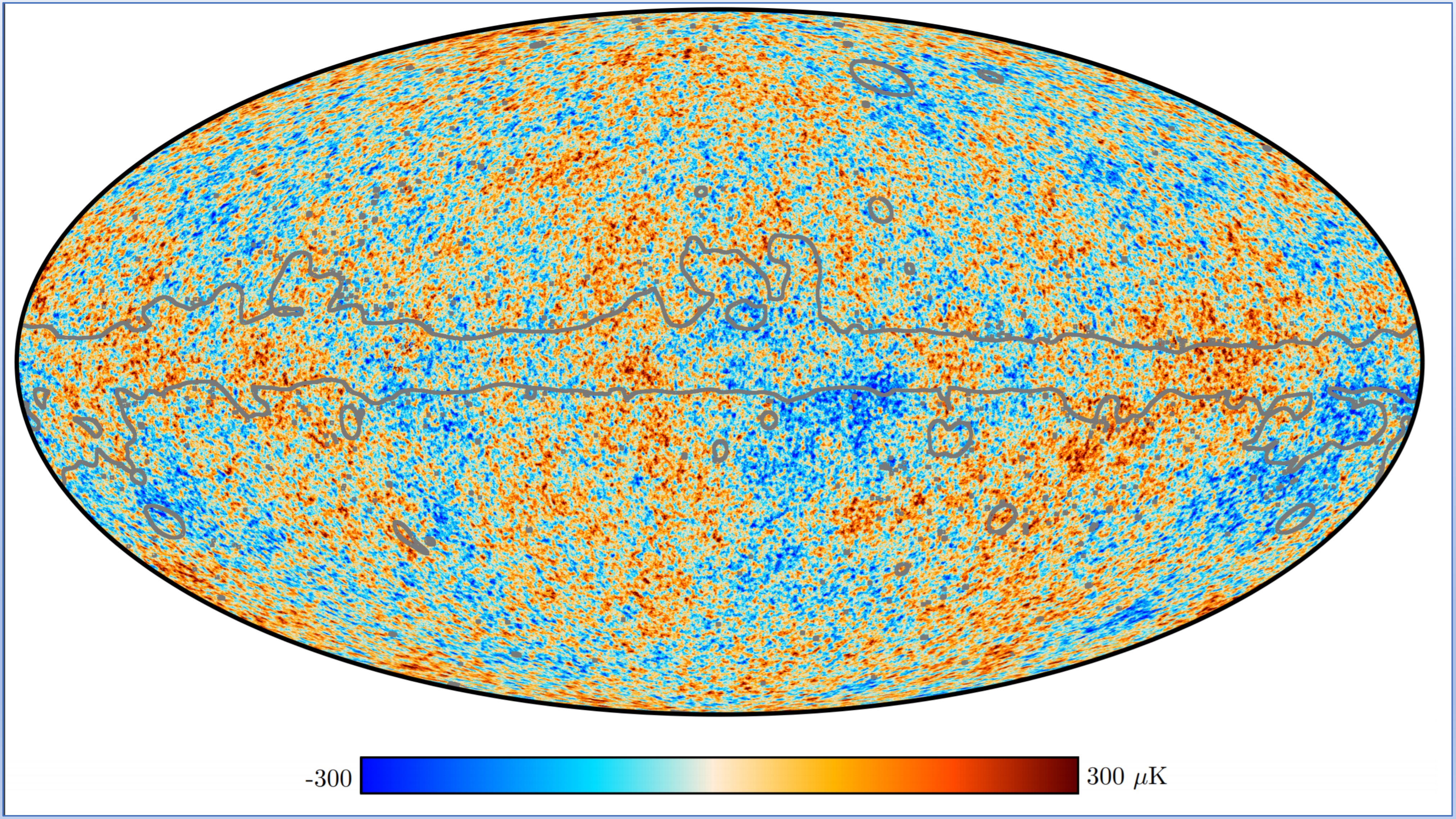
The PTOLEMY project: from a dream to a challenge

Marcello Messina, LNGS-INFN, May 2020

Best summary of the Universe history



Why we believe in Big Bang?

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1. Expansion of Universe

2. Light element abundances

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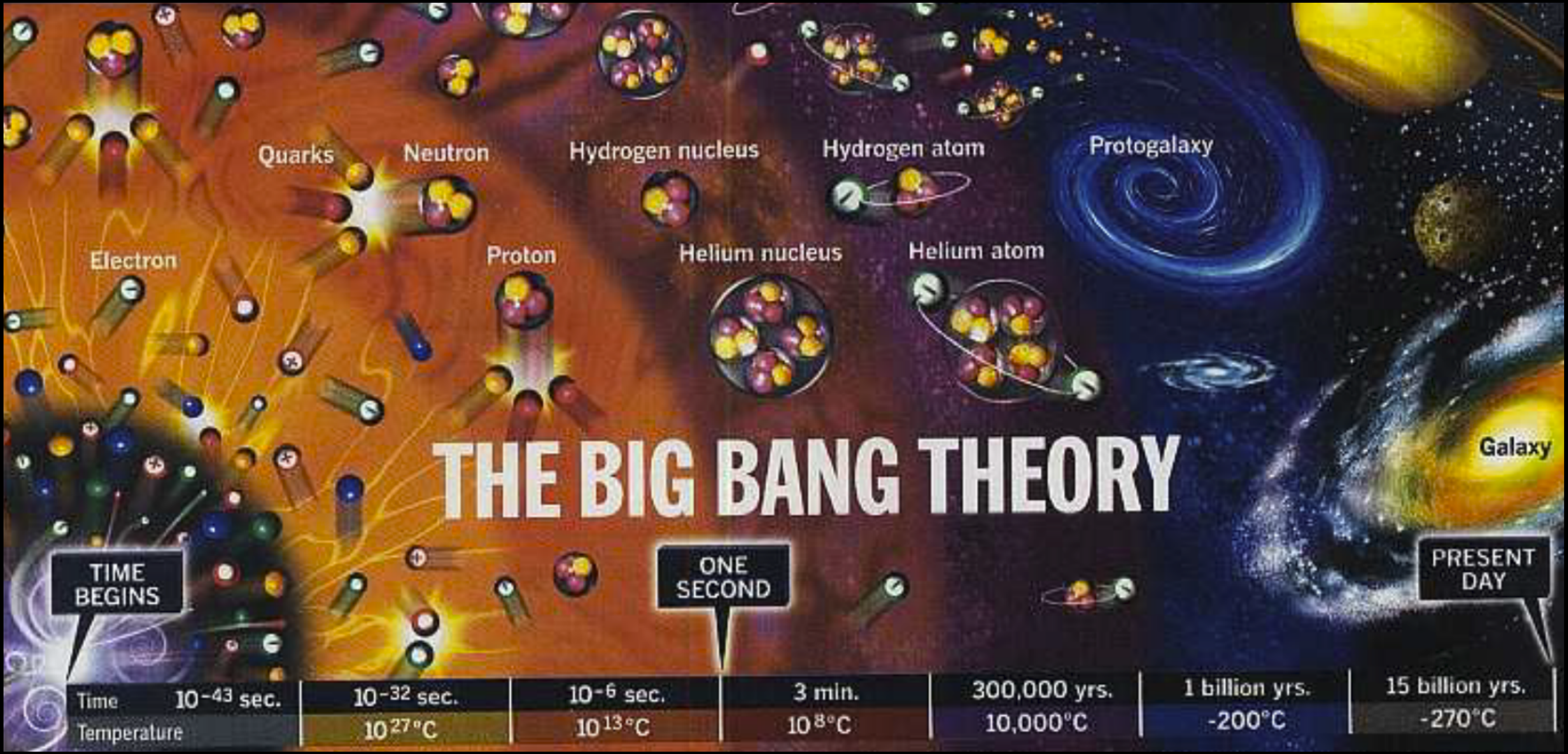
3. Cosmic Microwave Background

Why we believe in Big Bang?

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



Time	10^{-43} sec.	10^{-32} sec.	10^{-6} sec.	3 min.	300,000 yrs.	1 billion yrs.	15 billion yrs.
Temperature		10^{27}°C	10^{13}°C	10^{8}°C	10,000°C	-200°C	-270°C

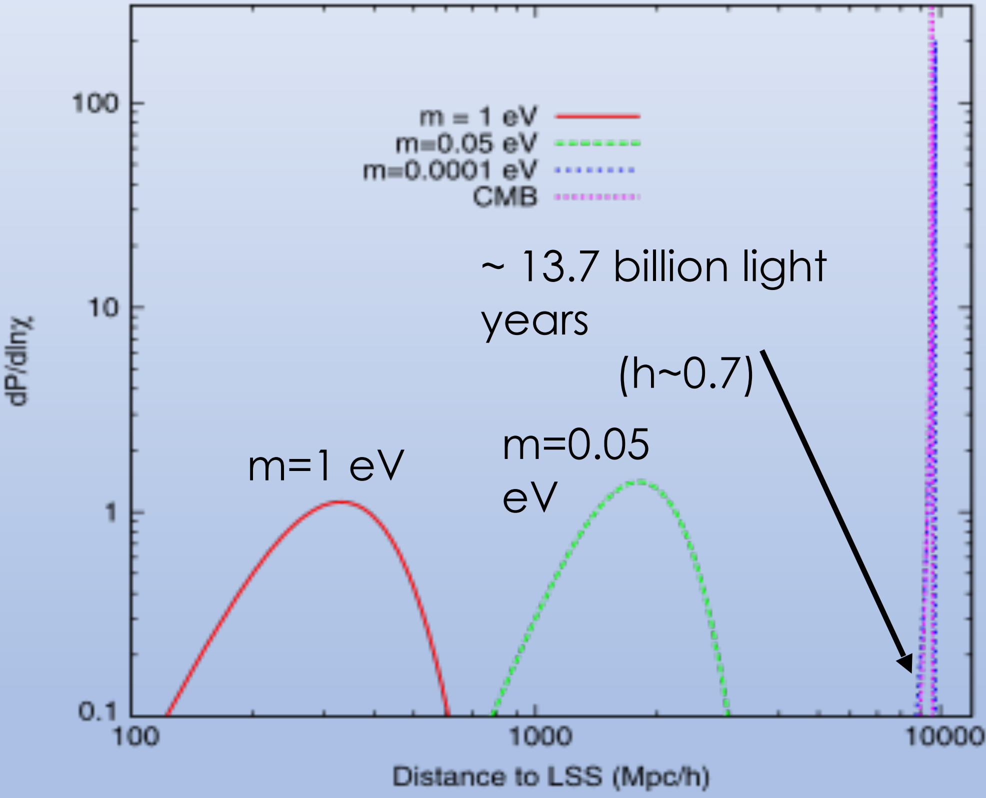
CNB ~ 1 sec

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



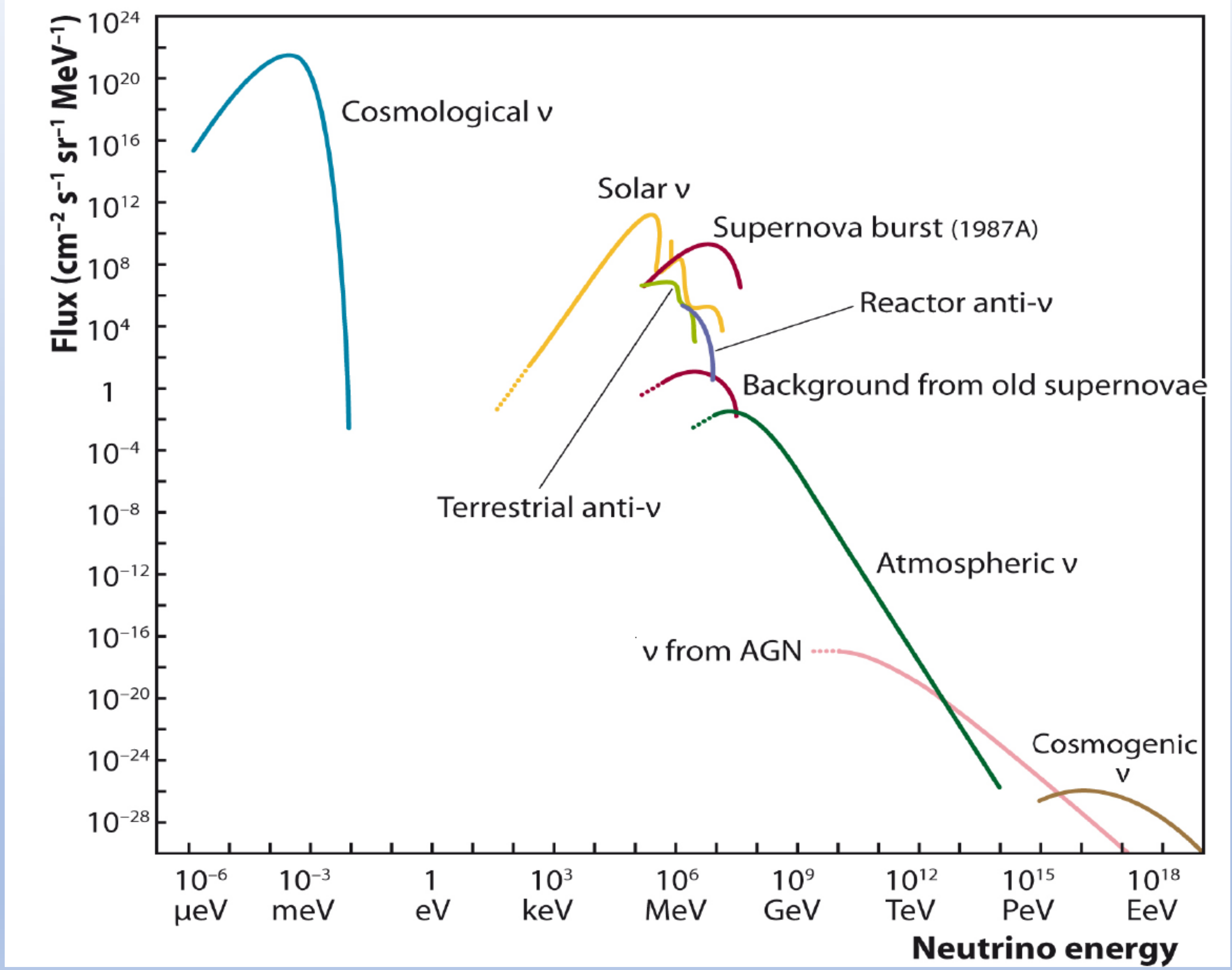
Due to the finite mass of the neutrinos and Hubble expansion, the relic neutrinos that arrive at Earth today (after 13.7 billion years of waiting for them) originate from distances less than 2 billion light years away.

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

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

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



Neutrino flow

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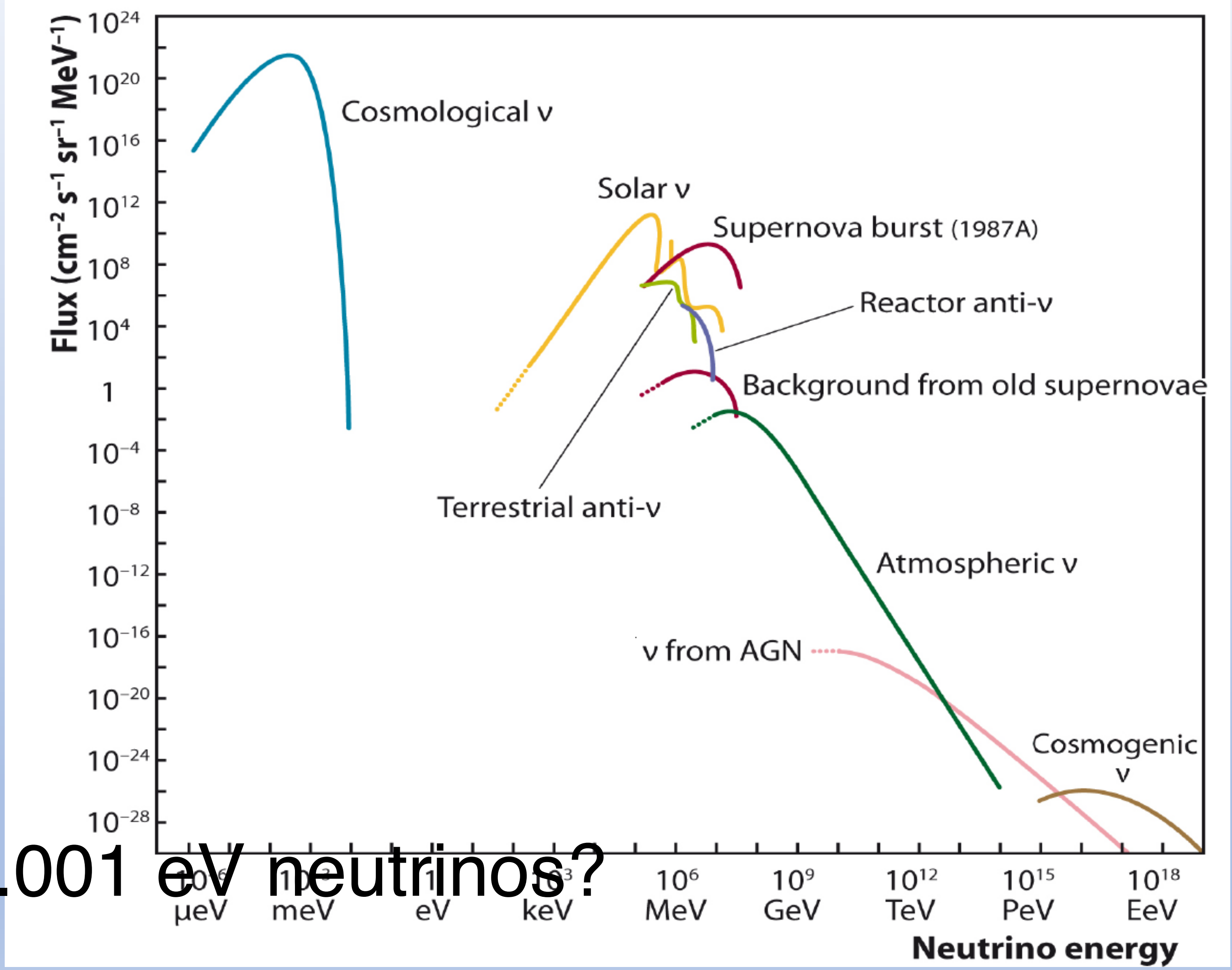
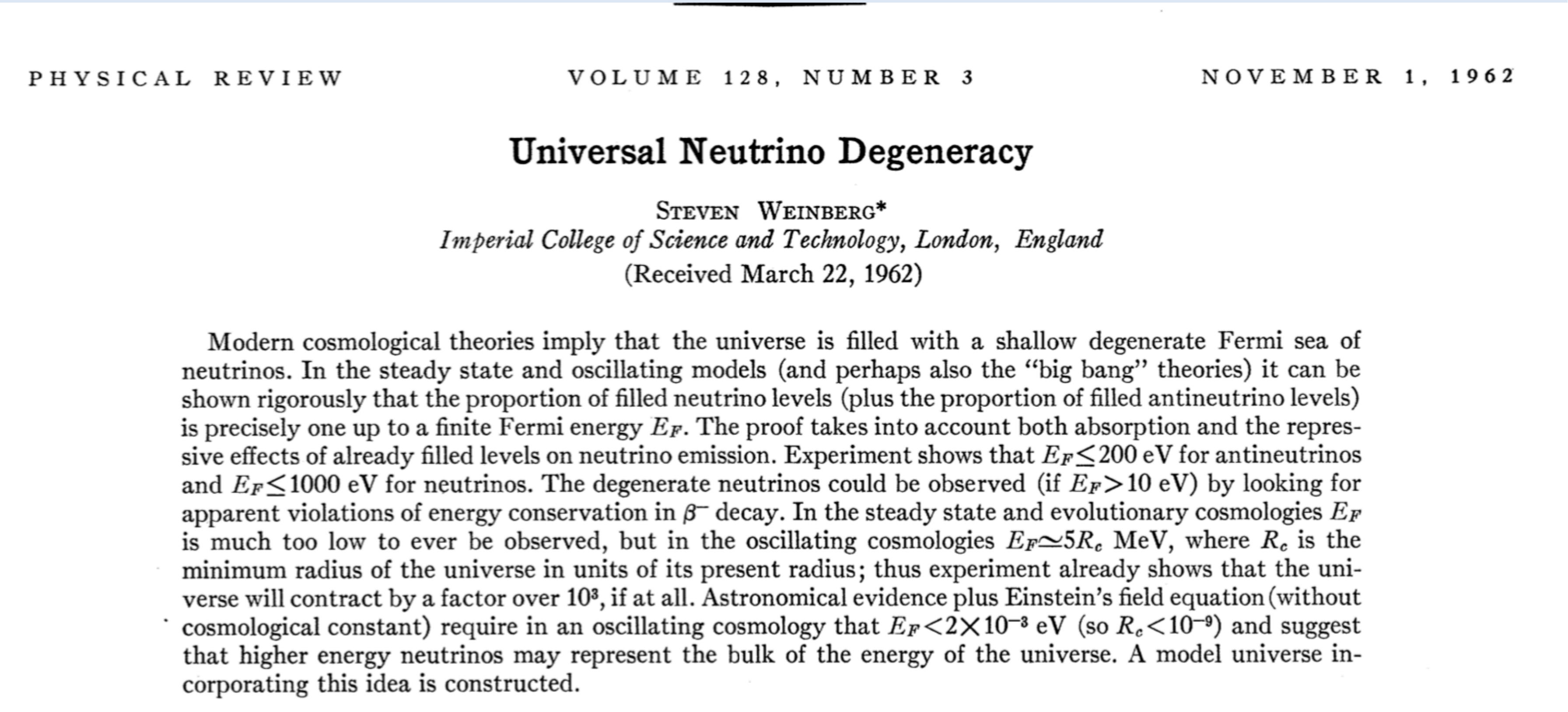


Is it possible to detect 0.001 eV neutrinos?

The status of CNB search before 2007

On 1962



PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

Universal Neutrino Degeneracy

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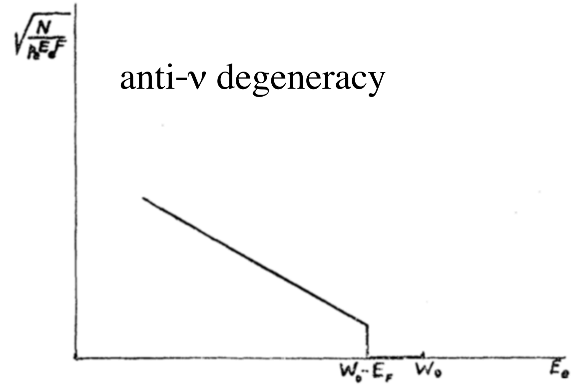
Imperial College of Science and Technology, London, England

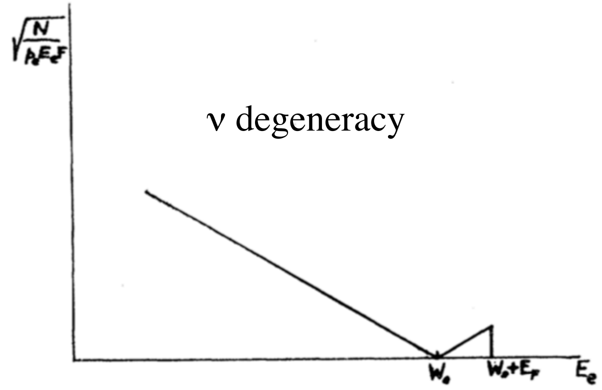
(Received March 22, 1962)

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 $E_F \leq 200$ eV for antineutrinos and $E_F \leq 1000$ 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 $E_F < 2 \times 10^{-3}$ 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.



anti-ν degeneracy

FIG. 1. Shape of the upper end of an allowed Kurie plot to be expected in a β^+ decay if neutrinos are degenerate up to energy E_F, or in a β^- decay if antineutrinos are degenerate.



ν degeneracy

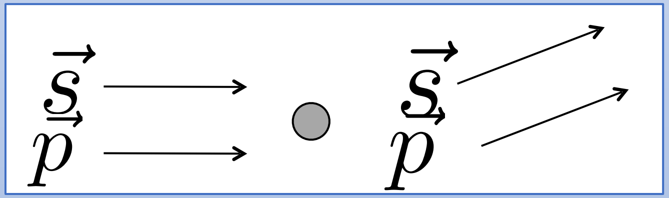
FIG. 2. Shape of the upper end of an allowed Kurie plot to be expected in a β^- decay if neutrinos are degenerate up to energy E_F, or in a β^+ decay if antineutrinos are degenerate.

Exploit massless neutrino scattering

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):

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

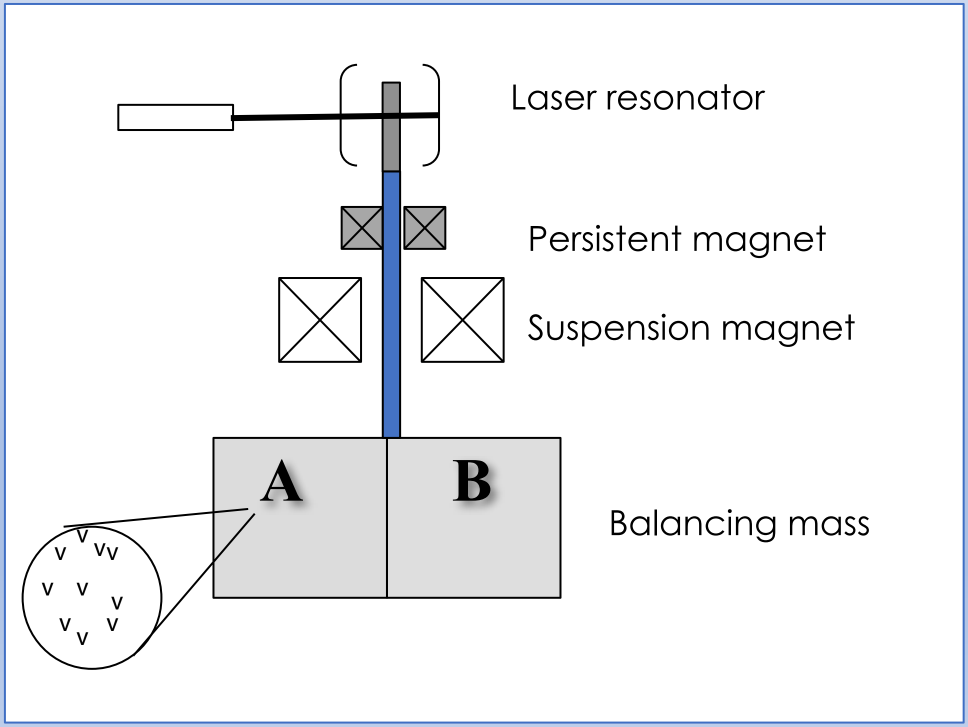


Torsion balance

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



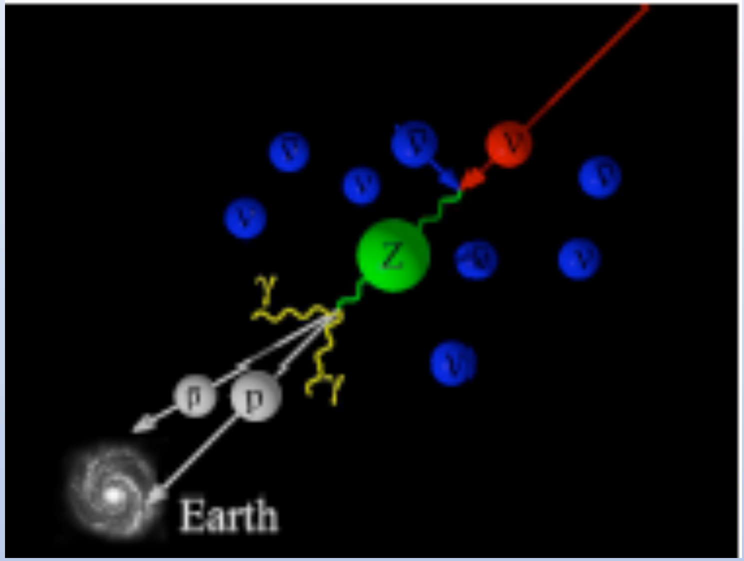
Since the ν wave length is ~ mm (λ) can be envisaged an enhancement of the interaction rate due to coherent sum of the invariant scattering amplitudes in a volume λ^3. Under this assumption:

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

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

Annihilation in the CMR of Z-boson

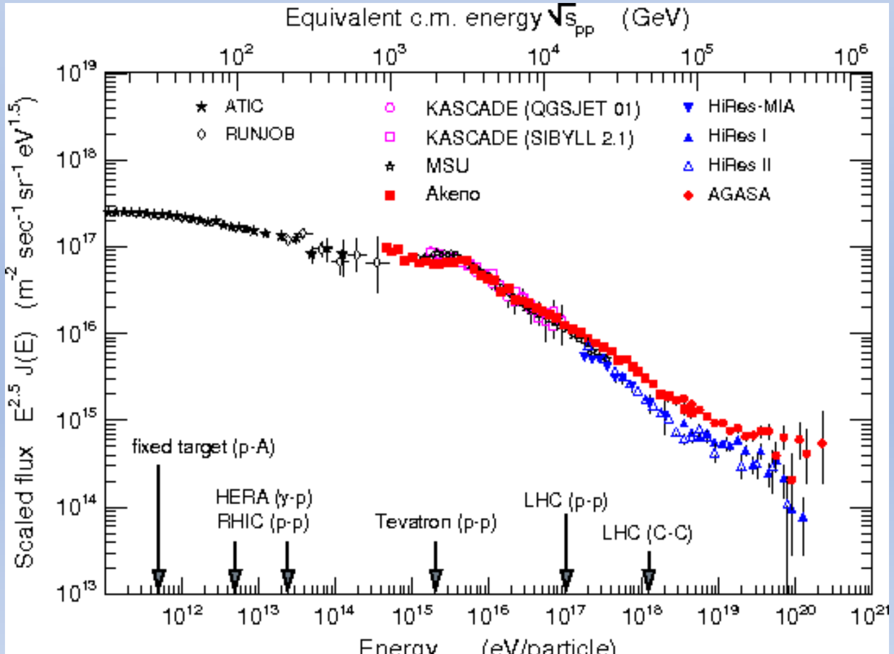
Is it possible to measure the CRN ?
Method 2



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).



Extreme acceleration of target

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.

In this case even with an accelerator ring (VLHC) of ~$4x10^4$ km length (Earth circumference) with E_{beam}~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

On 2007

Cosmological Neutrino Background
Where we are?

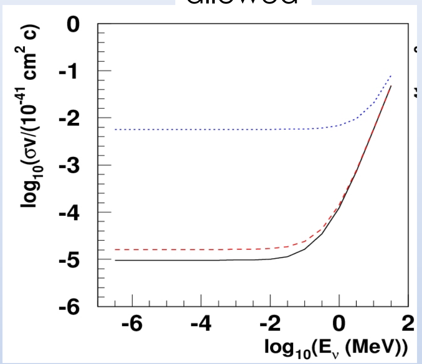
1. A process where the ν can contribute by means of its quantum numbers where no additional energy is required was clearly identified
2. Cross section to predict interaction rate evaluated
3. Neutrino mass is include in the energy balance?

