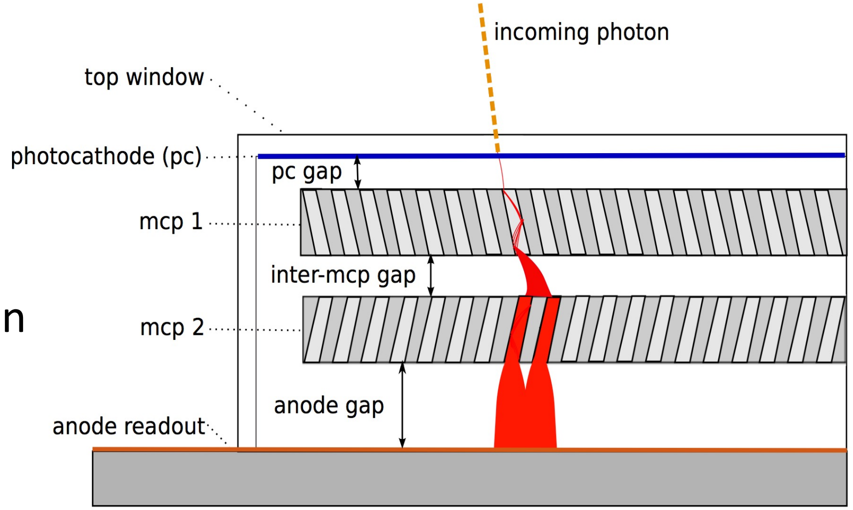


Fast light detectors: LAPPDs

For fast scintillators (e.g. WbLS),
sub-ns time resolution will be crucial

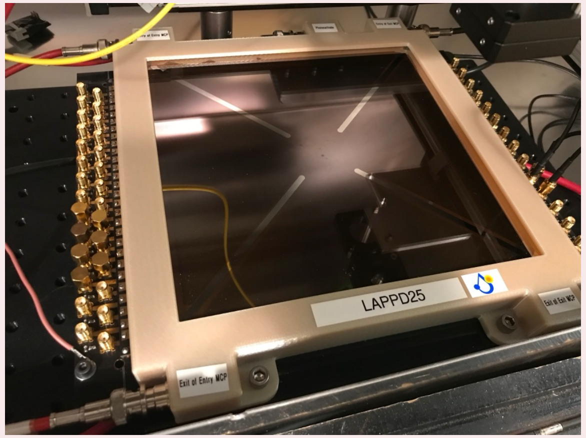
Large-Area Picosecond Photo-Detectors:

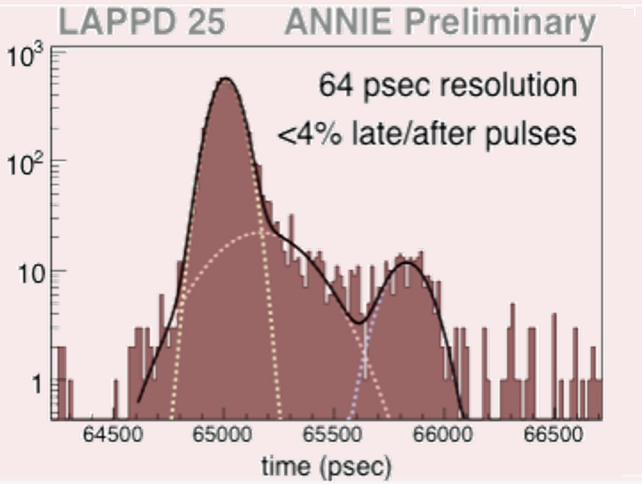
- flat, large area (20cm x 20cm) detectors
- standard photocathode, MCP-based amplification
- time resolution: ~60 ps
- spatial resolution: <1cm
- Manufactured by US company, Incom Inc.

