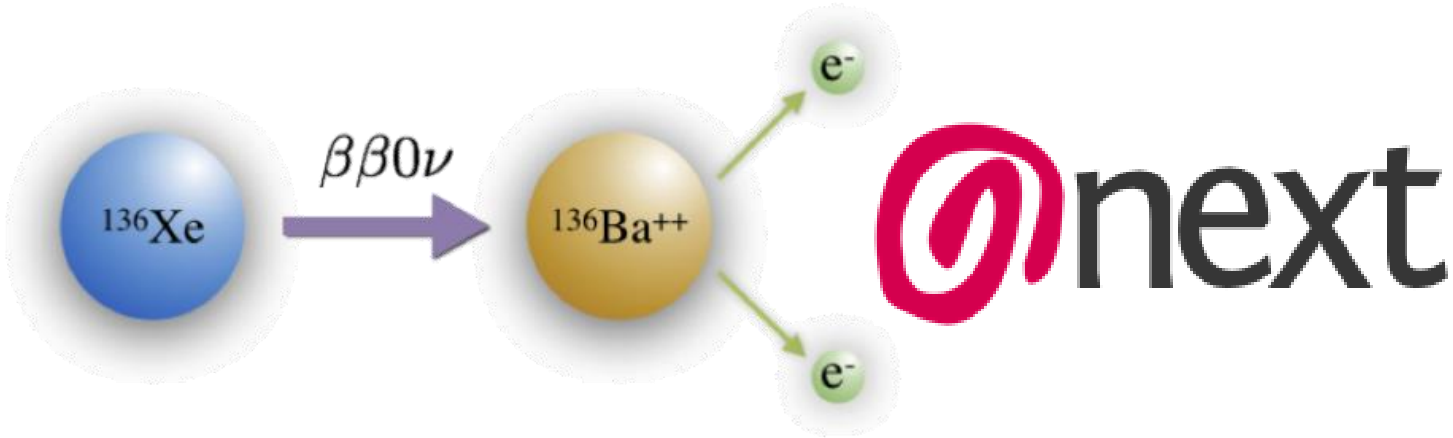
Ba-tagging with fluorescence bicolor molecules for background-free ββ0ν decay experiment



Detecting "tagging" the Ba^{++} signaling a ββ0ν process in TPC xenon chambers.

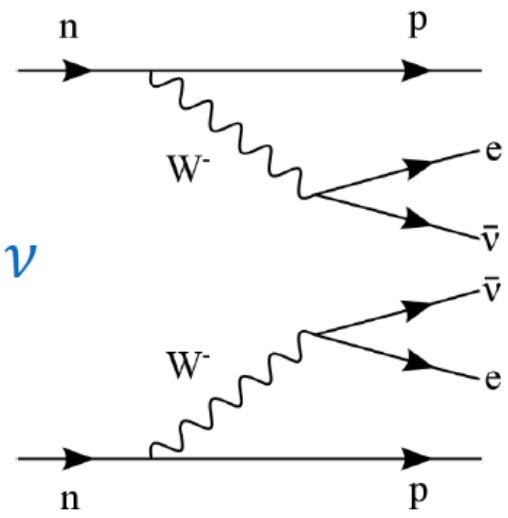
Ruben Gonzalez-Moreno on behalf of next

Zoraida Freixa[a,b] Iván Rivilla,[b,c] Borja Aparicio,[a] Pablo Herrero,[c,d] Francesc Monrabal,[b,c]
Celia Rogero,[d] Fernando P. Cossío,[a] Juan José Gómez-Cadenas[b,c]

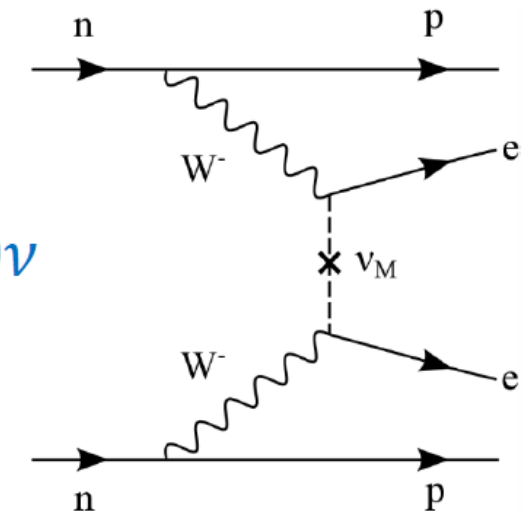
[a] University of the Basque Country (UPV/EHU), 20018 Donostia, Spain. [b] Ikerbasque, Basque Foundation for Science, 48009 Bilbao, Spain. [c] Donostia International Physics Center (DIPC), 20018 Donostia, Spain. [d] Materials Physics Center CFM (CSIC-UPV/EHU).20018, Donostia, Spain.

ββ0ν decay

$\beta\beta 2\nu$



$\beta\beta 0\nu$



$$ {}^{A}_{Z}X \longrightarrow {}_{Z+2}^{A}X + 2e^{-} + 2\bar{\nu}_e + Q_{\beta\beta} $$

$\Delta L = 0 \Rightarrow \bar{\nu}_e$ can be a Dirac or Majorana
Observed in 11 isotopes
$T_{1/2} \sim 10^{19} - 10^{21} y$

$Q_{\beta\beta}$ shared among 4 particles

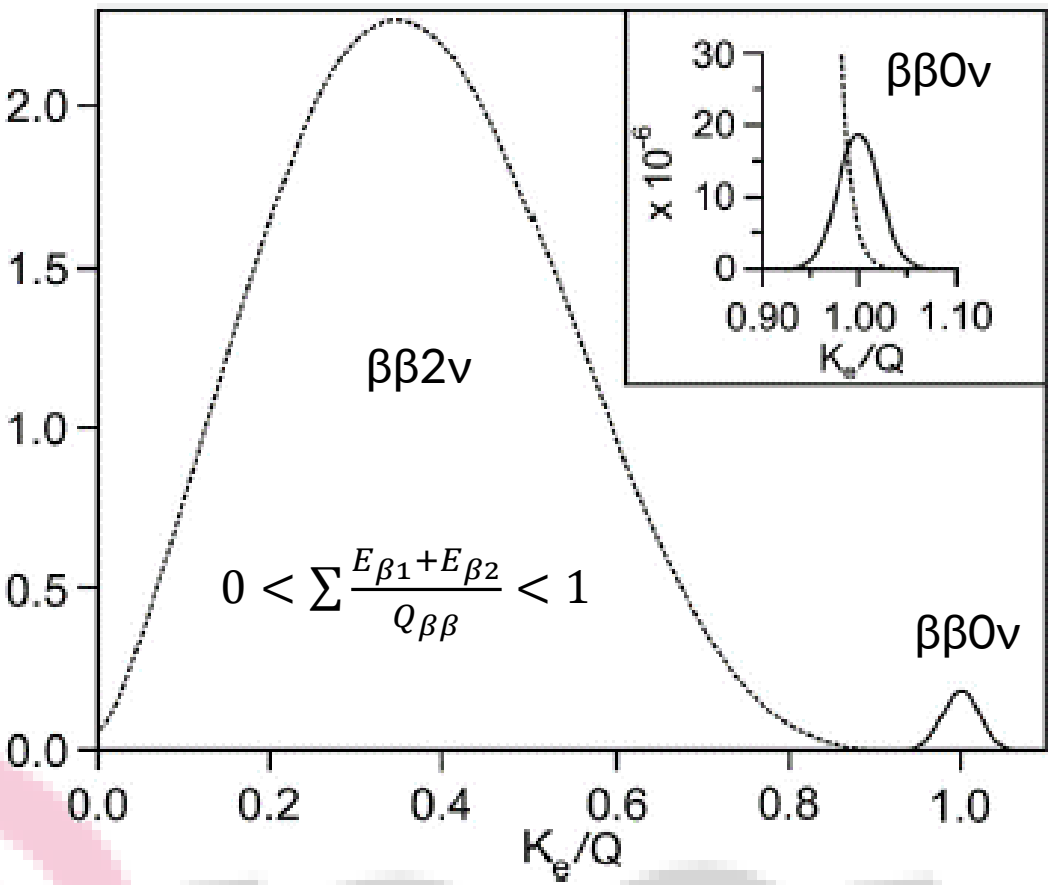
$$ {}^{A}_{Z}X \longrightarrow {}_{Z+2}^{A}X + 2e^{-} + Q_{\beta\beta} $$

$\Delta L = 2 \Rightarrow \bar{\nu}_e$ must be a Majorana
Not observed, yet!!
$T_{1/2} > 10^{26} y$

$Q_{\beta\beta}$ = electrons kinetic energy

Detection of ββ0ν

The observables in direct searches of ββ0ν decay are the kinematic parameters of the two emitted electrons.

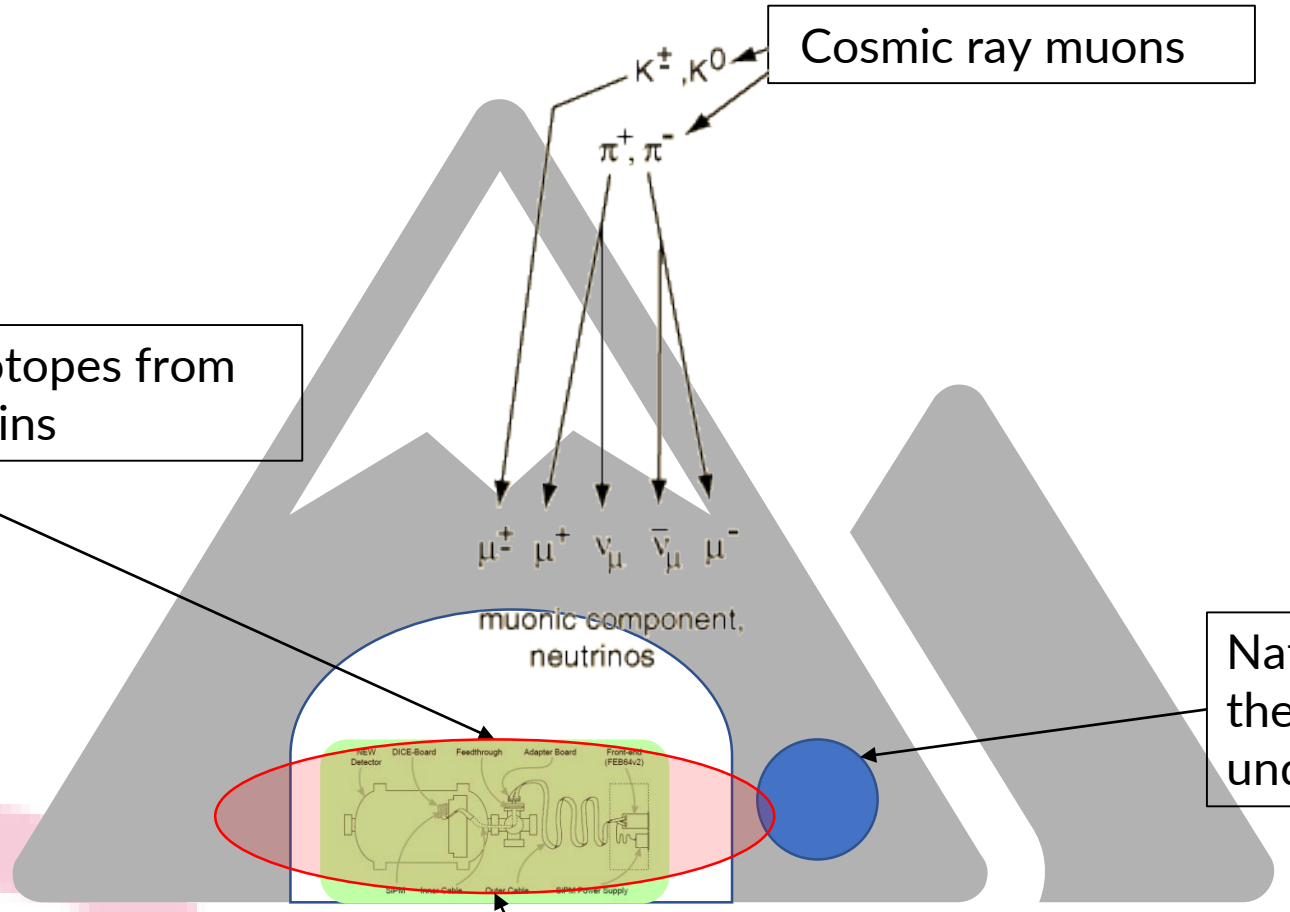


$$\sum \frac{E_{\beta 1}+E_{\beta 2}}{Q_{\beta\beta}} = 1$$

Orio, F., 2016. Nucl. Part. Phys. Proc. 273-275, 1795-1800.