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

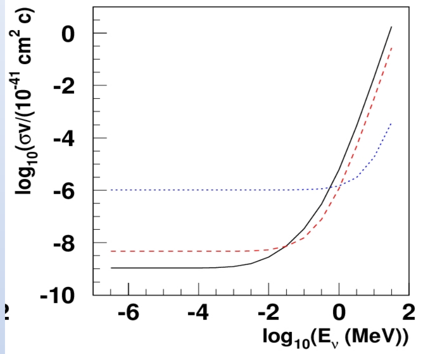
NCB Cross Section

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

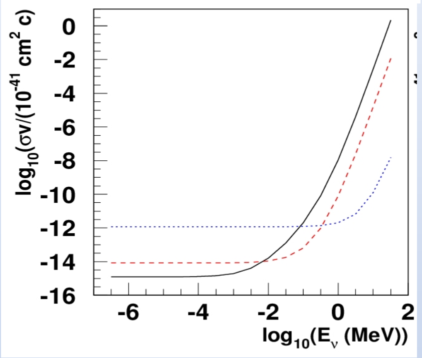
allowed



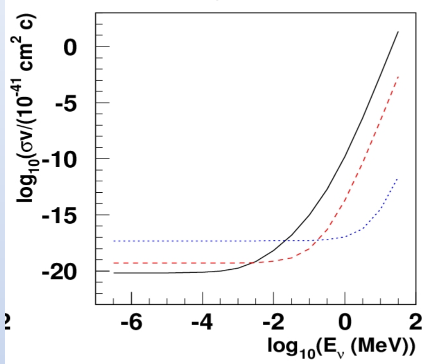
1st unique forbidden



2nd unique forbidden



3rd unique forbidden

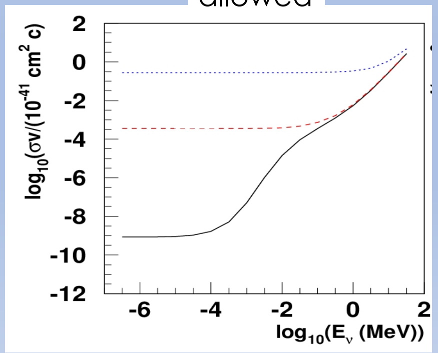


β- (top)

β+ (bottom)

—— Q_β = 1 keV
- - - Q_β = 100 keV
······ Q_β = 10 MeV

allowed



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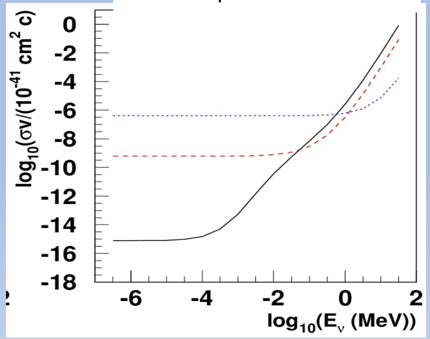

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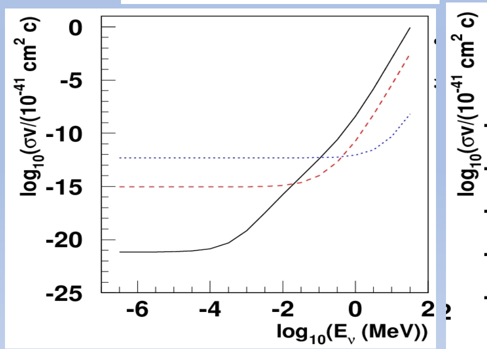

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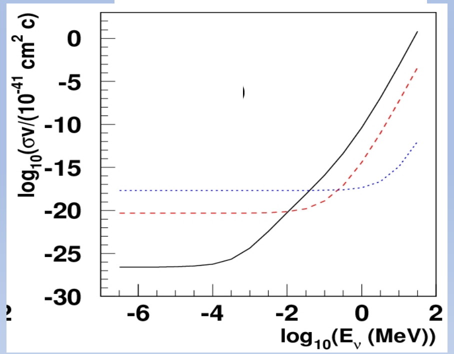
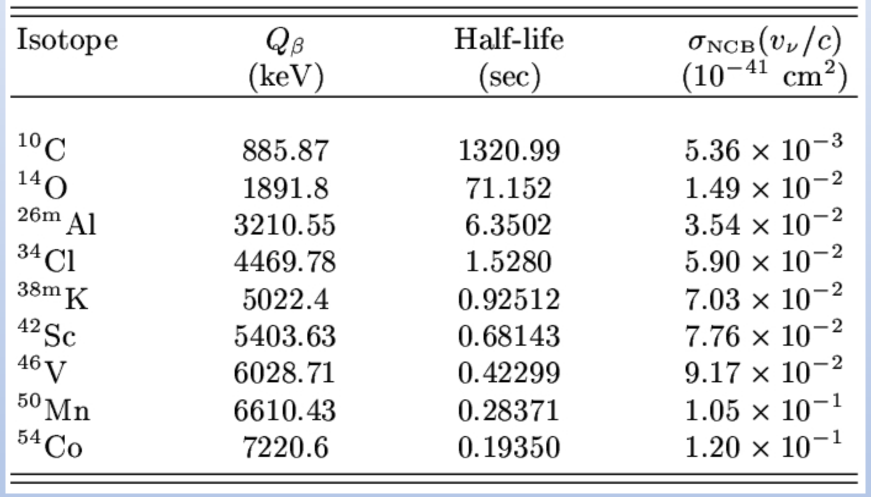


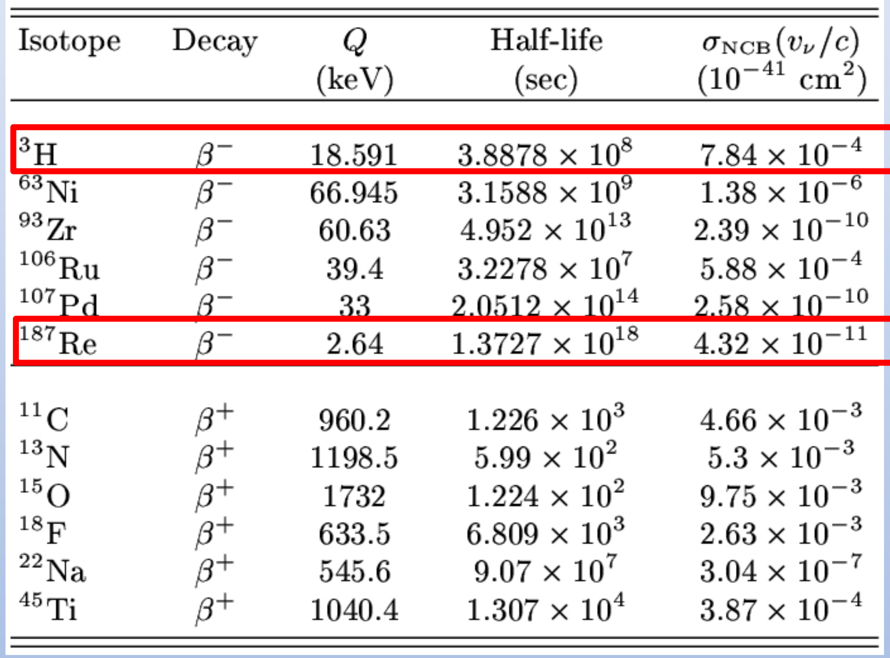
NCB Cross Section Evaluation

specific cases



Isotope	Q_β (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{10}C	885.87	1320.99	5.36×10^{-3}
^{14}O	1891.8	71.152	1.49×10^{-2}
^{26m}Al	3210.55	6.3502	3.54×10^{-2}
^{34}Cl	4469.78	1.5280	5.90×10^{-2}
^{38m}K	5022.4	0.92512	7.03×10^{-2}
^{42}Sc	5403.63	0.68143	7.76×10^{-2}
^{46}V	6028.71	0.42299	9.17×10^{-2}
^{50}Mn	6610.43	0.28371	1.05×10^{-1}
^{54}Co	7220.6	0.19350	1.20×10^{-1}

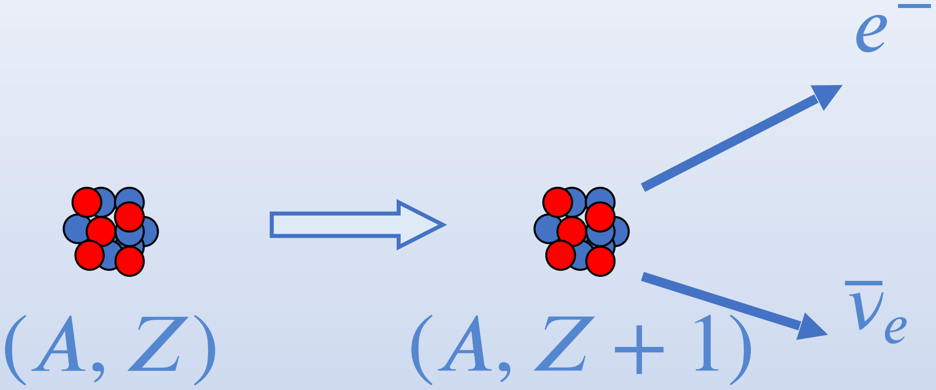
Super-allowed $0^+ \rightarrow 0^+$

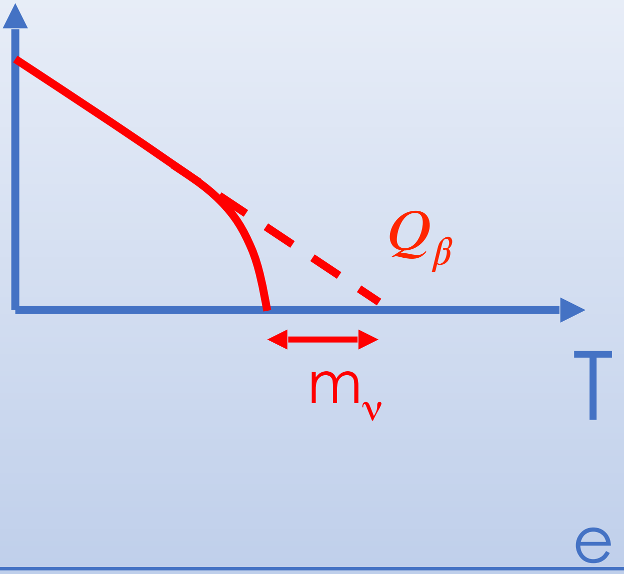


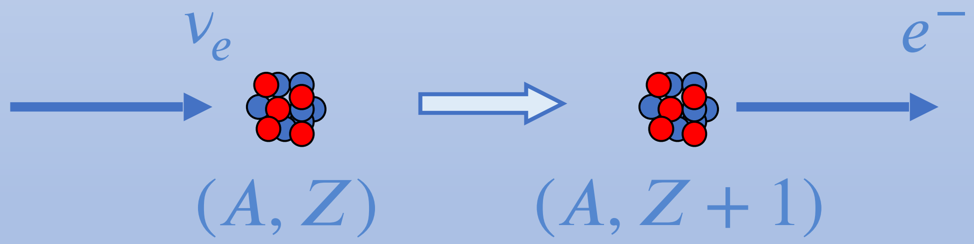
Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^8	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^9	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^7	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{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}

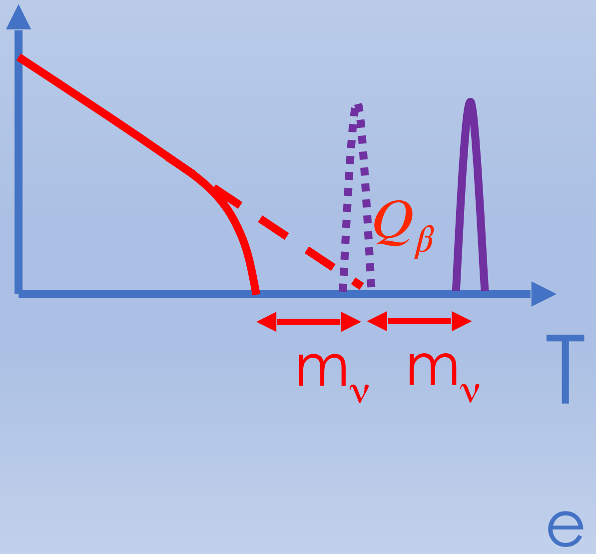
Nuclei having the highest product $\sigma_{\rm NCB}\ t_{1/2}$

Detection principle





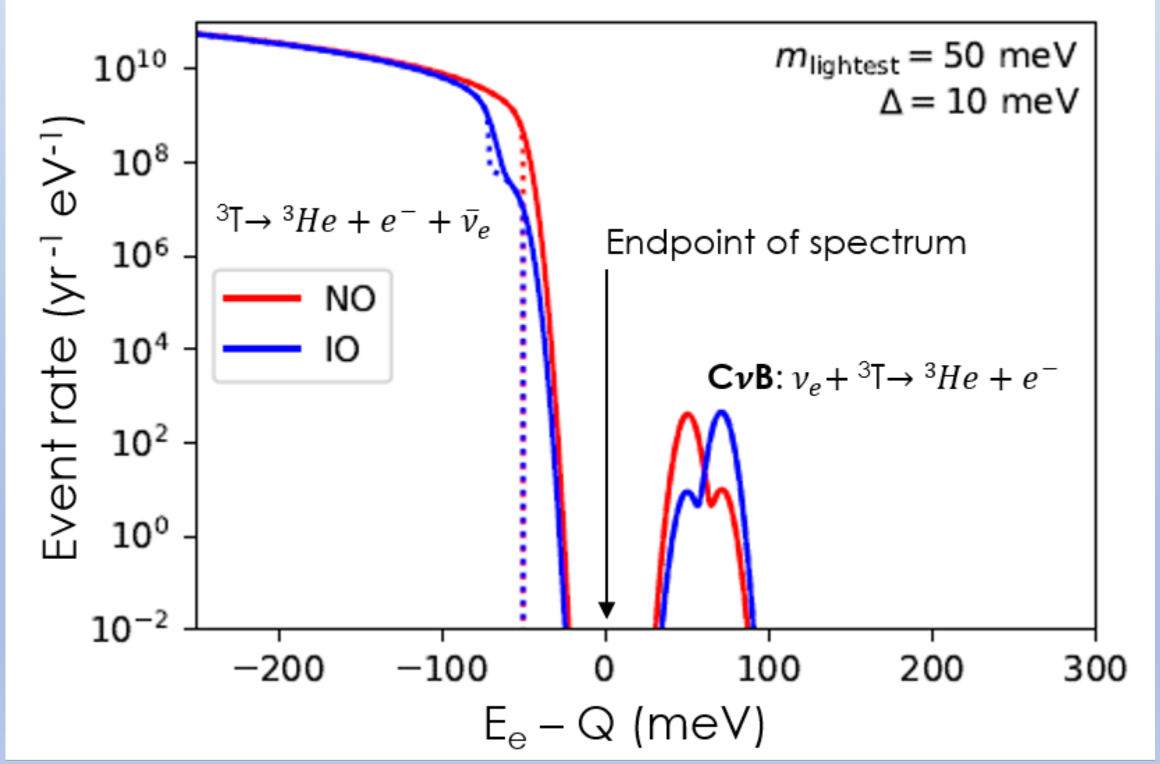




Why Tritium target?

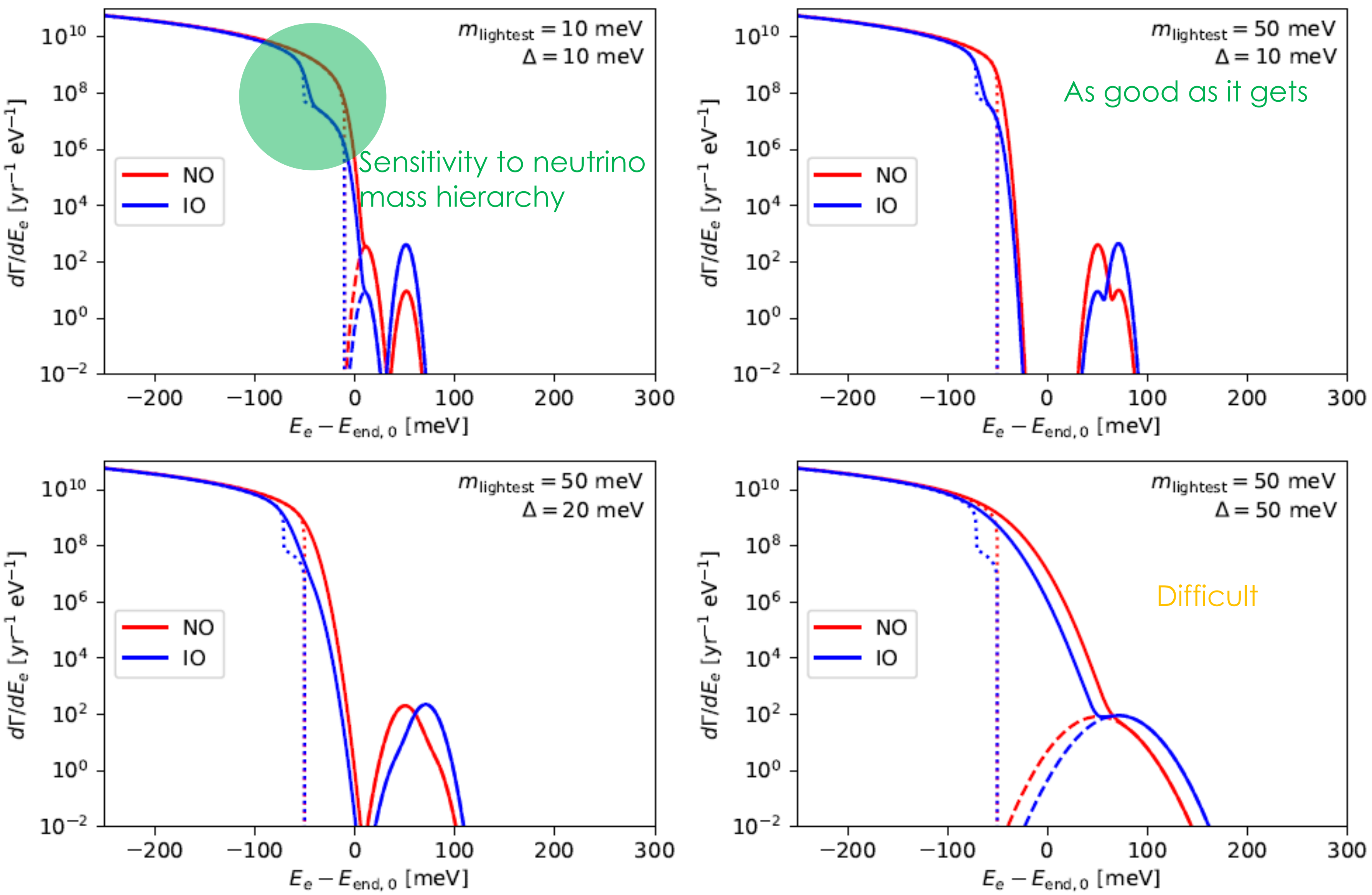
- High cross-section for neutrino capture
- Sizeable lifetime
- Low Q-value
- **Tritium beta decay ~10^{15} Bq/gram**

PTOLEMY collaboration, JCAP_047P_0219



Dreaming with opened eyes

PTOLEMY collaboration, JCAP_047P_0219



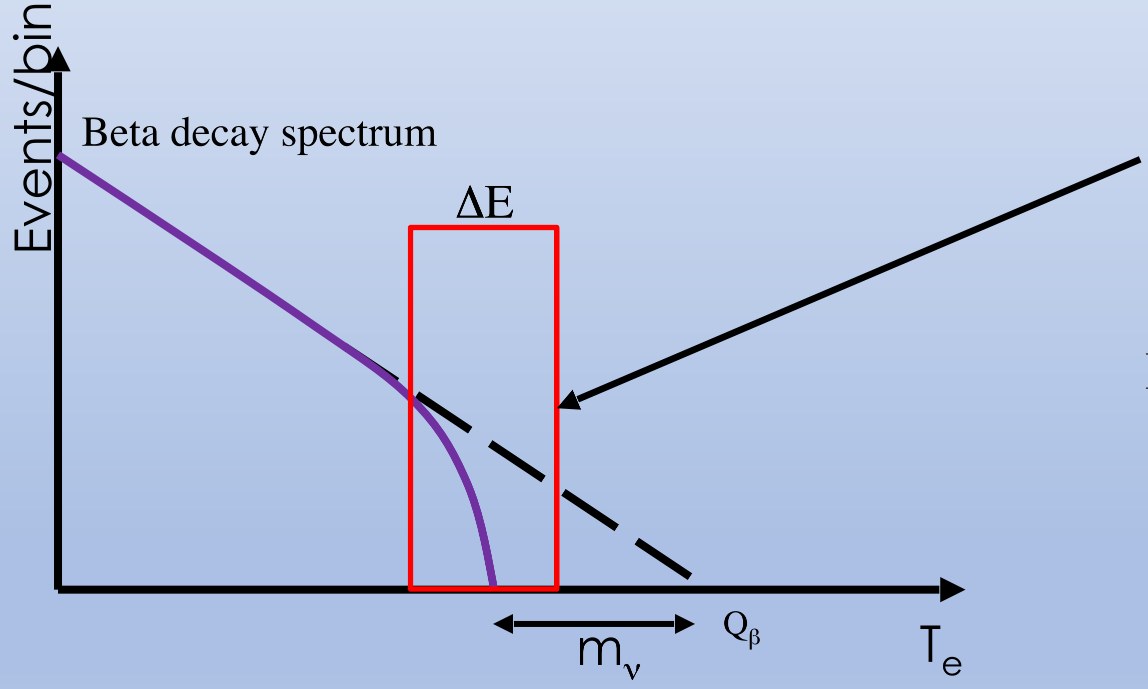
Sensitivity to neutrino mass hierarchy

As good as it gets

Difficult

Why do we need an electrostatic filter?

Answer:



1 g of tritium makes $5.6\text{x}10^{14}$ decay/s

Measuring interval (100÷200) $\boldsymbol{\sigma}$= 5 ÷10 eV

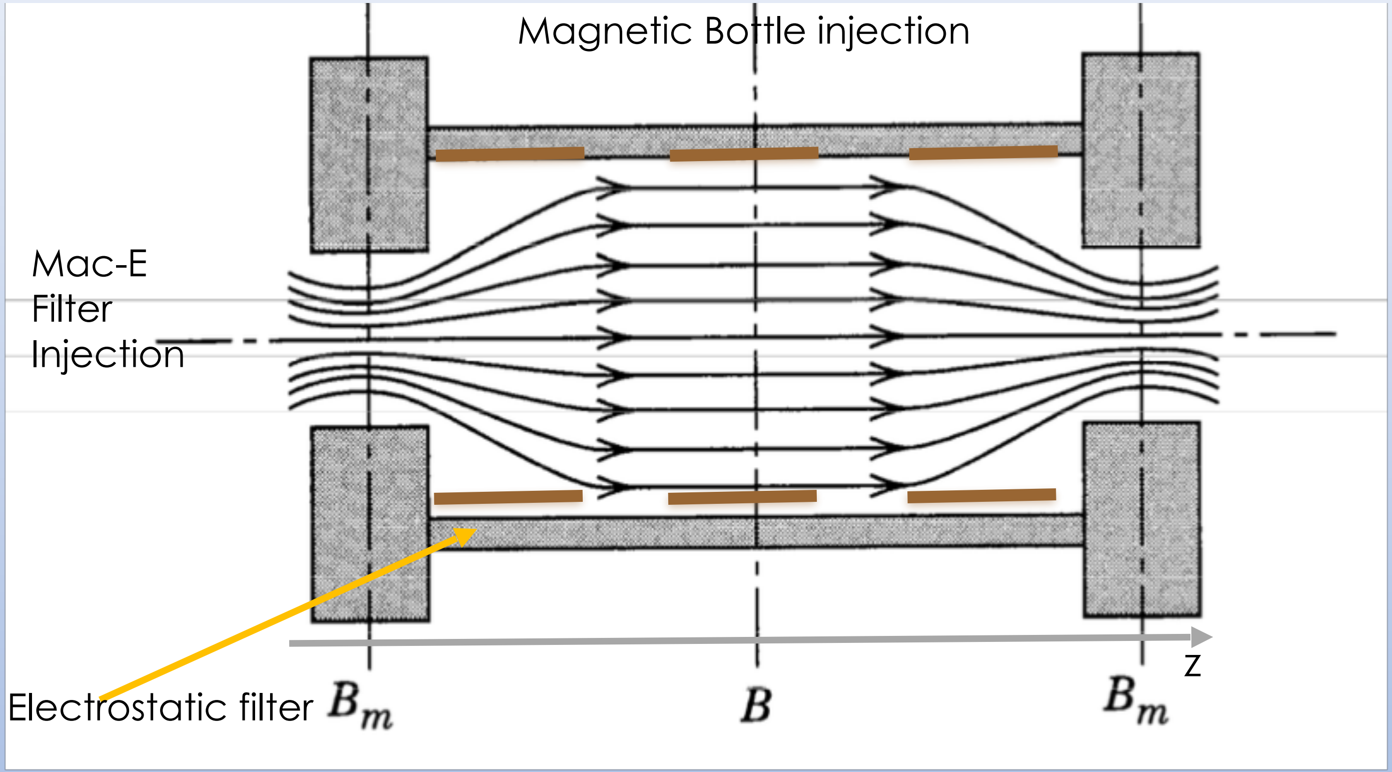
Fraction rate in the measurement range

$$\propto \left(\frac{\Delta E}{Q}\right)^3 = \left(\frac{2.5-5.}{18560}\right)^3 =(250\text{–}20000)\bullet 10^{-14}$$

Electrons to be analyzed for 1 g of T will be 5.610^{14} x $(250\text{–}20000)\bullet 10^{-14}$=($10^3$-$10^5$) event/s

Mac-E filter

The device consist of a magnetic bottle where particles are injected form the edge plus an electrostatic barrier



Jackson Fig 12.6

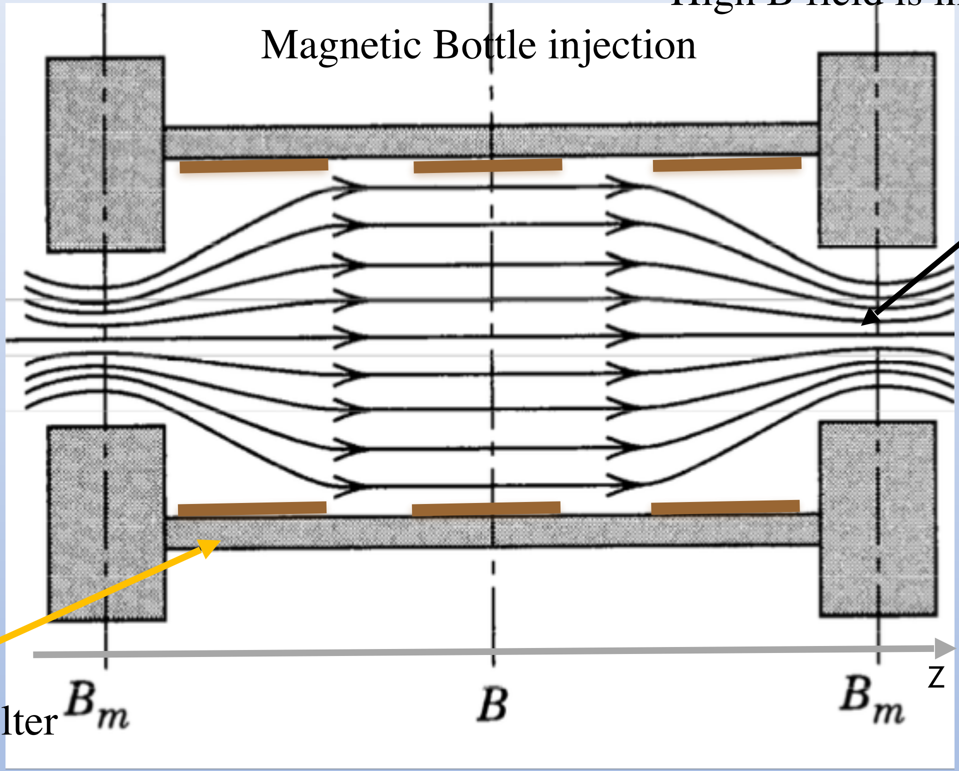
F $\propto \vec{\mu} \bullet \vec{\nabla} B$

Tends to straighten the particle momentum across field line direction

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

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

Limiting factor of a Mac-E filter



High B field is incompatible with high E resolution

Magnetic Bottle injection

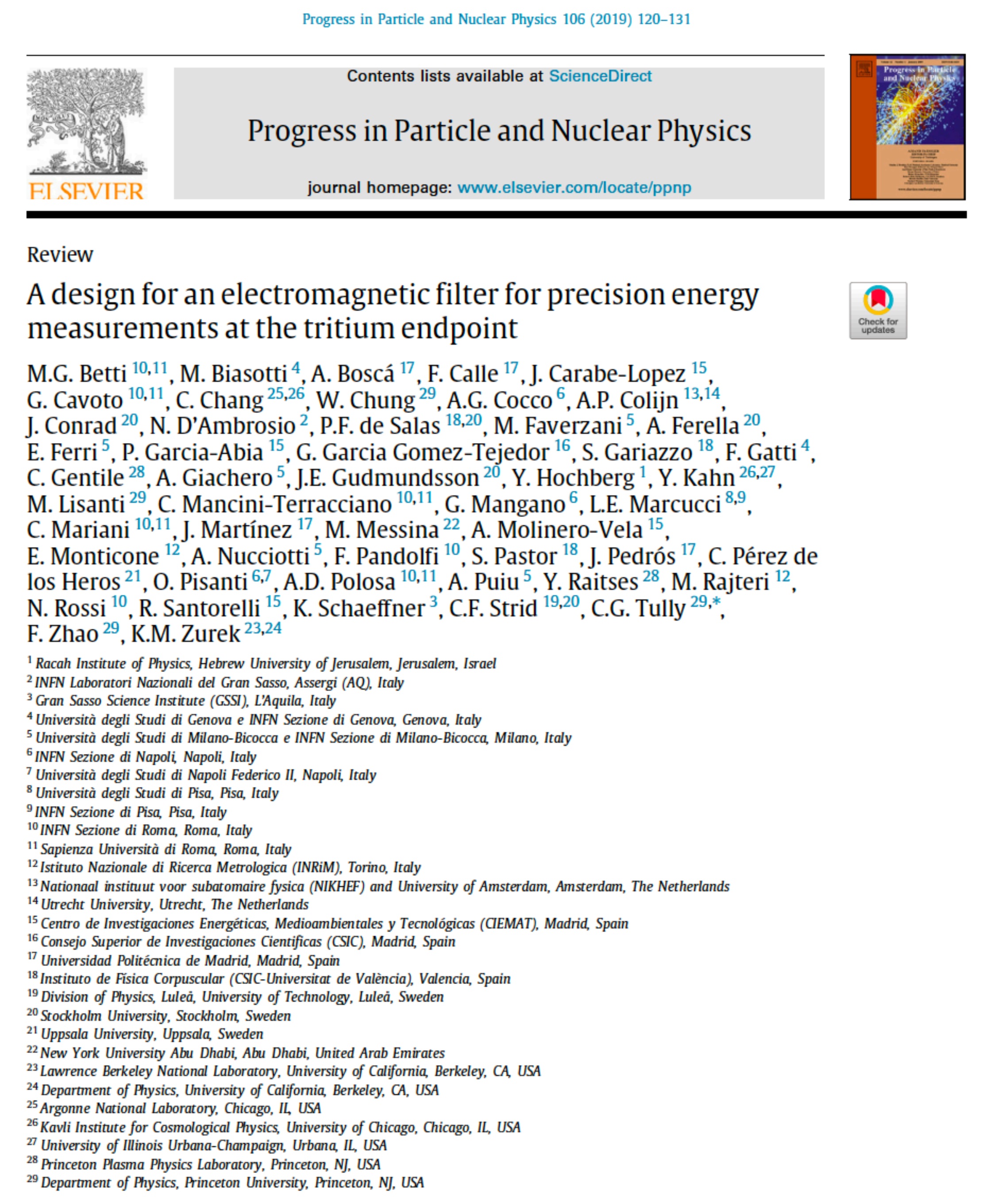
Mac-E
Filter
Injection

Decreasing B reduces in an
unacceptable way the efficiency

Electrostatic filter

Remain only one possibility: removing p_T in a controlled manner

PTOLEMY detector concept became feasible



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Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

A design for an electromagnetic filter for precision energy measurements at the tritium endpoint

M.G. Betti[10,11], M. Biasotti[4], A. Boscá[17], F. Calle[17], J. Carabe-Lopez[15], G. Cavoto[10,11], C. Chang[25,26], W. Chung[29], A.G. Cocco[6], A.P. Colijn[13,14], J. Conrad[20], N. D'Ambrosio[2], P.F. de Salas[18,20], M. Faverzani[5], A. Ferella[20], E. Ferri[5], P. Garcia-Abia[15], G. Garcia Gomez-Tejedor[16], S. Gariazzo[18], F. Gatti[4], C. Gentile[28], A. Giachero[5], J.E. Gudmundsson[20], Y. Hochberg[1], Y. Kahn[26,27], M. Lisanti[29], C. Mancini-Terracciano[10,11], G. Mangano[6], L.E. Marcucci[8,9], C. Mariani[10,11], J. Martínez[17], M. Messina[22], A. Molinero-Vela[15], E. Monticone[12], A. Nucciotti[5], F. Pandolfi[10], S. Pastor[18], J. Pedrós[17], C. Pérez de los Heros[21], O. Pisanti[6,7], A.D. Polosa[10,11], A. Puiu[5], Y. Raitses[28], M. Rajteri[12], N. Rossi[10], R. Santorelli[15], K. Schaeffner[3], C.F. Strid[19,20], C.G. Tully[29,*], F. Zhao[29], K.M. Zurek[23,24]

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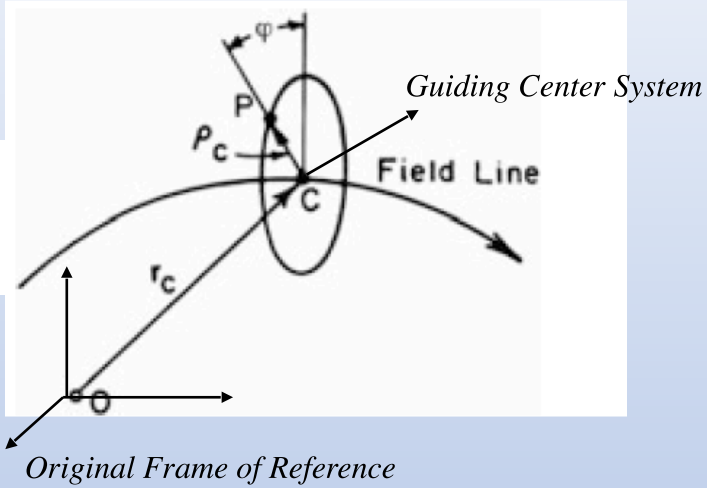
New filter Concept

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

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



Guiding Center System

Original Frame of Reference

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.

