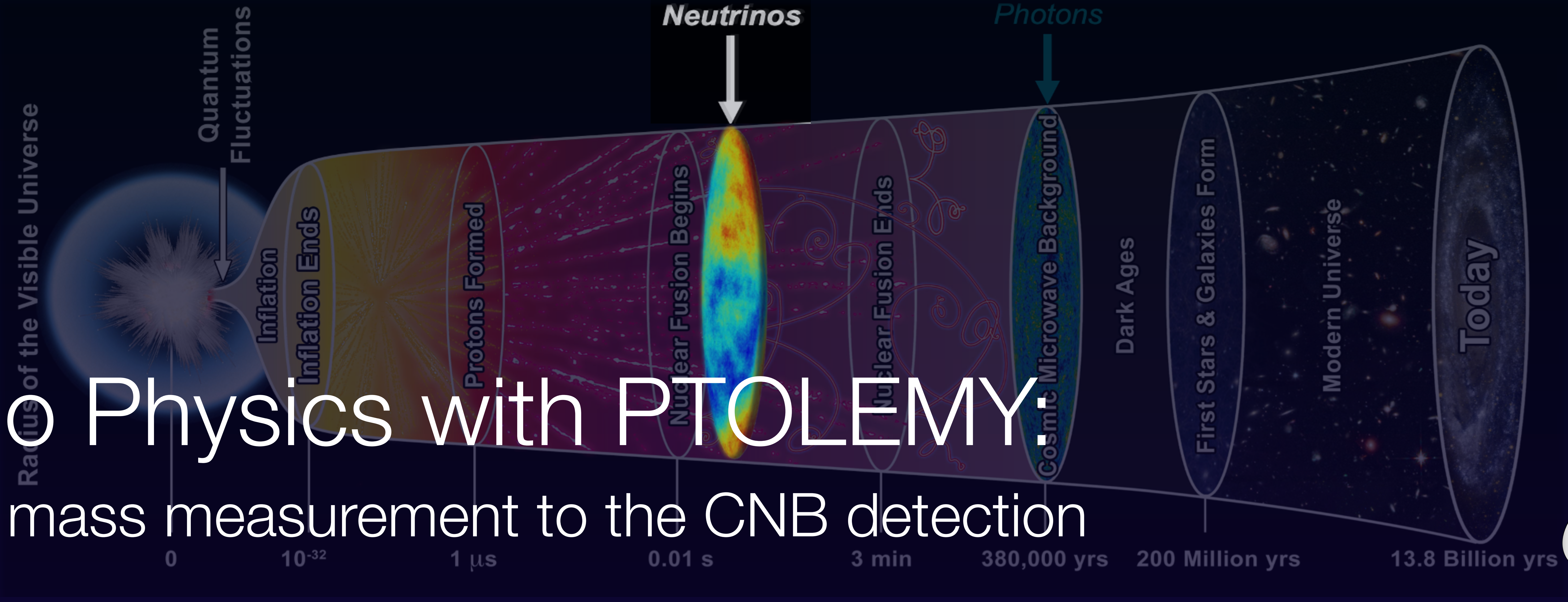
# Neutrino Physics with PTOLEMY:

## From the ν mass measurement to the CNB detection




GRAN SASSO SCIENCE INSTITUTE

INFN LNGS

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Presentation for NuMass 2026 Workshop "Determination of the Absolute Electron (Anti-)Neutrino Mass”
Karlsruhe, Germany, April 14 2026

Francesca Maria Pofi on the behalf of the PTOLEMY collaboration

PTOLEMY

# A Sea of 'Still' Neutrinos

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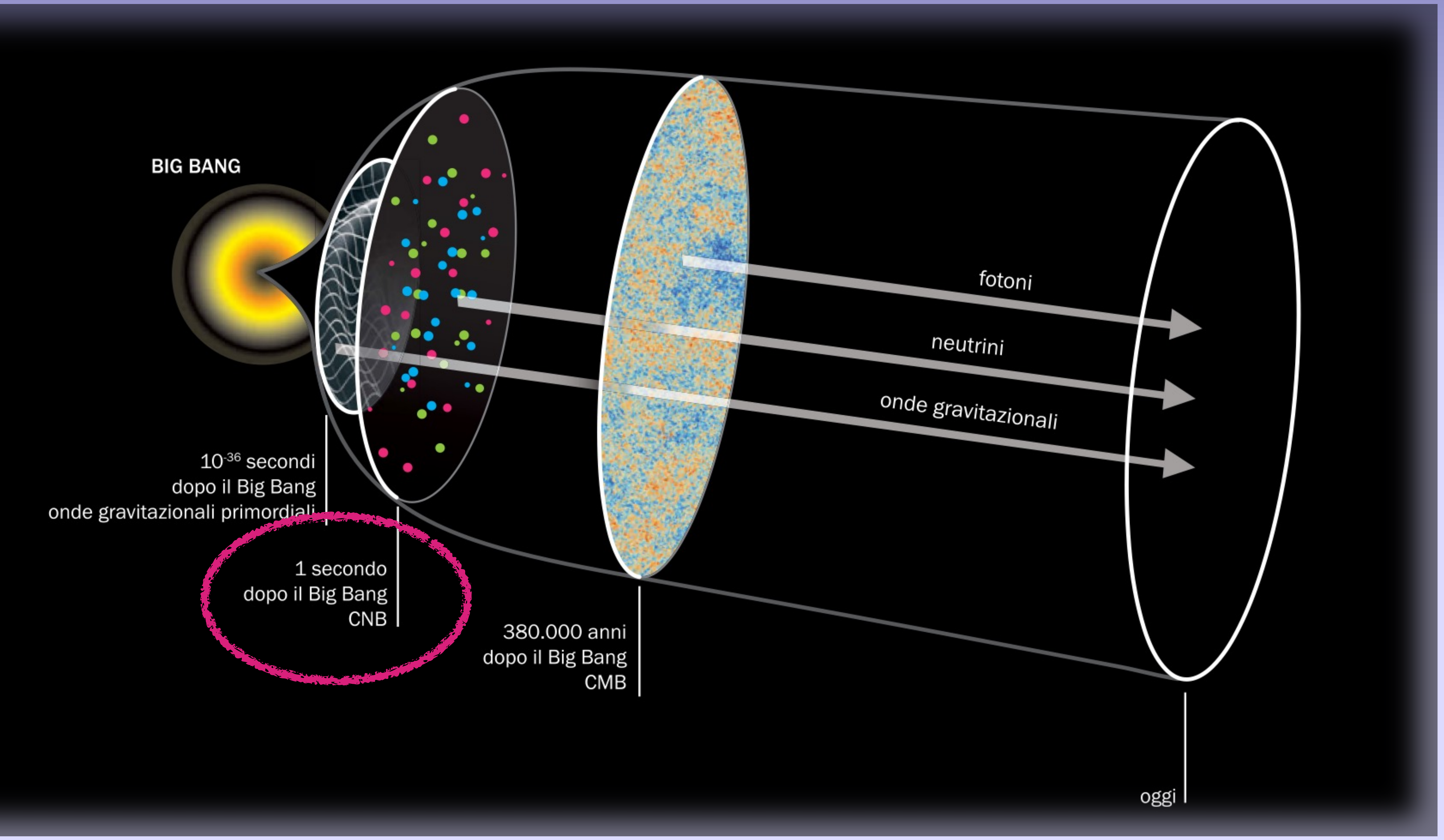
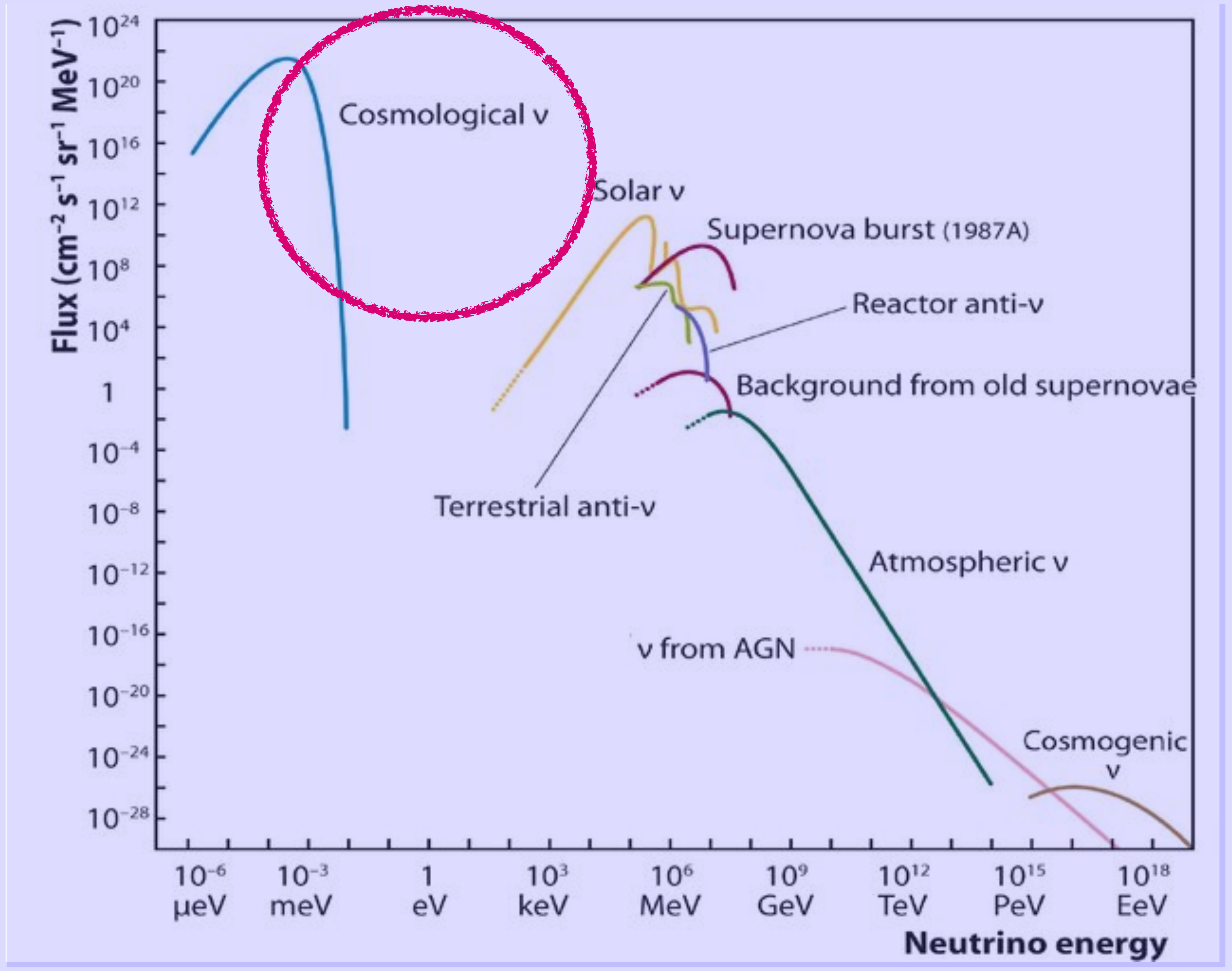



**Cosmic Neutrino Background (CNB)**

**Identikit:**

- Decoupling 1 sec after Big Bang
- Density $n_\nu \simeq 300/cm^3$
- Temperature $T_\nu \simeq 1.95$ K




- Most abundant neutrinos' source
- Extremely low energy $E_\nu \simeq 10^{-4}$ eV
  - ➡ Challenging detection: non-threshold reaction needed

# Two Measurements with One Observable

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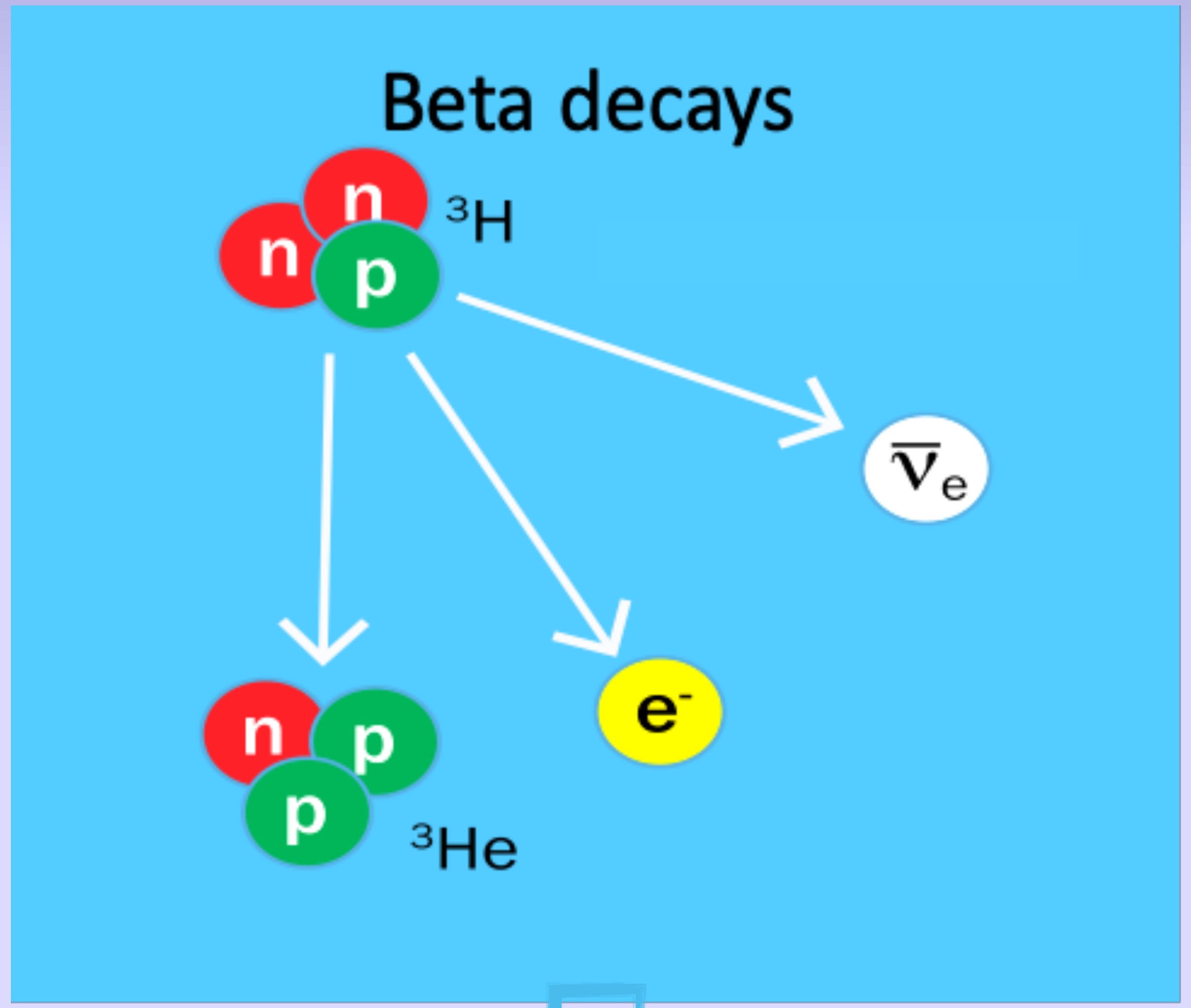
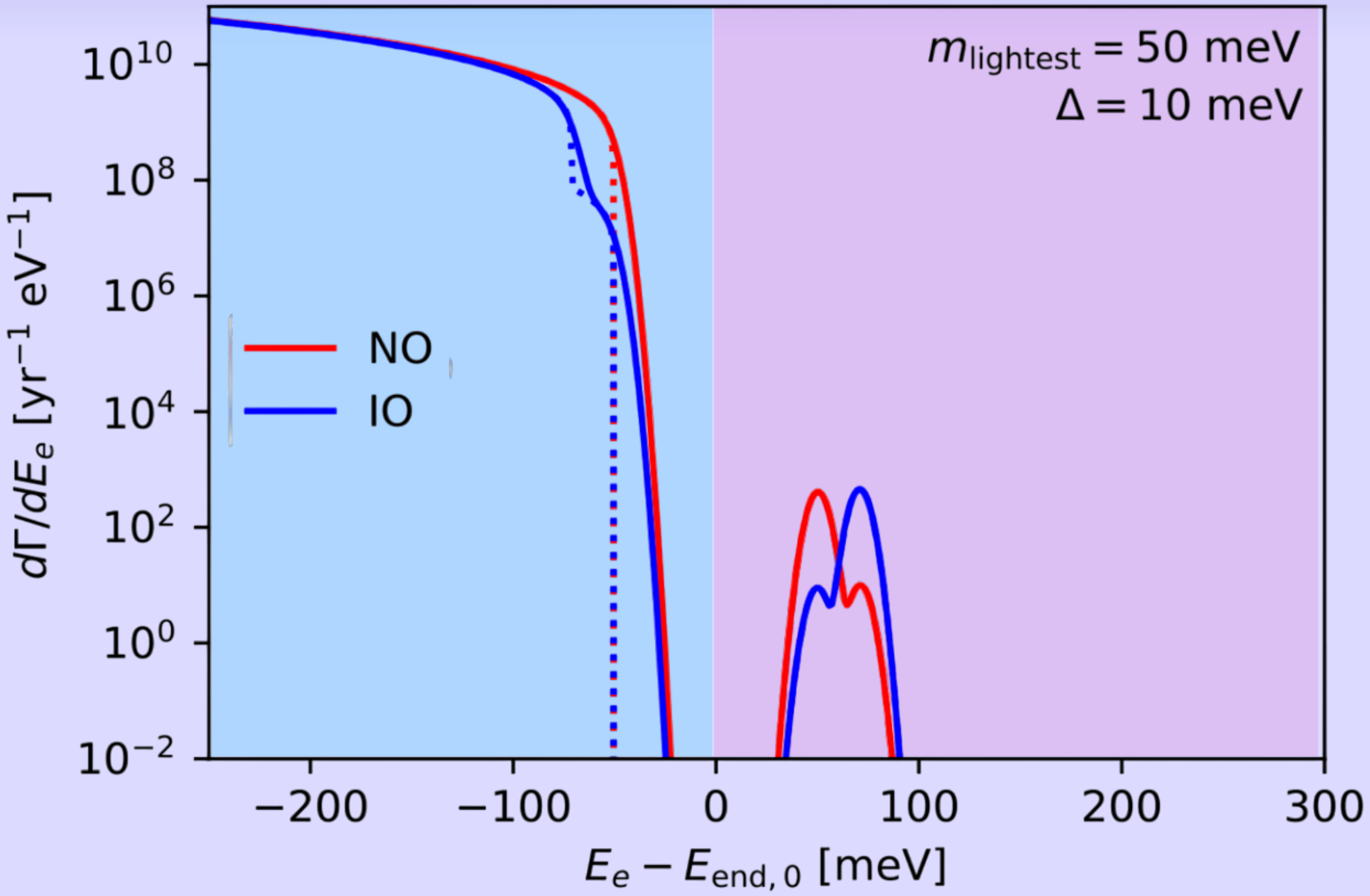
☑ Let's take a $\beta$-unstable nucleus eg Tritium ($^3H$) ⟶ What can we obtain *for free*?

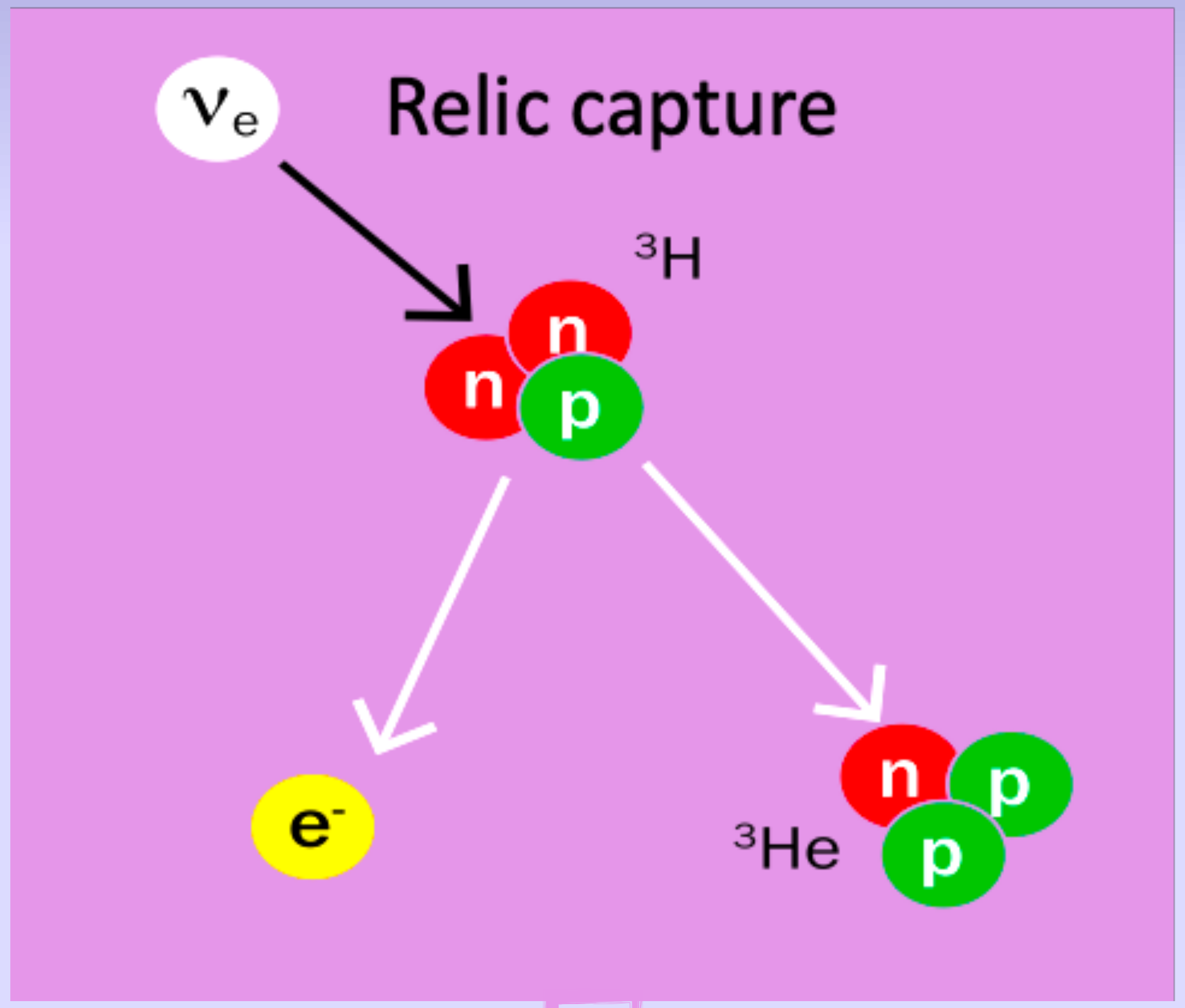



Neutrino Mass Measurement
from endpoint distortion

*(1st goal)*

IDEAL ATOMIC T CASE




First
Relic Neutrinos Detection

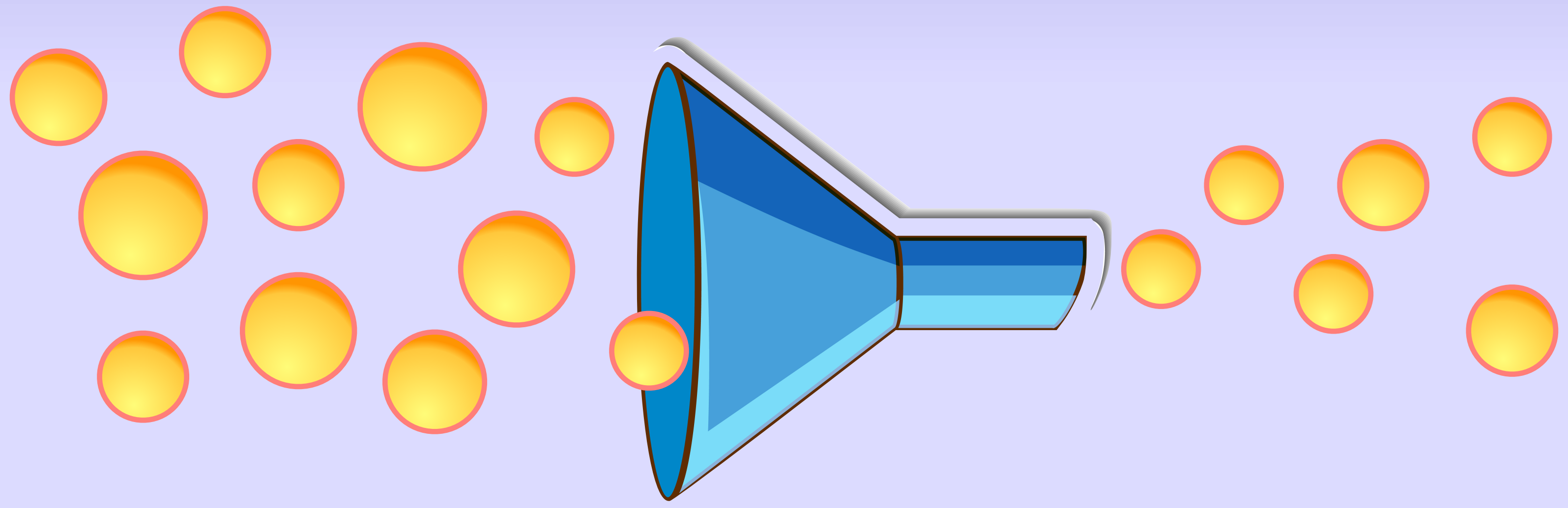
*(Final goal)*

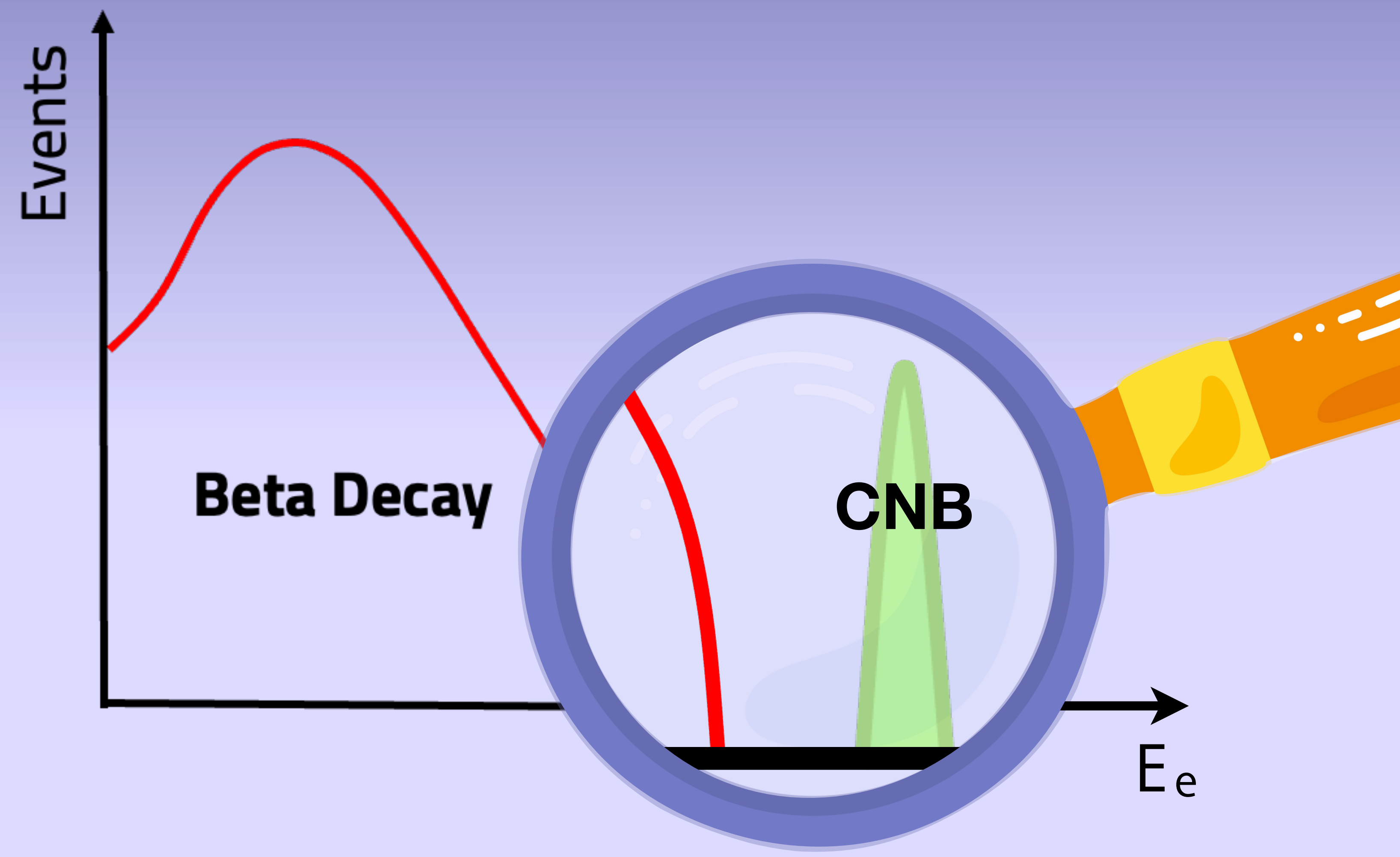
*A.G. Cocco, G. Mangano, M. Messina, JCAP 06 (2007) 015*

# PTOLEMY Ingredients

PTOLEMY

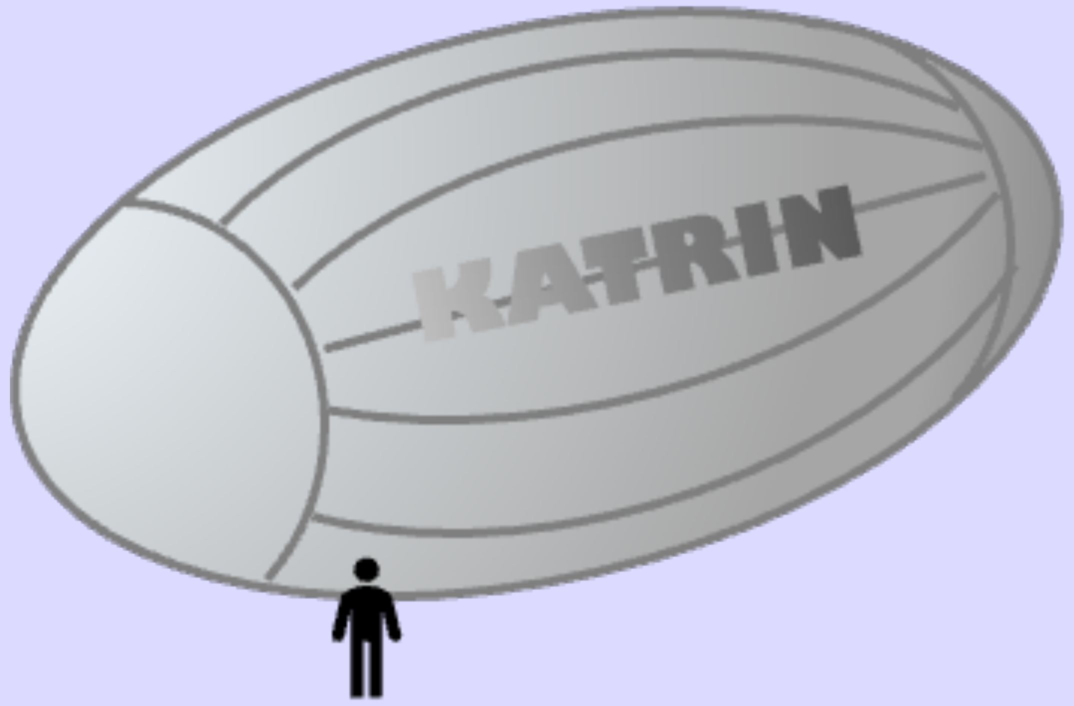
- ☑ Extremely accurate measurement of electron energy
  - $\mathcal{O}$(50 meV) resolution
  - ☑ Electron trigger + filtering



