UNIVERSITÉ DE GENÈVE

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

INFN Laboratorio Nazionale del Gran Sasso

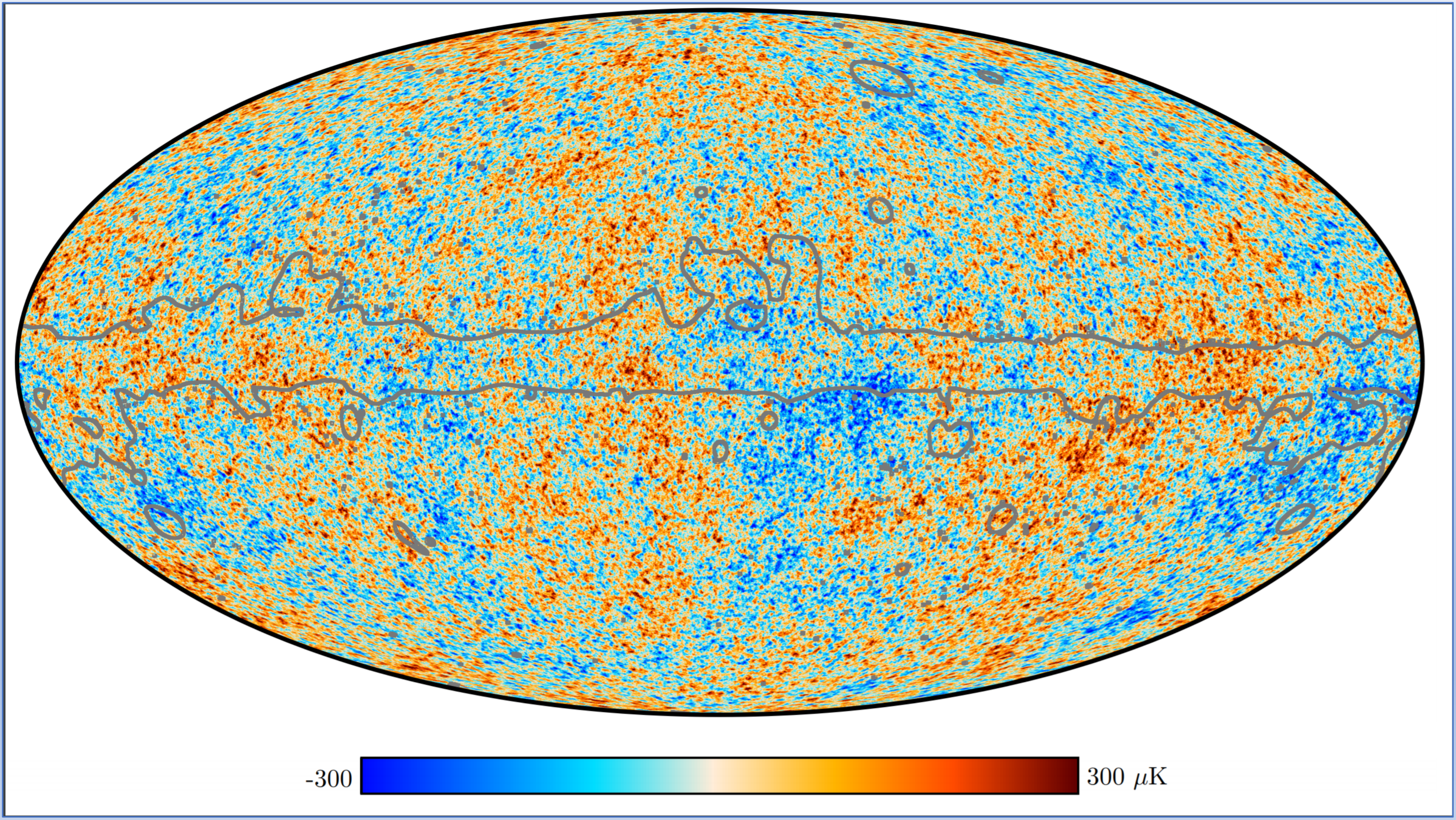
Marcello Messina, Primo Ricercatore INFN at LNGS,
Seminar at University of Geneva, Switzerland October 2019

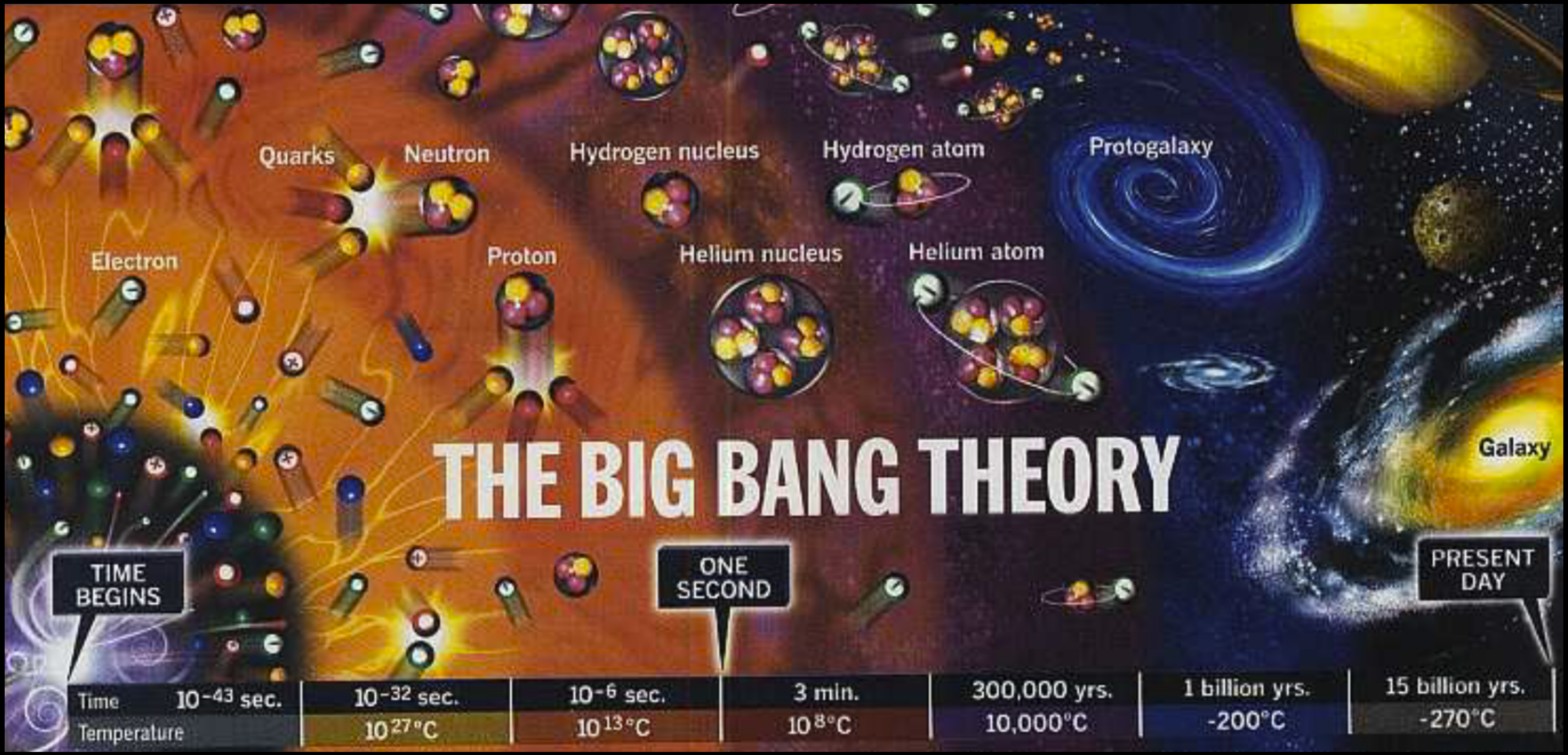
Why we believe in Big Bang?

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

The only photograph of the Universe

how it was 380000 y after the BB





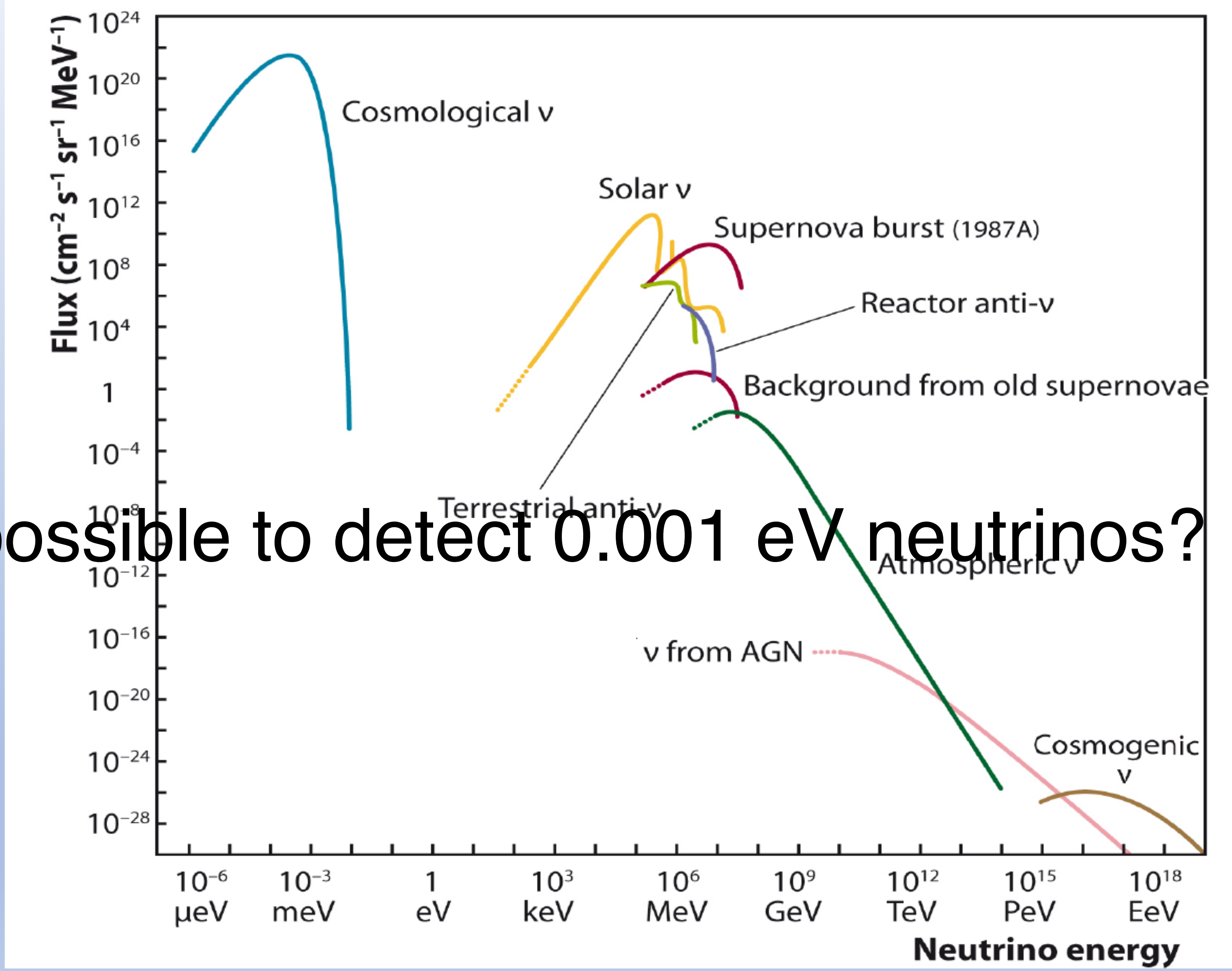
CNB ~ 1 sec

CMB ~ 380k yr

Neutrino flow

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

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



Is it possible to detect 0.001 eV neutrinos?

