Neutrinos and Beta Decay

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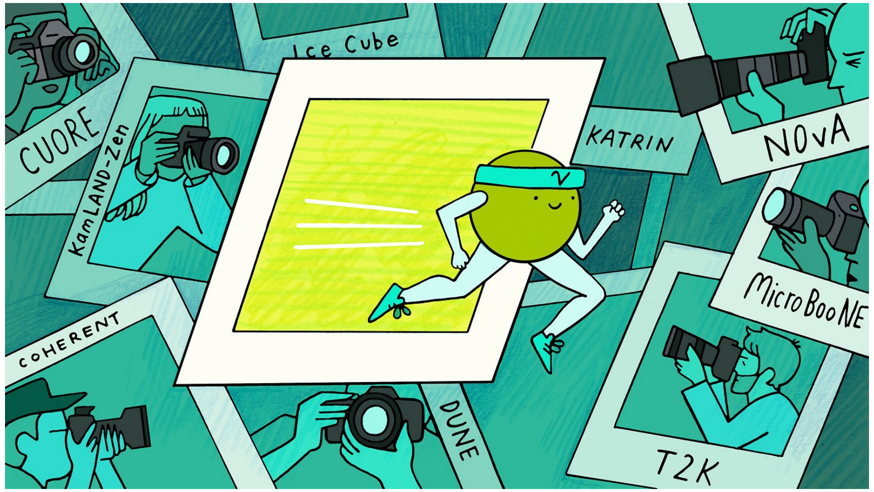
Pierre Granger, Beatrice Mauri, Corentin Ravoux (DPhP),
Rudolph Rogly (DPhN)

Neutrino overview

Neutrino (ν) is the most abundant massive fundamental particle in the universe, weakly interacting with matter. It can be produced with different sources in different types in terms of flavors, masses and energies.

Many experiments aimed to answer the neutrino unknowns:

- *Neutrino nature (Dirac or Majorana)*
- *Mass hierarchy*
- *Absolute mass scale*
- *CP violation*
- *Sterile neutrino*
- …



Neutrino sources:

- *Reactors*
- *Accelerators*
- *Beta decay*
- *The Big bang*
- *Earth*
- *Sun*
- *The atmosphere*
- *Supernovae*
- *Extragalactic sources*

From reactors

Courtesy to M. Licciardi

Current generation of experiments:

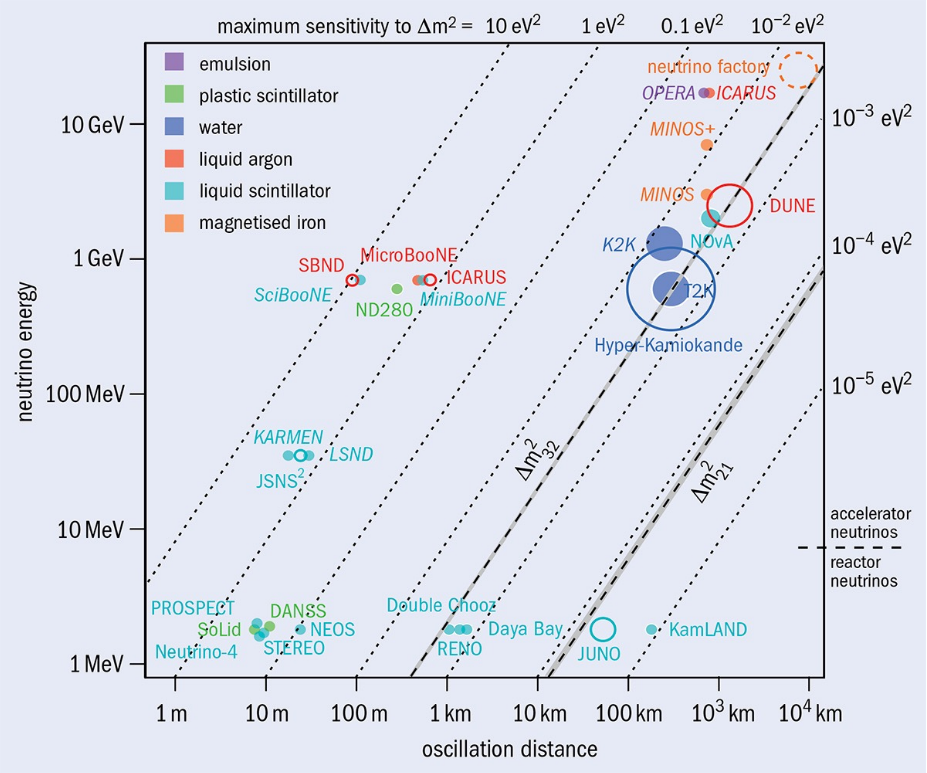
- *Measurement of reactor $\bar{\nu}_e$ spectrum (**shape and flux anomalies**).*
- *Search for **light sterile neutrino**, with $\Delta m^2_{new} \sim 0.1 - 10\ eV^2$.*
- *Neutrino **oscillation parameters**, e.g. θ_{13} (Daya-Bay, RENO, Double Chooz).*

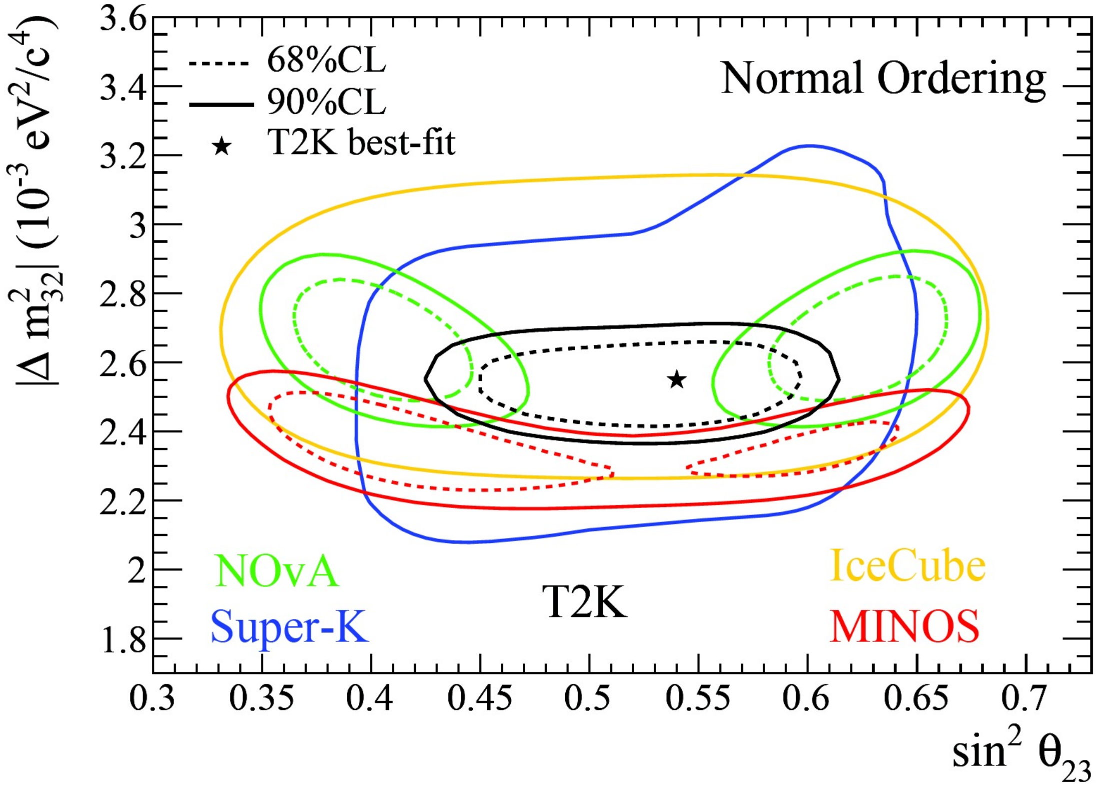
What comes next:

- *Neutrino **mass ordering** (JUNO).*
- *Probe new physics through novel channels for neutrino interaction, e.g. Coherent Elastic Neutrino-Nucleus Scattering aka **CEvNS** (NUCLEUS, RICOCHET, CONUS, MINER, CONNIE).*

From accelerators

- High fluxes and high energy neutrino beams are created by particle accelerators
- Short and Long baseline experiments





Next generation experiments aim at determining:

- θ_{23}
- δ_{CP}
- the mass hierarchy

Double beta decay

Double beta decay is the rare transition with the same mass number (A) that changes the nuclear charge (Z) by two units, the decay proceeds only if the initial nucleus is less bound than the final one or both the nucleus are more bound than the intermediate one (only possible in nature in the case of even-even nuclei).

The two-neutrino decay, $\beta\beta(2\nu)$,

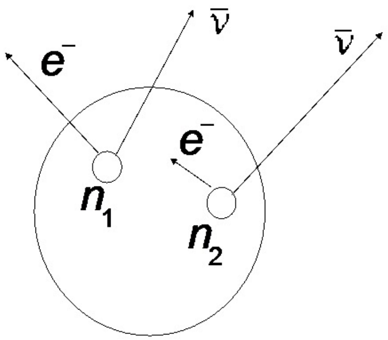
$$(Z, A) \rightarrow (Z+2, A) + e_1^- + e_2^- + \bar{\nu}_{e1} + \bar{\nu}_{e2}$$

conserves charge and lepton number

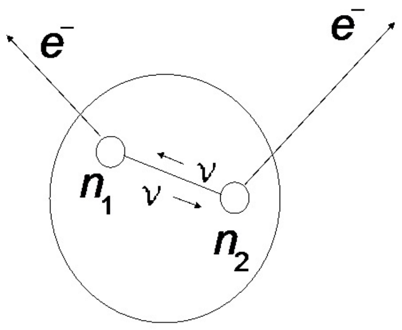
The neutrinoless decay, $\beta\beta(0\nu)$,

$$(Z, A) \rightarrow (Z+2, A) + e_1^- + e_2^-$$

violates lepton number conservation, forbidden in the standard electroweak theory



2νββ

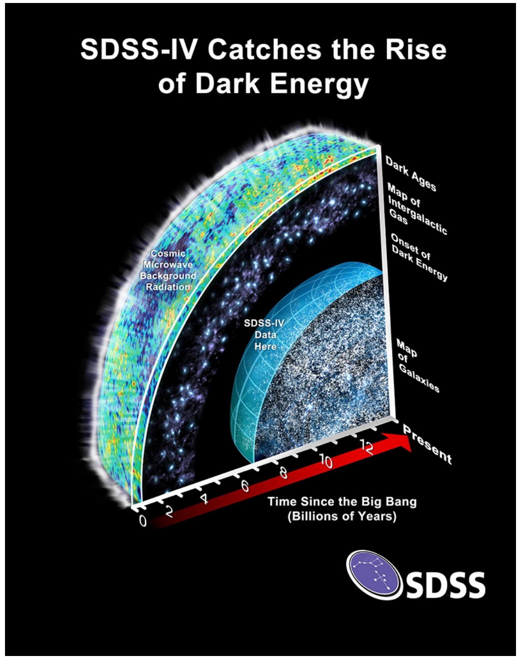


0νββ

A powerful tool to investigate Lepton Number Violation (LNV)

