PTOLEMY: Relic Neutrino Detection

Chris Tully

Princeton University

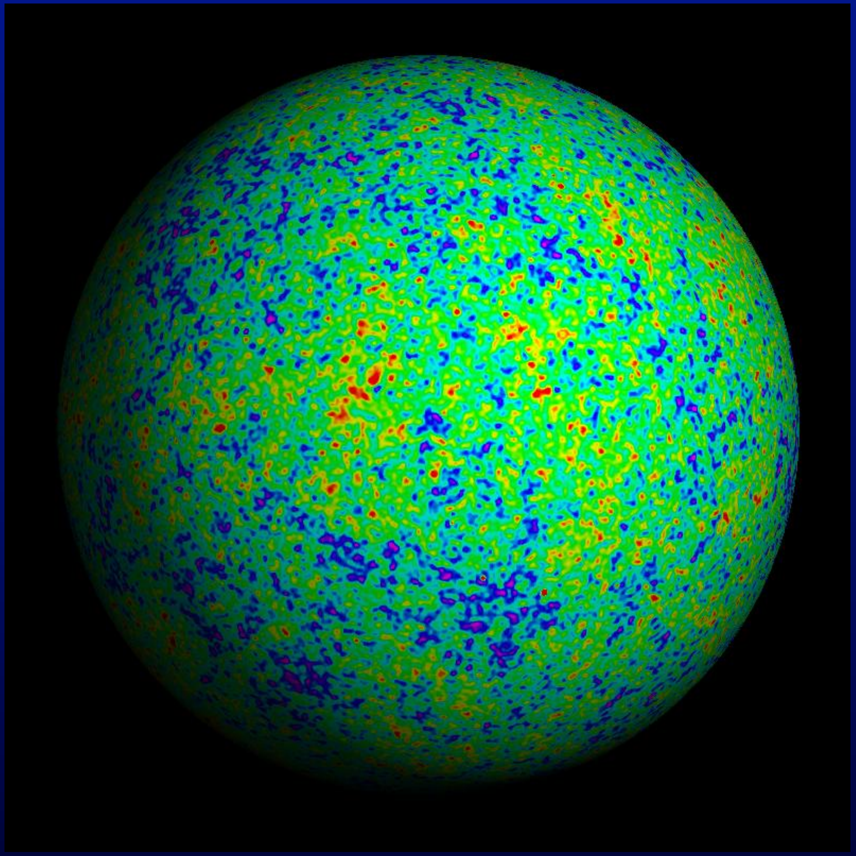
Opening New Windows to the Universe

Brookhaven Forum

BNL, November 3, 2021

PTOLEMY: 2015 MPS Targeted Grant Award from the SIMONS FOUNDATION

Celestial Globes



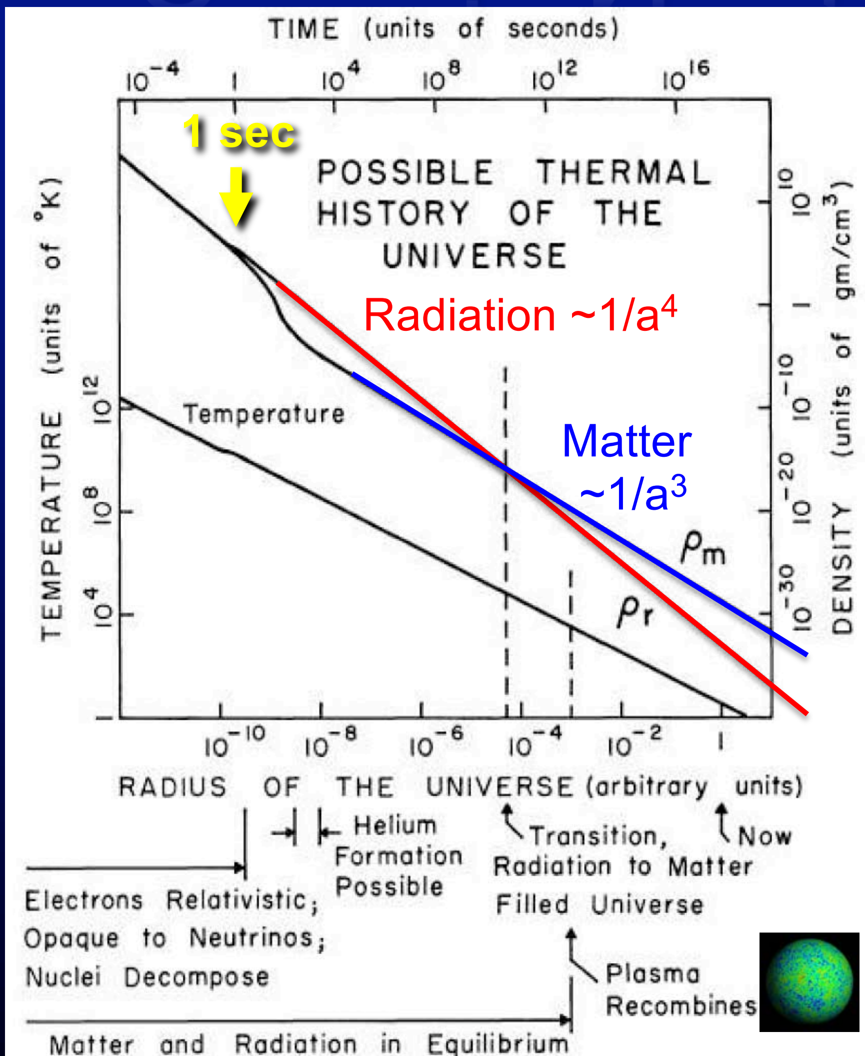
Adiabatic Density Anisotropies $\delta \sim 10^{-5}$
at $z \sim 1100$

Johann Schöner, c.1534

WMAP, c.2009

PTOLEMY papers: Over 100+ citations and growing

Cosmic Neutrino Background



Number density:

$n_\nu = 112/cm^3$

Temperature:

$T_\nu \sim 1.95K$

Time of decoupling:

$t_\nu \sim 1$ second

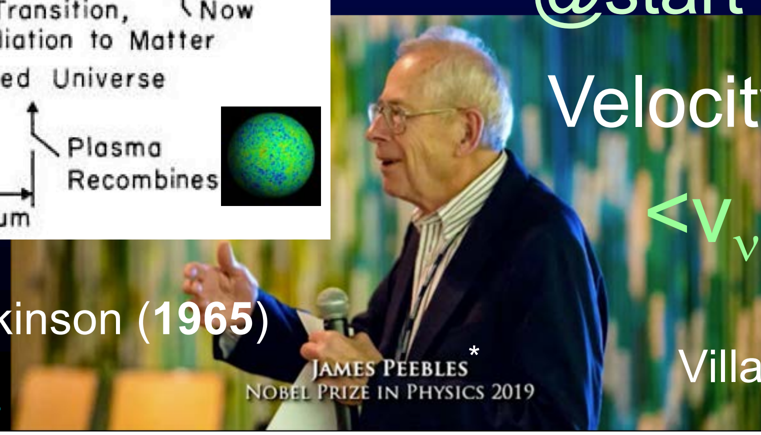
~50% of the Total Energy Density of the Universe

neutron/proton ratio @start of nucleosynthesis

Velocity distribution:

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

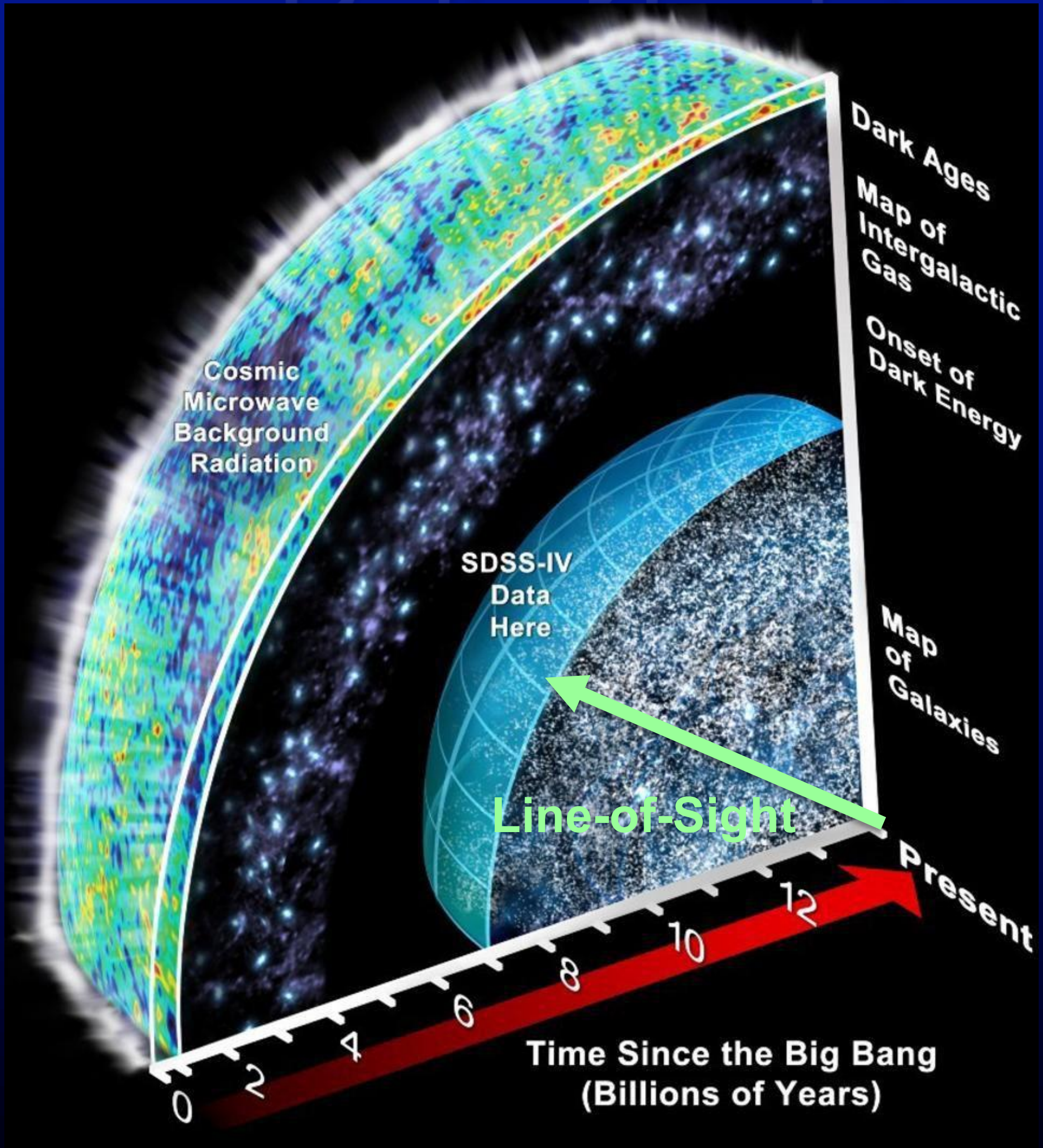
Non-linear distortions
Villaescusa-Navarro et al (2013)

