The PTOLEMY experiment, how to have a glance at the first second of the Universe

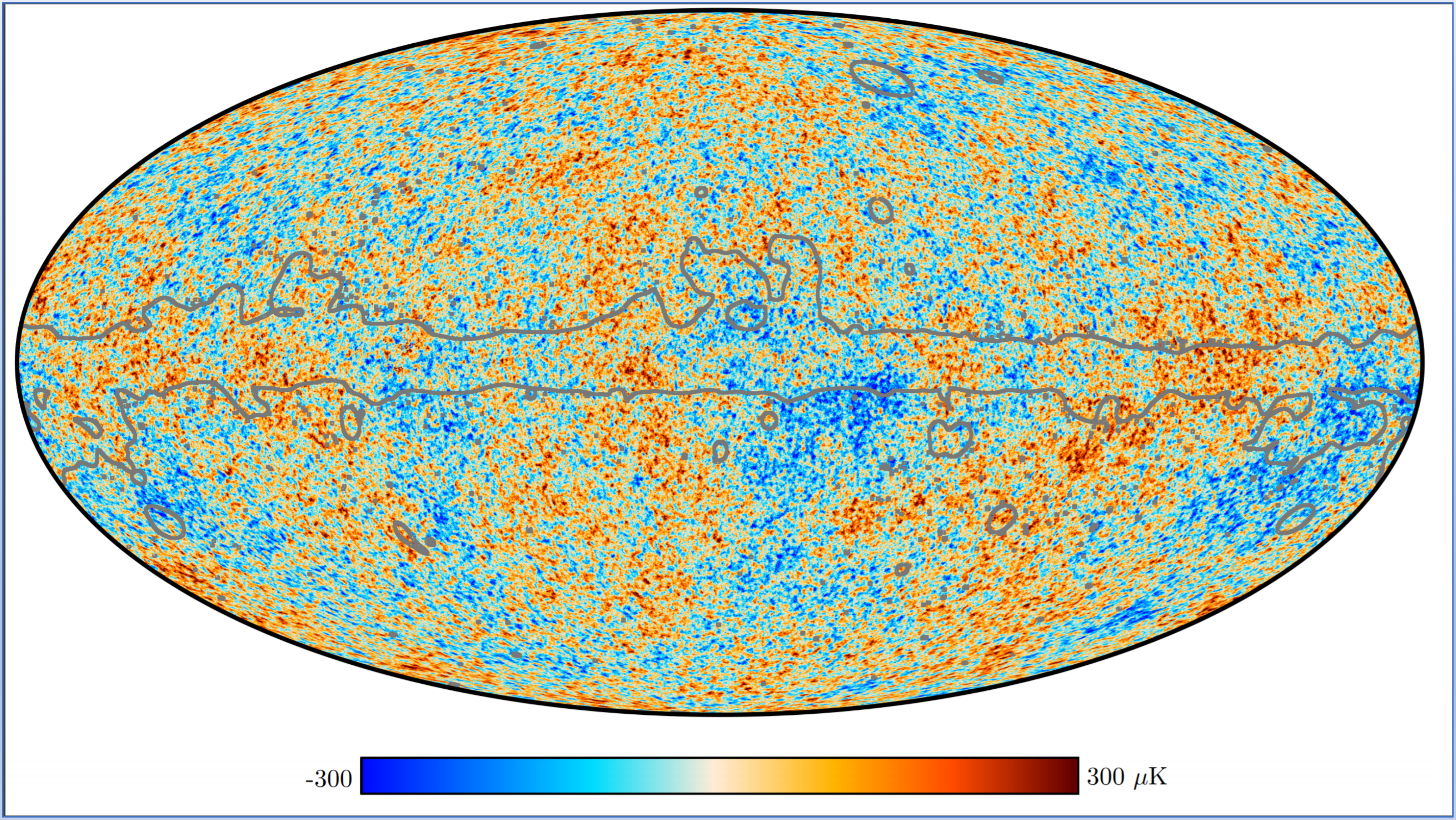
Marcello Messina Researcher at LNGS-INFN,

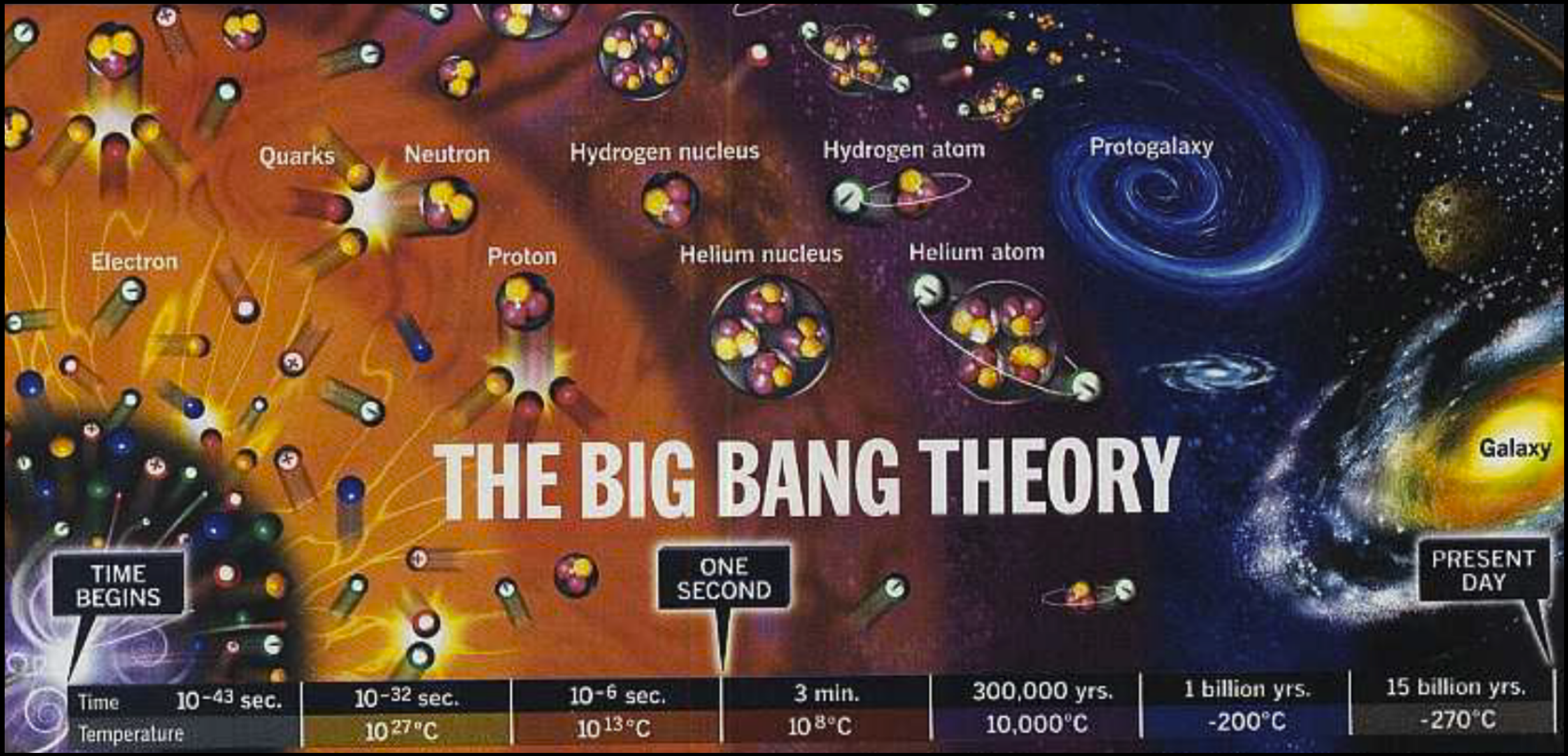
7° KSETA Plenary Workshop, Germany, February 2020

Why we believe in Big Bang?

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

Who told the history of the Universe so far?





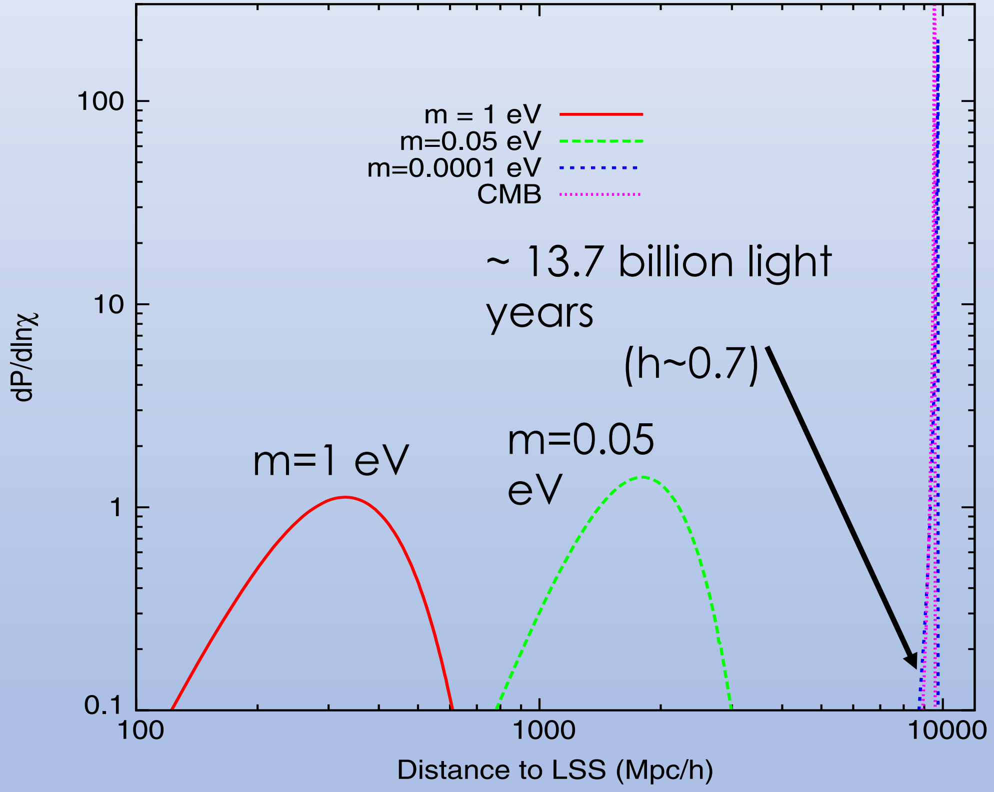
CNB ~ 1 sec

CMB ~ 380k yr

Neutrino Mass and Future Observations

At less than 1 second after the Big Bang, nearly 50% of the total energy density of the Universe was in the form of neutrino kinetic energy. This is the time when neutrinos thermally decoupled from matter and began free-streaming through the Universe.

S. Dodelson and M. Vesterinen,
"Cosmic Neutrino Last Scattering Surface (LSS),"
http://doi.org/10.1103/PhysRevLett.103.171301

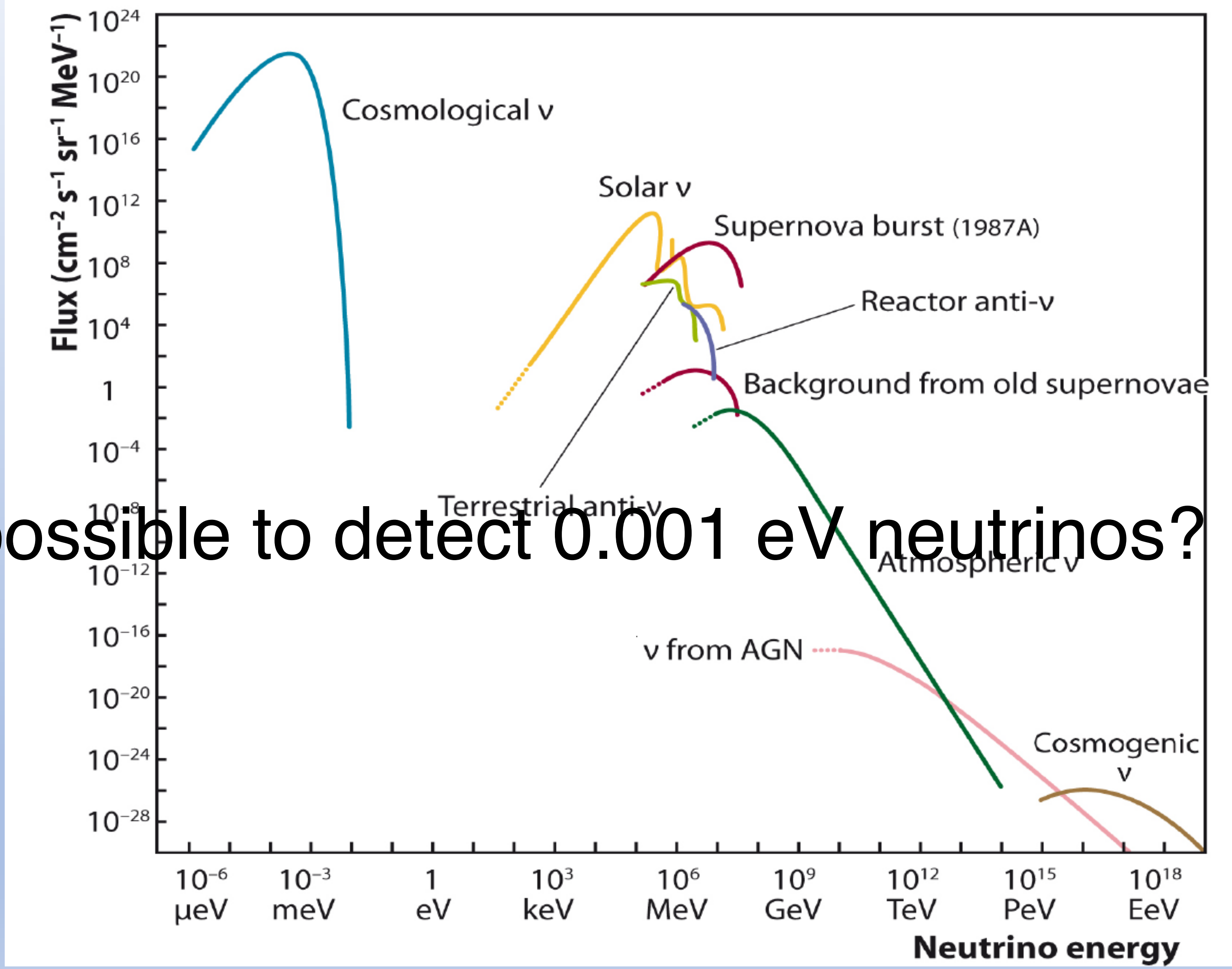


Due the finite mass of the neutrinos and Hubble expansion, the relic neutrinos that arrive at Earth today (after 13.7 billion years of waiting for them) originate from distances less than 2 billion light years away.
With extensive galaxy cluster survey data seen with optical and infra-red, we can directly compare to the original seeds of structure recorded by the neutrinos – two images of the same location in space separated by over 10 billion years.

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?

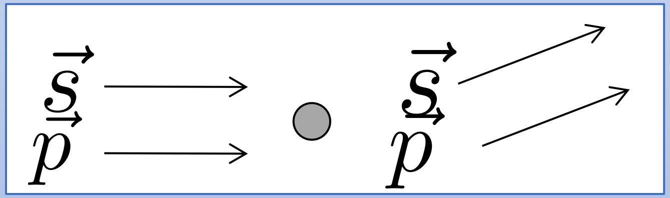
The detection methods proposed so far!

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 (ΔJ) (R.R. Lewis Phy. Rev. D21 663, 1980):

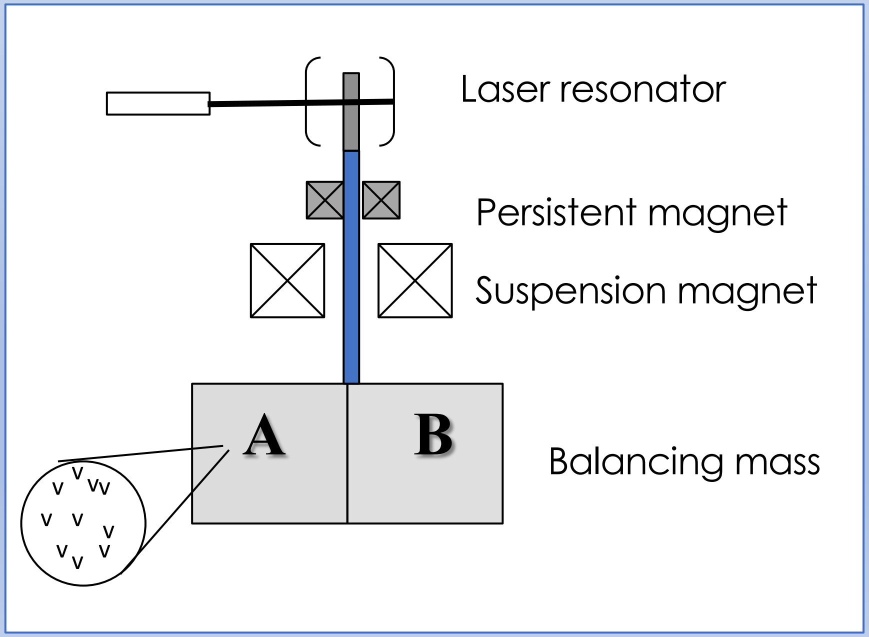
$$\Delta J = \lambda \Delta p$$



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 see $f = \left(\nu - \bar{\nu}\right) \neq 0$



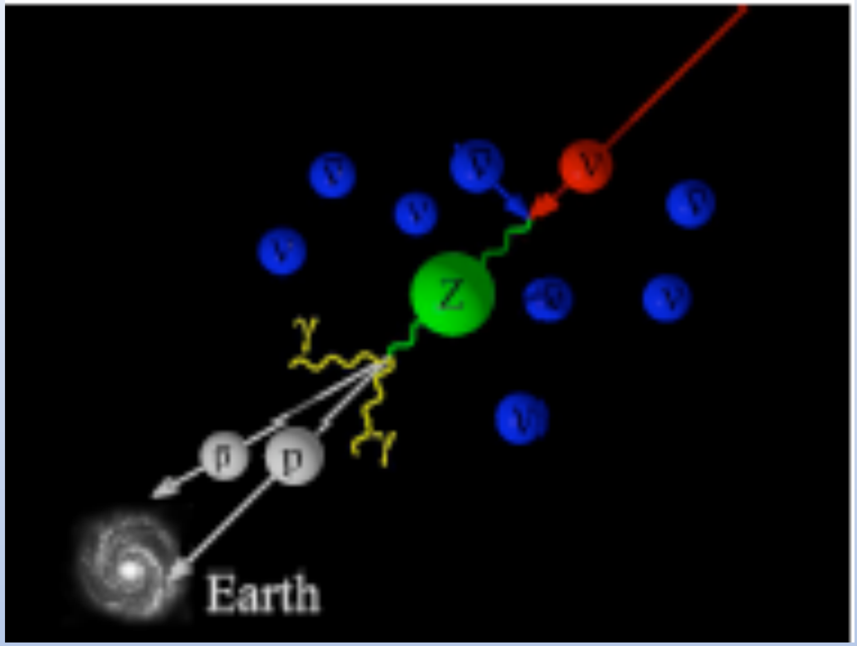
Since the n wave length is ~ mm (λ) can be envisaged an enhancement of the interaction rate due to coherent sum of the invariant scattering amplitudes in a volume λ^3. Under this assumption:

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

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

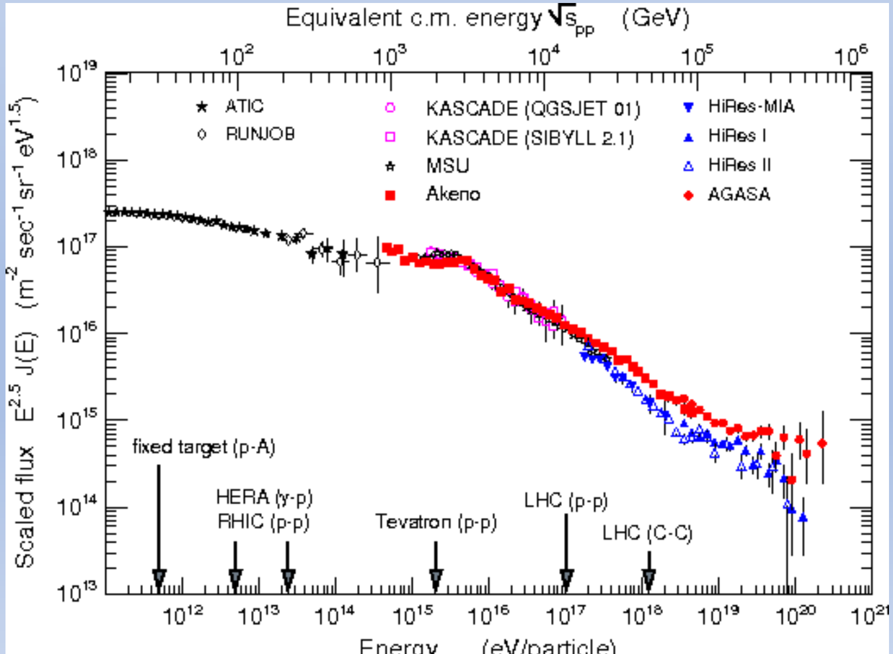
Is it possible to measure the CRN ?
Method 2



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 events excess 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 $\sim 4\times10^4$ 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 ?

