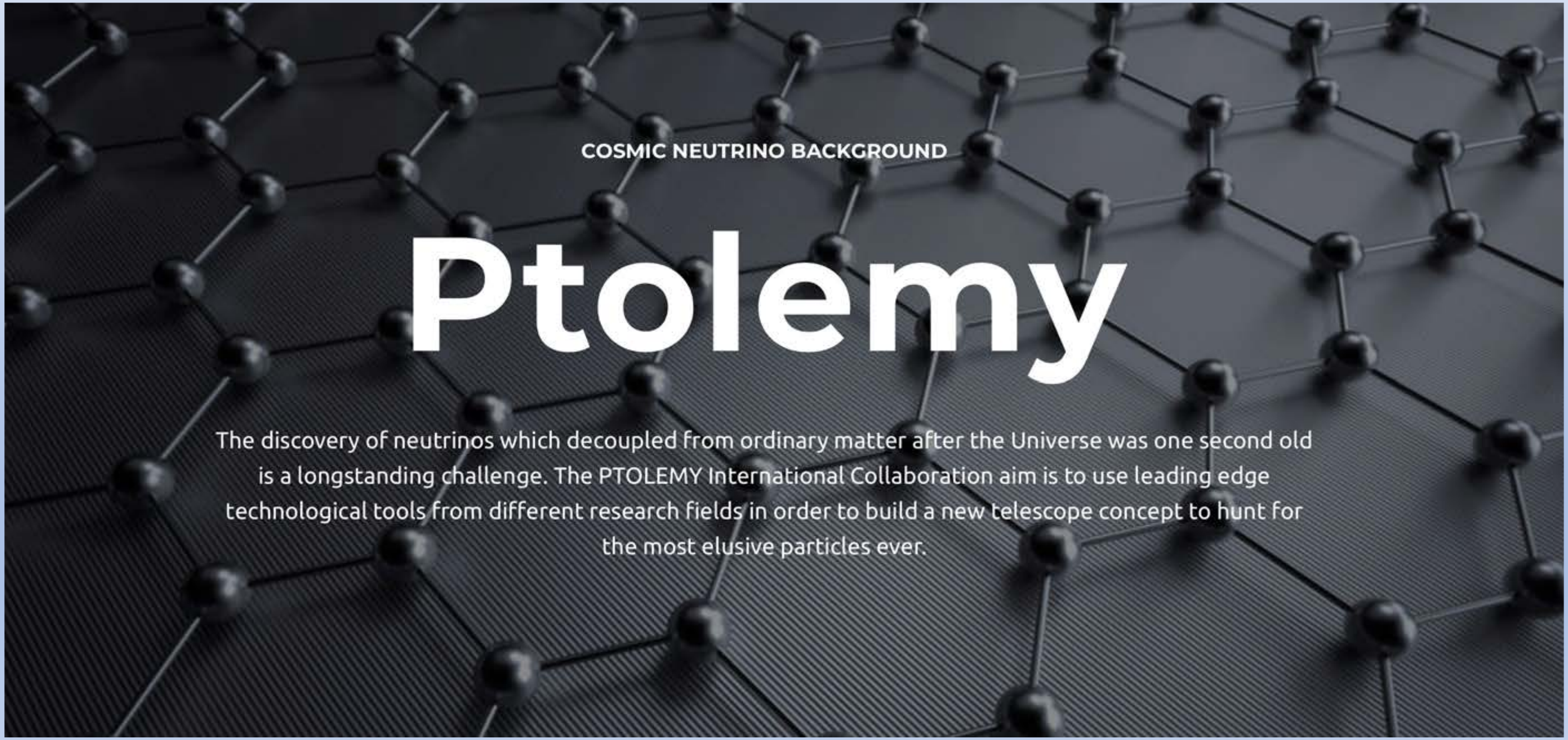
PTOLEMY: A detector for the oldest neutrinos in the Universe

Chris Tully (Princeton)

26 April 2023
L'Aquila Joint Astroparticle Colloquium
Gran Sasso Laboratory

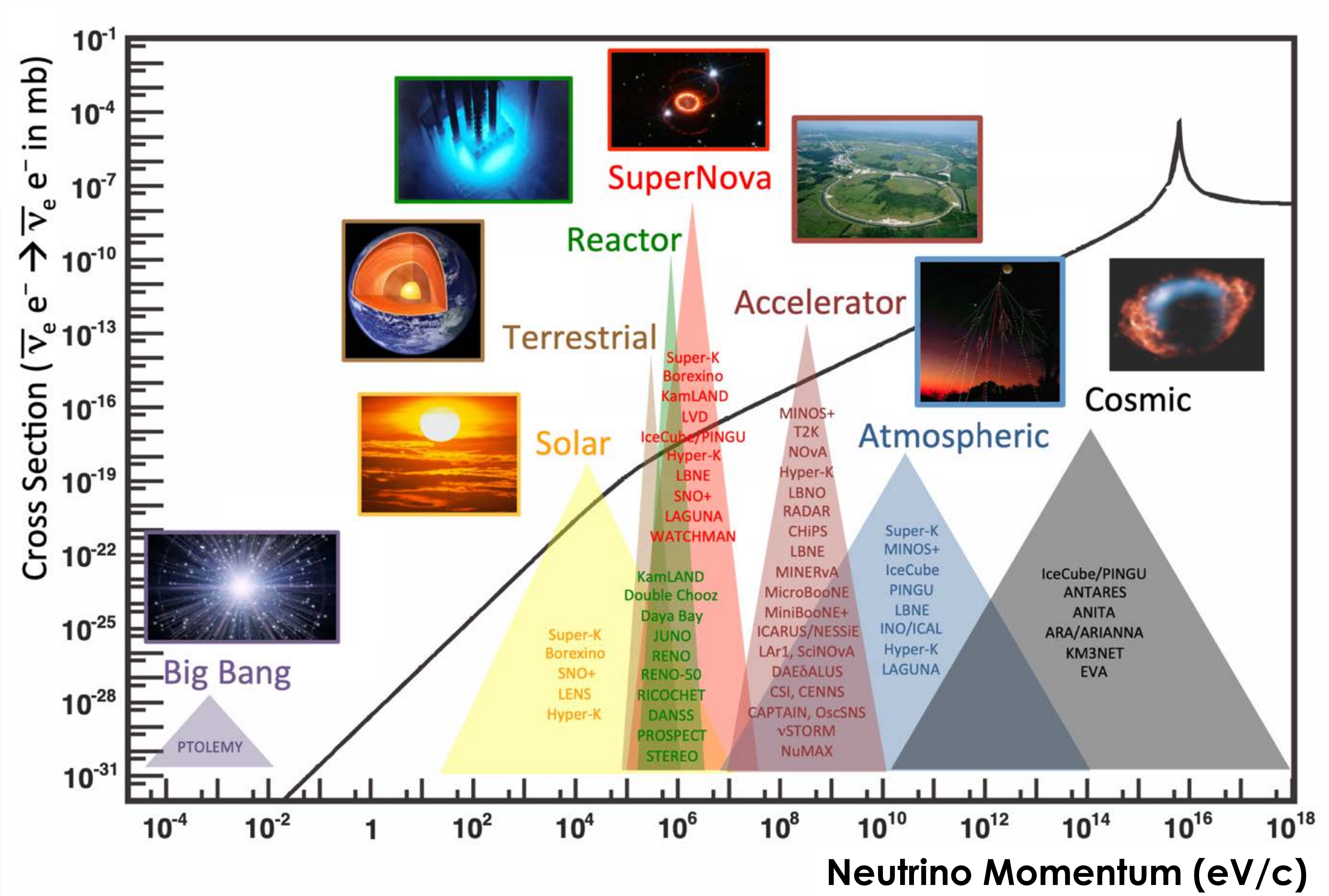


JOHN TEMPLETON FOUNDATION
Inspiring Awe & Wonder

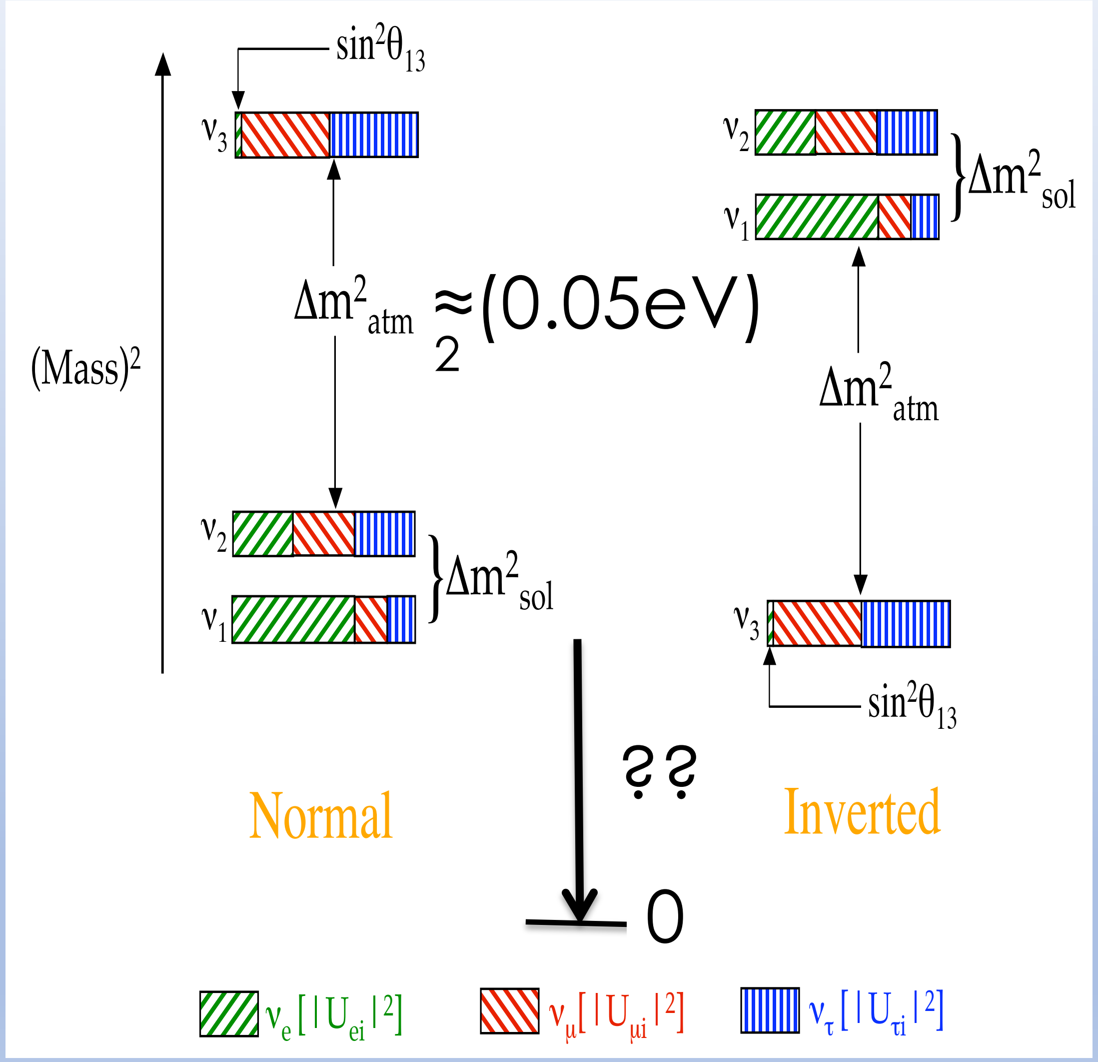
SIMONS FOUNDATION

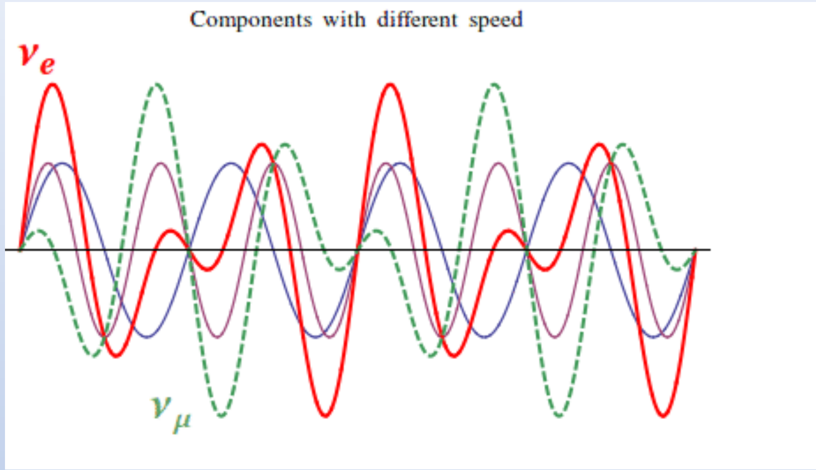
http://ptolemy.lngs.infn.it

Neutrinos sources across the Cosmos



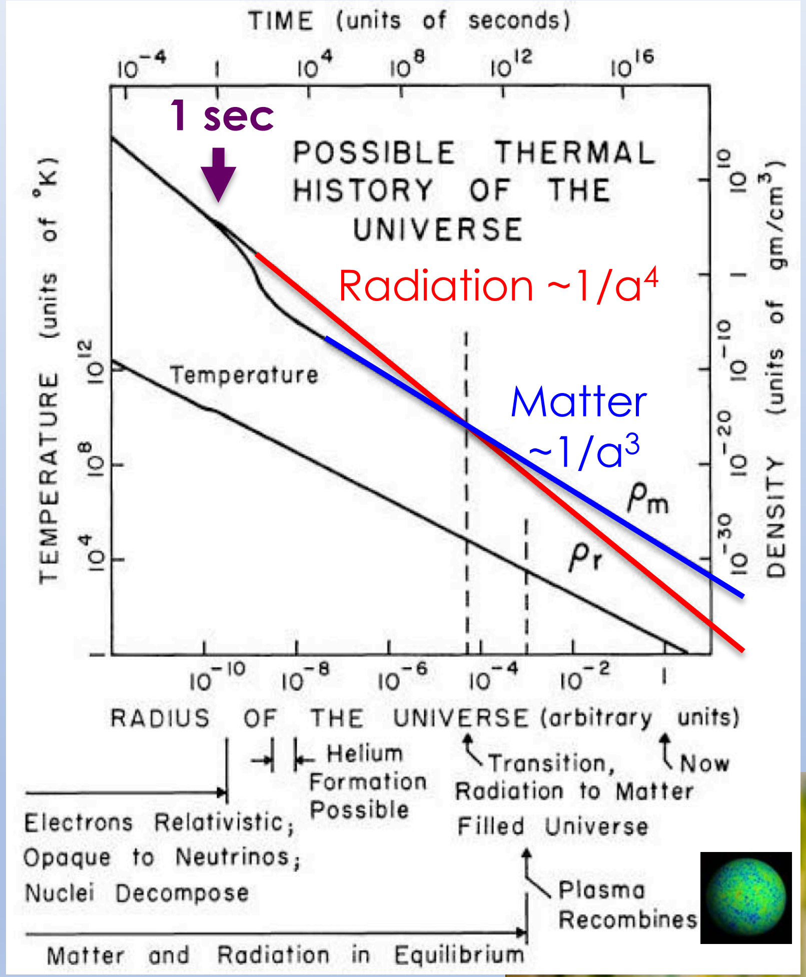
Neutrino Masses from Oscillations





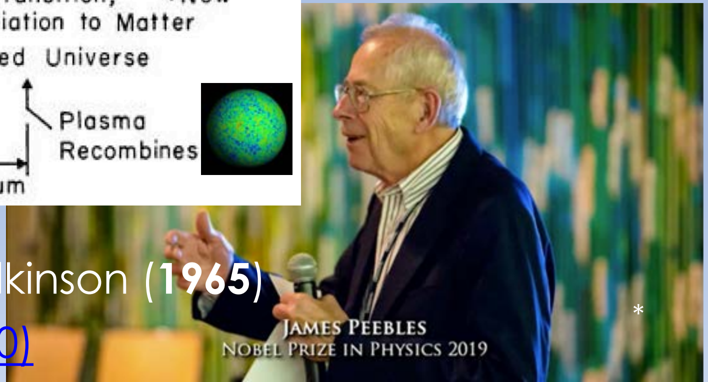
3 mass eigenstates
X
3 flavors
(electron, muon, tau)

Cosmic Neutrino Background



Dicke, Peebles*, Roll, Wilkinson (**1965**)

Cosmology's Century (2020)



*

Neutrino number density:

$n_\nu = 112/cm^3$

Temperature:

$T_\nu \sim 1.95K$

Time of decoupling:

$t_\nu \sim 1$ second

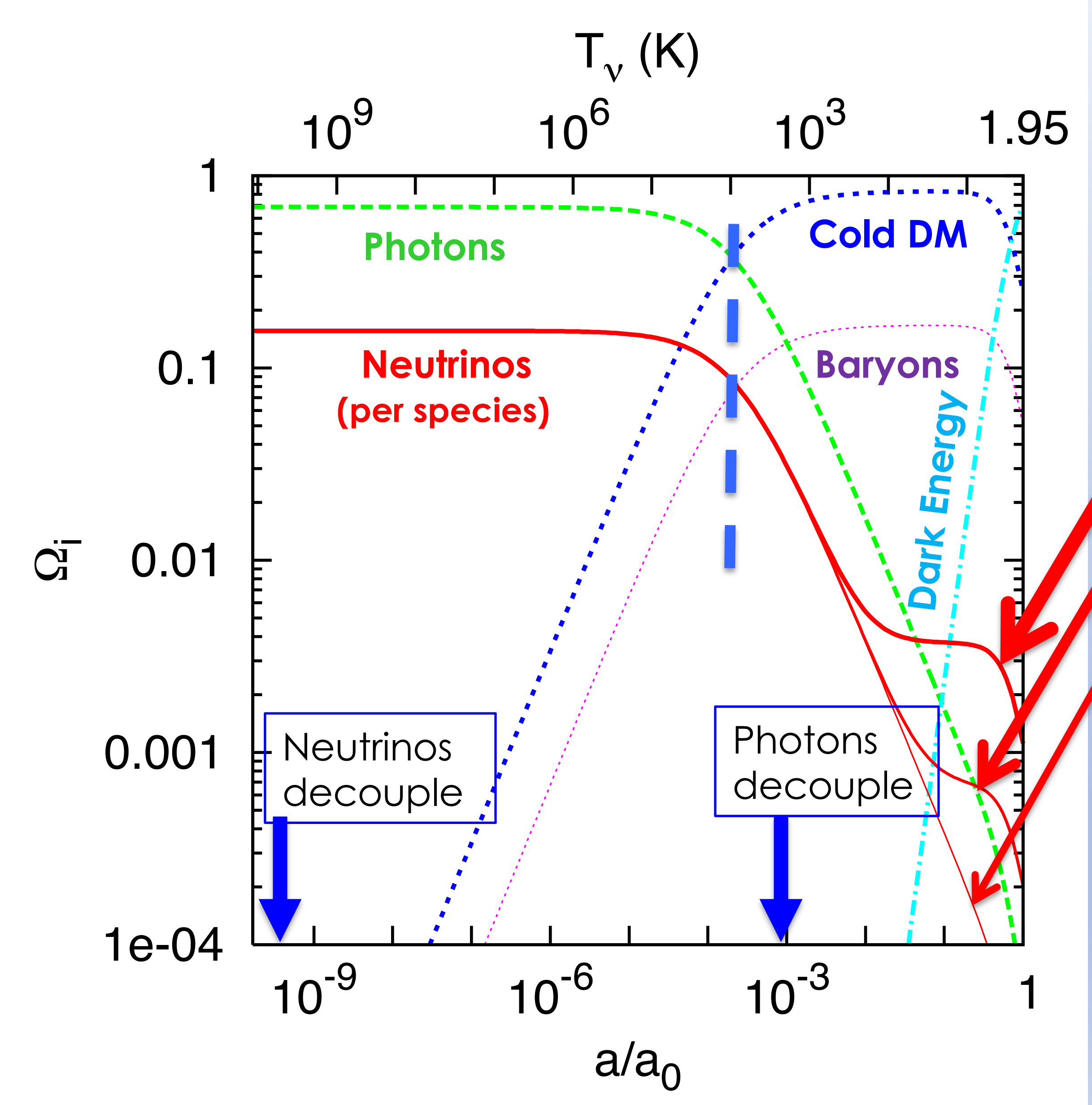
neutron/proton ratio @start of nucleosynthesis

Velocity distribution:

$\langle v_\nu \rangle \sim T_\nu / m_\nu$

Non-linear distortions Villaescusa-Navarro et al (2013)

Cosmic Elements

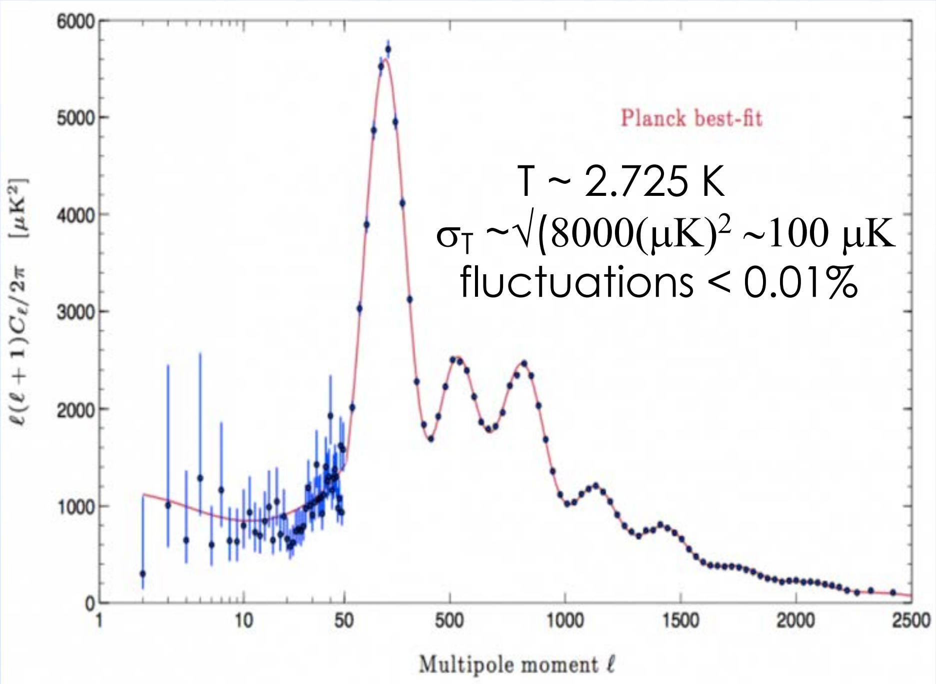


J. Lesgourgues

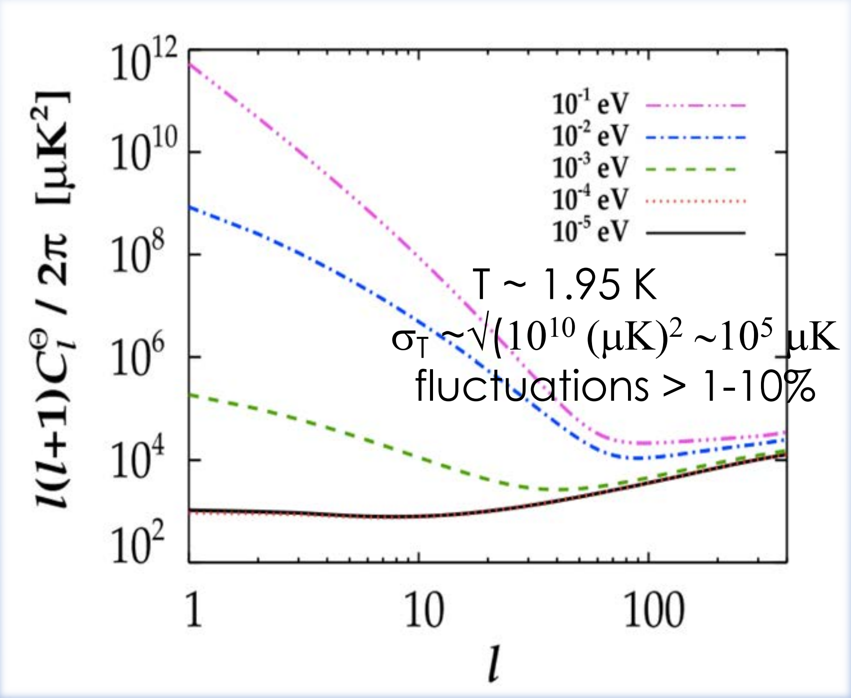
Individual neutrino contributions assuming Normal Hierarchy and m_3 = 0.05 eV, m_2 = 0.009 eV, m_1 = 0

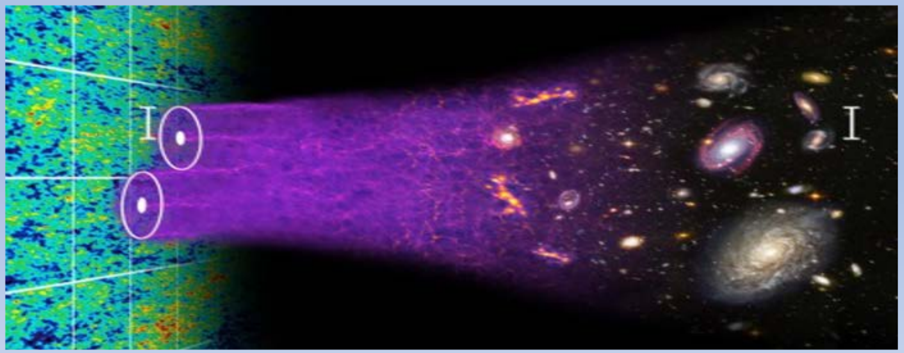
Neutrino Flux on the Sky

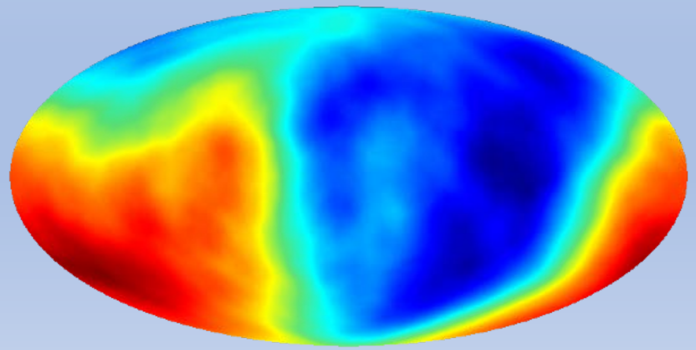
Cosmic Microwave Background (CMB)



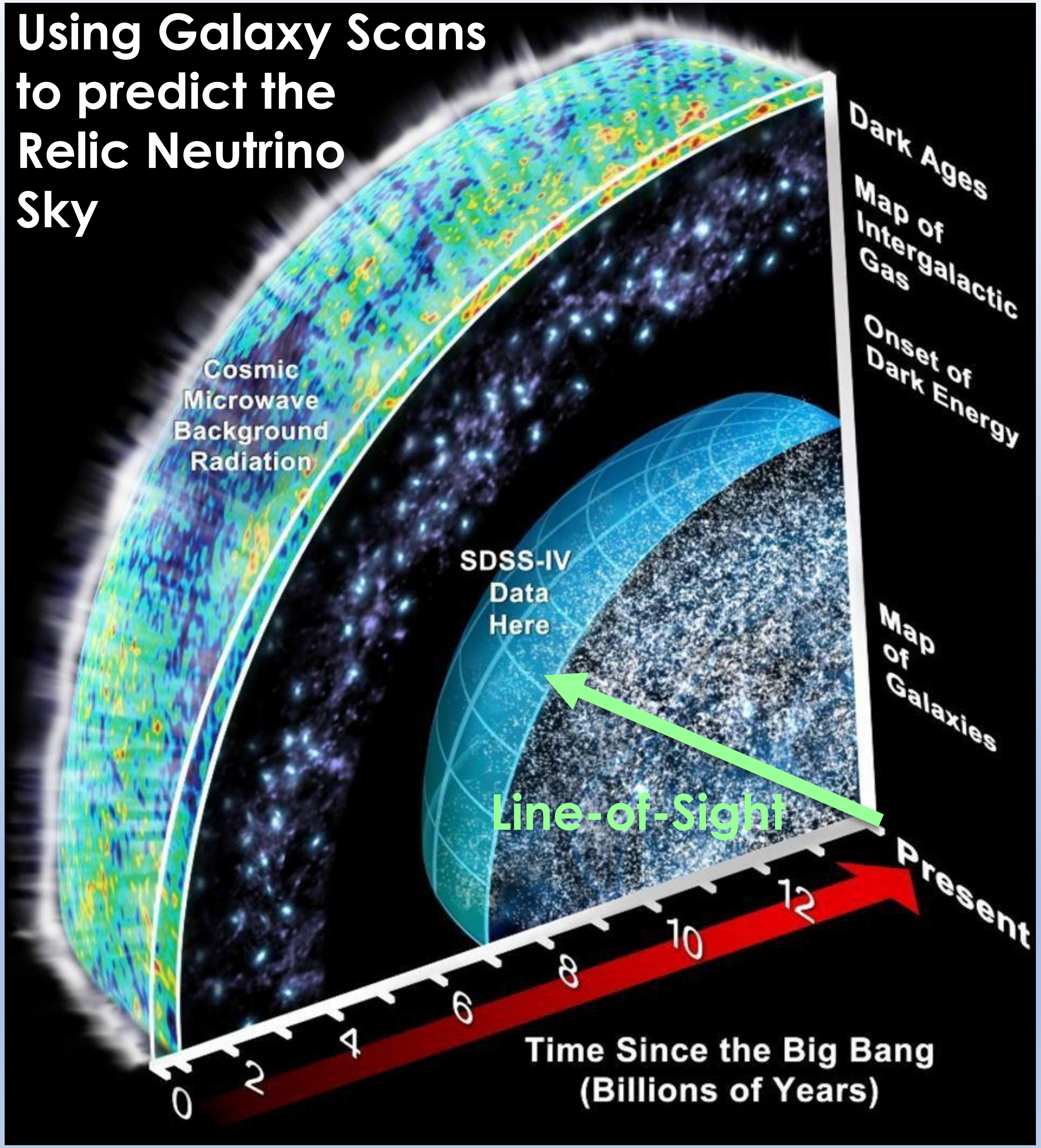
Cosmic Neutrino Background (CNB)

