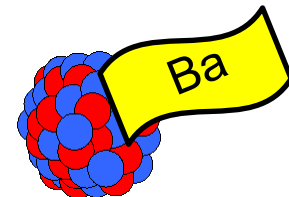


# Ion Extraction from gas for Ba-tagging in nEXO



?



# Double beta decay

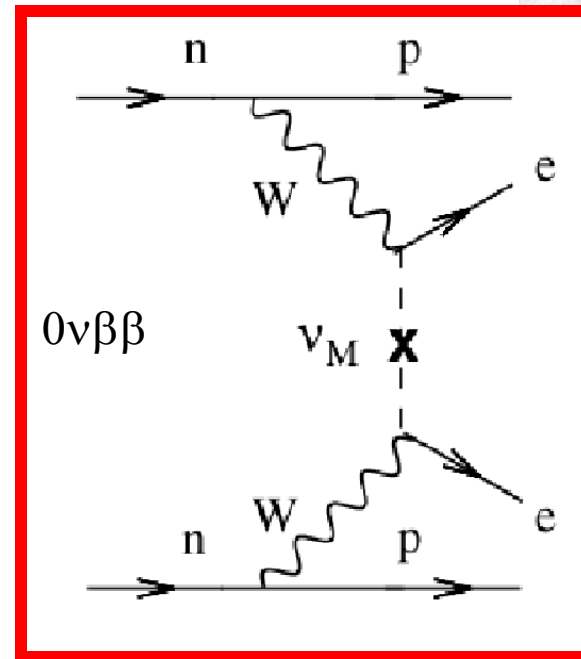
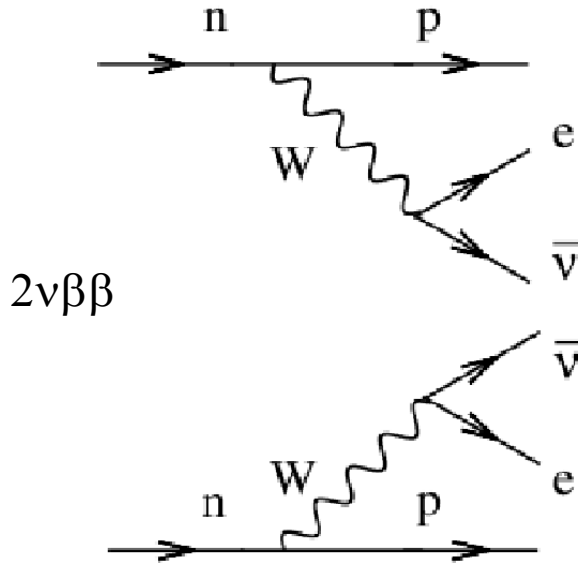


M. Goeppert-Mayer, Phys. Rev. 48 (1935) 512

The most promising approach to determine the nature of the neutrino!  
Lepton number is violated in this decay!

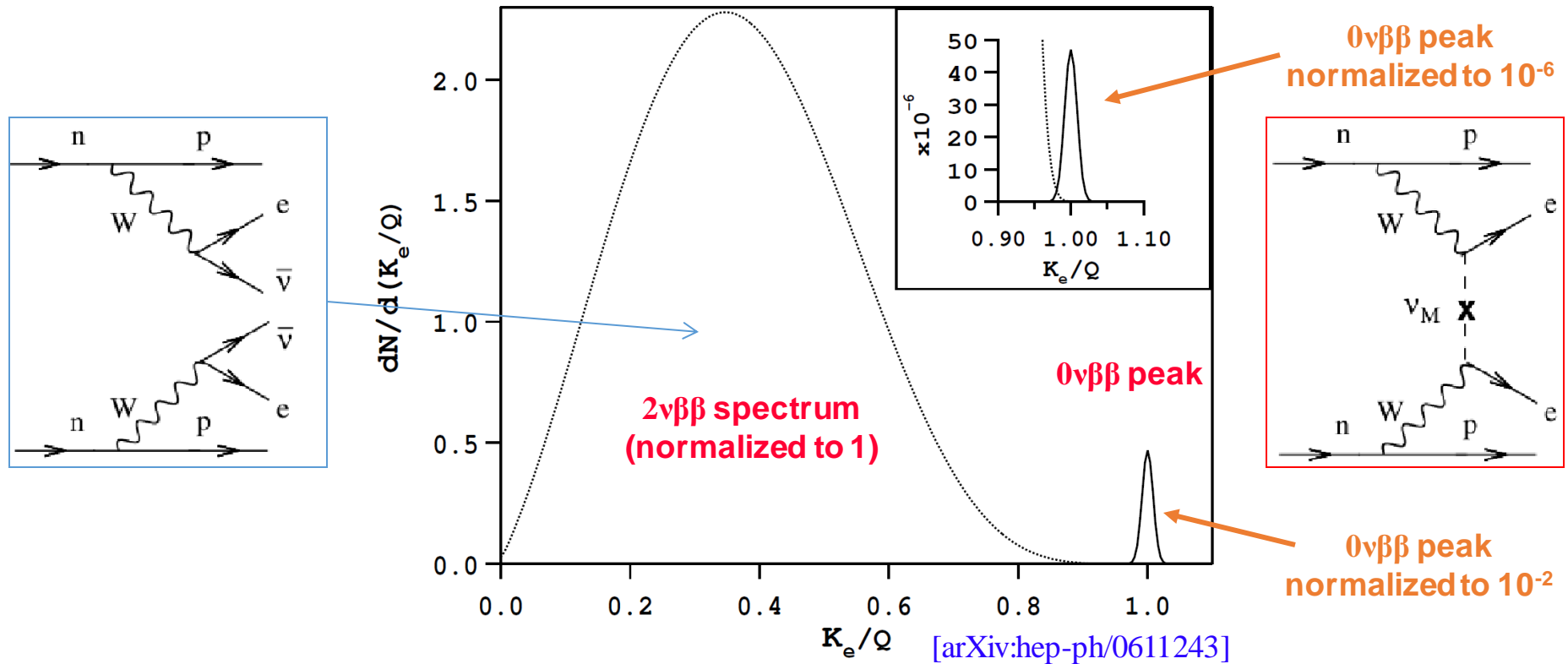


Ettore Majorana



This process can only occur for a Majorana neutrino!

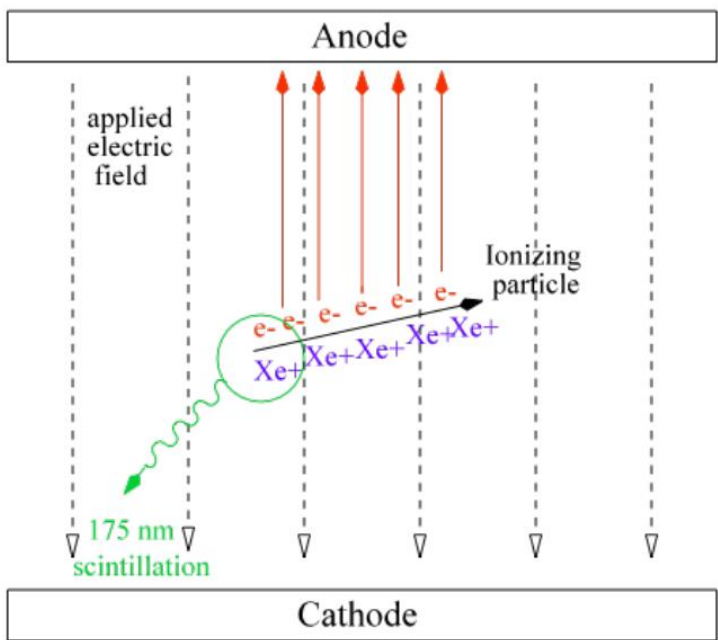
# Searching for $0\nu\beta\beta$



**An observation could provide some insight into the nature of  $\nu$ :**

- What is the absolute mass scale? How heavy is the neutrino?
- Why is the neutrino mass so small?
- **What is the nature of the  $\nu$ : Dirac or Majorana?**

# Searching for $0\nu\beta\beta$ in $^{136}\text{Xe}$ with nEXO



## Liquid-Xe Time Projection Chamber

- Liquid Xe at 168K
- Cryogenic electronics in LXe
- Detection of scintillation light and secondary charges
- 2D read out of secondary charges at segmented anode
- Full 3D event reconstruction:
  1. Energy reconstruction
  2. Position reconstruction
  3. Event Multiplicity

### Natural radiation decay rates

A banana	~10 decays/s
A bicycle tire	~0.3 decays/s
1 l outdoor air	~1 decay/min
100 kg of $^{136}\text{Xe}$ ( $2\nu$ )	~1 decay/10 min

$0\nu\beta\beta$  decay >10000 x rarer than  $2\nu\beta\beta$   
 Age of universe  $1.4 \times 10^{10}$  years

$T_{1/2}^{0\nu} > 10^{25}$  years !!