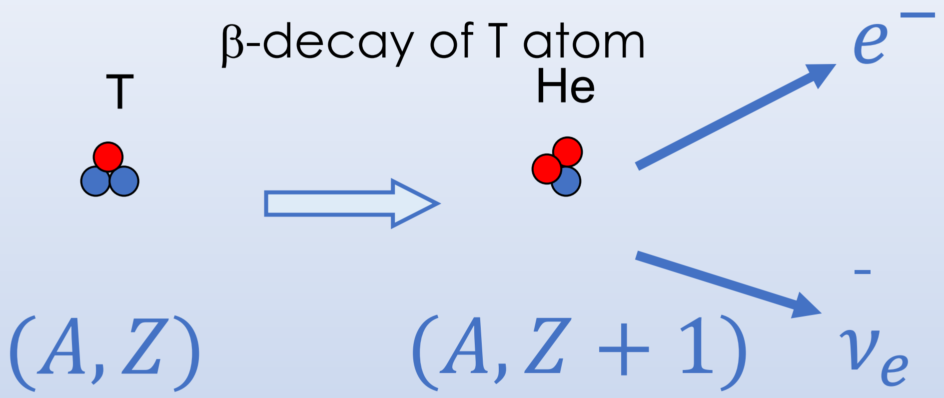
All methods proposed so far require unrealistic experimental apparatus or astronomical neutrino sources not yet observed and not even hypothesized .

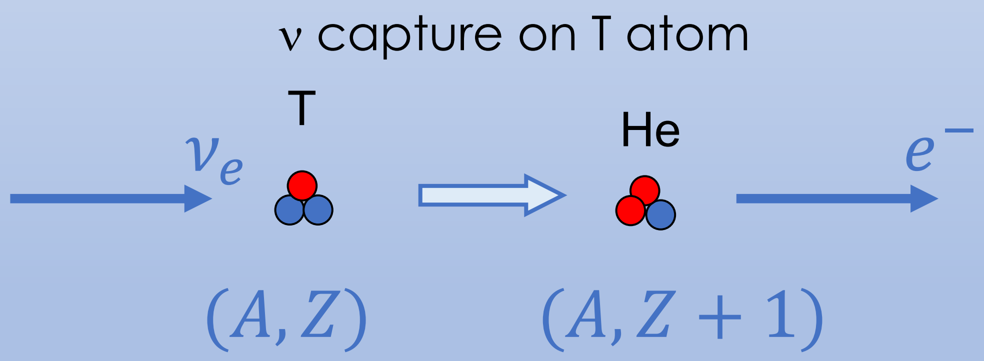
For reviews on this subject see:

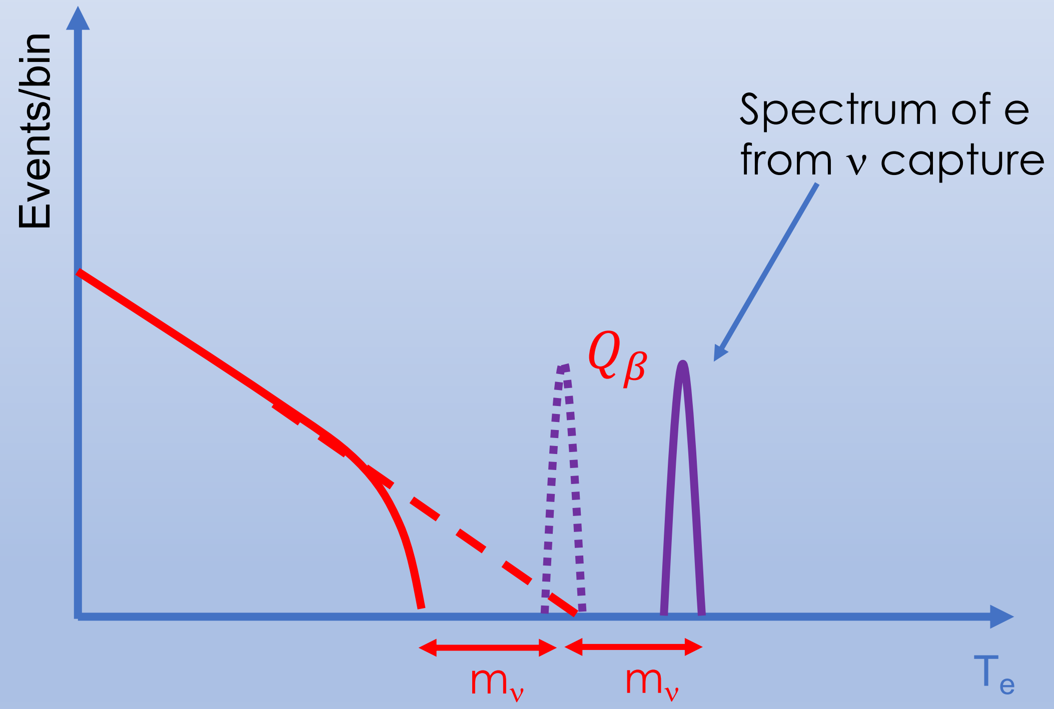
A.Ringwald "Neutrino Telescopes" 2005 – hep-ph/0505024

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

Detection principle



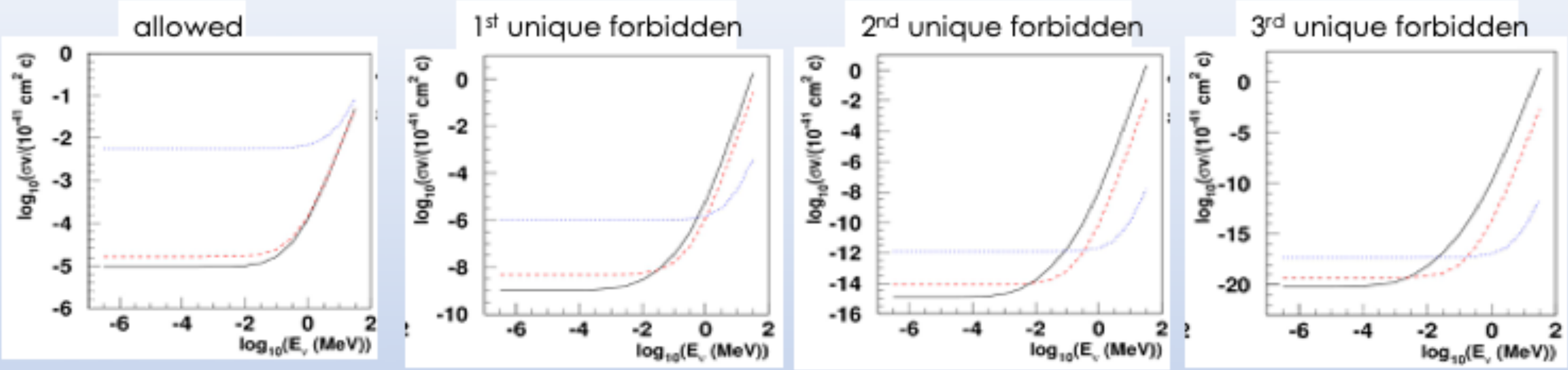




A.G. Cocco, G. Mangano and M. Messina, JCAP 06 (2007) 015
S Weinberg, *Phys. Rev.* (1962) 128:3, 1457

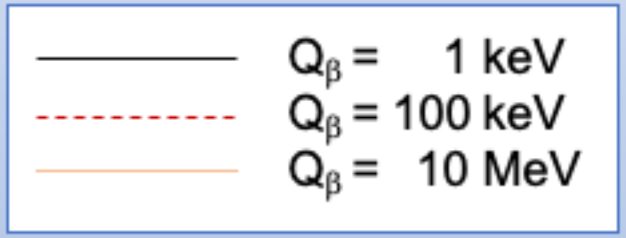
NCB Cross Section

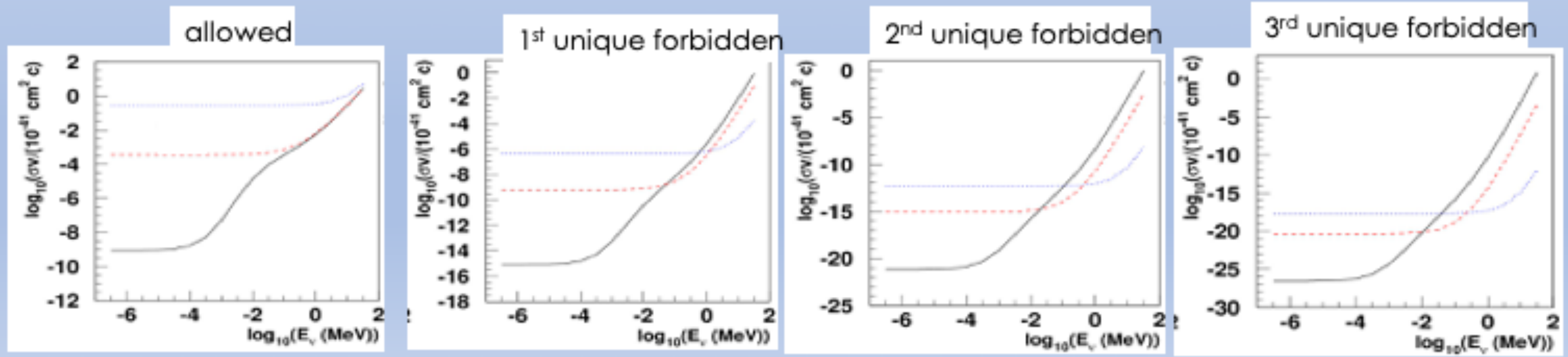
as a function of E_ν, Q_β for different nuclear spin transitions



β^- (top)

β^+ (bottom)

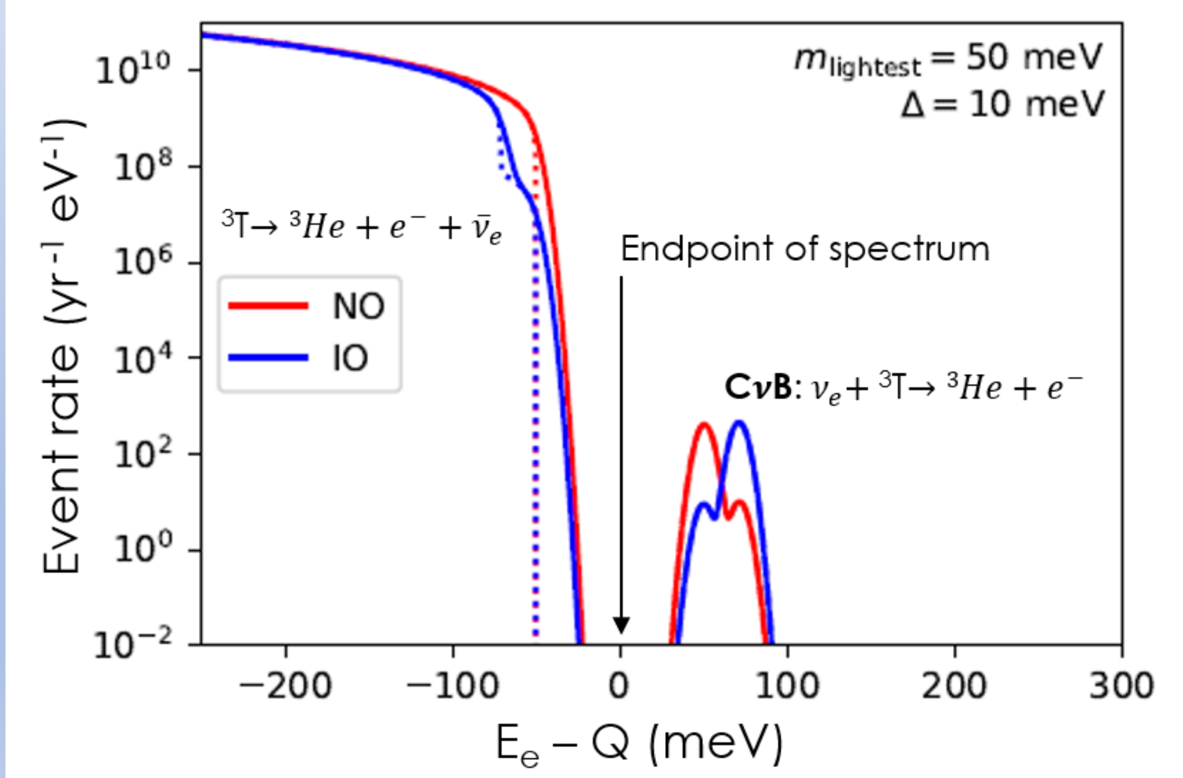




Why Tritium target?

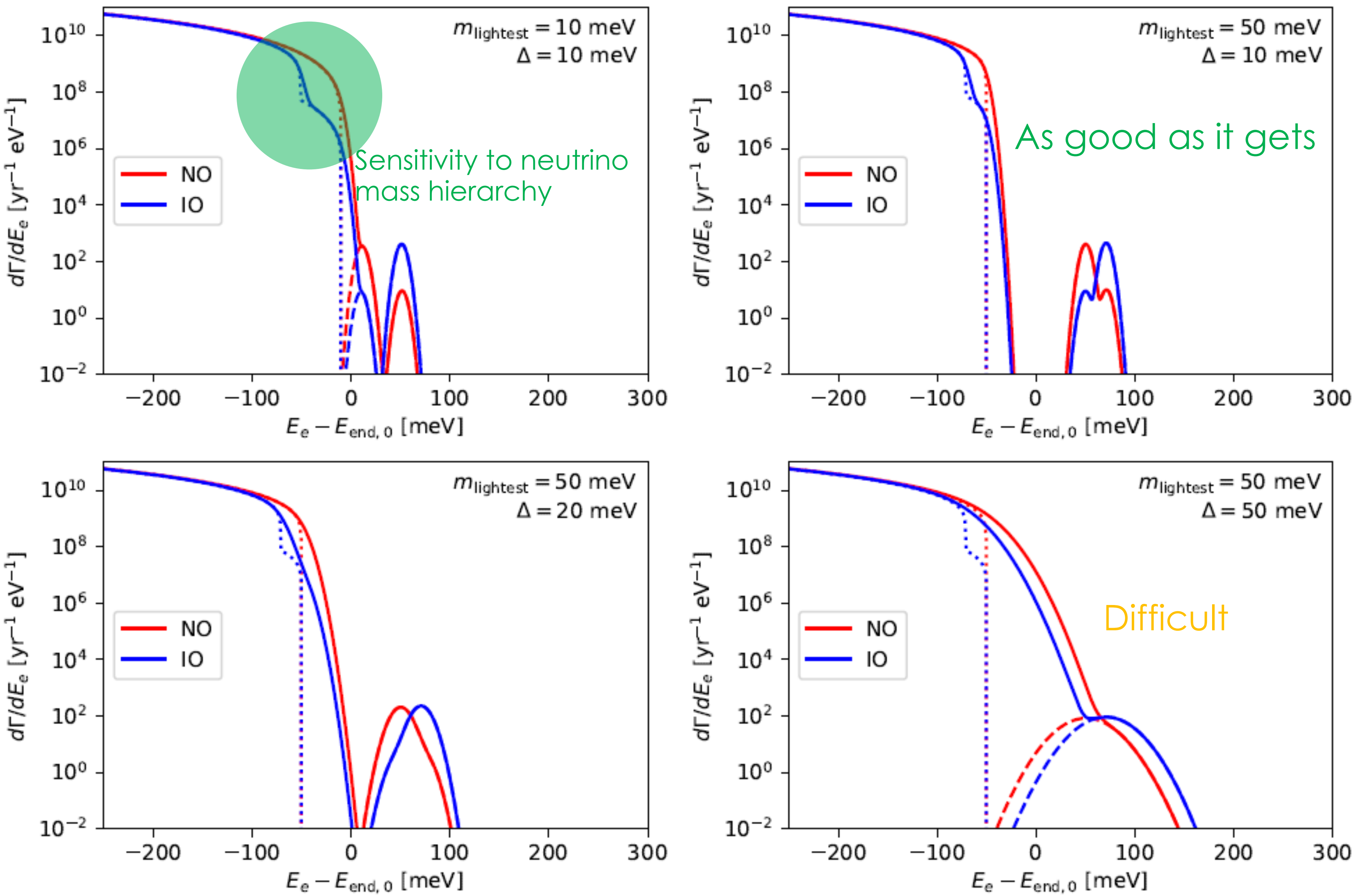
- High cross-section for neutrino capture
- Sizeable lifetime
- Low Q-value
- **Tritium beta decay ~10^{15} Bq/gram**

PTOLEMY collaboration **JCAP 1907 (2019) 047**



Several σ_E and m_ν scenarios

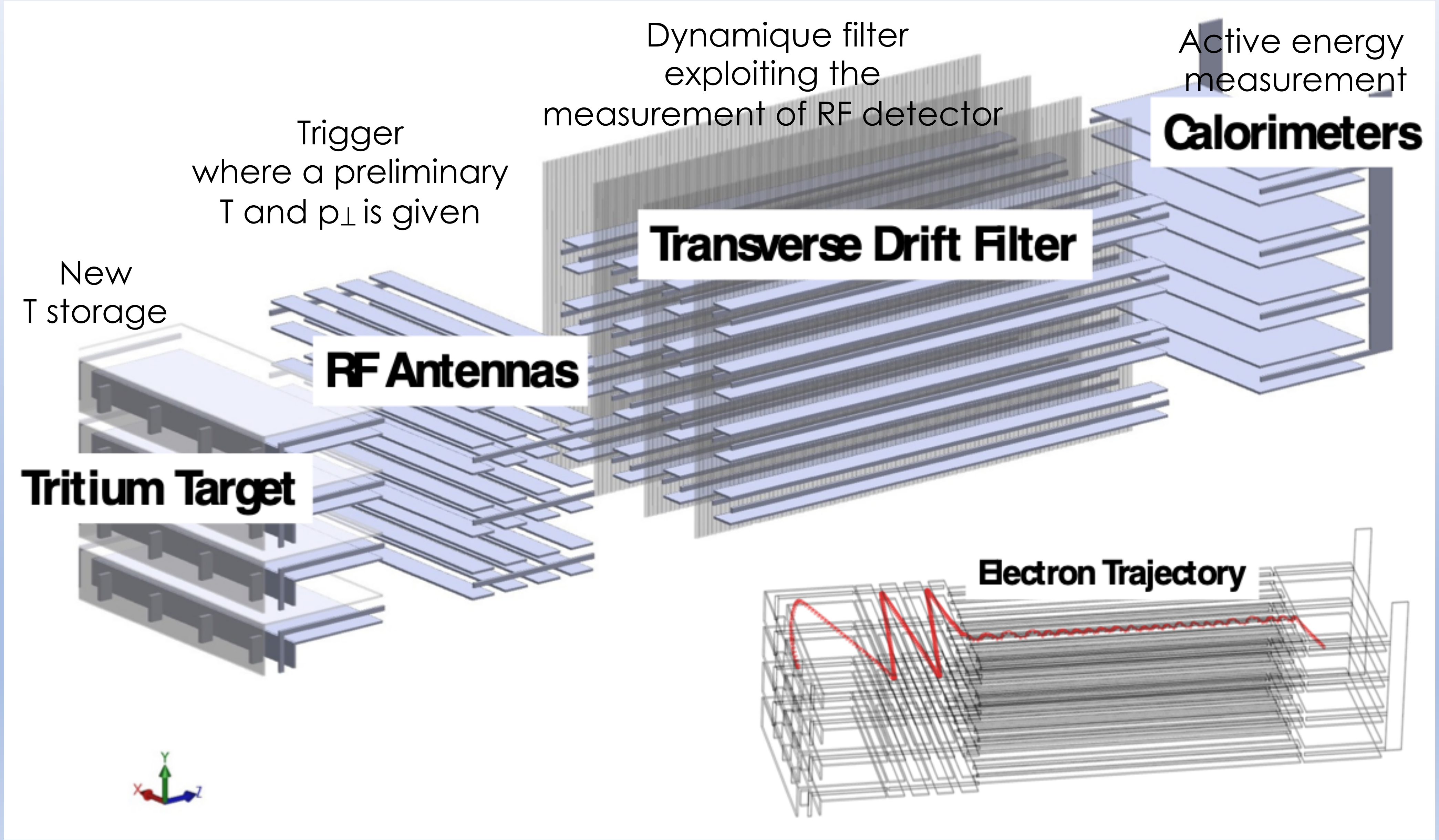
PTOLEMY collaboration **JCAP 1907 (2019) 047**



PTOLEMY experiment

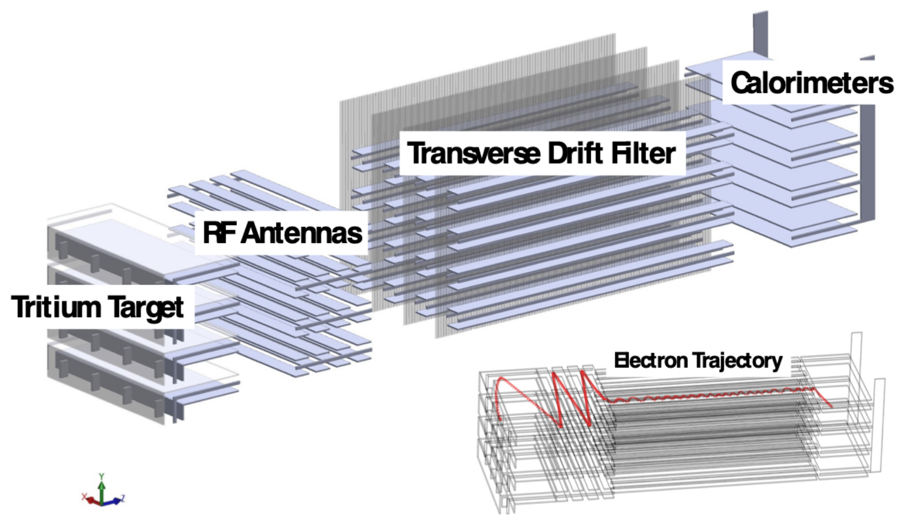
- Goal:
  1. Find evidence for CνB
  2. Accurate measurement of neutrino mass
  3. Light DM detection (not discussed in this talk)
- Key challenges:
  1. Extreme energy resolution is required
  2. Extreme background rates from the target