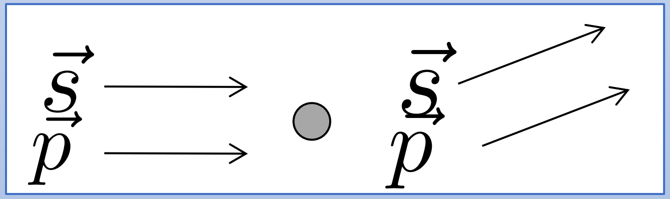
The status of CNB search before 2007

The longstanding question (I)

Is it possible to measure the CRN?
Method 1

The first method proposed for the detection of CRN was based on the fact that given the null mass of the neutrinos (today we know it is small) any variation of ν momentum (Δp) implies a variation of the ν spin (DJ) (R.R. Lewis Phy. Rev. D21 663, 1980):

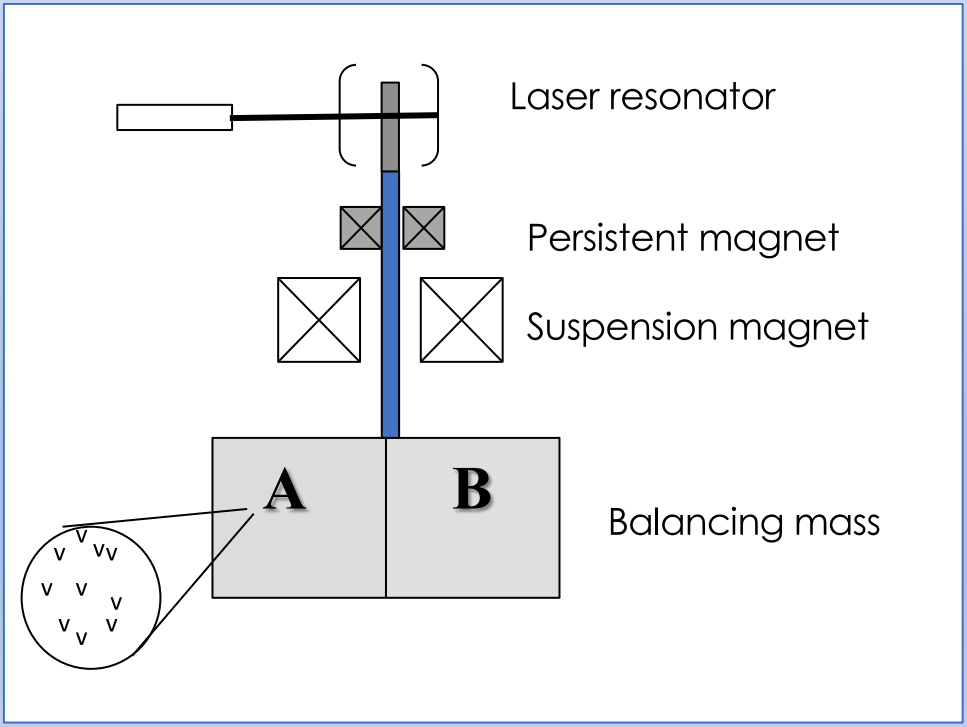
$$\Delta J = \lambda \Delta p$$



The longstanding question (II)

Is it possible to measure the CRN?
Method 1

Unfortunately what assumed by Lewis was shown by Cabibbo and Maiani (Phys. Lett. B114 115,1982) to vanish at first order in Fermi constant G_F.
But there is still an effect (Stodolsky Phys. Rev. Lett. 34, 110) at first order in G_F where a polarized target experiences a force due to the scattering with polarized neutrinos (only a tiny part of the CRN flux). The effect can only be seen if : $f = \left(\nu - \bar{\nu}\right) \neq 0$



Since the n wave length is ~ mm (λ) can be envisaged an enhancement of the interaction rate due to coherent sum of the invariant scattering amplitudes in a volume λ^3. Under this assumption:

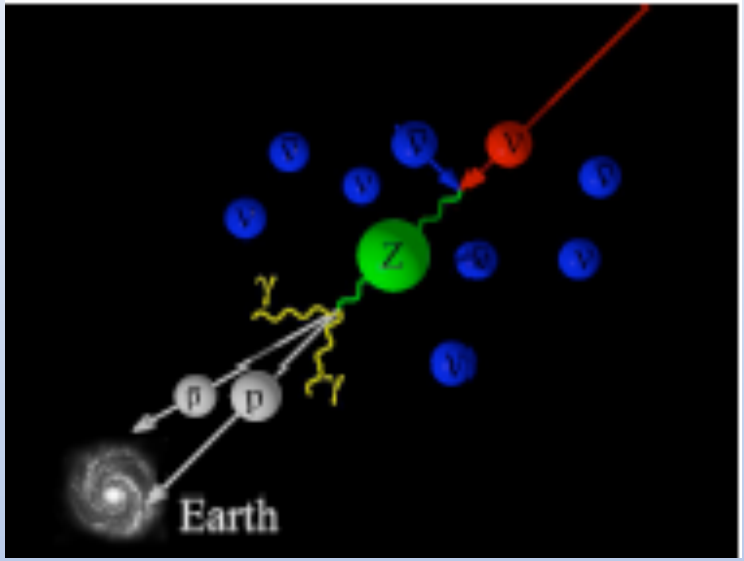
$$a_{G_F} \approx 10^{-27} \frac{cm}{\sec^2} f\left(\frac{\beta_{earth}}{10^{-3} c}\right)$$

The value of acceleration expected is almost 15 order of magnitude far from the current sensitivity of any accelerometers used today a “Cavendish” experiment.

The longstanding question

Is it possible to measure the CRN ?

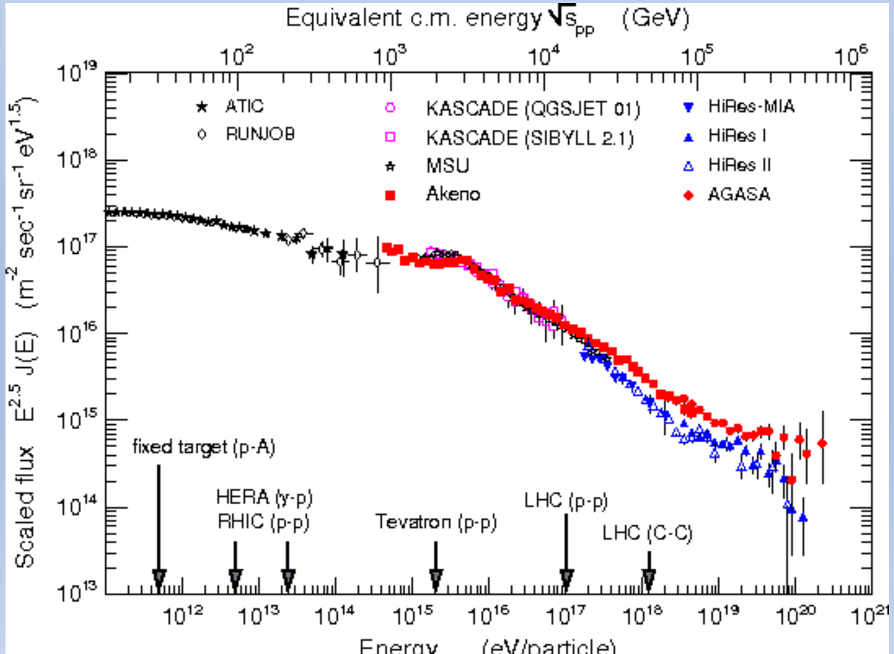
Method 2



The second method propose a resonant annihilation of EECn off CRN into Z-boson that occurs at energy:

$$E_{\nu_i}^{res} = \frac{m_Z^2}{2m_{\nu_i}} \approx 4x10^{21}\left(\frac{eV}{m_{\nu_i}}\right)eV$$

The signature would be a deep in the neutrino flux around 10^{22} eV or an excess of evnts of photons or protons beyond the GKZ deep (where the photons of CMB are absorbed by protons to produce pions).



The longstanding question

Is it possible to measure the CRN ?
Method 3

The third method propose the observation of interactions of extremely high energy protons from terrestrial accelerator beams with the relic neutrinos.

Accelerator

In this case even with an accelerator ring (VLHC) of $\sim 4\text{x}10^4$ km length (Earth circumference) with $E_{beam} \sim 10^7$ TeV the interaction rate would still be negligible.

Summarizing

Is it possible to measure the CNB?

All methods proposed so far require unrealistic experimental apparatus or astronomical neutrino sources not yet observed.

For reviews on this subject see:

A.Ringwald "Neutrino Telescopes" 2005 – hep-ph/0505024

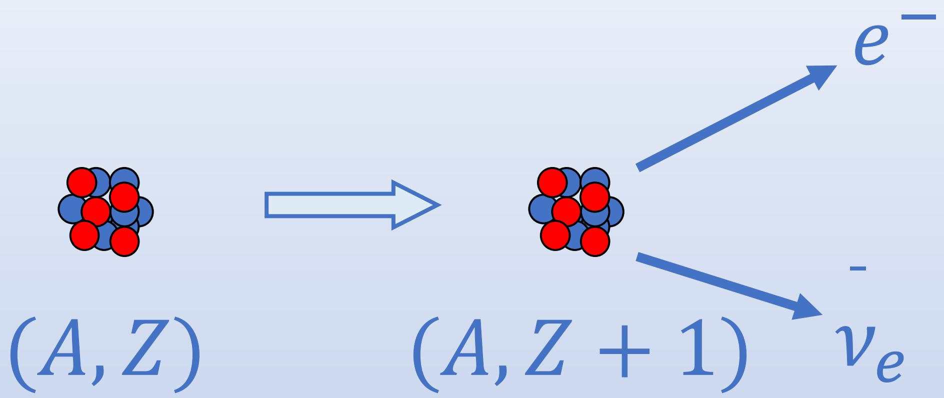
G.Gelmini G. B. Gemini Phys.Scripta T121:131-136,2005

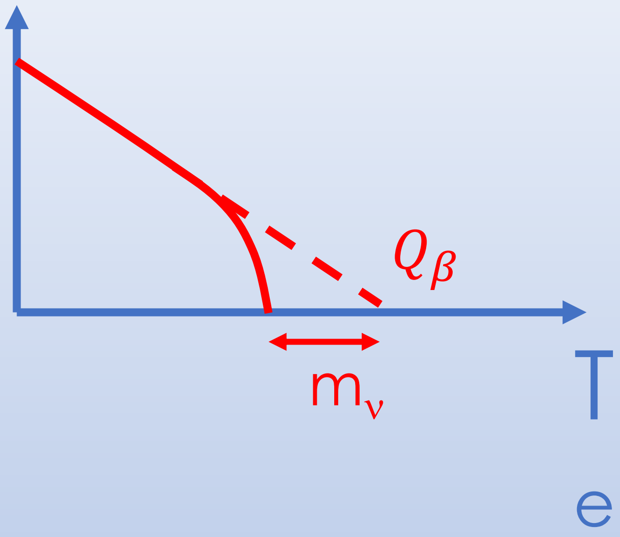
A new idea to detect

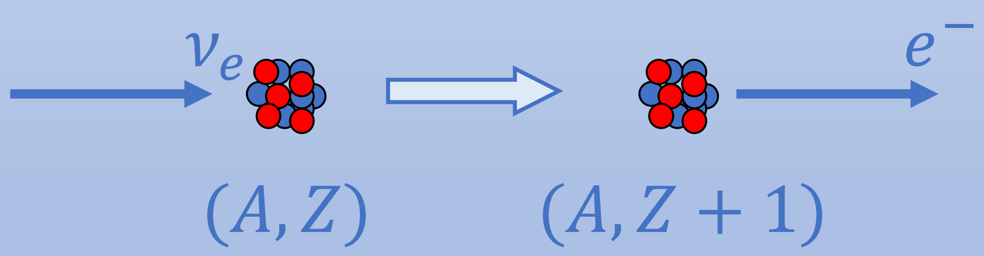
Cosmological Neutrino Background

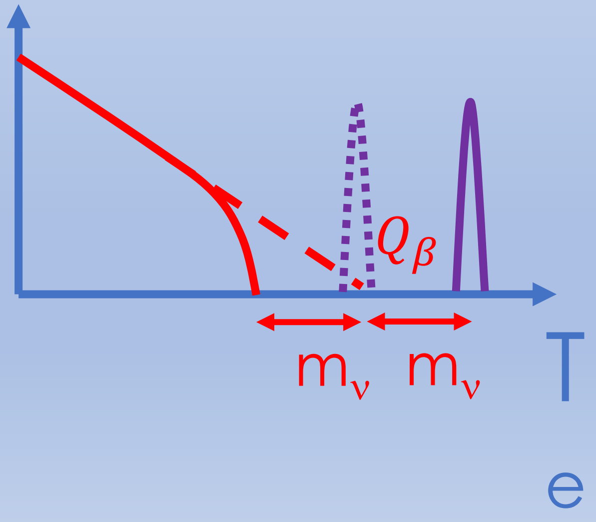
We need a process where the ν can contribute only via its quantum numbers where no additional energy is required!