First adiabatic invariant:

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

With v* the velocity of particle in CGS

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

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

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

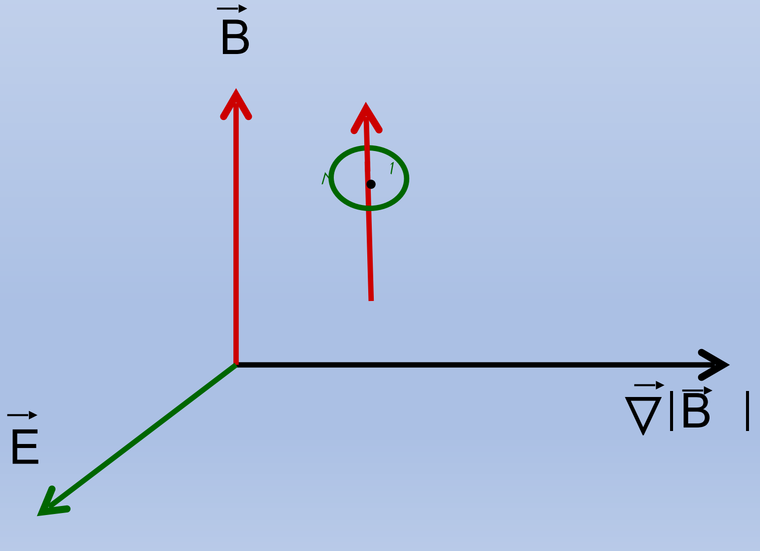
New concept EM filter

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

$\vec{E}$ x $\vec{B}$ drift

∇B drift

Static fields configuration



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

New concept EM filter

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

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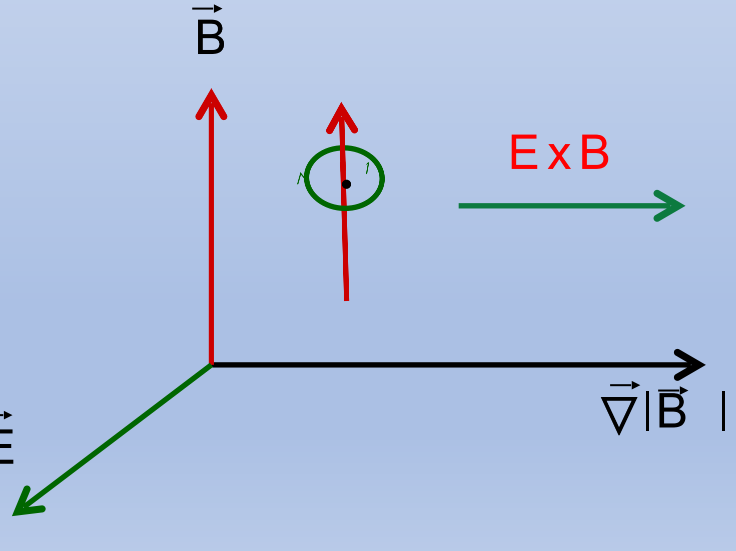

M.G. Betti et al., Prog. Part. Nucl. Phys. 106 (2019) 120-131

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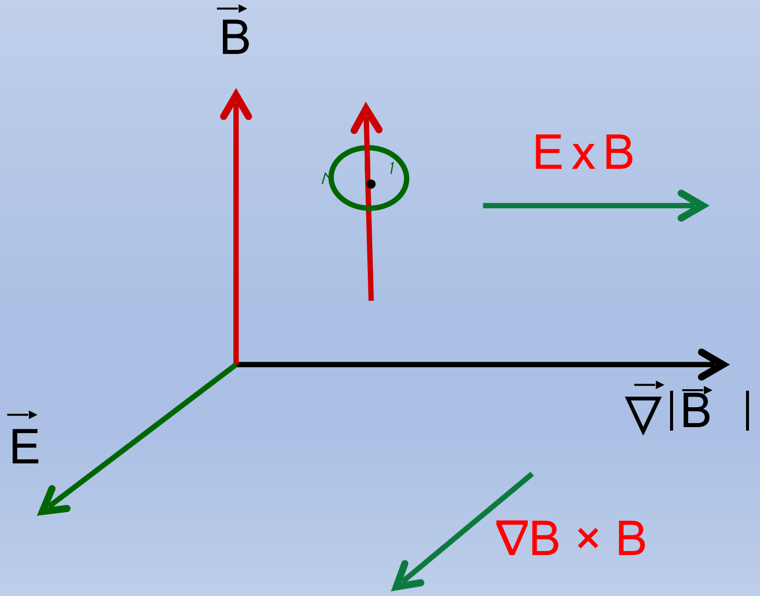
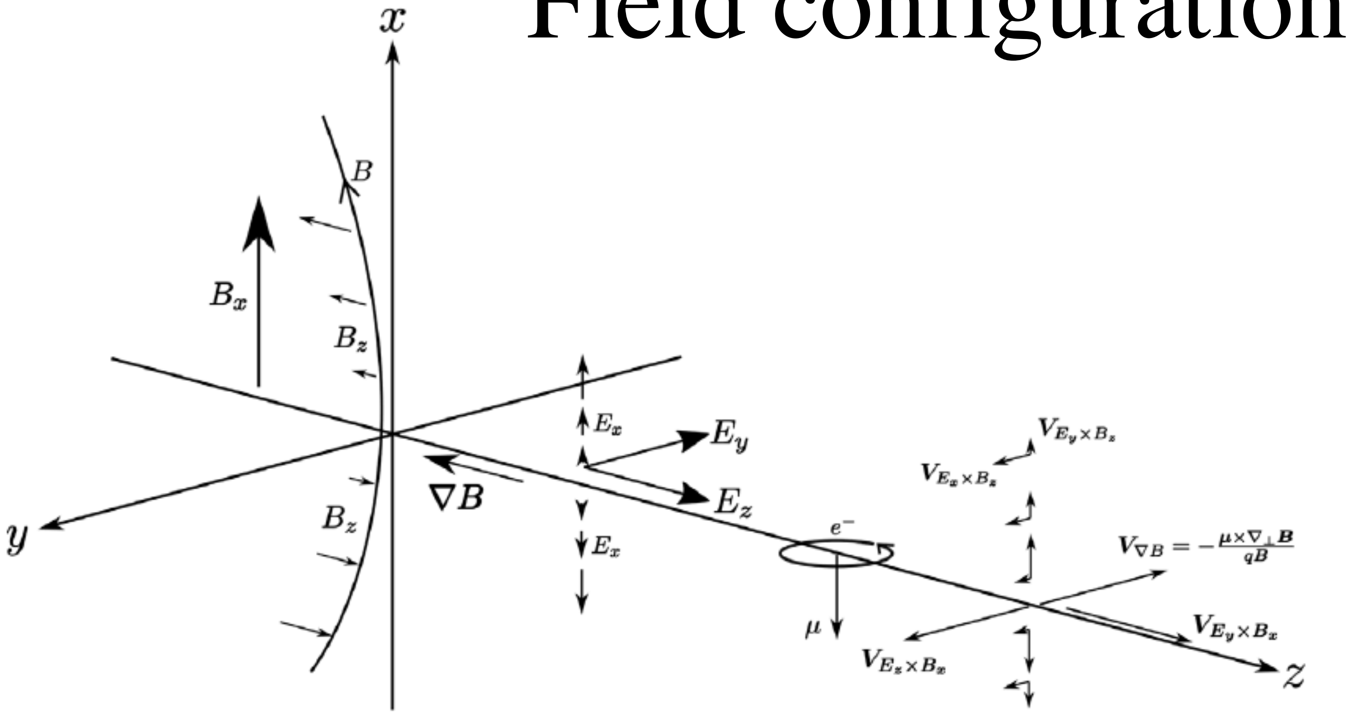
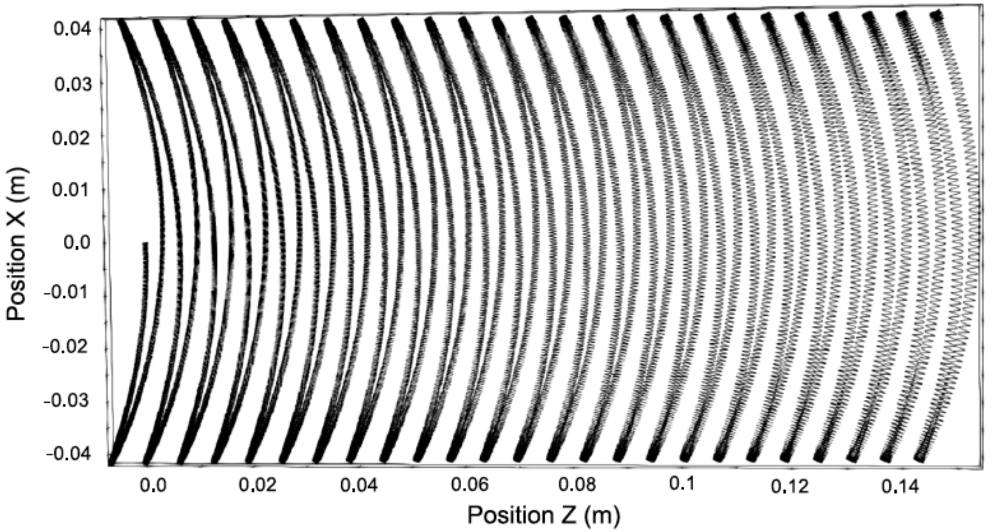


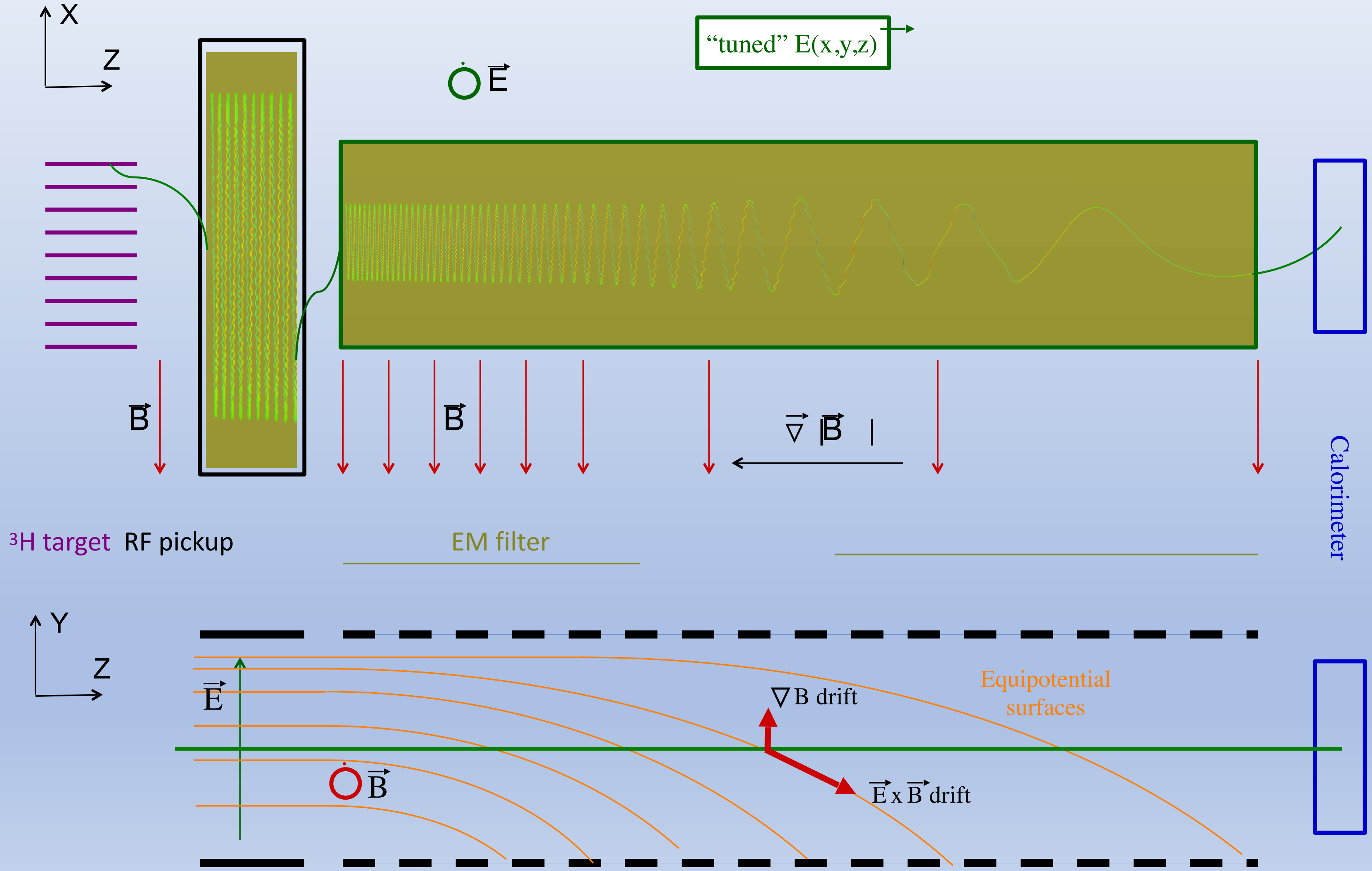
M.G. Betti et al., Prog. Part. Nucl. Phys. 106 (2019) 120-131

Field configuration

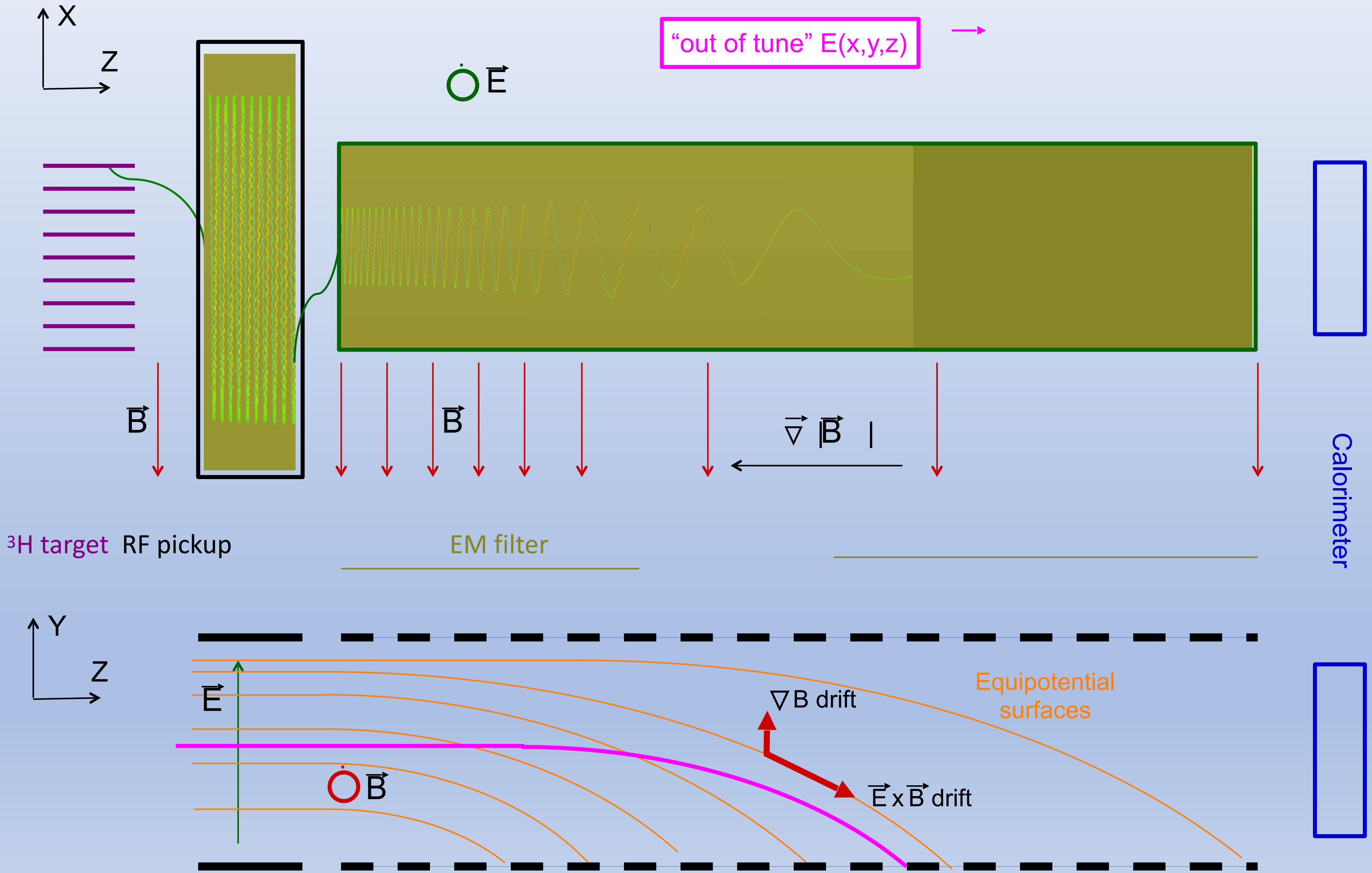




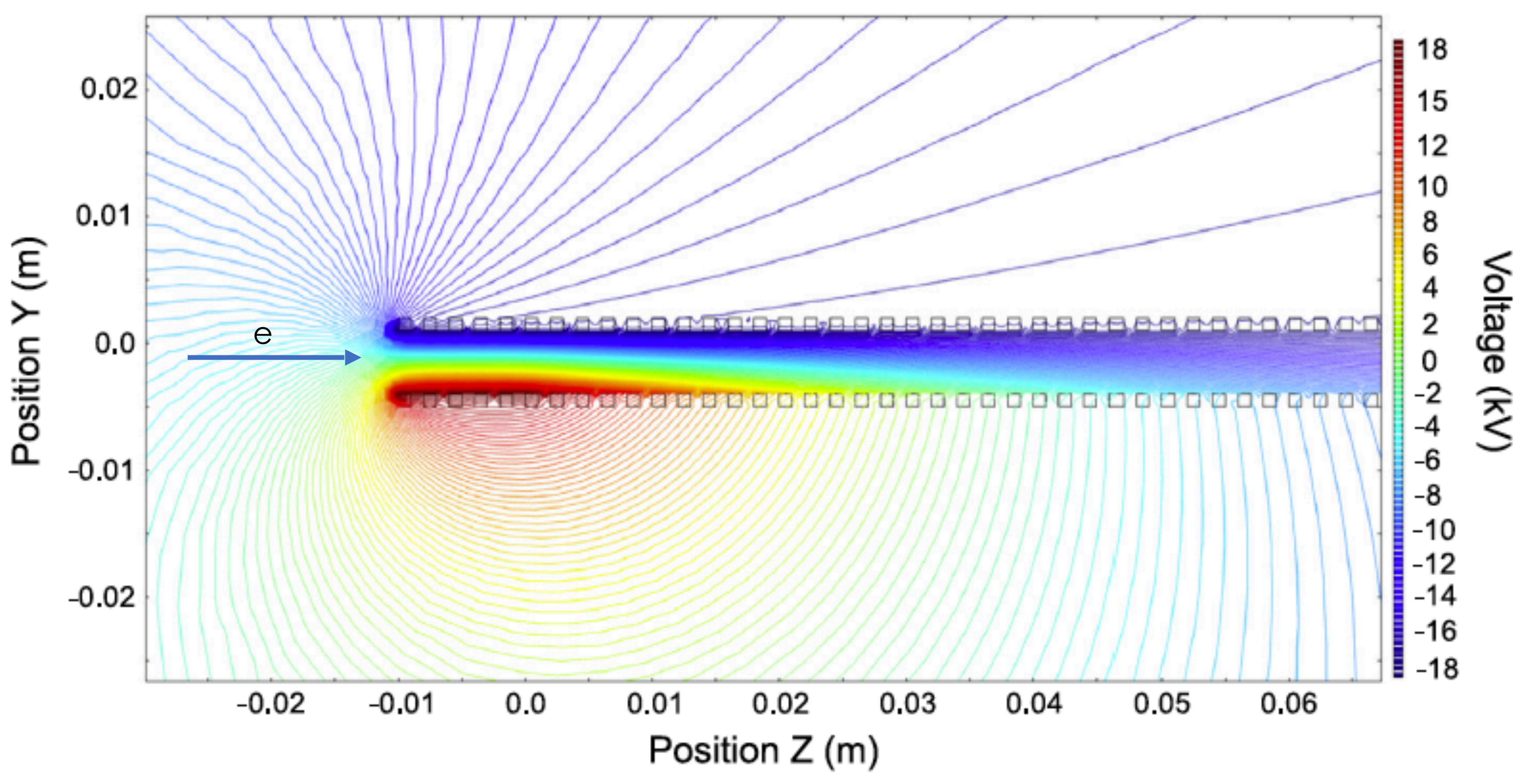
New concept EM filter
Dynamic tuning



New concept EM filter
Dynamic tuning



Filter configuration and performance



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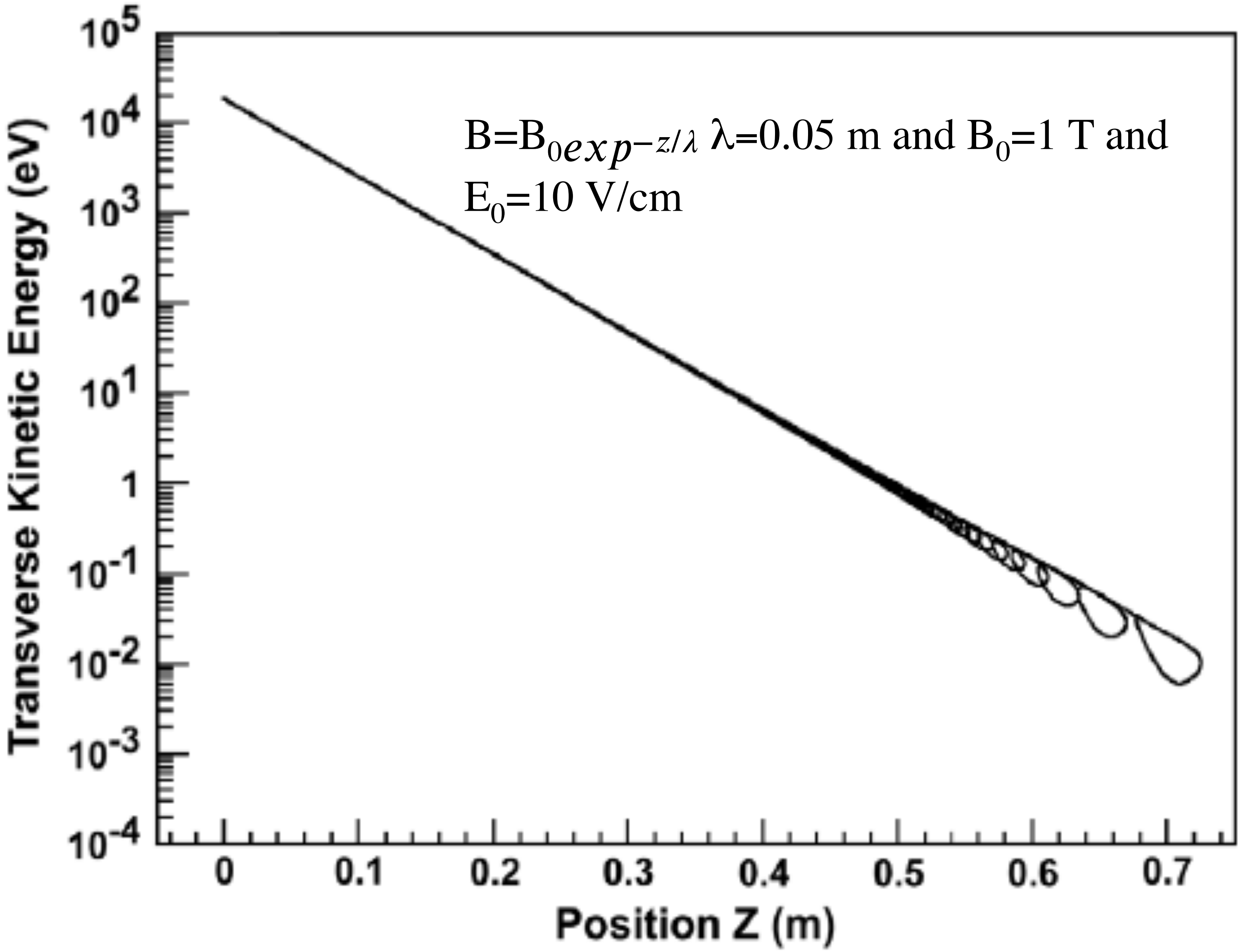
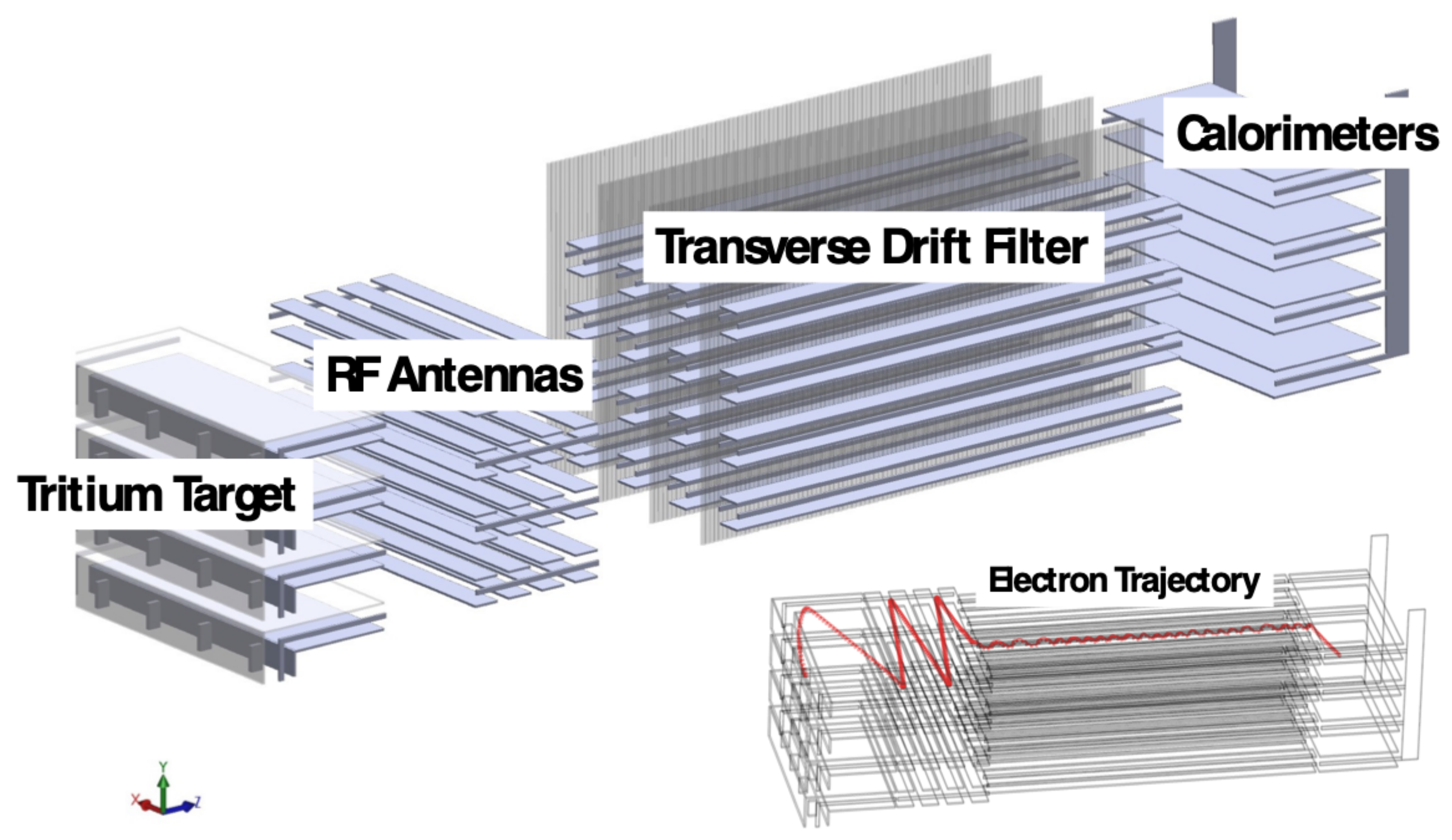


