Status and prospects of the PTOLEMY project

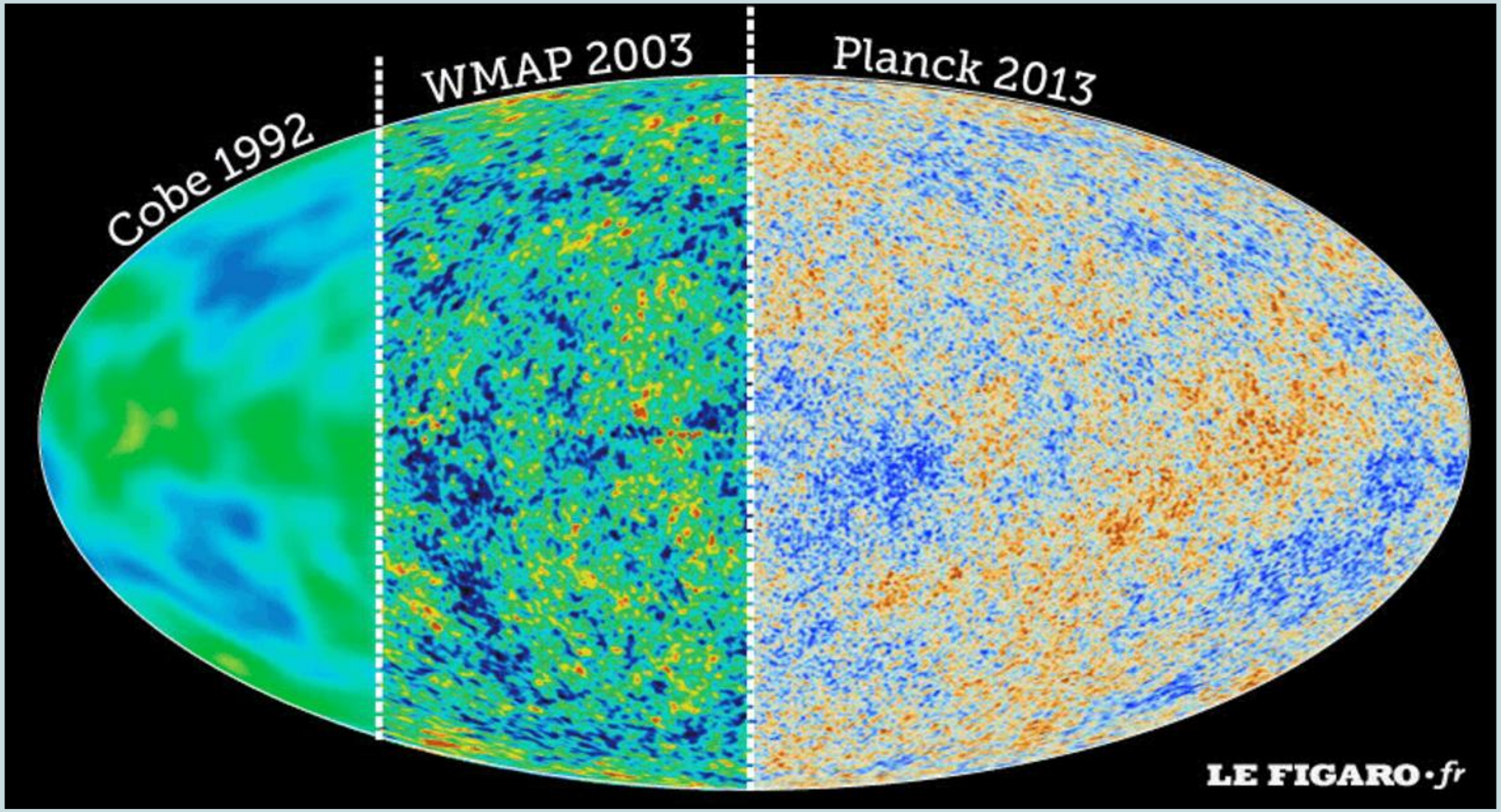
M Messina on behalf of the PTOLEMY collaboration

OUTLINE

- Short physics introduction
- PTOLEMY detector concept
- Conclusion and Outlook

The Gold-mine of Cosmologist

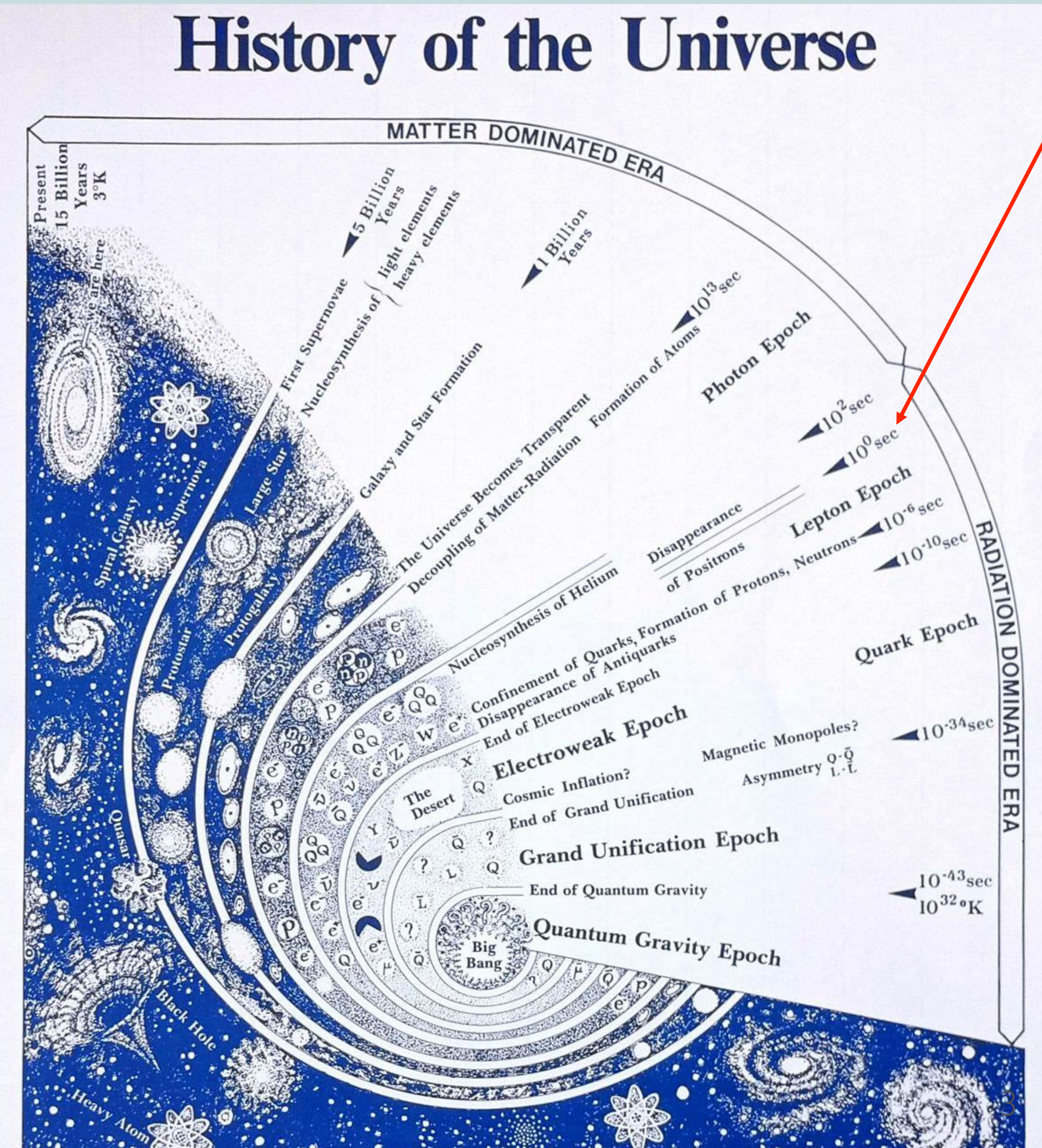
CMB: The oldest electromagnetic radiation in the universe



- Universe is **expanding**: Hubble's law: $v = H_0 D$ (~70 km/s/Mpc), 1919.
- **Cosmic microwave background**, Penzias & Wilson, 1964
- Abundance of **primordial elements**: ^4He, ^2H, ^7Li (?)
- **Galaxies morphology** and stars populations in time
- **Primordial gas cloud** (without heavy elements), 2011

The Big Bang

ν decoupling **The present Universe emerges from an Ultra-dense and high temperature initial state**



Time of decoupling:
1 second
neutron/proton ratio
@start of nucleosynthesis
Temperature:
T_ν=1.95 K
Number density:
n_ν=112/cm^3
Velocity distribution:
$<v_\nu> \sim T_\nu/m_\nu$

NEUTRINO FEATURES

- What we do know about neutrinos:

they are massive

well measured Δm_i^2

cosmic neutrino background
should be out there

- What we don't know about neutrinos:

absolute mass scale
$(m_\nu < 0.45 eV)$

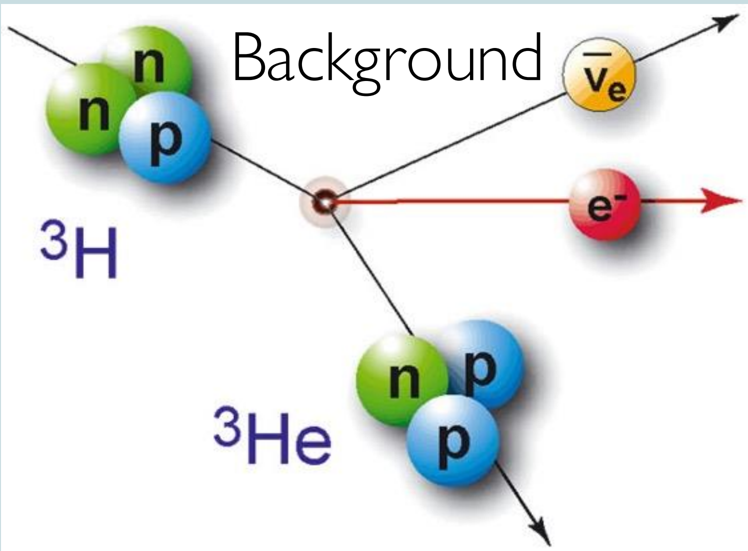
[KATRIN — recent publication
arXiv:2406.13516v1

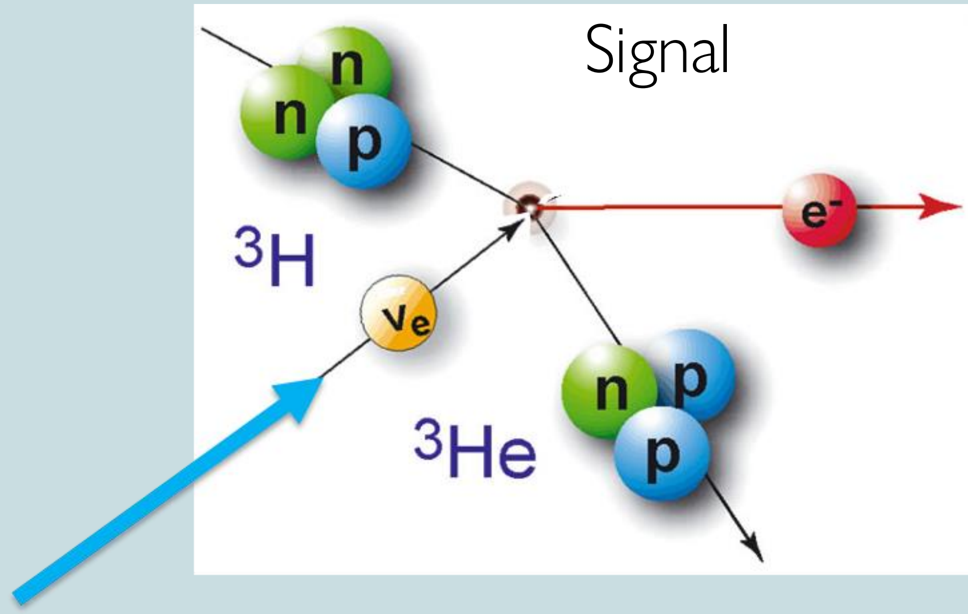
mass ordering
$(50 meV < m_{light} \simeq m_e \, or \, m_\tau)$

