PTOLEMY

Overview of PTOLEMY Critical Elements

Chris Tully (Princeton University)

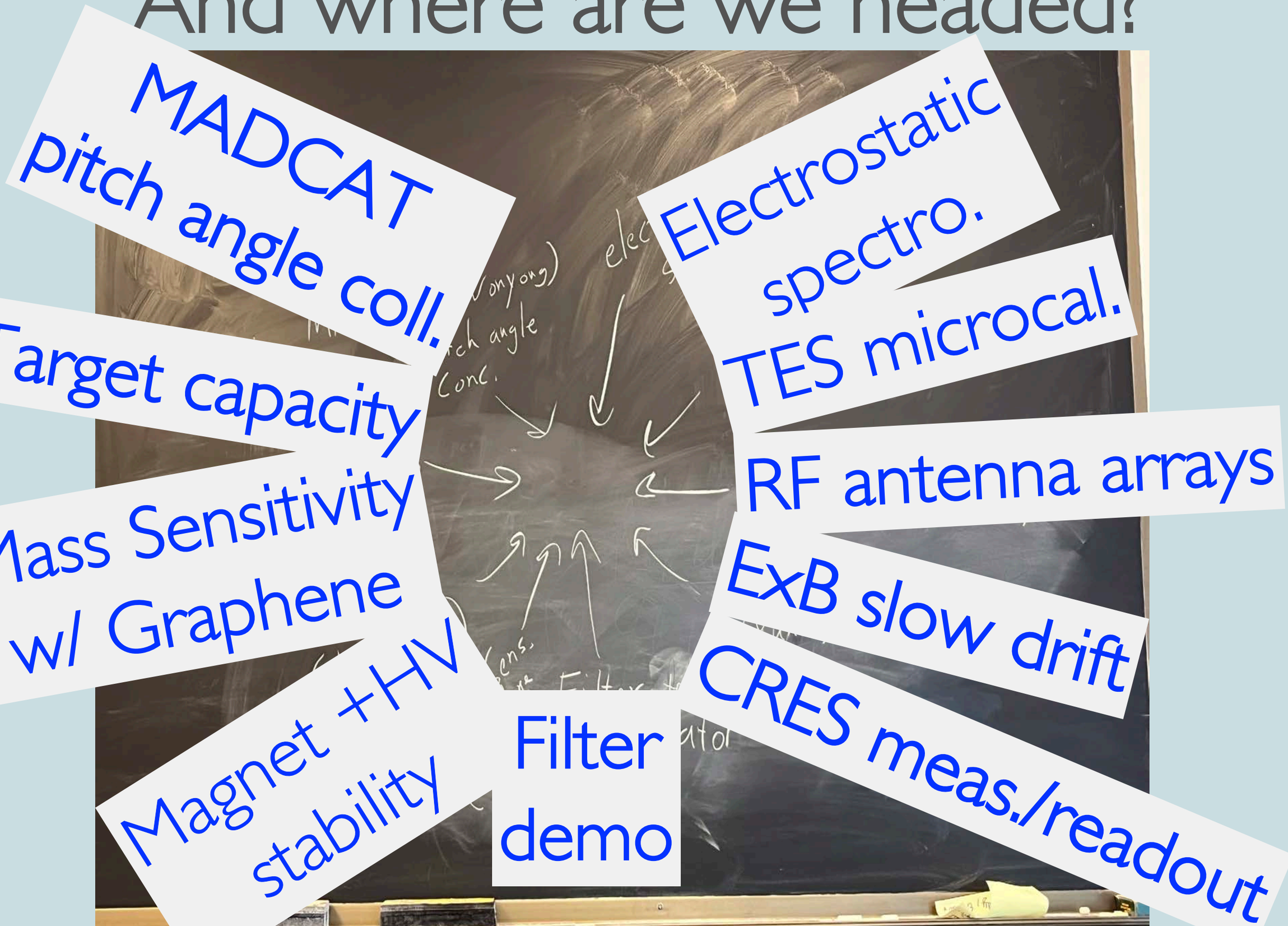
1 July 2025

PTOLEMY International Workshop at De Lindenberg

Nijmegen, The Netherlands

Where are we?

And where are we headed?



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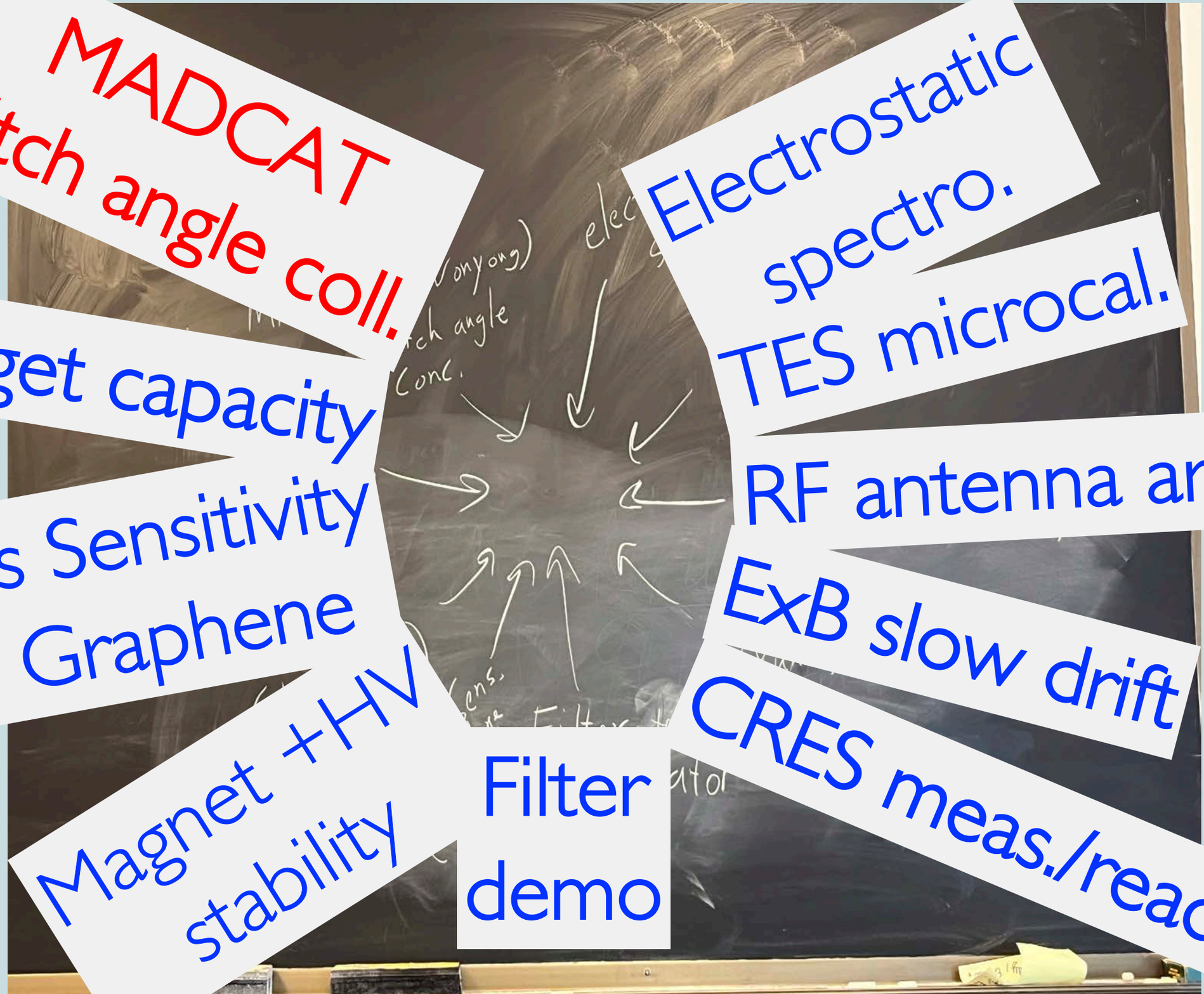
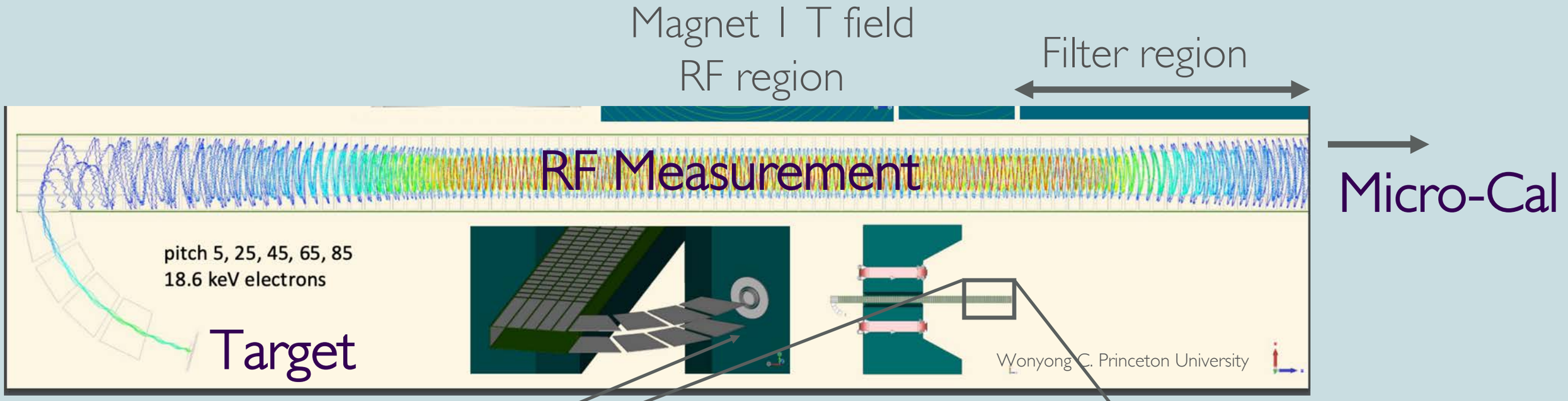
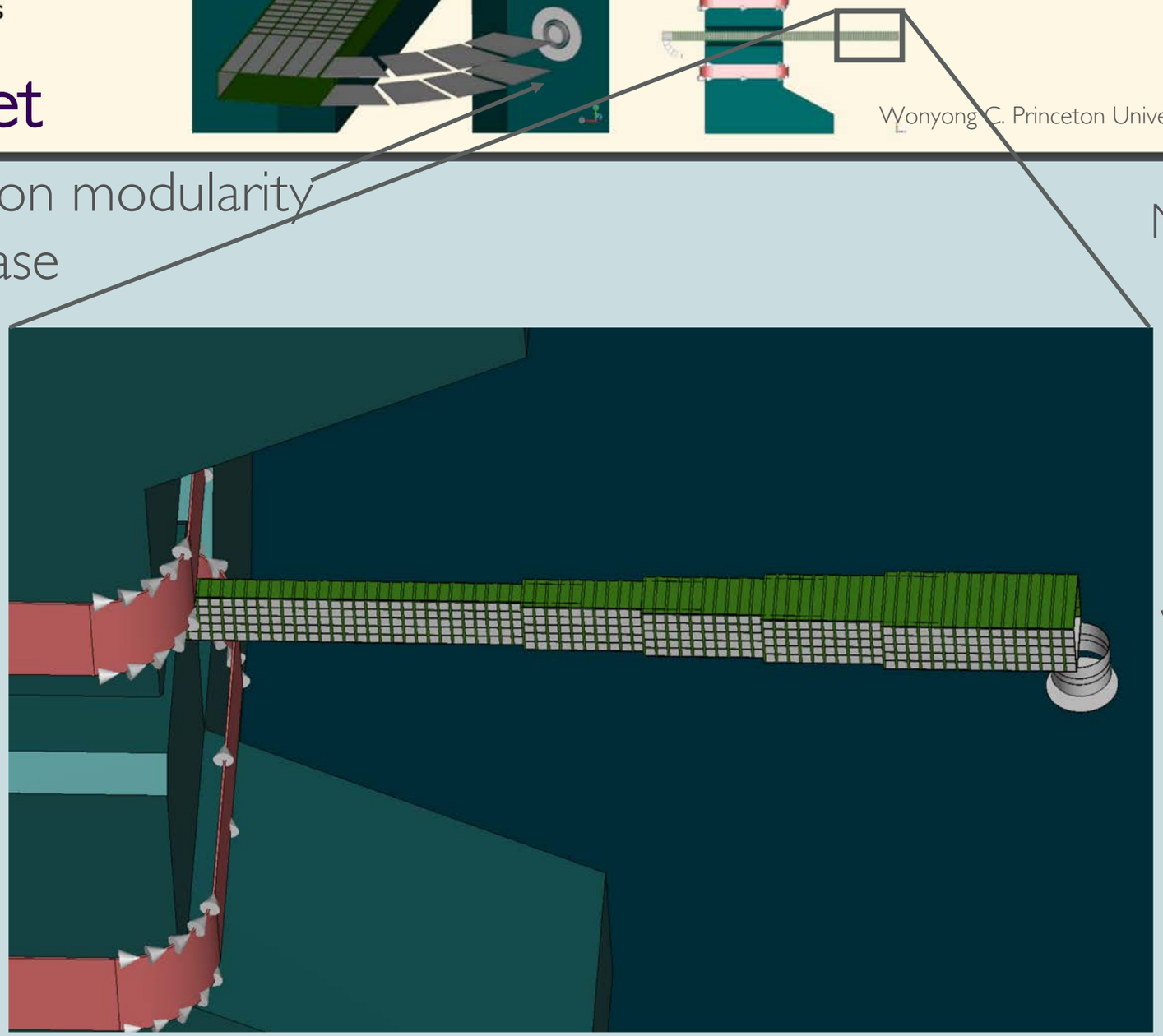


Detailed simulation of the PTOLEMY filter



Geometry relying on modularity approach to increase instrumented target mass



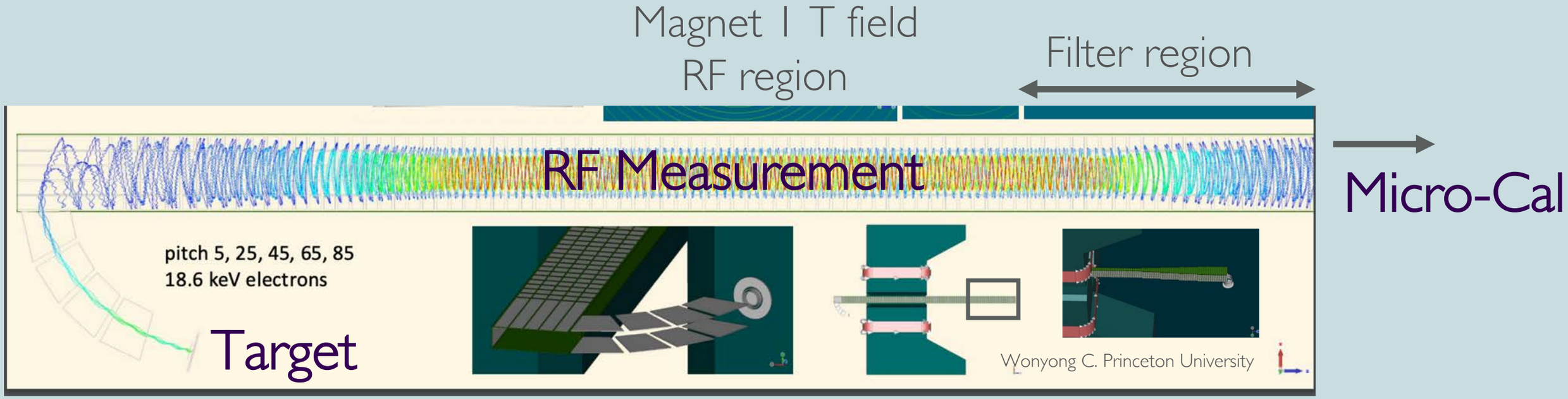
Micro-calorimeter region with focusing system to match beam and calorimeter array

Zero B Field FOCUSING with Einzel lens (90 degress)

