The novel neutrino nexus: SBND, JUNO, and DUNE

John Plows (U. of Liverpool)

Particle annual meeting

23/May/2024

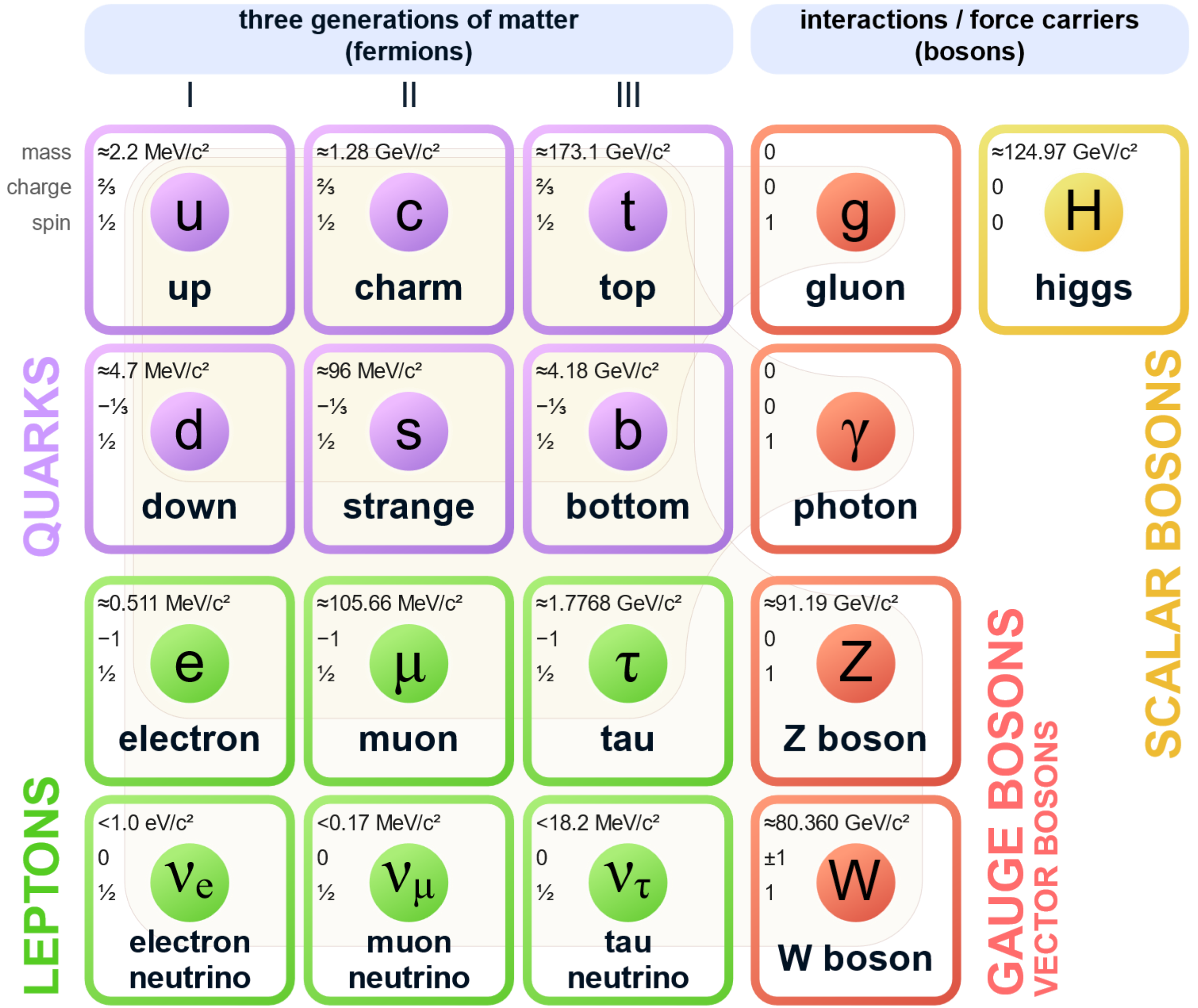
DEEP UNDERGROUND NEUTRINO EXPERIMENT

SHORT-BASELINE NEAR DETECTOR SBND

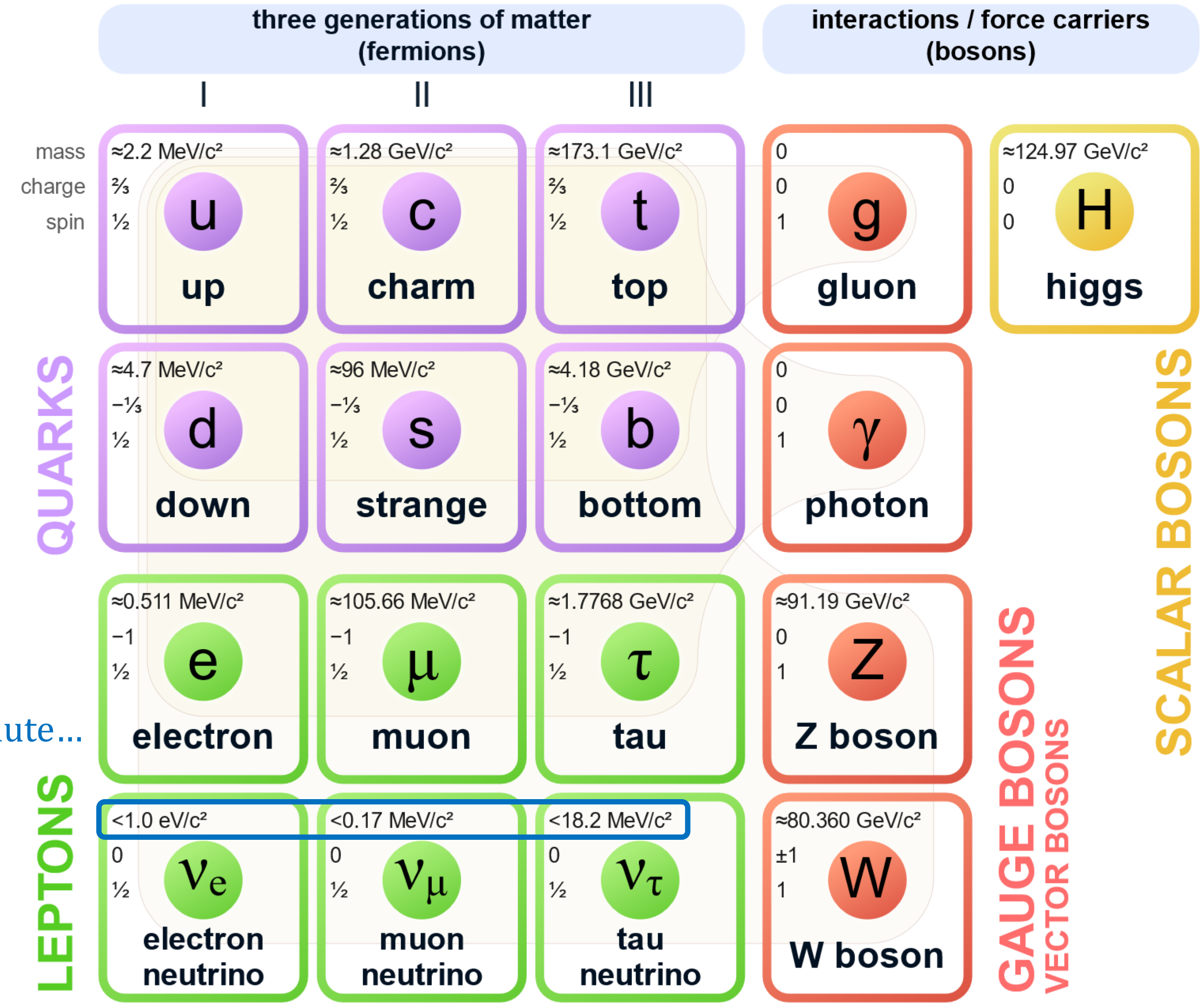
JUNO

UNIVERSITY OF LIVERPOOL

Standard Model of Elementary Particles



Standard Model of Elementary Particles



Wait a minute…

Open questions ??

- ? What is the neutrino mass hierarchy?
- ? Is there CP violation in the lepton sector?
- ? How do neutrinos interact with nuclei?
- ? Are neutrinos their own antiparticles?
- ? Where do neutrino masses come from?
  - ? Why are neutrinos so much lighter than charged leptons?
  - ? Can neutrinos provide a dark matter candidate?
- ? Can we measure the neutrino mass?

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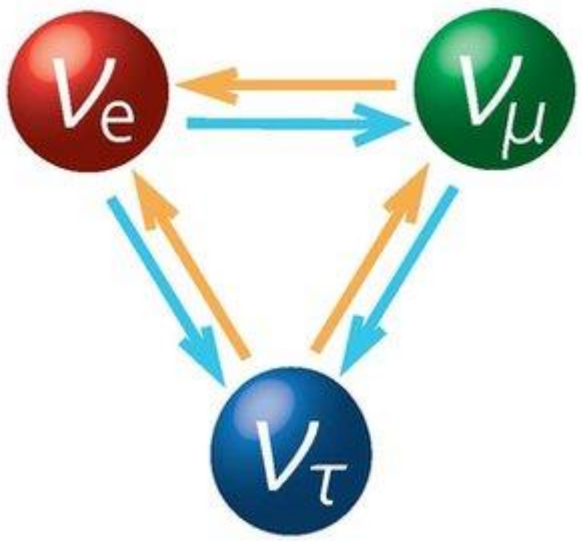
Almost all of these questions can be addressed by oscillation experiments!



Open questions ??

- ? What is the neutrino mass hierarchy? ✓
- ? Is there CP violation in the lepton sector? ✓
- ? How do neutrinos interact with nuclei? ✓
- ? Are neutrinos their own antiparticles?
- ? Where do neutrino masses come from?
  - ? Why are neutrinos so much lighter than charged leptons? ✗
  - ? Can neutrinos provide a dark matter candidate?
- ? Can we measure the neutrino mass? ✗

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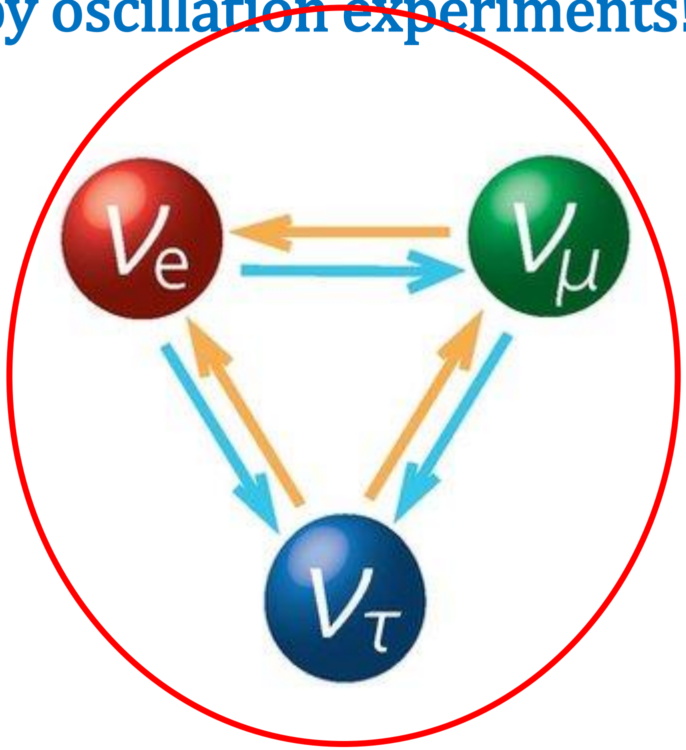
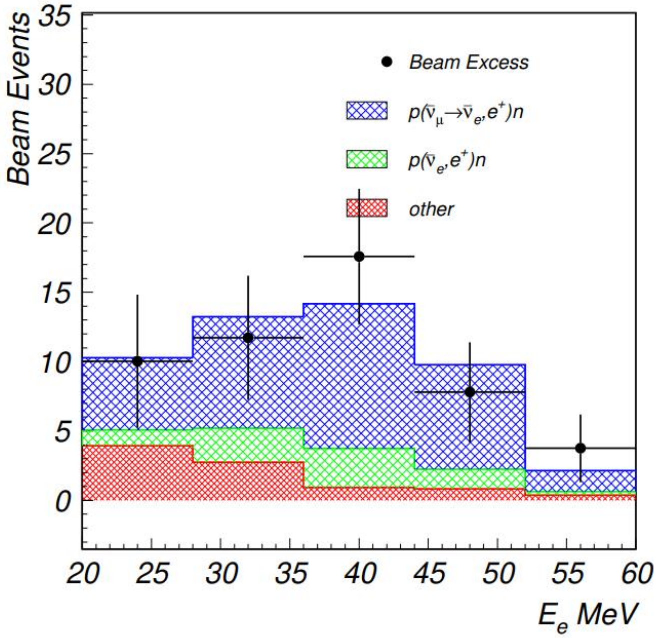
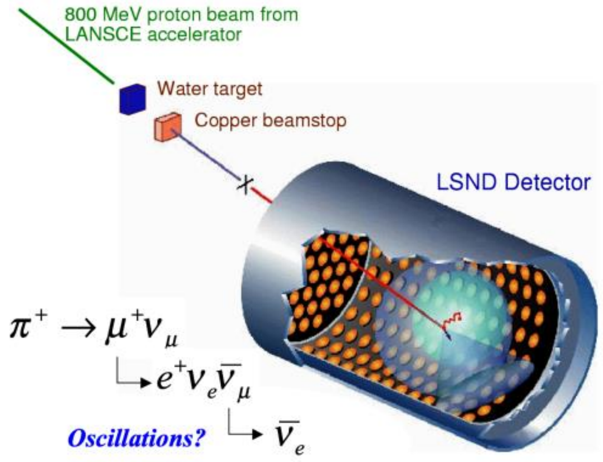


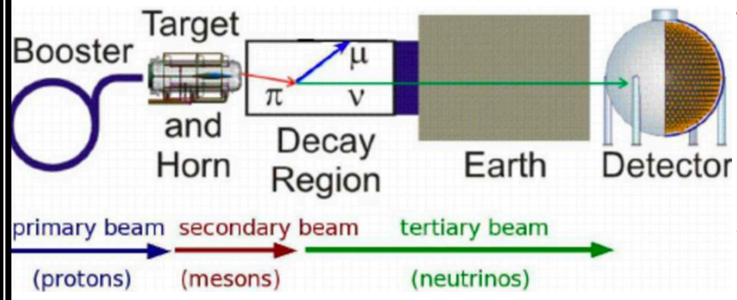
But is this the full picture…?

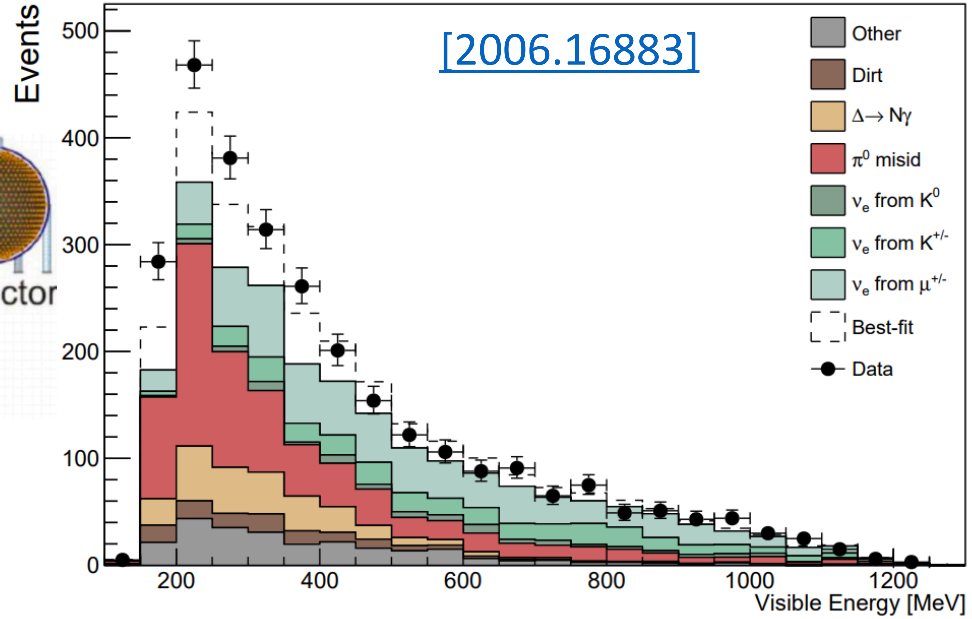
Enter anomalies

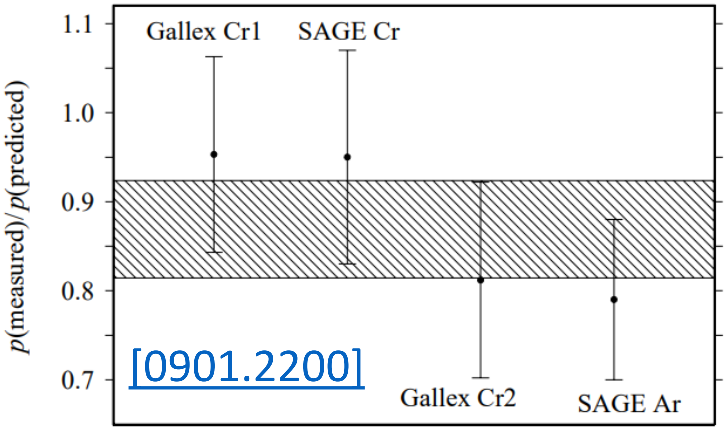
[hep-ex/0104049]