From Cosmology several limits at 95 % CL on Σm_ν from 0.56 to 0.11 eV

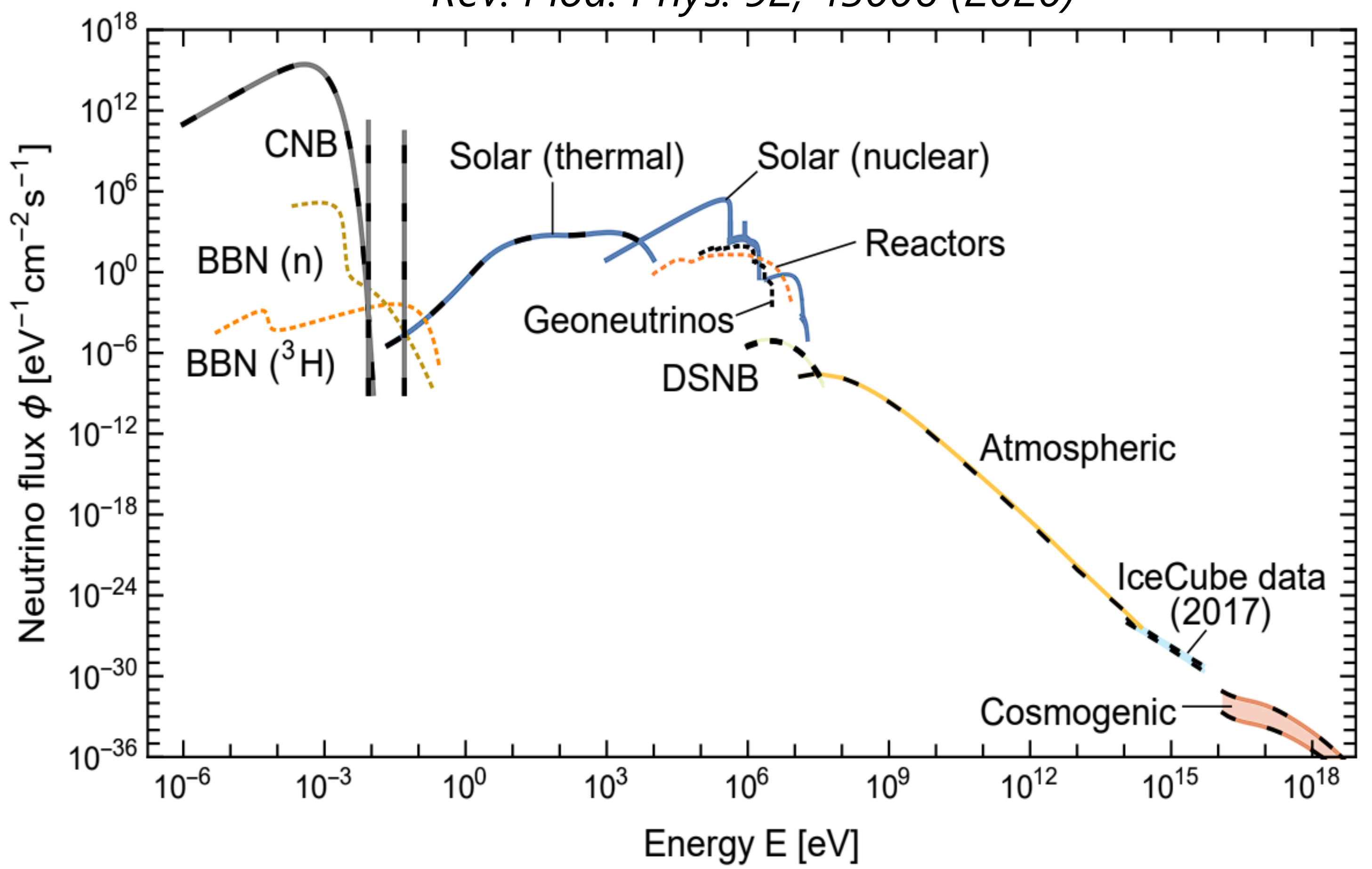
cosmic neutrino background
yet to be seen

PTOLEMY - RELIC NEUTRINO DETECTION STRATEGY

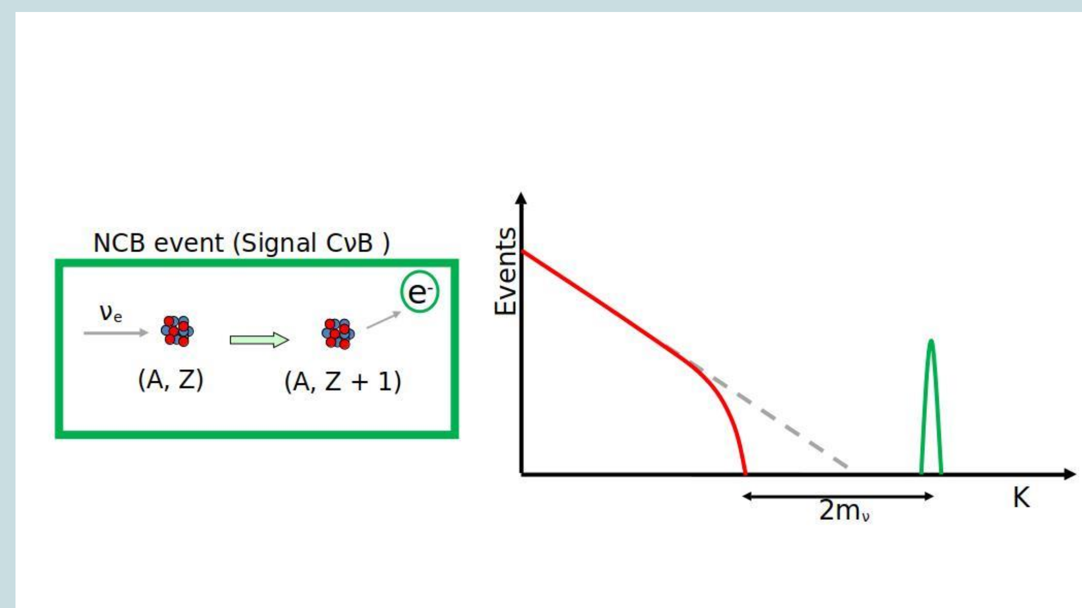




Rev. Mod. Phys. 92, 45006 (2020)



Signature of CνB



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)

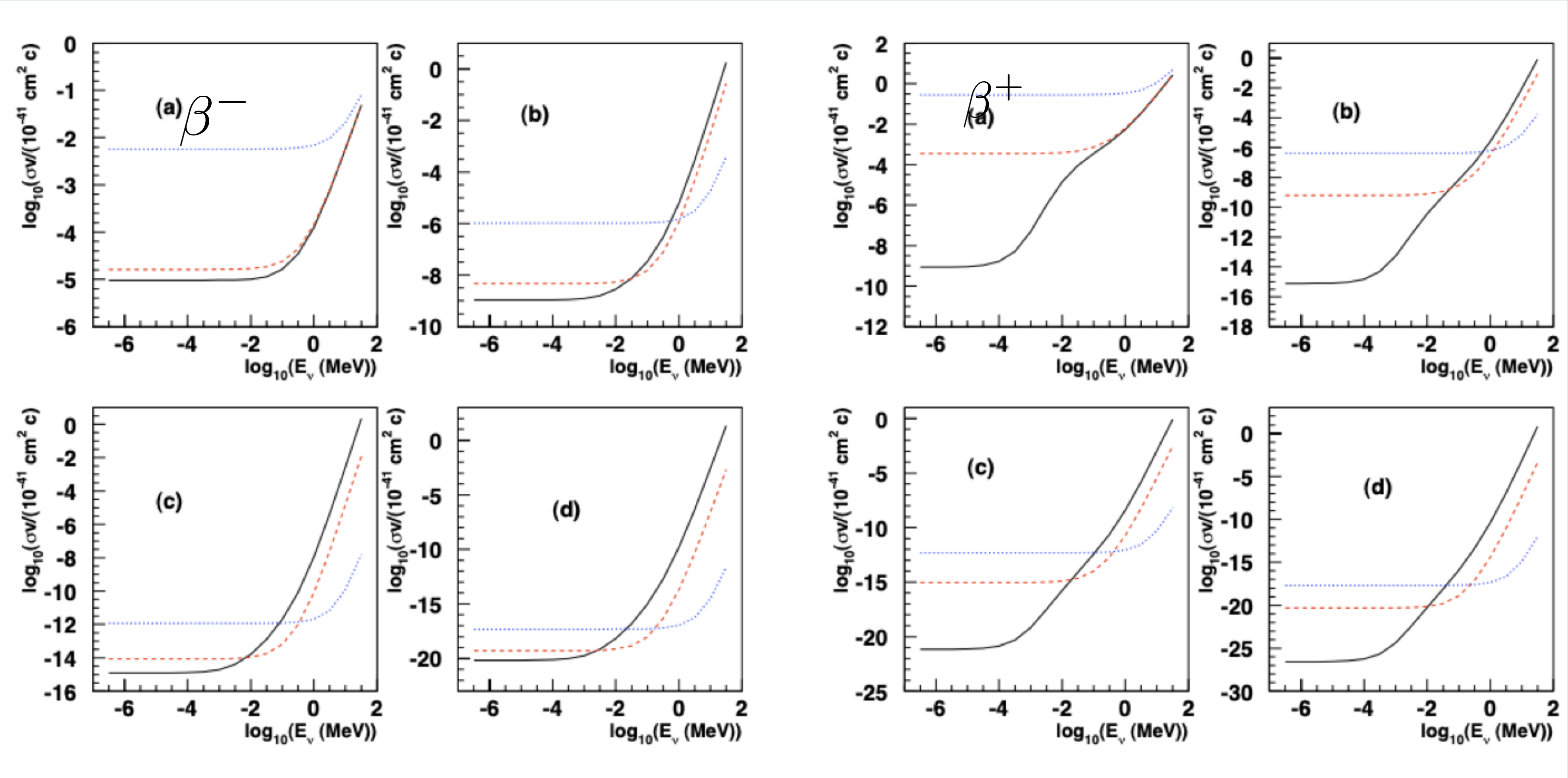
Modern cosmological theories imply that the universe is filled with a shallow degenerate Fermi sea of neutrinos. In the steady state and oscillating models (and perhaps also the "big bang" theories) it can be shown rigorously that the proportion of filled neutrino levels (plus the proportion of filled 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.