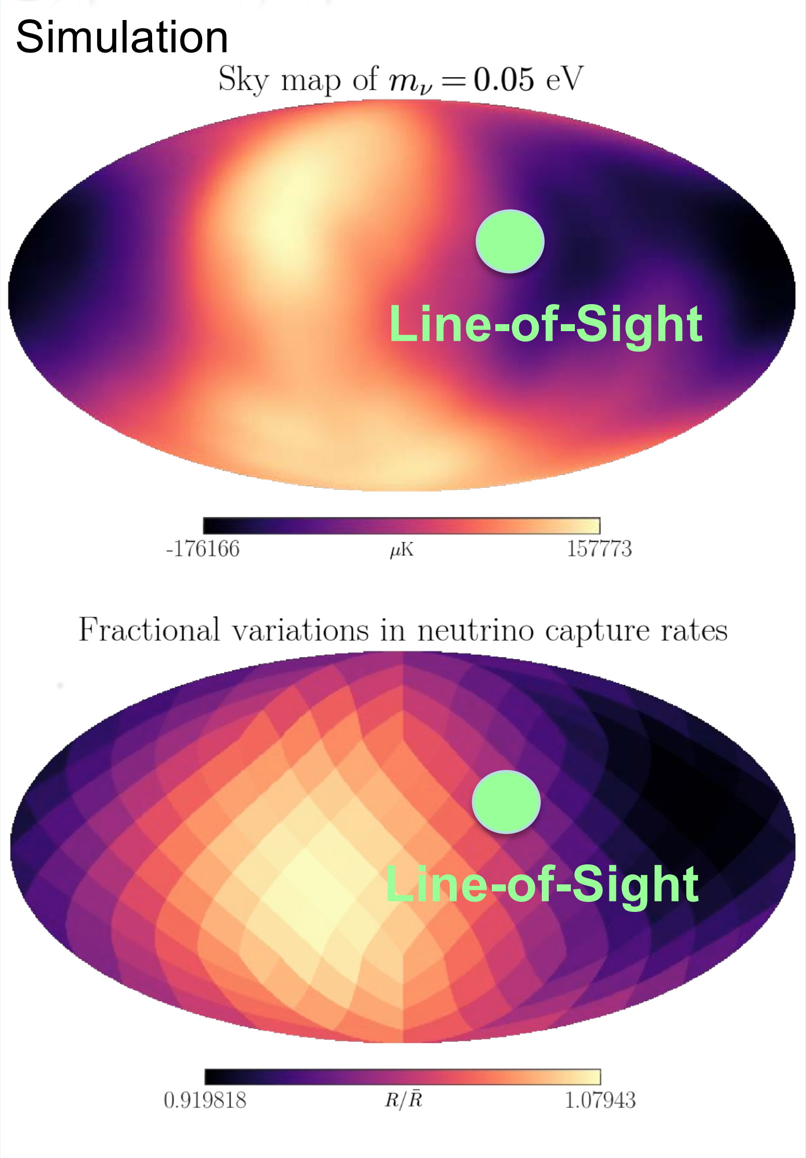


Dicke, Peebles*, Roll, Wilkinson (1965)

Cosmology's Century (2020)

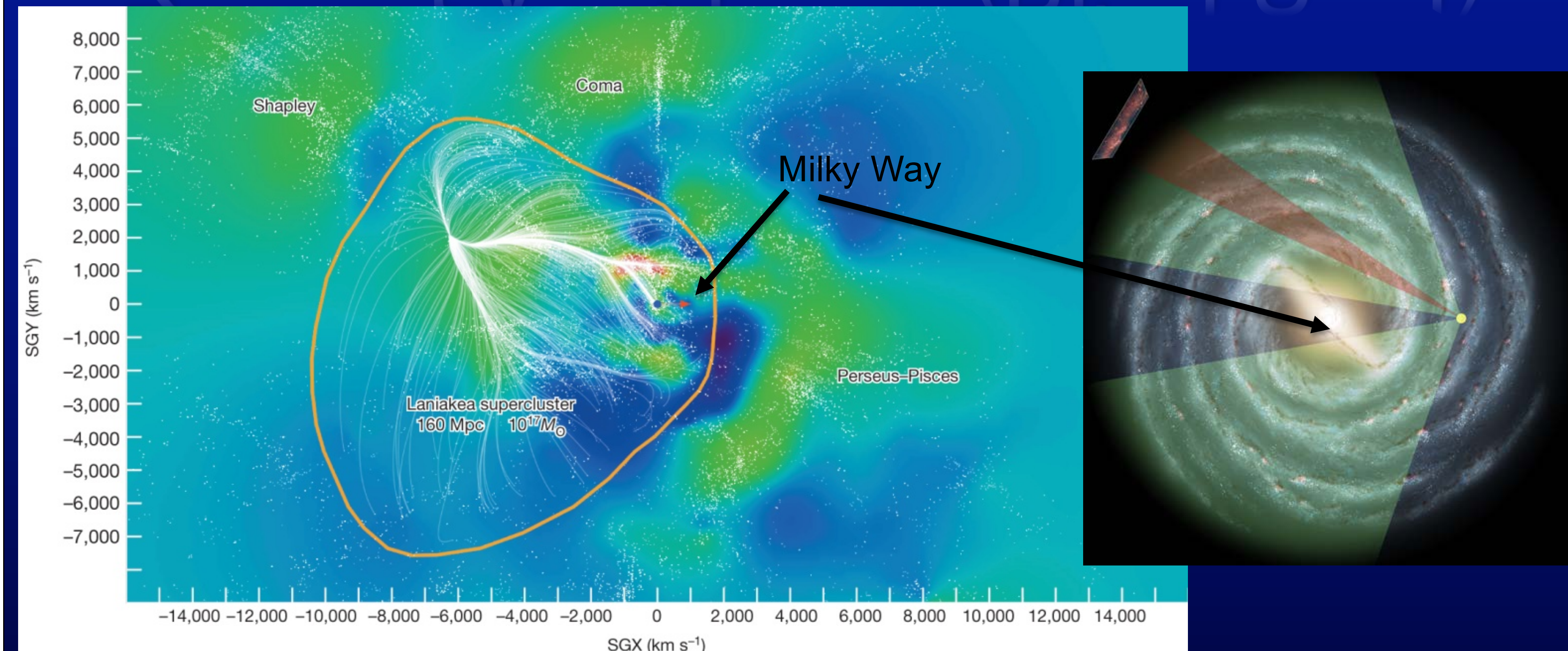
Relic Neutrino Sky Map





Tully, Zhang, http://arxiv.org/abs/2103.01274 First citation came from Jim Peebles
https://iopscience.iop.org/article/10.1088/1475-7516/2021/06/053
"Multi-Messenger Astrophysics with the Cosmic Neutrino Background", JCAP 06 (2021) 053

Zone of Avoidance (Blind Spot)



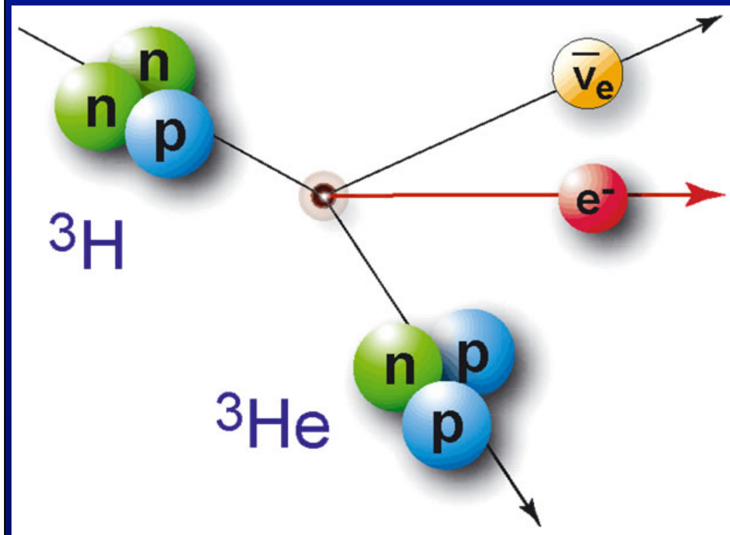
RB Tully *et al.* *Nature* **513** , 71-73 (2014)
http://doi.org/10.1038/nature13674

nature

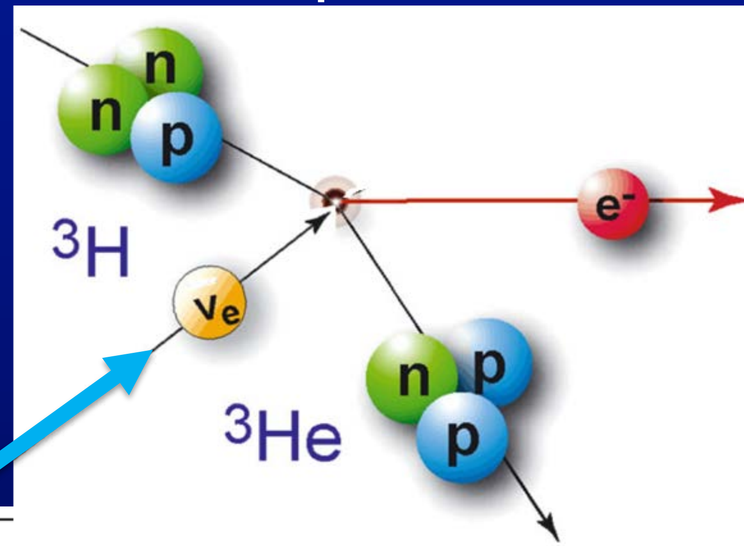
Neutrinos can see behind the Milky Way!
If relic neutrinos exist in the Universe today, then we can validate the over- and underdensities in the nearest 100-200 Mpc

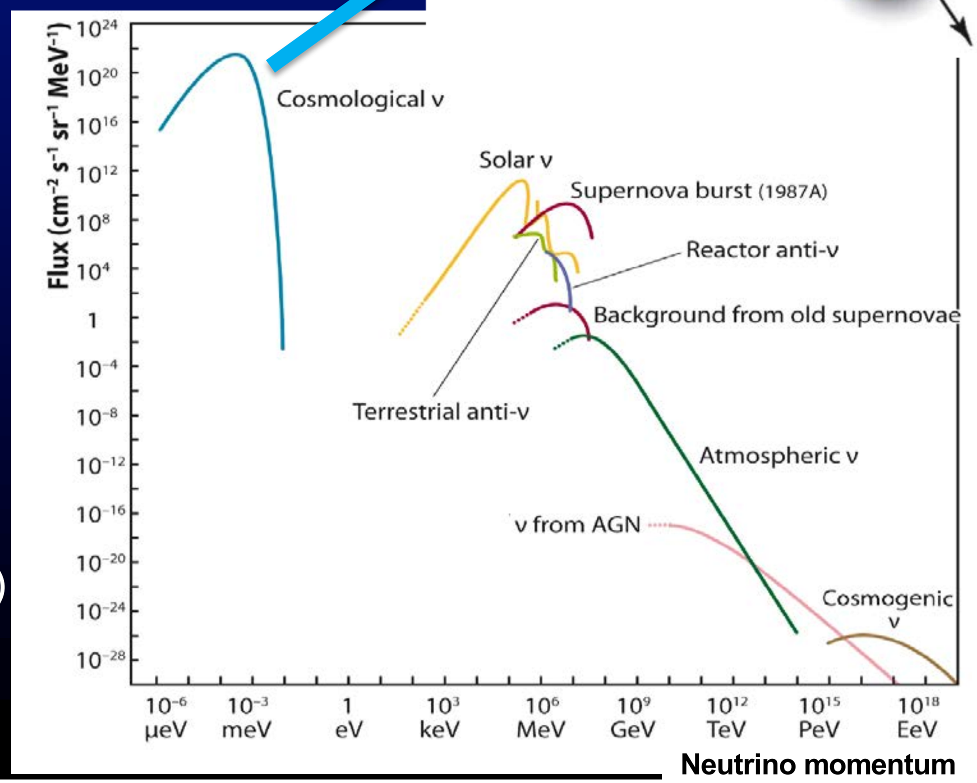
https://www.nytimes.com/2020/07/10/science/astronomy-galaxies-attractor-universe.html

Neutrino capture on Tritium



Tritium β-decay
(12.3 yr half-life)





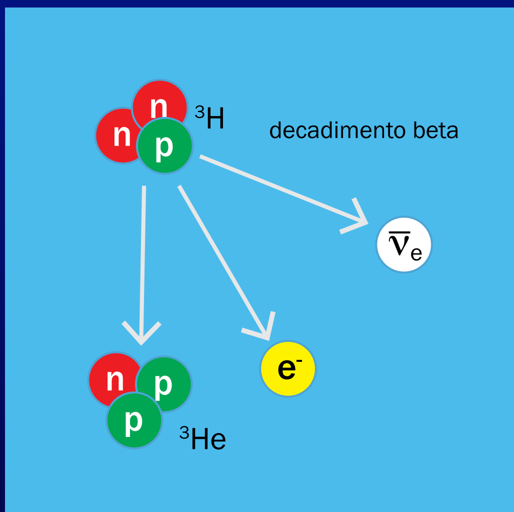
Neutrino momentum ~ 0.17 meV

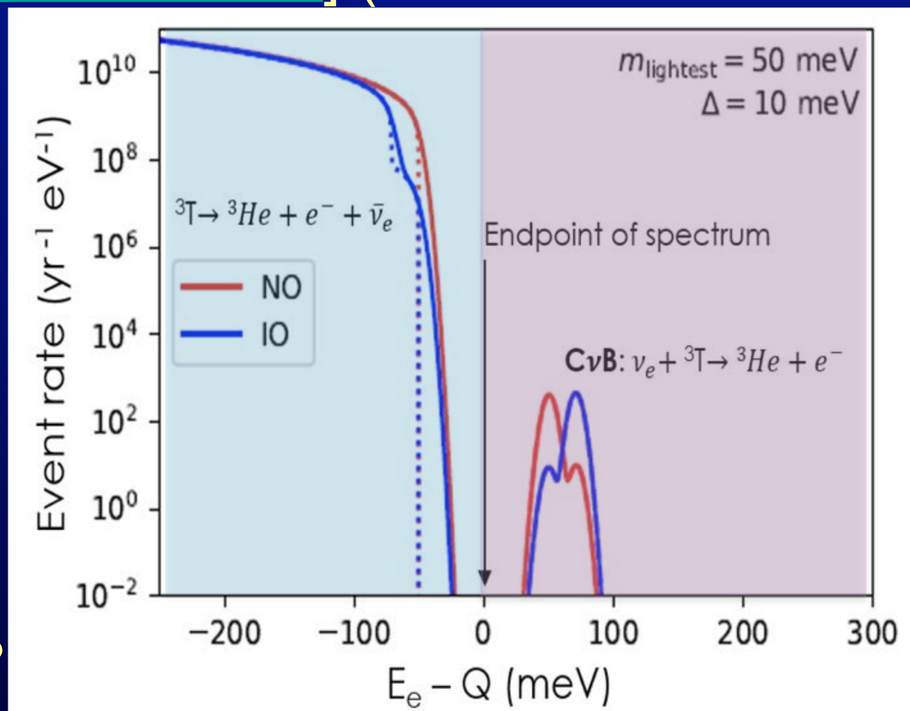
For m_ν = 50 meV,
KE = $p^2/2m$
= 0.17 meV (0.17 meV/100 meV)
= 0.3 μeV

