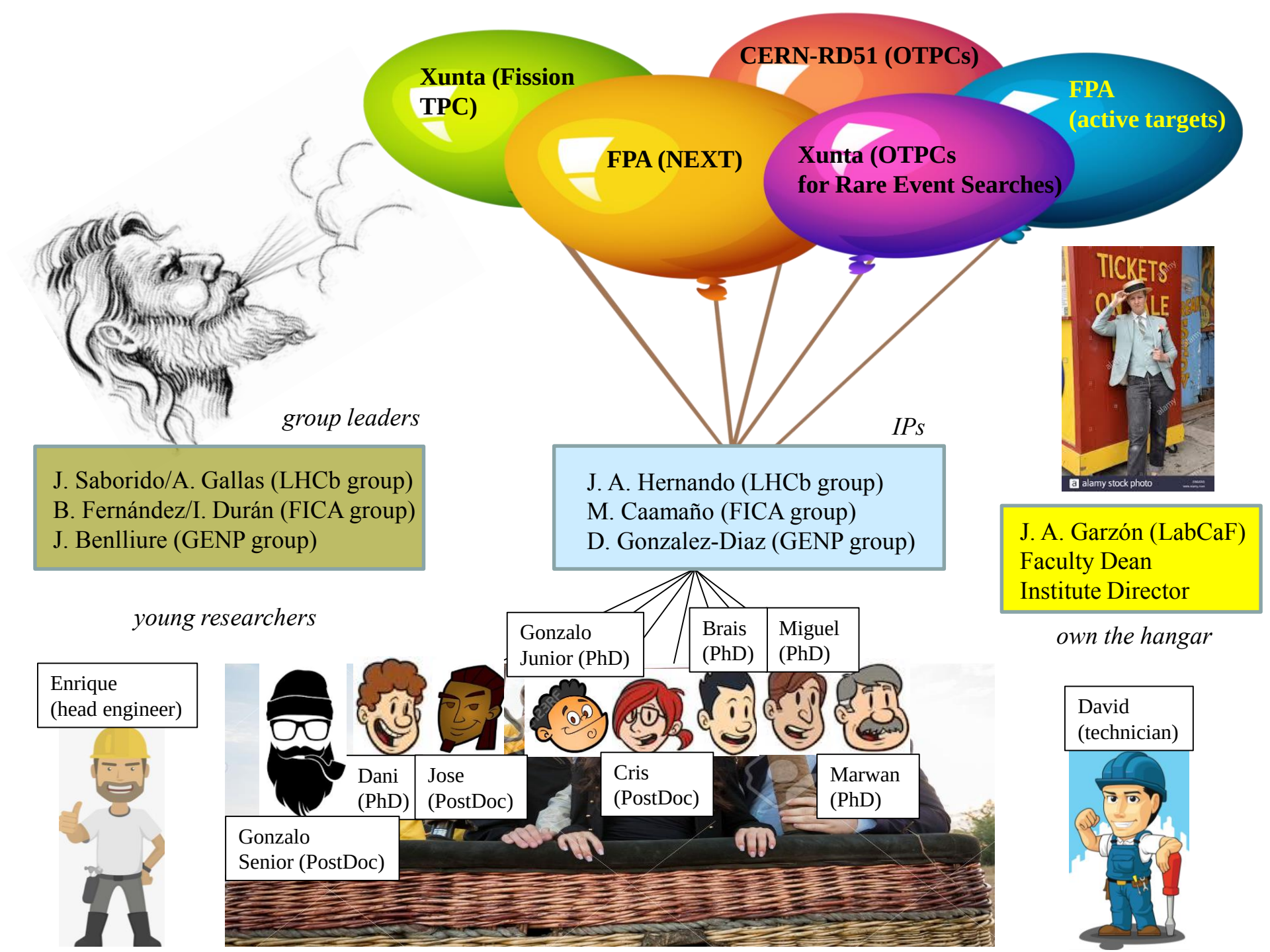
(WIMP) Dark Matter and the Nature of Neutrinos

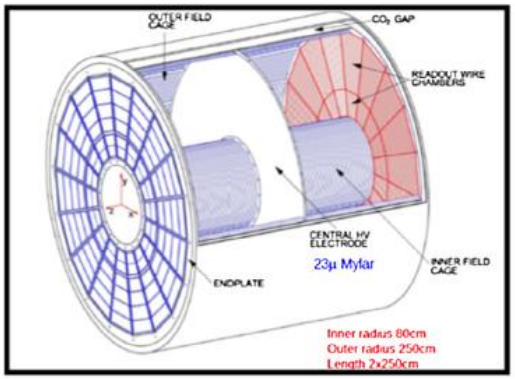
Diego Gonzalez Diaz

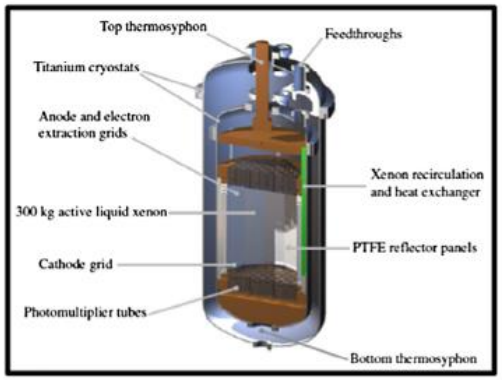
10/01/2019, IGFAE retreat, Santiago


Xunta (Fission TPC)
CERN-RD51 (OTPCs)
FPA (active targets)
FPA (NEXT)
Xunta (OTPCs for Rare Event Searches)
group leaders
IPs
J. Saborido/A. Gallas (LHCb group)
B. Fernández/I. Durán (FICA group)
J. Benlliure (GENP group)
J. A. Hernando (LHCb group)
M. Caamaño (FICA group)
D. Gonzalez-Diaz (GENP group)
TICKETS
alamy stock photo
J. A. Garzón (LabCaF)
Faculty Dean
Institute Director
own the hangar
young researchers
Enrique
(head engineer)
Gonzalo
Junior (PhD)
Brais
(PhD)
Miguel
(PhD)
Dani
(PhD)
Jose
(PostDoc)
Cris
(PostDoc)
Marwan
(PhD)
Gonzalo
Senior (PostDoc)
David
(technician)

what is common to this ‘Rare Event’ science?: Time Projection Chambers!

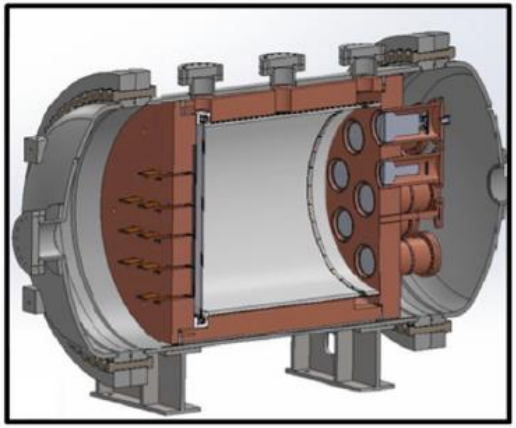
ALICE
(heavy ion reactions)

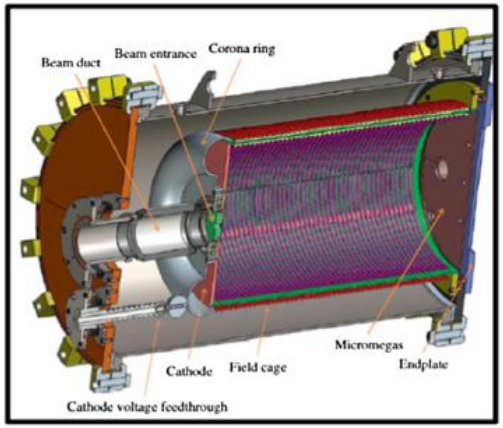




LUX
(Dark Matter)

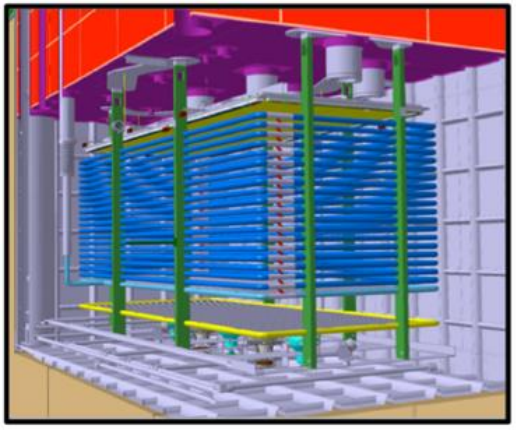
NEXT-NEW
($\beta\beta$0-decay)

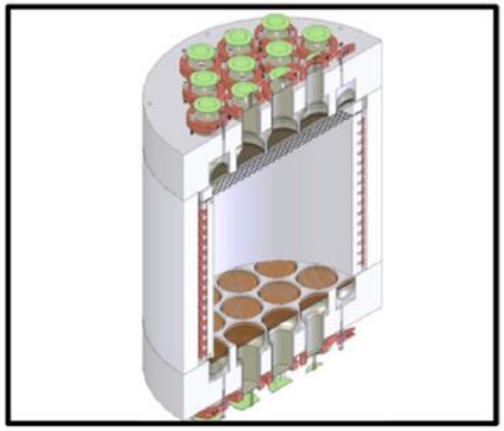




AT-TPC
(nuclear physics)

DUNE Far Detector
(neutrino oscillations)

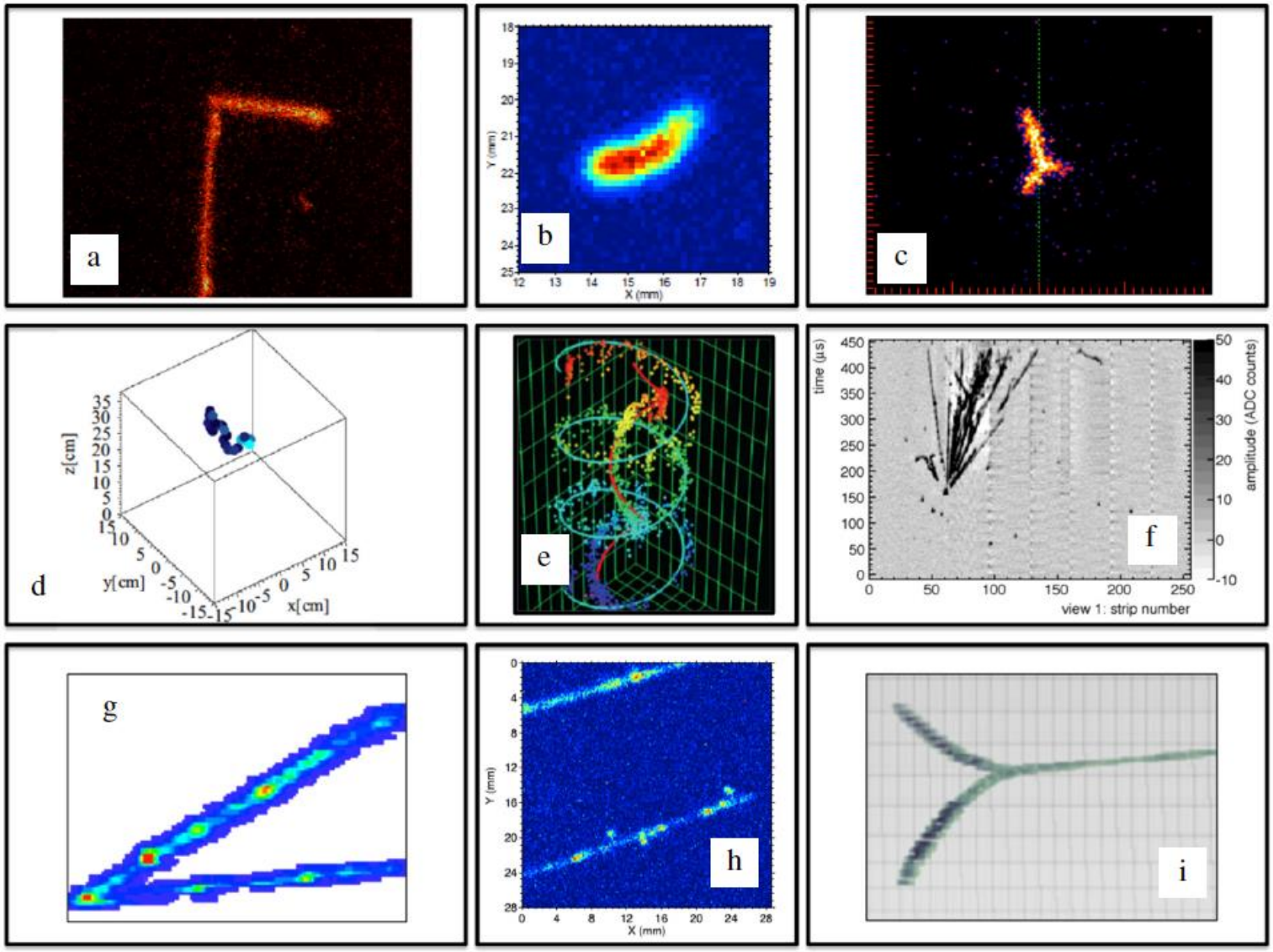




DarkSide-50
(Dark Matter)

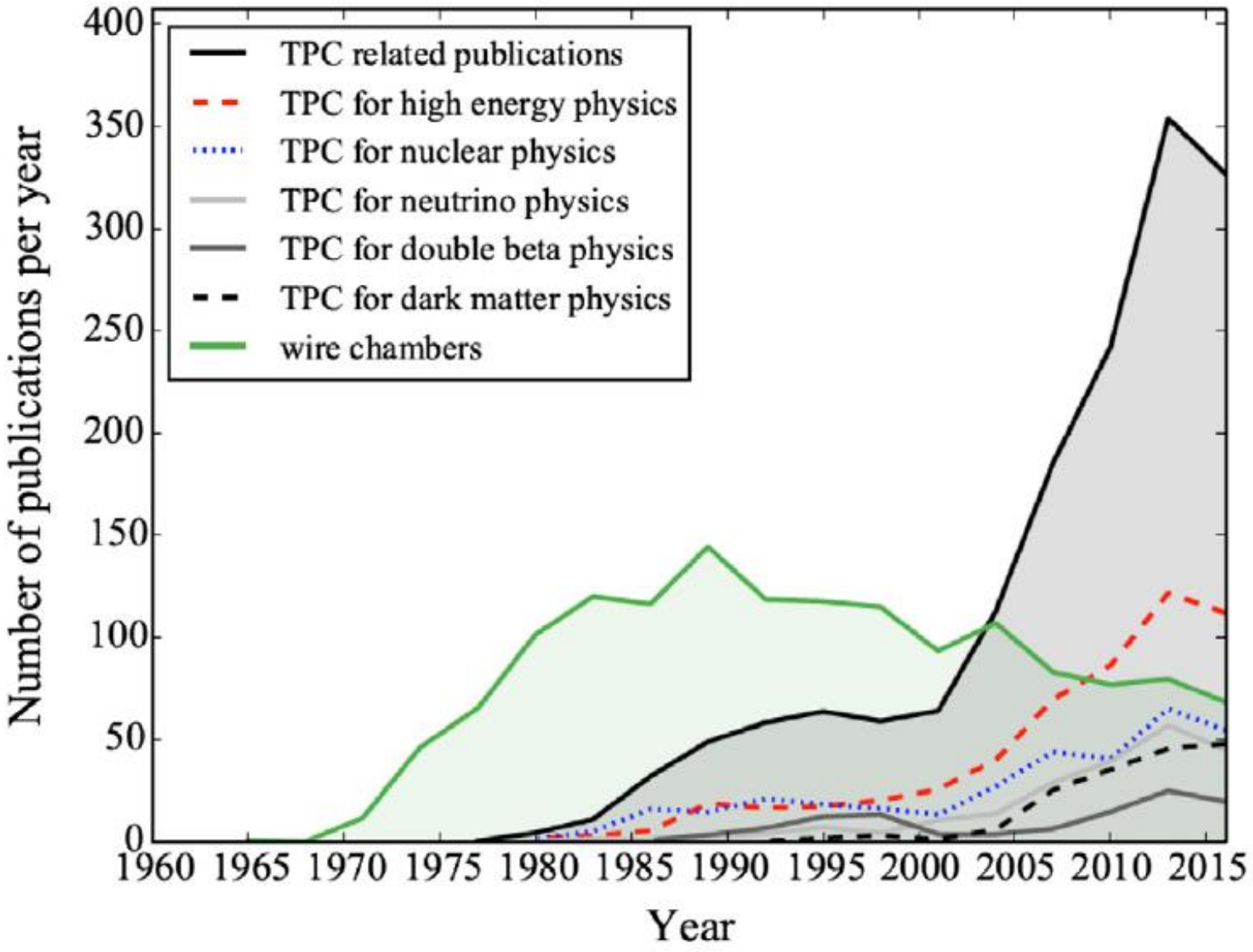
D. González-Díaz, F. Monrabal, S. Murphy, Nucl. Instr. Meth. A 878(2018)200

what is common to this ‘Rare Event’ science?: Time Projection Chambers!