$B=B_0 exp^{-z/\lambda}$ λ=0.05 m and B_0=1 T and E_0=10 V/cm

PTOLEMY: experiment layout



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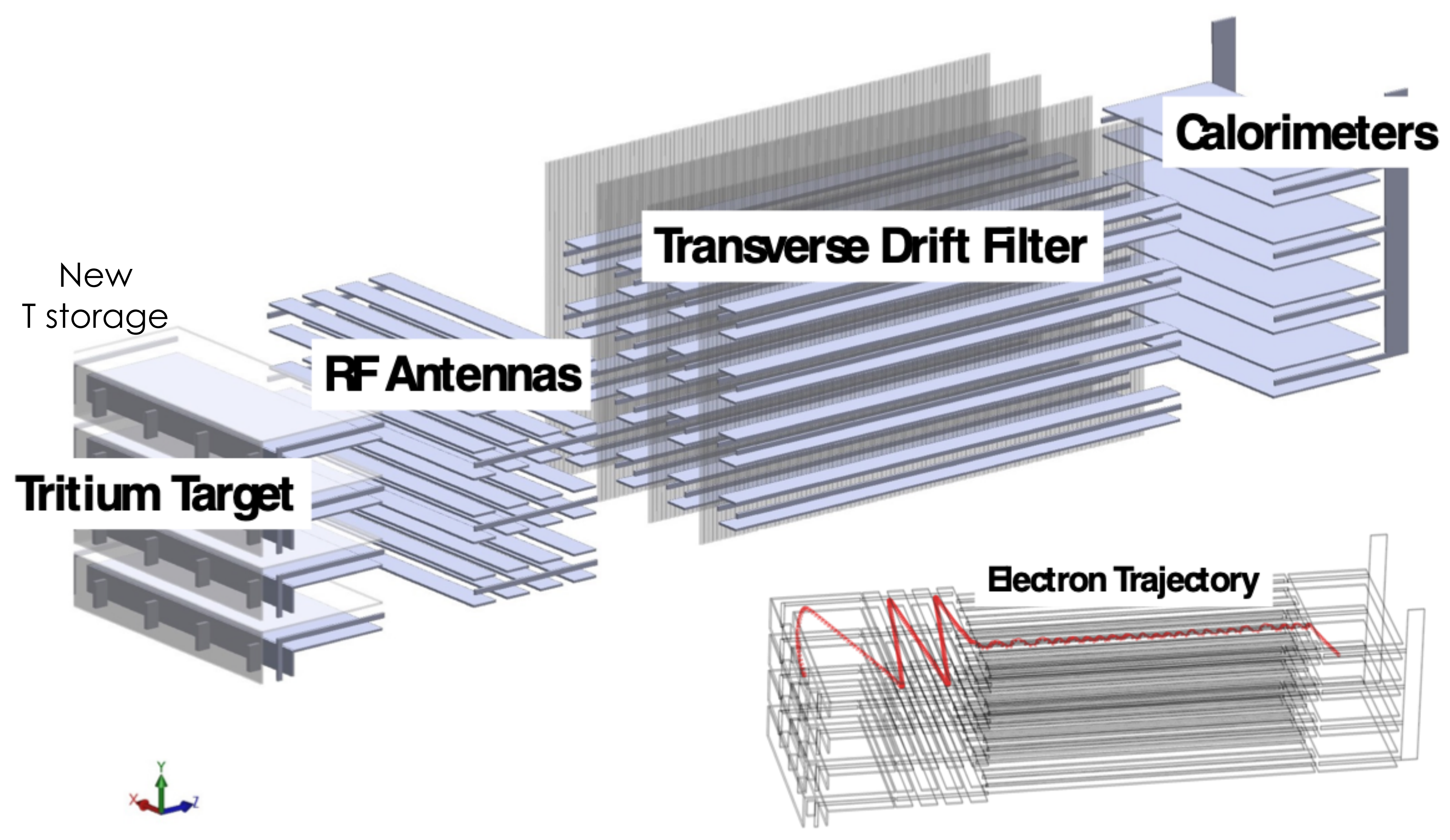

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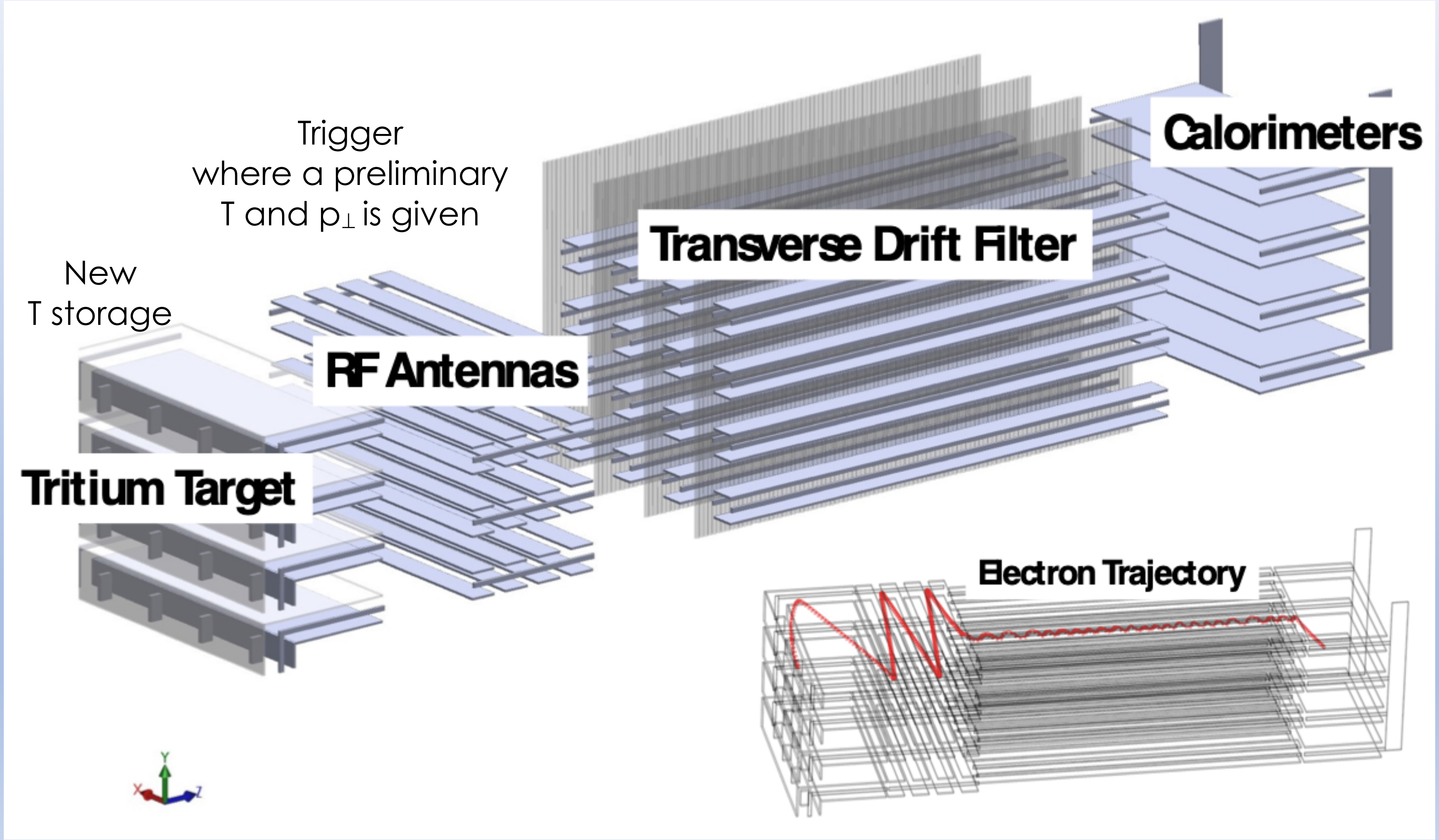
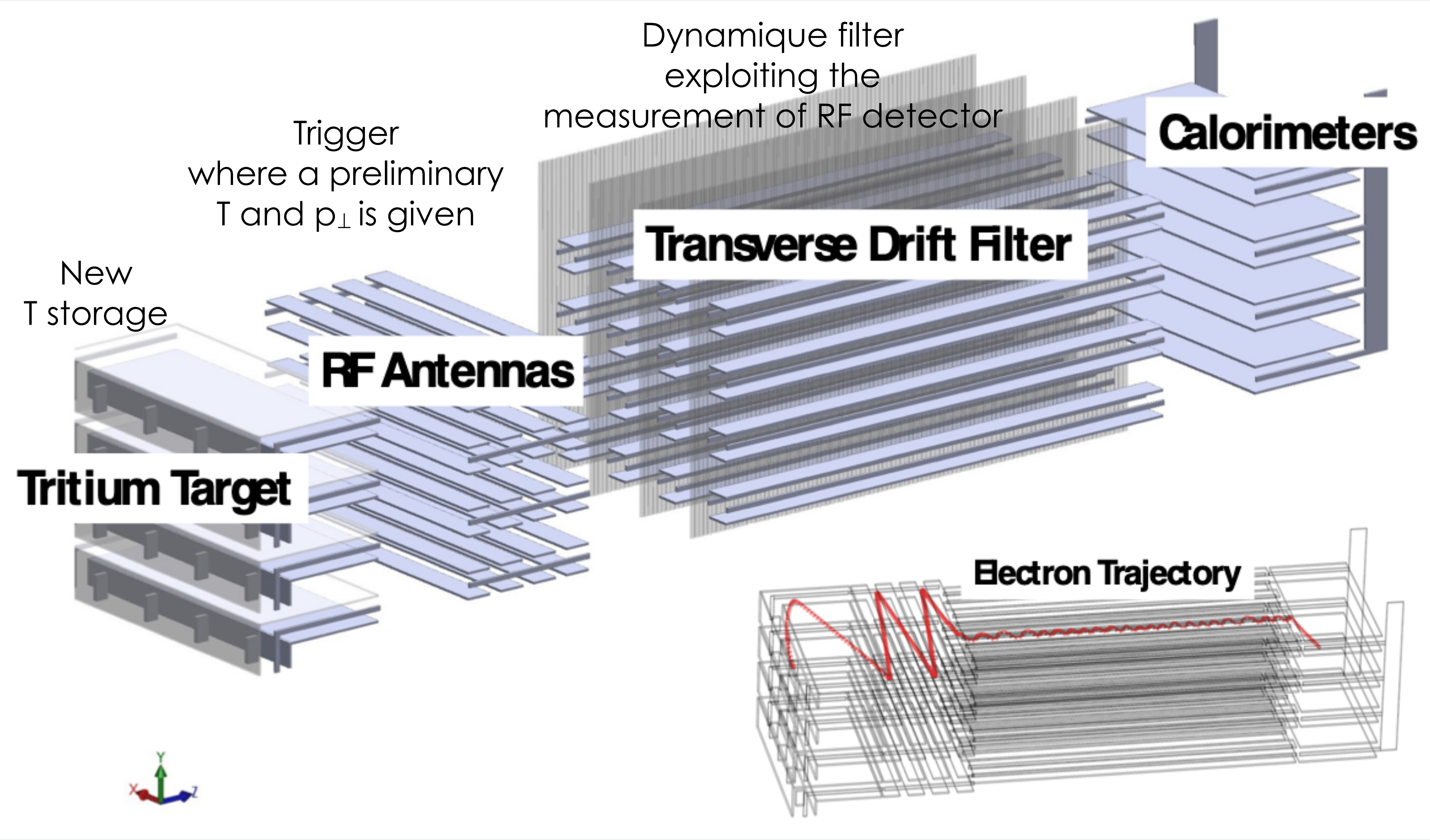


Trigger
where a preliminary
T and $p_\perp$ is given

New
T storage

PTOLEMY: experiment layout



Dynamique filter
exploiting the
measurement of RF detector

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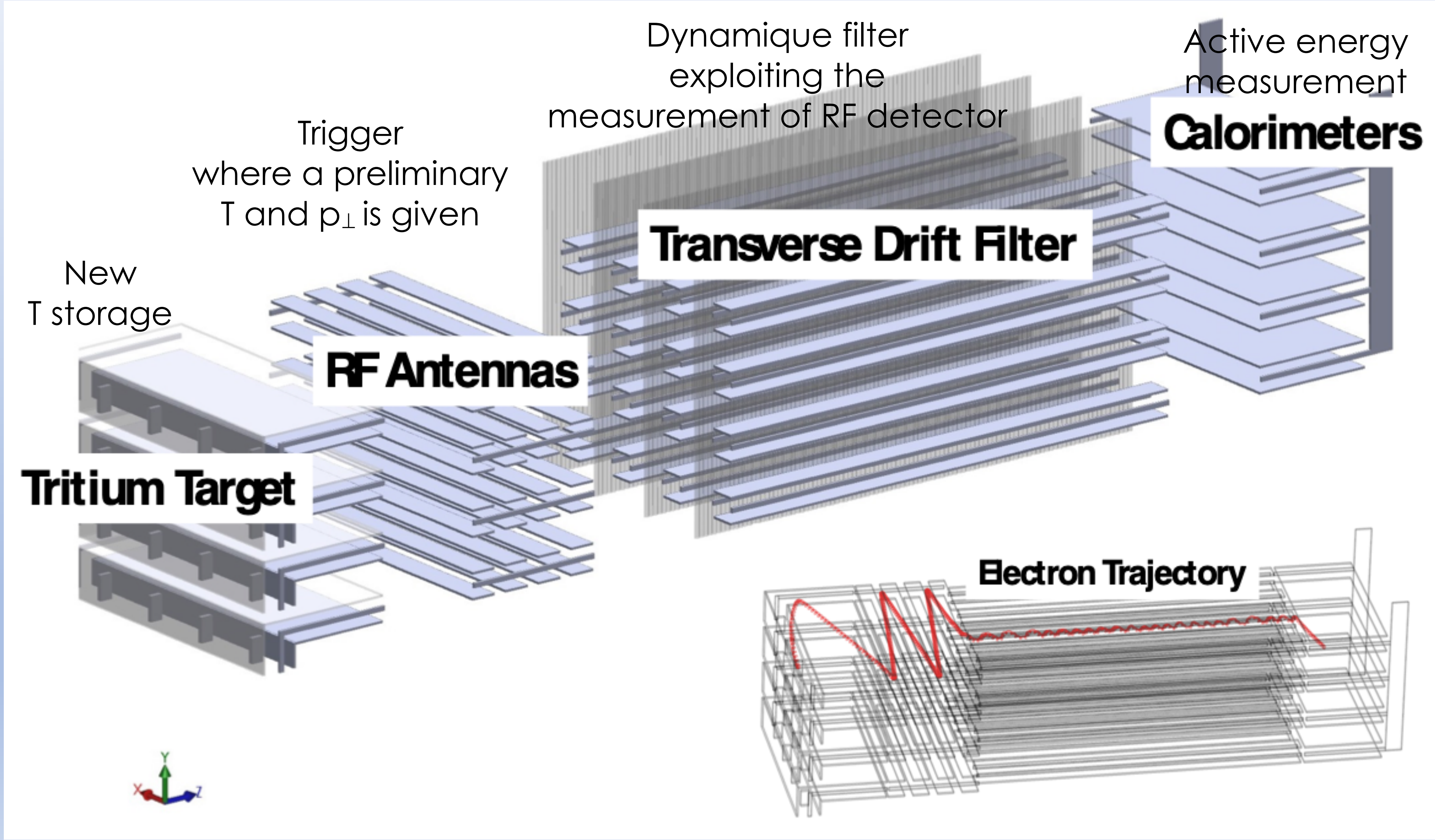

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where a preliminary
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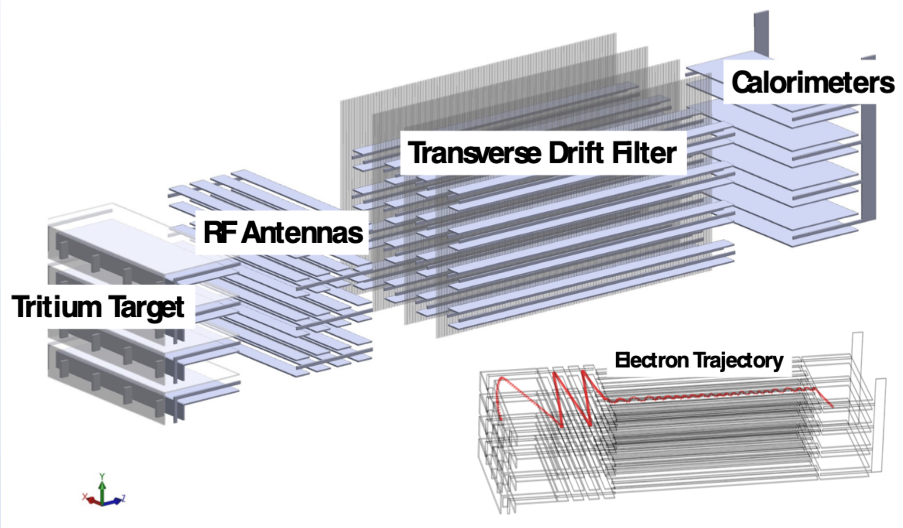
Dynamique filter
exploiting the
measurement of RF detector

Active energy
measurement

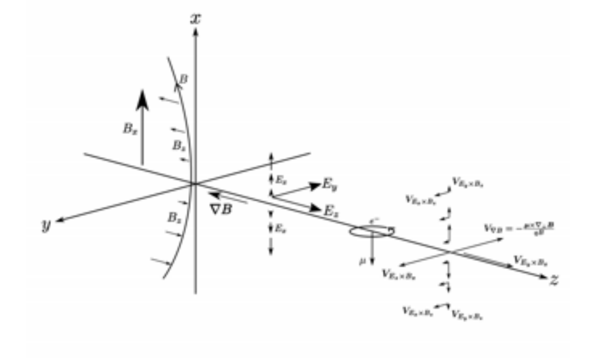
PTOLEMY: measurement principle

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



Step 1

A new way of storing atomic T



Step 2

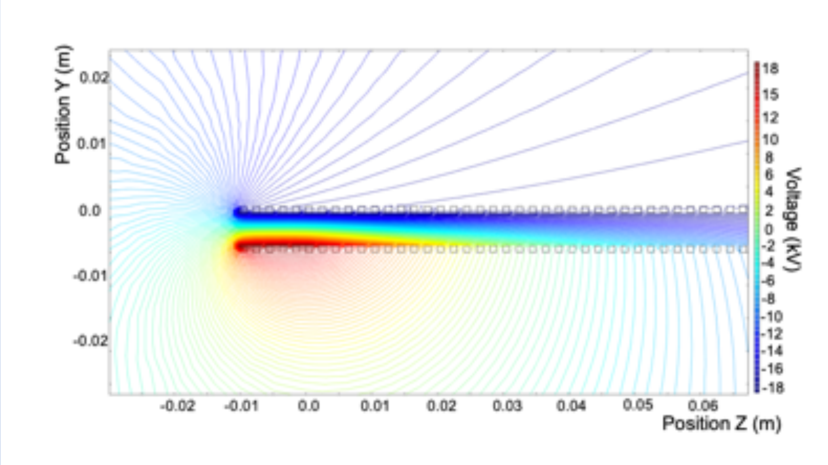
Electron RF emission is detected
Trigger good particles and give a preliminary evaluation of E and P_T

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

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

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”



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Between Step 3-4

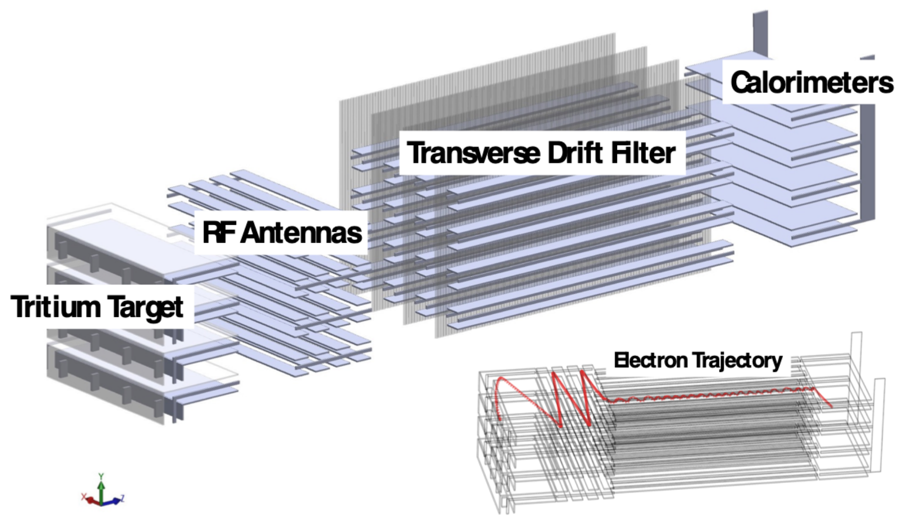
Electrostatic barrier will reduce T_L

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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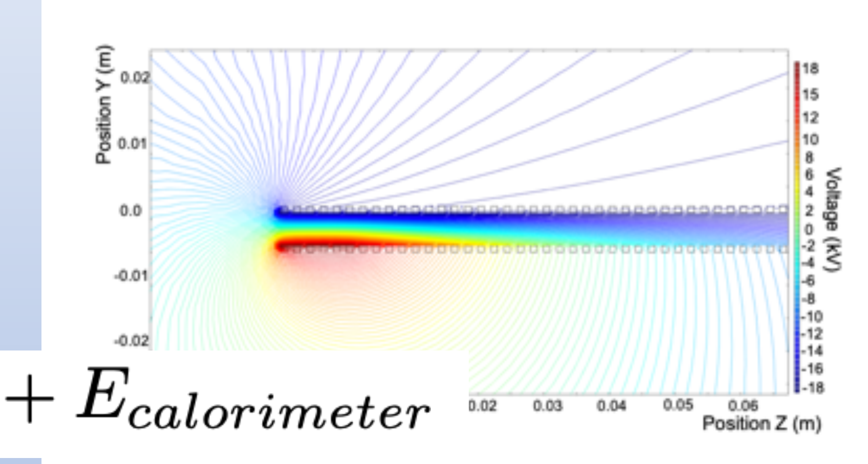
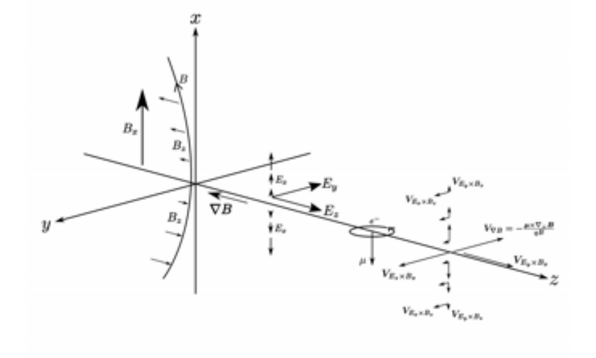


$$E_{electron} = q\cdot(V_{anode} - V_{source}) + E_{calorimeter}$$

Step 1

A new way of storing atomic T



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The particle is driven into the TES: T$_{tot}$=q(V$_{anode}$ -V$_{source}$)+ E$_{cal}$

Implementation of fundamental concepts on the PTOLEMY filter

1. The electron is transported from the graphene support to the RF region

2. A preliminary estimation of the total and transverse kinetic energy is obtained.

The feasibility of this measurement was already shown by the Project8 experiment.

$$f_\gamma \equiv \frac{f_c}{\gamma} = \frac{eB}{2\pi\gamma m_e}$$

$$P(\gamma,\theta) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{e^4}{m_e^2 c}B^2(\gamma^2-1)\sin^2\theta$$

3. Depending on the measured value of the transverse kinetic energy, the voltage levels in the filter are adjusted, prior to the electron entering the filter, such that for a given transverse kinetic energy, the electron drifts along a straight trajectory through the filter to within the accuracy of the initial RF measurement and in this process the transverse momentum is removed by rising up an electrostatic barrier.
4. At the exit of the filter the electron guided into the microcalorimeter to accomplish the final energy measurement based on a differential measurement.

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

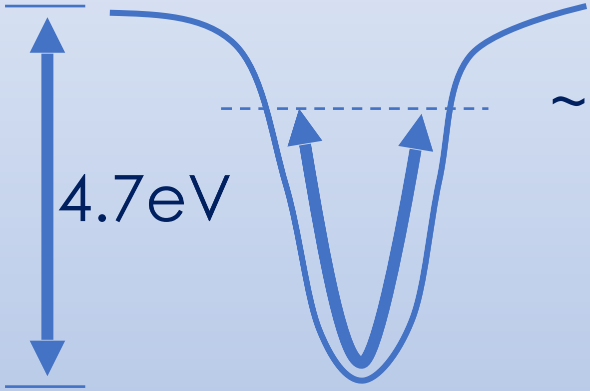
The Target

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

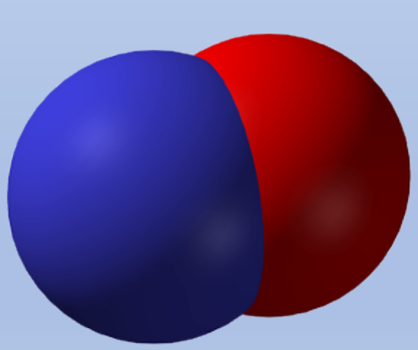
Molecular Broadening

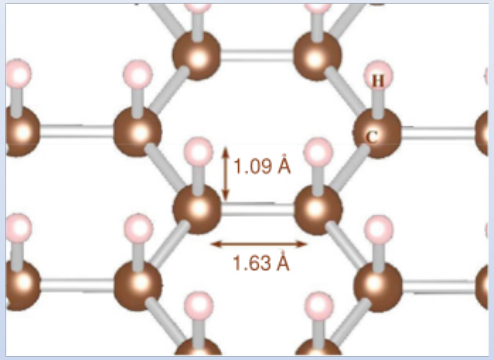
T-T → $(T\text{-}He^3)^*$



4.7eV

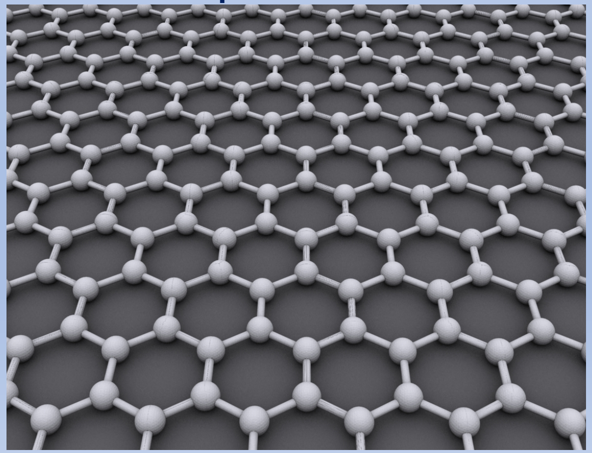
~3eV He^3 recoil at endpoint



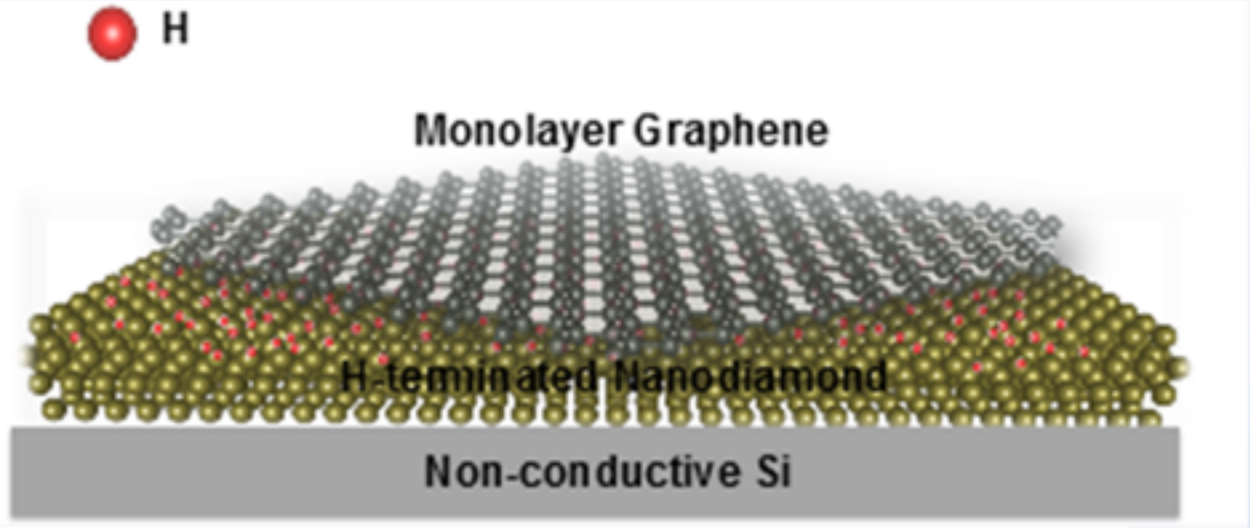


<3eV binding energy

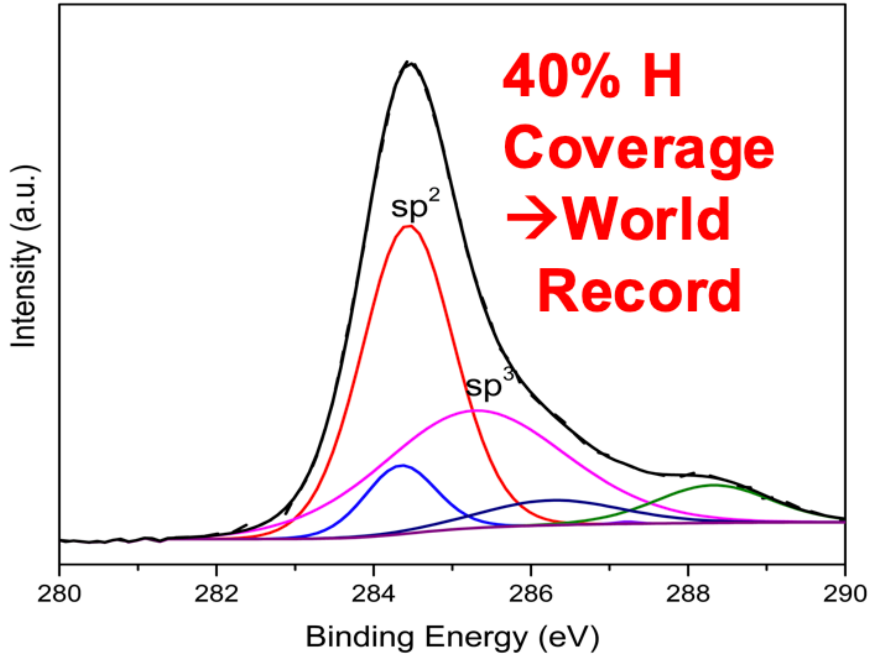
Graphene



Cold Plasma Loading



XPS Hydrogenation Results from Princeton



40% H Coverage →World Record

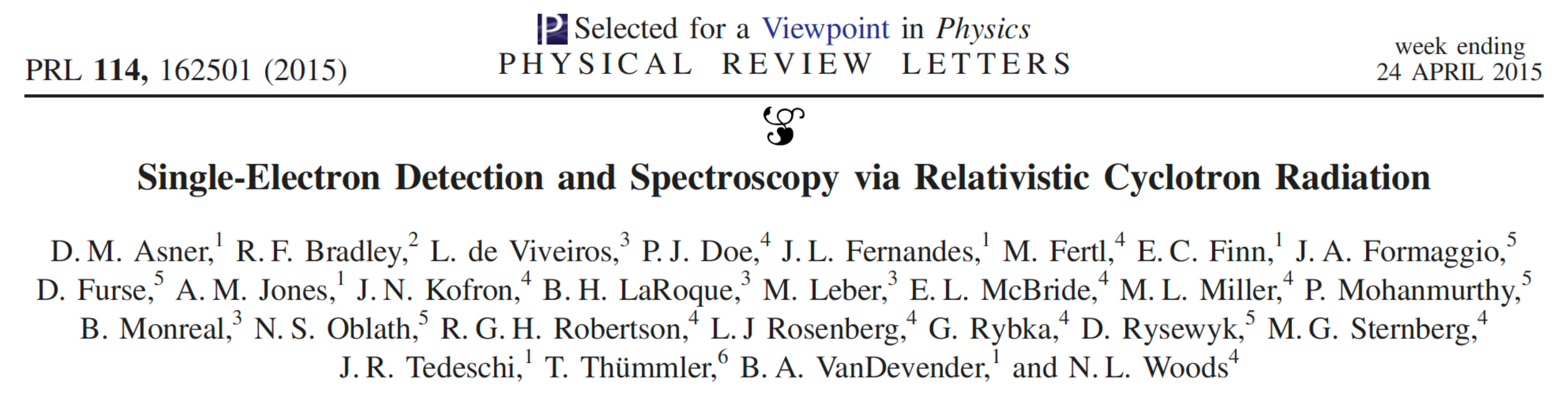
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Y. Raitses et al.