$$m_\nu = 0$$

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

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

Cocco, Mangano, Messina calculatedin the casde $m_\nu \neq 0$ case in 2007



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

PHYSICS OUTCOME

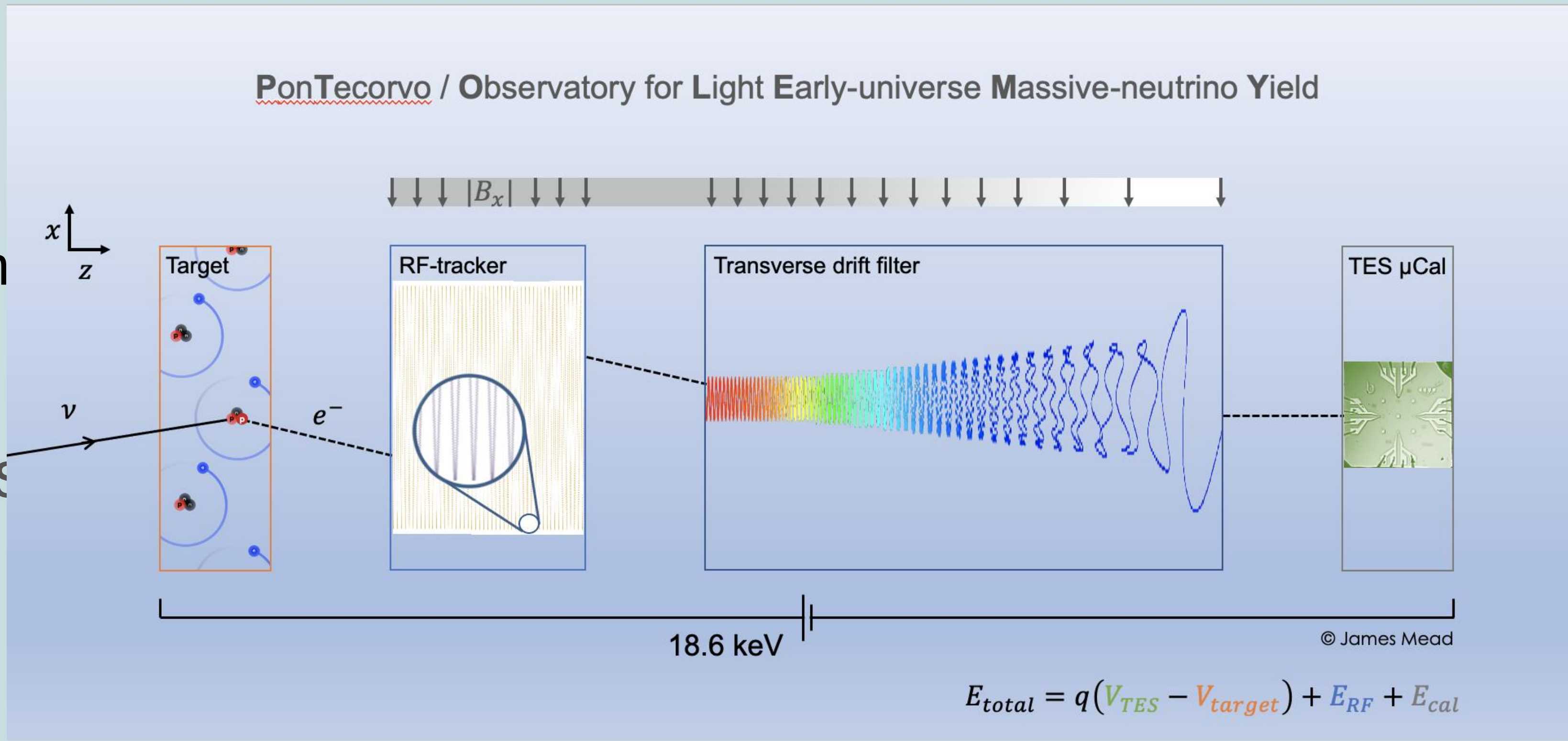
- Direct neutrino mass
- CNB
- Sterile Neutrinos
- Dirac/Majorana

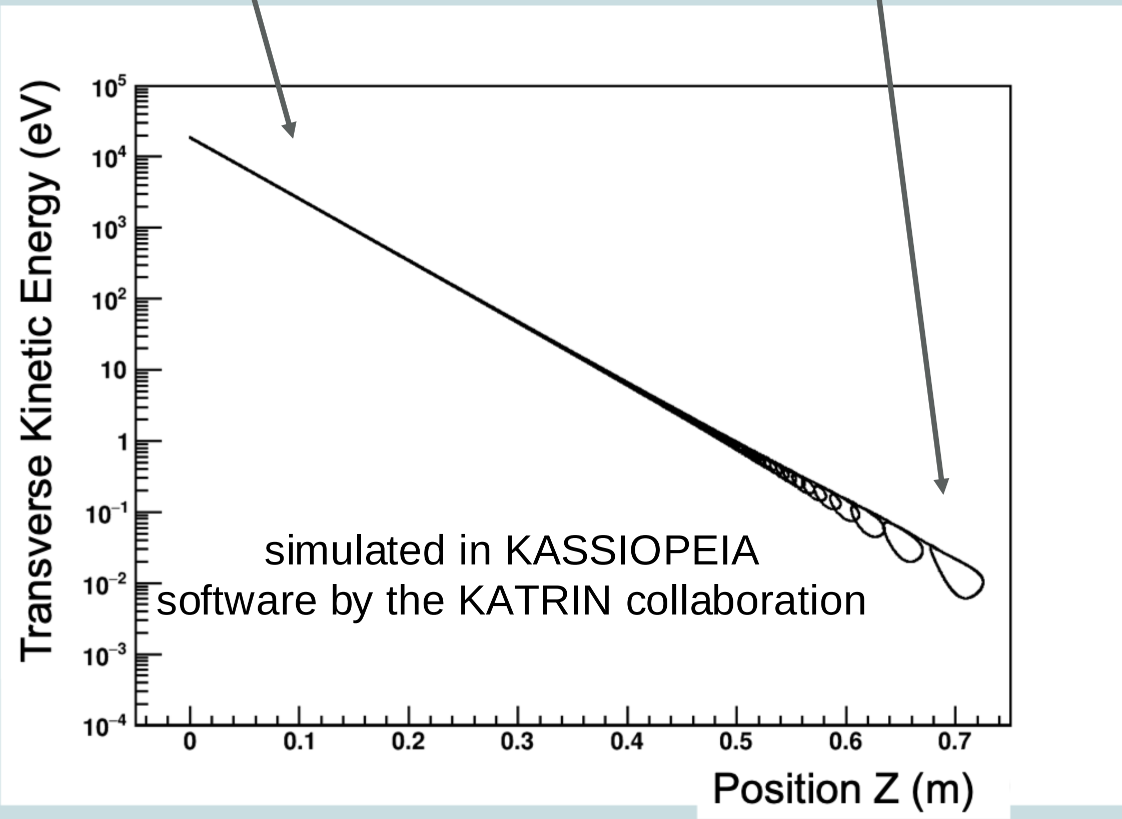
DETECTOR CONCEPT

Transverse drift filter:

New filter concept which exploits differen
dirft terms transforming kinetic energy in
eletrostatic potential one

18.6 keV ➠ 0.01 keV in 0.7 meters

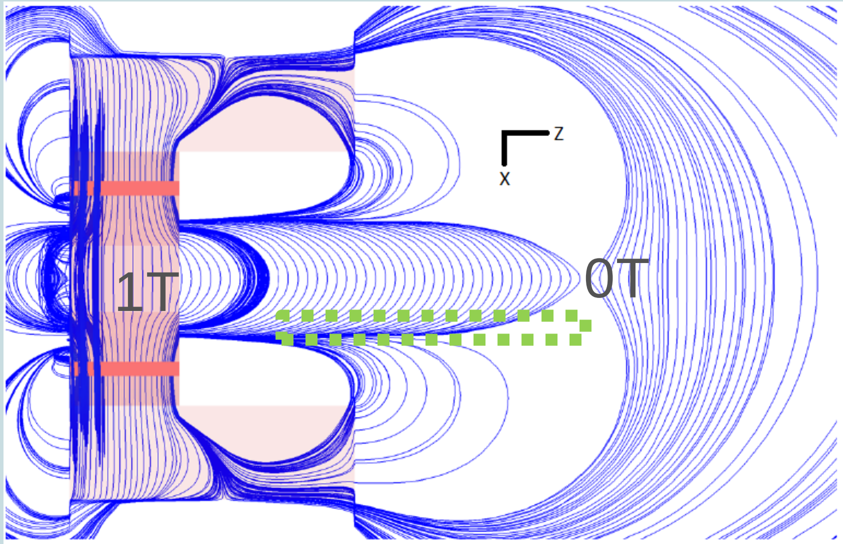




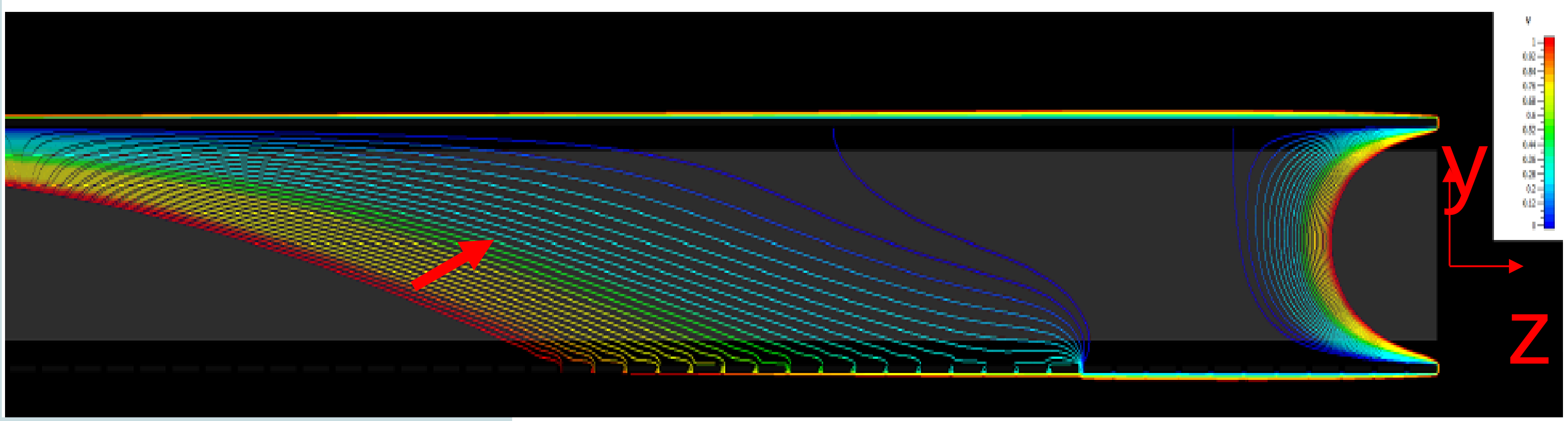
- PTOLEMY aims at using TES detectors with an envisaged resolution of $\Delta E \simeq 0.05 eV$
- However:
  1. TES' perform best with energies $O(10eV)$ need to slow the electrons down
  2. TES' are slow response detectors need to reduce the number of electrons coming from β-decay

PTOLEMY FILTER

Exponential decaying magnetic field

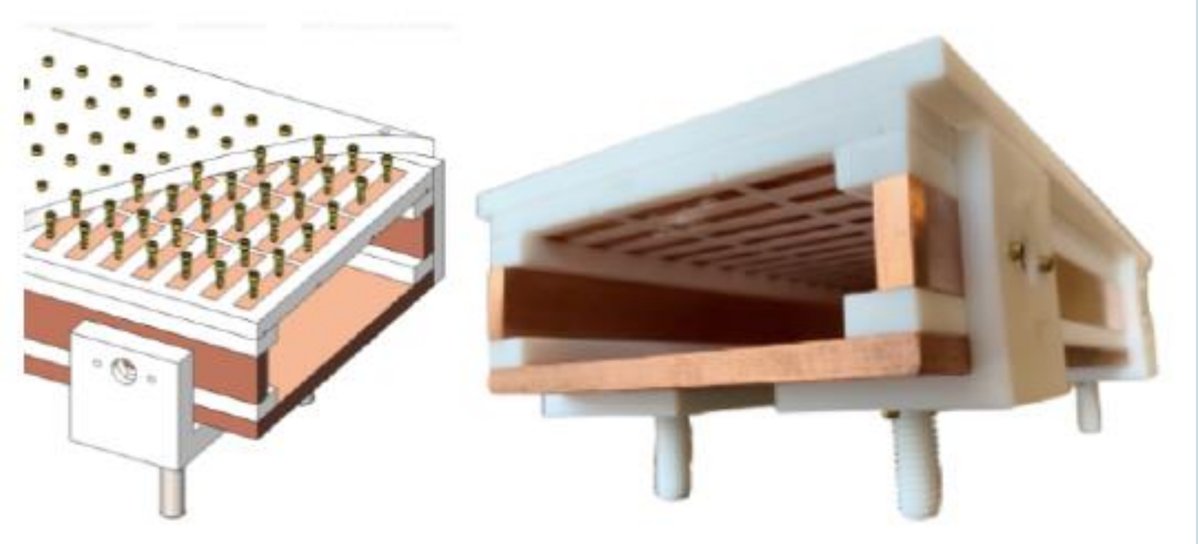


- Exponential decaying electric field



$$B_x = B_0 \cos\left(\frac{x}{\lambda}\right) e^{-z/\lambda} ,$$
$$B_y = 0 ,$$
$$B_z = -B_0 \sin\left(\frac{x}{\lambda}\right) e^{-z/\lambda} .$$

$$E_x = 0 ,$$
$$E_y = E_0 \cos\left(\frac{y}{\lambda}\right) e^{-z/\lambda} ,$$
$$E_z = -E_0 \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda} .$$



$$\boldsymbol{V}^y_{E\times B}(z)|_{x,y=0} = \frac{\boldsymbol{E}\times\boldsymbol{B}}{B_x^2} = \frac{E_z B_x \hat{\boldsymbol{y}}}{B_x^2} = \frac{E_z}{B_x}\hat{\boldsymbol{y}}$$

$$\boldsymbol{V}_{\nabla B-C} = \frac{1}{2} m (v_\perp^2 + 2 v_\parallel^2) \frac{\boldsymbol{B}\times\boldsymbol{\nabla}_\perp B}{qB^3} = (T_\perp + 2T_\parallel)\frac{\boldsymbol{B}\times\boldsymbol{\nabla}_\perp B}{qB^3}$$

