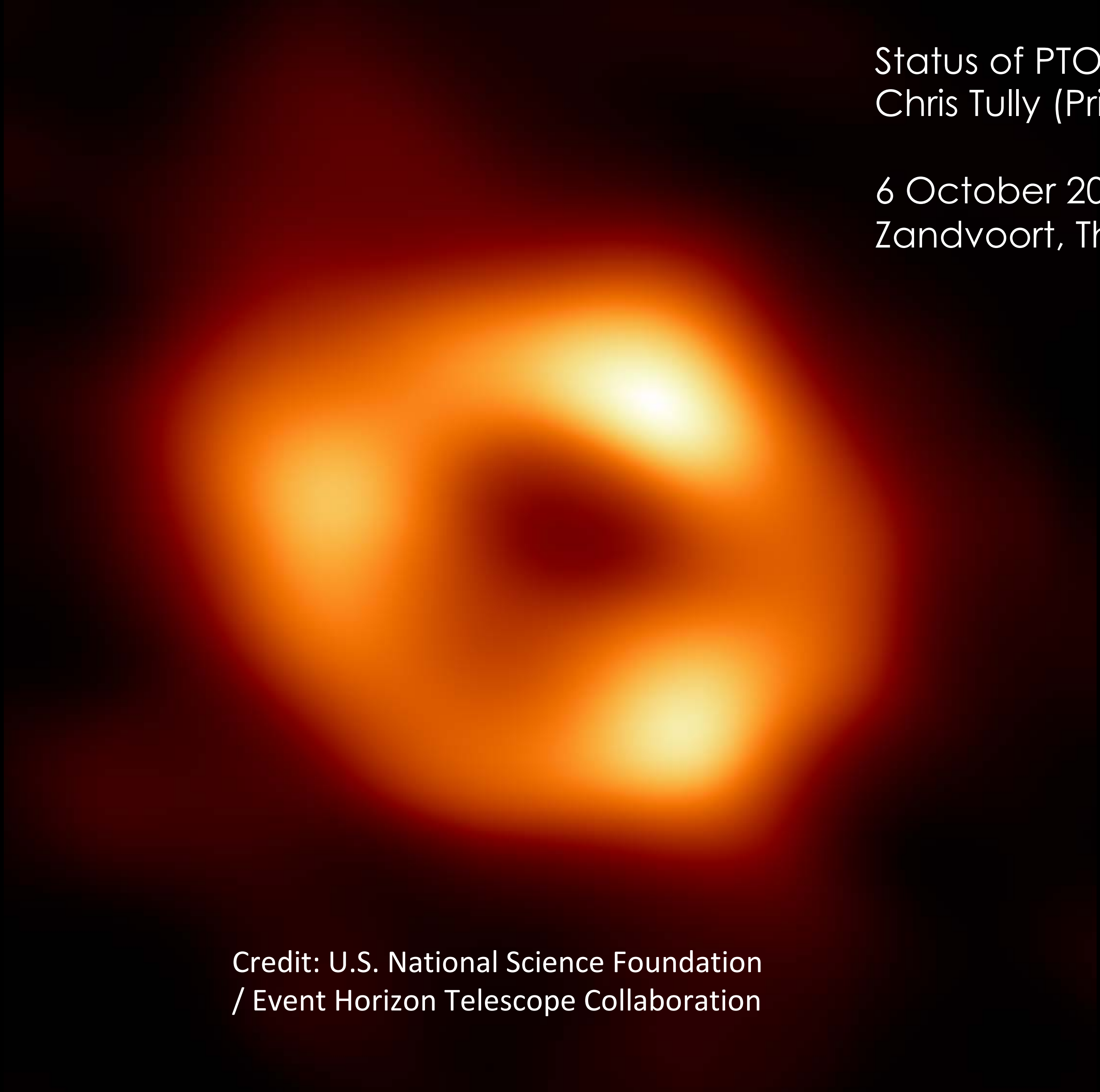
Status of PTOLEMY

Chris Tully (Princeton)

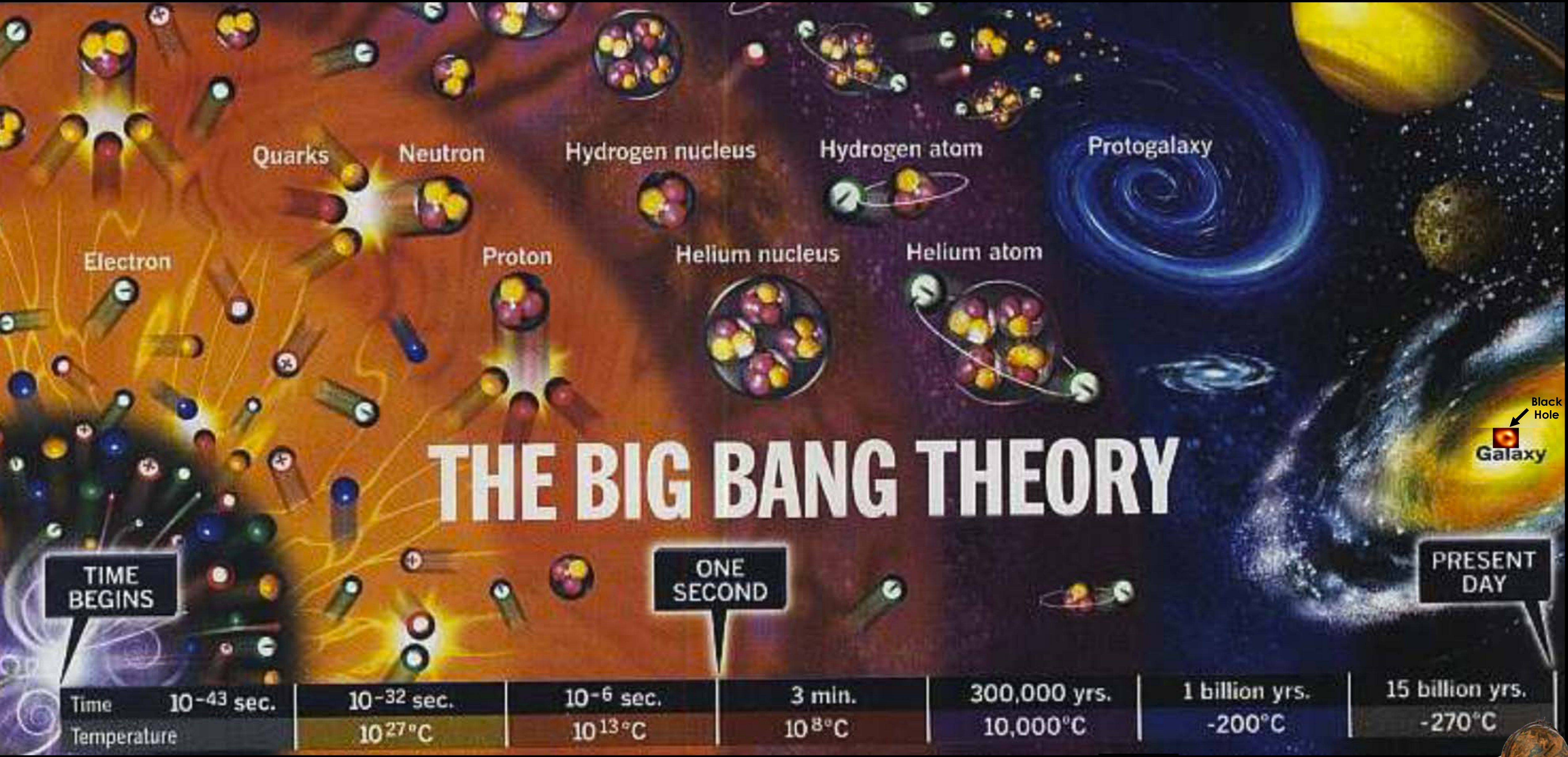
6 October 2022
Zandvoort, The Netherlands

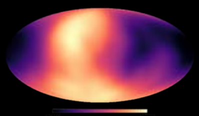


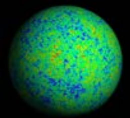
Credit: U.S. National Science Foundation
/ Event Horizon Telescope Collaboration

JOHN TEMPLETON FOUNDATION
Inspiring Awe & Wonder

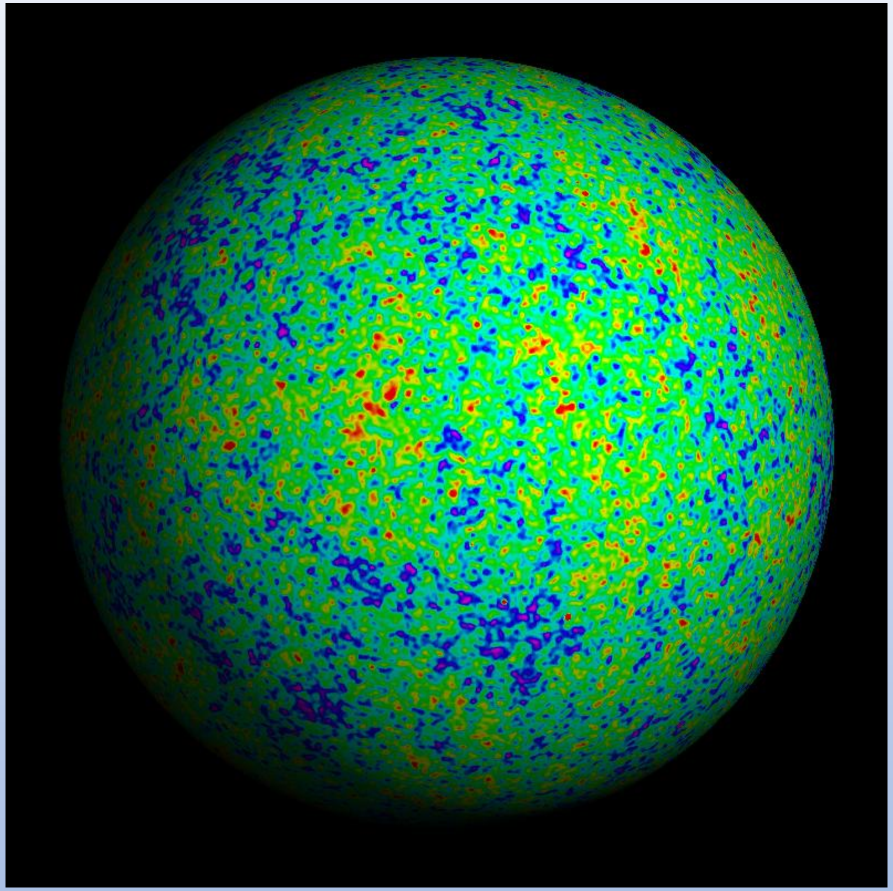
SIMONS FOUNDATION


Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
Black Hole
Galaxy
THE BIG BANG THEORY
TIME BEGINS
ONE SECOND
PRESENT DAY
Time
Temperature
10-43 sec.
10-32 sec.
10 27 °C
10-6 sec.
10 13 °C
3 min.
10 8 °C
300,000 yrs.
10,000°C
1 billion yrs.
-200°C
15 billion yrs.
-270°C





Celestial Globes

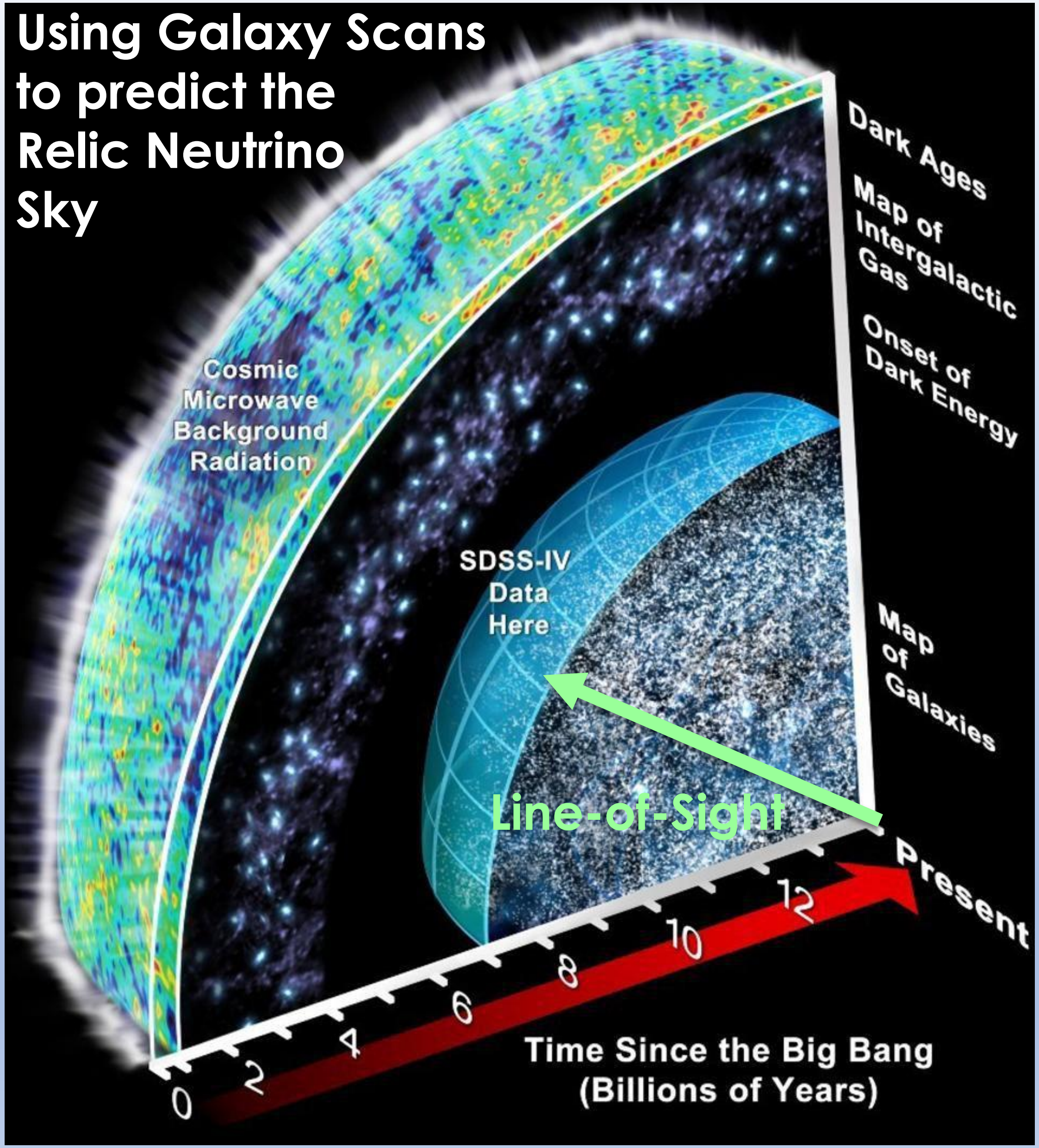


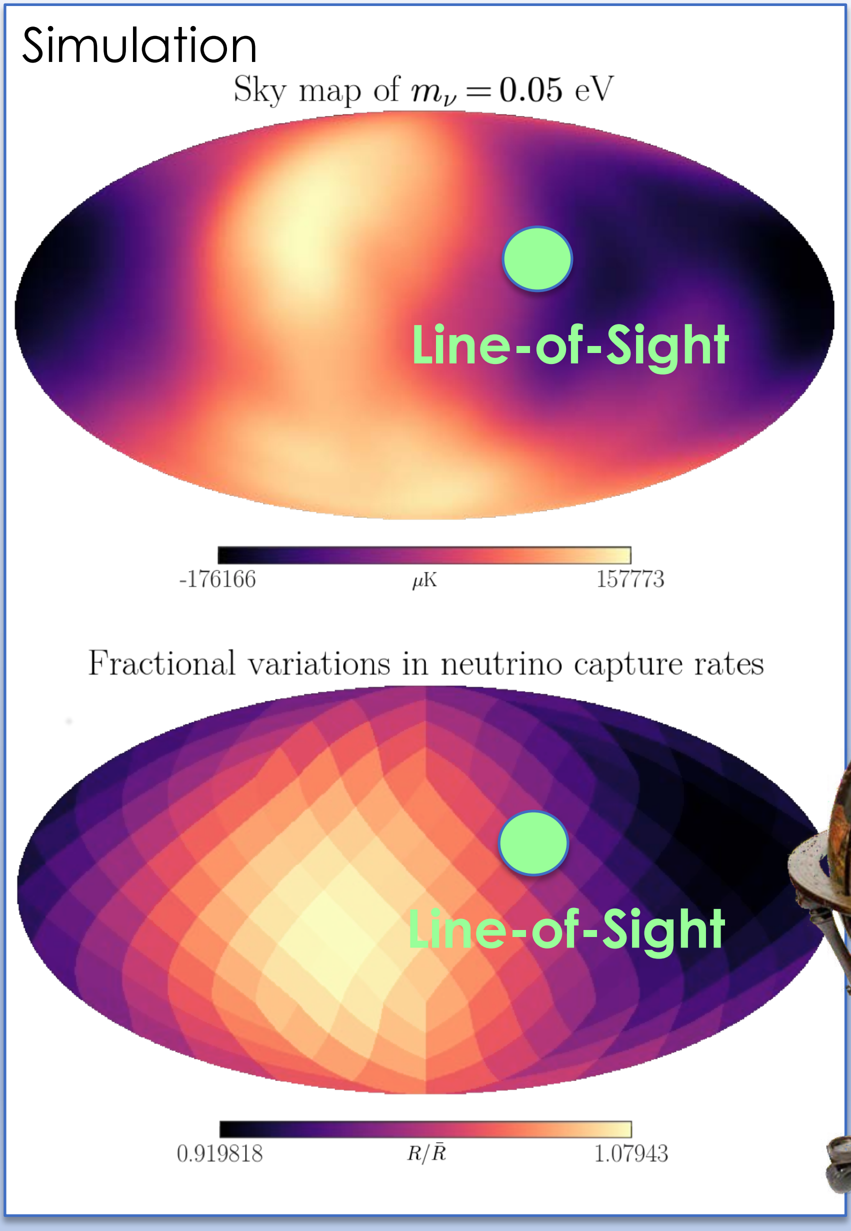
Adiabatic Density Anisotropies
$\delta \sim 10^{-5}$ at $z \sim 1100$

Johann Schöner, c.1534

WMAP, c.2009

PTOLEMY: Experiment to measure relic neutrinos from the Big Bang





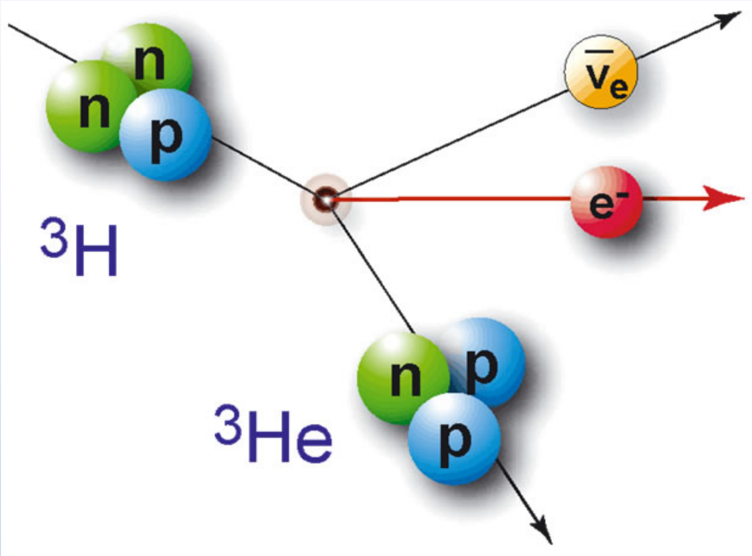
50meV neutrino mass → CNB w/ ~10% anisotropies

G. Zhang and C. Tully, https://arxiv.org/abs/2103.01274 (https://arxiv.org/abs/2201.01888) (Highlight article: Journal cover)

