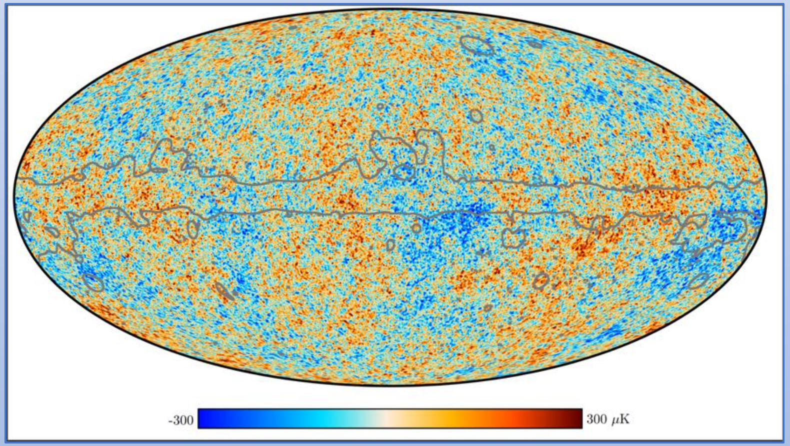
Neutrino mass with the PTOLEMY project

CSN II, zoom meeting 25 luglio 2025

M. Messina LNGS-INFN per conto della collaborazione PTOLEMY

Why we believe in the Big Bang?

1. Expansion of Universe
2. Light element abundances
3. Cosmic Microwave Background



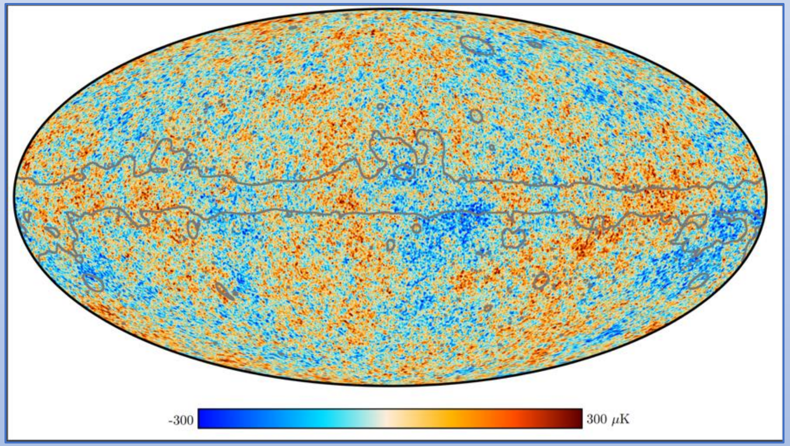
Why believe Big Bang?

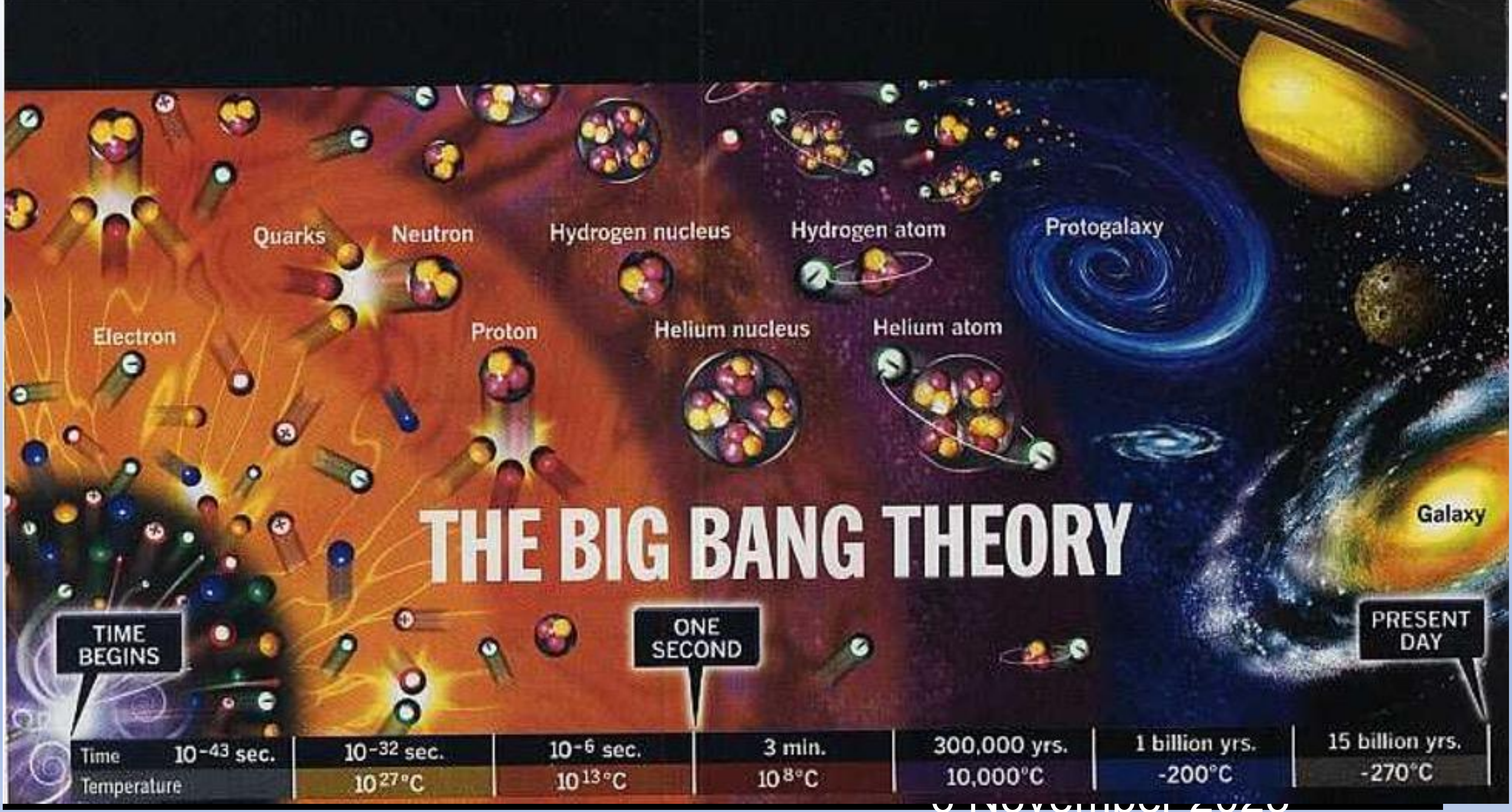
1. Expansion of Universe

2. Light element abundances

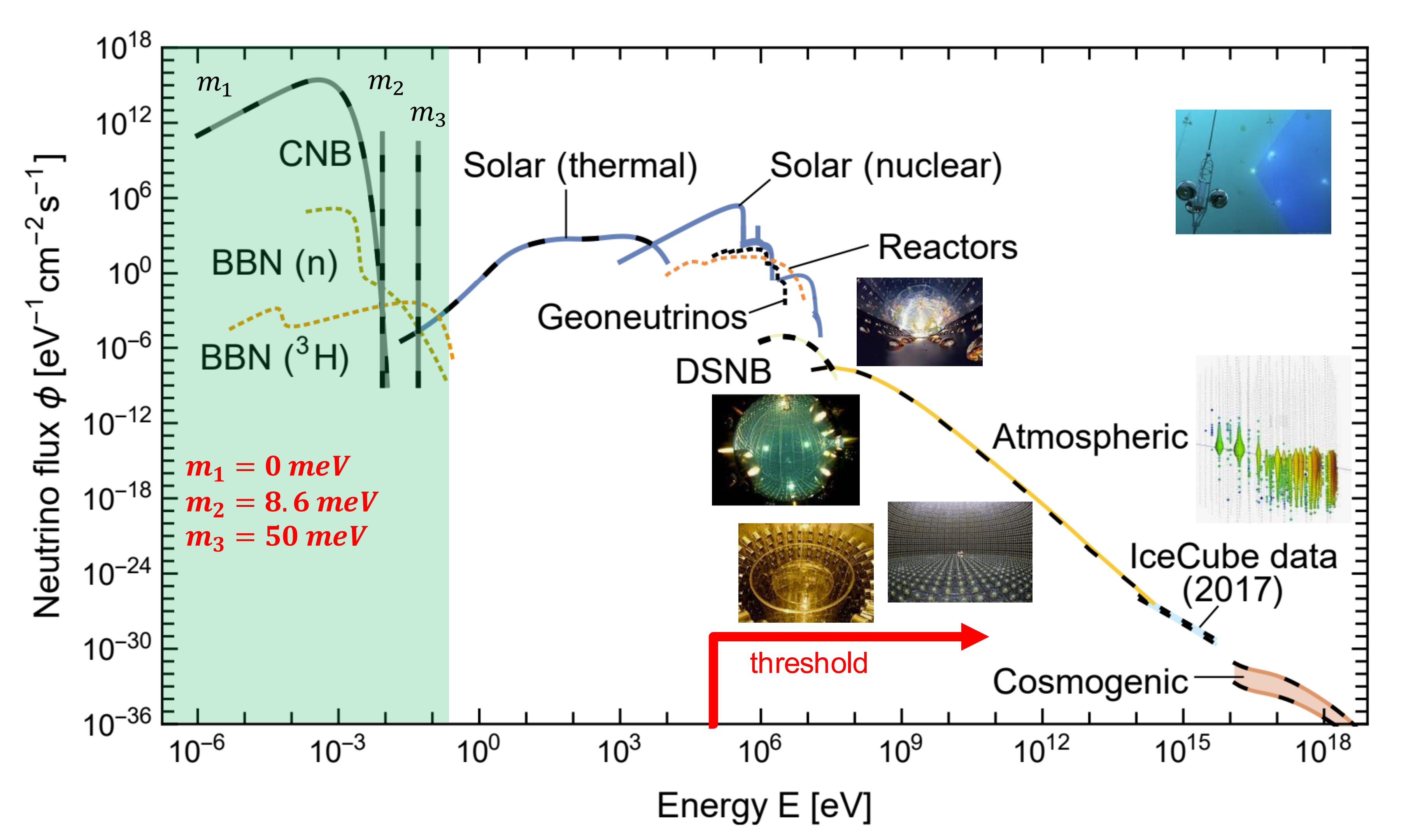
3. Cosmic Microwave Background

4. **Cosmic Neutrino Background**




Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
Galaxy
THE BIG BANG THEORY
TIME BEGINS
ONE SECOND
PRESENT DAY
Time
Temperature
10-43 sec.
10-32 sec.
10 27 °C
10-6 sec.
10 13 °C
3 min.
10 8 °C
300,000 yrs.
10,000°C
1 billion yrs.
-200°C
15 billion yrs.
-270°C

Grand Unified Neutrino Spectrum



https://arxiv.org/pdf/1910.11878.pdf

Where to look for $C\nu B$?

- or –

Is it possible to detect 0.010 eV neutrinos?

Induced beta decay

PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

Universal Neutrino Degeneracy

$m_\nu = 0$

STEVEN WEINBERG*
Imperial College of Science and Technology, London, England
(Received March 22, 1962)

Modern cosmological theories imply that the universe is filled with a shallow degenerate Fermi sea of neutrinos. In the steady state and oscillating models (and perhaps also the "big bang" theories) it can be shown rigorously that the proportion of filled neutrino levels (plus the proportion of filled antineutrino levels) is precisely one up to a finite Fermi energy E_F. The proof takes into account both absorption and the repressive effects of already filled levels on neutrino emission. Experiment shows that $E_F \lesssim 200$ eV for antineutrinos and $E_F \lesssim 1000$ eV for neutrinos. The degenerate neutrinos could be observed (if $E_F > 10$ eV) by looking for apparent violations of energy conservation in β^- decay. In the steady state and evolutionary cosmologies E_F is much too low to ever be observed, but in the oscillating cosmologies $E_F \simeq 5R_c$ MeV, where R_c is the minimum radius of the universe in units of its present radius; thus experiment already shows that the universe will contract by a factor over 10^3, if at all. Astronomical evidence plus Einstein's field equation (without cosmological constant) require in an oscillating cosmology that $E_F < 2\times10^{-3}$ eV (so $R_c < 10^{-9}$) and suggest that higher energy neutrinos may represent the bulk of the energy of the universe. A model universe incorporating this idea is constructed.

$$n_i = \frac{1}{e^{(\epsilon_i - \mu)/k_B T} + 1}$$

$$\frac{\mu}{k_B T} < 0.1$$

Cocco, Mangano, Messina calculated in 2007
the interation cross section and the rate with $m_\nu \neq 0$ case

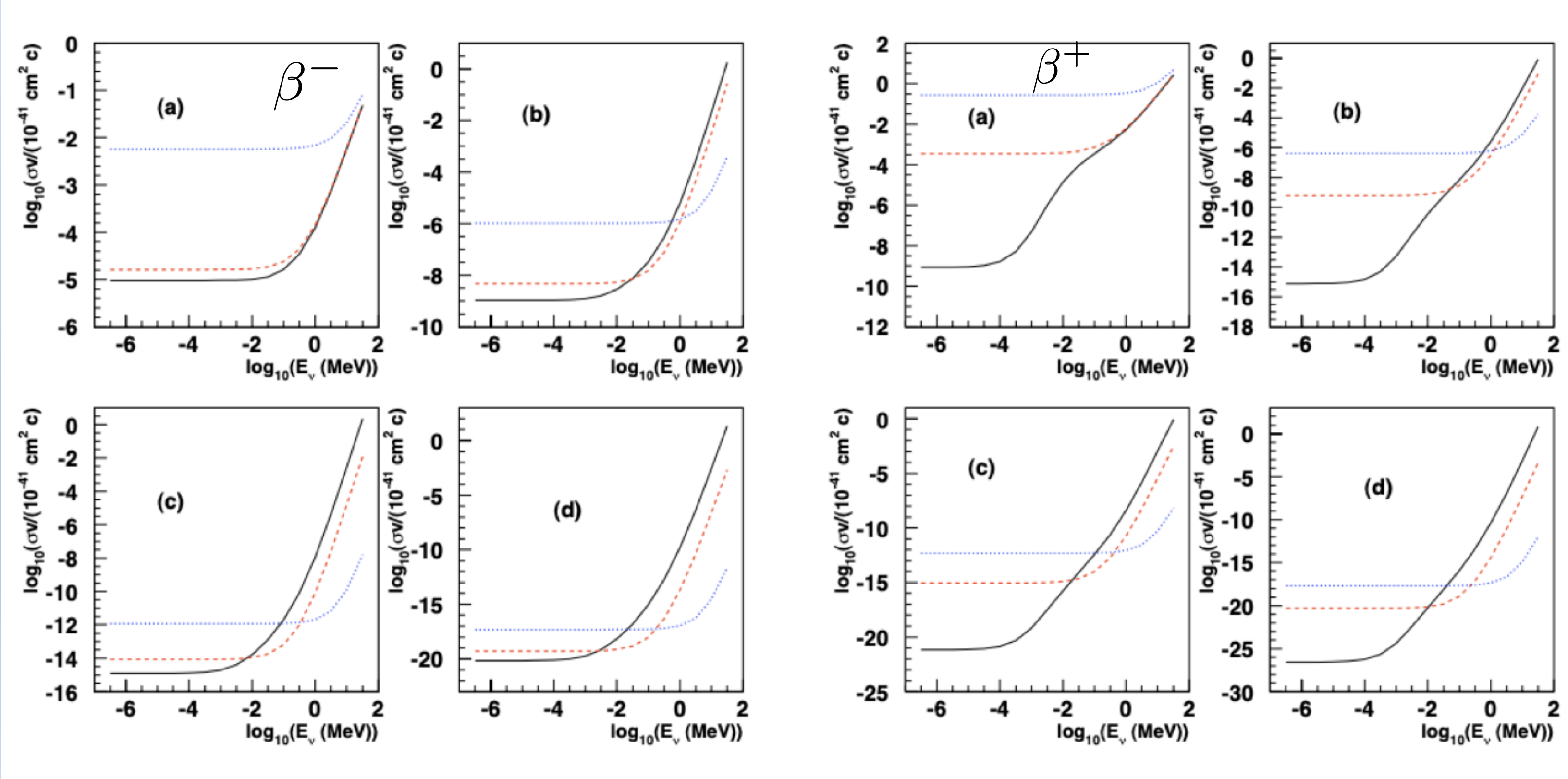
JCAP 0706:015,2007

CROSS SECTIONS

Tritium has the largest product of capture cross section and lifetime

$$^3H \rightarrow ^3He^+ + e^- + \bar{\nu}_e$$

$$\bar{\nu}_e + ^3H \rightarrow ^3He^+ + e^-$$



Detailed evaluation on 2007

JCAP 06 (2007) 015

of $\sigma x \tau$ renewed the dormant discussion on relic neutrino detection and paved the view to a possible experiment.