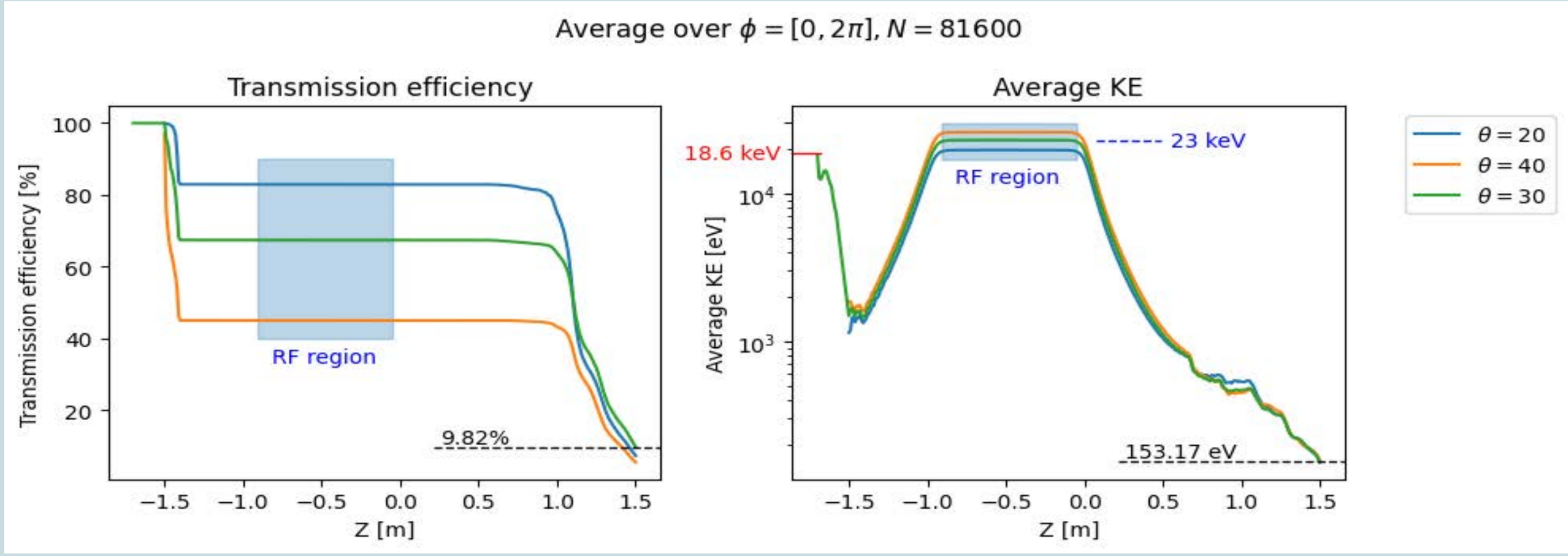
↓

Microcalorimeter

End-to-End Drift Collimation and Transmission Results



10% Static Transport Achieved!!! Down to 160eV



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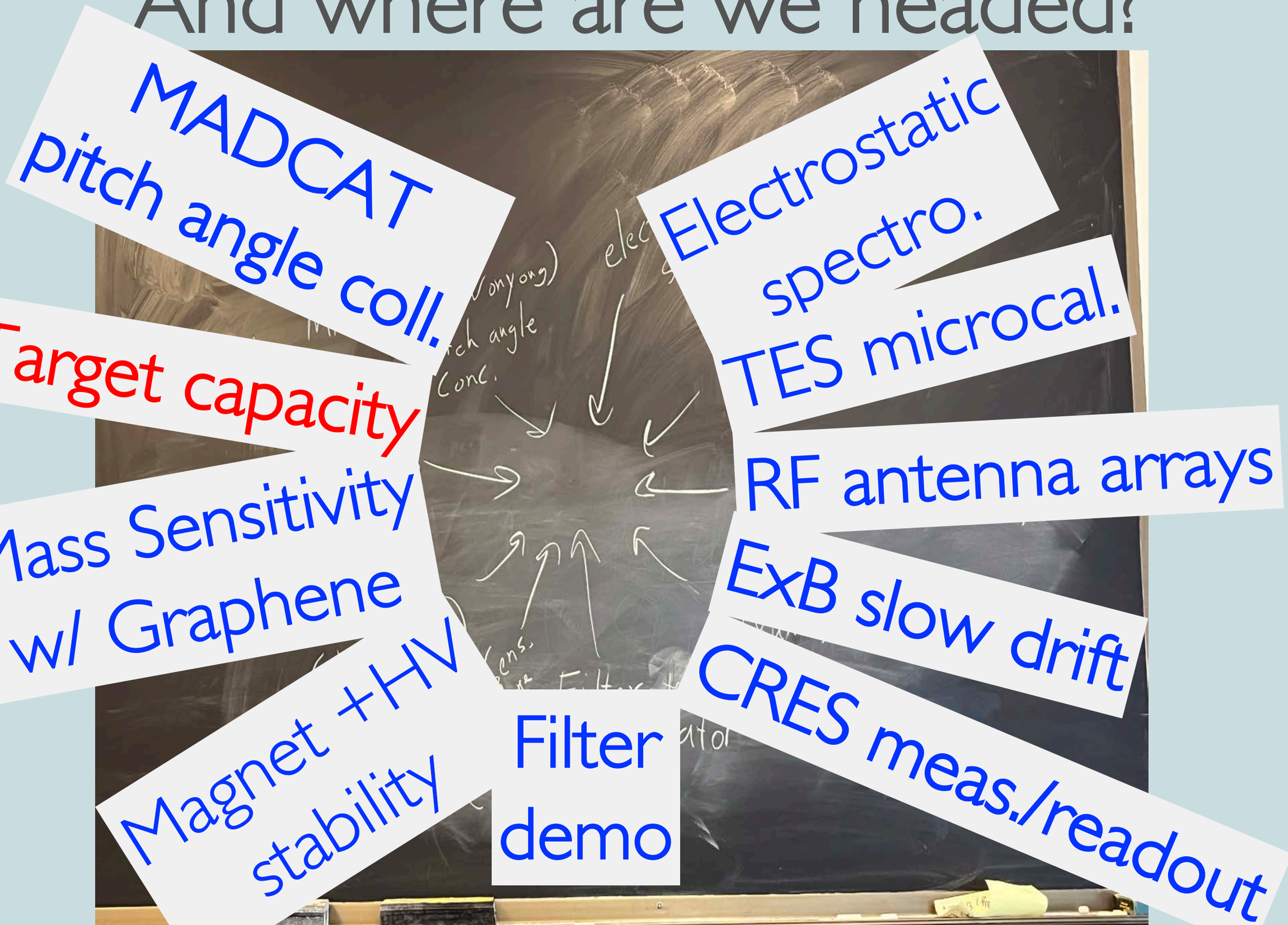
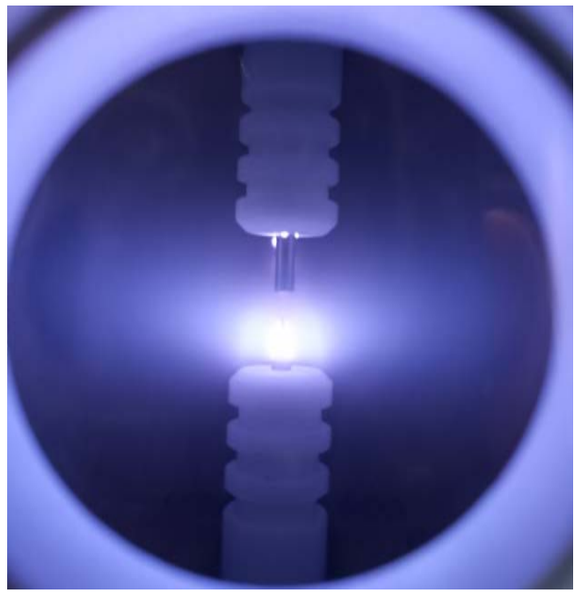
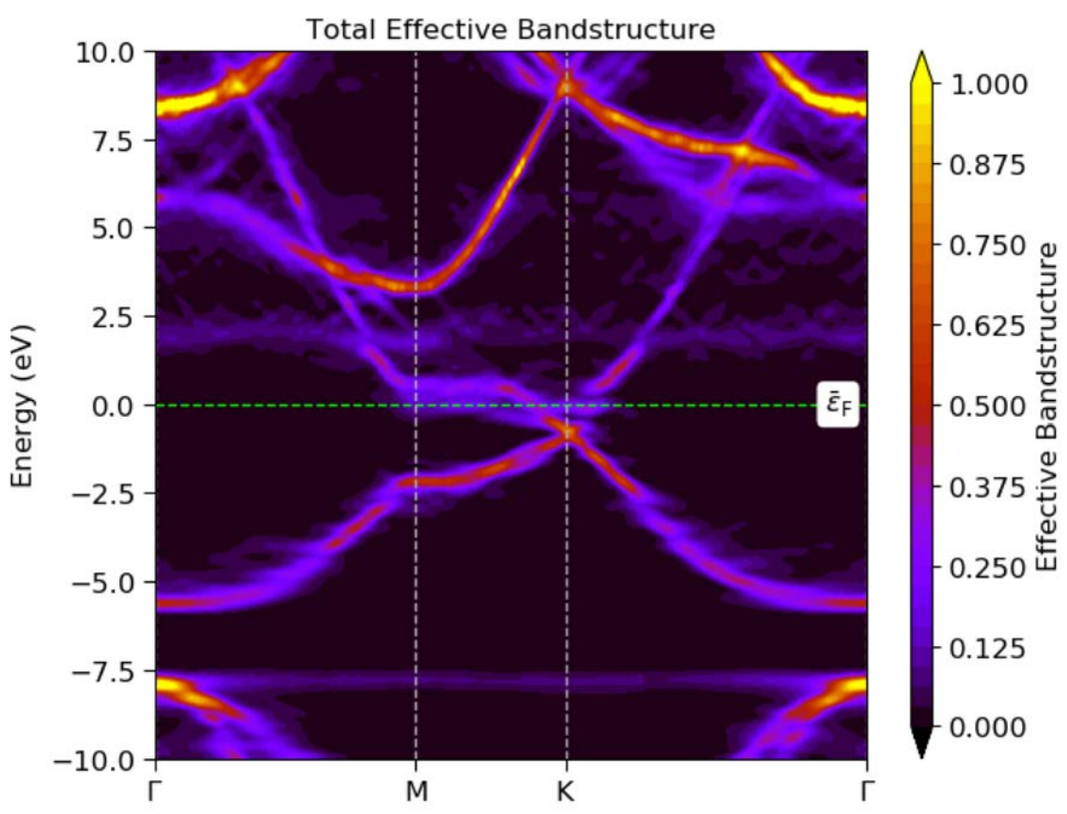
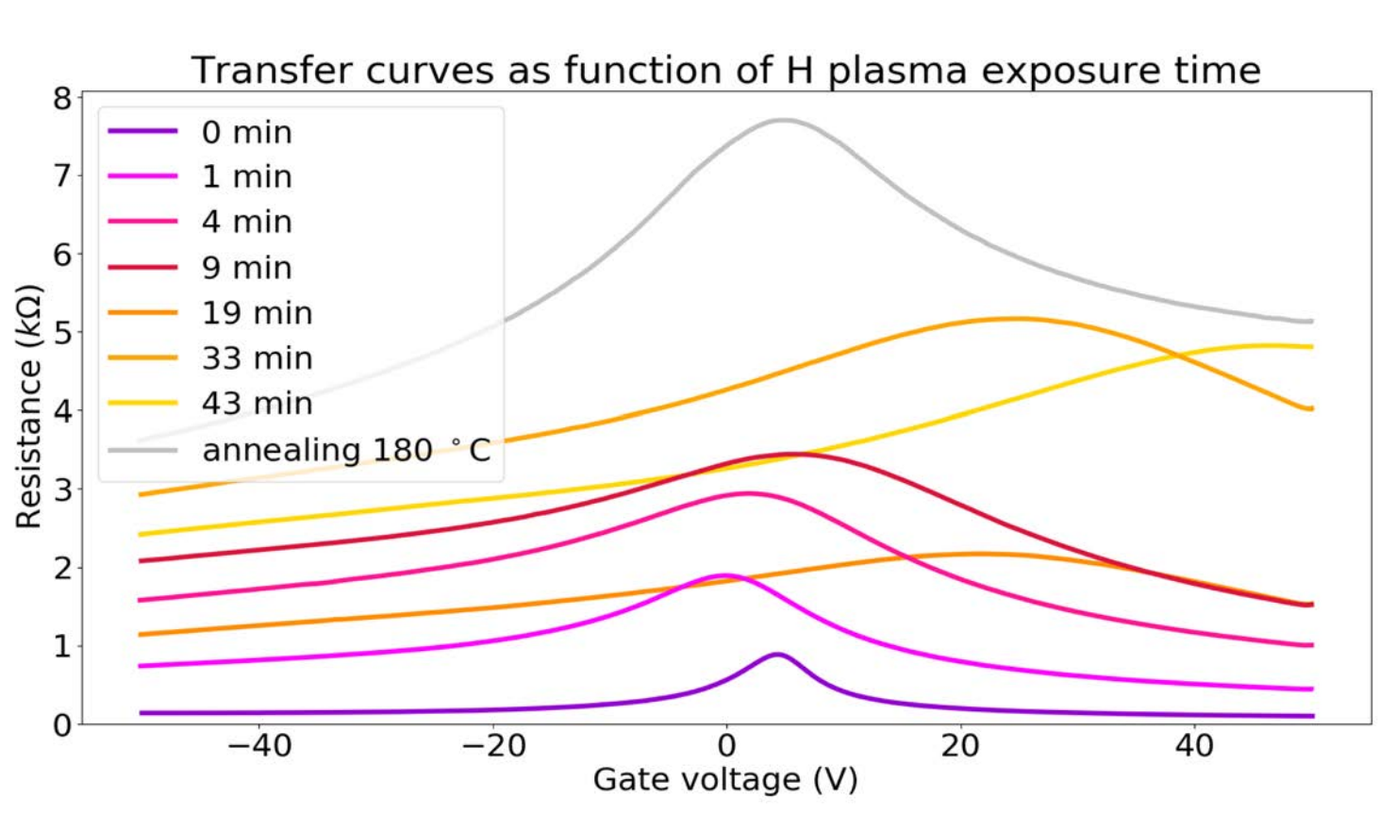


Hydrogen plasma graphene loading



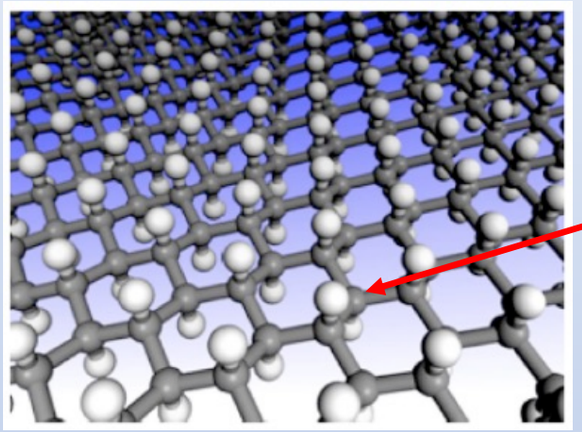




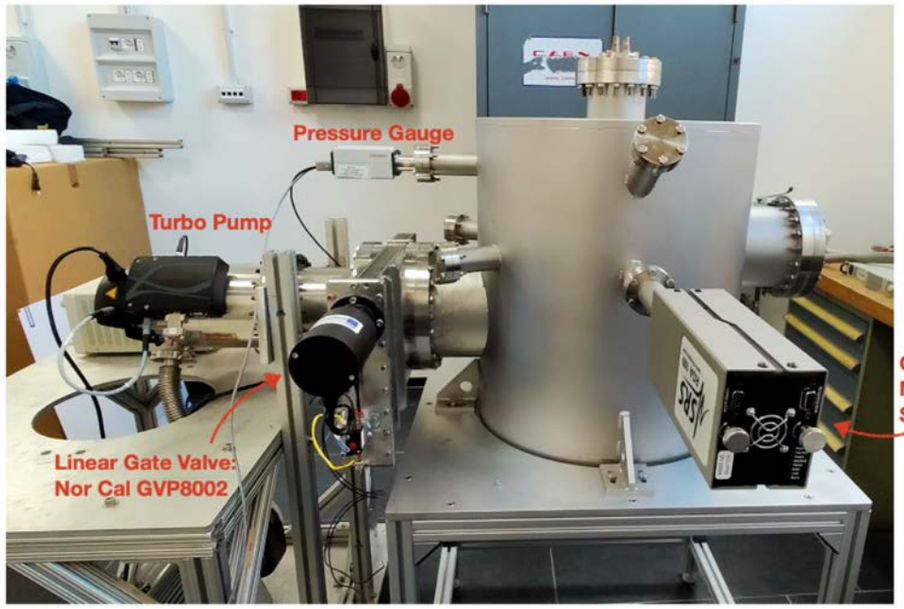
Radboud University

Fabrication of a Tritiated-Graphene Target/Source
Hydrogen and Deuterium loading on graphene at Roma1 and Roma3

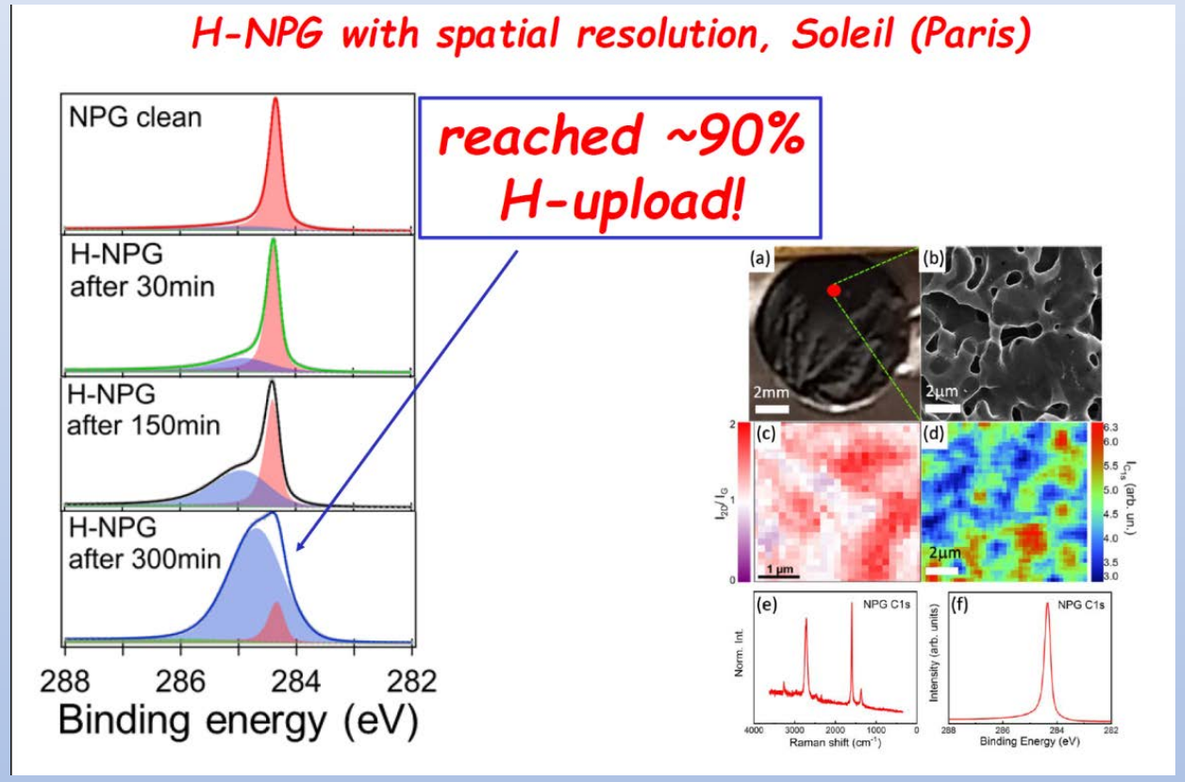
atomic H as a tool to '*pinch*' the sp^2 bonds towards a sp^3 configuration
while maintaining the planar nature of graphene



T-chamber in Rome side view:



H on Nanoporous Graphene (NPG):

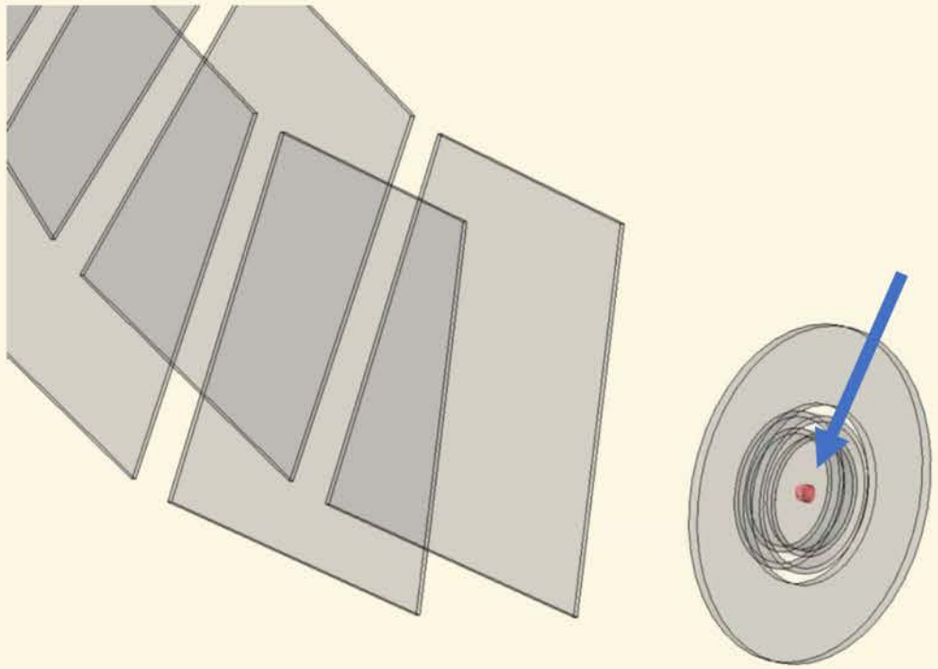


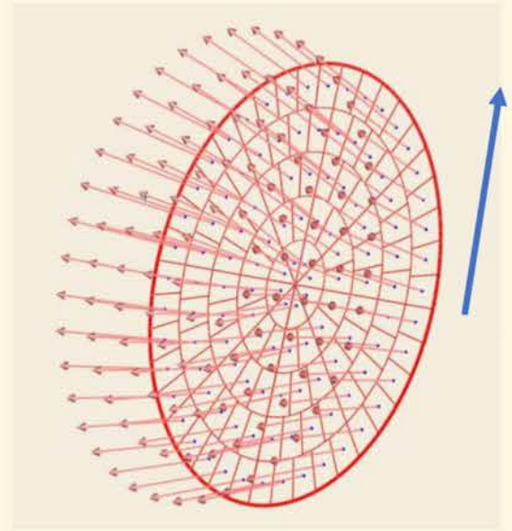
Betti et all, Nano Lett. **22**, 2971 (2022)

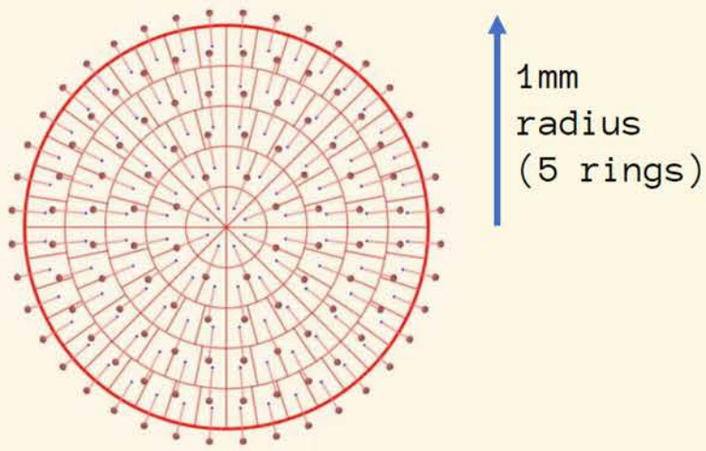
UKAEA's Active Gas Handling System
(tritium for JET, EU Tokamak) for
feasibility study & design requirement of a
new T loading chamber

Maximizing Target Capacity and Transfer Functions

Transmission Function Setup

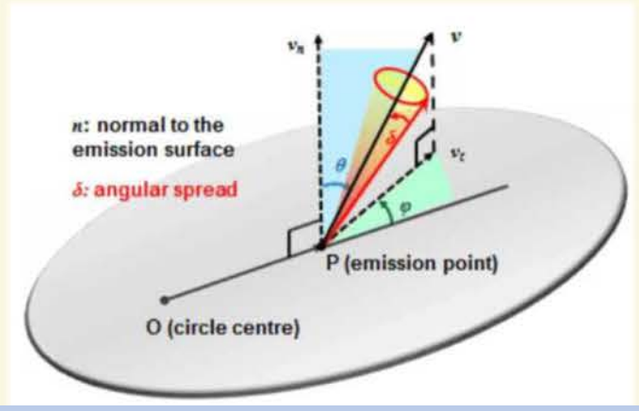






- 1mm radius circular area split into 50 rings (5 shown)
- Set pitch (theta) and emission phase angle (phi)

- Blocks of 10 deg pitch (5-15, 15-25, …, 75-85 deg)
  - Uniform distribution of +/- 5 deg about 10, 20, … , 80 deg pitches
  - Per pitch block: 8x fixed phi blocks in 45 deg steps (0, 45, … , 270, 315 deg)
  - 8 pitch blocks x 8 phi blocks = 64 blocks
  - 50 rings = 10,200 particles per block
  - Total N = 652,800 endpoint electrons
- ~3 days per block, running parallel batches on Princeton cluster



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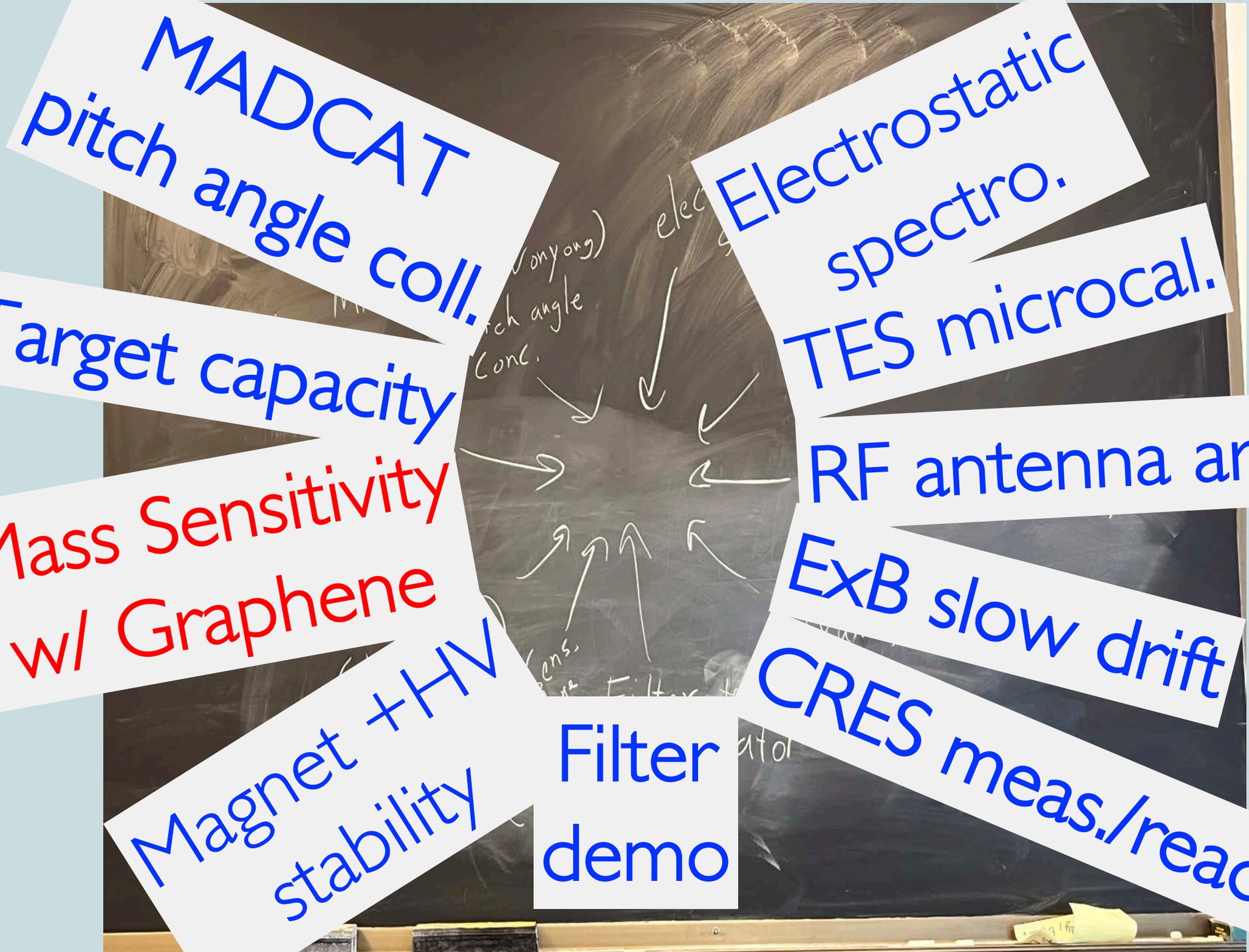
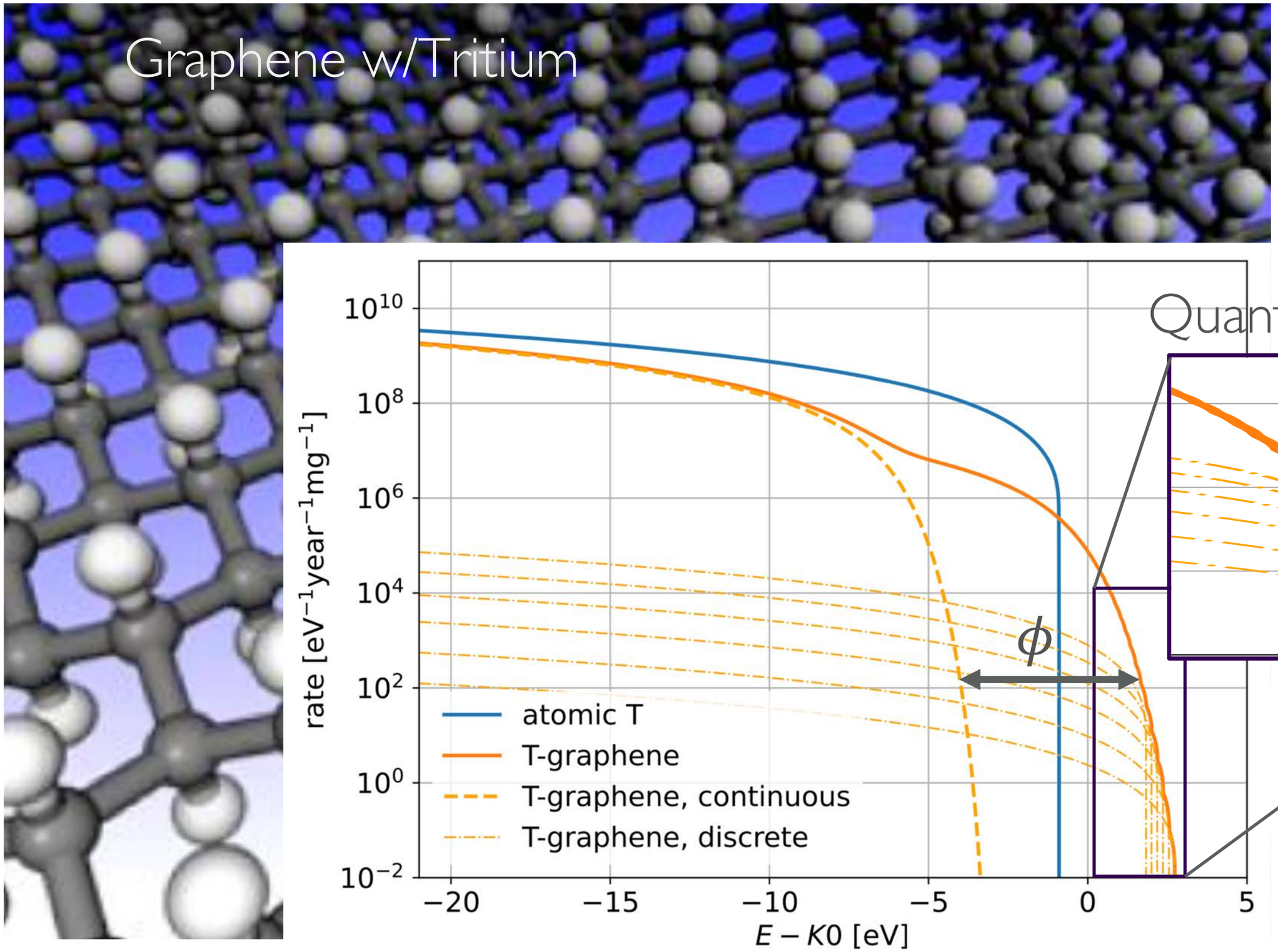


