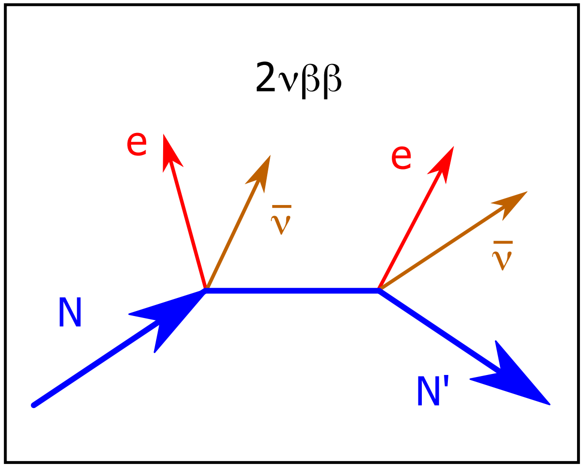
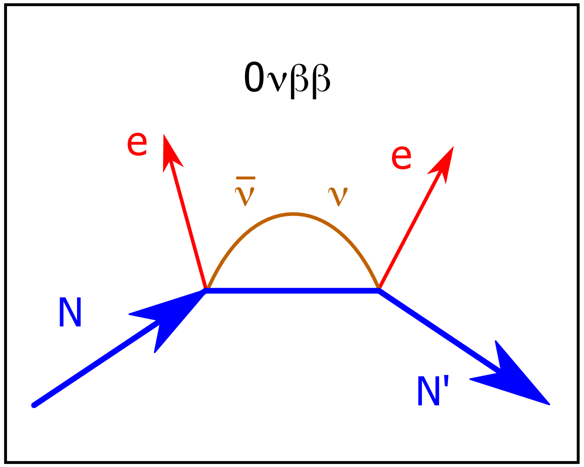
Recent results from EXO-200

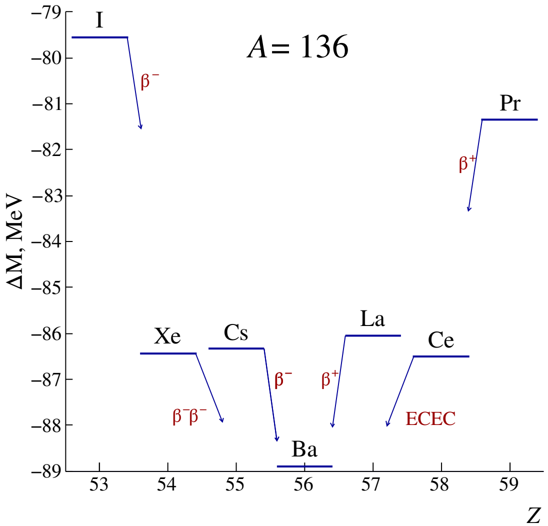
Belov V.A.
for EXO-200 coll.

The 5th international conference on particle physics and astrophysics

Double beta decay



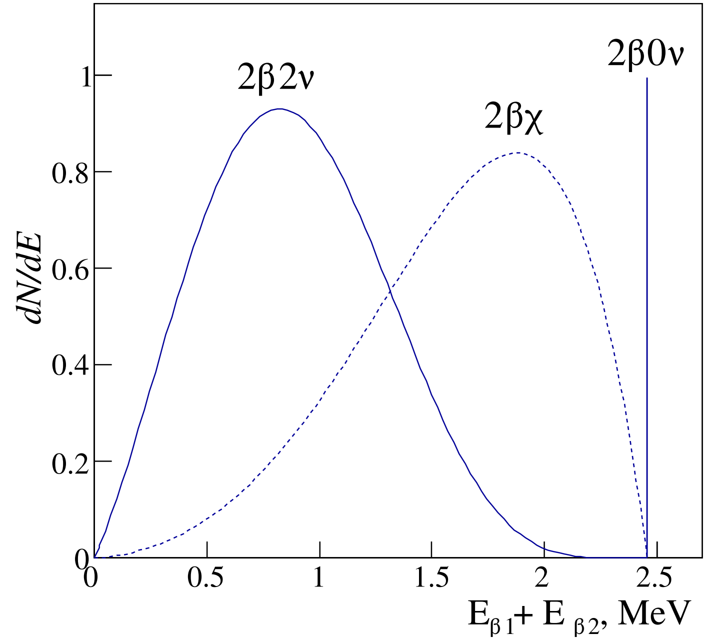




2ν mode
is a conventional 2nd order process in Standard Model discovered for many isotopes

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

Simulated double beta decay spectrum

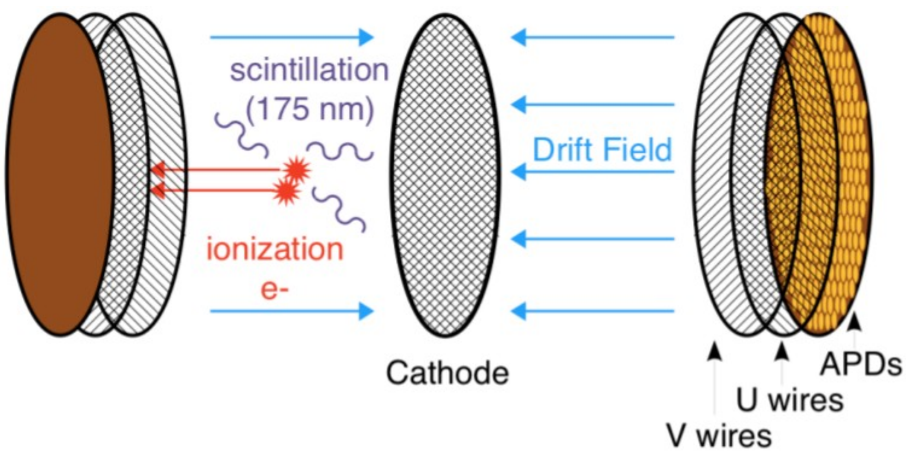


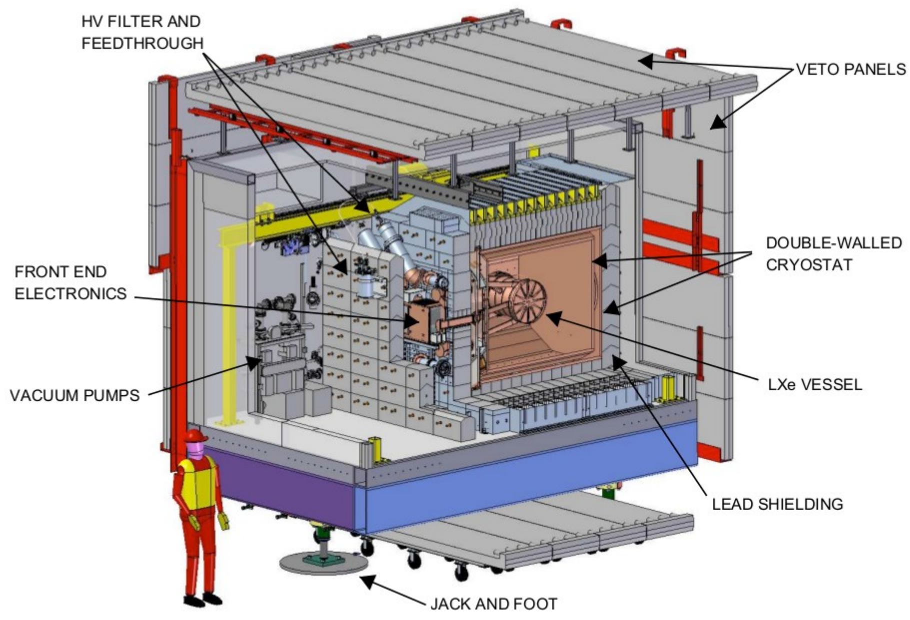
To reach high measurement sensitivity for 0ν mode one requires,

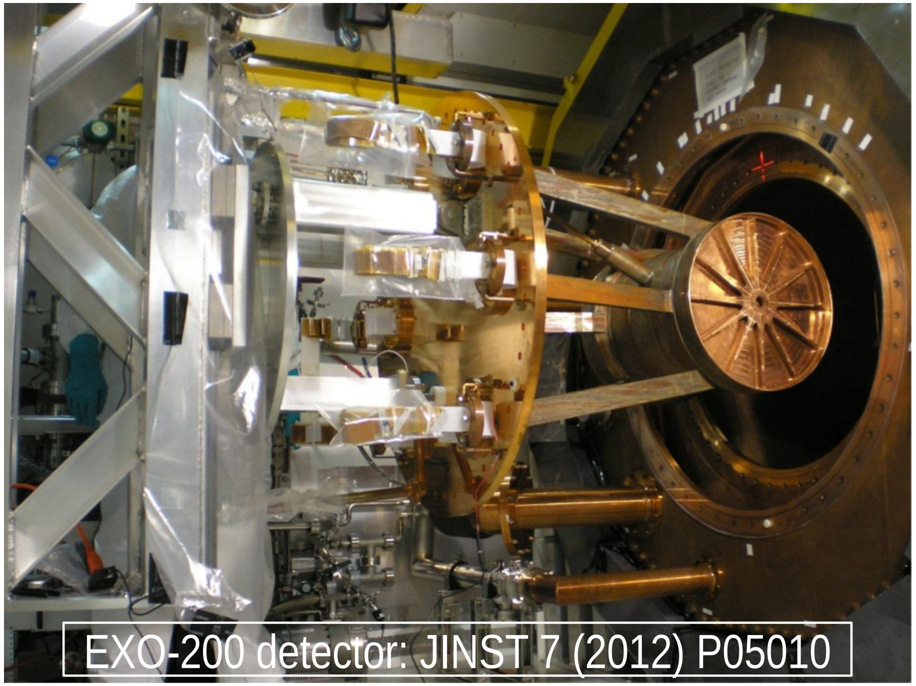
- High energy resolution
- Large Isotope mass
- Low background

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.