Several authors confirmed the cross section evaluation and added informations:

J. Phys. G: Nucl. Part. Phys. 35 025001

JCAP 08 (2014) 038

Selection of target

"Highish" cross-section

"Longish" lifetime

Isotope	Decay	Q_β (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^8	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^9	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^7	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^3	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^2	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^2	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^3	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^7	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^4	3.87×10^{-4}

Expected rate: 100 gram-year exposure

JCAP 0706:015,2007

m_ν (eV)	FD (events yr^{-1})	NFW (events yr^{-1})	MW (events yrs^{-1})
0.6	7.5 x0.5	90 x0.5	150 x0.5
0.3	7.5	23	33
0.15	7.5	10	12

Dirac

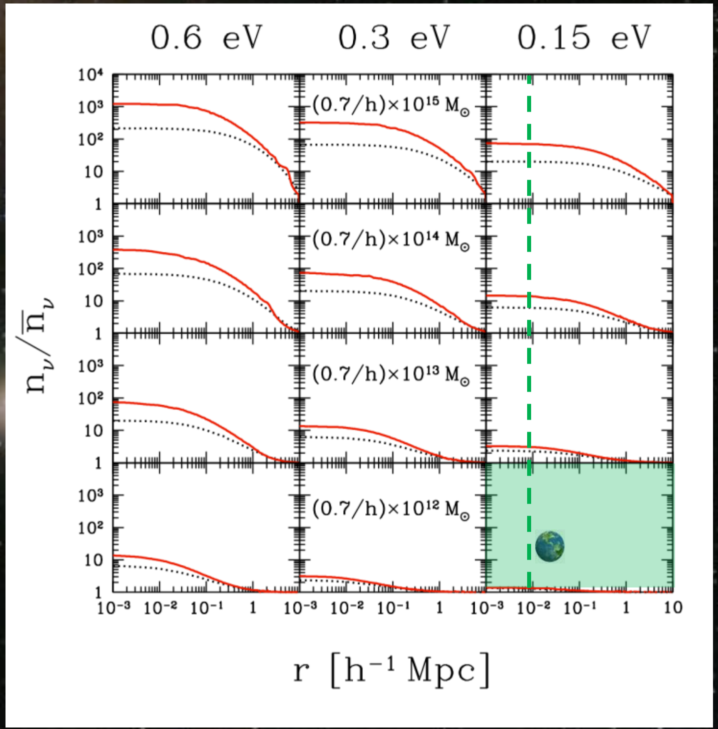
m_ν (eV)	FD (events yr^{-1})	NFW (events yr^{-1})	MW (events yrs^{-1})
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

Majorana

JCAP 076:015, 2007
JCAP 1408 (2014) 038

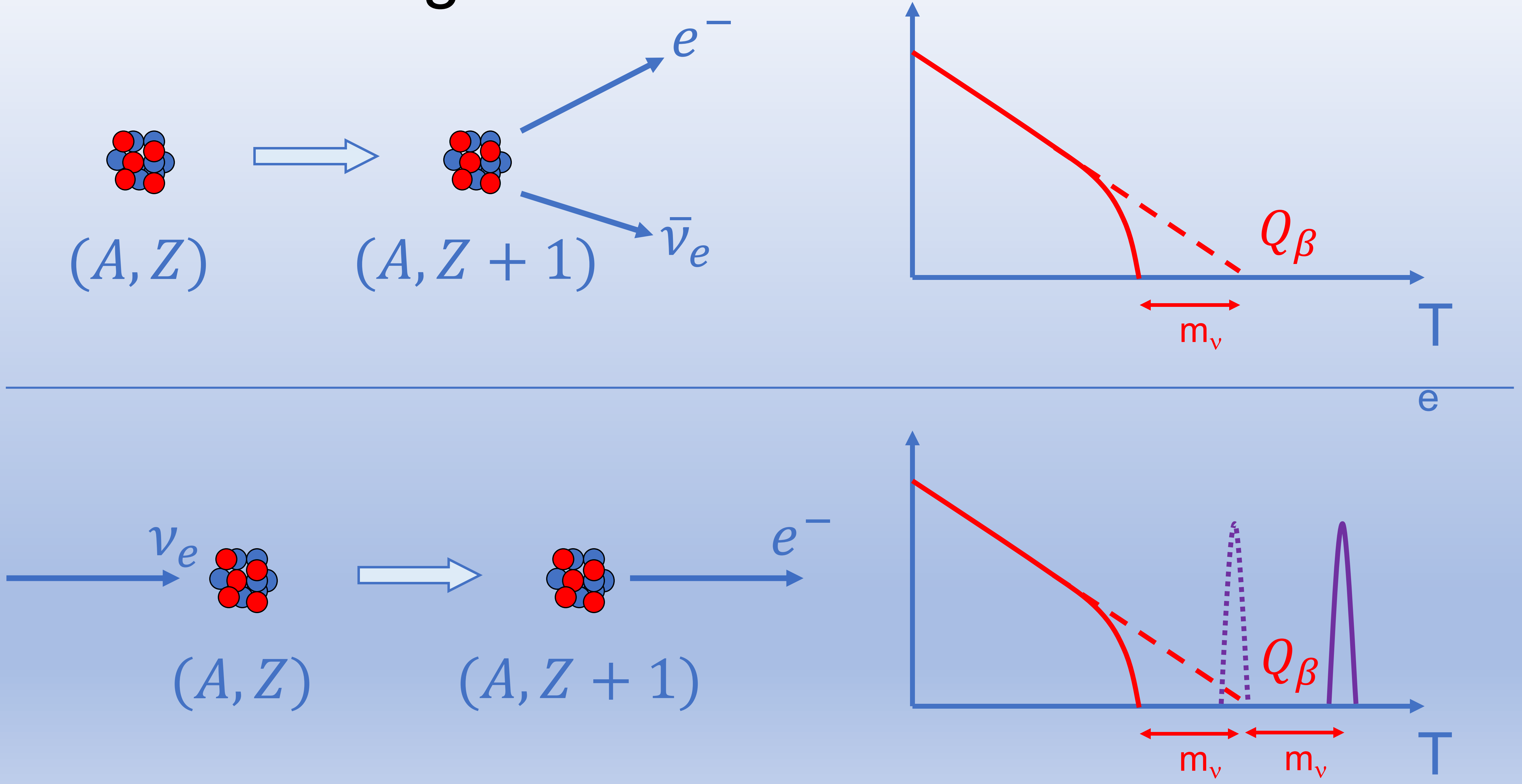
Exp

Gravitational clustering



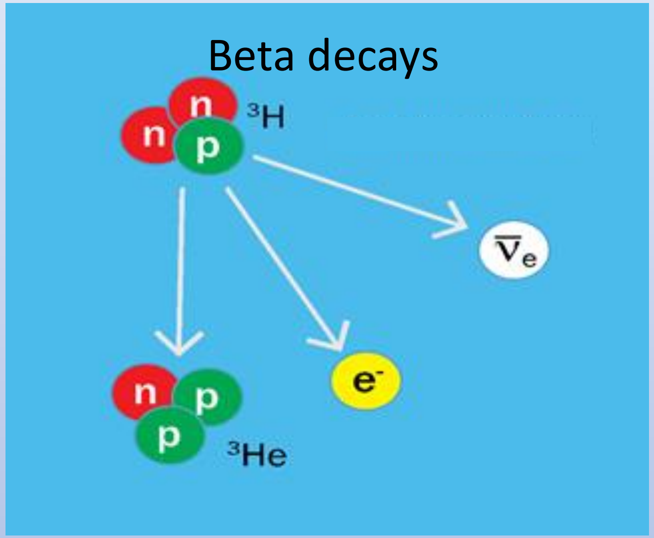
https://arxiv.org/pdf/hep-ph/0408241.pdf

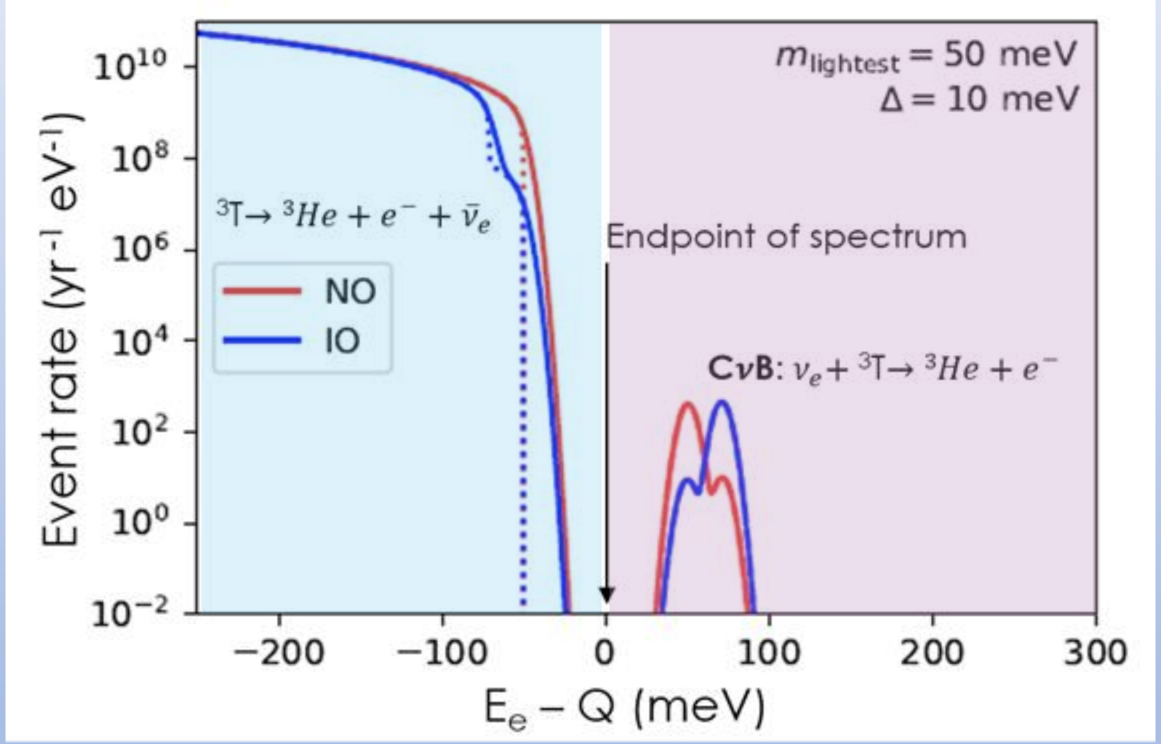
Signature of relic neutrinos

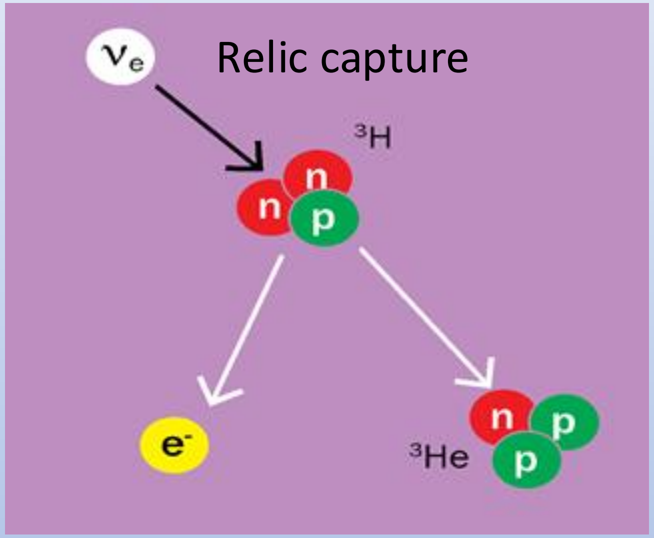


Detection concept: Neutrino Capture on β unstable nuclei

Proposal for their direct experimental detection in
[AG.Cocco, G.Mangano, M.Messina JCAP 06(2007)015]







M.G. Betti *et al* JCAP 07(2019)047

Electron flavor expected with

m ≳50meV

from **neutrino oscillations**

CνB Detection Requires:
energy resolution set by m_ν

Requirements on energy resolution for neutrino mass measurement are weaker than relic case (50 meV)

DocID	*Rev.*	*Validity*
INFN-PTOLEMY-QA-210	0.2	Rilasciato

Letter of Intent for the PTOLEMY project
document for INFN CNS2

Data: 25/06/2025
Rev. 0.2.1 - 25/06/2025

Authors and approvals

Editors	Checked by	Approved by
G.Cavoto, M.Messina	G.Cavoto, M.Messina, F.Virzi, F.M. Pofi, A.G.Cocco	PTOLEMY collaboration

Distribution

- Public document

Revision history

Rev.	Data	Description of updates	Authors/Editors
0.2.1	25/06/25	First draft	G.Cavoto, M.Messina

LoI:

2 years project **(Phase0)** to deliver a **CDR** for neutrino mass measurement.

We ask **support** above all to strengthen the collaboration and simultaneously address the remaining technical issue.

CDR:

will contain the **Demonstrator design** aiming at demonstrating the technology

REMARK:
demonstrator = detector for a competitive neutrino mass measurement

PTOLEMY first physics goal: neutrino mass

- Once the CDR will be delivered, in two years from now, the schedule for neutrino mass measurement will be clarified.

- Novelty elements of the PTOLEMY detector:
    - Novel concept of a **compact dynamic electromagnetic filter**
    - Atomic tritium on a graphene support (monoatomic layer of C atoms)
    - Differential energy measurement with unprecedented energy resolution

PTOLEMY Demonstrator

aims at showing the capability of the PTOLEMY collaboration to master technologies

As described in the LoI we focus on a Phase0 to demonstrate the technology and this is the topic on which we ask the CSN II to approve the project:

M1: Experimental Demonstration of the Filter Concept

M2: Feasibility study of tritium on graphene production

M3: Realistic design of 1 mug tritium target

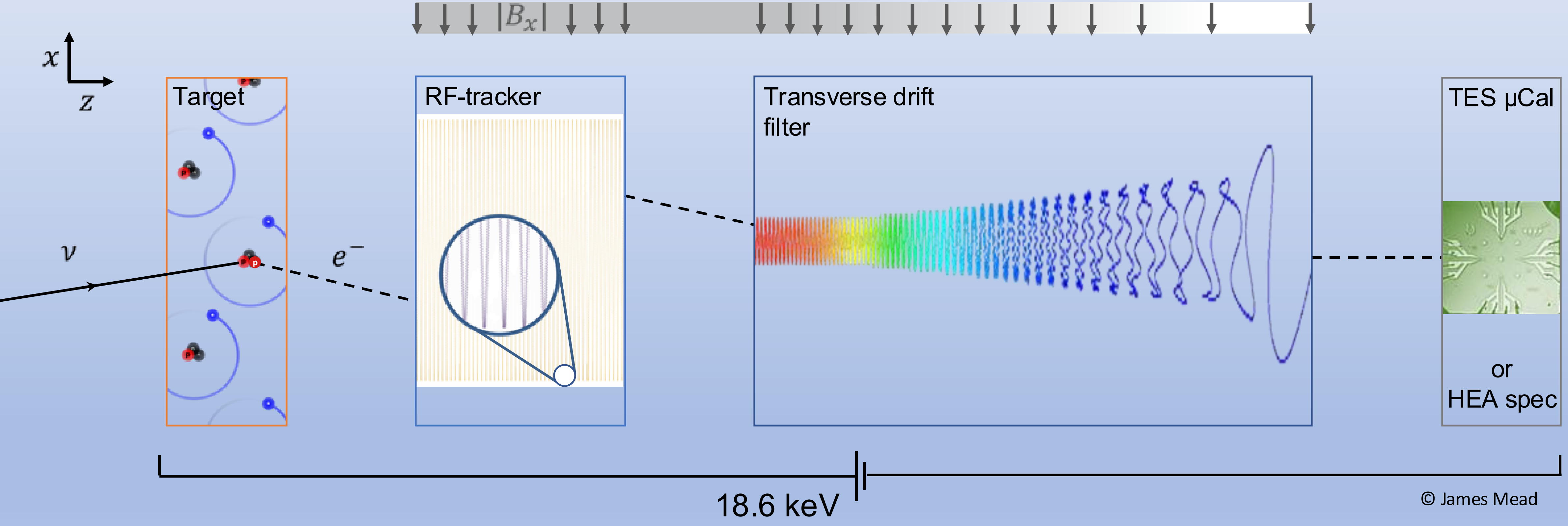
M4: RF detection

M5: Full simulation of a filter for neutrino mass experiment

M6: Conceptual design report ready (Detailing Phase1 time scale)

PTOLEMY detector scheme

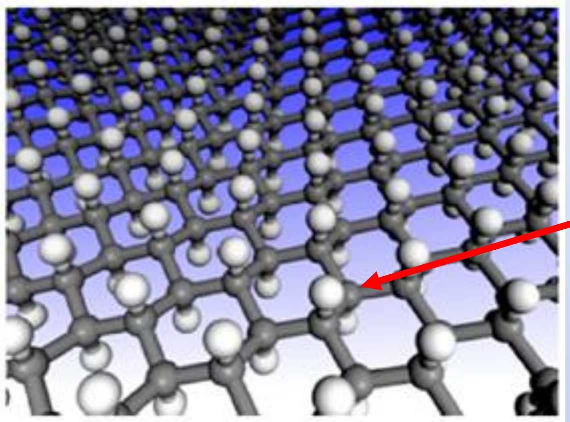
Pon**T**ecorvo / **P**rince**T**on **O**bservatory for **L**ight **E**arly-universe **M**assive-neutrino **Y**ield