Detection principle





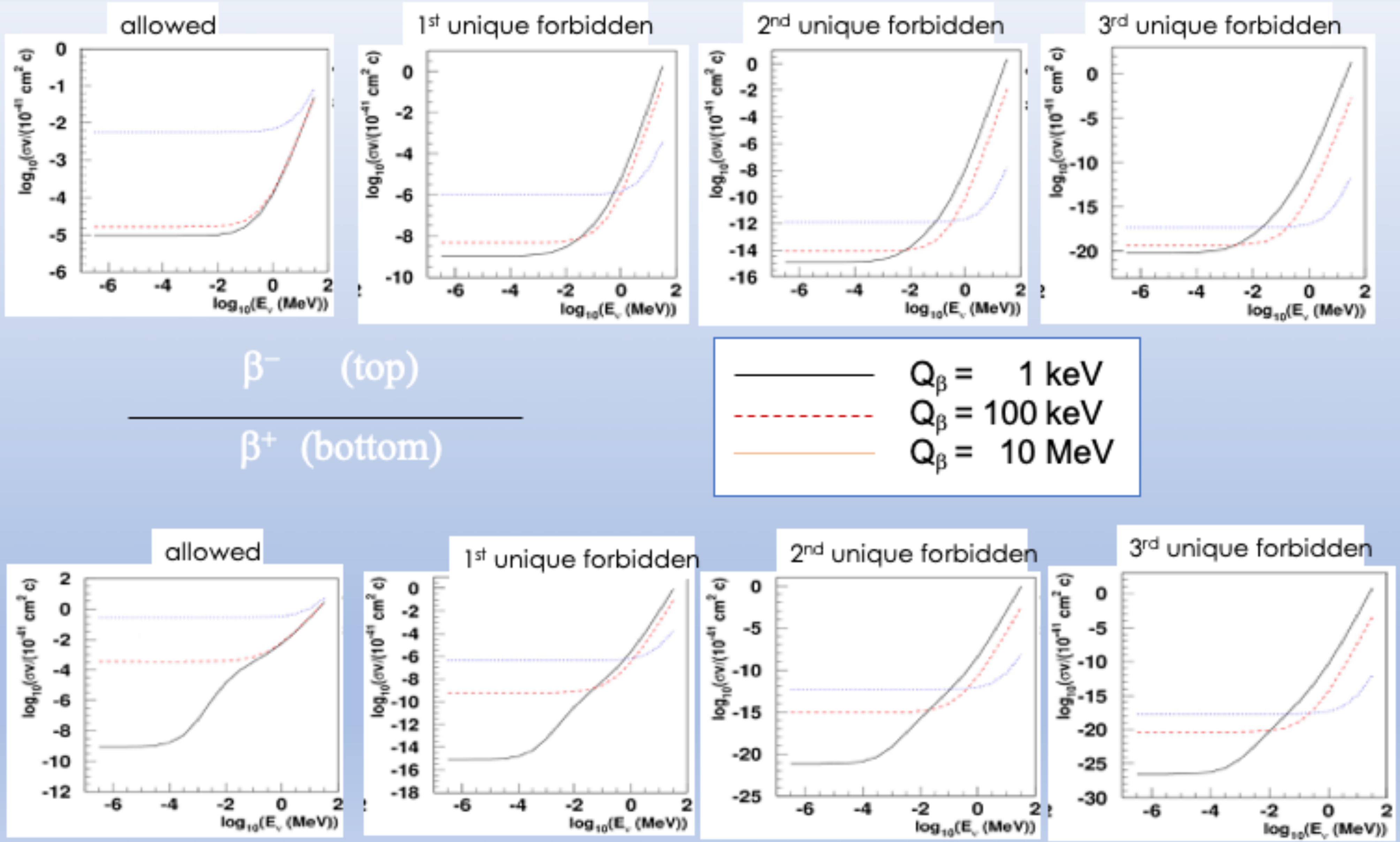




A.G.Cocco, G.Mangano and M.Messina JCAP 06(2007) 015

NCB Cross Section

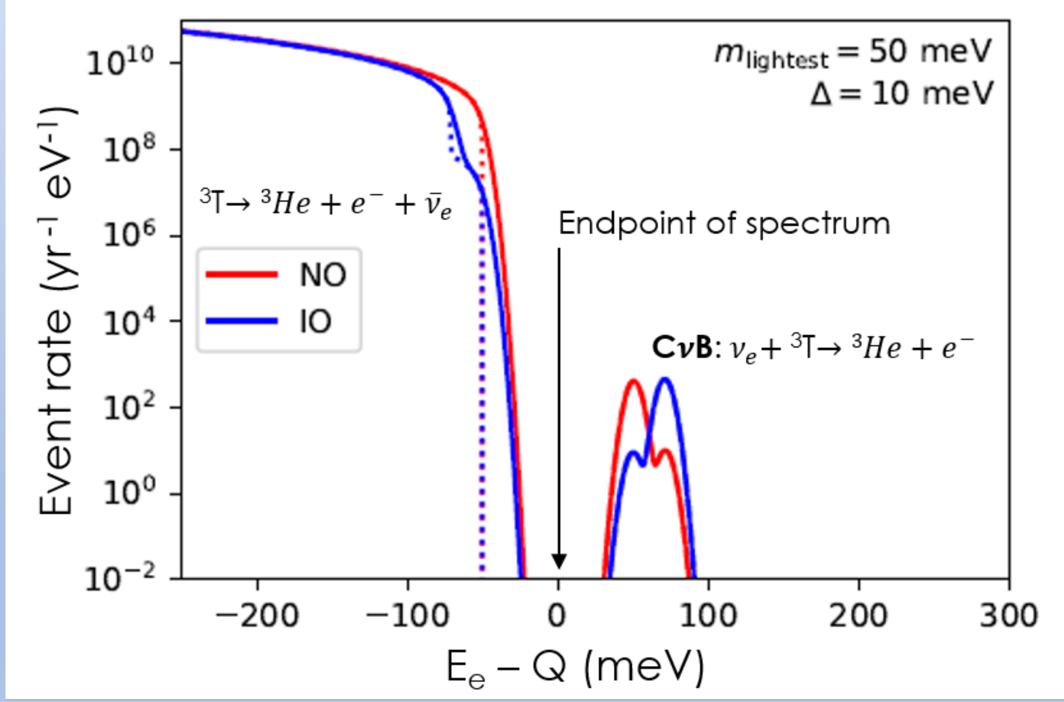
As function of E_ν and Q_β for different nuclear transitions



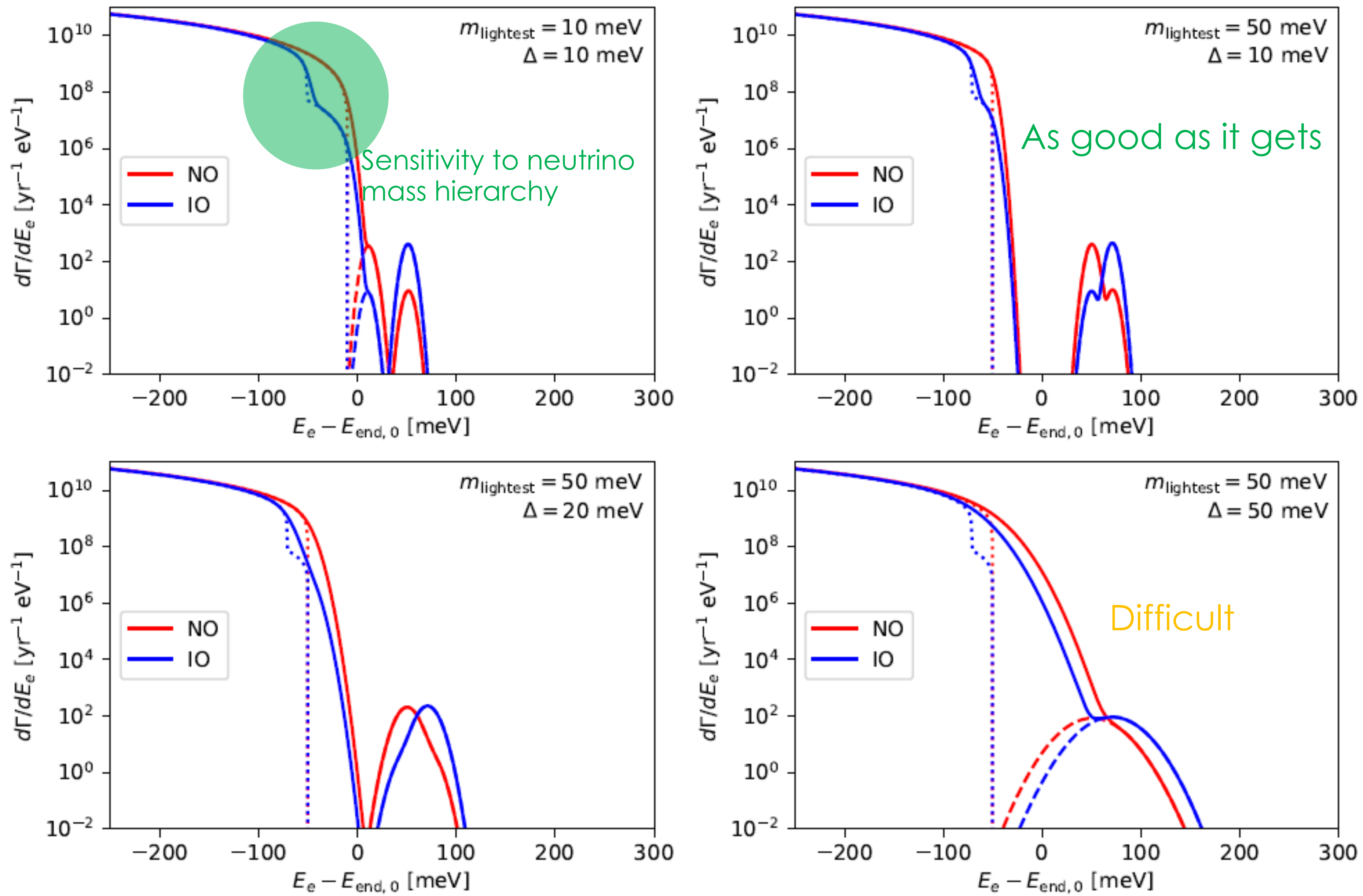
Why Tritium target?

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

PTOLEMY collaboration JCAP07(2019)047



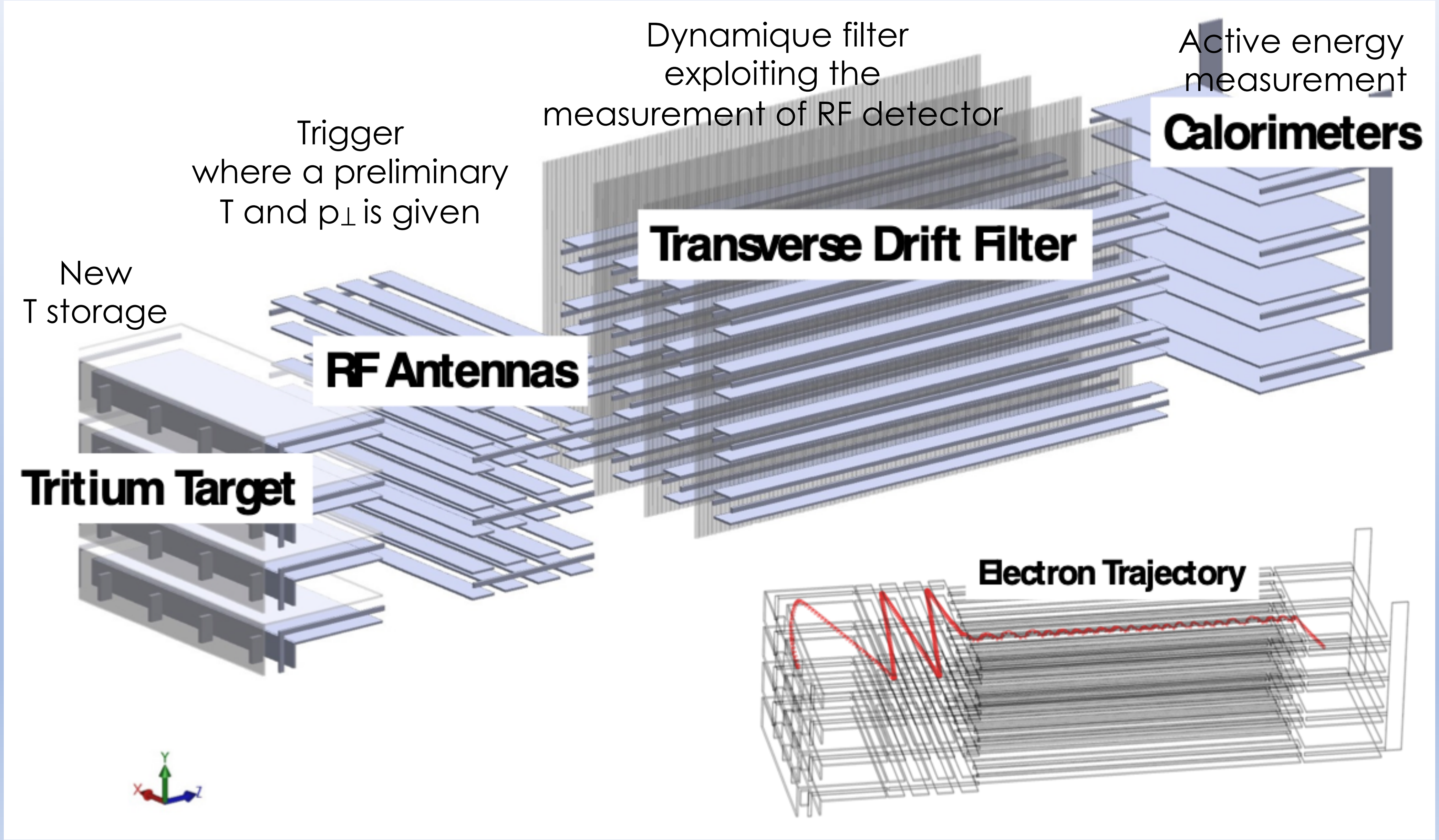
Several σ_E and m_ν scenarios



PTOLEMY experiment

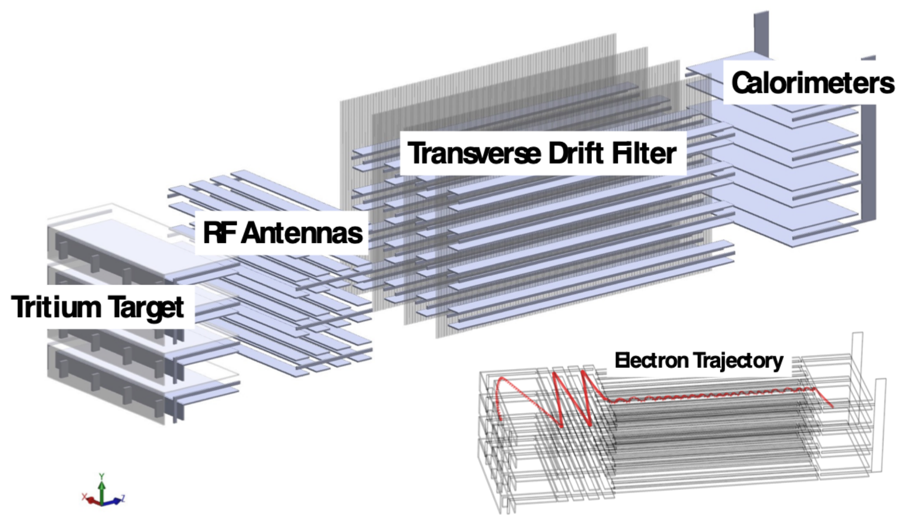
- Goal:
  1. Find evidence for CνB
  2. Accurate measurement of neutrino mass
  3. Light DM detection (not discussed in this talk)
- Key challenges:
  1. Extreme energy resolution is required
  2. Extreme background rates from the target

