

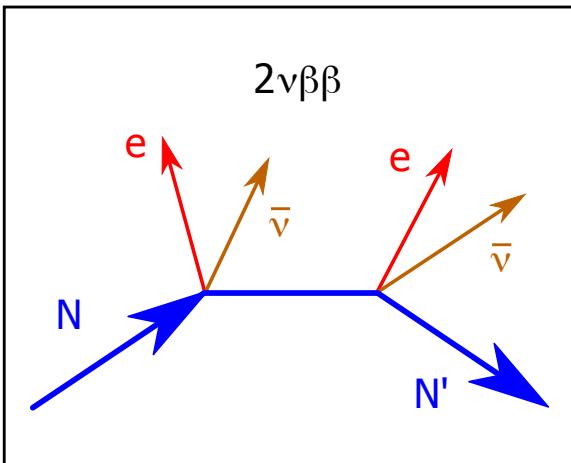
EXO-200 results

Belov V.A.
for EXO-200 coll.

24.10.2018

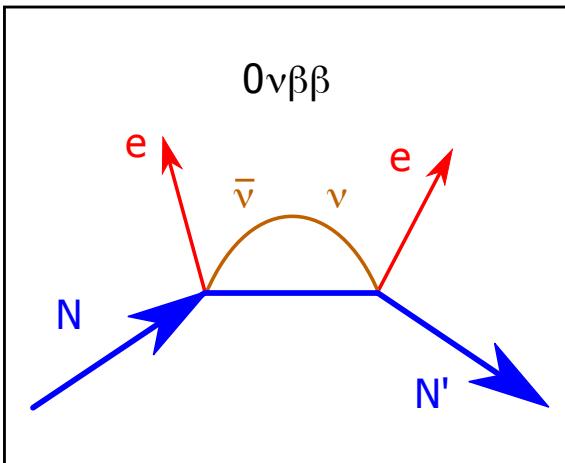
IV international conference on particle physics and astrophysics

Double beta decay



2ν mode

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

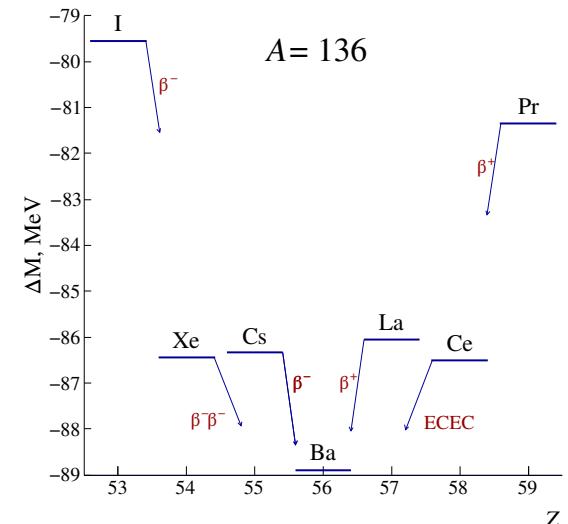


0ν mode

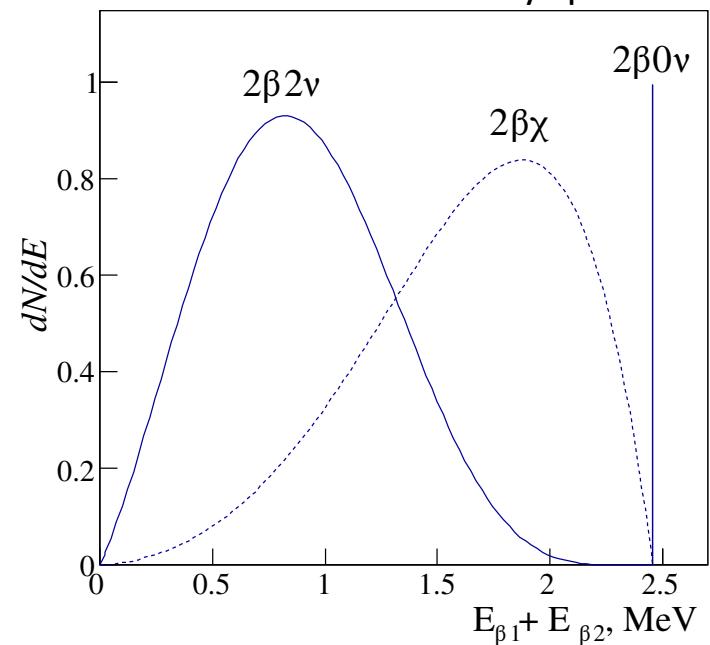
is a hypothetical process always means New Physics.
This is search for:
Lepton Number Violation
Majorana fermions

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

- High energy resolution
- Large Isotope mass
- Low background



Simulated double beta decay spectrum



University of Alabama, Tuscaloosa AL, USA — M Hughes, I Ostrovskiy, A Piepke, AK Soma, V Veeraraghavan

University of Bern, Switzerland — J-L Vuilleumier

University of California, Irvine, Irvine CA, USA — M Moe

California Institute of Technology, Pasadena CA, USA — P Vogel

Carleton University, Ottawa ON, Canada — I Badhrees, W Cree, R Gornea, K Graham, T Koffas, C Licciardi, D Sinclair

Colorado State University, Fort Collins CO, USA — C Chambers, A Craycraft, W Fairbank Jr, D Harris, A Iverson, J Todd, T Walton

Drexel University, Philadelphia PA, USA — MJ Dolinski, EV Hansen, YH Lin, Y-R Yen

Duke University, Durham NC, USA — PS Barbeau

Indiana University, Bloomington IN, USA — JB Albert, S Daugherty

Laurentian University, Sudbury ON, Canada — B Cleveland, A Der Mesrobian-Kabakian, J Farine, A Robinson, U Wichoński

University of Maryland, College Park MD, USA — C Hall

University of Massachusetts, Amherst MA, USA — S Feyzbakhsh, S Johnston, A Pocar

McGill University, Montreal QC, Canada — T Brunner, Y Ito, K Murray



The EXO-200 Collaboration

SLAC National Accelerator Laboratory, Menlo Park CA, USA — M Breidenbach, R Conley, T Daniels, J Davis,

S Delaquis, A Johnson, LJ Kaufman, B Mong, A Odian, CY Prescott, PC Rowson, JJ Russell, K Skarpaas, A Waite, M Wittgen

University of South Dakota, Vermillion SD, USA — J Daughhetee, R MacLellan

Friedrich-Alexander-University Erlangen, Nuremberg, Germany

G Anton, R Bayerlein, J Hoessl, P Hufschmidt, A Jamil, T Michel, M Wagenpfeil, G Wrede, T Ziegler

IBS Center for Underground Physics, Daejeon, South Korea — DS Leonard

IHEP Beijing, People's Republic of China — G Cao, W Cen, T Tolba, L Wen, J Zhao

ITEP Moscow, Russia — V Belov, A Burenkov, M Danilov, A Dolgolenko, A Karelina, A Kuchenkov, V Stekhanov, O Zeldovich

University of Illinois, Urbana-Champaign IL, USA — D Beck, M Coon, S Li, L Yang

Stanford University, Stanford CA, USA — R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, G Li, A Schubert, M Weber, S Wu

Stony Brook University, SUNY, Stony Brook, NY, USA — K Kumar, O Njoya, M Tarka

Technical University of Munich, Garching, Germany — W Feldmeier, P Fierlinger, M Marino

TRIUMF, Vancouver BC, Canada — J Dilling, R Krücken, Y Lan, F Retière, V Strickland

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

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.