→Need:

- high target mass
- high exposure
- low background rate
- good energy resolution



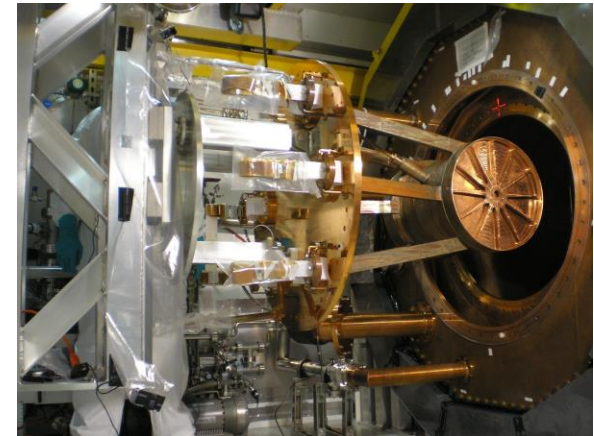
# EXO– Enriched Xenon Observatory

## The virtues of $^{136}\text{Xe}$ in a large TPC

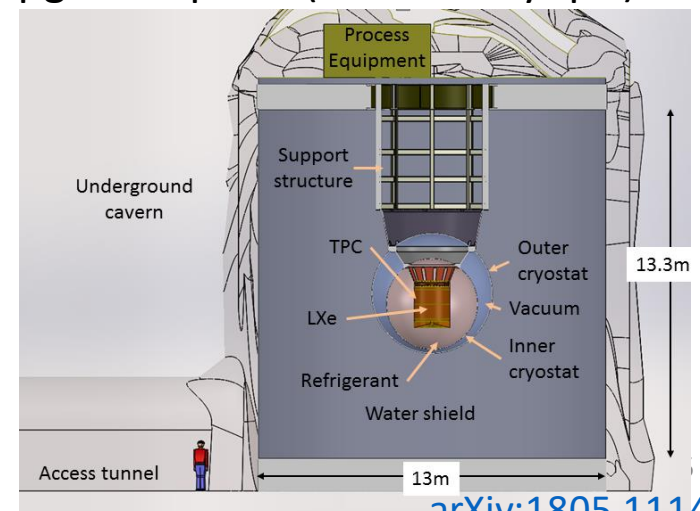
- **Easy to enrich**: 8.9% natural abundance but can be enriched relatively easily
- **Can be purified** continuously, and reused
- **High  $Q_{\beta\beta}$**  (2458 keV): higher than most naturally occurring backgrounds
- **Minimal cosmogenic activation**: no long-life radioactive isotopes
- **Energy resolution**: improves using scintillation and charge anti-correlation
- **LXe self shielding**
- Background can be potentially reduced by **Ba<sup>++</sup> tagging**

Phased approach:

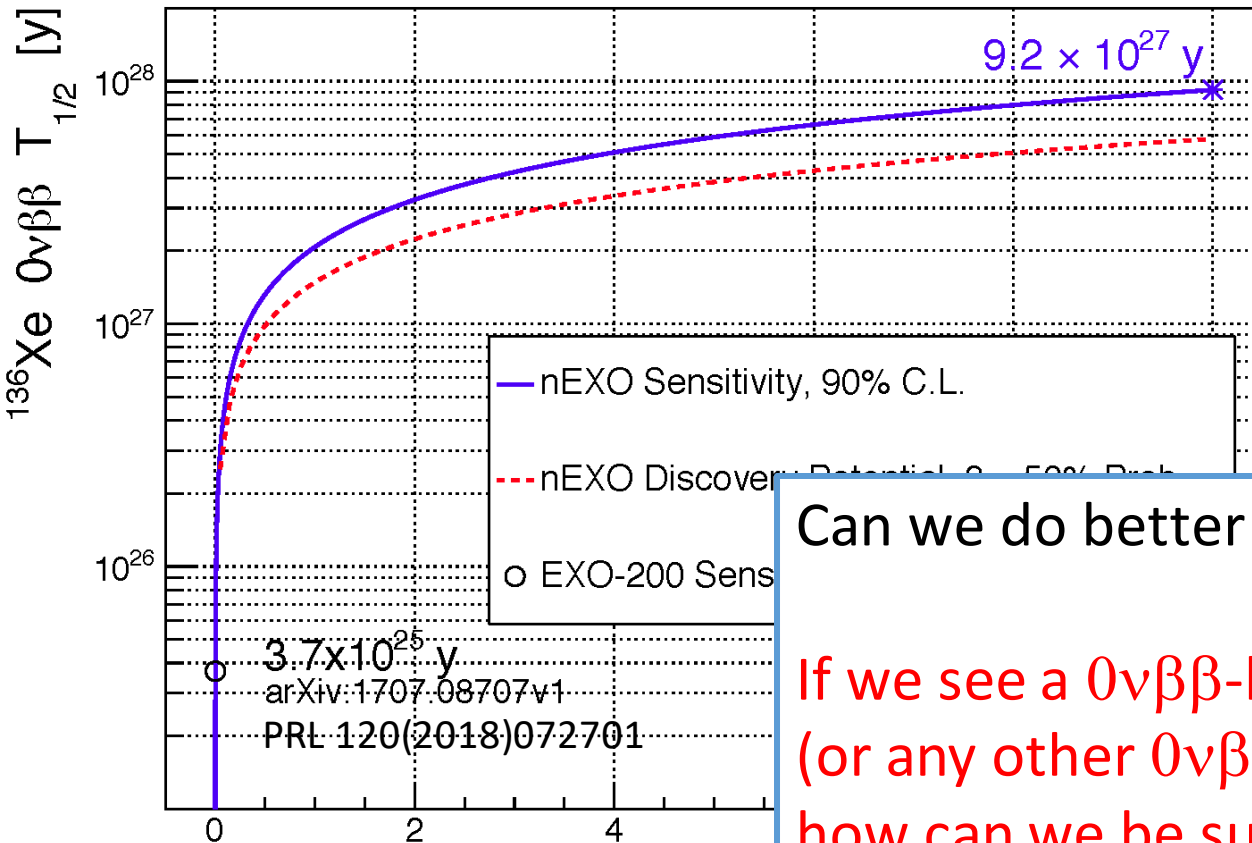
1. EXO-200: 200kg liquid-Xe TPC



2. nEXO: 5-ton liquid Xe TPC with Ba tagging upgrade option (SNO lab cryopit)



# nEXO Sensitivity & Discovery Potential



## Methodology:

- 3860 kg fiducial Xe
- 90% enrichment
- 1%  $\sigma E/E$  resolution
- Realistic background

Can we do better than this?

If we see a  $0\nu\beta\beta$ -like signal with nEXO (or any other  $0\nu\beta\beta$  detector), how can we be sure it really is  $0\nu\beta\beta$ ?