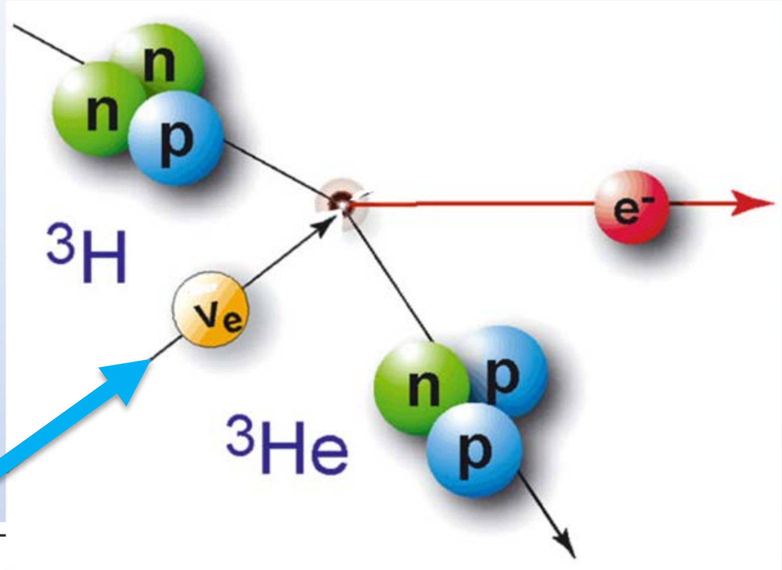
Neutrinos in the Early Universe

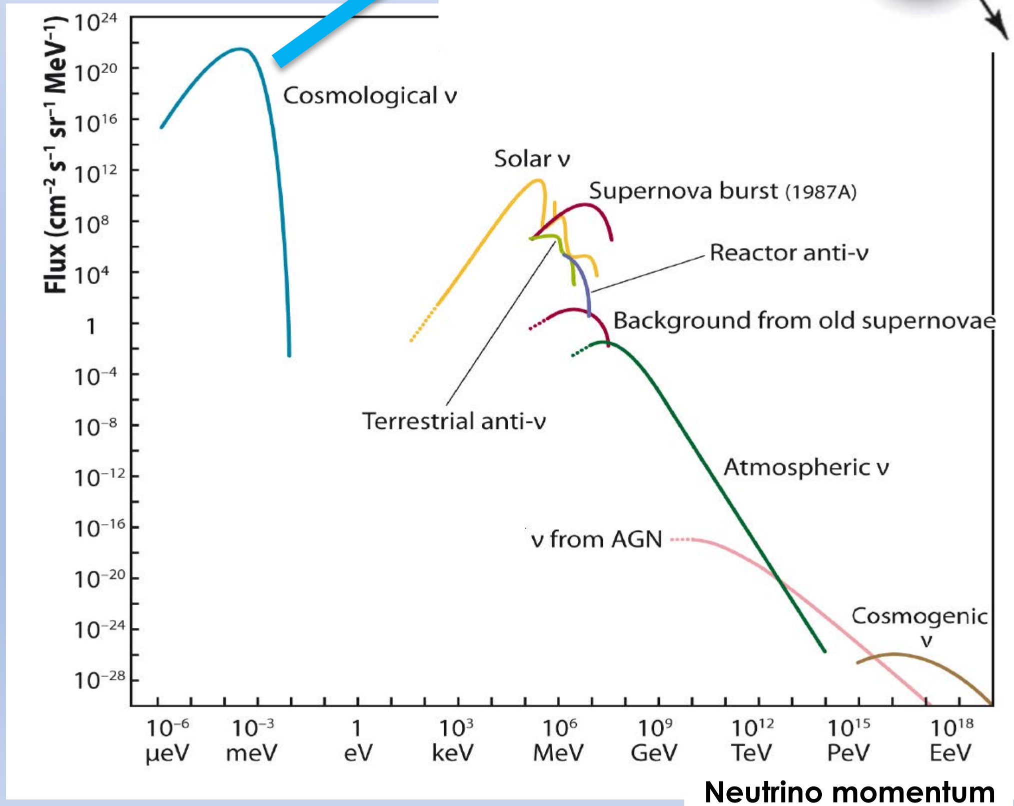
- Different from any other known fermion
  - Right-handed partner is a gauge singlet (no known charges of any kind in the Electroweak-scale Standard Model of Particle Physics)
  - Masses are significantly smaller than other fermions (only fermion that can have it's mass scale influenced by GUT-scale physics through the see-saw mechanism)
  - Lepton number violation through B-L gauge symmetry breaking could be responsible for wide-spread matter/anti-matter asymmetry in the current Universe
  - Decoupling time earlier than any other direct signatures from the hot Big Bang

Neutrino capture on Tritium



Tritium β-decay
(12.3 yr half-life)





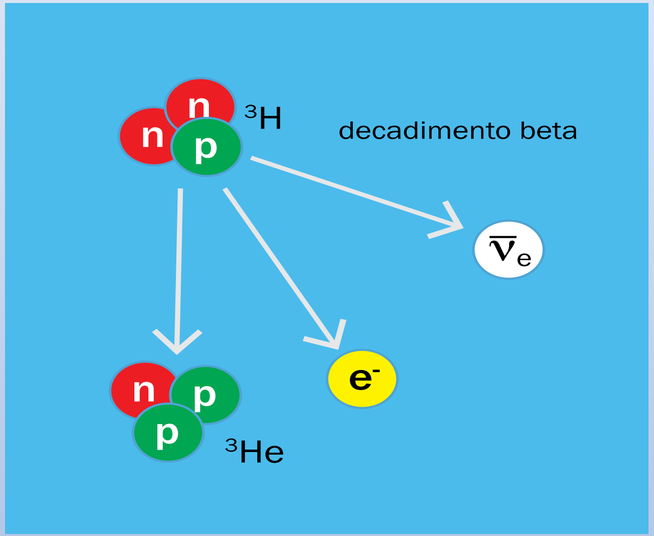
Neutrino momentum ~ 0.17 meV

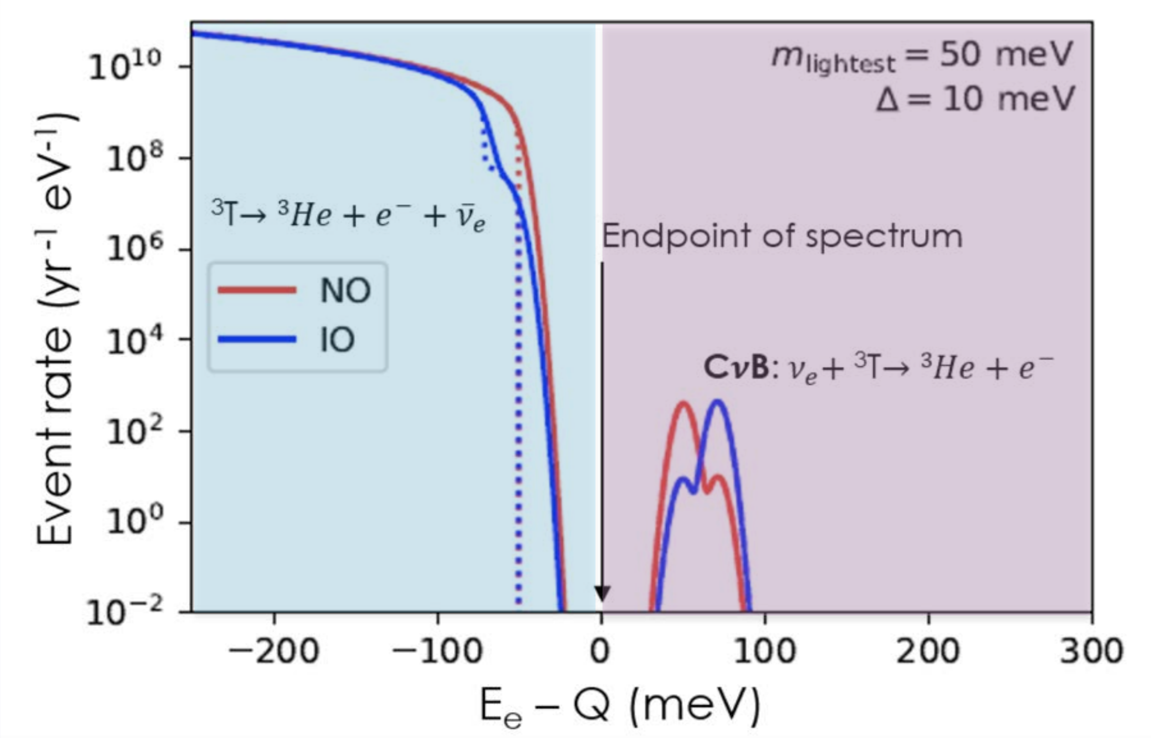
For m_ν = 50 meV,
KE = $p^2/2m$
= 0.17 meV (0.17 meV/100 meV)
= 0.3 μeV

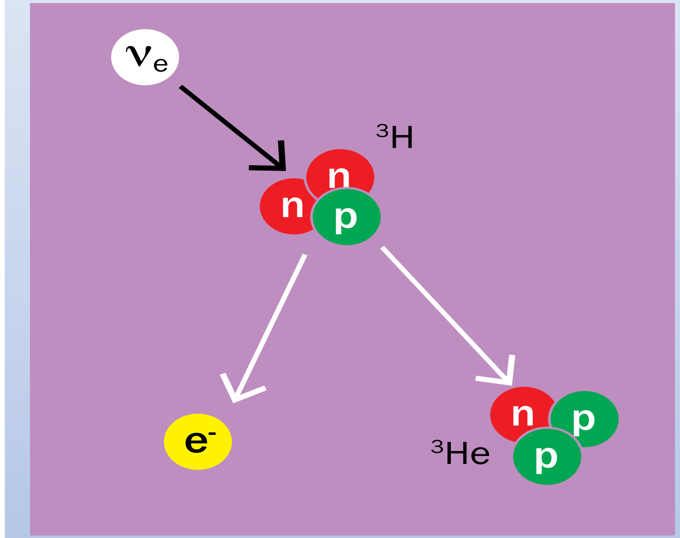
Ultra-Cold!

Detection Concept: Neutrino Capture

- Basic concepts for relic neutrino detection were laid out in a paper by Steven Weinberg in **1962** [*Phys. Rev.* 128:3, 1457] applied for the first time to massive neutrinos in **2007** by Cocco, Mangano, Messina [DOI: 10.1088/1475-7516/2007/06/015] and revisited in **2021** by Cheipesh, Cheianov, Boyarsky [https://arxiv.org/abs/2101.10069]







What do we know?

Gap (2m) constrained to

m < ~200meV

from **precision cosmology**

Electron flavor expected with

m > ~50meV

from **neutrino oscillations**

CνB Detection Requires:

few x 10^{-6} energy resolution set by m_ν

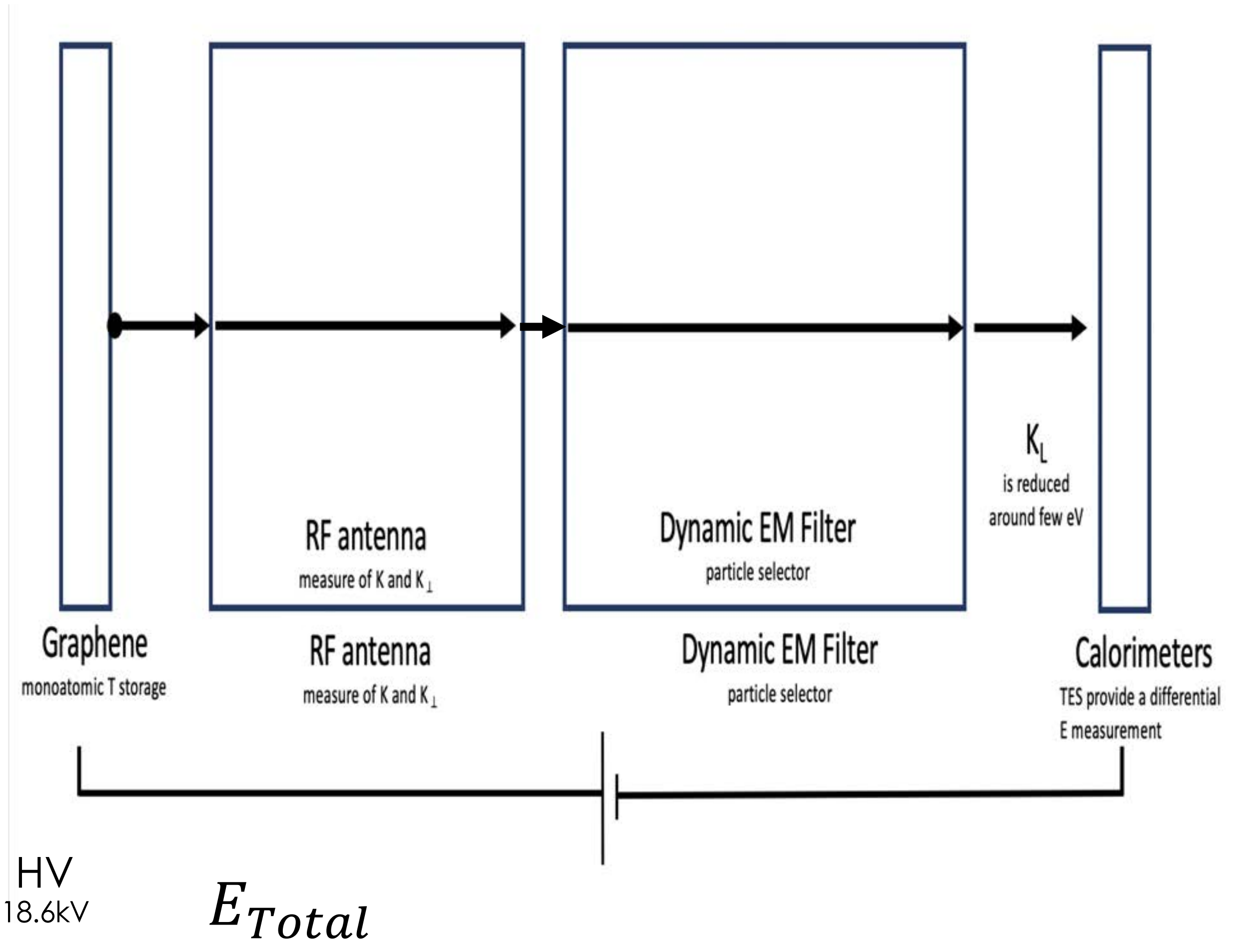
KATRIN ~ 10^{-4} (current limitation)

PTOLEMY: 10^{-4} x 10^{-2}

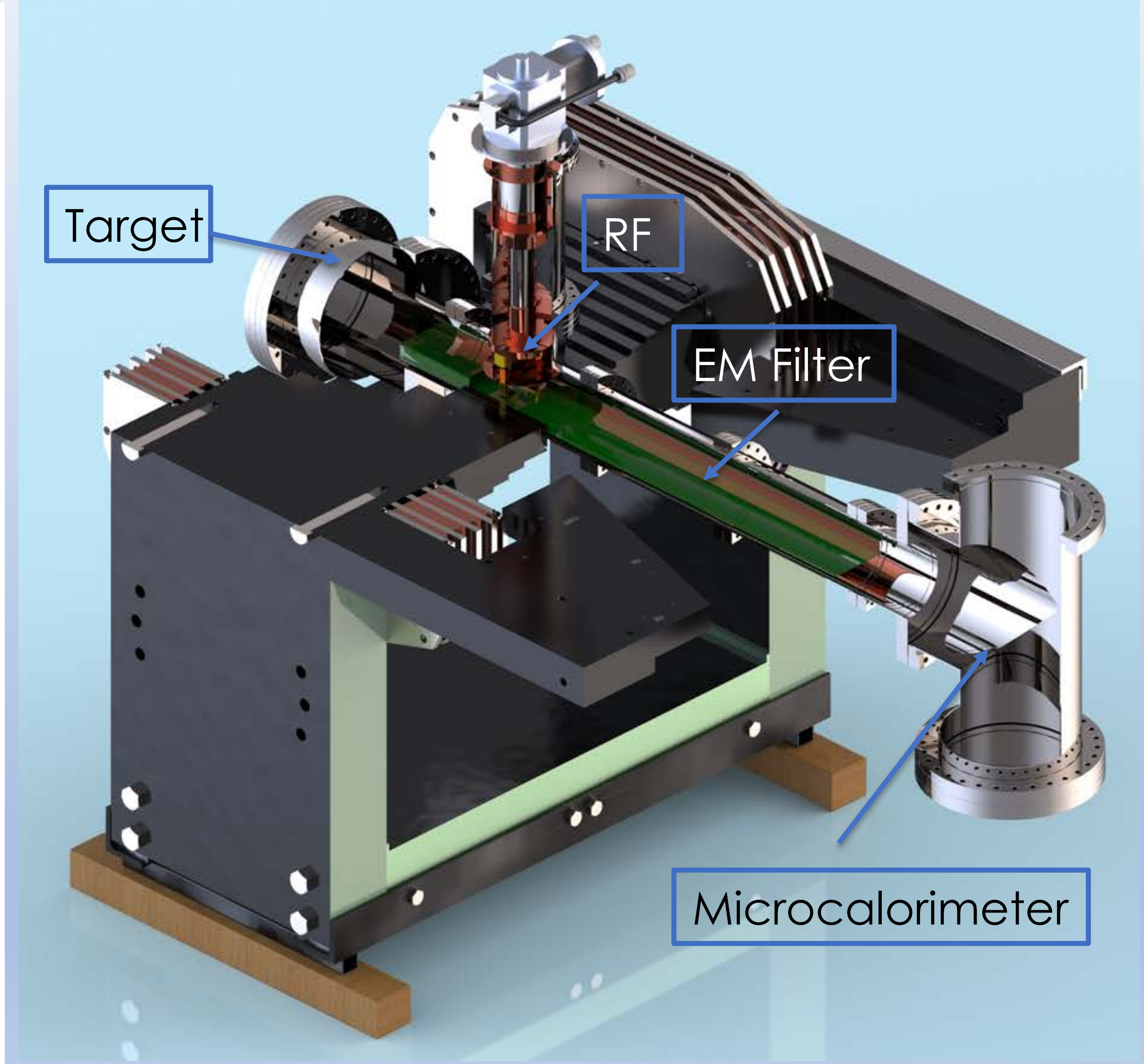
(compact filter) x (microcalorimeter)

PTOLEMY R&D Development Setup

Andi Tan (Princeton)



$$E_{Total} = q\left(V_{TES} - V_{Target}\right) + E_{RFcorr} + E_{cal}$$



New Developments on PTOLEMY

- Prototype filter magnet completed and tested
- Theoretical developments on target physics and >90% hydrogen loading on NPG graphene
- New RF calculations and antenna simulations w/ Dutch collaboration on front-end processing
- New TES performance – reaching 50 meV resolution for 15x15 μm^2 @ 52mK pixels
- End-to-end simulations in Kassiopeia for prototype
- Plans for LNGS full-prototype (funded jointly by JTF/Simons/NWO-NWA/PNRR)

Electromagnetic Filters

<u>MAC-E filter</u>

Magnetic Adiabatic Invariance

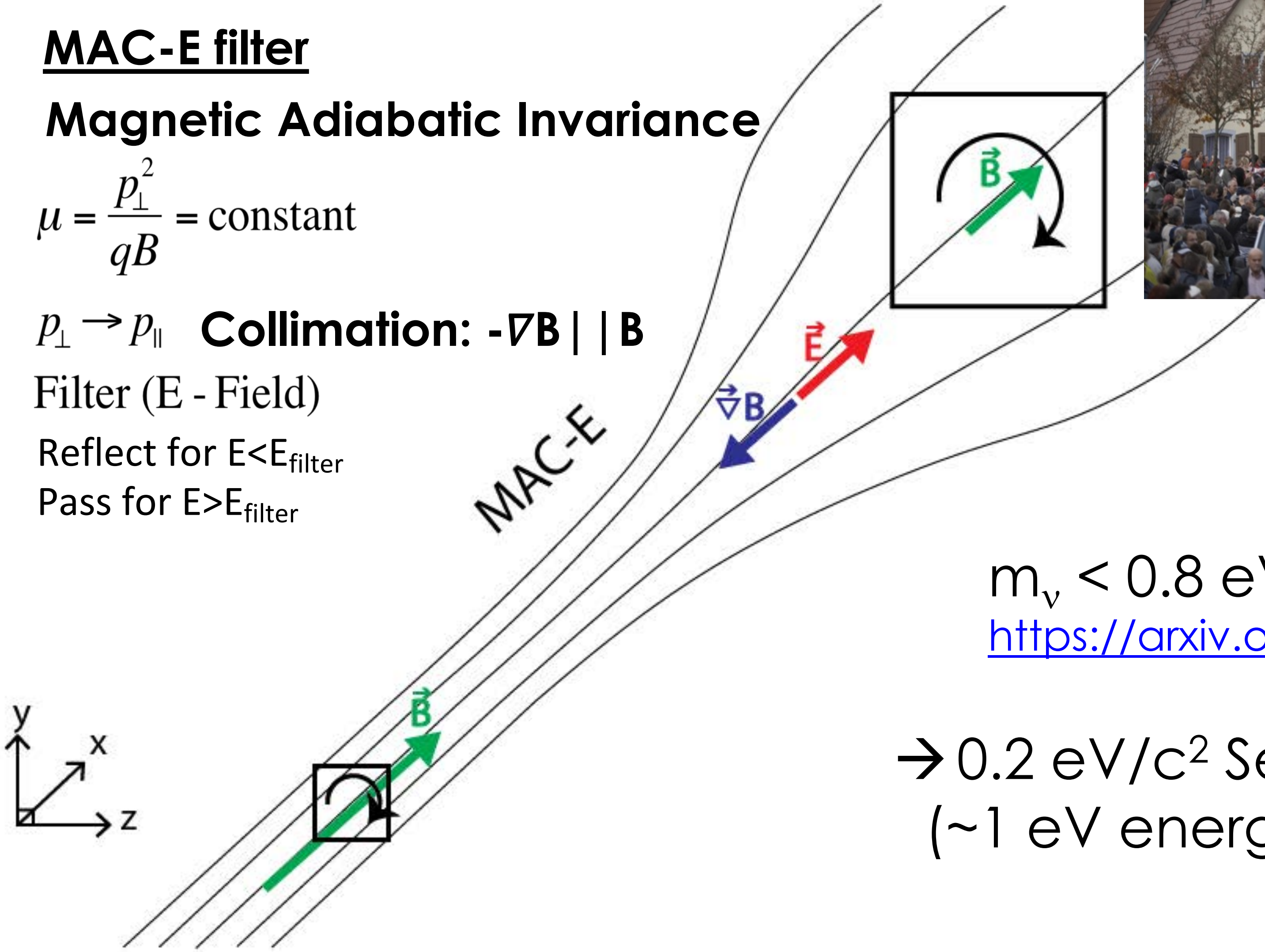
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