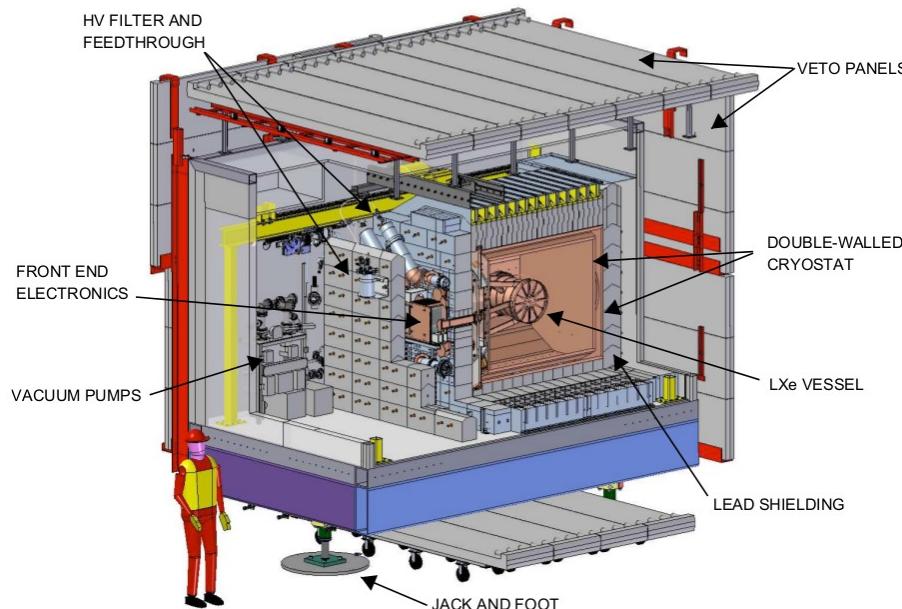
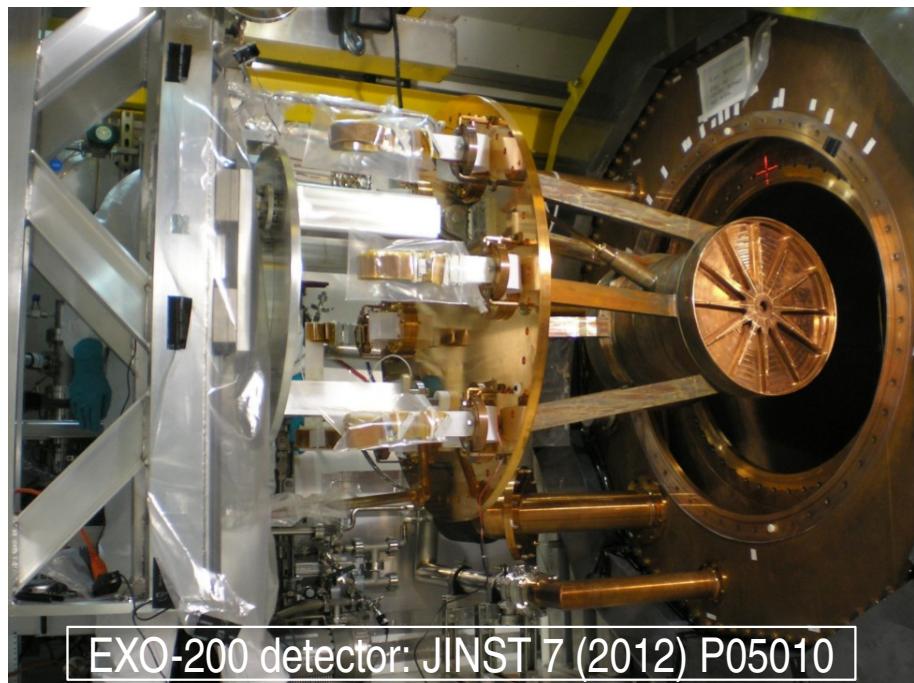
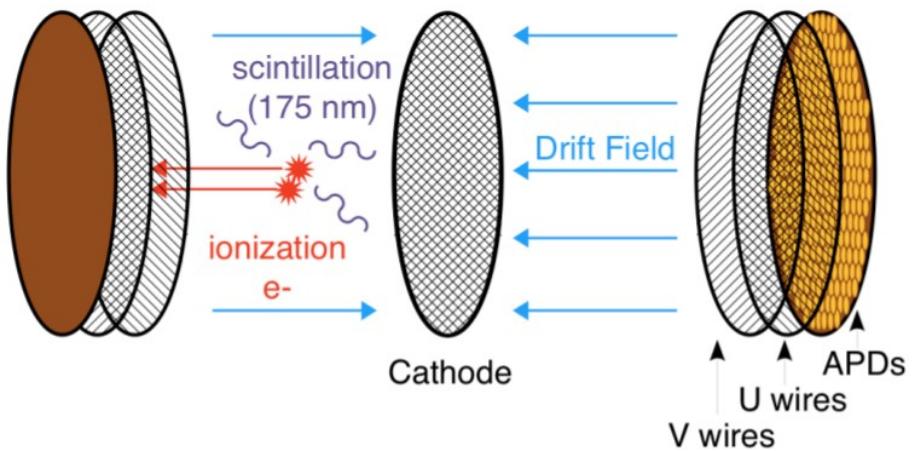
Energy resolution can be improved. Using scintillation light/ionization correlation.

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).

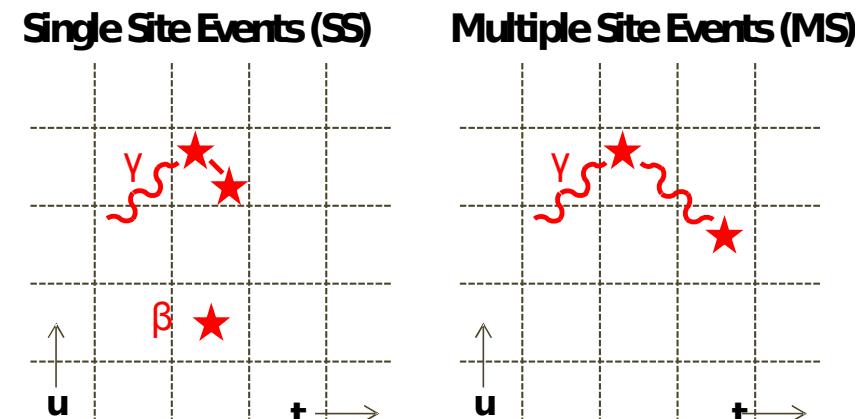
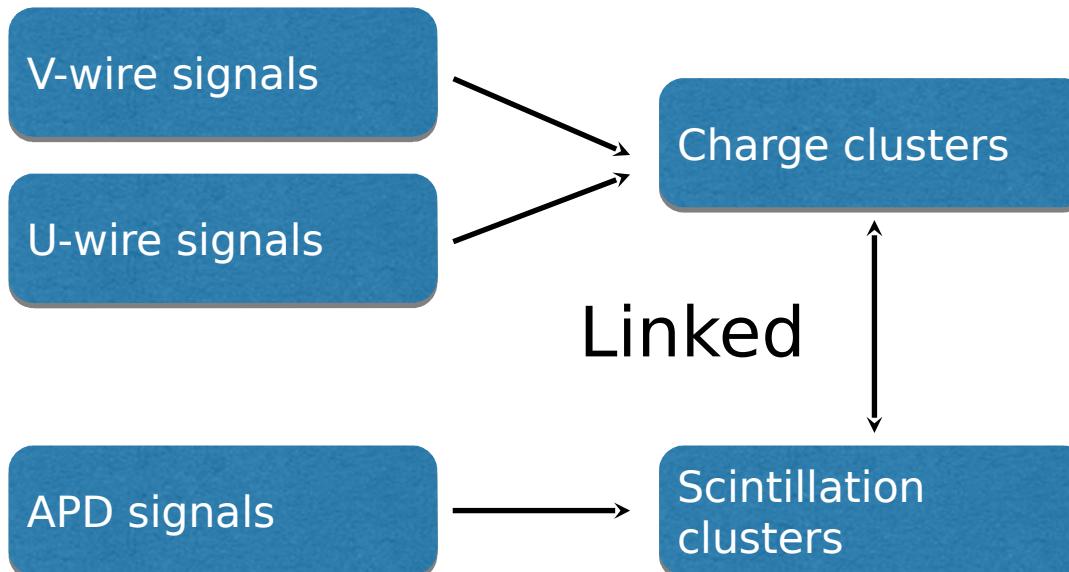
EXO-200 detector

- 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.



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 Standoff Distance (SD) that is distance from any cluster to the nearest wall

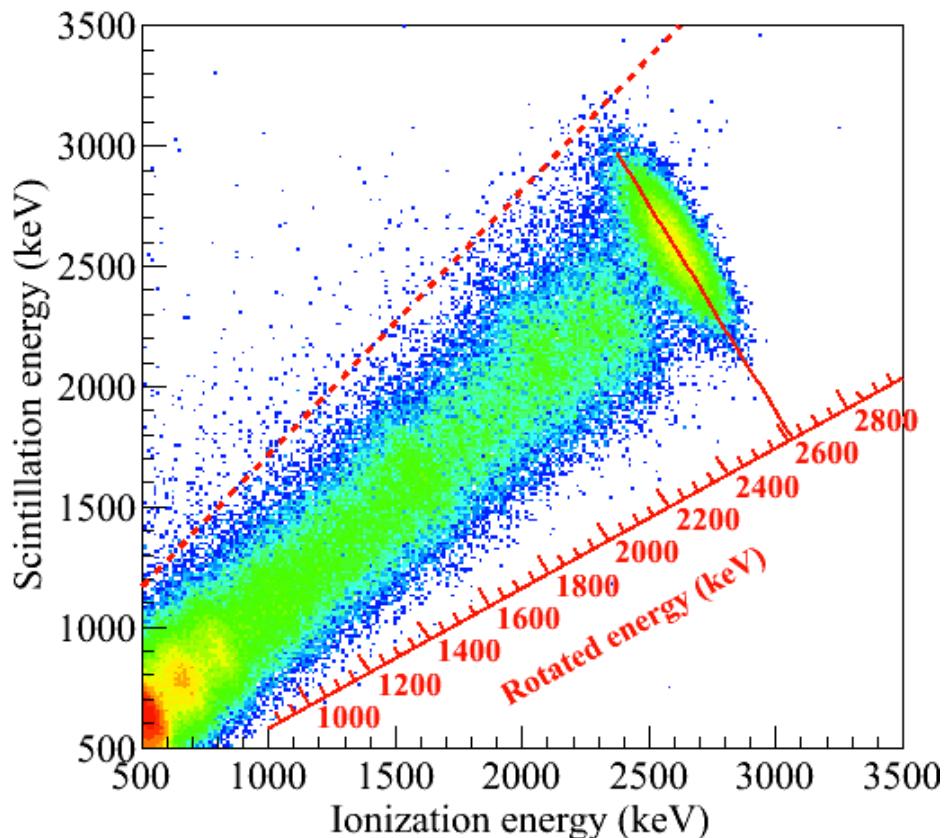


Efficiency to get into SS:
 $2\beta 0\nu$ ~90%
 γ 2.5 MeV ~30%

But we don't throw MS events away!