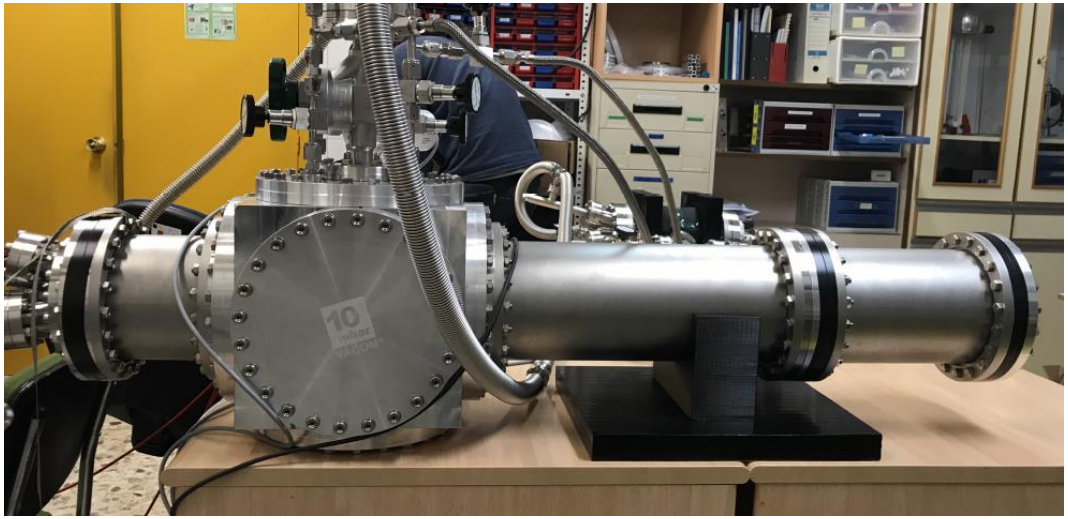
D. González-Díaz, F. Monrabal, S. Murphy, Nucl. Instr. Meth. A 878(2018)200

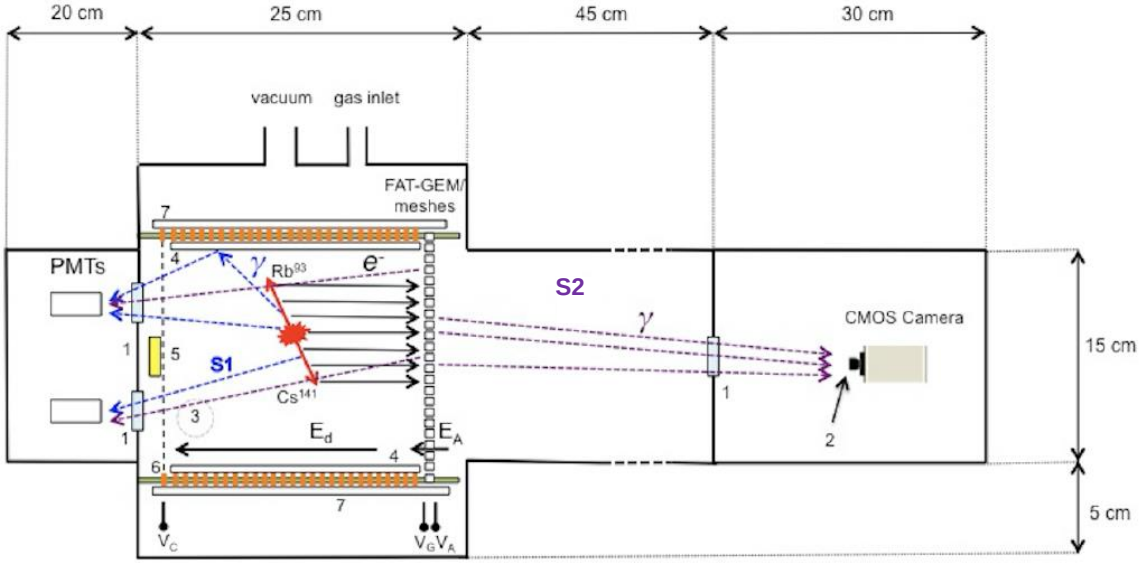
what is common to this ‘Rare Event’ science?: Time Projection Chambers!



D. González-Díaz, F. Monrabal, S. Murphy, Nucl. Instr. Meth. A 878(2018)200

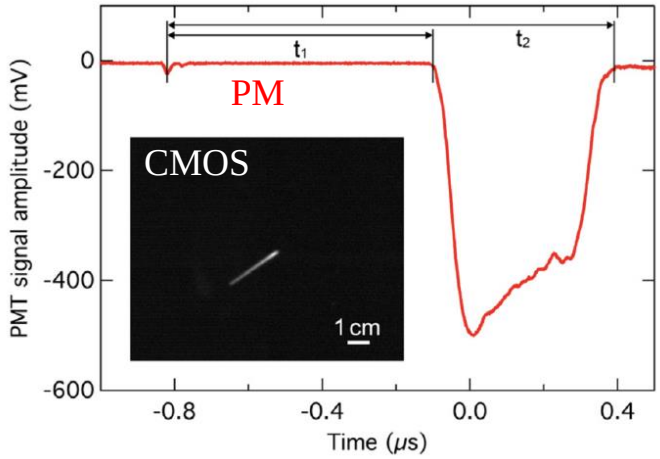
A new *optical* TPC at IGFAE ('Nausicaa1')





main characteristics

- Read out by optical means.
- 15cm diameter, 15cm height.
- Operated in CF_4-based mixtures.
- Capable to work up to 3bar.
- Position resolution by design: 150um.
- Dual readout (PM+CMOS camera).
- Versatile in order to accommodate different types of reactions.

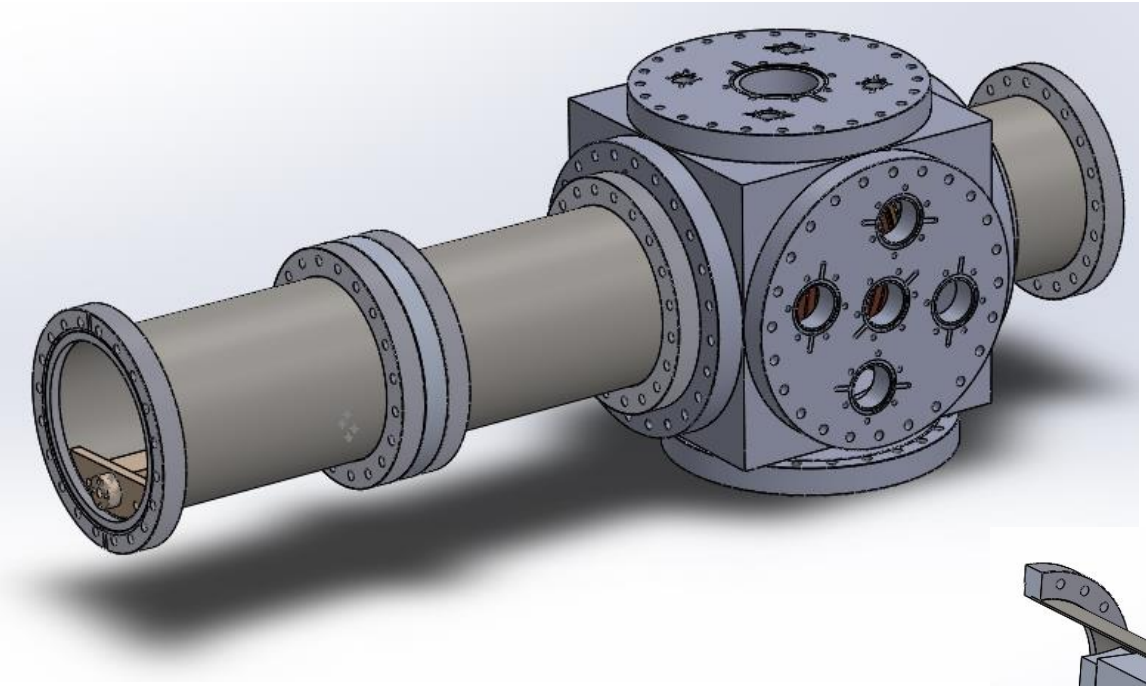


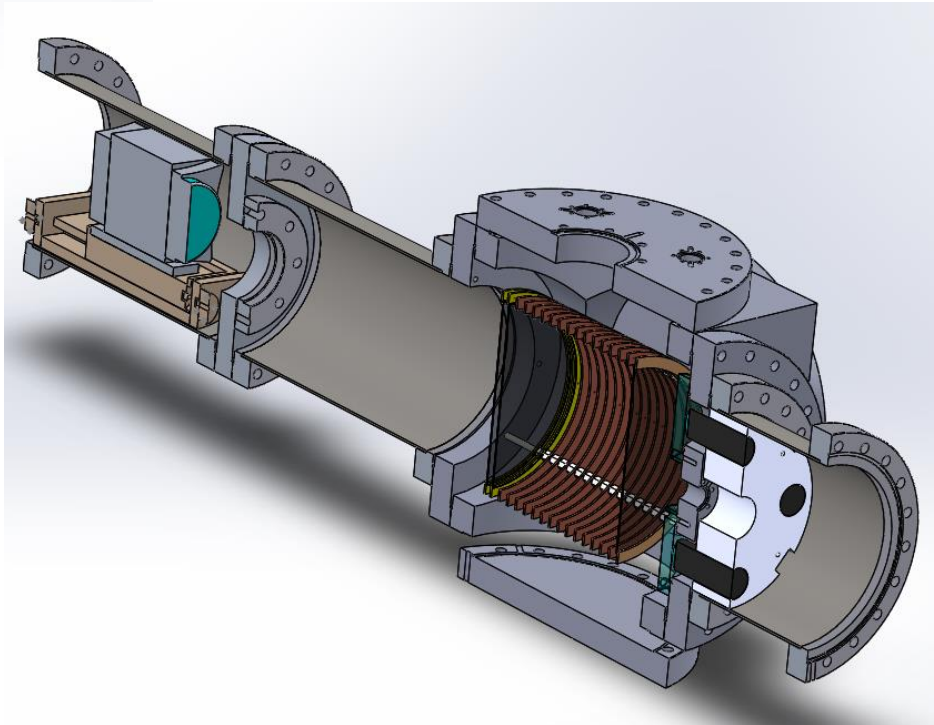
example from a similar camera at CERN GDD-lab

*F. M. Brunbauer, G. Galogczi, **D. González-Díaz**, et al., Nucl. Instr. Meth. A 886(2018)24*

Pablo Ameijeiras (TFG, February 2019)

A new *optical* TPC at IGFAE ('Nausicaa1')





Pablo Ameijeiras (TFG, February 2019)

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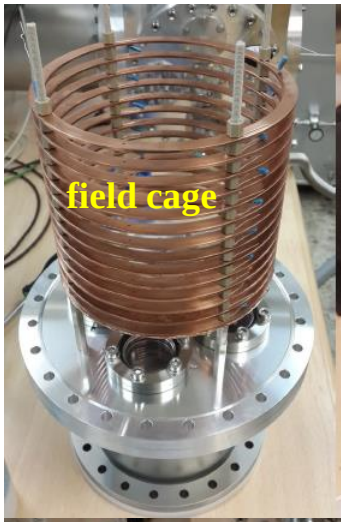
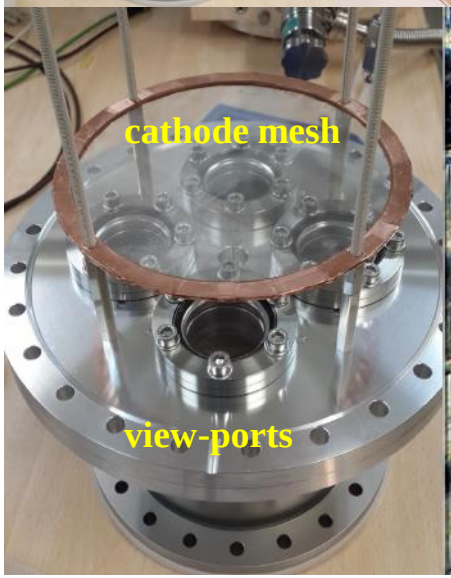
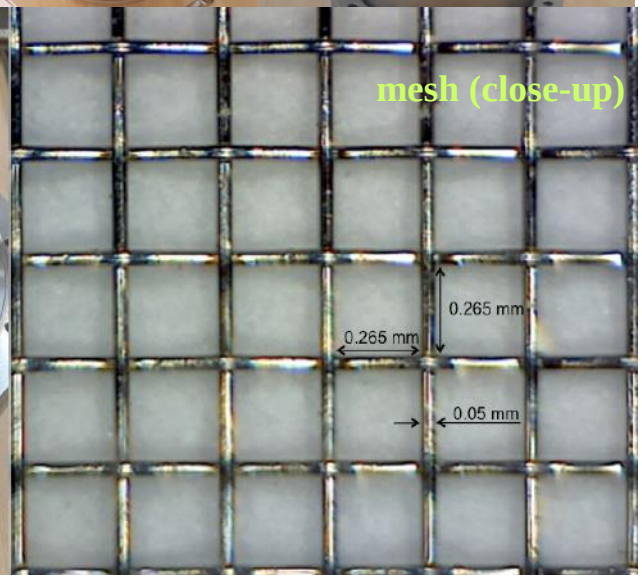
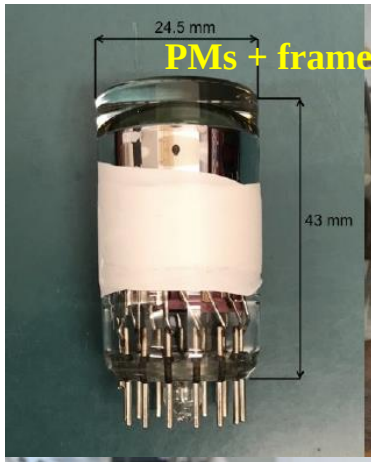
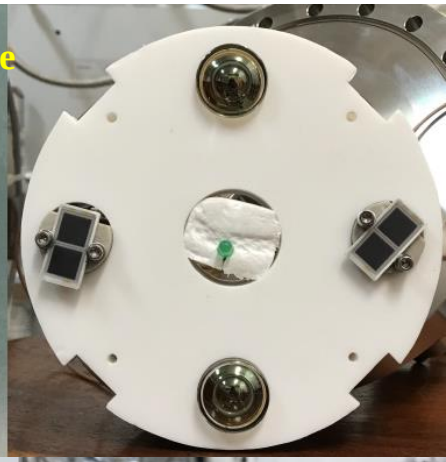
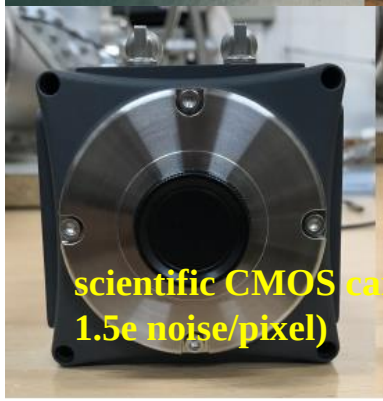


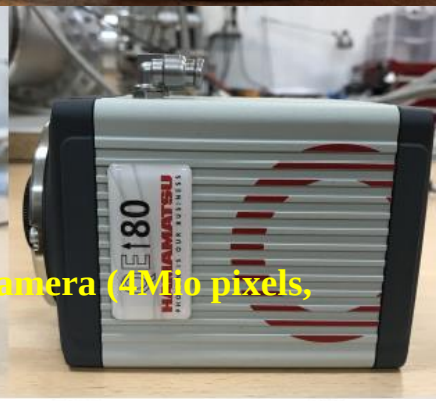


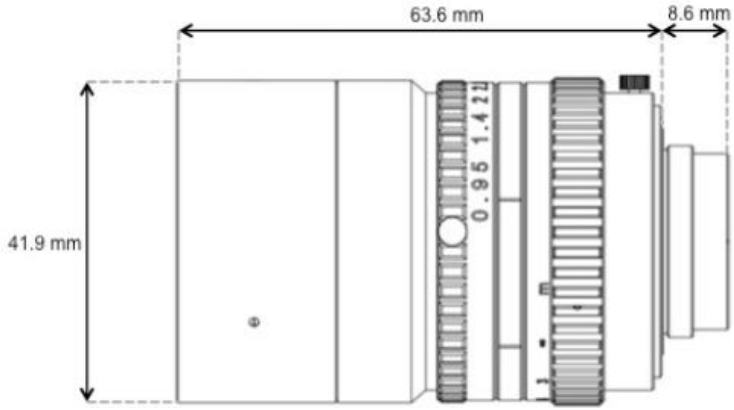












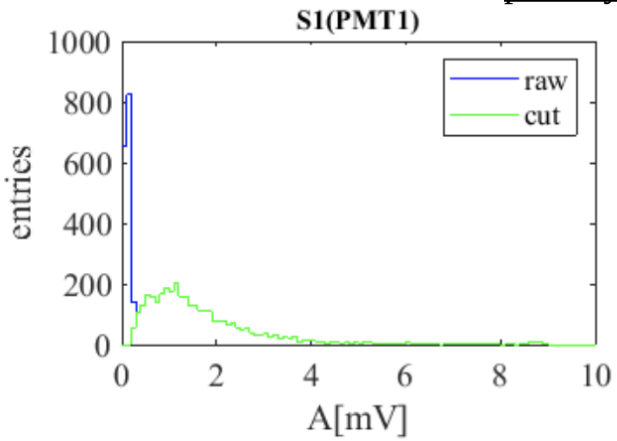
lens (f=17mm, N=0.95)

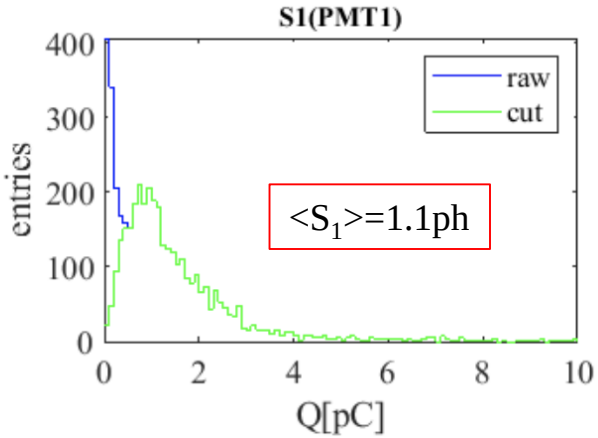
+ acquisition system, gas system, vacuum system, HV modules, analysis scripts, slow control…

Pablo Ameijeiras (TFG, February 2019)

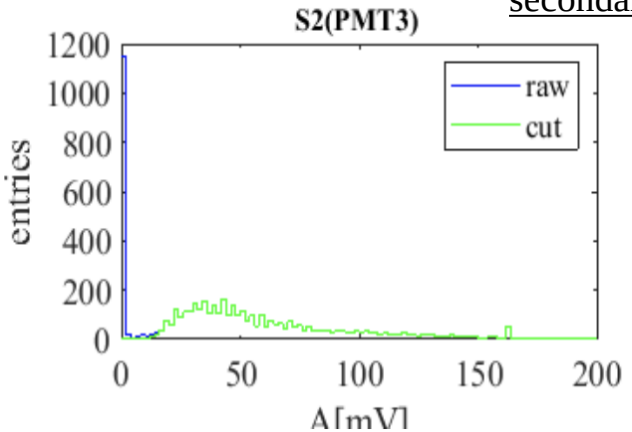
A new *optical* TPC at IGFAE ('Nausicaa1')

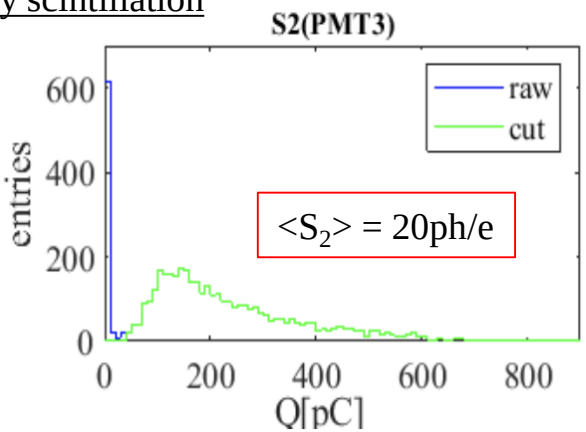
primary scintillation





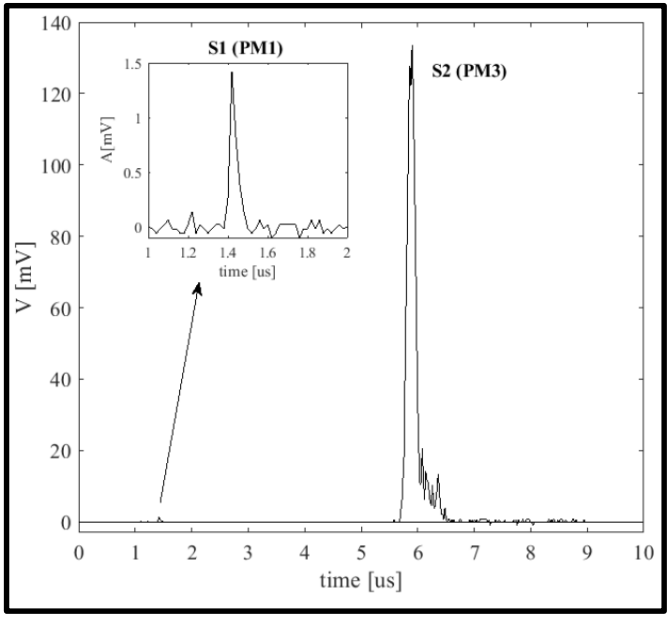
secondary scintillation





typical event:

α-particle from ^{241}Am (CF_4-gas, 0.5bar)



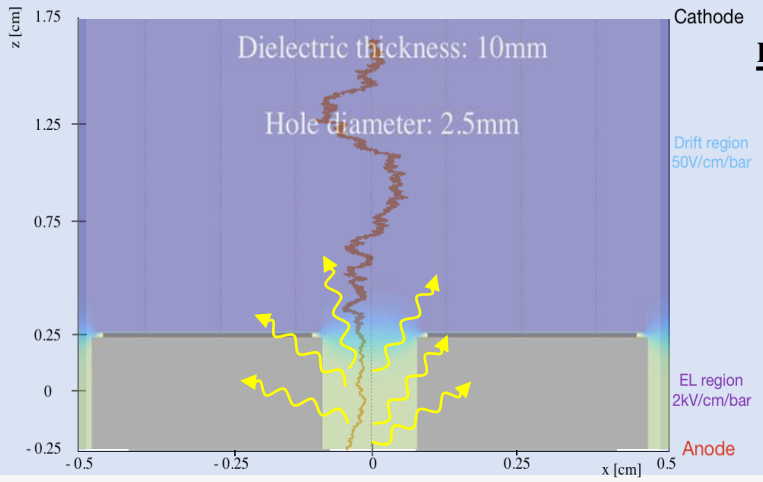
status

- Sensitivity to primary scintillation only for events close to the cathode.
- Modest optical gain, sufficient for ~1mm accurate track reconstruction.
- Ready to connect the CMOS camara and reconstruct tracks!.

