PTOLEMY: Detecting Relic Neutrinos from the Big Bang

Andi Tan
Princeton University

Particle Physics Seminar at BNL
3rd Feb 2022

Princeton
Tritium
Observatory for
Light,
Early-universe,
Massive-neutrino
Yield

PTOLEMY World-Wide Collaboration

Christopher Tully

Wonyong Chung

2015 Targeted Grant Award from the
SIMONS FOUNDATION

PPPL PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY
KICP Kavli Institute for Cosmological Physics at The University of Chicago
Argonne NATIONAL LABORATORY
Berkeley UNIVERSITY OF CALIFORNIA
BERKELEY LAB Lawrence Berkeley National Laboratory
POLITÉCNICA
IFIC INSTITUT DE FISICA CORPUSCULAR
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Stockholm University
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INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA
UNIVERSITÀ DEGLI STUDI DI GENOVA
SAPIENZA UNIVERSITÀ DI ROMA
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THE HEBREW UNIVERSITY OF JERUSALEM

טלסקופ ניטרינים קוסמיים

Telescopio di neutrini cosmologici

Kosmische neutrinotelescoop

Telescopio de neutrinos cósmicos

Kosmisk neutrinoteleskop

Cosmic neutrino telescope

Cosmic Neutrino Background

Frozen-out at ~ 1 s

Temperature

$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \sim 1.95\ \mathrm{K\ or\ 0.168\ meV}$$

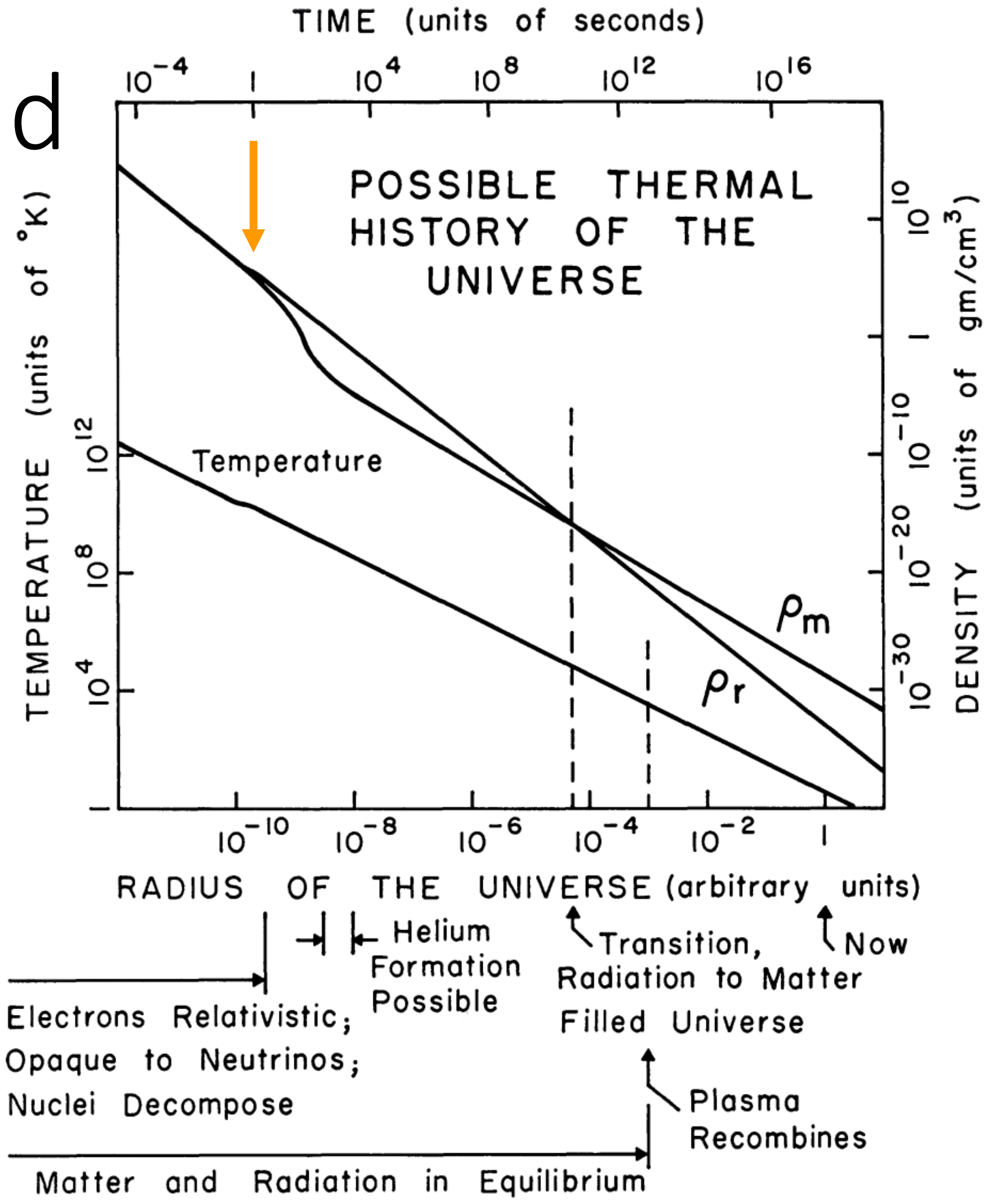
Number Density

$$n_\nu \sim 112\ /\mathrm{cm}^3 \text{ per flavor}$$

Momentum/Velocity Distribution

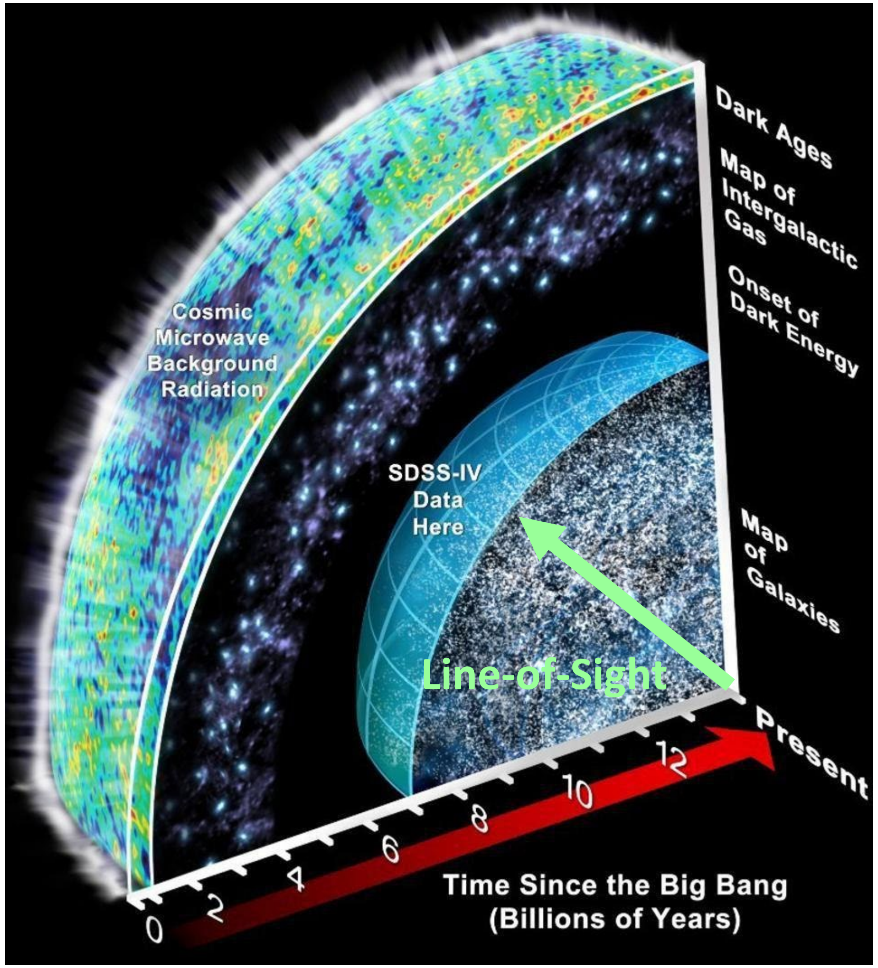
$$\langle v\rangle \sim 4.106\,\frac{T_\nu}{m_\nu}$$

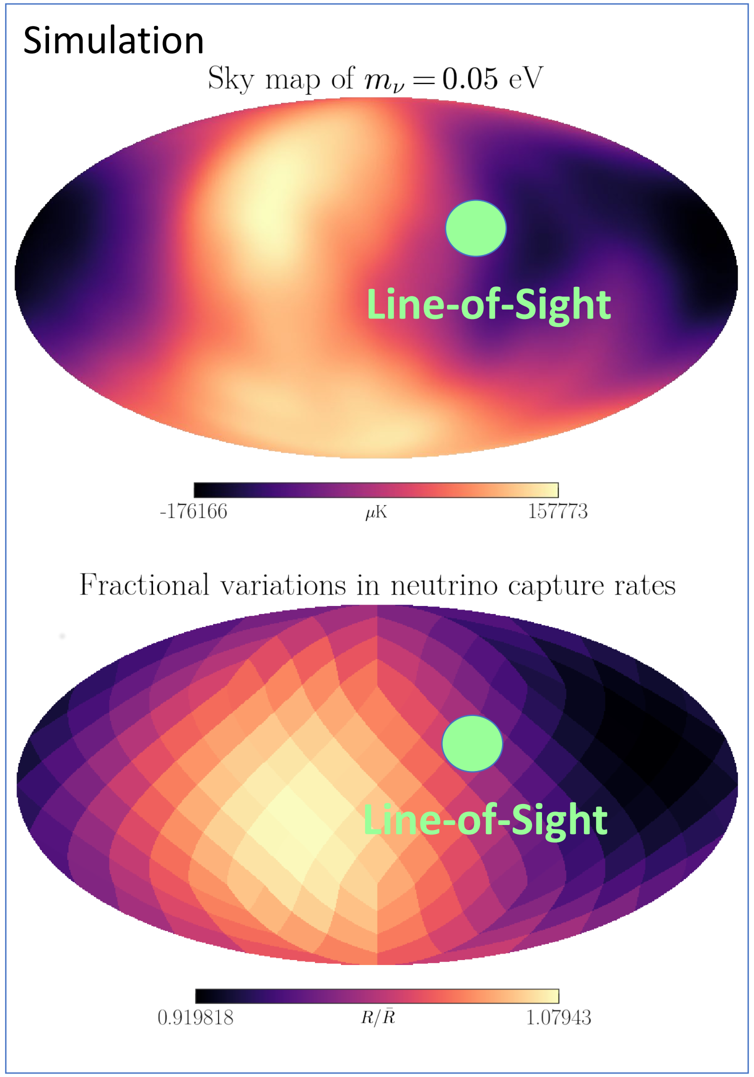
For $m_\nu = 50$ meV, $\langle v\rangle/c \sim 0.014$



Dicke, Peebles, Roll, and Wilkinson, 1965,
“Cosmic Black-Body Radiation.,” Astrophysical J **142**, 414.

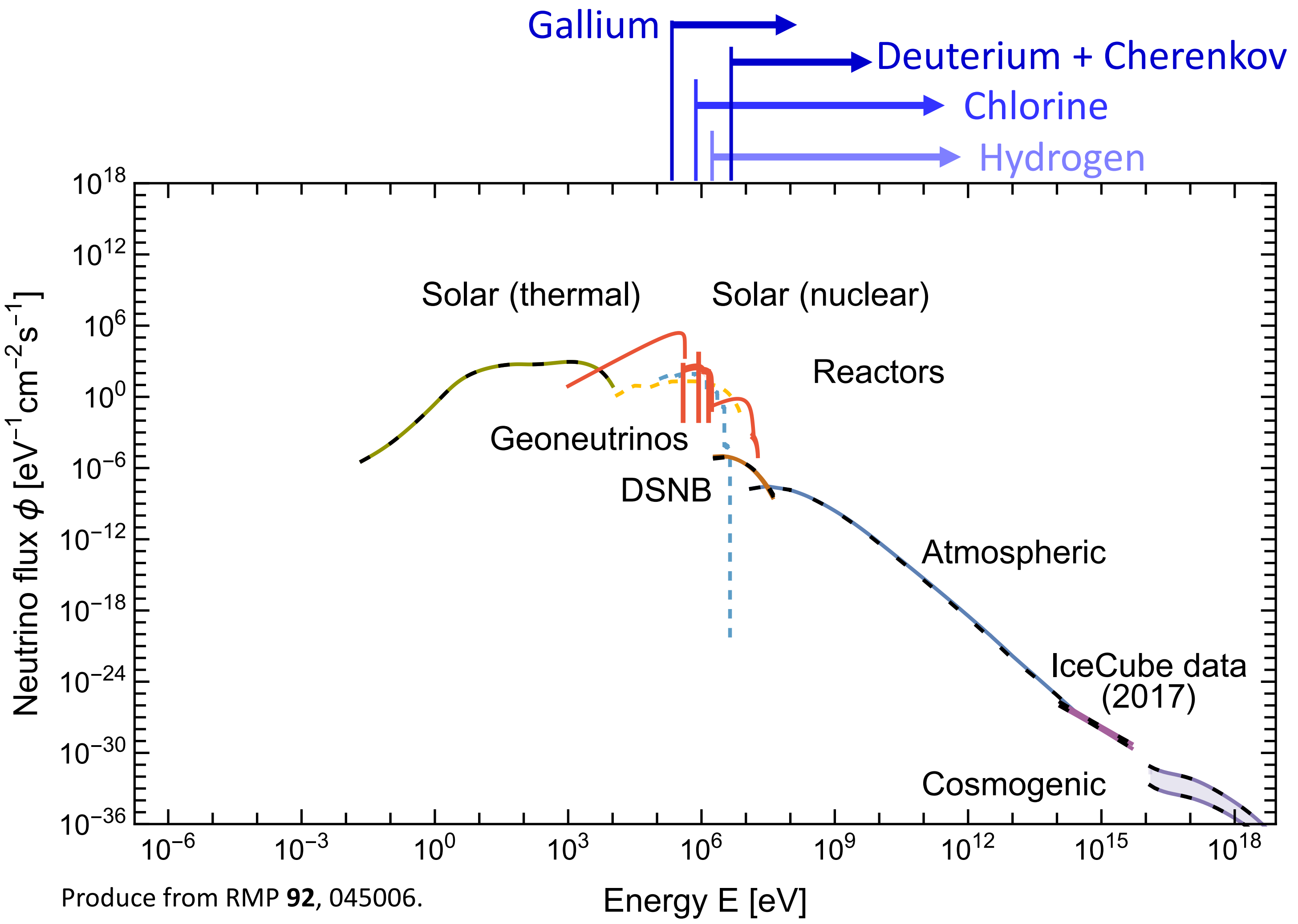
Relic Neutrino Sky Map





Tully, Zhang, “Multi-Messenger Astrophysics with the Cosmic Neutrino Background”, JCAP 06 (2021) 053

Cosmic Neutrino Background



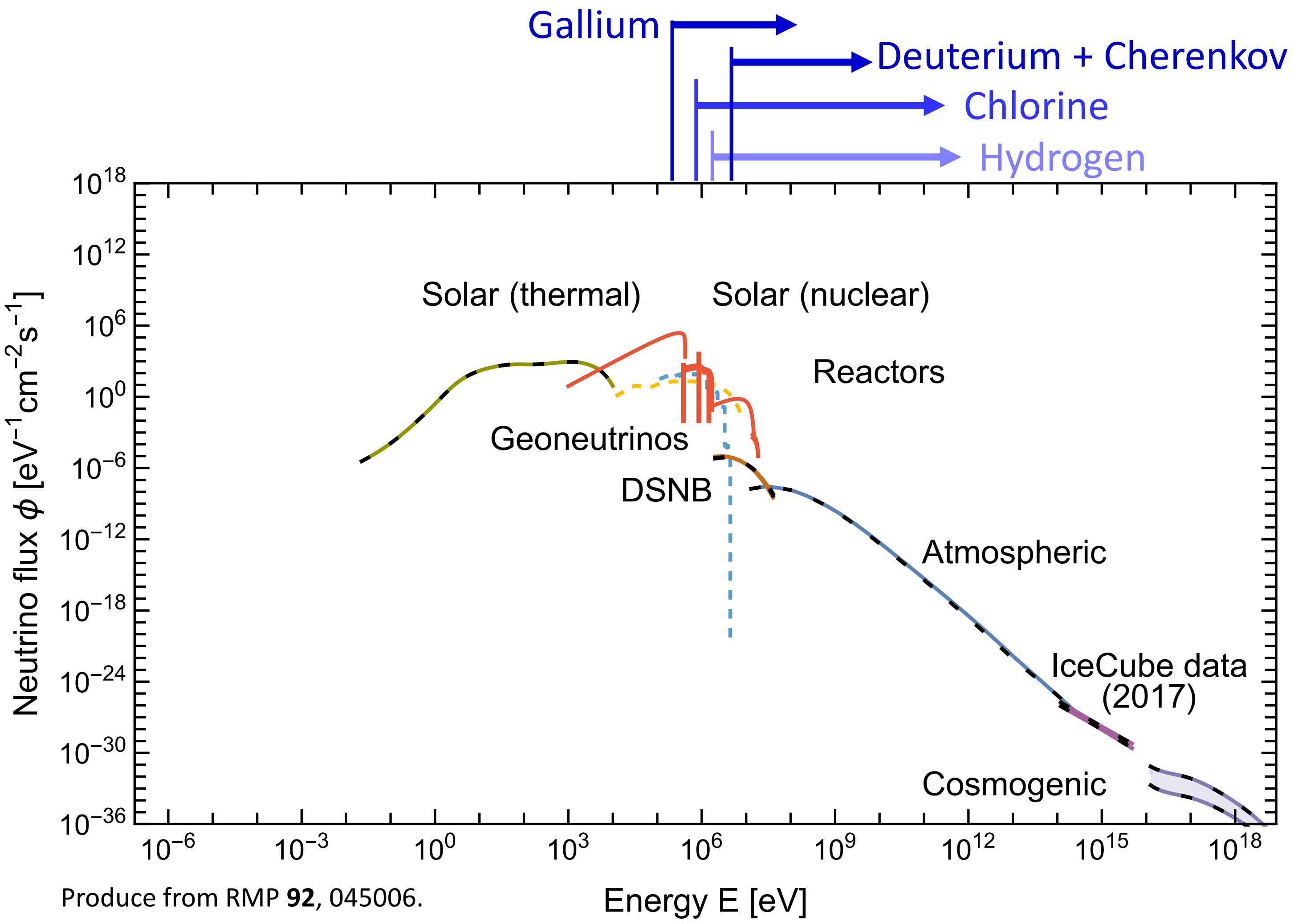
Produce from RMP **92**, 045006.

Neutrinos have been detected for more than 60 years.

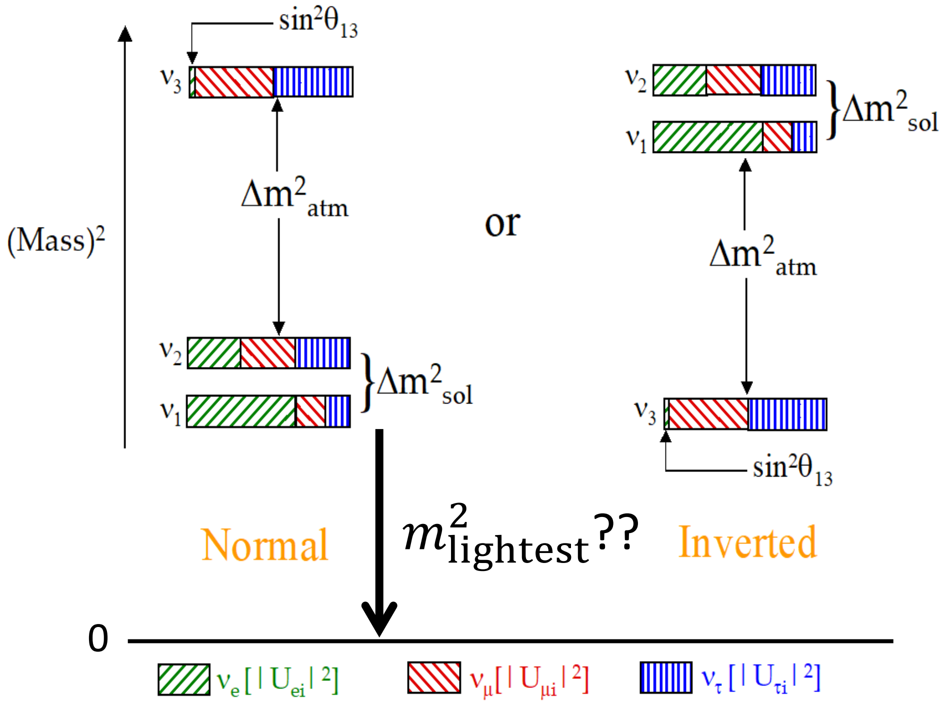
Previous methods have energy threshold in MeV.

With these experimental efforts, we know that neutrinos are not massless.

Cosmic Neutrino Background



Produce from RMP **92**, 045006.