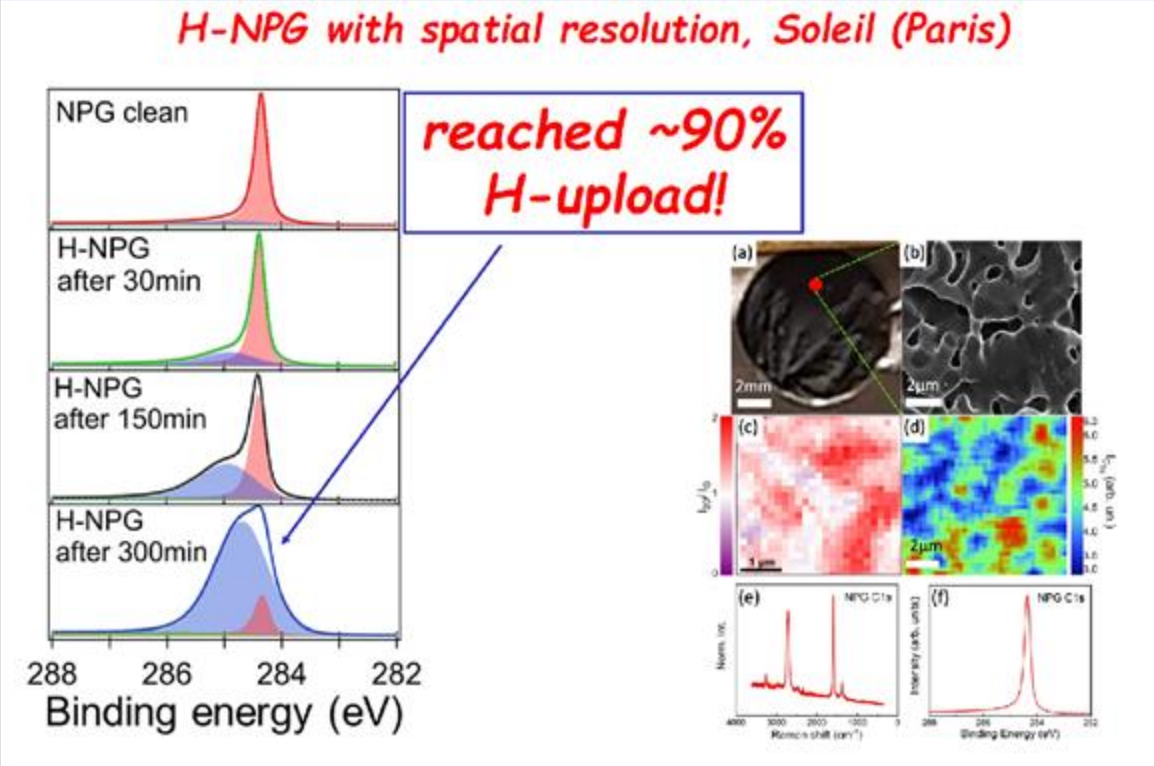
$$E_{total} = q(V_{TES} - V_{target}) + E_{RF} + E_{cal}$$

Hydrogen and Deuterium loading on graphene at Roma1 and Roma3

atomic H as a tool to '*pinch*' the sp^2 bonds towards a sp^3 configuration
while maintaining the planar nature of graphene

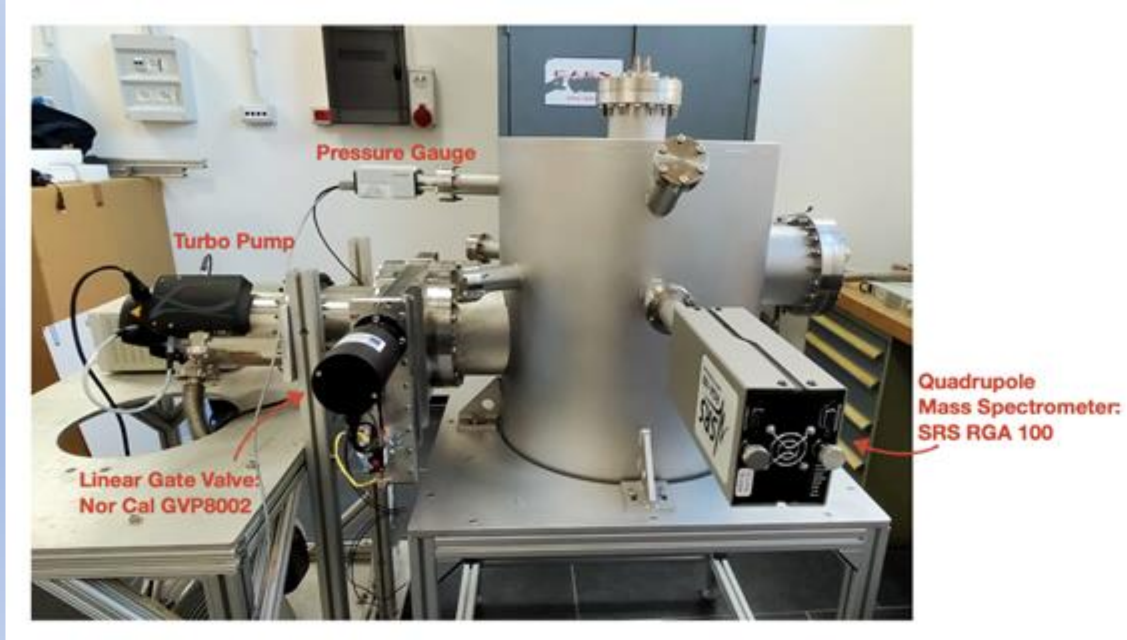


H on Nanoporous Graphene (NPG):



Betti et all, Nano Lett. **22**, 2971 (2022)

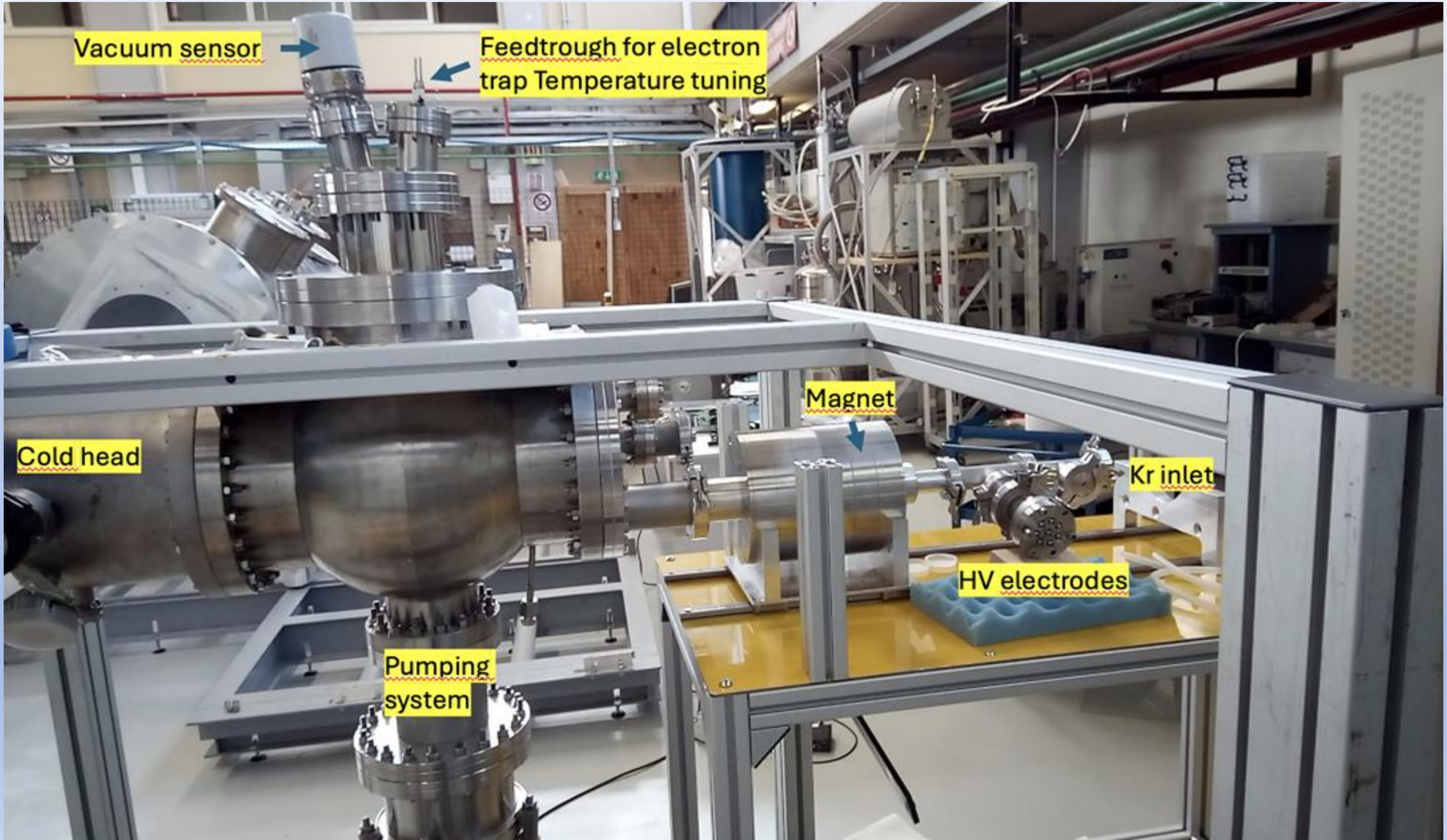
T-chamber in Rome side view:



UKAEA's Active Gas Handling System (tritium for JET, EU Tokamak) for **feasibility study & design requirement** of a **new T loading chamber**

Quote received few months ago

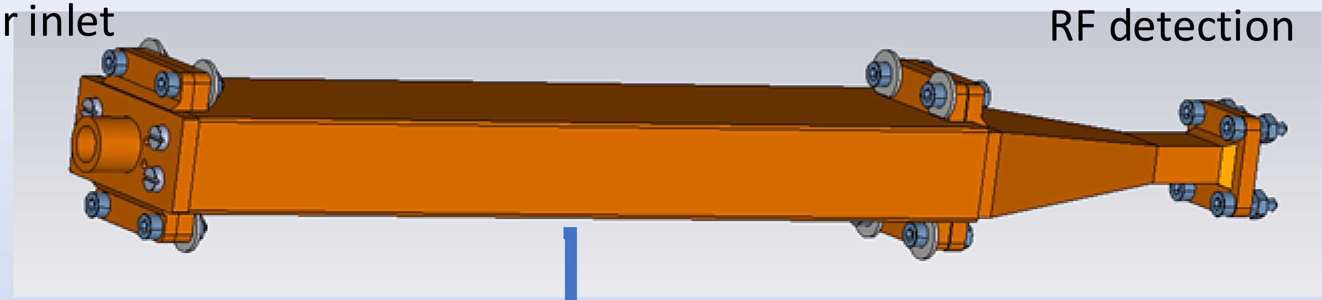
RF detection setup at LNGS: electron trap