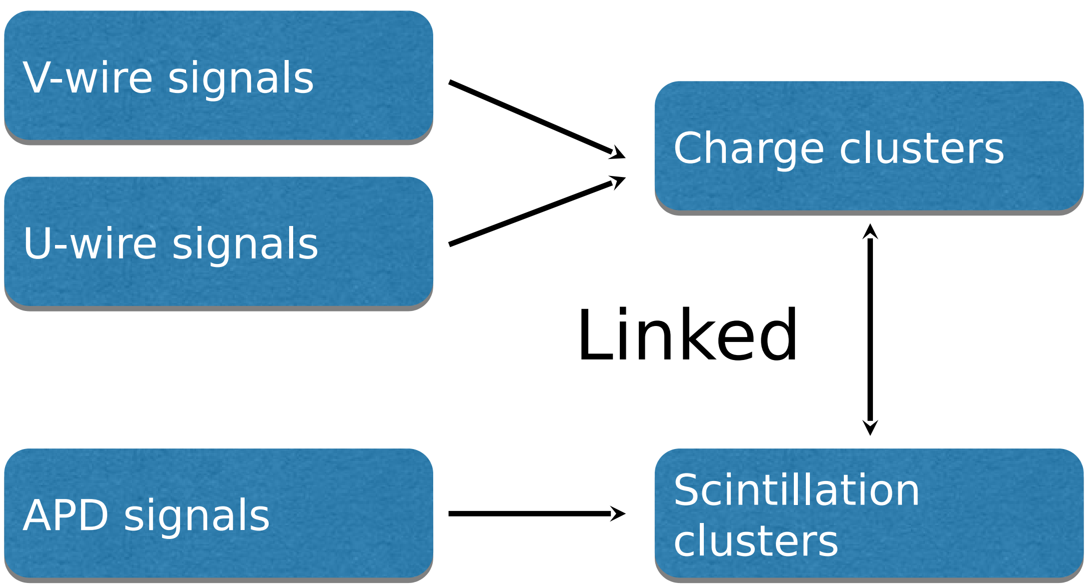


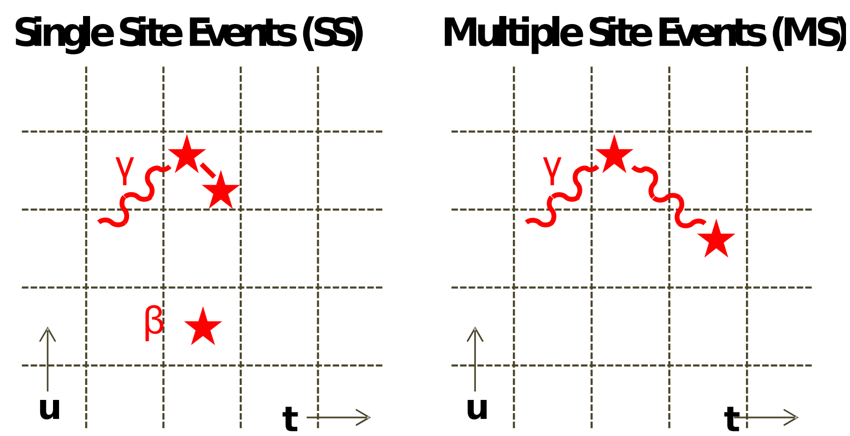




Event reconstruction

- Signal finding. Digital filters are used on waveforms from U,V wires and APDs
- Parameters of pulses (t, E) are estimated for both charge and light
- Pulses are combined into clusters producing position and energy
- Size of cluster is estimated from rise time and number of wires affected
- Position is used in form of Standof Distance (SD) that is distance from any cluster to the nearest wall





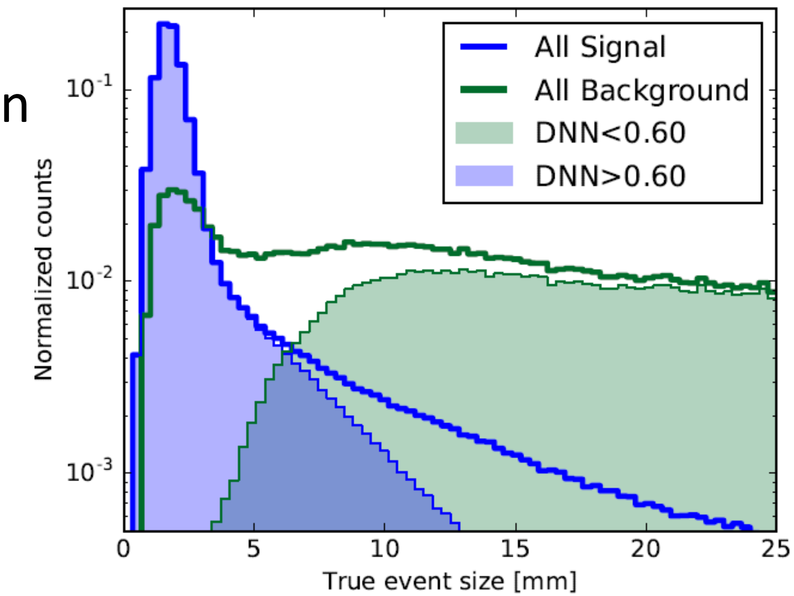
Efficiency to get into SS:	$2\beta0\nu$	~97%
	γ 2.5 МэВ	~30%

But we don’t throw MS events away!

We use them in the fit to help predict background

Analysis improvements

- De-noising adapted for Phase-II data
- Proper modeling of mixed collection/induction signals
- Relaxed 3D-cut lowers threshold for clusters
- Better cut on charge/light ratio
- Tighter event coincidence cut



Further enhance β/γ discrimination by use of additional information

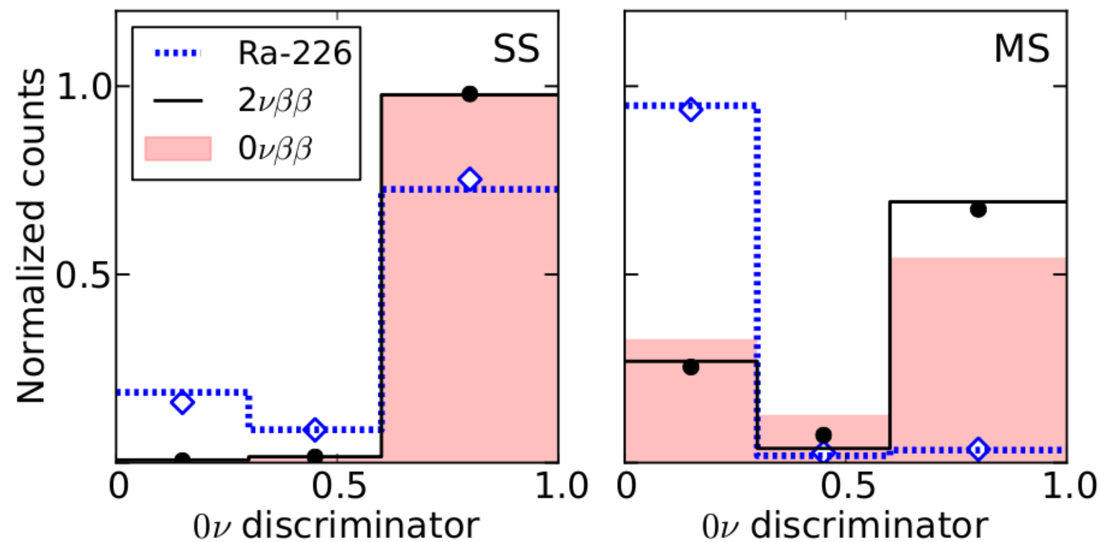
BDT → DNN using raw waveforms

Efficiency for 0νββ events

> 96%

Fitting 0νββ dataset

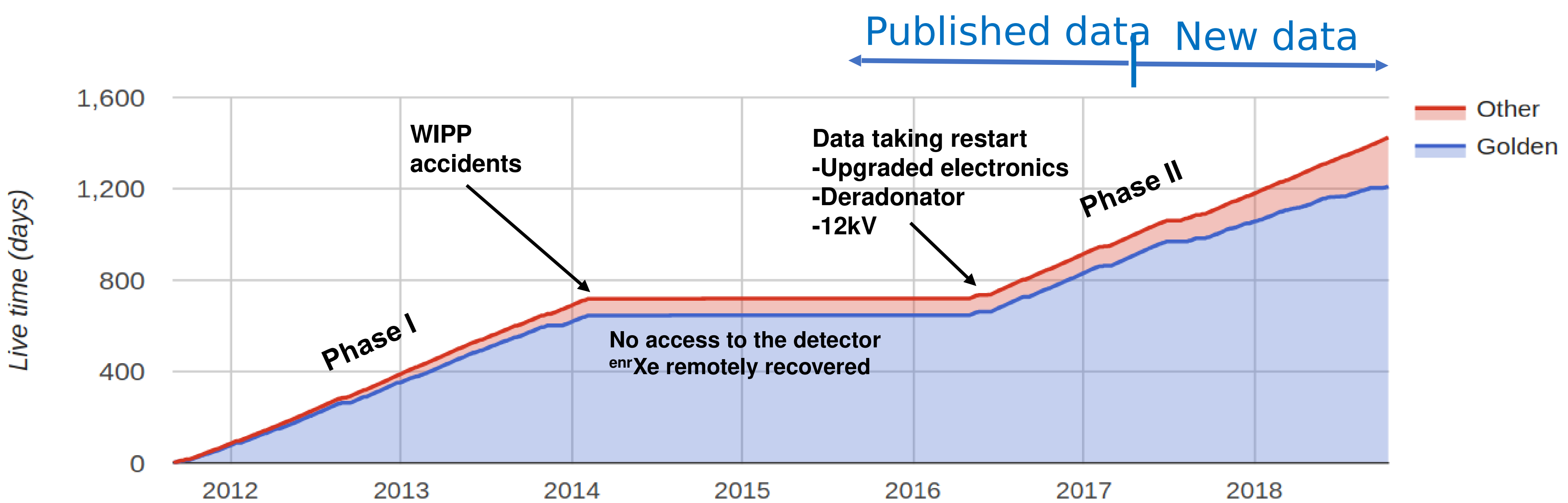
- Energy
- SS/MS classification
- 0ν discriminator (DNN)
- Standoff distance



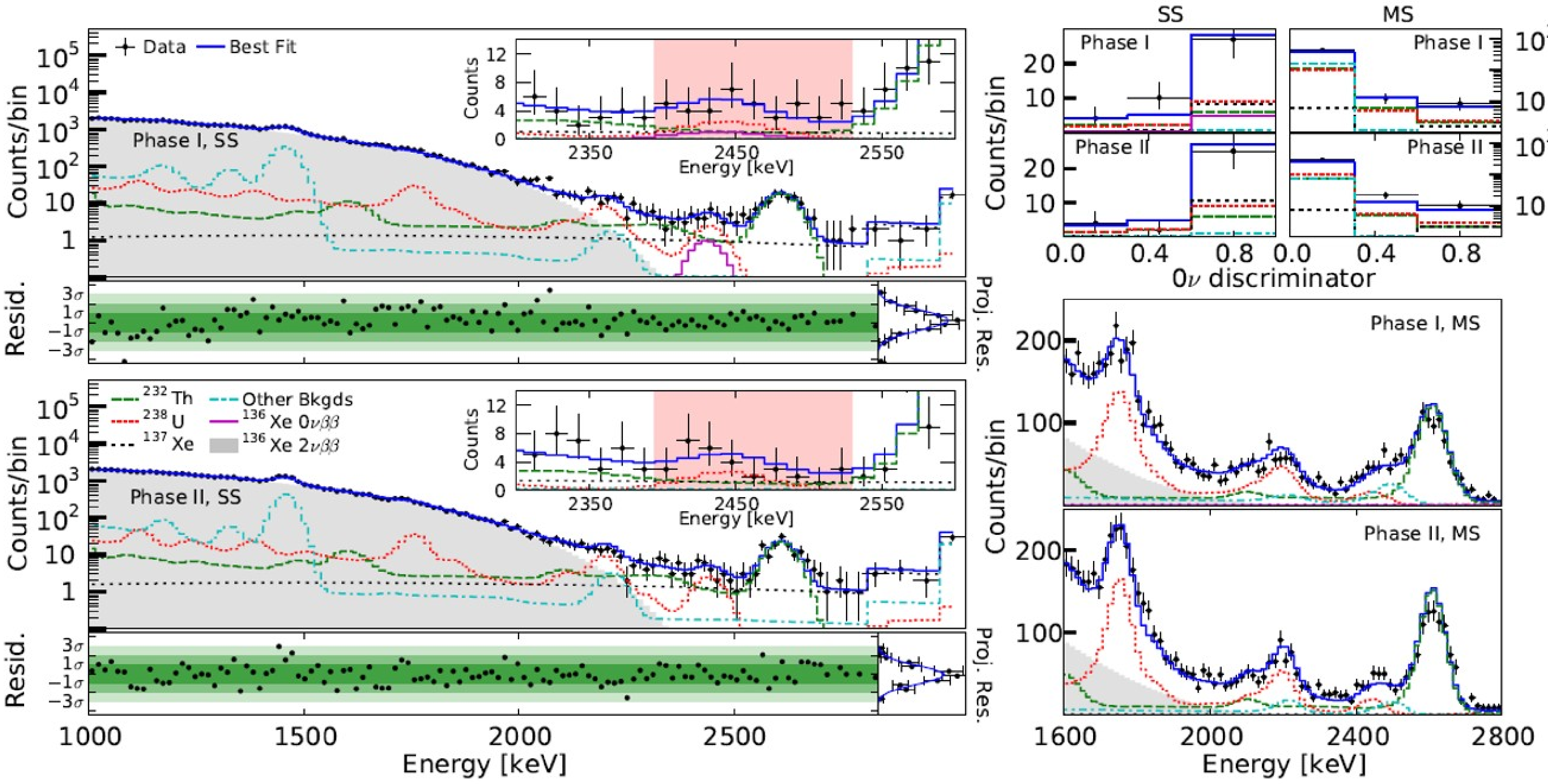
⇒ ~25% sensitivity improvement compared to energy + SS/MS alone