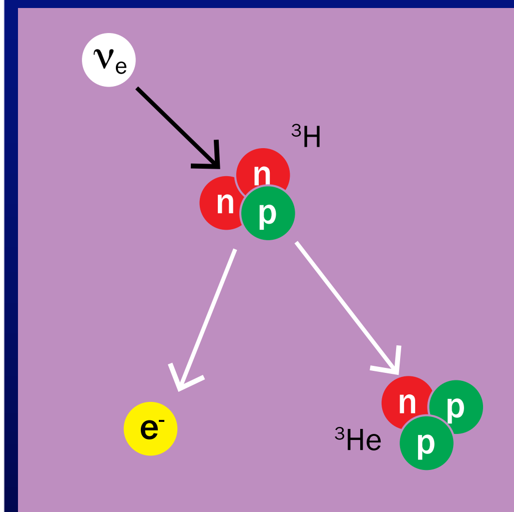
Ultra-Cold!

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] (no molecular smearing included)







What do we know?

Electron flavor expected with

m > ~50meV

from **neutrino oscillations**

Gap (2m) constrained to

m < ~200meV

from **precision cosmology**

CνB Detection Requires:

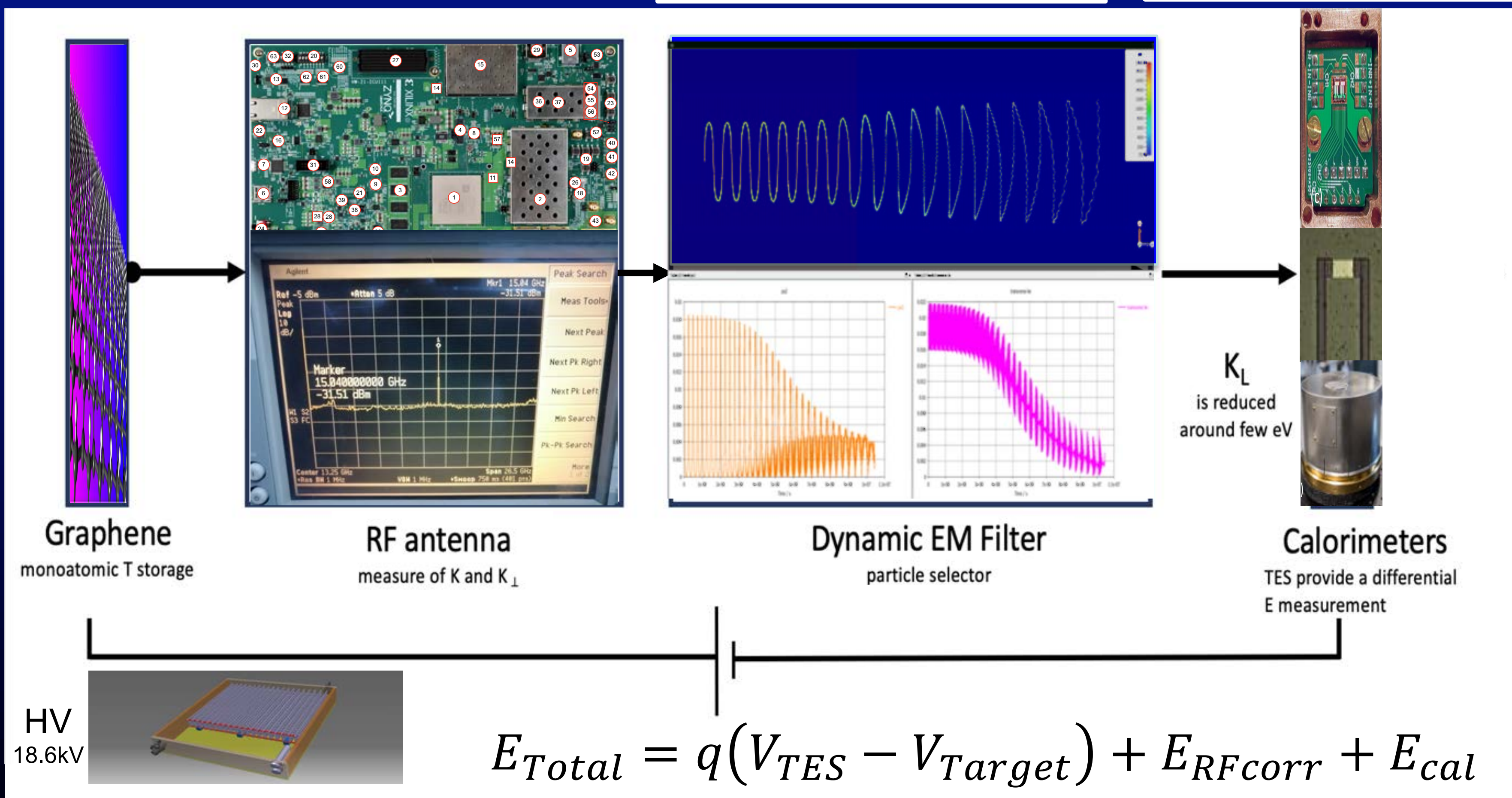
few x 10^{-6} energy resolution set by m_ν

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

PTOLEMY: 10^{-4} x 10^{-2}
(compact filter) x (microcalorimeter)

PTOLEMY Conceptual Block Diagram

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**



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

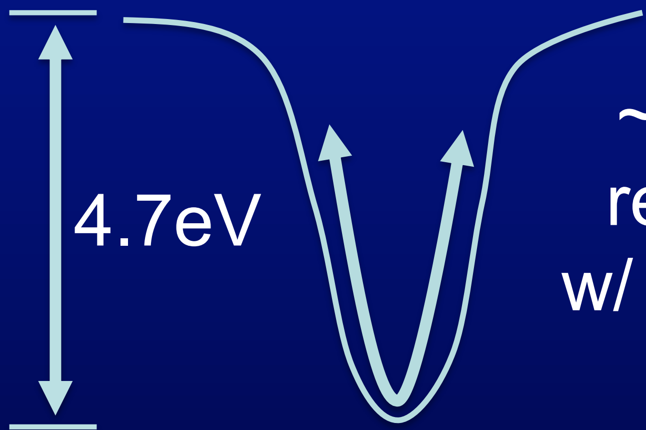
https://ptolemy.lngs.infn.it

Target: Molecular Broadening

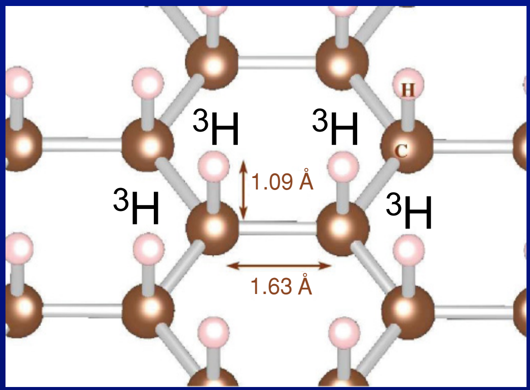
Gaseous target not ideal

T-T → $(T\text{-}He^3)^{+*}$

*Many close-spaced ro-vibrational excited states

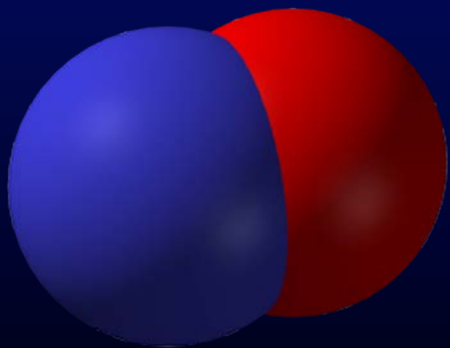


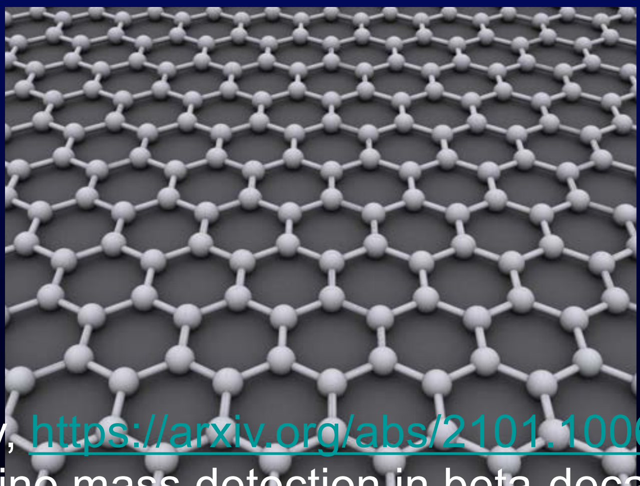
~1.7eV $(T\text{-}He^3)^{+*}$ recoil at endpoint w/ ~0.3eV spread(*)



~1eV binding energy

Planar target: Graphene





Yevheniia Cheipesh, Vadim Chianov, Alexey Boyarsky, https://arxiv.org/abs/2101.10069
“Heisenberg’s uncertainty as a limiting factor for neutrino mass detection in beta-decay”
Shmuel and Zohar Nussinov, https://arxiv.org/abs/2108.03695
“Quantum Induced Broadening – A Challenge for Cosmic Neutrino Background Discovery”

Graphene Hydrogenation

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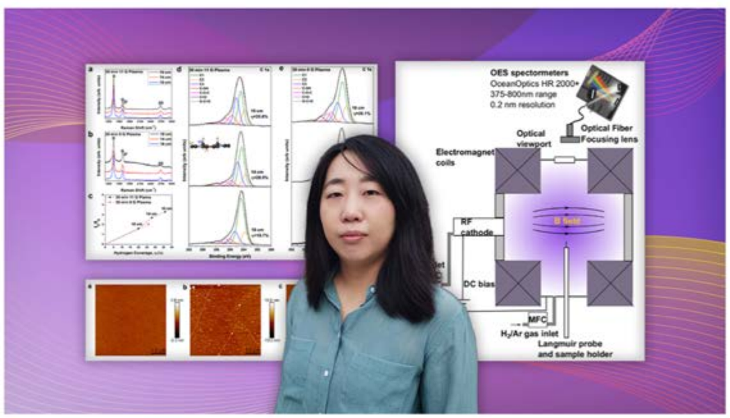
QUEST Research Magazine

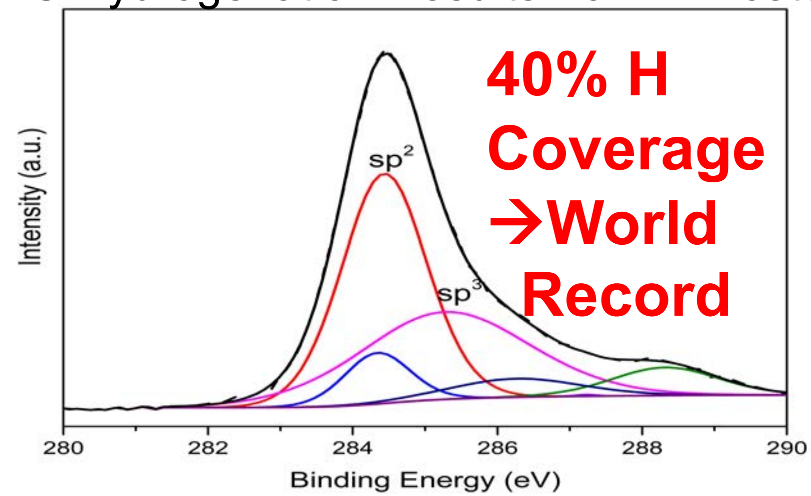
Plasma to the rescue: Scientists develop a path-setting method to enable vast applications for a promising nanomaterial