The answer might be Ba-tagging as a **future upgrade** to nEXO.

nEXO sensitivity

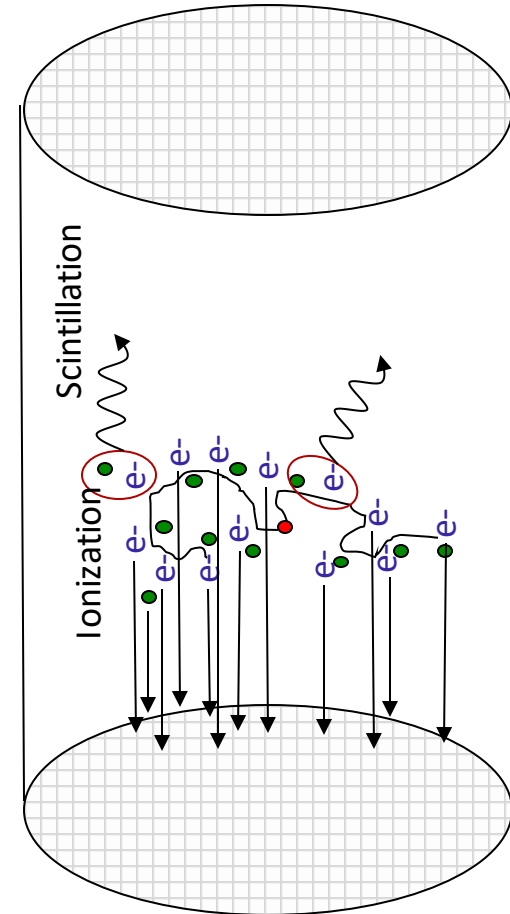
PRC 97(2018)065503, arXiv:1710

# Ba-tagging concept

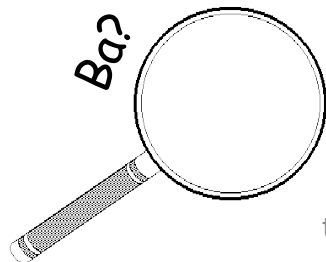
1. Is the event of interest?
  - Close to Q-value?
  - Beta-like event?
2. Localize event
3. Extract ion from detector volume and **separate it from Xe**
4. Identify ion: is it barium?



Anode

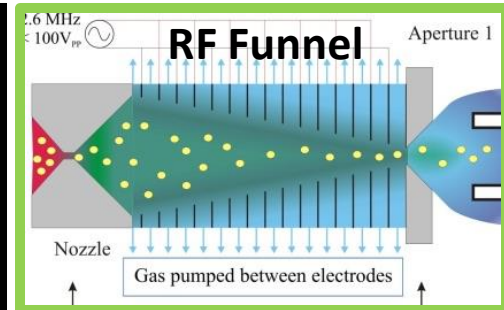
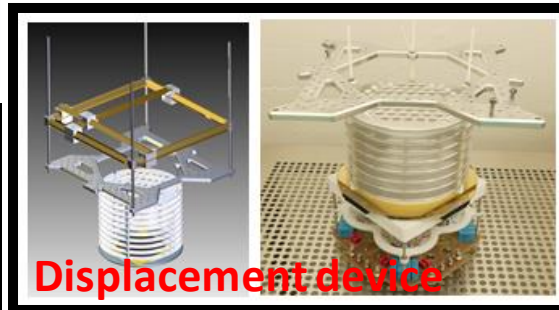
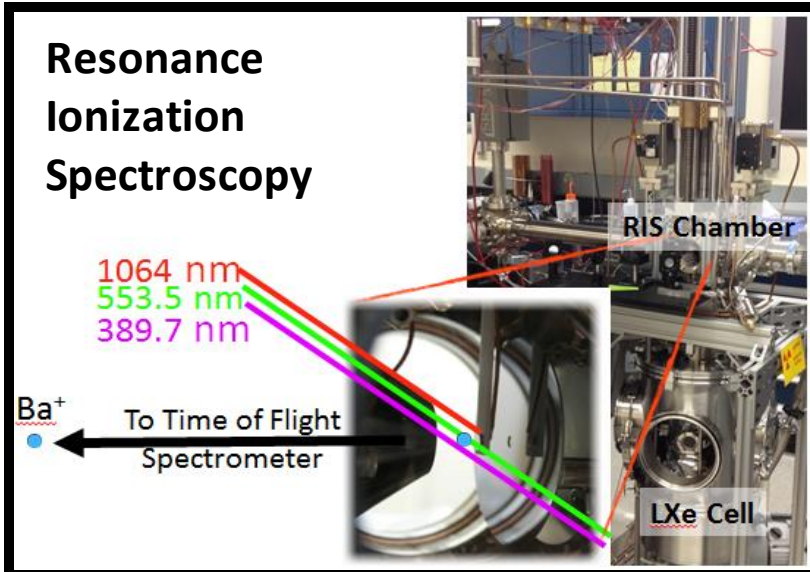
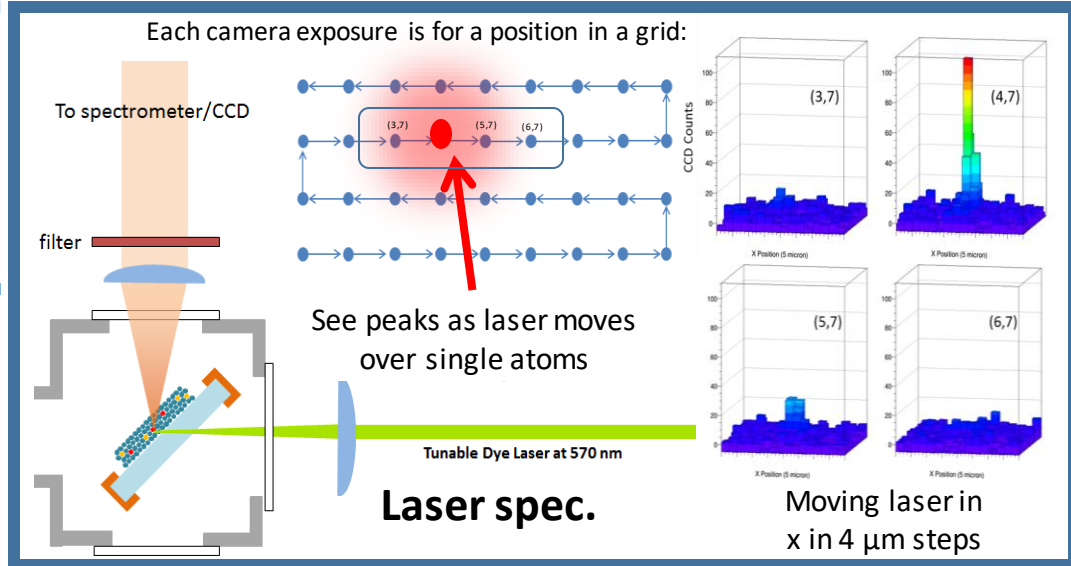
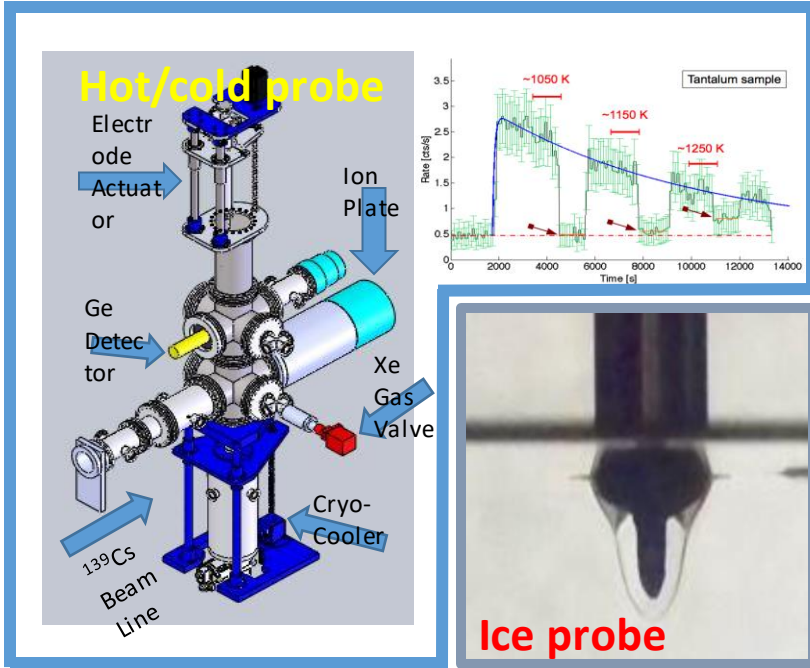


Cathode



Ba tagging R&D ongoing for liquid- and gas-phase detector

# Ba tagging for nEXO – a multi-faceted approach



## Recent nEXO Ba-tagging publications

Imaging individual Ba atoms in solid xenon for barium tagging in nEXO  
C. Chambers, et al., [arXiv:1806.10694](https://arxiv.org/abs/1806.10694), submitted to Nature.