PTOLEMY: experiment layout



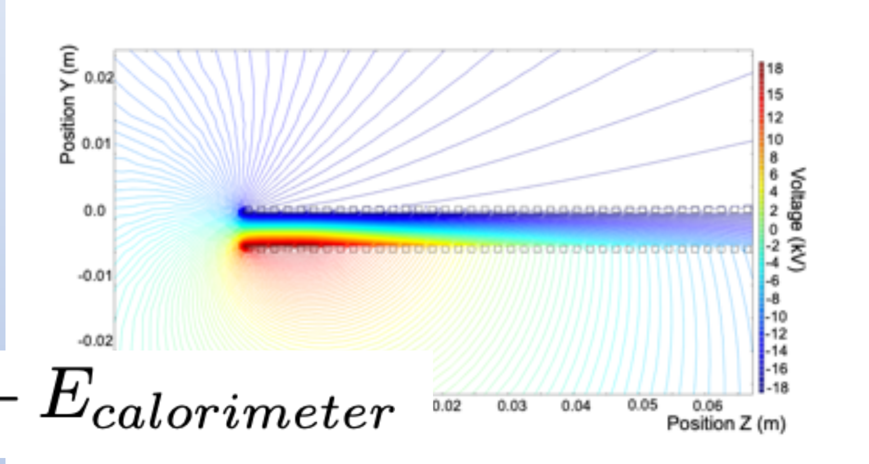
PTOLEMY: measurement principle

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



Step 3

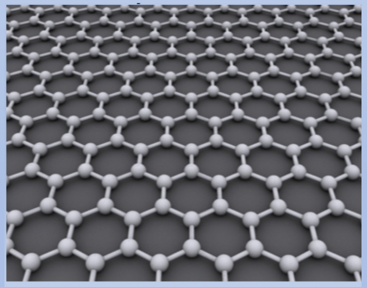
Transverse kinetic energy is removed.
Field properly set on ms time scale.
“Wrong particle will end up on one of the electrodes and the right one will pass”



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

Step 1

A new way of storing atomi



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

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

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

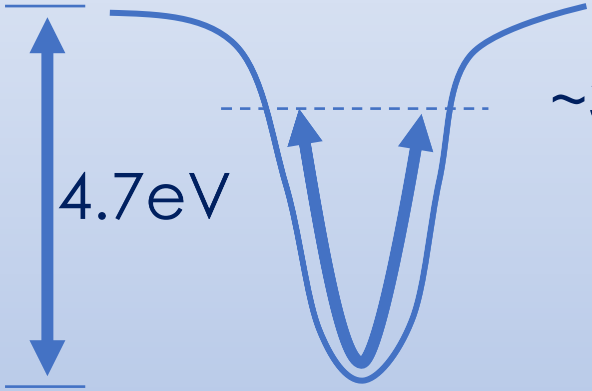
The particle is driven into the TES: $T_{tot}=q(V_{anode} - V_{source}) + E_{cal}$

PTOLEMY: The source

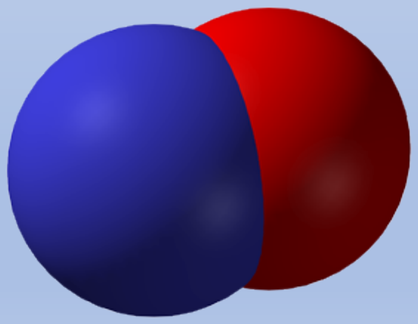
- Use **atomic T**
  - No vibrational modes in final state like for ^{3}He-^{3}T final state.
  - Limit to energy resolution not determined by target itself

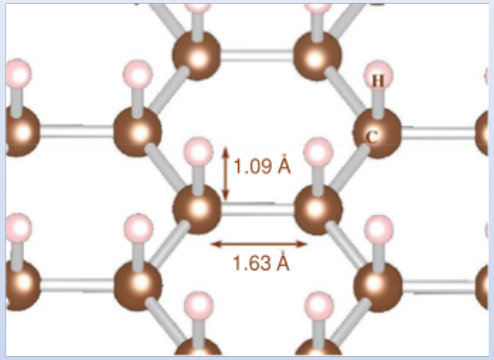
Molecular Broadening

T-T → $(T\text{-}He^3)^*$



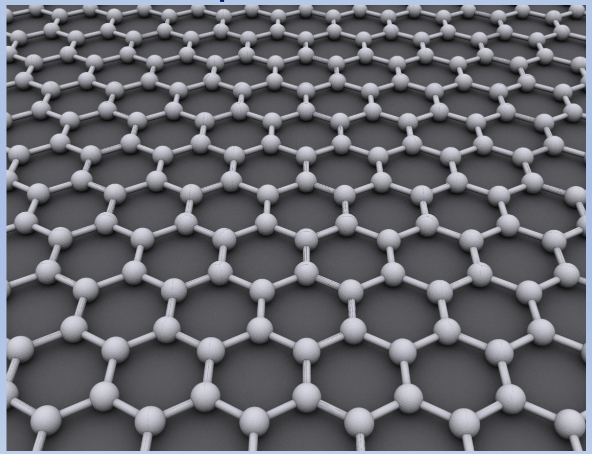
~3eV He^3 recoil at endpoint





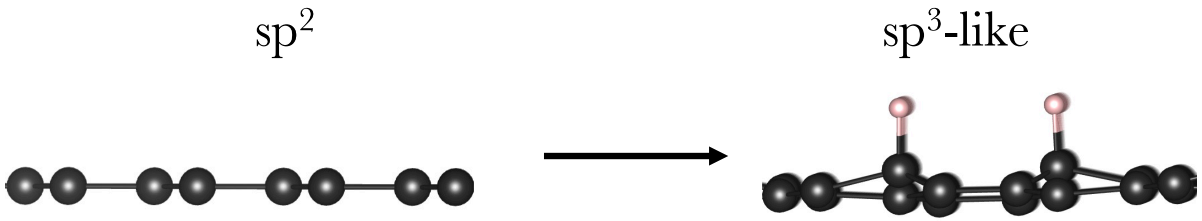
<3eV binding energy

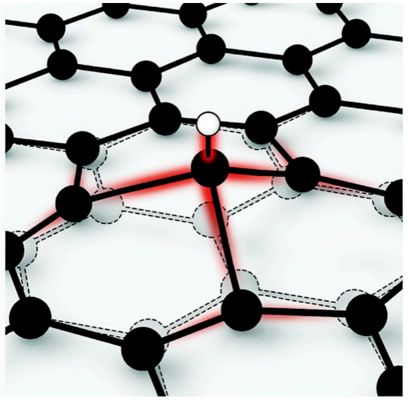
Graphene



Tritiated-Graphene Target

H/D approach to graphene leads to chemical bond formation coincident with sp^2 to sp^3-like rehybridization of a C atom.





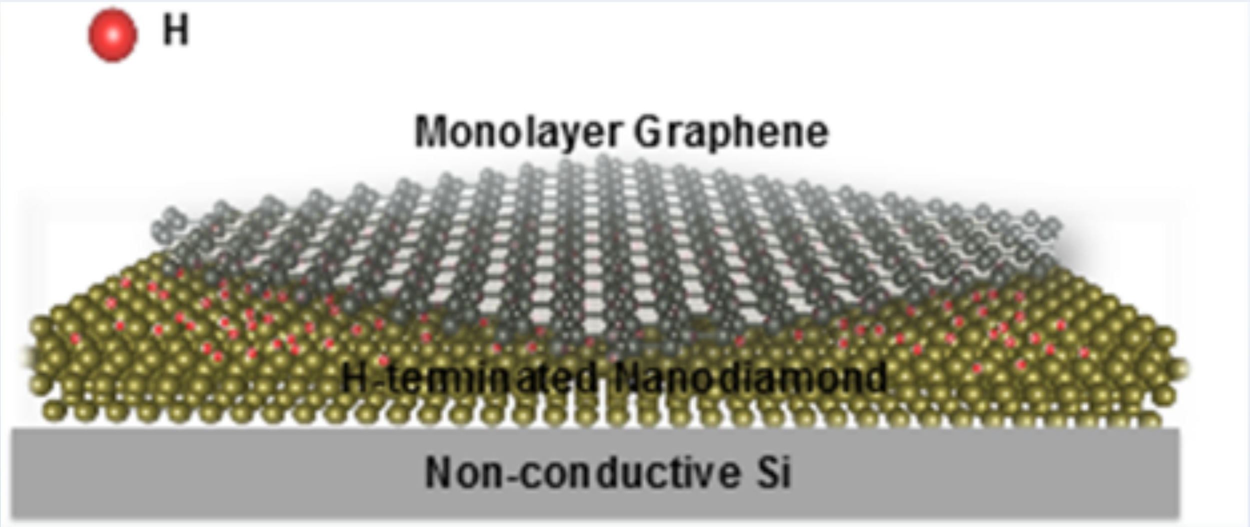
When hydrogen hits a graphene carbon if the incidence energy passes over the barrier, it forms a C-H covalent bond. Graphene dissipates energy in two ways: an up and down vibration of the sheet and a shock wave moving out across its surface.[1]

Ref: Jiang H. *et al.* Imaging covalent bond formation by H atom scattering from graphene. *Science* 26 Apr 2019. Vol. 364, Issue 6438, pp. 379-382

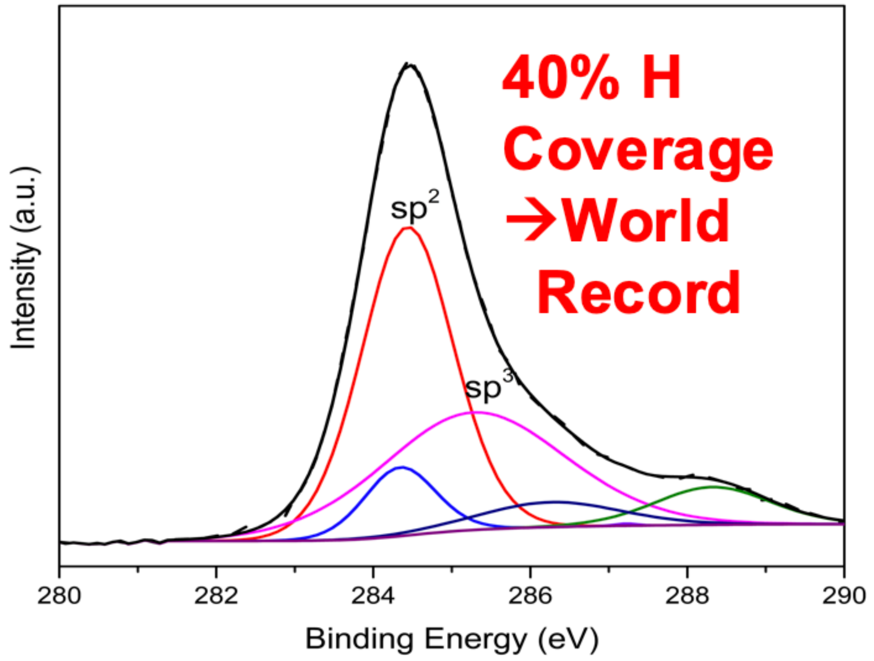
Advantages:
- → Statistical uniformity achieved for ~1% coverage
- → Stable at room temperature and in vacuum and/or air
- → Conductive at 1% coverage and provides a precision voltage reference
- → Sufficient for R&D program @LNGS

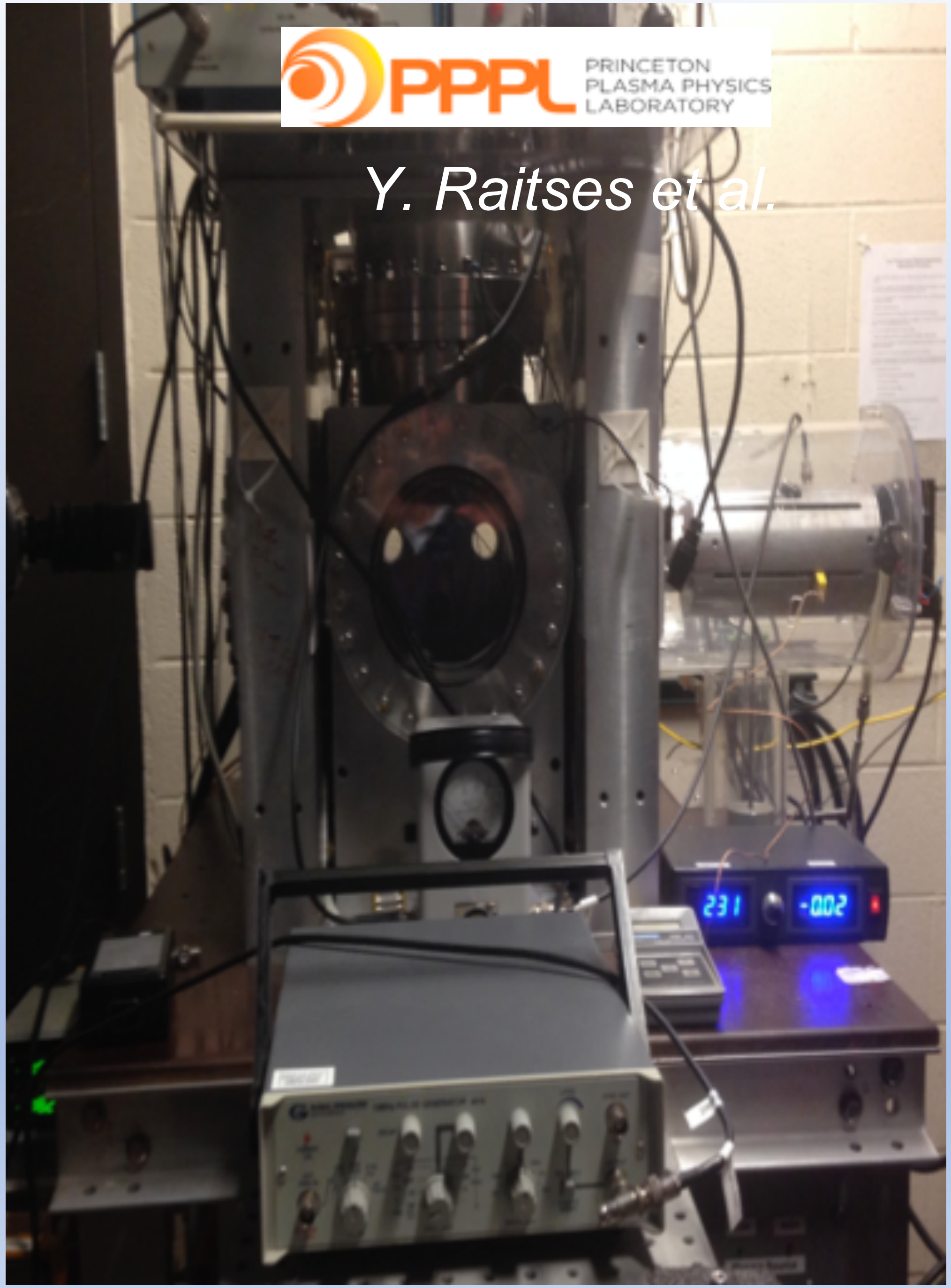
→ **Final-state molecular smearing will be measured directly** by repeating the recoil energy analysis in Reference[1] (done with ^{1}H) with ^{3}He atoms

Cold Plasma Loading



XPS Hydrogenation Results from Princeton

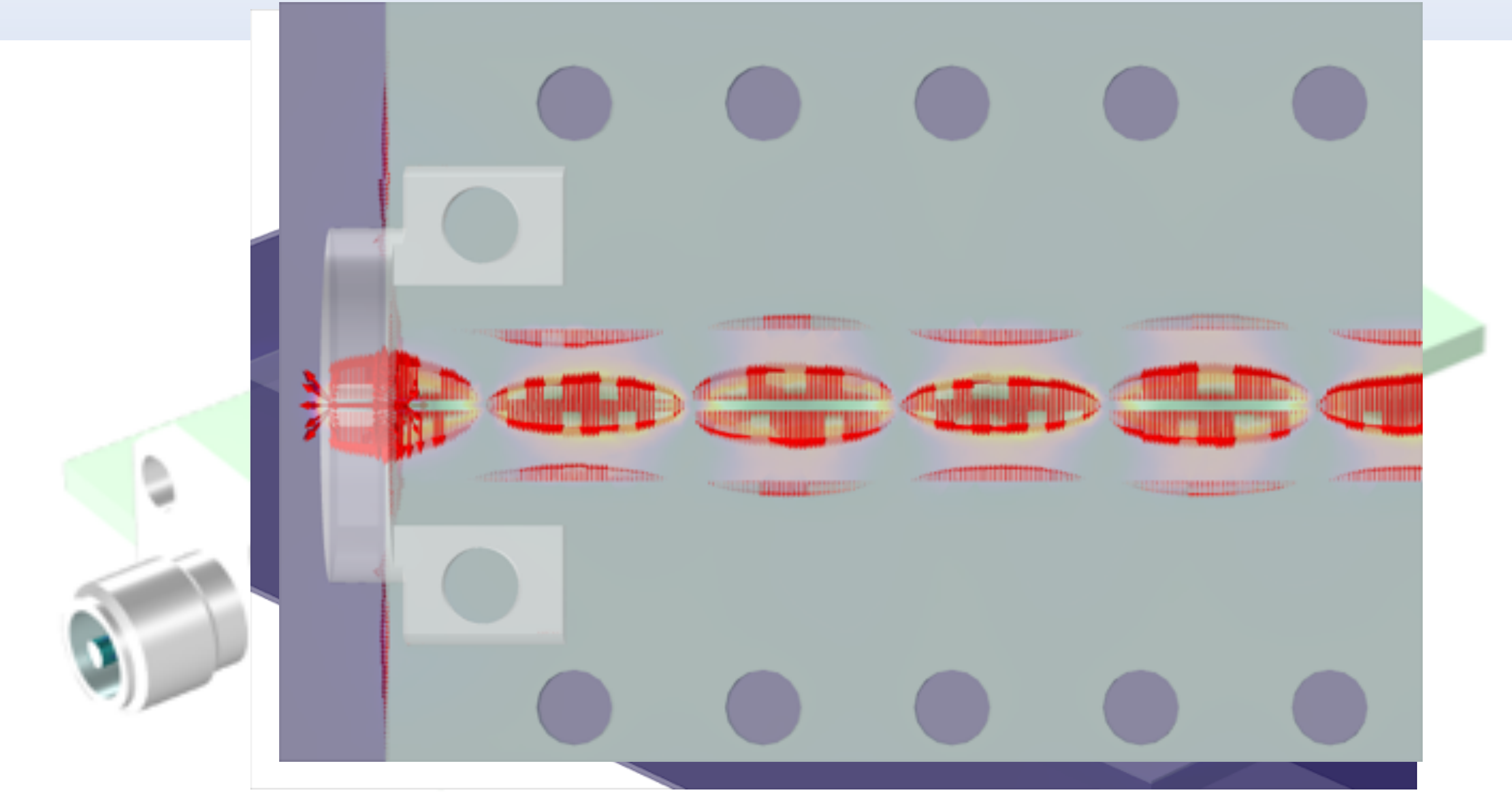




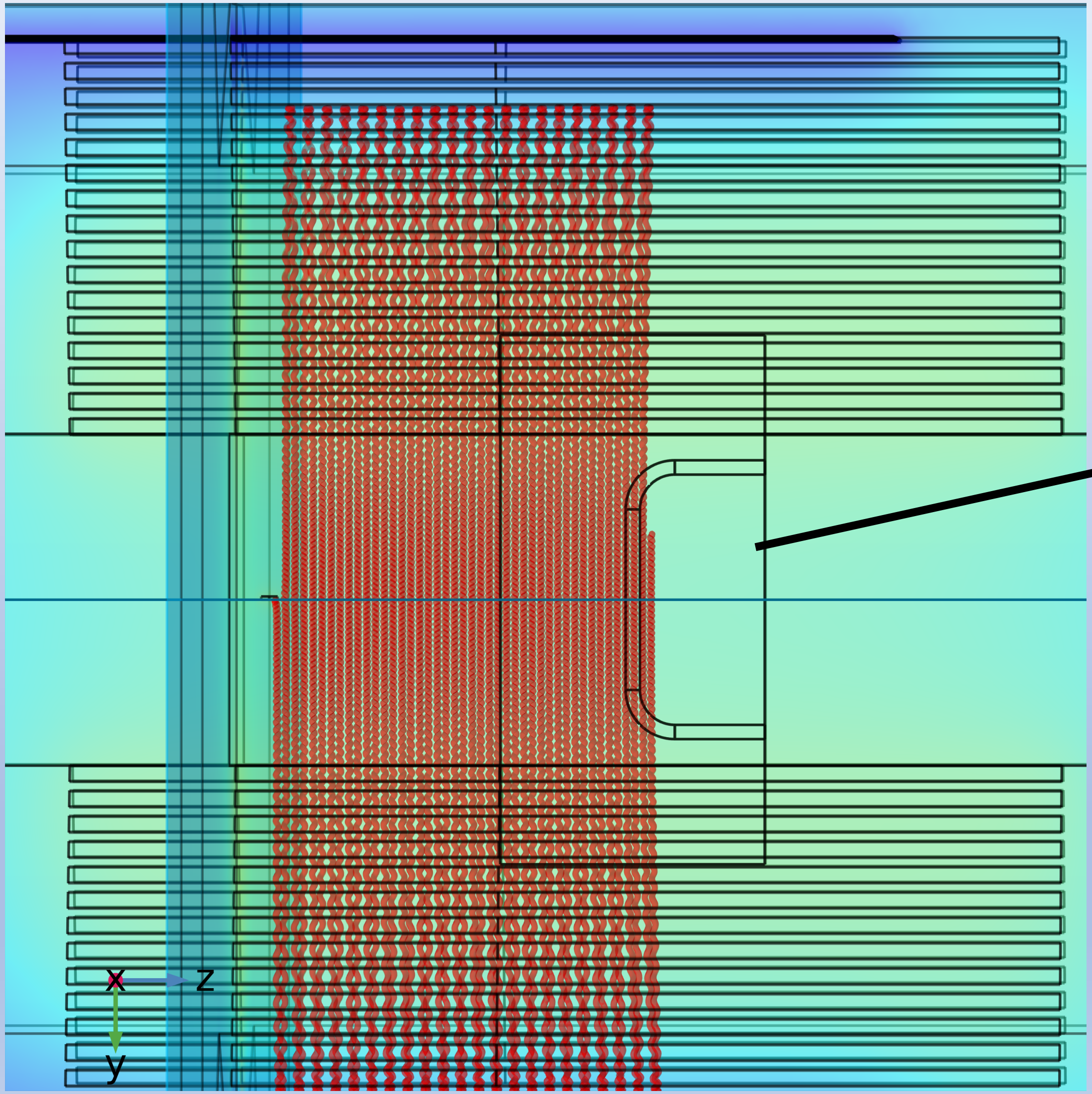
Investigation in the field of Co-Planar Waveguide started