Neutrinos in astrophysics

- Several sources: Big Bang, supernovae, sun
- From Big Bang:
  - Cosmic Neutrino Background
  - Gravitational interaction with Dark Matter and Baryons
- Spectrograph telescopes: eBOSS and DESI
  - Dark Energy oriented experiments
  - First year for DESI
  - Neutrino impacts the Universe structure



eBOSS

DESI

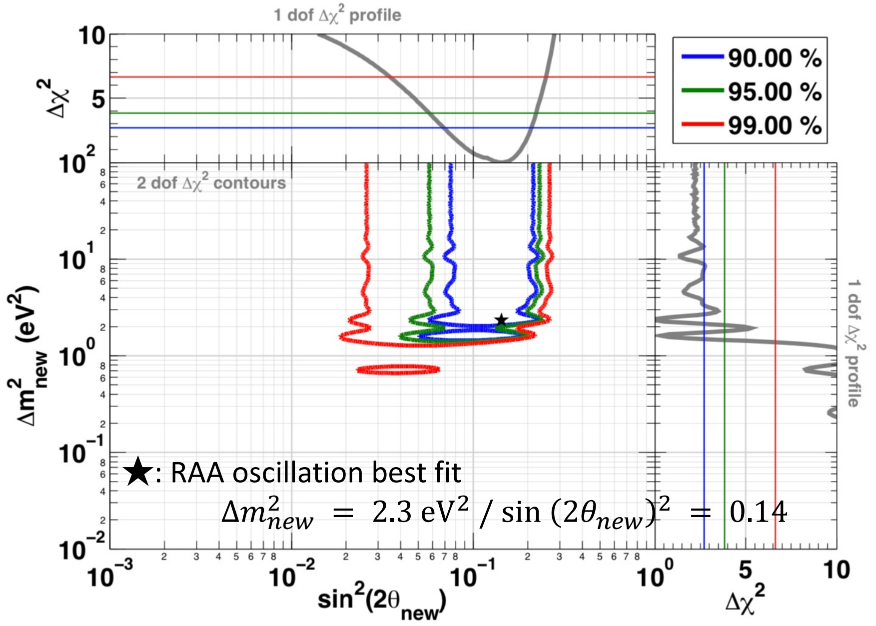
The STEREO experiment

Rudolph Rogly, CEA/Irfu/DPhN

Motivation

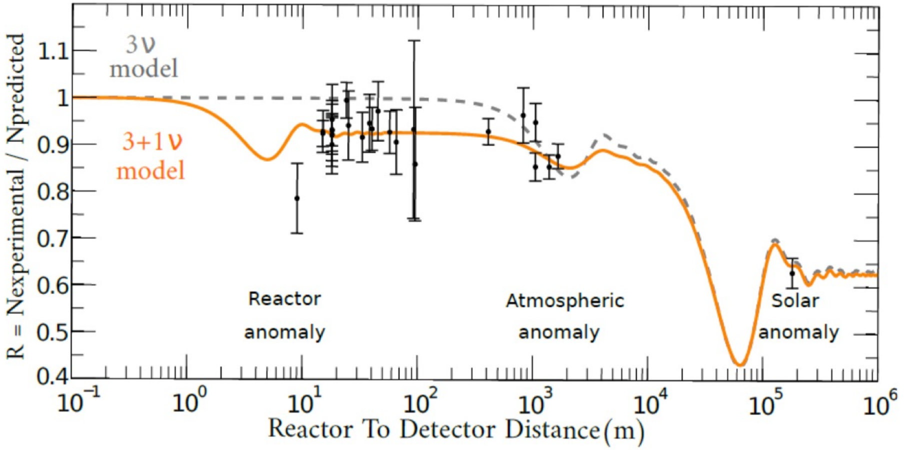
➢ Flux anomaly

Observed **~6% deficit** in measured fluxes at short-baseline, so-called **Reactor Antineutrino Anomaly (RAA)** – *PRD 83:073006 (2011)*



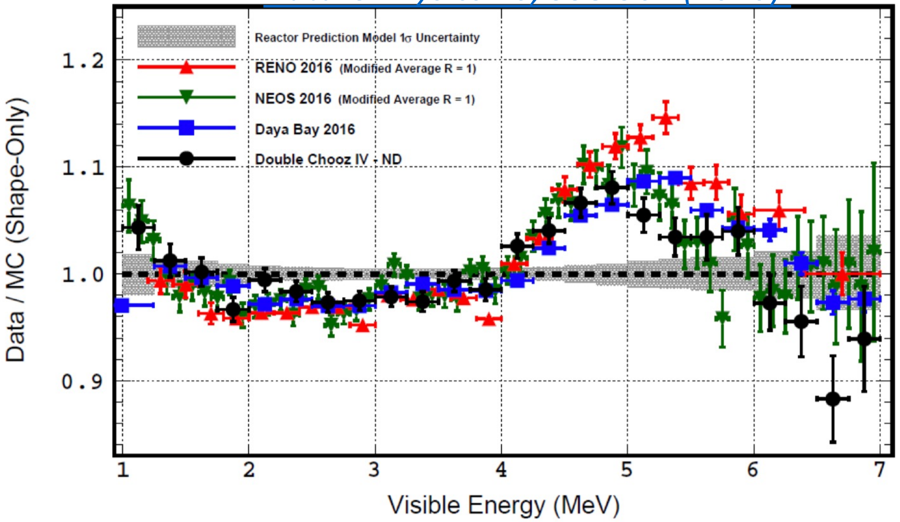
★: RAA oscillation best fit

$\Delta m^2_{new} = 2.3$ eV^2 / $\sin(2\theta_{new})^2 = 0.14$



Signature of the oscillation to a sterile state ?

Nature Physics 16, 558-564 (2020)



➢ Shape anomaly

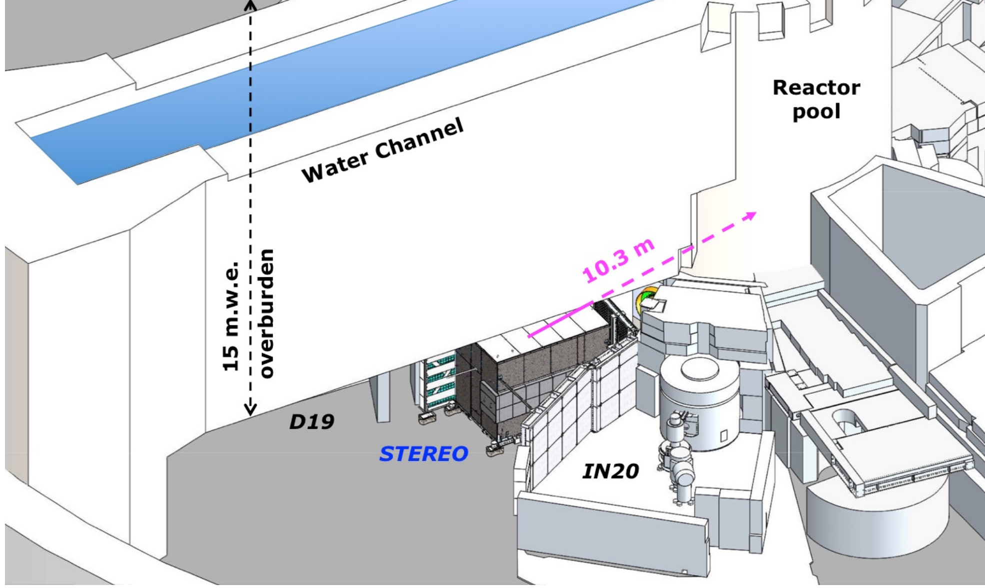
~10% local events excess observed by several lowly enriched in ^{235}U (LEU) experiments around 5 MeV wrt. Huber predicted shape.

Related to fuel composition ? Do U and Pu contribute to the same extent ?

The STEREO experiment [JINST 13 (2019) 07, P07009]

Experimental Site (ILL Grenoble, France):

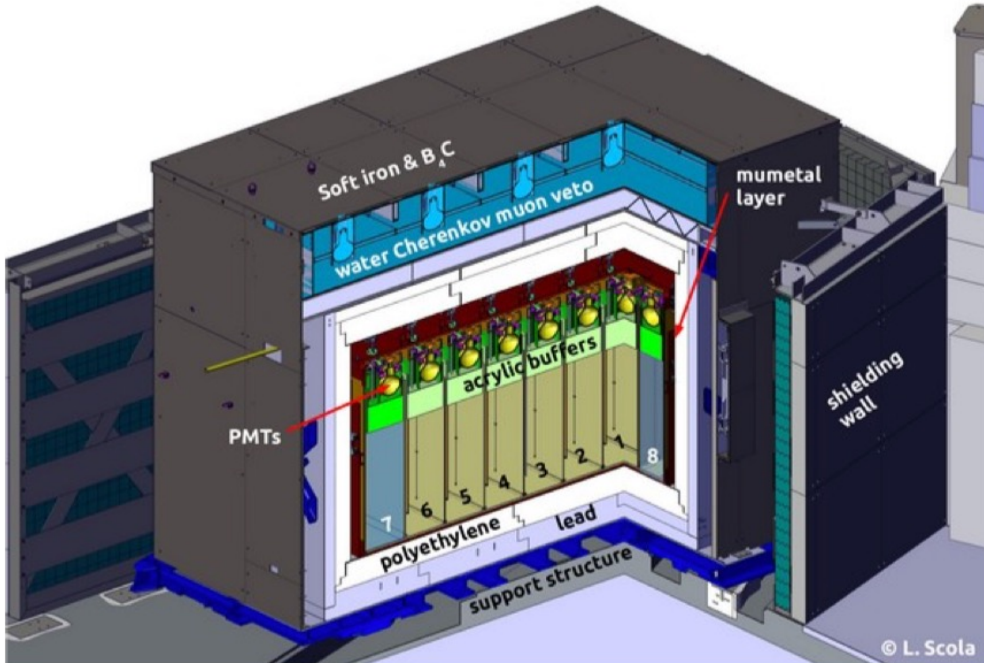
- Ground-level experiment.
- **Compact core** (Ø 40cm x 80 cm) and **short-baseline** (~10m) experiment to probe the RAA.
- 58MW$_{th}$ nominal power / HEU fuel (93% ^{235}U)
  → ***$\bar{\nu}$ flux purely from ^{235}U fissions***.



Detector Design:

- Segmented design for oscillation analysis, by **relative comparison between 6 identical target cells**.
- Heavy shielding + active muon veto + Pulse Shape Discrimination for background mitigation and rejection (achieved S:B of 0.8:1).
- Detection reaction via **Inverse beta decay** (IBD):

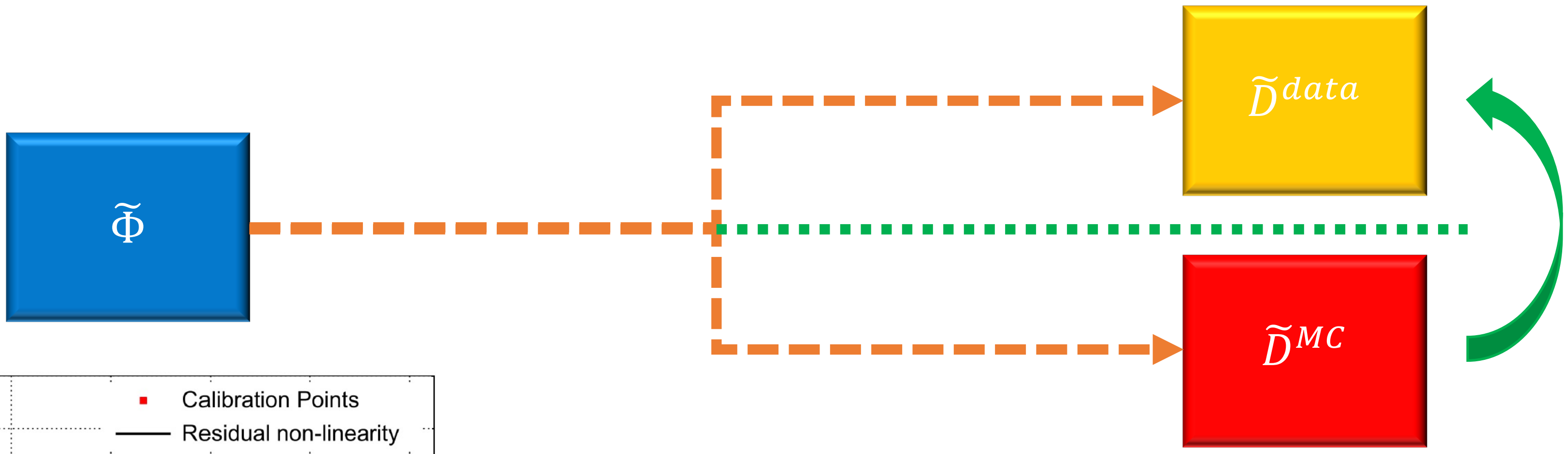
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Energy reconstruction [PRD 102,052002 (2020)]

