The PTOLEMY experiment, a path from a dream to a challenging project

Dipartimento di Fisica
Sapienza Università di Roma

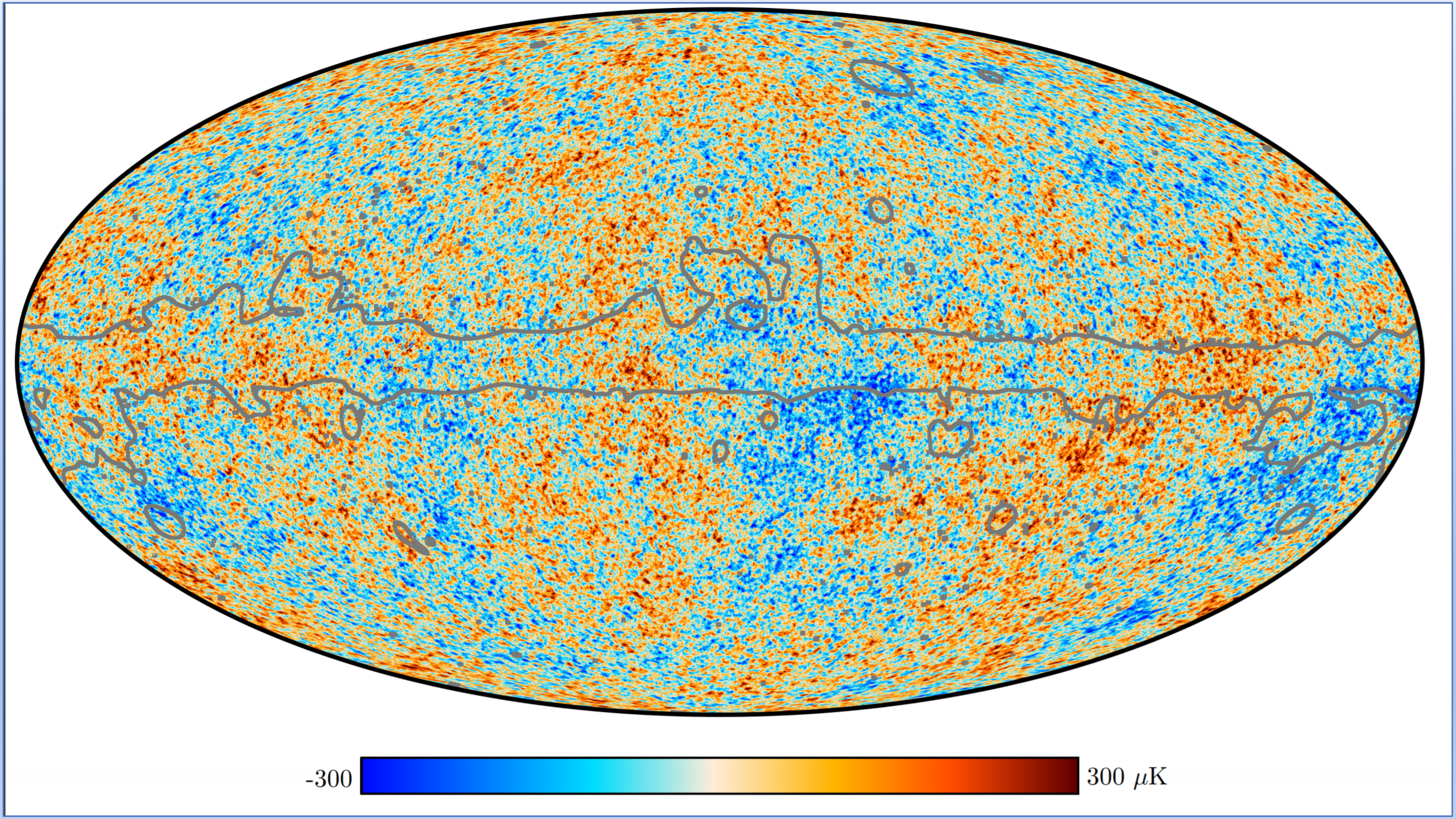
Amaldi Research Center

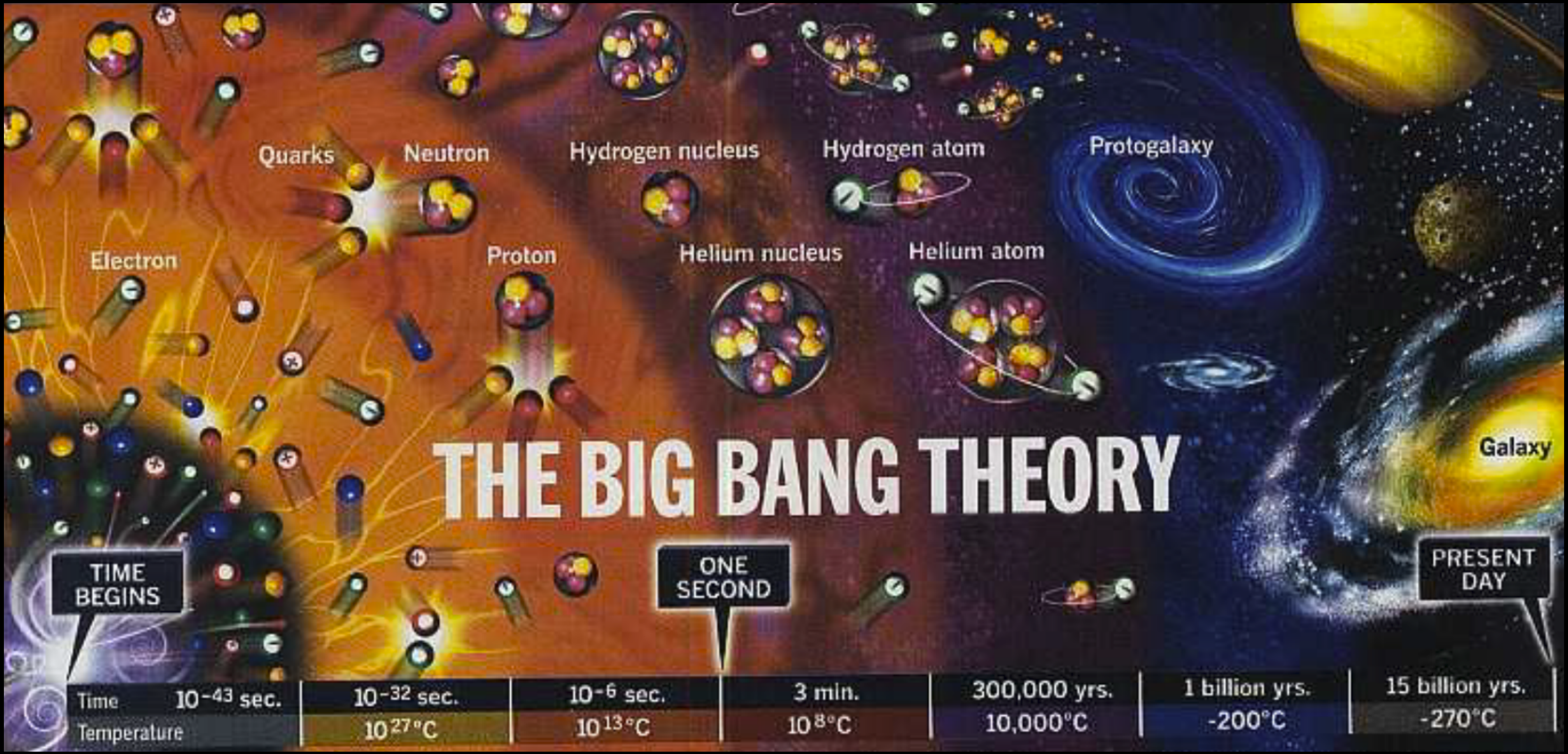
and

INFN Laboratorio Nazionale del Gran Sasso

Marcello Messina, WIN2019 Conference, Bari Italy, June 2nd to 8th

Who told the history of the Universe so far?





CNB ~ 1 sec

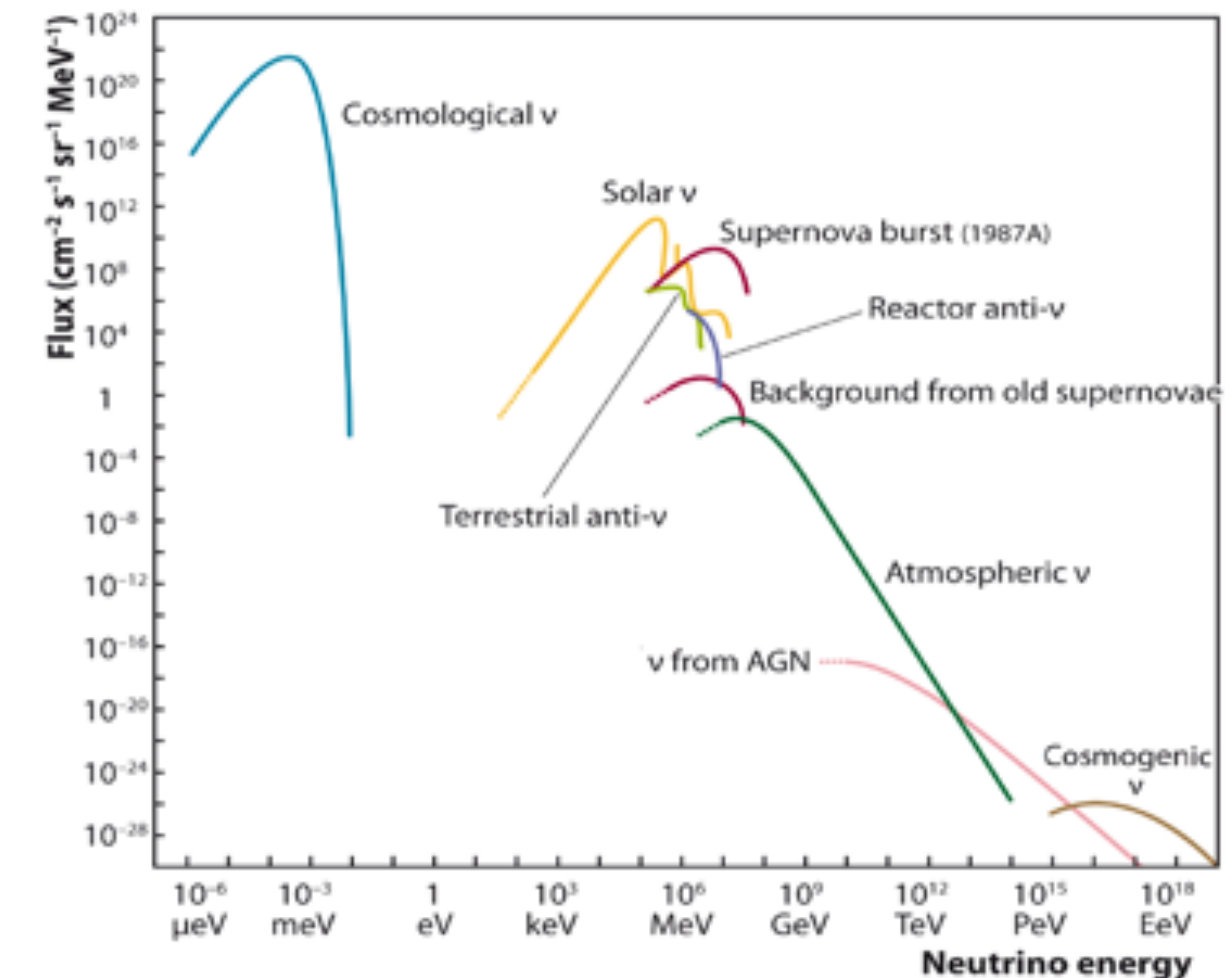
CMB ~ 380k yr

Neutrino flow

$T \approx 1.9\ K \Longrightarrow p_\nu \approx 0.001\ eV$

$n \approx 56\ cm^{-3} \times 6$

see S. Gariazzo talk's from Tuesday's afternoon astrophysics-session for more details



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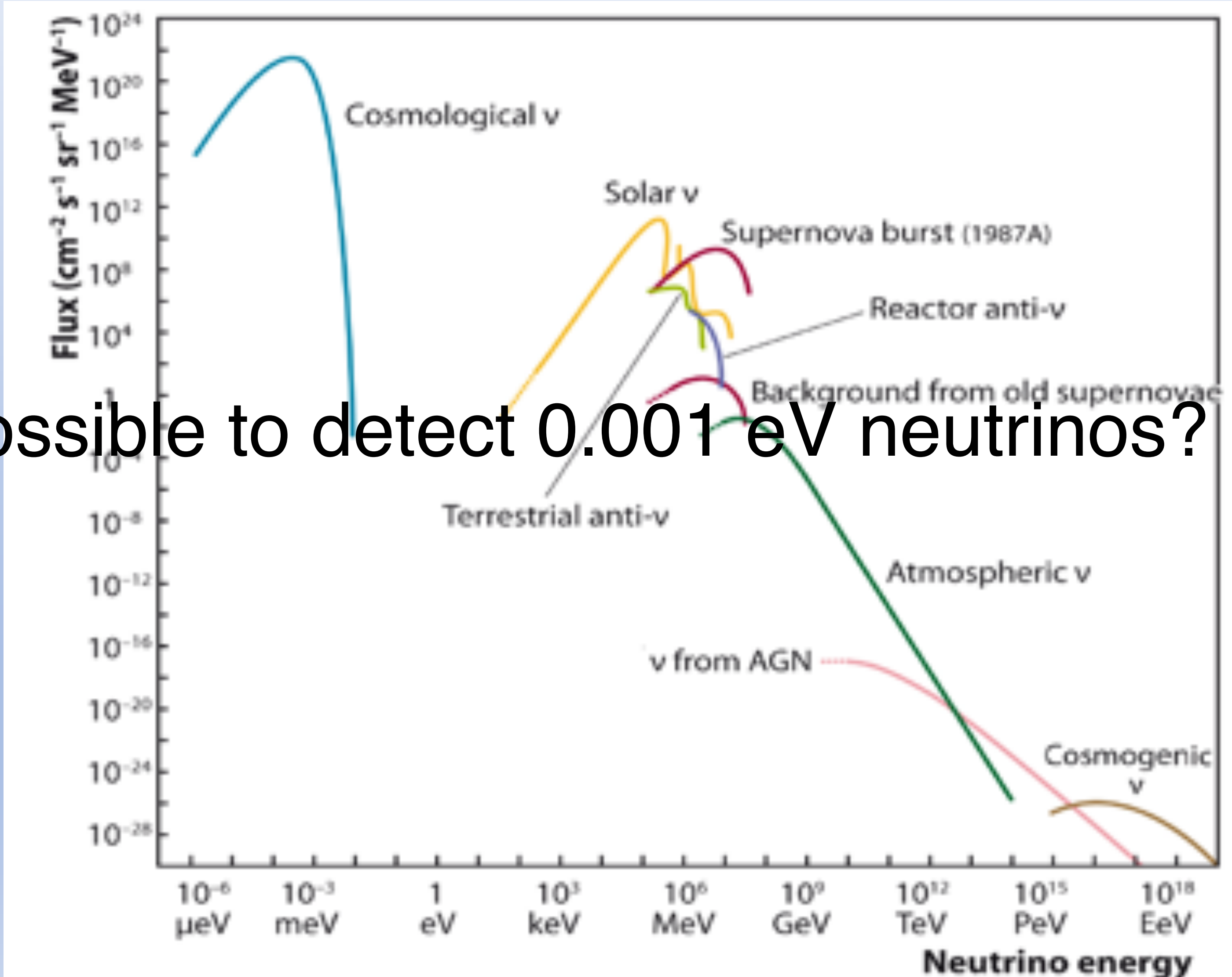
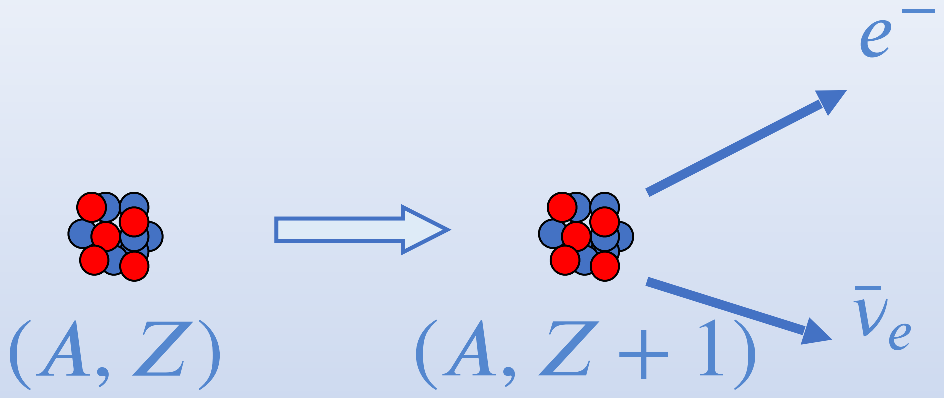
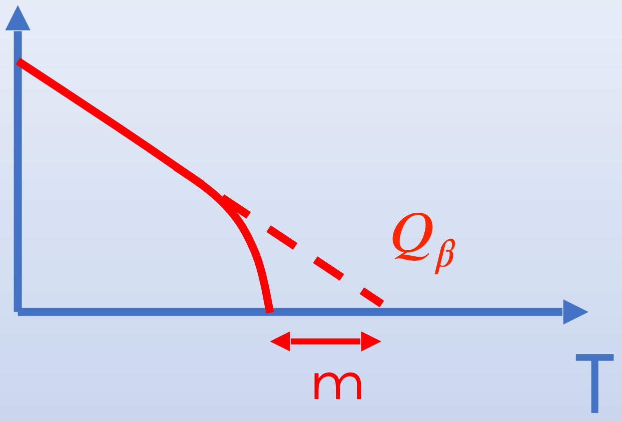
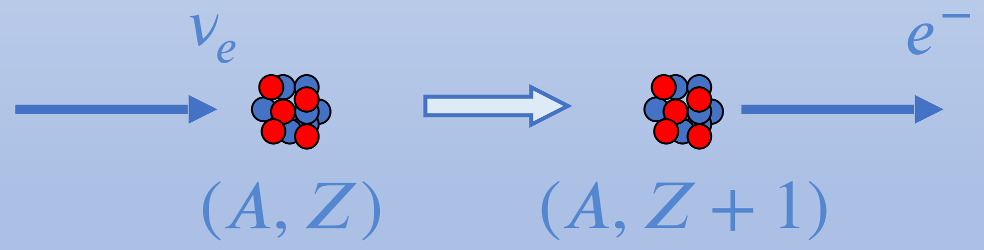
Is it possible to detect 0.001 eV neutrinos?