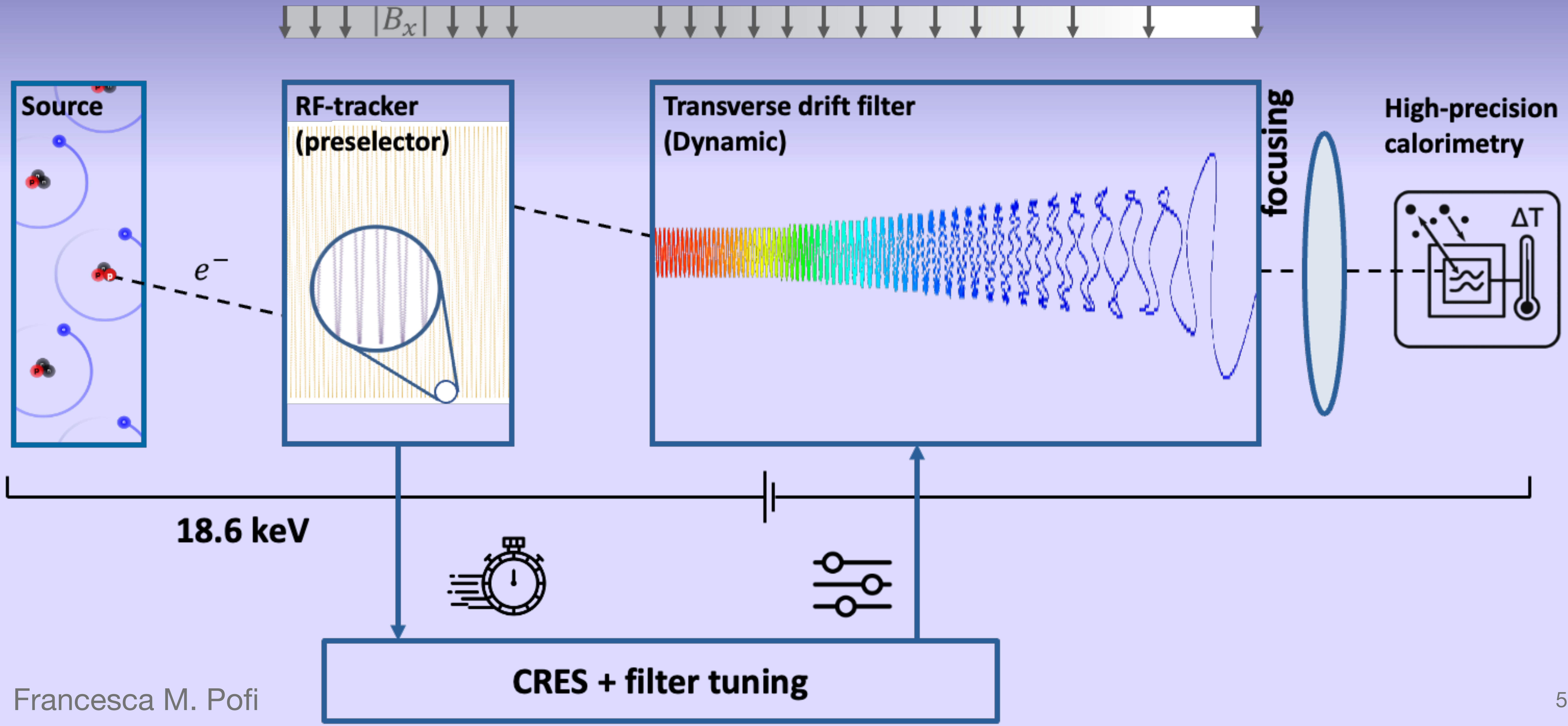



  - ☑ Electron slowdown


- ☑ Large target mass (very low cross section for ν capture)



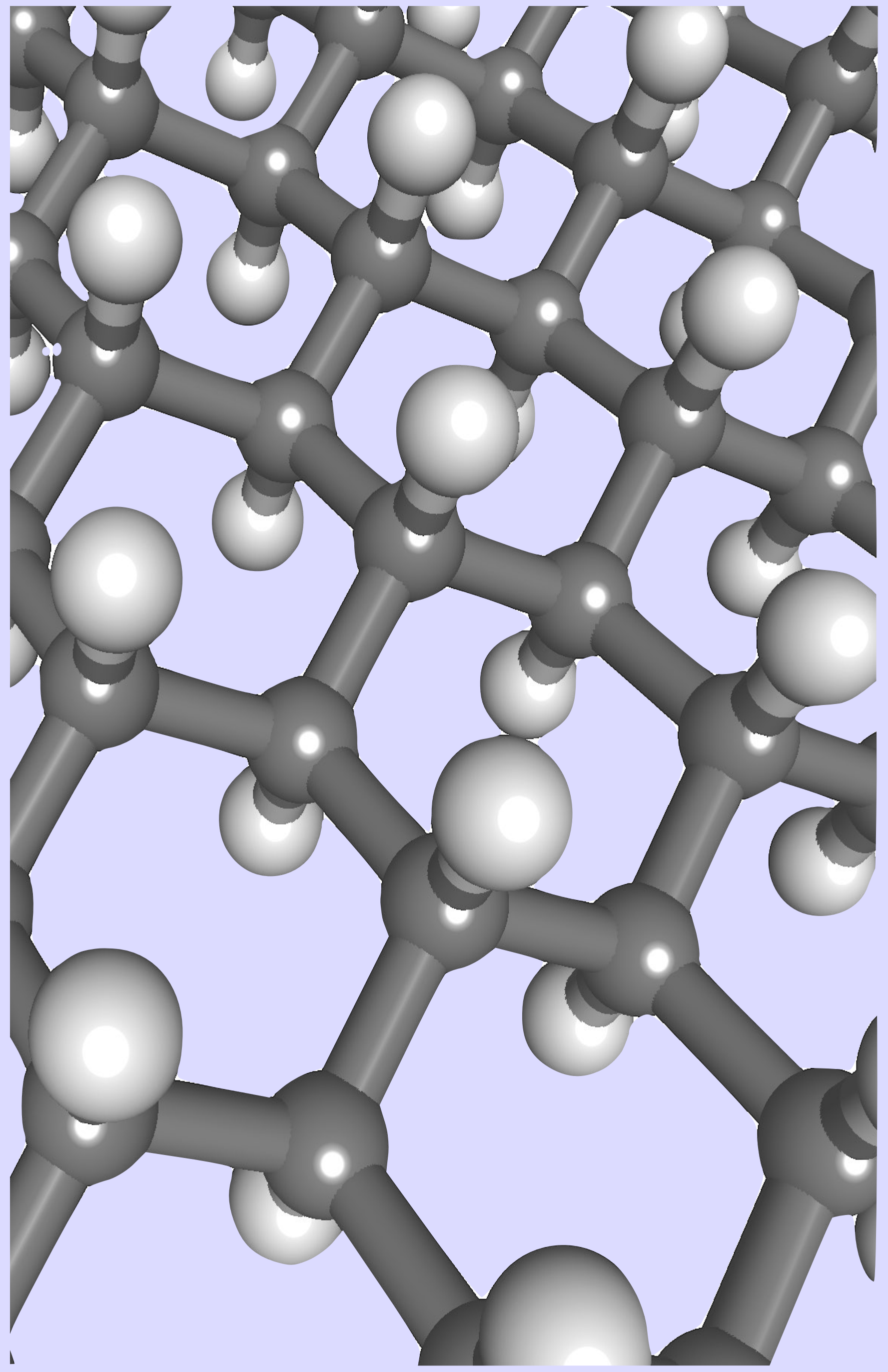
# A Multi-Disciplinary Detector



# Compact Atomic Tritium

**REQUIREMENTS:**

☑ Minimize $\beta$ electrons - target interactions ⟷ electron energy conserved



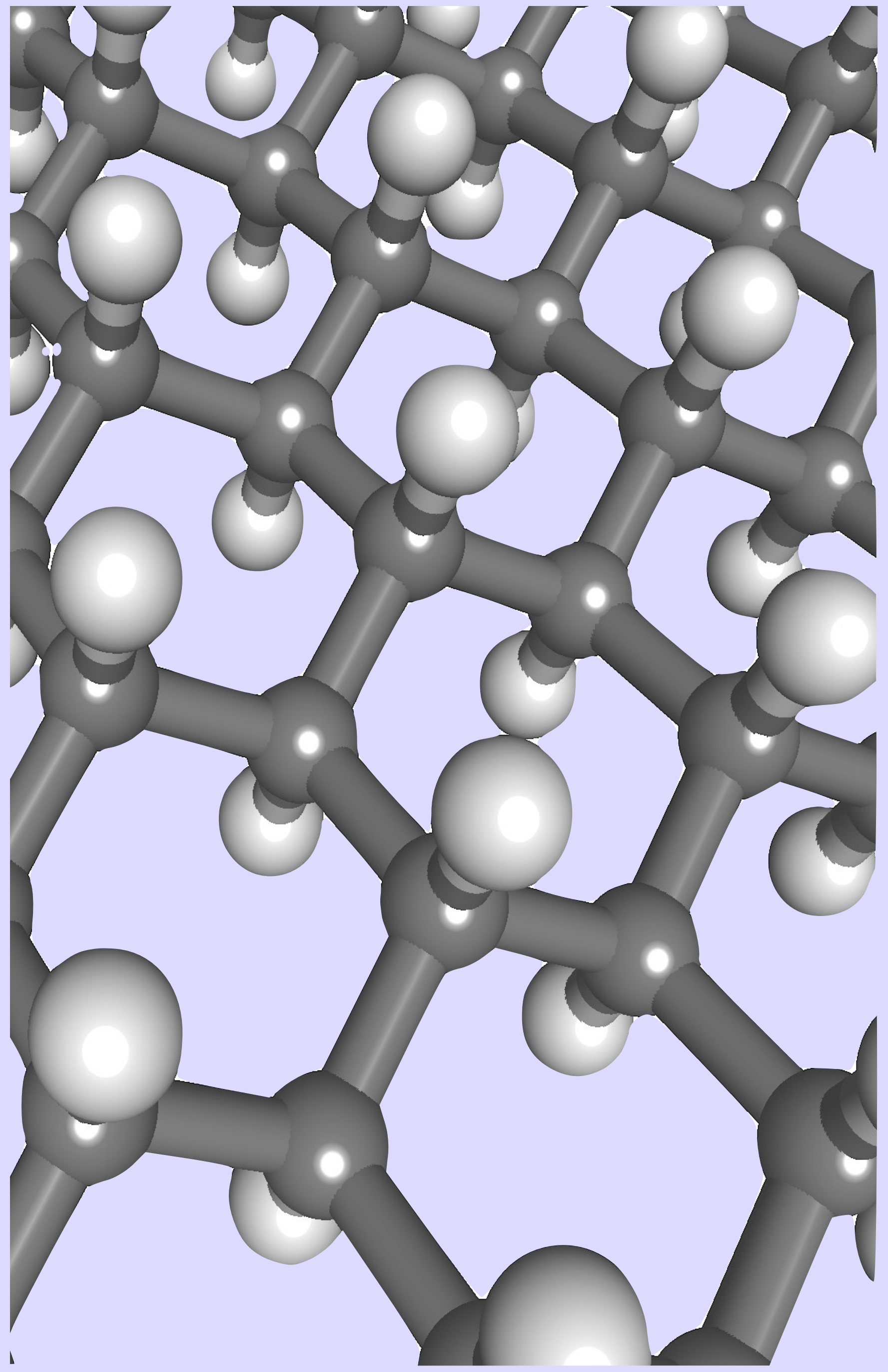
☑ Compact ⟷ possibility to store big quantities

☑ Stable ⟷ no tritium released into environment

⇩

**SOLUTION:**

*Atomic tritium chemically bound on* ***graphene sheets***



# Towards Tritiated Graphene

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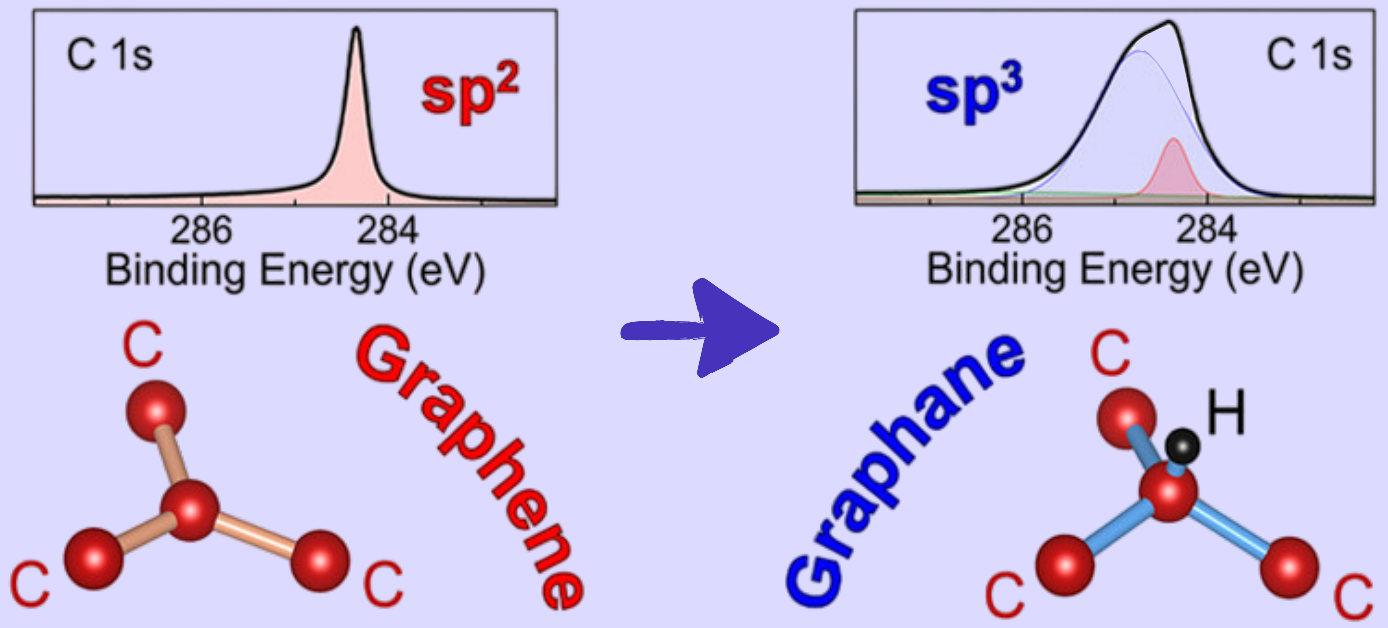
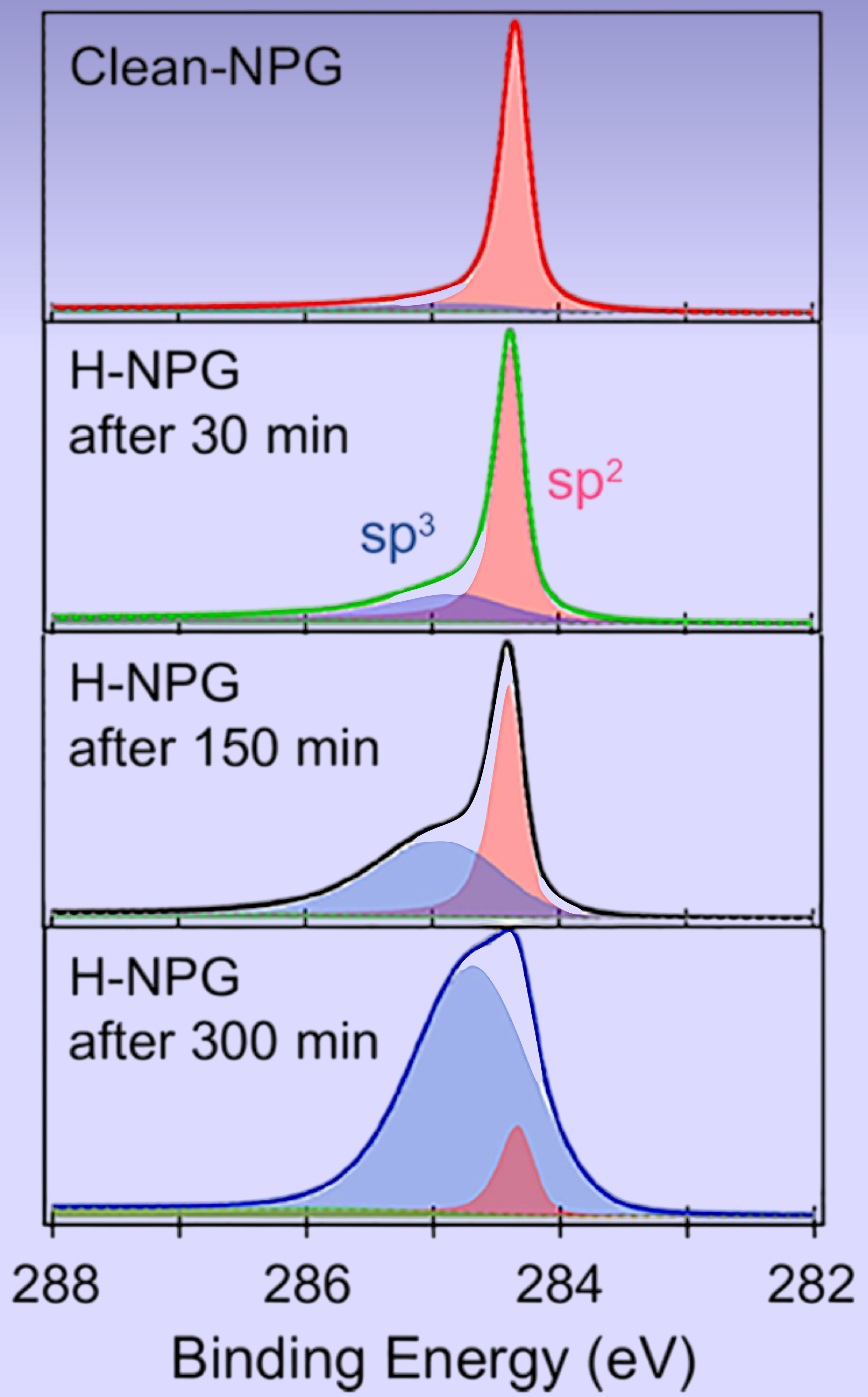
☆ 90% H loading reached on nanoporous graphene (near 1 H for each C)

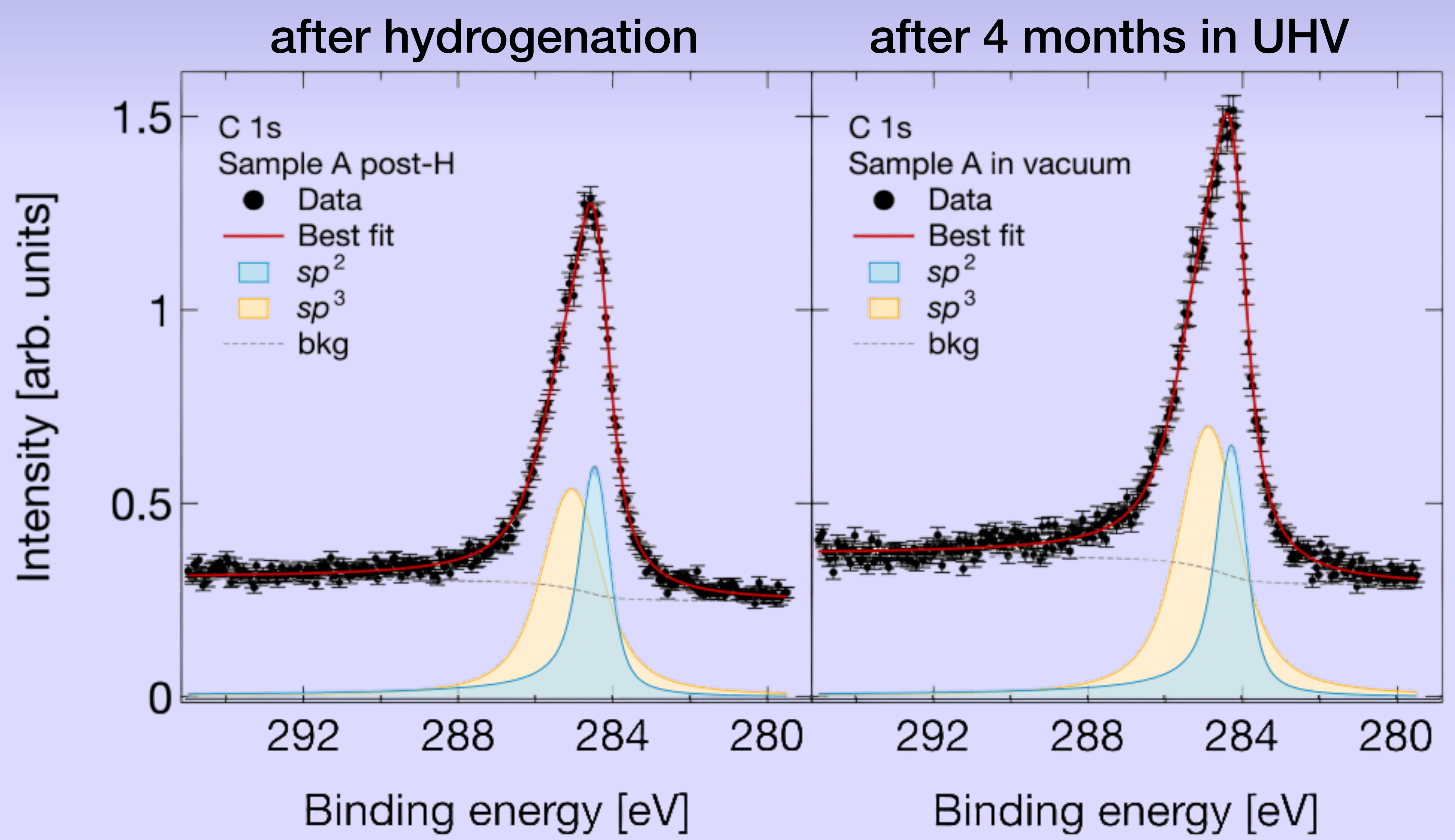
*M.G. Betti et al., Nano Letters 22 (2022) 2971*




☆ H-stability proven in UHV over several months

*A. Apponi et al., Applied Surface Science 723 (2026) 165658*




☆ 80% transmission for 900 eV electrons

*A. Apponi et al., Carbon 216 (2024) 118502*

higher energy studies ongoing!

*More details from A. Apponi this afternoon!*

# Consequences of having a Substrate

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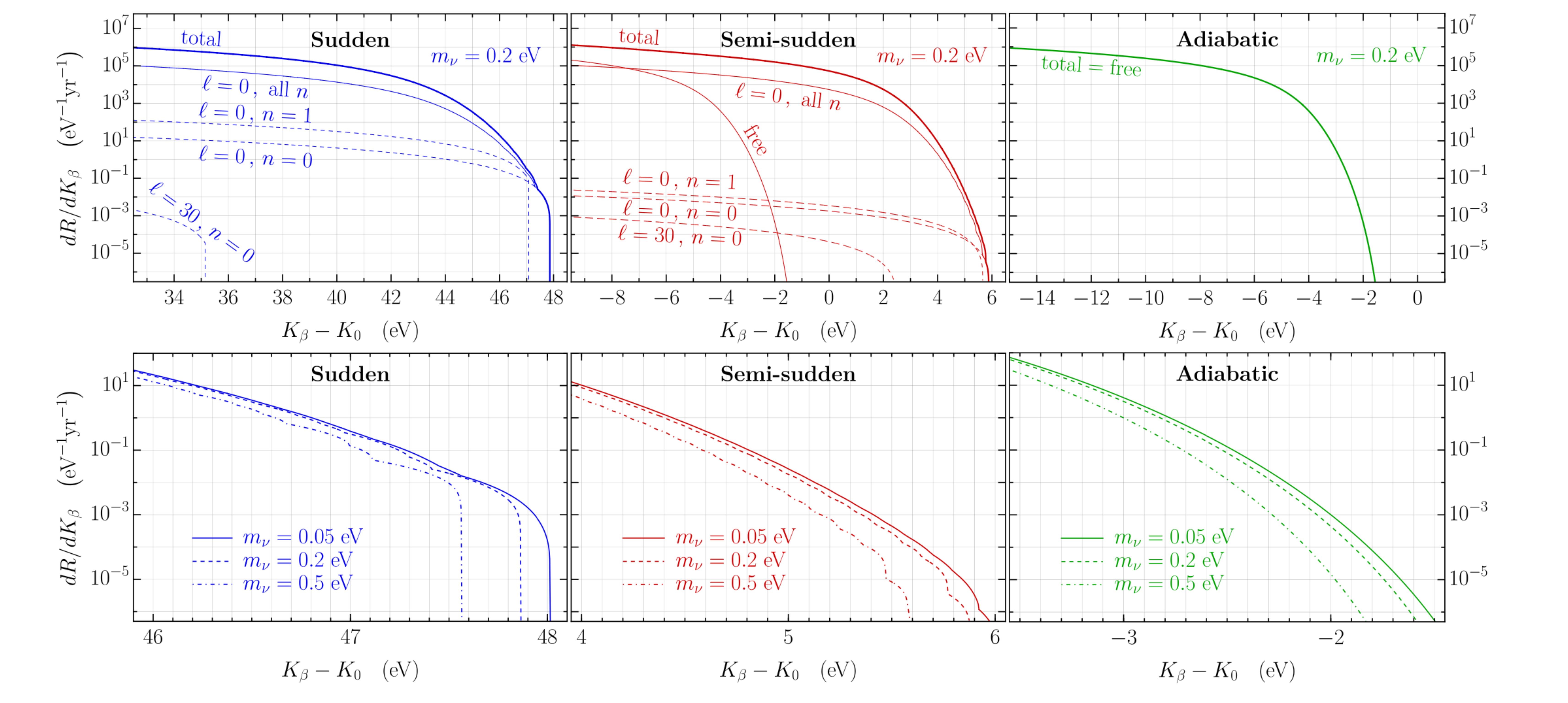
In-depth studies about spectrum theoretical predictions:

- ✳Combined nuclear quantum mechanics & DFT to model β-decay of tritium loaded on graphene
- ✳Quantification of effects due to C-$^3$H vibrations (more to come!)

*More details from A. Esposito this afternoon!*




A. Casale et al., Phys. Rev. C (2026)

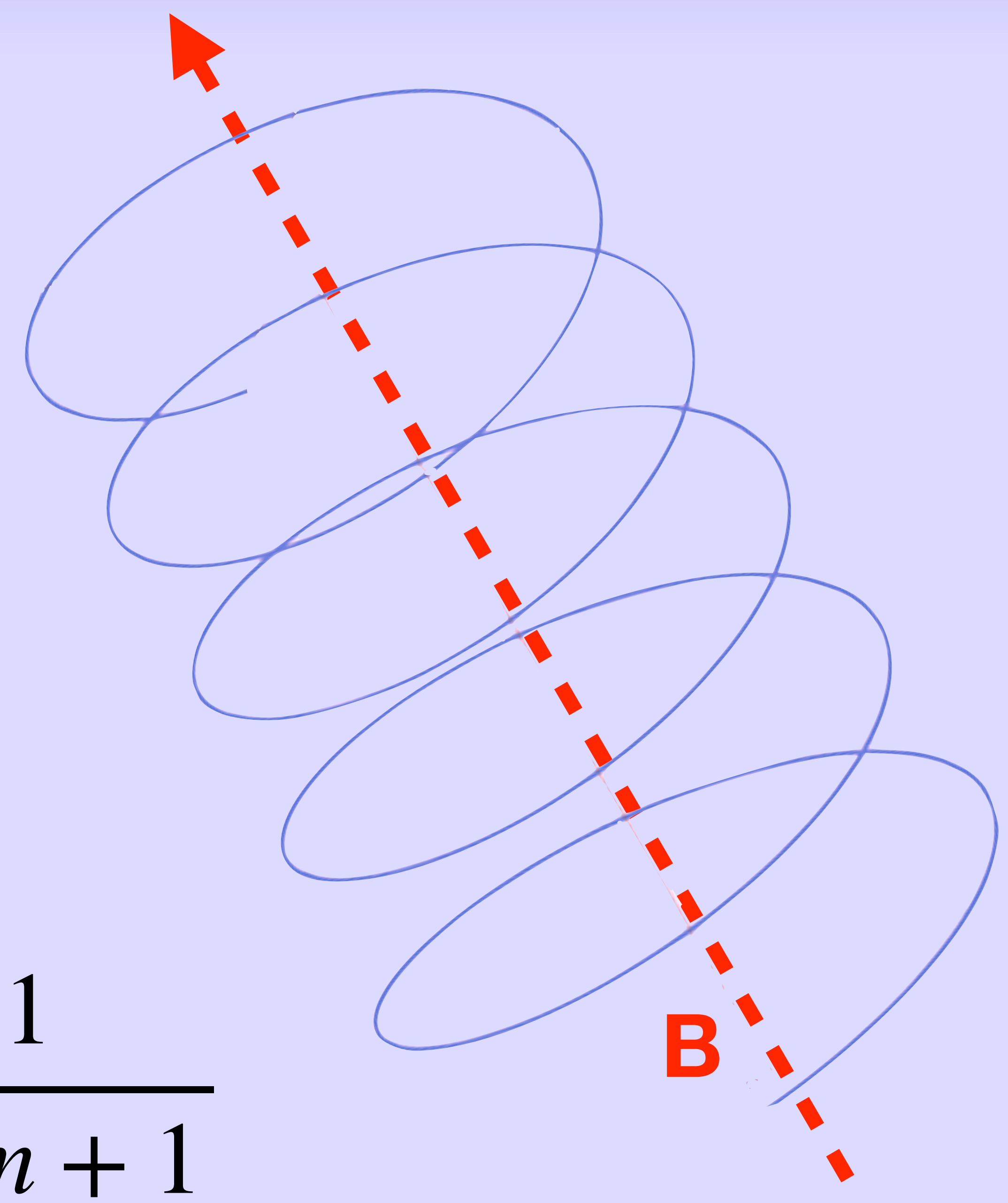
# Trigger with Non-Destructive Energy Measurement

**Aim:** filter trigger <--> determine if $\beta$ electron energy is near to $^3$H decay endpoint

- Fast: $\mathcal{O}$(100 μs)
- Raw measurement: $\mathcal{O}$(10 eV) resolution
- **Non-destructive**: initial electron energy not modified

**How?** *Cyclotron radiation spectroscopy - CRES ( thanks Project8! )*

uniform B field → cyclotron motion → **RF radiation** emission




➢ power $P(\gamma, \theta) = \frac{1}{4\pi\epsilon_0} \frac{2}{3} \frac{|q|^4 B^2}{m^2 c} (\gamma^2 - 1) \sin^2\theta$ ➢ frequency $f_c = \frac{1}{2\pi} \frac{|q| B}{m} \frac{1}{K/m + 1}$

