Gaseous Detectors for present and future experiments in Rare Event Searches

D. González-Díaz

(*on behalf of RP5: Dark Matter and the Nature of Neutrinos*)

25/04/2019, LIP-IGFAE meeting, Santiago de Compostela

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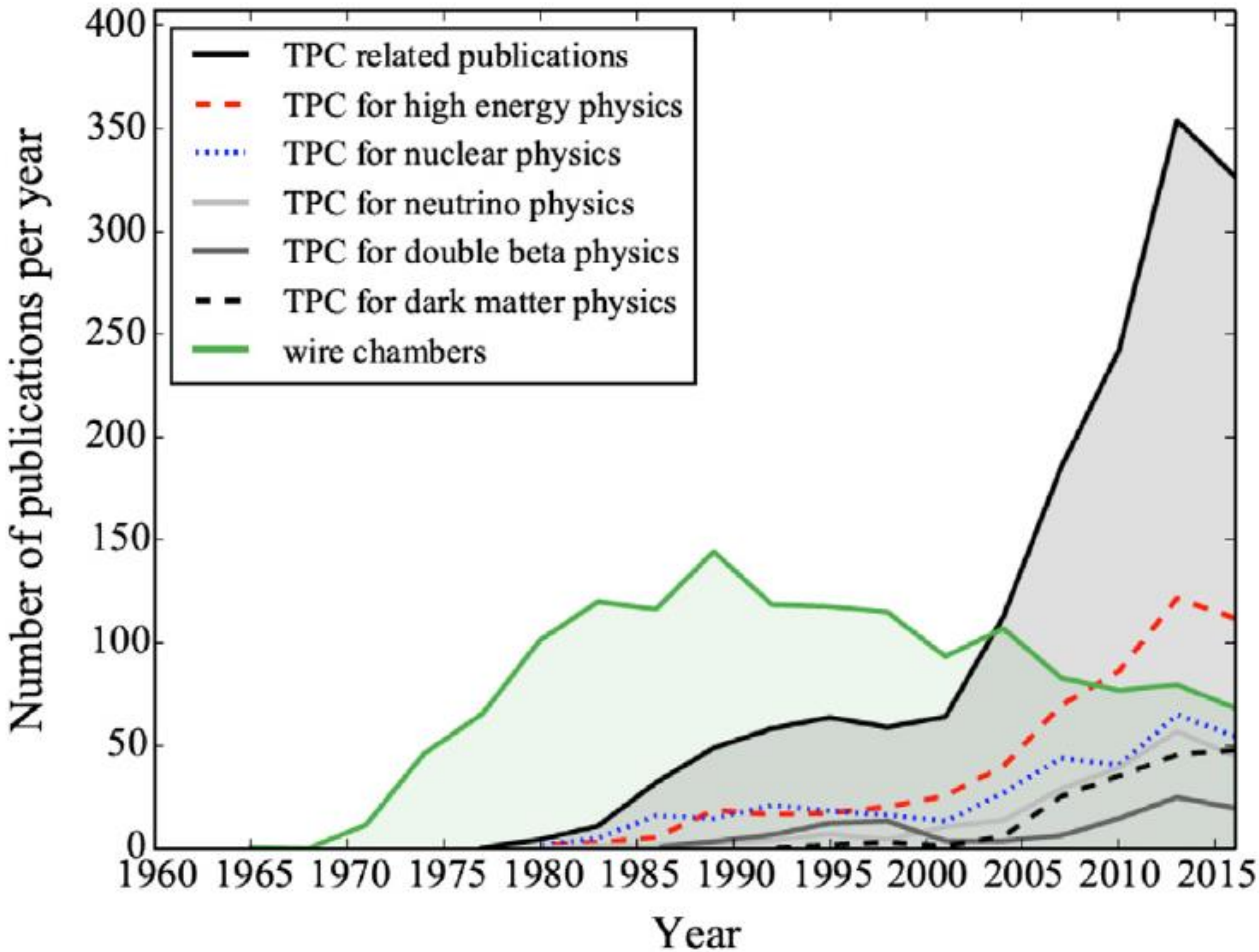
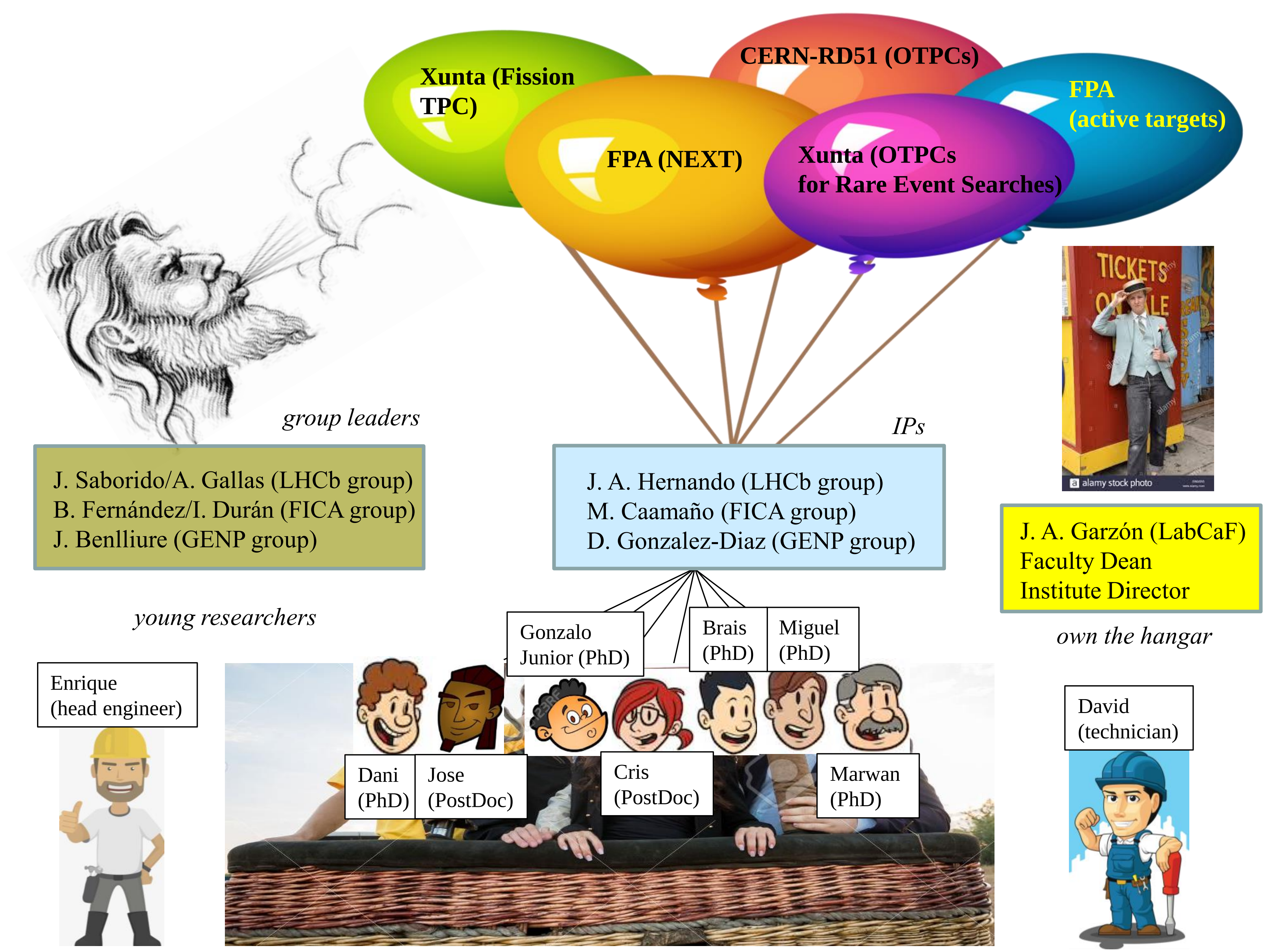
arguably the most successful gaseous detector concept to date: the Time Projection Chamber!



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



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

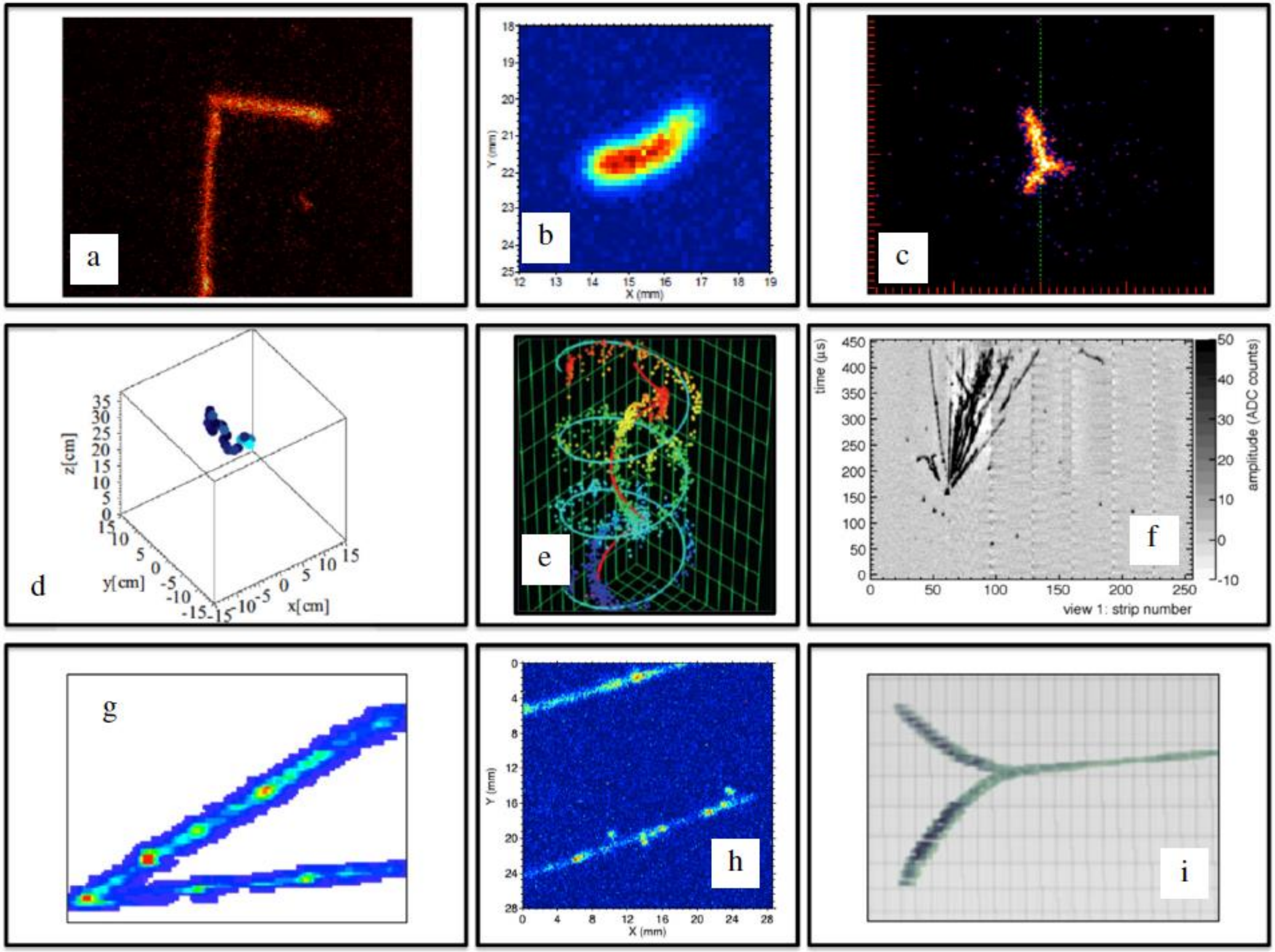
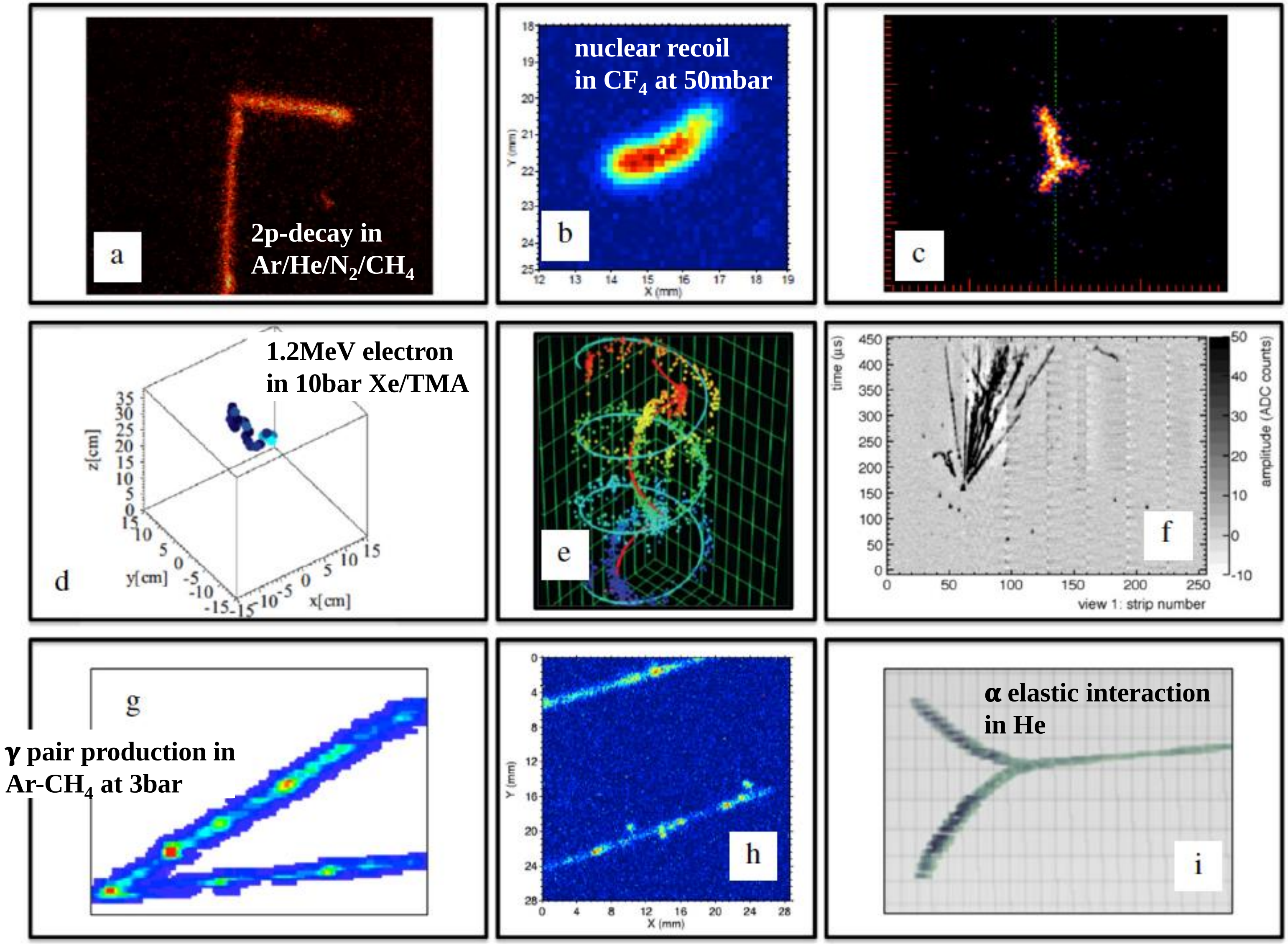


Fig. 3. Some representative images obtained with state of the art TPCs employed outside collider physics: a) β-delayed proton emission from ^{46}Fe [76]; b) a low energy C or F nucleus ($\varepsilon = 214\,\mathrm{keV}$) recoiling against a neutron [11]; c) a triple α event produced after the reaction $^{12}\mathrm{C}(\gamma,\alpha)^{8}\mathrm{Be}$ in a 150 mbar CO_2/N_2 active target [15]; d) a 1.275 MeV photoelectron from a ^{22}Na source in a 10 bar xenon/TMA admixture [36]; e) a low energy electron spiraling in a magnetic field, reconstructed in a $\sim 1\,\mathrm{cm}^3$ mini-TPC with an InGrid device [10]; f) a cosmic ray shower obtained with the dual-phase argon TPC of the WA105 collaboration [9]; g) pair production of a 74.3 GeV photon in the HARPO polarimeter, based on pressurized argon [77]; h) electrons with energies above 30 keV, reconstructed in 50 mbar of CF_4; i) elastic scattering between two α-particles at around 1 bar, reconstructed with the AT-TPC [78].



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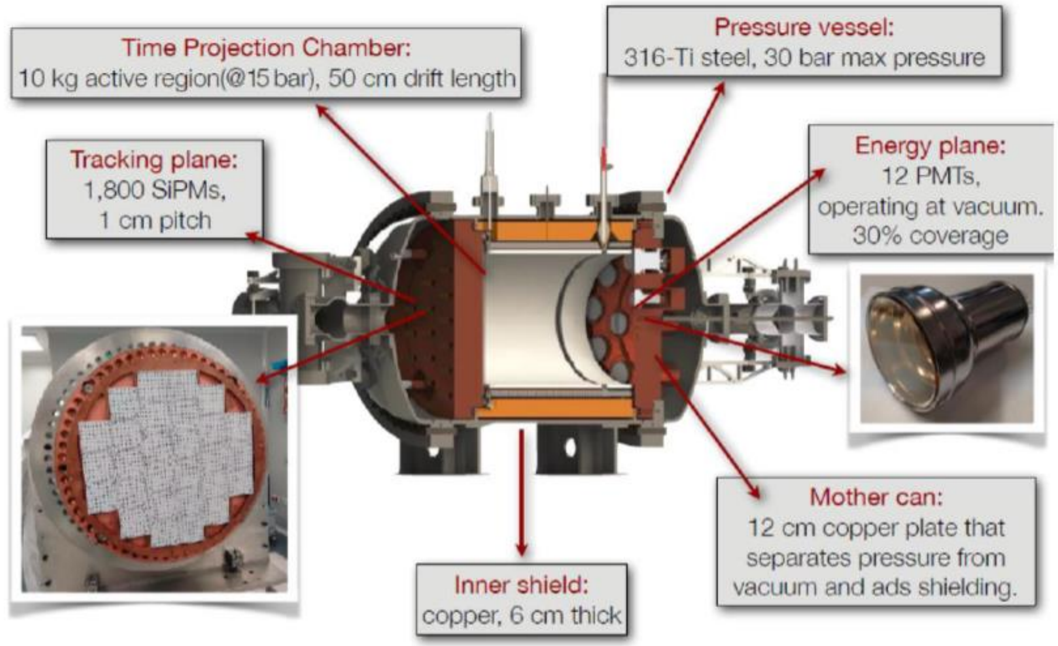
some highlights

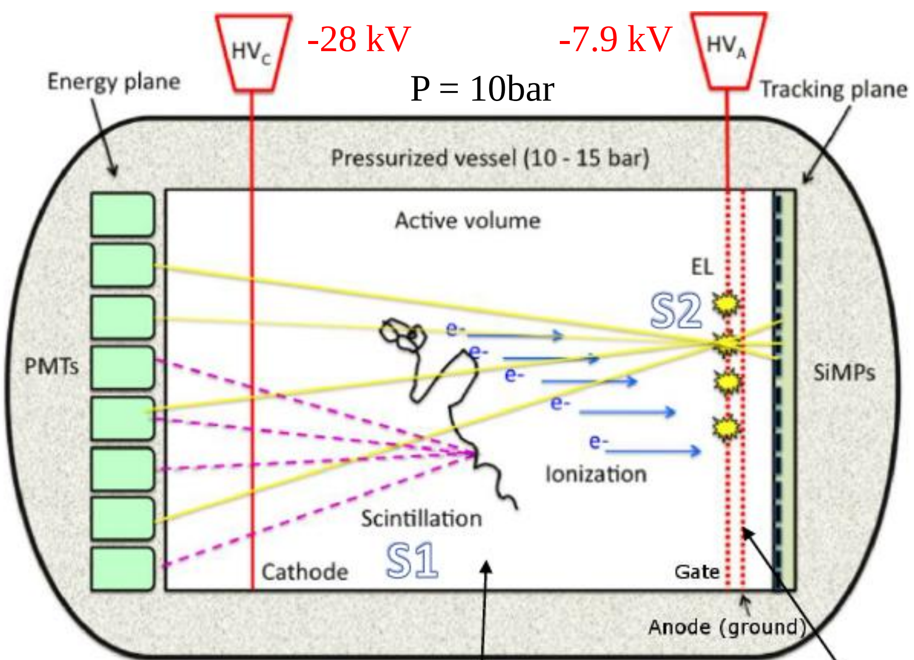
1. Status of NEXT-10 (**NEW**).
2. Status of the **IGFAE OTPC-lab**.
3. **Low-diffusion** mixtures for electroluminescence TPCs, NEXT-100 and beyond.
4. **New scintillating structures** for OTPCs (FAT-GEMs).
5. **New resistive GEMs (RPWELL) for cryogenic operation** in dual-phase detectors.
6. **New Optical TPC at IGFAE**.
7. **NEXT RPC-VETO**.
8. Scope.

1. Status of NEXT-10 (NEW)

- 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.

