PTOLEMY: Experimental Quest to Detect Relic Neutrinos from the Big Bang

Chris Tully

Princeton University

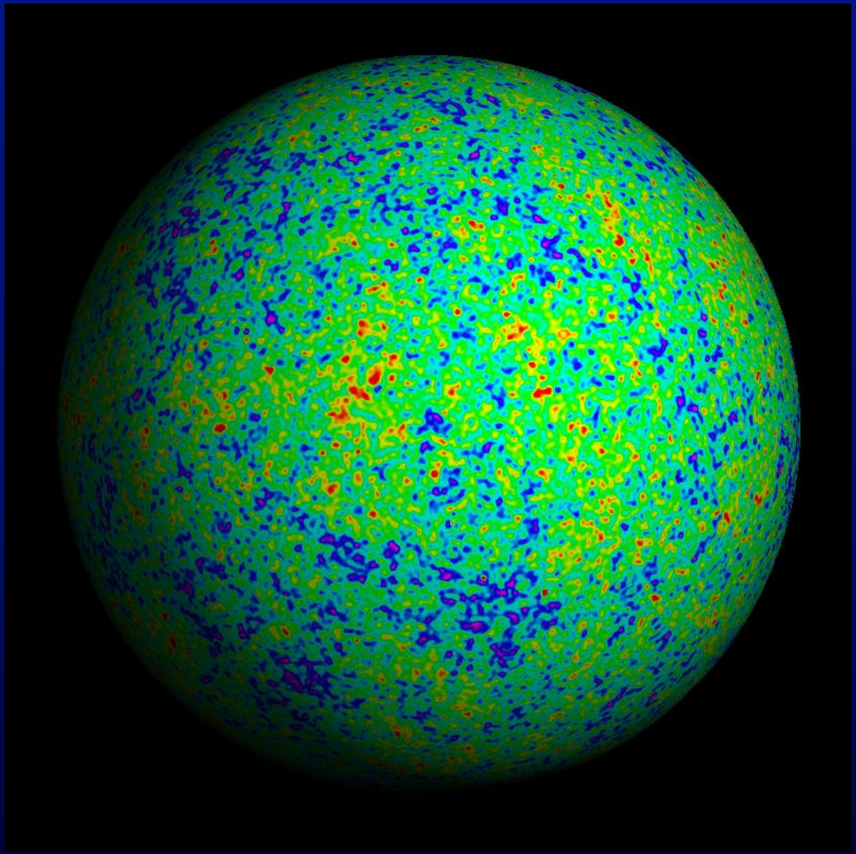
EPFL, Lausanne, Switzerland

6 December 2021

PTOLEMY: 2015 MPS Targeted Grant Award from the SIMONS FOUNDATION

Celestial Globes

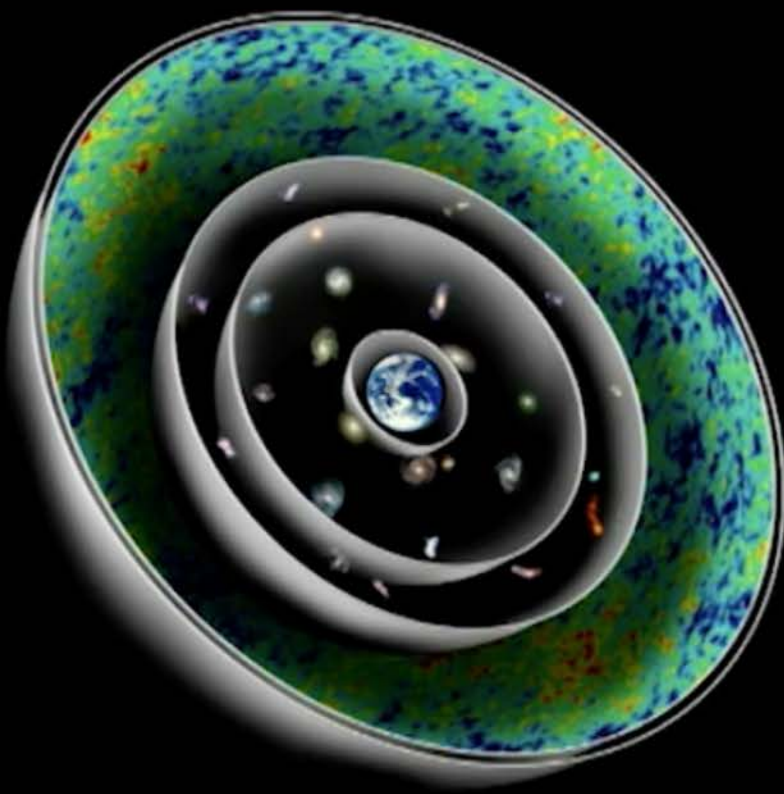
Johann Schöner, c.1534



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

WMAP, c.2009

Looking Back in Time

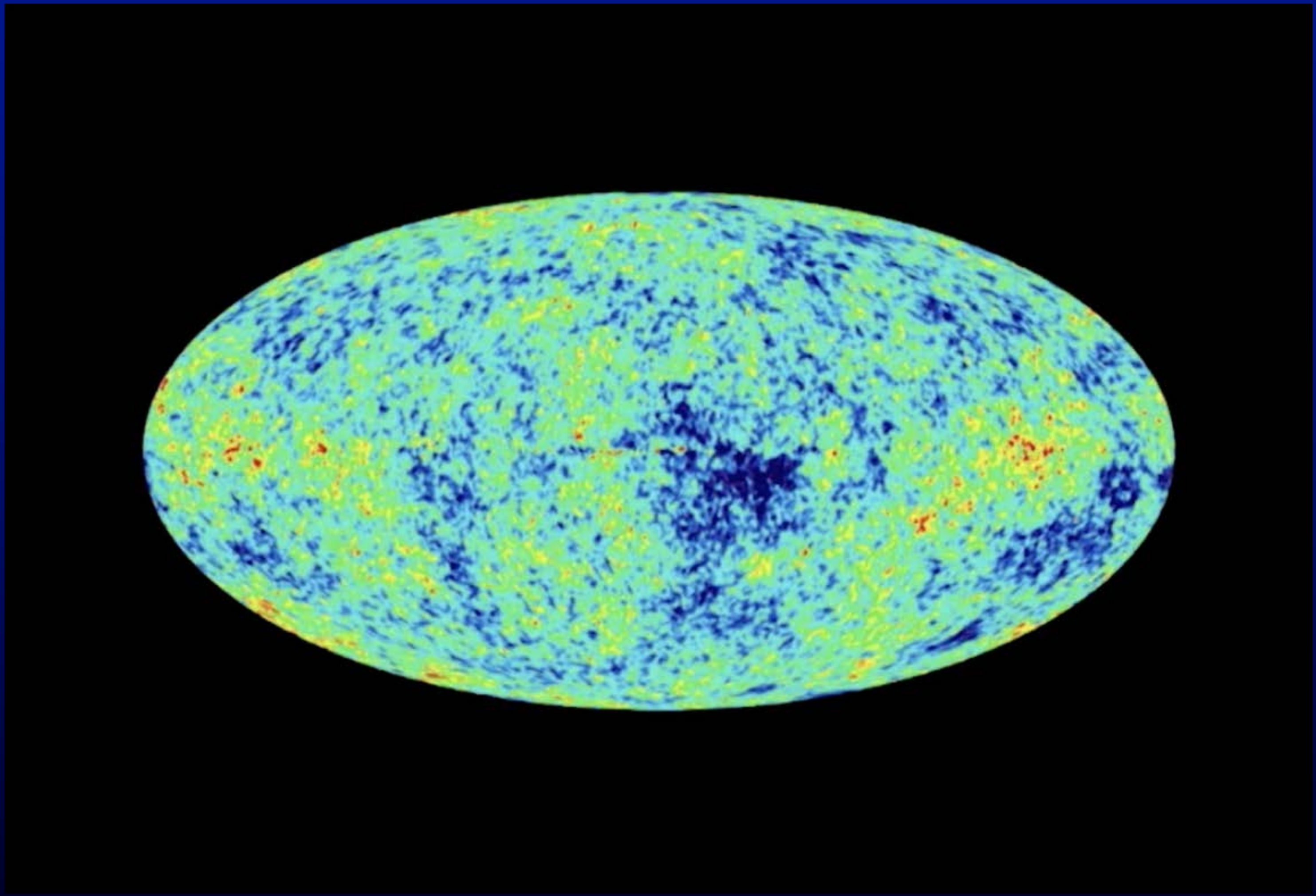


Le Sphere du Monde (1549)

https://iiif.lib.harvard.edu/manifests/view/drs:18260773$26i

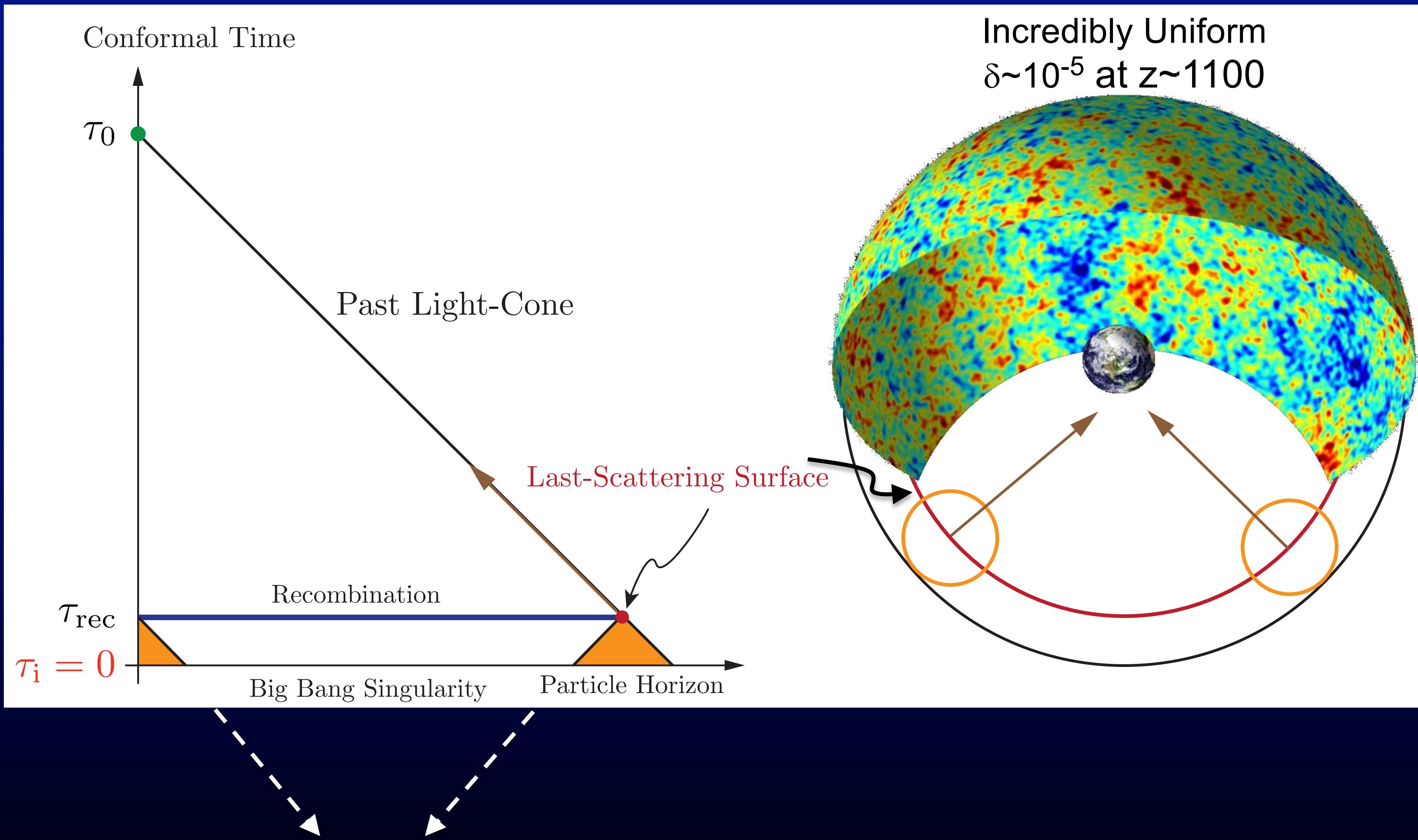
https://gravity.princeton.edu/events/gravity-initiative-opening-celebration-november-7-8-2019

Evolution from First Light to Today



https://gravity.princeton.edu/events/gravity-initiative-opening-celebration-november-7-8-2019

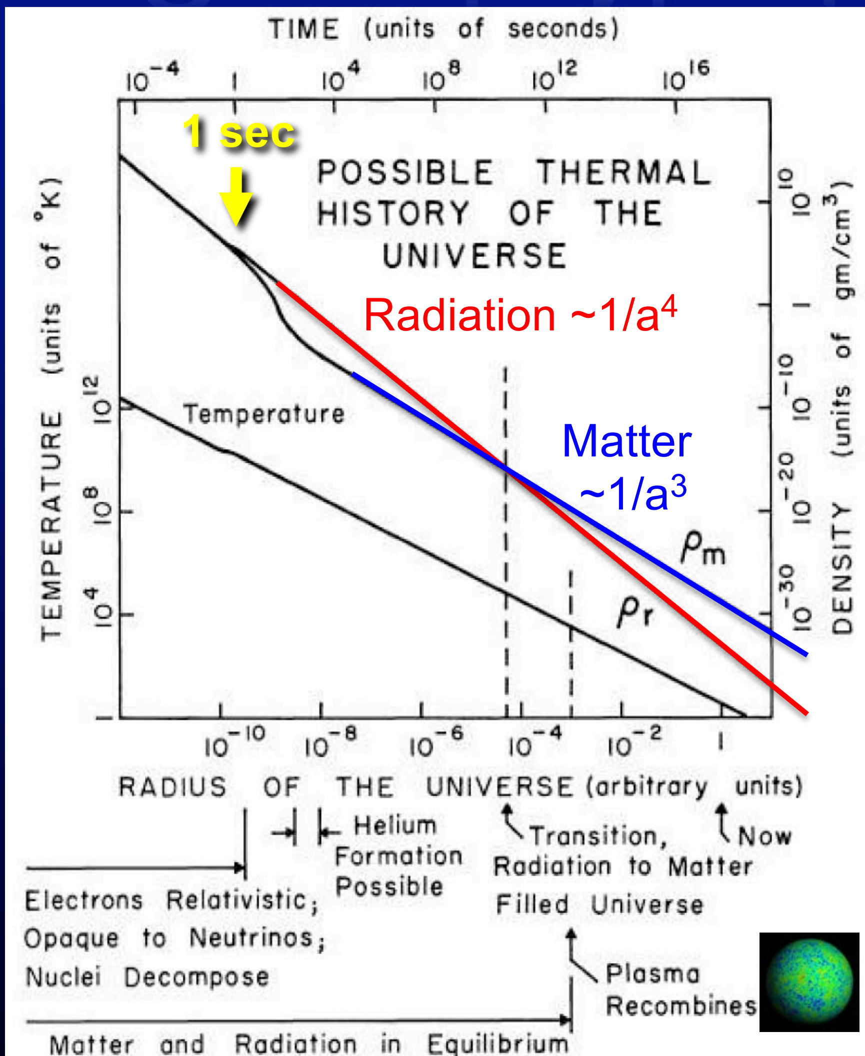
Big Bang Cosmology



Common Past?