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

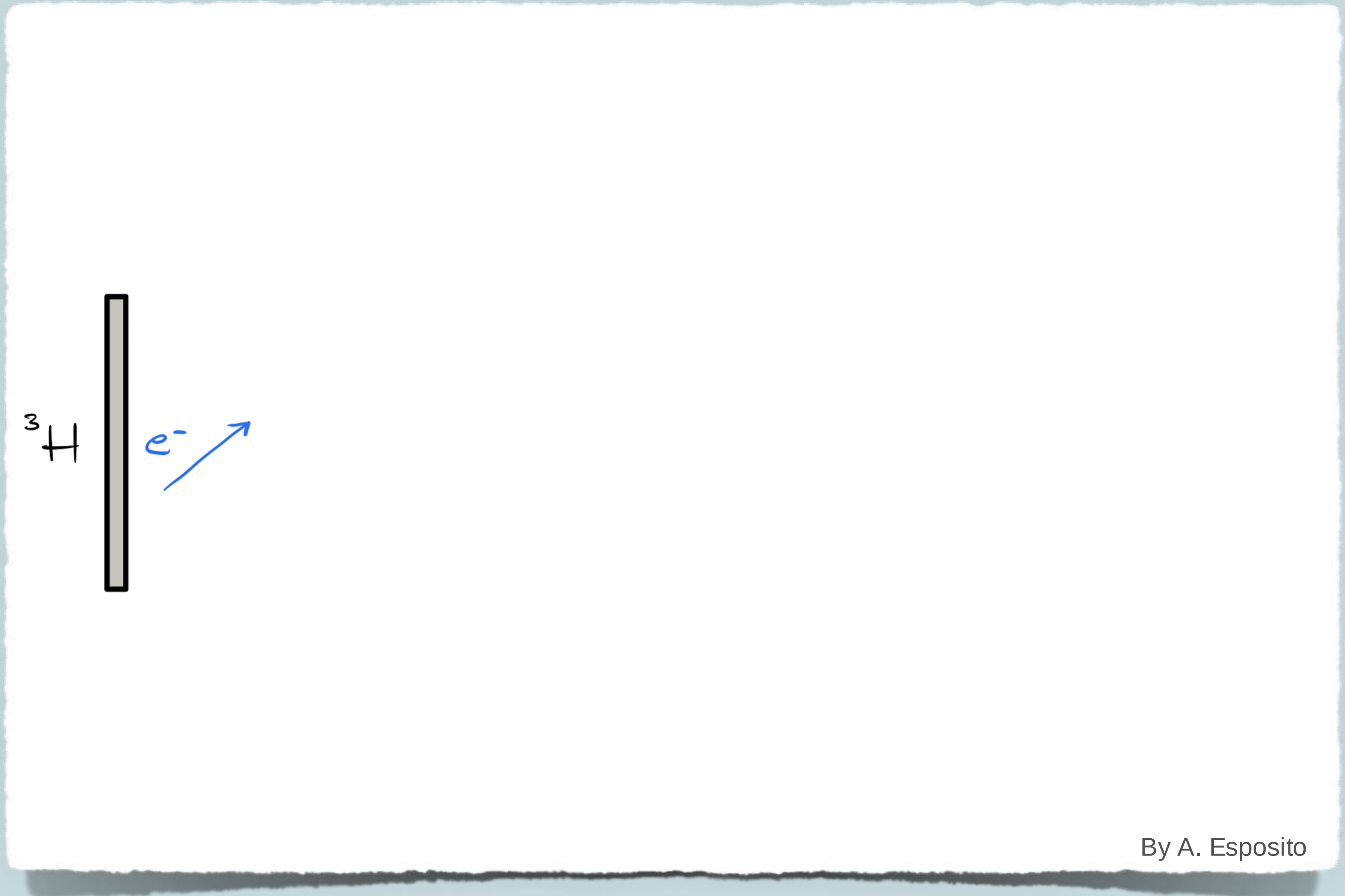
Prog.Part.Nucl.Phys. 106 (2019) 120-131

JINST 17 (2022) 05, P05021

PTOLEMY: THE IDEA

JINST 17 (2022) 05, P05021

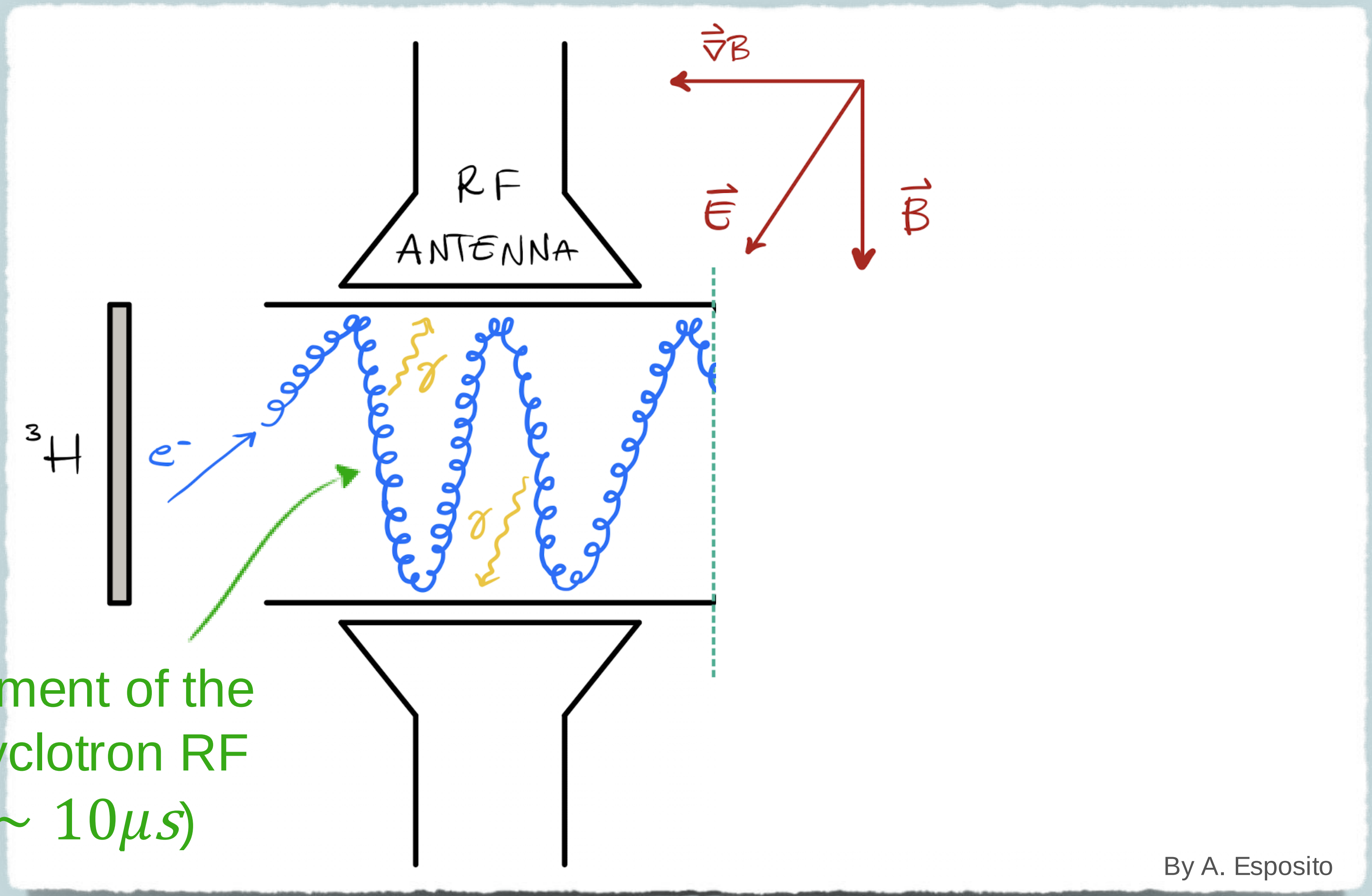
- A new electromagnetic filter idea based on RF detection and dynamic E setting



PTOLEMY: THE IDEA

JINST 17 (2022) 05, P05021

- A new electromagnetic filter idea based on RF detection and dynamic E setting

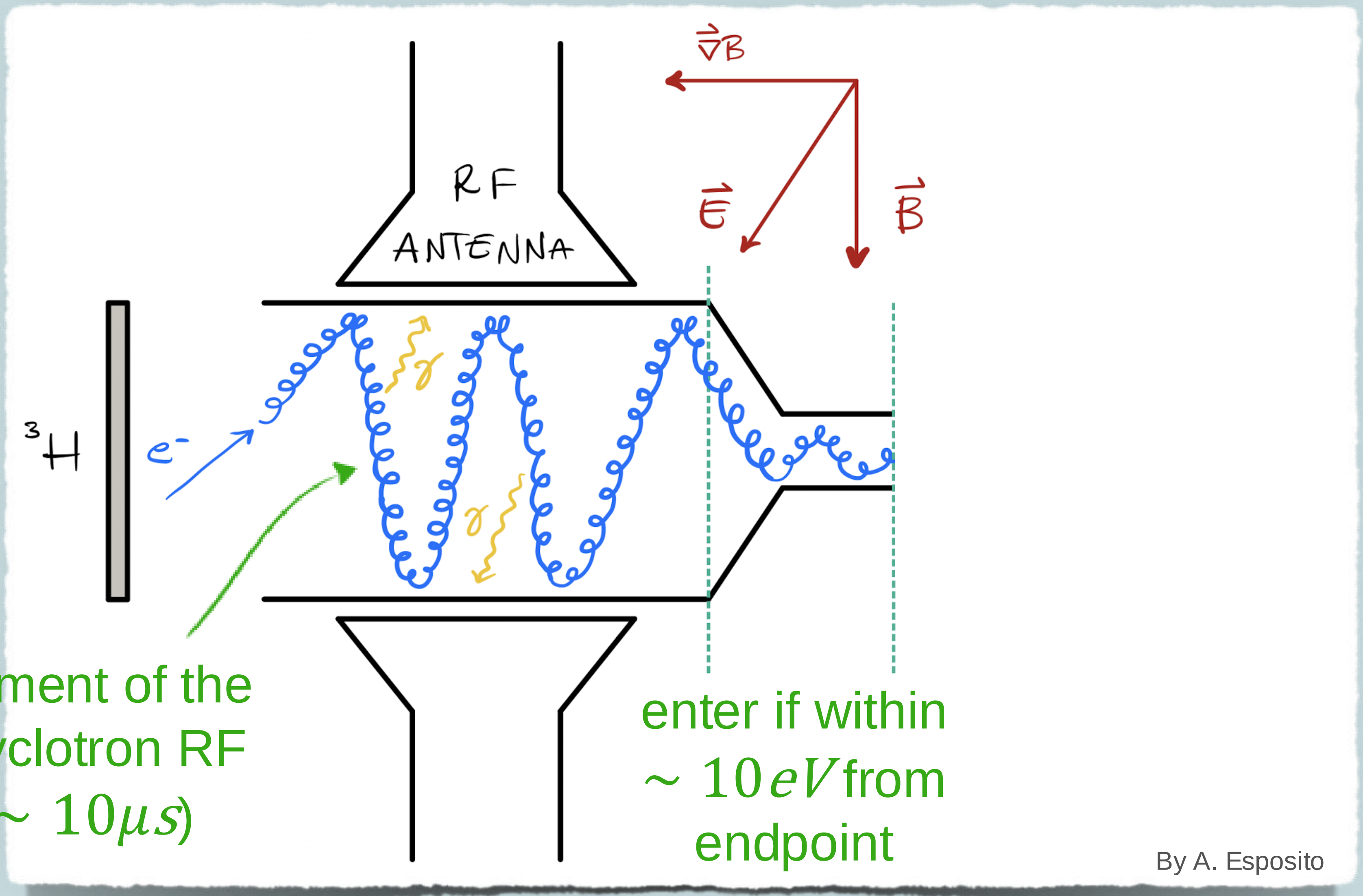


first measurement of the energy via cyclotron RF emission ($\sim 10\mu s$)

