NRC Kurchatov Institute
KCTEP

nEXO

Searching for Majorana neutrinos with nEXO

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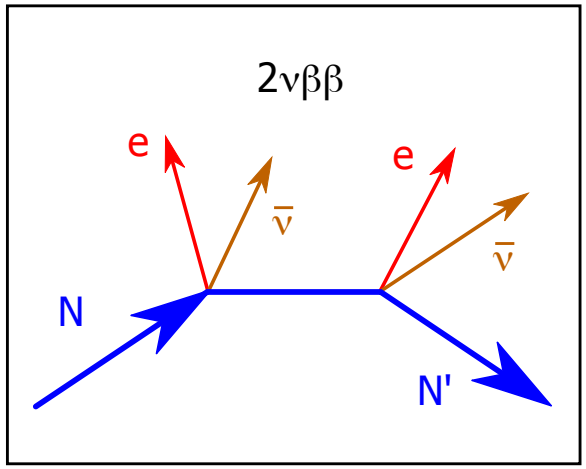
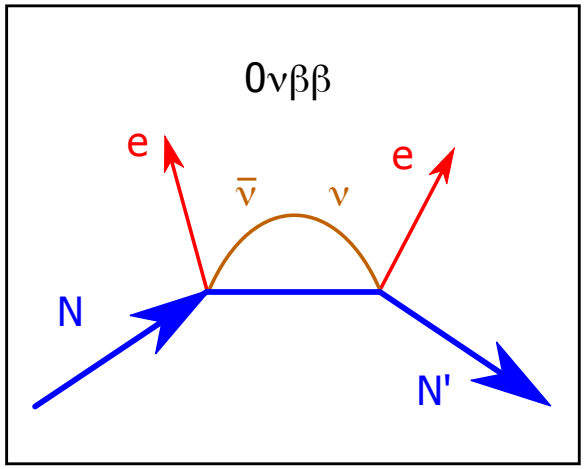
for nEXO coll.

TWENTY-FIRST LOMONOSOV
CONFERENCE August, 24-30, 2023
ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

Double beta decay



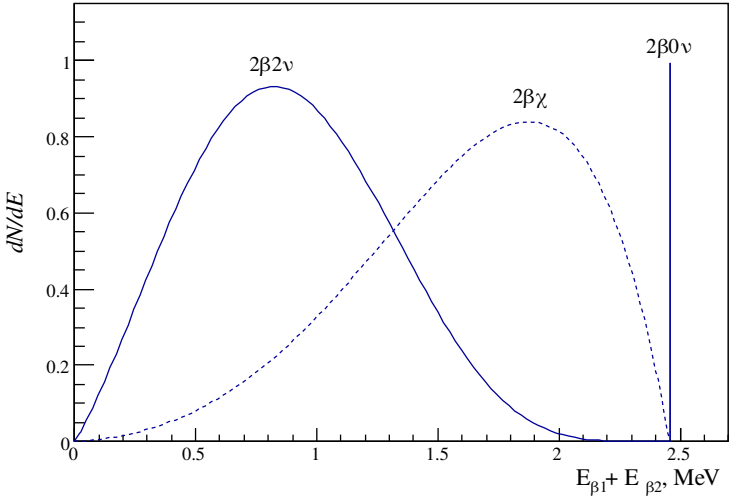


2ν mode
is a conventional 2nd order process in Standard Model discovered for many isotopes

0ν mode
is a hypothetical process always means New Physics.
This is search for:
Lepton Number Violation
Majorana fermions

To reach high measurement sensitivity for 0ν mode one requires:

- High energy resolution
- Large Isotope mass
- Low background



Why xenon

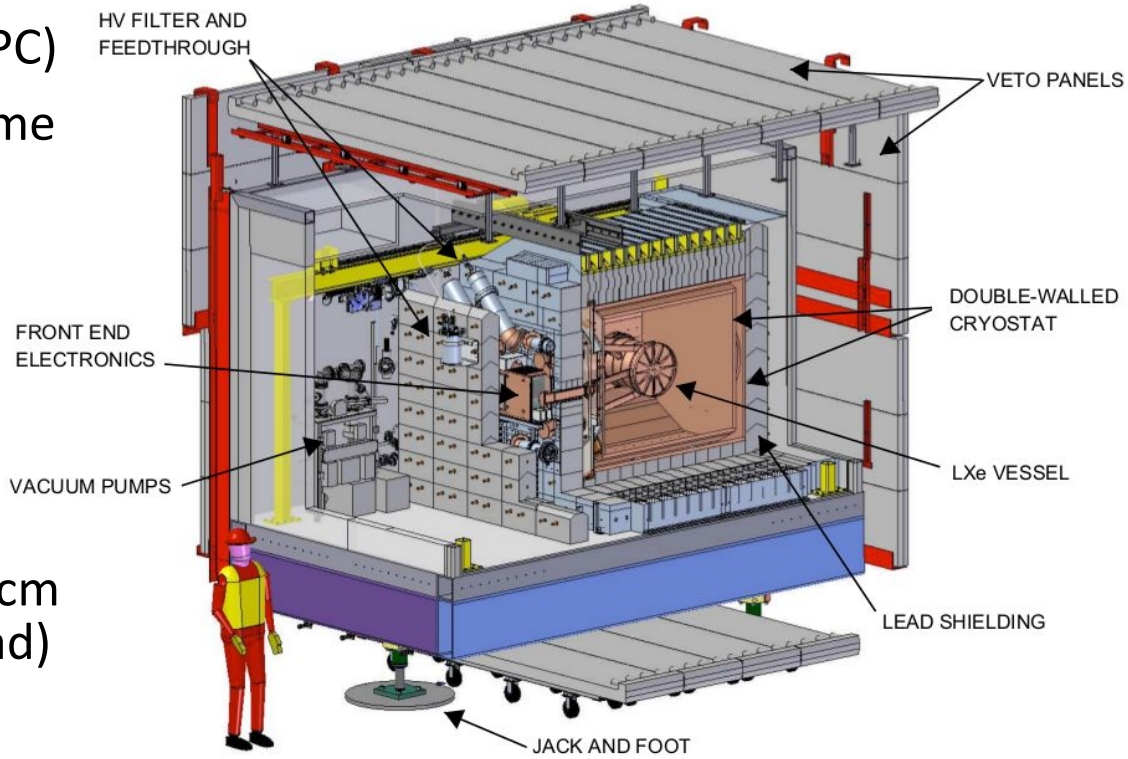
Energy resolution is poorer than the crystalline devices (~ factor 10), but...