We use them in the fit to help predict background

Combining ionization and scintillation

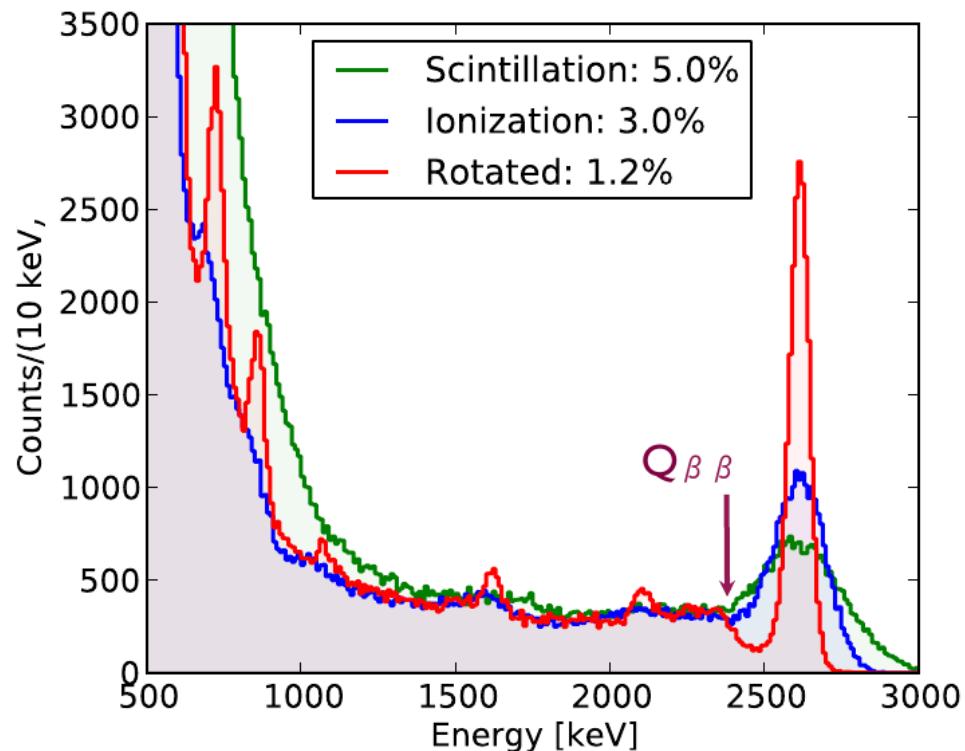


**EXO-200 has achieved $\sim 1.2\%$ energy resolution at the Q value.
nEXO will reach resolution $< 1\%$, sufficient to suppress background from $2\nu\beta\beta$.**

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

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

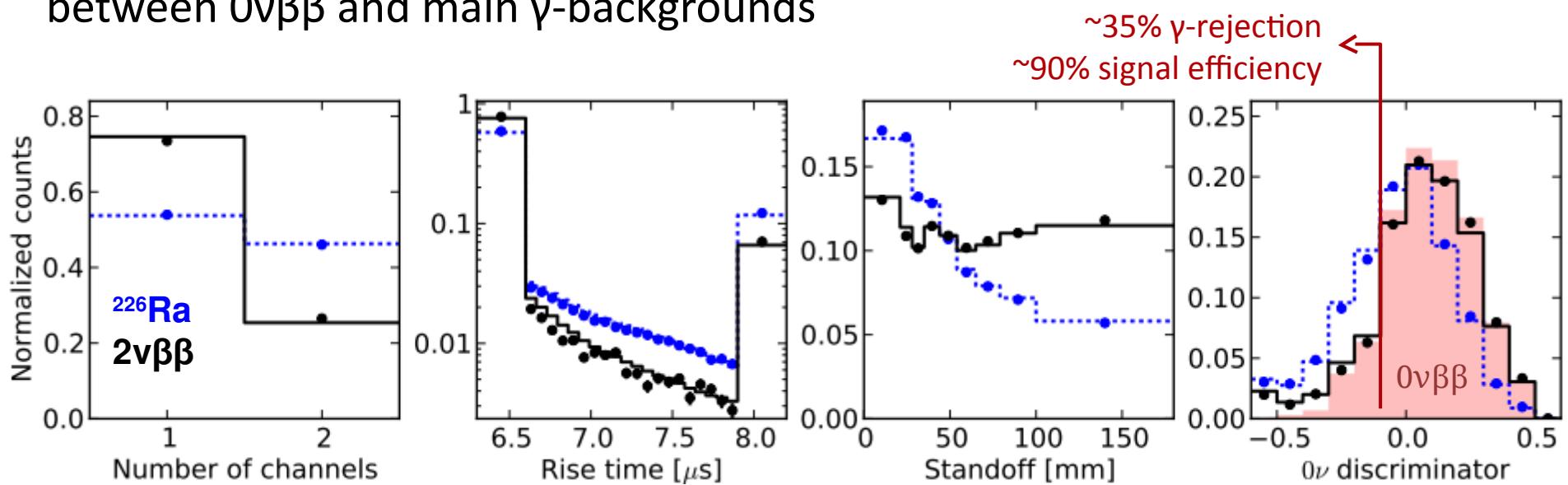
Mixing angle is chosen to optimize energy resolution at 2615 keV line.



Optimal discrimination

Enhance β/γ discrimination by use of additional information

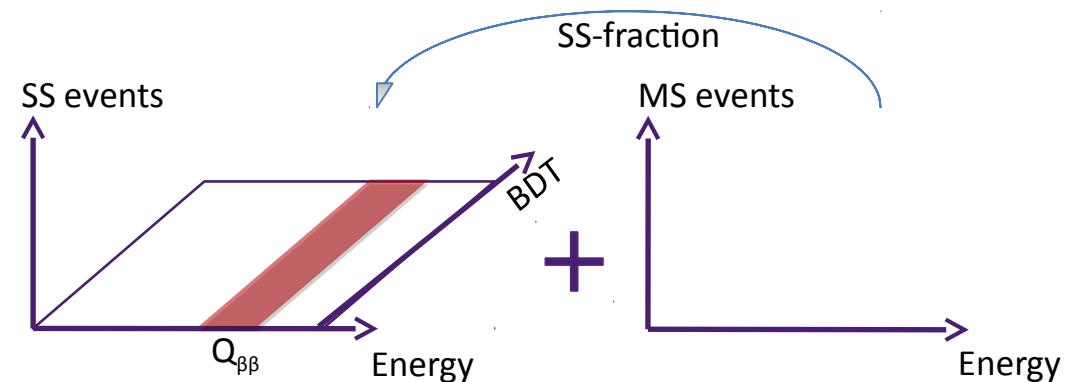
Using a boosted decision tree (BDT) to distinguish
between $0\nu\beta\beta$ and main γ -backgrounds