The RF detector

Ptroject8 experiment

status detection of the RF from single e



Selected for a Viewpoint in *Physics*

PRL **114,** 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

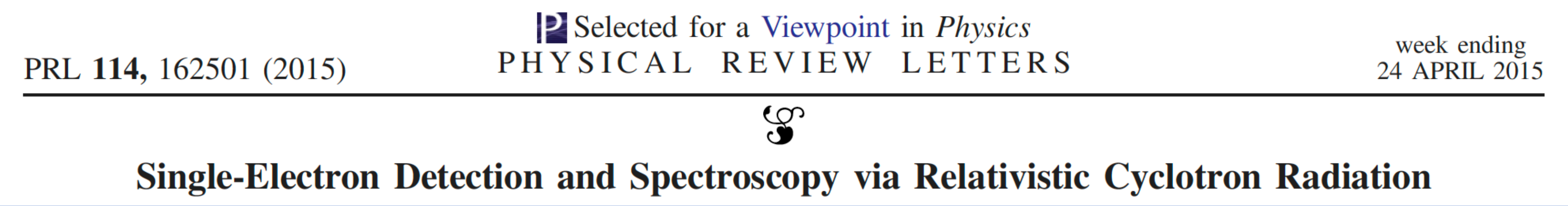
D. M. Asner,[1] R. F. Bradley,[2] L. de Viveiros,[3] P. J. Doe,[4] J. L. Fernandes,[1] M. Fertl,[4] E. C. Finn,[1] J. A. Formaggio,[5] D. Furse,[5] A. M. Jones,[1] J. N. Kofron,[4] B. H. LaRoque,[3] M. Leber,[3] E. L. McBride,[4] M. L. Miller,[4] P. Mohanmurthy,[5] B. Monreal,[3] N. S. Oblath,[5] R. G. H. Robertson,[4] L. J Rosenberg,[4] G. Rybka,[4] D. Rysewyk,[5] M. G. Sternberg,[4] J. R. Tedeschi,[1] T. Thümmler,[6] B. A. VanDevender,[1] and N. L. Woods[4]

The Project 8 Collaboration has constructed an experiment designed to detect cyclotron radiation from single electrons. At the heart of the experiment is a small volume hereafter referred to as the “cell,” in which a gaseous radioactive isotope is present at low pressure. In a uniform magnetic field (1T), electrons from decays inside the cell emit cyclotron radiation. The cell consists of a section of rectangular waveguide sized to capture and transmit the microwave radiation to the input of a low-noise radiofrequency receiver (LowNoiseFactory amplifier) and digitizer. The radioactive isotope 83mKr is a gamma-emitting isomer of 83Kr with a half-life of 1.8 h, in which internal conversion produces monoenergetic electron lines with kinetic energies of 17 830.0(5), 30 227(1), 30 424(1), 30

The gain of this amplifier cascade is 54 dB, making the noise contribution from the components following these amplifiers negligible. The frequency band of interest (from 25 to 27 GHz) is mixed down with a local 24.2 GHz oscillator to a center frequency of 1.8 GHz. A second mixer with a variable local oscillator frequency combines with a ow-pass filter to select a frequency sub-band of 125 MHz for narrow-band signal analysis. Signals are digitized at 250 mega-samples per second with a free-running 8-bit digitizer and recorded to disk.

Ptroject8 experiment (II)

status detection of the RF from single e



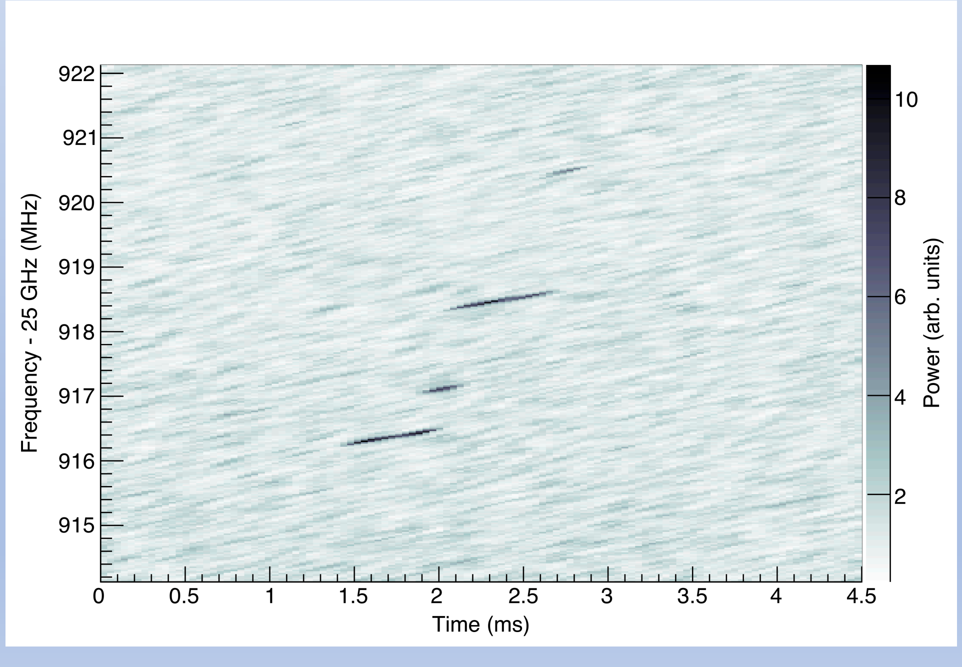
Selected for a Viewpoint in *Physics*

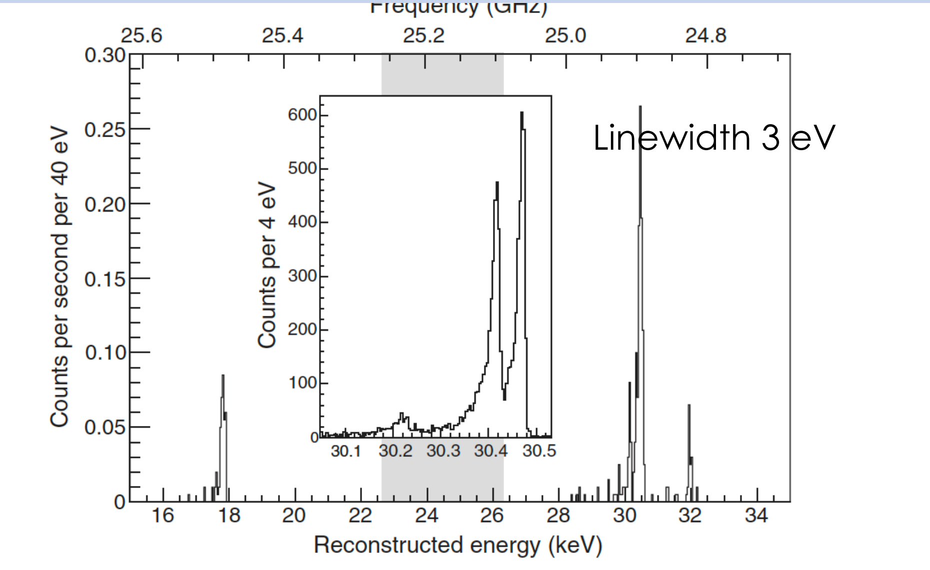
PRL **114,** 162501 (2015)

PHYSICAL REVIEW LETTERS

week ending
24 APRIL 2015

Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation



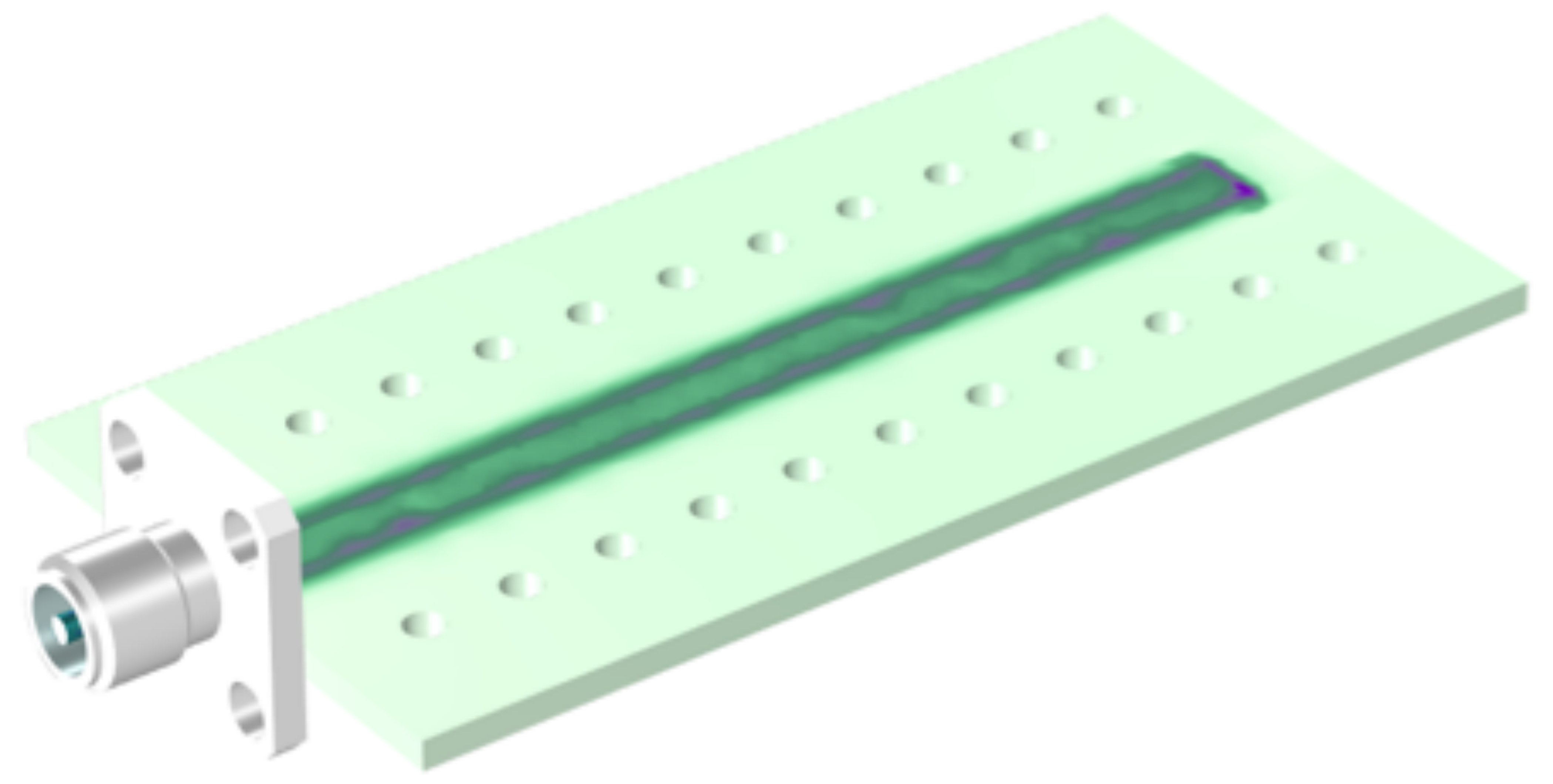


Linewidth 3 eV

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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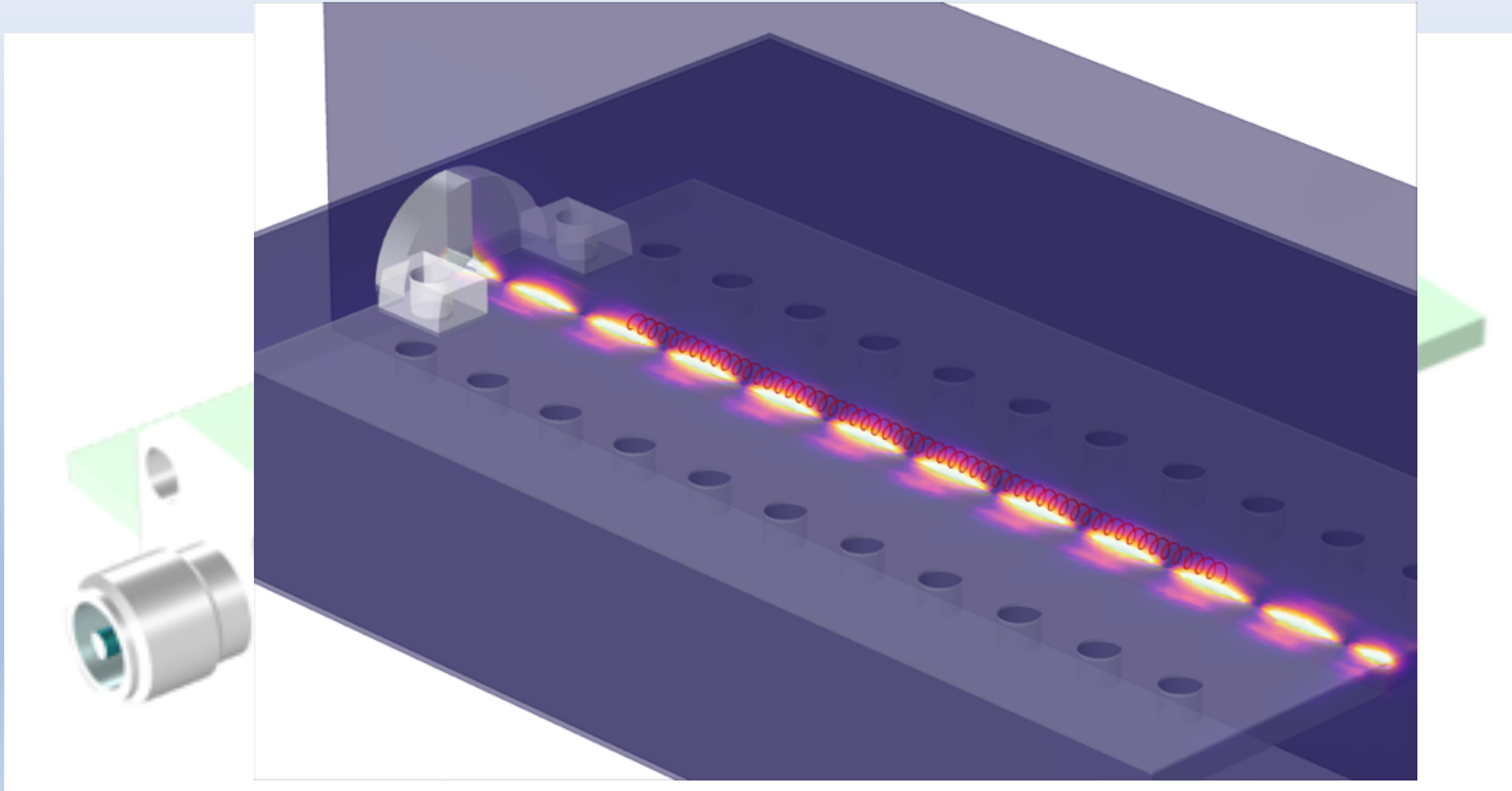

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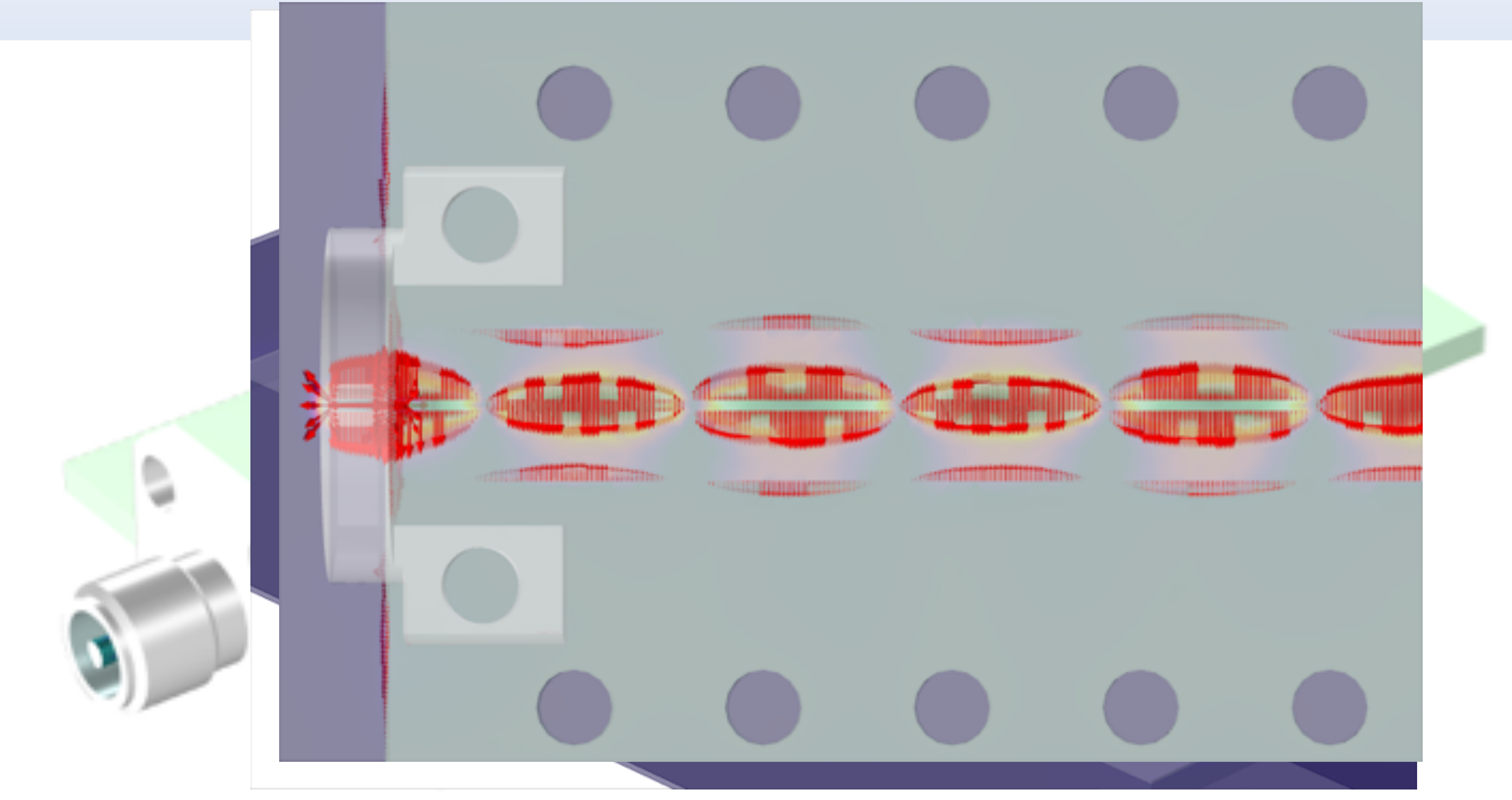
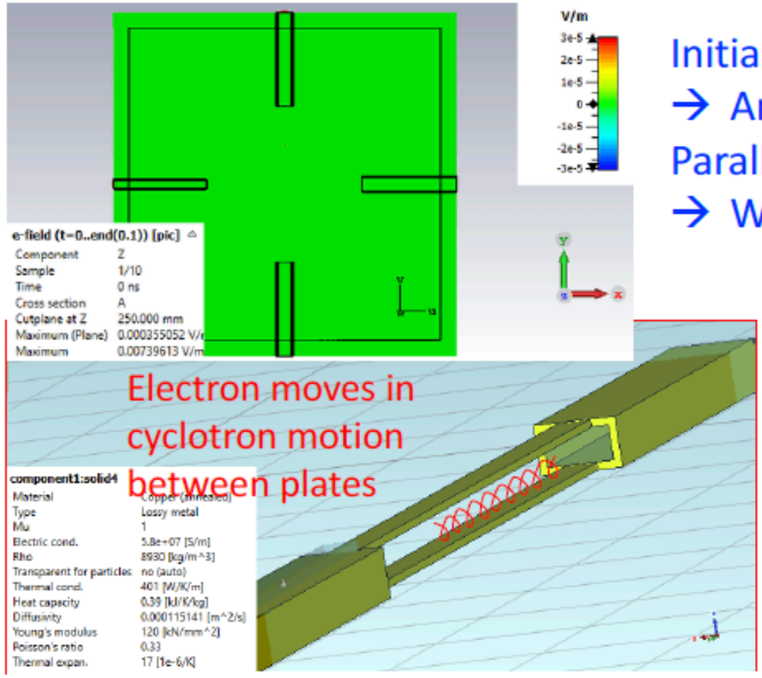


Dynamical simulation of RF signal

Dynamical simulation of RF signal



e-field (t=0..end(0.1)) [pic]

Component	Z
Sample	1/10
Time	0 ns
Cross section	A
Cutplane at Z	250.000 mm
Maximum (Plane)	0.000355052 V/
Maximum	0.00739613 V/m

component1:solid4

Material	Copper (annealed)
Type	Lossy metal
Mu	1
Electric cond.	5.8e+07 [S/m]
Rho	8930 [kg/m^3]
Transparent for particles	no (auto)
Thermal cond.	401 [W/K/m]
Heat capacity	0.39 [kJ/K/kg]
Diffusivity	0.000115141 [m^2/s]
Young's modulus	120 [kN/mm^2]
Poisson's ratio	0.33
Thermal expan.	17 [1e-6/K]

Electron moves in cyclotron motion between plates

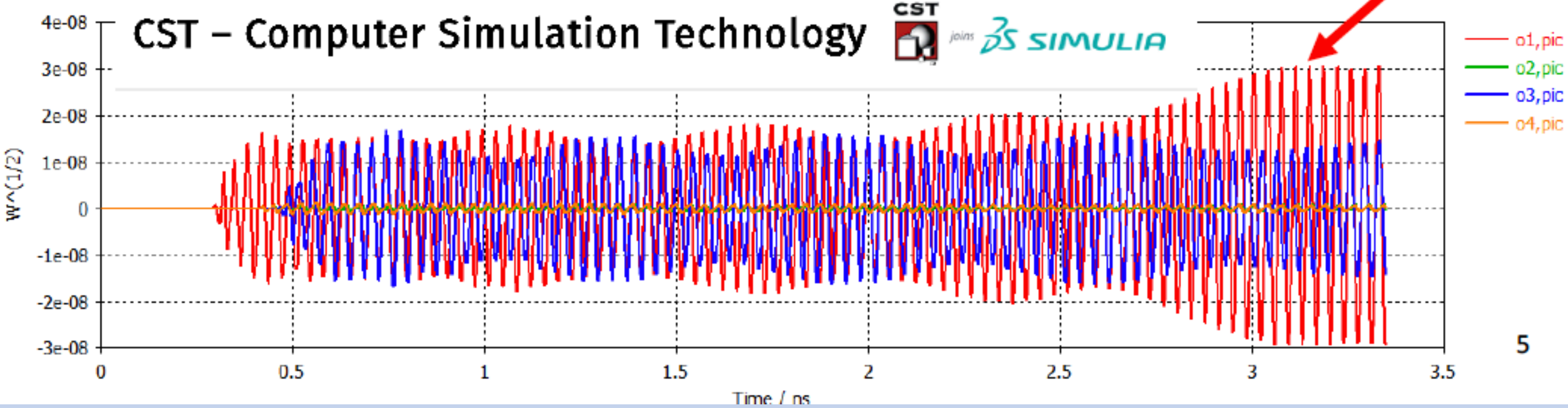
Initial calculations using CST RF modeling tools:
→ Antenna configured to transition from Parallel Plate Waveguide to Rectangular Waveguide
→ Working on FPGA-accelerated parameter fitting

P_{signal}~0.1 fW

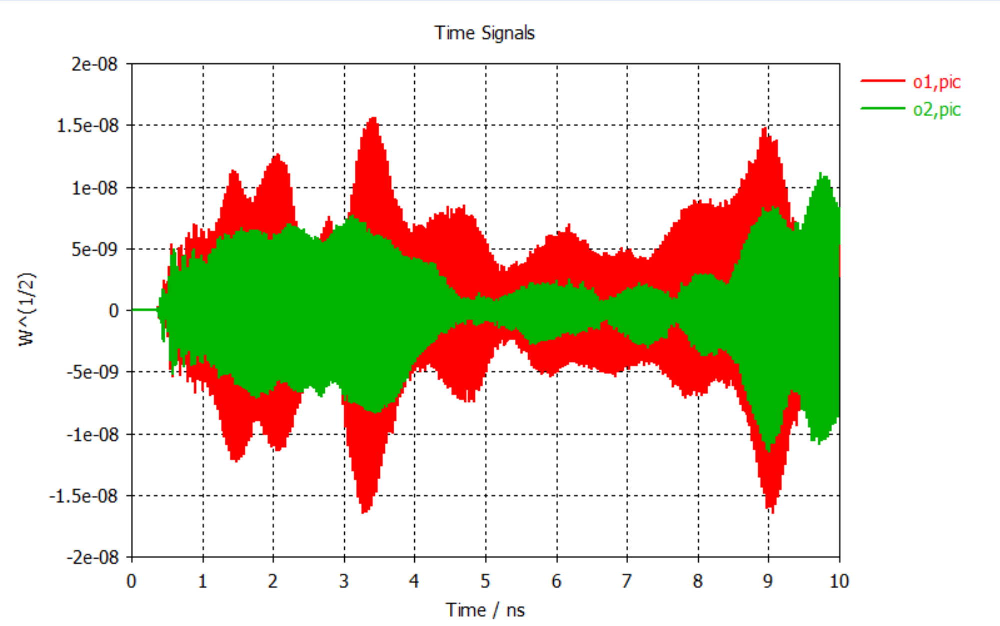
T_{LNA} ~6K

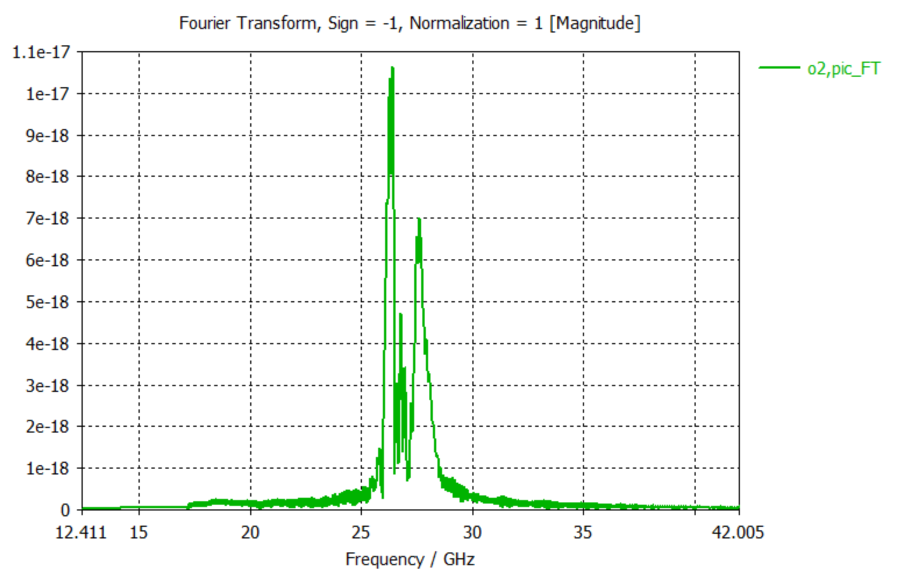
Dicke Radiometer eqn.
→ SNR~10 for 10^{-5}s