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

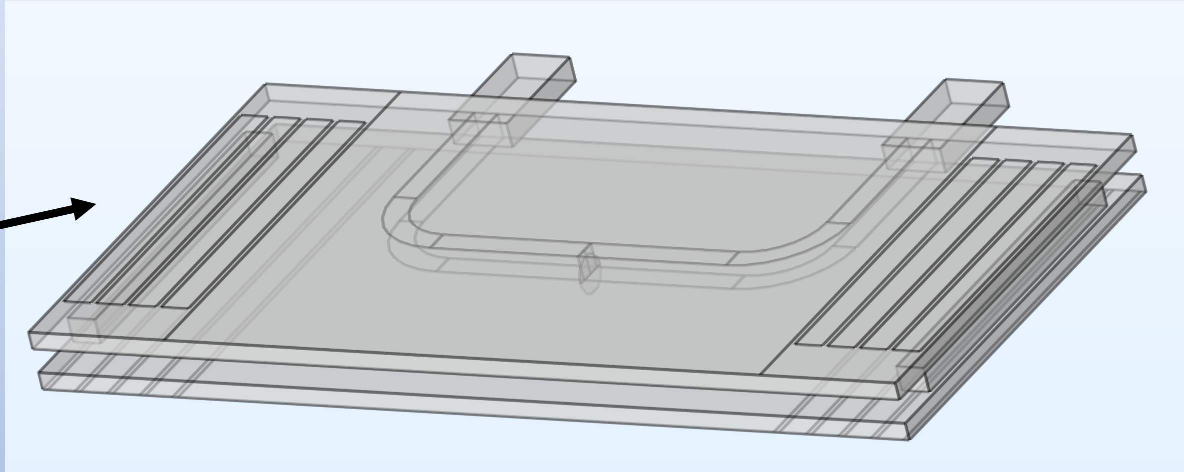
Exercise form COMSOL library



RF Antenna

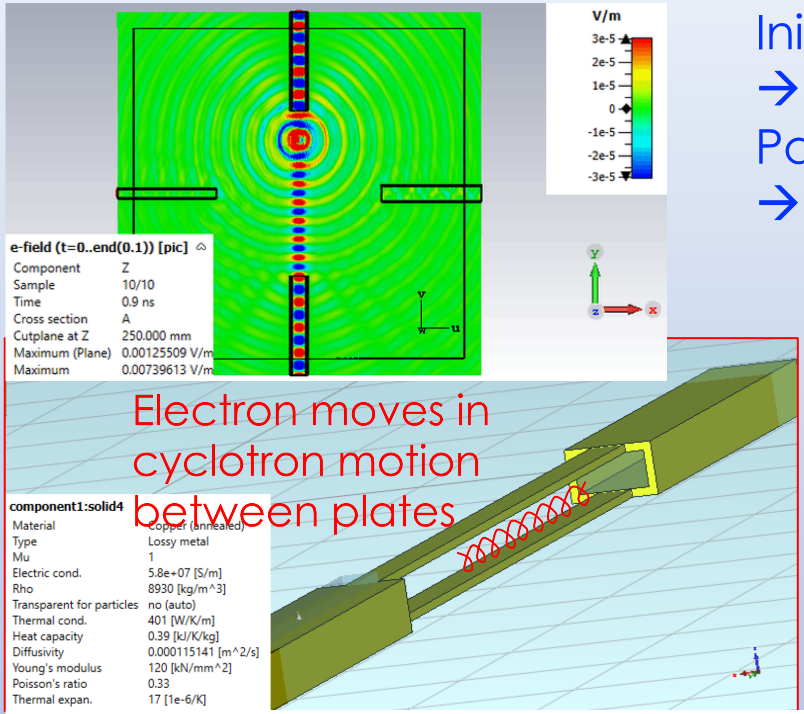


Parallel-Plate Waveguide interfaced to WR42 Rectangular Waveguide on both e



Electron in cyclotron motion passes through parallel-plate region, slowly drifting between waveguide plates capturing ~0.1 fW of RF power (~10,000 bounces in ~10 microseconds)

Dynamical Simulation of RF Signal



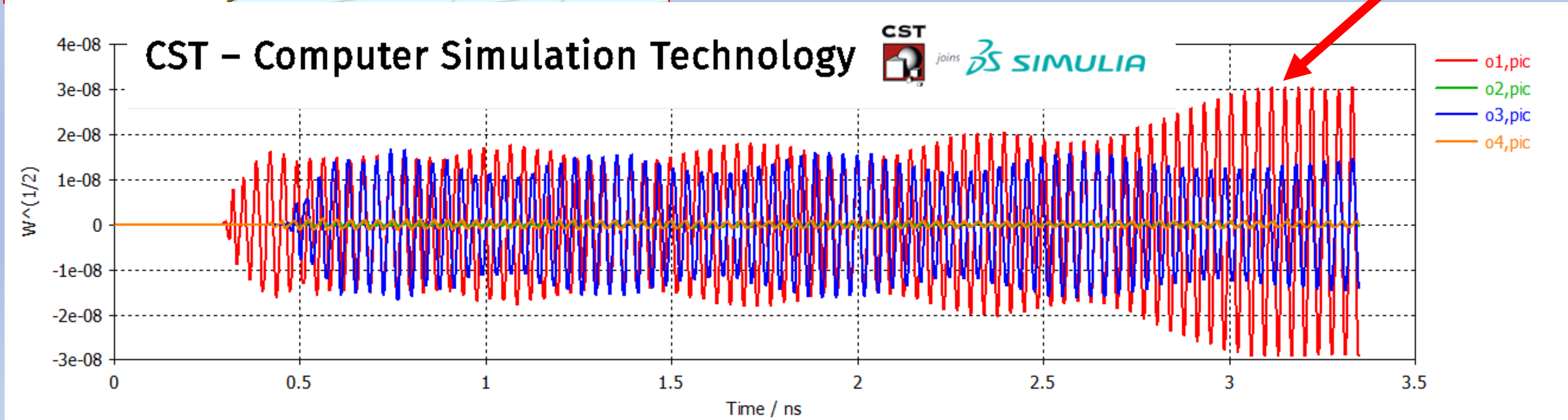
Initial calculations using CST RF modeling tools:
→ Antenna configured to transition from Parallel Plate Waveguide to Rectangular Waveguide
→ Working on FPGA-accelerated parameter fitting with ZYNQ RF

P_{signal}~0.1 fW

T_{LNA} ~6K

Dicke Radiometer eqn.
→ SNR~10 for 10^{-5}s

Normalization to Project 8 (https://arxiv.org/abs/1703.02037)

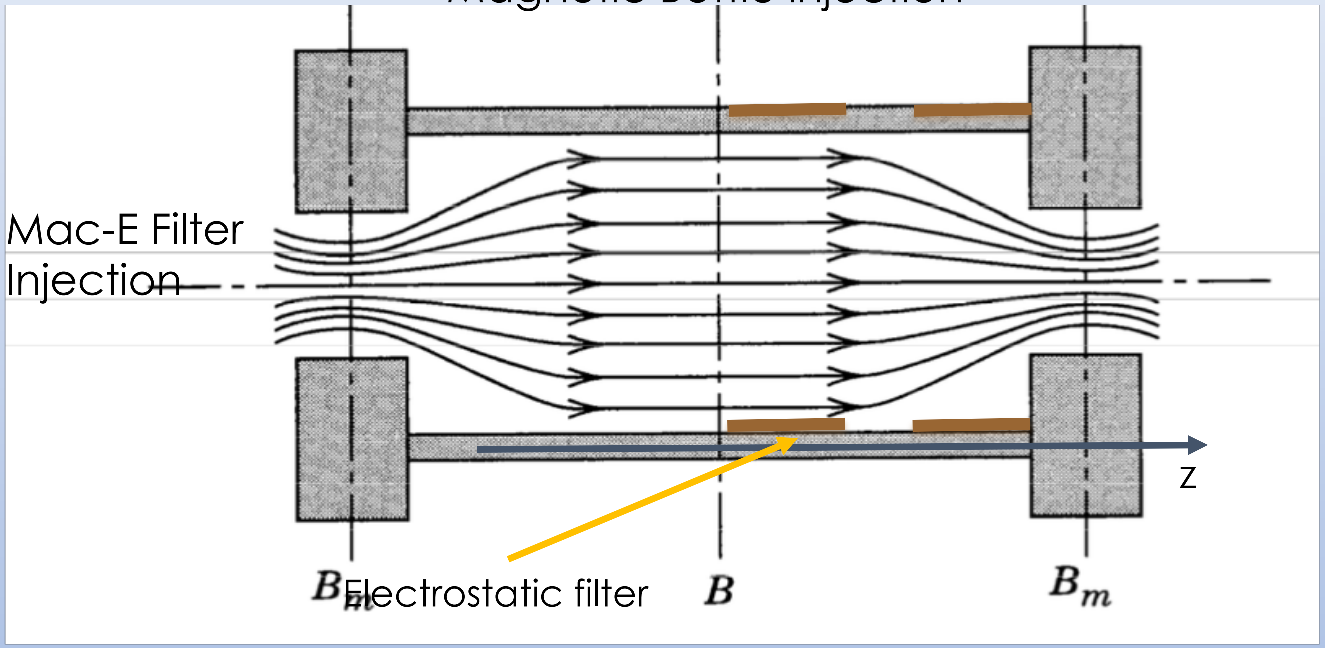


Mac-E filter

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

Jackson Fig 12.6

Magnetic Bottle injection



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

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

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

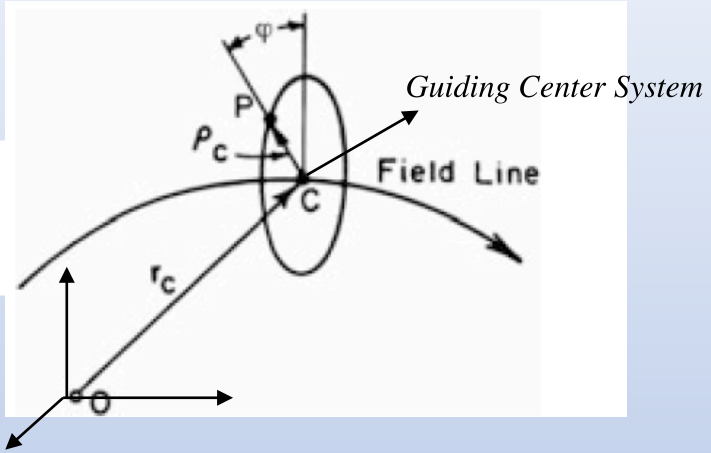
$$\left(\frac{\Delta E}{Q}\right)^3$$

is reduced to 700 Hz if ΔE ~ 2 eV

New filter Concept

Formulas from Progress in Particle and Nuclear Physics 106 (2019) at pg 122

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



Adiabaticity condition

$$\rho_c \ll \left| \frac{B}{\nabla B} \right|, \left| \frac{E}{\nabla E} \right| ; \text{ and}$$

$$\tau_c \ll \left| \frac{B}{dB/dt} \right|, \left| \frac{E}{dE/dt} \right| ;$$

$$\boldsymbol{V} = \boldsymbol{V}_\perp + \boldsymbol{V}_\parallel$$

Total phase-averaged velocity of CGS trajectory with parallel and perpendicular component w.r.t. B field.

$$\mu = \frac{m v_\perp^{*2}}{2B}$$

$$\boldsymbol{v} = \boldsymbol{v}_\perp + \boldsymbol{v}_\parallel \text{ by } \boldsymbol{v}_\perp^* = \boldsymbol{v}_\perp - \boldsymbol{V}_D \text{ and } \boldsymbol{v}_\parallel^* = \boldsymbol{v}_\parallel - \boldsymbol{V}_\parallel \approx 0.$$

With v^* the velocity of particle in CGS

$$\frac{dT_\perp}{dt} = -q\boldsymbol{E} \cdot \boldsymbol{V}_D = -q\,\boldsymbol{E} \cdot (q\boldsymbol{E} - \mu \nabla B) \times \frac{\boldsymbol{B}}{qB^2} = \frac{\mu}{B^2} \boldsymbol{E} \cdot (\nabla B \times \boldsymbol{B})$$

Where $T_\perp$ kinetic energy of gyromotion in CGS

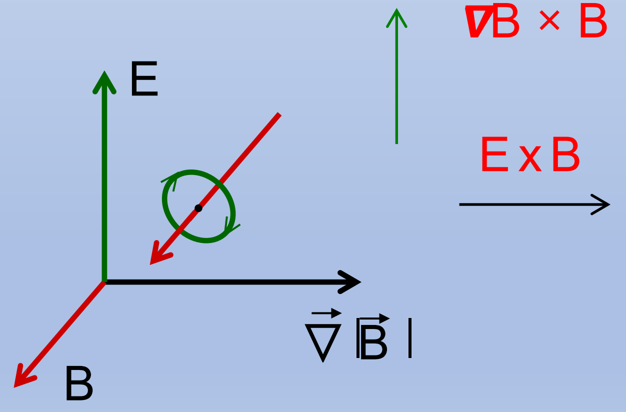
New concept EM filter

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



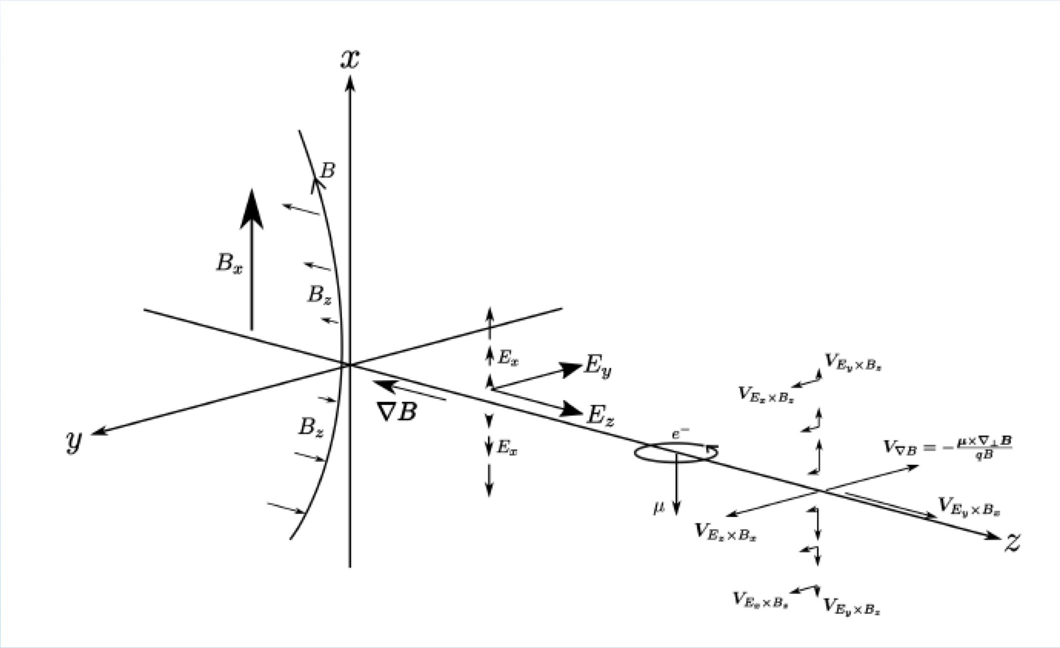
M.G. Betti et al., Prog. Part. Nucl. Phys. 106 (2019) 120-131

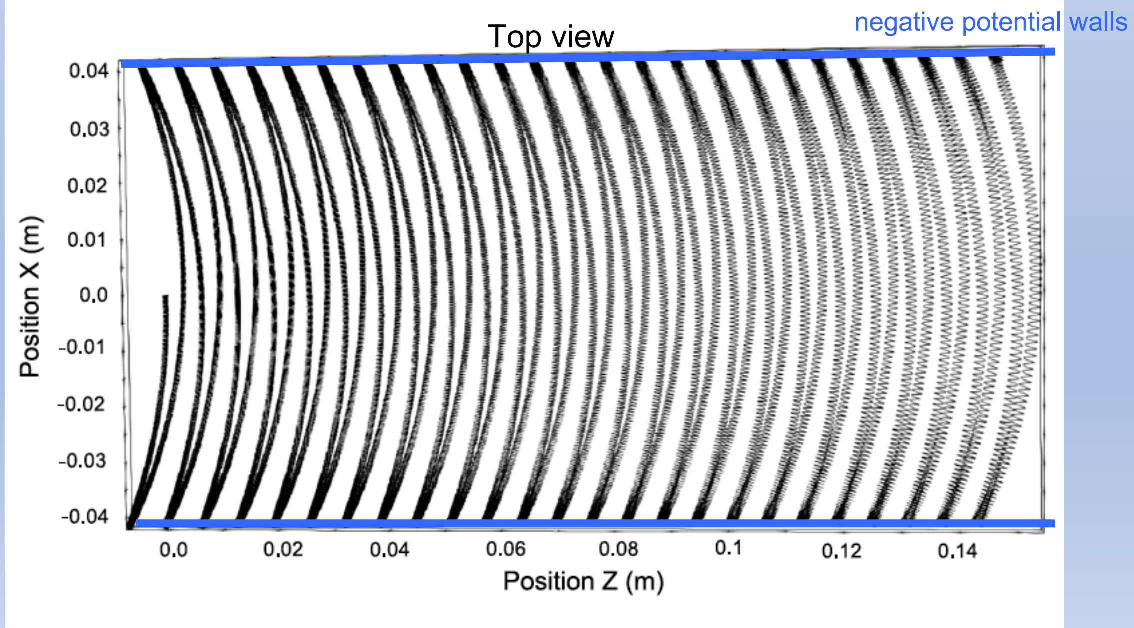
New concept EM filter

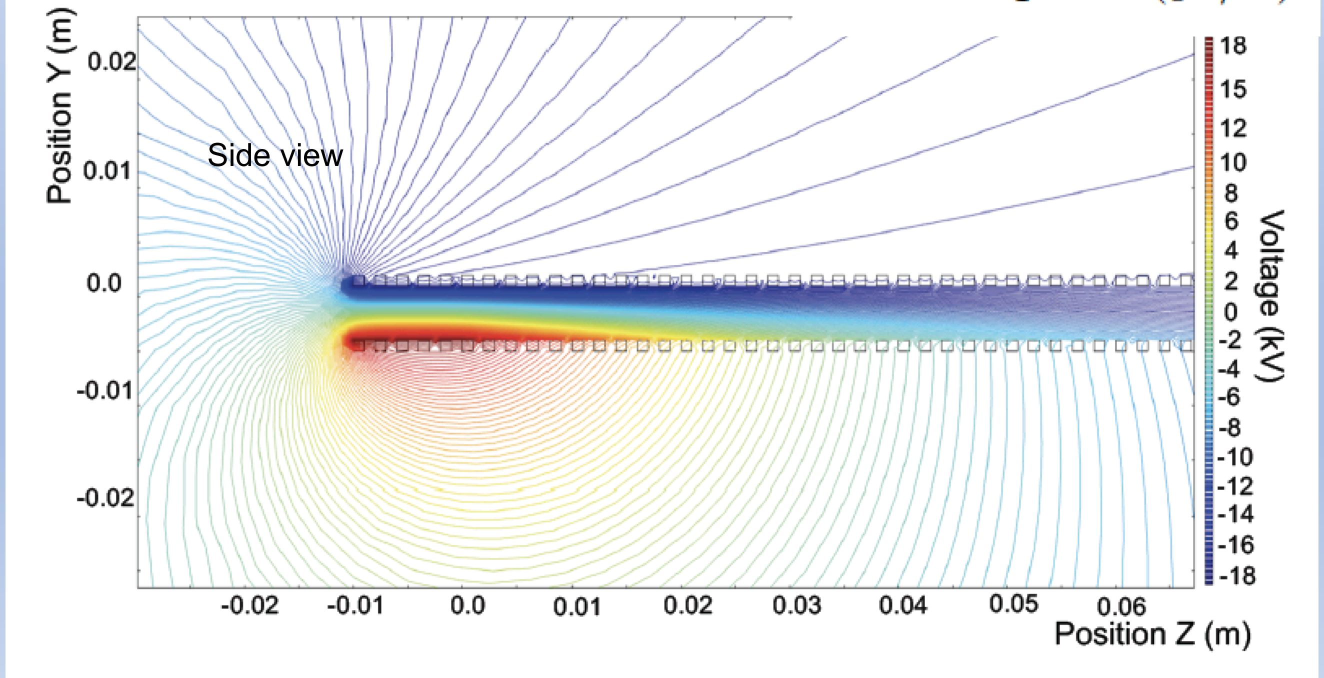
$$E_x = 0\,,$$
$$E_y = E_0 \cos\left(\frac{y}{\lambda}\right) e^{-z/\lambda}\,,$$
$$E_z = -E_0 \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda}\,,$$