PTOLEMY: 2D MATERIAL - GRAPHENE



Other graphene structures also under study

$\phi \equiv$ "Atomic" work function

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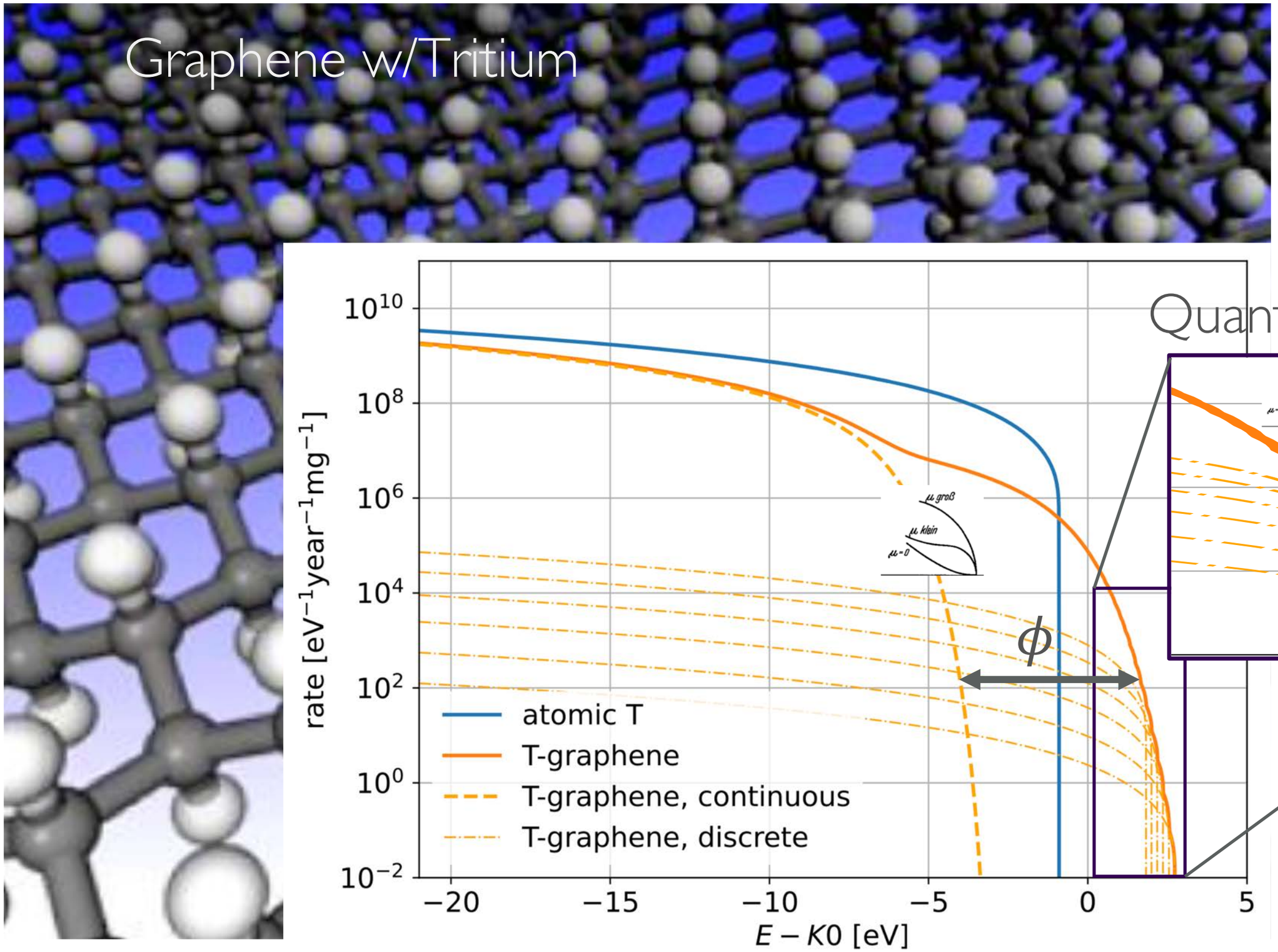

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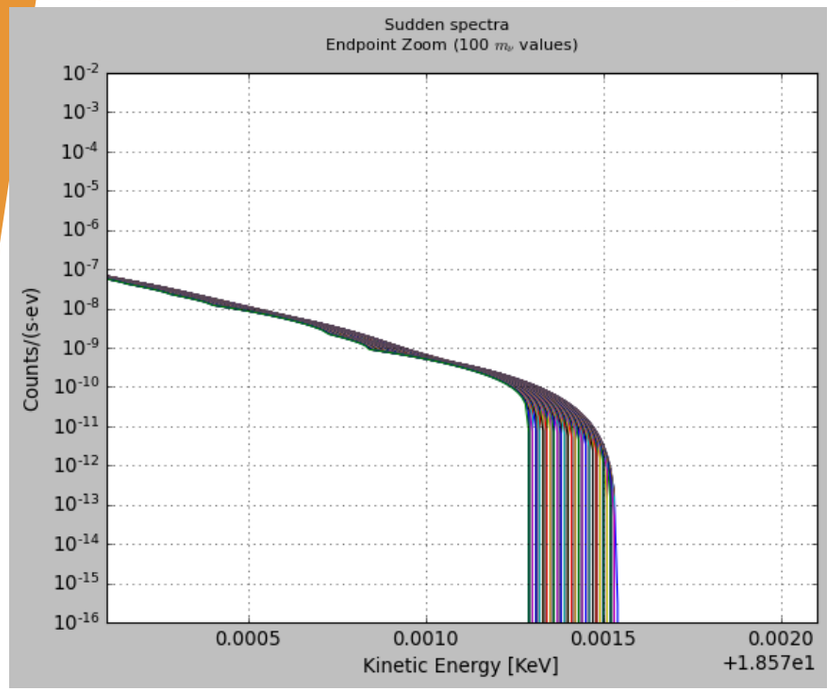
Graphene-induced spectral deformations

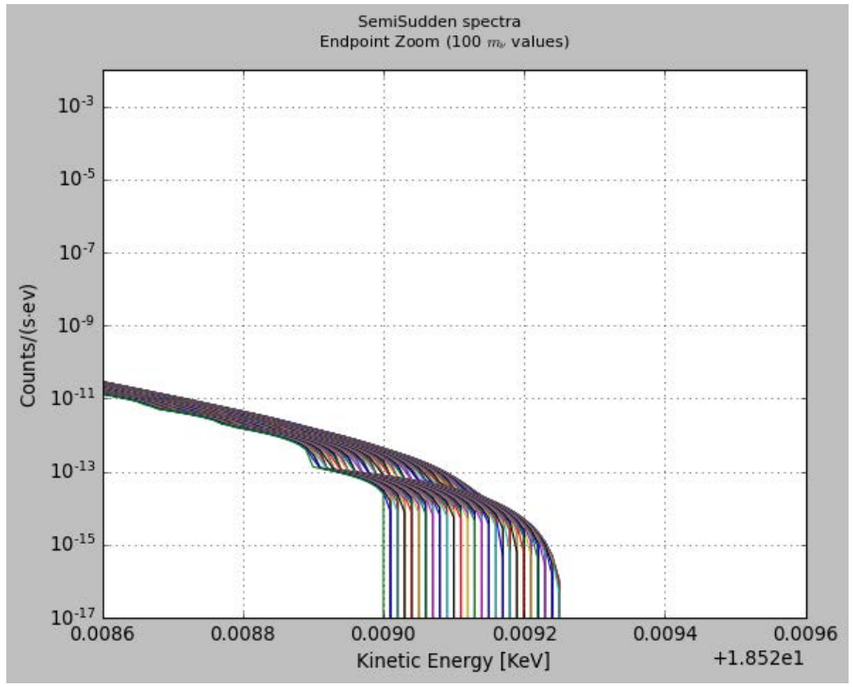
- **Discrete spectrum:** bound final state - **$^3He^+$ remains bound to the graphene**
- **Continuous spectrum:** ionized final state – **$^3He^+$ is ejected from the graphene**
- **Three recipes** used to **compute numerically the modified spectra** [Angelo Esposito]:

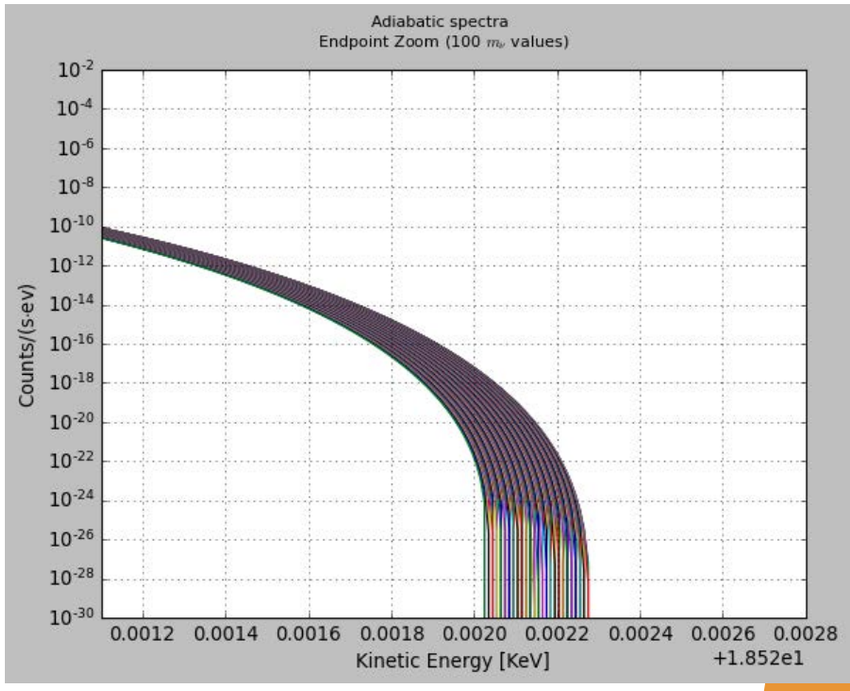
Sudden : for each position of the helium, electron density fixed as it was when the tritium was sitting at its equilibrium position (discrete + continuous)

Semi-sudden : for each position of the helium, electron density fixed as it was when the tritium was at the same position as the helium (discrete + continuous)

Adiabatic: allow the whole system to relax to the new configuration (only continuous)

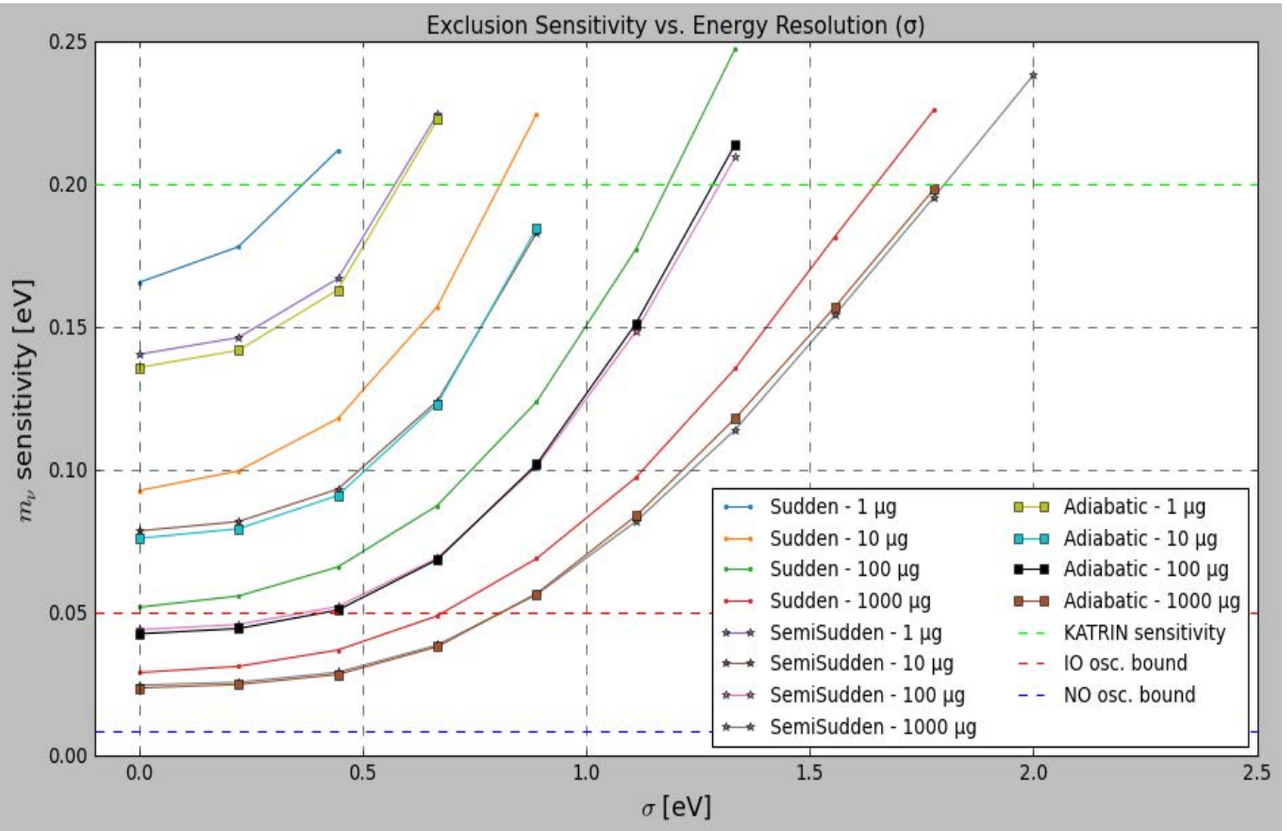


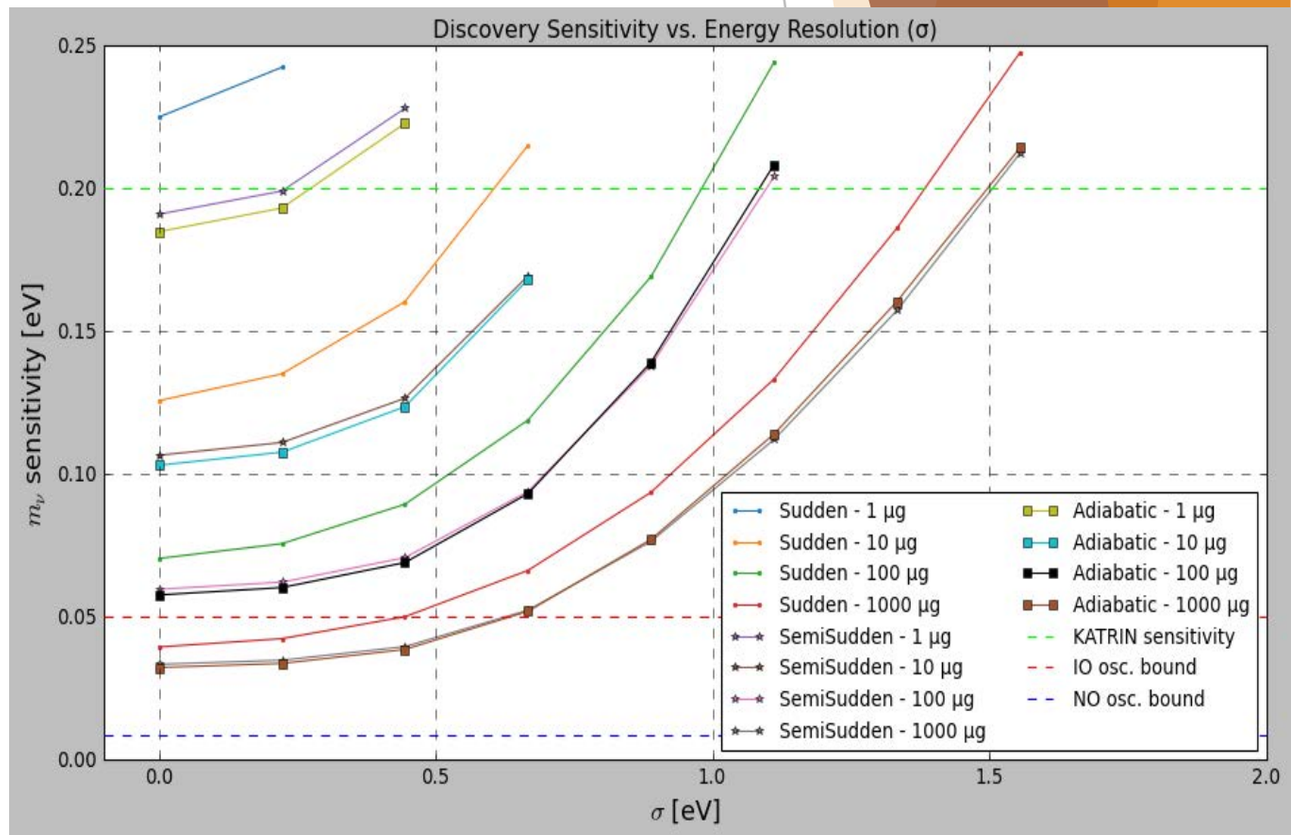




PL method:
90% CL exclusion sensitivity

PL method:
3σ CL discovery sensitivity





Theory paper on solid state effects on the electron spectrum & consequent theory systematics on m_ν extraction (A. Casale, A. Esposito G. Menichetti, V. Tozzini)