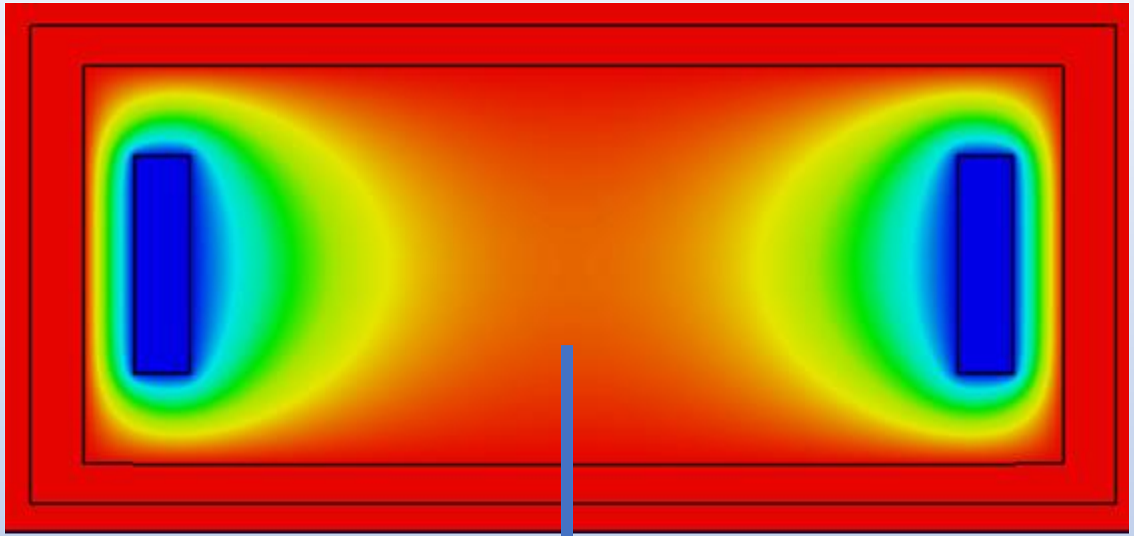


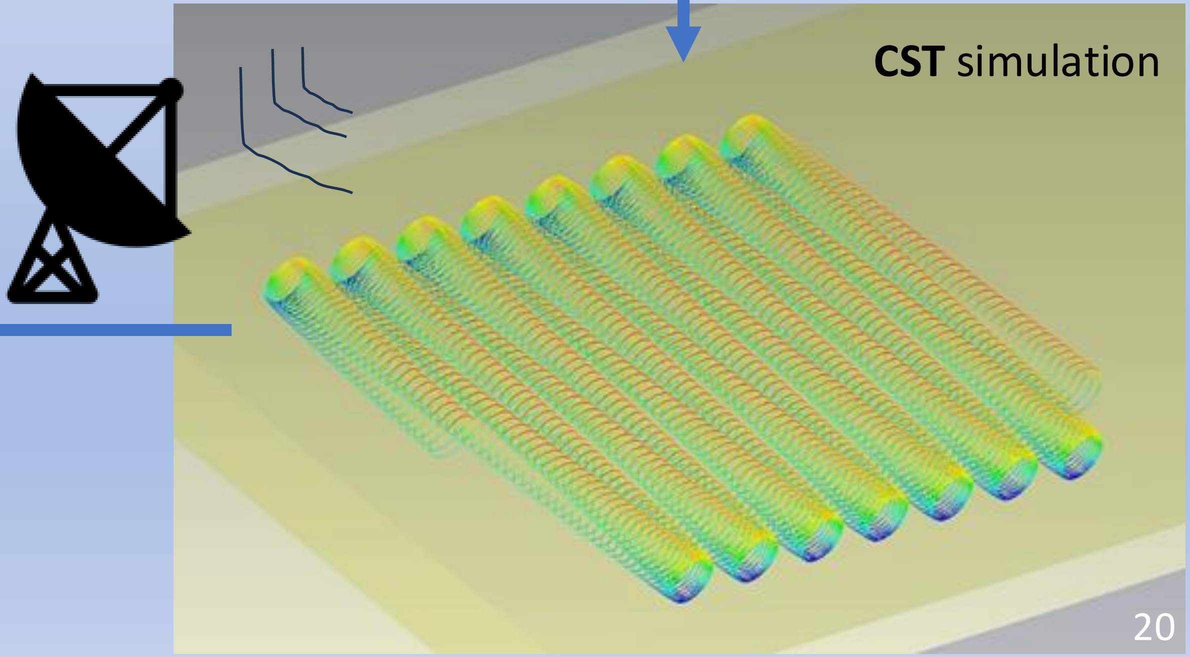
Electron cyclotron RF radiation studies

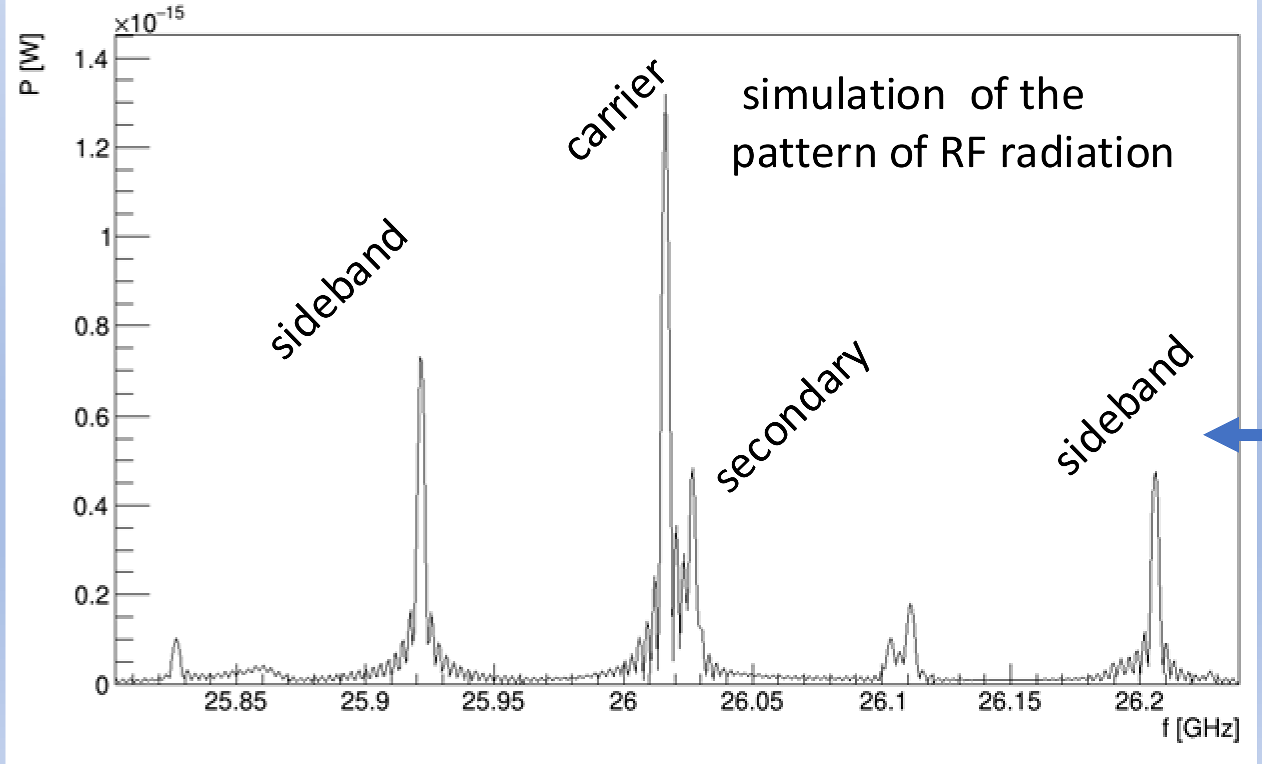
Kr inlet

RF detection



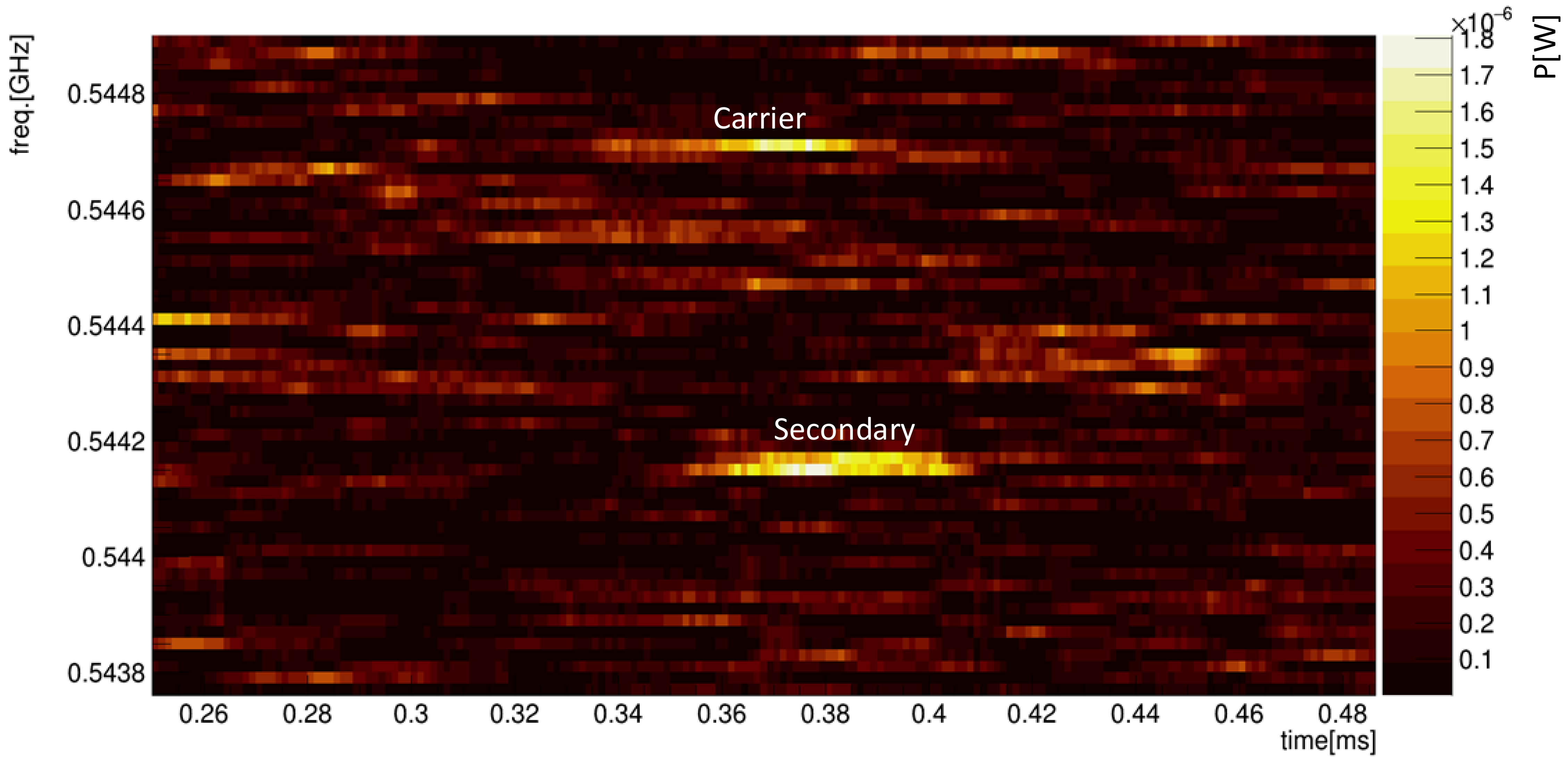






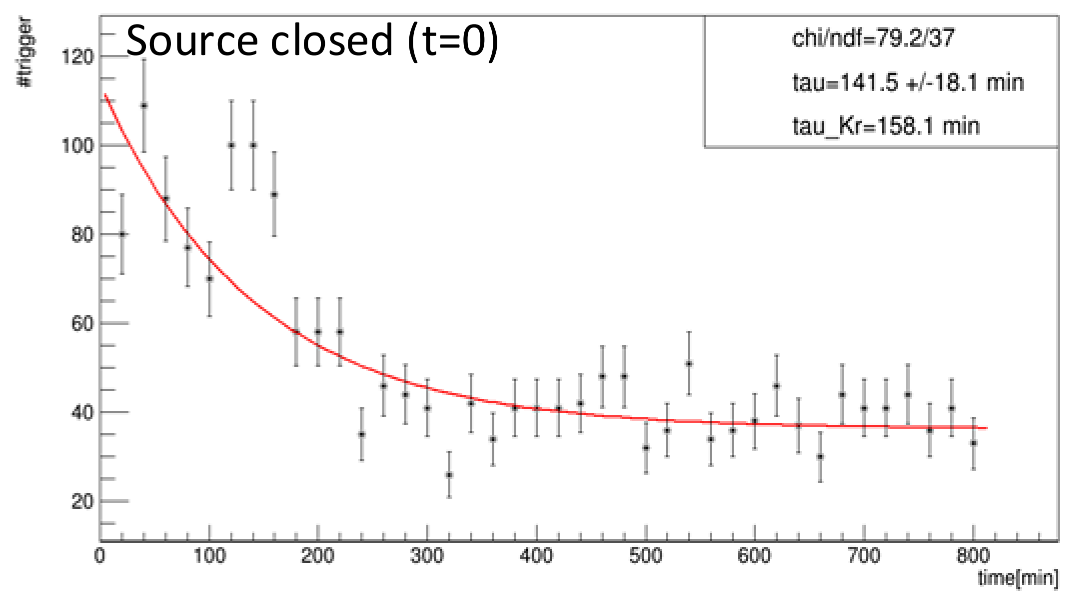
Candidate electron events

RF emission frequency vs time of single electron in the permanent magnet



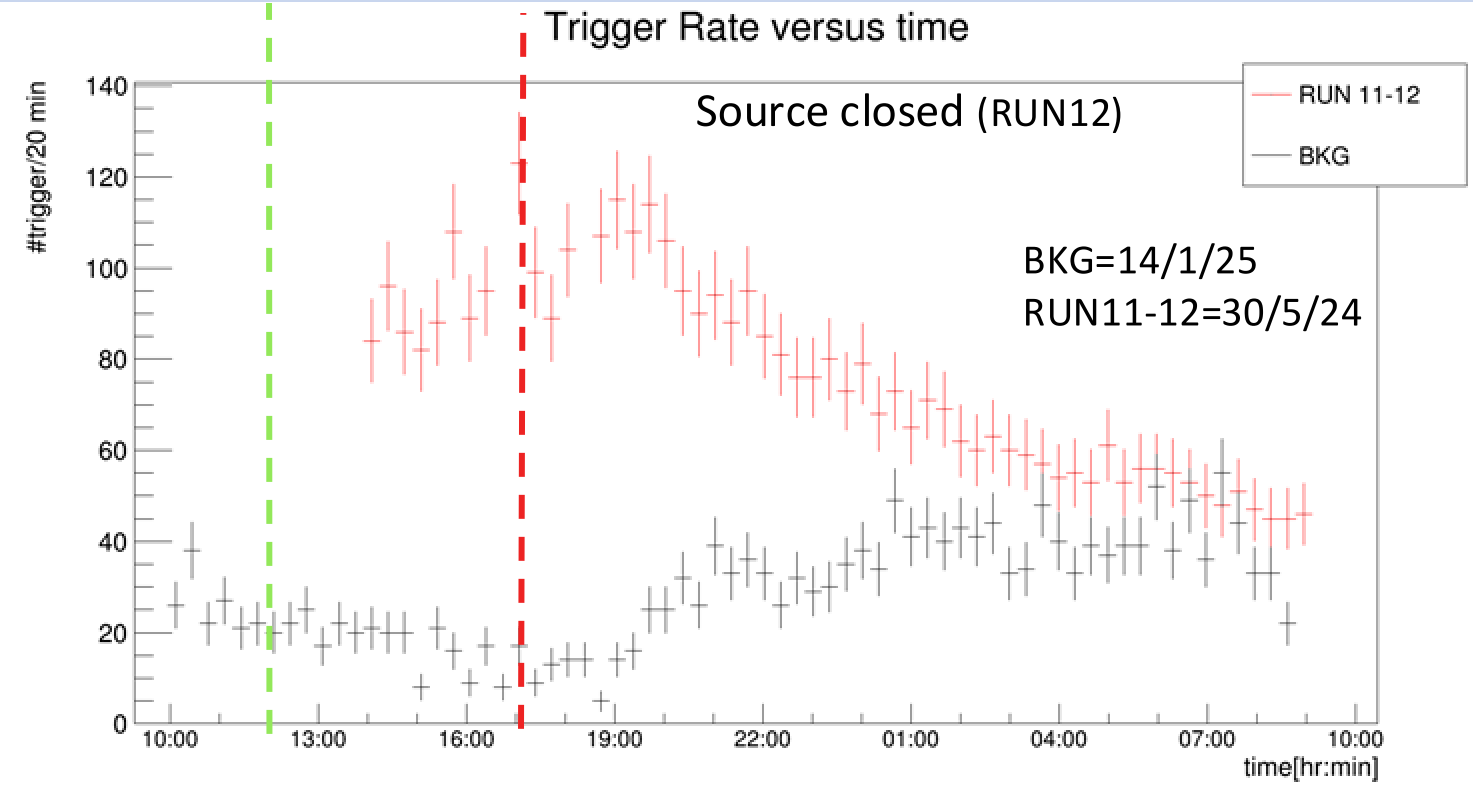
Electron signature: trigger rate (data)

Source: $^{85}Rb \rightarrow {}^{83m}Kr$
Lifetime Kr = 158.1 min



Source open (RUN11)

Source closed (RUN12)

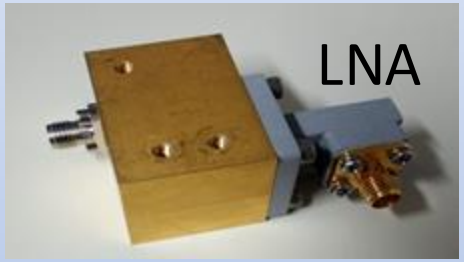


- $Freq_{RF}$= 26 GHz
- P_{RF}= 1 fW

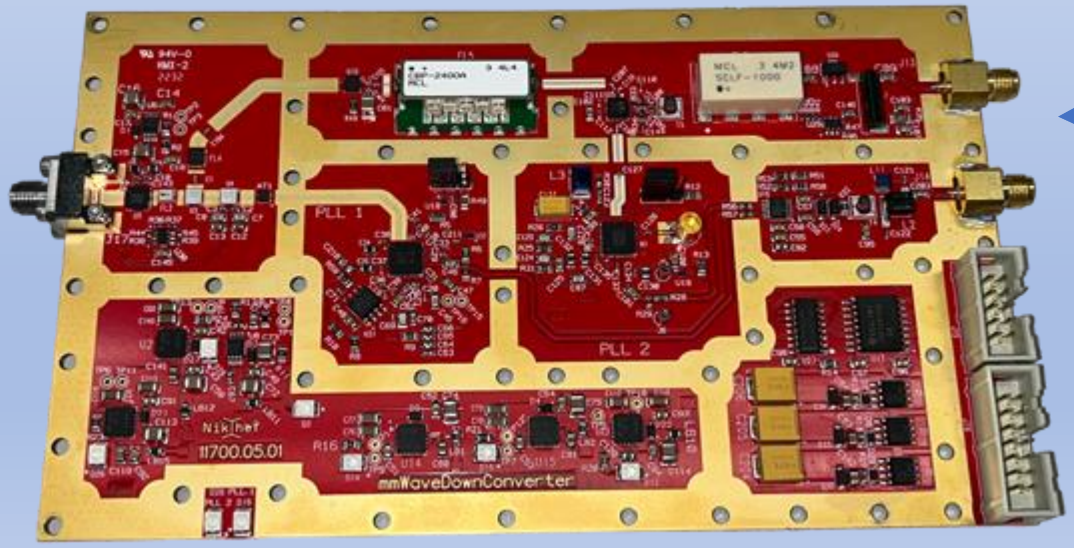
Electronic chain:
Low noise amplification + down-conversion

- $Freq_{IF}$= 550 MHz
- P_{RF}=2 μW

RF readout electronics



RTO64 used for DAQ



Dedicated downconverter developed @ NIKHEF

DAQ with FPGA trigger under development @ NIKHEF

PTOLEMY filter: years of development

Particle trajectories can be calculated/predicted analytically:

- Given the following field configuration:

$$V(x,y,z) = T'_\perp \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda}$$

$$E_x = 0$$

$$E_y = \frac{T'_\perp}{\lambda} \cos\left(\frac{y}{\lambda}\right) e^{-z/\lambda}$$

$$E_z = -\frac{T'_\perp}{\lambda} \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda}$$

$$B_x = B_0 \cos\left(\frac{x}{\lambda}\right) e^{-z/\lambda}$$

$$B_y = 0$$

$$B_z = -B_0 \sin\left(\frac{x}{\lambda}\right) e^{-z/\lambda}$$

- The drift balancing condition along z is:

$$\boldsymbol{V}^y_{E\times B}(z) = \boldsymbol{V}_{\nabla B}(z)$$

$$\frac{\boldsymbol{E}\times\boldsymbol{B}}{B_x^2} = -\frac{\boldsymbol{\mu}\times\boldsymbol{\nabla}_\perp \boldsymbol{B}(z)}{qB(z)}$$

- With $x \ll \lambda$,

$$\frac{E_z}{B_x}\hat{\boldsymbol{y}} = -\frac{\mu}{qB_x}\frac{dB_x}{dz}\hat{\boldsymbol{y}}$$

$$\approx \frac{E_z}{B} = -\frac{\mu}{qB}\frac{\partial B_x}{\partial z}$$

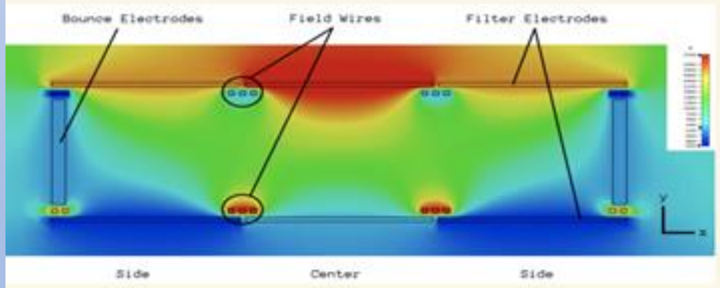
$$-\frac{T'_\perp}{B_0\lambda}\sin\left(\frac{y_0}{\lambda}\right) = \frac{\mu}{q\lambda}$$

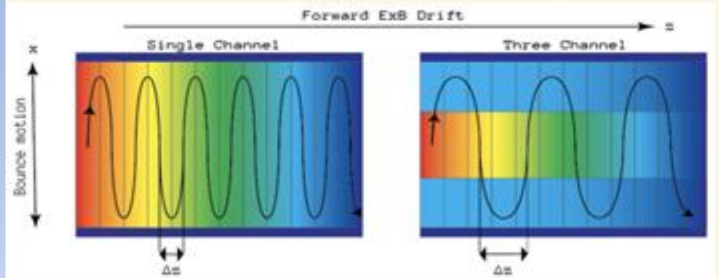
- Solving for $T'_\perp$ and rewriting $\mu = \dfrac{T_{\perp 0}}{B_0 e^{-z_0/\lambda}}$,

