Cosmic Neutrino Background: Experimental Program to Detect Relic Neutrinos from the Big Bang

Chris Tully

Princeton University

CNB White Paper Kick-Off Meeting

Snowmass 2021

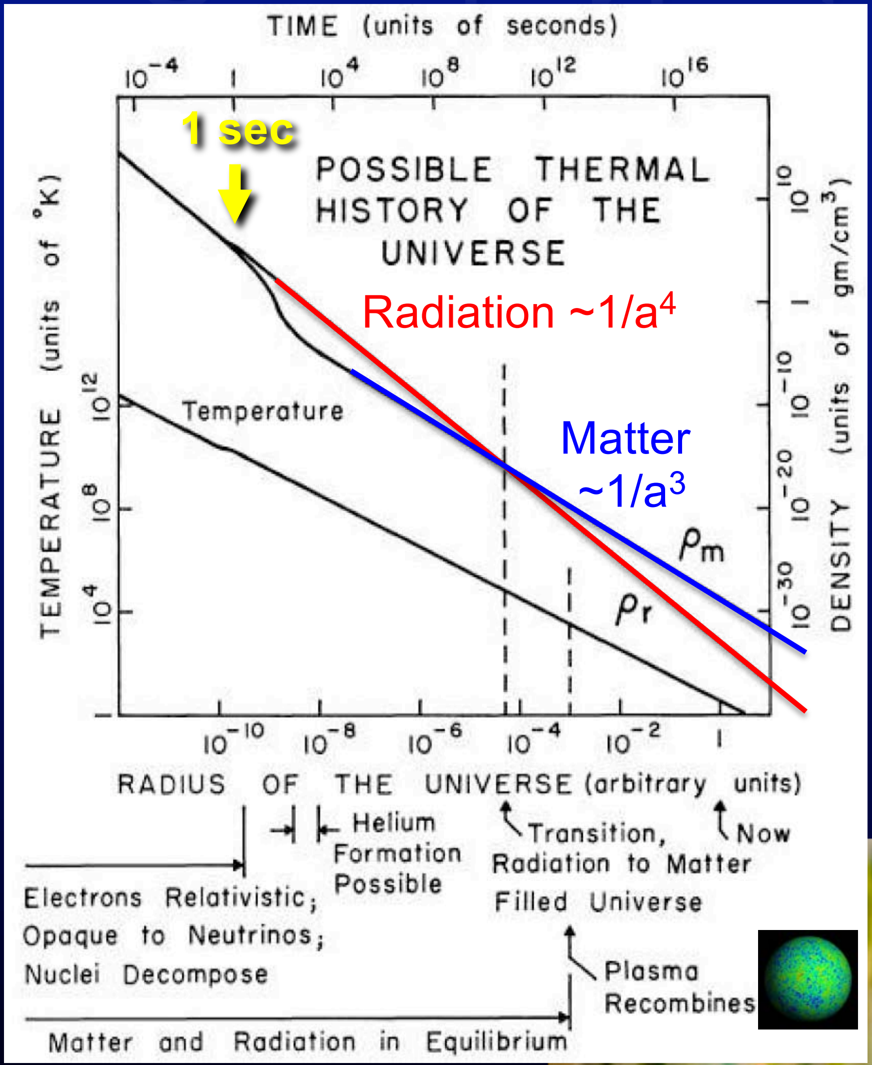
December 10, 2021

Overview

- (Very) Brief Motivation and Theory
- (Very) Brief Summary of Experimental Approaches
  - Experimental Challenges for Neutrino Capture on β-decay nuclei (NCB)
- Status of PTOLEMY (NCB)
  - TES Microcalorimeter
  - Transverse Drift filter + Precision HV
  - RF tracking
  - Target
  - Timeline
- CNB White Paper draft

PTOLEMY papers: Over 100+ citations and growing

Cosmic Neutrino Background



Number density:

$n_\nu = 112/\text{cm}^3$

Temperature:

$T_\nu \sim 1.95\text{K}$

Time of decoupling:

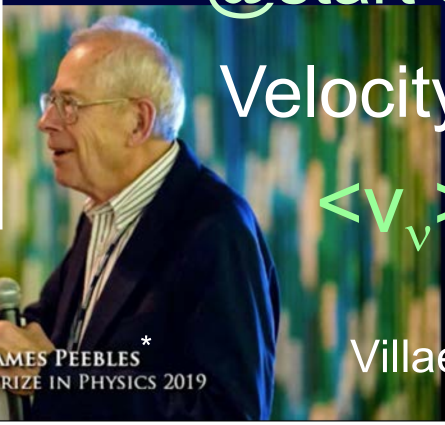
$t_\nu \sim 1$ second

~50% of the Total Energy Density of the Universe

neutron/proton ratio @start of nucleosynthesis

Velocity distribution:

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

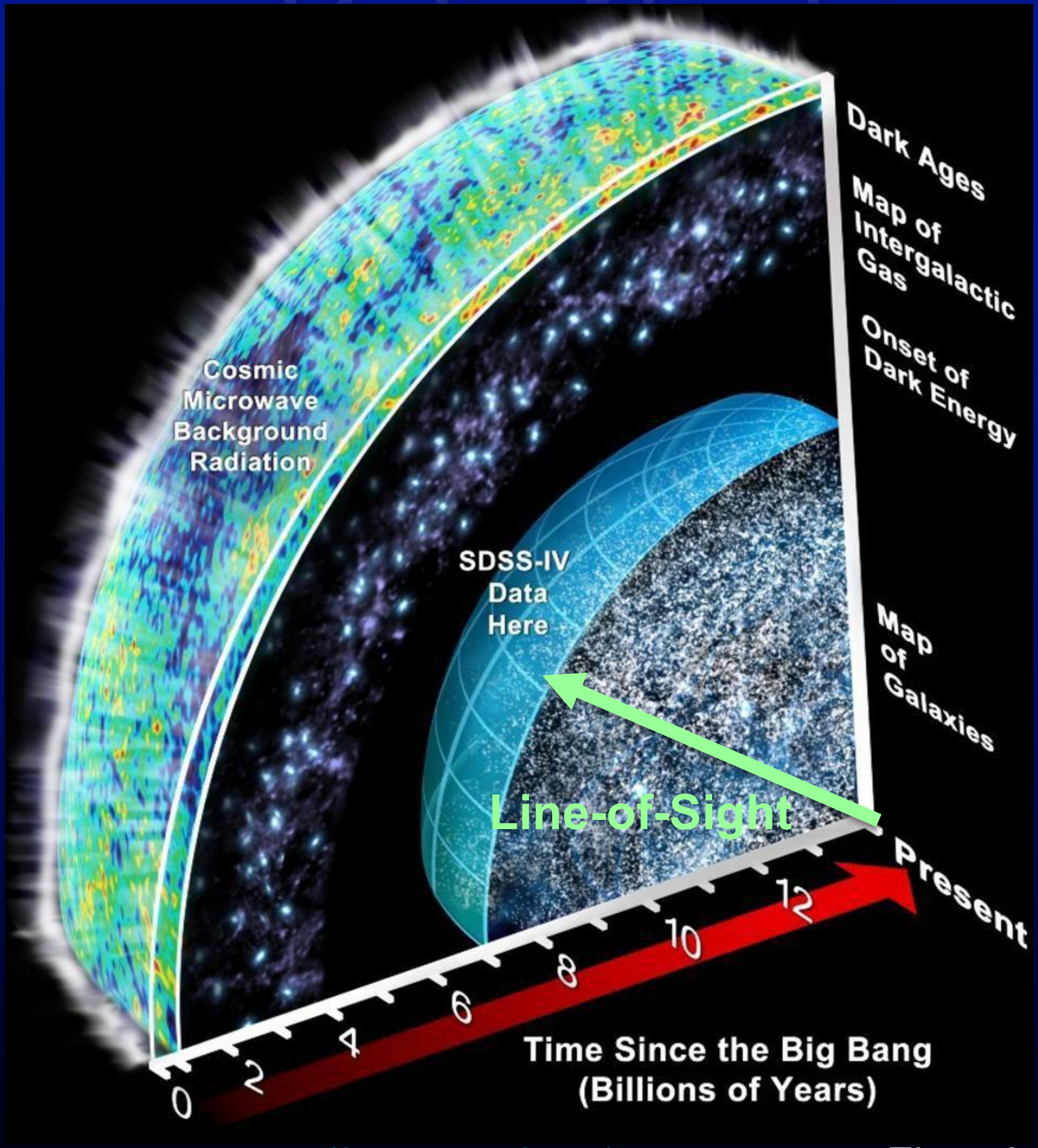


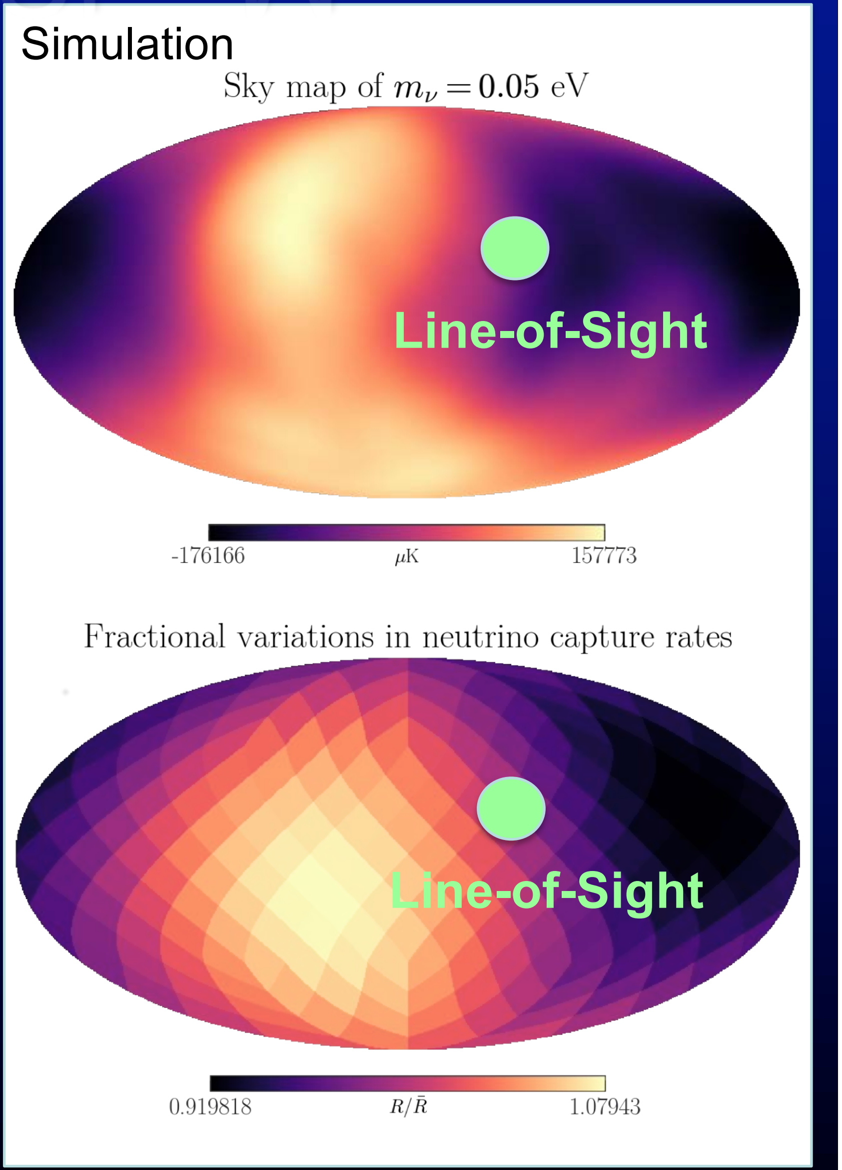
Dicke, Peebles*, Roll, Wilkinson (1965)

Cosmology's Century (2020)

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

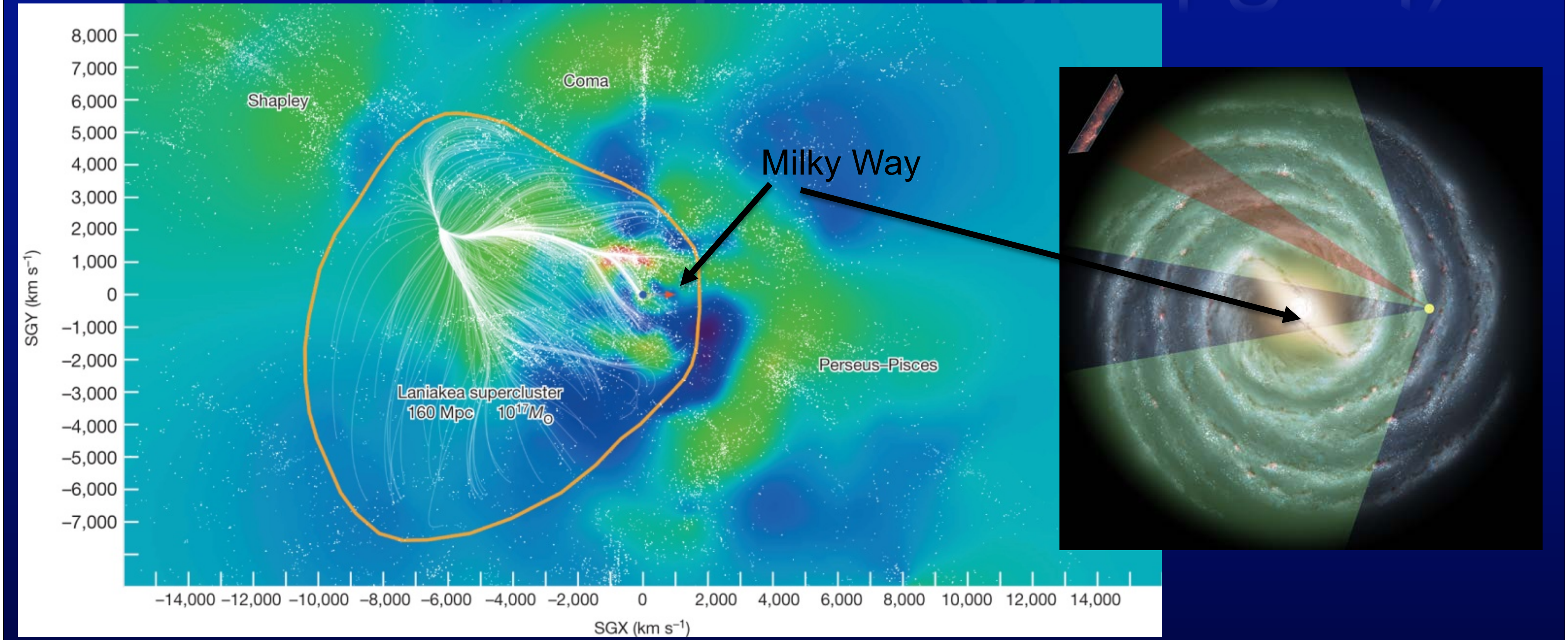
Relic Neutrino Sky Map





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

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

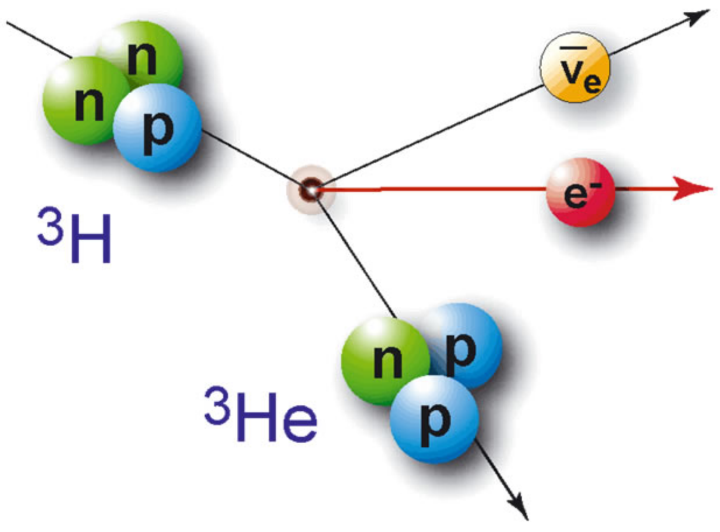
https://www.nytimes.com/2020/07/10/science/astronomy-galaxies-attractor-universe.html

(Very) Brief Overview of Direct Detection Methods

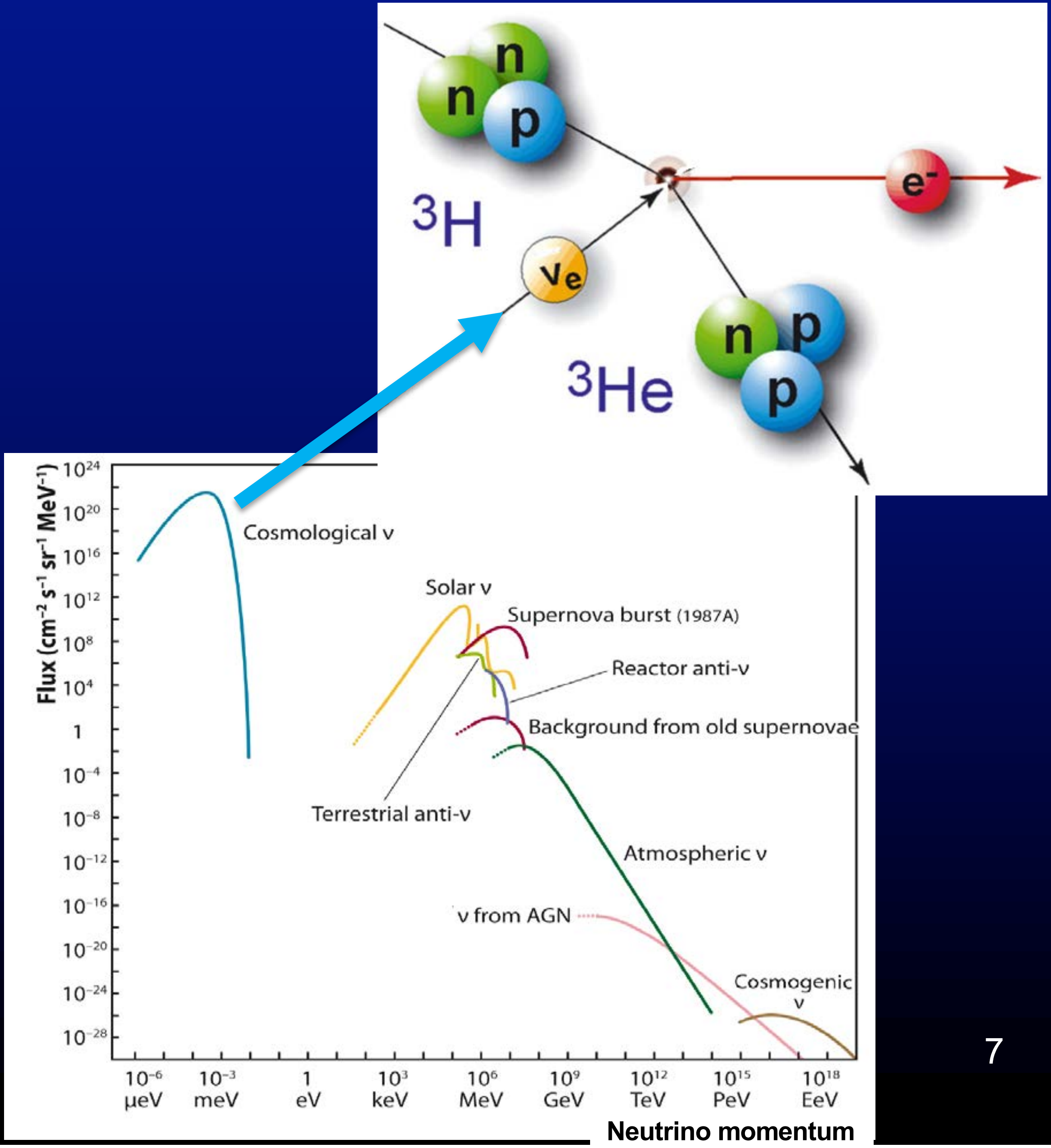
REVIEW article: "Looking for cosmic neutrino background" by Chiaki Yanagisawa, Front. Phys., 10 June 2014 https://doi.org/10.3389/fphy.2014.00030

- Coherent force effects (~2mm de Broglie λ) (too weak)
  - Refraction/Total Reflection (cancels for uniform density – revisit differential component with anisotropy?)
  - Polarized targets w/ large lepton number violation (non-SM ?)
- Incoherent neutrino wind effects (10^{10} smaller than LIGO)
  - Mechanical drag (too small)
  - Decoherence effects on nuclear spin systems (only initial thoughts so far?)
- CNB Transparency of Ultra-High Energy Neutrinos
  - $\nu\nu \rightarrow Z$ resonant scattering $M_Z \sim \sqrt{2mE}$, (10^7 higher energy than current record)
- Scattering off high-energy beams (hard to control)
  - Driving transitions (too few and mixed into beam)
- Pauli Blocking of β-decay endpoint (too few)
- Pauli Blocking of γ+Z (RENP) radiative atomic transition w/ superradiance (too few)
- Neutrino capture on β-decay nuclei (NCB) (close, off by ~1-2 orders of magnitude)
  - Increasing S/N with angular correlations, time modulations, … (?)