Fitting $0\nu\beta\beta$ discriminators

- Energy
- SS/MS
- BDT

$\Rightarrow \sim 15\% \text{ sensitivity improvement}$



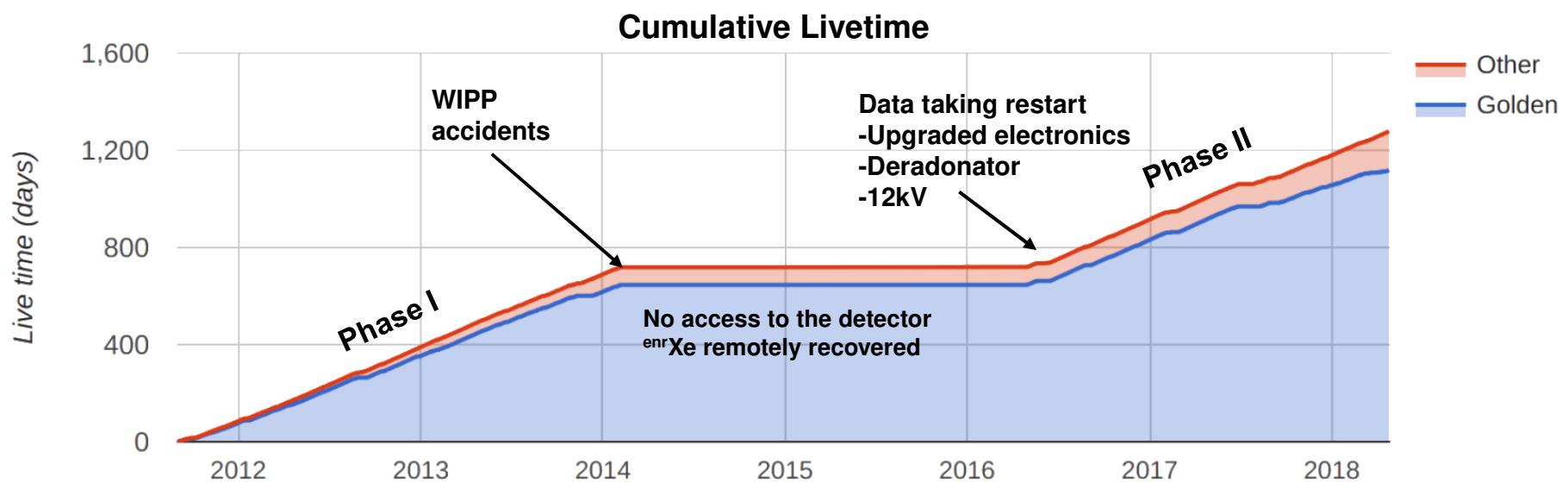
Data collection

Phase-I

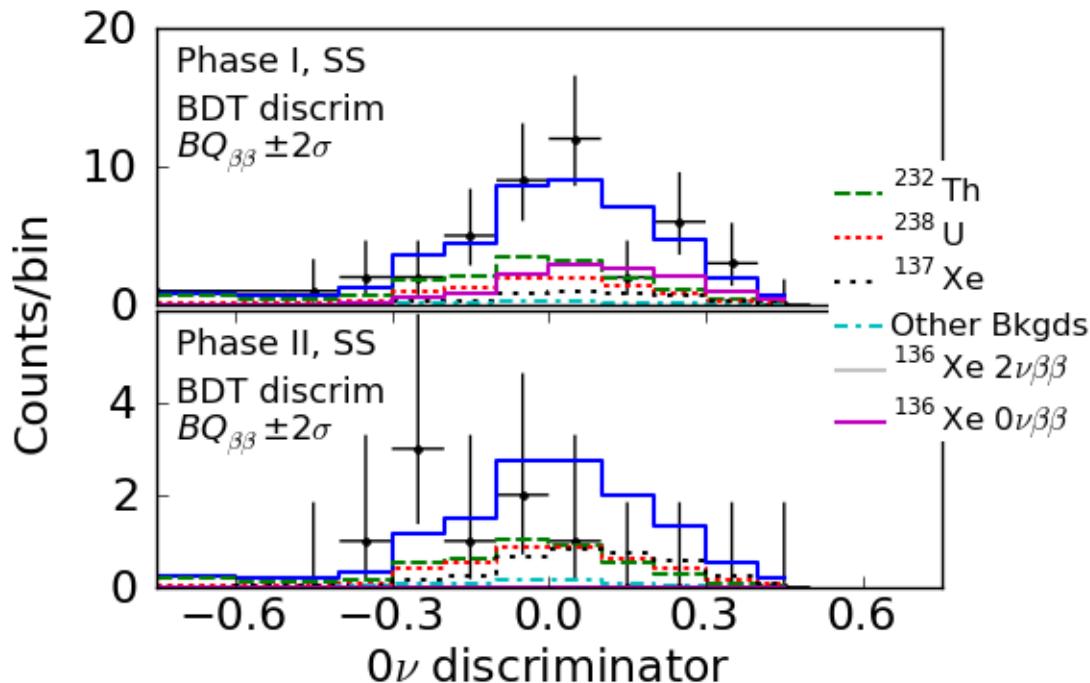
- Sep 2011 to Feb 2014
 - Total live time 596.7 days
- Selected physics results
 - The most precise $2\nu\beta\beta$ measurement
 - *Phys. Rev. C* **89**, 015502 (2013)
 - Stringent $0\nu\beta\beta$ searches
 - *Nature* **510**, 229 (2014)
 - Sensitivity $T_{1/2}^{0\nu\beta\beta} > 1.9 \times 10^{25}$ yr (90%CL)

Phase-II

- Access regained 2015 after stop imposed by WIPP accident
- Jan – May 2016
 - Hardware upgrades
- Stable data taking since May 2016
- Run to the end in Dec 2018
- **About 4 years of data on disks**
 - *Look forward for new results!*



$2\beta 0\nu$ measurement

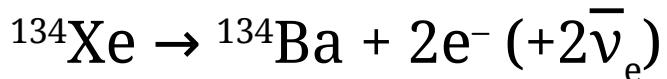


Contributions to $BQ \pm 2\sigma$	Phase I, cts	Phase II, cts
^{232}Th	15.8	4.8
^{238}U	9.4	4.2
^{137}Xe	4.4	3.6
Total	30.7 ± 6.0	13.2 ± 1.4
Data	43	8

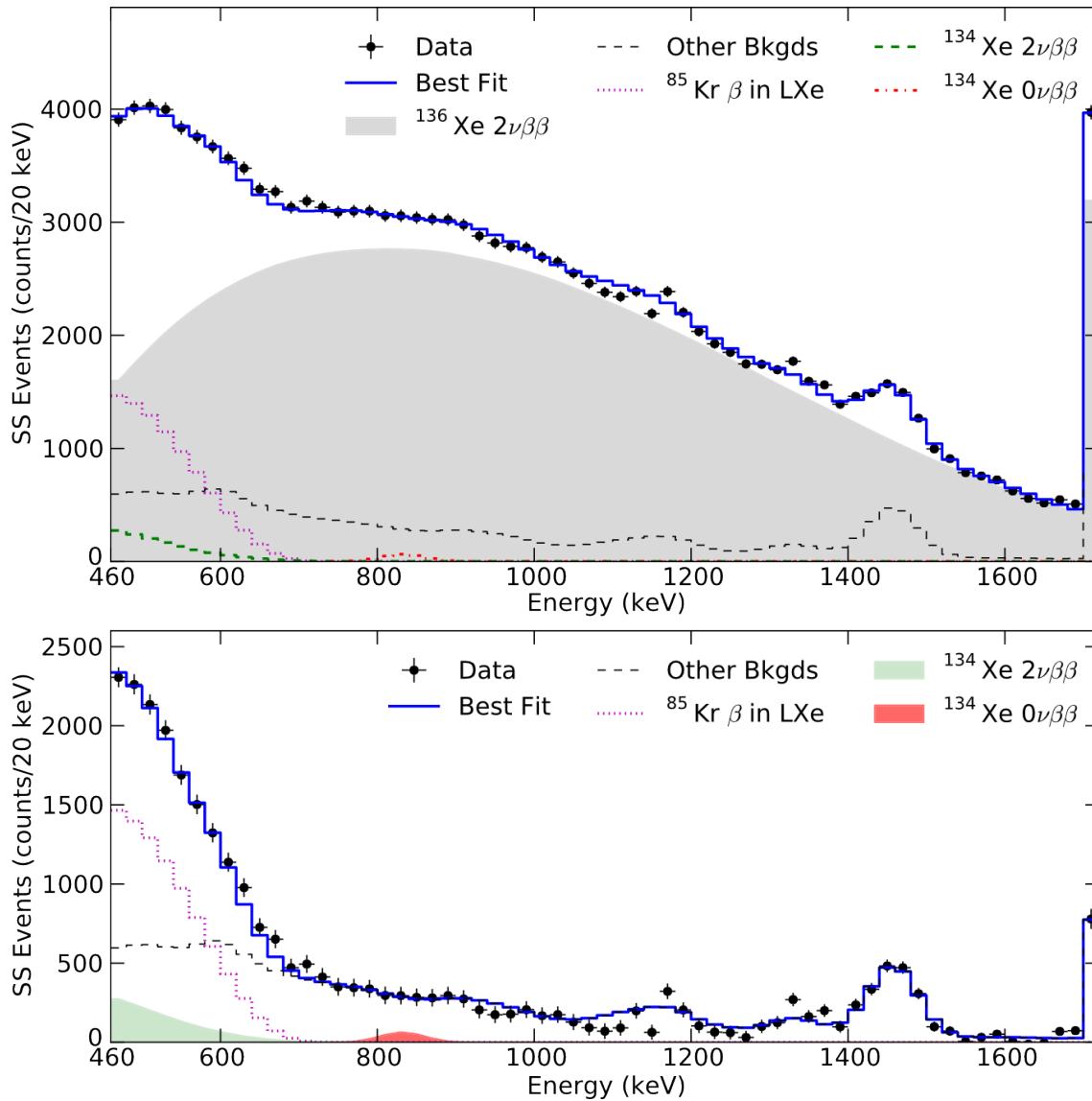
- Total exposure $177.6 \text{ kg}\cdot\text{yr}$
- Background index in ROI $(1.5 \pm 0.2) \times 10^{-3} / (\text{kg}\cdot\text{yr}\cdot\text{keV})$
- **Sensitivity $3.7 \cdot 10^{25} \text{ yr}$ (90% CL)**
- $T_{1/2}(0\nu\beta\beta) > 1.8 \cdot 10^{25} \text{ yr}$
- $\langle m_{\beta\beta} \rangle < 147\text{--}398 \text{ meV}$ (90% CL)