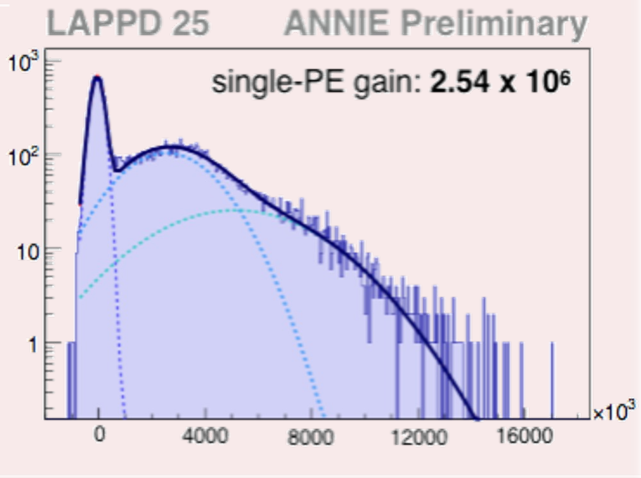


Schematic of LAPPD

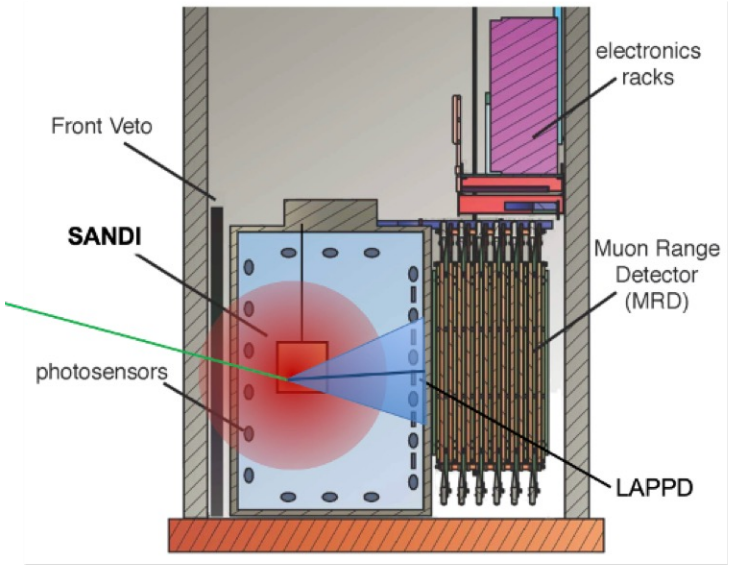
LAPPD test for ANNIE







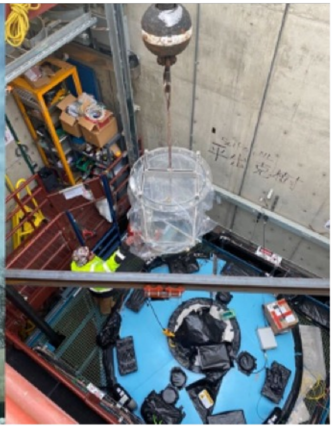
First SANDI deployment in March '23

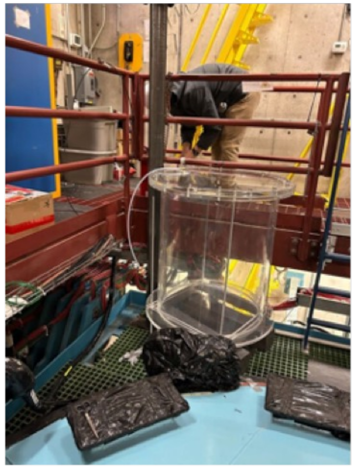


WbLS (BNL): 0.5% organic fraction

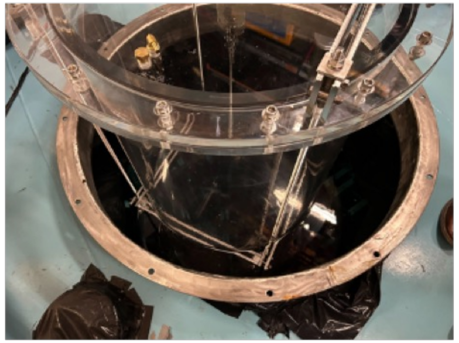
Goals for first run:

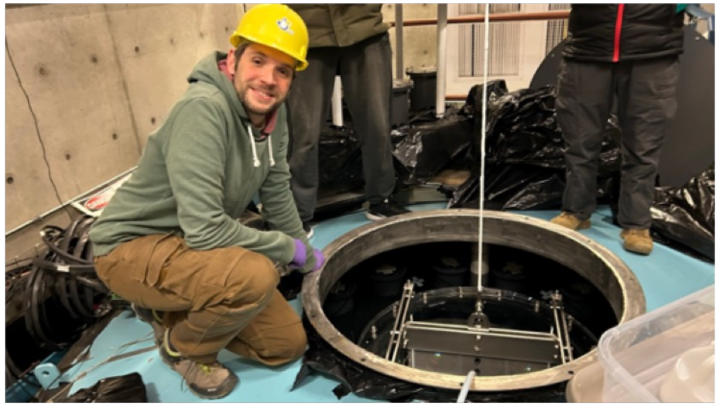
- detect scintillation of hadrons
- use LAPPDs for C/S separation
- detect neutron capture on H
- show general compatibility for second run: SANDI filled with Gd-loaded WbLS





removed in May after taking 2 months worth of beam data



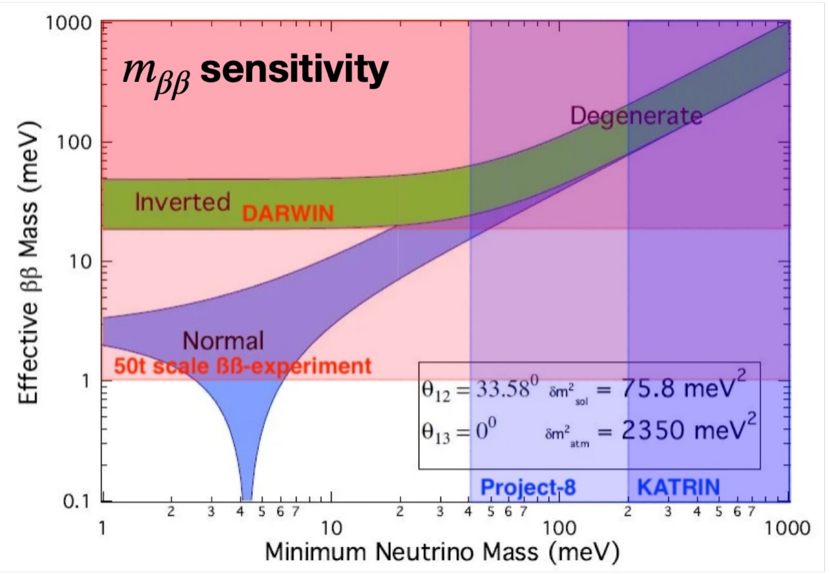


SANDI vessel & support frame inserted in Jan

Insertion of vessel inside ANNIE tank in March

NuDoubt++ — Demonstrator for next-generation $0\nu\beta\beta$ search

- Project: 100 kg-scale (isotope) demonstrator for ββ-search in advanced (opaque and/or hybrid) scintillator detector
- Physics goals for demonstrator phase
  - demonstrate background rejection capability required for next-generation 50-ton-scale (isotope) experiment → meV ββ mass
  - first measurement and spectroscopy of still unobserved 2vECβ+ and 2v2β+ decays by pressurized ^{78}Kr or ^{124}Xe loading
- Time line
  - currently: R&D on basic scintillators (both opaque and hybrid) and pressurized noble gas loading
  - run with local 1t-demonstrator in Kupferberg Keller and/or upgrade existing OSIRIS setup (~2026)
  - two-year run with full loading in deep lab in 2029
- synergies with JUNO-ββ, Theia, LiquidO efforts



event ID in hybrid Cherenkov/Scintillation detector