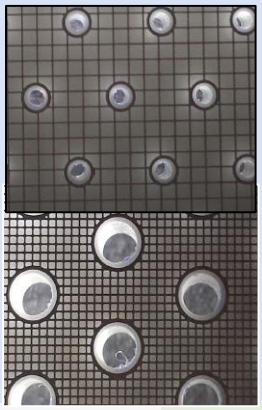
next steps

- Install **FAT-GEM** in anode in order to increase optical gain.
- Install CMOS camera.
- Install Teflon reflector.
- Install 2 additional PMs.
- Upgrade system to allow 10bar operation.
- Start to reconstruct tracks!.

Pablo Ameijeiras (TFG, February 2019)



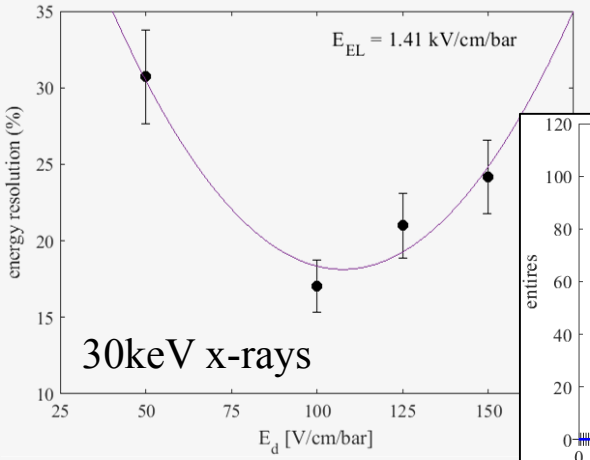
novel scintillating structures developed at Santiago (IGFAE)!

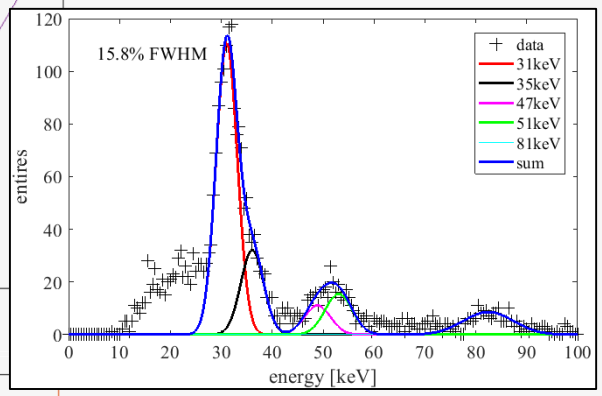


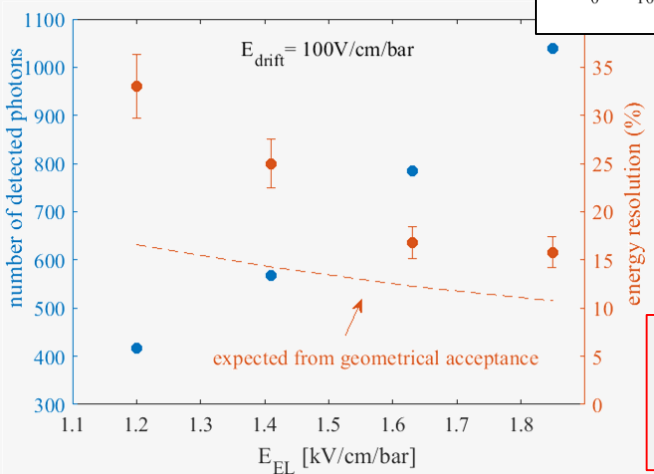
FAT-GEM: *a 'super-thick' (5mm) acrylic-based GEM with semitransparent 'gate' plane*

several geometries procured at the RD51 workshop for optimization

preliminary results in Ar/Xe at ~90/10 (10bar)





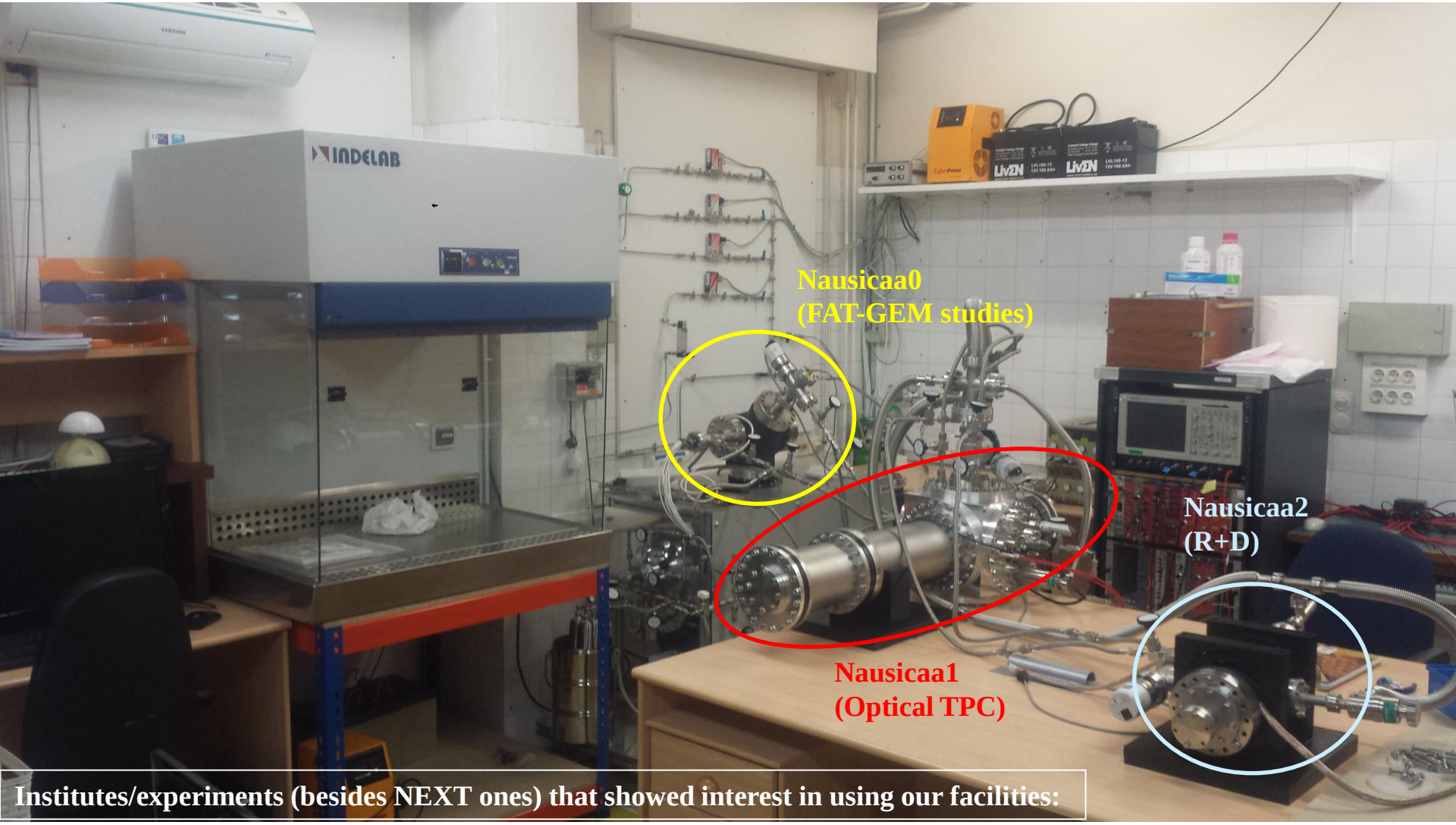


Full systematic studies planned for January-March + publication!

main characteristics of FAT-GEM (*Field-Assisted Transparent Gaseous Electroluminescent Multiplier*)

- Transparent.
- Homogeneous (advantageous for CNC-drilling).
- Inexpensive.
- Customizable (e.g., allows resistive or wavelength-shifting coatings)
- Robust against discharges (and very low capacitance).
- Easy to scale.
- Versatile: spectrum of emission can be easily tuned.
- Compatible with high-pressure operation.
- Ultimate energy resolution close to Fano factor, position resolution: mm-scale.

status of lab (06-01-2019)



Institutes/experiments (besides NEXT ones) that showed interest in using our facilities:

- **DarkSide** (CIEMAT) -> New ideas for nucleus/e identification in pure Ar, Xe chambers (**EXPLORA project**). — ongoing
- **DUNE** (Fermilab, Harvard) -> implementation of To information with Ar/Xe, Ar/Xe/CH_4 mixtures. — ongoing
- **CYGNO** (INFN) -> Directional detection of Dark Matter with He/CF_4 (**ERC consolidator grant**). — hanging
- **MSU-FRIB** -> New ceramic and multi-layer GEMs for dual-phase operation in pure Ar, Xe chambers. — stacked

ββ0ν actitivities

ββ0ν: the name of the game (I)

experiment

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

ββ0ν: the name of the game (I)
experiment

efficiency

exposure (kg y)

isotopic abundance

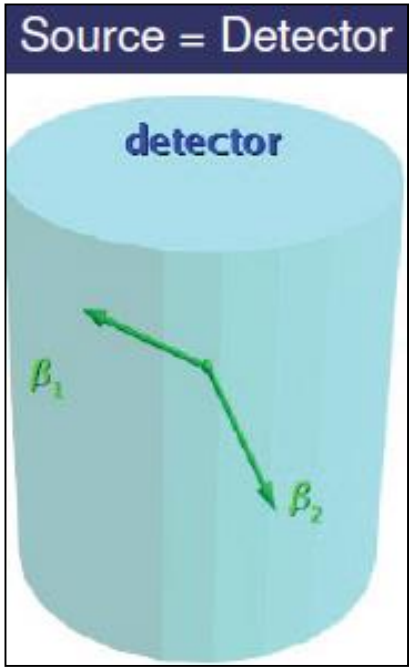
$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

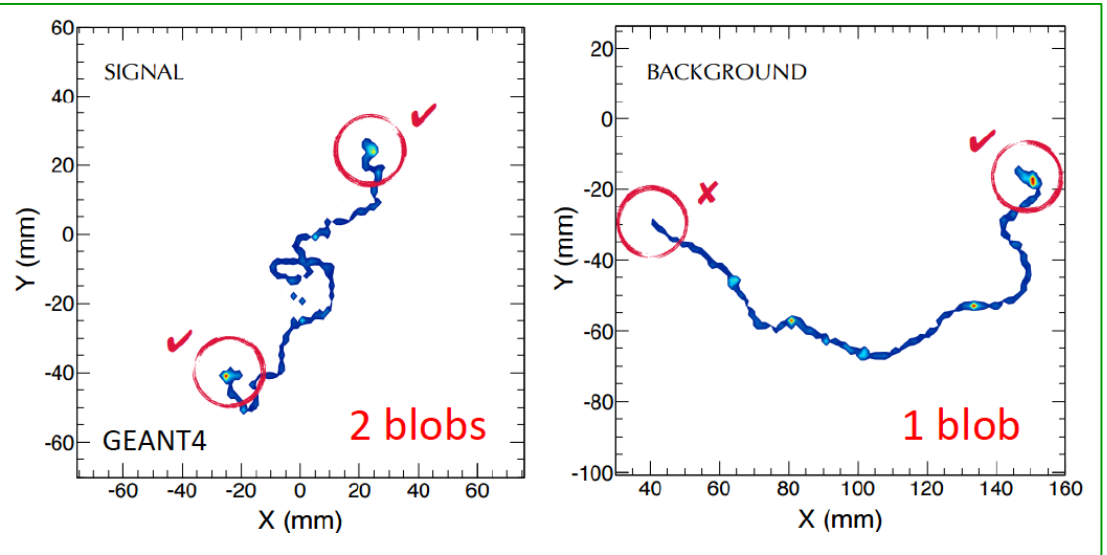
number of sigmas for claim at a given confidence level

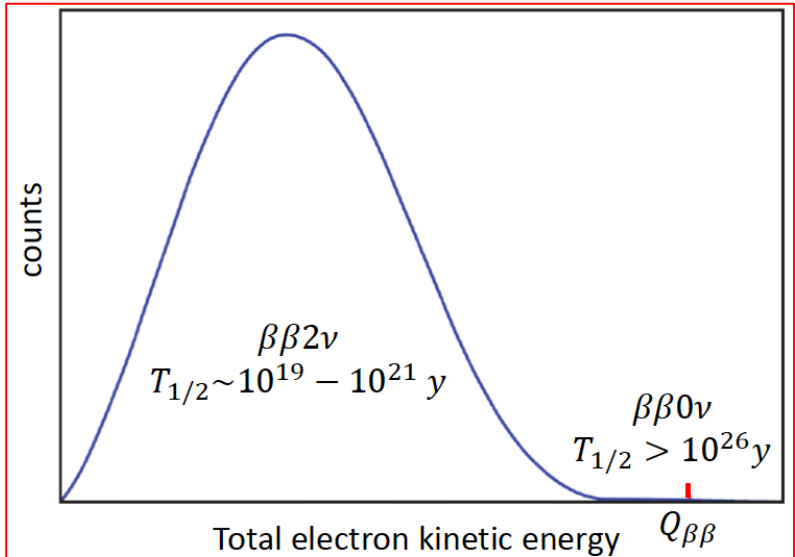
molecular weight

background [cts/keV/kg/y]

energy resolution [keV]





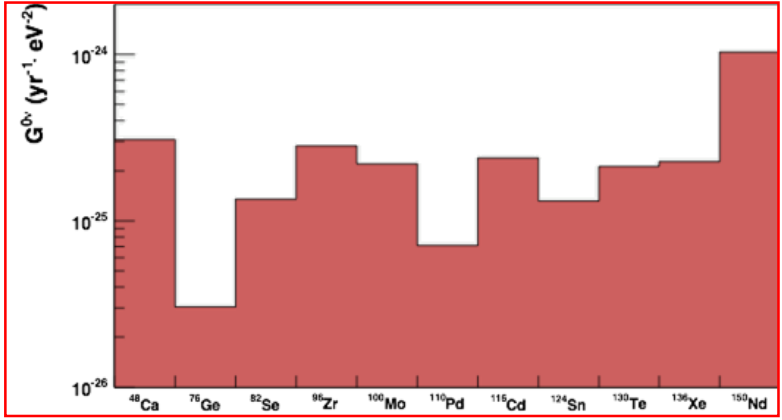


ββ0ν: the name of the game (II)

theory

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$

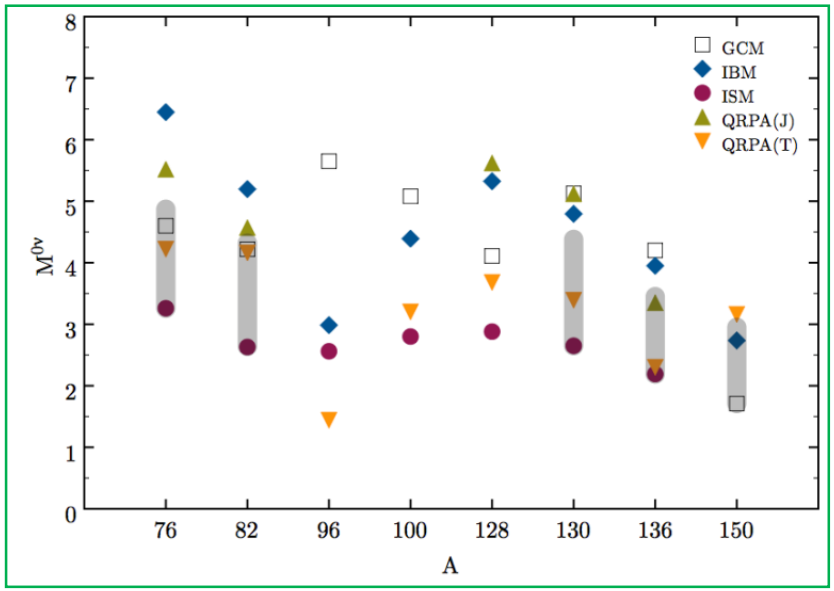
ββ0ν: the name of the game (II)
theory



phase-space factor

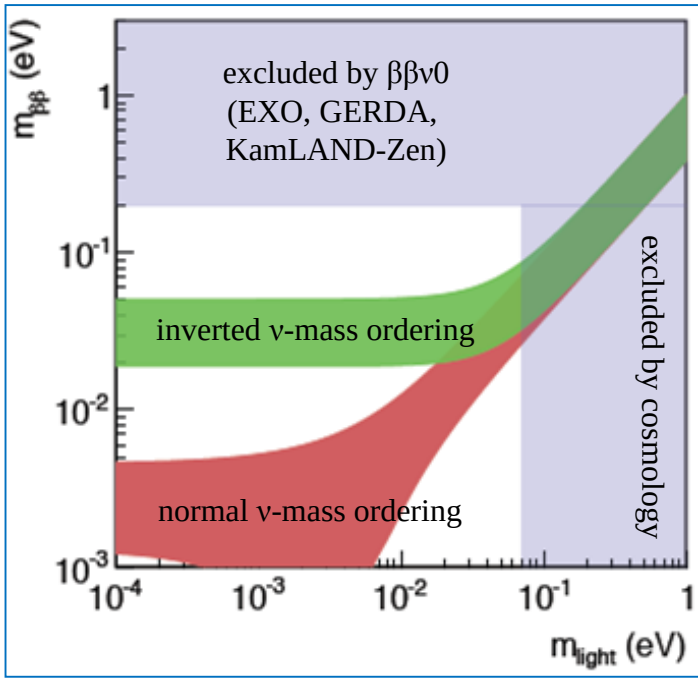
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,m^2_{\beta\beta}$$