Pitch angle: $\theta$

Electron kinetic energy: $K$

# Exploiting Frequency Modulation

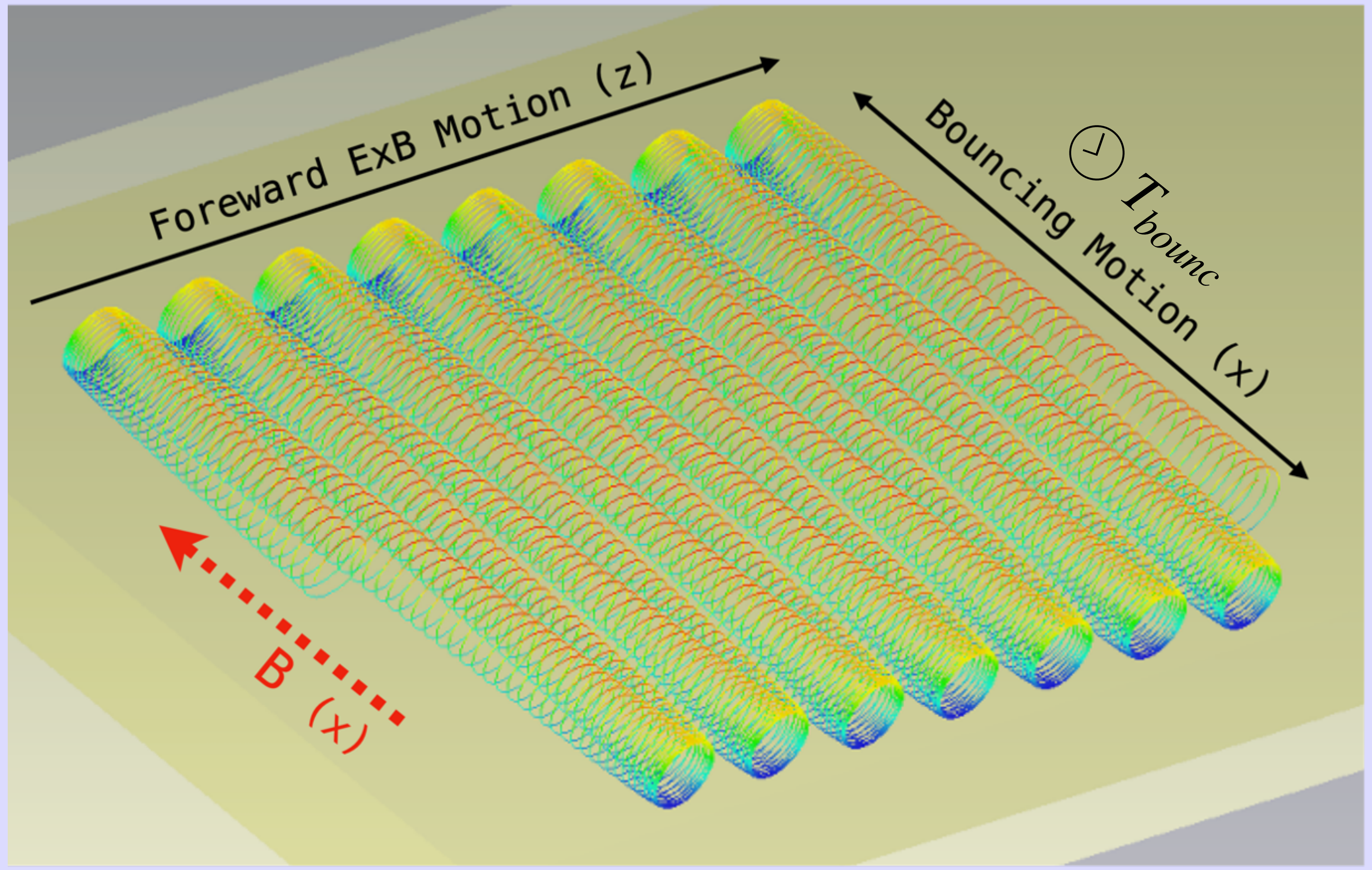
*base*: uniform magnetic field (1 T)

+

*extra*: ➢ bouncing electrodes (longer signal)

➢ uniform electric field (drift)

=

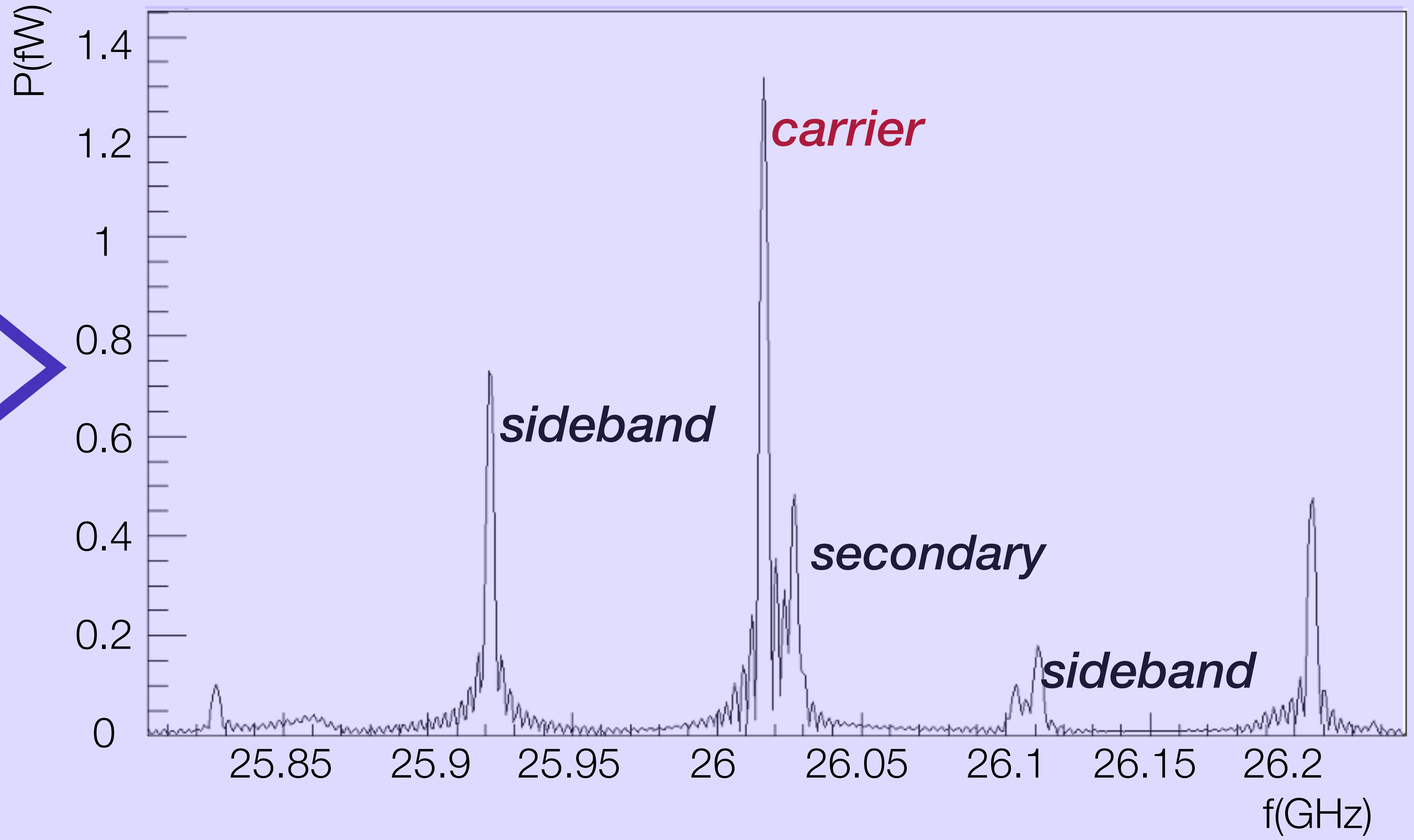



main frequency $f_c$ (carrier)

+

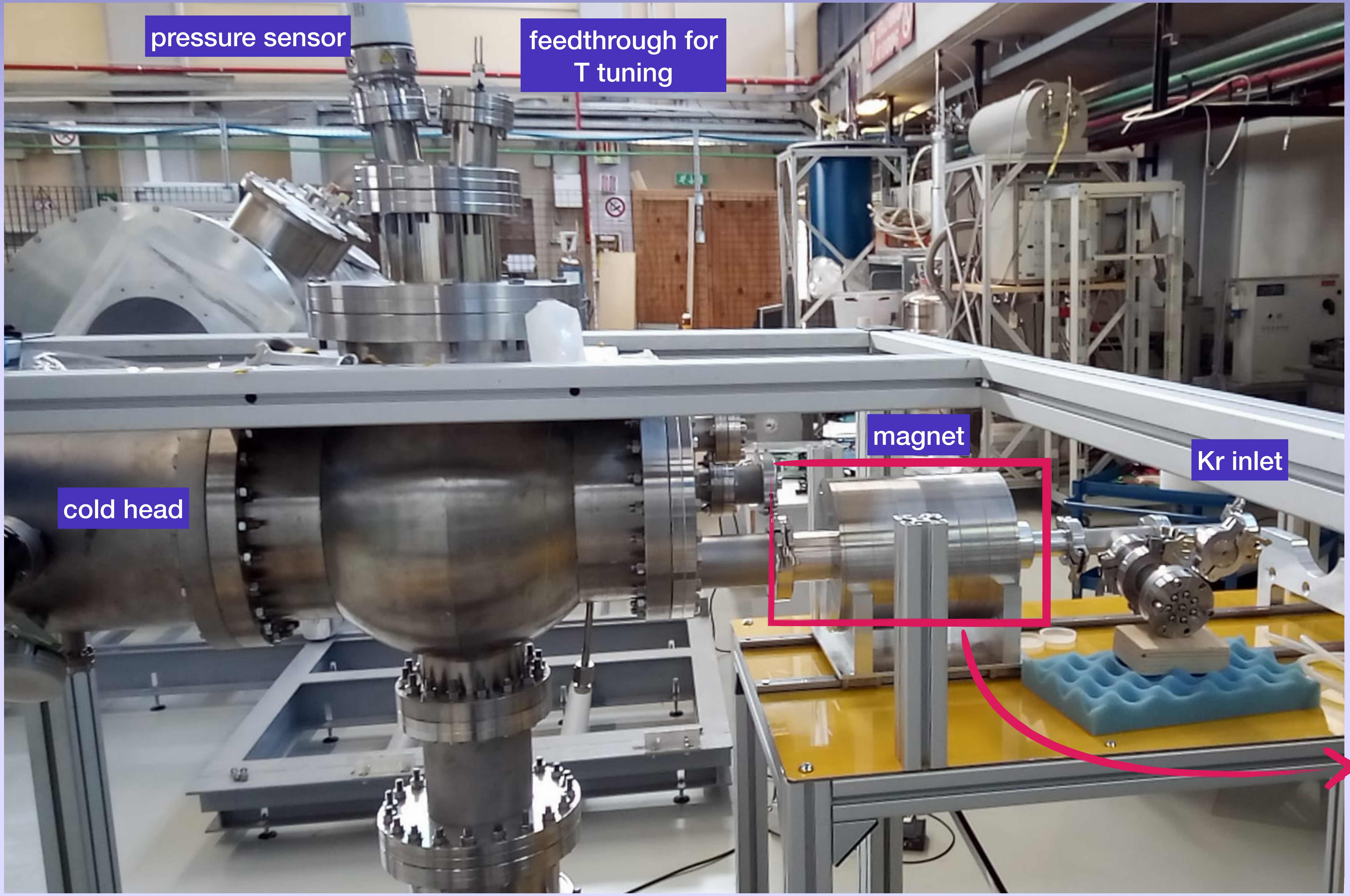
side bands @ $\Delta f = 1/T_{bounc}$ distance

$\theta$ reconstruction from $K_{//}$




***Expected signal:*** $f_c \simeq$ ***27 GHz,*** $P$***=***$\mathcal{O}$***(1 fW)***

# CRES R&D Setup @ LNGS

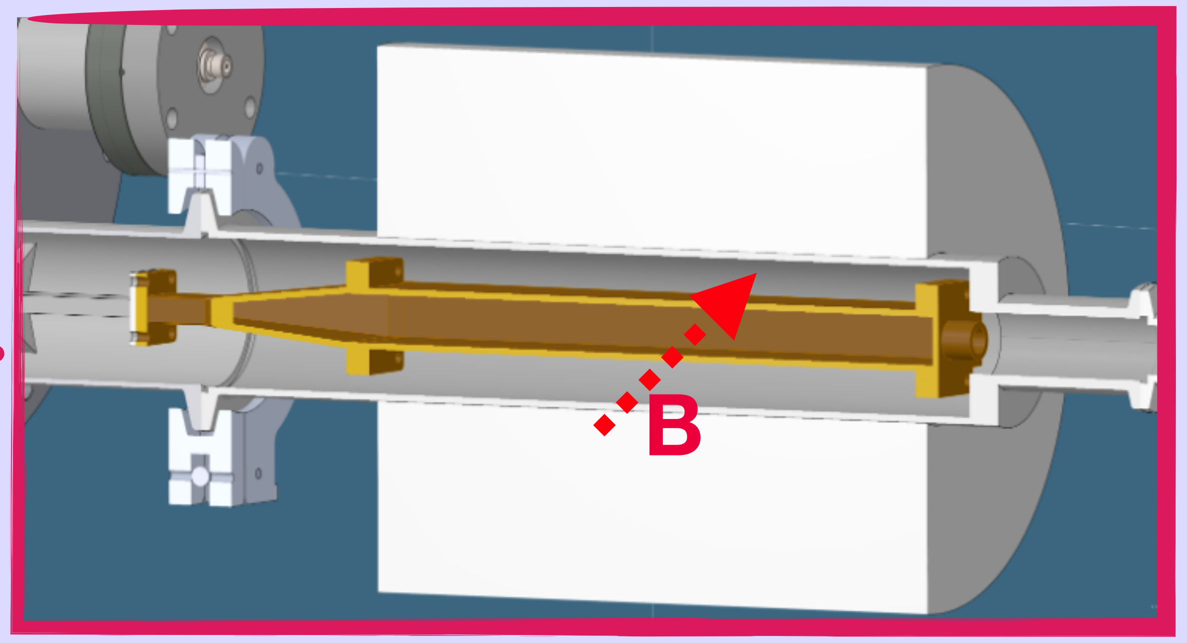



*Electron trap* setup to study RF radiation emission

Electron source: $^{83m}$Kr injection $\longmapsto$ 30.4 keV $e^-$ (L line)

B field: Halbach cylinder permanent magnet (1 T)

*More details from F. Virzi this morning!*

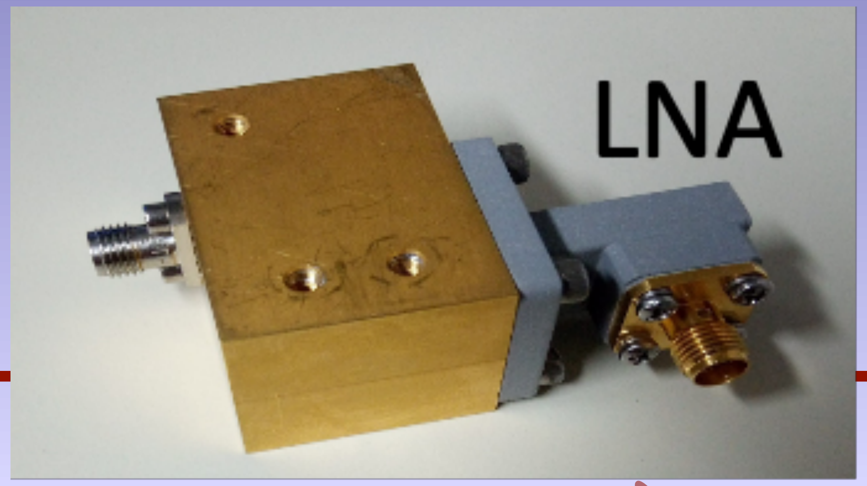


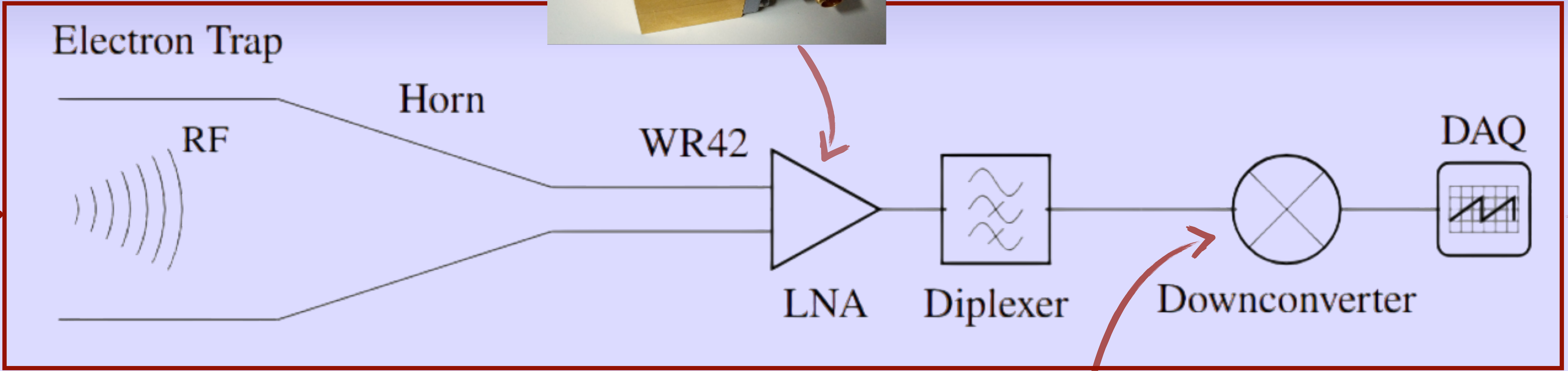
# R&D for RF Detection Chain

INPUT

f = 26 GHz

P = 1fW



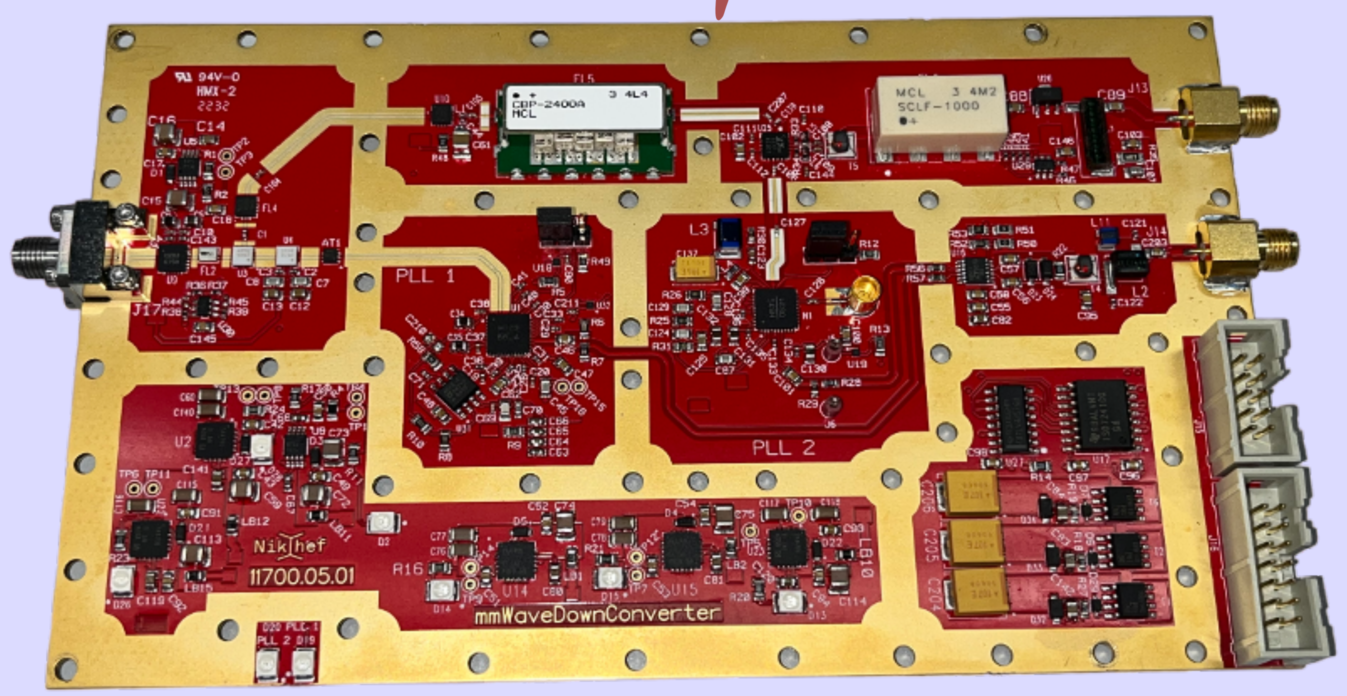




OUTPUT

f = 550 MHz

P = 2 μW

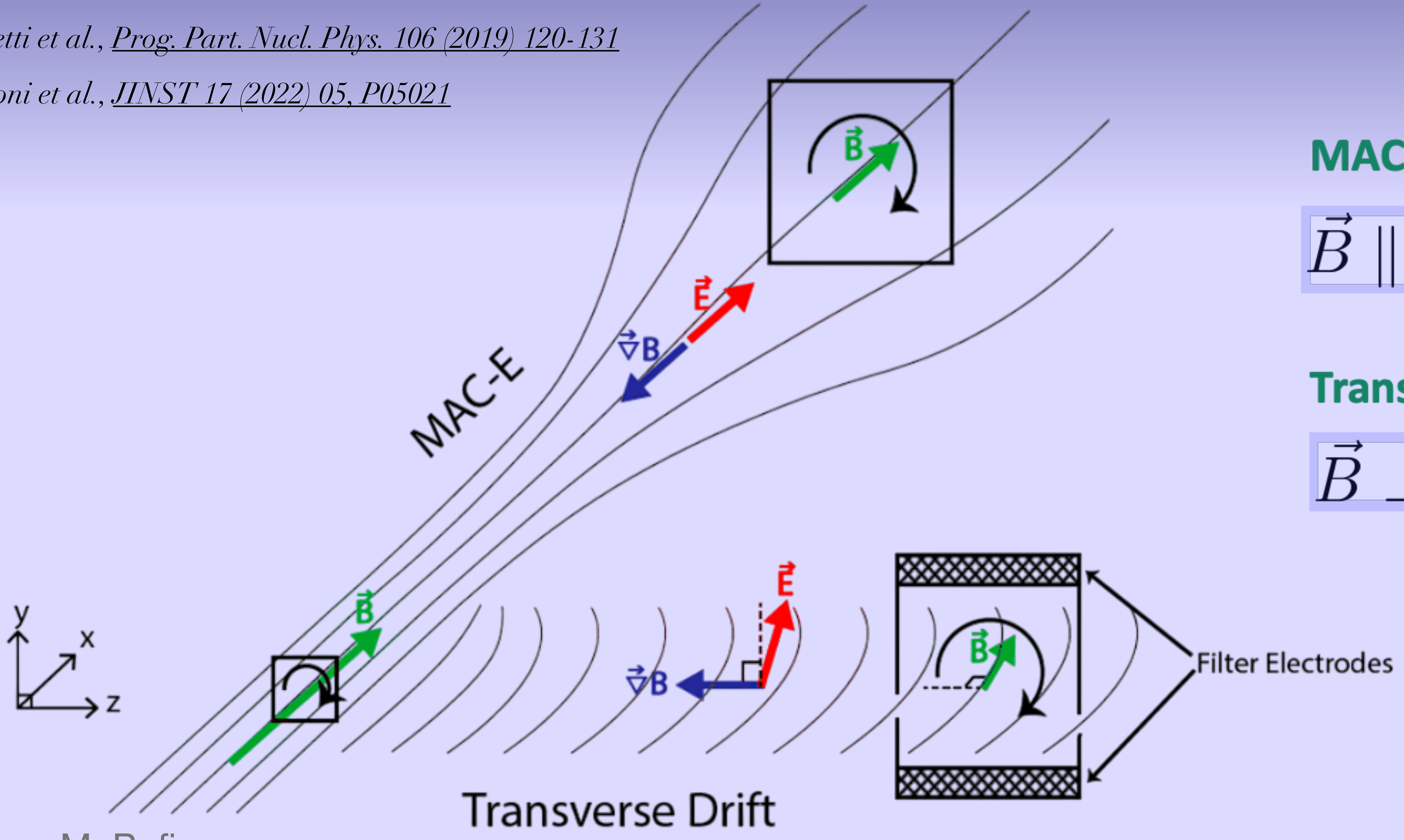
* Dedicated downconverter developed @ NIKHEF
  * DAQ with FPGA trigger developed @ NIKHEF now under test @ LNGS



# New Transverse Drift Concept

*M.G. Betti et al., Prog. Part. Nucl. Phys. 106 (2019) 120-131*

*A. Apponi et al., JINST 17 (2022) 05, P05021*




**MAC-E filter**

$$\vec{B} \parallel \nabla B \parallel \vec{E}$$

**Transverse Drift**

$$\vec{B} \perp \nabla B \perp \vec{E}$$

# Filter within One Meter

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**E Field** → E x B drift → motion along filter
→ potential hill

✚ **B Field** → ∇B x B drift → motion against increasing potential

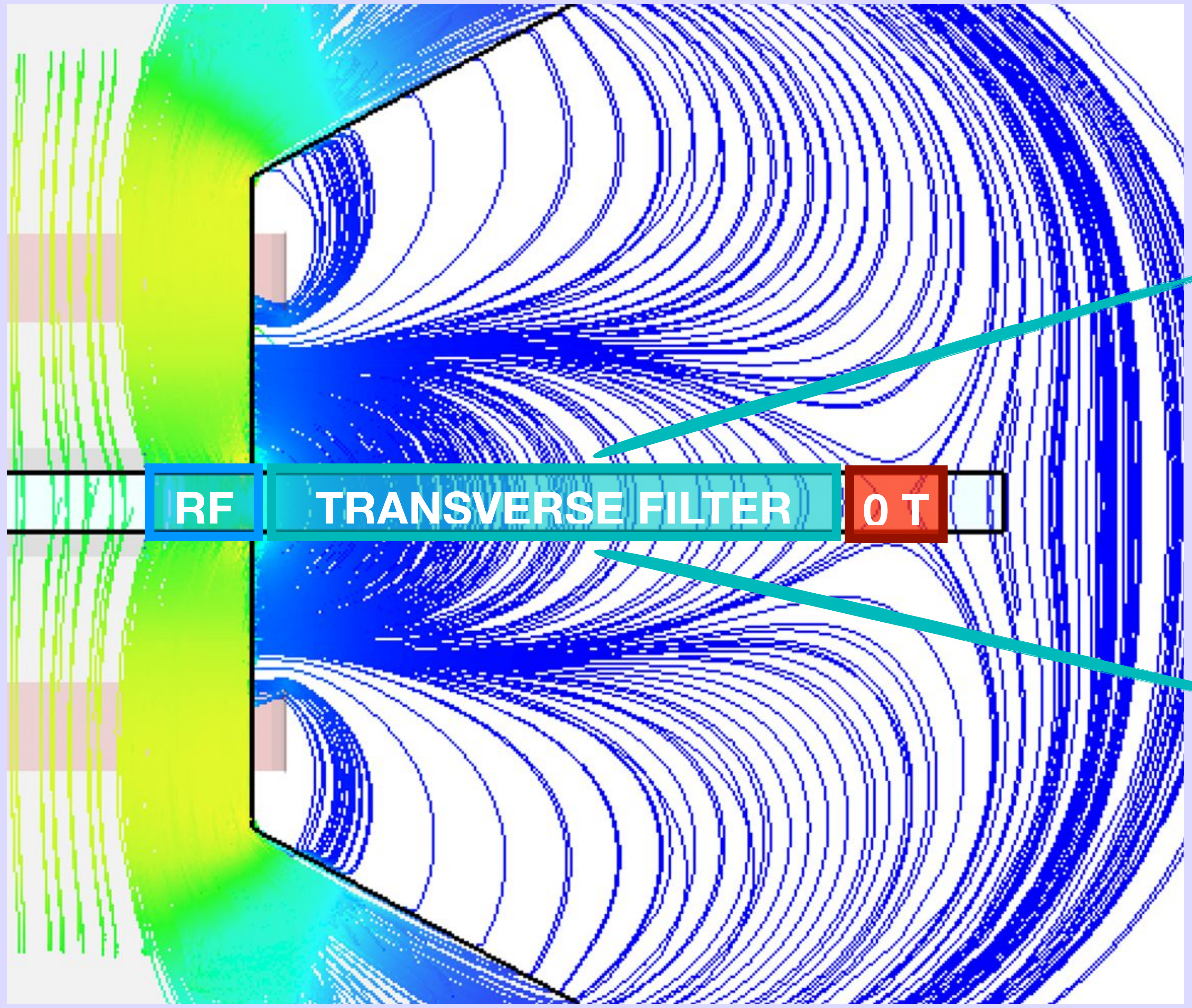
➢ with exponential decay @ same rate → transverse drift balancing