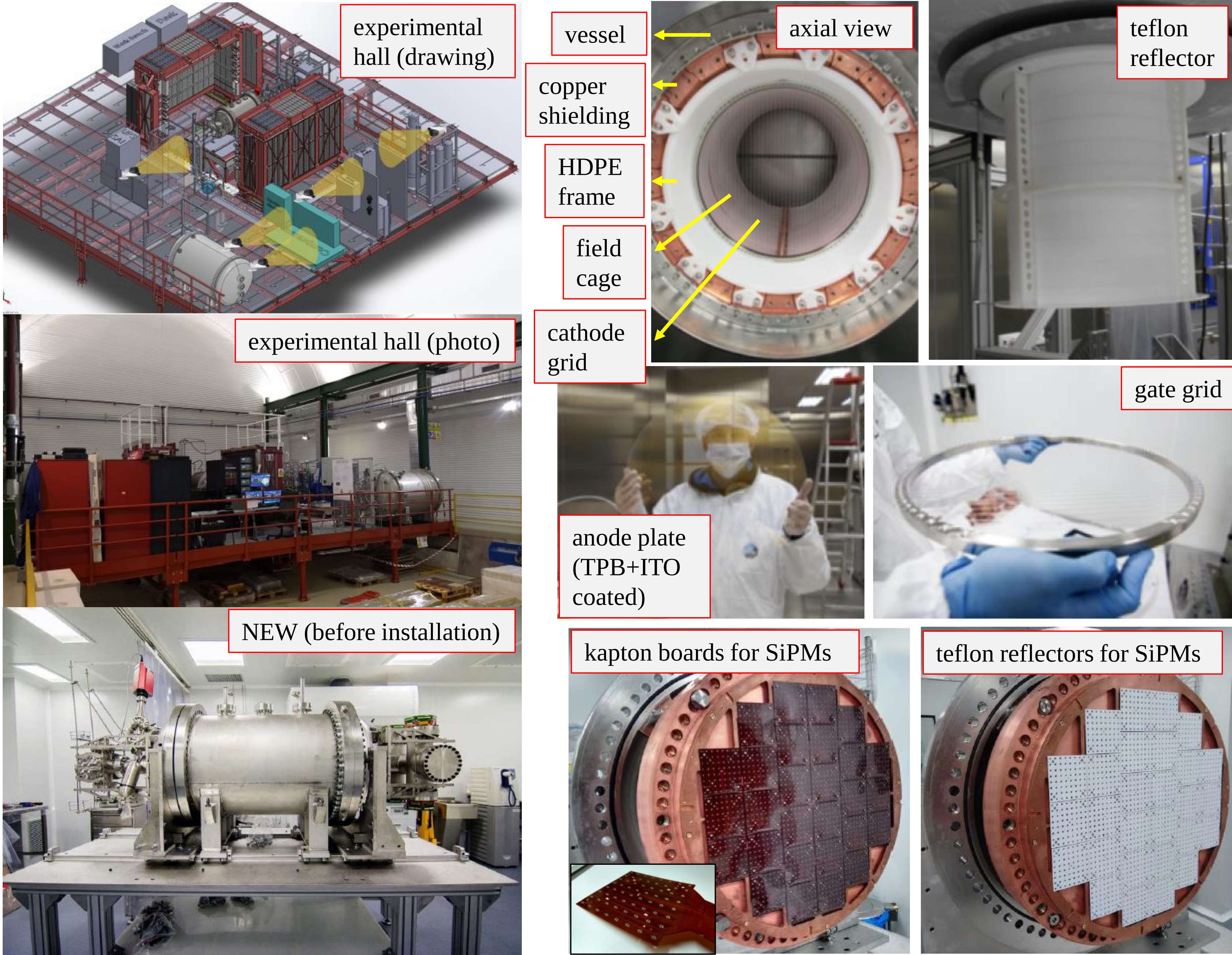


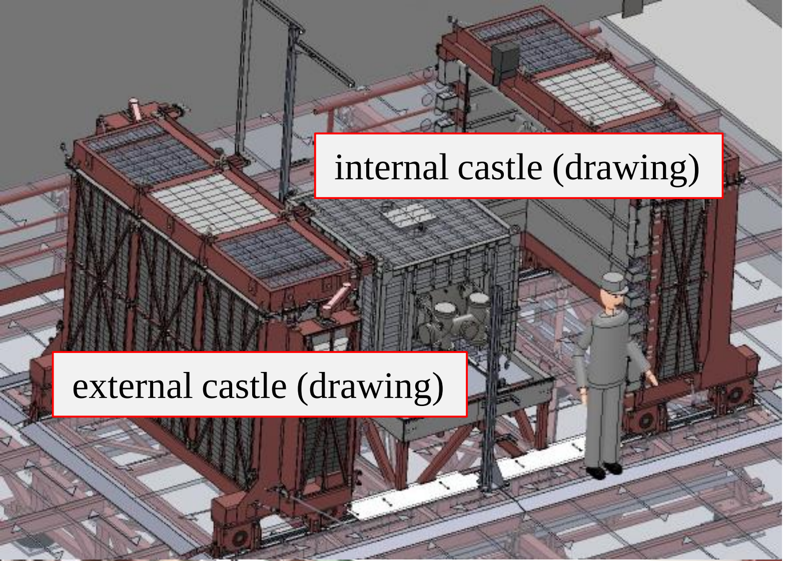
NEW

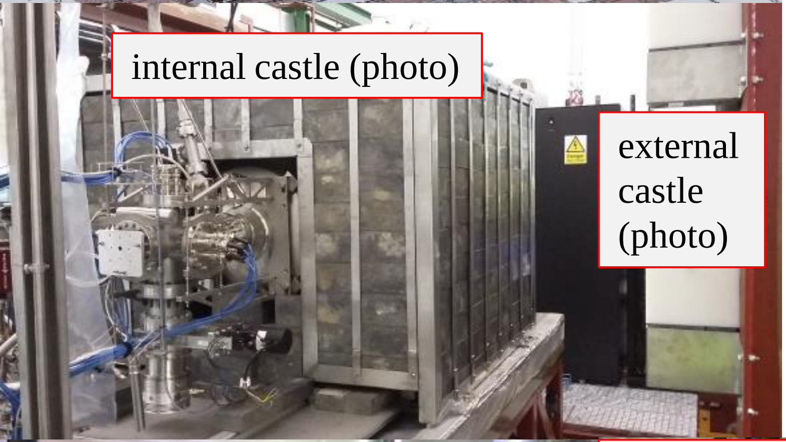


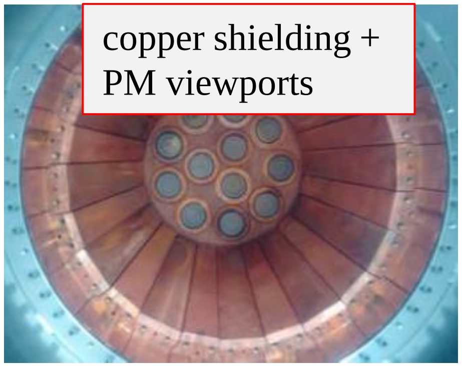
E_{drift} = -53 kV/cm/bar E_{EL} = -1.32 kV/cm/bar

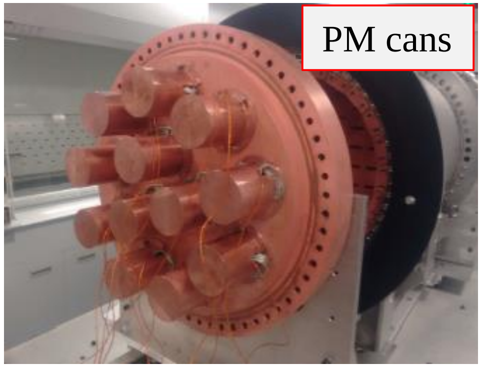
- 10kg technology demonstrator.
- 1st stage of NEXT-100.
- Taking data in 2018 (^{136}Xe depleted) and 2019 (^{136}Xe enriched).
- ➡ Aimed at measuring **ββ2ν** and setting **ββ0ν** limits.


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

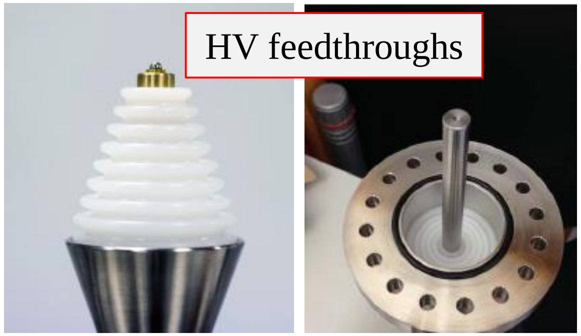


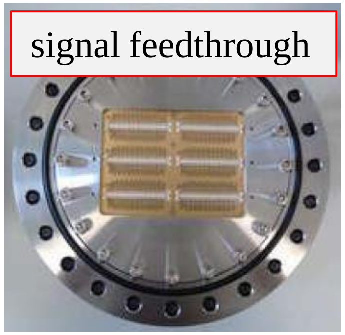






emergency recovery vessel (*misused NEXT-100 vessel*!)



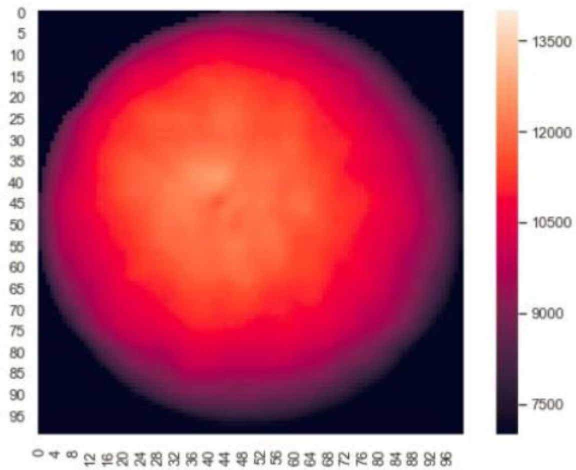


+ front-end electronics, data acquisition boards, computer farm, slow control, gas system…

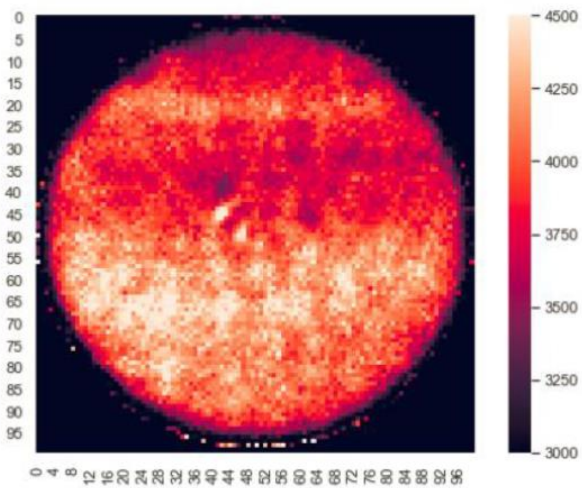
I. energy resolution

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

calibration/detector modelling



Geometrical S2 map



Electron lifetime map

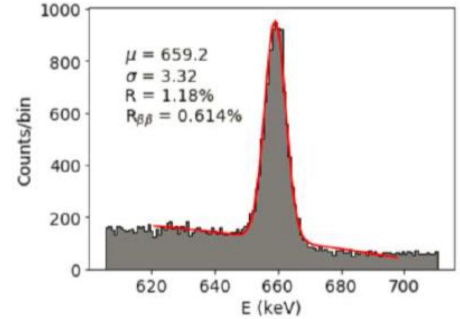
energy distribution

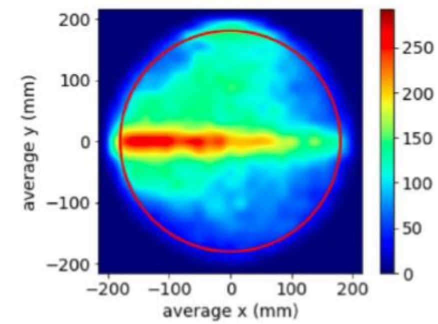
track barycenter

^{137}Cs 662 keV

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

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

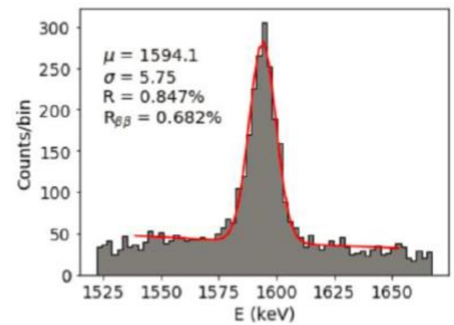


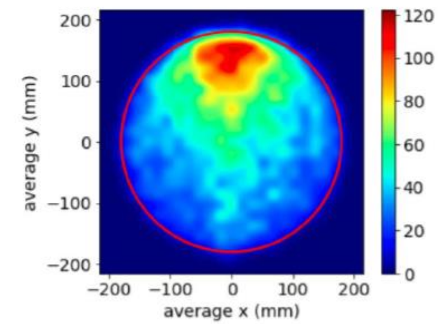


^{208}Tl 1593 keV e^+e^- escape peak

Extrapolates to

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

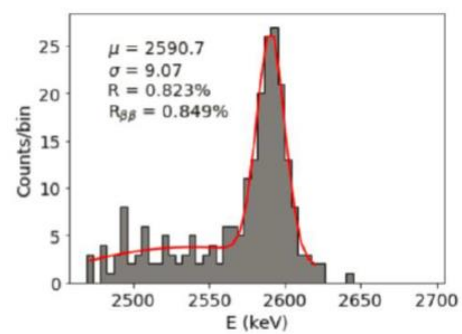


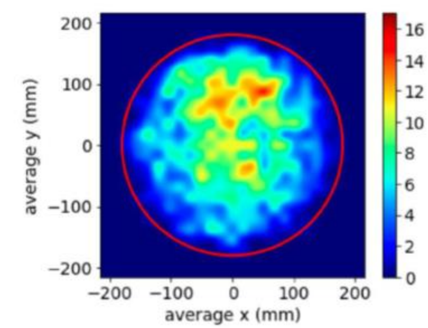


^{208}Tl 2615 keV full absorption peak

Extrapolates to

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



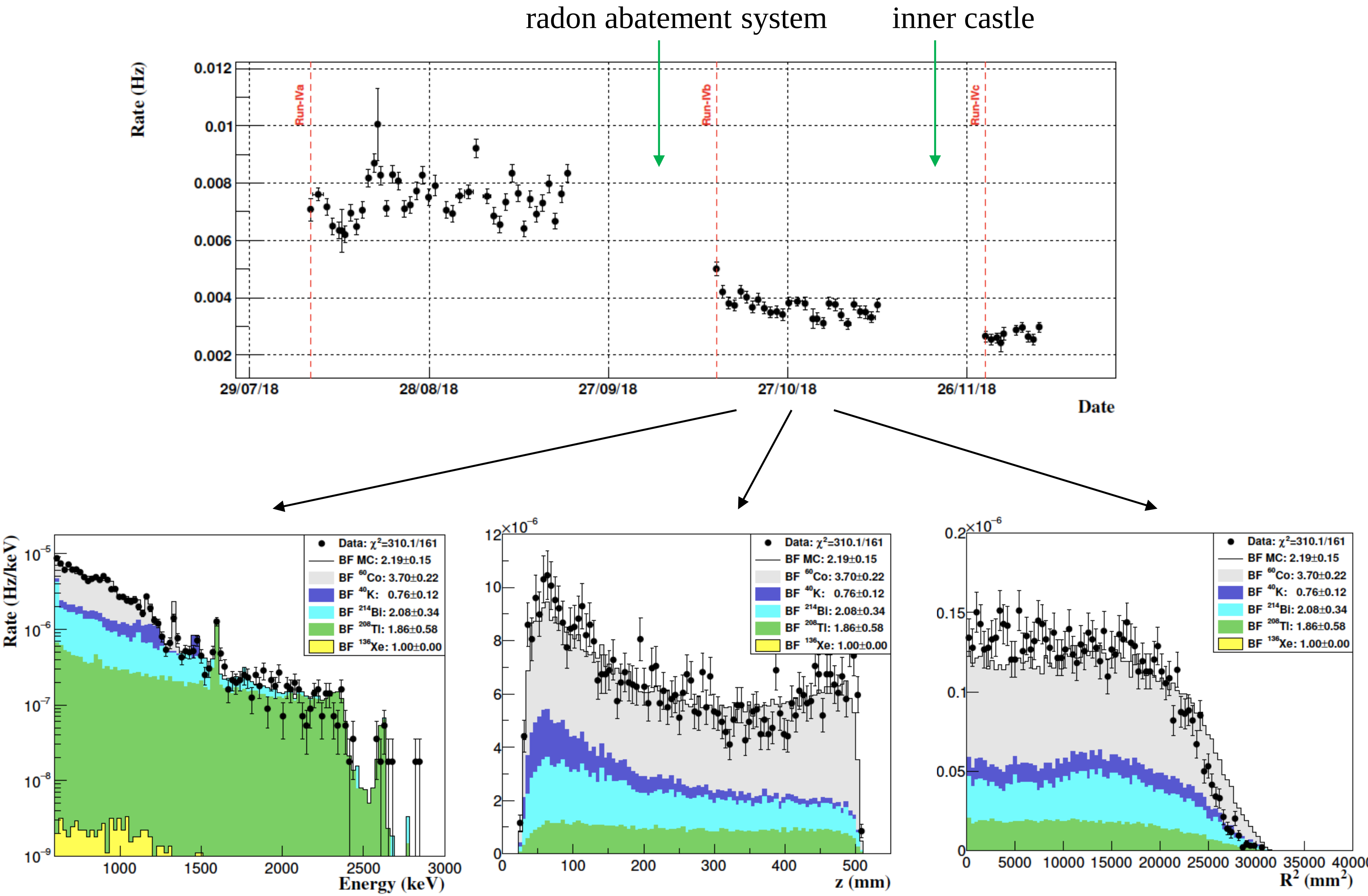


G. Martínez-Lema, J. A. Hernando-Morata, B. Palmeiro et al., JINST 13 (2018) no.10, P10014

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

II. background level

~ x1.5-2 higher than expected

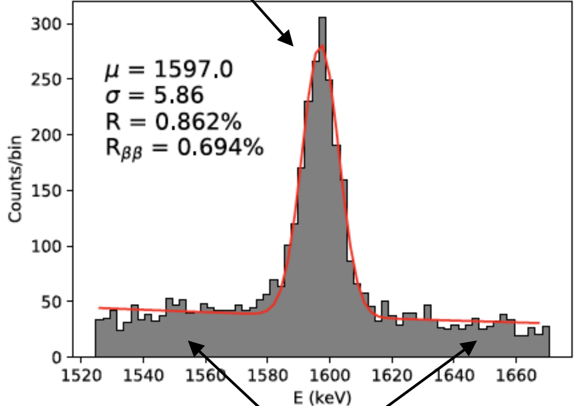


*with **B. Palmeiro***

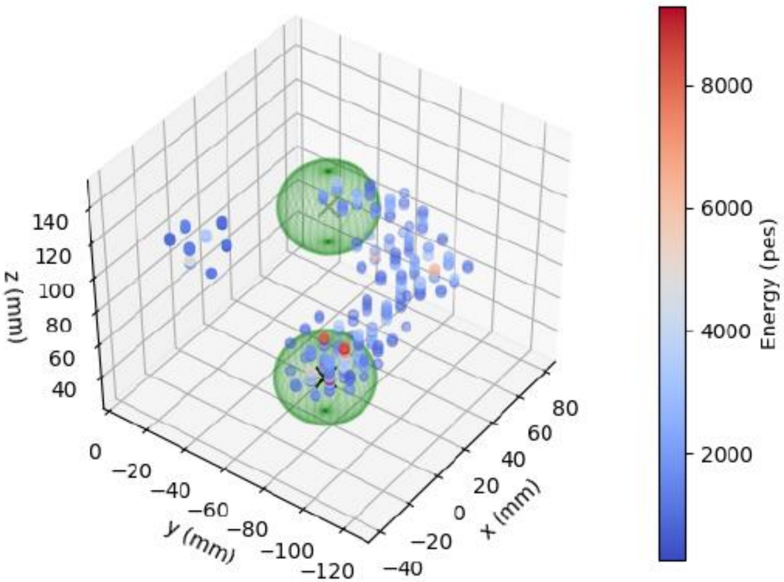
III. background suppression

within expectations!

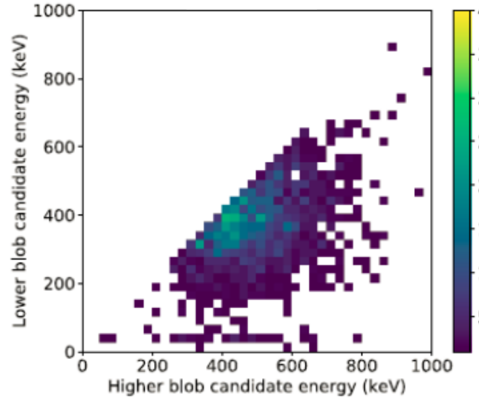
double escape peak ^{208}Tl (2e$^-$)



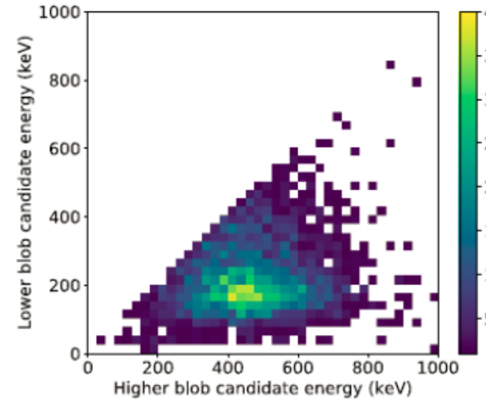
Compton (1e$^-$)

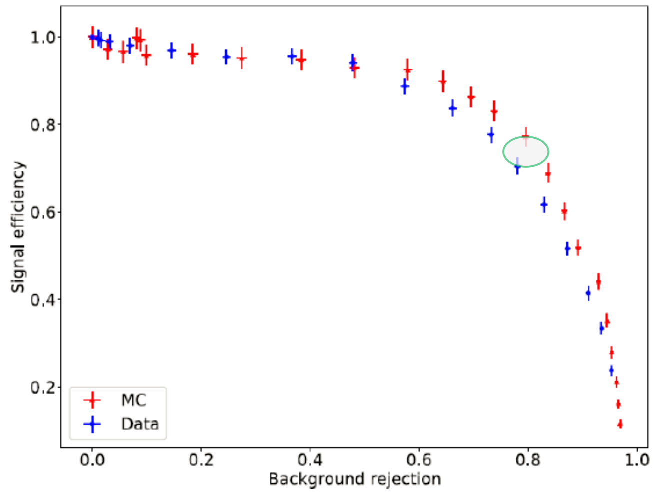


double escape peak ^{208}Tl (2e$^-$)



Compton (1e$^-$)





optimum cut:

- 77.3% efficiency
- 20.5% background acceptance

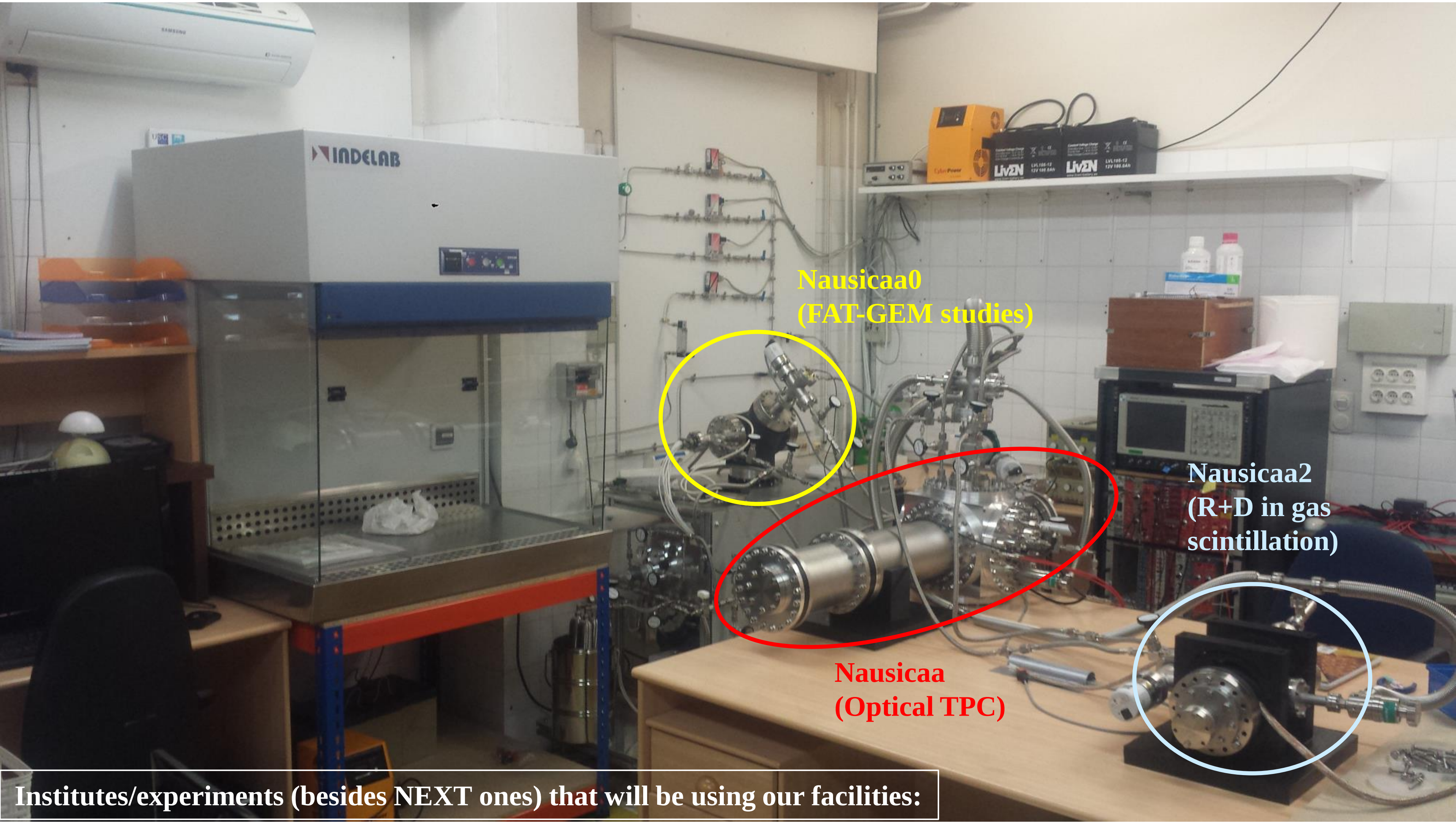
much better seems to be possible with neural networks (under study!)