Phys. Rev. Lett. **120**, 072701

Search for ^{134}Xe decay



$$\text{Q value} = 825.8 \pm 0.9 \text{ keV}$$



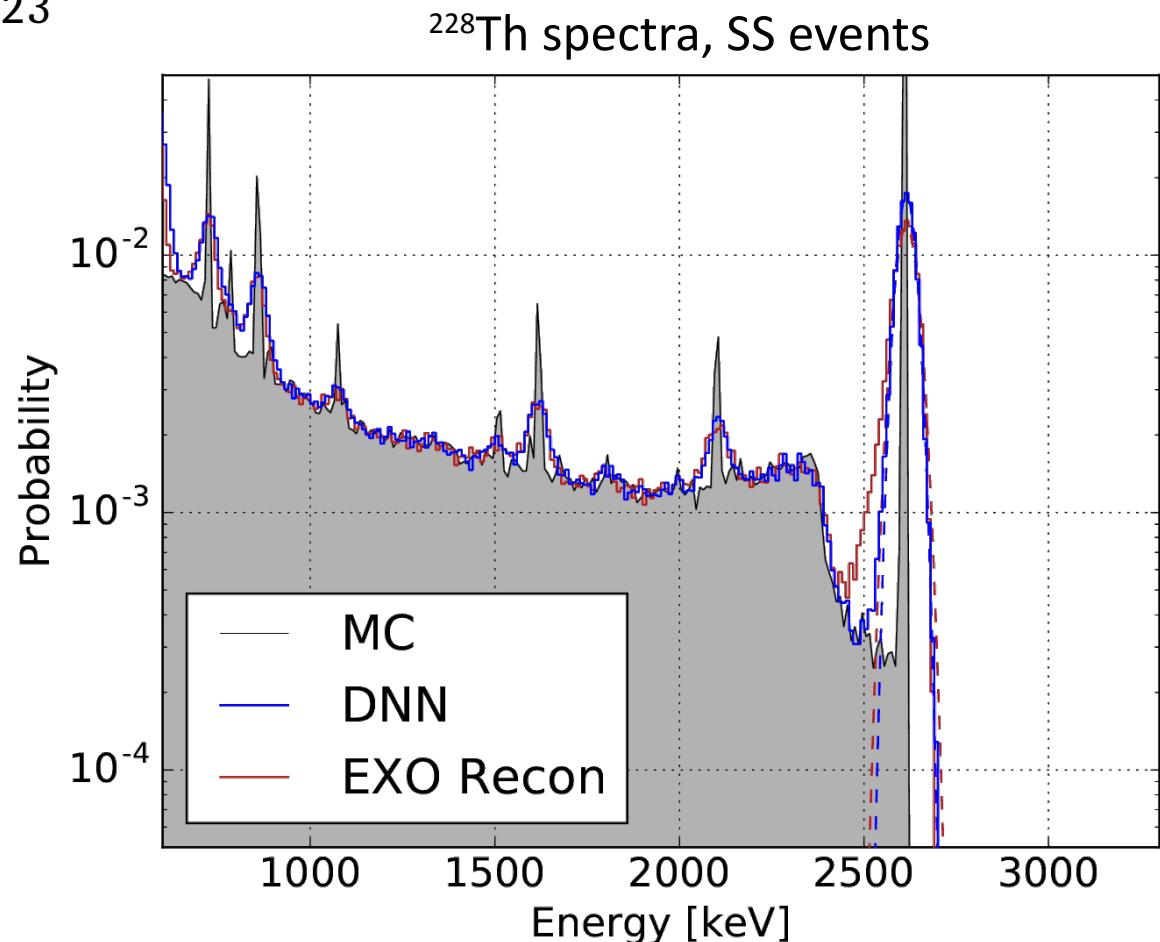
- Results from EXO-200 measurement
Phys. Rev. D 96, 092001, 2017
- $T_{1/2}(2\beta 2\nu) > 8.7 \cdot 10^{20} \text{ yr}$
(Theoretical predictions $\sim 10^{24} - 10^{25} \text{ yr}$)
- $T_{1/2}(2\beta 0\nu) > 1.1 \cdot 10^{23} \text{ yr}$
- Improved by factors of 10^5 and 2 respectively compared to previous measurements.
- Lower scintillation noise in Phase II will improve search sensitivity

Deep neural networks

- Deep neural networks is a method of machine learning
- It found broad use in industry with extremely good results
- Raw waveforms were used in this study to directly extract parameters
- Network was trained using Monte-Carlo data

S. Delaquis et al 2018 JINST 13 P08023

- We were able to reconstruct energy and position
- Energy resolution is slightly better with DNN than with conventional reconstruction
- We also validated with real calibration data
- Work for event identification and classification has already started



EXO-200 and beyond

- Operated a 200 kg scale LXe TPC for 5 years
- Made the **most precise** measurement of ^{136}Xe halflife
- Measured **residual backgrounds are very low**
- Achieved stable **electron lifetime of ~3 ms** or better
- Utilized **self-shielding in monolithic detector**
- Demonstrated power of **β/γ discrimination** (SS/MS)
- Upgraded electronics (get to **1.2% energy resolution !**)
- It's time to think about tonne-scale experiment!
- We are entering the “golden era” of $\beta\beta$ decay experiments as detector sizes exceed interaction length
- 5000 kg homogenous liquid xenon detector nEXO
- It isn't just 30 EXO-200 experiments
- Our aim is to reach more than $\times 100$ sensitivity