PTOLEMY: experiment layout



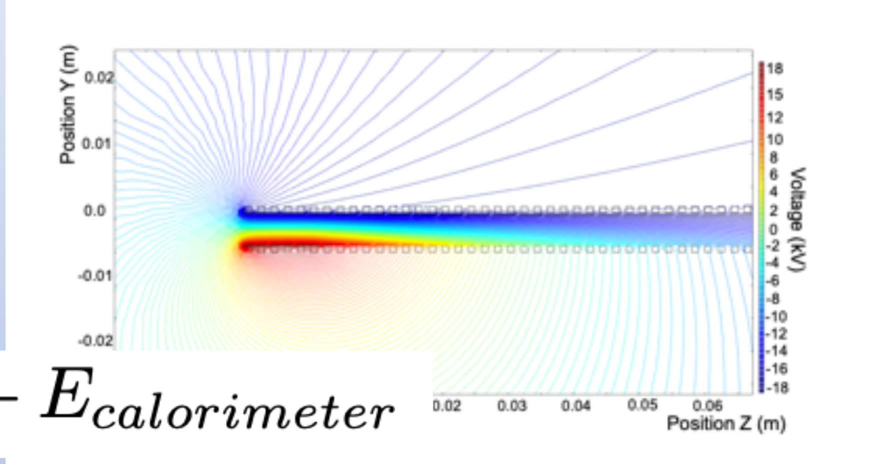
PTOLEMY: measurement principle

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



Step 3

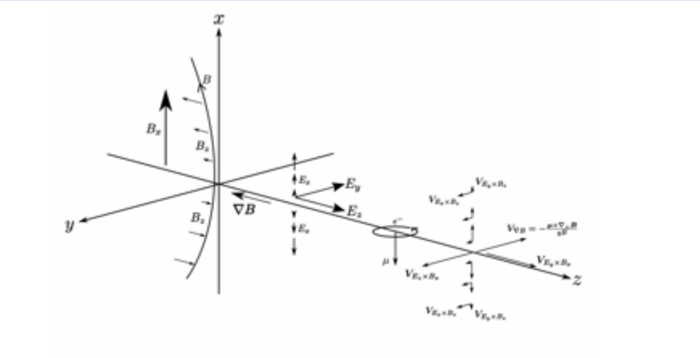
Transverse kinetic energy is removed.
Field properly set on ms time scale.
"Wrong particle will end up on one of the electrodes and the right one will pass"



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

Step 1

A new way of storing atomic T



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

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

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

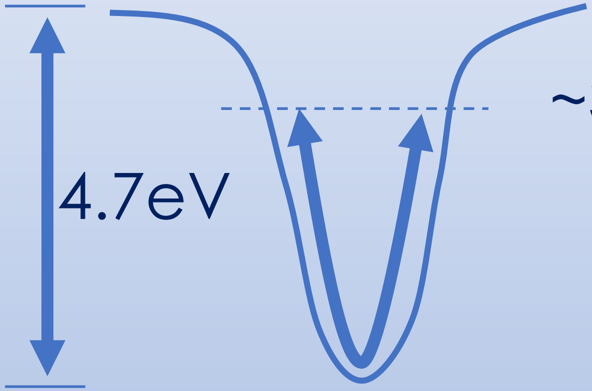
The particle is driven into the TES: $T_{tot}=q(V_{anode} - V_{source}) + E_{cal}$

PTOLEMY: The source

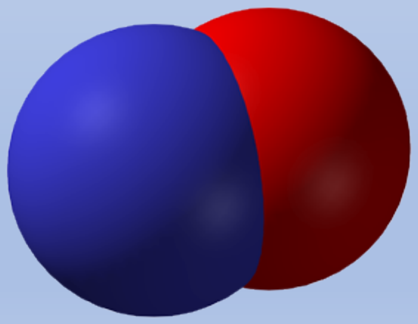
- Use **atomic T**
  - No vibrational modes in final state like for ^3He-^3T final state.
  - Limit to energy resolution not determined by target itself