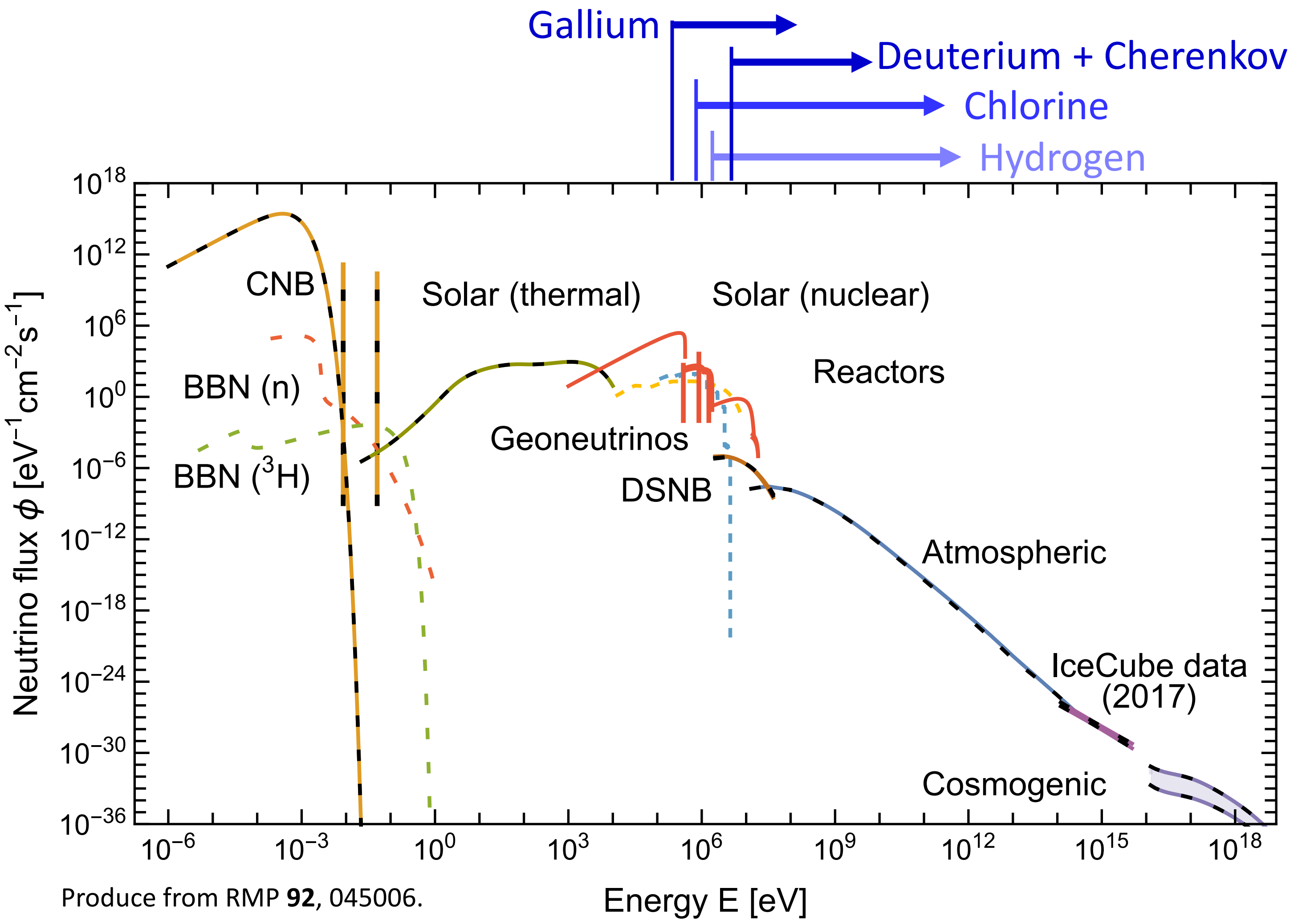


Neutrinos are produced or detected in flavor eigenstates but propagate in mass eigenstates which causes the flux to oscillate.

Oscillation gives the Δm^2_{sol} and $|\Delta m^2_{\text{atm}}|$. Therefore, 2 possible mass hierarchies exist.

The absolute mass of the lightest mass eigenstates is unknown.

Cosmic Neutrino Background



Produce from RMP **92**, 045006.

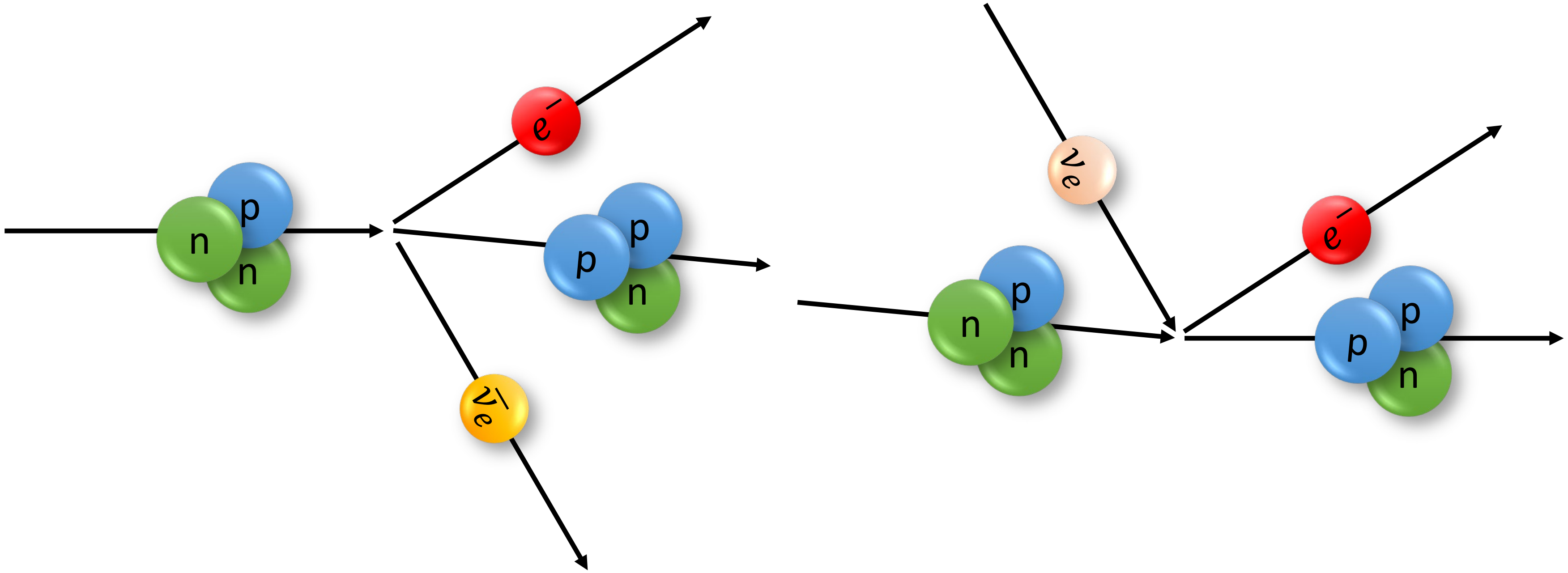
- The CNB is shown for a minimal mass spectrum here for 0, 8.6, and 50 meV, producing a blackbody spectrum plus two monochromatic lines for nonrelativistic neutrinos with energies corresponding to their masses.
- Detection requires a reaction with no threshold.

Detecting CNB Using Capture on Tritium

- Steven Weinberg laid out basic concepts for CNB detection in 1962
- Cocco, Mangano, Messina applied to massive neutrinos in 2007

$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$

$^{3}\mathrm{H} + \nu_e \rightarrow {}^{3}\mathrm{He} + e^{-}$



Tritium as target:

- High σ_{NCB},
- Availability,
- Lifetime,
- Low Q.

* Weinberg,. *Phys Rev* **128**, 1457–1473 (1962).

Cocco, Mangano & Messina, *J Phys Conf Ser* **110, 082014 (2008).

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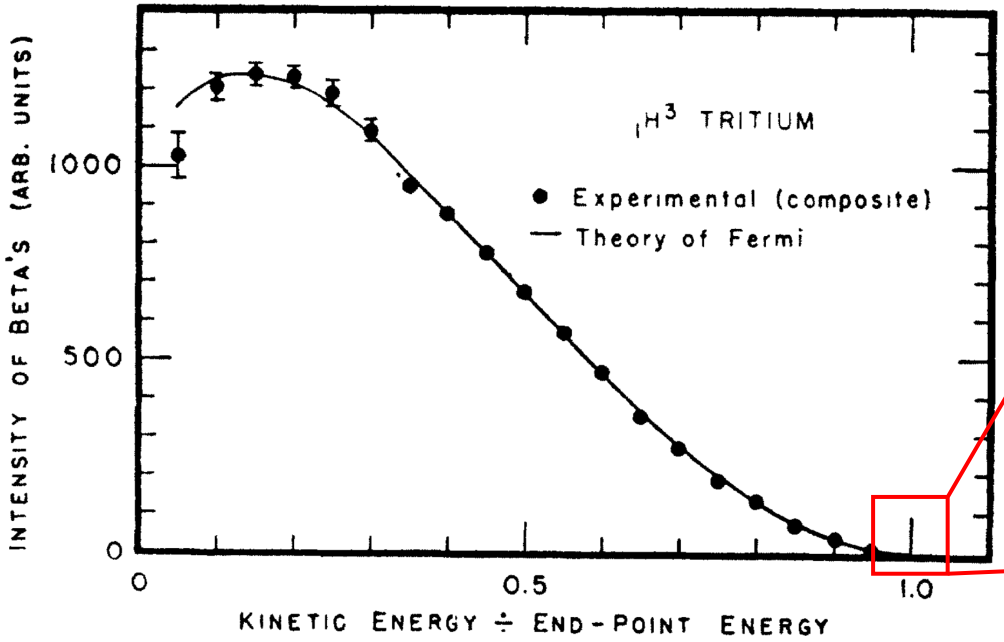
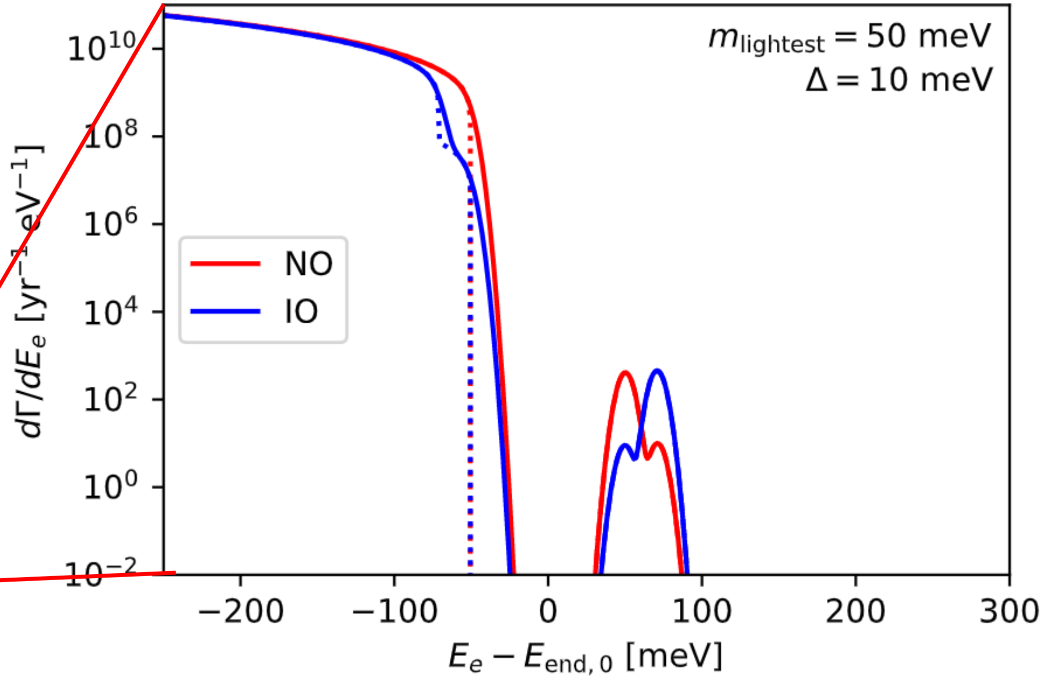
$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e \qquad\qquad {}^{3}\mathrm{H} + \nu_e \rightarrow {}^{3}\mathrm{He} + e^{-}$$



Phys Rev **77**, 402–403 (1950).



JCAP **2019**, 047–047 (2019).

Capture Rates Estimation

- Target mass: 100 grams of tritium (2×10^{25} nuclei),
- $\sigma_{\mathrm{NCB}} \cdot v_\nu / c = 7.84 \times 10^{-45}$ cm² *,
- (Very Rough) Estimate of Relic Neutrino Capture Rate:

$$\lambda_\nu \sim N_\nu v_\nu \sigma_{\mathrm{NCB}} N_{\mathrm{T}}$$
$$= 56 \times (7.84 \times 10^{-45} \times 3 \times 10^{10}) \times (2 \times 10^{25}) \times (3 \times 10^7\ \mathrm{s/yr})$$
$$= 7.5\ \text{evt/yr}$$

- In Majorana case, $\lambda_\nu \sim 15$ evt/yr.
- Gravitational clumping could potentially increase the local number of relic neutrinos.

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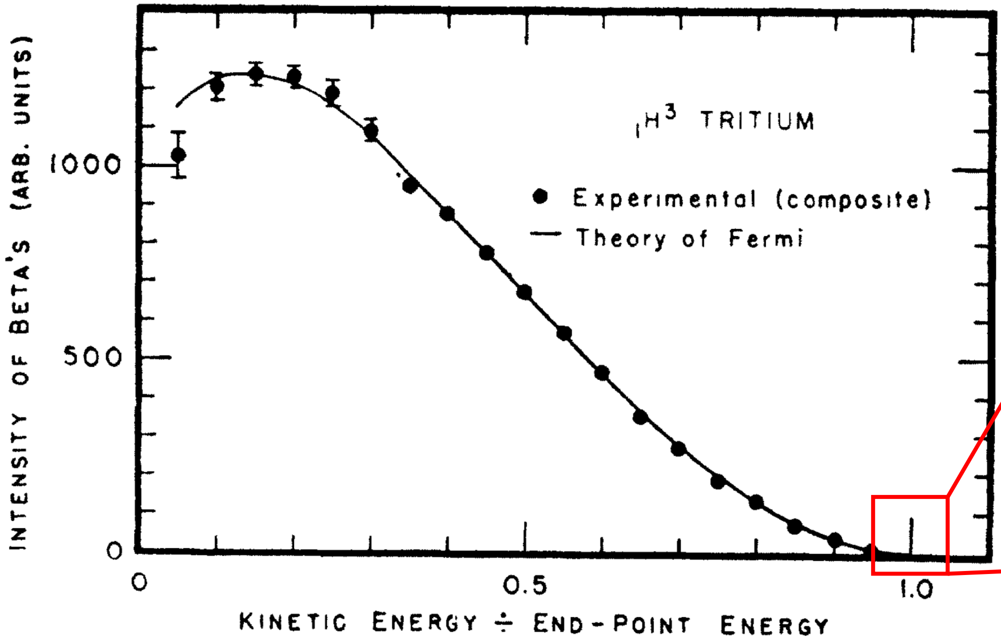
* J Phys Conf Ser **110**, 082014 (2008)

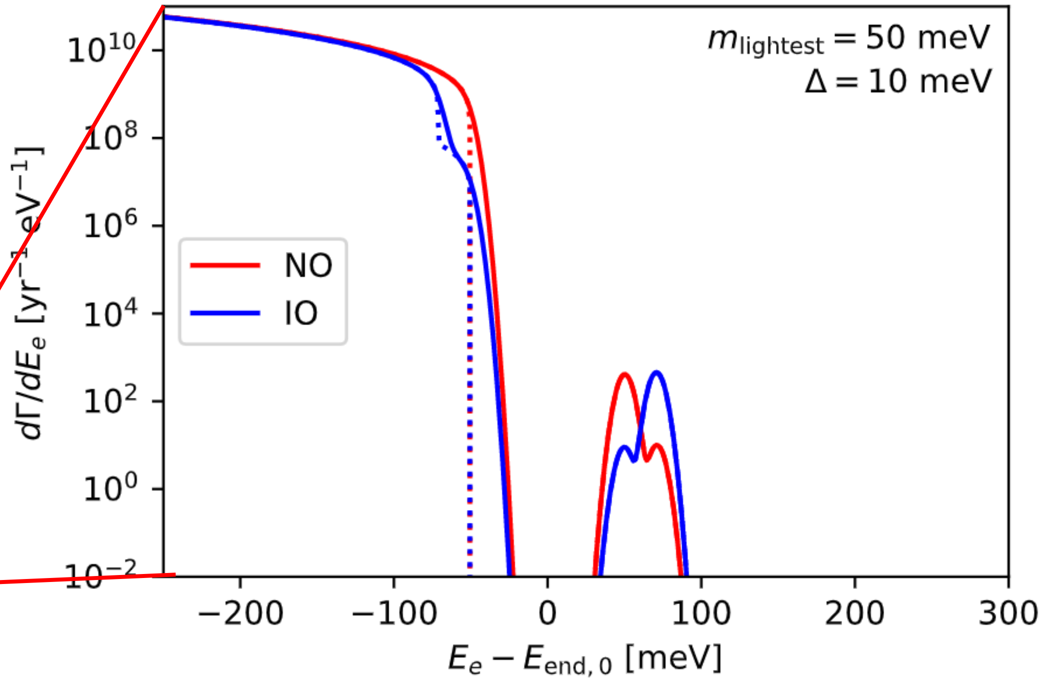
Detecting CNB Using Capture on Tritium

Increase S/N ratio by

- filtering away the low energy electrons to the last 1eV window, which increases $\lambda_\nu/\lambda_\beta$ by 10^{13};
- cutting-edge energy resolution $\Delta\sim\mathcal{O}(10\text{ meV})$, i.e., $\Delta/Q\sim10^{-6}$.



Phys Rev **77**, 402–403 (1950).



JCAP **2019**, 047–047 (2019).

Target:
Relic Neutrino Capture

→

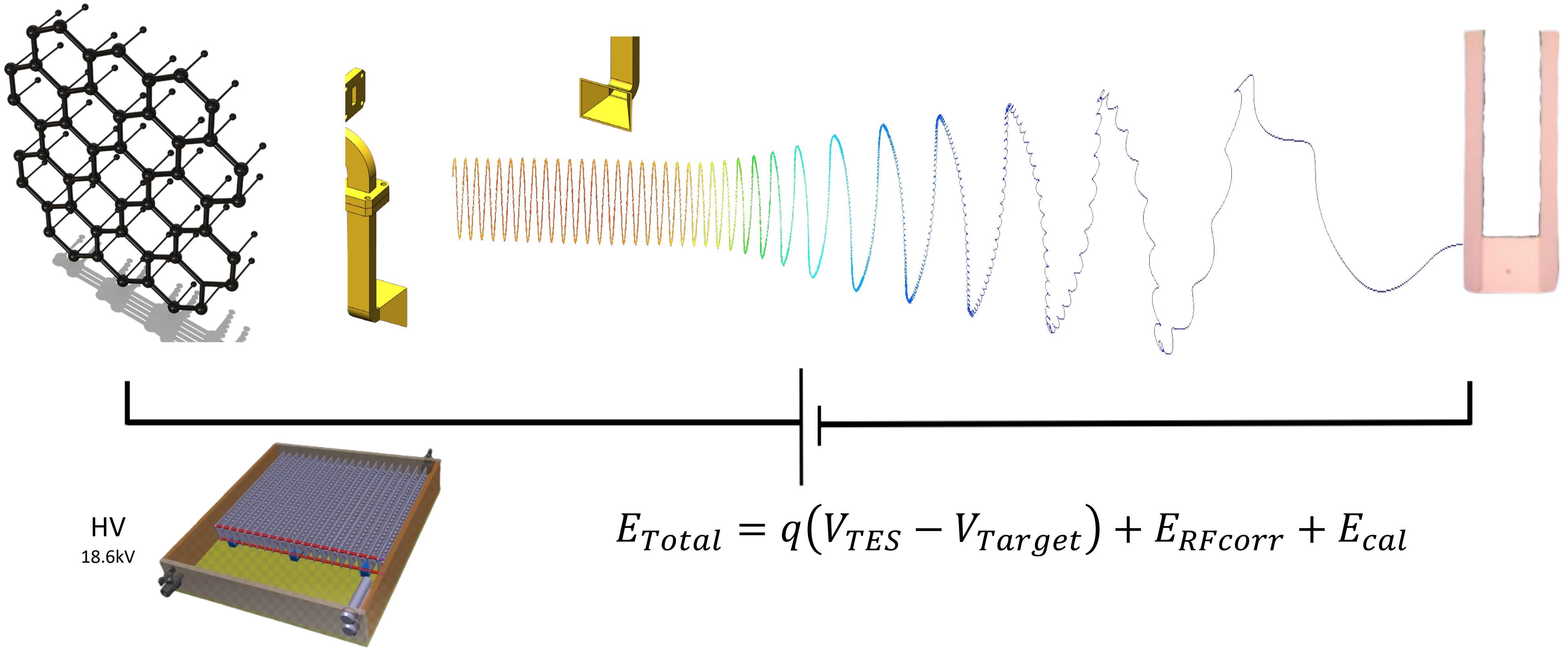
RF Tracker:
Electron Pre-Measurement

→

Dynamic Filter:
Selects endpoint electron in narrow 10^{-4} energy window

→

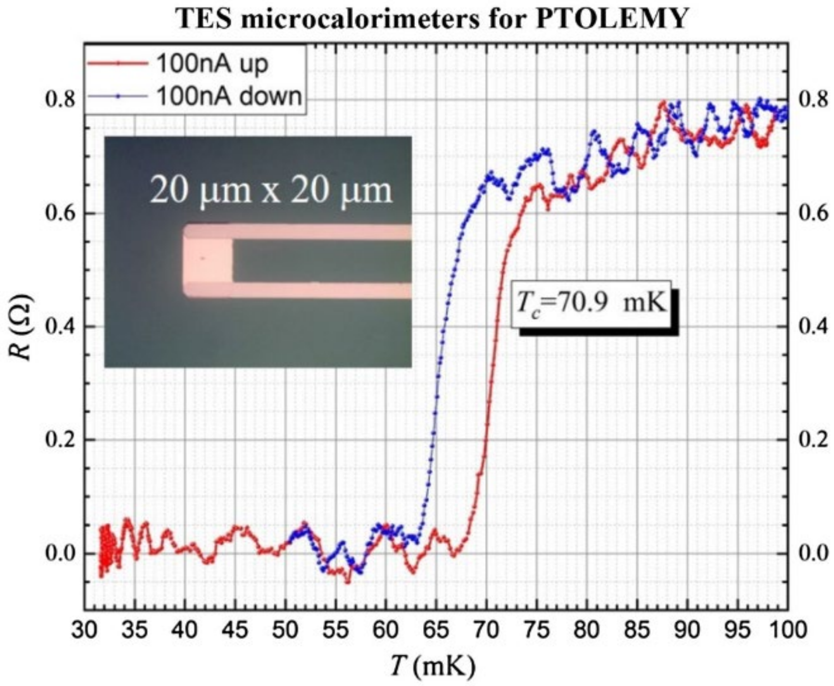
Micro-calorimeter:
Measures few eV electron to 10^{-2} energy resolution