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

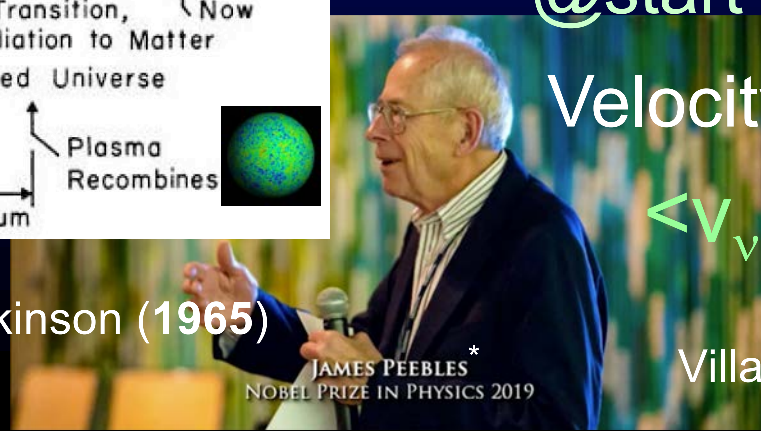
neutron/proton ratio @start of nucleosynthesis

Velocity distribution:

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

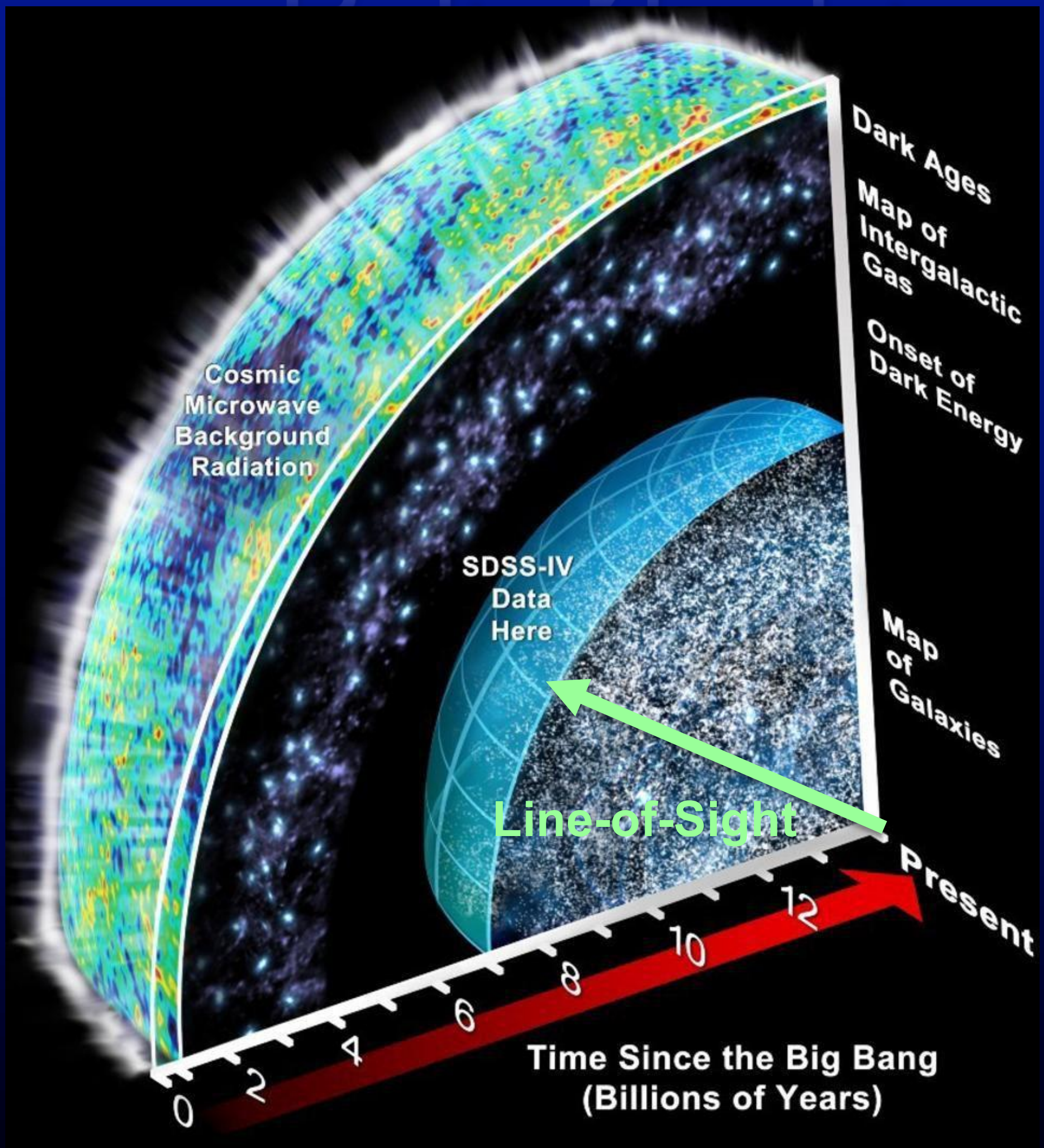
Non-linear distortions
Villaescusa-Navarro et al (2013)

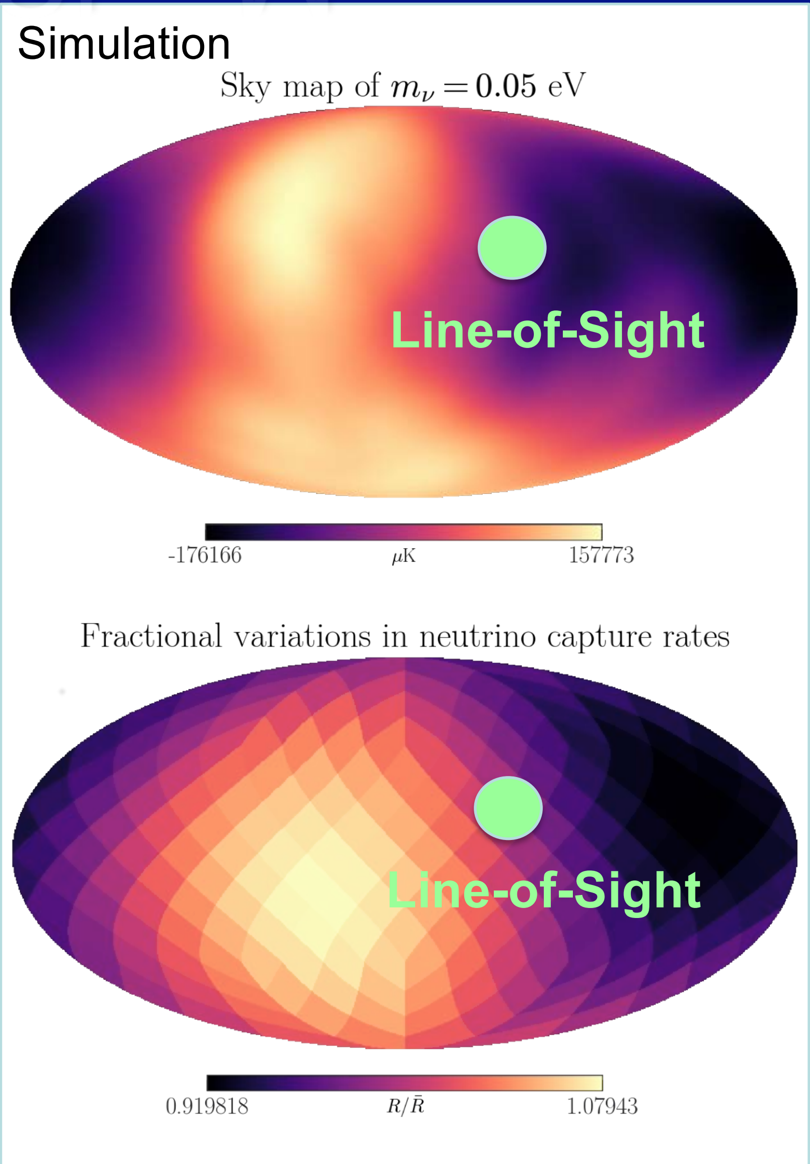
Dicke, Peebles*, Roll, Wilkinson (**1965**)



Cosmology's Century (2020)

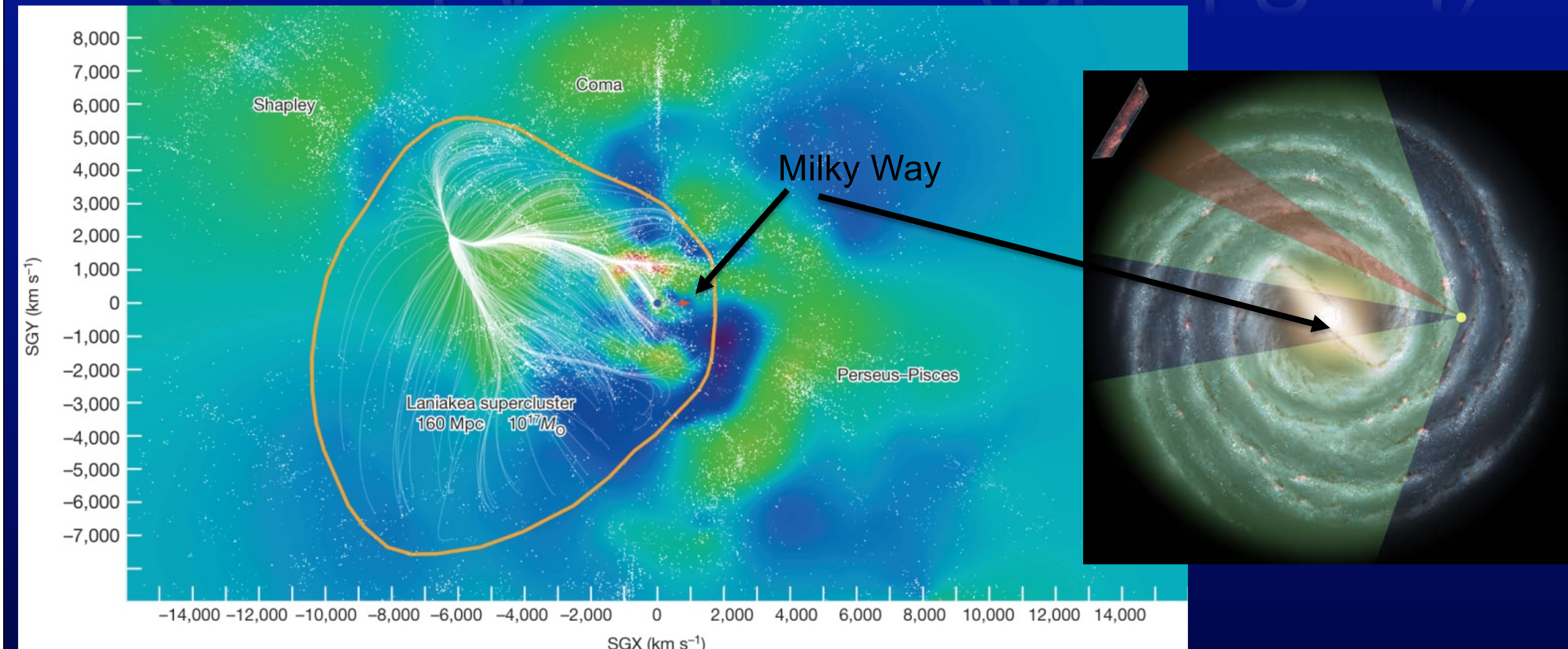
Relic Neutrino Sky Map





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)

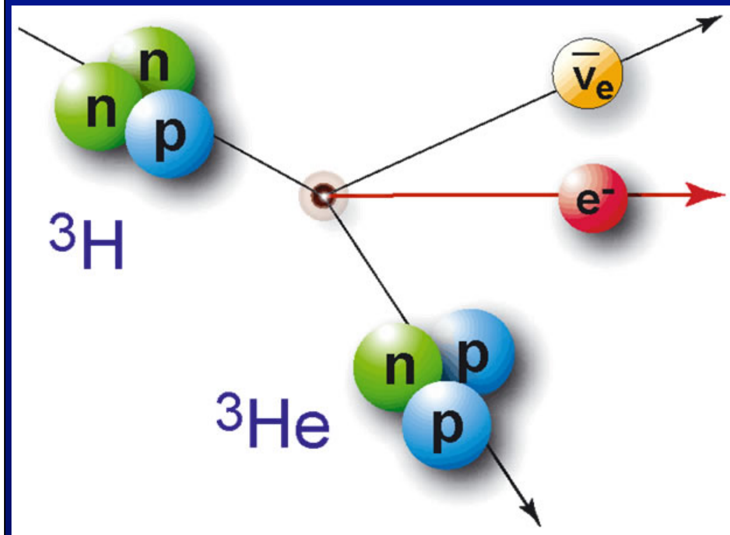


RB Tully *et al.* *Nature* **513** , 71-73 (2014)
http://doi.org/10.1038/nature13674

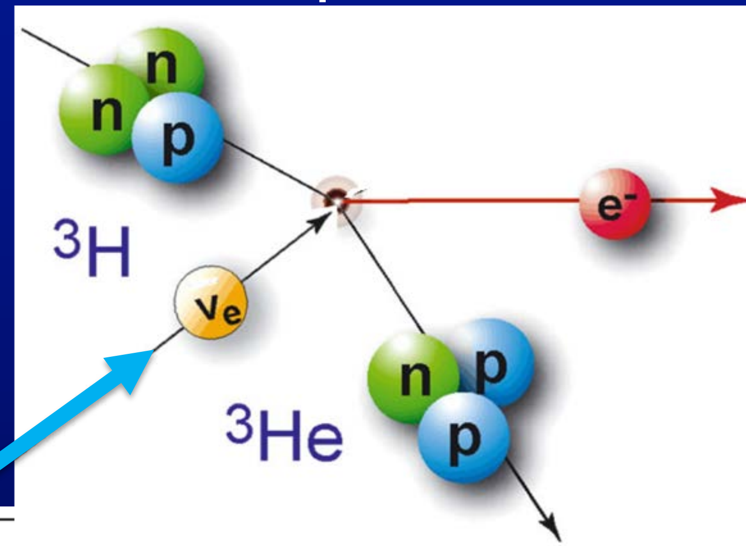
Neutrinos can see behind the Milky Way!
If relic neutrinos exist in the Universe today, then we can validate the over- and underdensities in the nearest 100-200 Mpc

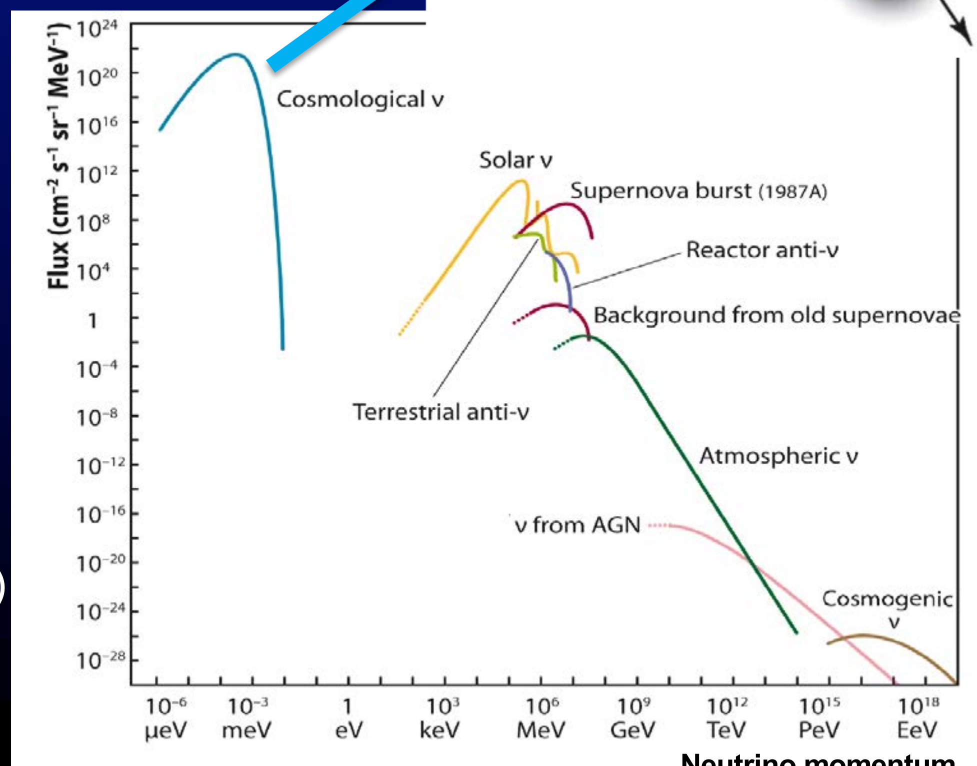
https://www.nytimes.com/2020/07/10/science/astronomy-galaxies-attractor-universe.html

Neutrino capture on Tritium



Tritium β-decay
(12.3 yr half-life)