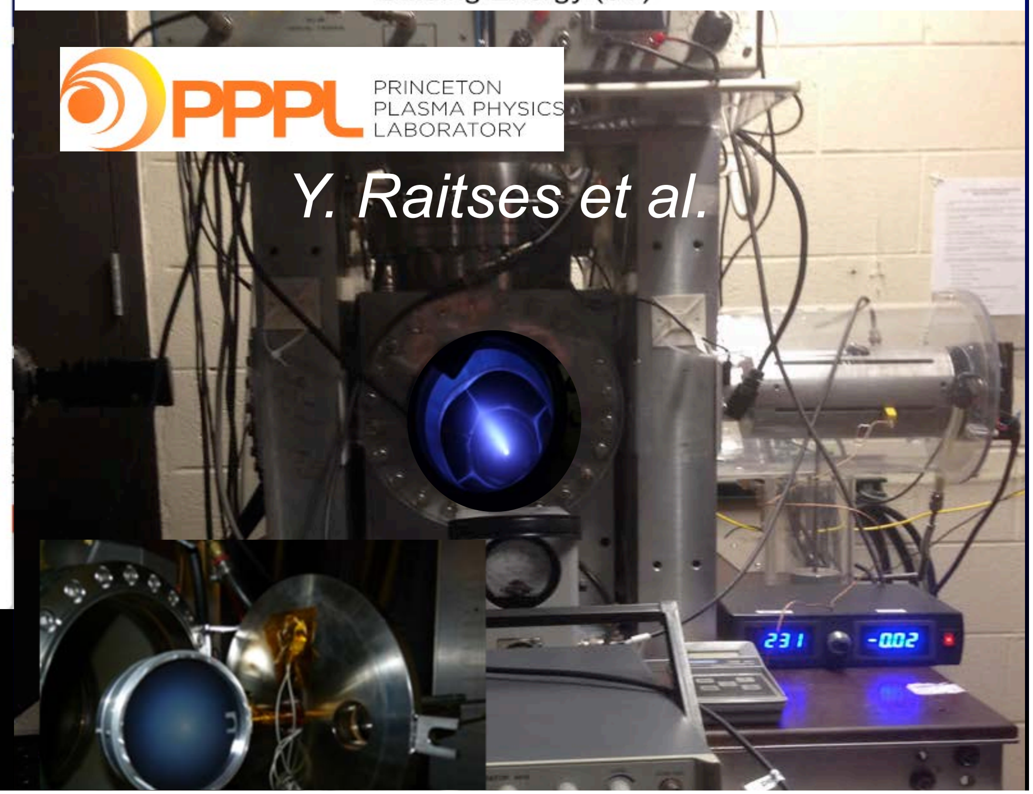


Physicist Fang Zhao with figure from her paper. (Photo courtesy of Fang Zhao.)

John Greenwald

XPS Hydrogenation Results from Princeton

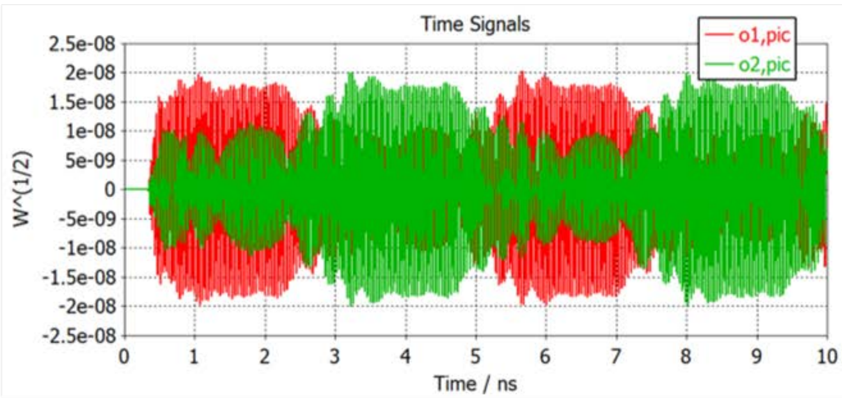




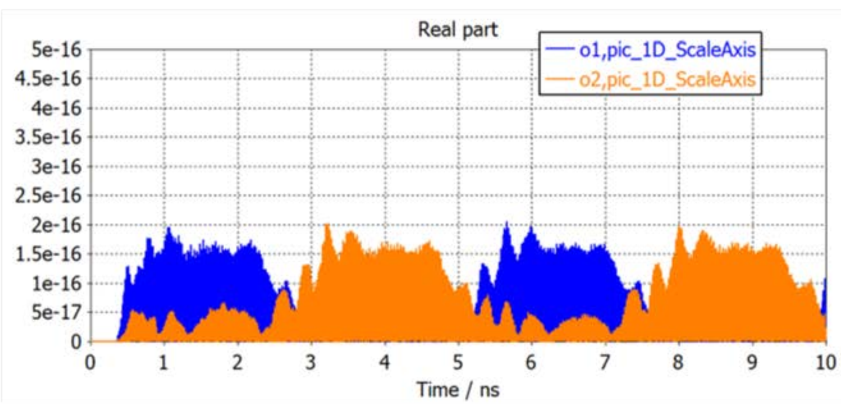
Research support from the John Templeton Foundation

RF Tracking

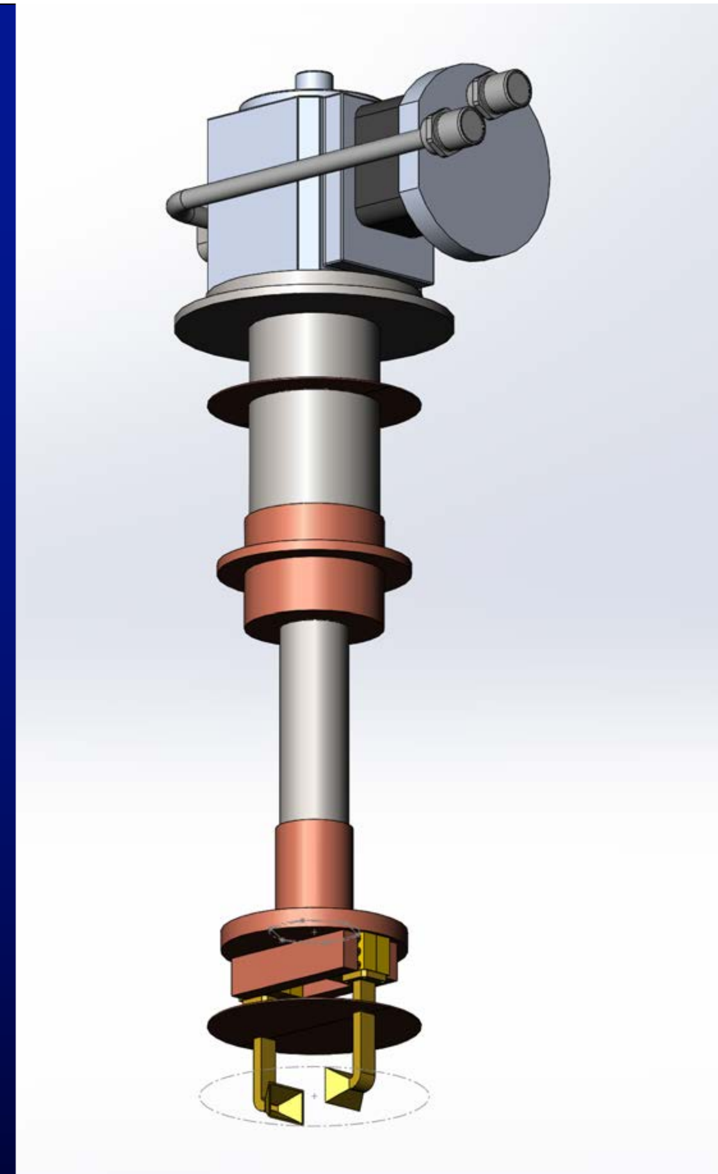
Time Series (~26 GHz)

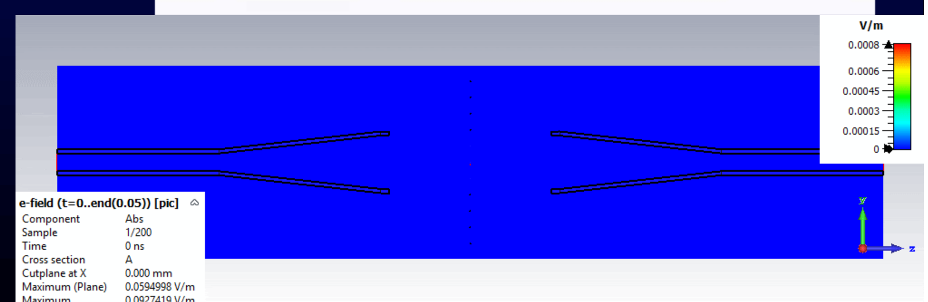


Power(~0.1 fW)



Right Left Right Left





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

Postdoc position on PTOLEMY R&D

We are looking for a postdoc to work on RF detection R&D for relic neutrino detection with PTOLEMY. The position – 2+1 years - will be at the University of Amsterdam and at the Dutch Institute for Subatomic Physics (Nikhef). At the national level we collaborate with the Dutch institute for applied research (TNO) and we have access to the Nikhef electronics and mechanical workshops. International work is in the context of the PTOLEMY collaboration.

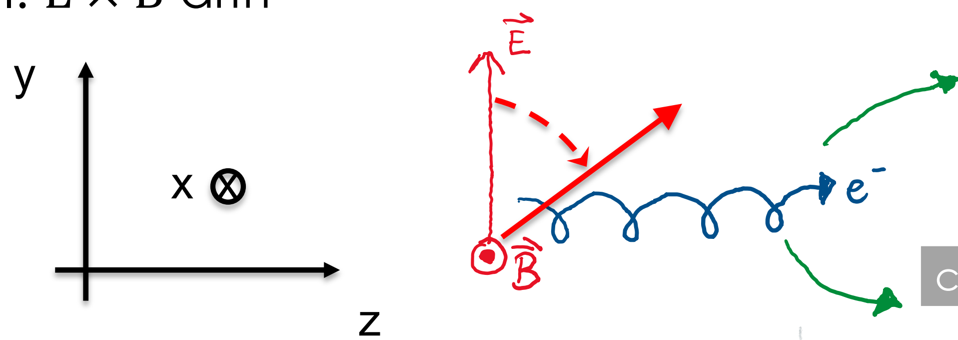
The ideal candidate would be a particle physicist with relevant experience in RF detection. The R&D work is aimed at obtaining an RF antenna, readout and DAQ system that can be applied in demonstrator setups that are currently under development at LNGS (Italy) and Princeton University.

Please contact prof. dr. Auke-Pieter Colijn (colijn@nikhef.nl) for more information on this position.