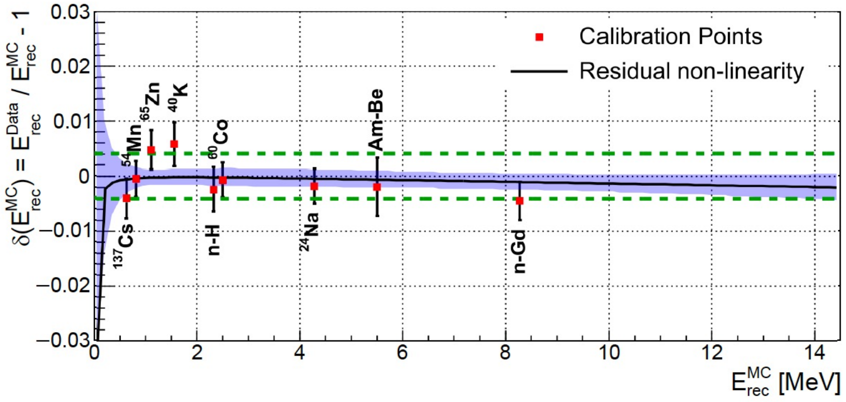
$E_{true} = E_{\bar{\nu}_e}$

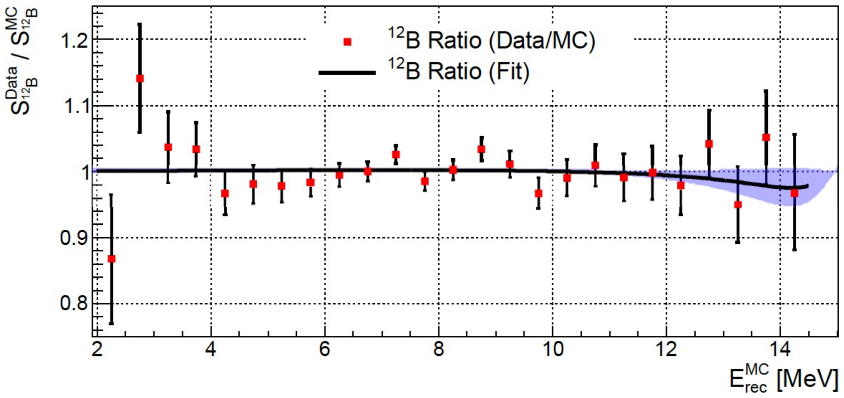
$E_{rec} = E_{e^+}$



Same space ?

→ Energy scale/Calibration





Energy scale derived from a **global fit** of:

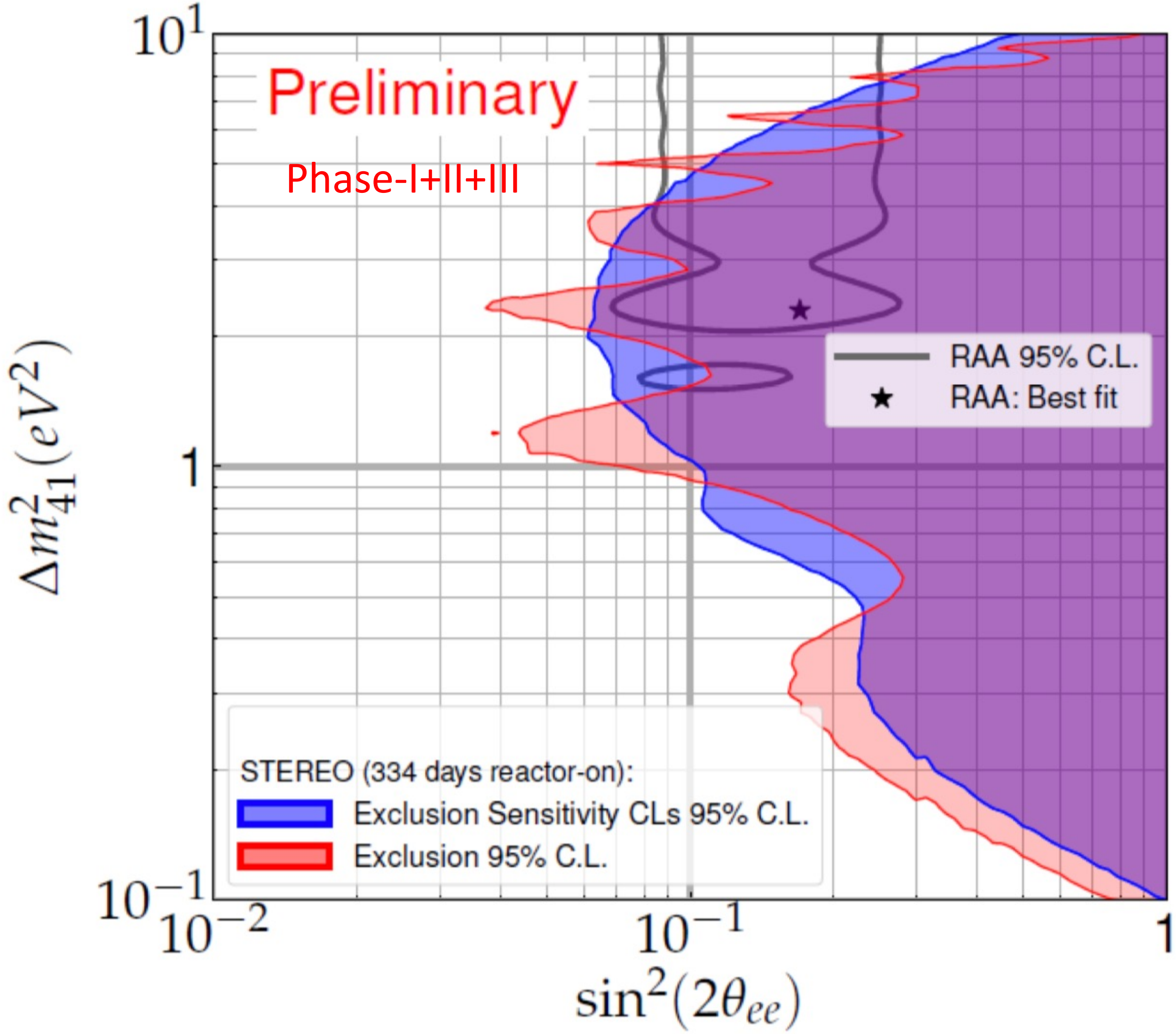
- ❑ Calibration data taken with point-like radioactive sources in each cell, at different heights.
- ❑ Cosmogenic ^{12}B beta spectrum ($Q_\beta = 13.4$ MeV).

All Data-MC residuals contained within a ±1% band for all cells.

STEREO exclusion oscillation contour

- $\Delta\chi^2$ distributions estimated with pseudo-experiments.
- No-oscillation hypothesis p-value = 0.17 (not rejected).
- RAA best fit rejected at more than 4σ.

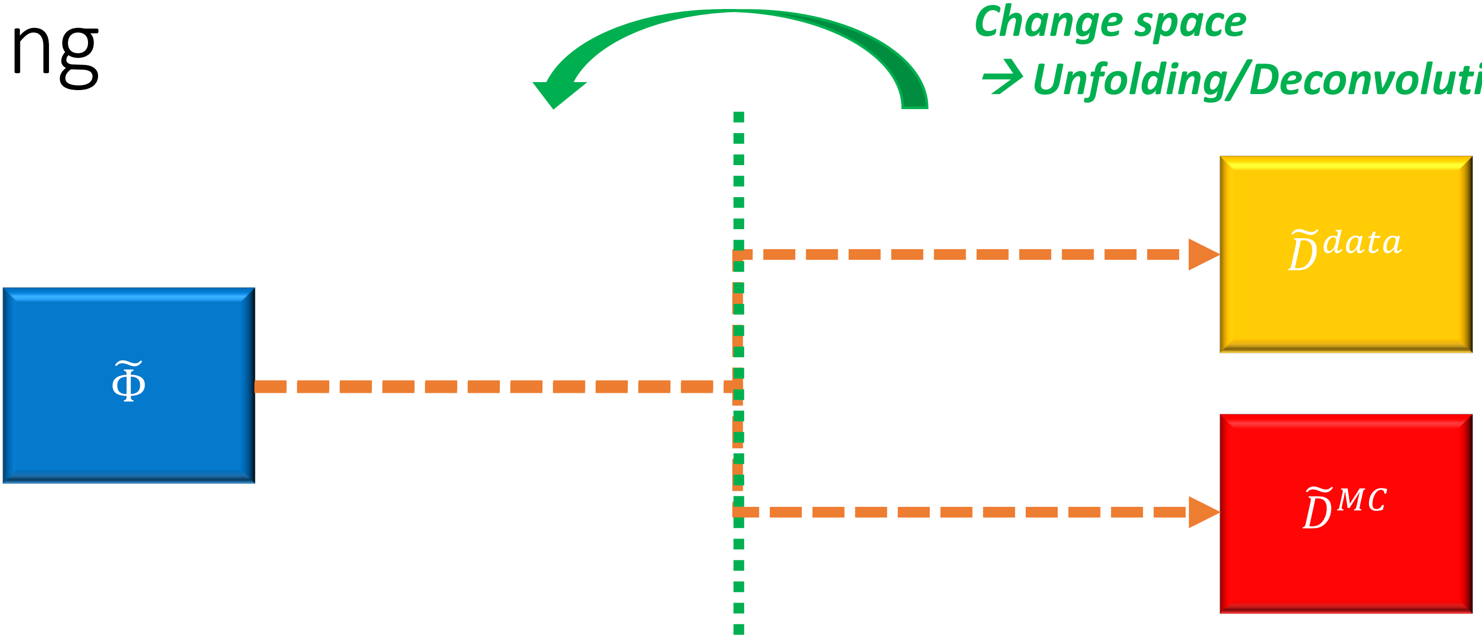
$\bar{\nu}_e$



Unfolding

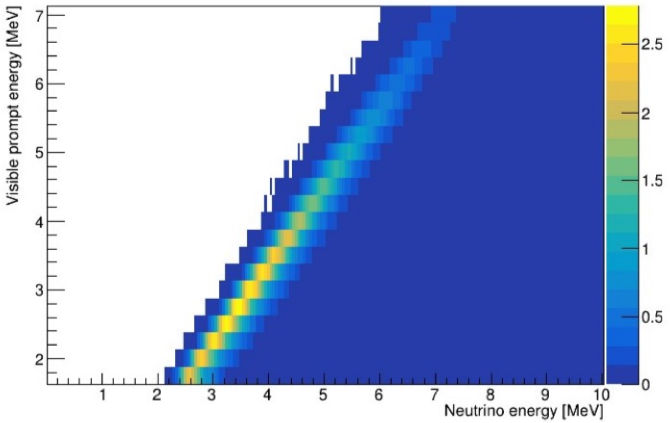
$E_{true} = E_{\bar{\nu}_e}$

$E_{rec} = E_{e^+}$



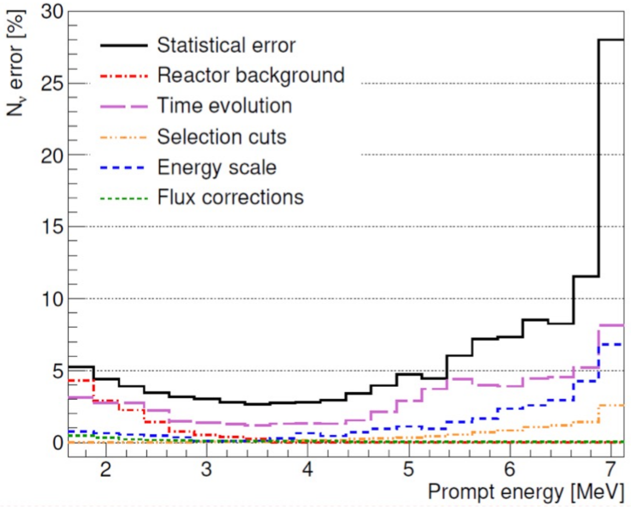
Change space
→ Unfolding/Deconvolution

What you need…



Response Matrix
(Transitions $E_{true} \rightarrow E_{rec}$)