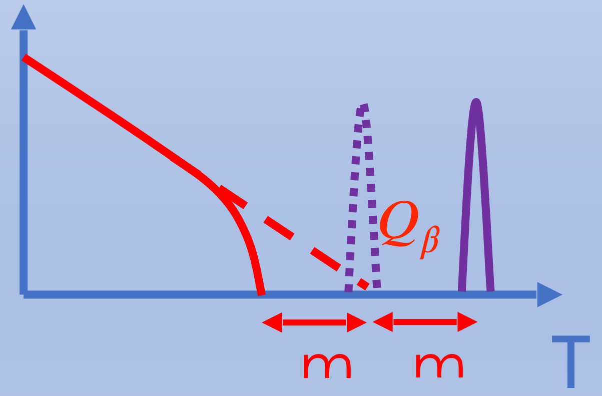


Detection principle





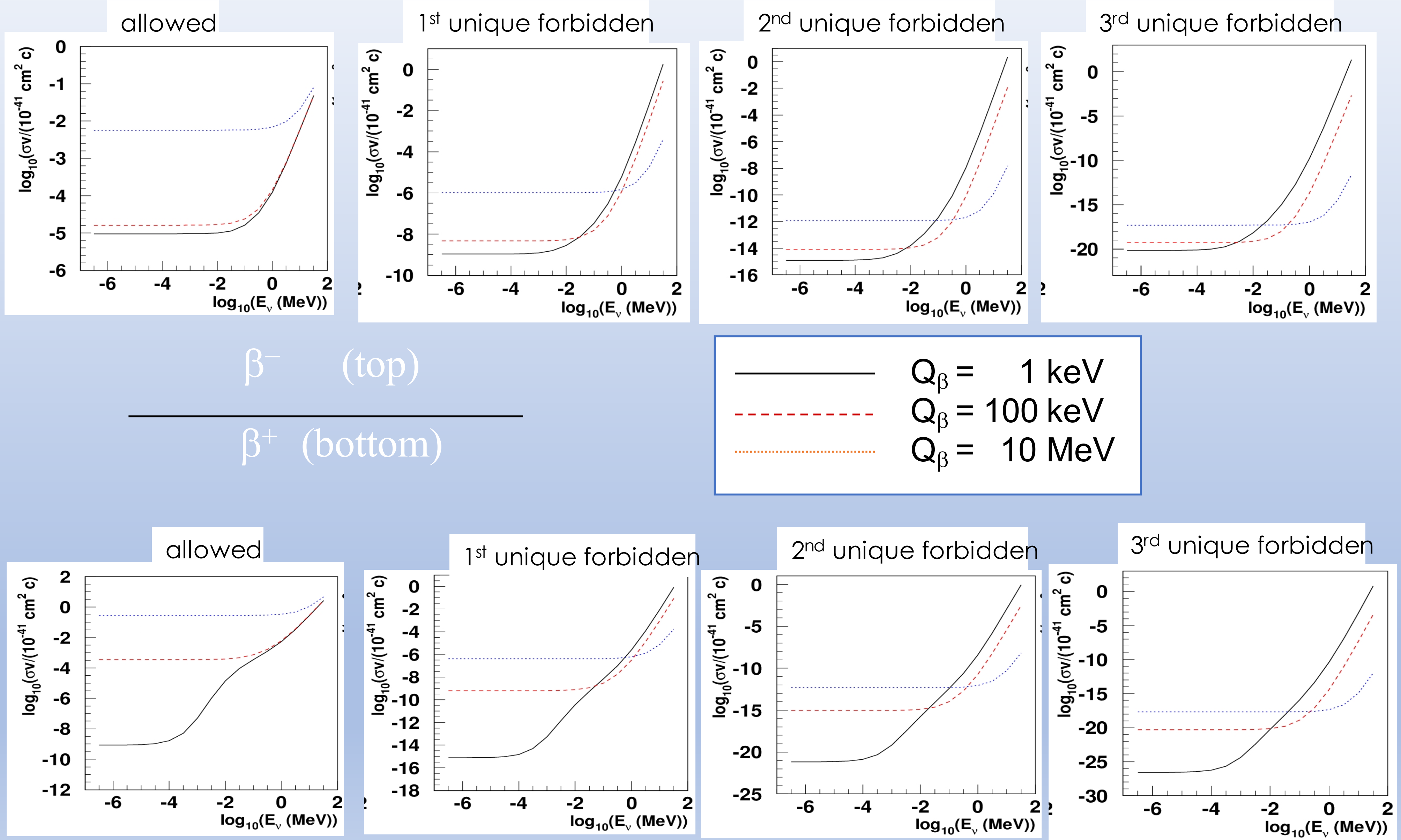




A.G.Cocco, G.Mangano and M.Messina JCAP 06(2007) 015

NCB Cross Section

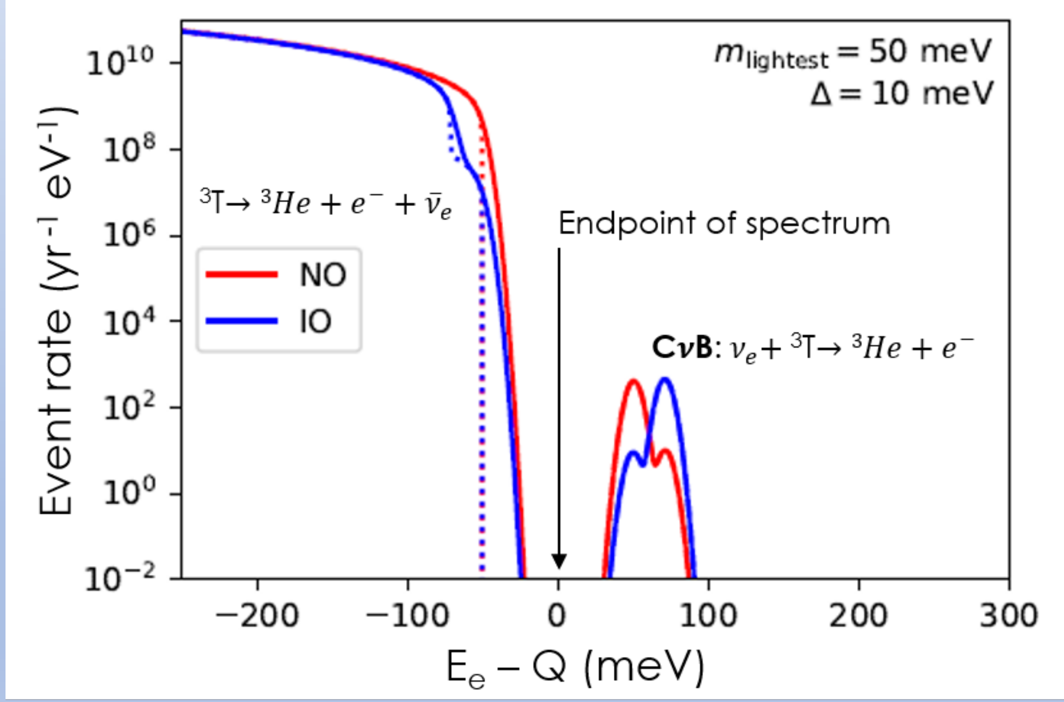
as a function of E_ν, Q_β for different nuclear spin transitions



Why Tritium target?

- High cross-section for neutrino capture
- Sizeable lifetime
- Low Q-value
- **Tritium beta decay ~10^{15} Bq/gram**

PTOLEMY collaboration e-Print: arXiv:1902.05508, submitted to JCAP



See S. Gariazzo talk's from Tuesday's afternoon astrophysics-session for more details

PTOLEMY experiment

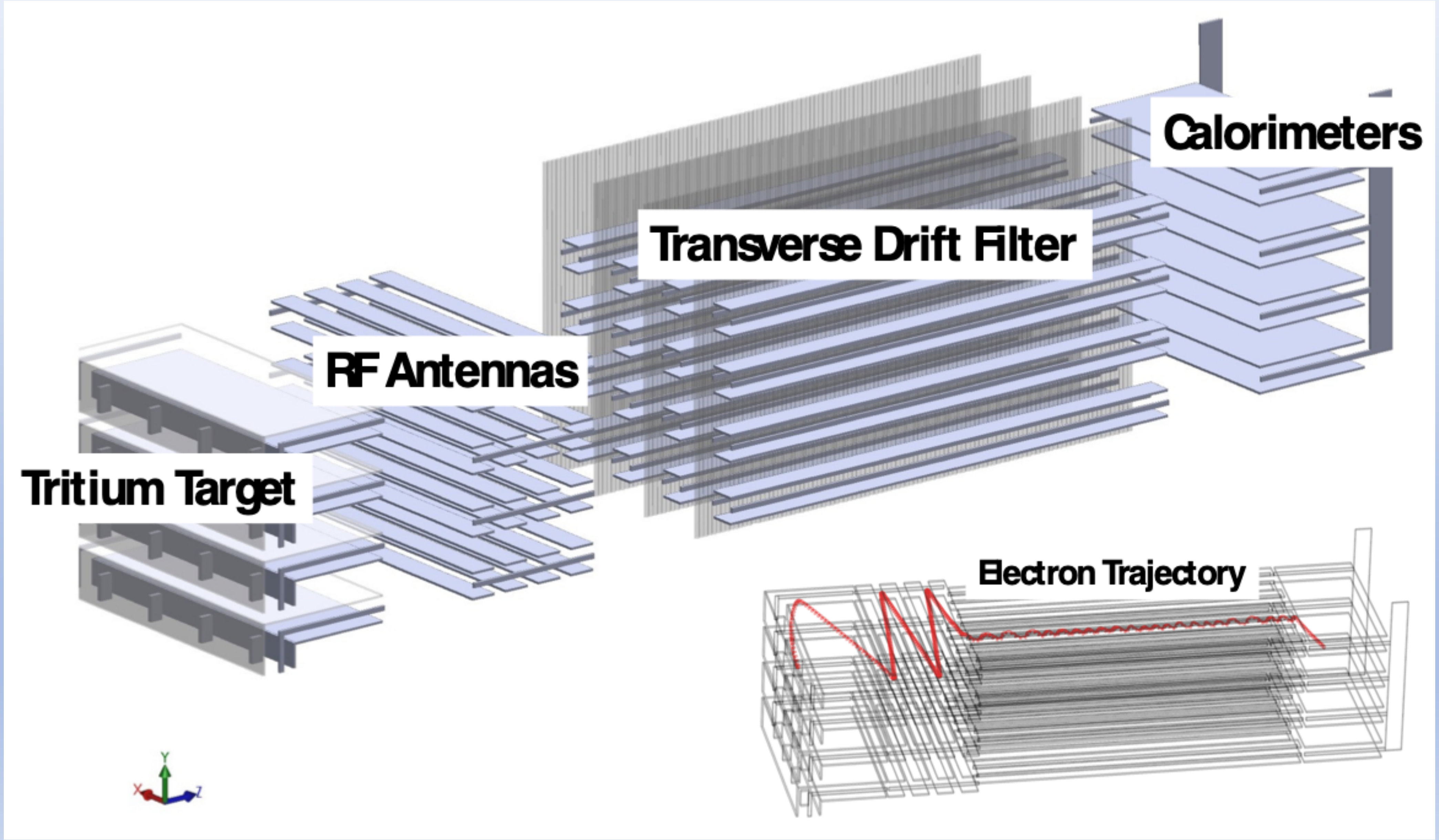
- Goal:

  1. Find evidence for CvB
  2. Accurate measurement of neutrino mass
  3. Light DM detection (not discussed in this talk)

- Key challenges:

  1. Extreme energy resolution is required
  2. Extreme background rates from the target

PTOLEMY: experiment layout



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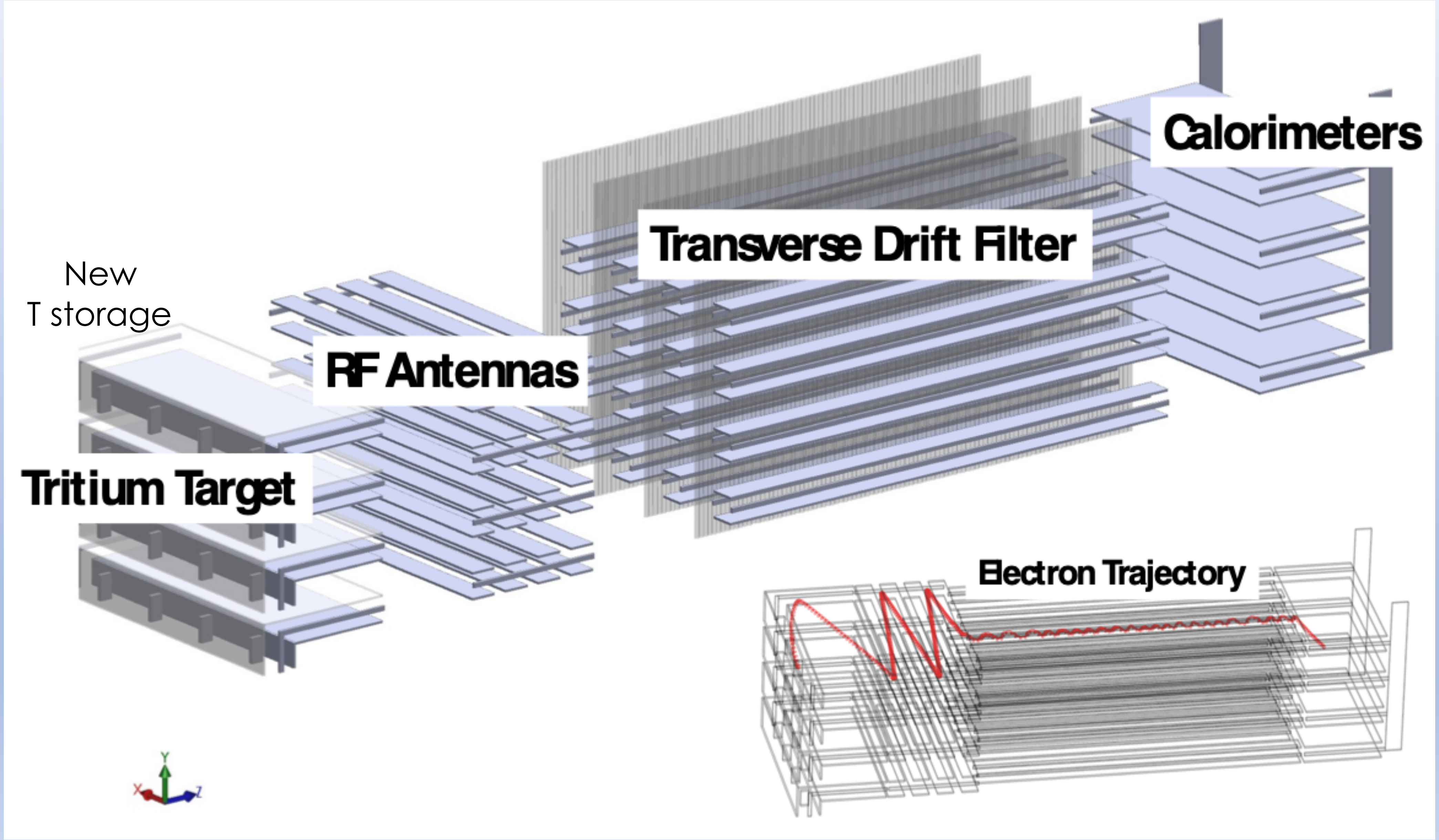

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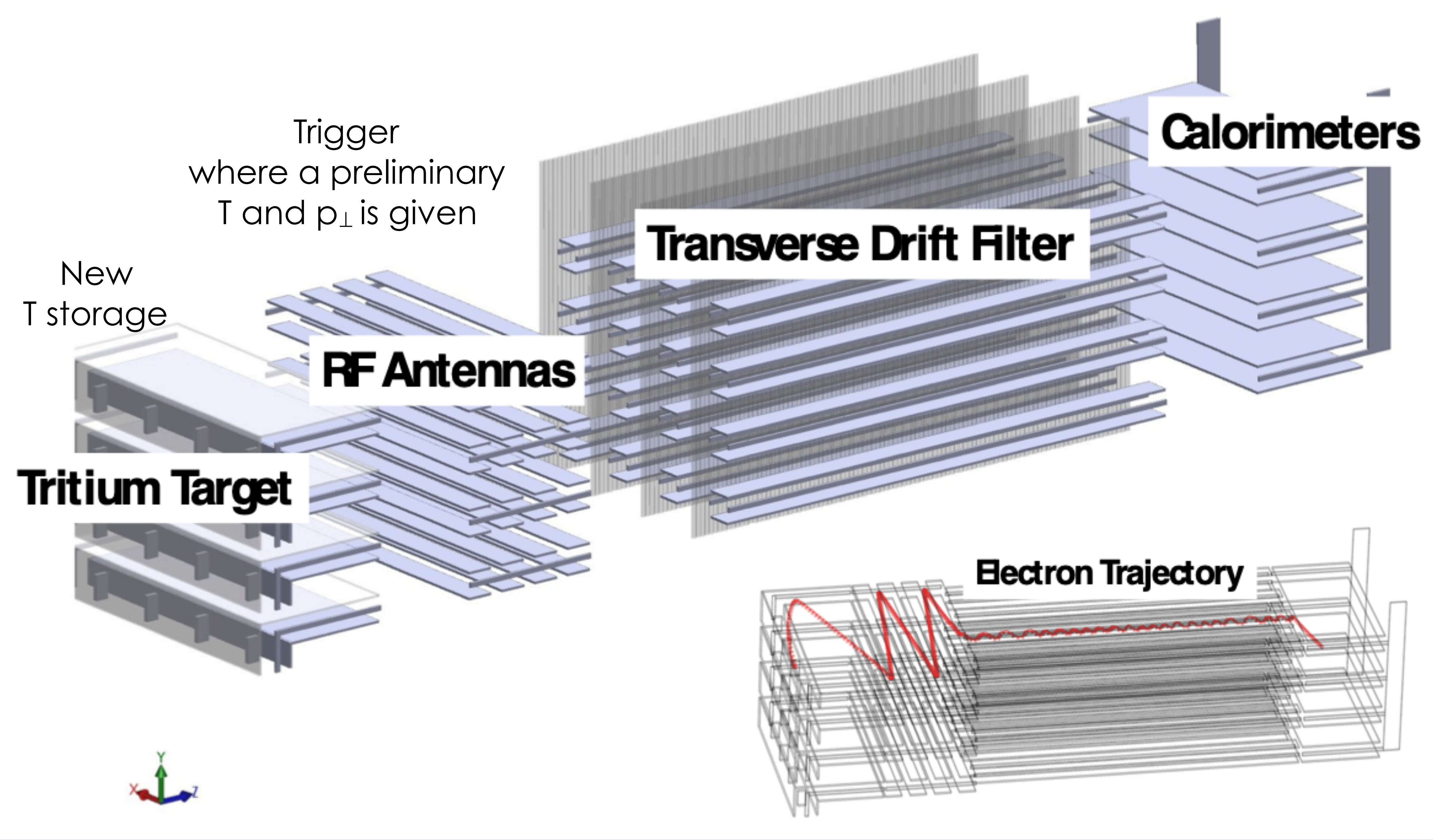

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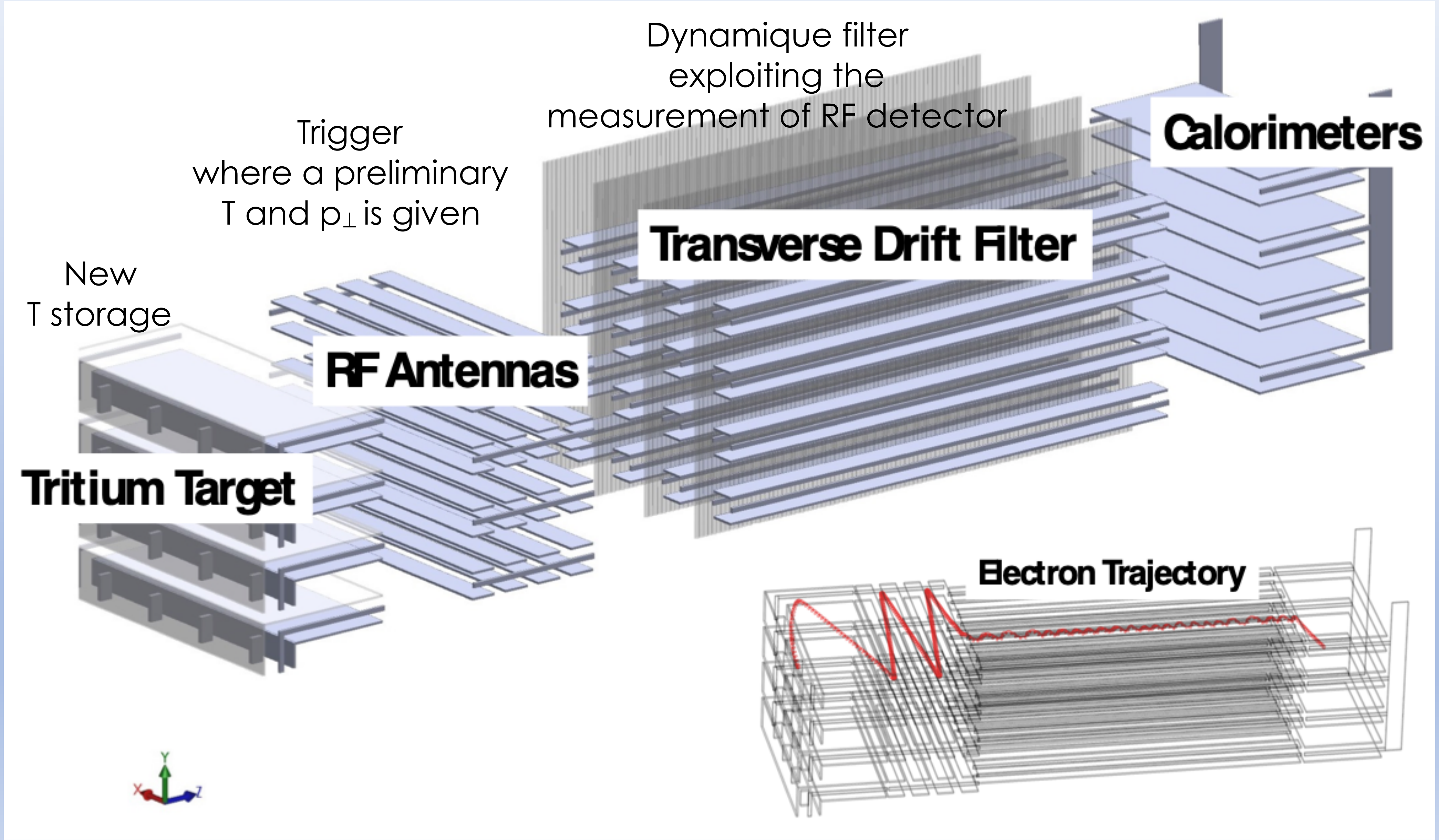

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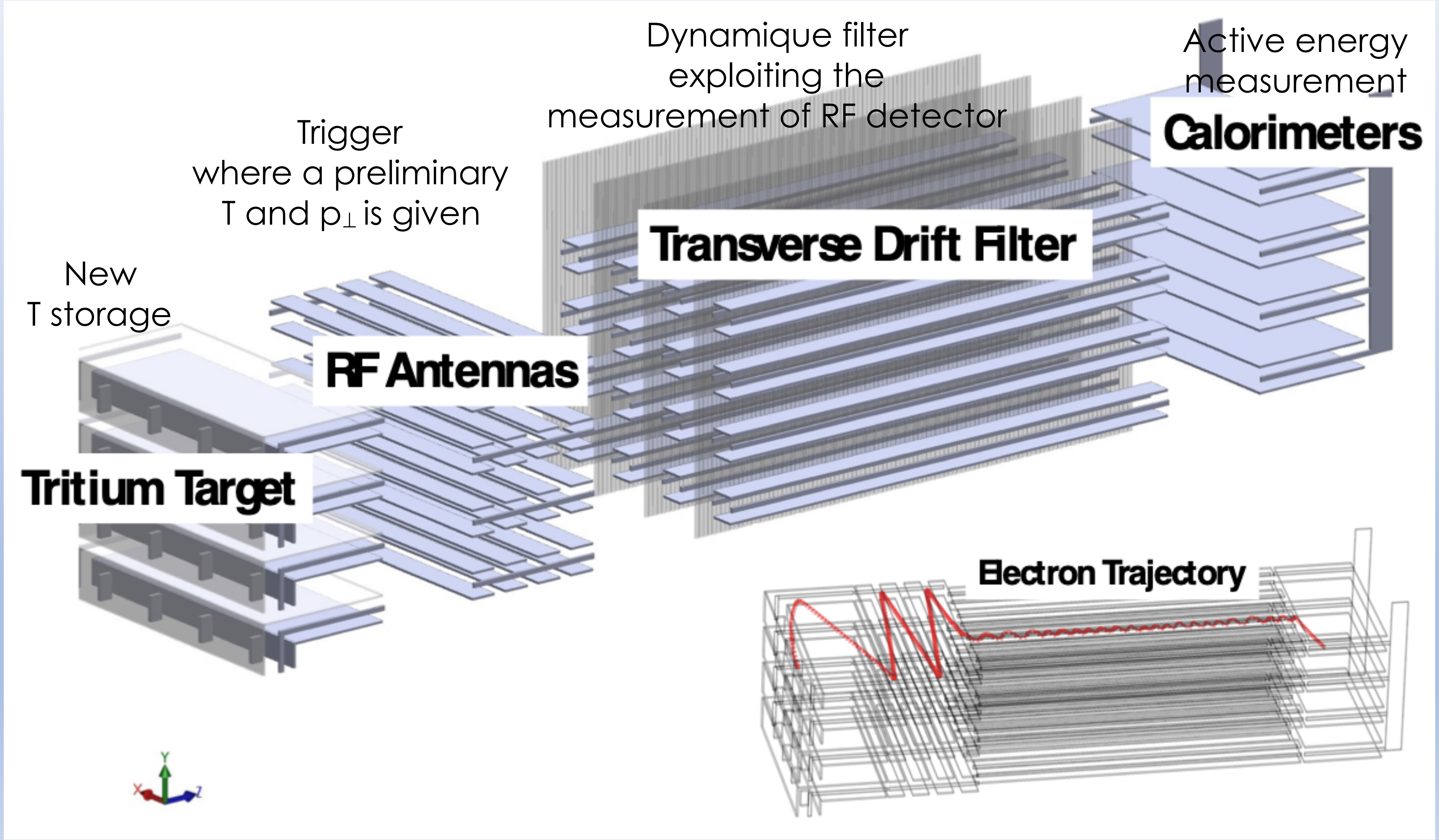
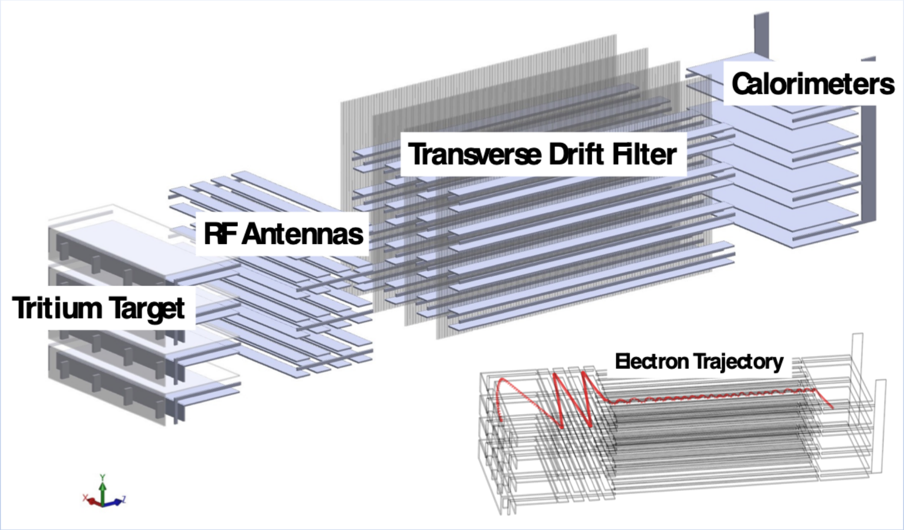