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

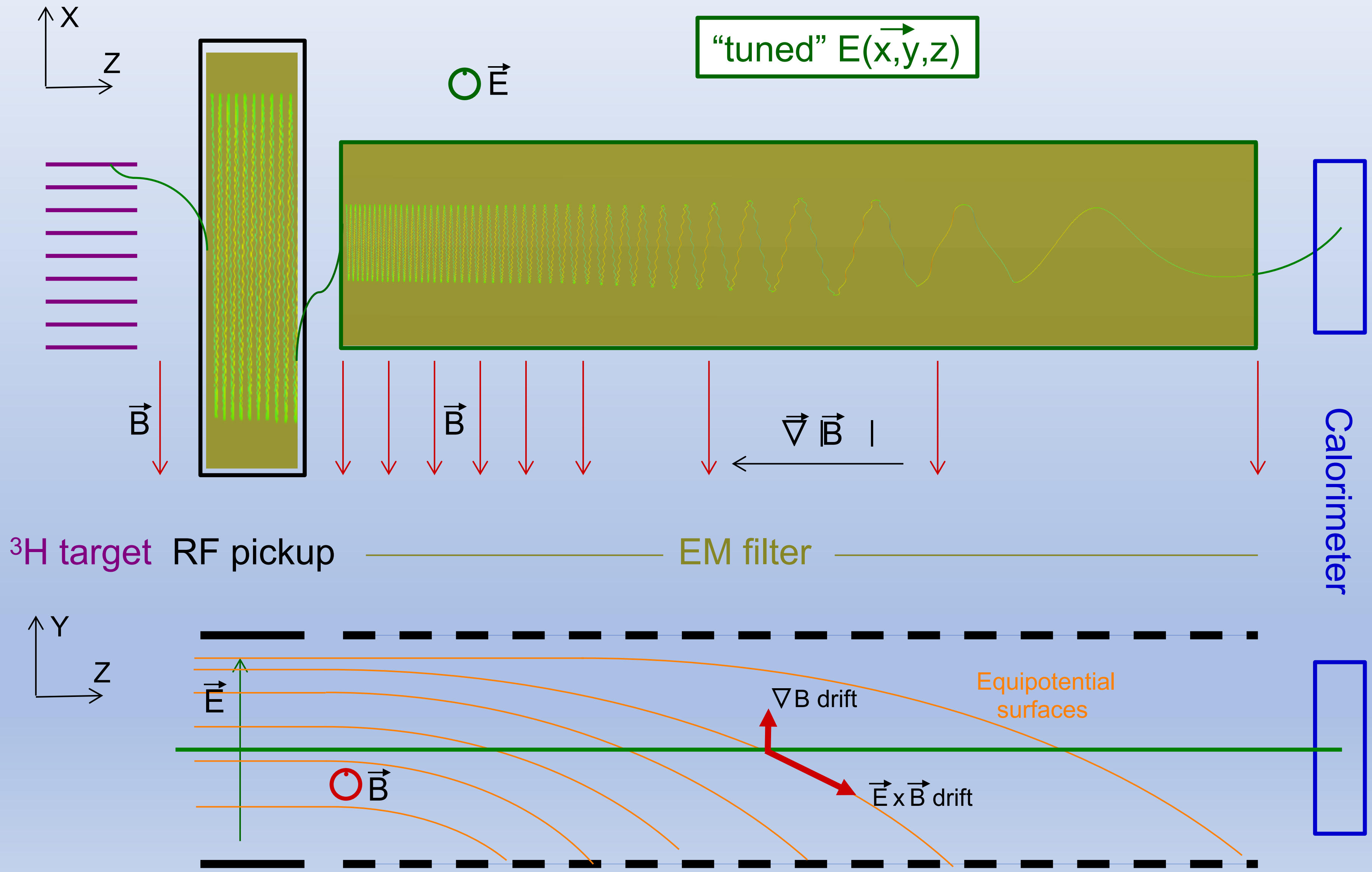
$$E_0 = -\frac{\mu B_0}{q\lambda \sin\left(y_0/\lambda\right)}$$



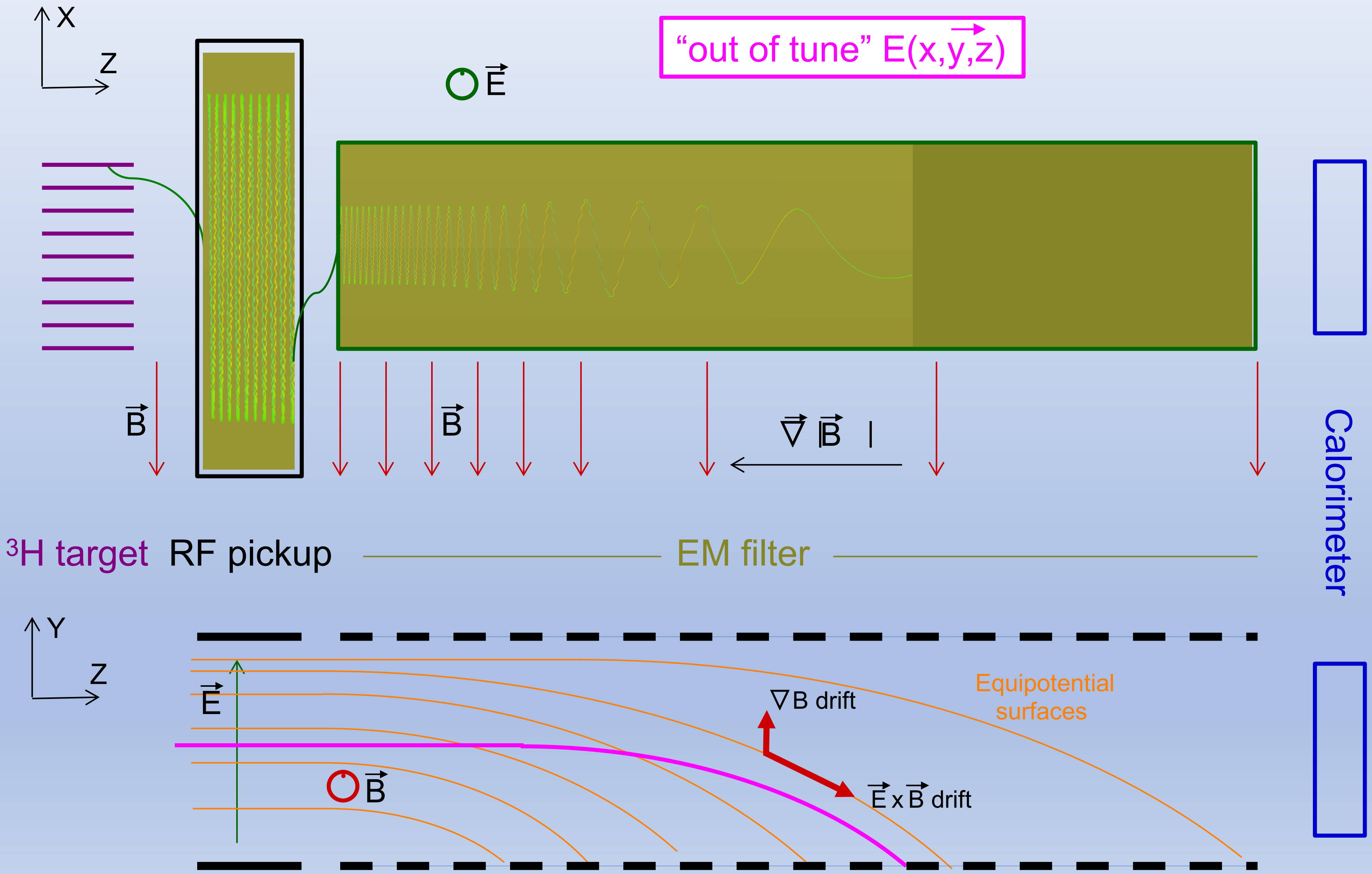




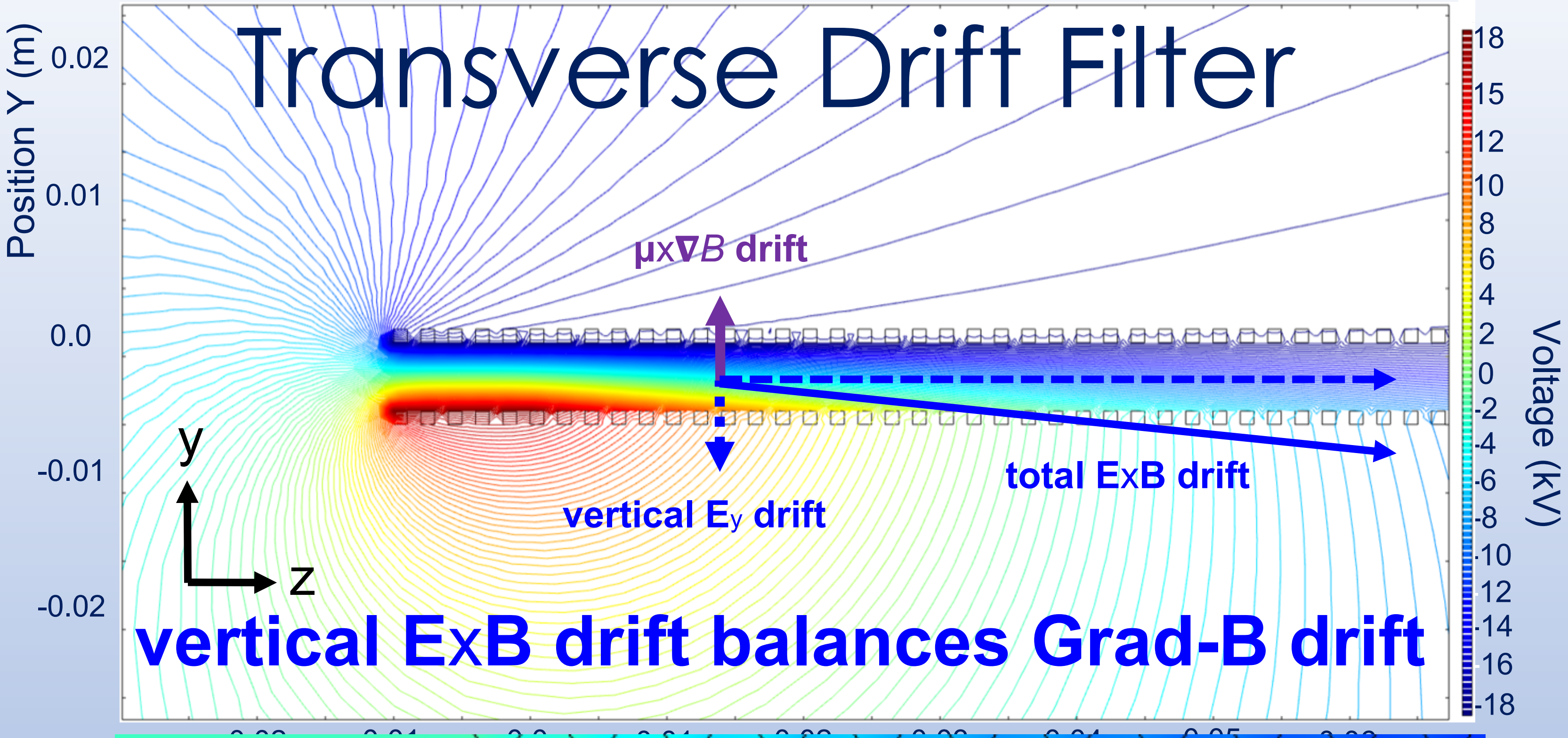
New concept EM filter
Dynamic tuning

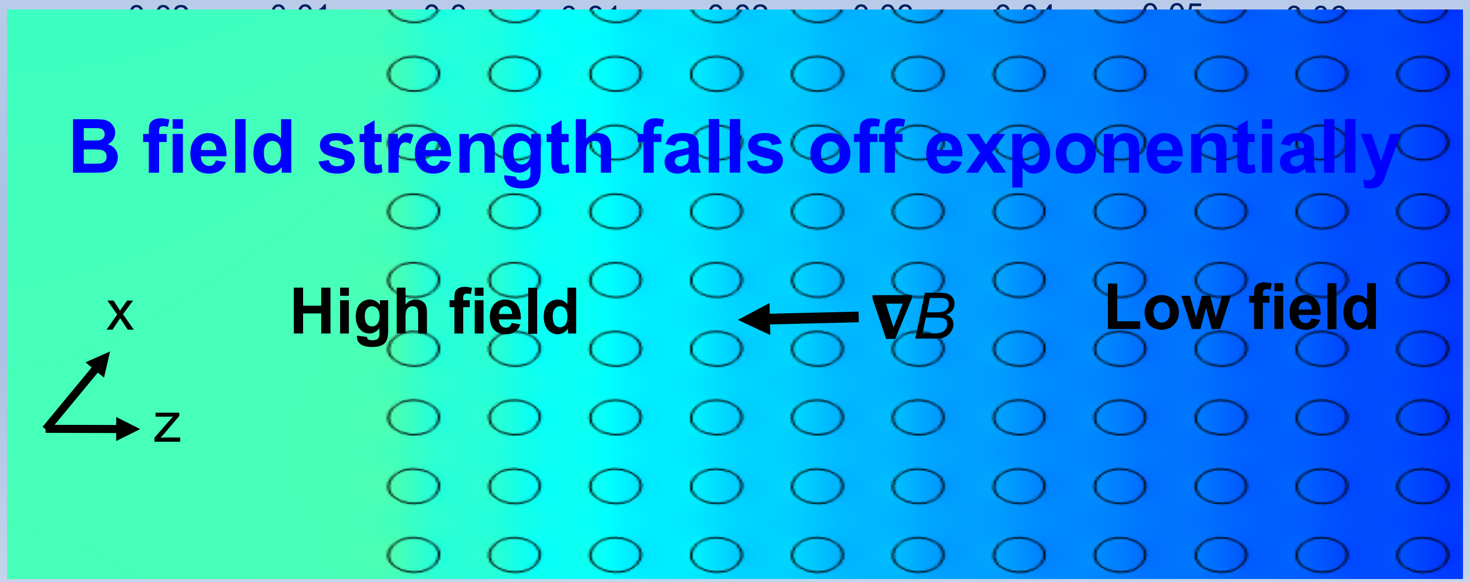


New concept EM filter
Dynamic tuning

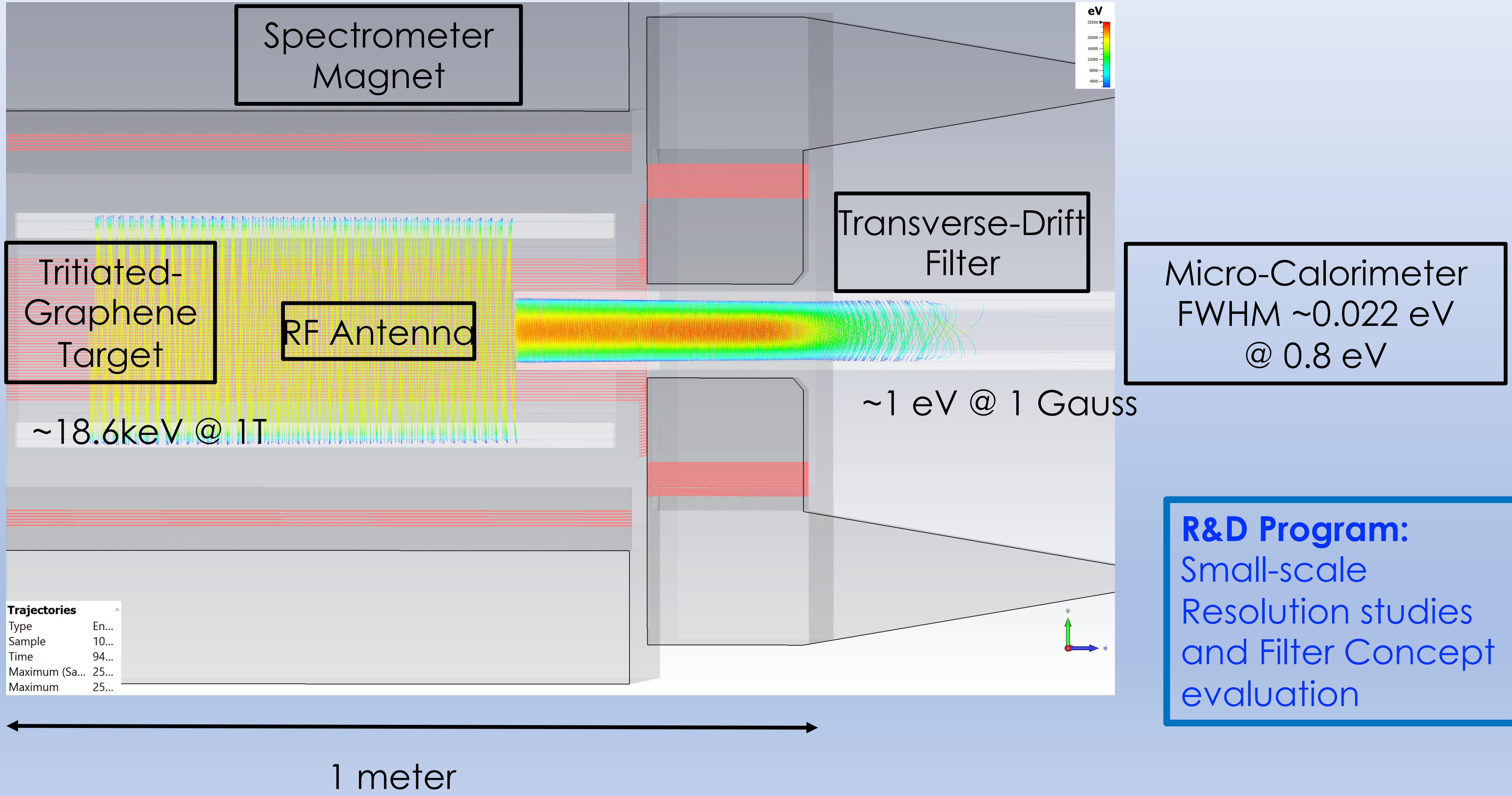



PTOLEMY


Transverse Drift Filter
Position Y (m)
0.02
0.01
0.0
-0.01
-0.02
μx∇B drift
vertical Ey drift
total ExB drift
y
z
Voltage (kV)
18
15
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
vertical ExB drift balances Grad-B drift

