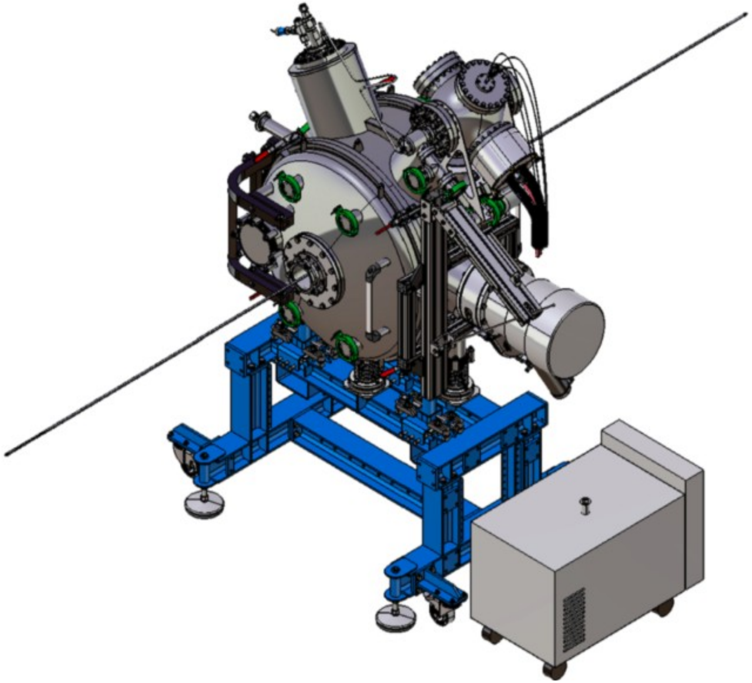
* Liquid **Xe**non **M**edical **I**maging **S**ystem



*Talk by Eugene Semenov:*

# Feasibility evaluation of nuclear fuel homogeneity control with XEMIS2* camera

*PhD hours @ Subatech*

*Nantes, France*

*13 July, 2023*

*Collaboration*

orano [2]

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

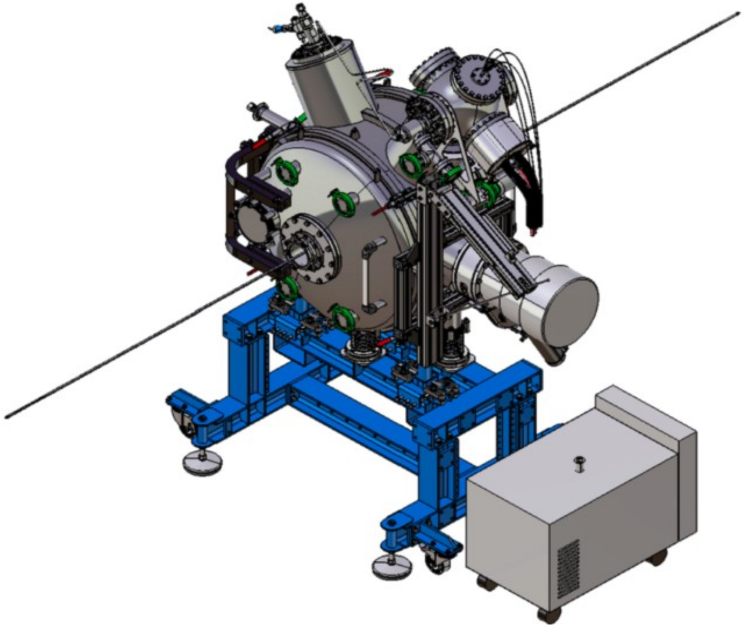
cnrs [1]

Nantes Université

Subatech

Talk by Eugene Semenov:

# Feasibility evaluation of nuclear fuel homogeneity control with XEMIS2 camera



PhD hours @ Subatech

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Team

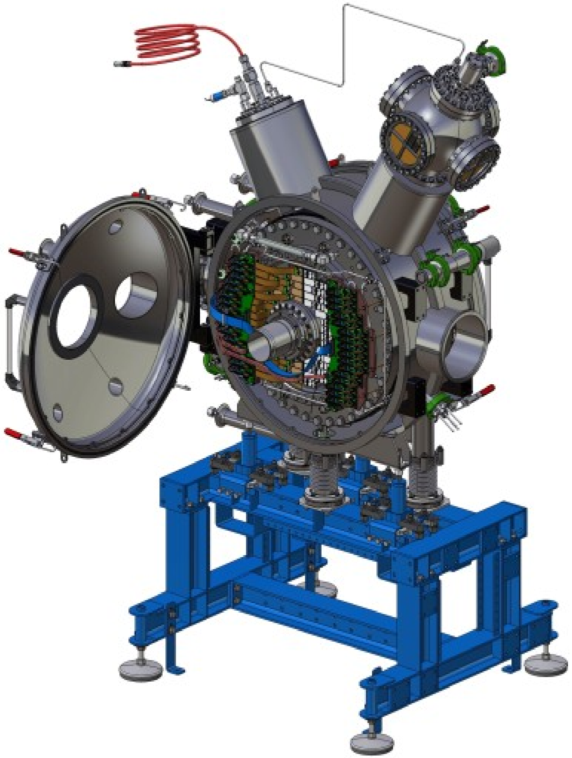
- Eugene Semenov[1]
- Nicolas Beaupere[1]
- Andre Charre[2]
- Abibatou **Ndiaye**[2]
- Amandine Spiteri[2]
- Dominique **Thers**[1]

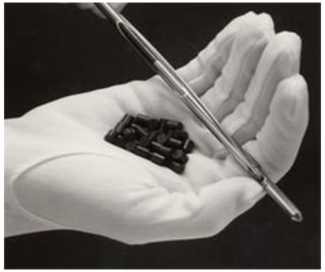
Collaboration

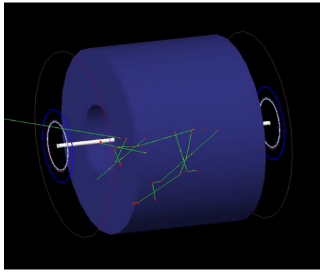
2 orano

1 IMT Atlantique Bretagne-Pays de la Loire École Mines-Télécom, cnrs, Nantes Université

# CONTENT

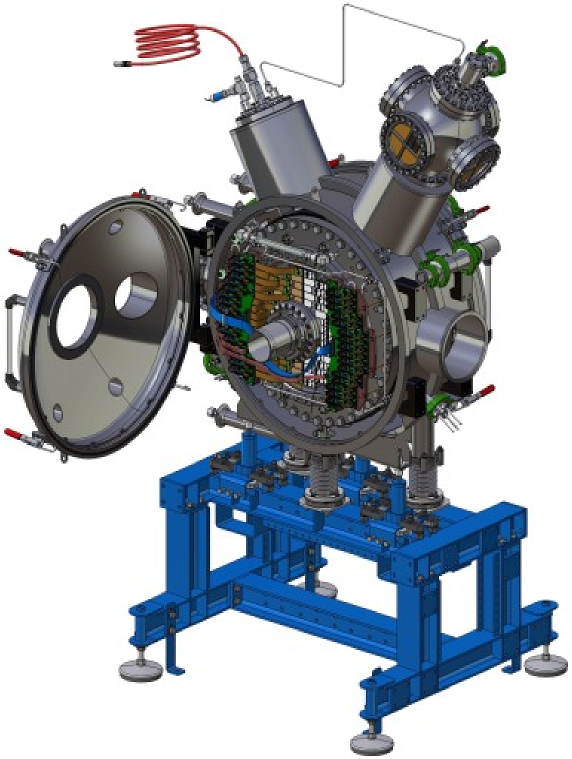


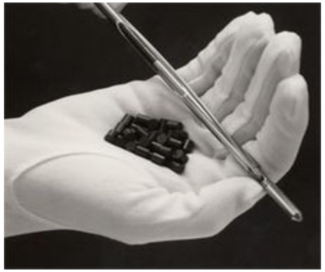


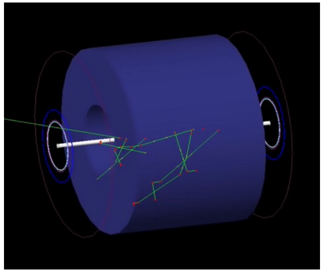


- XEMIS2 overview
- 3γ-imaging
- Object to image
- Control methods:
  - *Scanning & Counting*
  - *Compton tracking*
- Conclusions