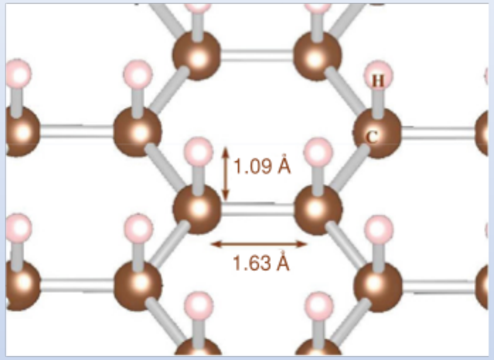
Molecular Broadening

T-T → $(T\text{-}He^3)^*$



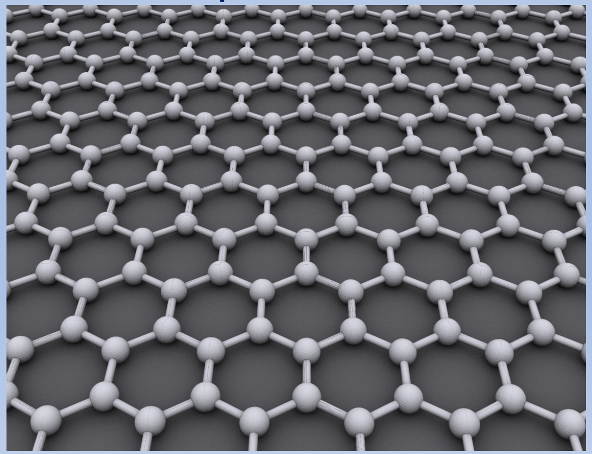
~3eV He^3 recoil at endpoint



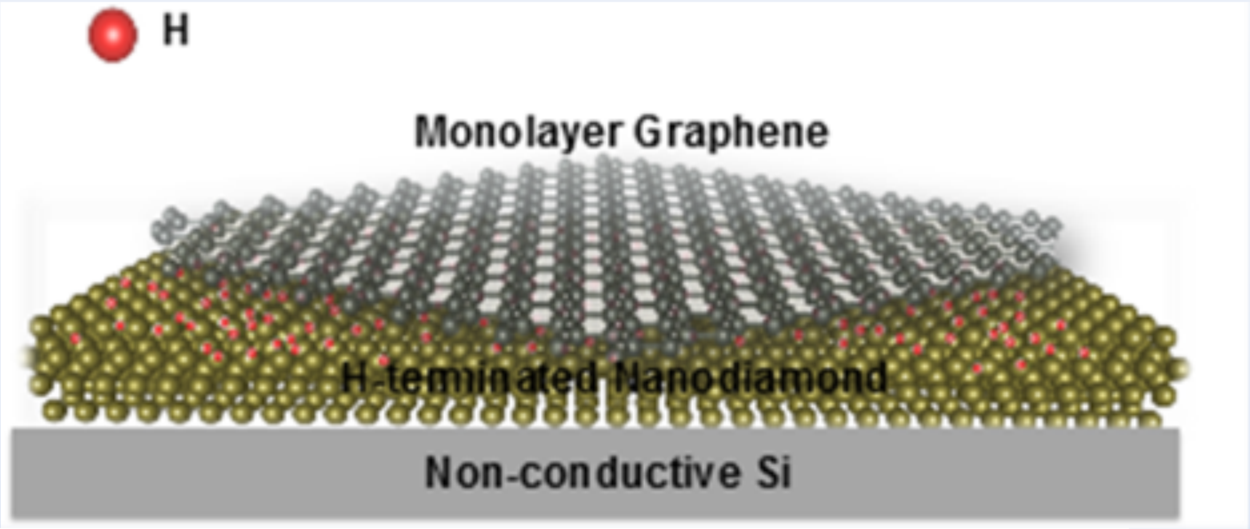


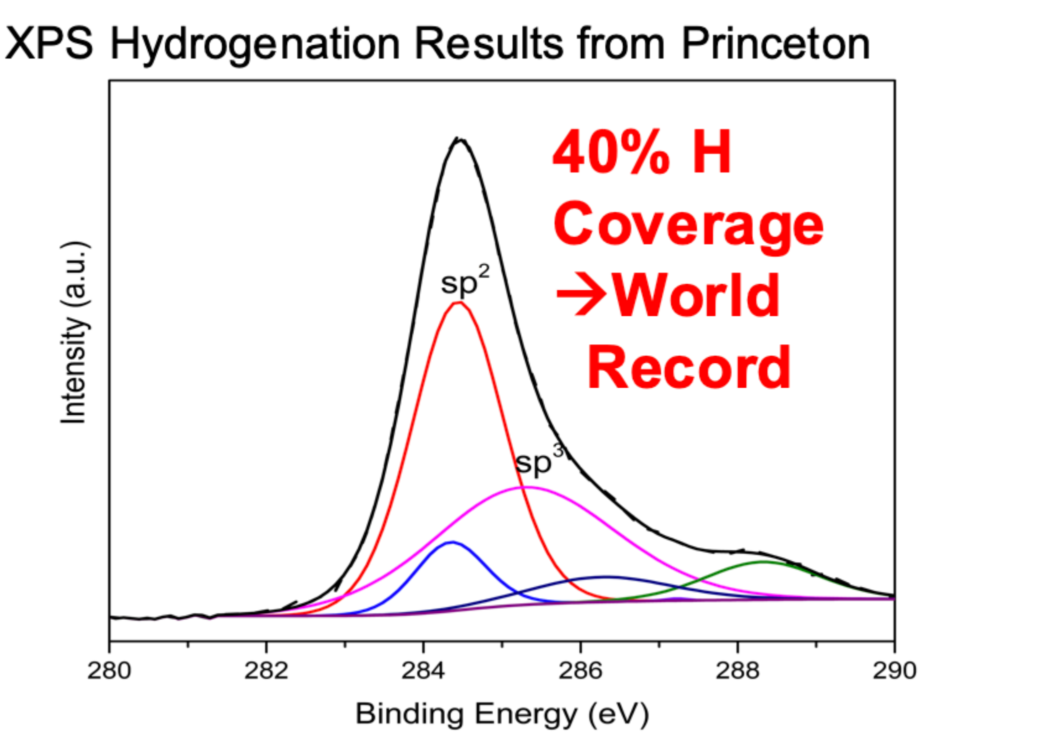
<3eV binding energy

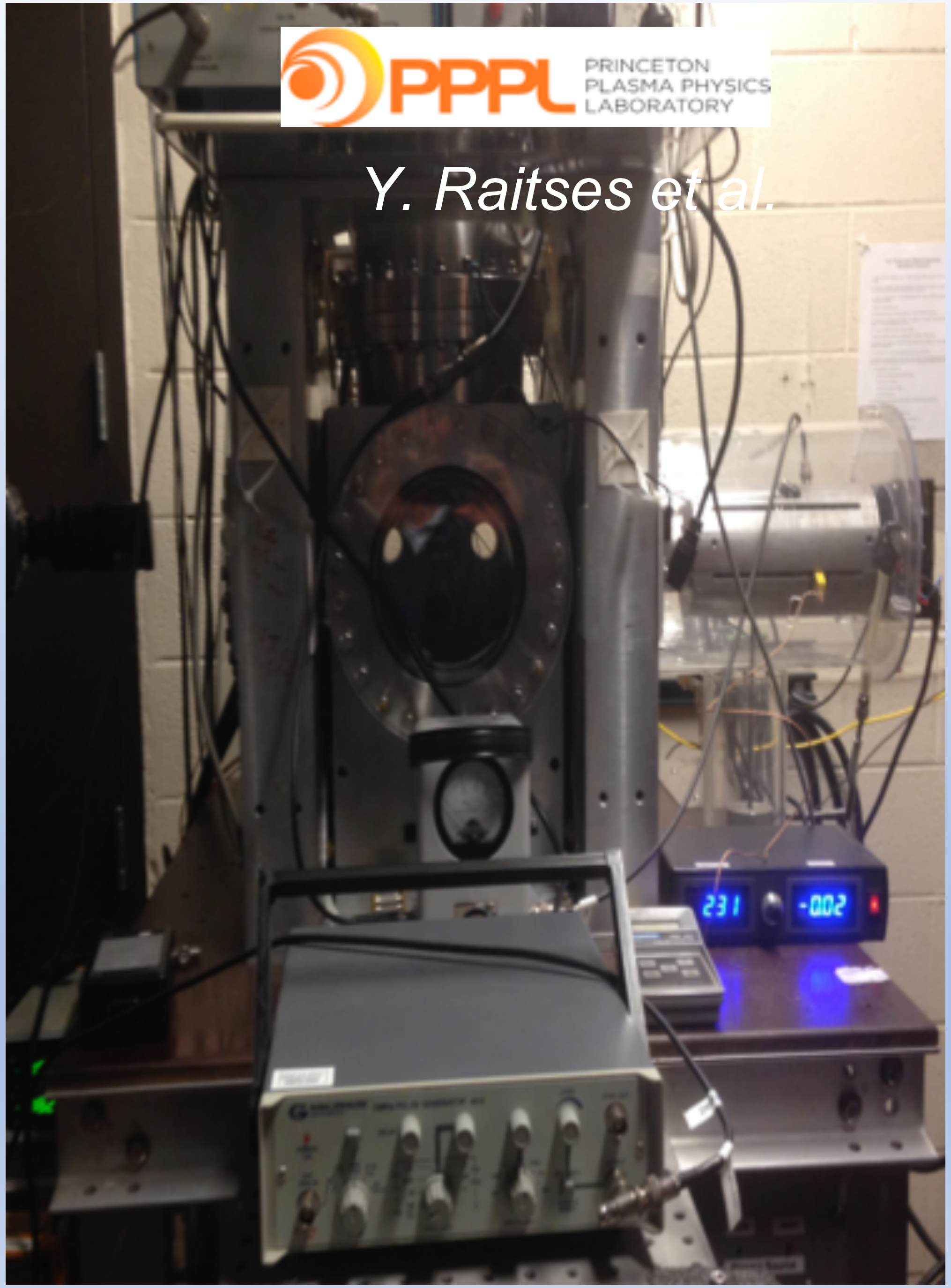
Graphene



Cold Plasma Loading



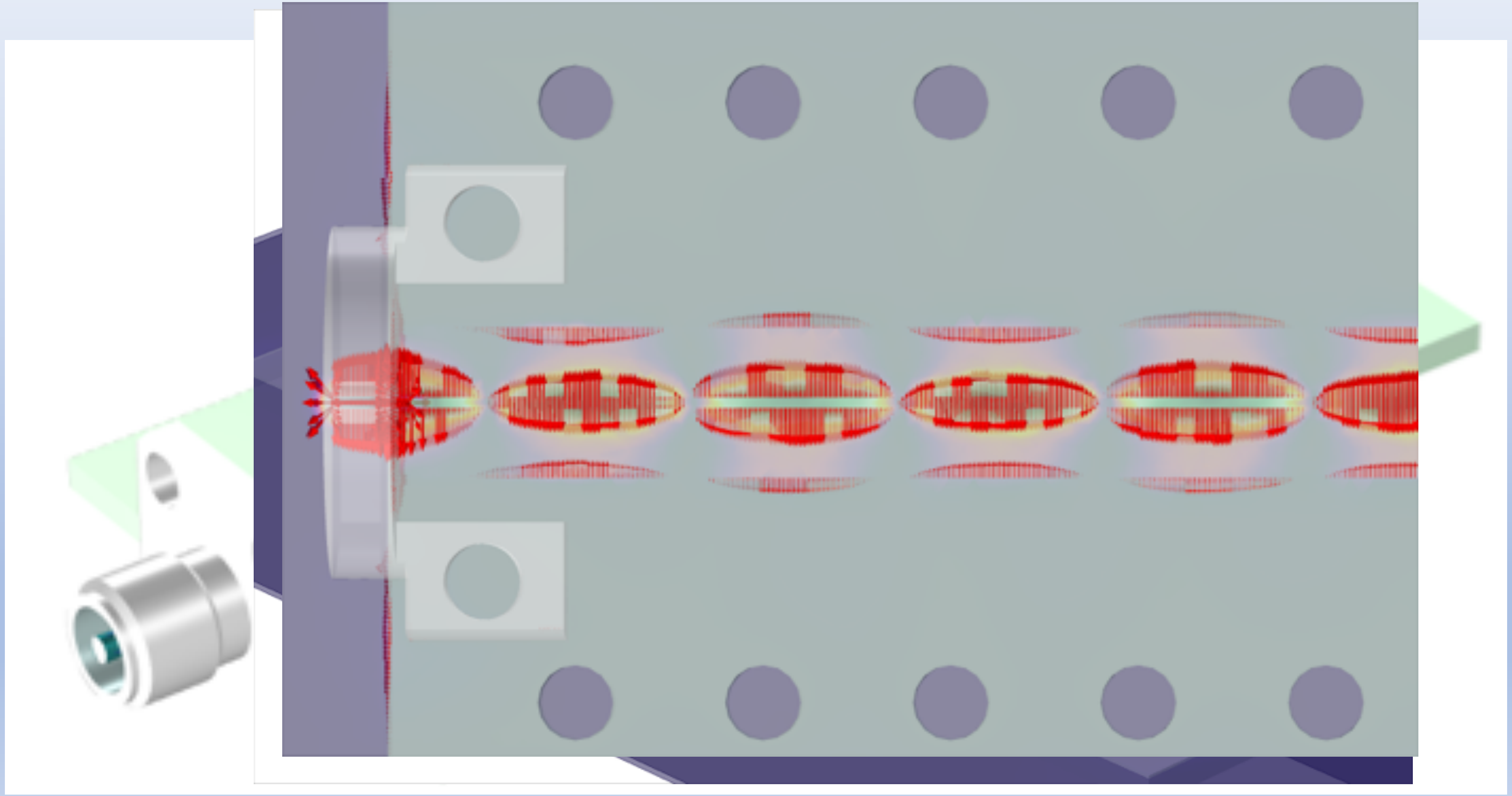




Investigation in the field of Co-Planar Waveguide started

The voltage signal propagating to a SMA connector is shown by arrow map.

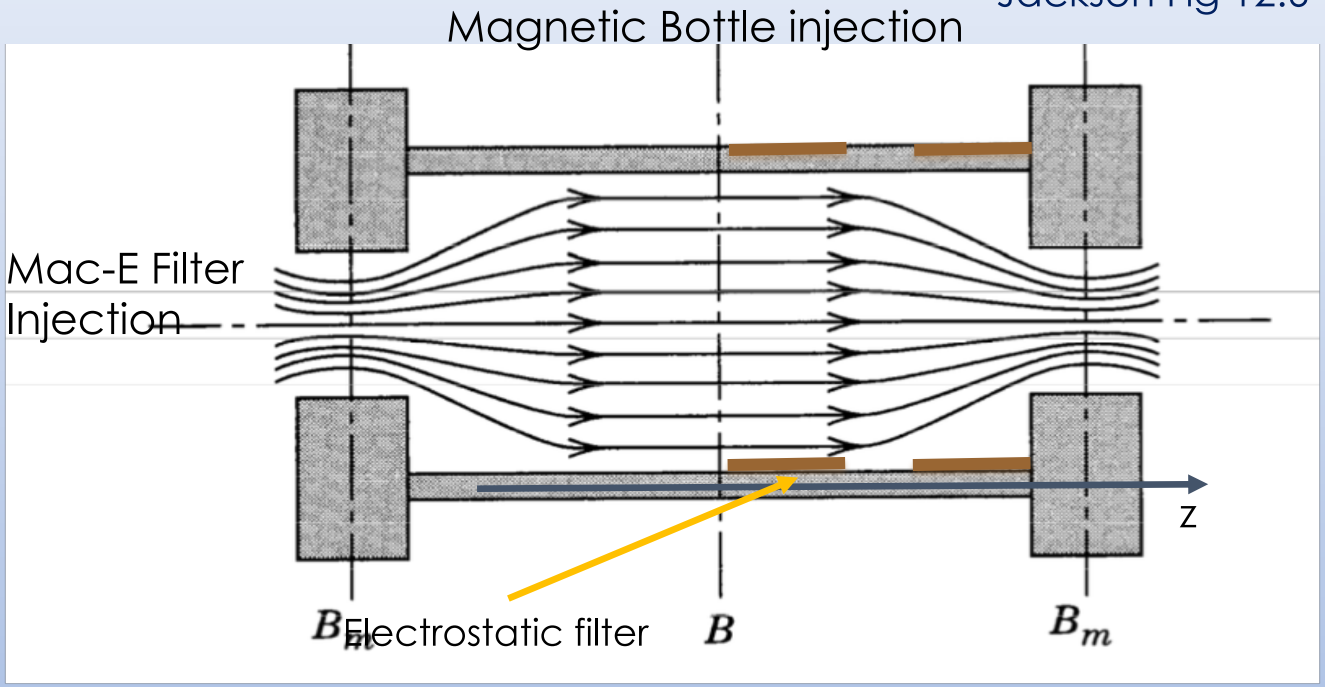
Exercise form COMSOL library



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



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

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

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 ΔE ~ 2 eV

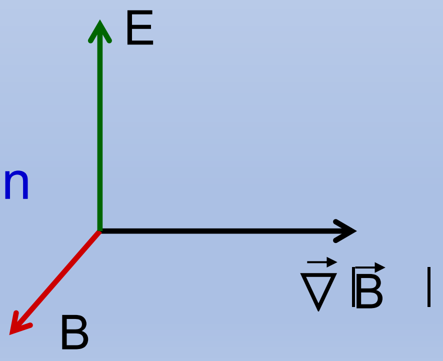
New concept EM filter

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

$\vec{E} \times \vec{B}$ drift ∇B drift

First adiabatic invariant: $$\mu = \frac{mv_\perp^{*2}}{2B}$$

Static fields configuration

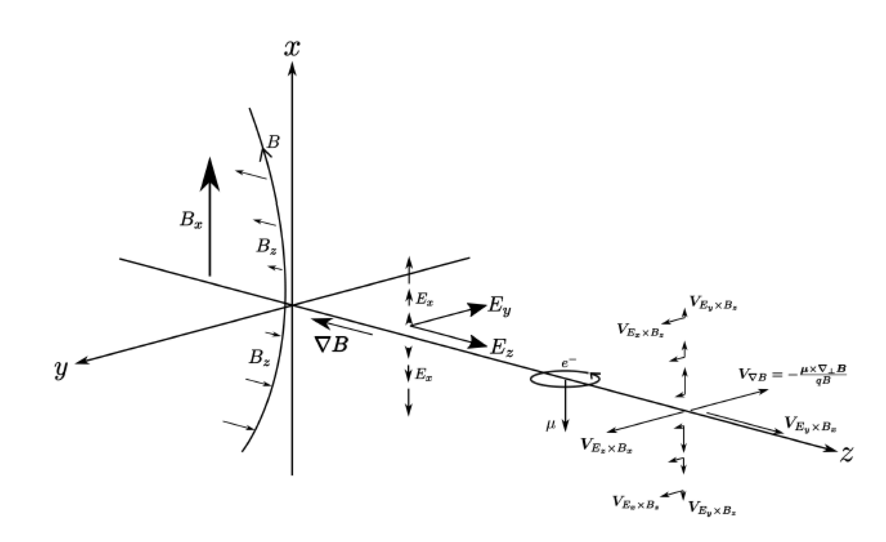


M.G. Betti et al., Prog. Part. Nucl. Phys. 106 (2019) 120-131

New concept EM filter

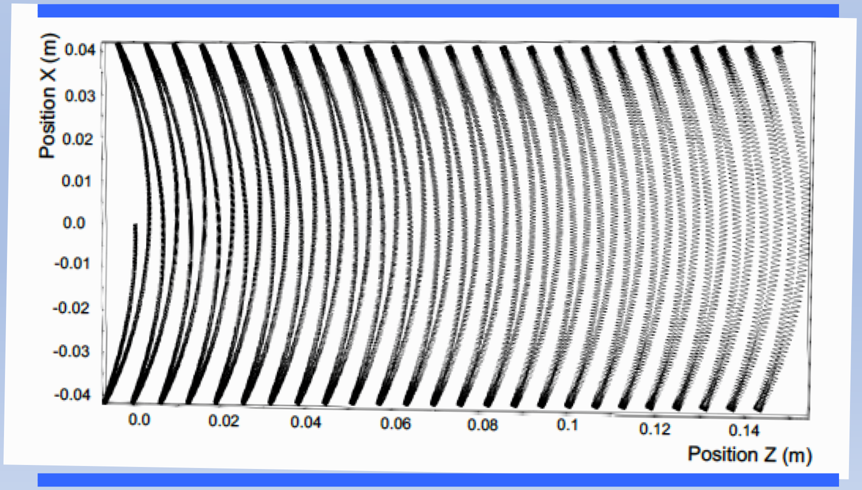
$$E_x = 0 \; ,$$
$$E_y = E_0 \cos\left(\frac{y}{\lambda}\right) e^{-z/\lambda} \; ,$$
$$E_z = -E_0 \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda} \; ,$$
$$B_x = B_0 \cos\left(\frac{x}{\lambda}\right) e^{-z/\lambda} \; ,$$
$$B_y = 0 \; ,$$
$$B_z = -B_0 \sin\left(\frac{x}{\lambda}\right) e^{-z/\lambda}$$

