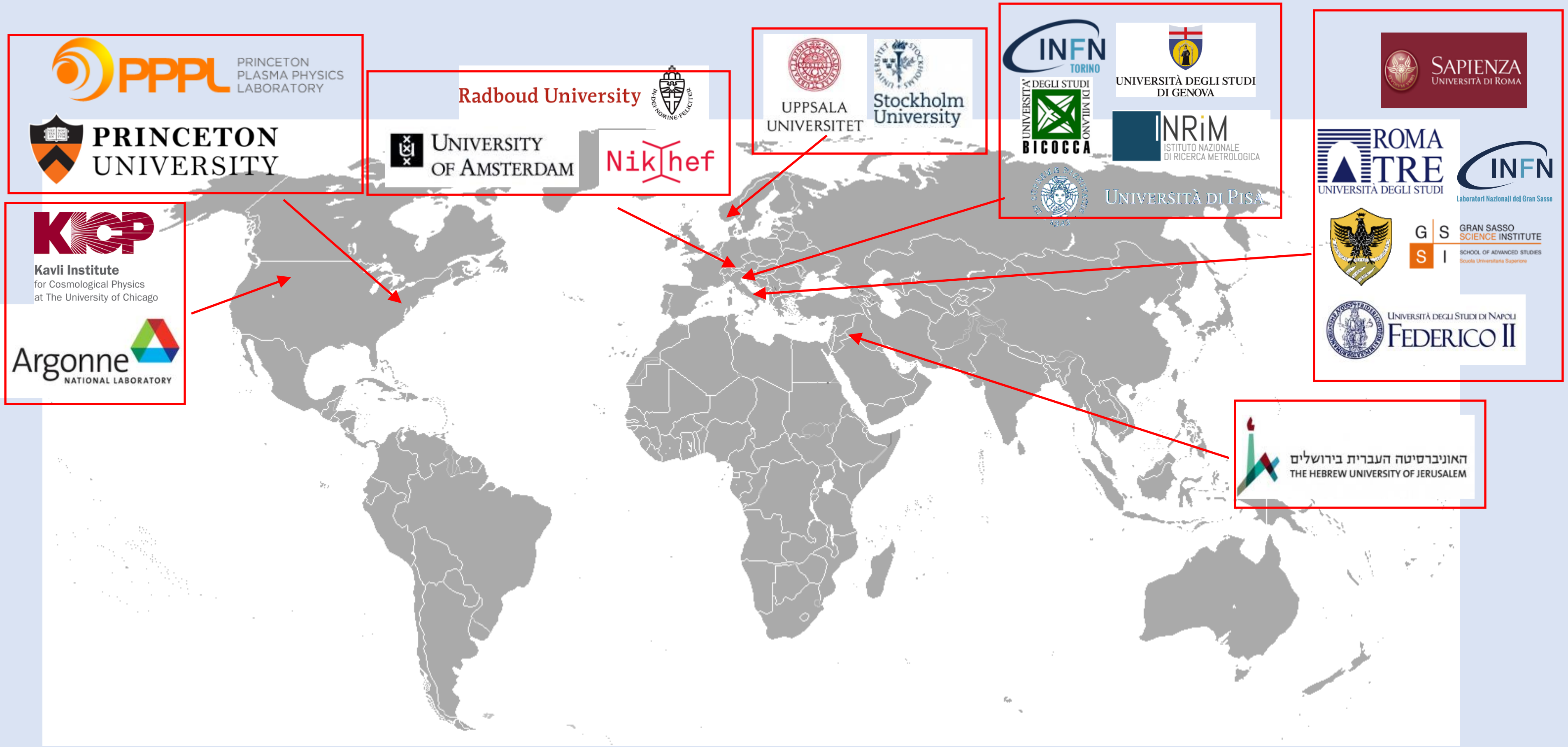
Relic neutrinos detection and mass measurement in the PTOLEMY project.

Seminario all'Universita' di Milano Bicocca May 28th 2025

M Messina, LNGS-INFN

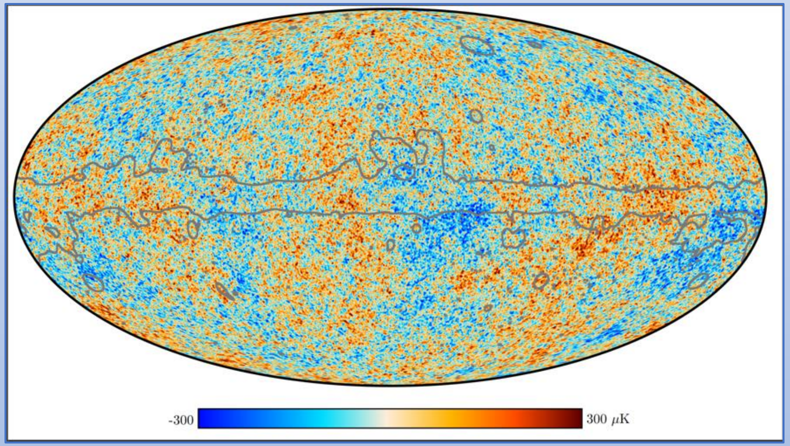


Why we believe in the Big Bang?

1. Expansion of Universe

2. Light element abundances

3. Cosmic Microwave Background



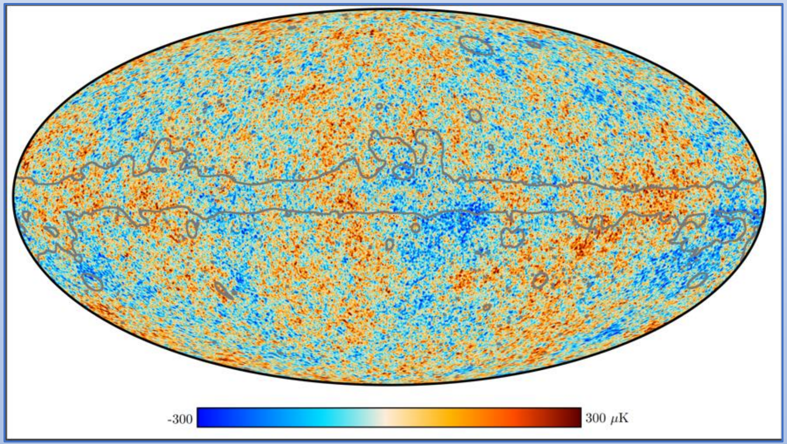
Why believe Big Bang?

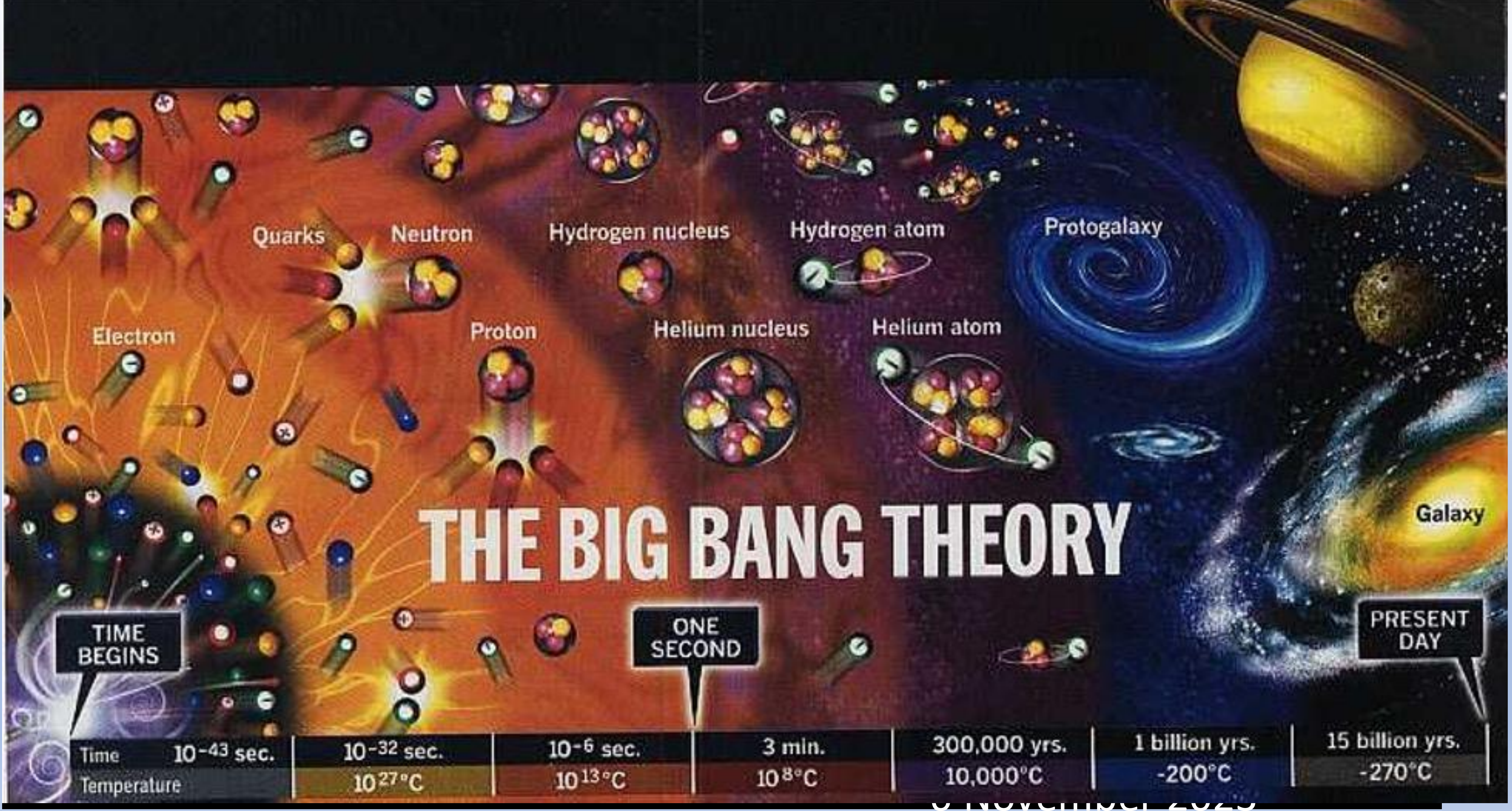
1. Expansion of Universe

2. Light element abundances

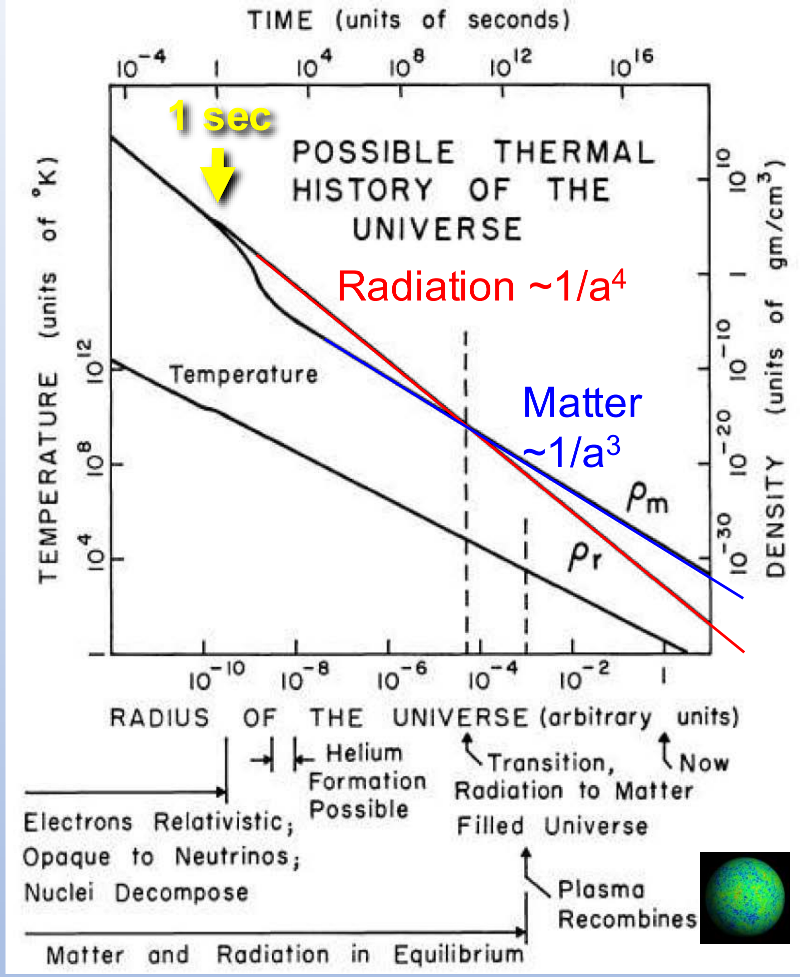
3. Cosmic Microwave Background

4. **Cosmic Neutrino Background**




Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
THE BIG BANG THEORY
Galaxy
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

Cosmic Neutrino Background



Dicke, Peebles*, Roll, Wilkinson (**1965**)

[Cosmology's Century (2020)]

Number density:

$n_\nu = 112/cm^3$

Temperature:

$T_\nu \sim 1.95K$

Time of decoupling:

$t_\nu \sim 1$ second

~50% of the Total Energy Density of the Universe @ 1 sec

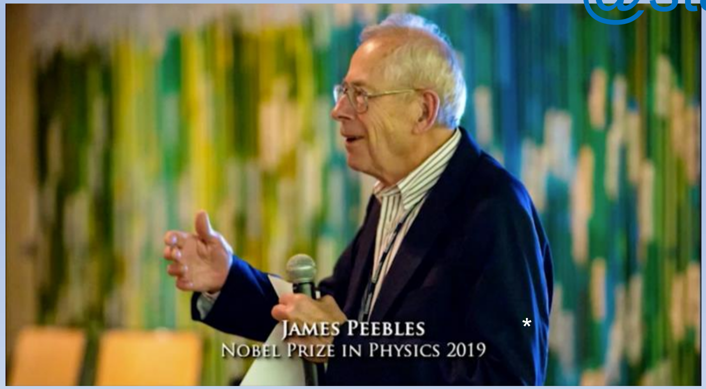
neutron/proton ratio @start of nucleosynthesis

→ ^4He

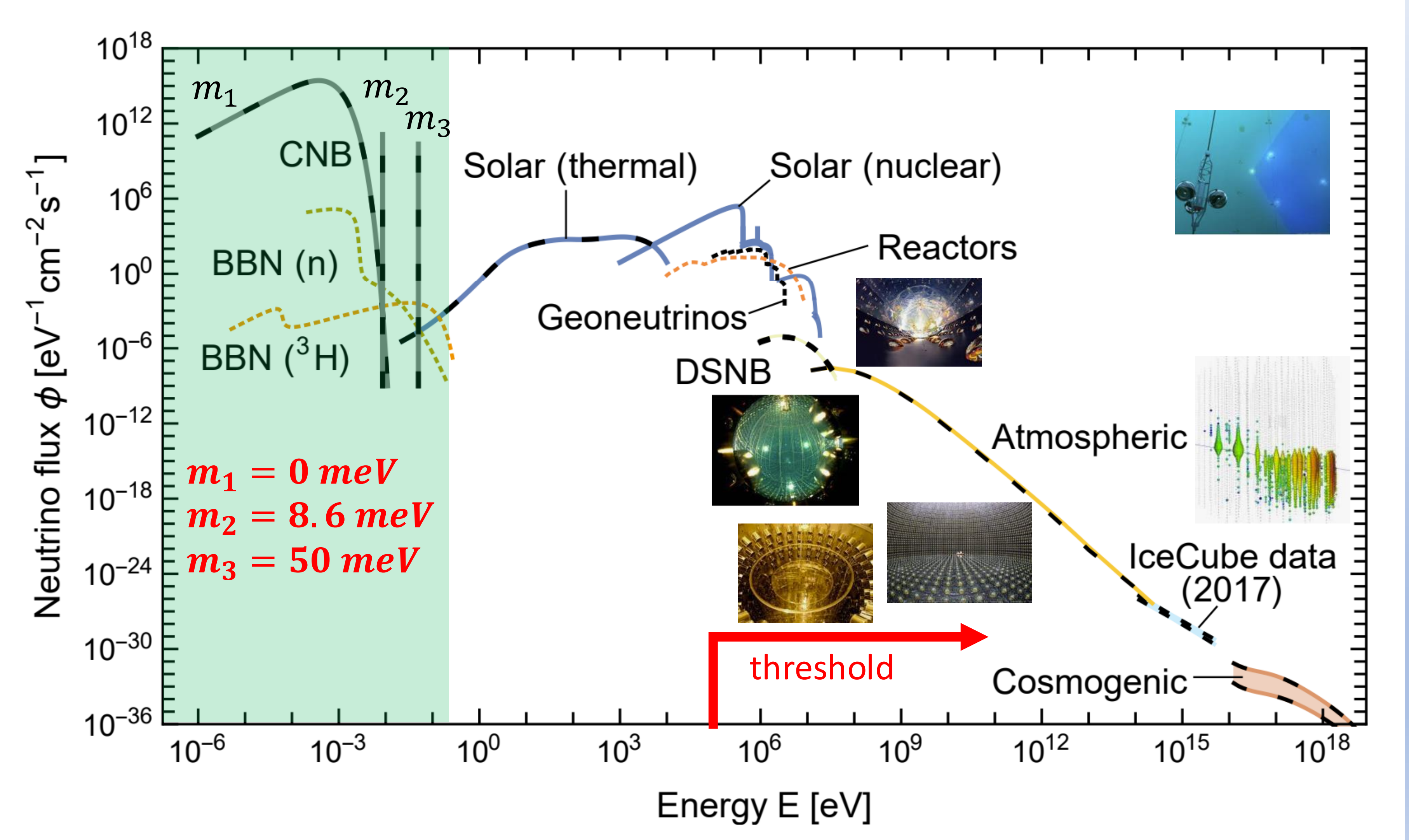
^2H

(^3He)

^7Li



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

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

$m_\nu = 0$

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

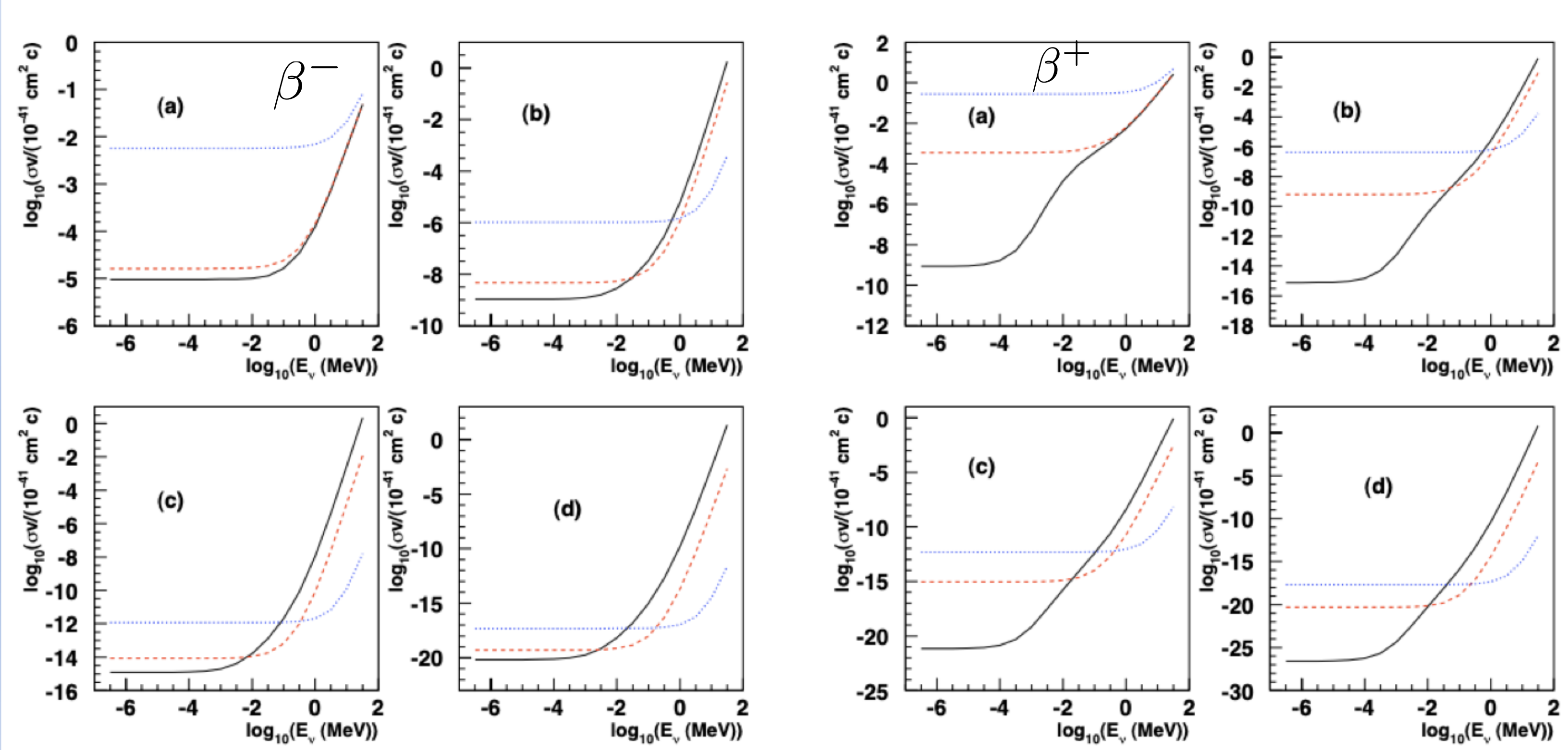
JCAP 0706:015,2007

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

Dirac

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

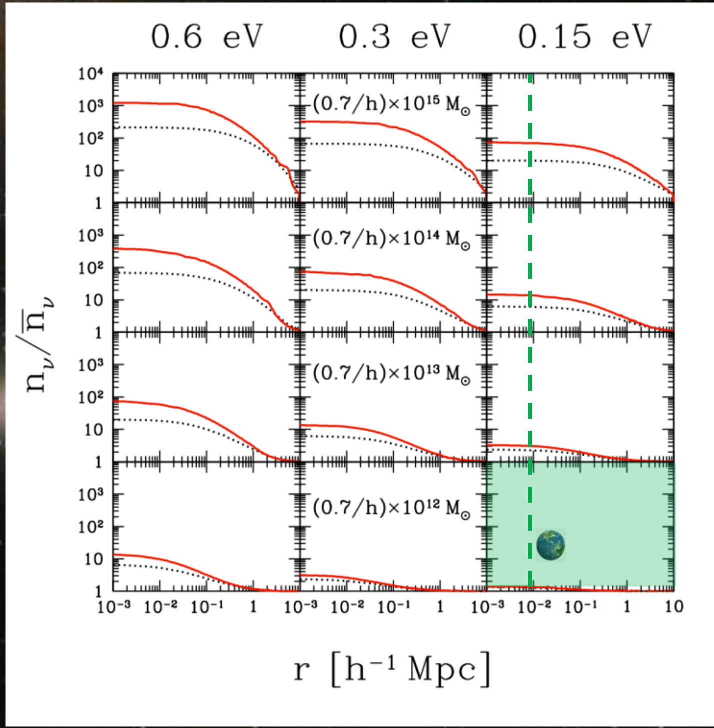
Majorana

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

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

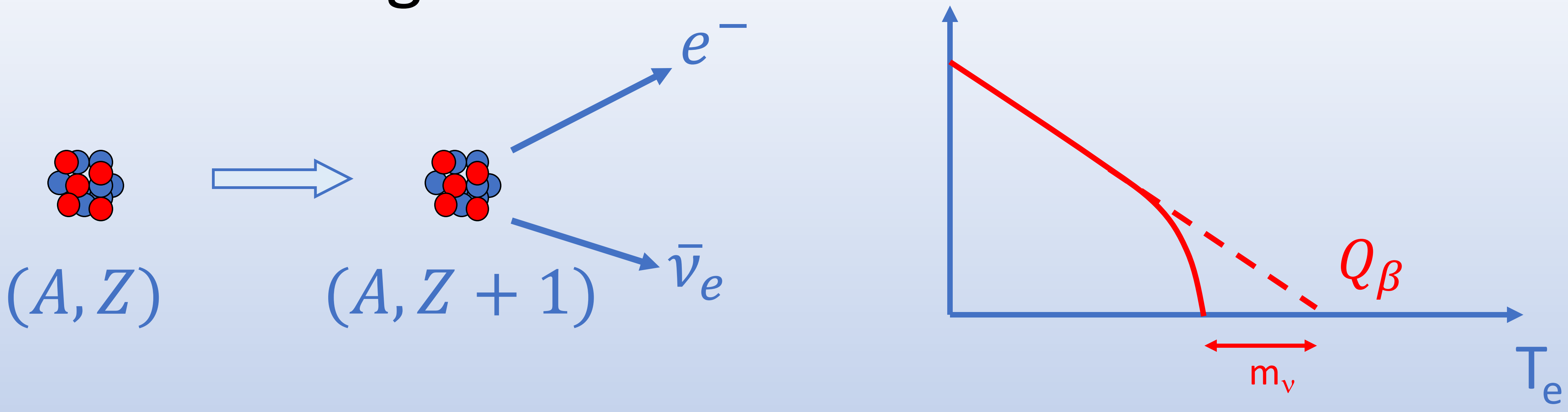
Exp

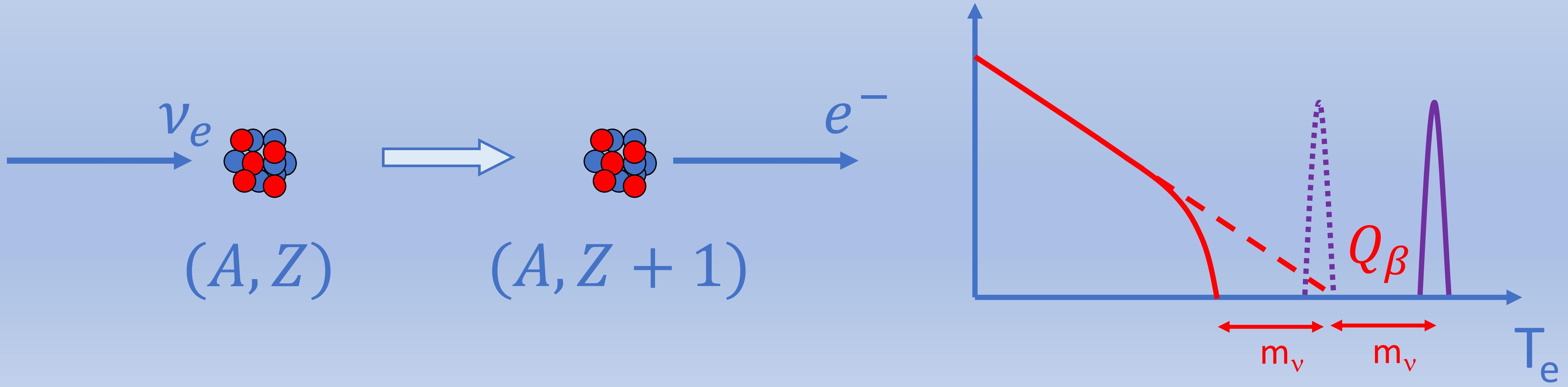
Gravitational clustering



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

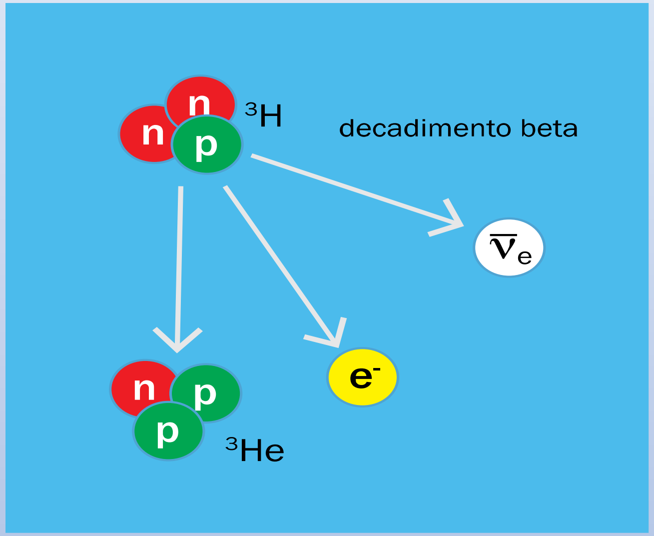
Signature of relic neutrinos

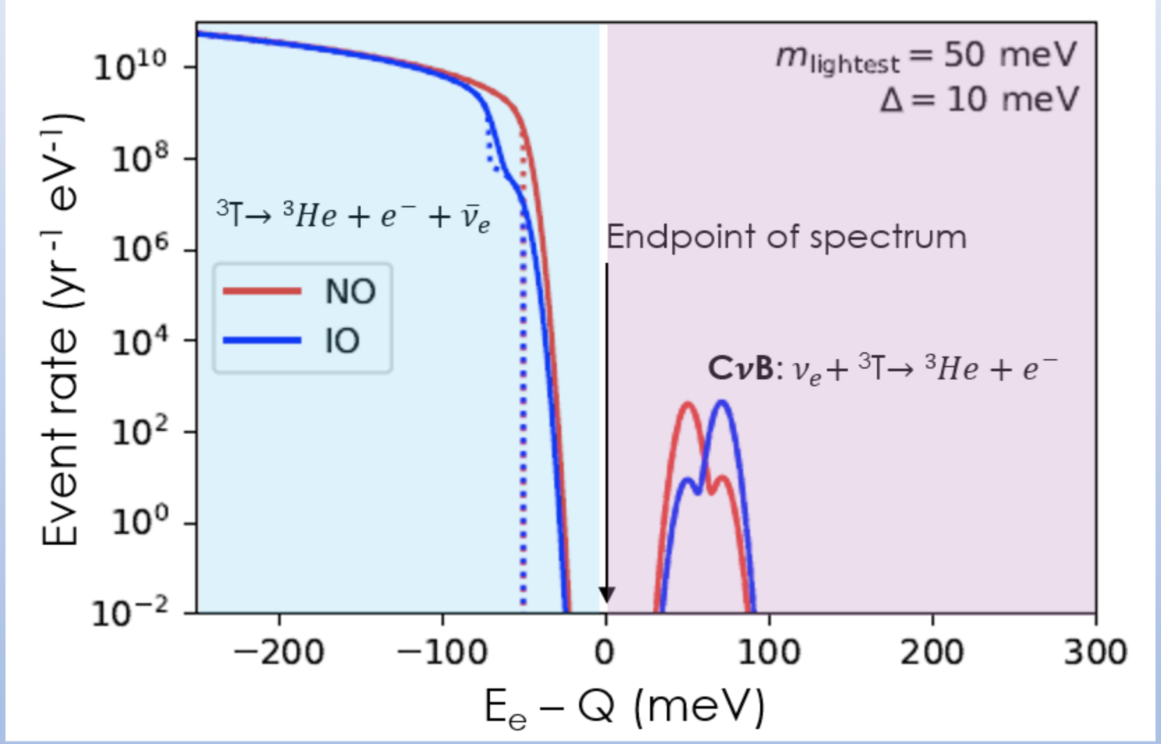




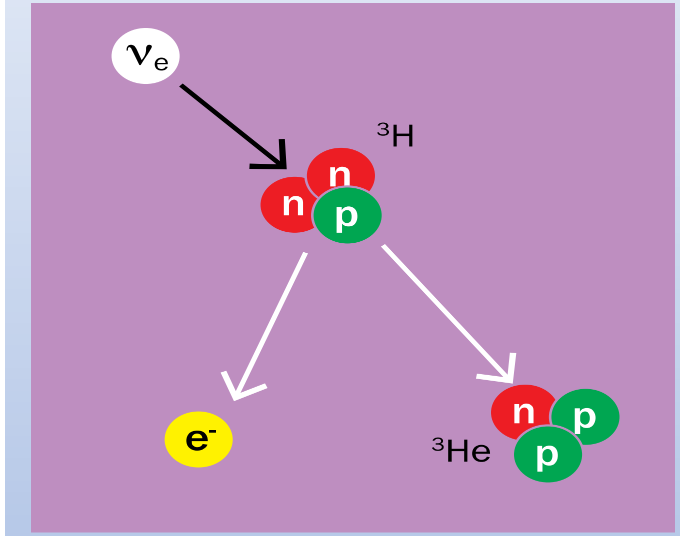
Detection concept: Neutrino Capture on β unstable nuclei

- Basic concept for relic neutrino detection rooted in a paper by Steven Weinberg in **1962** [*Phys. Rev.* 128:3, 1457]; applied for the first time, in case of massive neutrinos, to lay out a proposal for their direct experimental detection in **2007** by A.G.Cocco, G.Mangano and M.Messina. [JCAP 06(2007)015 DOI: 10.1088/1475-7516/2007/06/015]





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



What do we know?