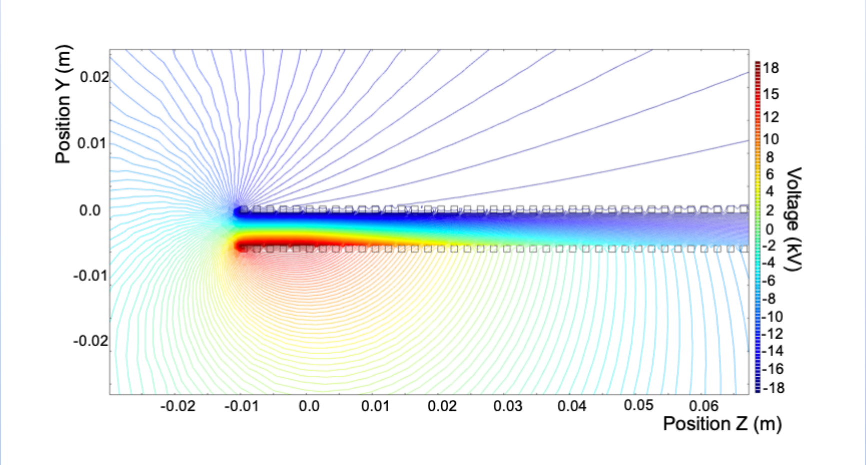
PTOLEMY: measurement principle

M. G.Betti et al., Progress in Particle and Nuclear Physics, **106** (2019),120-131



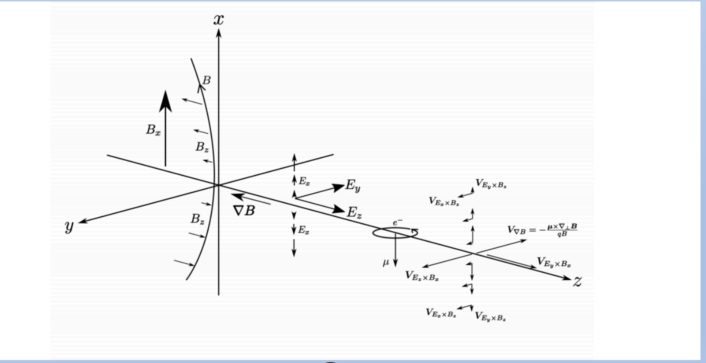
Step 3

Transverse kinetic energy is removed.
Field properly set on ms time scale.
"Wrong particle will end up on one of the electrodes and the right one will pass"



Step 1

A new way of storing atomic T



$$\mathbf{V}_D = \mathbf{V}_\perp = \left(qE + F - \mu\nabla B - m\frac{d\mathbf{V}}{dt}\right) \times \frac{\mathbf{B}}{qB^2}$$

$$\frac{dT_\perp}{dt} = -qE \cdot V_D = -qE\,(qE - \mu\nabla(B)) \times \frac{B}{qB^2} \quad \mu = \frac{mv_\perp^{*2}}{2B}$$

Step 2

Electron RF emission is detected
Trigger good particles and give a preliminary evaluation of E and P_T

$$2\pi f_c = \frac{qB}{m_e c^2} \cdot \frac{1}{\gamma}$$

$$P_{tot} = \frac{1}{4\pi\epsilon_0} \frac{8\pi^2 q^2 f_c^2}{3c} \frac{\beta_\perp^2}{1-\beta^2}$$

Between Step 3-4

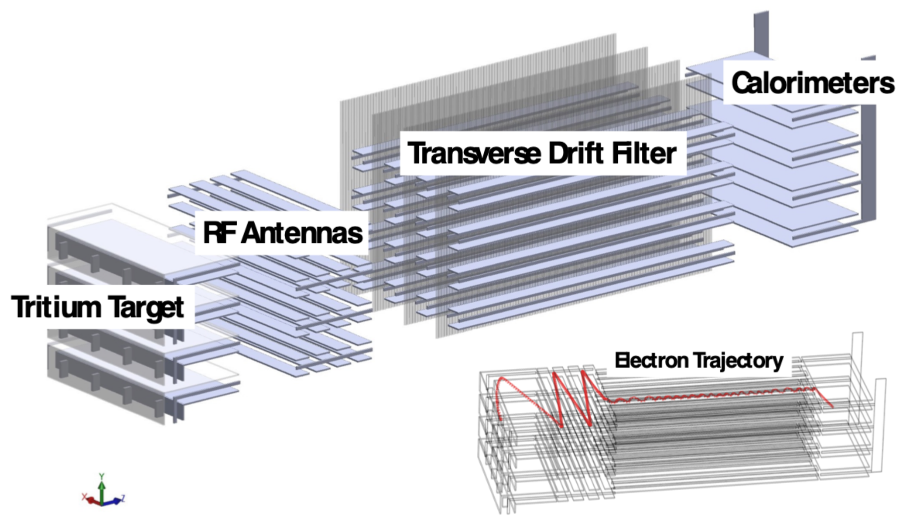
Electrostatic barrier will reduce T_L

Step 4

The particle is driven into the TES: $T_{tot}=q(V_{anode} - V_{source}) + E_{cal}$

PTOLEMY: measurement principle

M. G.Betti et al., Progress in Particle and Nuclear Physics, **106 (**2019),120-131



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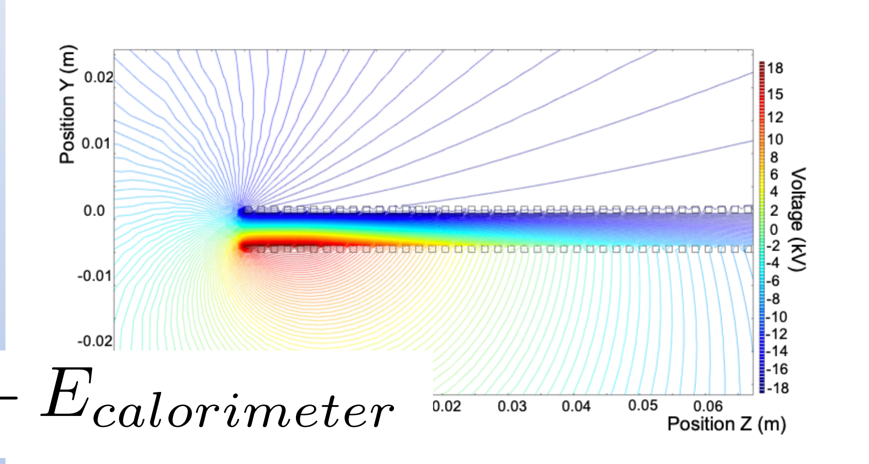

$$E_{electron} = q \cdot (V_{anode} - V_{source}) + E_{calorimeter}$$

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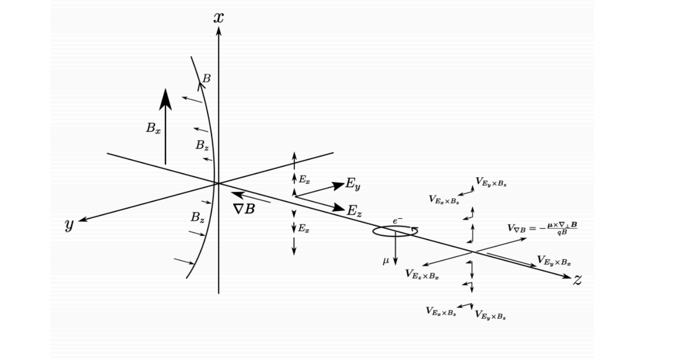

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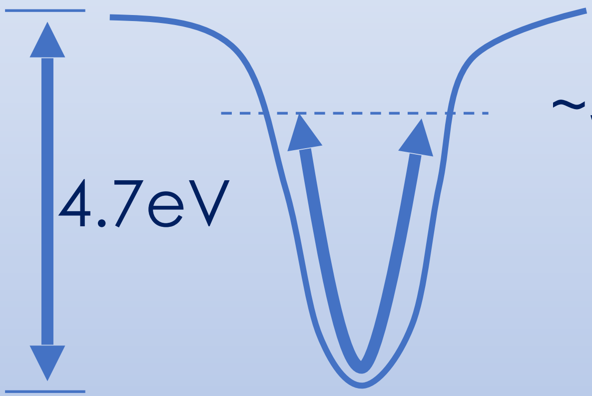
PTOLEMY: The source

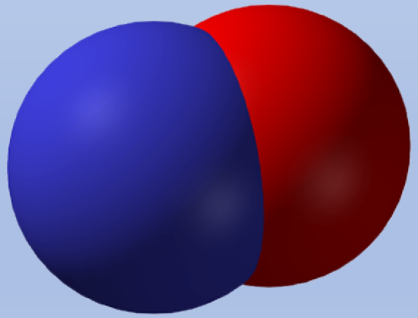
- Use **atomic T**
  - No vibrational modes in final state like for ^{3}He-^{3}T final state.
  - Limit to energy resolution not determined by target itself