$$E_0 = -\frac{\mu B_0}{q\lambda \sin\left(y_0/\lambda\right)}$$

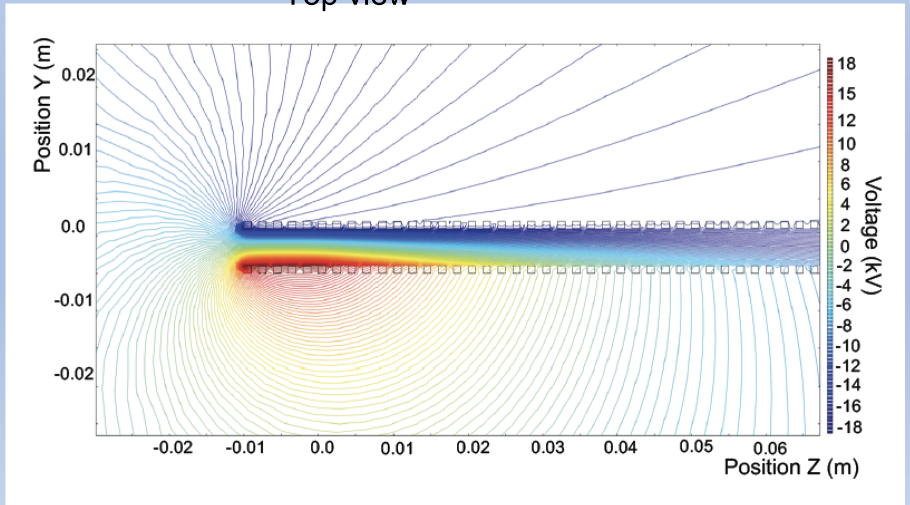


Side view

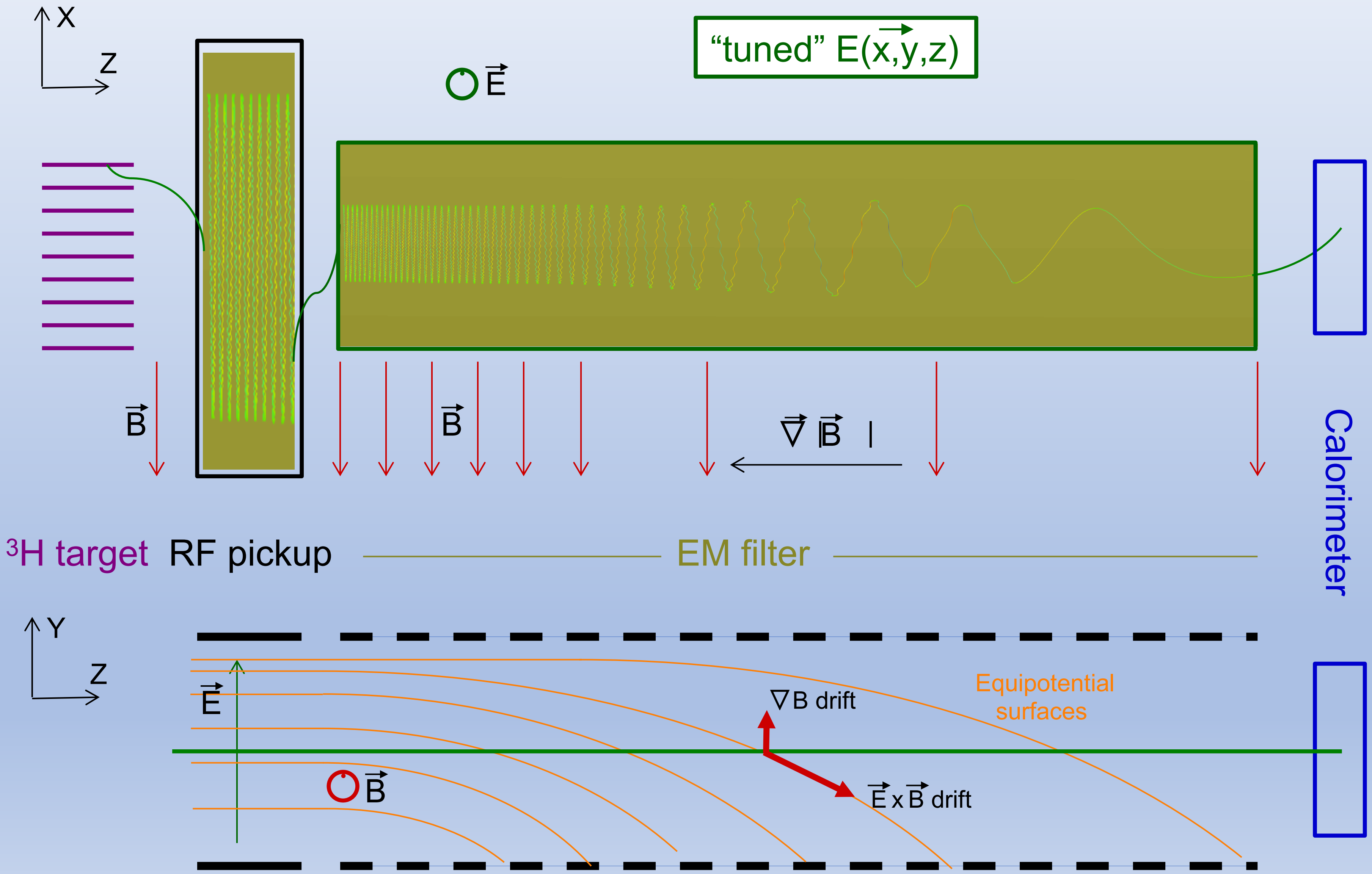
negative potential walls



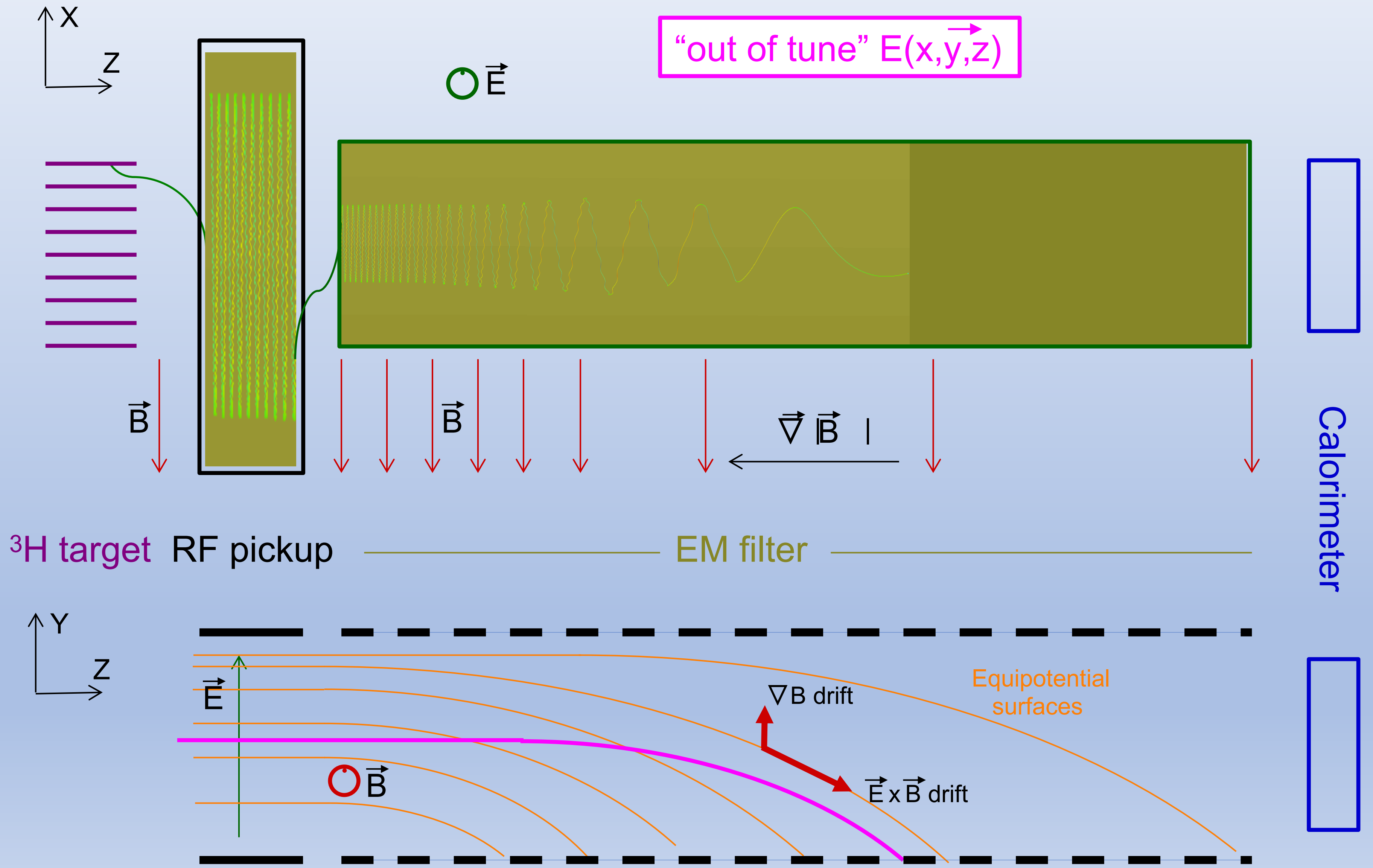
Top view



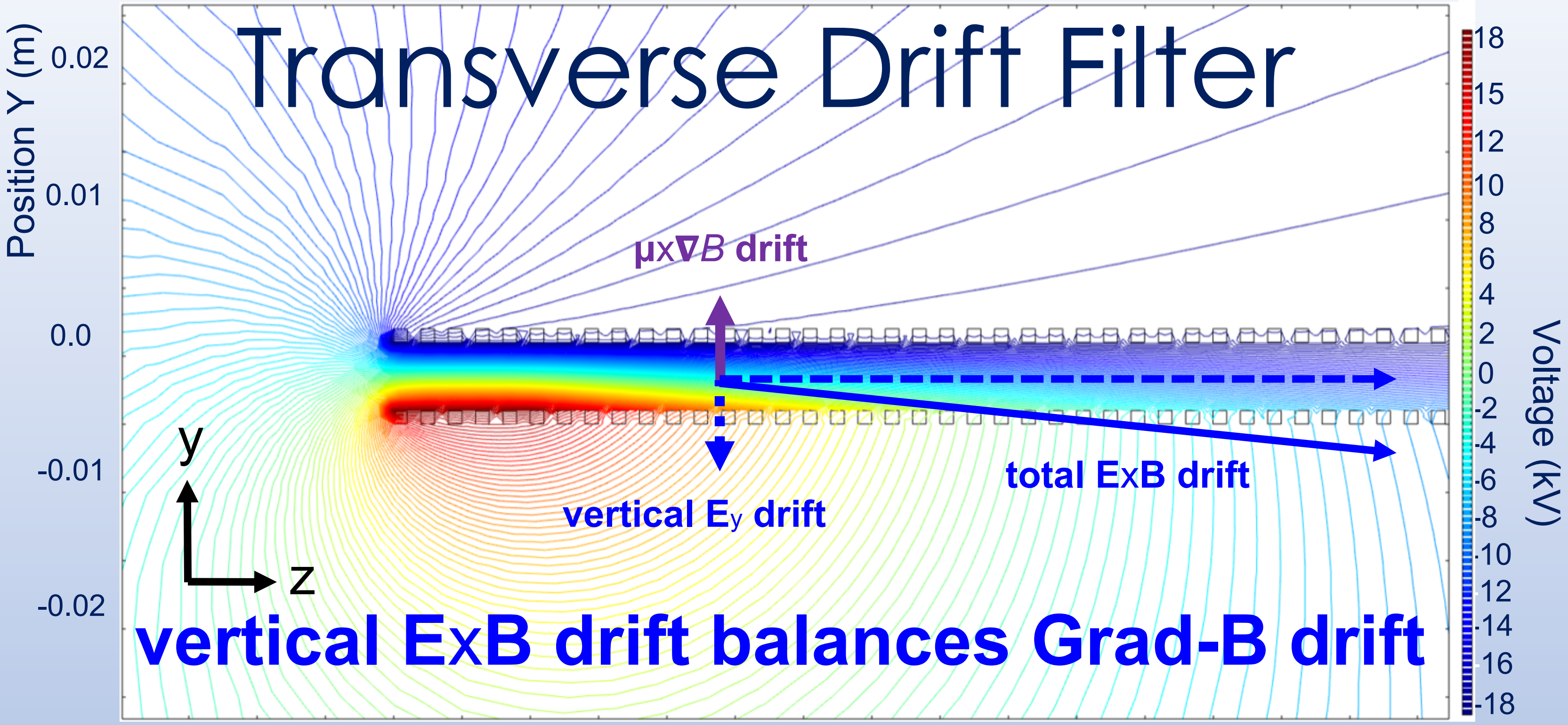
New concept EM filter
Dynamic tuning

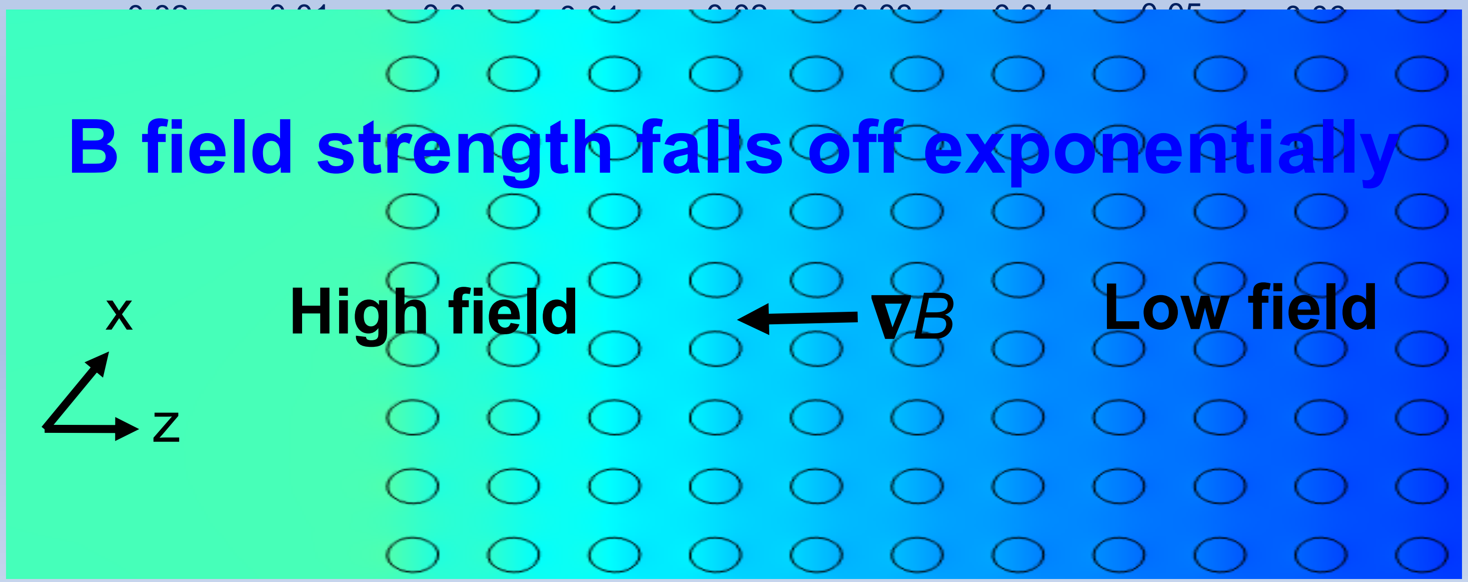


New concept EM filter
Dynamic tuning



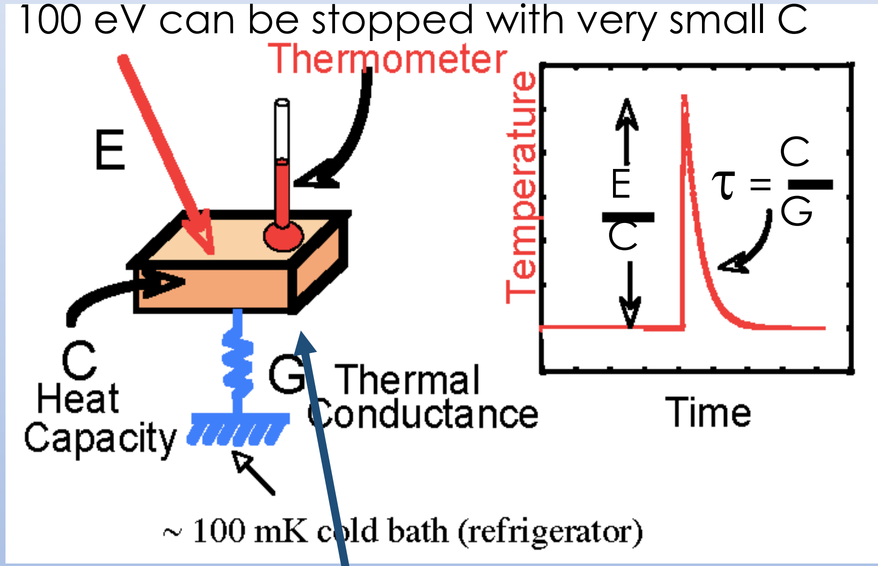
Transverse Drift Filter





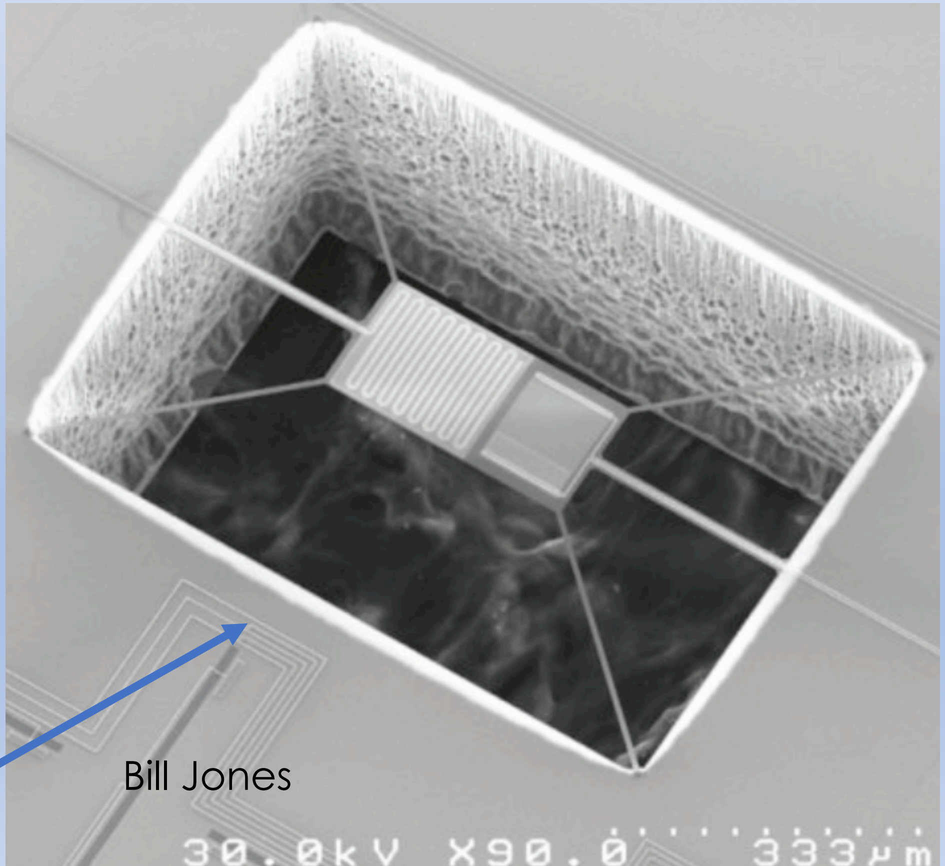