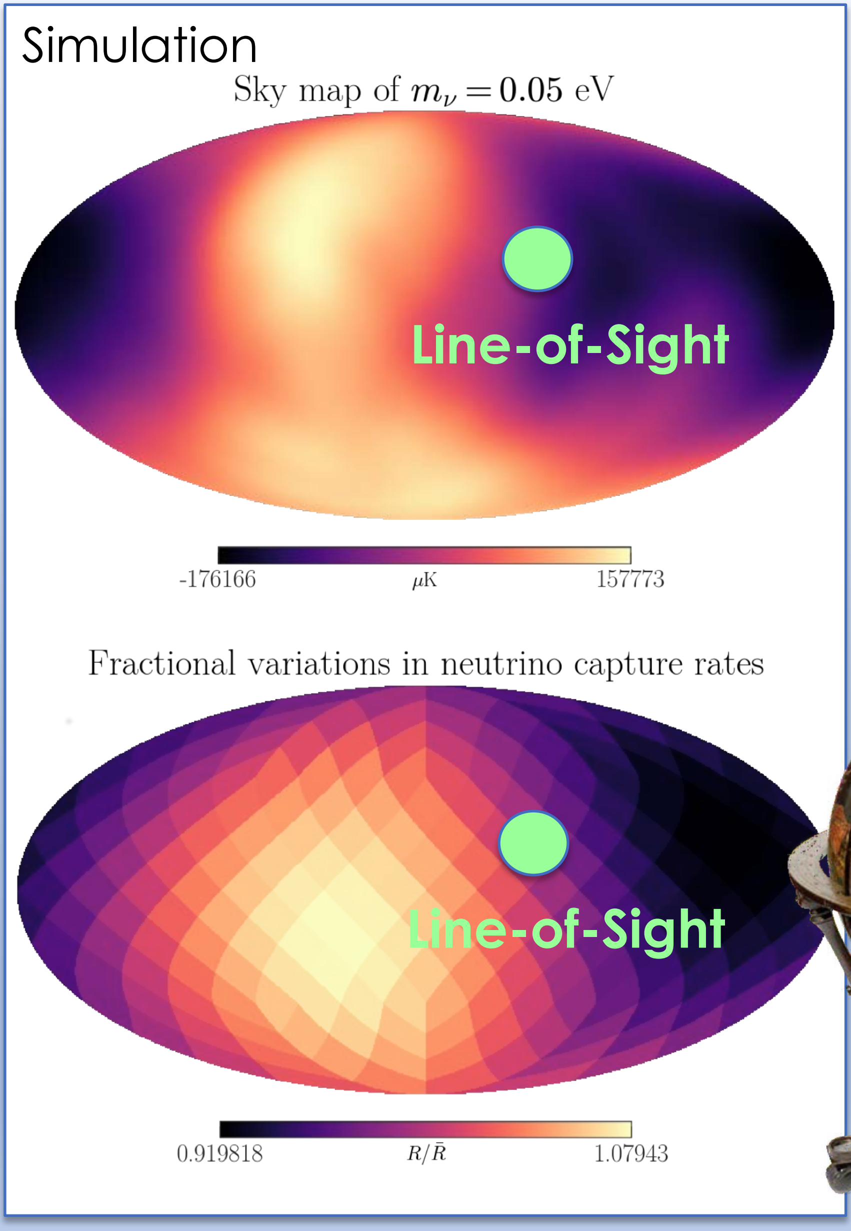






PTOLEMY: Experiment to measure relic neutrinos from the Big Bang

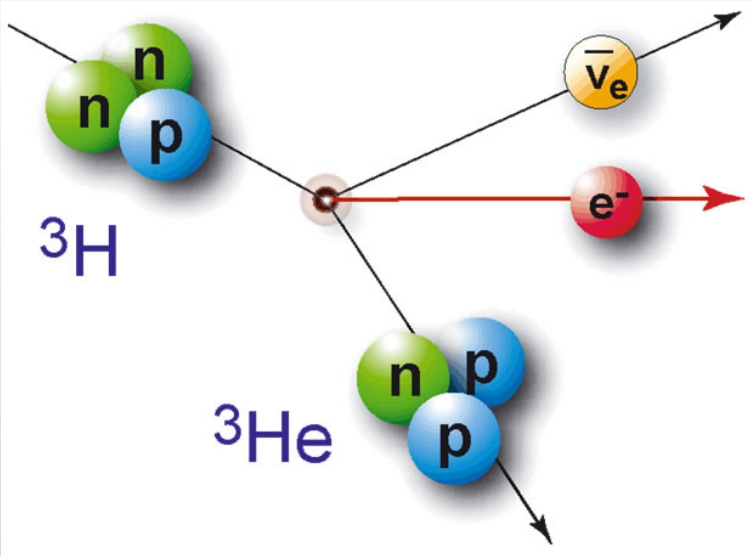




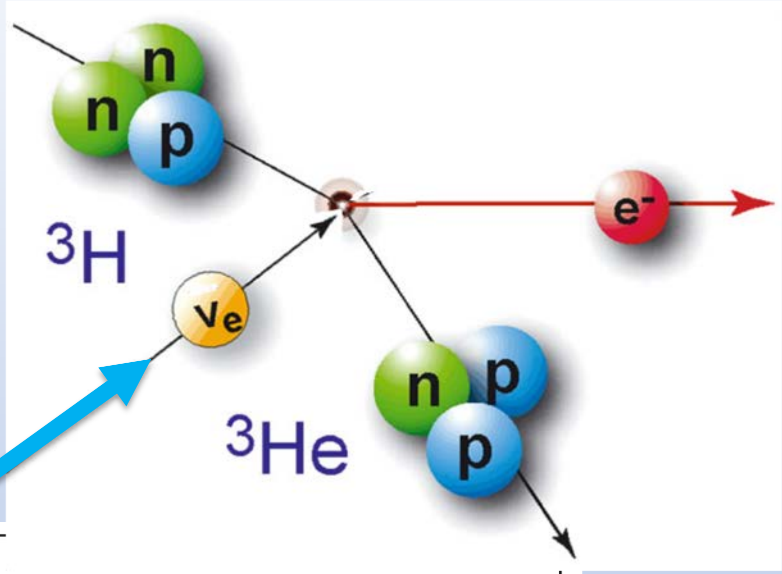
50meV neutrino mass → CNB w/ ~10% anisotropies

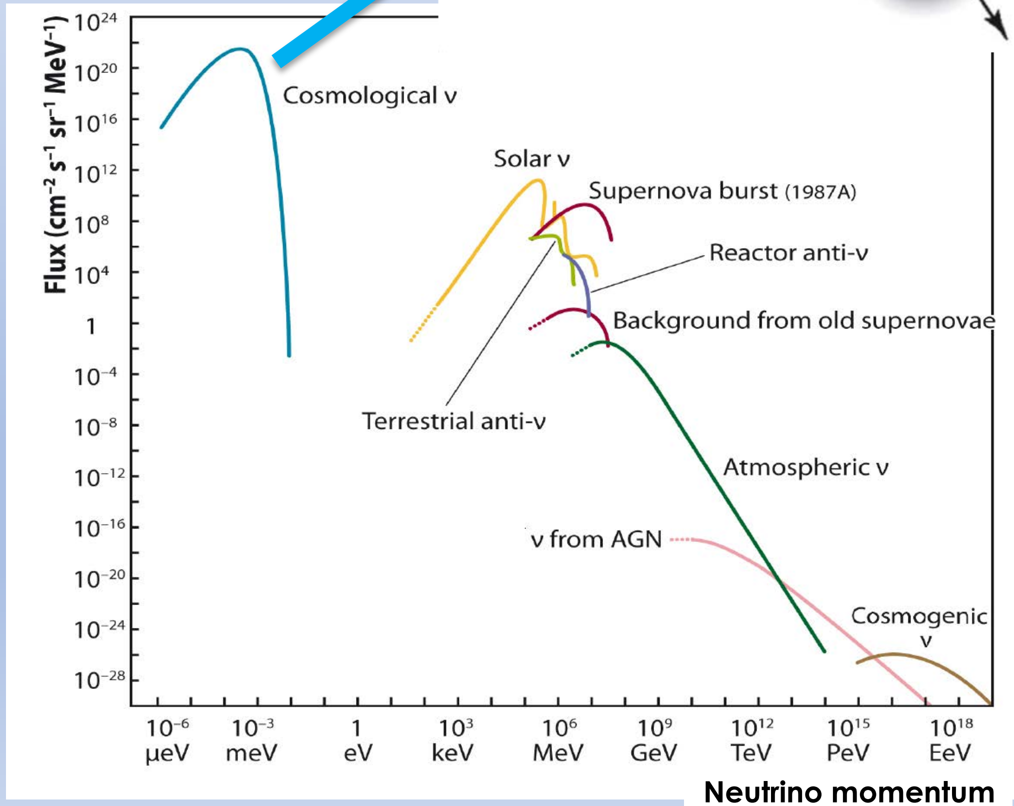
G. Zhang and C. Tully, https://arxiv.org/abs/2103.01274 (https://arxiv.org/abs/2201.01888) (Highlight article: Journal cover)

Neutrino capture on Tritium



Tritium β-decay
(12.3 yr half-life)





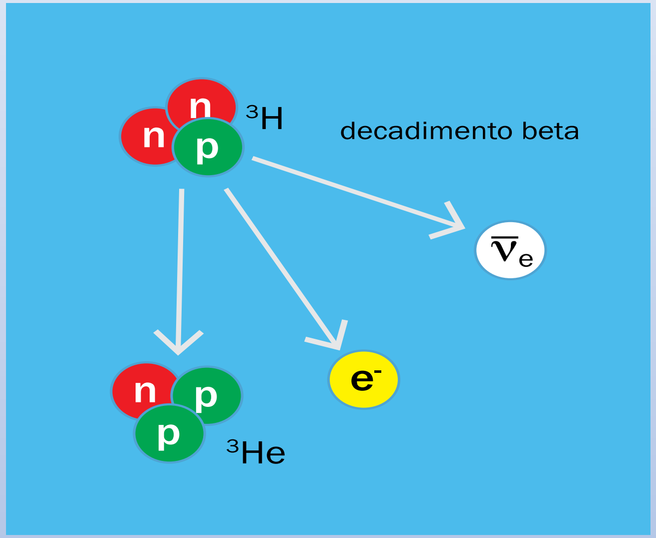
Relic neutrino momentum ~ 0.17 meV

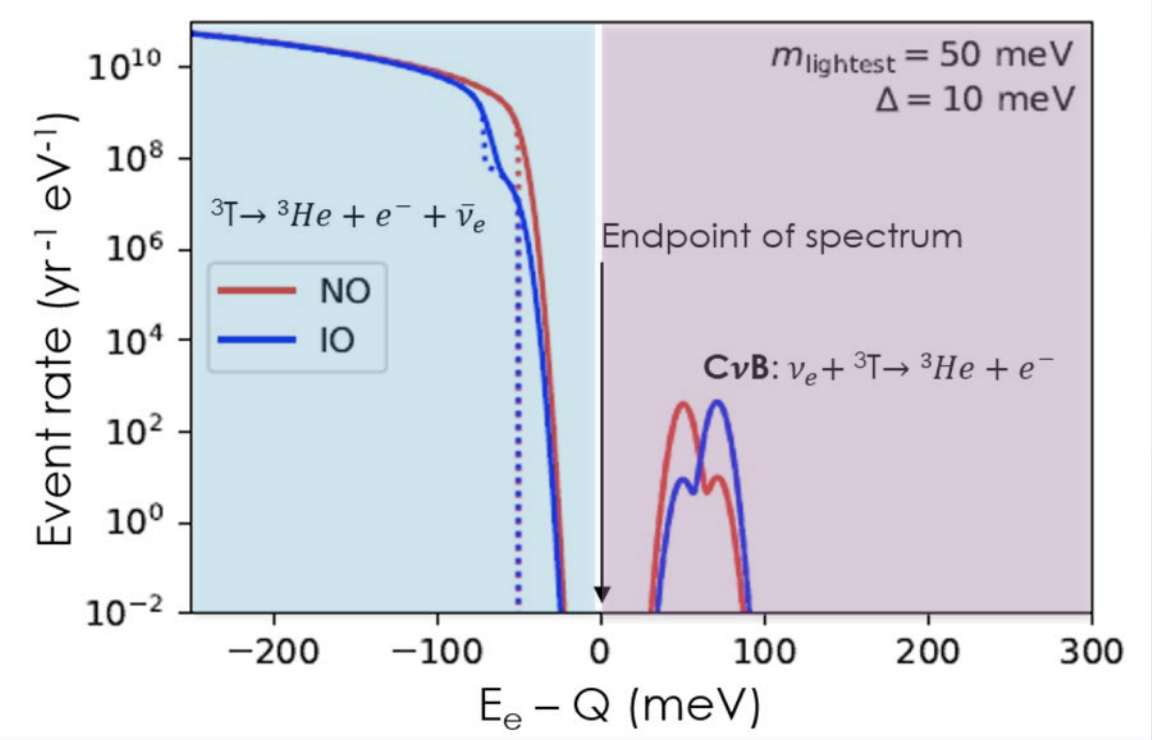
For m_ν = 50 meV,
KE = $p^2/2m$
= 0.17 meV (0.17 meV/100 meV)
= 0.3 μeV

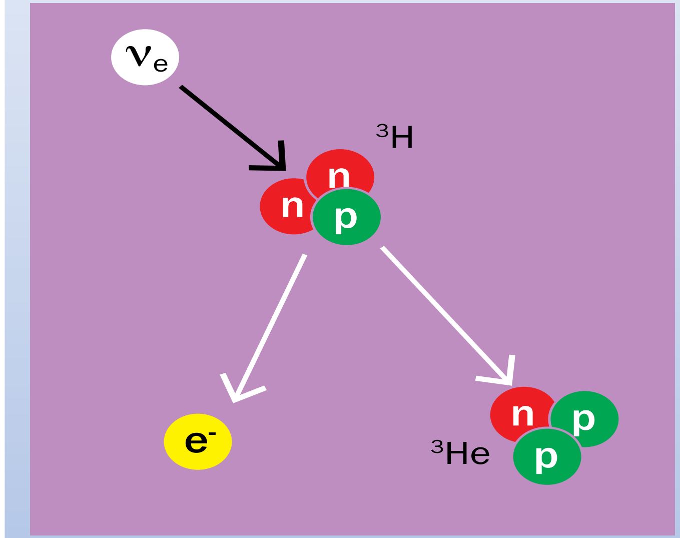
Ultra-Cold!

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:

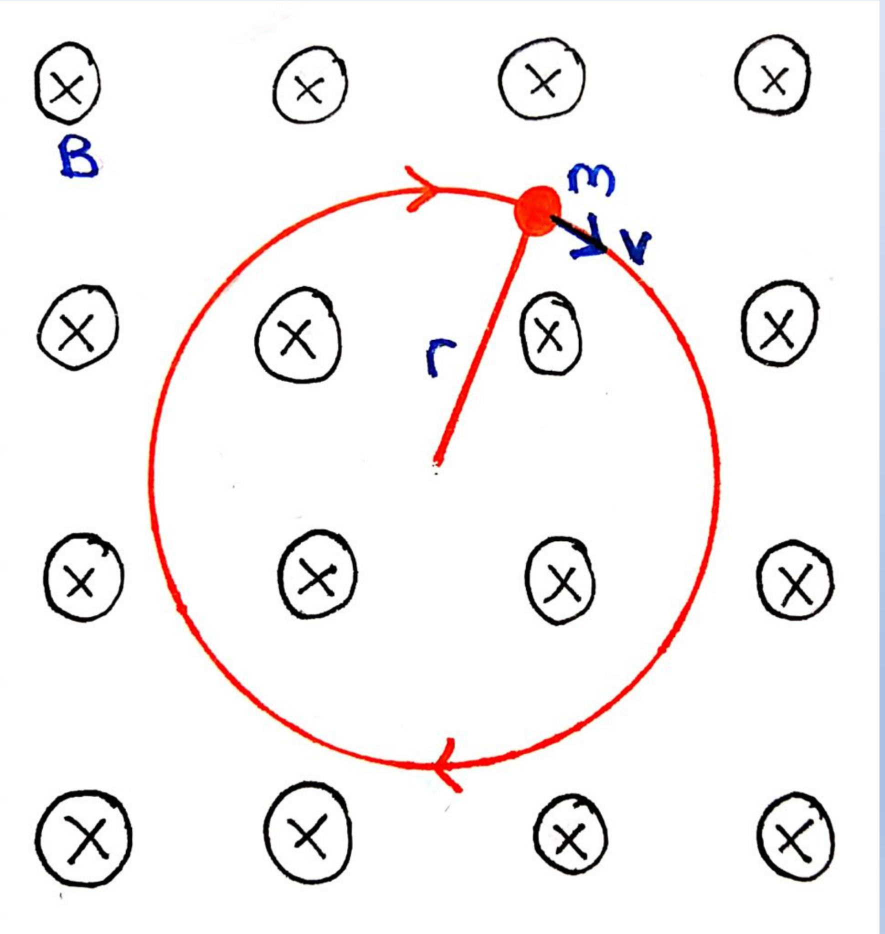
few x 10^{-6} energy resolution set by m_ν

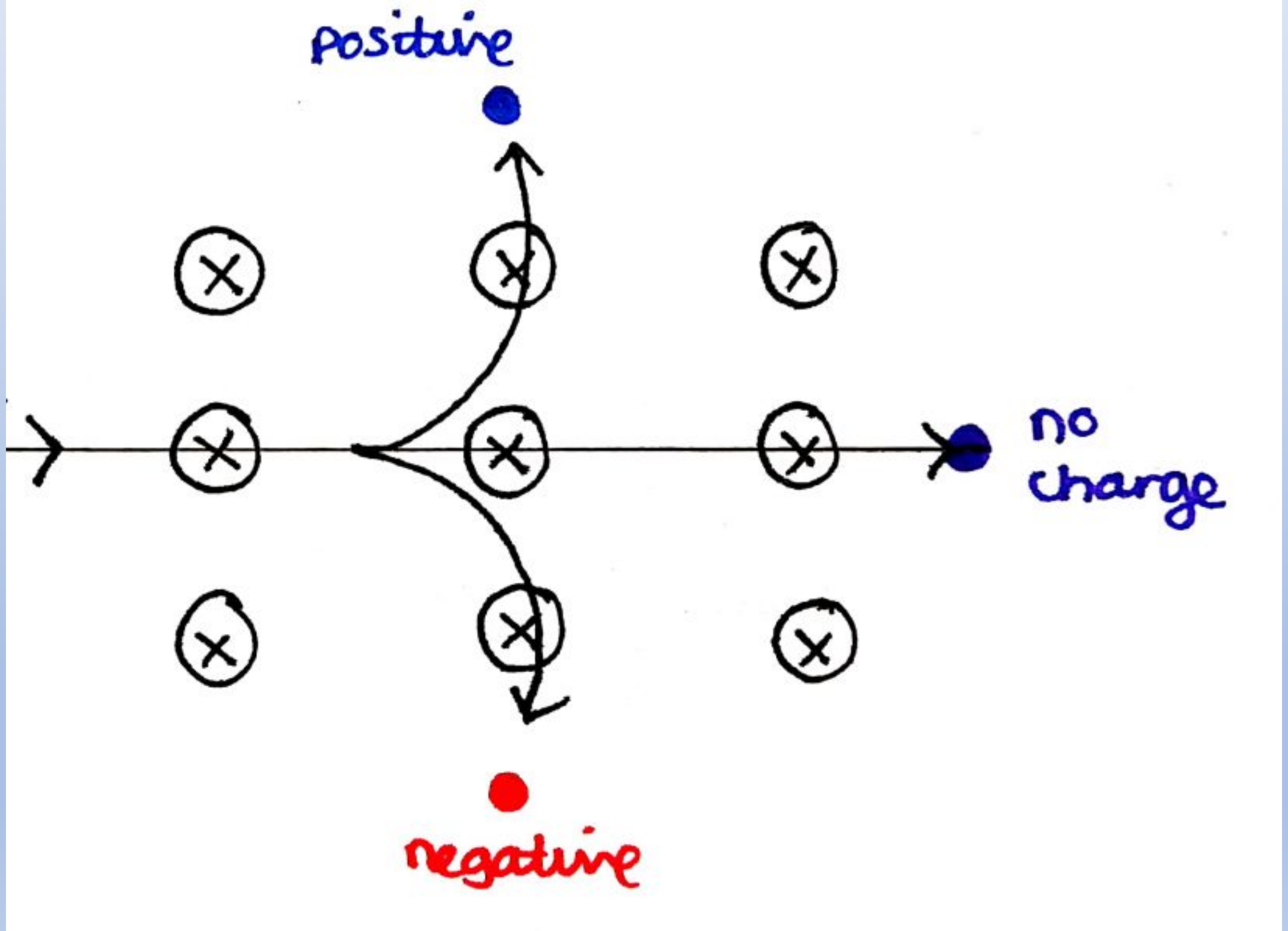
KATRIN ~ 10^{-4} (current limitation)

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

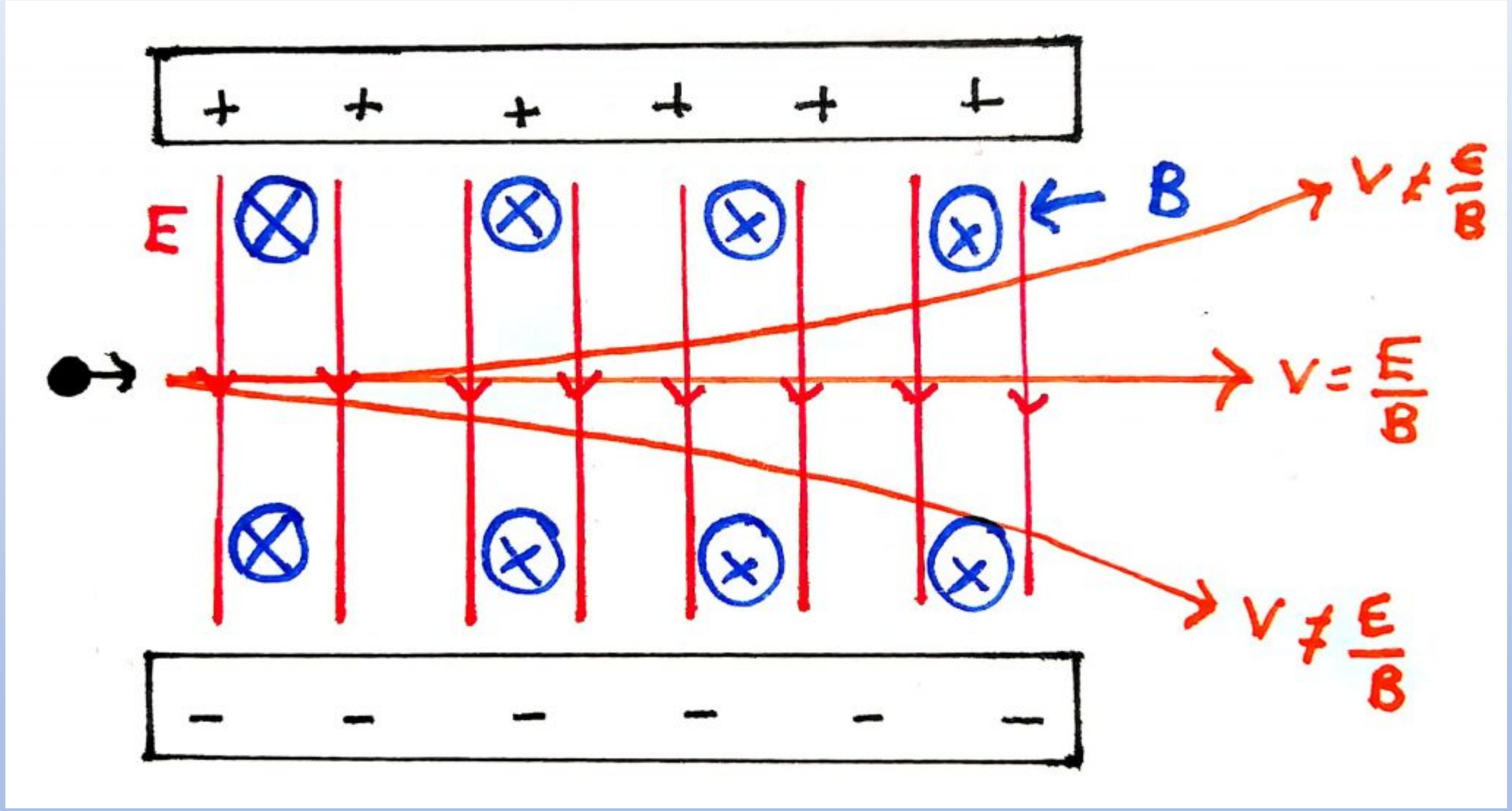
(compact filter) x (microcalorimeter)

Motion of a Charged Particle in a B Field





Classic Velocity Selector

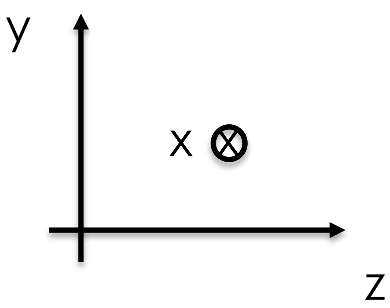


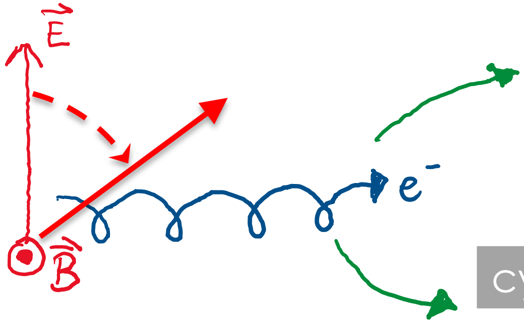
Is this the only way to select velocity?

PTOLEMY Filter Concept

Auke Pieter Colijn (PATRAS 2019)

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

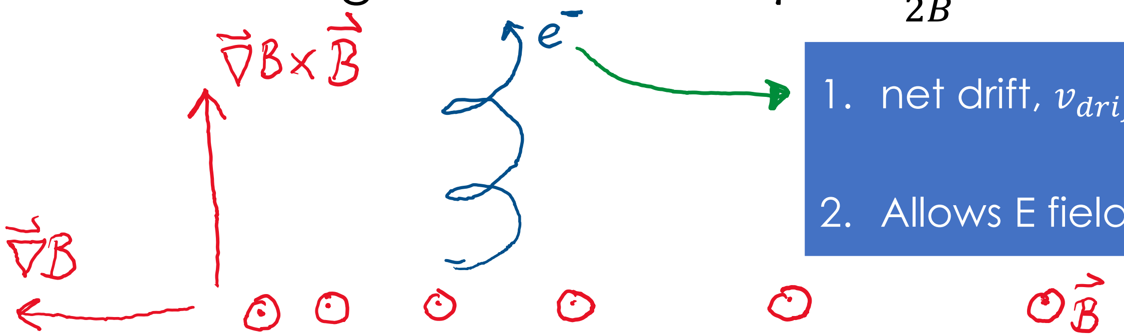




1. net drift, $v_{drift} = E/B$
2. no work, drift along equipotential planes

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 (!): $\frac{dT_\perp}{dt} = e\vec{E} \cdot \vec{v}_{drift}$

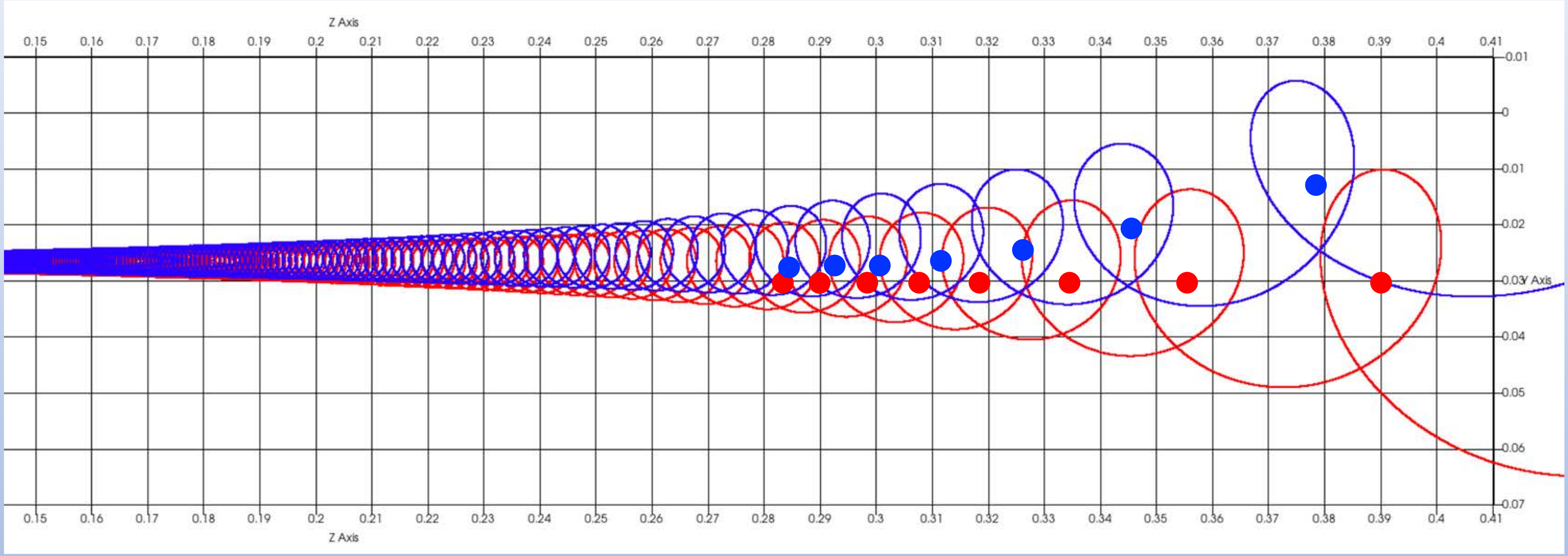
$$V^y_{E\times B}(z)|_{x,y=0} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B_x^2} = \frac{E_z B_x \hat{\boldsymbol{y}}}{B_x^2} = \frac{E_z}{B_x}\hat{\boldsymbol{y}}$$

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

Enforce zero drift in y (rotate E):

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

Bingo!