+

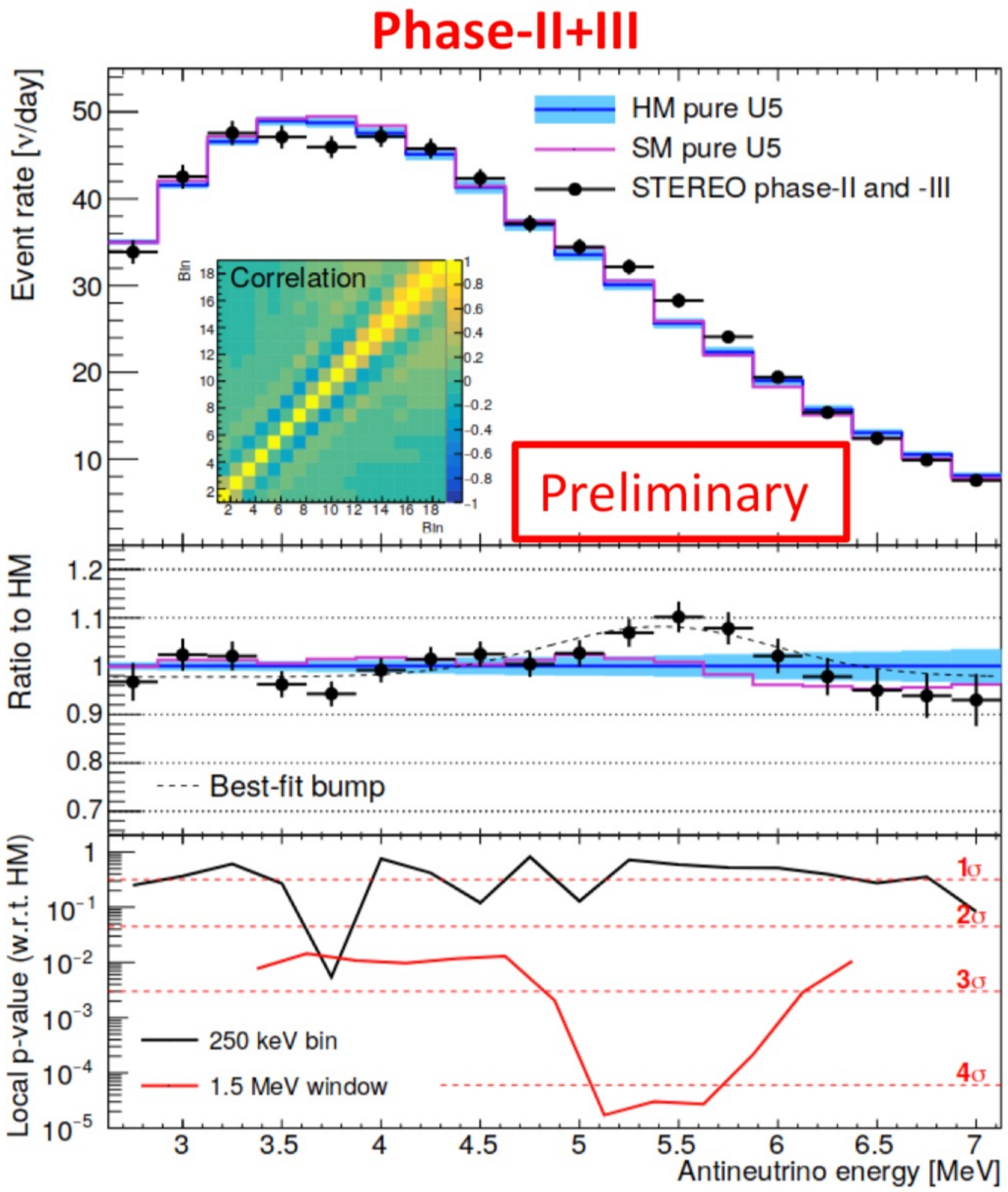


Error budget
(Statistics and systematics)

+

Regularization technic:
Tikhonov (STEREO),
Wiener-SVD (PROSPECT)…

STEREO spectrum shape analysis



- Provide a **reference ^{235}U antineutrino spectrum** to be used for comparisons with other measured antineutrino spectra (e.g. LEU spectra) or predicted spectra (e.g. Huber model).

- 5.1σ local events excess observed wrt. Huber around 5.4 MeV in antineutrino energy: $A = 10.7 \pm 2.1\%$.

- In favor of « equally shared » $(A \approx 9\%)$ scenario over « U5-only » scenario $(A \approx 16\%)$.

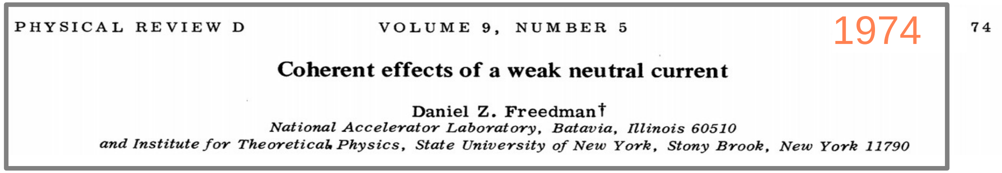
- Updated results to come!
  - Finish the analysis of STEREO full dataset (ongoing).
  - **Joint analysis with PROSPECT**, another HEU experiment (arXiv:2107.03371)

Outer Veto prototype for the CEνNS detection at nuclear reactors

Beatrice Mauri, 2nd year PhD student

6th September 2021, PhD-Days

The Coherent Elastic Neutrino Nucleus Scattering (CEνNS) process



PHYSICAL REVIEW D VOLUME 9, NUMBER 5 74

Coherent effects of a weak neutral current

Daniel Z. Freedman†

National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

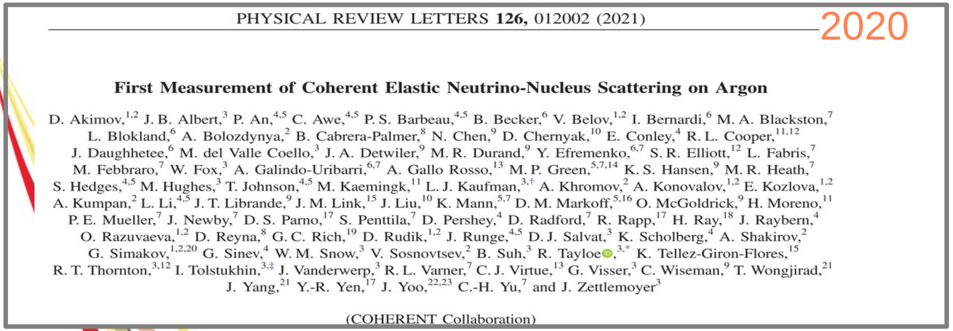
1974

RESEARCH D. Akimov et al Science 357 (2017), 1123

NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering

2017



PHYSICAL REVIEW LETTERS **126,** 012002 (2021)

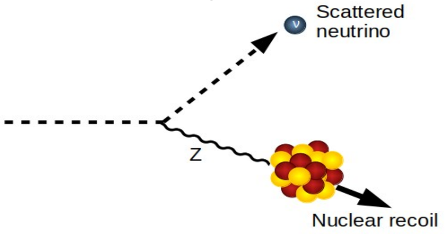
First Measurement of Coherent Elastic Neutrino-Nucleus Scattering on Argon

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4,5] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] I. Bernardi,[6] M. A. Blackston,[7] L. Blokland,[6] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] N. Chen,[9] D. Chernyak,[10] E. Conley,[4] R. L. Cooper,[11,12] J. Daughhetee,[6] M. del Valle Coello,[3] J. A. Detwiler,[9] M. R. Durand,[9] Y. Efremenko,[6,7] S. R. Elliott,[12] L. Fabris,[7] M. Febbraro,[7] W. Fox,[3] A. Galindo-Uribarri,[6,7] A. Gallo Rosso,[13] M. P. Green,[5,7,14] K. S. Hansen,[9] M. R. Heath,[7] S. Hedges,[4,5] M. Hughes,[3] T. Johnson,[4,5] M. Kaemingk,[11] L. J. Kaufman,[3,†] A. Khromov,[2] A. Konovalov,[1,2] E. Kozlova,[1,2] A. Kumpan,[2] L. Li,[4,5] J. T. Librande,[9] J. M. Link,[15] J. Liu,[10] K. Mann,[5,7] D. M. Markoff,[5,16] O. McGoldrick,[9] H. Moreno,[11] P. E. Mueller,[7] J. Newby,[7] D. S. Parno,[17] S. Penttila,[7] D. Pershey,[4] D. Radford,[7] R. Rapp,[17] H. Ray,[18] J. Raybern,[4] O. Razuvaeva,[1,2] D. Reyna,[8] G. C. Rich,[19] D. Rudik,[1,2] J. Runge,[4,5] D. J. Salvat,[3] K. Scholberg,[4] A. Shakirov,[2] G. Simakov,[1,2,20] G. Sinev,[4] W. M. Snow,[3] V. Sosnovtsev,[2] B. Suh,[3] R. Tayloe,[3,*] K. Tellez-Giron-Flores,[15] R. T. Thornton,[3,12] I. Tolstukhin,[3,‡] J. Vanderwerp,[3] R. L. Varner,[7] C. J. Virtue,[13] G. Visser,[3] C. Wiseman,[9] T. Wongjirad,[21] J. Yang,[21] Y.-R. Yen,[17] J. Yoo,[22,23] C.-H. Yu,[7] and J. Zettlemoyer[3]

(COHERENT Collaboration)

2020

If momentum transfer sufficiently low → the neutrino scatters off the target nucleons as a whole



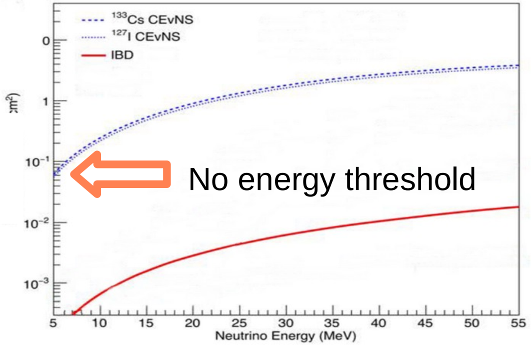
Signature: **unique nuclear recoil** with typical energy range 10's eV to few 10's keV

Cross section: 10 to 1000 times greater compared to the standard neutrino detection channels

→ cross section proportional to the square of the neutrons number of the target nucleus

→ **10's g to kg** detectors

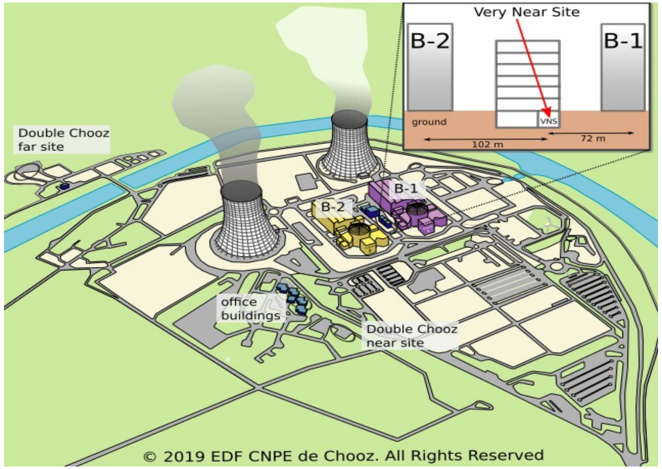
New way to prove **physics beyond the Standard Model**



No energy threshold

The NUCLEUS experiment in a nutshell

CHOOZ Nuclear Power Plant (France)



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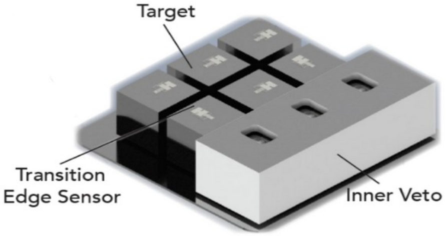
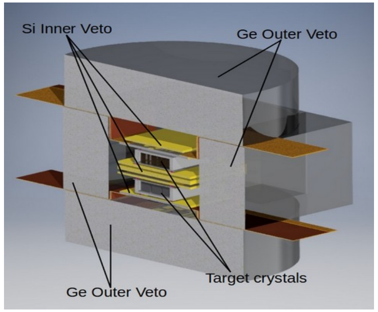
- **Very Near Site**: 24 m^2 basement room in administrative building between two 4.25 Gw_{th} reactors
- Baseline: 72 m to B1 and 102 m to B2
- ϕ_ν~1.7 x 10^{12} ν/cm^2/s, E_ν<10 MeV

Veto system against the background radioactivity: Fundamental !