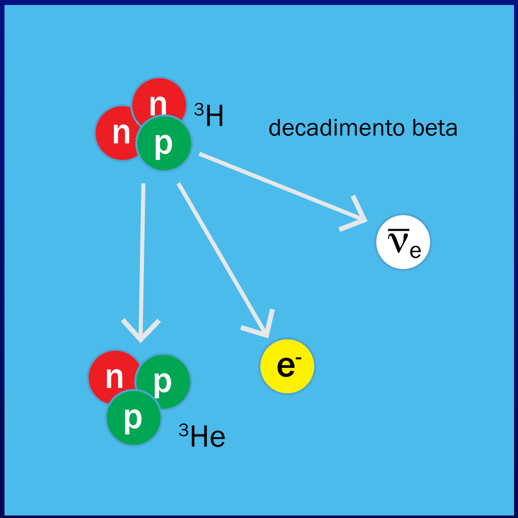
Neutrino momentum ~ 0.17 meV

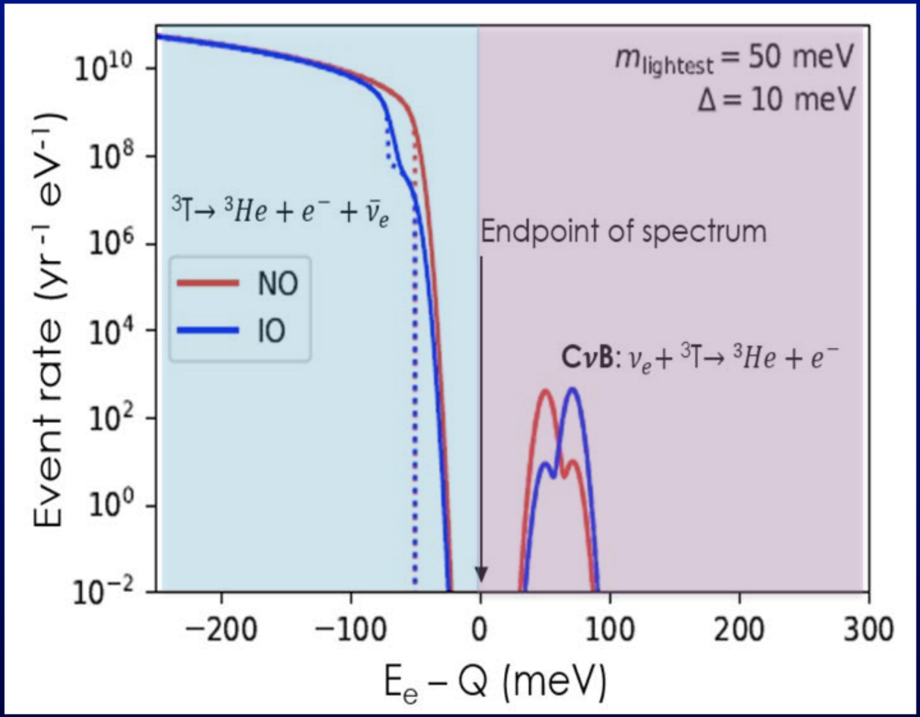
For m_ν = 50 meV,
KE = $p^2/2m$
= 0.17 meV (0.17 meV/100 meV)
= 0.3 μeV

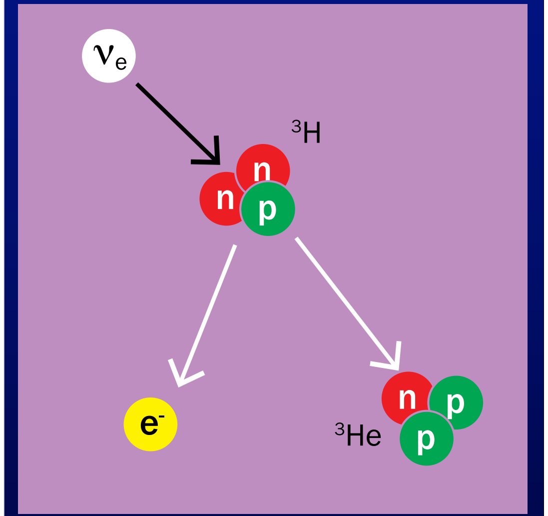
Ultra-Cold!

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] 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:

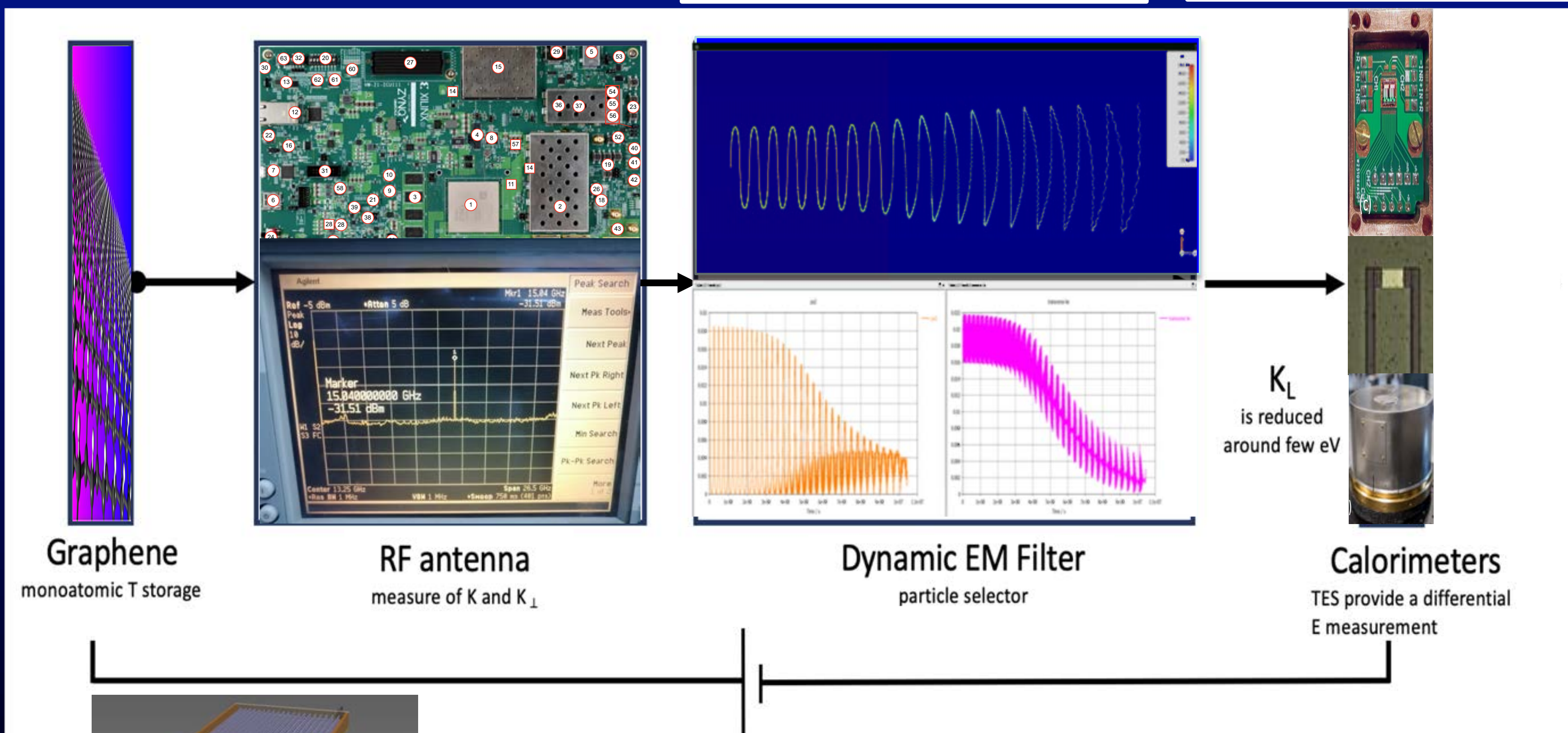
few x 10^{-6} energy resolution set by m_ν

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

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

PTOLEMY Conceptual Block Diagram

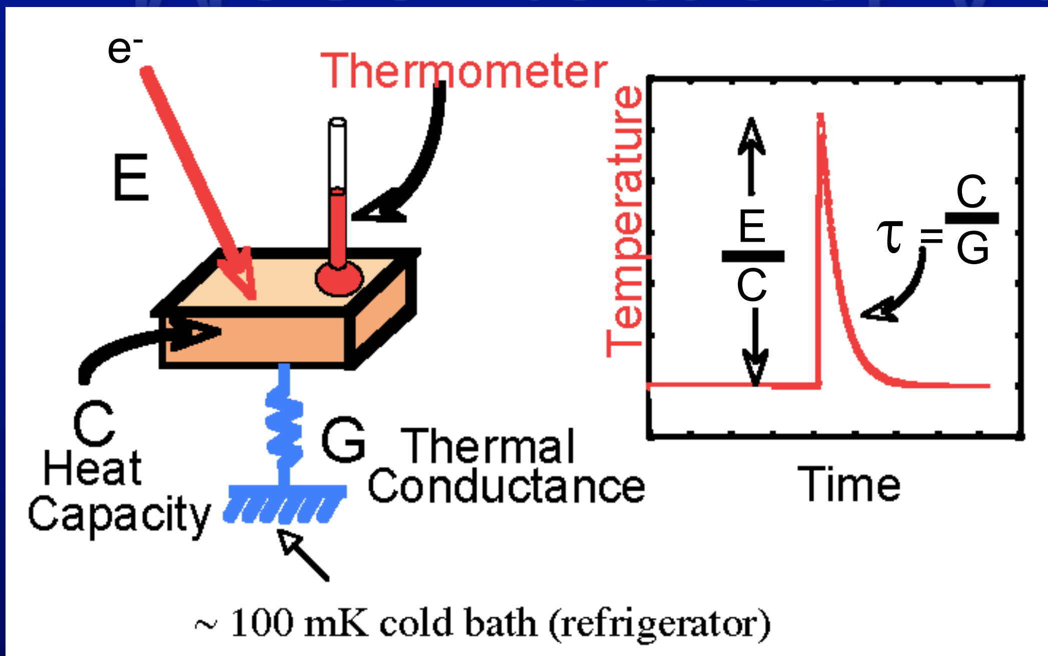
Target: Relic Neutrino Capture → **RF Tracker: Electron Pre-Measurement** → **Dynamic Filter: Selects endpoint electron in narrow 10^{-4} energy window** → **Micro-calorimeter: Measures few eV electron to 10^{-2} energy resolution**



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

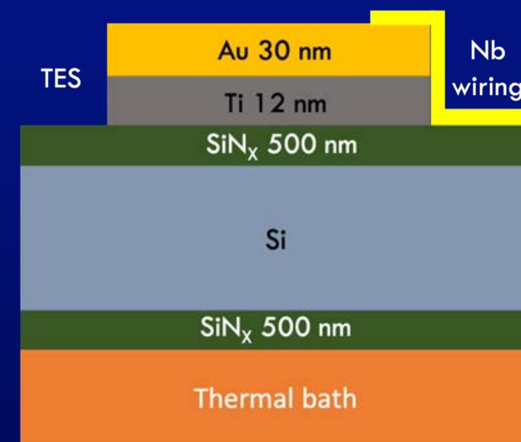
https://ptolemy.lngs.infn.it

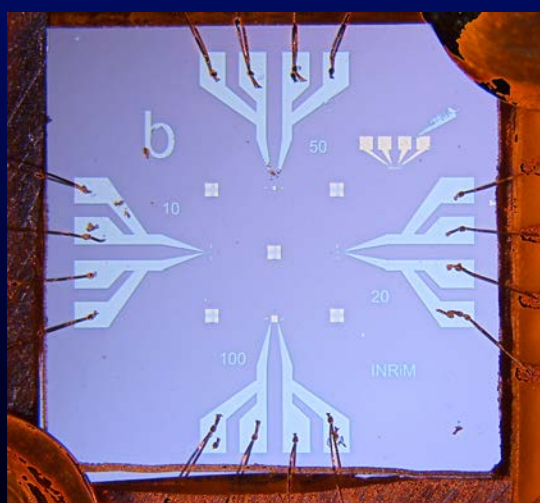
Measurement Arm: μCal

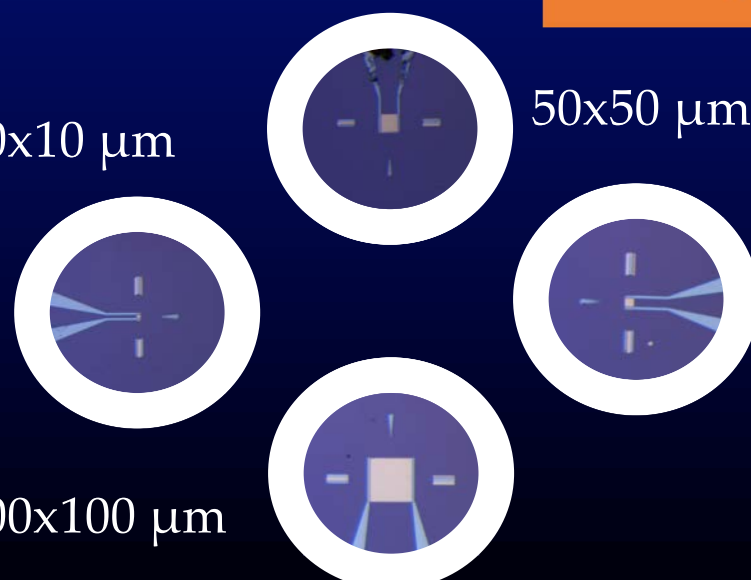


Thin sensors:

~1 eV electron can be stopped with very small C







10x10 μm

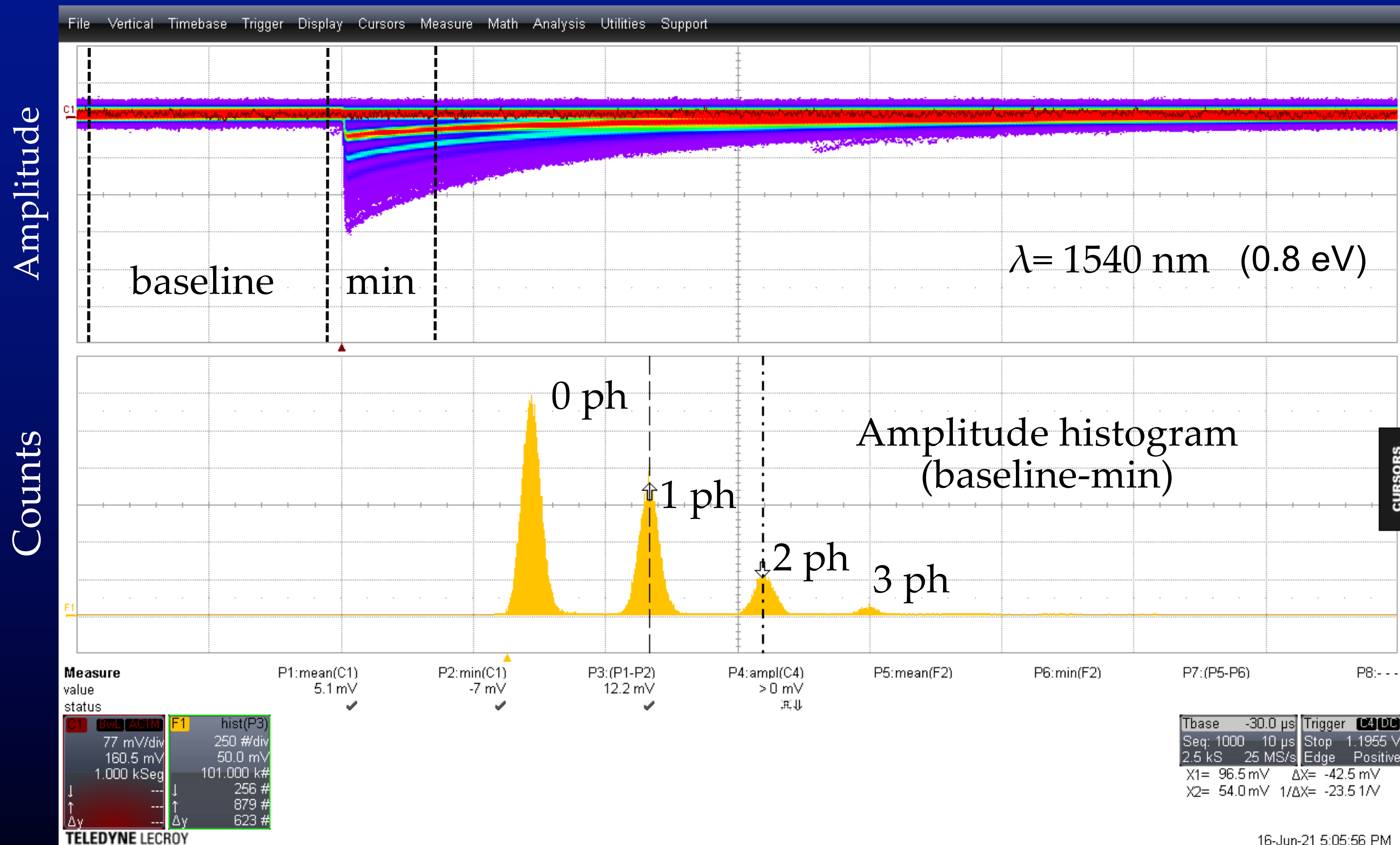
50x50 μm

20x20 μm

100x100 μm

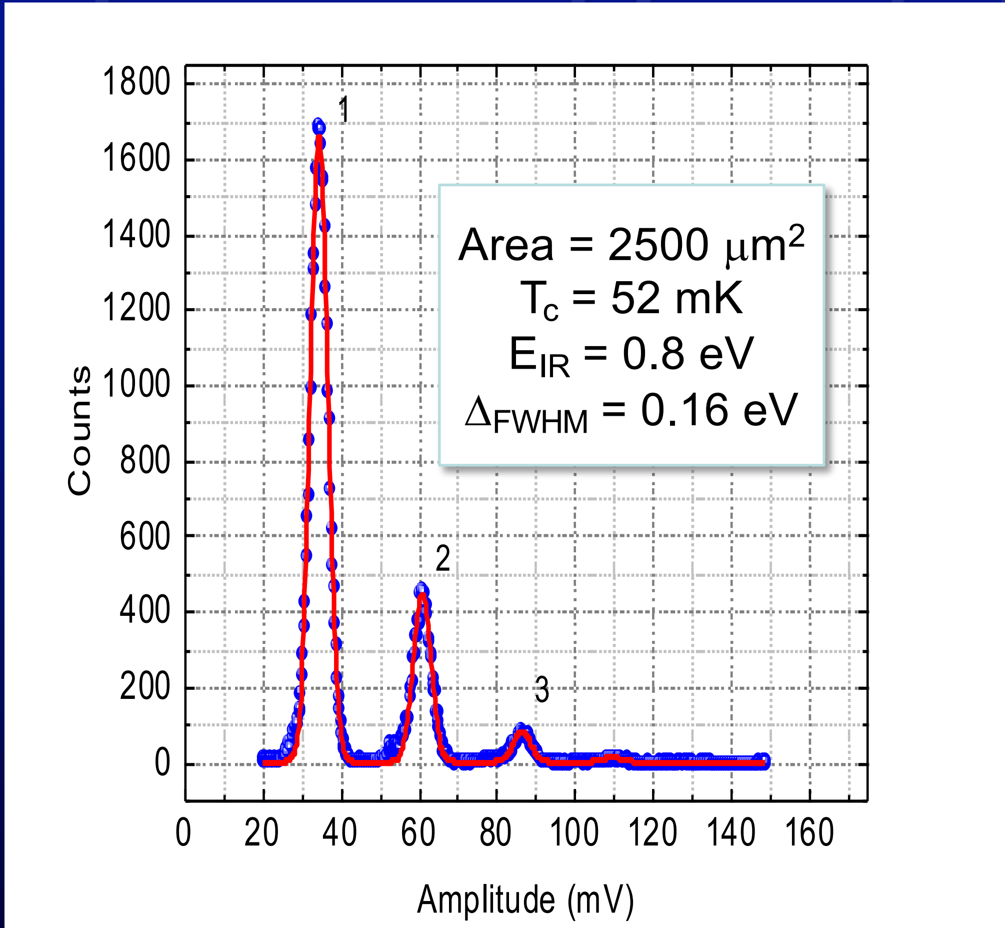
Mauro Rajteri, Eugenio Monticone and others, https://doi.org/10.1007/s10909-019-02271-x
"TES Microcalorimeter for PTOLEMY", J. Low Temp. Phys. 199 (2020) 138-142.

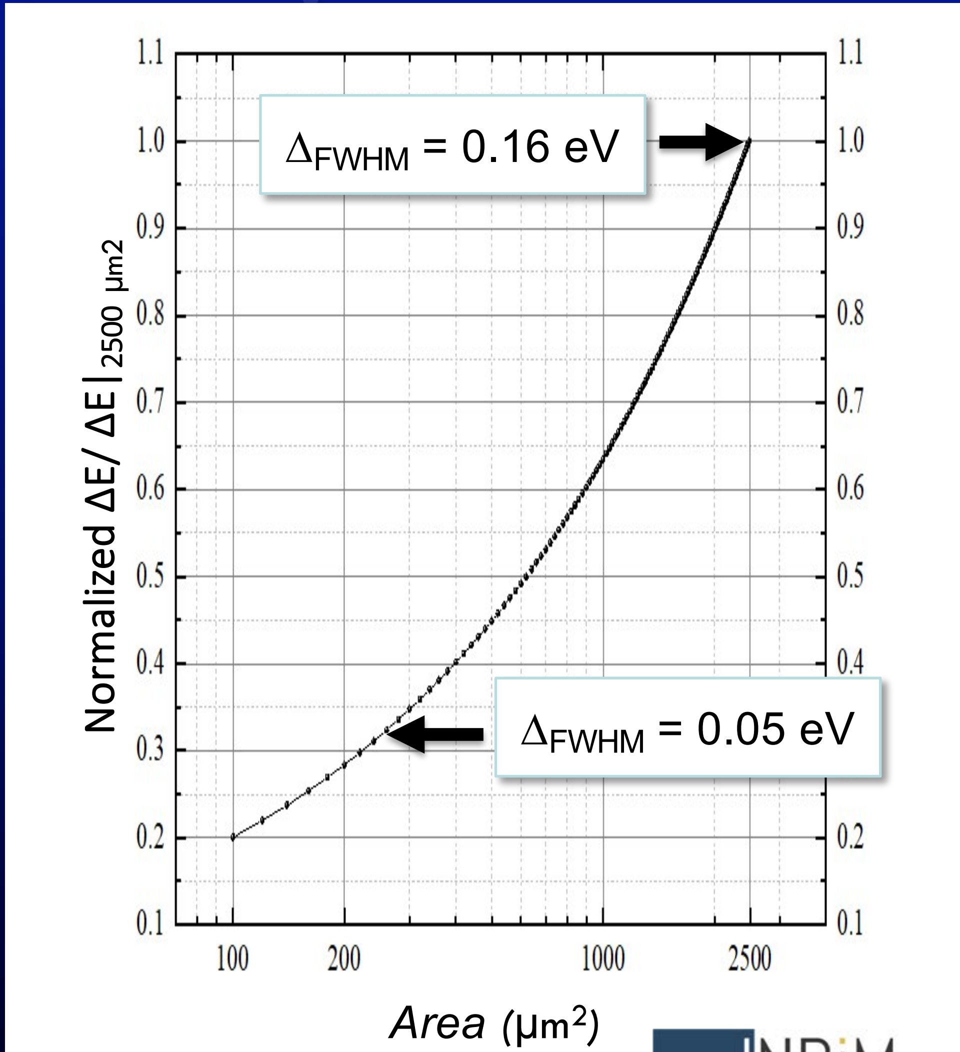
Single IR Counting



C. Pepe, E. Monticone, M. Rajteri

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





Resolution of ~ m_ν :

Area ~ 15 μm x 15 μm

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

C. Pepe, E. Monticone, M. Rajteri

→ Demonstrate with electrons

Electromagnetic Filters

MAC-E filter

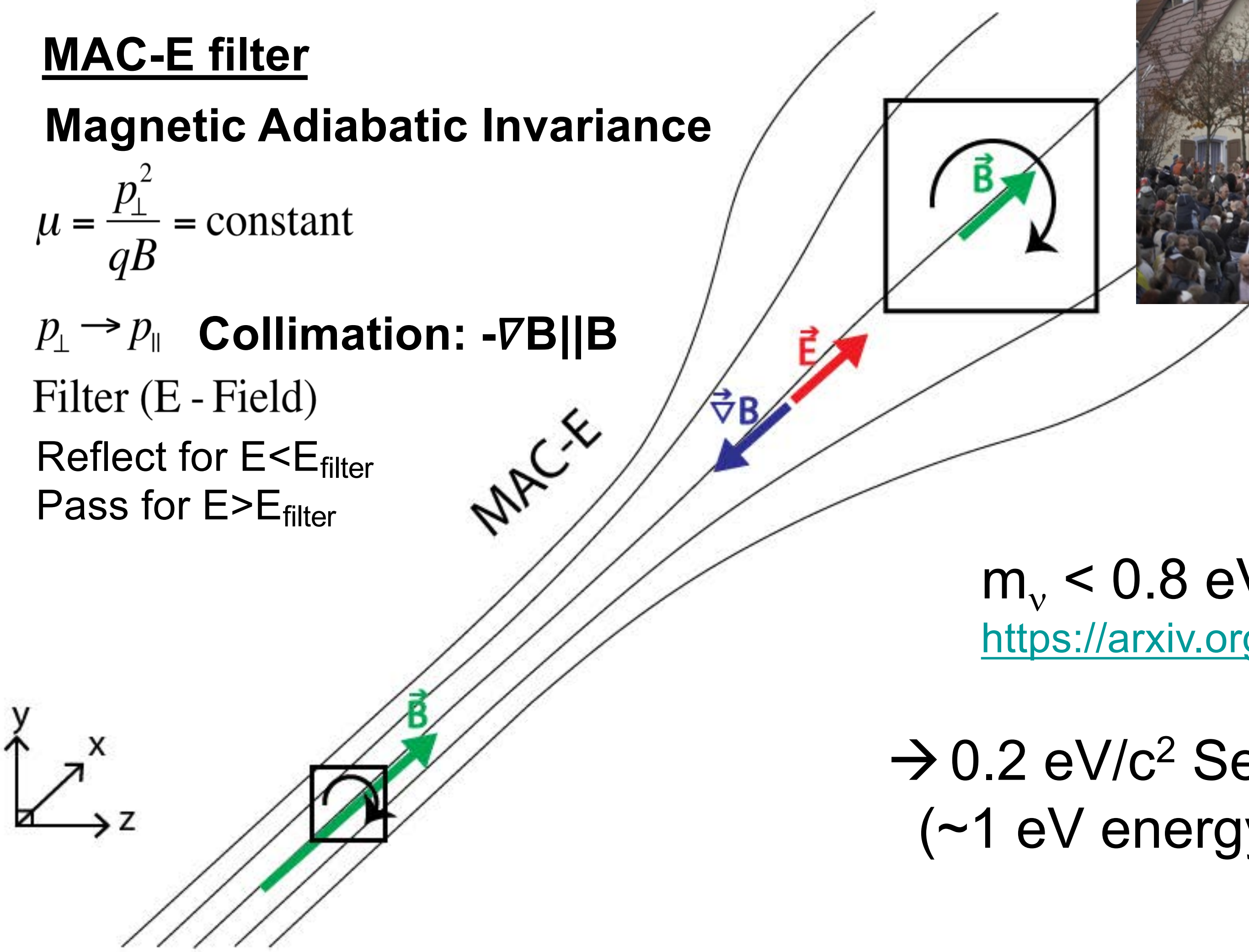
Magnetic Adiabatic Invariance

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

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

Filter (E - Field)

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



KATRIN

~1200m^3

$m_\nu < 0.8$ eV/c^2 (90% CL)
https://arxiv.org/abs/2105.08533

→ 0.2 eV/c^2 Sensitivity Goal
(~1 eV energy resolution)

Electromagnetic Filters

Transverse Drift filter

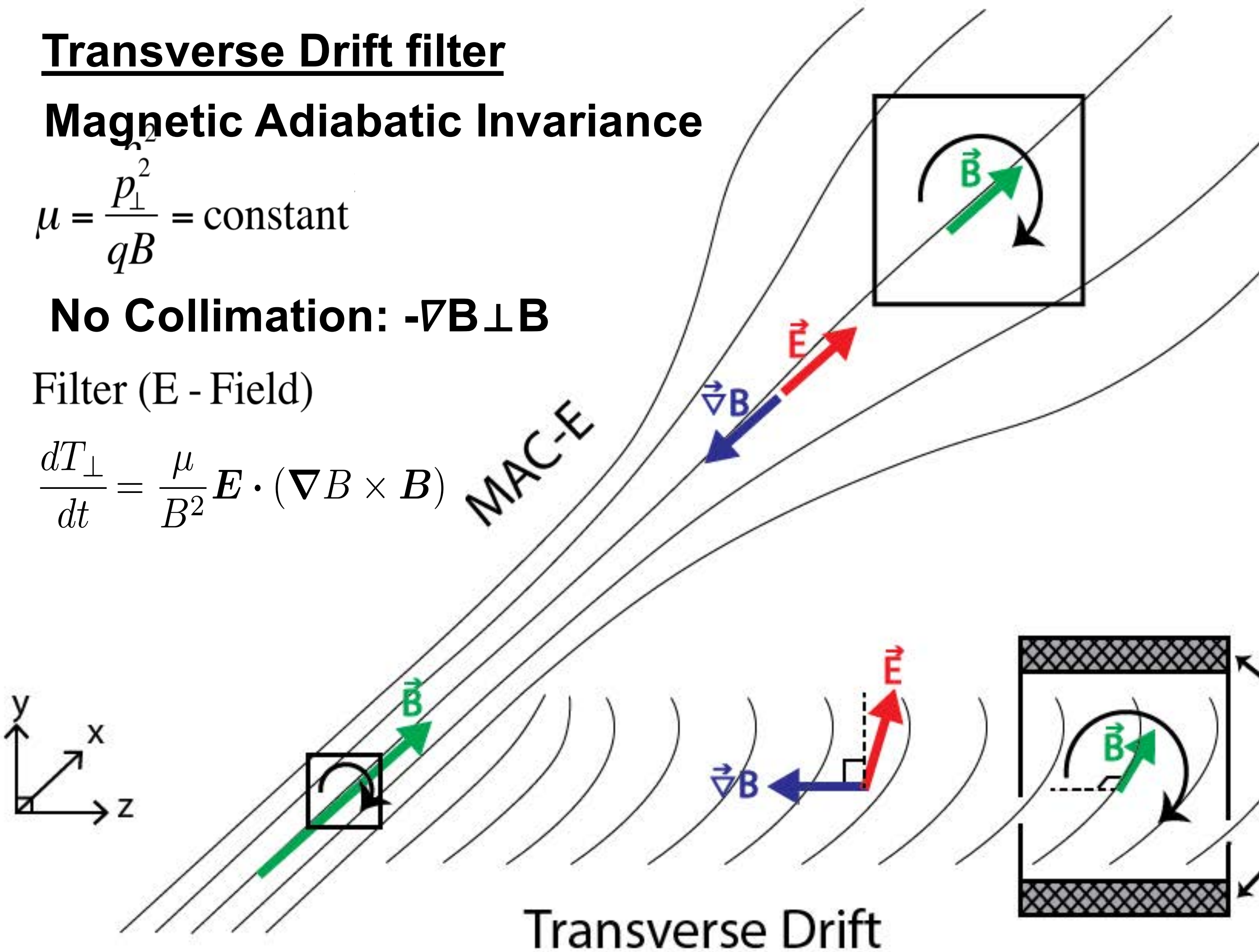
Magnetic Adiabatic Invariance

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

No Collimation: -∇B⊥B

Filter (E - Field)

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



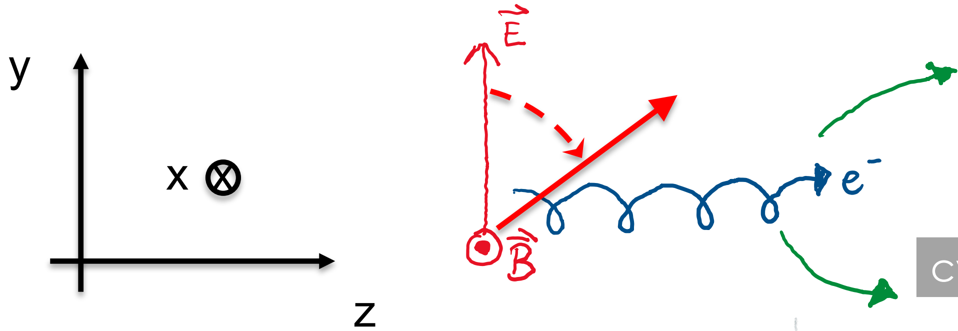
PTOLEMY

~1m^3

PTOLEMY Filter Concept

Auke Pieter Colijn (PATRAS 2019)

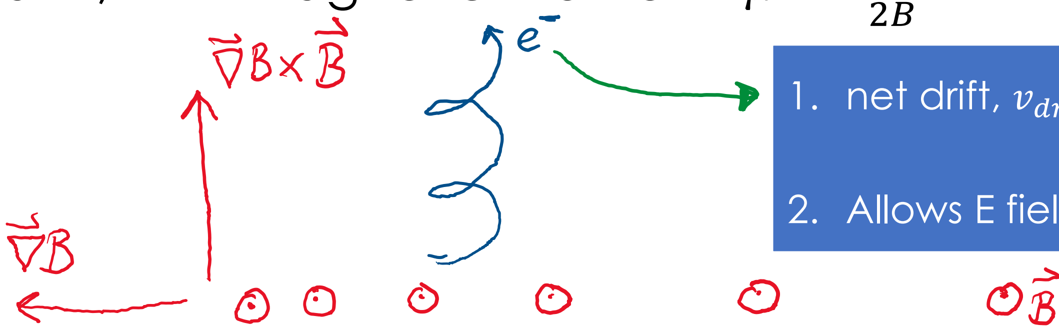
I: $\vec{E} \times \vec{B}$ drift



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

cyclotron motion – detectable RF

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



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

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

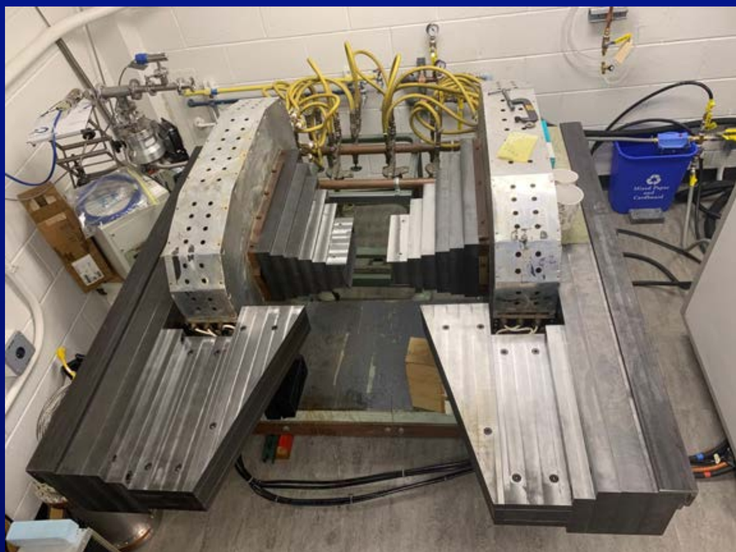
$$V_{\nabla B}(z)|_{x,y=0} = -\frac{\boldsymbol{\mu} \times \boldsymbol{\nabla}_\perp \boldsymbol{B}(\boldsymbol{z})}{qB(z)} = -\frac{\mu}{qB_x} \frac{dB_x}{dz} \hat{\boldsymbol{y}}$$