nuclear matrix element



~100kg

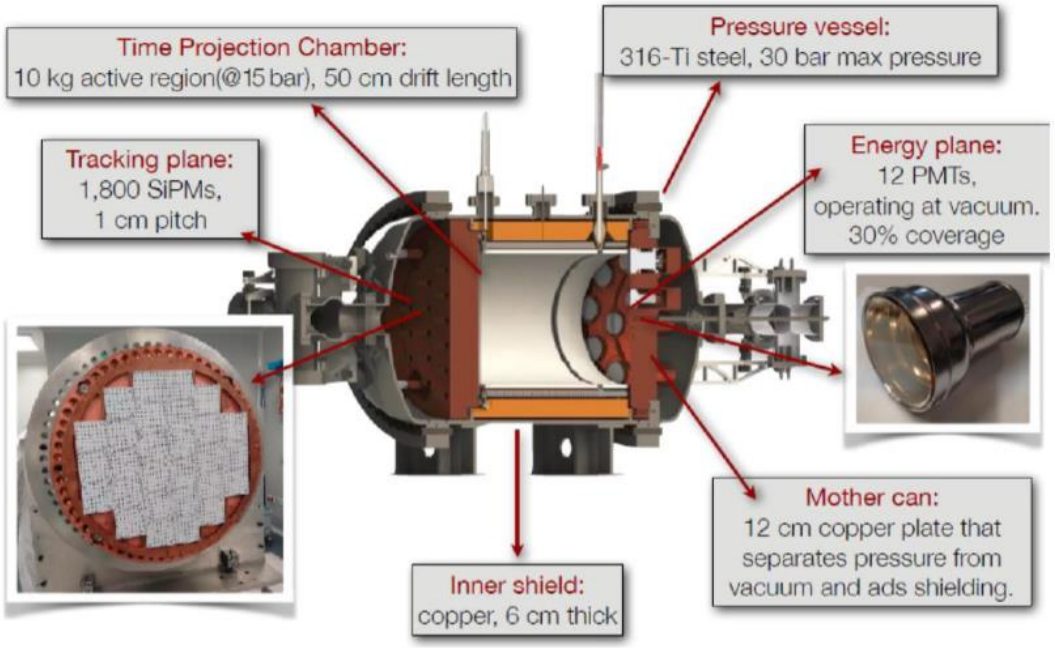
~1ton



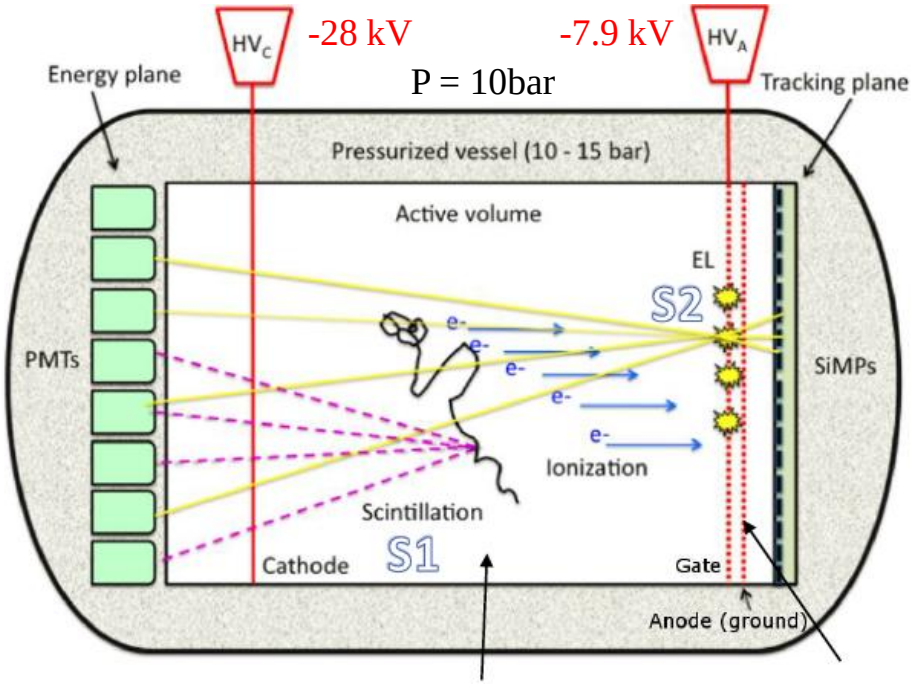
ν oscillations

$$m_{\beta\beta} = ||U_{e1}|^2 m_1 + e^{i\alpha_1}|U_{e2}|^2 m_2 + e^{i\alpha_2}|U_{e3}|^2 m_3|$$

- High Pressure electroluminescent Time Projection Chamber (largest ever).
- Photomultiplier plane (for calorimetry).
- Silicon photomultiplier plane (for tracking).
- Made with radiopure materials.
- Installed in underground lab (LSC).
- Lead 'castle' to shield from external γ's.
- Radon abatement system.
- ⇨ Outstanding energy and topology reconstruction.

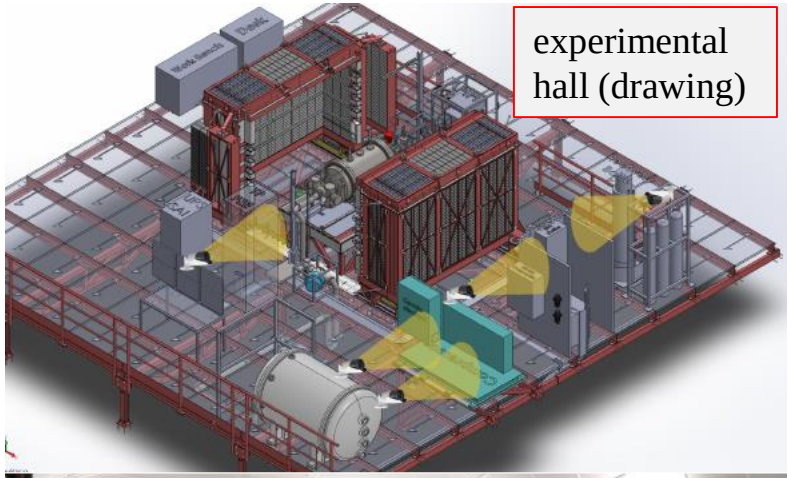


NEW



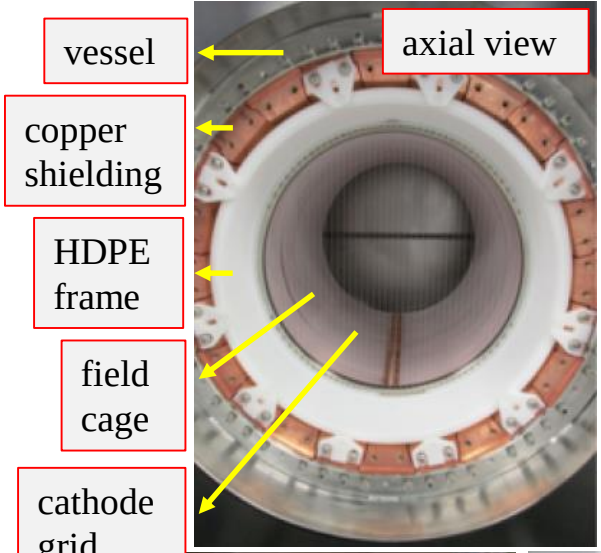
E_{drift} = -53 kV/cm/bar E_{EL} = -1.32 kV/cm/bar

- 10kg technology demonstrator.
- 1st stage of NEXT-100.
- Taking data in 2018 (^{136}Xe depleted) and 2019 (^{136}Xe enriched).
- ⇨ Aimed at measuring **ββ2ν** and setting **ββ0ν** limits.


experimental hall (drawing)


experimental hall (photo)

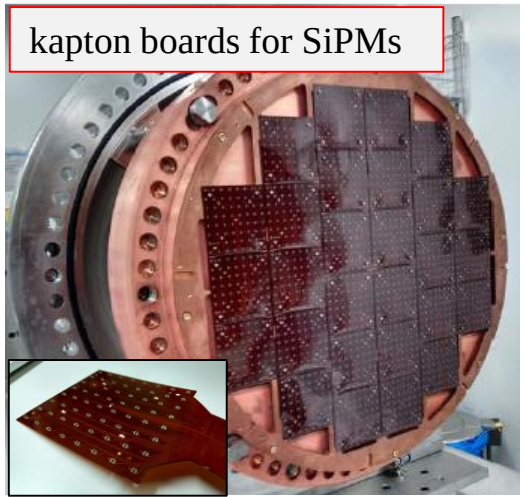

NEW (before installation)

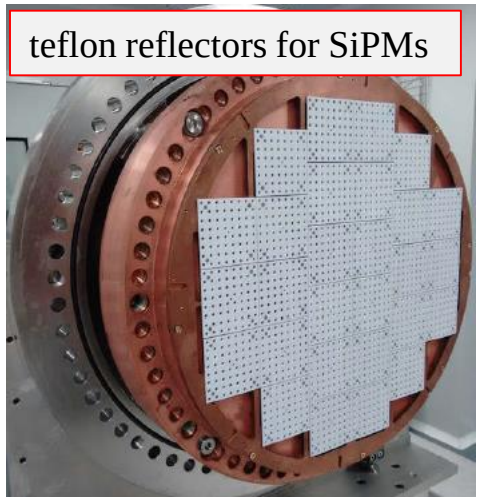

vessel
copper shielding
HDPE frame
field cage
cathode grid
axial view

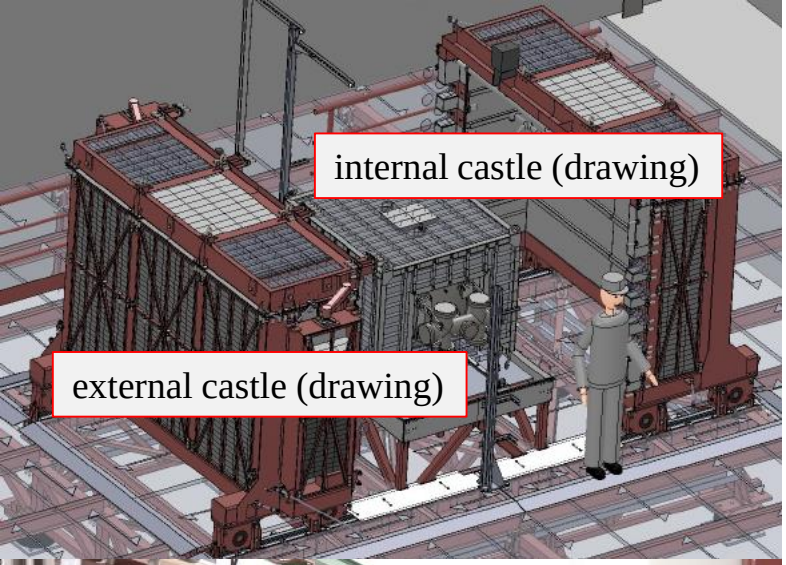

teflon reflector


anode plate (TPB+ITO coated)


gate grid


kapton boards for SiPMs

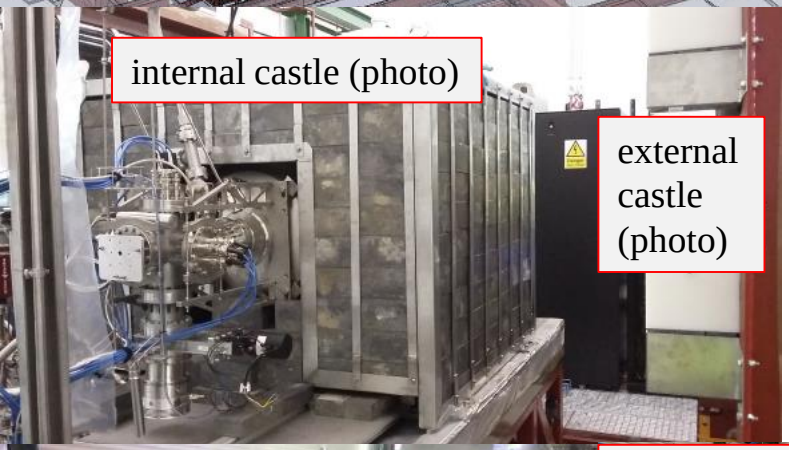

teflon reflectors for SiPMs


internal castle (drawing)

external castle (drawing)

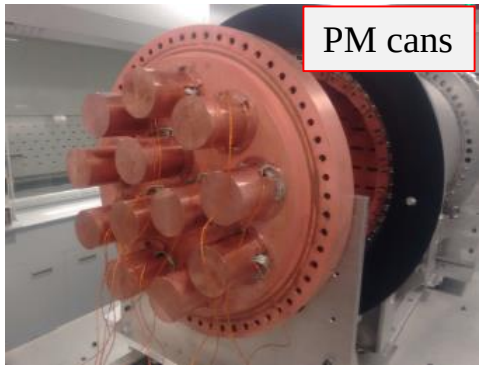

radon abatement system


compressor

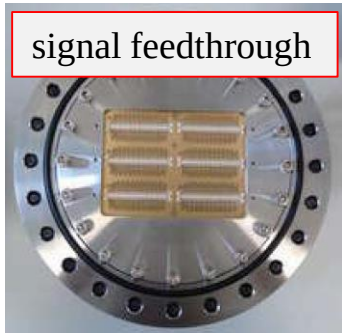

internal castle (photo)

external castle (photo)


copper shielding + PM viewports


PM cans


HV feedthroughs


signal feedthrough


cryo-recovery vessel

emergency recovery vessel (*misused NEXT-100 vessel*!)

+ front-end electronics, data acquisition boards, computer farm, slow control, gas system…

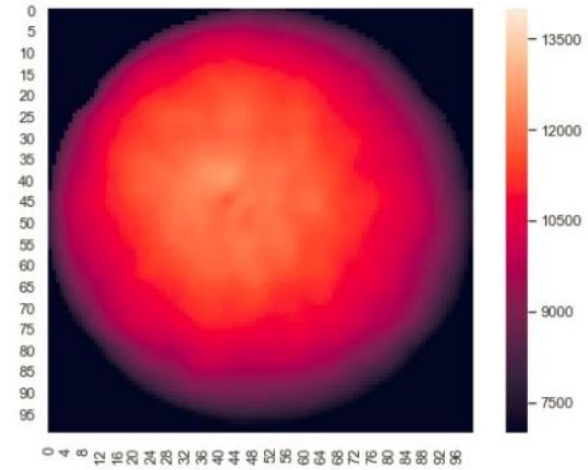
main NEXT results
(ongoing campaign)

- Operation with final NEW configuration since May 2018.
- Intense participation in shifts (total group time: 4-5 months)