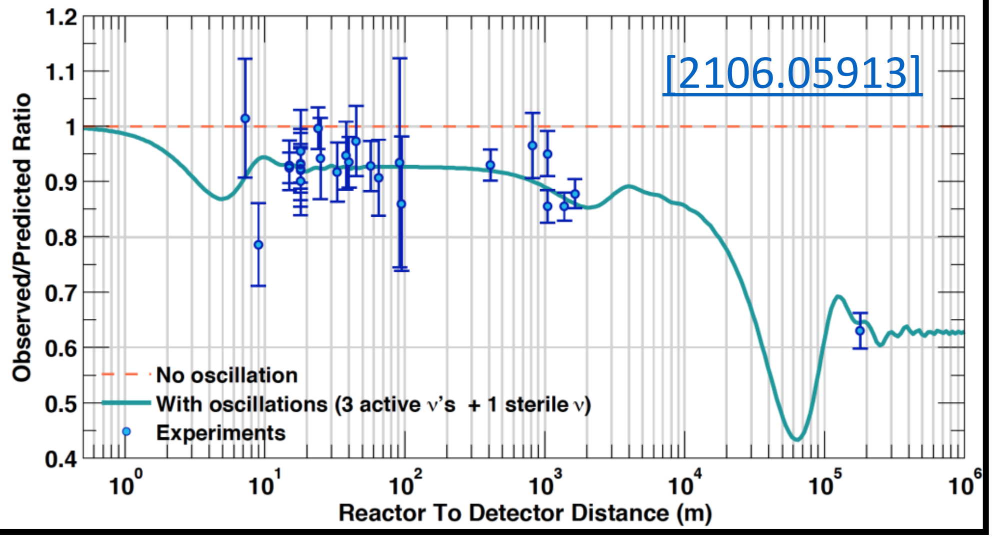




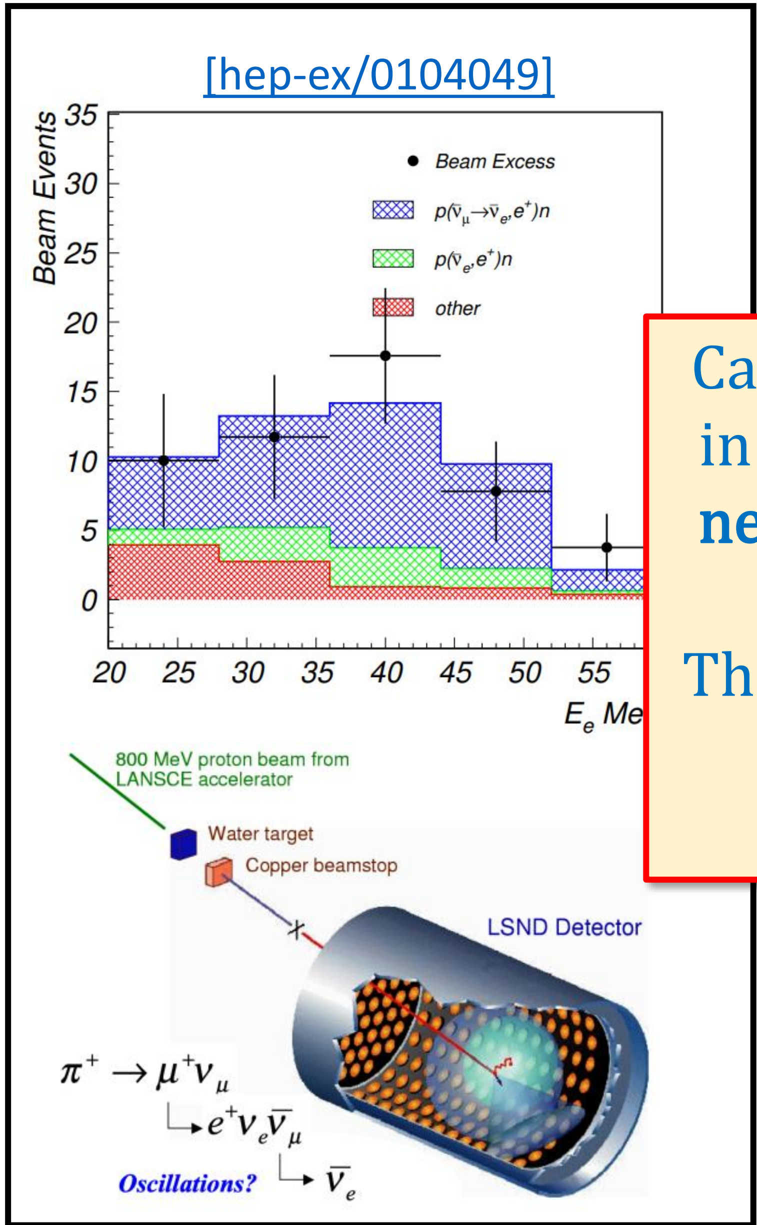


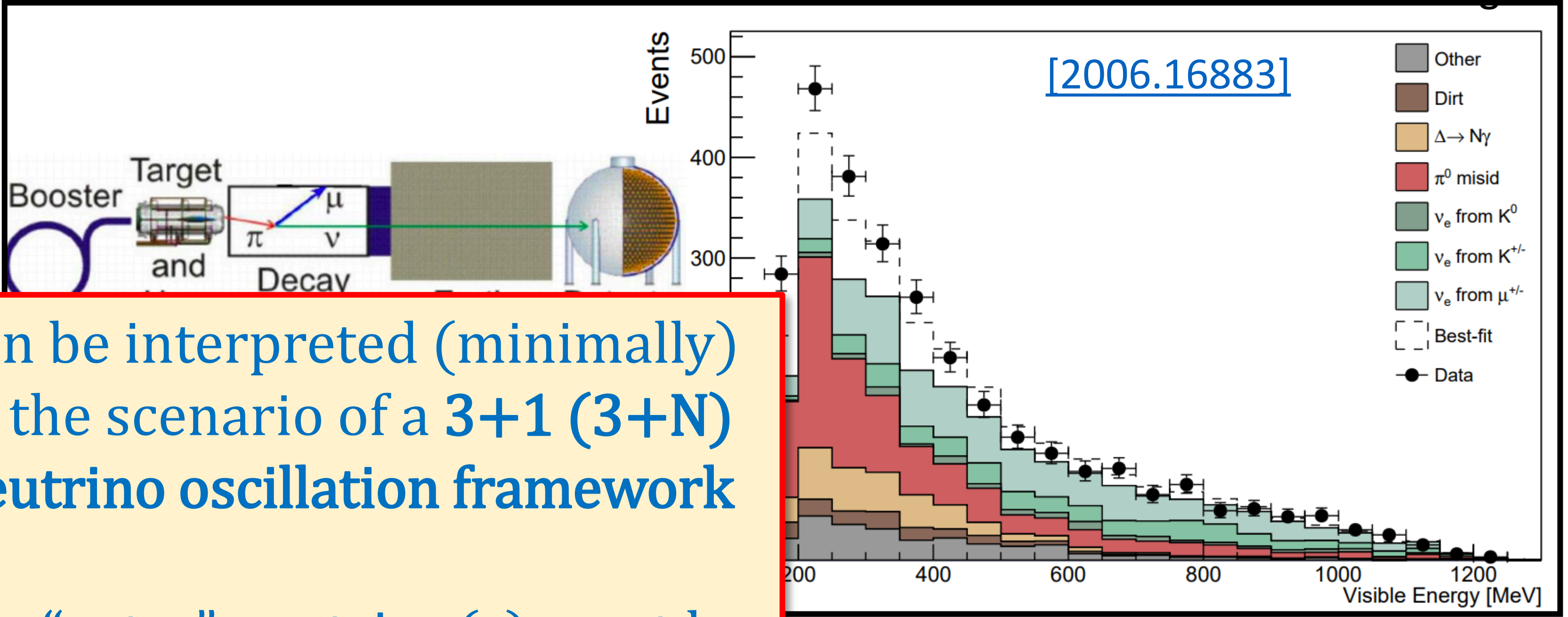






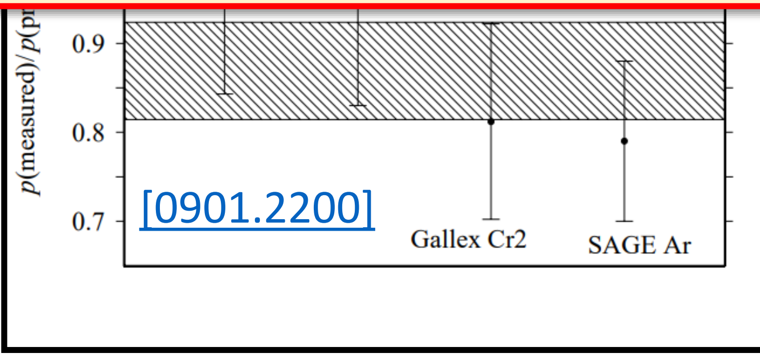
Enter anomalies

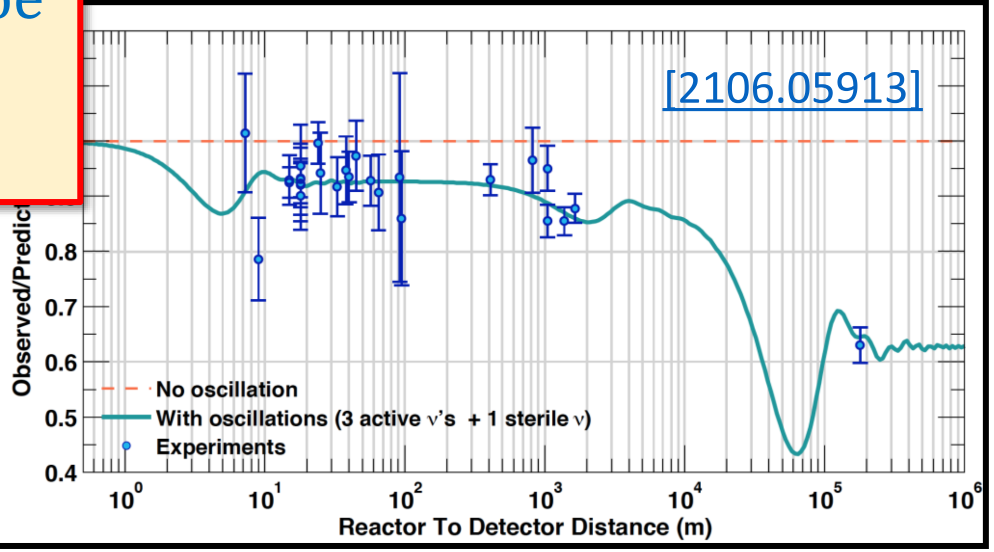




Can be interpreted (minimally) in the scenario of a **3+1 (3+N) neutrino oscillation framework**

The "extra" neutrino(s) must be **sterile** and **light** ($\Delta m^2_{N1} \sim \mathcal{O}(1\ \mathrm{eV}^2)$)





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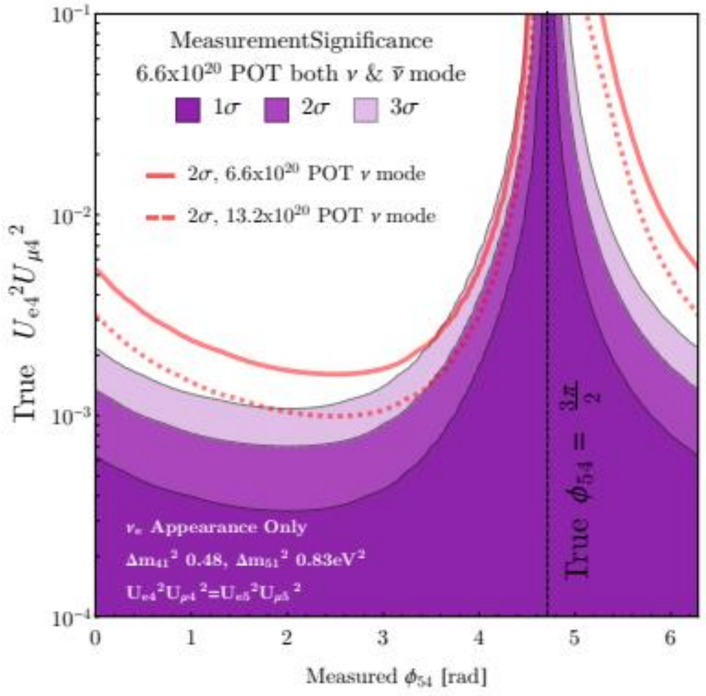
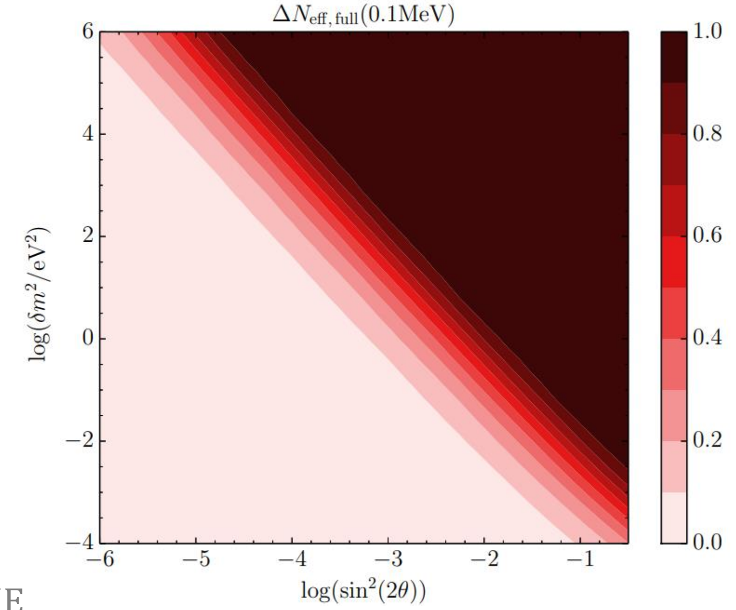
Sterile neutrinos would **revolutionise our understanding of particle physics**

- Definitive proof the Standard Model is incomplete
  - νMSM ([hep-ph/0503065]) predicts **3+3 model** with one light and two quasi-degenerate heavy neutrinos
  - Hint for **neutrino mass mechanism** (type-I seesaw)
- Breaks the three-flavour oscillations! (re-interpret limits on δ_{CP} -- **not necessarily zero if we don't see CPV in active neutrion sector**)
  - Extra CP-violating phases from extra degrees of freedom!
- Far-reaching consequences in cosmology (dark matter candidate, can source matter - antimatter asymmetry)



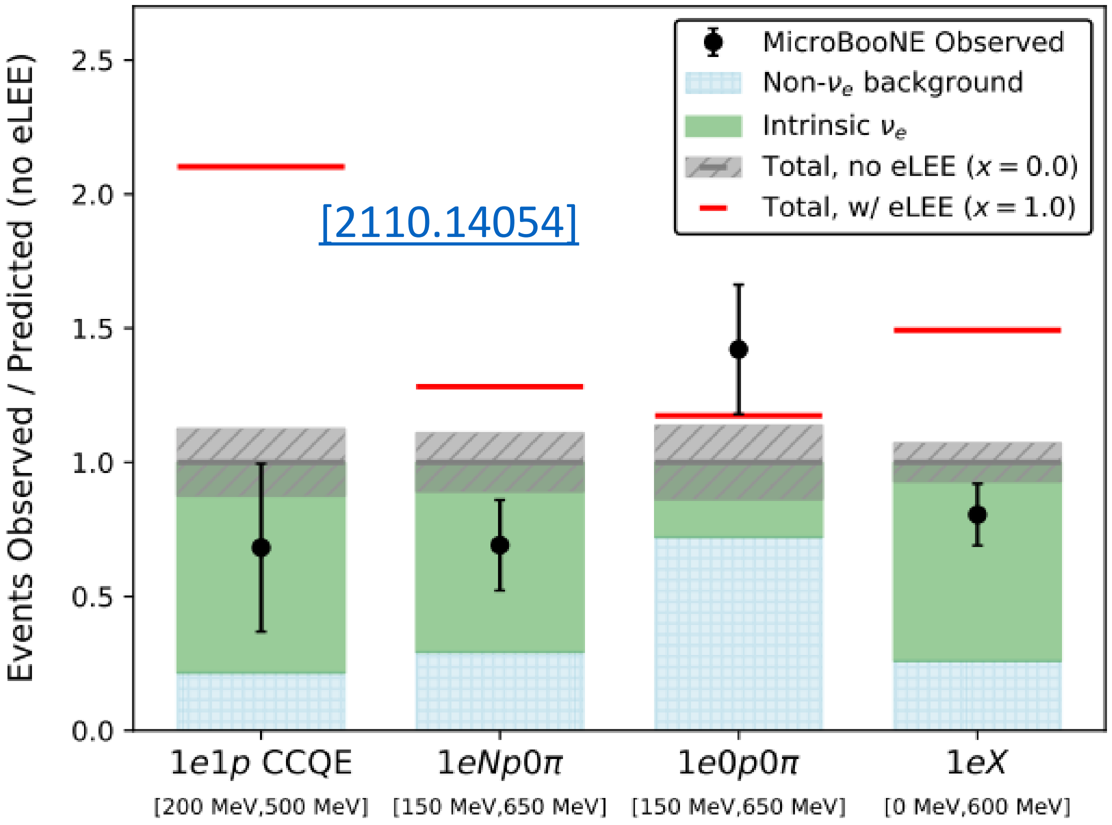
[1702.01758]



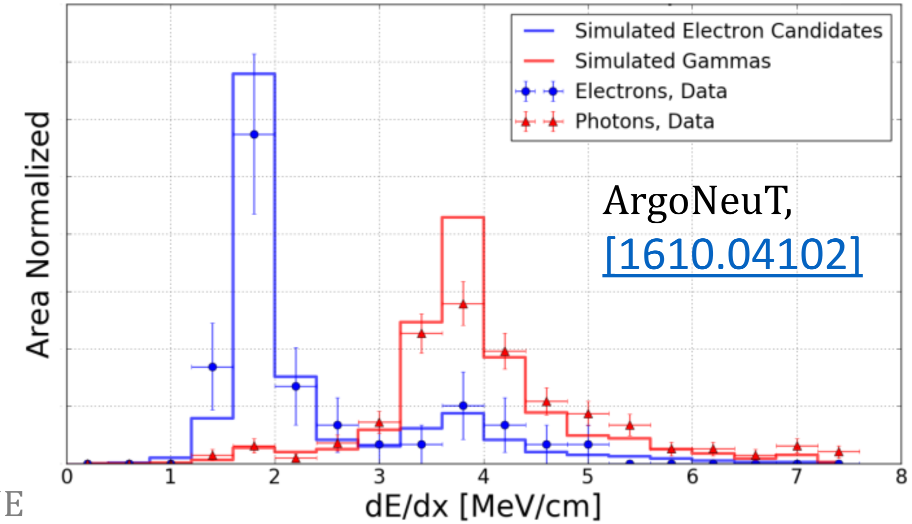
[1506.05266]

Possible, but *likely?*

- MicroBooNE (LAr technology) at BNB ⇒ ~same L/E_ν as MiniBooNE
  - LAr better at reconstructing e, γ and differentiating these signals (Čerenkov rings from e, γ extremely difficult to distinguish)
- Found **no evidence of MiniBooNE excess**
  - This **does not rule out** the sterile neutrino (see e.g. [2111.10359])

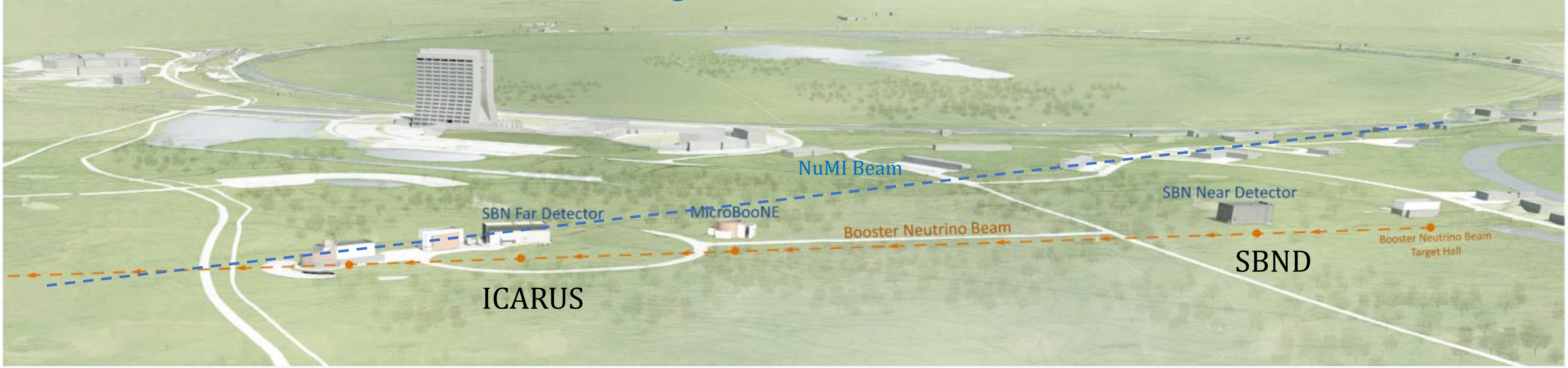


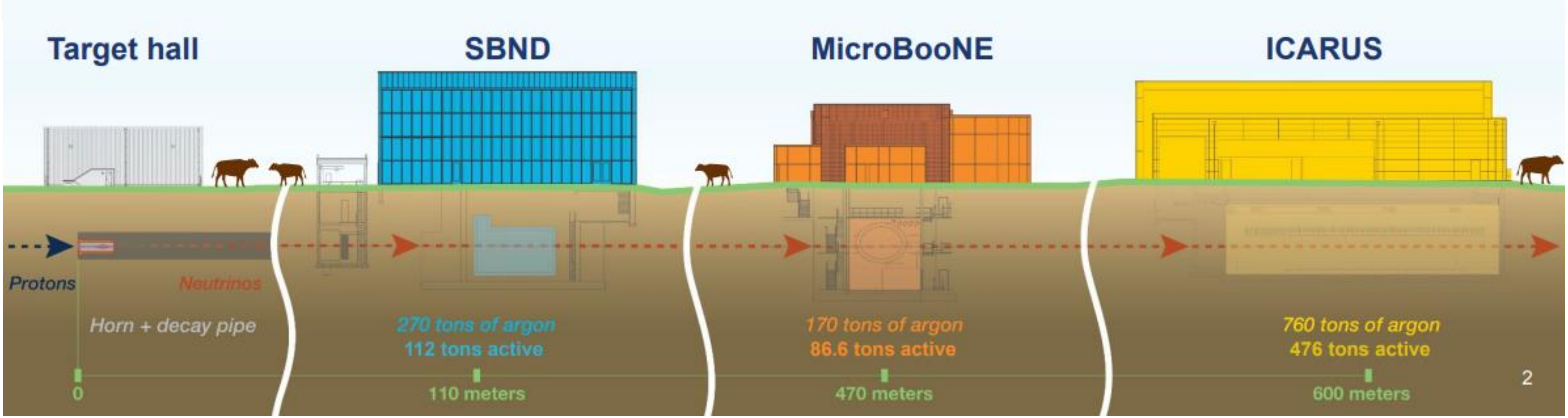
- **Alternative explanations?**
  - Modification to "3+1" scenario? (3+1 already disfavoured by MiniBooNE)
  - Mis-identification of signal events at MiniBooNE?
  - Mis-modelling of backgrounds?
  - Exotic physics?