Background matters

Background sources



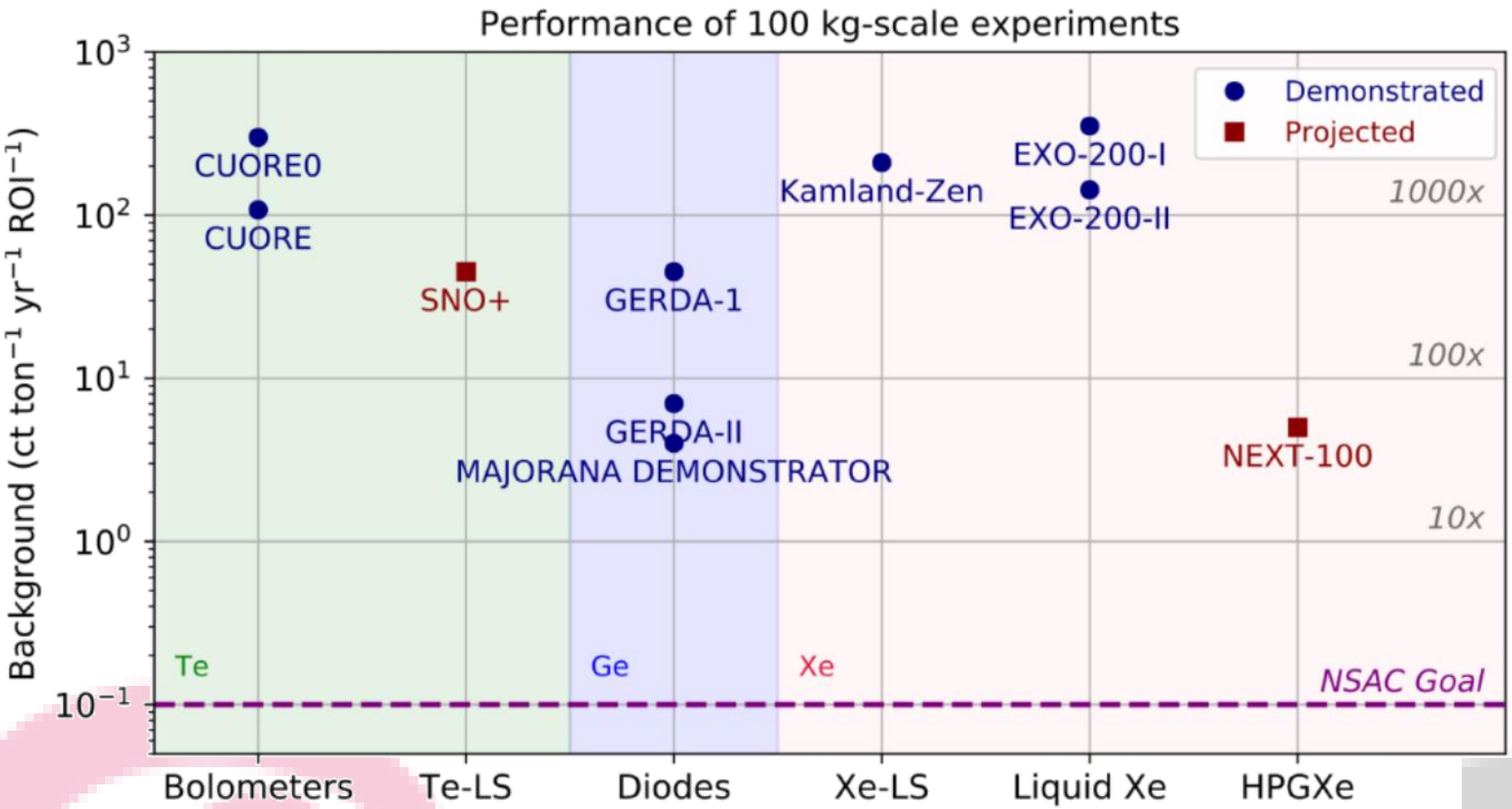
Cosmic ray muons

Trace amount of radioisotopes from the natural U and Th chains

Natural radioactivities from the rock walls of underground laboratory

Cosmogenic production of radioisotopes in situ

Background reduction

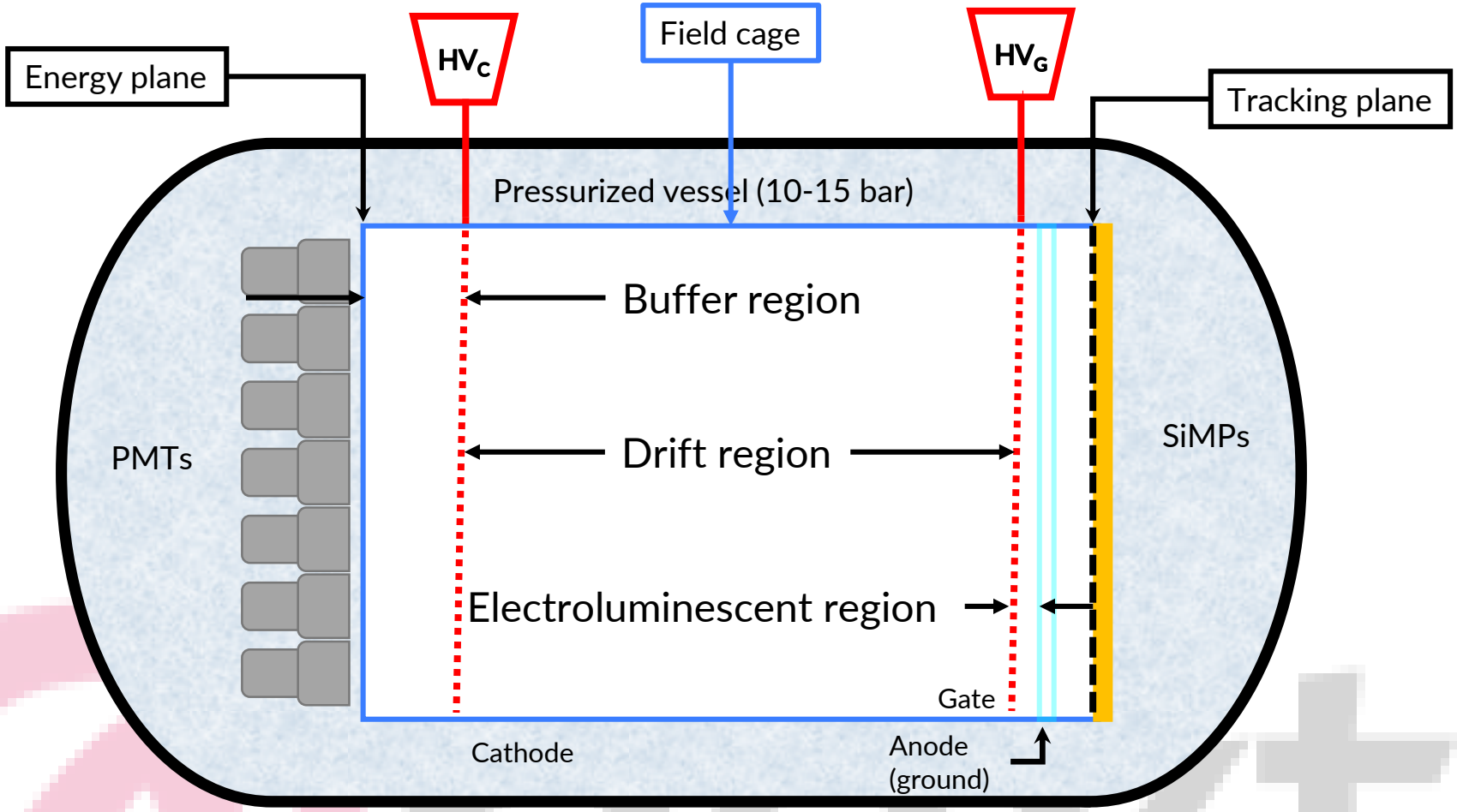


NEXT collaboration

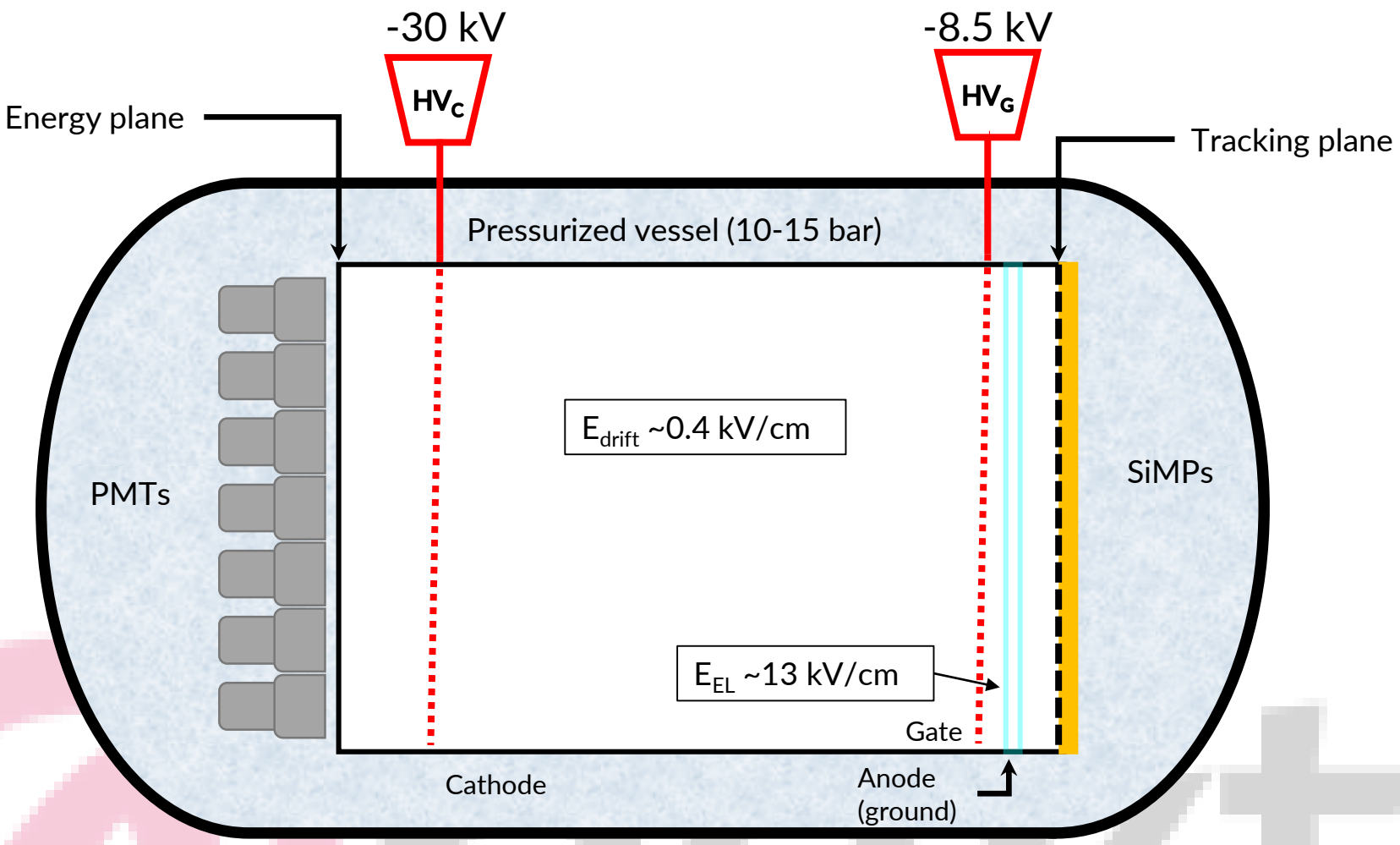
Neutrino Experiment with Xenon TPC

- Search for $\beta\beta0\nu$ in ^{136}Xe in a *high pressure xenon gas* time projection chamber (TPC).
- High pressure (10-15 bar) is required to assemble enough mass in reasonable volume.
- Working in gas allows:
  - Excellent energy resolution (already 1%, aiming at ~0.5% at $Q_{\beta\beta}$ =2.458 MeV)
  - Track topology enables discriminating γ-induced electrons from $\beta\beta$ events
- Currently operating NEXT-White (~10kg of Xe enriched to 91% ^{136}Xe), moving to NEXT-100 (100 kg)
- Radiopure detector, running under the Pyrenees at Laboratorio Subterráneo de Canfrac (LSC)