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

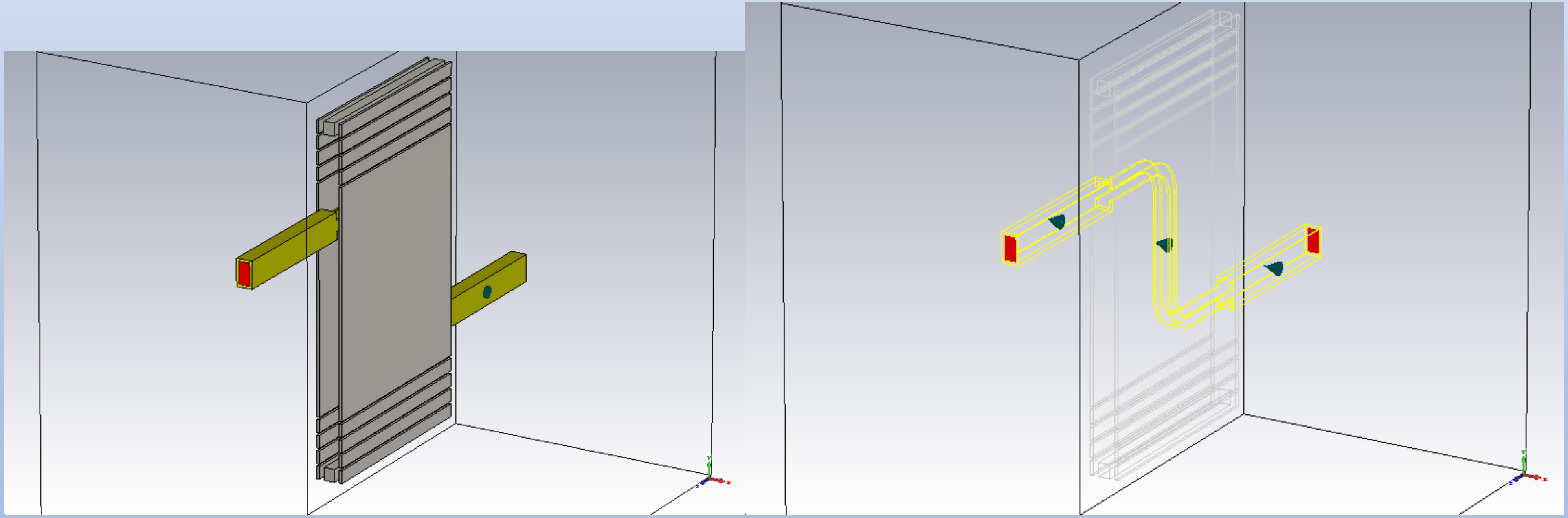

CST – Computer Simulation Technology

RF signal simulation

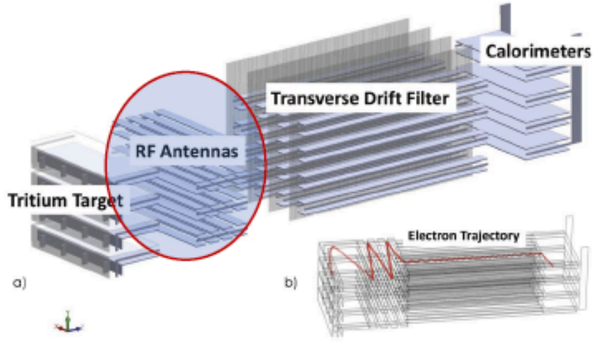


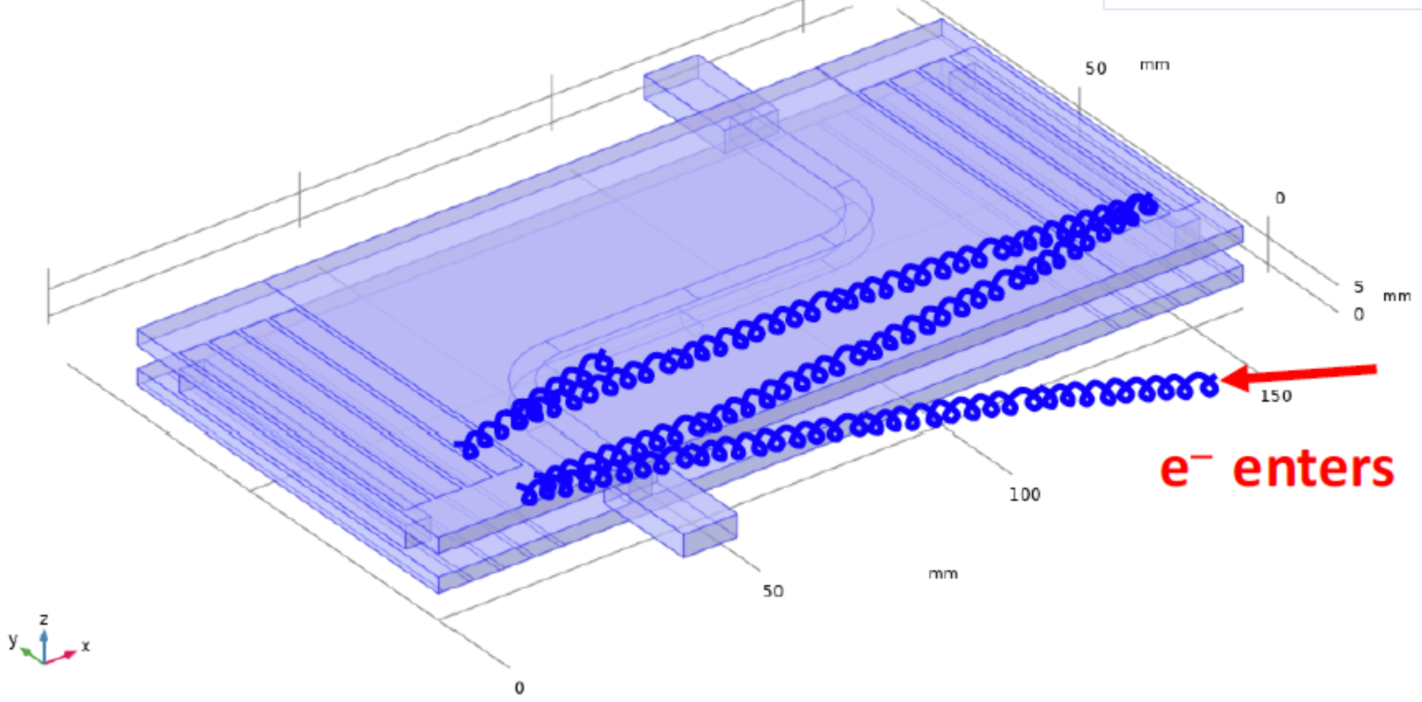


Test different Antennas geometry



RF Tracking System





e⁻ enters

RF detection

two different approaches

Reference number:

An electron with 18.6 keV transverse energy in 1 T field radiate 7.3 meV/μs (1.2 fW) at 27 GHz

Two Possible approaches

1. Detect RF signal fast enough: 0.5 μs and study its features. In this time frame the energy lost is negligible.

Consequences

Fast witch of voltage setting.
Discrete sets of ntuple-V values?
No critical. This will affect only
The electron transfer function.

$$E=q(V_{anode}-V_{target})+E_{cal}$$

2. Exploit multiple deflections and correct for it. The RF signal will tell us how many reflections the e had and so the trajectory.

Consequences

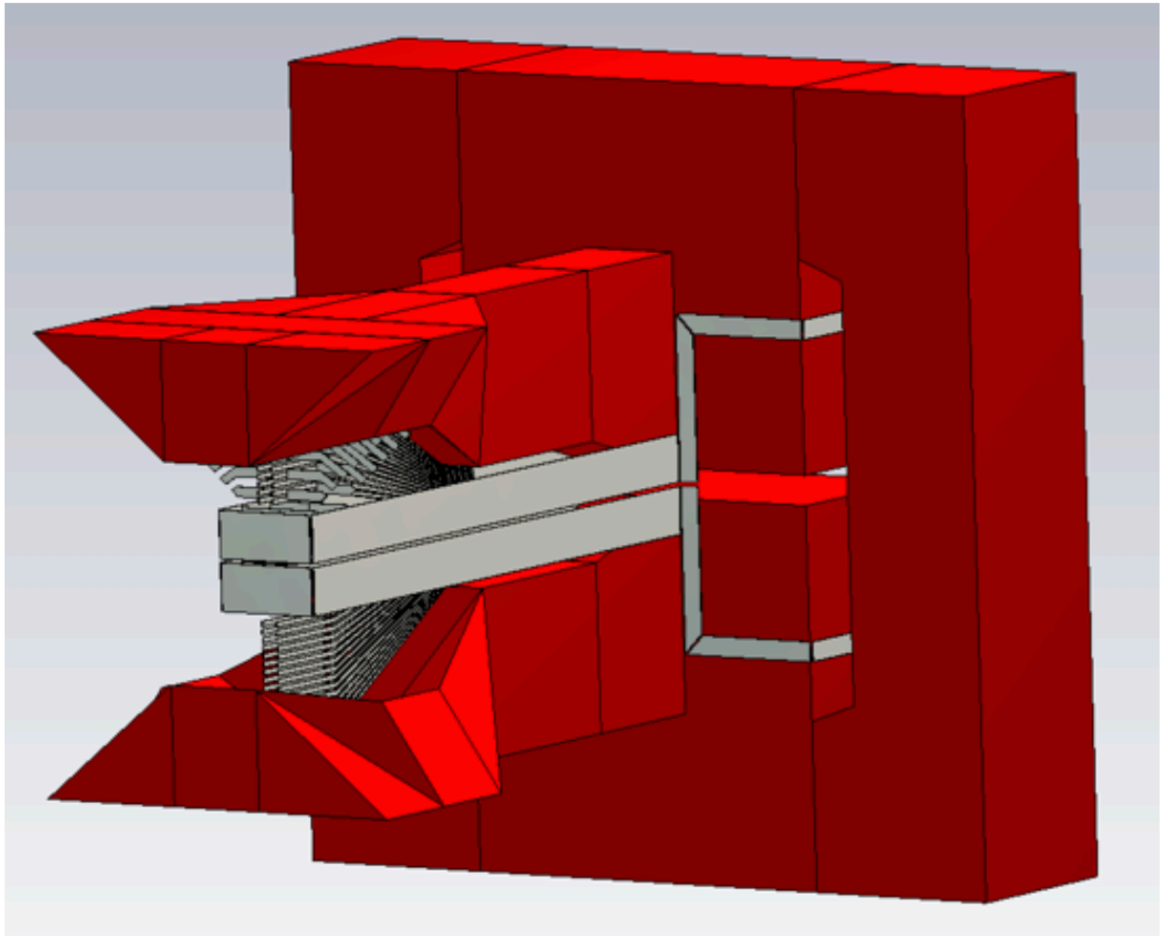
Possible systematic effect on total
Energy measurement

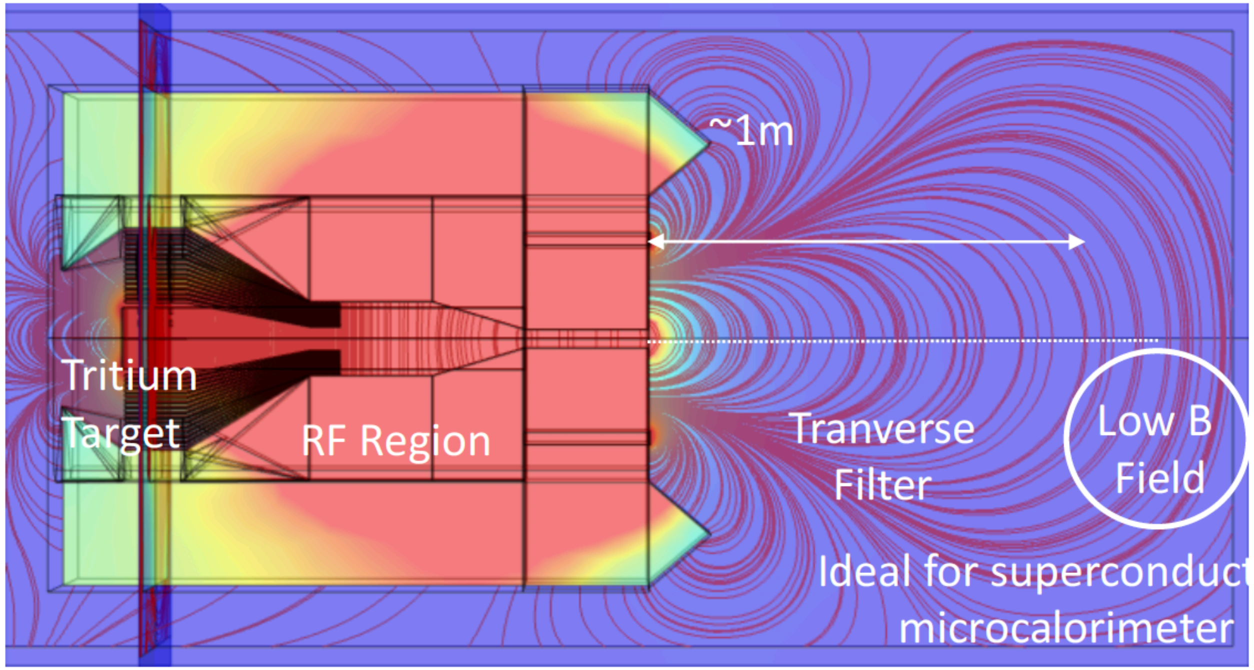
$$E=q(V_{anode}-V_{target})+E_{cal}+RF_{correction}$$

The Magnet

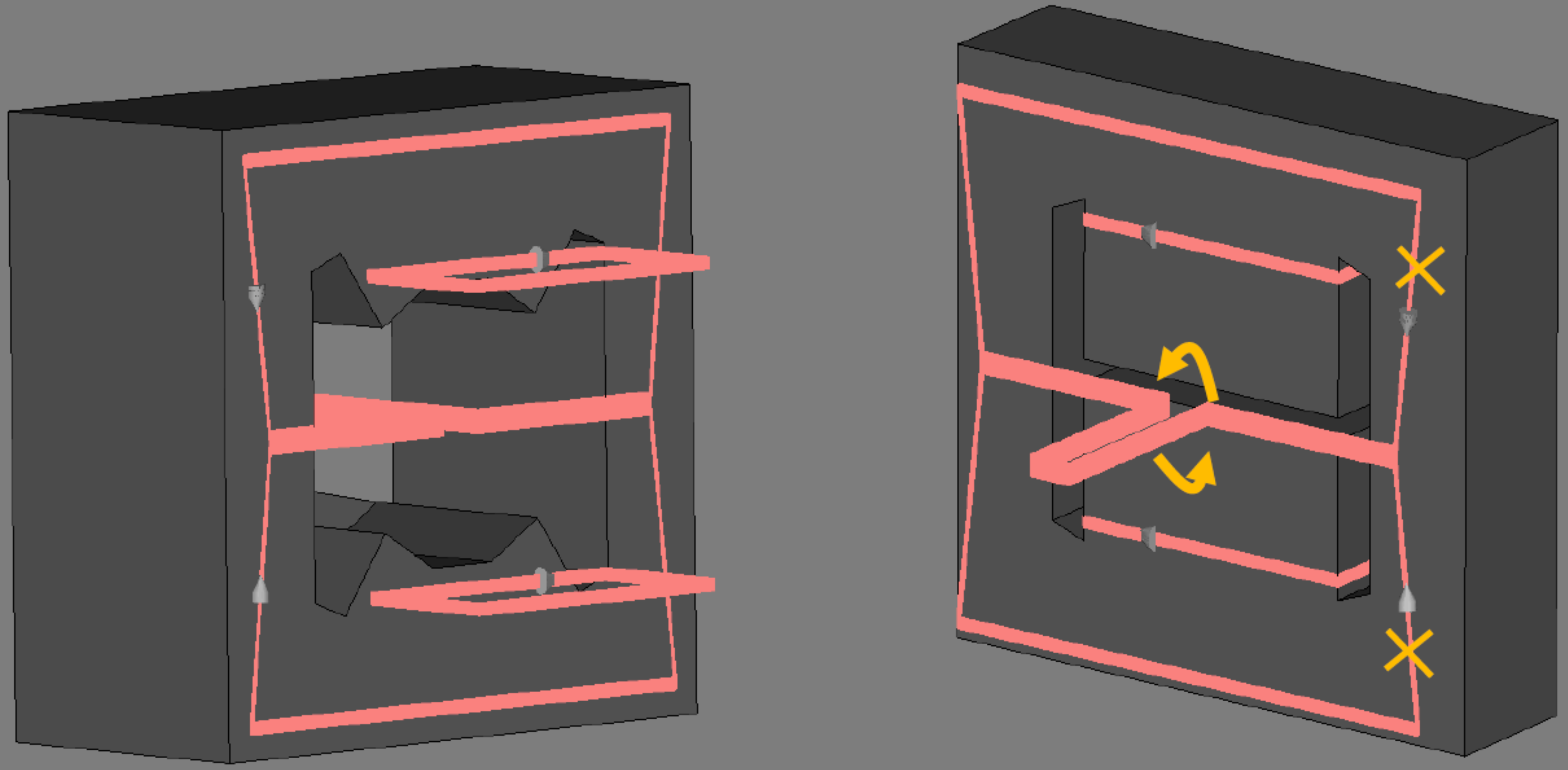
Magnet geometry under study

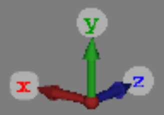
This is a key ingredient to realize efficiently the whole elector transport form graphene support to the RF region, then to the filter and finally to the TES.

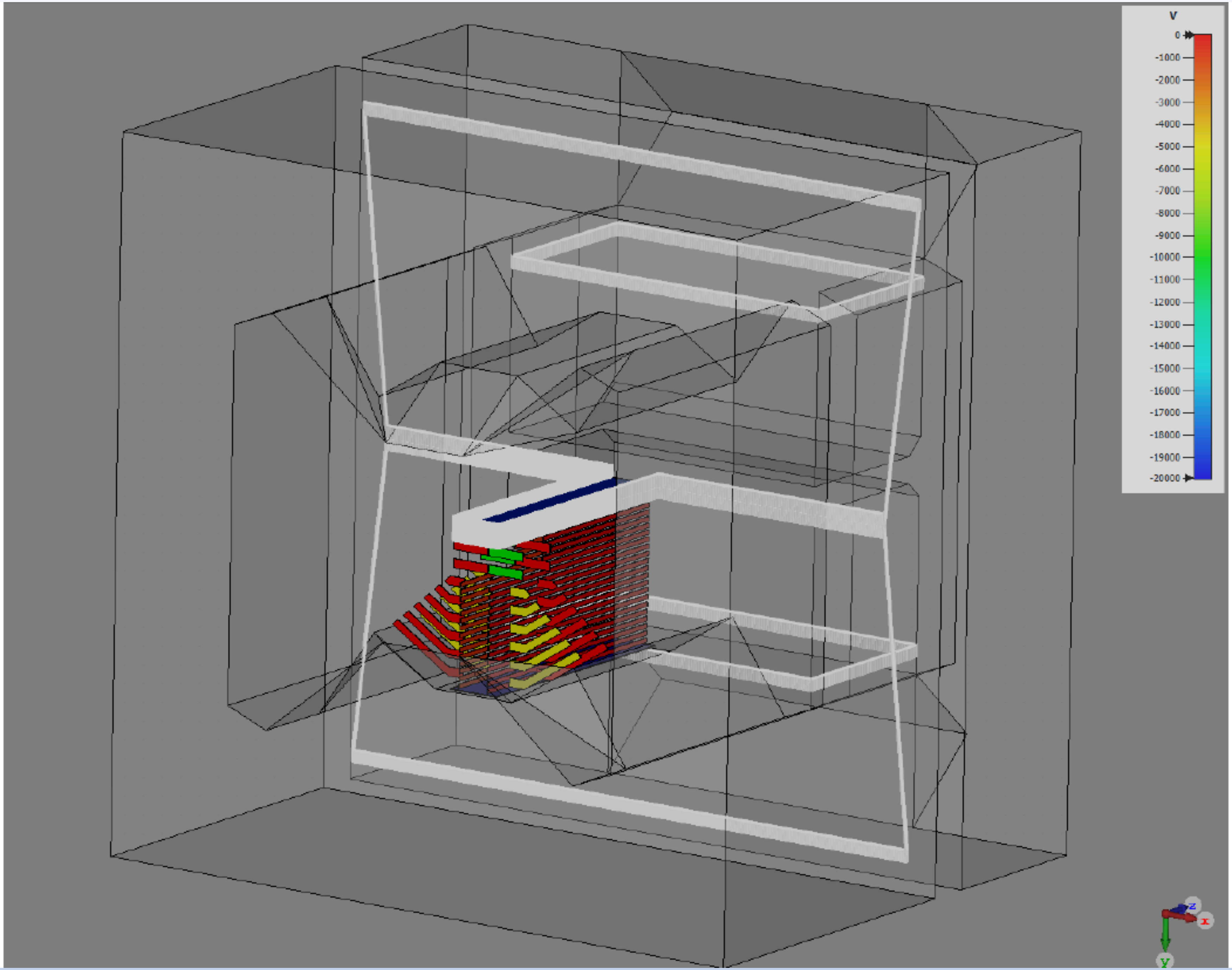




Still working on coil placement (alternative coil path)

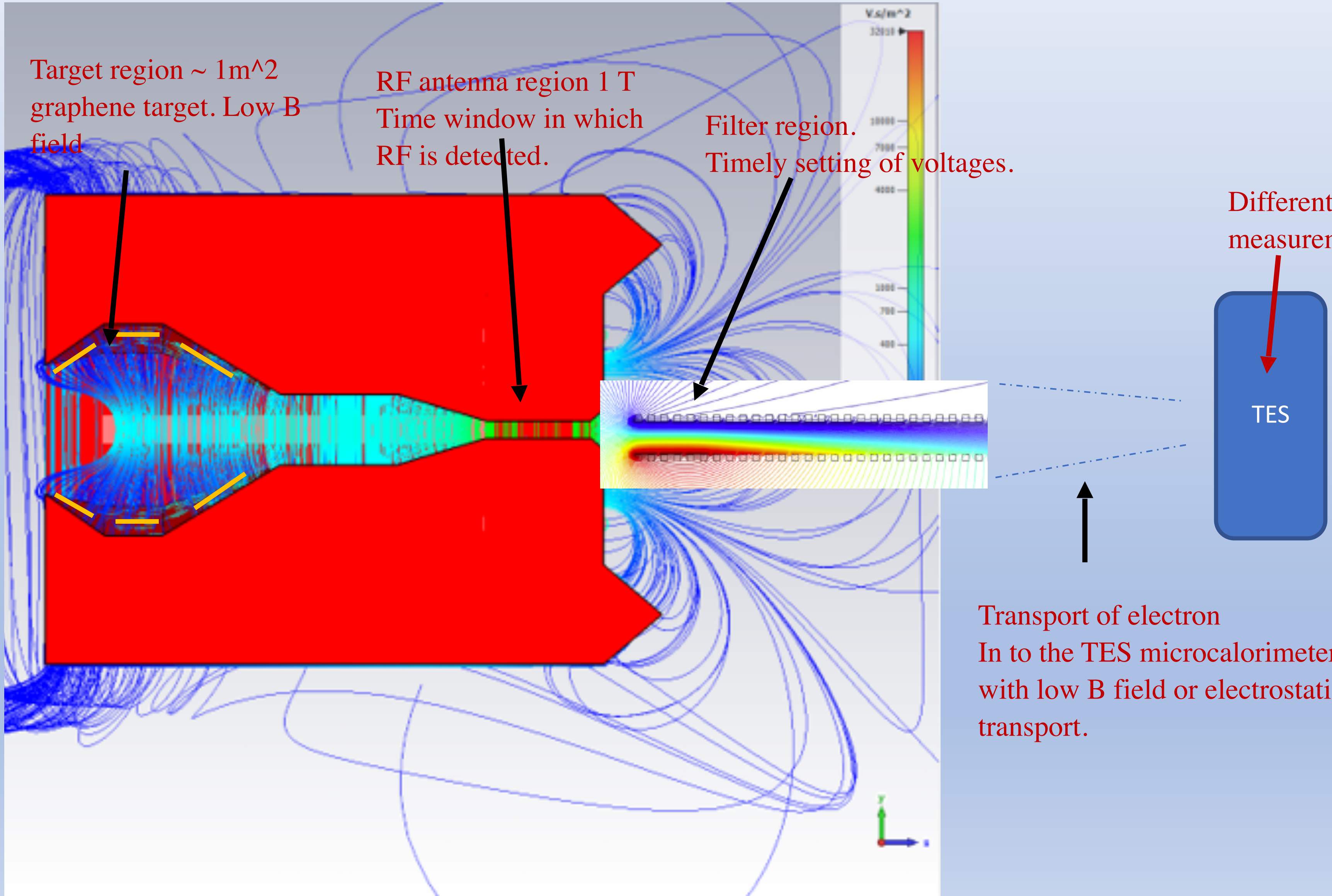





V
0
-1000
-2000
-3000
-4000
-5000
-6000
-7000
-8000
-9000
-10000
-11000
-12000
-13000
-14000
-15000
-16000
-17000
-18000
-19000
-20000
z
x
y

Magnet geometry under study

This is a key ingredient to realize efficiently the whole elector transport form graphene support to the RF region, then to the filter finally to the TES.



Target region ~ 1m^2 graphene target. Low B field

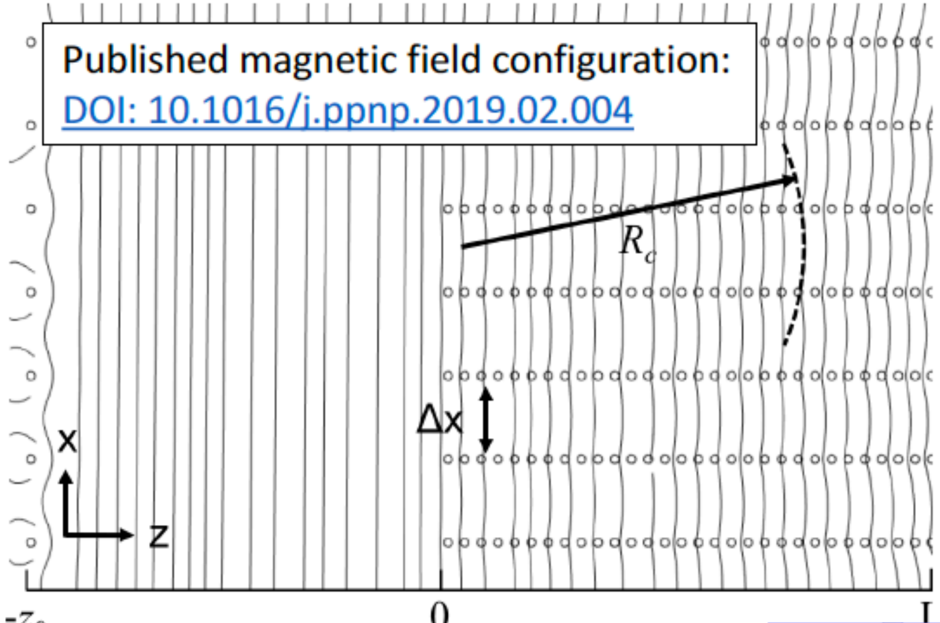
RF antenna region 1 T
Time window in which RF is detected.

Filter region.
Timely setting of voltages.

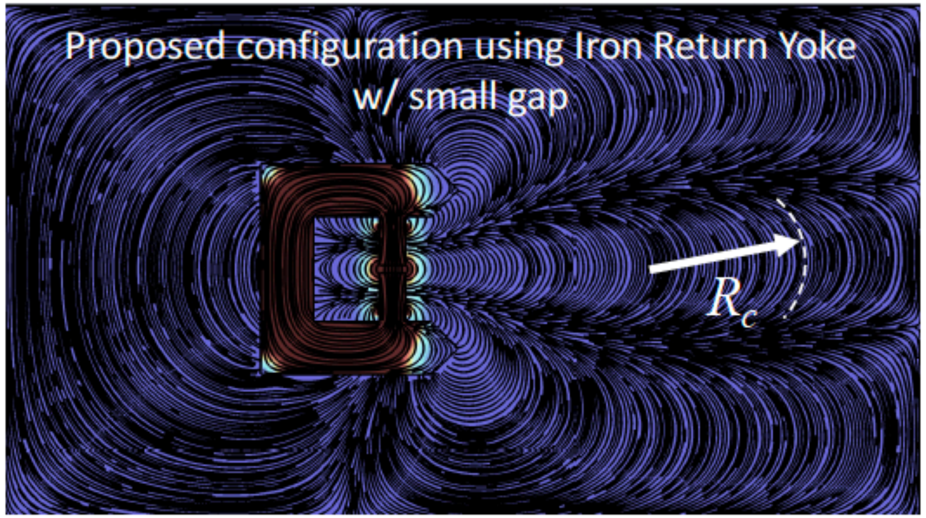
Differential energy measurement

Transport of electron
In to the TES microcalorimeter with low B field or electrostatic transport.