Data collection

- Operation concluded in Dec 2018, with 1181.3 days of live time
- Phase-I from Sep 2011 to Feb 2014
  - The most precise $2\nu\beta\beta$ measurement *Phys. Rev. C* ***89****, 015502 (2013)*
  - Stringent $0\nu\beta\beta$ searches *Nature* ***510****, 229 (2014)*
- Phase II begins on Jan 2016 with system upgrades
  - First result with upgraded detector *Phys. Rev. Lett. 120, 072701 (2018)*
- This talk, results with complete dataset!

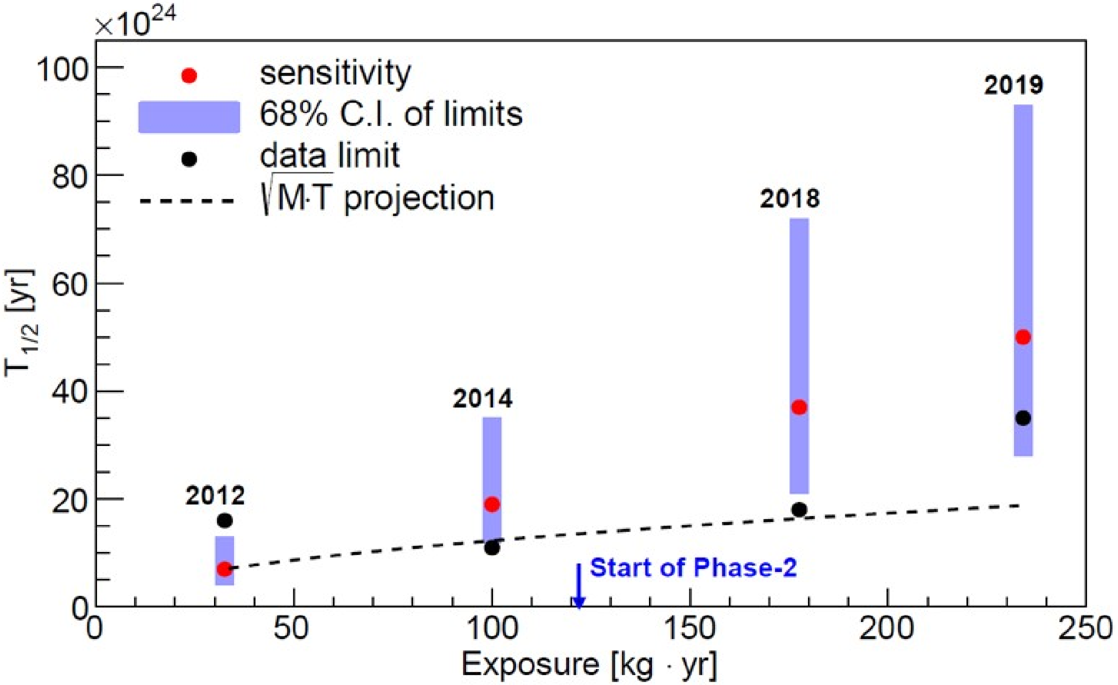


Full Phase-II fit



No statistically significant signal observed

$2\beta0\nu$ result



Contributions to BQ±2σ	Phase I, cts	Phase II, cts
^{232}Th	12.6	12.0
^{238}U	10.0	8.2
^{137}Xe	8.7	9.3
Total	**32.3±2.3**	**30.9±2.4**
Data	***39***	***26***

- Total exposure 234.1 kg·yr
- Background index in ROI $(1.7 \pm 0.2) \times 10^{-3}$ /(kg·yr·keV)
- **Sensitivity $5.0 \cdot 10^{25}$ yr (90% CL)**
- $T_{1/2}(0\nu\beta\beta) > 3.5 \cdot 10^{25}$ yr (90% CL)
- $\langle m_{\beta\beta} \rangle <$ 93–286 meV

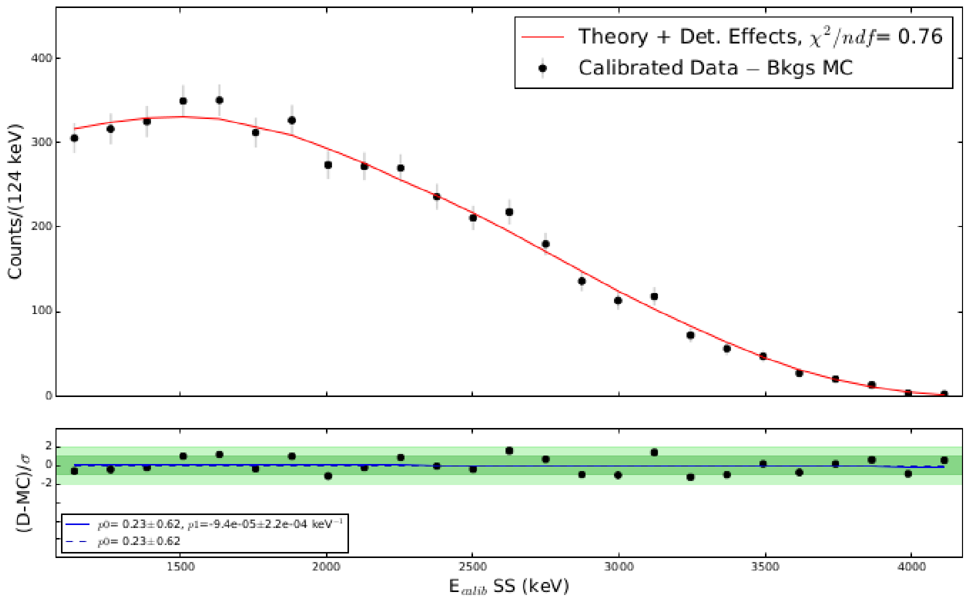
Phys.Rev.Lett. 109 (2012) 032505
Nature 510 (2014) 229-234
Phys.Rev.Lett. 120 (2018) 072701
Phys.Rev.Lett. 123 (2019) 161802

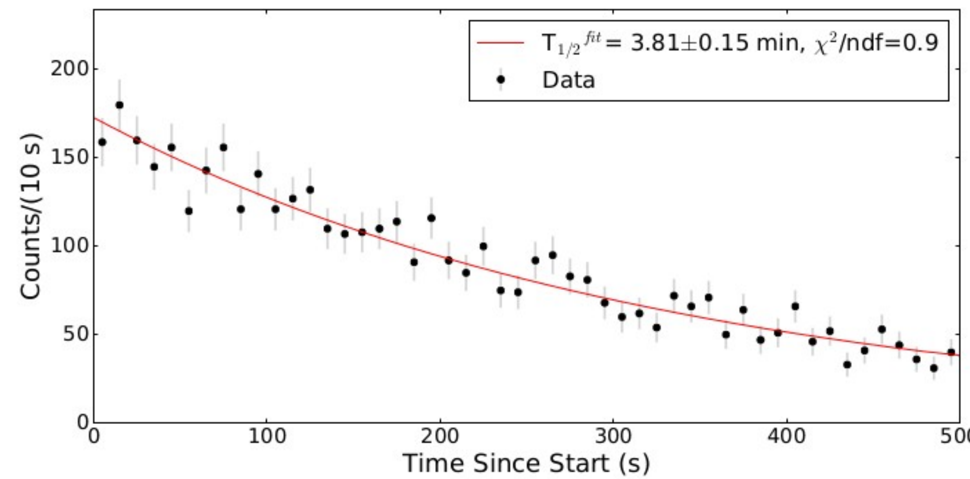
^{137}Xe beta-decay

- The core of the "reactor anomaly" is the discrepancy between measured and predicted neutrino energy spectra
- Many forbidden β-decays play an important role in combined reactor antineutrino spectrum
- The problem is also connected to uncertainty on value of the effective g_A and enhancement of NME by meson-exchange currents
- The ^{137}Xe decay is a perfect candidate:
  - good energy region
  - non-trivial shape
  - GS-GS transition is mostly independent of g_A and mesonic enhancement
  - GS-ES transition (30%) has mild dependence on g_A
- EXO-200 is a perfect detector to measure energy spectra of this decay

^{137}Xe $(7/2^-) \rightarrow$ ^{137}Cs $(7/2^+\ GS)$

- Good candidate to validate theoretical shape calculations
- Acquired data during EXO-200 calibration with AmBe source 18'Nov
- Selected data sample contains >99% ^{137}Xe
- Observed half-life is 3.81±0.15 min (ref. 3.818±0.013)
- Experimental shape matches simulated shape
- Energy calibration is constrained to sub-percent level
- The residuals show no statistically significant energy dependence