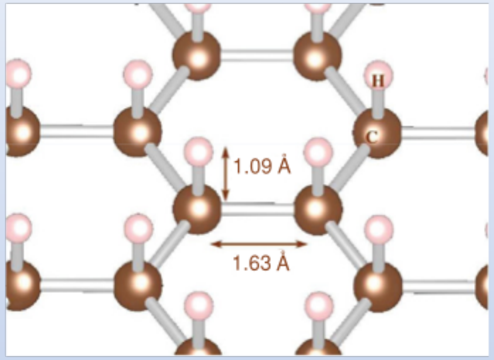
Molecular Broadening

T-T → $(T\text{-}He^3)^*$



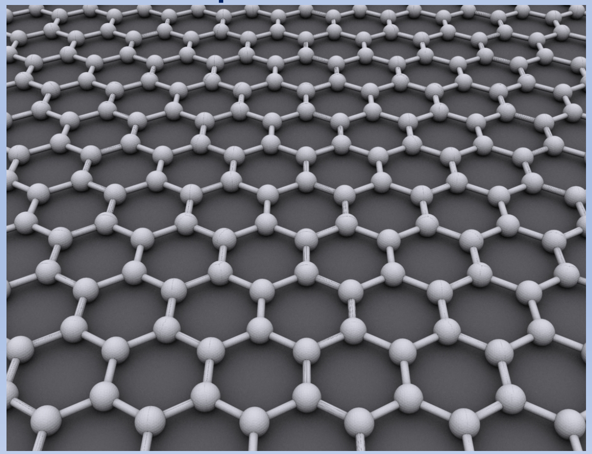
~3eV He^3 recoil at endpoint



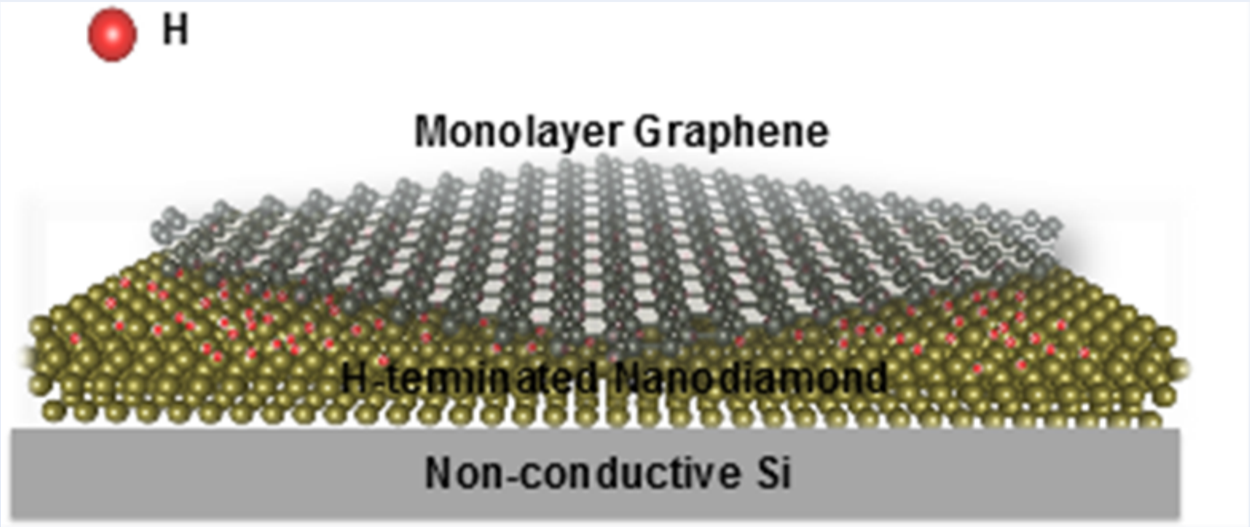


<3eV binding energy

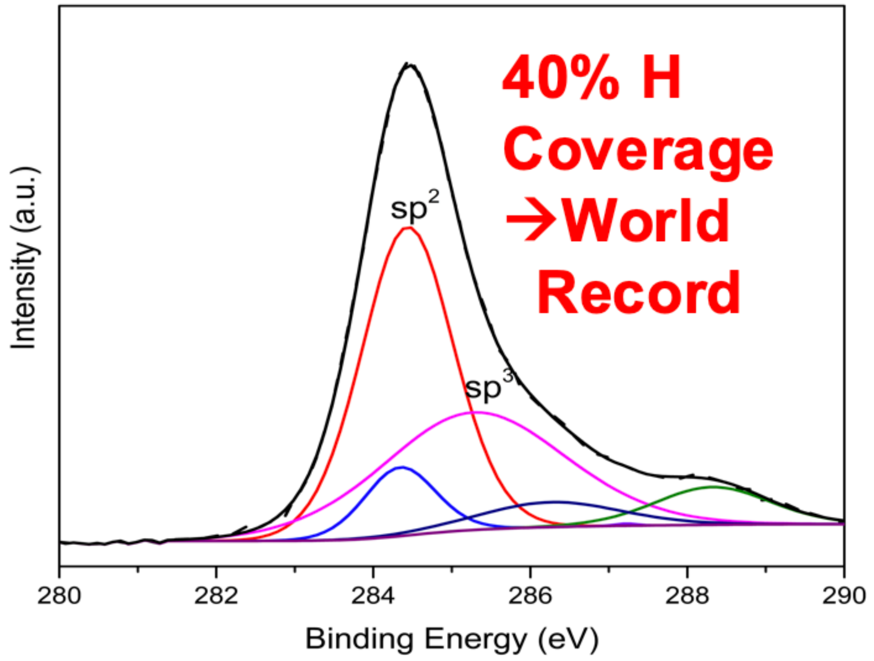
Graphene

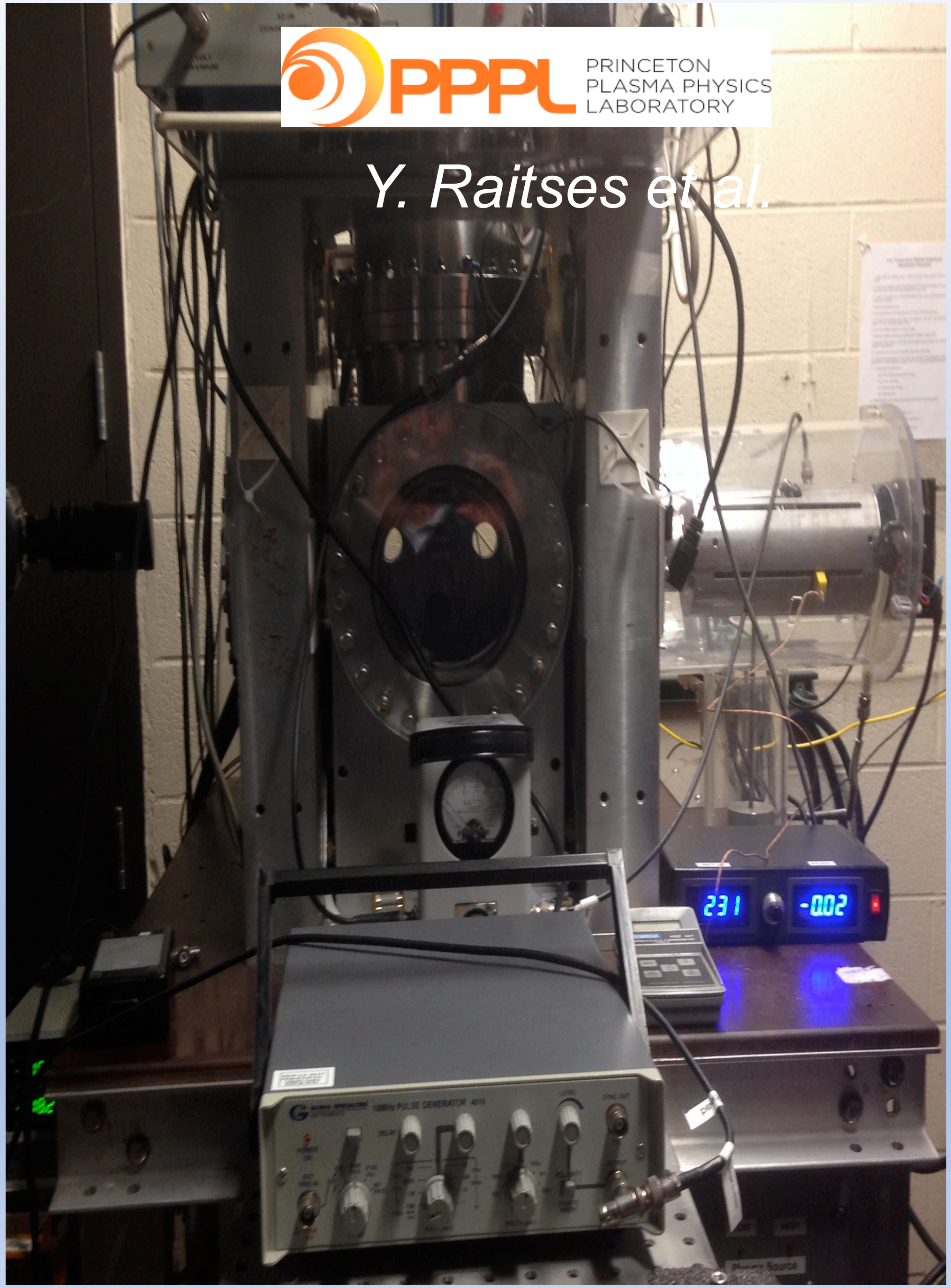


Cold Plasma Loading



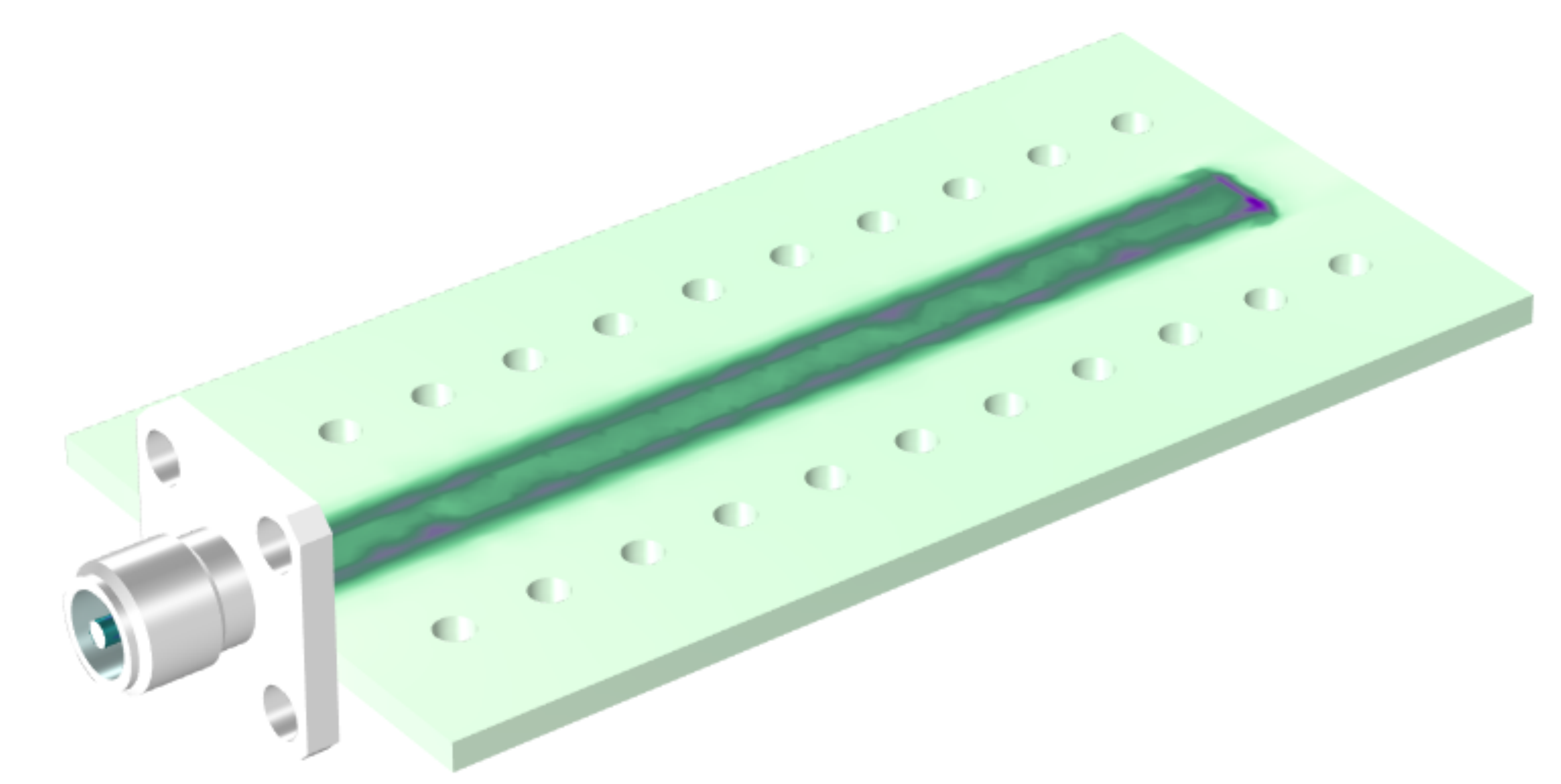
XPS Hydrogenation Results from Princeton





Investigation in the field of Co-Planar Waveguide started

The voltage signal propagating to a SMA connector is shown by arrow map.
Exercise form COMSOL library



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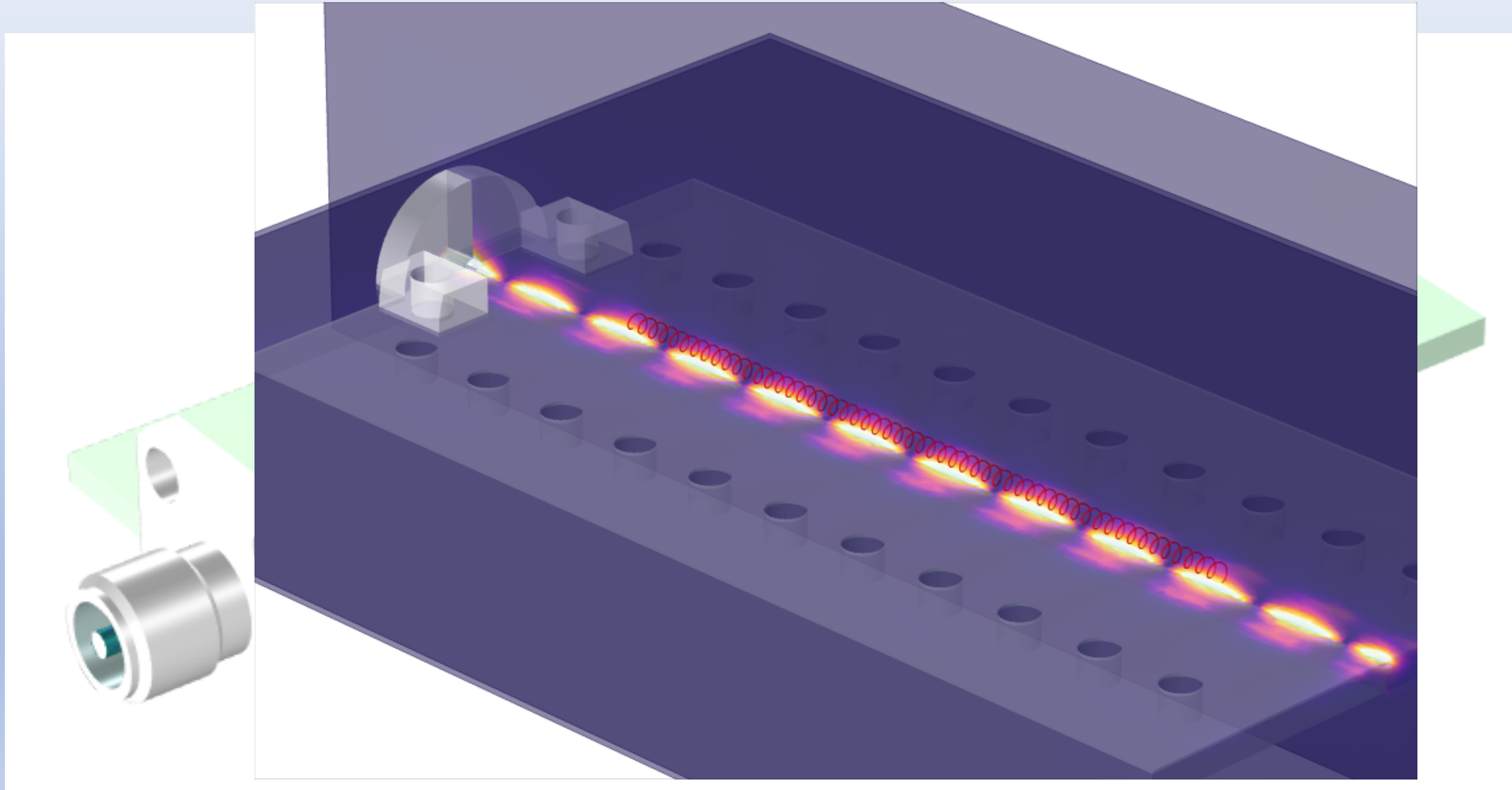

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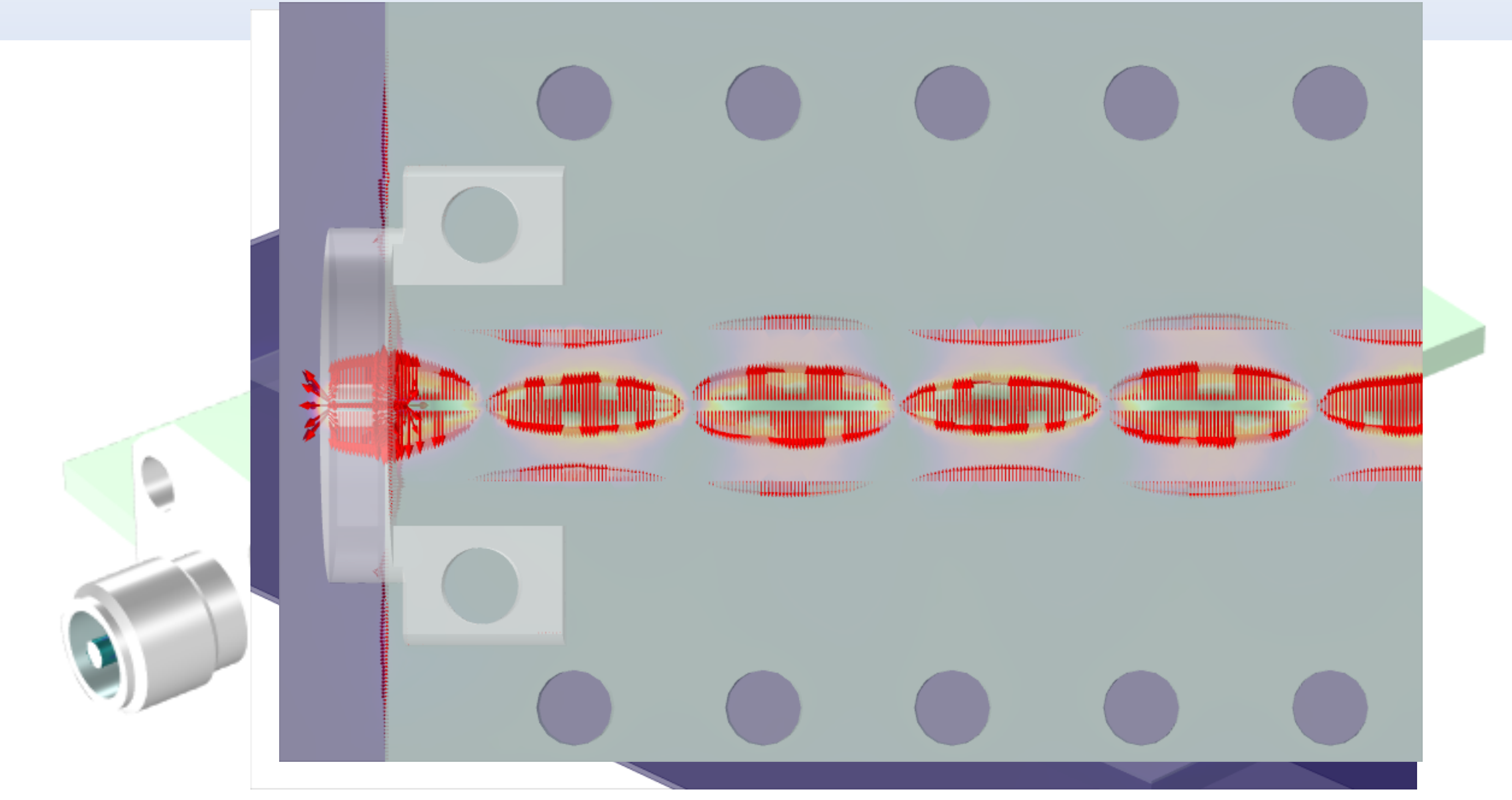
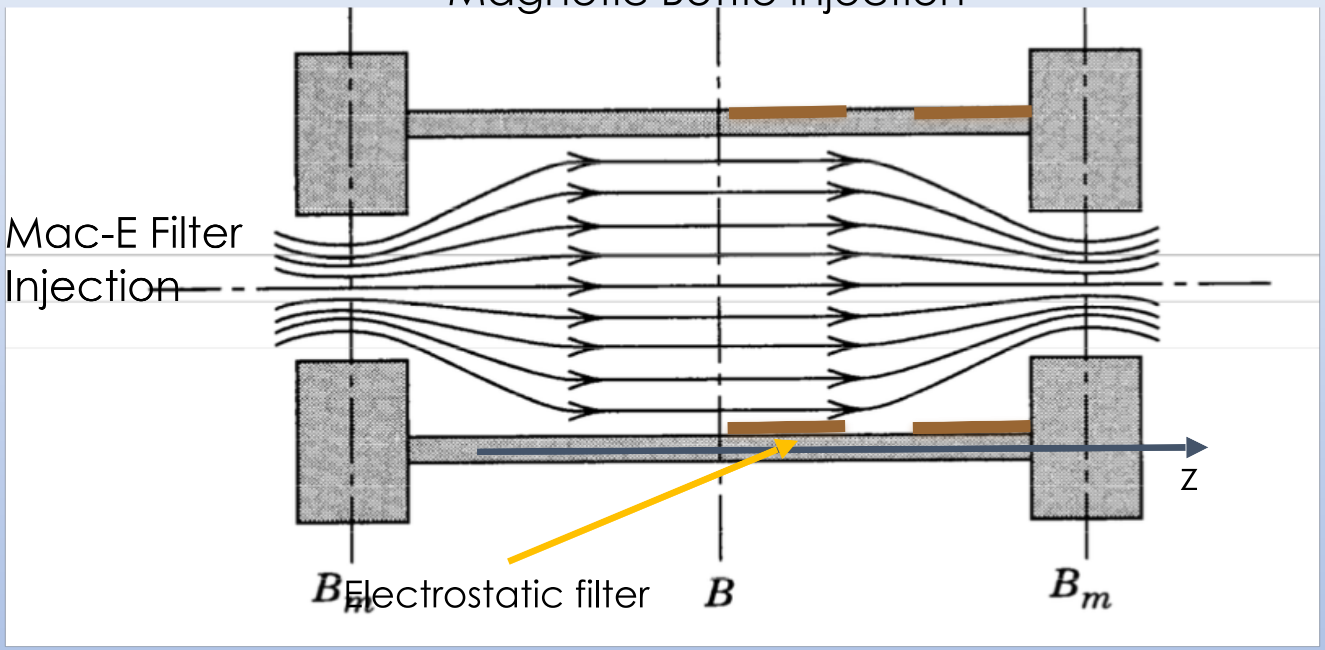


Mac-E filter

This device consist of a magnetic bottle where particles are injected from the edge plus an electrostatic filter.