$p_\perp \rightarrow p_\parallel$ **Collimation: -∇B | | B**

Filter (E - Field)

Reflect for $E<E_{filter}$

Pass for $E>E_{filter}$



KATRIN

~1200m^3

$m_\nu < 0.8$ eV/c^2 (90% CL)

https://arxiv.org/abs/2105.08533

→ 0.2 eV/c^2 Sensitivity Goal

(~1 eV energy resolution)

Electromagnetic Filters

Transverse Drift filter

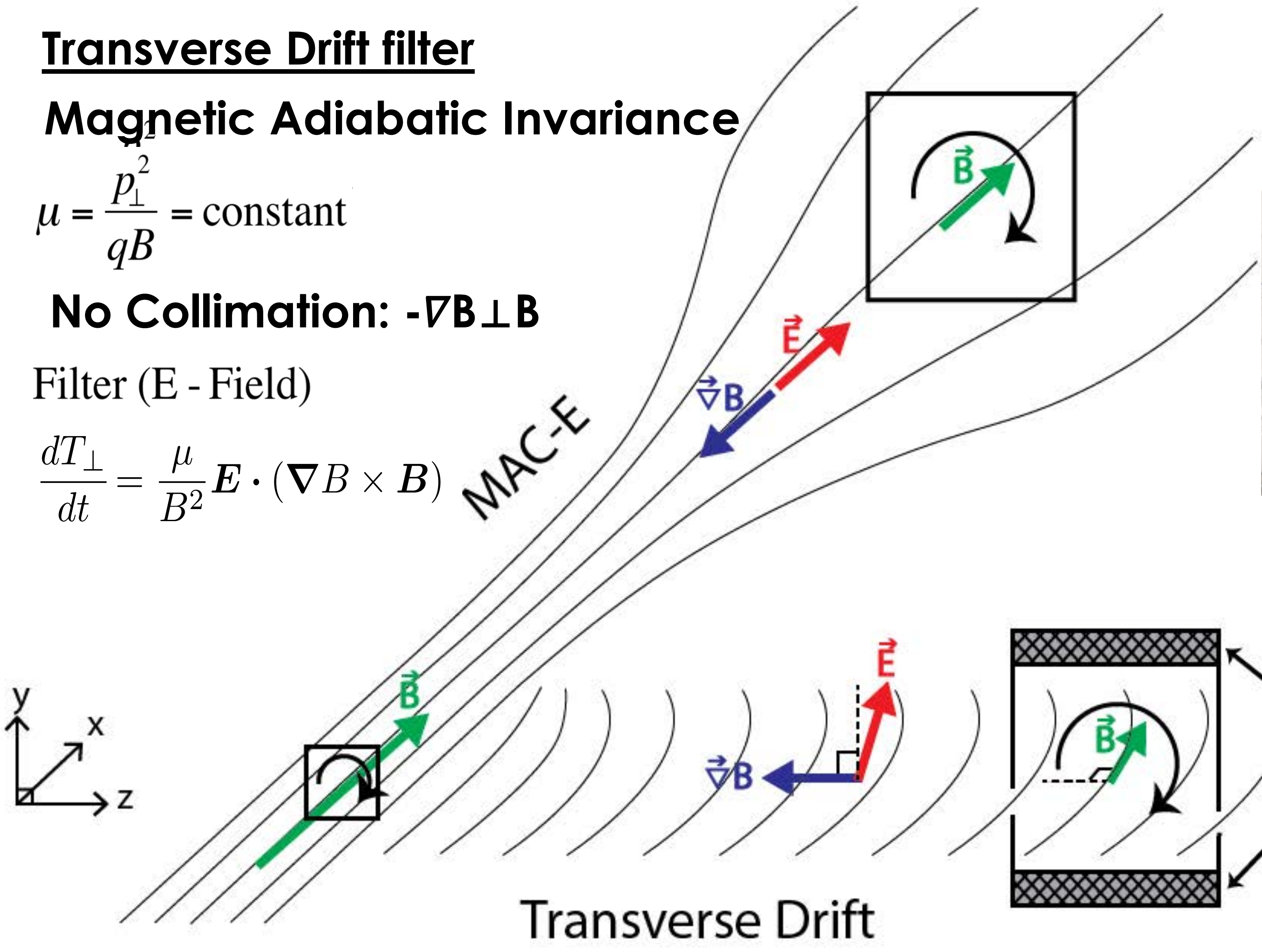
Magnetic Adiabatic Invariance

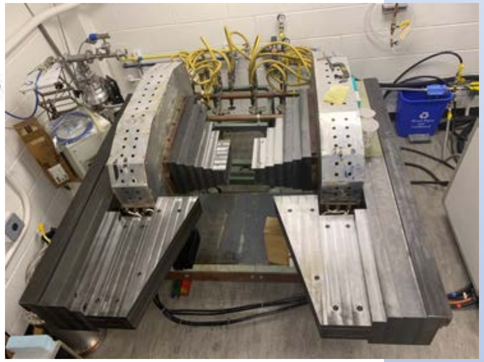
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

No Collimation: -∇B⊥B

Filter (E - Field)

$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\boldsymbol{E}\cdot(\boldsymbol{\nabla}B \times \boldsymbol{B})$$





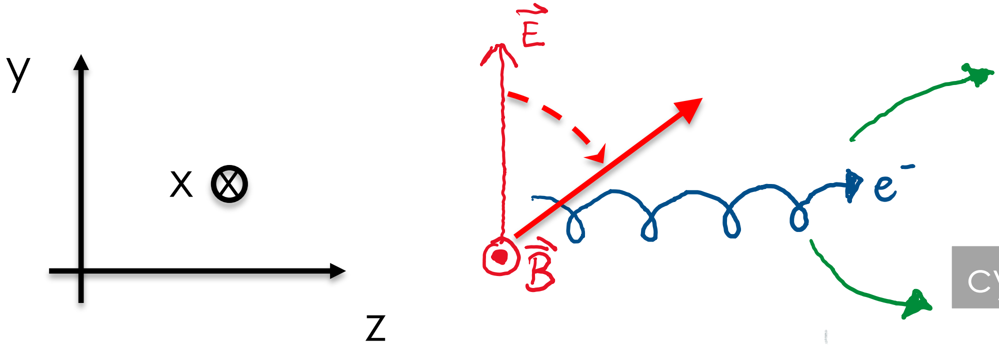
PTOLEMY

~1m^3

PTOLEMY Filter Concept

Auke Pieter Colijn (PATRAS 2019)

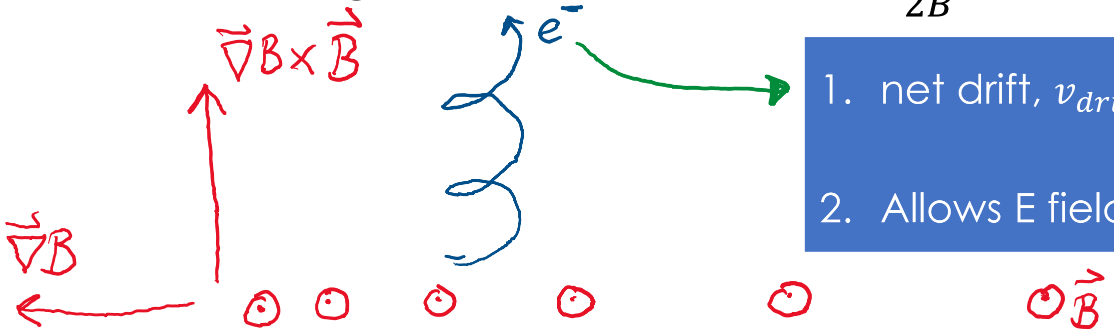
I: $\vec{E} \times \vec{B}$ drift



1. net drift, $v_{drift} = E/B$
2. no work, drift along equipotential planes

cyclotron motion – detectable RF

II: $\frac{\mu}{B^2}\vec{\nabla}B \times \vec{B}$ drift, with magnetic moment $\mu = \frac{m_e v_\perp^2}{2B}$



1. net drift, $v_{drift} = \mu \frac{|\vec{\nabla}B|}{B}$
2. Allows E field to work (!): $\frac{dT_\perp}{dt} = e\vec{E} \cdot \vec{v}_{drift}$

$$V^y_{E\times B}(z)|_{x,y=0} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B_x^2} = \frac{E_z B_x \hat{\boldsymbol{y}}}{B_x^2} = \frac{E_z}{B_x}\hat{\boldsymbol{y}}$$

$$V_{\nabla B}(z)|_{x,y=0} = -\frac{\boldsymbol{\mu} \times \boldsymbol{\nabla}_\perp \boldsymbol{B(z)}}{qB(z)} = -\frac{\mu}{qB_x}\frac{dB_x}{dz}\hat{\boldsymbol{y}}$$

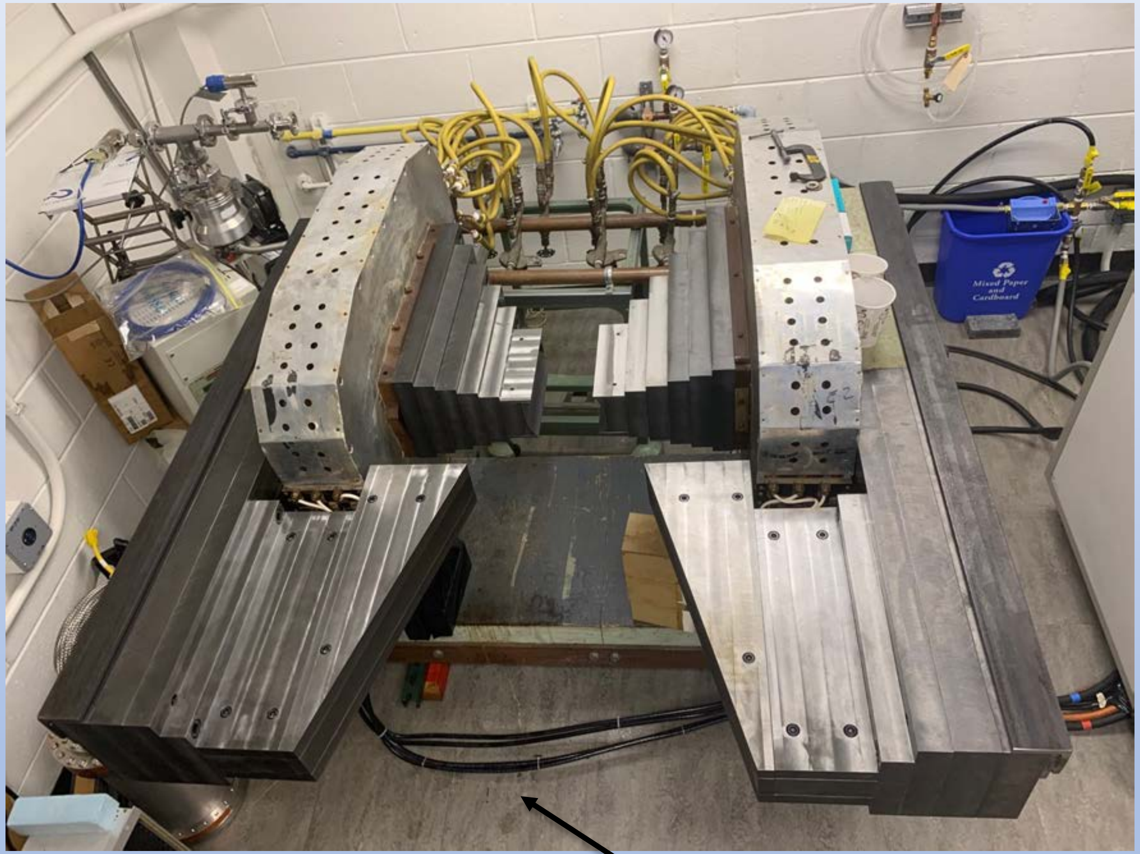
<u>Enforce zero drift in y (rotate E):</u>

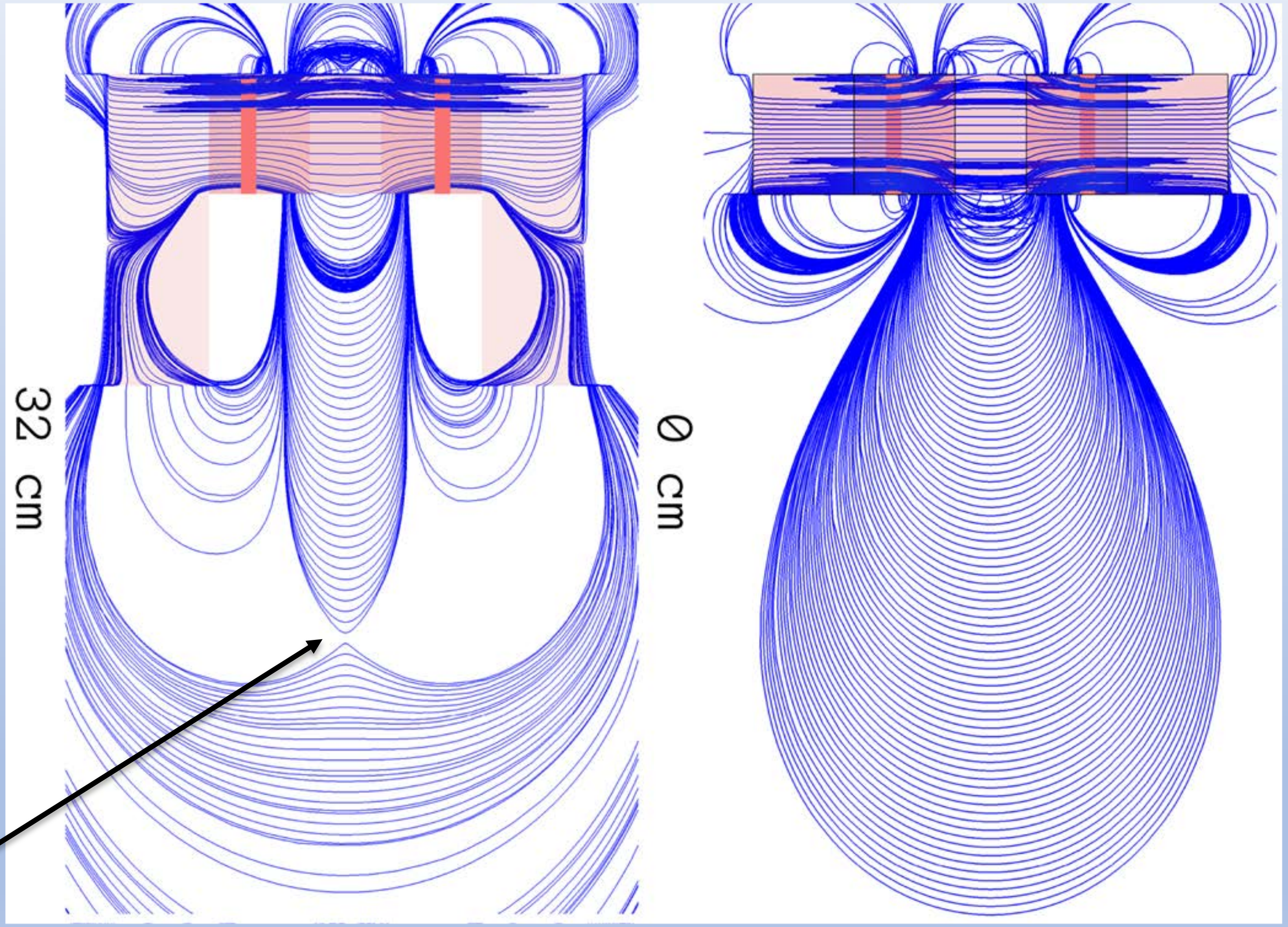
$$\xrightarrow{\text{yields}} \quad E_z(z)|_{y=0} = -\frac{\mu}{q}\frac{dB_x(z)}{dz}$$

First Version of the PTOLEMY filter

PTOLEMY
filter@Princeton

Wonyong
Chung





Andi
Tan

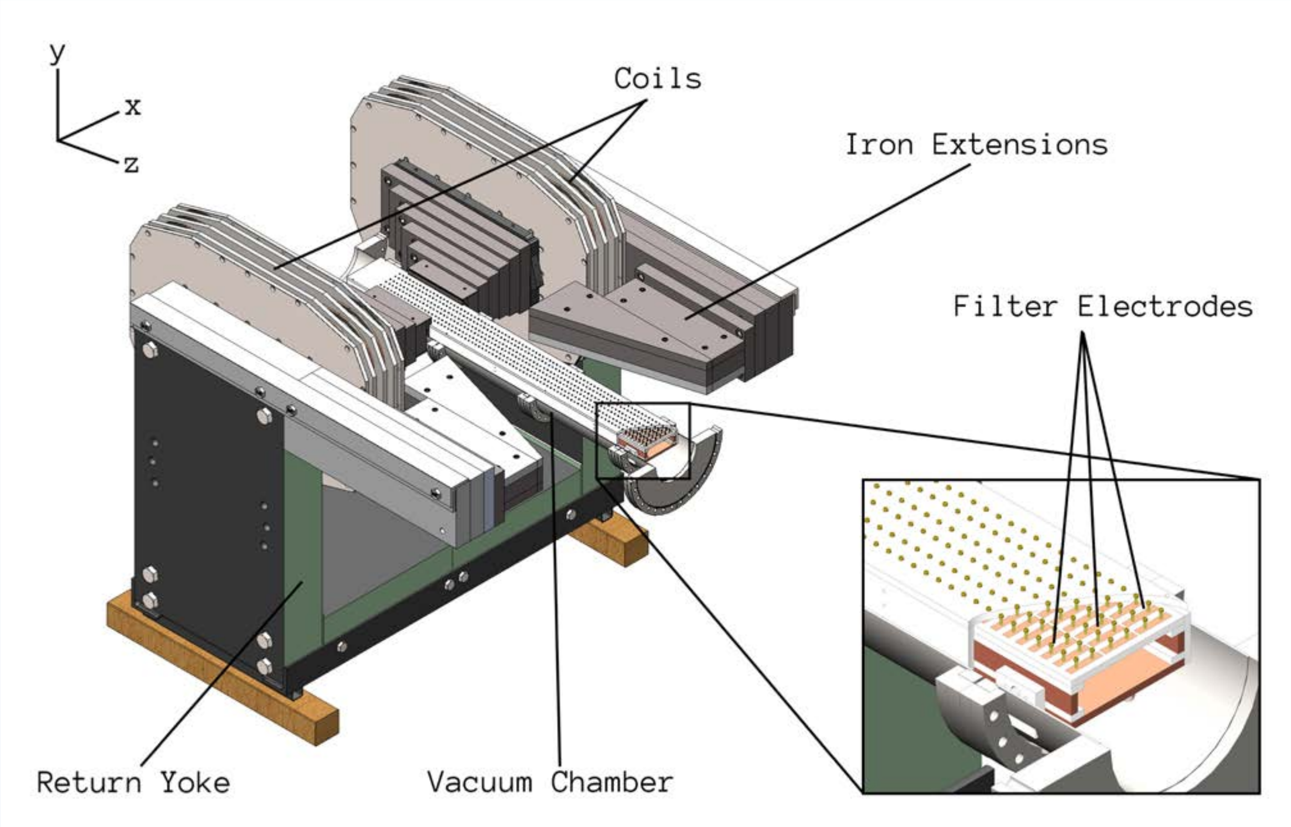
Zero field (location for TES microcalorimeter)