Calorimetric measurement
based on Transition Edges Sensors technology

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

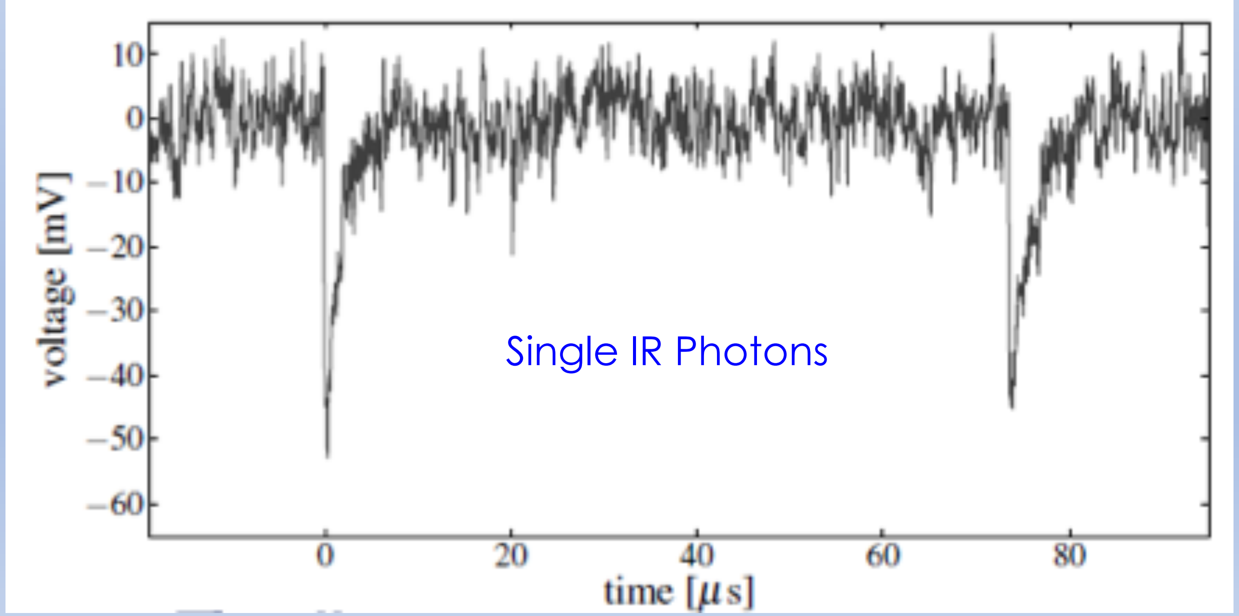


SPIDER island TES example

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)

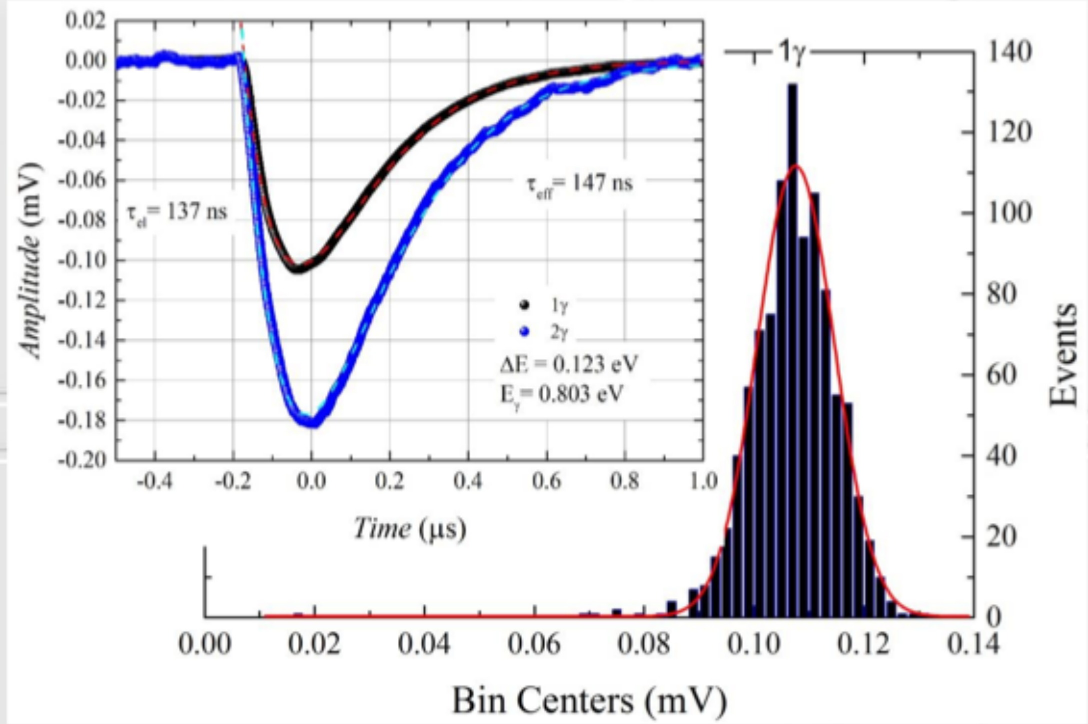


Microcal for IR Photons

IR TES achieve 0.12 eV resolution at 0.8 eV for single IR photons

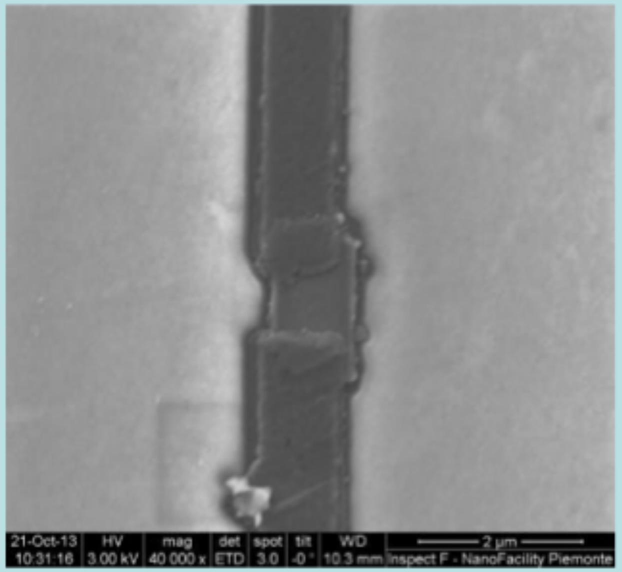
Results from INRIM (Torino) - Istituto Nazionale di Ricerca Metrologica