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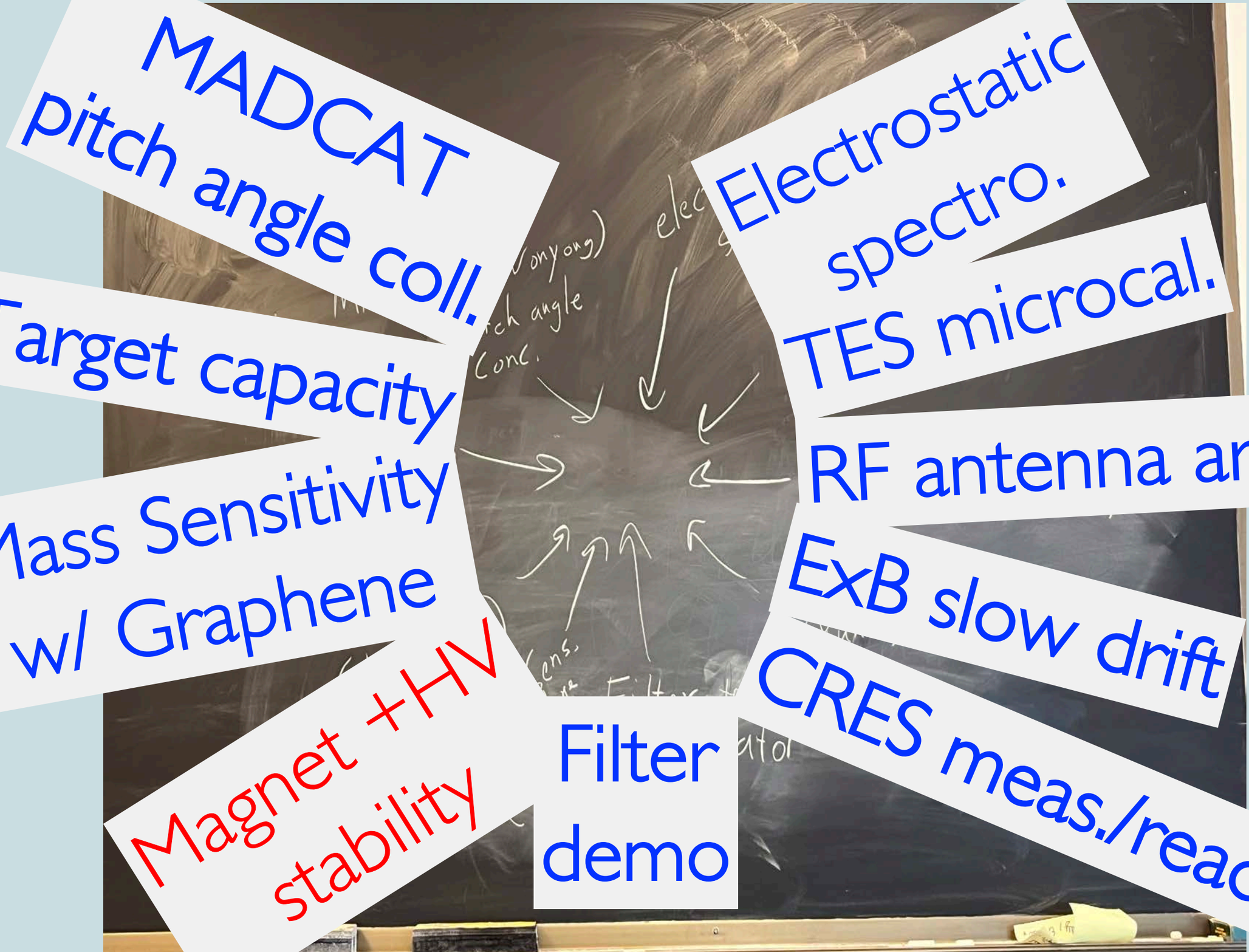
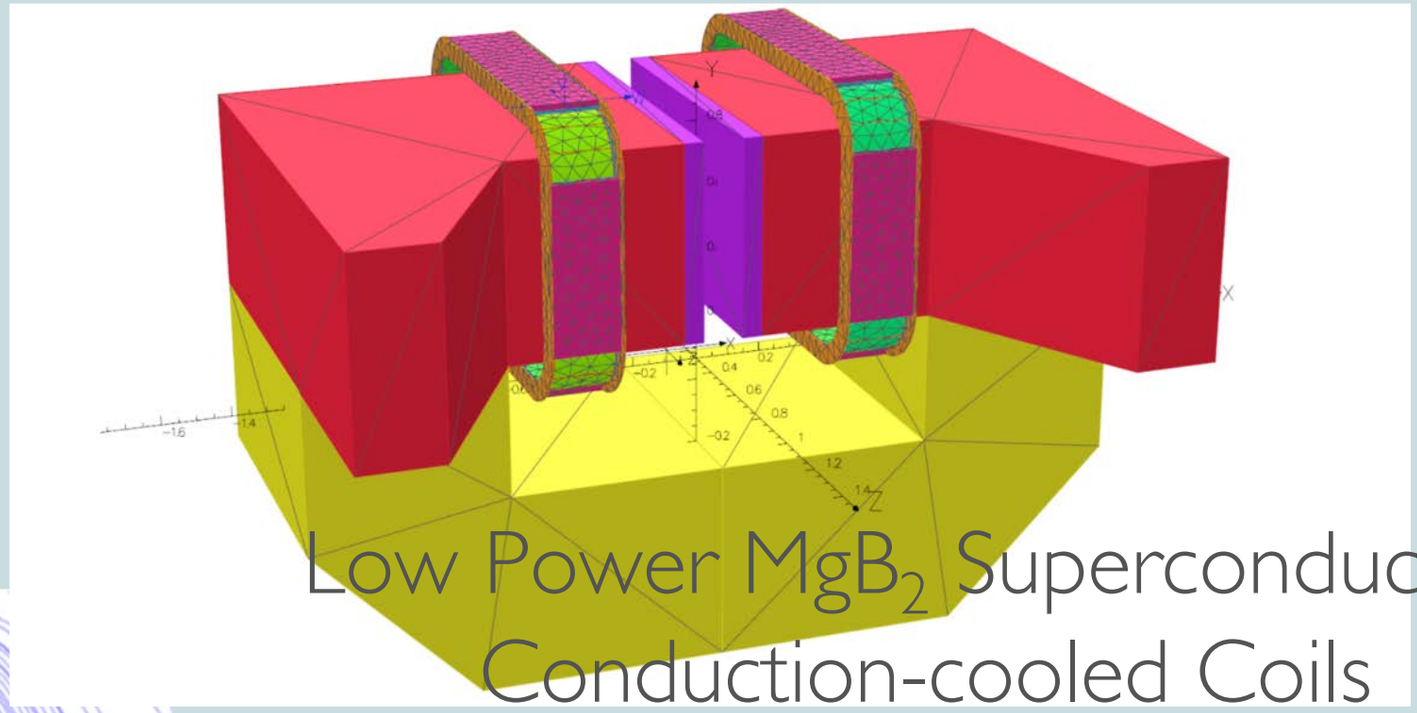


DEMONSTRATOR MAGNET

BEING BUILT AND WILL BE INSTALLED AT THE LNGS
KEY ELEMENT TO REALIZE THE PTOLEMY EXPERIMENT

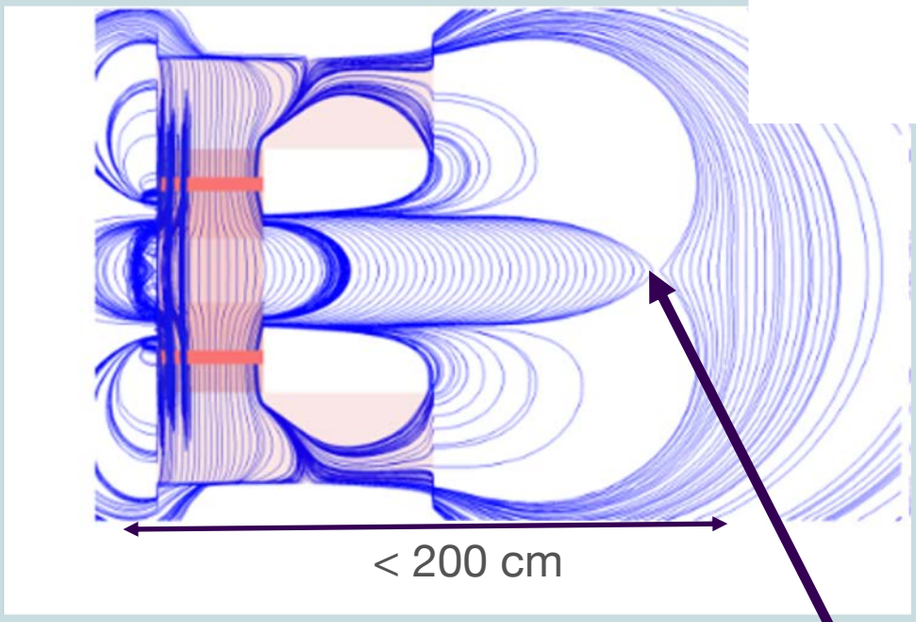
Construction ASG/Suprasys consortium of a SC dipole with special attention to the fringe field

Under construction in Genova → Shipment to CERN → LNGS



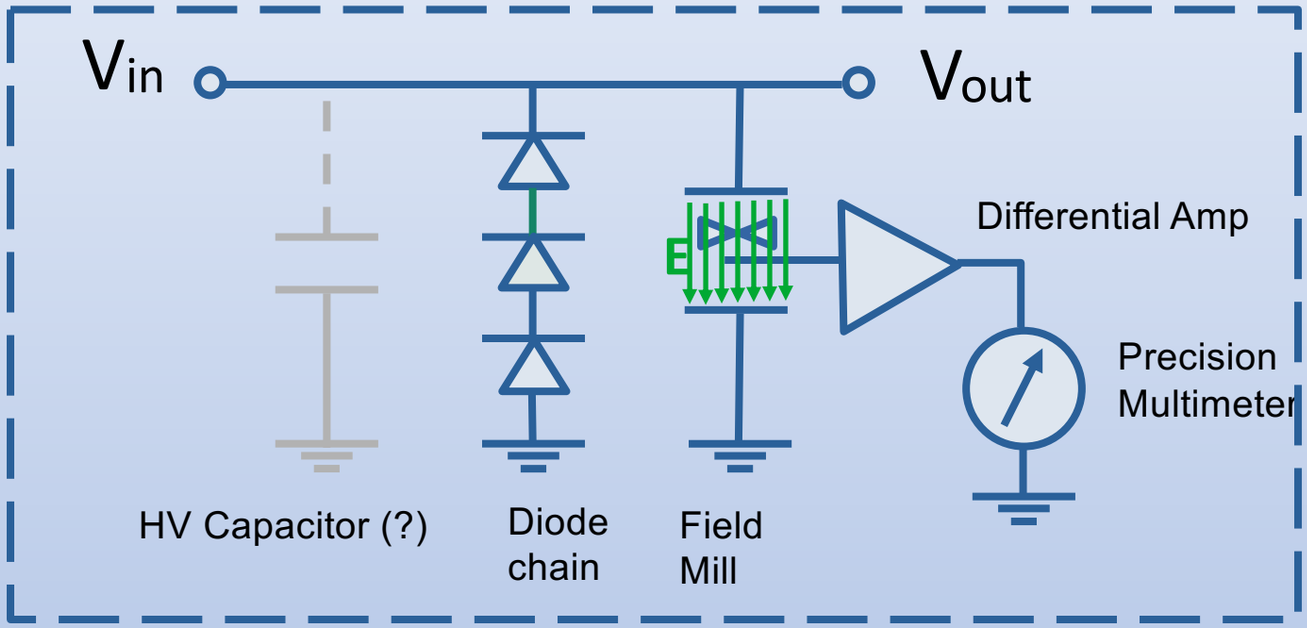
Low Power MgB_2 Superconducting Conduction-cooled Coils

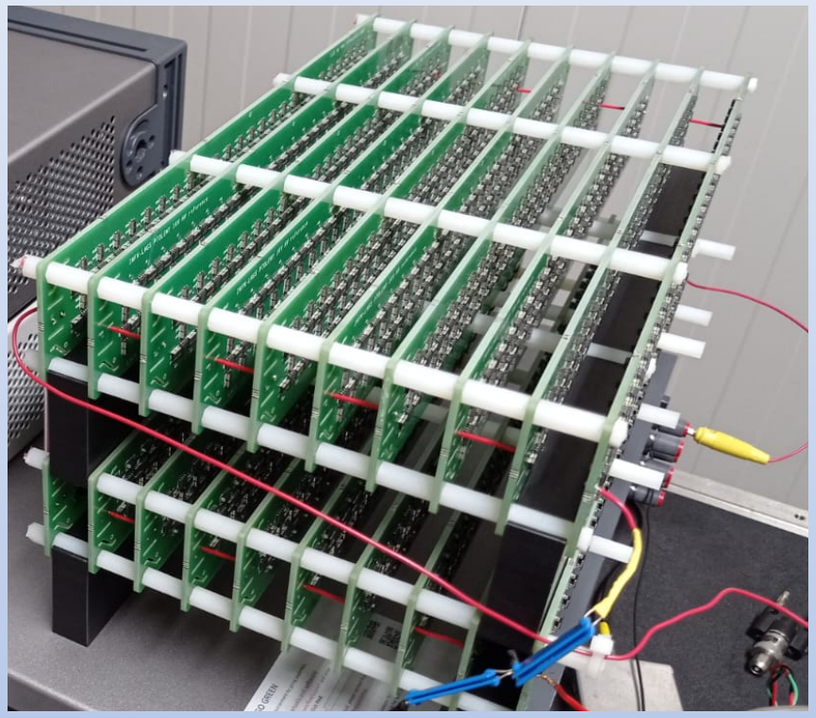
Simulated B-map



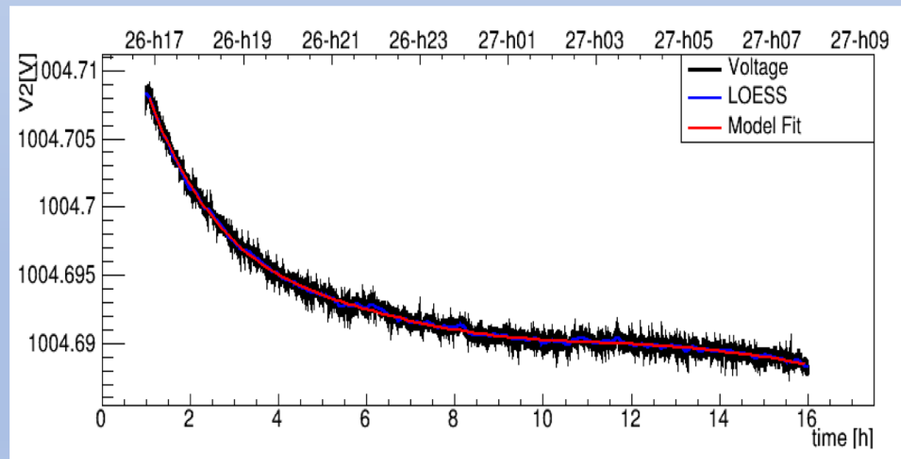
Zero B field saddle point key feature of the field map

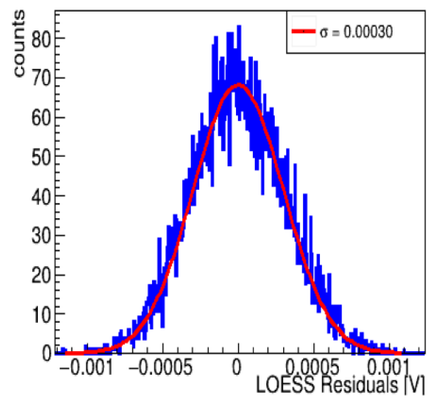
HV High precision stability (LNGS)

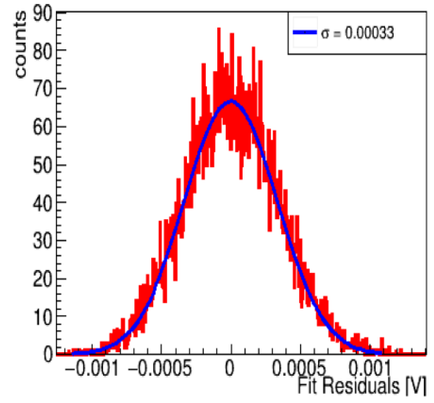




Climatic chamber - N_2







Single board (1 kV)

σ = 0.3 mV

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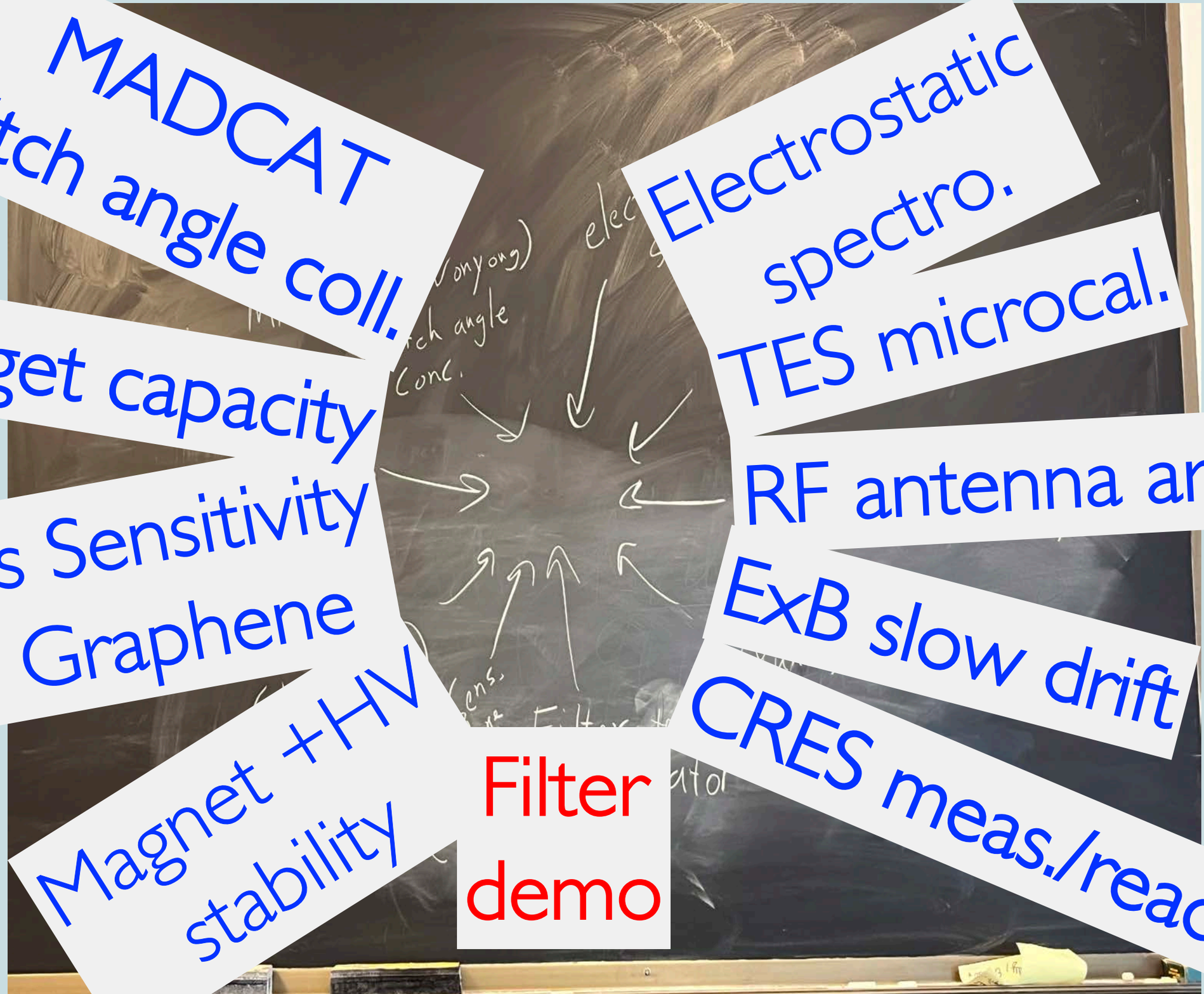
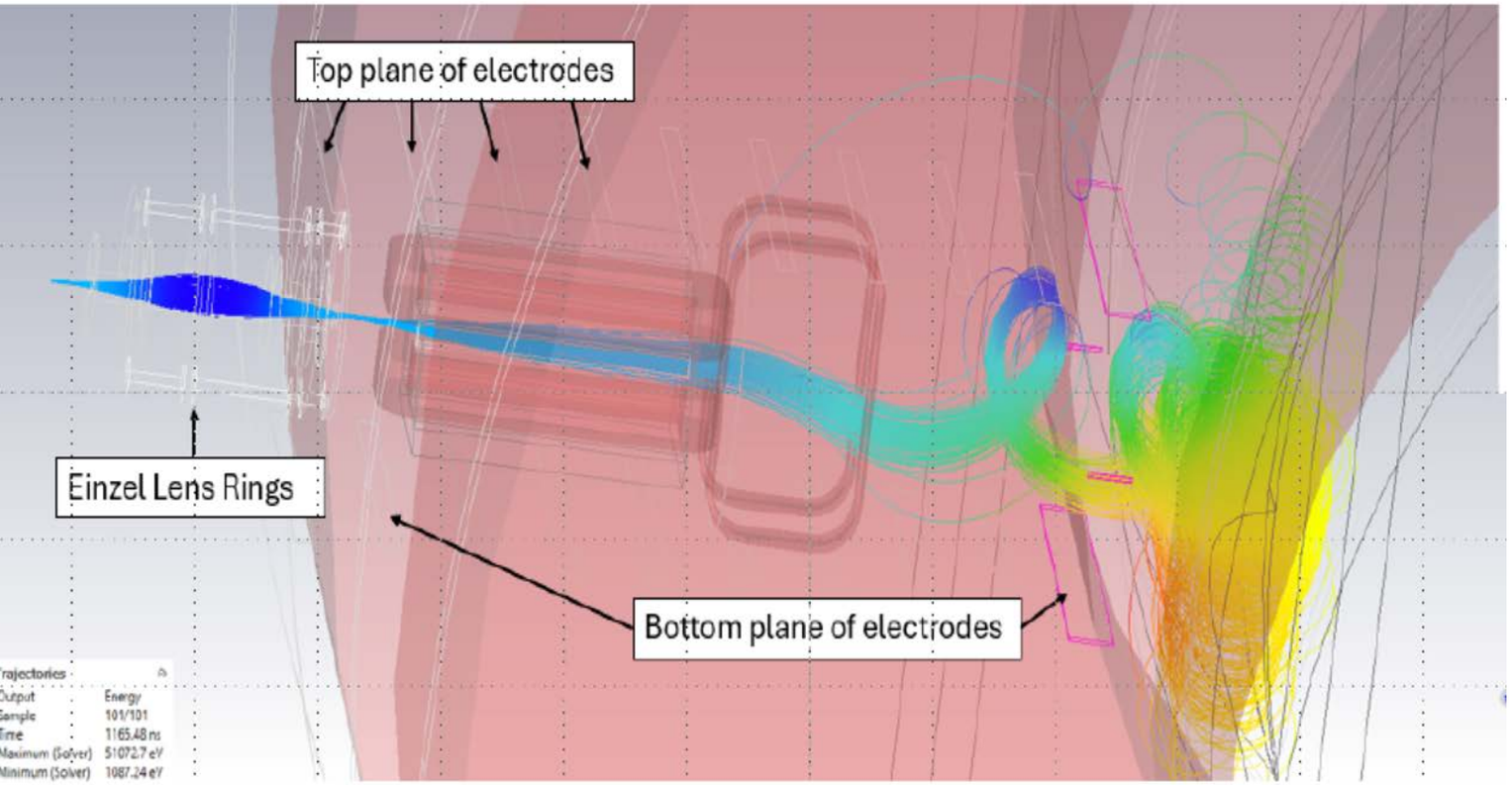
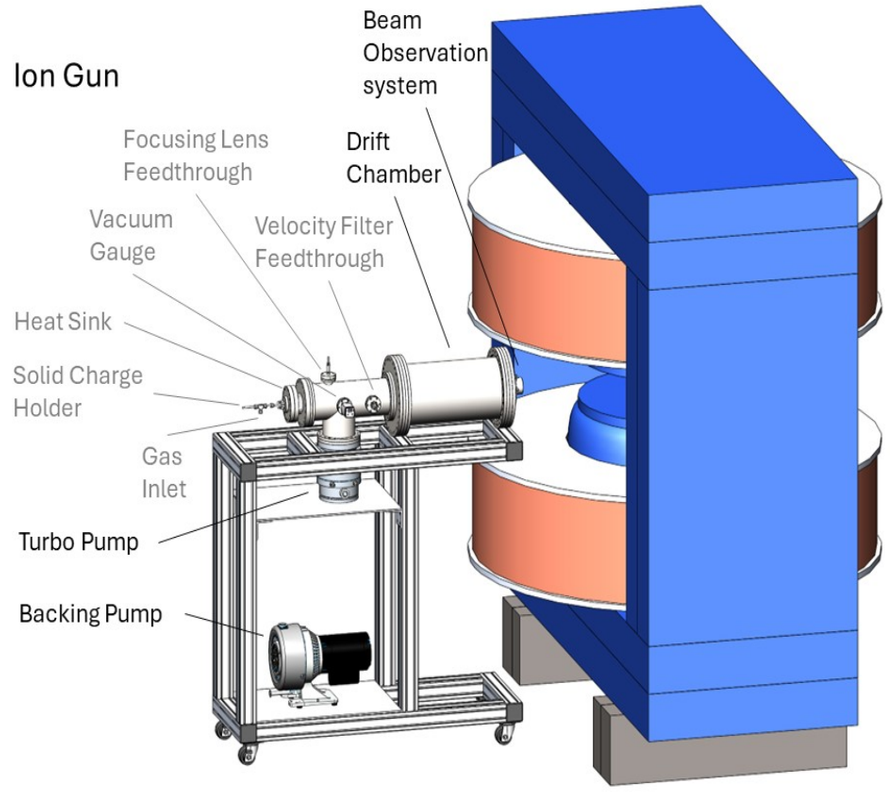
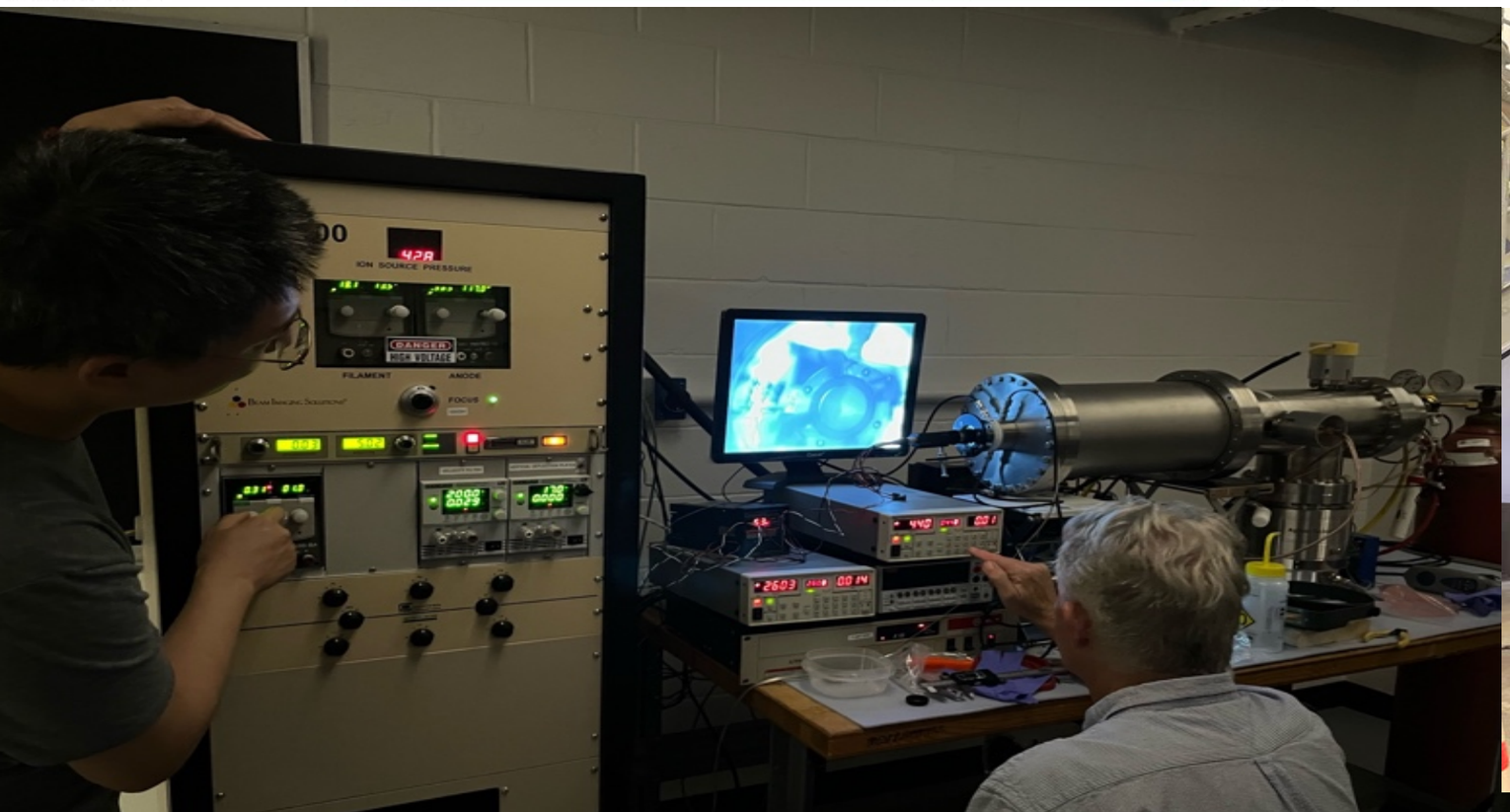