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

2. Status of the IGFAE OTPC-lab

circa March 2017

now

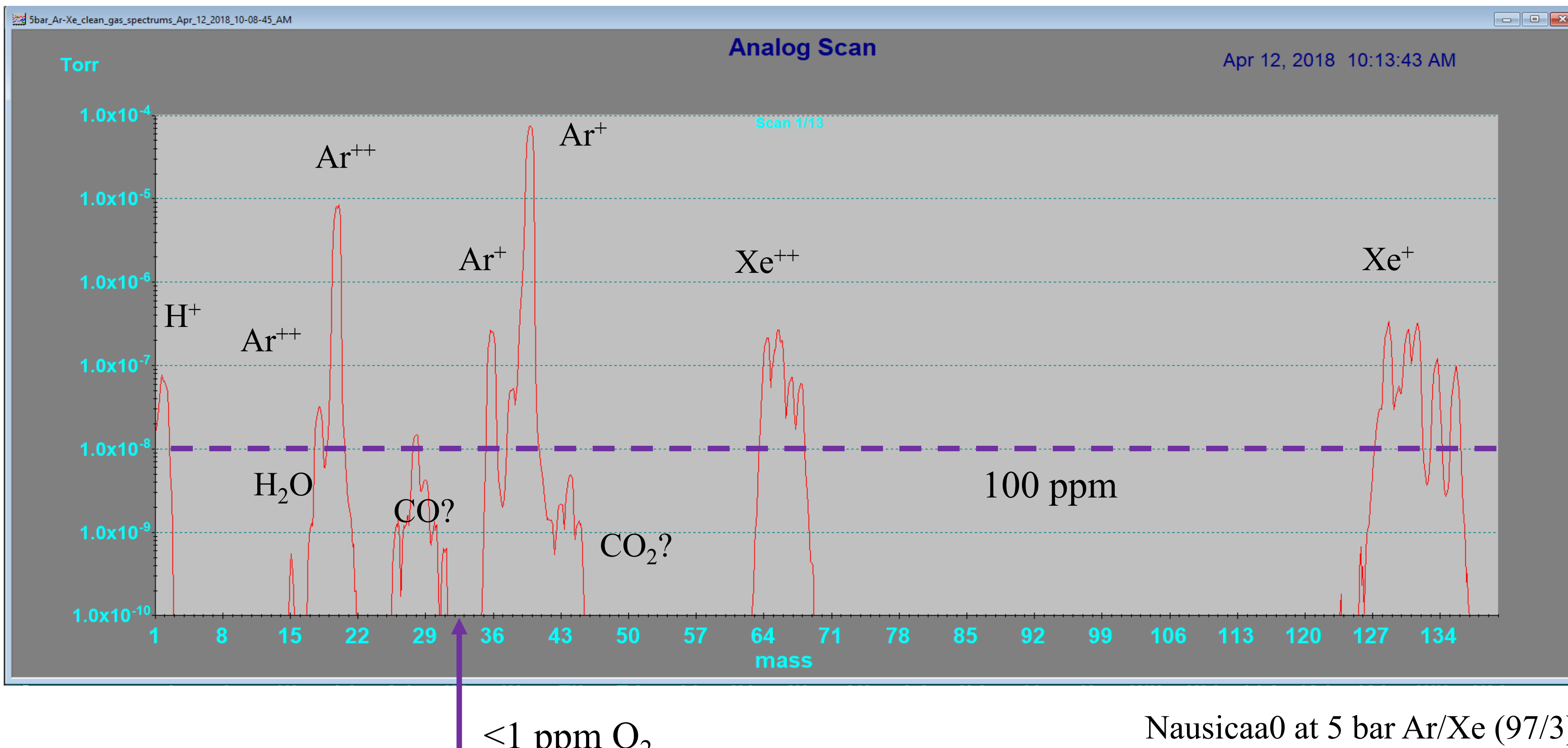


Institutes/experiments (besides NEXT ones) that will be using our facilities:

- **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**). — ongoing
- **MSU-FRIB** -> New ceramic and multi-layer GEMs for dual-phase operation in pure Ar, Xe chambers. — stacked

main assets

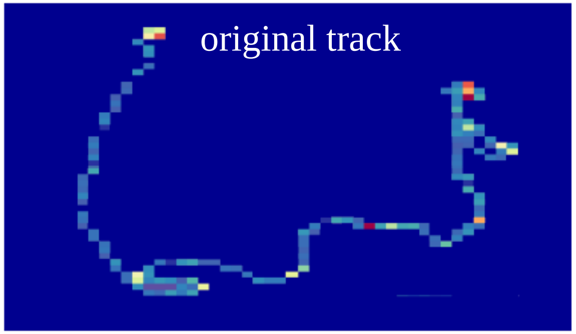
1. Commissioned in the range 0-10bar, with gas quality down to less than 1ppm of O_2 (directly monitored). ONLY metal-metal seals!.
2. Possibility of gas recirculation and recovery (essential for operation with xenon).
3. Several optical sensors and a custom spectro-photometer for the range 400-900nm.
4. Several test setups and radioactive sources for different scintillation structures.
5. An optical TPC.



Nausicaa0 at 5 bar Ar/Xe (97/3)
measured through leak in valve

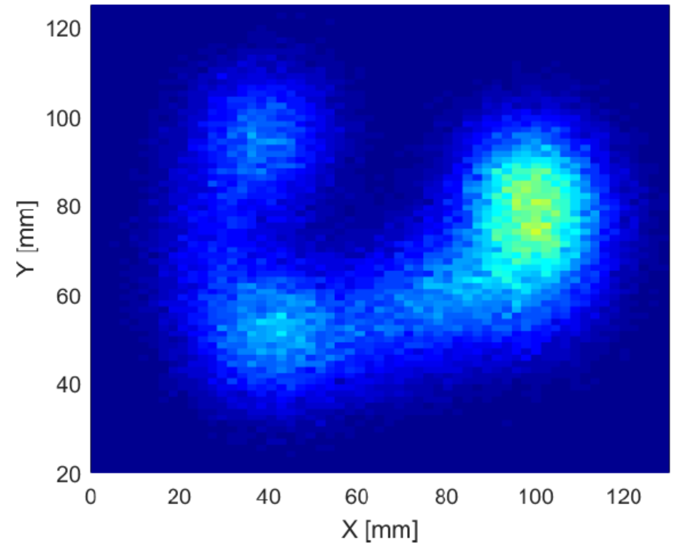
3. Low-diffusion scintillating mixtures

Modeling and simulations done at IGFAE



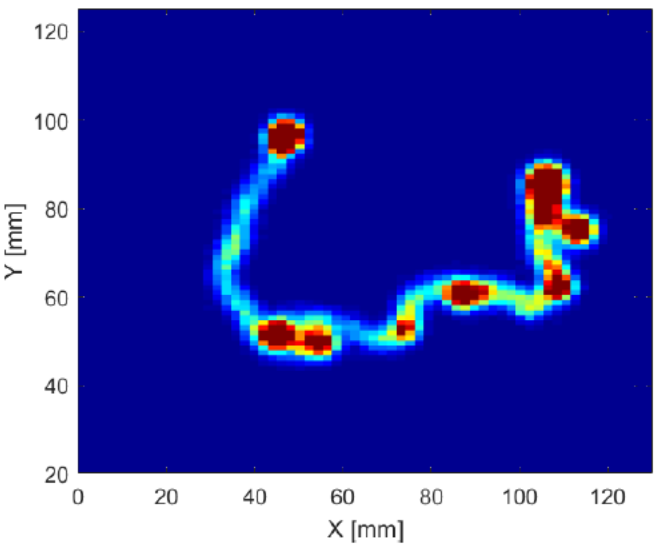
pure Xe

after ~1m charge drift

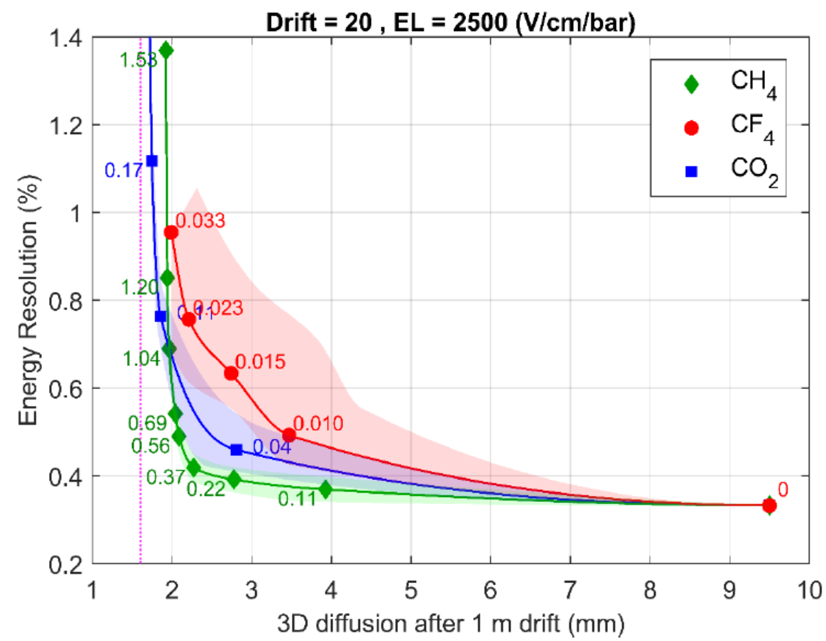


Xe ‘magic’ mixture

after ~1m charge drift



NEXT-100 extrapolation based on data at 1bar + simulation



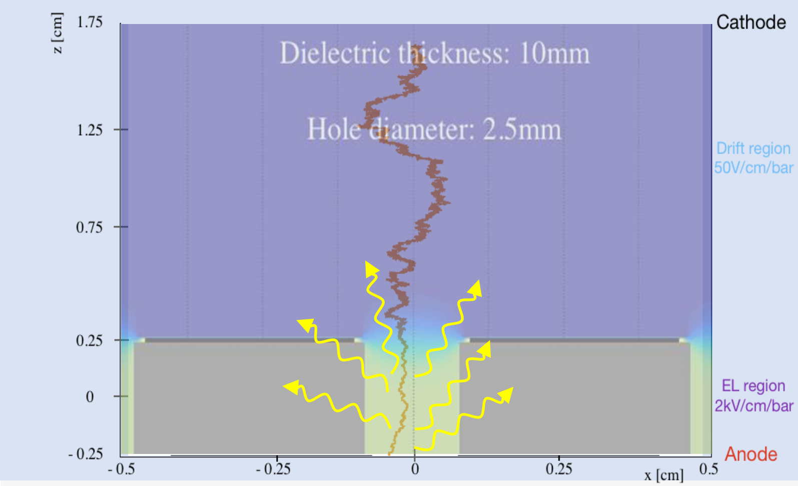
C. A. O. Henriques, C. M. B. Monteiro, ***DGD*** et al., JHEP01(2019)027.

R. Felkai, F. Monrabal, ***DGD*** et al., Nucl. Instr. Meth. A 905(2018)82.

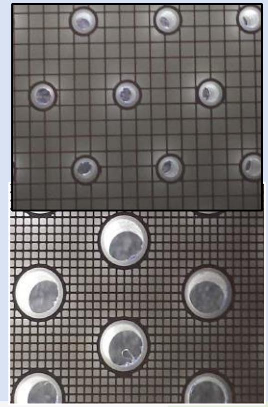
C. D. R. Azevedo, ***DGD*** et al., Nucl. Instr.Meth. A 877(2018)157.

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

4. New scintillating structures for OTPCs (FAT-GEMs)



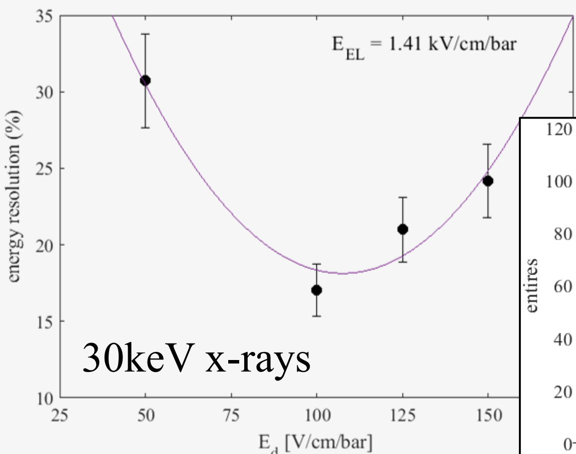
FAT-GEM (for electroluminescence TPCs)



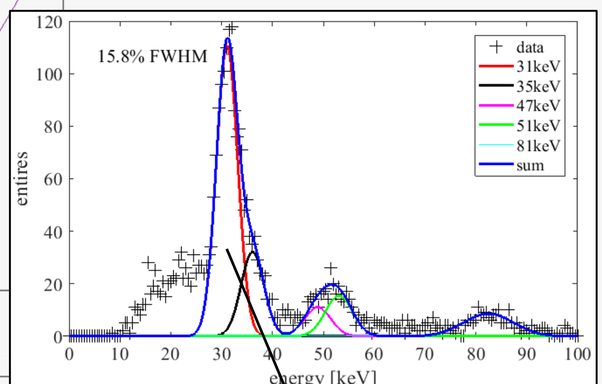
FAT-GEM: *a 'super-thick' (5mm) acrylic-based GEM with semitransparent 'gate' plane*

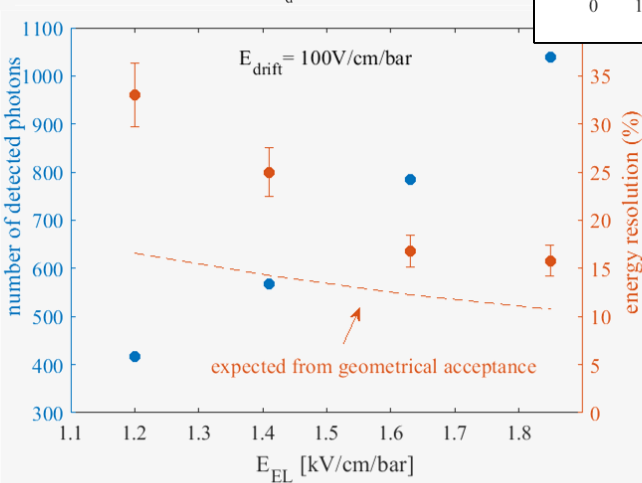
several geometries procured at the RD51 workshop

designed, tested, optimized at IGFAE



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





1.75%@$Q_{\beta\beta,\ ^{136}Xe}$

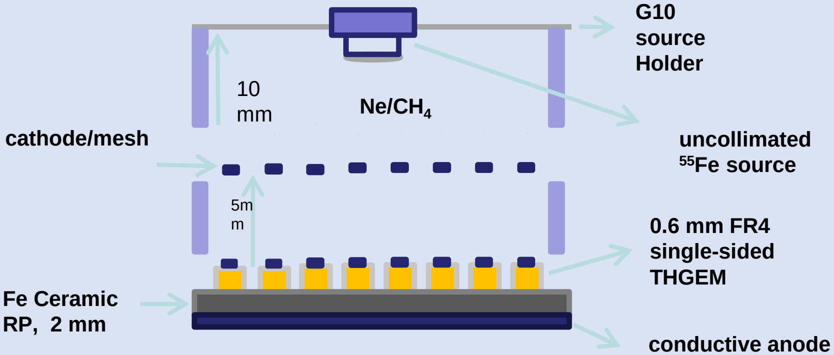
0.98%@$Q_{\beta\beta,\ ^{136}Xe}$ in ongoing campaign!

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

- Radiopure.
- Transparent.
- Homogeneous (advantageous for CNC-drilling).
- Inexpensive.
- Customizable (e.g., allows resistive or wavelength-shifting coatings)
- Easy to scale.
- Compatible with high-pressure operation.
- Ultimate energy resolution close to Fano factor, position resolution: mm-scale.

DGD, et al., 'new MPGD-based structures for electroluminescence TPCs'. *MPGD conference*, *La Rochelle, May-2019.*

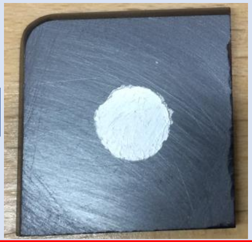
5. New resistive GEMs (RPWELL) for cryogenic operation in dual-phase detectors.



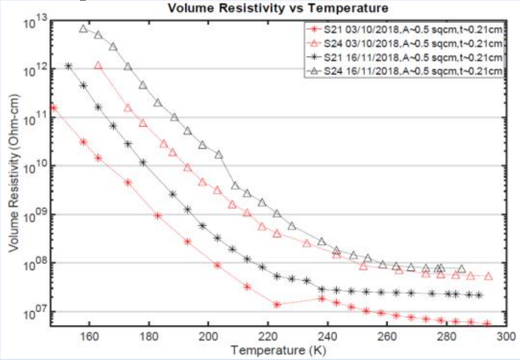
measurements at Weizmann Institute (A. Roy)

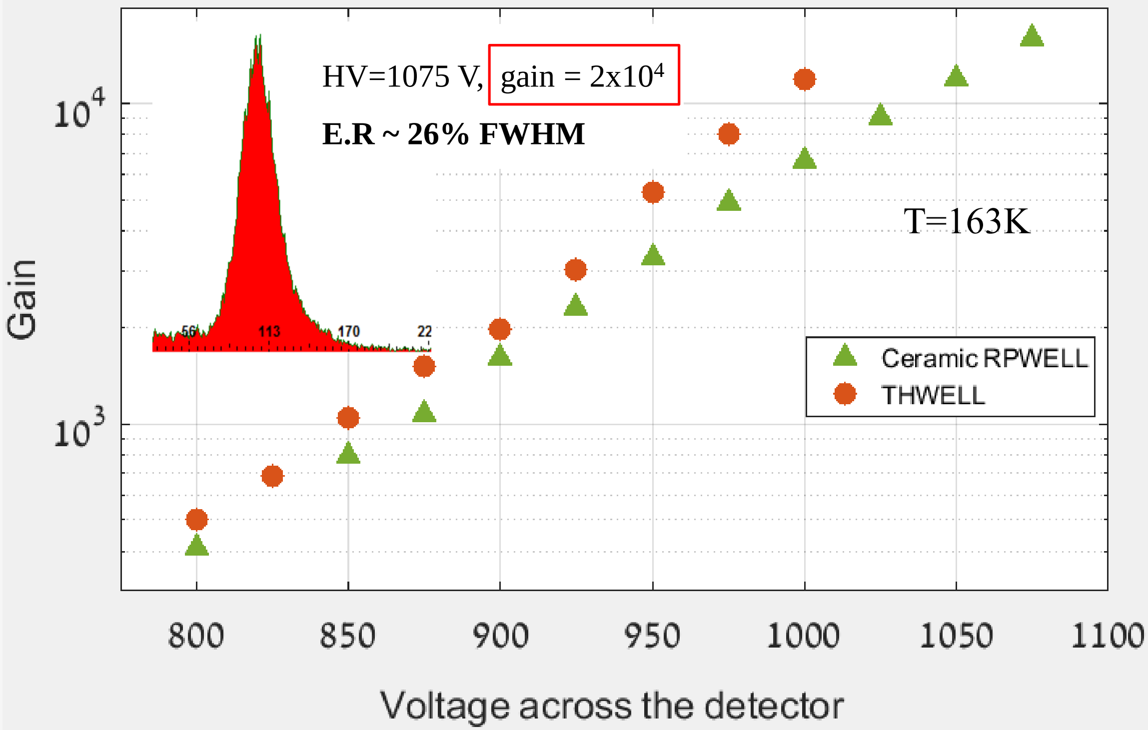
RP-WELL (for cryogenic operation)

standard thick-GEM coupled to a resistive electrode



developed by IGFAE in collaboration with ICMM





first operation of a spark-protected gaseous detector at LXe temperature!

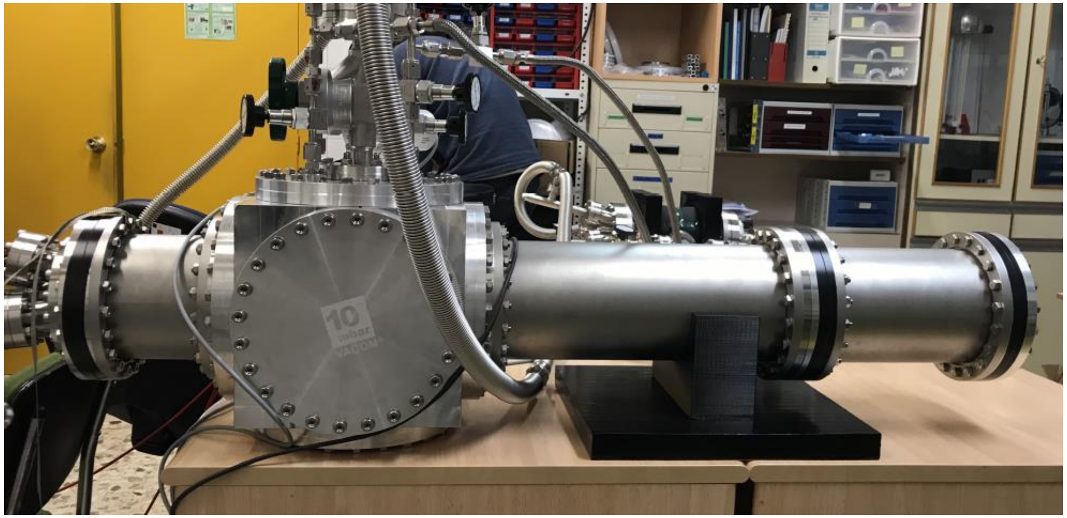
main characteristics of this new material for 'cryo'-RPWELLs

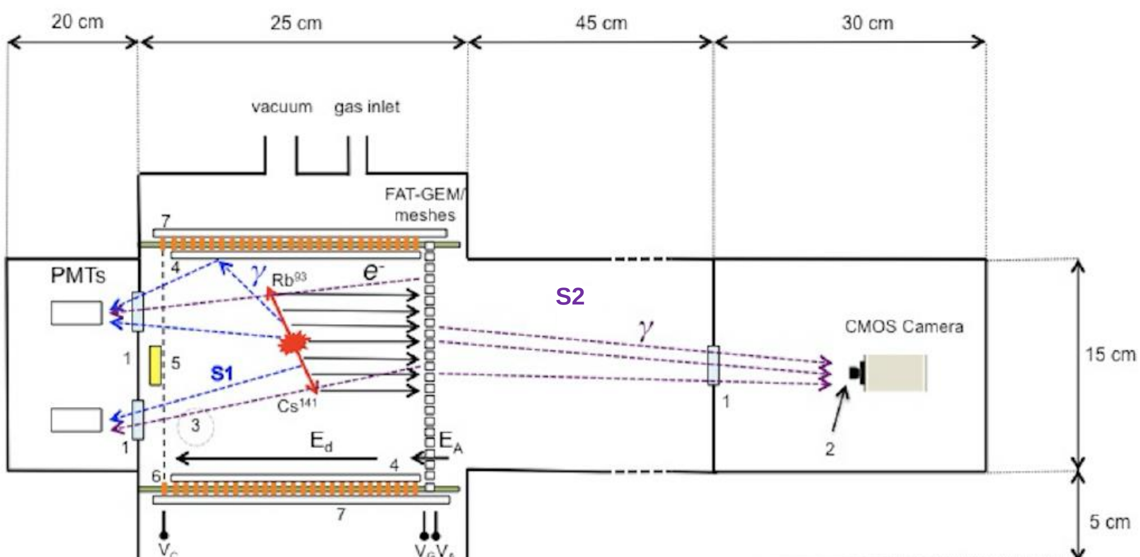
- Allows resistivity adjustment via post-processing.
- Inexpensive and scalable.
- Operation at LAr temperature in principle possible (under development).
- Allows gains in excess of 10^4 (canonical number for single-photon detection capability).
- Operation of spark-protected gaseous detectors at arbitrary temperature may be feasible through this approach.