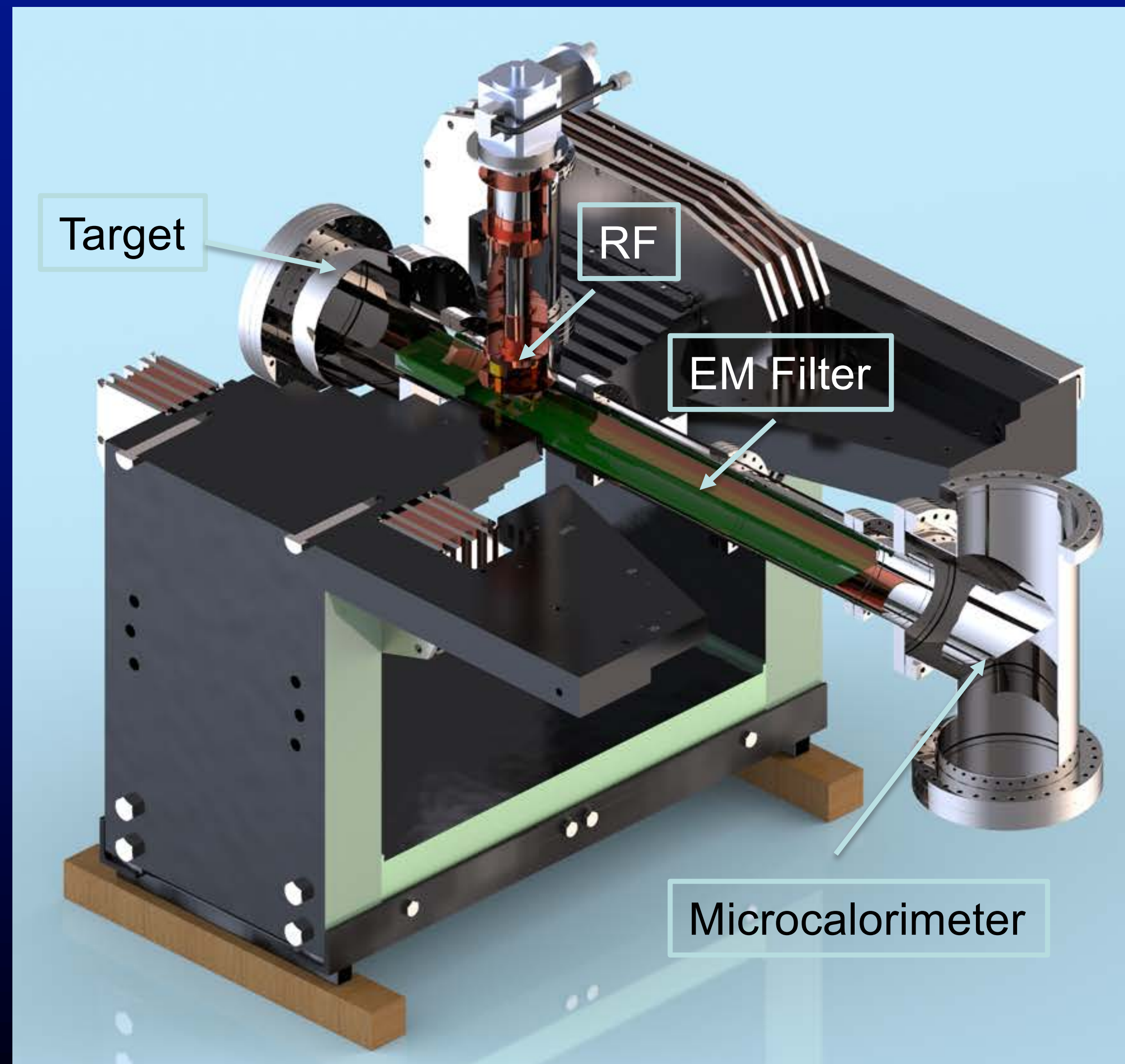
Enforce zero drift in y (rotate E):

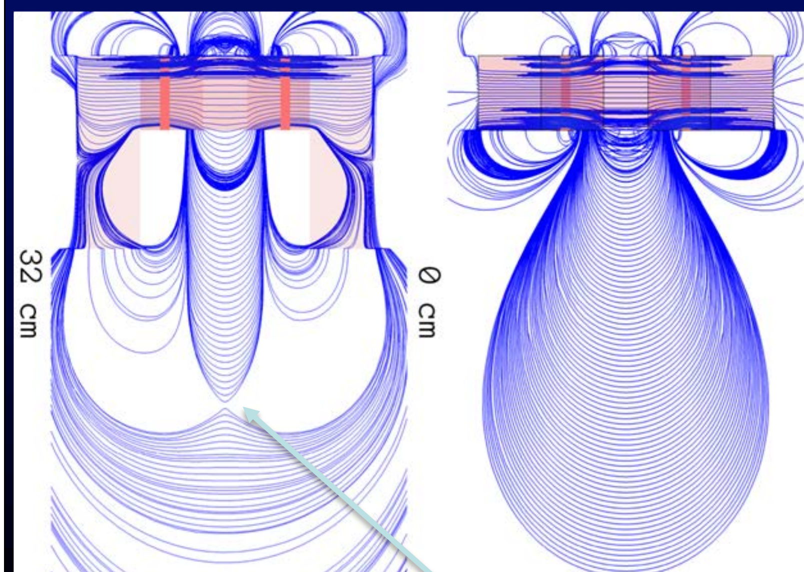
$$\xrightarrow{\text{yields}} \quad E_z(z)|_{y=0} = -\frac{\mu}{q} \frac{dB_x(z)}{dz}$$

Filter R&D Development Setup

Andi Tan (Princeton)





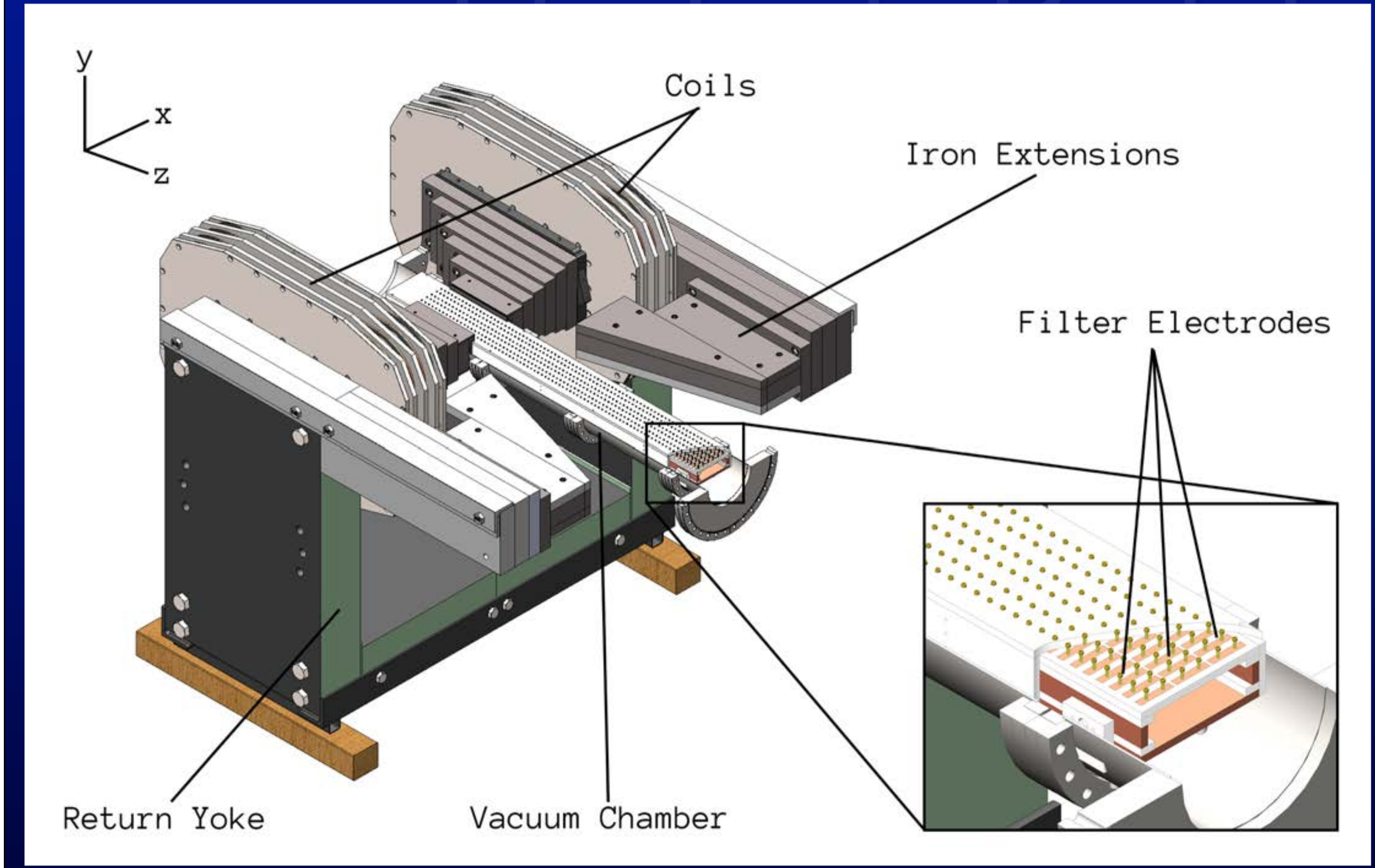


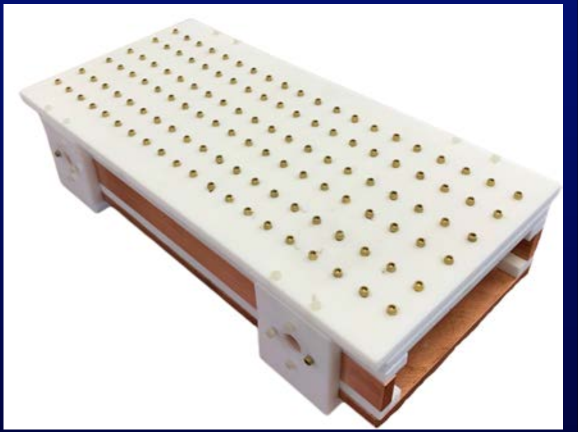
Wonyong Chung (Princeton)

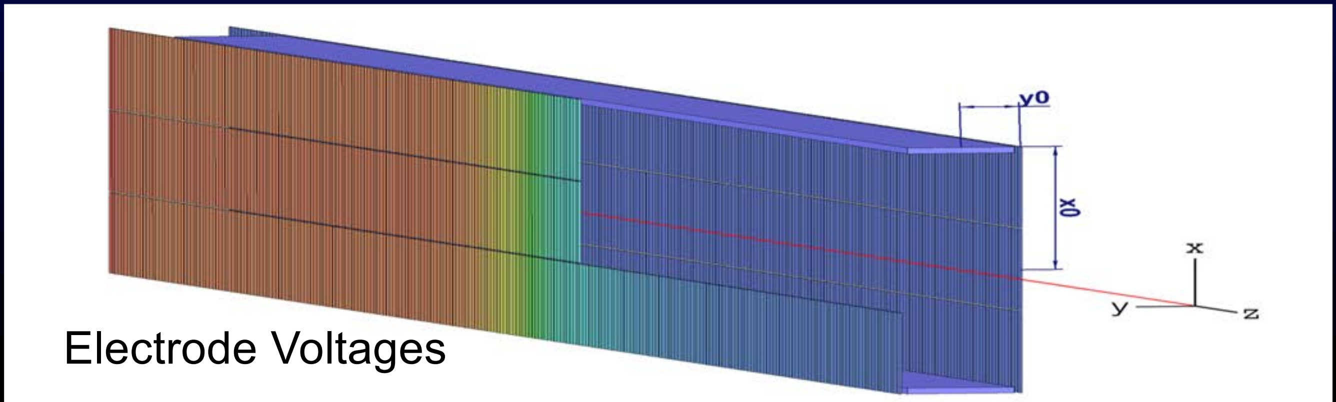
Zero field (location for TES microcalorimeter)

Electrode Prototype

Andi Tan (Princeton)







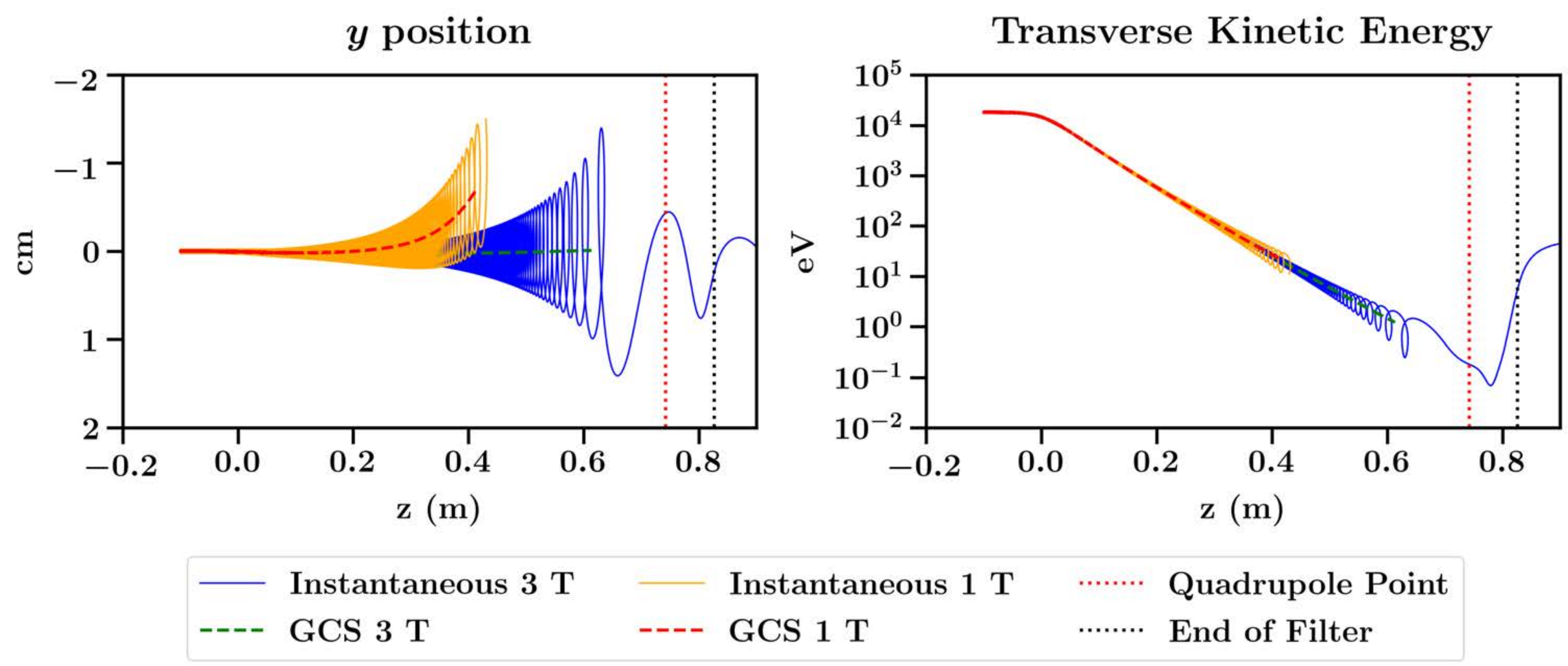
Wonyong Chung
(Princeton)