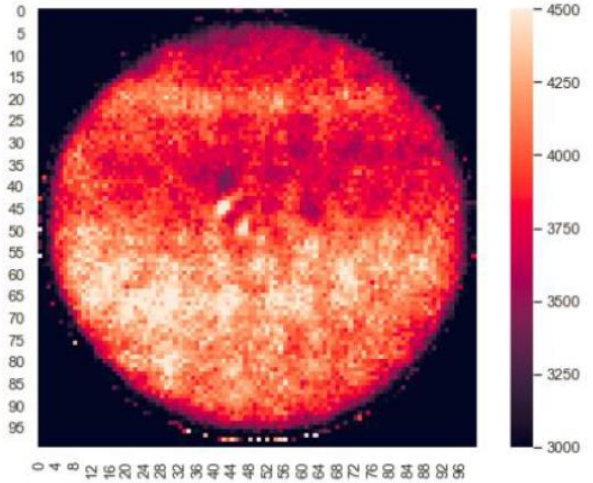
I. energy resolution

Goal 1% FWHM at $Q_{\beta\beta}$

calibration/detector modelling



Geometrical S2 map



Electron lifetime map

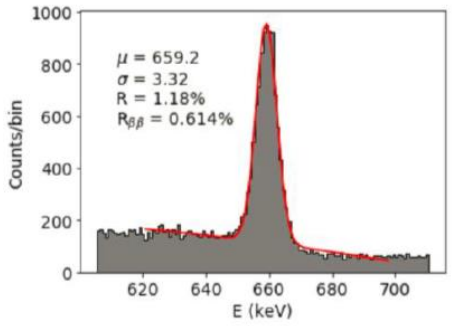
energy distribution

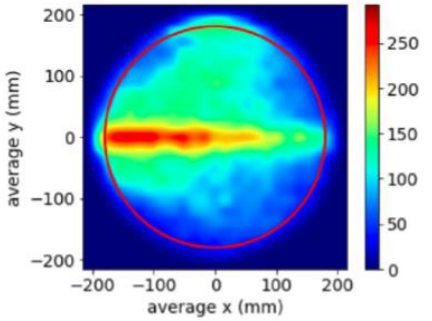
track barycenter

^{137}Cs 662 keV

Extrapolates $(1/\sqrt{E})$ to

0.61% FWHM at $Q_{\beta\beta}$

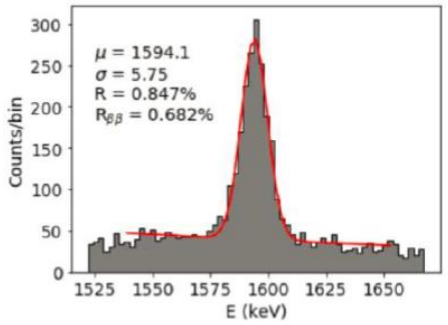


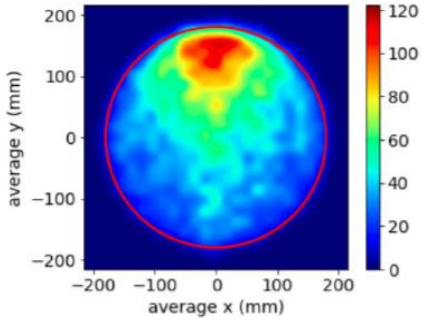


^{208}Tl 1593 keV e^+e^- escape peak

Extrapolates to

0.68% FWHM at $Q_{\beta\beta}$

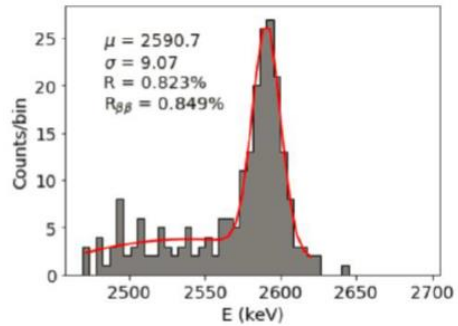


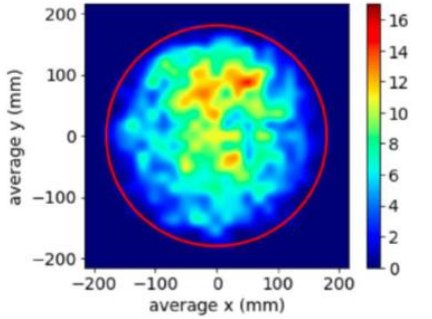


^{208}Tl 2615 keV full absorption peak

Extrapolates to

0.85% FWHM at $Q_{\beta\beta}$





G. Martínez-Lema, J. A. Hernando-Morata, B. Palmeiro et al., JINST 13 (2018) no.10, P10014

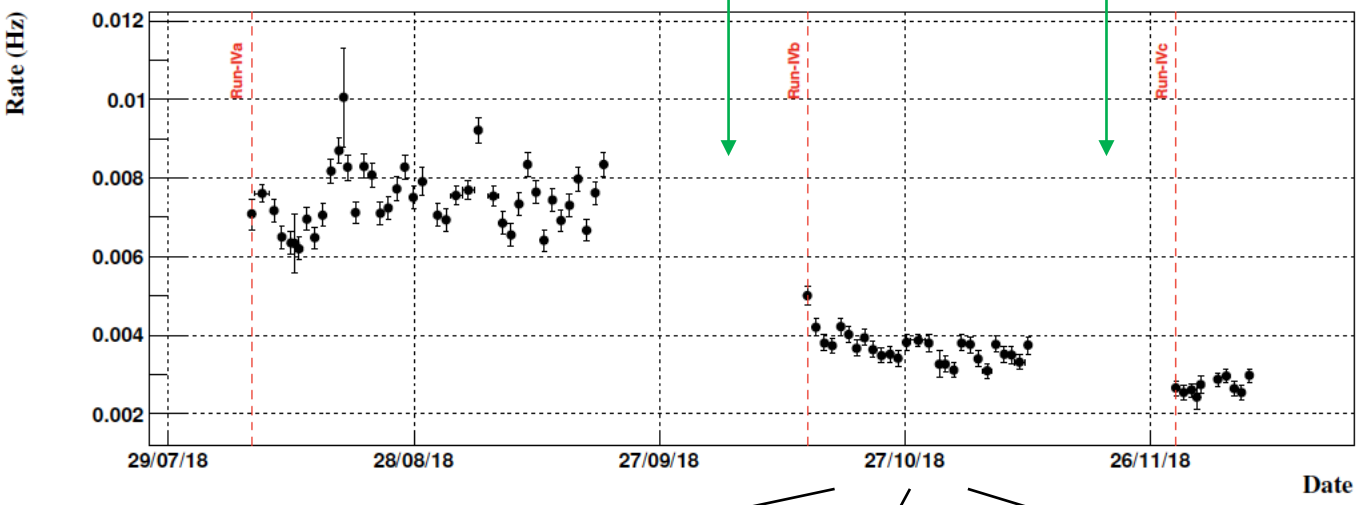
J. Renner, P. Ferrario, G. Martínez-Lema et al., JINST 13 (2018) no.10, P10014

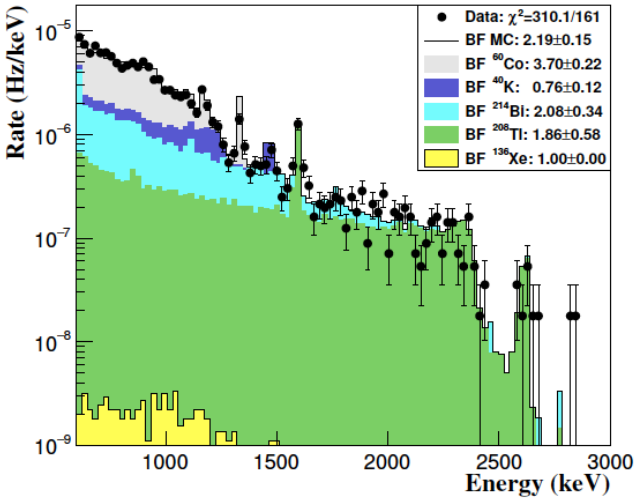
II. background level

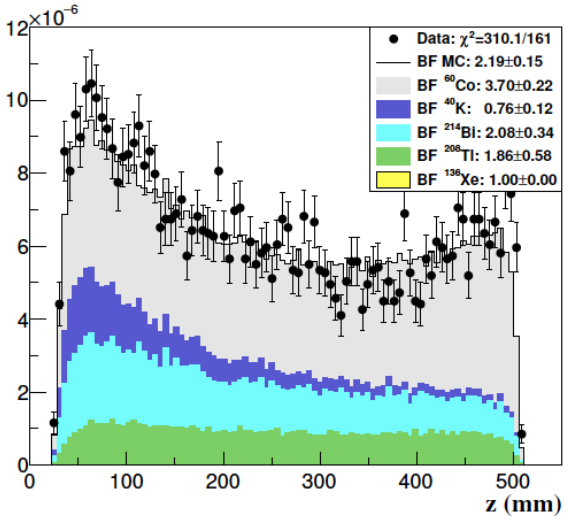
~ x1.5-2 higher than expected

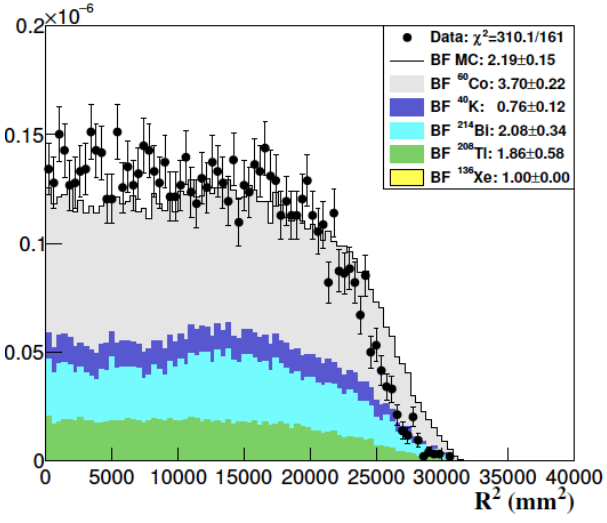
radon abatement system

inner castle





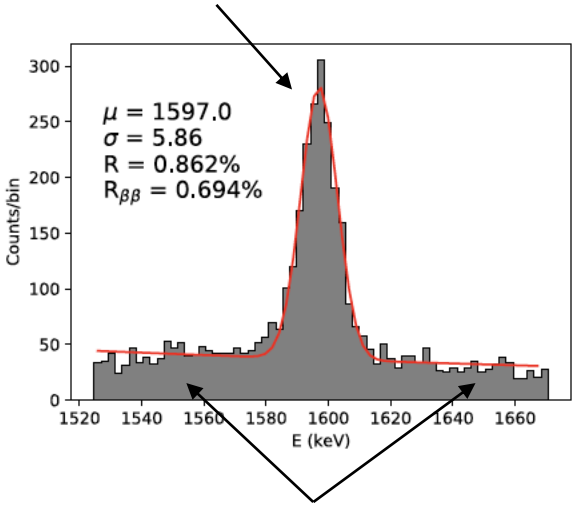




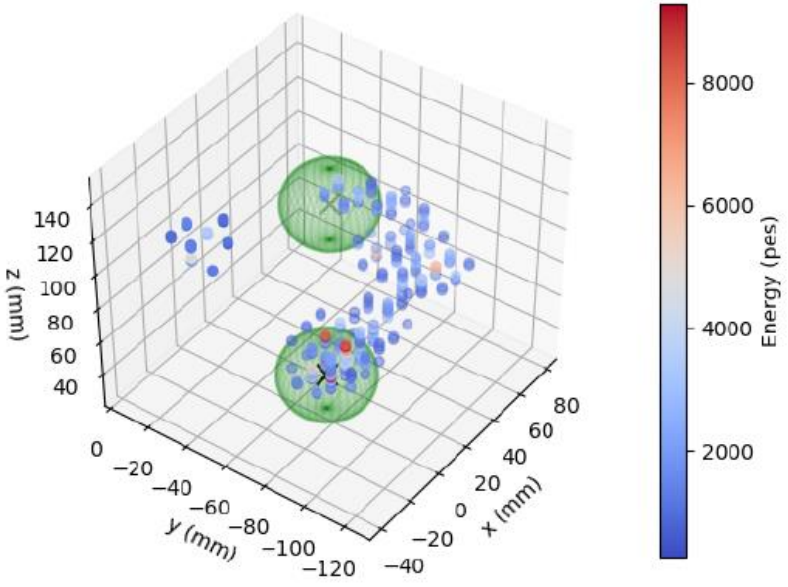
III. background suppression

within expectations!

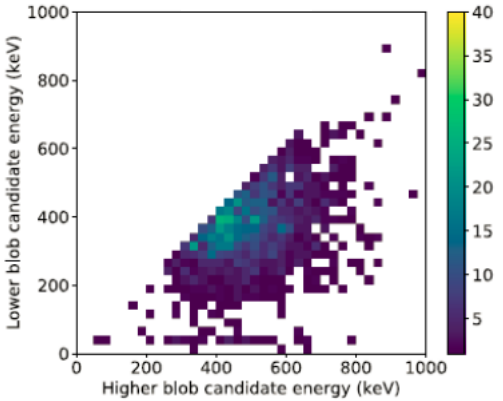
double escape peak ^{208}Tl (2e$^-$)



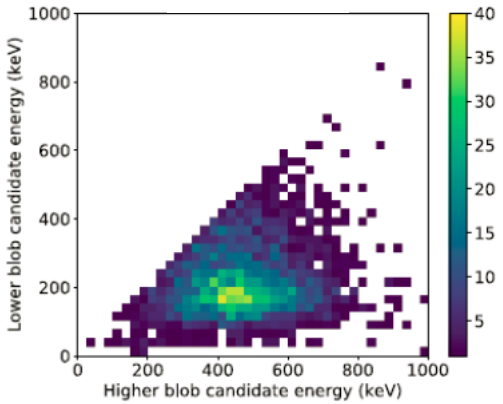
Compton (1e$^-$)

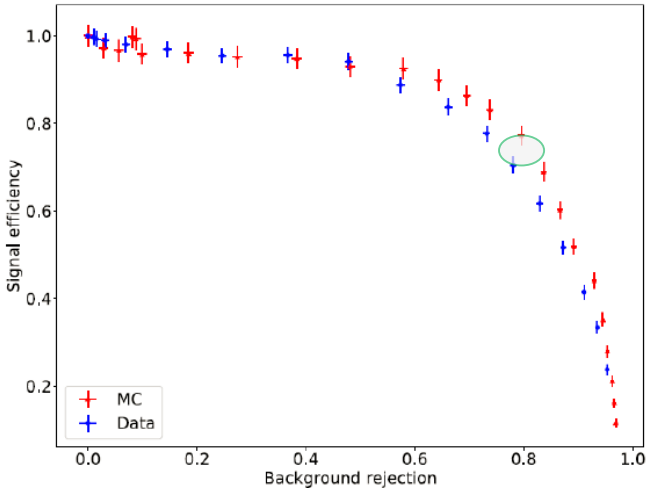


double escape peak ^{208}Tl (2e$^-$)



Compton (1e$^-$)





optimum cut:

- 77.3% efficiency
- 20.5% background acceptance

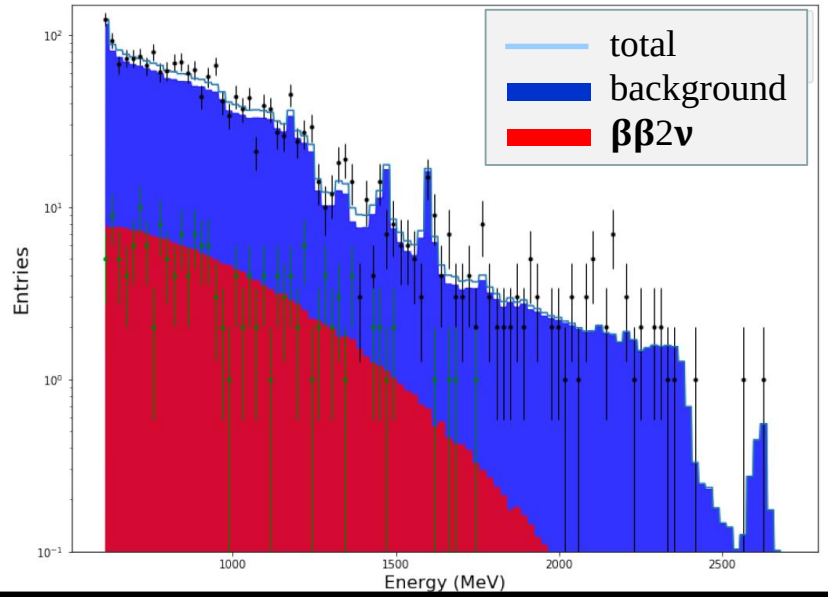
much better seems to be possible with neural networks (under study!)

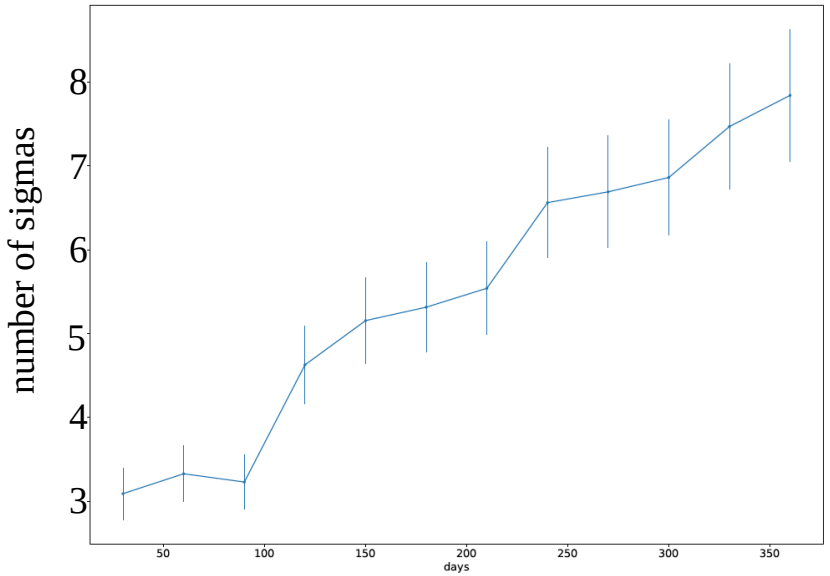
G. Díaz-López, J. A. Hernando-Morata, TFM, July 2018

IV. projections

ββ2ν, NEW (up to ~Jun 2019)

B. Palmeiro

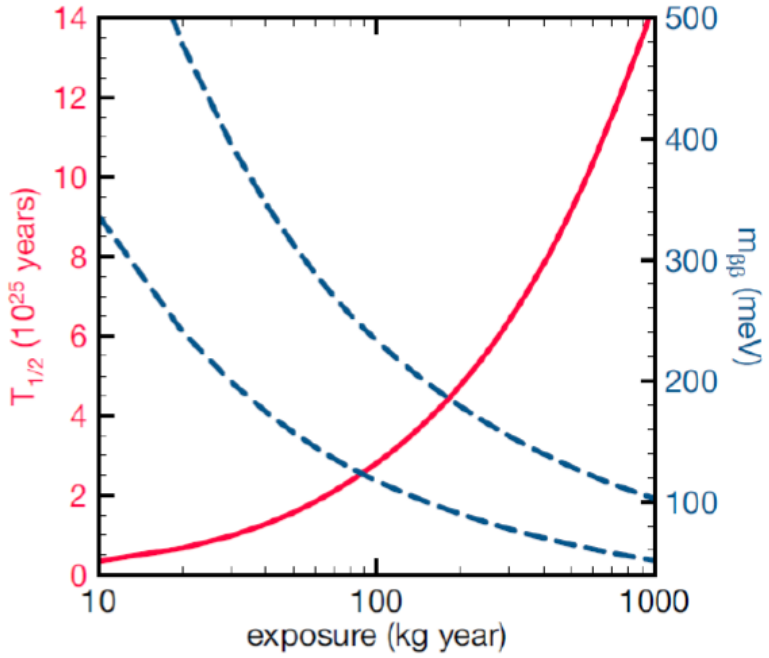




ββ0ν, NEXT-100 (from ~Jun 2020)

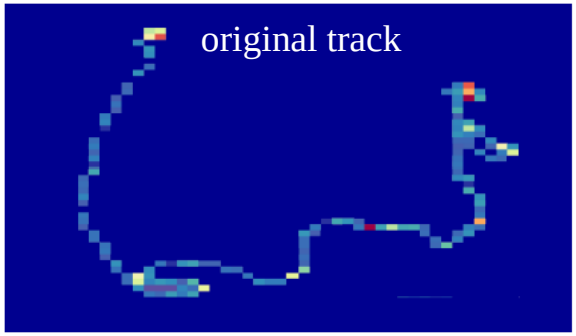
Background: $4 \cdot 10^{-4}$ counts/keV/kg/yr (~0.5-1 counts/100 kg/yr for 0.5-1% FWHM)

Dashed lines: largest and smallest estimations for the nuclear matrix elements



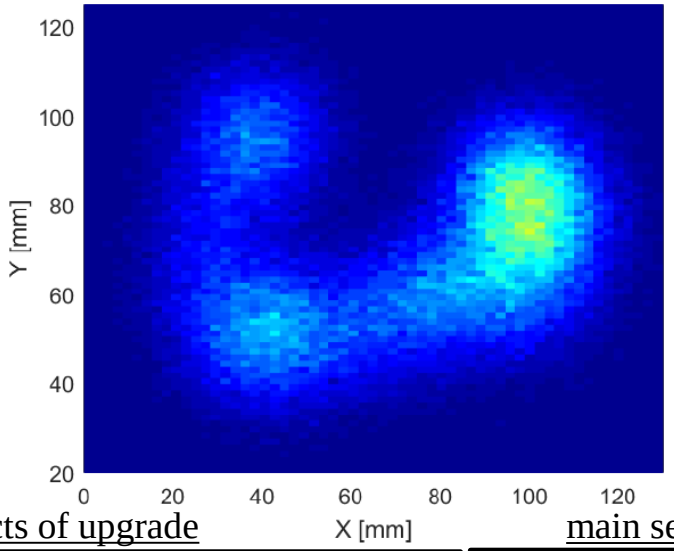
IGFAE expected to coordinate the installation of the neutron and muon VETO! (FPA call evaluation by March)

V. towards 1ton (improving topological information!)



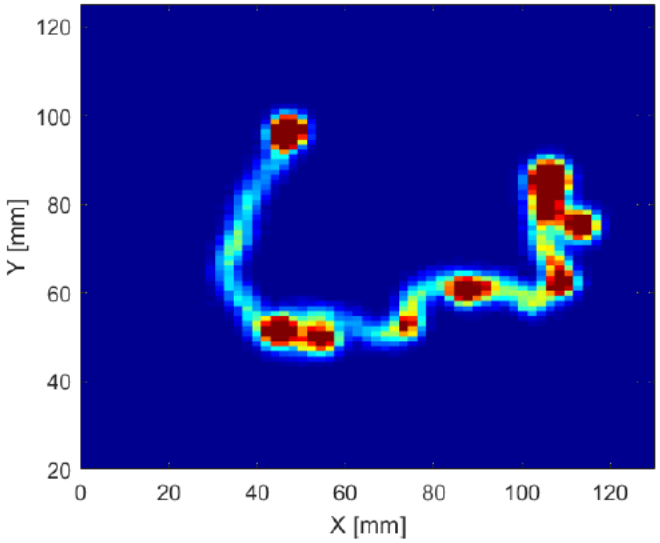
pure Xe

after ~1m charge drift



Xe 'magic' mixture

after ~1m charge drift



main aspects of upgrade

- Reduction of charge diffusion by a factor ~5.
- Optimization of Neural Network analysis.
- Much more compact/robust EL-region by a factor ~3 + deconvolution techniques.
- Development of ASIC for finer readout!.

room-T operation + He-proof PMTs

low-T operation + all-SiPM solution

main setups

- IFIC.
- Ben Gurion Univ.
- **IGFAE.**
- Coimbra Univ.