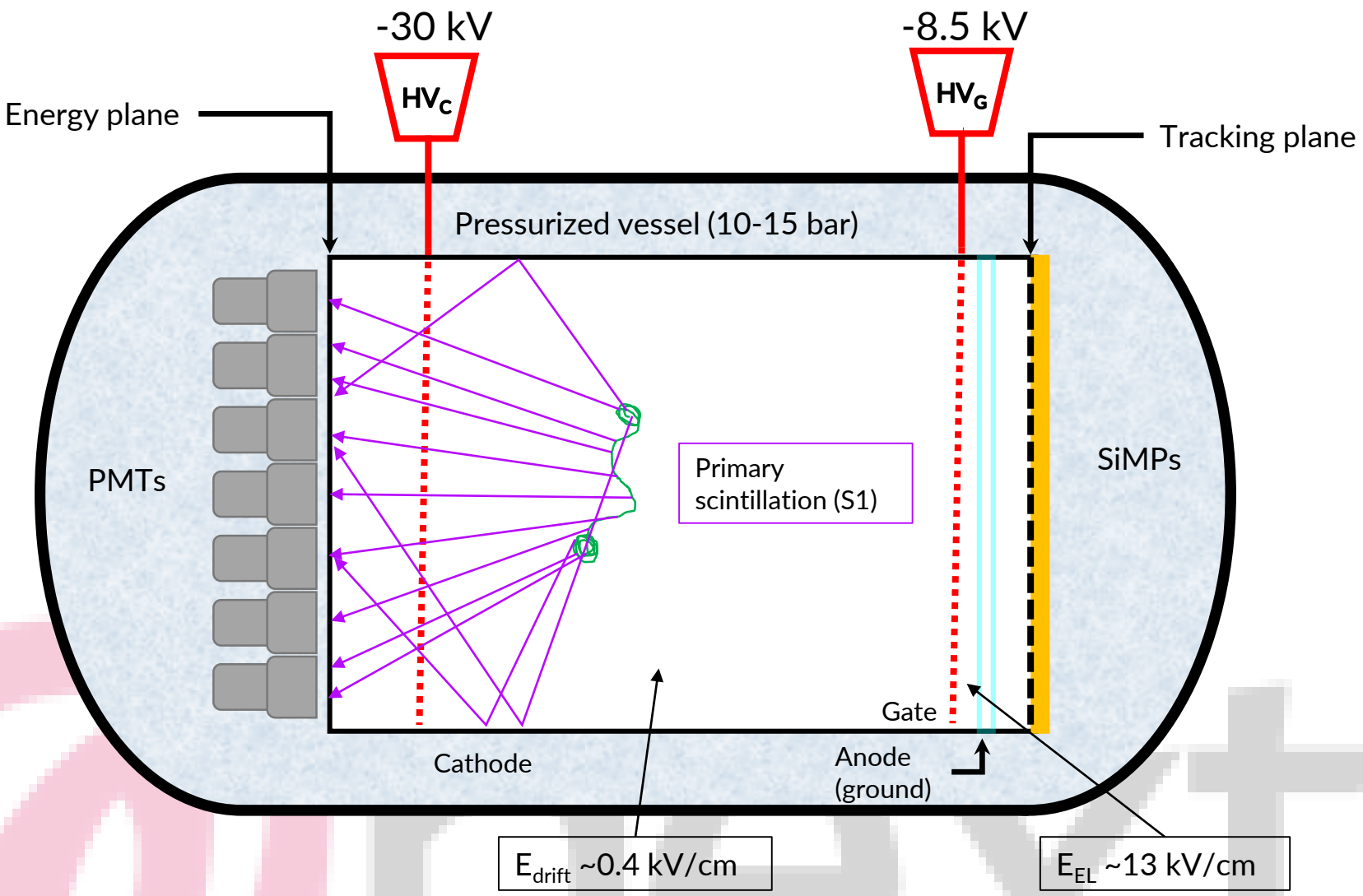
TPC-HPXe136 EL detection at NEW



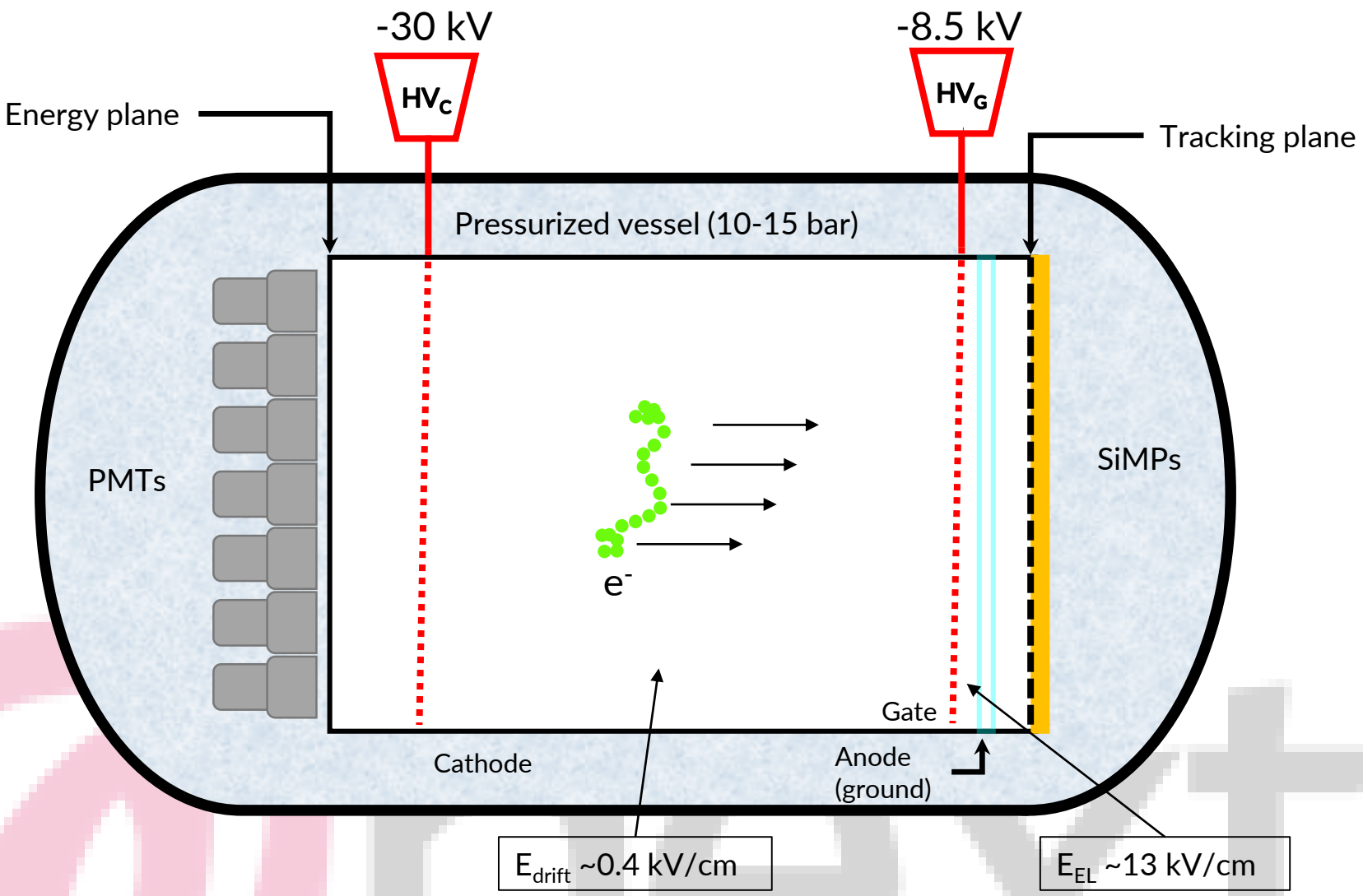
TPC-HPXe136 EL detection at NEW



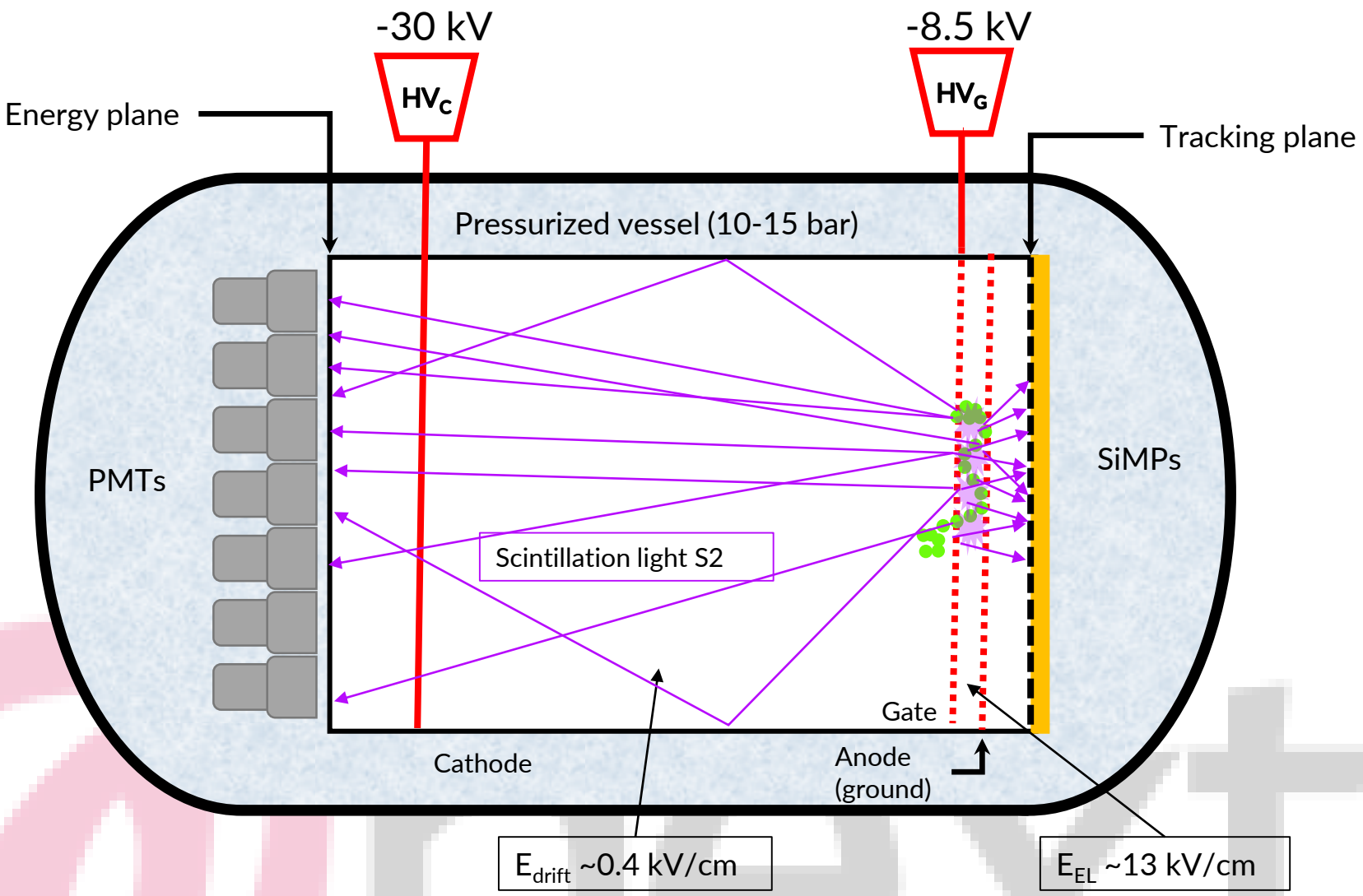
TPC-HPXe136 EL detection at NEW



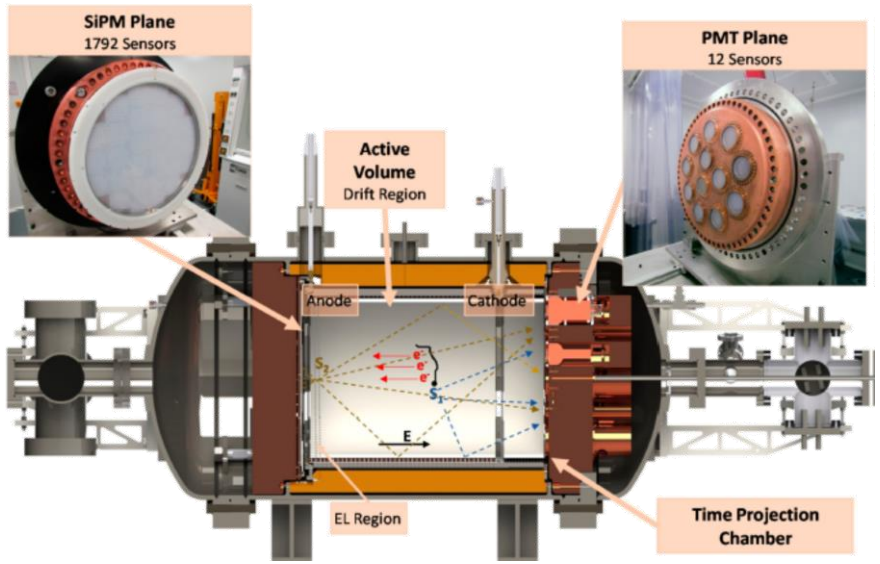
TPC-HPXe136 EL detection at NEW



TPC-HPXe136 EL detection at NEW

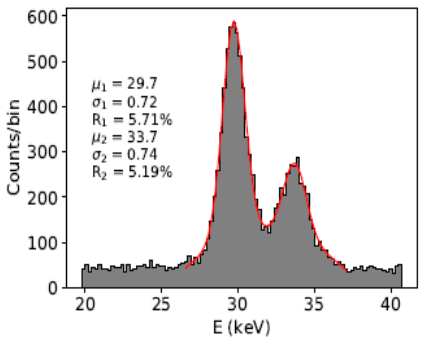


NEW: NEXT-White running…

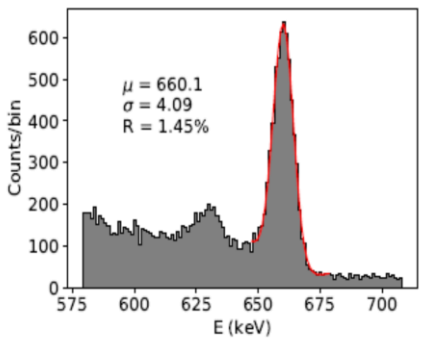


Energy resolution ~1% FWHM

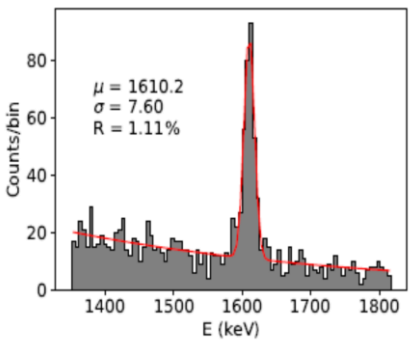
Xe x-ray peaks



^{137}Cs photo-peak



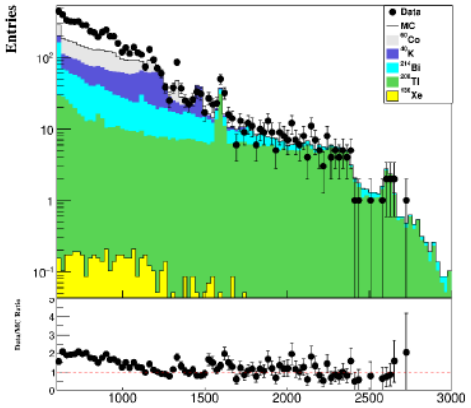
Double-escape peak

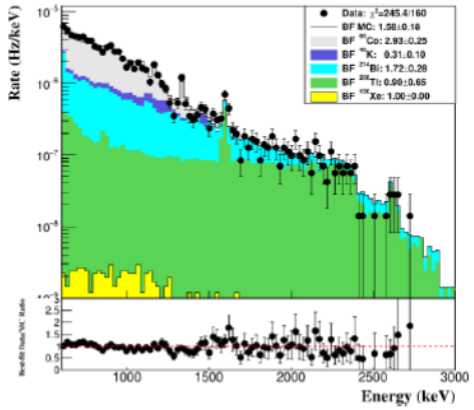


$$\frac{\Delta E}{E(Q_{\beta\beta})} = (1.02 \pm 0.09)\%\ FWHM$$