Gap (2m) constrained to

m ≲ 200meV

from **precision cosmology**

Electron flavor expected with

m ≳50meV

from **neutrino oscillations**

CνB Detection Requires:

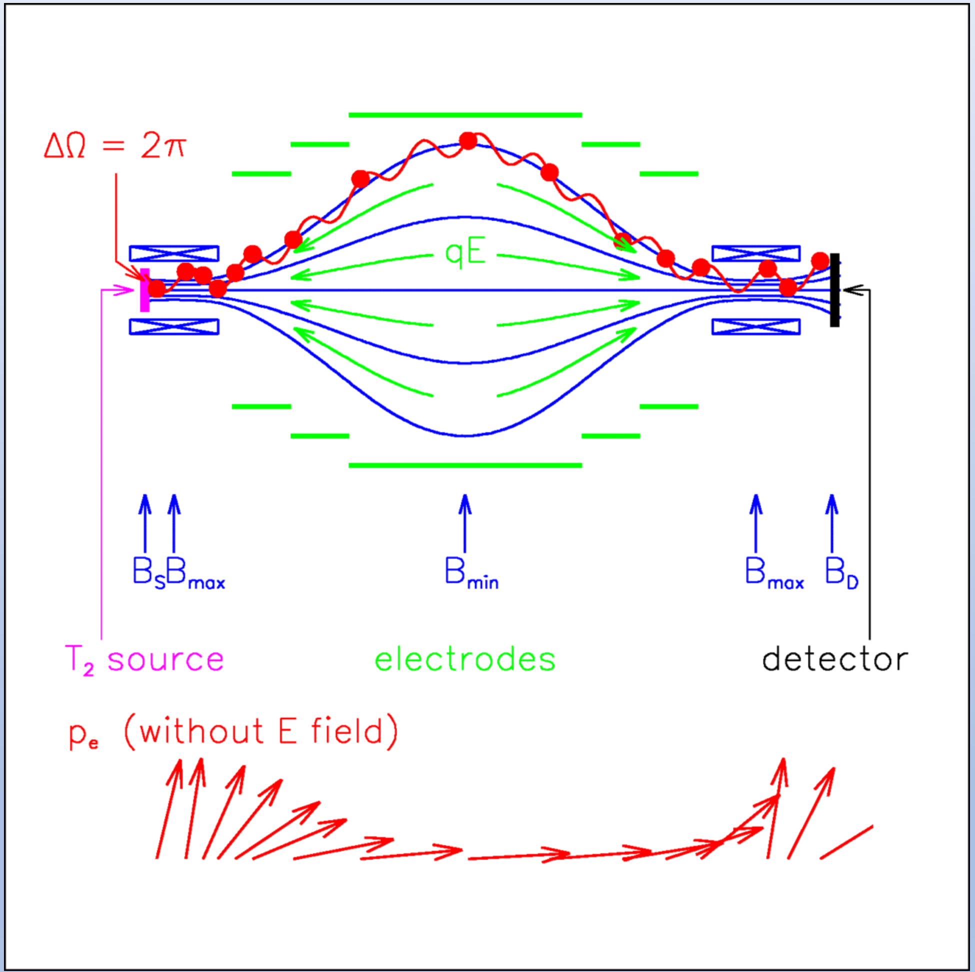
energy resolution set by m_ν

PTOLEMY target resolution: ~ 50 meV

Before carrying on
we can’t miss to mention
the KATRIN experiment

The principle of the Mac-E filter*

Two superconducting solenoids produce a magnetic field B. The beta electrons, which are starting from the tritium source in the left solenoid, are guided magnetically on a cyclotron motion around the magnetic field lines into the spectrometer (2p solid angle).



***from Katrin webpage**

The principle of the Mac-E filter (I)

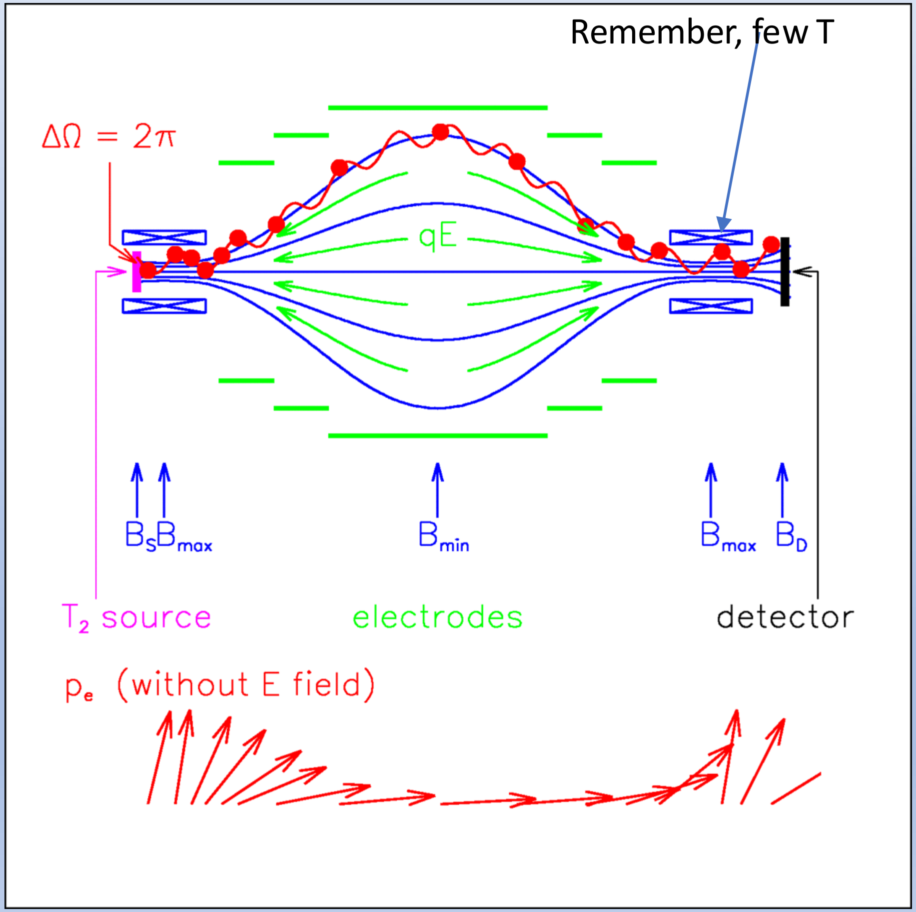
On their way to the center of the spectrometer the magnetic field B drops by many orders of magnitude. Therefore, the magnetic gradient force

$$F_{grad} = (\vec{m} \cdot \vec{\nabla}) \cdot \vec{B}$$

transforms most of the cyclotron energy into longitudinal motion. Thus, because of the slowly varying magnetic field B the momentum transforms adiabatically, therefore the magnetic moment μ that in a non-relativistic approximation is:

$$\mu = \frac{E_\perp}{B}$$

does not change! Condition of adiabaticity



Features and LIMITS of the KATRIN detector

- Pros:
- Simple Filter concept
- Cons:
- Too large volume
- Poor energy resolution
- To increase sensitivity, one musts increase volume
- Collecting electron from any direction

New Filter concept

<u>Transverse Drift filter</u>

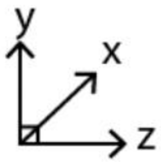
Magnetic Adiabatic Invariance

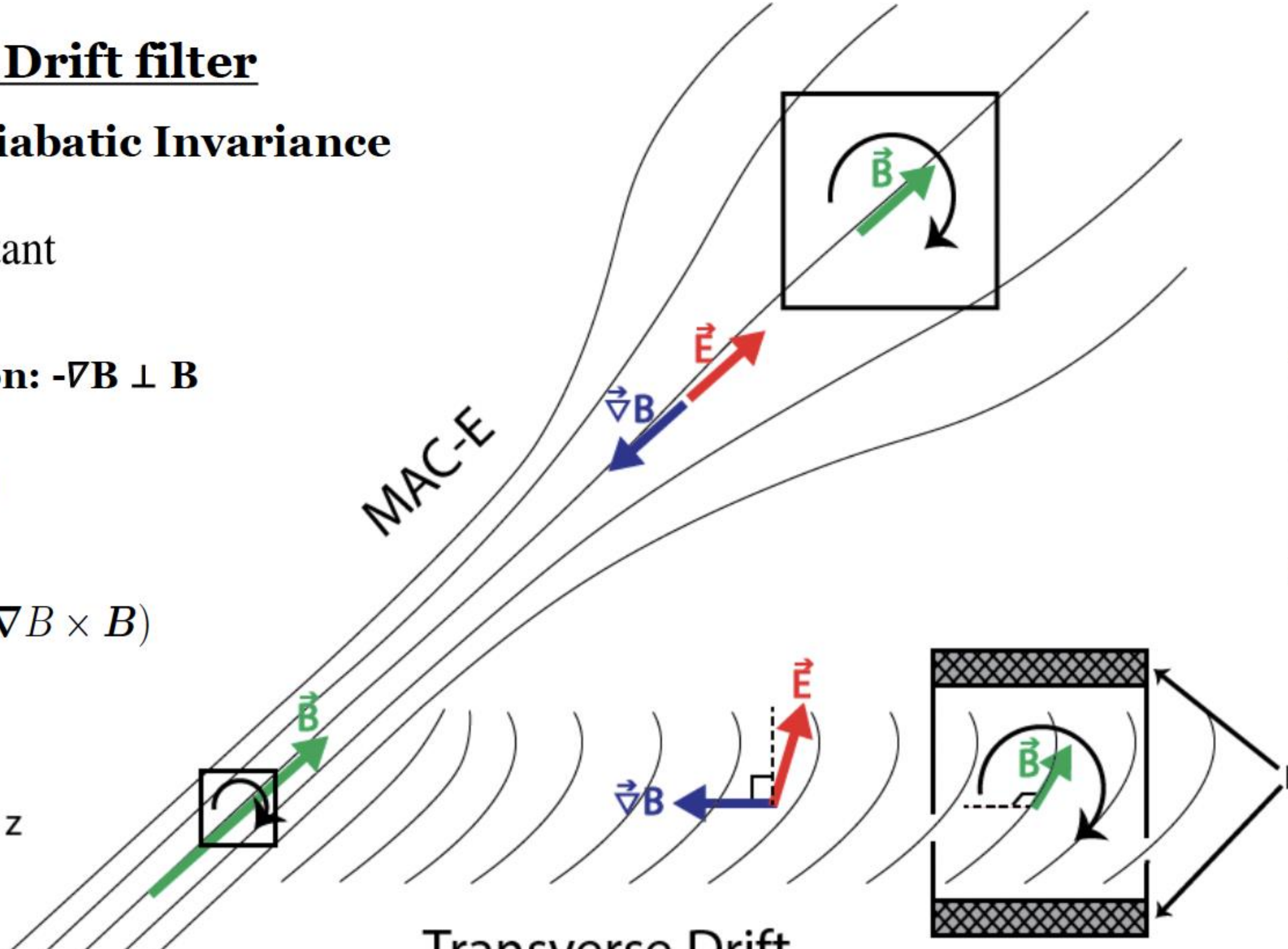
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

No Collimation: -∇B ⊥ B

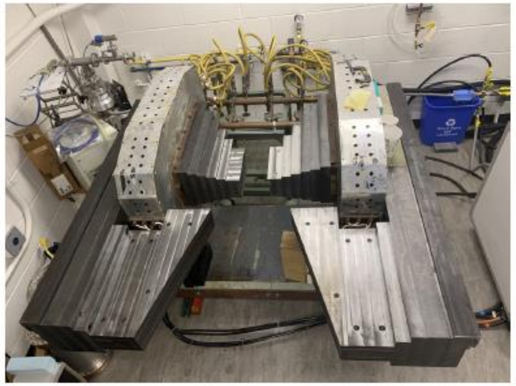
Filter (E-field)

$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\boldsymbol{E}\cdot(\boldsymbol{\nabla}B \times \boldsymbol{B})$$





PTOLEMY



~1 m³

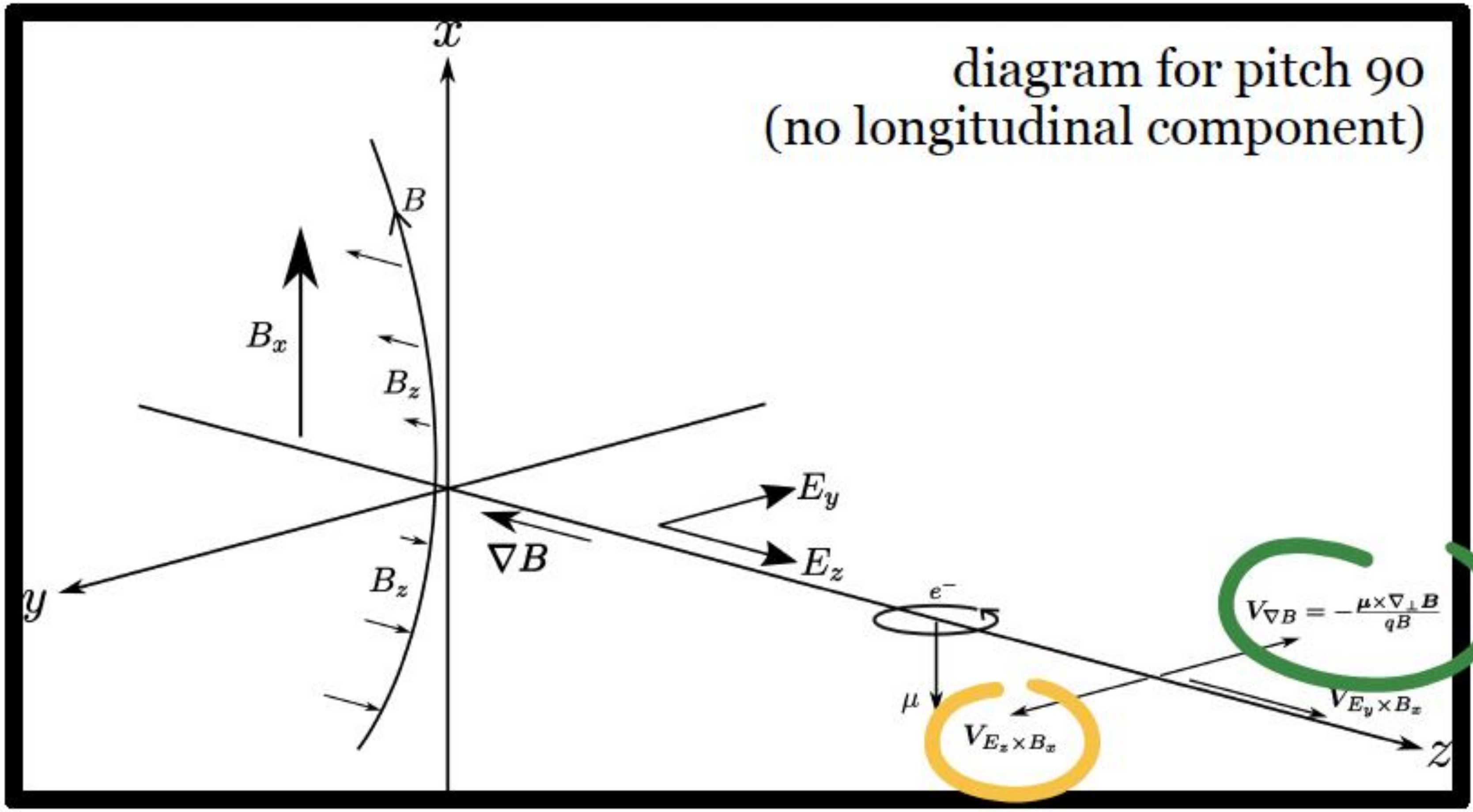
New filter concept: transverse drift

$$_{ift} = \frac{1}{q}\frac{F \times B}{B^2}$$

- ExB drift act
  drift does wo
  - Reducti
    KE of g
- Set E_z x B dr
  produce line
- Potential inc
  draining trai

r pitch 90:

$$= B_0 \cos\left(\frac{x}{\lambda}\right) e^{-z/\lambda},$$
$$= 0,$$
$$= -B_0 \sin\left(\frac{x}{\lambda}\right) e^{-z/\lambda}$$
$$= 0,$$
$$= E_0 \cos\left(\frac{y}{\lambda}\right) e^{-z/\lambda},$$
$$= -E_0 \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda}$$



Grad-B

ExB

nes a line

ExB drift (in uniform B) follows equipotential lines

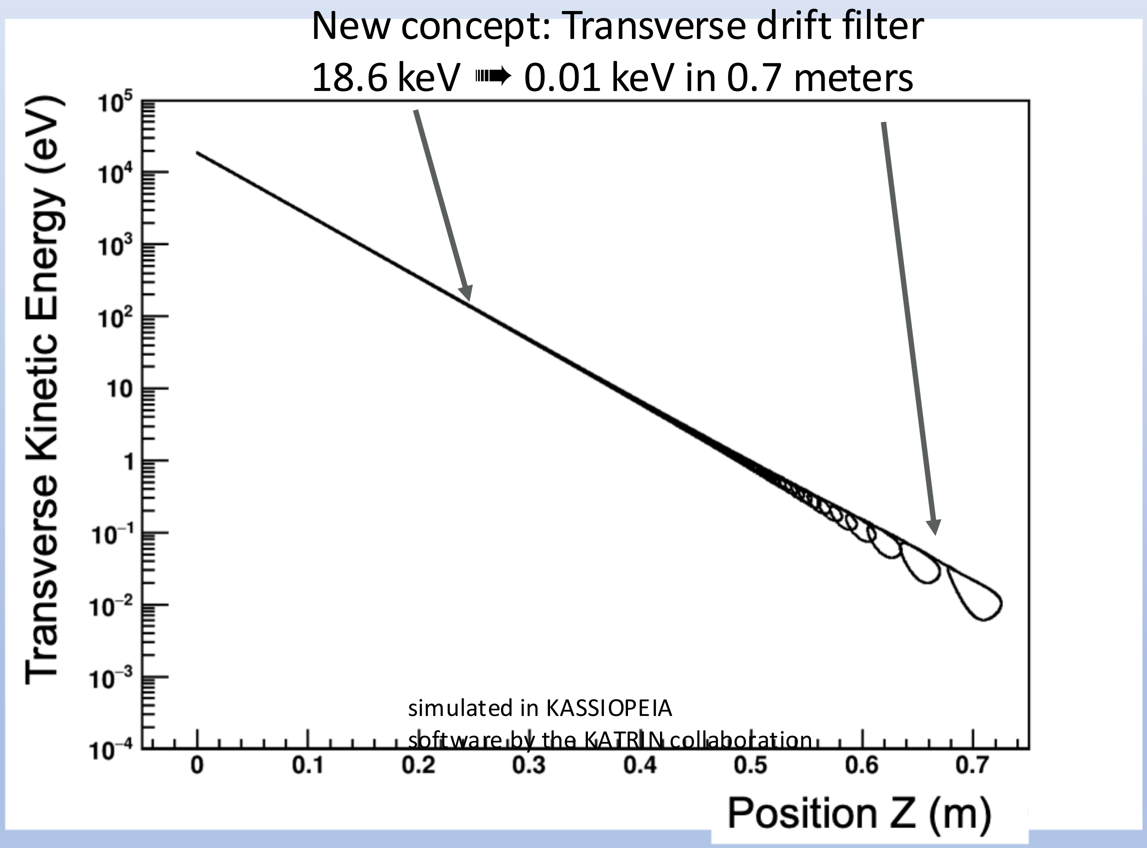
PTOLEMY Collaboration, PPNP **106** (2019) 120-131

Kinetic energy degradation

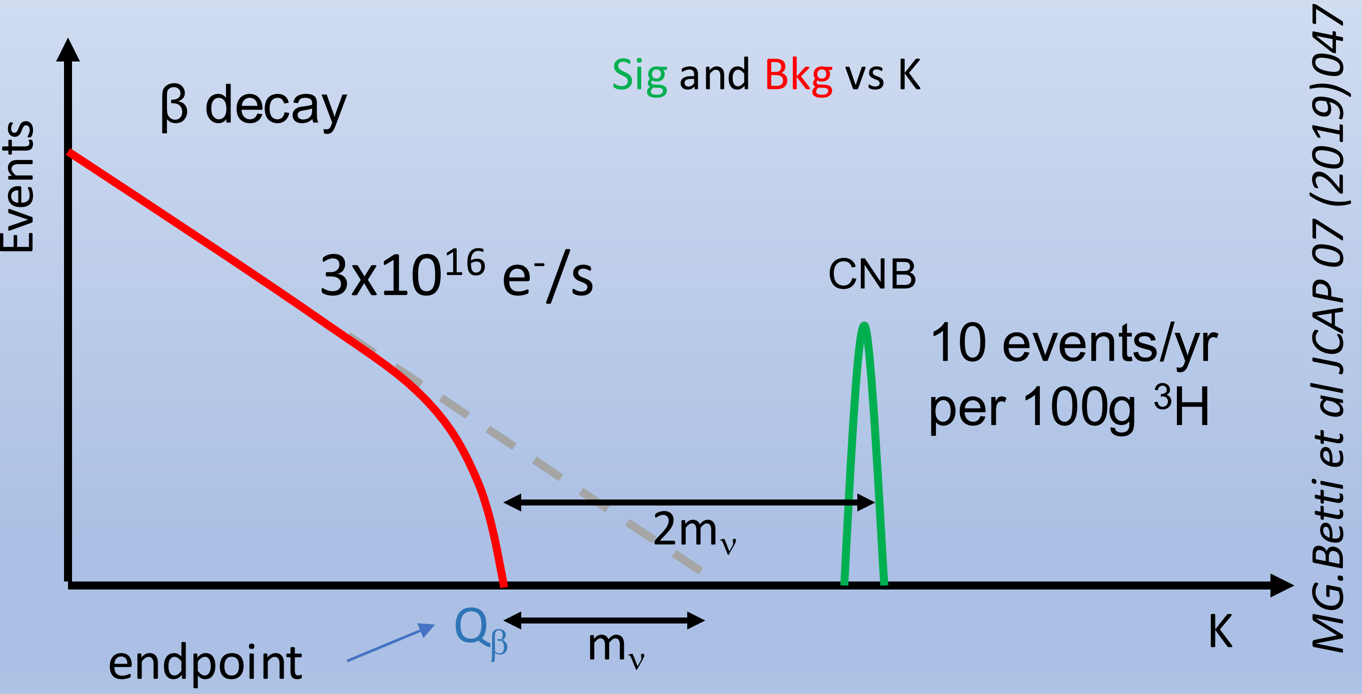
$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\boldsymbol{E}\cdot(\boldsymbol{\nabla}B\times\boldsymbol{B})$$

Prog.Part.Nucl.Phys. 106 (2019) 120-131

Once the kinetic energy is reduced high performance calorimetric measurements can be done



Measurement summary



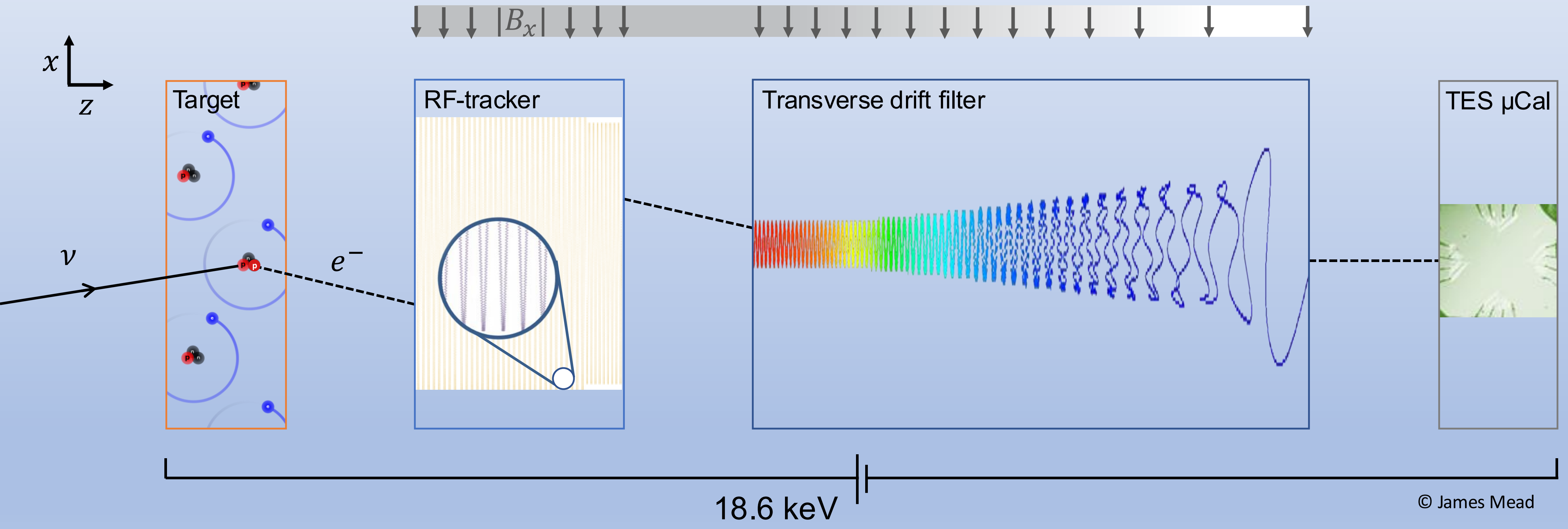
$m_\nu < 0.45$ eV

KATRIN *arXiv:2406.13516v1 [nucl-ex] 19 Jun 2024*

- Extreme energy resolution
- New filter to cope with high rate
- Atomic Tritium on graphene support

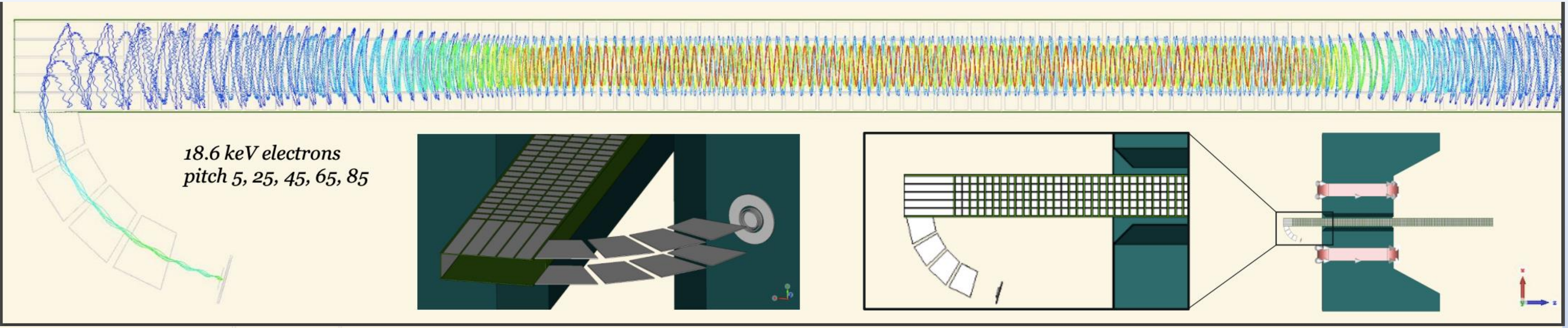
PTOLEMY detector schema

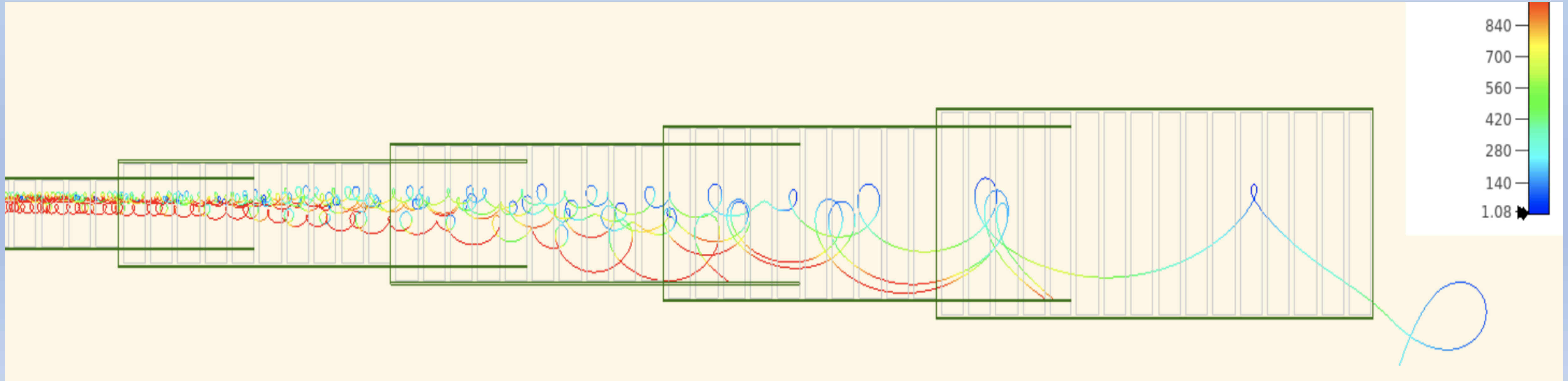
Pon**T**ecorvo / **P**rince**T**on **O**bservatory for **L**ight **E**arly-universe **M**assive-neutrino **Y**ield



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

Full demonstrator simulation (Princeton)

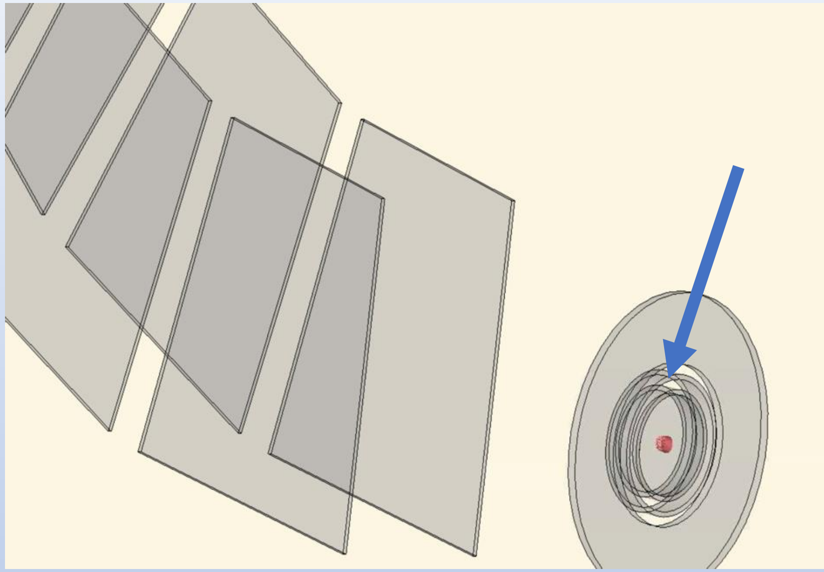


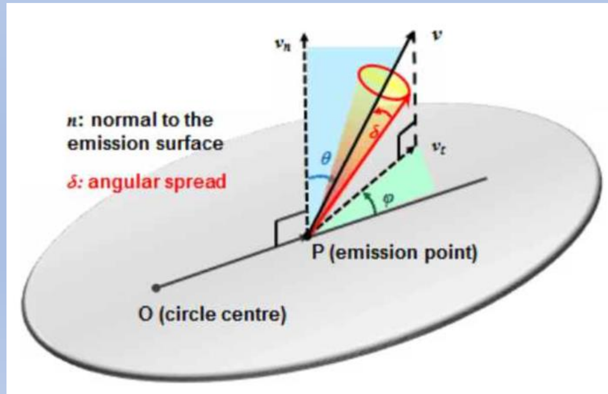


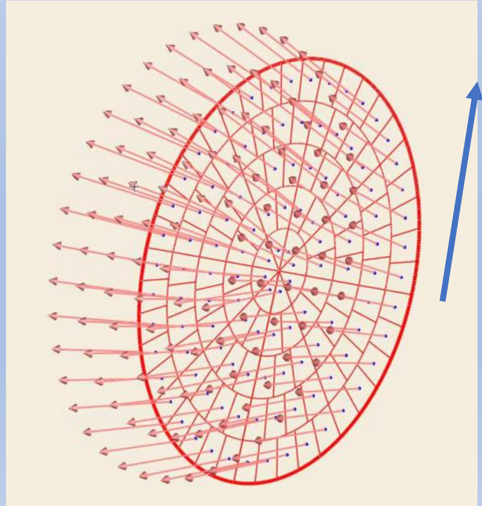
Transmission Simulation Setup

- 1 mm radius circular area split into 50 rings (**5 shown**)
- 50 rings = 10,200 particles
- Uniform distribution of pitch θ within a 10 degree window
- 8 fixed phi Φ emission angles
- All electrons with initial KE = 18.6 keV
- E.g.
  θ = 30±5, Φ = 0 (N=10,200)
  θ = 30±5, Φ = 45 (N=10,200)
  …
  θ = 30±5, Φ = 315 (N=10,200)

θ = 30±5, Φ = 0..315 → N=81,600
θ = 40±5, Φ = 0..315 → N=81,600
…







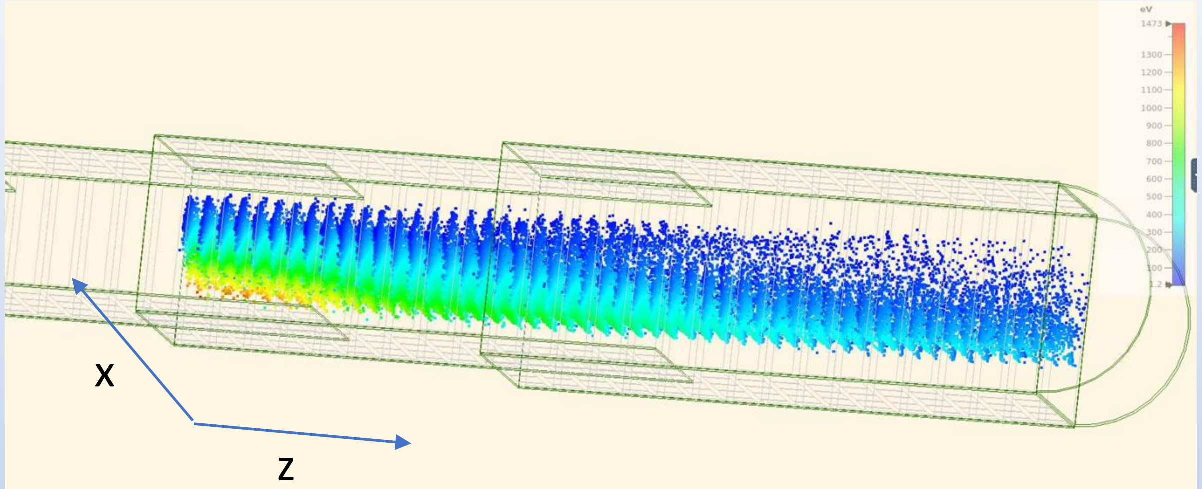
1mm
radius
(5 rings)