PTOLEMY: THE IDEA

JINST 17 (2022) 05, P05021

- A new electromagnetic filter idea based on RF detection and dynamic E setting

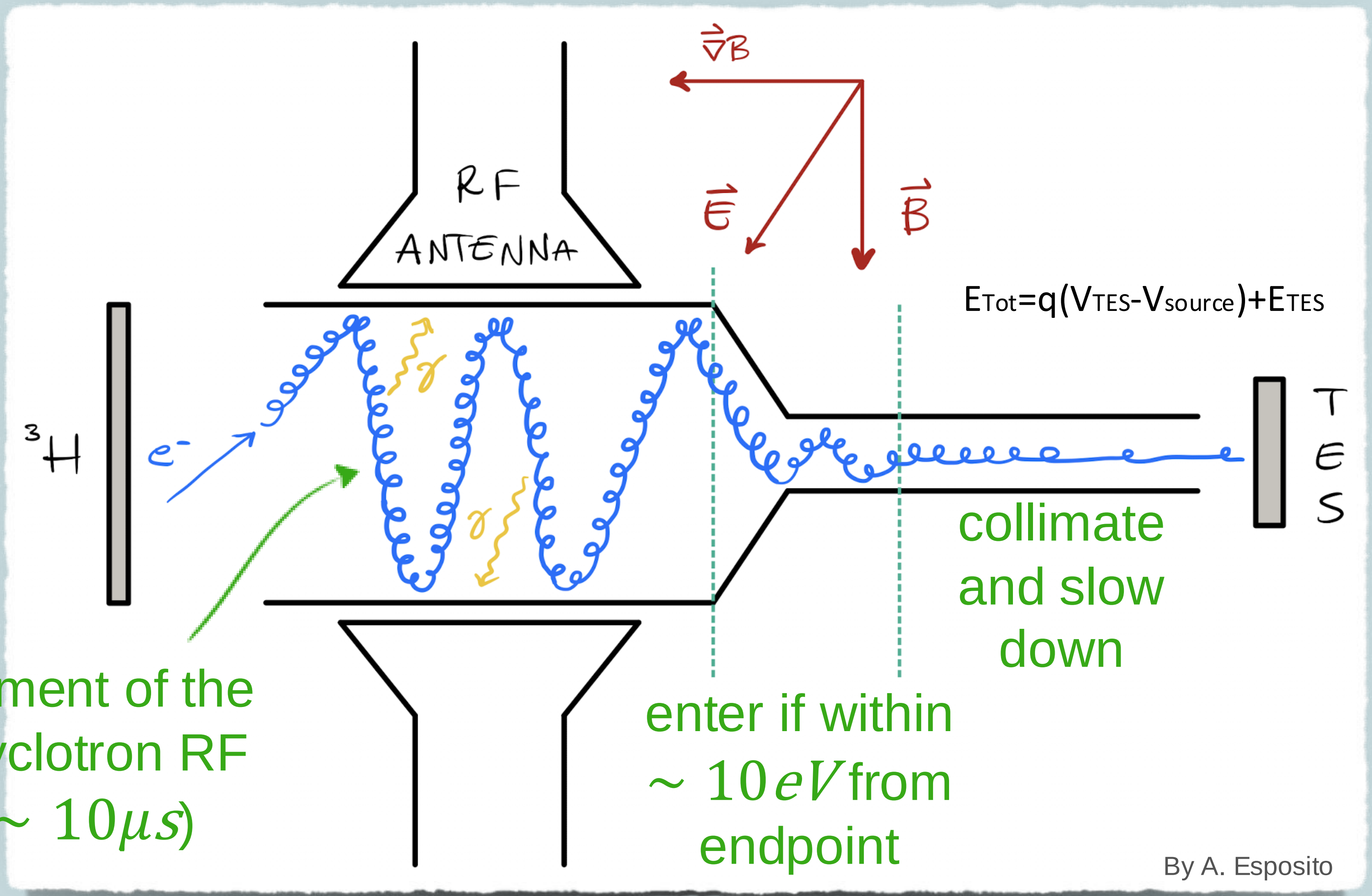


PTOLEMY: THE IDEA

JINST 17 (2022) 05, P05021

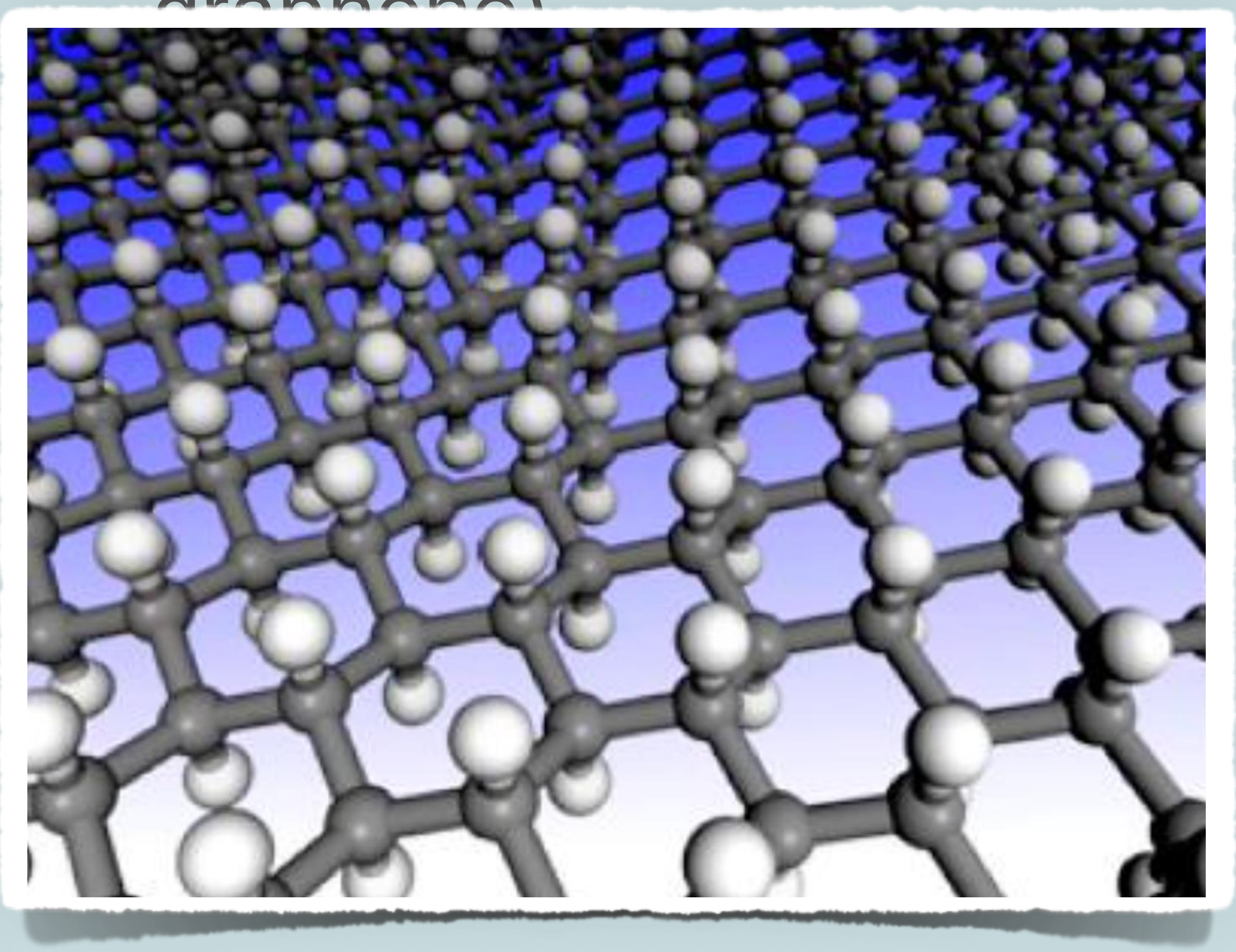
- A new electromagnetic filter idea based on RF detection and dynamic E setting

ΔV known to 1 ppm precision

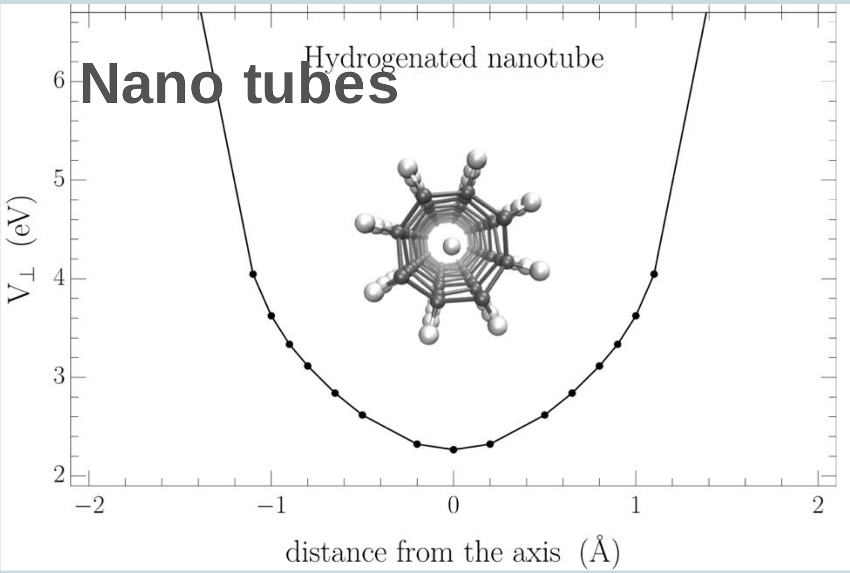


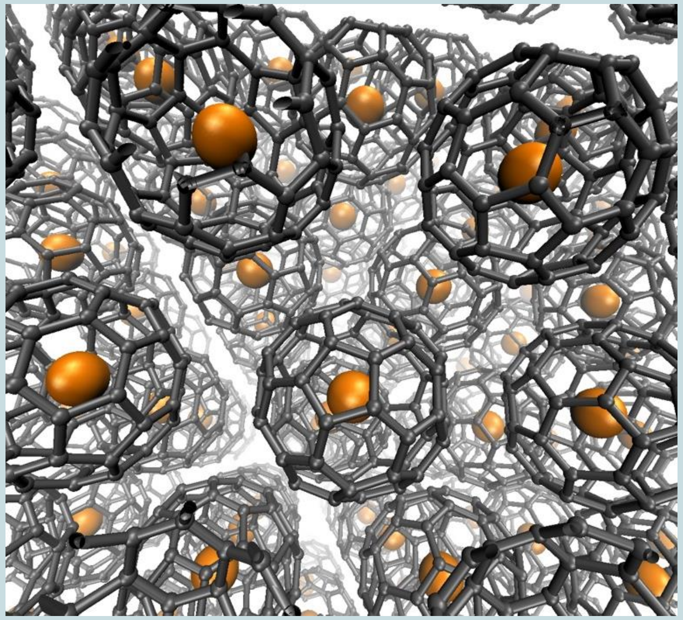
PTOLEMY: ATOMIC TARGET

- PTOLEMY has to deal with large instrumented mass. Distribute atomic tritium on a solid state substrate (e.g. graphene)