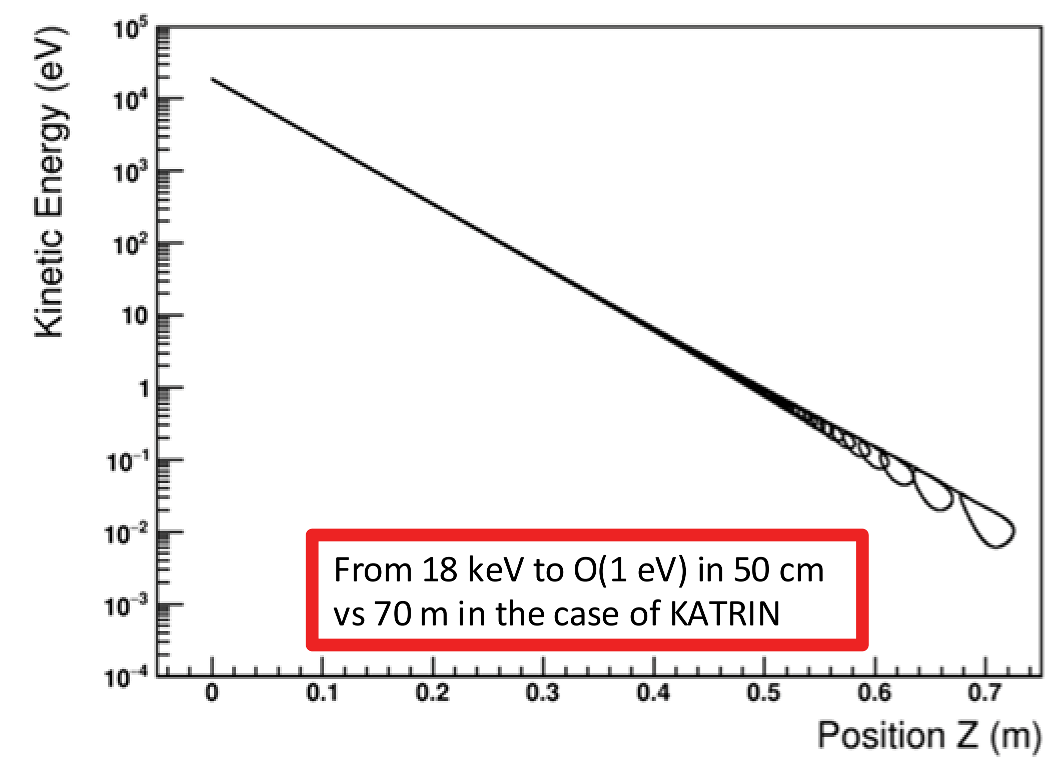
$$T'_\perp = -\frac{T_{\perp 0} e^{z_0/\lambda}}{q \sin\left(\frac{y_0}{\lambda}\right)} = -\frac{T_{\perp 0} e^{z_0/\lambda}}{\sin\left(\frac{y_0}{\lambda}\right)} \text{ [eV]}$$

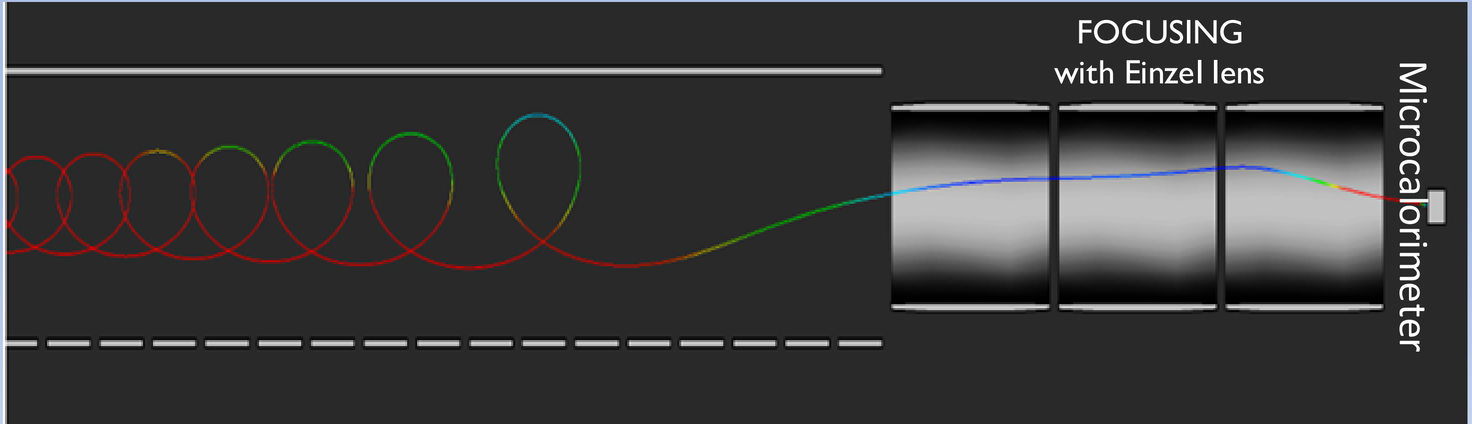
- Rearranging,

$$\boxed{T_{\perp 0} = -T'_\perp \sin\left(\frac{y_0}{\lambda}\right) e^{-z_0/\lambda}}$$





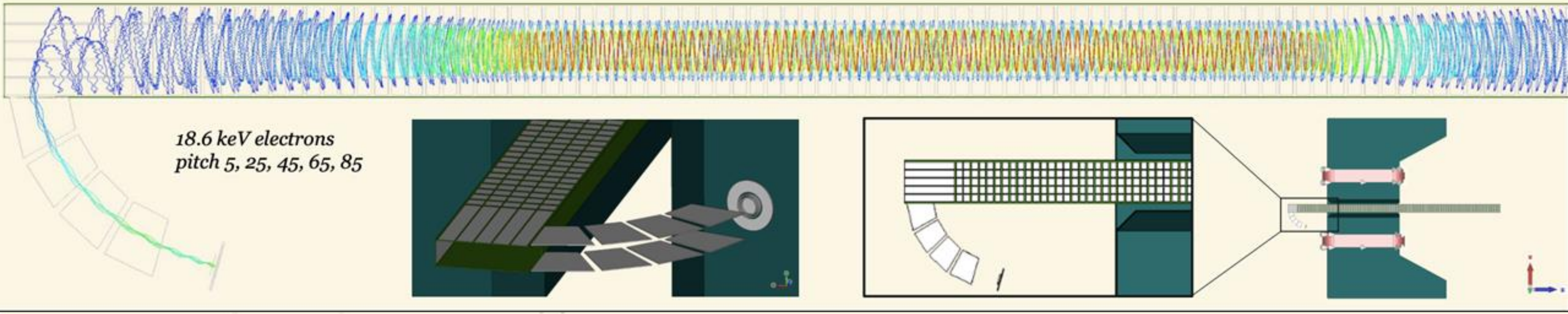


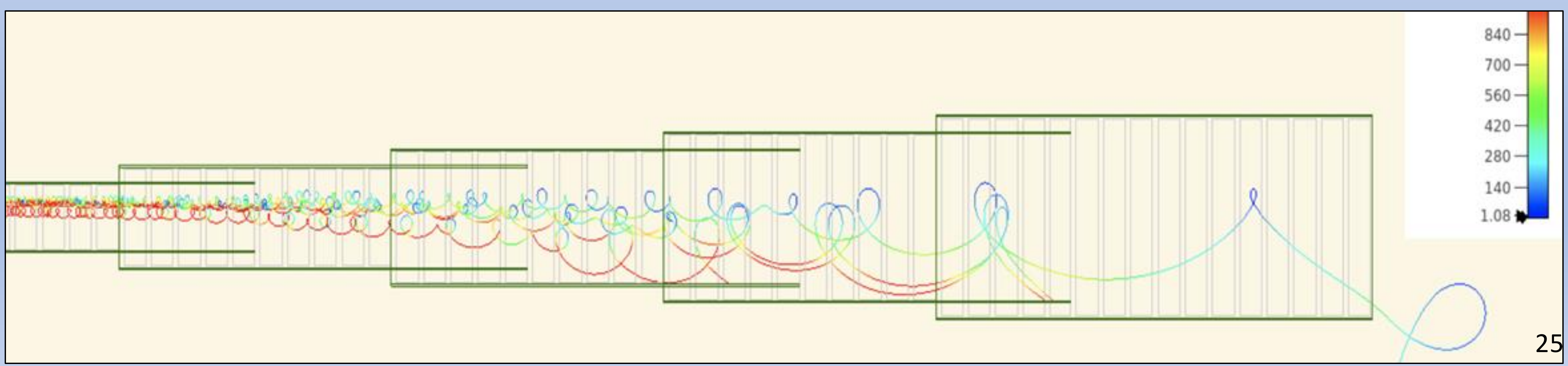


Implementation and optimization of the PTOLEMY transverse drift electromagnetic filter
A.Apponi et al, JINST 17 (2022) 05, P05021

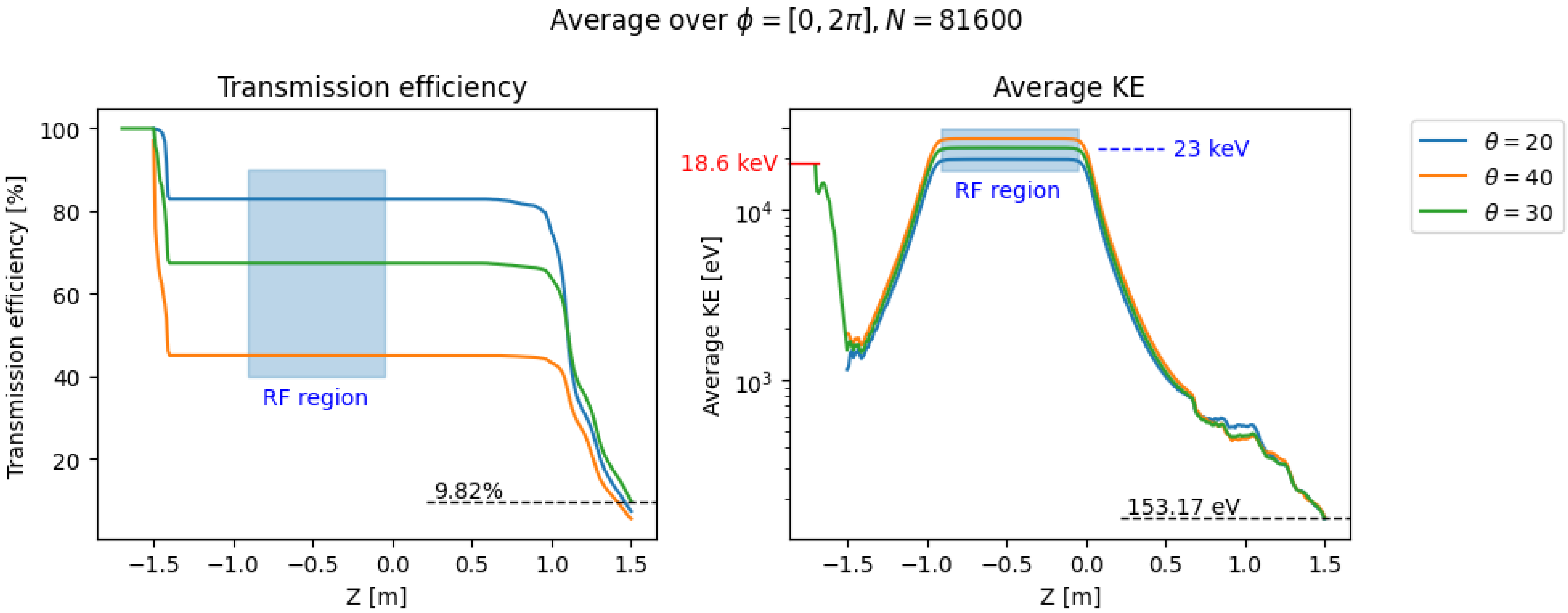
A design for an electromagnetic filter for precision energy measurements at the tritium endpoint
M.G.Betti et al, Prog.Part.Nucl.Phys. 106 (2019) 120-131

Simulation (Princeton) of 100 ng target mass



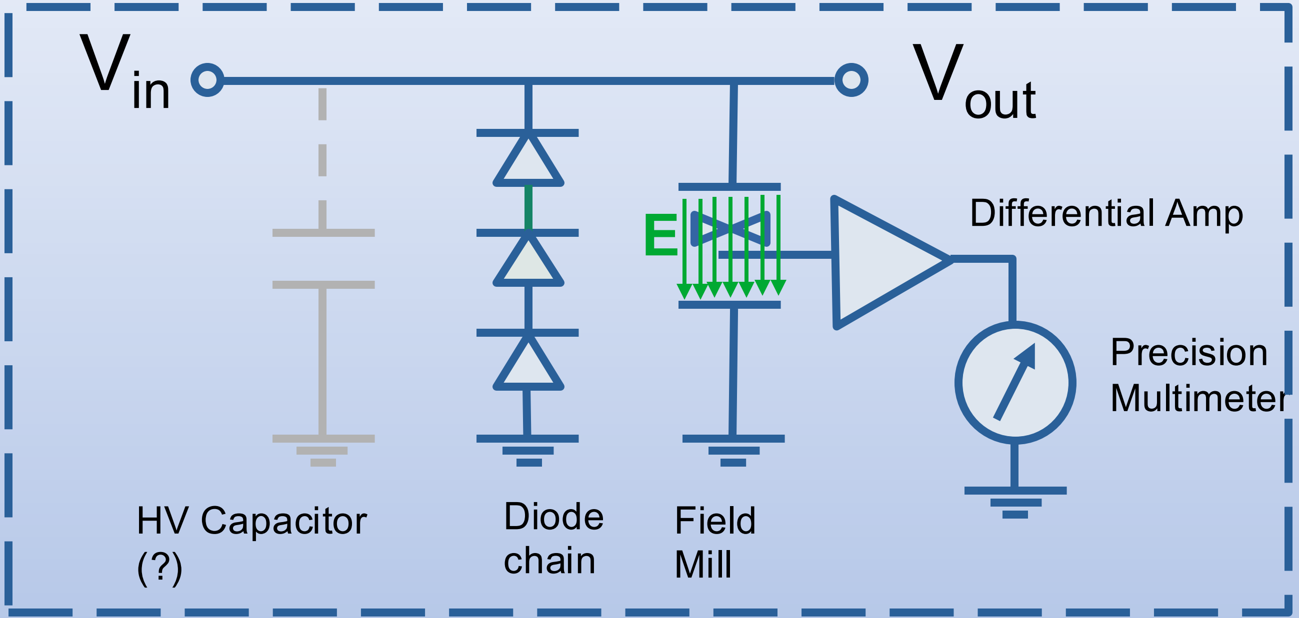


Showing θ = 20±5, 30±5, 40±5 averaged over Φ bins

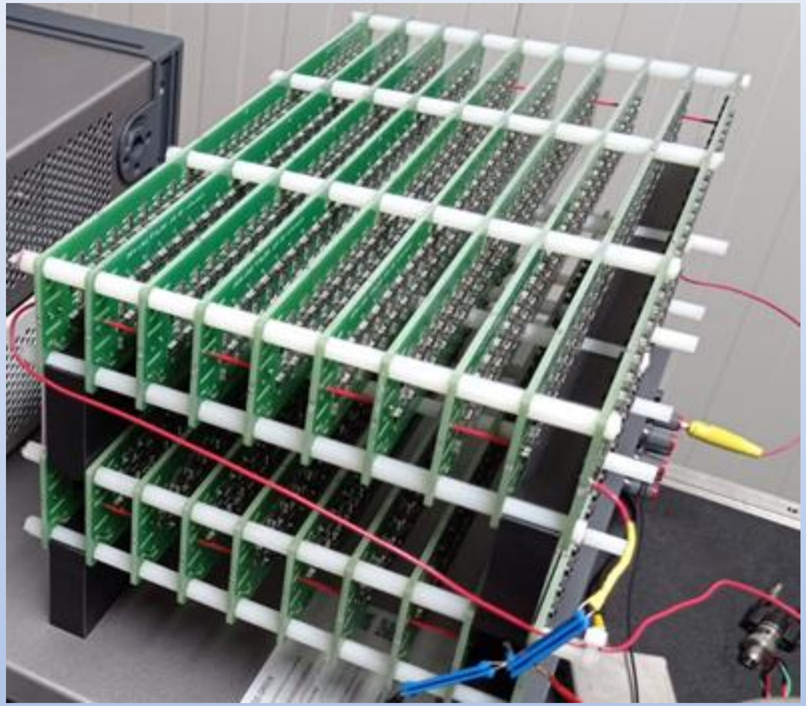


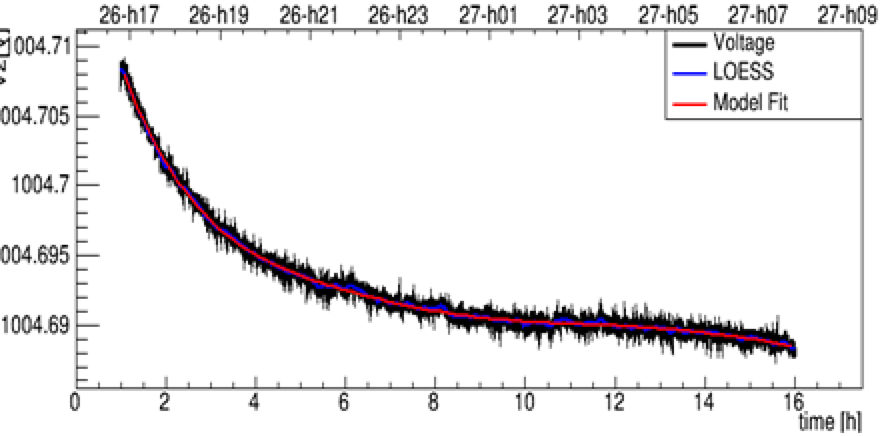
HV High precision stability (LNGS)

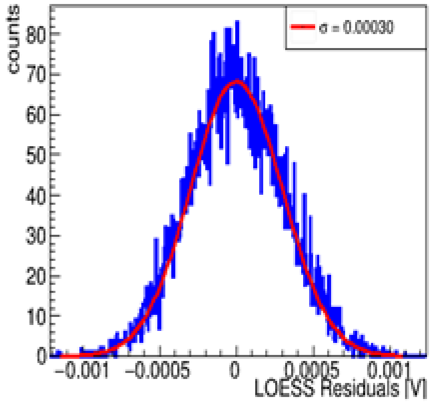
$$E_{total} = q\left(V_{TES} - V_{target}\right) + E_{RF} + E_{cal}$$