A. Roy, S. Bressler, MM, DGD, et al., '*First results of a high-gain Resistive-Plate Well (RPWELL) detector at 163K'. MPGD conference, La Rochelle, May-2019.*

6. New Optical TPC (OTPC) at IGFAE

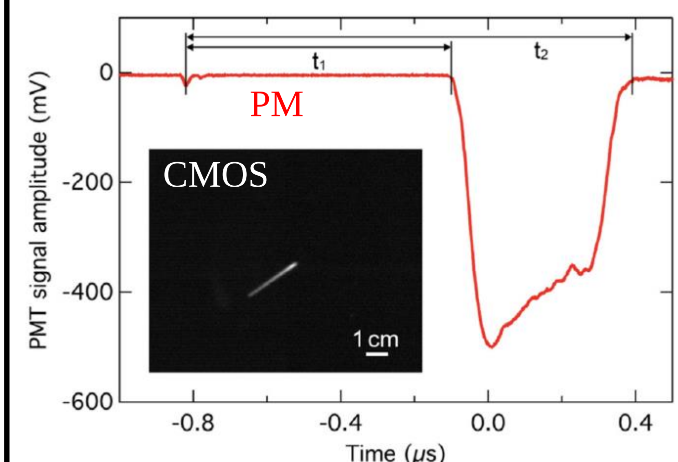
A new *optical* TPC at IGFAE ('Nausicaa')





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.

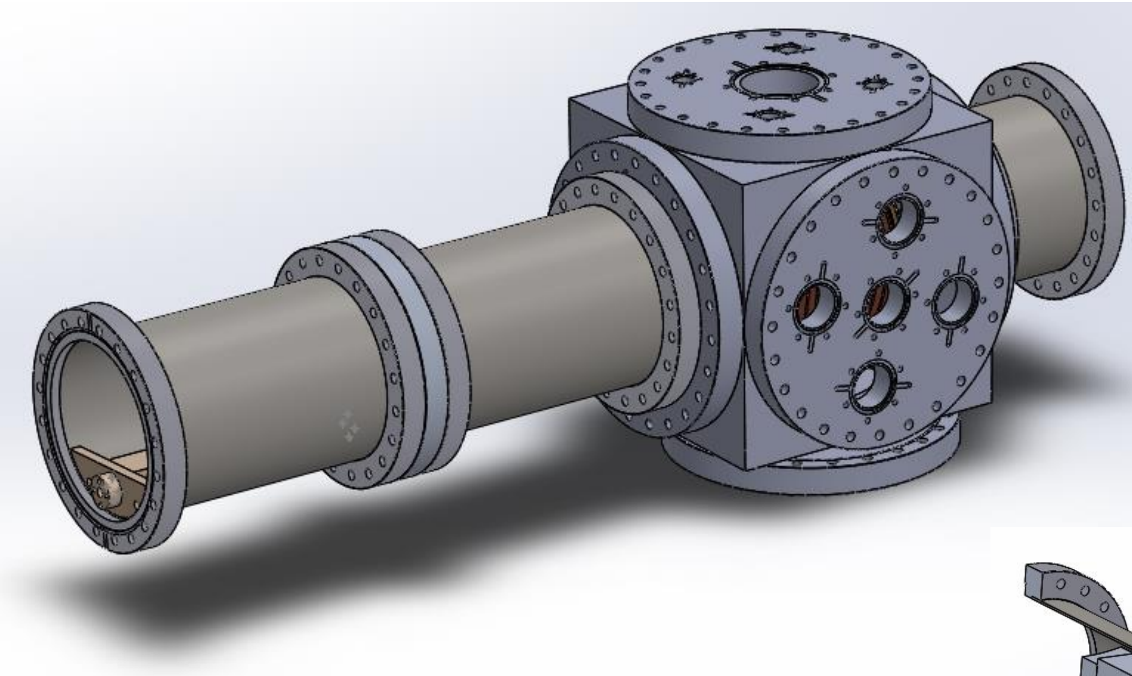


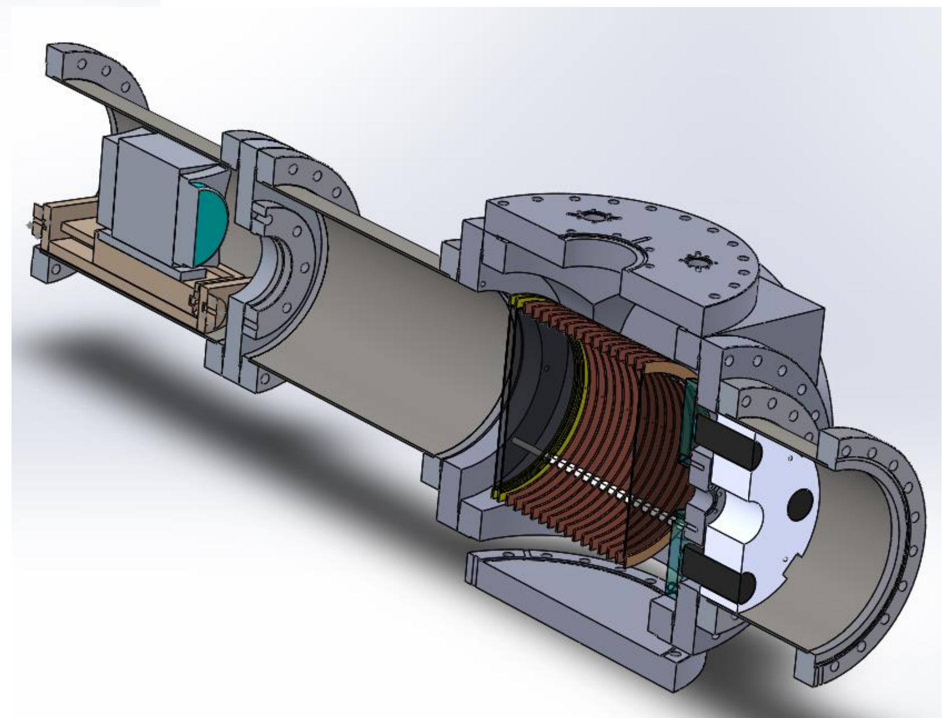
example from a similar camera at CERN GDD-lab

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

Pablo Ameijeiras (TFG, February 2019)

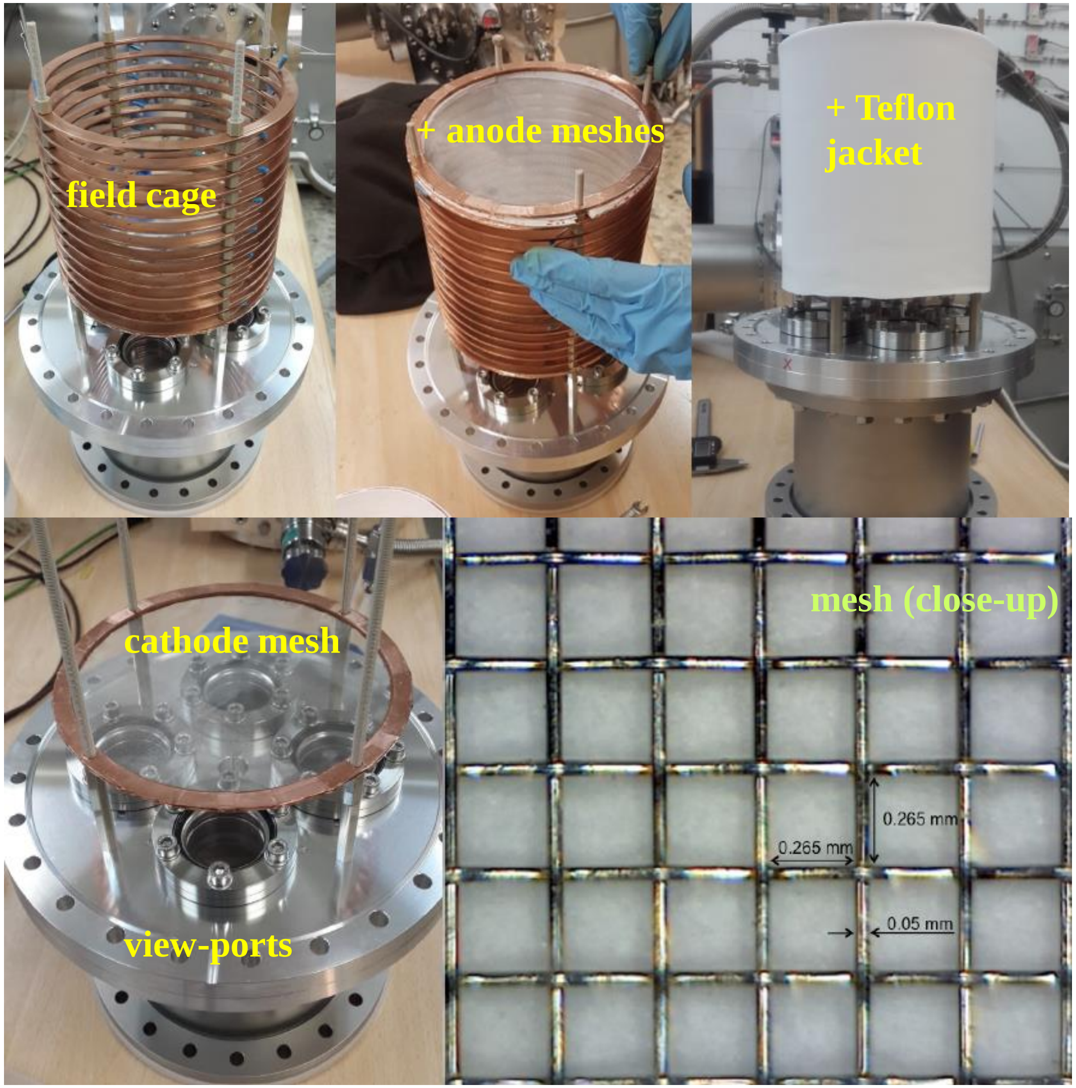
A new *optical* TPC at IGFAE ('Nausicaa')

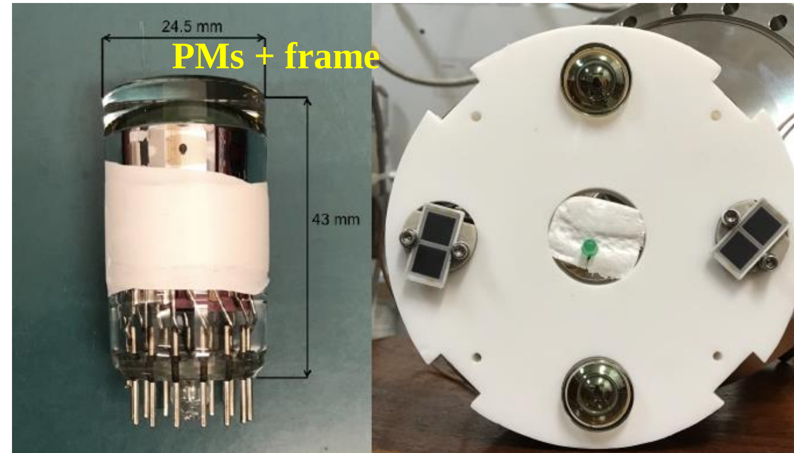




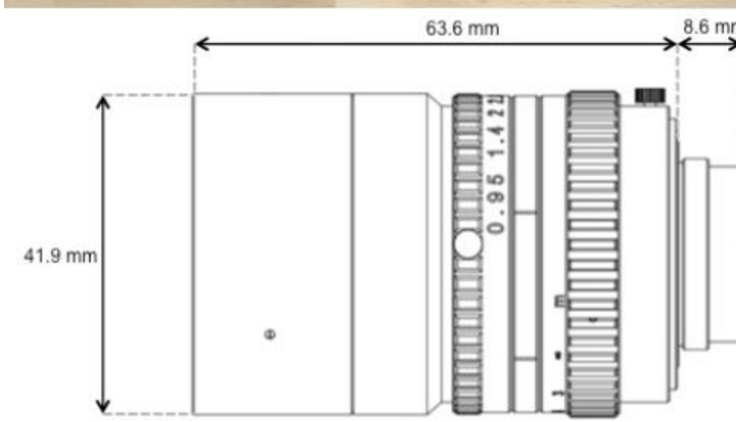
Pablo Ameijeiras (TFG, February 2019)

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





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

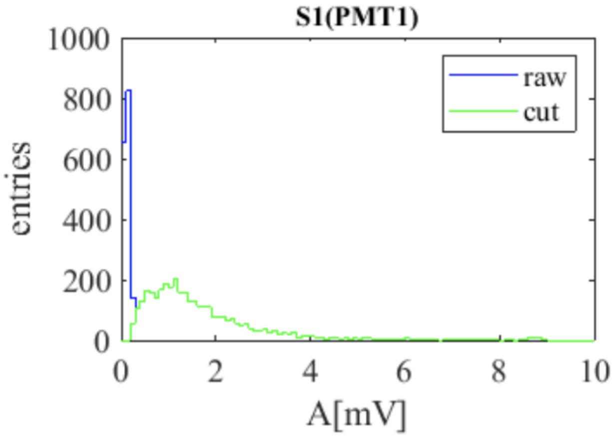


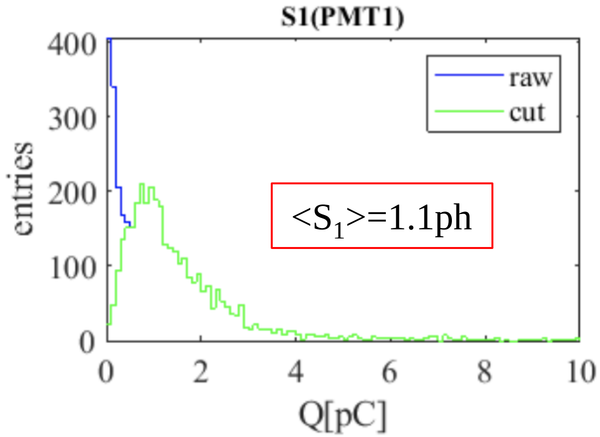
lens (f=17mm, N=0.95)

Pablo Ameijeiras (TFG, February 2019)

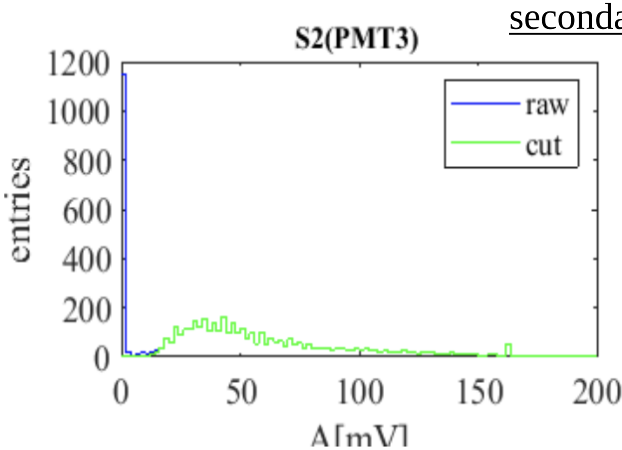
A new *optical* TPC at IGFAE ('Nausicaa1')

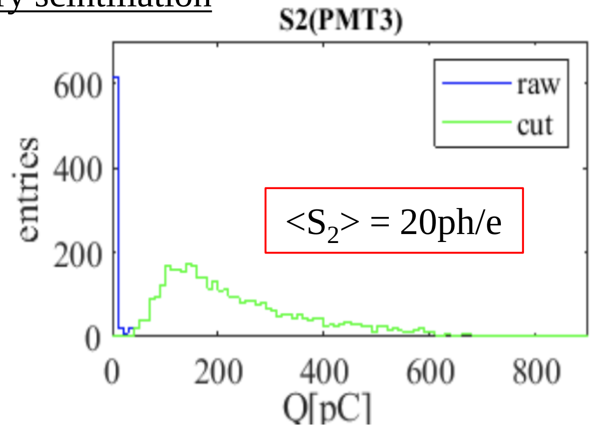
primary scintillation





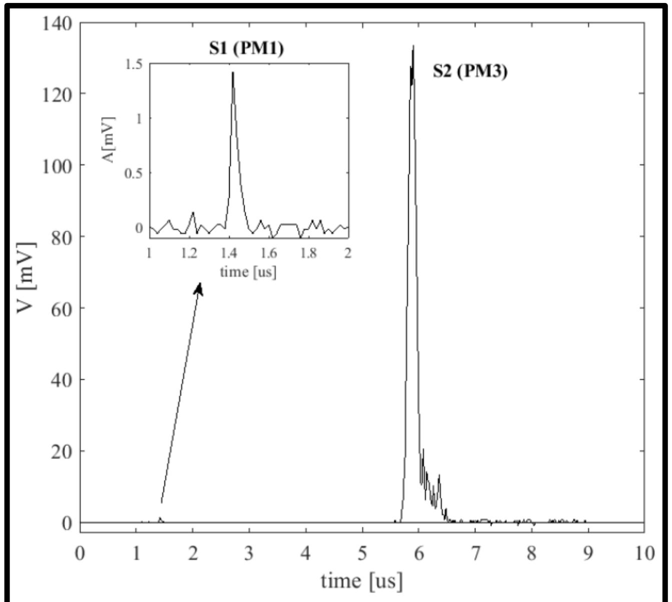
secondary scintillation





typical event:

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



status

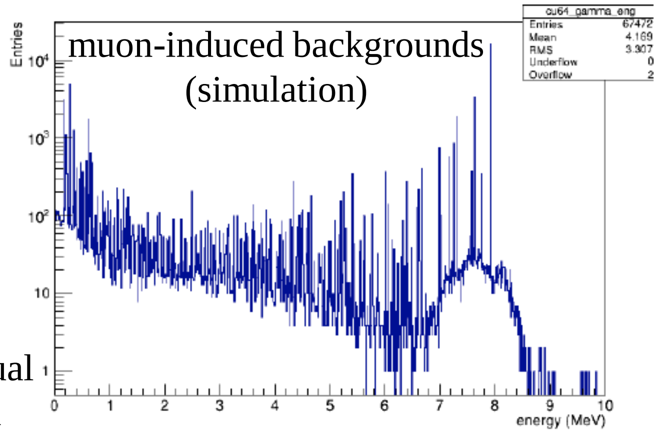
- Sensitivity to primary scintillation only for events close to the cathode.
- Modest optical gain, sufficient for ~1mm accurate track reconstruction.
- Ready to connect the CMOS camara and reconstruct tracks!.

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!.

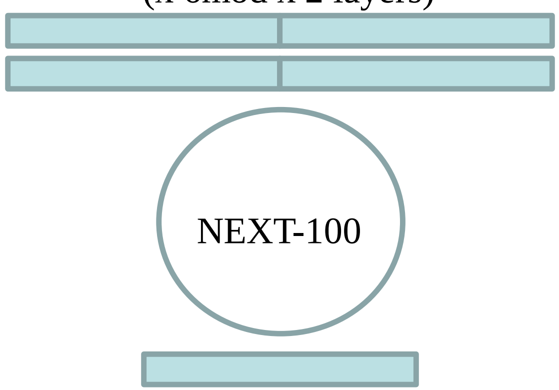
Pablo Ameijeiras (TFG, February 2019)

7. NEXT-VETO
(in collaboration with LIP-Coimbra)

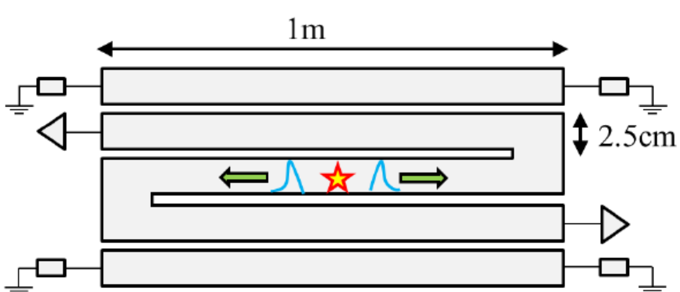


conceptual design

~1.5m x 1.5m
(x 6mod x 2 layers)



detector concept

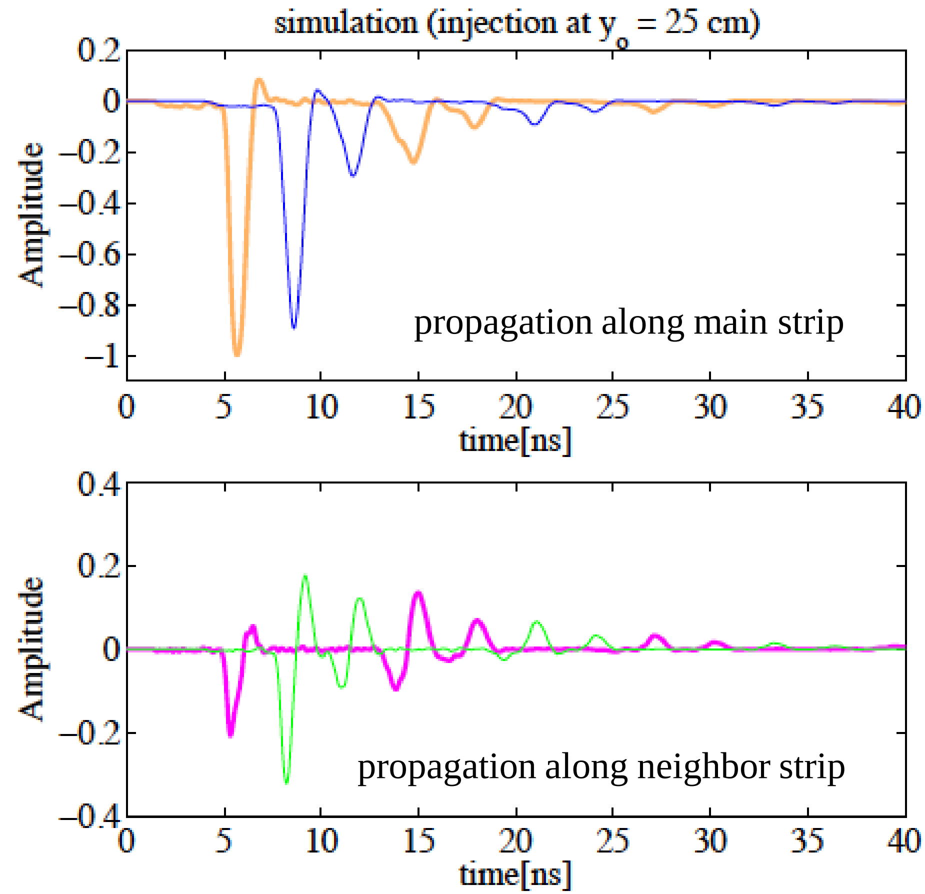


serpentine/delay-line readout
(at least x10 saving!)