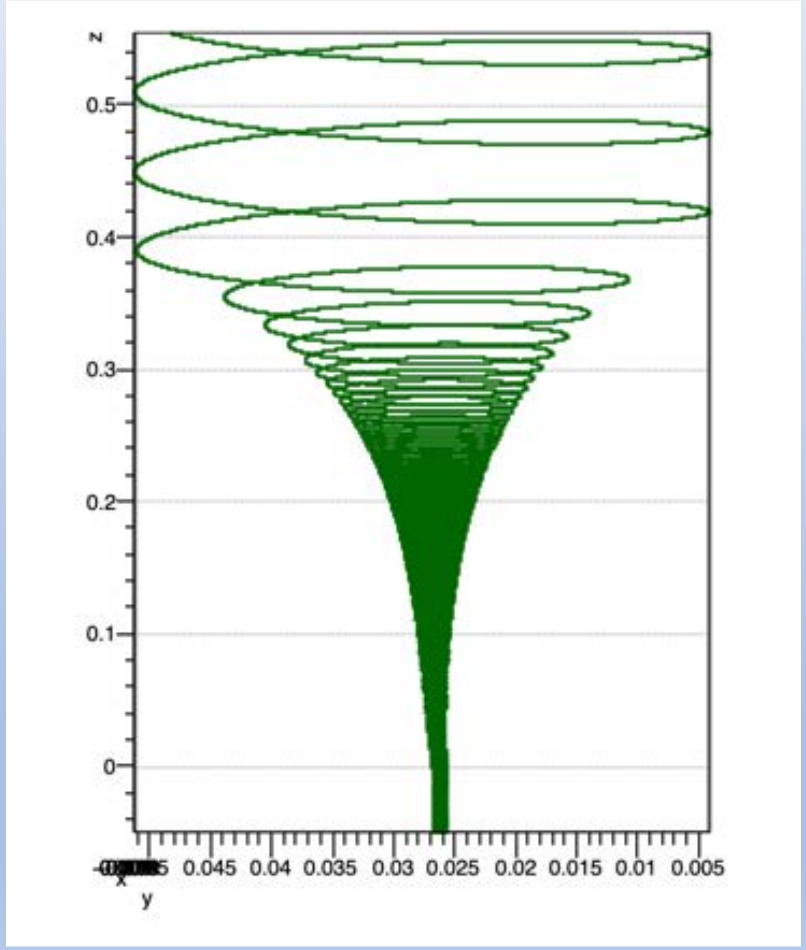


Selected velocity based on cyclotron drift

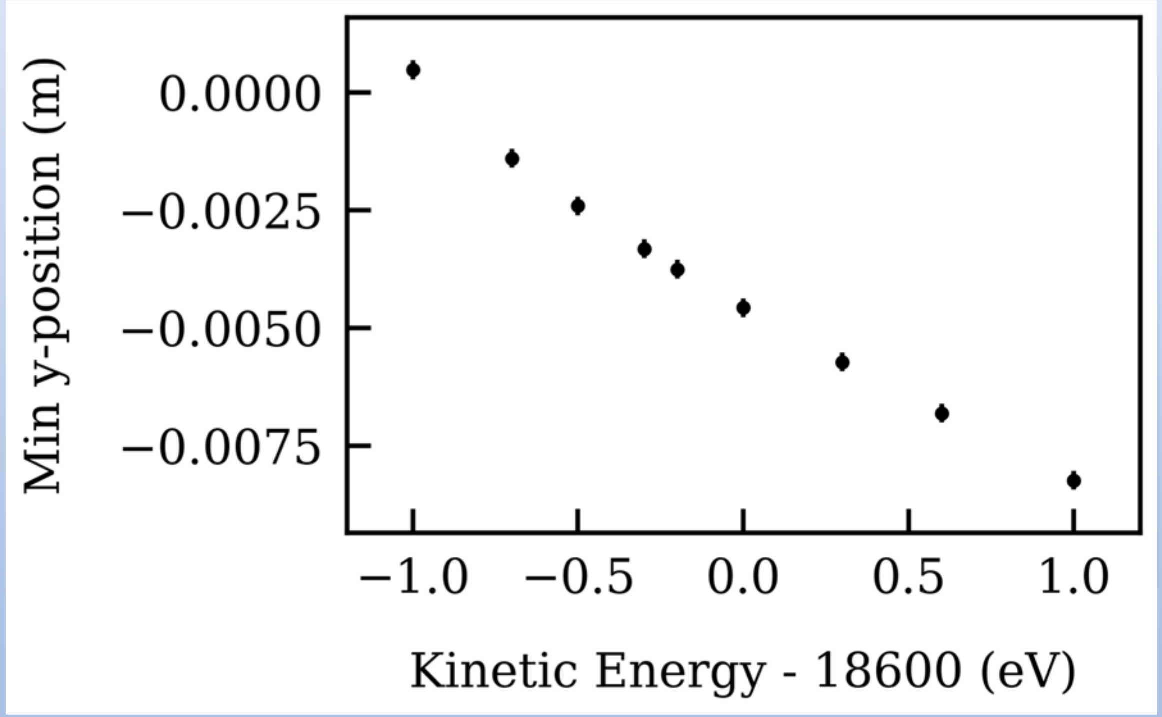
New type of particle accelerator (useful for fusion reactor heating) https://www.intechopen.com/chapters/82927

How well can one select velocities?

400mm



45mm

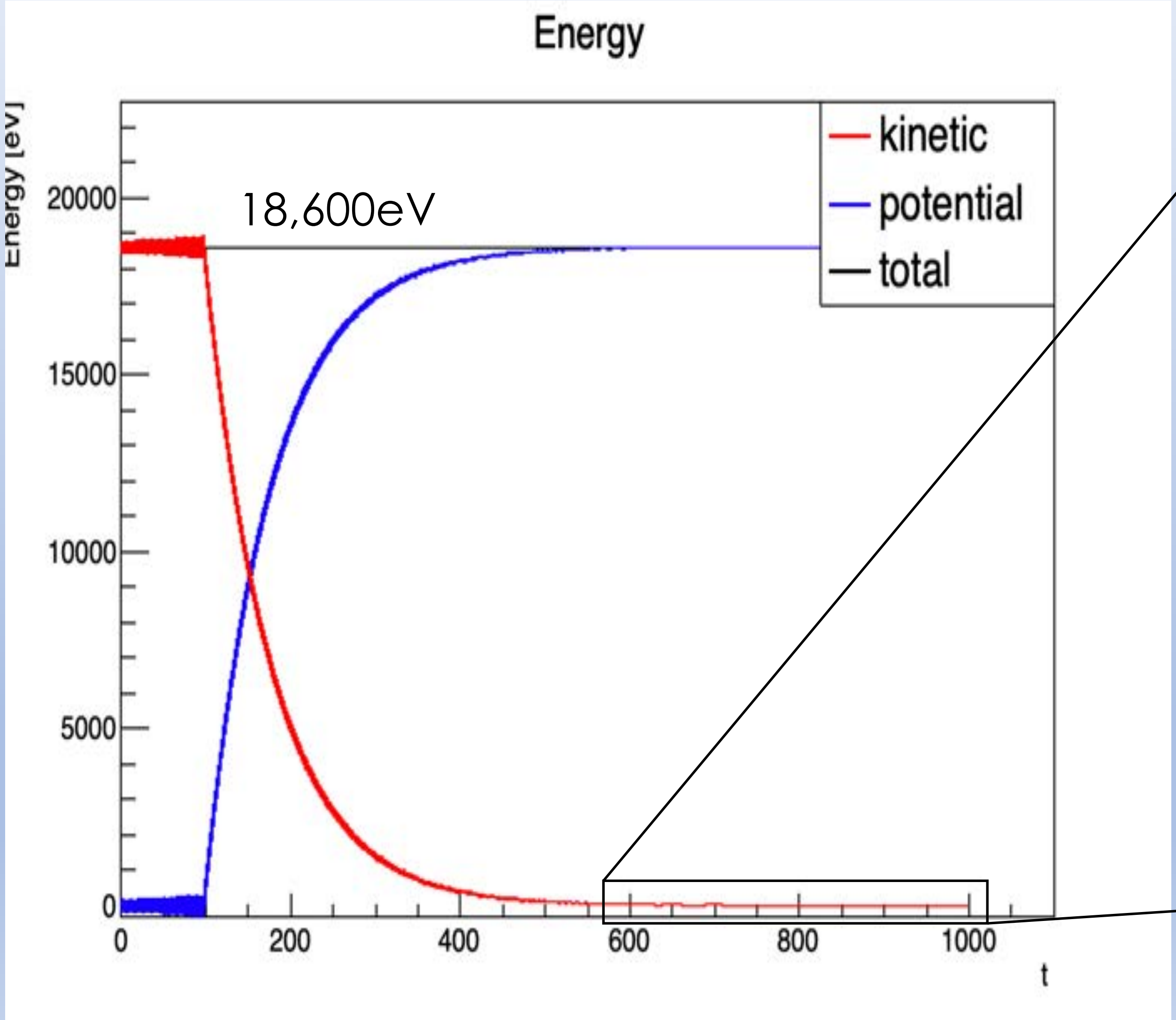


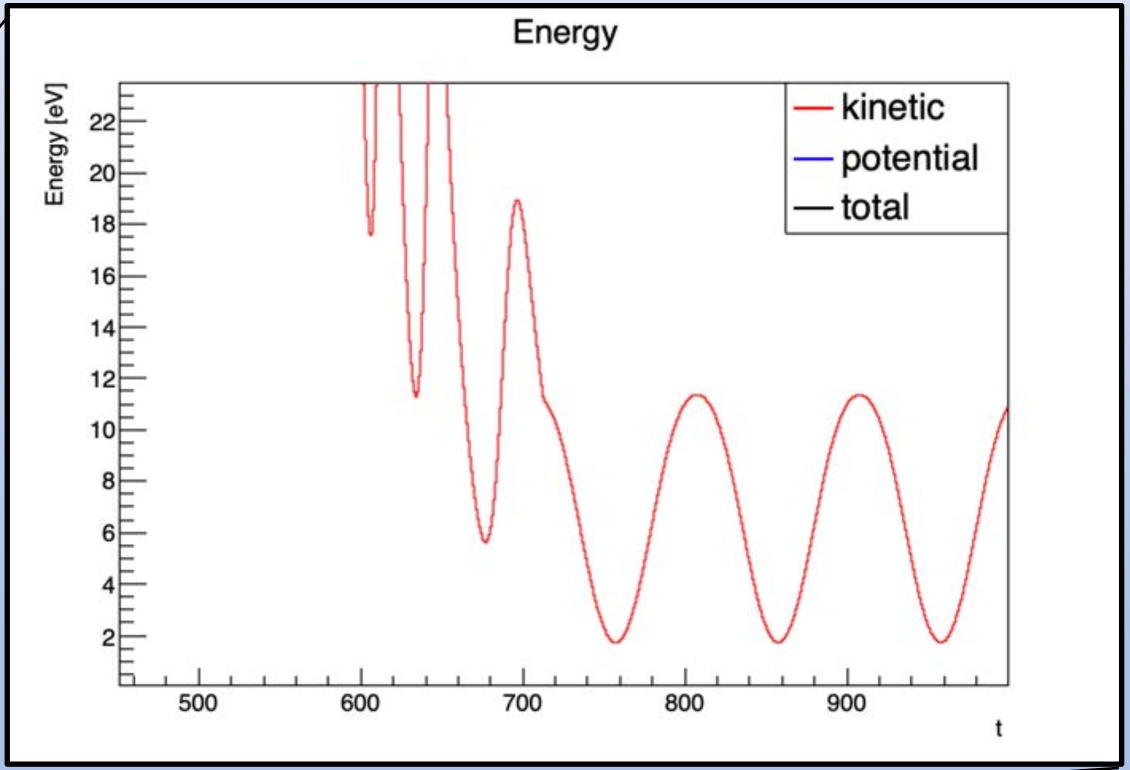
Deflection is ~ 4mm/eV
(over a drift distance of 400mm)

Lorentz4 Code

https://github.com/gkrossi/lorentz4

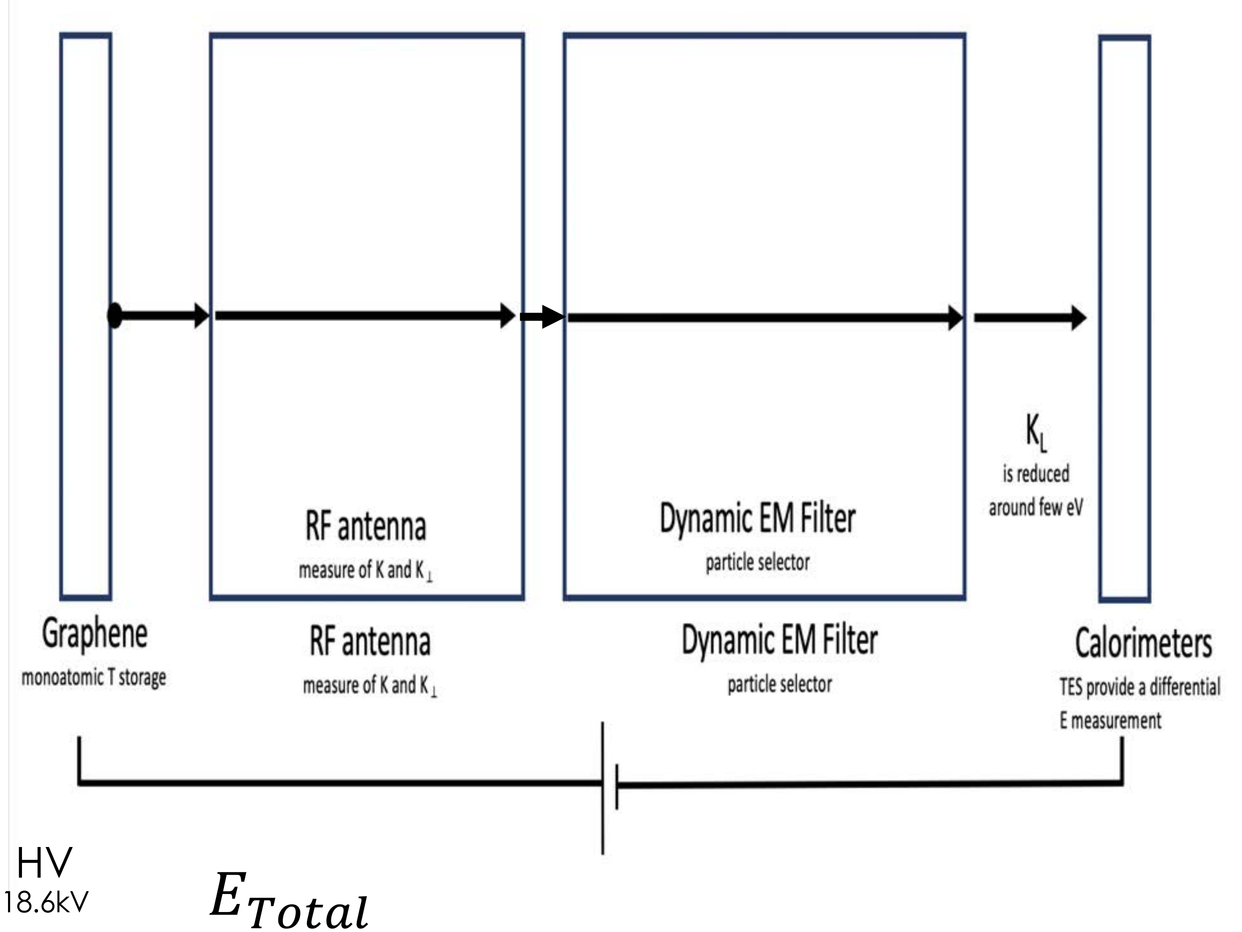
LNGS software
Nicola Rossi
Marcello Messina



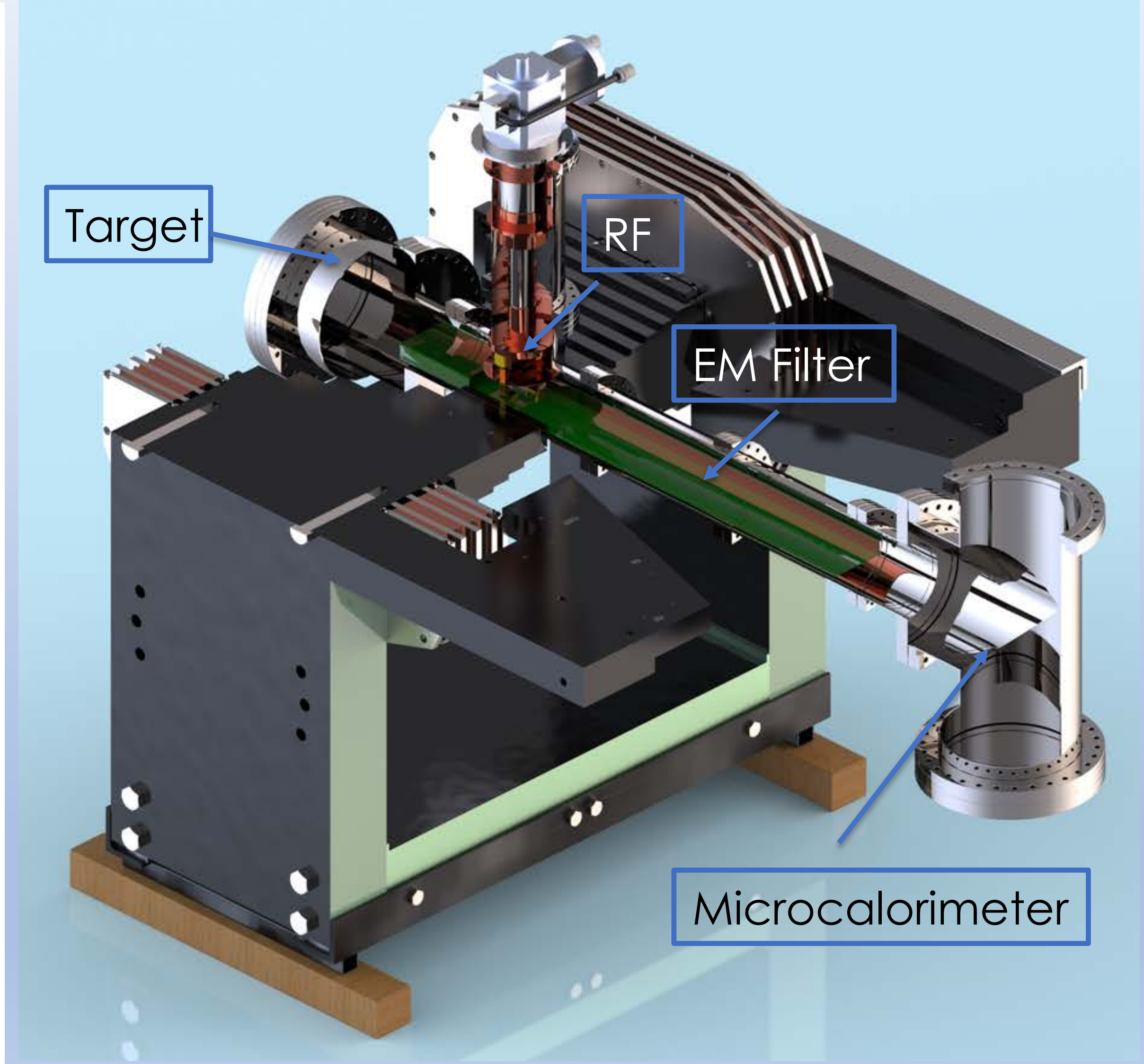


PTOLEMY R&D Development Setup

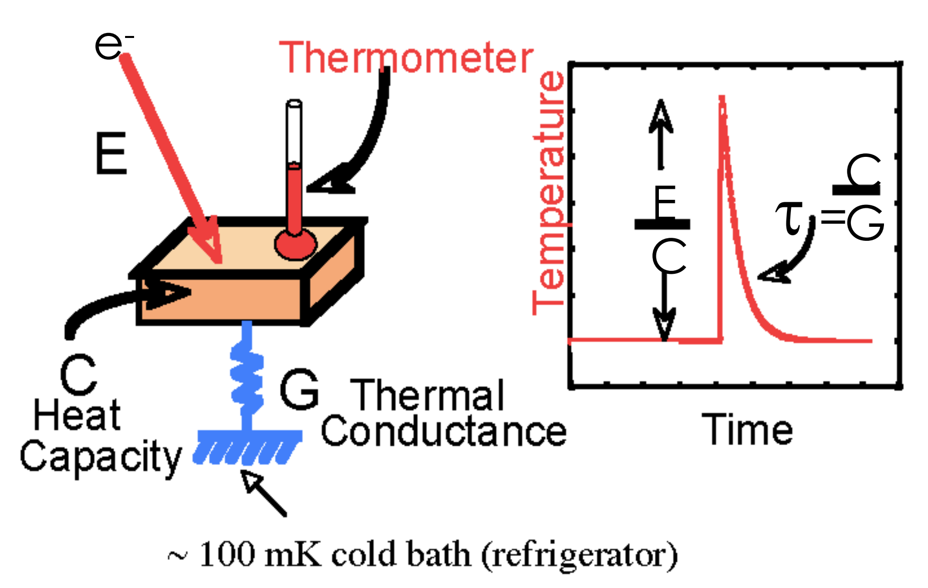
Andi Tan (Princeton)