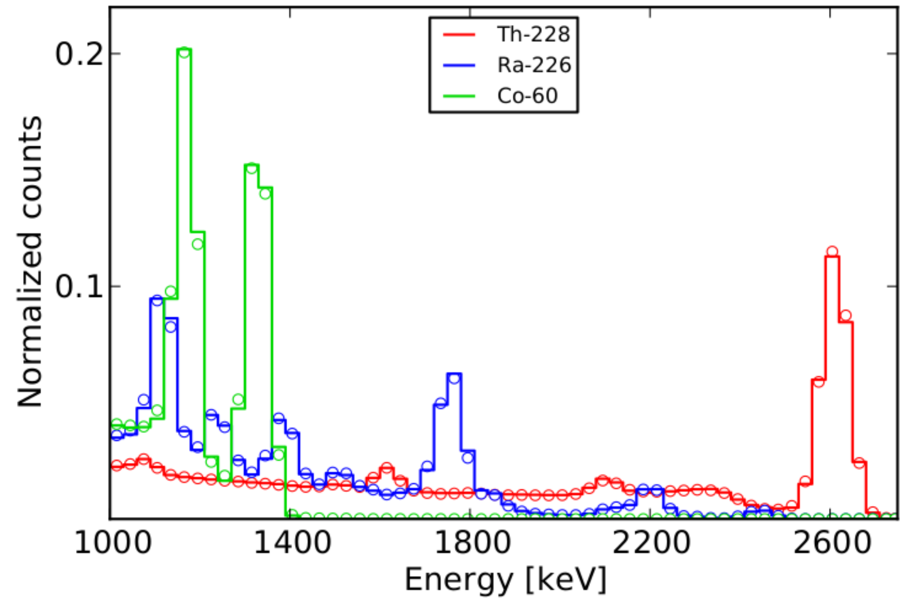


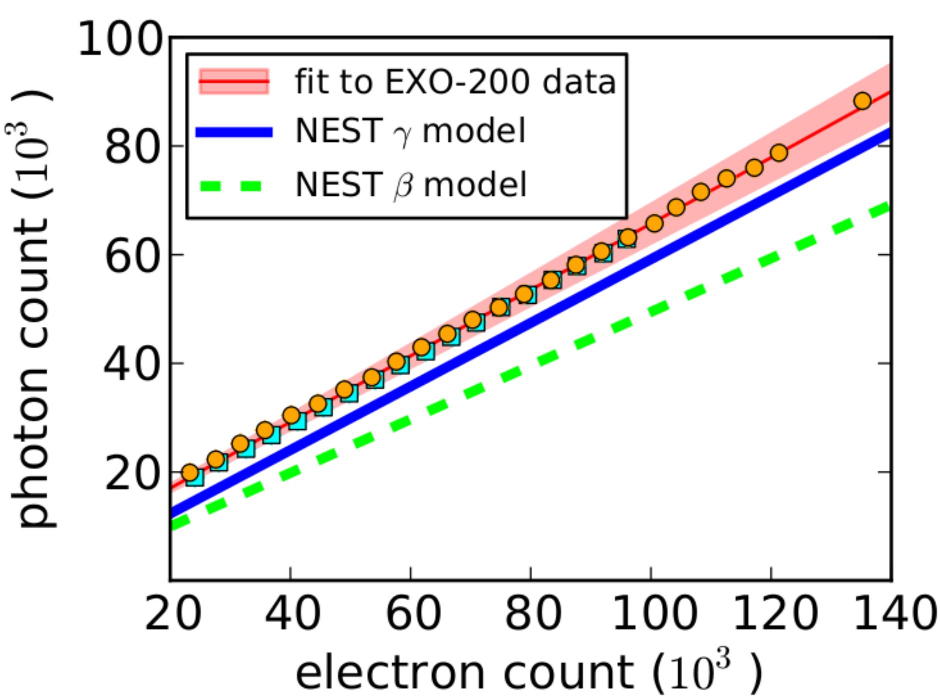


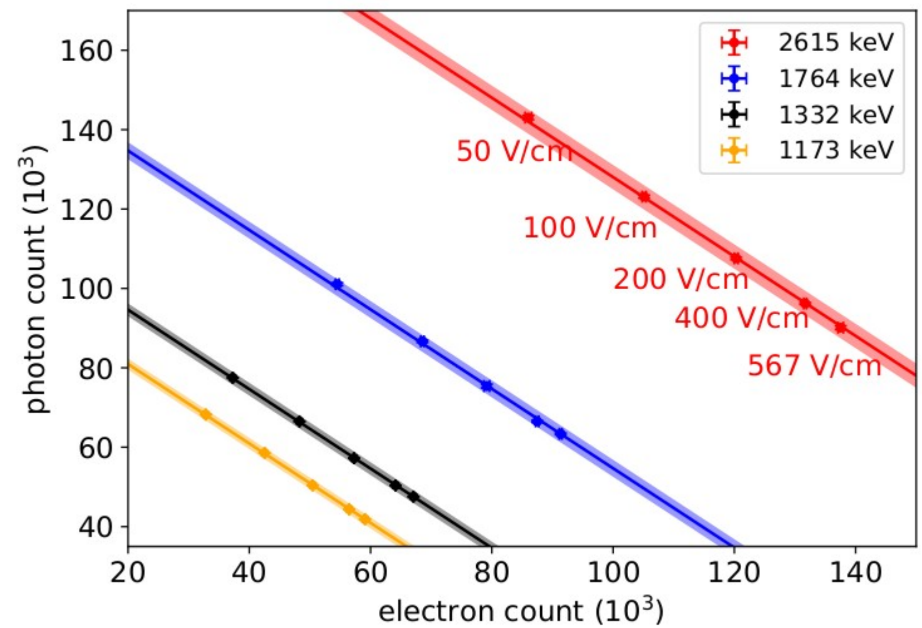
Phys.Rev.Lett. 124 (2020) 232502

Ionization and scintillation yield

- Absolute yield measurement at MeV-scale
- MC describes energy spectra very well
- Using ^{228}Th, ^{226}Ra and ^{60}Co sources
- Found W = 11.5 ± 0.5(syst.) ± 0.1(stat.) eV
- Contradicts with NEST (W = 13.3 eV), but within range of other measurements
-







Phys.Rev. C 101 (2020) 065501

Conclusion

- EXO-200 was the first experiment with hundreds of kg of isotope to run
- Operation was finished, full dataset is analyzed
- No sign of 2β0ν signal observed in EXO-200 data
- $\langle m_{\beta\beta} \rangle <$ 93–286 meV
- While main search is complete more physics searches are underway
- Precise measurement of ^{137}Xe beta-spectra shape is ongoing, theoretical calculations are compatible
- Absolute charge and light yields are measured for liquid xenon in ~MeV region, noticeable discrepancy from NEST model observed
- Stay tuned for other results
- 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

The EXO-200 Collaboration

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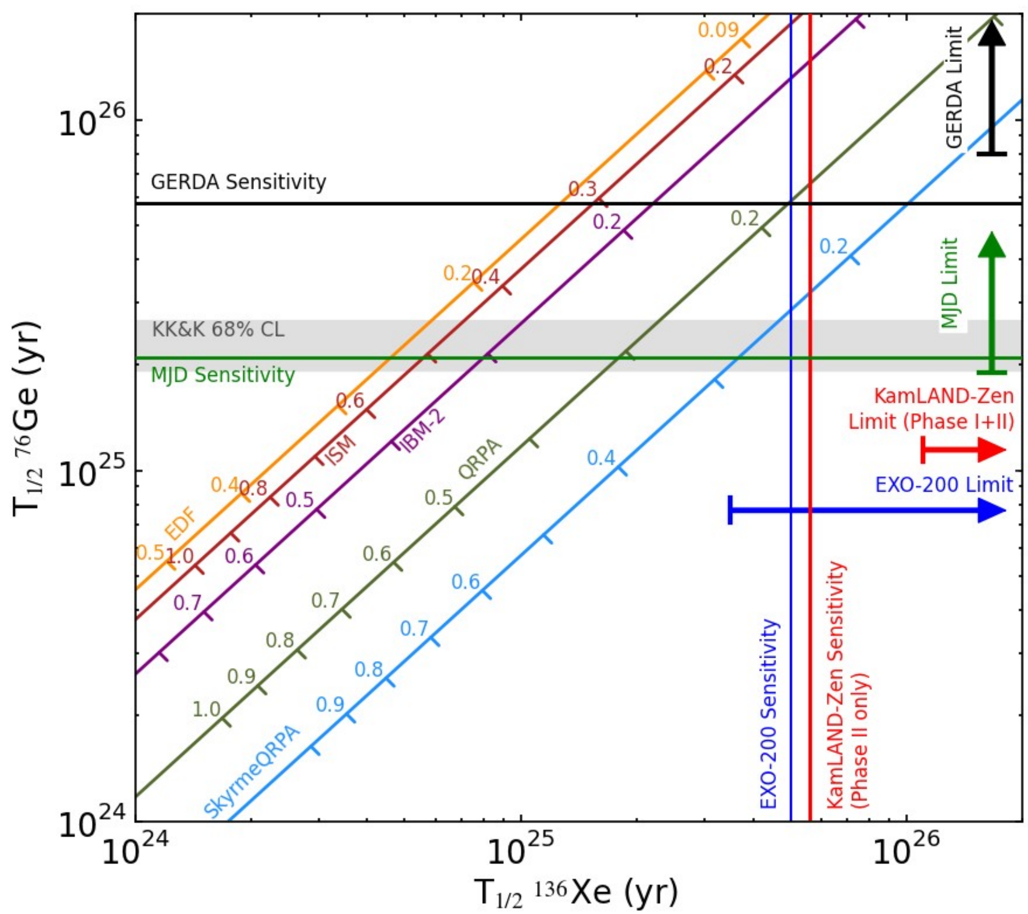
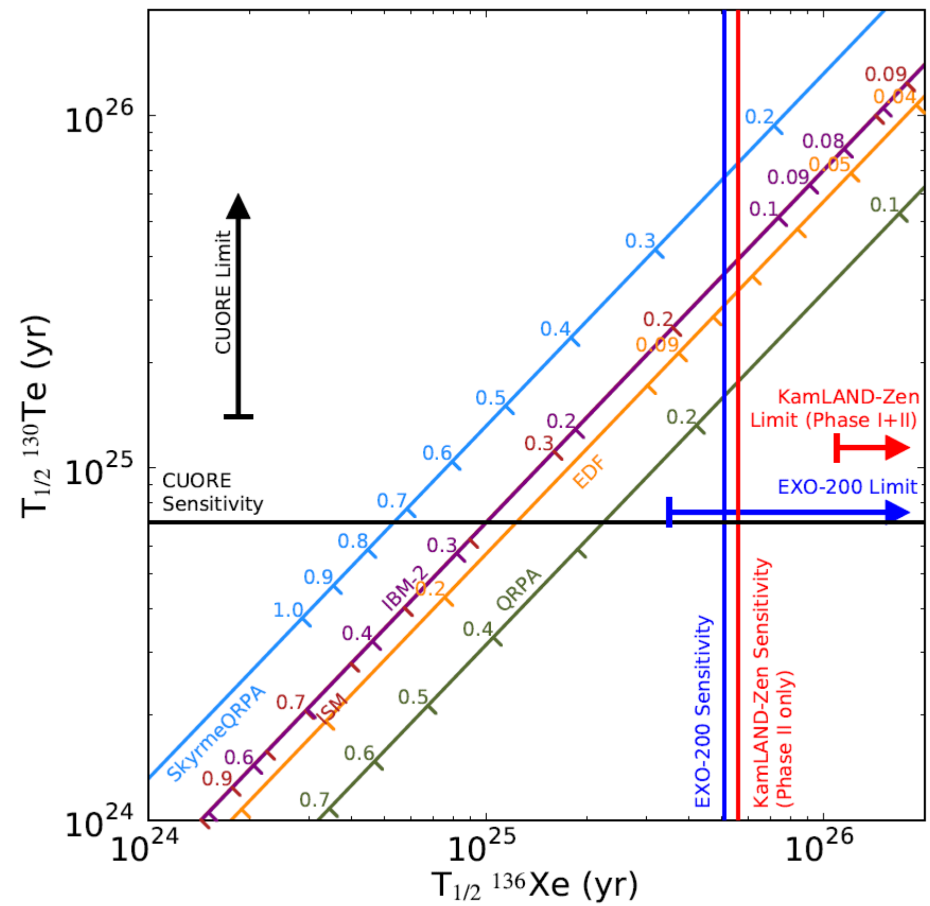
Yale University, New Haven CT, USA — A Jamil, Z Li, D Moore, Q Xia