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)

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

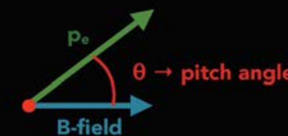
https://www.nwo.nl/en/researchprogrammes/dutch-research-agenda-nwa/research-along-routes-consortia-nwa-orc/awards-nwa-orc

Larmor formula

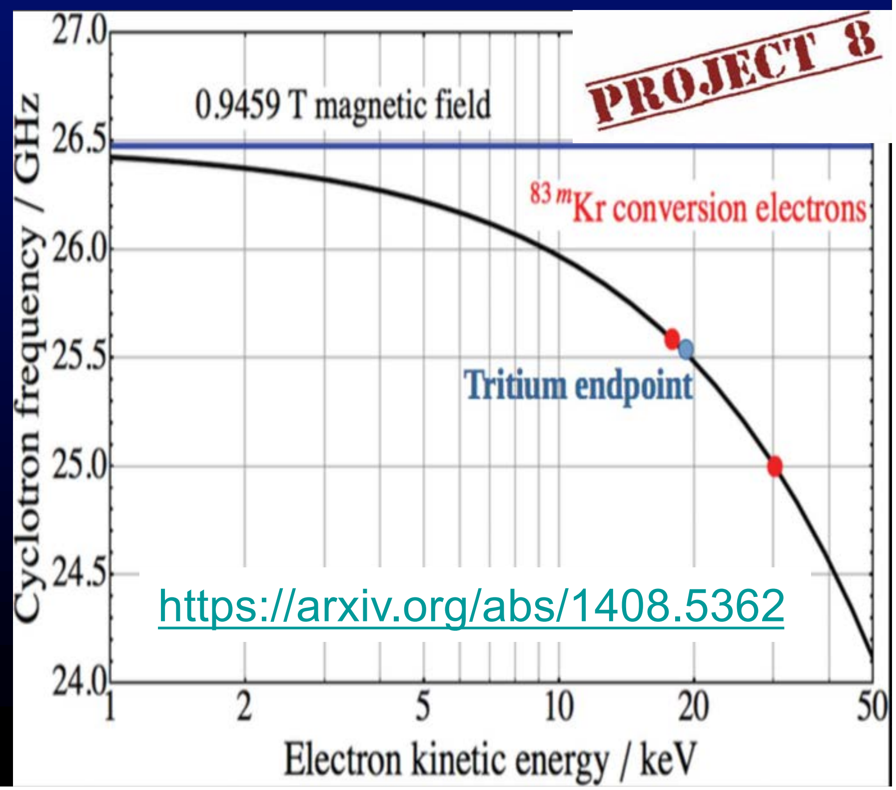
$$P(\gamma,\theta) = \frac{1}{4\pi\varepsilon_0}\frac{2}{3}\frac{q^4B^2}{c\,m_e^2}(\gamma^2-1)\sin^2\theta$$

Emitted power

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



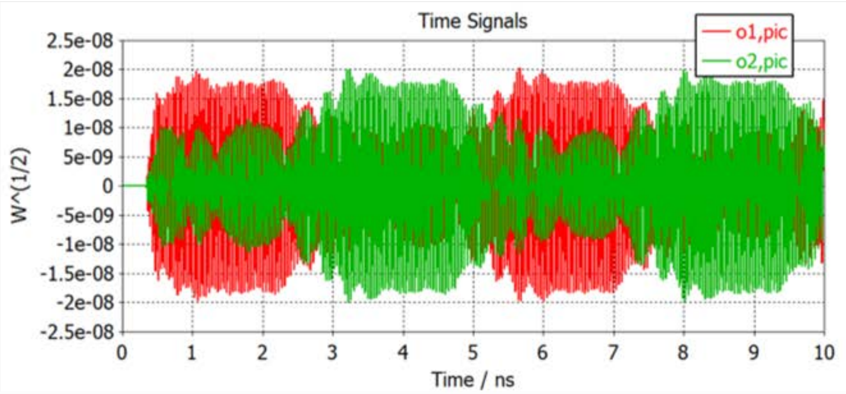
→ Low-noise cryogenic RF-system needed!



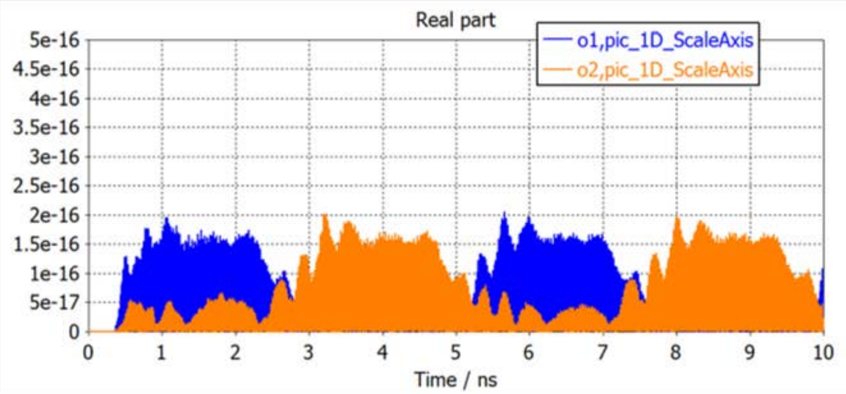
https://arxiv.org/abs/1408.5362

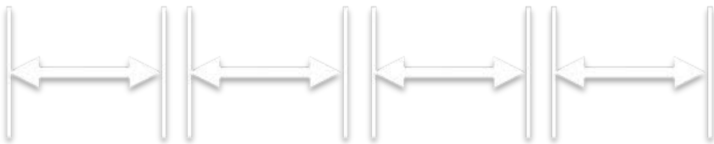
RF Tracking

Time Series (~26 GHz)

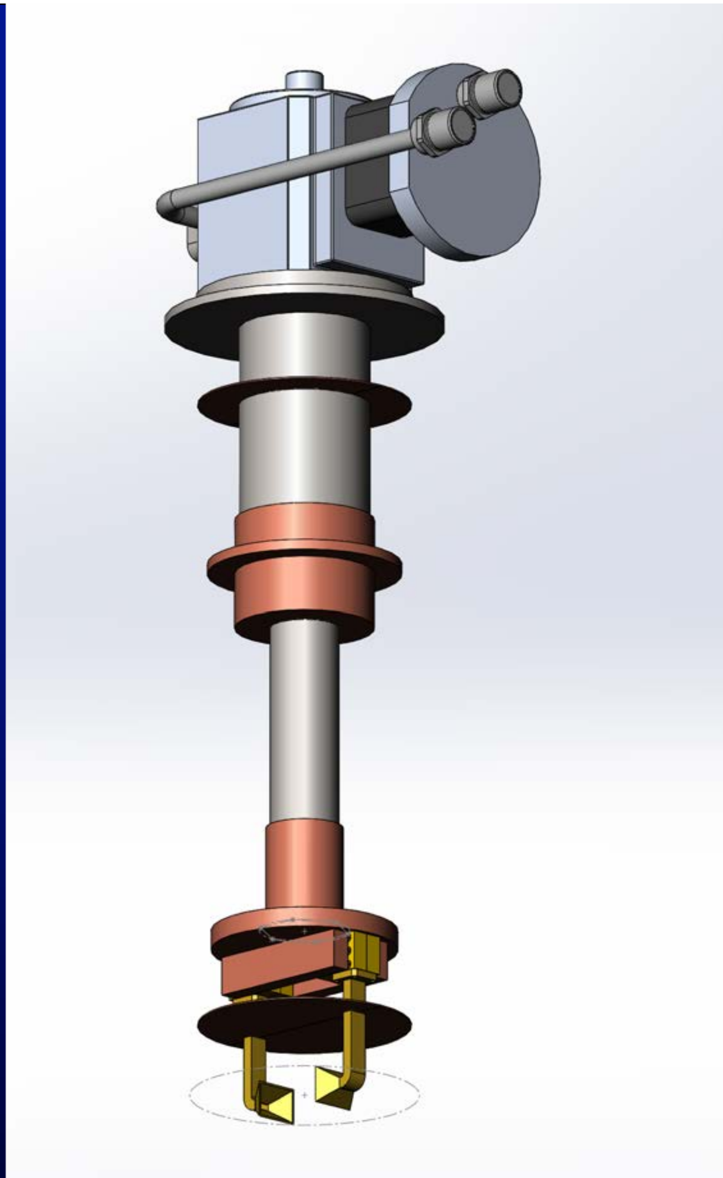


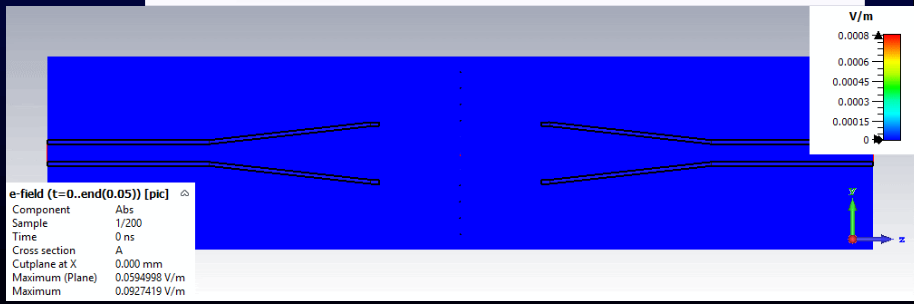
Power(~0.1 fW)





Right Left Right Left



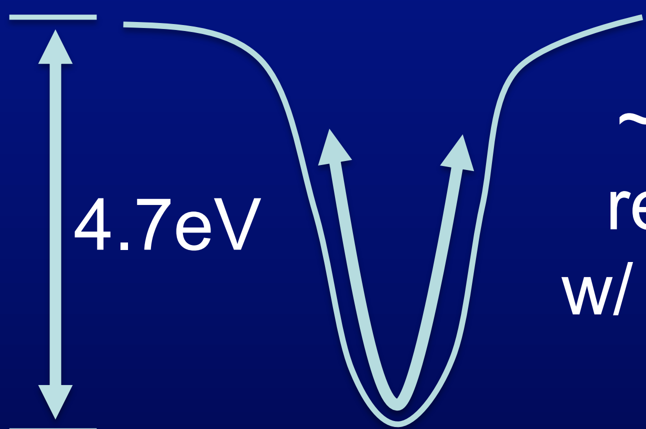


Target: Molecular Broadening

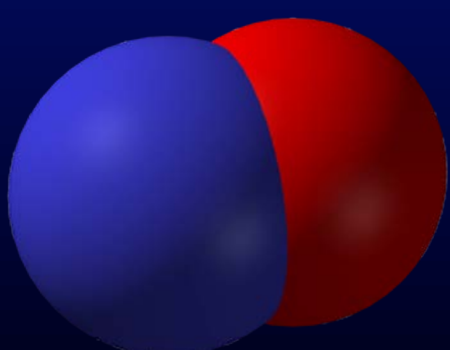
Gaseous target not ideal

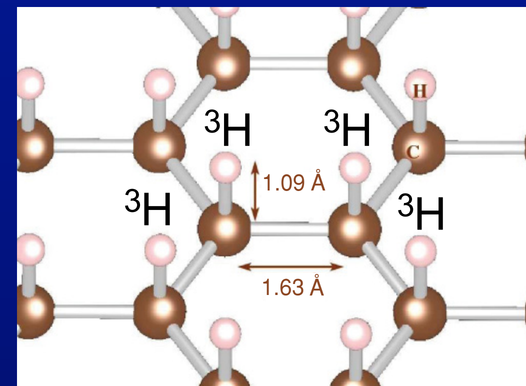
T-T → $(\text{T-He}^3)^{+*}$

*Many close-spaced ro-vibrational excited states



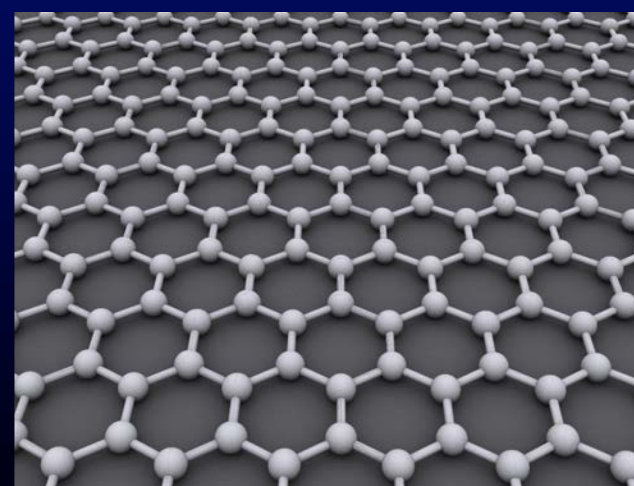
~1.7eV $(\text{T-He}^3)^{+*}$ recoil at endpoint w/ ~0.3eV spread(*)





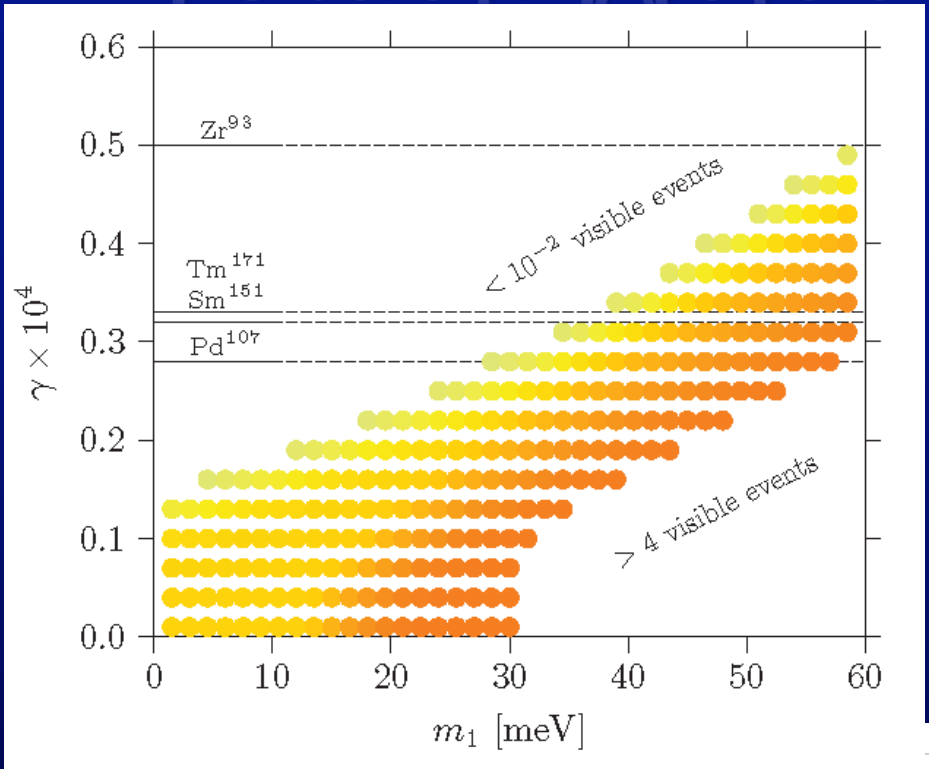
~1eV binding energy

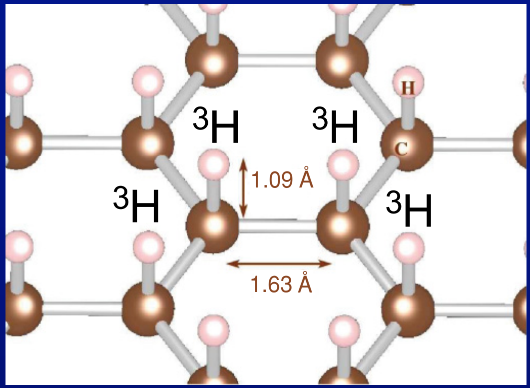
Planar target: Graphene



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

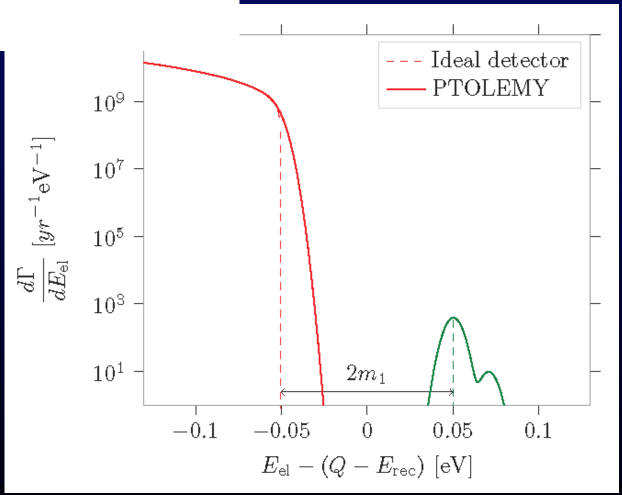
Target: Molecular Broadening

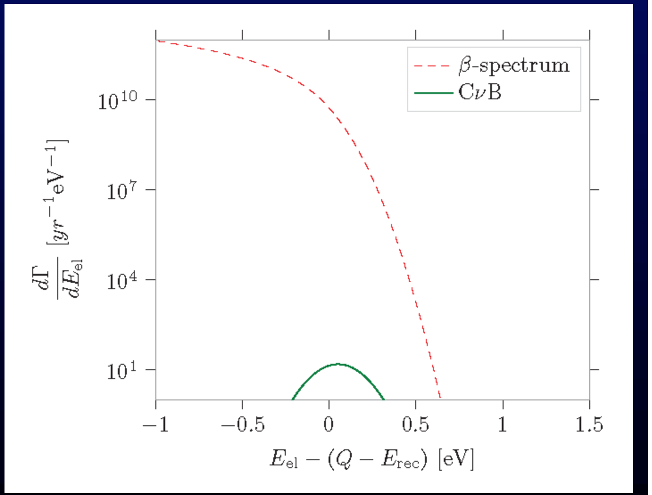




Too "Localized"