# CONTENT







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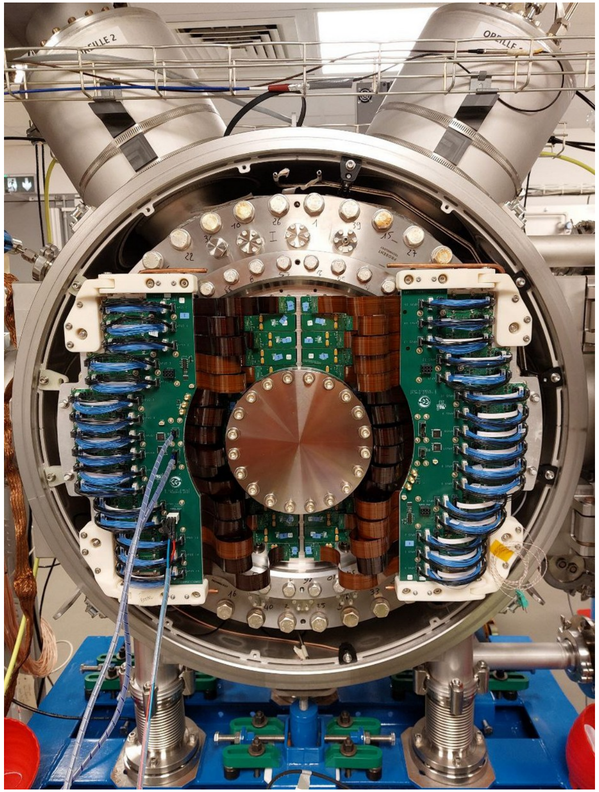
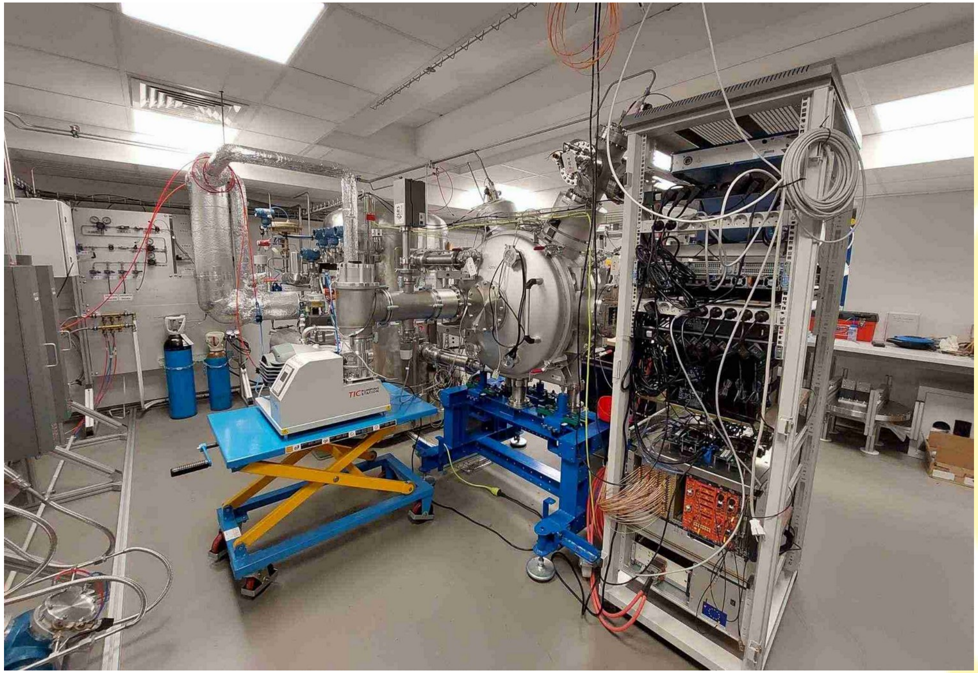
# XEMIS2

## **General view** [Nantes Hospital]



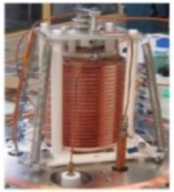


*XEMIS2 is located at CHU Nantes CIMA*,*
***Final stage of tests** is ongoing*
***Camera closed**: end of year*

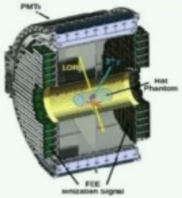
** Centre d’Imagerie Multimodale Appliquée*

# XEMIS2

| THEN | NOW | FUTURE |
|---|---|---|
| **XEMIS1** R&D | **XEMIS2** Small animal imaging | **XEMIS3** Whole body imaging |



**30 kg**
**12 cm drift TPC**

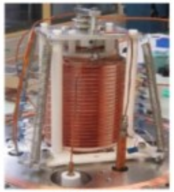


**200 kg**
**2 x 12 cm drift TPC**

**Toward 2 tons**
**2 m long**
**12 cm radial drift TPC**

# XEMIS2

| THEN | NOW | FUTURE |
| --- | --- | --- |
| **XEMIS1** R&D | **XEMIS2** Small animal imaging | **XEMIS3** Whole body imaging |



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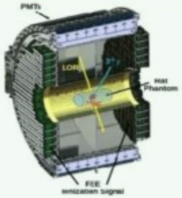


**200 kg**
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**2 m long**
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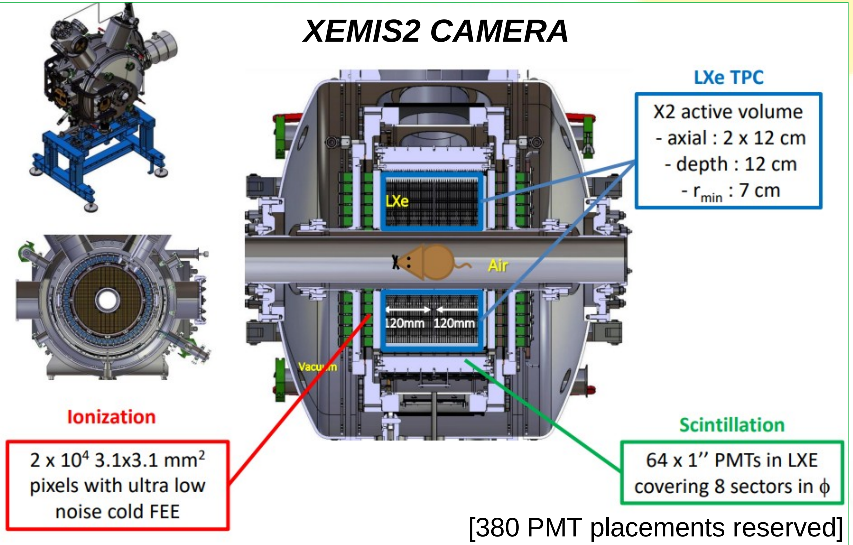
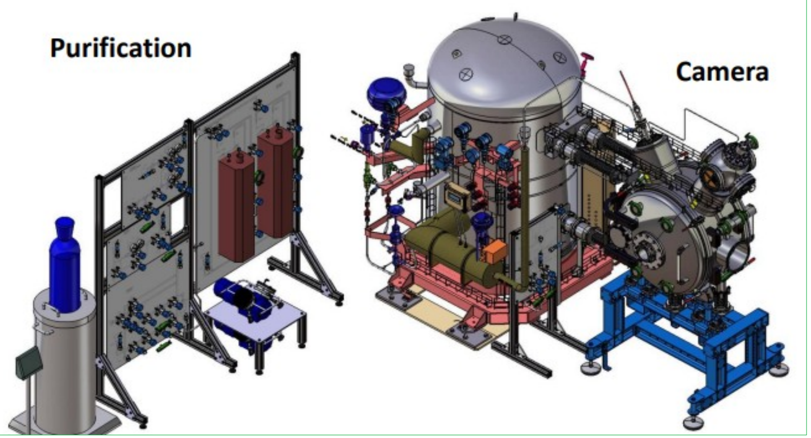
## *XEMIS2 CAMERA*



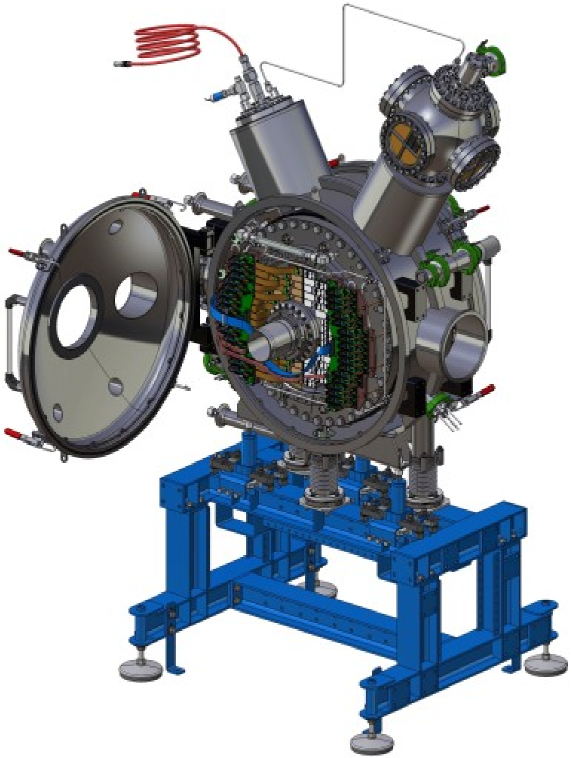

[380 PMT placements reserved]