Jackson Fig 12.6



$$J_i = \oint p_i dq_i \to J = \oint P_\perp dl = \frac{e}{c}(B\pi a^2)$$

$$v_{||}^2 = v_0^2 - v_{\perp 0}^2 \frac{B(z)}{B_0}$$

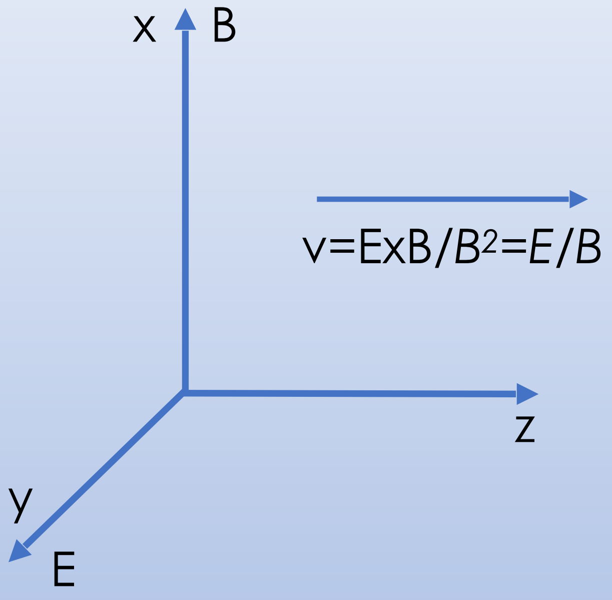
1 g of tritium gives 5.6 10^{14} Hz of decay rate that thanks to the attenuation factor

$$\left(\frac{\Delta E}{Q}\right)^3$$

is reduced to 700 Hz if $\Delta E \sim 2$ eV

New filter concept

E vector B filter (speed selector)



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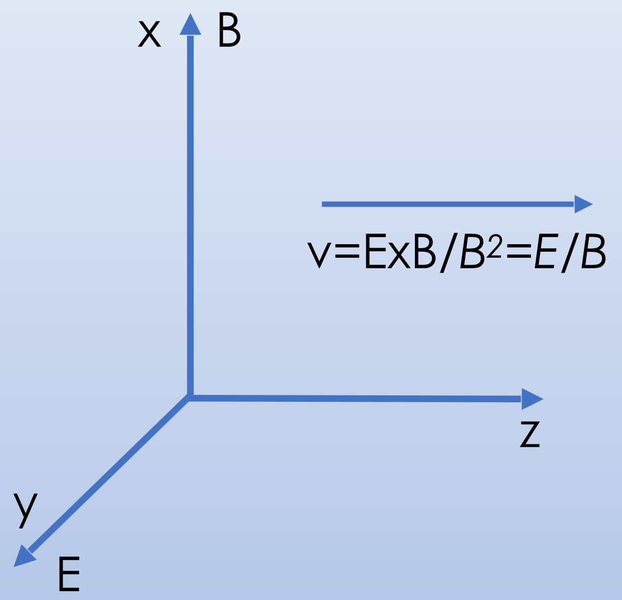

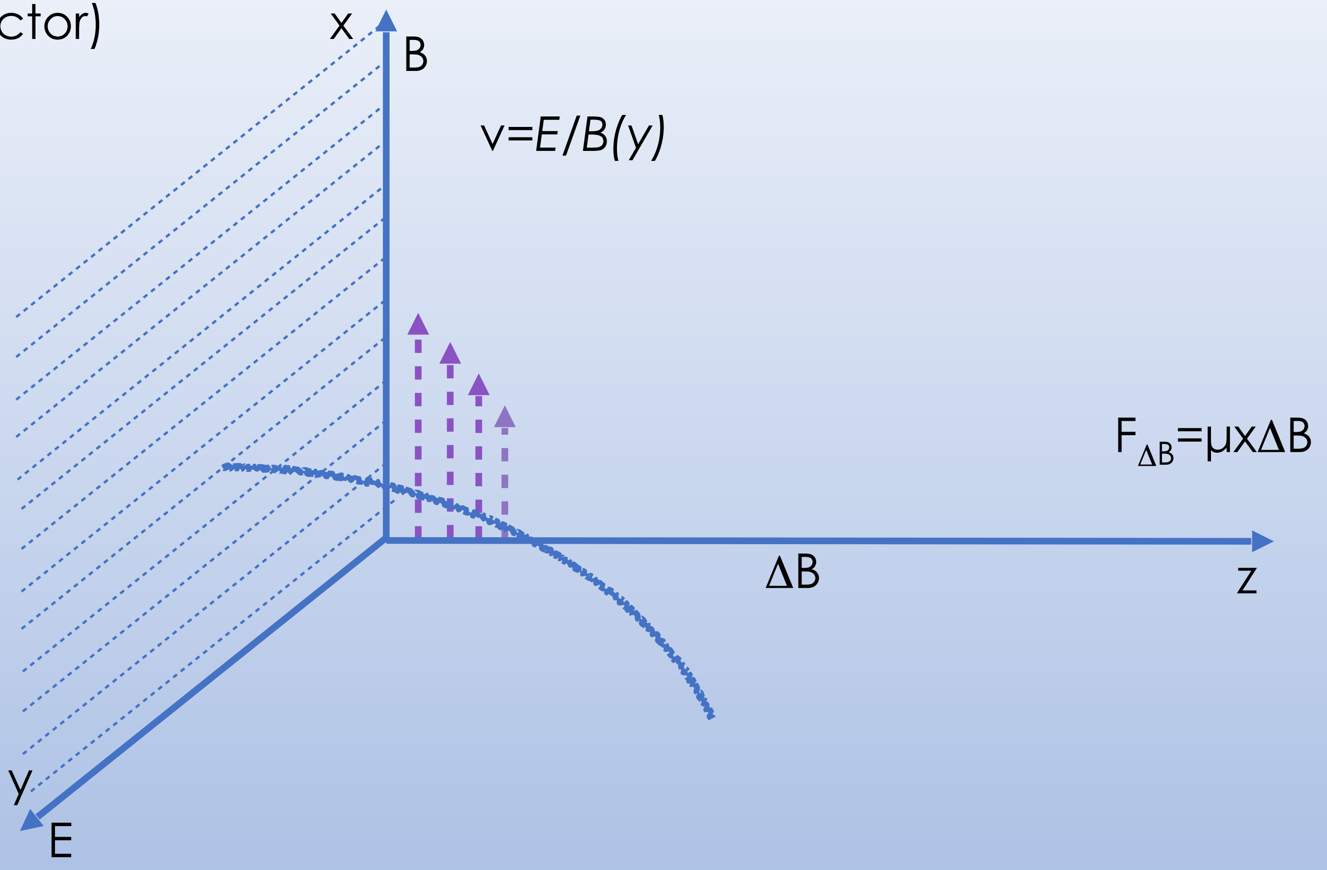

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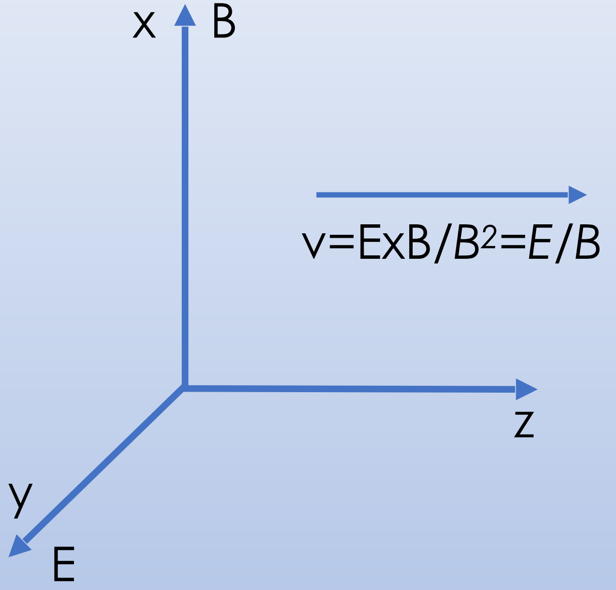