Thank you

Comparison

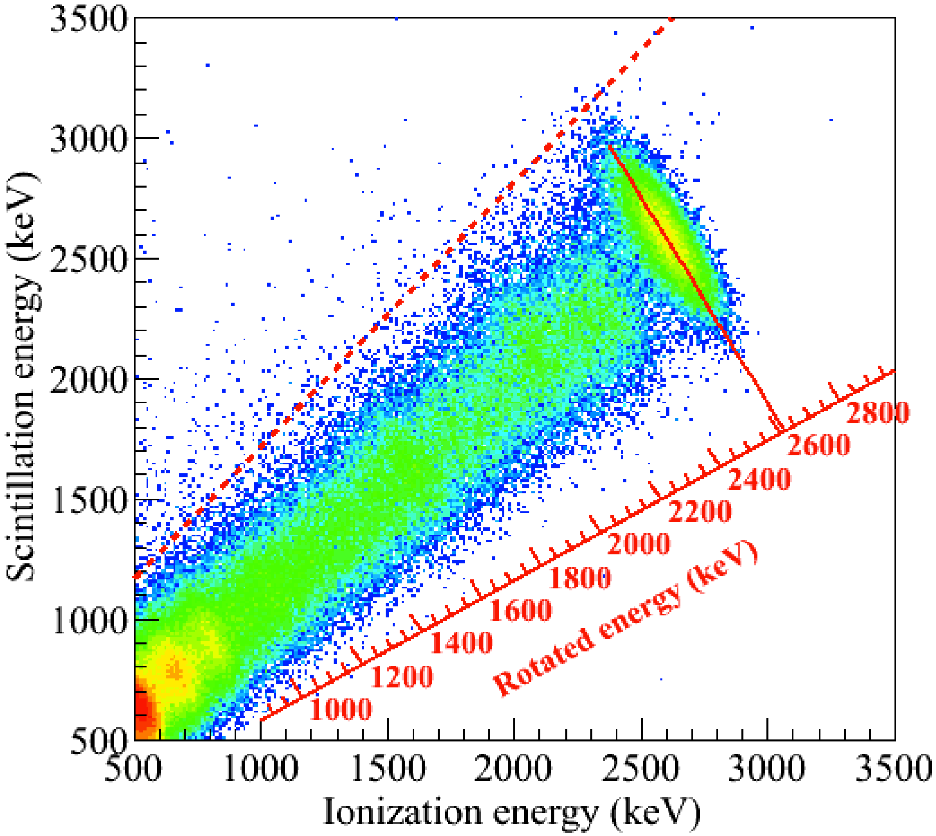




EXO-200: Phys.Rev.Lett. 123 (2019) 161802
GERDA: *PRL 120 (2018) 132503*
KamLAND-Zen: *PRL 117 (2016) 082503*
KK&K Claim: *Mod. Phys. Lett., A21 (2006) 1547*

EXO-200: *Phys.Rev.Lett. 123 (2019) 161802*
CUORE: *PRL 120 (2018) 132501*
Sensitivity in PRL 115 (2015) 102502

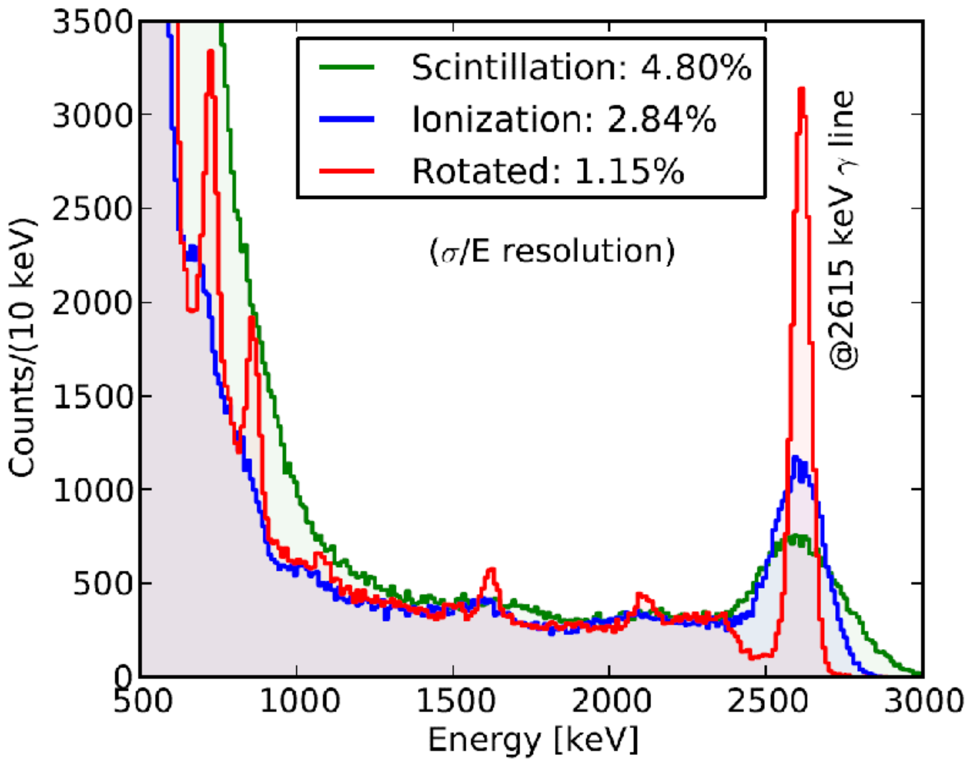
Combining ionization and scintillation



Properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)

E. Conti et al. Phys. Rev. B68 (2003) 054201

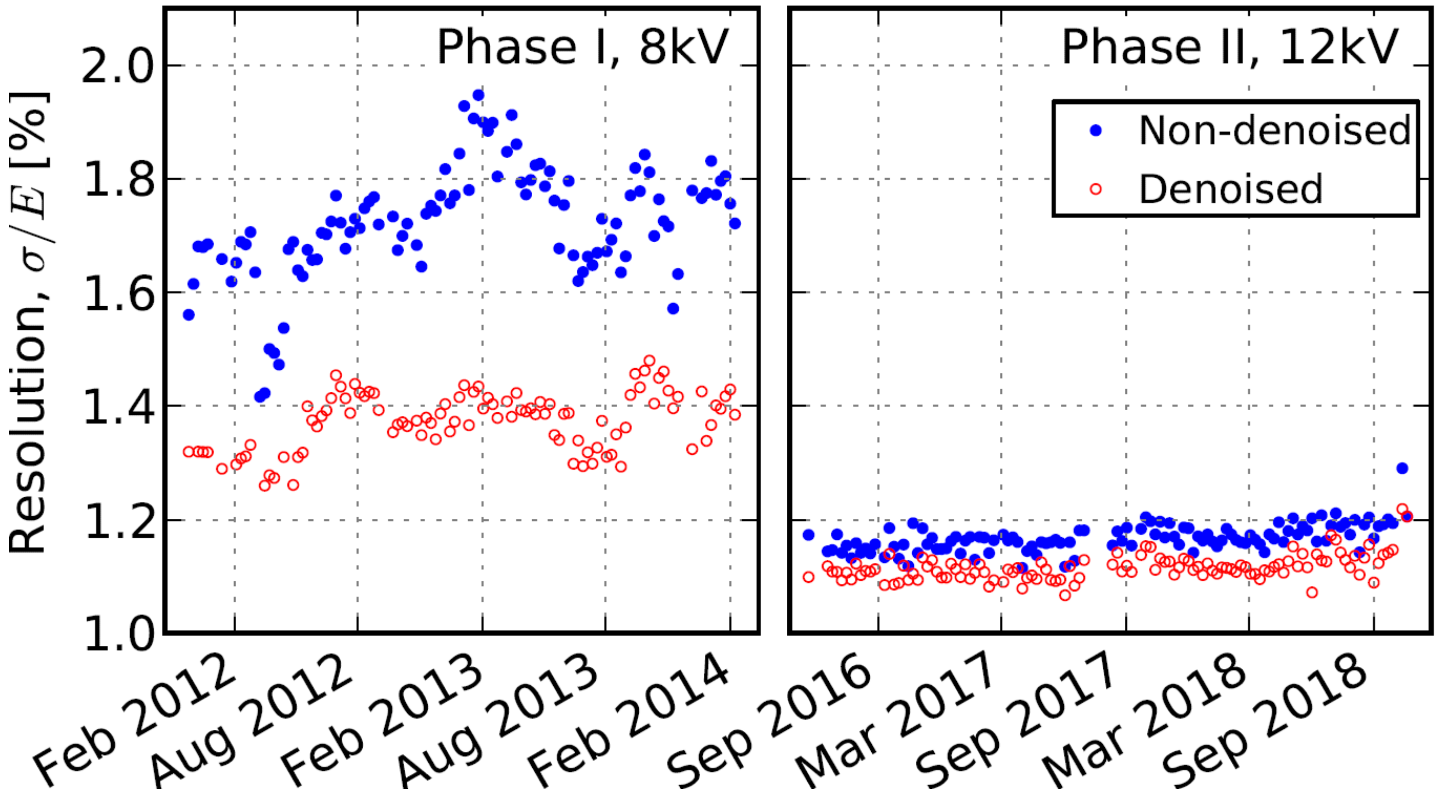
Mixing angle is chosen to optimize energy resolution at 2615 keV line.



EXO-200 has achieved
1.35% (Phase-I) and 1.15% (Phase-II)
energy resolution at the Q value.
nEXO will reach resolution < 1%,
sufficient to suppress background
from 2νββ.