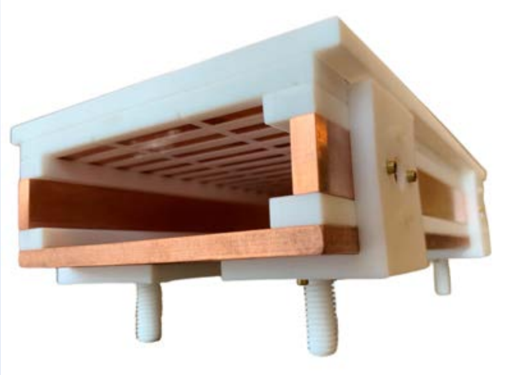
Supported by:

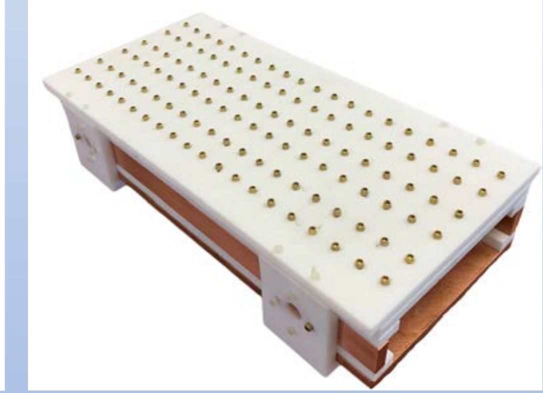
SIMONS FOUNDATION

Electrode Prototype

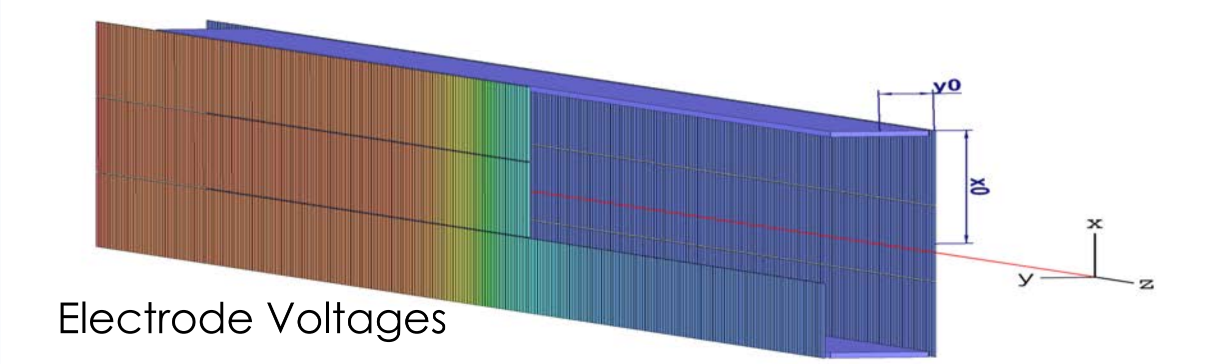
Andi Tan (Princeton)





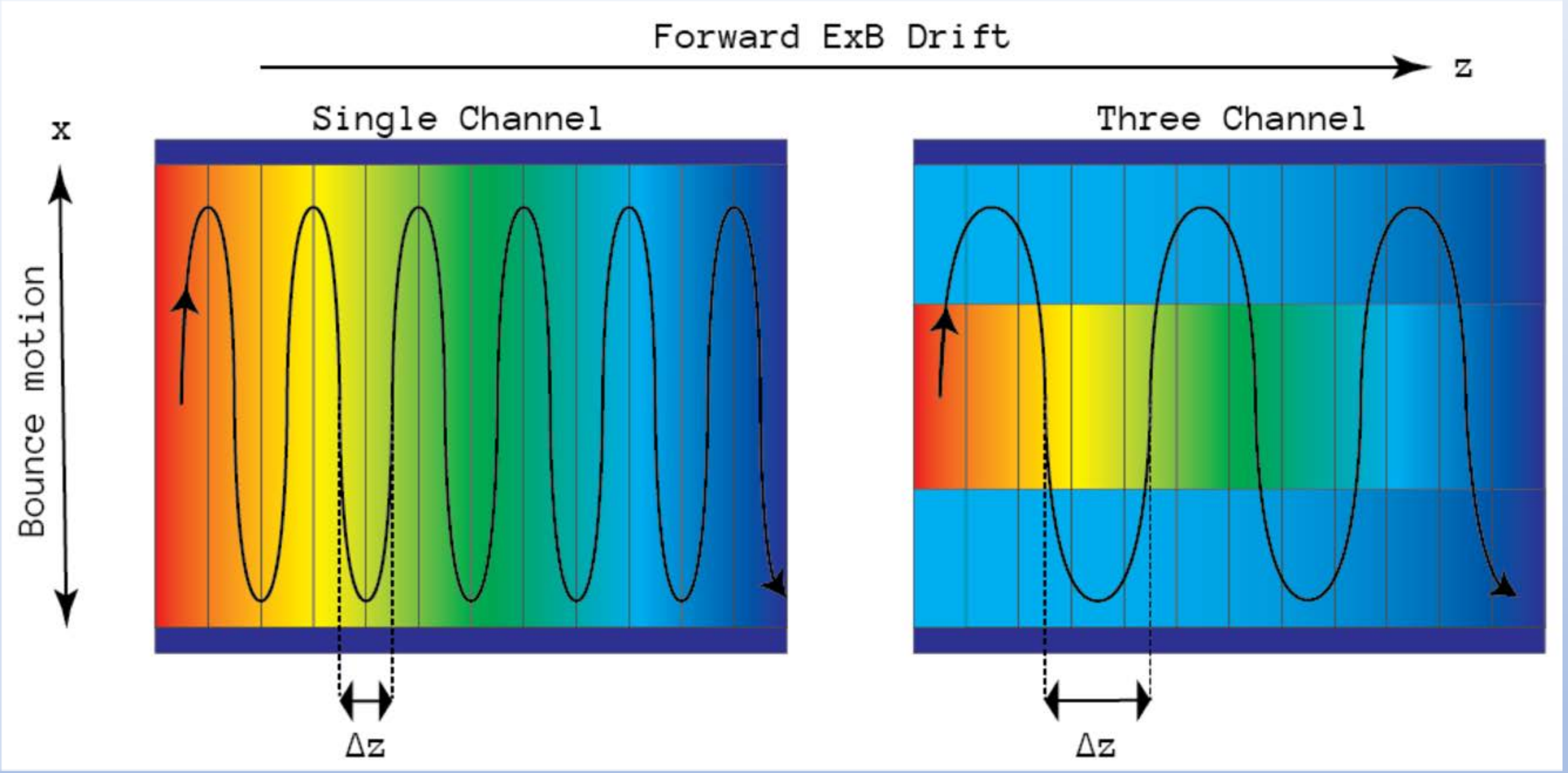


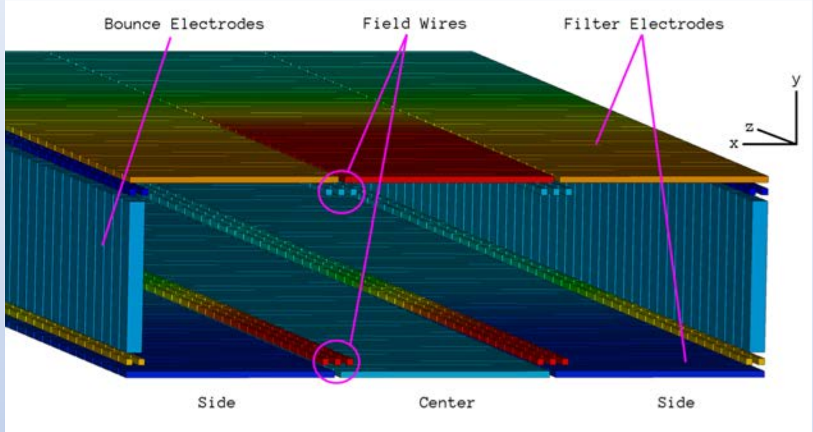
Wonyong
Chung
(Princeton)

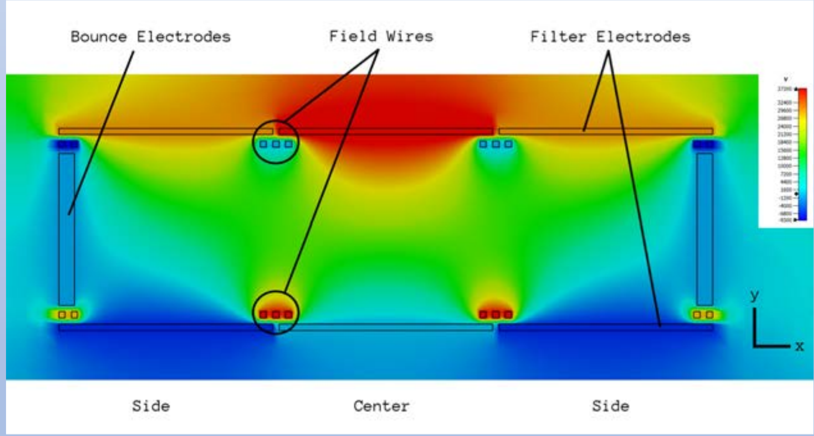


Electrode Voltages

Bobsledding (pushing electron up potential)







Transverse "Selector"
(one channel)

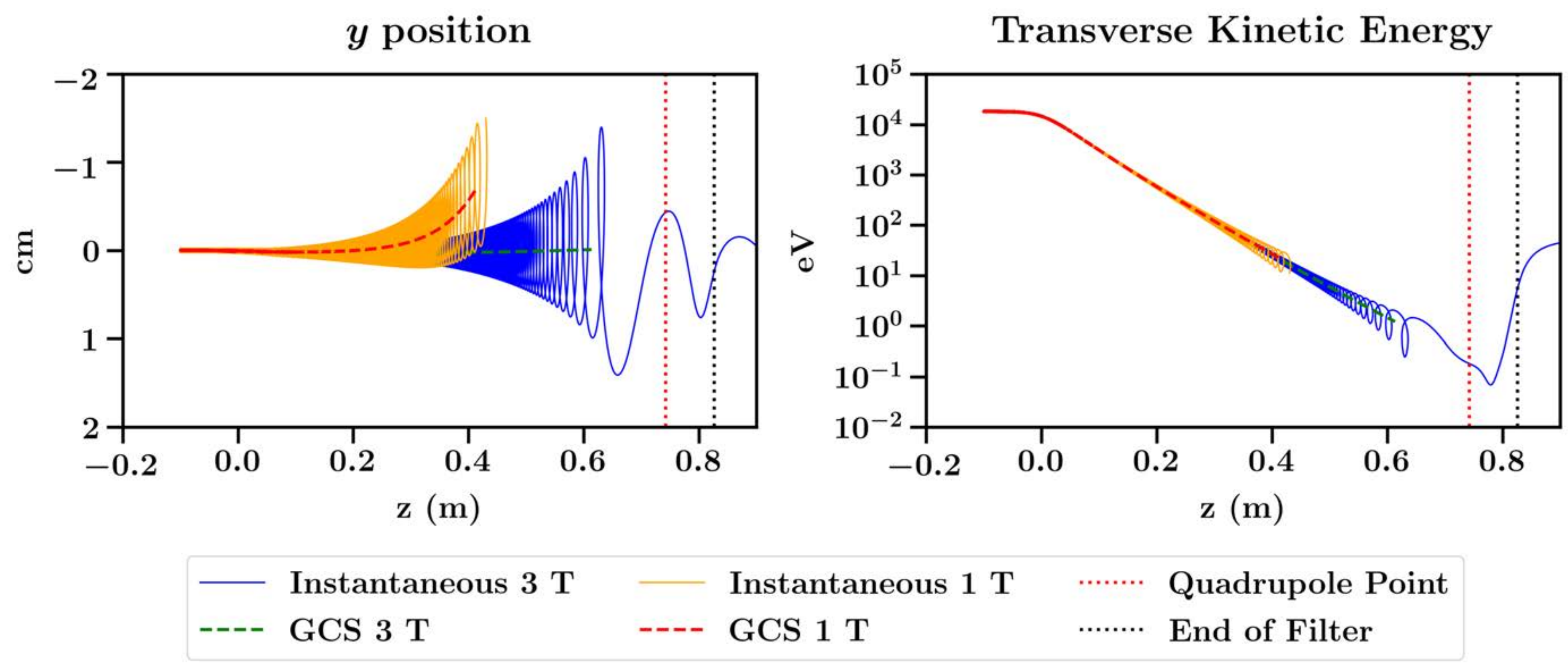
Dynamically Adjusted
(side channels)
to Total Energy "Selector"

Filter Performance

Improves as B^2 for a fixed filter dimension

18.6 keV @ 1T → ~10eV (in 0.4m)

18.6 keV @ 3T → ~1eV (in 0.6m)

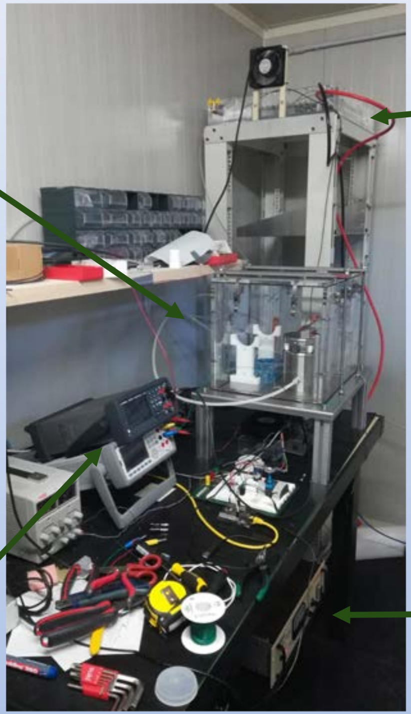


PTOLEMY Collaboration, https://arxiv.org/abs/2108.10388
"Implementation and Optimization of the PTOLEMY Electromagnetic Filter" (in peer-review)
https://iopscience.iop.org/article/10.1088/1748-0221/17/05/P05021

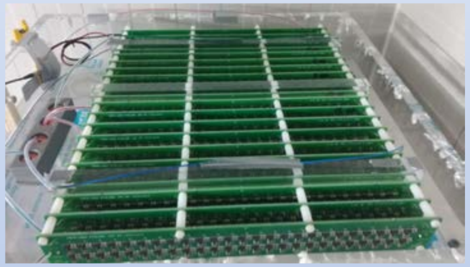
HV Stability and Monitoring

@LNGS

Field mill box



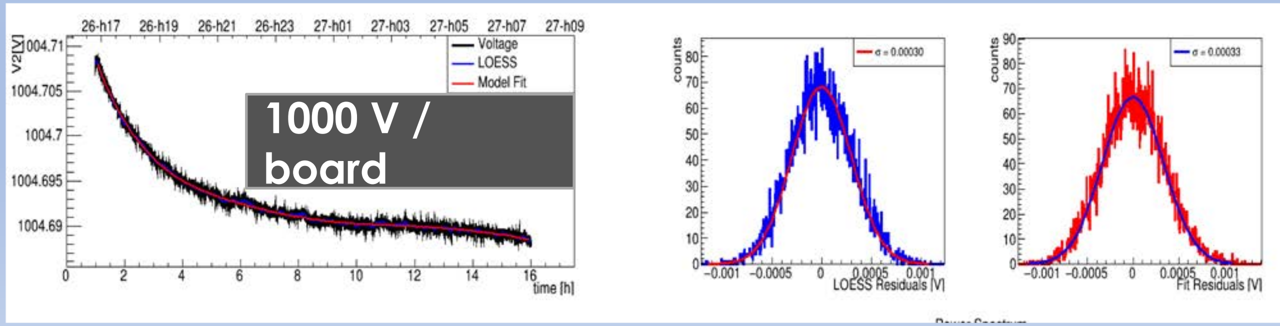
Diodes box



High precision voltmeter Keysight®

Power supply Bertan®

environmental parameter stabilization (dT ~ 0.1°C, Pressure < 1mBar, humidity 0%)



Single board
σ = 0.3 mV

Expect $\sqrt{N_{boards}}$:
~1.4mV@20kV

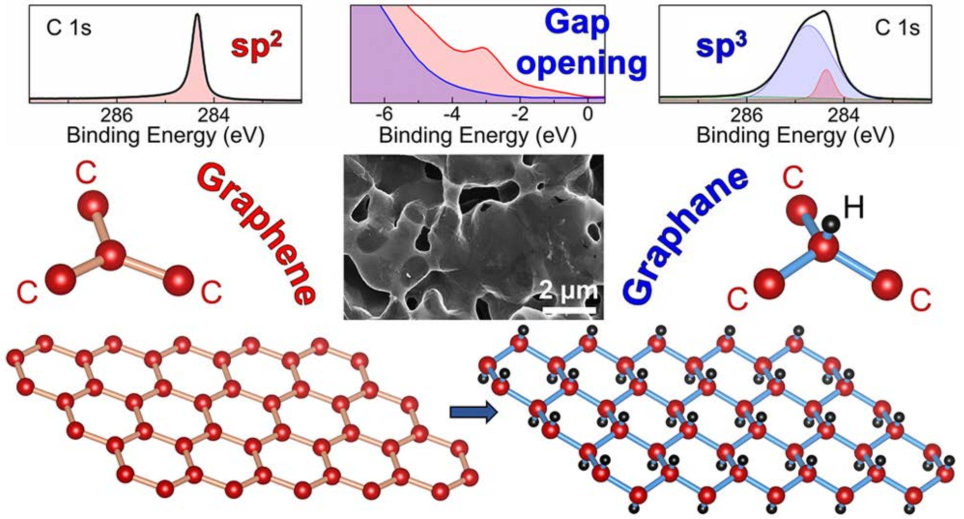
Field Mill ~50mV

Gap Opening in Double-Sided Highly Hydrogenated Free-Standing Graphene

Maria Grazia Betti,* Ernesto Placidi, Chiara Izzo, Elena Blundo, Antonio Polimeni, Marco Sbroscia, José Avila, Pavel Dudin, Kailong Hu, Yoshikazu Ito, Deborah Prezzi,* Miki Bonacci, Elisa Molinari, and Carlo Mariani

Cite This: *Nano Lett.* 2022, 22, 2971−2977

ABSTRACT: Conversion of free-standing graphene into pure graphane—where each C atom is sp^3 bound to a hydrogen atom—has not been achieved so far, in spite of numerous experimental attempts. Here, we obtain an unprecedented level of hydrogenation (≈90% of sp^3 bonds) by exposing fully free-standing nanoporous samples—constituted by a single to a few veils of smoothly rippled graphene—to atomic hydrogen in ultrahigh vacuum. Such a controlled hydrogenation of high-quality and high-specific-area samples converts the original conductive graphene into a wide gap semiconductor, with the valence band maximum (VBM) ∼ 3.5 eV below the Fermi level, as monitored by photoemission spectromicroscopy and confirmed by theoretical predictions. In fact, the calculated band structure unequivocally identifies the achievement of a stable, double-sided fully hydrogenated configuration, with gap opening and no trace of π states, in excellent agreement with the experimental results.