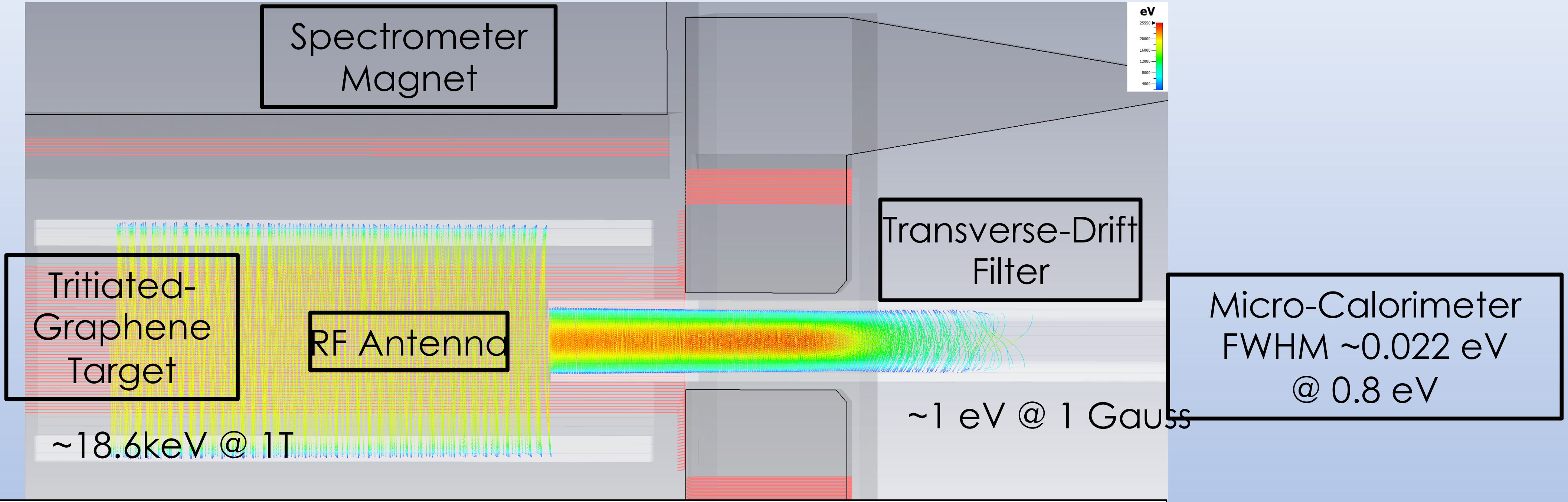

B field strength falls off exponentially
x
z
High field
∇B
Low field

Block Diagram of the PTOLEMY Spectrometer



R&D Program:
Small-scale Resolution studies and Filter Concept evaluation

Block Diagram of the PTOLEMY Spectrometer

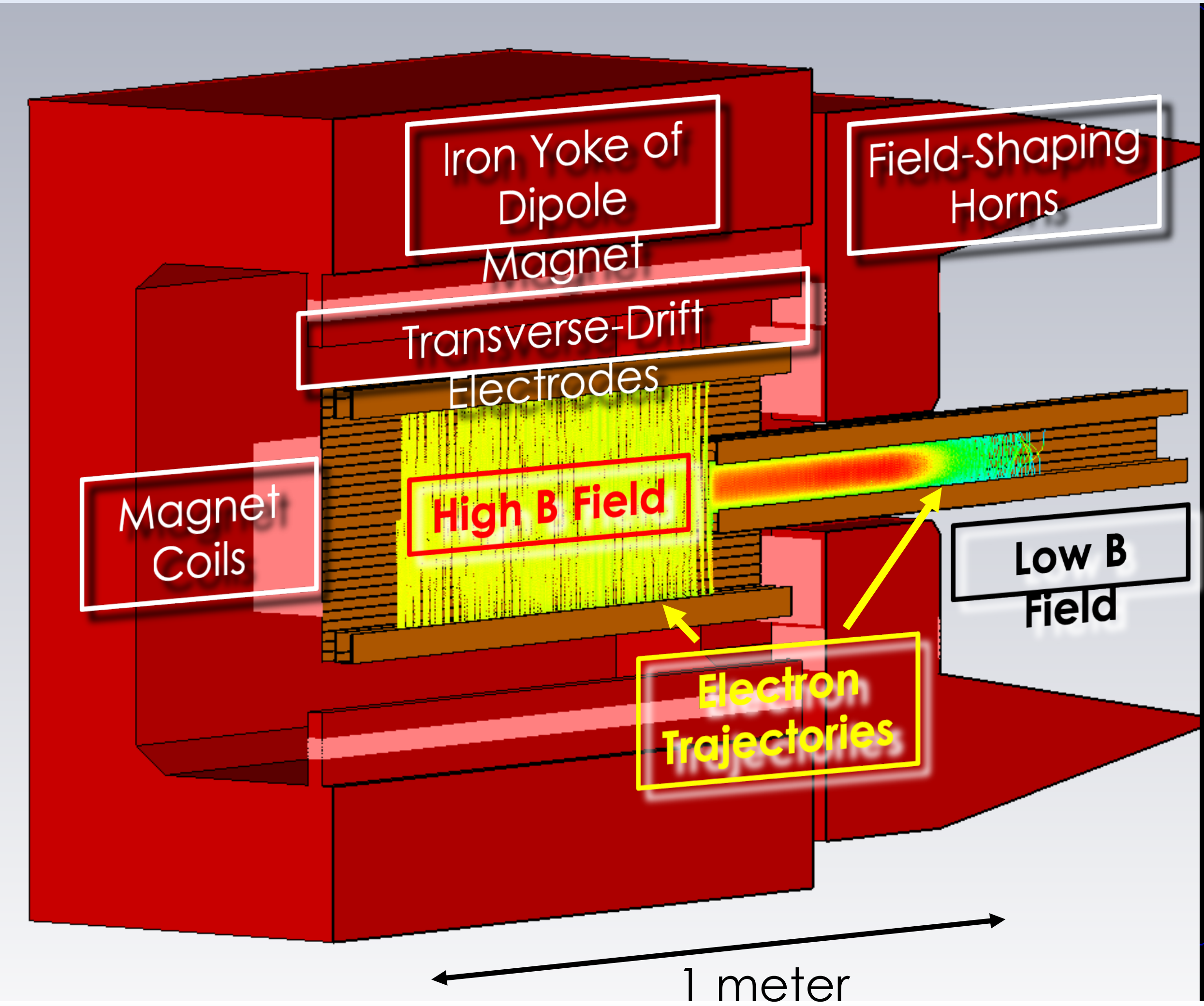


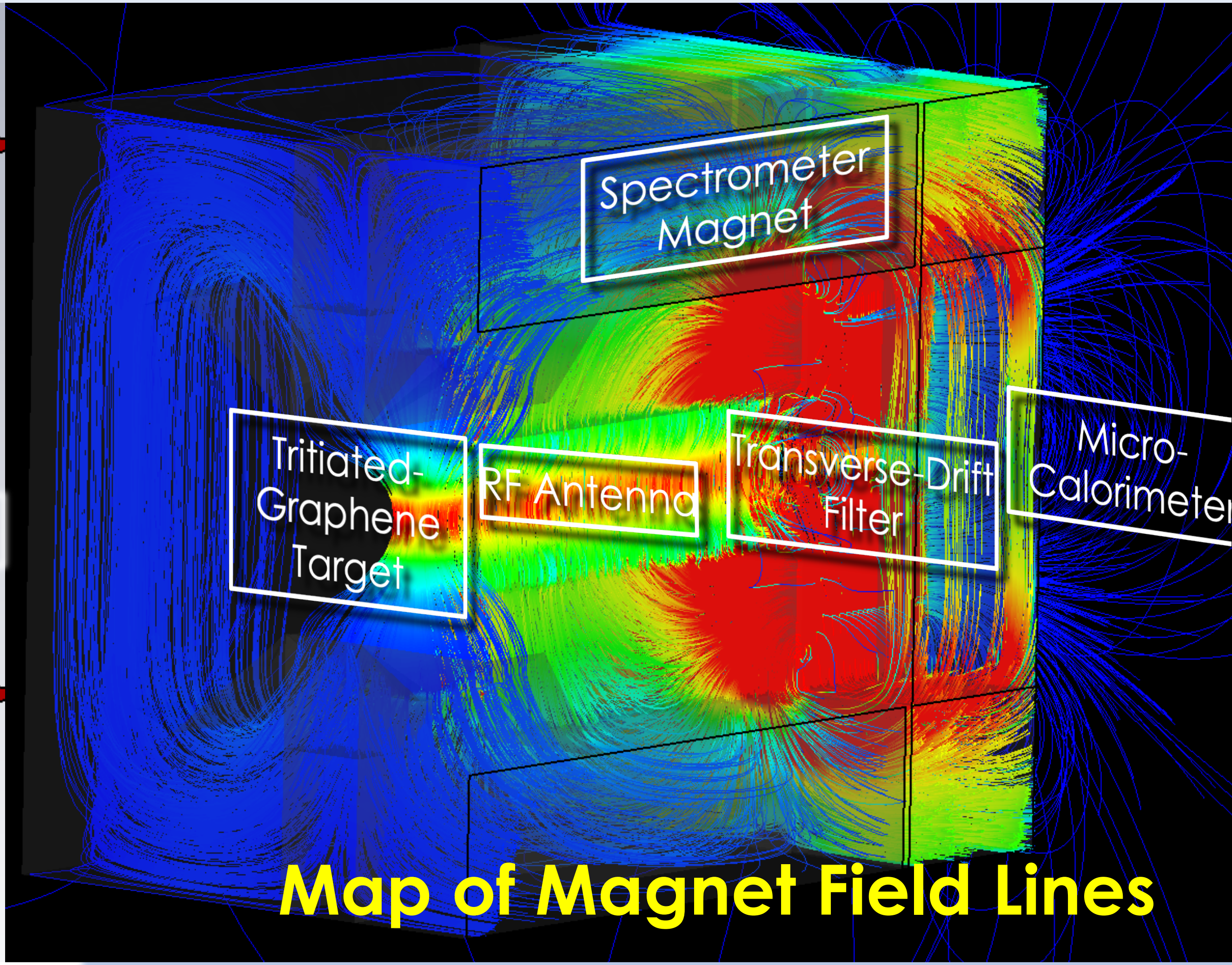
Principle of Operation:

1. Electrons from weakly-bound tritium originate from a cold target surface.
2. Electrons drift through an RF Antenna region where the electron momentum components are measured to ~ few eV resolution.
3. Filter electrodes are set ~ 1 msec in advance of electrons entering filter.
4. Kinetic energy of electrons drained as they climb a potential under gradient-B drift.
5. Electrons of ~ few eV in a low B field region are transported into a micro-calorimeter.

R&D Program:
Small-scale resolution studies and Filter Concept evaluation

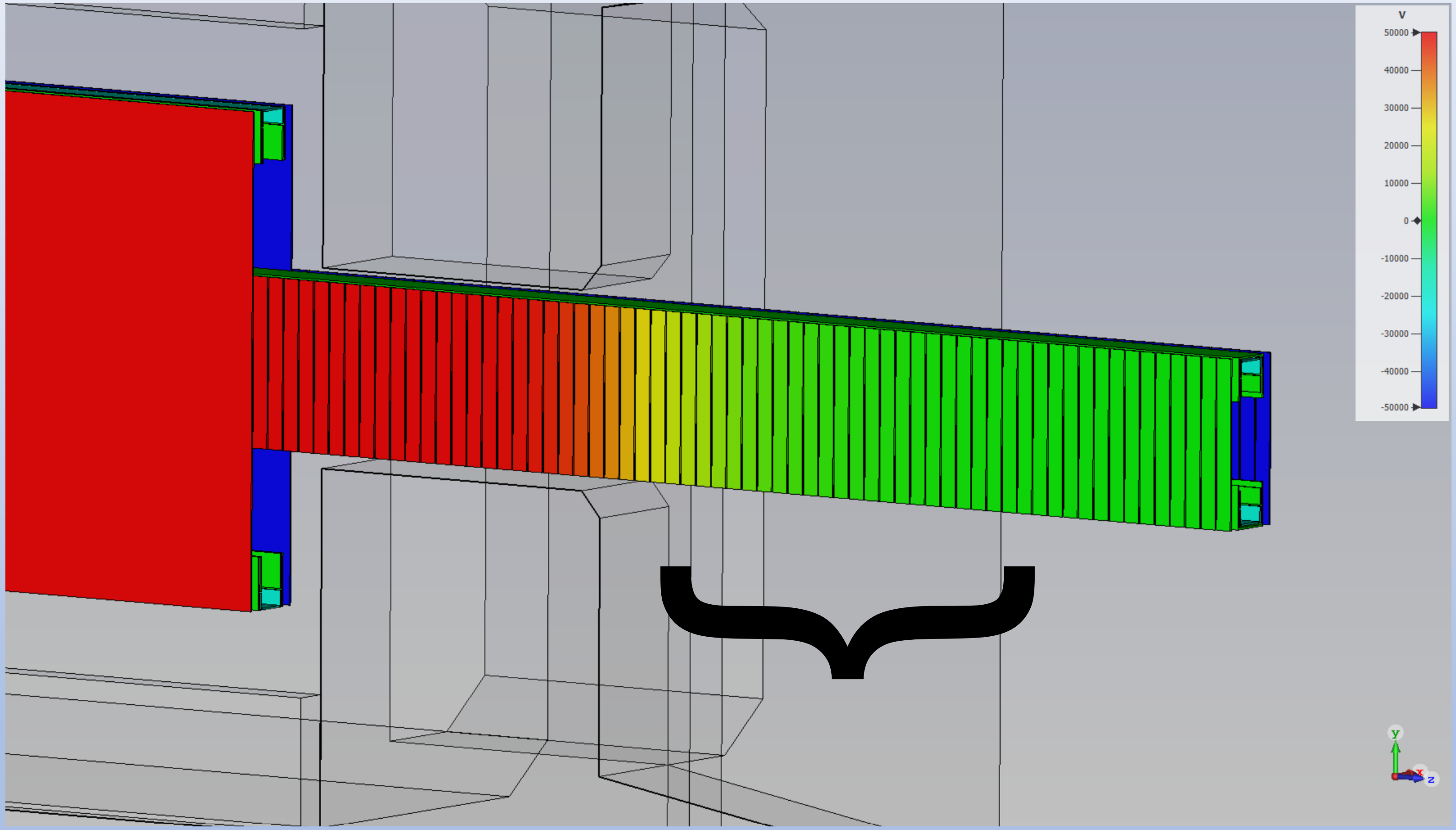
Physical Layout of First Spectrometer





(Left) Cross-Sectional View (Sliced in Half): Red – Iron Yoke, Pink – Current Coils, Brown – Electrodes, Rainbo

Initial Implementation of Filter Electrodes



Voltage profile on filter electrodes fixed according to B field
Only the overall magnitude of the voltage/charge is adjusted

Major Challenge:
Fixed voltage division electrode array is charged up in ~100 microsec

→ Capacitances in series with a leading ~few pF HV electrode

→ Charge stored locally is transferred to the final LV electrode of the low capacitance series filter array and allowed to settle for ~10 time constants

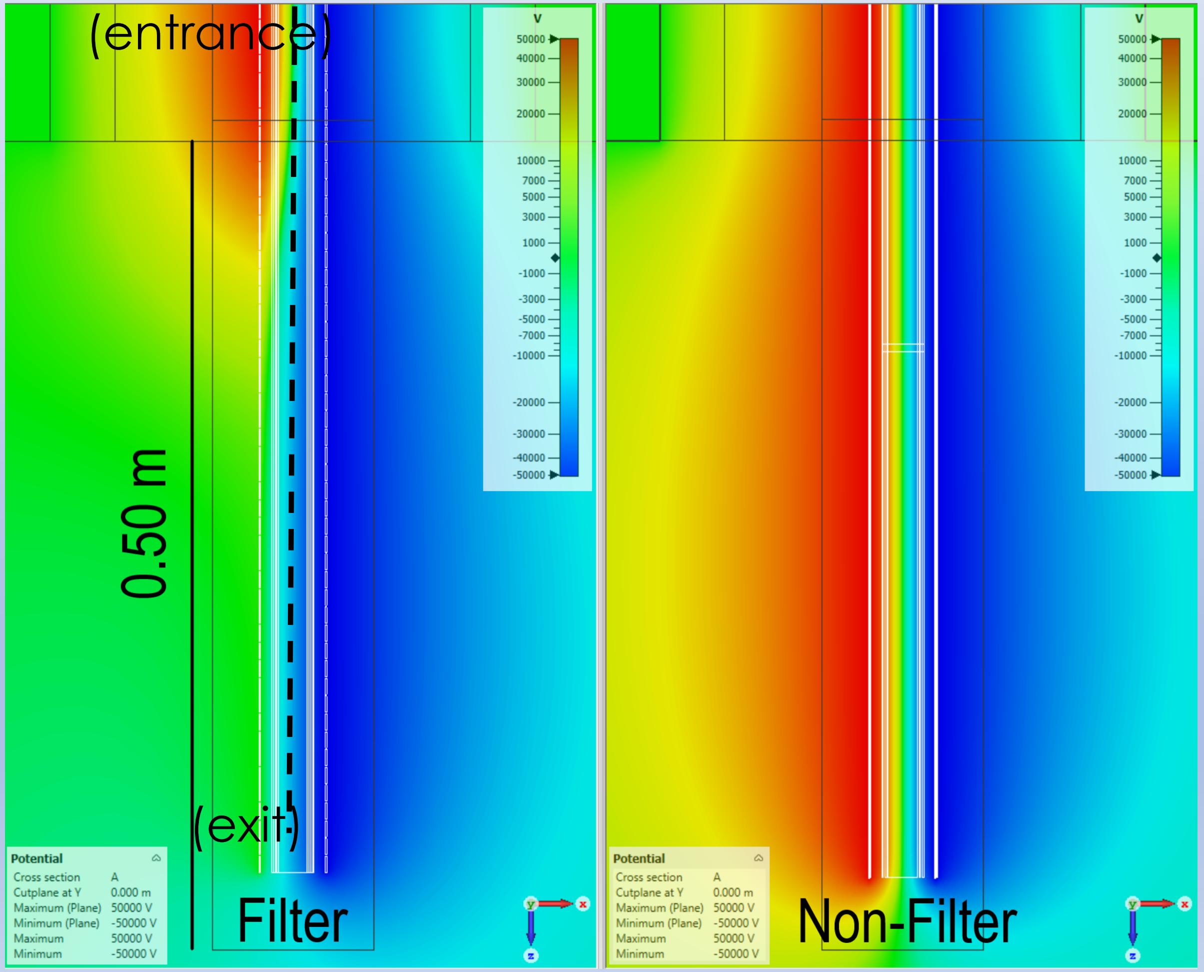
→ Remaining electron momentum parallel to B field removed by final LV electrode voltage difference relative to grounded micro-calorimeter surface.

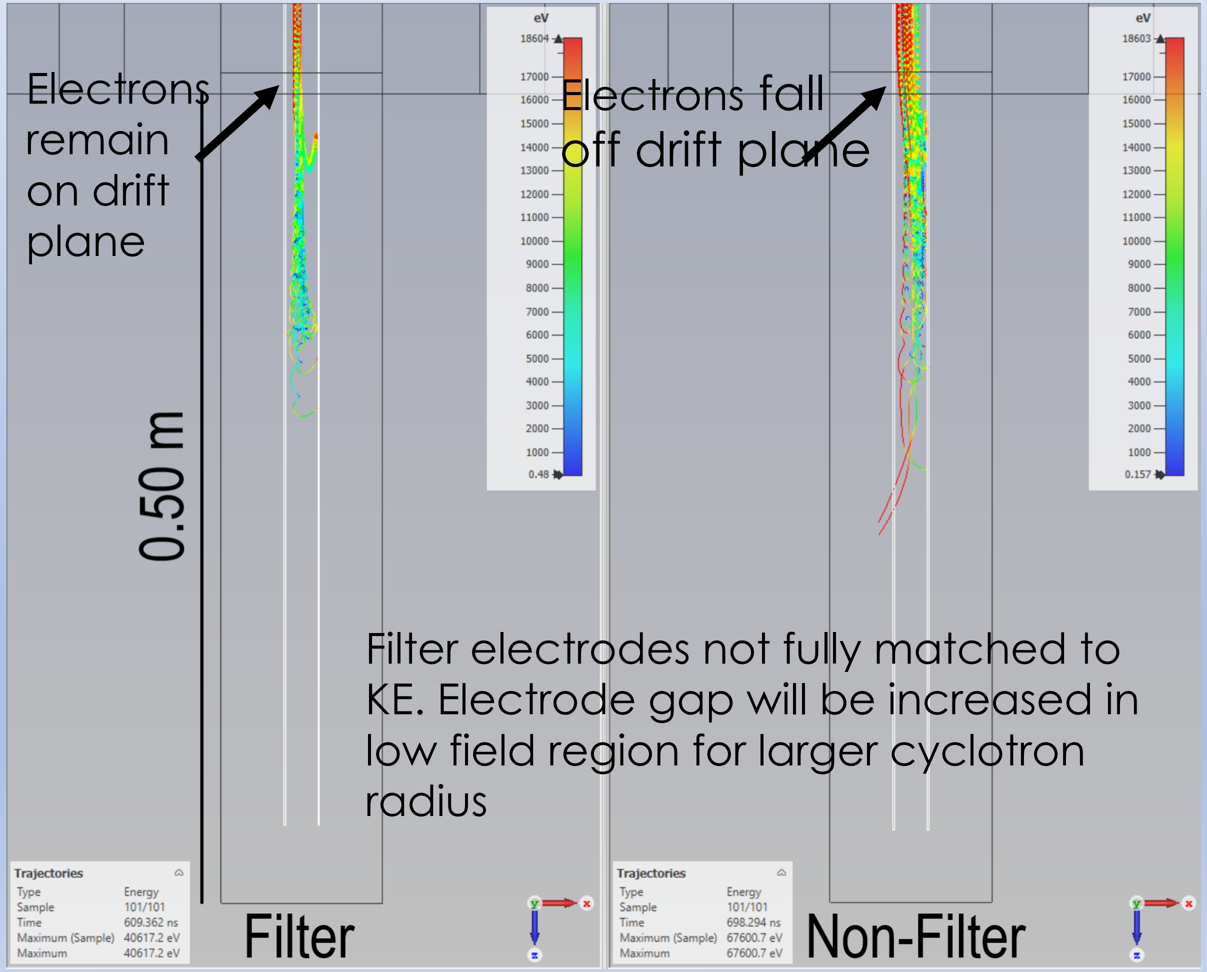
→ Precision/Stability of Target to micro-calorimeter voltage difference sets HV resolution, not filter voltages – filter voltages affect transmission efficiency.