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

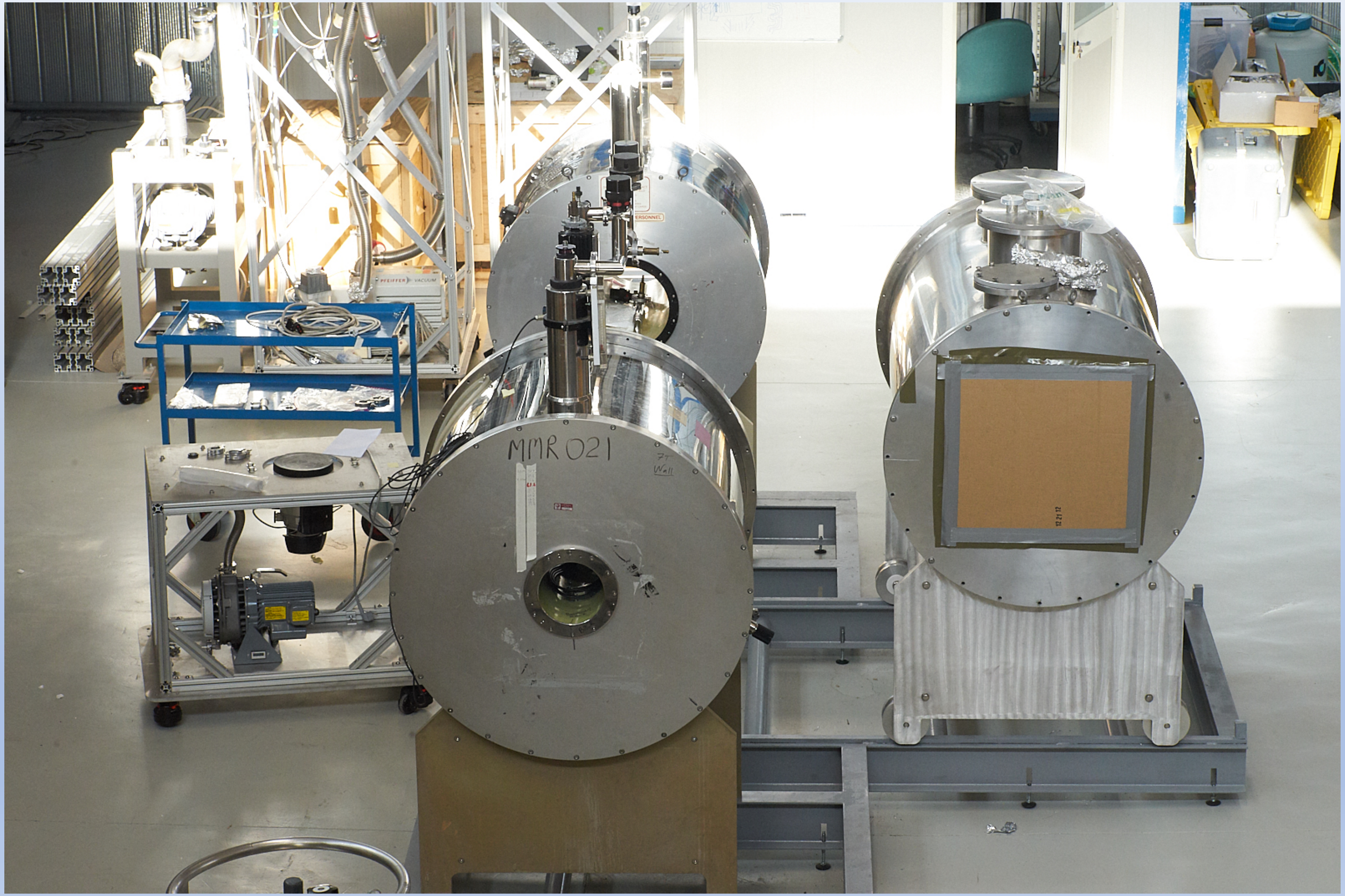


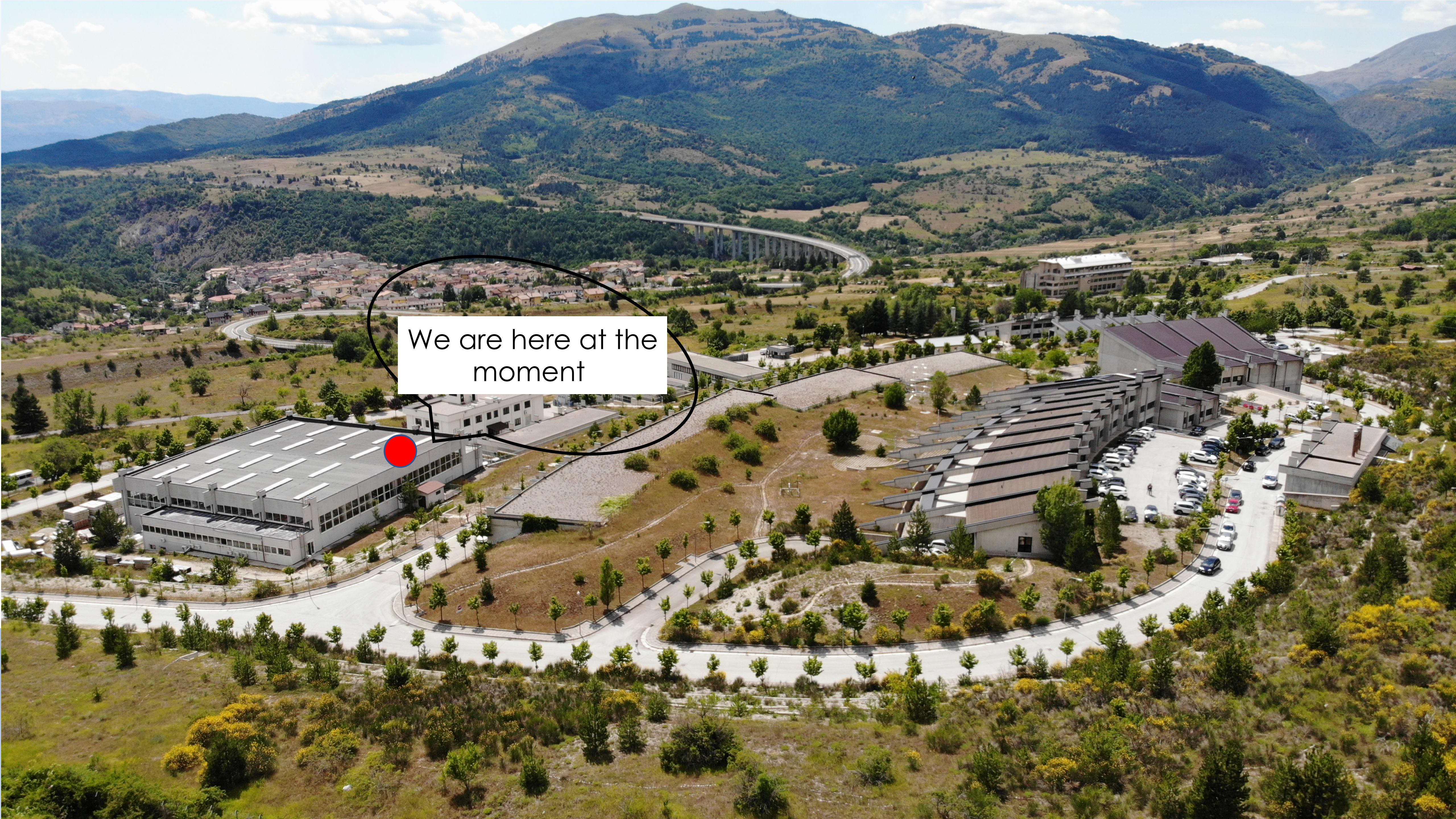
$\tau_{etf} = 147\text{ns}$ $\Delta E_{FWHM} = 0.12$ eV @ 1545nm

1 μm × 1 μm



Experimental site at LNGS




We are here at the moment

Light Dark Matter search

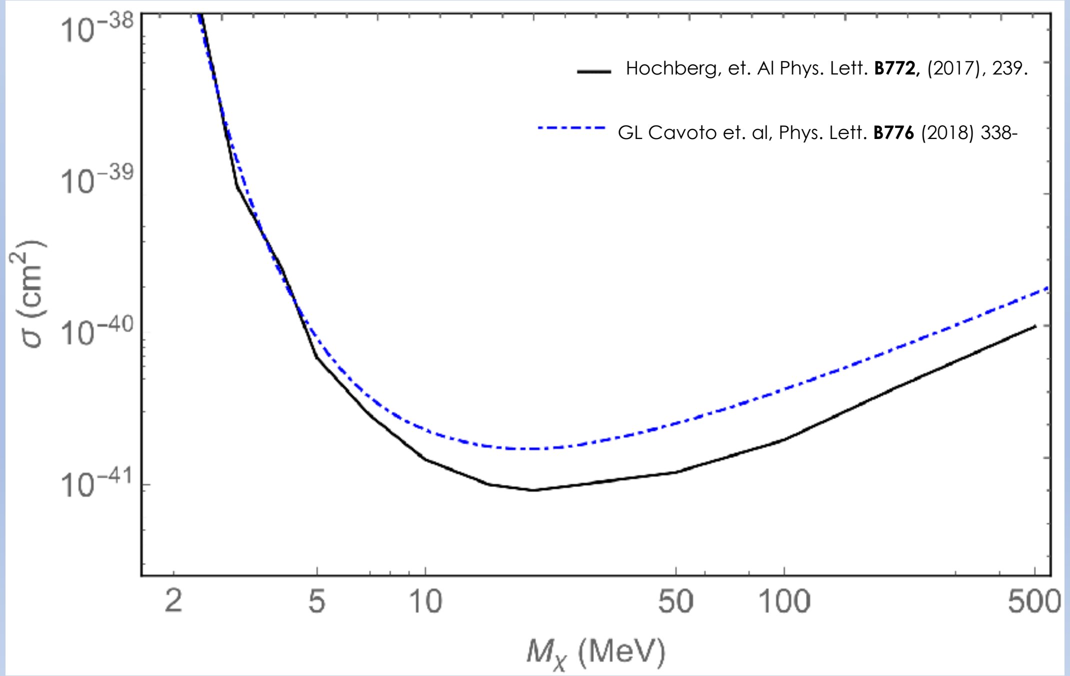
Side project potentially very much interesting

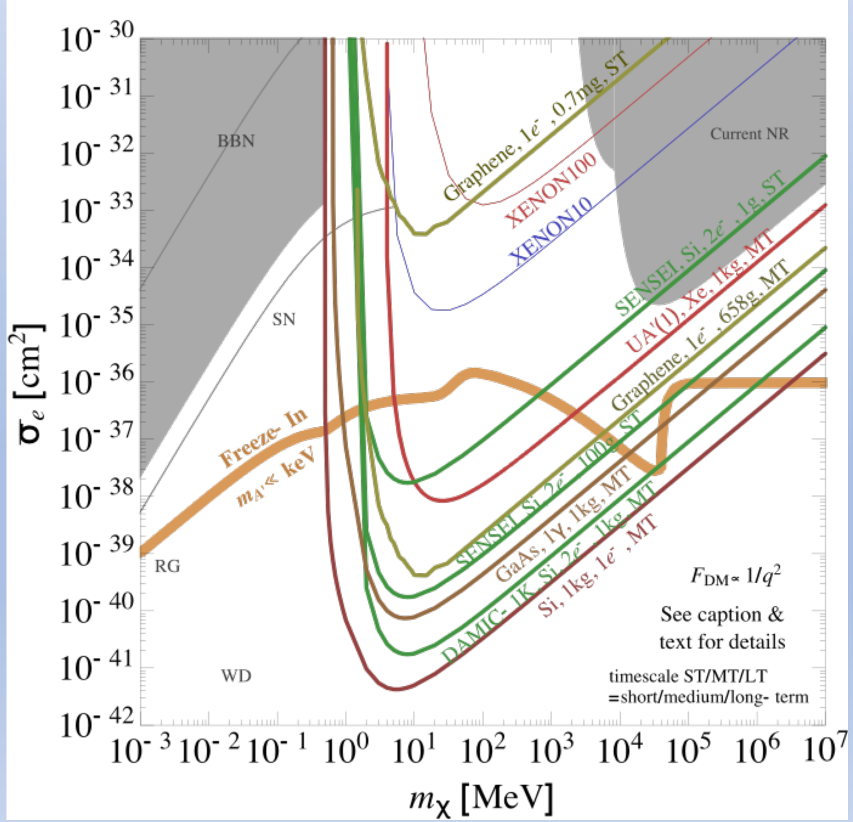
- Hochberg, et. al, "Directional Detection of Dark Matter with 2D Targets", Phys. Lett. **B772,** (2017), 239.
- GL Cavoto et. Al, "Sub-GeV Dark Matter Detection with Electron Recoils in Carbon Nanotubes "Phys. Lett. **B776** (2018) 338-344

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.

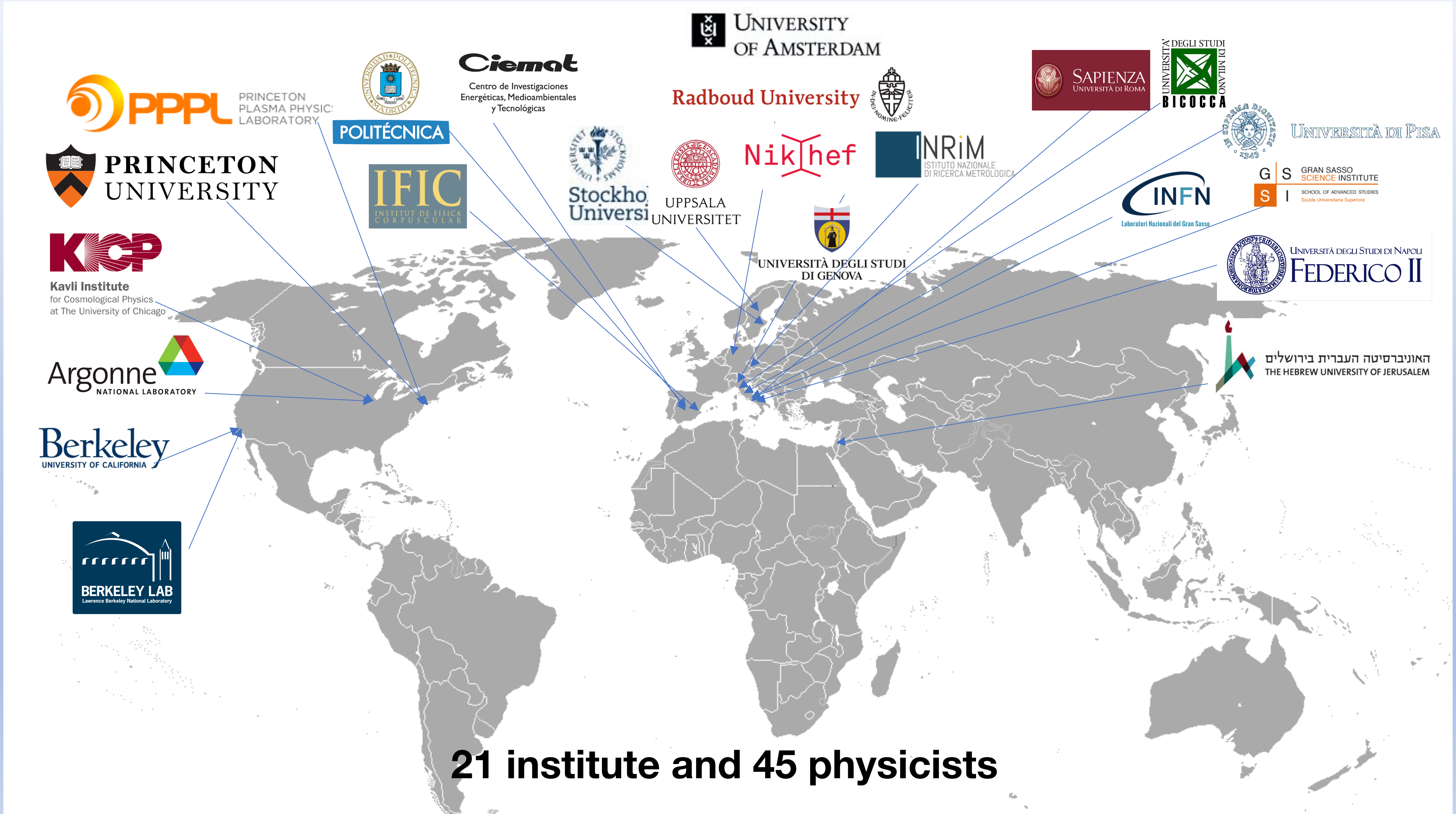
The requirements crucial for the PTOLEMY CNB detection project could be also very much beneficial for Light DM search:

- 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**