PTOLEMY Filter Concept

Auke Pieter Colijn (PATRAS 2019)

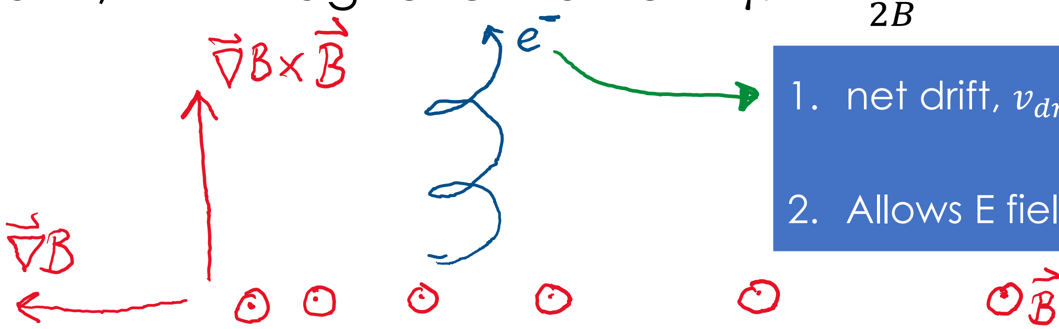
I: $\vec{E} \times \vec{B}$ drift



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

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

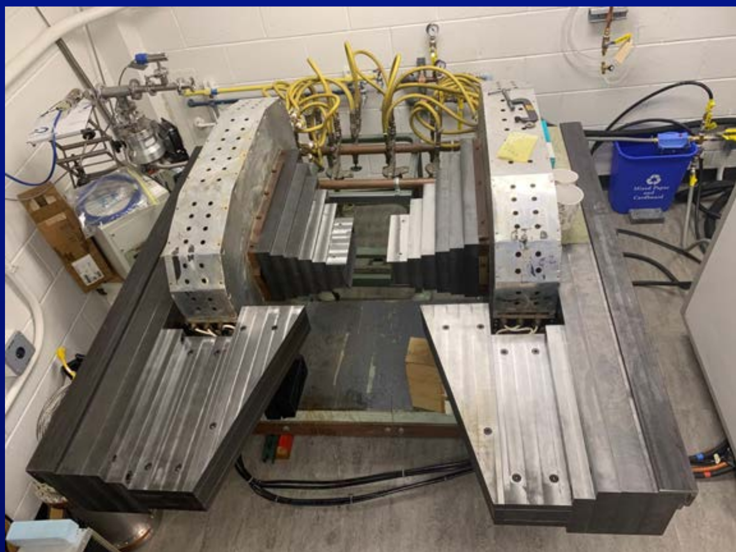
$$V_{\nabla B}(z)|_{x,y=0} = -\frac{\boldsymbol{\mu} \times \boldsymbol{\nabla}_\perp \boldsymbol{B(z)}}{qB(z)} = -\frac{\mu}{qB_x}\frac{dB_x}{dz}\hat{\boldsymbol{y}}$$

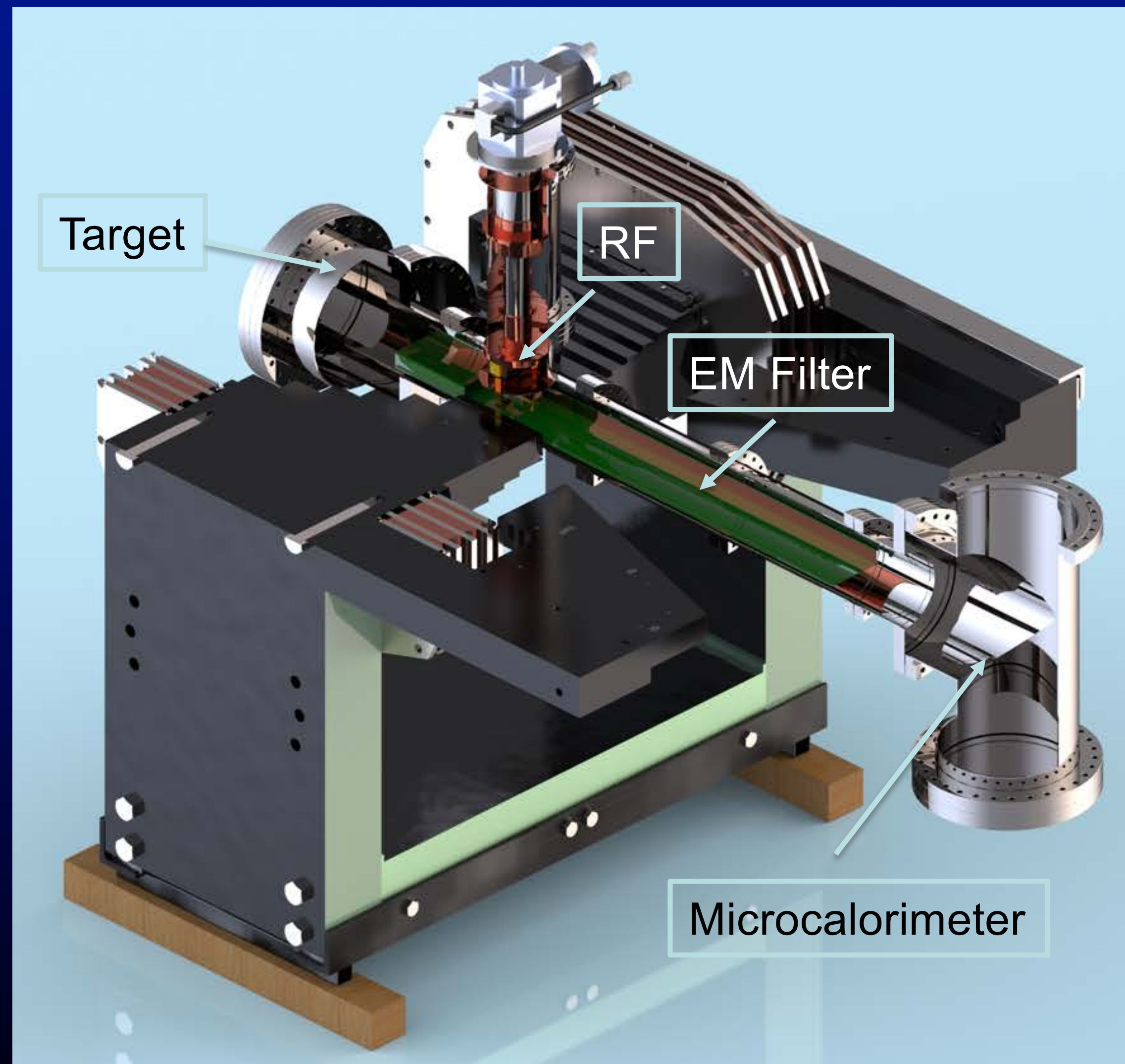
Enforce zero drift in y (rotate E):

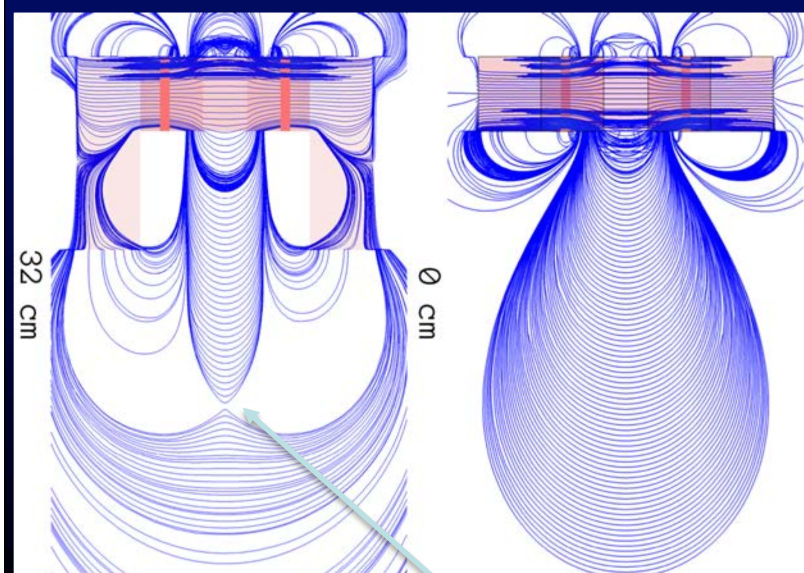
$$\xrightarrow{\text{yields}} \quad E_z(z)|_{y=0} = -\frac{\mu}{q}\frac{dB_x(z)}{dz}$$

Filter R&D Development Setup

Andi Tan (Princeton)





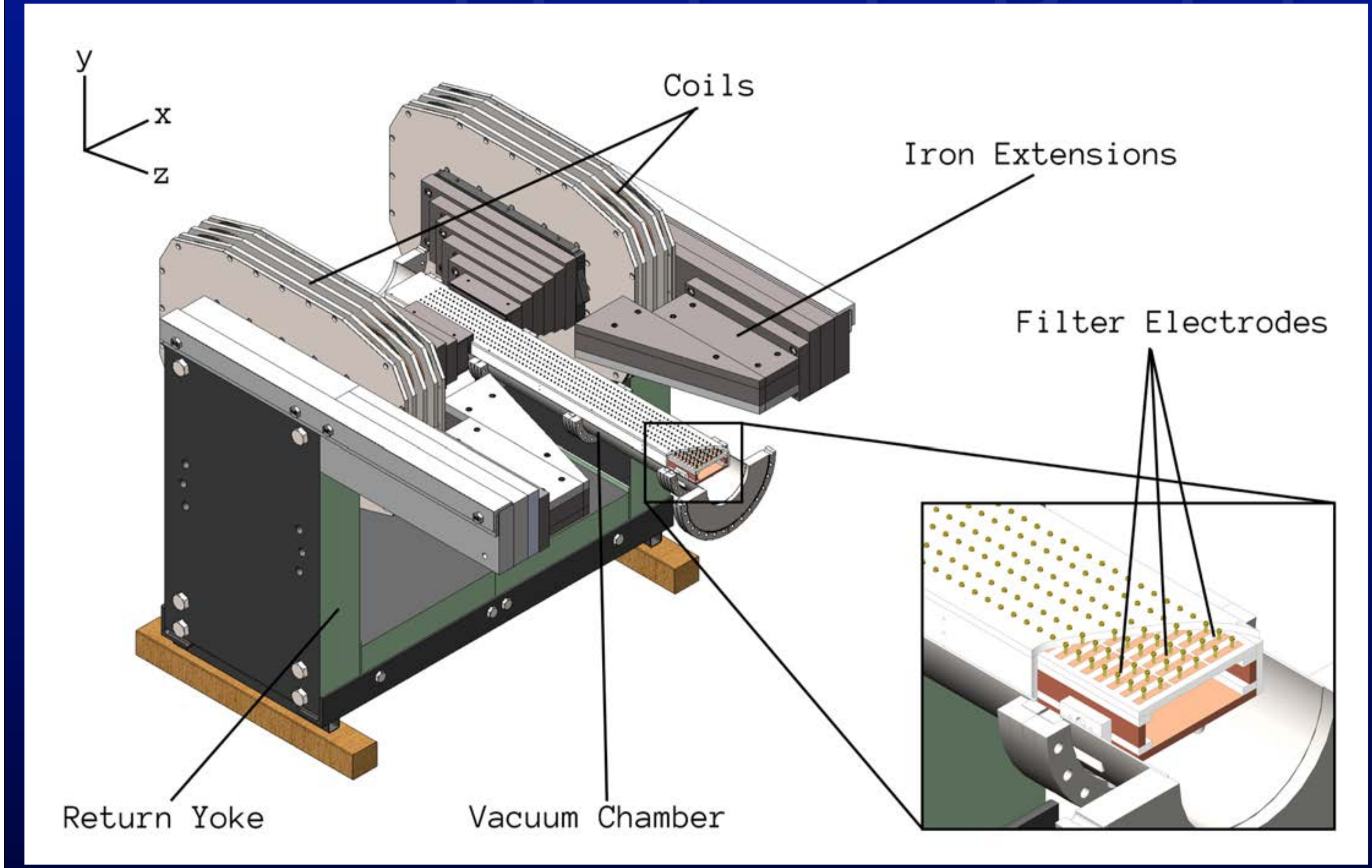


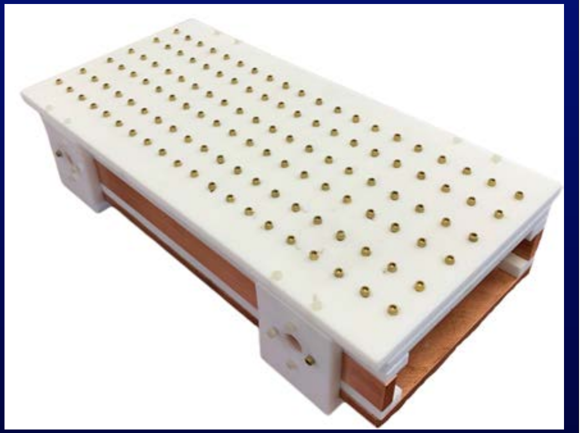
Wonyong Chung (Princeton)