- Monolithic detector. Xenon can form detection medium, allow self shielding, surface contamination minimized. Very good for large scale detectors.
- Has high Q value. Located in a region relatively free from natural radioactivity.
- Isotopic enrichment is easier. Xe is already a gas & ^{136}Xe is the heaviest isotope.
- Xenon is “reusable”. Can be purified & recycled into new detector (no crystal growth).
- Minimal cosmogenic activation. No long lived radioactive isotopes of Xe.
- Energy resolution can be improved. Using scintillation light/ionization correlation.
- Particle identification. Slightly limited, but can be used to tag alphas from Rn chain.

… admits a novel coincidence technique. Background reduction by Ba daughter tagging (M.Moe PRC 44, R931, 1991).

EXO-200 detector

- Double Time Projection Chamber (TPC)
- 110 kg of liquid xenon in active volume enriched to 80.6 in ^{136}Xe
- Reading both ionization and scintillation
- Drift field 564 V/cm
- Comprehensive material screening program
- Massive background shielding (> 50 cm of HFE, 5 cm of copper, 25 cm of lead)
- Located in salt mine at 1600 m.w.e.



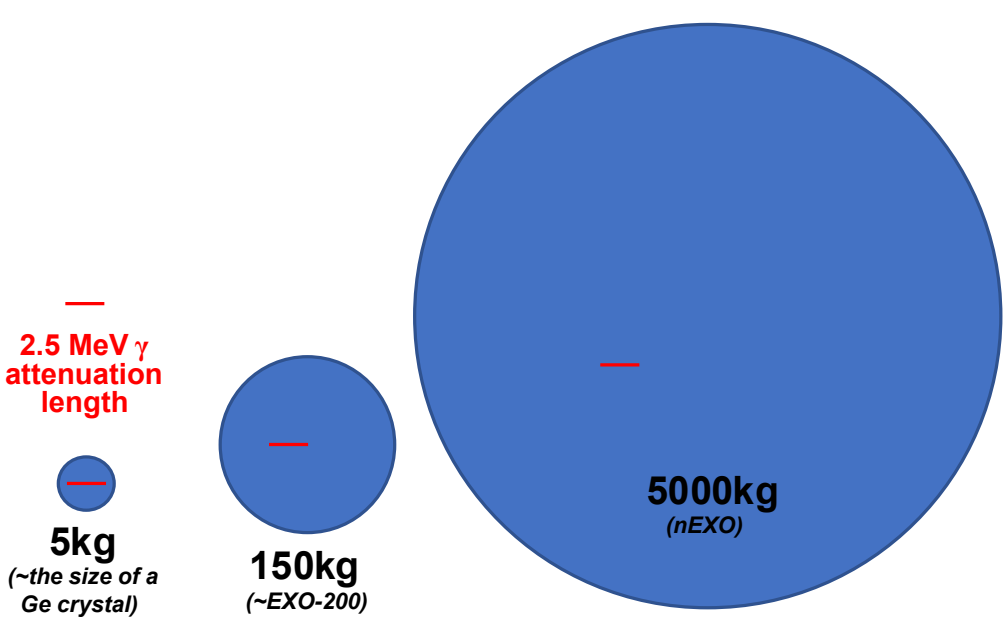
EXO-200 detector: JINST 7 (2012) P05010

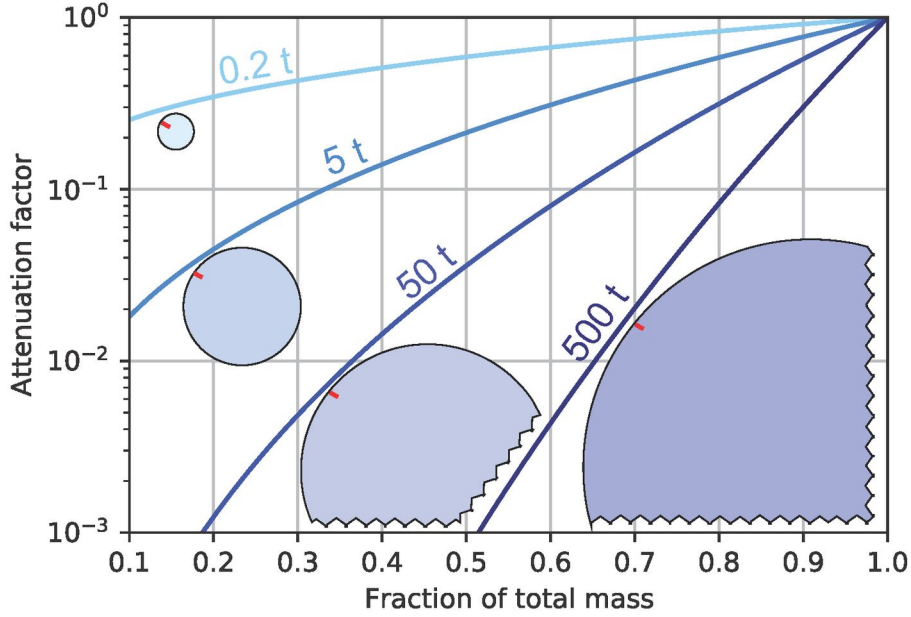
EXO-200 results

- EXO-200 was the first experiment with hundreds of kg of isotope to run
- Very good ~1% energy resolution in entire volume
- Excellent background that was successfully predicted before turning on the detector
- Full qualification of intrinsic, natural and external sources of background radiation
- Sensitivity increased linearly with exposure
- EXO-200 demonstrated power of LXe technology and our ability to use it
- Success of EXO-200 paves the way for 5-ton next generation experiment (nEXO) with projected half-life sensitivity ~10^{28} yr