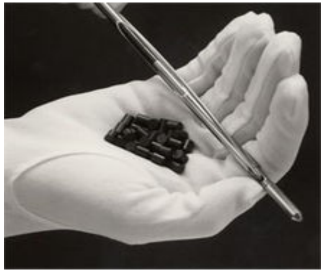


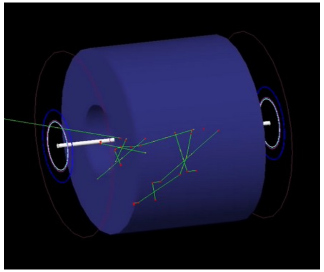

## XEMIS2:

- *Nuclear Medical Imaging with **3γ technique** and **LXe***
- *High Rate Single Phase LXe Time Projection Chamber*

# CONTENT







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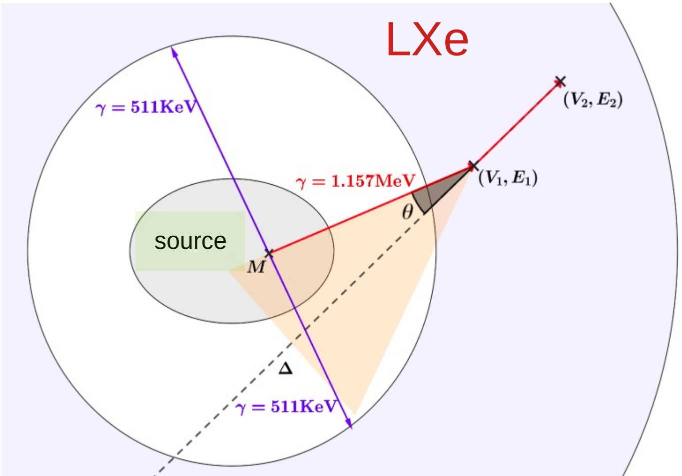
# 3γ-IMAGING

**Classic way** [medical application]




*3γ-imaging scheme. Credits: M.Latif, LS2N, CRCI2NA*

Source:

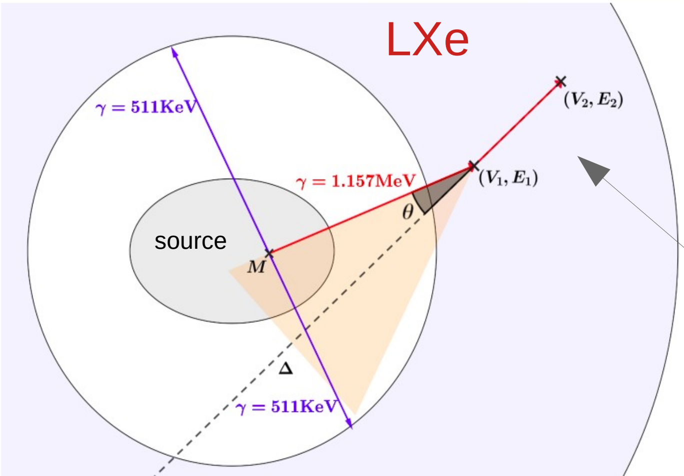
$${}^{44}_{21}\mathrm{Sc} \xrightarrow{\beta^+} {}^{44}_{20}\mathrm{Ca}^* + \nu_e + e^+ \xrightarrow{\gamma} {}^{44}_{20}\mathrm{Ca} + \nu_e + e^+ + \gamma$$

Goal:

Direct 3D location of the radioactive source

# 3γ-IMAGING

## **Classic way** [medical application]




*3γ-imaging scheme. Credits: M.Latif, LS2N, CRCI2NA*

### Source:

$$^{44}_{21}\mathrm{Sc} \xrightarrow{\beta+} {}^{44}_{20}\mathrm{Ca}^* + \nu_e + e^+ \xrightarrow{\gamma} {}^{44}_{20}\mathrm{Ca} + \nu_e + e^+ + \gamma$$

### Measure:

*$V_1$, $V_2$ – hits positions*
*$E_1$, $E_2$ – energy deposited*

$$\Delta = \overrightarrow{V_2V_1}\ ;$$

$$\theta = \arccos\left(1 - \frac{m_e c^2 E_1}{E_0(E_0 - E_1)}\right)\ ;$$

### $^{44}$Sc-pharmaceutics:

Emission γ:
~100% of $E_\gamma$ = 1.157 MeV
Fast emission [2.61 ps]