Filter Demo


Top plane of electrodes
Einzel Lens Rings
Bottom plane of electrodes
Trajectories
Output
Energy
Sample
101/101
Time
1165.48 ns
Maximum (Solver)
51072.7 eV
Minimum (Solver)
1087.24 eV


Ion Gun
Beam Observation system
Focusing Lens Feedthrough
Drift Chamber
Vacuum Gauge
Velocity Filter Feedthrough
Heat Sink
Solid Charge Holder
Gas Inlet
Turbo Pump
Backing Pump


ION SOURCE PRESSURE
DANGER
HIGH VOLTAGE
FILAMENT
ANODE
FOCUS

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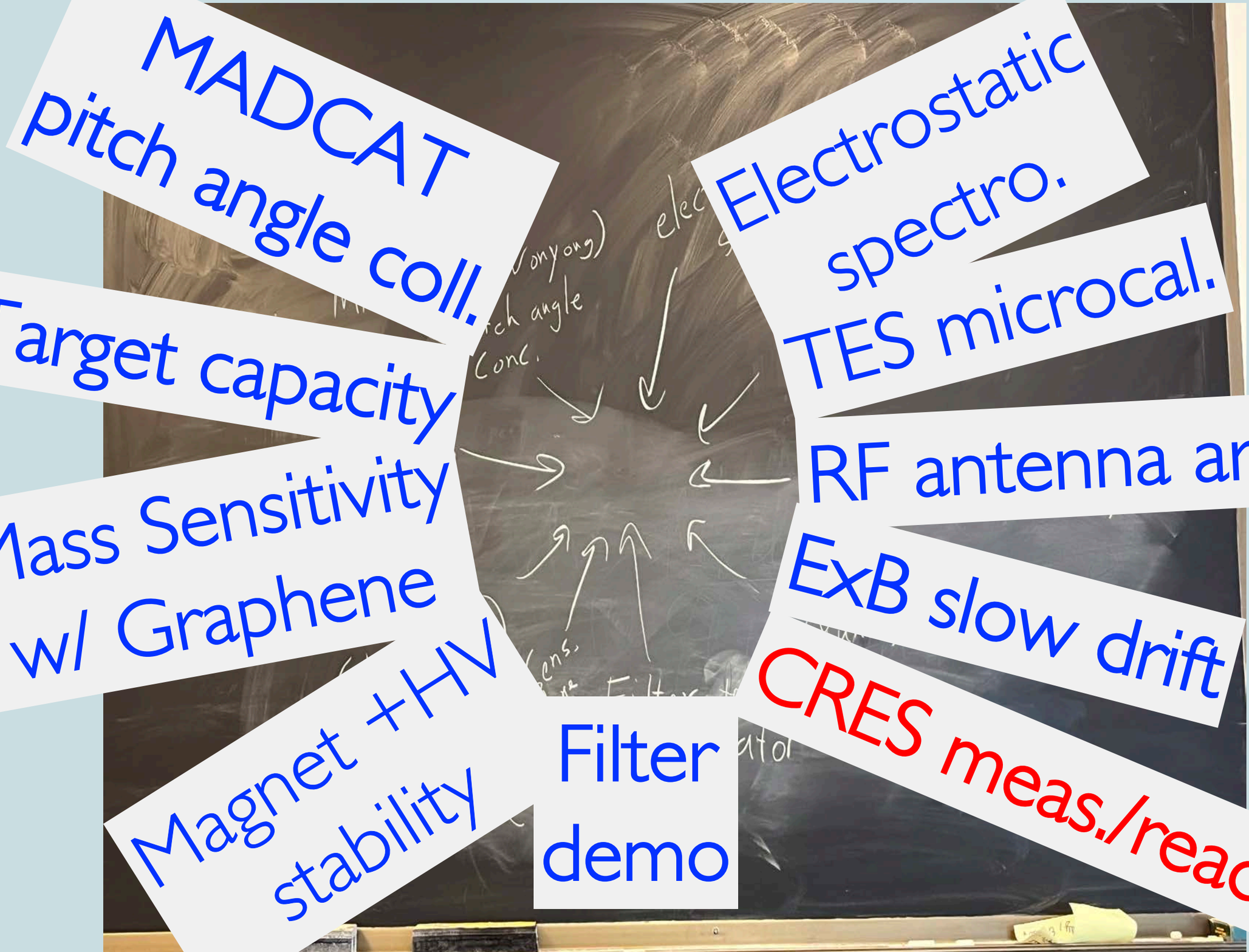
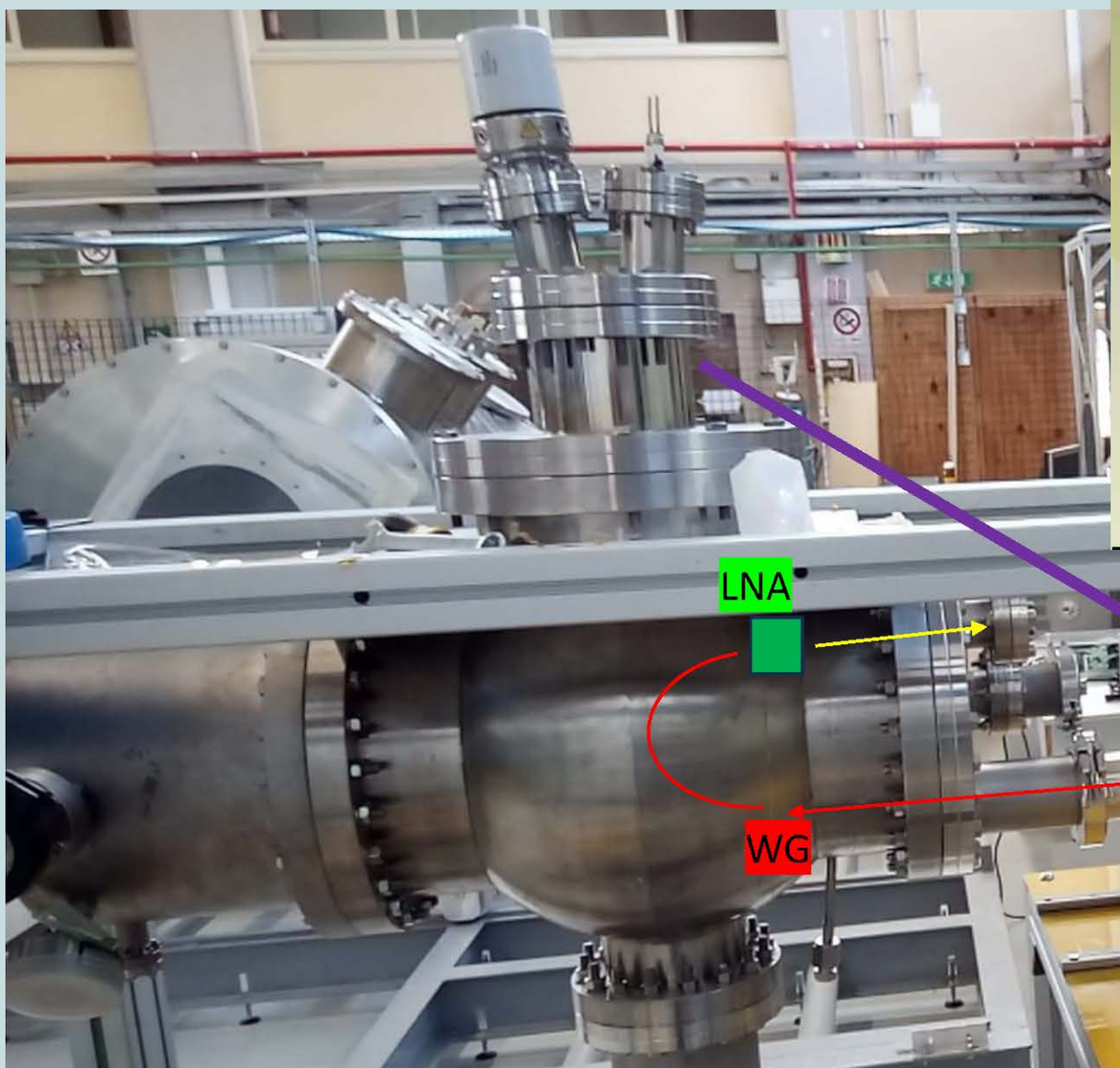
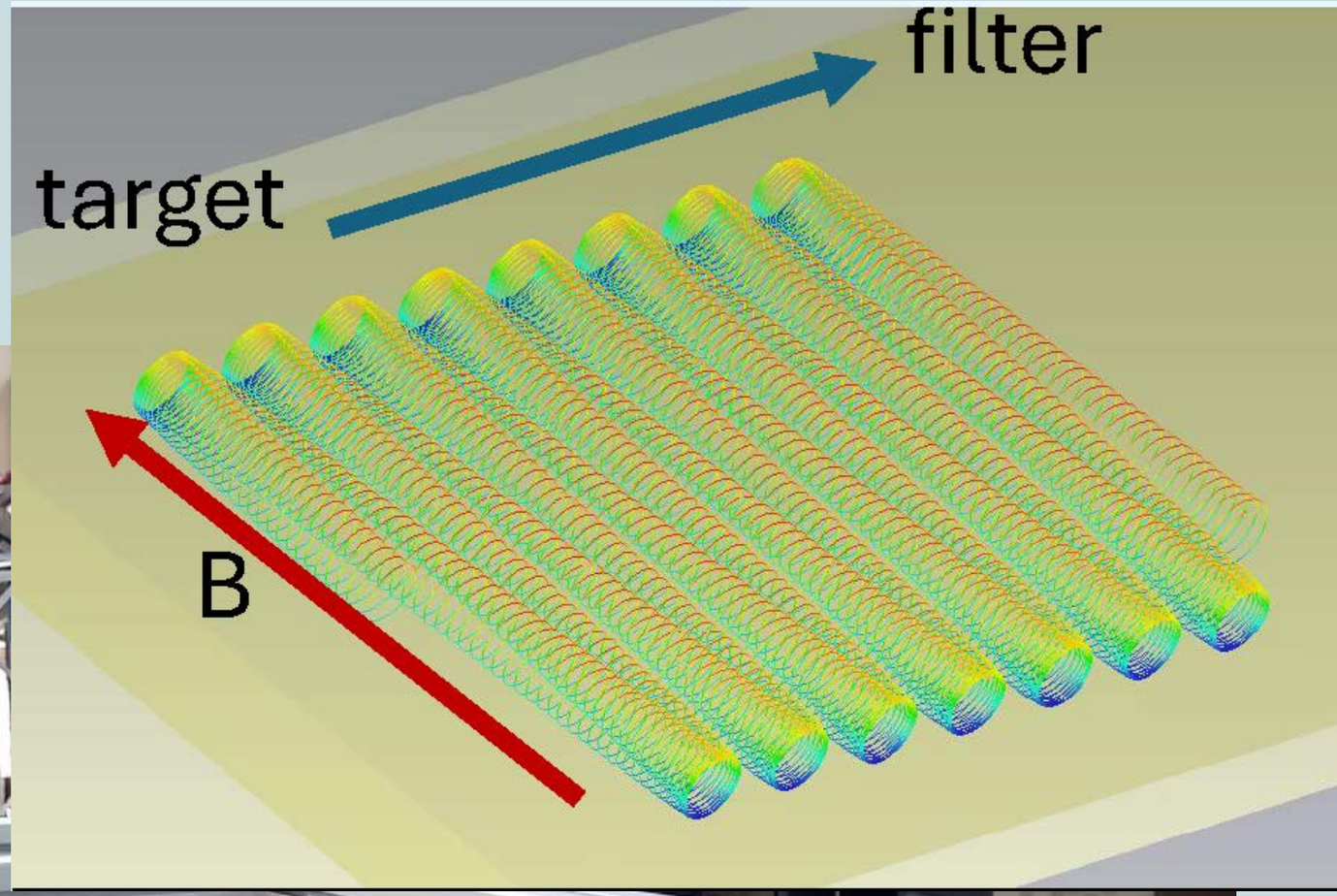


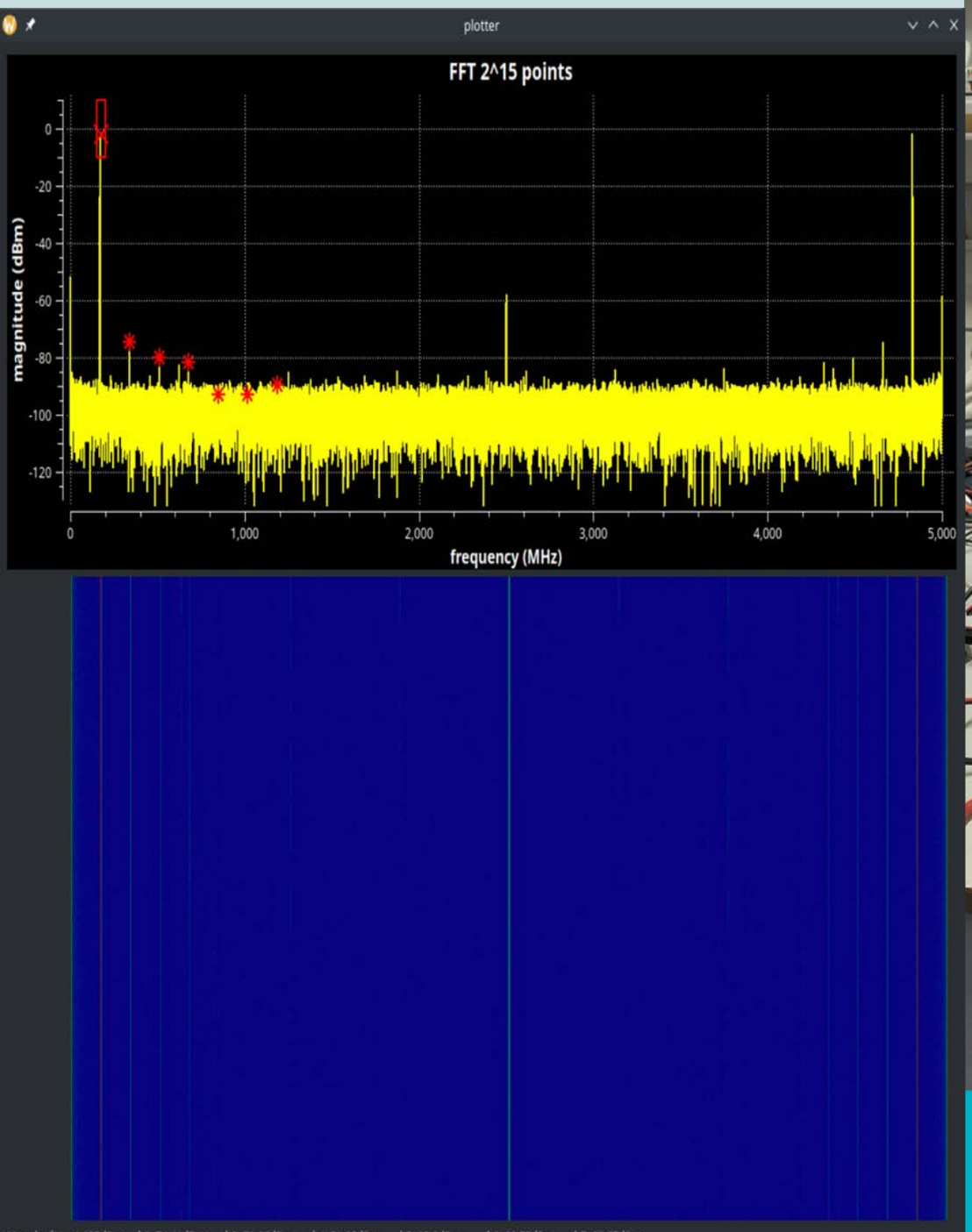
RF MEASUREMENTS
NON-DESTRUCTIVE ELECTRON TAG

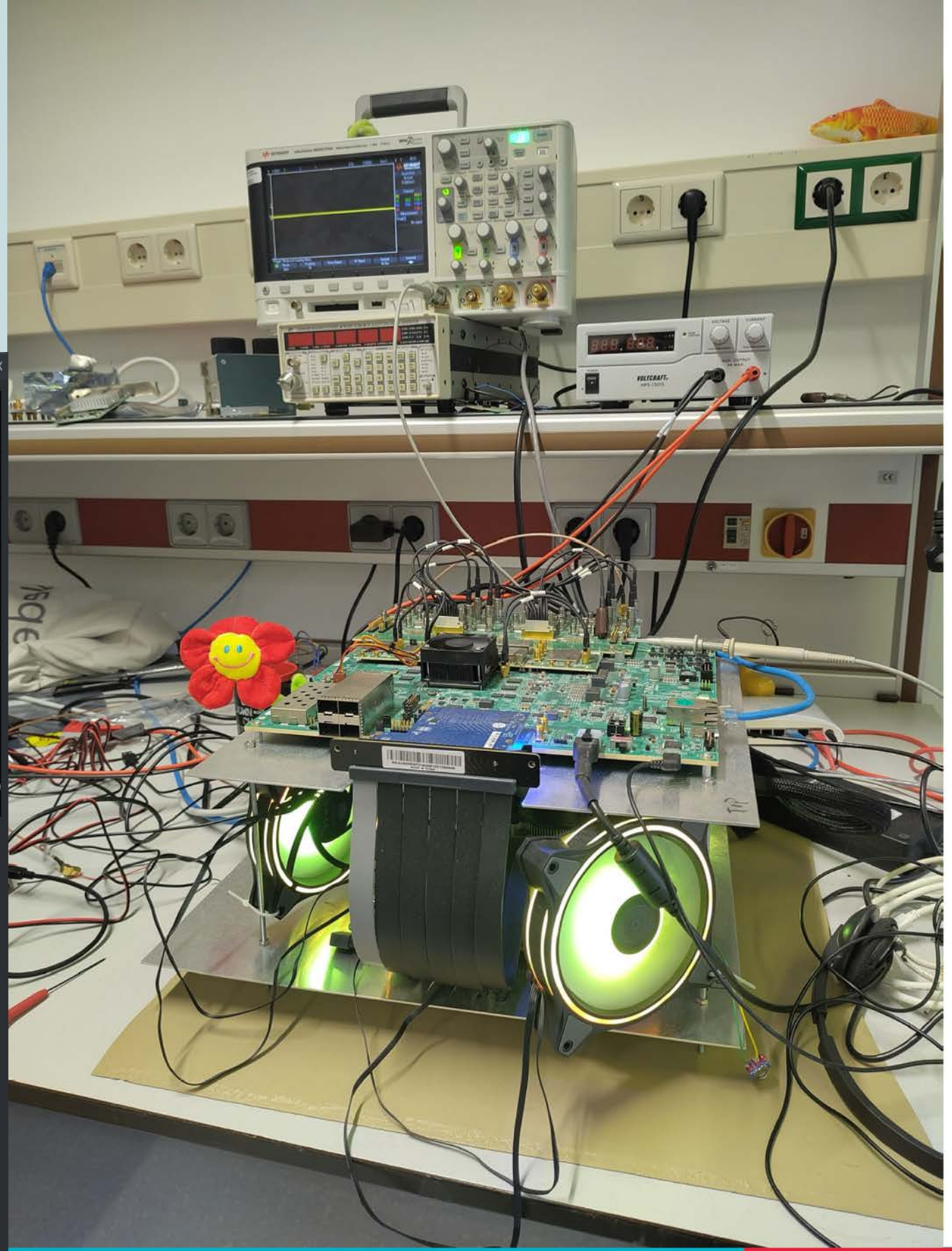
Can we detect the (semi-relativistic) electron on its way to the micro-calorimeter?