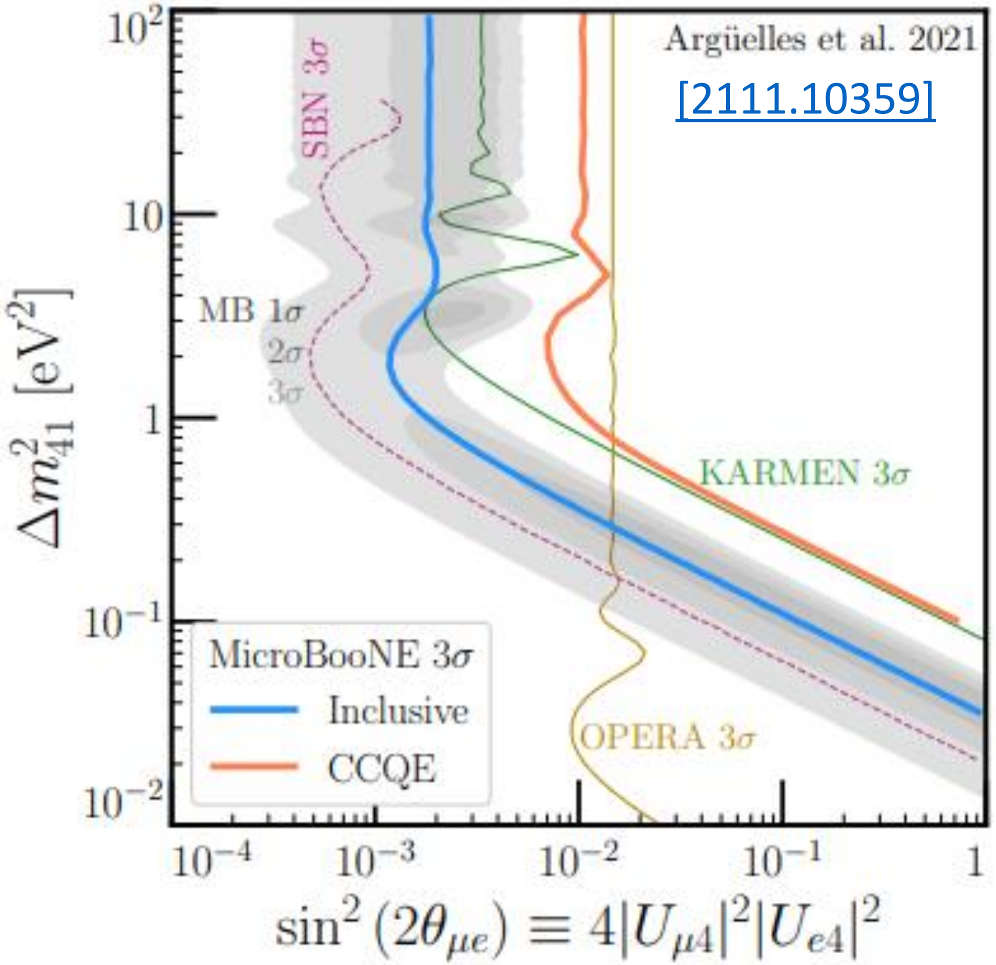
ArgoNeuT, [1610.04102]

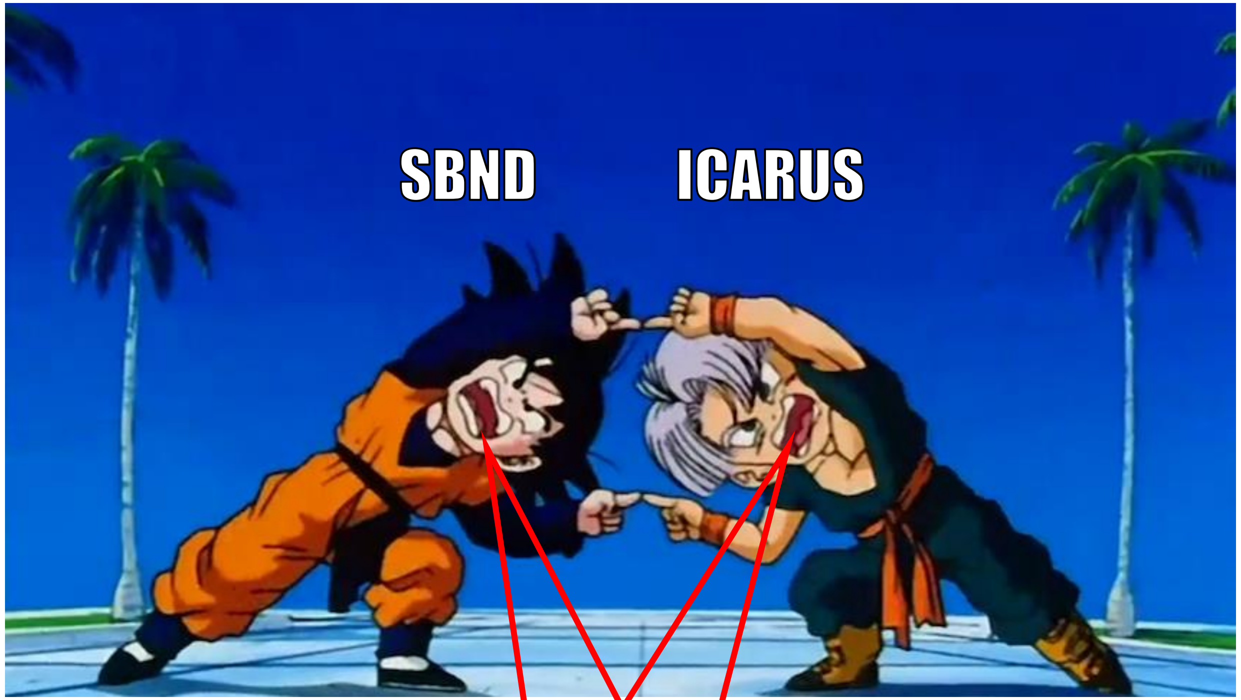
Extending MicroBooNE's reach…





SBN programme reach





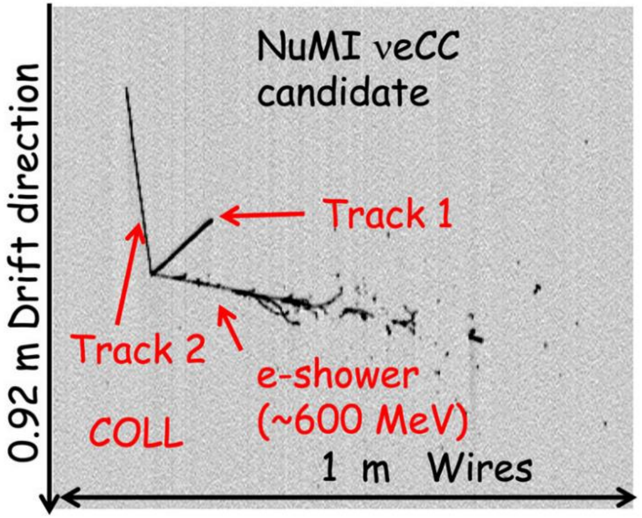
Sterile is not dead yet!

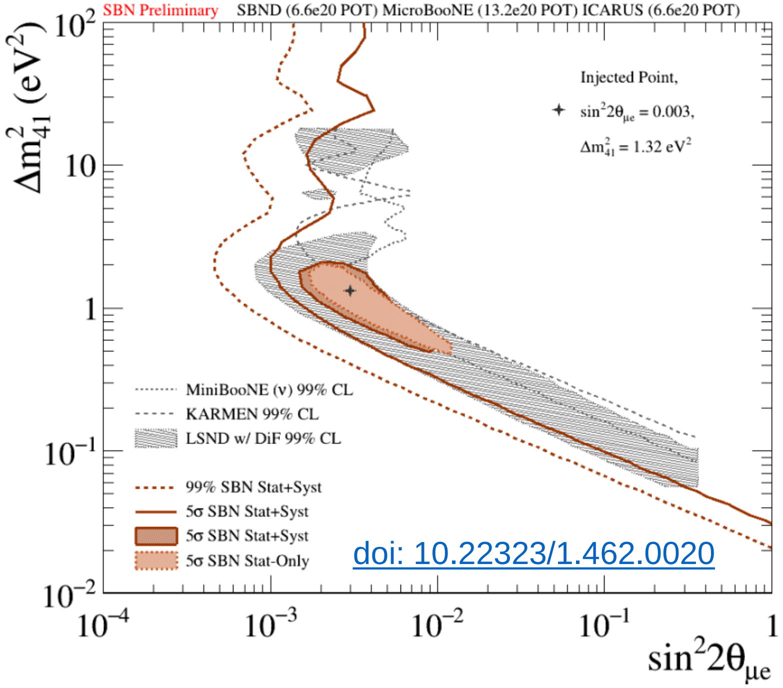
SBND measures the **unoscillated** spectrum and performs **high-precision interaction measurements**

ICARUS measures the **oscillated** spectrum

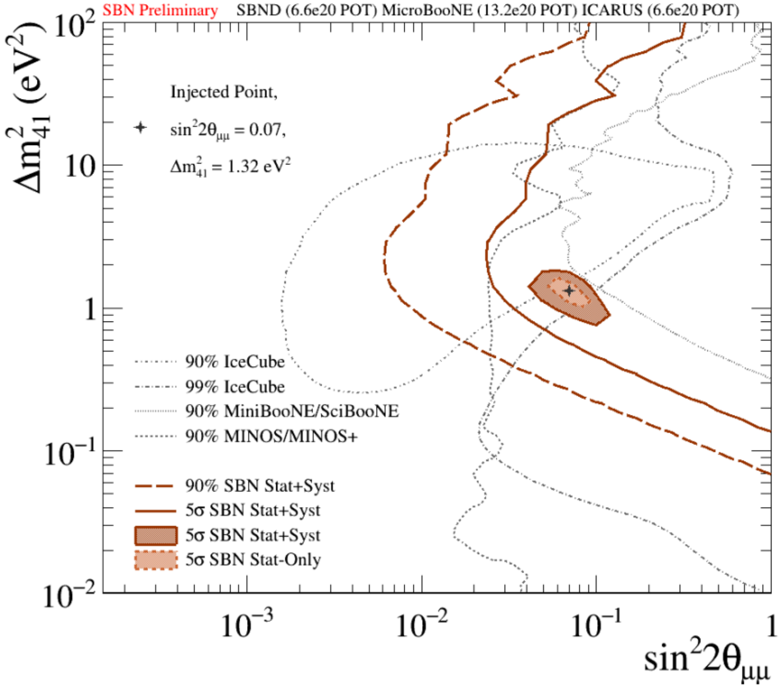
A tale of two detectors

- SBND (in progress) and ICARUS (started data-taking 2021) are same material and same beamline as μBooNE
- SBND projected rate of **$\sim 10^{21}$ POT / year** over 3-4 years
  - Extreme statistics for **neutrino-argon interactions**
  - Excellent test bed for **exotic physics beyond the SM**
- ICARUS also sensitive to off-axis NuMI beam
  - Sensitive to low-energy ν_e





doi: 10.22323/1.462.0020



The SBN programme has **3 main physics goals**:

1. Accept or rule out **definitively** the **short-baseline anomalies**

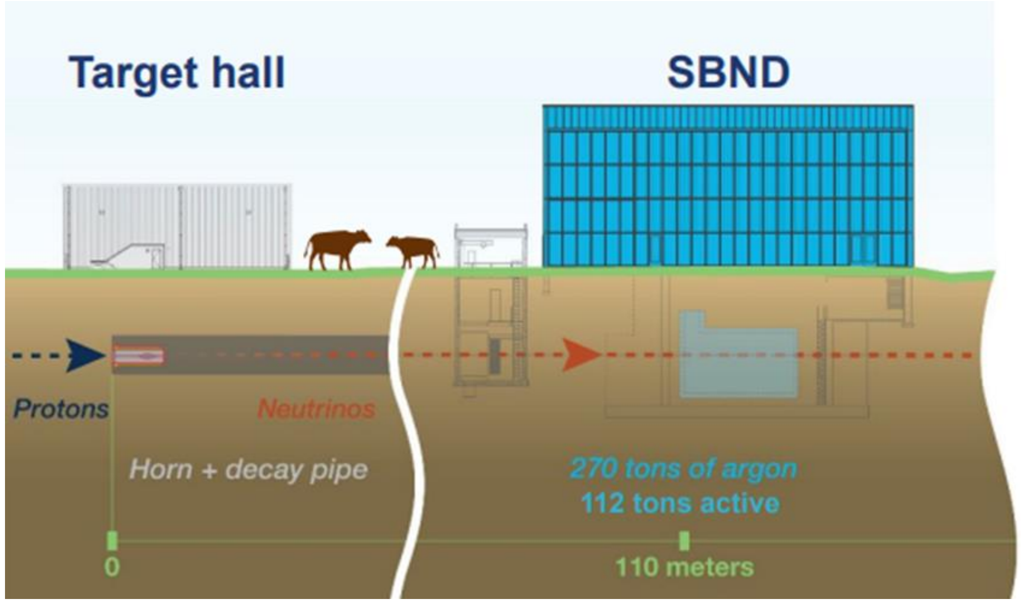
2. Precisely measure **neutrino-argon interactions** in preparation for next-generation long-baseline experiments (**DUNE**)

3. Search for exotic signatures **beyond the Standard Model**

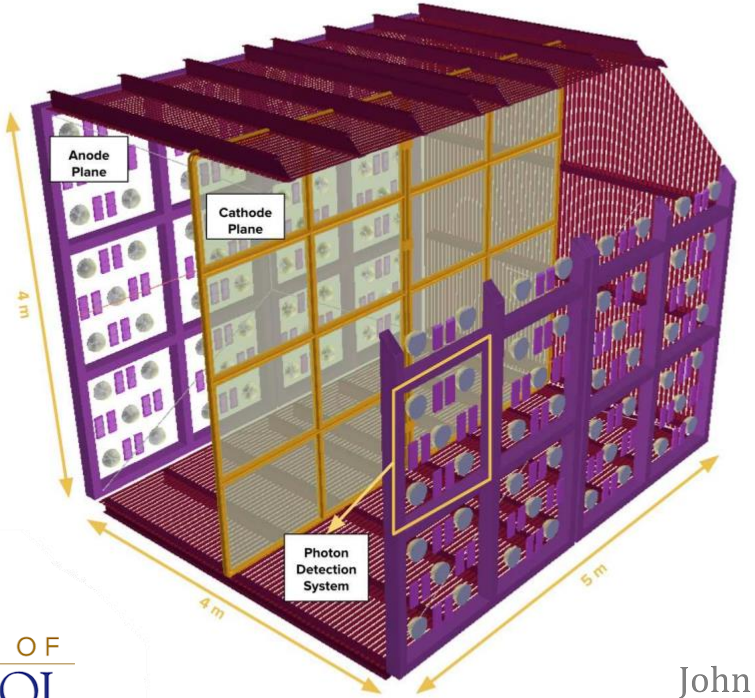
4. Characterise the **performance of LAr** detectors for DUNE

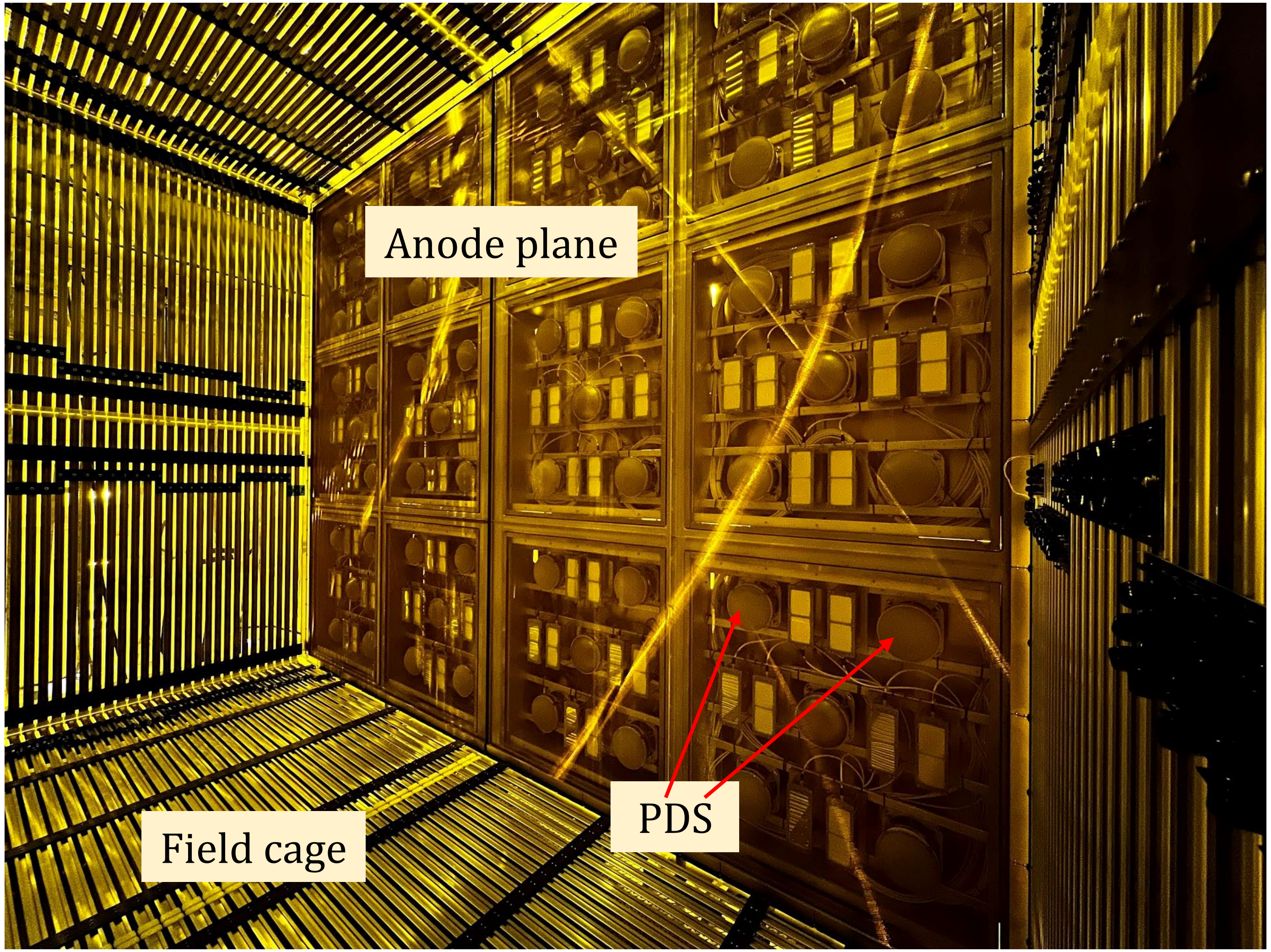
The SBN programme has 3 main physics goals:

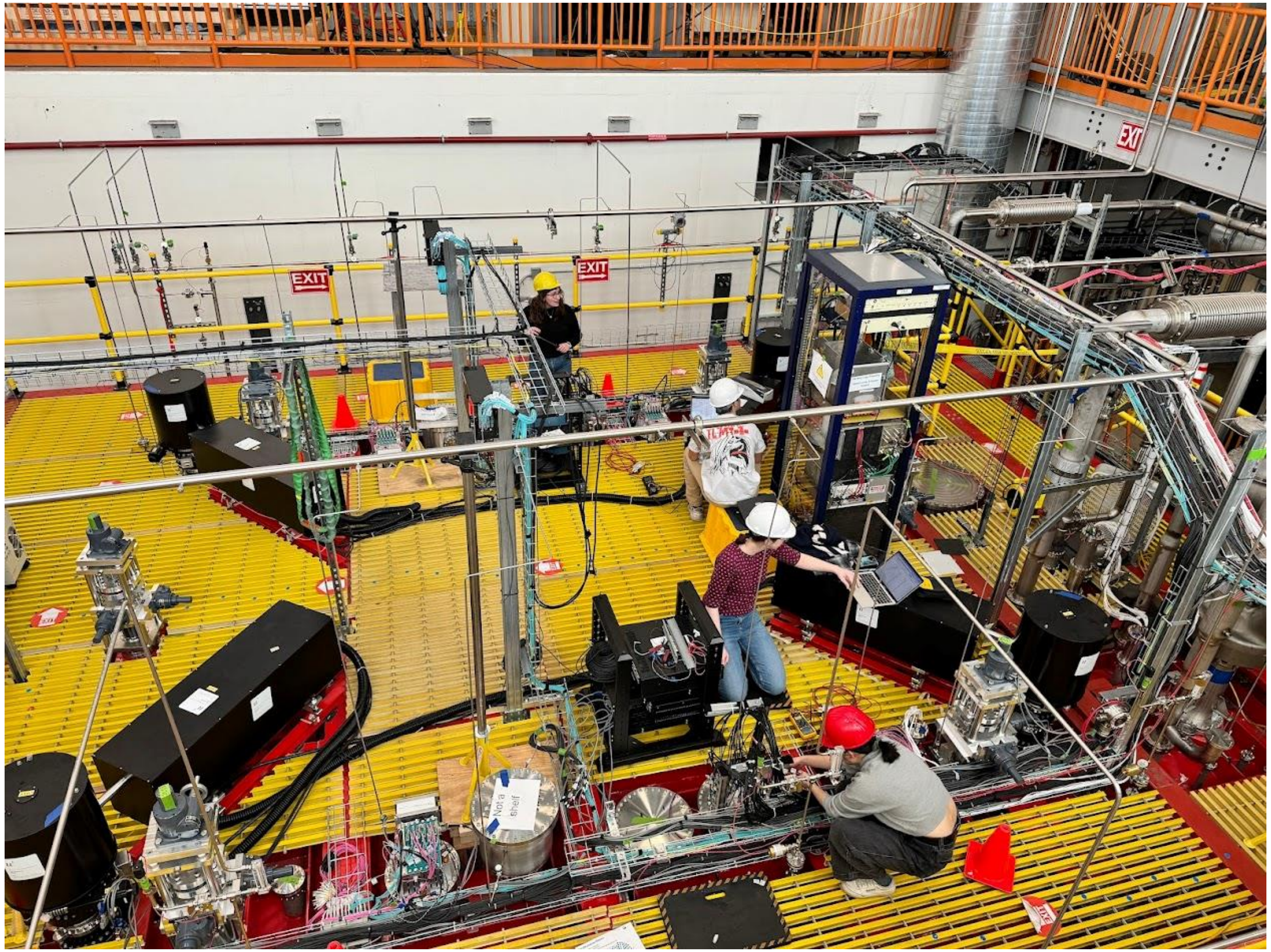
1. Accept or rule out **definitively** the **short-baseline anomalies**
   SBND input **crucial**
2. Precisely measure **neutrino-argon interactions** in preparation for next-generation long-baseline experiments (**DUNE**) SBND **high statistics**
3. Search for exotic signatures **beyond the Standard Model**
   SBND **high statistics** and **low background**
4. Characterise the **performance of LAr** detectors for DUNE