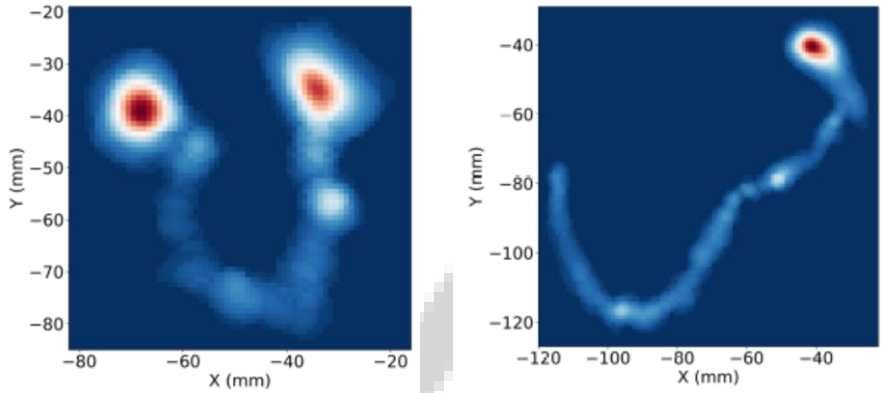
J. Renner *et al.*(NEXT collaboration), 2018 *JINST*13 P10020, arXiv:1808.01804.

Background characterization



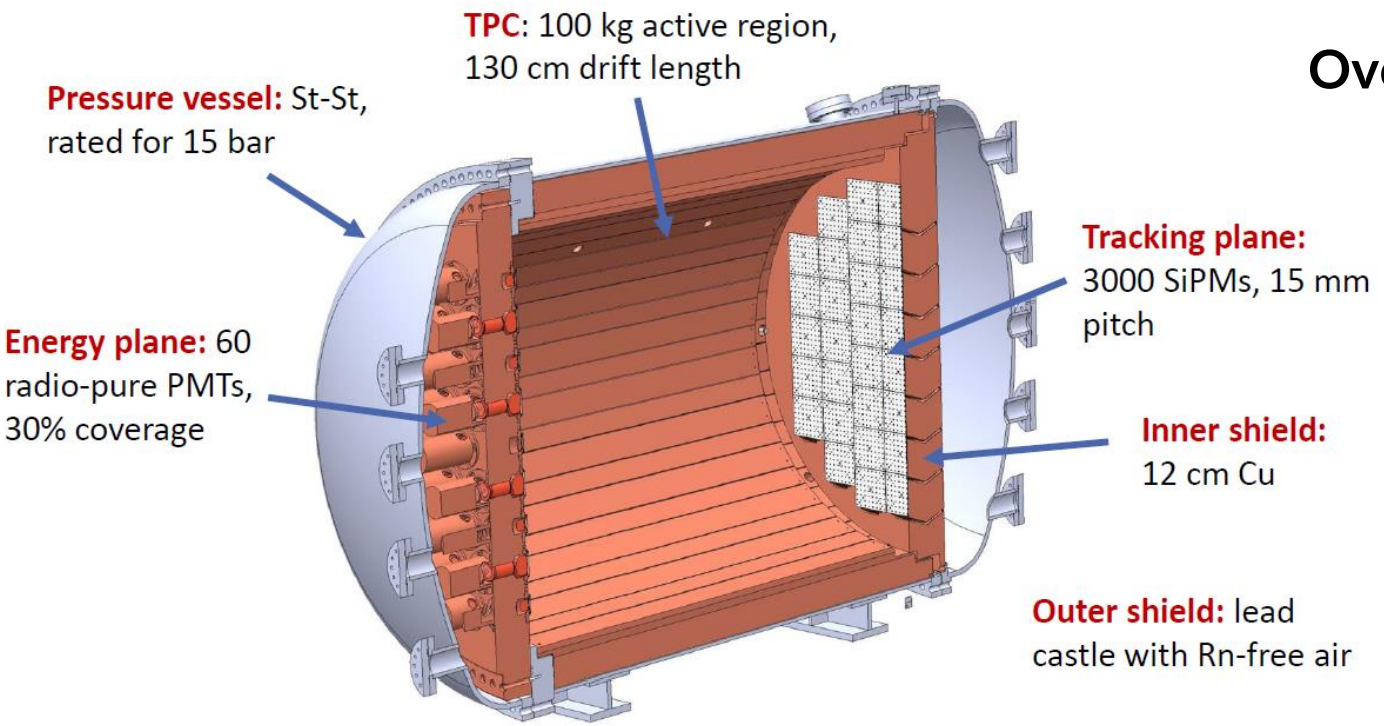


Blobs background discrimination



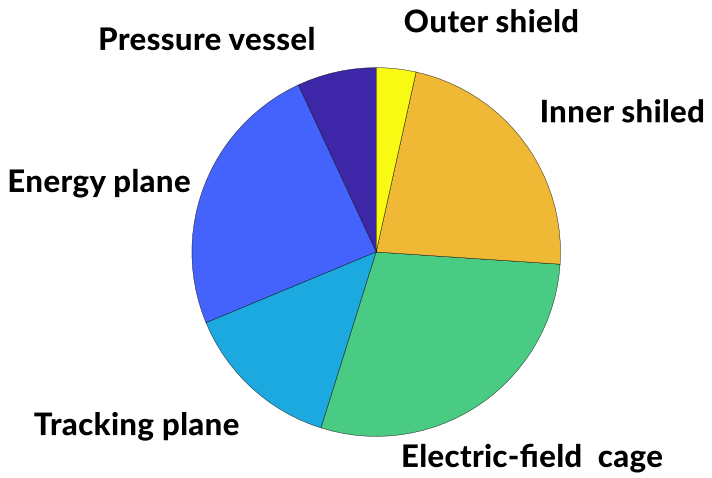
A.Simón *et al.*(NEXT collaboration), 2021, arXiv:210511931v1

NEXT: challenges ahead. NEXT-100



Overall detector background rate for NEXT-100

$< 4 \times 10^{-4}\ [cts\ keV^{-1}\ kg^{-1}\ year^{-1}]$



External sources of background rate for NEXT-100

$< 10^{-5}[cts\ keV^{-1}\ kg^{-1}\ year^{-1}]$ or below

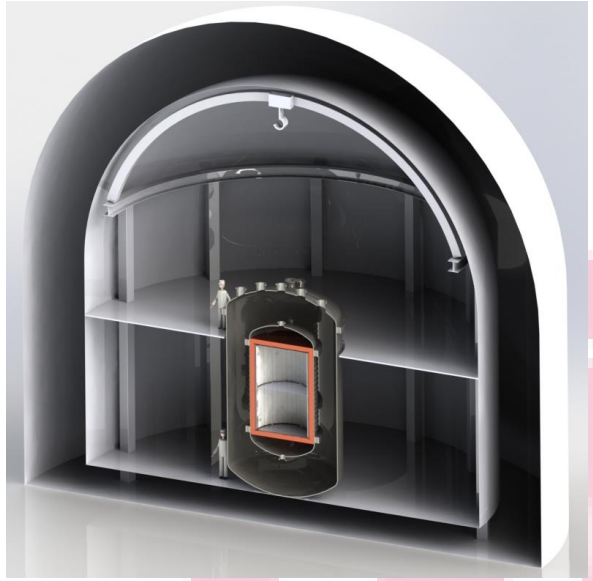
Virtually background free for 100kg-scale ➡ $T_{1/2}^{0\nu} < 10^{26} y$