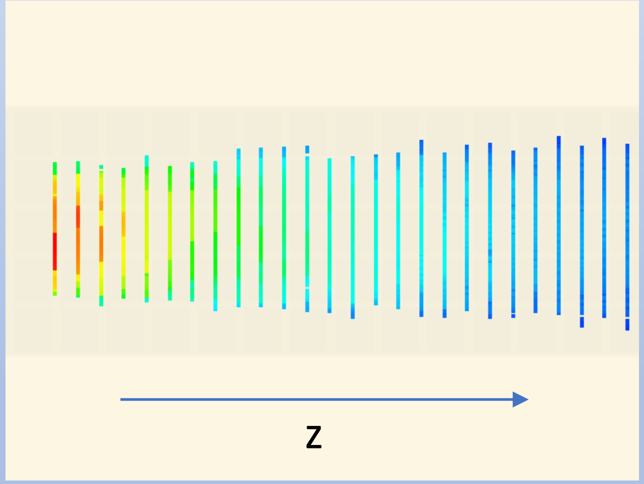
Methodology

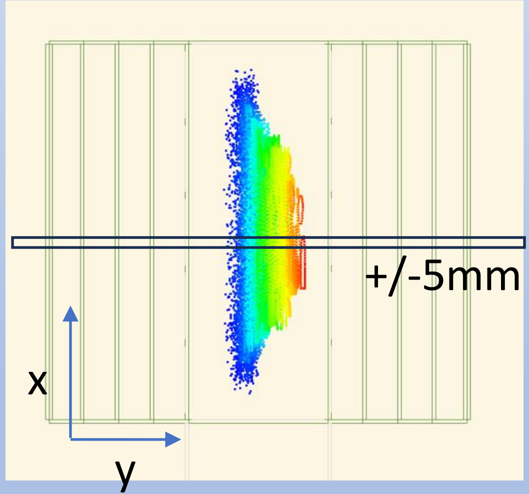
- 2D plane monitors placed every 1 cm in z
  - 11x6 cm in (x,y) centered at (0,0)
- Record individual particle hit information (incl. multiple hits per particle due to cyclotron motion)

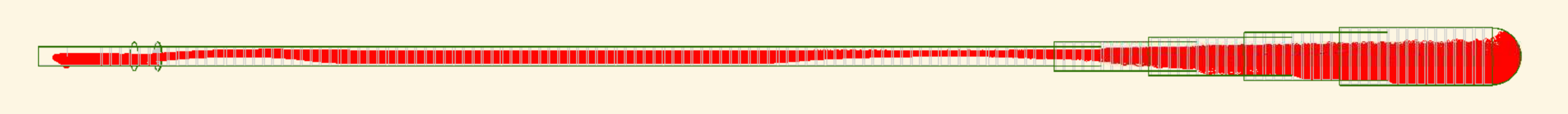
At each Z coordinate:

- **Transmission efficiency:** Extract # of unique particle hits per plane, express as percentage of N
- **Average KE:** Take average over all hits (incl. duplicates)
- **Pitch angle:** Calculate instantaneous pitch angle from momentum components for hits within 5mm of x=0, then take average pitch over these hits

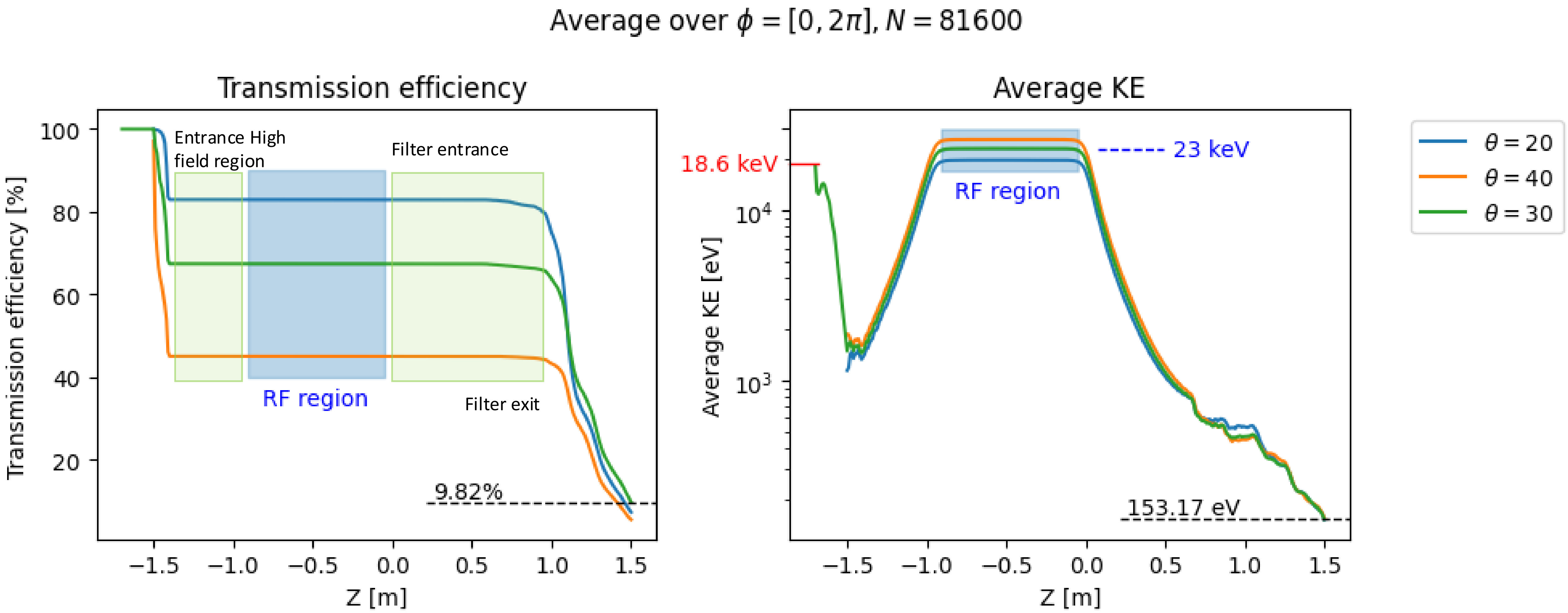








Showing θ = 20±5, 30±5, 40±5 averaged over Φ bin



PTOLEMY: Energy

- Energy measurement from ΔV and calorimeter:

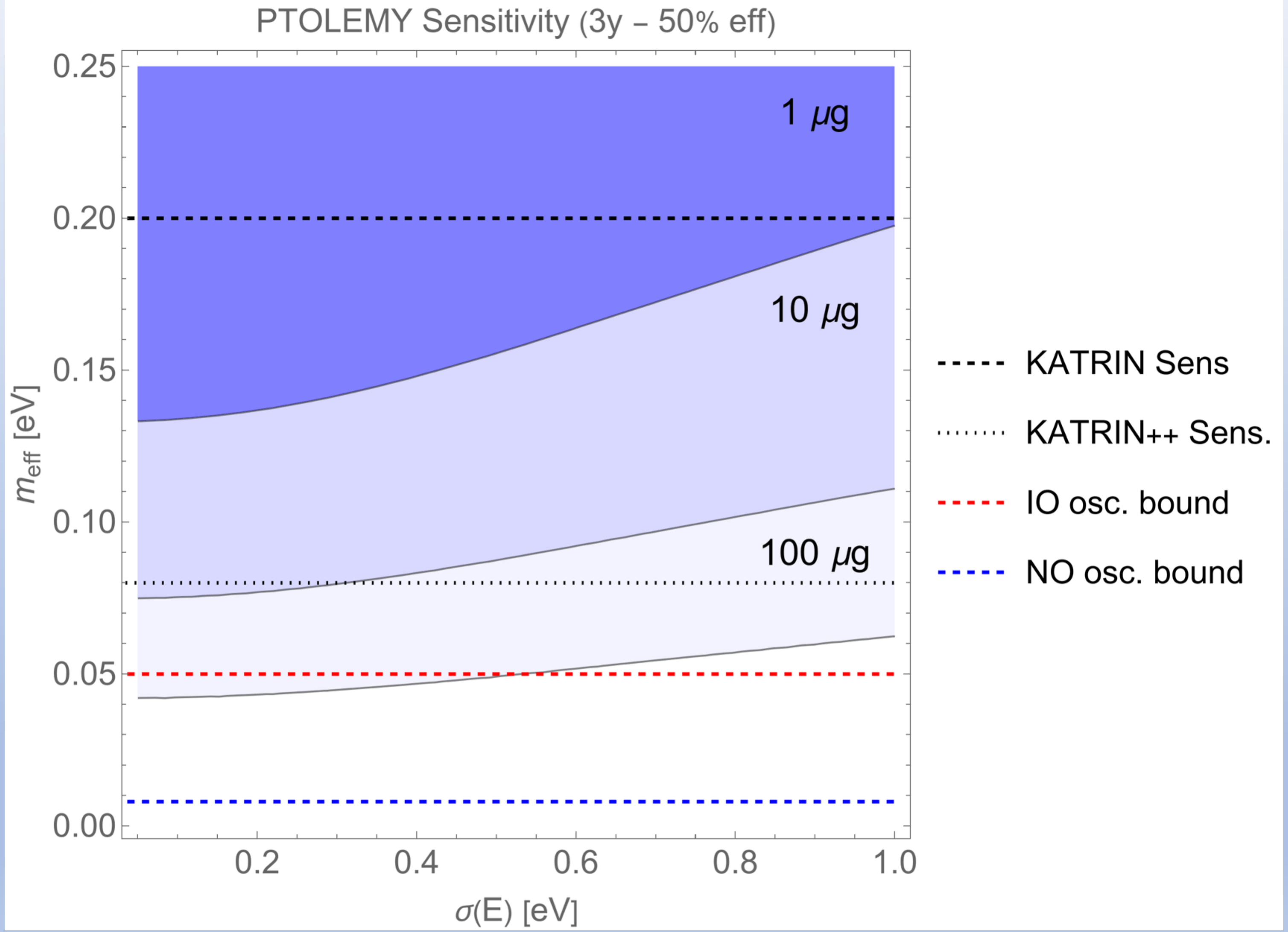
$$E_e = e\,(V_{cal} - V_{source}) + E_{RF} + E_{cal}$$

- Calorimeter energy resolution must be O(50meV)
    1. Transition Edge Sensors
    2. State-of-the-art 50 meV@100eV with photons

- Voltage stability (alias overall energy scale) better than 10-20mV

- NOTE: internal voltages are actively adjusted for each interesting electron

Sensitivity as a function of tritium mass



Remarks:

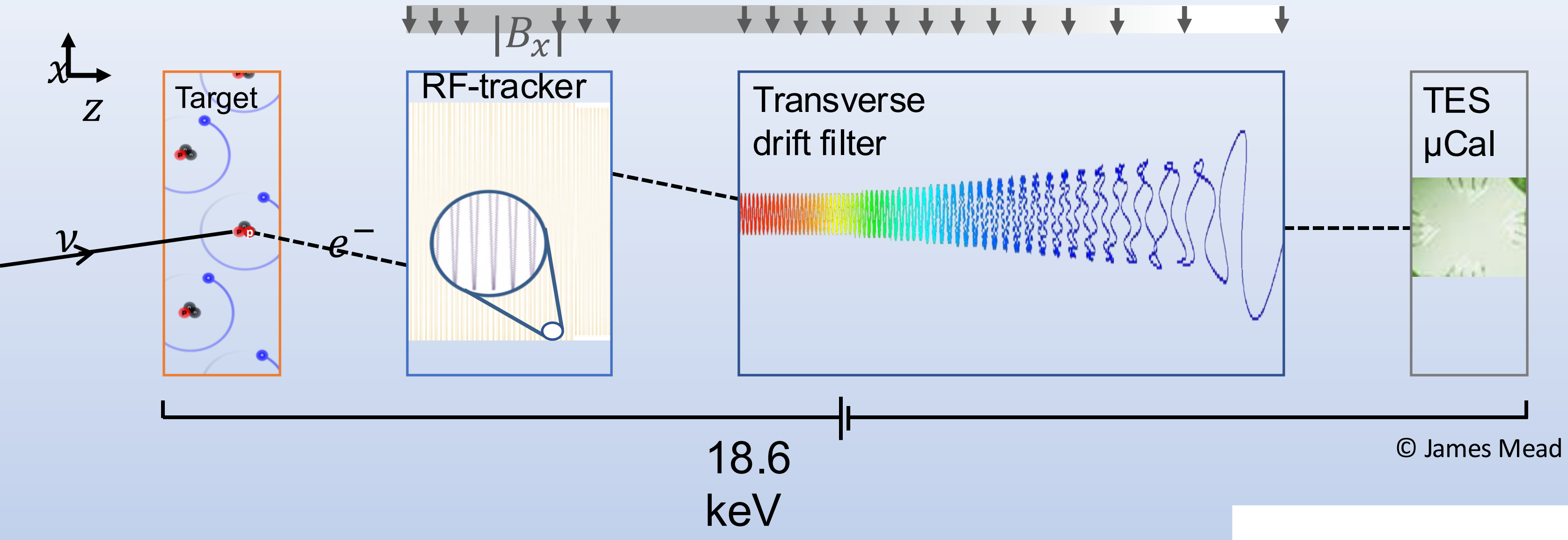
- the sensitivity is weakly dependent upon the energy resolution (500 meV is already a good starting point)

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

- 100 μg (0.5 m^2) can potentially probe the neutrino mass down to the IO scenario

In preparation a theory paper on solid state effects on the electron spectrum, and consequent theory systematics on m_{ν} extraction (A. Casale, A. Esposito G. Menichetti, V. Tozzini)

Systematics

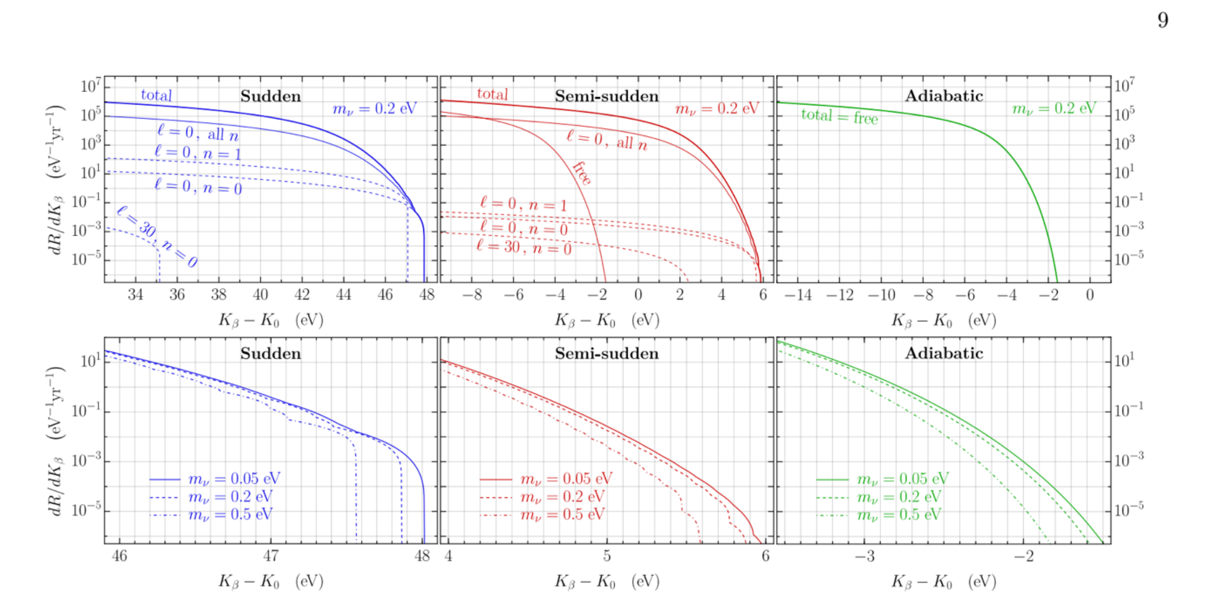


1) Theory aspects:
further understanding of e ground level is needed

https://arxiv.org/pdf/2504.13259

2) Overall energy scale know at < 10 meV

3) RF correction known at better than 10 %



Overview of the R&Ds in the PTOLEMY project

1. RF measurement from single electron emission (LNGS/Nikhef)
2. Graphene loading capability (Roma1)
3. Graphene transmission measurement and electrostatic analyser (Roma3)
4. TES design optimization at National Institute of Metrology (INRiM)
5. Demonstrator SC magnet design and construction (LNGS/Princeton)
6. HV system development setting the overall energy scale (LNGS)

PTOLEMY Demonstrator at LNGS

We aim at

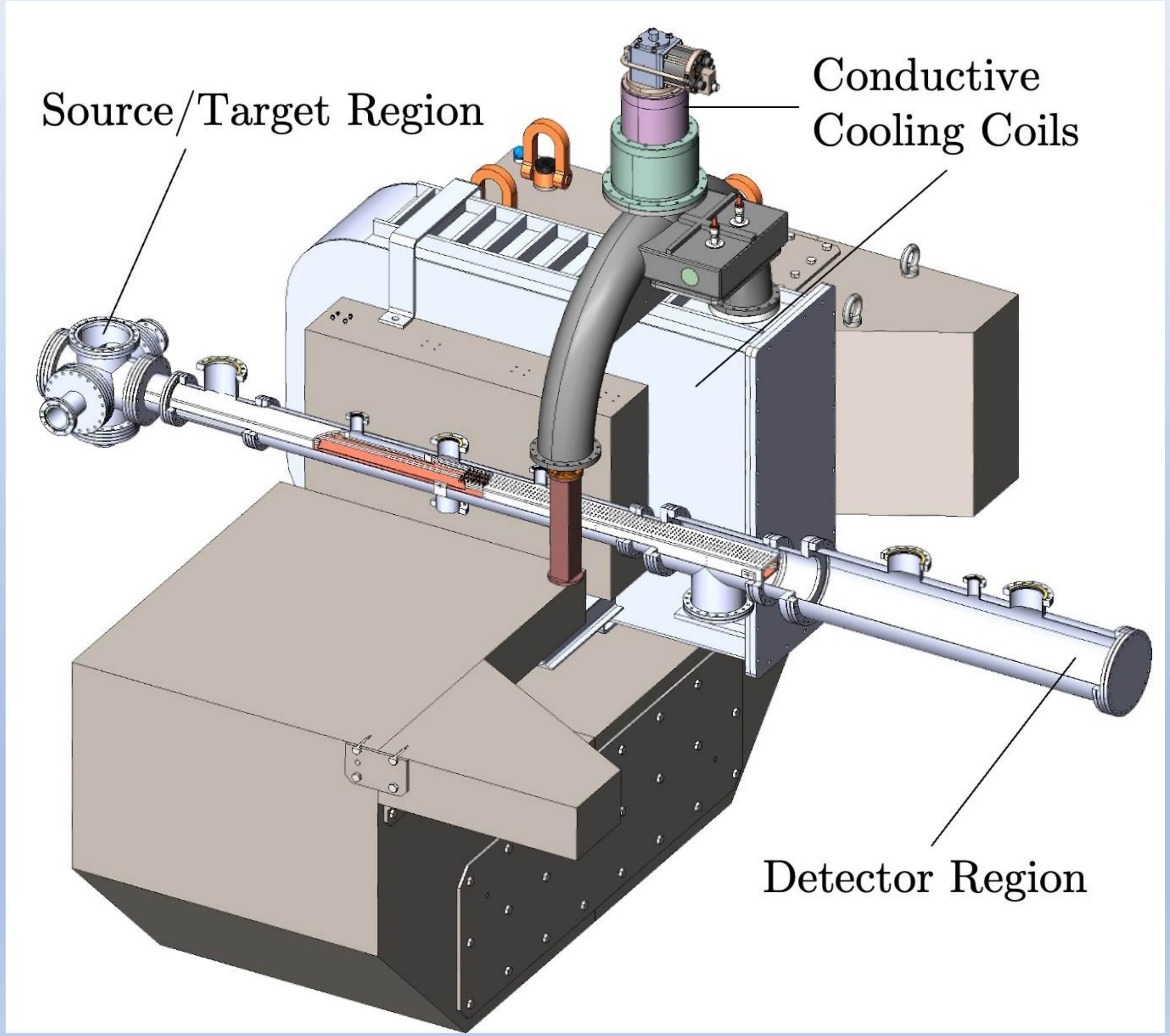
Proof the capability of the new filter concept to transport the electrons from Target/source to the electron calorimeter and simultaneously select electrons in the ROI (10-100 eV around the T endpoint)

The baseline option of the demonstrator setup is (Phase-0):

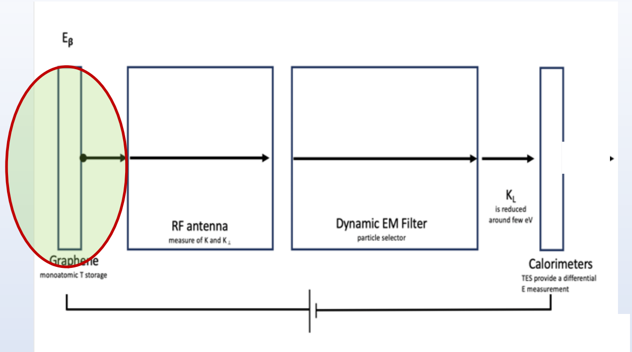
1) Run the filter with full functionalities
2) Electron provided by calibration sources
3) Energy measurement realized by means of a standard Silicon Drift Detector

In a second step (Phase-1, 2027-) we aim at exploiting the features of Transition Edge Sensor (TES) calorimeters with the targeted energy resolution and start to use T loaded graphene

Assembly of the DEMONSTRATOR

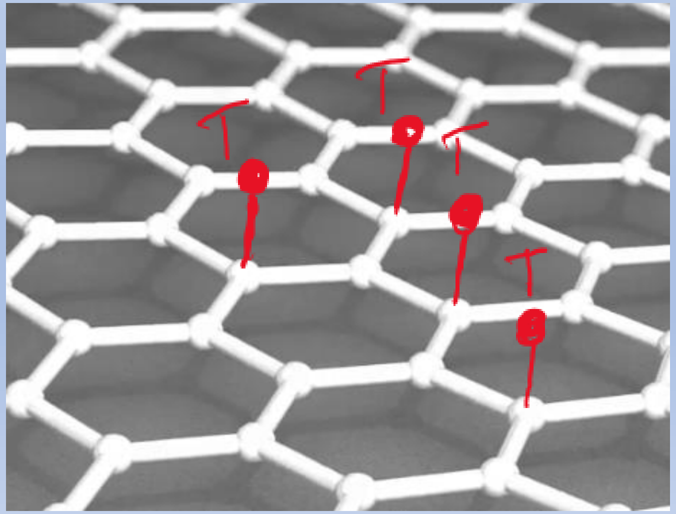


PTOLEMY: tritium target

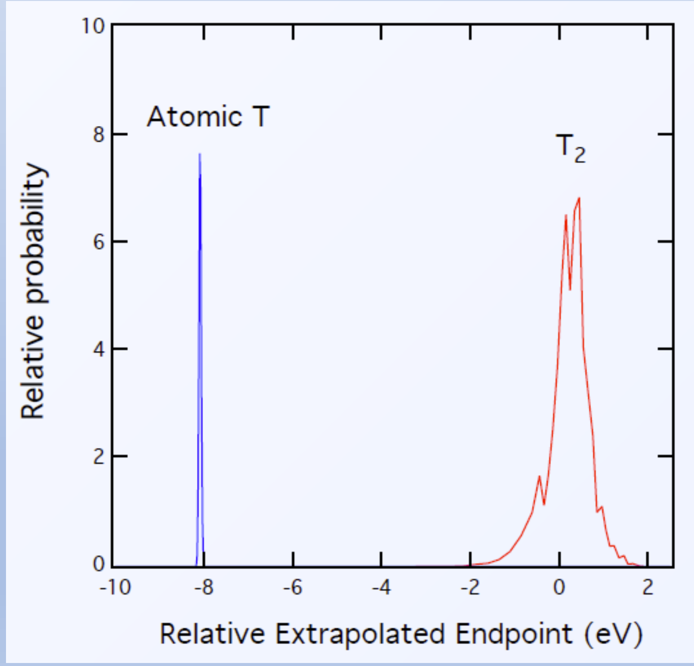


- Use **atomic ^3T**
  - No ro-vibrational modes in final state like for ^3He-^3T final state.
  - Limit to energy resolution not determined by target itself

- dE/dx of electrons imposes extremely **thin targets**
- We investigate ^3T loosely bound to graphene
  - Theoretical maximum is about 0.2 mg tritium per m^2

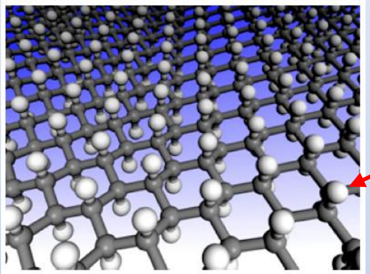


Max 1-tritium for every C



Hydrogen and Deuterium loading on graphene and nano-porous graphene at Roma3

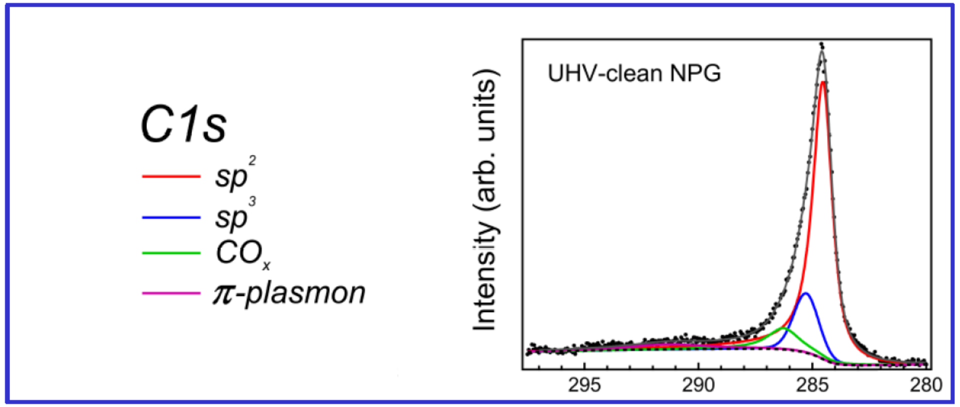
atomic H as a tool to '*pinch*' the sp2 bonds towards an sp3 configuration while maintaining the planar nature of graphene



sp3 H-C bond

how to estimate the H (or D):C upload → directly from a quantification of the sp3 bond spectroscopic signal from the XPS C 1s core level:

$$\%H/C = I_{sp3} / (I_{sp3} + I_{sp2}) = \Theta$$



Abdelnabi et alii, Nanomat. **11**, 130 (2021) method: atomic **H at ~0.2 eV** kinetic energy by hot-capillary in vacuum

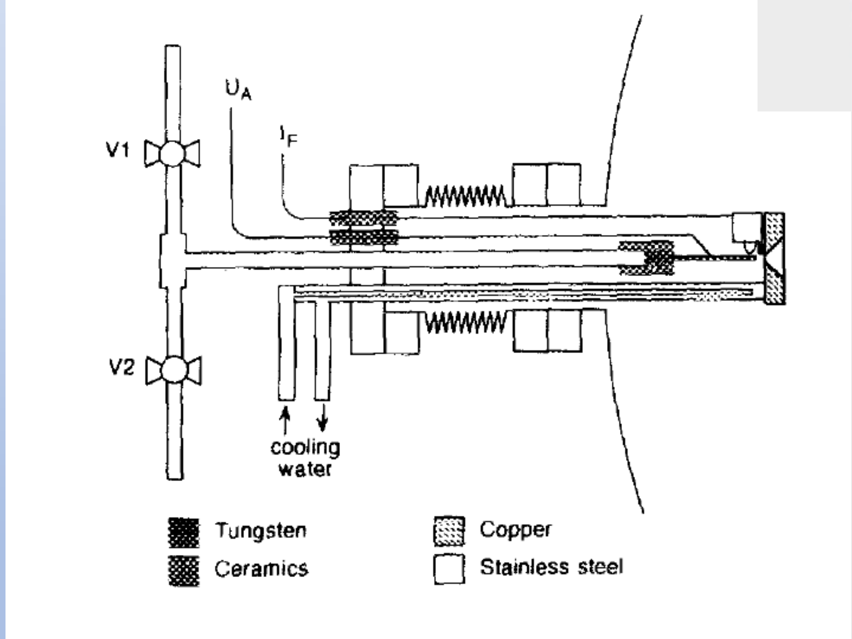
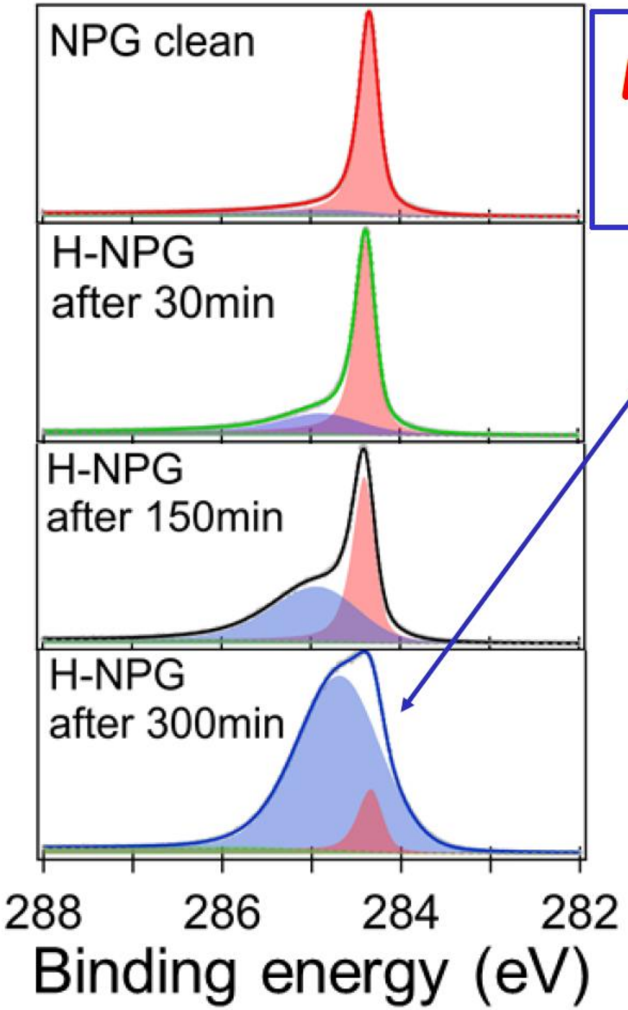


FIG. 1. Schematic drawing of the atomic hydrogen source.

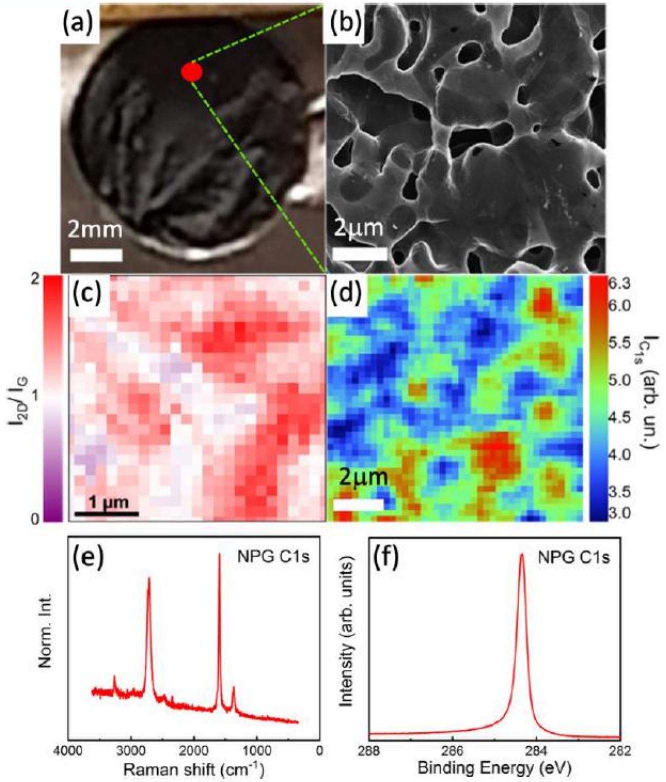
H_2 flow into a capillary with hot-spot (~2000 C) in UHV → more than 95% molecules cracked in **atomic H** concentrated onto the sample

Bischler and Bertel, J. Vac. Sci. Technol. A **11**, 458 (1993) high-quality atomic H cracking through capillary in UHV

H-NPG with spatial resolution, Soleil (Paris)



reached ~90% H-upload!