**FINAL RESULT:**

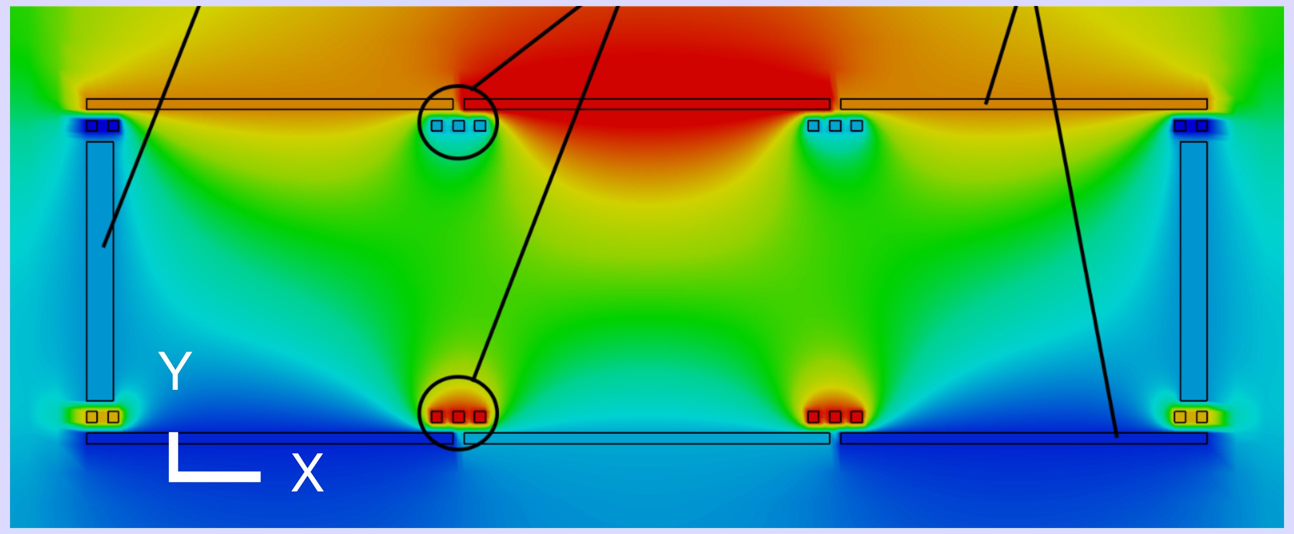
Electrons' **slowdown** + **filtering**

➢ with controlled trajectory

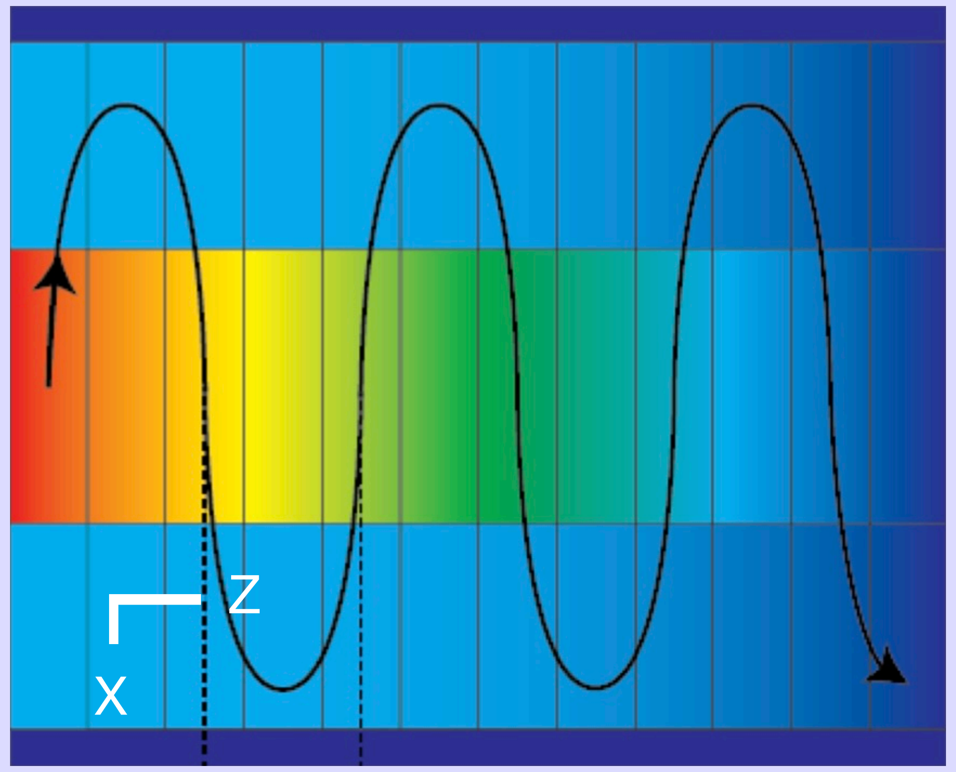
➢ in short space (~1 m)




front view




top view



# Dynamical Filter: Two Possible Scenarios

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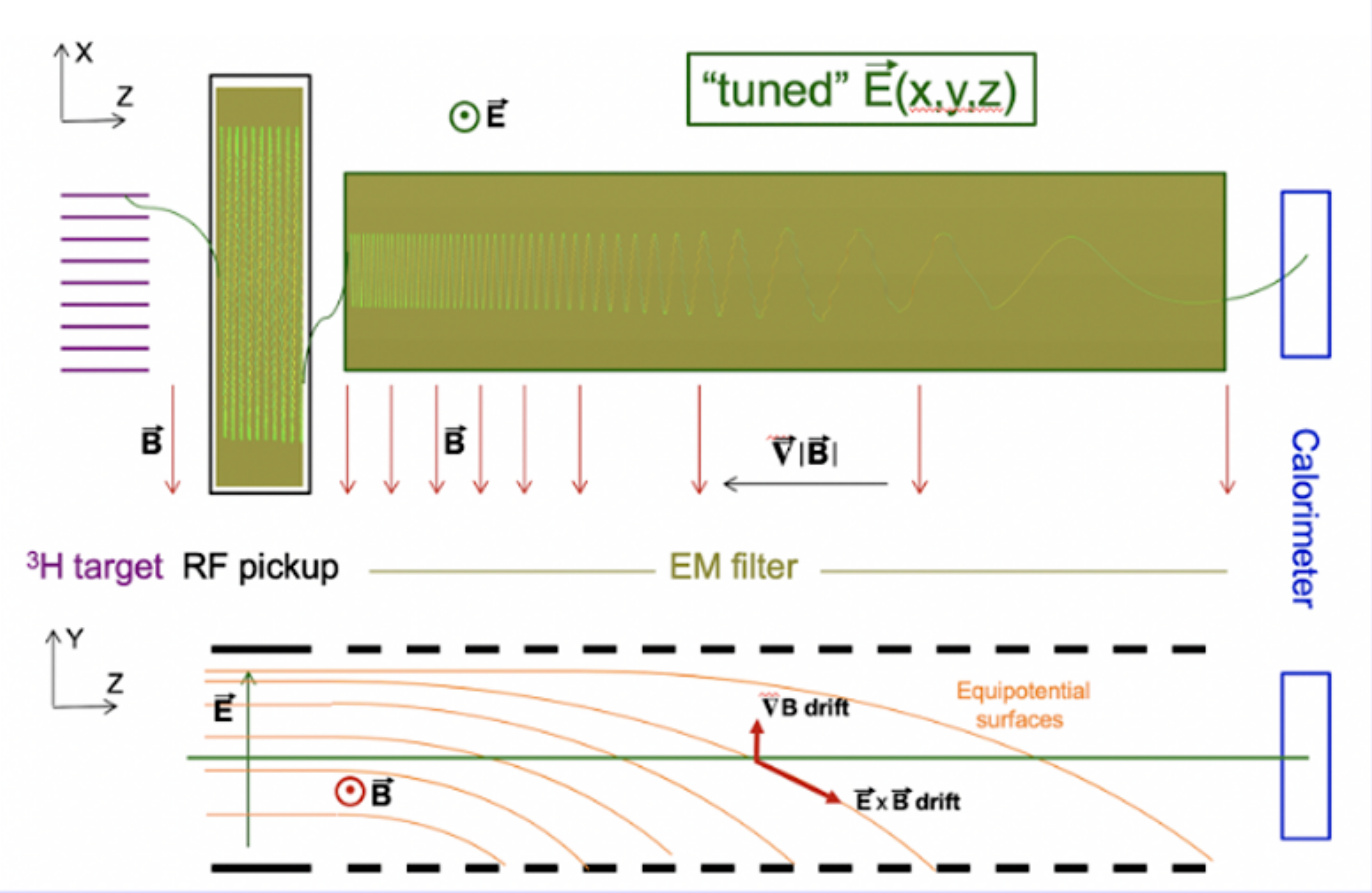
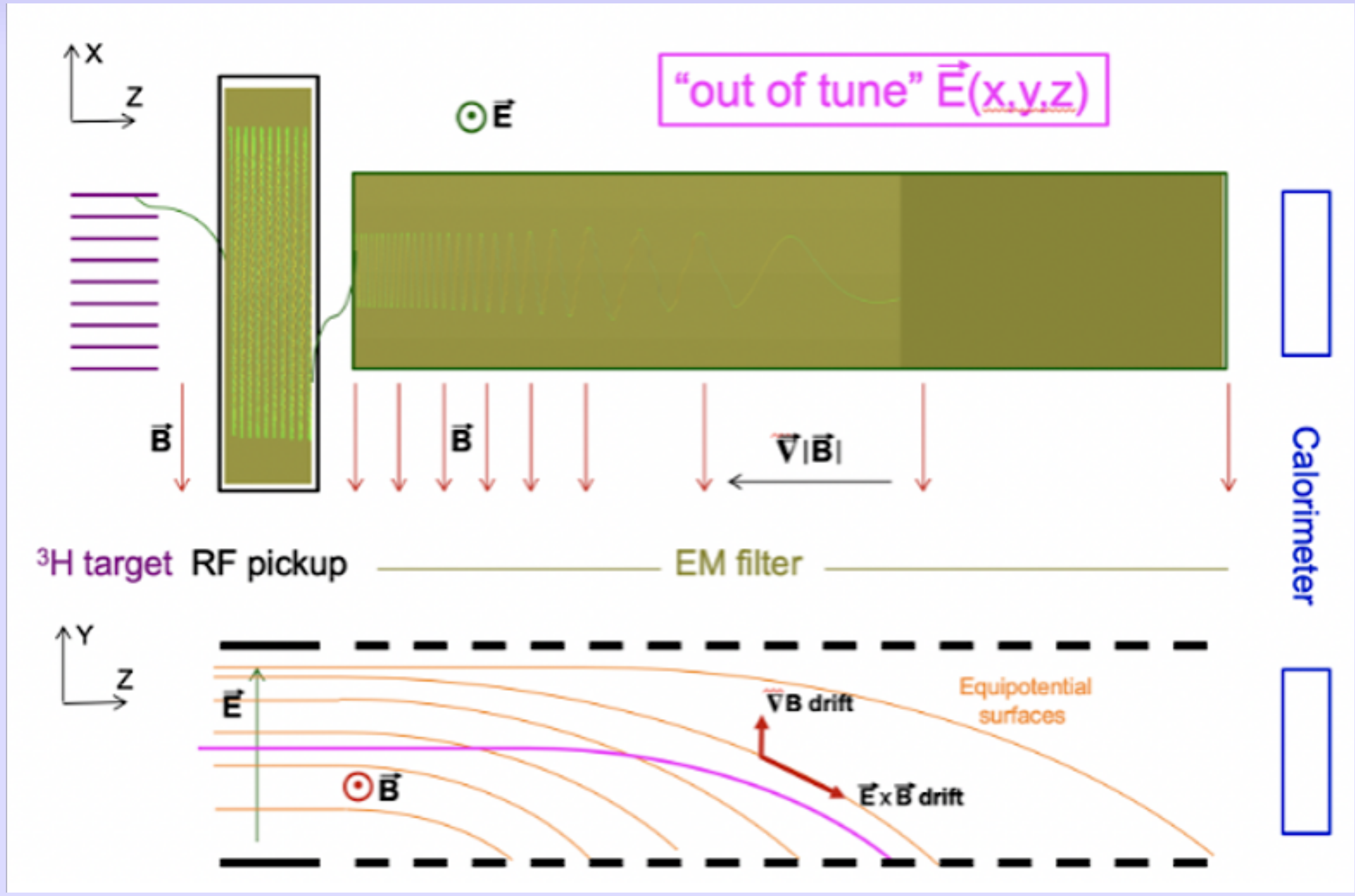
RF pickup → $K_e$ inside ROI* → Tuned $\vec{E}$

**Result: electron passes** ✓




RF pickup → $K_e$ out of ROI* → Out of tune $\vec{E}$

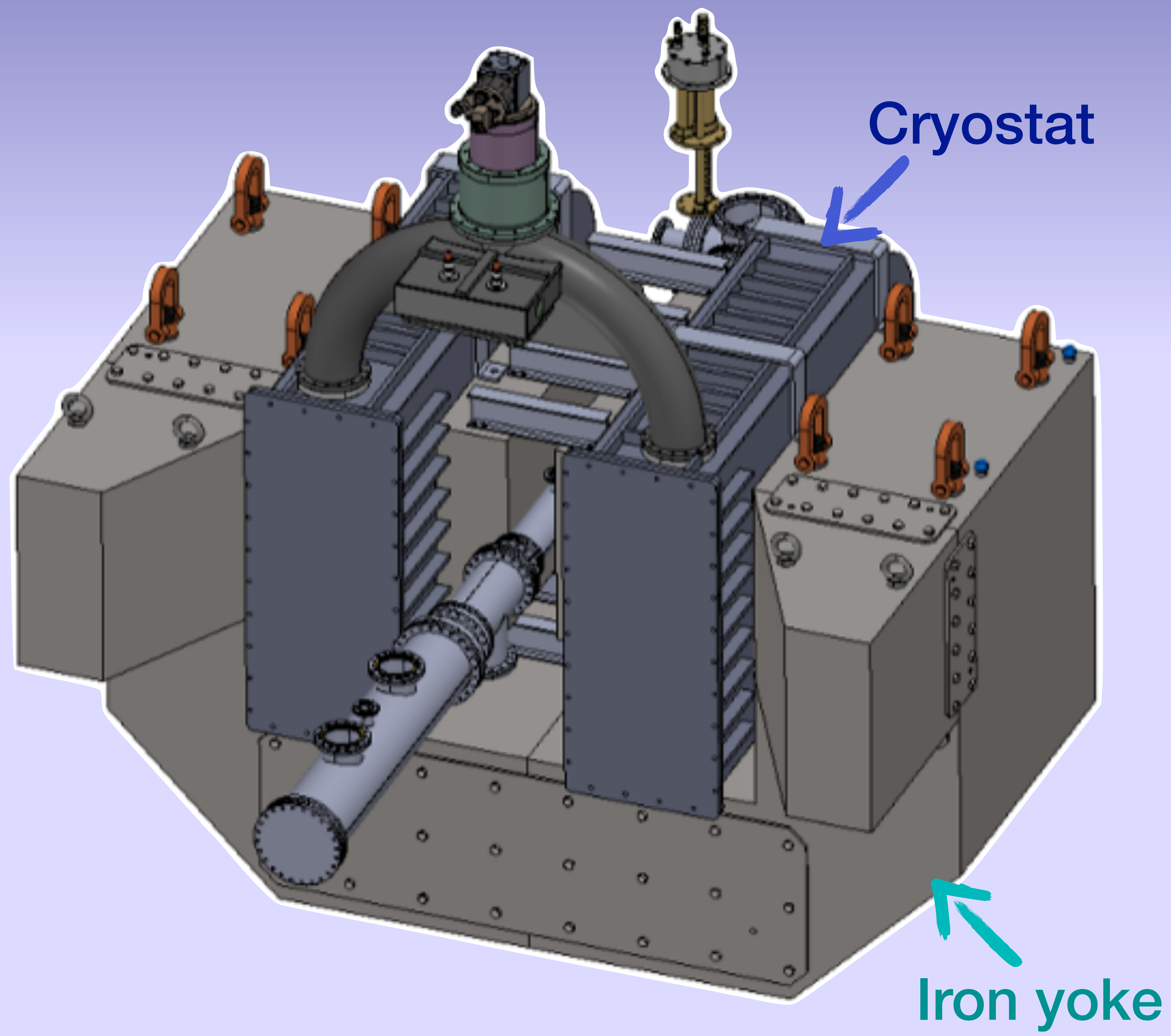
**Result: electron doesn't pass** ✗




*ROI = 10 eV window around $\beta$-spectrum endpoint*

# Magnet Under Construction

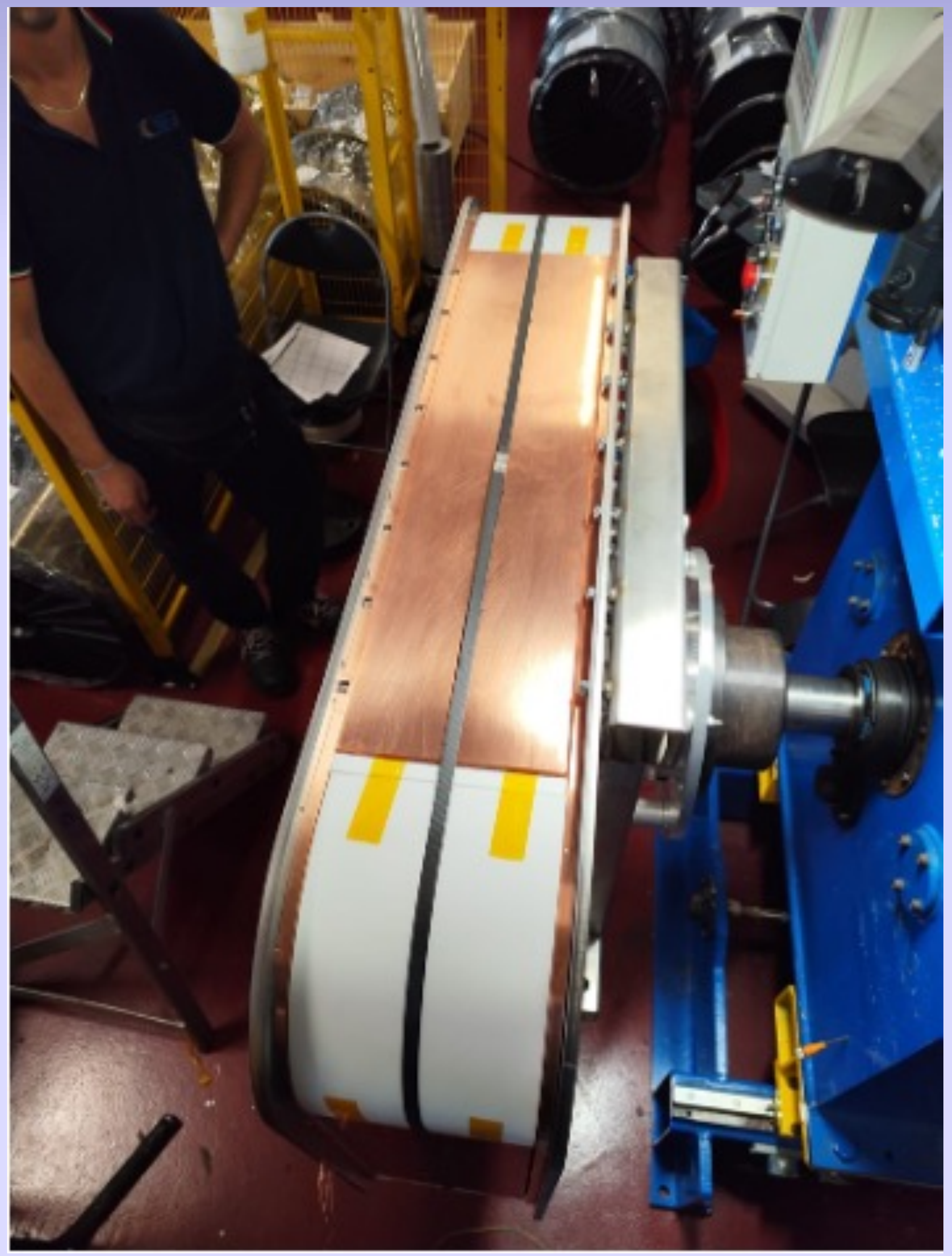
PTOLEMY




- ASG (Genova) & Suprasys (Bilbao)
  - Planned: High precision B Field map @ CERN in 2026

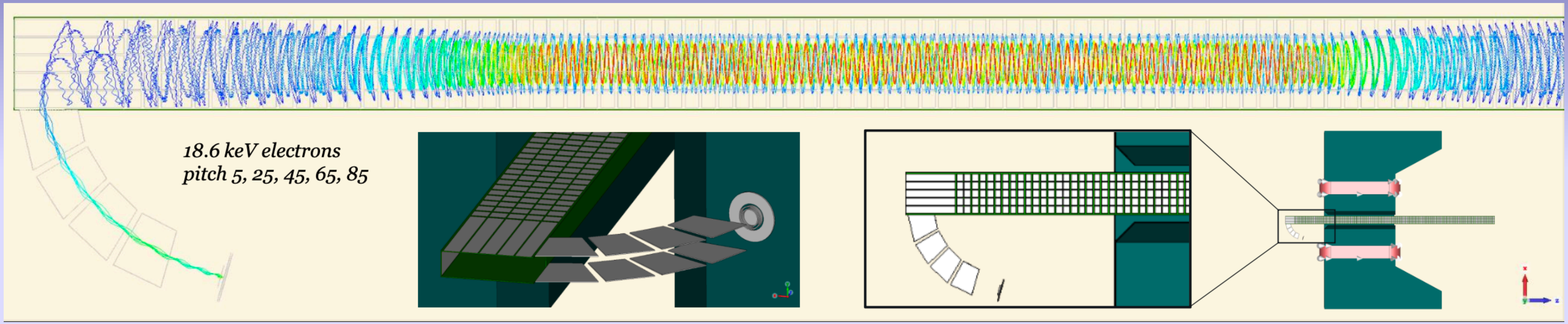
Yoke construction

Superconductive coils assembling



***NEW!*** *cooldown tests of the coil ongoing - cold mass near operational temperature in 4/5 days*

# Simulations in Multiple Frameworks

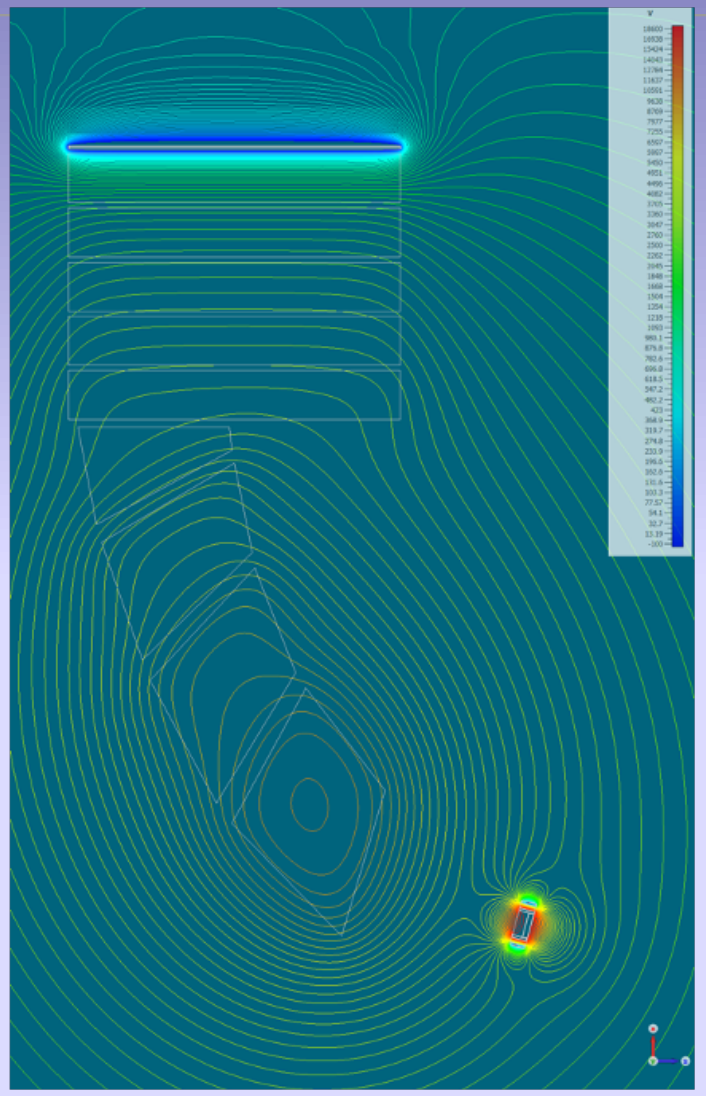


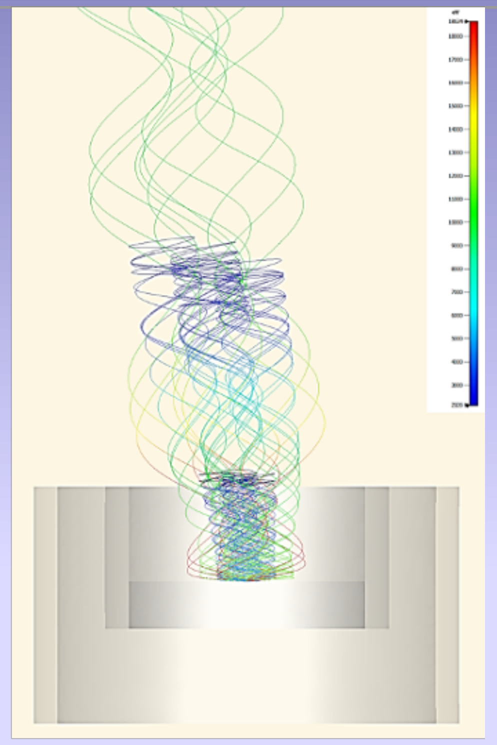

- ➢ Transmission simulation from target to detection region ongoing
- ➢ Filter parameters optimisation <-> efficiency studies feedback
- ➢ Working on different simulation frameworks: - CST®
  - Kassiopeia® &
  - COMSOL®

**Lorentz4 ( NEW!)**

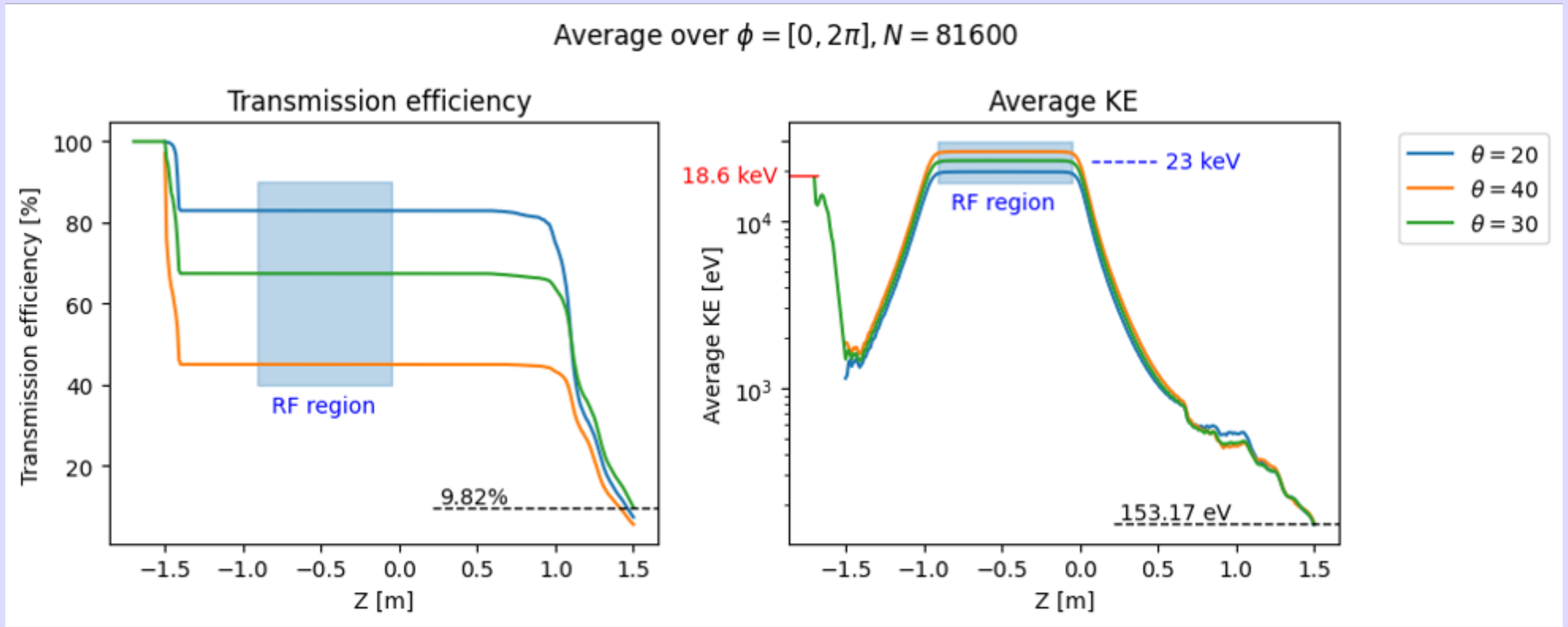
*open source simulation software under development by the collaboration*

# Preliminary Transport Studies





- Ideas for electron injection: permanent magnet case for target
  - Unconstrained trajectories ⇨ follow field lines
  - From higher to lower B field ⟺ mini MAC-E filter
  - Back into high field for the RF using transverse drift acceleration




- First transmission efficiency studies
  - 2 mm diameter circular target
  - **Static** configuration
- average of 10% transport efficiency over a range of pitch angles

*More details from F. Virzi on Thursday!*

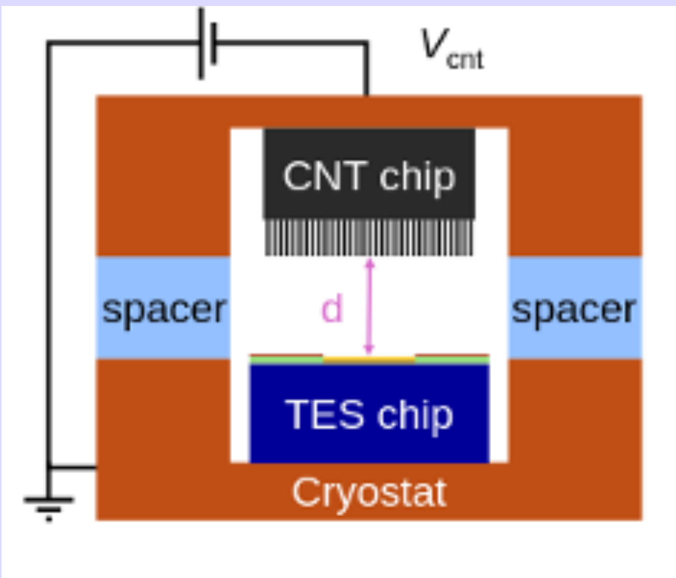
# Promising Results with TES

- ➢ Usually employed in photon detection → < 50 meV resolution on 0.8 eV on $\gamma$s
  *L. Lolli et al. Appl. Phys. Lett. 103 (2013) 041107*
- ➢ Detection concept valid for electron absorption too!

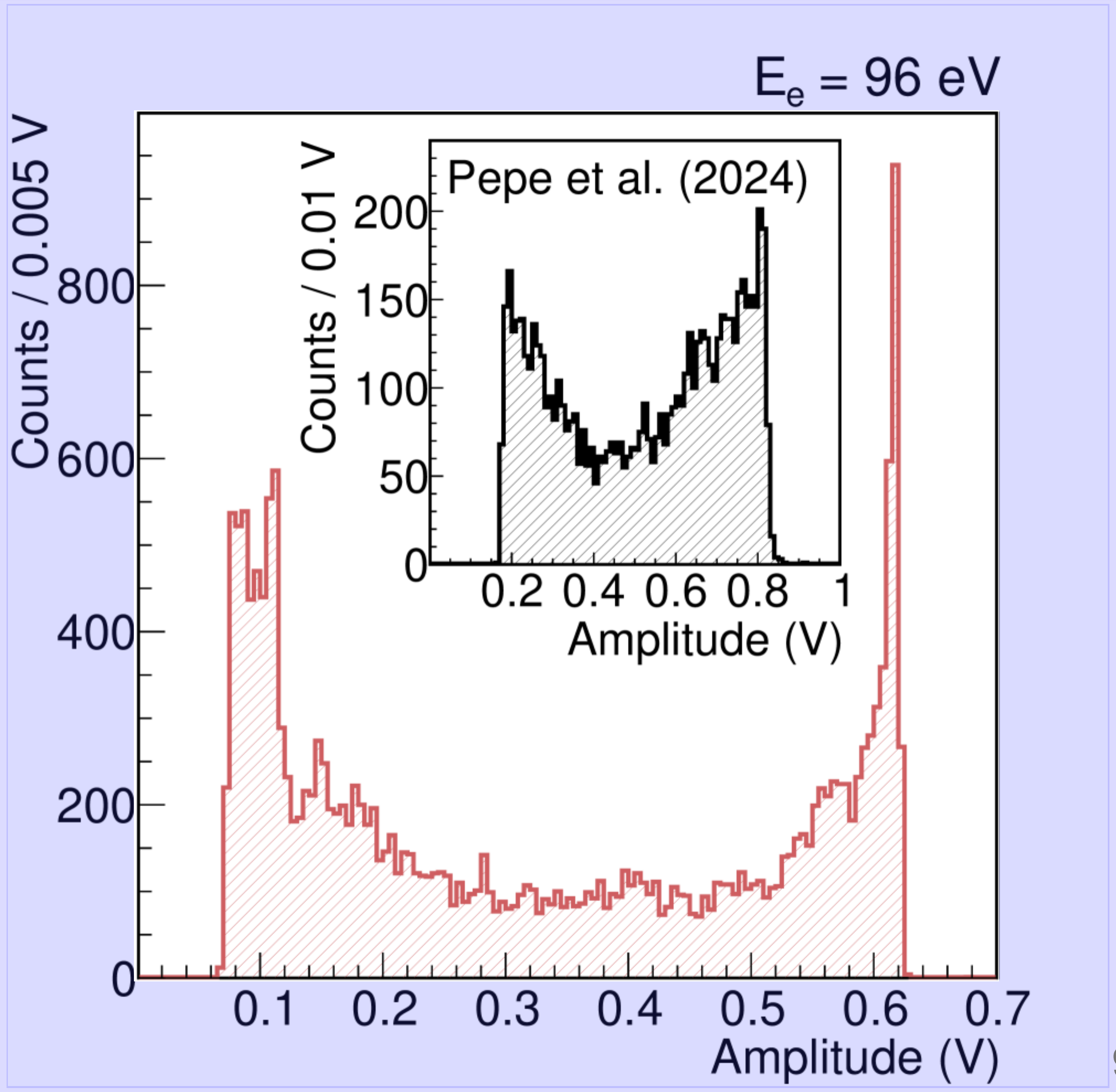
*More details from B. Corcione on Thursday!*

**IN PTOLEMY:**

- ➢ Innovative idea of using carbon nanotubes as cold $e^-$ source
- ➢ First results: $\mathcal{O}$(1 eV) resolution on ~100 eV $e^-$
  *C. Pepe et al., Phys. Rev. Applied 22 (2024) 4*




- ➢ **Last results:**
  *A. Ammendola et al., arXiv:2602.21694v1 [physics.ins-det]*
  - ✓ $\mathcal{O}$(0.5 eV) resolution on ~100 eV $e^-$
  - ✓ x20 improvement in FWHM → significant back-scattering suppression