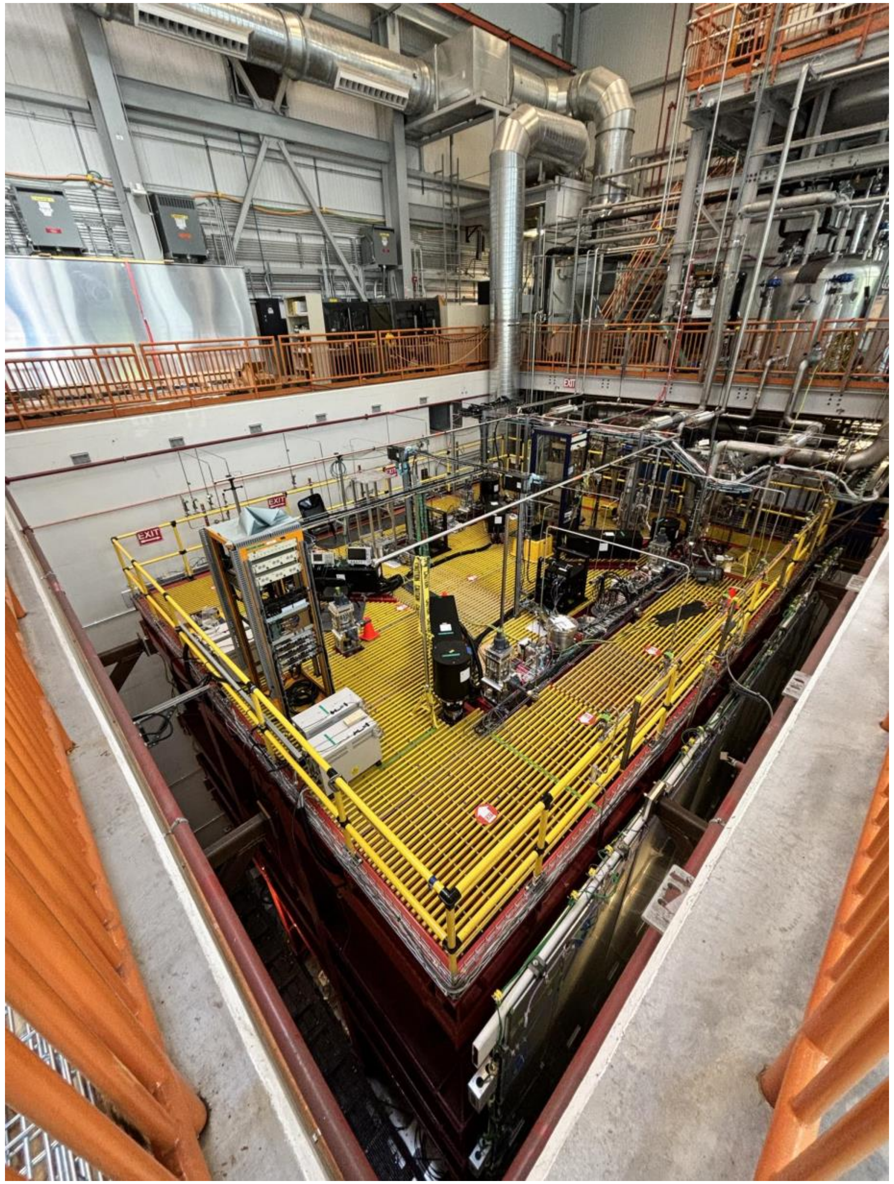


4x4x5 m^3
112 ton LAr
active






EXIT
EXIT
EXIT
Not a shelf



Liverpool at SBND

Academics:

- Costas Andreopoulos (IB)
- Christos Touramanis
- Kostas Mavrokoridis

Research staff:

- David Payne
- Marco Roda
- John Plows

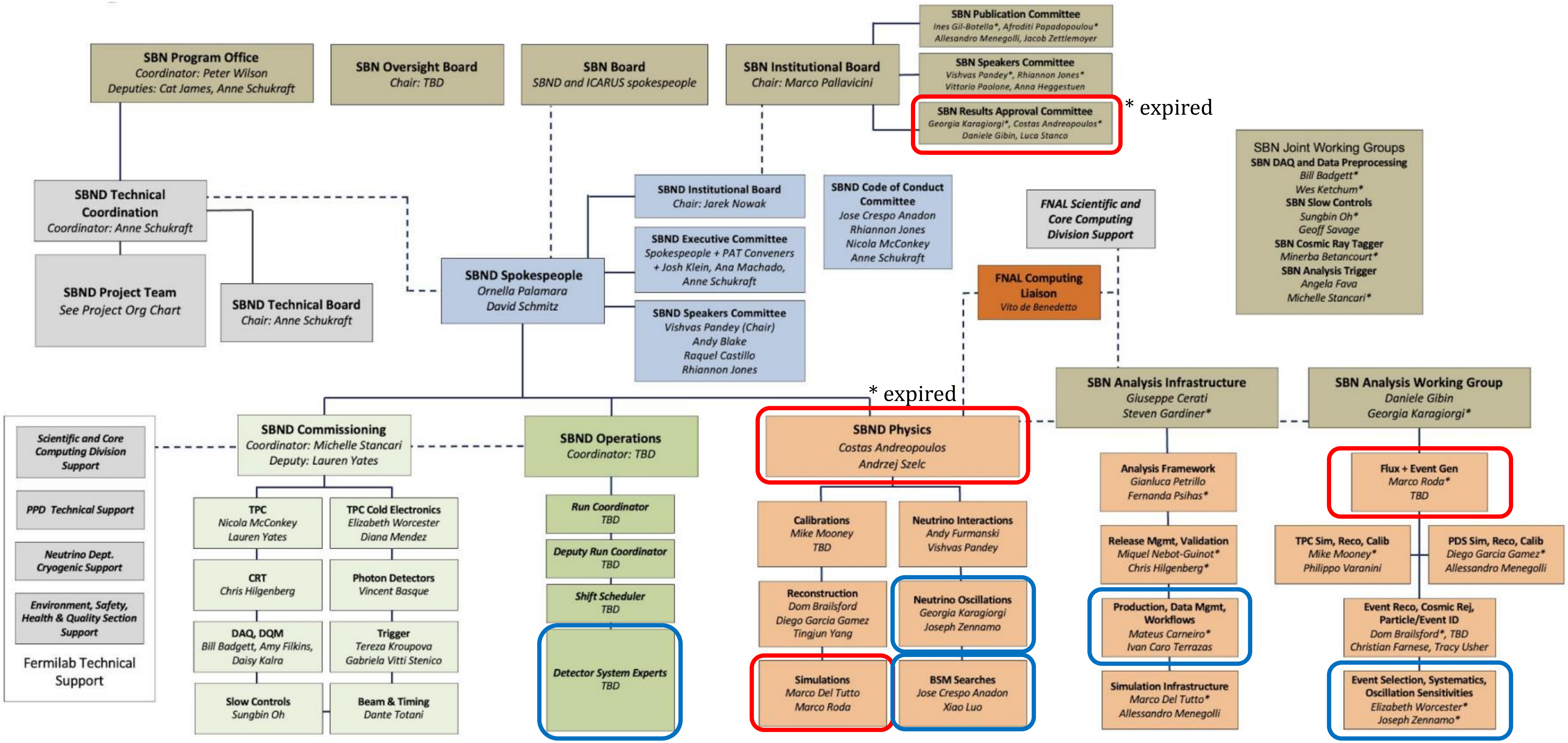
PhD students:

- Beth Slater
- Liam Jones (incoming!)

Making **key contributions** in:

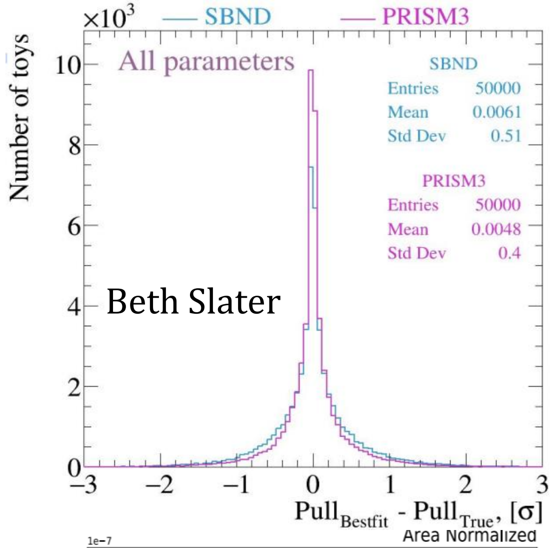
- Oscillation analyses (VALOR group -- Costas, Beth, John)
- Neutrino interaction simulations (Marco)
- Flux simulations (Marco)
- BSM simulations (John)
- Expert detector operations (David, Beth)

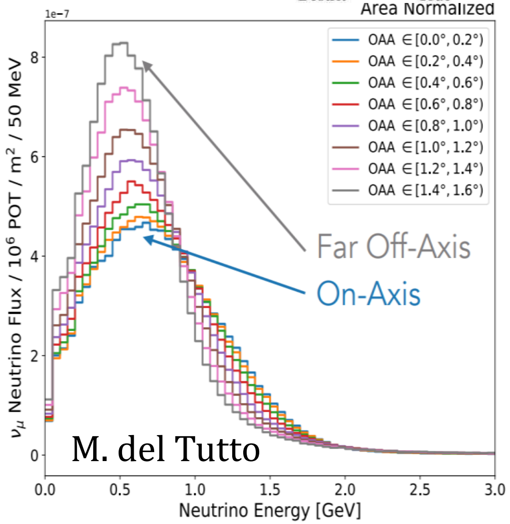
Liverpool has recently maintained leadership in key SBND roles and keeps presence in many groups!



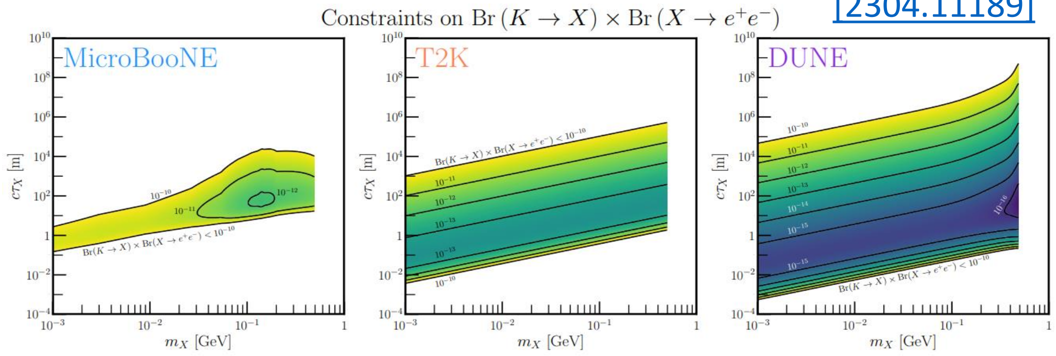
Status and plans for near future

- SBND is **almost ready to take data** and will be a **key physics driver in the next few years**
- There is much potential for physics exploitation here!
  - Examine **sensitivity using SBND-PRISM concept**
  - Improve systematics using PRISM (flux gets narrower as $\theta\uparrow$)
  - Develop machinery to **constrain systematics + flux using data**
    - Similar as in T2K case, especially break syst / flux degeneracies
  - Develop and cross-check in-house model-dependent BSM simulation with **model-independent exotic-particle** generator
  - Develop **tuned predictions for neutrino-argon scattering using SBND**
- Support detector on-site with experts
  - David currently on LTA (18 months total)
  - John hoping to do short-term secondment to work on calibration
  - Travel funding by INTENSE, PROBES, SENSE grants + URA
- All this to be within ~5 years from now, **first data arriving this year!**



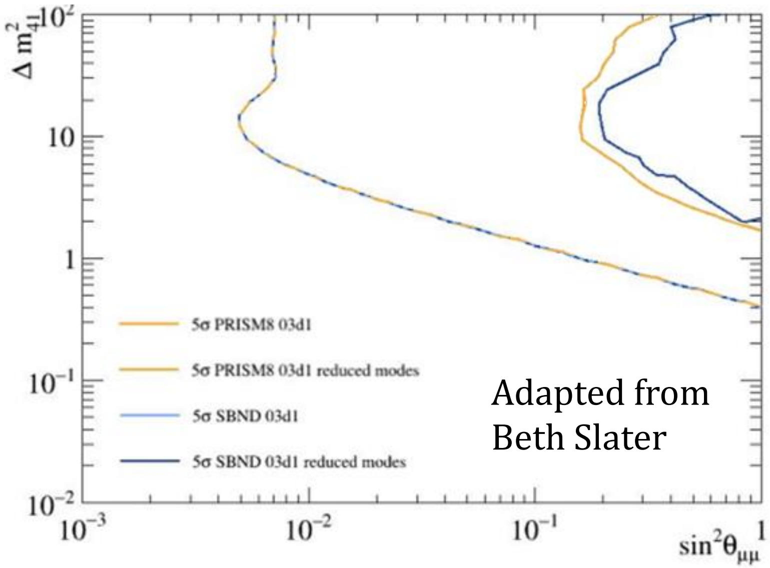


[2304.11189]



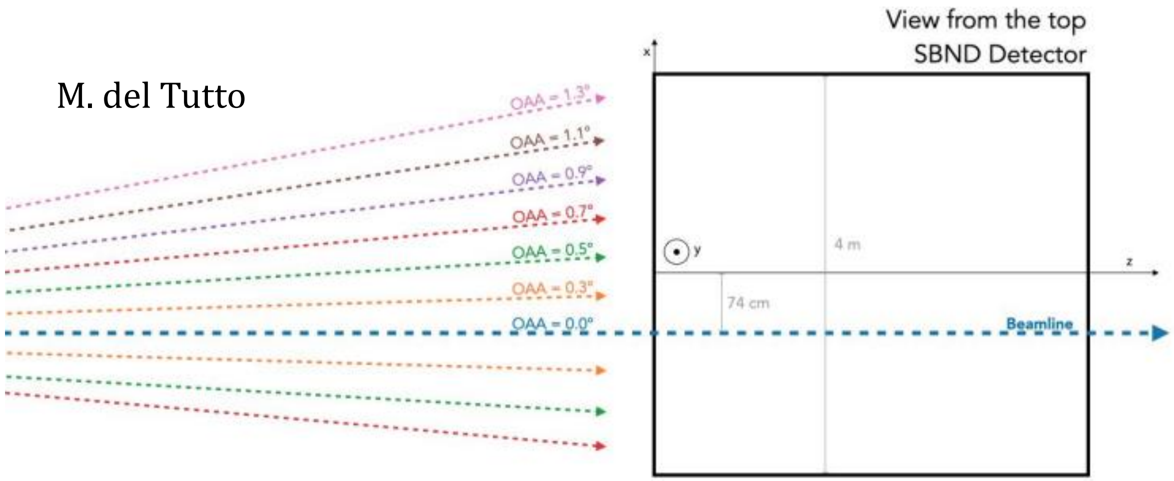
PRISM concept

- Flux shape **changes with off-axis angle**
  - Peaks at lower energy, harder spectrum
- SBND spans up to ~1.6° off axis (~3m at 110 m baseline)
- **Handle to break flux / cross-section syst degeneracy**
- **Constrains backgrounds for BSM searches**

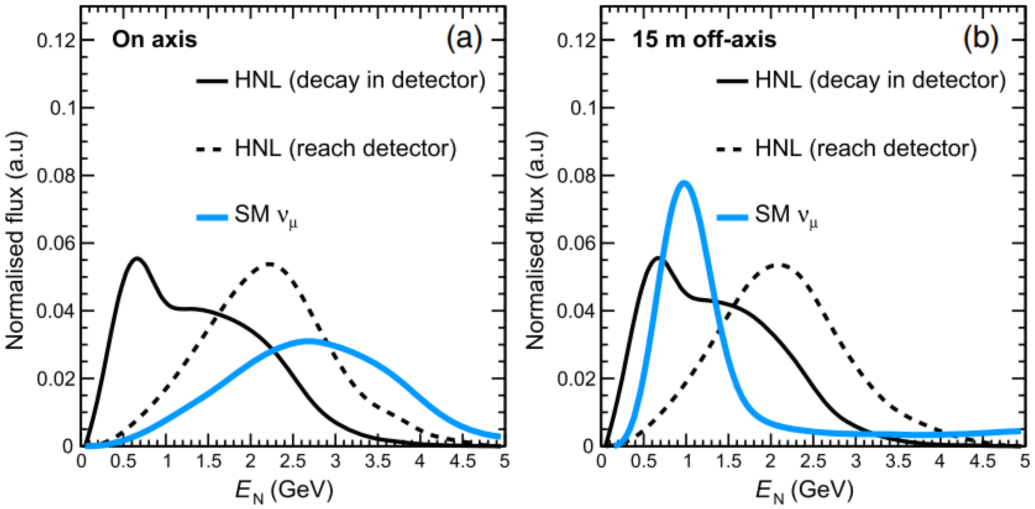


Adapted from Beth Slater

M. del Tutto



[2211.10210] (DUNE ND)

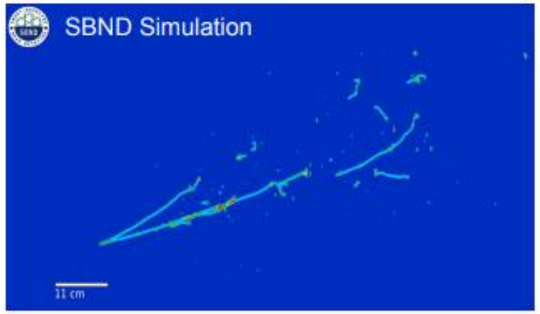


BSM signatures in SBND

R. Jones, Status of SBND, ICHEP 2022

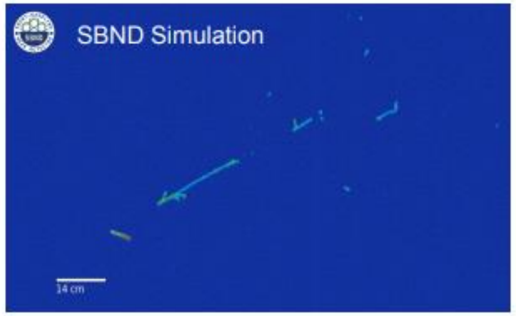
✓ = realisation of LLP

Dark Neutrinos



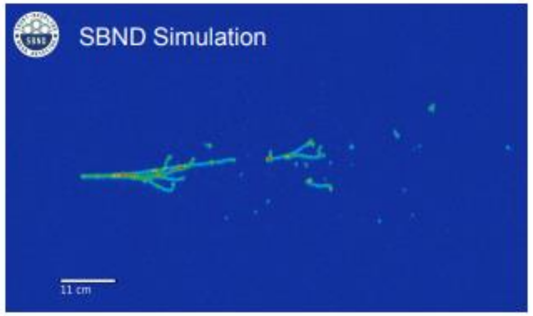
e^+e^- pair with or w/o hadronic activity