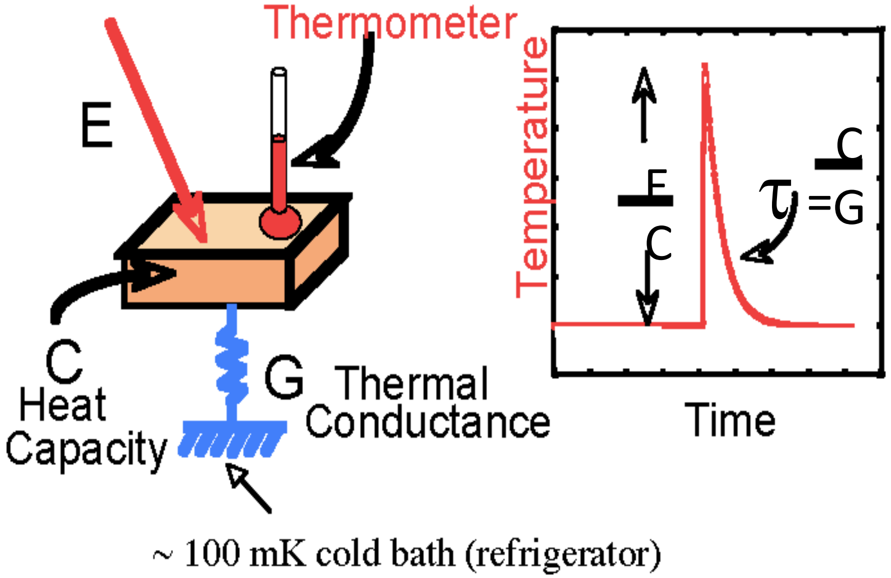


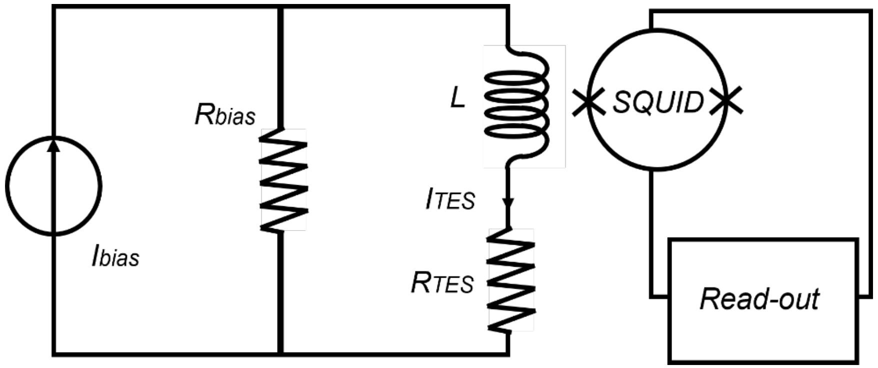
$$E_{Total} = q\left(V_{TES} - V_{Target}\right) + E_{RFcorr} + E_{cal}$$

µCal - Transition-Edge Sensors

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



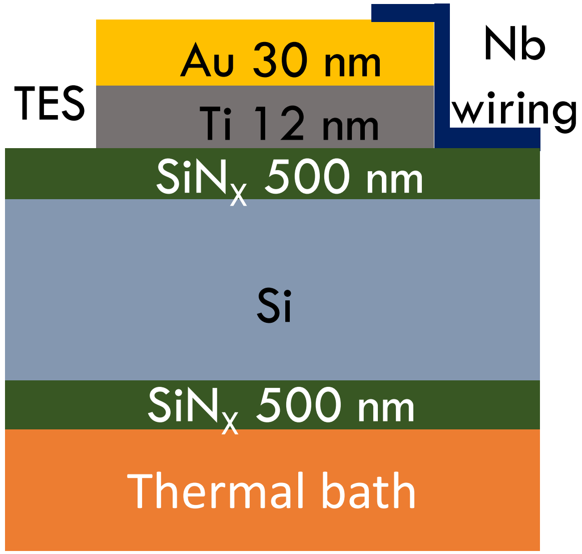


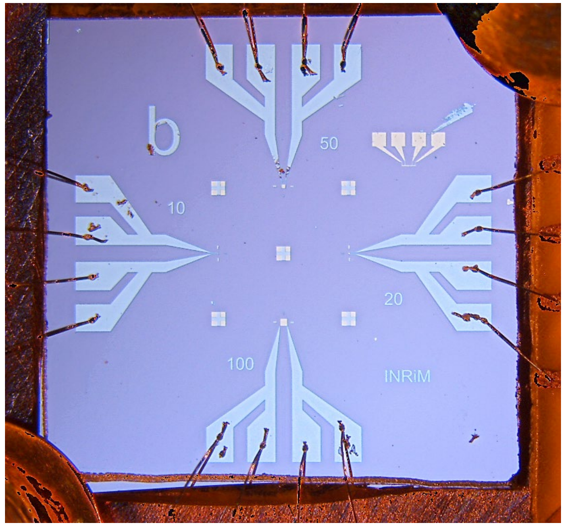


Mauro Rajteri, Eugenio Monticone and others,
https://doi.org/10.1007/s10909-019-02271-x
"TES Microcalorimeter for PTOLEMY", J. Low Temp. Phys. 199 (2020) 138-142.

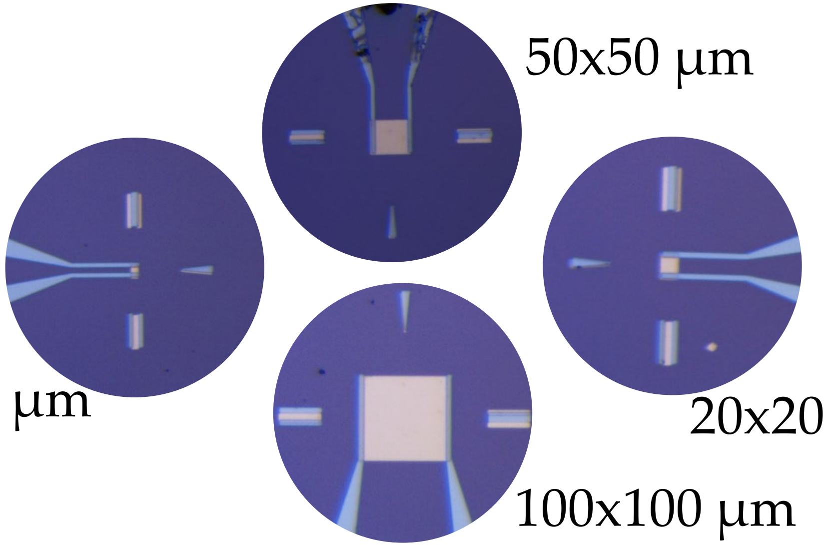
INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

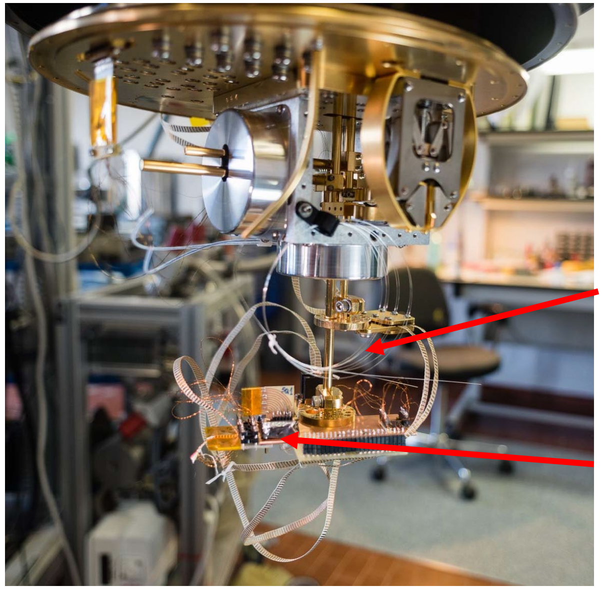
TES development





TES Layout 2021

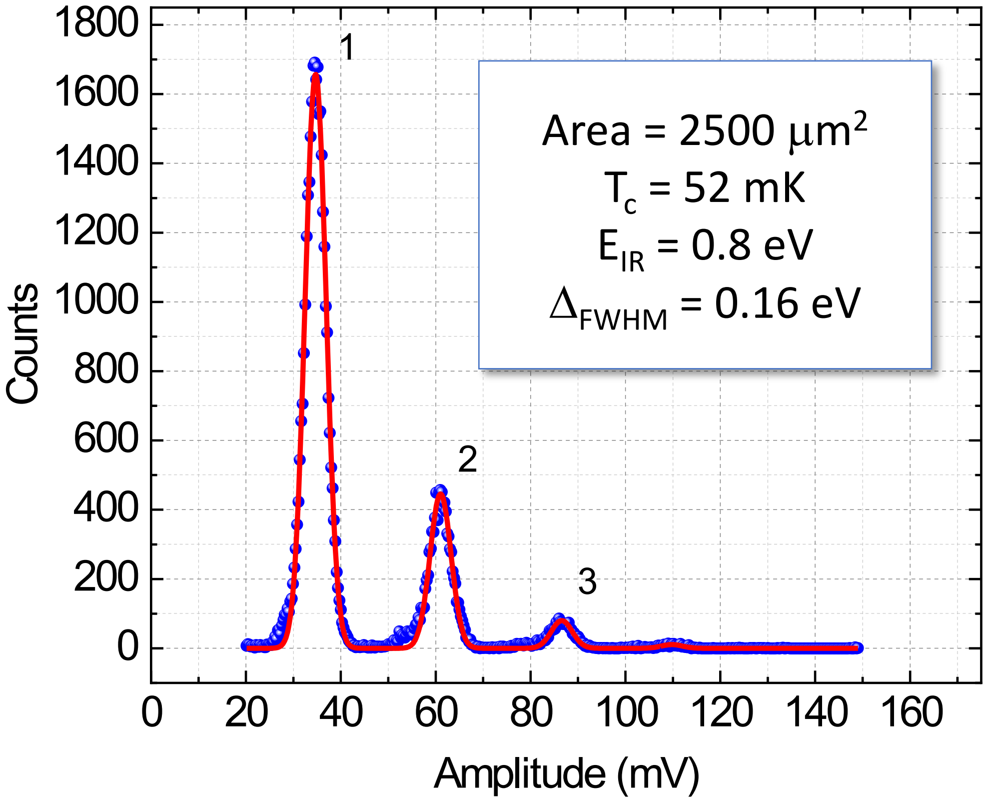


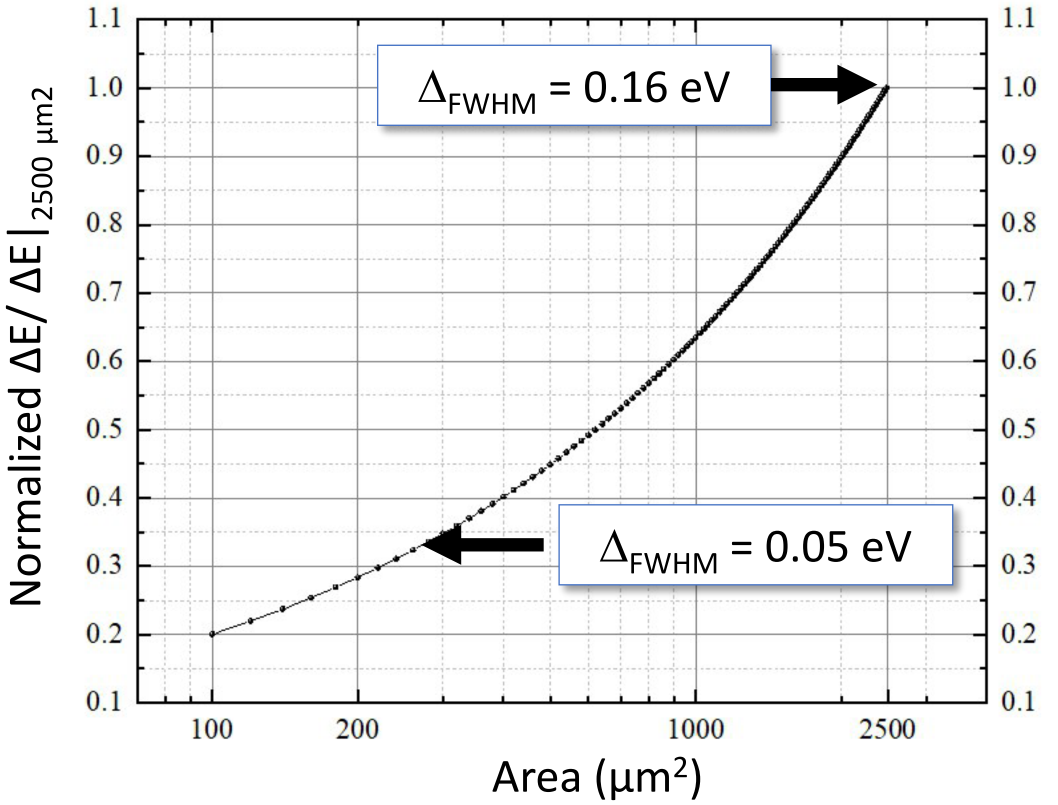


TES evaluated initially by IR photons in ADR setup at INRiM

Optimize the thickness of Ti/Au to tune energy resolution $\Delta \propto T_c^{3/2} t^{1/2}$, where t is Ti Thickness.

Supported by
JOHN
TEMPLETON
FOUNDATION





Resolution of ~ m_ν :
Area ~ 15 μm x 15 μm

→ Demonstrate with electrons

Electromagnetic Filters

Magnetic Adiabatic Invariance

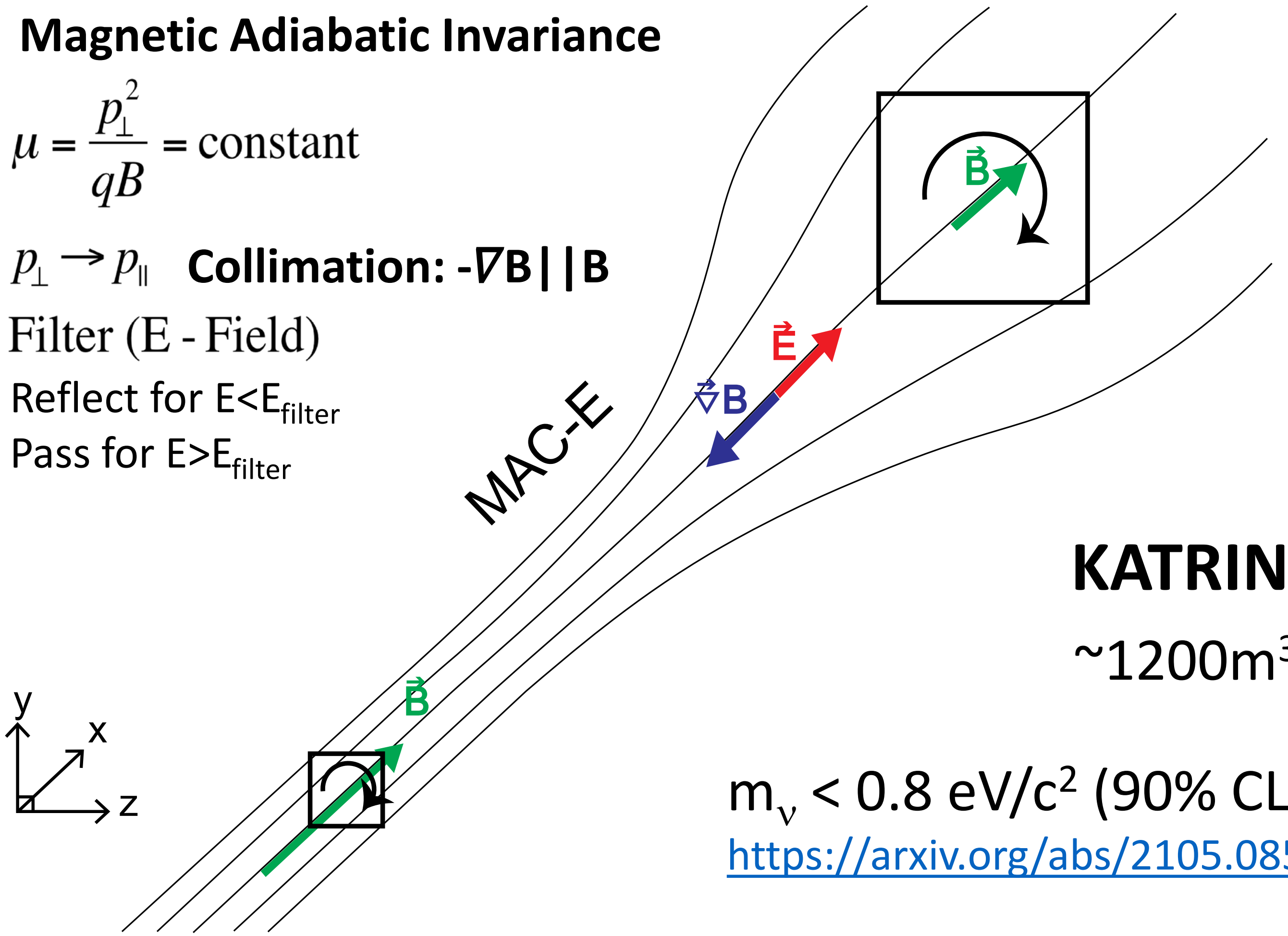
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

$p_\perp \to p_\parallel$ **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