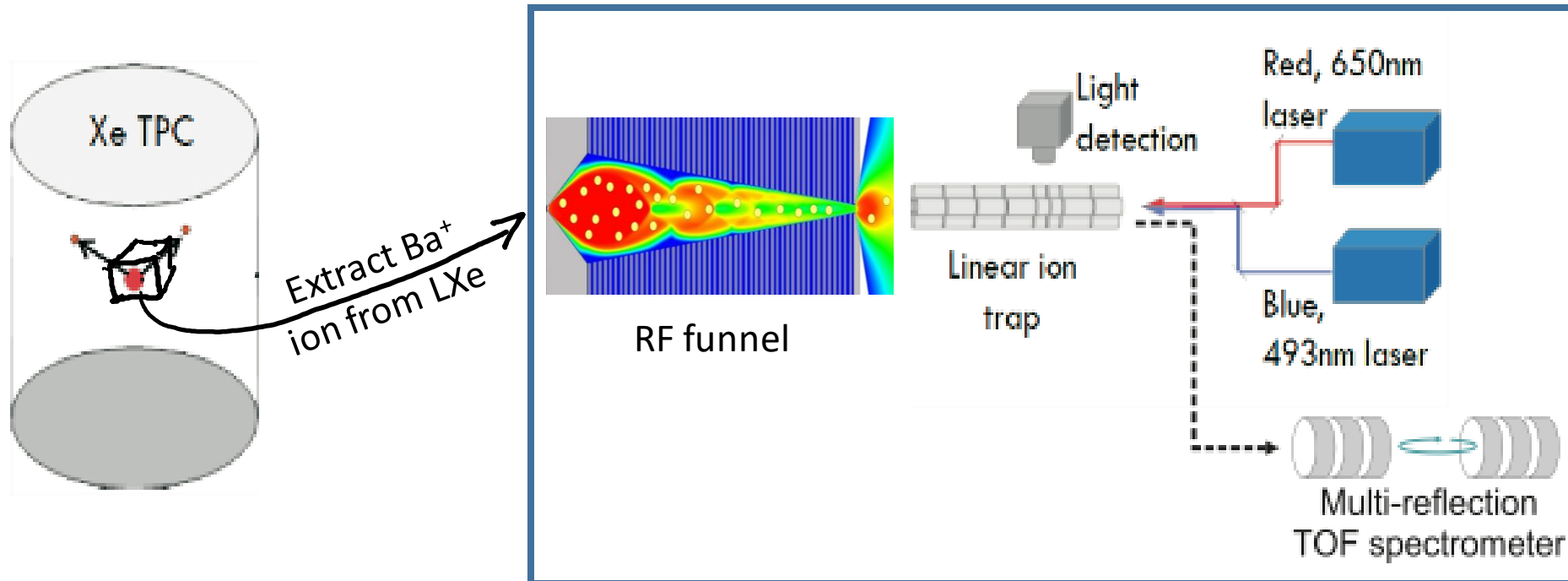
An RF-only ion-funnel for extraction from high-pressure gases  
T. Brunner, et al., *Int. J. Mass Spec.* 379, 110 (2015), [arXiv:1412.1144](https://arxiv.org/abs/1412.1144).

Spectroscopy of Ba and Ba<sup>+</sup> deposits in solid xenon for barium tagging in nEXO  
B. Mong, et al., *Phys. Rev. A* 91, 022505 (2015), [arXiv:1410.2624](https://arxiv.org/abs/1410.2624).

An apparatus to manipulate and identify individual Ba ions from bulk liquid Xe  
K. Twelker et al., *Rev. Sci. Instrum.* 85, 095114 (2014), [arXiv:1407.0618](https://arxiv.org/abs/1407.0618).

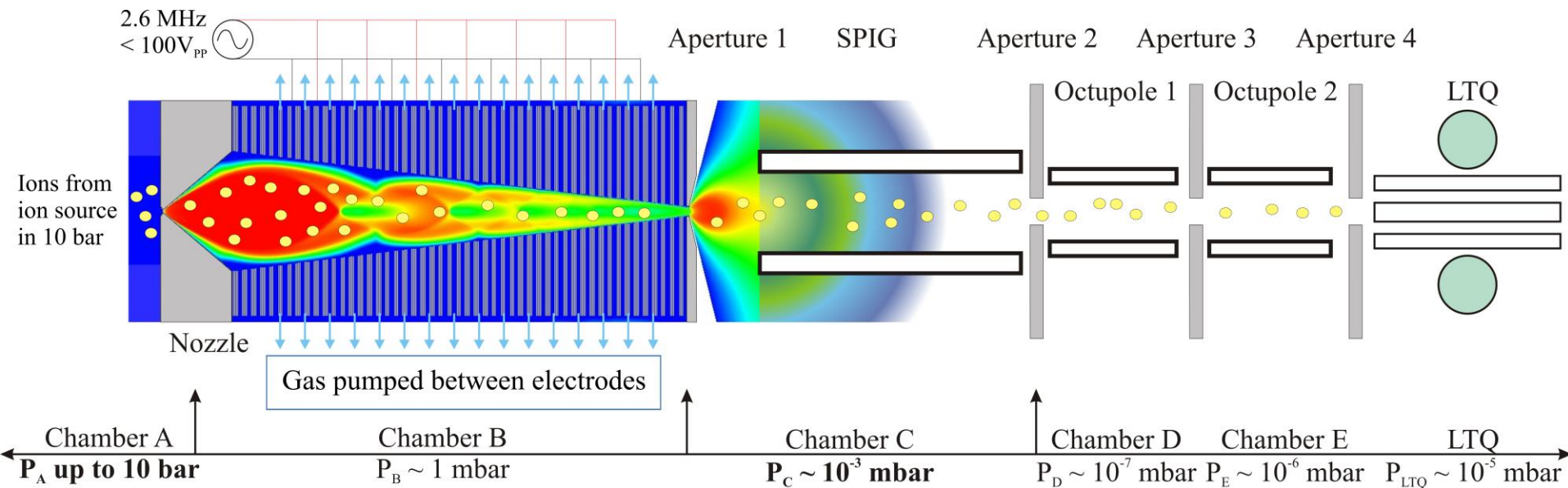


# Concept: nEXO RF-funnel based Ba-ion extraction and identification



- Extract Ba<sup>+</sup> from liquid Xe TPC into a Xe gas environment
- Extract Ba<sup>+</sup> with a Xe gas jet into a low pressure chamber
- After nozzle, pump Xe gas away and guide Ba<sup>+</sup> to identification