Other solution are under study



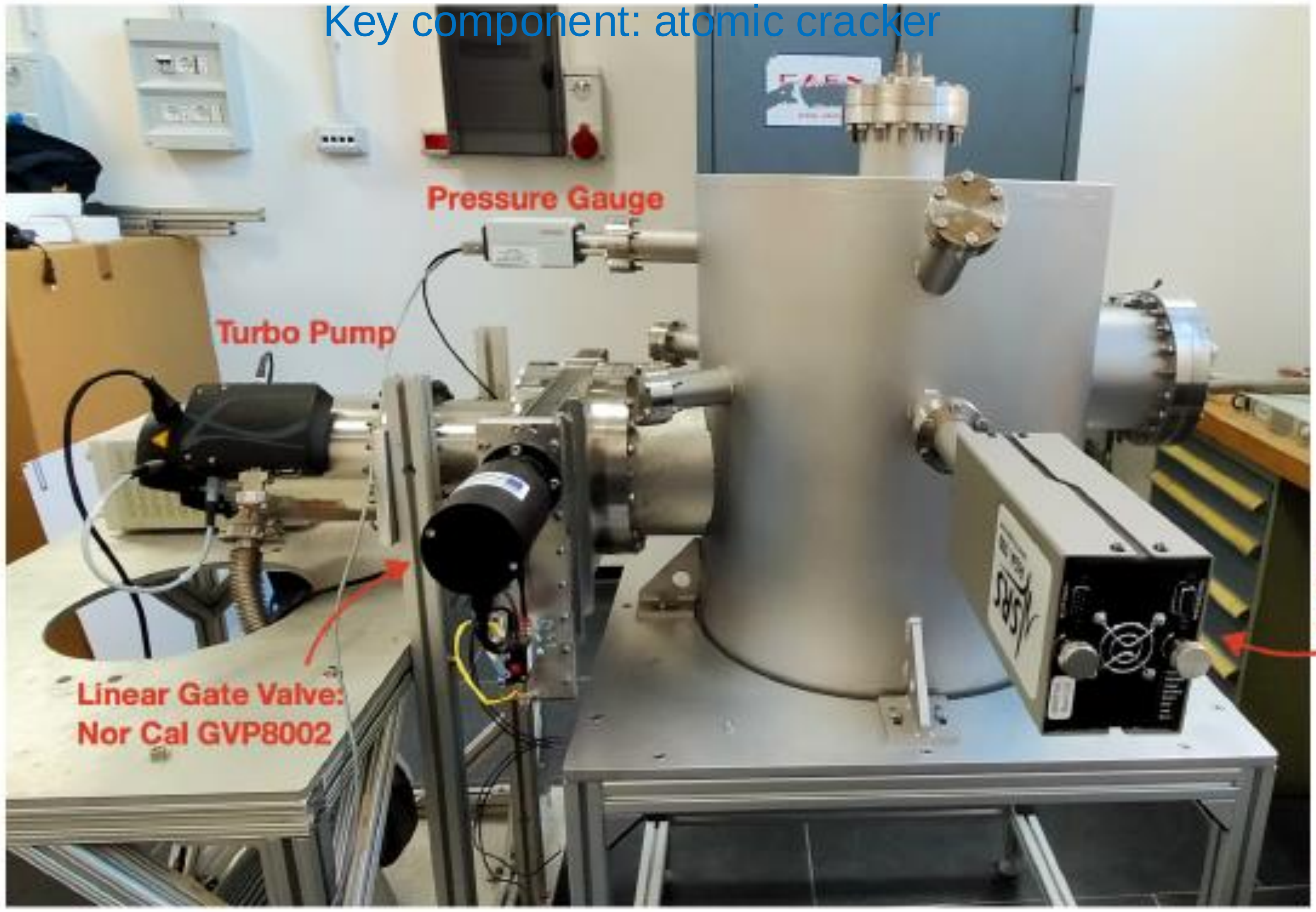


Fullerene

Loading chamber

Tritium loading chamber

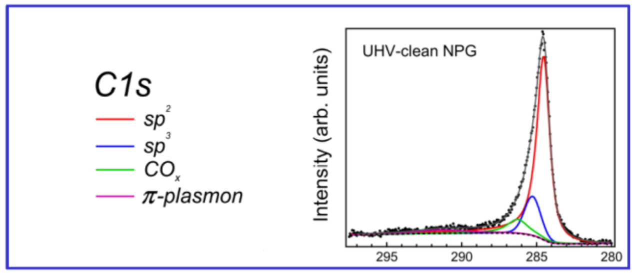
Key component: atomic cracker



T loading chamber designed and built in Rome in the framework of the PTOLEMY R&D. Loading technique tested up to 90 % loading efficiency measured with H and D.

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:

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

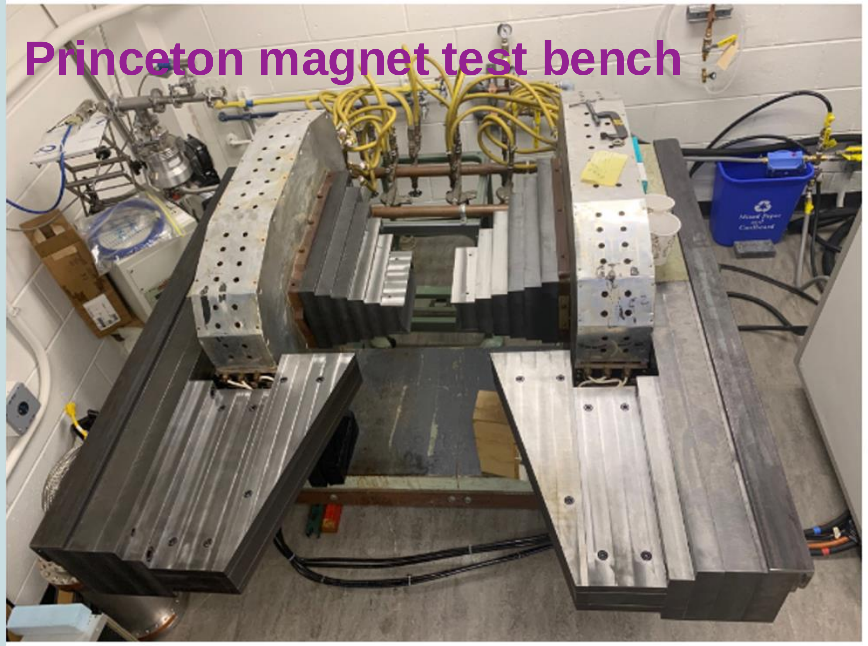


Abdelnabi et alii, Nanomat. 11, 130 (2021)

1 MG Betti et al, Dielectric response and excitations of hydrogenated free-standing graphene, Carbon Trends, September 2023, 100274;
2 MG Betti et al, Homogeneous Spatial Distribution of Deuterium Chemisorbed on Free-Standing Graphene, Nanomaterials 2022, 12(15), 2613;