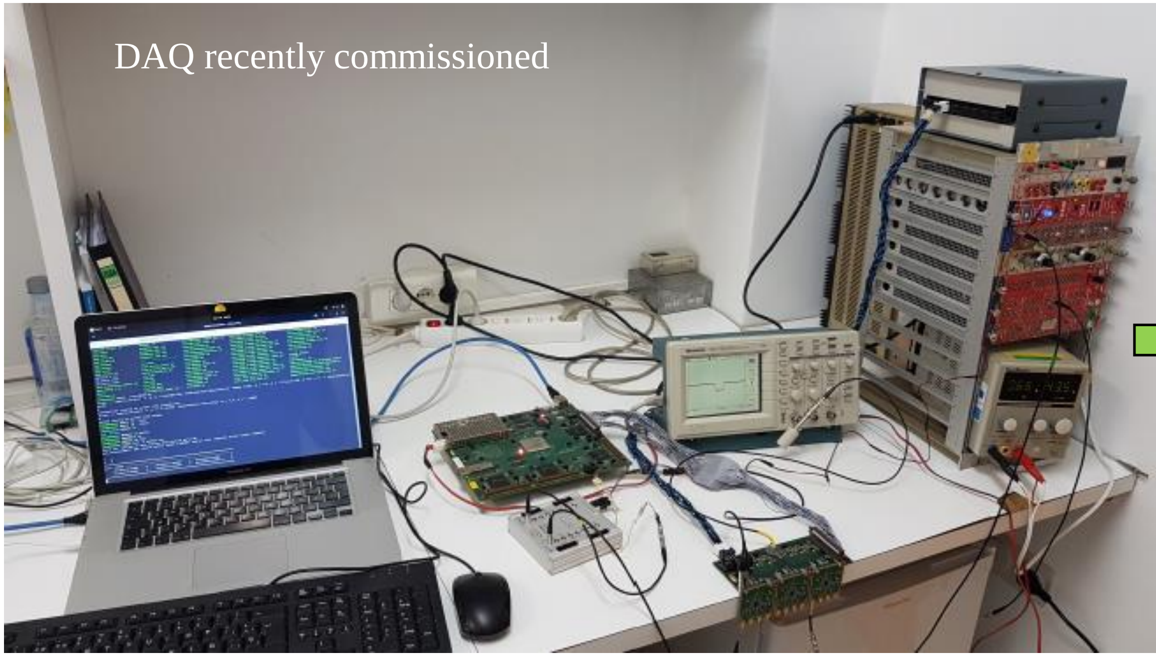
requires detailed understanding of signal transmission in electrically long structures (electrical length = more than 100)

$$C_m/C_0 = L_m/L_0$$

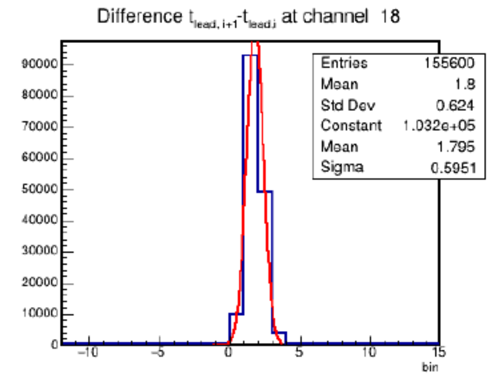
(signals propagating along a 1m-long strip)

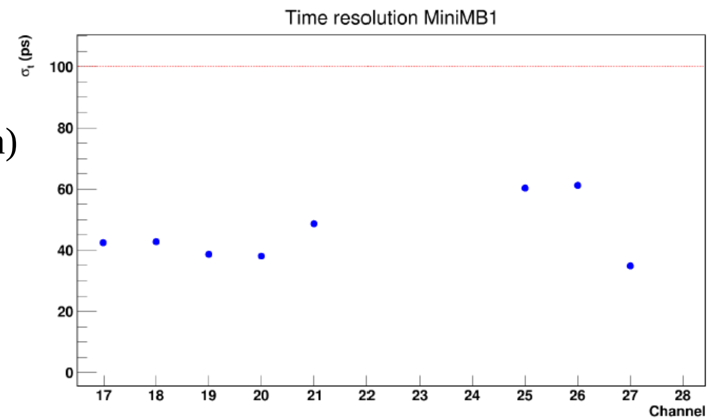


K. Watanabe (with DGD), NIM A 925(2019)188.
DGD et al., JINST 12(2017)no.03, C03029.

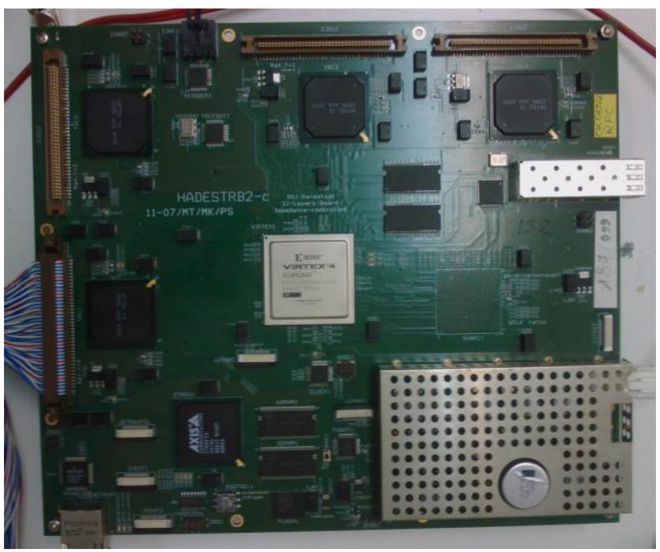


60ps time resolution
(~40ps per channel)





TRB (trigger and readout board)



DBO (amplification/discrimination)

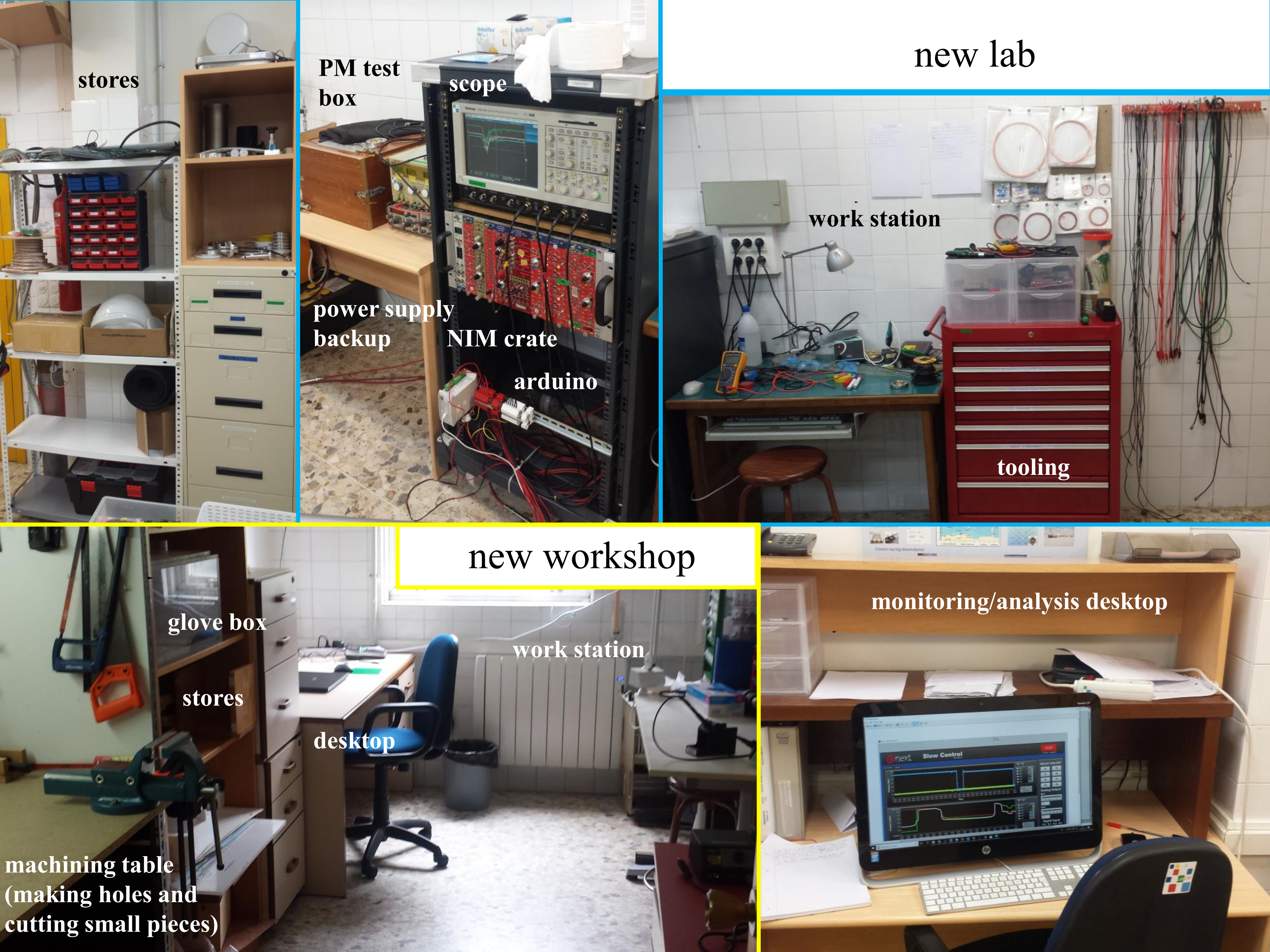
MBO (service board)

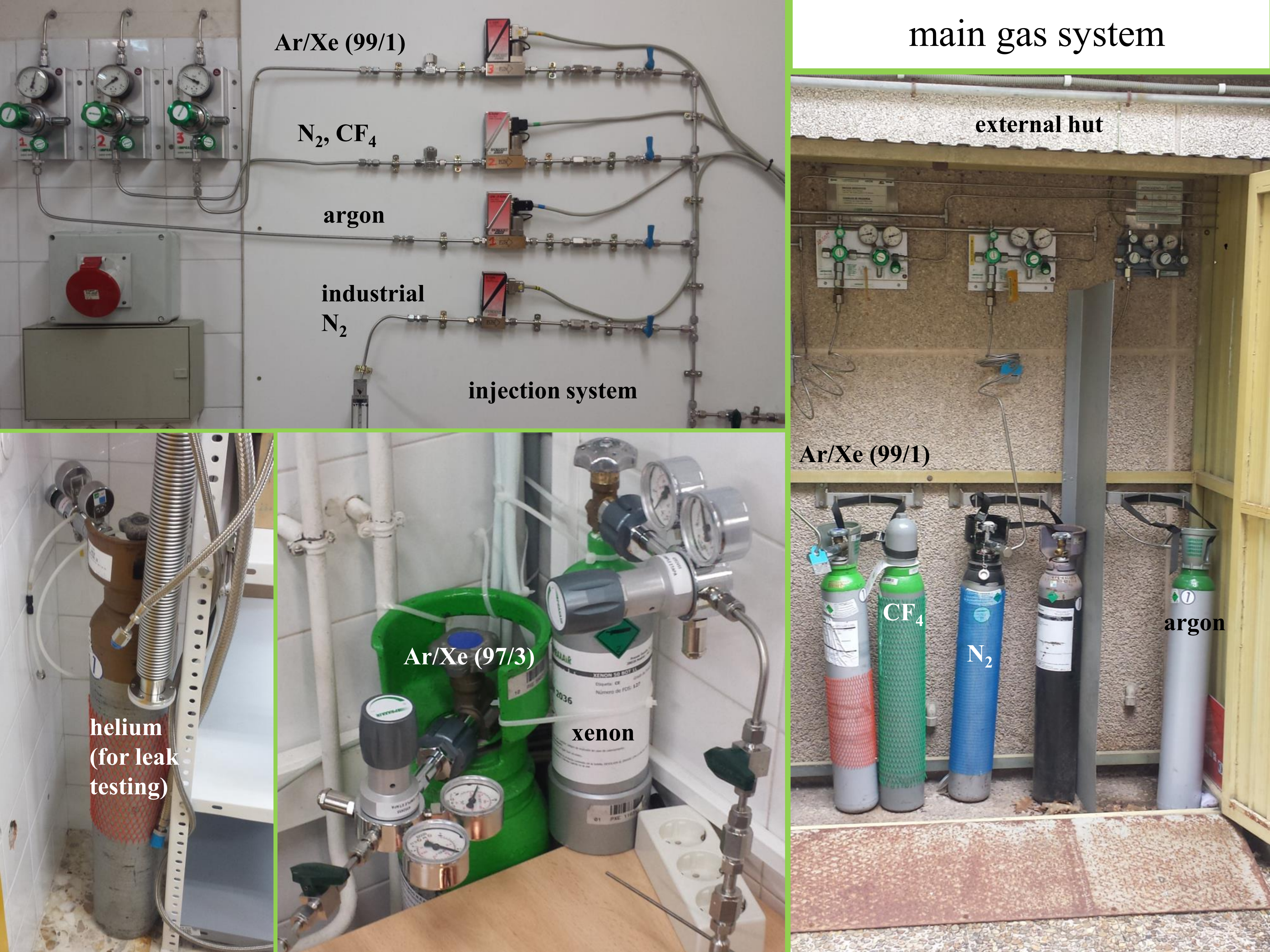
J. Cuenca, M. Morales, with support from LIP-Coimbra

outlook

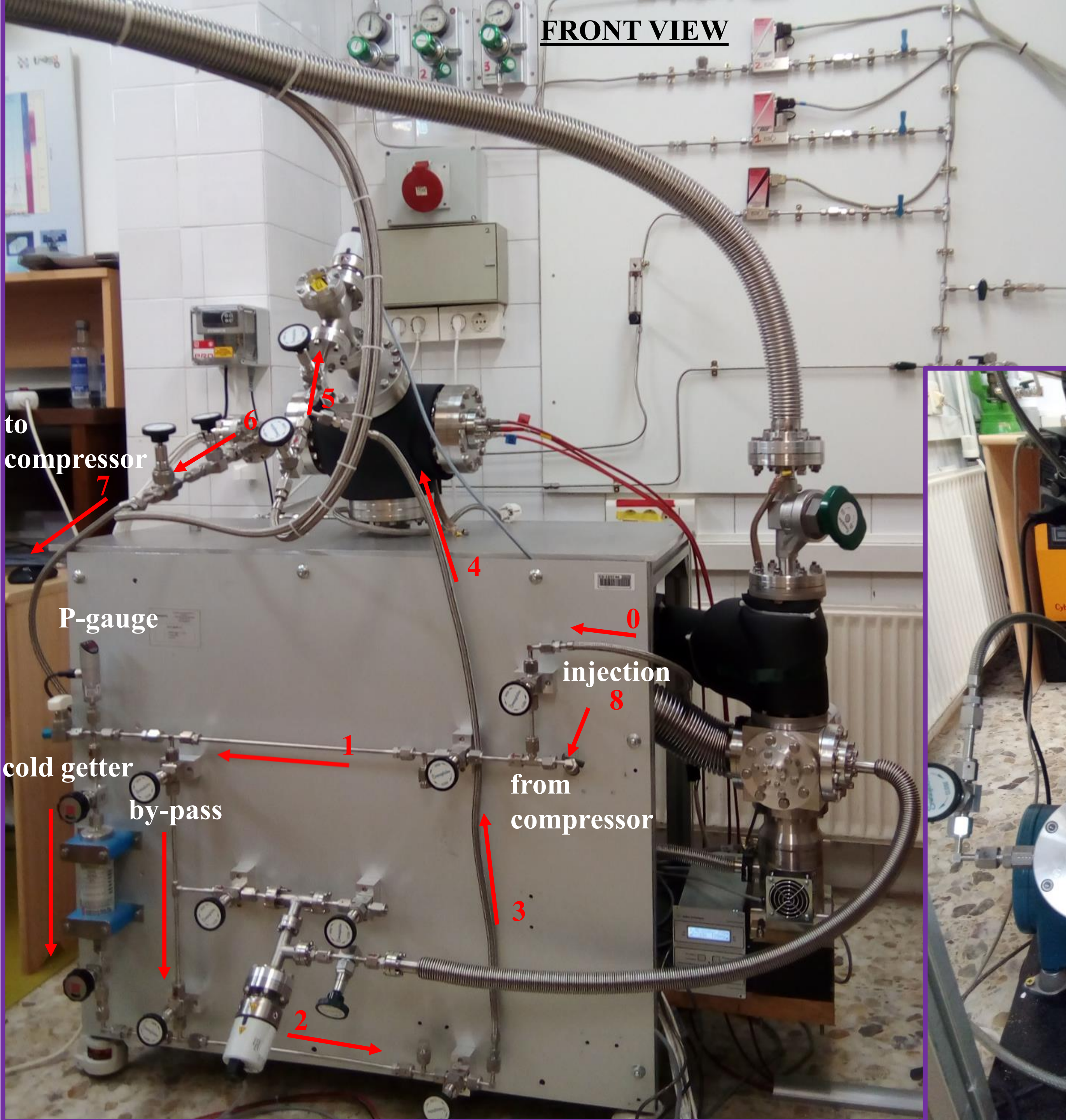
1. Push the above lines.
2. Perform He/CF_4 , Ar/Xe/CH_4, Ar, Xe systematic studies in the context of CYGNO, DUNE and DarkSide collaborations, together with people from related institutes.

V. Appendix

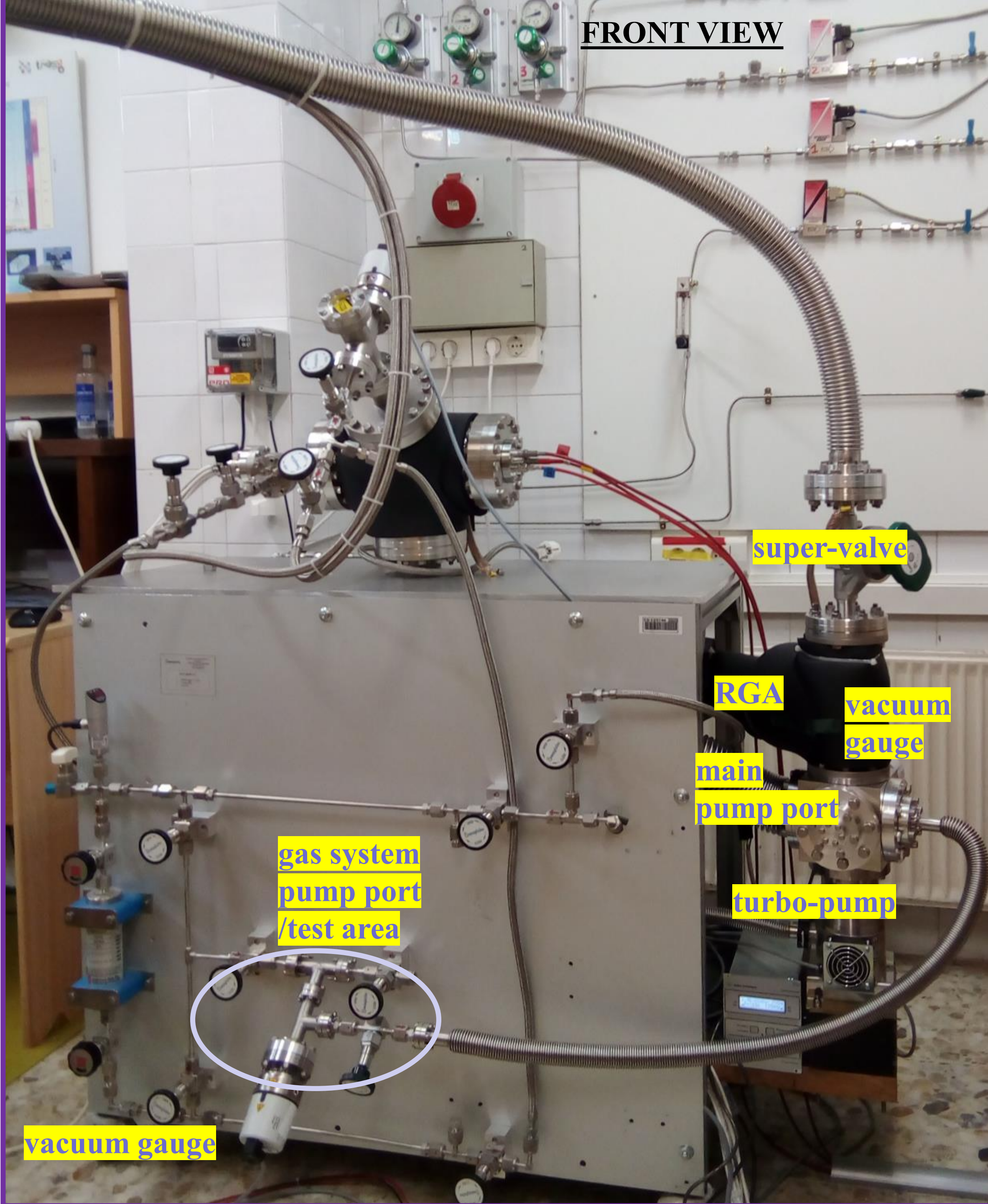

stores
PM test box
scope
power supply backup
NIM crate
arduino
new lab
work station
tooling
new workshop
glove box
stores
desktop
work station
machining table (making holes and cutting small pieces)
monitoring/analysis desktop
Slow Control


main gas system
Ar/Xe (99/1)
N2, CF4
argon
industrial N2
injection system
external hut
Ar/Xe (99/1)
CF4
N2
argon
helium (for leak testing)
Ar/Xe (97/3)
xenon

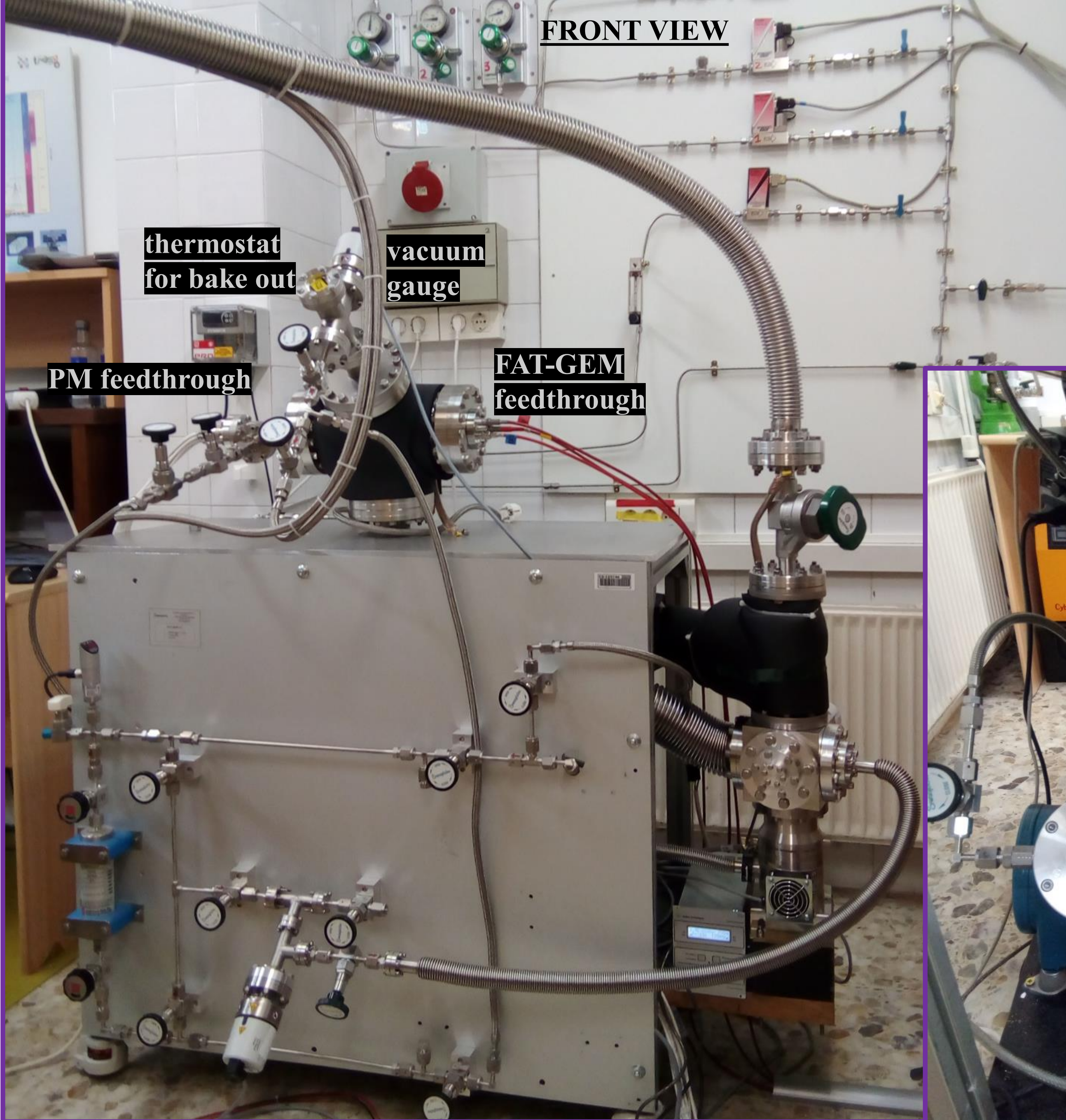
main test system
(Nausicaa0)