# RF-funnel ion extraction prototype



## RF-funnel concept by V. Varentsov:

- Converging-diverging nozzle
- 2 Stacks total 301 electrodes (0.1 mm thick)
- **0.25 mm electrode spacing**
- RF-field applied to electrodes
- **$P_0 = 10$  bar!** to 1 mbar in only one stage
- Xe gas is recaptured by a cryo pump

$$V_{RF} = 120 \text{ V}, f = 10 \text{ MHz}$$

Simulated funnel  $Ba^+$   
transmission  $\sim 95\%$

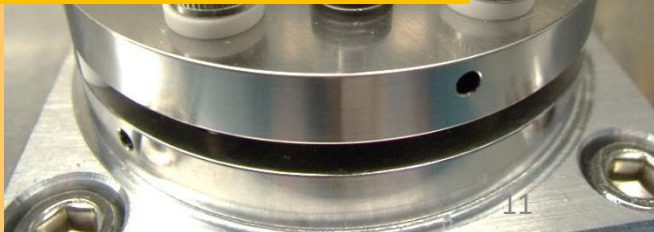
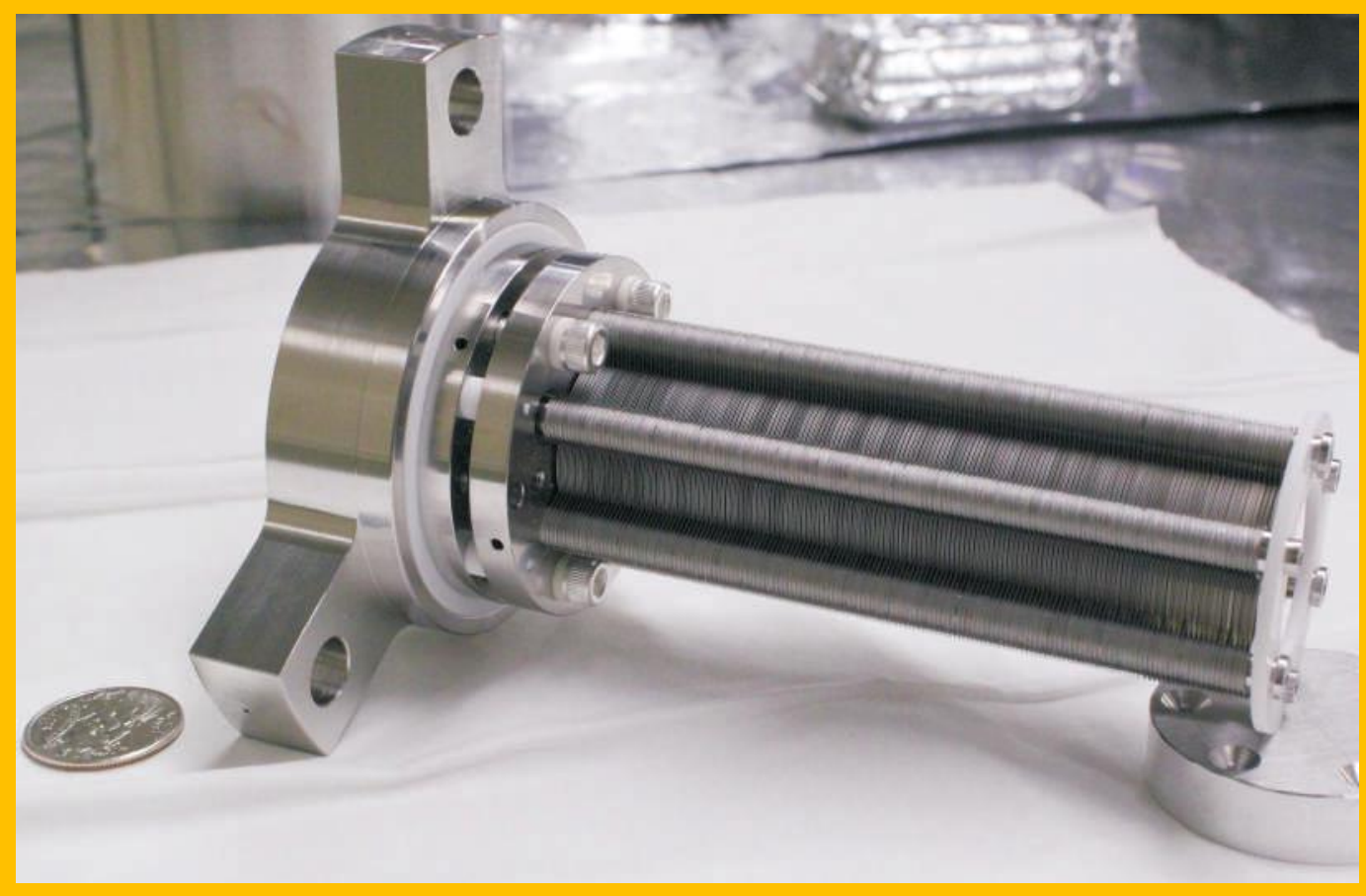
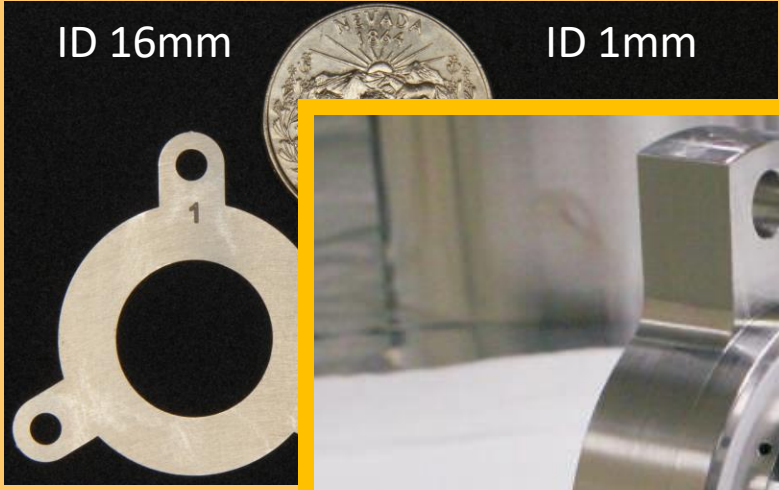
$$V_{RF} = 25 \text{ V}, f = 2.6 \text{ MHz}$$

Simulated funnel  $Ba^+$   
transmission  $\sim 72\%$

# RF-funnel assembly

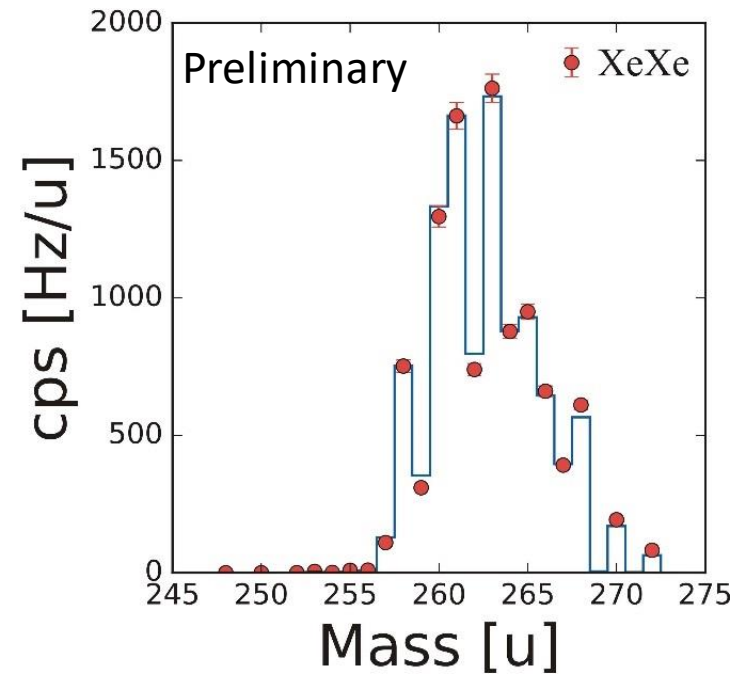
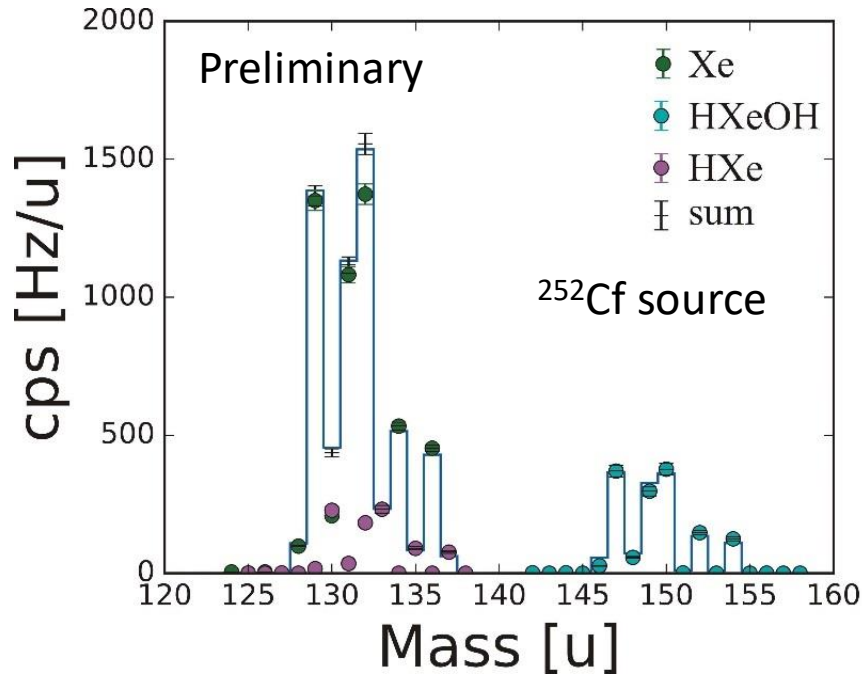
ID 16mm