Neutrino capture on β-decay nuclei



β-decay nuclei
(Tritium)



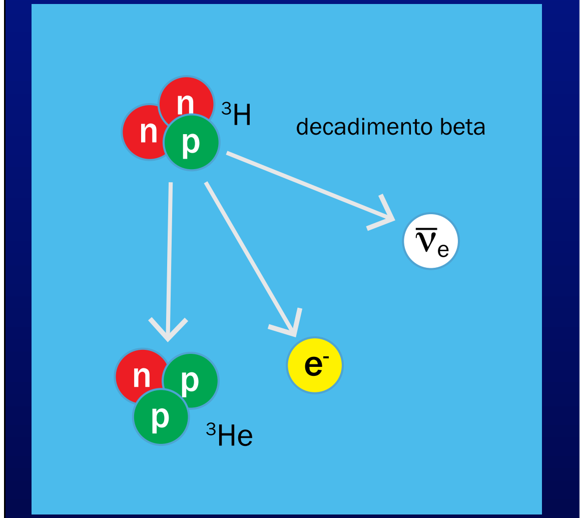
Neutrino momentum ~ 0.17 meV

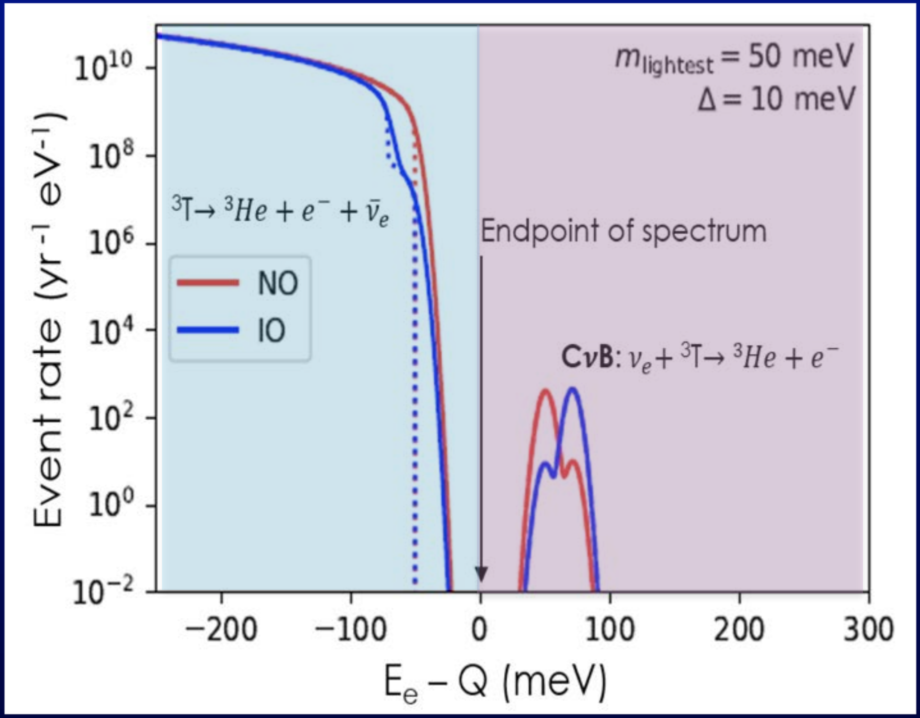
For m_ν = 50 meV,
KE = $p^2/2m$
= 0.17 meV (0.17 meV/100 meV)
= 0.3 μeV

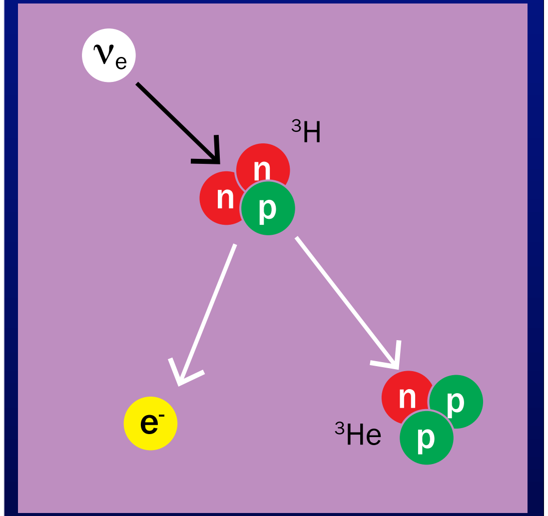
Ultra-Cold!

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?

Electron flavor expected with

m > ~50meV

from **neutrino oscillations**

Gap (2m) constrained to

m < ~200meV

from **precision cosmology**

CνB Detection Requires:

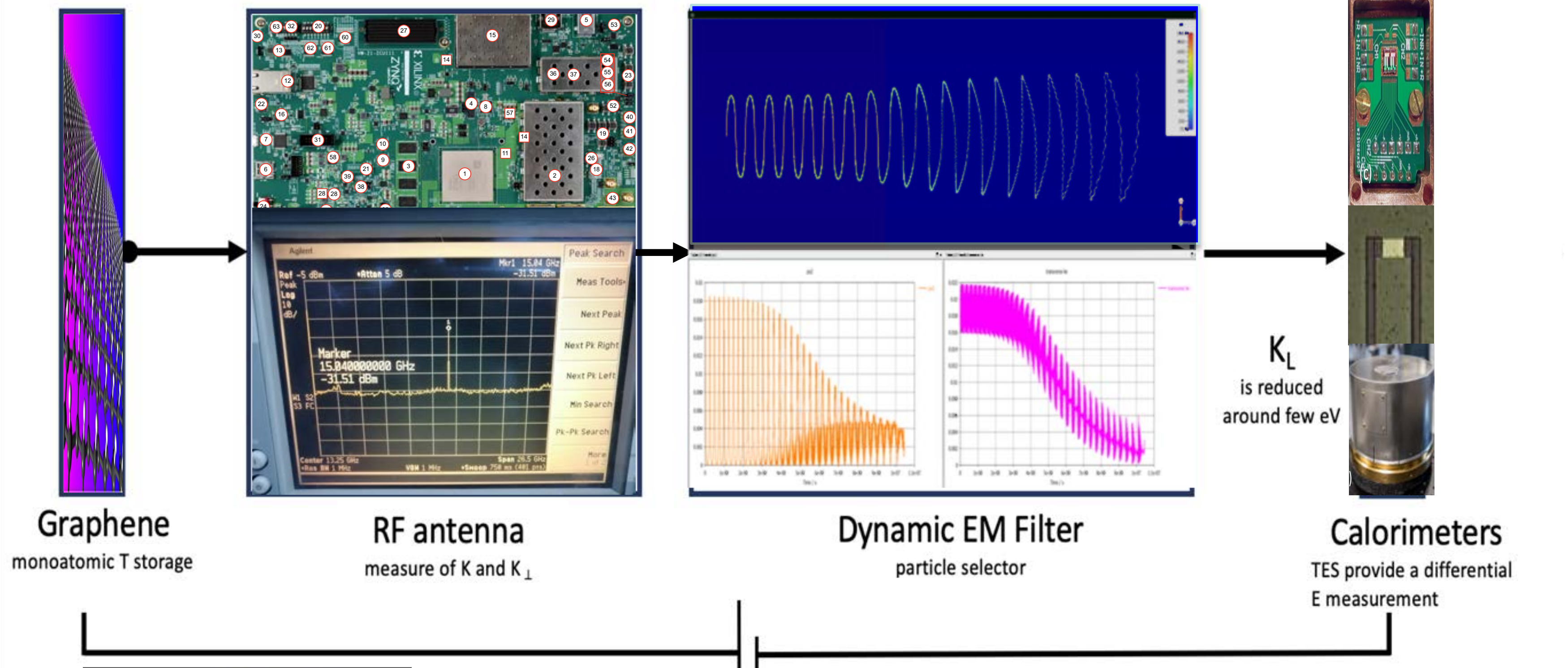
few x 10^{-6} energy resolution set by m_ν

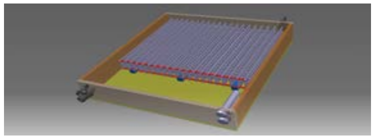
KATRIN ~ 10^{-4} (current limitation)

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

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 SPAIN
- **RFA** Auke-Peter Colijn, NIKHEF
  - **RF readout** Alfredo Cocco, INFN LNGS
  - **RF CST simulation** Luca Ficcadenti, INFN Roma
  - **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, INFN LNGS
- **MCA** Mauro Rajteri, INRiM Torino
  - **Multi TES readout** Angelo Nucciotti, Uni. Bicocca and INFN MiB
  - **High Res. TES** Mauro Rajteri, INRiM Torino
  - **TES Film development** Flavio Gatti, Uni Genova and INFN Genova

LNGS support:
electronic workshop,
mechanical workshop,
cryogenic service,
chemical service,
radio-protection service

External Institutions
(Contacts)

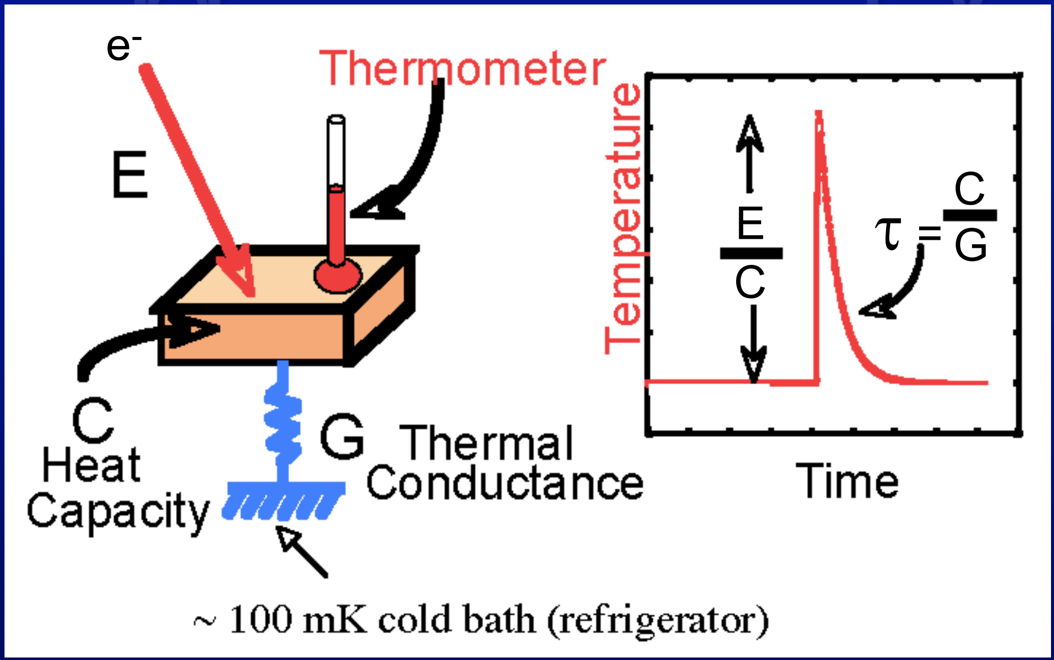
TLK
Magnus Schlösser
Karlsruhe Germany

JTF & Simons
Chris Tully
Princeton USA

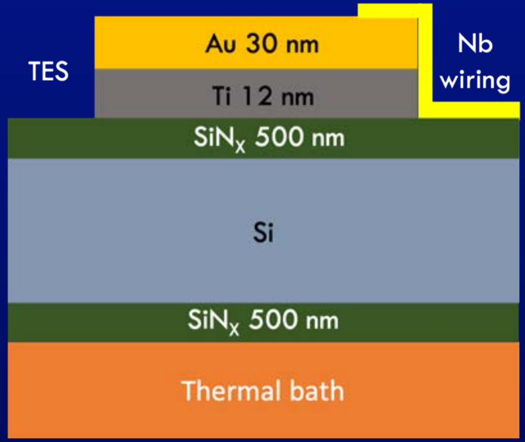
DRC/NWO
Auke-Peter Colijn
NIKHEF

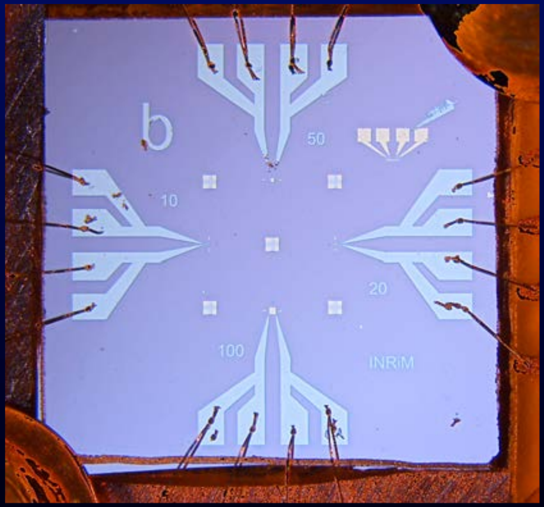
INFN
Marcello Messina
LNGS

Measurement Arm: μCal



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





50x50 μm

10x10 μm

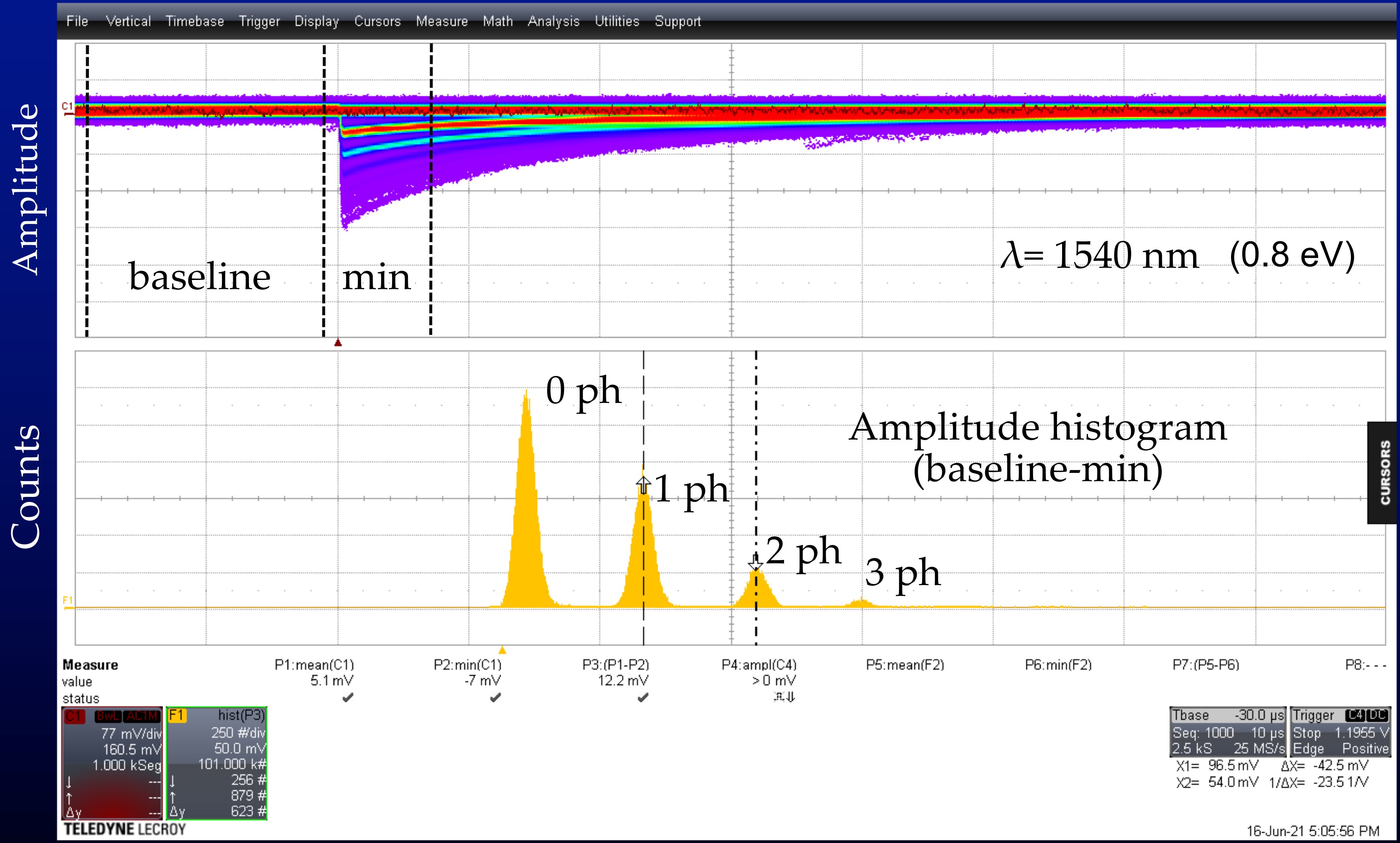
20x20 μm

100x100 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.