NUCLEUS Outer Veto (OV): final configuration

- For an efficient reduction of background events induced by ambient ɣ's and neutrons
- 6 HPGe crystals with 2.5 cm thickness
- Active ionizing detectors
- Hosting the target detectors
- Working in anti coincidence with the target detectors

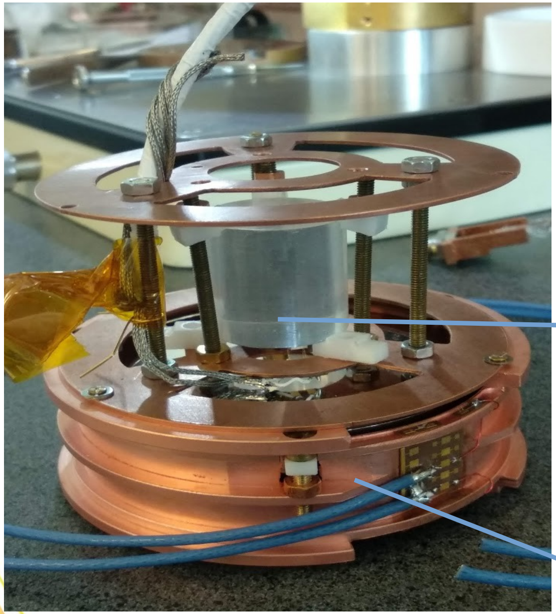




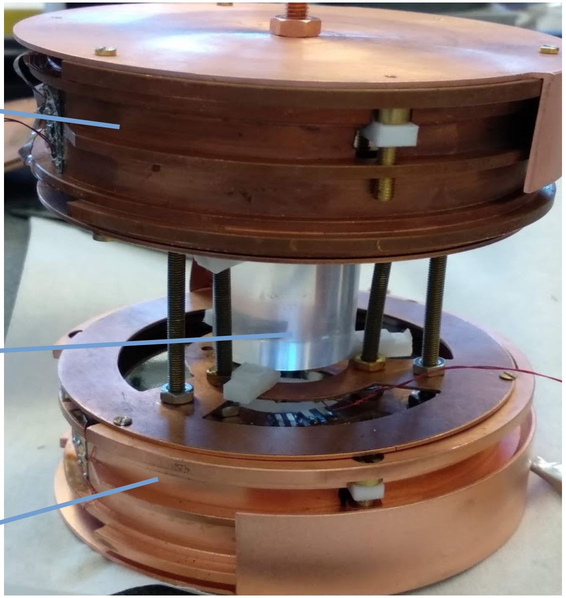
NUCLEUS OV prototype

2 tests performed at IJCLab (Orsay, France)

1st Test



2nd Test



HPGe crystal (Interdigit Detector, ID)

- d=7cm, h=2cm, m=400g
- Impurity density < 10^{10} cm^{-3}
- Electrodes: inter-leaved geometry (concentric rings)

Bolometers At Sub KeV Energy Thresholds

BASKET detector as target detector (Li_2WO_4+ Neutron Transmutation Doped sensor)

HPGe crystal

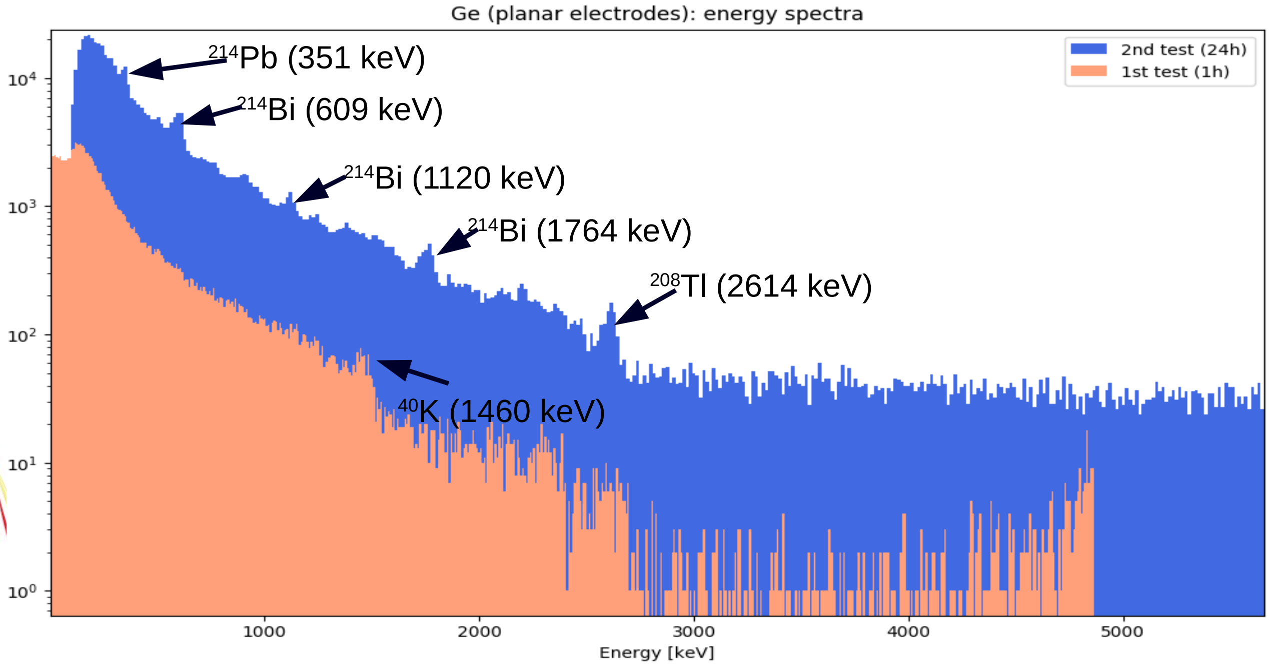
- d=7cm, h=2cm, m=400g
- Impurity density < 10^{10} cm^{-3}
- Electrodes: full Al layer (co-planar geometry) on both sides

NUCLEUS OV prototype

	1^{st} Test: Actuator cryostat	2^{nd} Test: Ulisse cryostat
Electronics	Cold	Room temperature *
Amplifiers	Current amplifier	Low noise voltage amplifiers
Cryostat	Pulse tube cryostat	Pulse tube cryostat
Lead shield	No	yes
Capacitance on which the charge is integrated	90 pF	> 500 pF
Electrodes bias	0 and 1.5 V	0 and 10 V (for both Ge detectors)
Filters	Butterworth high-pass (1 kHz) and optimum filter	Butterworth band-pass (20 Hz and 250 Hz) and optimum filter
Run temperature	17 mK	20 mK
Run duration	1 h	24 h

* electronics not optimized for ionization measurements

NUCLEUS OV prototype



	1st Test: planar electrodes	2st Test: planar electrodes	2st Test: ID
Energy resolution (FWHM) [keV]	71±3 @ 1460 keV	52.6±5 @ 2614 keV	38±2 @ 2614 keV
Energy threshold (5σ) [keV]	2.3 *	45	55.7
Bsl resolution (FWHM) [keV]	1.1	21.3	26.2
Sensitivity [nV/keV]	842	94.7	38
Rise-time [us]	2	107	118

* (in not optimized cryogenic conditions)

Conclusions and next steps

- NUCLEUS requirements satisfied in the 1st test
- 2nd test shows:
  - a cold electronics is indispensable
  - strong pile-up reduction due to the lead shield
- 3rd test under analysis:
  - same detector used in 2nd test
  - in the Actuator cryostat (cold electronics!)
  - with additional lead shield
  - in optimized cryogenic conditions
  - preliminary results: very promising. Stay tuned!

STAY TUNED!

- In future: 2nd test OV prototype will be used to test the NUCLEUS electronics in Munich

Thank you for your attention!

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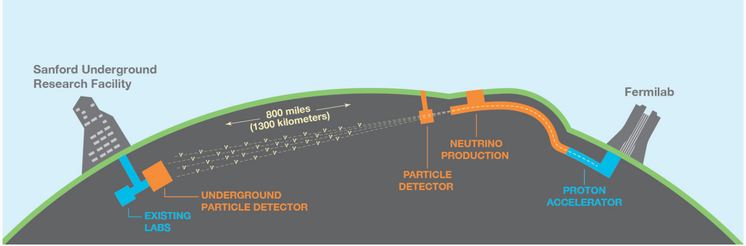
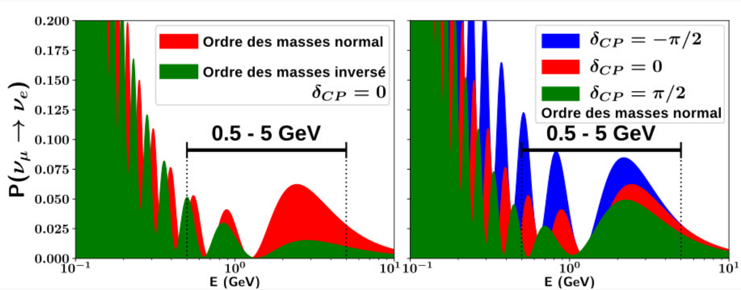
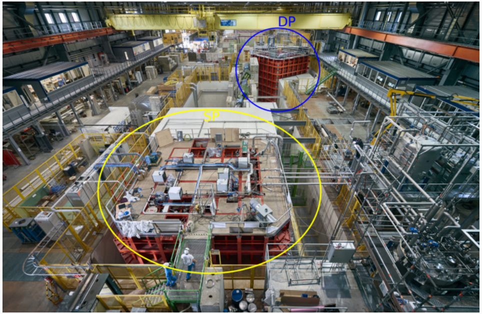
The DUNE experiment



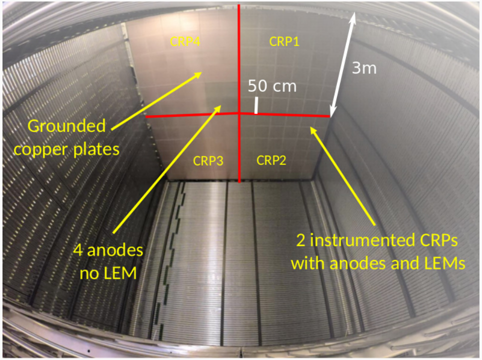


- Neutrinos oscillate between mass states
- Measuring the neutrinos energy, flavour and flux at a Near Detector and a Far Detector allows to measure the oscillation parameters
- DUNE mostly aims at measuring δ_{CP}