C. A. O. Henriques, C. M. B. Monteiro, ***D. González-Díaz*** et al., JHEP01(2019)027.

R. Felkai, F. Monrabal, ***D. González-Díaz*** et al., Nucl. Instr. Meth. A 905(2018)82.

C. D. R. Azevedo, ***D. González-Díaz*** et al., Nucl. Instr.Meth. A 877(2018)157.

C. A. O. Henriques, C. M. B. Monteiro, C. D. R. Azevedo, ***D. González-Díaz*** et al., Phys. Lett. B, 773, 10(2017)663

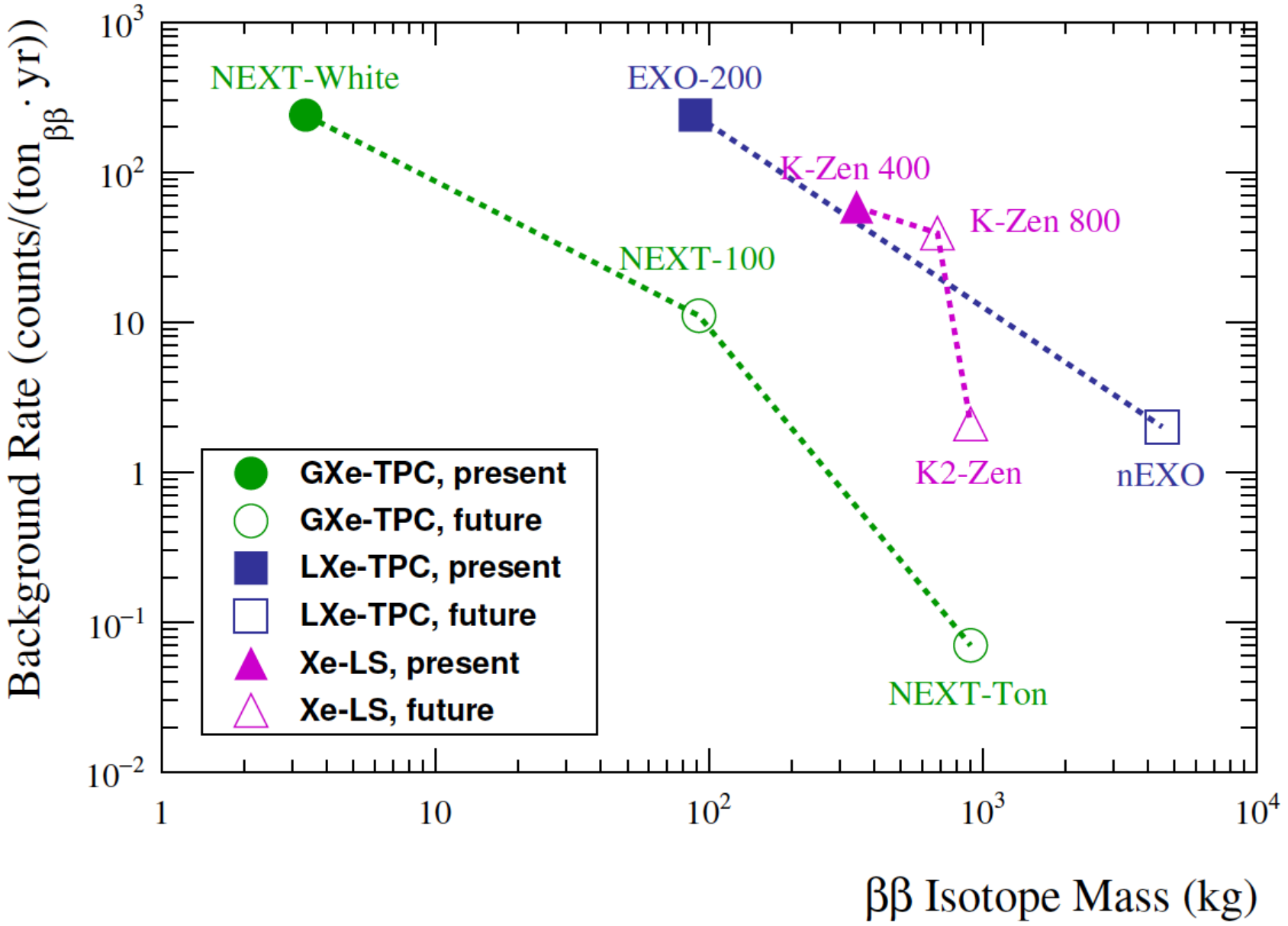
conclusions

- World-class lab devoted to Optical-TPCs and related experiments.
- Interest and support from the leading neutrino, dark matter, and nuclear physics experiments.
- Success achieved largely thanks to virtually ALL the experimental section of the Institute.
- As with any new line, with limited funding, we are still very fragile. Existence of a credit scheme or dedicated project-funding scheme by IGFAE is essential for us.

- NEW detector smoothly operating during 2018 (and for at least half a year more), excellent energy resolution (better than 1%), good topological rejection (improvements expected).
- During 2019: **ββ2ν** measurement (first time in gaseous xenon)**,** first **ββ0ν** limits. Important contributions from NN analysis expected (Josh Renner, IGFAE-fellow starting in June).
- NEXT-100 construction starts end 2019. IGFAE will be responsible for the new RPC-VETO (this line was jointly started by LIP and IGFAE in 2001, and resulted in big international success).
- Towards NEXT-ton: novel gas mixtures, FAT-GEM structures.

Appendix

comparison with leading experiments



effect of g_A

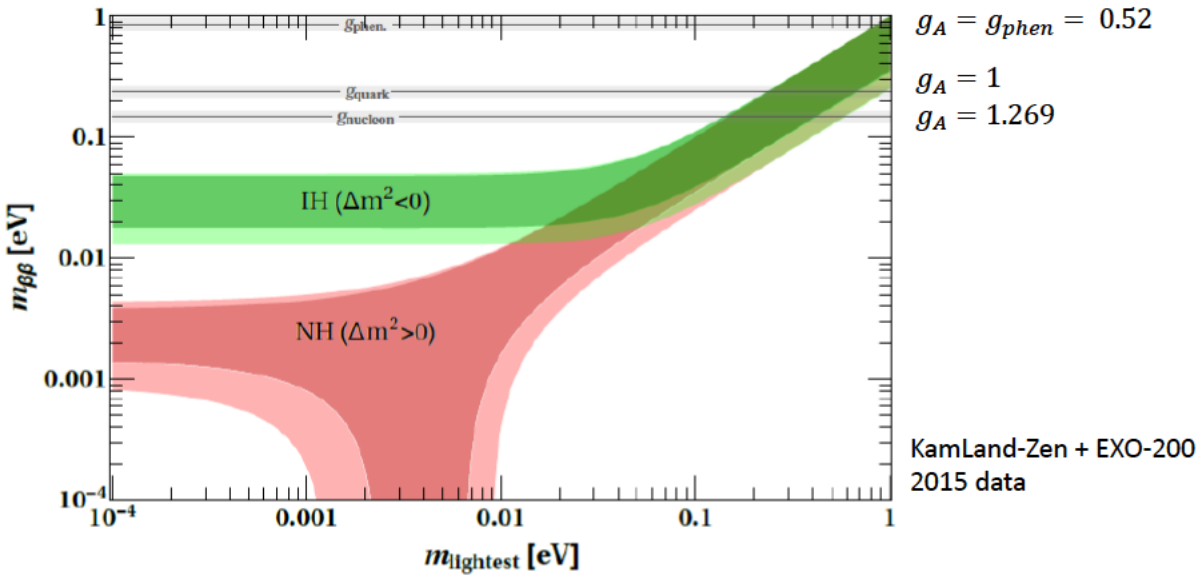
$g_A = 1.269$ for weak interaction and decays of nucleons

Quenching effects inside the nucleus *may* considerably reduce g_A

Conservatively one should consider several options:

$$g_A = \begin{cases} g_{nucleon} = 1.269 \\ g_{quark} = 1 \\ g_{phen.} = g_{nucleon} \cdot A^{-0.18} \end{cases}$$

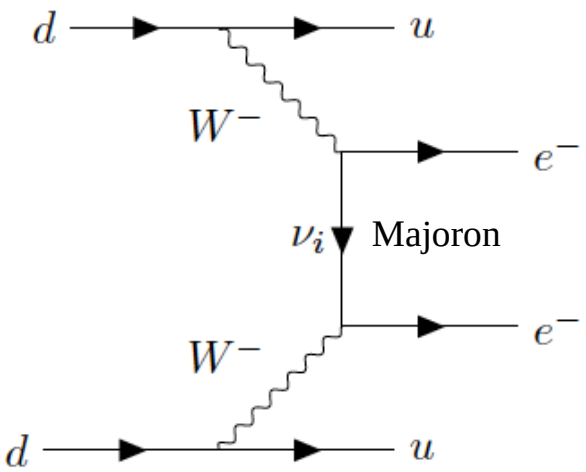
The degree of g_A quenching is unknown. The expression for $g_{phen.}$ is based on $2\nu\beta\beta$ half-lives and may be different for $0\nu\beta\beta$

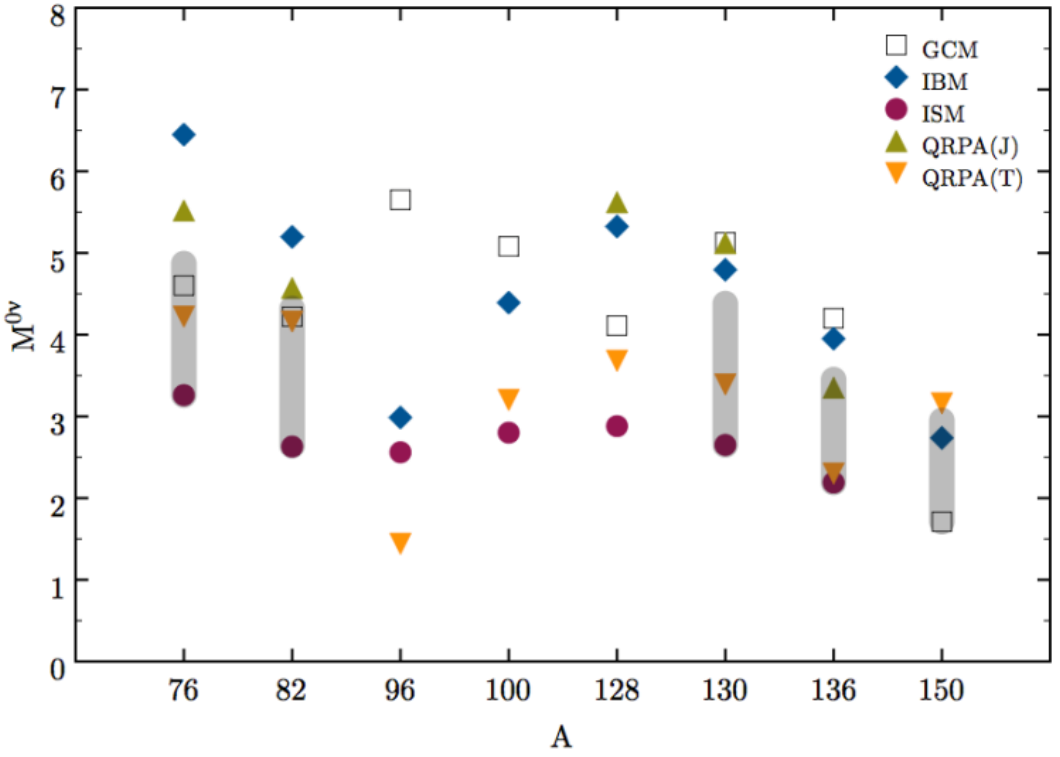


For ^{136}Xe taking $g_A = g_{phen}$ pushes up the limit on $m_{\beta\beta}$ by a factor of $\gtrsim 5$

effect of $M^{0\nu}$

$g_A = 1.25$

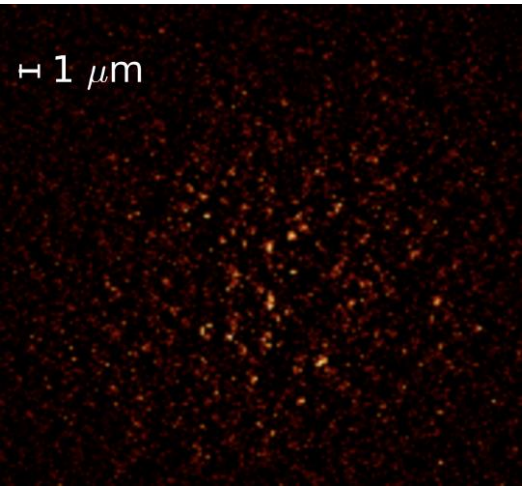


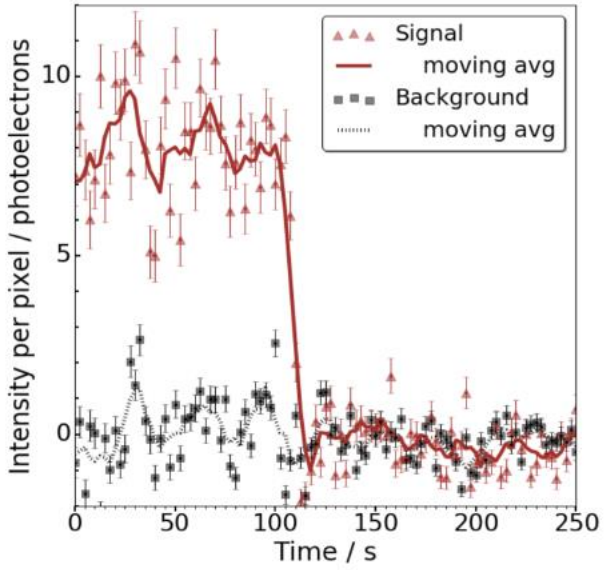


Barium tagging

when looking into a single spot

Ba ions made shine in solution

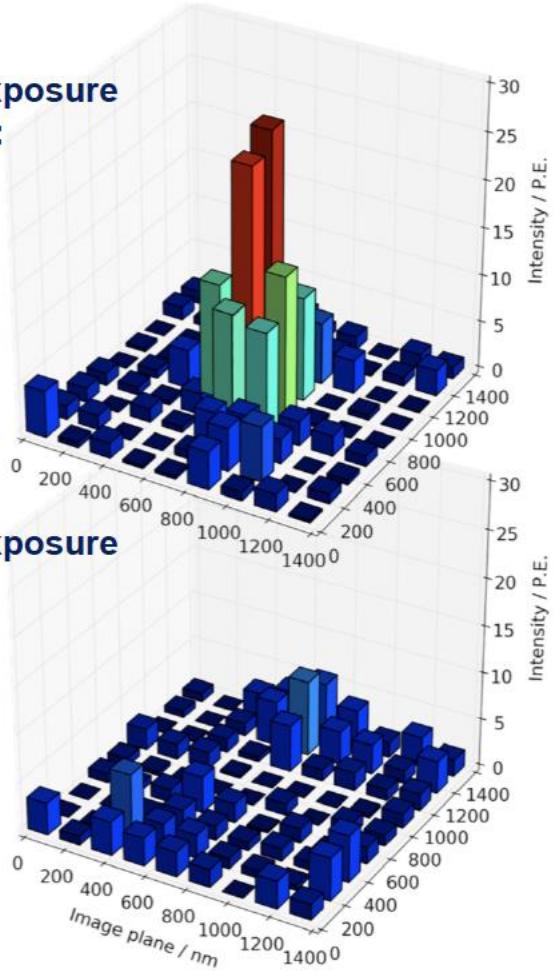




Phys.Rev.Lett. 120 (2018) no.13, 132504

0.5s exposure before:

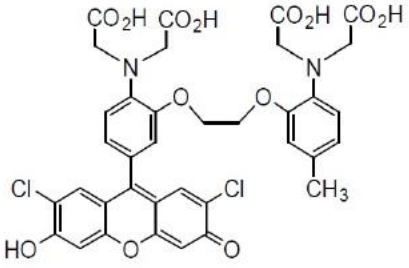
0.5s exposure after:



Barium tagging (next!)

next goal was to achieve a suitable molecule that could work in dry phase, not in a solution, e.g., in Xenon!.