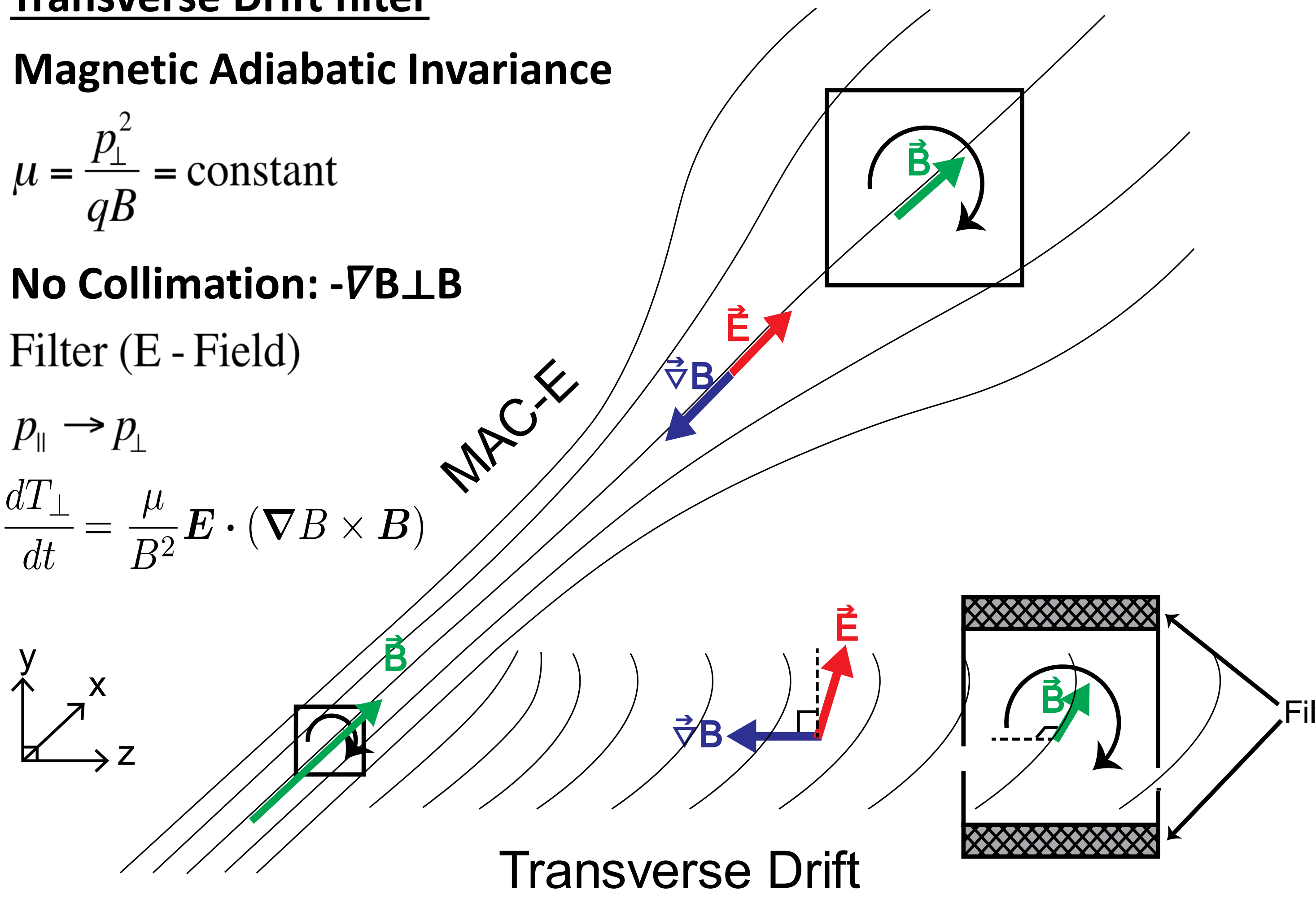
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

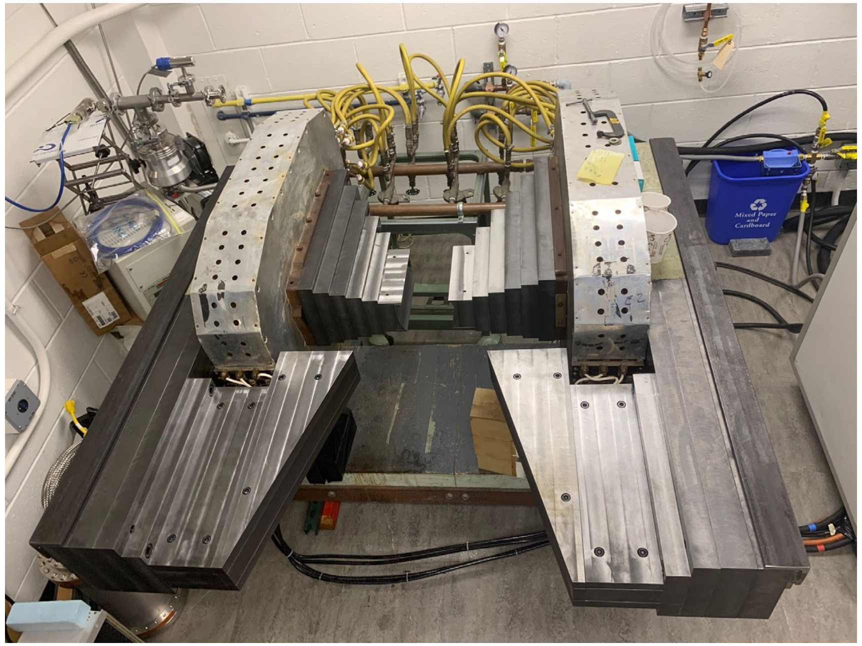
No Collimation: -∇B⊥B

Filter (E - Field)

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

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

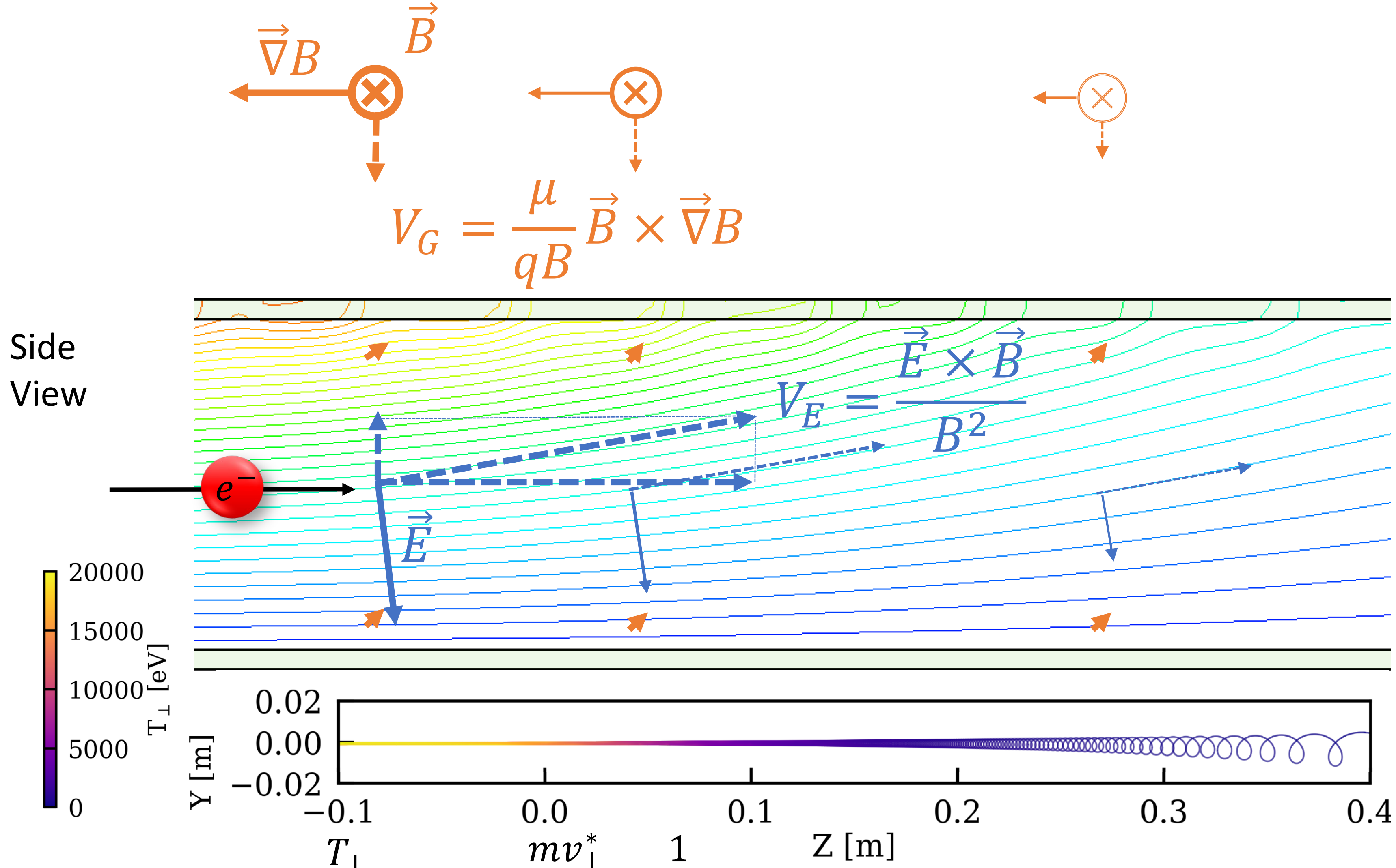




PTOLEMY

~1m^3

PTOLEMY Electromagnetic Filter



$$\mu = \frac{T_\perp}{B} \qquad \rho_C = \frac{mv_\perp^*}{qB} \propto \frac{1}{\sqrt{B}}$$

Control electrons by:

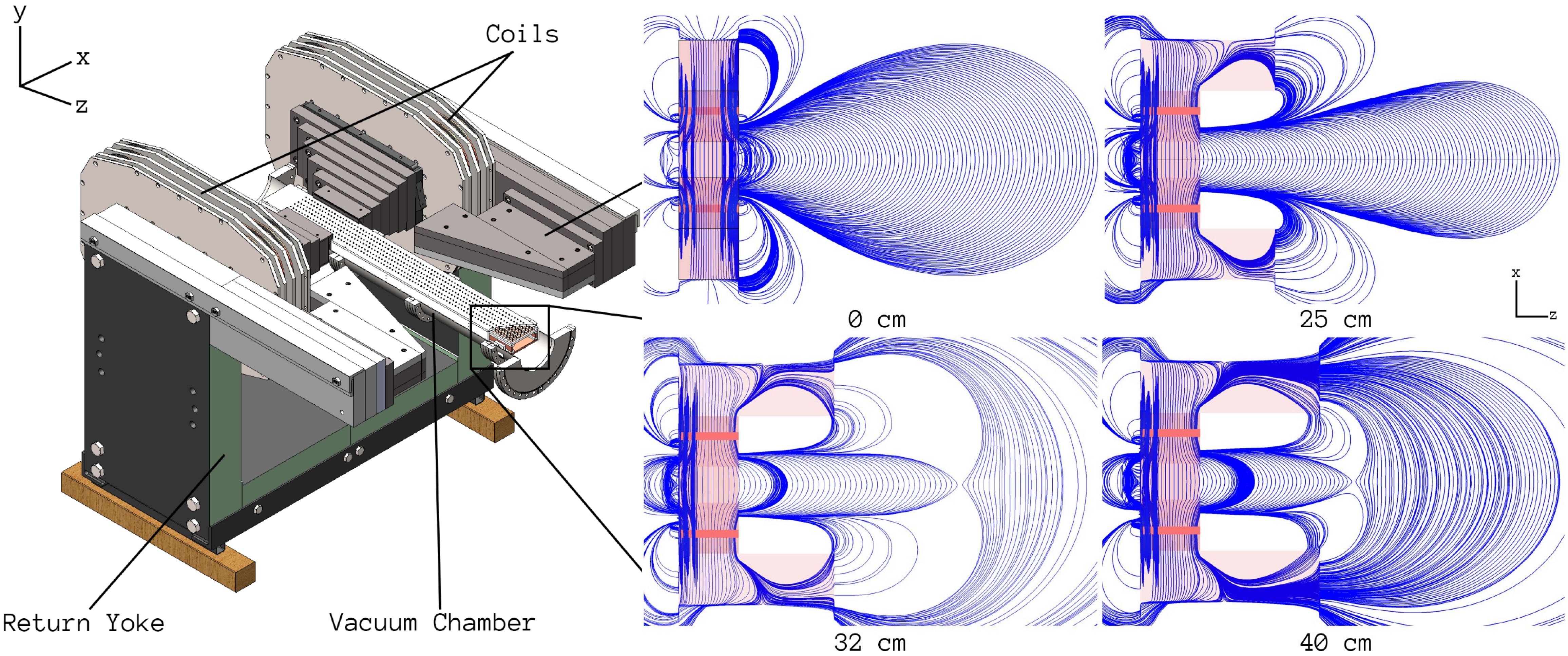
- B field
- Bounce potential

Filter (push them up the potential hill) & Guide them to the colorimeter by:

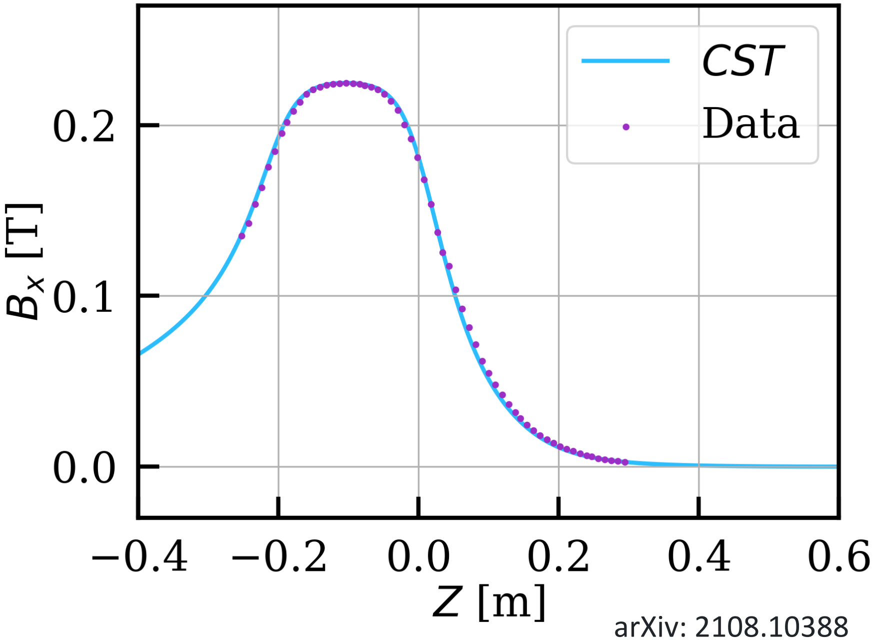
- $E \times B$ drift
- $B \times \nabla B$ drift
- Curvature

$E \times B$ term drifts along the equal potential lines. Therefore, combine it with $B \times \nabla B$ term.

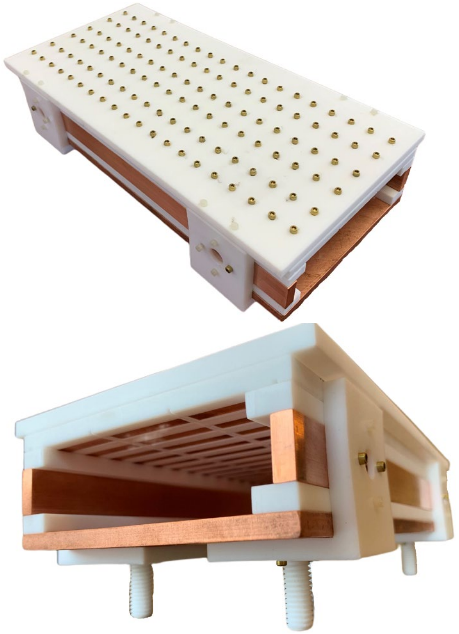
Design of the Demonstrator



Construction of the Demonstrator



arXiv: 2108.10388



The B_x field was mapped out by digital 3-axis hall magnetic sensors.

Initial test at low power found good agreement between the measured and simulated fields.

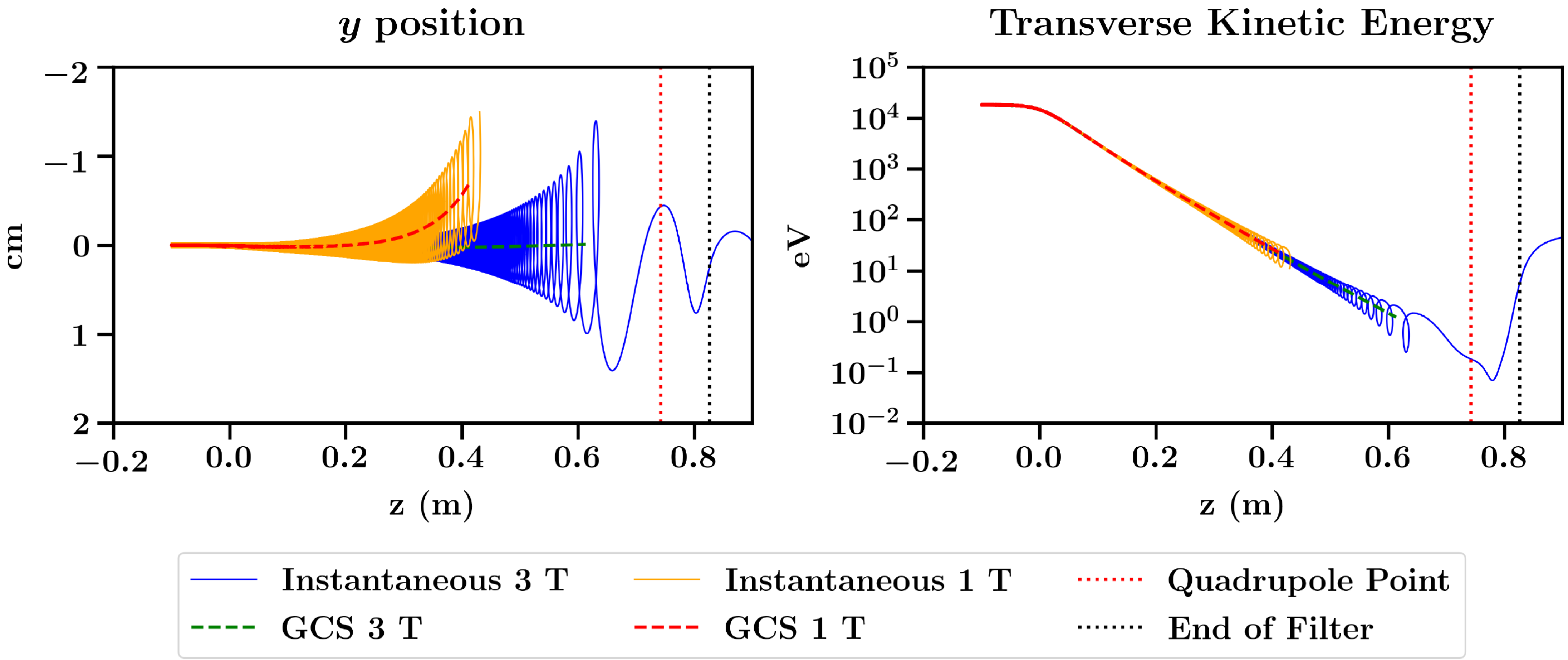
A shorter version of filter was built for investigation.

Filter Performance

Improves as B^2 for a fixed filter dimension

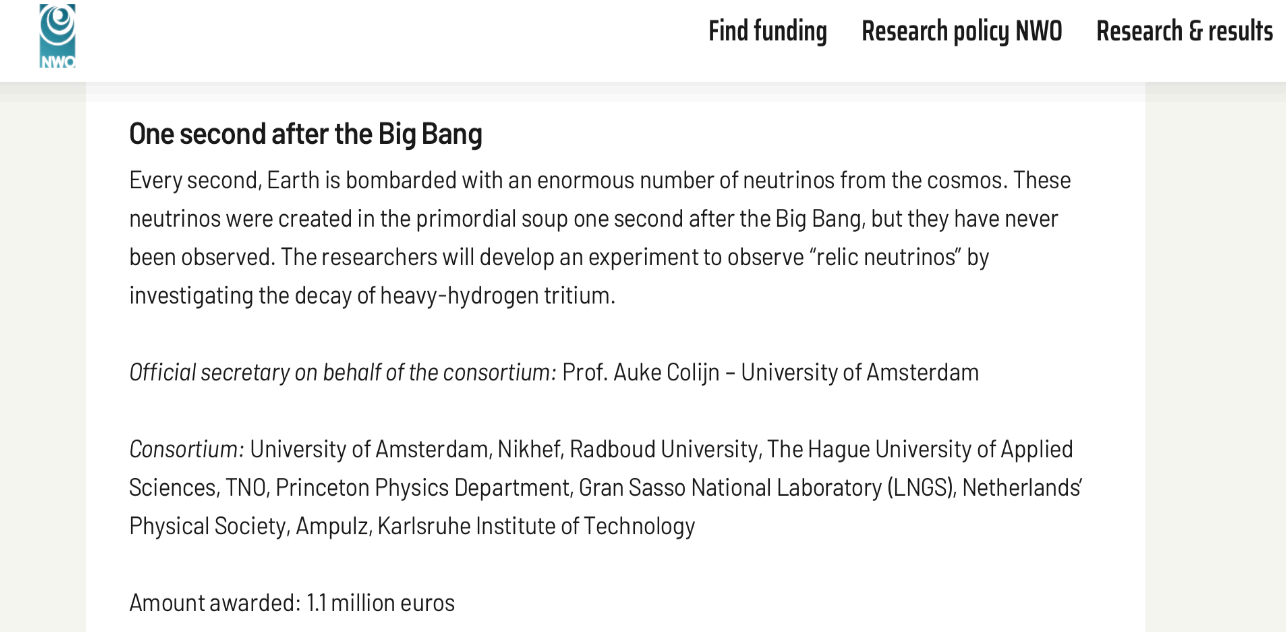
18.6 keV @ 1T → ~10eV (in 0.4m)

18.6 keV @ 3T → ~1eV (in 0.6m)