# A Gift from Condensed Matter Labs

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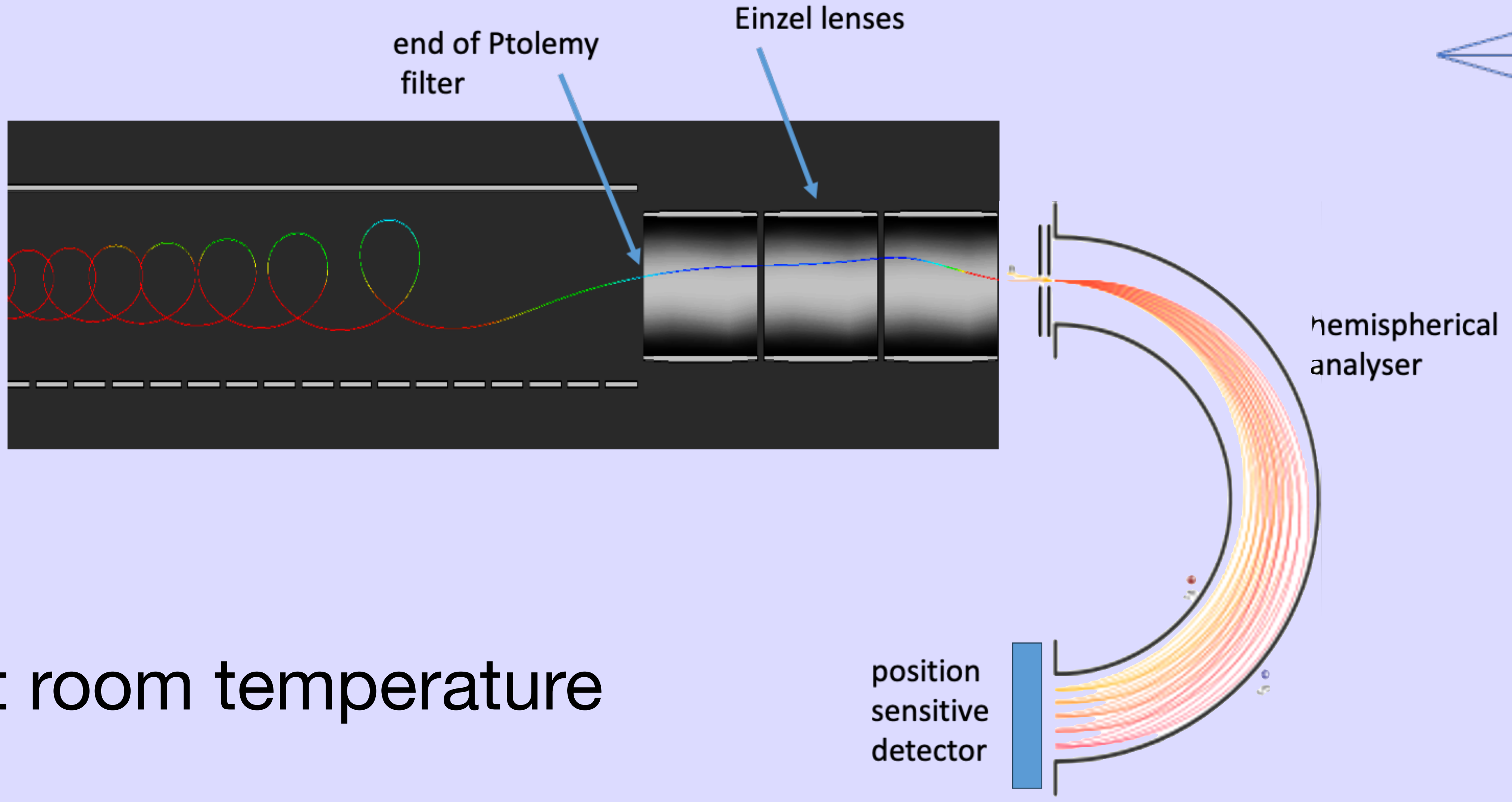
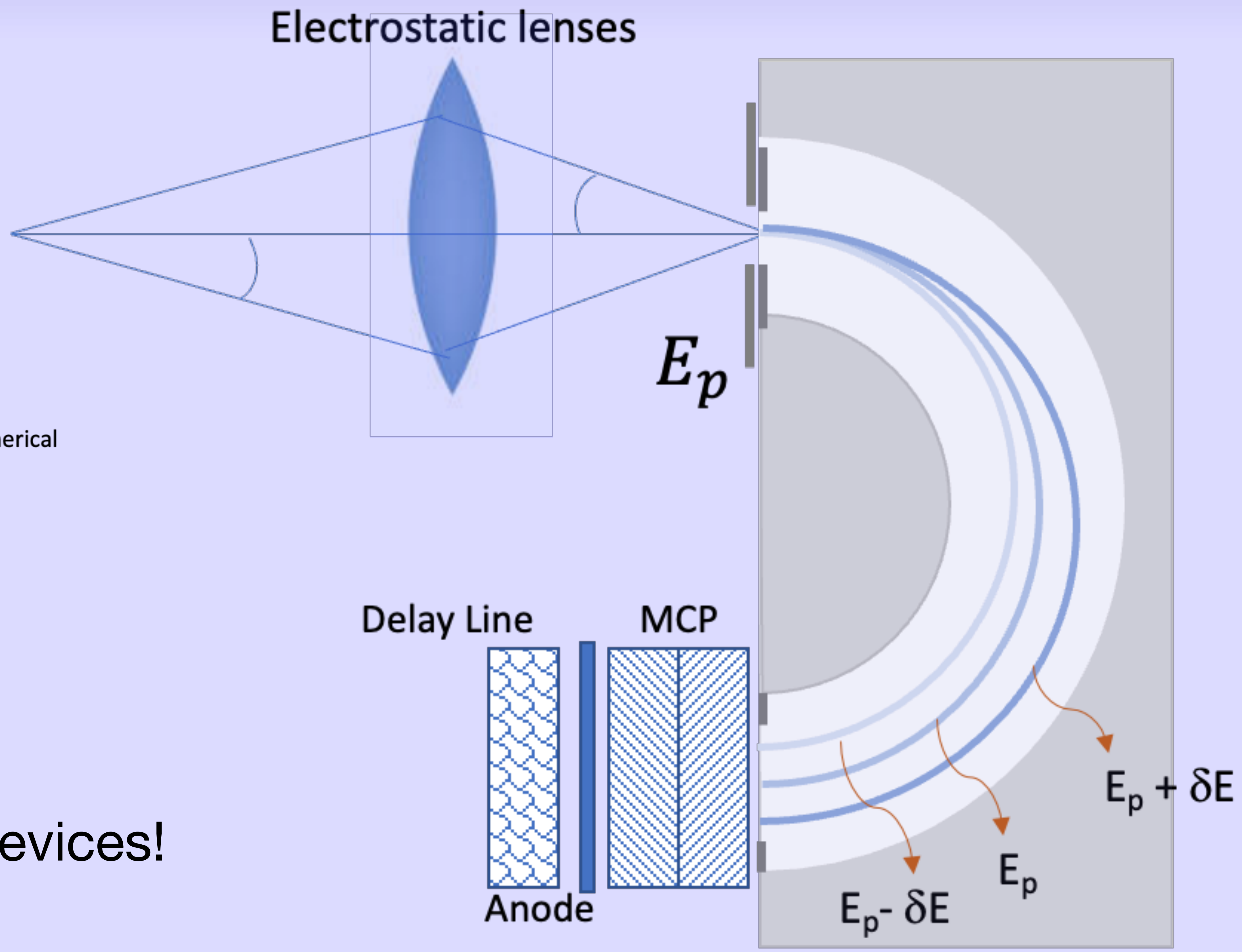
- ➢ Electron Analyser operation:
  hemispherical condenser → e-path optimised for energy $E_p$ → position detection at exit

- ➢ Standard in photoemission spectroscopy

**Valid Phase-0 option in PTOLEMY:**




- ➢ Working at room temperature

- ➢ $\mathcal{O}$(meV) resolution already achieved from commercial devices!

# Extensive Experience @ Roma Tre

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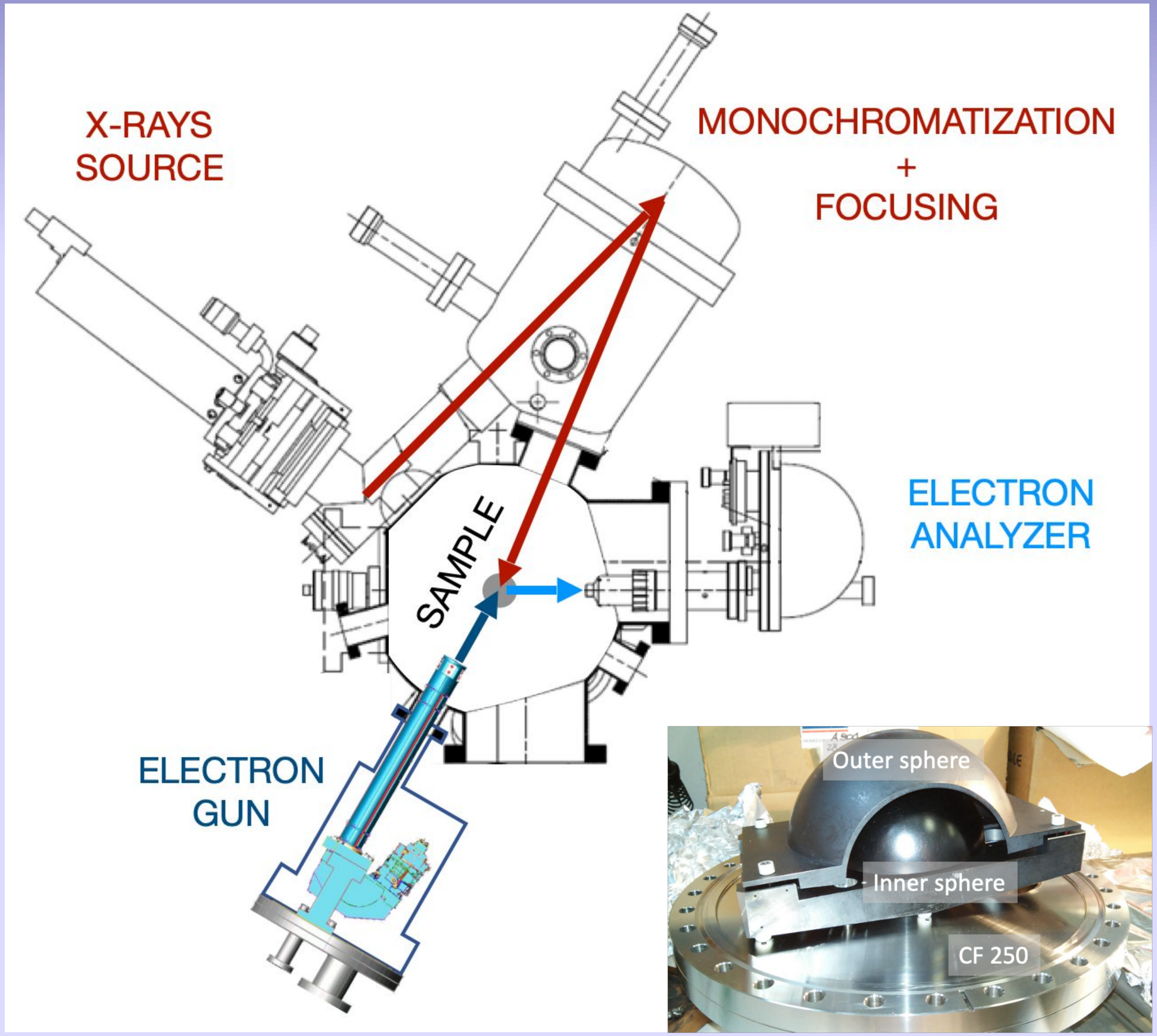
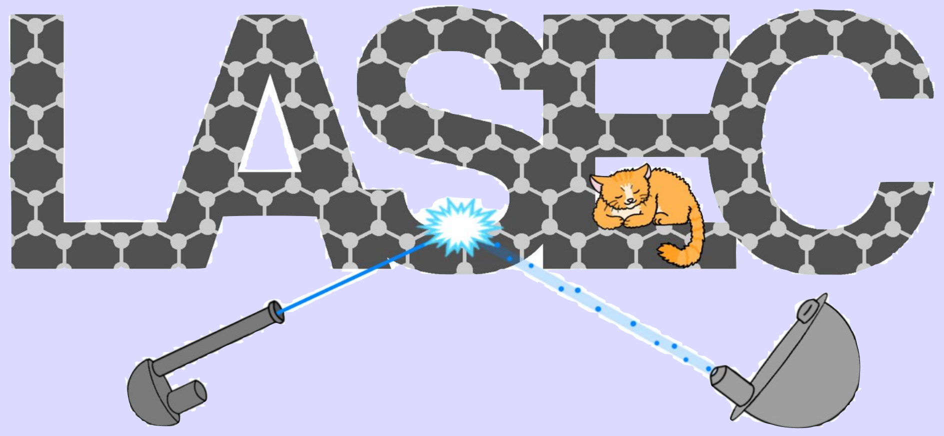
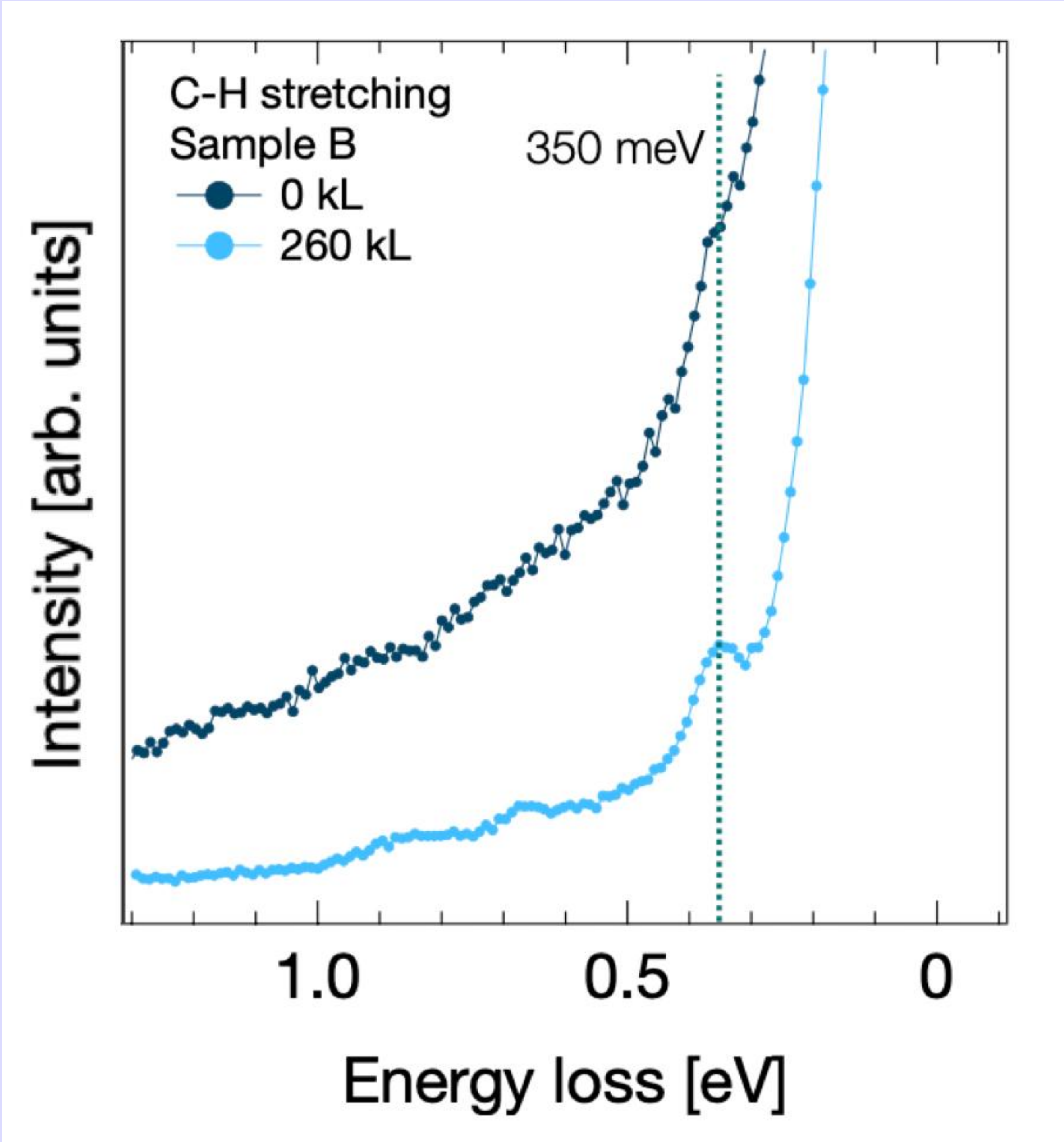



- ➢ Energy loss measurement on 90 eV electrons
  - ➢ C-H stretching mode @ 350 meV visible ⟷ 60 meV resolution!



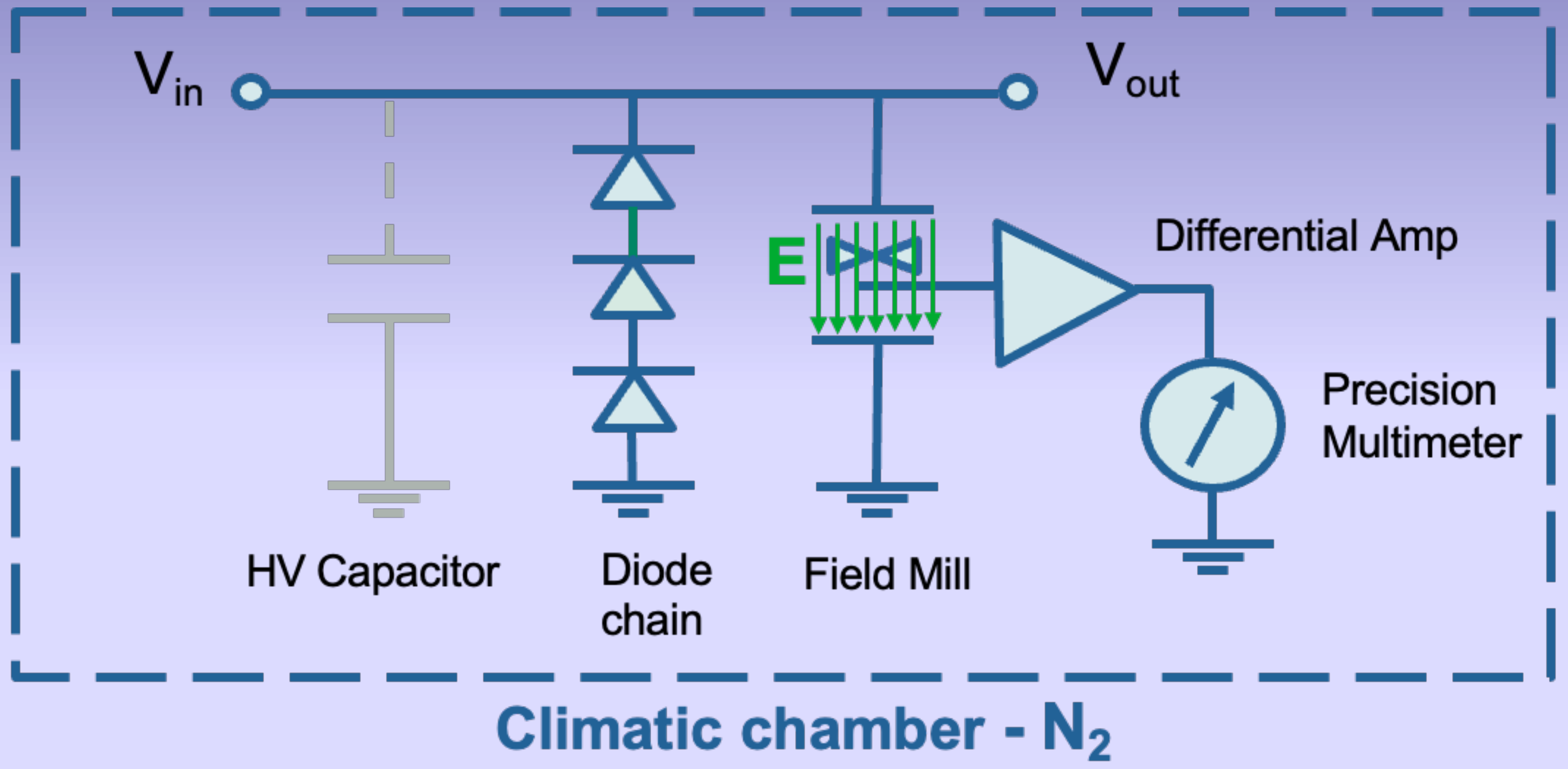

*More details from A. Apponi this afternoon!*

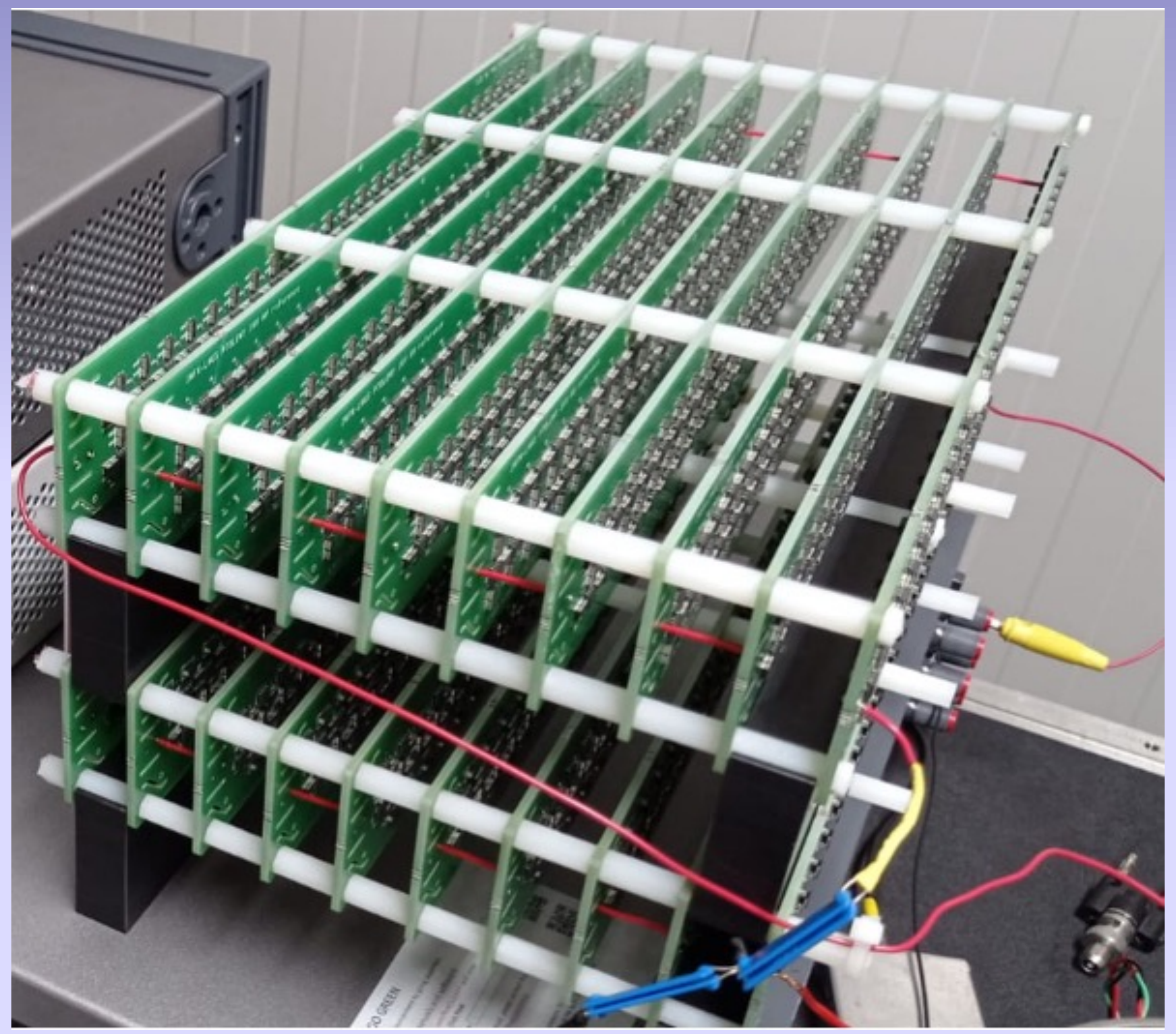


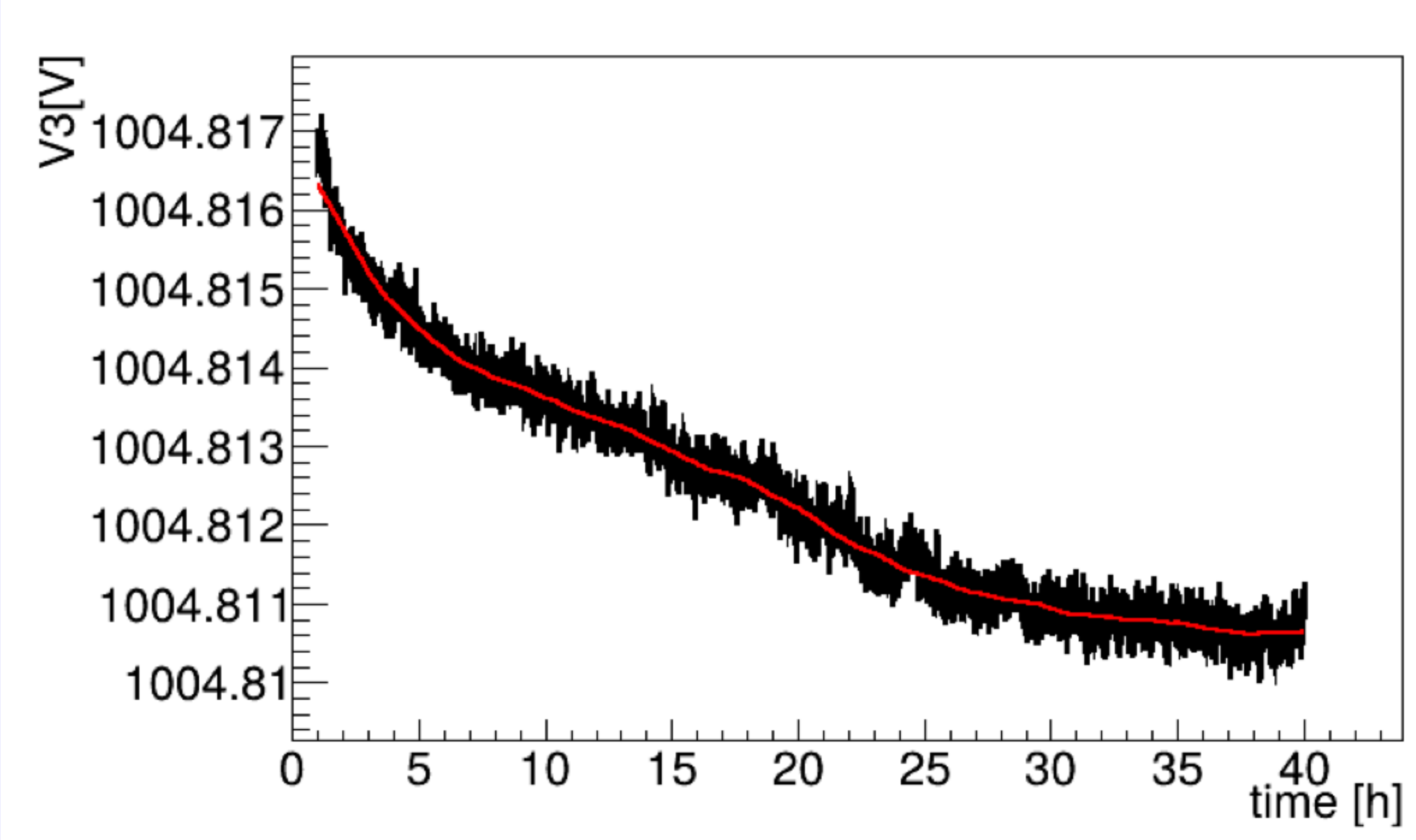

*A. Apponi et al., SSRN preprint 10.2139/ssrn.6297127*

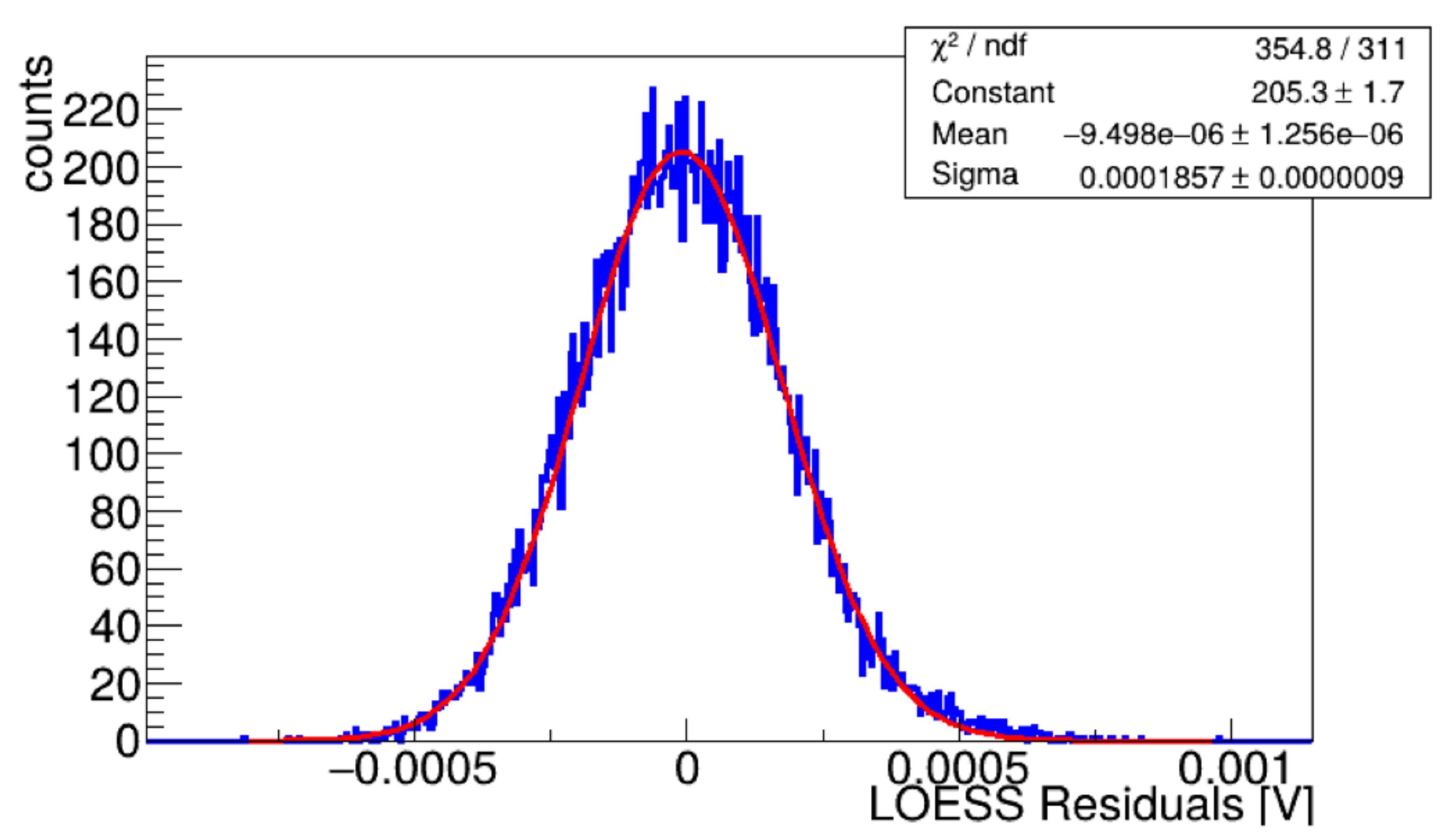
# A Key Ingredient for Energy Reconstruction

- 20 boards (2000 voltage references)
- 1 kV each board
- Field Mill for readout






**Last result:**

On a single board (1 kV)

$\sigma \lesssim 0.2$ mV

= 0.2 ppm!