QUANTUM SPREAD

- Distributing tritium on flat graphene has one drawback

spatially localized tritium ⇨ uncertainty on tritium's momentum ⇨ spread in final electron energy

[Cheipesh, Cheianov, Boyarsky — PRD 2021, 2101.10069]

- A simple semi-classical estimate:

fluctuating momenta

$$\mathbf{p}_T = \Delta\mathbf{p}_T$$

$$\mathbf{p}_{He} = \bar{\mathbf{p}}_{He} + \Delta\mathbf{p}_{He}$$

$$\mathbf{p}_e = \bar{\mathbf{p}}_e + \Delta\mathbf{p}_e$$

energy and momentum conservation returns

$$\Delta E_e \simeq \left| \frac{\mathbf{p}_e \cdot \Delta\mathbf{p}_T}{E_{He}} \right| \sim \frac{p_e}{m_{He}} \frac{1}{\Delta x_T}$$

spread of initial tritium wave function $\left(\Delta x_T \sim 0.1\ \text{Å}\right)$

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energy and momentum conservation returns

$$\Delta E_e \simeq \left| \frac{\mathbf{p}_e \cdot \Delta\mathbf{p}_T}{E_{He}} \right| \sim \frac{p_e}{m_{He}} \frac{1}{\Delta x_T} \sim 0.6 - 0.8 \text{ eV}$$

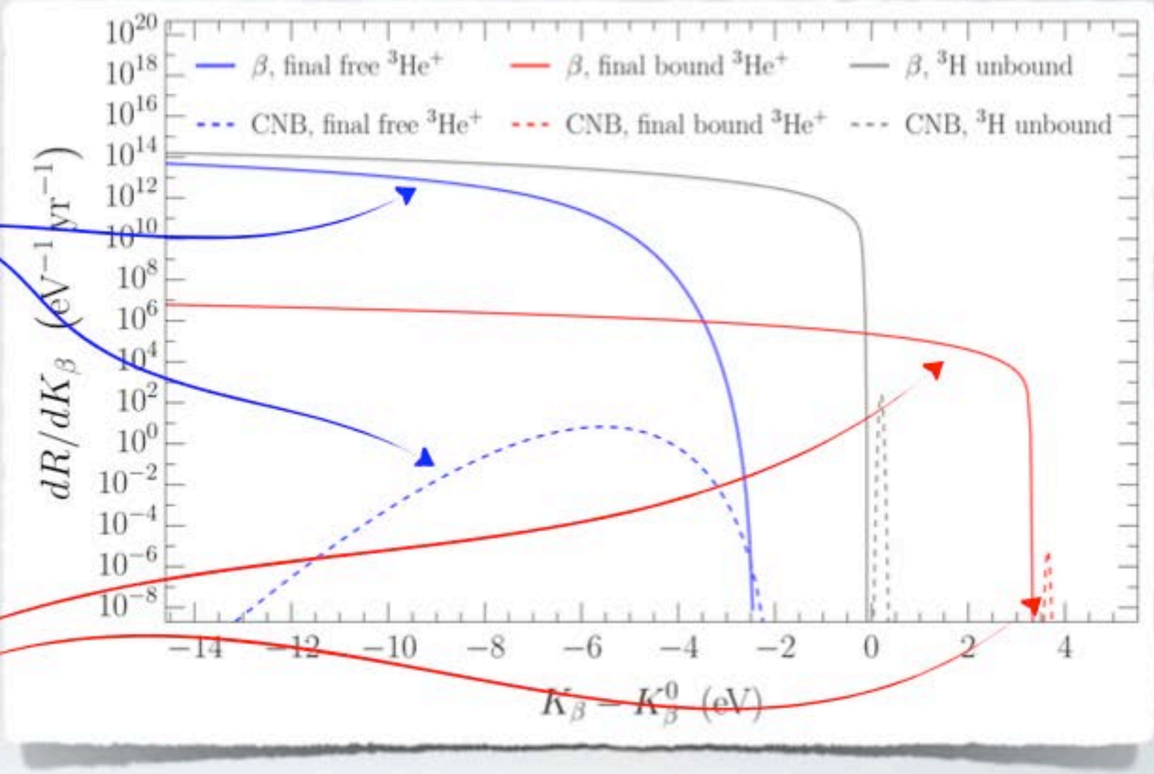
spread of initial tritium wave function $\left(\Delta x_T \sim 0.1\,\text{Å}\right)$

an order of magnitude larger than the wanted energy accuracy

QUANTUM SPREAD

- The resulting rate is

^{3}**He$^+$ is mostly freed** from the graphene ⟶ the **cosmic neutrino peak disappears** under the decay spectrum



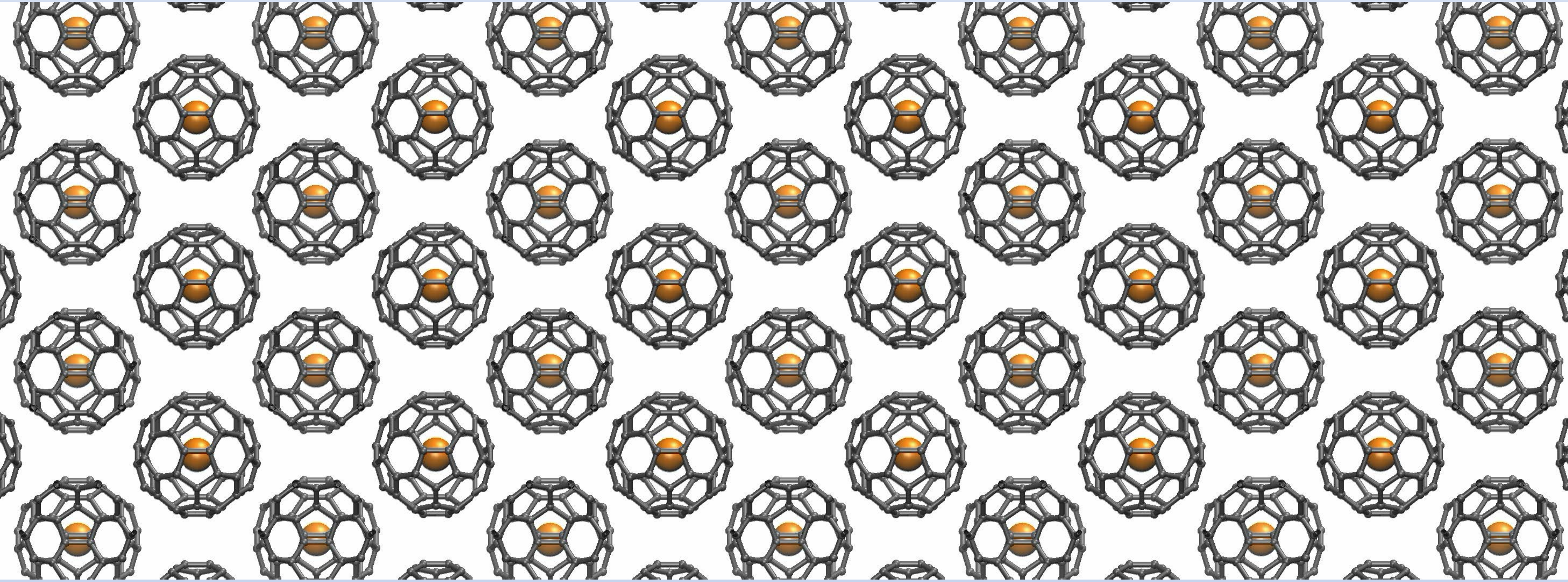
When the ^{3}**He$^+$ remains bound in the ground state** the peak is well separated ⟶ it is however **exponentially unlikely**

[PTOLEMY – 2203.11228]

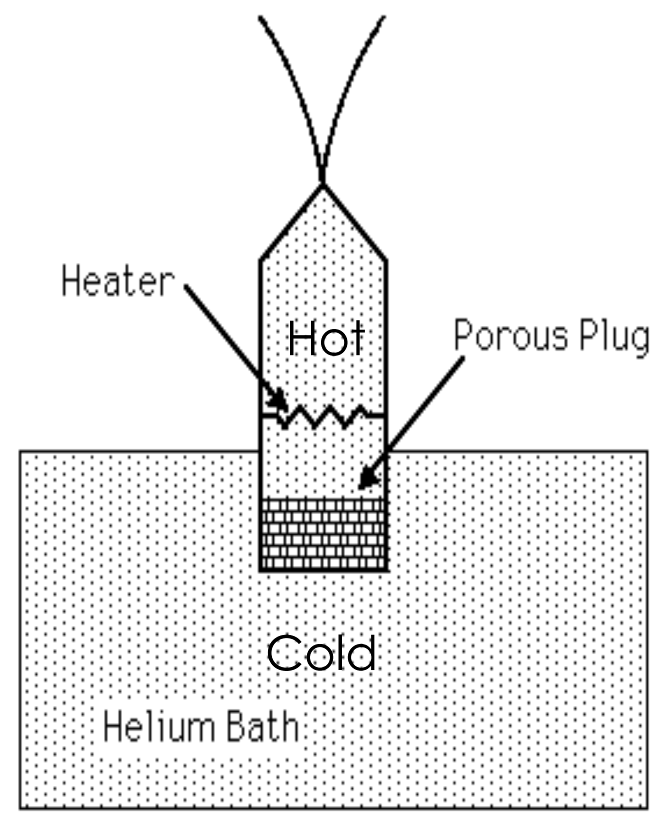
Collaboration with Savannah River National Laboratory for Tritium Loading

CNT, NPG, CVD-G, and De-localized Atomic T Geometries

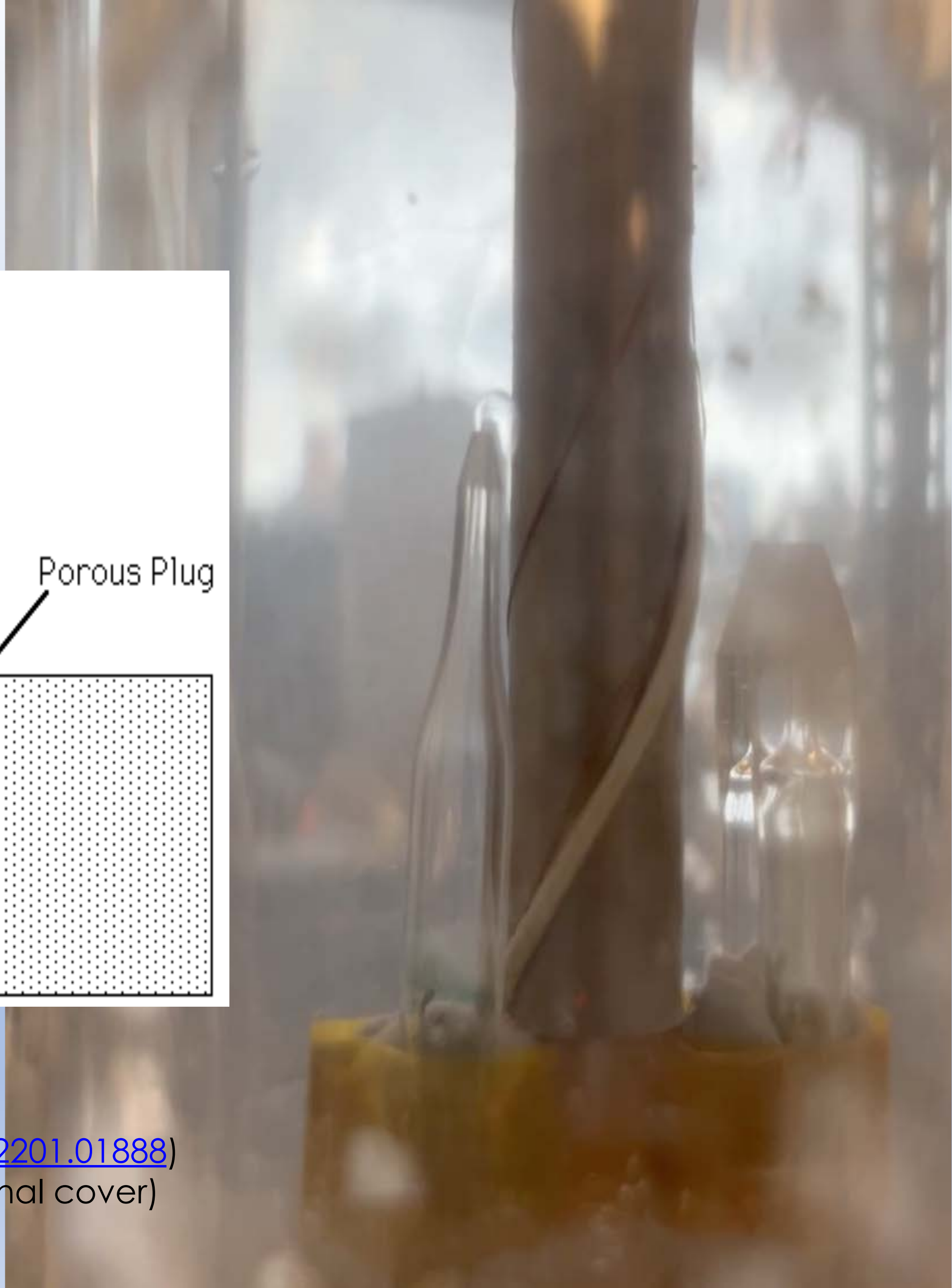
~2Å flat potential – not chemically active