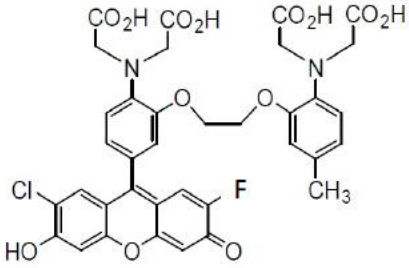
Ca^{++} (in solution)



BAPTA, fluorescein-Cl

FLUO-3

f = 17

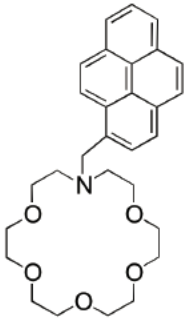


BAPTA, fluorescein-CF

FLUO-4

f=85

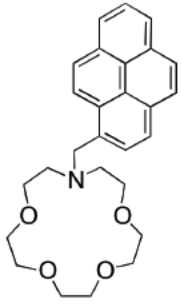
Ba^{++} (dry)



18c6, pyrene:

NEXT-1

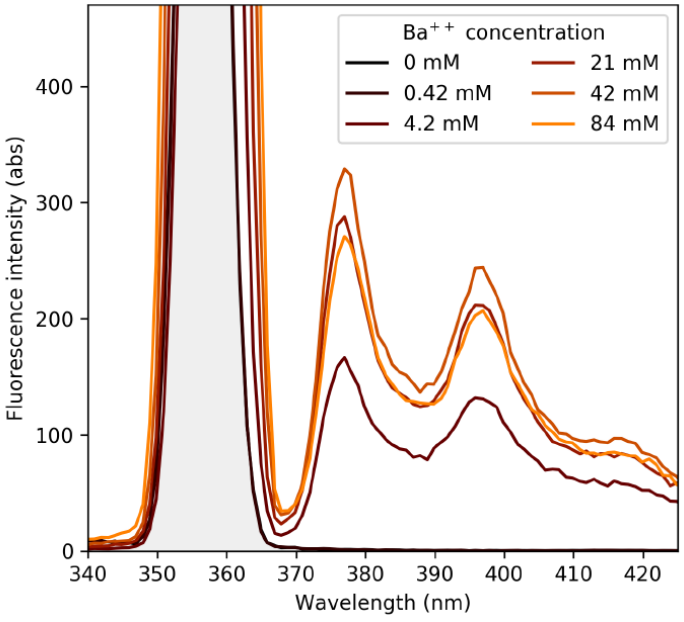
f=6

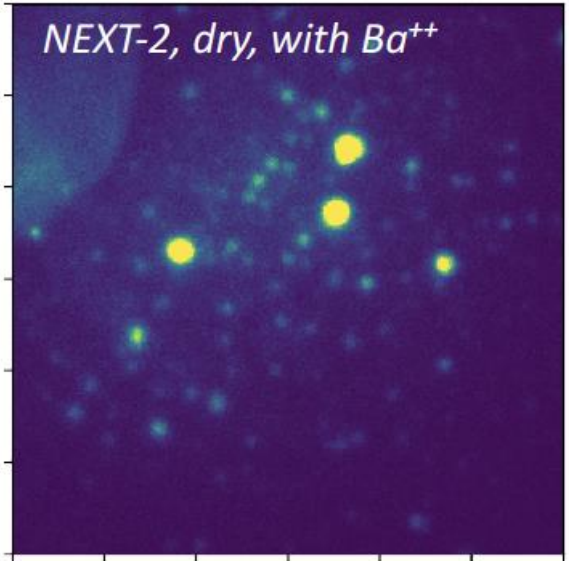


15c5, pyrene:

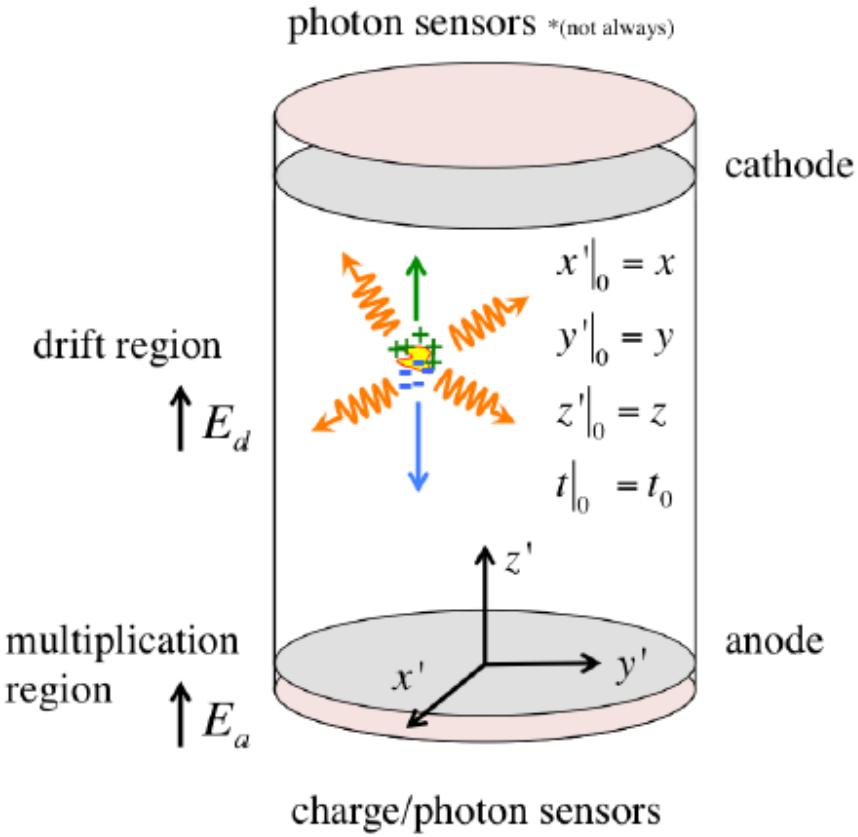
NEXT-2

f=205



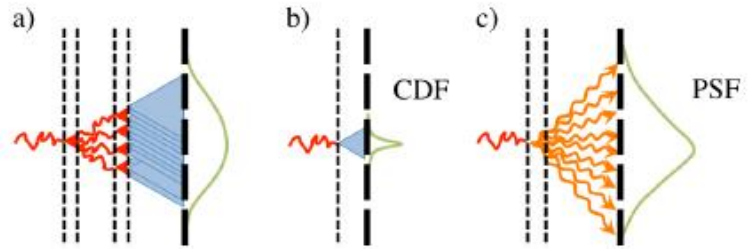


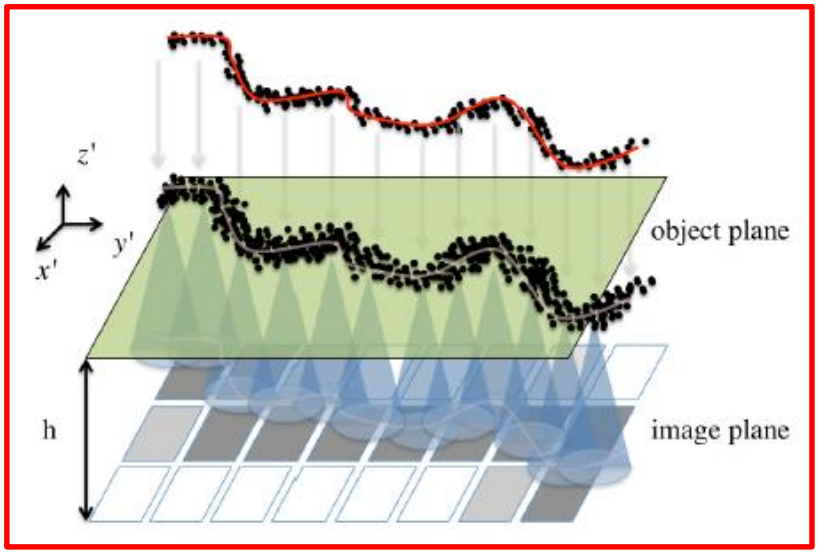
A generic TPC for rare event searches



- Aimed at complex topologies and maximal collection of event information.
- Seamless! (no beam pipe).
- Usually no space-charge issues.
- No ageing issues (interaction rate is low).
- Radiopurity issues (in some cases).
- B-field seldom found.

A generic image formation process in a TPC





point spread function

$$\delta(x'-x, y'-y) \rightarrow \mathcal{PSF}_{xy}(x'-x, y'-y)$$

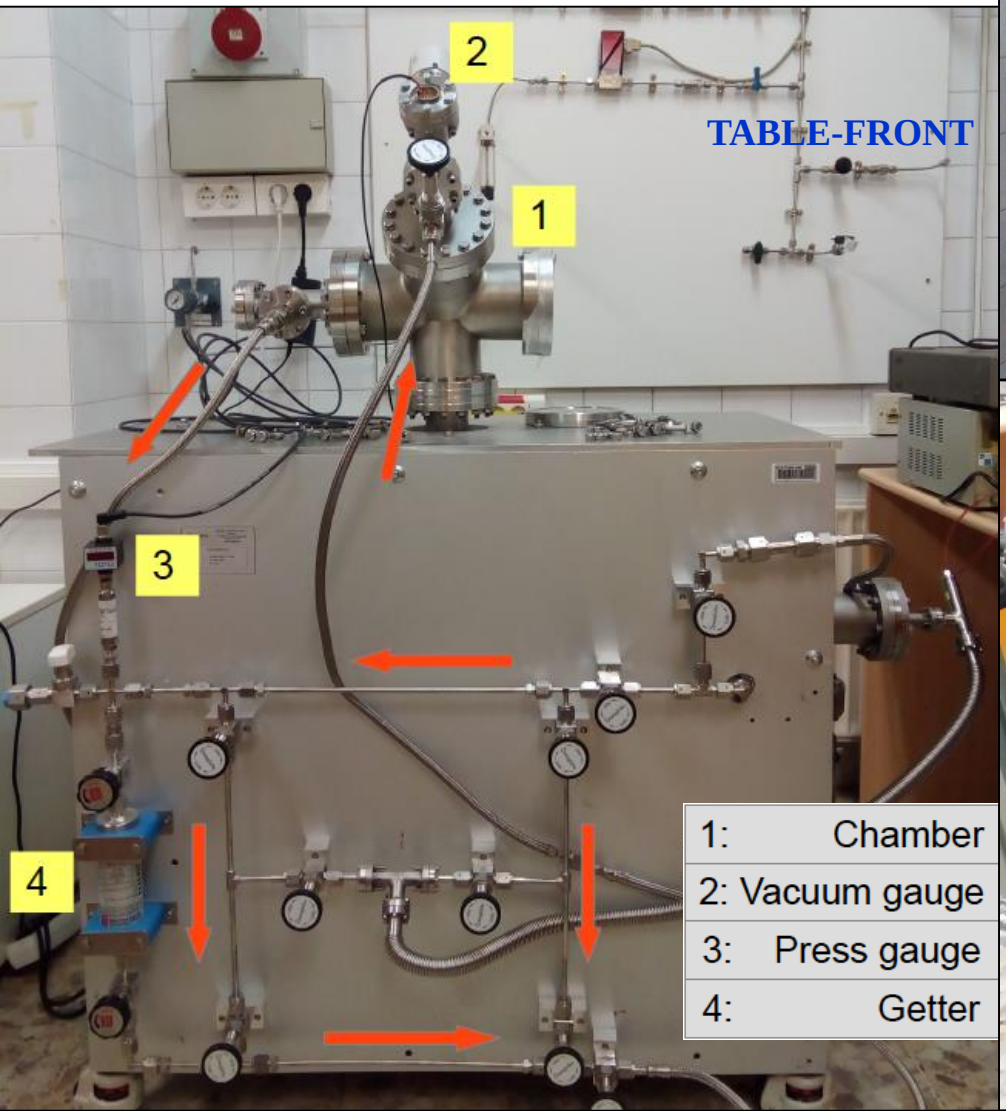
impulse response function

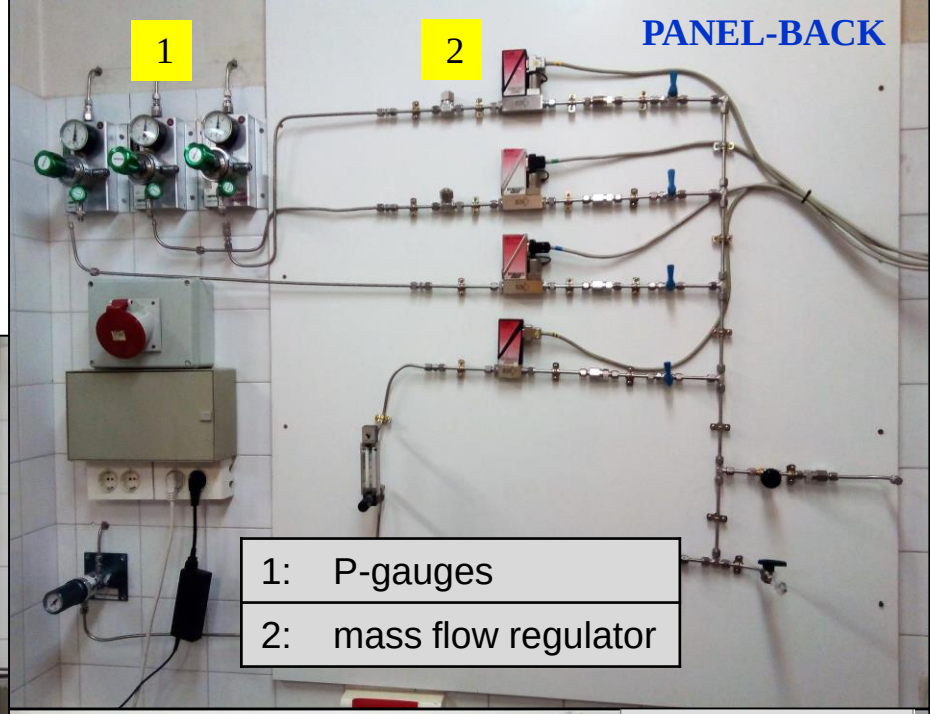
$$\delta(t-t_0) \rightarrow \mathcal{IRF}(t-t_0)$$

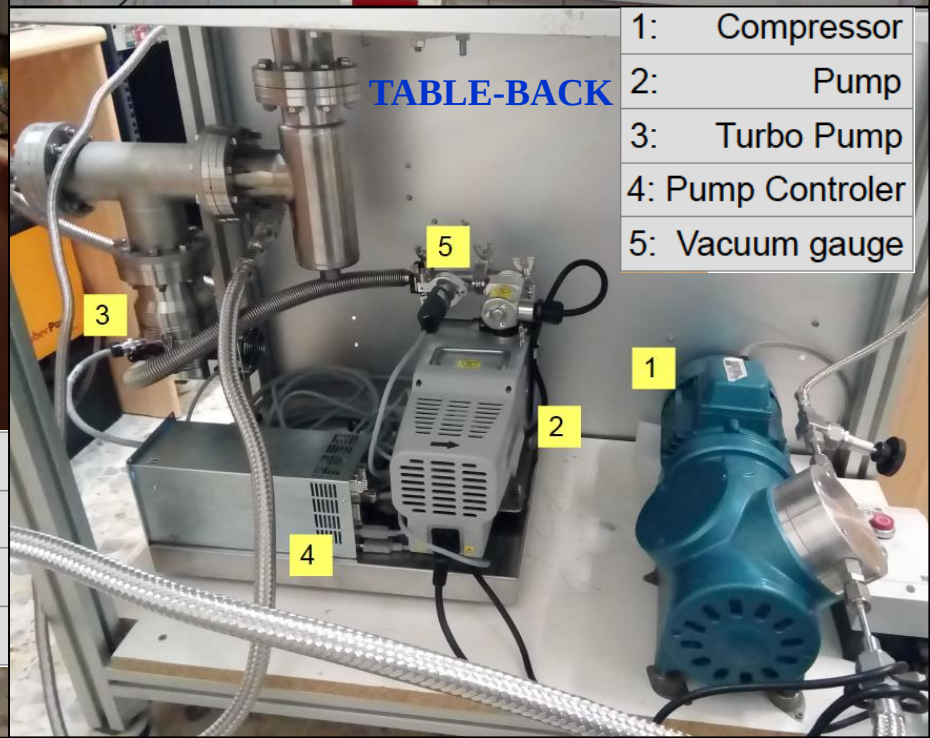
$$\sigma^{*,2}_{\mathcal{PSF}_{xy}} \simeq \sigma^2_{\mathcal{PSF}_{xy}} + D^{*,2}_T z$$

$$\sigma^{*,2}_{\mathcal{PSF}_z} \simeq v_d^2 \cdot \sigma^2_{IRF} + D^{*,2}_L z$$

enabling assets II(b)
(gas, purification and vacuum system)

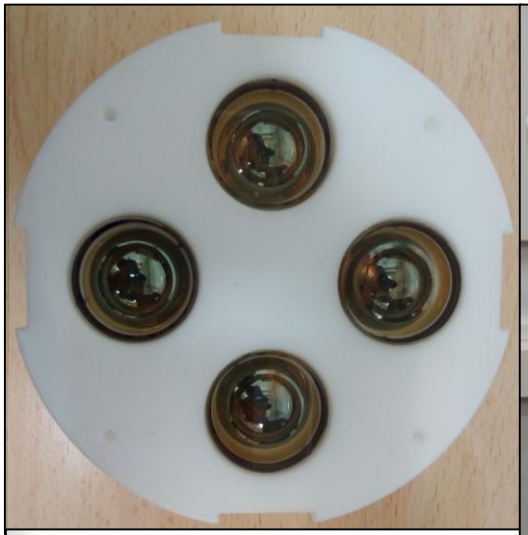


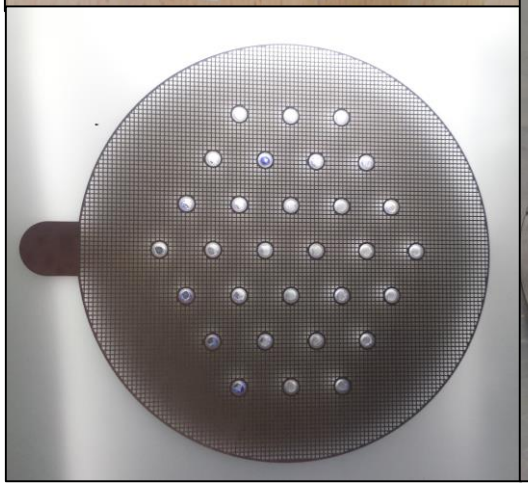




enabling assets III
(chamber for sensor characterization: Nausicaa0)