*A. Ammendola et al., arXiv:2512.19437v1 [physics.ins-det]*

Francesca M. Pofi

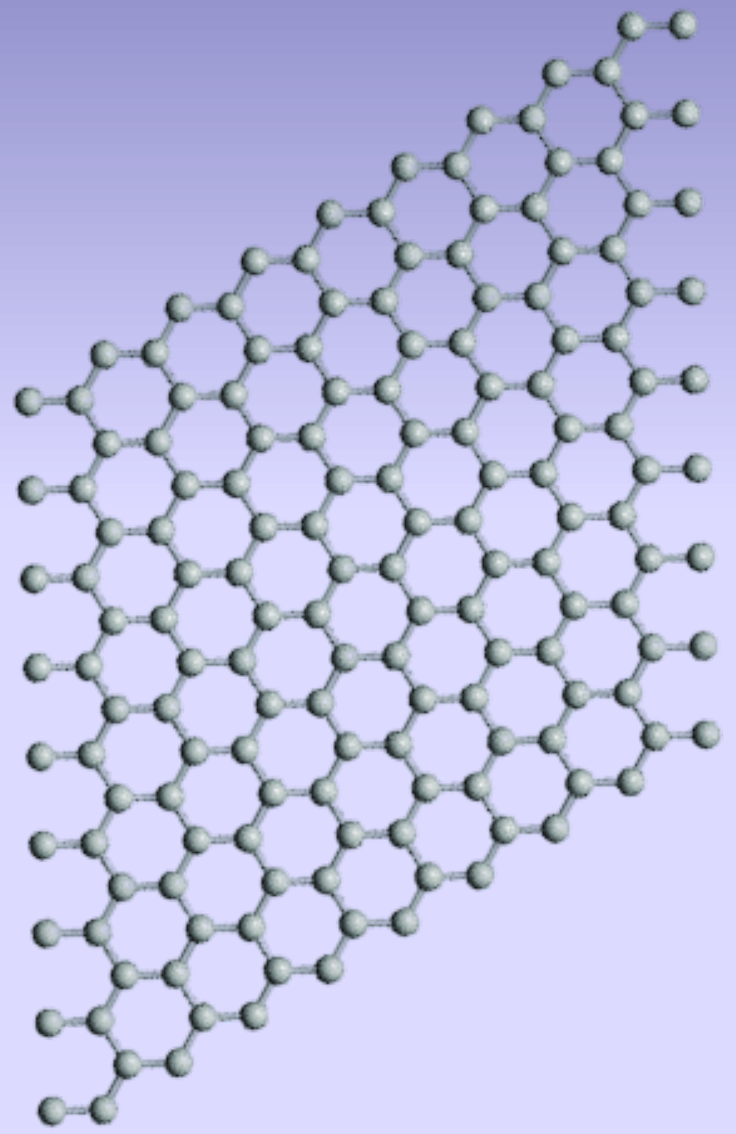
# Sensitivity: Let's Shape the Target

With:

- Exposure = 3 years
- Efficiency = 50 %

Using as **source**:

- 7 x 7 $cm^2$ tritiated graphene
- Fully loaded $\boldsymbol{\rho}$ = 0.2 $mg/m^2$



- **1 μg** Tritium
- ~170 MBq activity

*Expected number of $\beta$ emissions from tritium:*

$$N_{dec} = \left( \frac{m_{\text{source}} \mathcal{N}_A}{A_{(^3H)}} (1 - e^{-t_{\text{expo}}/\tau_{^3H}}) \right) \times 0.5 \simeq 2.2 \cdot 10^{16} \text{events}$$

# Competitive on Neutrino Mass with Just 1 μg Tritium

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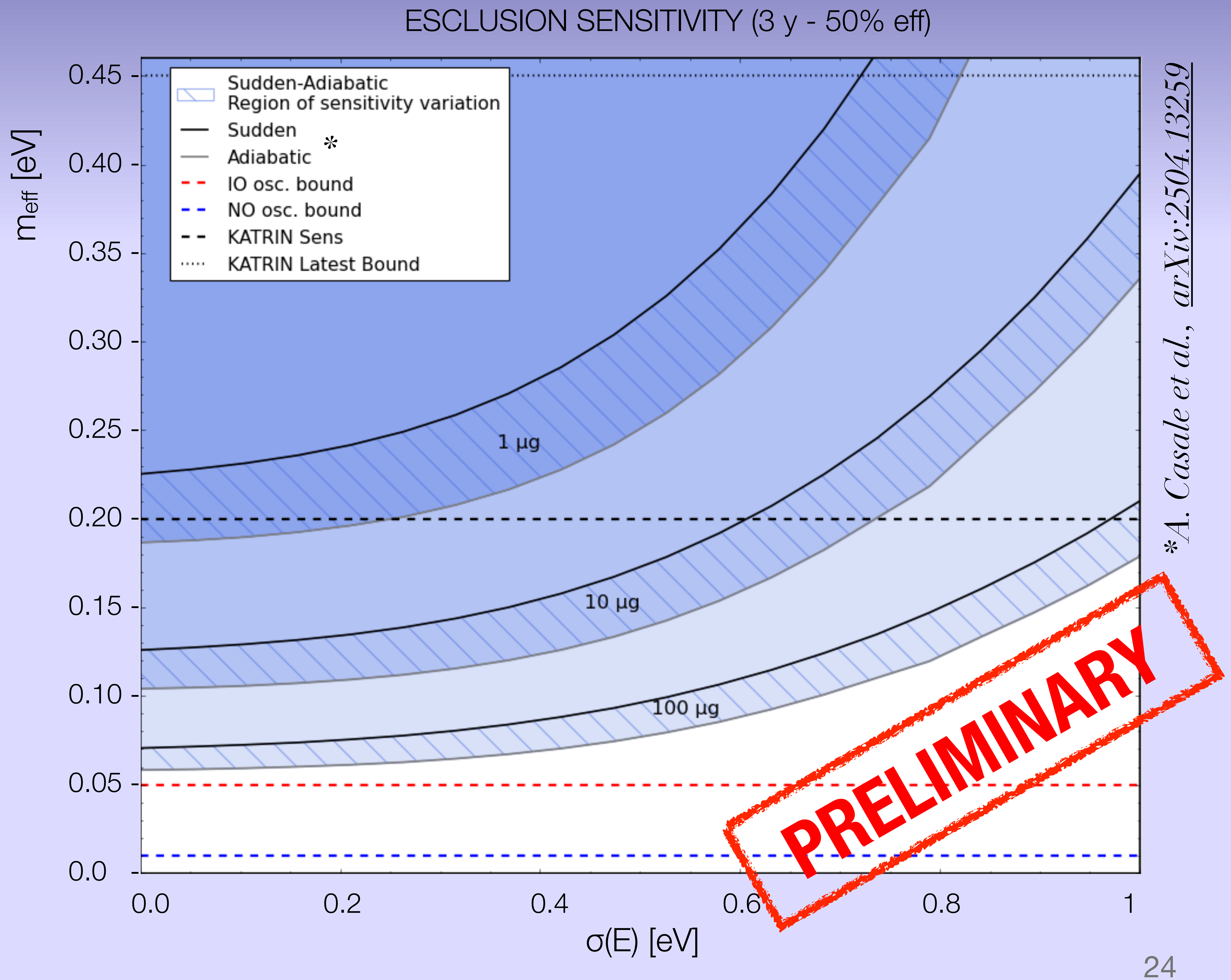
**Aim: effective neutrino mass** sensitivity study by varying target mass

**How?** Profile Likelihood method

**Projected Result:**

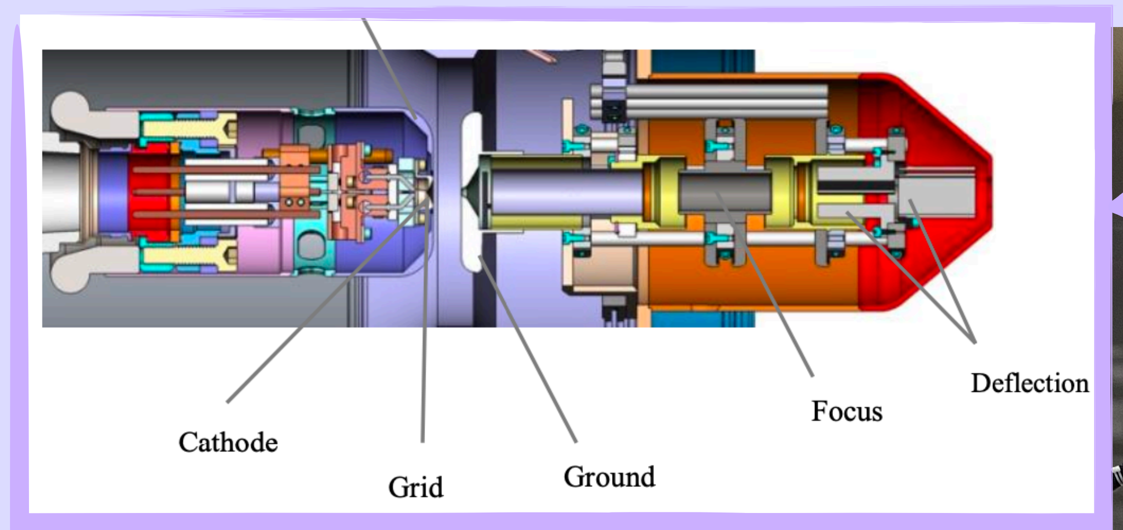
- ➢ Sensitivity weakly dependent upon energy resolution
- ➢ Competitive with forthcoming generations *with 1 μg*
- ➢ Close to probe the IO scenario *with 100 μg*

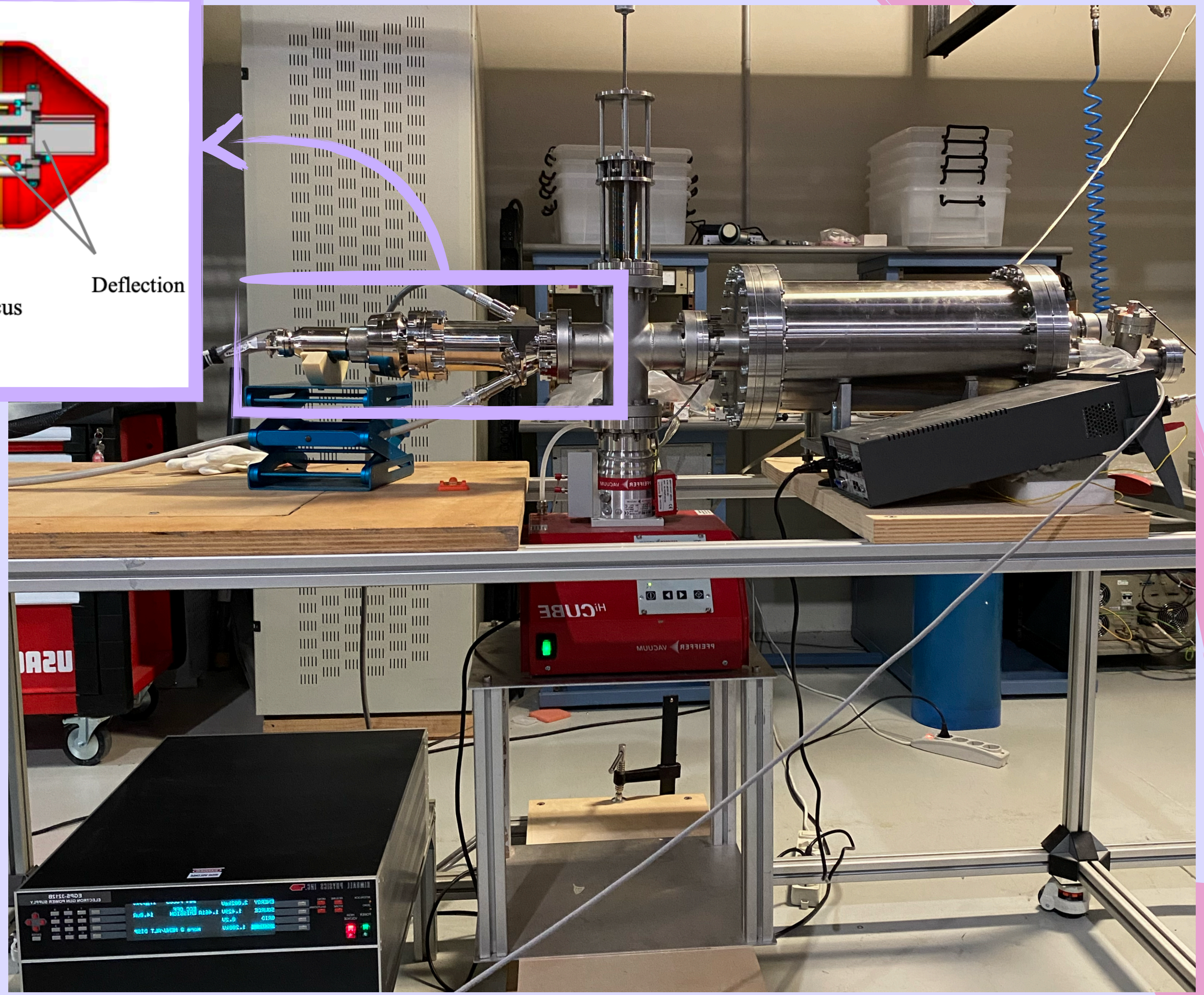


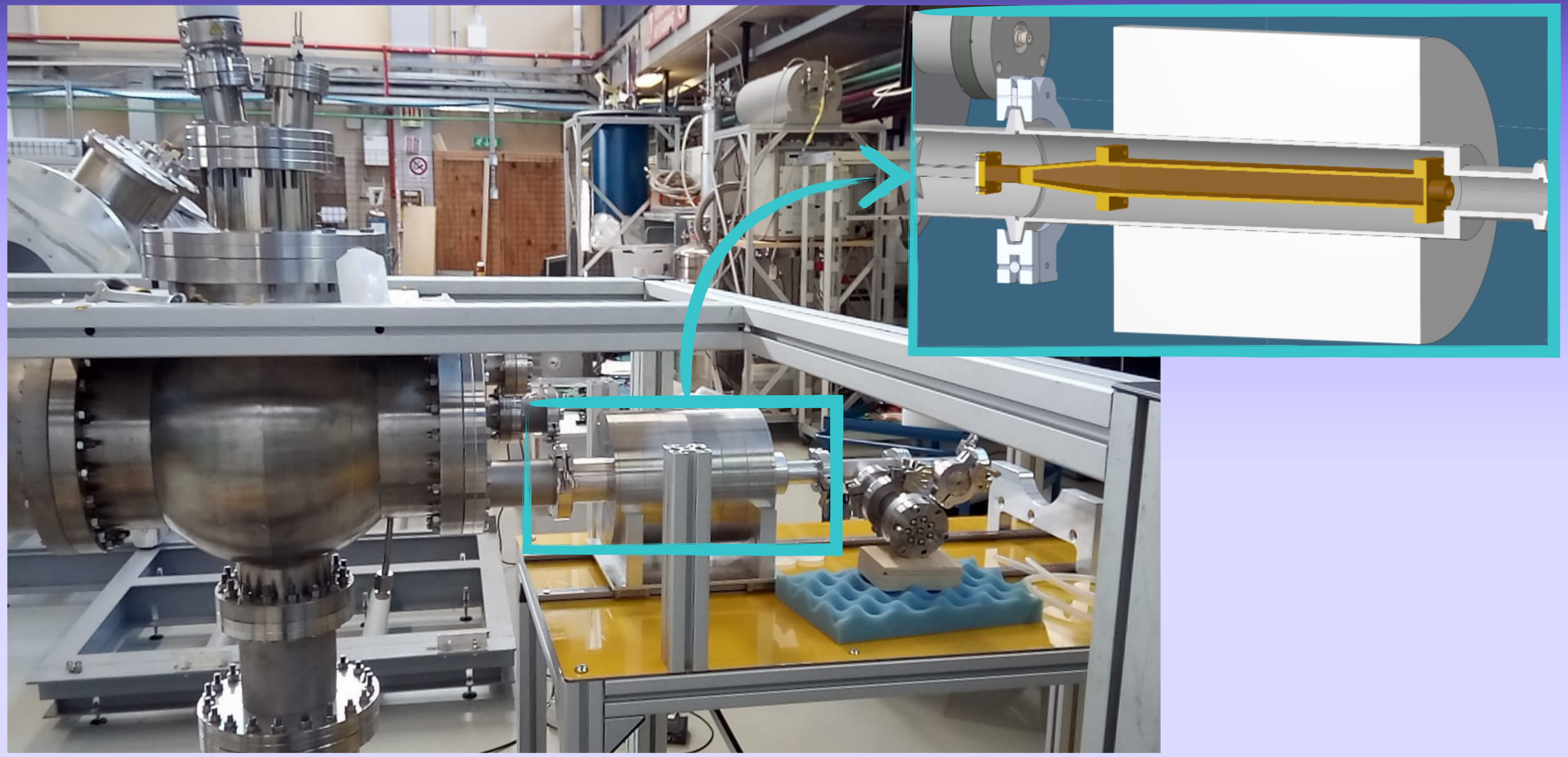

*A. Casale et al., arXiv:2504.13259

# Towards PTOLEMY Demonstrator @ LNGS

☑ RF detection with $^{83m}$Kr injection

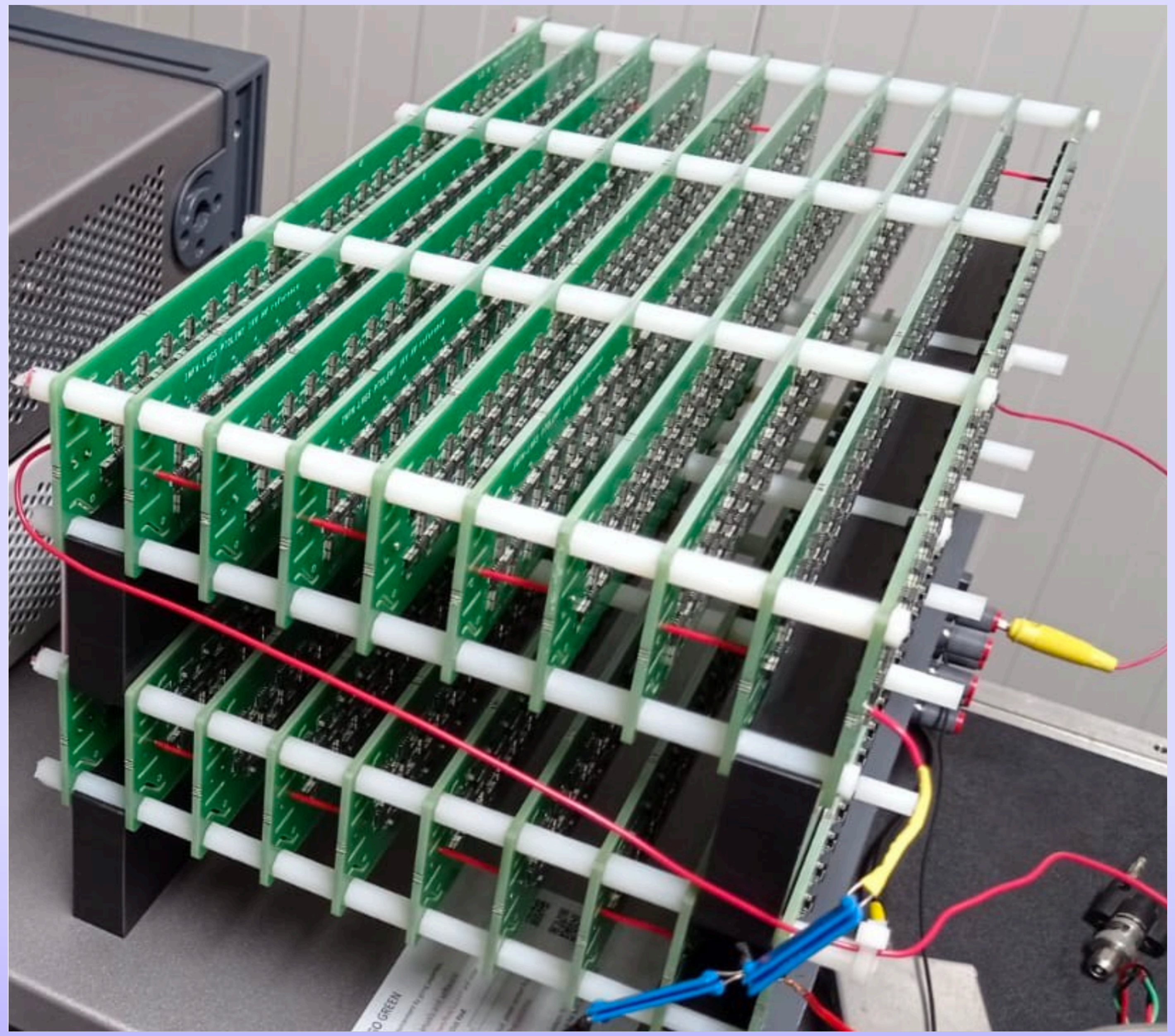




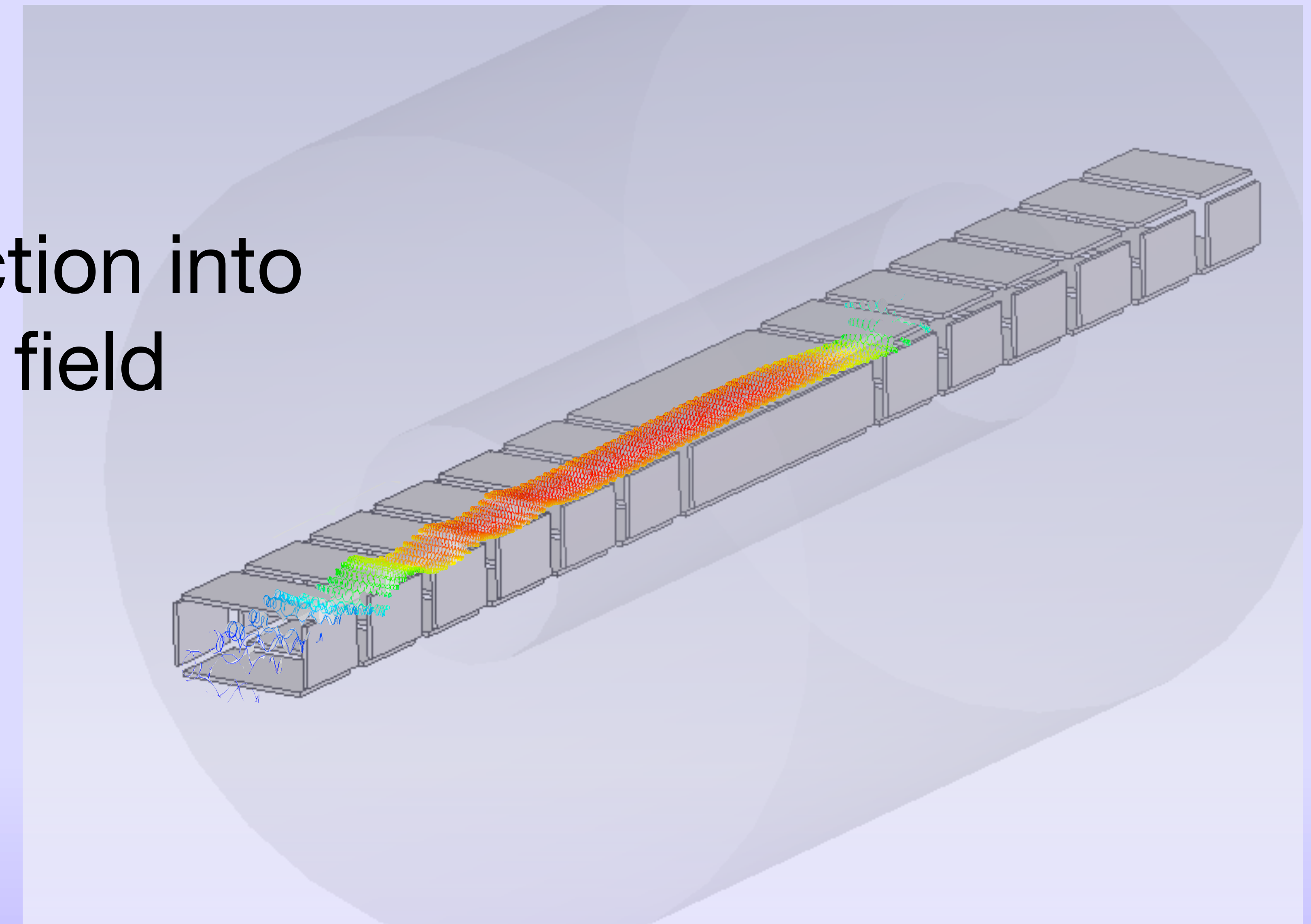
☑ Electron beam setup for transverse drift filter calibration

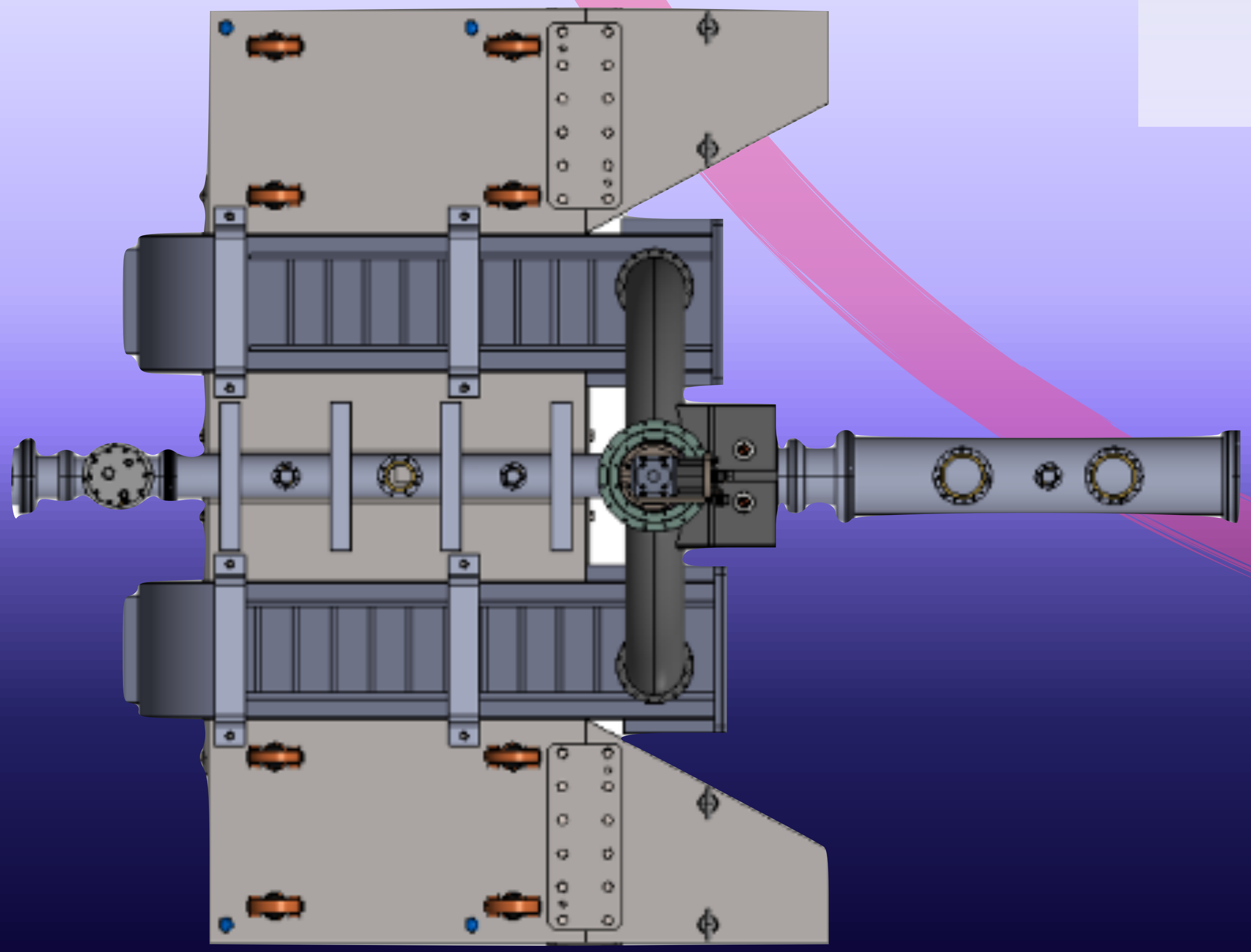
# Towards PTOLEMY Demonstrator @ LNGS



- [x] High stability HV system

- [ ] Electron injection into 1 T magnetic field





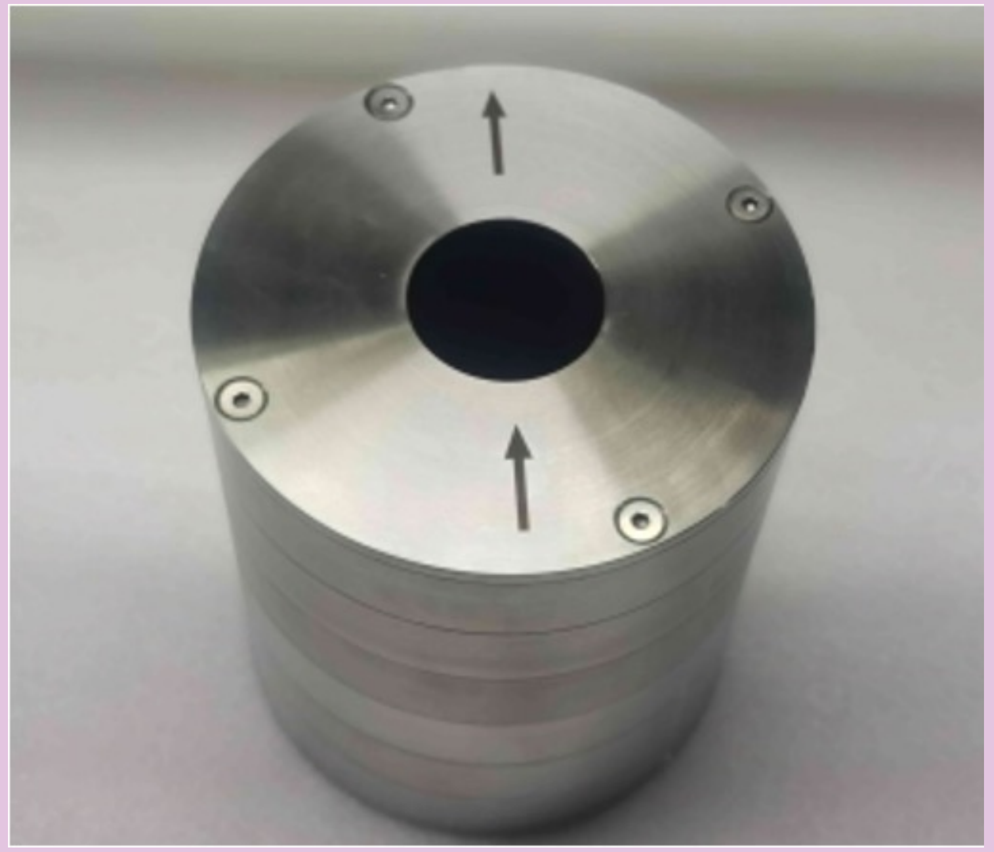
- [ ] Magnet for transverse drift filter in late *2026!*

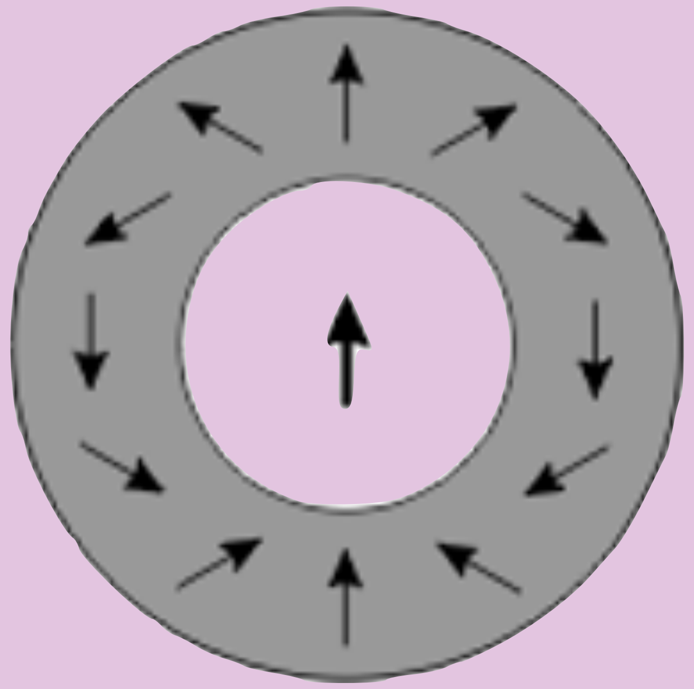
# A Compact Setup @ LNGS for Filter Drifts Proof-of-Principle

# Introducing the Main Characters

## Magnet @ LNGS:

- Halbach cylinder permanent magnet
- 185 mm length,
  170 mm external ⌀, 50 mm internal ⌀
- 1 T uniform magnetic field
  in *limited region inside*

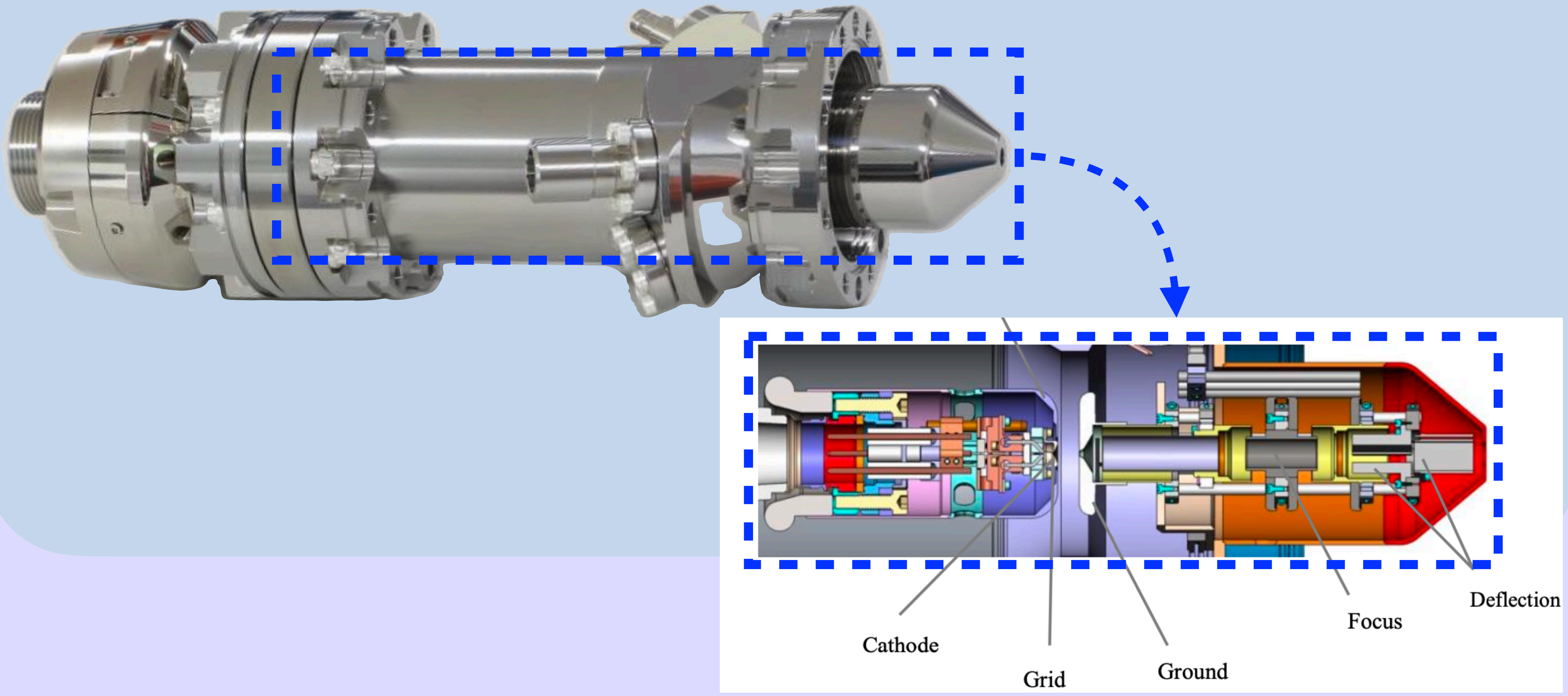




## Electron gun:

- Kimball Physics EMG-4212A Electron Gun
- 1 to 20 keV electron energy
  (with guaranteed performances)
- Electrostatic Focus and Deflection
- Tungsten filament source

➡ Characterisation ongoing!