Optimal
"Heavy" Targets

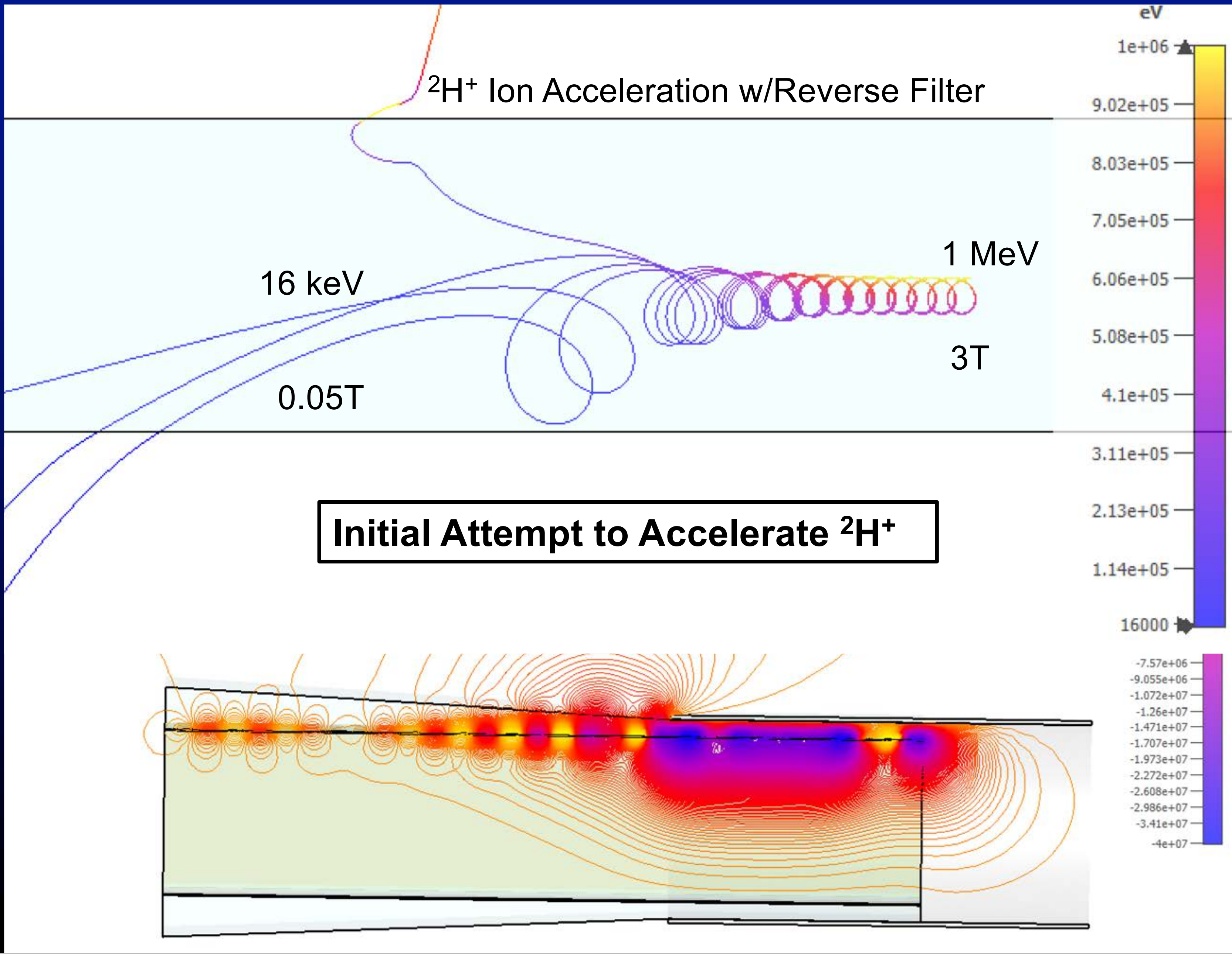




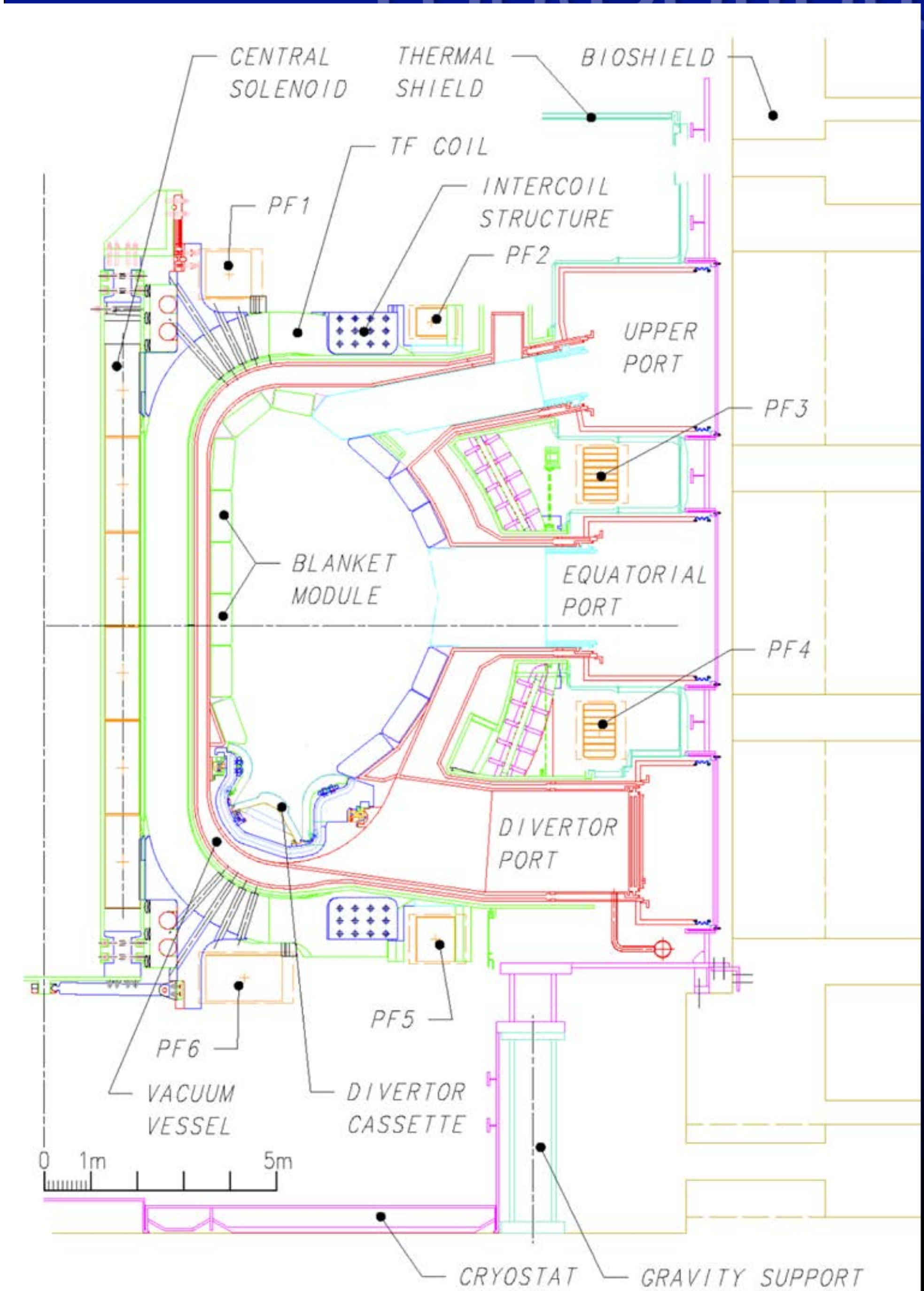
Yevheniia Cheipesh, Vadim Cheianov, Alexey Boyarsky, https://arxiv.org/abs/2101.10069
"Navigating the pitfalls of relic neutrino detection"

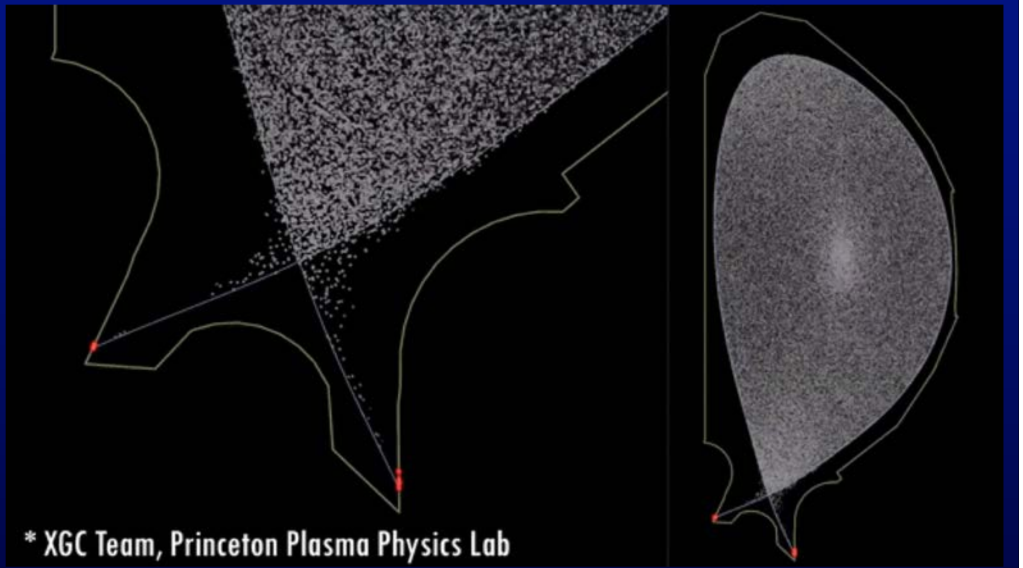
Plasma Heating w/ Reverse Filter

Andi Tan
(Princeton)



Top/Bottom ITER Ports

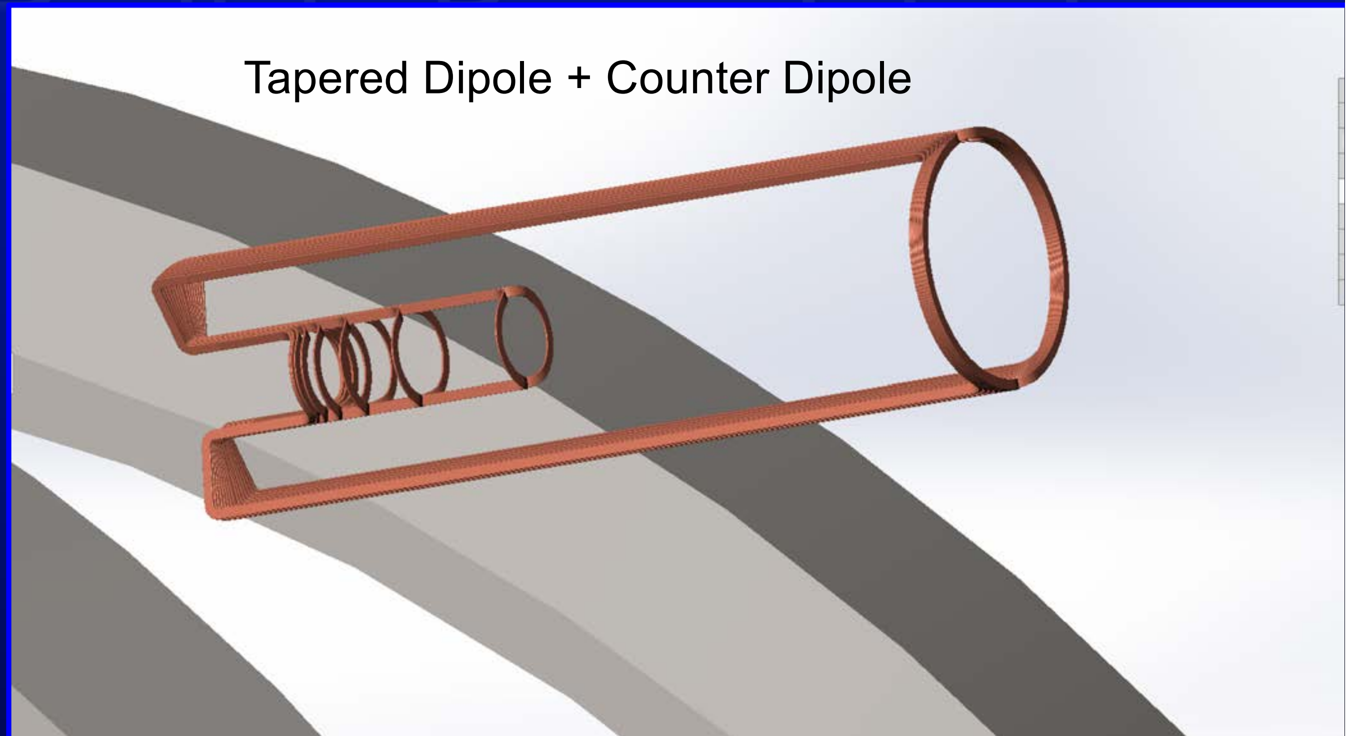


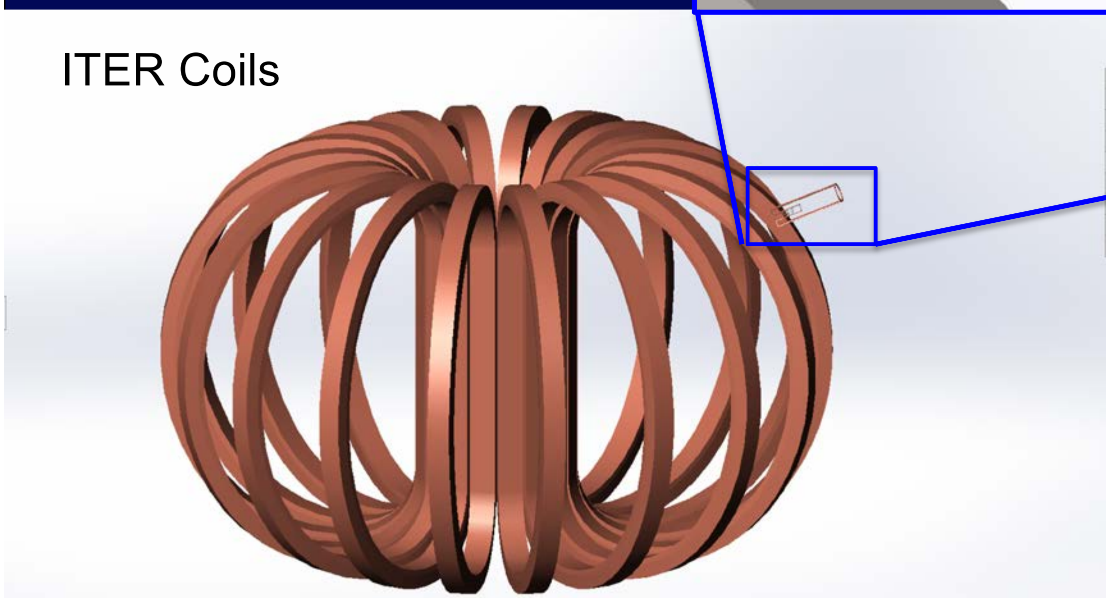


Source: YouTube ITER The Divertor Section, XGC code team is lead by CS Chang @ PPPL