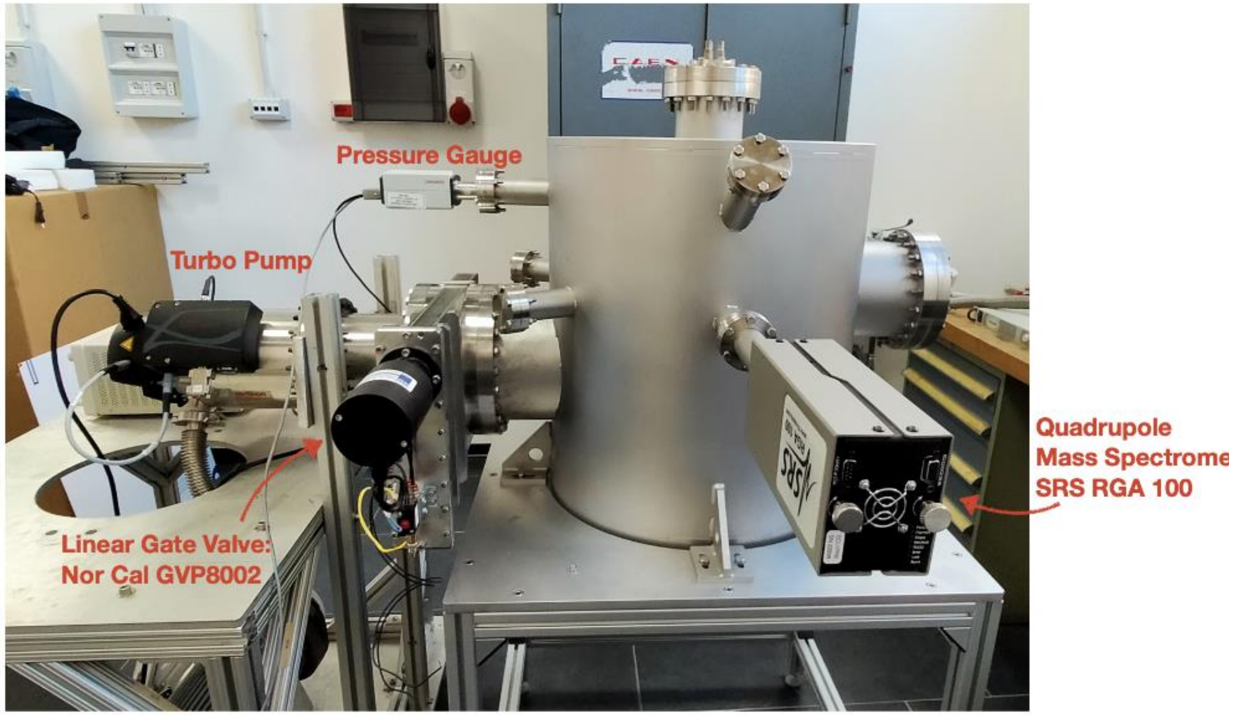


Betti et all, Nano Lett. **22**, 2971 (2022)

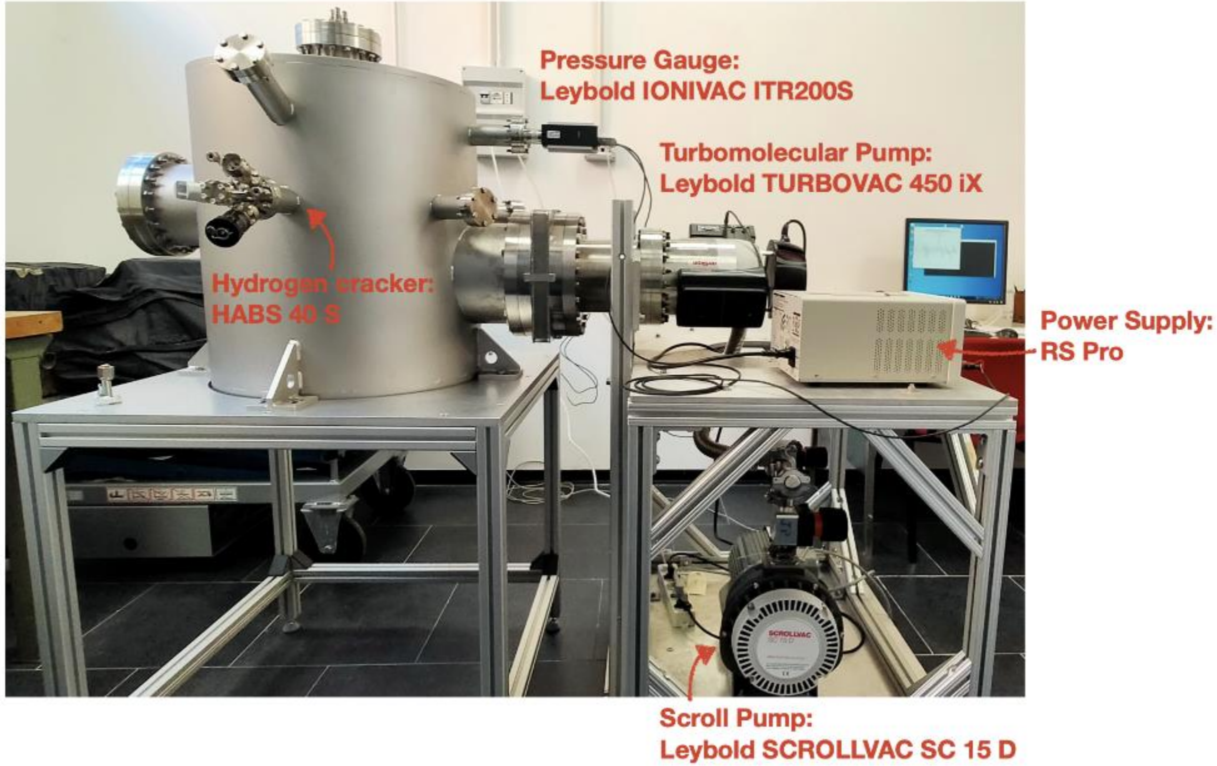
T-loading setup in Roma1

we need a lab. capable to deal with T gas
system tested with H^2

T-chamber R side view



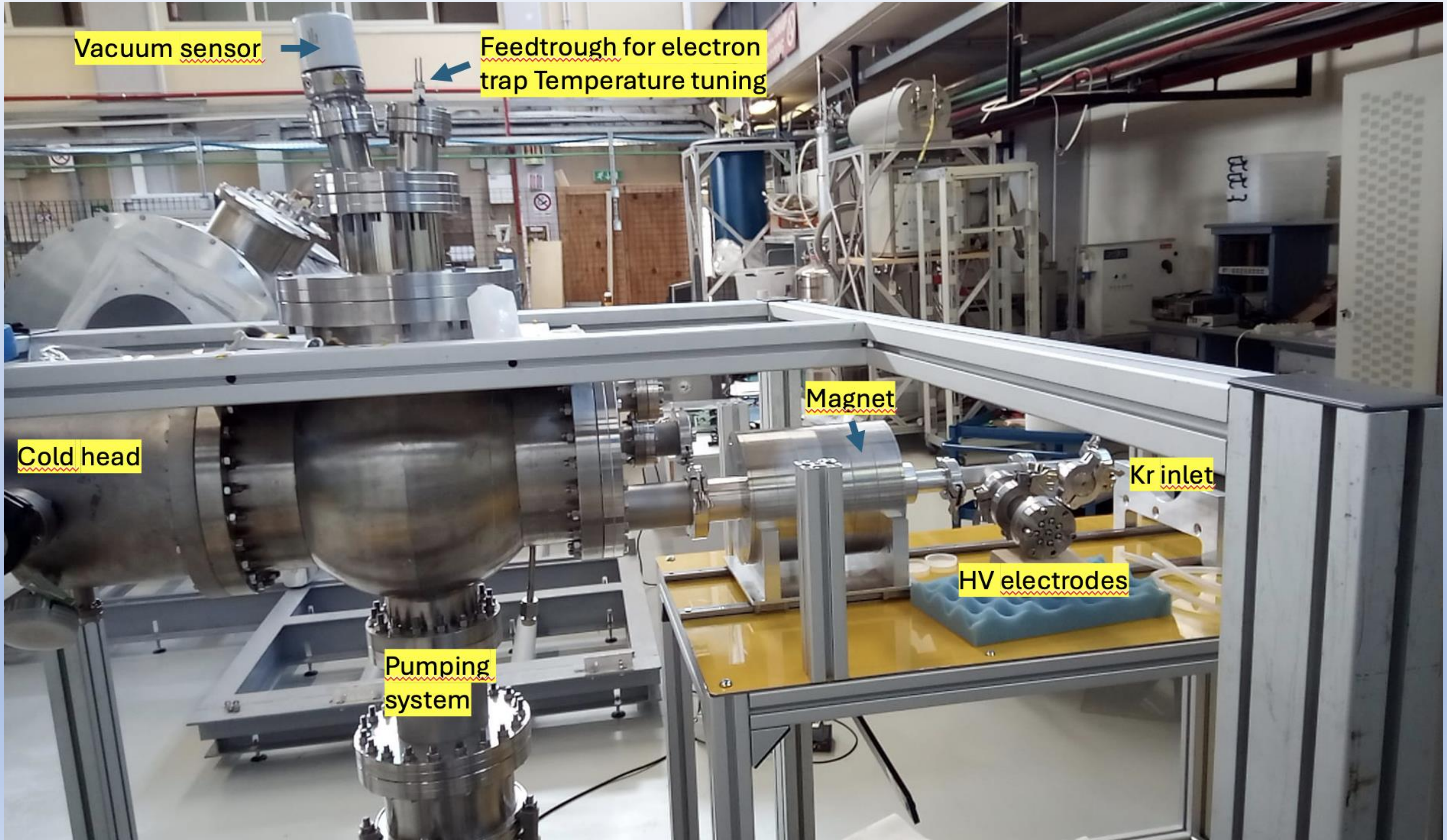
T-chamber L side view



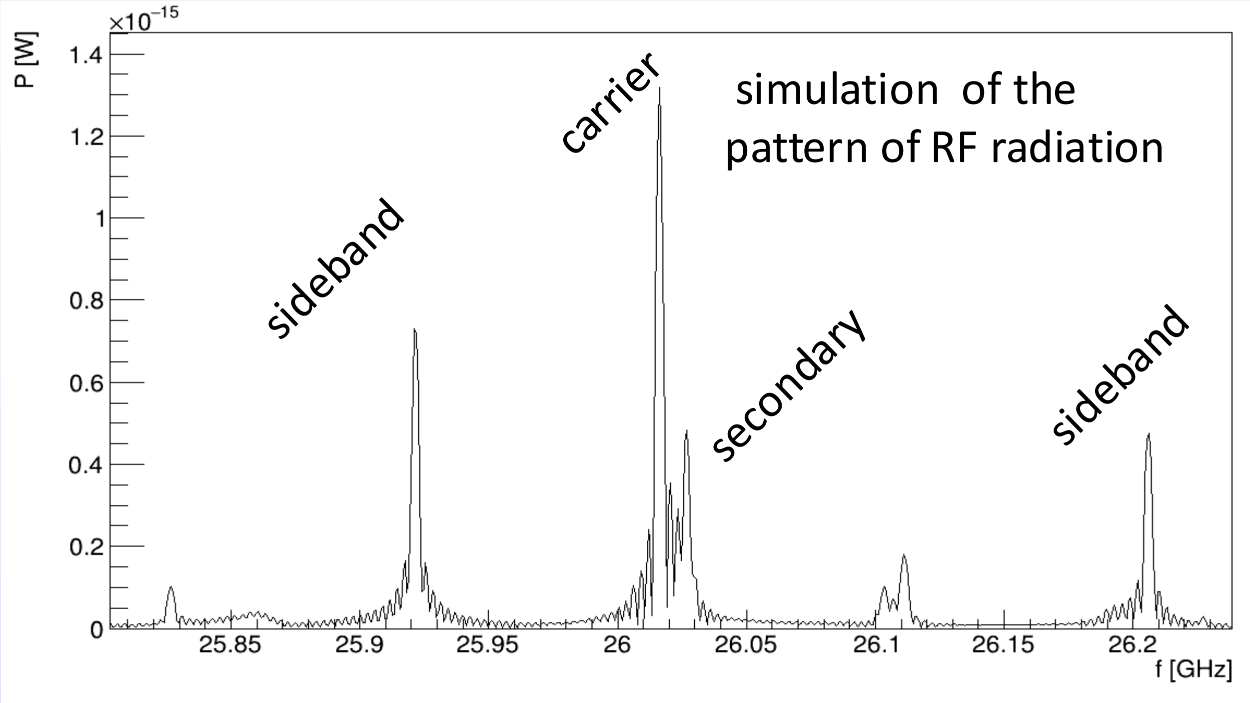
Single electron RF emission detection

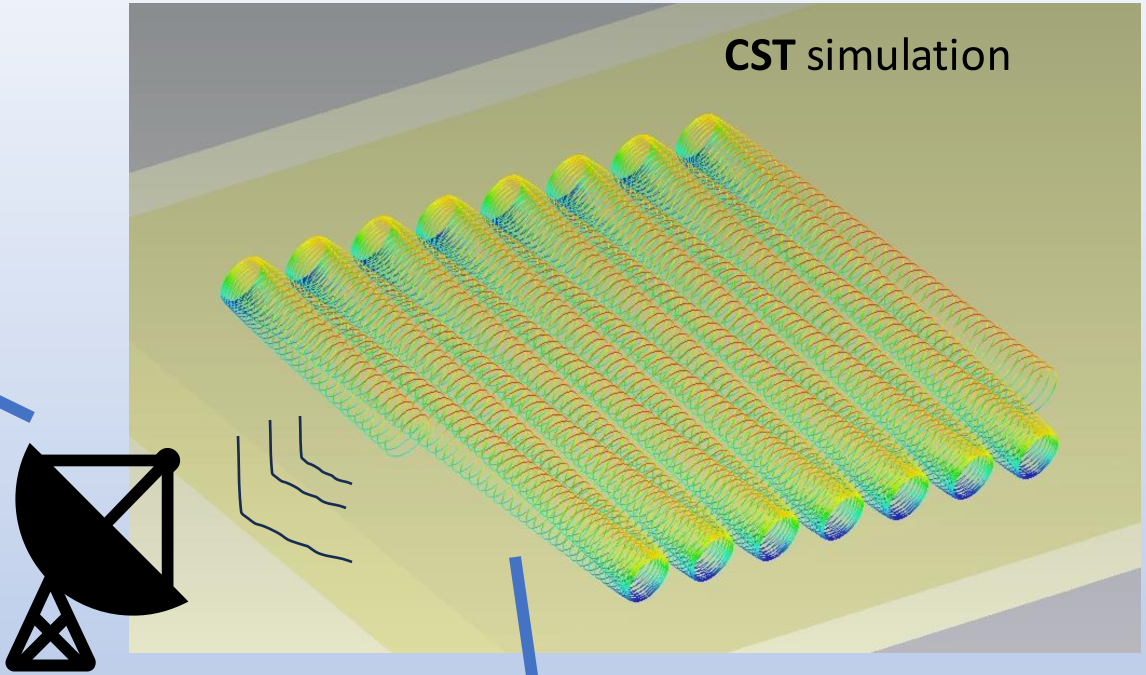
Aim:	Detect single electron RF emission signal @ 27 GHz at low intensity (~ 1 fW) in a relatively short time (hopefully below 100 μs)
Purpose(s):	First measurement of this kind in the PTOLEMY Collaboration First step toward the demonstrator Key steps to build the GANTTChart for funding agencies
Setup:	Permanent magnet (1 Tesla field) hosting an “electron trap”

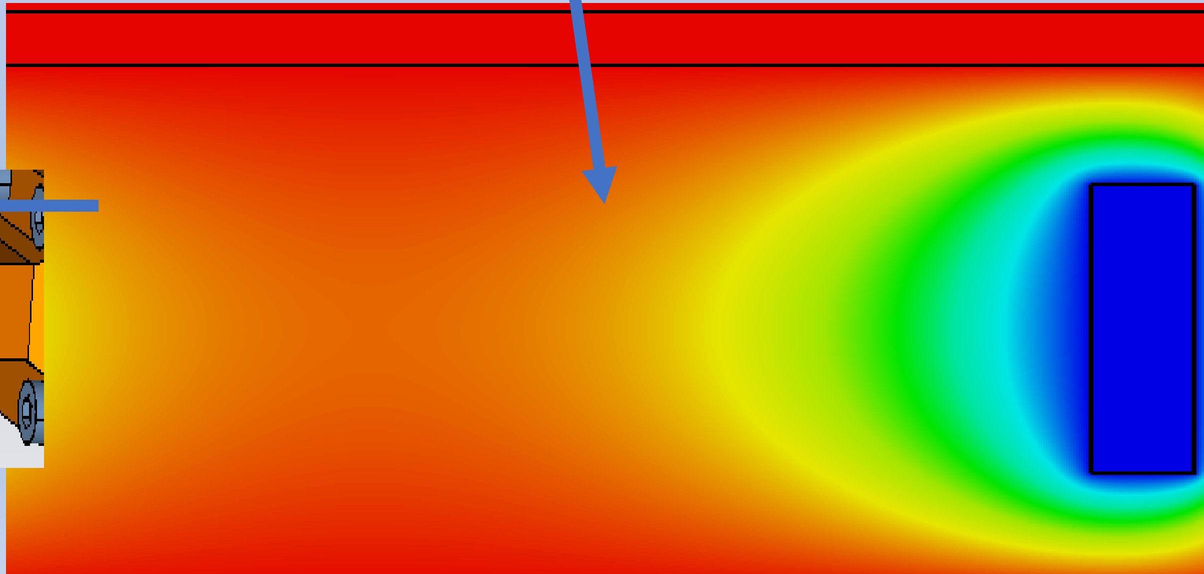
RF detection setup at LNGS: electron trap

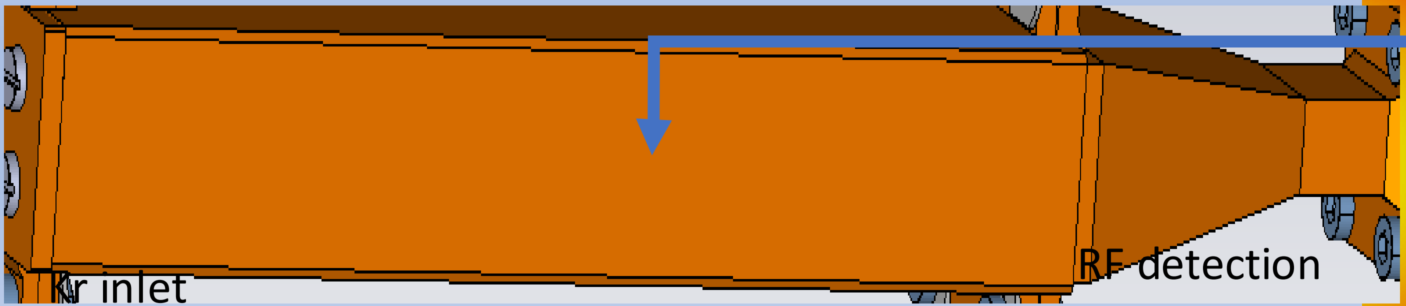


Electron cyclotron RF radiation studies



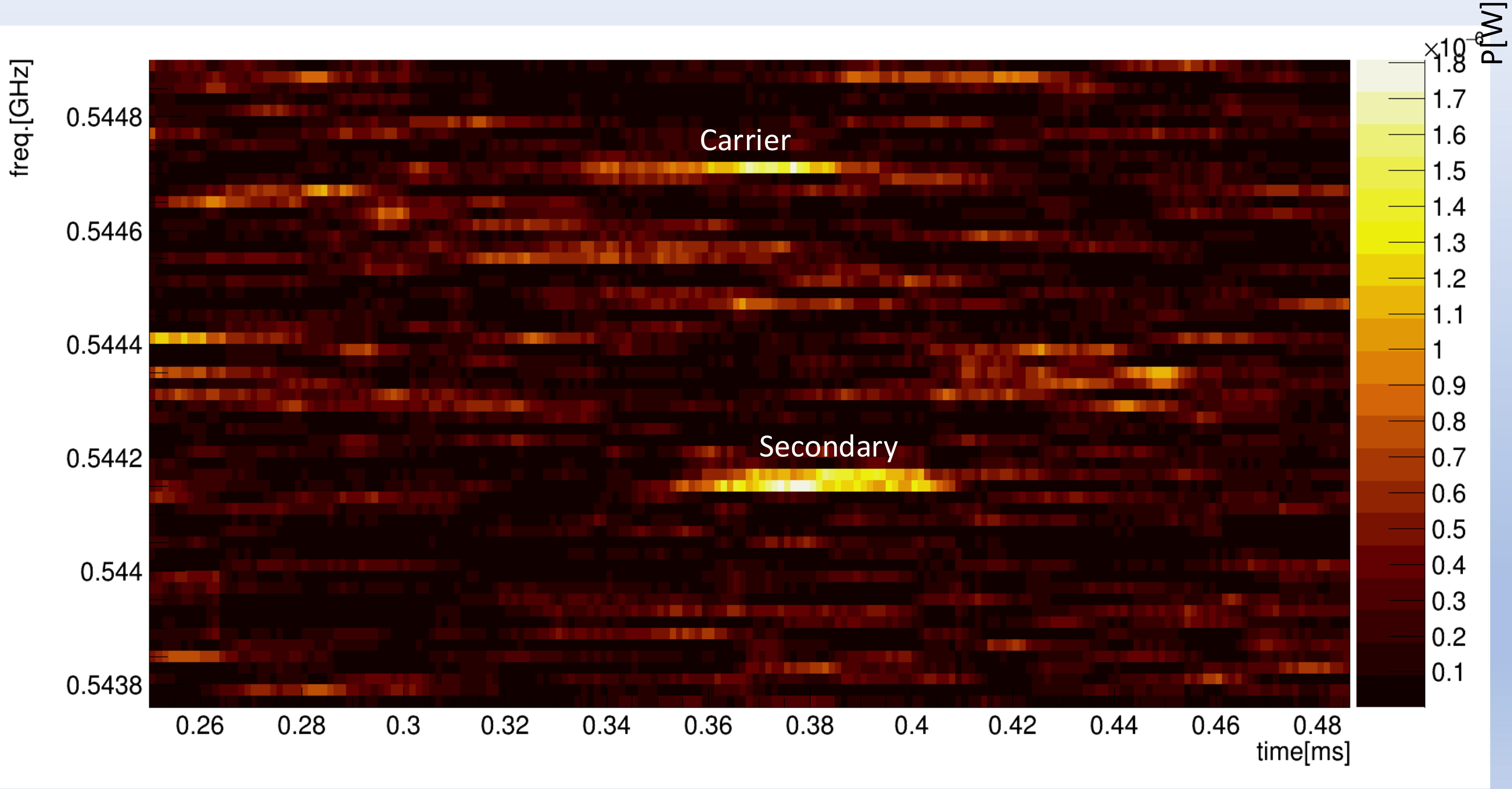






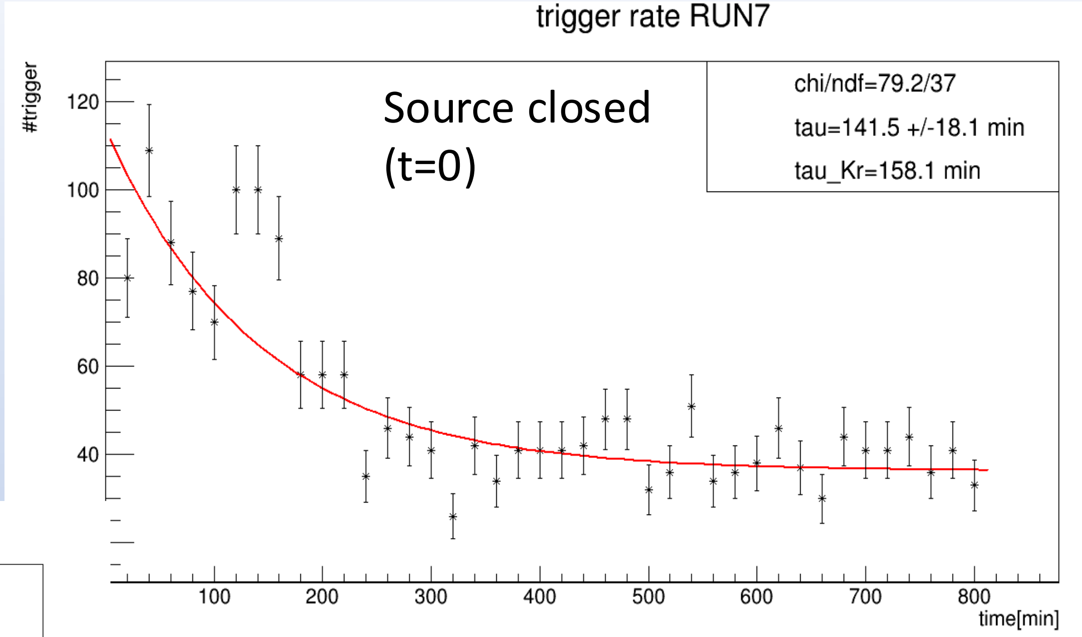
Candidate electron events

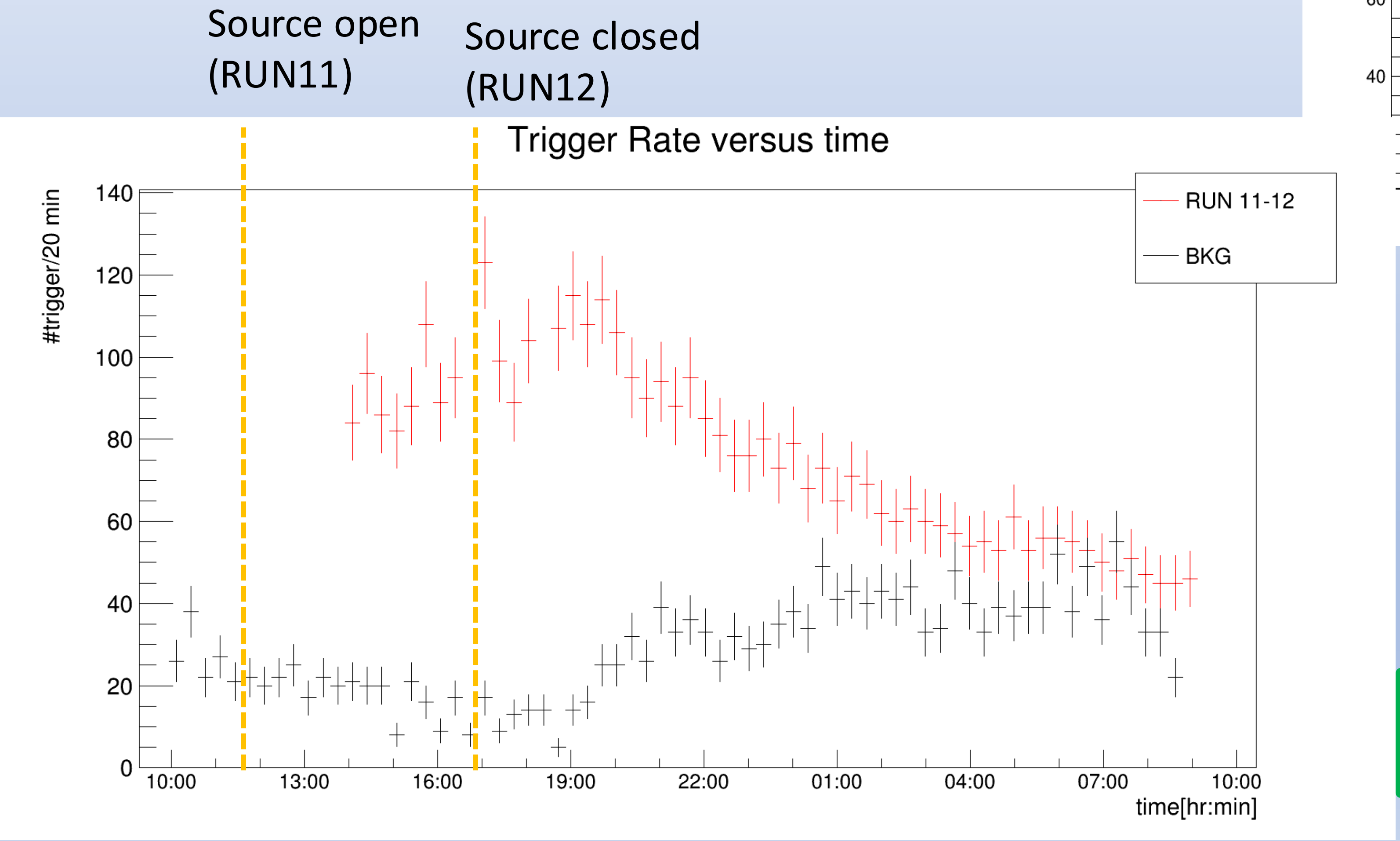
RF emission frequency vs time of single electron in the permanent magnet

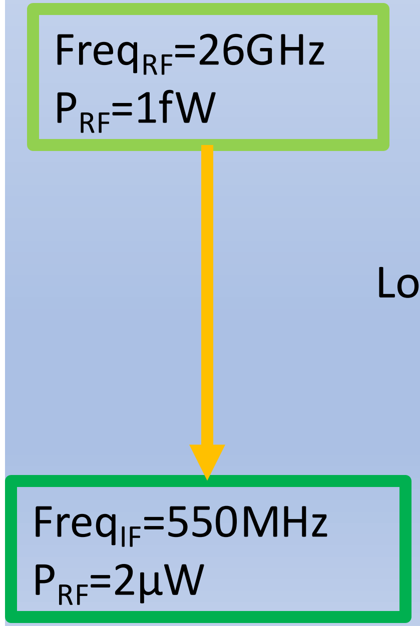


Electron signature: trigger rate (data)

Source: ^{85}Rb-> ^{83m}Kr
Lifetime Kr=158.1 min

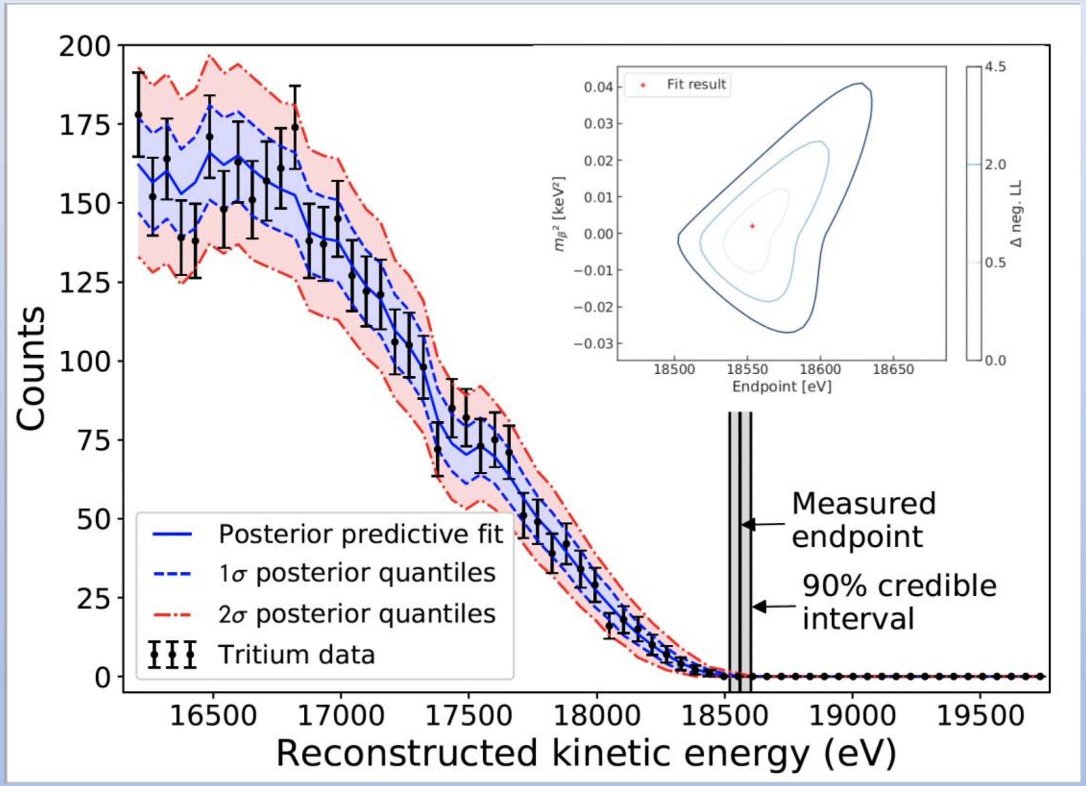






Electronic chain:
Low noise amplification +
down-conversion

Recent Project 8 Tritium RF Measurement



https://arxiv.org/abs/2203.07349

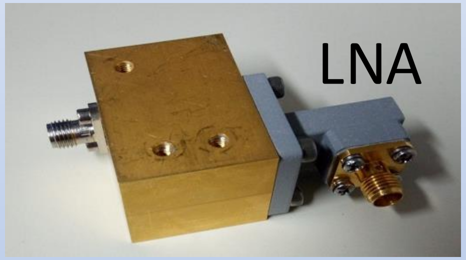
RF measurement background levels extremely low.