Transition Magnetic Moment



Photon shower and hadronic activity

Axion-like Particles ✓



High-energy e^+e^- or $\mu^+\mu^-$

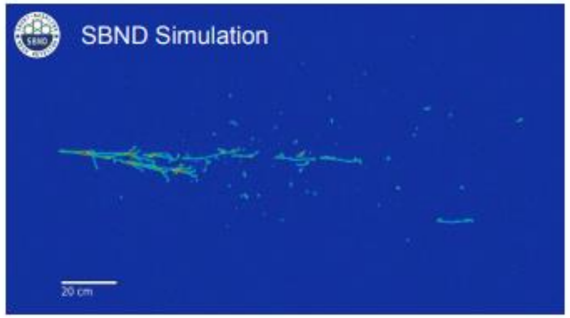
Example signatures and event displays for various BSM scenarios

Not an exhaustive list

Some diagram credit: Pedro Machado

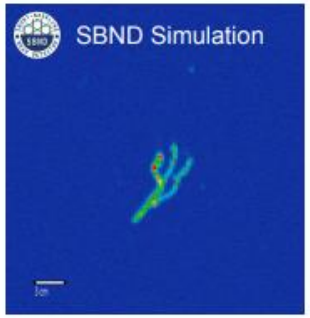
Slide credit: Marco Del Tutto

Heavy Neutral Leptons ✓



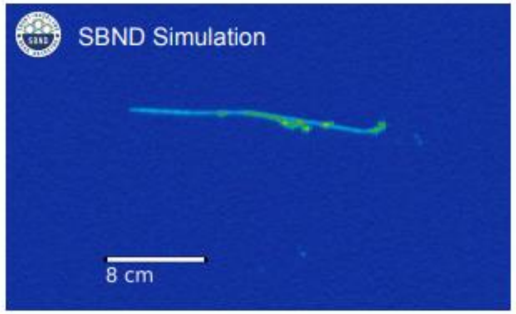
e^+e^-, $\mu^+\mu^-$ or $\mu\pi$

Higgs Portal Scalar ✓



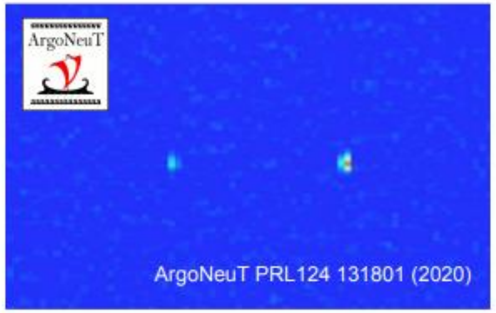
e^+e^- or $\mu^+\mu^-$, no hadronic activity

Light Dark Matter ✓



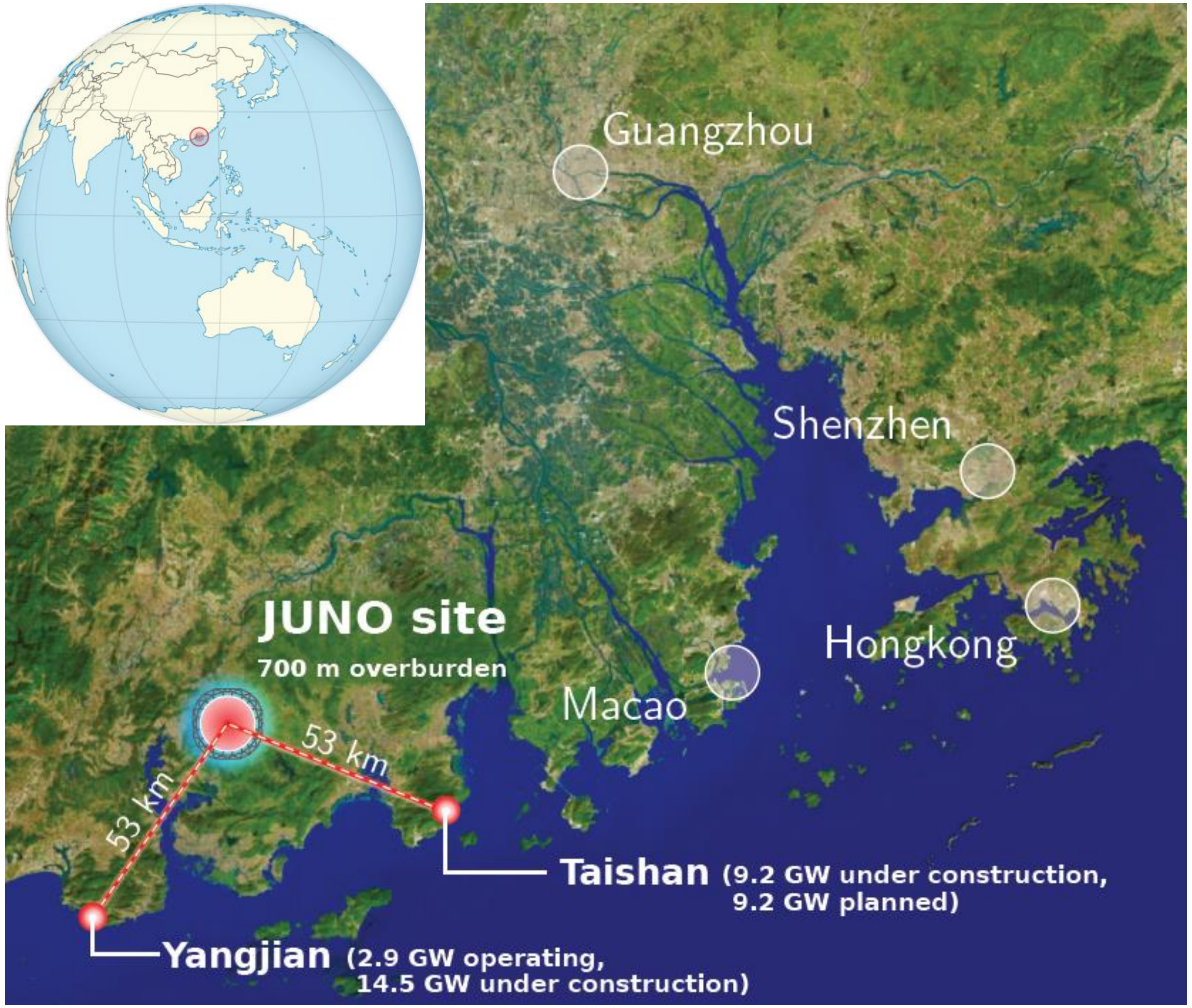
Electron scattering

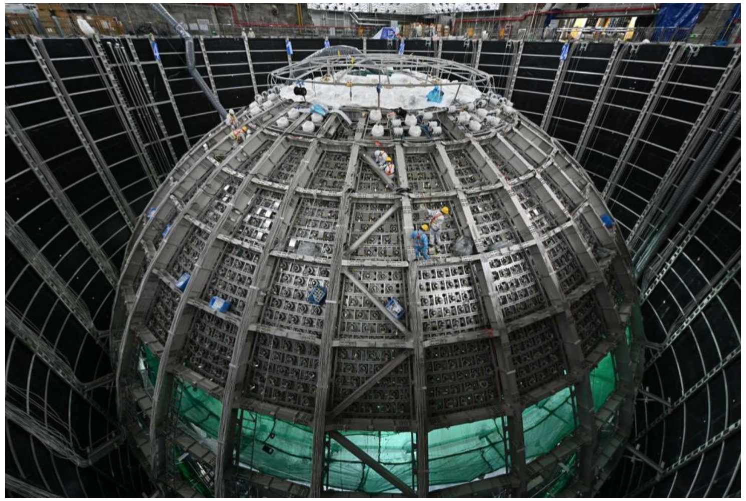
Millicharged Particles ✓

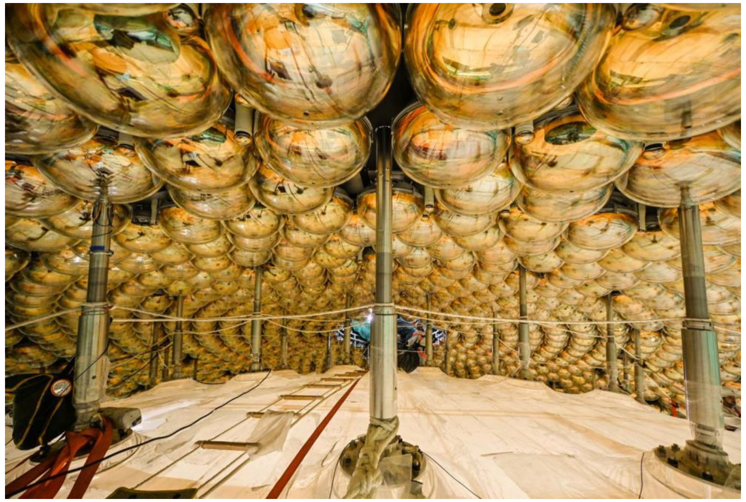


Blips/faint tracks

Meanwhile, across the pond…





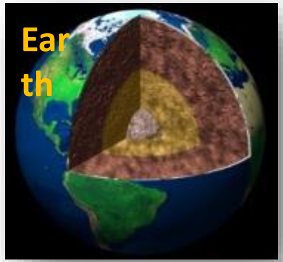


JUNO - A multi-purpose observatory

~60 IBDs per day

Several per day

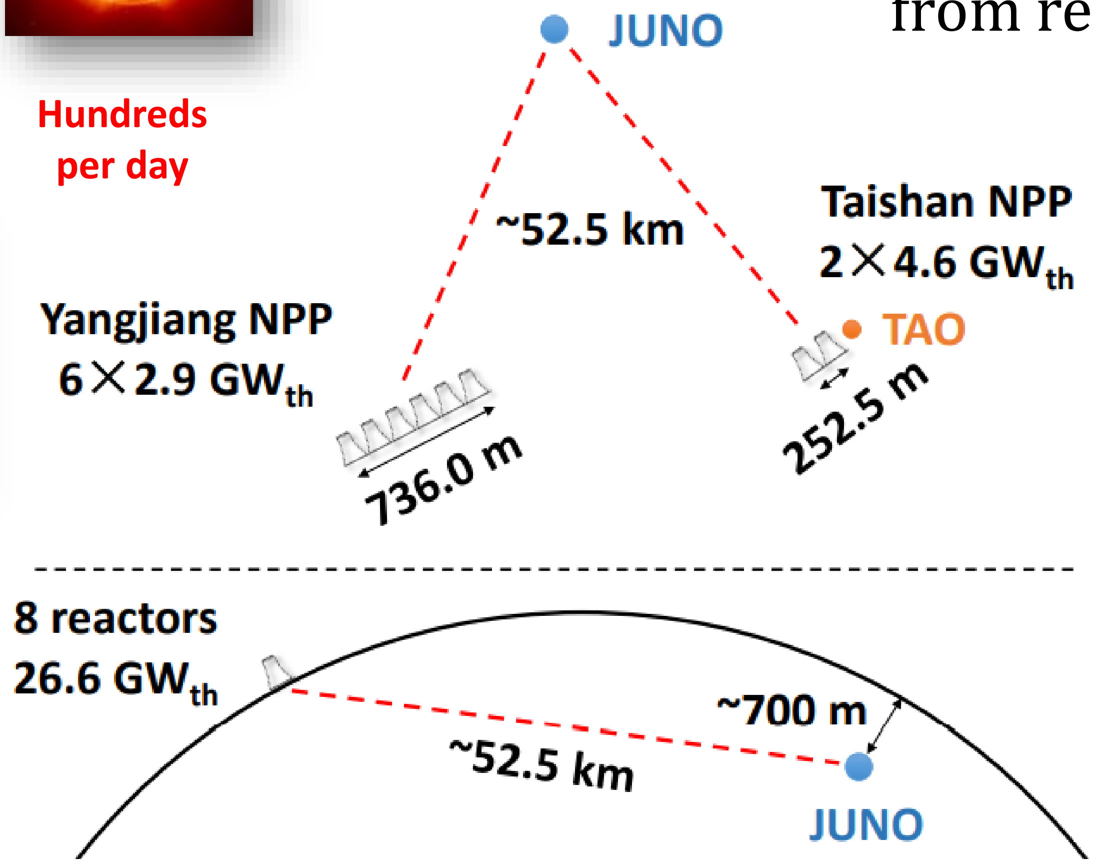
Hundreds per day

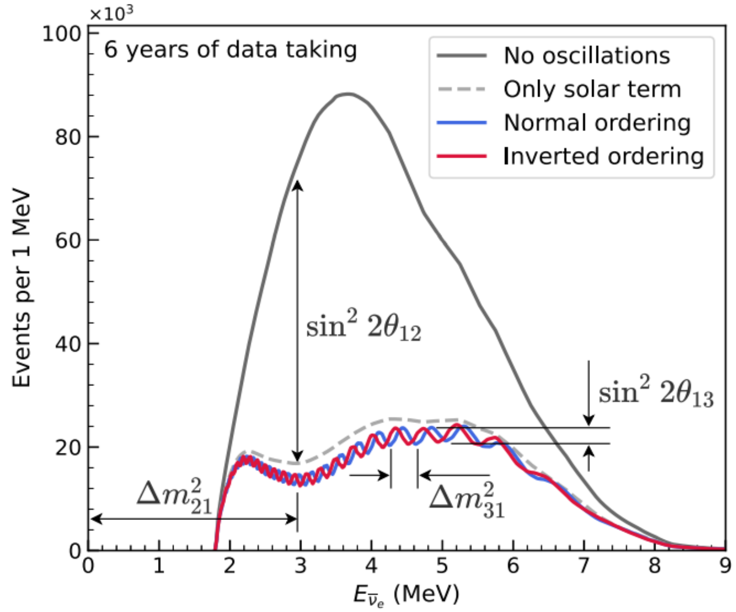


Several IBDs per day

~5000 IBDs for CCSN @10 kpc

A **complementary programme** to determine the mass ordering from reactors… and more!

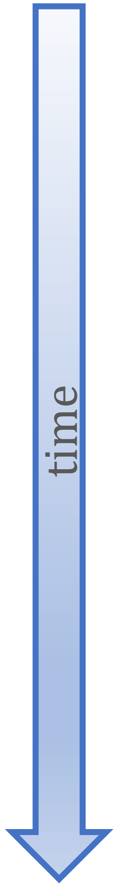


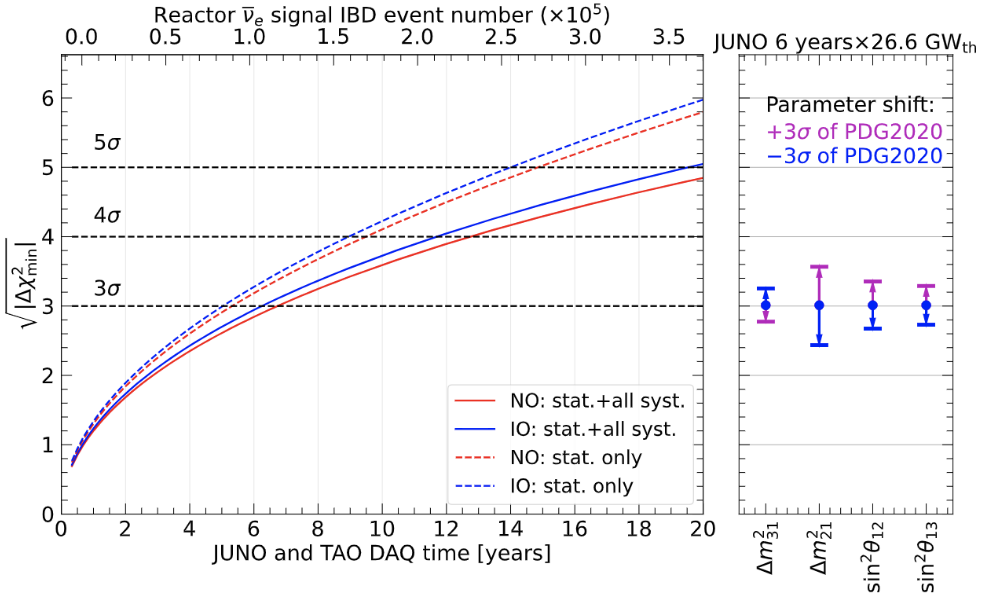


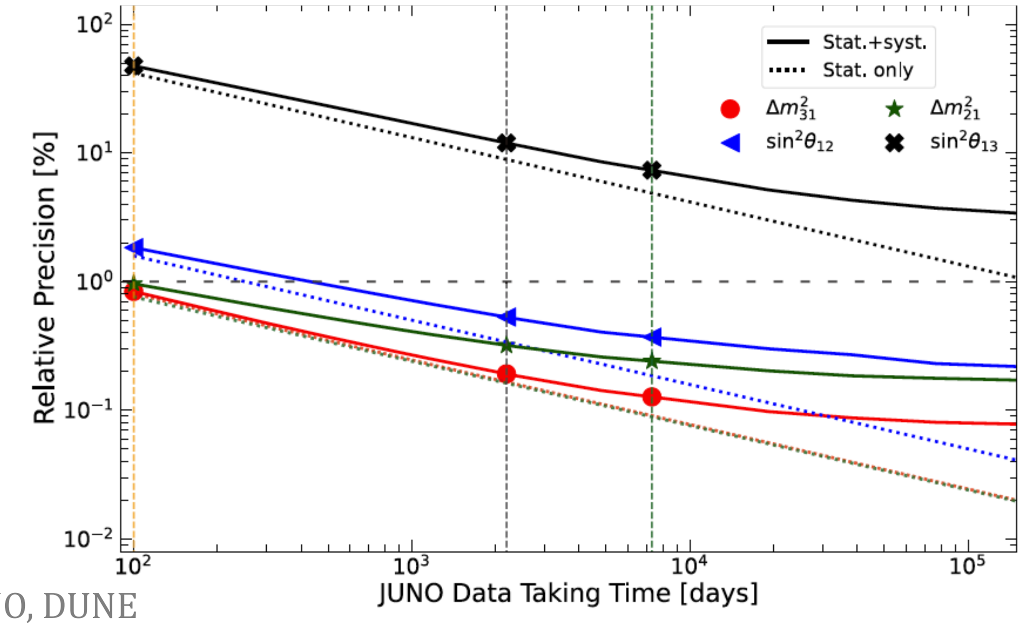
JUNO overview

[2104.02565]

- JUNO goals:
  - **Determine mass ordering** (expected ~3σ with 6 yr running on reactor data)
  - Measure 3-flavour oscillation parameters with **high precision** ($\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$ 0.6% or better with 6 yr reactor data)
  - Detect **burst supernova neutrinos**
  - **First detection** of diffuse supernova neutrino background (**DSNB**)
  - Contribute to studies of **solar / atmospheric** neutrinos + **geo**neutrinos
  - Set limit on **nucleon decay / BSM**
  - Test **Majorana (?) nature** with neutrinoless double-beta decay







Liverpool @ JUNO

- Currently have observer status
  - Looking to upgrade to full membership in next few months!
- Academics:
  - Costas Andreopoulos (VALOR, atmospheric analysis, physics simulations)
- Students:
  - Liam Jones (ML based reconstruction)
  - Yaoqi Cao (co-supervised, @ Warwick -- physics simulations)

- Travel funding by Royal Society
  - Request has been made to STFC for extra travel funds + contribution to common fund
- Looking to enhance links with sister campus at XJT-LU

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  - Yaoqi Cao (co-supervised, @ Warwick -- physics simulations)

Mass ordering and atmospheric analyses **position us for early DUNE analyses** with atmospherics!

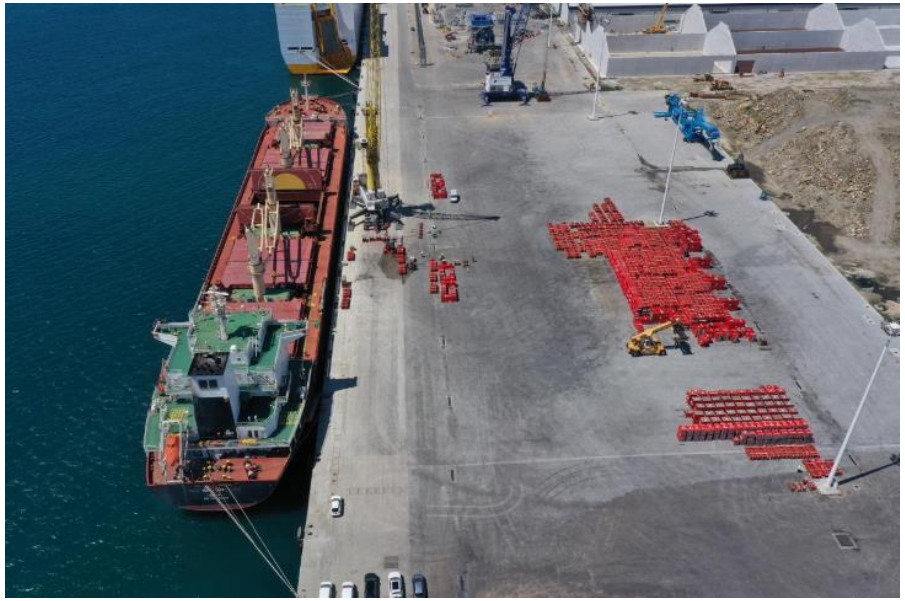
First physics of DUNE : atmospherics

- Travel funding by Royal Society
  - Request has been made to STFC for extra travel funds + contribution to common fund
- Looking to enhance links with sister campus at XJT-LU

But then…

DUNE - Highlights from the past 12 months

- Underground excavation at SURF completed: 800,000 tons of rock moved to surface, 5,000 m^3 concrete poured underground, 1,000,000 person-hours of work without any "lost time incident'.
- First cryostat iron is en route in the Atlantic; second one in production.
- P5 gave DUNE Phase I completion highest priority (Recommendation 1).
- First cryostat installation underground begins in 2025.