Single IR Counting

INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA



```
Measure   P1:mean(C1)   P2:min(C1)   P3:(P1-P2)   P4:ampl(C4)   P5:mean(F2)   P6:min(F2)   P7:(P5-P6)   P8:- - -
value          5.1 mV        -7 mV      12.2 mV        > 0 mV
status              ✔            ✔            ✔           ⇓

C1  BwL ACTM       F1      hist(P3)
     77 mV/div            250 #/div
    160.5 mV               50.0 mV
   1.000 kSeg           101.000 k#
↓          ---     ↓          256 #
↑          ---     ↑          879 #
Δy         ---     Δy         623 #

Tbase       -30.0 µs   Trigger      C4 DC
Seq: 1000      10 µs   Stop      1.1955 V
2.5 kS       25 MS/s   Edge      Positive
 X1=  96.5 mV       ΔX=  -42.5 mV
 X2=  54.0 mV     1/ΔX=  -23.5 1/V

16-Jun-21 5:05:56 PM
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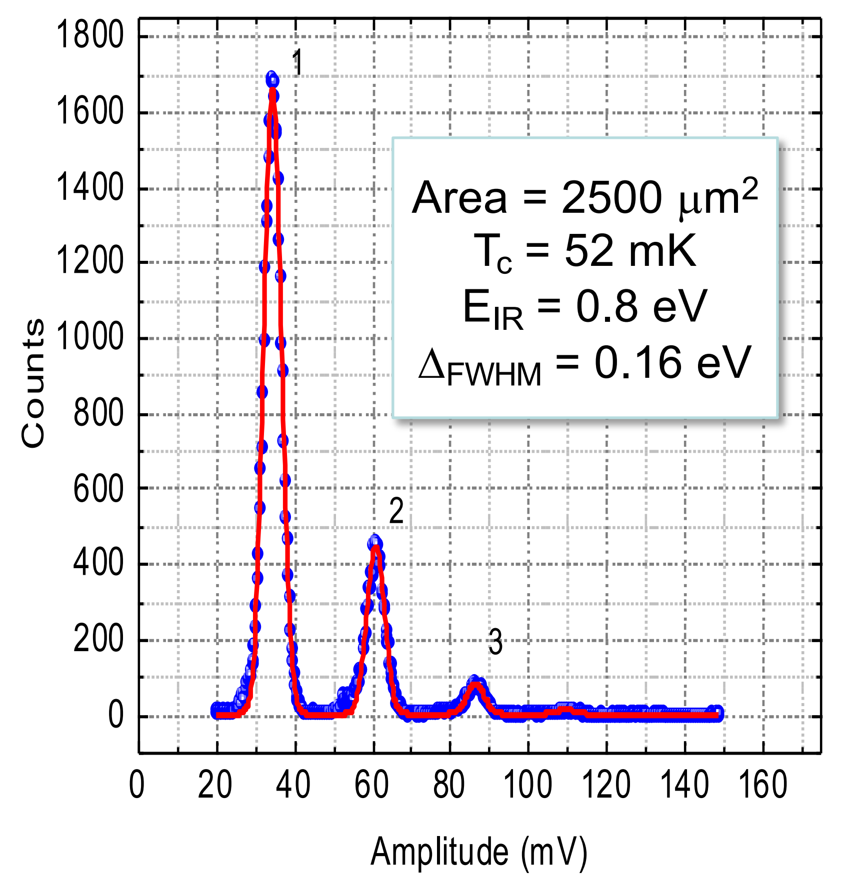
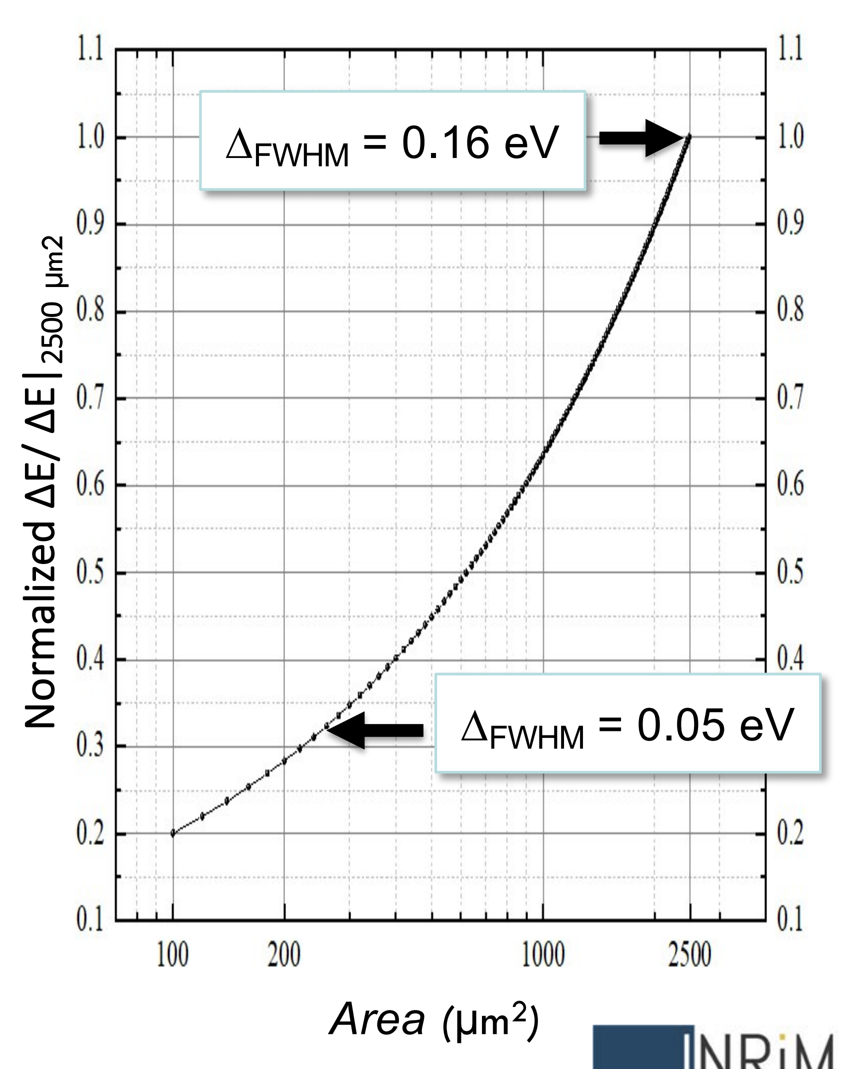
C. Pepe, E. Monticone, M. Rajteri

Energy Resolution: $\Delta_{FWHM} \sim m_\nu$



Area = 2500 μm^2
T_c = 52 mK
E_{IR} = 0.8 eV
Δ_{FWHM} = 0.16 eV



Δ_{FWHM} = 0.16 eV

Δ_{FWHM} = 0.05 eV

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Resolution of ~ m_ν :

Area ~ 15 μm x 15 μm

→ Demonstrate with electrons

C. Pepe, E. Monticone, M. Rajteri

Electromagnetic Filters

MAC-E filter

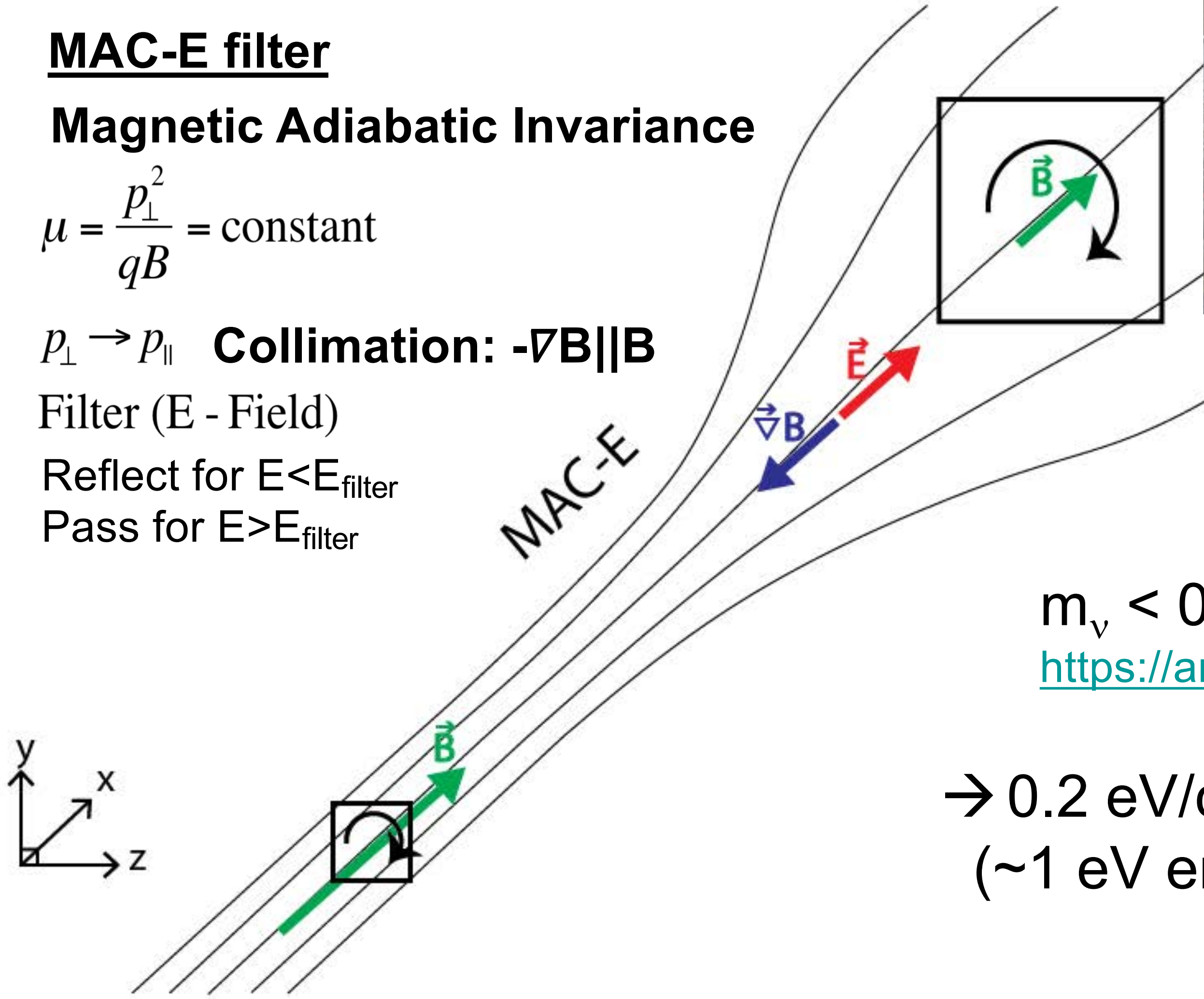
Magnetic Adiabatic Invariance

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

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

Filter (E - Field)

Reflect for $E < E_{\text{filter}}$
Pass for $E > E_{\text{filter}}$



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

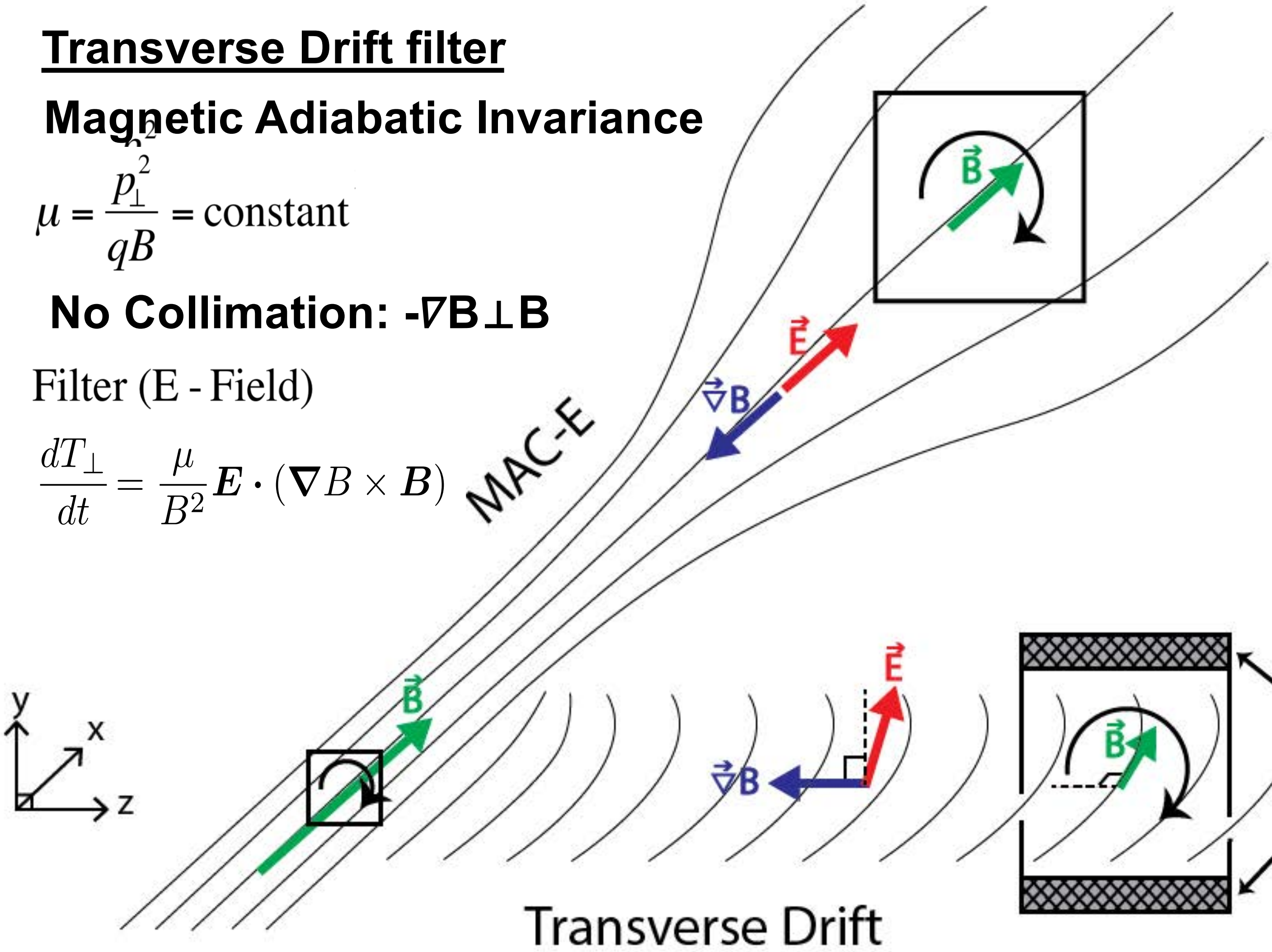
Magnetic Adiabatic Invariance

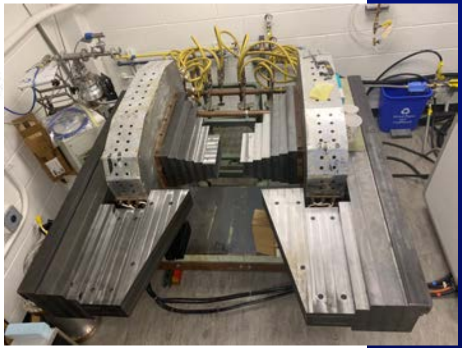
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