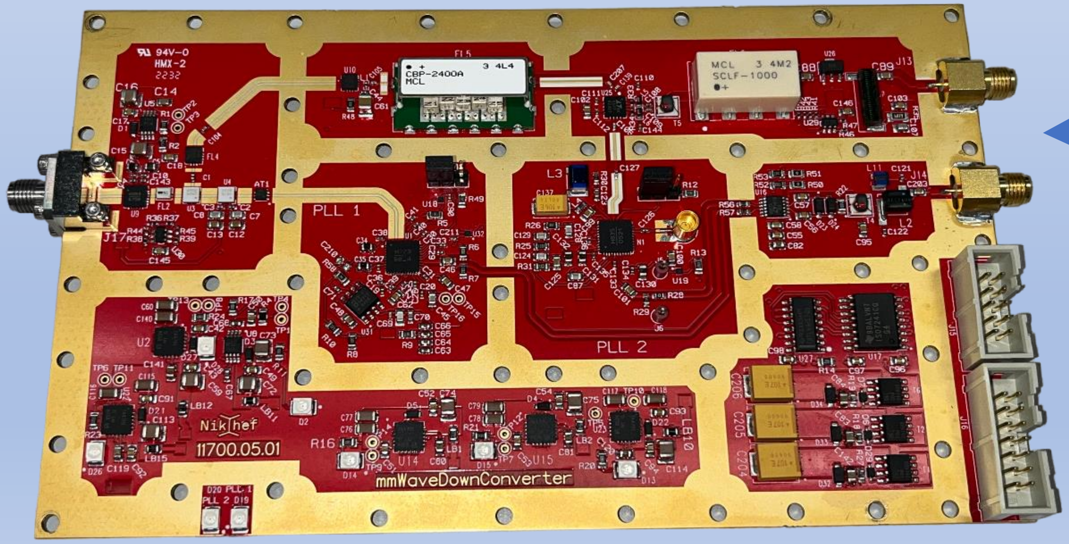
No events observed above endpoint,
Setting upper limit on background rate

< 3×10^{-10} /eV/s (90% CL)

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

RF readout electronics





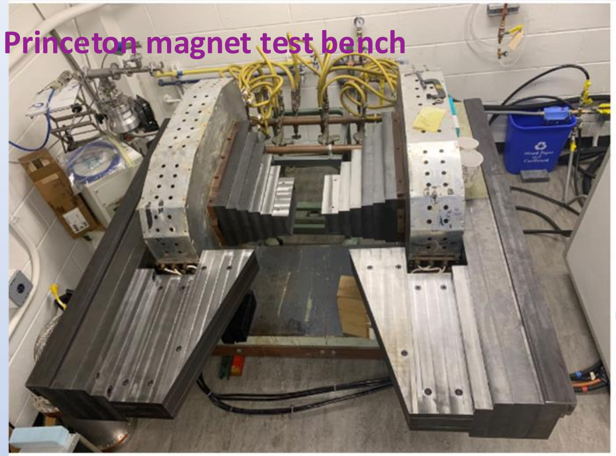
RTO64 used for DAQ

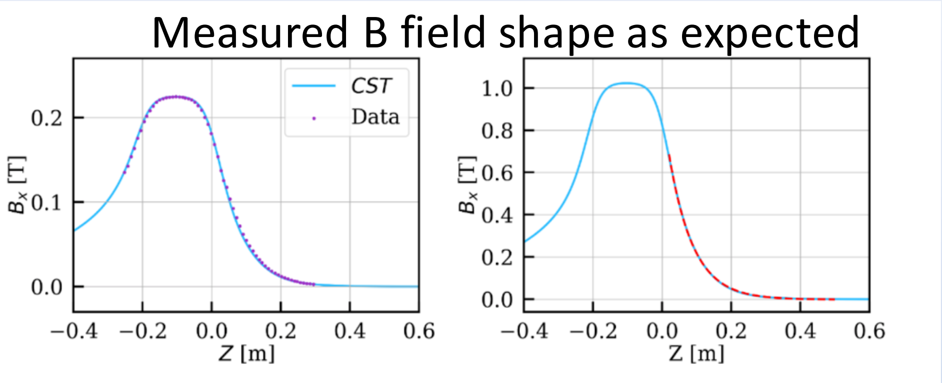
Dedicated downconverter developed @ NIKHEF

DAQ with FPGA trigger under development @ NIKHEF

A special Magnet

Being rebuilt in a larger size and will be installed at the LNGS
Key elements to realize the transverse drift and the Demonstrator of the PTOLEMY project

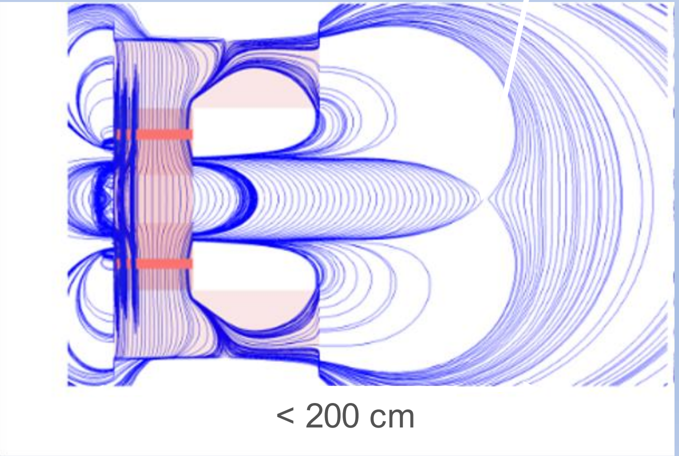


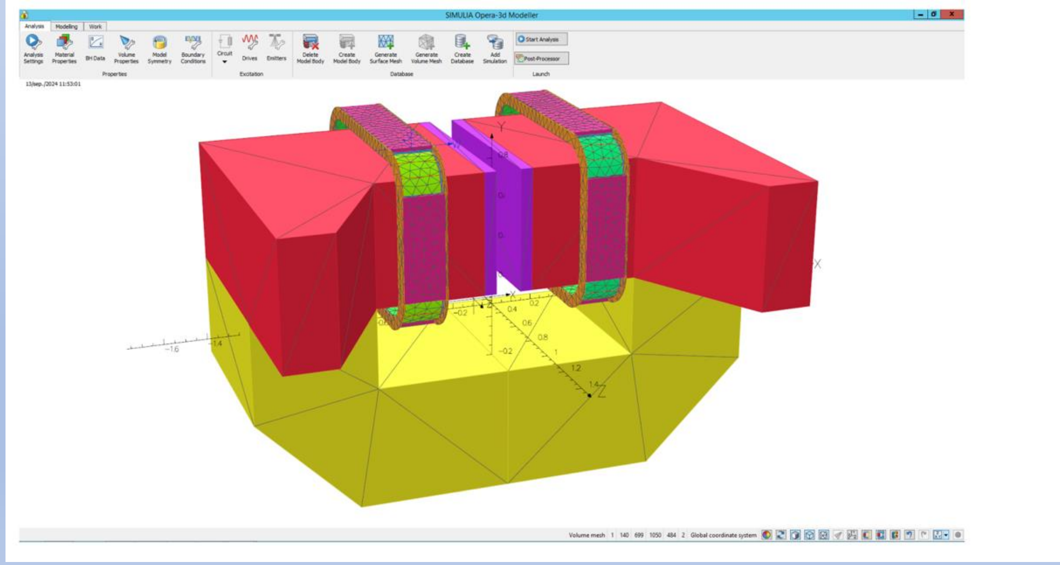


Construction ASG/Suprasys consortium of a SC dipole **with special attention to the fringe field**

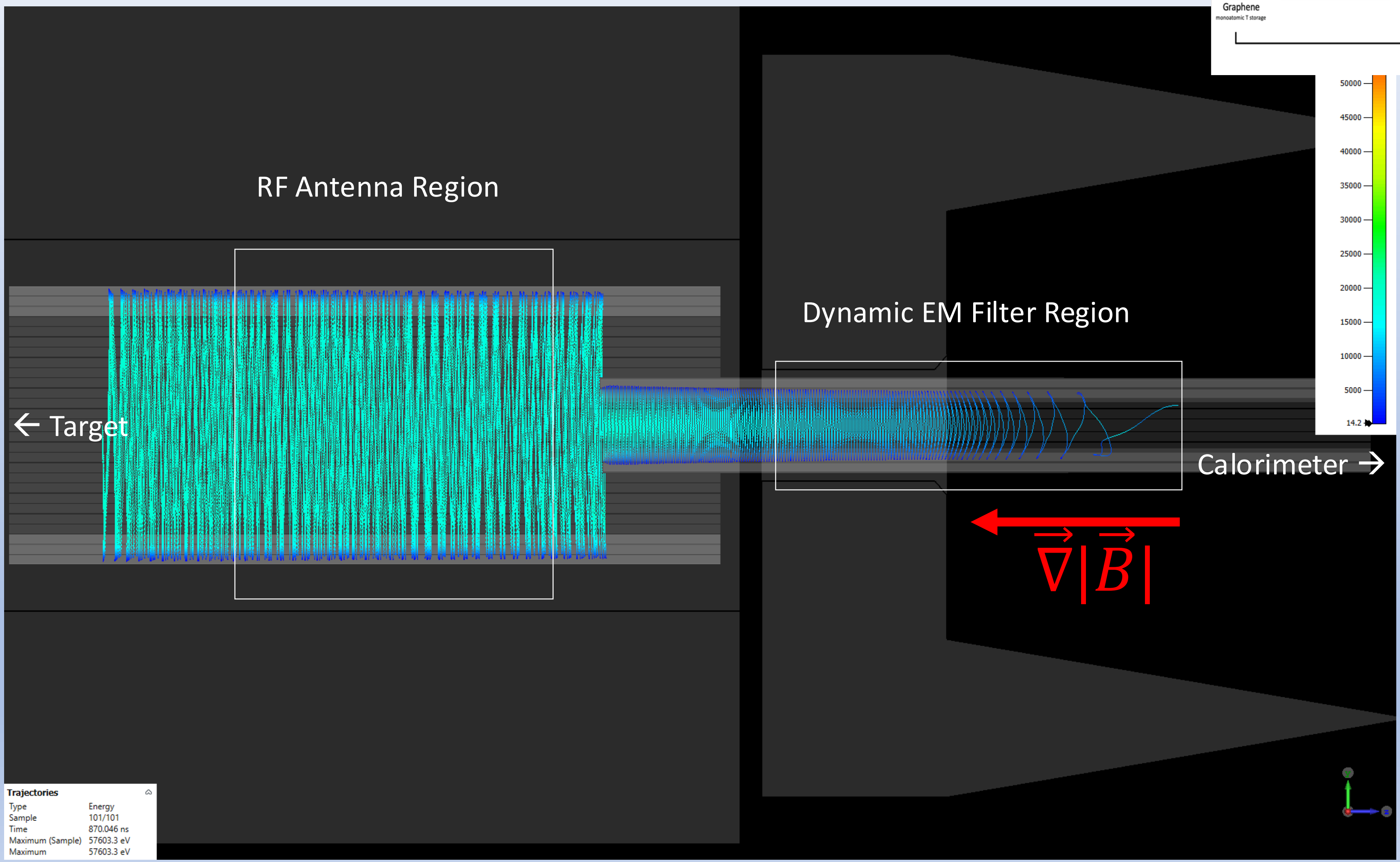
Saddle point key features of the field map

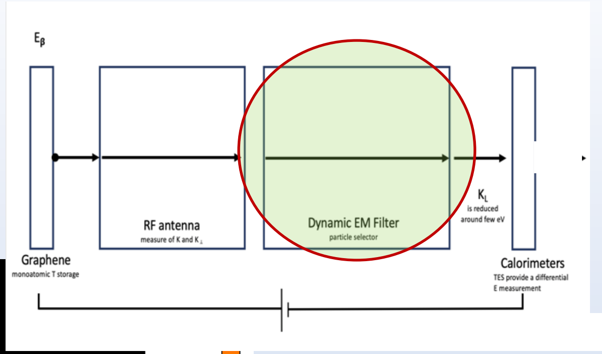
Simulated B-map





Electron Transport: RF pickup & Filter





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 $\boldsymbol{x} \ll \boldsymbol{\lambda}$,

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

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

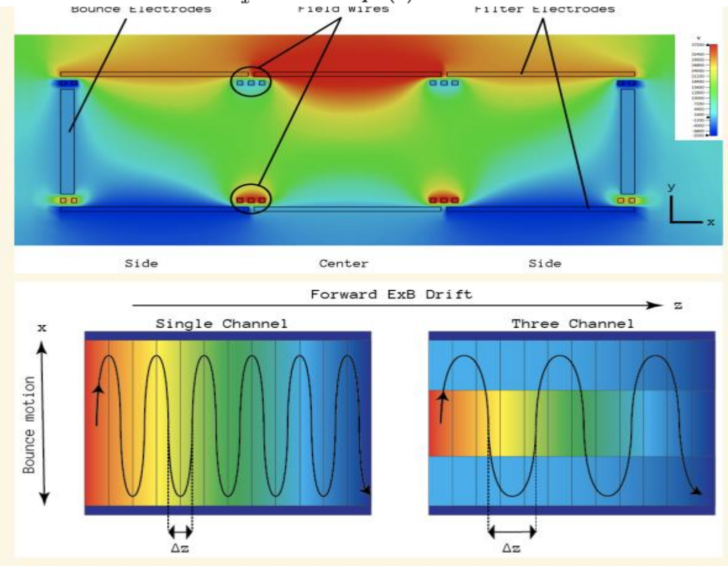
$$-\frac{T'_\perp}{B_0\lambda}\sin\left(\frac{y_0}{\lambda}\right) = \frac{\mu}{q\lambda}$$

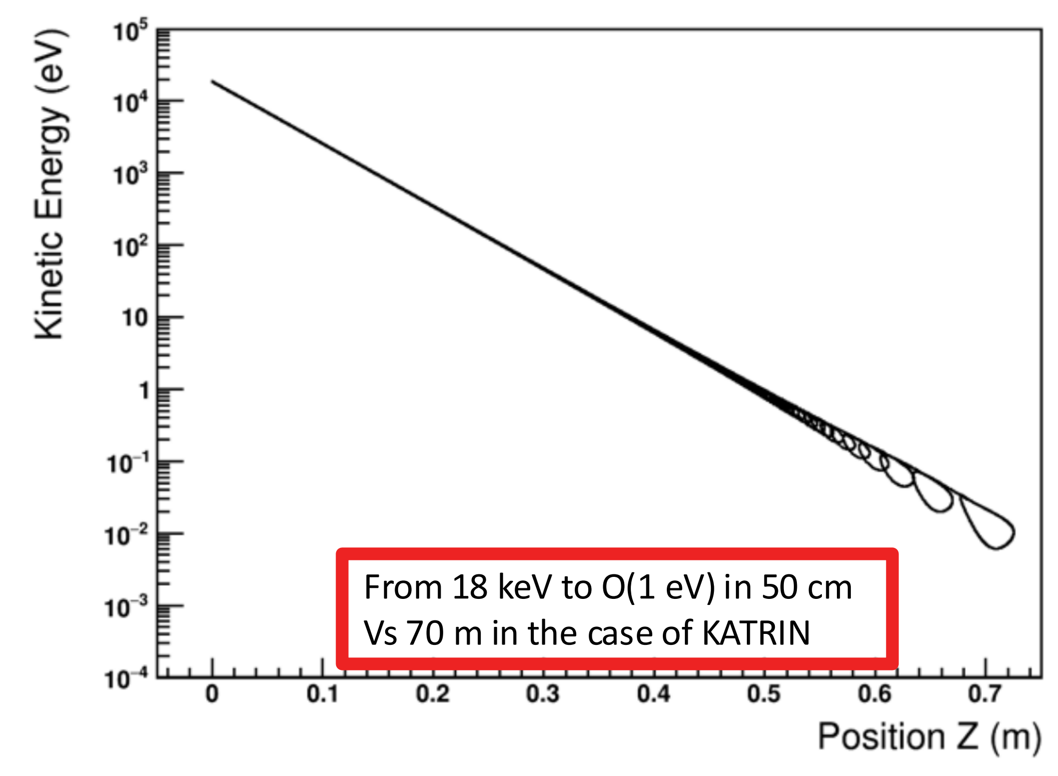
- Solving for $T'_\perp$ and rewriting $\mu = \dfrac{T_{\perp 0}}{B_0 e^{-z_0/\lambda}}$,

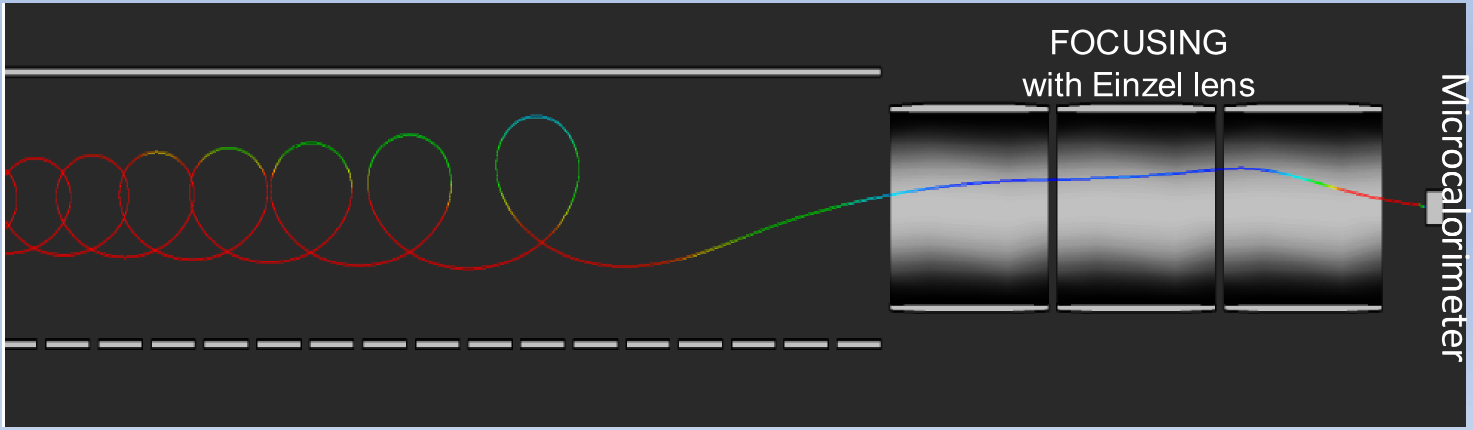
$$T'_\perp = -\frac{T_{\perp 0} e^{z_0/\lambda}}{q\sin\left(\frac{y_0}{\lambda}\right)} = -\frac{T_{\perp 0} e^{z_0/\lambda}}{\sin\left(\frac{y_0}{\lambda}\right)} \text{ [eV]}$$

- Rearranging,

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







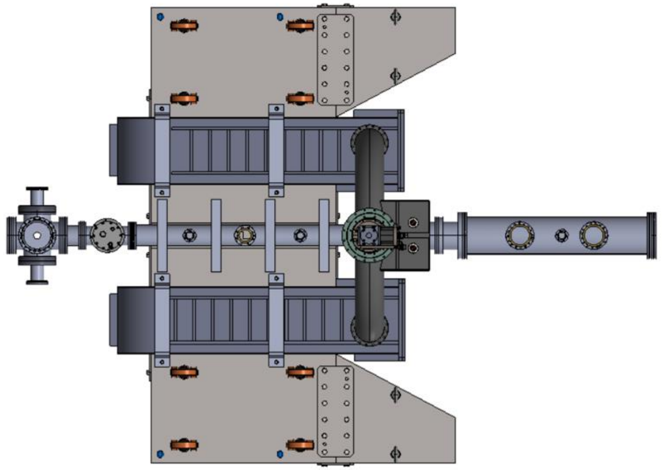
Implementation and optimization of the PTOLEMY transverse drift electromagnetic filter
A.Apponi et al, JINST 17 (2022) 05, P05021

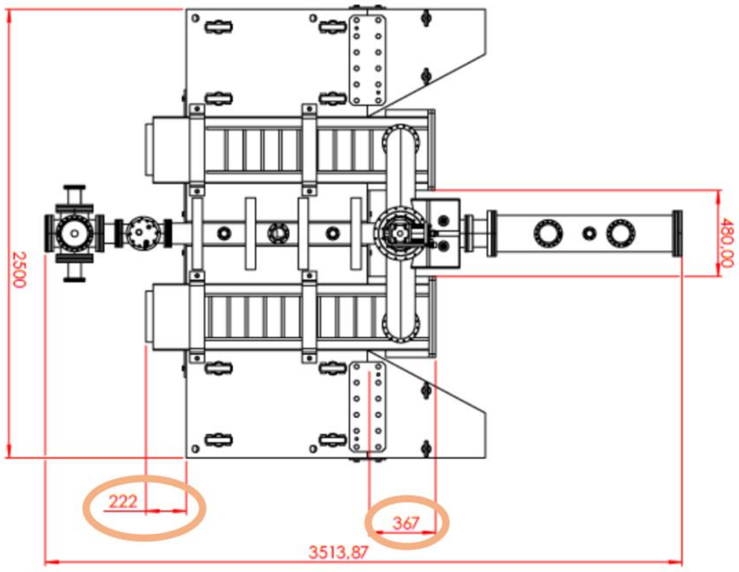
A design for an electromagnetic filter for precision energy measurements at the tritium endpoint
M.G.Betti et al, Prog.Part.Nucl.Phys. 106 (2019) 120-131

Demonstrator parts under constructions: magnet, order issued

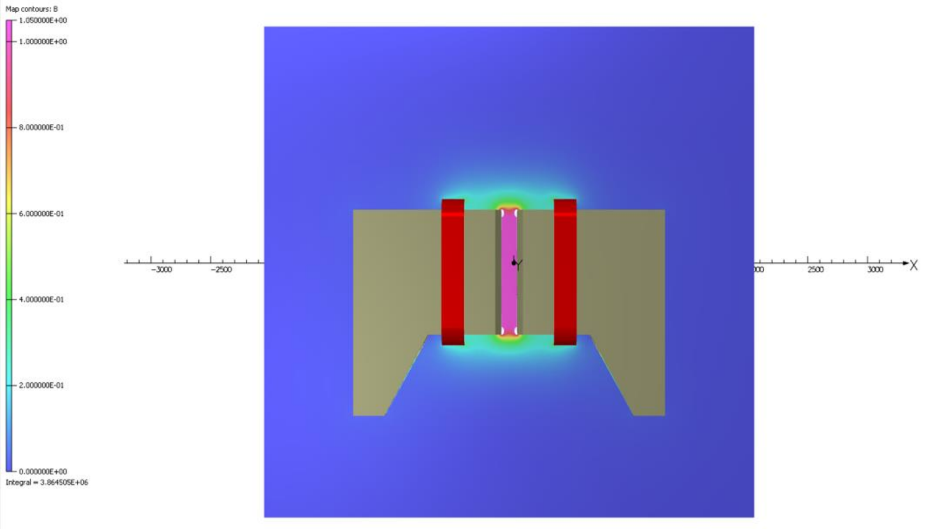
Magnet: Key subsystem

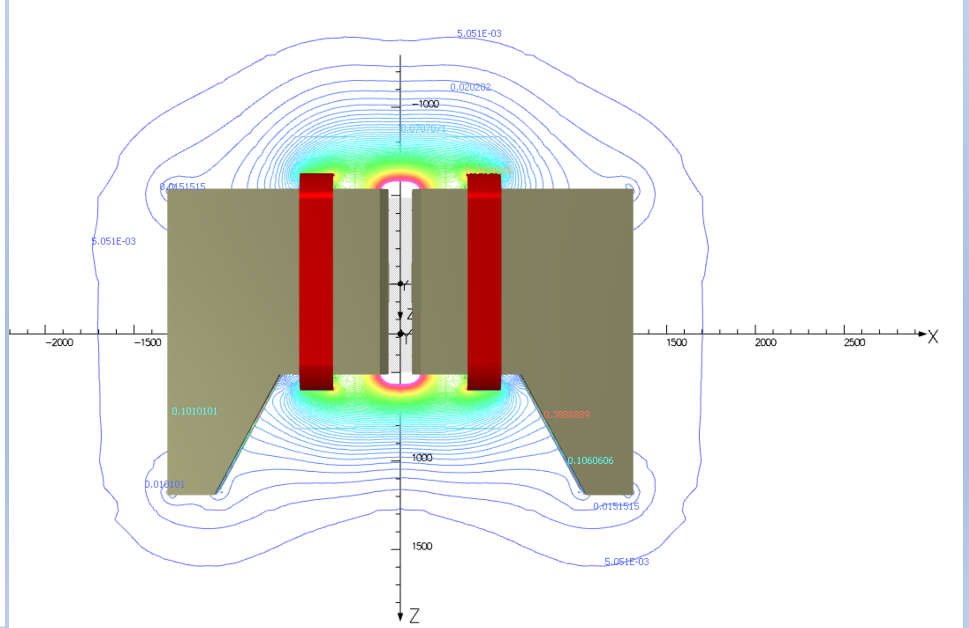
ASG (Genova)/Suprasys(Bilbao)





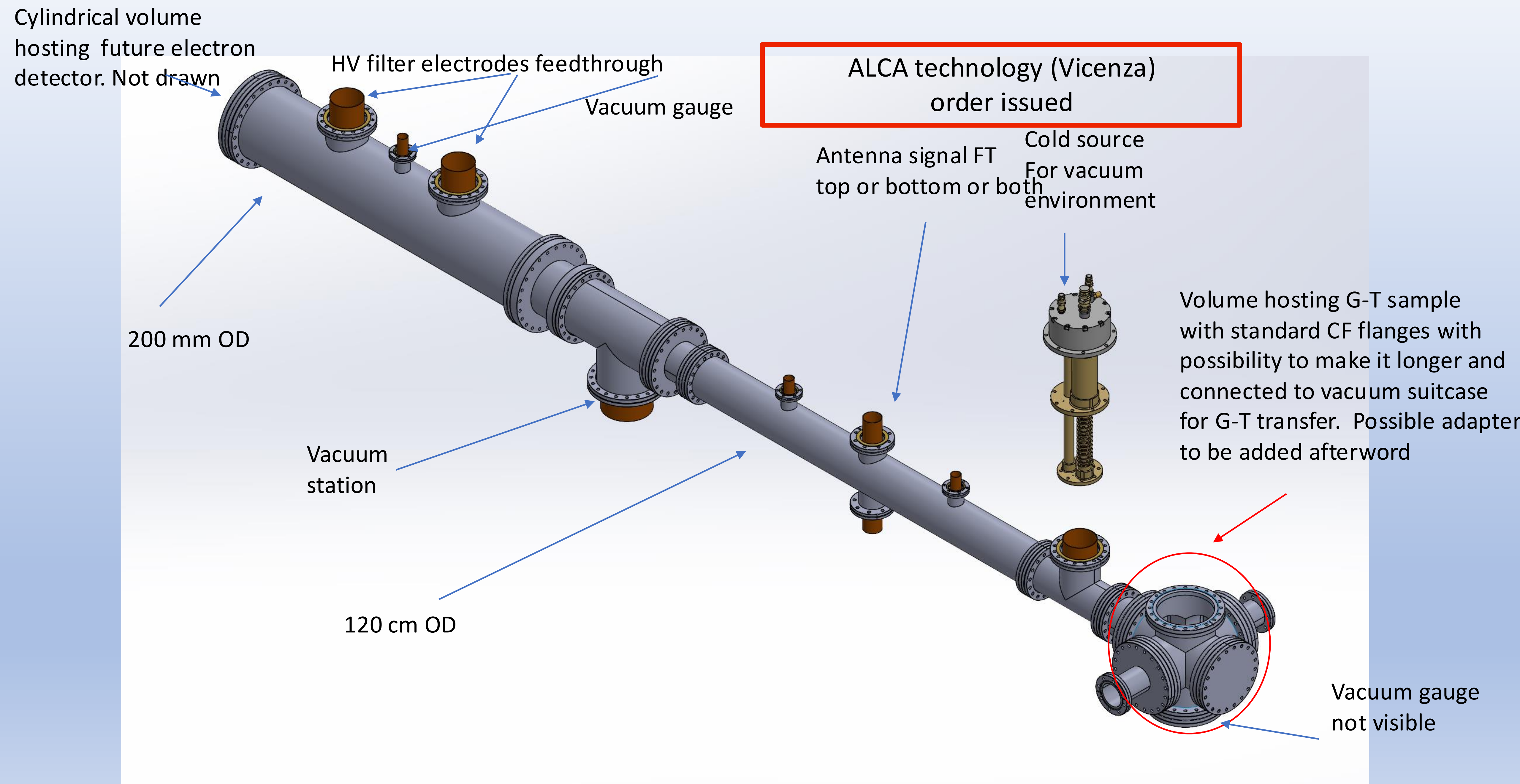
Magnet commissioning by summer



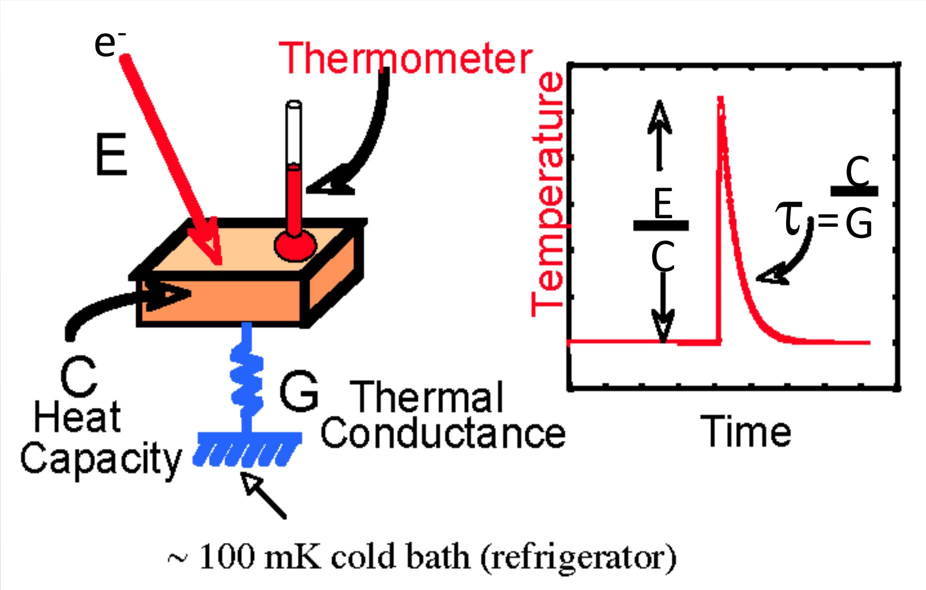


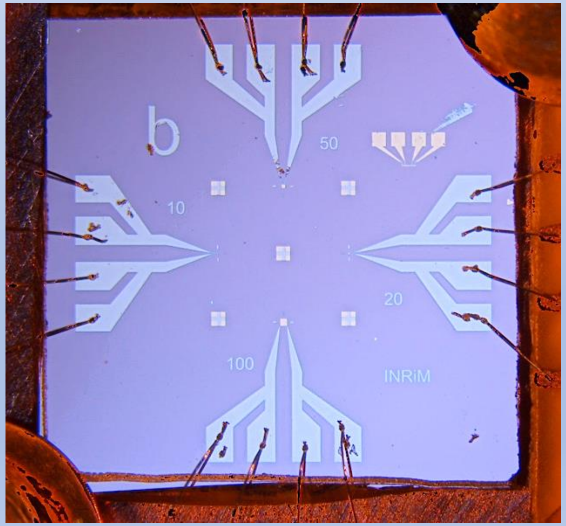
Demonstrator parts under constructions: vacuum chamber

ALCA technology (Vicenza)
order issued



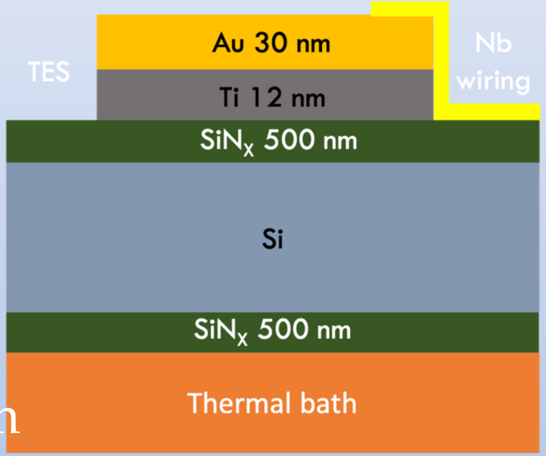
High precision e⁻ measurement: TES μCal

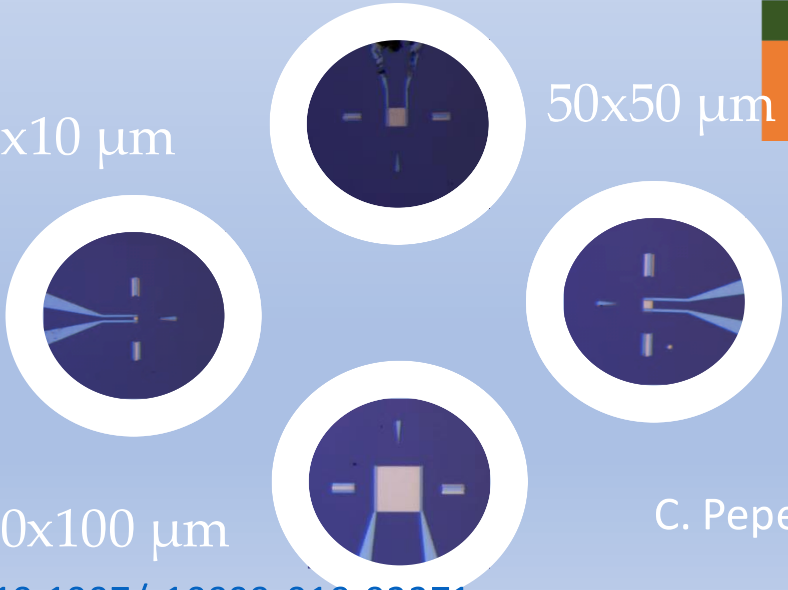




Thin sensors:

~1 eV electron can be stopped with very small C





10x10 μm

50x50 μm

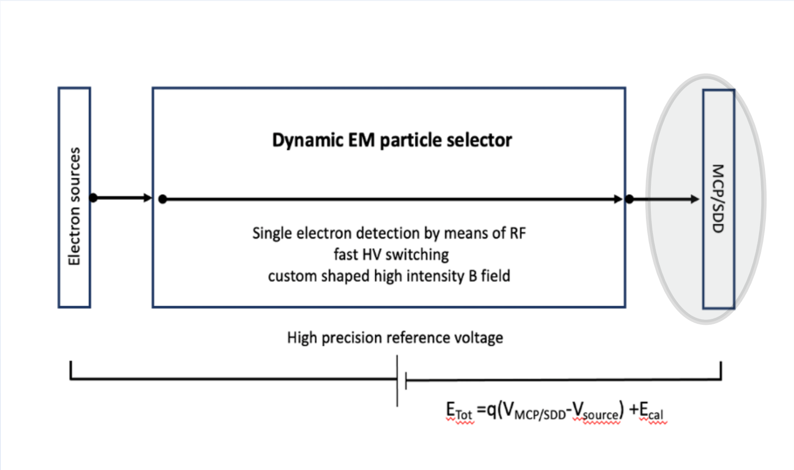
20x20 μm

100x100 μm

C. Pepe, E. Monticone, M. Rajteri

Mauro Rajteri, Eugenio Monticone and others, https://doi.org/10.1007/s10909-019-02271-x
"TES Microcalorimeter for PTOLEMY", J. Low Temp. Phys. 199 (2020) 138-142.