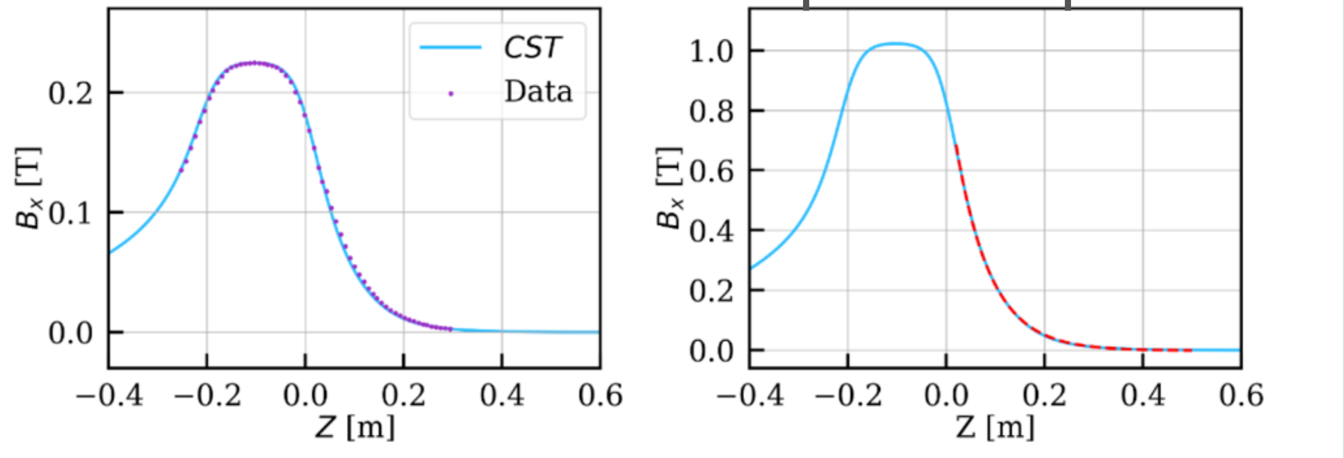
A SPECIAL MAGNET

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



Filter electrodes

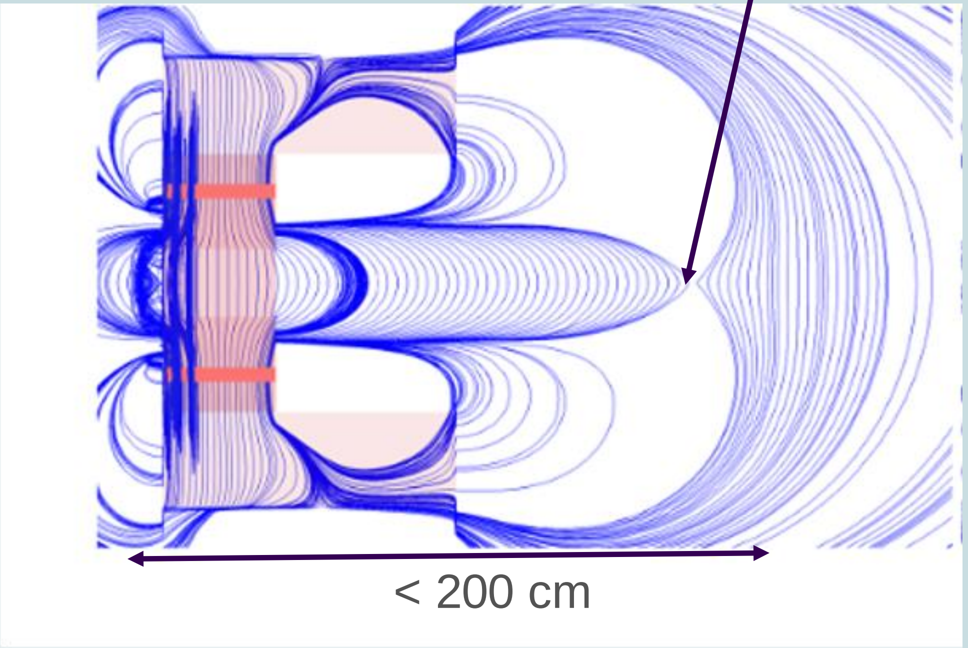
Measured B field shape as expected

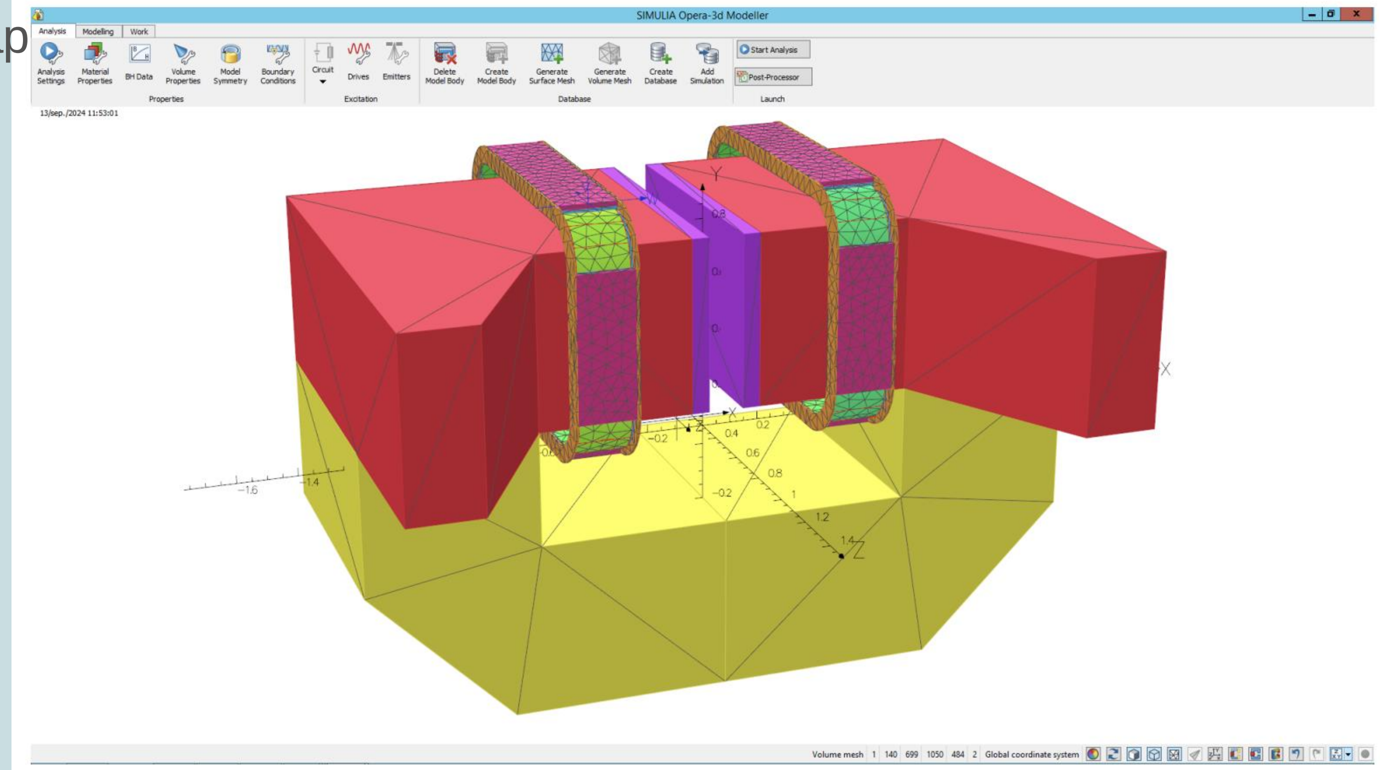


Construction ASG/Suprasys consortium of a SC dipole with special attention to the fringe field

Saddle point key features of the field map

Simulated B-map



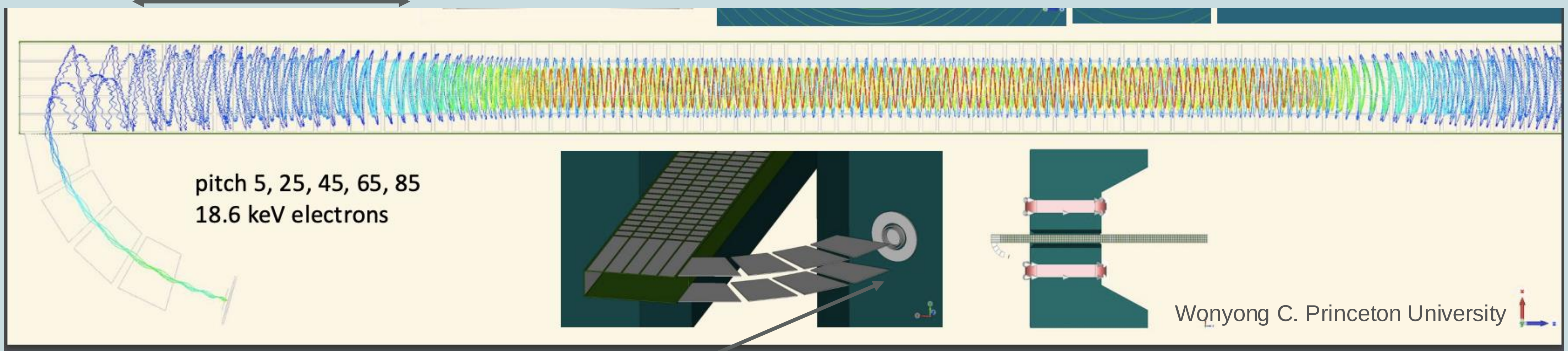


Detailed simulation of the filter

Magnet 1 T field
RF region

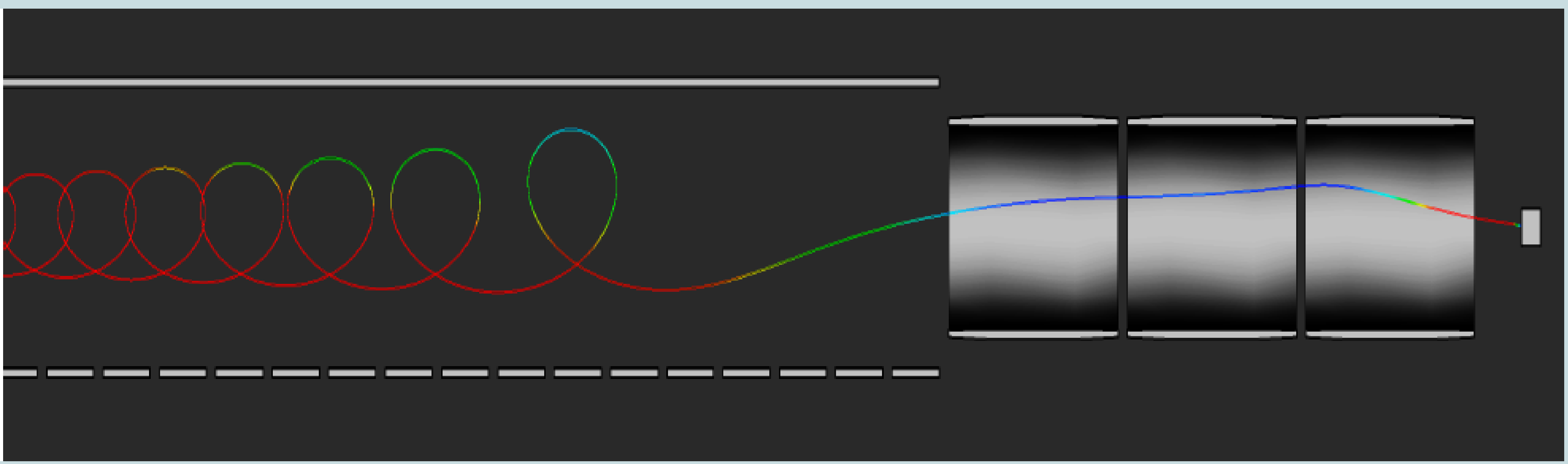
Filter region

Micro-calorimeter region with focusing system to match beam and calorimeters array