RF Antenna and Readout

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



Find funding Research policy NWO Research & results

One second after the Big Bang

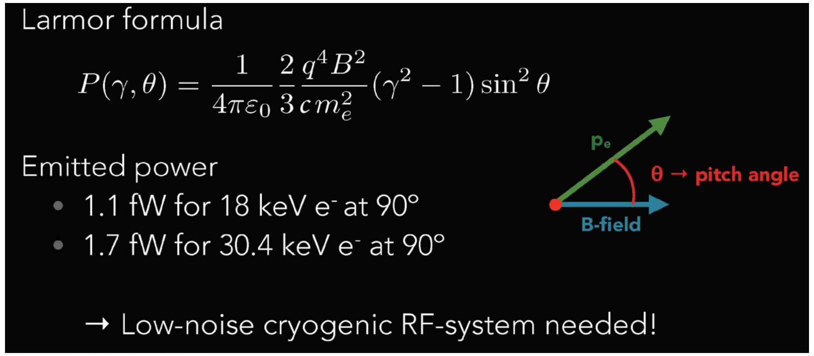
Every second, Earth is bombarded with an enormous number of neutrinos from the cosmos. These neutrinos were created in the primordial soup one second after the Big Bang, but they have never been observed. The researchers will develop an experiment to observe “relic neutrinos” by investigating the decay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

https://www.nwo.nl/en/researchprogrammes/dutch-research-agenda-nwa/research-along-routes-consortia-nwa-orc/awards-nwa-orc



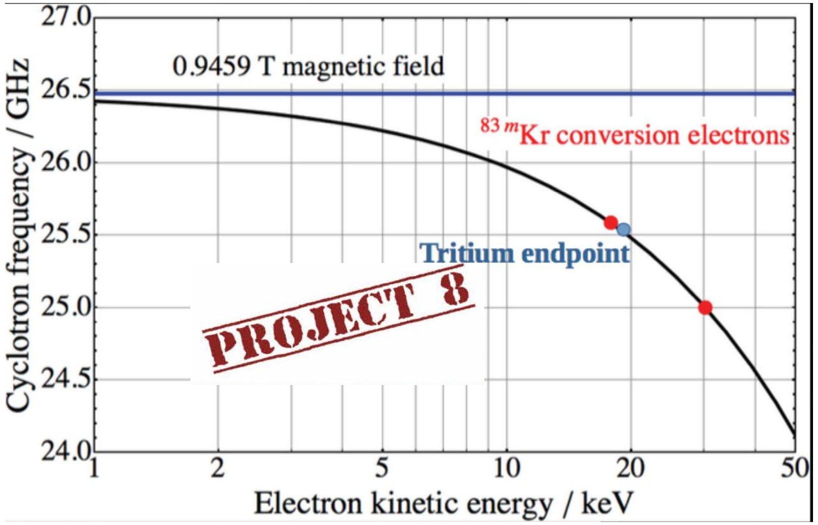
Larmor formula

$$P(\gamma,\theta) = \frac{1}{4\pi\varepsilon_0}\frac{2\,q^4B^2}{3\,c\,m_e^2}(\gamma^2-1)\sin^2\theta$$

Emitted power

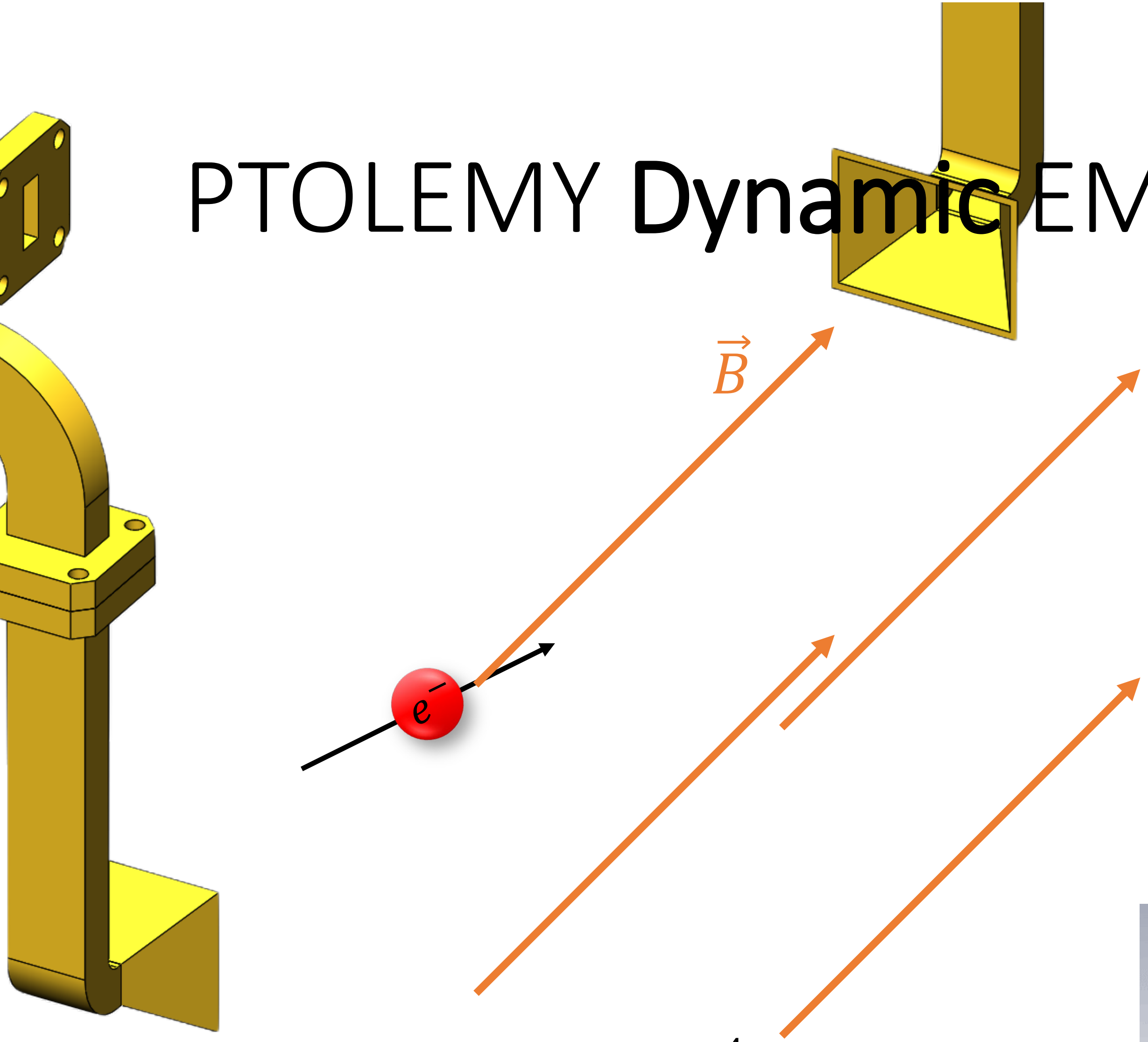
- 1.1 fW for 18 keV e^- at 90°
- 1.7 fW for 30.4 keV e^- at 90°

→ Low-noise cryogenic RF-system needed!



https://arxiv.org/abs/1408.5362

PTOLEMY **Dynamic** EM Filter

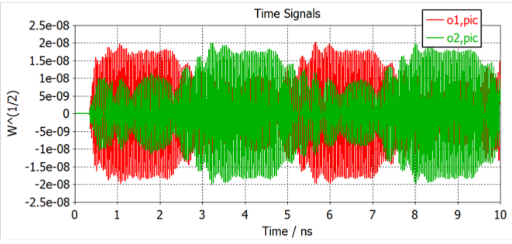


- The E field setting depends on the pitch angle
- Exploit the RF signal for initial parameter assessing.
- For 18.6 keV ($\beta = 0.2625$), 1.1 fW RF emitted at 90°

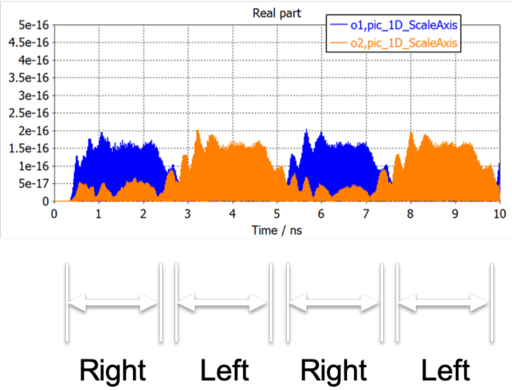
$$P(\gamma,\theta) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{e^4}{m_e^2 c}B^2(\gamma^2-1)\sin^2\theta$$

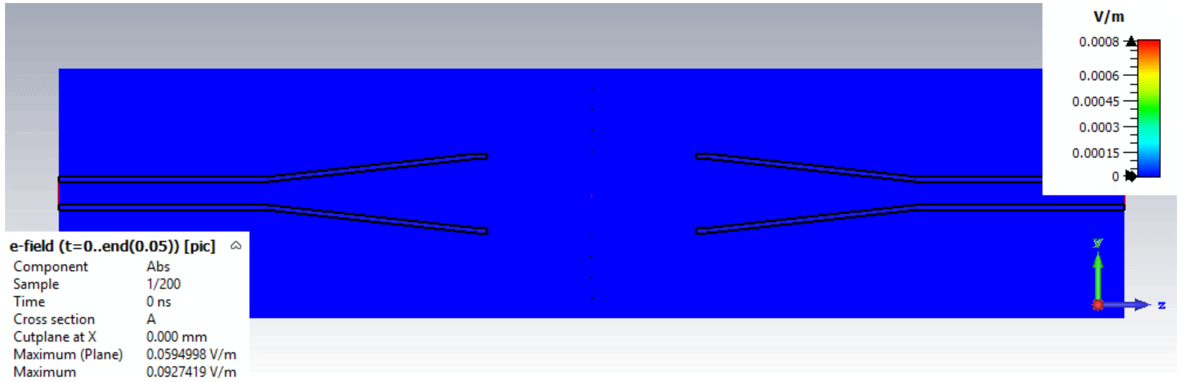
PRL 114, 162501 (2015) Project 8

Time Series (~26 GHz)



Power(~0.1 fW)





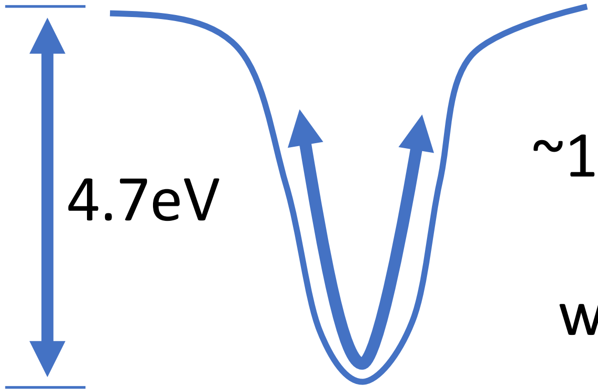
e-field (t=0..end(0.05)) [pic]

Component	Abs
Sample	1/200
Time	0 ns
Cross section	A
Cutplane at X	0.000 mm
Maximum (Plane)	0.0594998 V/m
Maximum	0.0927419 V/m

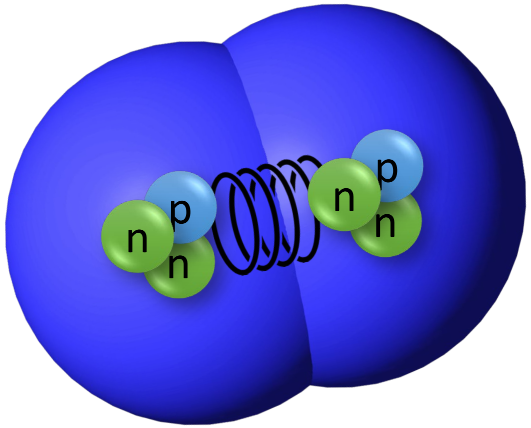
Gaseous target not ideal

$T\text{-}T \rightarrow (T\text{-}He^3)^{+*}$

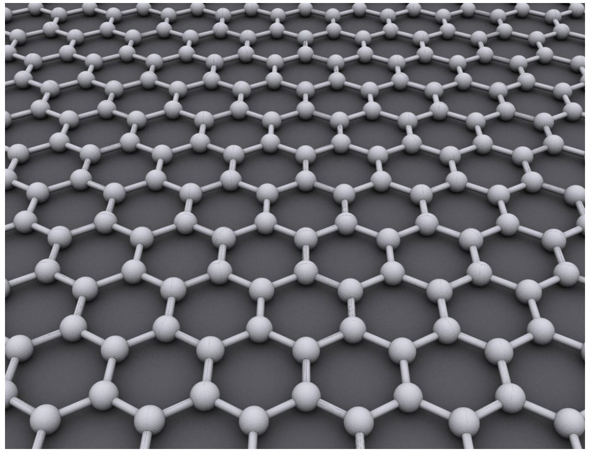
*Many close-spaced
ro-vibrational excited states



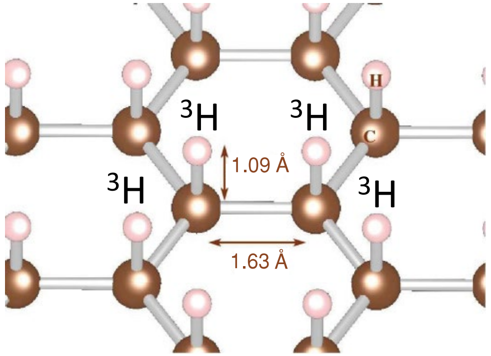
~1.7eV $(T\text{-}He^3)^{+*}$ recoil
at endpoint
w/ ~0.3eV spread(*)



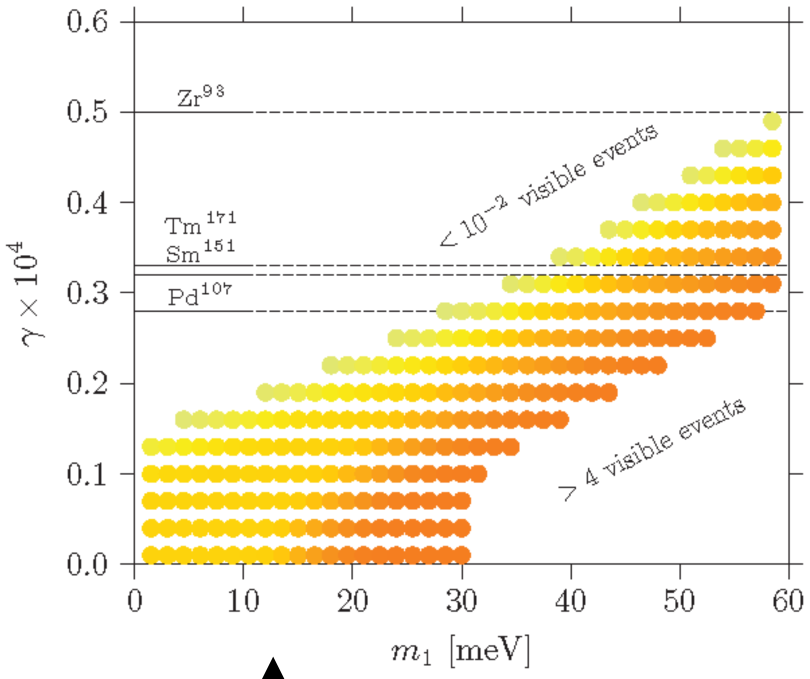
Planar target: Graphene



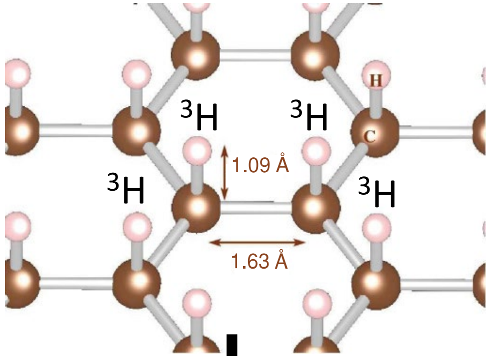
~1eV binding
energy



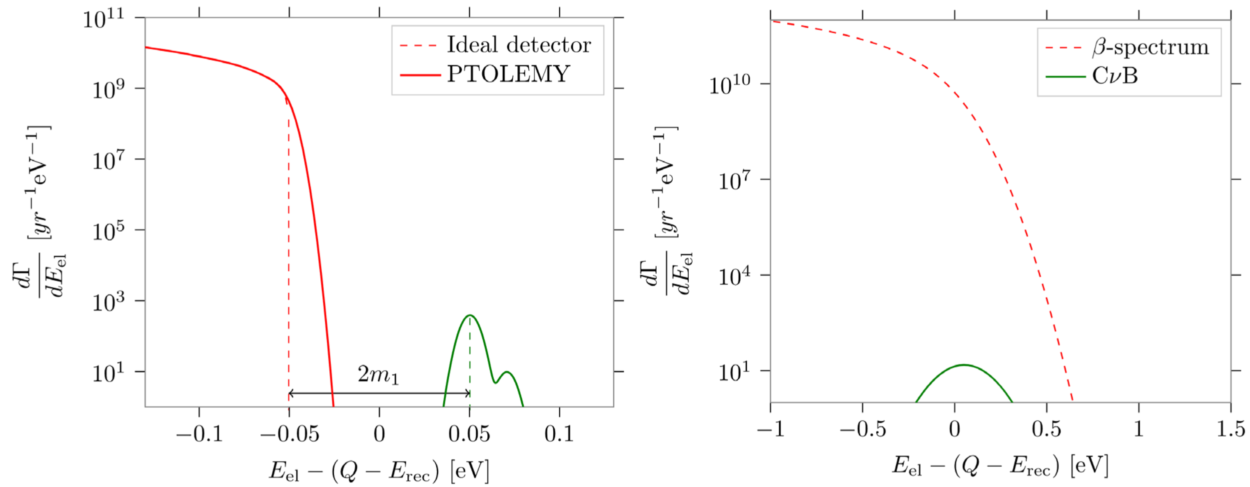
Target: Molecular Broadening



Optimal
“Heavy” Targets

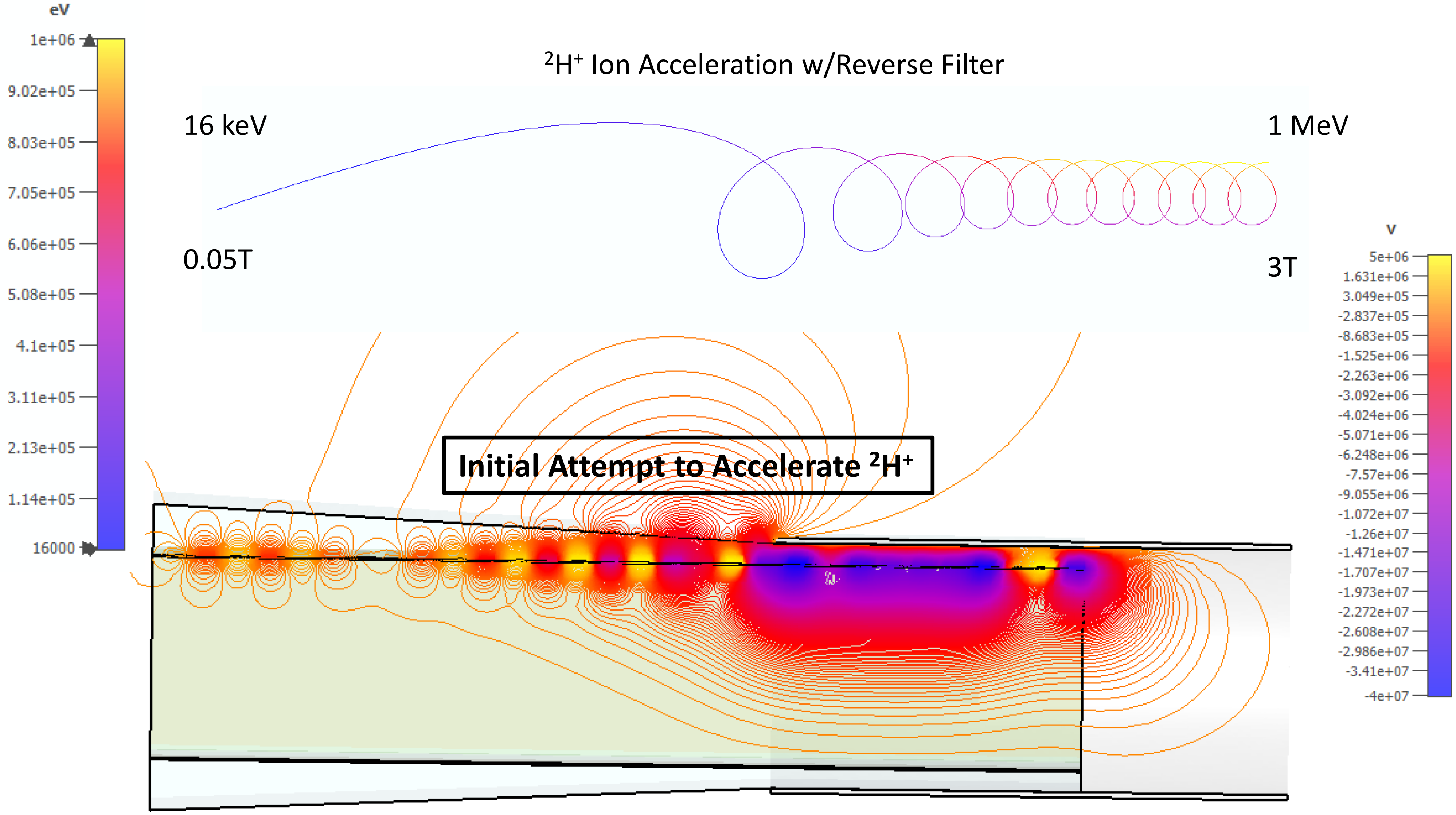


Too “Localized”