Liverpool @ DUNE

- Academics:
  - Christos Touramanis (APA Consortium leader, DUNE executive board, DUNE FD technical board, ProtoDUNE-2)
- Research staff:
  - Marco Roda (ProtoDUNE-2 operational monitoring, PDS control software)
  - Carlos Chavez (in charge of winder robots)
  - Krishanu Majumdar (APA database developer + process software support)
  - John Plows (BSM simulation development)
- Technicians:
  - David Sim (winder head mechanics)
  - Matthew Brown (CERN support for APA integration)

Liverpool maintains **high responsibility for construction** of far detector components!
2 of the 3 APA Factory physicists
STFC-Daresbury: **full responsibility for APA delivery**

Future plans

- New ProtoDUNE run from mid-June (NP04 full and HV nominal, very good purity) -- **same hardware / software as in FD**
  - Christos on LTA at CERN
  - Marco from beginning of JUNE until end September
  - Move argon to vertical-drift NP02 incl. long commissioning
- DAQ - < 2 yr for final development + installation in 2026 Q3
  - Funding to be approved by STFC to 2027
- Deliver 137 APA detectors (Nov 2027 onwards)
  - 8 complete, 4 built
  - 4 highly capable winders, with 5th being commissioned
  - Production lines July 2024, January 2025 commissioning
  - Building construction database for APA building operation and data logging + improving winder speeds + QA processes

Summary

- Multiple contributions across wide experimental landscape
- SBND - excellent imaging, rich sterile + BSM reach
  - Expecting **5σ test** of light sterile neutrino hypothesis in SBN!
  - Extreme rate of data means **high-precision** interaction programme for DUNE
  - Liverpool analyses continue to prepare ground for eventual data taking / physics exploitation in short term
- JUNO - broad experimental outlook
  - Becoming more closely affiliated with JUNO
  - Preparing oscillation framework for atmospheric analyses in medium term
- DUNE - continuing expert construction and DAQ work
  - Crucial contributions aligning with P5 recommendations

Backup

Summary of the short-baseline neutrino anomalies

[1903.04608]

Four main 'anomalies' have been observed in neutrino experiments at short-baseline, consistent with the mixing of the standard neutrinos with a fourth, non-weakly-interacting 'sterile' species – the data could be indicating a heavier, mostly-sterile mass state with mass splittings $\Delta m^2_{43} \approx \Delta m^2_{42} \approx \Delta m^2_{41} \sim \mathcal{O}(1\,\mathrm{eV}^2)$.

- **LSND:** Stopped pion source with a detector optimized to probe $\bar{\nu}_e$ via inverse beta decay. A 3.8σ excess of events over backgrounds was observed, compatible with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations with $L/E \approx 1\,\mathrm{m/MeV}$ (19).

- **MiniBooNE:** Accelerator neutrino source with the capability of producing a dominant ν_μ or $\bar{\nu}_\mu$ beam. Excesses of $\nu_e(\bar{\nu}_e)$ events in $\nu_\mu(\bar{\nu}_\mu)$ mode were observed over backgrounds, amounting to a $4.5\sigma(2.8\sigma)$ discrepancy from expectations. The observed excesses are found to be compatible with LSND within a sterile neutrino framework (6).

- **The 'Reactor anomaly':** A reevaluation of the $\bar{\nu}_e$ fluxes from nuclear reactors with improved theoretical uncertainties led to a deficit in many past experiments in the total number of events with respect to theoretical expectations at the 3σ level (22, 23). The size of these theoretical uncertainties has been under debate (24). More recently, some spectral features have been observed consistent with sterile neutrino oscillations with $\Delta m^2 \sim \mathrm{eV}^2$ (25, 26).

- **The 'Gallium anomaly':** An overall deficit in the number of ν_e events from radioactive sources (27, 28) with respect to theoretical expectations (29) at the 3σ level was seen during calibration runs of solar neutrino experiments (30, 31, 32).

Category	Model	Final state	LEE signal properties			References
			energy dist.	angular dist.	timing	
Flavor transitions	SBL oscillations	e^-	✓	✓	✓	Reviews and global fits [22–24, 53, 54]
	SBL oscillations with invisible sterile decay	e^-	✓	✓	✓	[55, 56]
	SBL oscillations with anomalous matter effects	e^-	✓	✓	✓	[57–62]
	neutrino-flavor-changing bremsstrahlung	e^-	✓	–	✓	[63]
Decays in flight	SBL oscillations with visible sterile decay	e^-	✓	✓	✓	[64–68]
	heavy neutrino decay	γ / e^+e^- / $\gamma\gamma$	✓	✗	✗	[69, 70]
Scattering	neutrino-induced upscattering	γ / e^+e^- / $\gamma\gamma$	✓	✗	✓	DS [36–41, 71–73], TMM [74–84]
	dark particle-induced upscattering	γ / e^+e^- / $\gamma\gamma$	✓	✗	✓	[85]

[2308.02543]

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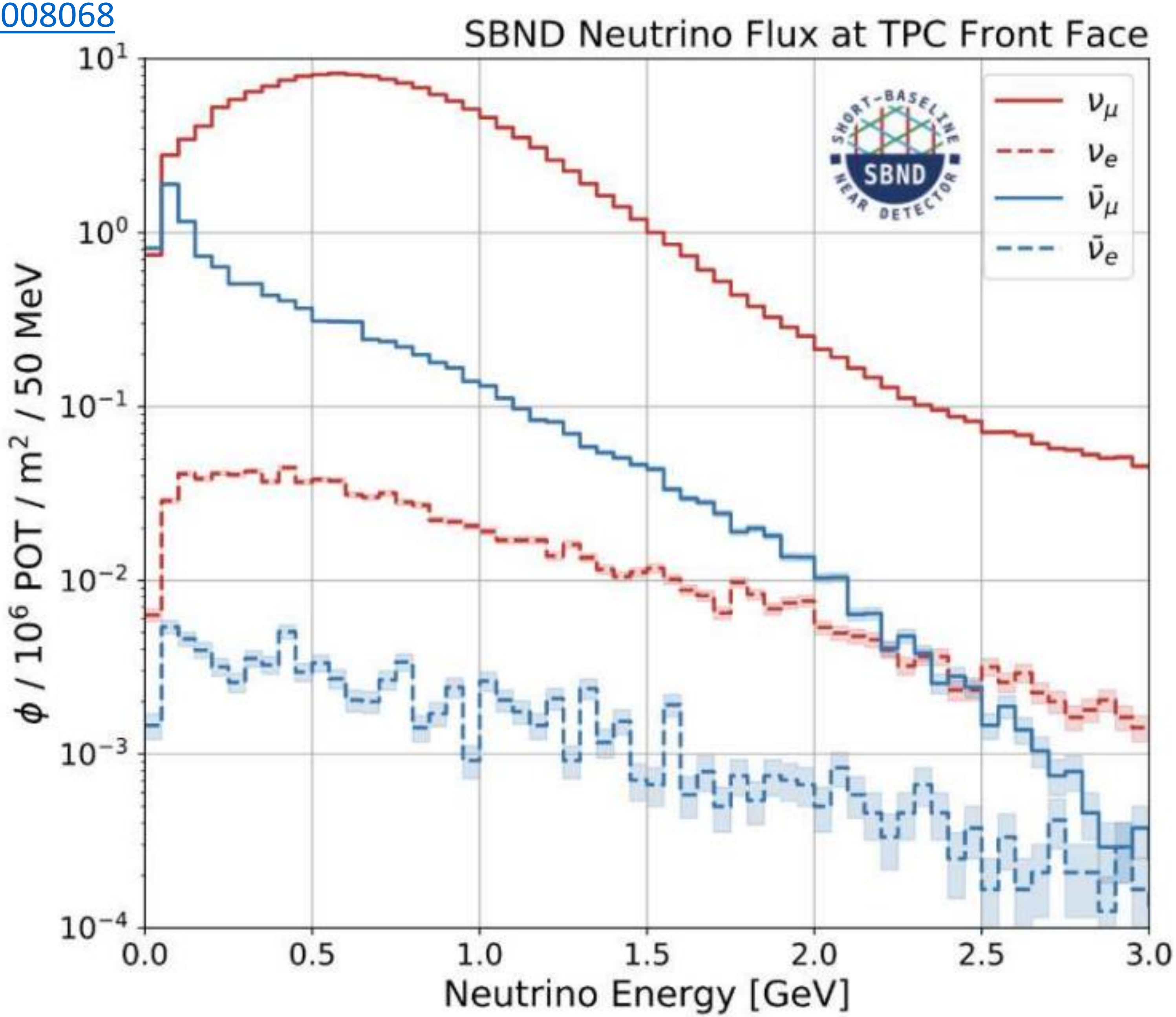
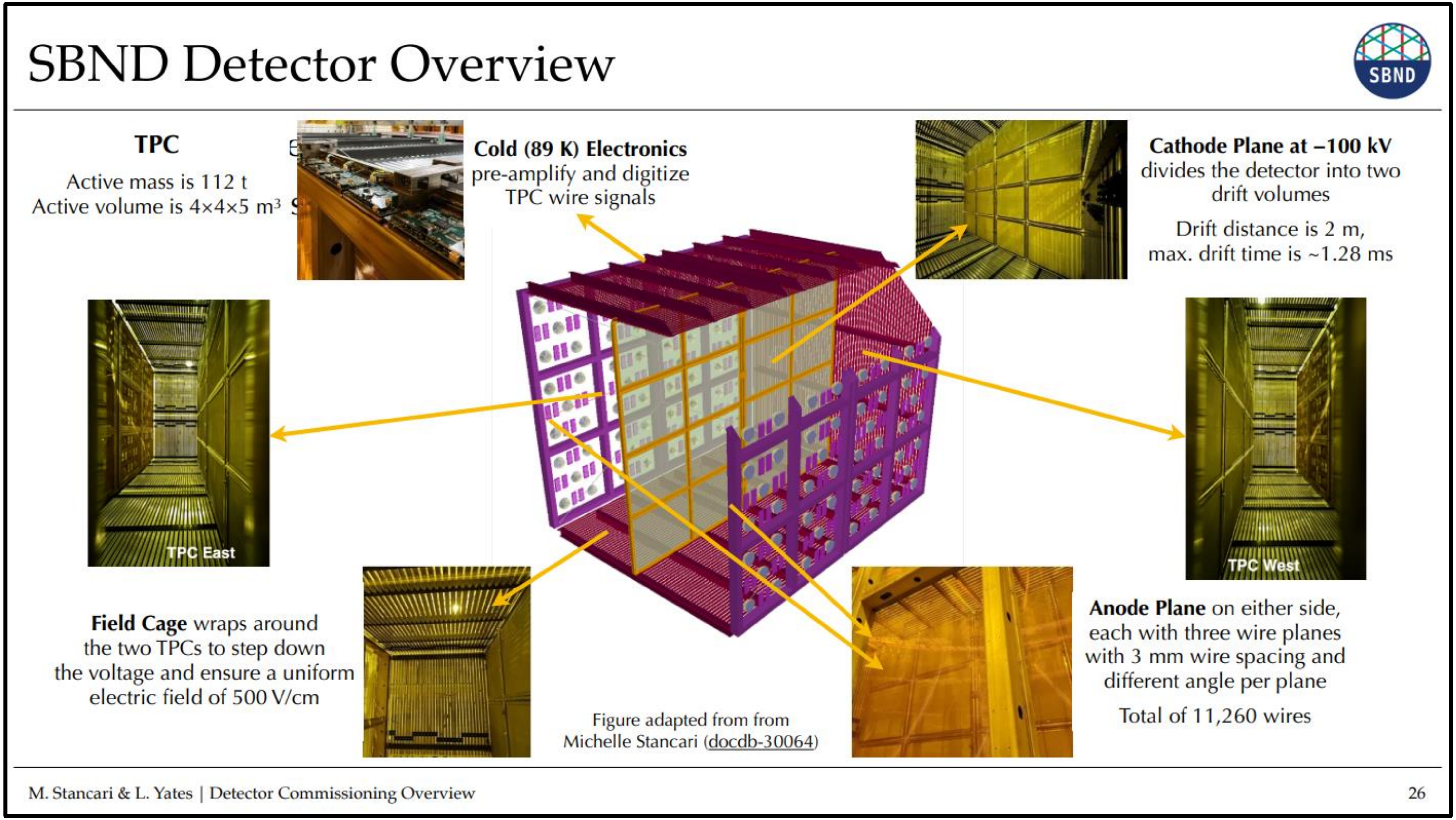
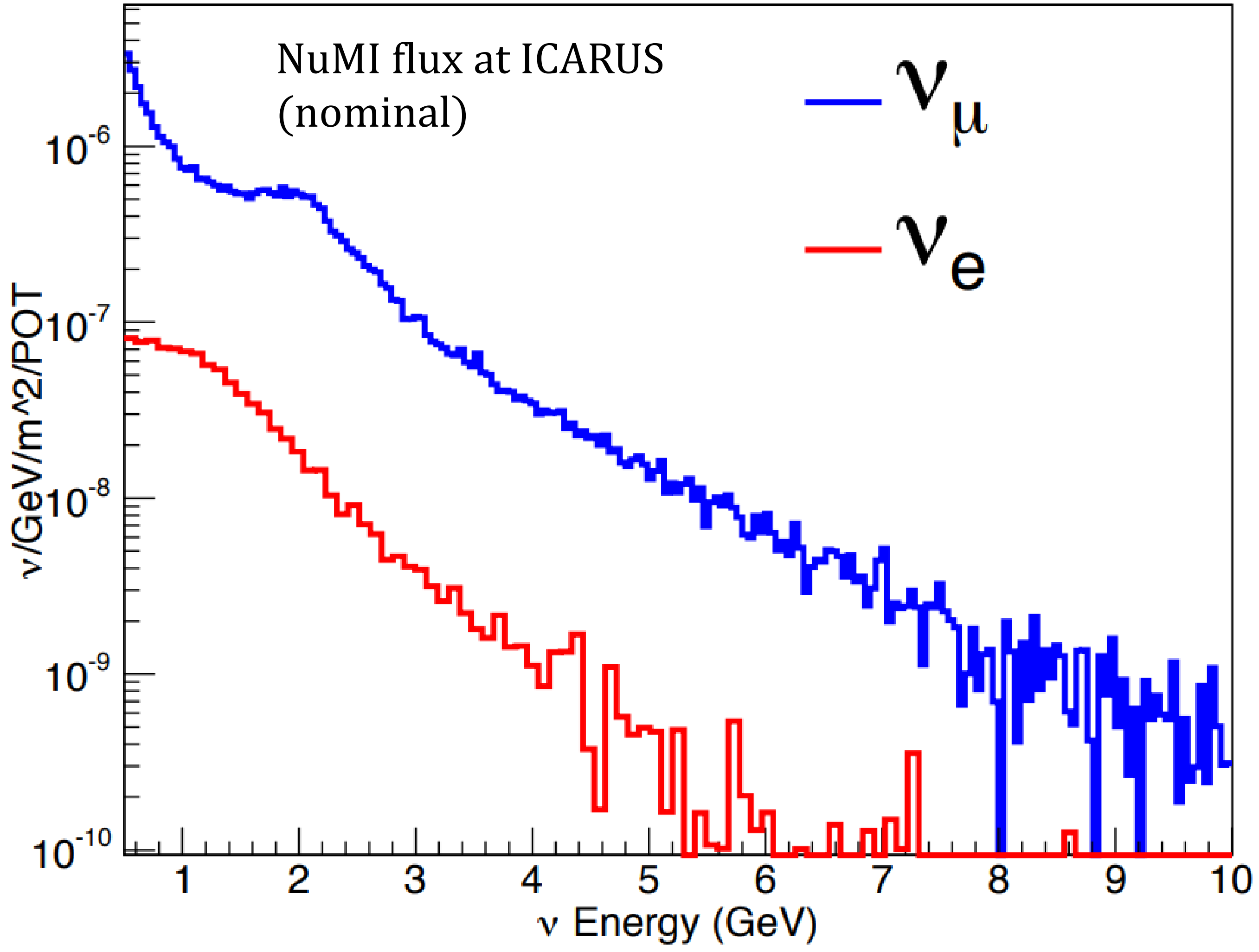
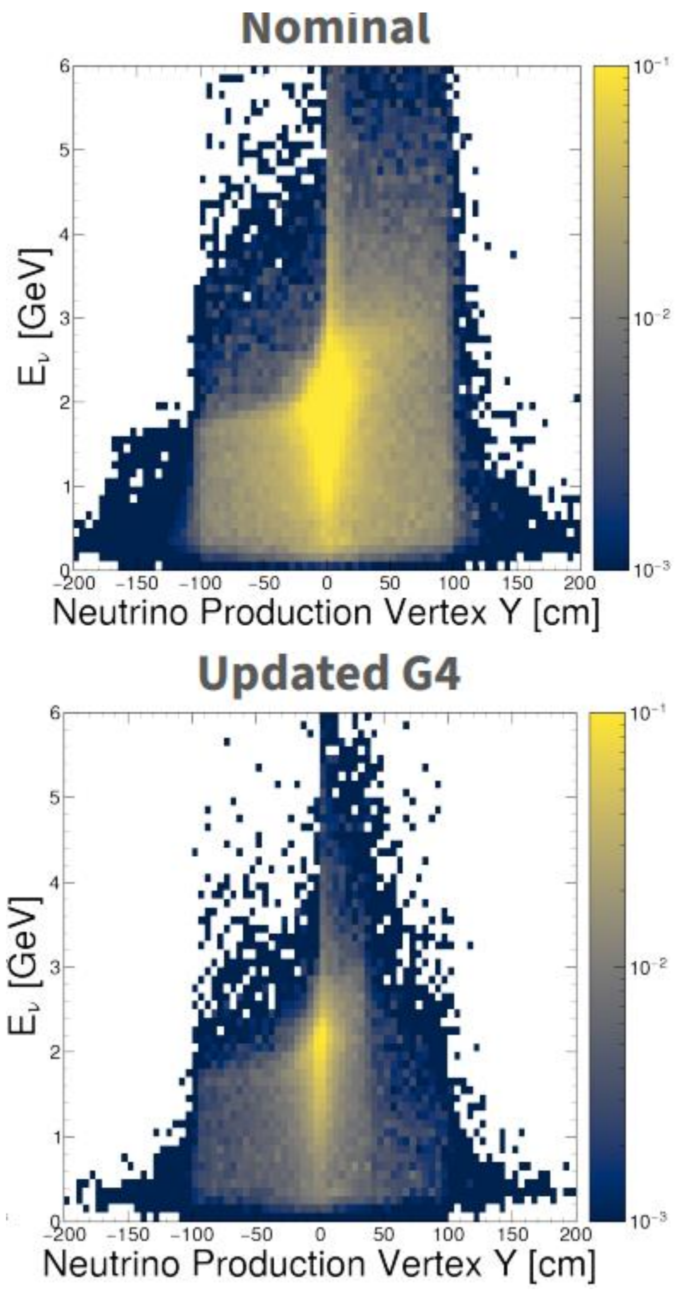
doi: 10.3390/psf2023008068