No Collimation: -∇B⊥B

Filter (E - Field)

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





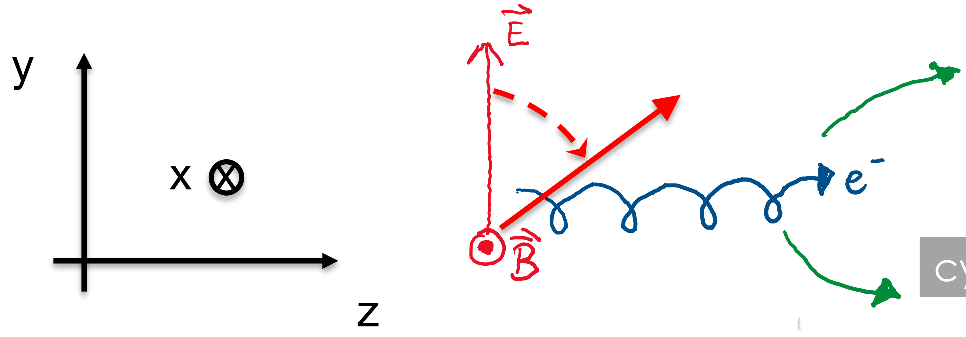
PTOLEMY

~1m^3

PTOLEMY Filter Concept

Auke Pieter Colijn (PATRAS 2019)

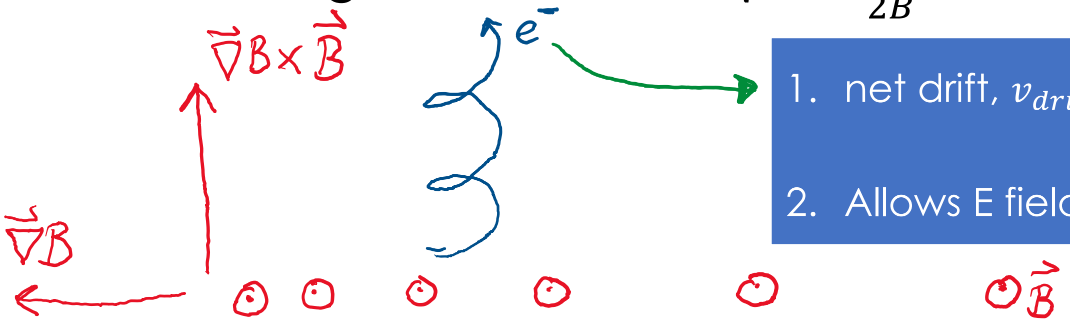
I: $\vec{E}\times\vec{B}$ drift



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

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

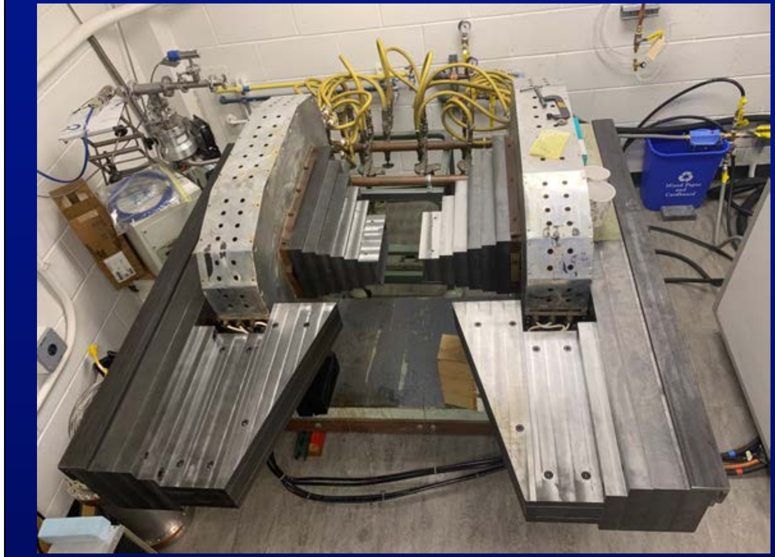
$$V_{\nabla B}(z)|_{x,y=0} = -\frac{\boldsymbol{\mu}\times\boldsymbol{\nabla}_\perp\boldsymbol{B}(z)}{qB(z)} = -\frac{\mu}{qB_x}\frac{dB_x}{dz}\hat{\boldsymbol{y}}$$

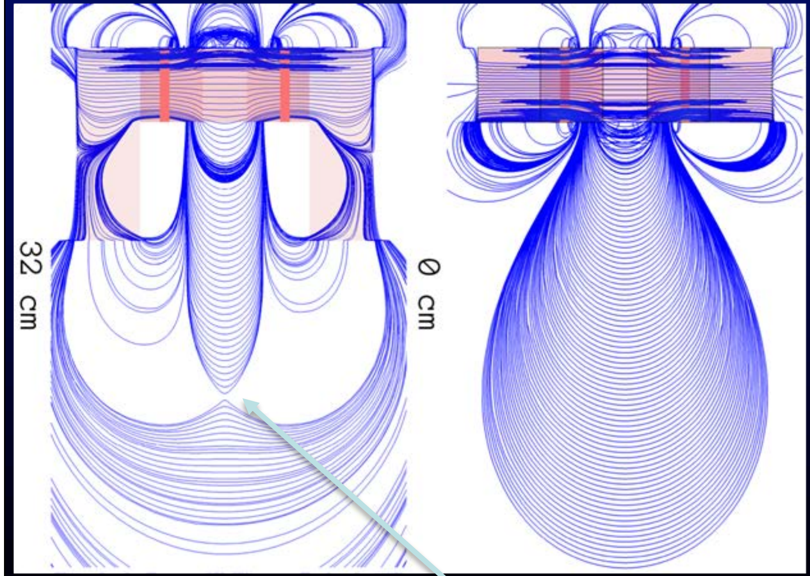
Enforce zero drift in y (rotate E):

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

Filter R&D Development Setup

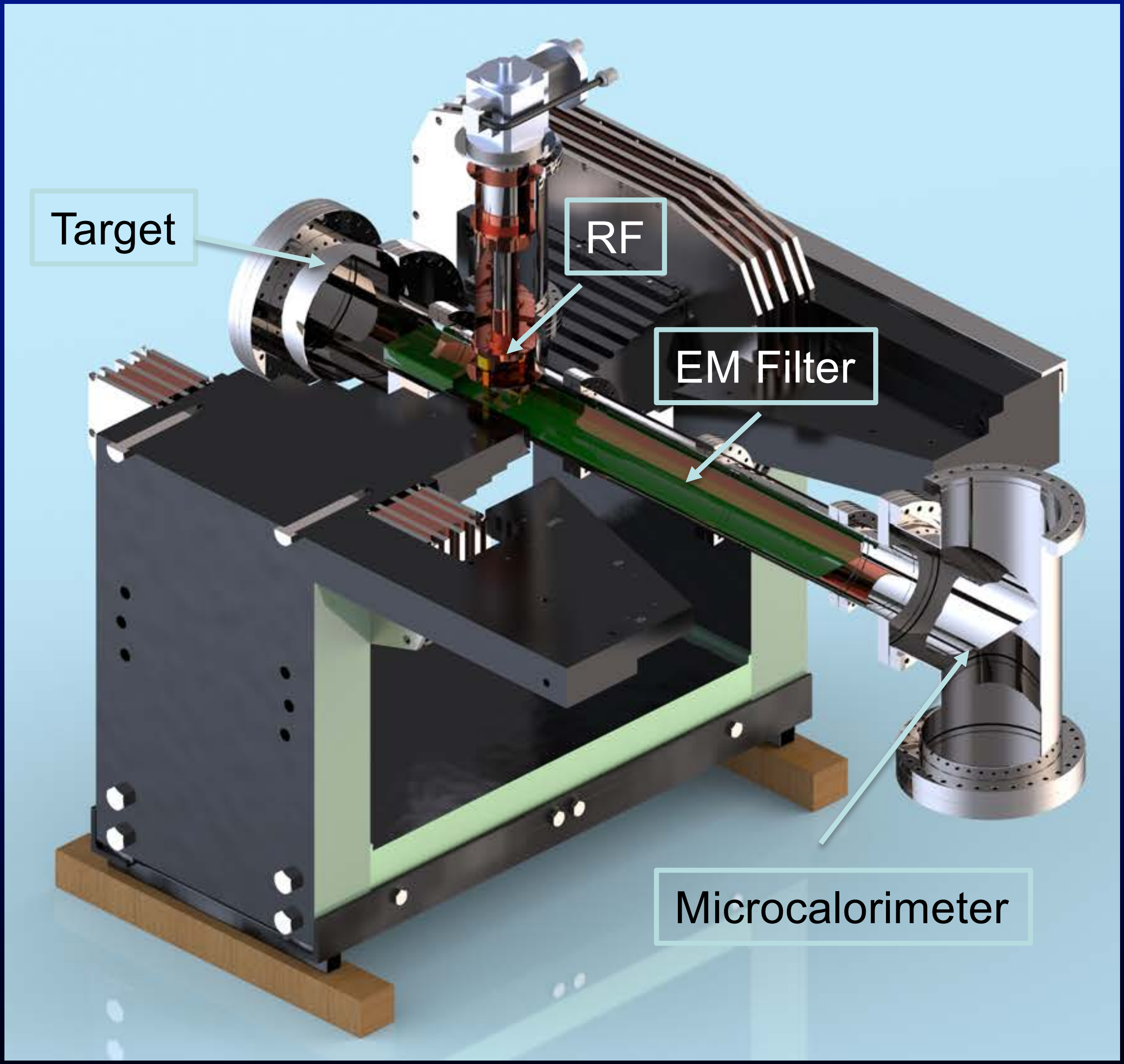
Andi Tan (Princeton)



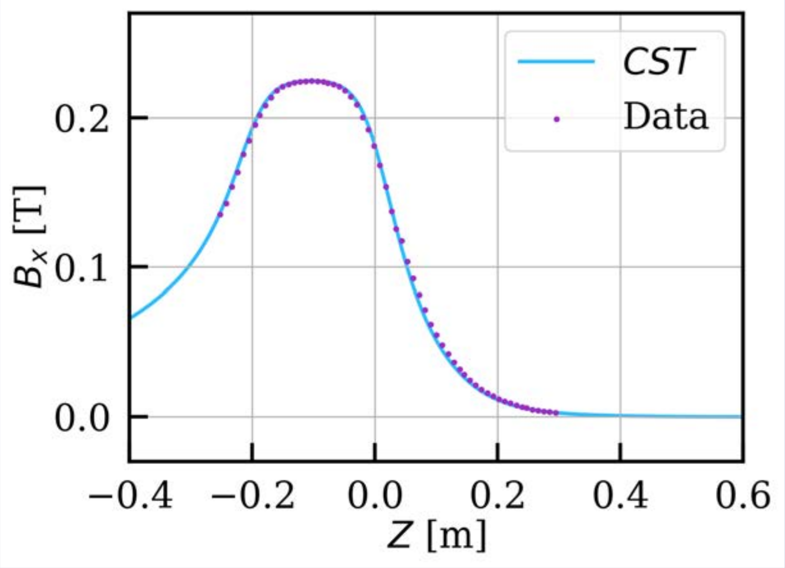


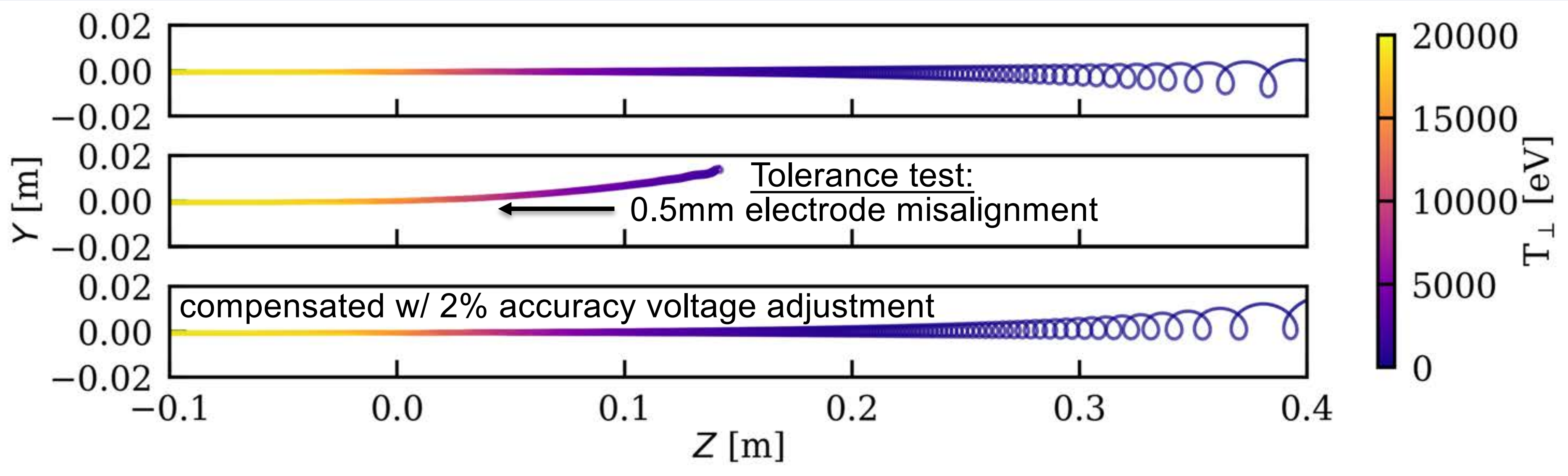
Wonyong Chung
(Princeton)

Zero field (location for TES microcalorimeter)



Achieves Required Magnetic Field Map





Tolerance test:
0.5mm electrode misalignment

compensated w/ 2% accuracy voltage adjustment

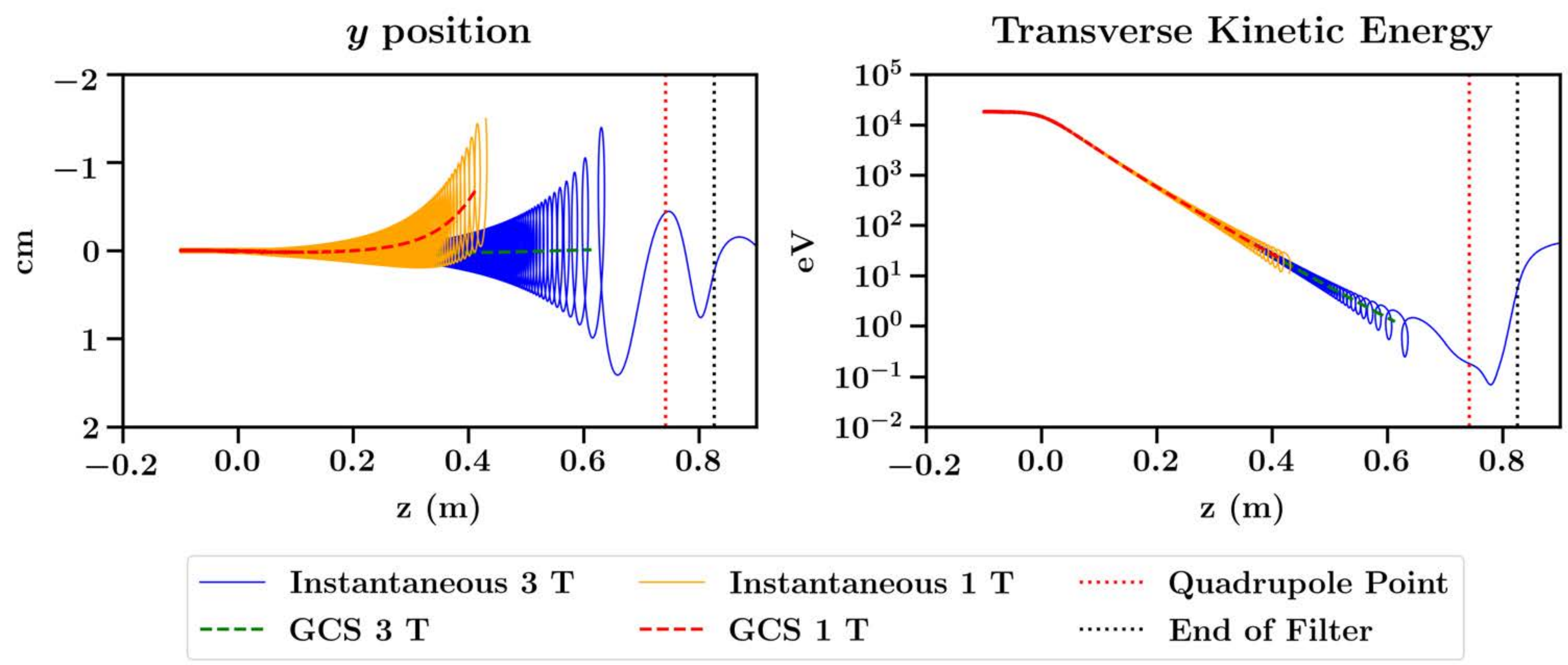
PTOLEMY Collaboration, https://arxiv.org/abs/2108.10388
“Low Field Optimization of the PTOLEMY Electromagnetic Filter” (in peer-review)

Filter Performance

Improves as B^2 for a fixed filter dimension

18.6 keV @ 1T → ~10eV (in 0.4m)

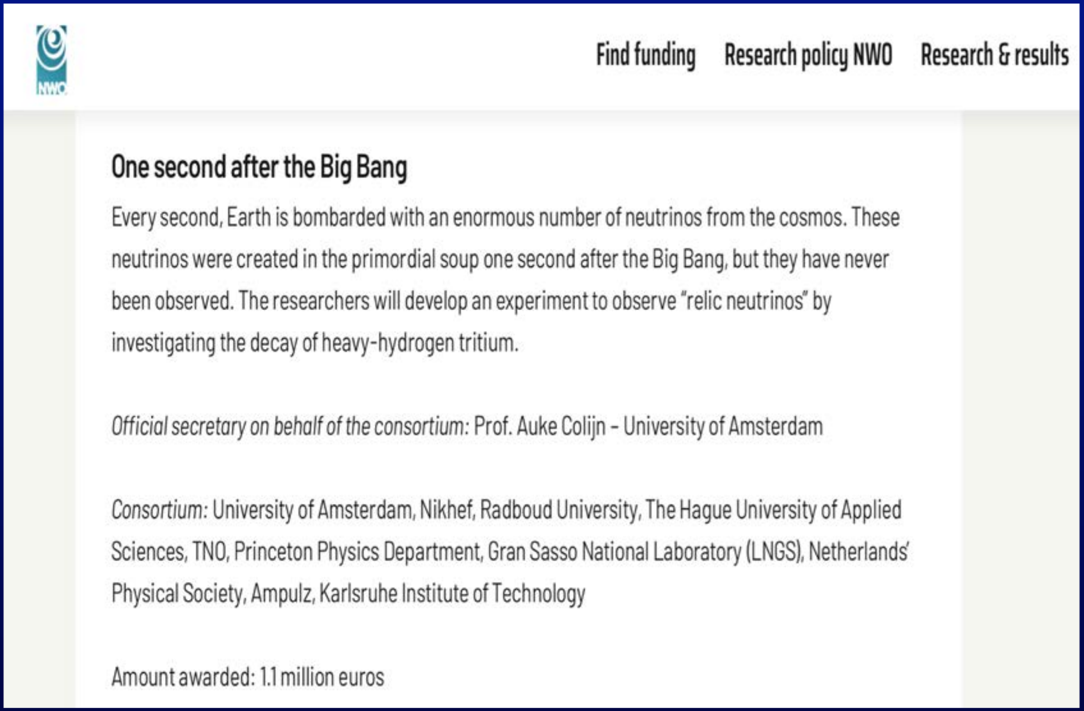
18.6 keV @ 3T → ~1eV (in 0.6m)



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

RF Antenna and Readout

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



One second after the Big Bang

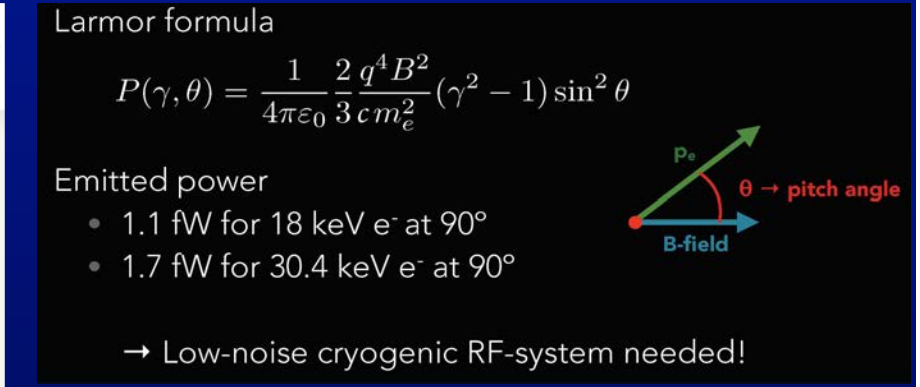