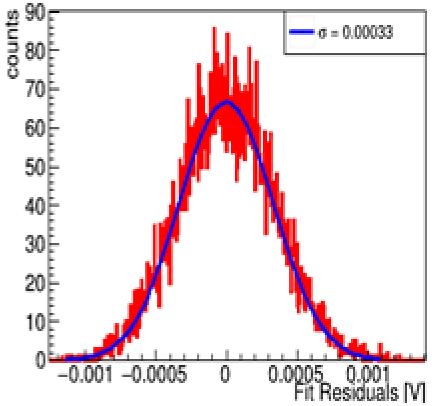


Climatic chamber - N_2









Single board (1 kV)

σ = 0.3 mV

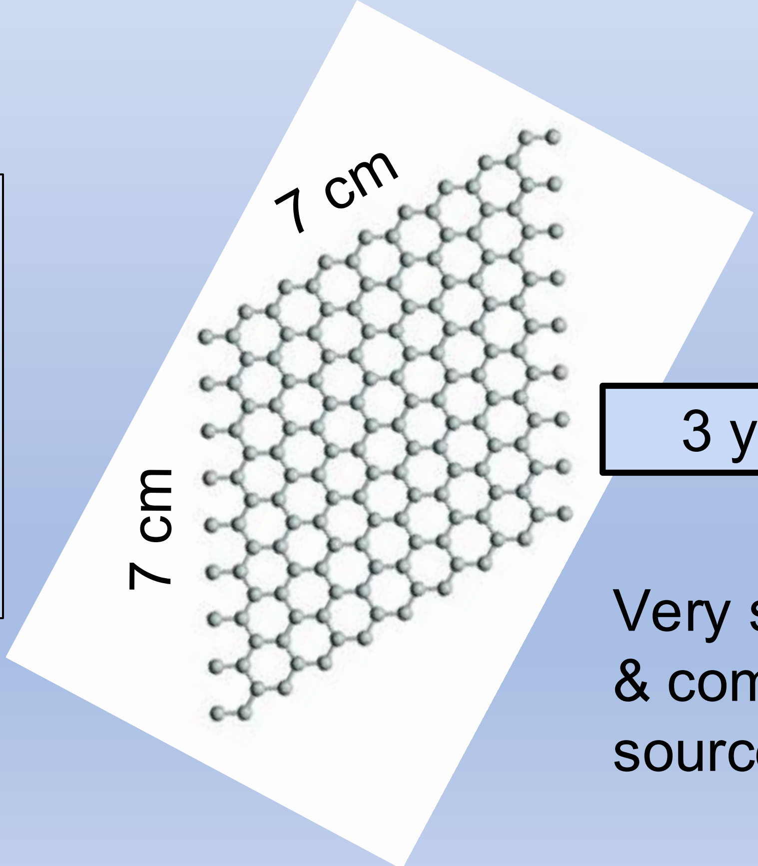
Reference source

Total number of β emissions from tritium:

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

Exposure:
3 years

Efficiency:
50%



3 years

Very small & compact source

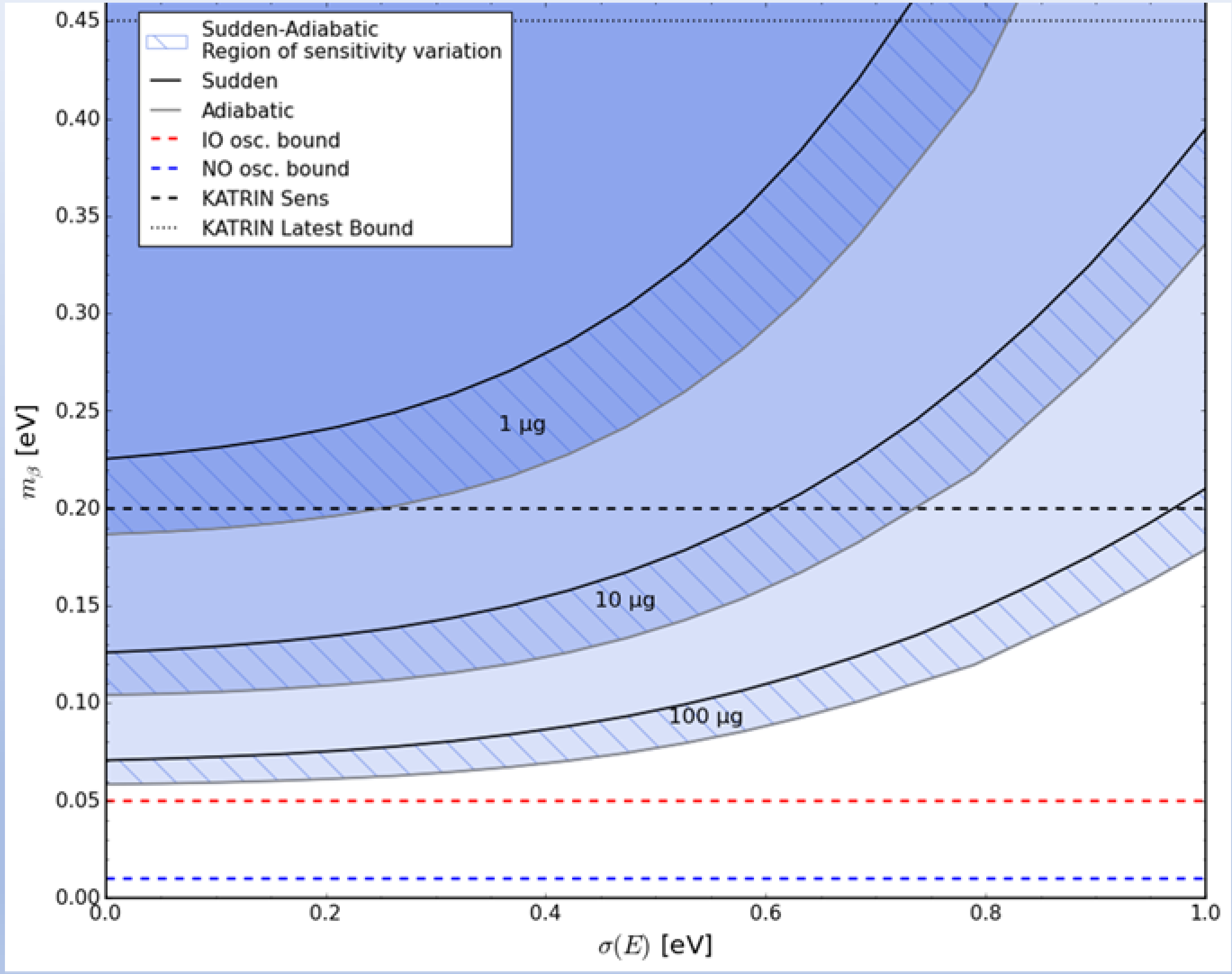
Source:
ρ = 0.2 mg/m^2
(full loading)

1µg (50 cm^2)

716 MBq
(19.3 mCi)

Sensitivity for different tritium masses

50 % eff. and 3 years data-taking



Remarks:

- sensitivity weakly dependent upon energy resolution (400 meV is already a good starting point)

- 1 μg potentially comparable or even better than projection of best technology on the market

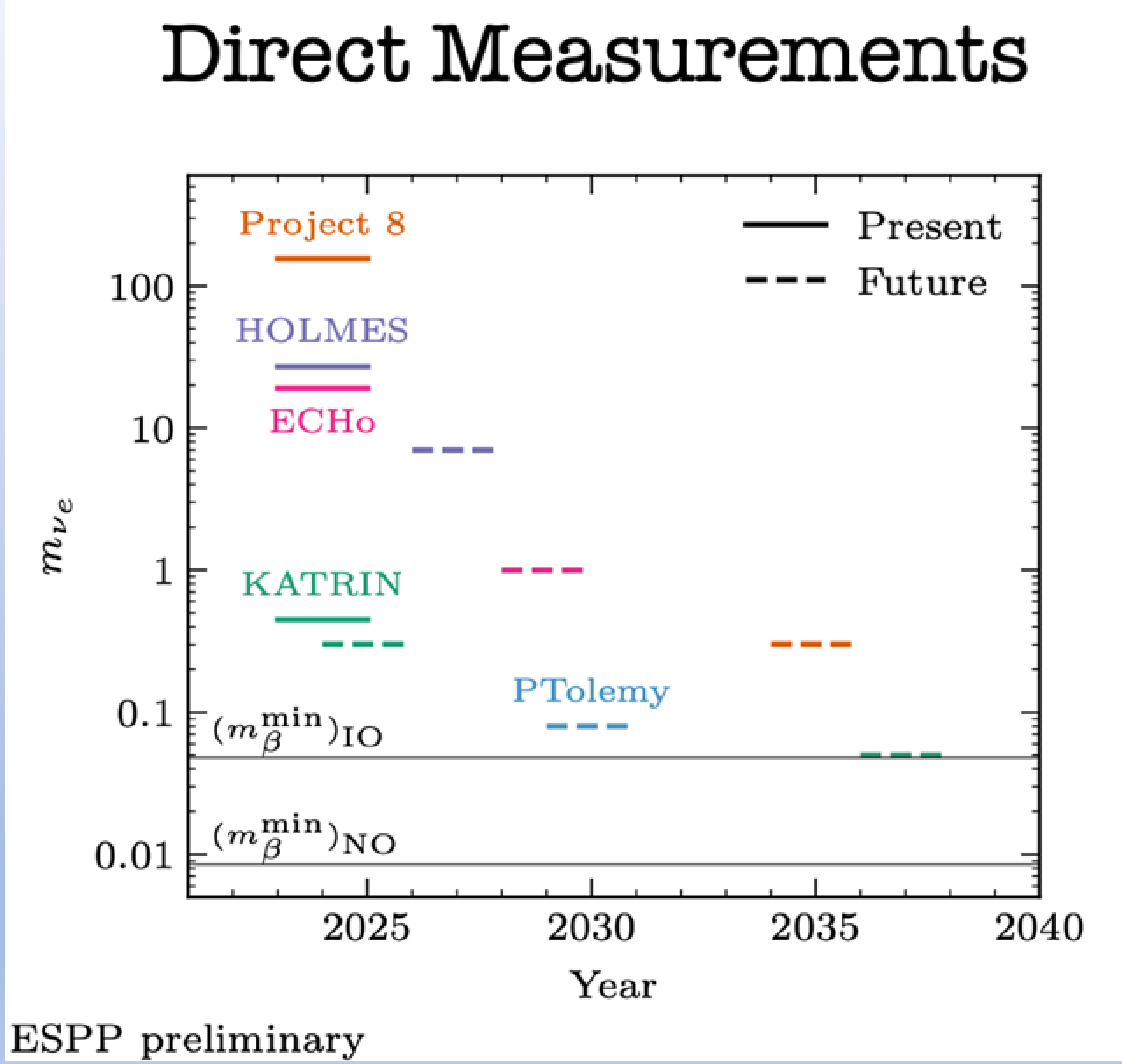
- 100 μg (0.5 m^2) close to probe the IO scenario

Theory paper on solid state effects of the electron spectrum & consequent theory systematics on m_ν extraction
(A. Casale, A. Esposito G. Menichetti, V. Tozzini) submitted https://arxiv.org/pdf/2504.13259

Neutrino Mass Future

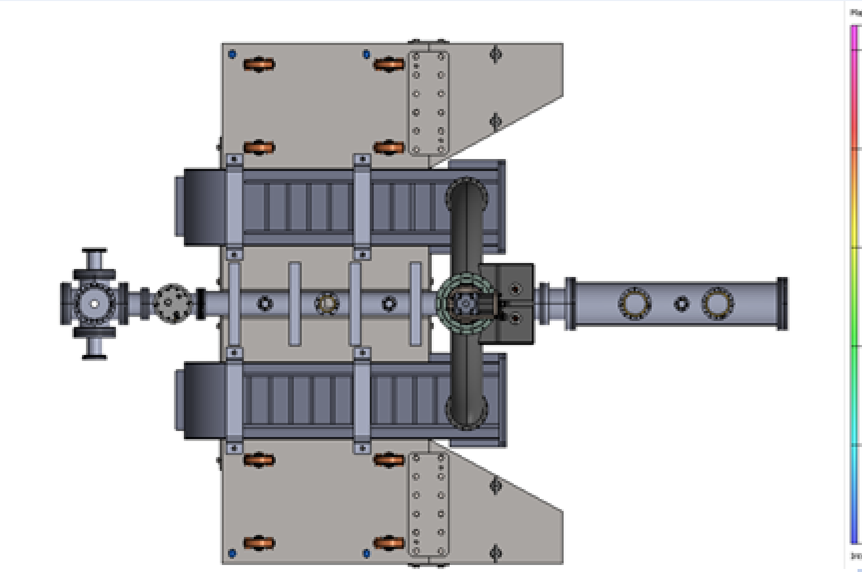
PTOLEMY unique feature:
same detector
but scalable target

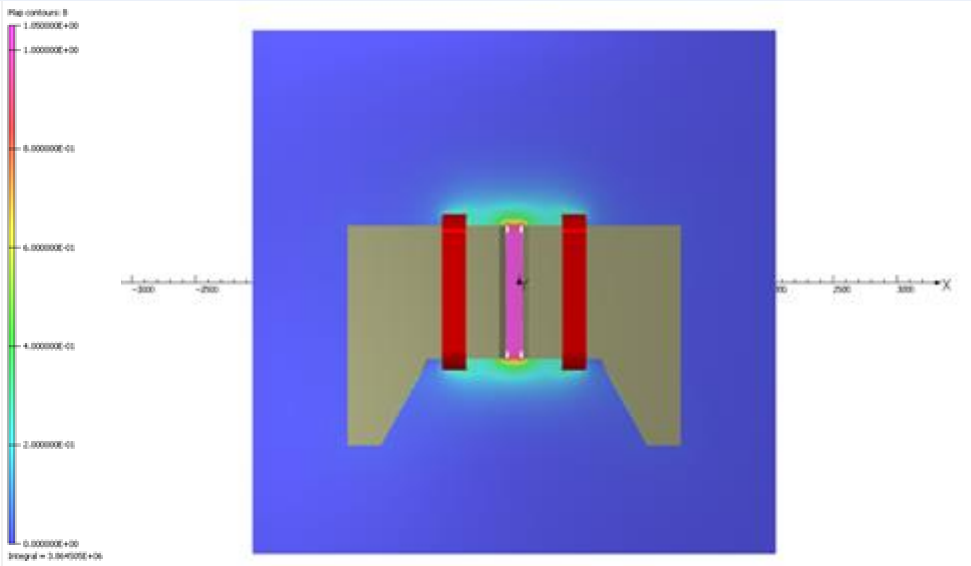
further limit lowering in future years



J. Formaggio (MIT) – ESPPU 2025

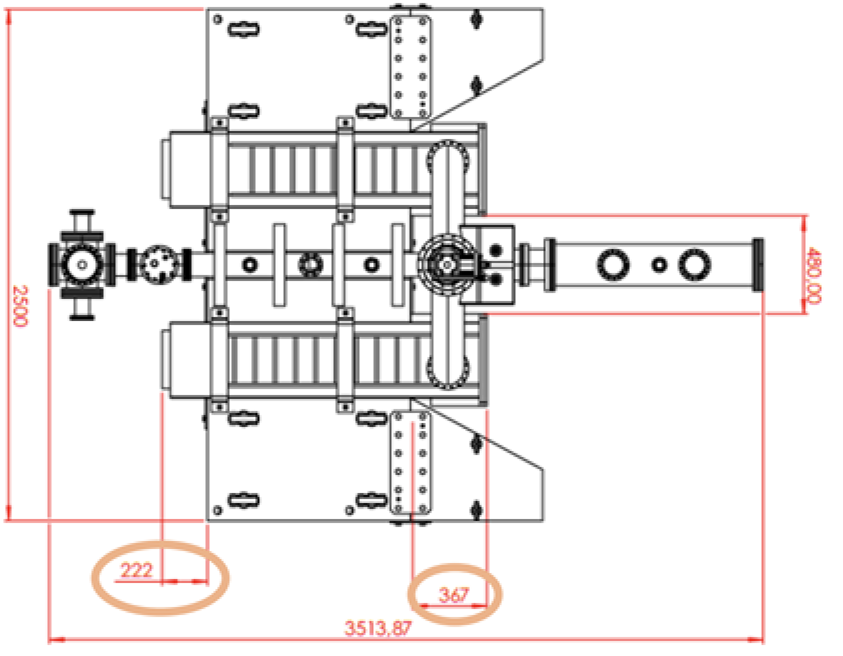
Demonstrator parts under constructions: magnet, order issued





Magnet: Key subsystem

ASG (Genova)/Suprasys(Bilbao)