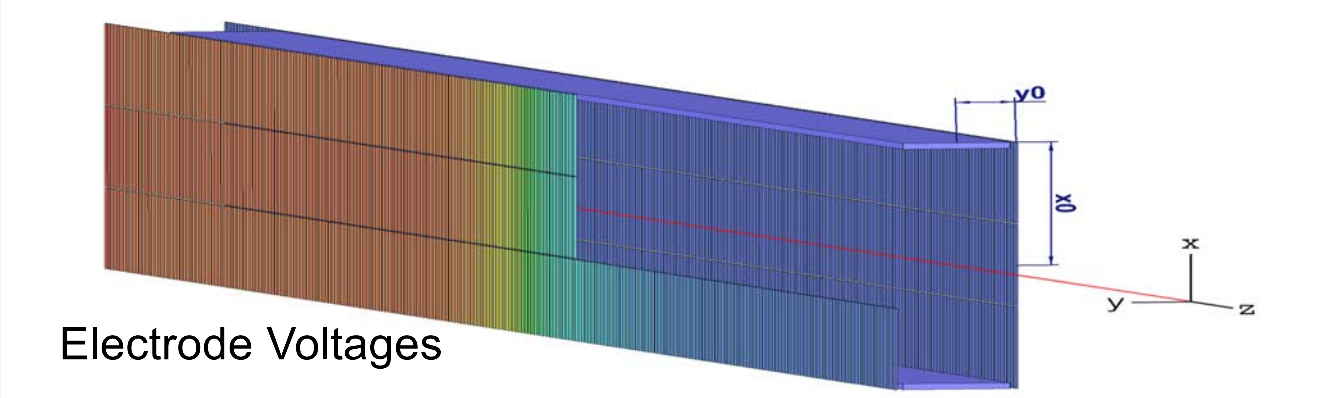
Zero field (location for TES microcalorimeter)

Electrode Prototype

Andi Tan (Princeton)







Electrode Voltages

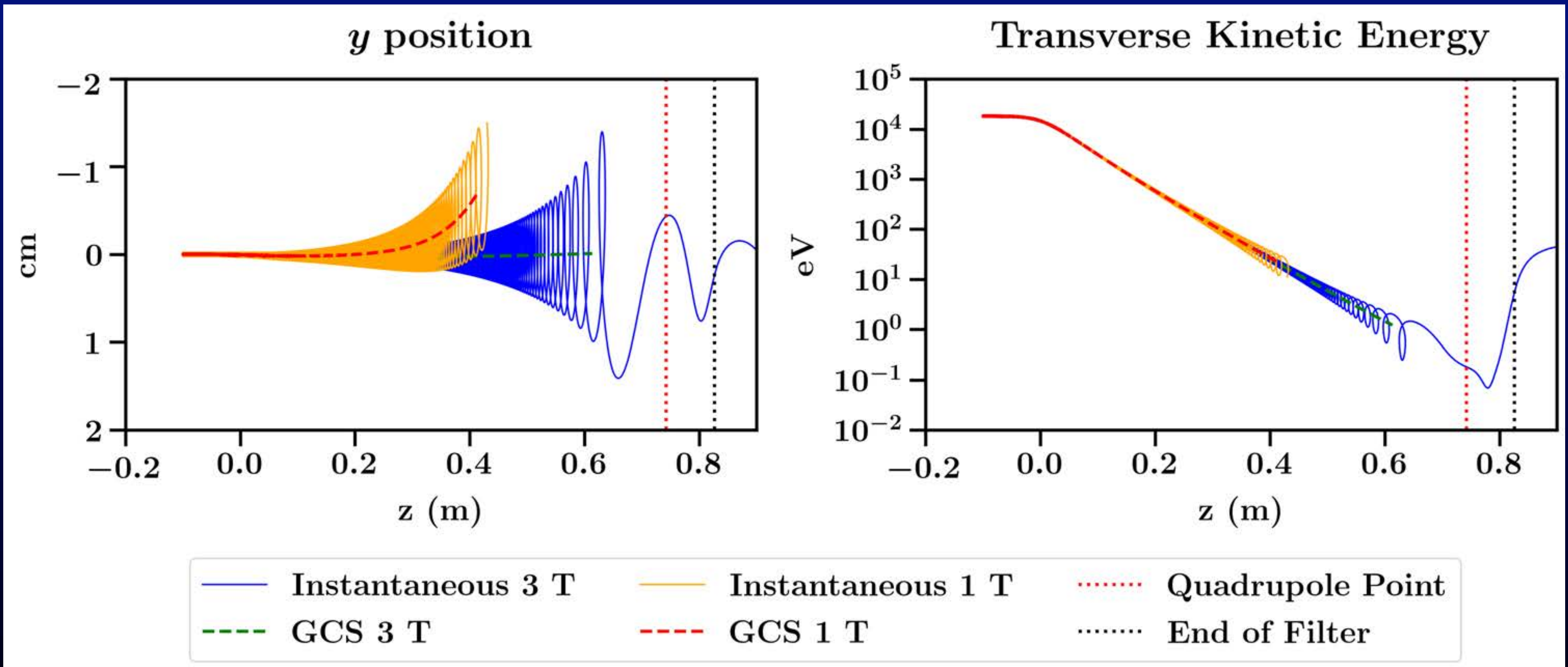
Wonyong Chung (Princeton)

Filter Performance

Improves as B^2 for a fixed filter dimension

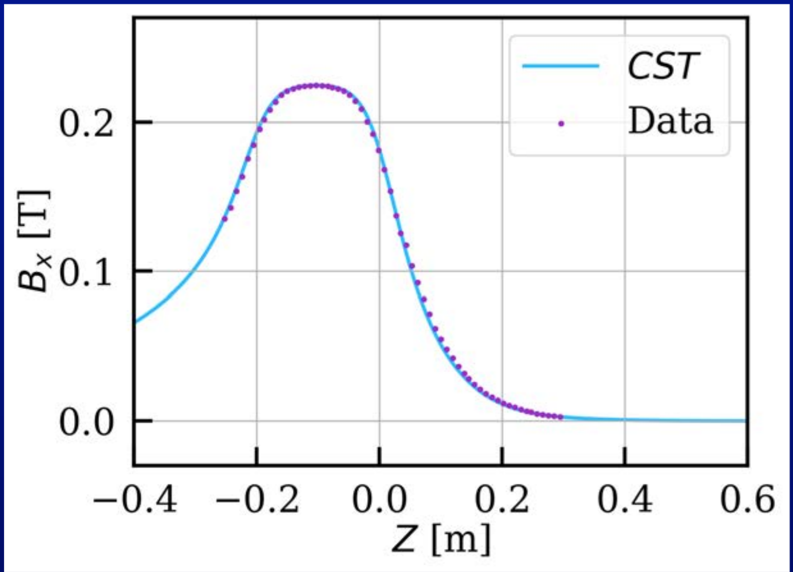
18.6 keV @ 1T → ~10eV (in 0.4m)

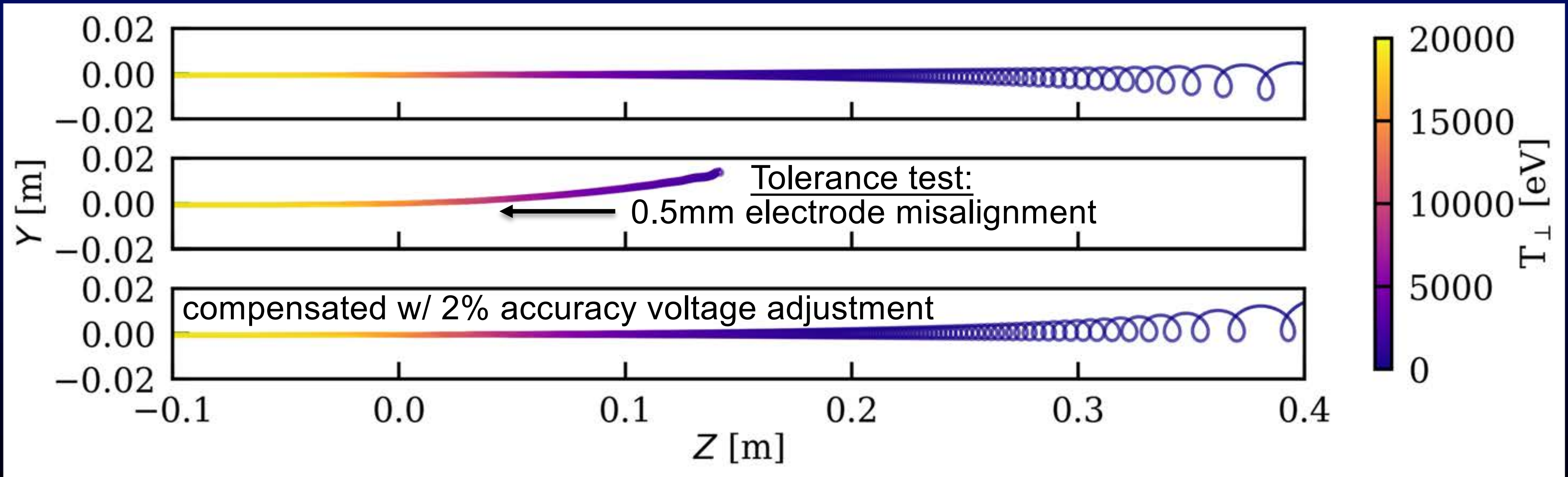
18.6 keV @ 3T → ~1eV (in 0.6m)



PTOLEMY Collaboration, https://arxiv.org/abs/2108.10388
"Low Field Optimization of the PTOLEMY Electromagnetic Filter" (in peer-review)

Achieves Required Magnetic Field Map



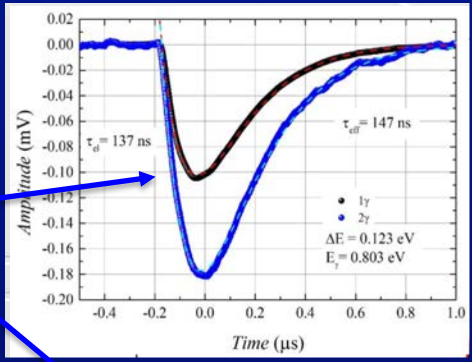


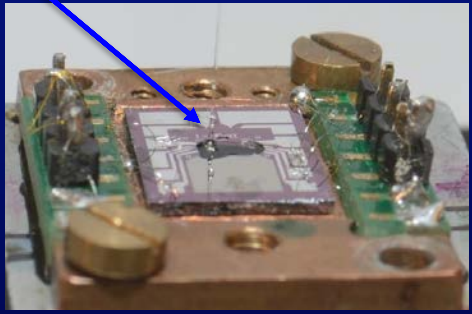
PTOLEMY Collaboration, https://arxiv.org/abs/2108.10388
"Low Field Optimization of the PTOLEMY Electromagnetic Filter" (in peer-review)

MicroCalorimeter R&D

$$E_e = e(V_{cal} - V_{target}) + E_{cal} + RF_{corr}$$

Now: 0.11 eV @ 0.8 eV and 106 mK and 10x10 μm^2
TiAuTi 90nm [Ti(45nm) Au(45nm)] (τ ~137 ns)





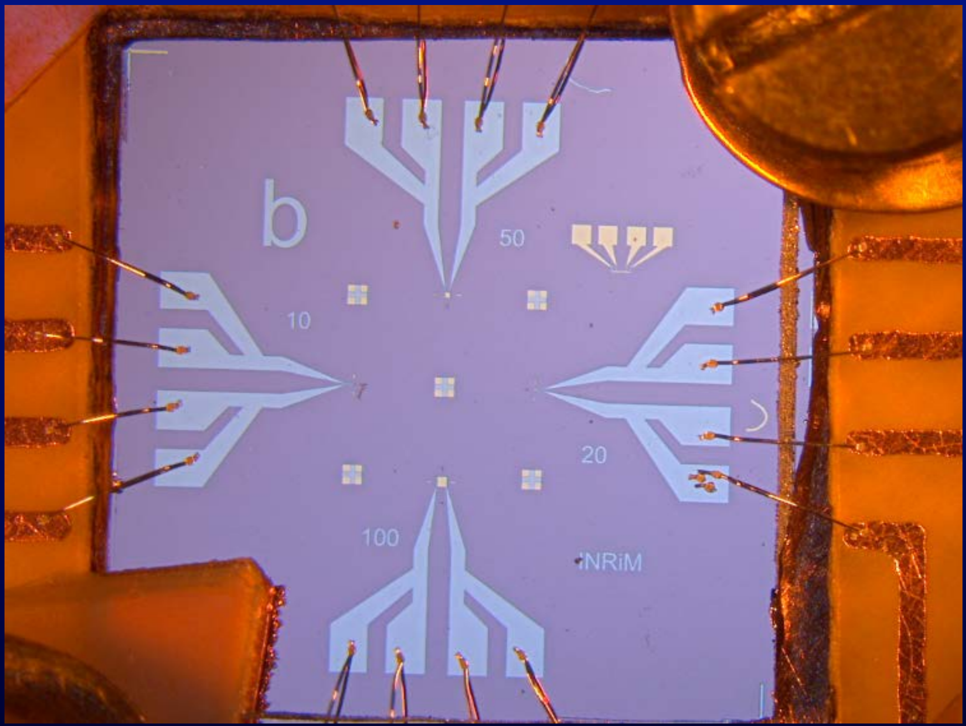
Design Goal (PTOLEMY): ΔE_{FWHM} = 0.05 eV @ 10 eV
translates to $\Delta E \propto E^{\alpha}$ $(\alpha \leq 1/3)$
ΔE_{FWHM} = 0.022 eV @ 0.8eV

$$\Delta E_{FWHM} \approx 2.36 \sqrt{4 k_B T_c^2 \frac{C_e}{\alpha} \sqrt{\frac{n}{2}}}$$