ProtoDUNE-DualPhase: a liquid argon TPC prototype for DUNE



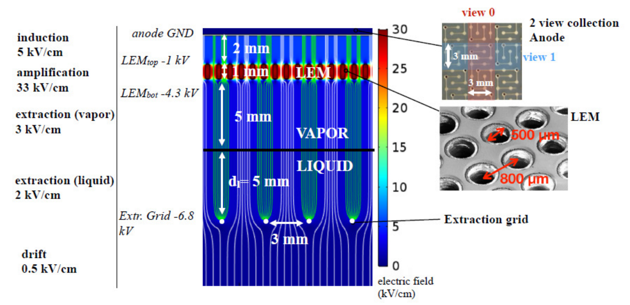
Neutrino patform at CERN

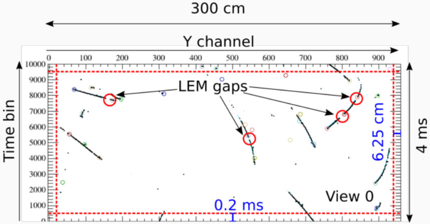


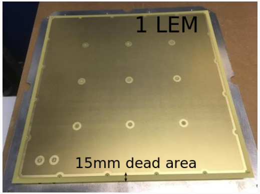
- 300t LAr
- 6m drift length

- Charge readout with CRPs (Charge Readout Planes)
- Light readout with PMTs

Working principle of a dual phase TPC

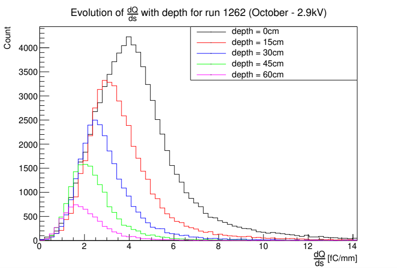


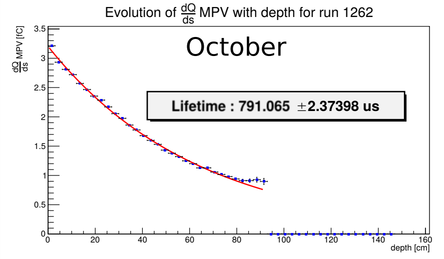


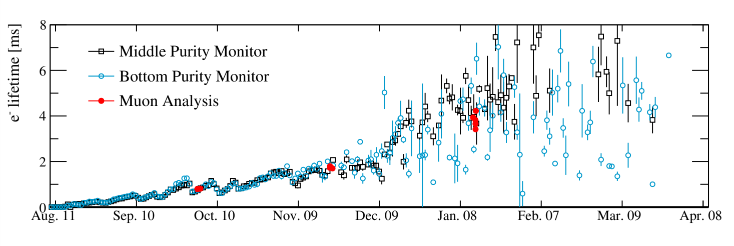


- Drift field generated by cathode and field cage
- Extraction field between grid and LEM botton electrode
- Amplification field in LEMs holes
- Readout in two directions by charge collection of the anode

Estimating argon purity from charge attenuation

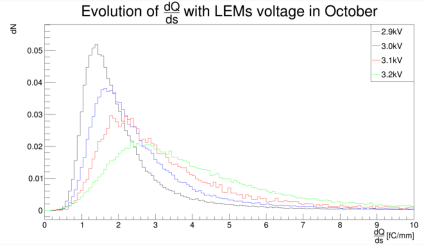


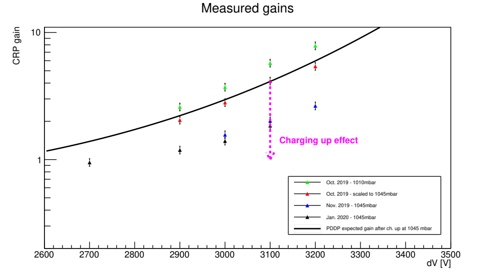


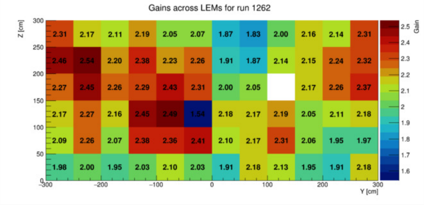


- Impurities in the argon capture drifting electrons
- The evolution of the measured charge as function of depth allows to estimate the purity

Measuring the CRP gains



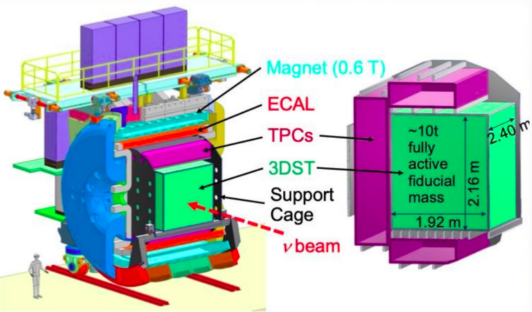


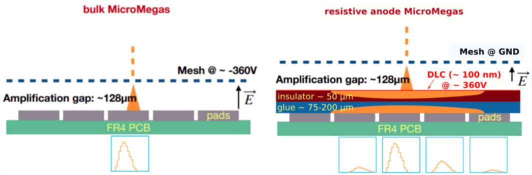


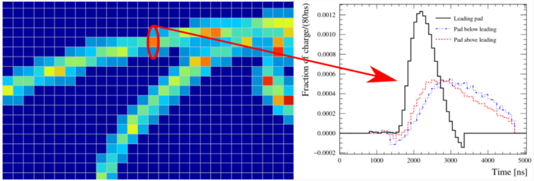
2.31	2.17	2.11	2.19	2.05	2.07	1.87	1.83	2.00	2.16	2.14	2.31
2.46	2.54	2.20	2.38	2.23	2.26	1.91	1.87	2.14	2.15	2.24	2.32
2.27	2.45	2.26	2.29	2.43	2.31	2.00	2.05		2.17	2.26	2.37
2.17	2.27	2.16	2.45	2.49	1.54	2.18	2.17	2.19	2.05	2.11	2.18
2.09	2.26	2.07	2.38	2.36	2.41	2.10	2.17	2.31	2.06	1.95	1.97
1.98	2.00	1.95	2.03	2.10	2.03	1.91	2.18	2.13	1.95	1.91	2.18

- The gain increases with LEM voltage
- Cosmics energy loss distributions can be fitted in order to estimate the CRP gains.
- A LEM by LEM map can be made where we see the gain inhomogeneities

A proposed design for the SAND Near Detector

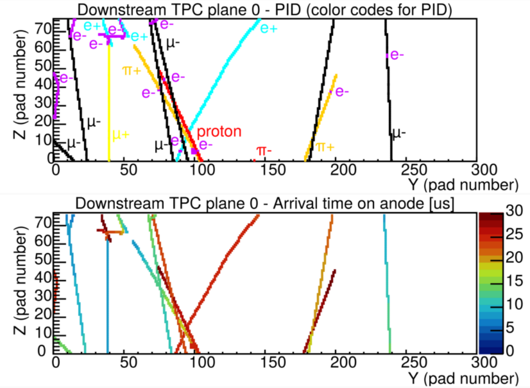




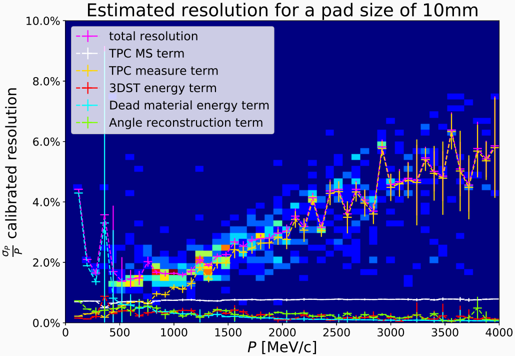


- 3DST: target made of scintillating cubes read in 3D by optic fibers. Allows to track the particles in 3D and to measure neutrons energy by ToF.
- 3 TPCs: tracking chambers instrumented with resistive micromegas. Allows to precisely measure the momentum of charged particles and to make PID.

Simulations results



Simulated event display for one full spill

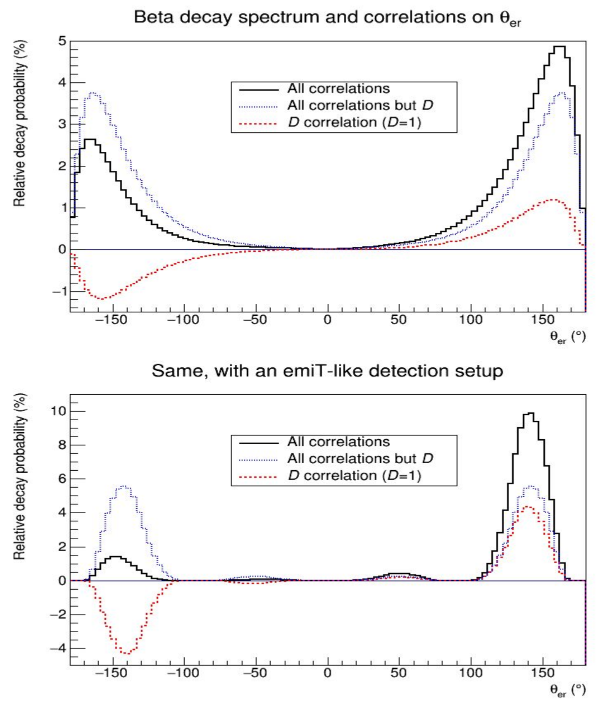


Estimation of the total resolution on the muon momentum measured by the TPC

Detection of Beta decay in laser oriented trapped radioactive isotopes for the MORA Project

Matter's Origin from the RadioActivity of trapped and oriented ions

PhD DAY, September 6,2021
CEA, Saclay



- Precise Measurement of the D correlation in the nuclear beta decay of trapped and oriented ions.
- Combining technically the high trapping efficiency of a trap with laser orientation techniques.
- **First focus on 23Mg+,** Depending on the beta decay transition observed, the MORA apparatus should additionally permit a probe of the Final State Interactions (FSI) effects.

Physics Motivation:

- **The D parameter offers the possibility to search for new CP-violating interactions.**

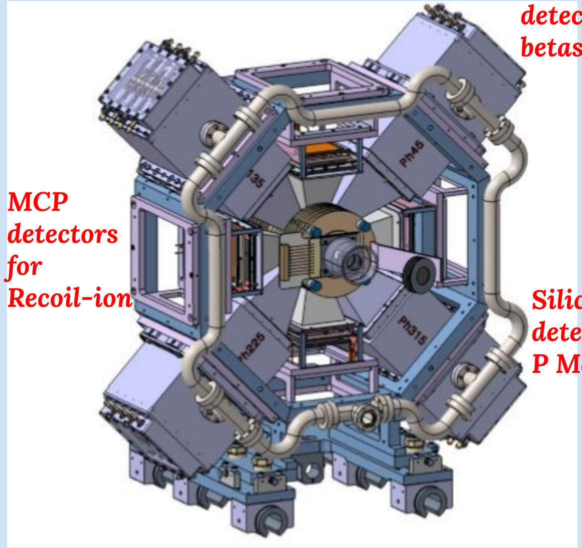
- A large CP violation has to be discovered to account for this large matter-antimatter asymmetry, at a level predicted to occur in the Standard Model.

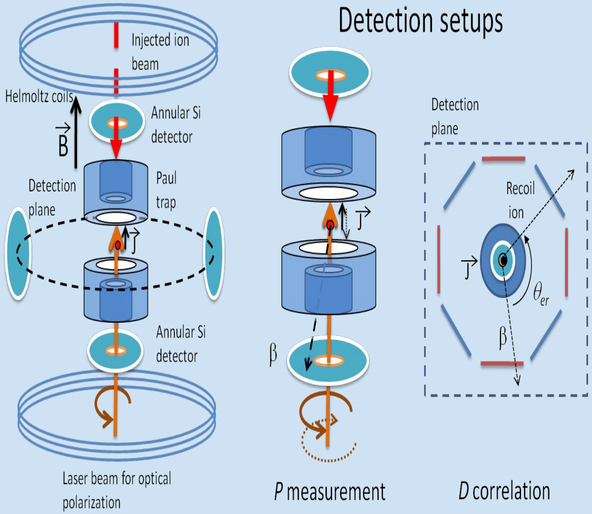
Project Focus:

- Proof-of-principle of in-trap laser orientation techniques.
- D- correlation measurement in the decay of 23Mg+ ions at **JYFL** (2021-2023)
- D- correlation measurement at the future DESIR facility. ***Highest accuracy for measurements incl. neutron decay.***(2024-..)

THE MORA PROJECT

The Detection setup:





Measurement of D correlation parameter

- An octagonal arrangement of 6 cm diameter recoil ion and positron detectors placed at 10 cm from the trap center.
- The asymmetry in the number of coincidences recorded at average θer angles being defined clockwise with respect to the spin direction gives D value.

The *D* correlation is measured in the azimuthal plane of the trap by an arrangement of beta and recoil ion detectors.