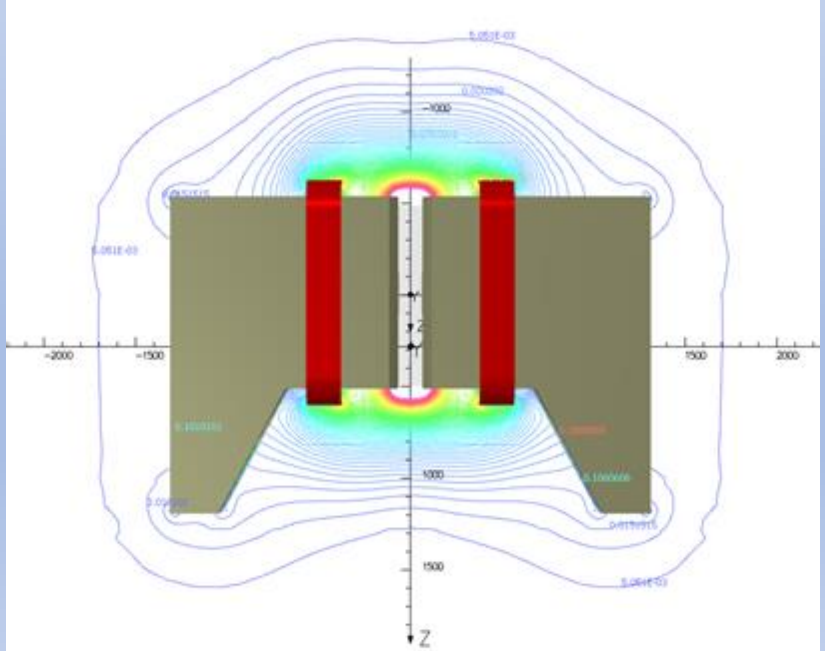
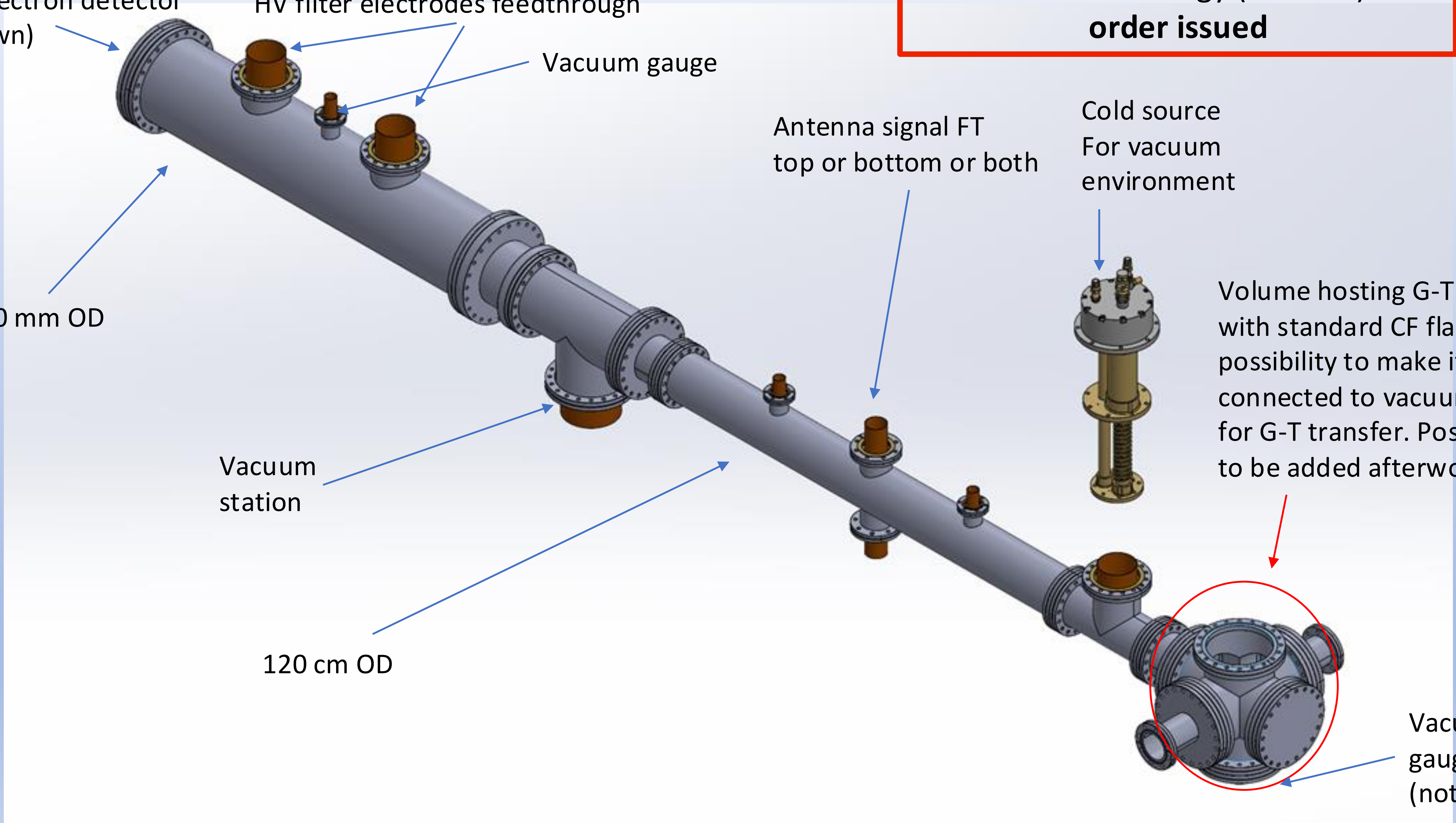


Photo gallery

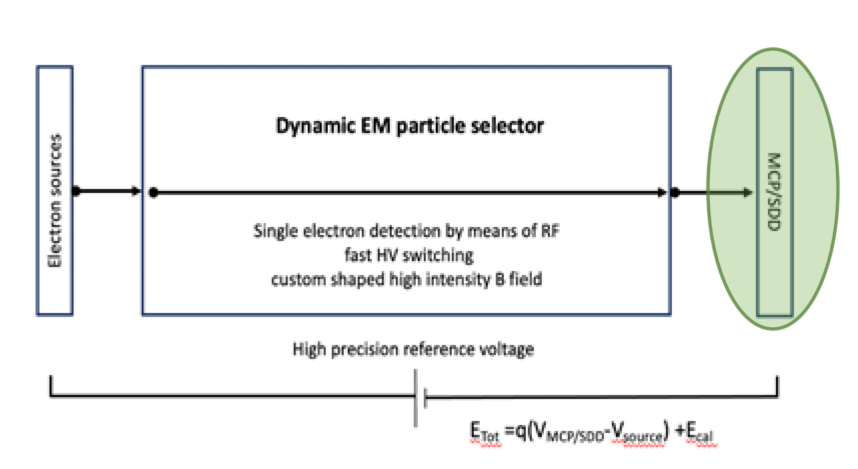
Demonstrator parts under constructions: vacuum chamber

ALCA technology (Vicenza)
order issued



Novelty elements of pahse1

Calorimetry at INRiM



Based on the expertise of the INRiM

electron detection with TES!

Key elements: high quality TES and new e-source based on nanostructures

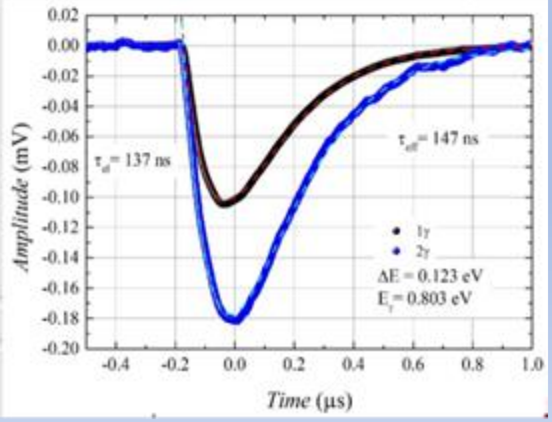
On γ: 0.11 eV @ 0.8 eV and 106 mK and 10x10 μm^2

TiAuTi 90nm [Ti(45nm) Au(45nm)] (τ ~137 ns)

Design Goal (PTOLEMY): ΔE_{FWHM} = 0.05 eV @ 10 eV

translates to $\Delta E \propto E^{\alpha}$ $(\alpha \leq 1/3)$

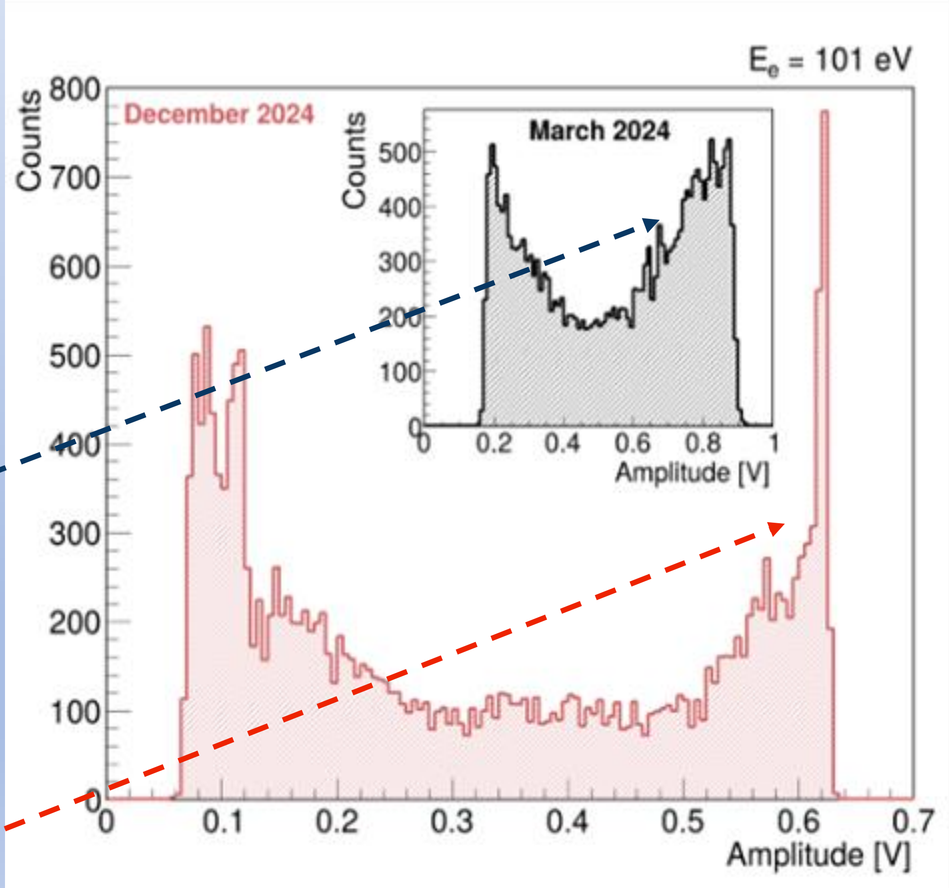
ΔE_{FWHM} = 0.022 eV @ 0.8 eV



to e$^-$ detection

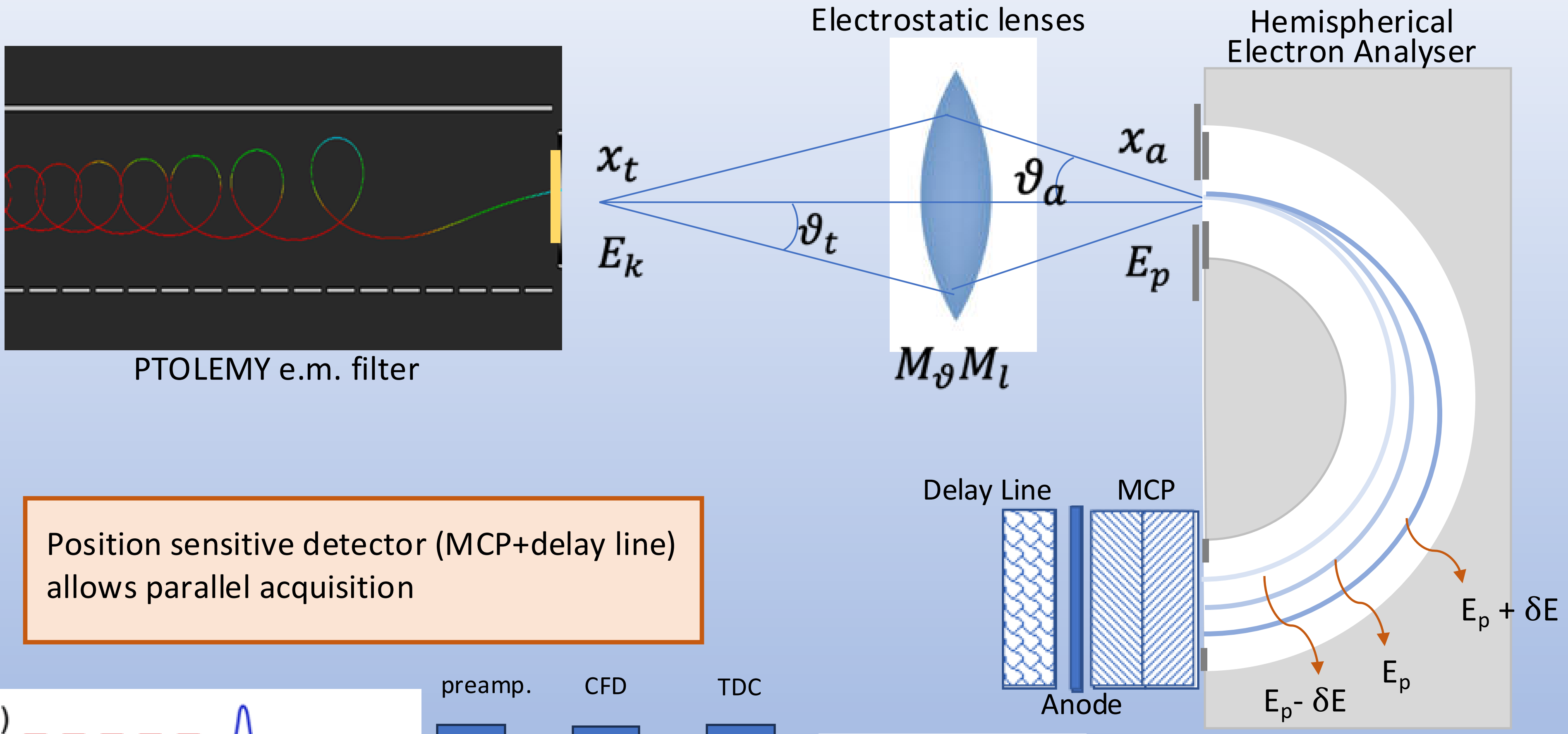
First measurement of electrons @ 100 eV with resolution ~1-1.5 eV

Phys.Rev.Applied 22 (2024) 4, L041007



FWHM reduced by factor 30 in last results!

Alternative energy measurement: Electrostatic analyser



Electron optic basic equation

Helmholtz – Lagrange law

$$x_t \vartheta_t \sqrt{E_k} = x_a \vartheta_a \sqrt{E_p}$$

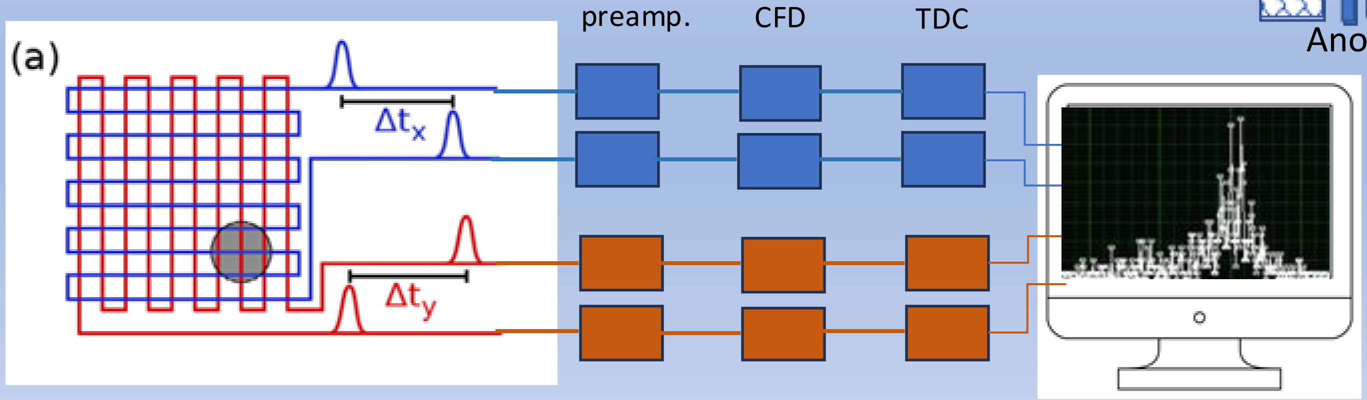
Two concentric hemispheres for the energy selection

Energy resolution (bandpass energy):

$$\frac{\Delta E}{E_p} = \frac{x}{2R_0} + \frac{\vartheta^2}{4}$$

ΔE: energy resolution
E_p : pass energy
x: slit width
R_0: mean radius
θ: accepted angle