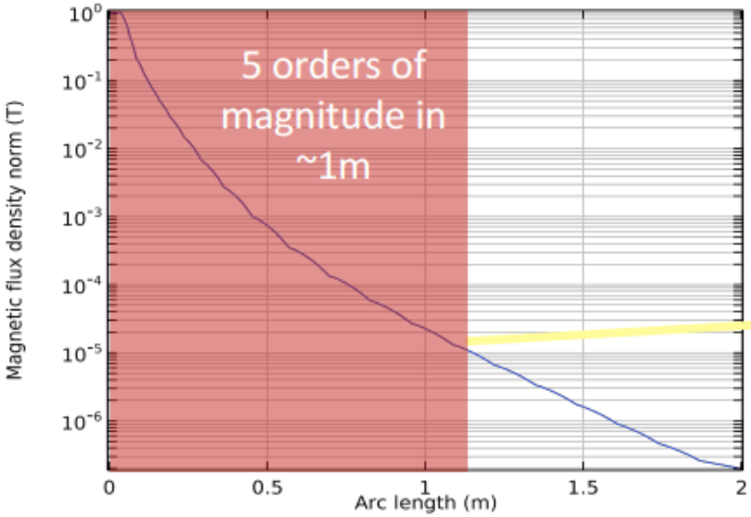
Magnetic Field for Transverse Drift

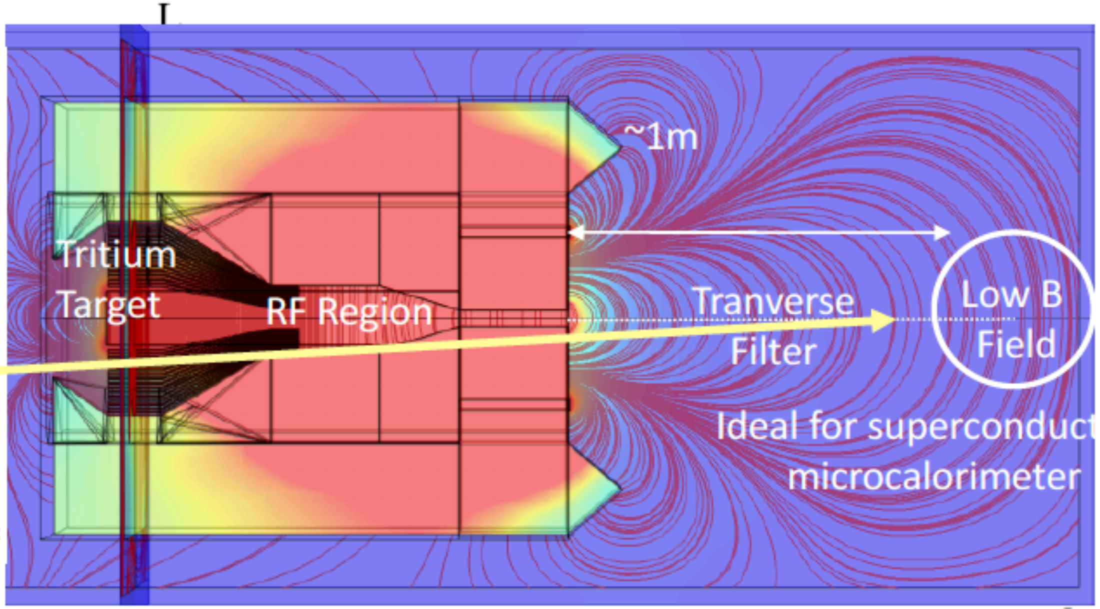


Published magnetic field configuration:
DOI: 10.1016/j.ppnp.2019.02.004



Proposed configuration using Iron Return Yoke w/ small gap

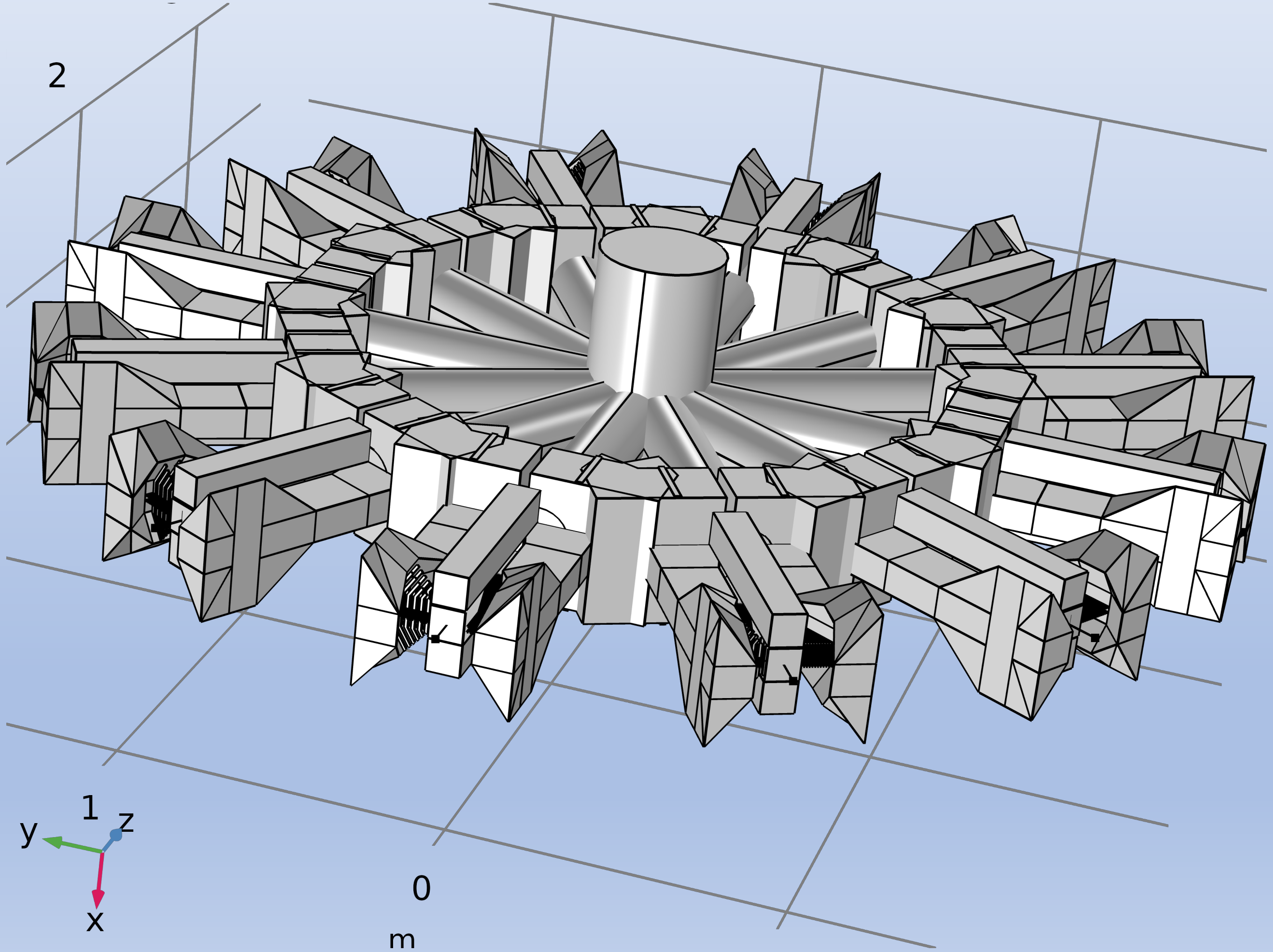




Ideal for superconduct microcalorimeter

Possible multiple channels geometry

~ 1 m^2 of graphene per module with 0.2 mg of T (full loading) x 12 modules ~ 2 mg of T



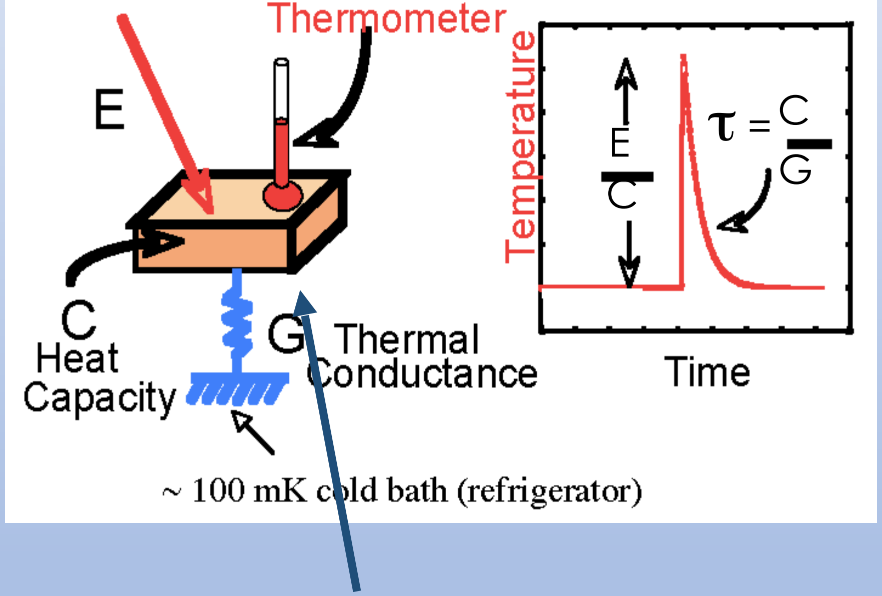
The μCalorimeter

Calorimetric measurement

based on Transition Edges Sensors technology

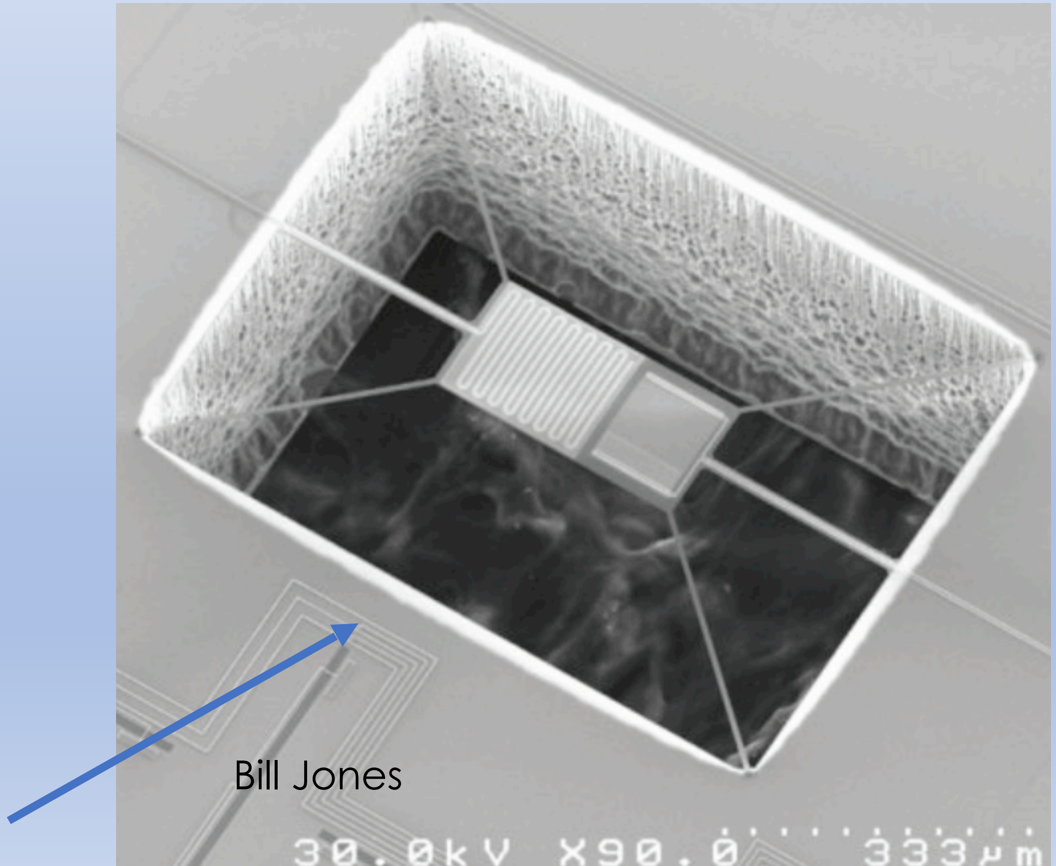
Resolution of ~0.55eV at 1keV and ~0.15eV at 0.1keV operating at 70-100mK under investigation (Clarence Chang ANL, Moseley et. al. GSFC/NASA)

100 eV can be stopped with very small C



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

TES sensor

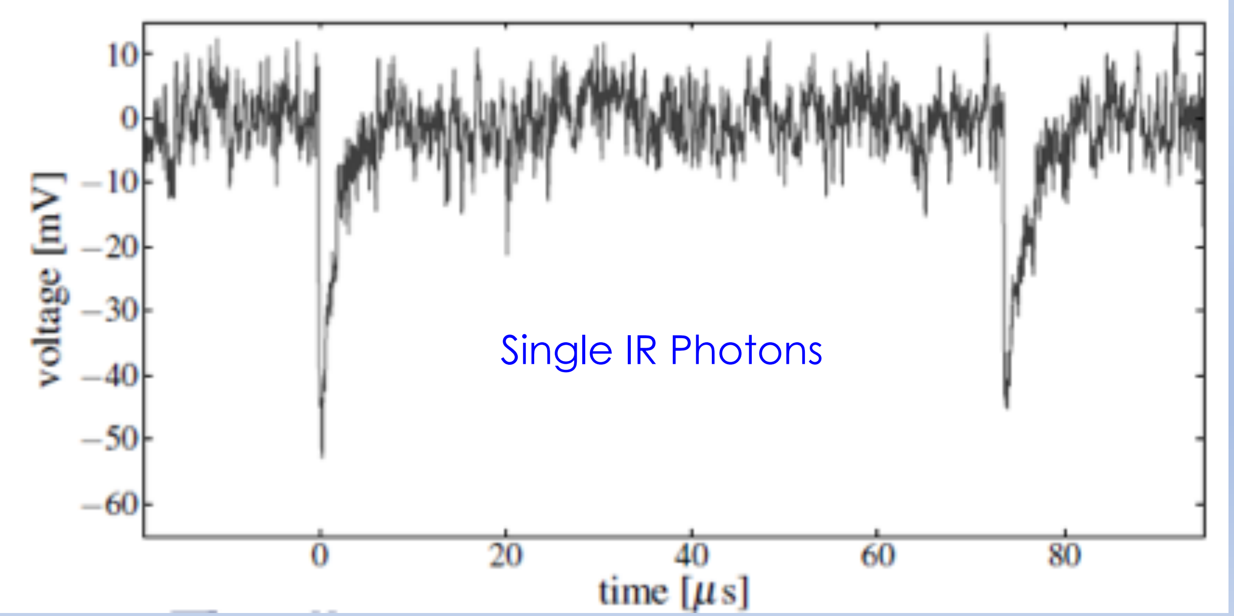


SPIDER island TES example

Microcal Energy Resolution

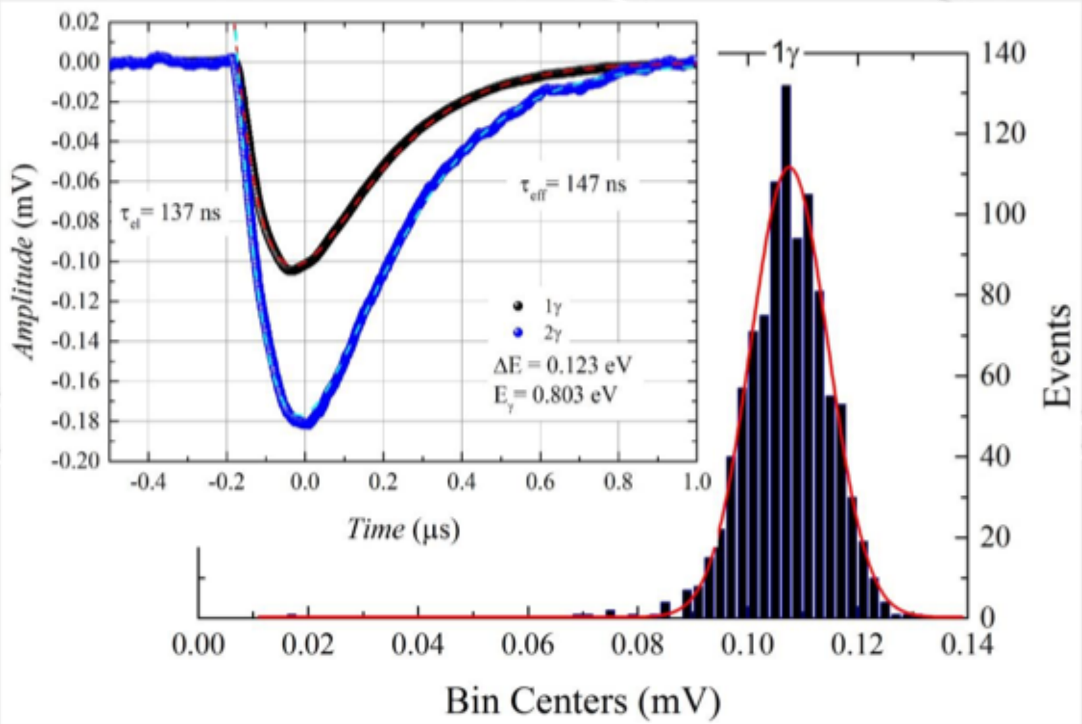
- Pushing down microcal resolution – 0.15eV@100eV (~100mK) no longer the focus
    - Most TES work is headed toward extremely low heat capacitance (absorber thickness ~15μm → 10nm for ~10eV electron)
    - 0.05eV@10eV (and further linear improvements from pushing down to 50mK)

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



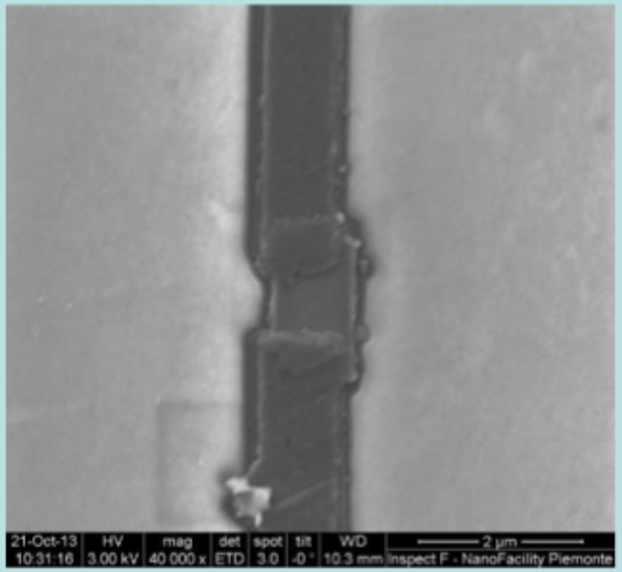
$\tau_{etf} = 147\text{ns}$

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

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

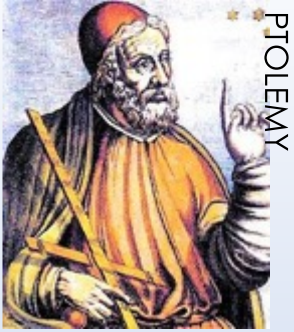
$$\sigma_E = 0.05\text{eV}$$

1 μm × 1 μm

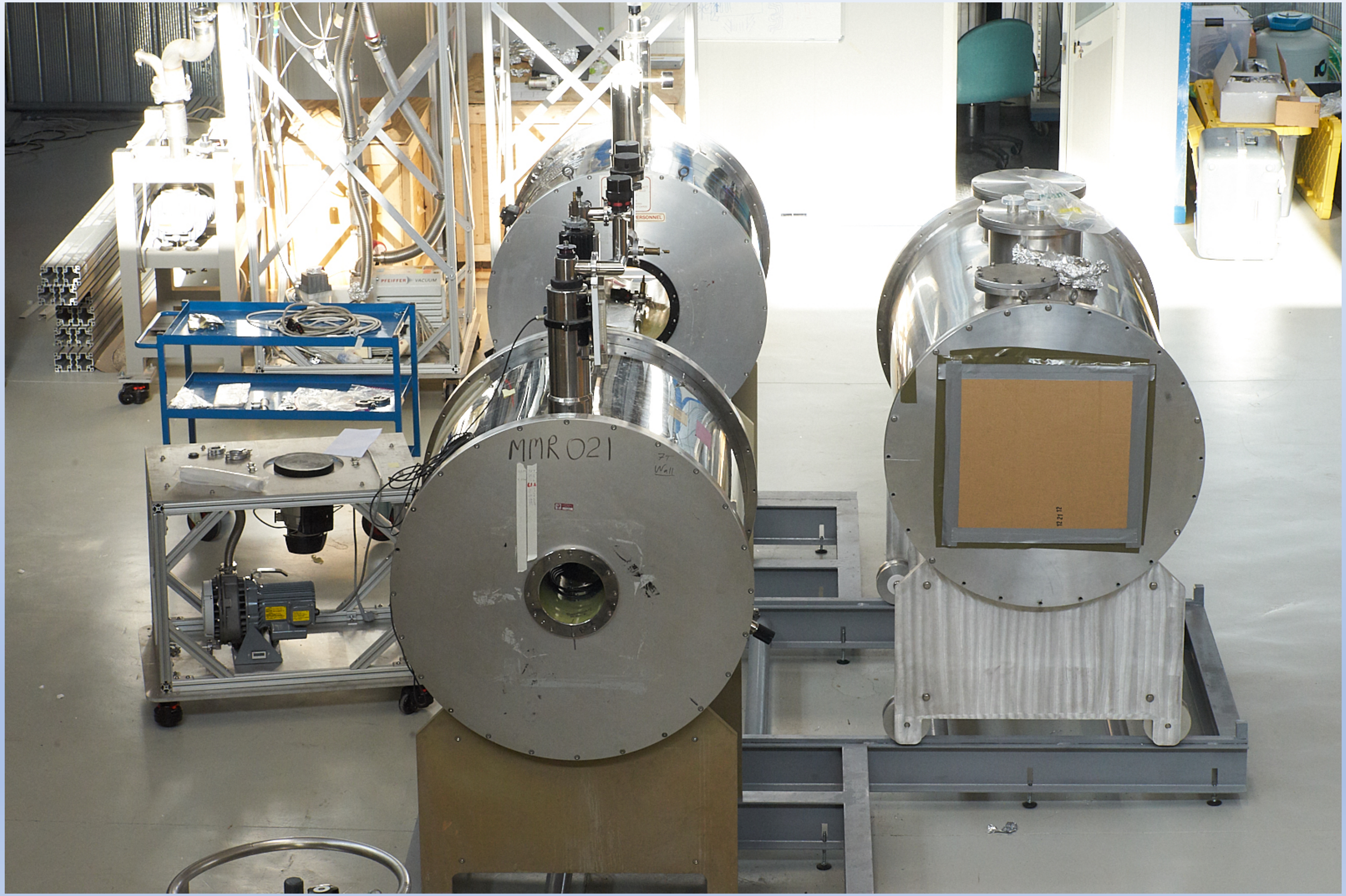


C. Portesi *et al*, IEEE Trans App Supercond, 25, 3, (2015)

The LNGS laboratory



Experimental site at LNGS

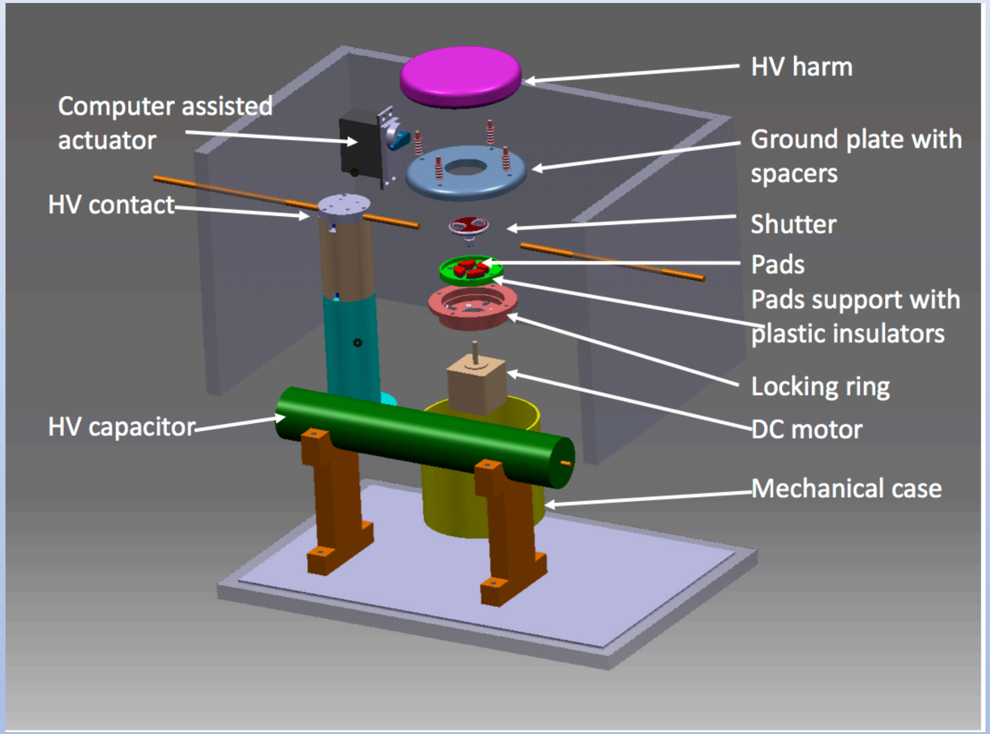


Voltage generation with extreme stability

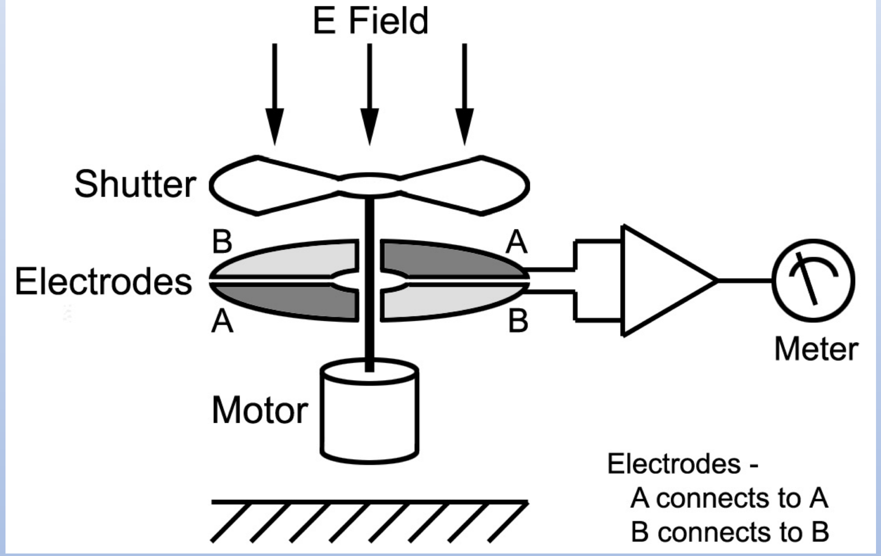
Required by energy scale requirement

LNGS R&D activities

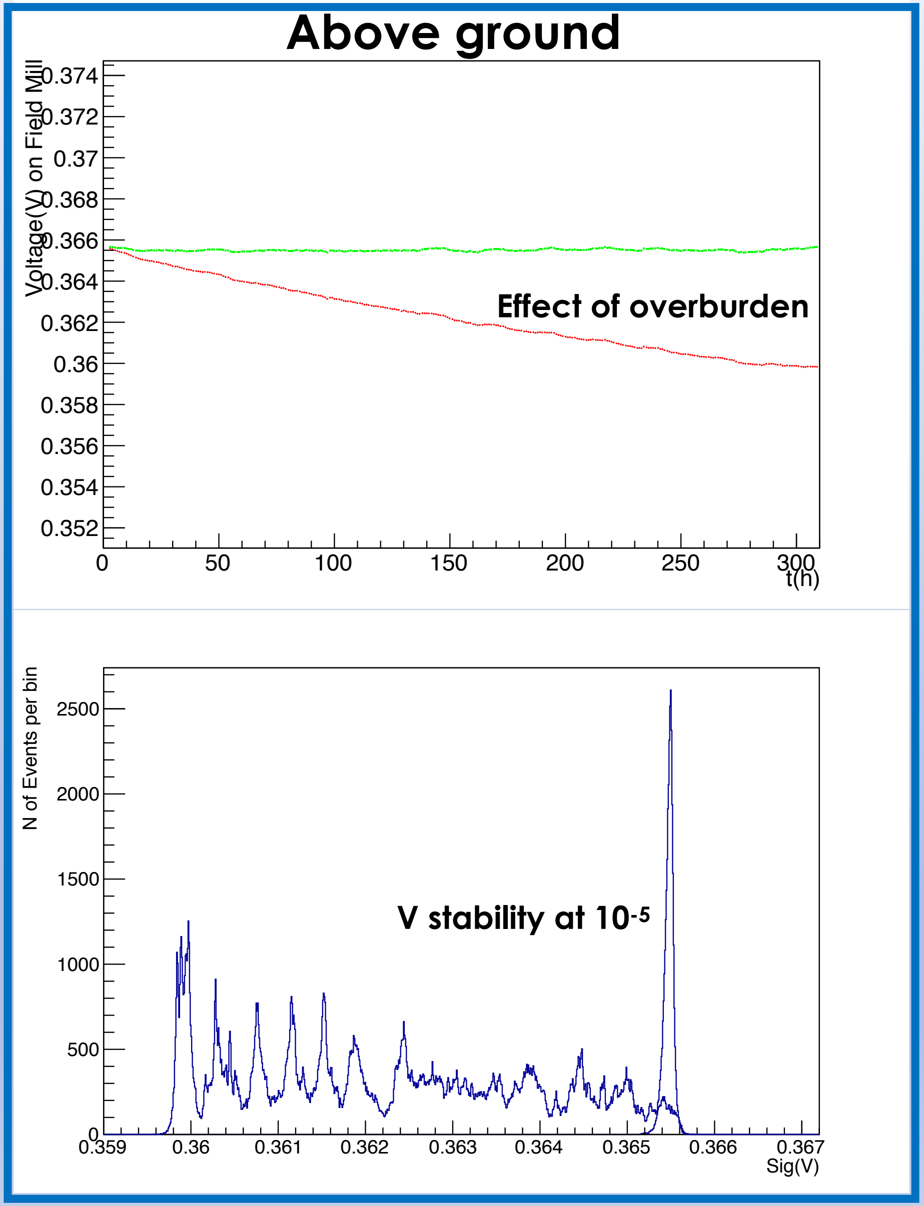
Exploded view of the HV-HS system



Field Mill concept



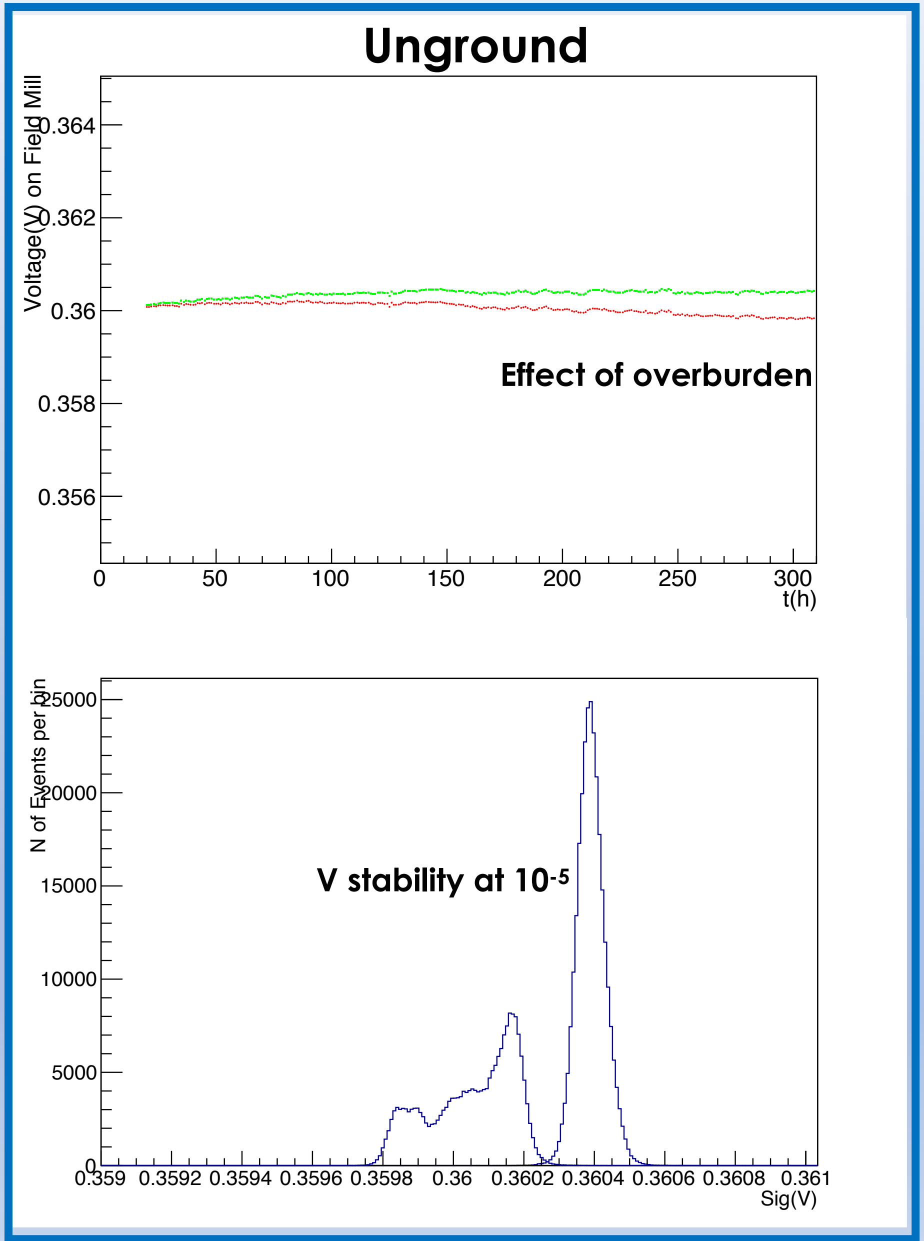
Preliminary data



Above ground

Effect of overburden

V stability at 10^{-5}



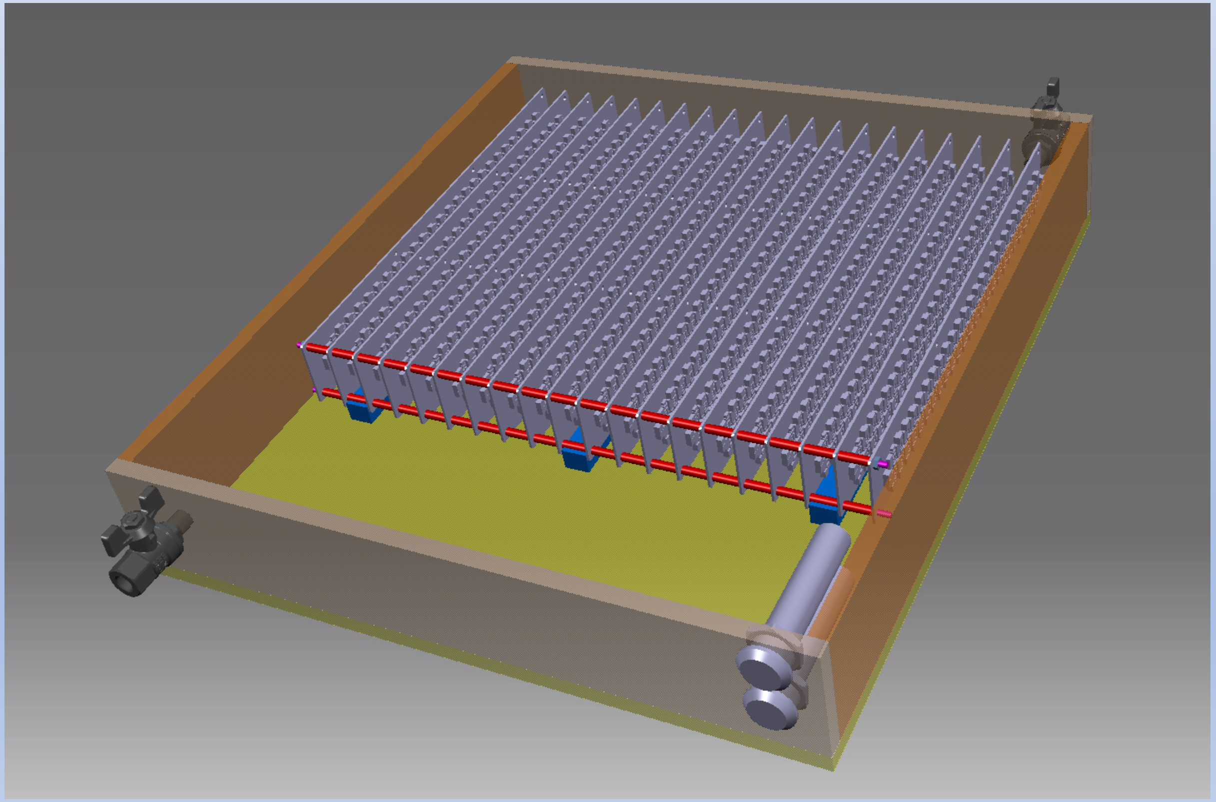
Unground

Effect of overburden

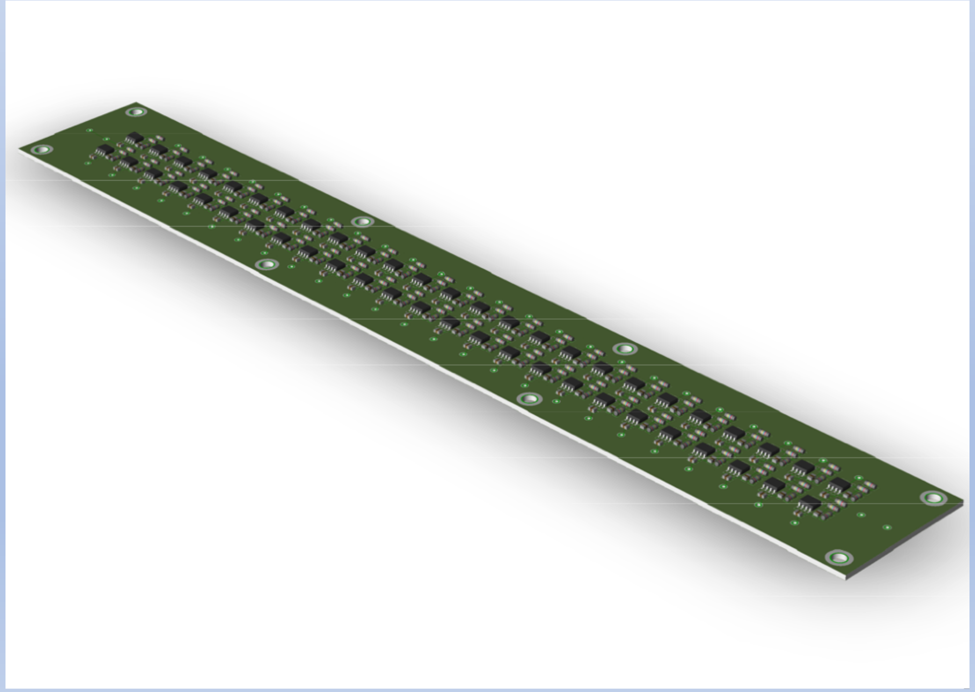
V stability at 10^{-5}

Voltage Generation with High Stability

20 boards able to generate 20 kV. The output can be any voltage from 0 to 20kV with step of 40 V