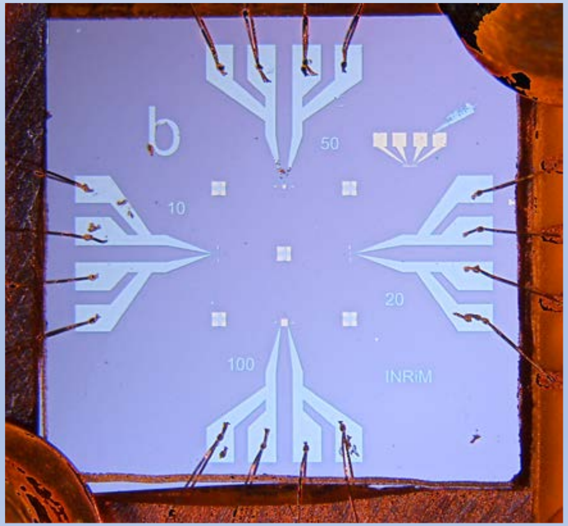


$$E_{Total} = q(V_{TES} - V_{Target}) + E_{RFcorr} + E_{cal}$$

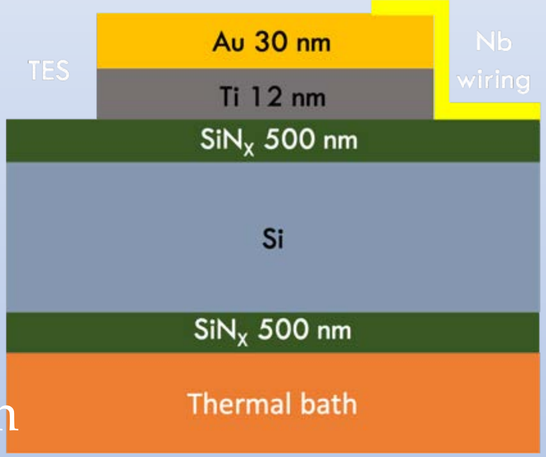


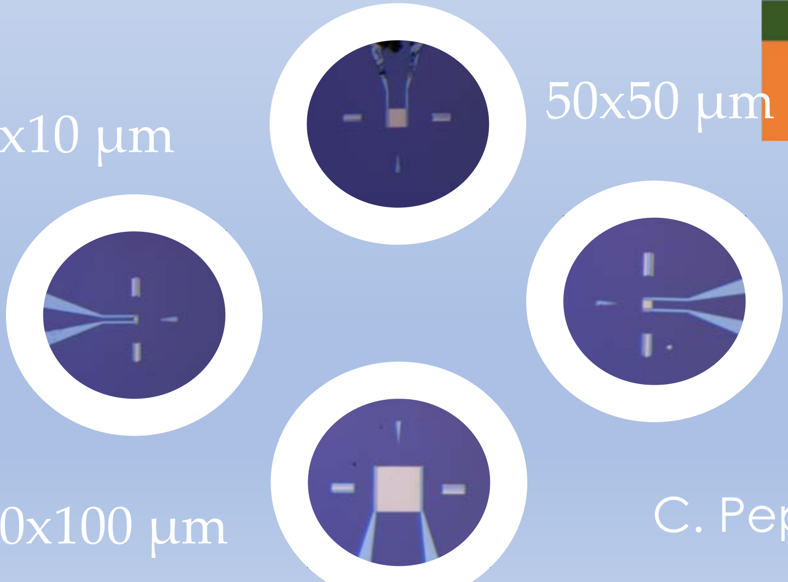
Measurement Arm: µCal





Thin sensors:
~1 eV electron can be stopped with very small C





10x10 µm

50x50 µm

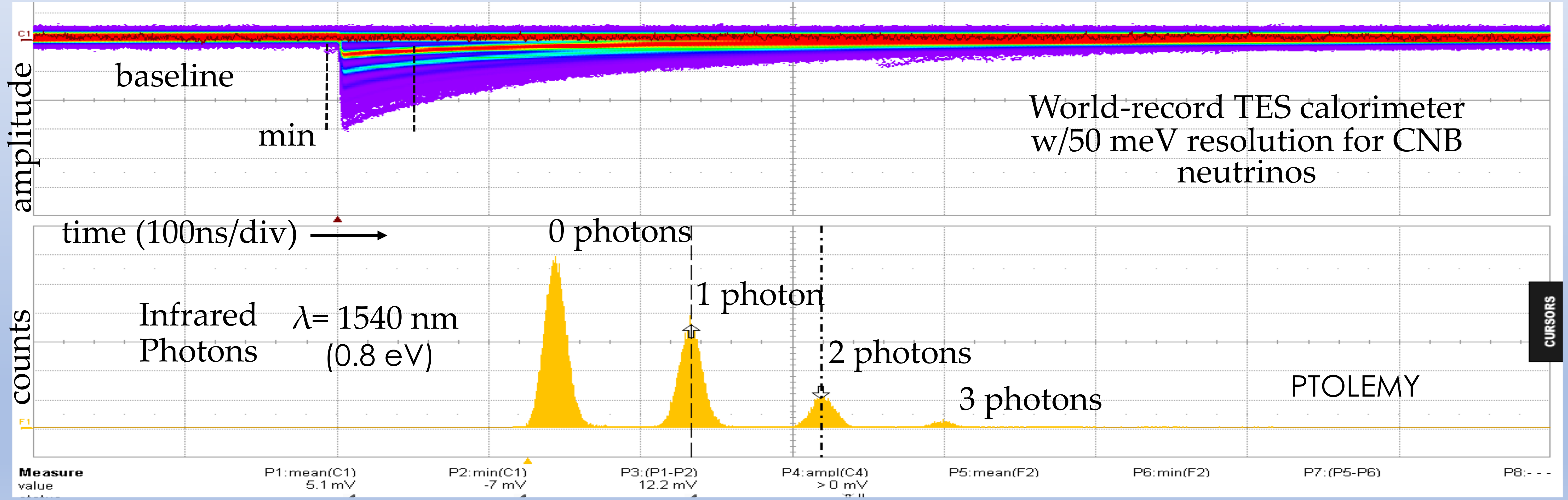
20x20 µm

100x100 µm

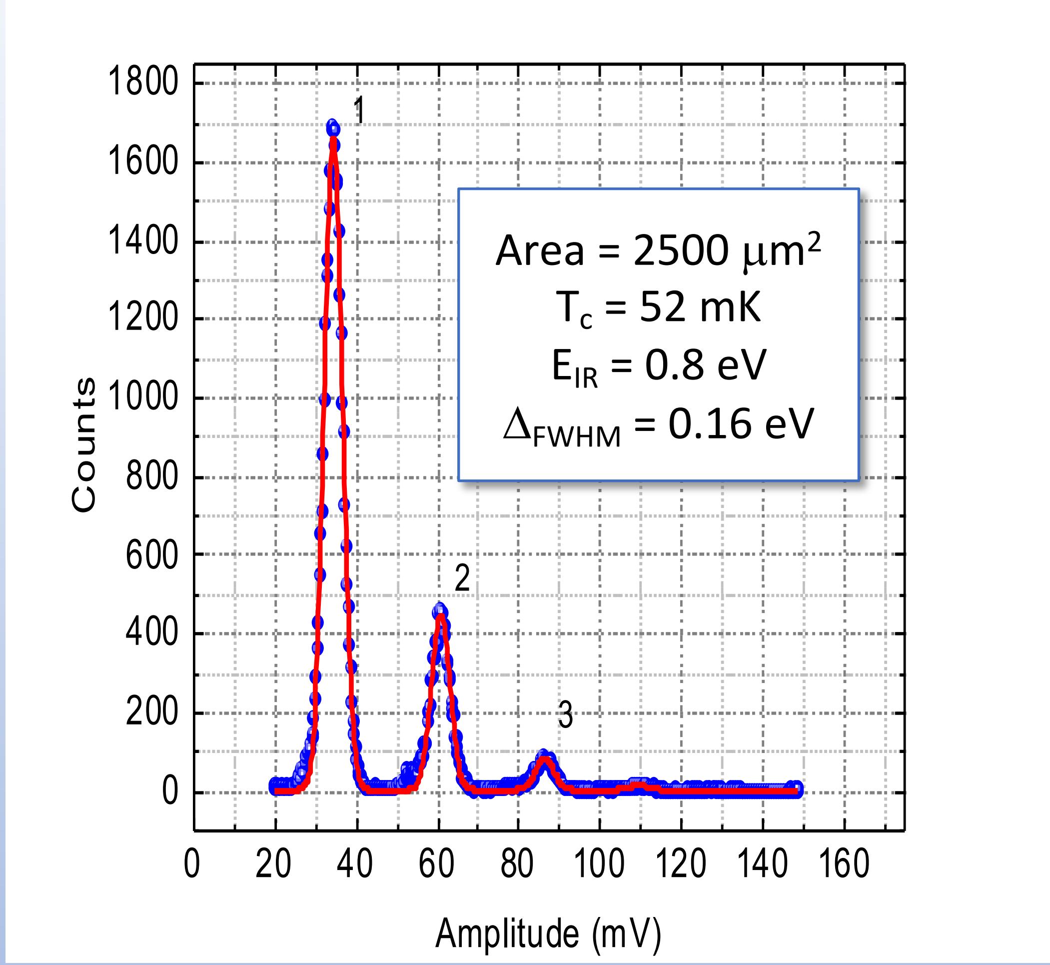
C. Pepe, E. Monticone, M. Rajteri

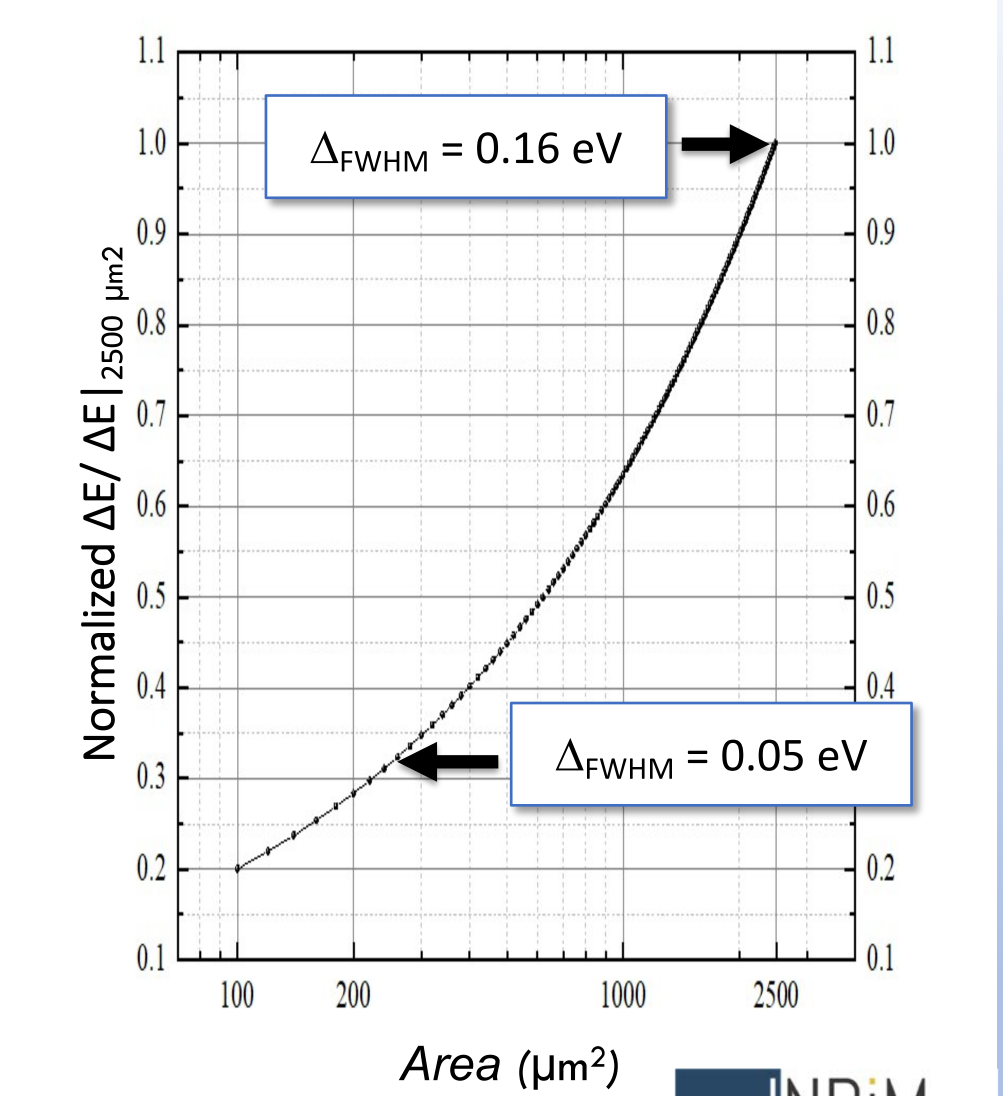
Mauro Rajteri, Eugenio Monticone and others, https://doi.org/10.1007/s10909-019-02271-x
"TES Microcalorimeter for PTOLEMY", J. Low Temp. Phys. 199 (2020) 138-142.

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

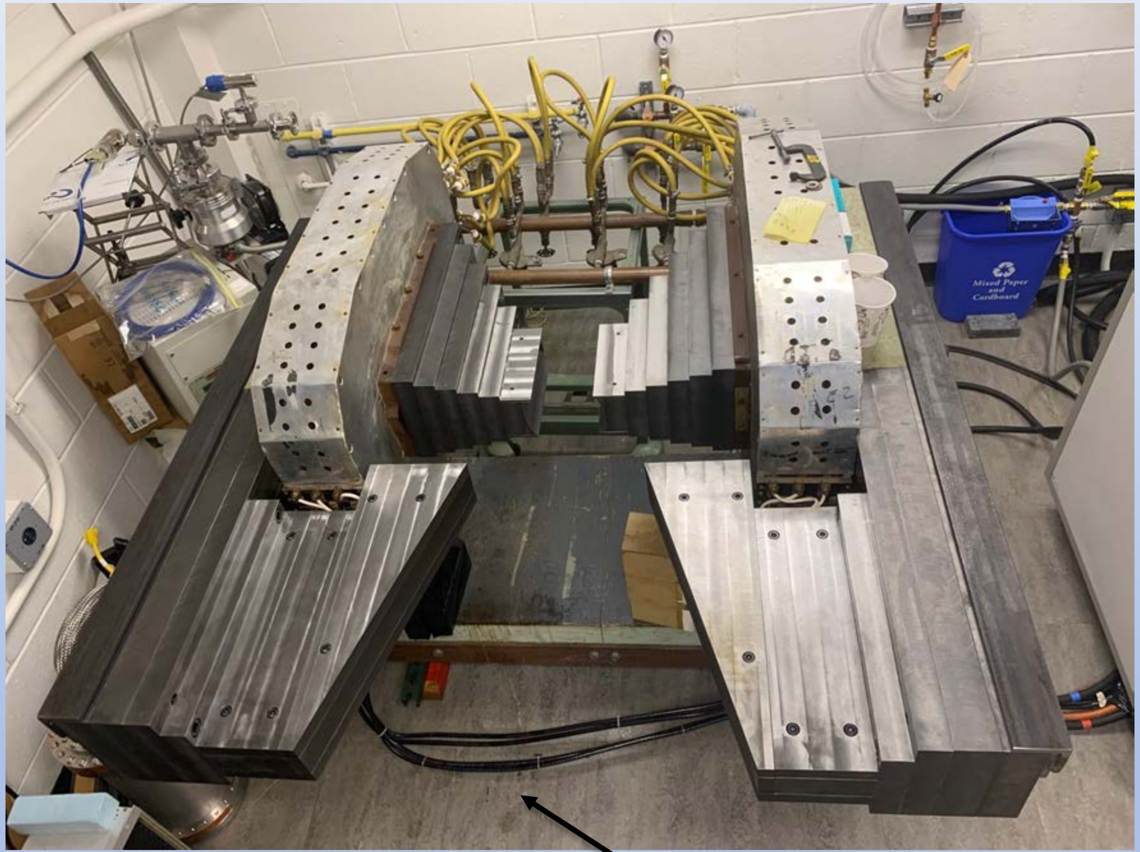
C. Pepe, E. Monticone, M. Rajteri

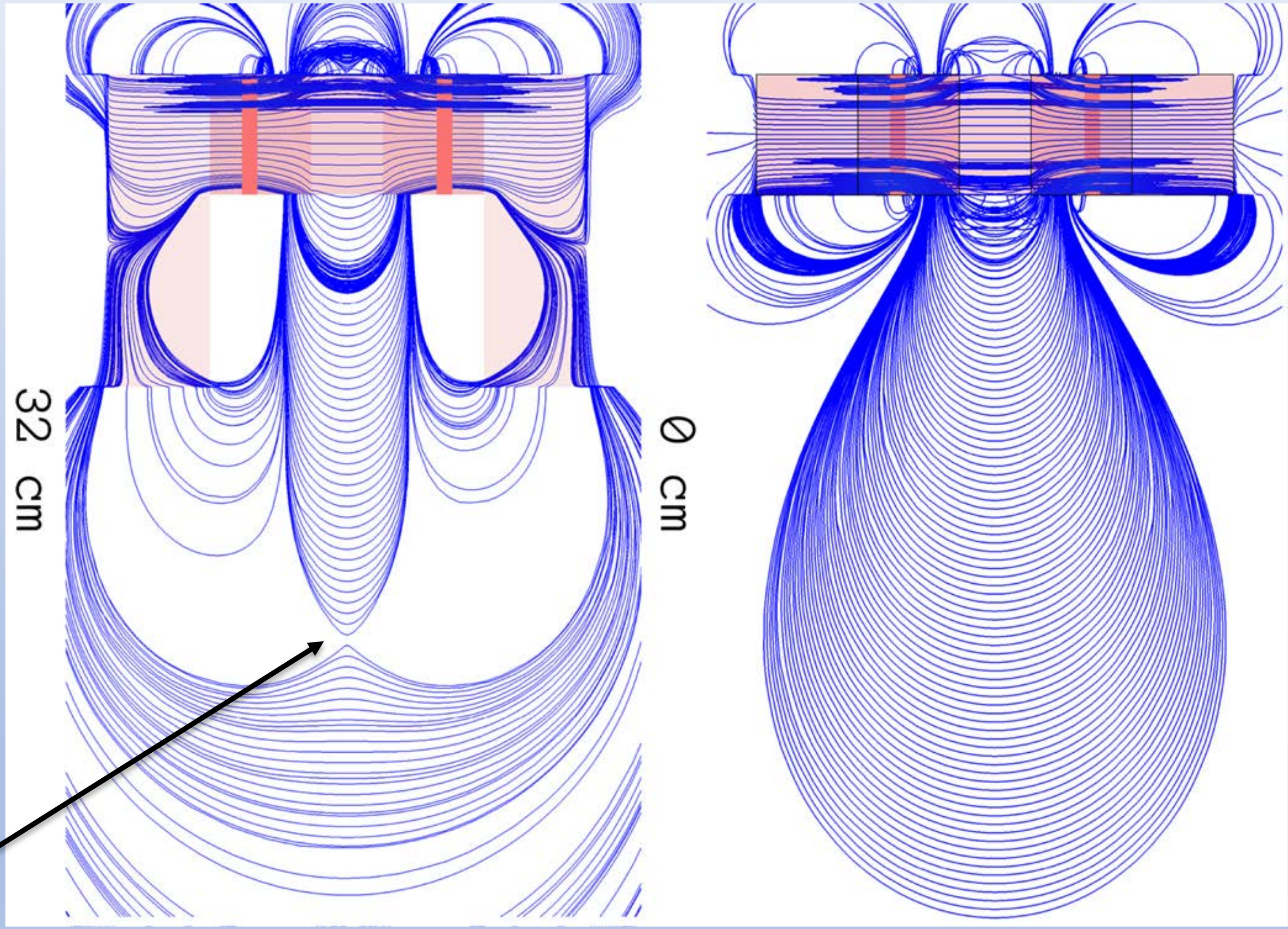
→ Demonstrate with electrons

First Version of the PTOLEMY filter

PTOLEMY
filter@Princeton

Wonyong
Chung



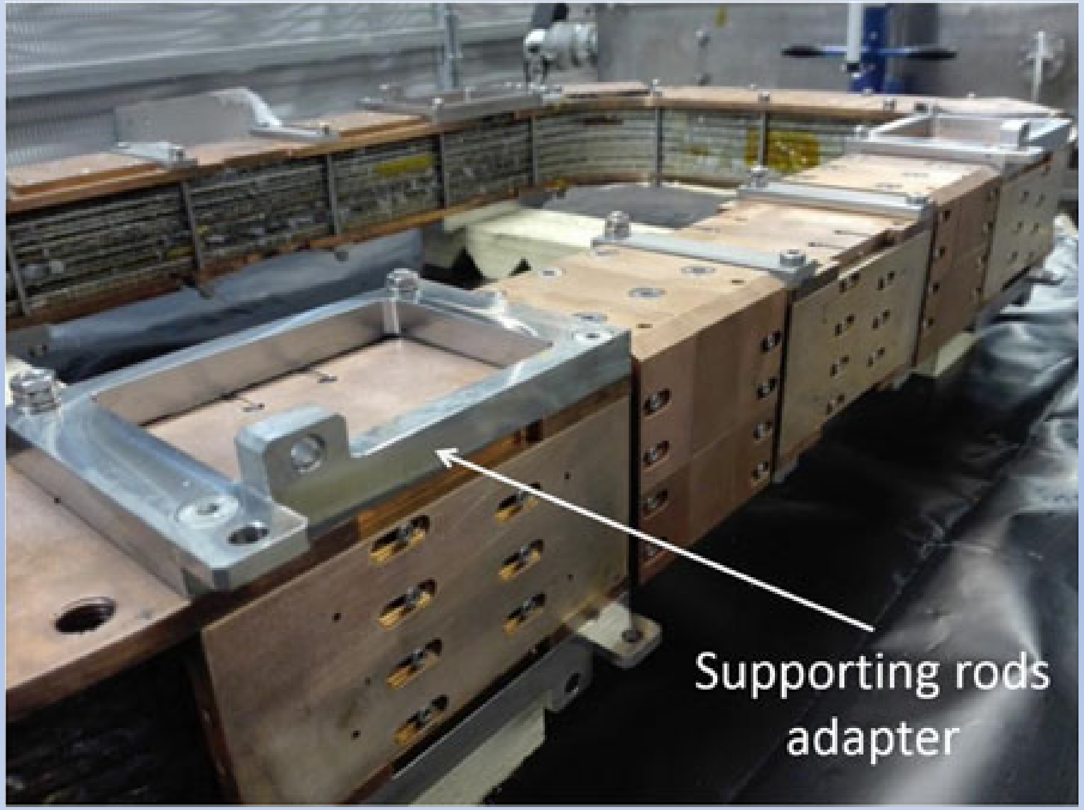


Andi
Tan

Zero field (location for TES microcalorimeter)

Conduction-Cooled Superconducting Coils

- LNGS magnet sepecifications within ~20% of a Wind Generator system made by ANSALDO designed in Spain (~10 Open MRI similar commercial systems sold per year)
  - This is the preferred option and reduces 70kW→10kW power



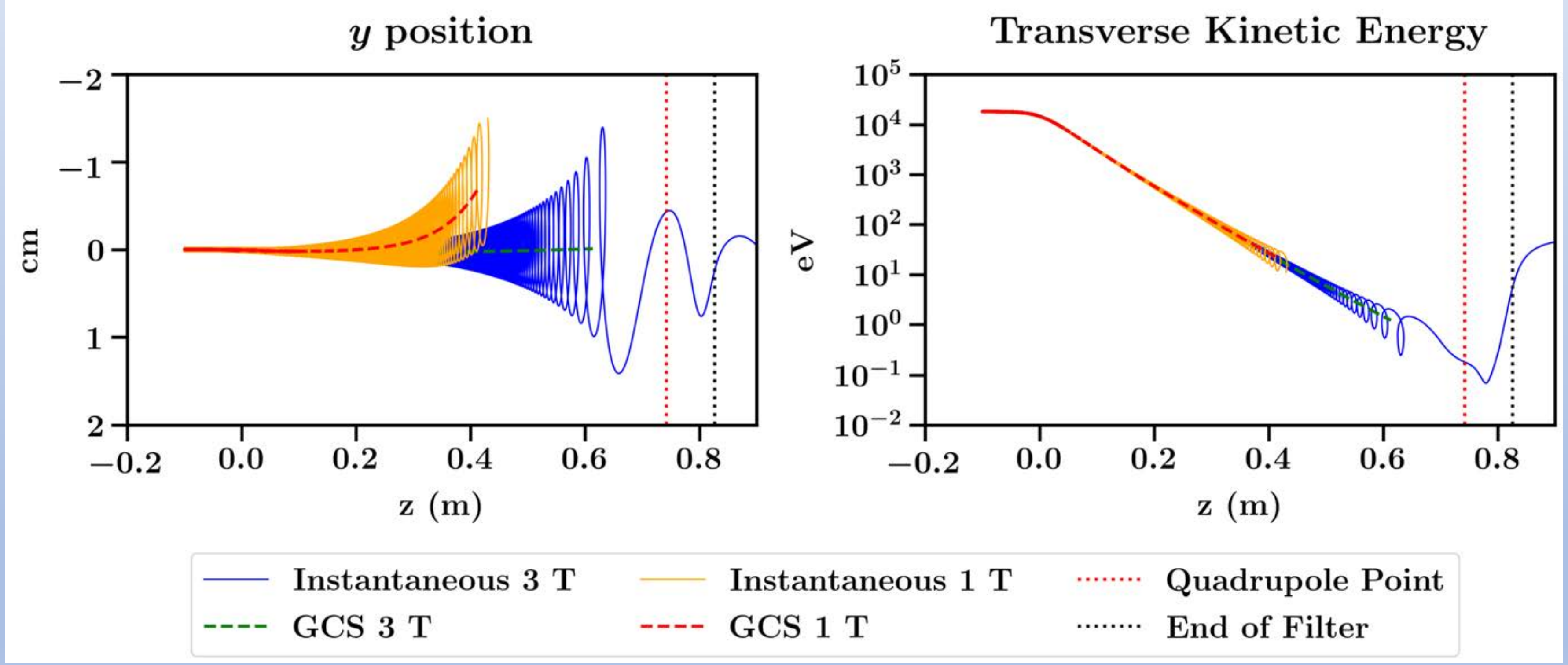
Packed with multi-layer thermal insulation

Filter Performance

Improves as B^2 for a fixed filter dimension

18.6 keV @ 1T → ~10eV (in 0.4m)

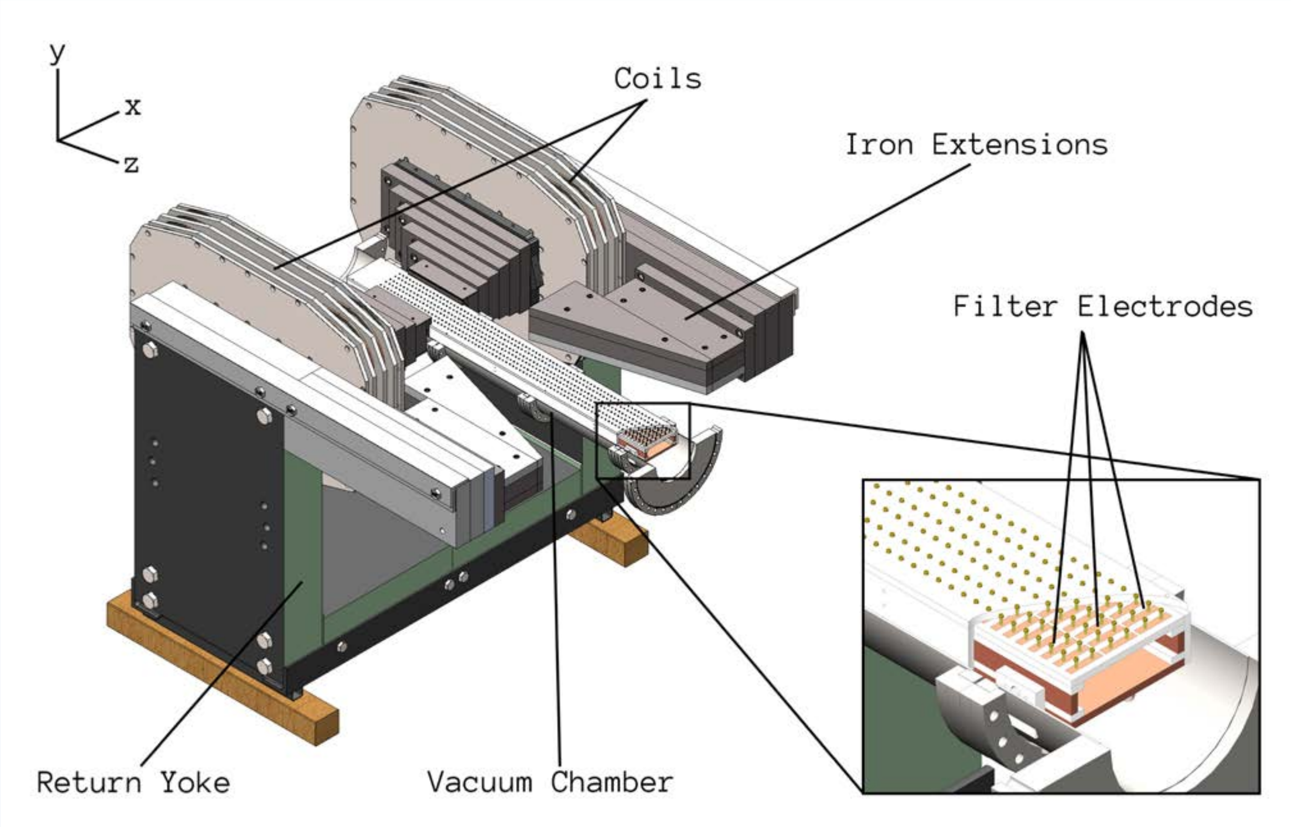
18.6 keV @ 3T → ~1eV (in 0.6m)

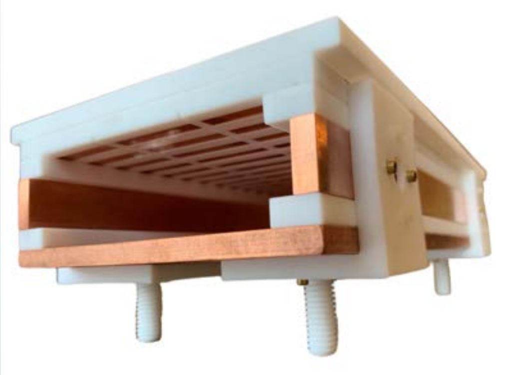


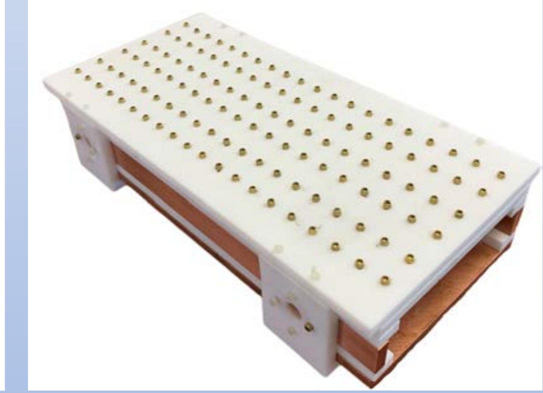
PTOLEMY Collaboration, https://arxiv.org/abs/2108.10388
"Implementation and Optimization of the PTOLEMY Electromagnetic Filter"
https://iopscience.iop.org/article/10.1088/1748-0221/17/05/P05021

Electrode Prototype

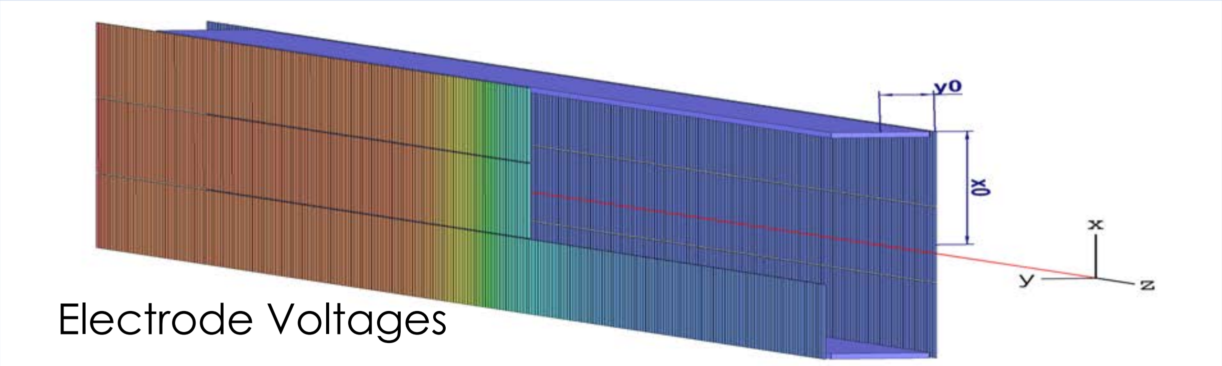
Andi Tan (Princeton)