Every second, Earth is bombarded with an enormous number of neutrinos from the cosmos. These neutrinos were created in the primordial soup one second after the Big Bang, but they have never been observed. The researchers will develop an experiment to observe "relic neutrinos" by investigating the decay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



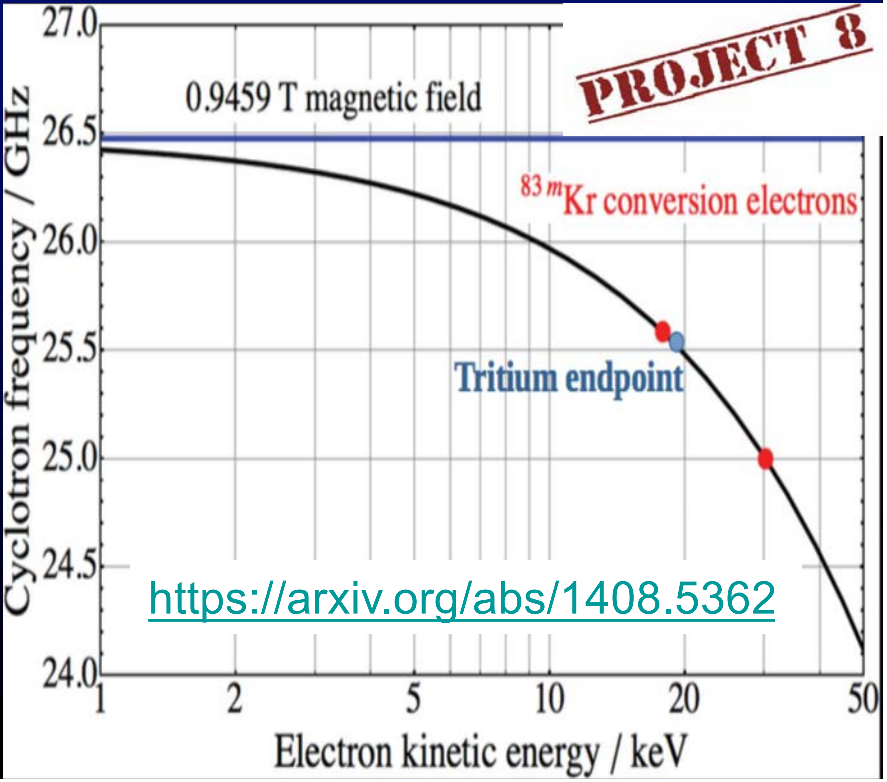
Larmor formula

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

Emitted power

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

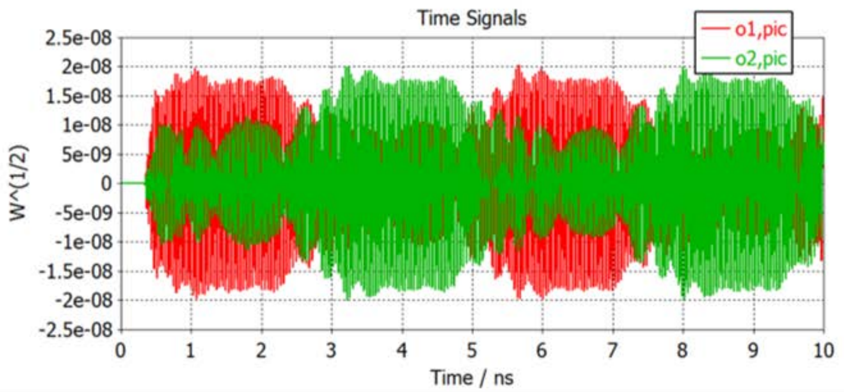
→ Low-noise cryogenic RF-system needed!



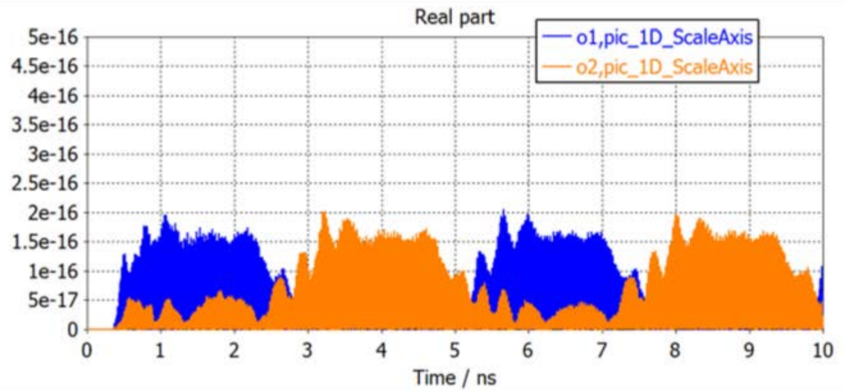
https://arxiv.org/abs/1408.5362

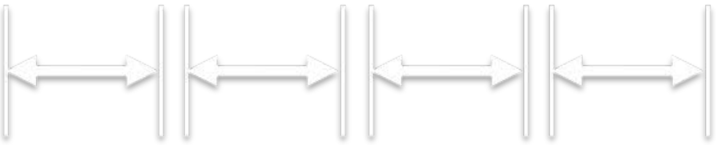
RF Tracking

Time Series (~26 GHz)

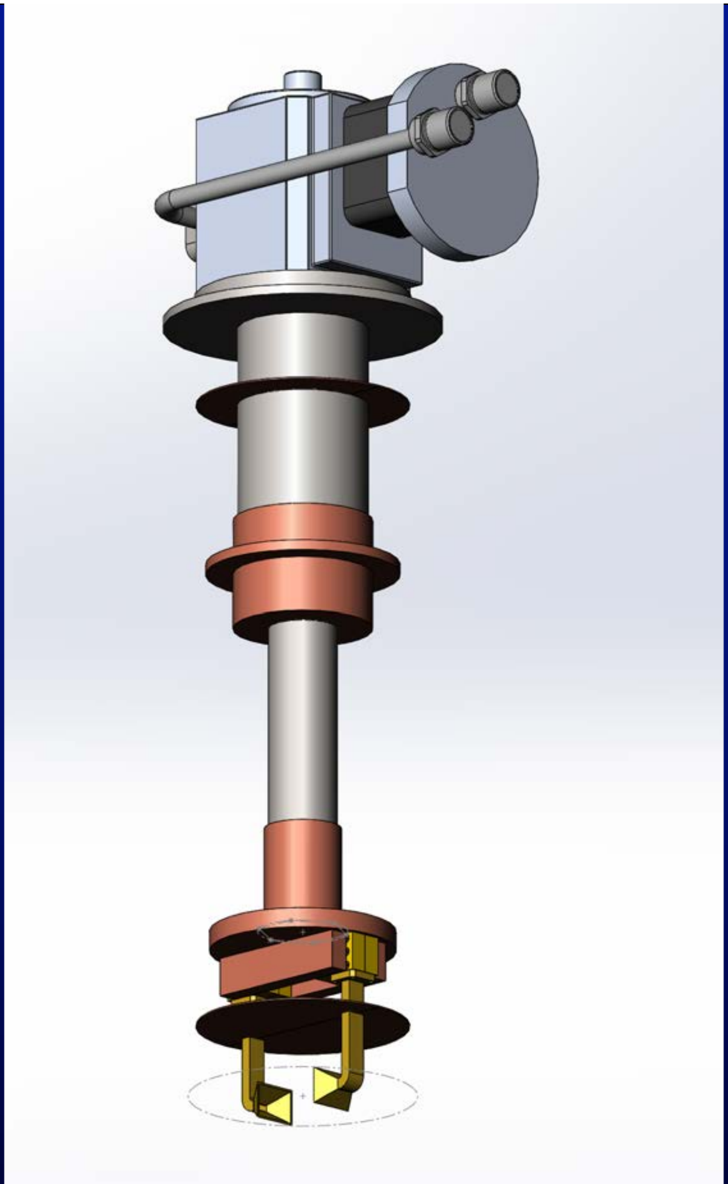


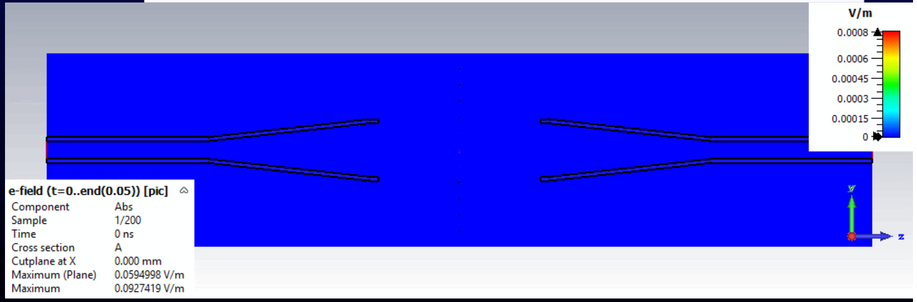
Power(~0.1 fW)





Right Left Right Left





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

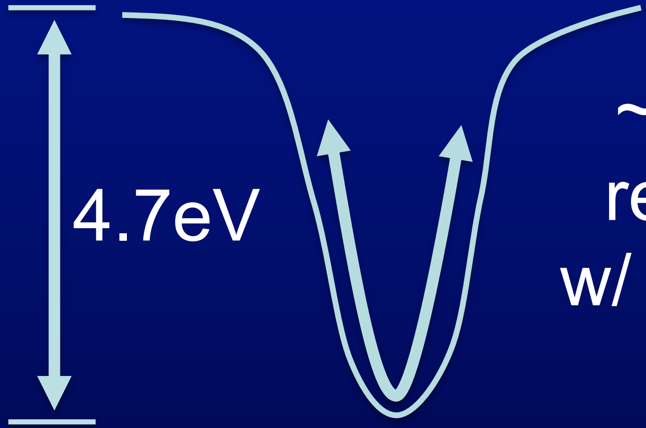
Component	Abs
Sample	1/200
Time	0 ns
Cross section	A
Cutplane at X	0.000 mm
Maximum (Plane)	0.0594998 V/m
Maximum	0.0927419 V/m

Target: Molecular Broadening

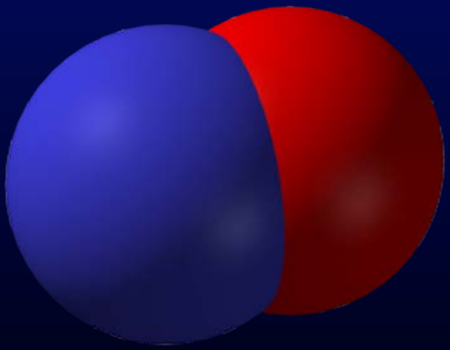
Gaseous target not ideal

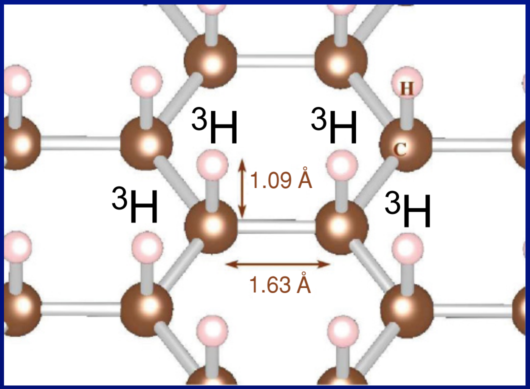
T-T → $(\text{T-He}^3)^{+*}$

*Many close-spaced ro-vibrational excited states



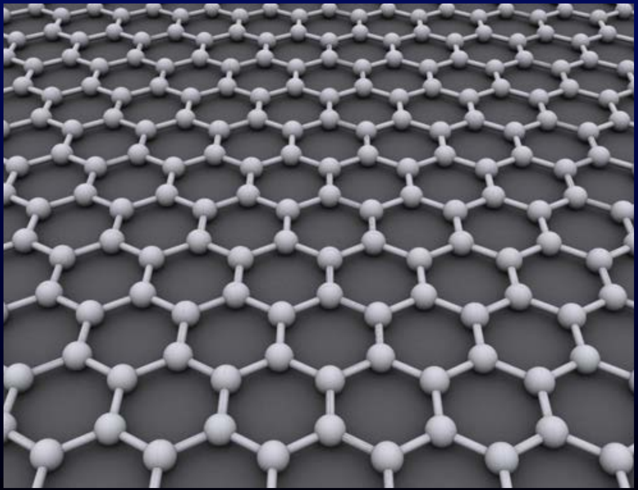
~1.7eV $(\text{T-He}^3)^{+*}$ recoil at endpoint w/ ~0.3eV spread(*)





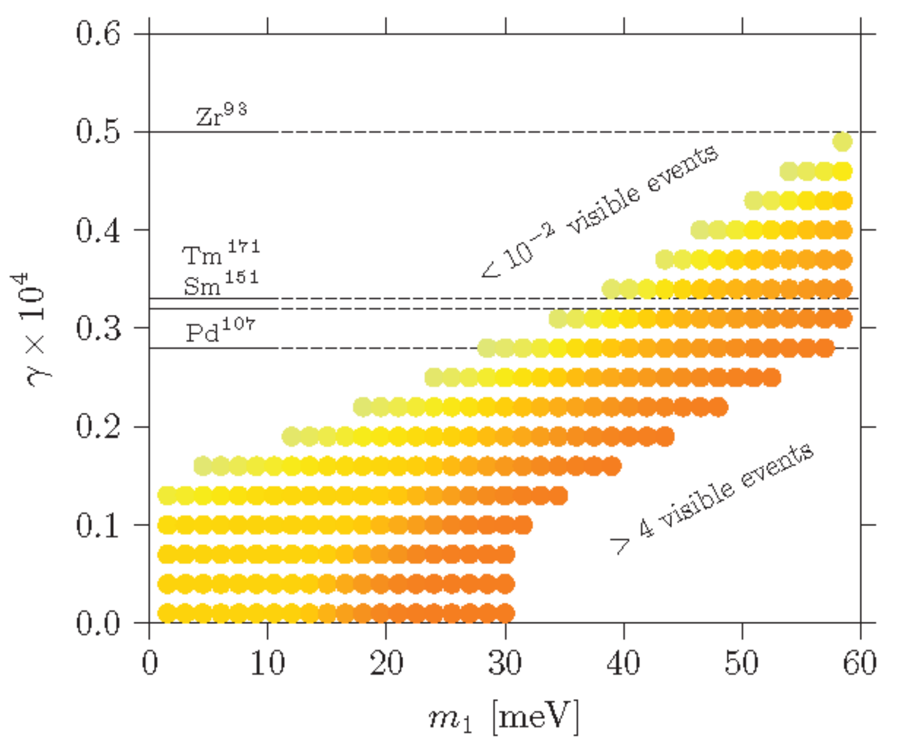
~1eV binding energy

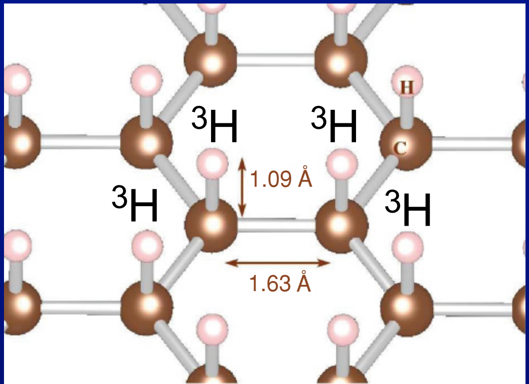
Planar target: Graphene



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

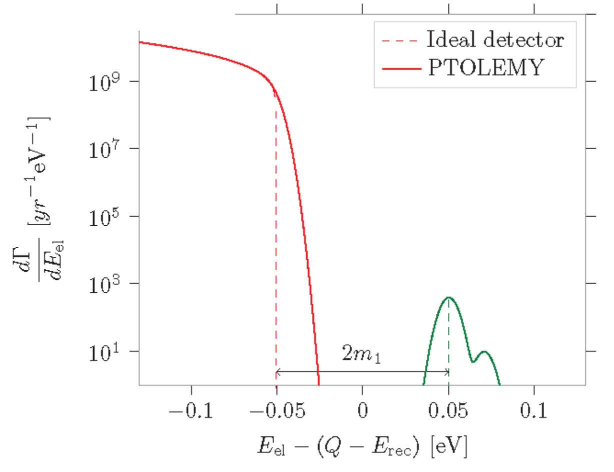
Target: Molecular Broadening

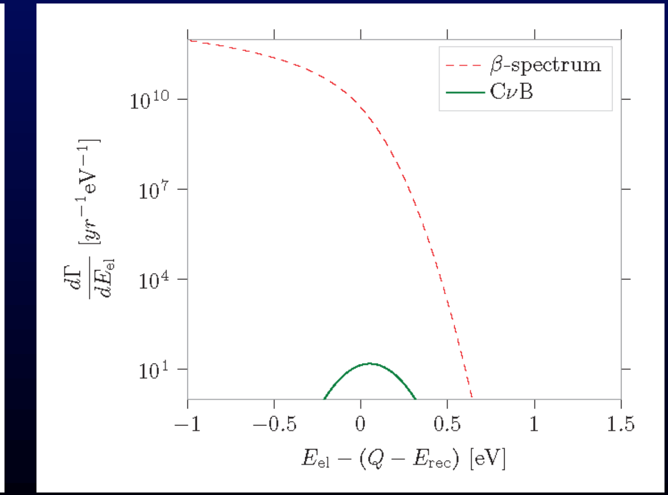




Too “Localized”

Optimal
“Heavy” Targets





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

Next Steps for PTOLEMY