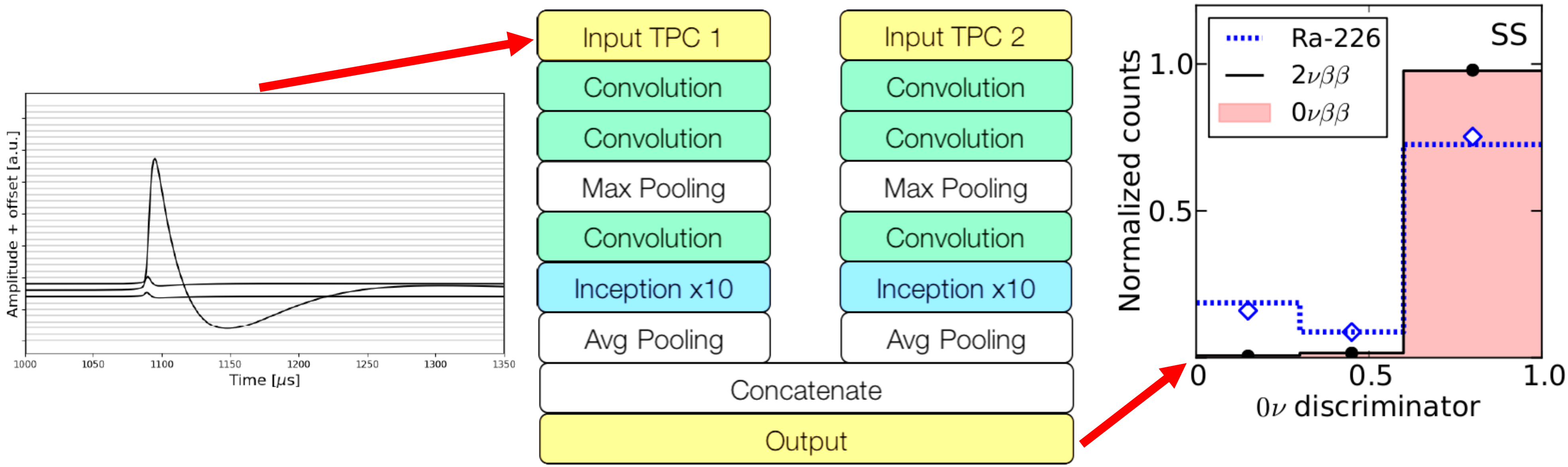
Energy resolution

- Energy resolution (σ/E) at $Q_{\beta\beta}$ value
  Phase I: 1.35±0.09% Phase II: 1.15±0.02%
- Phase II hardware Improvements
  - Cathode HV increased from -8kV to -12kV
  - Front end electronics upgraded to remove excess correlated noise on APDs
- Analysis Improvements
  - Denoising algorithm to optimally estimate light energy now applied to Phase II
  - Improved modeling of mixed collection/induction signals



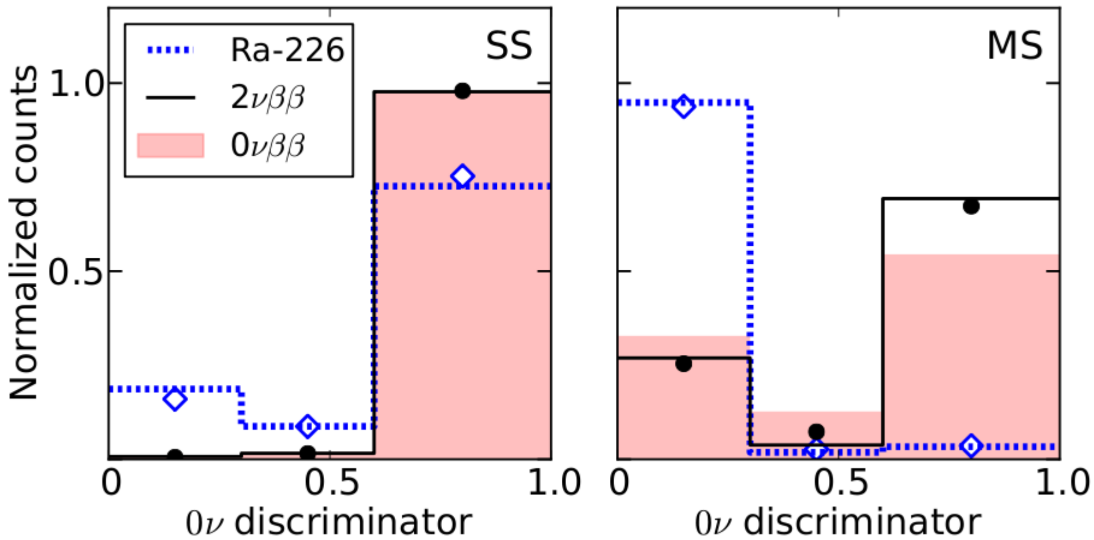
Neural networks with EXO-200

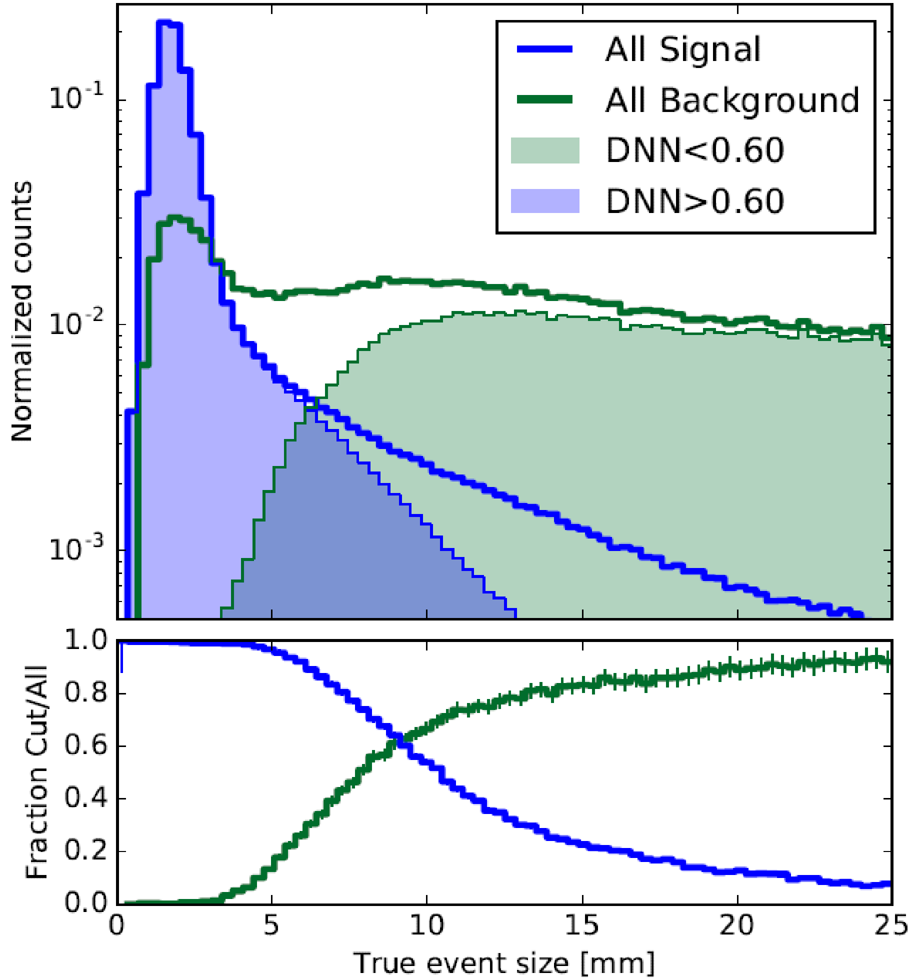
- Improved Energy Reconstruction in EXO-200 with Deep Neural Networks (DNN)
  - *S. Delaquis et al., JINST 13 (2018) no.08, P08023*
- Use lower level information such as images of U-Wire Signals
- Build DNN based 0νββ discriminator
  - Output “Signal-likeness”



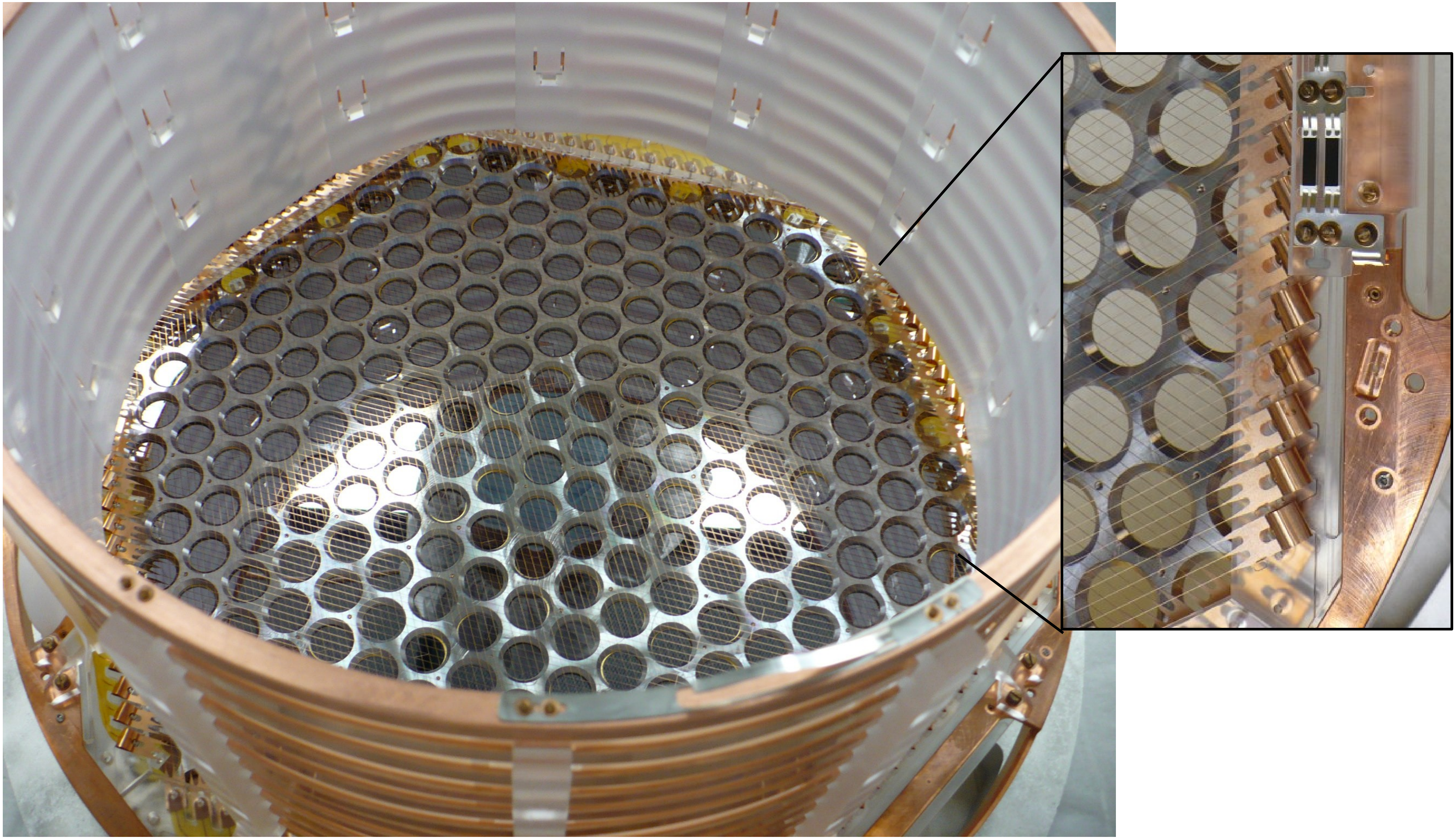
DNN discriminator for 2β0ν

- Signal-likeness correlates with size
- Validated with Data/Simulation agreement
  - γ Calibration Sources (Background-Like)
  - 2νββ data (Signal-Like)