The polarization along the trap axis by superimposing a circularly polarized laser beam with the injected ion beam

The Trap and detection configuration will allow for the simultaneous measurement of the D correlation and monitoring of the degree of polarization

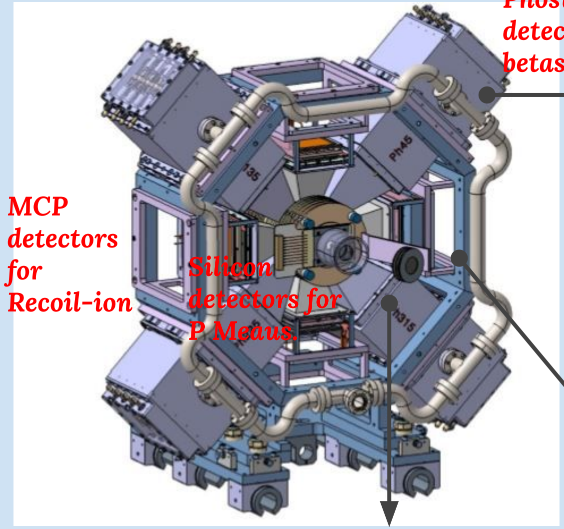
$$\frac{N^{\uparrow}_{\beta+} - N^{\downarrow}_{\beta+}}{N^{\uparrow}_{\beta+} + N^{\downarrow}_{\beta+}} \propto A_\beta \cdot P$$

$$A_\beta \frac{\langle \vec{J} \rangle}{J} \cdot \frac{\vec{p_e}}{E_e}$$

$$D \propto \left(\frac{N^{(\theta_{er} \in [0,\pi])}_{(\beta r)coin} - N^{(\theta_{er} \in [0,-\pi])}_{(\beta r)coin}}{N^{(\theta_{er} \in [0,\pi])}_{(\beta r)coin} + N^{(\theta_{er} \in [0,-\pi])}_{(\beta r)coin}} \right)$$

THE MORA PROJECT

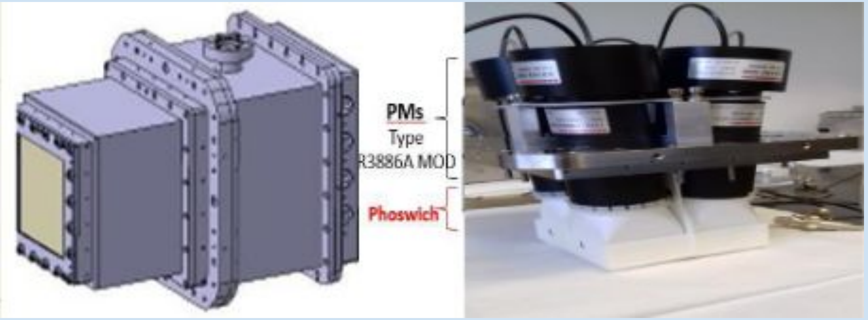
The Detection setup:



Phoswich detector for betas

MCP detectors for Recoil-ion

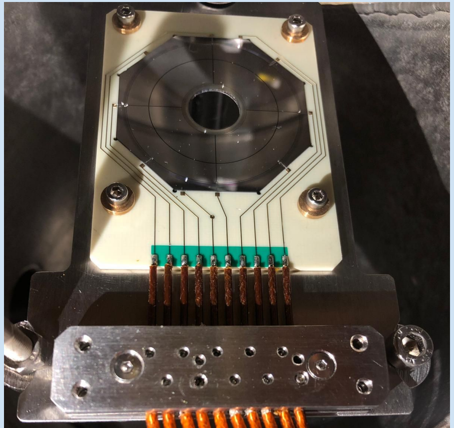
Silicon detectors for P Meaus.



Combination of two plastic scintillators:

- *Thin scintillator (0.5 mm , τ=1.8 ns)*

- *Thick scintillator (5 cm , τ=285 ns) (+ Mylar+ Téflon)*



2 annular Si detectors on the axis of the trap.

Recoil ion detectors consisting :
- *Micro-Channel Plates (50*50) with accelerating grids .*
- *position-sensitive anode*

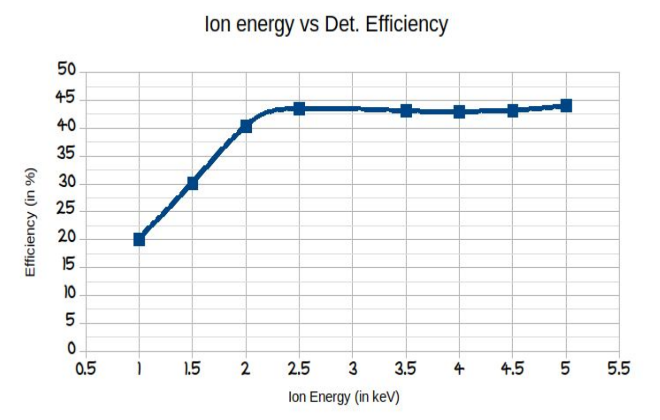
THE MORA PROJECT

Current status :

Detection:

SI *Detectors* for polarization meas. Has been tested successfully and have acquired resolution of 20-30 keV with betas.

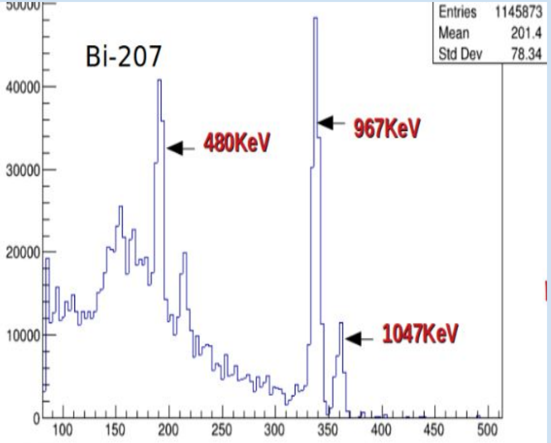
MCP *Detectors* for recoil ion detection are being tested lately and have an efficiency of 45% for (1-6 keV) energy ions.



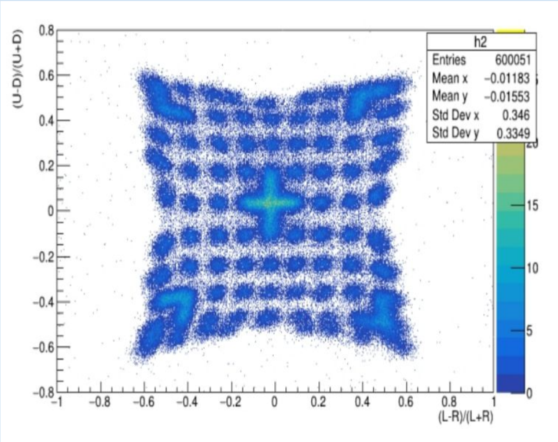
Trapping:

Testings being started with the beam line with an offline alkali source (^{23}Na) and successful trapping inside the MORATrap.

14% trapping efficiency

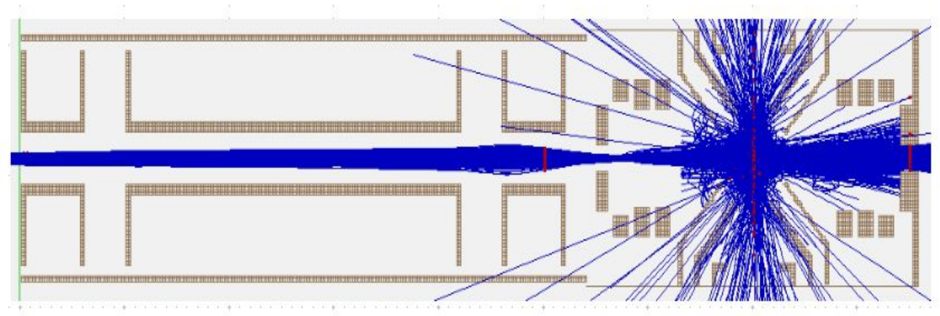


Si detector response with an electron source(Bi-207)



$$\tilde{X} = \frac{Qleft - Qright}{Qleft + Qright} \qquad \tilde{Y} = \frac{Qtop - Qbottom}{Qtop + Qbottom}$$

Detector raw Image construction with offline alkali(Na) ion source using a calibration masque on Multi-channel plates.



SIMION simulations for MORA beamline

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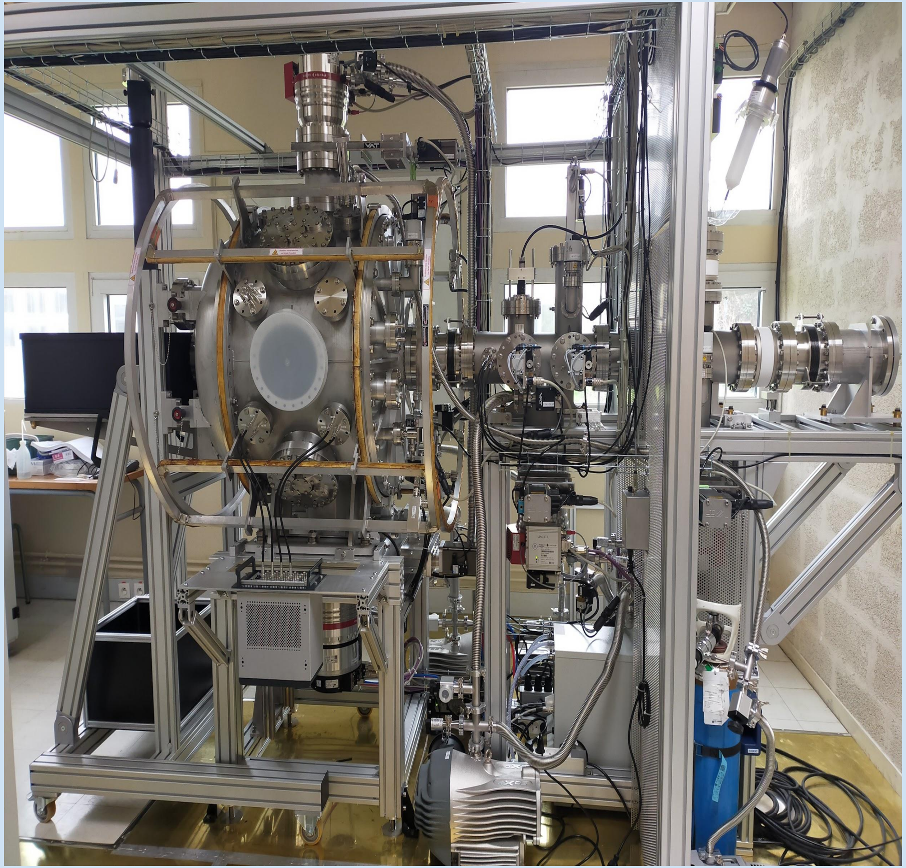
Current status and Outlook:



MORA beamline setup @LPC, Caen

- Setup ready to move to JYFL in the beginning of Oct, 2021
- Proof of Principle of Polarization and first Measurement of D correlation parameter (January,2022-2023)
- Higher Accuracy approach with D correlation measurement in future DESIR facility.
  - Expected improvement of 1 order of magnitude on the sensitivity to *Im*(CV/CA).
  - Probing new Physics beyond the level predicted in Standard Model in TeV scale,
  - Probing of Final state Interaction effects in the case of ^{23}Mg.

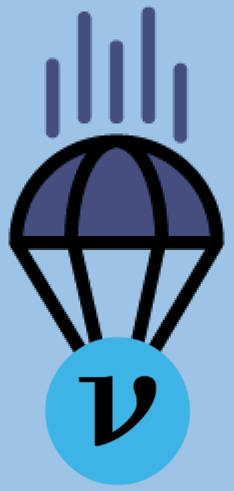
THE MORA PROJECT

Thanks for your attention!!