nEXO pCDR

ArXiv: 1805.11142

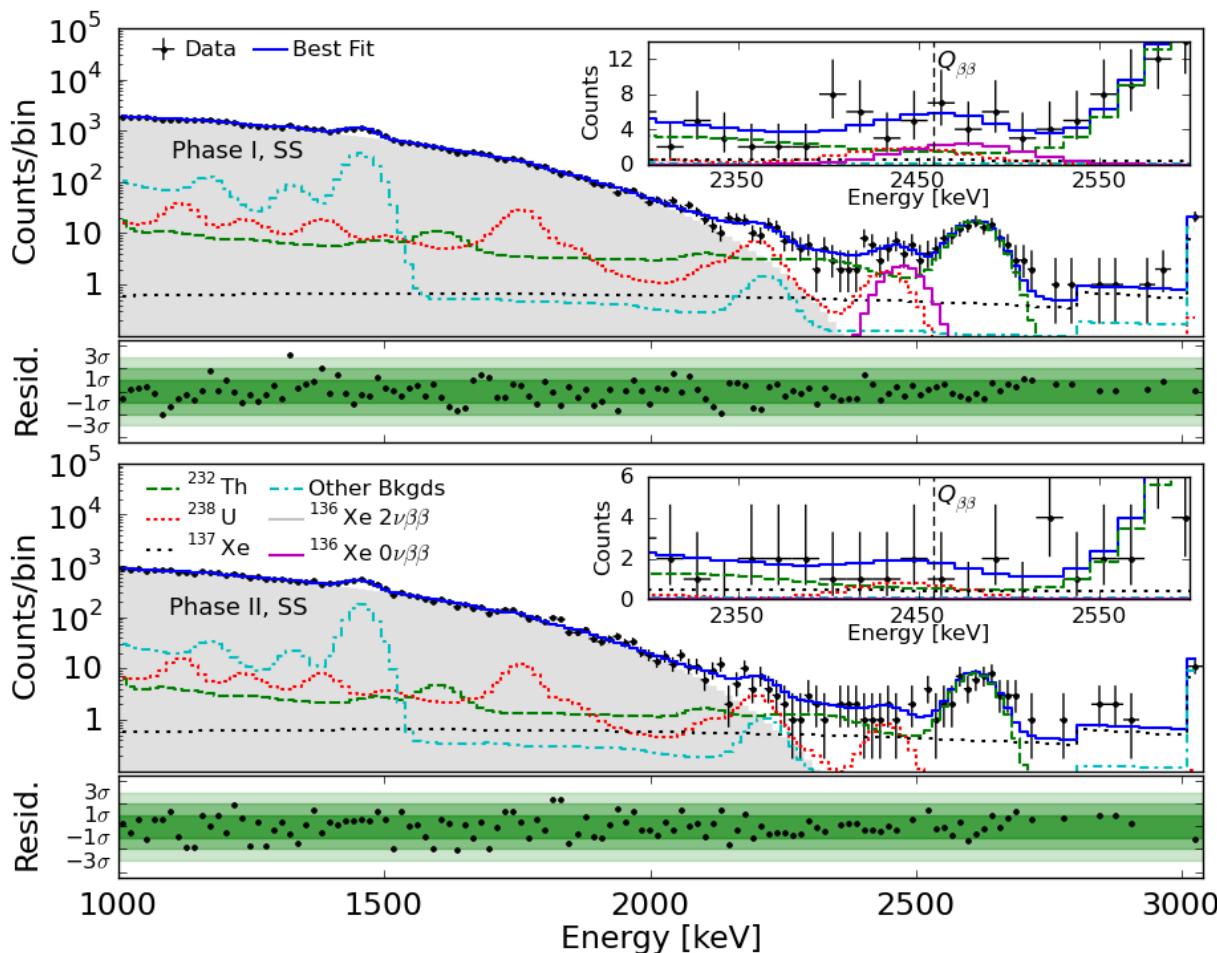


Thank you

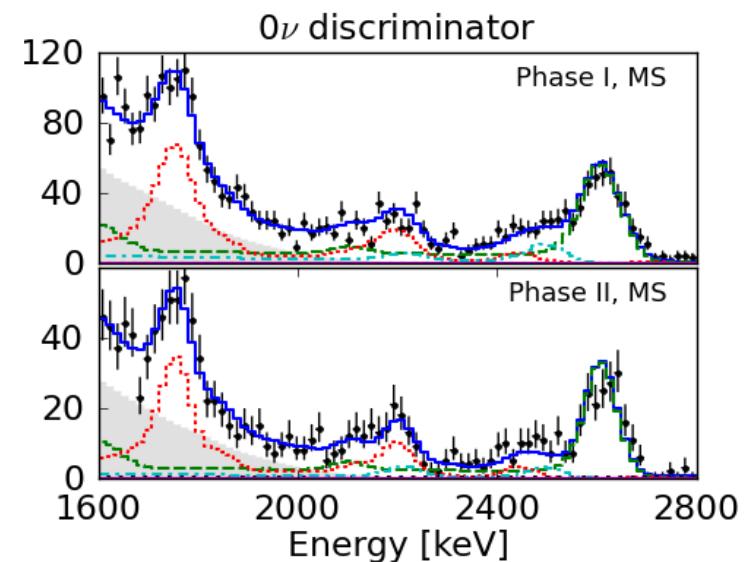


$2\beta 0\nu$ measurement

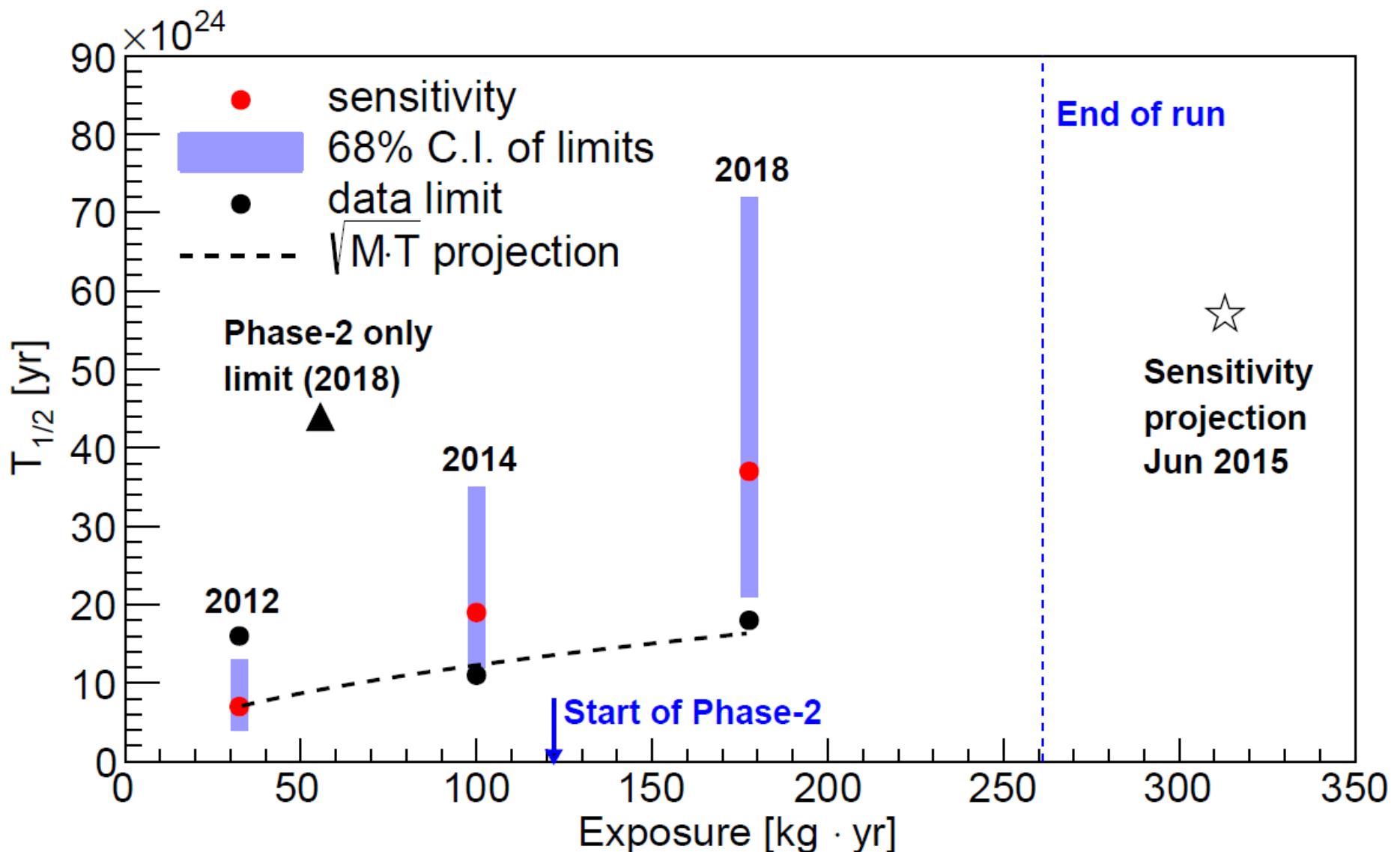
- Spectra from Phase-I and Phase-II are fitted separately
- Result comes from combination of profiles
- No statistically significant excess: **combined p-value $\sim 1.5\sigma$**



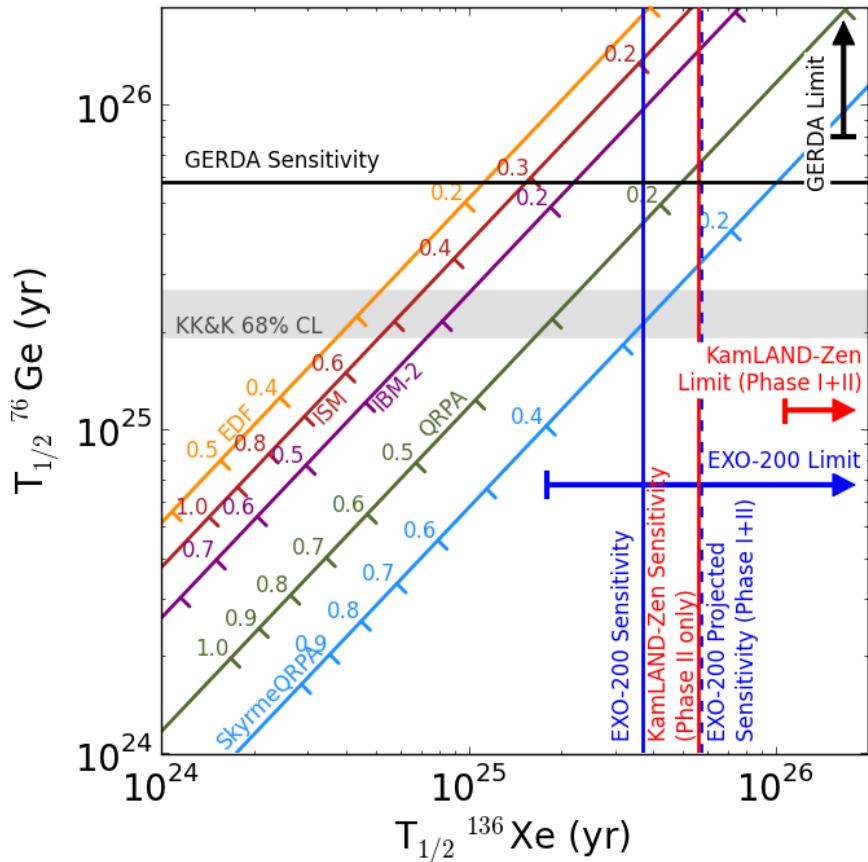
Systematics	Phase I (%)	Phase II (%)
Detection efficiency	82.4 ± 3.0	80.8 ± 2.9
Shape differences	± 6.2	± 6.2
SS/MS fraction	± 5.0	± 8.8