Emission β+
$E_{max}$ = 1.474 MeV
$T_{1/2}$ = 4 h
effective range : 2.8 mm

### Have:

*LOR reconstruction [$e^+$]*
*+ Compton telescope [LXe]*

### Resolution:

*Spatial → axis **Δ** of the cone*
*Energy → opening angle **θ***

### Production:

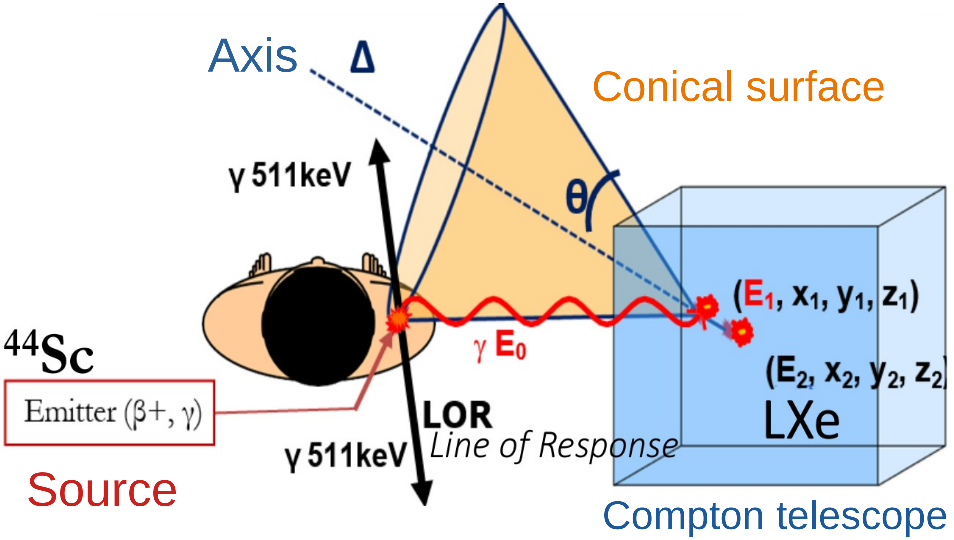
***ARRONAX** cyclotron*

### Goal:

Direct 3D location of the radioactive source

# 3γ-IMAGING

## **Summarize** [medical application]




Looking for crossing points → emitter's position

## XEMIS2:

*Low activity [~20 kBq] + good resolution**

## Specificity:

*Mono-energetic γ & e+ source*

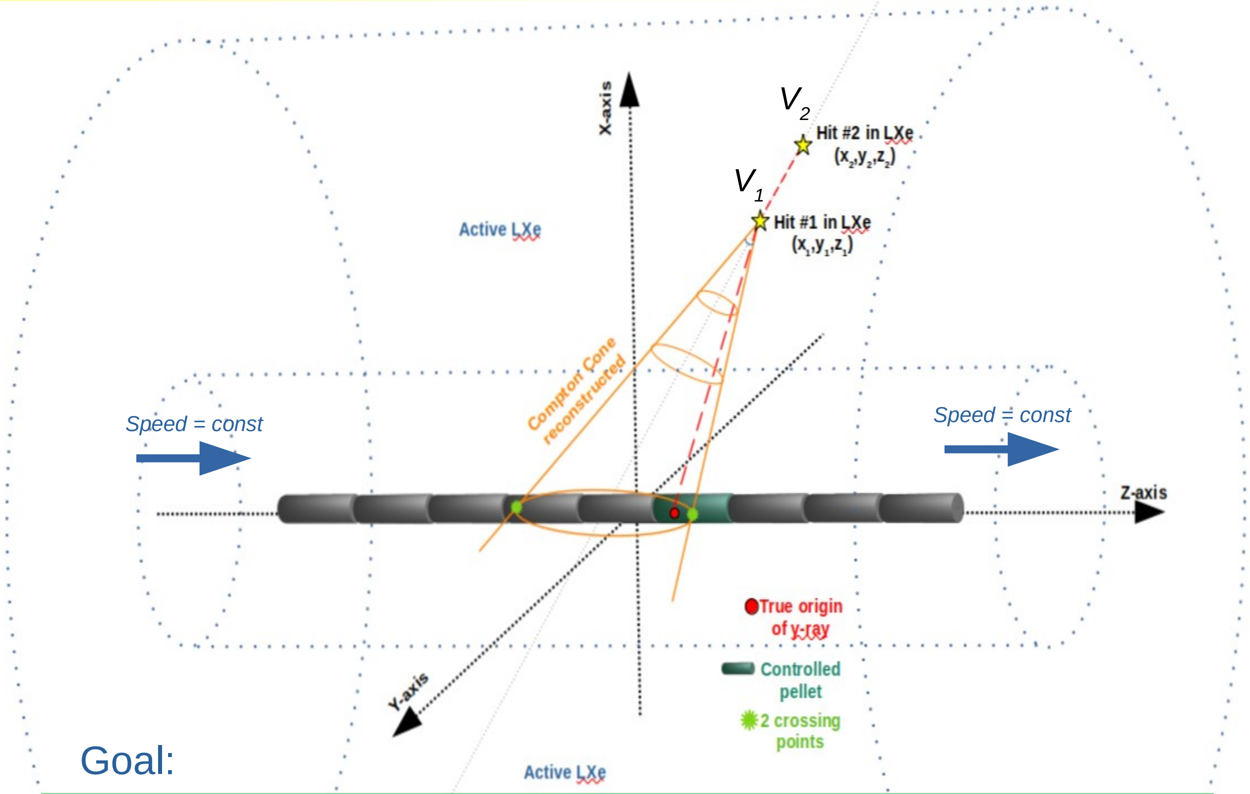
## Research done:

*Events **selection** and **topology***

σ(**x,y**) = 100 µm σ(**z**) = 100 µm for single scatter
σ(**E**) = 3.5 %
*for $^{22}$Na, single scatter, 2 kV.cm$^{-1}$*
σ(**θ**) = 2º

**Y. Xing*, "Studies and optimization of ionization signal measurement for the 3-gamma imaging XEMIS2 liquid xenon Compton camera", PhD thesis @ ***Subatech***

# Fuel control application [this work]




## Source:

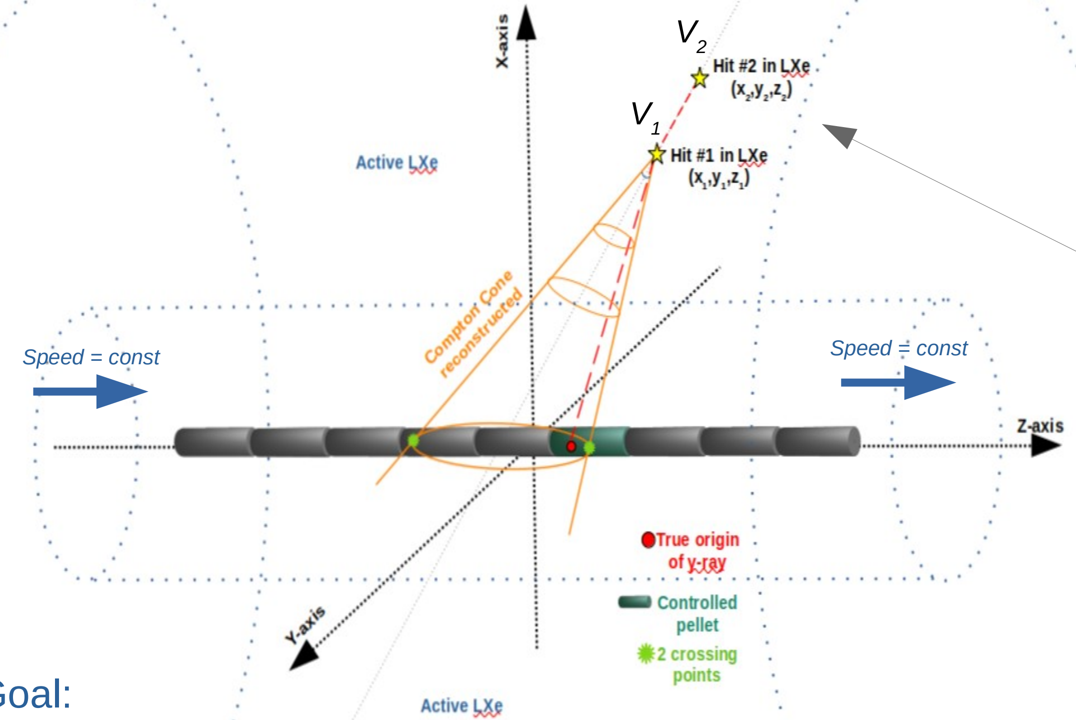
- *Nuclear fuel pellets*
- *Moving along Z-axis*
- *Spectrum of γ-rays*

## Goal:

Find **cone's crossing points** with **Z-axis** → image & control

First time probe such **source and geometry**!

# Fuel control application [this work]




## Source:

- *Nuclear fuel pellets*
- *Moving along Z-axis*
- *Spectrum of γ-rays*

## Measure:

*$V_1$, $V_2$ – hits positions*
*$E_1$, $E_2$ – energy deposited*

## Challenge:

- *Emission spectrum*
- *Control parameters*
- *High activity [total γ]*
- *Low statistics [useful γ]*

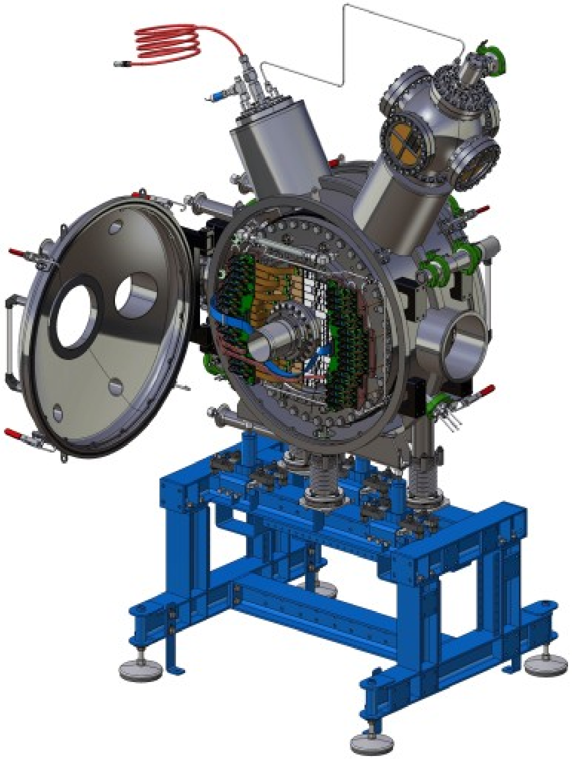
***To be continued...***

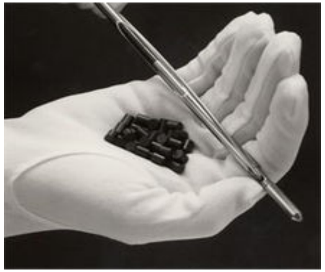
## Goal:

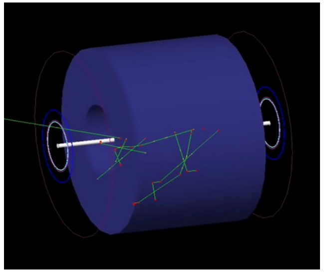
Find cone's crossing points with Z-axis → image & control

First time probe such **source and geometry**!