Yevheniia Cheipesh, Vadim Cheianov, Alexey Boyarsky, https://arxiv.org/abs/2101.10069
“Navigating the pitfalls of relic neutrino detection”

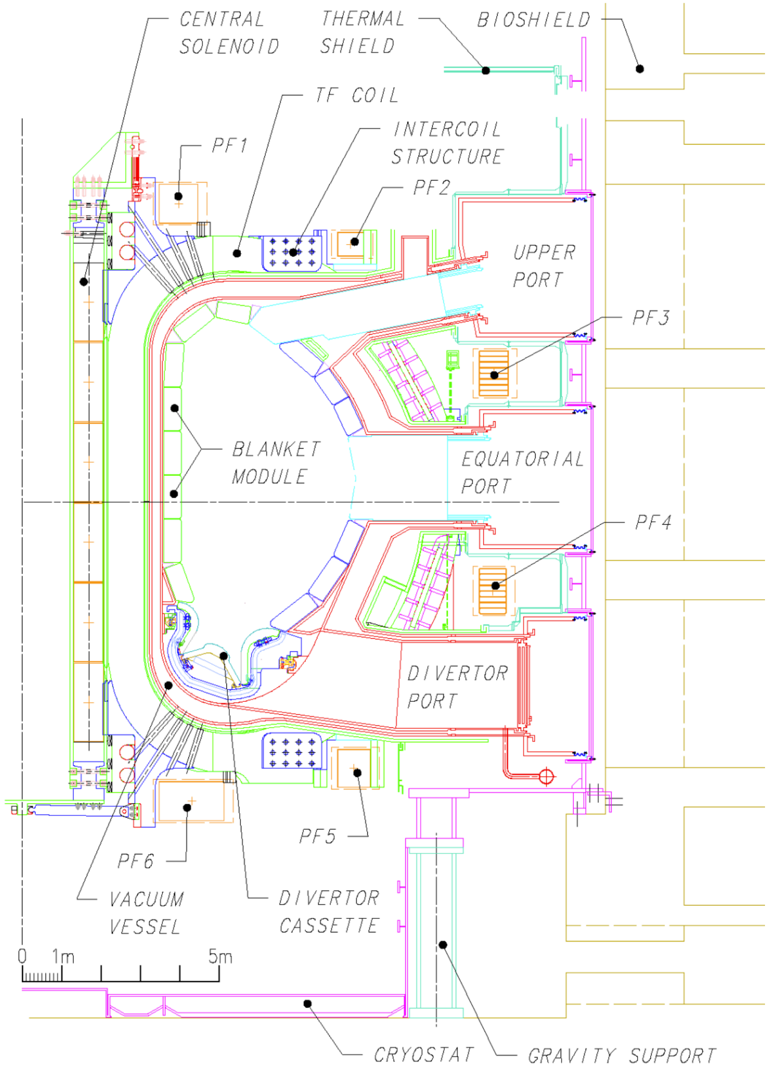
Plasma Heating w/ Reverse Filter

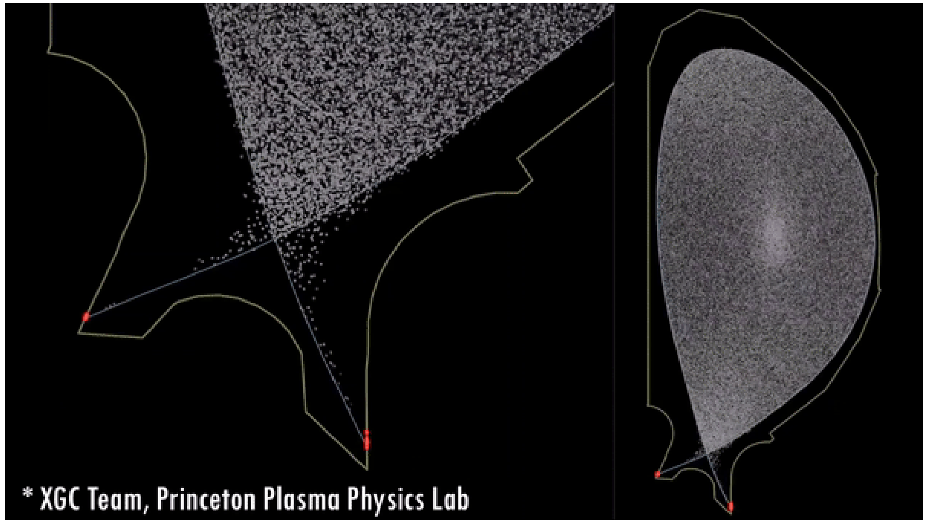


$^2H^+$ Ion Acceleration w/Reverse Filter

Initial Attempt to Accelerate $^2H^+$

ITER Ports

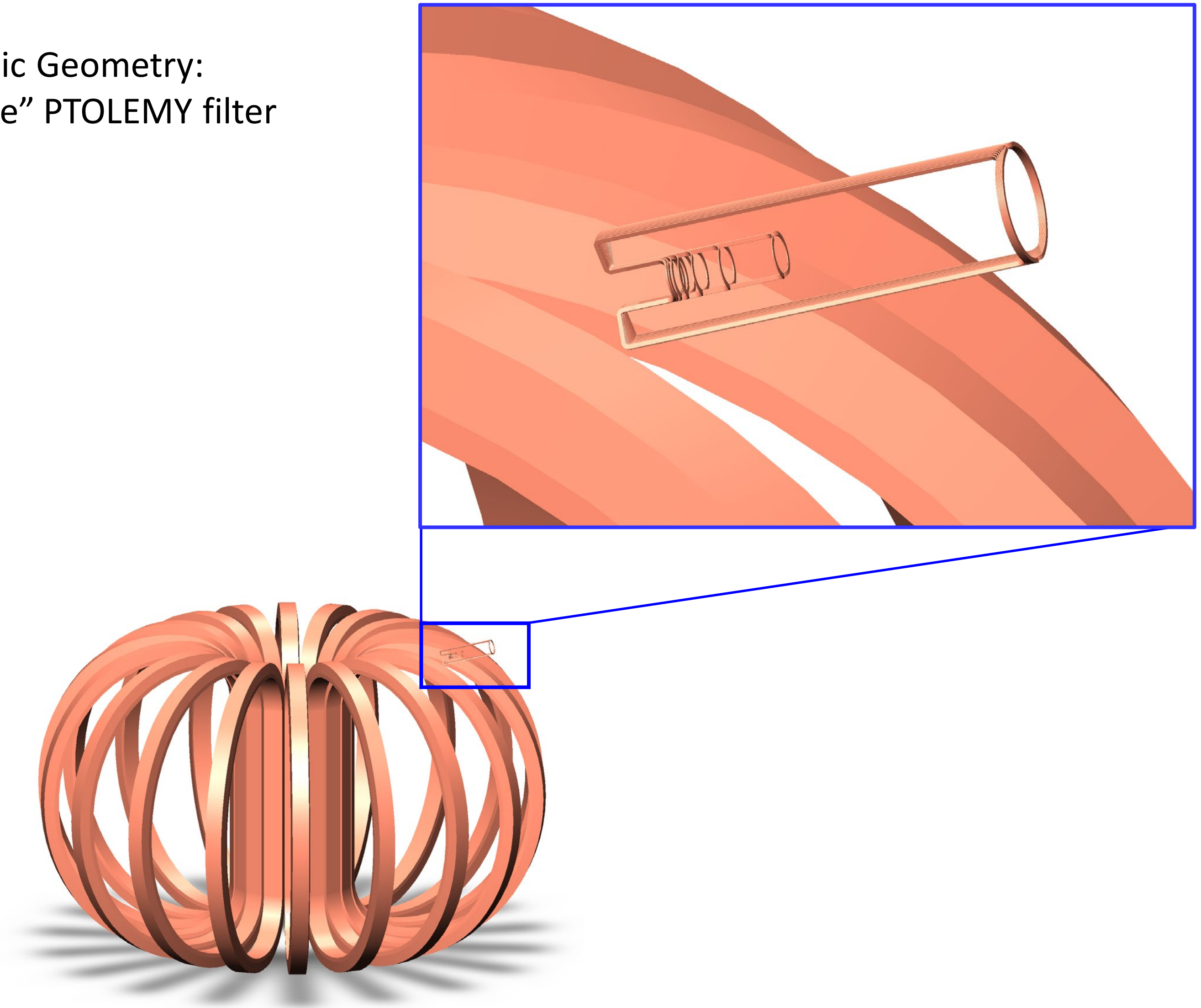




Source: YouTube ITER The Divertor Section, XGC code team is lead by CS Chang @ PPPL

Charged Particle Beam Injector

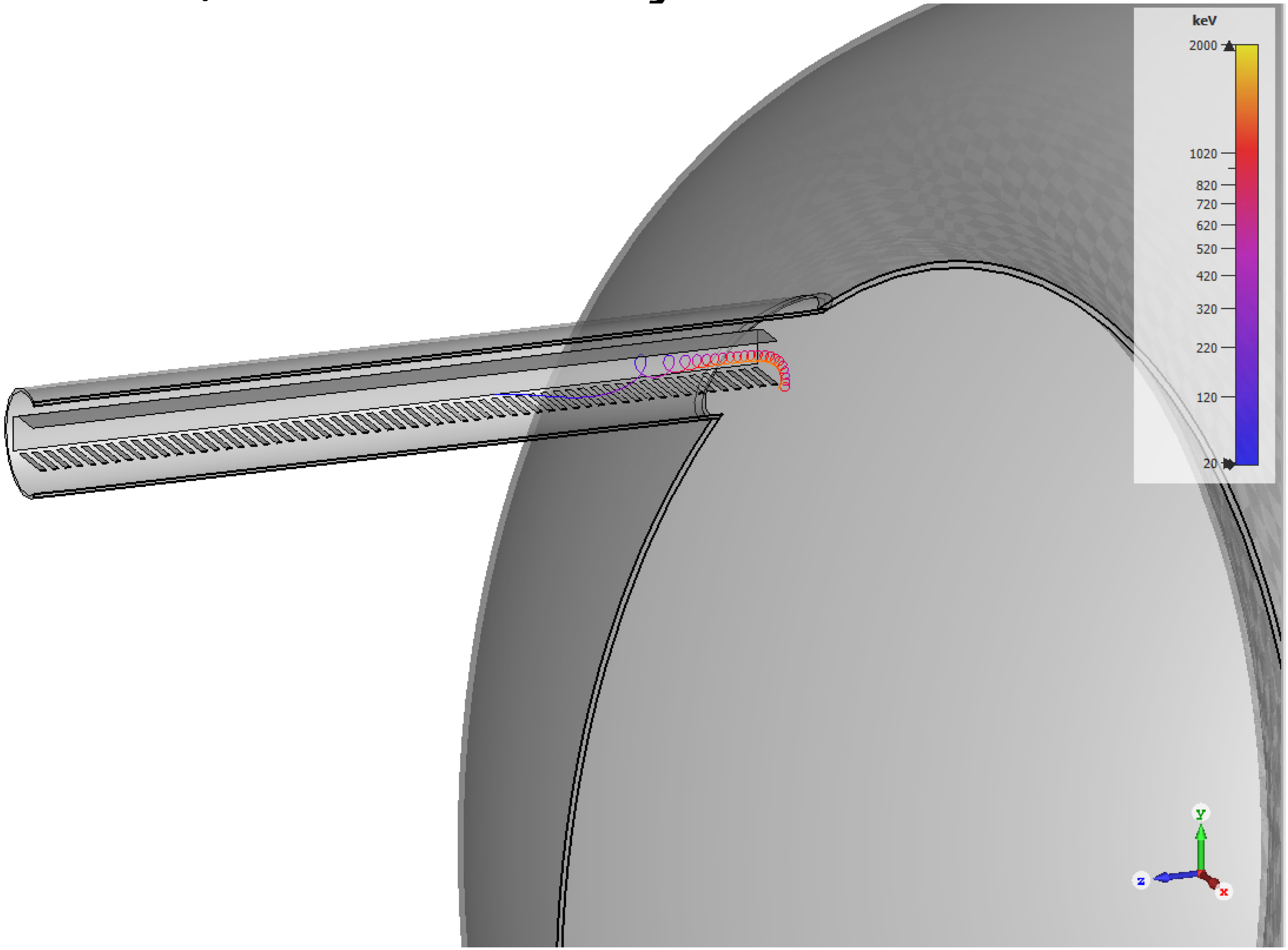
Magnetic Geometry:
“Reverse” PTOLEMY filter



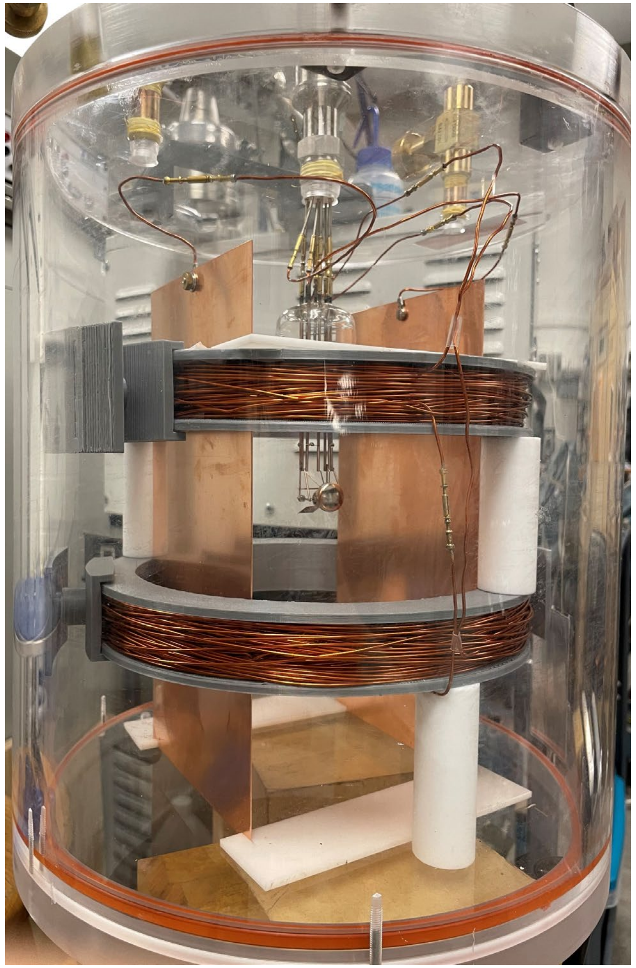
Tapered Dipole
+
Counter Dipole

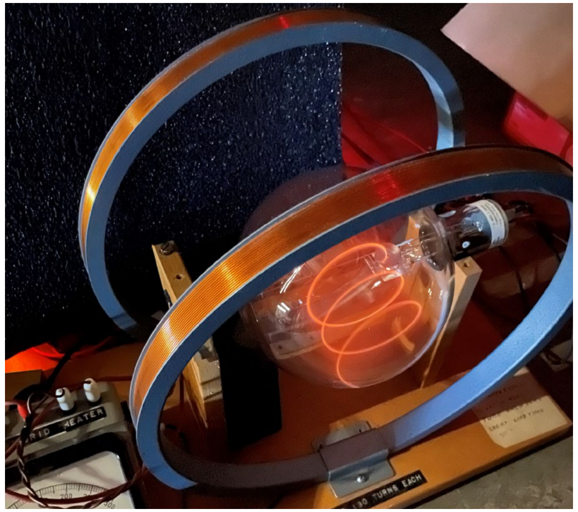
ITER Coils

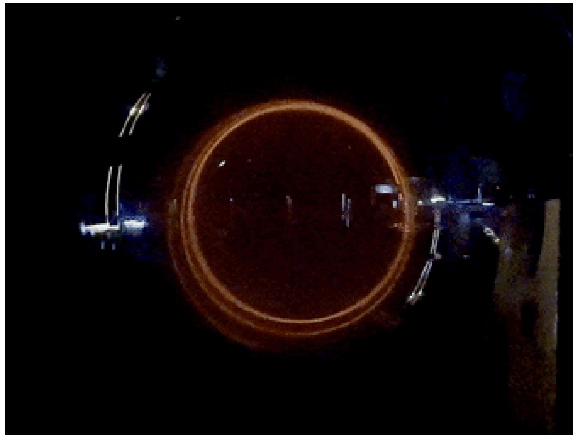
First Results w/Toroidal Injection

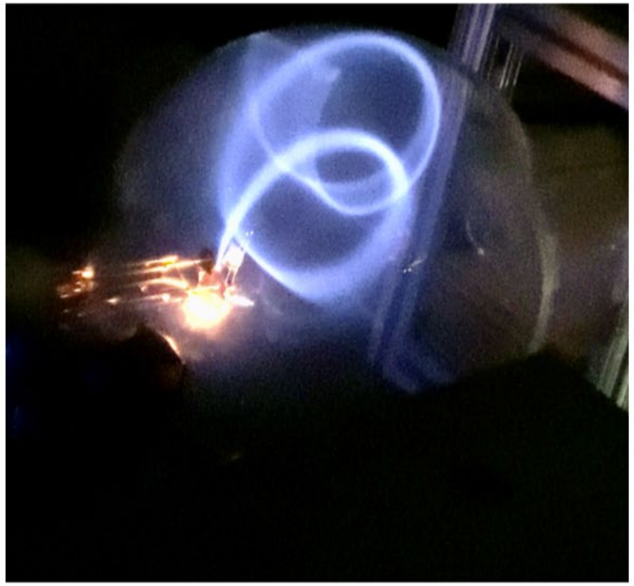


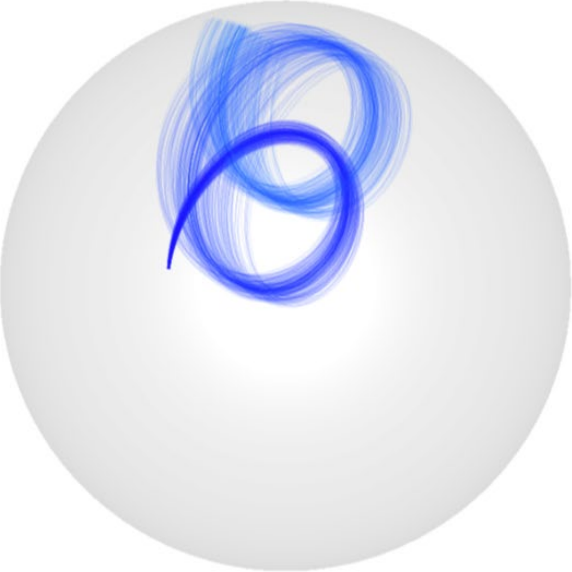
A great project for high school students.

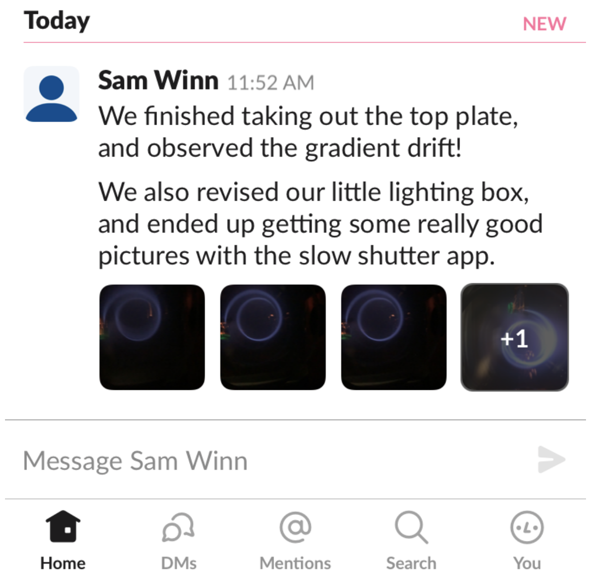










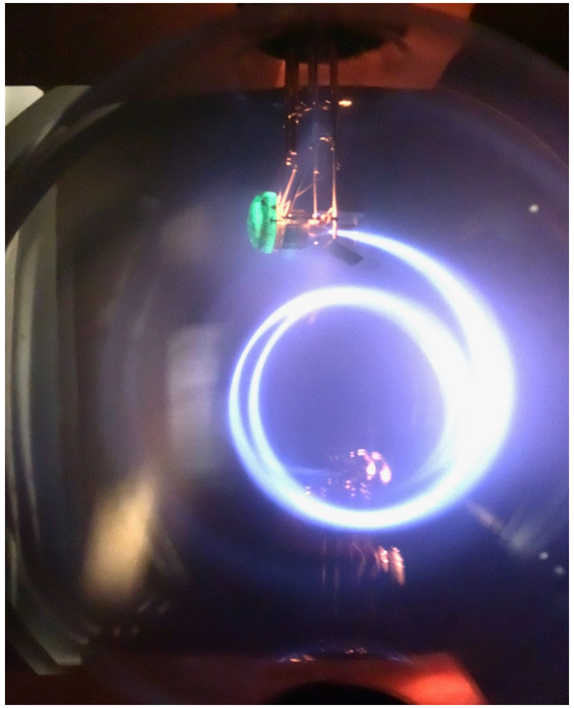


Today

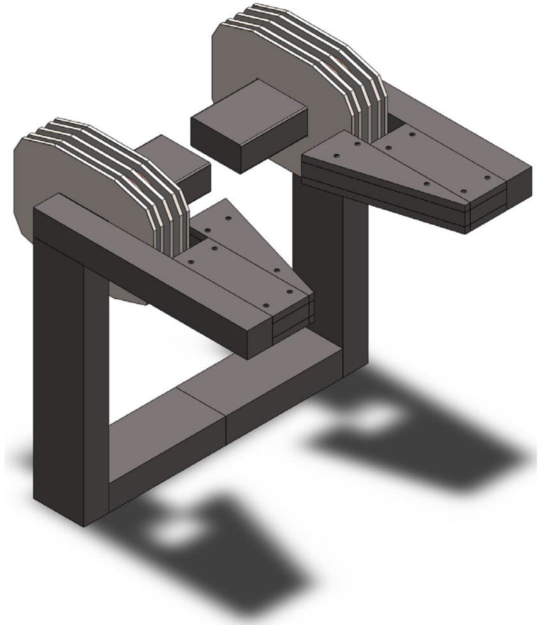
Sam Winn 11:52 AM

We finished taking out the top plate, and observed the gradient drift!