First Run of Transverse Drift Filtering

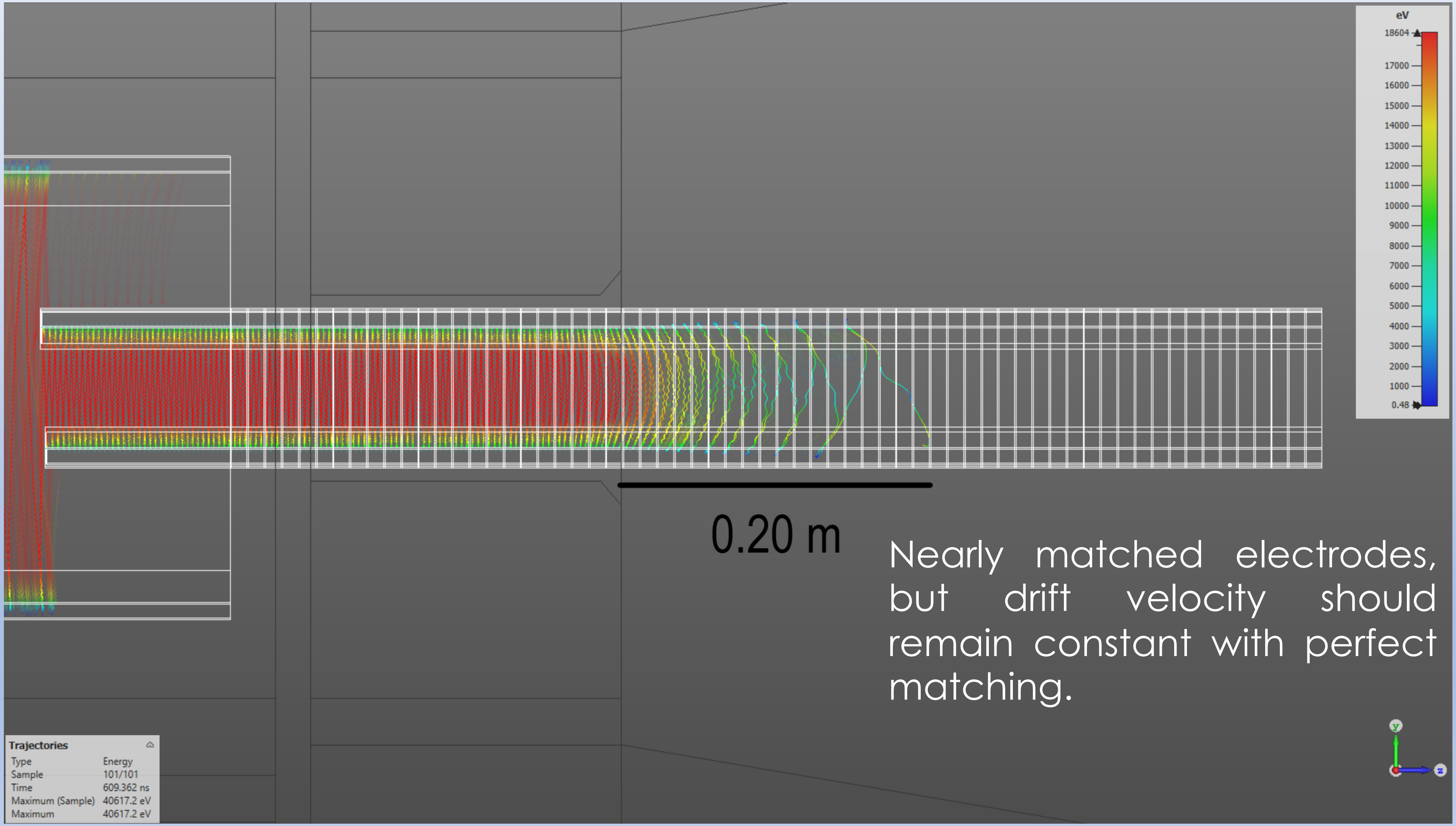
Electron Drift Plane:

Only electrons entering the filter with a transverse Kinetic Energy matching the programmed electrode voltages will remain on the central drift plane and have their transverse KE drained away.





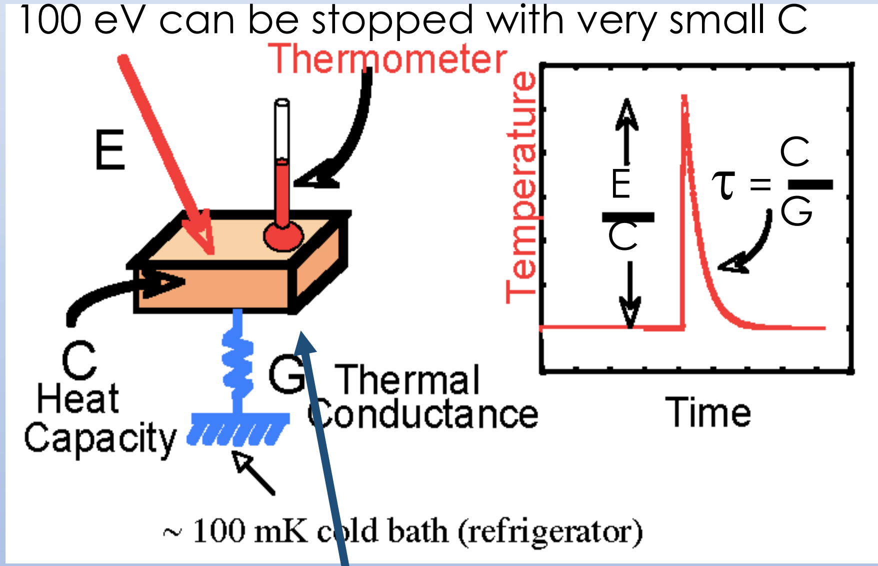
First Results – Finer Adjustment Needed



Nearly matched electrodes, but drift velocity should remain constant with perfect matching.

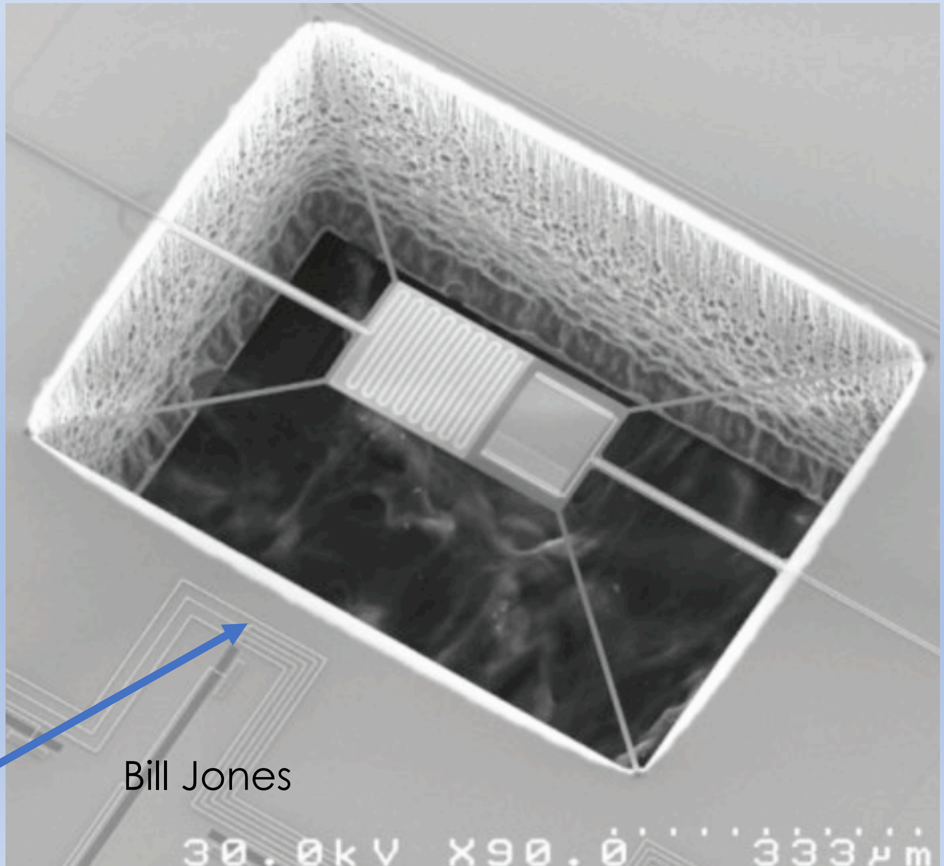
Calorimetric measurement
based on Transition Edges Sensors technology

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

Micro-Calorimeter

Total Resolution: $E_e = e\left(V_{cal} - V_{target}\right) + E_{cal} + RF_{corr}$

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

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

ΔE_{FWHM} = 0.022 eV @ 0.8eV

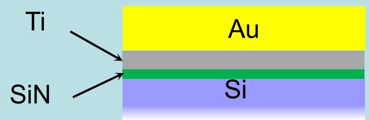
$$\Delta E_{FWHM} \approx 2.36\sqrt{4k_B T_c^2 \frac{C_e}{\propto}\sqrt{\frac{n}{2}}}$$

$\Delta E \propto T^{3/2}$ ⇨ T_c= 36 mK @10x10 μm² (t=90 nm)

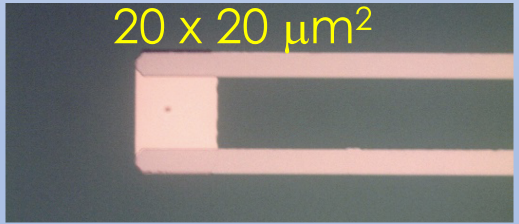
⇨ T_c= 46 mK @10x10 μm² (t=45 nm)

T_c=42 mK with:
Ti=11 nm and Au=27 nm

TiAu



Best solution in terms of heat capacity



INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

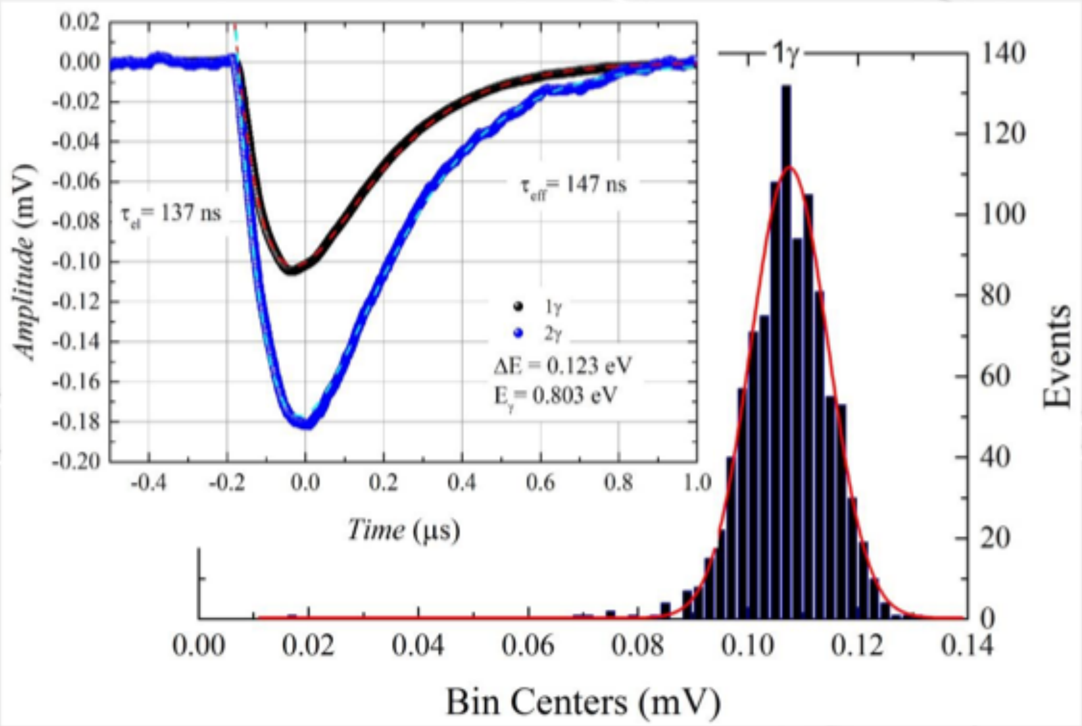
UNIVERSITÀ DEGLI STUDI DI GENOVA

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

Microcal for IR Photons

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



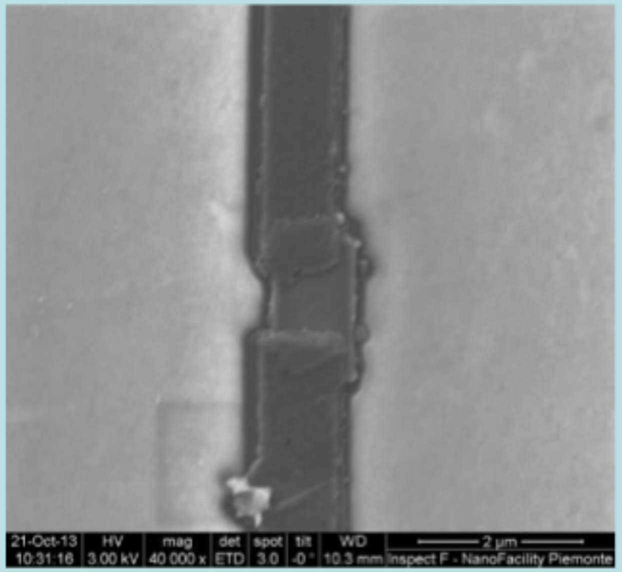
Results from INRIM (Torino) - Istituto Nazionale di Ricerca Metrologica

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

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

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

1 µm × 1 µm



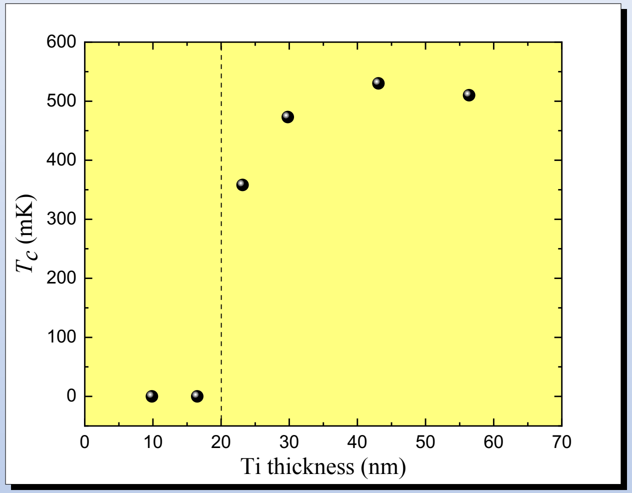
C. Portesi *et al*, IEEE Trans App Supercond, 25, 3, (2015)

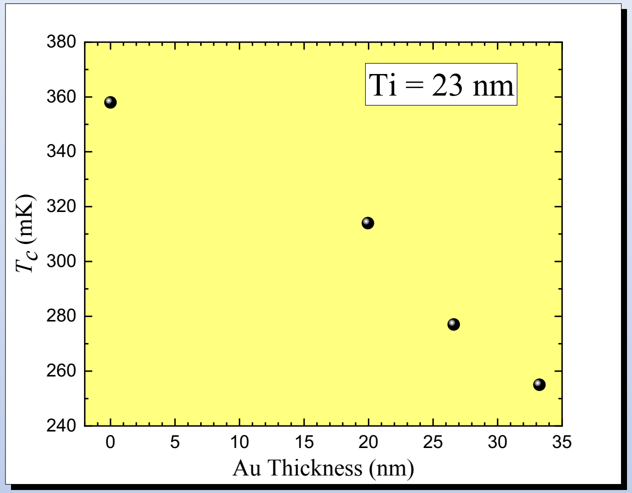
Initial Tests of Transition Curves (Films and TES)