# CONTENT







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# OBJECT TO IMAGE

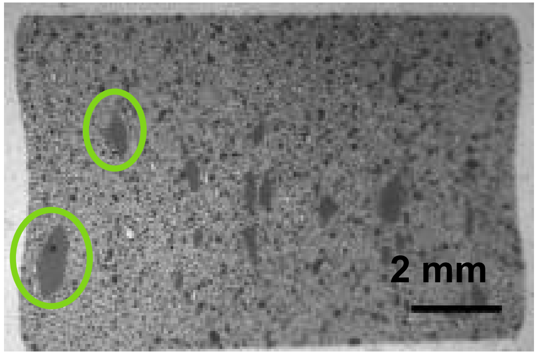
**MOX** [$UO_2$+$PuO_2$ pellets]

## Goal:

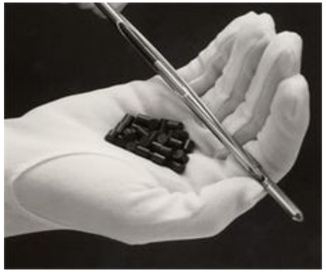
Detect **heterogeneity** of fixed* sizes, shape & $PuO_2$ concentration

**not in the scope*

***Pu excess*** *in a MOX pellet:*




***non-uniform distribution of Pu in fuel****



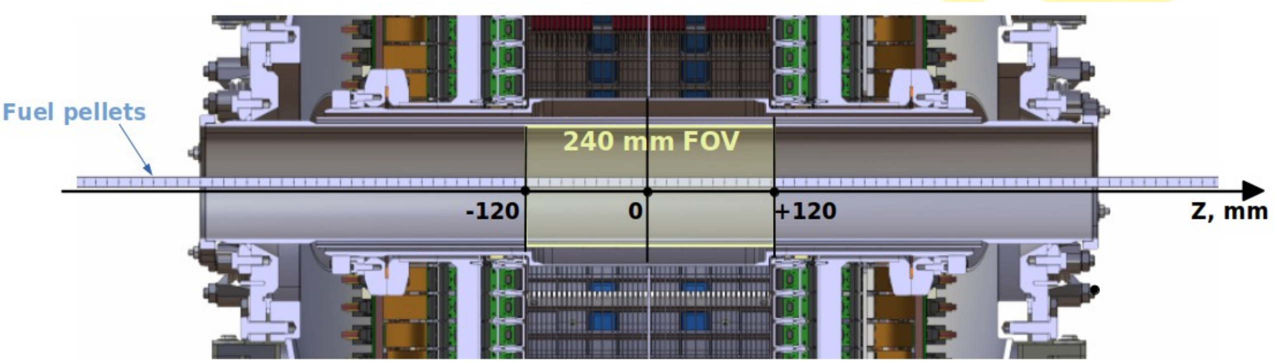
## Specificity:

- ***ρ ~ 11 g/cm³***
- *High γ activity*
- *Emission spectrum*
- *Moving in FOV*
- *Control parameters*

## $PuO_2$ isotopes:

| |
|---|
| $^{238}Pu$ |
| $^{239}Pu$ |
| $^{240}Pu$ |
| $^{241}Pu$ |
| $^{242}Pu$ |
| $^{241}Am$ |

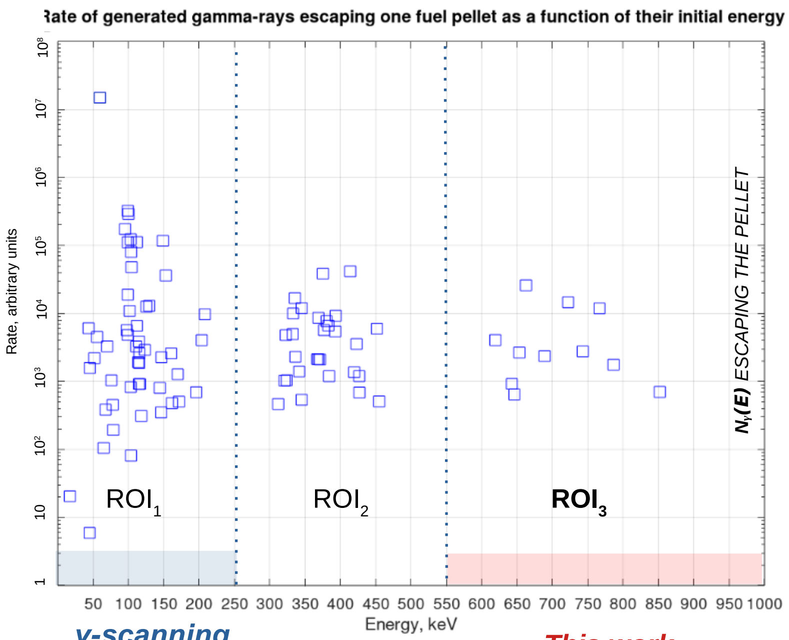
***Fuel pellets moving in XEMIS2 FOV***

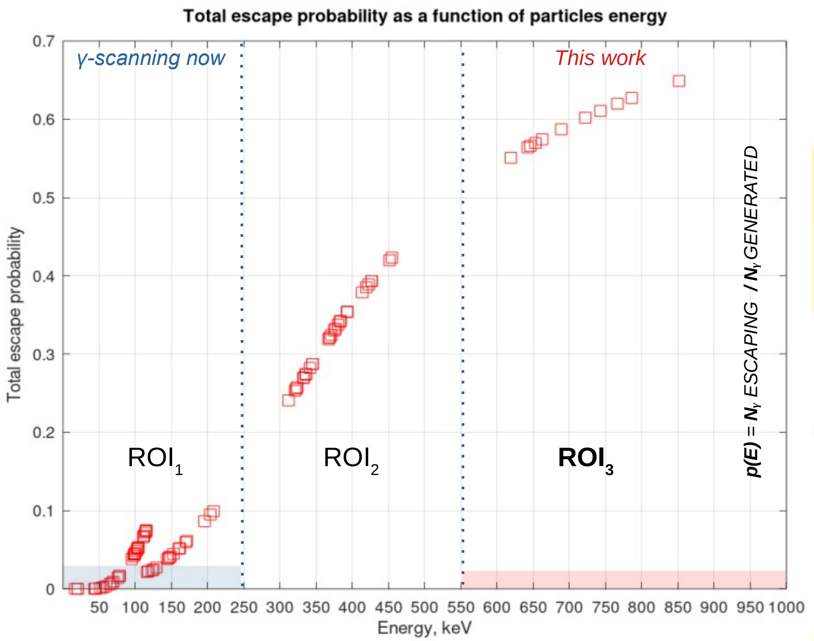



****Example** of alpha-autoradiography results*

# OBJECT TO IMAGE

**MOX** [$UO_2$+$PuO_2$ pellets]




***γ-scanning now***

***This work***

+ Noise study done: γ of $UO_2$ can be neglected

+ Noise study to be finalized: neutrons from $^{238}Pu$

## Systematic bias ~ absorption:

Strong :
$ROI_1$ [$E_\gamma$ < 250 keV]
Moderate :
$ROI_2$ [250 keV < E < 550 keV]
Small :
**$ROI_3$** [$E_\gamma$ > 550 keV]

## Challenge:

*Statistics & attenuation are opposite!*

# OBJECT TO IMAGE

**MOX** [$UO_2$+$PuO_2$ pellets]

+ Noise study done: γ of $UO_2$ can be neglected

+ Noise study to be finalized: ***n*** from $^{238}Pu$

## Detection threshold:

Impossible : $ROI_1$ + any scenario
Better : $ROI_2$, but strong bias ~ scenarios
Ideal : **$ROI_3$**, but **need good stats**

## Shielding study:

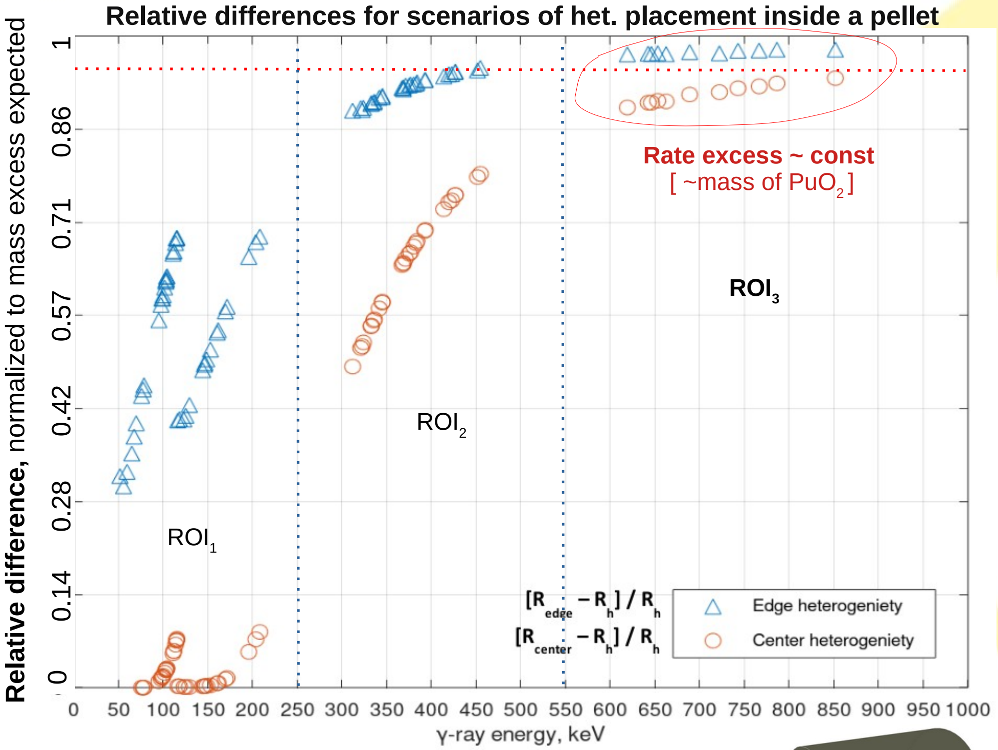
$ROI_1$ + $ROI_2$ γ – removed
with 1mm thick W-cylinder