We also revised our little lighting box, and ended up getting some really good pictures with the slow shutter app.



Next Steps



Validate entire measurement arm @ few x 10^{-6}

→ Build full-scale iron magnet and filter @ LNGS
→ Complete two full design cycles of TES @ INRiM
→ Integrate measurement arm with RF tracker
(supported by Dutch Research Council grant)

https://www.simonsfoundation.org/2021/01/11/dutch-research-council-awards-1-1-million-euros-to-neutrino-hunting-ptolemy-project/

Supported by

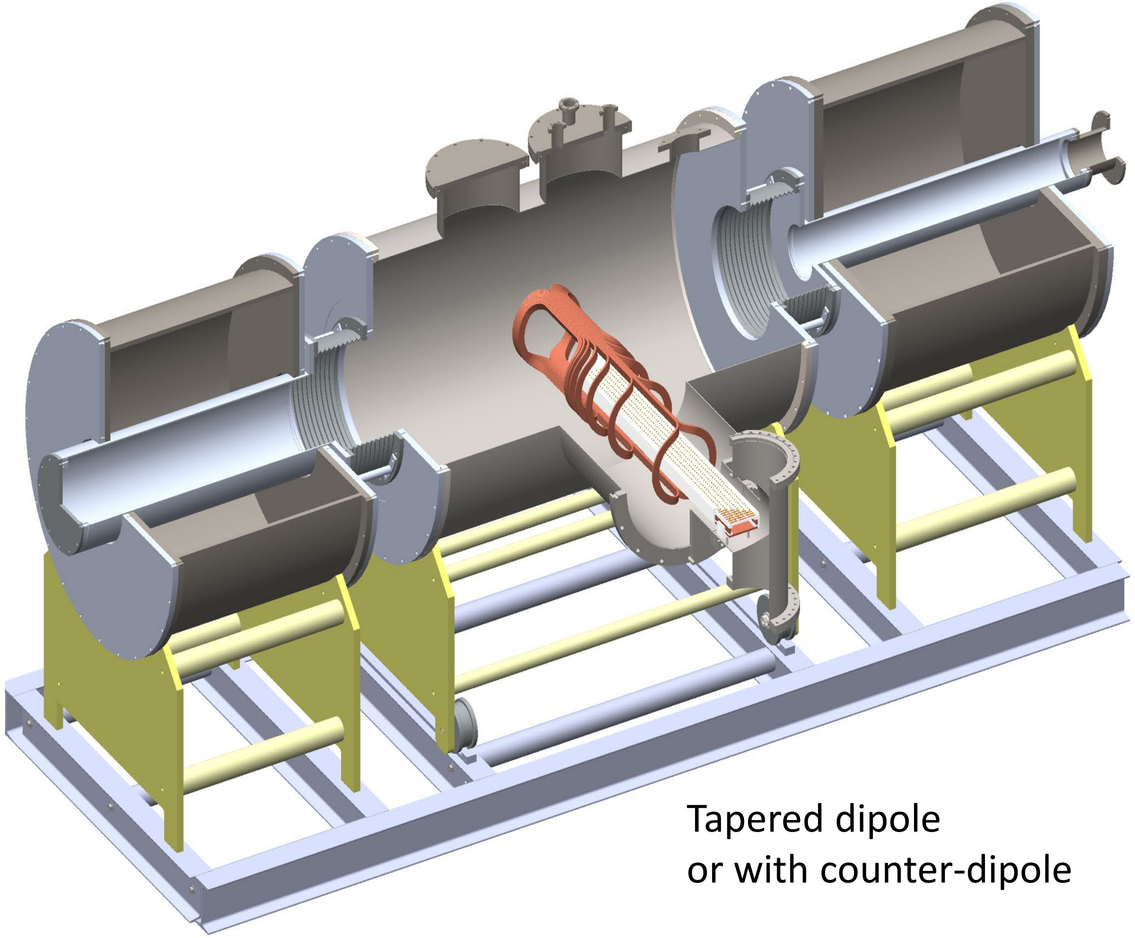
JOHN TEMPLETON FOUNDATION

SIMONS FOUNDATION

Produce filter and target with a scalable technology

→ Design/test a superconducting coil filter magnet
→ Design/test a Large-Area target geometry
→ Integrate with end-to-end tracking simulations

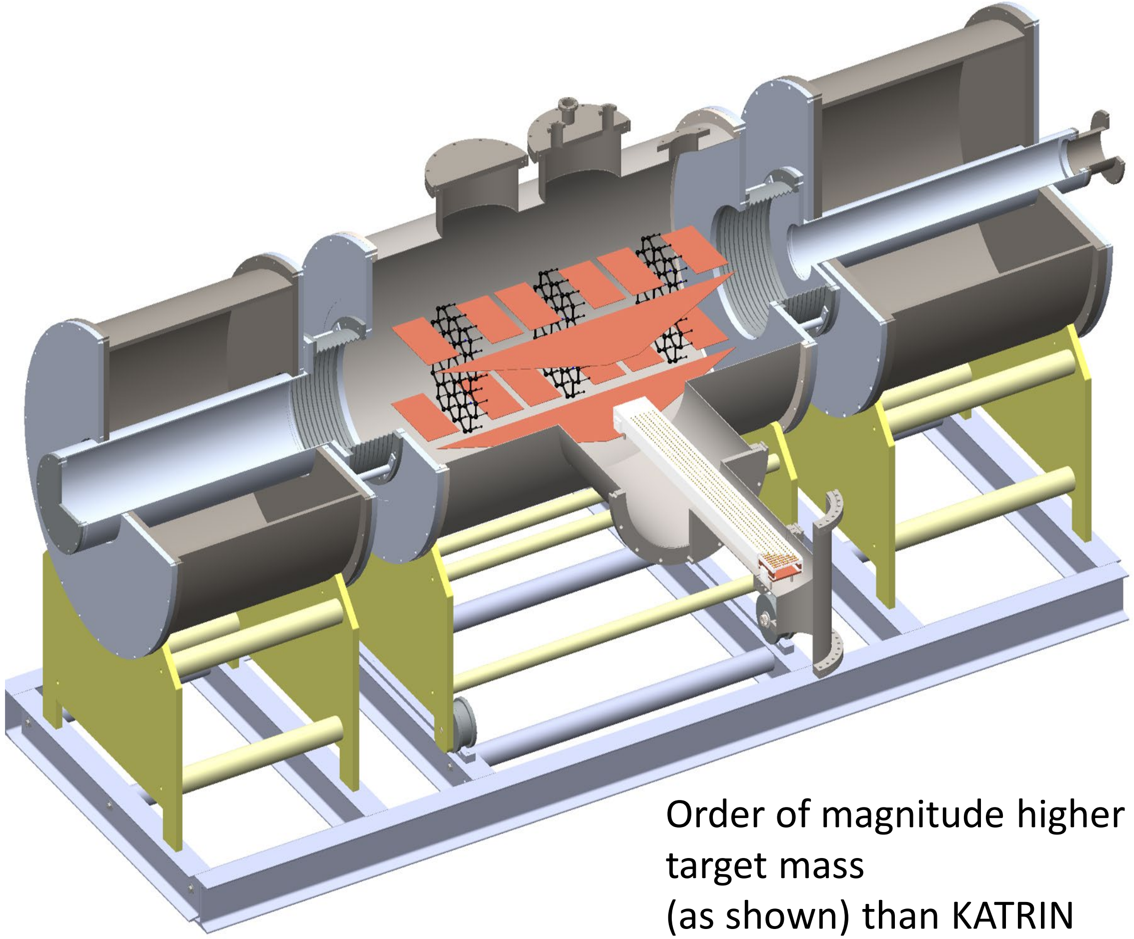
Superconducting Coil Design



Tapered dipole
or with counter-dipole

Integrate into existing dual-SC magnet setup @ LNGS

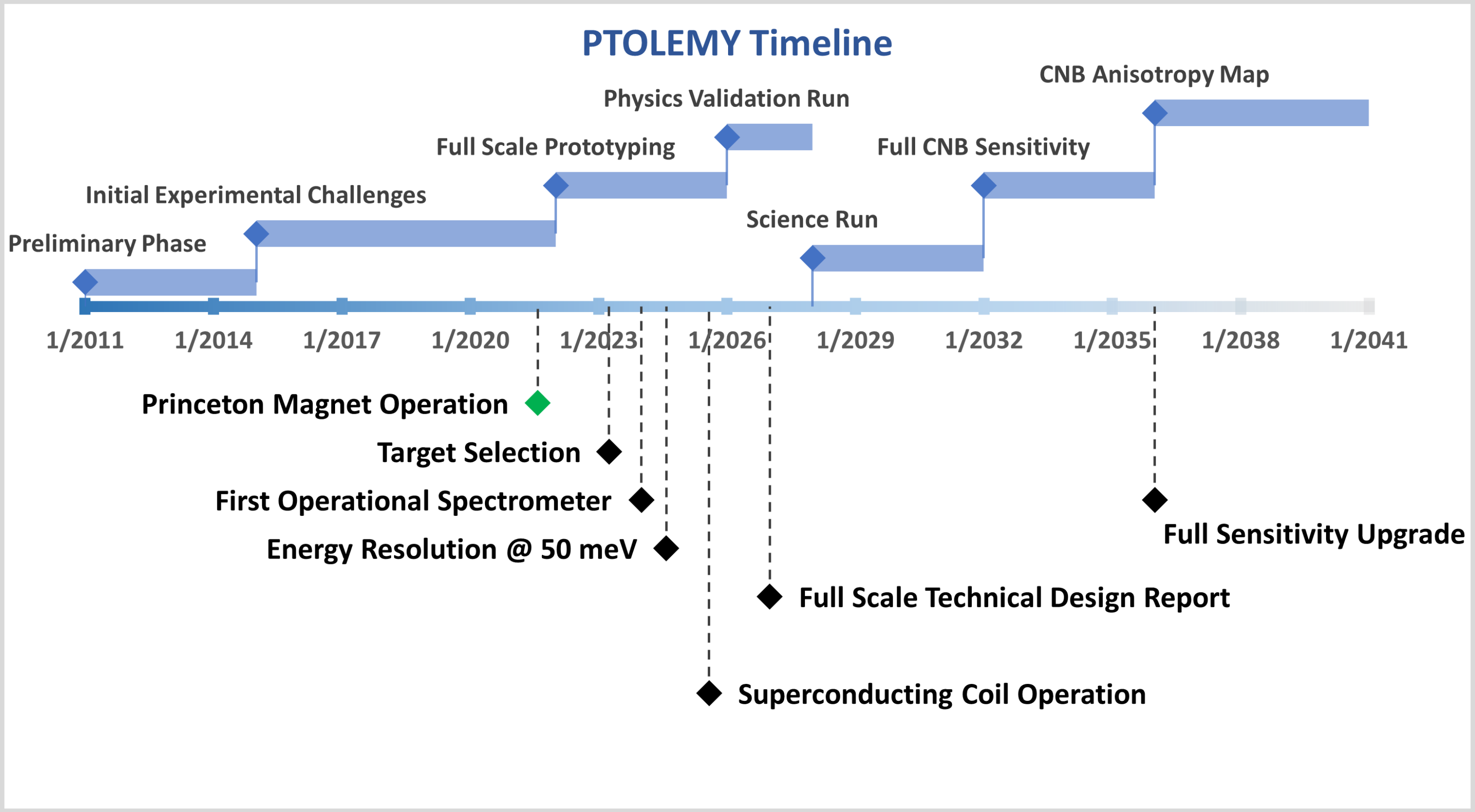
Large Area Target Design



Order of magnitude higher
target mass
(as shown) than KATRIN

Target Area and Quantum Properties are final frontiers for PTOLEMY

Yevheniia Cheipesh, Vadim Cheianov, Alexey Boyarsky, https://arxiv.org/abs/2101.10069
“Navigating the pitfalls of relic neutrino detection”



Physics Goals:

- Establish experimental baseline for first CνB Experiment

Based on validation of:

Measurement arm precision

Quantum smearing predictions

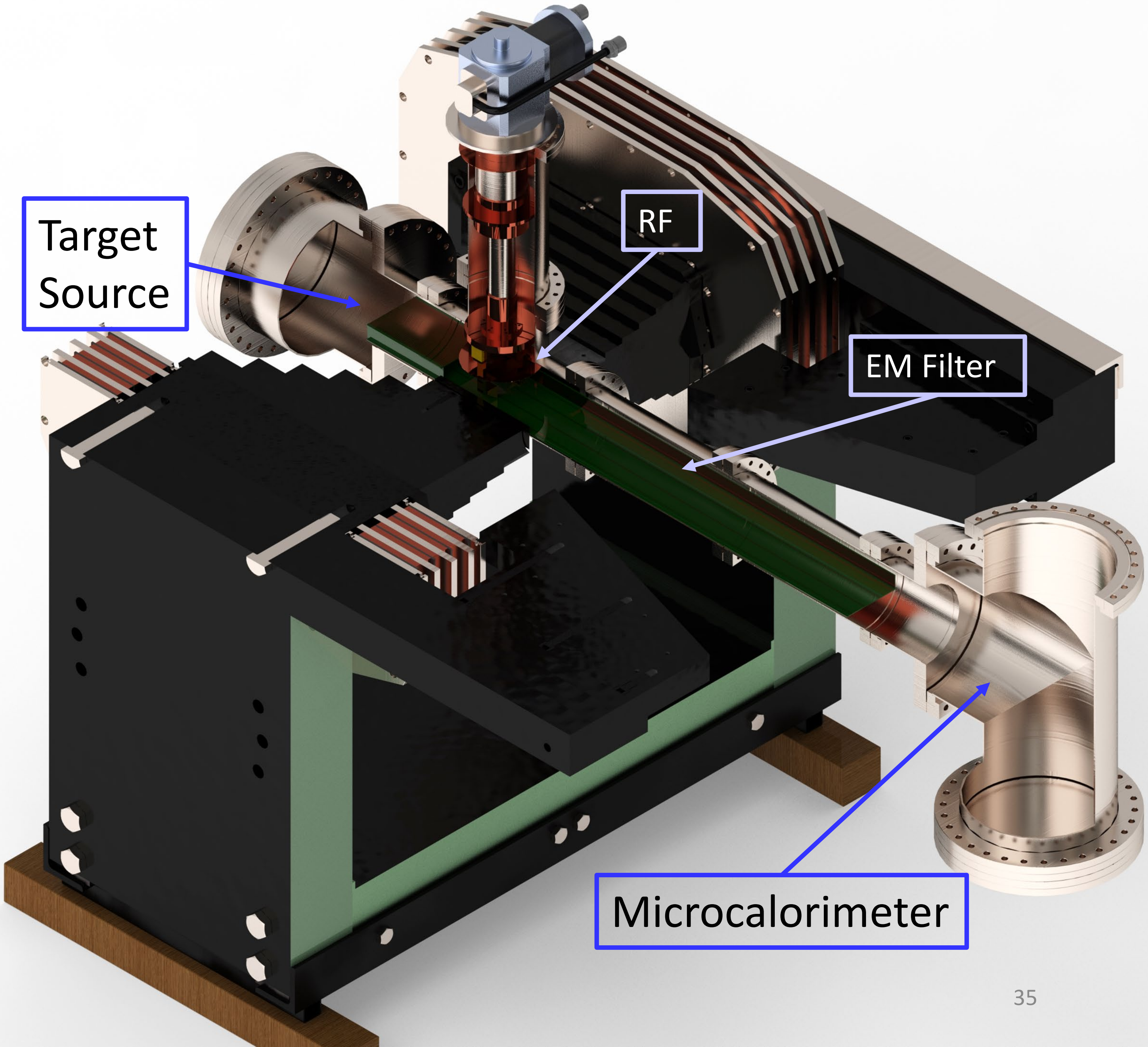
Scalability of technology

→ Leverage prototype system to explore new physics

CNB detection principles have evolved into concrete designs

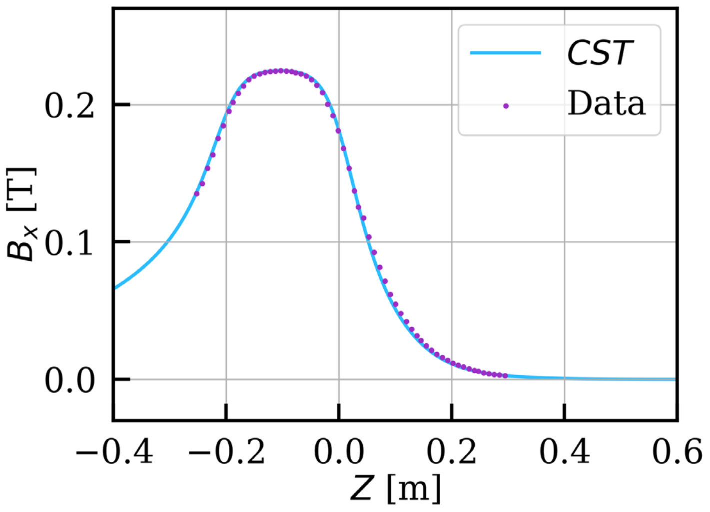
Prototype construction has yielded good results with several publications.

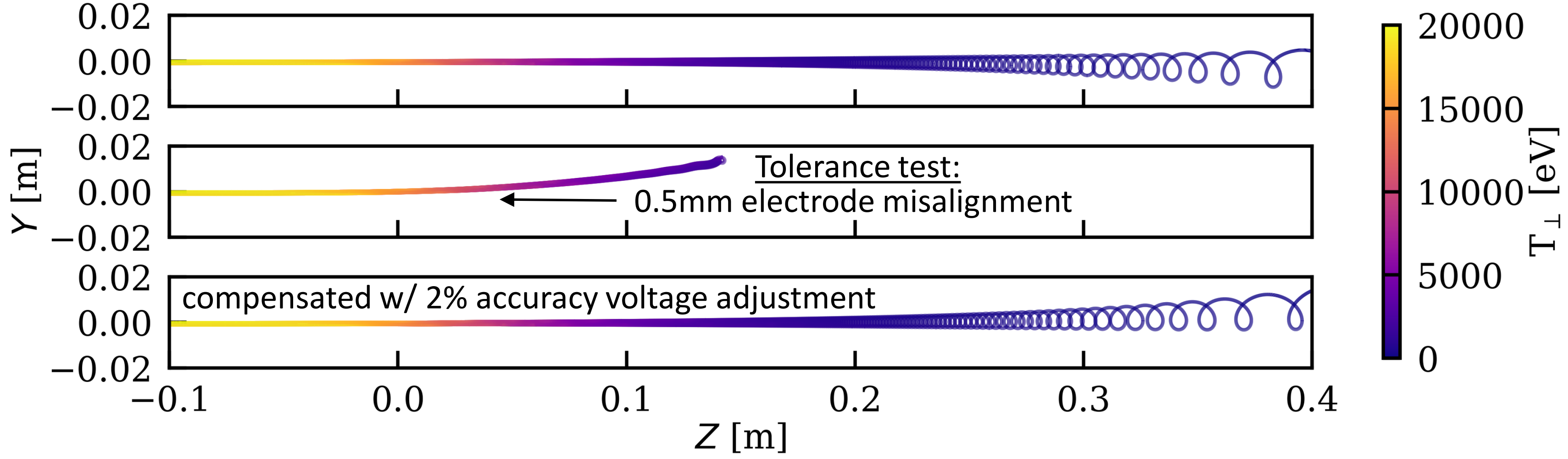
We hope to enter an exciting new phase with PTOLEMY this year with a rich experimental program.