ID 1mm



# Ion extraction in xenon gas

Spectra of ions extracted from 2.1 bar Xe

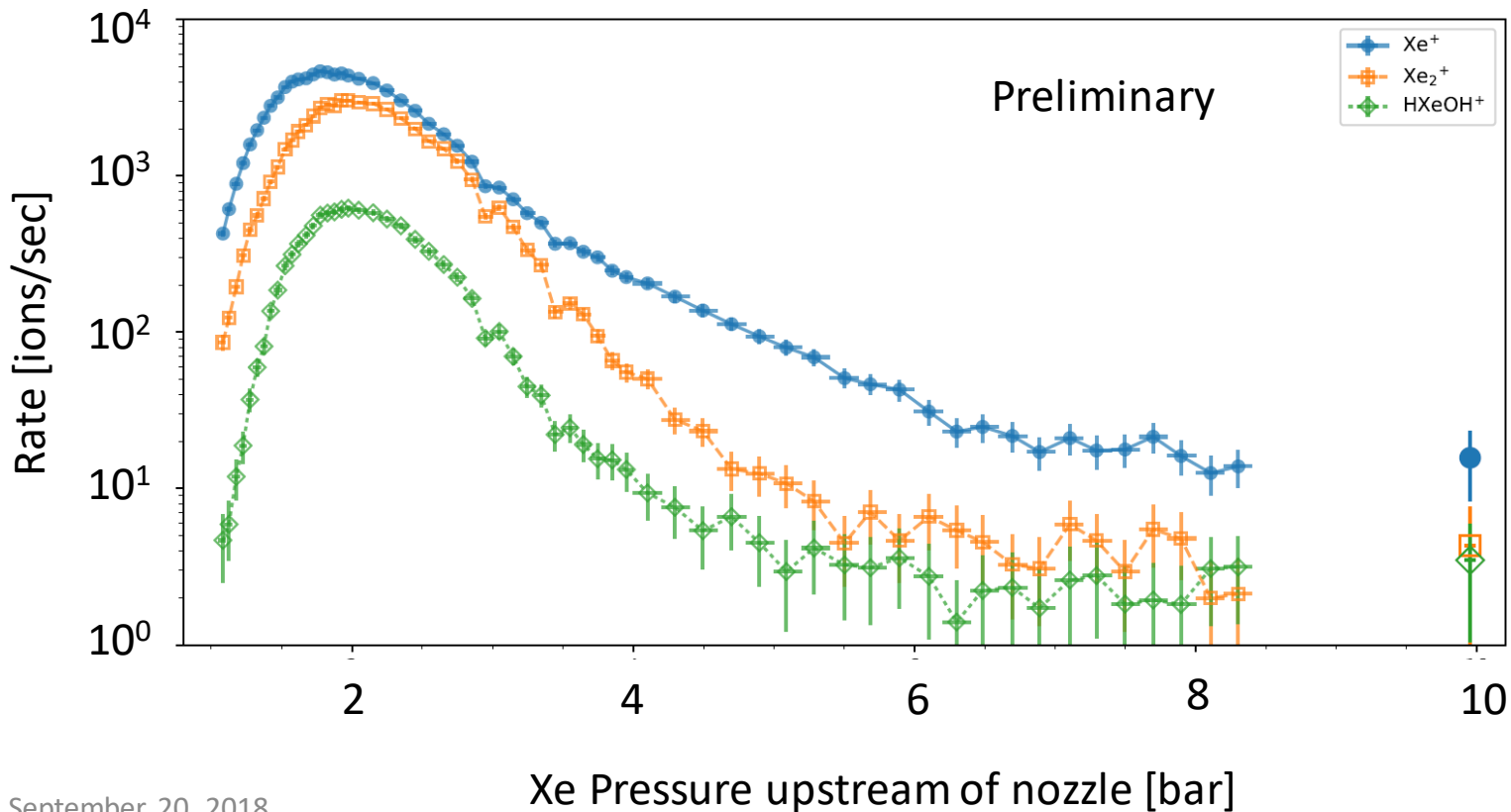


- Ions extracted up to 10 bar!
- Gd-148 and Cf-252 ion sources used
- Ions extracted from Ar, Kr, and Xe

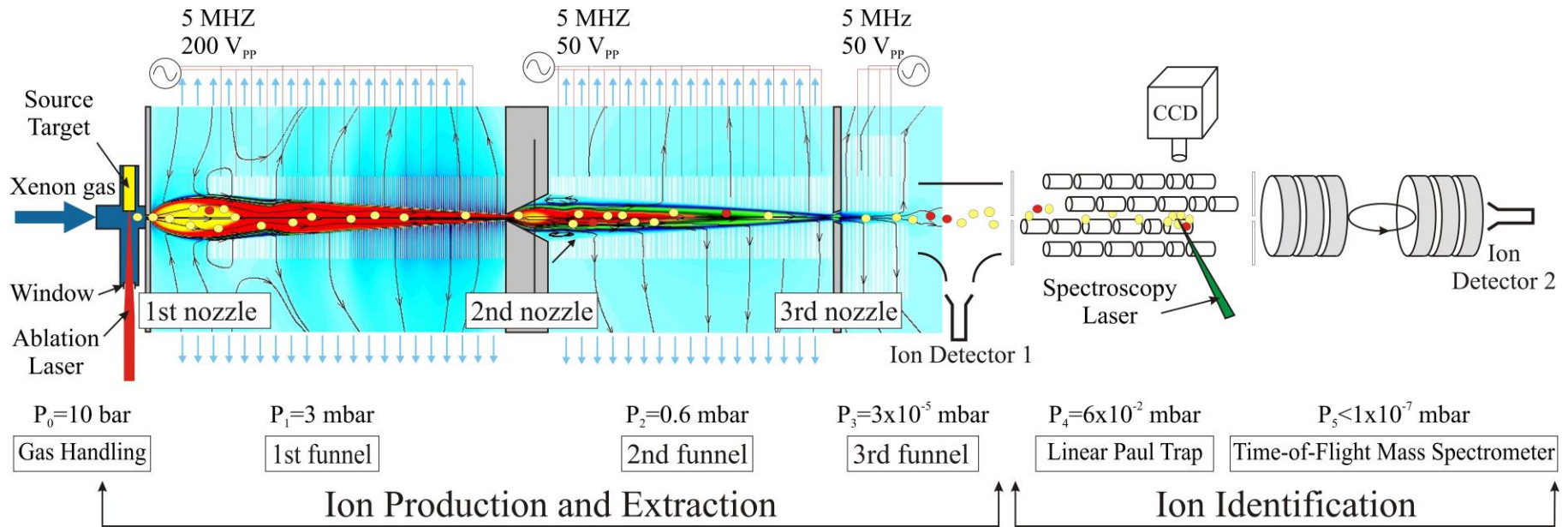
- Ba-ions not identified!
- Fission products not identified!
- Ion extraction efficiency unknown!