## Systematic bias ~ absorption:

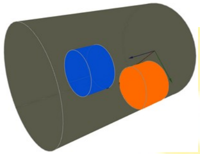
Strong : $ROI_1$ [$E_γ$ < 250 keV]
Moderate : $ROI_2$ [250 keV < $E_γ$ < 550 keV]
Small : $ROI_3$ [$E_γ$ > 550 keV]

## Challenge:

*Statistics & attenuation are opposite!*




**$R_{edge}$** – *rate in LXe – case of "at the **edge**" het. placement*
**$R_{center}$** – *rate in LXe – case of "at the **center**" het. placement*
**$R_h$** – *rate in LXe – case of homogeneous pellet*



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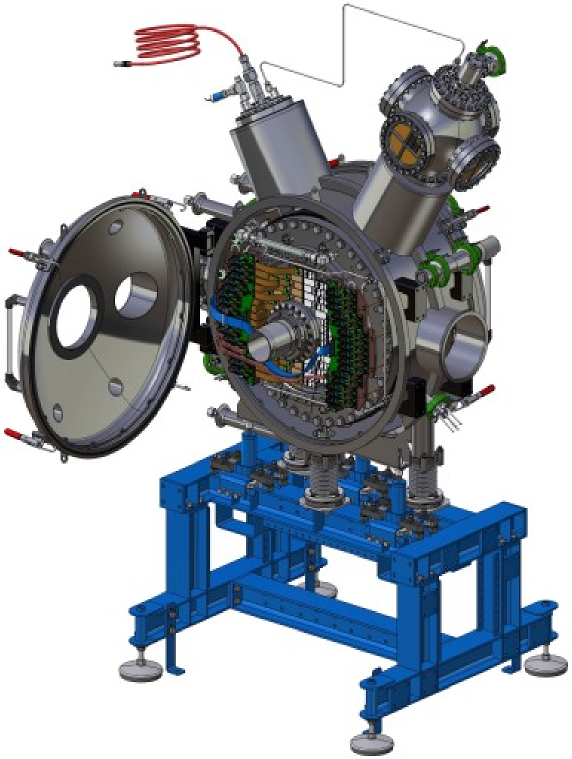

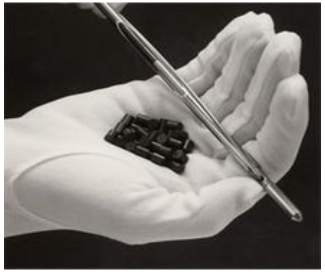

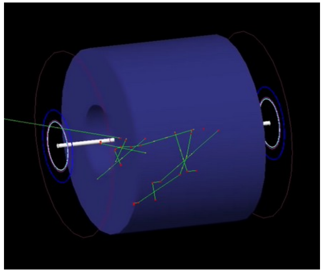

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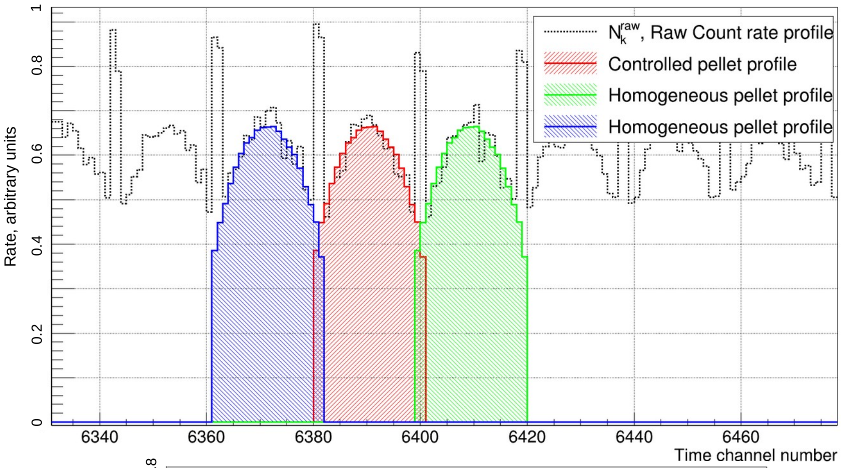
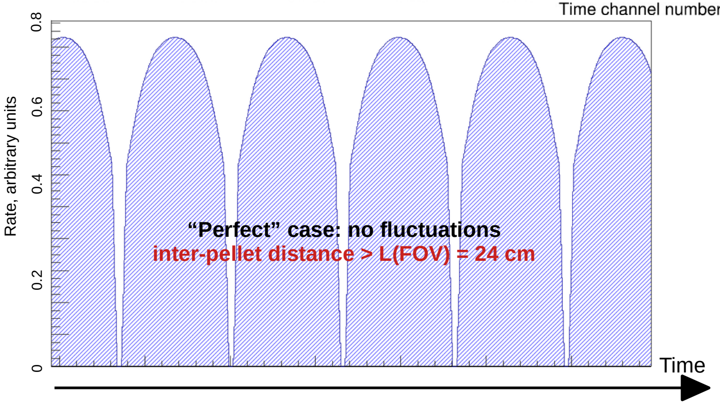
I. Geant4 simulation: source + XEMIS2

II. Methods development

*Count rate profiles from **moving** pellets in FOV*




## Ideas:

- *Find observables*
- *Bias: **fluctuations** from each pellet*
- *Compare with **excess expected***
- *Find **control efficiency***

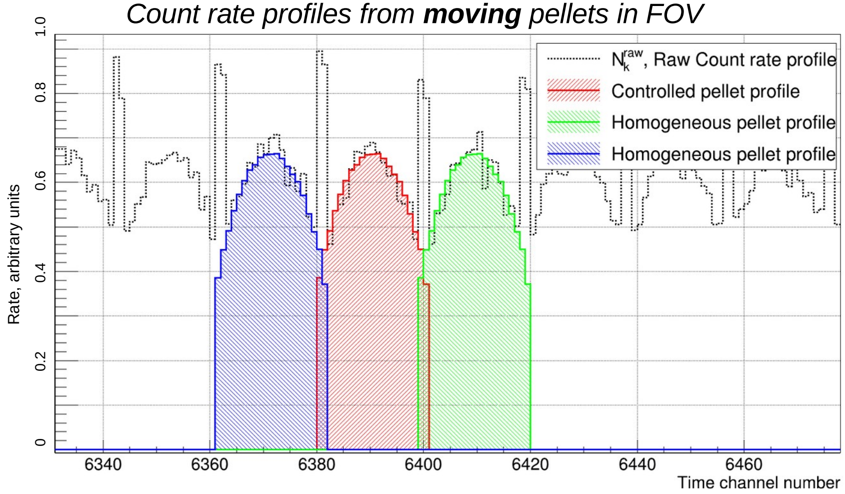
## Specificity:

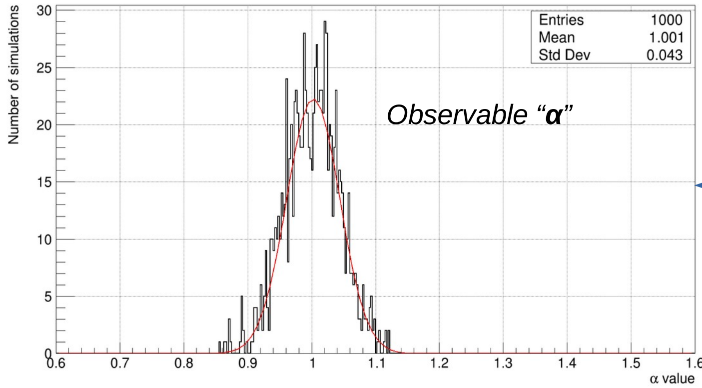
- *Subtract BKG from non-controlled pellets*
- *Study inter-pellet distance*
- ***Is it enough?***

I. Geant4 simulation: source + XEMIS2

II. Methods development

*Count rate profiles from **moving** pellets in FOV*




## Ideas:

- *Find observables*
- *Bias: **fluctuations** from each pellet*
- *Compare with **excess expected***
- *Find **control efficiency***

## Specificity:

- *Subtract BKG from non-controlled pellets*
- *Study inter-pellet distance*
- ***Is it enough?***