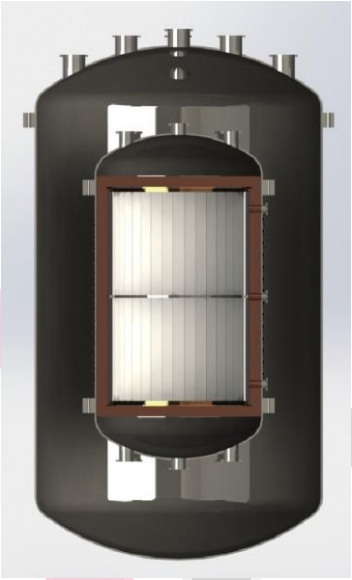
NEXT: Last (but one?) Goal. NEXT-Ton

$$Ton - scale\ generation\ goal \Rightarrow T^{0\nu}_{1/2} < 10^{28} y$$

NEXT: Two approaches developed in parallel

- Phase 1, *High Definition*: incremental approach, using/improving existing technology.
  - Background budget reduction ➡ PMTs replacement by SiPMs (cold operation)
  - Background rejection improvement ➡ e^- diffusion reduction in gas mixtures ($Xe\text{-}CH_4$)
- Phase 2, Barium Tagging: based on disruptive new concept (SMFI Ba^{++} tagging)





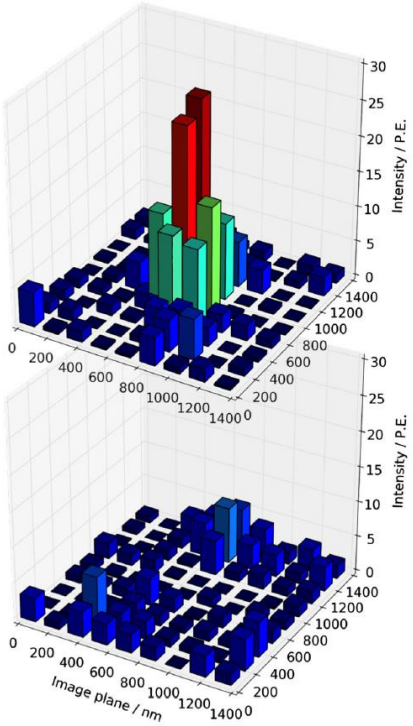
Total background rate expected:

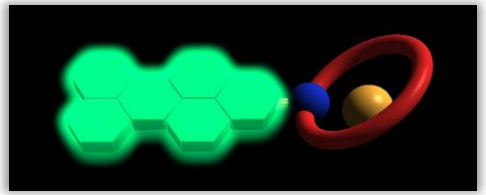
- Phase 1: $3 \cdot 10^{-3}$ [cts keV^{-1} ton^{-1} $year^{-1}$] virtually background free in ton scale
- Phase 2: $3 \cdot 10^{-6}$ [cts keV^{-1} ton^{-1} $year^{-1}$] truly background free

Ba-tagging on TPC: Idea origin and evolution

Idea[1,2]:

- Nygren.[3]: Exploit single molecule fluorescent imaging (SFMI) to visualize (tag) a single Ba^{++} ion.





Evolution:

- McDonald et al.[4]: Proof of concept fluorescent imaging (SFMI) of single Ba^{++} ion

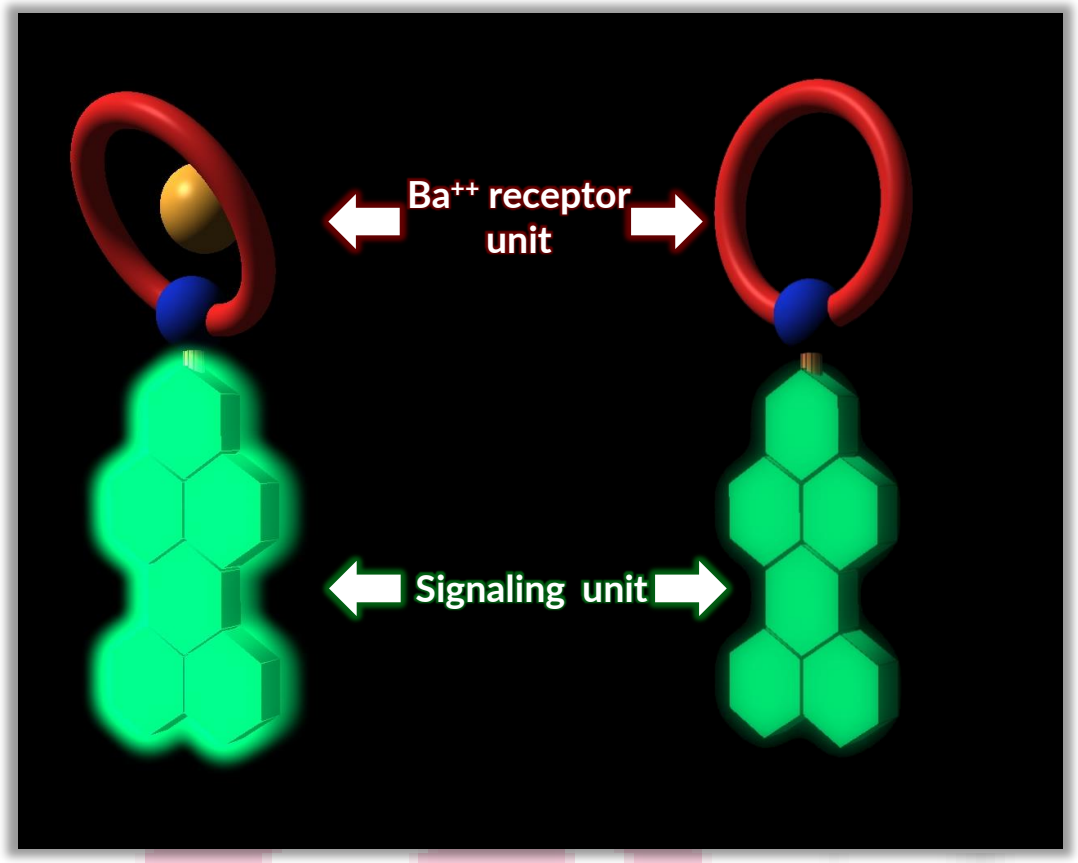
Two complementary R&D Lines:

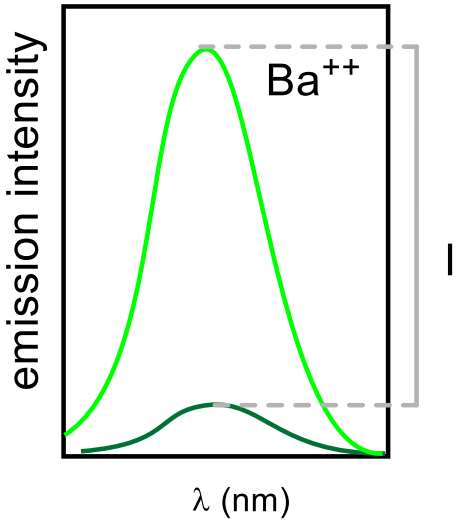
- **BOLD**
  - Fluorescent bicolor indicators (FBI)
  - TPA microscopy
  - Metalenses
- **GodXilla**
  - On-Off indicators
  - RF carpets
  - CRAB detection concept.
- **Goal**: Proof the feasibility of barium tagging in a future ton-scale NEXT detector, using small/medium/large-scale demonstrators in a scale of ~5 years.

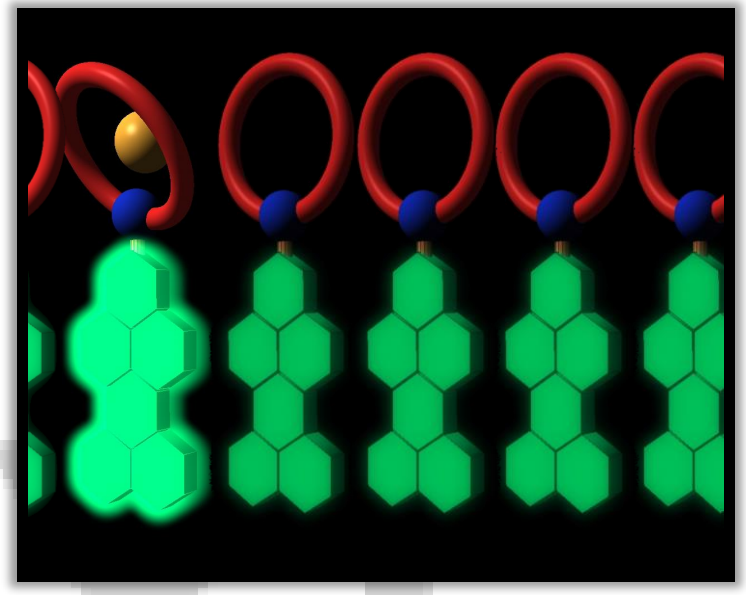
1. Moe, M. K. Phys. Rev. C 44, 931–934 (1991).
2. nEXO Collaboration. Nature 569, 203–207 (2019).Sinclair, D. et al. J. Phys. Conf. Ser. 309, 012005 (2011).
3. Nygren, D. R. J. Phys. Conf. Ser. 650, 012002 (2015).
4. McDonald, A. D. et al. Phys. Rev. Lett. 120,132504 (2018).