LXe is a good option for a very large detector

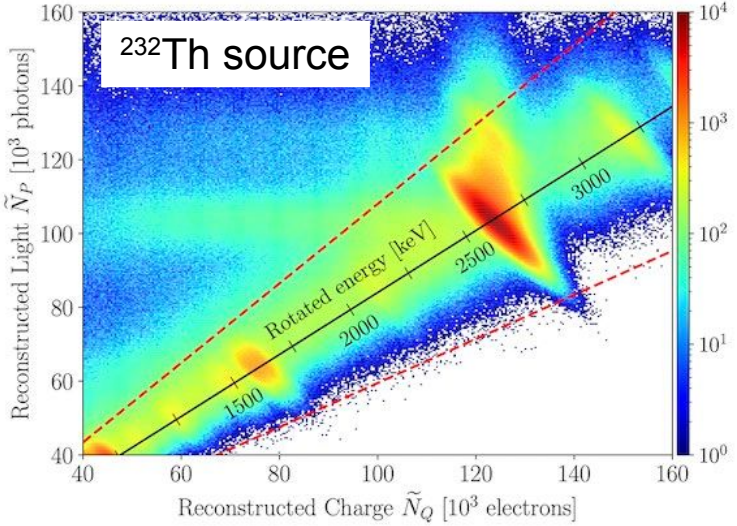
- Shielding of detectors for 2β is more complicated than for WIMP searches, because attenuation length of corresponding gammas is much bigger
- Monolithic/homogeneous construction is key due to benefits of self shielding when detector size becomes much bigger than attenuation length

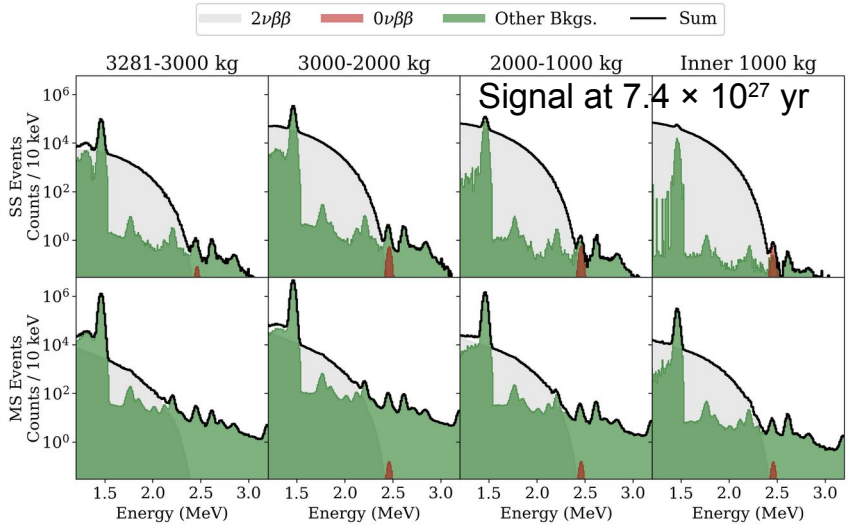




LXe is a good option for a very large detector

- The homogeneous detector with advanced topological reconstruction has a proven track record for γ background identification and rejection.
- The ratio of scintillation to ionization allows to quantify background due to radon contained in the LXe by tagging alphas.

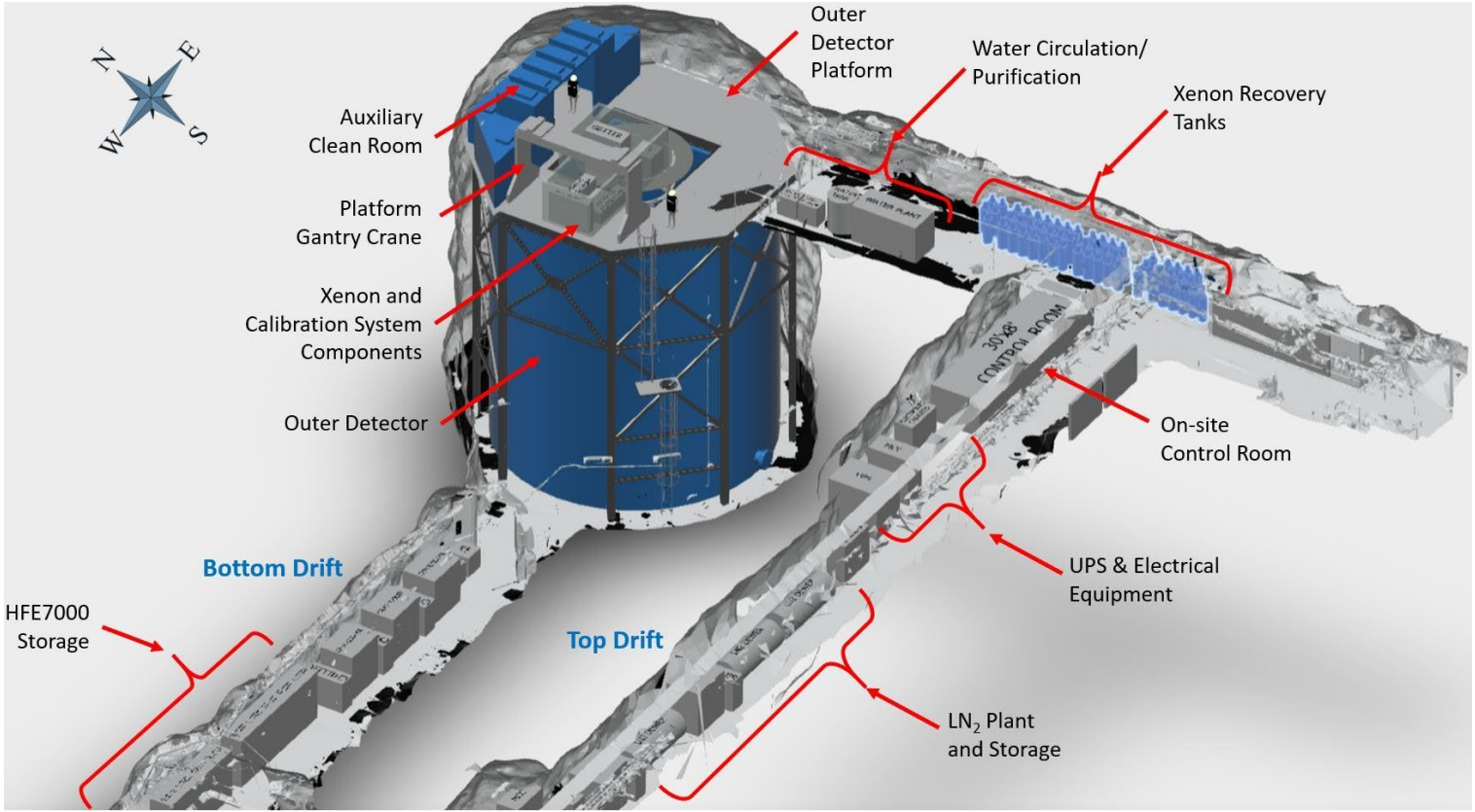




- Multi-parameter analysis also makes the measurement robust with currently unknown backgrounds.
- The energy resolution, still important, is good enough, once the scintillation and ionization are used in tandem. nEXO will have a resolution <1% at the Q-value.