Calorimetry at INRiM



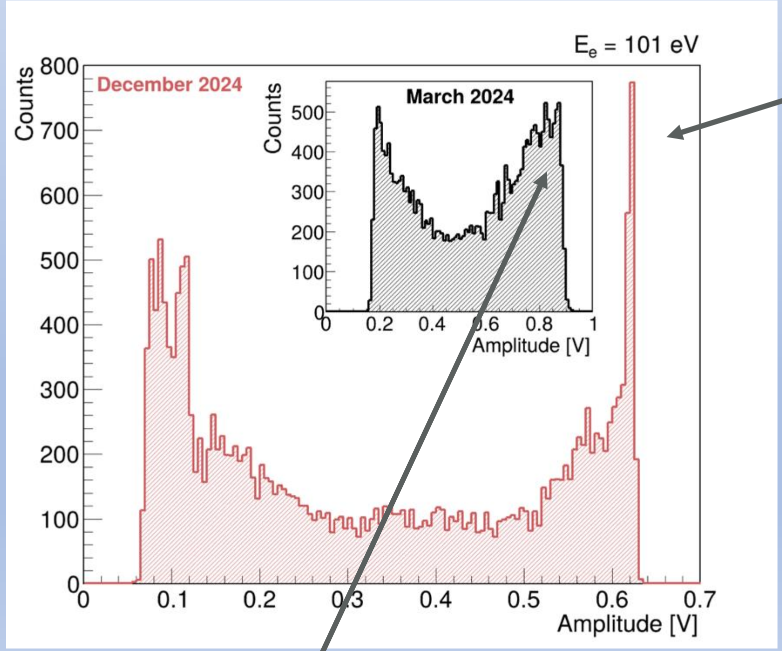
Now: 0.11 eV @ 0.8 eV and 106 mK and 10x10 μm²
TiAuTi 90nm [Ti(45nm) Au(45nm)] (τ ~137 ns)

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

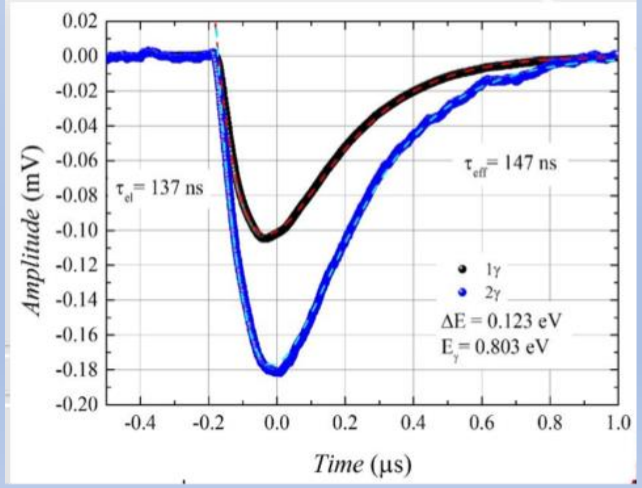
translates to $\Delta E \propto E^{\alpha}$ $(\alpha \leq 1/3)$

ΔE_{FWHM} = 0.022 eV @ 0.8 eV

Based on the expertise of the INRiM electron detection with TES!
Key elements: high quality TES and new e-source based on nanotubes



Further improvement
In few months resolution at <0.2 eV

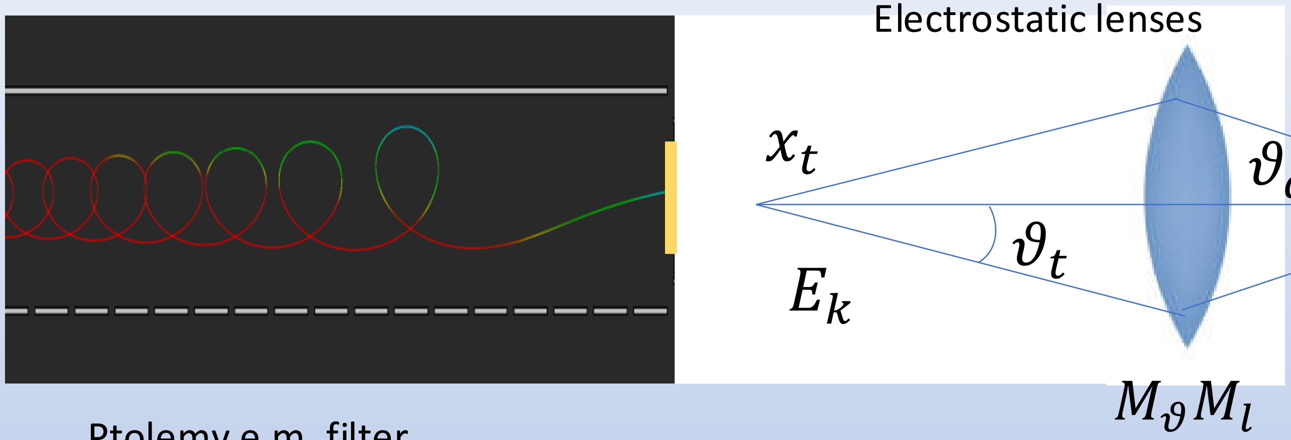


Phys.Rev.Applied 22 (2024) 4, L041007

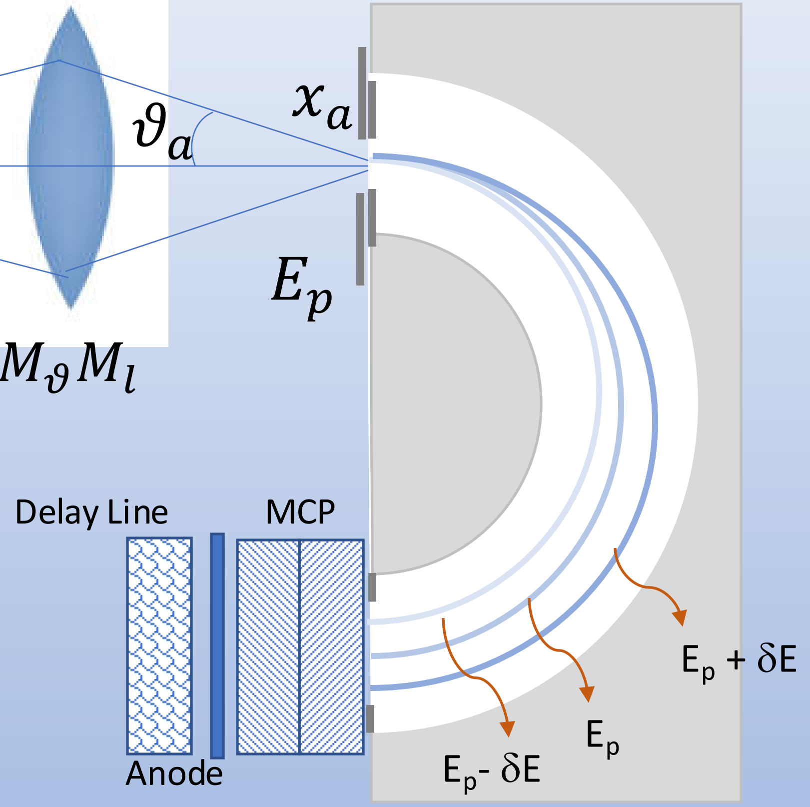
First measurement of electrons at 100 V with a resolution ~1-1.5 eV

Alternative energy measurement

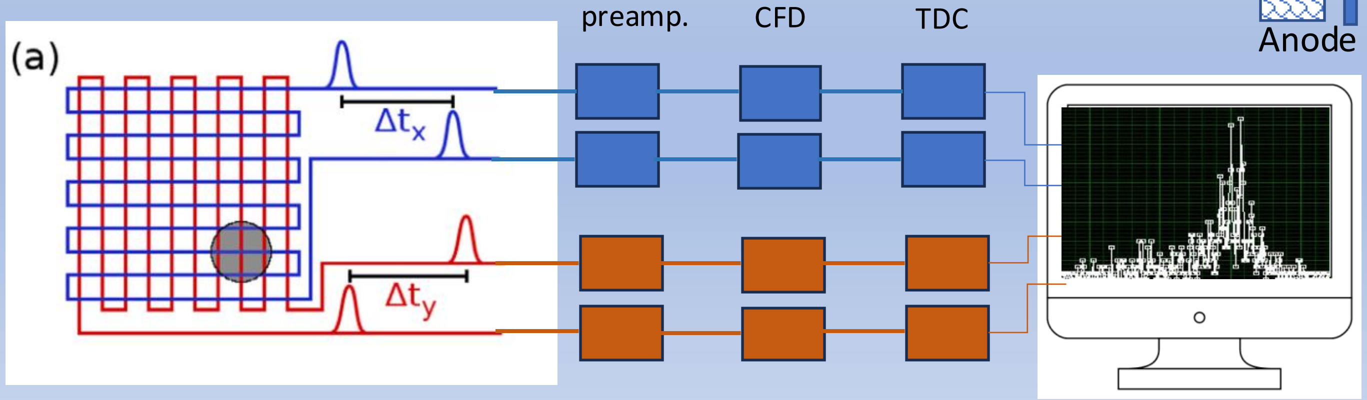
Electrostatic electron analyser



Ptolemy e.m. filter



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



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

Commercial Electron analyser

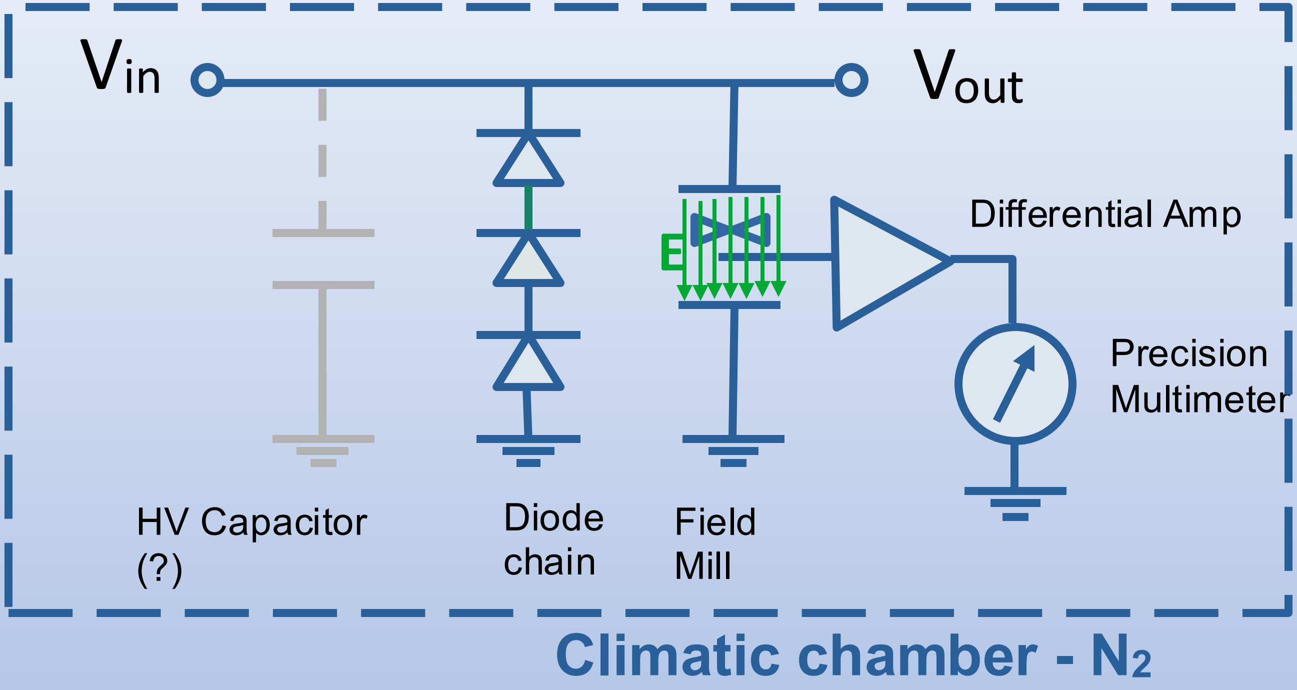
from Scientaomicron

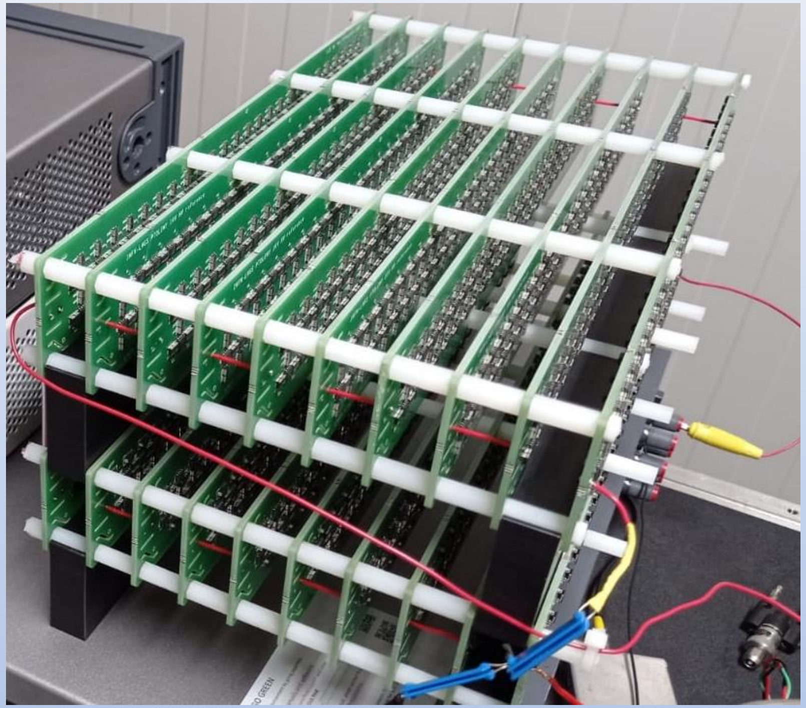
Energy resolution	< 40 meV FWHM at 6 kV < 100 meV FWHM at 10 kV
Transmission mode energy range	5 eV – 10 000 eV
Angular modes	± 22°, ± 30°
Angular mode energy range	100 eV – 10 000 eV
Deflection mode energy range	-
Deflection mode Spin scan	-
Operating pressure	< 10^{-5} mbar
Mounting flange	DN200CF (10" O.D.)

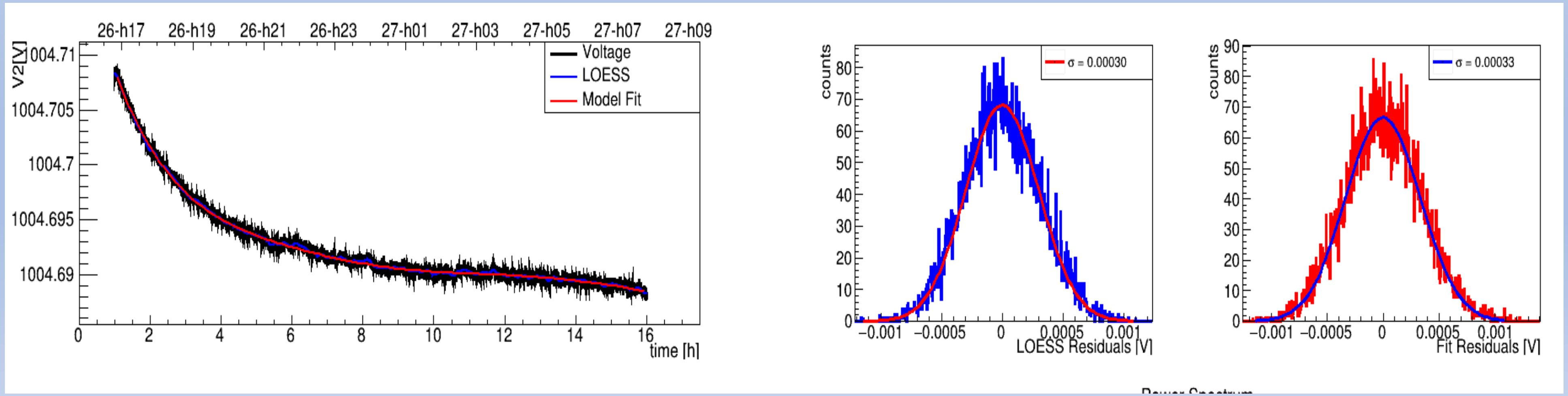
For full specifications and more information about product options, please do not hesitate to contact your local sales representative.

Find the contact details here: Contact Us

HV High precision stability (LNGS)







Single board (1 kV)

σ = 0.3 mV

To Conclude

A message to young researchers that are considering to join this project

The PTOLEMY project is very challenging, and we have a long way in front of us.

However, there are so many import and interesting results that we can gain, while pushing further the knowledge, that makes the path more as interesting as the final goal.

We aim at showing the demonstrator functioning at LNGS by next year

Contact: marcello.messina@lngs.infn.it; web: https://ptolemy.lngs.infn.it/

BACKUP

1. Neutrino wind – coherent scatter

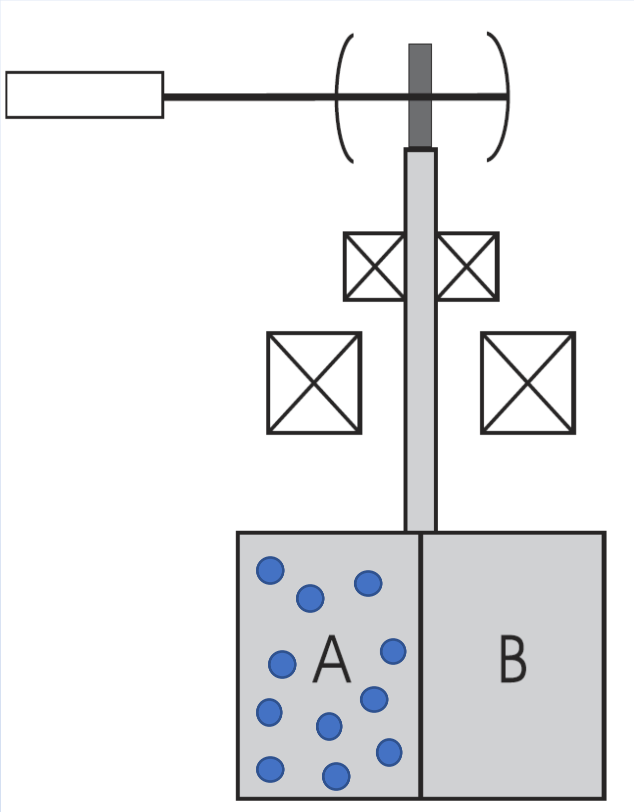
- Velocity of solar system w.r.t CMB frame $\beta \approx 10^{-3}$

- **Coherent Acceleration -** $\boldsymbol{\sigma_{\nu N} \propto G_F^2}$

✓ De Broglie $\lambda \approx 2 - 3\text{mm}$

✓ $a_{NR-D/M} = O\left(10^{-27}\,\frac{cm}{s^2}\right)$ for non-relativistic neutrinos

$a \approx 10^{-13} cm/s^2$ achieved so far



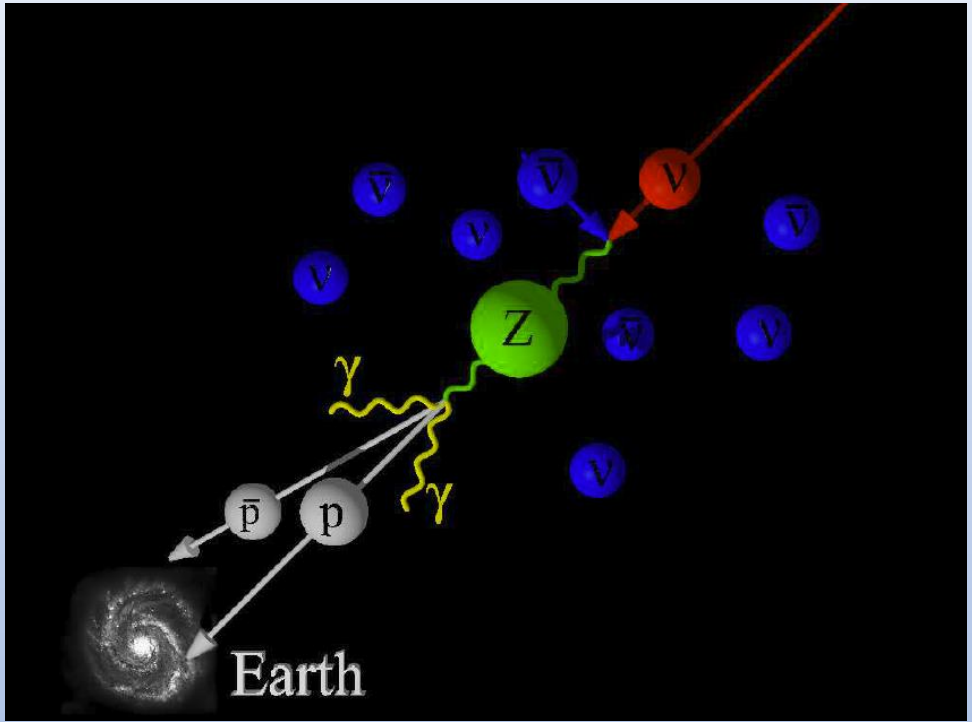
… and worry about solar ν and WIMP backgrounds

2. Cosmic neutrinos

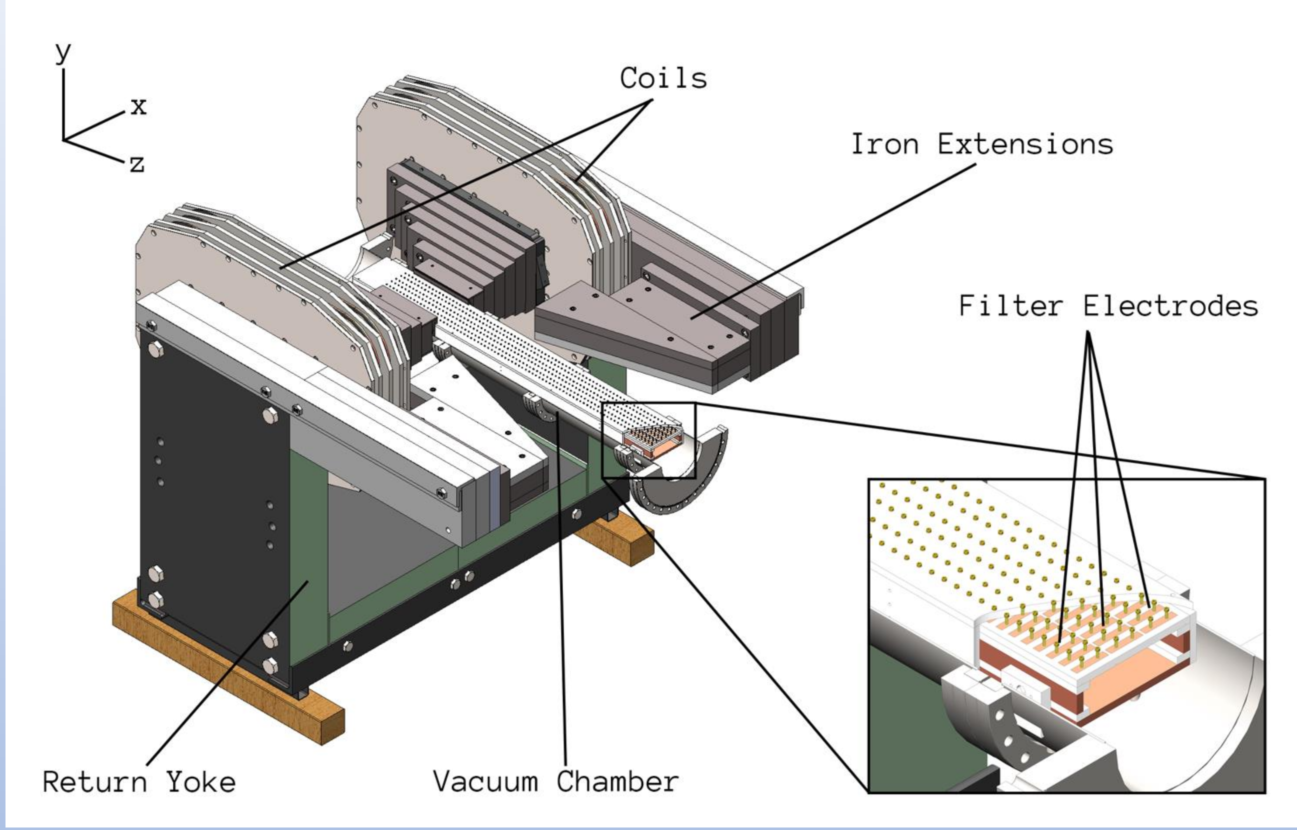
- Interact with high energy ν:

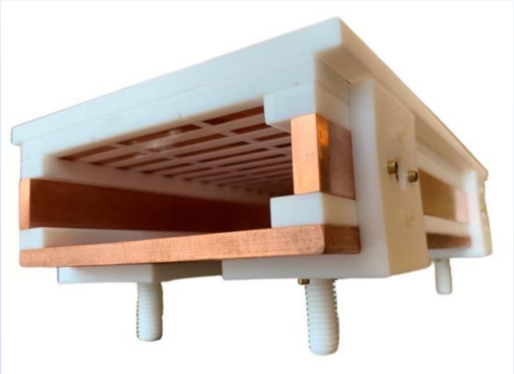
$$E_{\nu_i} \approx 4 \cdot 10^{21} \left(\frac{eV}{m_{\nu_i}}\right) eV$$

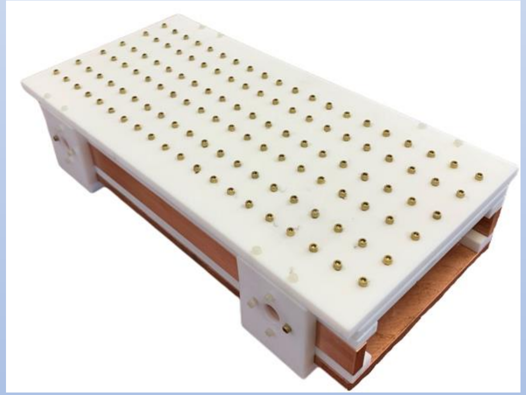
- Signature:
    1. Dip of high energy ν flux
    2. Exces of high energy γ, proton flux

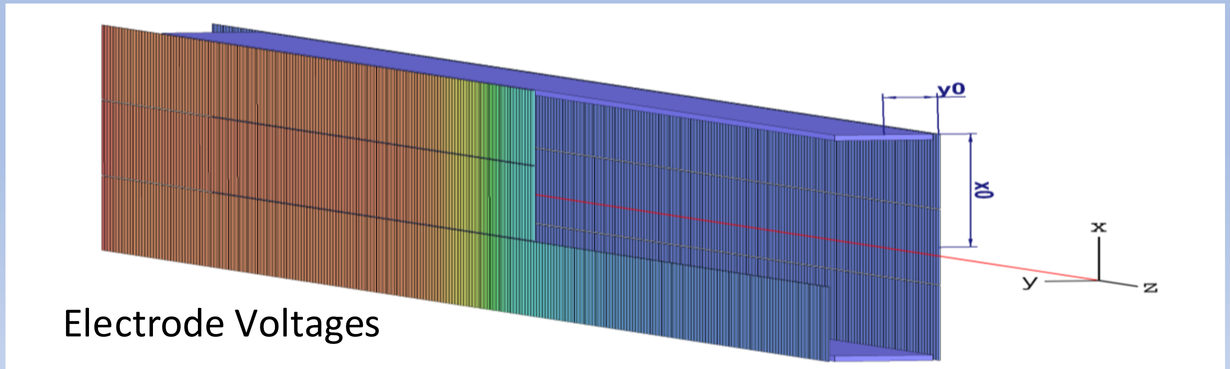


PTOLEMY Demonstrator at LNGS: filter electrodes prototype

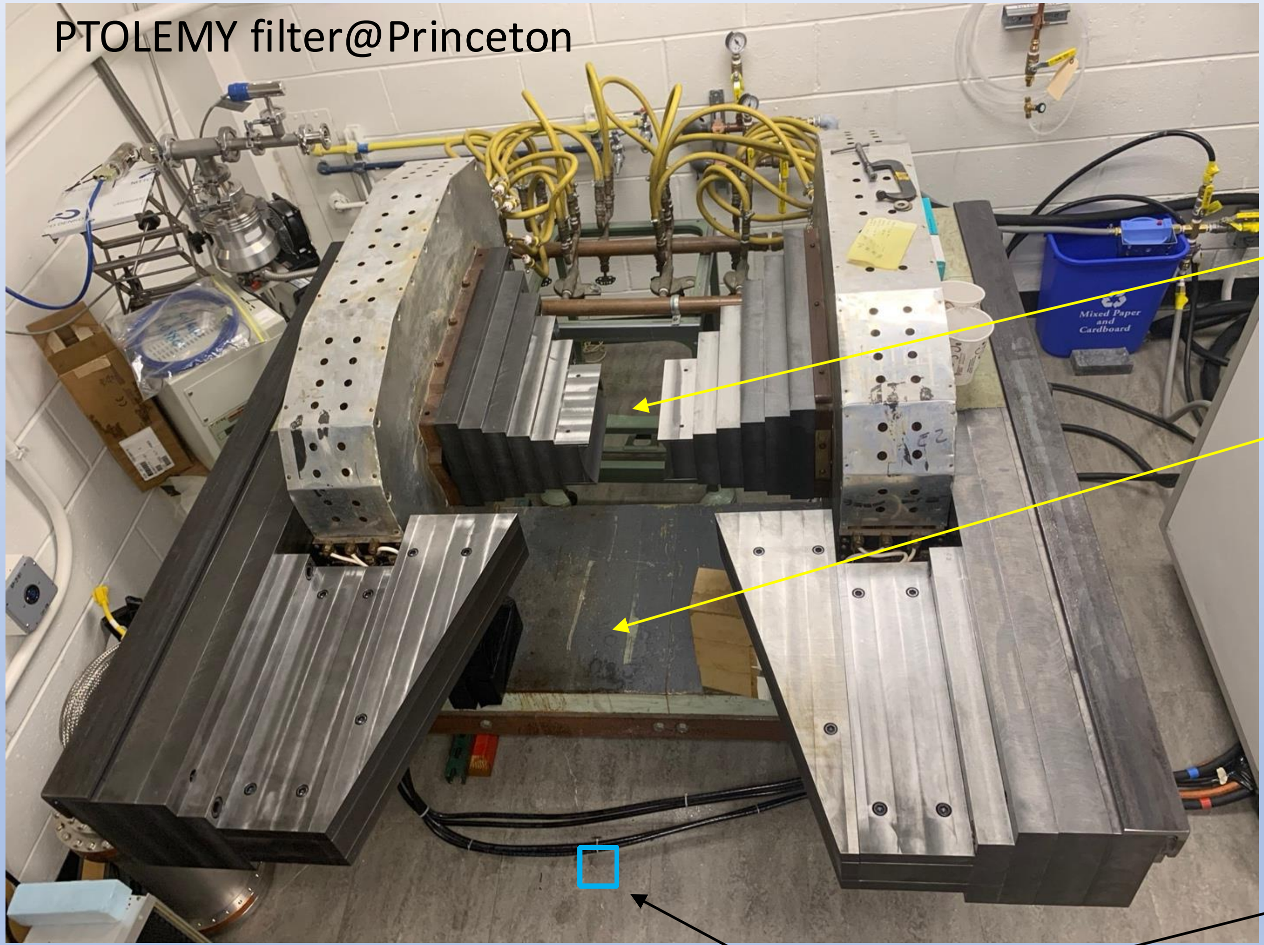






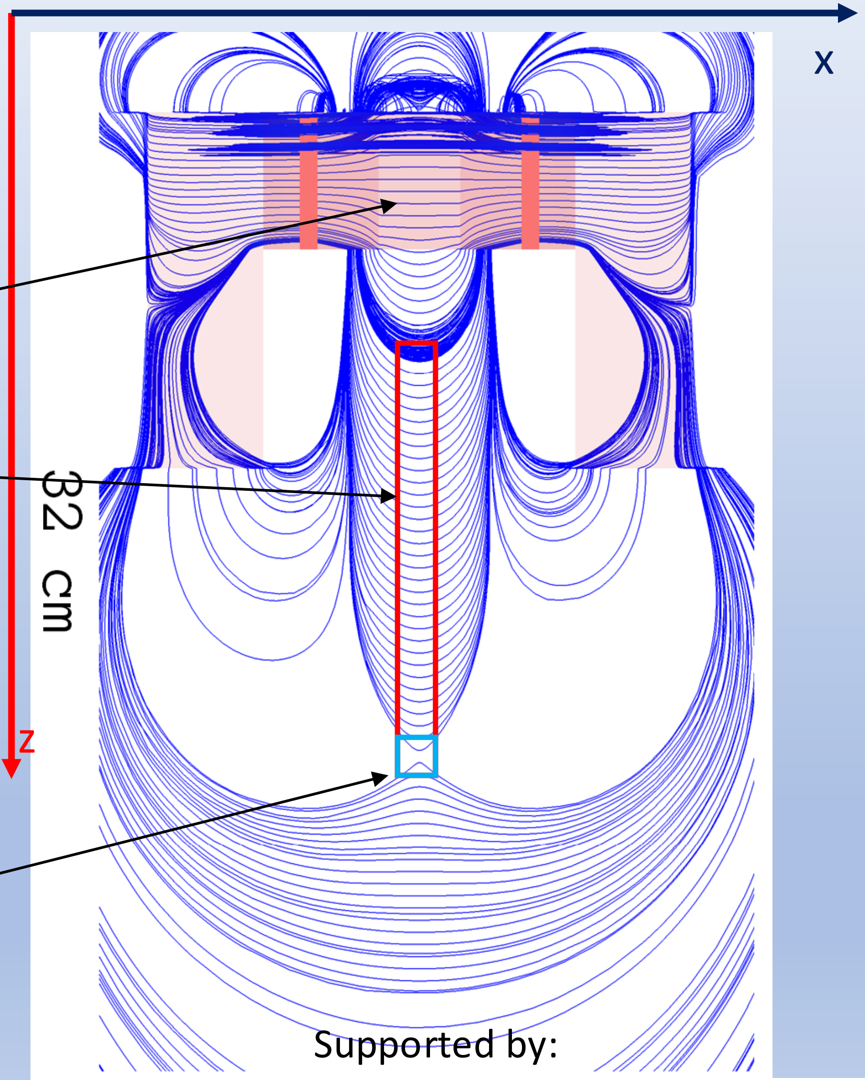


First Version of the PTOLEMY magnet



RF pickup region

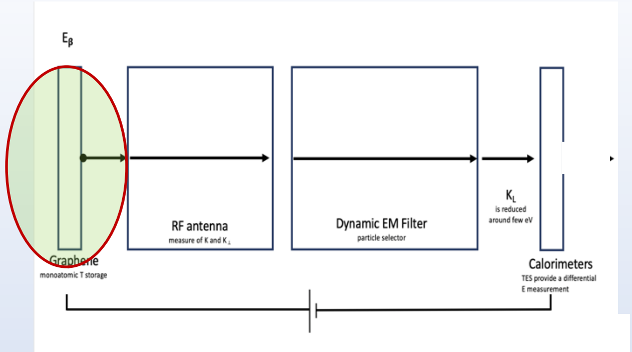
Filter region



Zero field (location for TES microcalorimeter)