Ba-tagging on next: GodXilla

Dry single Ba^{++} ion detection with off-on fluorescence

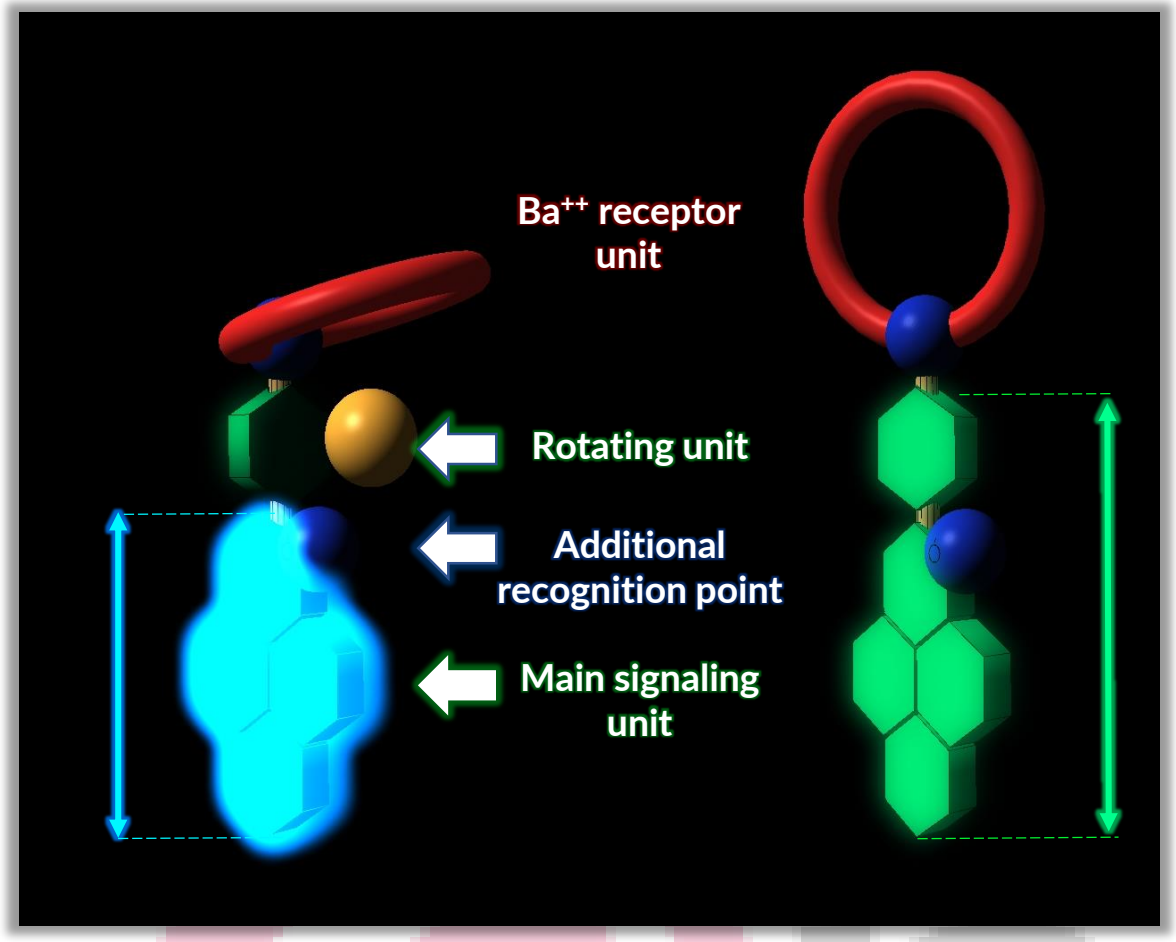


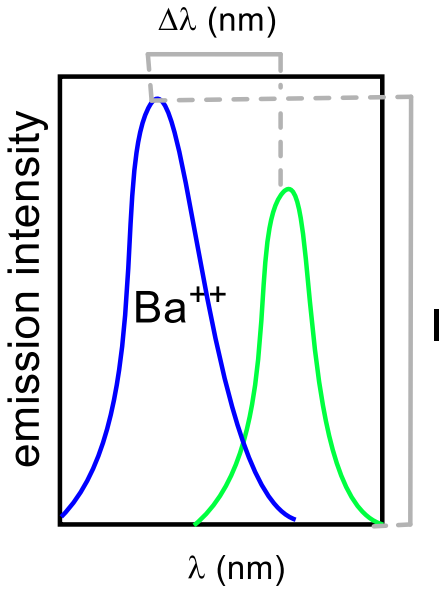


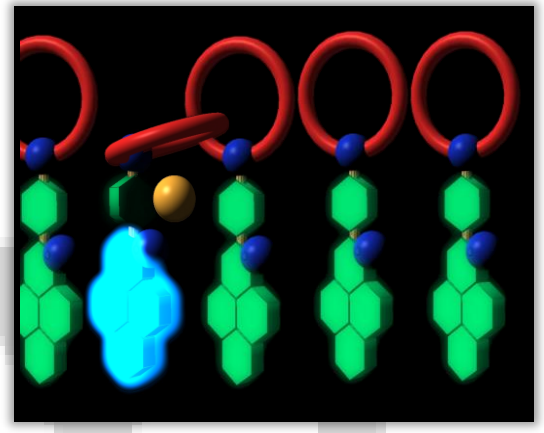


Ba-tagging on next: BOLD

Barium atOm Light Detector (BOLD) ➡ **Fluorescent Bi-color Indicator (FBI)**

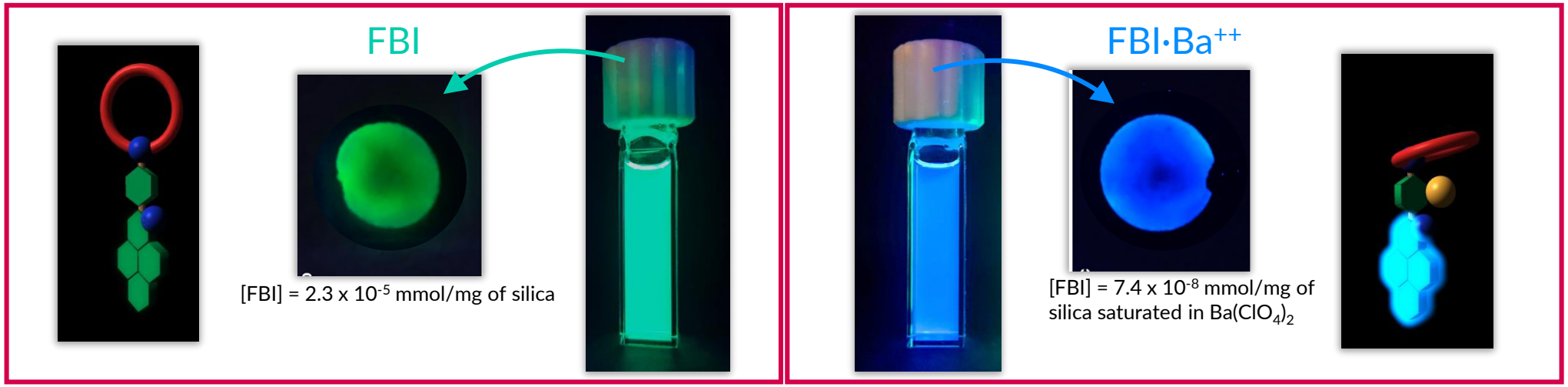




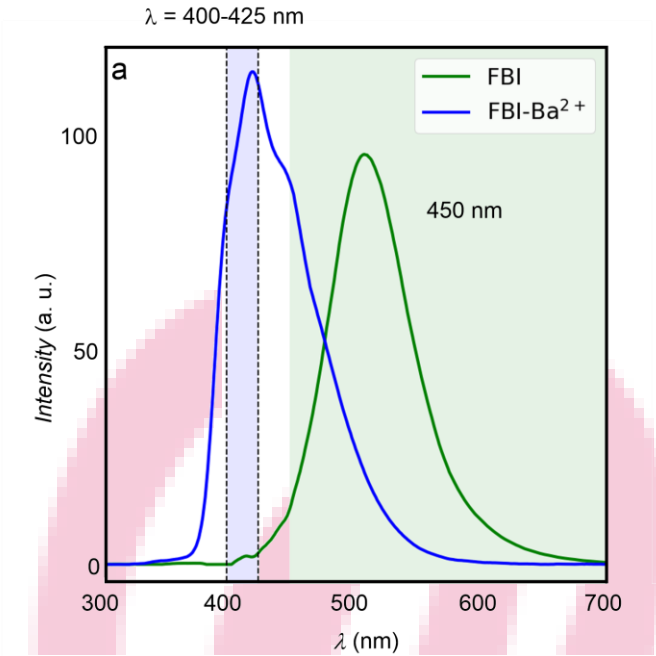


Ba-tagging on next: BOLD

Ba^{++} sensing in solid support



Excitation @ 365 nm

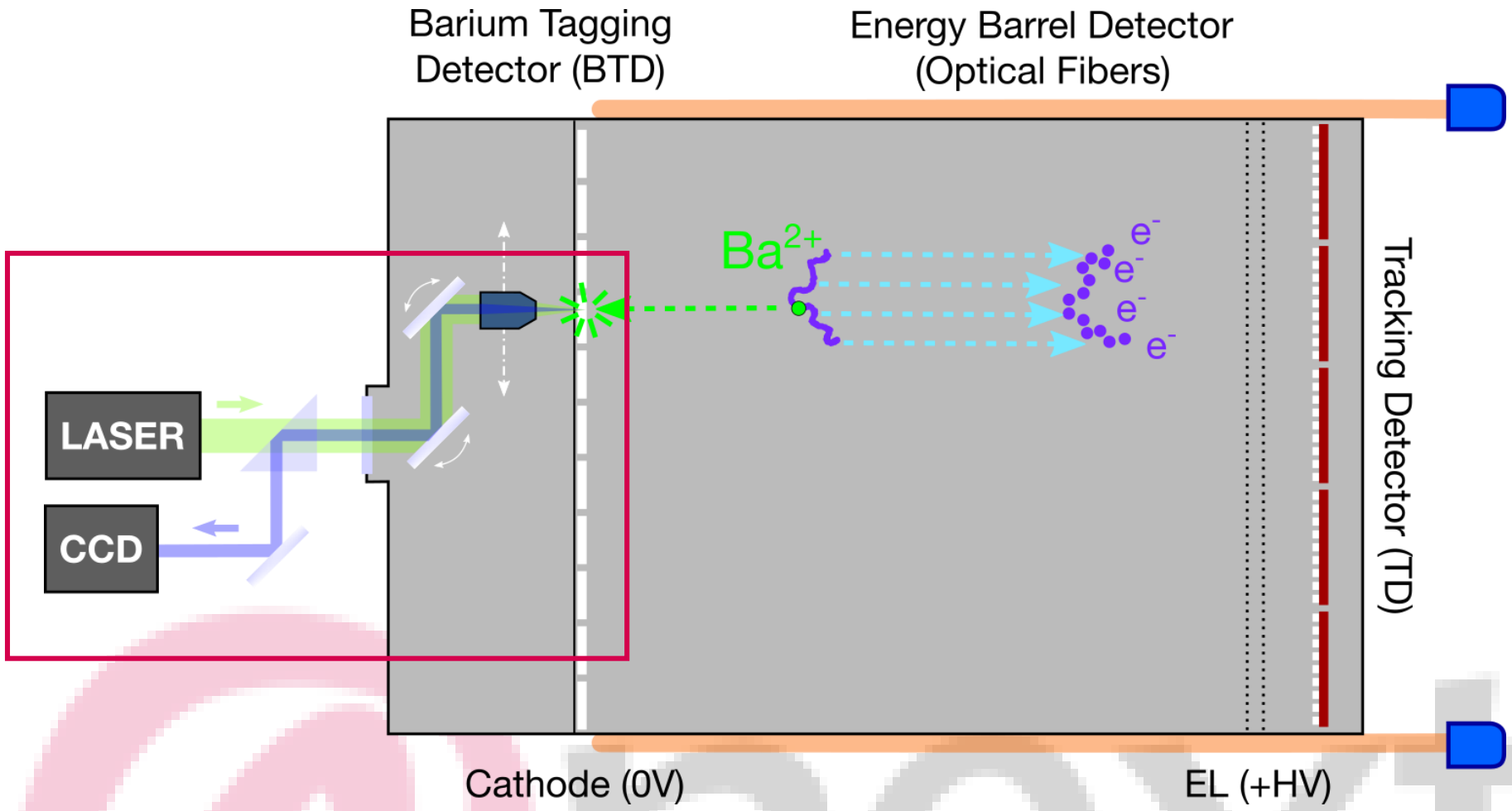


"Fluorescent bicolour sensor for low-background neutrinoless double β decay experiments", Nature 2020, 583, 48-54.