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

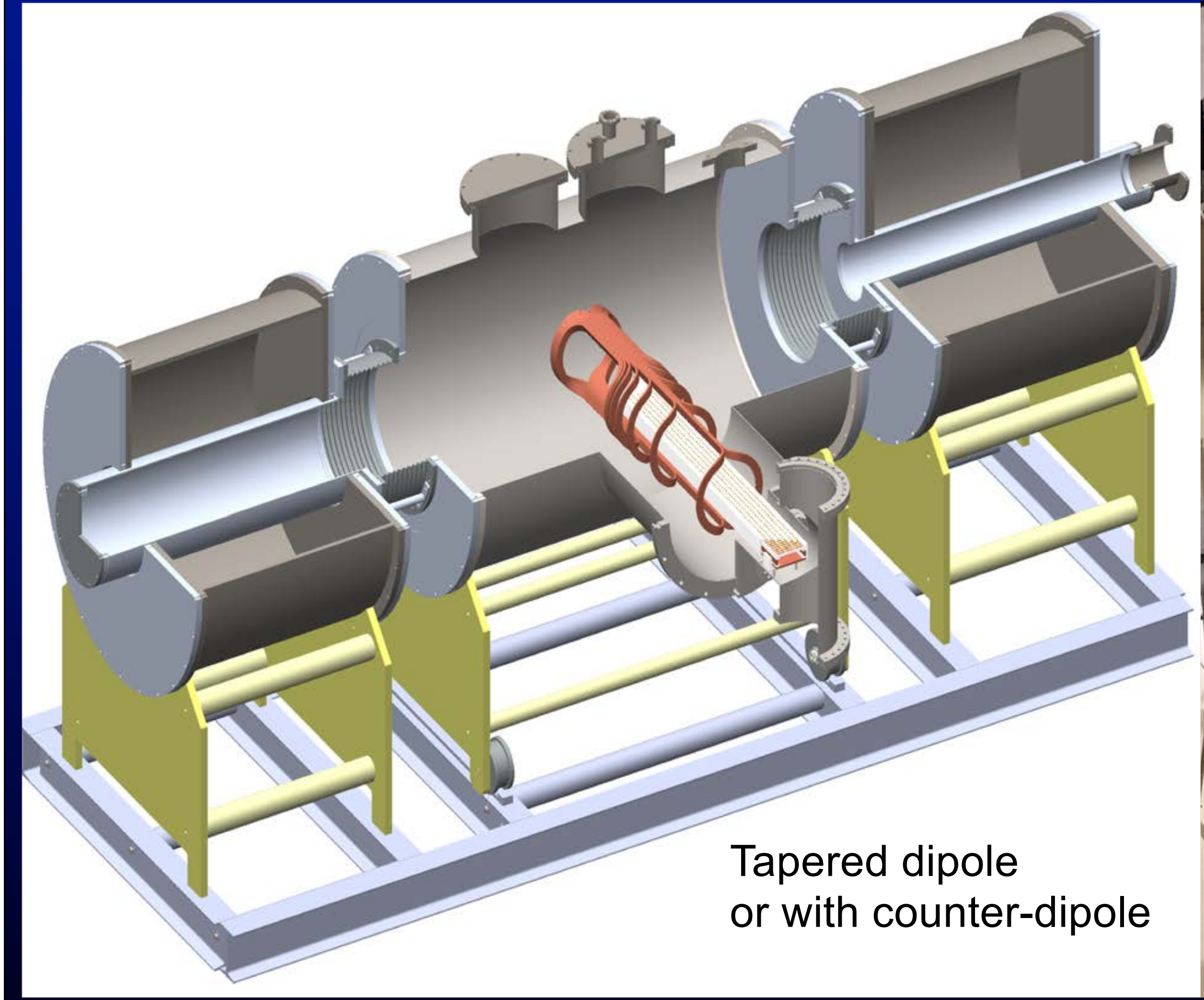
→ Build full-scale iron magnet and filter @ LNGS
→ Complete two full design cycles of TES @ INRiM
→ Integrate measurement arm with RF tracker (supported by Dutch Research Council grant)

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

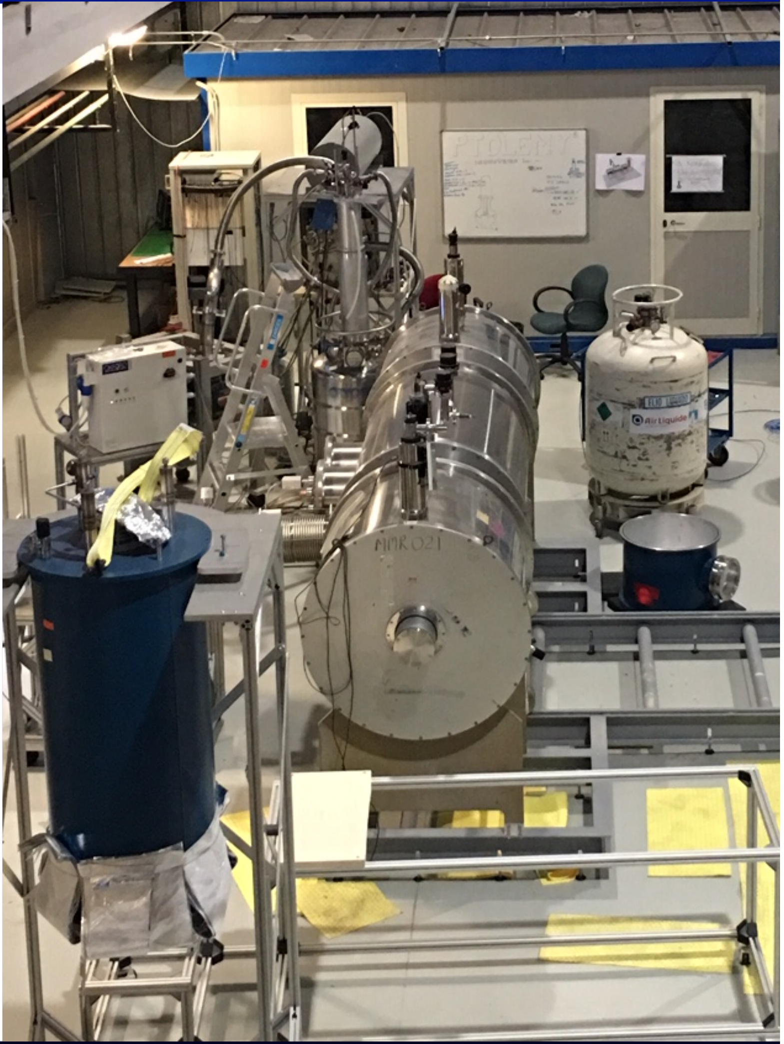
Produce filter and target with a scalable technology

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

Superconducting Coil Design

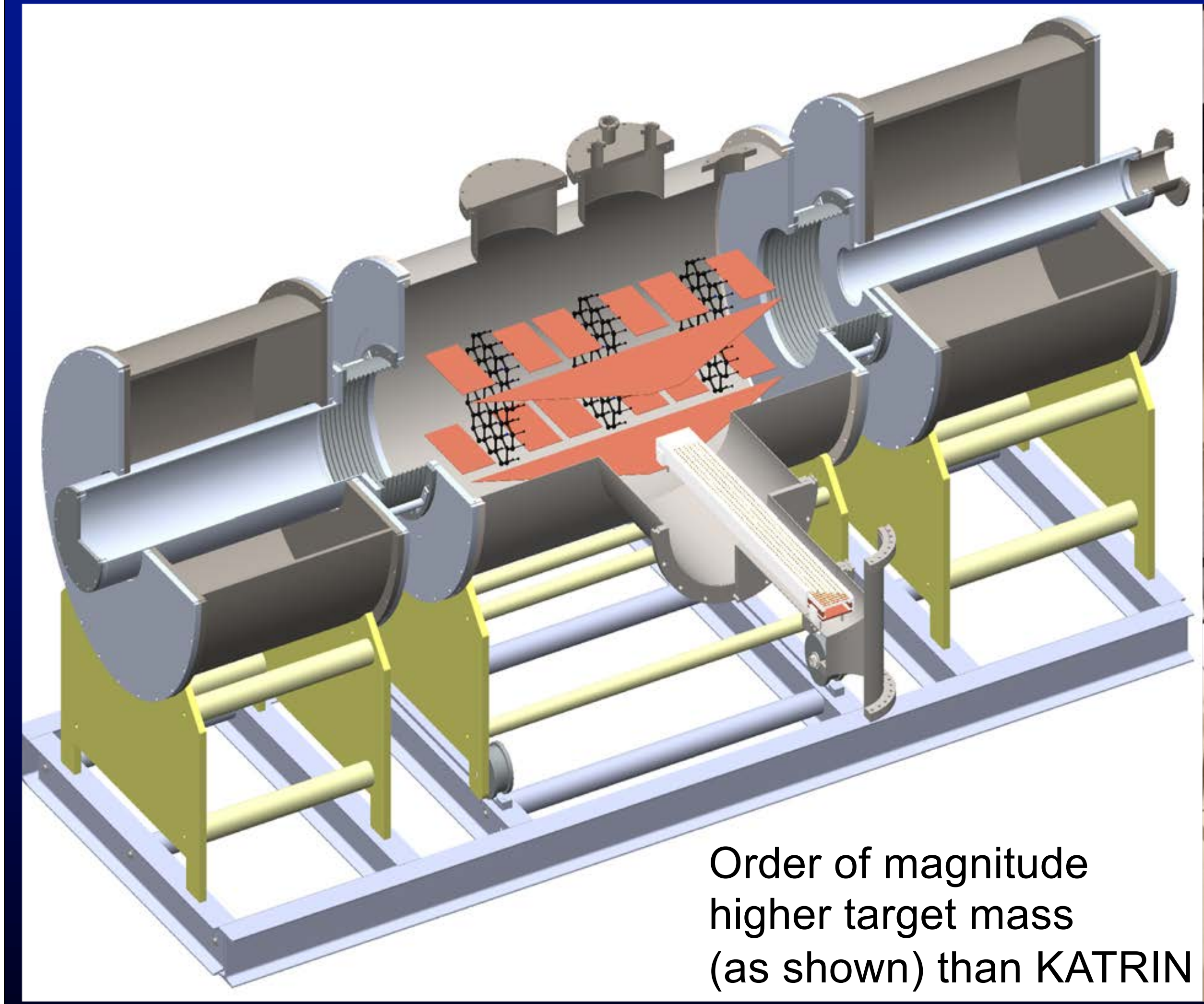


Tapered dipole
or with counter-dipole

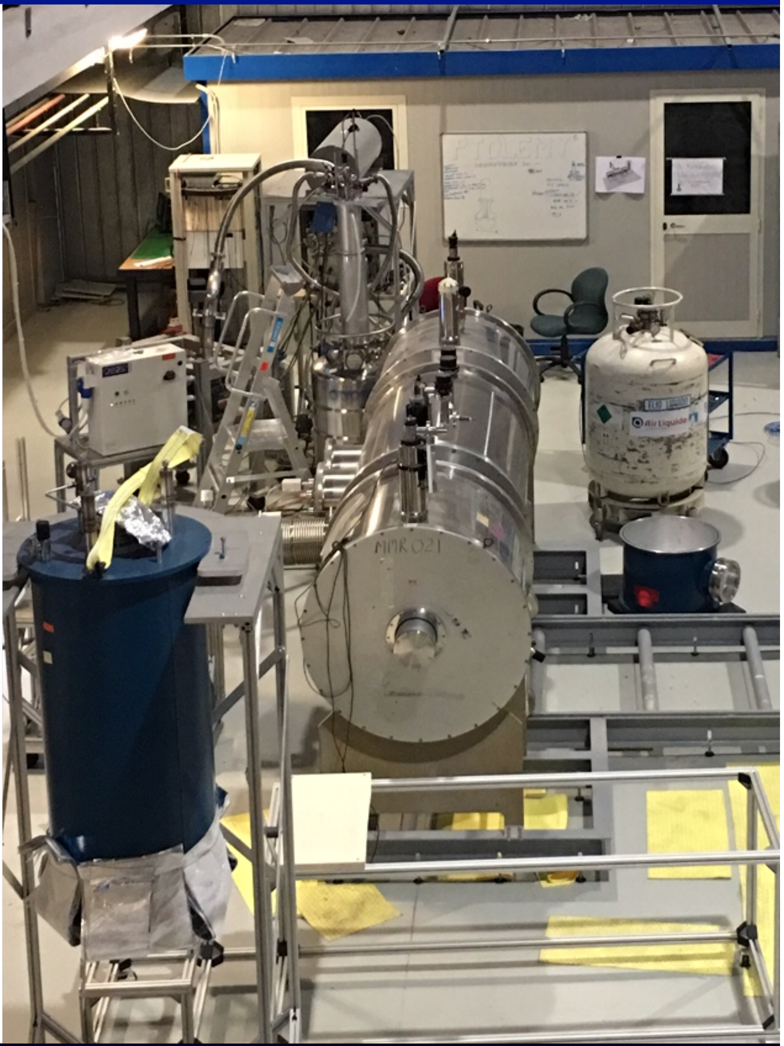


Integrate into existing dual-SC magnet setup @ LNGS

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”

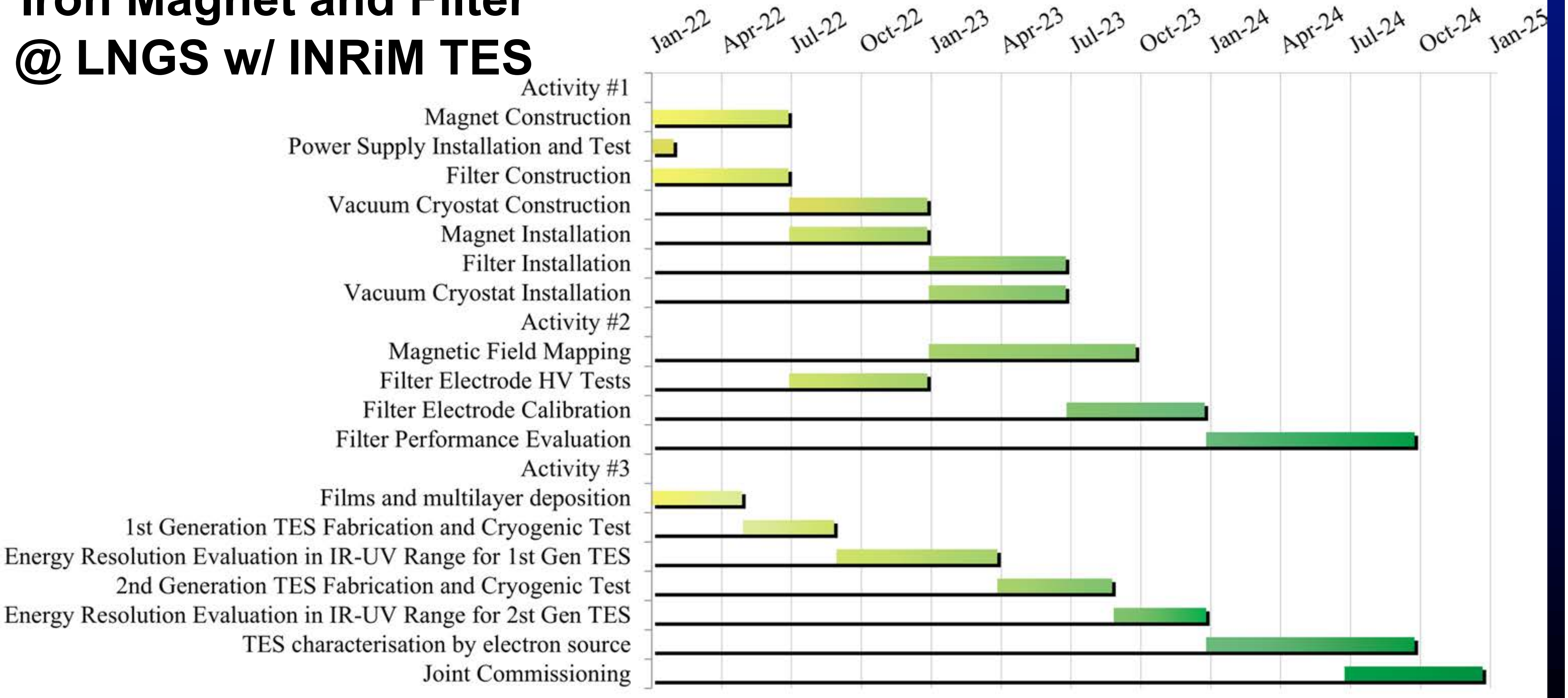
Project Timeline (3-year program)

Program of Validating Measurement Arm (3-year program)

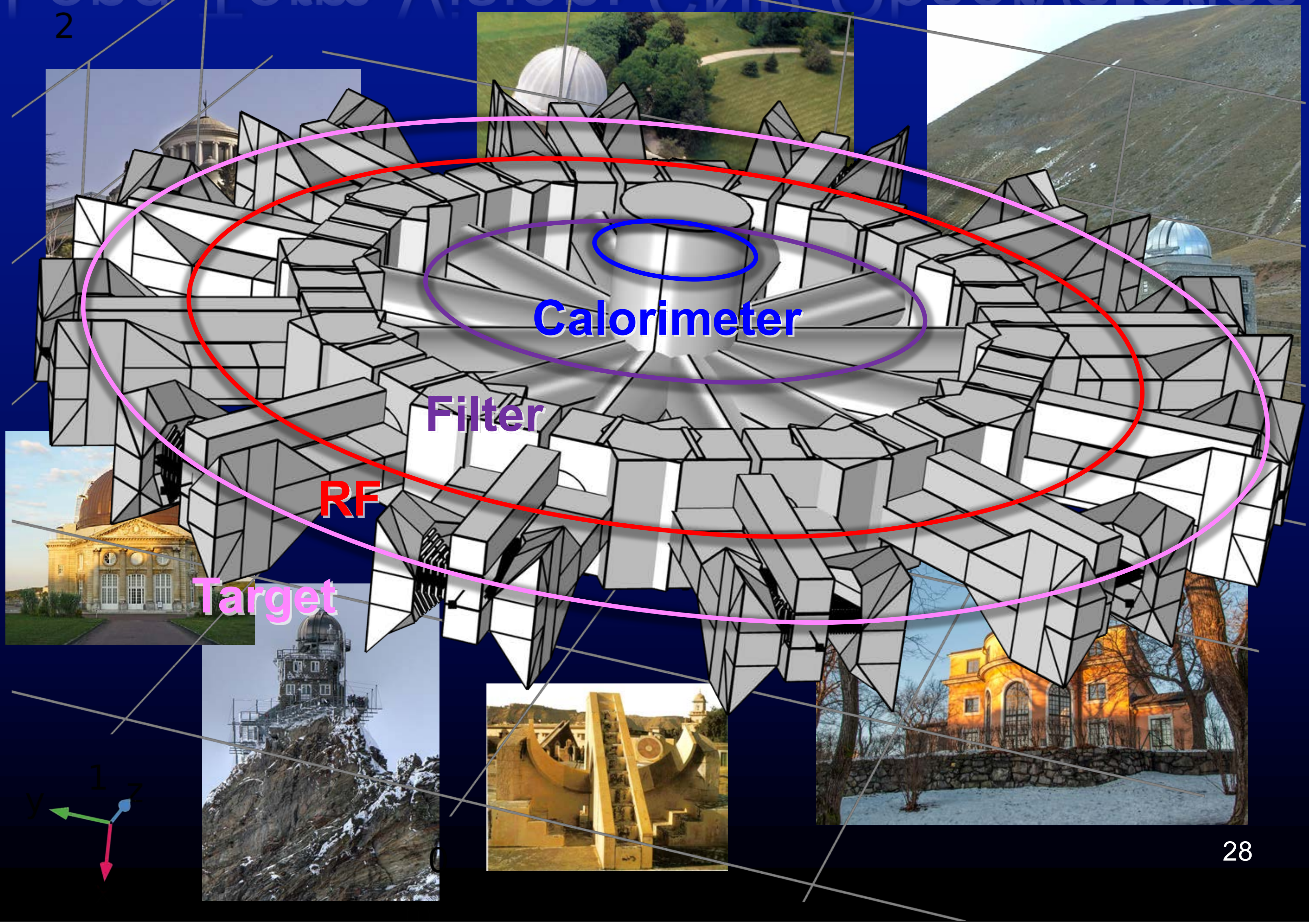
Target physics studies expected through 2021-2023 and fabrication/testing 2023-2025 w/ interface to filter in 2025

Physics program possible starting from ~2025-2026+

Iron Magnet and Filter @ LNGS w/ INRiM TES



Long-Term Vision: CNB Observatories



Physics Validation Program

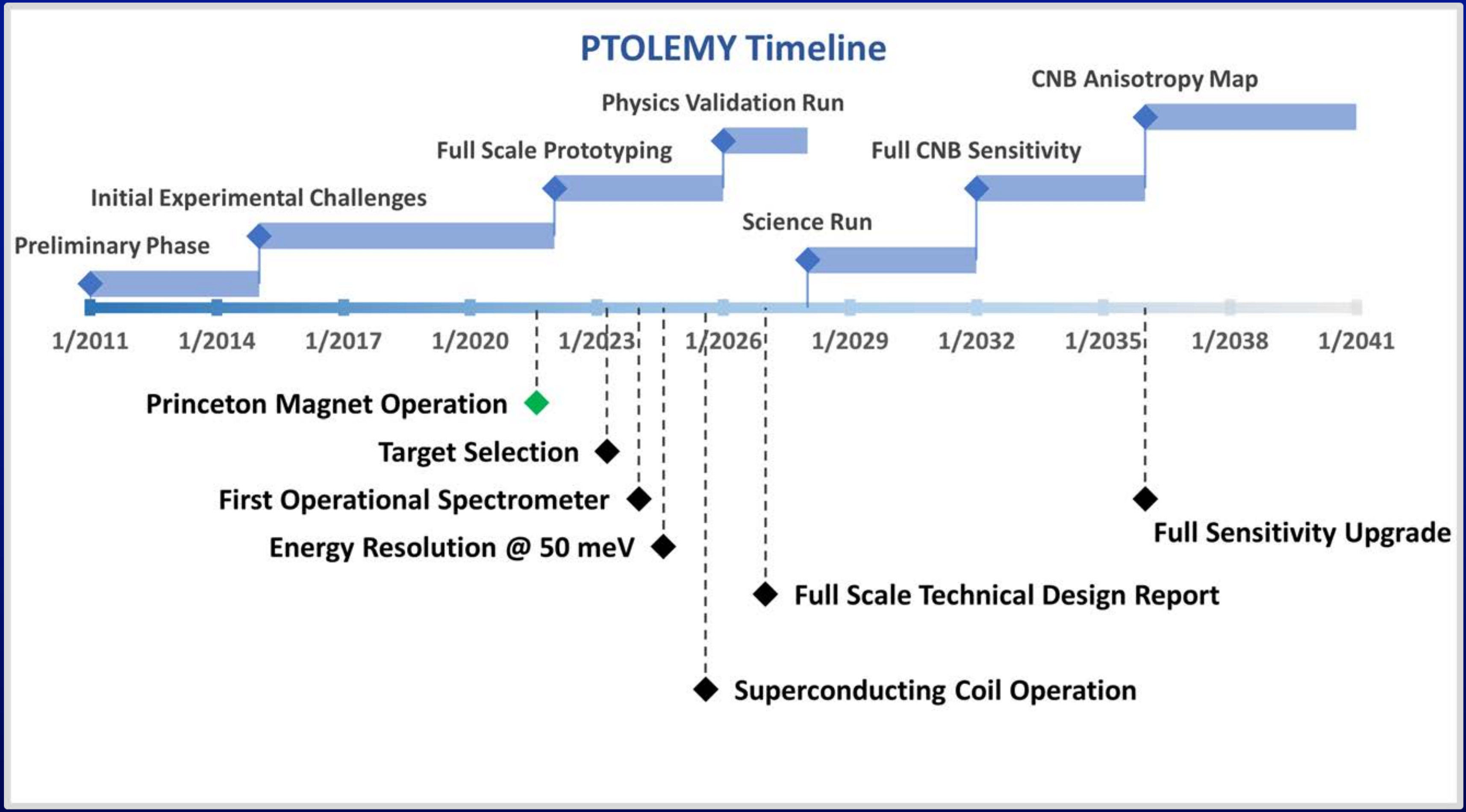
Validate β-decay recoil physics:

- Precision endpoint measurements for candidate target nuclei and substrates
- Differential energy measurements of recoil ions compared to theory
- Push sensitivity on neutrino mass measurements

Explore/build physics programs on:

- Sterile neutrino program on β-decay spectrum
- Novel directional DM CNT targets
  - ANDROMeDa (Aligned Nanotube Detector for Research On MeV DarkMatter) – recently funded
- Co-incidence ee-targets using 2D TMDC for 0vbb
- GFET GNR-based sensor development for dir-DM

New areas w/ high sensitivity detectors…