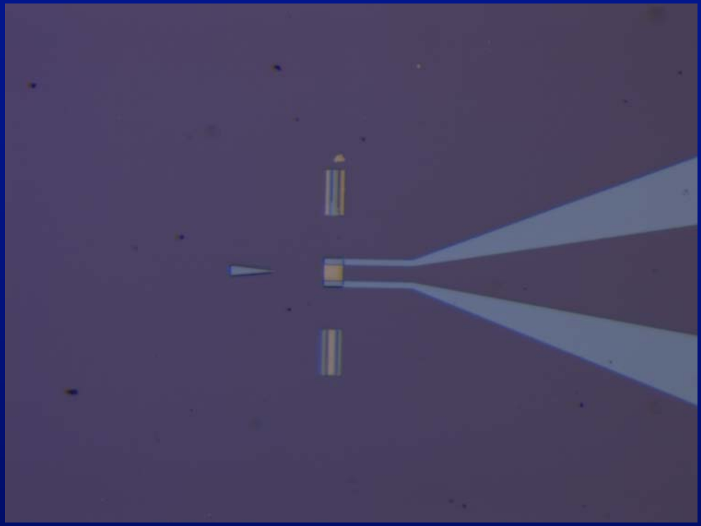
$\Delta E \propto T^{3/2}$ ⇨ T_c= 36 mK @10x10 μm^2 (t=90 nm)

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA · ROMA TRE UNIVERSITÀ DEGLI STUDI · INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

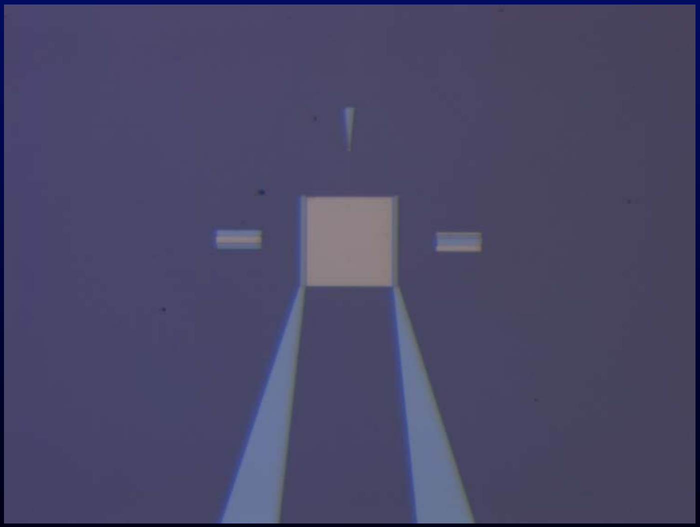
TES Layout 2021



20 μm x 20 μm



100 μm x 100 μm



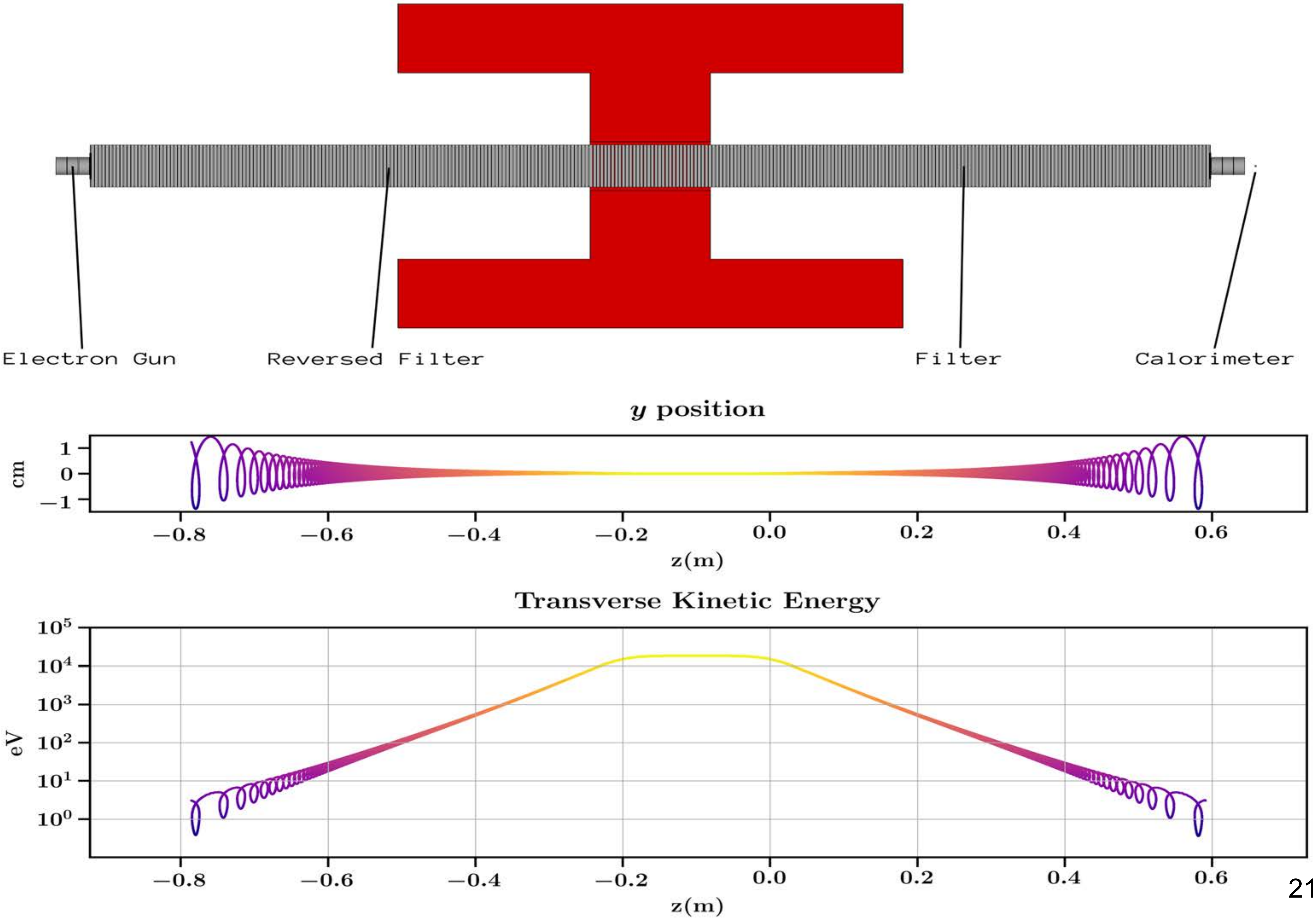
Mauro Rajteri, Eugenio Monticone and others, https://doi.org/10.1007/s10909-019-02271-x
“TES Microcalorimeter for PTOLEMY”, J. Low Temp. Phys. 199 (2020) 138-142.

End-to-End Evaluation

→ Use electrons
→ Well-known conversion line source at 17.83 keV
isotopically emitted from ^{83m}Kr (1.8 hour half-life)
following ^{83}Rb decay (86 day half-life)
→ Controlled source with known emission angle
Operate e-gun with the high B field region?

Time-reversal symmetry allows the filter to run
“in reverse” and act as an acceleration mechanism
→ The rear side of the magnet already has a reversed magnetic field relative to the electric fields

Reverse Filter



Next Steps for PTOLEMY

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/

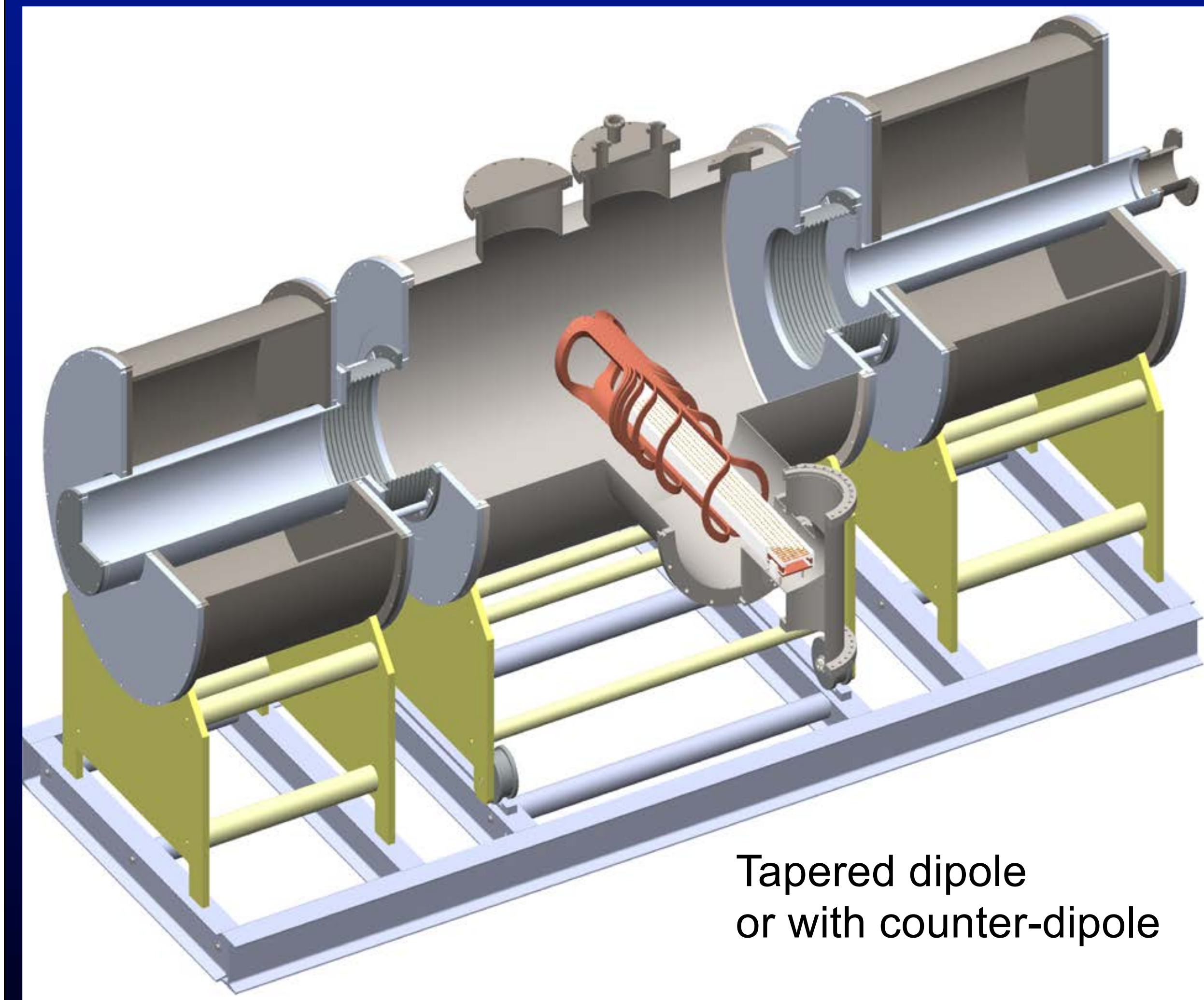
Produce filter and target with a scalable technology