# A Compact version of Accelerator Filter

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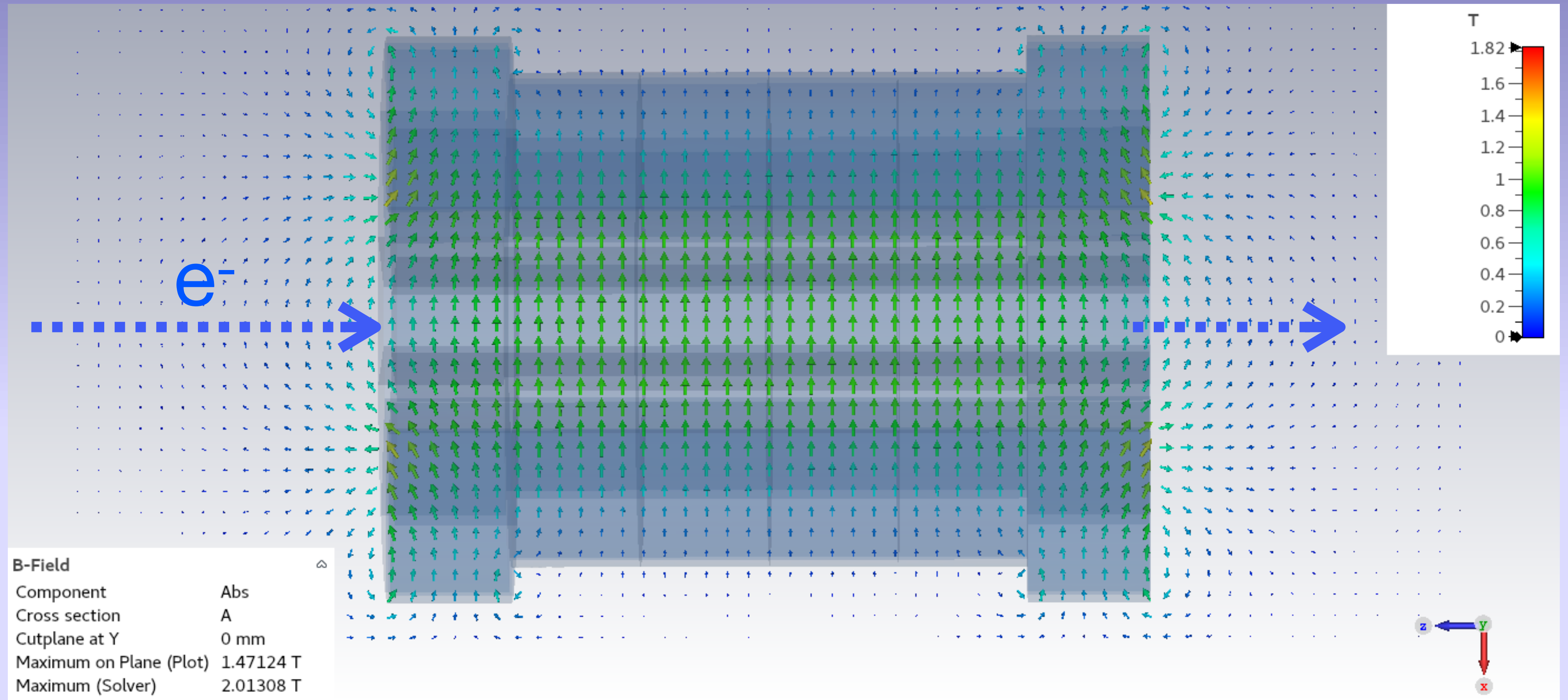
☼ Idea: $e^-$ passage trough 1 T magnetic field proof-of-principle

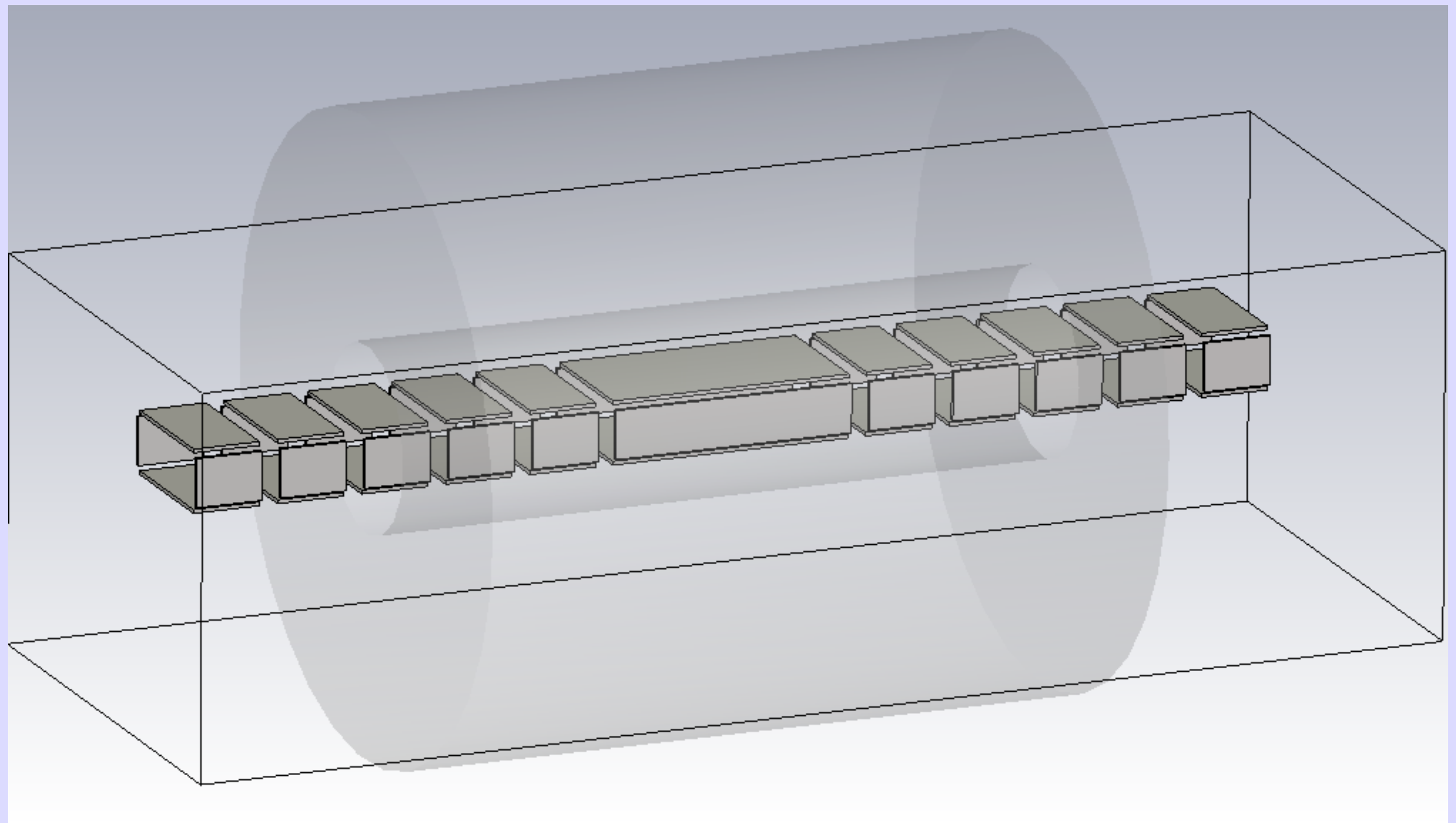
- Become familiar with same drift exploited in filter
- Develop an injection system for
  ❏ RF R&D setup & ❏ PTOLEMY filter calibration




> How? Very compact *single channel accelerator* + *decelerator filter*

> Geometry = chain of electrodes' sets
*(2 bouncing + 1 top + 1 bottom each)*

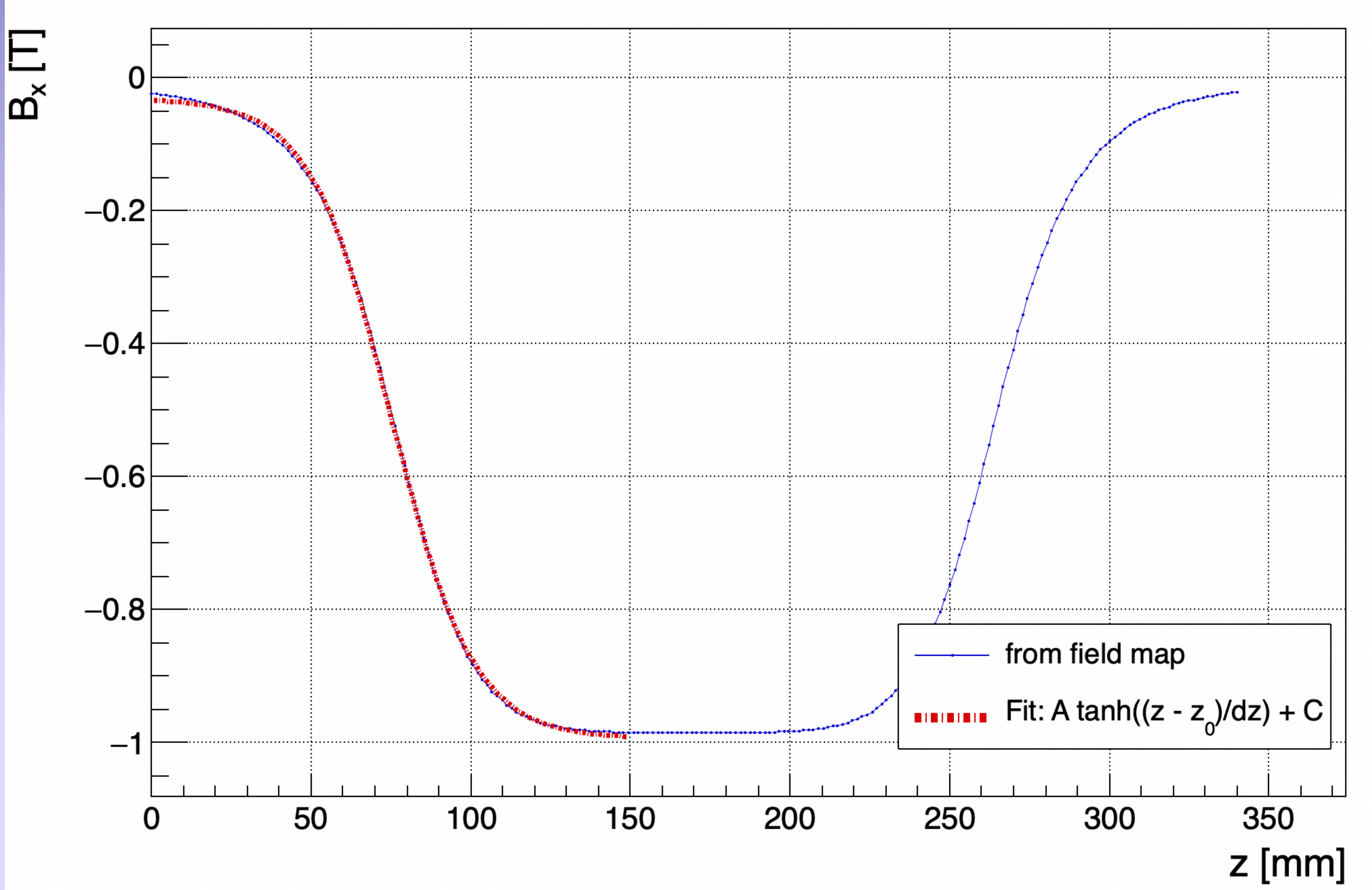
- 5 sets of injection electrodes
- "RF electrodes" (longer set - covering uniform B region)
- 5 sets of ejection electrodes

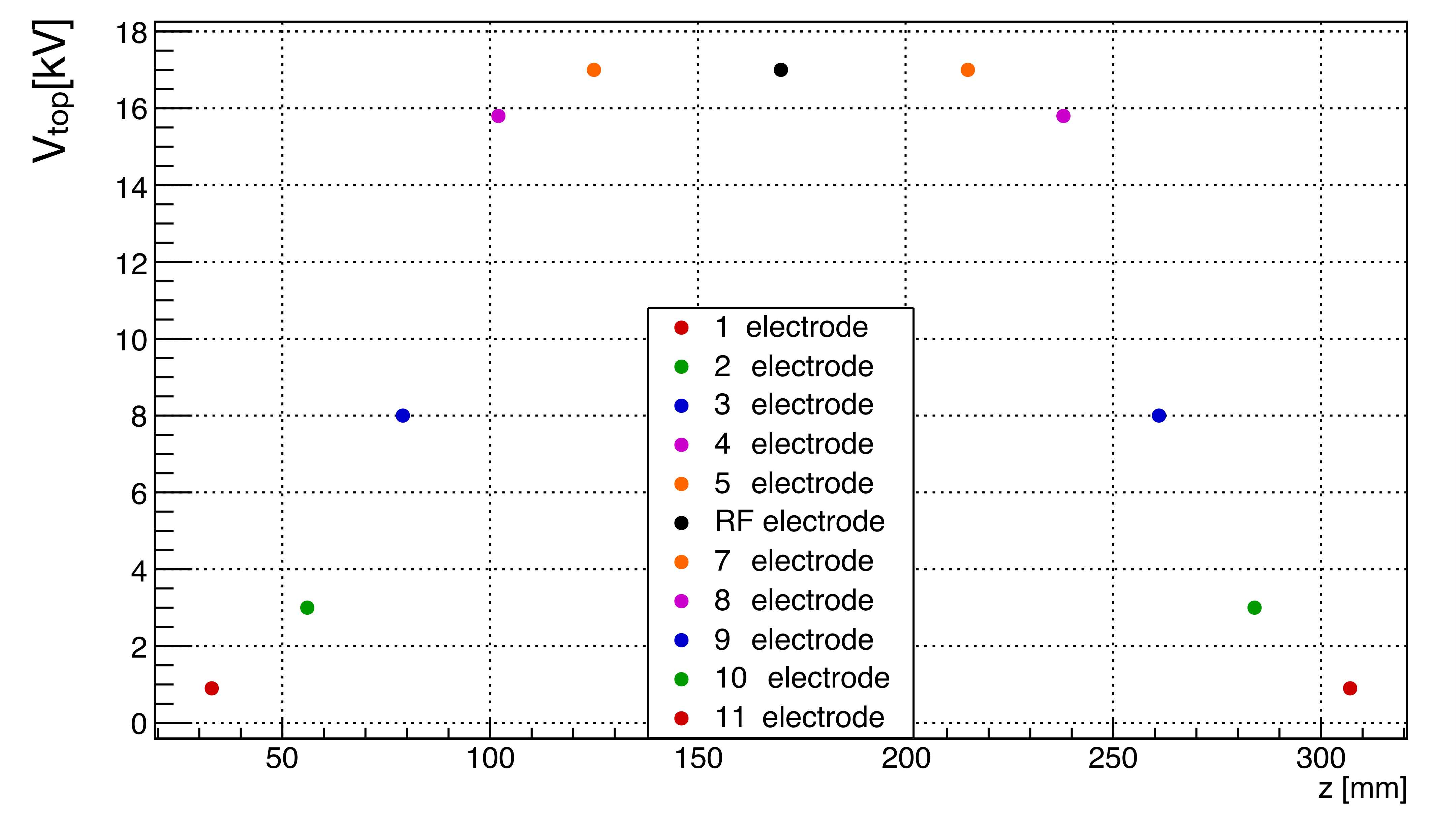


# Sigmoidal Profile for Top Voltages

> Let's have a look to $B_x(x,y=0)$ vs z profile:

- very steep magnitude increase: from 0 to 1 T in ~15 cm
- Sigmoidal shape, fitted with $tanh$



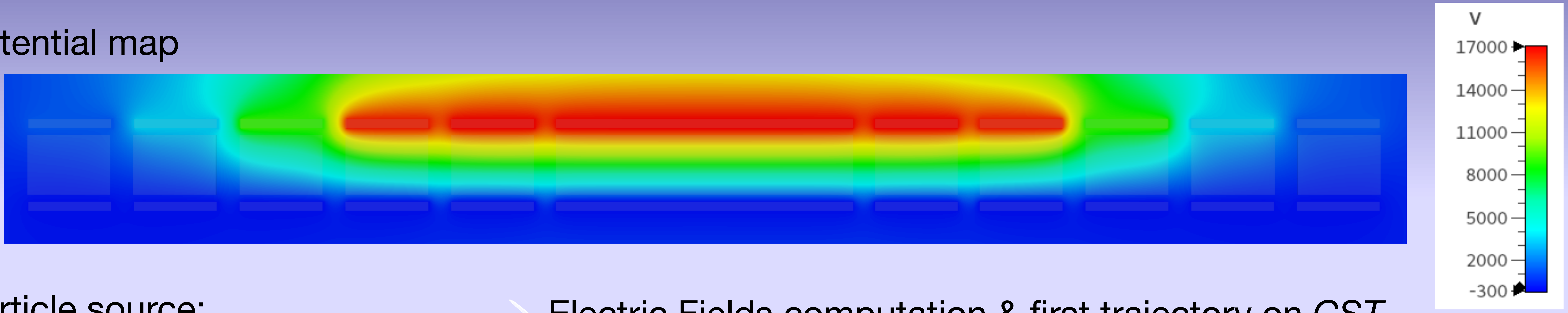




> Voltages applied to top electrodes:

- Injection following a sigmoidal (smoother) profile
- RF voltages matching 5th electrodes' ones
- Ejection with mirrored voltages wrt center ($\nabla B$ inversion → E in -z direction to compensate!)

# First Trajectories from CST

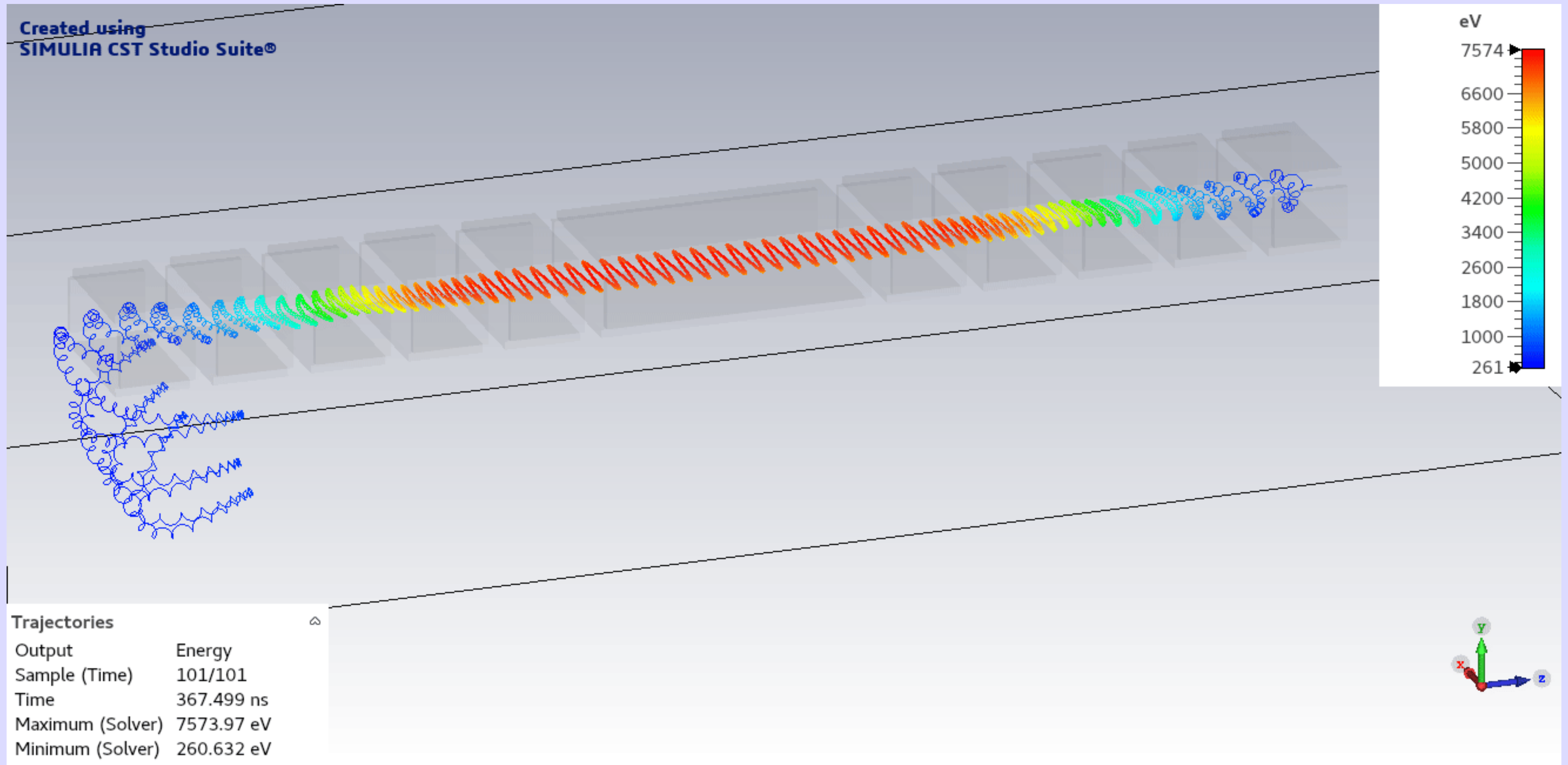
> Potential map



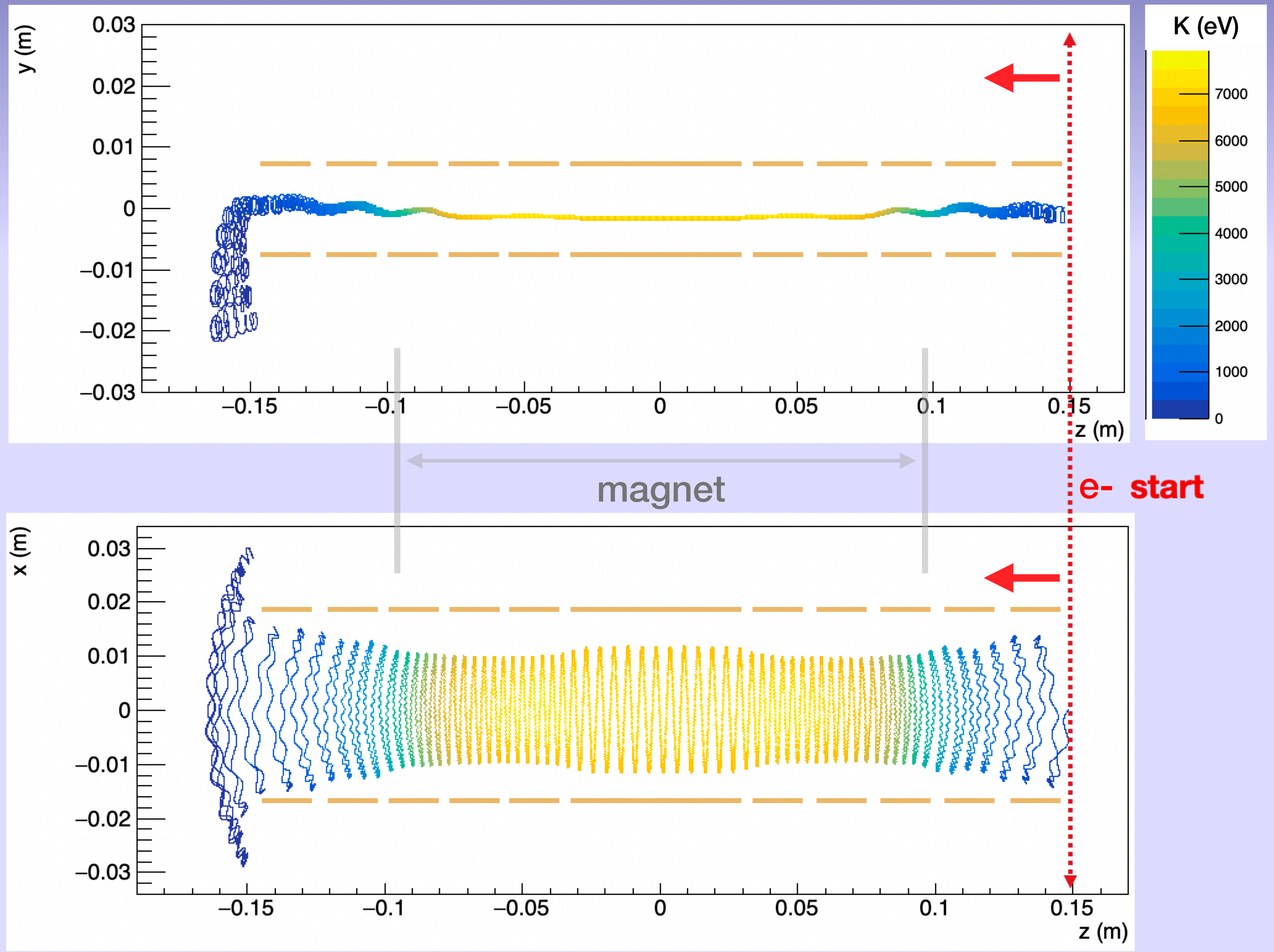

> Particle source:

- 700 eV electron
- 6 cm far from magnet (Bx = 35 mT)
- Pitch angle of 50°
- Centered in xy plane

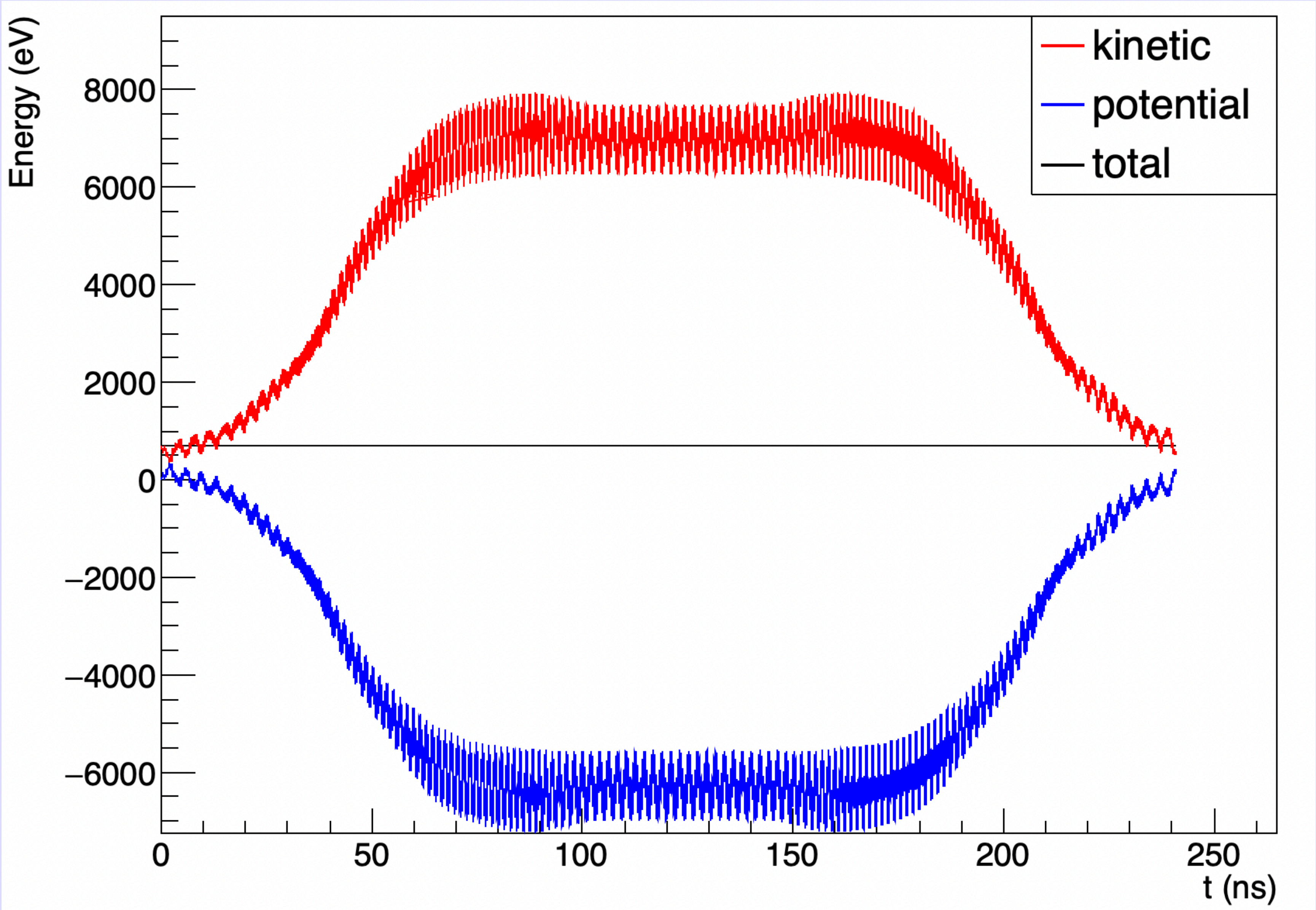
> Electric Fields computation & first trajectory on *CST Studio Suite*



# Energy Transformation




- yz trajectory projection showing **drifts balance**
  - ✓ Electron well kept in central region
- Kinetic energy from 700 eV to ~ 7 keV and viceversa in ~ 30 cm!