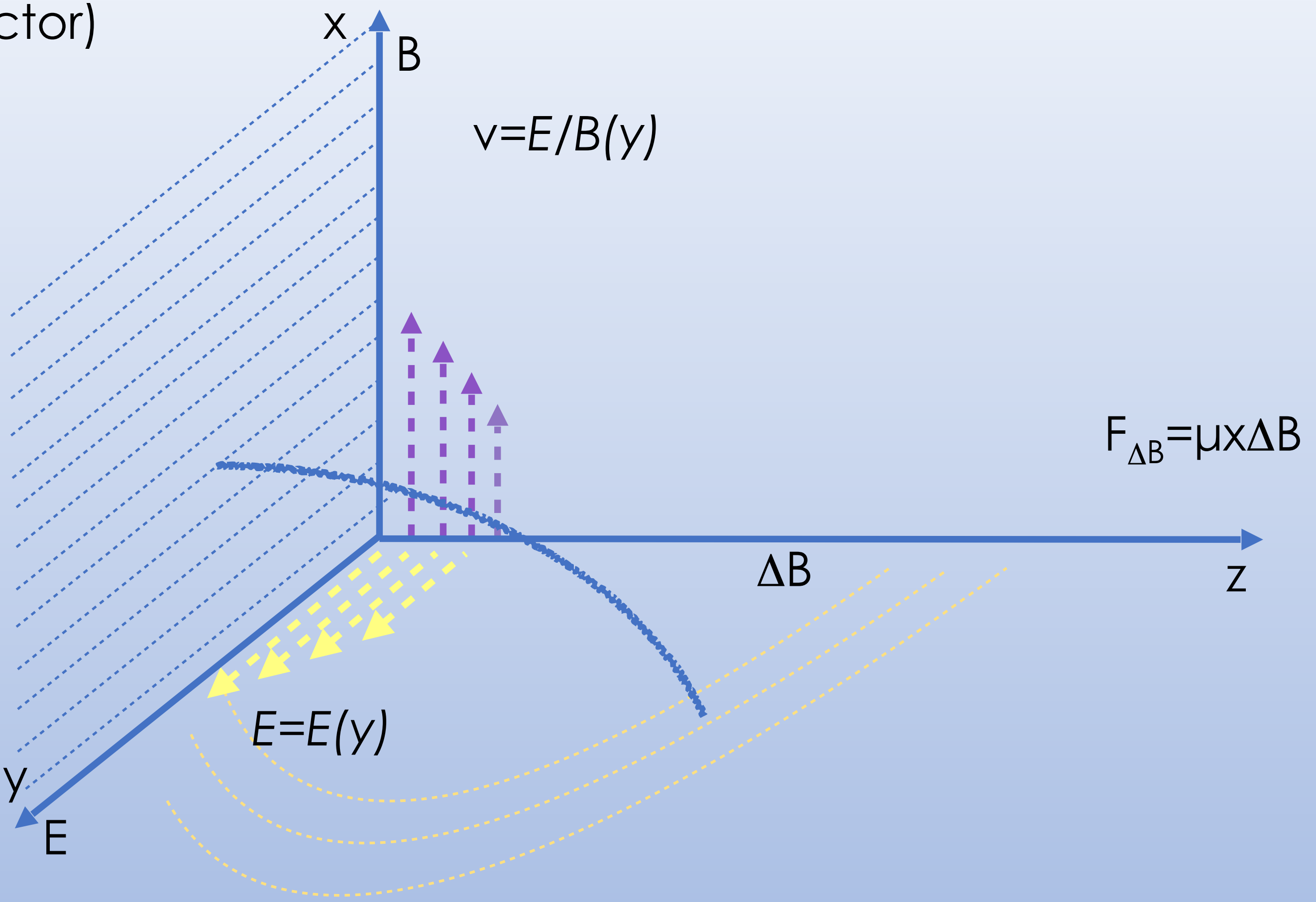

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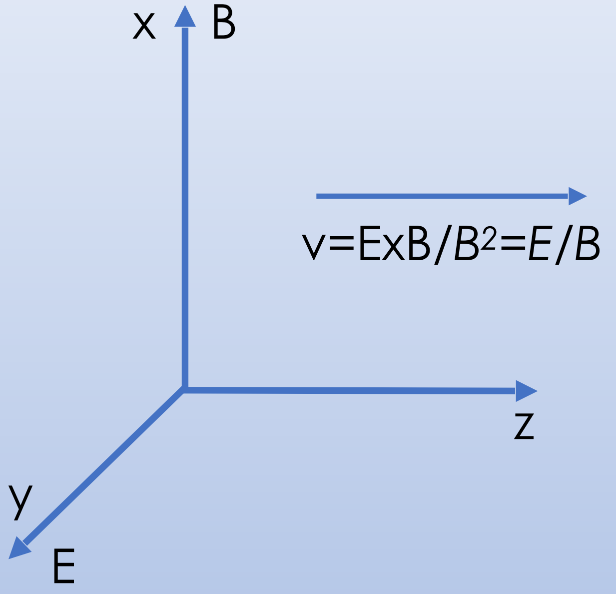
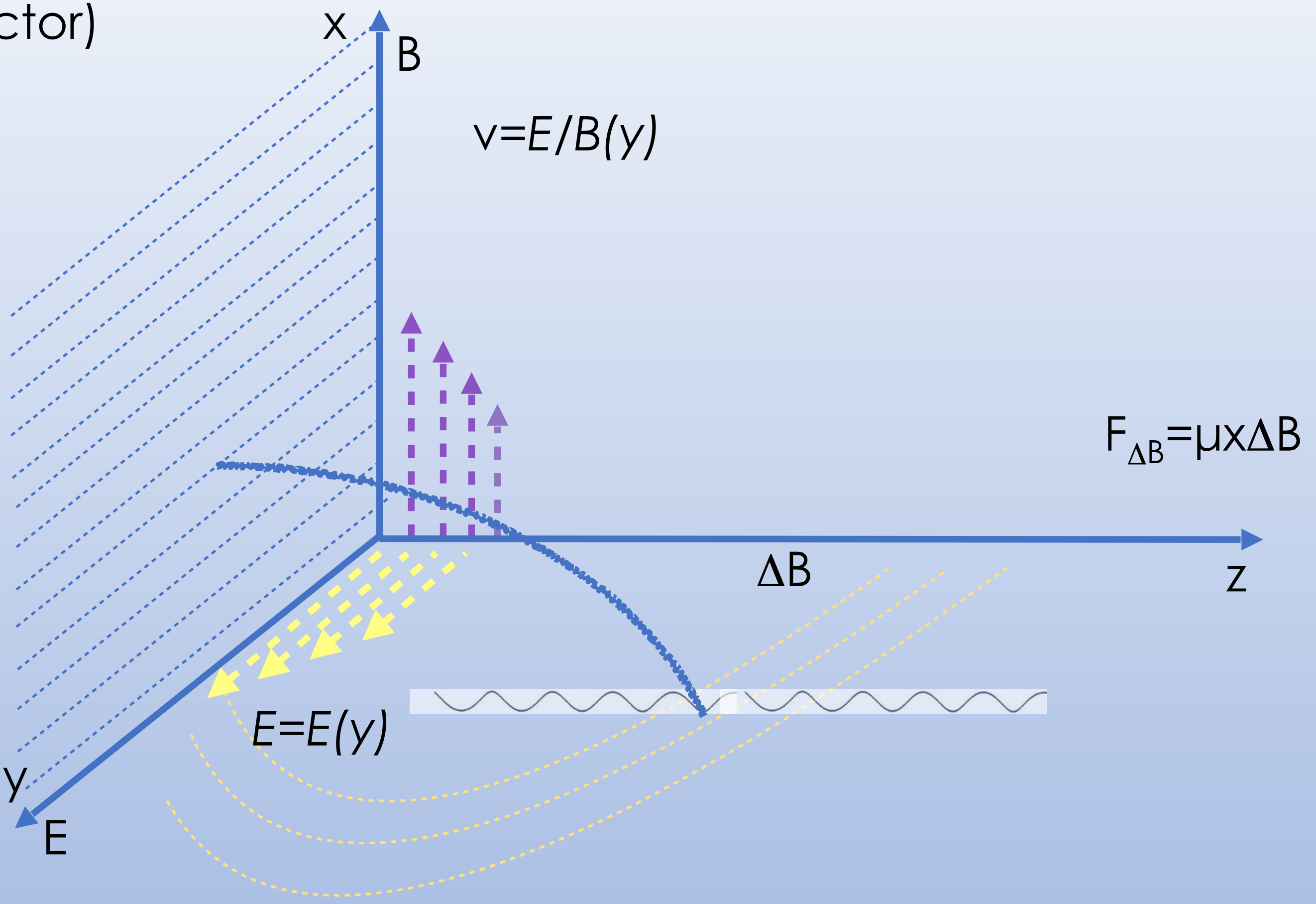
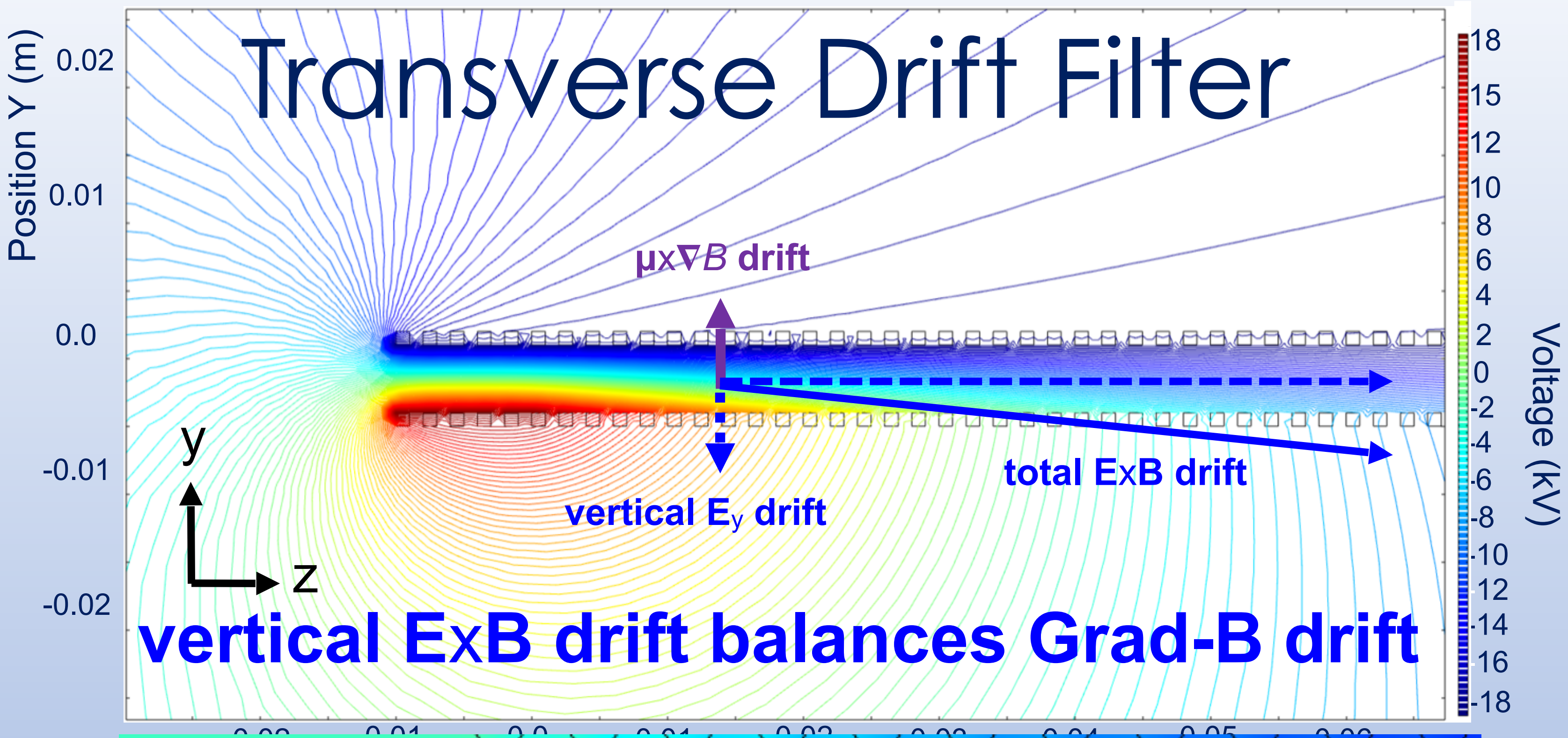
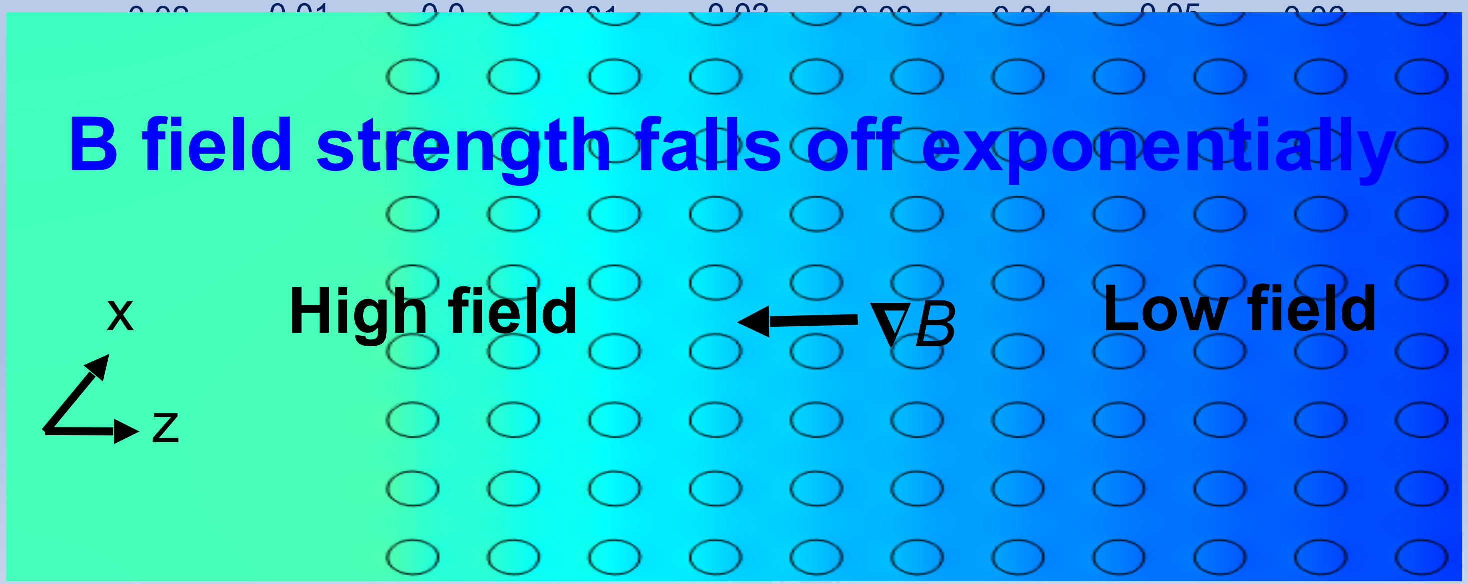




The particle is forced to move on a straight line since the ΔB effect force it to climb an electric barrier transforming the kinetic transverse energy in potential energy. This way the particle trajectory is strengthened by removing p_T.

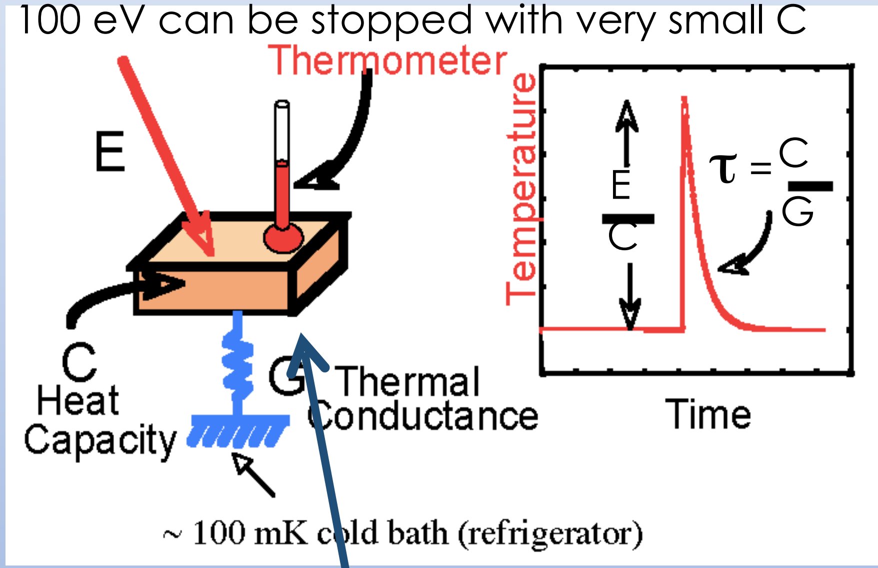
Transverse Drift Filter





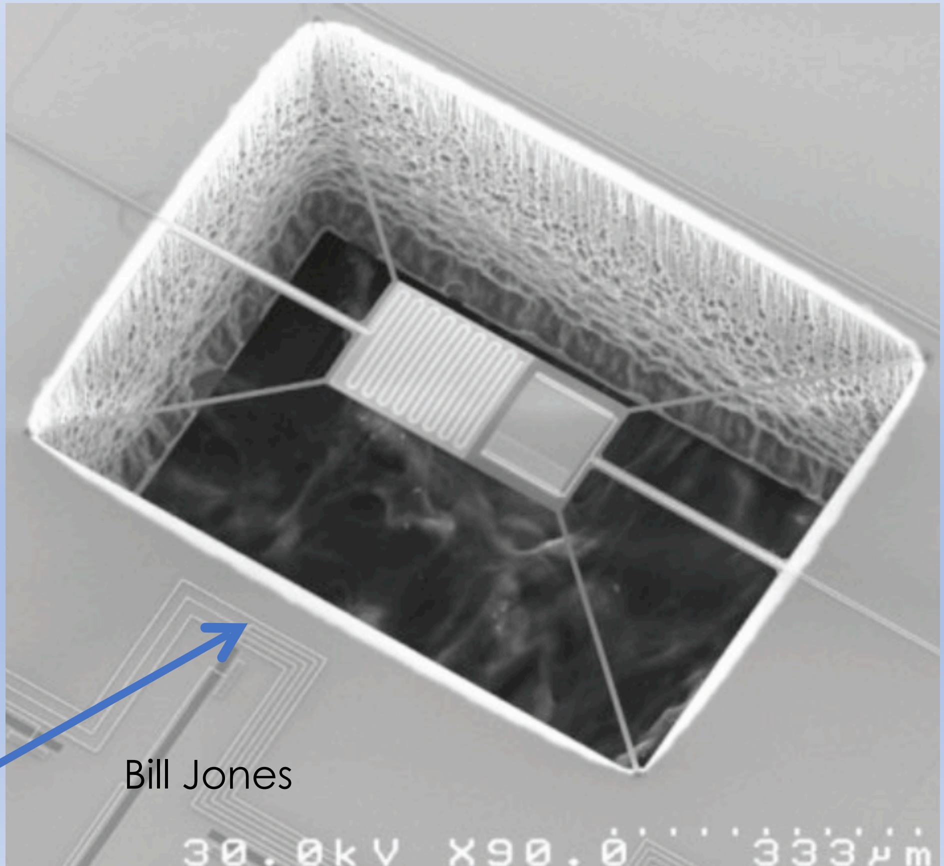
Calorimetric measurement
based on Transition Edges Sensors technology

Resolution of ~0.55eV at 1keV and ~0.15eV at 0.1keV operating at 70-100mK under investigation (Clarence Chang ANL, Moseley et. al. GSFC/NASA)



100 eV electron can be stopped in a very small absorber absorber i.e. small C

TES sensor

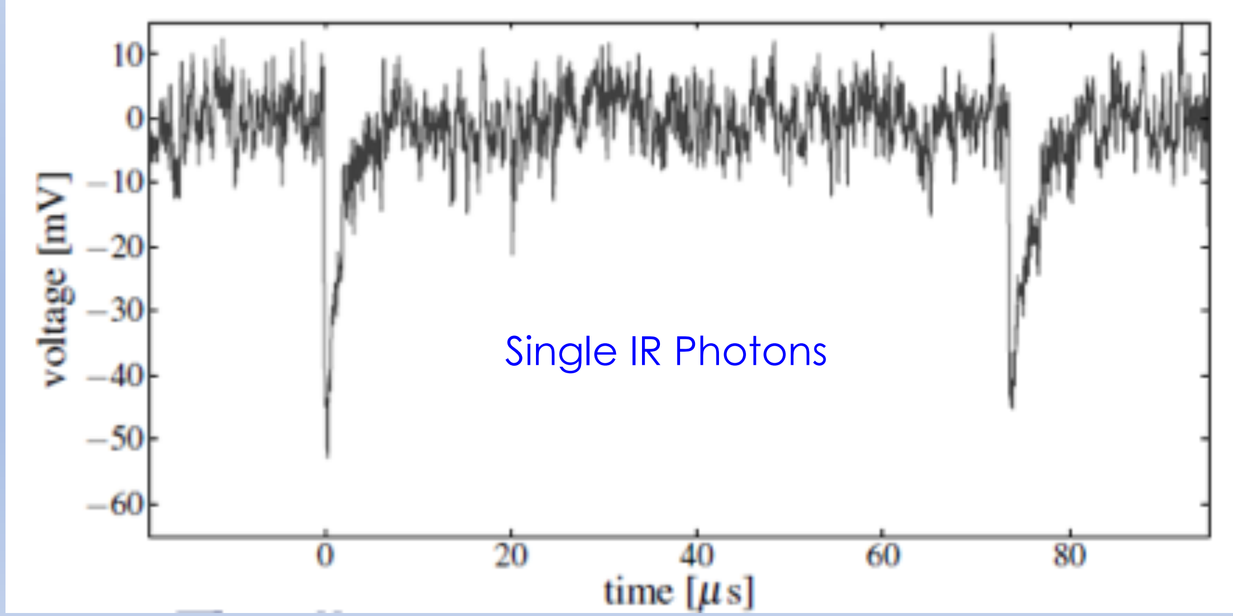


SPIDER island TES example

Microcal Energy Resolution

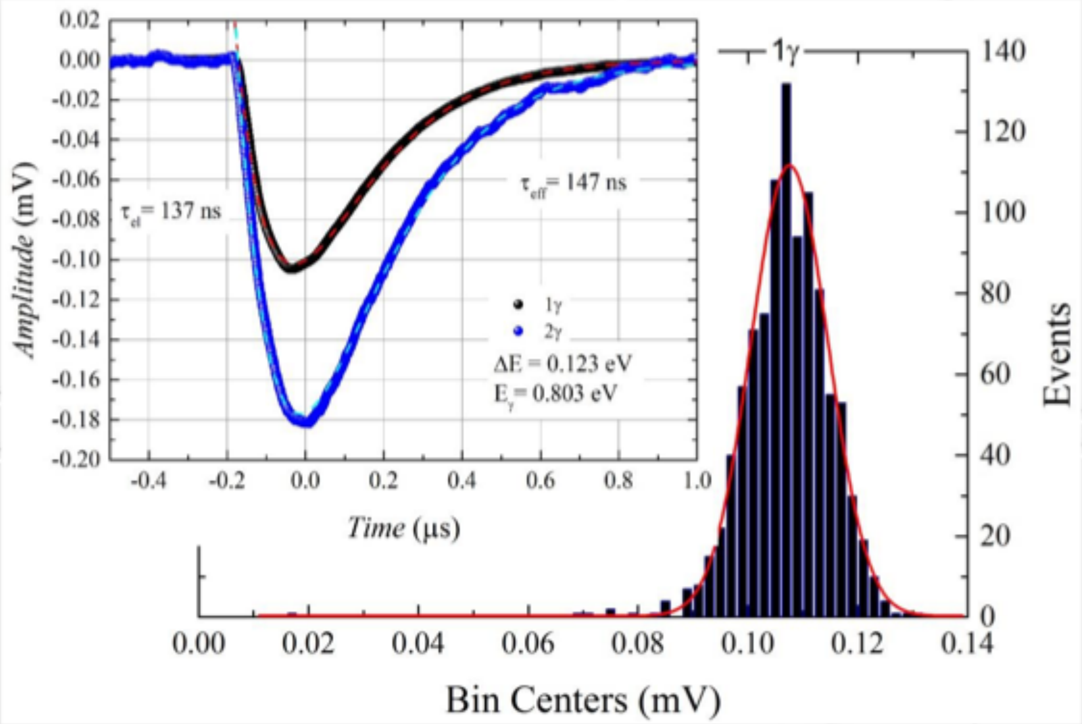
- Pushing down microcal resolution – 0.15eV@100eV (~100mK) no longer the focus
  - Most TES work is headed toward extremely low heat capacitance (absorber thickness ~15μm → 10nm for ~10eV electron)
  - 0.05eV@10eV (and further linear improvements from pushing down to 50mK)