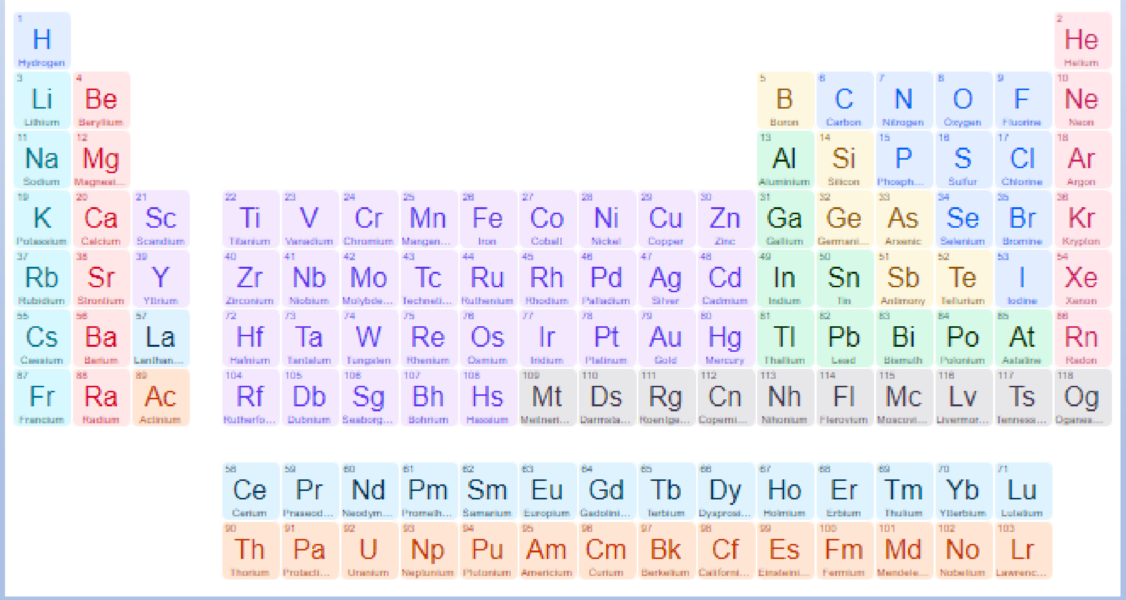
Supported by:

SIMONS FOUNDATION



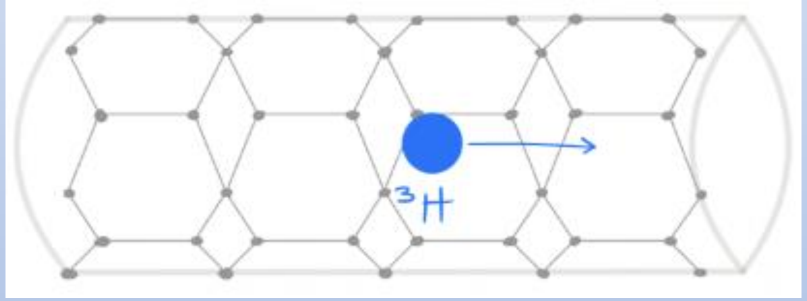
Ways to solve?

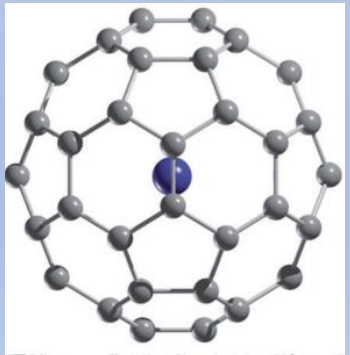
Strategy 1: find other target material



from Mendeleyev et al

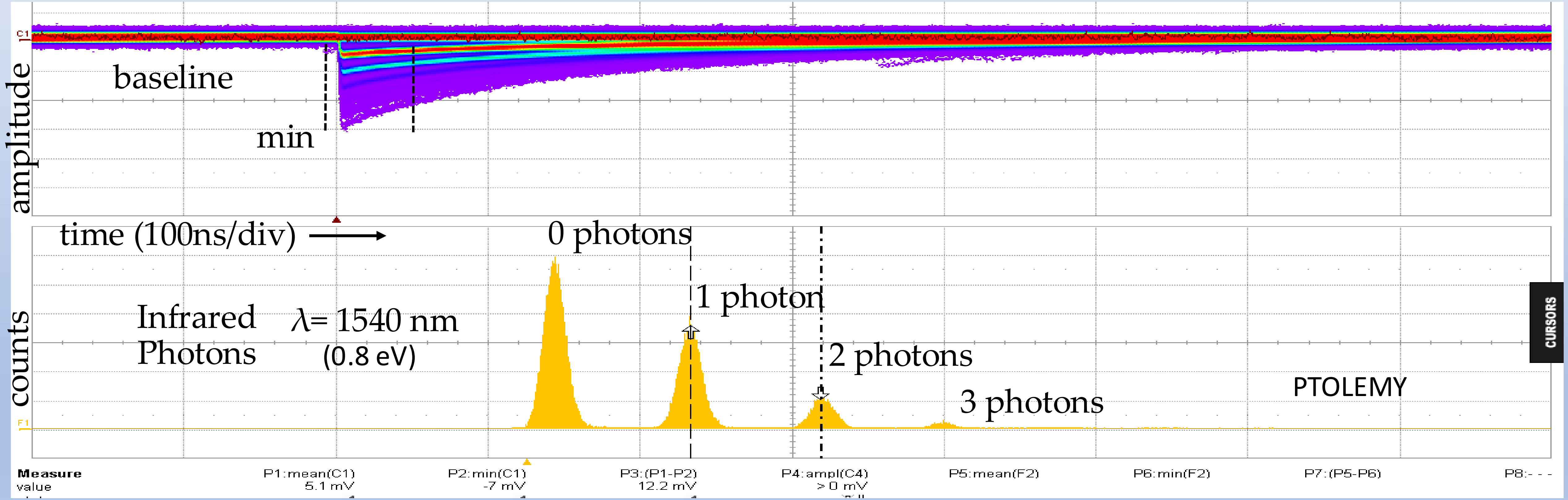
Strategy 2: alternative ^{3}H storage





from A. Esposito

World-record TES calorimeter 50 meV resolution for CNB neutrinos



C. Pepe, E. Monticone, M. Rajteri

Funding:

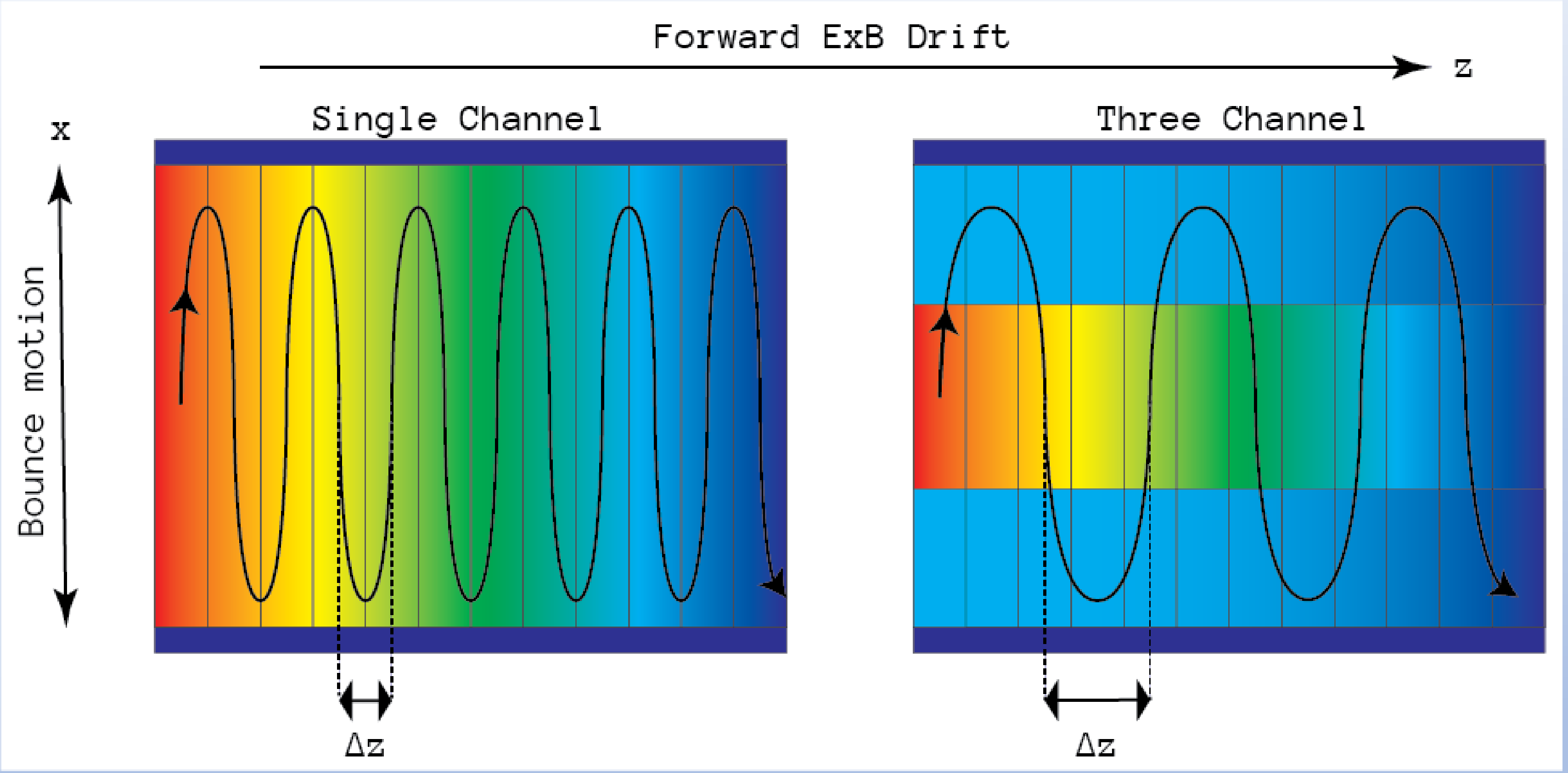
- CSN2 (2018-2021): 205 kE
- CSN5 (2022-): 50 kE
- Call of the “Agenzia per la coesione territoriale”, participation as partner of a bigger LNGS project on metal 3D printing. 400 kE out of 2ME for the PTOLEMY project (First in the ranking but not yet delivered).This 300 kE will be dvoted to the of the SC demonstrator magnet. 100 kE for researhc contract.
- PRIN2022: Proposal for a budget of 250 kE mainly to run demonstraor. Waiting for the answer.

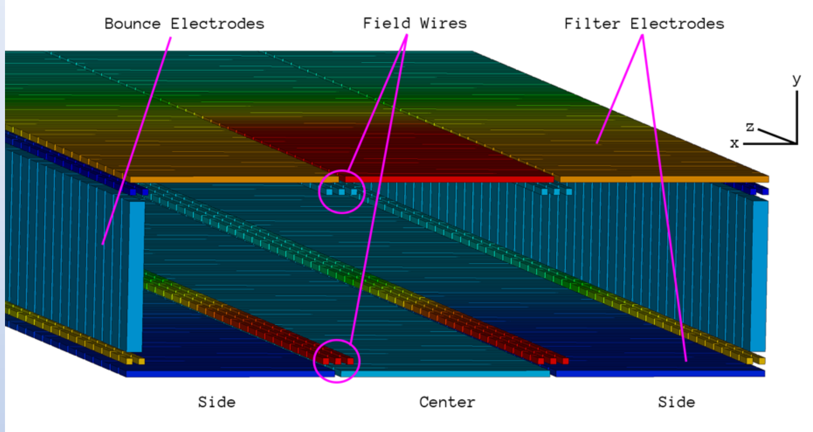
- Dutch Research Council (NL) (2021-): 1.3 million Euro
  Research Grant of “One Second after the Big Bang”
  The topic of the grant is ”**RF antenna design and large scale readout chain implementation**.”
  LNGS is a partner in this grant. One PhD position is awarded and one PostDoc, 60% based at LNGS with 100 kE budget, are foreseen.

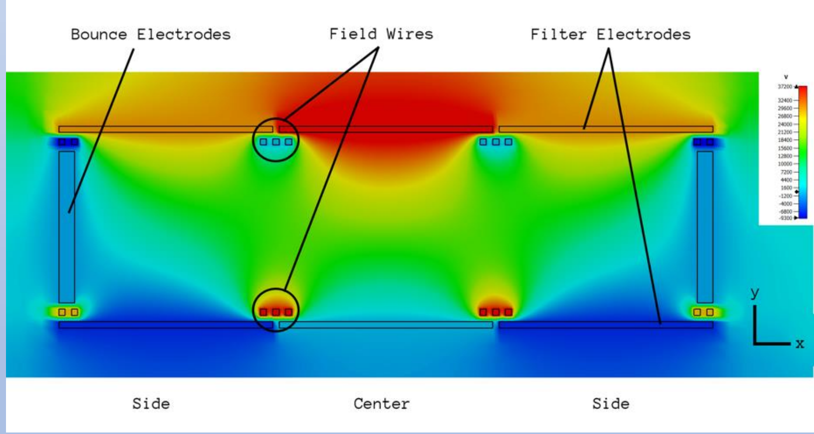
- Princeton Univ., Simons and Templeton Foundations (2016-): 1 M$ from J Templeton Foundation and 1.3 M$ from J Simons Foundation out of which 0.75 M$ will go in TES development and demonstrator running.

With this financial plan, even though with have some uncertainty, we are sure to be able to accomplish
Pahse-0: running the new filter and measure the end to end electron transfer function from target to the measuring point where electron energy will be measured by means of an SDD.
Then endpoint measurement of T loaded on graphene will follow.

Bobsledding (pushing electron up potential)





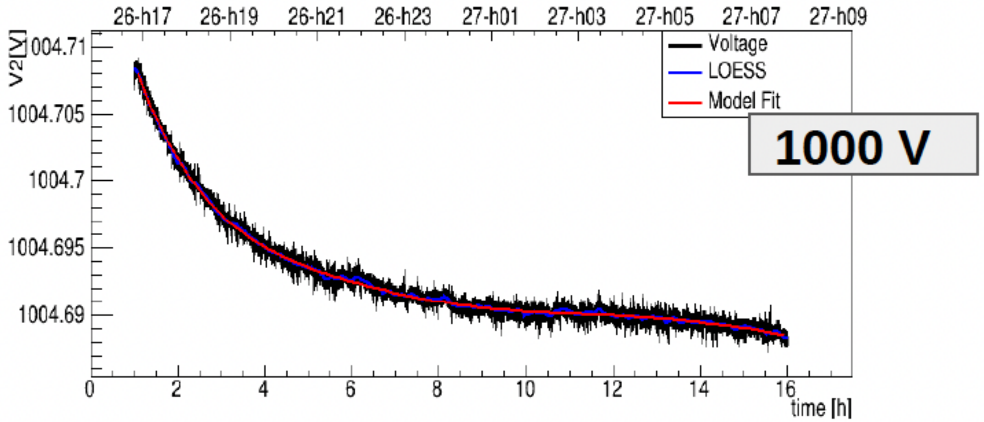


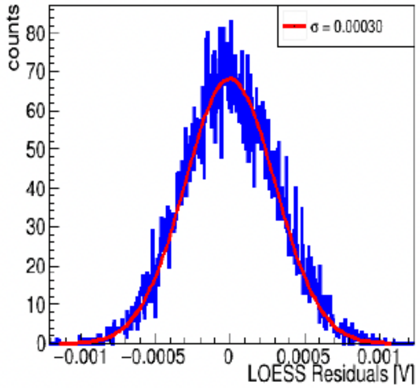
Transverse "Selector"
(one channel)

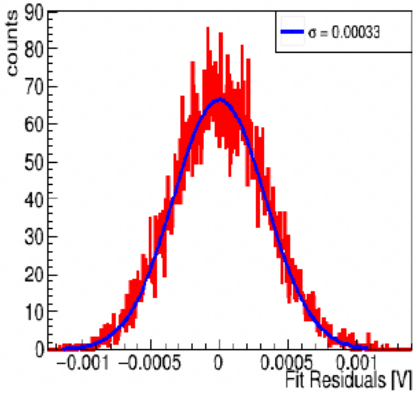
Dynamically Adjusted
(side channels)
to Total Energy "Selector"

Data set at 10000 V

Intrinsic diode resolution

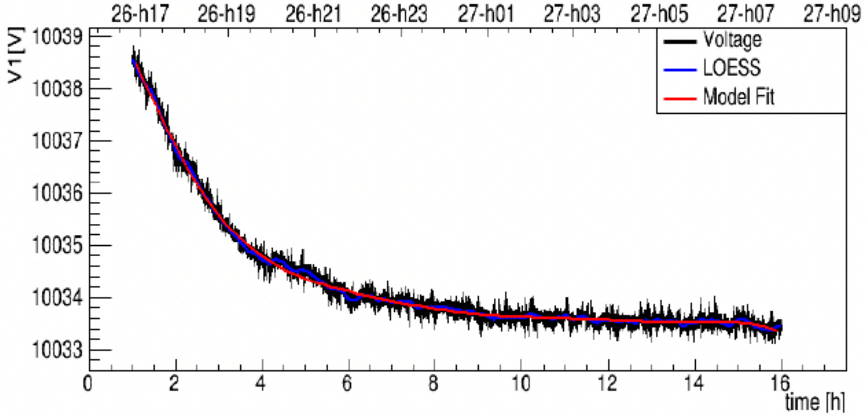


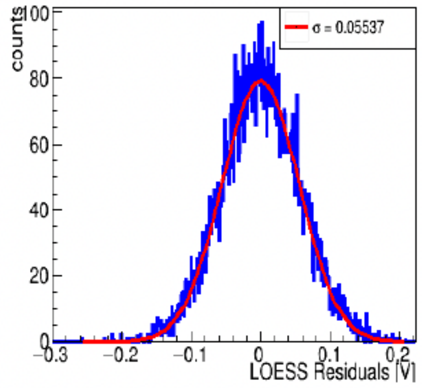


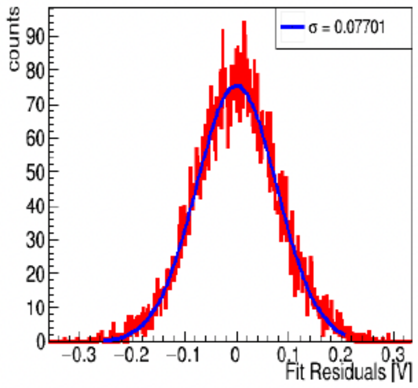


Single board

σ = 0.3 mV
(over 1000 V)







10 board series

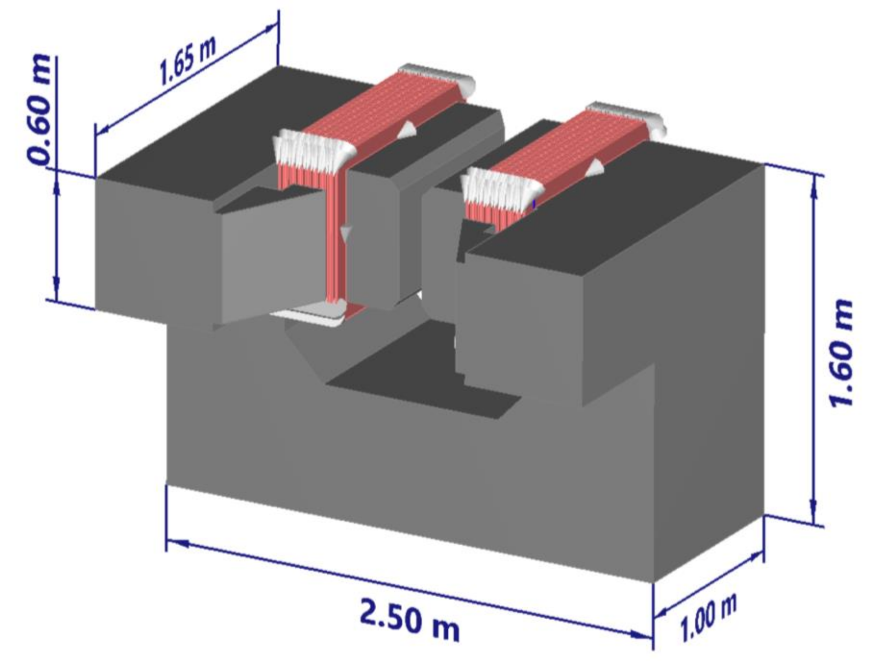
sigma = 50 mV

σ(intrisic) = sqrt(10) x 0.3 ~ 1mV (<< 50 mV !!!)

The intrinsic resolution is way better than the present measurement method!!!

Conduction Cooled Superconducting Coils

- LNGS magnet specifications within ~20% of an Open MRI system made by ASG/Suprasys (about 10 commercial systems delivered per year)
- Order issued, concept design frozen and the construction phase has started



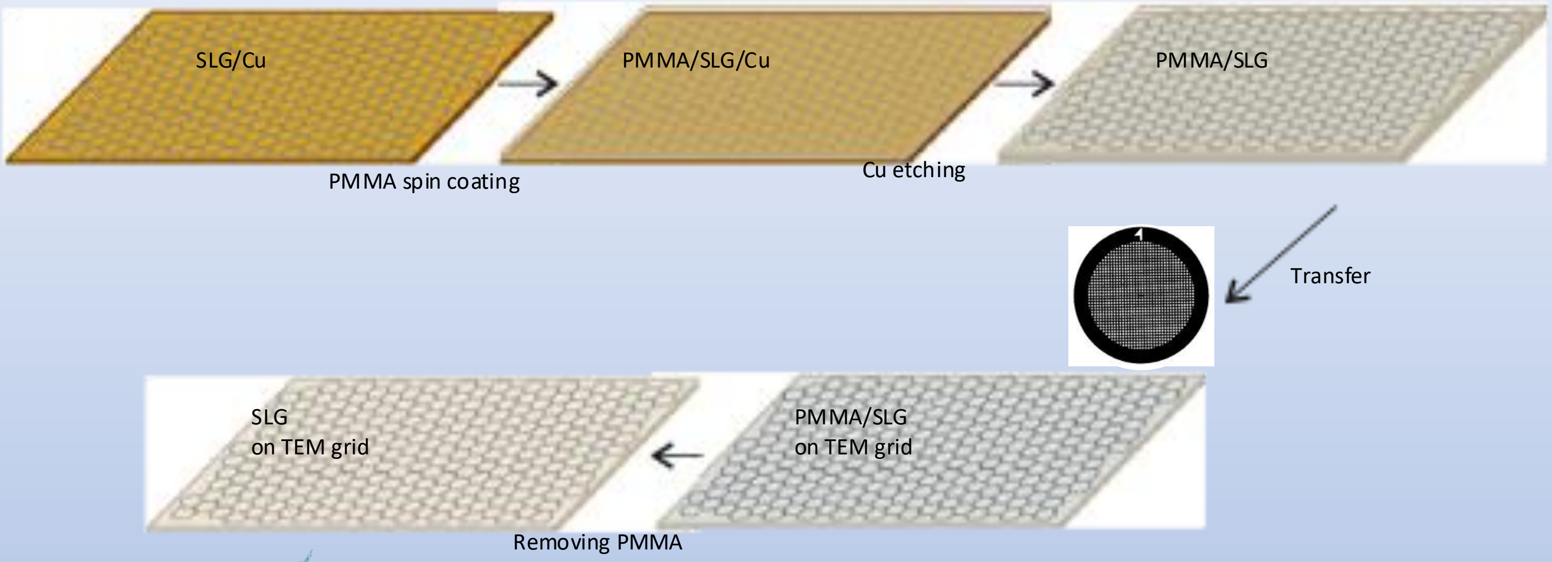
Packed with multi-layer thermal insulation

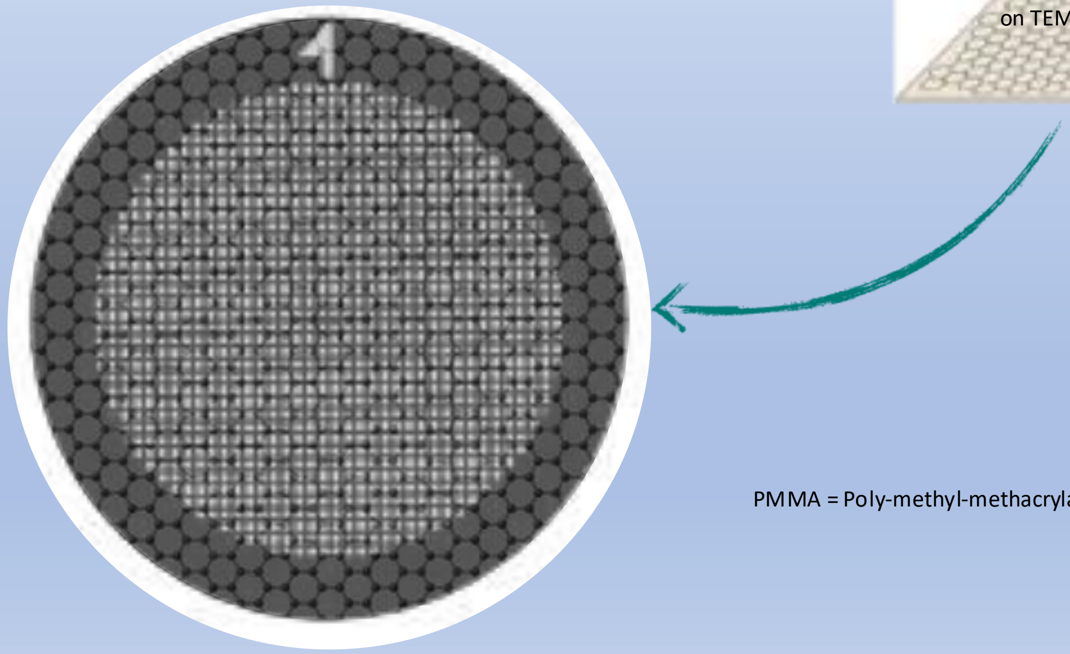
SC coils magnet

Sample preparation: graphene growth and transfer on TEM grid

Mono-/tri- layer graphene on nickel TEM grid:

- G2000HAN - Ted Pella Inc.
- 2000 mesh per inch → 12.5 μm pitch
- Hole width 6.5 μm
- Nominal geometrical transmission 41%

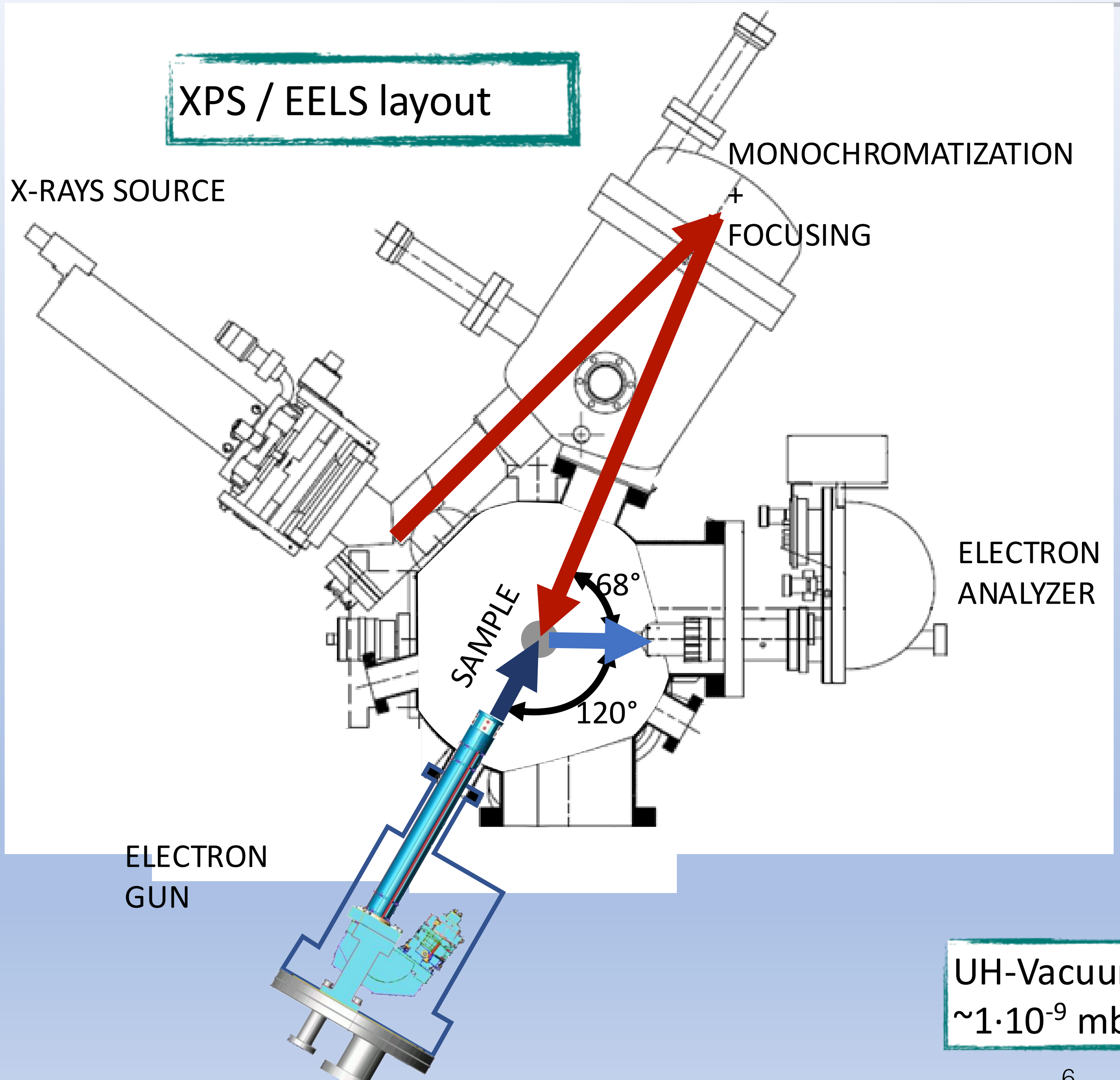




Camilla Coletti talk tomorrow

PMMA = Poly-methyl-methacrylate $(C_5O_2H_8)_n$

The LASEC experimental layout (Roma3)



Al Kα source:

- hv = 1486.7 eV
- Resolution 0.35 eV
- Analyser wf = 4.3 eV
- Tot resolution = 0.46 eV

Custom-made monochromatic electron gun:

- Continuous electron beam
- Tuneable energy 30 - 900 eV
- Resolution = 45 meV

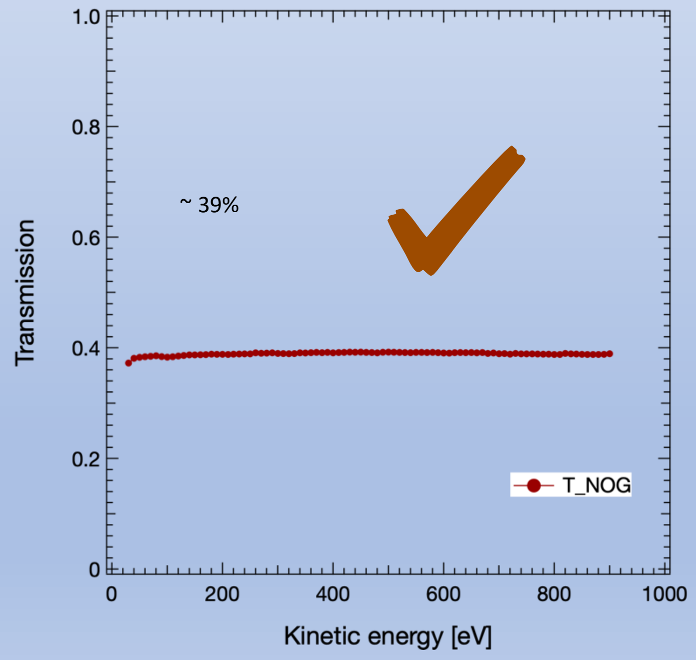
UH-Vacuum
~$1\cdot10^{-9}$ mbar

Transmission through mono- and tri- layer graphene

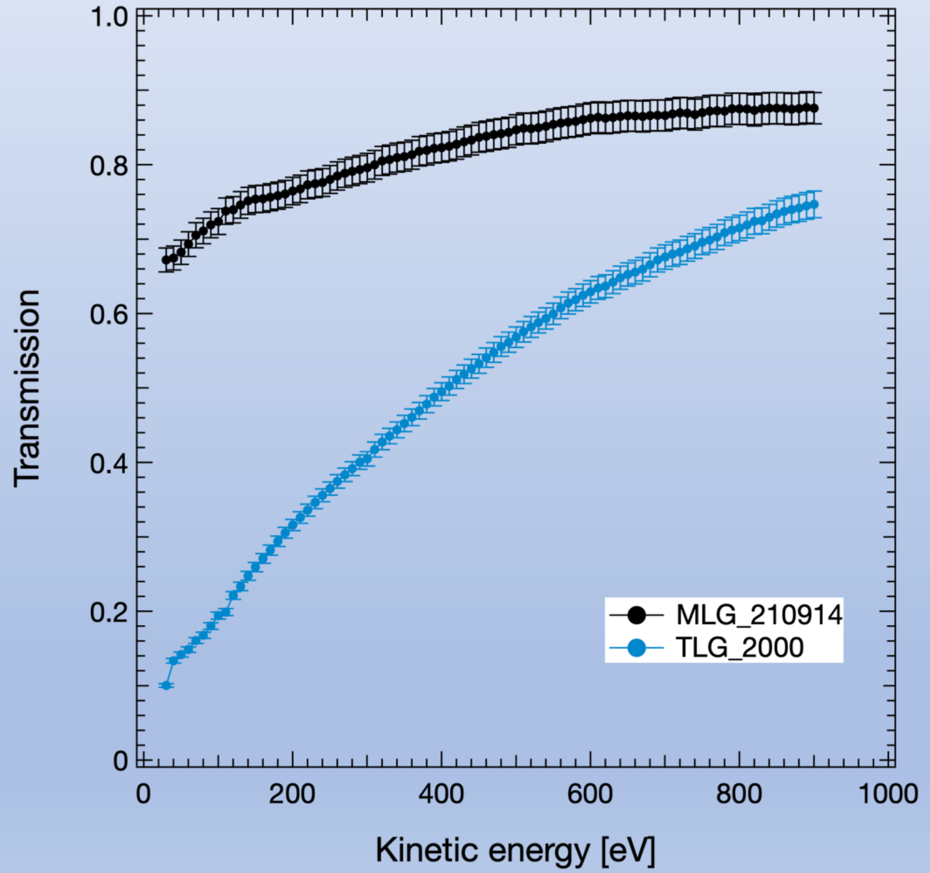
$\frac{I_{NOG}}{I_0}$ ⟶grid without graphene
(i.e. geometrical transmission)

- Nominal geometrical transmission

  41%
- Uncertainty 1.7% (not shown ~same size of the dots)



$\frac{I_{xLG}}{I_0 \cdot 0.39}$ ⟶ grid with graphene (net of the 39% grid transparency)



QUANTUM SPREAD

Distributing tritium on flat graphene has one drawback

Spatially localized tritium → Uncertainty on tritium momentum → Spread in final electron energy

A semi-classical estimate:

fluctuating momenta

$$p_T = \Delta p_T$$
$$p_{He} = \bar{p}_{He} + \Delta p_{He}$$
$$p_e = \bar{p}_e + \Delta p_e$$

energy and momentum conservation returns

$$\Delta E_e \simeq \left| \frac{p_e \cdot \Delta p_T}{E_{He}} \right| \sim \frac{p_e}{m_{He}} \frac{1}{\Delta x_T} \sim 0.2 - 0.8 eV$$

larger than desired

Spread of initial tritium wave Function $\Delta x_T \sim 0.1 \text{Å}$

Slide by Angelo Esposito at NuMass 2022

PTOLEMY Concept simulation

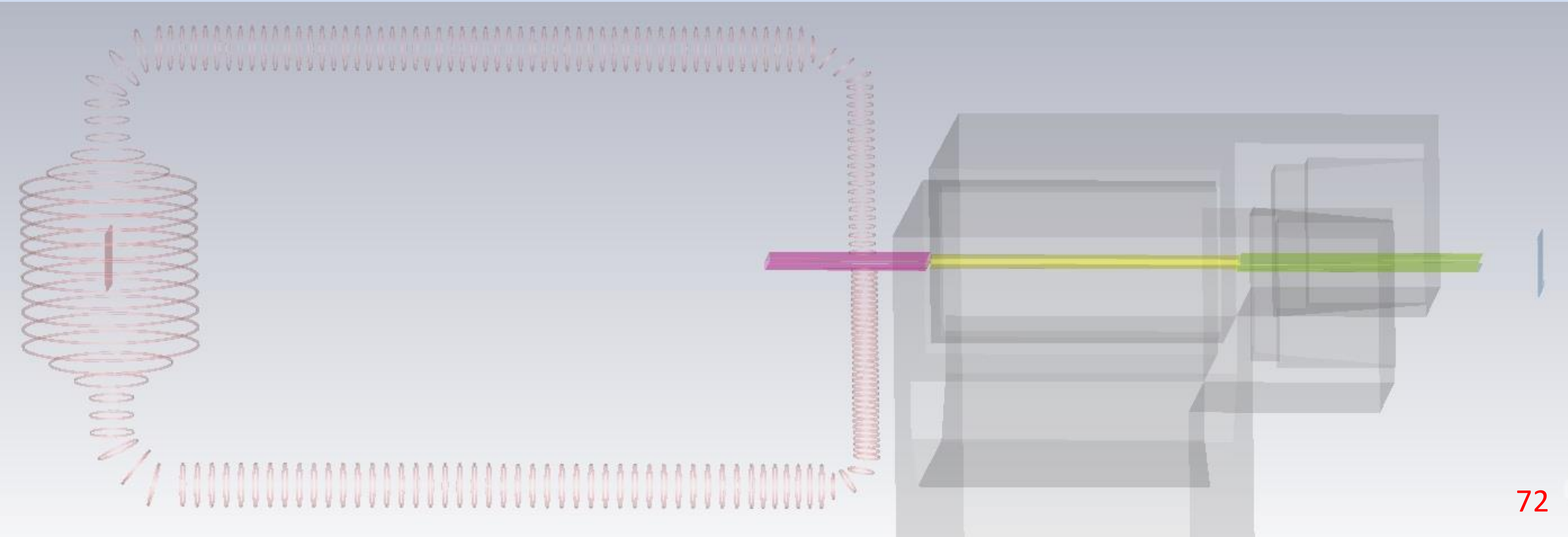
Target

Injection

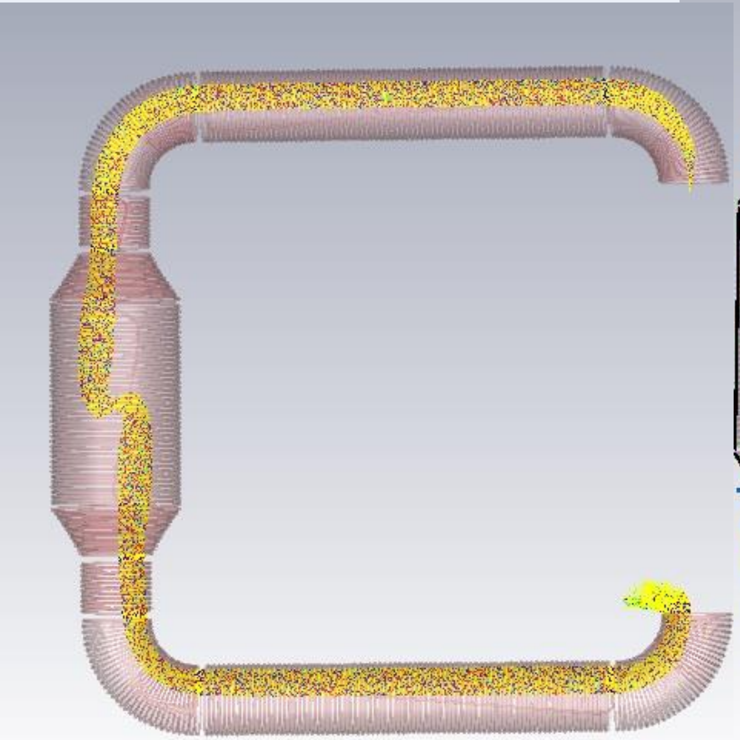
RF antenna

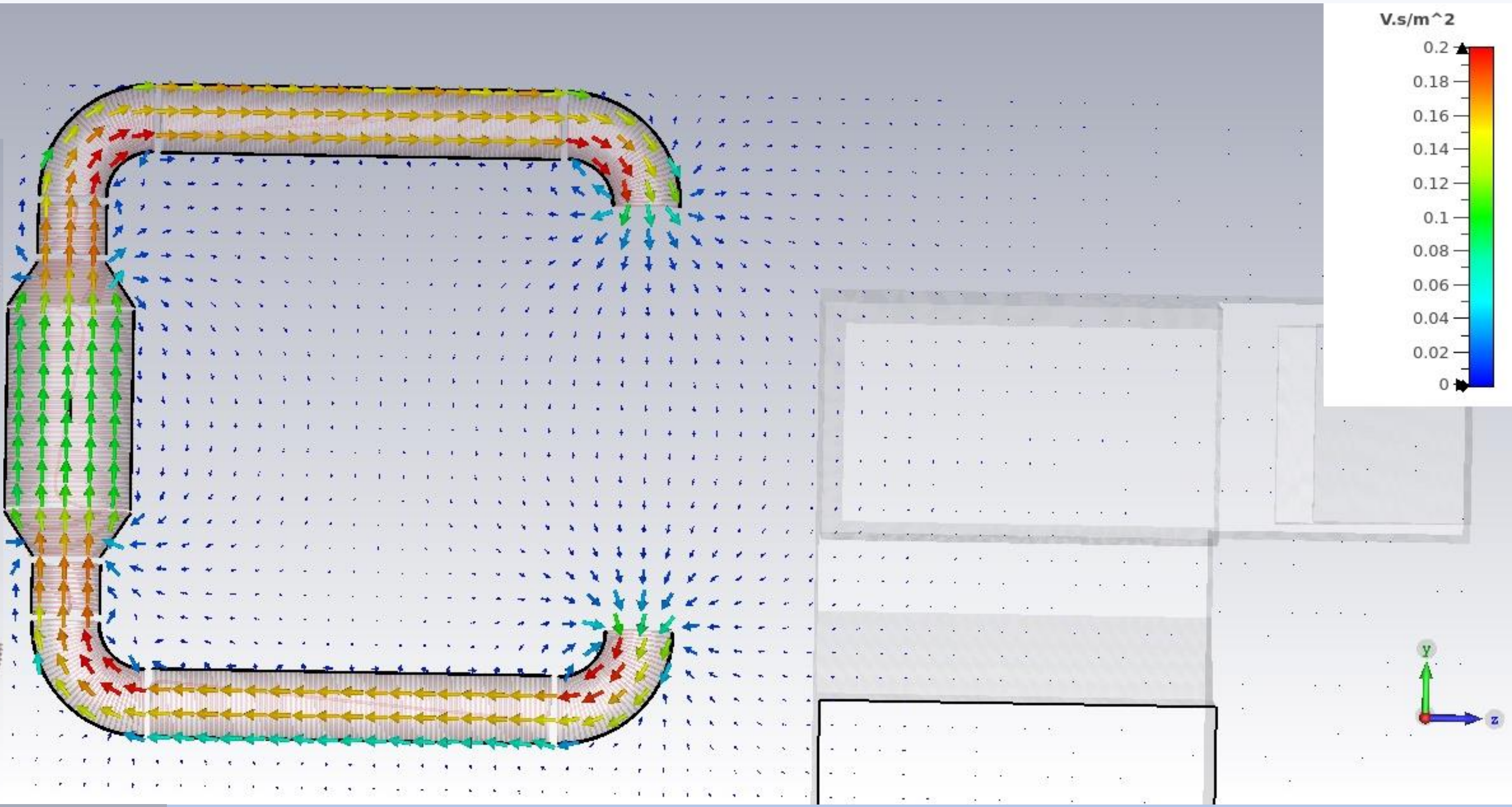
Filter

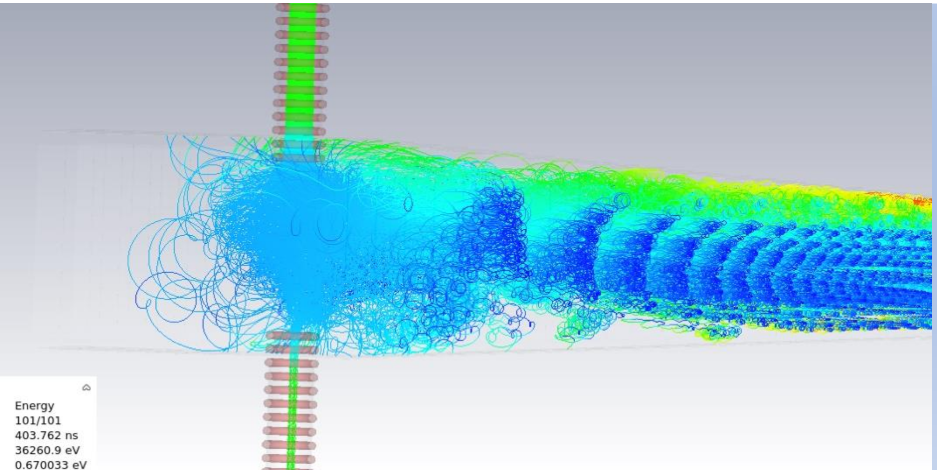
TES



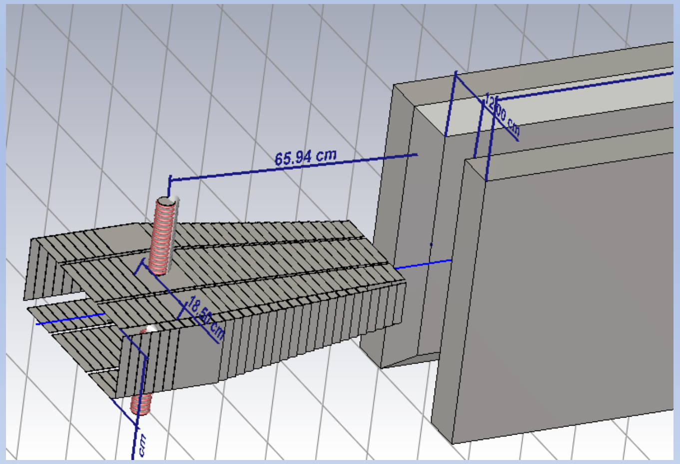
Transport coils







PRELIMINARY



Electromagnetic Filters

<u>MAC-E filter</u>

Magnetic Adiabatic Invariance

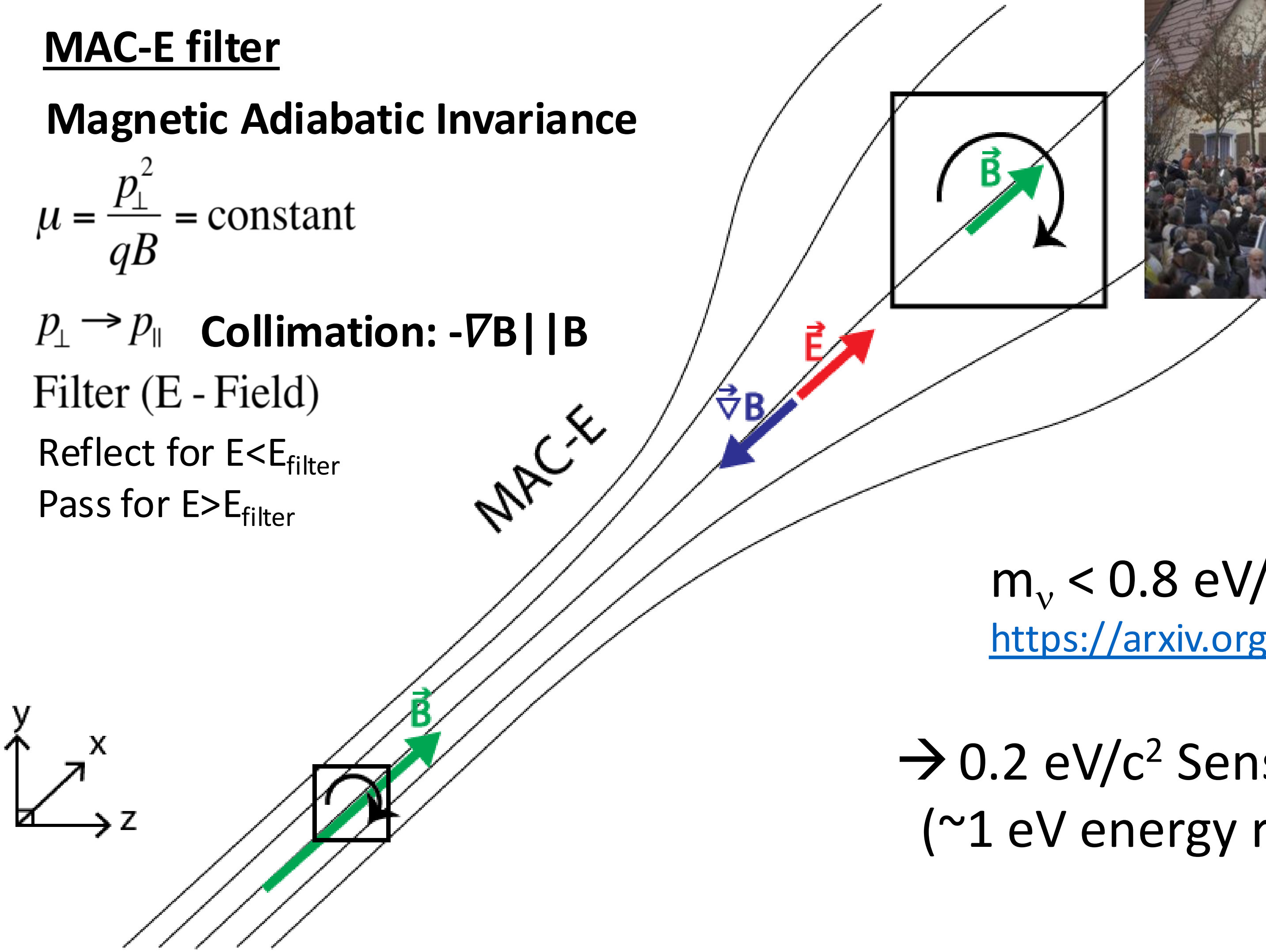
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

$p_\perp \rightarrow p_\parallel$ **Collimation: $-\nabla B || B$**

Filter (E - Field)

Reflect for $E<E_{filter}$

Pass for $E>E_{filter}$



KATRIN

~1200m^3

$m_\nu < 0.8$ eV/c^2 (90% CL)

https://arxiv.org/abs/2105.08533

→ 0.2 eV/c^2 Sensitivity Goal

(~1 eV energy resolution)

Electromagnetic Filters

Transverse Drift filter

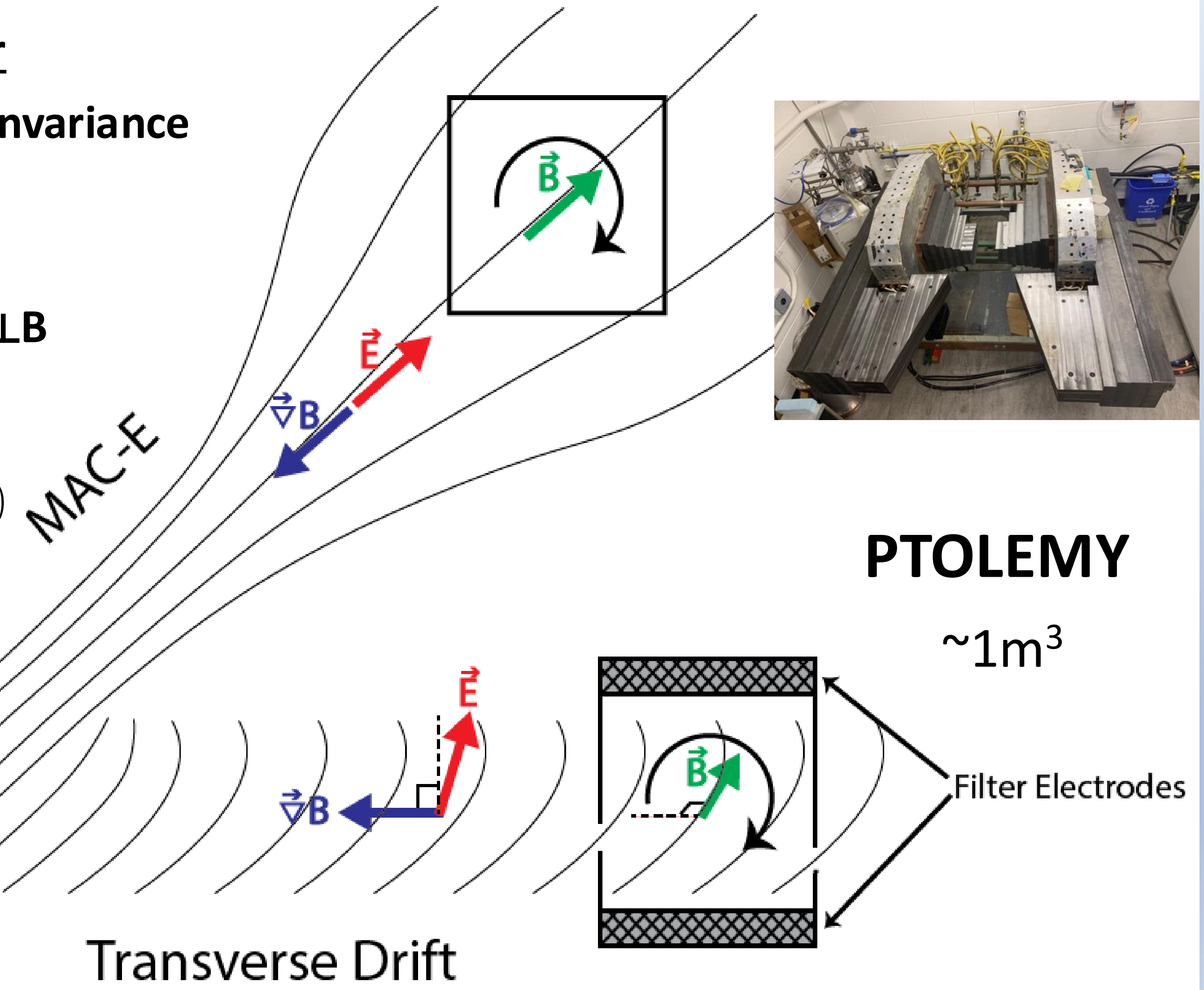
Magnetic Adiabatic Invariance

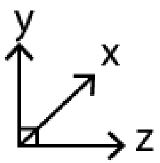
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

No Collimation: -∇B⊥B

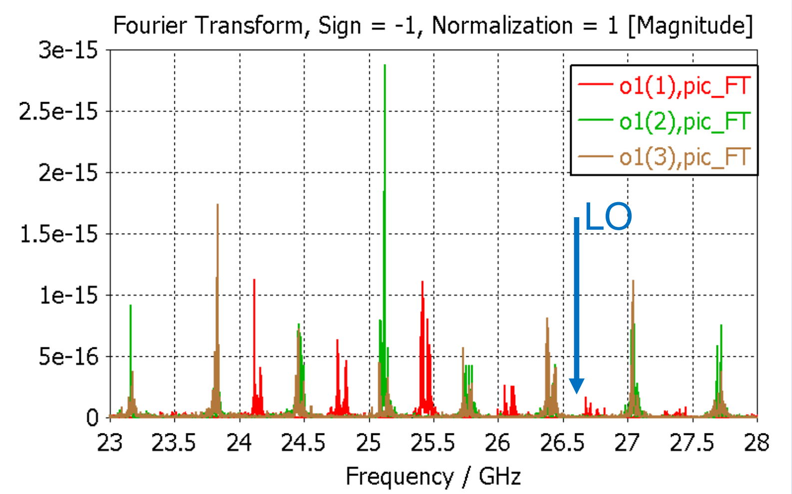
Filter (E - Field)

$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\boldsymbol{E}\cdot(\boldsymbol{\nabla}B \times \boldsymbol{B})$$

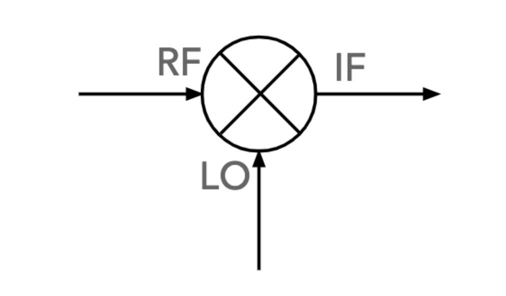




Preliminary RF signal FFT analysis (CST)



CST RF signal
+
simulated mixing
LO = 26.7 GHz
+
re-sampling (0.1 ns)
+
FFT

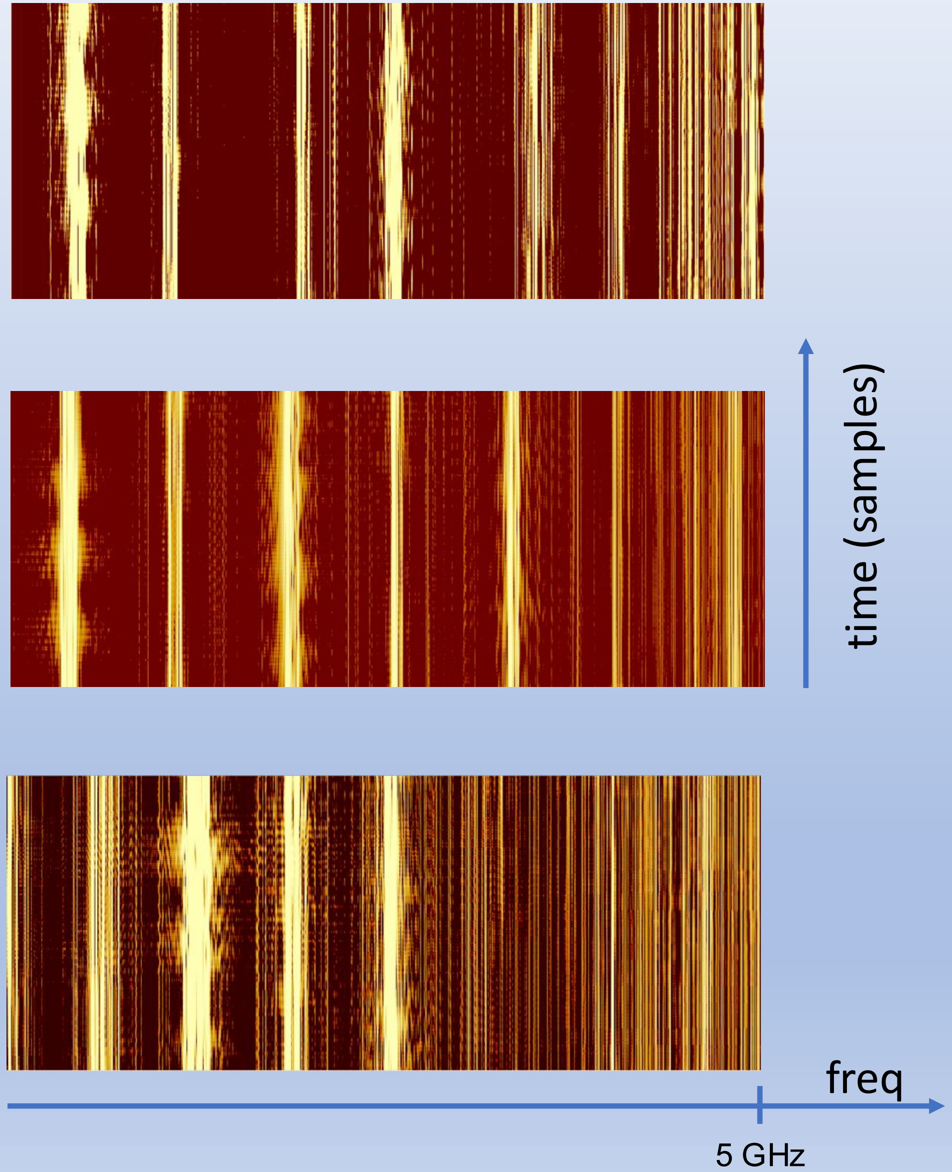


Pitch angle

45°

60°

83°



QUANTUM SPREAD

Distributing tritium on flat graphene has one drawback

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larger than desired

Spread of initial tritium wave Function $\Delta x_T \sim 0.1\text{Å}$

Slide by Angelo Esposito at NuMass 2022

QUANTUM SPREAD

- Distributing tritium on flat graphene has one drawback

spatially localized tritium ⇨ uncertainty on tritium's momentum ⇨ spread in final electron energy

[Cheipesh, Cheianov, Boyarsky — PRD 2021, 2101.10069]

- A simple semi-classical estimate:

fluctuating momenta

$$\mathbf{p}_T = \Delta\mathbf{p}_T$$

$$\mathbf{p}_{He} = \bar{\mathbf{p}}_{He} + \Delta\mathbf{p}_{He}$$

$$\mathbf{p}_e = \bar{\mathbf{p}}_e + \Delta\mathbf{p}_e$$

energy and momentum conservation returns

$$\Delta E_e \simeq \left| \frac{\mathbf{p}_e \cdot \Delta\mathbf{p}_T}{E_{He}} \right| \sim \frac{p_e}{m_{He}} \frac{1}{\Delta x_T} \sim 0.6 - 0.8 \text{ eV}$$

spread of initial tritium wave function $(\Delta x_T \sim 0.1\,\text{Å})$

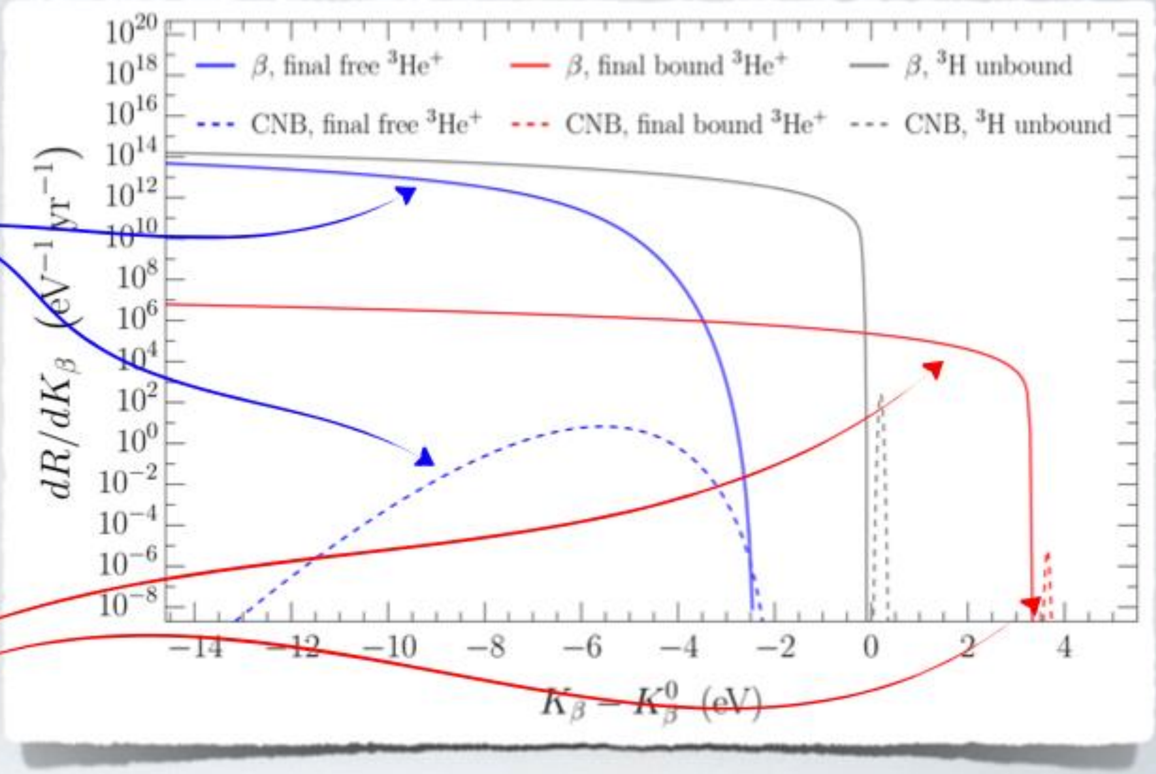
an order of magnitude larger than the wanted energy accuracy

QUANTUM SPREAD

PTOLEMY Collaboration, A. Apponi et all, DOI: 10.1103/PhysRevD.106.053002

- The resulting rate is

$^3He^+$ **is mostly freed** from the graphene ⟶ the **cosmic neutrino peak disappears** under the decay spectrum



When the $^3He^+$ **remains bound in the ground state** the peak is well separated ⟶ it is however **exponentially unlikely**

[PTOLEMY – 2203.11228]

Collaboration with Savannah River National Laboratory for Tritium Loading

CNT, NPG, CVD-G, and De-localized Atomic T Geometries

~2Å flat potential – not chemically active