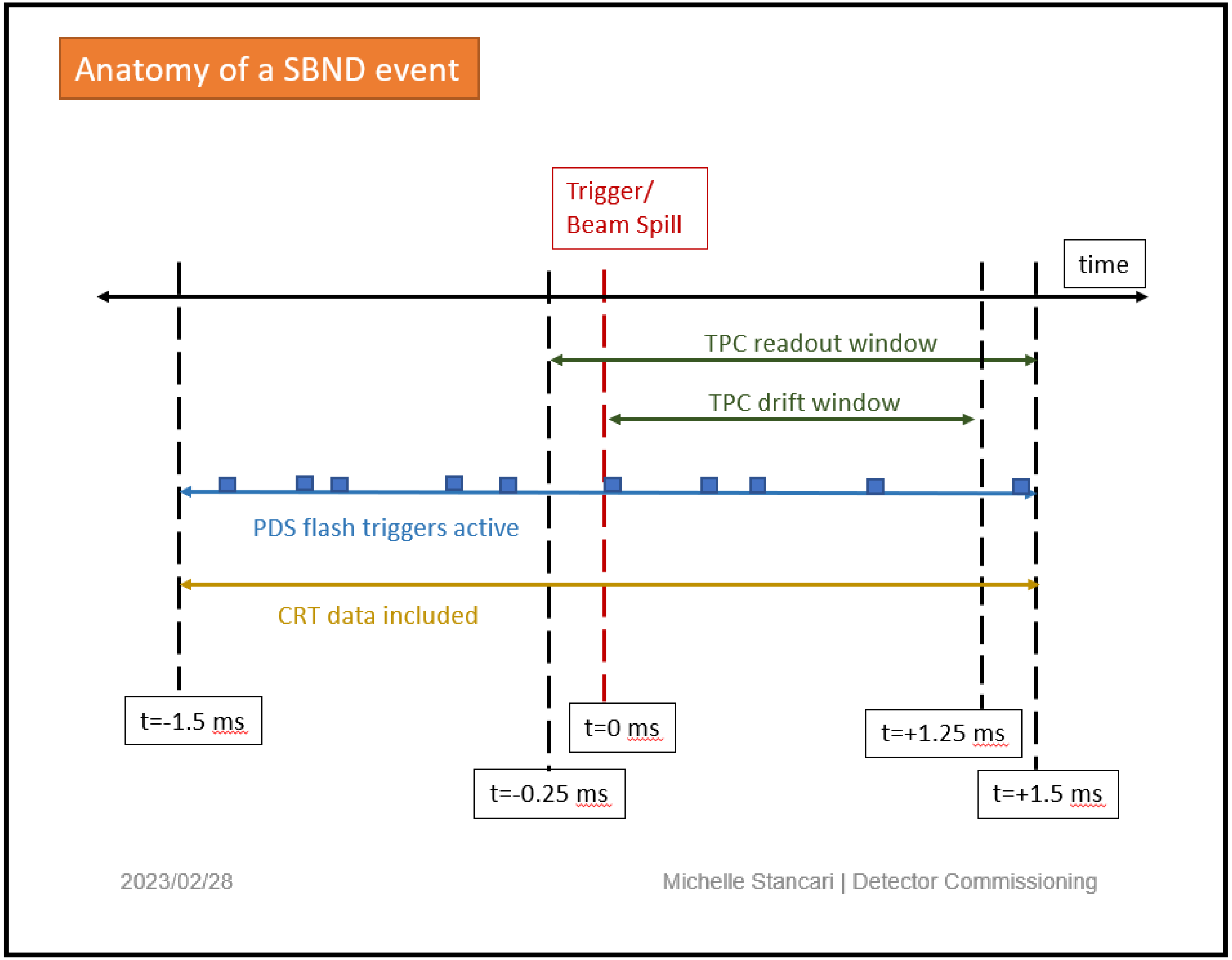


From SBND December collaboration meeting





Updates to NuMI flux in progress

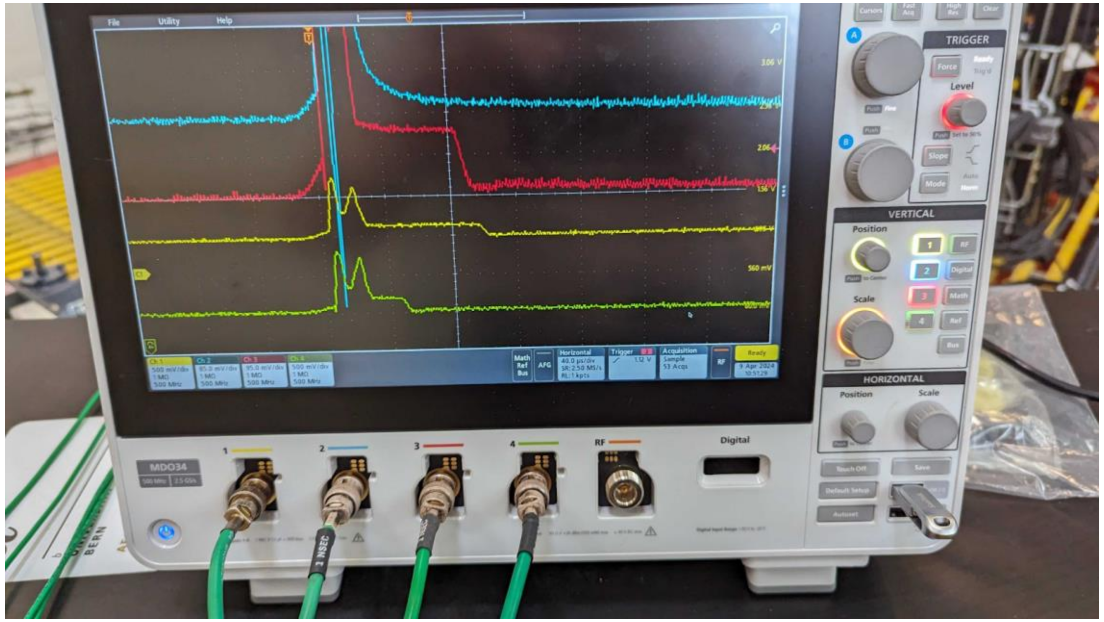

Anatomy of a SBND event
Trigger/
Beam Spill
time
TPC readout window
TPC drift window
PDS flash triggers active
CRT data included
t=-1.5 ms
t=-0.25 ms
t=0 ms
t=+1.25 ms
t=+1.5 ms
2023/02/28
Michelle Stancari | Detector Commissioning

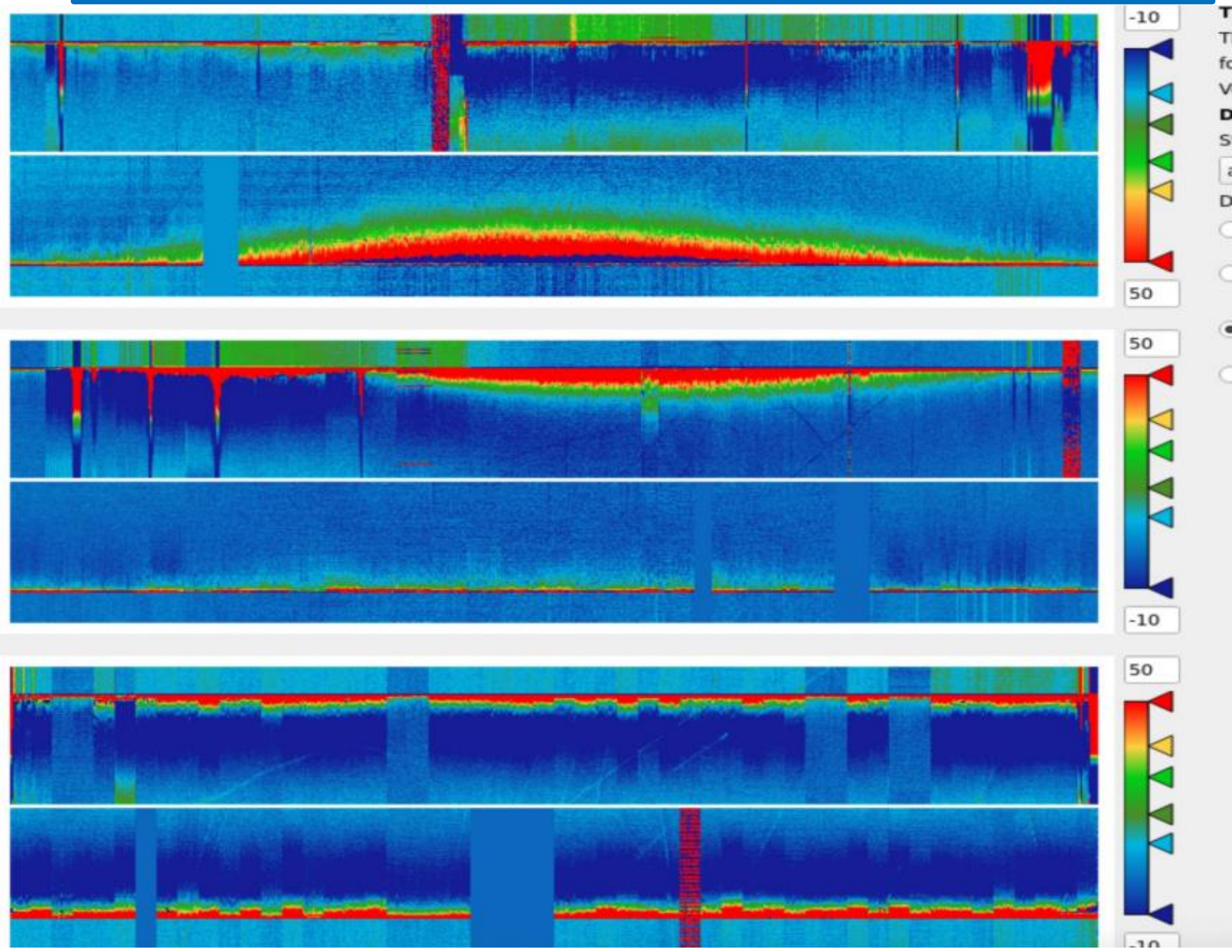
What is a sunset event?

Simultaneously observed . . . .

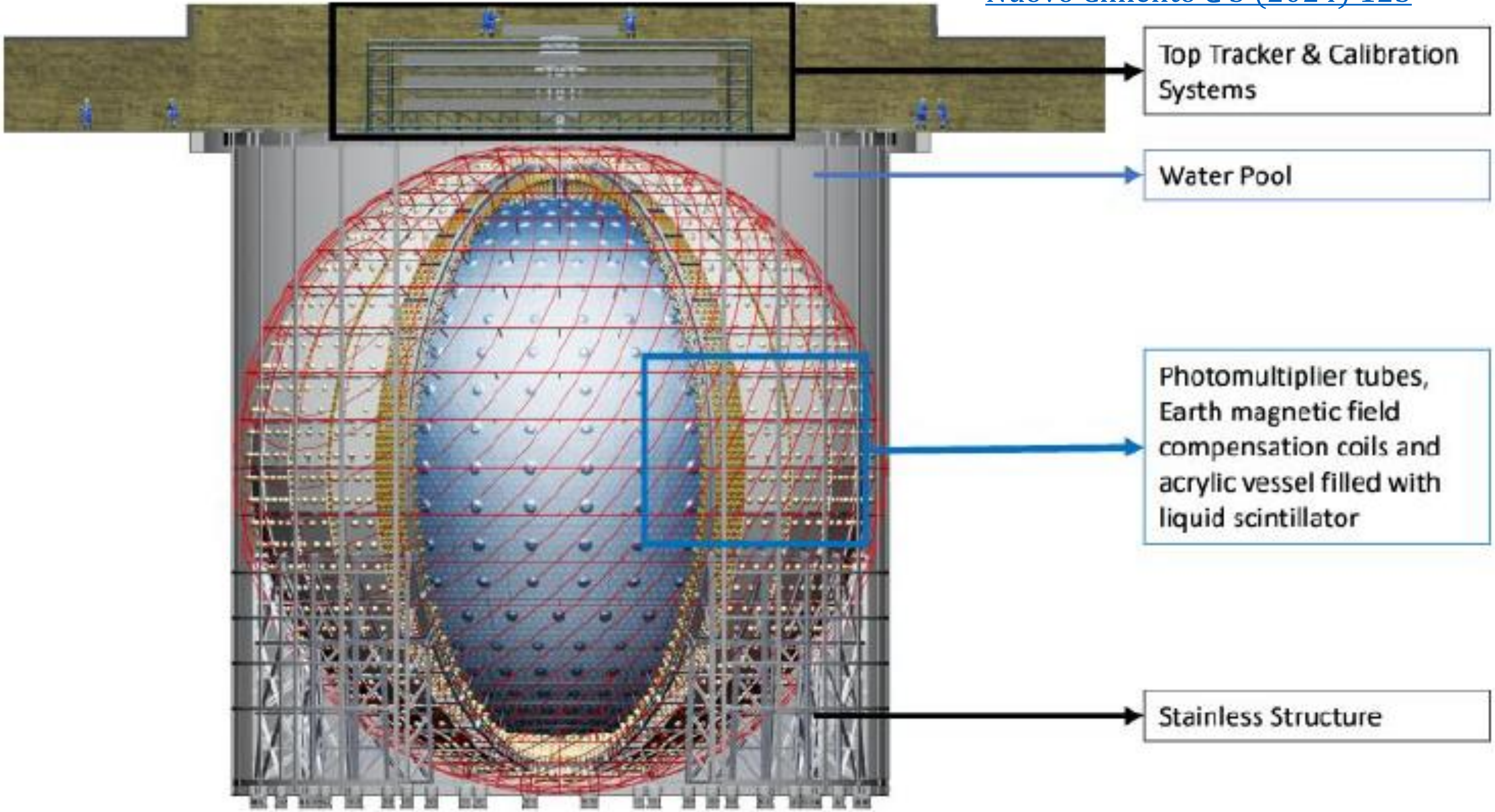
- Large signal in every channel of the TPC readout (8 streaming to oscilloscopes)
- Spike in cathode current
- Spike in SWbottom Field Cage module voltage/current monitoring
- A burst of noise in OFF PMTs
- Large light signal (on top of noise burst) in ON PMTs
- Digital corruption in the TPC wire data

Observed during TPC ramp-up, investigating electric field of field-cage to correct -- small delay!





Nuovo Cimento **C** 3 (2024) 123



Taishan Antineutrino Observatory (TAO)

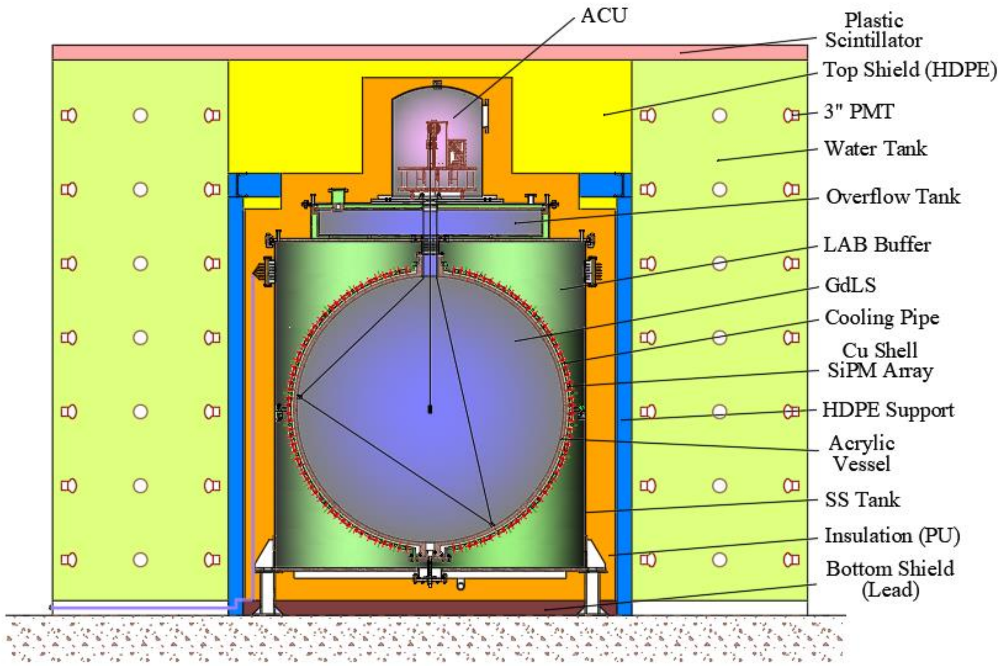
Goals: [2005.08745]

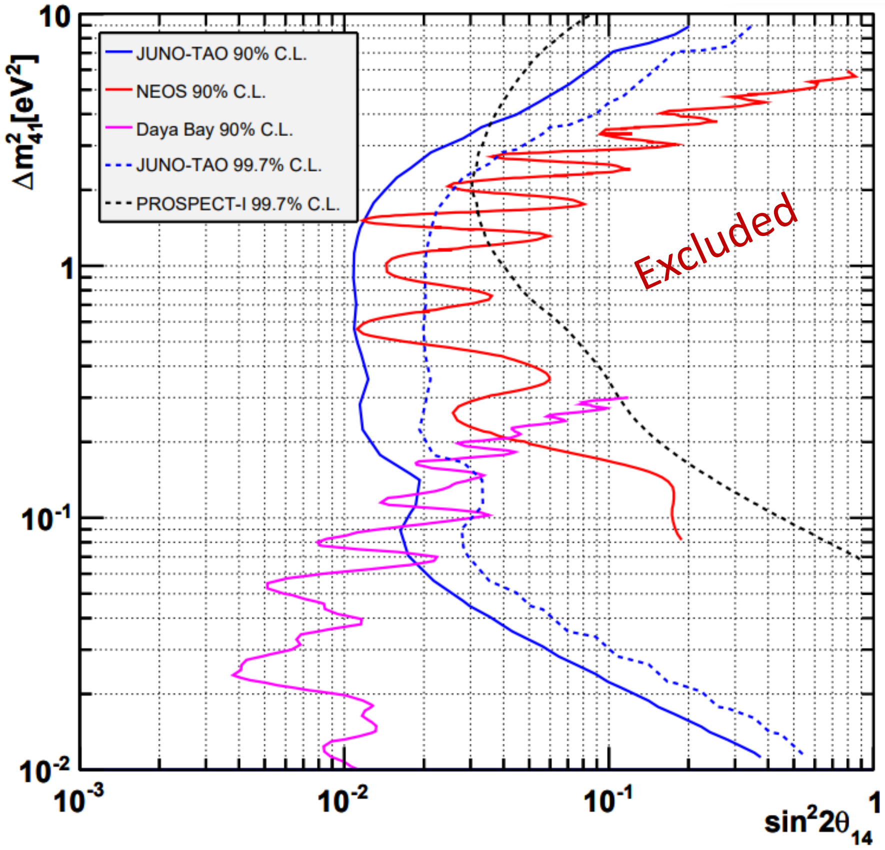
1. Measure the reactor antineutrino spectrum with unprecedented energy resolution and see its fine structure for the first time.