Example:
IR TES cameras also very active (~0.3 eV resolution achieved at 0.8 eV for single IR photons)



Microcal for IR Photons

IR TES achieve 0.12 eV resolution at 0.8 eV for



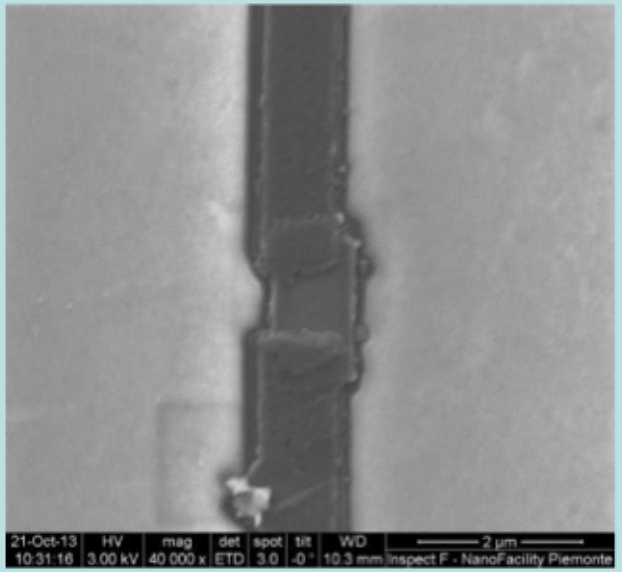
Results from INRIM (Torino) - Istituto Nazionale di Ricerca Metrologica

$\sigma_E = 0.05\,\mathbf{eV}$

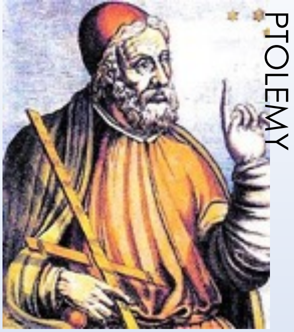
$\tau_{etf} = 147\text{ns}$

$\Delta E_{FWHM} = 0.12$ eV @ 1545nm

1 µm × 1 µm

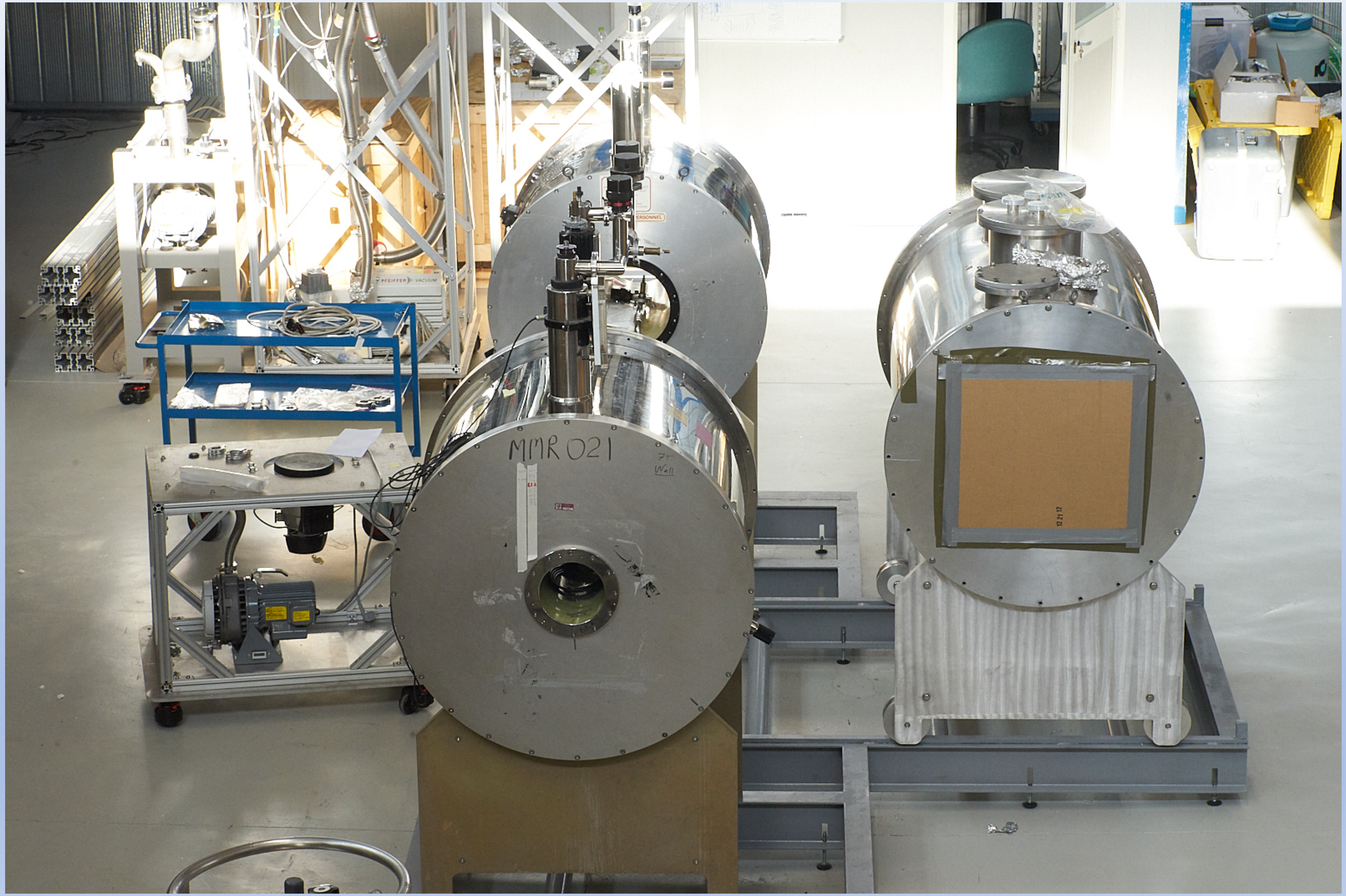


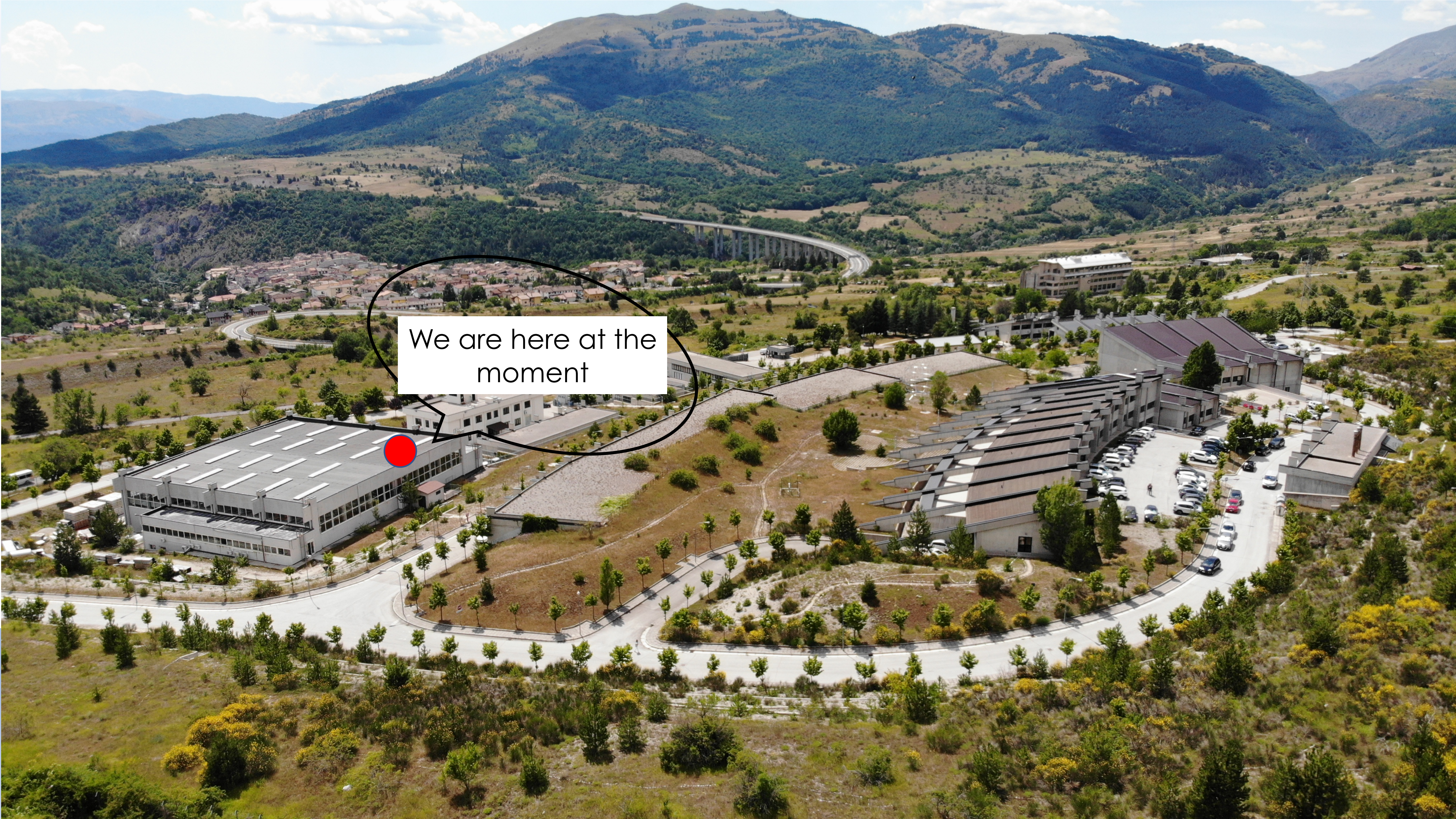
C. Portesi *et al*, IEEE Trans App Supercond, 25, 3, (2015)



PTOLEMY

Experimental site at LNGS




We are here at the moment

Light Dark Matter search

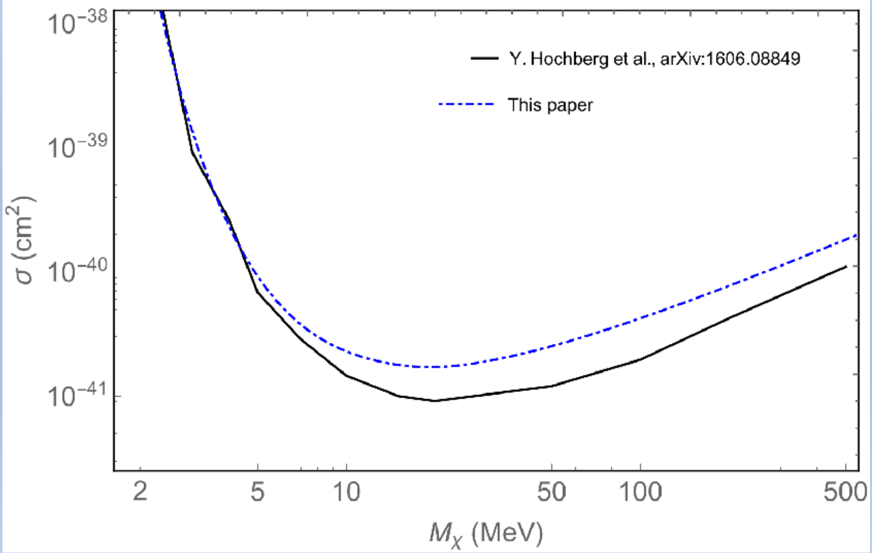
Side project potentially very much interesting

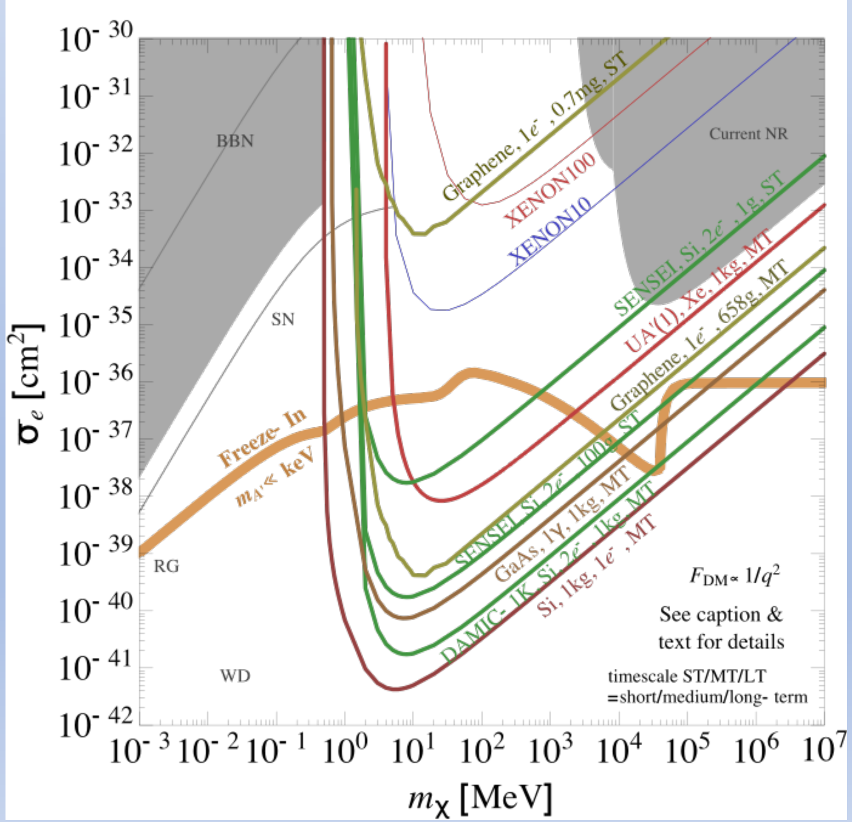
- Hochberg, et. al, 2016. "Directional Detection of Dark Matter with 2D Targets", Phys. Lett. **B772,** (2017), 239.
- GL Cavoto et. Al, "Sub-GeV Dark Matter Detection with Electron Recoils in Carbon Nanotubes "Phys.Lett. **B776** (2018) 338-344

In both papers the interaction of light DM with electrons in C nano-structure are discussed. With two different approaches, some directionality features of C nano-ribbon or nano-tube structure are shown. Thus a technical run of the PTOLEMY detector without T would provide interesting results in a region of sensitivity lacking of DM hunting activity. Any electron popping up form C nano-structure could be signature of DM interaction.

The requirements crucial for the PTOLEMY CNB detection project could be also very much beneficial for Light DM search:

- C with with ^{14}C contamination at better than one per 10^{18}
- electron selection capability
- and very high energy resolution





World-map of the PTOLEMY Collaboration

21 institute and 45 physicists

The first two papers

1) M. G.Betti et al.,
"A design for an electromagnetic filter for precision energy measurements at the tritium endpoint"
Progress in Particle and Nuclear Physics, **106 (**2019),120-131
https://doi.org/10.1016/j.ppnp.2019.02.004

2) M. G.Betti et al.,
"Neutrino Physics with the PTOLEMY project",
JCAP_047P_0219,
arXiv:1902.05508

To Conclude

1. Something completely different

2. Physics program: **Relic Neutrino's, Light DM, Neutrino mass**

3. Technological challenge: **New support for T**, **extreme high rate, extreme energy resolution**