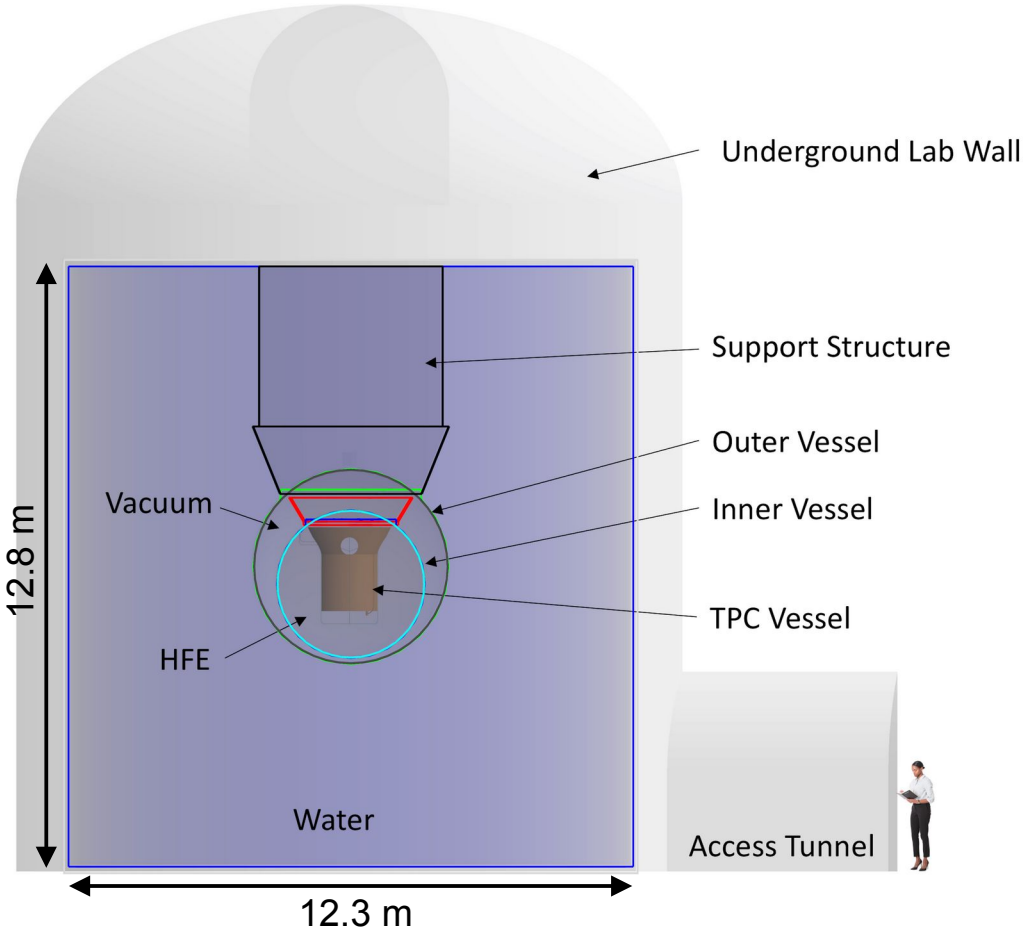
Experiment location

The SNOLAB Cryopit is the favourite location for nEXO and plenty of site engineering for us has been already carried out by SNOLAB



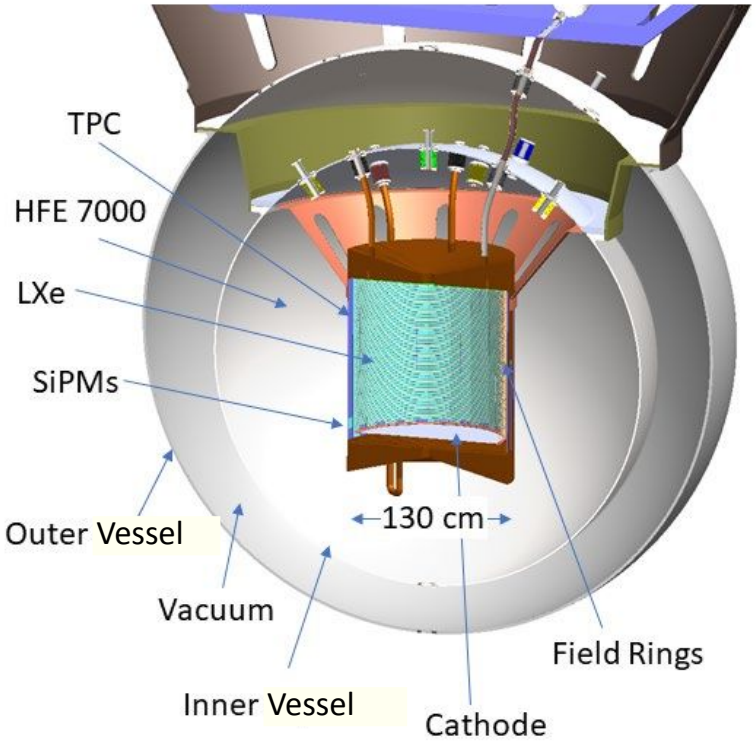
Mine shaft and Water tank

- Pure water passive shielding to suppress external gamma and neutrons
- Active veto water Cherenkov detector to tag cosmic muons
- Steel cylinder tank equipped with PMTs and reflective coating
- Contains required support structures to hold cryostat and interconnections
- Already funded by CFI