# Pressure dependant ion extraction

- Ion extraction from Xe gas using a  $^{252}\text{Cf}$  source ( $\sim 3\text{kBq}$ )
- Inconclusive results. System limited by:
  - Ion production method
  - Ion identification method

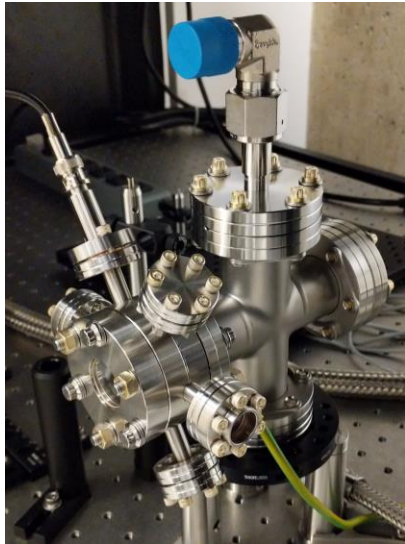


# Improved RF-funnel concept

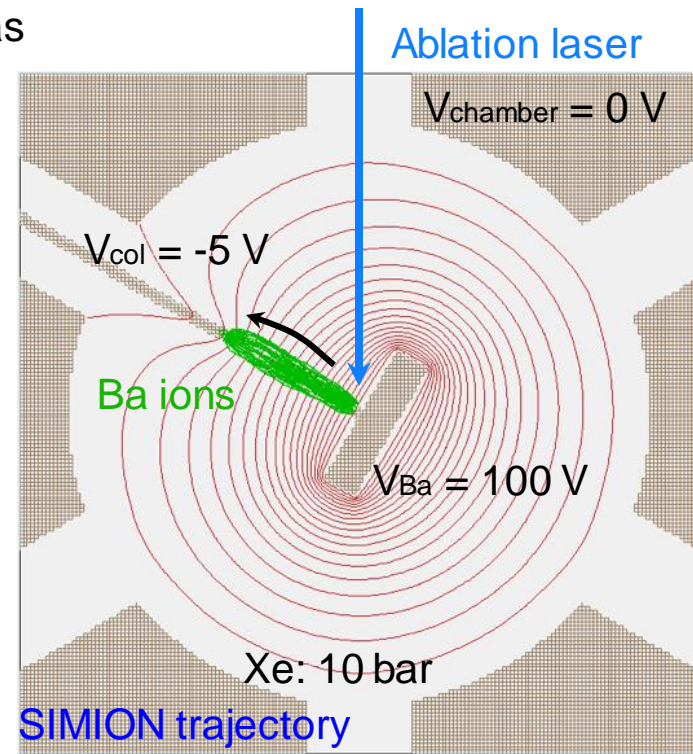
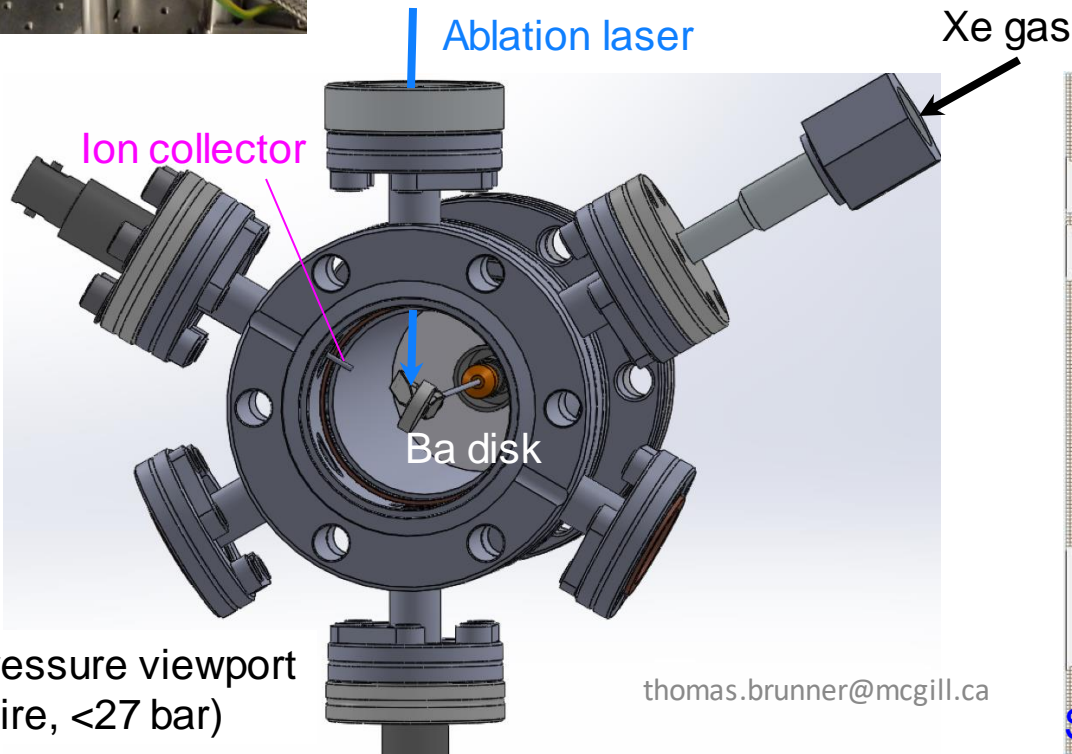


- Collaborative development of an improved ion-extraction system (Carleton, McGill, TRIUMF)
- Laser-ablation ion source in high pressure Xe gas
- Double (triple) RF funnel for improved operation → improved pumping
- Ba<sup>+</sup>-ion identification through laser-fluorescence spectroscopy (element specific)
- Ion identification via time-of-flight mass spectrometry (Greifswald/ISOLDE design)

# Setup for Laser Ablation Ion Source Test in High-Pressure Xe Gas



- Goals of Ba laser ablation source in high-pressure Xe gas
  - High-intensity: ion current reading ( $> \text{pA} = 10^6 \text{ ions/s}$ ) for absolute efficiency measurements of ion extraction through RF funnel
  - Cleaner ion beams: ideally fewer Xe ions and molecules



High-pressure viewport  
(Sapphire,  $< 27 \text{ bar}$ )