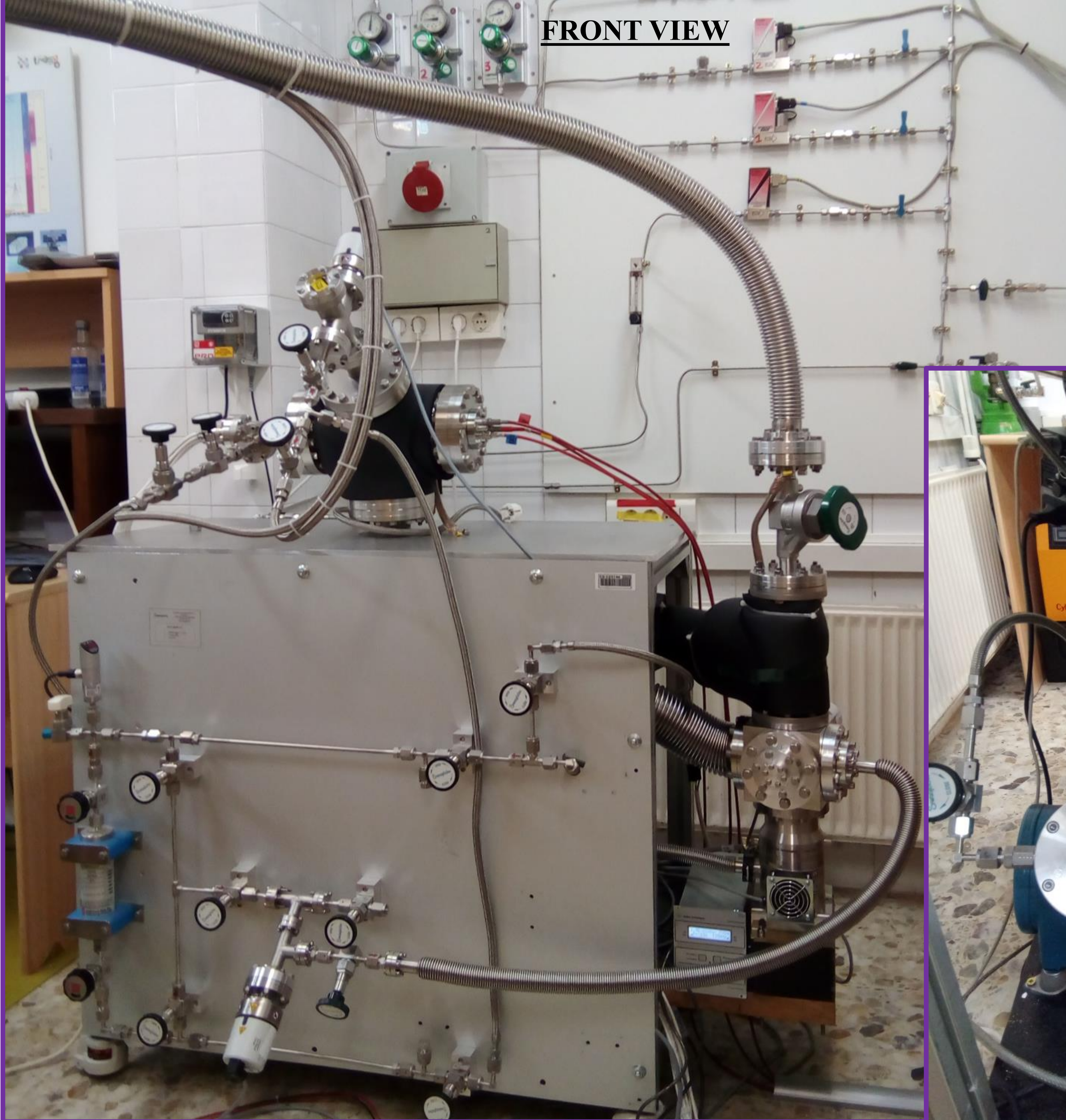
main test system (Nausicaa0)



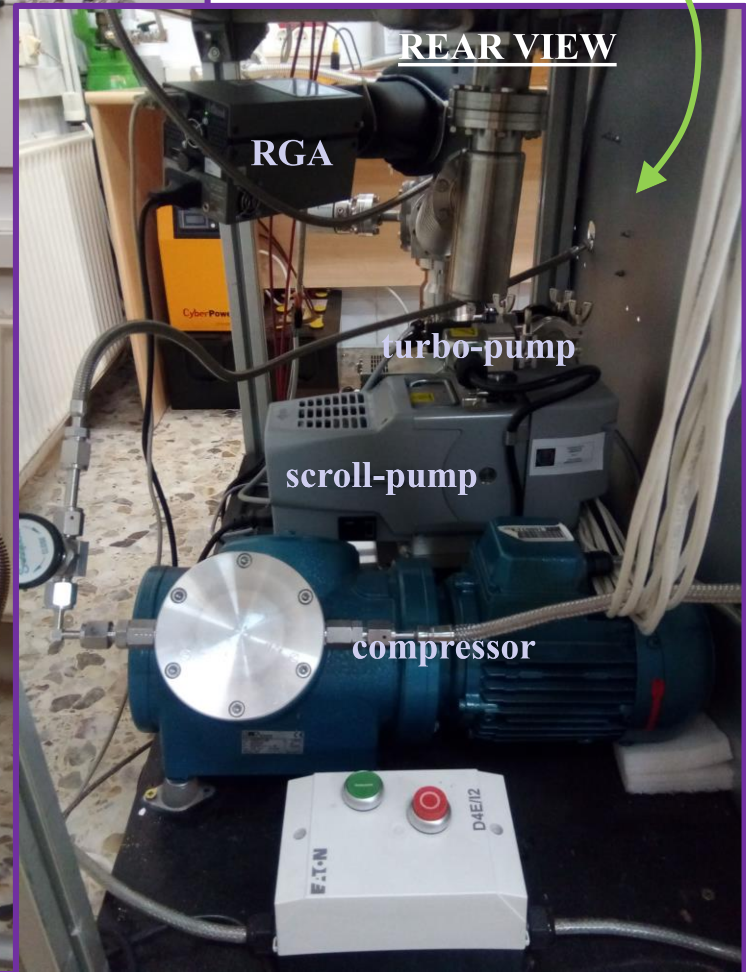
main test system (Nausicaa0)



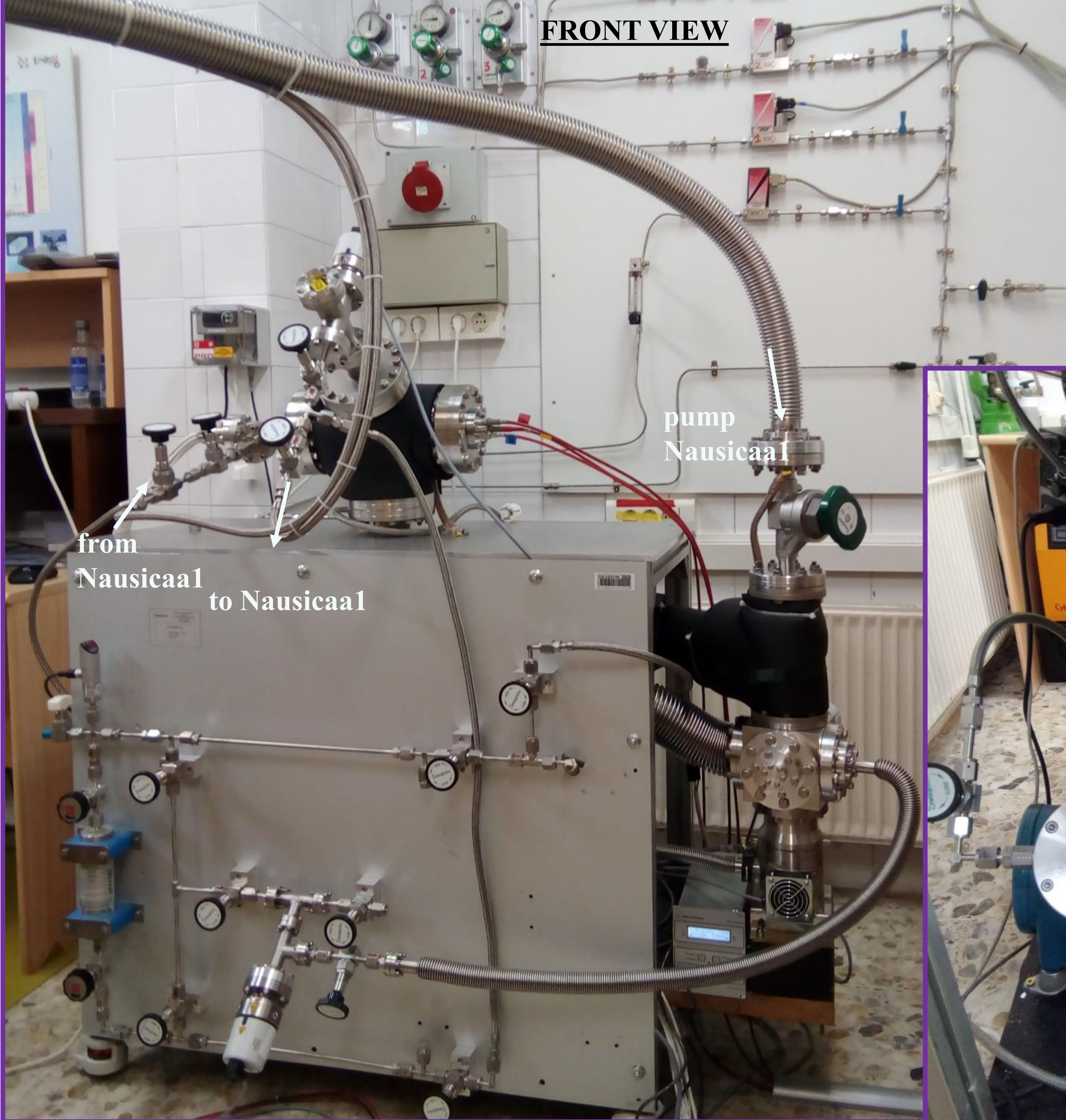
main test system (Nausicaa0)



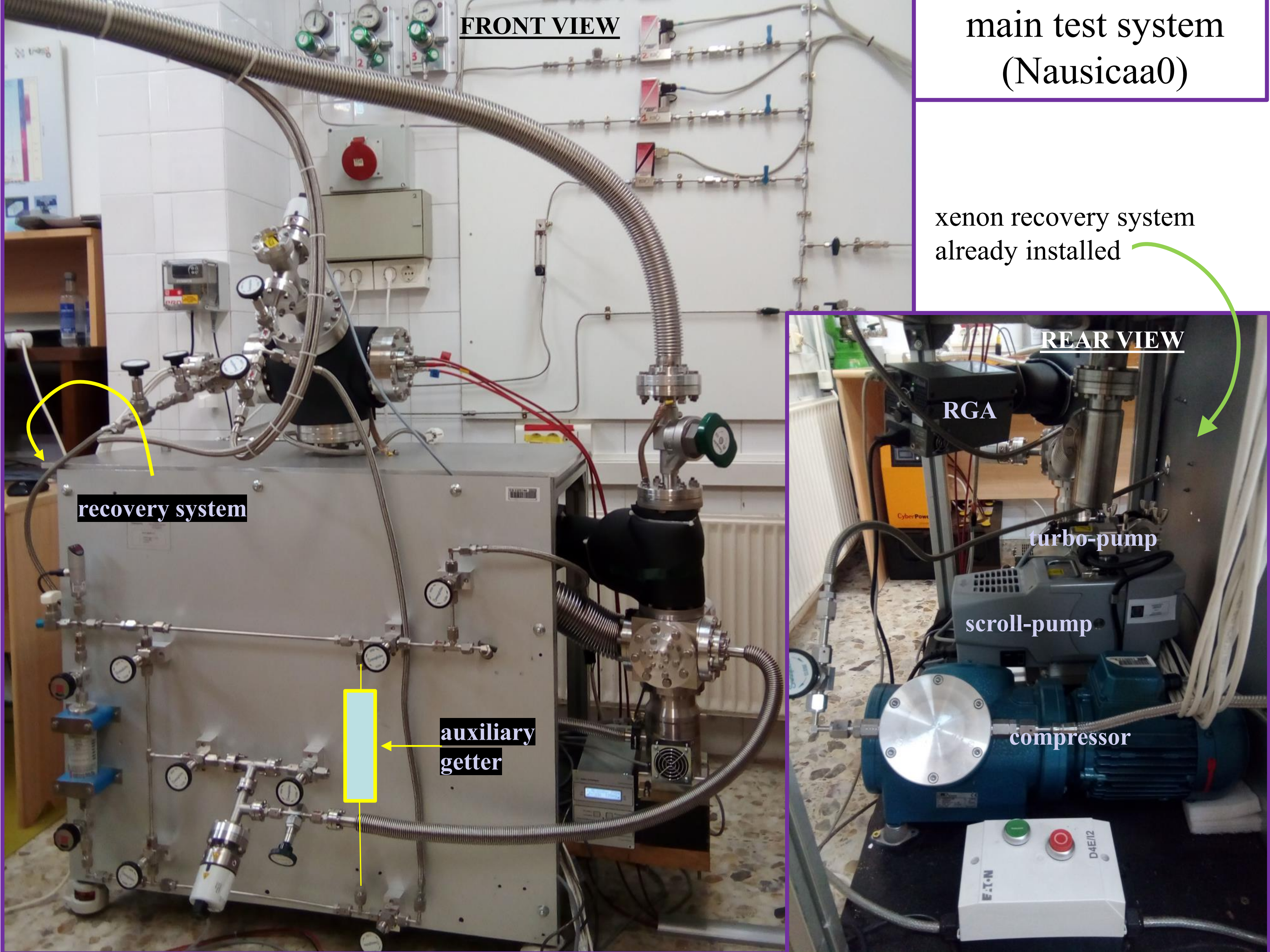
xenon recovery system already installed



main test system
(Nausicaa0)



main test system (Nausicaa0)



ββ0ν: the name of the game (I)

experiment

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

ββ0ν: the name of the game (I)
experiment

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

efficiency

isotopic abundance

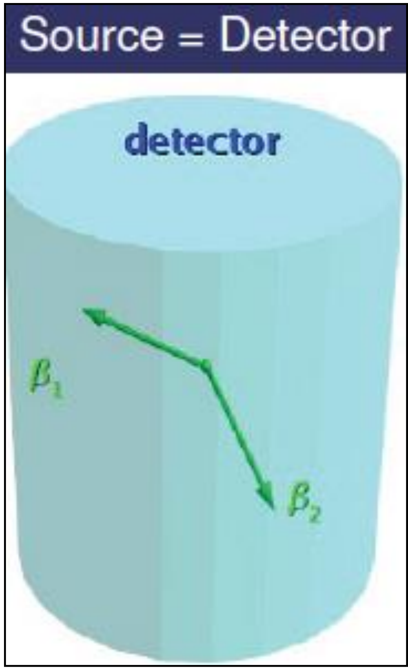
exposure (kg y)

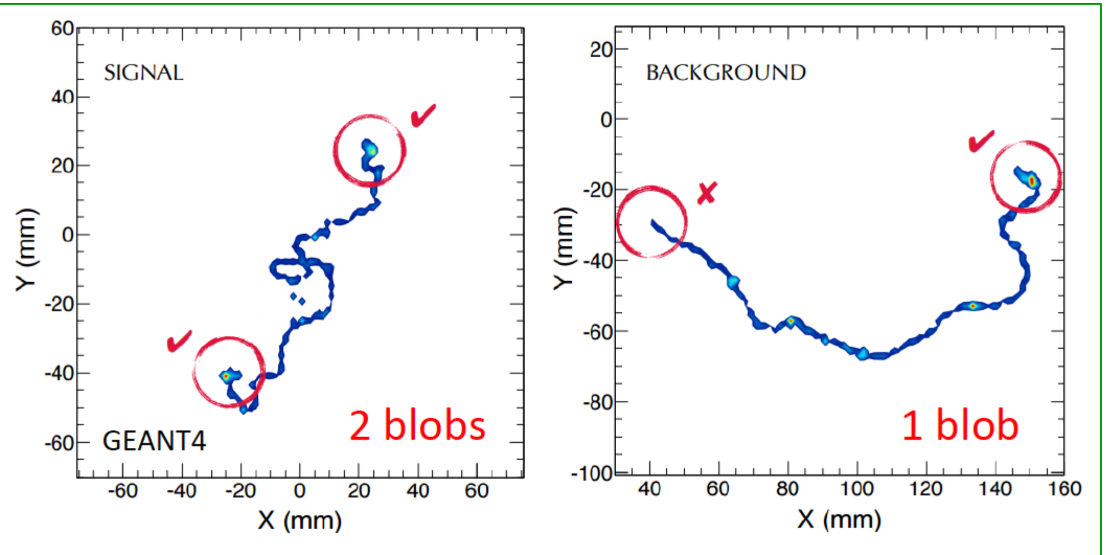
number of sigmas for claim at a given confidence level

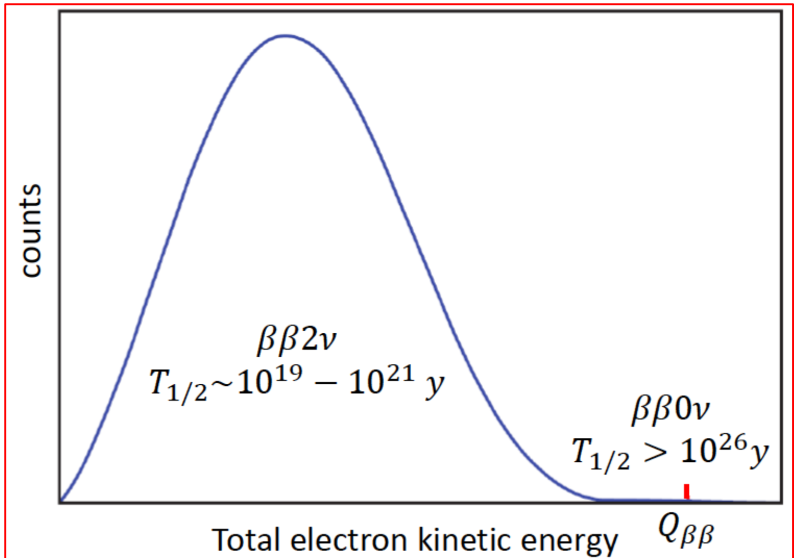
molecular weight

background [cts/keV/kg/y]

energy resolution [keV]



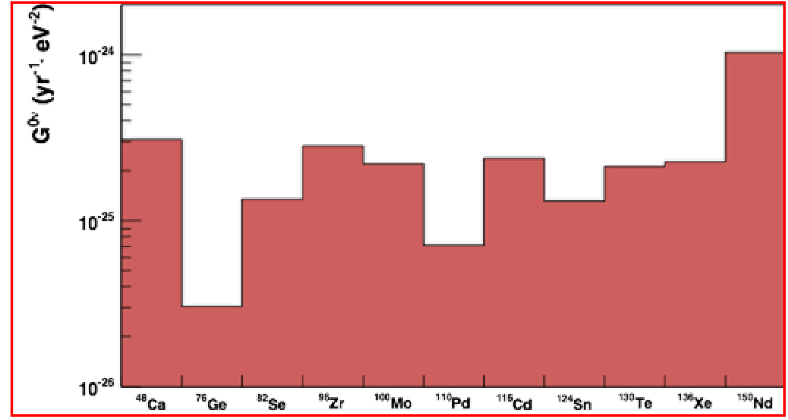




ββ0ν: the name of the game (II)
theory

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

ββ0ν: the name of the game (II)
theory



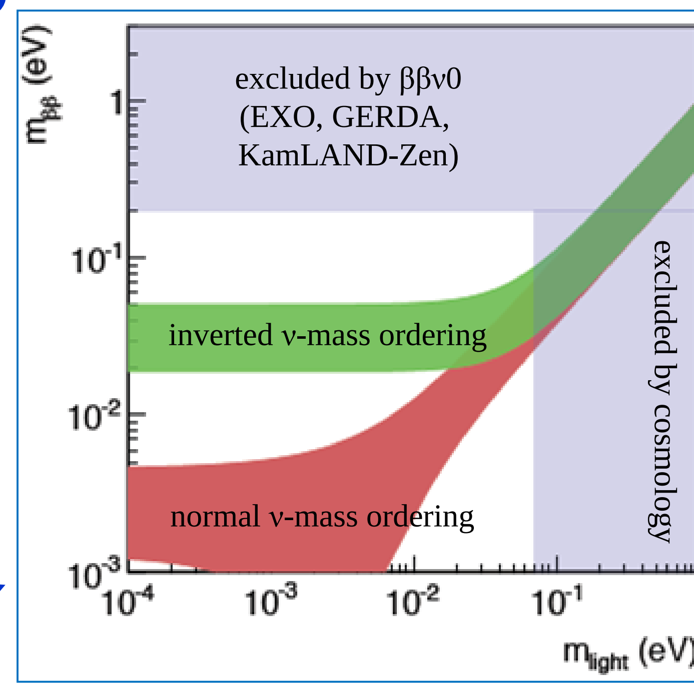
phase-space factor

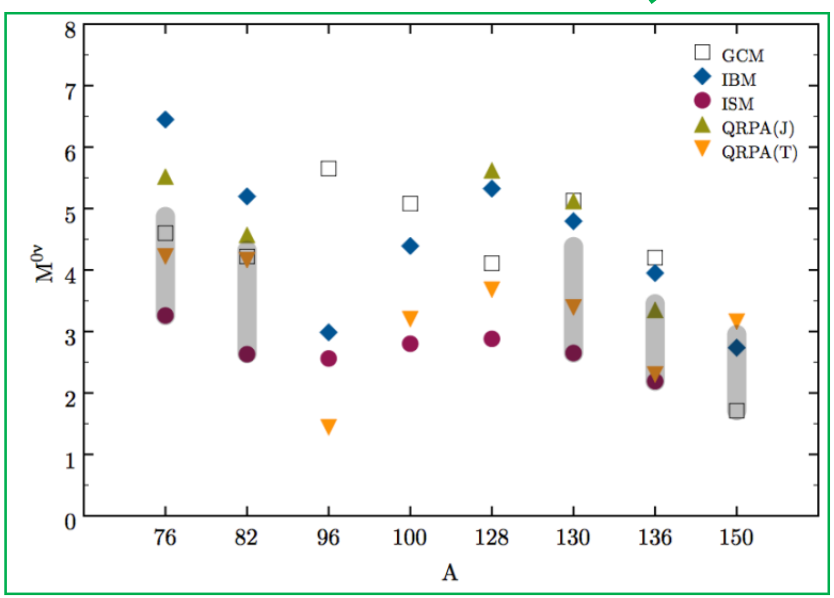
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,m^2_{\beta\beta}$$

nuclear matrix element

~100kg

~1ton





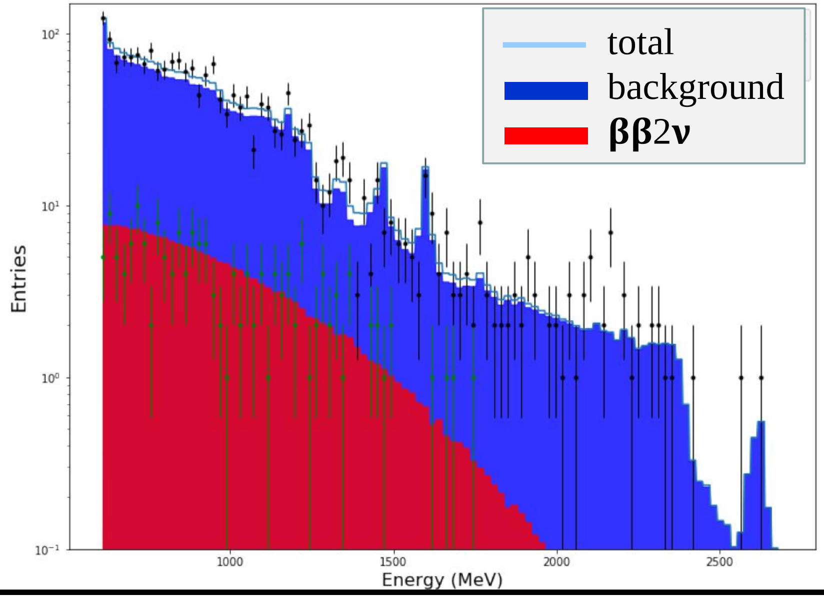
ν oscillations

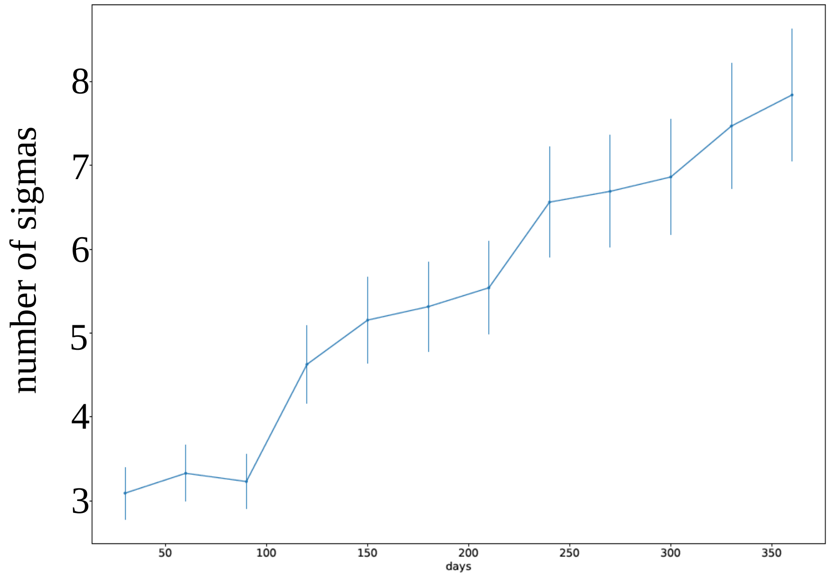
$$m_{\beta\beta} = ||U_{e1}|^2 m_1 + e^{i\alpha_1}|U_{e2}|^2 m_2 + e^{i\alpha_2}|U_{e3}|^2 m_3|$$