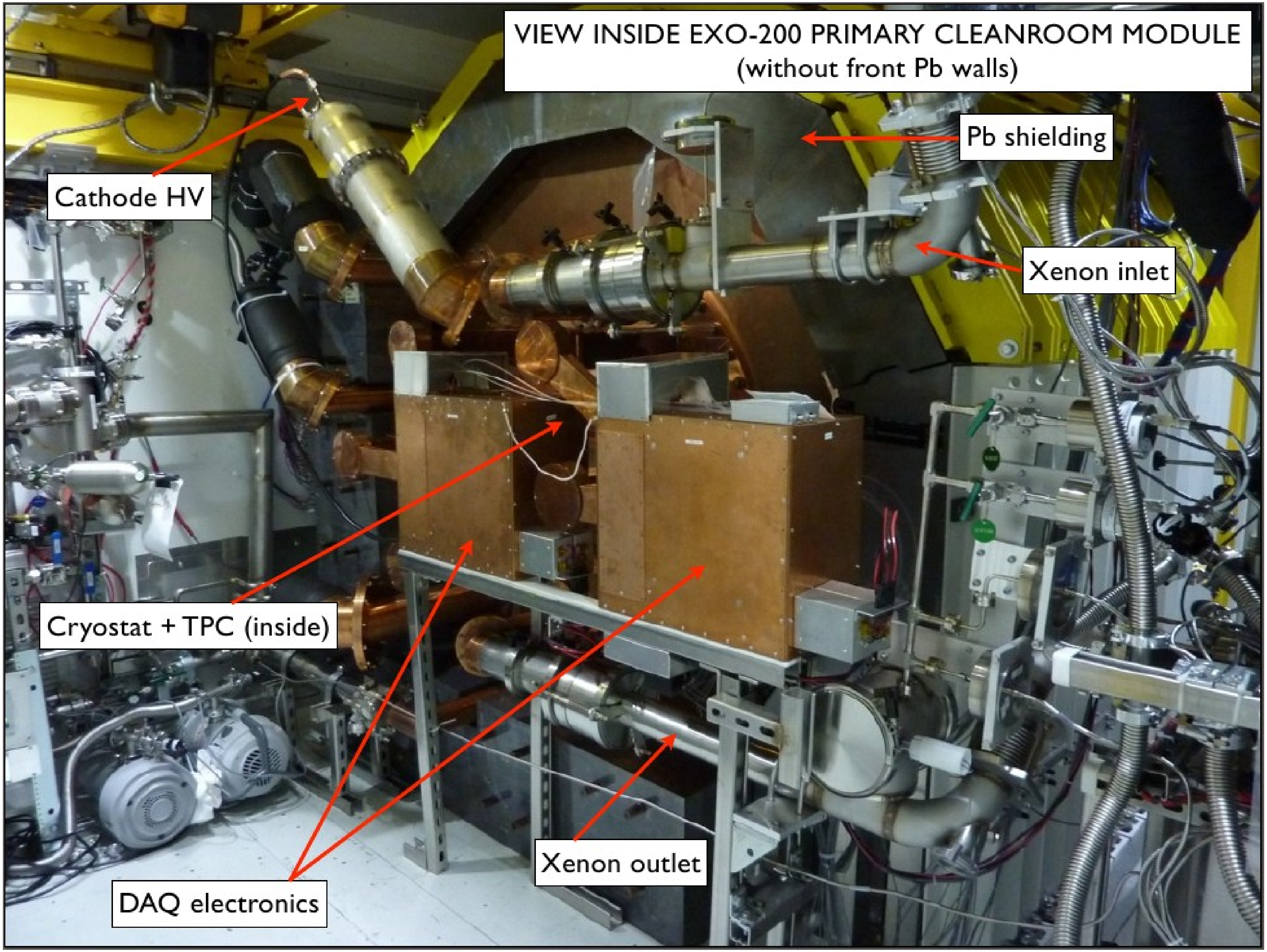




EXO-200 inside



EXO-200 overview

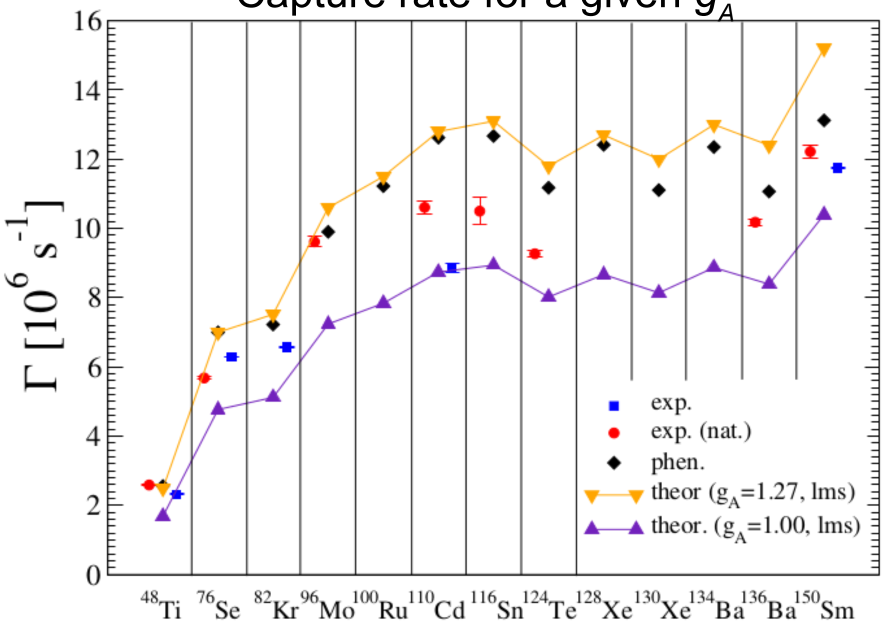


Muon capture rates

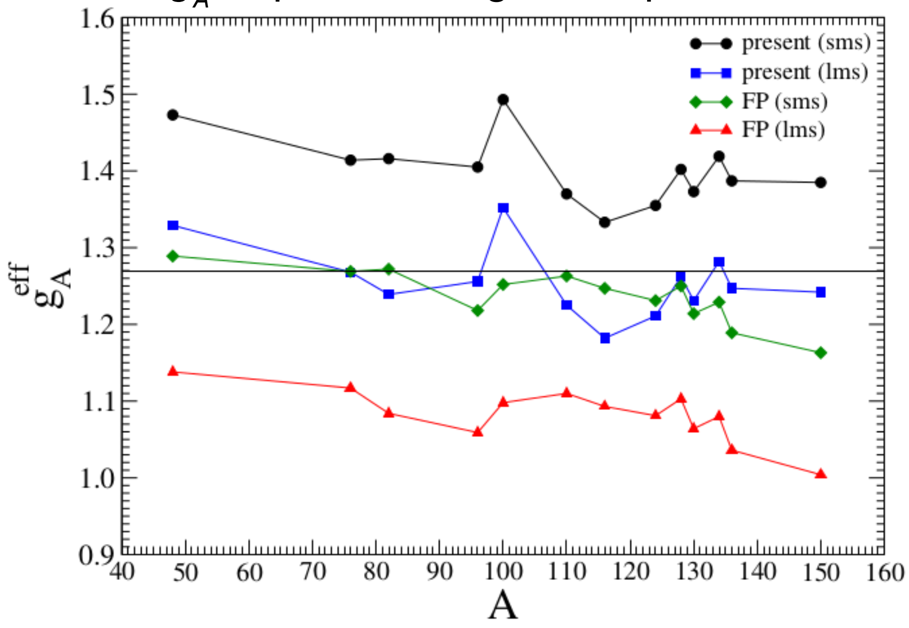
- QRPA is used to evaluate total muon capture rates
- Results are in good agreement with the experimental values
- There is no necessity for an empirical quenching of the axial current coupling constant g_A from standard value 1.27
- No matter what $g_A \geq 1.0$ is required to reproduce the experimental muon capture rates

F. Šimkovic, R. Dvornický and P. Vogel, *Phys.Rev.* ***C*** **102** (2020) 3, 034301

Capture rate for a given g_A

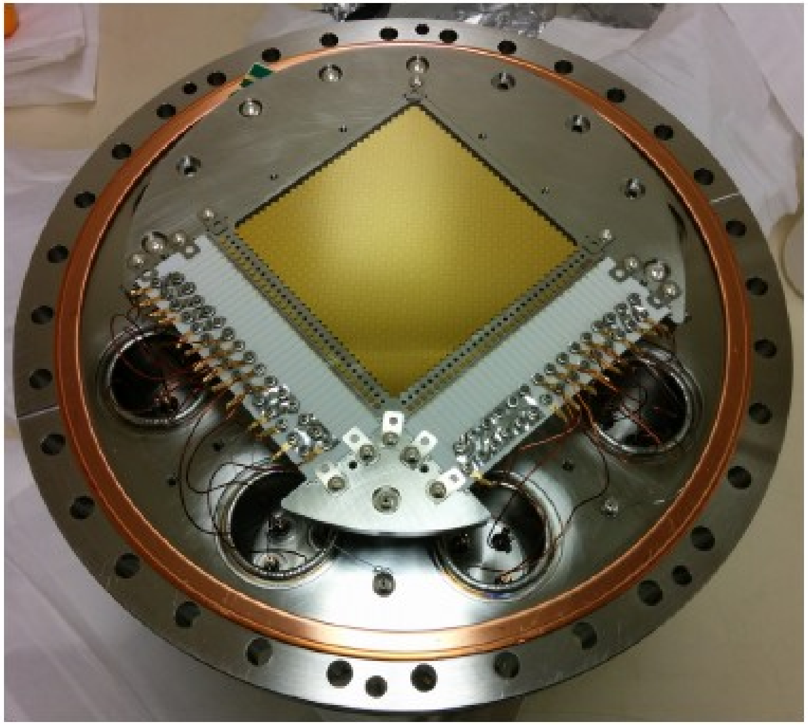


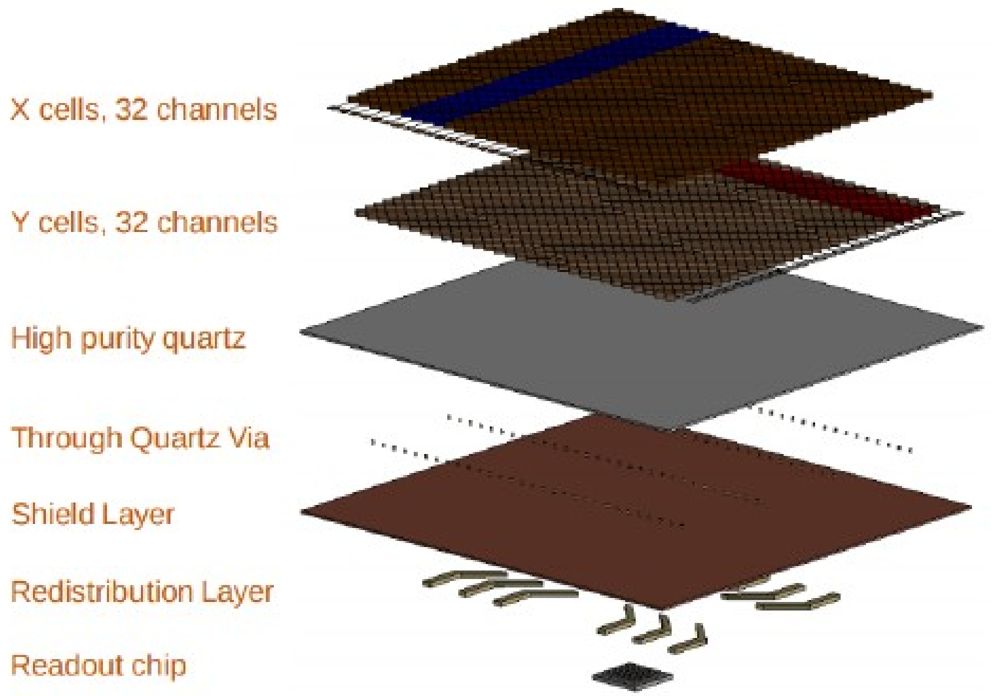
g_A required for a given capture rate



nEXO charge tiles

- Orthogonal, noble-metal strips of 10 cm length on a quartz substrate
- Each strip consists of small metal pads linked diagonally, lying parallel to either the X- or the Y-axis.