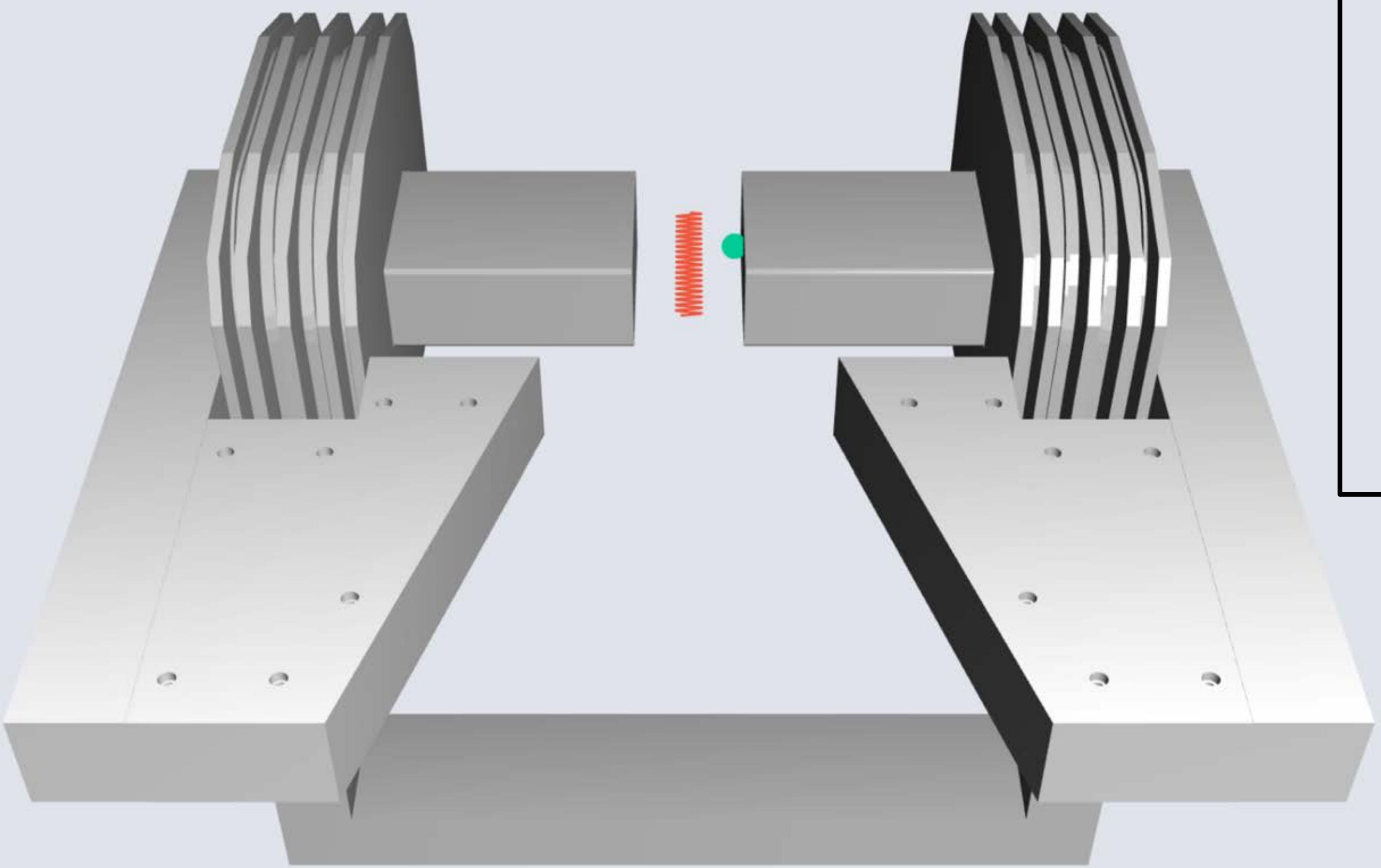


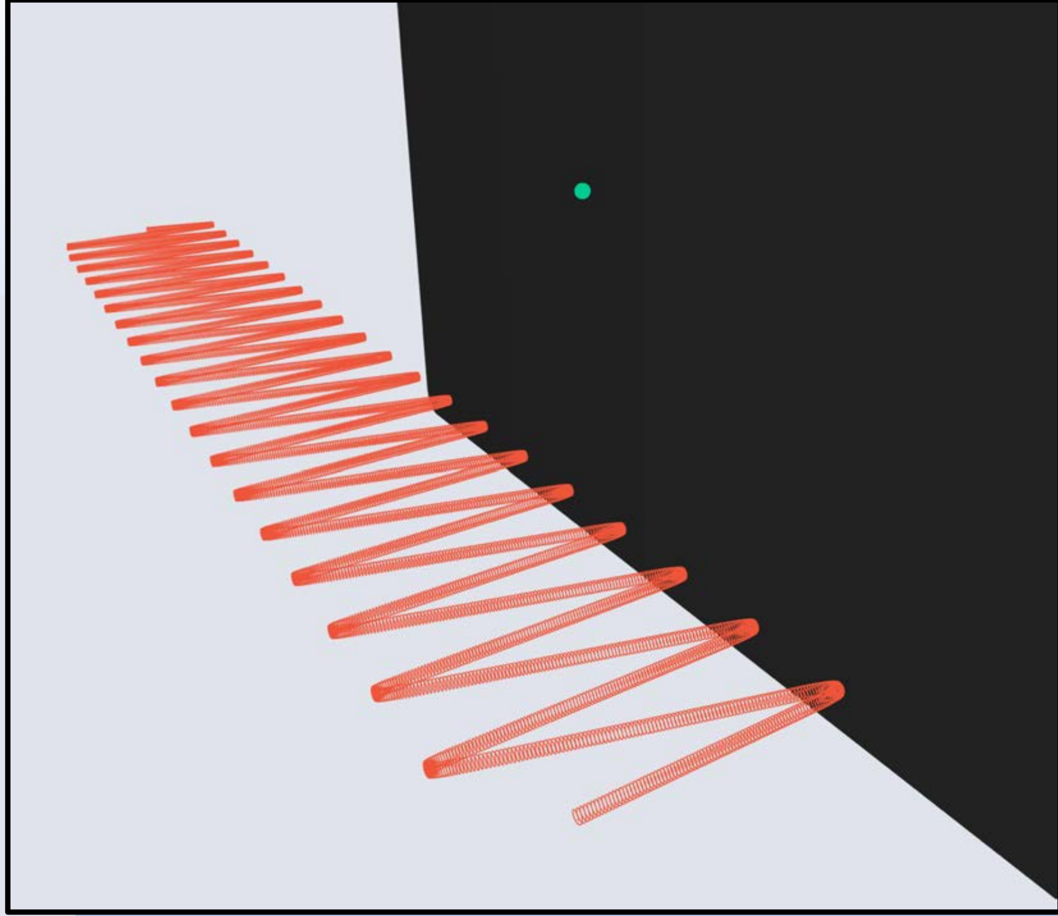


Wonyong Chung (Princeton)

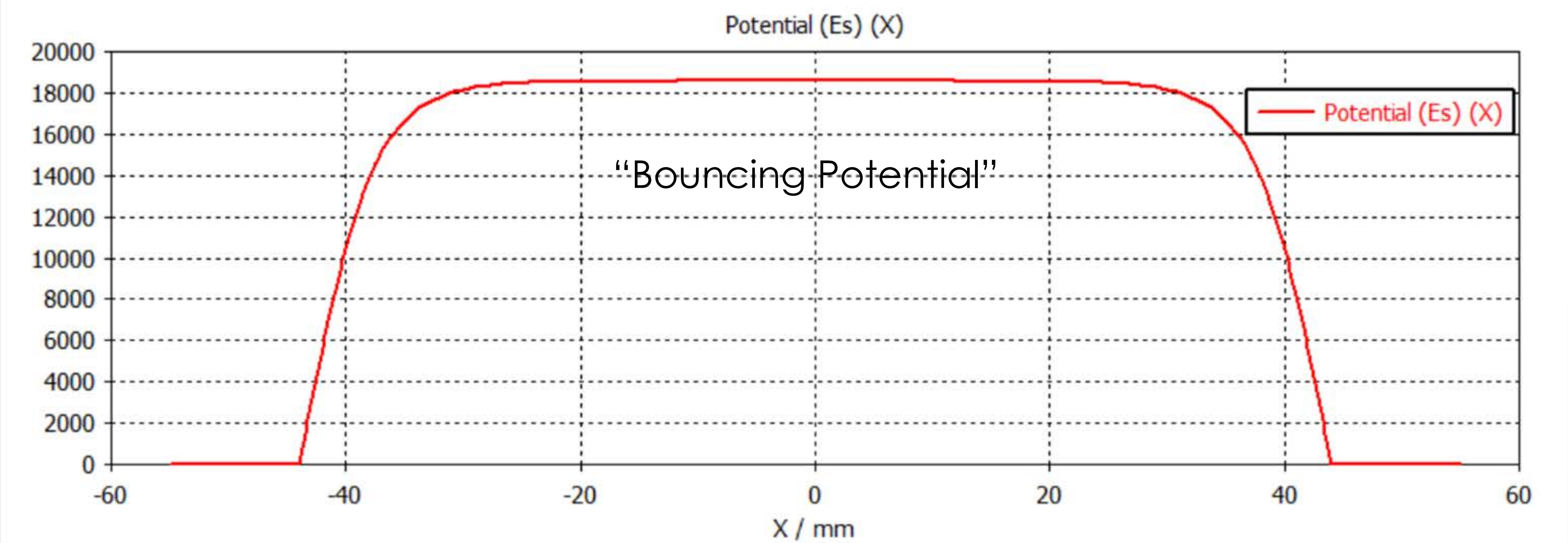


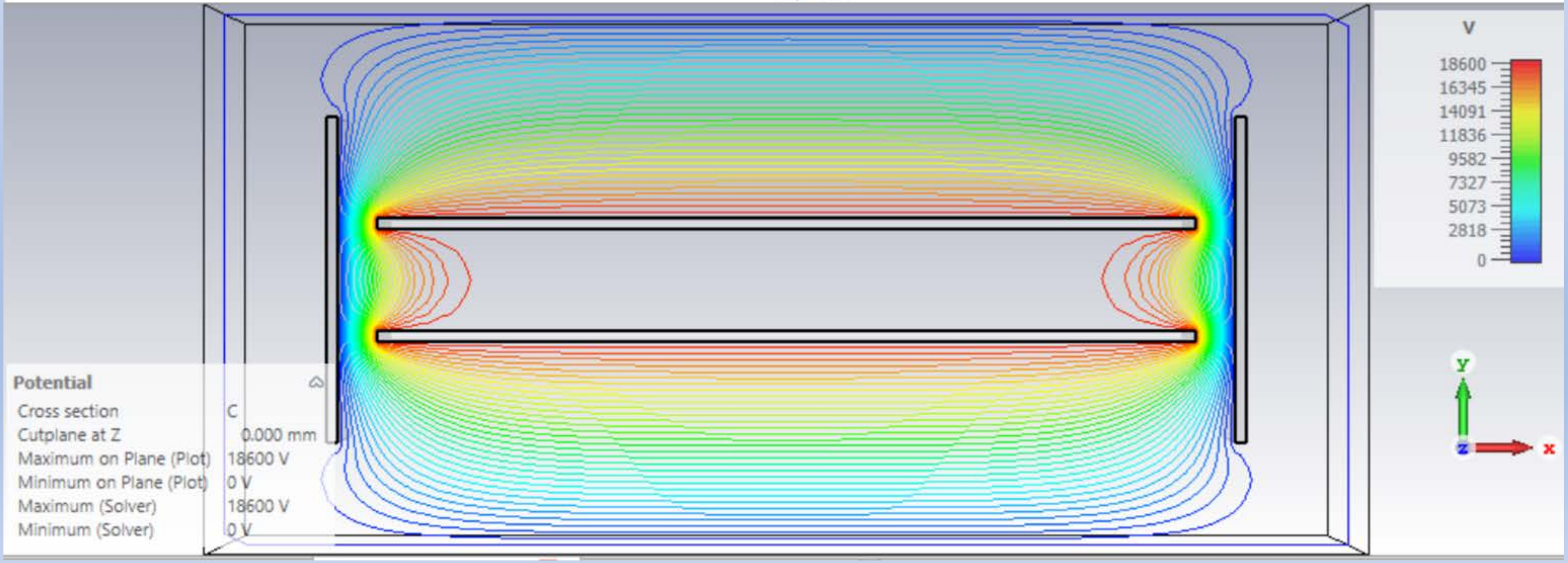
Pitch 85 Long Trajectory

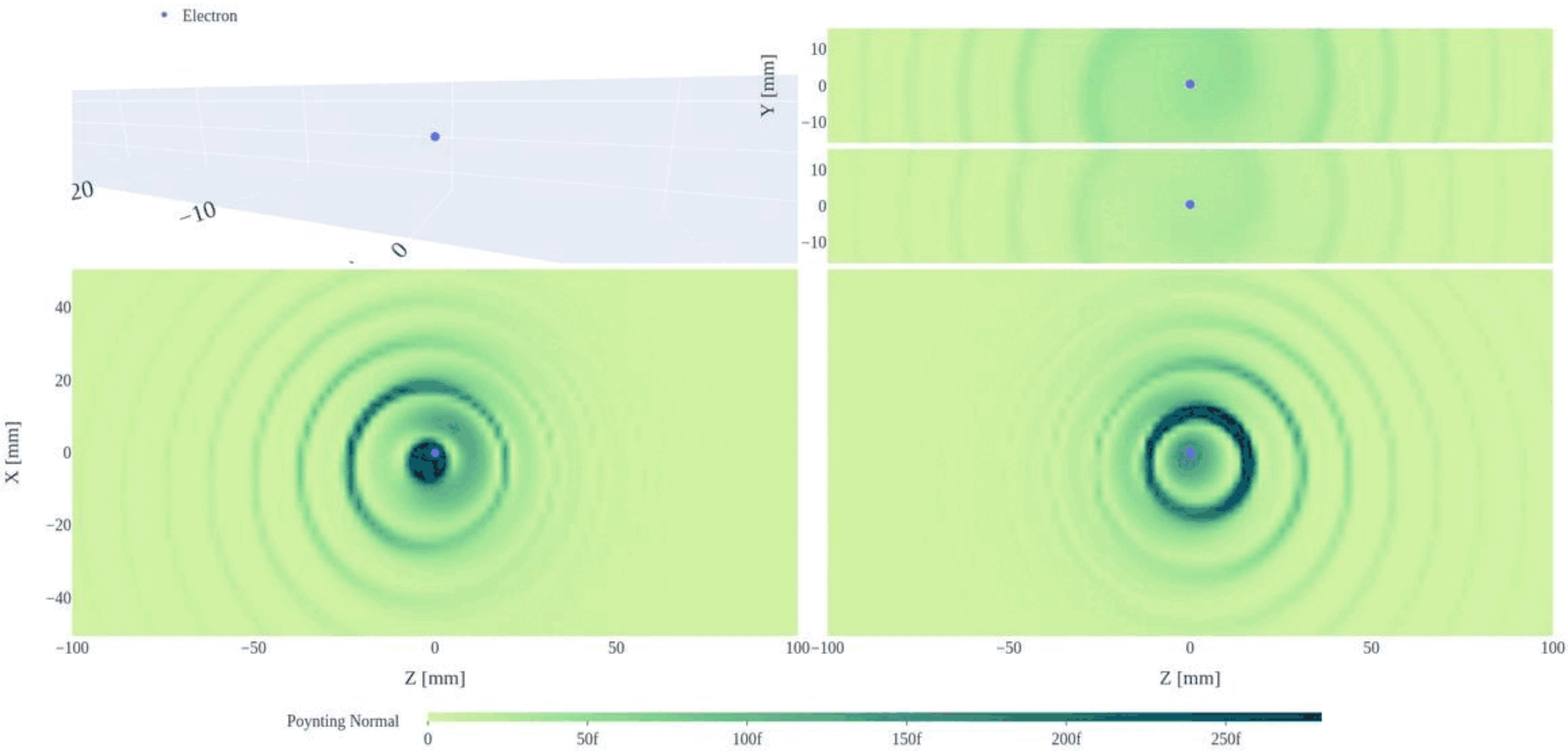


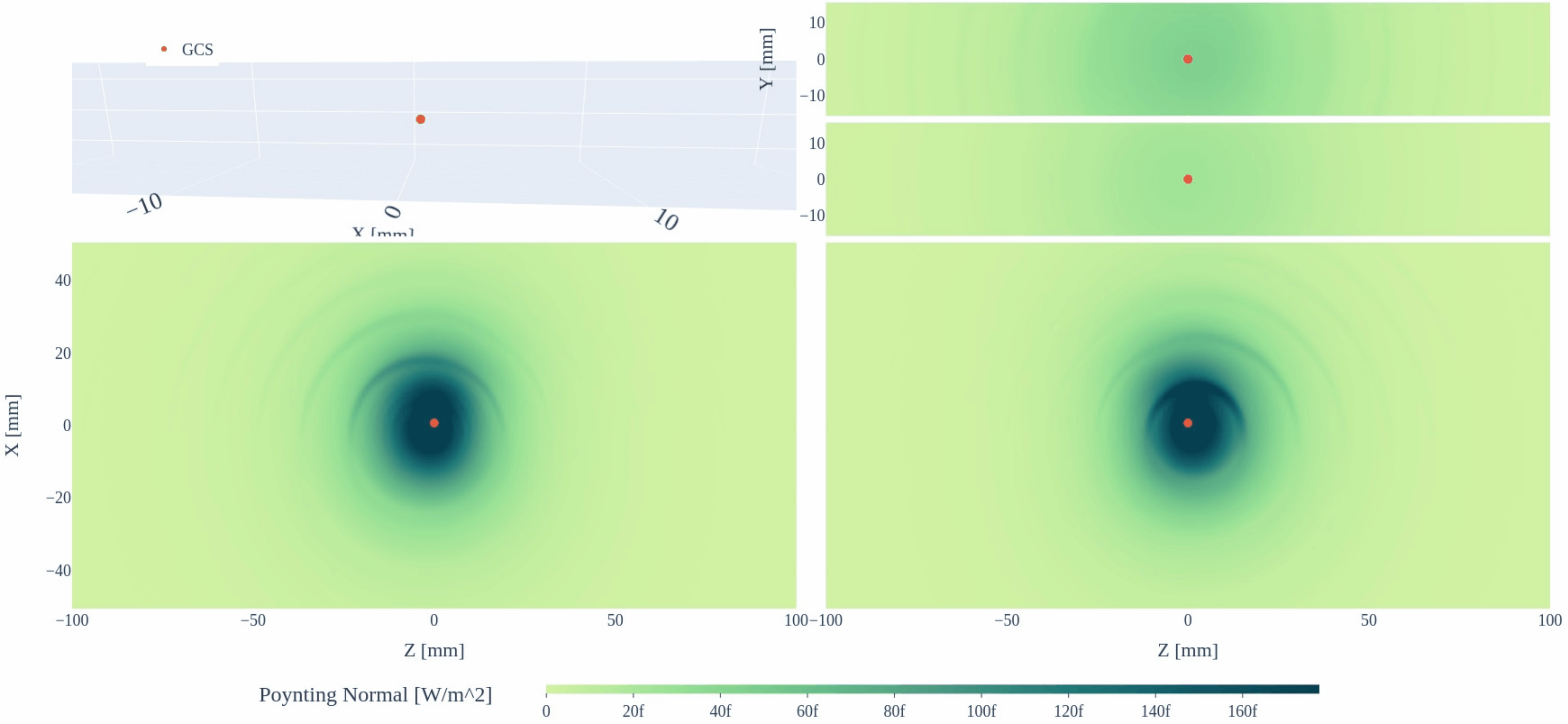


Andi Tan (Princeton)


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)
"Bouncing Potential"

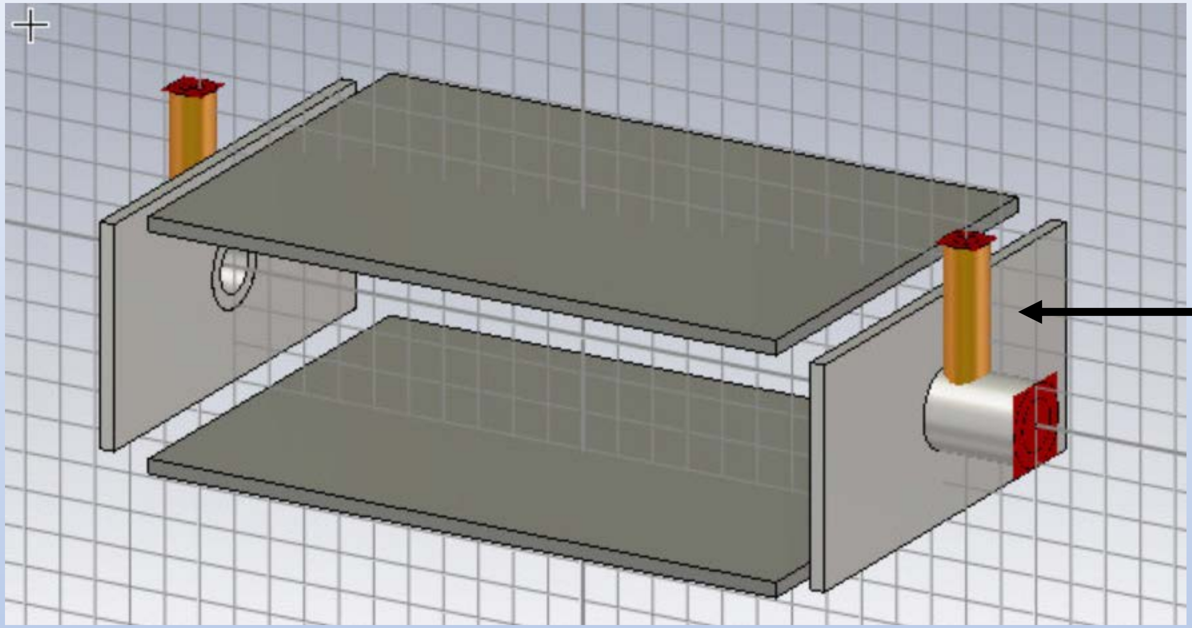

V
18600
16345
14091
11836
9582
7327
5073
2818
0
Potential
Cross section C
Cutplane at Z 0.000 mm
Maximum on Plane (Plot) 18600 V
Minimum on Plane (Plot) 0 V
Maximum (Solver) 18600 V
Minimum (Solver) 0 V
Y
Z
X

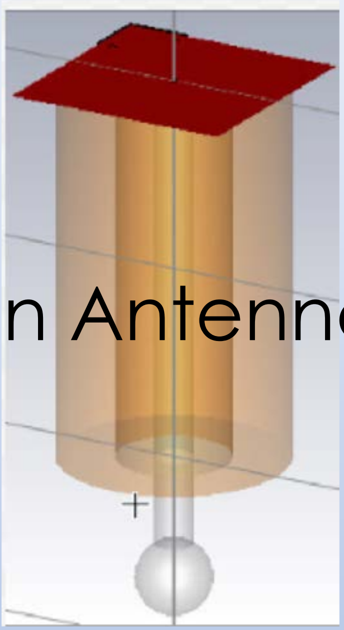

Electron
20
−10
0
10
0
−10
Y [mm]
10
0
−10
40
20
0
−20
−40
X [mm]
−100
−50
0
50
100
−100
−50
0
50
100
Z [mm]
Z [mm]
Poynting Normal
0
50f
100f
150f
200f
250f


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

Antenna Design Studies

Yuno Iwasaki (Princeton)

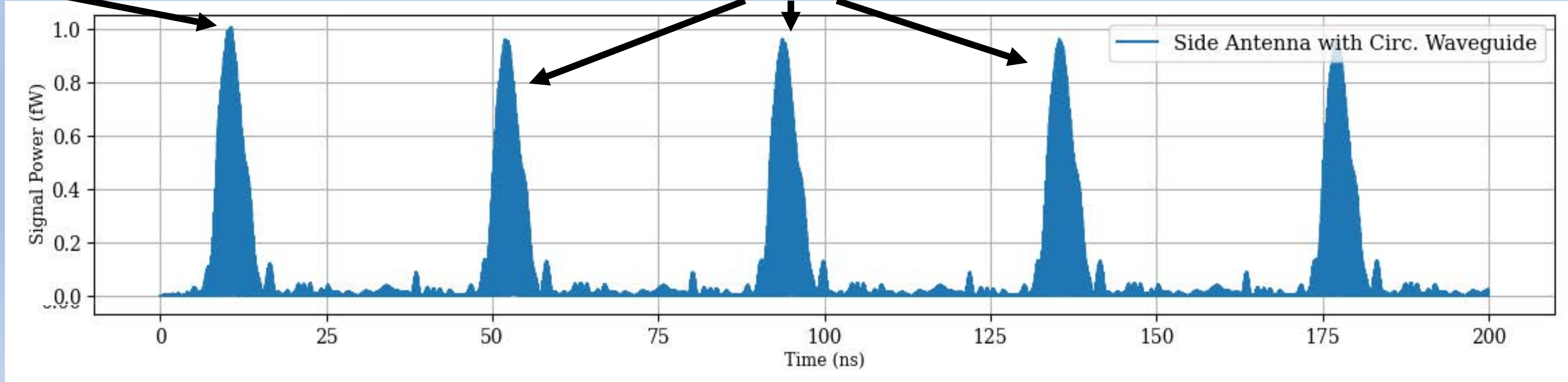


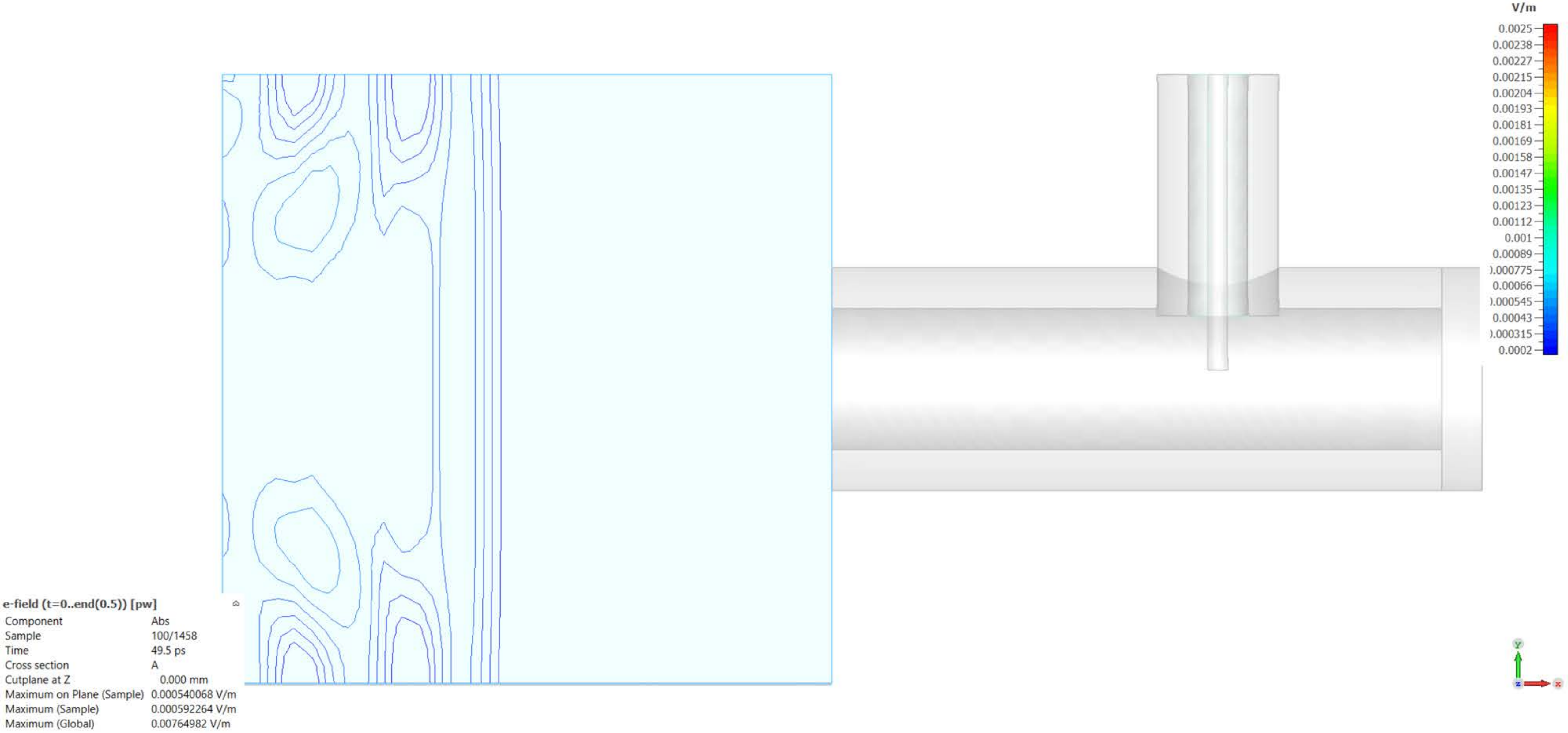


Pin Antenna

1fW peak (87.3% of total, Avg. 5%) @27 GHz

Bouncing (every ~40ns)





V/m
0.0025
0.00238
0.00227
0.00215
0.00204
0.00193
0.00181
0.00169
0.00158
0.00147
0.00135
0.00123
0.00112
0.001
0.00089
0.000775
0.00066
0.000545
0.00043
0.000315
0.0002
e-field (t=0..end(0.5)) [pw]
Component Abs
Sample 100/1458
Time 49.5 ps
Cross section A
Cutplane at Z 0.000 mm
Maximum on Plane (Sample) 0.000540068 V/m
Maximum (Sample) 0.000592264 V/m
Maximum (Global) 0.00764982 V/m

RF Antenna and Readout

Dutch-led Consortium: *started 9/1/21 (5-year)

https://www.nwo.nl/en/projects/nwa129219231

Find funding | Research policy NWO | Research & results

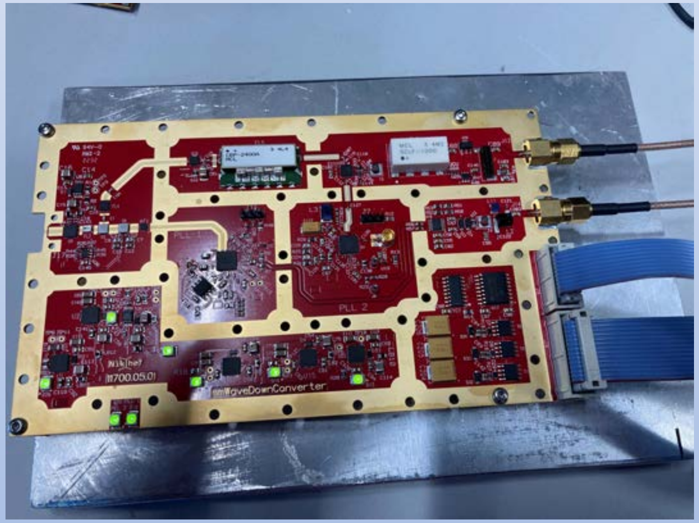
One second after the Big Bang

Every second, Earth is bombarded with an enormous number of neutrinos from the cosmos. These neutrinos were created in the primordial soup one second after the Big Bang, but they have never been observed. The researchers will develop an experiment to observe "relic neutrinos" by investigating the decay of heavy-hydrogen tritium.