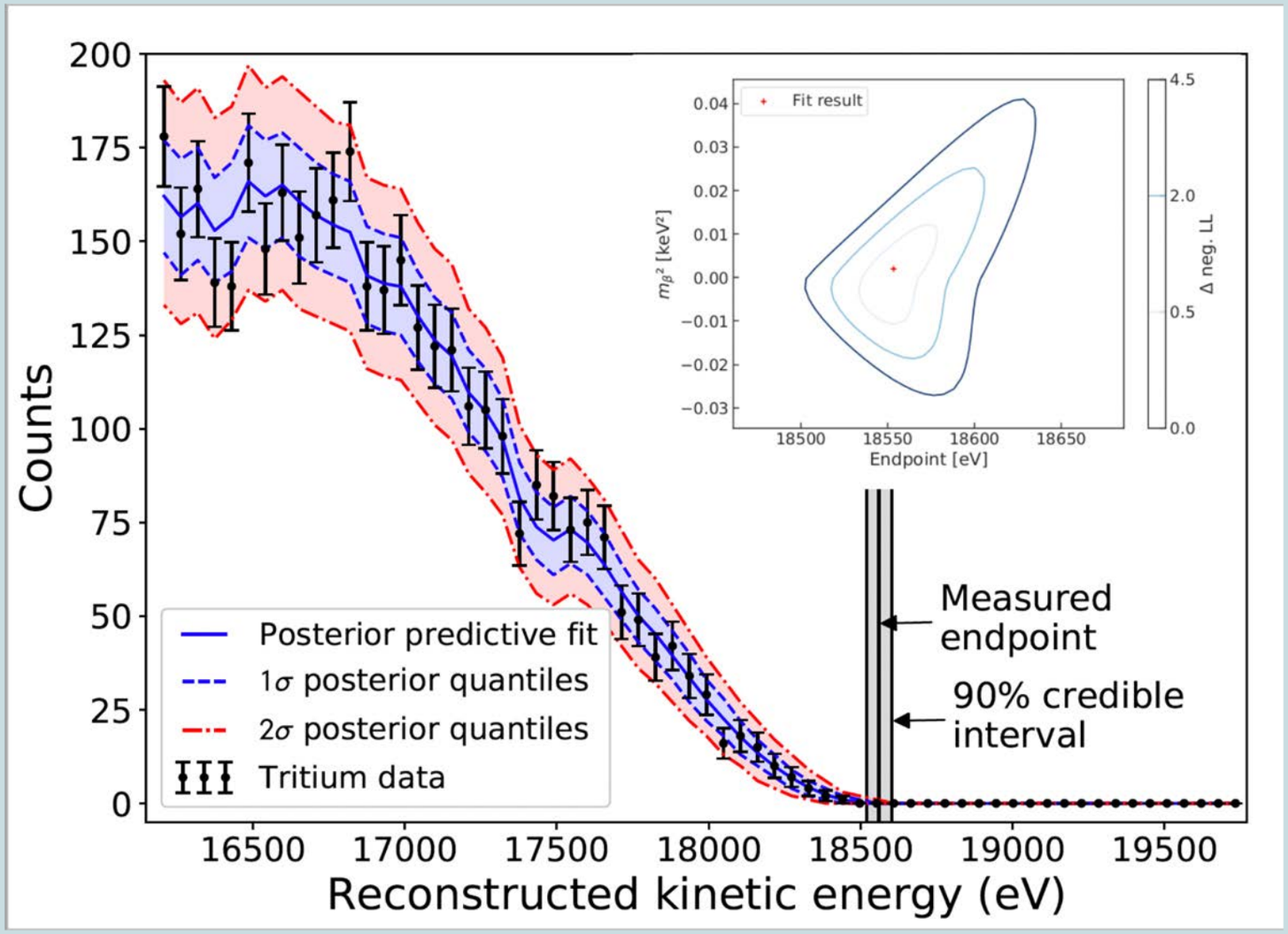
RF Readout





Nikhef

RECENT PROJECT 8 TRITIUM RF MEASUREMENT



https://arxiv.org/abs/2203.07349

RF measurement background levels extremely low.

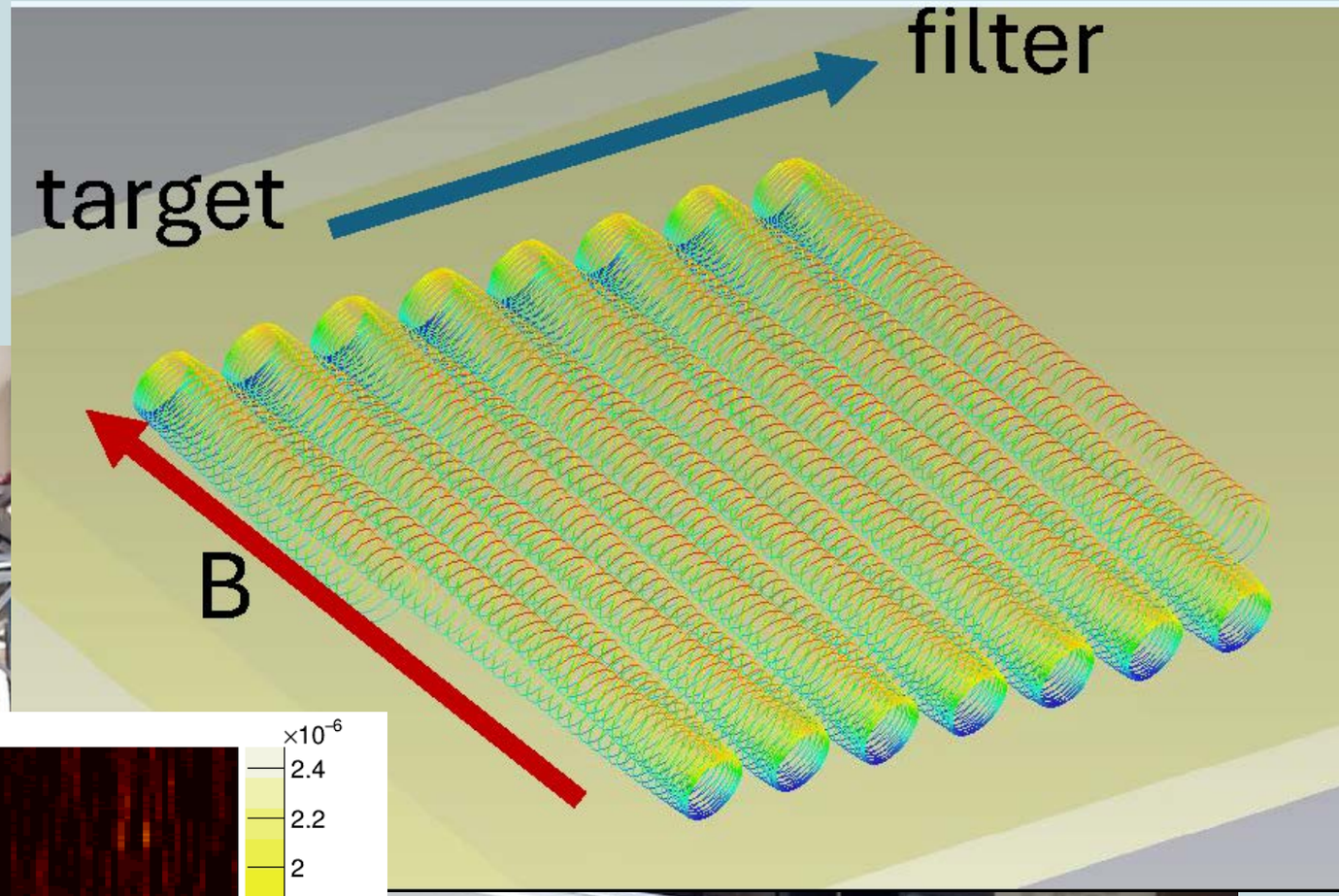
No events observed above endpoint,
Setting upper limit on background rate

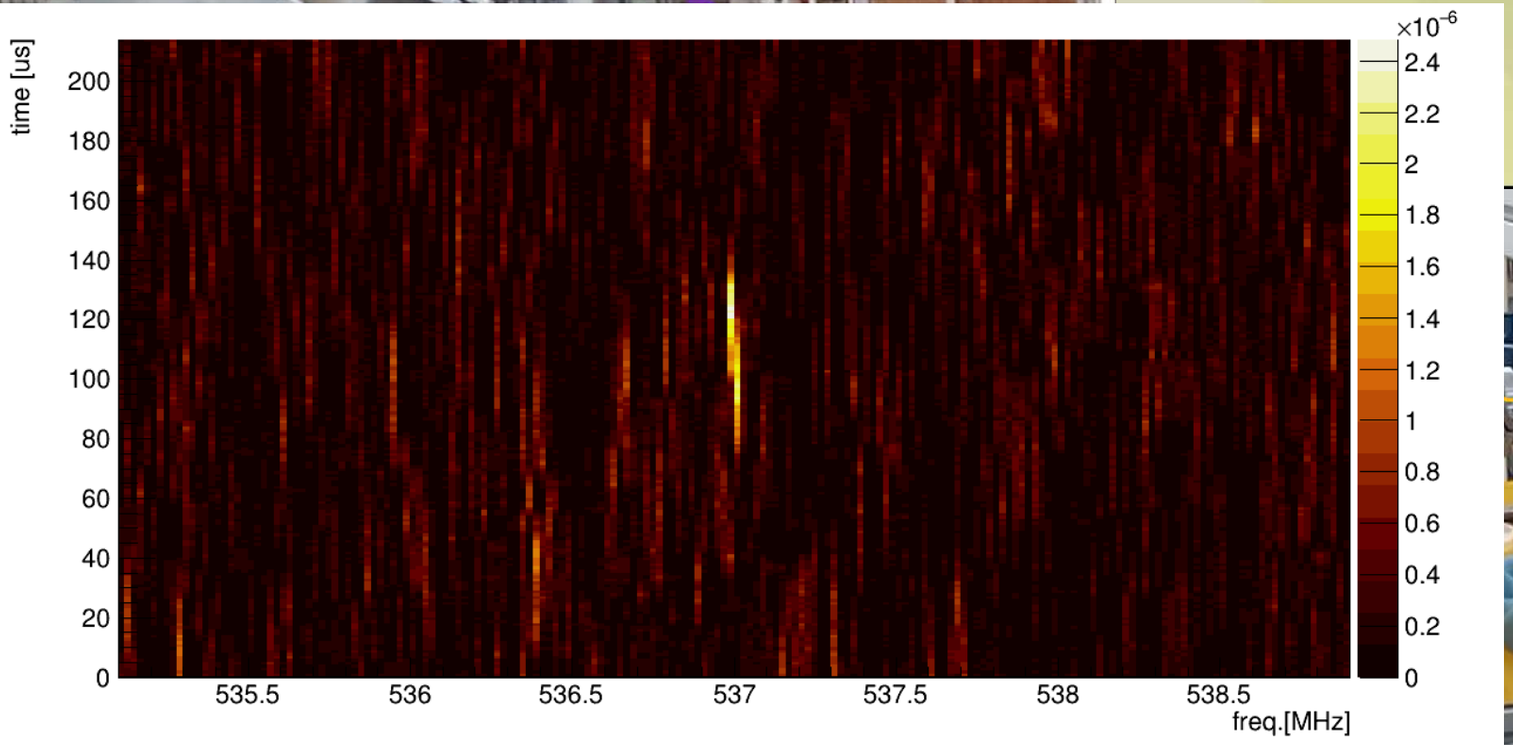
$< 3 \times 10^{-10}$ /eV/s (90% CL)

→ Background Rate
< 1 event per eV
in 100 years!

ACHIEVED!! RF MEASUREMENTS NON-DESTRUCTIVE ELECTRON TAG

Can we detect the (semi-relativistic) electron on its way to the micro-calorimeter?





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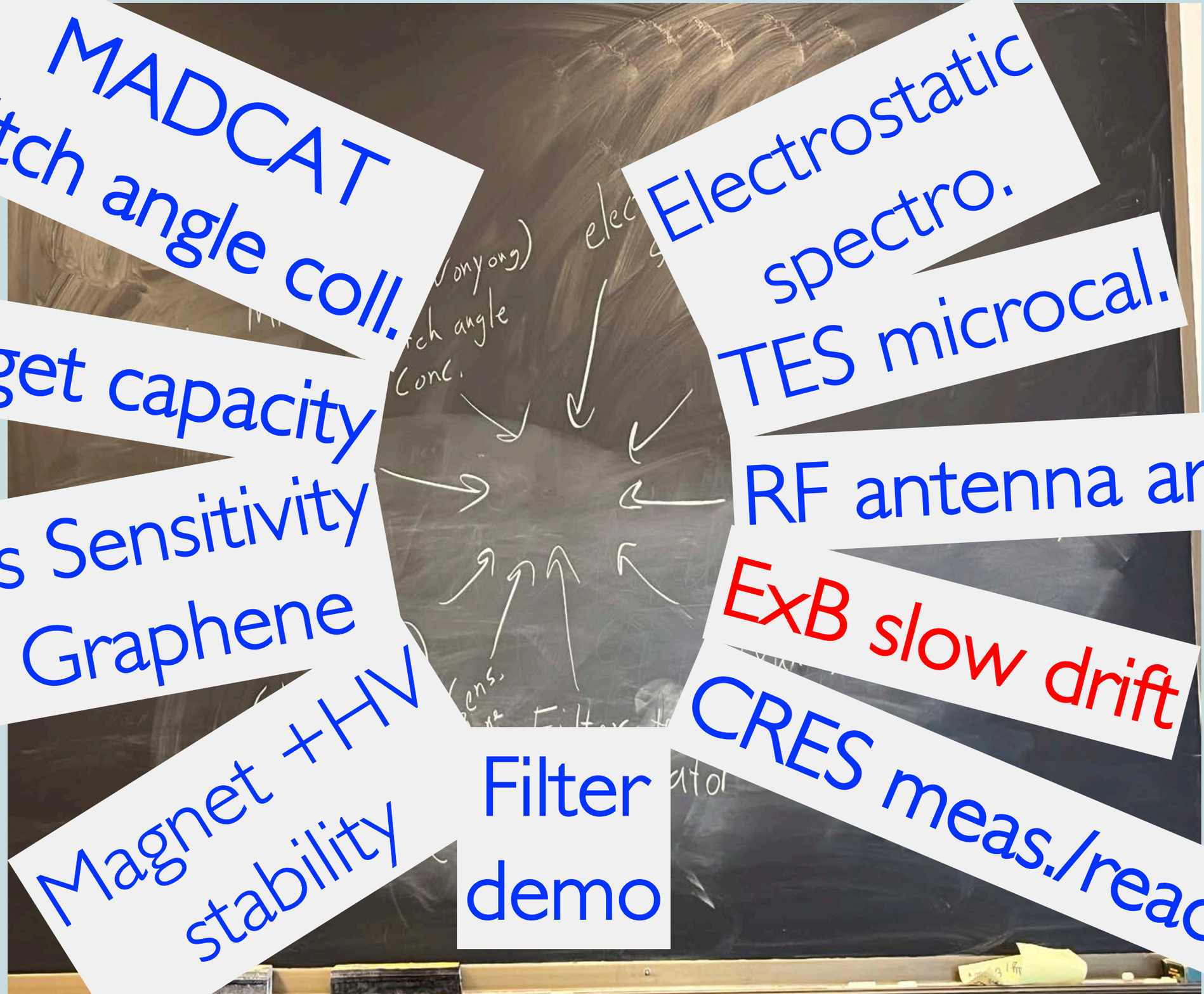
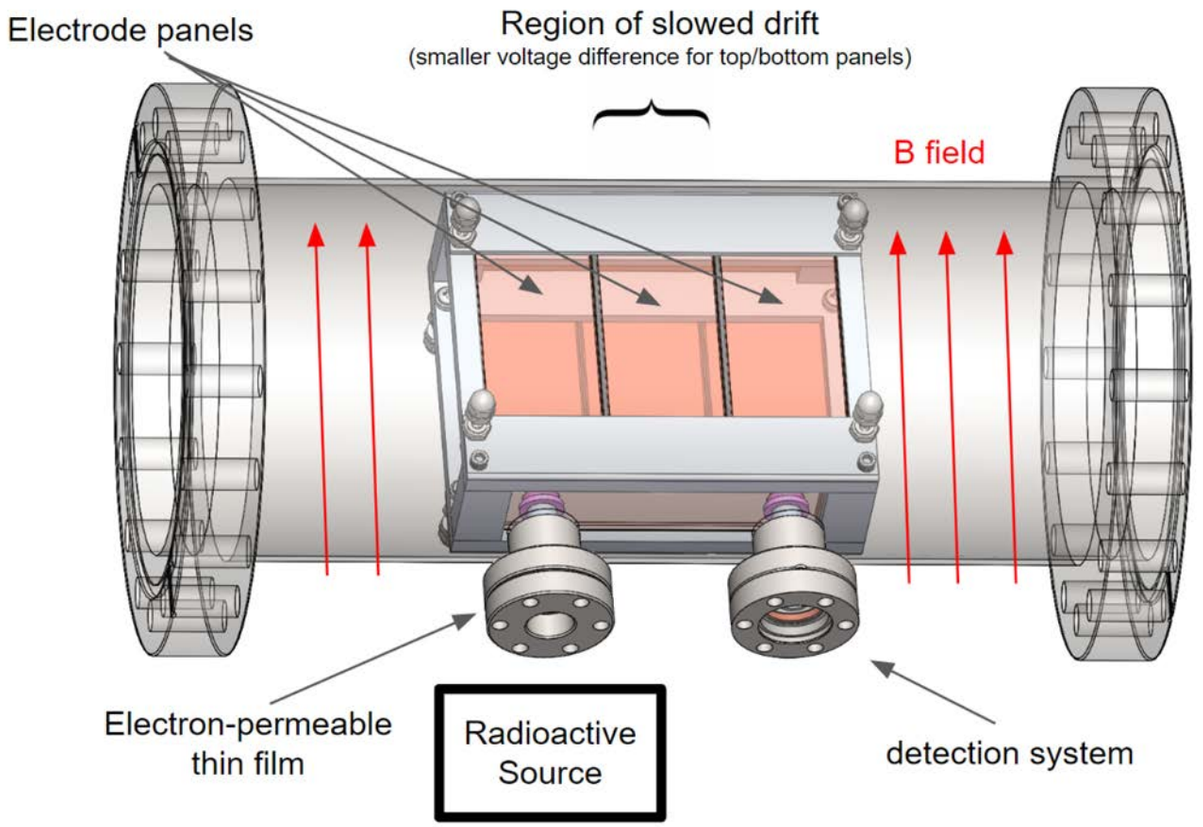
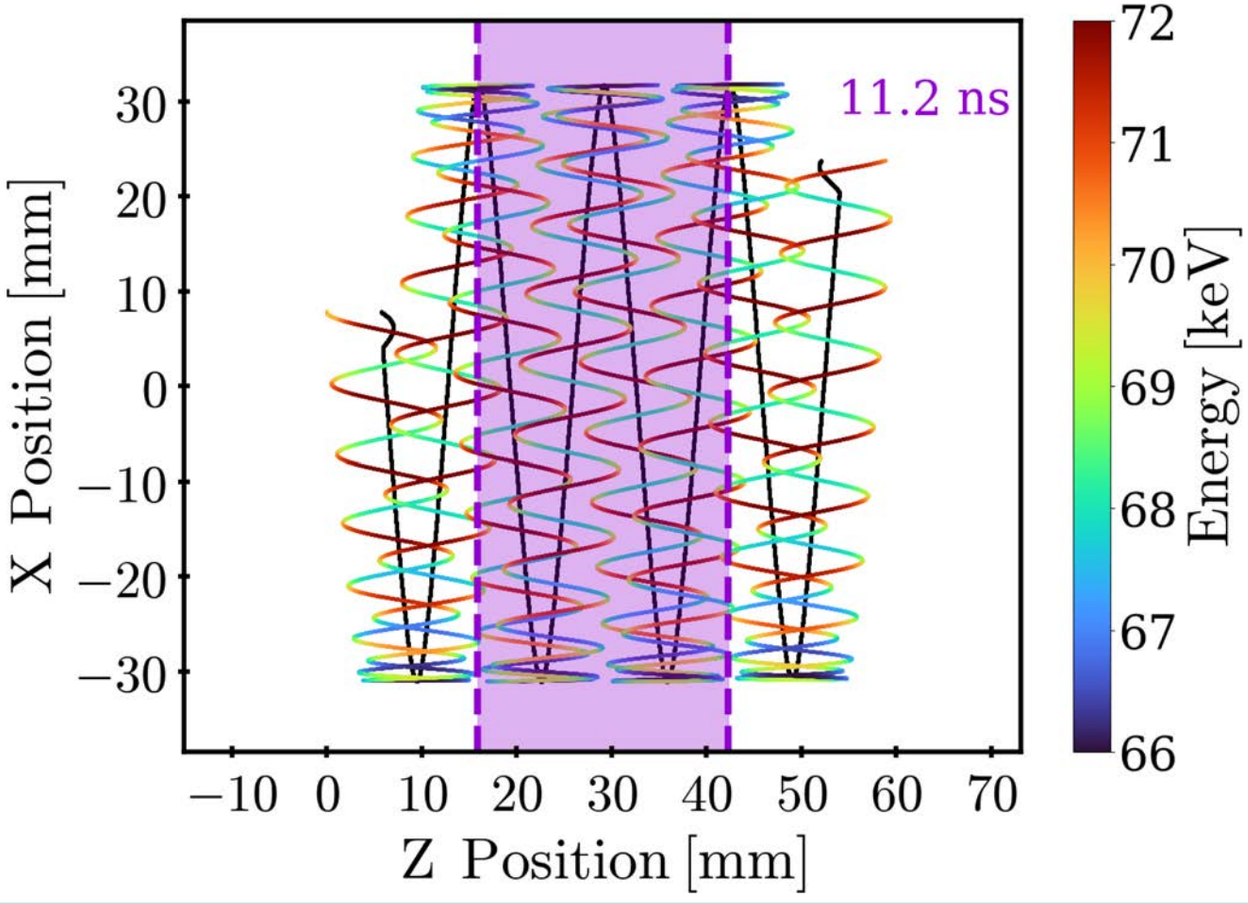
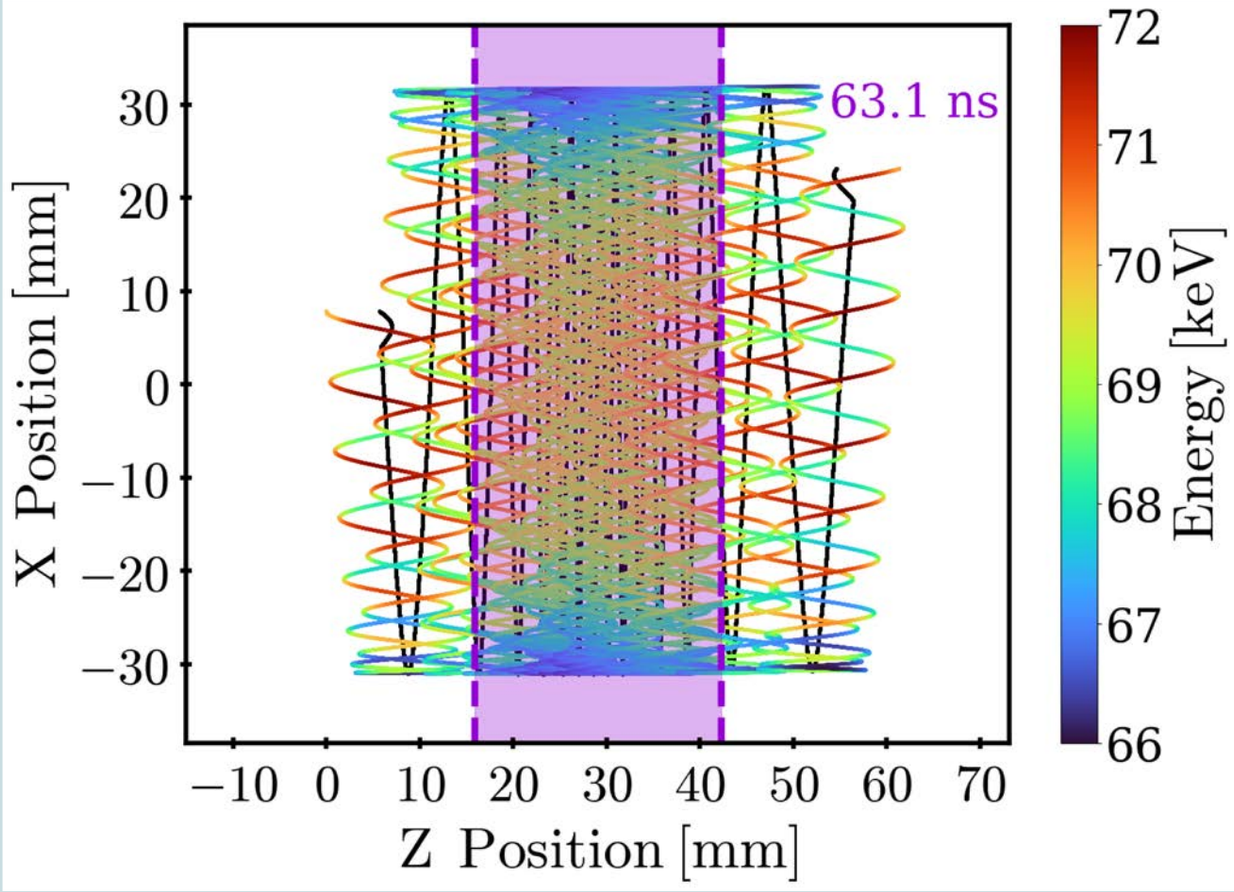