## Observable example:

- *1000 simulations of **homogeneous** pellet*
- *inter-pellet distance of **0 mm** (fuel rod)*
- *To compare:*
  ***Uncertainty** vs **excess** expected*

# CONTROL METHODS Scanning & Counting

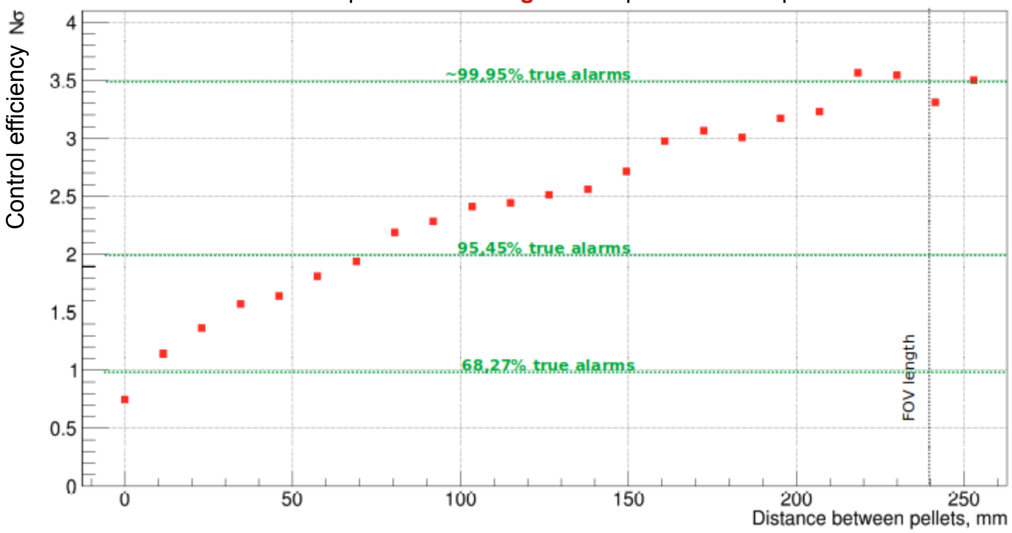
Done:

- *Inter-pellet distance study*
- *Defined true and false alarms*

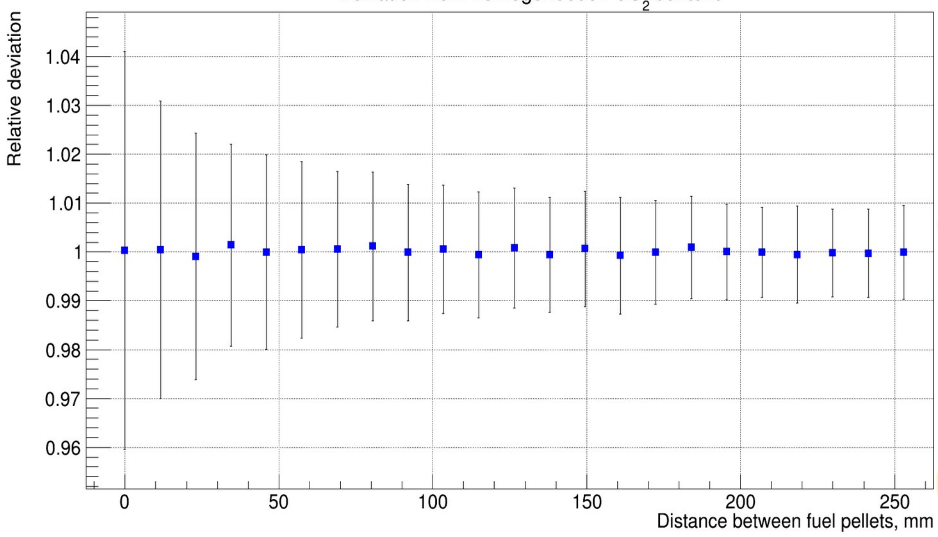
To be defined:

- *Target control efficiency*
- *Suitable for control?*

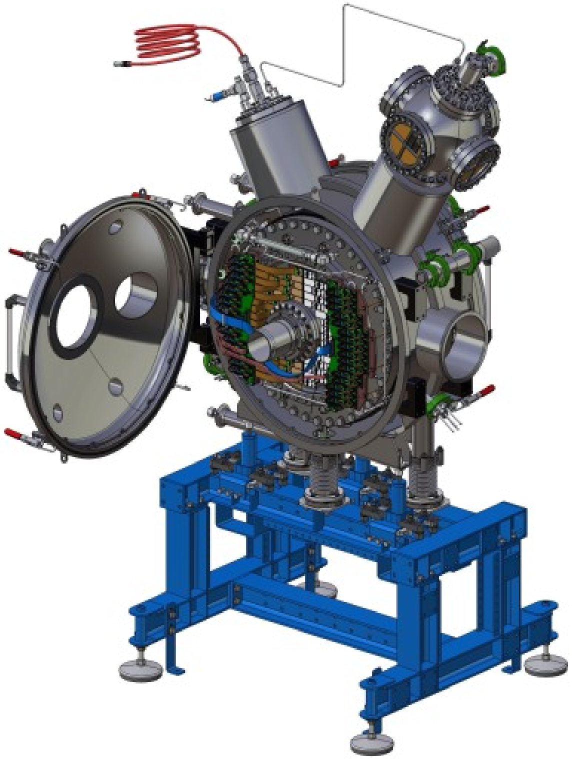
Example: One **heterogeneous** pellet in a sample

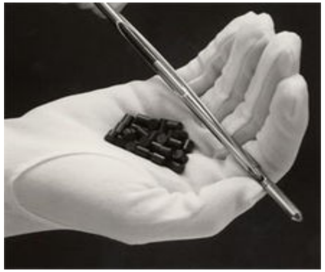


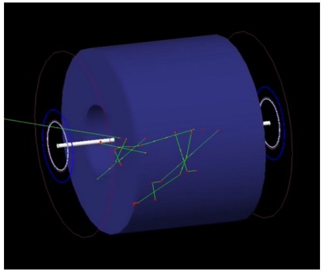

Deviation from homogeneous $PuO_2$ content



# CONTENT







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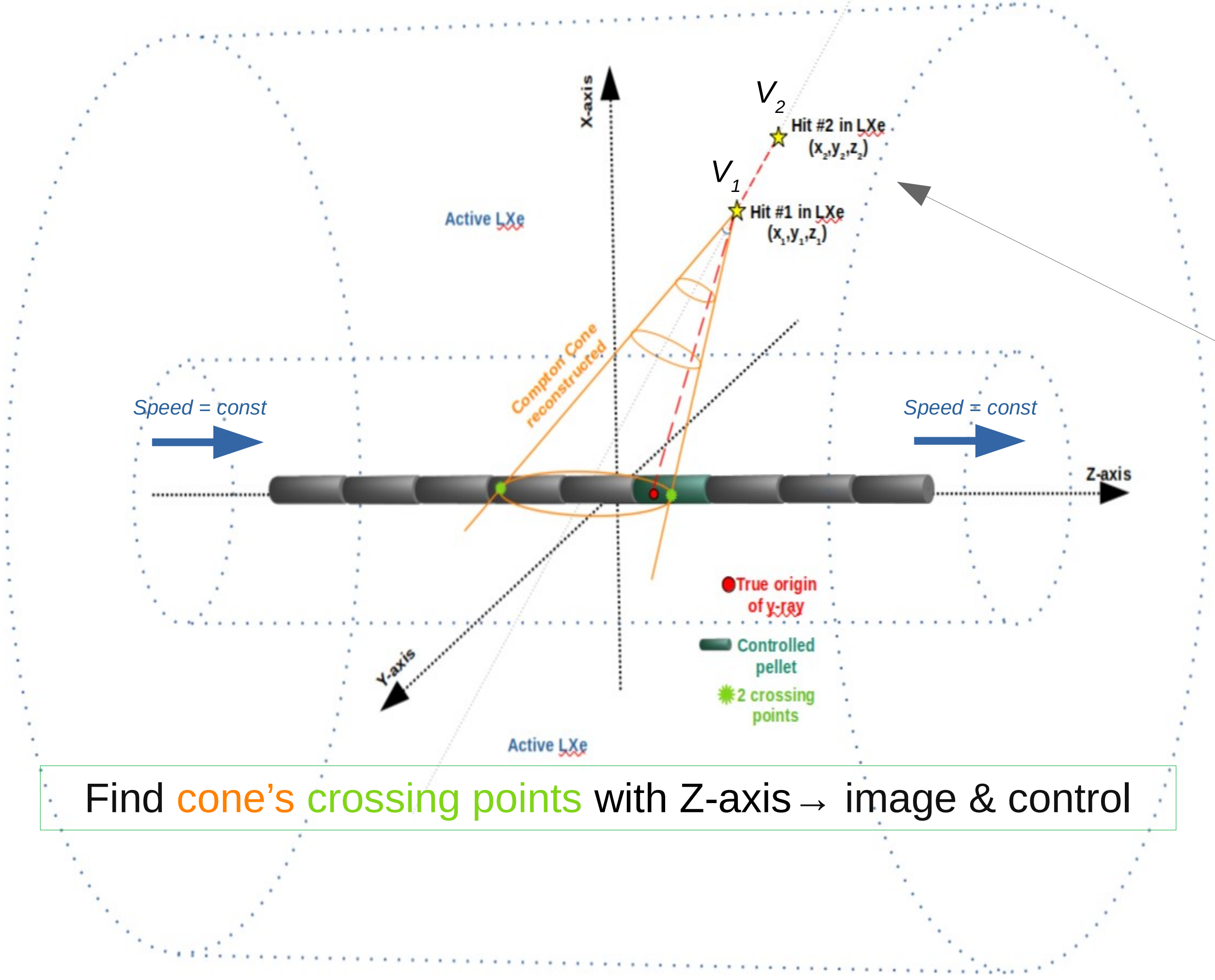
# CONTROL METHODS Compton tracking