# The Real Case: From Electron Source

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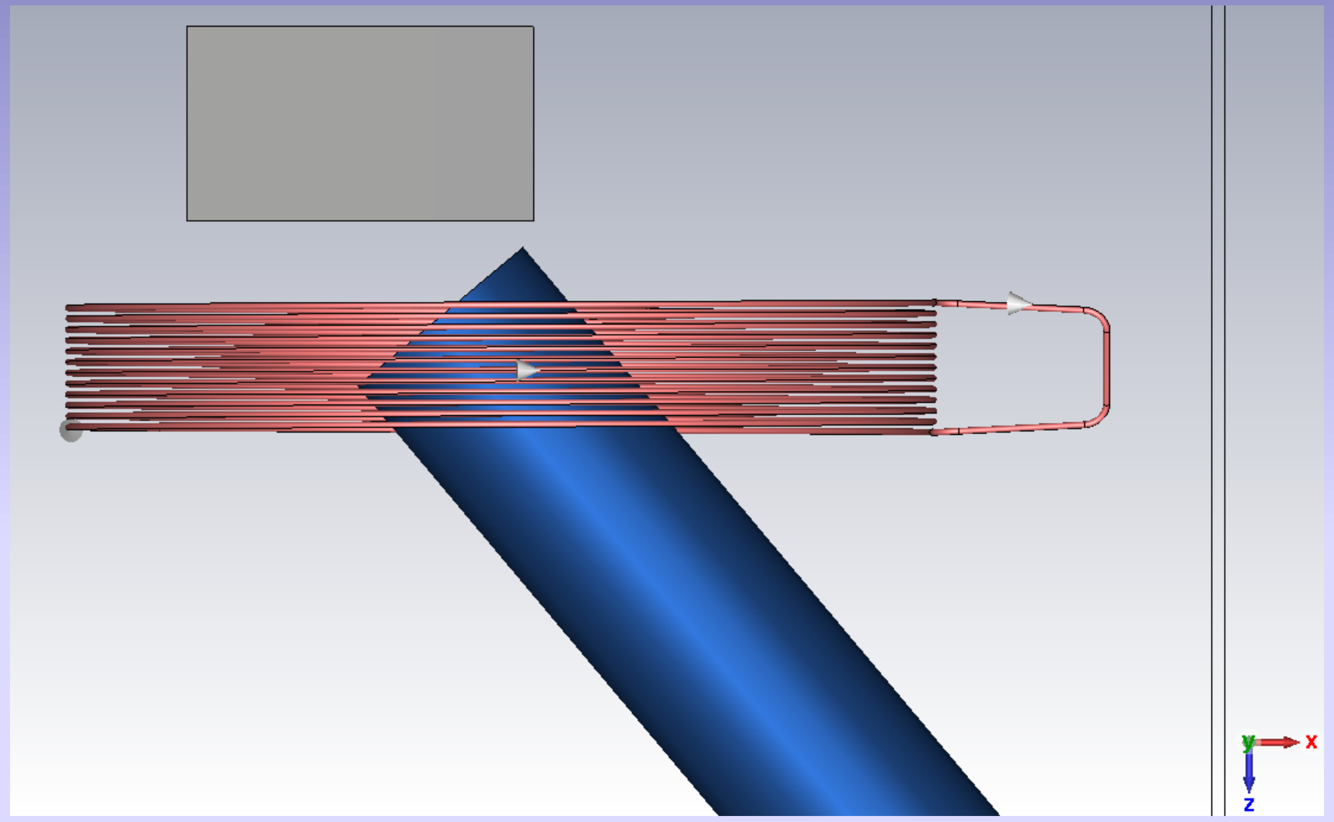
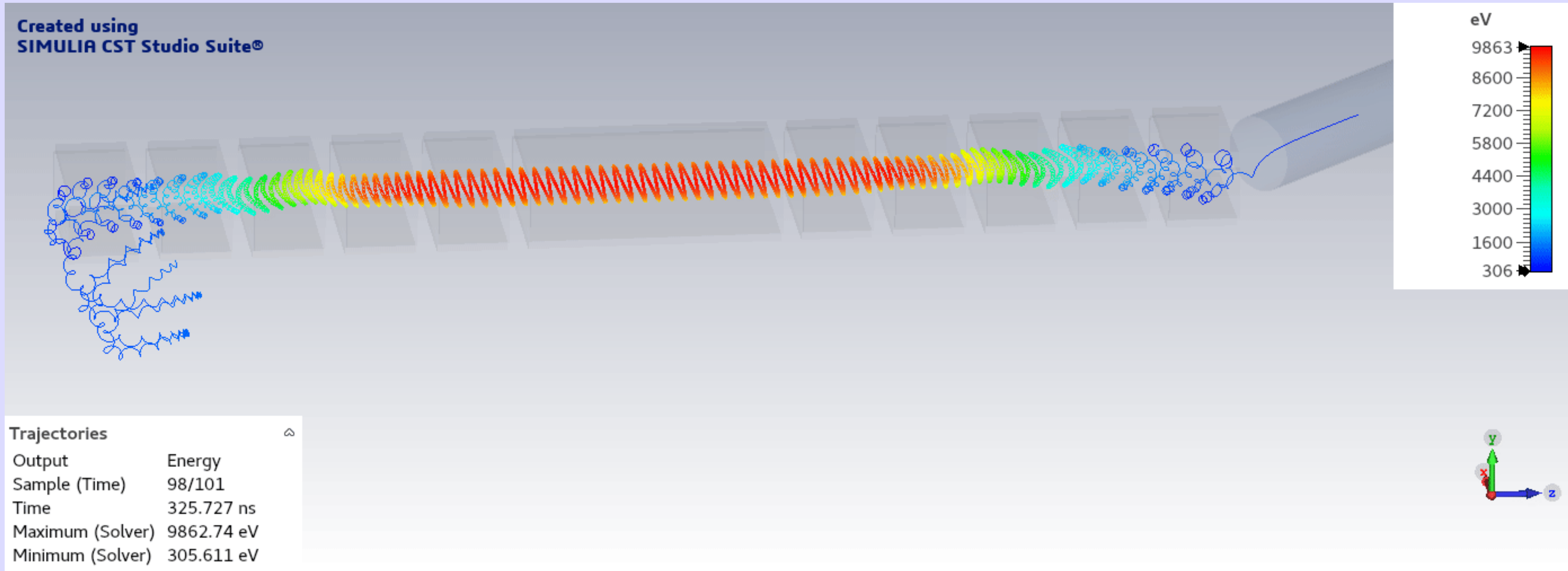
- Aim: bring electrons from e-gun to 1st electrode
  - Allowing focusing
  - With convenient entrance angle

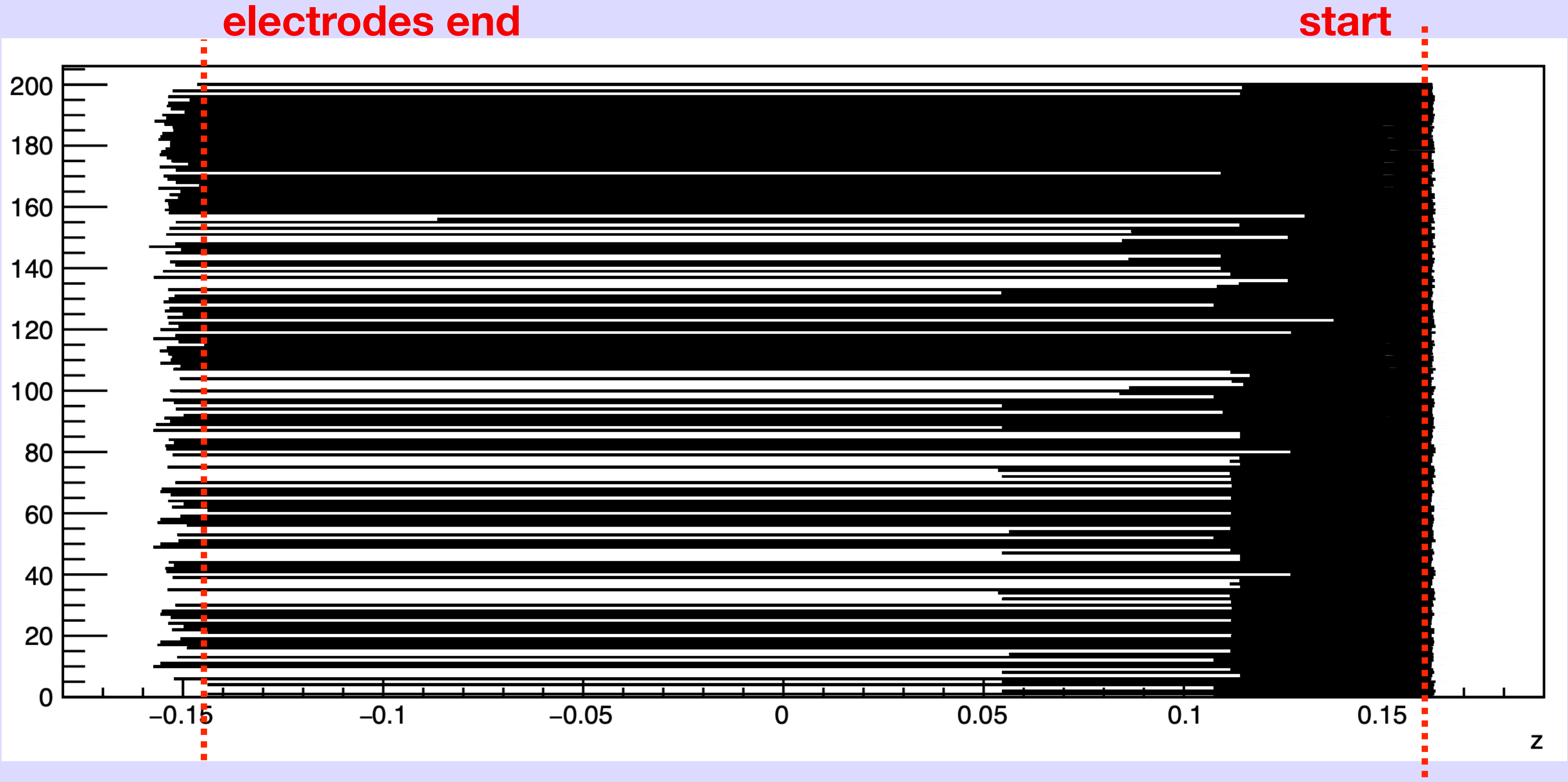


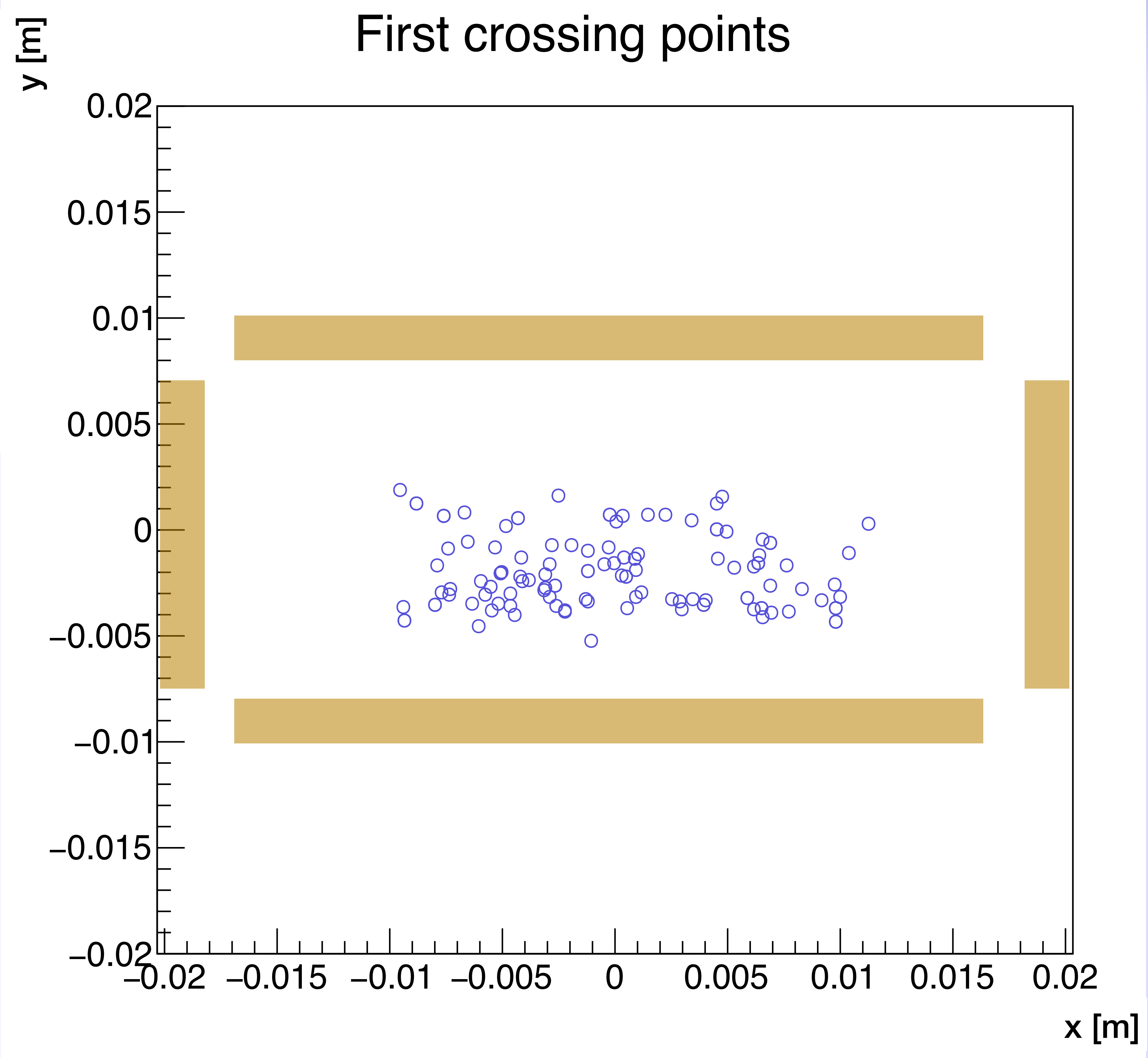
- Possible solution: Focus path screened by mu-metal + coils



# Promising Transport Efficiency

- *Lorentz4* Montecarlo
  to simulate e-gun focused inside mu-metal:
  - 2 mm spot size
  - 5° angle spread
- 123 over 200 electrons reaching end of chain!
  ~60% efficiency



# From Simulations to an Actual Design

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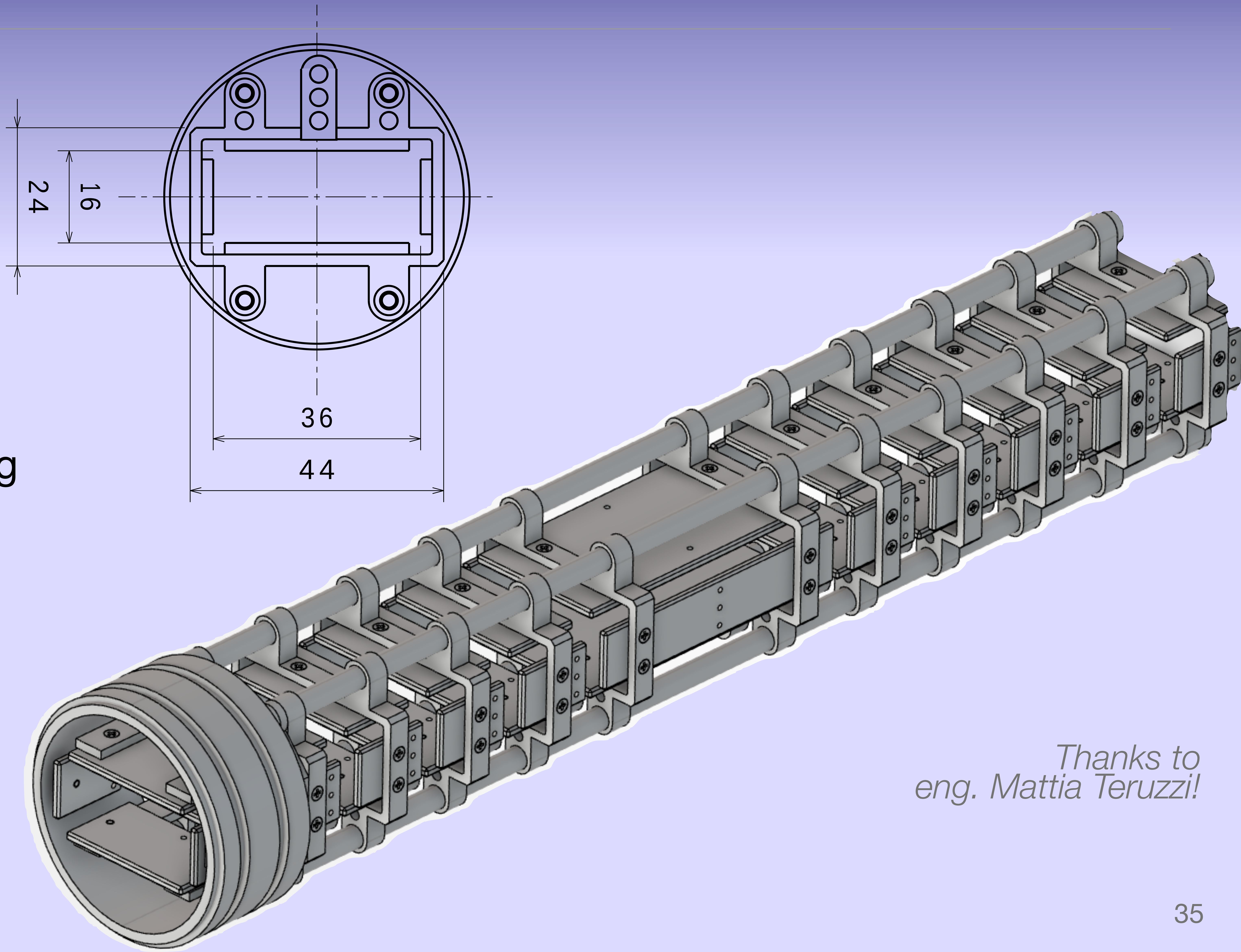
- Copper electrodes 2 mm thickness
- Mechanical supports in PEEK
    - lightweight and compact design
    - modular, chain-like assembly
    - through-holes for HV cable routing
    - through-holes to fix electrodes
- Spacer rods to maintain distances between elements




*Thanks to eng. Mattia Teruzzi!*

# Next Steps

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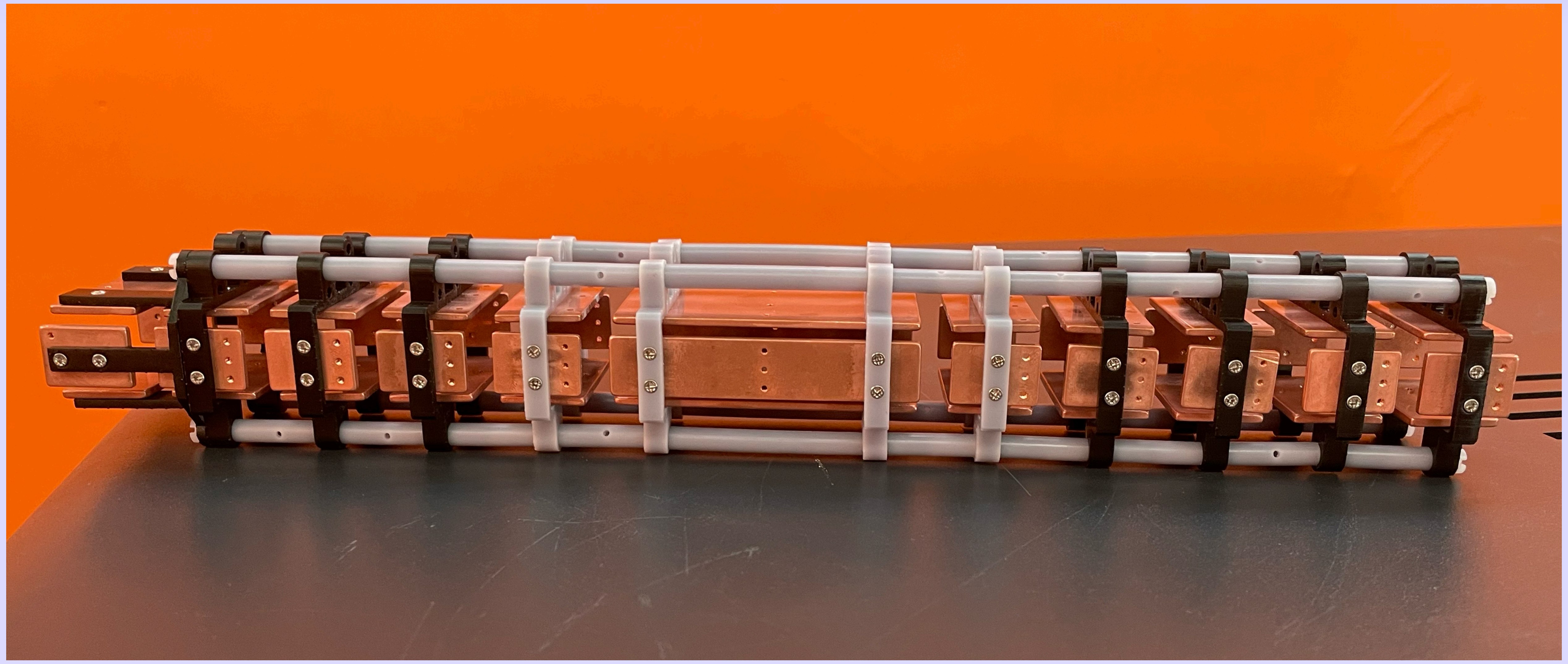
- Electrodes chain + 3D printed supports just realised by LNGS Mechanical Workshop (thanks!)



▷ ONGOING:

- Simulations for injection optimisation
- vacuum chamber fabrication @ LNGS mechanics workshop

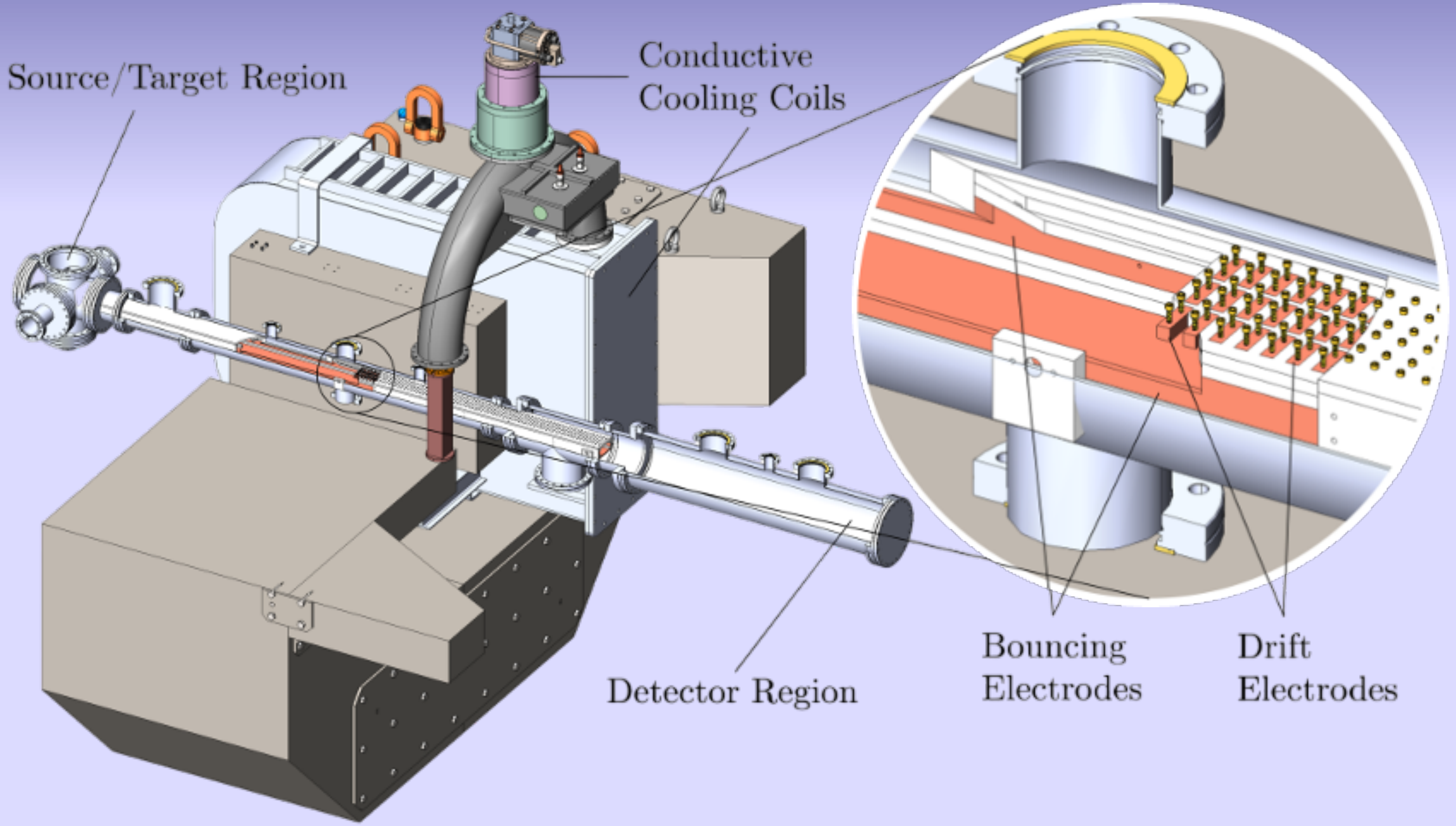
▷ In the next month:

- MCP, SDD test
- Setup assembling and voltages connections

▷ New setup:

- Visualisation on phosphor screen
- Measurements with MCP & SDD

# Demonstrator Look



# PTOLEMY Roadmap

PTOLEMY

**Phase 0:**

**Demonstrator**

*(No tritium)*

- ✳Full demonstrator assembling @ LNGS
- ✳RF measurement in SC magnet
- ✳Injection of calibration electrons
- ✳Detection of electrons with commercial devices

**2026-2027**

**Phase 1:**

**Proof of ultimate resolution**

- ✳Optimisation of filter parameters
- ✳Ultra-high stable HV running
- ✳ Detection of electrons with final device & $\mathcal{O}(50\ meV)$ resolution

**2027-2030**

**Phase 2:**

**Run with Tritium**

- ✳Samples of tritiated graphene ★
- ✳$\beta$-spectrum reconstruction
- ✳Comparison with theoretical models
- ✳Packaged target 1 $\mu g \rightarrow 100\ \mu g$

**2030 →**

**Phase 3:**

**Scale-up for CNB**

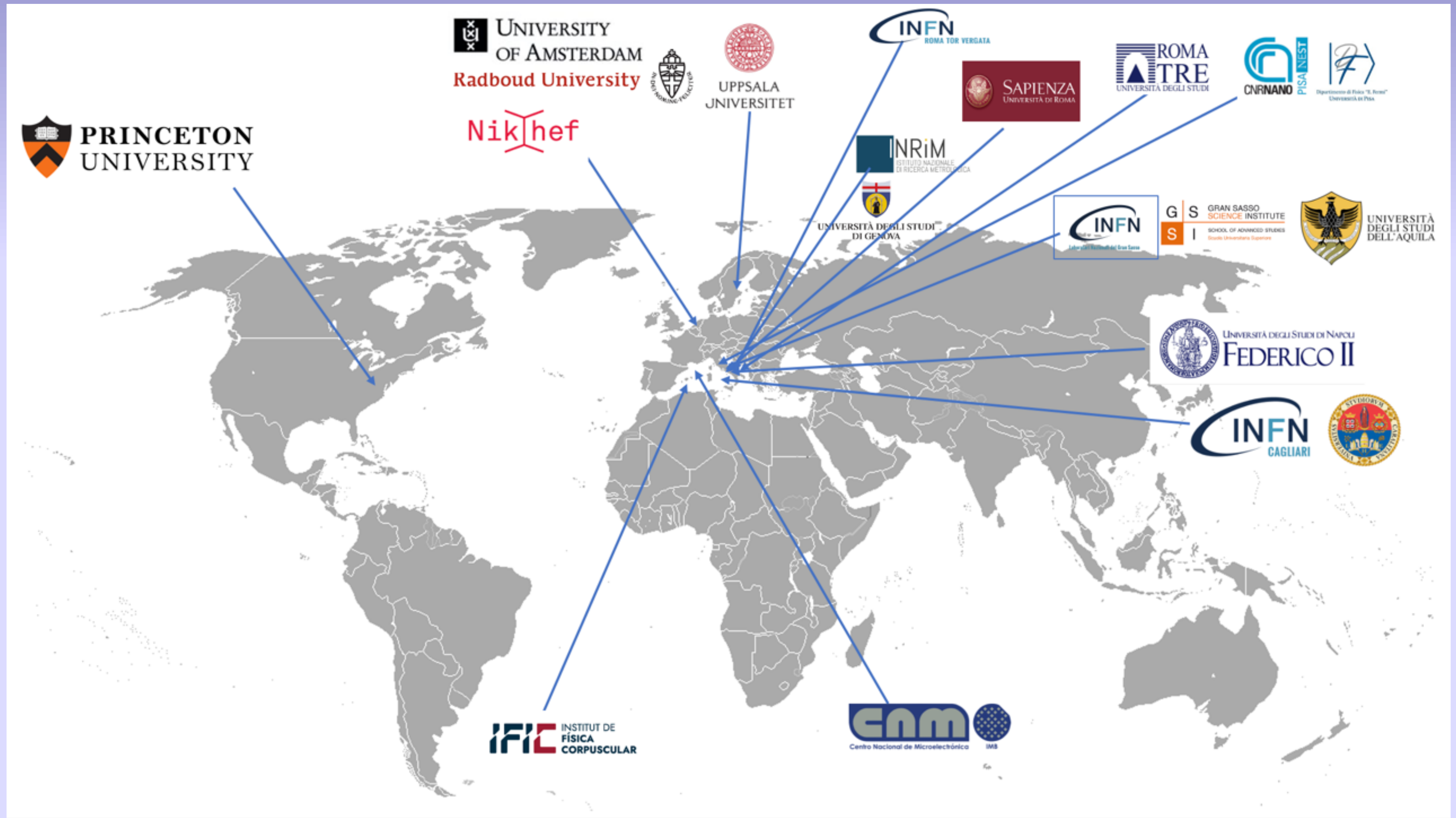
- ✳Multiple detectors
- ✳target 100 $\mu g \rightarrow \mathcal{O}(g)$

→ → →

★ *Feasibility studies for transportable target ongoing with UKAEA*

# The Collaboration

PTOLEMY




*L'Aquila, Collaboration Meeting December 2025*

# Recap & Outlook

PTOLEMY

- ✩Challenging project: extremely precise energy measurement with high background
    - ✩ Innovative concept of electromagnetic transverse drift filter
- ✩Demonstrator under construction @ LNGS from late 2026
- ✩Competitive on **neutrino mass measurement** with small target

**Outlook:**

Phase 0: Demonstrator

Phase 1: proof of ultimate resolution

Phase 2: $\beta$-spectrum measurement

Phase 3: upgrade for CNB