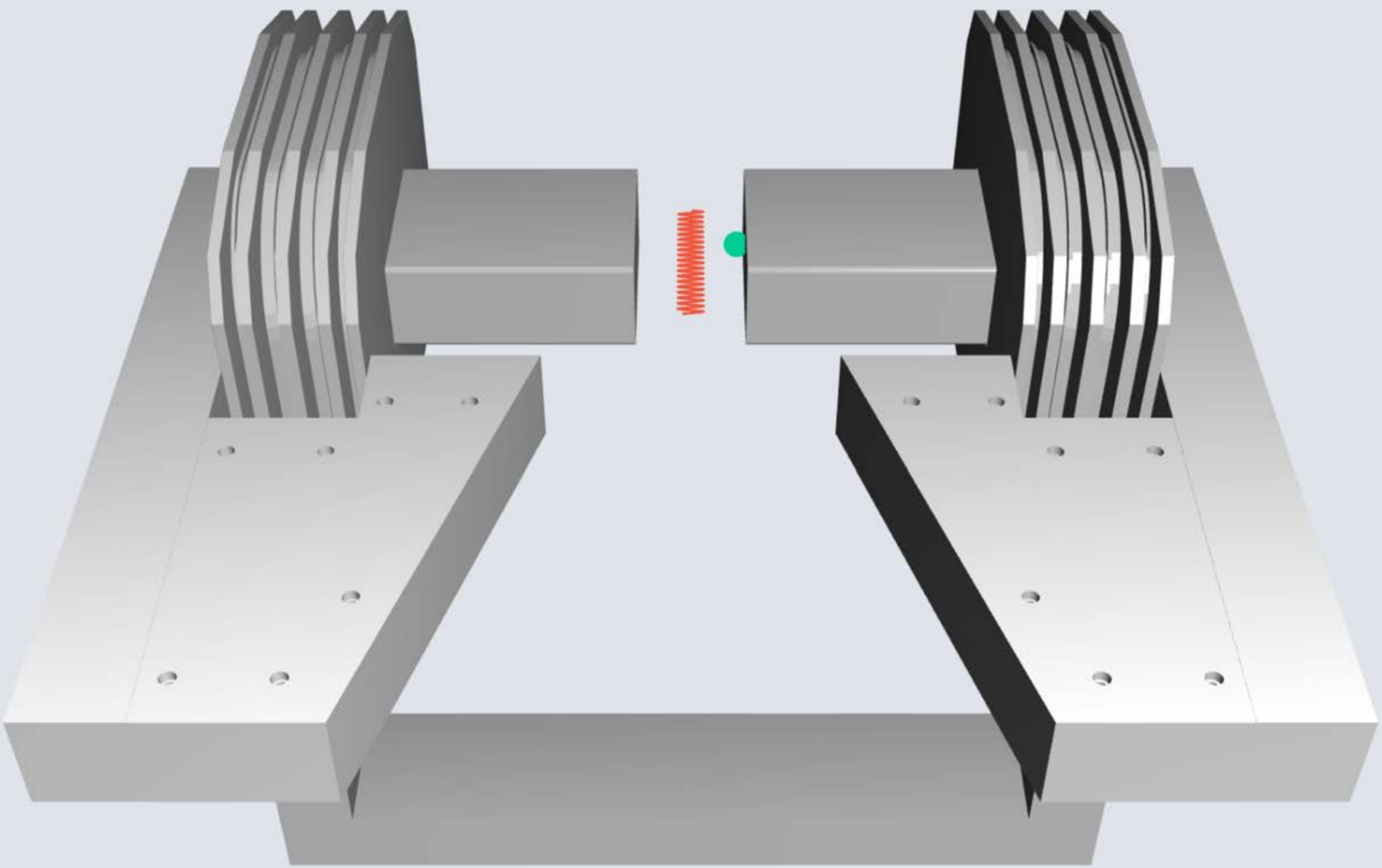
Superfluid Fountain

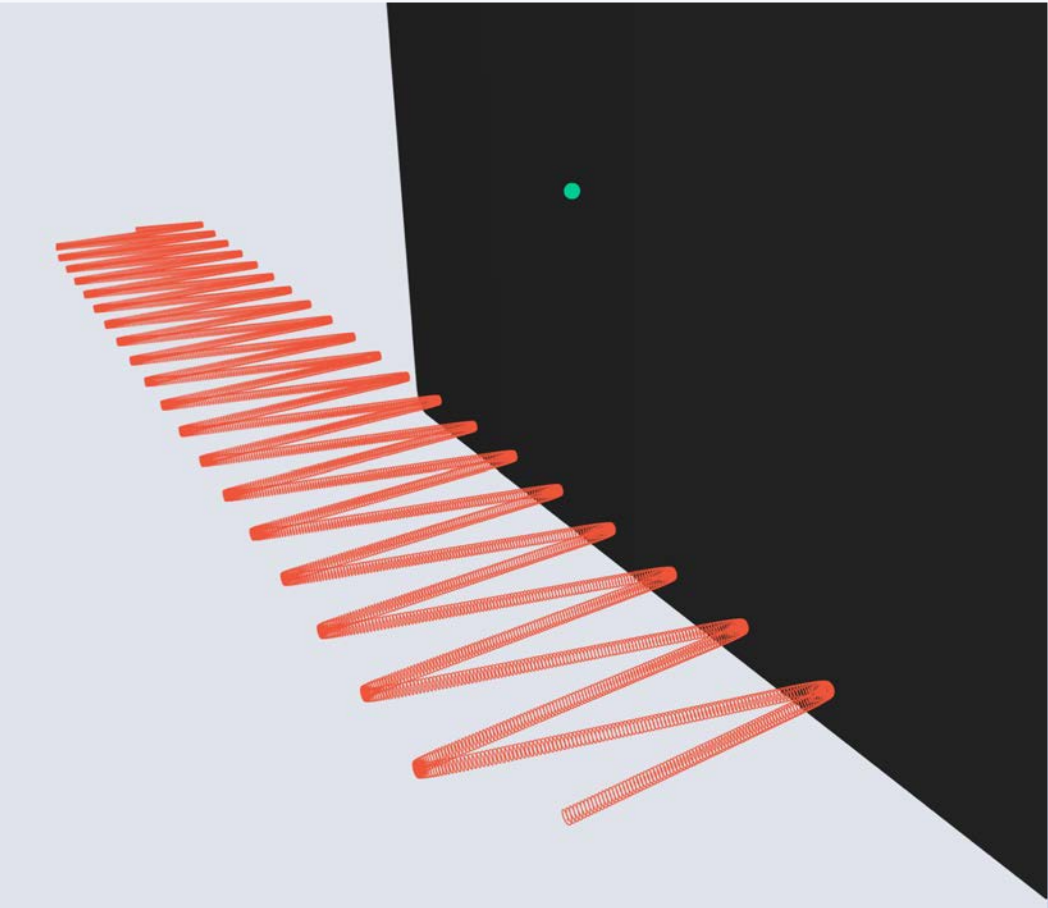


G. Zhang and C. Tully
(https://arxiv.org/abs/2201.01888)
(Highlight article: Journal cover)

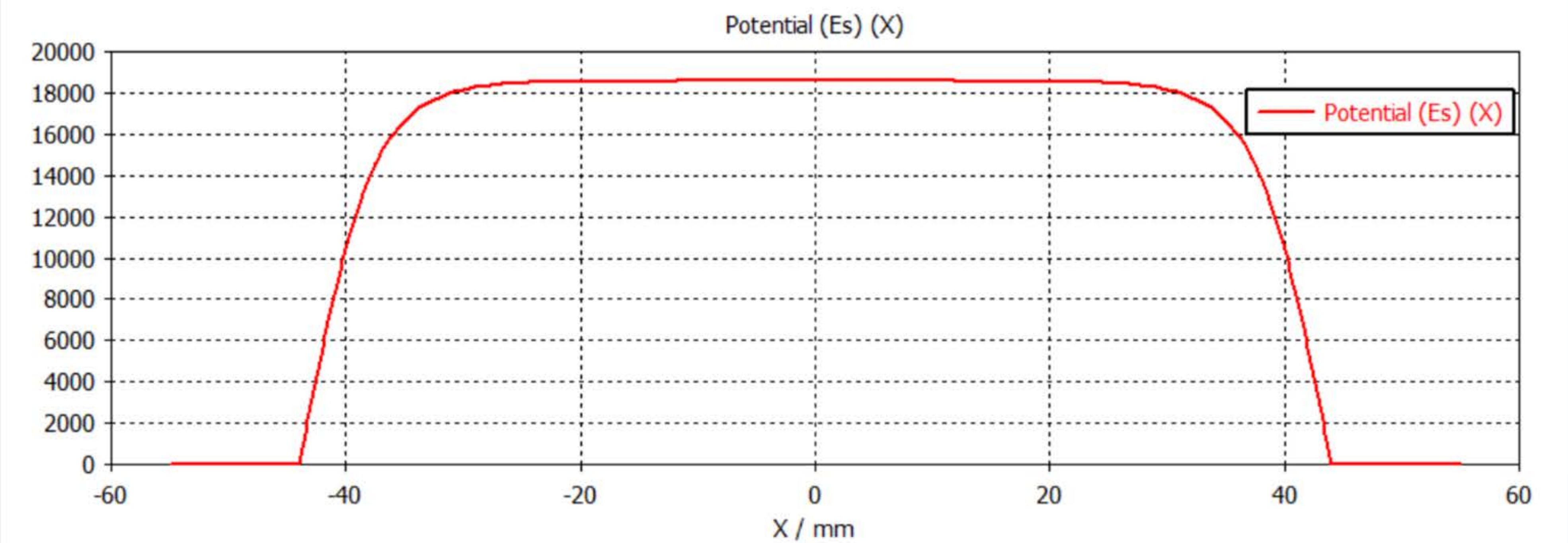


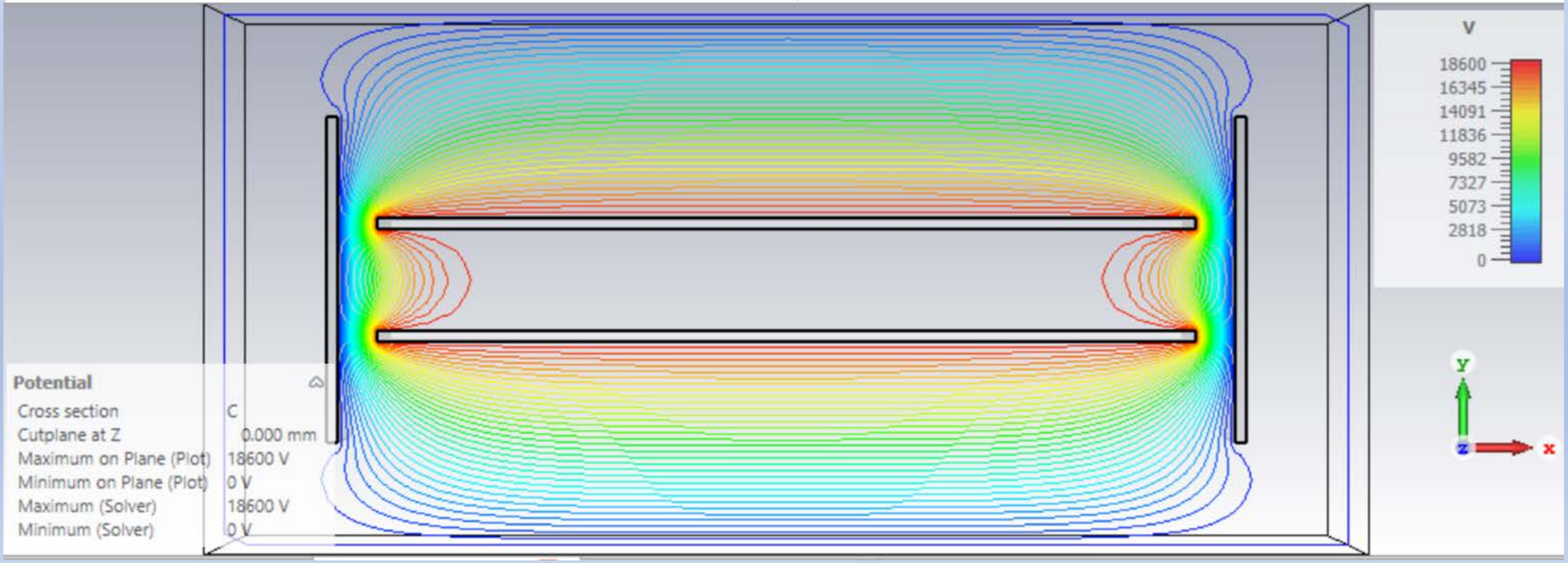
Pitch 85 Long Trajectory

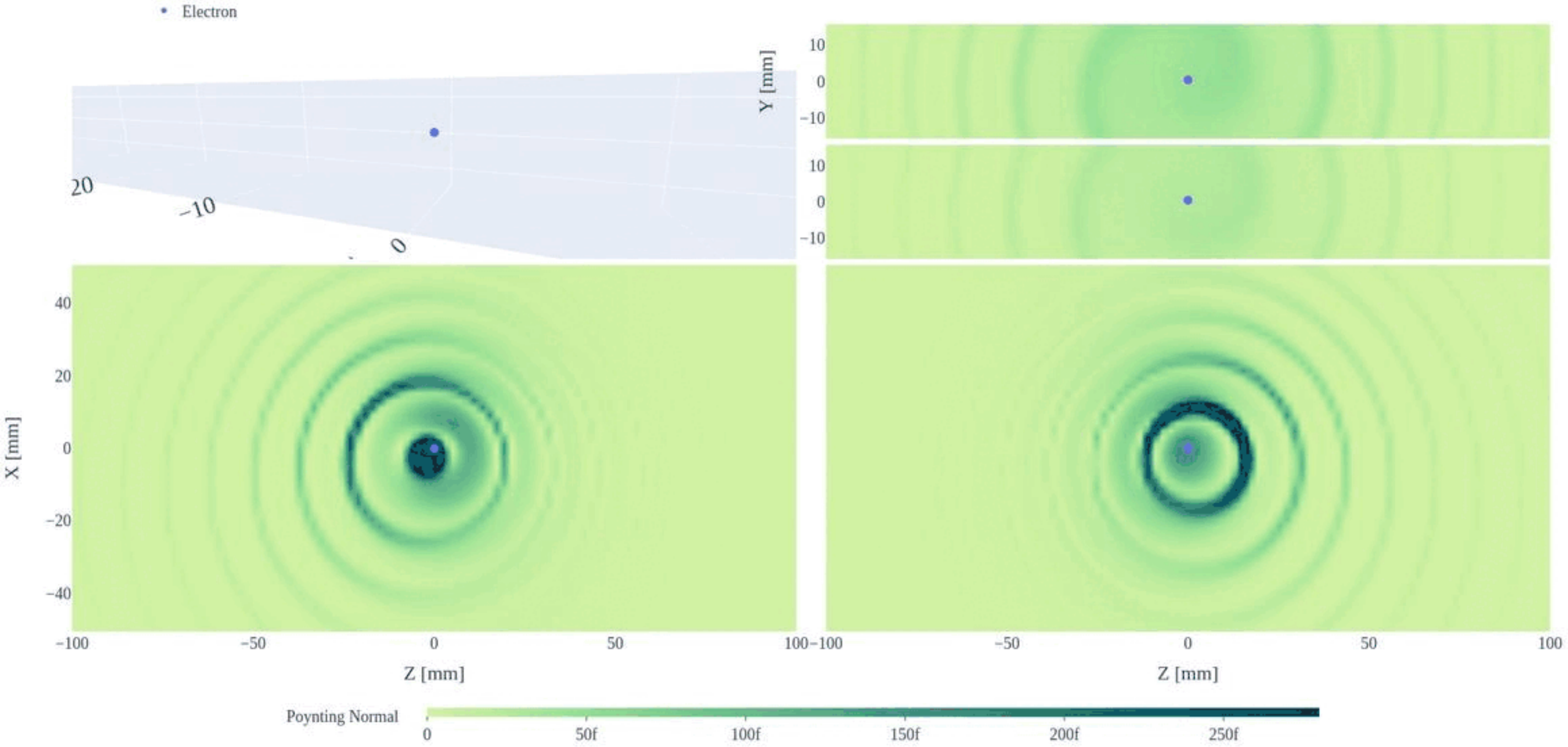


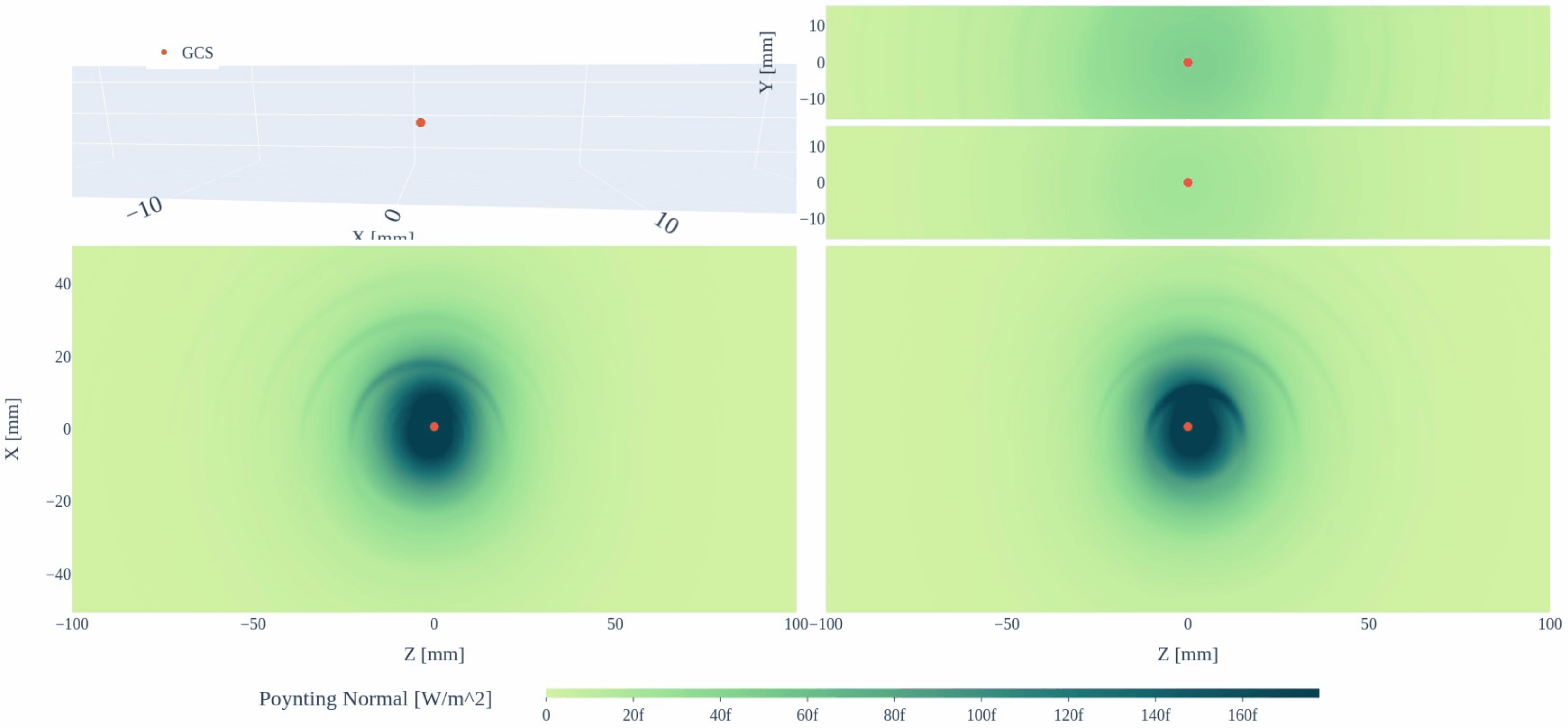


Andi Tan (Princeton)


Potential (Es) (X)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
-60
-40
-20
0
20
40
60
X / mm
Potential (Es) (X)

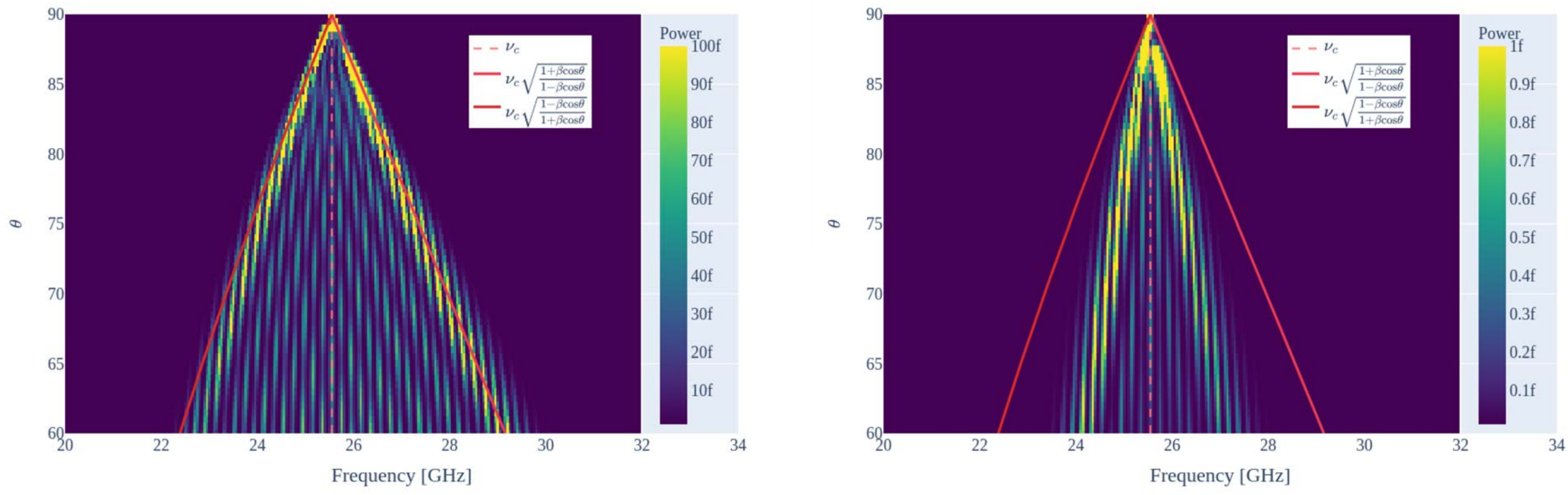

V
18600
16345
14091
11836
9582
7327
5073
2818
0
Potential
Cross section C
Cutplane at Z 0.000 mm
Maximum on Plane (Plot) 18600 V
Minimum on Plane (Plot) 0 V
Maximum (Solver) 18600 V
Minimum (Solver) 0 V
Y
Z
X


Electron
Y [mm]
X [mm]
Z [mm]
Z [mm]
Poynting Normal
0
50f
100f
150f
200f
250f


GCS
−10
0
10
X [mm]
Y [mm]
10
0
−10
10
0
−10
X [mm]
40
20
0
−20
−40
−100
−50
0
50
100
−100
−50
0
50
100
Z [mm]
Z [mm]
Poynting Normal [W/m^2]
0
20f
40f
60f
80f
100f
120f
140f
160f

Doppler Shifting vs. Antenna Position

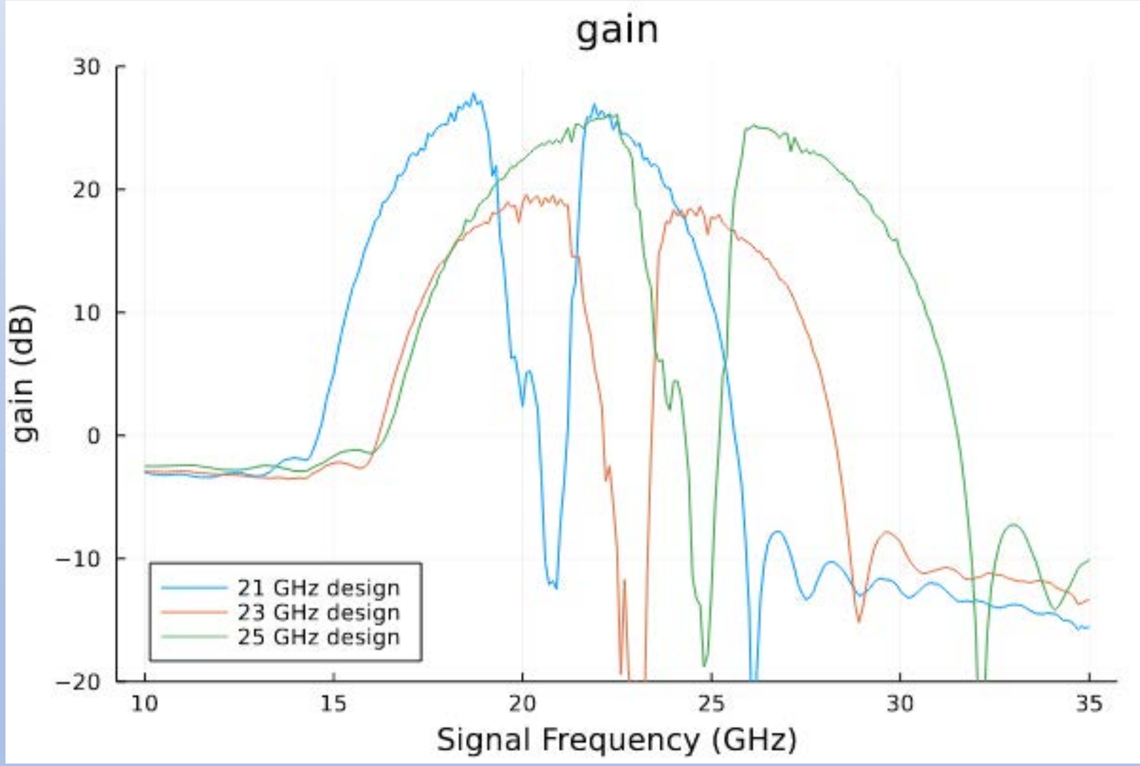
Andi Tan (Princeton)

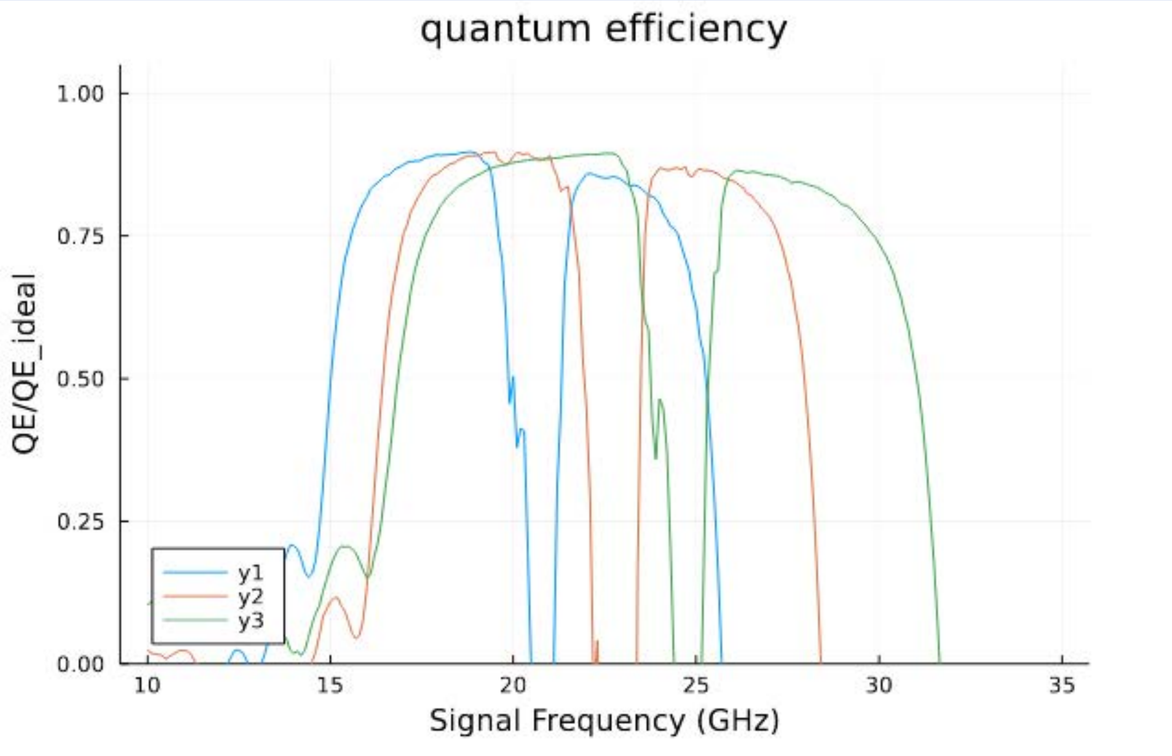


Antenna Angular Gain not yet applied – still evaluating options

Quantum-Limited Parametric Amp

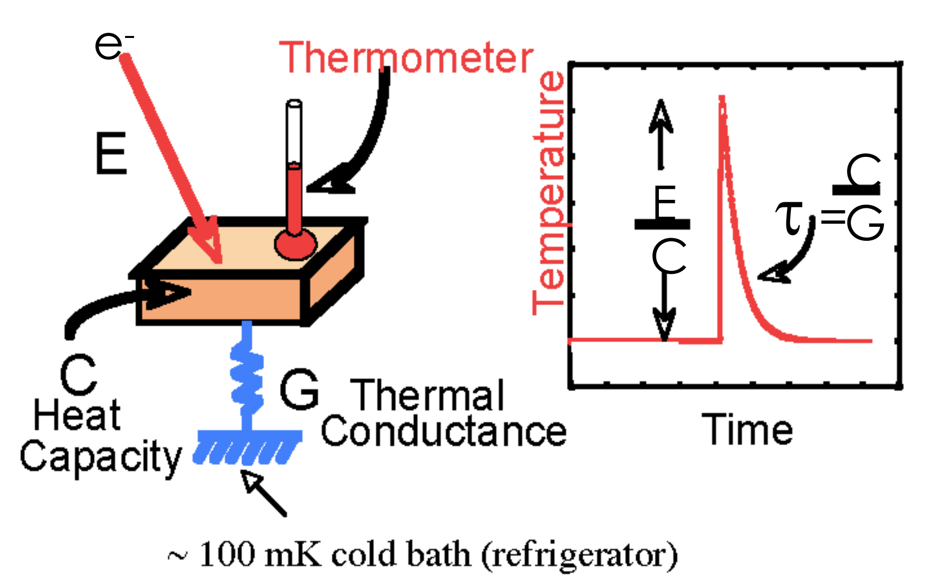
High Frequency Josephson Traveling Wave Parametric Amp (TWPA)