Find cone's crossing points with Z-axis → image & control

## Source:

- ***Nuclear fuel pellets***
- *Moving along Z-axis*
- *Spectrum of γ-rays*

## Measure:

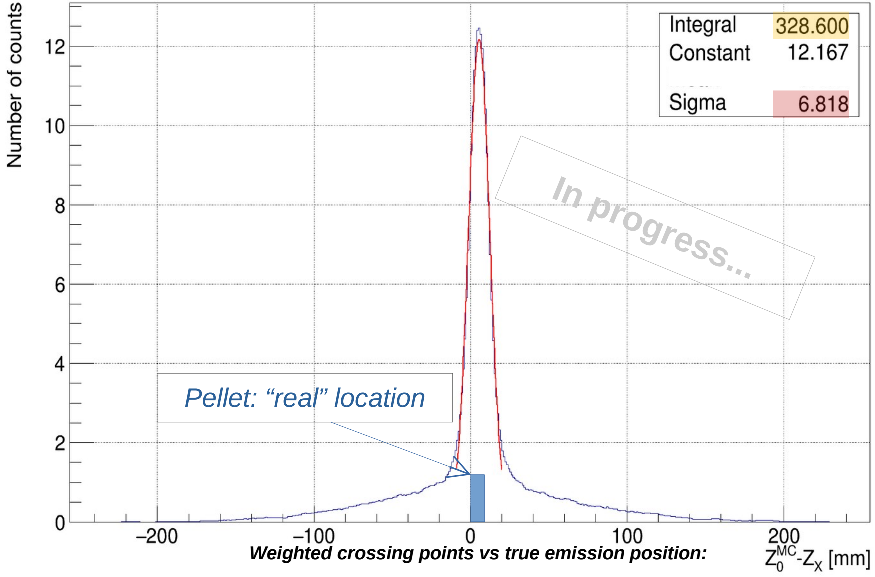
*$V_1$, $V_2$ – hits positions*
*$E_1$, $E_2$ – energy deposited*

## Challenge:

- *Emission spectrum*
- *Control parameters*
- *High activity [total γ]*
- *Low statistics [useful γ]*

First time probe such **source and geometry**!

# CONTROL METHODS  Compton tracking




## Algorithm:

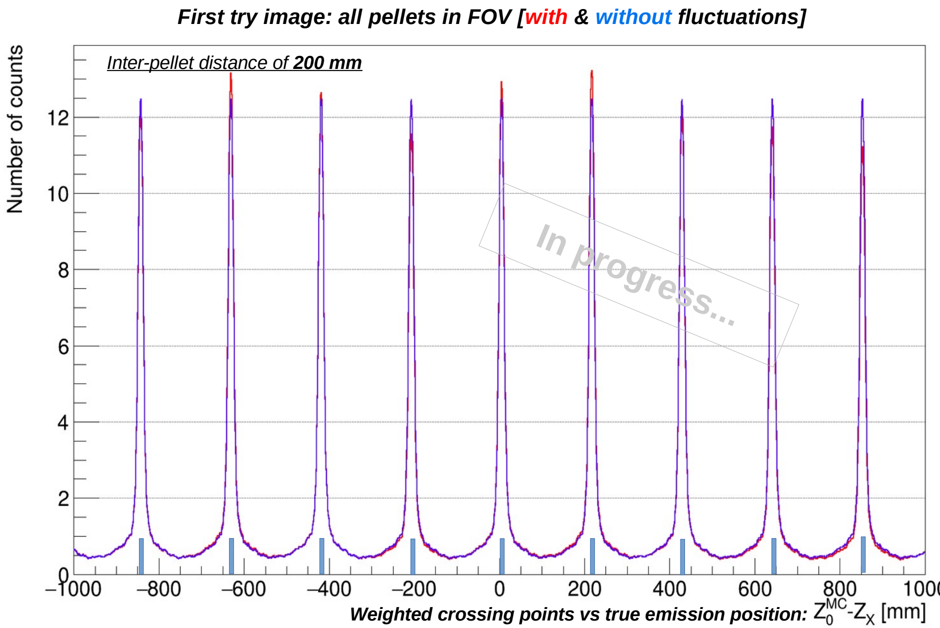
1. Image of controlled pellet
2. Image of all pellets in FOV
3. Detect the expected excess
4. Compare to fluctuations

## Work in progress:

1. Improve events selection & cuts
   *"Integral" → increased step-by-step*
2. Compton Tracking in-depth
3. New topology? [3-hit events, ...]
4. Very **promising** and interesting to industry

Target: spatial resolution ~ pellet size

# CONTROL METHODS
## Compton tracking

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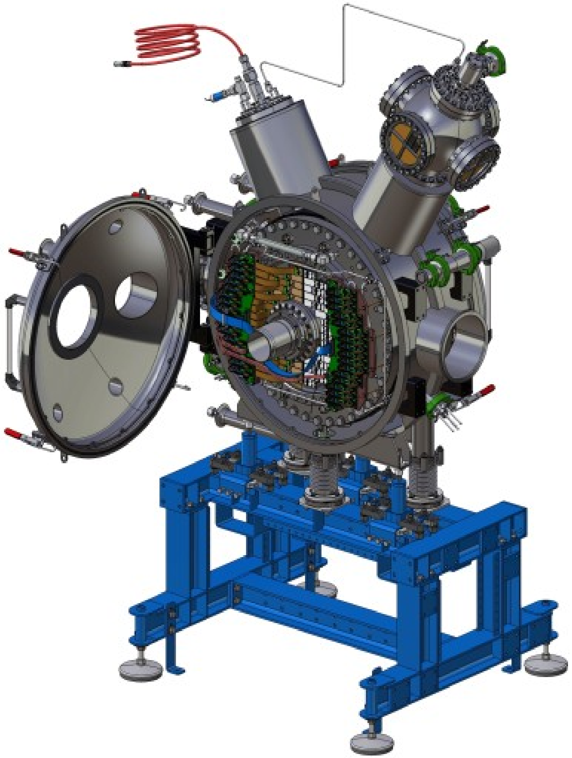
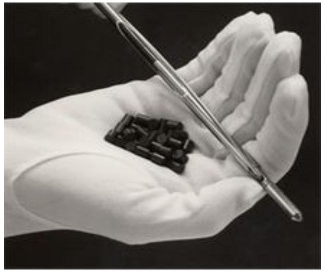
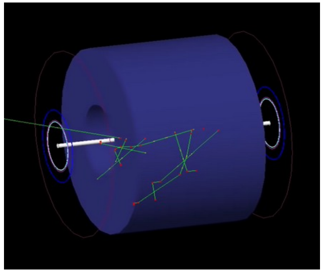
# CONTENT







- XEMIS2 overview
- 3γ-imaging
- Object to image
- Control methods:
  - *Scanning & Counting*
  - *Compton tracking*
- Conclusions

# CONCLUSIONS

- Feasibility not yet established...
- ...work is **in progress** right now!
- Very promising first results
- New application of imaging with LXe

- **Experiment** planned with XEMIS2 during the PhD
- Measure camera response with $^{137}Cs$

- More **background** studies needed
- Step-by-step **improvement**:
  events selection, topology, cuts, etc...
- ...lead to better **resolution** and **control**

*Many thanks to **ORANO** & **Subatech's Xenon group** that make this work possible.*