- The FBI maintains its **fluorescent properties in solid phase** (silica gel)
- Calculated **discrimination factor** FBI·Ba^{++} vs FBI = **(2.5±0.6) x 10^4**

Ba-tagging on next: BOLD

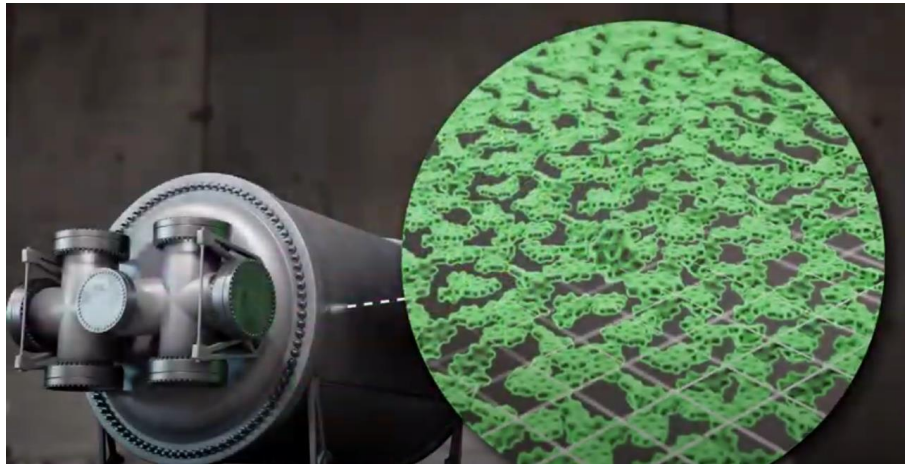
"BOLD" concept with fully active cathode, SiPM-based tracking and Energy Barrel Detector

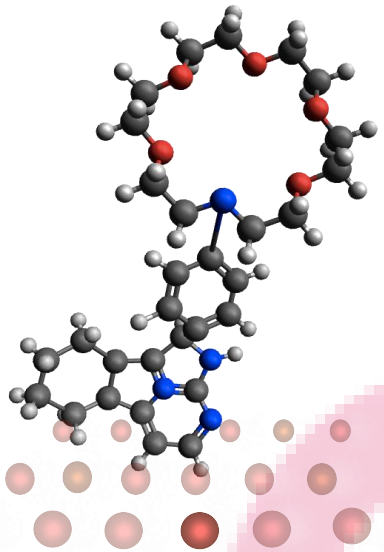


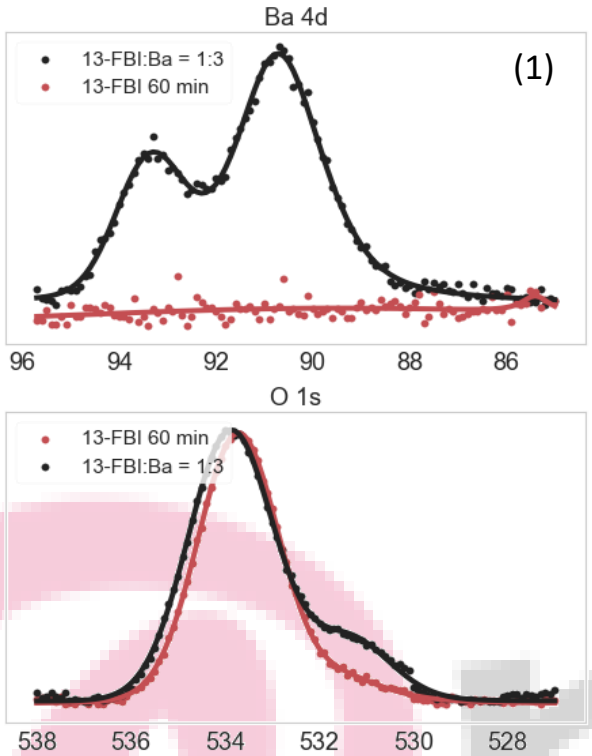
BOLD @next: Ba-sensitive surface evolution

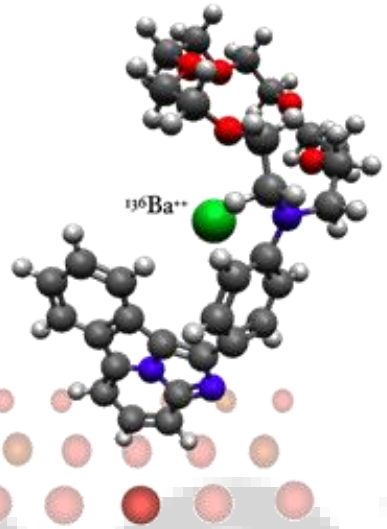
UHV deposition on substrates of interest

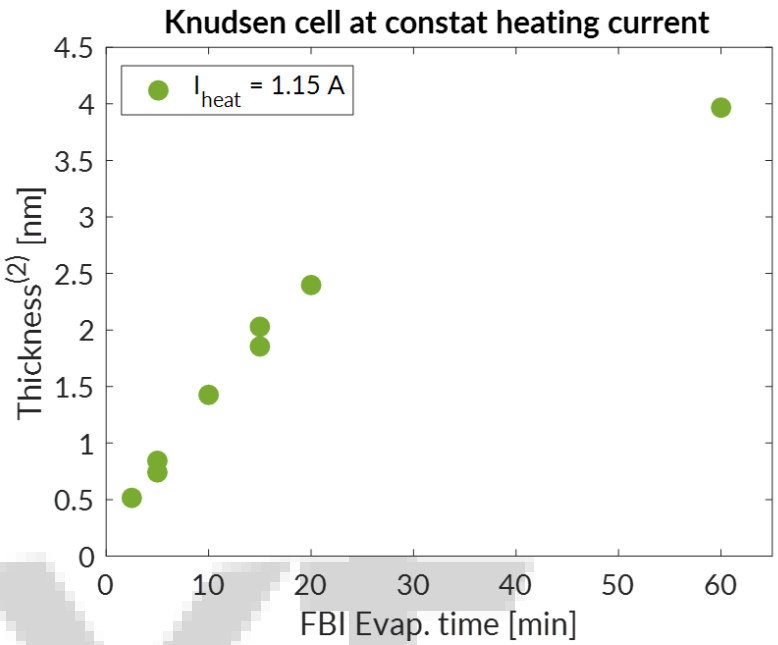
- Successful deposition very thin film (few nm) on quartz and fused silica.
- Ongoing UHV deposition on transparent conductive oxides (first candidate, ITO)











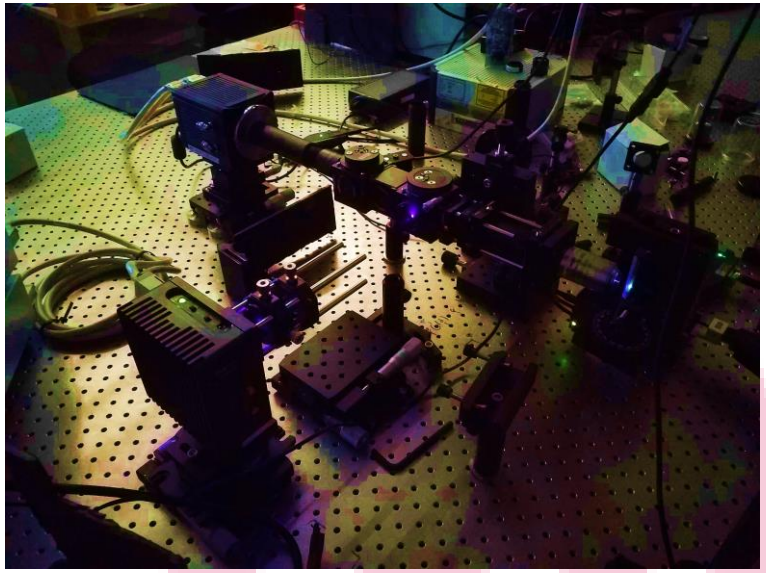
1. P. Herrero et al. work in progress at Nanophysics Lab. @ CFM-CSIC

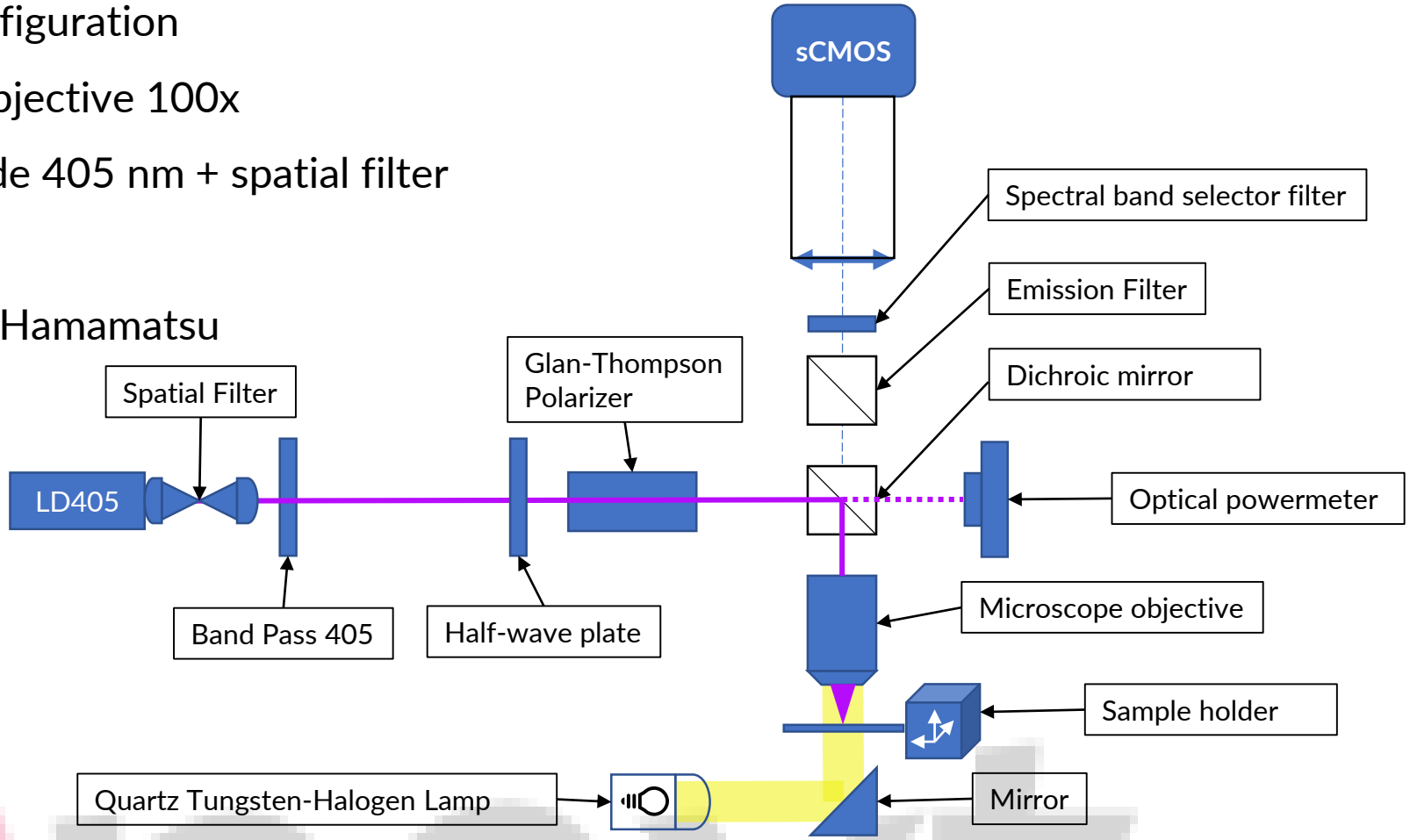
2. Thickness estimation based on Jablonski, A. et al.(2009), Surf. Interface Anal., 41: 193-204. https://doi.org/10.1002/sia.3005

BOLD next: Optical test bench

Main features

- Epi-illumination microscope configuration
- Infinity corrected Microscope objective 100x
- Light source: NICHIA Laser Diode 405 nm + spatial filter
- Power tuning system
- sCMOS: ORCA –Flash 4.0 from Hamamatsu