Detector overview

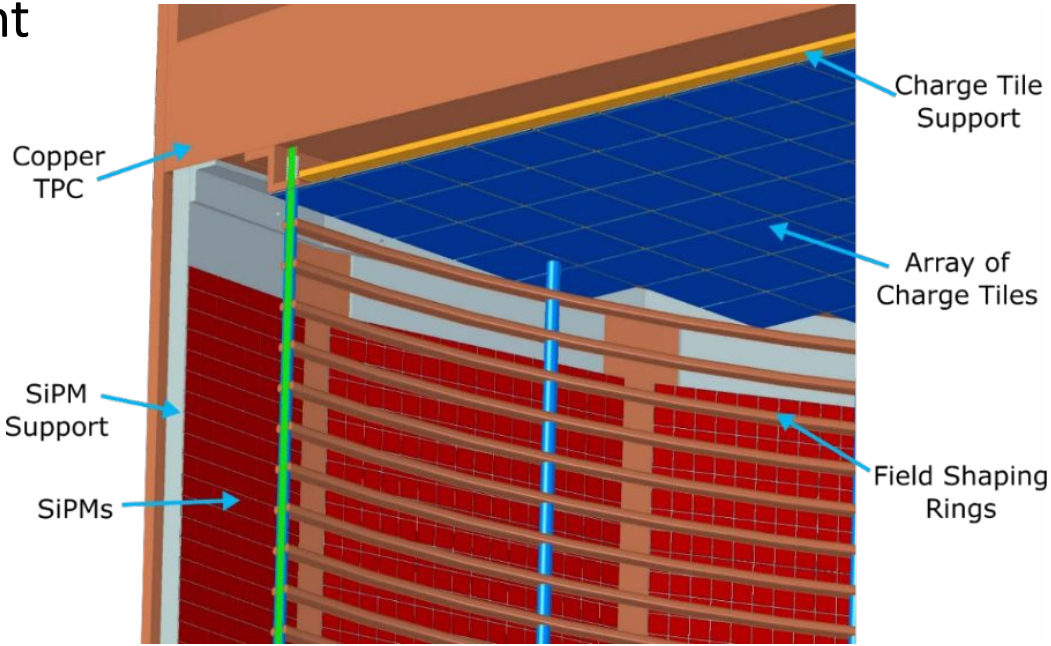
nEXO detector is an evolution from EXO-200, with specific R&D done over the last 10 years



	EXO-200:	*nEXO:*	Improvements:
Vessel and cryostat	Thin-walled commercial Cu w/HFE	*Thin-walled electroformed Cu w/HFE*	Lower background
High voltage	Max voltage: 25 kV (end-of-run)	*Operating voltage: 50 kV*	Full scale parts tested in LXe prior to installation to minimize risk
Cables	Cu clad polyimide (analog)	*Cu clad polyimide (digital)*	Same cable/feedthrough technology, R&D identified 10x lower bkg substrate and demonstrated digital signal transmission
e^- lifetime	3-5 ms	*5 ms (req.), 10 ms (goal)*	Minimal plastics (no PTFE reflector), lower surface to volume ratio, detailed materials screening program
Charge collection	Crossed wires	*Gridless modular tiles*	R&D performed to demonstrate charge collection with tiles in LXe, detailed simulation developed
Light collection	APDs + PTFE reflector	*SiPMs around TPC barrel*	SiPMs avoid readout noise, R&D demonstrated prototypes from two vendors
Energy resolution	1.2%	*1.2% (req.), 0.8% (goal)*	Improved resolution due to SiPMs (negligible readout noise in light channels)
Electronics	Conventional room temp.	*In LXe ASIC-based design*	Minimize readout noise for light and charge channels, nEXO prototypes demonstrated in R&D and follow from LAr TPC lineage
Background control	Measurement of all materials	*Measurement of all materials*	RBC program follows successful strategy demonstrated in EXO-200
Larger size	>2 atten. length at center	*>7 atten. length at center*	Exponential attenuation of external gammas and more fully contained Comptons

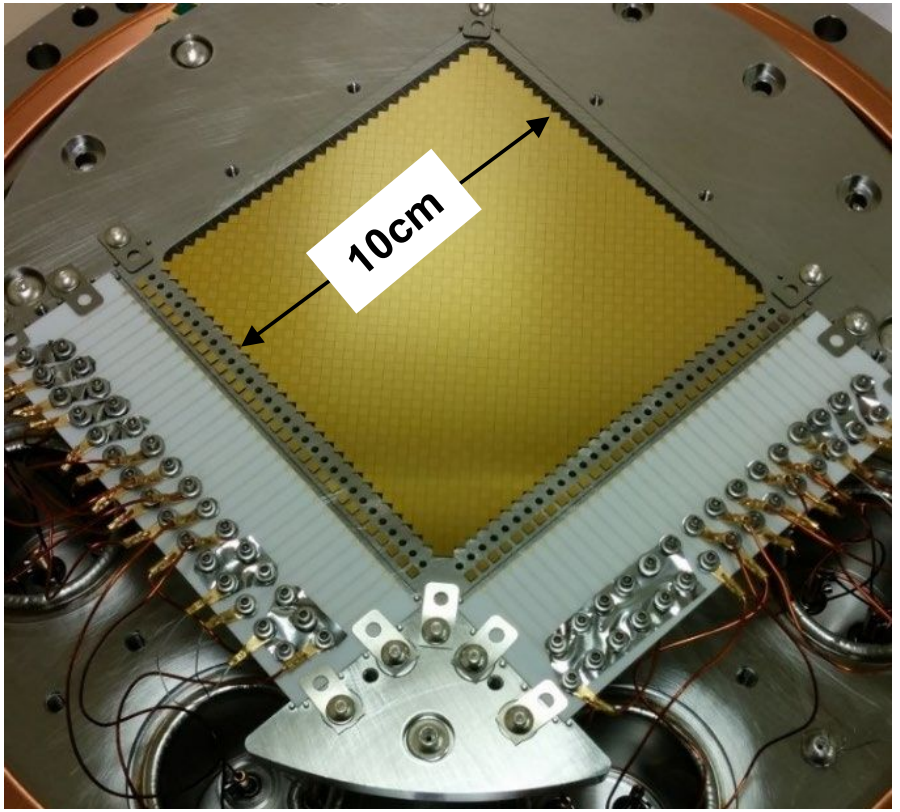
Detector internals

- Single drift TPC, anode on top, cathode at the bottom
- Right cylinder ~130 cm, thin TPC vessel of ultra pure electroformed copper
- ~4800 kg of liquid xenon with enrichment 90% of ^{136}Xe
- Refrigerated by surrounding coolant liquid
- Charge and light readout
- Drift field 400 V/cm
- Estimated energy resolution <1%
- Ultra clean for electronegative impurities to reach 10 ms electron lifetime