Circuit based on REF5010 from Texas Instrument. The stability aimed at is ~ 10^{-6} at 20 kV. The Russian National Institute of Metrology achieved a similar results.

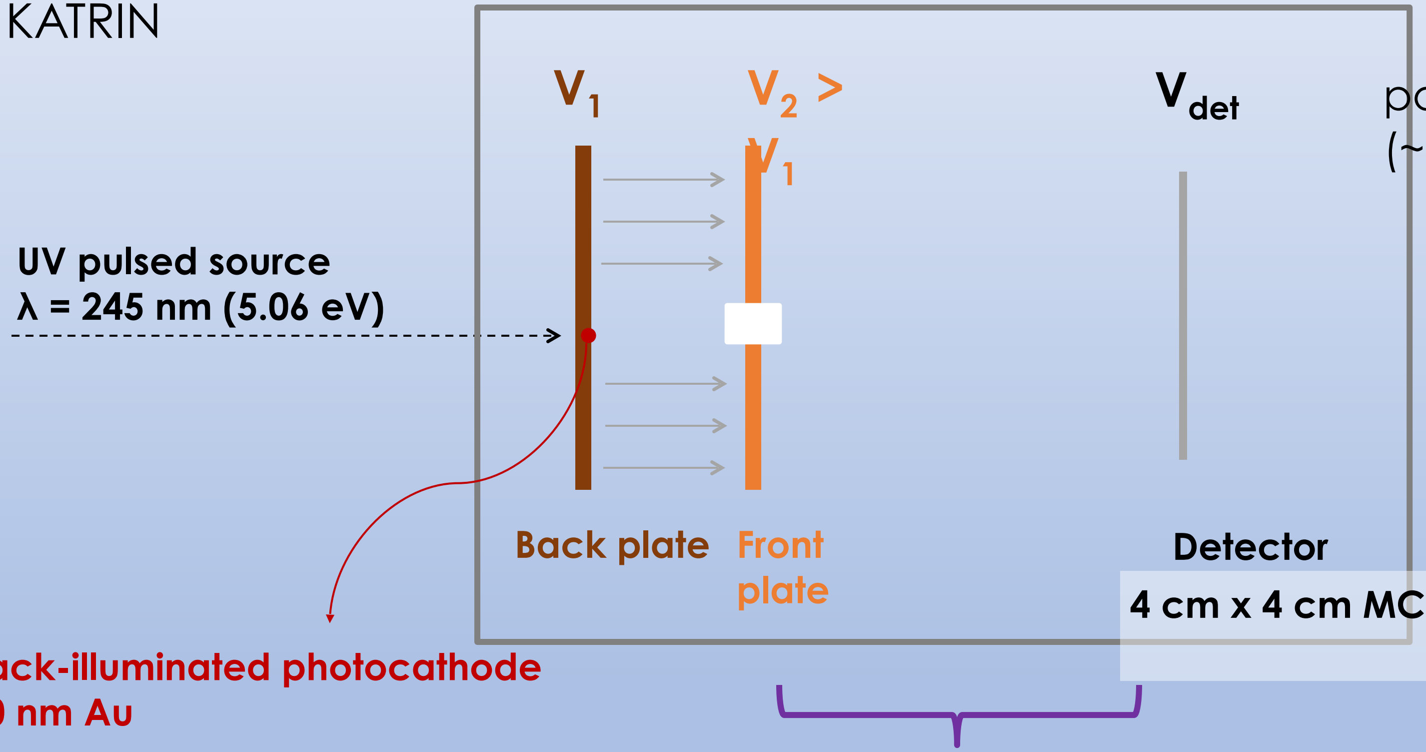


e^- source with energy definition <0.5 eV

PhD work of K. Rozwadowska

E-gun at LNGS

Design idea as developed by KATRIN



V_1

$V_2 > V_1$

V_{det}

Back plate

Front plate

Detector

4 cm x 4 cm MCP

Vacuum chamber

$P \approx 10^{-6}$ mbar

Electron absorption on the path from source to detector (~15 cm): $1.5*10^{-5}$

UV pulsed source
λ = 245 nm (5.06 eV)

Back-illuminated photocathode
20 nm Au

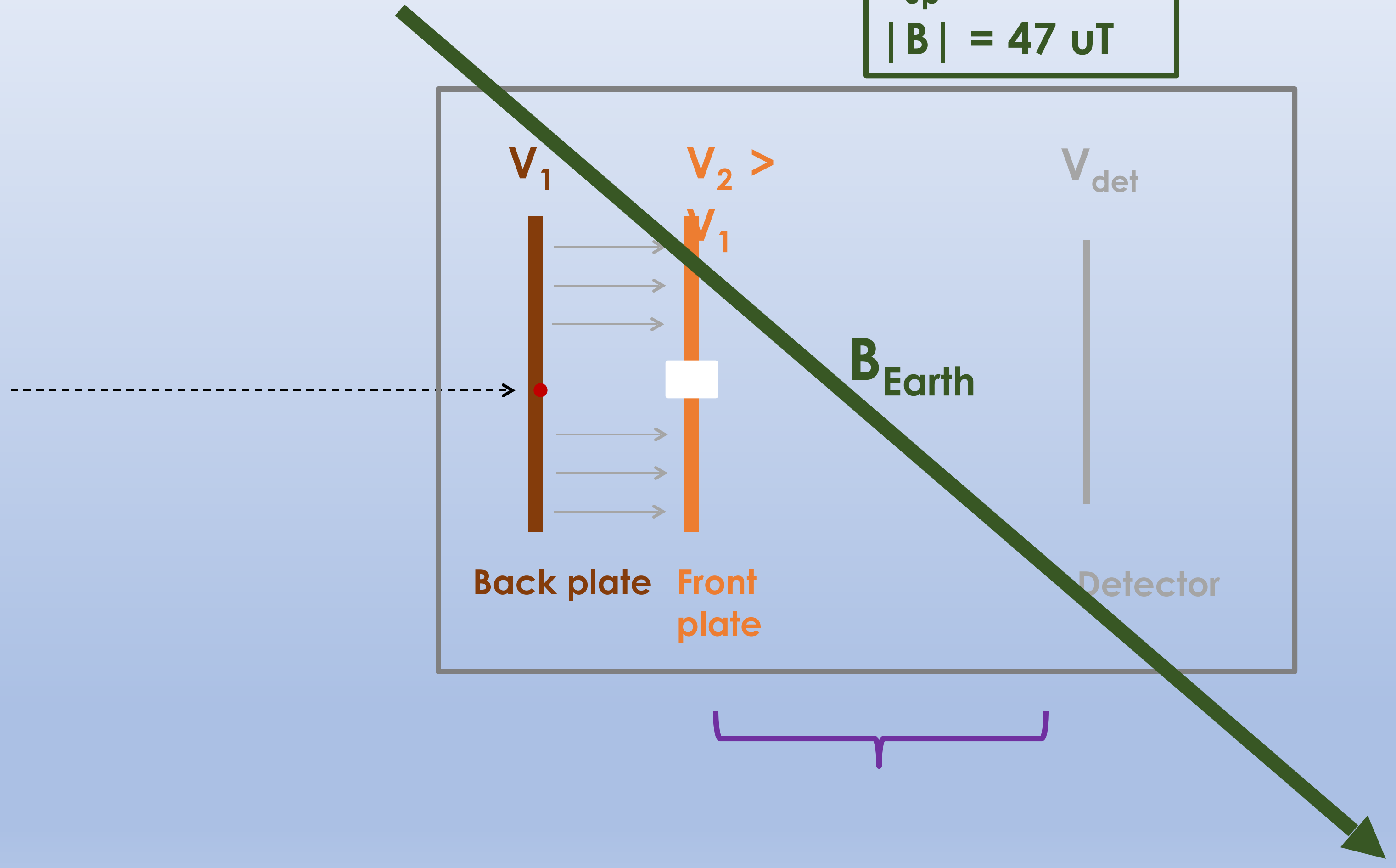
W_{Au} = 5.1± 0.1 eV [doi:10.1103/PhysRevB.2.1]

W_{Au} = 3.78 ± 0.04 eV
measured by KATRIN with 20 nm Au at 300 K
[doi: 10.1140/epjc/s10052-017-4972-9]

Electrostatic focusing system may be introduced

E-gun at LNGS

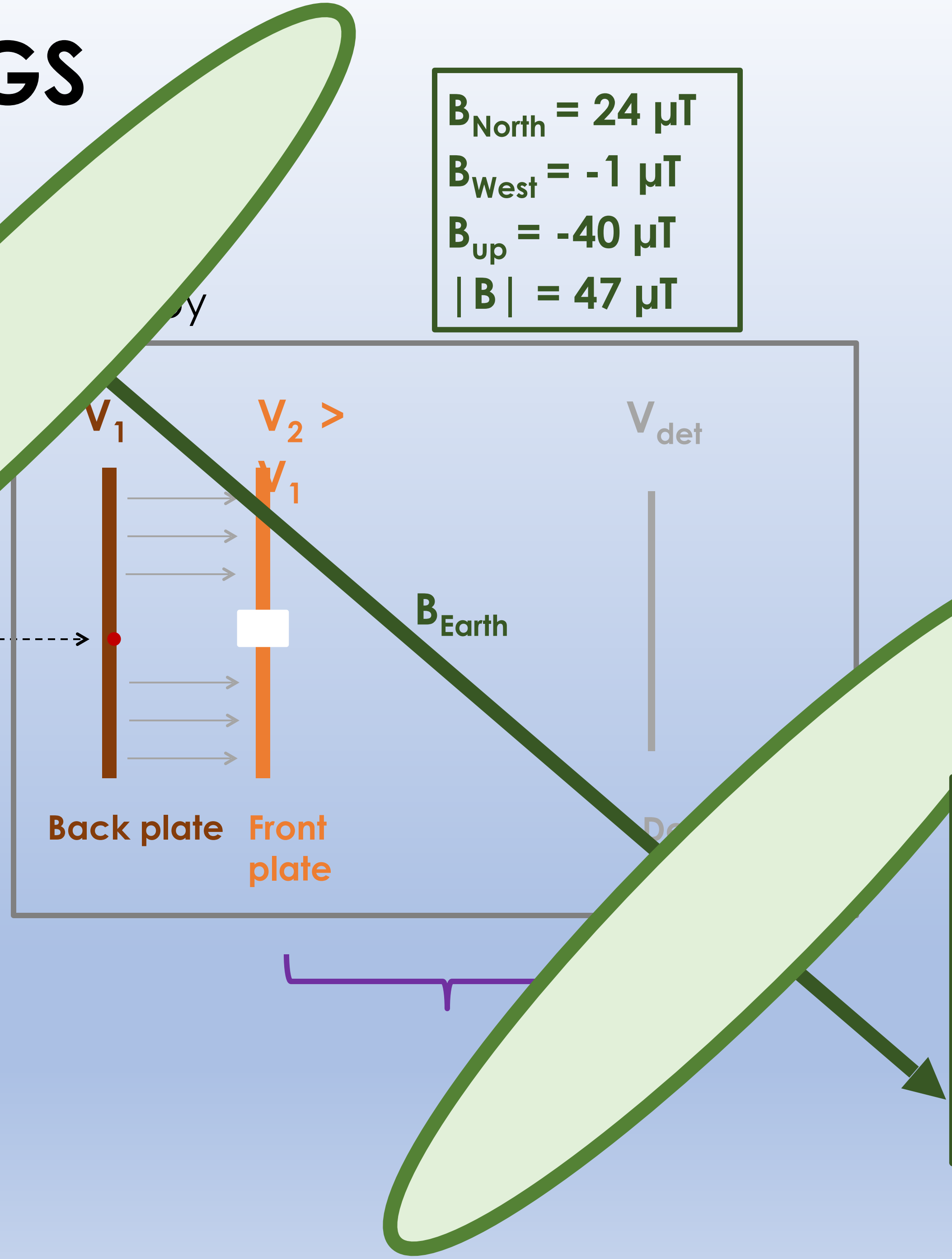
B_{North} = 24 uT
B_{West} = -1 uT
B_{up} = -40 uT
|B| = 47 uT



E-gun at LNGS

Design idea as d [illegible] y
KATRIN

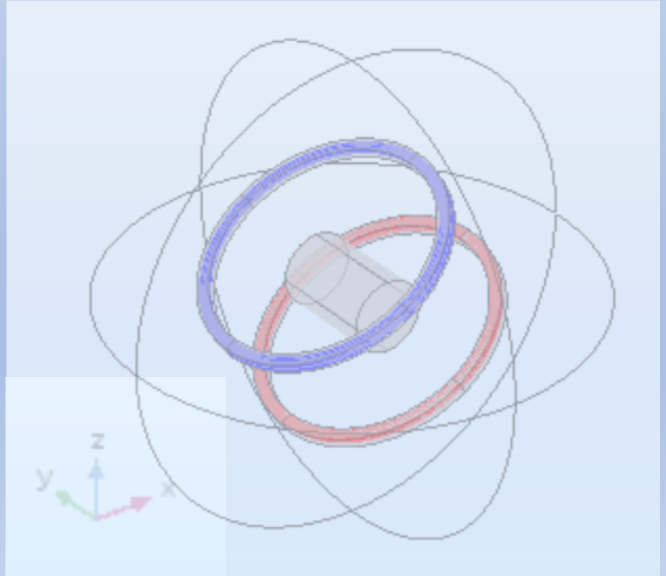
B_{North} = 24 μT
B_{West} = -1 μT
B_{up} = -40 μT
|B| = 47 μT

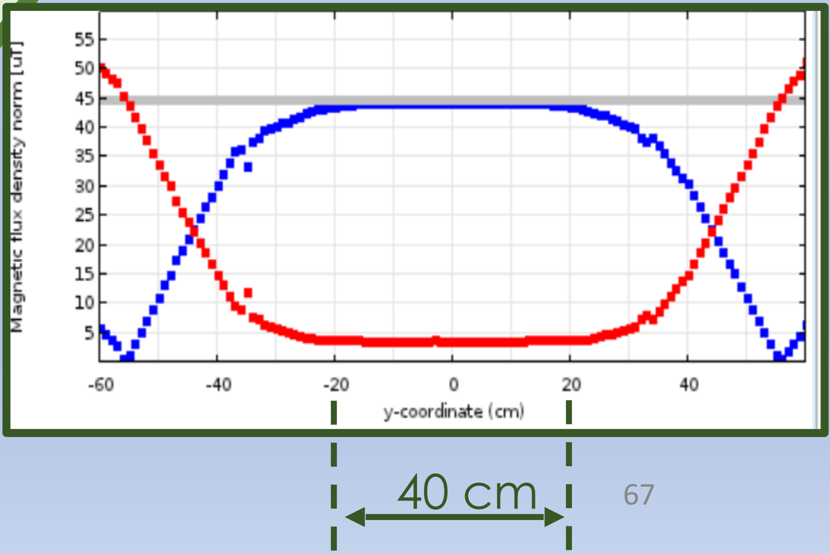


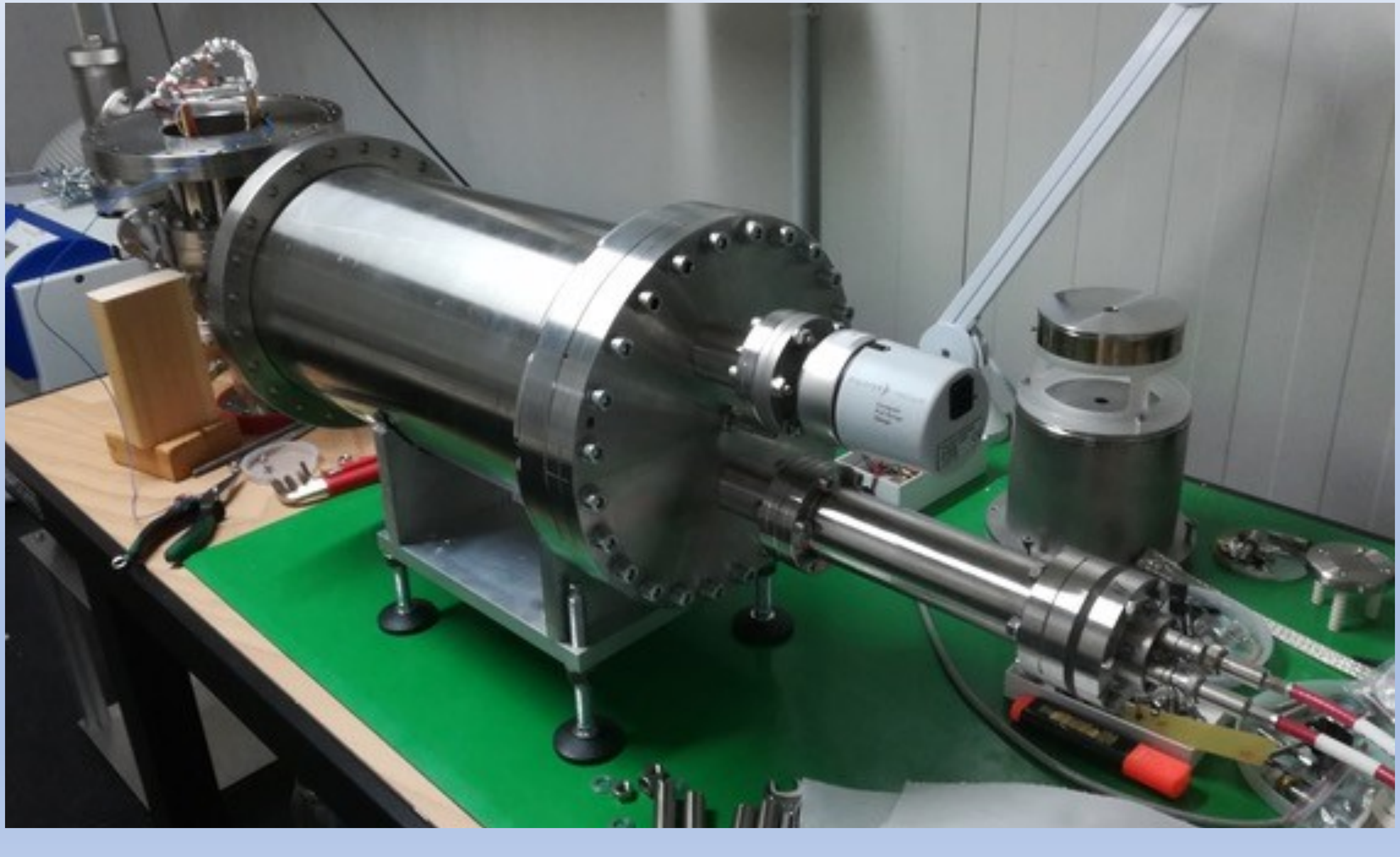
Helmholtz coil to compensate the magnetic field

r = 50 cm, n = 25 turns, I = 1 A

Gives ~ 40 cm x 40 cm x 40 cm volume with B < 5 μT








We are here at the moment

Light Dark Matter search

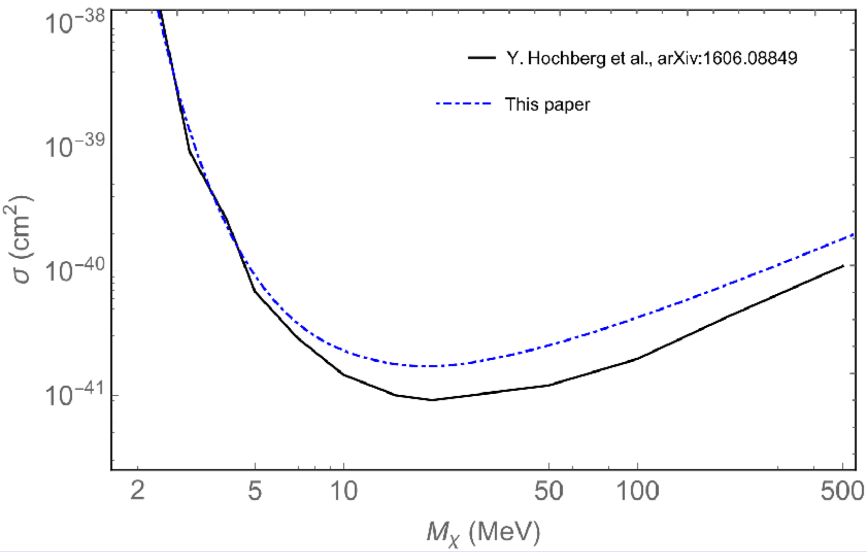
Side project potentially very much interesting

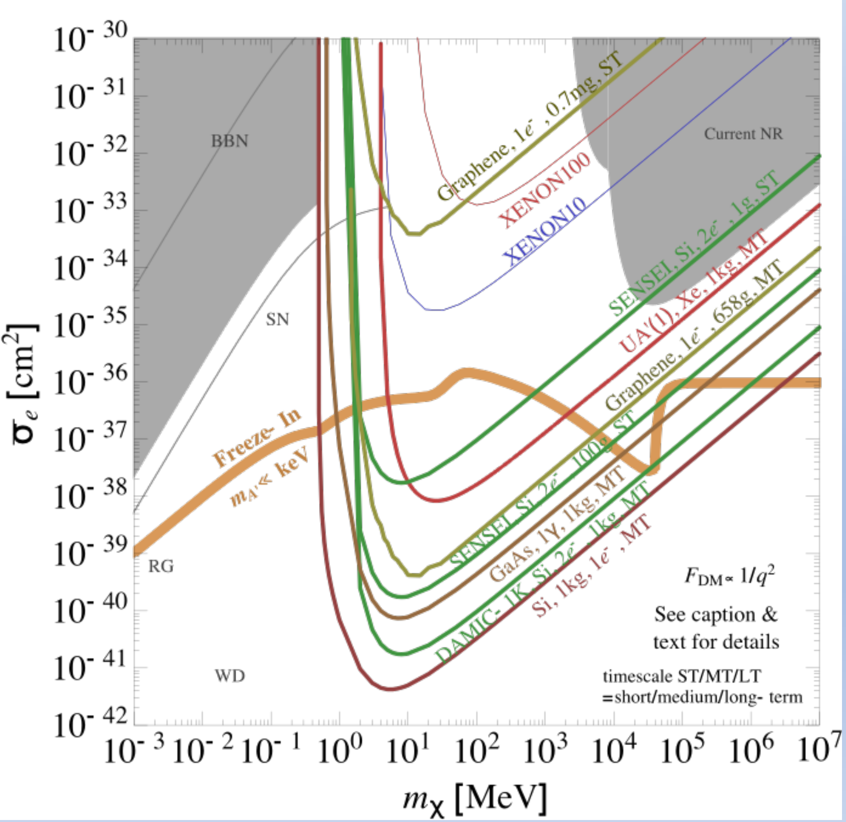
- Hochberg, et. al, 2016. “Directional Detection of Dark Matter with 2D Targets", Phys. Lett. **B772,** (2017), 239.
- GL Cavoto et. Al, “Sub-GeV Dark Matter Detection with Electron Recoils in Carbon Nanotubes “Phys.Lett. **B776** (2018) 338-344

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.

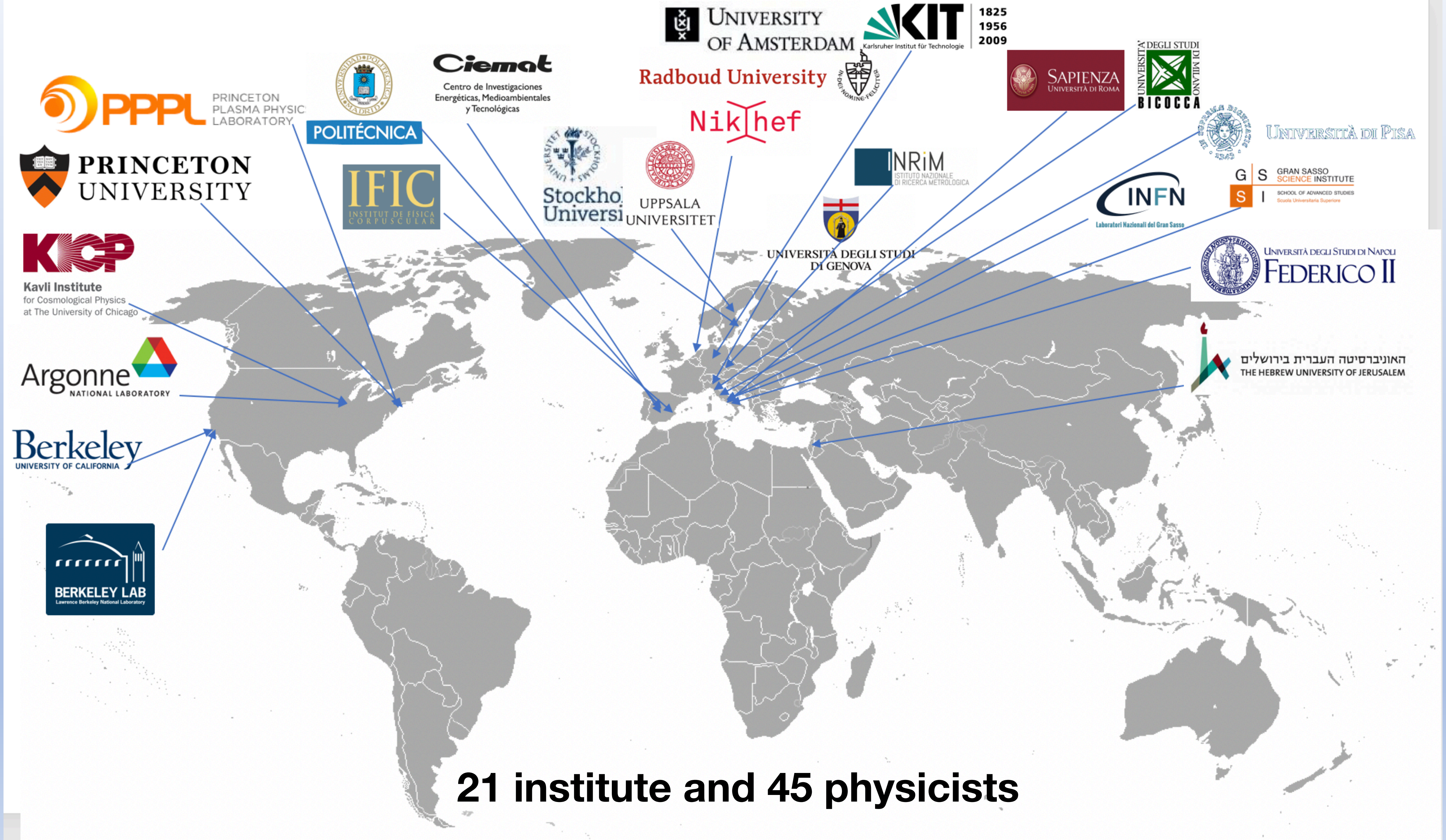
The requirements crucial for the PTOLEMY CNB detection project could be also very much beneficial for Light DM search:

- 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**