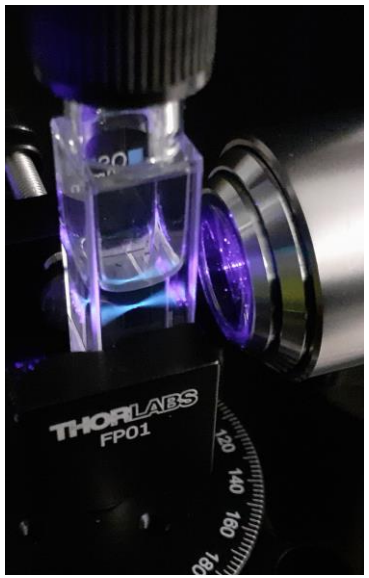


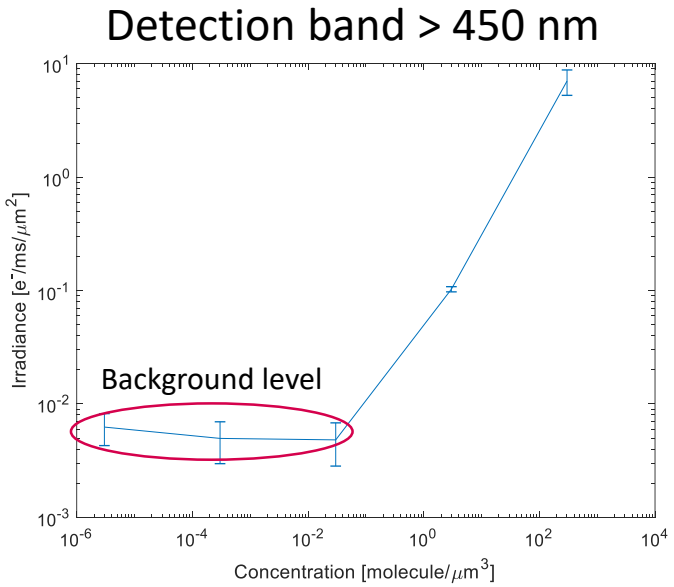


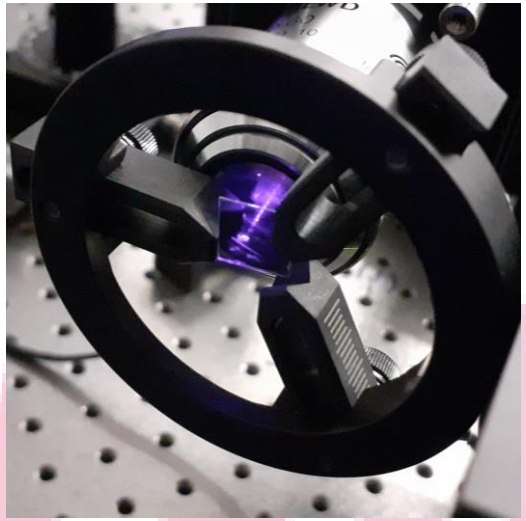
BOLD next: Very first data

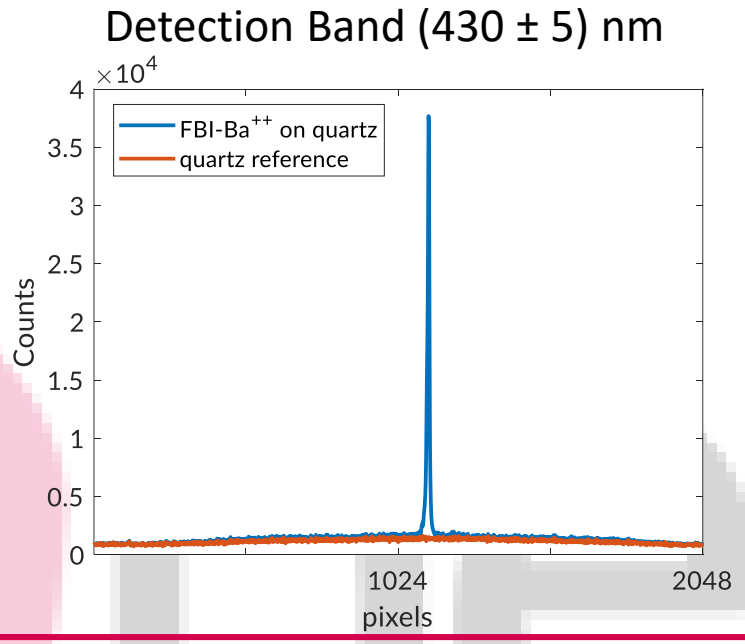
Preliminary characterization

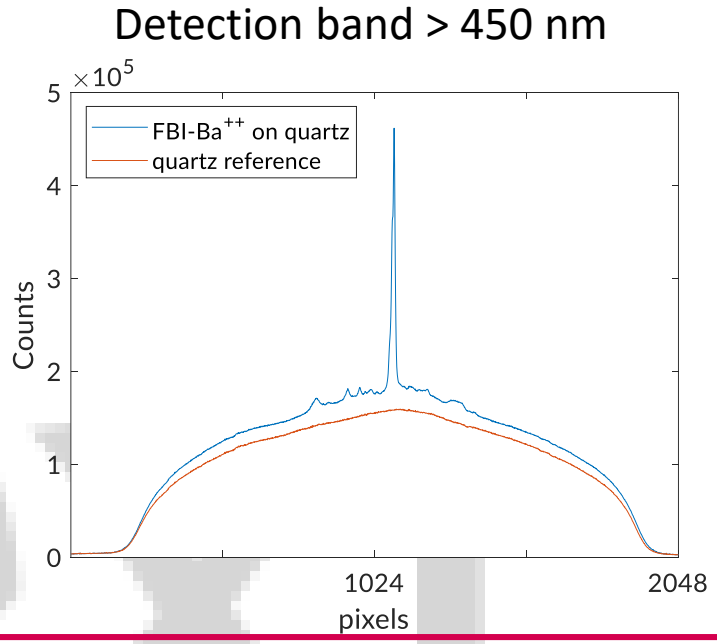
- Detection limit in function of the concentration of FBI in Acetonitrile solutions
- Qualitative confirmation of fluorescence of FBI-Ba^{++} UHV deposited on quartz.





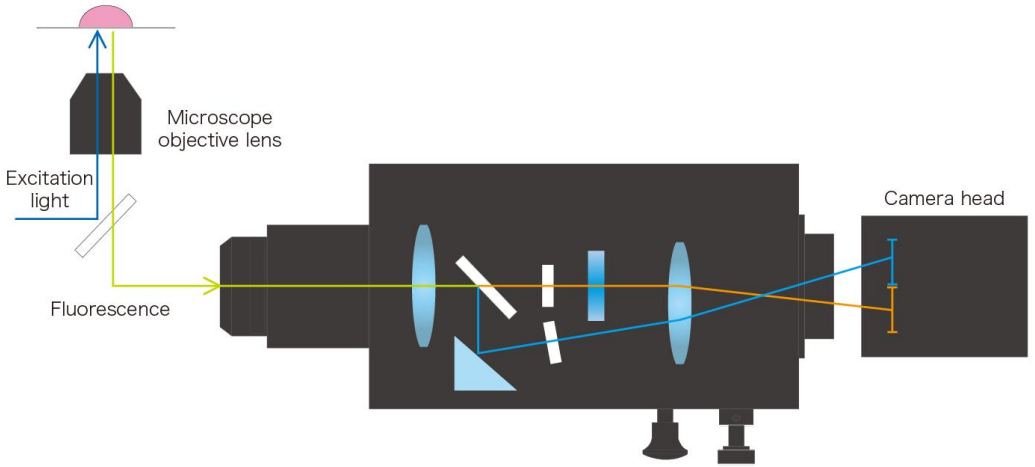




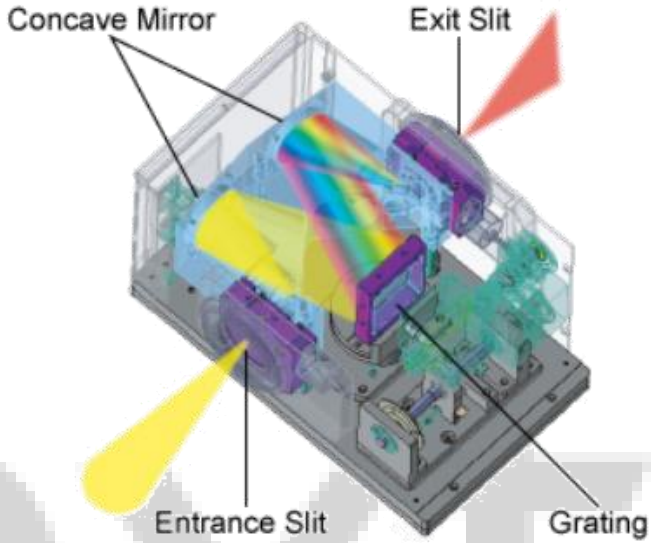


BOLD@next : Optical test bench extended capabilities

- W-VIEW GEMINI Image splitting optics from Hamamatsu.

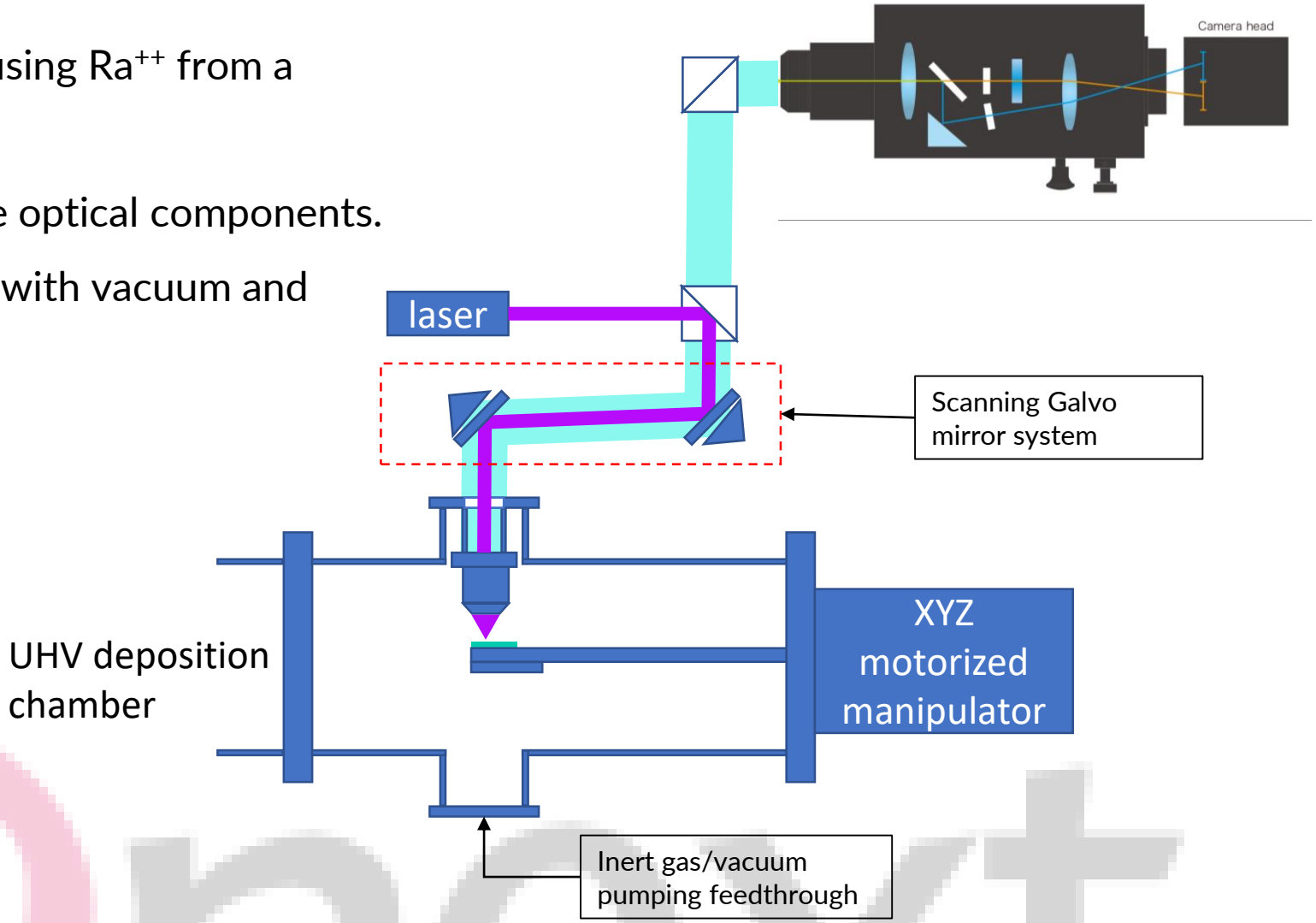


- Monocromator for spectral analysis of the sequence of samples generated in the development of the Ba-molecular trap surfaces



Additional features

- One-atom detection proof using Ra^{++} from a radioactive source.
- In vacuum/inert atmosphere optical components.
- Optical window compatible with vacuum and inert atmosphere.



Summary and outlook

- The high-pressure Xe TPC has unique advantages, making it a leading candidate for the ton-scale $\beta\beta0\nu$search era.
- NEXT-White demonstrated superb energy resolution and effective track reconstruction on the 10-kg scale. Background is low and well understood.
- NEXT-100 will demonstrate the technology on the 100-kg scale, providing competitive limits within a few years.
- The NEXT collaboration pursues promising directions for major background reduction, critical for the ton-scale detector: Ba tagging + topology improvement + higher radiopurity.
- NEXT BOLD and GodXilla probes of concept mark the route to realizable Ba-tagging detectors ready for the ton-scale $\beta\beta0\nu$ search era.

THE END

Thank you for you attention

Back-up slides

Monolayer formation of fluorescence bicolor molecules