Position sensitive detector (MCP+delay line) allows parallel acquisition

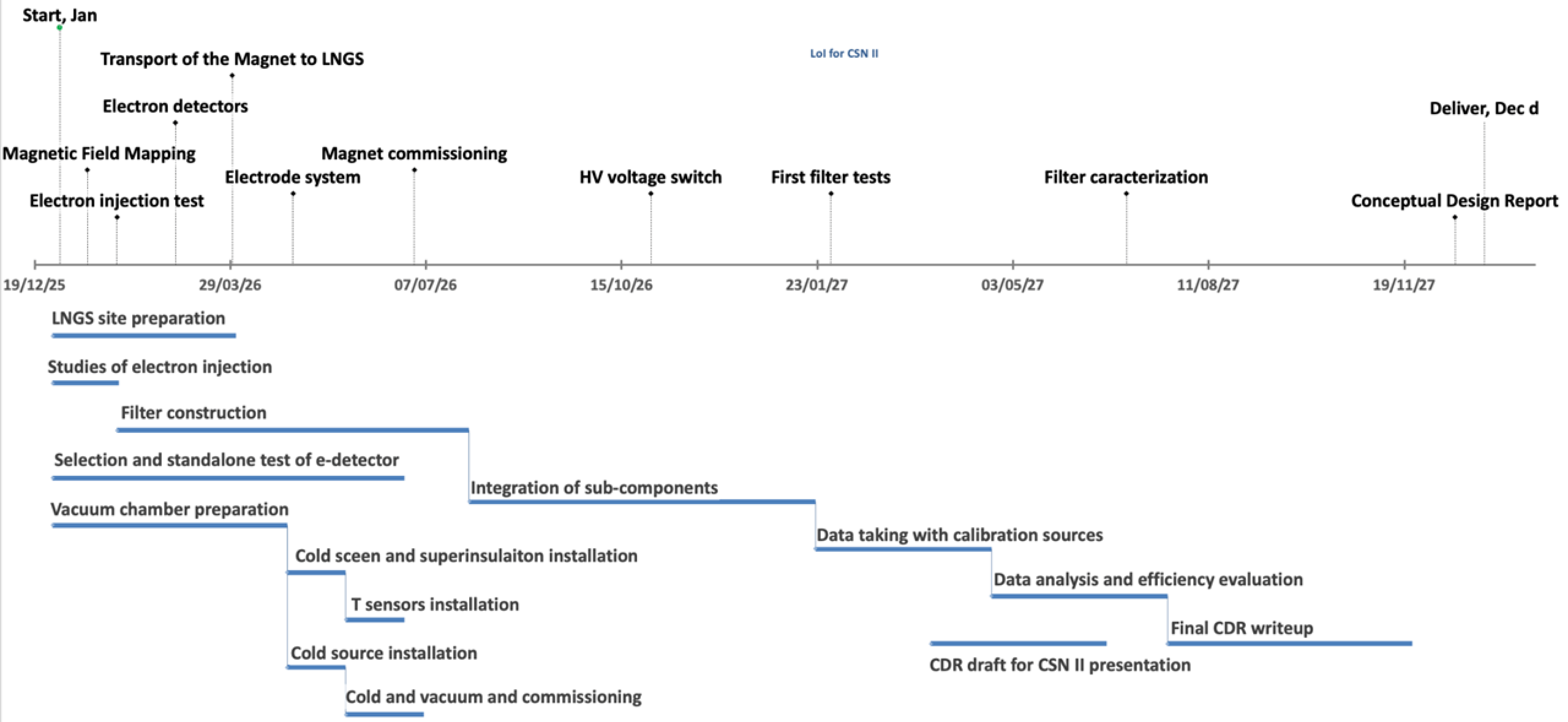


Commercial Electron Analyser

from Scientaomicron

Detector	Multi-channel (snapshot acquisition) Particle counting
Energy resolution	From <1.0 meV FWHM
Transmission mode energy range	0.5 eV – 1 500 eV
Deflection & Angular modes	± 3.5°, ± 7°, ± 15°
Angular mode energy range	From 0.5 eV – 1 500 eV
Deflection mode energy range	From 0.5 eV – 200 eV
Deflection mode Spin scan	Yes
Operating pressure	< 10-5 mbar
Mounting flange	DN200CF (10" O.D.)
Electrostatic 3D Focus Adjustment	Yes

GANTT



Start, Jan
Transport of the Magnet to LNGS
LoI for CSN II
Electron detectors
Deliver, Dec d
Magnetic Field Mapping
Magnet commissioning
Electrode system
HV voltage switch
First filter tests
Filter caracterization
Electron injection test
Conceptual Design Report
19/12/25
29/03/26
07/07/26
15/10/26
23/01/27
03/05/27
11/08/27
19/11/27
LNGS site preparation
Studies of electron injection
Filter construction
Selection and standalone test of e-detector
Integration of sub-components
Vacuum chamber preparation
Data taking with calibration sources
Cold sceen and superinsulaiton installation
Data analysis and efficiency evaluation
T sensors installation
Final CDR writeup
Cold source installation
CDR draft for CSN II presentation
Cold and vacuum and commissioning

Detailed list of Researchers
Non Italians

Name	FTE	Institute	Task / Responsibility
PI A.P. Colijn		University of Amsterdam and Nikhef	Analogical and Digital electronics
P. Bos			
J. Mead			
M. Naafs			
G. Visser			
PI Prof. C.G. Tully		Princeton University	Filter design/simulation and tests, Magnet, RF Antenna
A. Tan			
W. Chung			
M. Farino			
A. Langella			
PI N. de Groot		University of Radboud	Graphene studies and measurement
I. van Rens			
PI C. Perez de los Heros		Uppsala University	Editorial board

Detailed list of Researchers Italians

PI M. Cadeddu	30%	INFN-CA	T handling, safety procedure and authorizations
L. Ferro (PhD)	30%		
R. Pavarani	30%		
A. Santucci	30%		
M. Sestu (PhD)	30%		
PI E. Celasco	20%	University of Genova and INFN-GE	Magnetic field measurement and cryogenics
S. Farinon	5%		
PI G.P. Mangano	20%	University of Napoli and INFN-NA	Theorist
O. Pisanti	20%		theorist
PI M. Messina	60%	INFN-LNGS	Infrastructure, Magnet, Calibration, RF
A.G. Cocco	60%		
N. D'Ambrosio	20%		
A. Ferella	30%		
N. Rossi	40%		
S. Nahornyi	50%		
F.M. Pofi (PhD)	100 %		
F. Virzi (PhD)	100%		

Detailed list of Researchers Italians II

PI V. Tozzini	20%	INFN-PI and NANO-CNR Pisa	Theorist
L.E. Marcucci	20%		theorist
G. Menichetti	20%		theorist
M. Viviani	20%		theorist
PI G.L. Cavoto	30%	Sapienza University and INFN-Roma1	Tritium loading on graphene
M.G. Betti	20%		
B. Corcione (PhD)	100%		Electron detection
G. De Bellis	30%		HV developments
A. Esposito	20%		Theorist
L. Ficcadenti	30%		
G. Galbato Muscio (PhD)	30%		HV developments
L. Ginevra	20%		
C. Mariani	30%		Tritium loading on graphene
F. Pandolfi	40%		Electron detection
A.D. Polosa	10%		Theorist
I. Rago	30%		Graphene scale-up
PI G. Salina	30%	INFN-Roma2	DAQ and FPGA programming
Roberto Ammendola	10%		
Cosmin Marin(PhD)	50%		
V. Narcisi	30%		
PI A. Ruocco	40%	Roma Tre University and INFN-Roma3	Graphene target scale-up
A. Apponi	20%		CNS5 grant synergic (GREEAT)
O. Castellano (PhD)	40%		Nanostructures hydrogenation
S. Ritarossi	40%		

Some Numbers:

- 12 groups from 4 countries
- 8 INFN units participating
- 52 scientists in the Collaboration
  - Out of which 39 italians with tot ~**14. FTE**
- 77 scientists supporting the Collaboration

Financial Request

Costs 2026

INFN unit	FTE per INFN unit	Travel (kE)	hardware (kE)
CA	1.5	5	
GE	0.25	2.5	10 (SJ) magnet transport
NA	0.4	2	
LNGS	4.8	8.	
PI	0.8	2	
Roma1	3.9	10.5	6 e-detector
Roma2	1.2	3	
Roma Tre	1.5	5	5 graphene test production
Tot	14.35	37	21

Table 2: Residual costs for year 2026

Costs 2027 (expected)

INFN unit	FTE per INFN unit	Travel	hardware
CA	1.5	5	
GE	0.25	2.5	
NA	0.4	2	
LNGS	4.8	8.	
PI	0.8	2	
Roma1	3.9	10.5	
Roma2	1.2	3	
Roma Tre	1.5	5	
Tot	14.35	38	

Table 3: Residual costs for year 2027 (expected)

To conclude:
activities ongoing in 2025

1) Graphene hydrogenation demonstrated, to be ported to tritium - no scientific show-stopper. Collaboration with UKAEA ongoing

2) Magnet at CERN by fall 2025 for field map measurement, electrodes design ongoing

3) RF radiation detection well advanced - to be integrated in the demonstrator

4) Several electron sources for calibration, HV stability close to requirement

5) First e-detection with standard detector.

Outlooks

- First magnet operation in 2026
- CDR in preparation for July 2027 CSN II meeting
- Define a T0 for a possible physics data-taking of 3 years

Papers production

Filter papers plus:

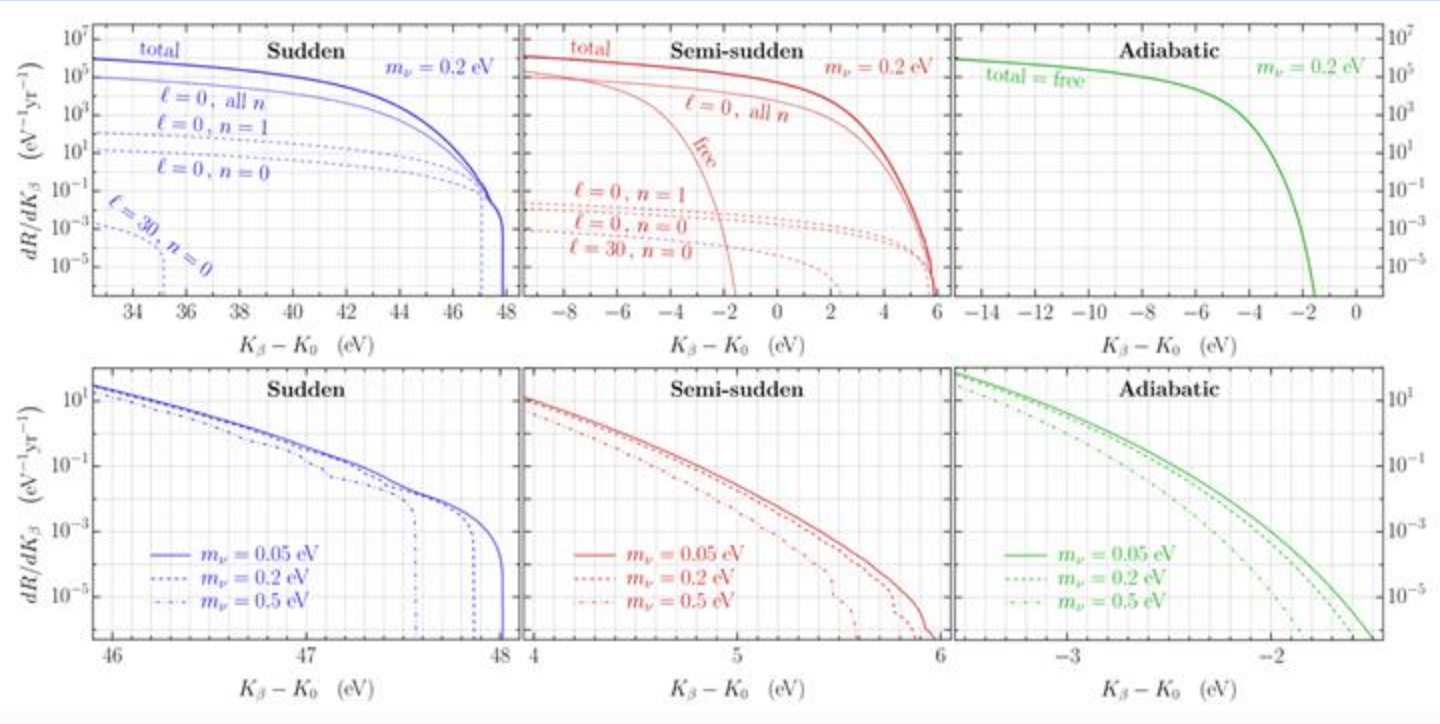
1. Low energy electron measurement
2. Stability of H/D on graphene (hints on T stability)
3. First RF measurement of single e- in a PTOLEMY setup (in preparation)
4. HV reference voltage (written)
5. Demonstrator setup (editing ongoing)
6. Theory paper on beta-decay endpoint
7. Sensitivity curves based on novel theory models on tritium-carbon bound state.
8. LoI where Phase0 and Phase1 contents are defined

Backup

Systematics

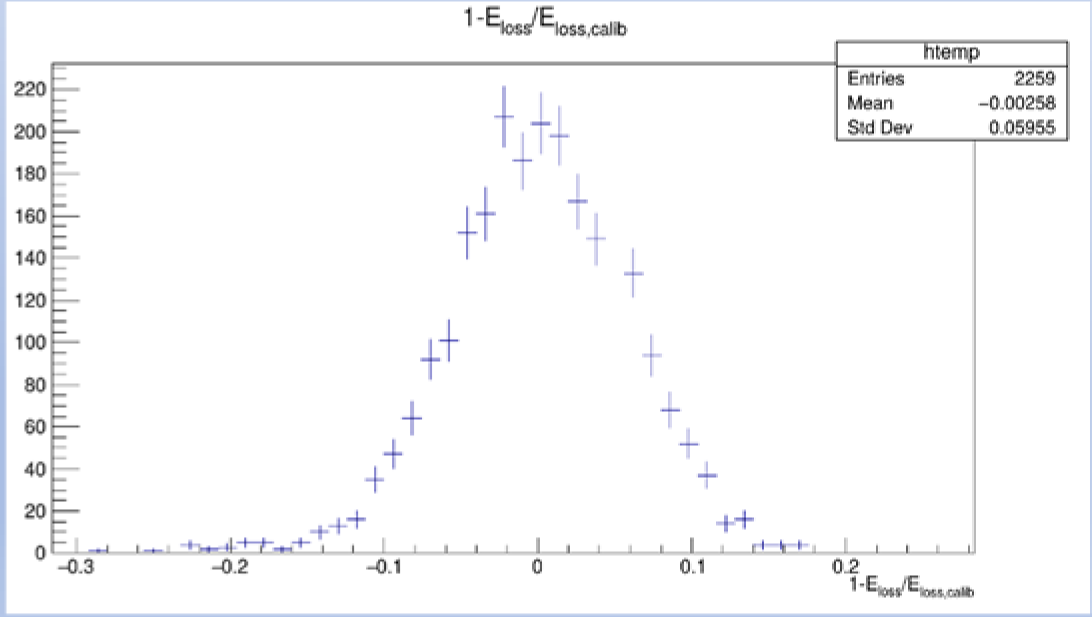
1) Theory aspects:
   further investigation of e ground level is needed

   A. Casale, A. Esposito G. Menichetti, V. Tozzini
   https://arxiv.org/pdf/2504.13259

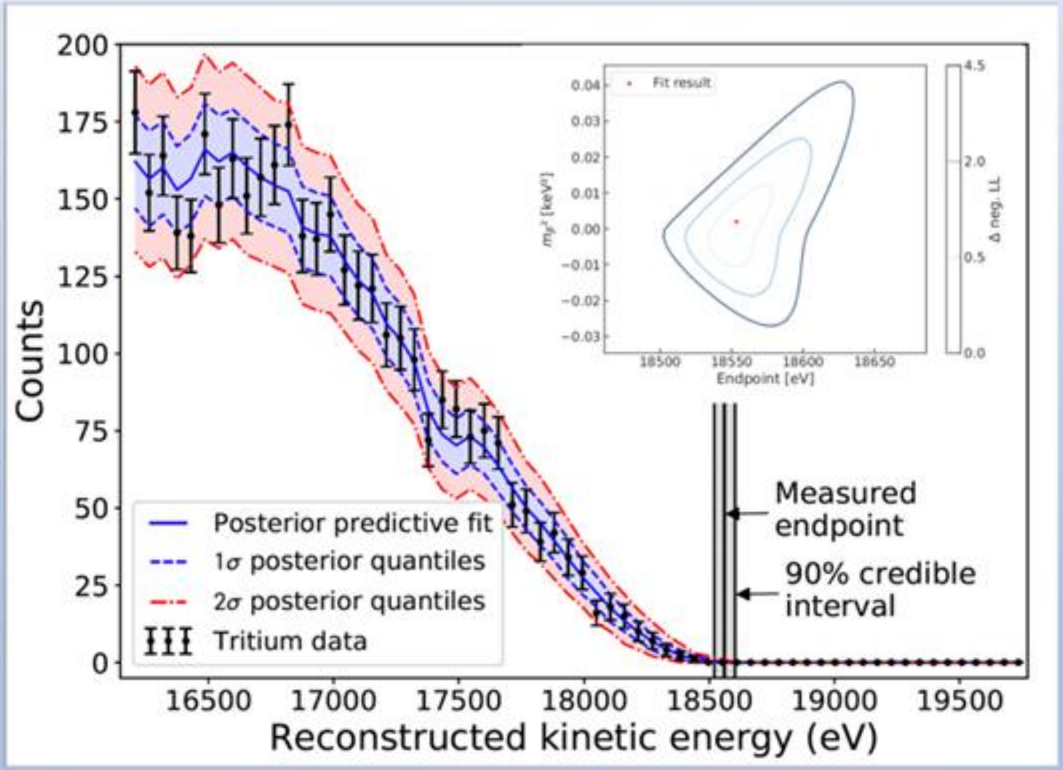


2) Overall energy scale known at better than 5 meV

3) RF correction known at better than 10%



Recent Project 8 Tritium RF Measurement



https://arxiv.org/abs/2203.07349

RF measurement background levels extremely low.

No events observed above endpoint,
Setting upper limit on background rate

< 3×10^{-10} /eV/s (90% CL)

→ Background Rate < 1 event per eV in 100 years!