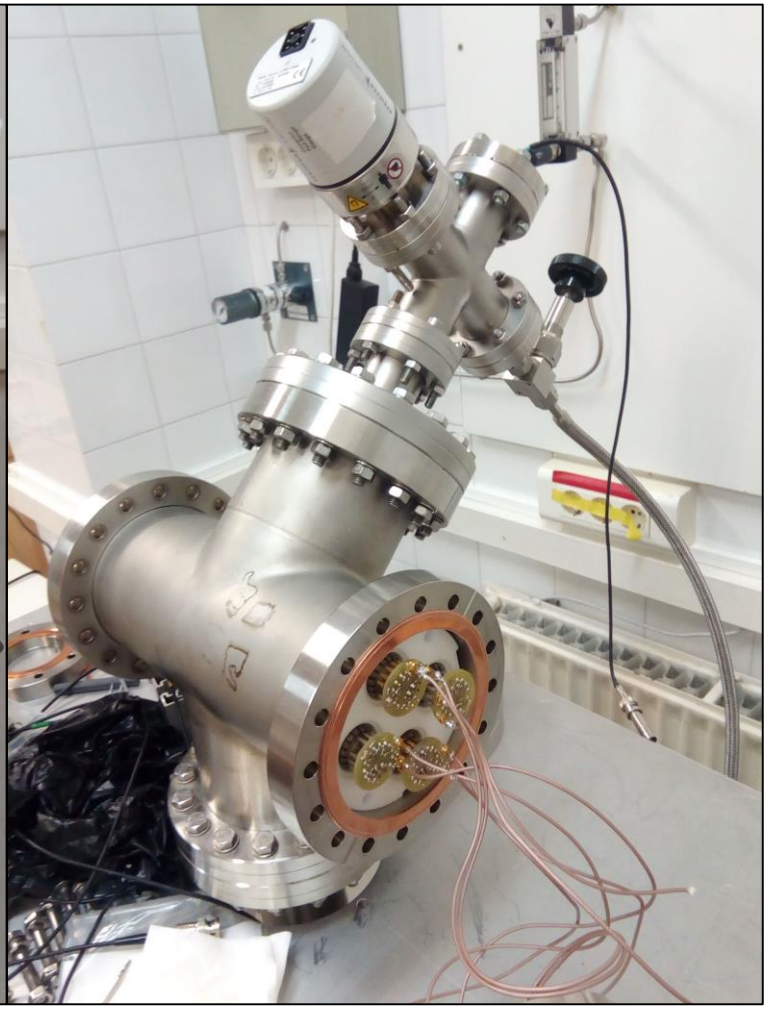
PMT teflon-frame



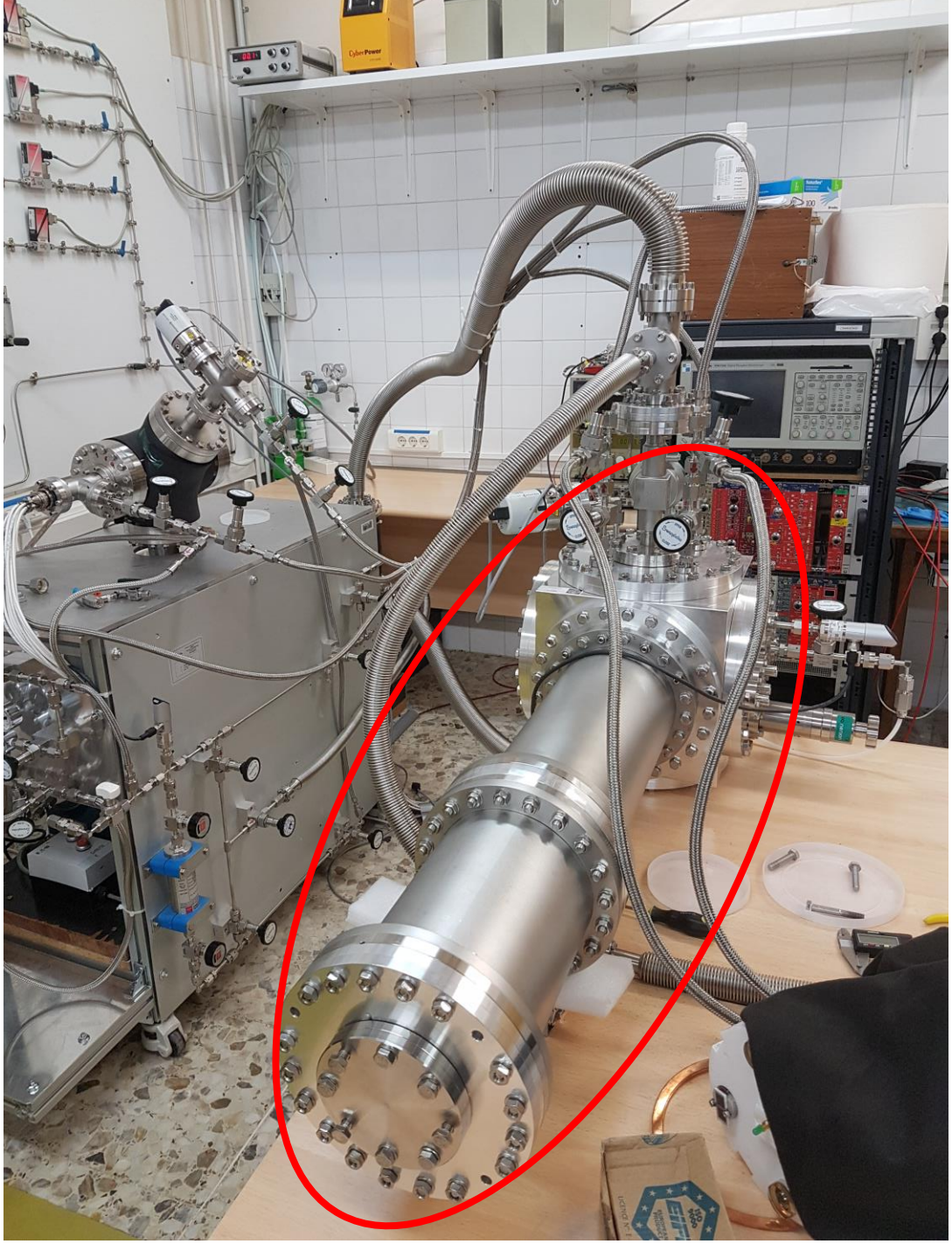


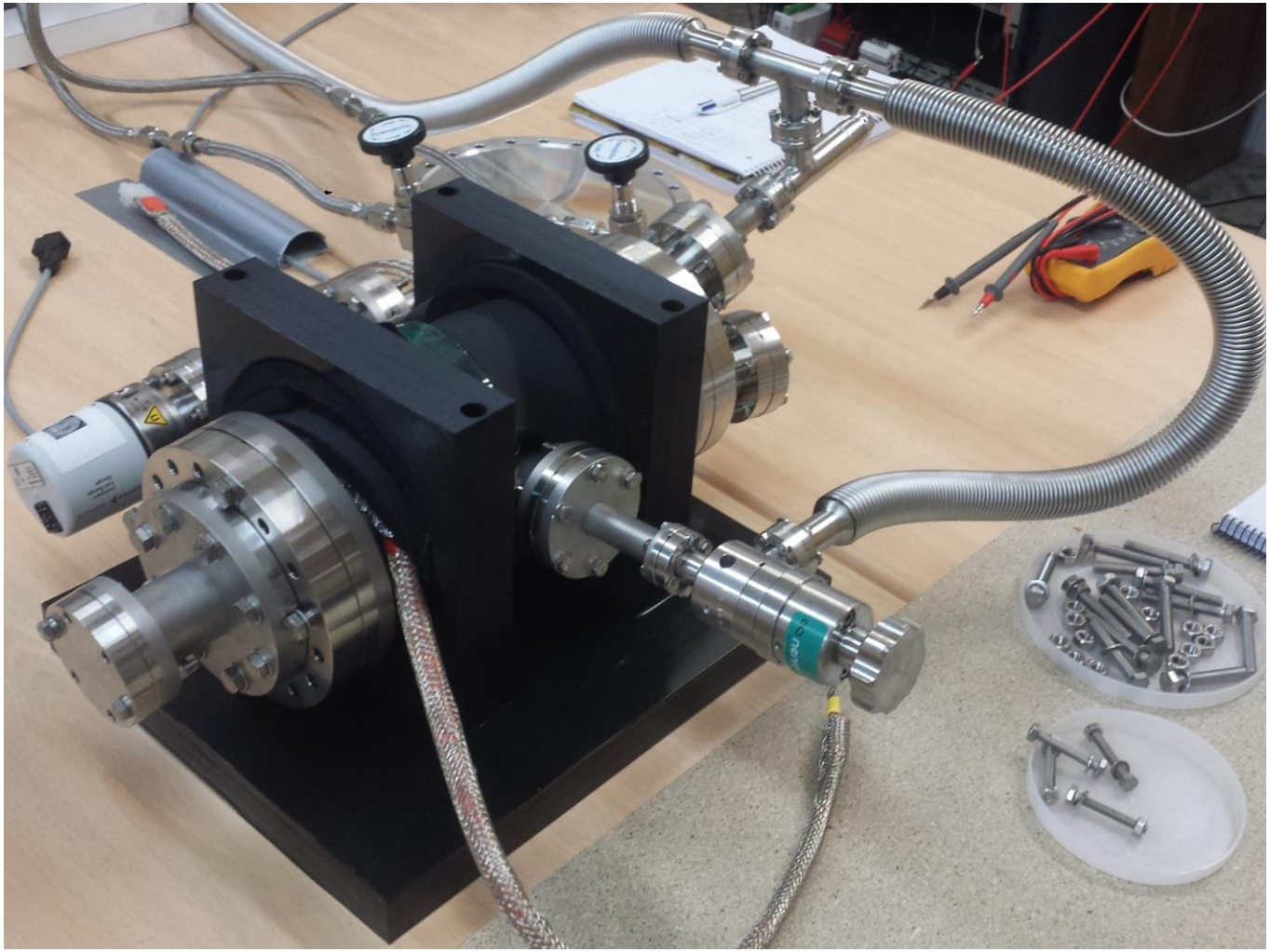
acrylic hole-based scintillator
(akin to GEMs, but x100 larger)

test assembly



Nausicaa0 general view

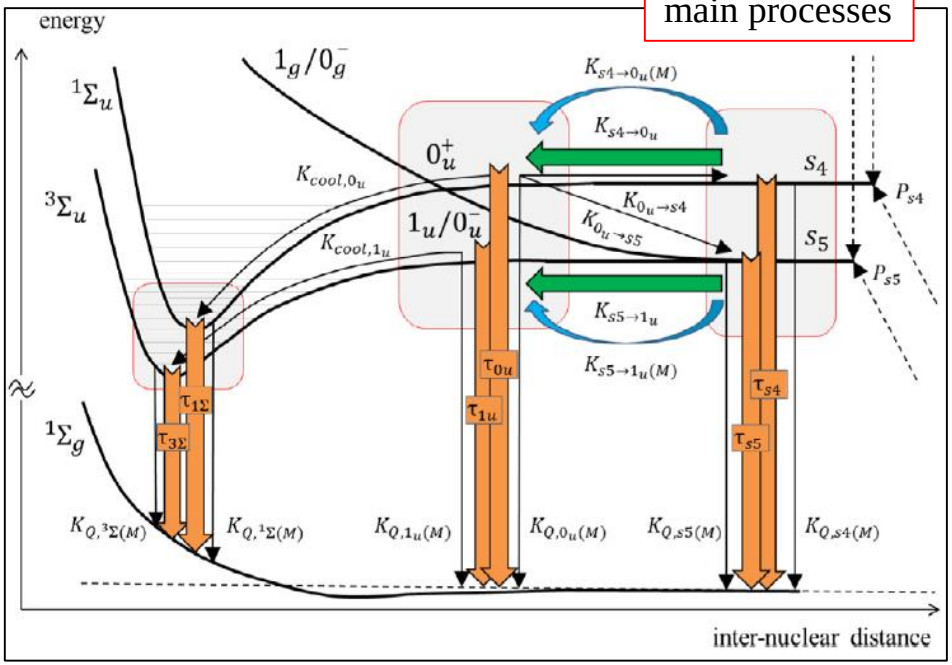




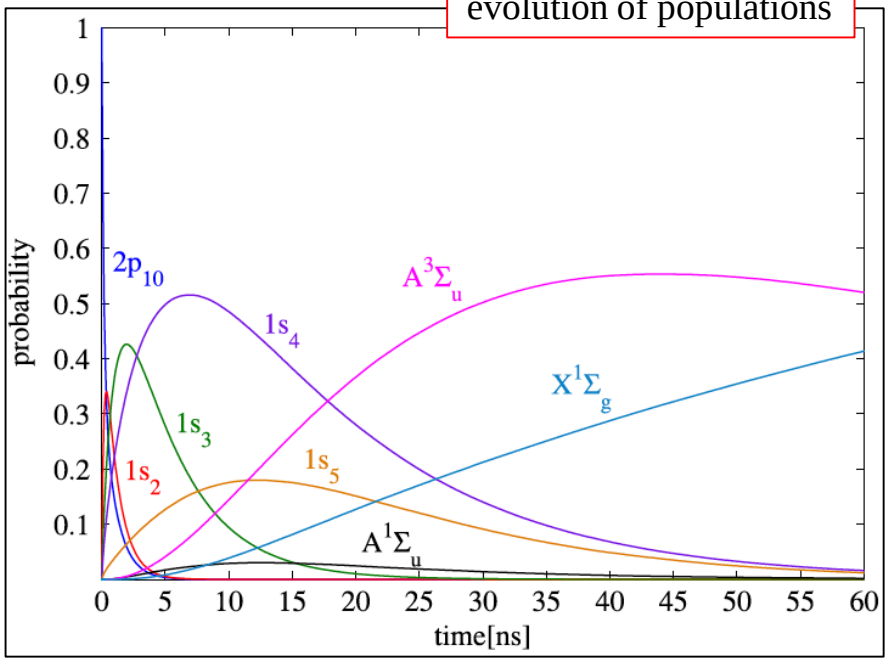
Fully equipped for R&D on scintillation in the pressure range from 0-10, with monitoring of gas quality through RGA.

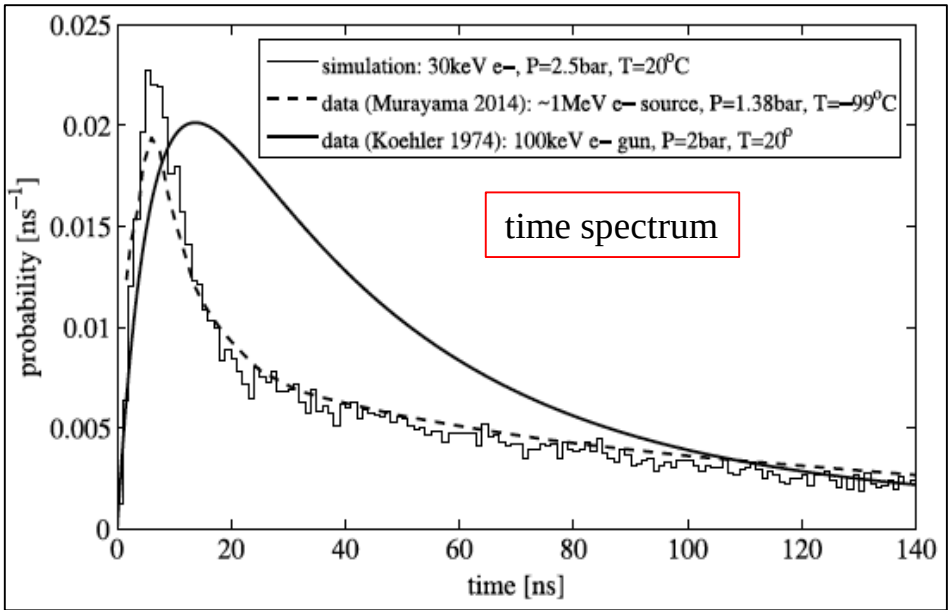
enabling assets VI (full description of cascade of excited states down to scintillation)

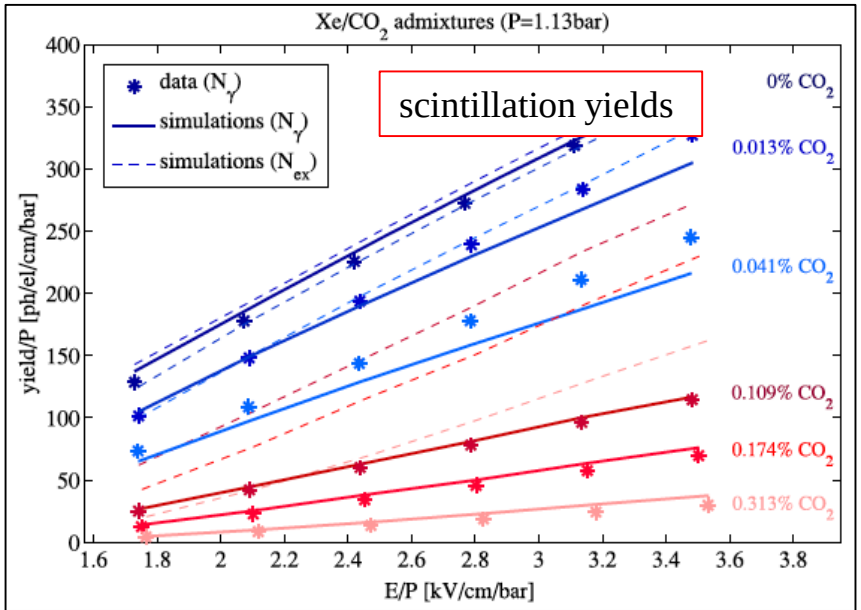
main processes



evolution of populations

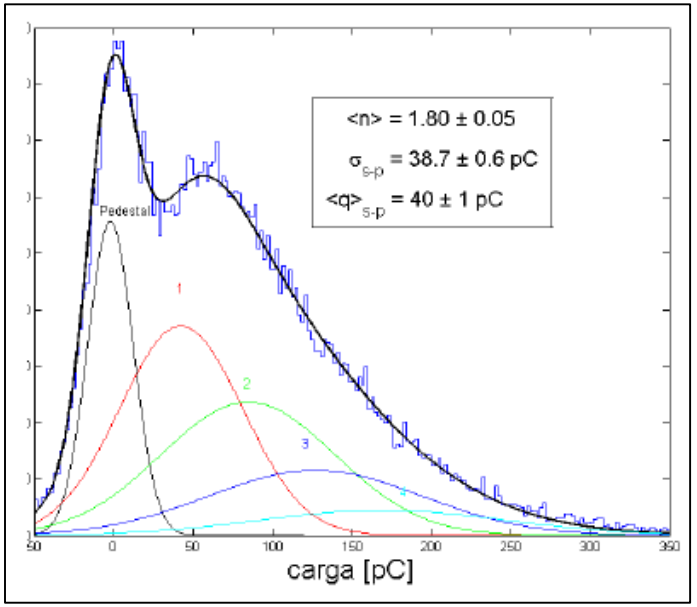






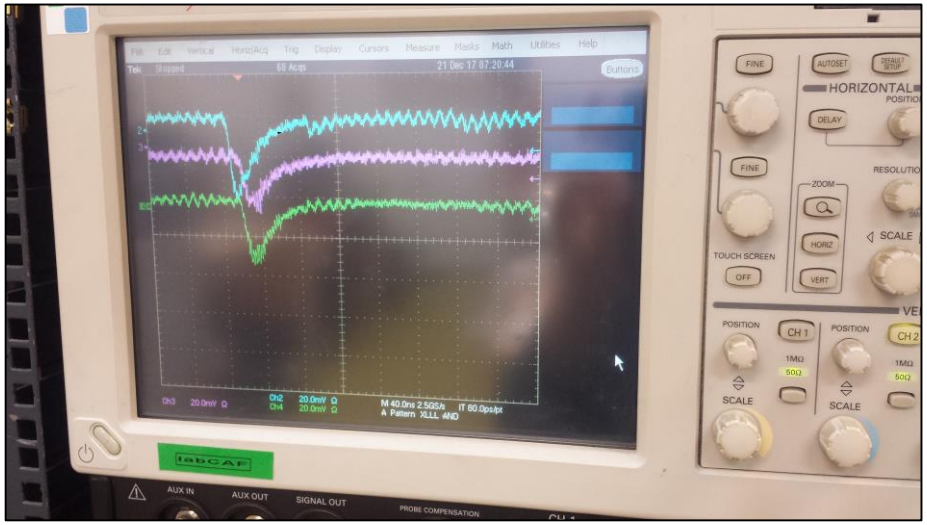
enabling assets VII
(some working parameters achieved)

- Vacuum level achieved (with Nausicaa0 fully assembled): 5×10^{-6} mbar (after just one night).
- Gas system pressurized up to 10bar with a leak rate 10^{-5}-10^{-4} mbar l s^{-1}.
- Nausicaa0 rated up to 10bar (presently working at 3bar).
- Single-photon sensitivity proven. →



- First results from scintillation from the new NEXT EL-tiles.

↘ (yesterday evening)



- voltage across the tile: 5kV
- drift field: 1kV/cm/bar
- pressure: 3bar
- signal seen in 3PMTs simultaneously