IV. projections

ββ2ν, NEW (up to ~Jun 2019)

B. Palmeiro

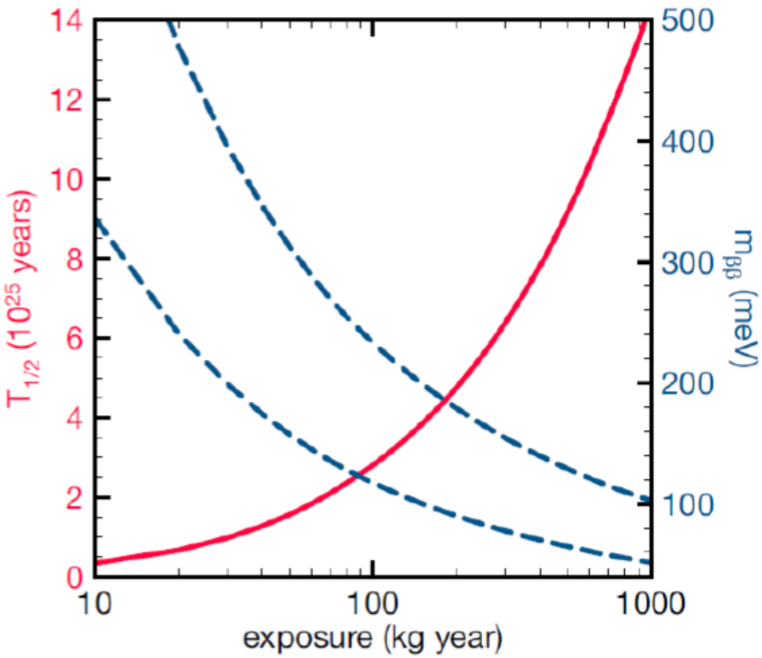




ββ0ν, NEXT-100 (from ~Jun 2020)

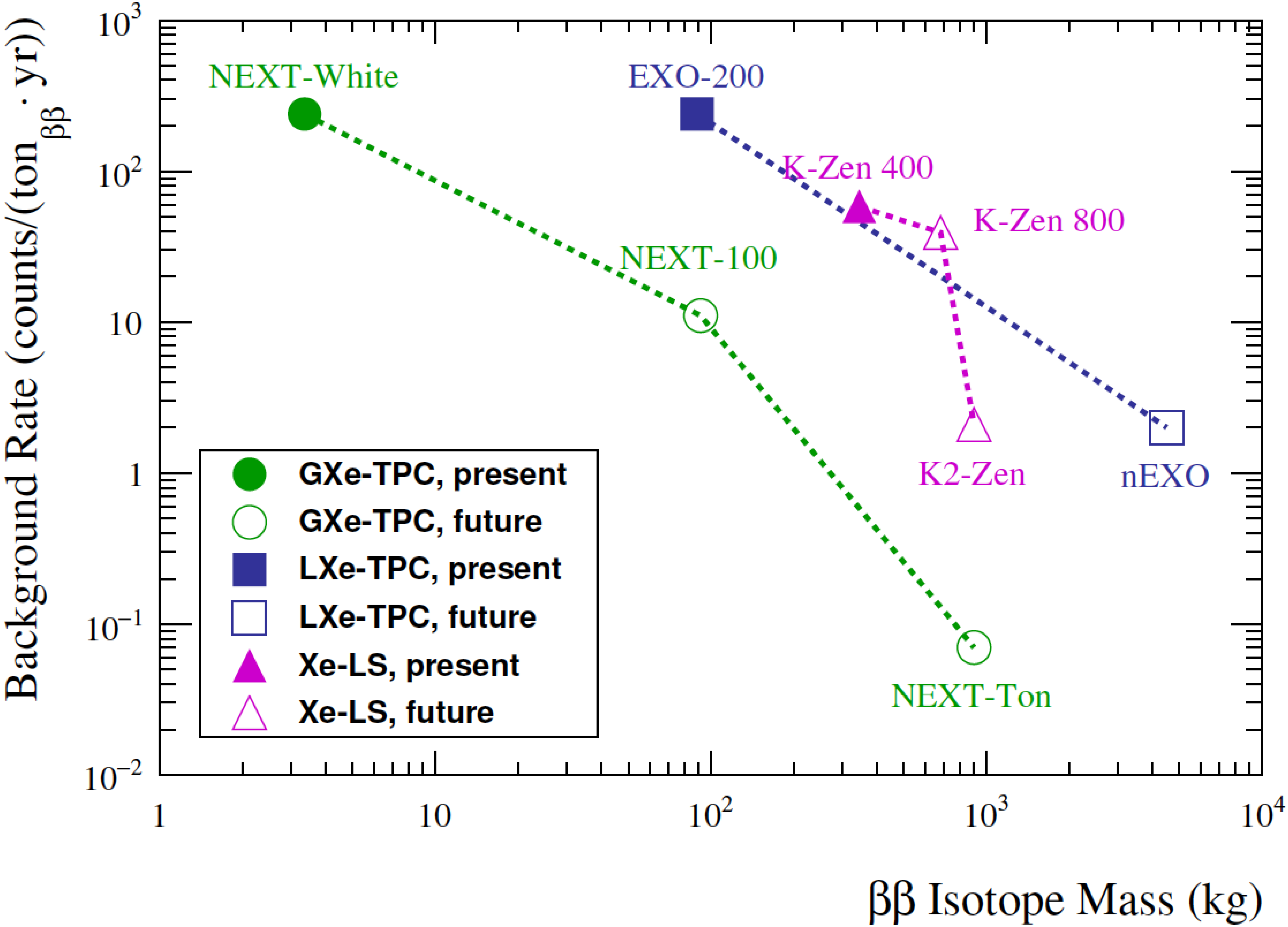
Background: $4 \cdot 10^{-4}$ counts/keV/kg/yr (~0.5-1 counts/100 kg/yr for 0.5-1% FWHM)

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

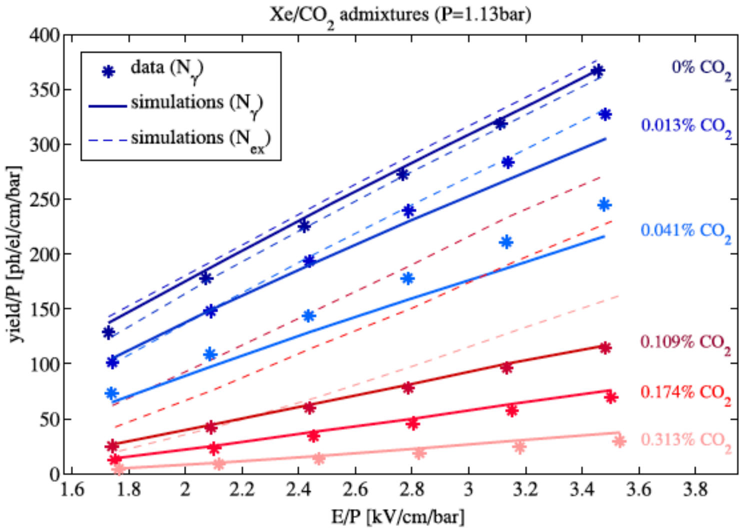


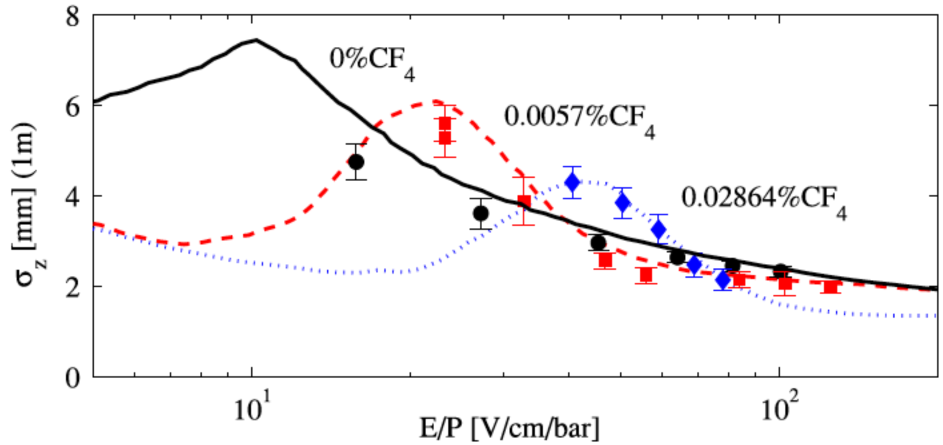
IGFAE expected to coordinate the installation of the neutron and muon VETO! (FPA call evaluation by March)

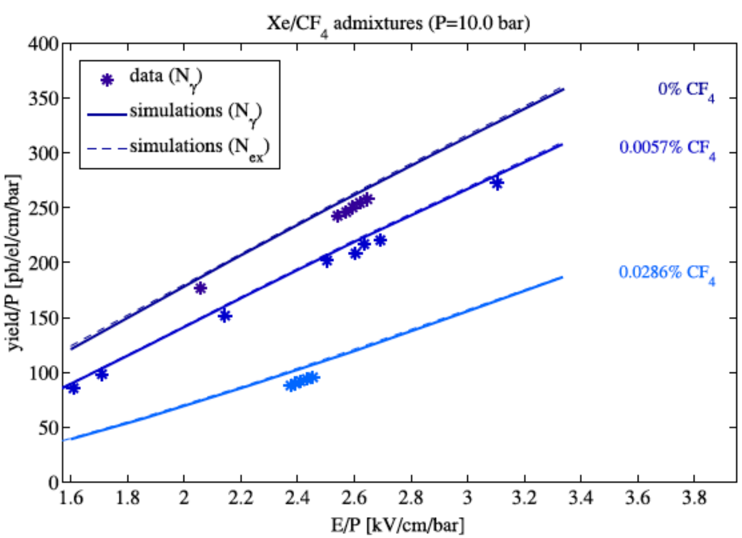
comparison with leading experiments



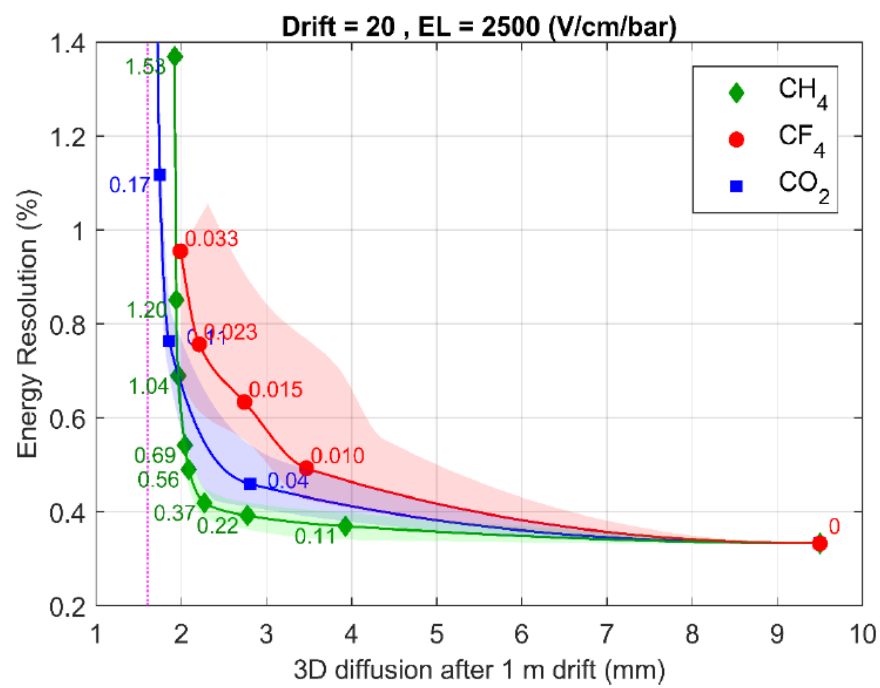
Magic mixtures for low diffusion EL-TPCs







results extrapolated to NEXT-100



effect of g_A

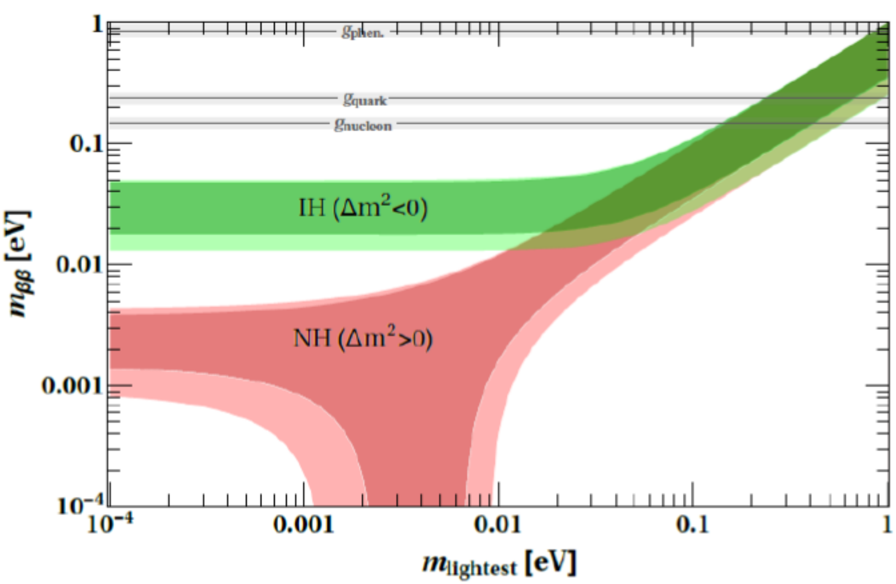
$g_A = 1.269$ for weak interaction and decays of nucleons

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 $0\nu\beta\beta$



$g_A = g_{phen} = 0.52$

$g_A = 1$

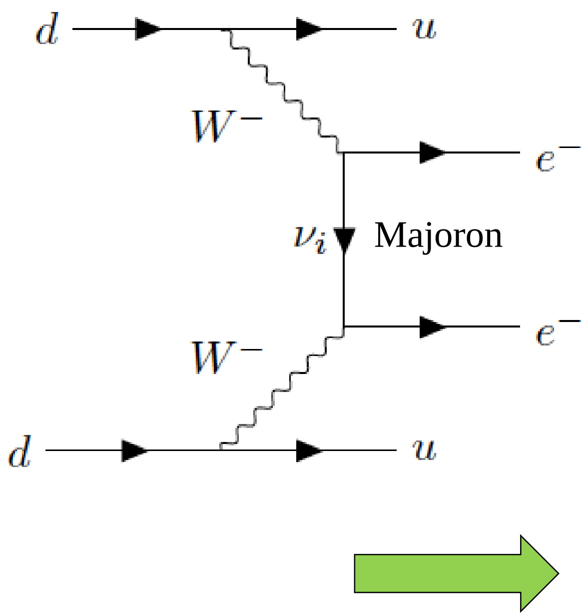
$g_A = 1.269$

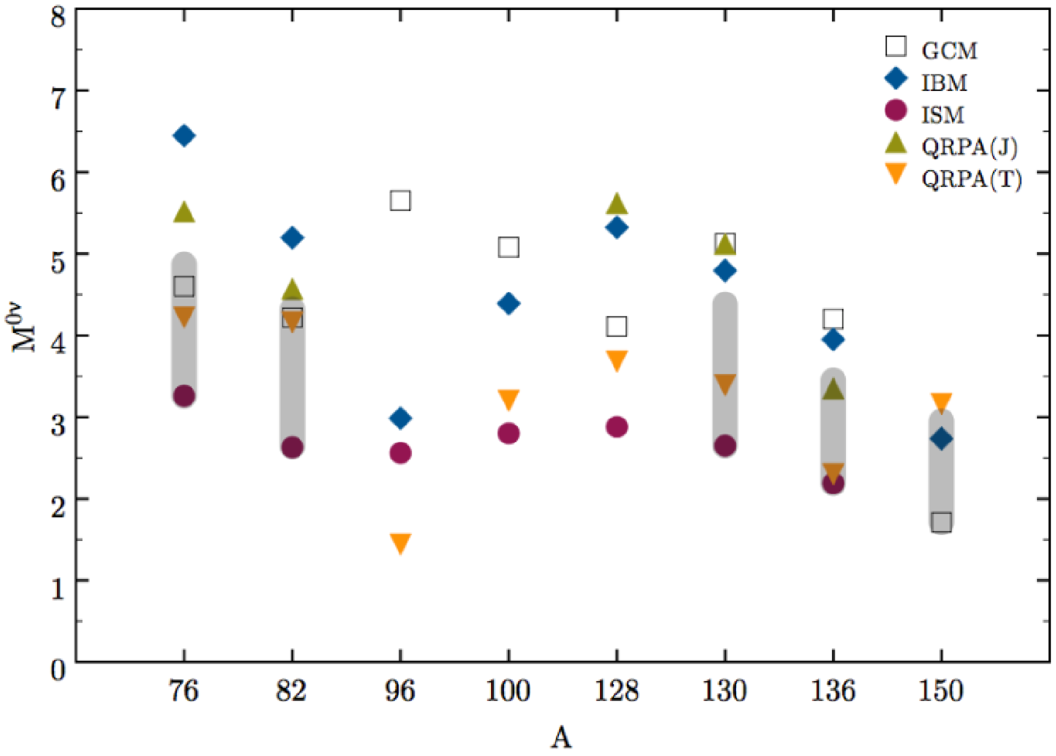
KamLand-Zen + EXO-200
2015 data

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

effect of $M^{0\nu}$

$g_A = 1.25$

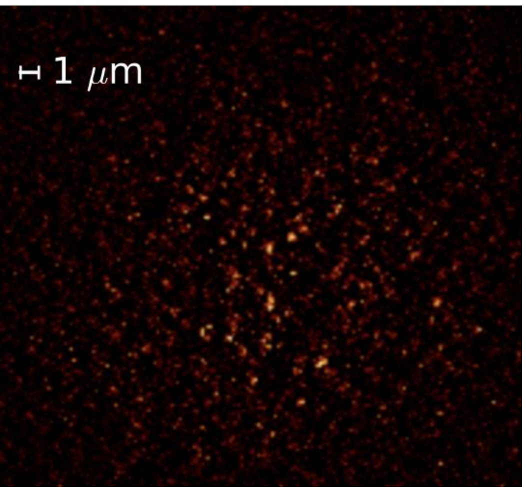


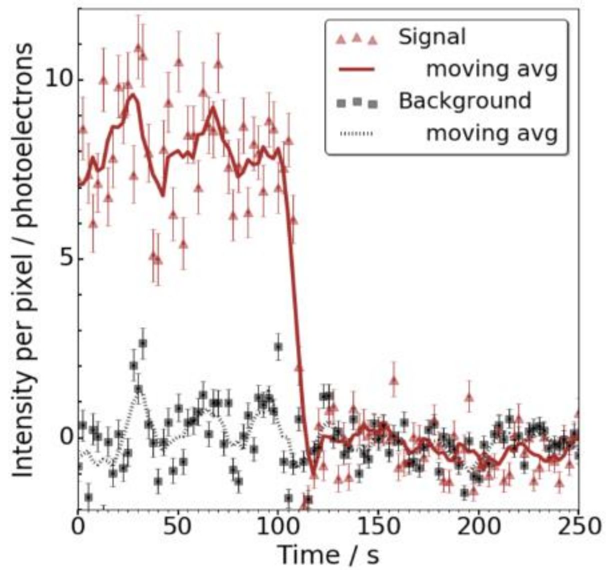


Barium tagging

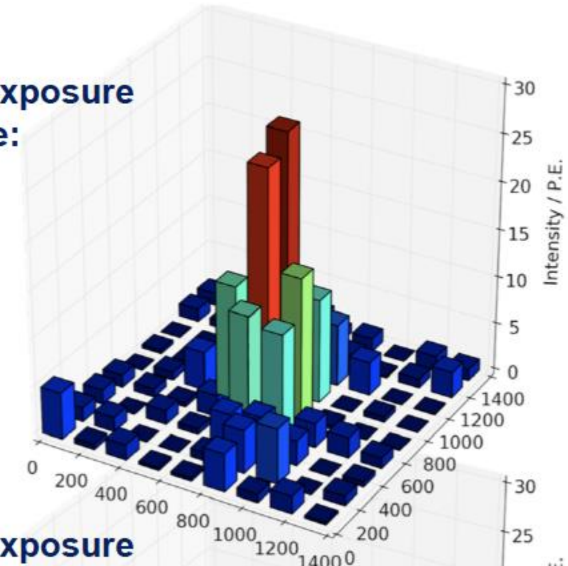
when looking into a single spot

Ba ions made shine in solution

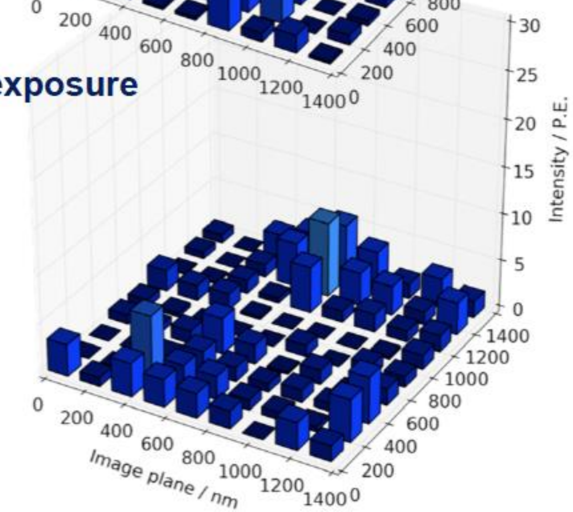




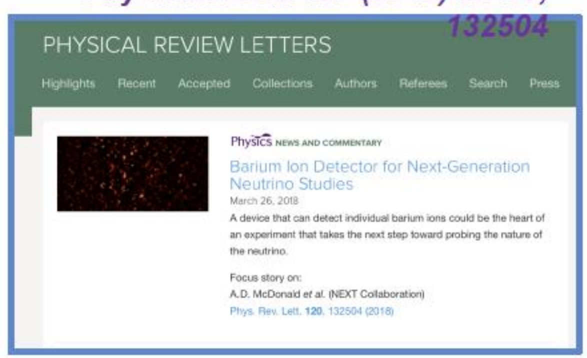
0.5s exposure before:



0.5s exposure after:



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



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Physics NEWS AND COMMENTARY

Barium Ion Detector for Next-Generation Neutrino Studies

March 26, 2018

A device that can detect individual barium ions could be the heart of an experiment that takes the next step toward probing the nature of the neutrino.