Official secretary on behalf of the consortium: Prof. Auke Colijn – University of Amsterdam

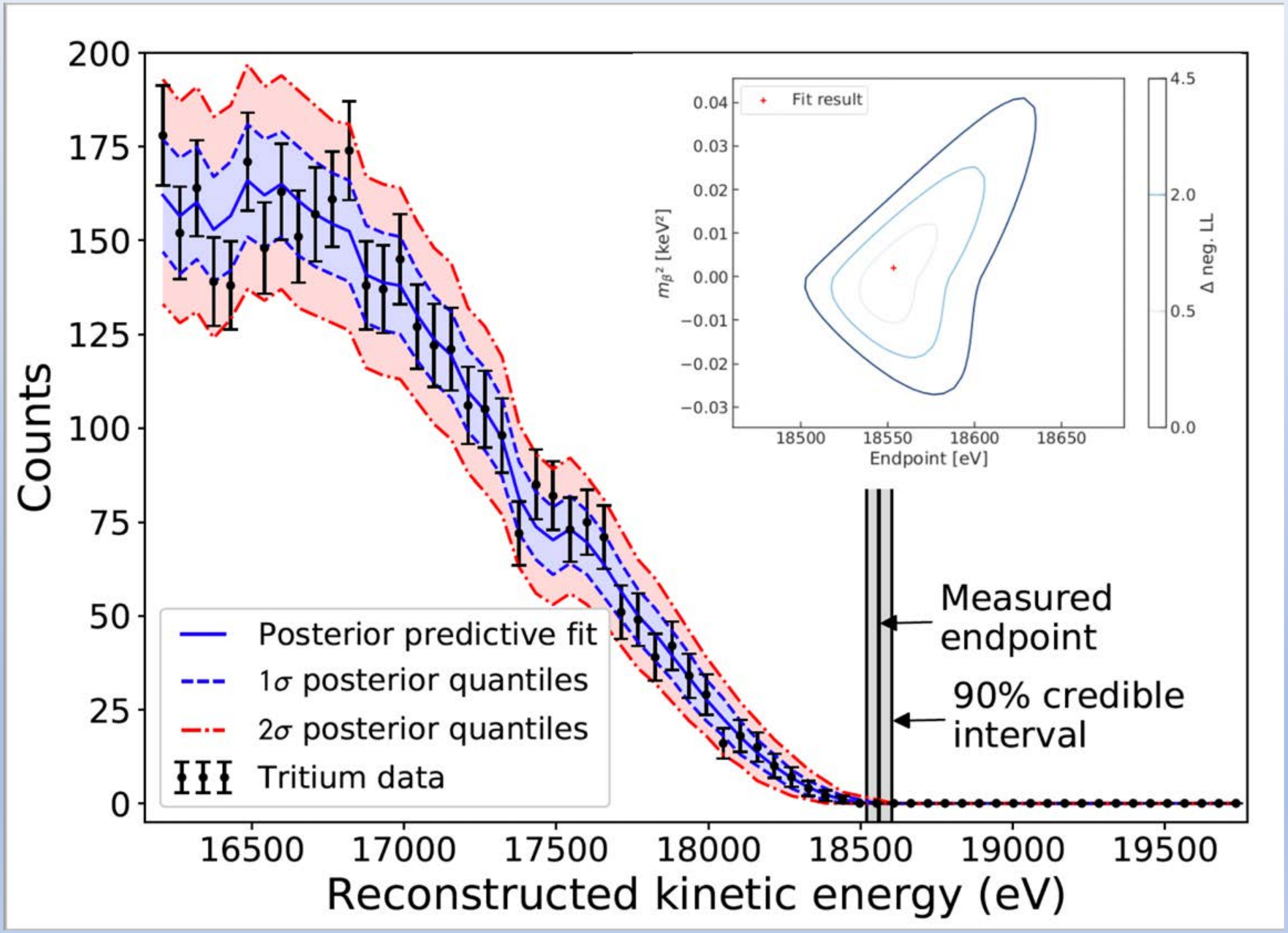
Consortium: University of Amsterdam, Nikhef, Radboud University, The Hague University of Applied Sciences, TNO, Princeton Physics Department, Gran Sasso National Laboratory (LNGS), Netherlands' Physical Society, Ampulz, Karlsruhe Institute of Technology

Amount awarded: 1.1 million euros



Further Antenna design work by TNO and digital processing at Univ. of Amsterdam

Recent Project 8 Tritium Measurement



https://arxiv.org/abs/2203.07349

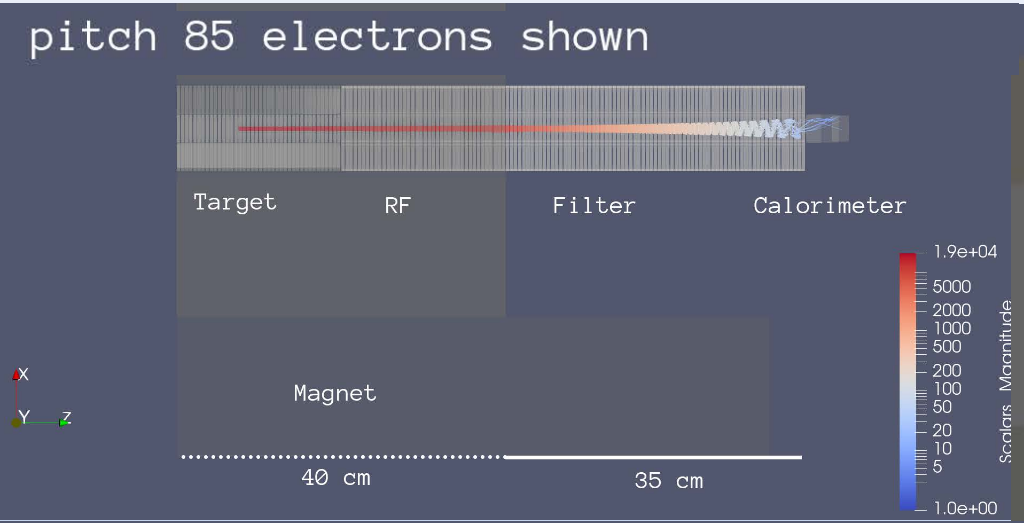
RF measurement background levels extremely low.

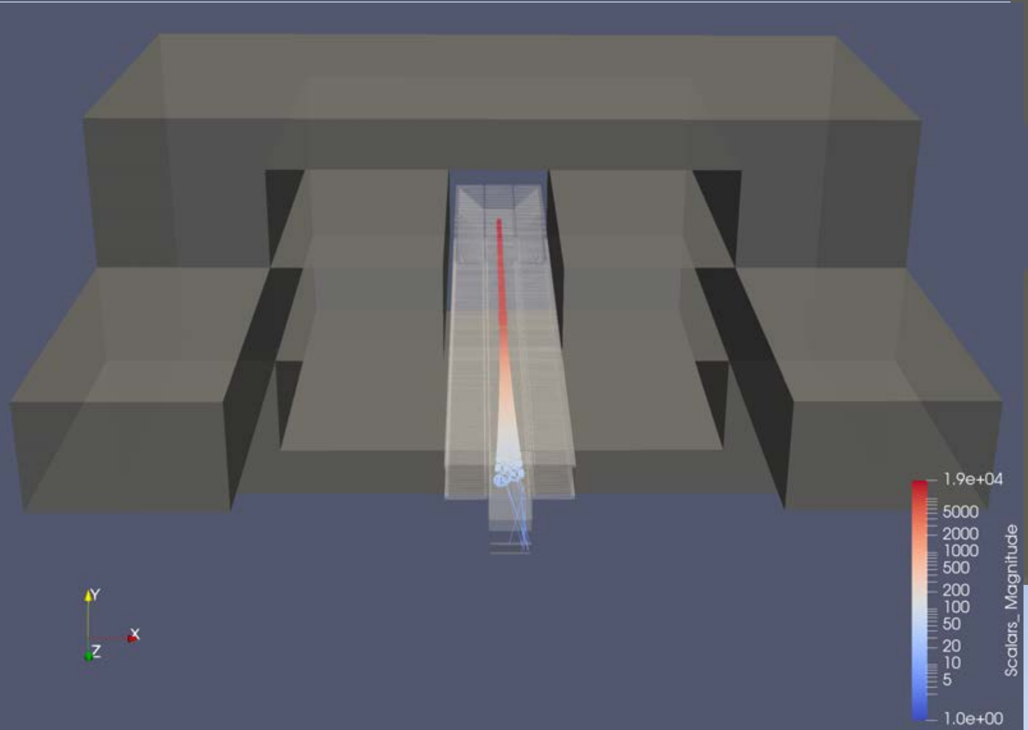
No events observed above endpoint, Setting upper limit on background rate

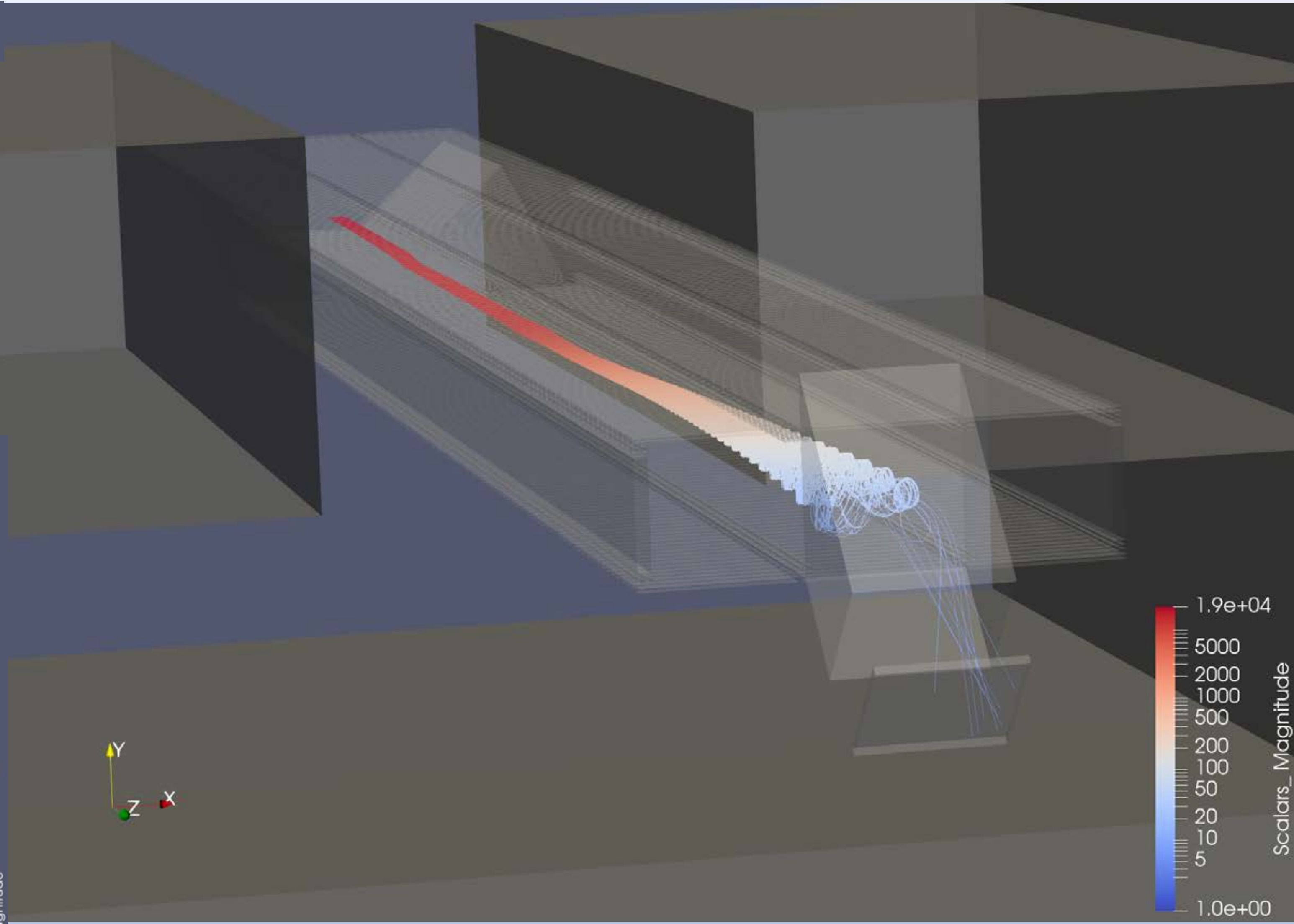
< $3x10^{-10}$ /eV/s (90% CL)

→ < 1 event per eV in 100 years!

End-to-end Transport w/Kassiopeia

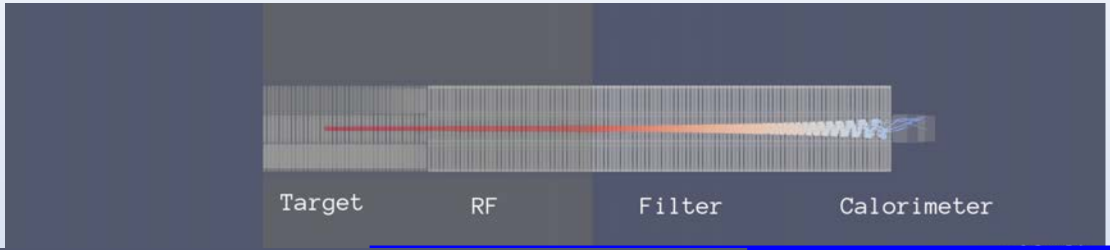




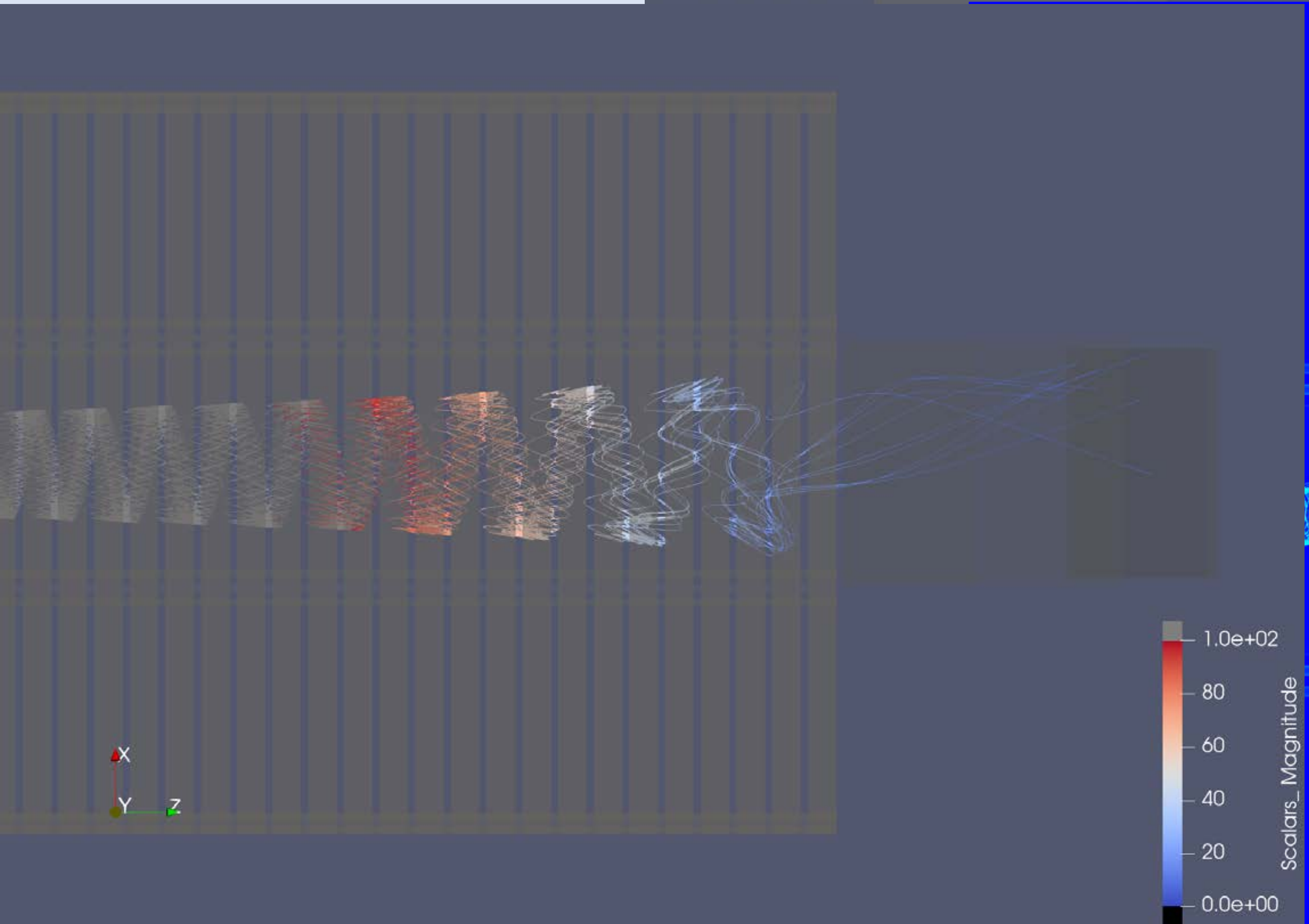


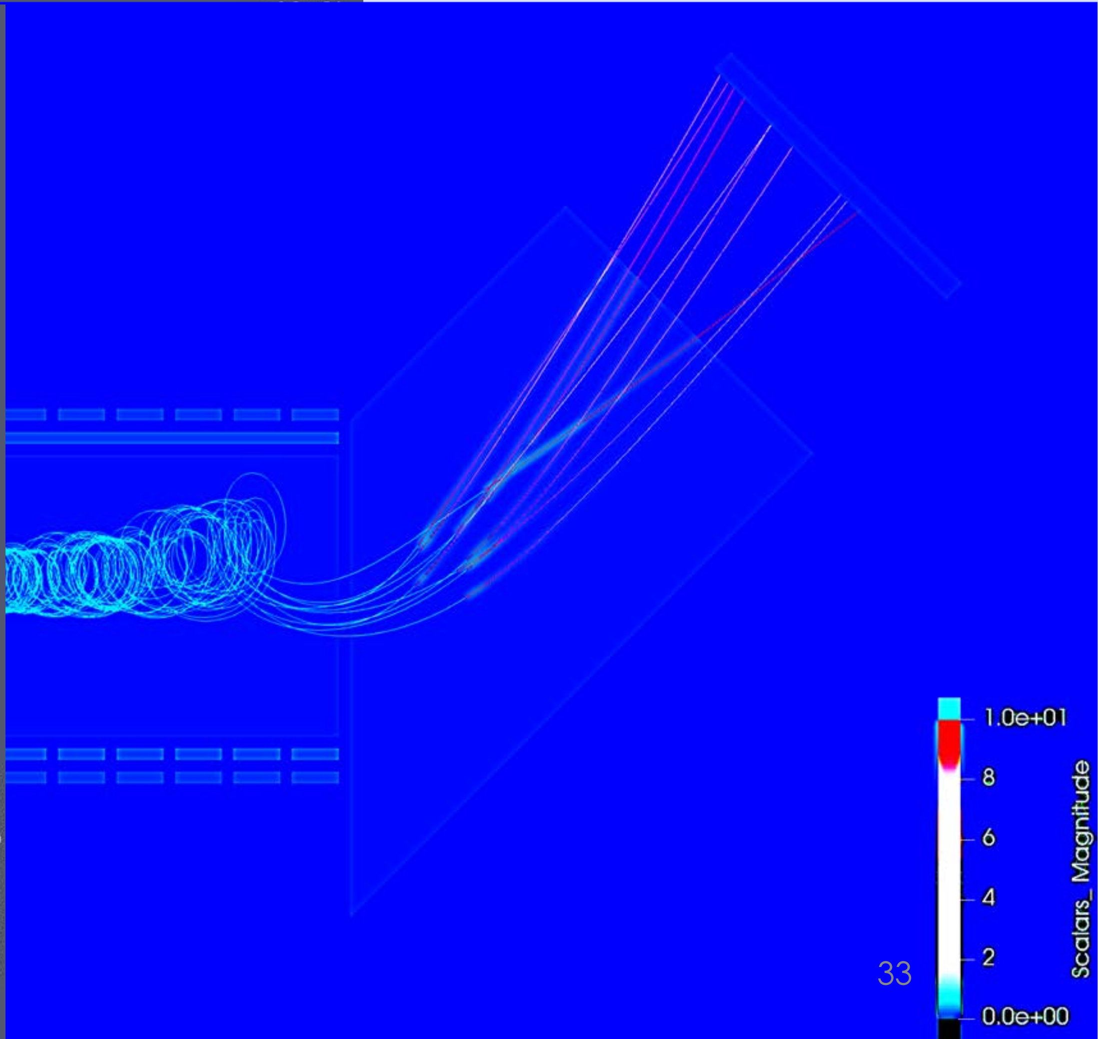
Wonyong Chung (Princeton)

Zero-Field Calorimeter Transition



Wonyong Chung (Princeton)



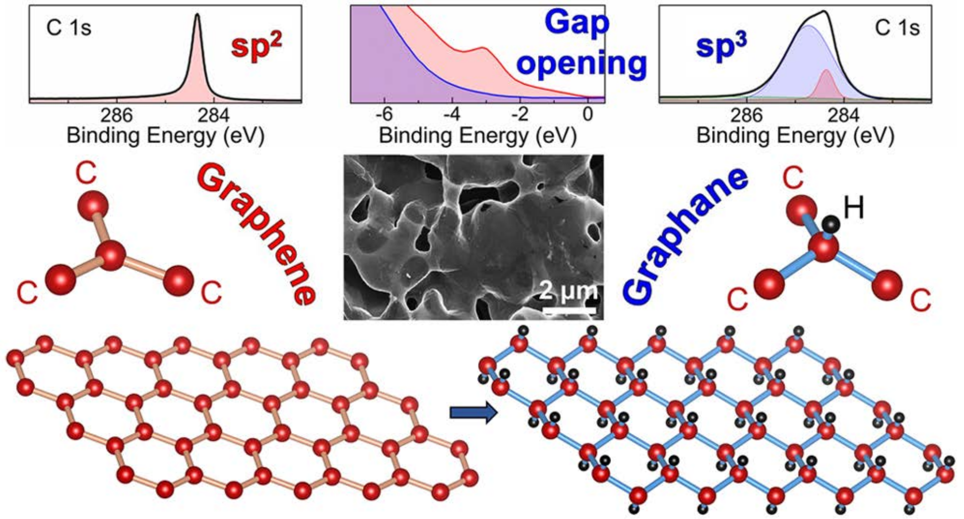


Gap Opening in Double-Sided Highly Hydrogenated Free-Standing Graphene

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.



https://pubs.acs.org/doi/10.1021/acs.nanolett.2c00162

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

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

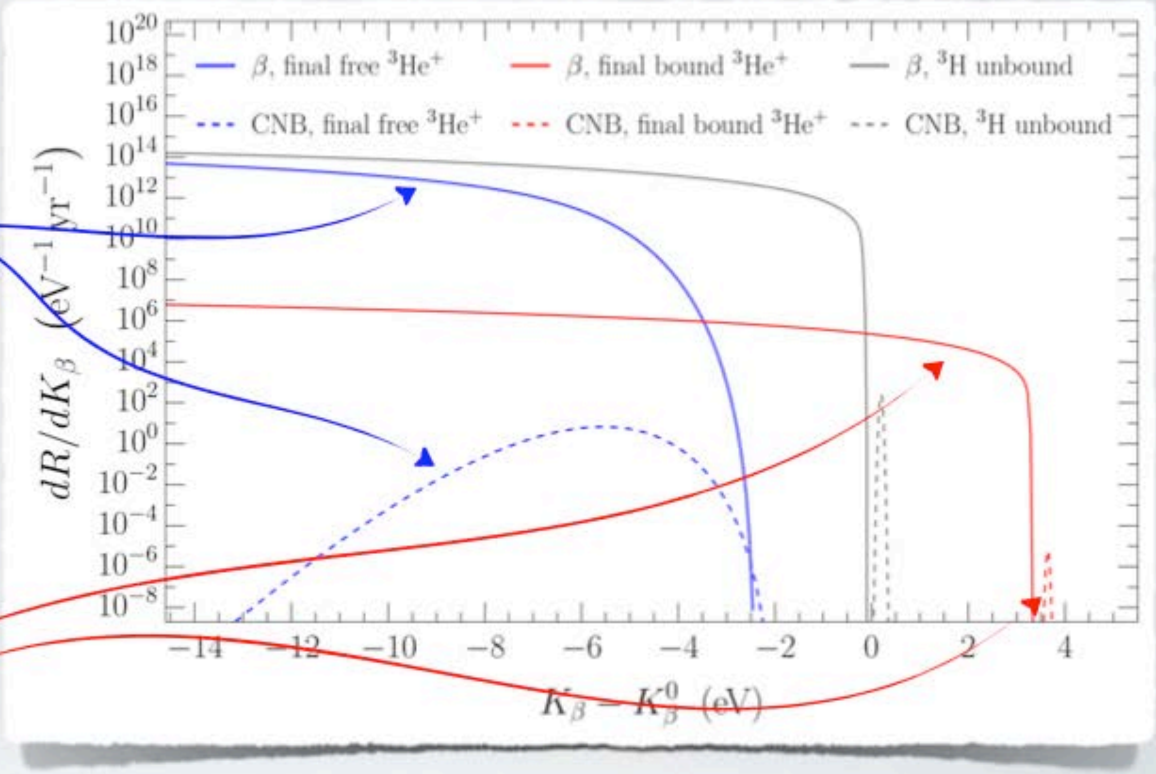
spread of initial tritium wave function $(\Delta x_T \sim 0.1\,\text{Å})$

an order of magnitude larger than the wanted energy accuracy

QUANTUM SPREAD

- The resulting rate is

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



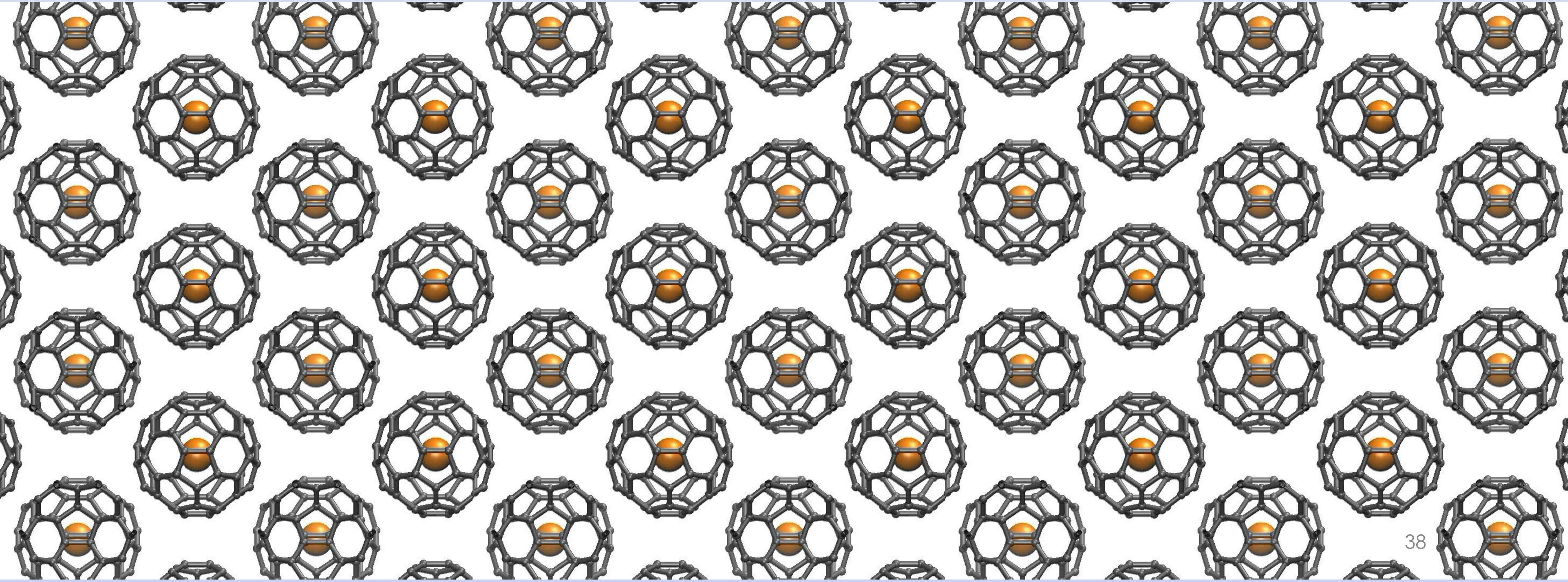
When the $^3He^+$ **remains bound in the ground state** the peak is well separated ⟶ it is however **exponentially unlikely**

[PTOLEMY – 2203.11228]

Collaboration with Savannah River National Laboratory for Tritium Loading

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

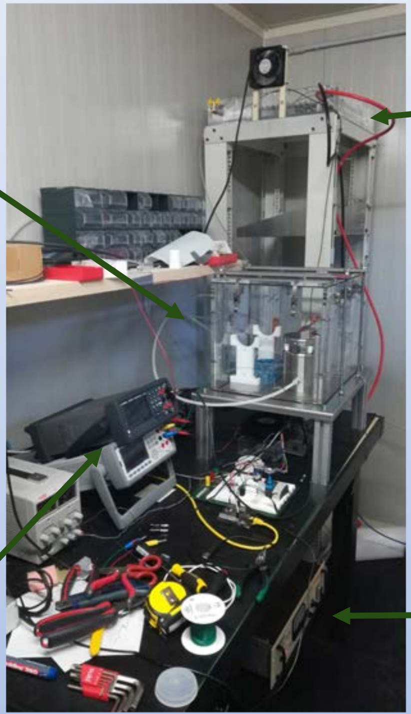
~2Å flat potential – not chemically active