2. Provide a reference spectrum for JUNO, other experiments, and nuclear databases

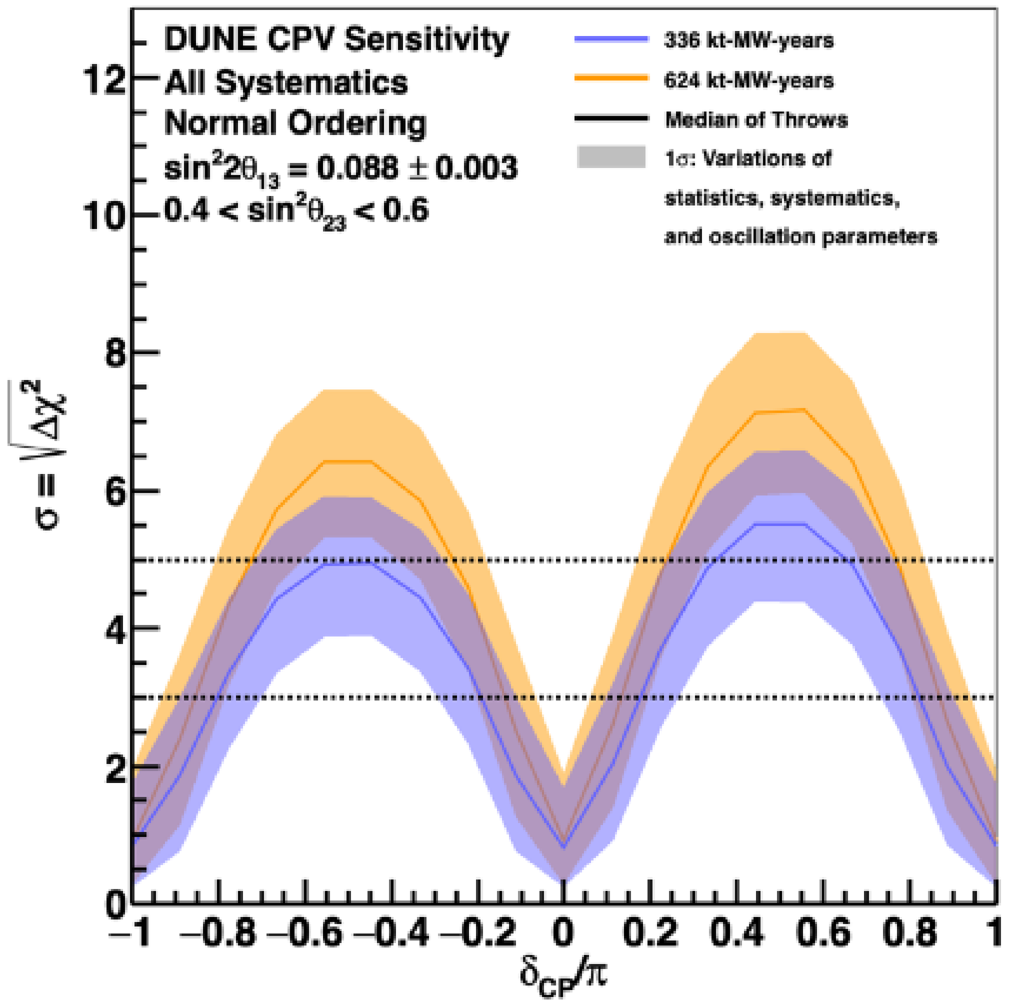
3. Search for light sterile neutrinos

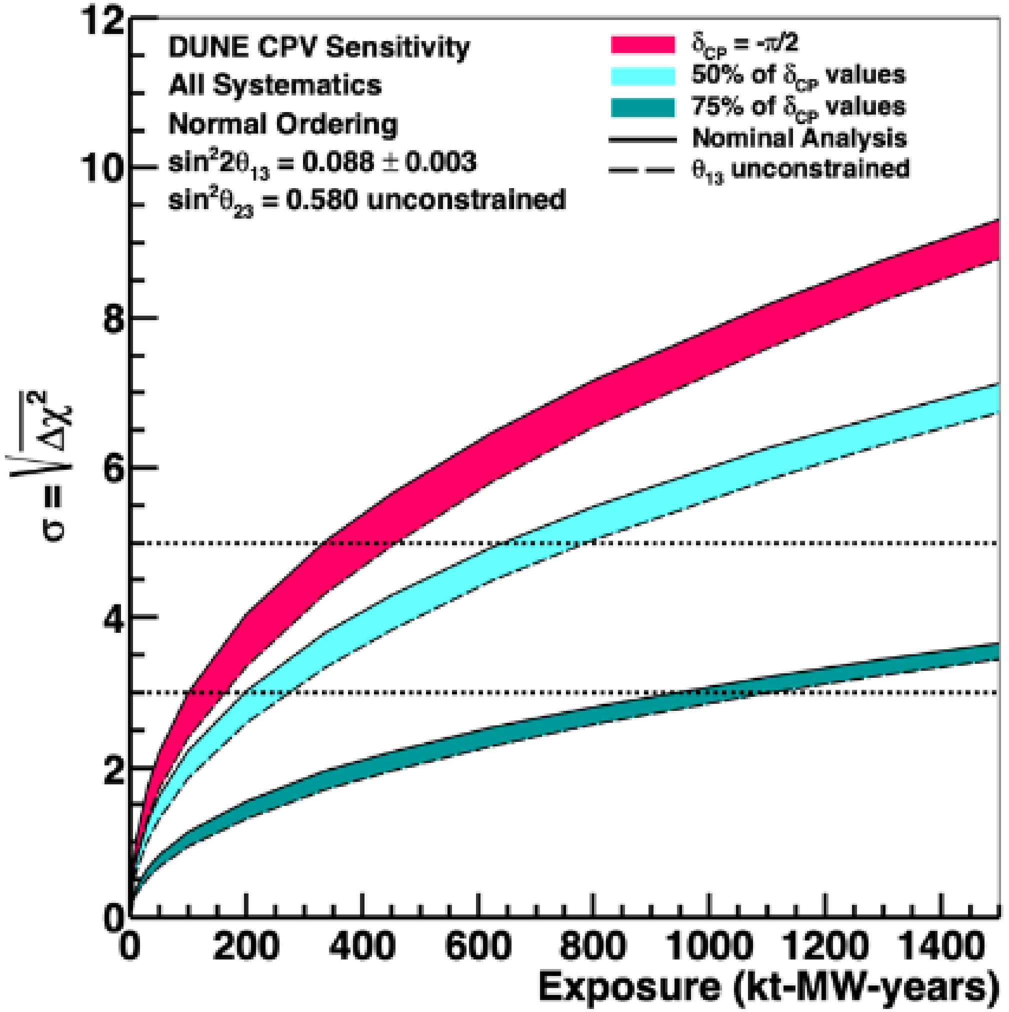
4. Make improved measurements of isotopic yields & spectra





DUNE CPV sensitivity (3-flavour)





Snowmass summary, [2203.06100]

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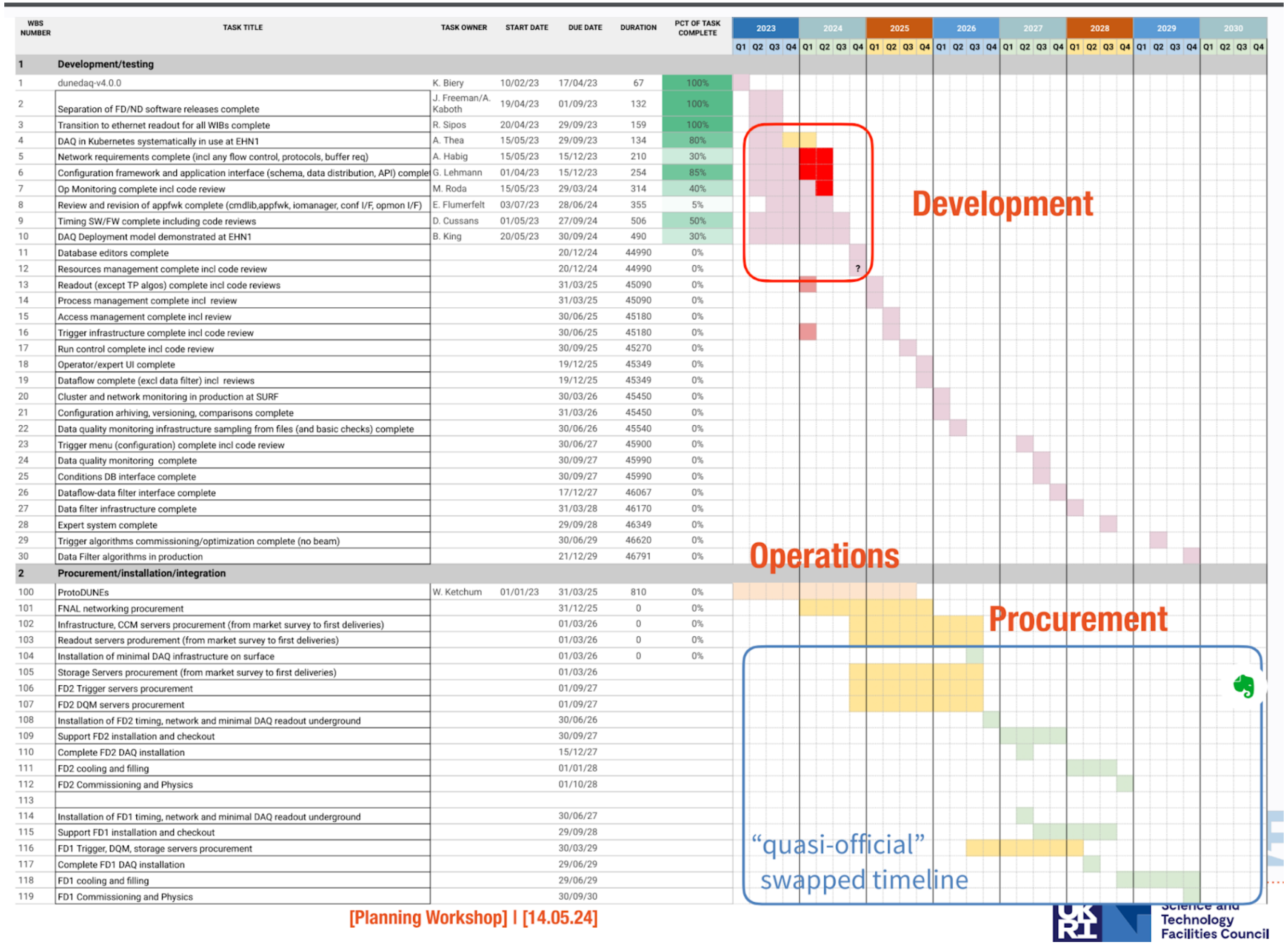
- Beyond ProtoDUNE
  - < 2 years for the final development of the DAQ
  - Installation starts in 2026 Q3
- Liverpool responsibility
  - Operational Monitoring
    - Current main effort
    - Expected to be completed by next year
      - Possible slip due to ProtoDUNEs support
  - Supervisor system
    - To ensure high uptime for Supernova analyses
  - DQM
    - After the previous parts are completed
- DAQ funding to be approved by STFC
  - To cover up to 2027
  - At the moment we are running on bridge funding



WBS NUMBER	TASK TITLE	TASK OWNER	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
1	**Development/testing**					
1	dunedaq-v4.0.0	K. Biery	10/02/23	17/04/23	67	100%
2	Separation of FD/ND software releases complete	J. Freeman/A. Kaboth	19/04/23	01/09/23	132	100%
3	Transition to ethernet readout for all WIBs complete	R. Sipos	20/04/23	29/09/23	159	100%
4	DAQ in Kubernetes systematically in use at EHN1	A. Thea	15/05/23	29/09/23	134	80%
5	Network requirements complete (incl any flow control, protocols, buffer req)	A. Habig	15/05/23	15/12/23	210	30%
6	Configuration framework and application interface (schema, data distribution, API) complet	G. Lehmann	01/04/23	15/12/23	254	85%
7	Op Monitoring complete incl code review	M. Roda	15/05/23	29/03/24	314	40%
8	Review and revision of appfwk complete (cmdlib,appfwk, iomanager, conf I/F, opmon I/F)	E. Flumerfelt	03/07/23	28/06/24	355	5%
9	Timing SW/FW complete including code reviews	D. Cussans	01/05/23	27/09/24	506	50%
10	DAQ Deployment model demonstrated at EHN1	B. King	20/05/23	30/09/24	490	30%
11	Database editors complete			20/12/24	44990	0%
12	Resources management complete incl code review			20/12/24	44990	0%
13	Readout (except TP algos) complete incl code reviews			31/03/25	45090	0%
14	Process management complete incl review			31/03/25	45090	0%
15	Access management complete incl review			30/06/25	45180	0%
16	Trigger infrastructure complete incl code review			30/06/25	45180	0%
17	Run control complete incl code review			30/09/25	45270	0%
18	Operator/expert UI complete			19/12/25	45349	0%
19	Dataflow complete (excl data filter) incl reviews			19/12/25	45349	0%
20	Cluster and network monitoring in production at SURF			30/03/26	45450	0%
21	Configuration arhiving, versioning, comparisons complete			31/03/26	45450	0%
22	Data quality monitoring infrastructure sampling from files (and basic checks) complete			30/06/26	45540	0%
23	Trigger menu (configuration) complete incl code review			30/06/27	45900	0%
24	Data quality monitoring complete			30/09/27	45990	0%
25	Conditions DB interface complete			30/09/27	45990	0%
26	Dataflow-data filter interface complete			17/12/27	46067	0%
27	Data filter infrastructure complete			31/03/28	46170	0%
28	Expert system complete			29/09/28	46349	0%
29	Trigger algorithms commissioning/optimization complete (no beam)			30/06/29	46620	0%
30	Data Filter algorithms in production			21/12/29	46791	0%
2	**Procurement/installation/integration**					
100	ProtoDUNEs	W. Ketchum	01/01/23	31/03/25	810	0%
101	FNAL networking procurement			31/12/25	0	0%
102	Infrastructure, CCM servers procurement (from market survey to first deliveries)			01/03/26	0	0%
103	Readout servers produrement (from market survey to first deliveries)			01/03/26	0	0%
104	Installation of minimal DAQ infrastructure on surface			01/03/26	0	0%
105	Storage Servers procurement (from market survey to first deliveries)			01/03/26		
106	FD2 Trigger servers procurement			01/09/27		
107	FD2 DQM servers procurement			01/09/27		
108	Installation of FD2 timing, network and minimal DAQ readout underground			30/06/26		
109	Support FD2 installation and checkout			30/09/27		
110	Complete FD2 DAQ installation			15/12/27		
111	FD2 cooling and filling			01/01/28		
112	FD2 Commissioning and Physics			01/10/28		
113						
114	Installation of FD1 timing, network and minimal DAQ readout underground			30/06/27		
115	Support FD1 installation and checkout			29/09/28		
116	FD1 Trigger, DQM, storage servers procurement			30/03/29		
117	Complete FD1 DAQ installation			29/06/29		
118	FD1 cooling and filling			29/06/29		
119	FD1 Commissioning and Physics			30/09/30		

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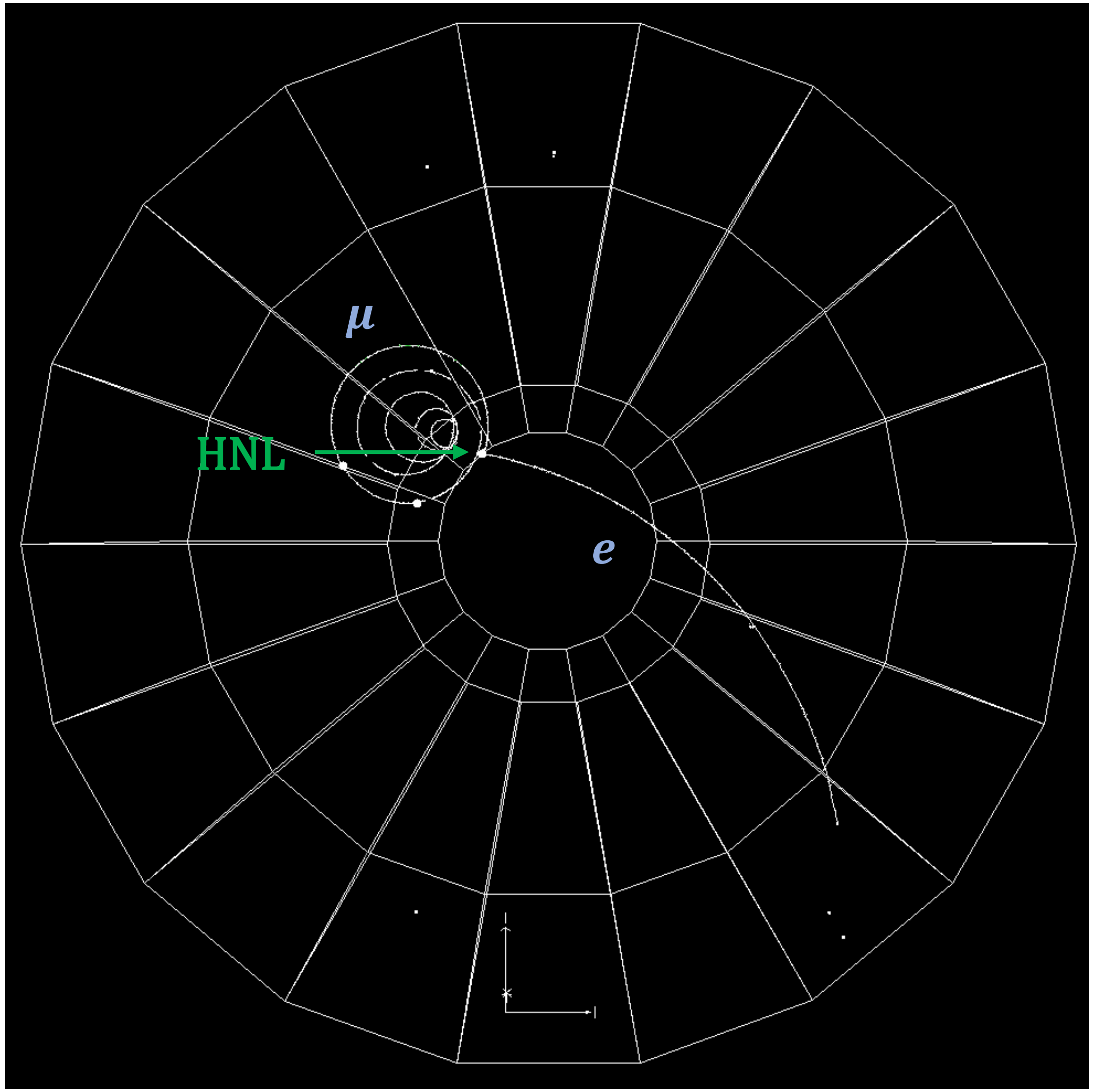
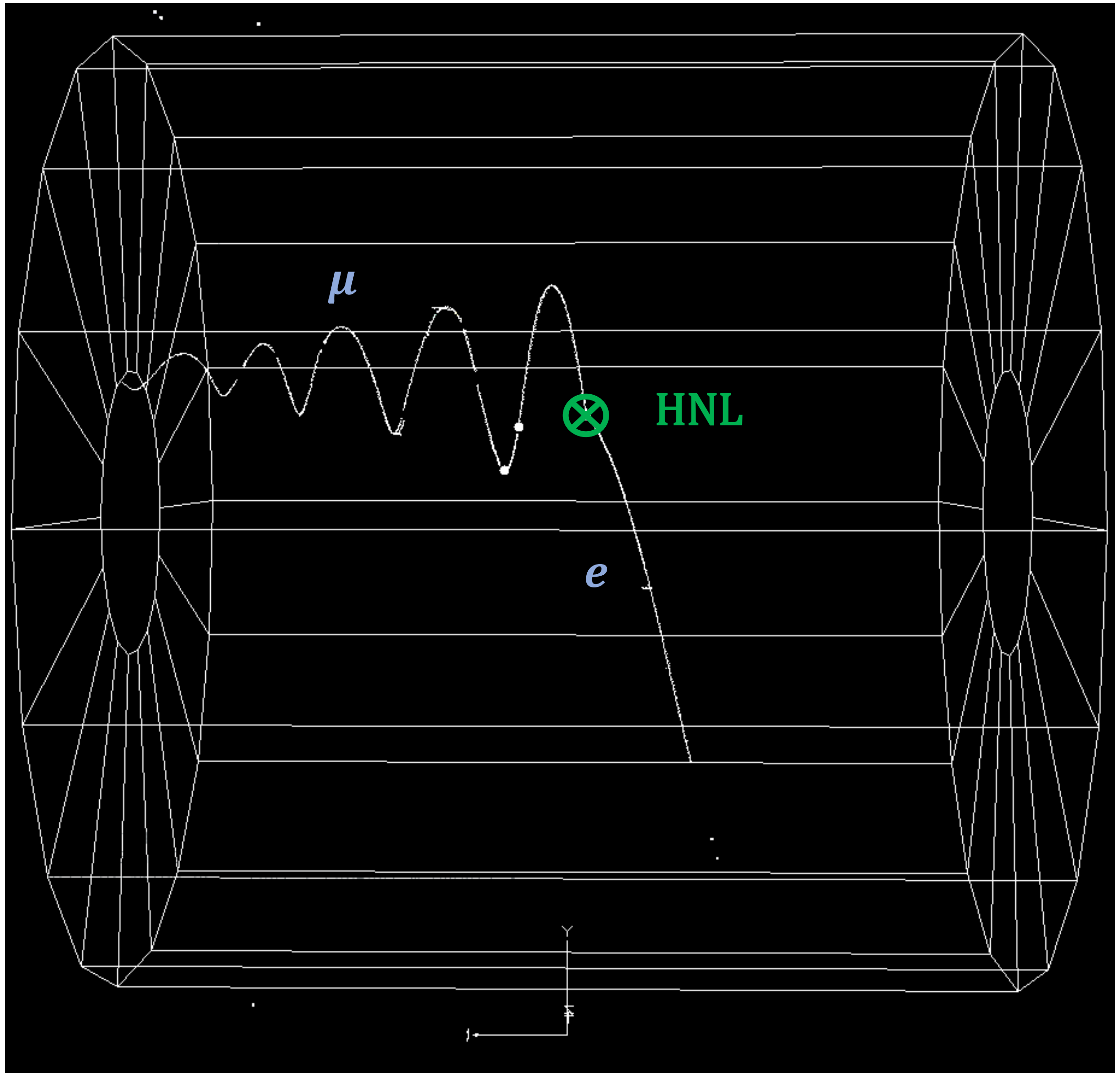
DUNE plan to completion

- A dedicated Task Force analysed the risks for the two Far Detectors timeline and recommended to first complete the cryostat for FD2-VD (vertical drift with CRP readout).
- Thai aim is to have the first FD operating in 2029, the second FD in 2030, neutrino beam and Near Detector in 2031. First main physics will be atmospheric neutrinos.
- DUNE Phase II "Re-envisioned" by P5:
  - Fermilab Main Ring upgrade (ACE-MIRT) to cycle faster and provide 2.1 MW proton beam before 2035.
  - Far Detector 3, LAr similar to FD2.
  - More Capable Near Detector (GAr TPC with ECAL inside magnetic field) at a slightly longer timescale.
- HEPAP Facilities Subpanel outcome:
  - Phase I, ACE-MIRT, FD3 "Absolutely Central" for science and "Ready to initiate construction" technically (highest rankings).
  - MCND "Absolutely Central" & "Significant scientific/engineering challenges remain".





$N_4(1\ \text{GeV}) \rightarrow \nu_e(353\ \text{MeV}) + \mu^-(200\ \text{MeV}) + \text{e}^+(447\ \text{MeV})$