Focus story on:

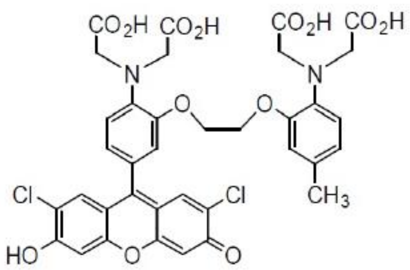
A.D. McDonald *et al.* (NEXT Collaboration)

Phys. Rev. Lett. **120**, 132504 (2018)

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!.

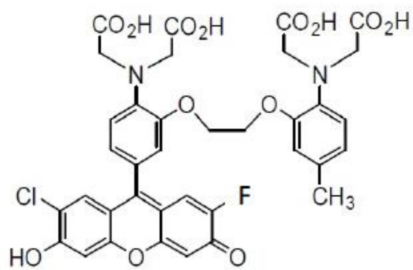
Ca^{++} (in solution)



BAPTA, fluorescein-Cl

FLUO-3

f = 17

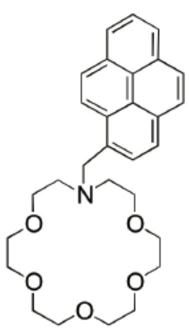


BAPTA, fluorescein-CF

FLUO-4

f=85

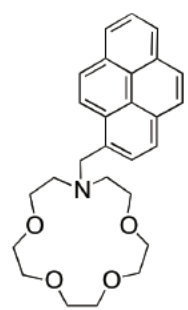
Ba^{++} (dry)



18c6, pyrene:

NEXT-1

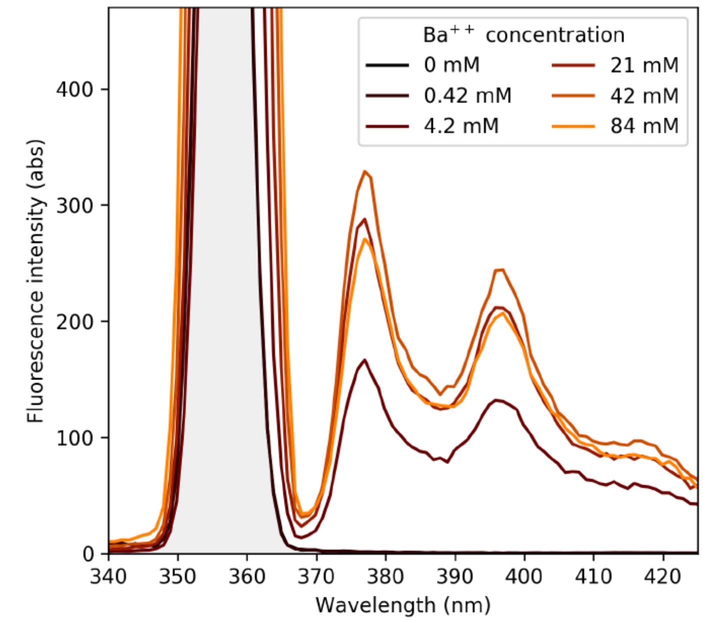
f=6

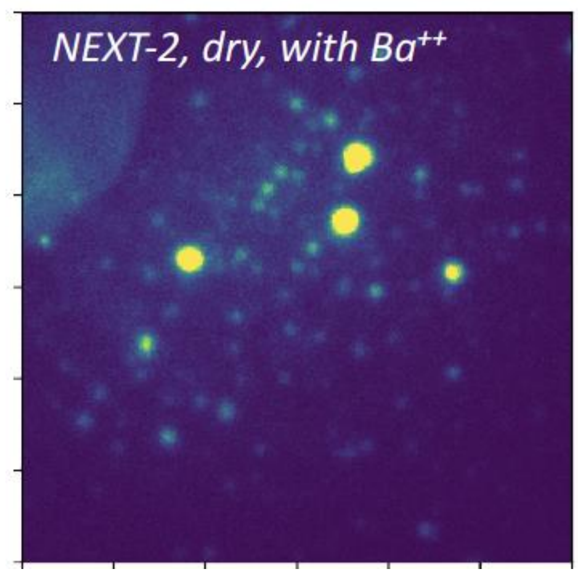


15c5, pyrene:

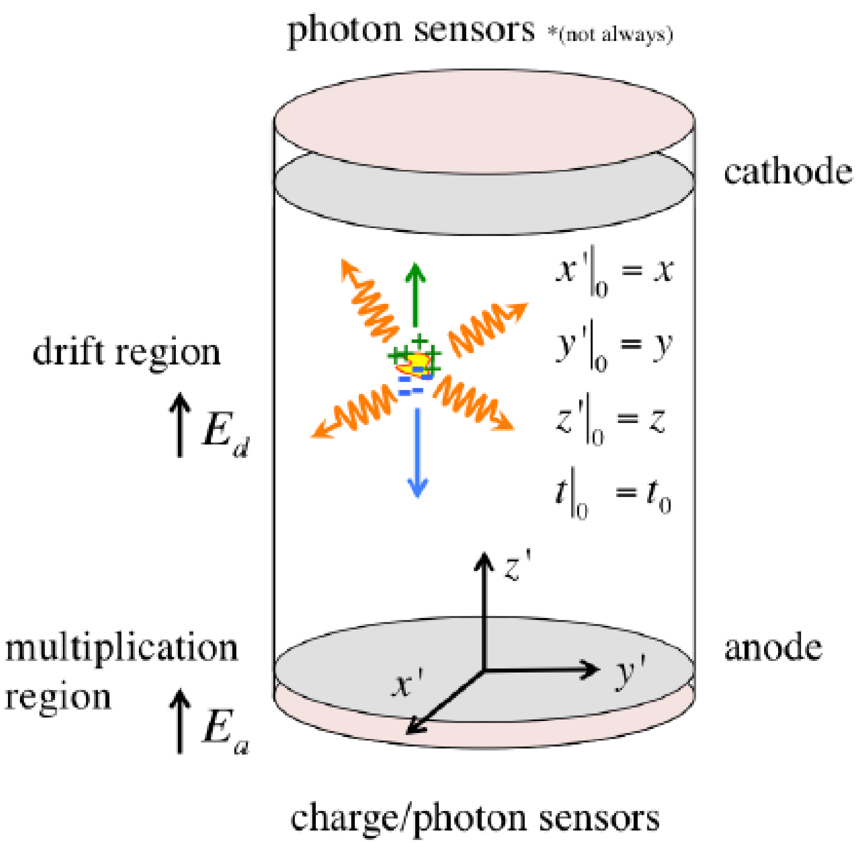
NEXT-2

f=205



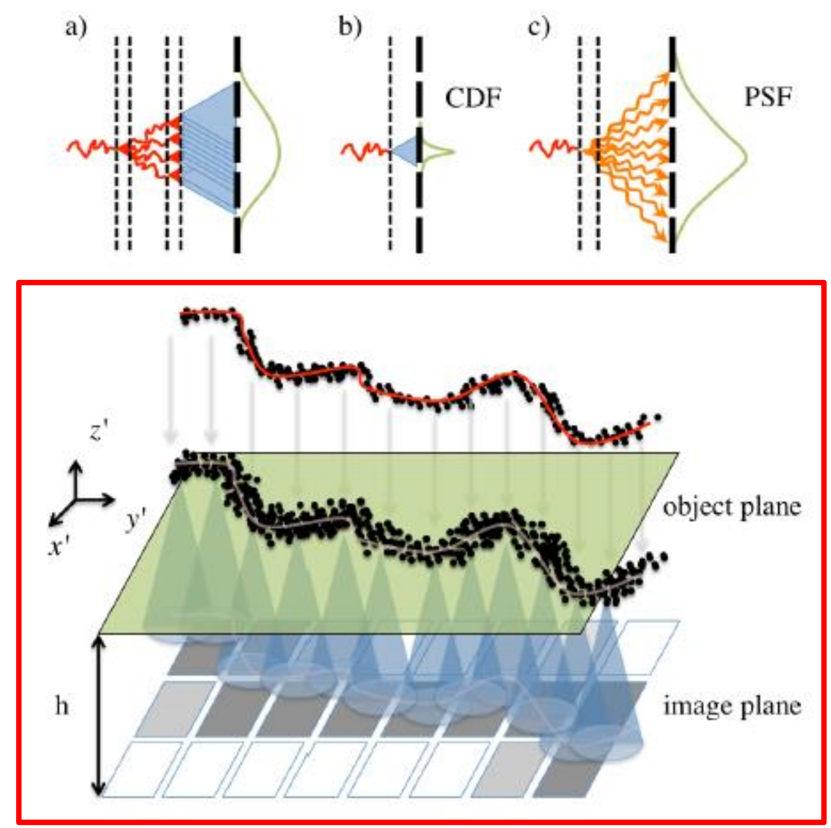


A generic TPC for rare event searches



- 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

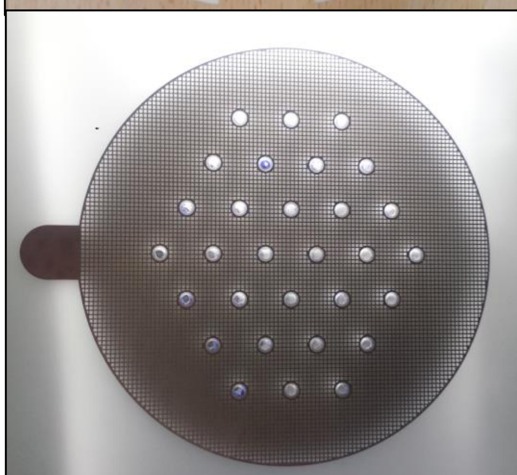
$$\delta(t-t_0) \rightarrow \mathcal{IRF}(t-t_0)$$

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

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

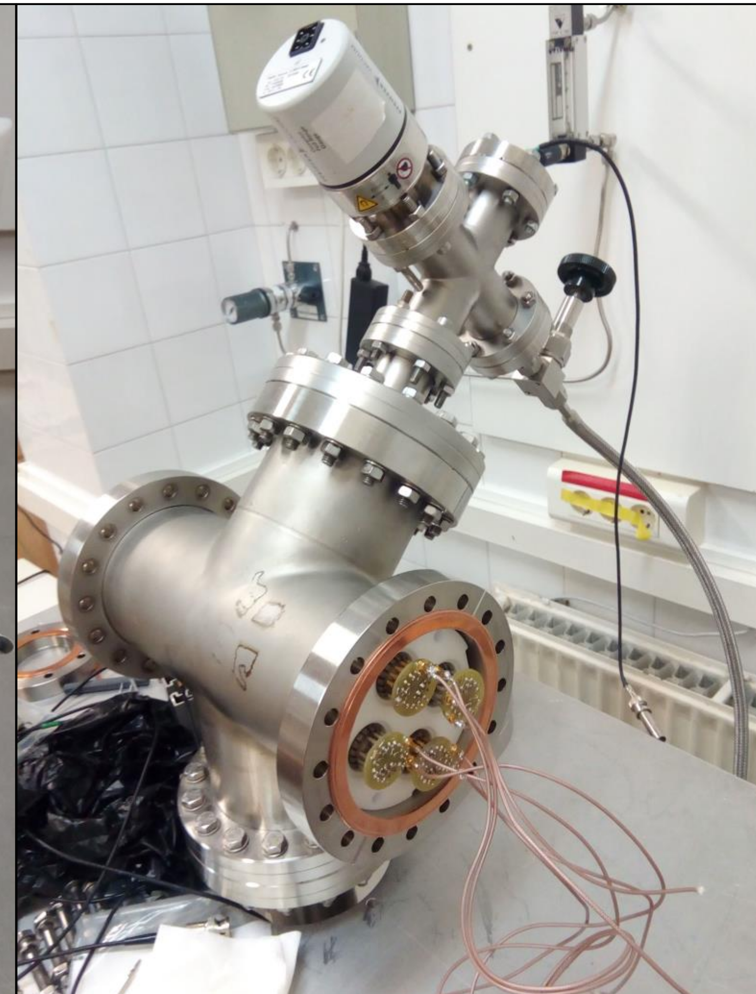
enabling assets III
(chamber for sensor characterization: Nausicaa0)

PMT teflon-frame



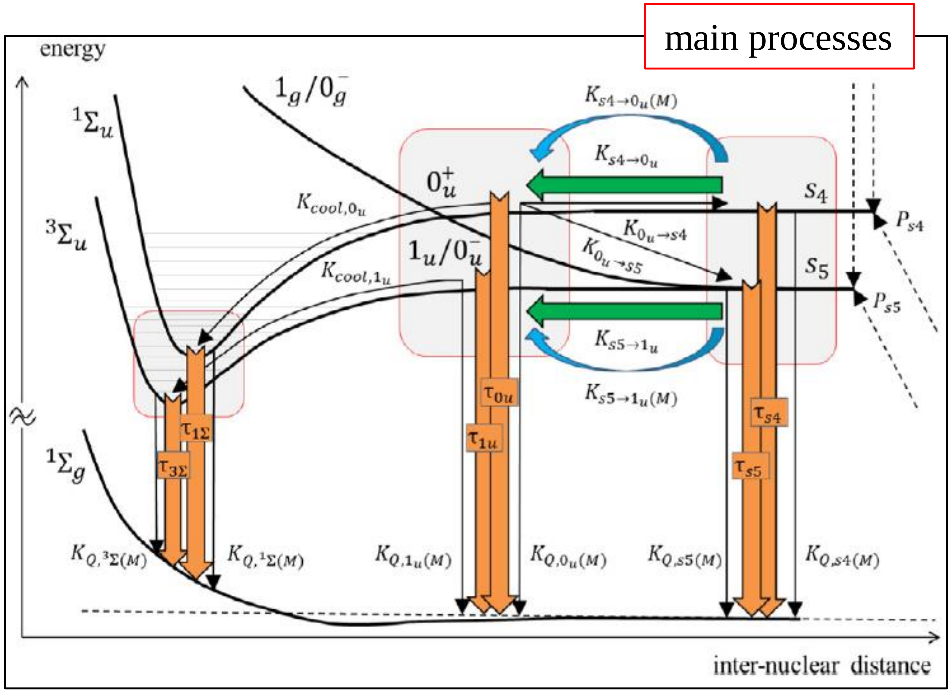
acrylic hole-based scintillator
(akin to GEMs, but x100 larger)

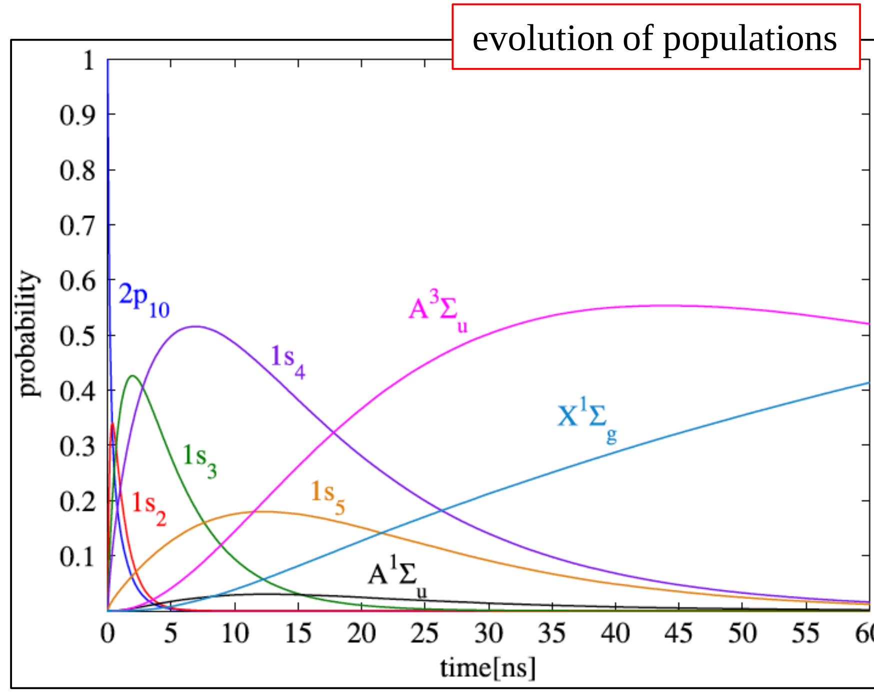
test assembly

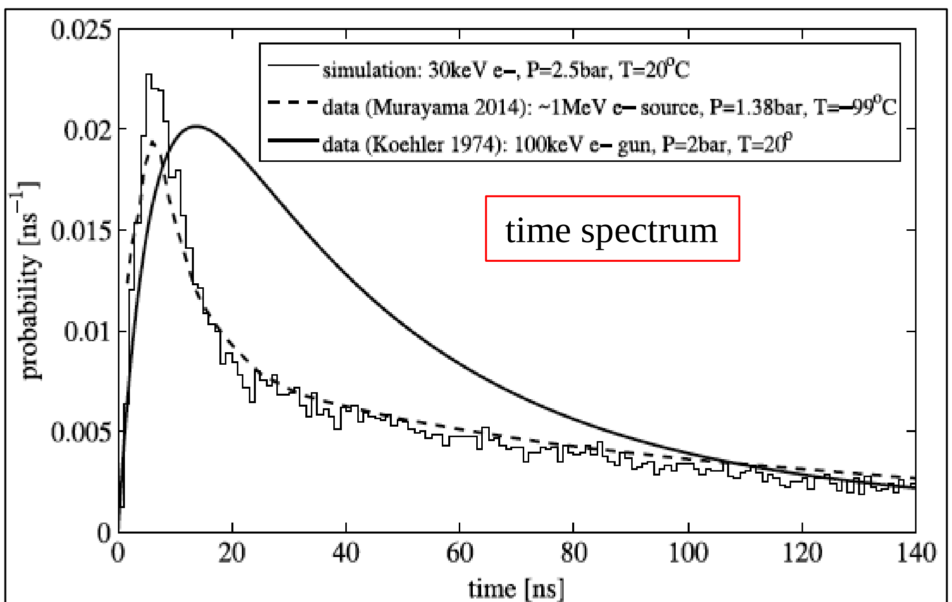


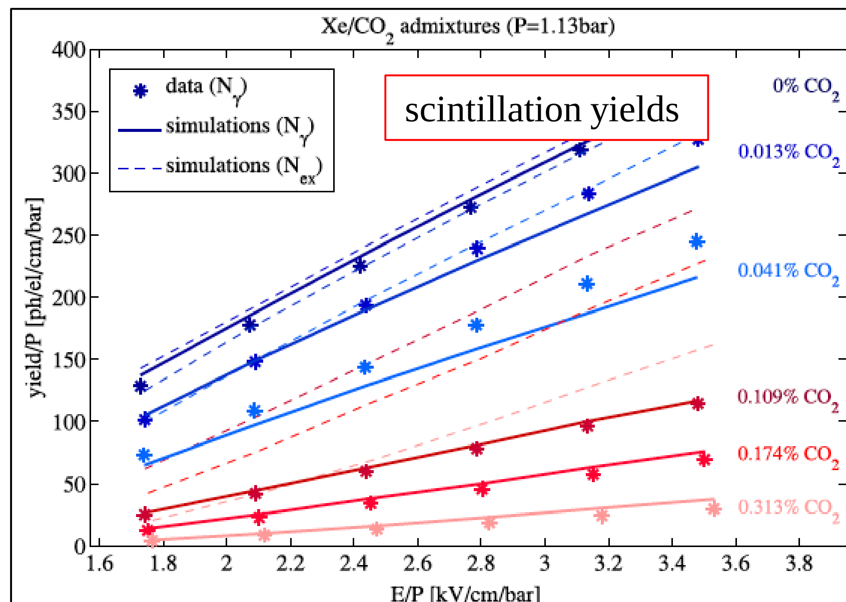
Nausicaa0 general view

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



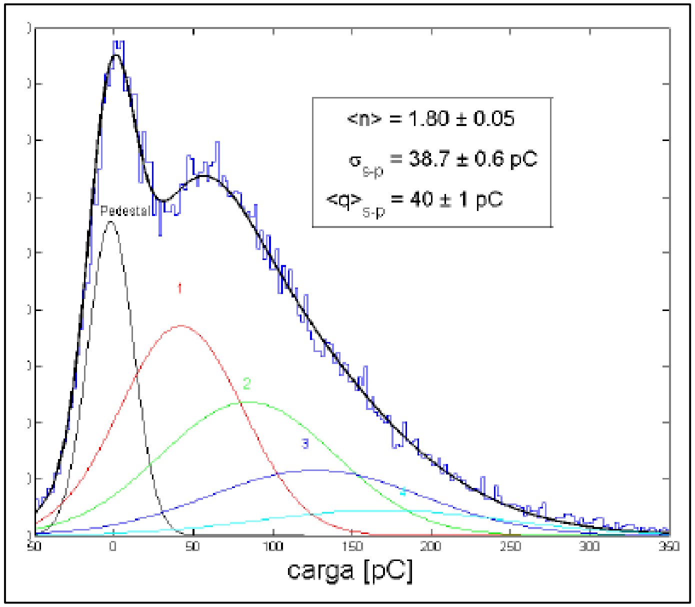




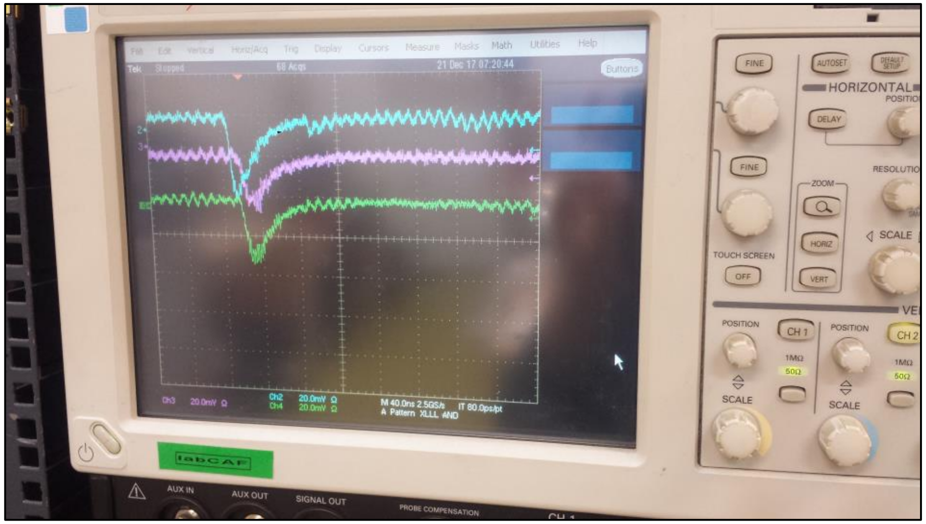


enabling assets VII
(some working parameters achieved)

- 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