Geometry relying on modularity approach to increase instrumented mass

FOCUSING
with Einzel lens

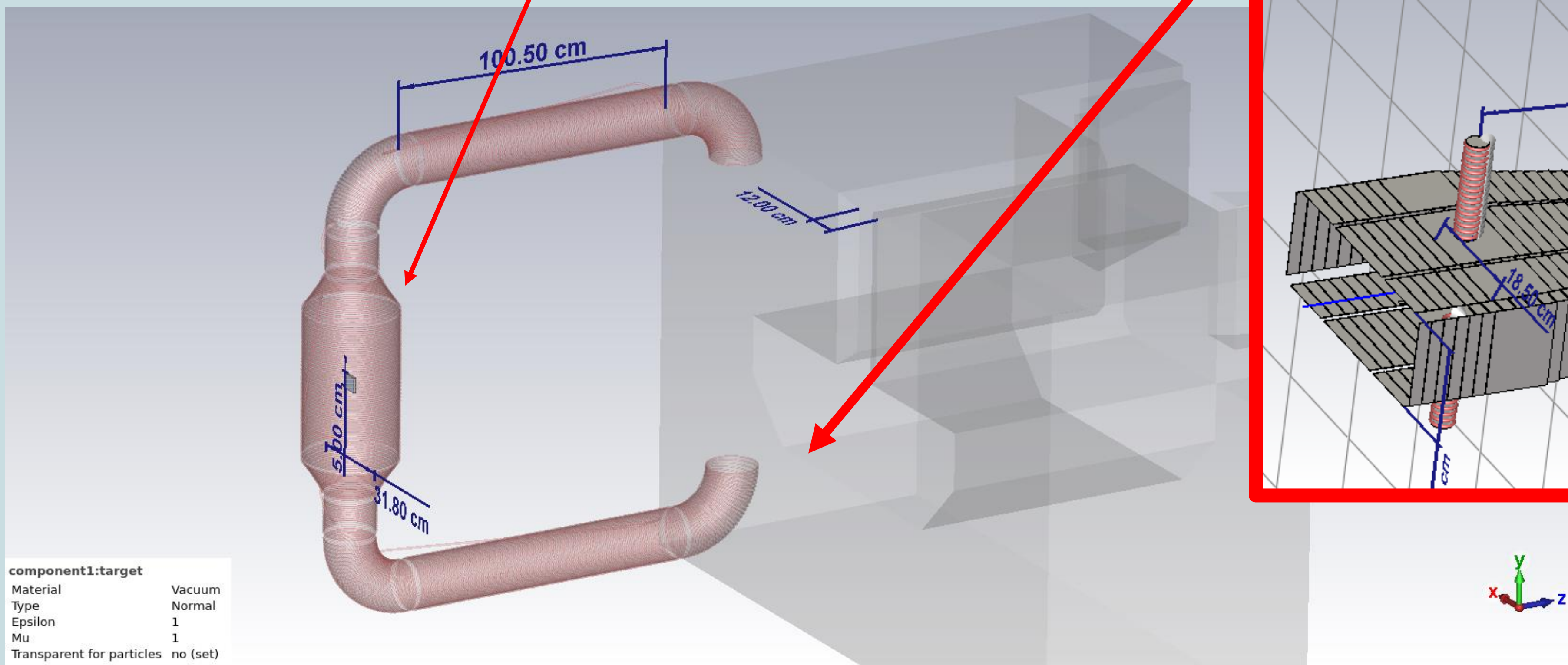


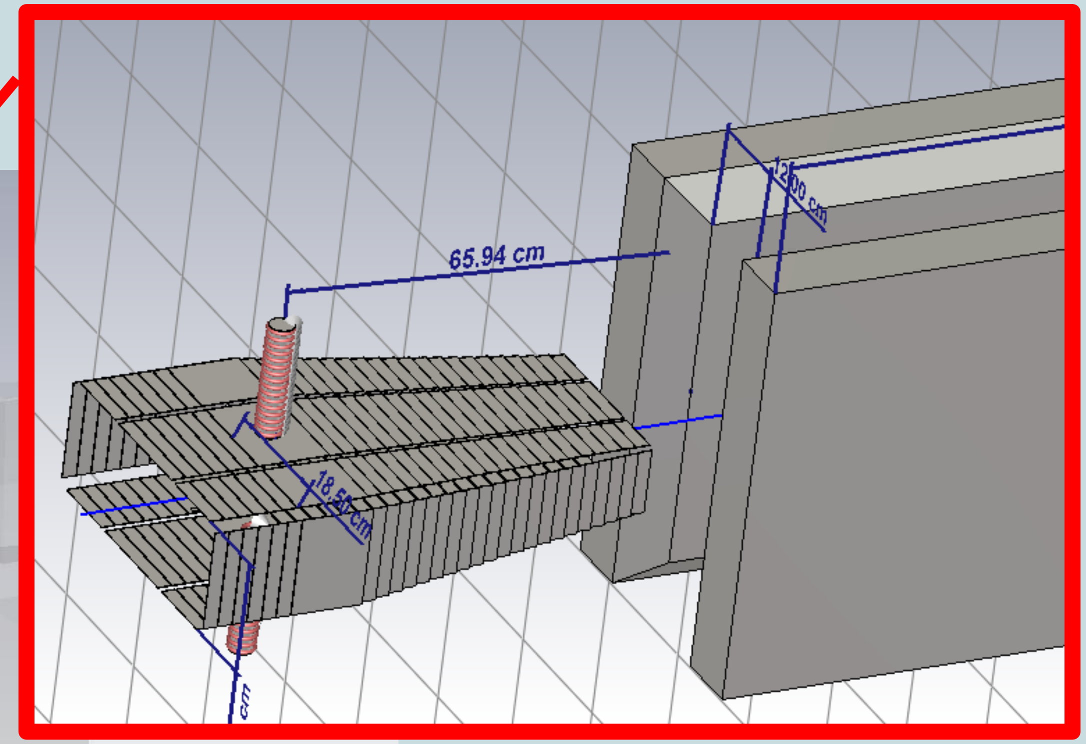
Microcalorimeter

More than a single geometry under study

easy to accommodate micrograms

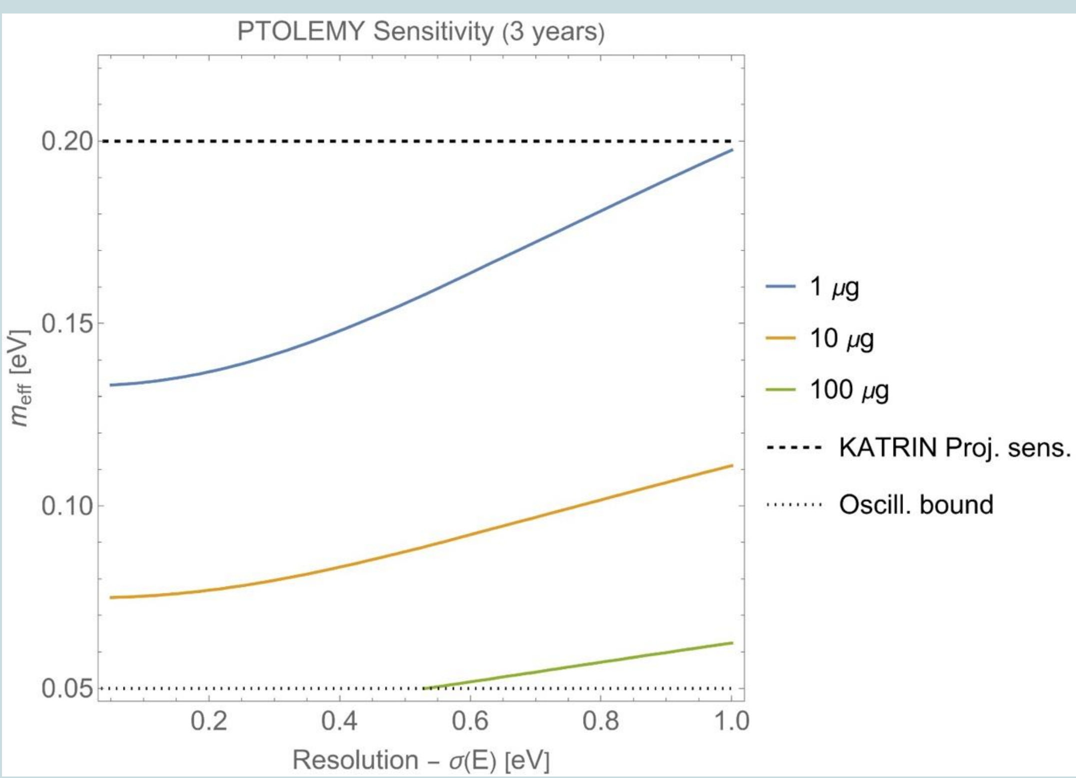
Graphene tails in a solenoid



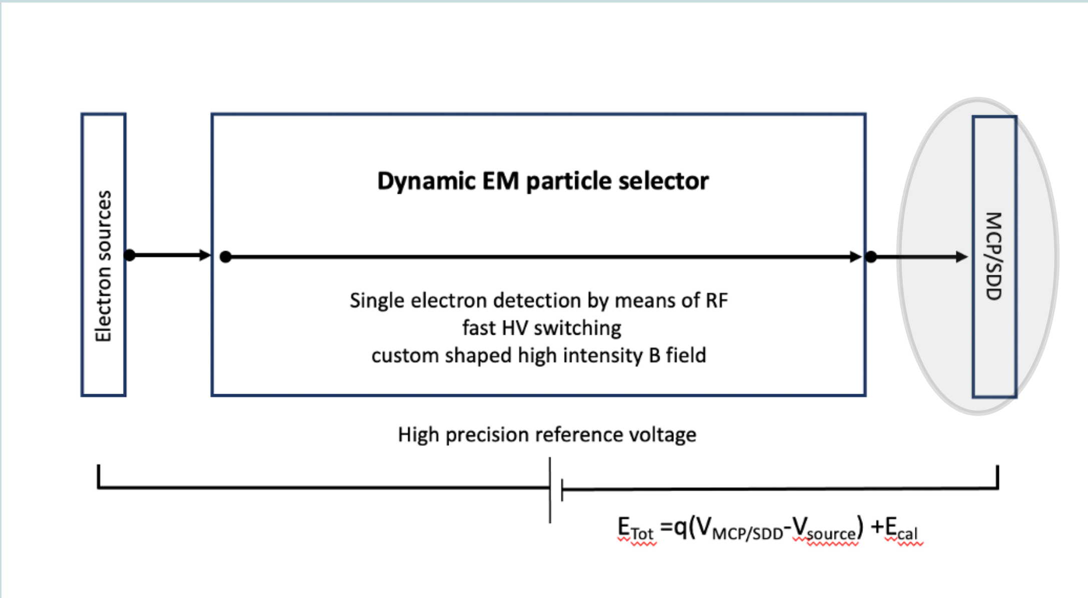


Preliminary estimation of sensitivity curves

Only energy resolution included



CALORIMETER



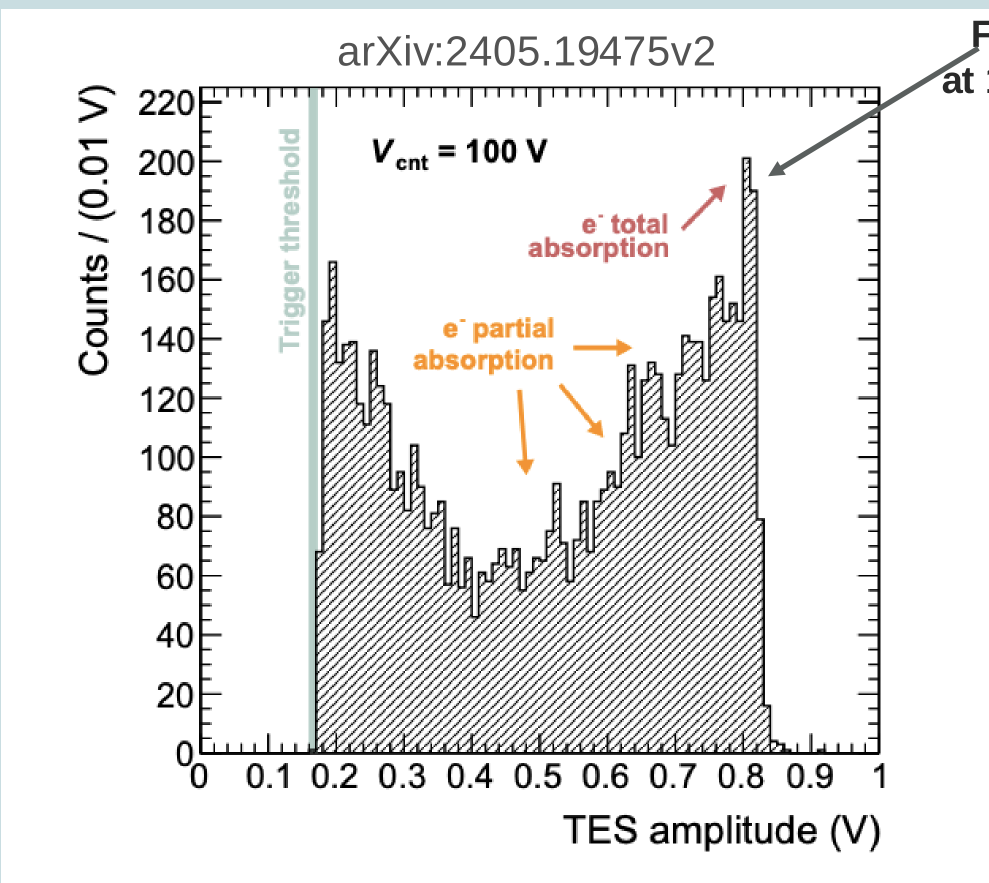
Now: 0.11 eV @ 0.8 eV and 106 mK and 10x10 μm^2
TiAuTi 90nm [Ti(45nm) Au(45nm)] (τ ~137 ns)

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

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

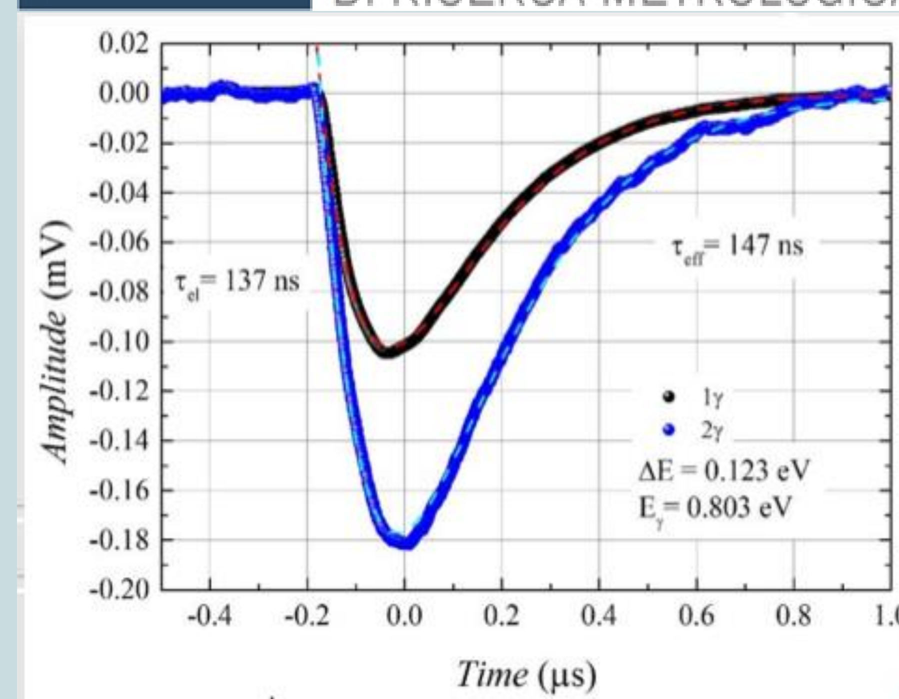
ΔE_{FWHM} = 0.022 eV @ 0.8 eV

Based on the expertise of the INRiM an important results have been achieved on electron measurement with TES. Key elements of the measurements: performing TES and new e-source based on nanostructures



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

INRiM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA



The PTOLEMY Collaboration
Institution Board recently constituted

CONCLUSION

- PTOLEMY aims at eventually detect cosmic neutrino background on a long term time scale
- The detector prototype will be ready at LNGS by the next year
- Prototype baseline option is: T embedded on graphene; New concept EM filter; electron energy resolution measured in several steps (MCP/SDD). Ultimately operating TES with sub-eV energy resolution.
- Ultimate goals of the Demonstrator: instrumented mass ~ hundreds of μg, energy resolution 50-100 meV, T storage solution will come from optimization of atomic T support structure. Time scale 5 years.
- “Intermediate” physics results of the Demonstrator: neutrino mass measurements (or limit) at level or better than present limtis.