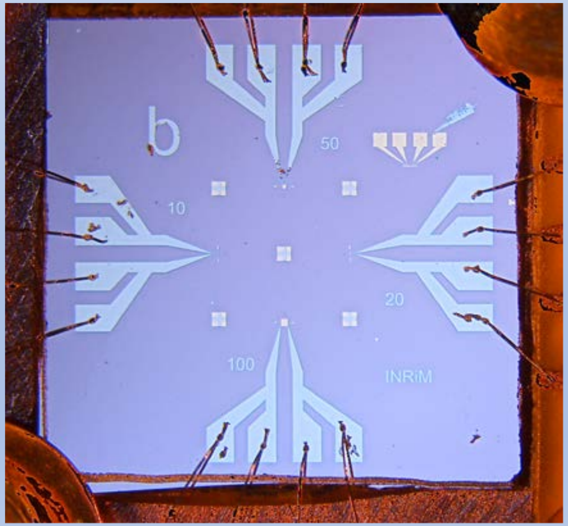




Joint Project w/ MIT and Project 8

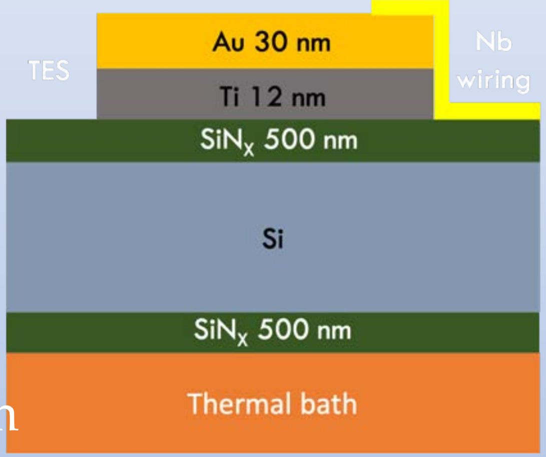
Measurement Arm: µCal

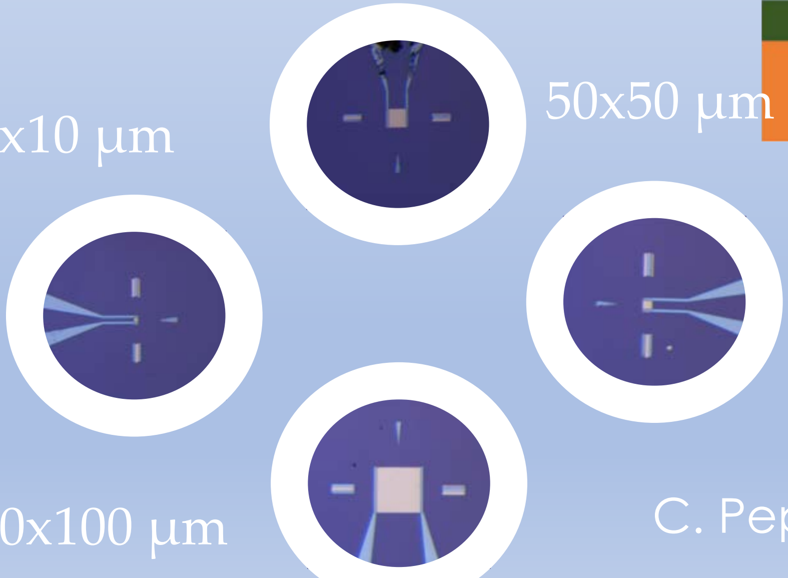




Thin sensors:

~1 eV electron can be stopped with very small C

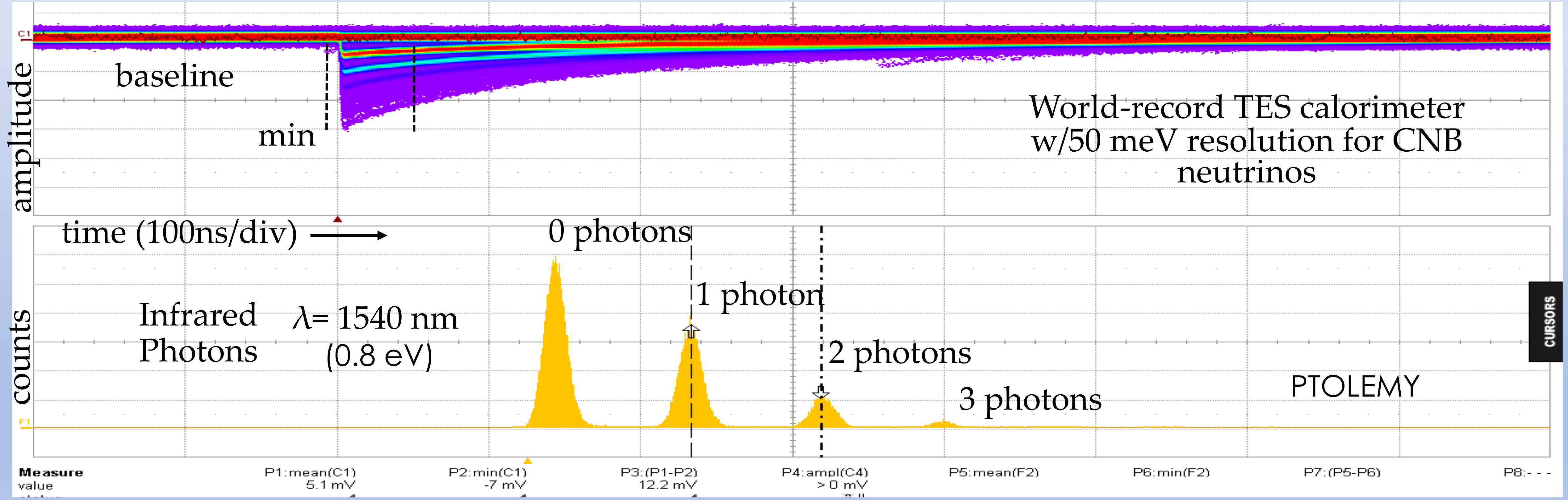




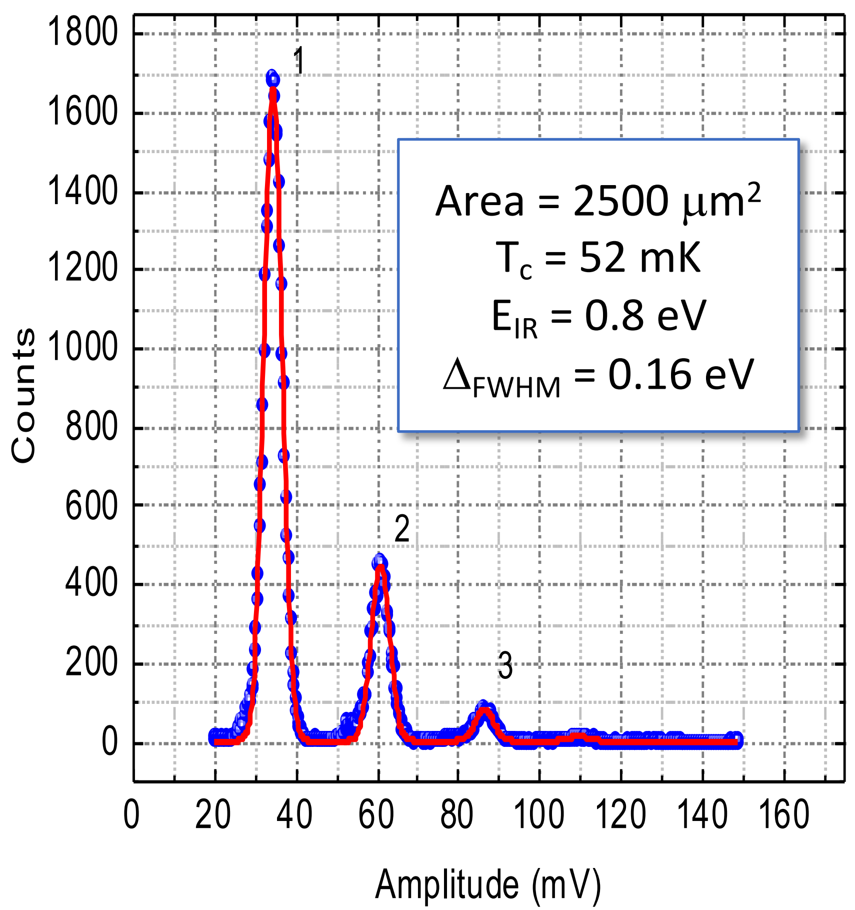
C. Pepe, E. Monticone, M. Rajteri

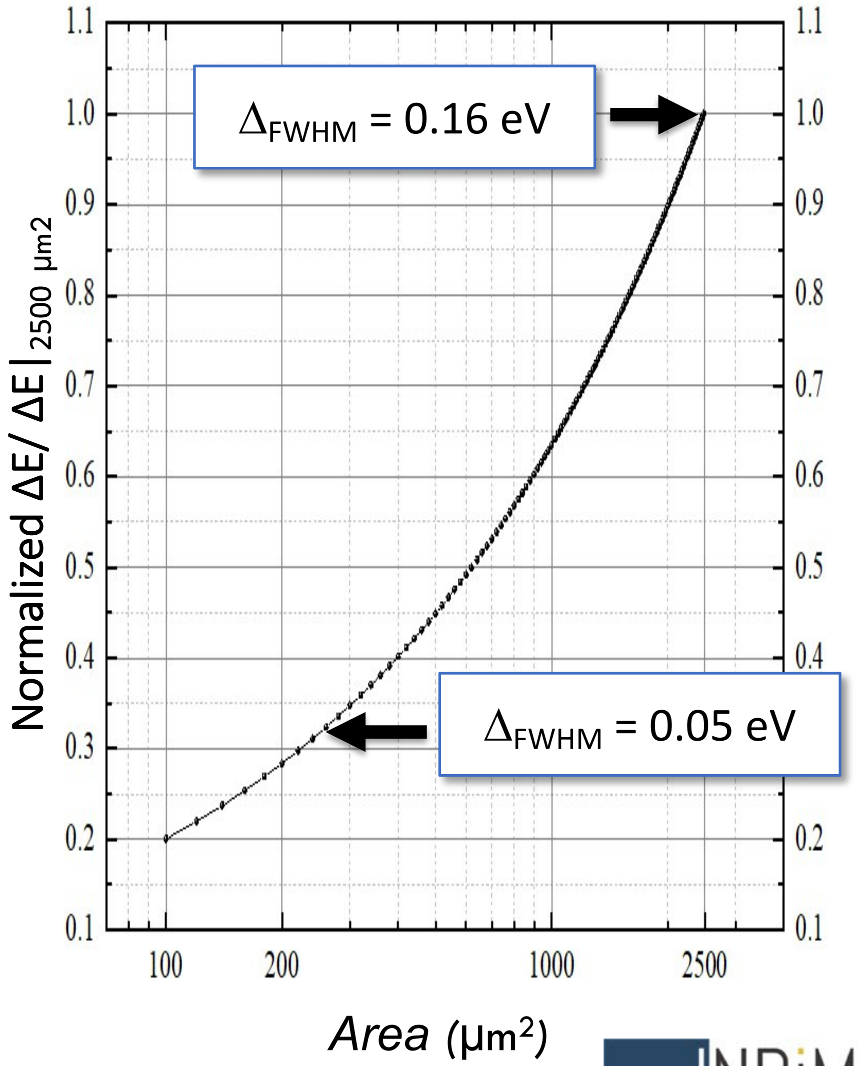
Mauro Rajteri, Eugenio Monticone and others, https://doi.org/10.1007/s10909-019-02271-x
"TES Microcalorimeter for PTOLEMY", J. Low Temp. Phys. 199 (2020) 138-142.

1% energy resolution at optical photon energies, i.e. measures the wavelength of a 500nm photon to a few nm



C. Pepe, E. Monticone, M. Rajteri





INRiM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA

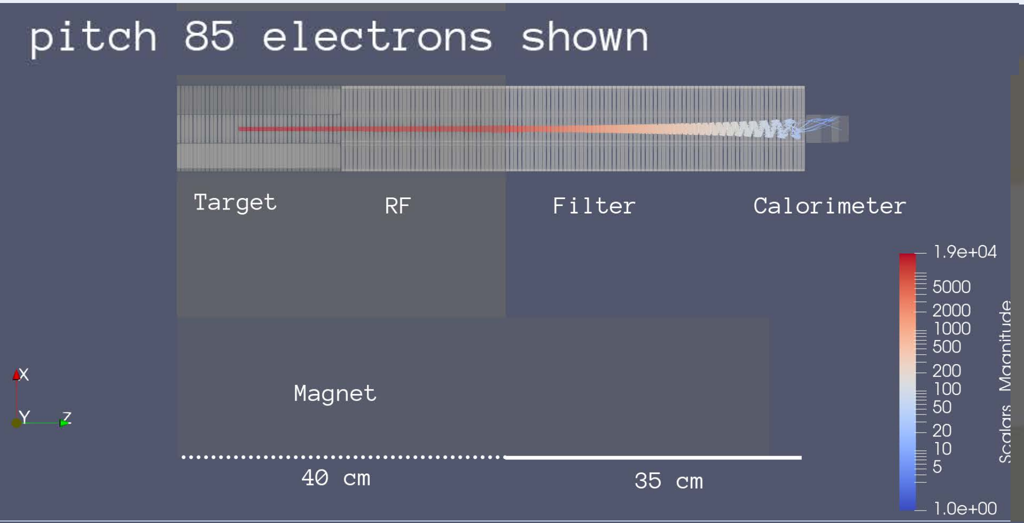
Resolution of ~ m_ν :