ExB Slow Drift







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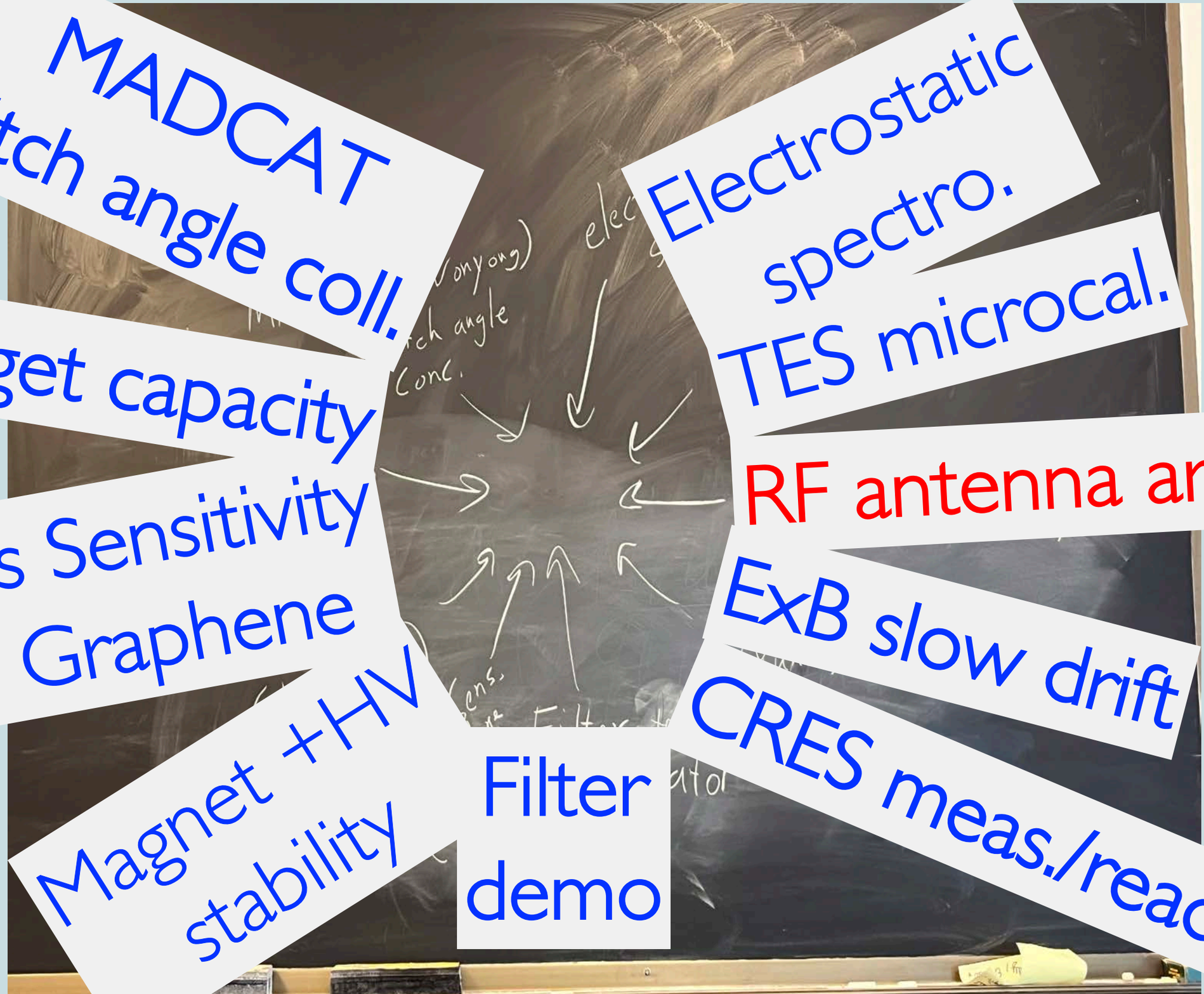
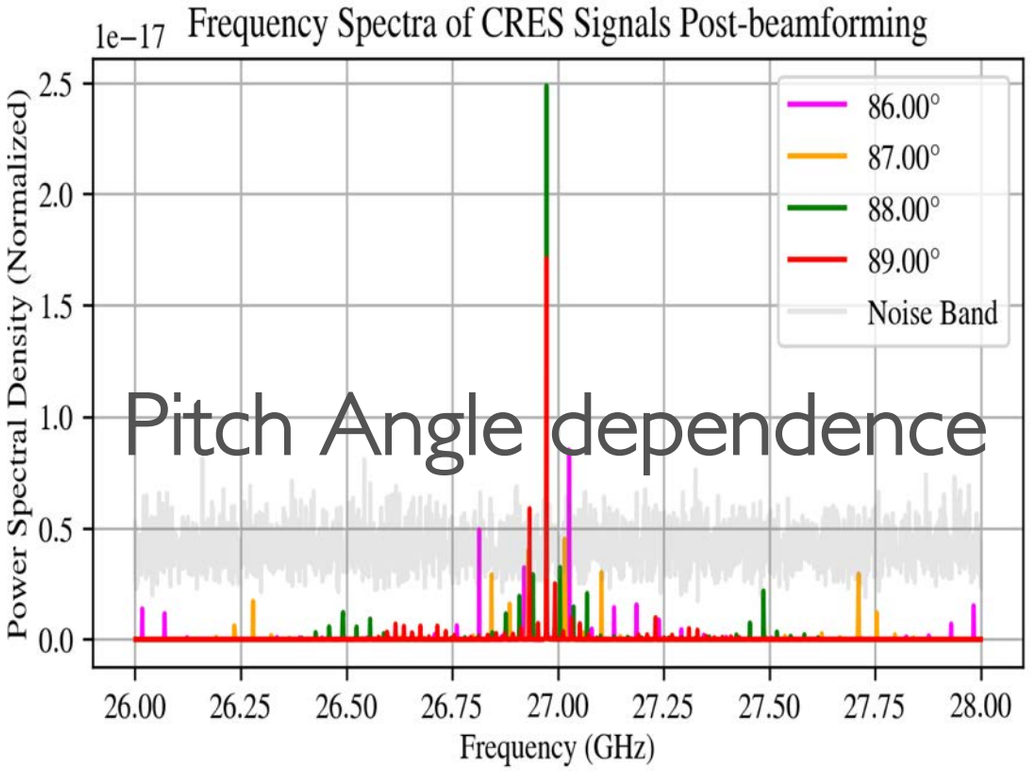
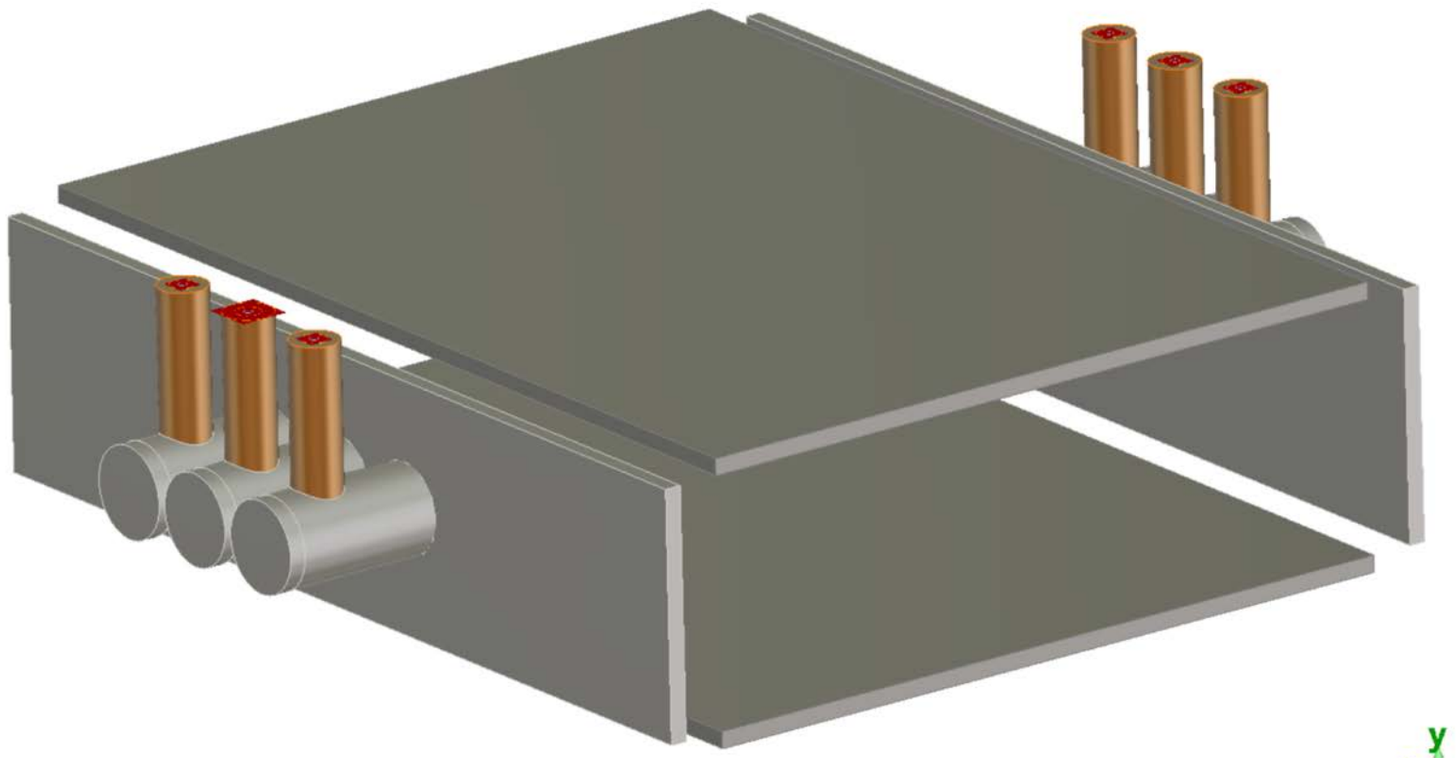
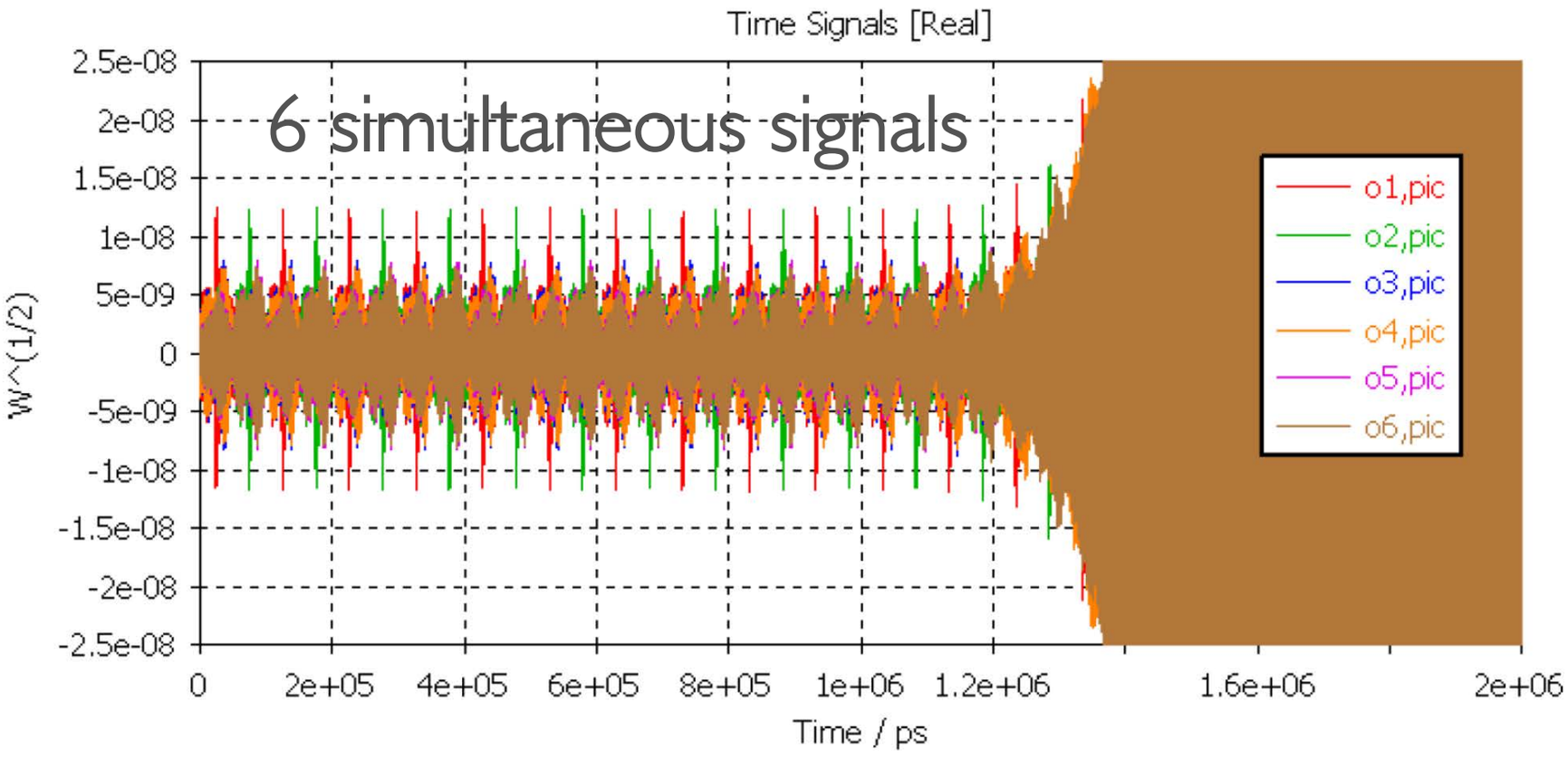


RF Antenna Array

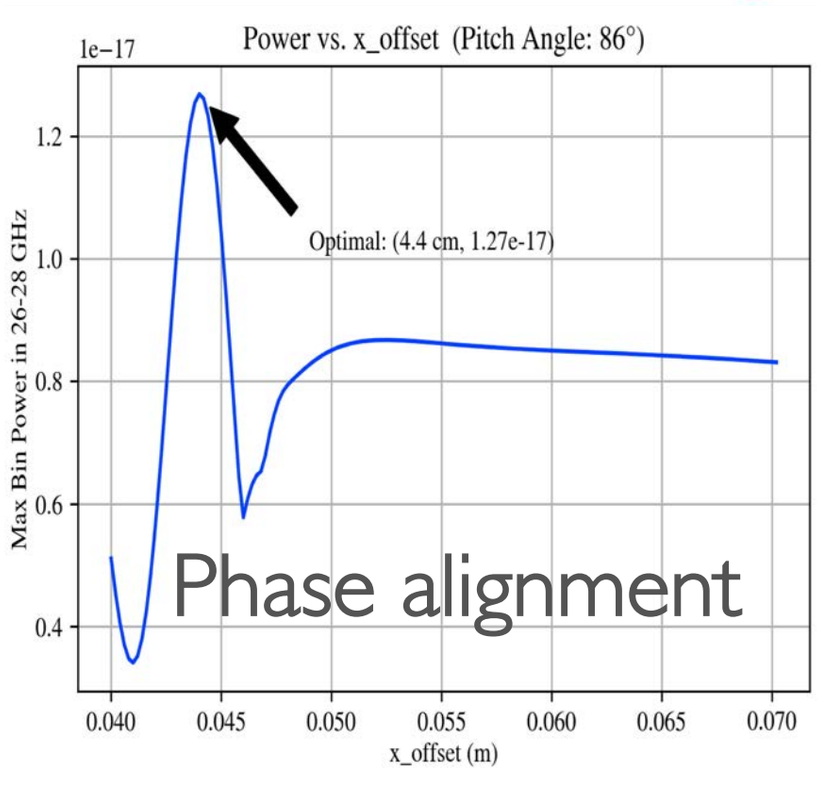


Pitch Angle dependence



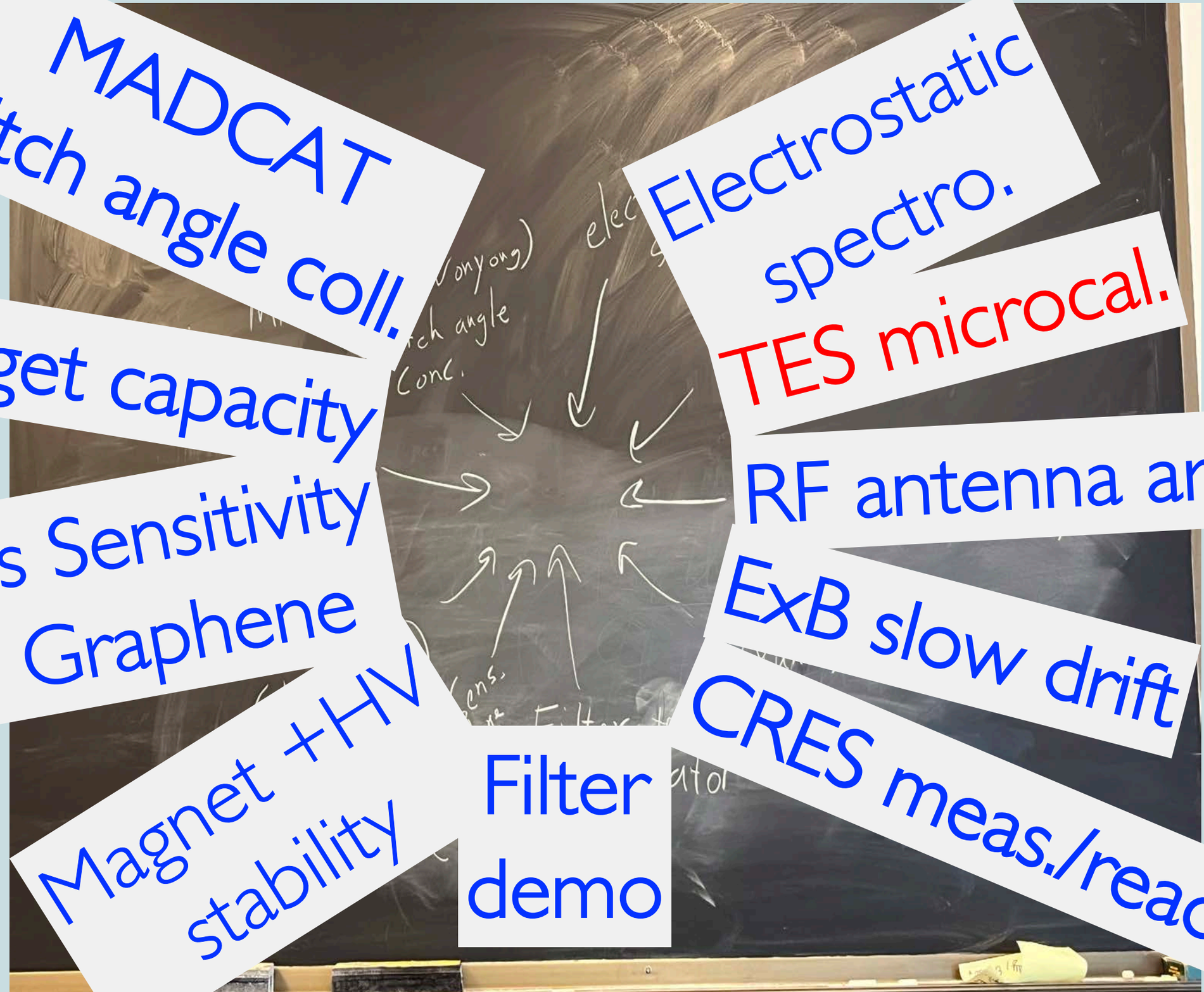


6 simultaneous signals

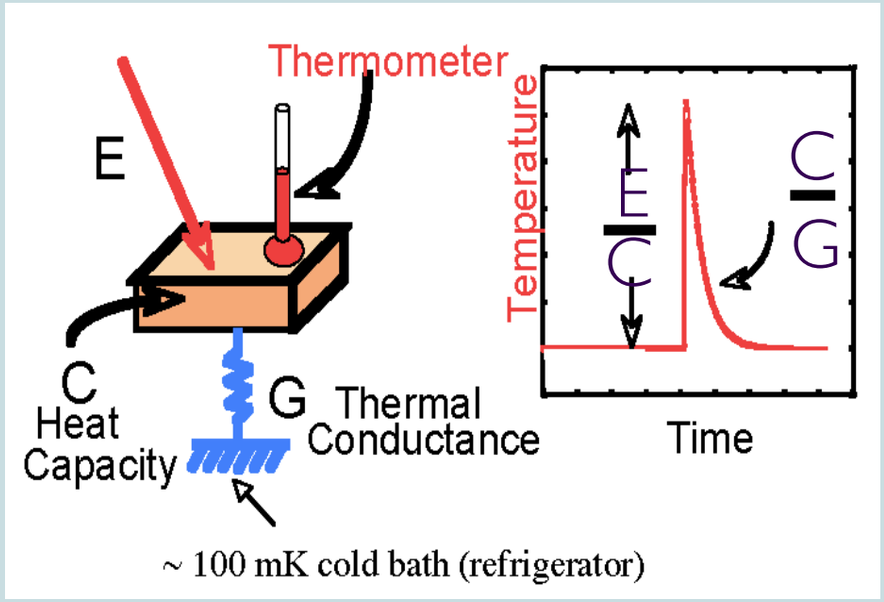


Phase alignment

Where are we?
And where are we headed?