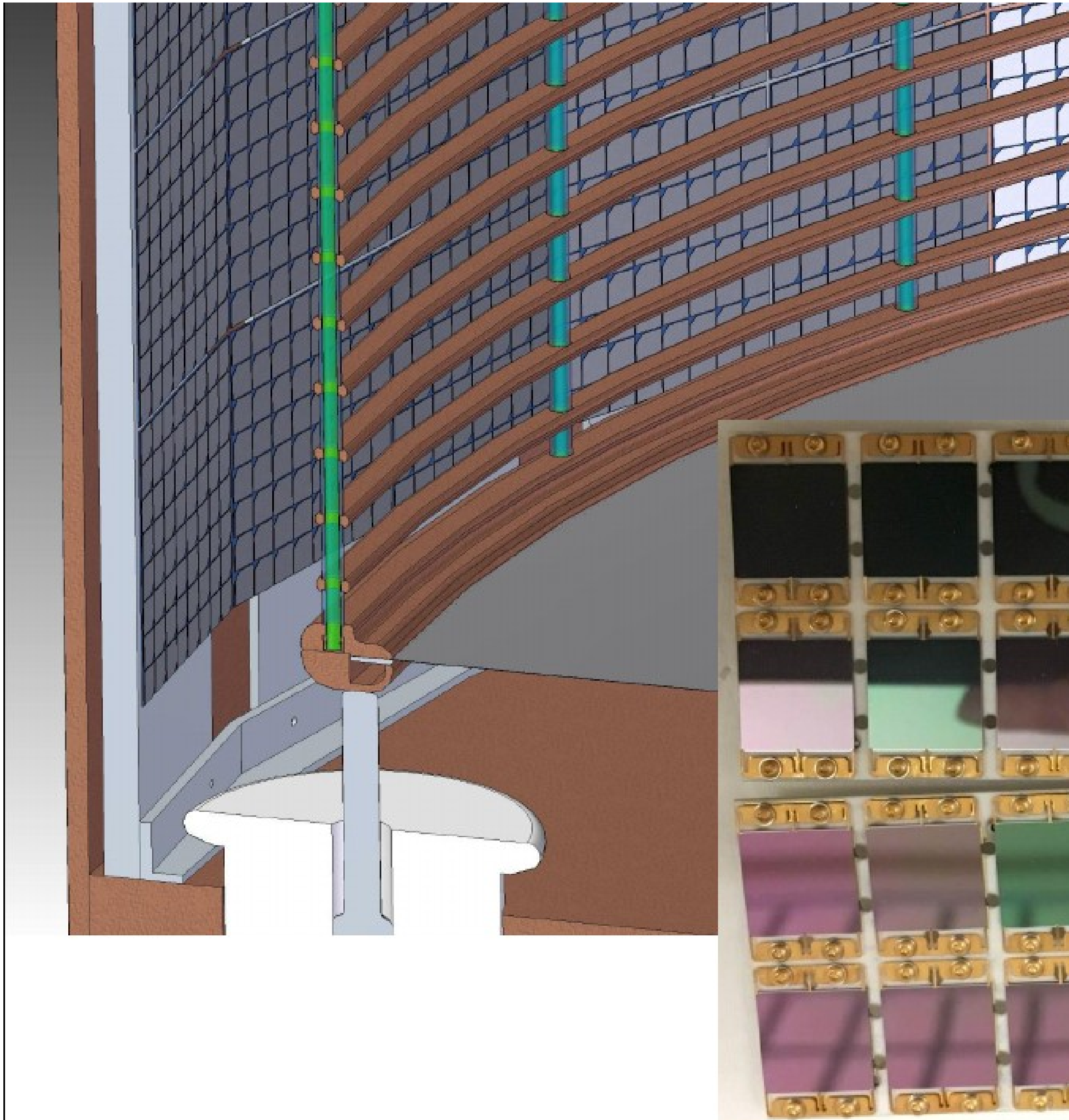




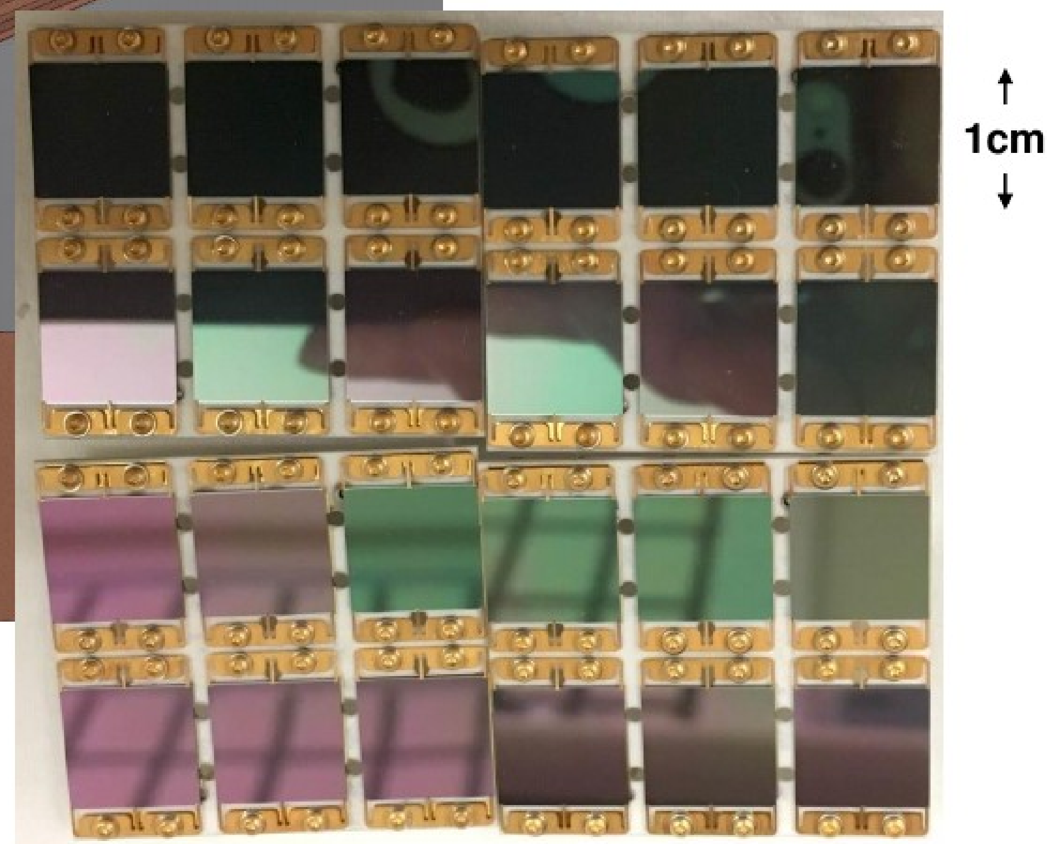
In going R&D:

- Improving fabrication process.
- Investigating different readout schemes.
- Integrating with cold electronics.

nEXO photodetectors



Need ~4m^2 of VUV-sensitive SiPMs



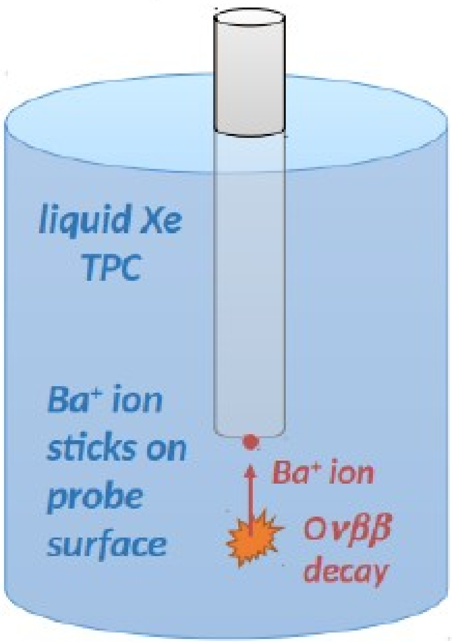
nEXO Ba tagging

Goal of barium tagging:

- Recover and identify xenon decay daughter barium if present
- Suppress background to almost background free

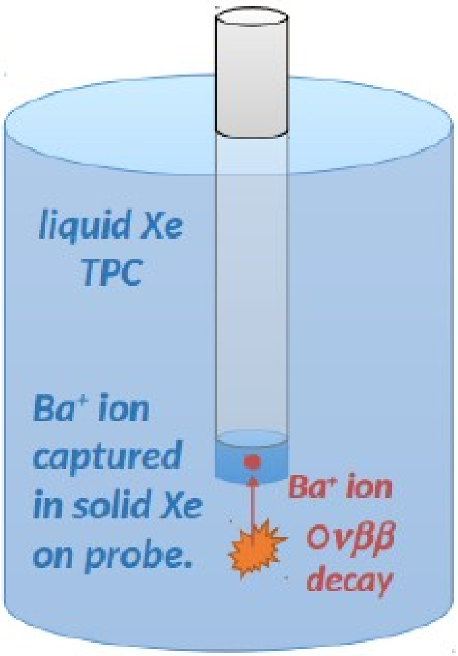
Several concepts are being investigated:

Conducting Probe



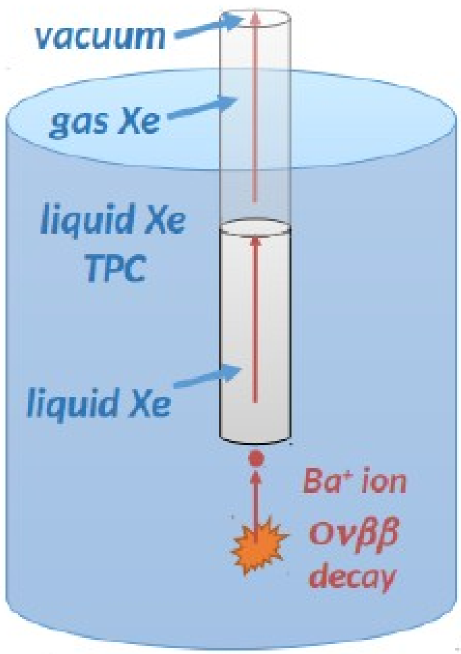
Probe removed to vacuum; Ba^+ identified by (1) laser ablation/resonance ionization or (2) thermal desorption/ionization

Cold probe [3]



Probe removed to vacuum; Ba/Ba^+ identified laser fluorescence single atom imaging in SXe

Capillary extraction [4]



Ba^+ "sucked" out of LXe through capillary into ion trap and identified laser fluorescence and MRTOF spectroscopy

[3] B. Mong et al., "Spectroscopy of Ba and Ba^+ deposits in solid xenon for barium tagging in nEXO", Phys. Rev. A 91, (2015) 022505

[4] T. Brunner et al., "An RF-only ion-funnel for extraction from high-pressure gases", Int J. Mass Spec., 379, 110-120 (2015)