EXO-200 progress



Comparison

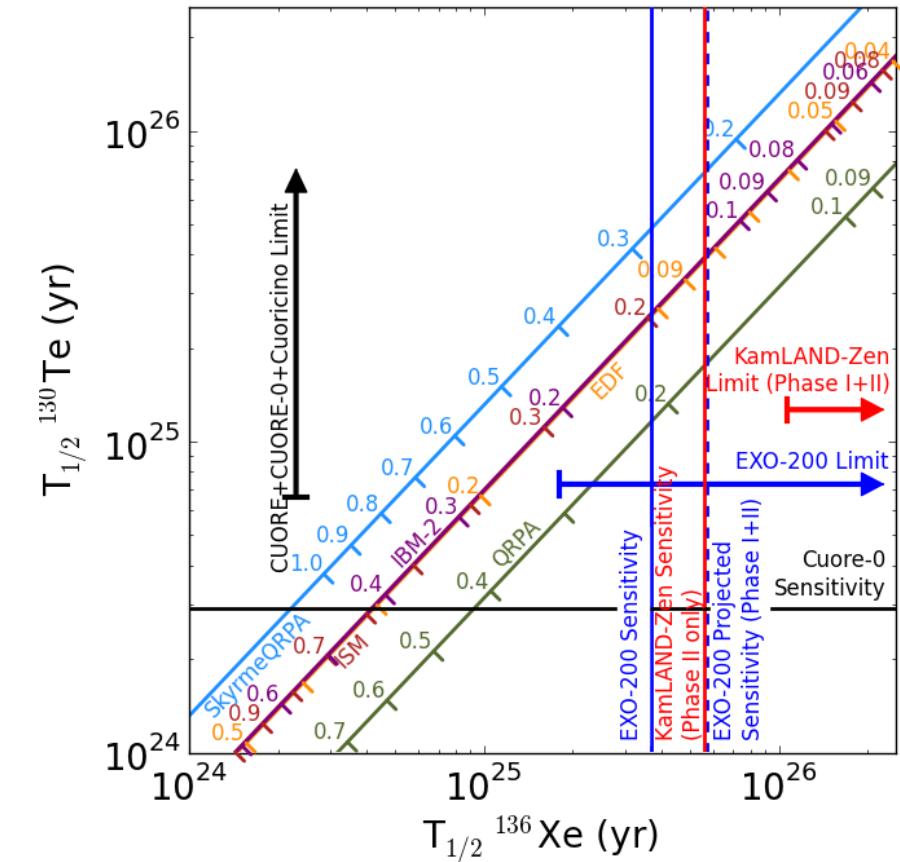


EXO-200: *this result, arXiv: 1707.08707*

GERDA: *arXiv:1710.07776*

KamLAND-Zen: *PRL 117 (2016) 082503*

KK&K Claim: *Mod. Phys. Lett., A21 (2006) 1547*

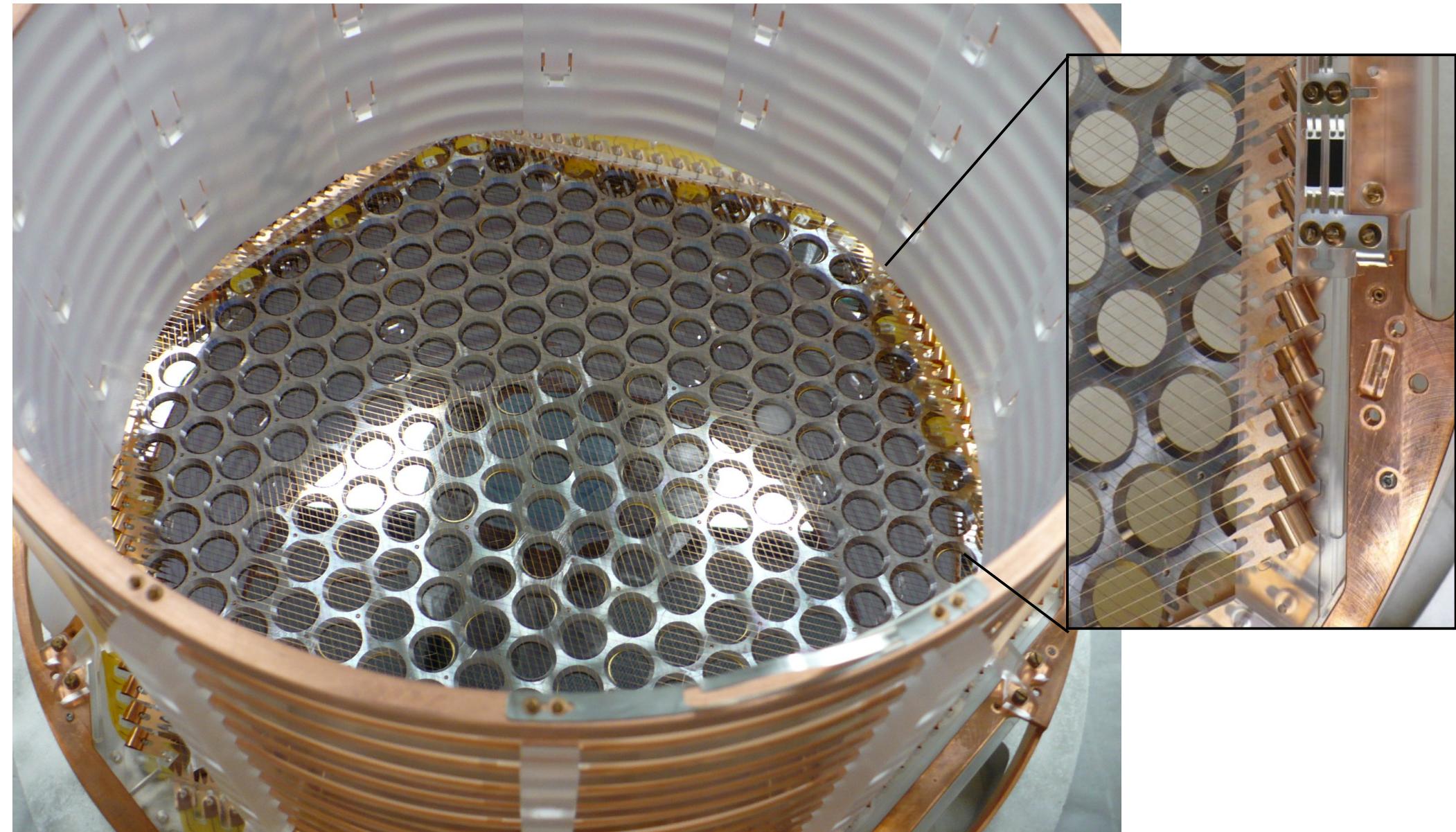


EXO-200: *this result, arXiv: 1707.08707*

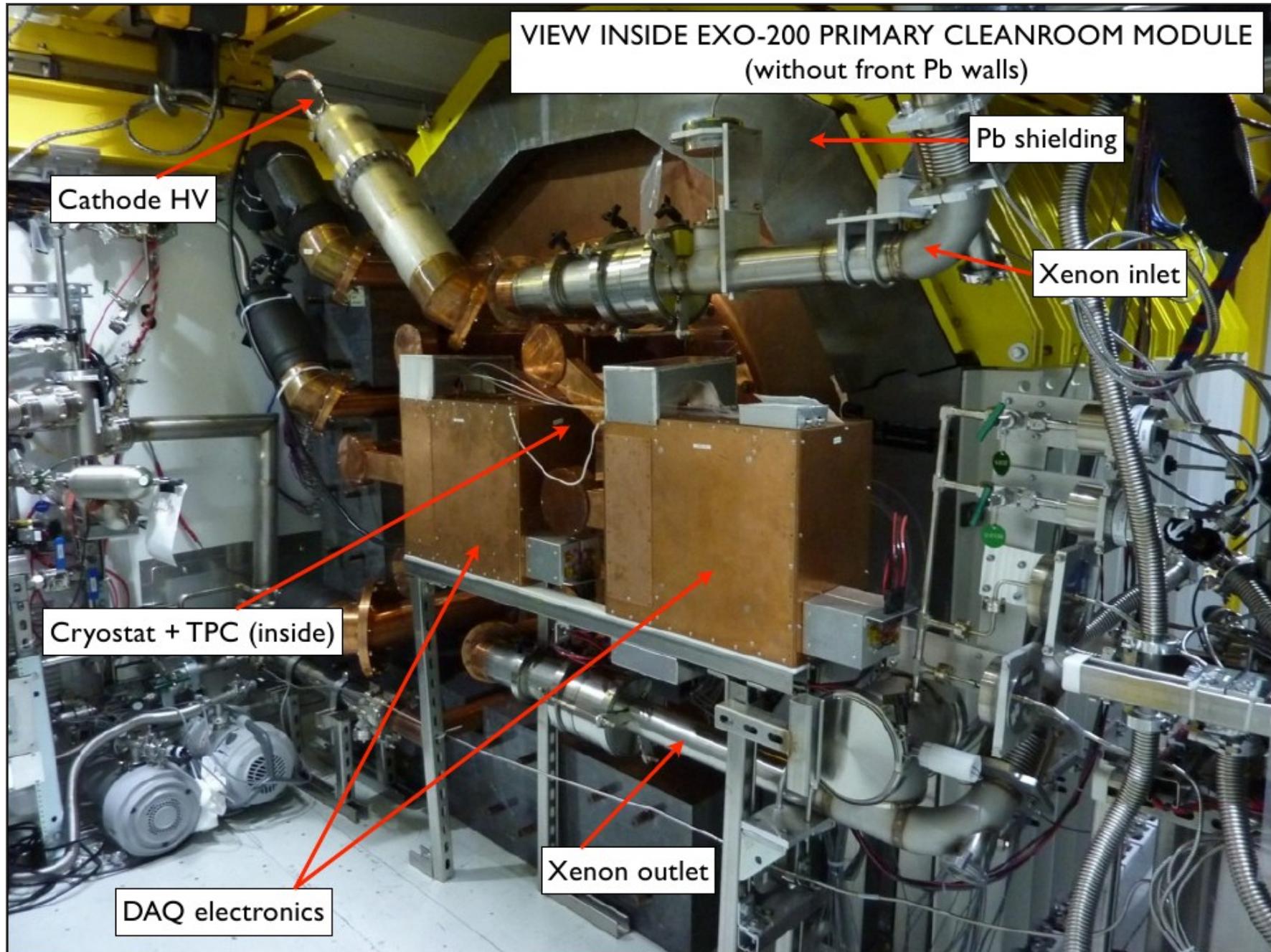
CUORE: *talk by O. Cremonesi @ TAUP-2017*

Sensitivity in *PRL 115 (2015) 102502*

EXO-200 inside



EXO-200 overview



Xenon purity and radon level

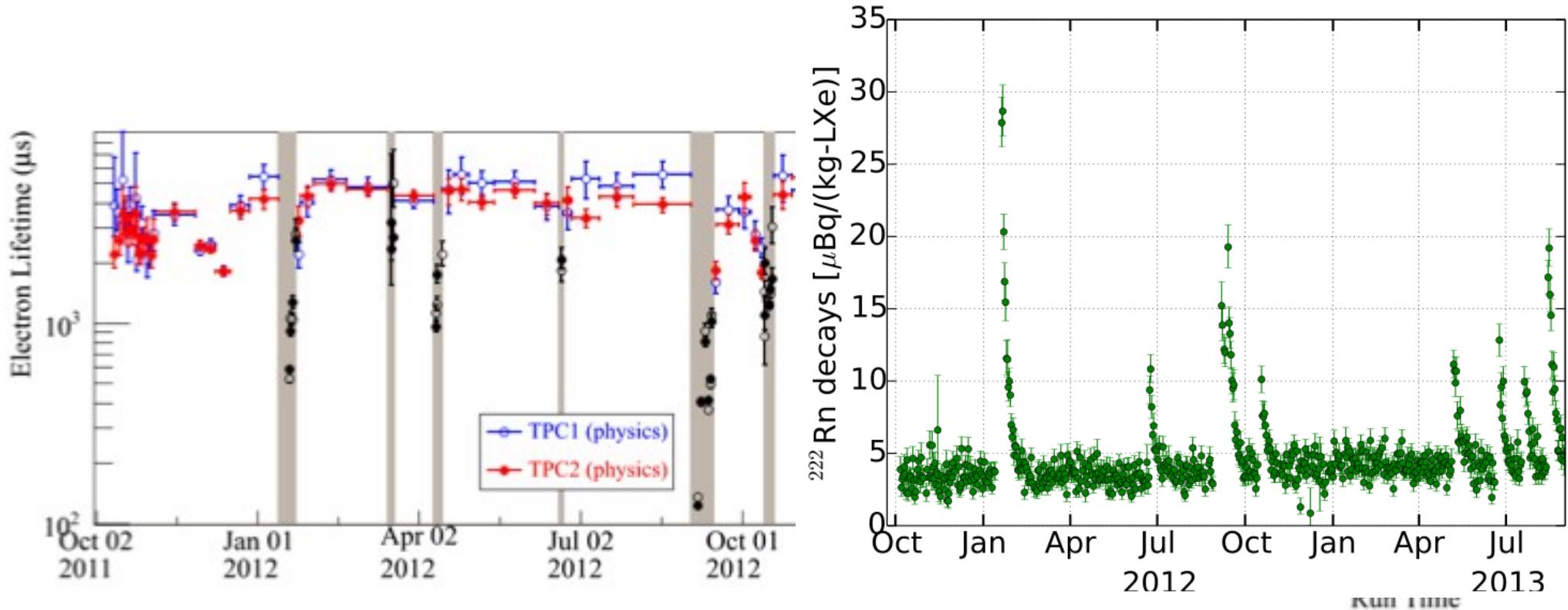
Непрерывная циркуляция ксенона через высокотемпературные очистители SAES с использованием специально сконструированного насоса.

[Neilson et al. (2011) arXiv:1104.5041v1]