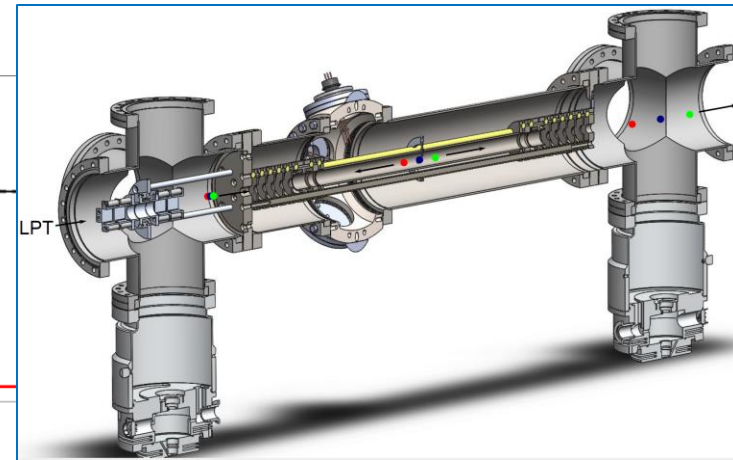
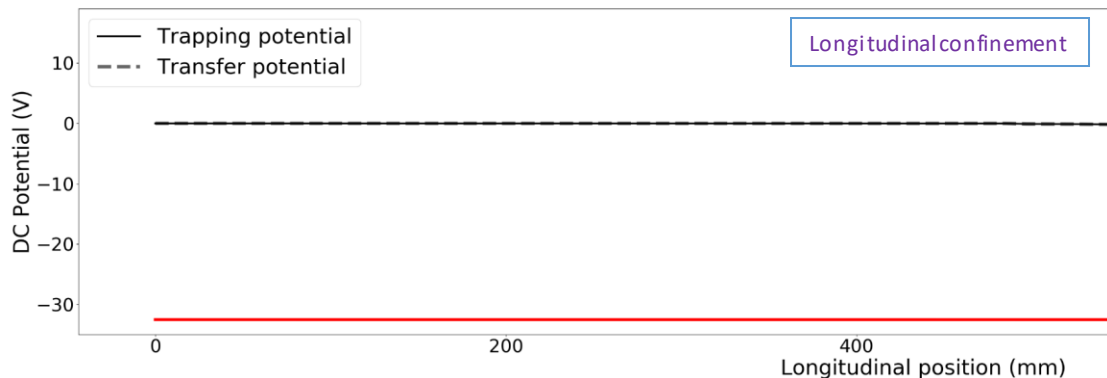
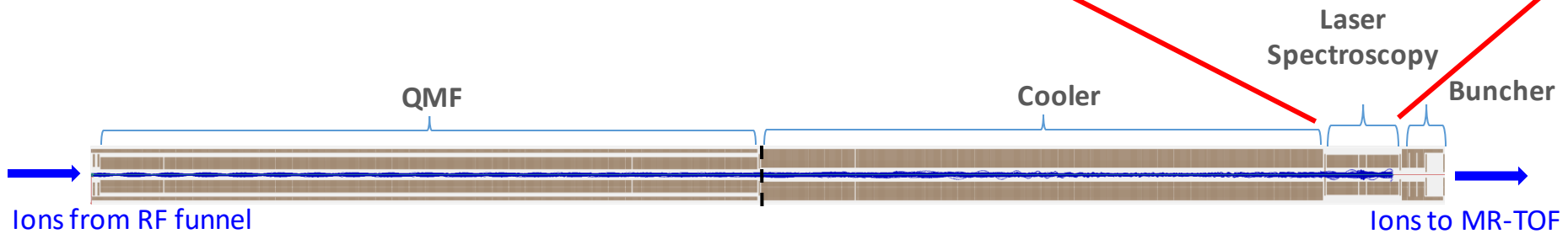
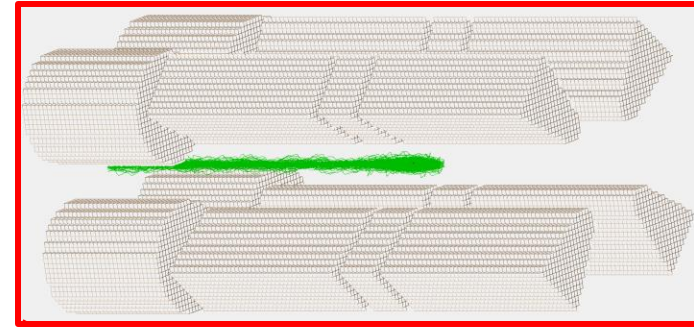
thomas.brunner@mcgill.ca

SIMION trajectory

# Linear Paul trap development

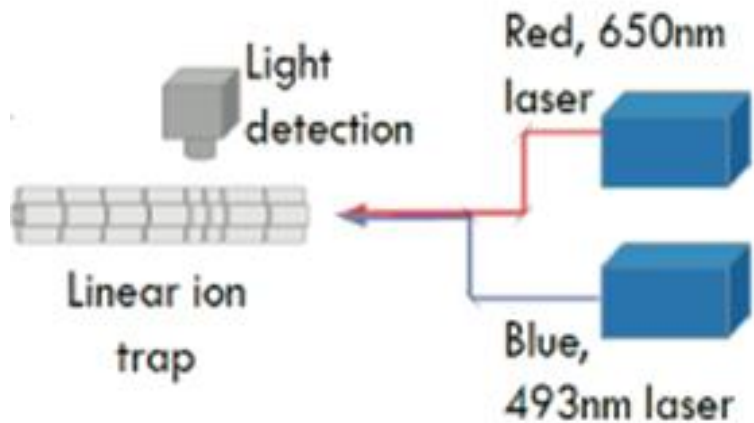
- Quadrupole mass filter (QMF): selectively transport ions of  $A/z=136$
- Cooler: Ion cooling with helium buffer gas
- Store ions for laser spectroscopy  $\rightarrow$  open geometry
- Bunch ions for a Multi-Reflection Time-of-Flight mass spectrometer (MT-TOF)

Optical access for laser spectroscopy

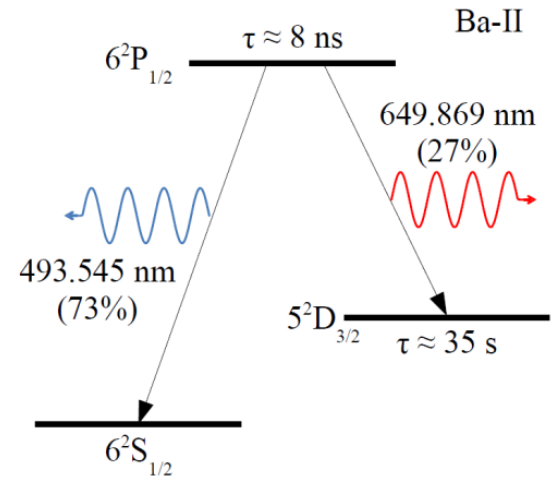




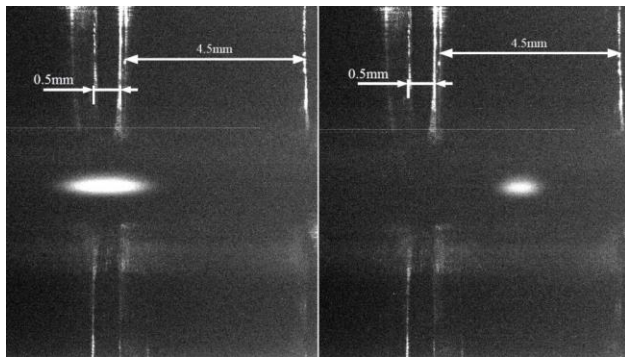
# Ba ion detection & identification



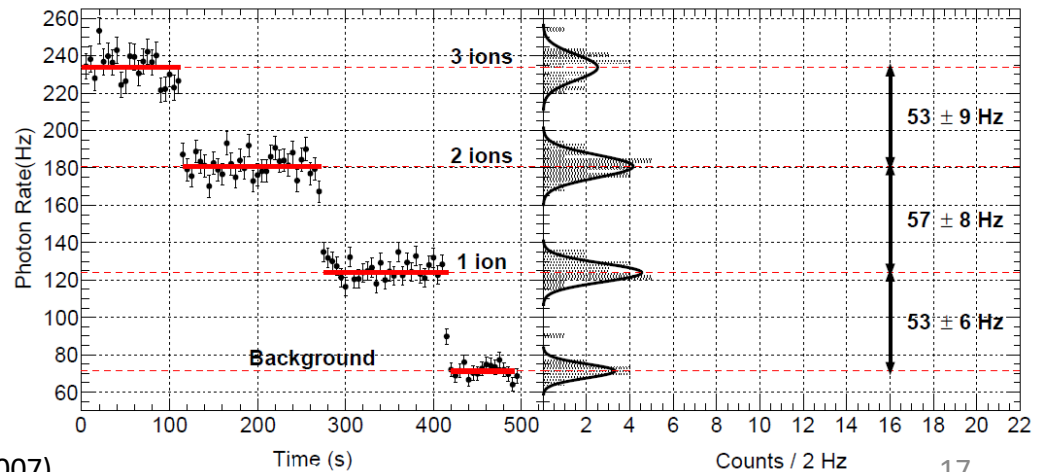
*Using a relatively simple and well understood fluorescing system*



*Demonstrated ion cloud imaging and accurate position control*



*Demonstrated single ion sensitivity using intermodulation technique (background control)*



# Summary and Outlook

- Observation of  $0\nu\beta\beta$  would imply new physics.
- Ba-tagging allows identification of  $0\nu\beta\beta$  events as true  $\beta\beta$ -decays.
- Ba-tagging is a challenging endeavor and the collaboration is exploring different approaches, one of them using a RF ion funnel.
- Ion-extraction from GXe of up to 10 bar has been achieved.
- Planned upgrades to the RF-funnel setup based on lessons learned  
→ Improve ion production and increase ion-detection sensitivity.



Recently renovated lab at McGill.  
We are looking for people to join  
our Ba-tagging developments.

# Thanks to the TITAN group at TRIUMF...



Especially Jens Dilling, Ania Kwiatkowski, Dan Lascar, Kyle Leach and Mel Good.

... and Victor Varentsov at GSI and FAIR (Germany).





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