Spare slides

Achieves Required Magnetic Field Map



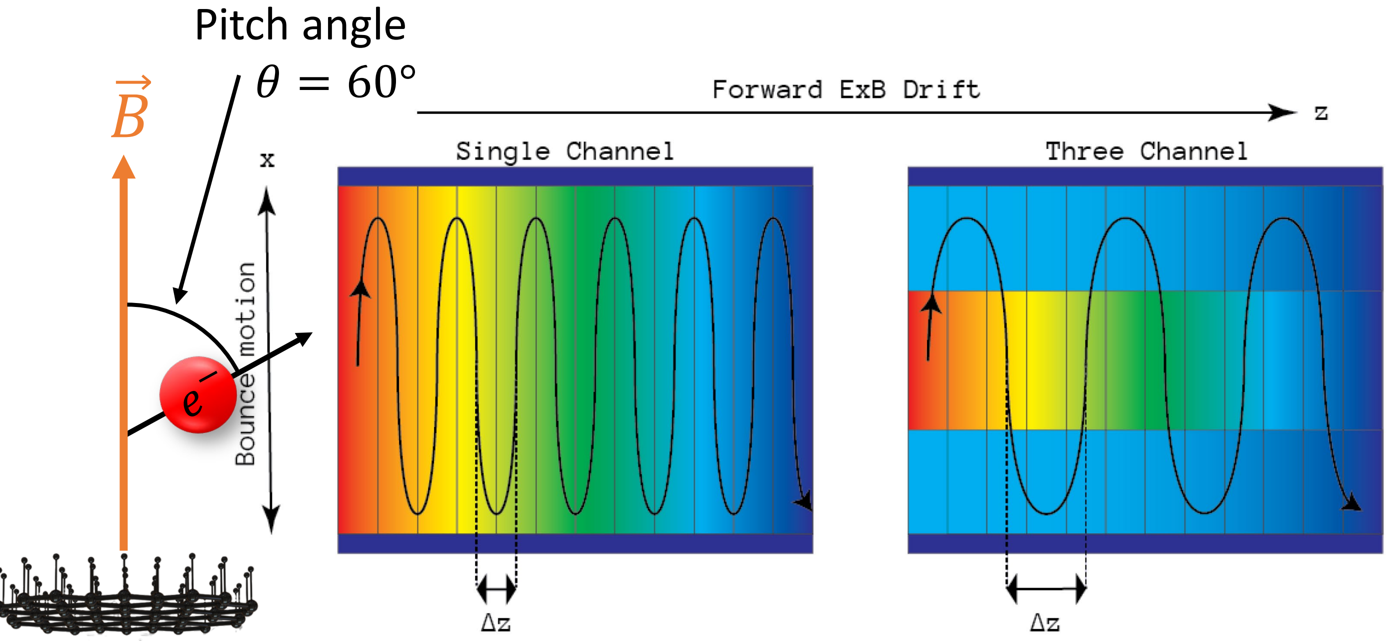


Tolerance test:
0.5mm electrode misalignment

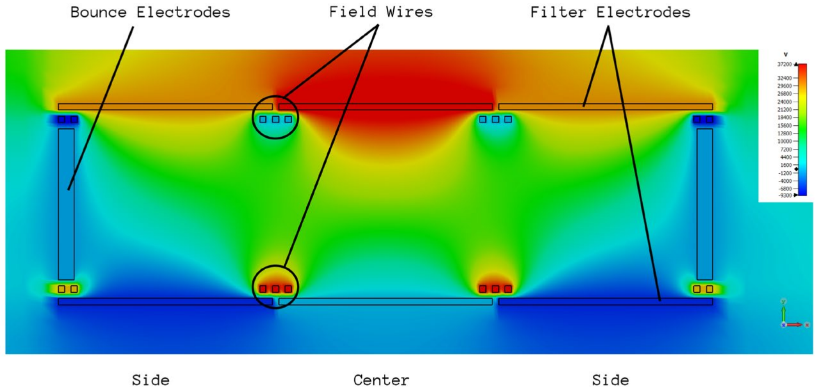
compensated w/ 2% accuracy voltage adjustment

https://arxiv.org/abs/2108.10388

PTOLEMY EM Filter with 3 Channels



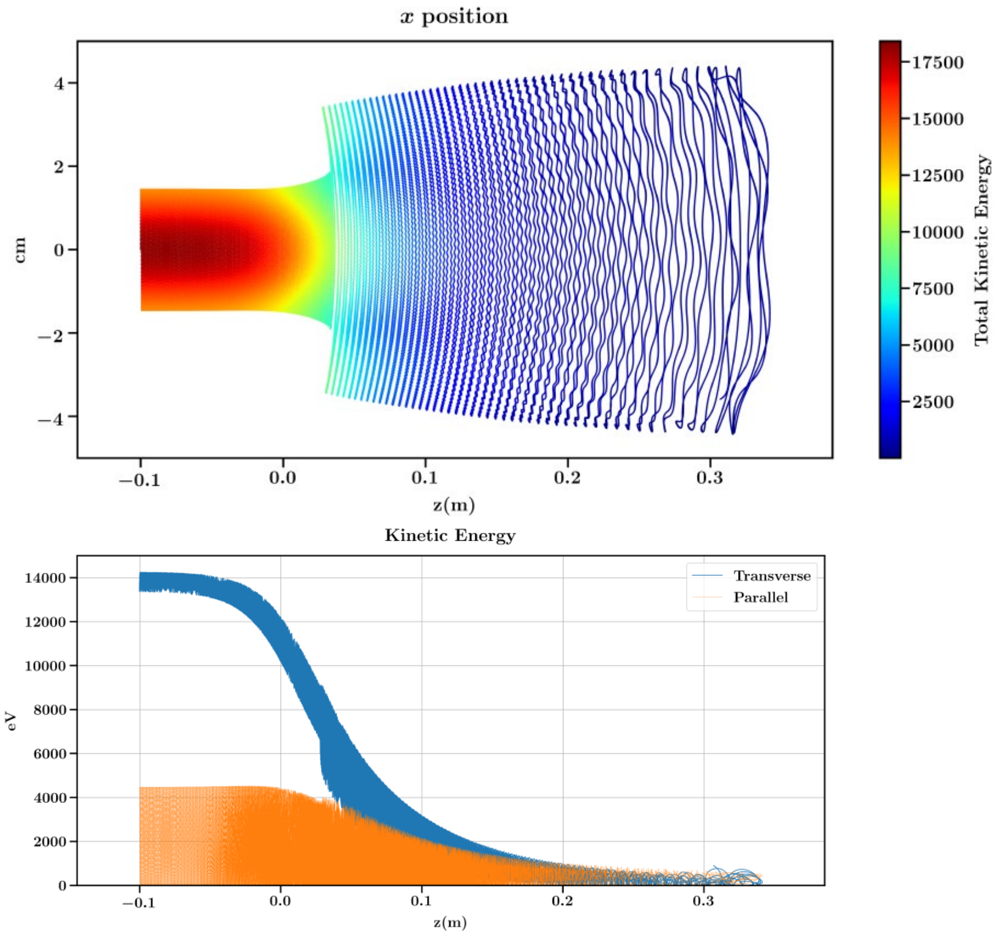
Top View



arXiv: 2108.10388

- To increase the acceptance for high pitch angle ones, we split the bounce direction into 3 channels (central, side).
- Electrons linger in the side well longer in a 3-channel design, s.t. the parallel kinetic energy drains faster than the transverse one to avert a runaway drift.
- By raising the side well potentials, the electrons enter the side well with lower parallel kinetic energy than the single channel design.

PTOLEMY 3-Channel EM Filter

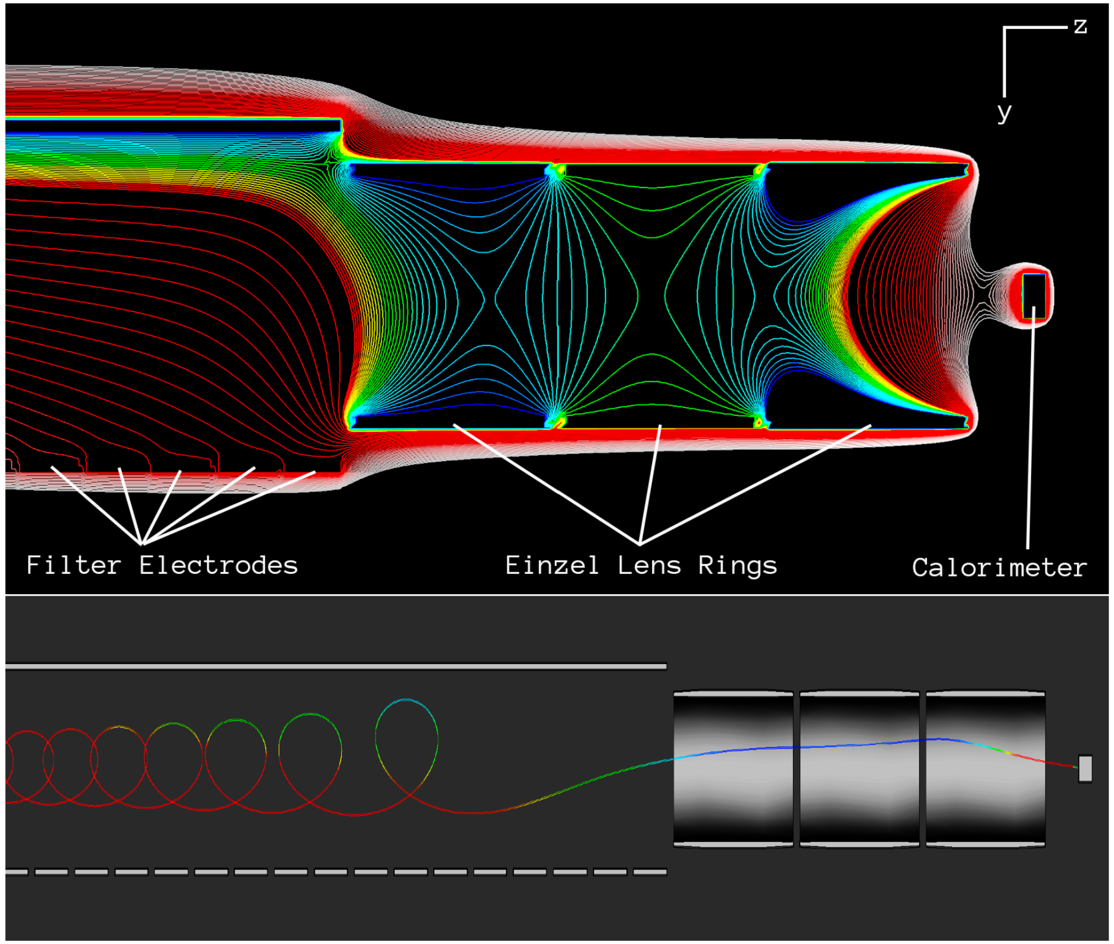


- An example of the trajectory (top view) of an electron with $\theta = 60°$ in a 3-channel filter.
- Both its parallel and transverse kinetic energies drains as it drifts along +z direction where the B field decays.

arXiv: 2108.10388 submitted to RSI

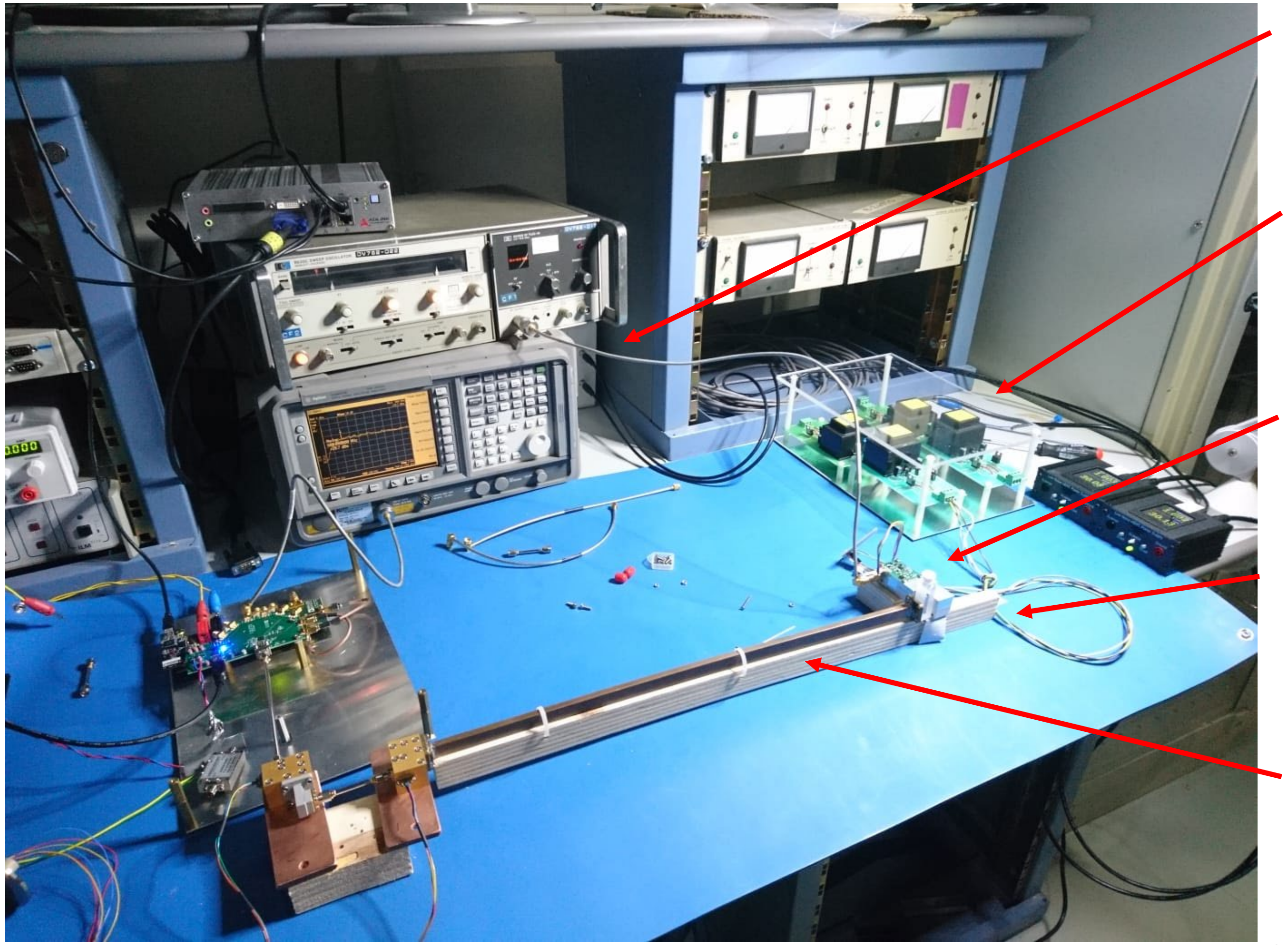
Filter Exit to Calorimeter

- An Einzel Lens is designed to direct electrons with $\mathrm{T}\sim\mathcal{O}(1\ \mathrm{eV})$.
- It is an electrostatic focusing device consists of 3 conducting rings.
- The center ring is set at lower potential to bend the trajectory and focusing the beam.
- The spread of focal points depends on the initial RF measurement accuracy and filter efficiency.



arXiv: 2108.10388 (in peer-review)

LNGS RF Setup



Signal injection: ~13 GHz

4 Low voltage channels

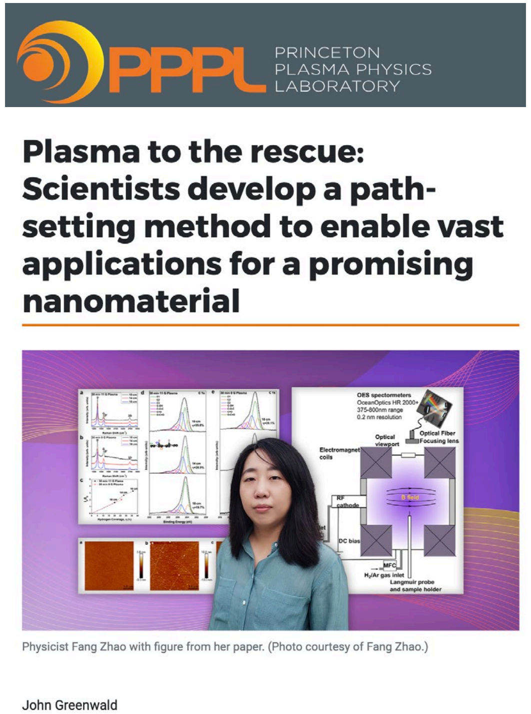
Frequency multiplier

Calibrated 1 cm
water absorber

WR42 Waveguide
from Princeton

Alfredo Cocco, George Korga, Marcello Messina

Tritium Source

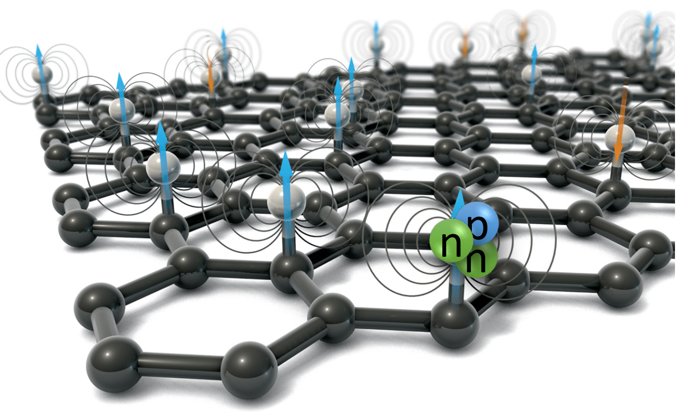


PPPL PRINCETON PLASMA PHYSICS LABORATORY

Plasma to the rescue: Scientists develop a path-setting method to enable vast applications for a promising nanomaterial

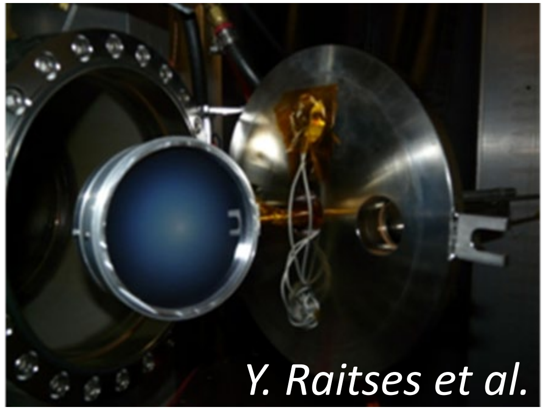
Physicist Fang Zhao with figure from her paper. (Photo courtesy of Fang Zhao.)

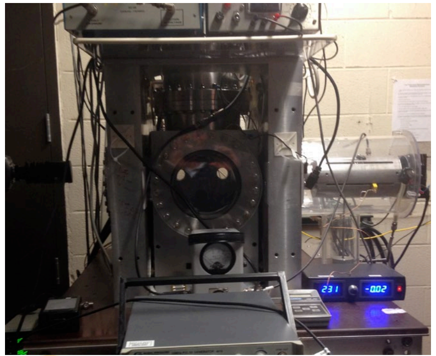
John Greenwald



Courtesy: C. BICKEL/*SCIENCE*

JOHN TEMPLETON FOUNDATION

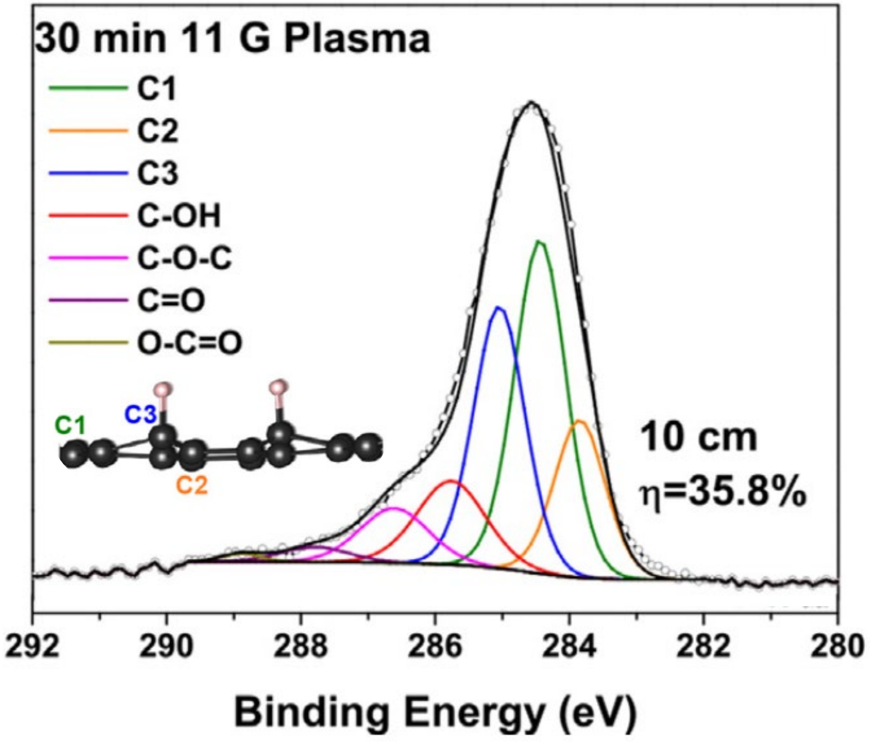




PPPL PRINCETON PLASMA PHYSICS LABORATORY

- Atomic tritium Source
  - No ro-vibrational modes in final state like for diatomic molecular source (4.7 eV covalent bond)
- Tritium load on graphene
  - 0.7-1.0eV covalent bond
  - High coverage
  - Stable at room temperature
  - Polarized T -> directionality *
- Other ideas
  - Au(111)
  - Superfluid Helium

*Lisanti, Safdi, and Tully, PRD **90**, 073006 (2014)



Carbon 177 (2021) 244-251