Charge readout

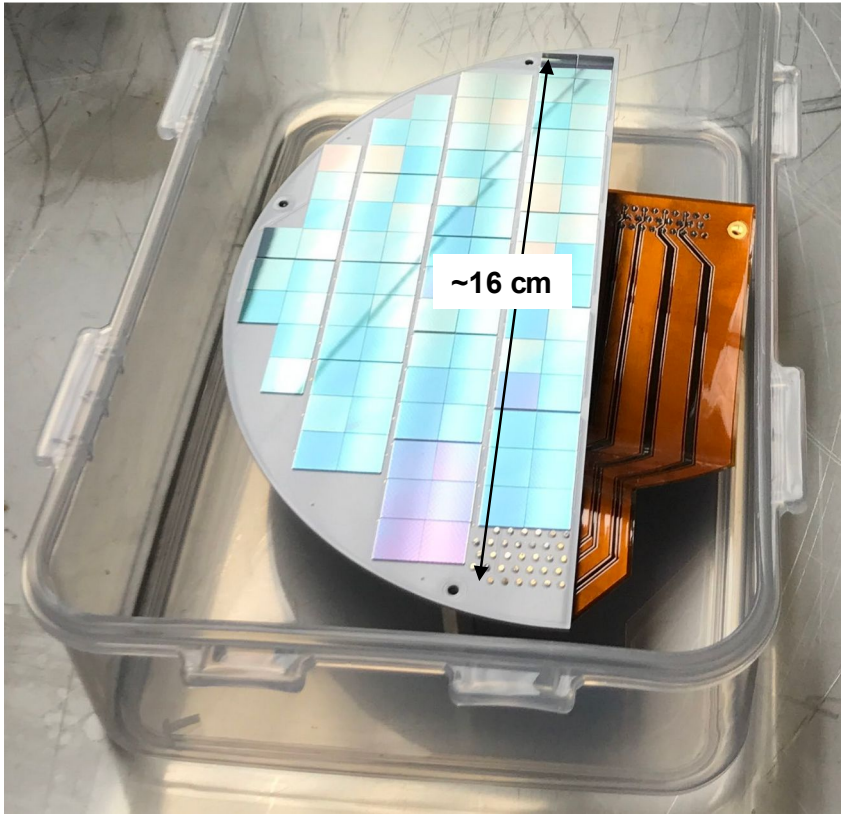
- Segmented anode at the top is made of solid tiles 96×96 mm
- Tile is low background fused silica with TSV (through-silicon-vias)
- Tile is tightly covered with 4.2×4.2 mm charge-sensitive metal pads
- Pads are connected into orthogonal strips like checker board with effective 6 mm pitch
- Low noise front end electronics in LXe right above the anode plane
- Working samples already in hand and tested



Ionization tile: JINST 13 (2018) P01006

Light readout

- Photosensors are on a ‘barrel’ behind field shaping rings
- Naturally VUV-sensitive 1 cm SiPMs with TSV to cover 4.6 m^2 area
- Silicon or fused silica interposer to hold and connect SiPMs and front-end electronics in LXe behind the barrel
- HPK and FBK 6 mm samples are tested
- Photon detection efficiency 20–25%
- Coherent avalanches 10–20%
- Dark noise 0.2–0.3 Hz/mm^2
- New 10 mm samples arrived

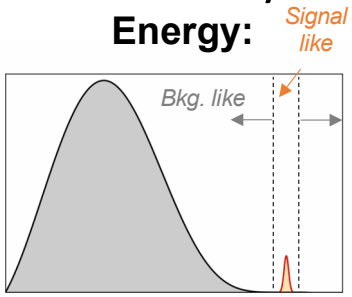


SiPM: Eur.Phys.J.C 82 (2022) 12, 1125

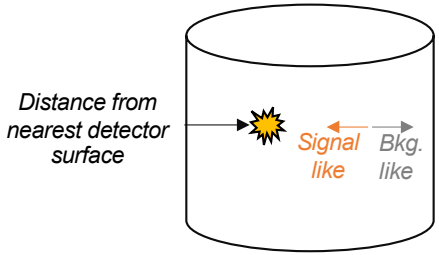
Signal and background

- nEXO measures multiple parameters for each event to robustly identify a 0νββ signal
- Multi-parameter analysis provides much more information than just energy

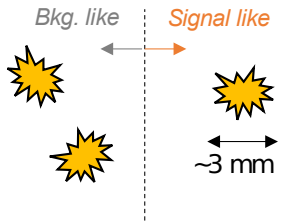
Energy:



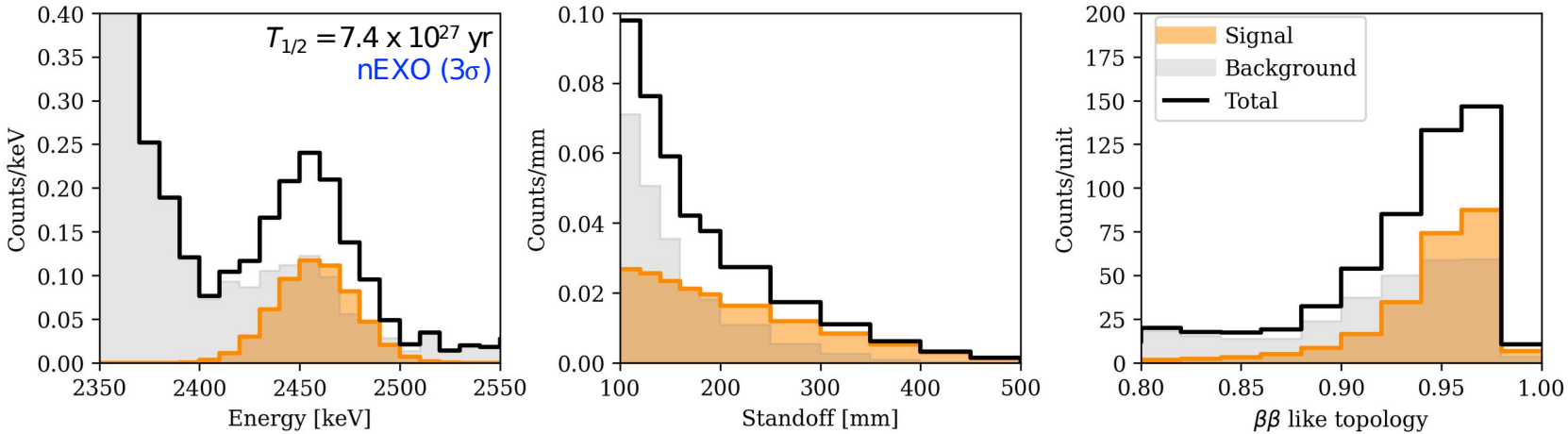
Standoff:



Topology:

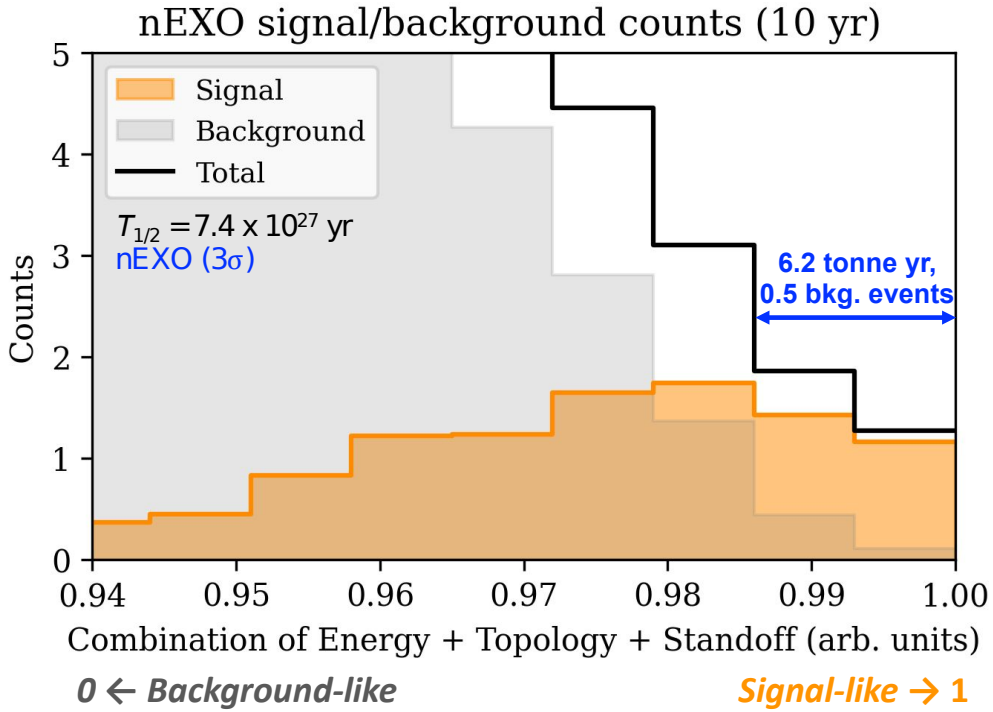


1D projections of simulated nEXO signal and backgrounds:



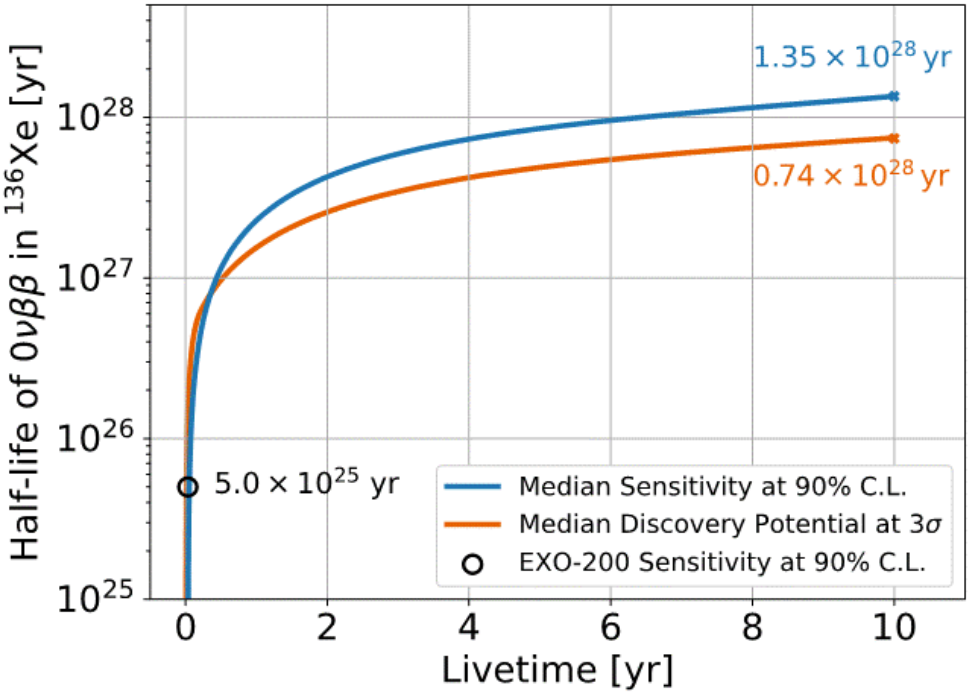
Signal and background

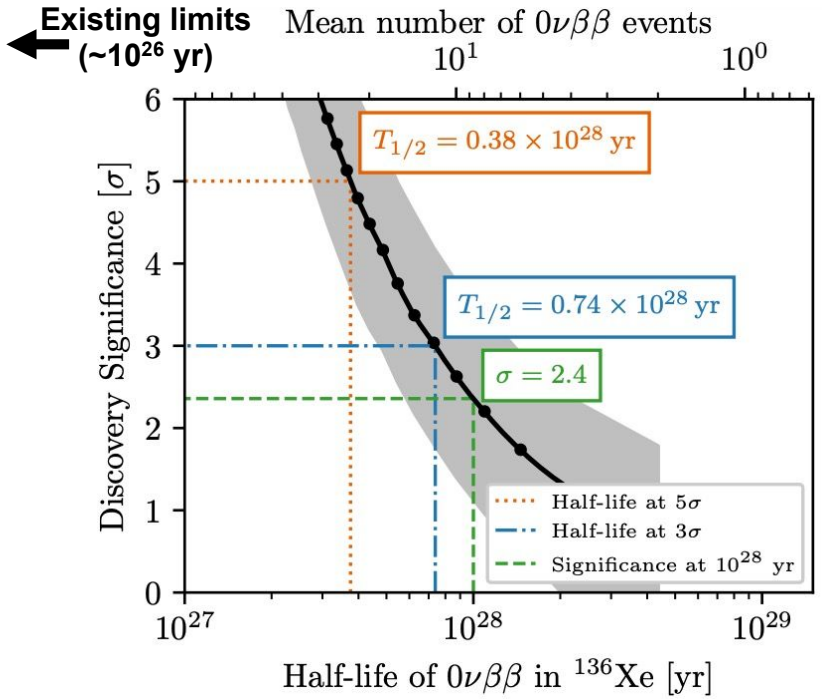
- Data from background dominant regions isn't just thrown away, it is used for simultaneous precise measurement of background *in situ*
- Likelihood fit allows optimal weighting between signal and background combining energy, topology, and standoff over full 3D parameter space
- For those who wants a 'crystal clear signal' we do have a background free spot with reasonable statistics
- Any unknown external background would leave hundreds of events at low standoff and will be noticed
- Any unknown internal background can be checked by filling with natural or depleted xenon



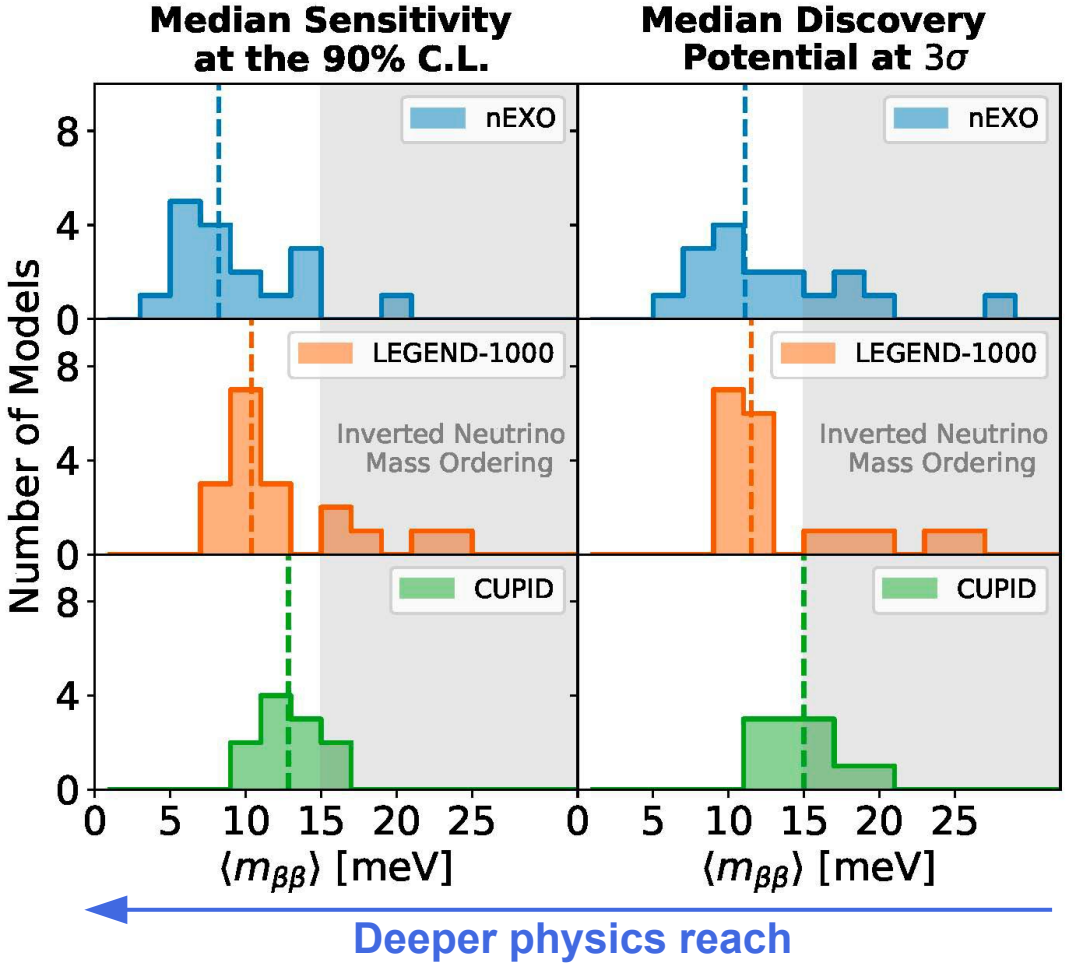
Sensitivity

- nEXO is a discovery experiment, which will search for 0νββ with half-life sensitivity approximately 2 orders of magnitude beyond existing experiments
- nEXO sensitivity reaches 10^{28} yr in 6.5 yr data taking





Comparison with other experiments



- nEXO 3σ discovery sensitivity for the median NME model considered is 11.1 meV, reaching beyond IO further into NO
- nEXO extends the $T_{1/2}$ reach into new physics by ~2 orders of magnitude, with substantial chance of making a discovery
- nEXO has a slightly better physics reach with respect to other experiments (but the NME uncertainty is large)

Sensitivity: J.Phys.G 49 (2022) 1, 015104

Conclusion

- nEXO is a project since 2022
- It is an important part of a long-range plan, since a healthy neutrinoless double-beta decay program requires several isotopes
- Liquid xenon is well developed & scalable technology
- Complex multiparameter analysis provides robustness to unknown backgrounds and background fluctuations
- nEXO extends the $T_{1/2}$ reach into new physics by ~2 orders of magnitude, with substantial chance of making a discovery
- Can probe effective Majorana neutrino masses down to 15 meV
- nEXO can make a discovery by itself, by repeating the experiment with non-enriched Xenon to confirm that a signal goes away
- nEXO is a world-wide effort, including, for the time being, 9 Countries, 33 institutions, 186 collaborators

Thank you