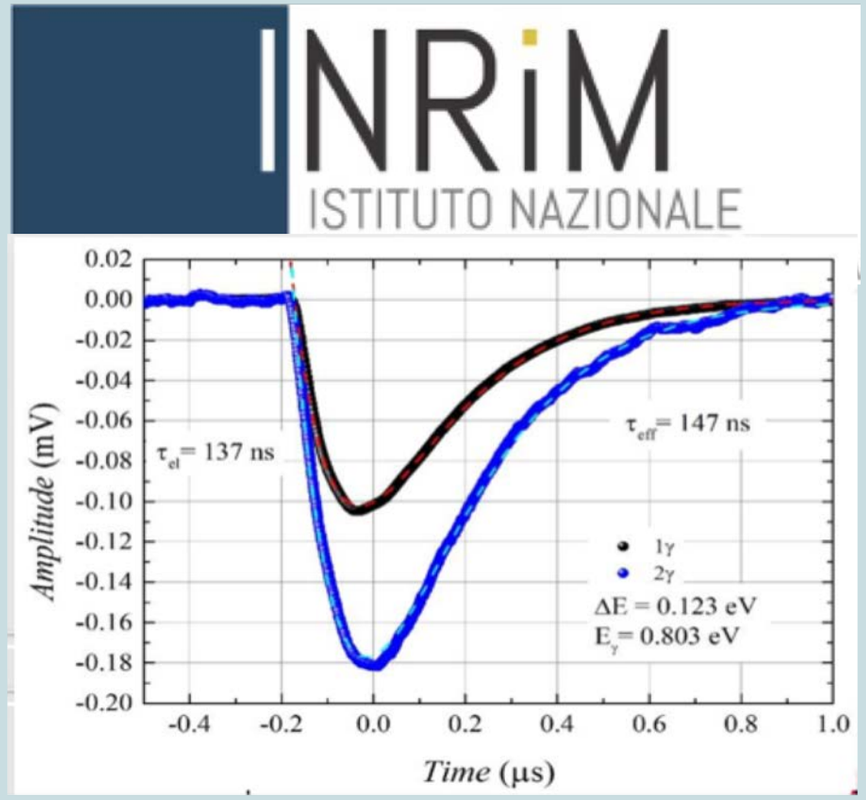
MICRO-CALORIMETER



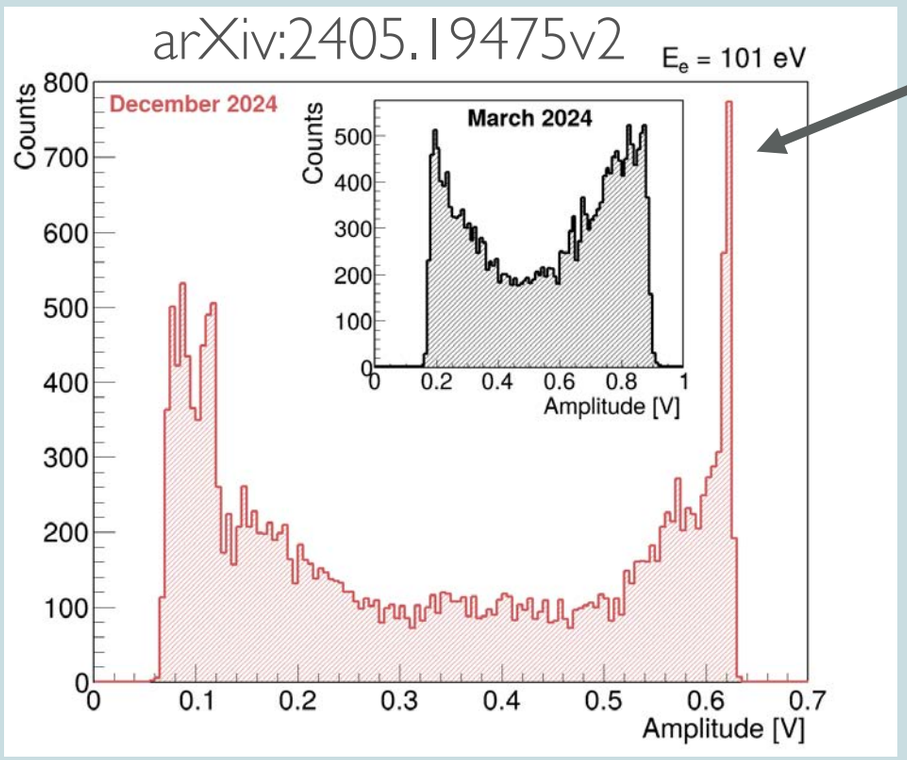
Design Goal (PTOLEMY): ΔE_{FWHM} = 0.05 eV @ 10 eV

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

ΔE_{FWHM} = 0.022 eV @ 0.8 eV

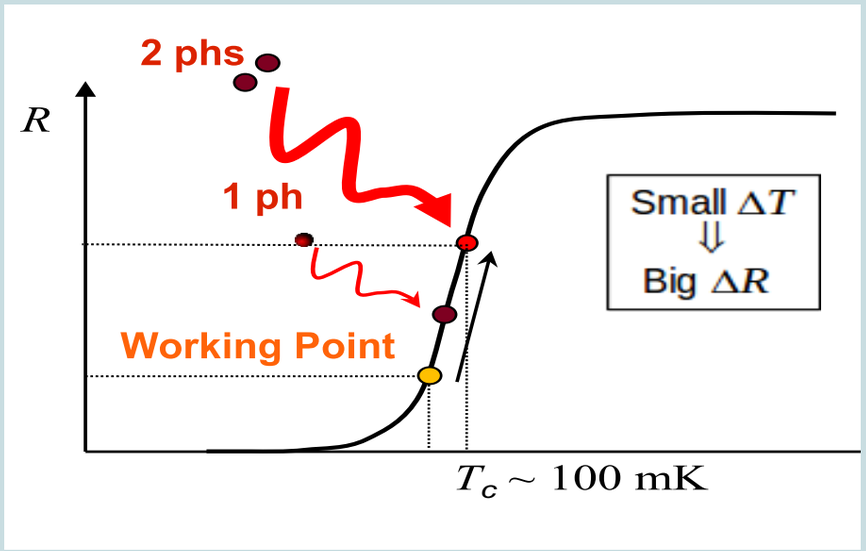


Based on the expertise of the INRiM important results have been achieved on electron measurement with TES.
Key elements of the measurements: performing TES and new e-source based on nanostructures

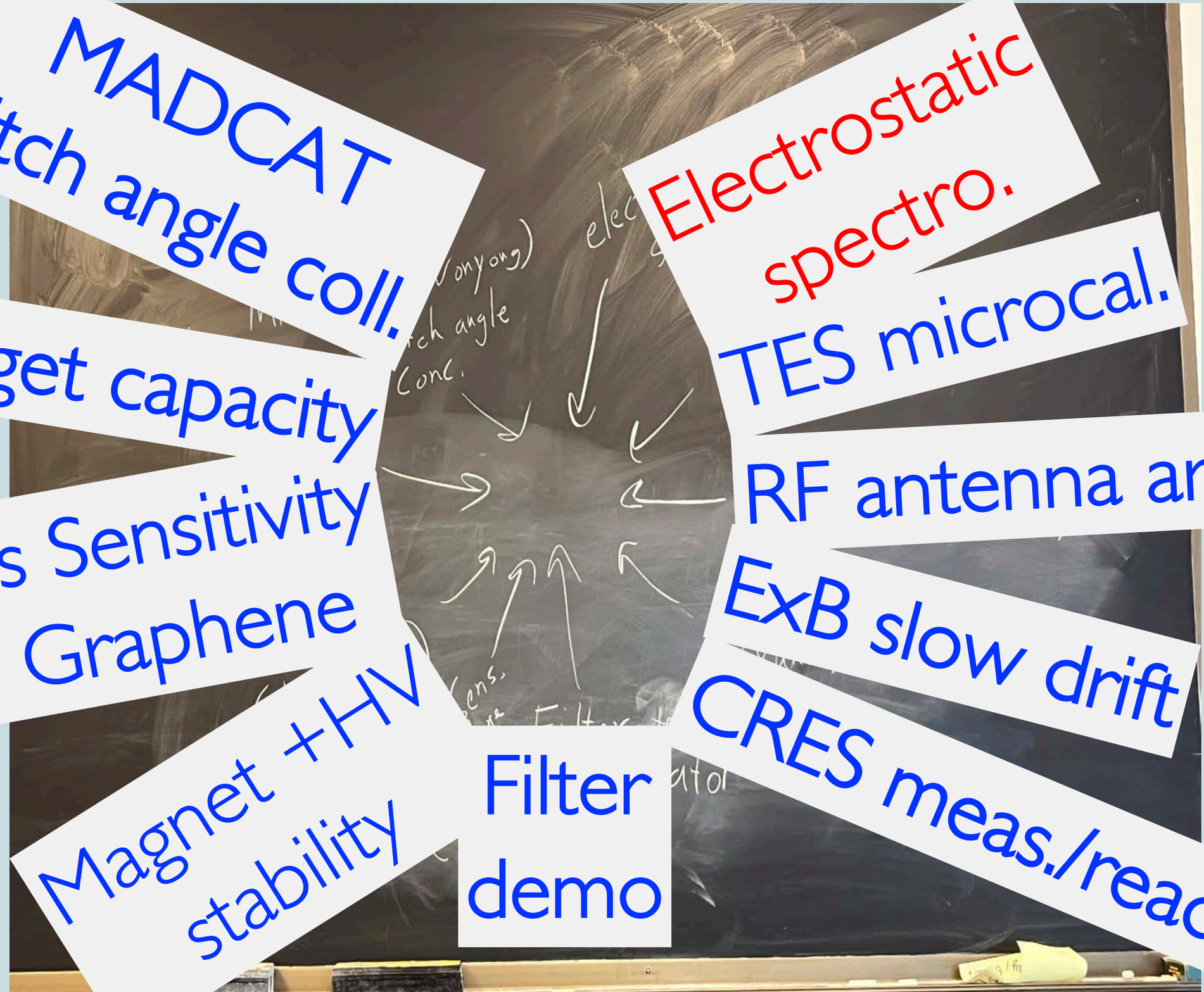


First measurement of electrons
at 100 V with resolution of ~1-1.5 eV

Best in the World!

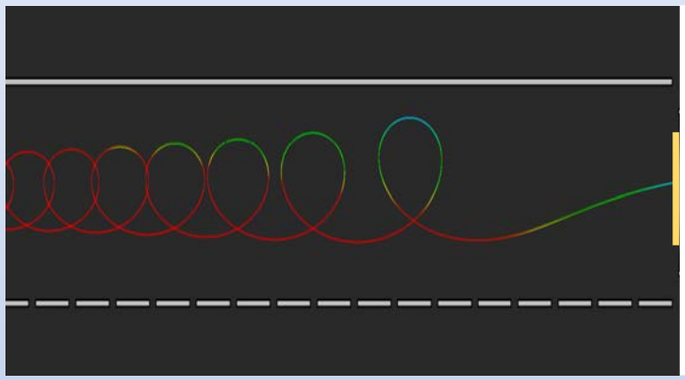


Where are we?
And where are we headed?

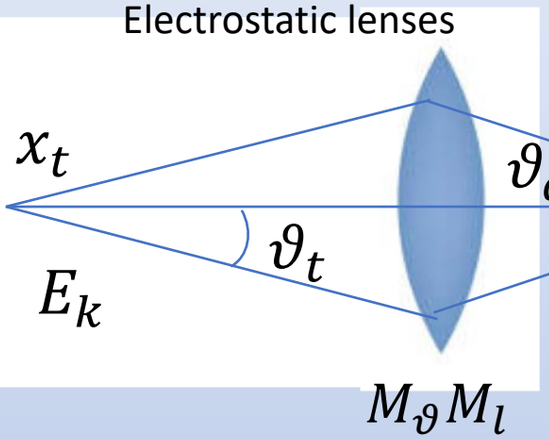


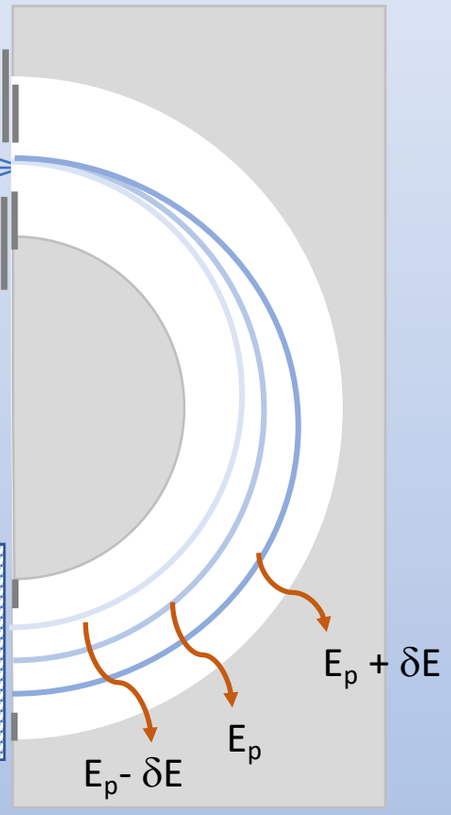
Precision energy measurement from Condensed Matter/ARPES

Electostatic analyser

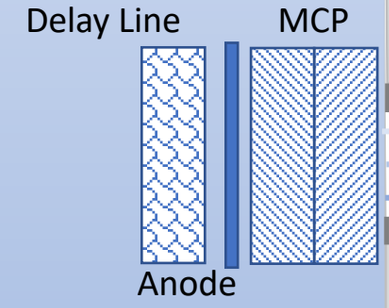


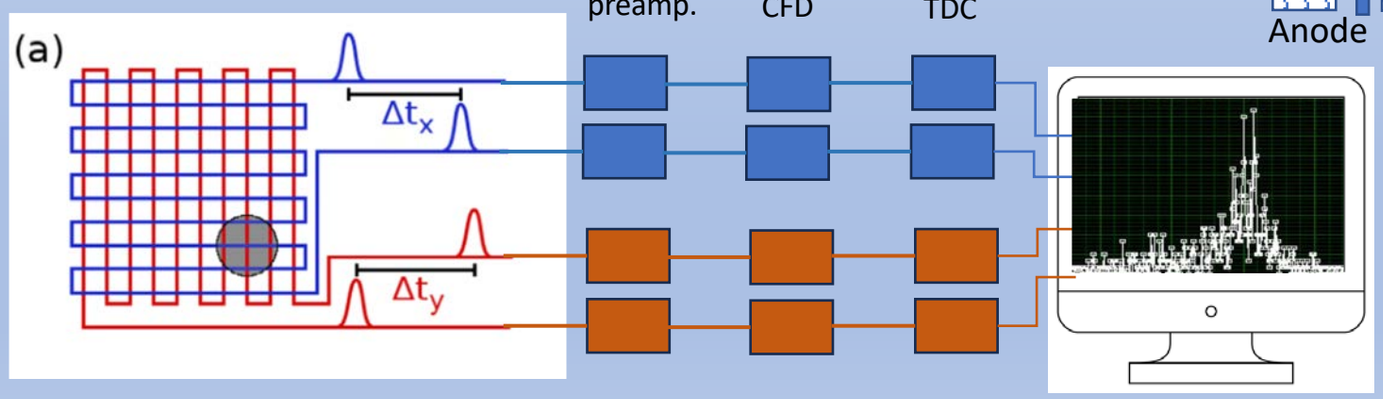
Ptolemy e.m. filter





Position sensitive detector (MCP+delay line) allows parallel acquisition





Specs Phoibos 225

Electron optic basic equation

Helmholtz – Lagrange law

$$x_t \vartheta_t \sqrt{E_k} = x_a \vartheta_a \sqrt{E_p}$$

Two concentric hemispheres for the energy selection

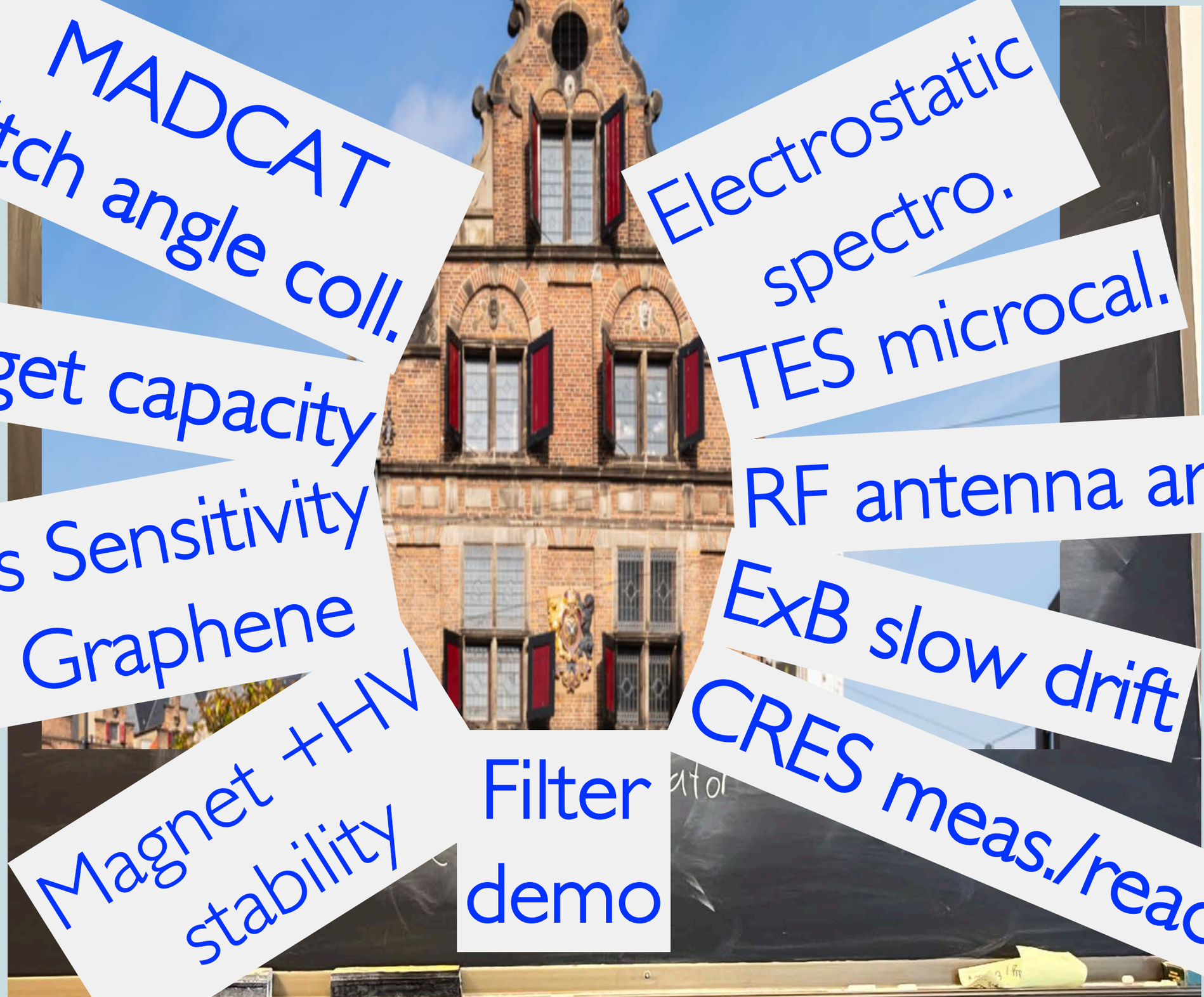
Energy resolution (bandpass energy):

$$\frac{\Delta E}{E_p} = \frac{x}{2R_0} + \frac{\vartheta^2}{4}$$

ΔE: energy resolution
E_p : pass energy
x: slit width
R_0: mean radius
θ: accepted angle

~few meV energy resolution

The Waag for ν neutrino mass



MADCAT pitch angle coll.

Electrostatic spectro.

TES microcal.

Target capacity

Mass Sensitivity w/ Graphene

RF antenna arrays

ExB slow drift

Magnet +HV stability

Filter demo

CRES meas./readout

CONCLUSION

- PTOLEMY's goal is to eventually detect the cosmic neutrino background
- The detector prototype will be ready at LNGS by the end of this year
- Prototype baseline option is: T embedded on graphene; New concept EM filter; electron energy resolution measured in several steps (SDD/electrostatic spec/TES). Ultimately operating with sub-eV energy resolution.
- Ultimate goals of the Demonstrator: instrumented mass ~ hundreds of μg, energy resolution 50-100 meV, T storage solution will come from optimization of atomic T support structure. Time scale 5 years.
- "Intermediate" physics program of Demonstrator: neutrino mass measurements (or limits) beyond what has been achieved by all previous experiments.
- Submitted letter of intent to European Strategy for Particle Physics 2026 (#28)
- Submitted LOI to INFN CNS-II

The PTOLEMY Collaboration

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BACKUP