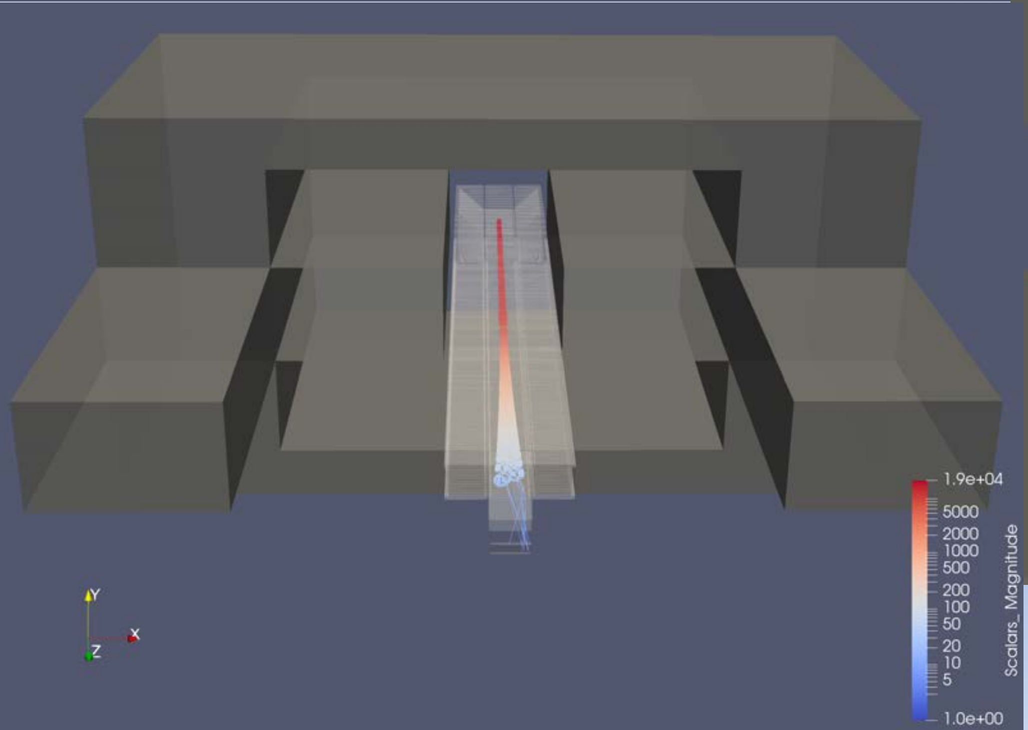
Area ~ 15 μm x 15 μm

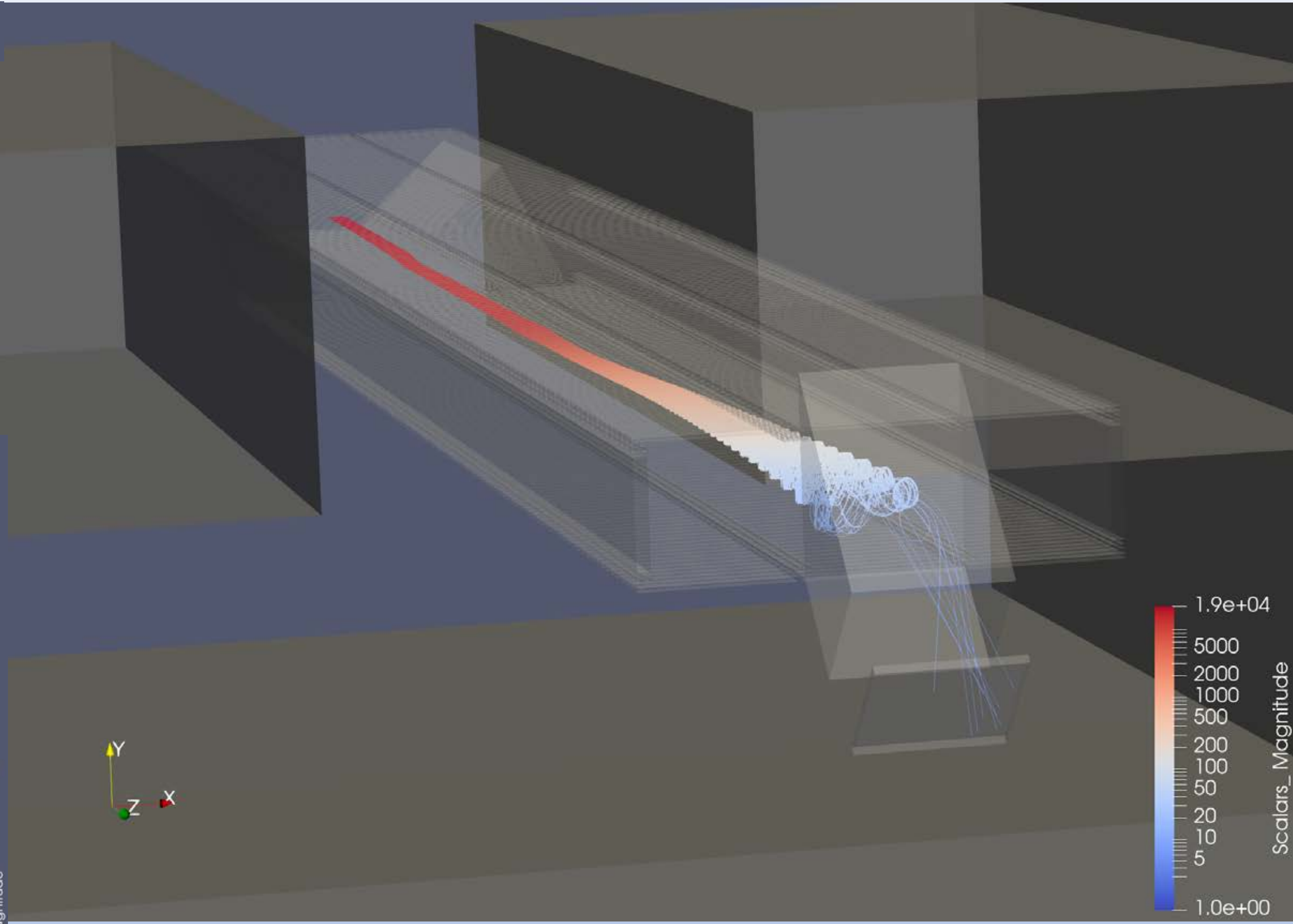
C. Pepe, E. Monticone, M. Rajteri

→ Demonstrate with electrons

End-to-end Transport w/Kassiopeia

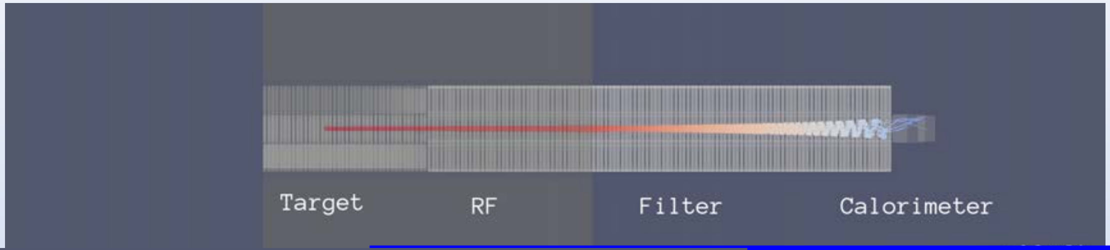




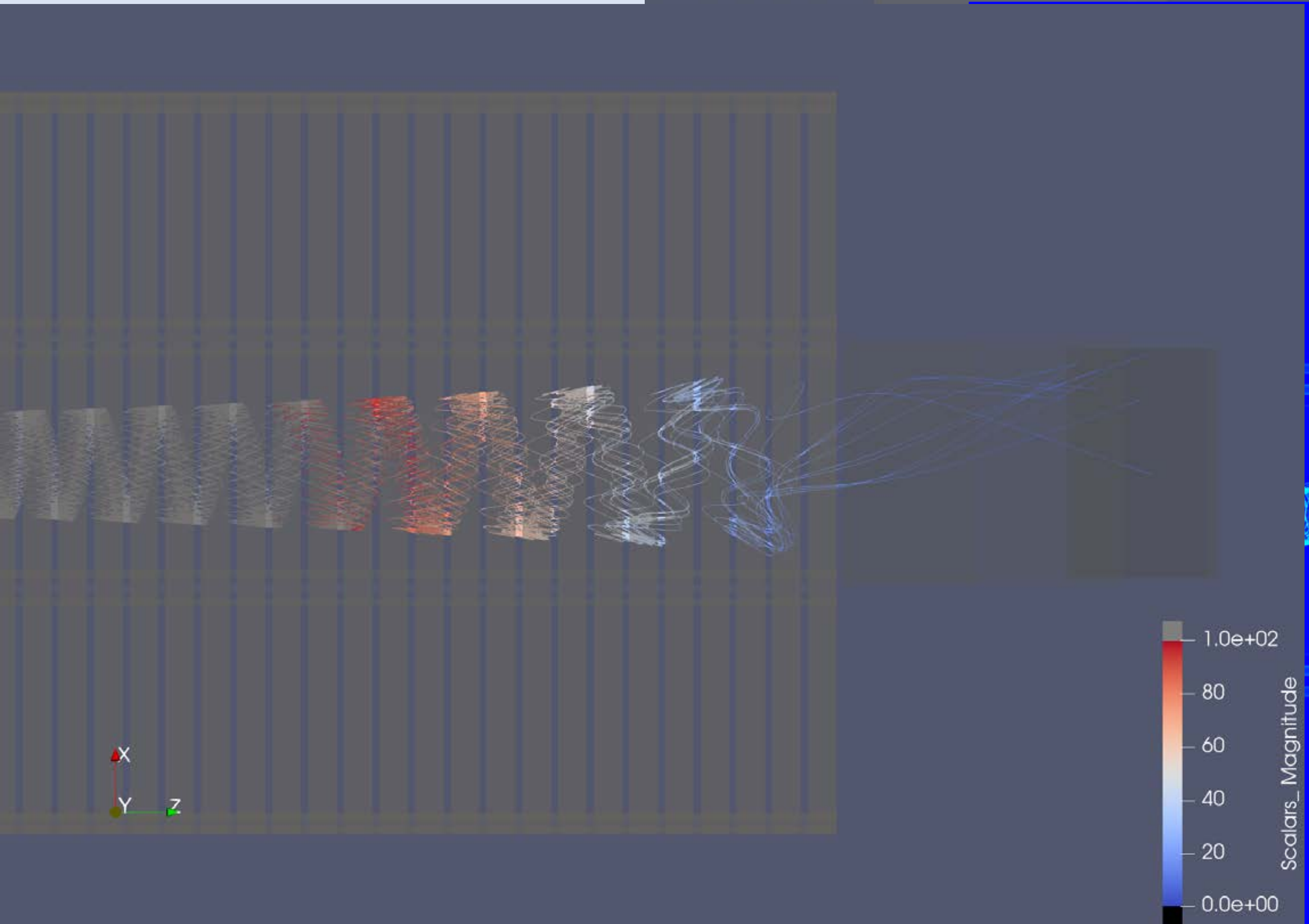


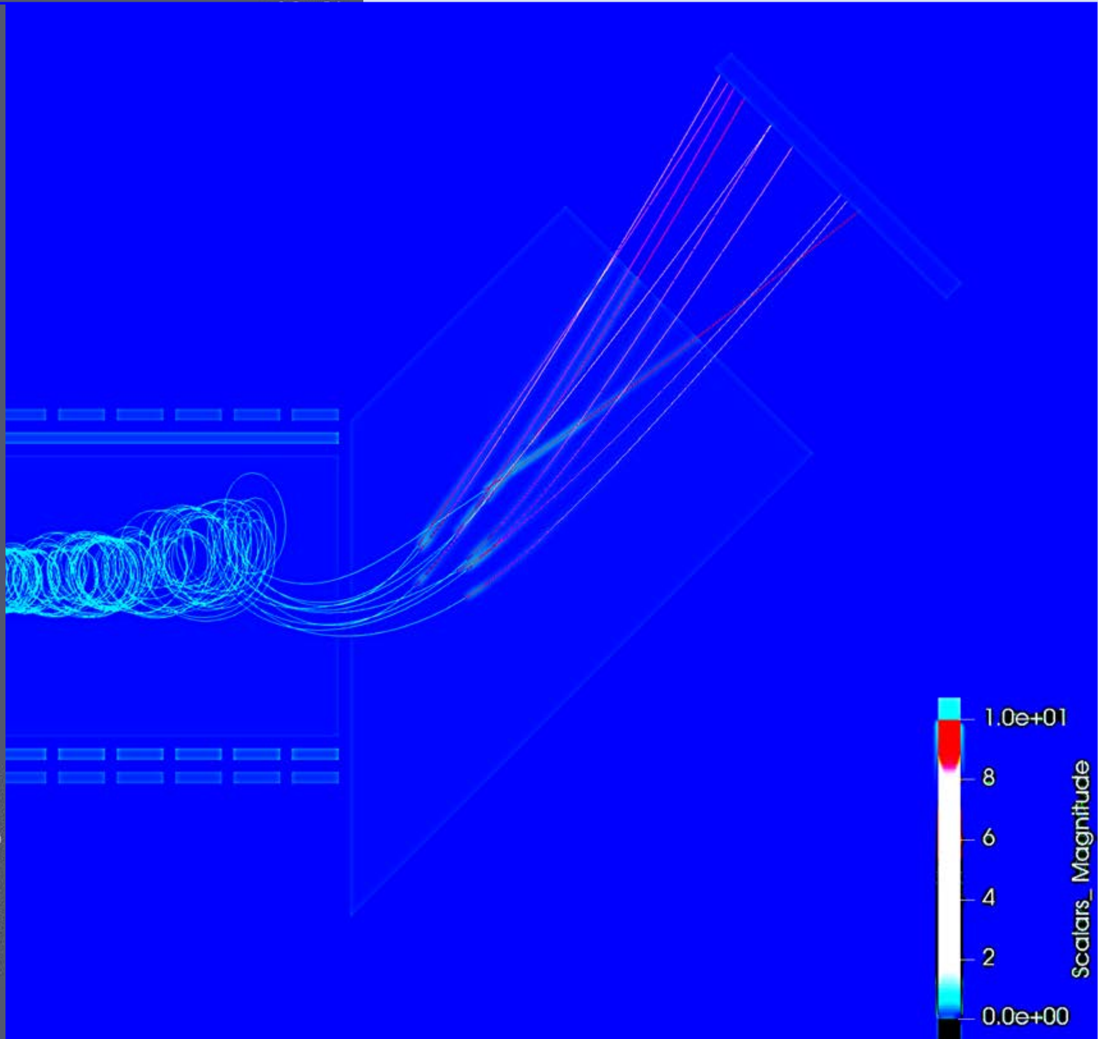
Wonyong Chung (Princeton)

Zero-Field Calorimeter Transition



Wonyong Chung (Princeton)



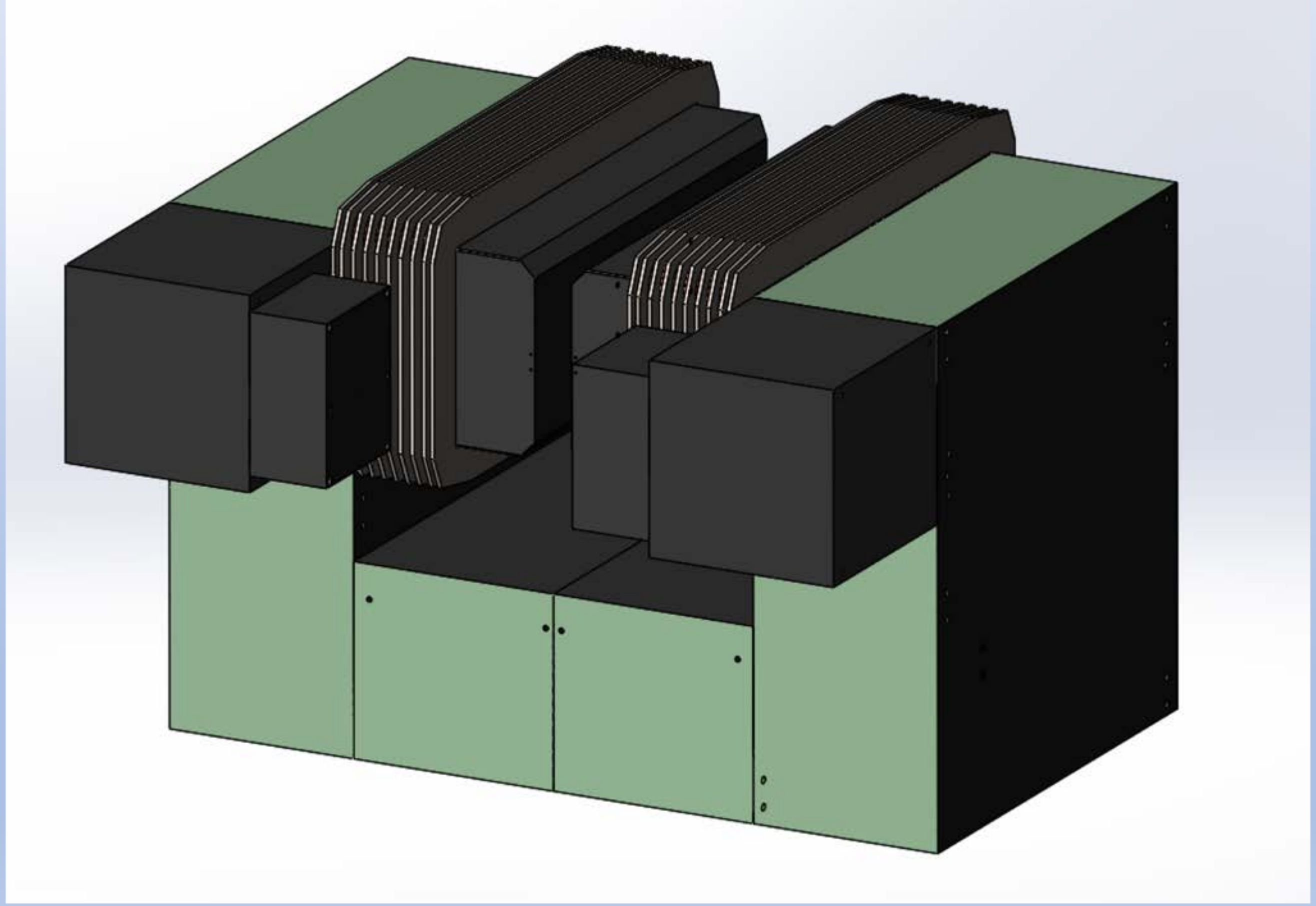


LNGS Full-Scale Prototype

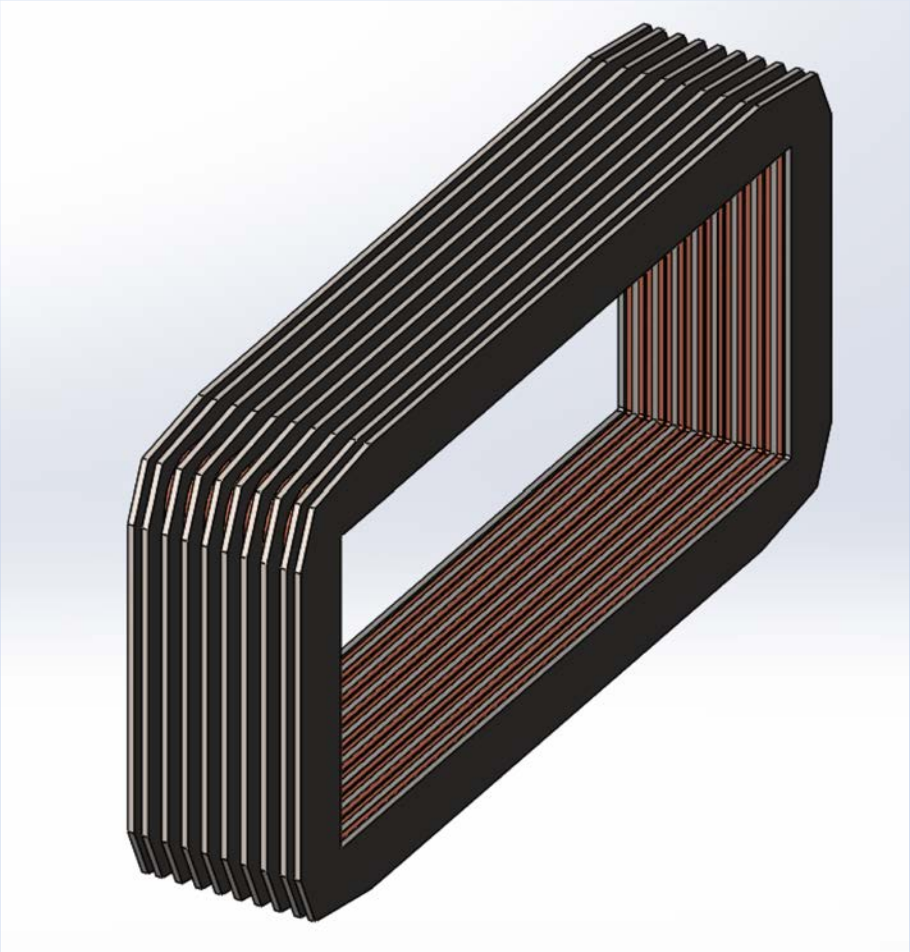
JOHN TEMPLETON FOUNDATION
Inspiring Awe & Wonder

- Based on an initial test integration at Princeton:
    - Iron-return flux magnet
    - small 14-C target
    - RF antenna
    - Cryostat
    - Filter electron HV
    - Tagging silicon detector
- Validate the construction design of the LNGS prototype and launch fabrication in Fall 2022
- Operate through 2024, then switch to superconducting coil

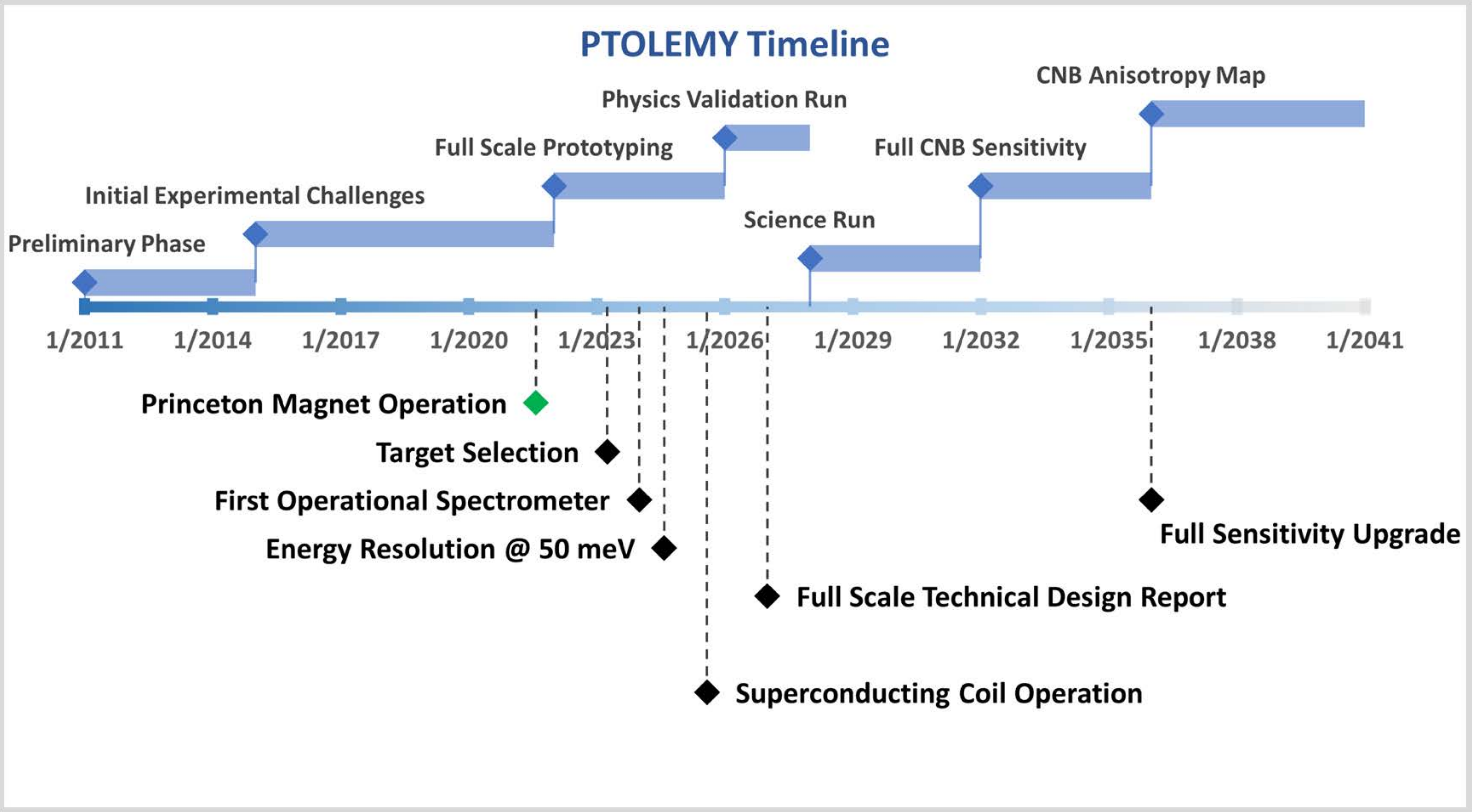
LNGS Magnet Design



Coil and Power Supply Specs submitted to Danfysik



Andi Tan (Princeton)


PTOLEMY Timeline
CNB Anisotropy Map
Physics Validation Run
Full Scale Prototyping
Full CNB Sensitivity
Initial Experimental Challenges
Science Run
Preliminary Phase
1/2011
1/2014
1/2017
1/2020
1/2023
1/2026
1/2029
1/2032
1/2035
1/2038
1/2041
Princeton Magnet Operation
Target Selection
First Operational Spectrometer
Energy Resolution @ 50 meV
Full Sensitivity Upgrade
Full Scale Technical Design Report
Superconducting Coil Operation

Summary

- The sustained effort in PTOLEMY R&D is a testament to the importance we place on pushing the frontier of early Universe neutrino cosmology
- We are headed for a break through on detecting the absolute neutrino mass with our new high precision measurement system
- The future of CNB detection is in our hands and we have to do everything we can to carry that responsibility forward until it can be finally achieved

1. Are there general topics that you would like to see addressed by the community in order to improve our physics reach? Theory, experimental techniques, new ideas?
Strongly in favor of joint theory-exp efforts on target physics. Program of measurements to identify final-state systems that are optimal for neutrino mass observables.

2. What possibilities do you see for future synergies, cooperation and collaborations in this community? Beyond this workshop, what would be good ways to begin and promote these collaborations?
PTOLEMY electron RF-tracking and Project 8 RF energy measurements (and KATRIN time-tagging?) could learn a lot from each other. Perhaps a review article on RF techniques.

3. How do you see the next 5-10 years unfolding? What milestones do you expect? What roadblocks are you worried about? How will the different approaches compare with each other?
LNGS full-scale PTOLEMY prototype operational by 2024. Full endpoint electron target-to-TES energy resolution of 50 meV is the expected milestone (excluding target physics). Roadblocks are primarily in the challenges of commissioning the new filter. Beyond 2024, filter and target scalability are milestones (next slide).

4. If and when a direct experiment measures a neutrino mass, what will be necessary to persuade the community of the validity of the measurement -- especially if the value conflicts with cosmological constraints?
Independent methods and systematic controls over target physics and measurements systems.

5. What topics or questions would you like to introduce for this discussion?
More collaboration on the future of the neutrino mass measurements.

Milano-Bicocca, Italy
7 June 2022
Chris Tully

Antenna Studies