Среднее время жизни электрона

~3 мс обеспечивает на максимальном времени дрейфа 110 мкс уменьшение сигнала <3%.

Восстановление после остановок занимает несколько дней



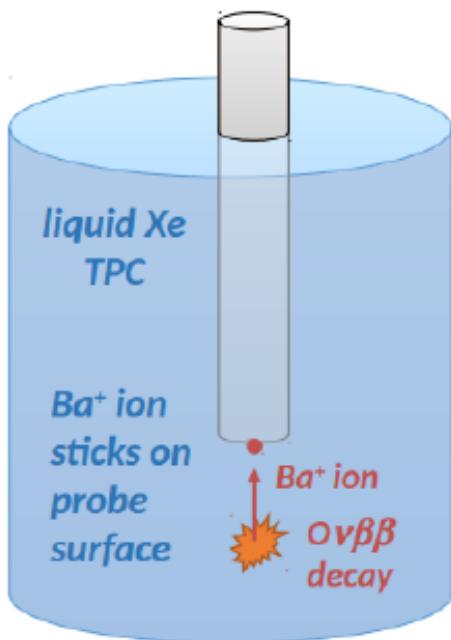
nEXO Ba tagging

Goal of barium tagging:

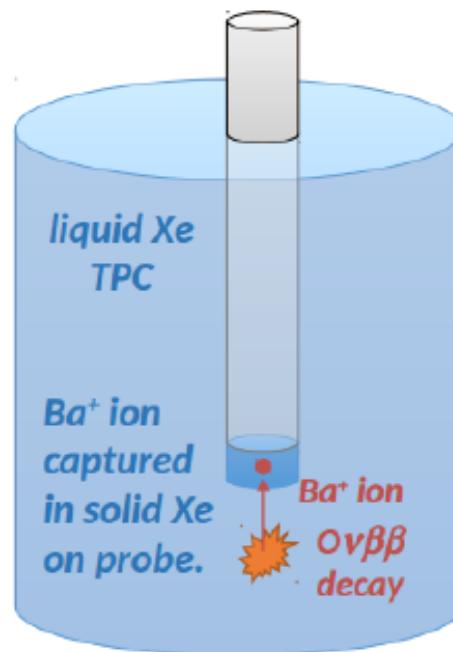
- Recover and identify xenon decay daughter barium if present
- Suppress background to almost background free

Several concepts are being investigated:

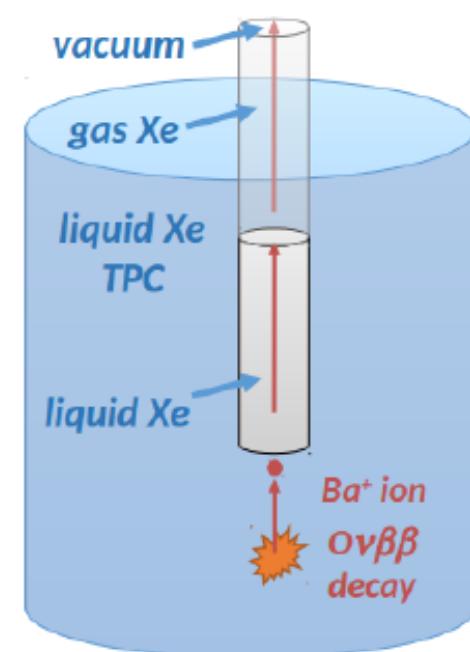
Conducting Probe



Cold probe ³



Capillary extraction ⁴



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

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

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)