:)

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

PhD-Days: Neutrinos in Cosmology



Corentin Ravoux – DPhP

Supervisors: Eric Armengaud, Nathalie Palanque-Delabrouille, Christophe Yèche

06 September 2021

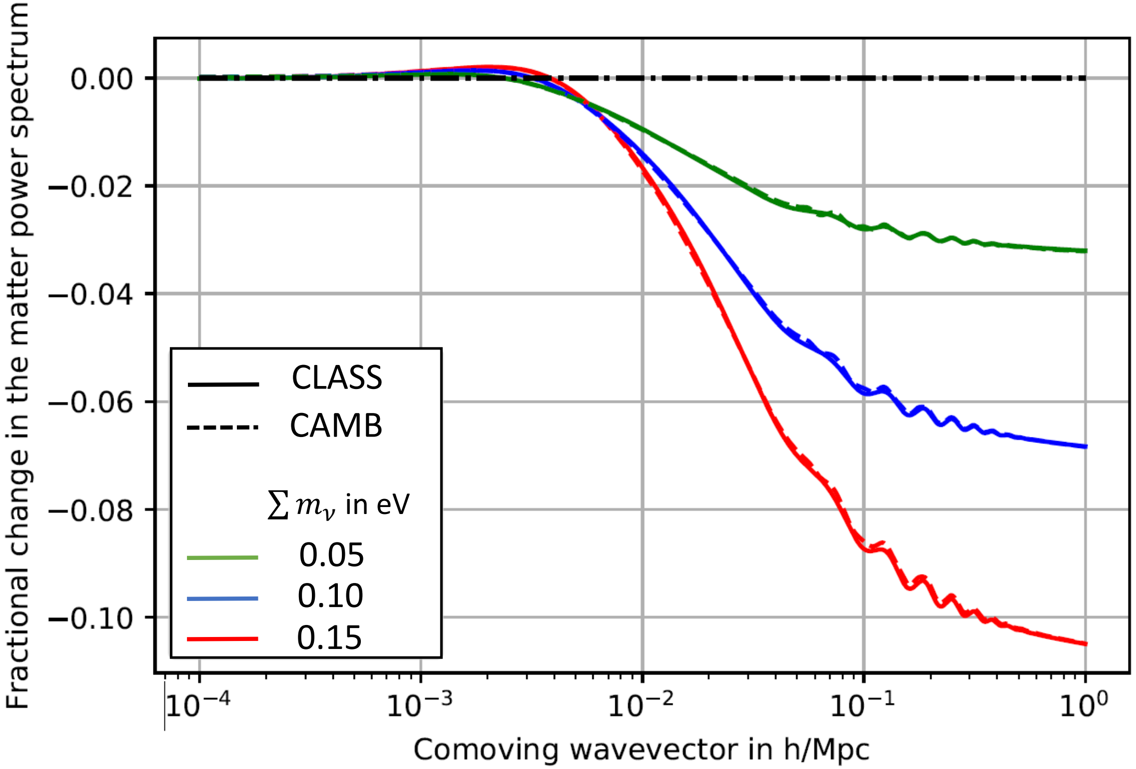
Neutrino impact on Cosmology

- Cosmology: Sum of neutrino mass $\sum m_\nu$ impact large-scale structure formation

  - Free streaming length: $\lambda_{FS} \sim \left(\frac{\pi v_{th}^2}{G\bar{\rho}}\right)^{1/2}$

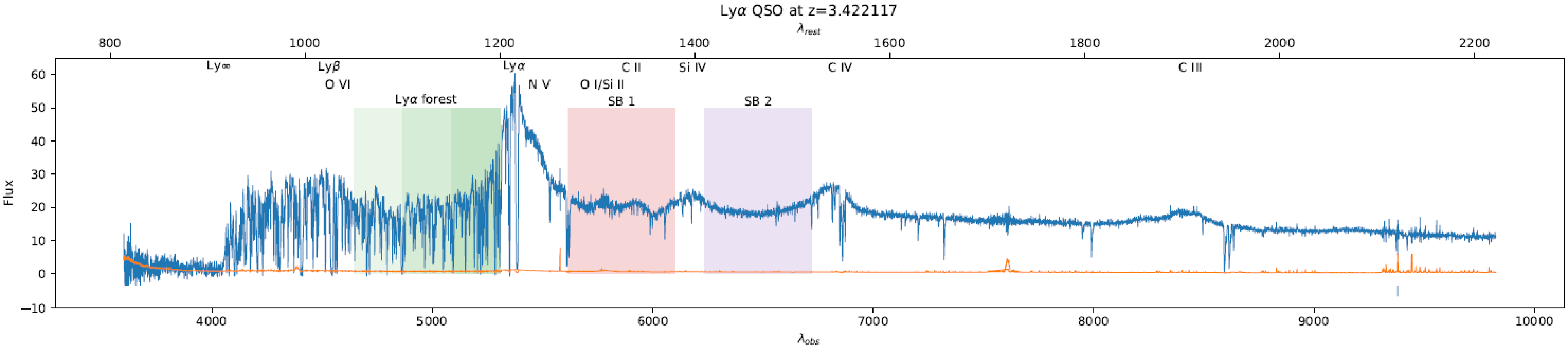
  - With their large speed, neutrinos do not cluster like Dark Matter and Baryons

  → Smoothing of small scales



Tracer: Lyman-alpha forest

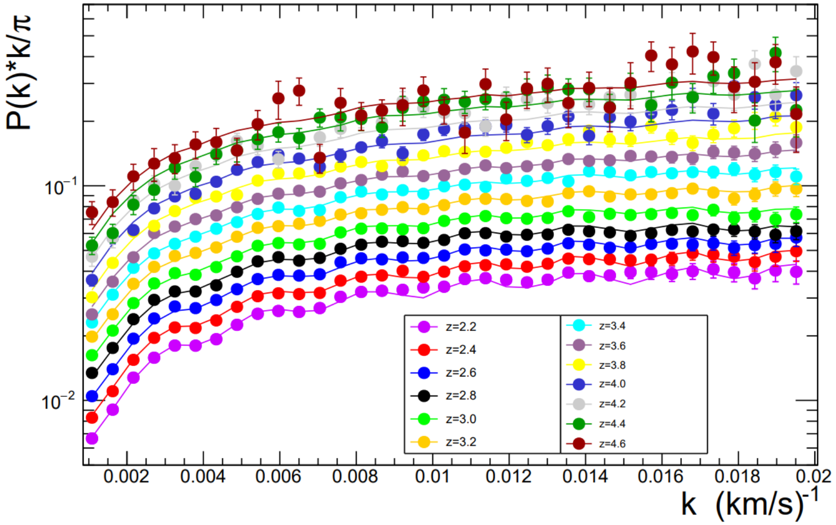
- Lyman-alpha: transition of neutral Hydrogen at 1215.67 Å
- Lines on the QSO spectra at $\lambda_{\mathrm{obs}} = (1 + z_{abs})\lambda_{\mathrm{Ly\alpha}}$ caused by absorber at z_{abs}
- Data: QSO observation from survey validation and 1st year of DESI



Lyman-alpha forest = Non-linear tracer of the neutral Hydrogen in the Intergalactic medium

One dimensional power spectrum

- Correlation of Lyman-alpha forest along sightline
- Measurement on eBOSS (Chabanier et al. 2019)
- Constraints on neutrino mass (Palanque-Delabrouille et al. 2020):



P1D + CMB + BAO + WL

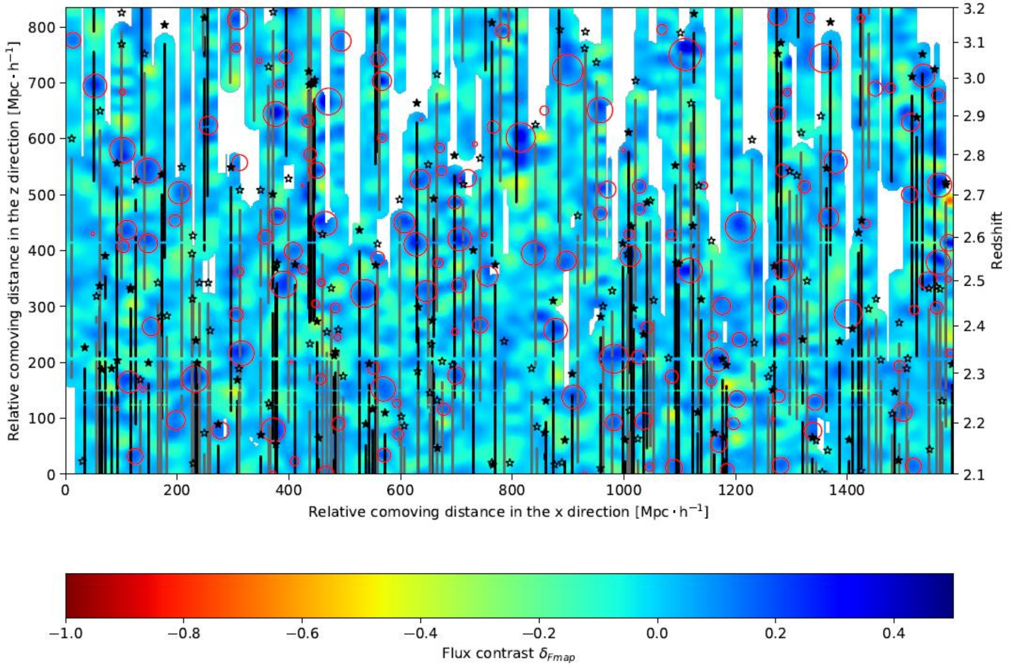
$$\boxed{\sum m_\nu < 0.09\ eV}$$

95 % CL

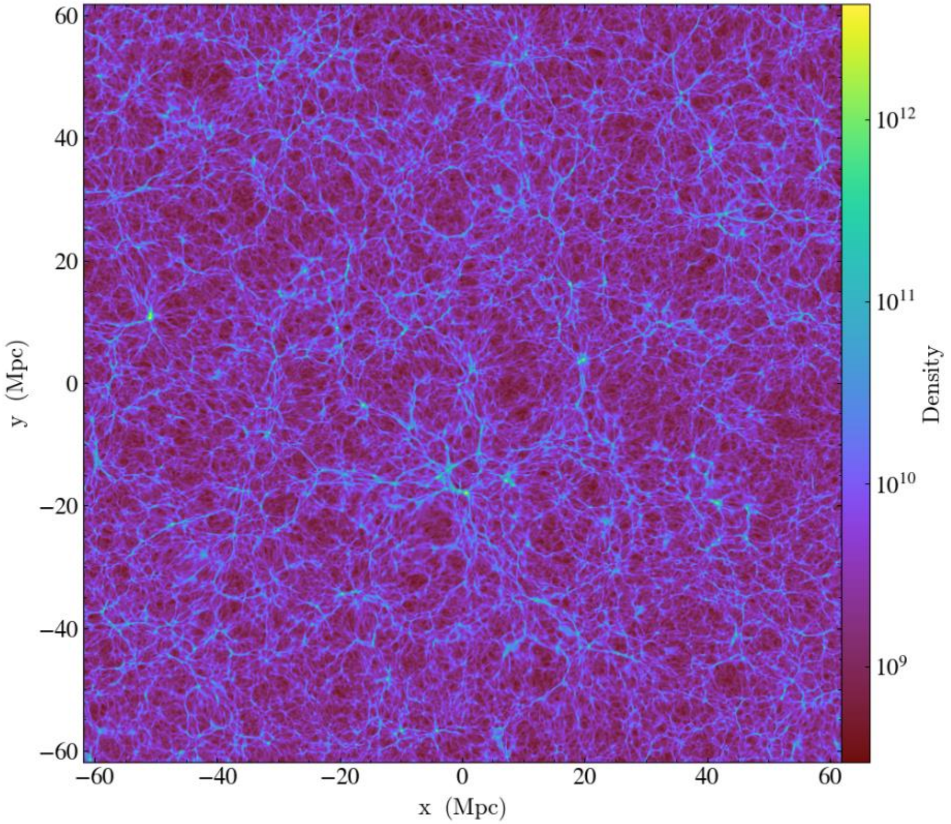
- <u>Current work</u>:
  - P1D measurement on first DESI data (Contribution to analysis pipeline)
  - Improved hydrodynamic simulations and emulation grid for constraints (Walther et al. 2021)

Use of 3D information

- Lyman-alpha tomography (Ravoux et al. JCAP07(2020)010)
  - Largest map of primordial universe
  - First measurement of cosmic void correlation at high redshift (Ravoux et al. in prep.)



- Large Hydro simulations for P3D on Jean-Zay using GPU



Take-home message

- Neutrinos have a mass-dependent impact on the formation of large-scale structure
- Using Lyman-alpha forest statistical properties gives constraints on sum of masses
- Current works aim to use full 3D information