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 World-Wide Collaboration

PPPL
PRINCETON
PLASMA PHYSIC
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

Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

Stockholm
University

UPPSALA
UNIVERSITET

UNIVERSITY
OF AMSTERDAM

Radboud University

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UNIVERSITÀ DI ROMA

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BICOCCA

UNIVERSITÀ DI PISA

INFN
Laboratori Nazionali del Gran Sasso

GSSI
GRAN SASSO
SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

טלסקופ ניטרינים קוסמיים

Telescopio di neutrini cosmologici

Kosmische neutrinotelescoop

Telescopio de neutrinos cósmicos

Kosmisk neutrinoteleskop

Cosmic neutrino telescope

2015 Targeted Grant Award from the SIMONS FOUNDATION

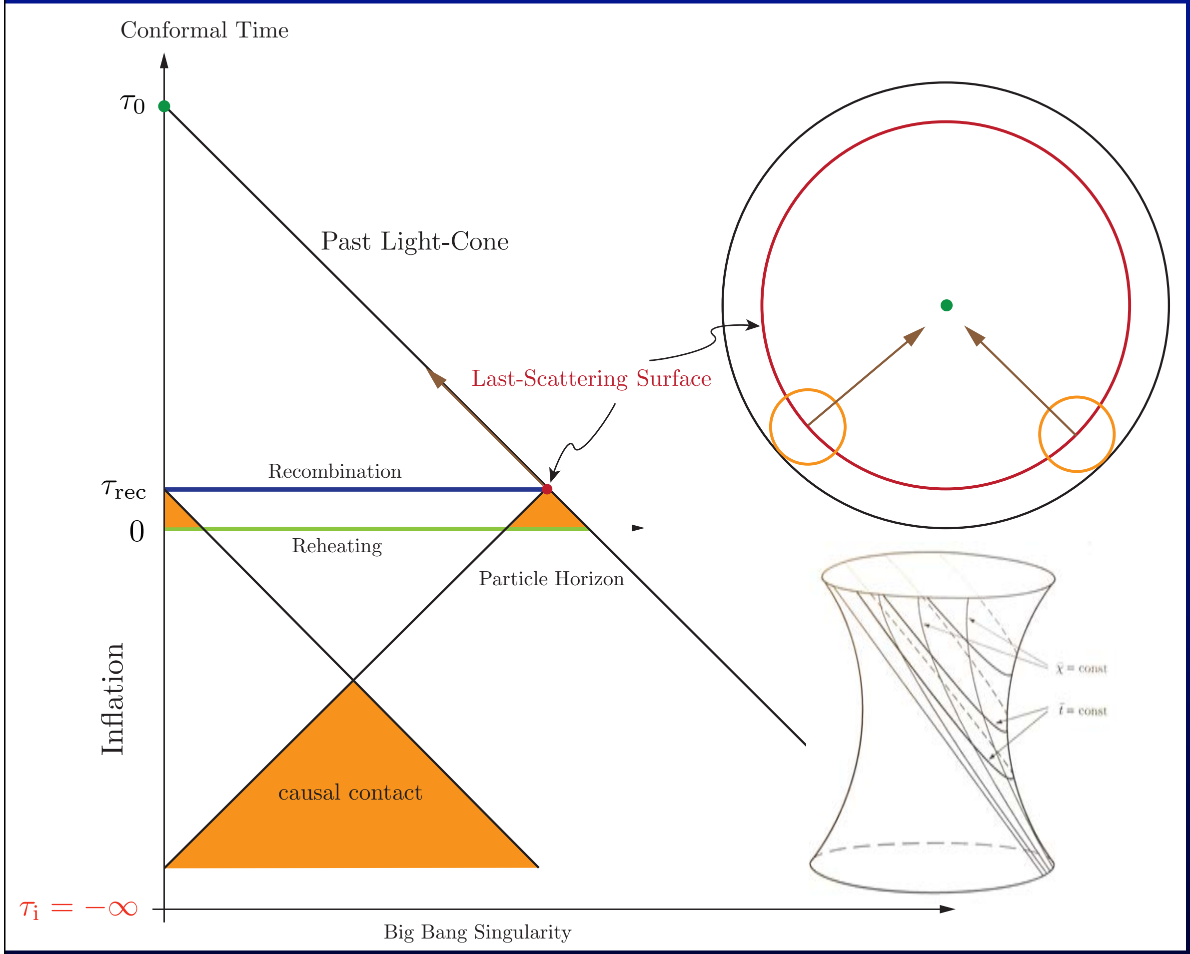
CNB White Paper Draft

Access will be provided through Overleaf.com :

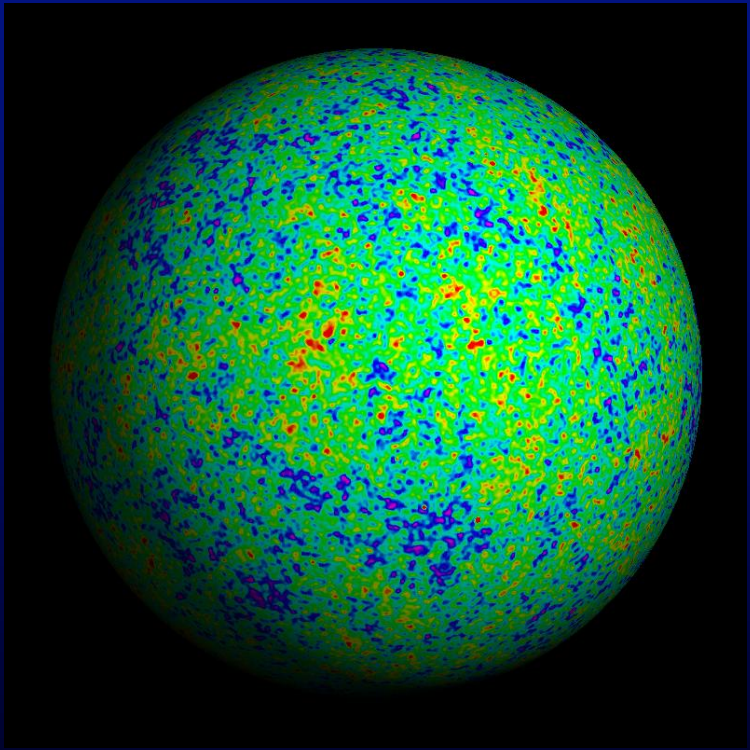
https://www.overleaf.com/read/cbfzvgctvckp

ADDITIONAL SLIDES

Big Bang Cosmology

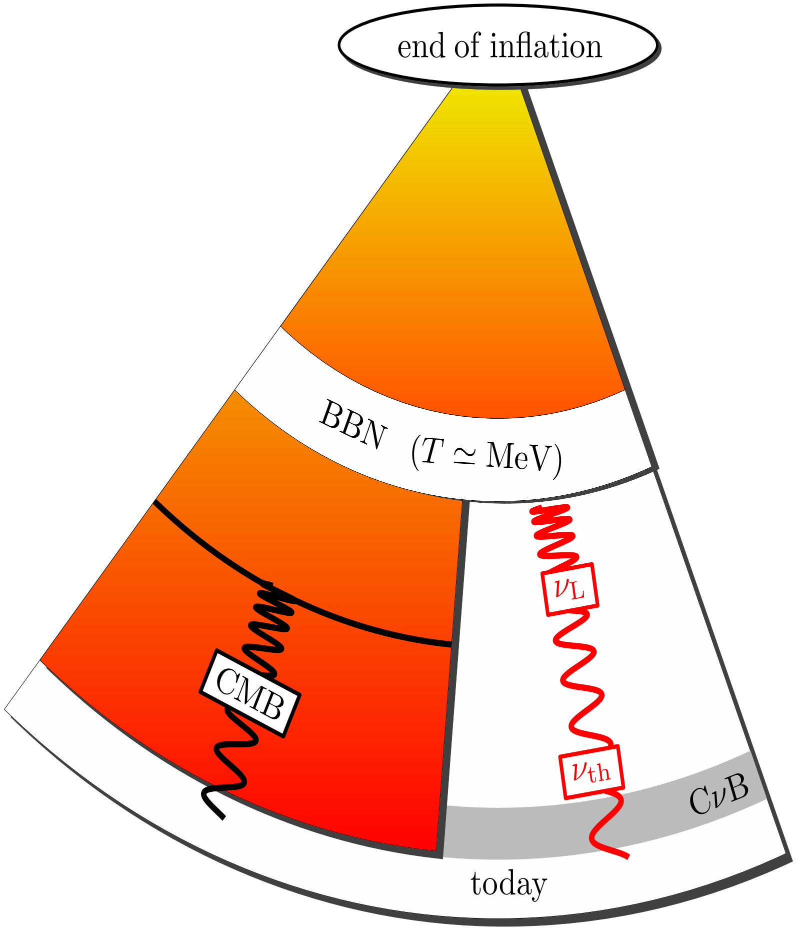


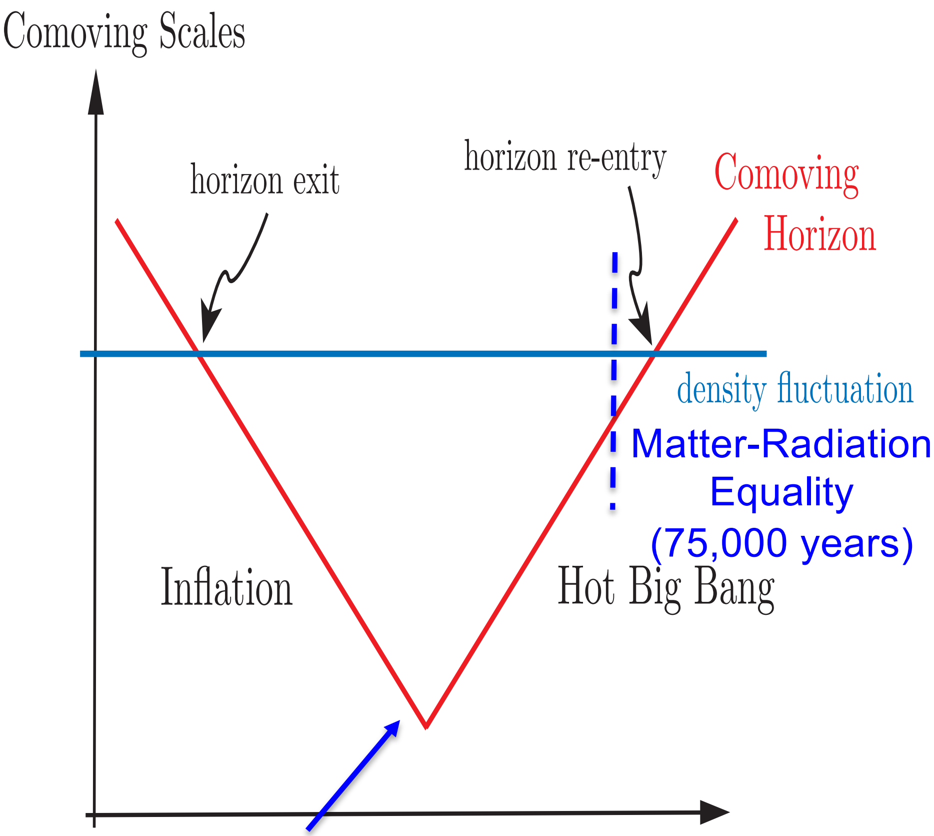
Adiabatic Density Anisotropies
$\delta \sim 10^{-5}$ at $z \sim 1100$



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

Inflation → Hot Big Bang



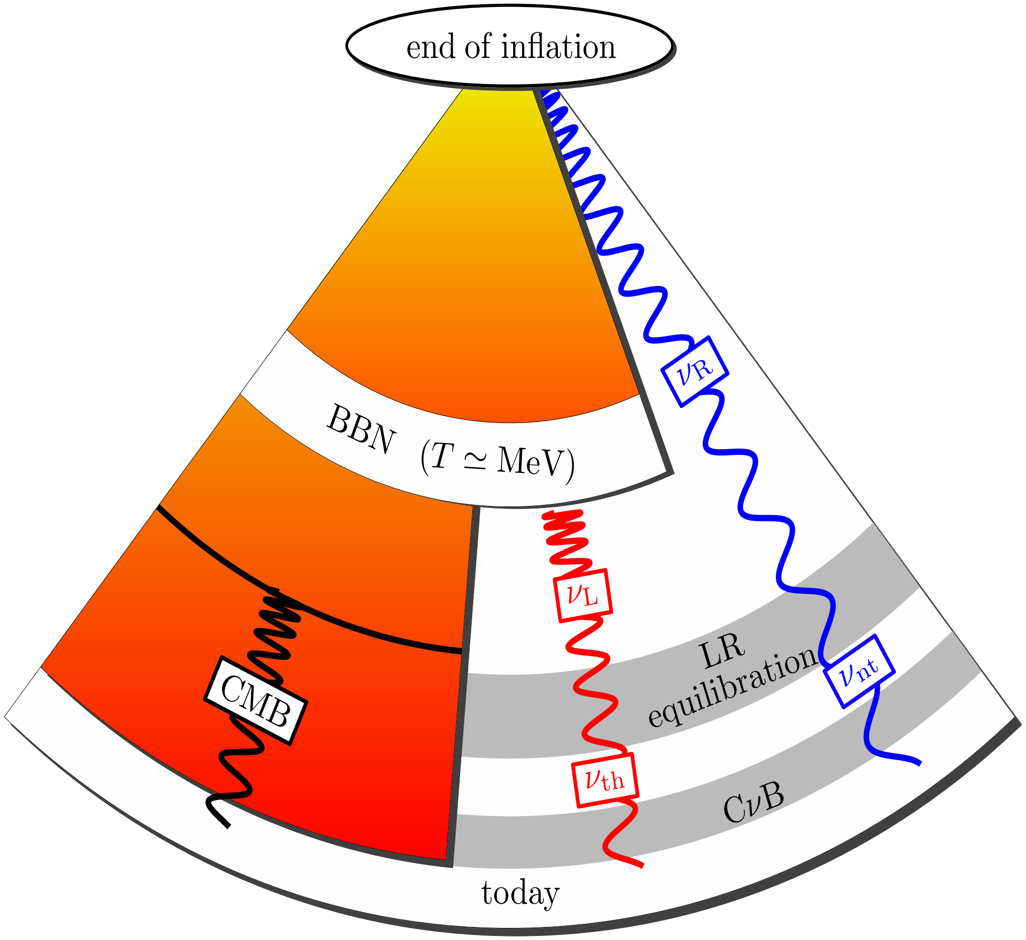


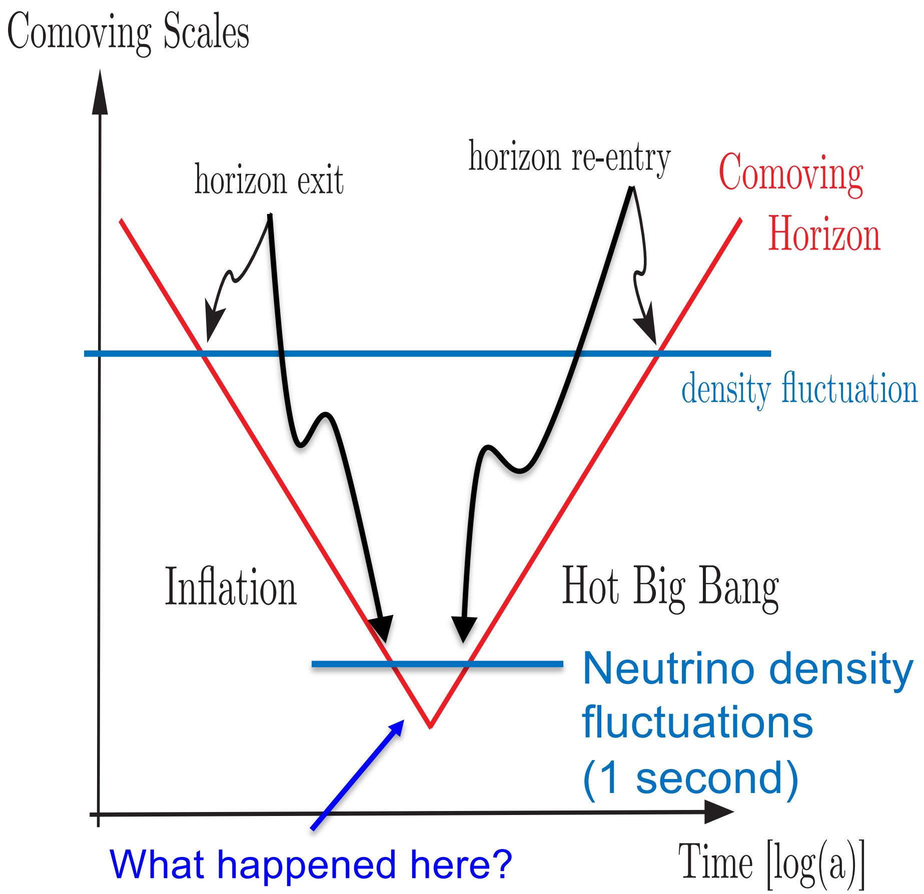
Matter-Radiation Equality (75,000 years)

What happened here?

Baumann (TASI 2012)

Inflation → Hot Big Bang



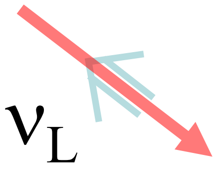


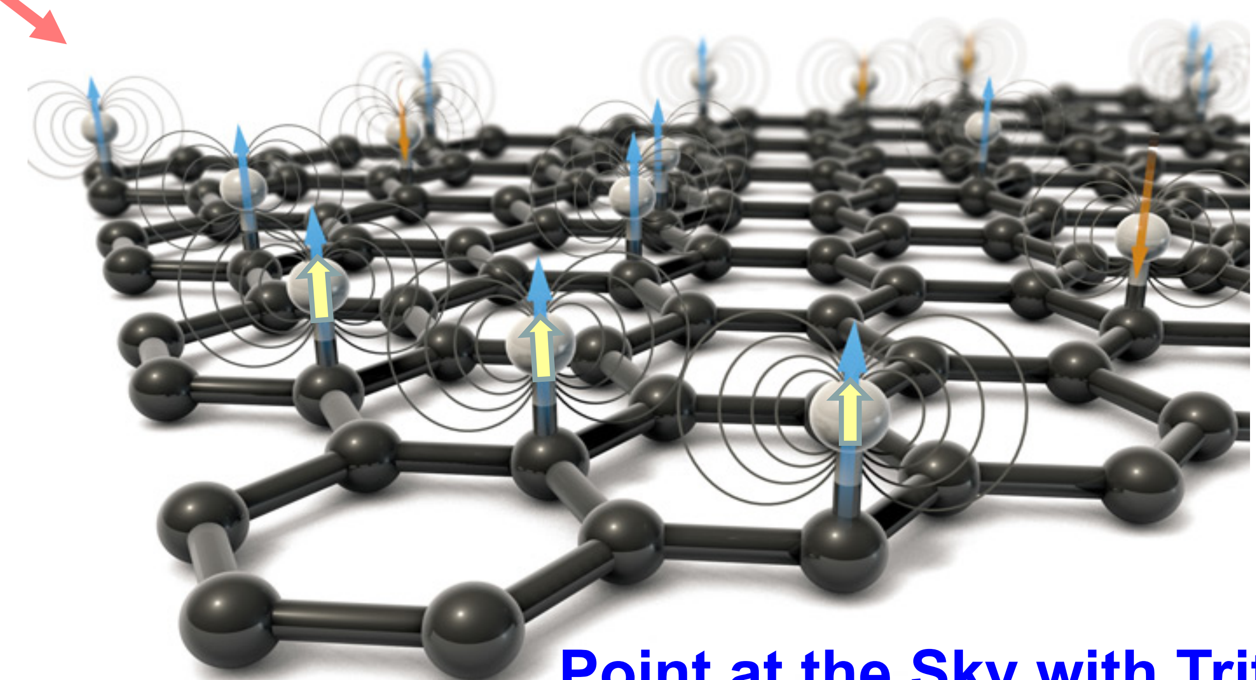
Neutrino density fluctuations (1 second)

What happened here?

Ratz
(Erice 2017)

Polarized Tritium Target





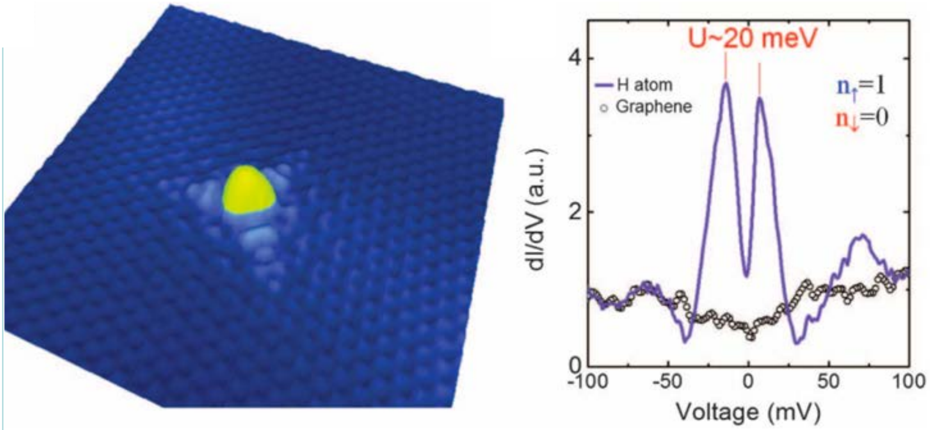
Lisanti, Safdi, CGT, 2014.
10.1103/PhysRevD.90.073006
Akhmedov, 2019.
10.1088/1475-7516/2019/09/031