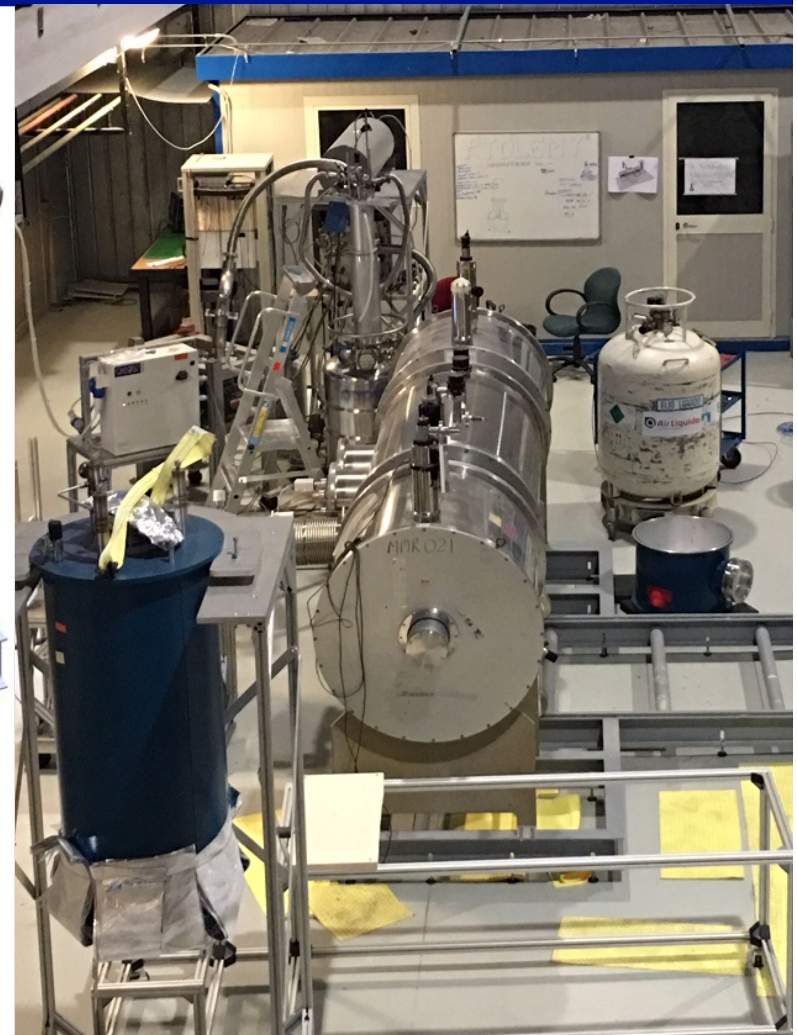
→ Design/test a superconducting coil filter magnet

→ Design/test a Large-Area target geometry

→ Integrate with end-to-end tracking simulations

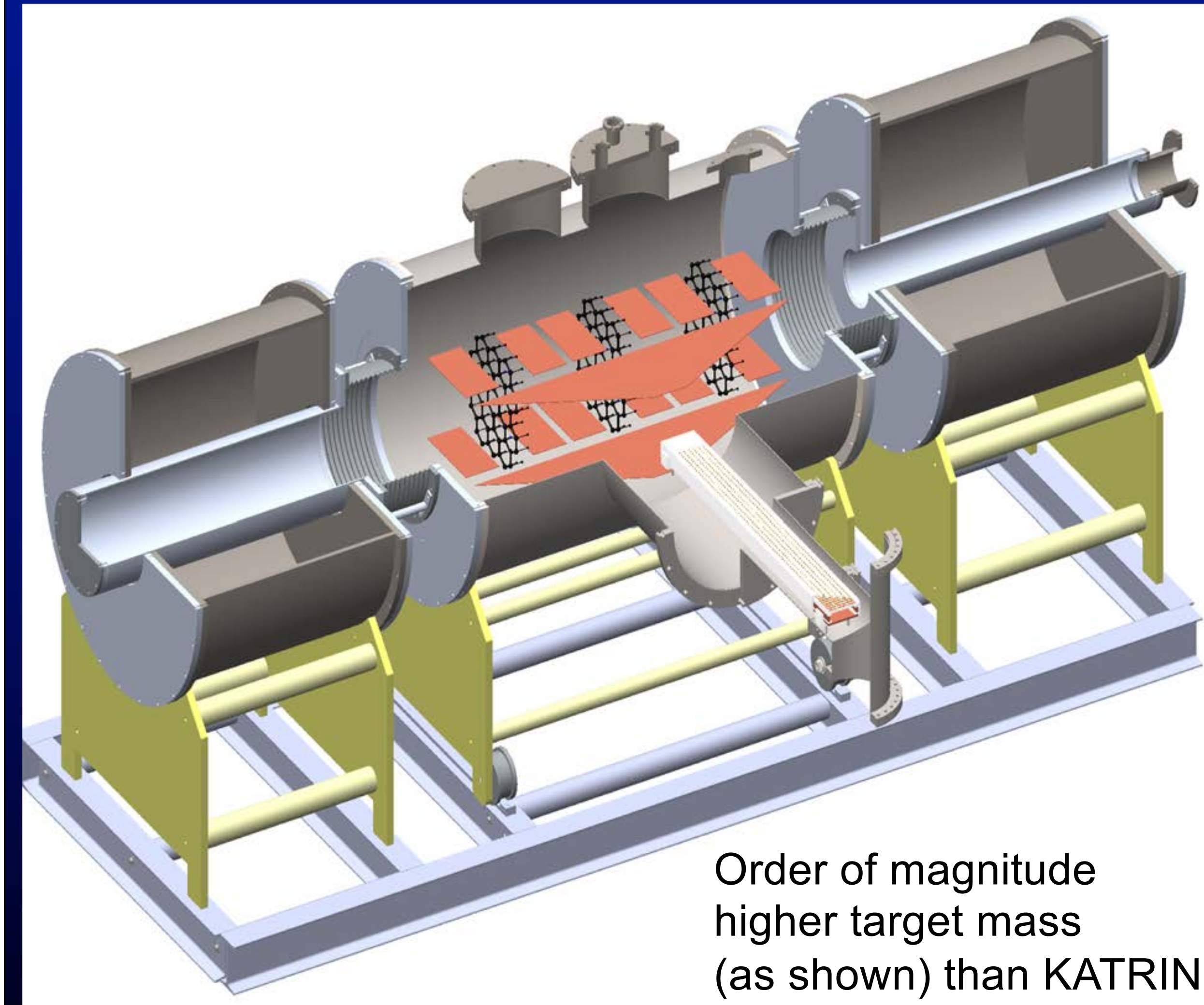
Superconducting Coil Design

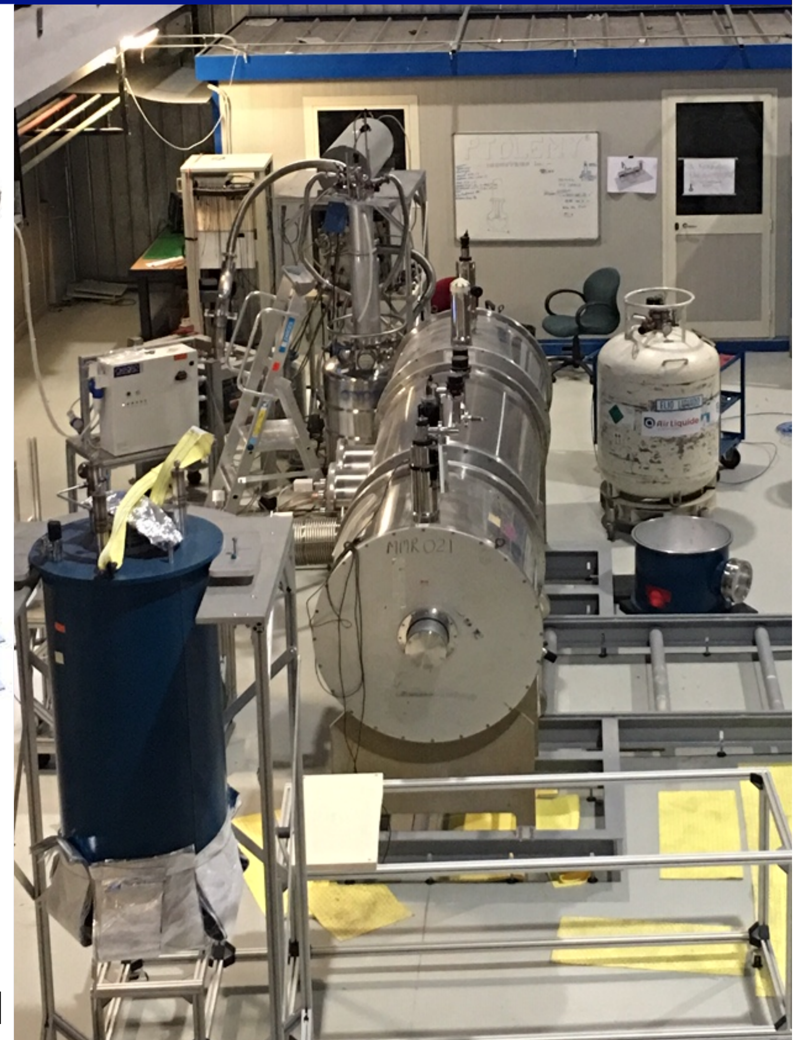




Integrate into existing dual-SC magnet setup @ LNGS

Large Area Target Design





Target Area and Quantum Properties are final frontiers for PTOLEMY

Recent Papers on Quantum-Induced Broadening: https://arxiv.org/abs/2101.10069, https://arxiv.org/abs/2108.03695

Project Timeline

Program of Validating Measurement Arm (3-year program)

in parallel with

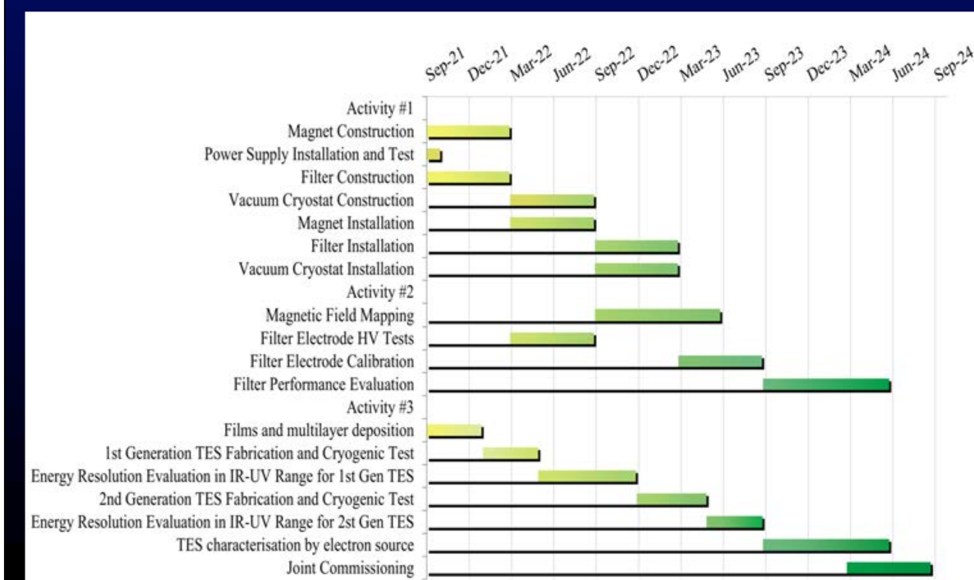
Design/test of Superconducting Magnet/Large-Area Target

Starting in 2021, expect full SC magnet design, fabrication and commissioning through summer 2024

Target physics studies expected through 2021-2023 and fabrication/testing 2023-2025 w/ interface to filter in 2025

Physics program possible starting from ~2025-2026+

Iron Magnet and Filter @ LNGS w/ INRiM TES



Physics Goals:

- Establish experimental baseline for first CνB Experiment

<u>Based on validation of:</u>

Measurement arm precision

Quantum smearing predictions

Scalability of technology

→ Leverage prototype system to explore new physics

PTOLEMY Contacts

R&D_PTOLEMY
Marcello Messina (LNGS)
Chris Tully (Princeton)

Theory panel
Gianpiero Mangano
Uni Napoli

ESC/GRT
Gianluca Cavoto
Uni. Sapienza
and INFN Roma

Electron Gun
Alessandro Ruocco
Uni. RomaTre
and INFN RomaTre

Graphene engineering
Fernando Calle
Uni. Poli.Madrid
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RFA
Auke-Peter Colijn
NIKHEF

RF readout
Alfredo Cocco
INFN LNGS

RF CST simulation
Luca Ficcadenti
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RF front-end Electronics and antenna design
Auke-Peter Colijn
NIKHEF

EMF
Chris Tully
Uni. Princeton
USA

HV electrodes
Nicola Rossi
LNGS INFN

EM Filter Deployment
Marcello Messina
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MCA
Mauro Rajteri
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Multi TES readout
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High Res. TES
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TES Film development
Flavio Gatti
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LNGS support:
electronic workshop,
mechanical workshop,
cryogenic service,
chemical service,
radio-protection service

External Institutions
(Contacts)

TLK
Magnus Schlösser
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JTF & Simons
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ADDITIONAL SLIDES