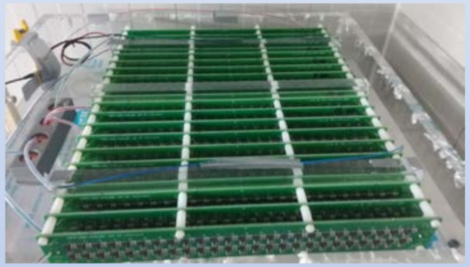
HV Stability and Monitoring

@LNGS

Field mill box



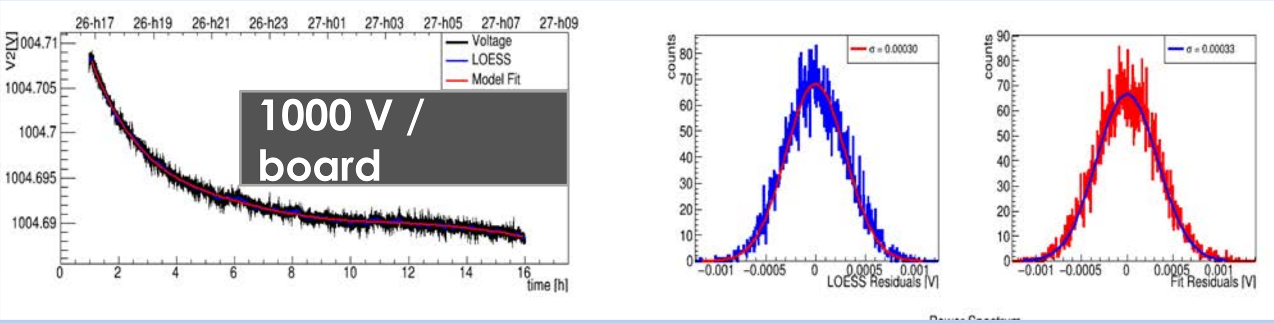
Diodes box



High precision voltmeter Keysight®

Power supply Bertan®

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



1000 V / board

Single board
σ = 0.3 mV

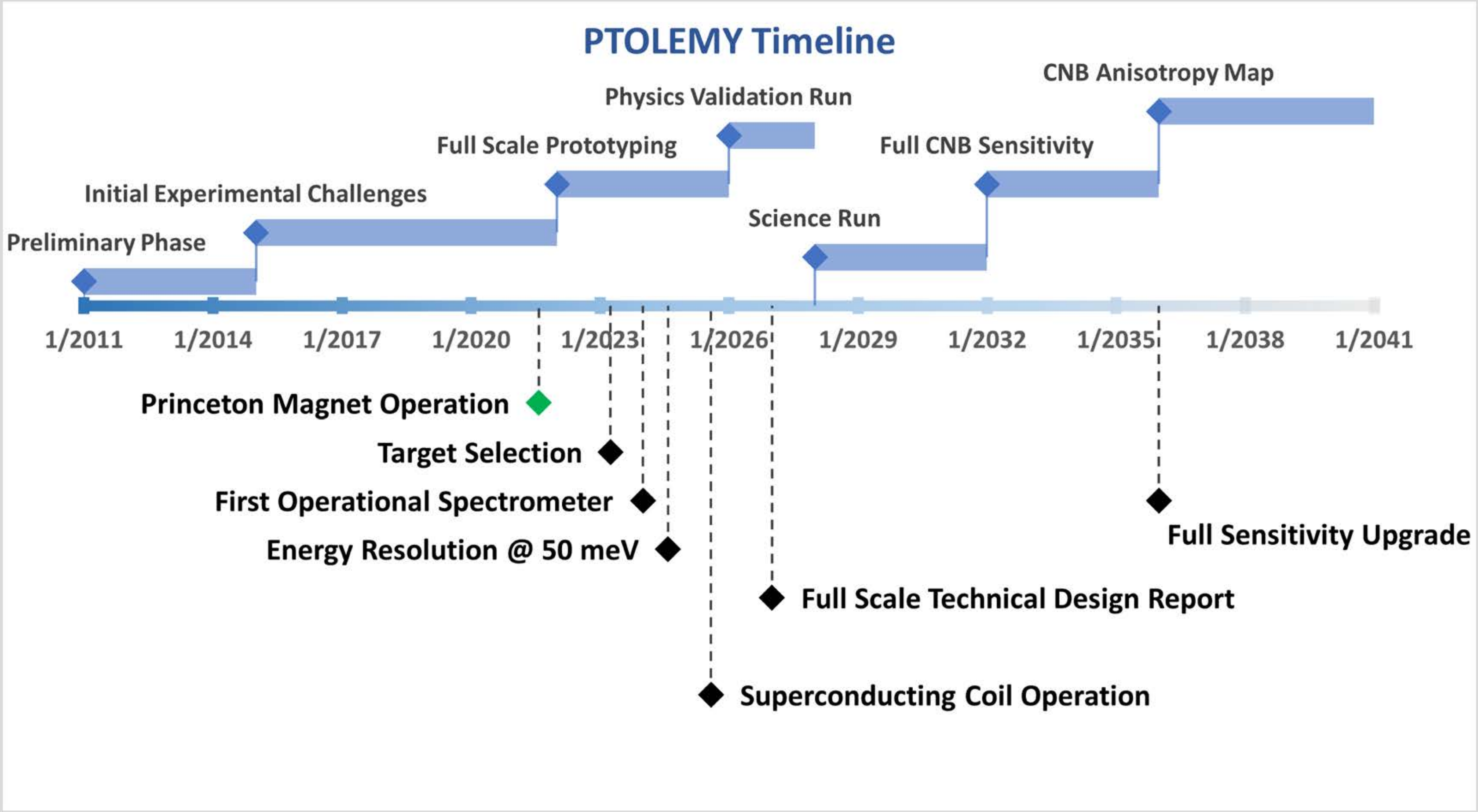
Expect $\sqrt{N_{boards}}$:
~1.4mV@20kV

Field Mill ~50mV

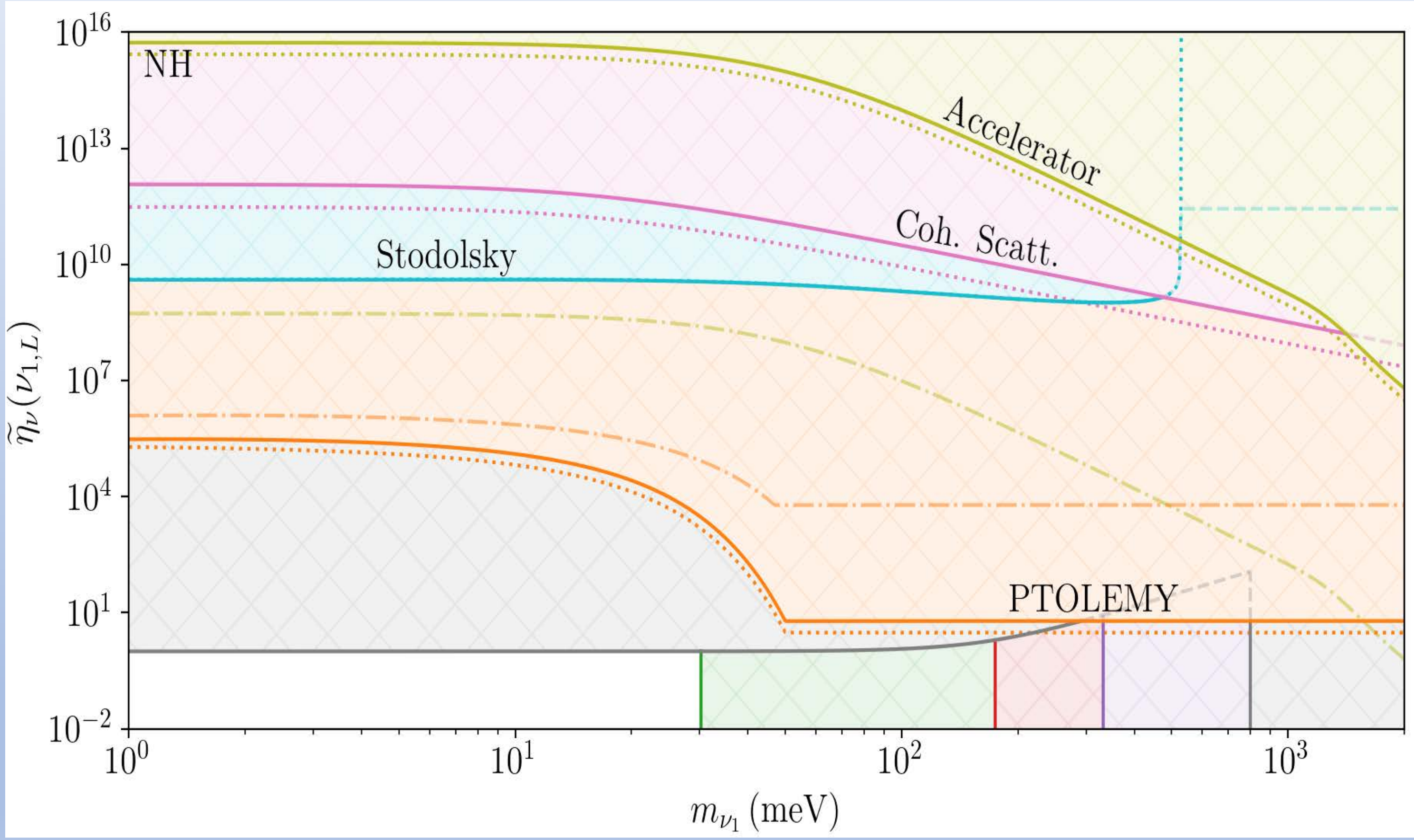
LNGS Full-Scale Prototype

JOHN TEMPLETON FOUNDATION
Inspiring Awe & Wonder

- Features of prototype:
  - Iron-return flux magnet @1T w/ conduction-cooled SC coils
  - small (few cm^2) tritium-loaded graphene target from SRNL w/Rome hydrogen loading system
  - RF antenna @26.5GHz from Univ.of Amsterdam/TNO
  - PTOLEMY filter with high precision HV reference
  - Vacuum cryostat interface to TES microcalorimeter fridge
- Fabrication in progress on most elements (SC coil approval soon)
- Operate through 2024 for first tritium data release


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

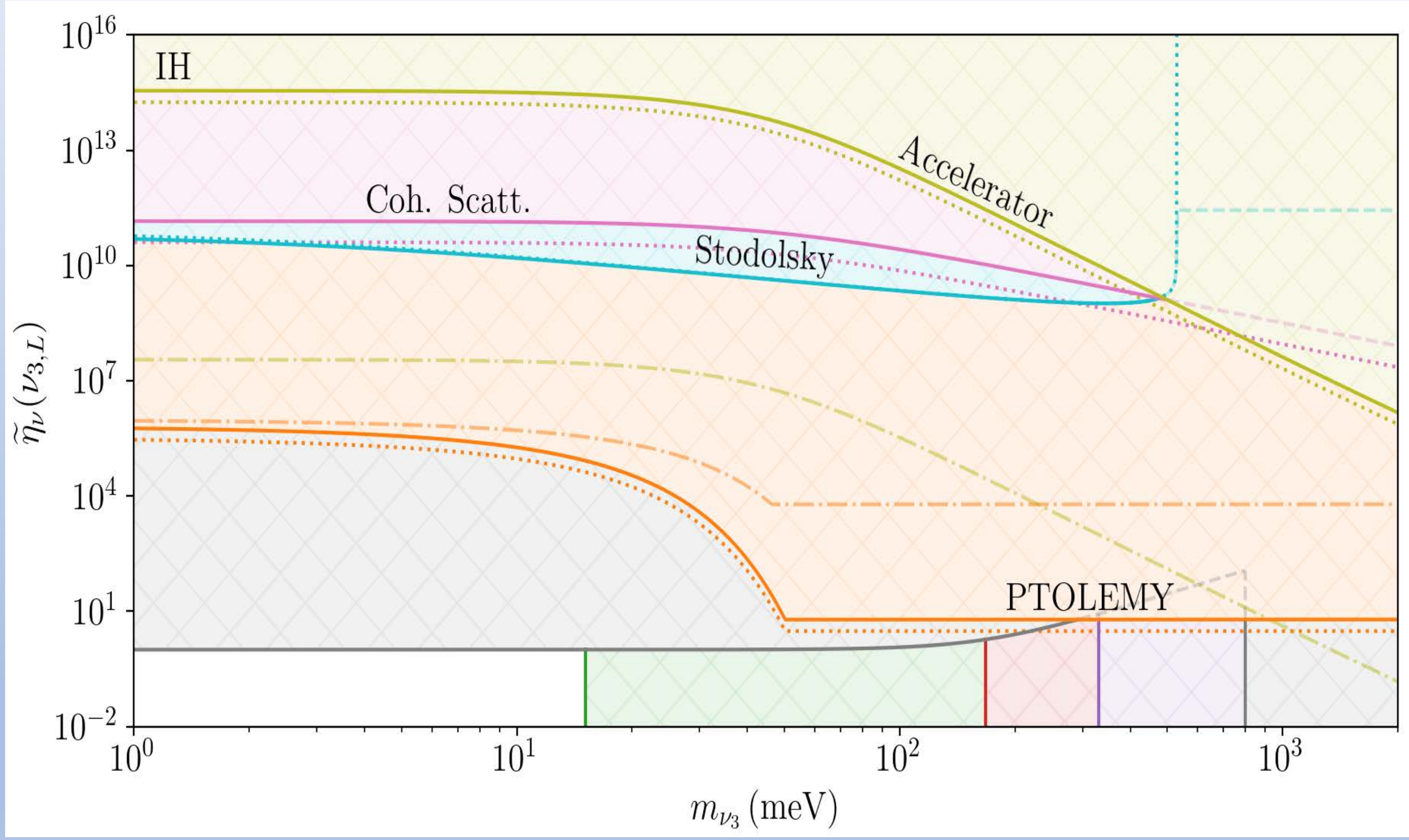
Relic Neutrino Exp Search Sensitivities (NH)



Curve	Description
Orange	PTOLEMY sensitivity to Dirac (solid) and Majorana (dotted) neutrinos, standard method. Time dependent method for Dirac neutrinos (dot-dashed).
Cyan	Stodolsky effect sensitivity to Dirac (solid) and Majorana (dotted) neutrinos.
Pink	Coherent scattering sensitivity to Dirac (solid) and Majorana (dotted) neutrinos.
Light green	Accelerator sensitivity to Dirac (solid) and Majorana (dotted) neutrinos. Using an optimistic setup for Dirac neutrinos (dot-dashed).
Grey	Excluded by theory and experiment for $T_{\nu_i} = T_{\nu,0}$ (solid, Figures 9 and 10). Excluded by KATRIN (dashed, Figures 11 and 12).
Blue	Excluded by Pauli exclusion principle for $T_{\nu_i} \neq T_{\nu,0}$.
Purple	Strongest mass bound on unstable Dirac neutrinos, from cosmology.
Red	Strongest mass bound on unstable Majorana neutrinos, from KamLAND-Zen.
Green	Strongest mass bound on stable neutrinos, from cosmology.

https://arxiv.org/abs/2207.12413

Relic Neutrino Exp Search Sensitivities (IH)



Curve	Description
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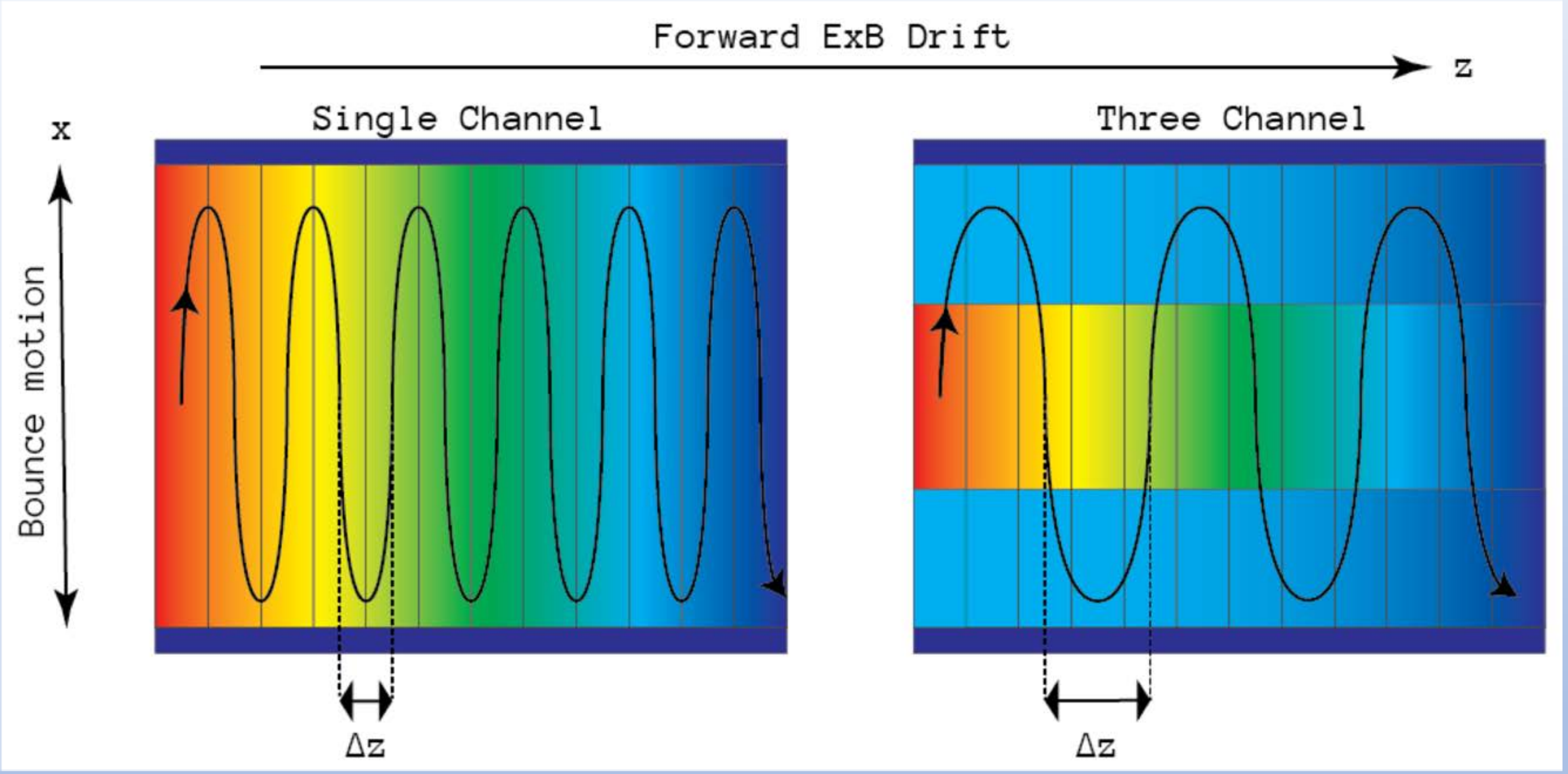
https://arxiv.org/abs/2207.12413

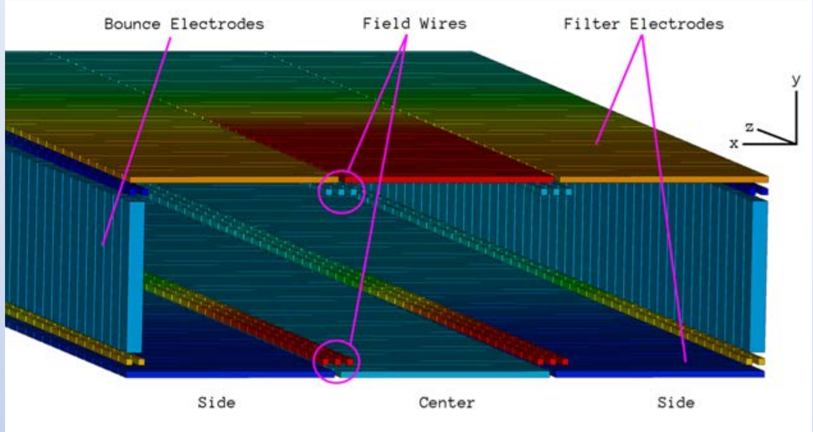
Outlook

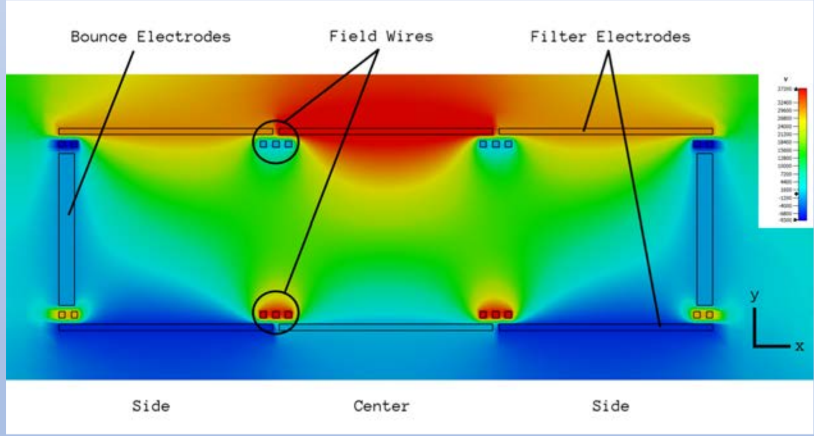
- The sustained effort in PTOLEMY R&D is a testament to the importance our dedicated group of collaborators place on pushing the frontier of early Universe neutrino cosmology – clever ingenuity is behind many advances
- PTOLEMY expects to become the leader in tritium endpoint energy measurement resolution within the next 2 years
  - Next stop (w/ more target mass): absolute neutrino mass

Backup

Bobsledding (pushing electron up potential)



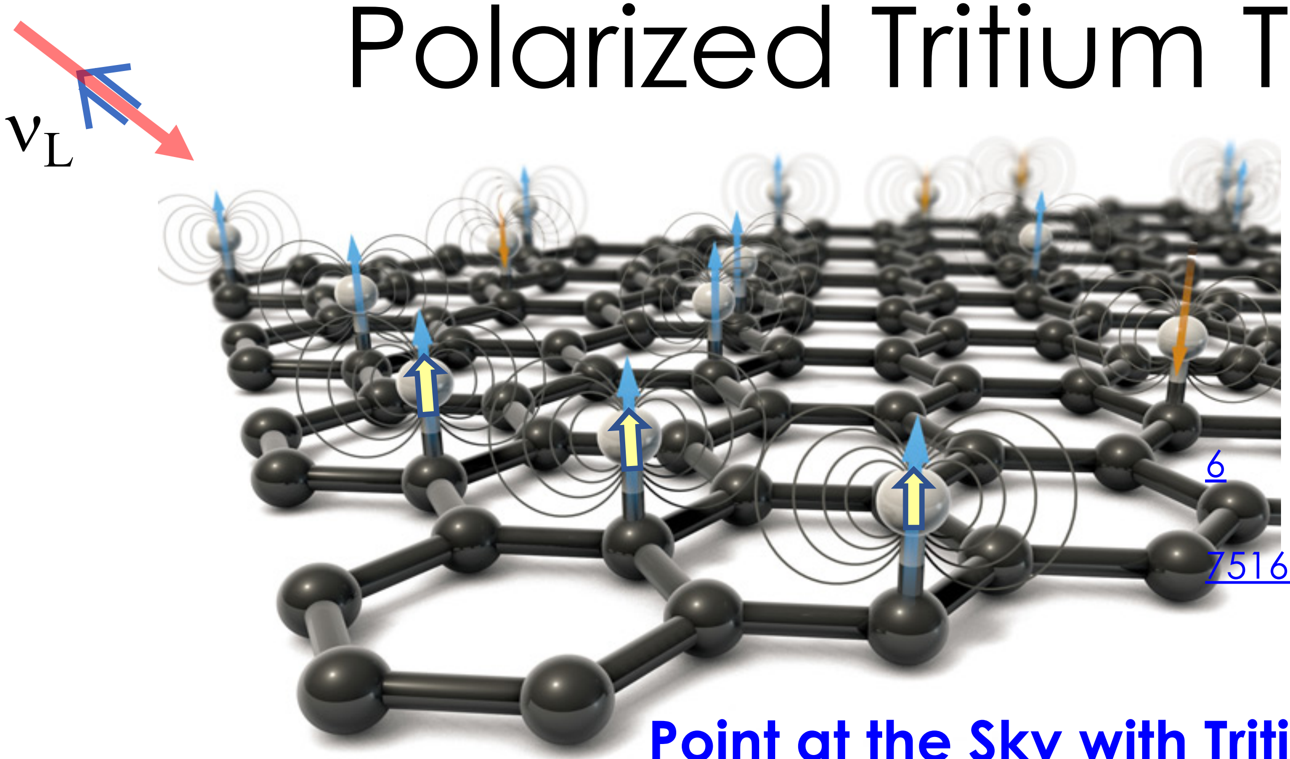




Transverse "Selector"
(one channel)

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

Polarized Tritium Target

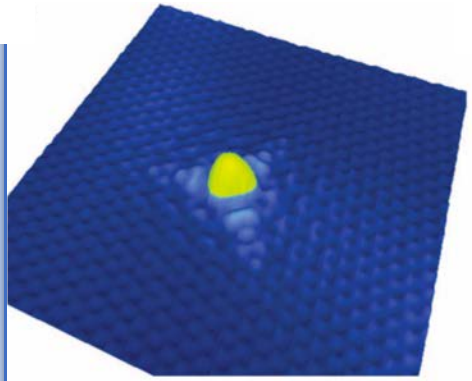


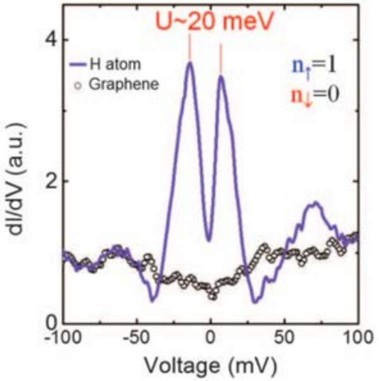
Lisanti, Safdi, CGT, 2014. 10.1103/PhysRevD.90.073006
Akhmedov, 2019. 10.1088/1475-7516/2019/09/031

Point at the Sky with Tritium Nuclear Spin ⇑

Detection (capture) of cold neutrinos:

$d\sigma/d\cos\theta$ (v/c) ~ $(1+\cos\theta)$

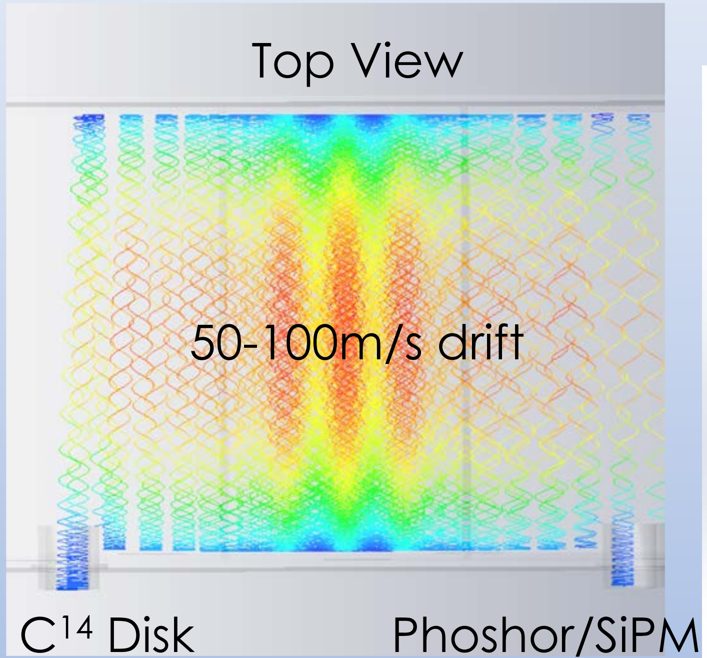


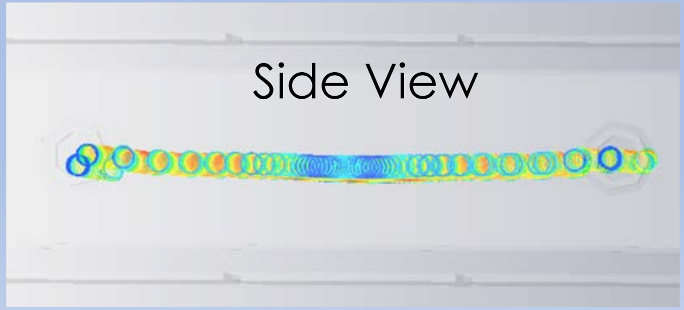


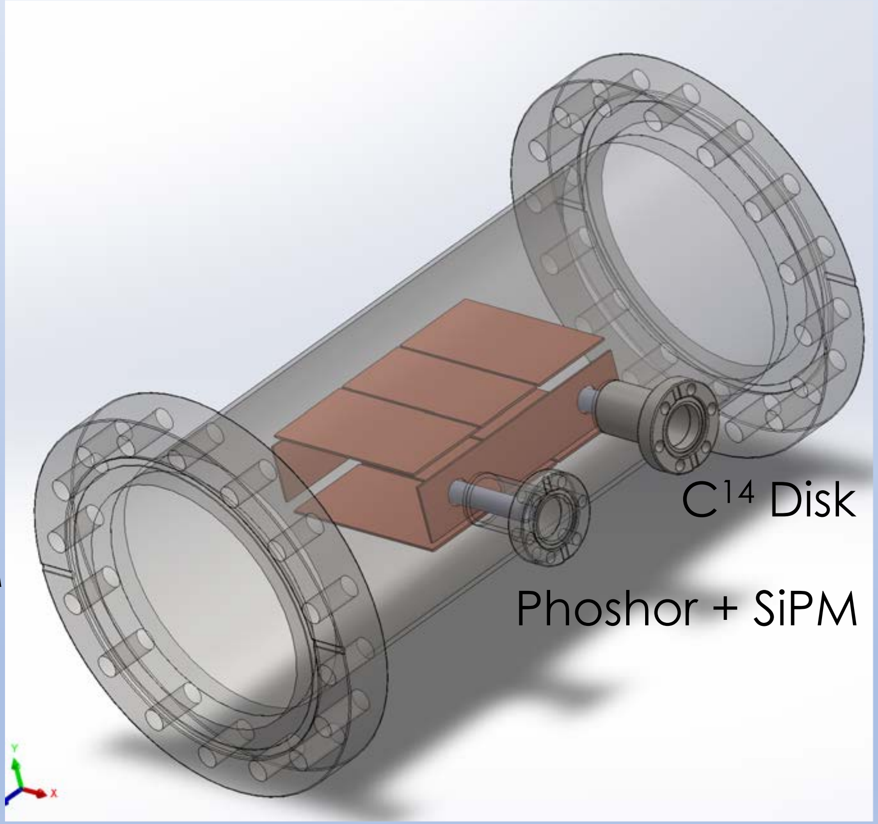
Hydrogen doping on graphene reveals magnetism

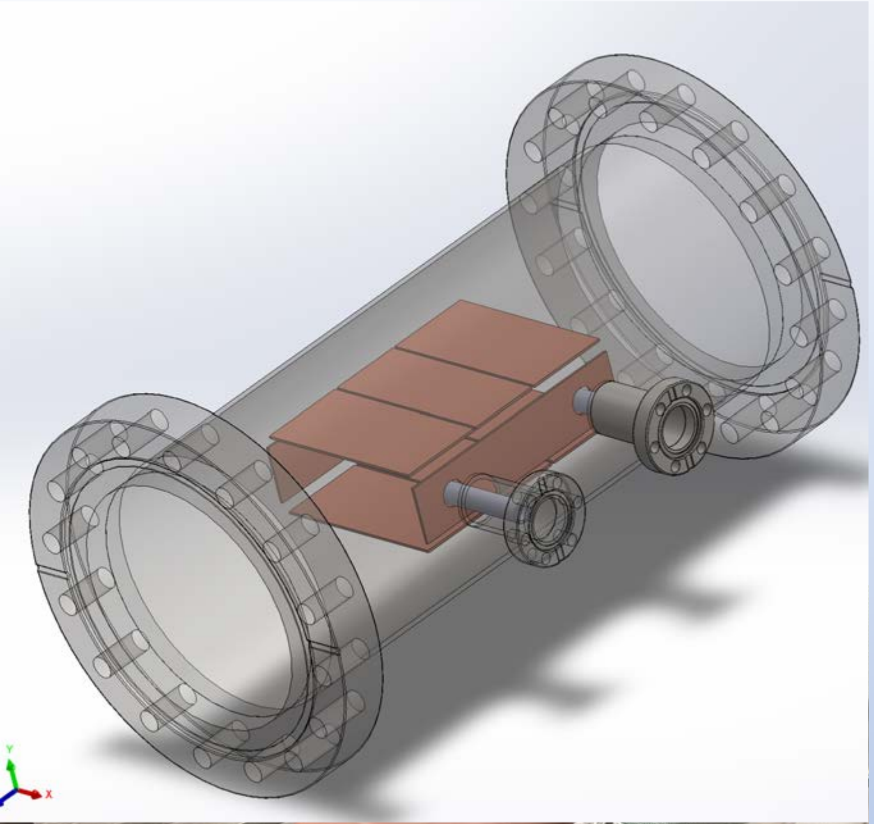
Gonzalez-Herrero, H. *et al.* Atomic-scale control of graphene magnetism by using hydrogen atoms. *Science (80).* **352,** 437–441 (2016).