Point at the Sky with Tritium Nuclear Spin ⇧

Detection (capture) of cold neutrinos:

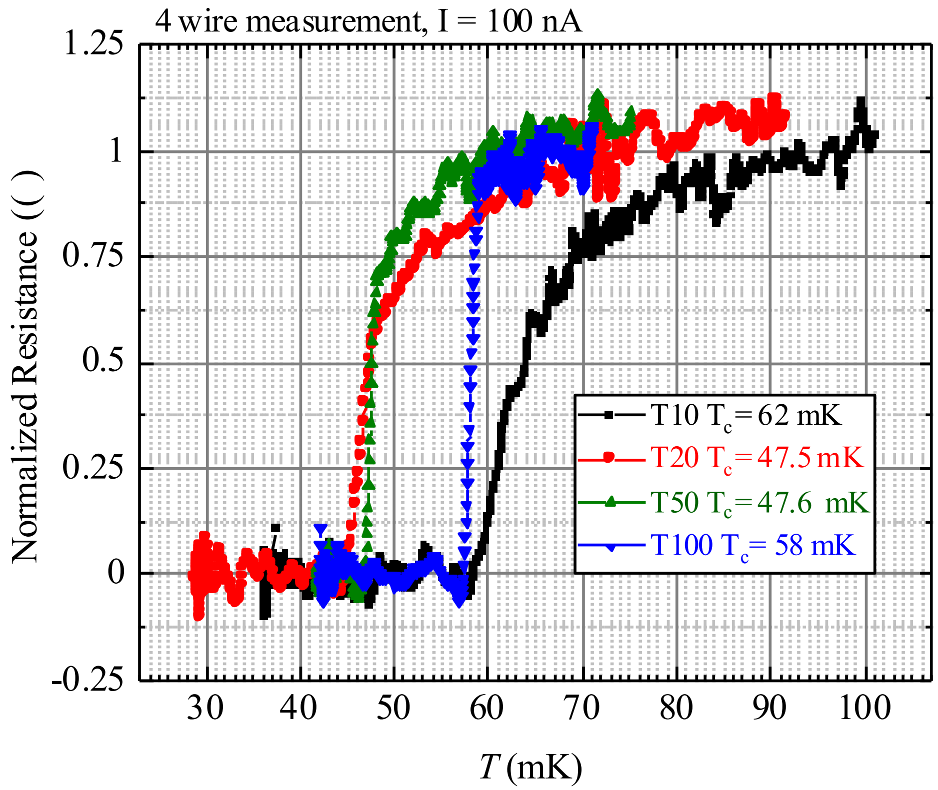
$d\sigma/d\cos\theta\ (v/c) \sim (1+\cos\theta)$

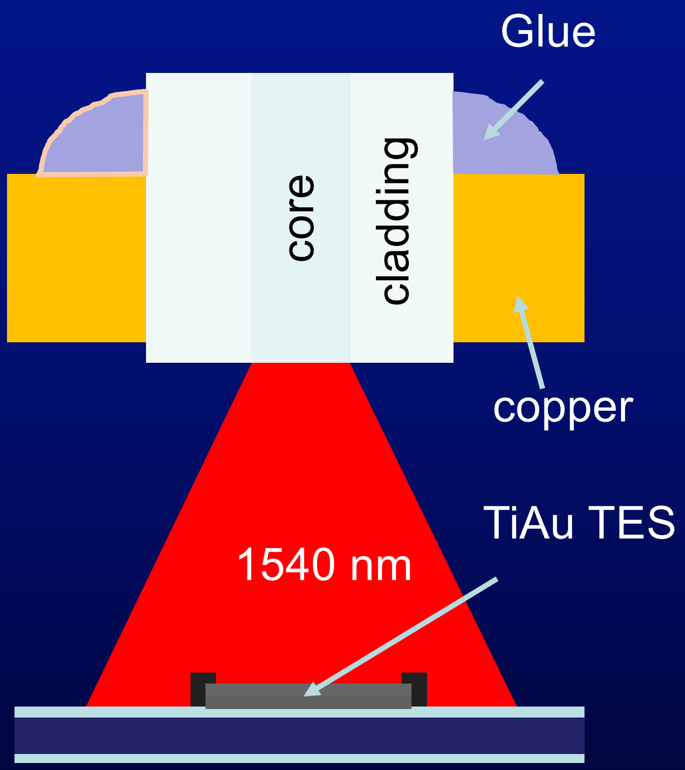
Hydrogen doping on graphene reveals magnetism



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

Critical Temperature and IR Photons



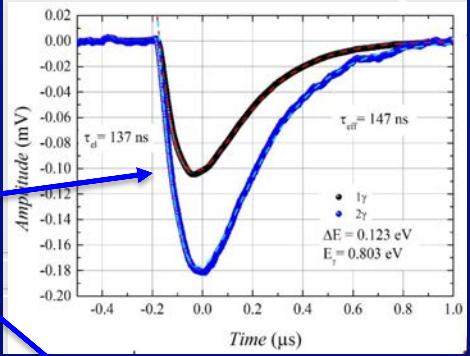


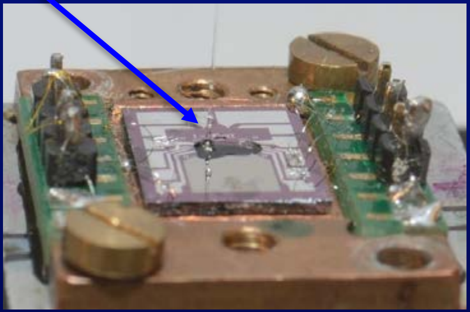
Fiber-TES distance ~ 2mm
(Not in scale)

MicroCalorimeter R&D

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

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

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

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

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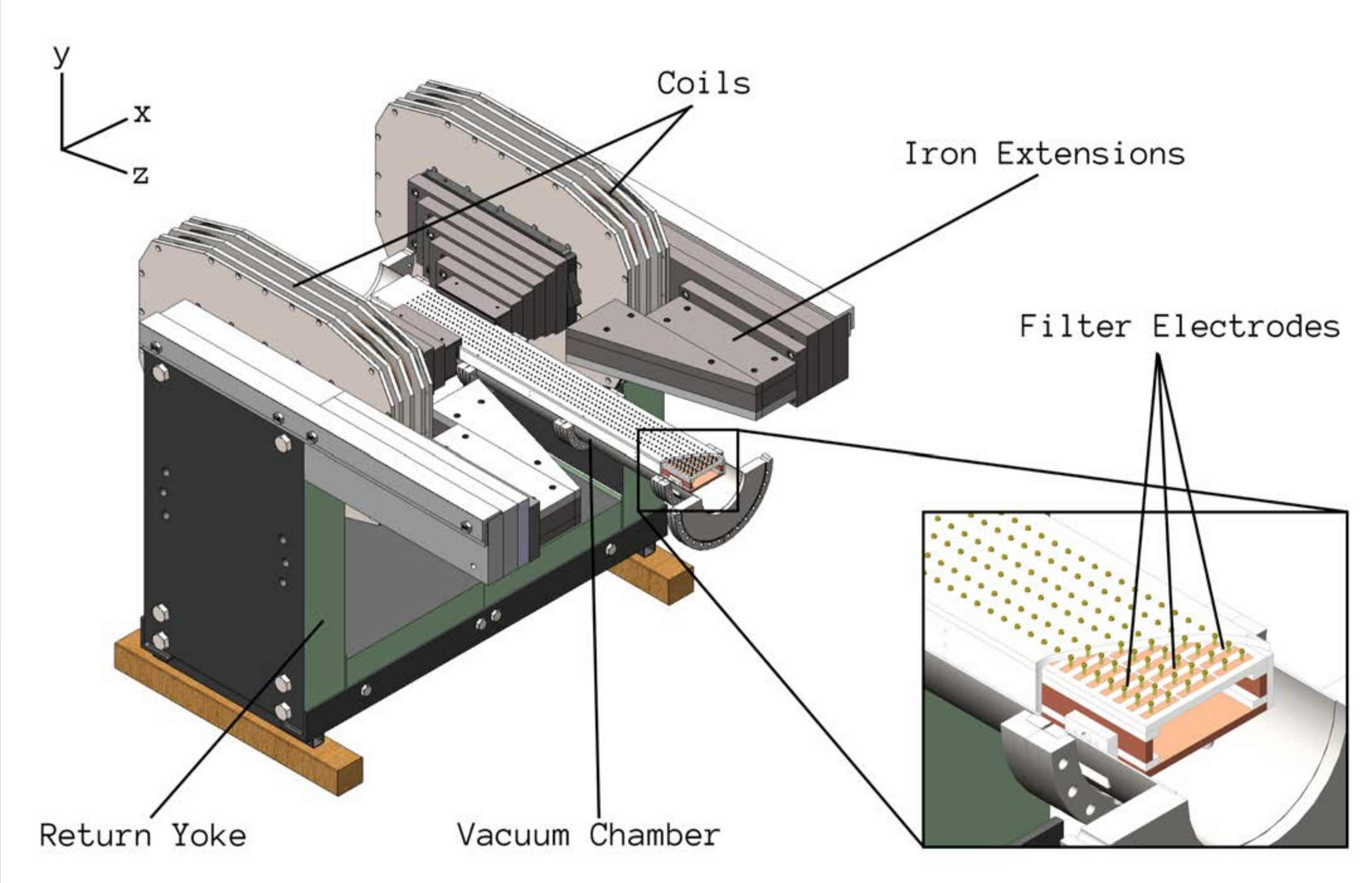
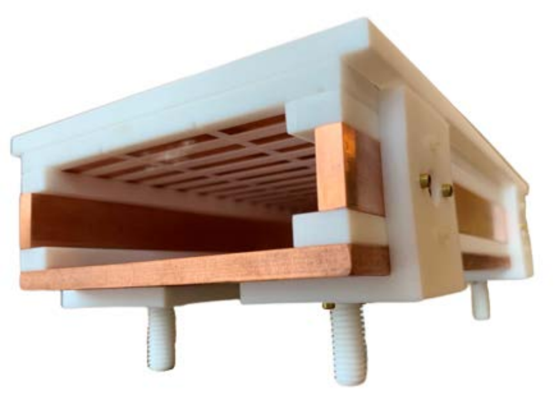
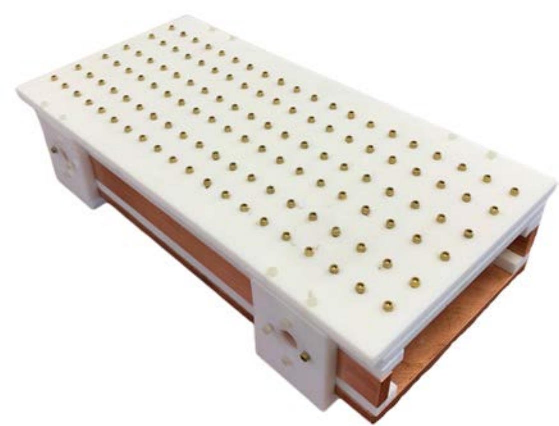
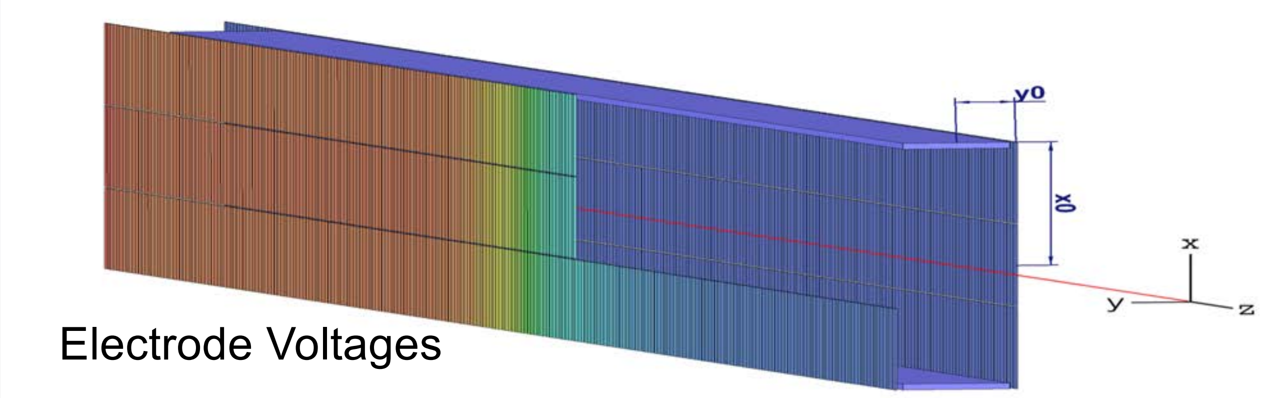
Electrode Prototype

Andi Tan (Princeton)





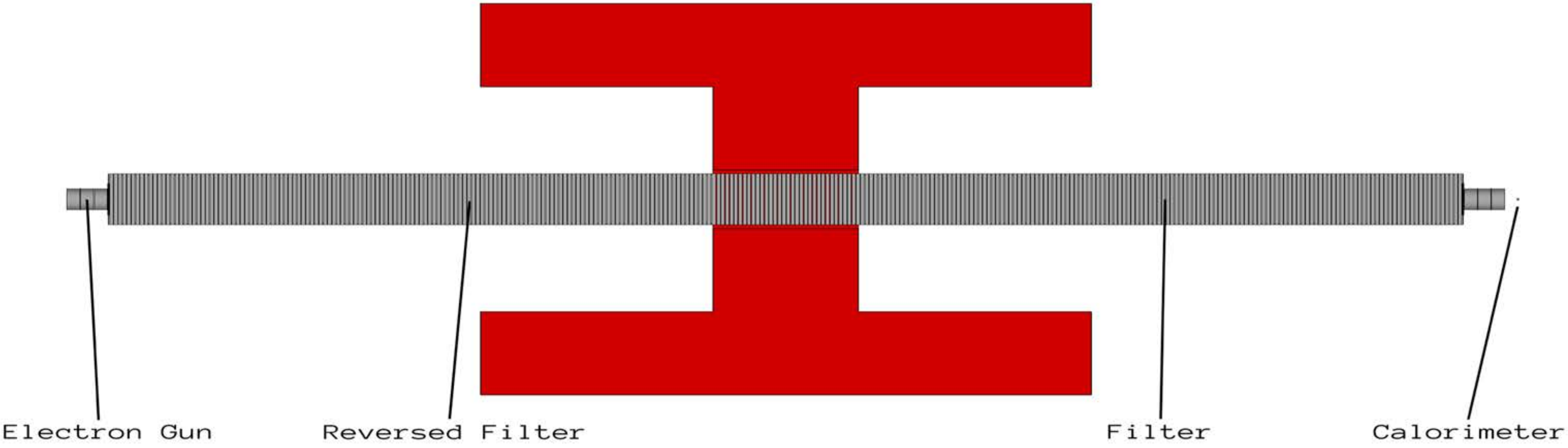


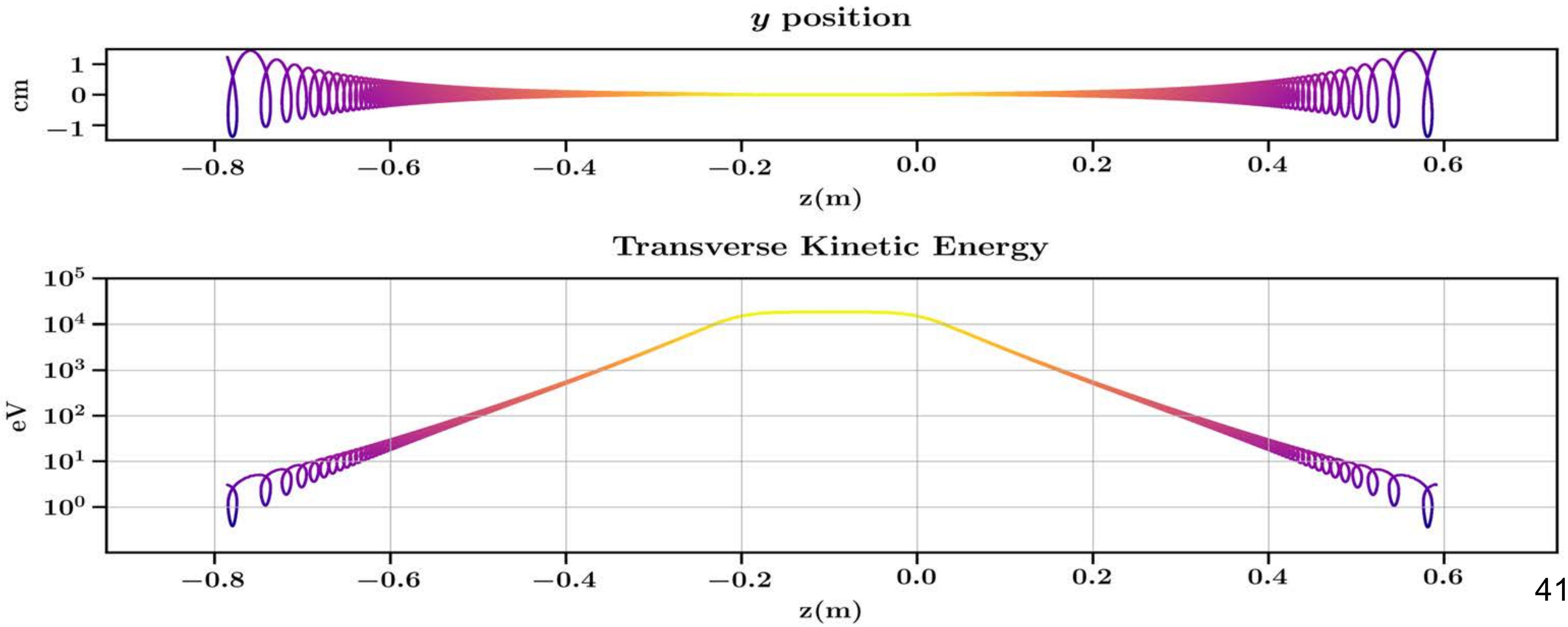


Electrode Voltages

Wonyong Chung
(Princeton)

Reverse Filter





Graphene Hydrogenation

PRINCETON UNIVERSITY

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PPPL PRINCETON PLASMA PHYSICS LABORATORY

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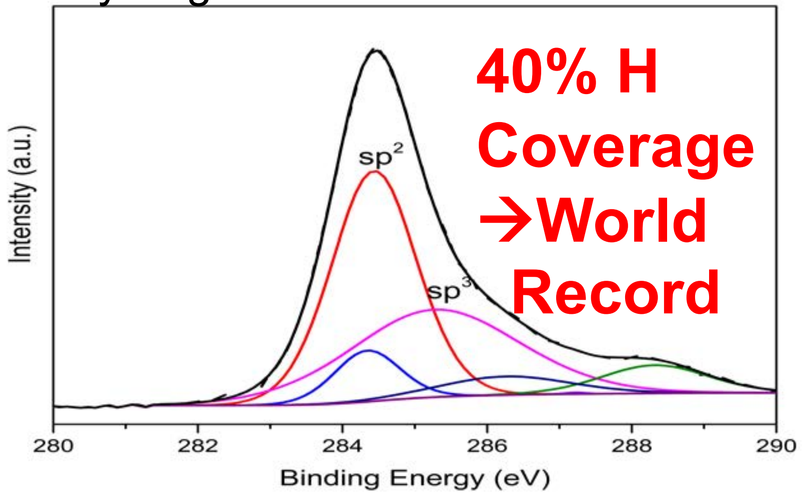
QUEST Research Magazine

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

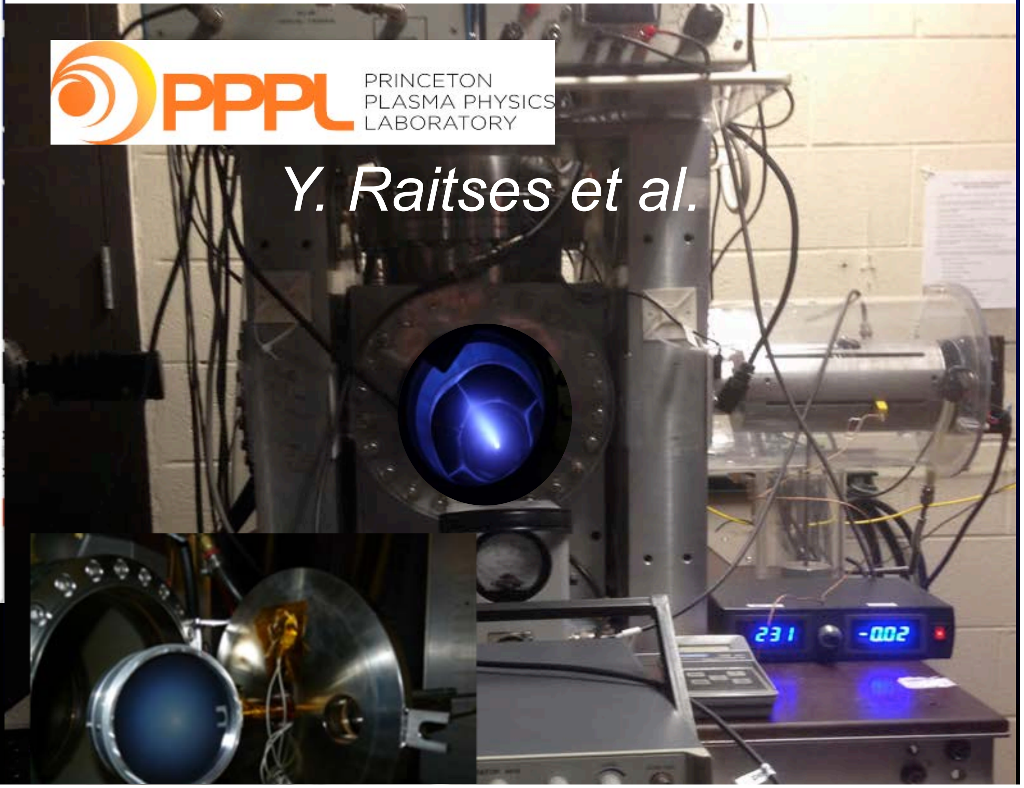
Physicist Fang Zhao with figure from her paper. (Photo courtesy of Fang Zhao.)

John Greenwald

XPS Hydrogenation Results from Princeton



40% H Coverage →World Record



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Y. Raitses et al.

Research support from the John Templeton Foundation