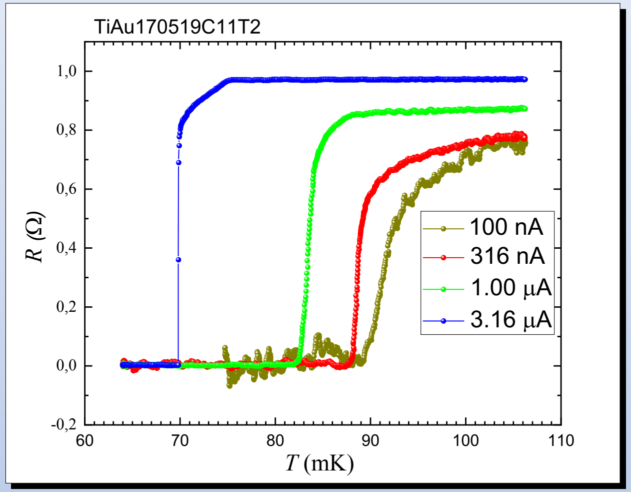
Experimental

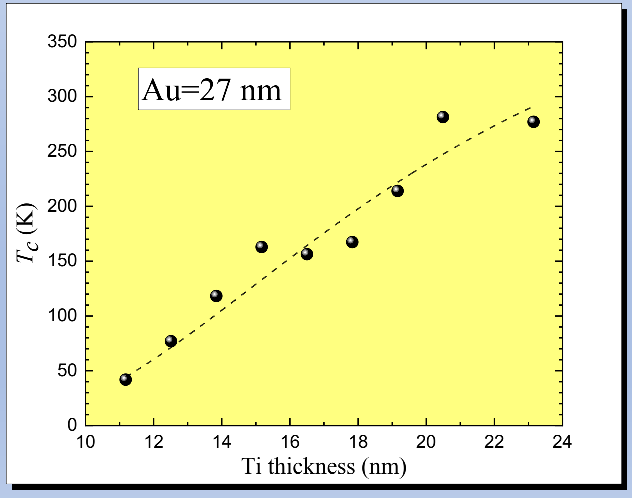
Films

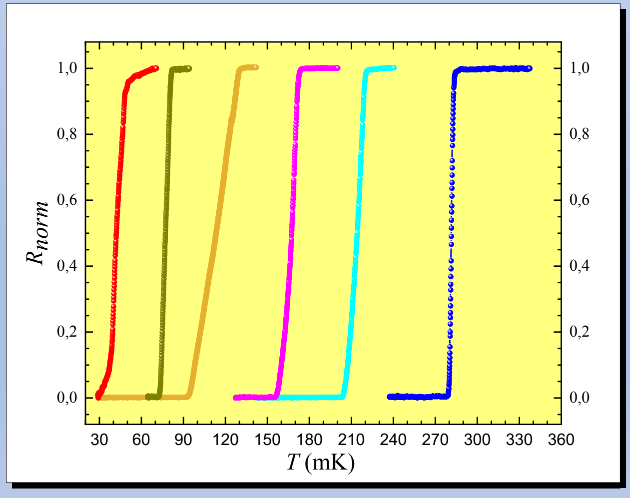
TESs

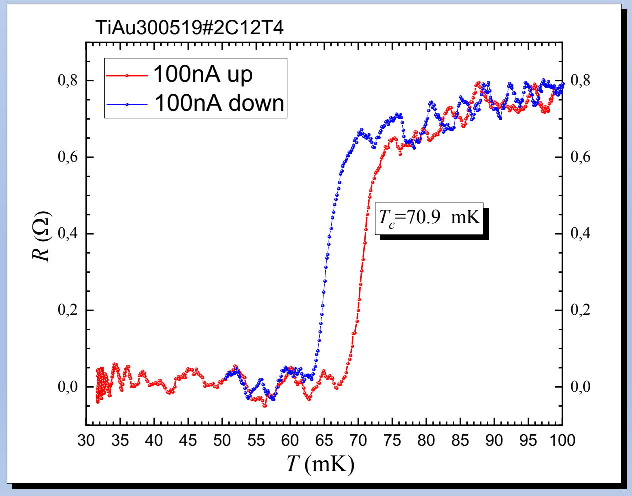




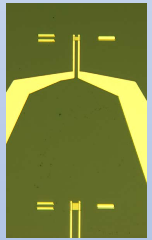








100 μm²

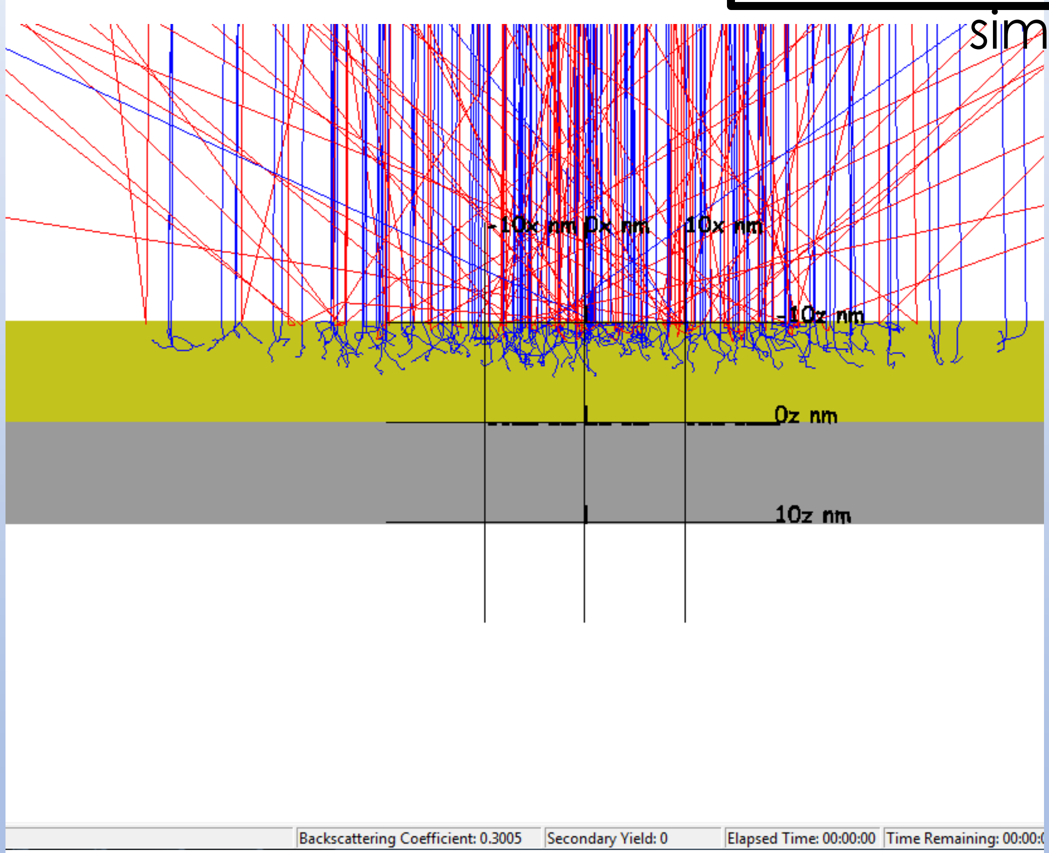


400 μm²

Backscatter Simulations

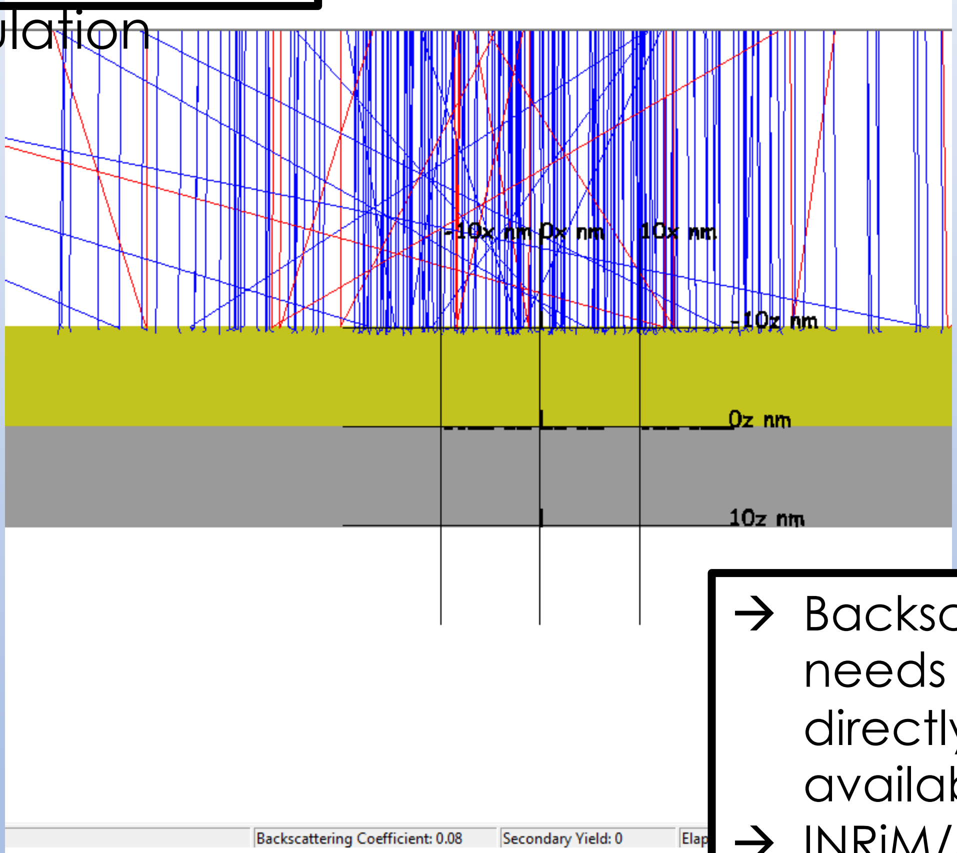
CASINO electron simulation

500 eV



Backscattering = 30%

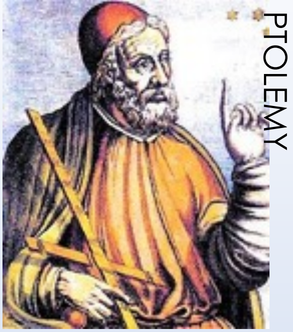
100 eV



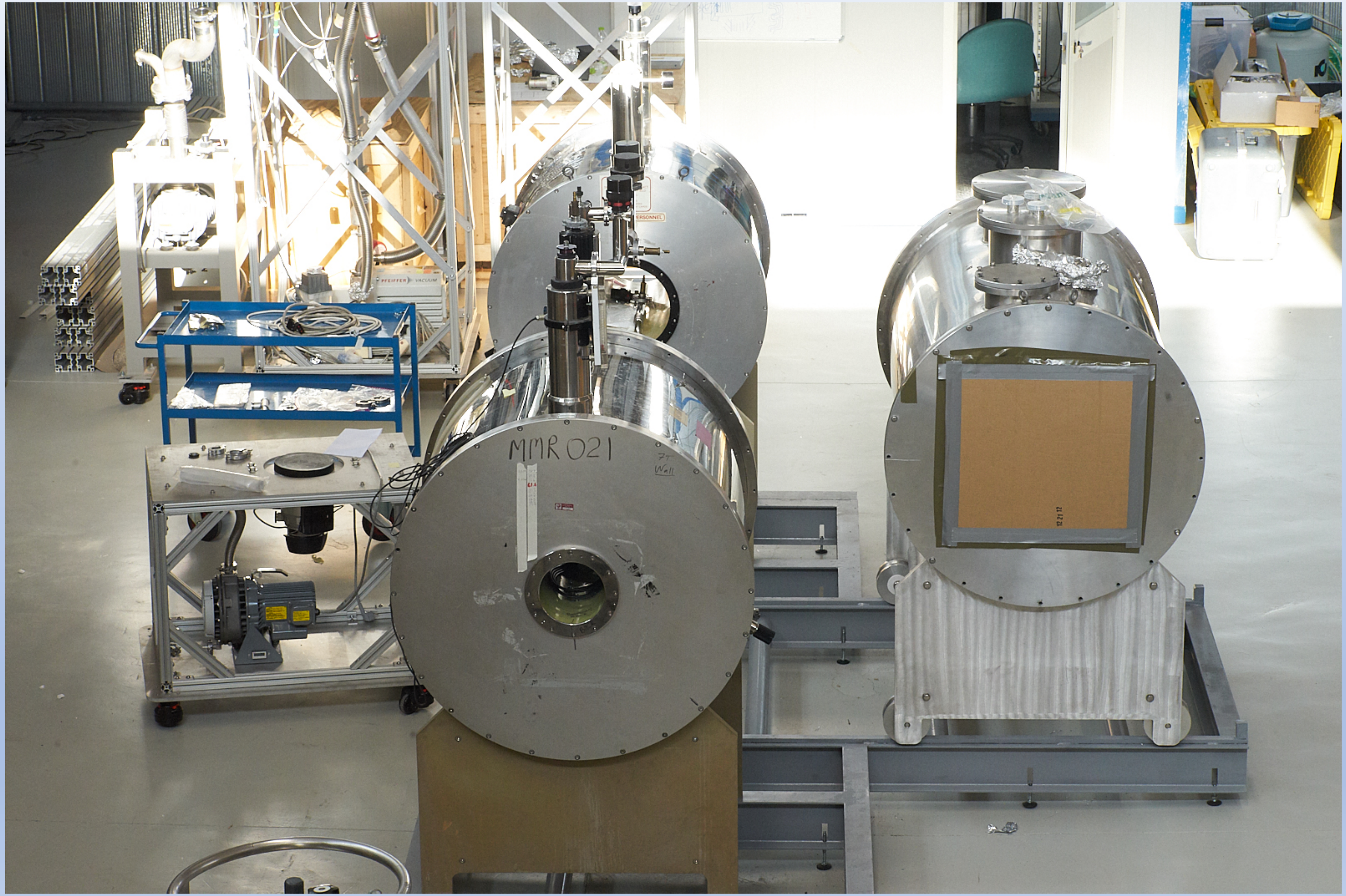
Backscattering = 8%

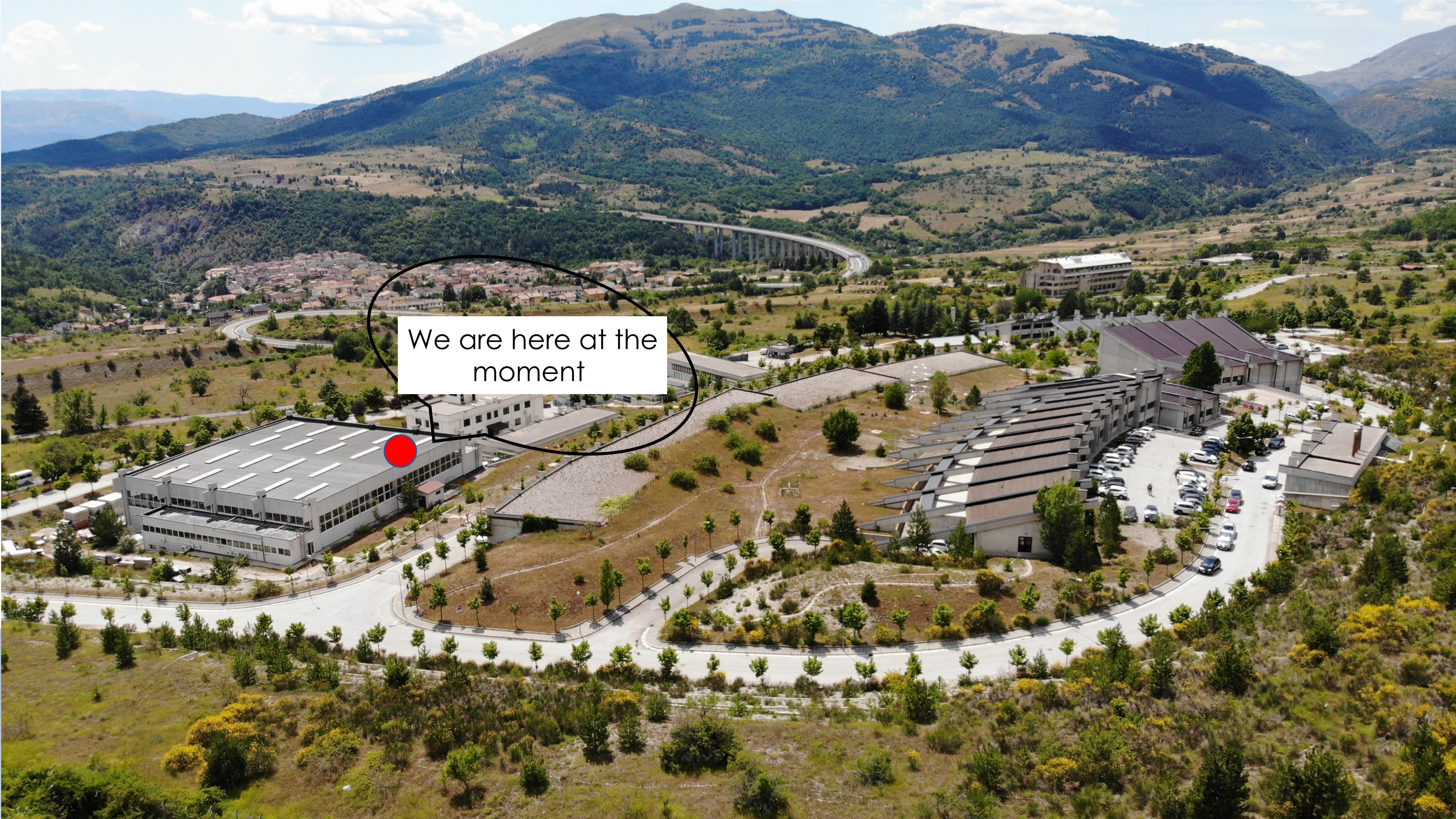
} TES

- → Backscatter below 100eV needs to be measured directly – no simulations available for 10 eV or less
- → INRiM/MIB/LNGS are developing electron source evaluation (currently using IR photons of ~0.8eV)



Experimental site at LNGS




We are here at the moment

Light Dark Matter search

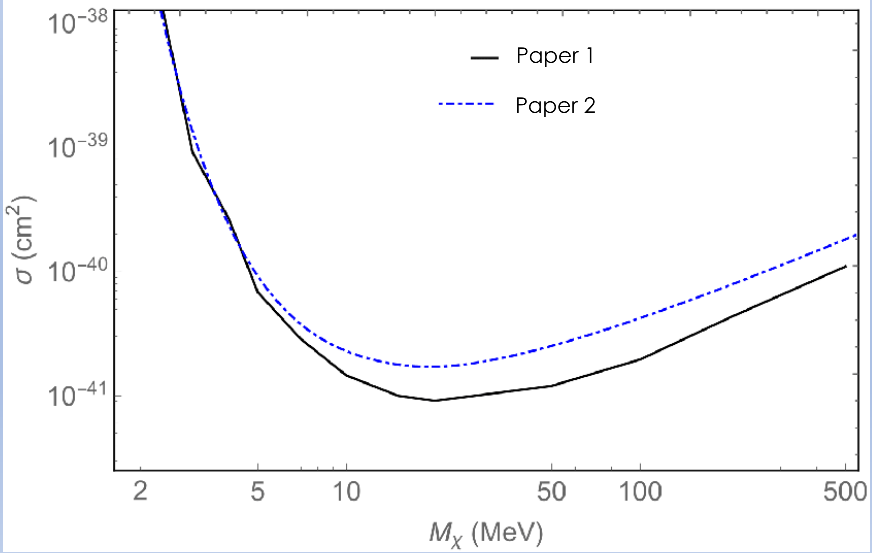
Side project potentially very much interesting

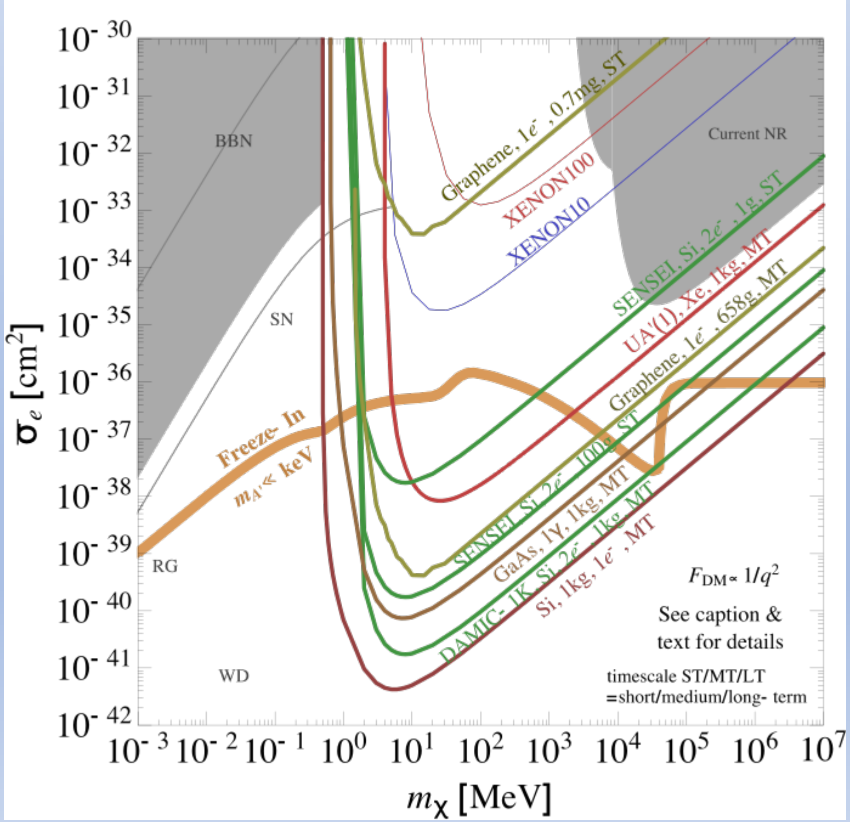
1. Hochberg, et. al, 2016. "Directional Detection of Dark Matter with 2D Targets", Phys. Lett. **B772,** (2017), 239.
2. GL Cavoto et. Al, "Sub-GeV Dark Matter Detection with Electron Recoils in Carbon Nanotubes "Phys.Lett. **B776** (2018) 338-344

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.

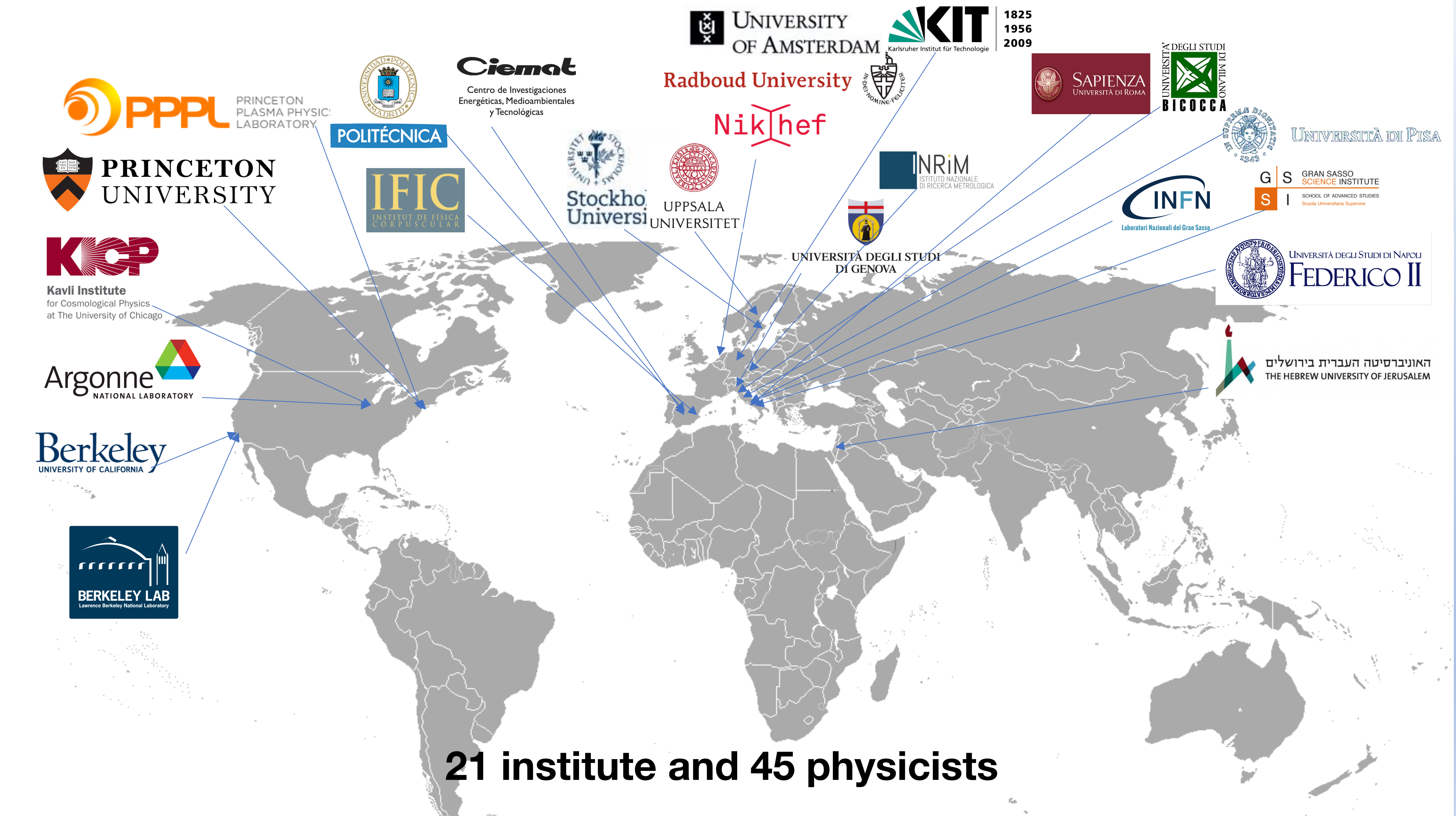
The requirements crucial for the PTOLEMY CNB detection project could be also very much beneficial for Light DM search:

- 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

Recent Publications

[PTOLEMY Collaboration] http://ptolemy.lngs.infn.it

New ExB Filter concept:
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,
https://doi.org/10.1016/j.ppnp.2019.02.004, e-Print: arXiv:1810.06703

TES Microcalorimeters for PTOLEMY, M. Rajteri, M. Biasotti, M. Faverzani, E. Ferri, R. Filippo, F. Gatti, A. Giachero, E. Monticone, A. Nucciotti, A. Puiu, J. Low Temp. Phys. (2019).
https://doi.org/10.1007/s10909-019-02271-x

Physics Program (CNB, Mass, Sterile):
Neutrino physics with the PTOLEMY project, M.G. Betti et al.,
JCAP **07** (2019) 047, https://doi.org/10.1088/1475-7516/2019/07/047,
e-Print: arXiv:1902.05508

To Conclude

We hope that PTOLEMY R&D is providing an interesting set of possibilities for the future of neutrino mass observables

Significant progress has been made in the last year towards the design of a new filter concept and we are evaluating with simulation the parameter specifications that will be required in the construction process

Our overlap with the neutrino mass measurement community has been and continues to be of enormous help to our effort