Ultra-slow electron drift region

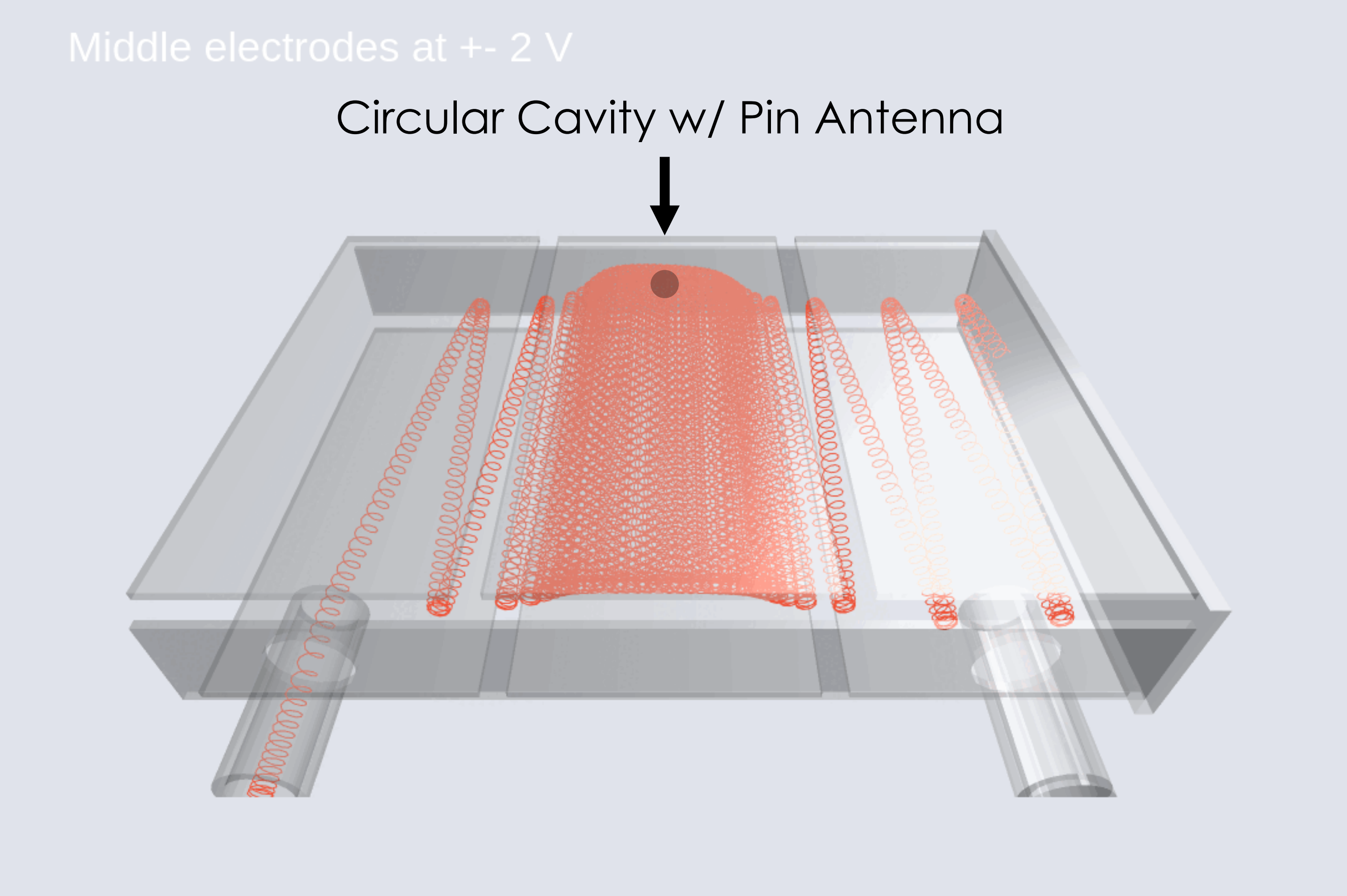






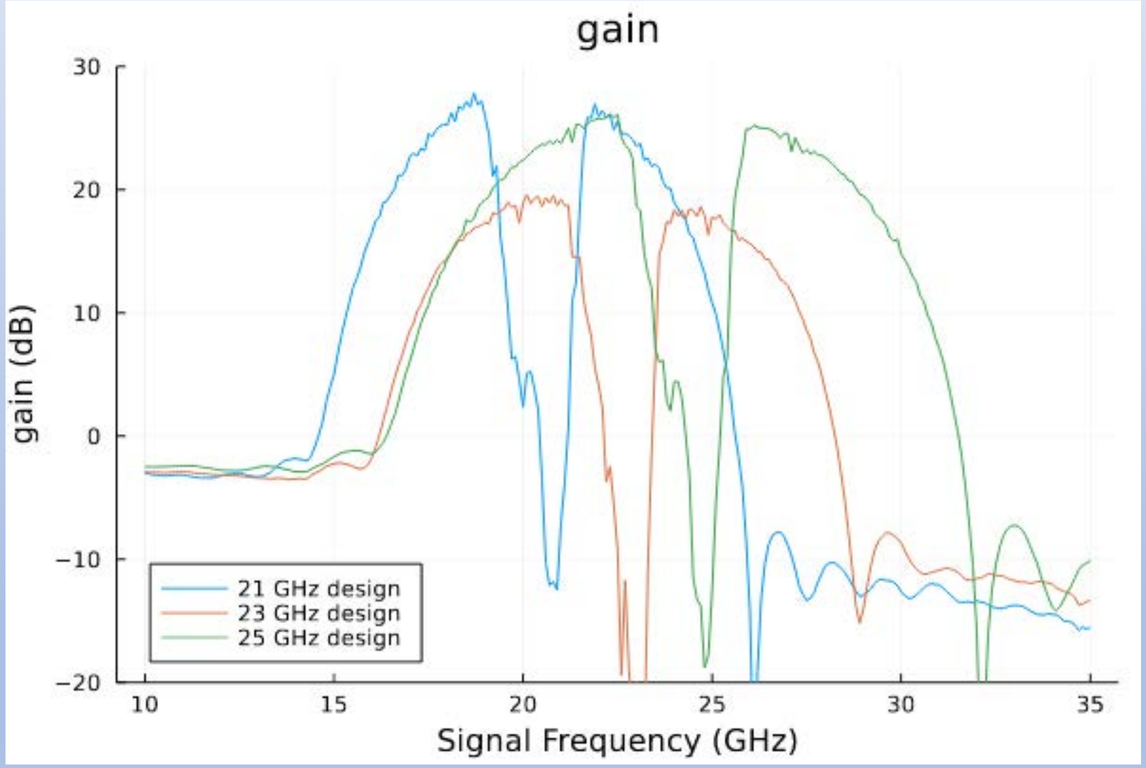


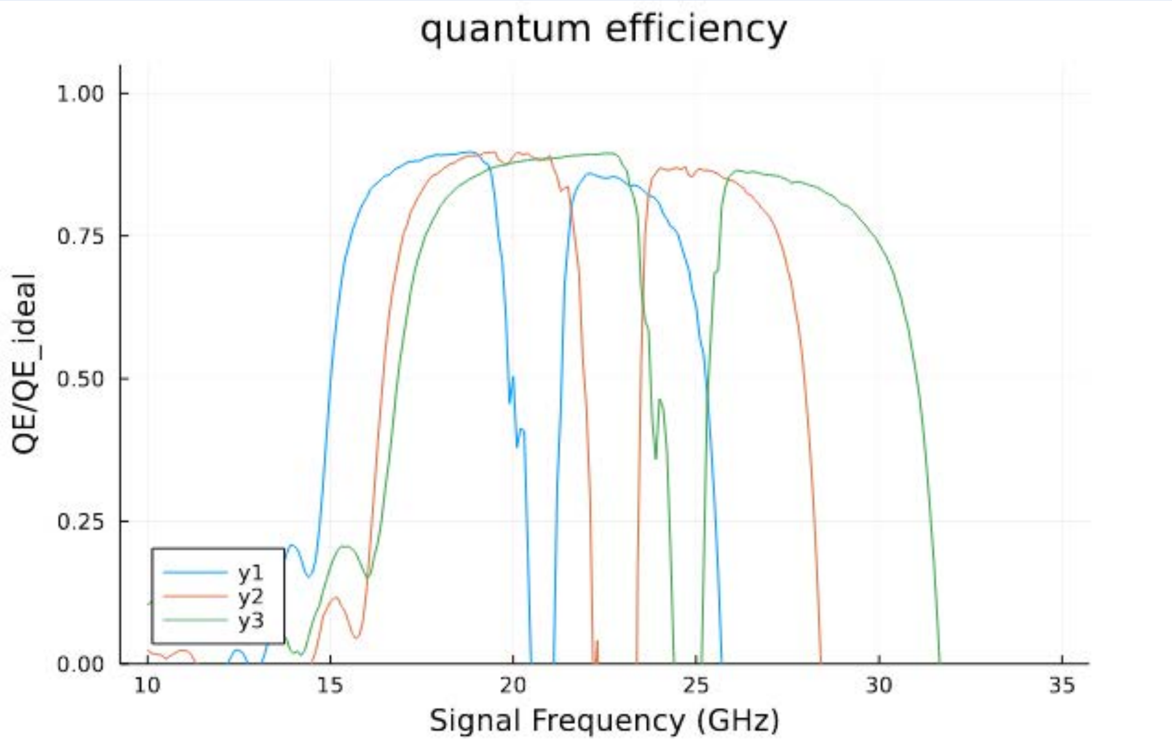
Scanning ExB Voltages to Maximize Duration of Antenna Signal



Quantum-Limited Parametric Amp

High Frequency Josephson Traveling Wave Parametric Amp (TWPA)





Joint Project w/ MIT and Project 8

Electromagnetic Filters

MAC-E filter

Magnetic Adiabatic Invariance

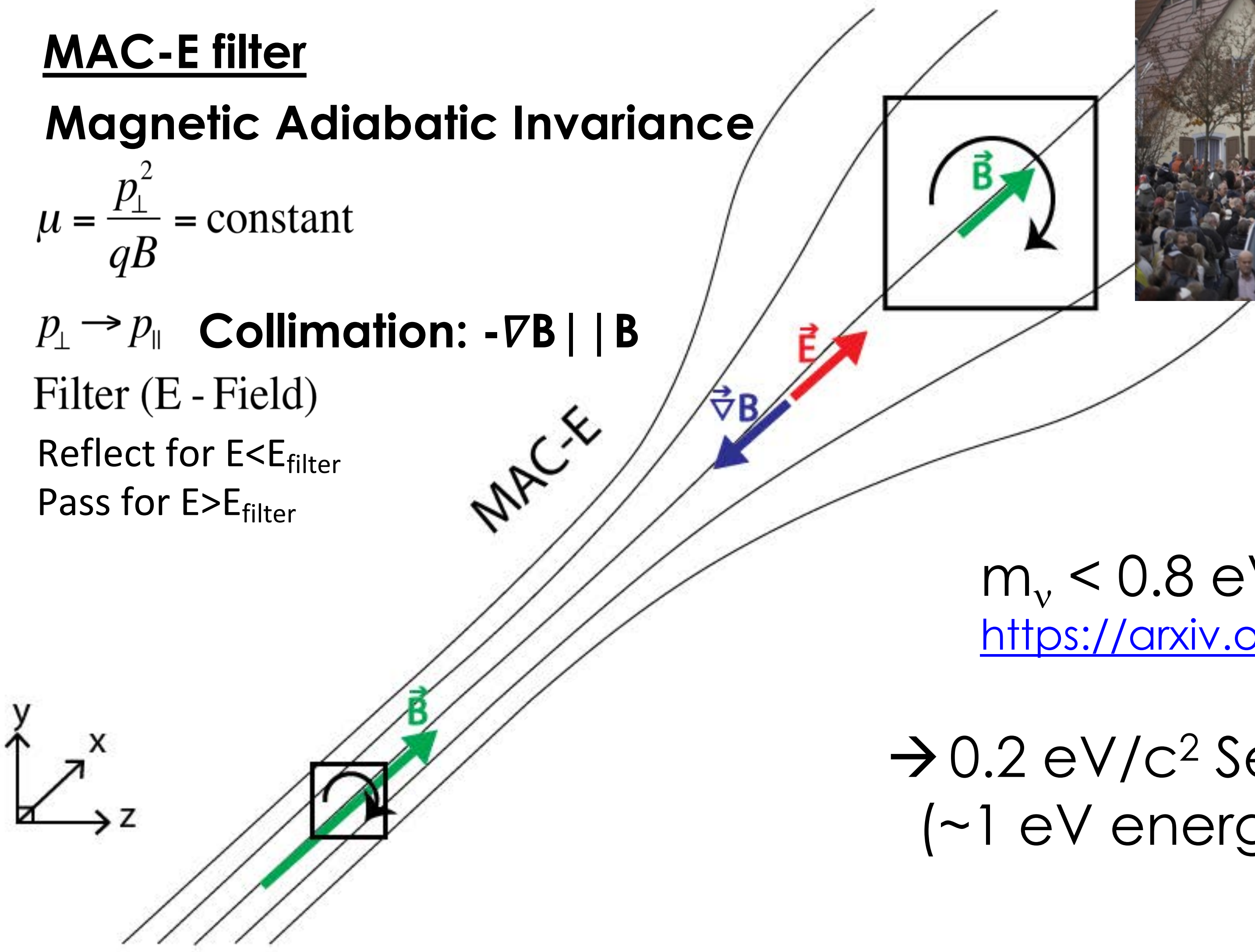
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

$p_\perp \rightarrow p_\parallel$ **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

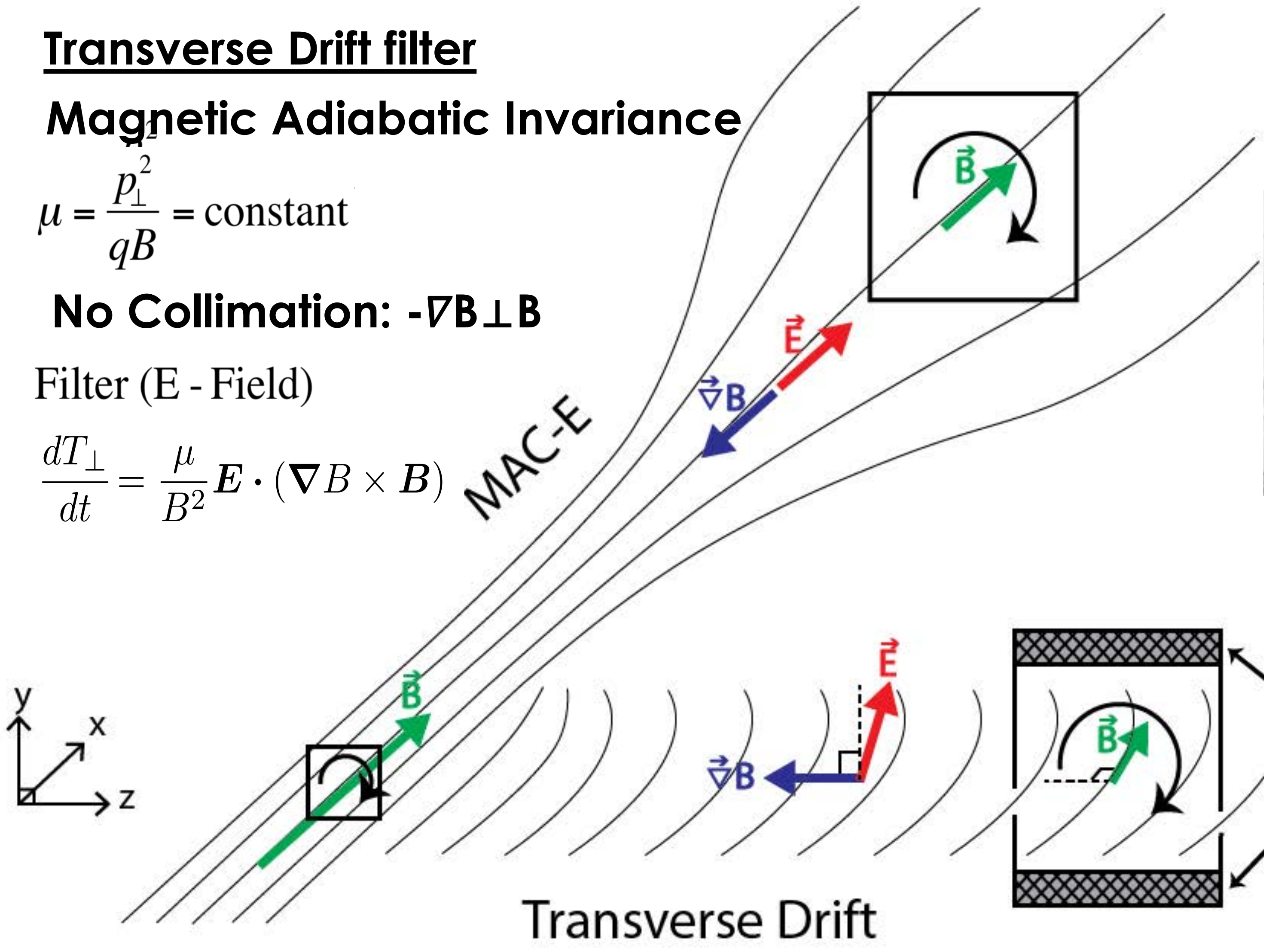
Magnetic Adiabatic Invariance

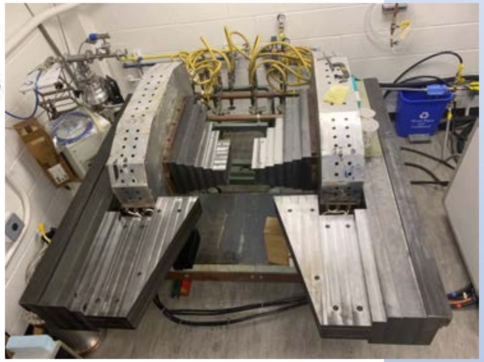
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

No Collimation: -∇B⊥B

Filter (E - Field)

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

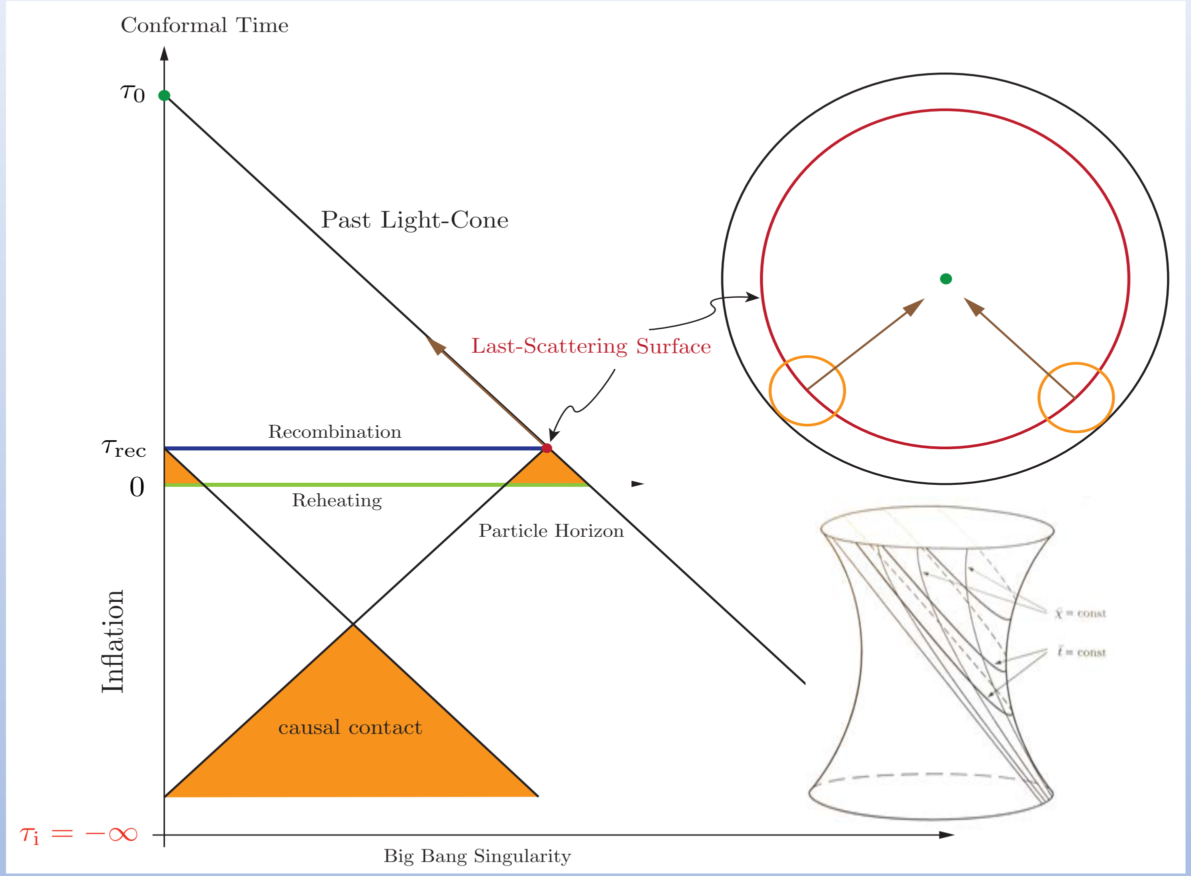




PTOLEMY

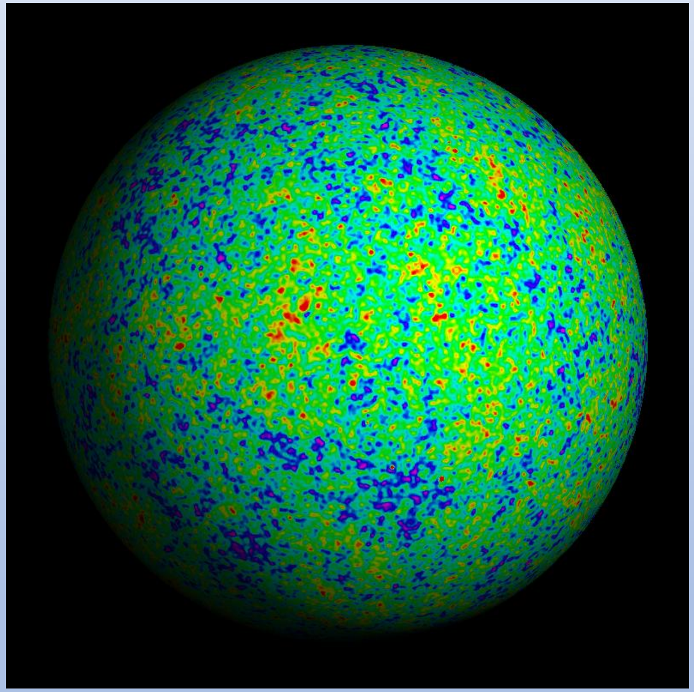
~1m^3

Big Bang Cosmology



Adiabatic Density Anisotropies

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



Where we think there is an initial $\tau_i=0$ Big Bang Singularity is believed to be the “end” of an inflation period that slowly pulled out (>60 e-folds $a(\tau) \sim e^{H\tau}$) of a “de Sitter”-like spacetime

Axions and Relic Neutrinos

- Early Universe models trend toward having axion and neutrino sector implications:
  - Both involve relatively low masses
  - Both have unique coupling terms including non-SM
  - Both see some stopping blocks at BBN and CMB
  - Both have possibilities for late Universe generation in warm-inflation-like models
  - Experiments are distinct in terms of wave-like or target-based particle detection, but interesting parameter spaces can be correlated depending on the model

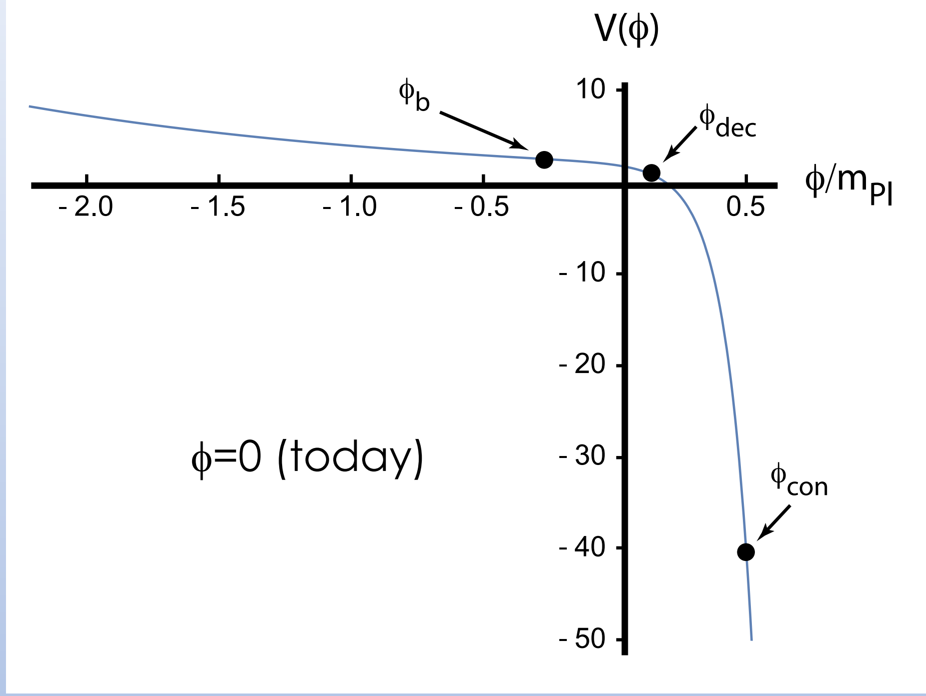
Where neutrinos come in

1 MeV ~ 70x10^{39} km/s per Mpc

- Example: F. Takahashi, W. Yin, and A. Guth, "QCD axion window and low-scale inflation", 10.1103/PhysRevD.98.015042 (2018). https://arxiv.org/abs/1805.08763
  - $H_{inf} < \mathcal{O}(1)$ MeV no fine-tuning of misalignment angle needed
  - Upper bound on axion scale relaxed → wave-like particles with dark matter abundance
  - *Reheating?* Right-handed neutrinos coupled to the inflaton (B-L Higgs?)
  - *Inflaton-Radiation equality, followed by perturbative right-handed neutrino decays to Higgs and leptons (resonant leptogenesis?)*
  - *Heavier right-handed neutrino radiative correction increases spectral index*

Rich era of axion experiments – but with neutrinos a close buddy

End of Expansion

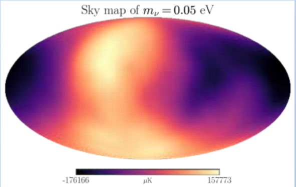


Frictional term $\propto \dot{\phi}$

may couple to gauge singlets:

- Right-handed neutrinos??

→ CNB w/ high local density and much more uniform



Dipole ~ 8% → <1%

Quad ~ 4% → <0.5%

C. Andrei, A. Ijjas and P.J.Steinhardt, The End of Expansion, https://arxiv.org/abs/2201.07704

A. Ijjas and P.J. Steinhardt, The End of Expansion and Dark Radiation (tentative title), in preparation

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