Charged Particle Beam Injector

Magnetic Geometry:
"Reverse" PTOLEMY filter

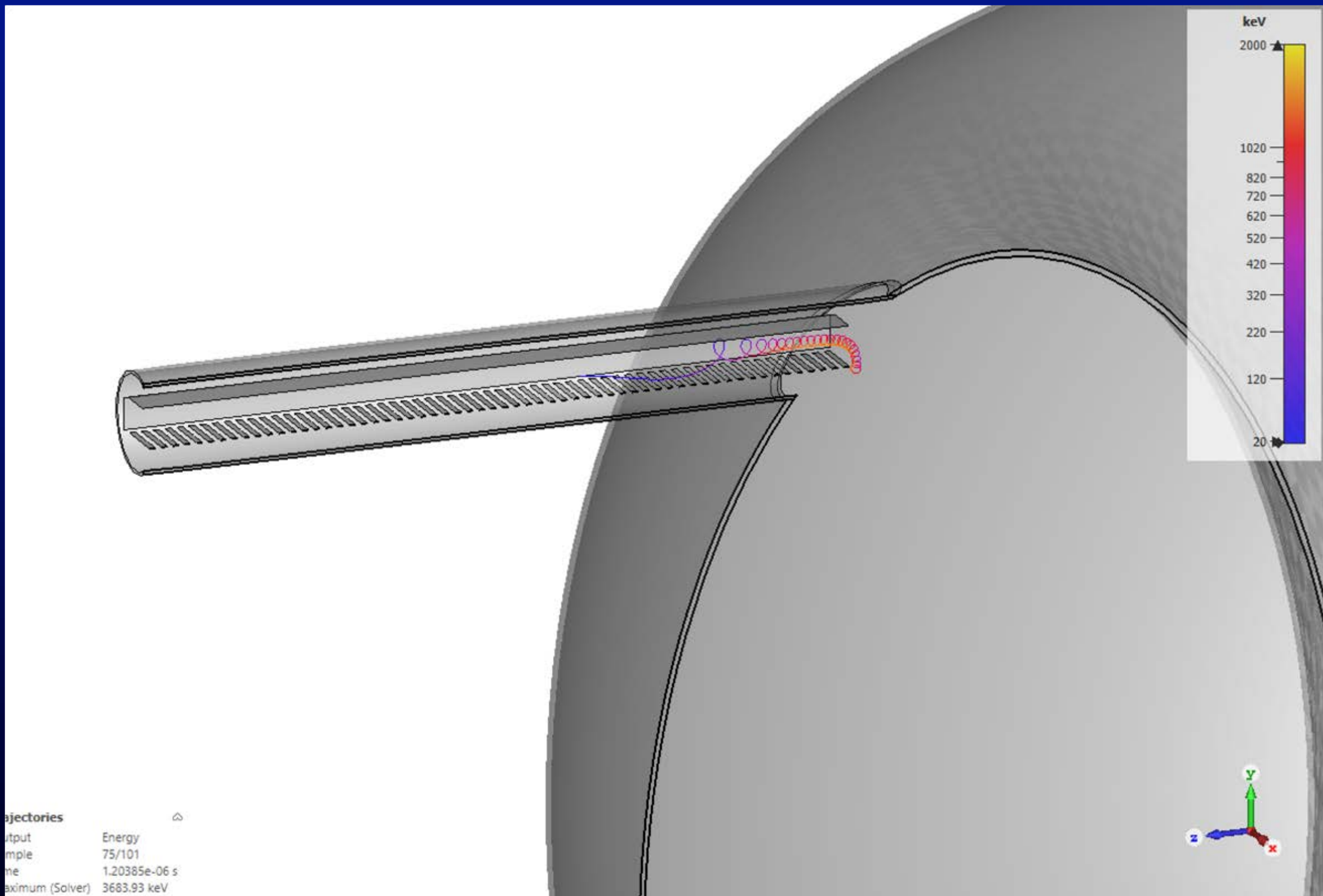




Andi Tan
(Princeton)

First Results w/Toroidal Injection

Andi Tan
(Princeton)



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/

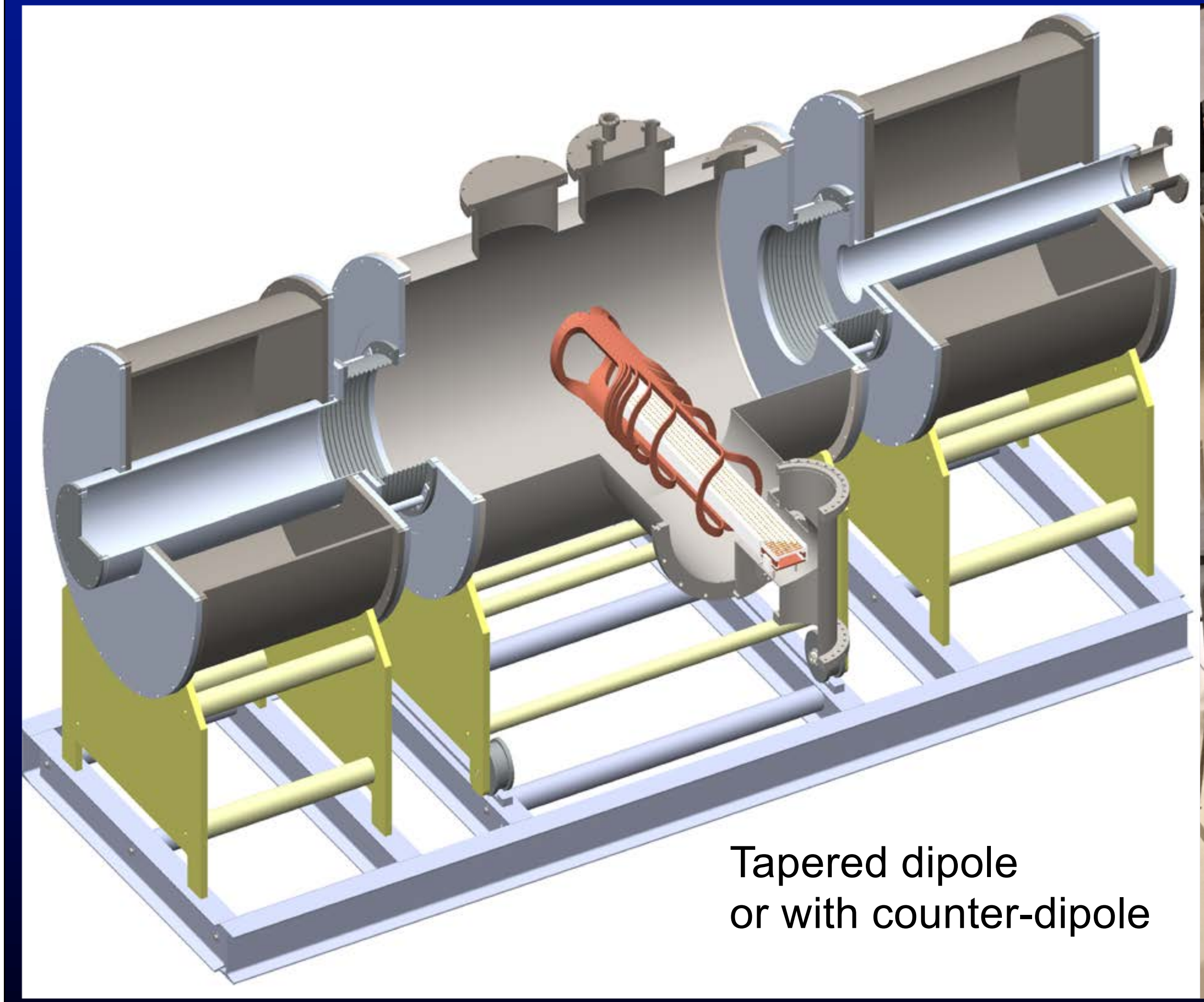
Produce filter and target with a scalable technology

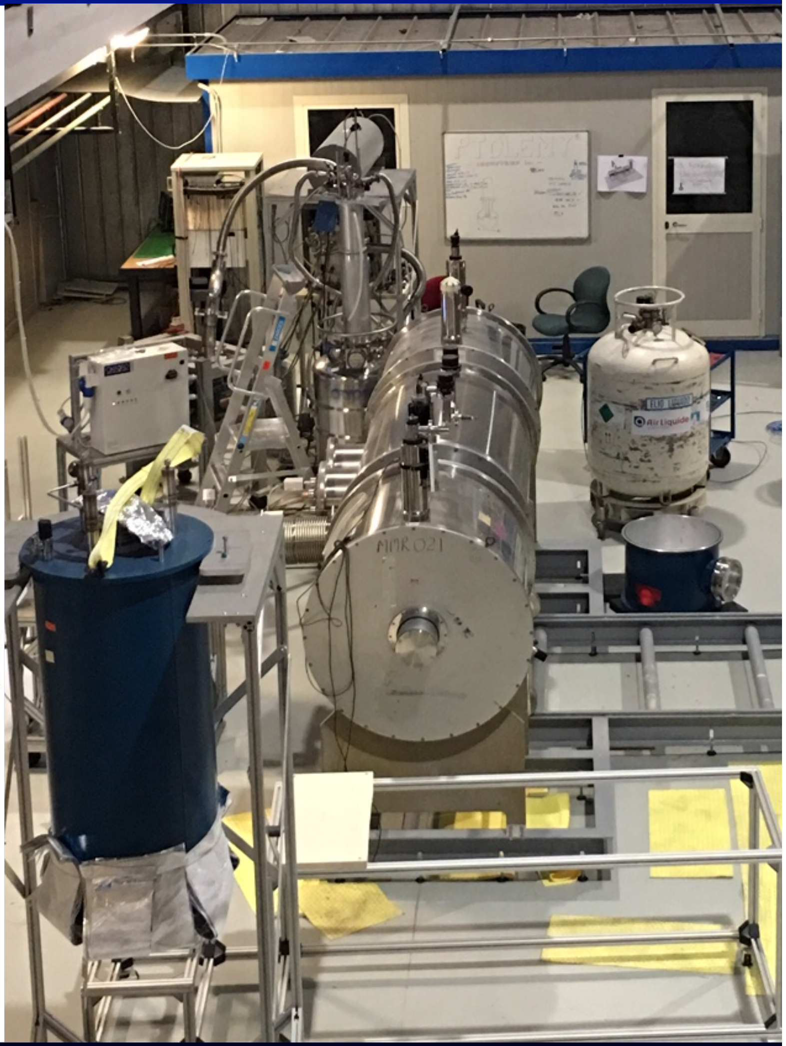
→ Design/test a superconducting coil filter magnet

→ Design/test a Large-Area target geometry

→ Integrate with end-to-end tracking simulations

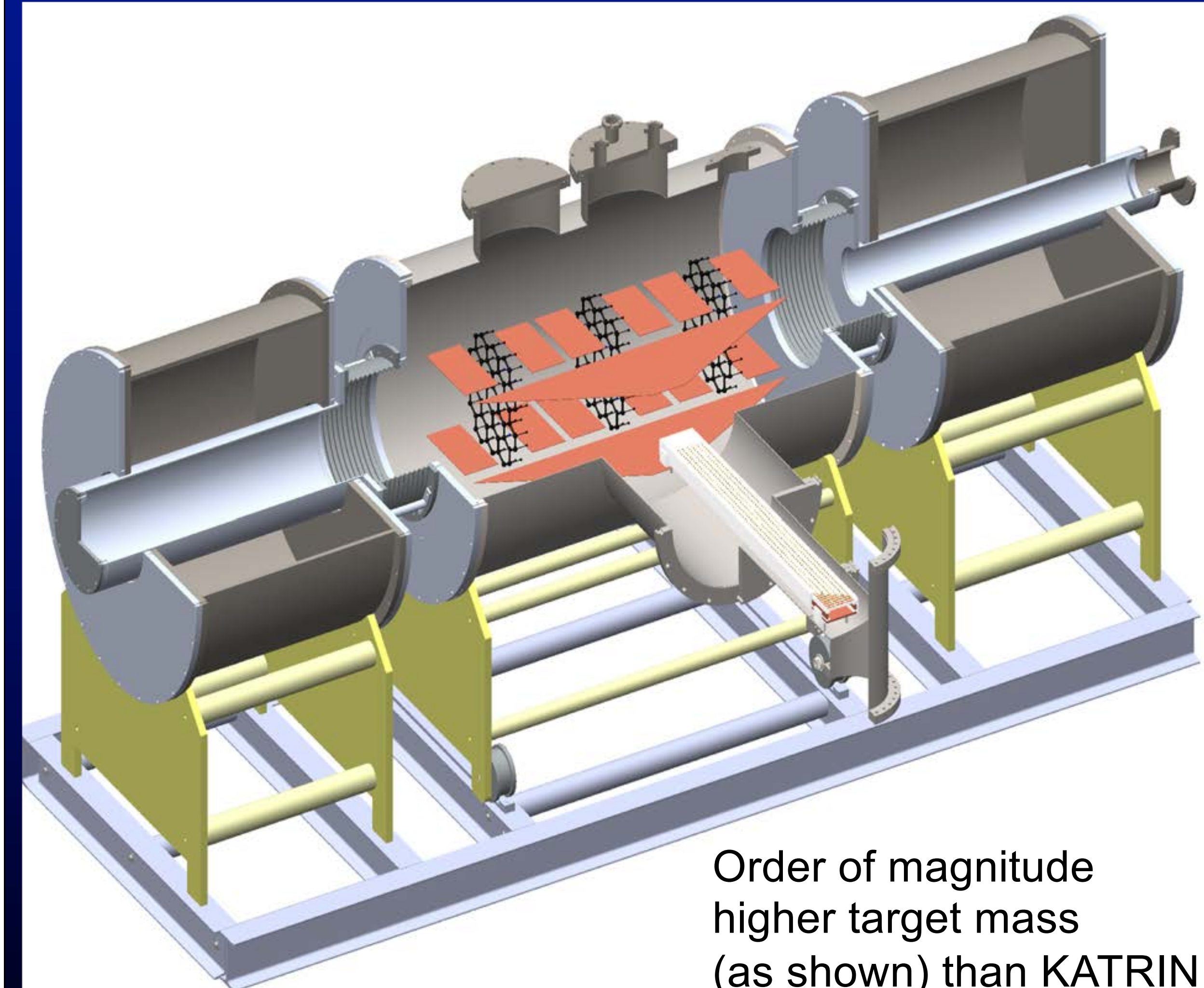
Superconducting Coil Design



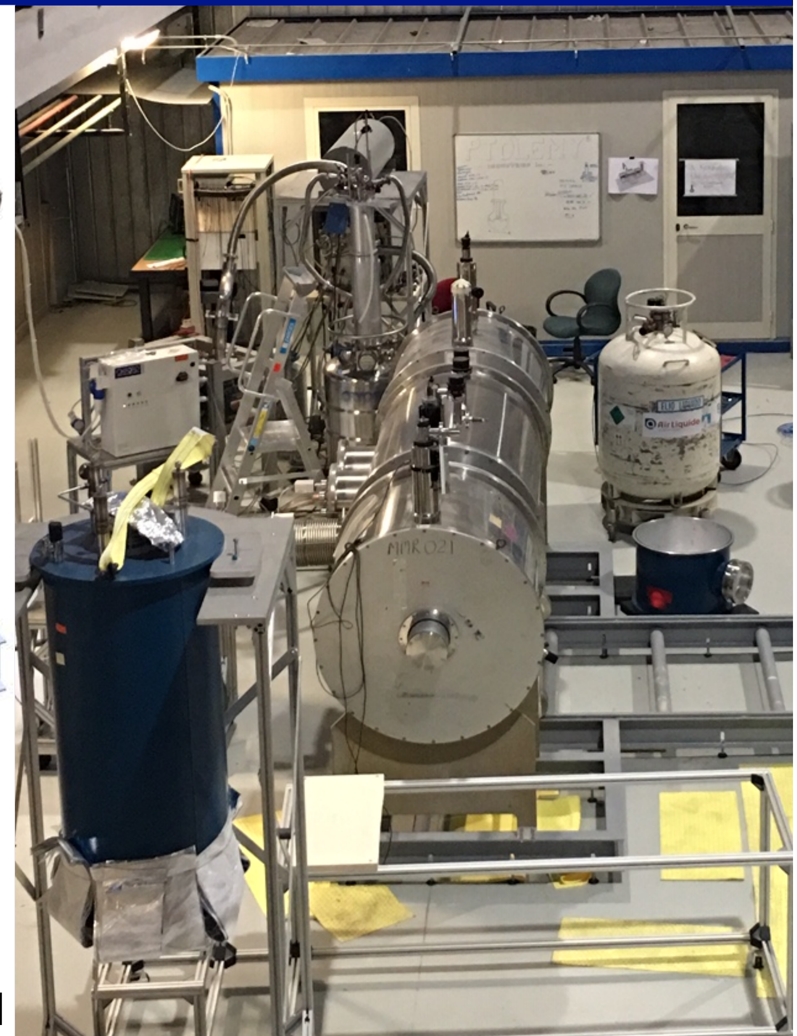


Integrate into existing dual-SC magnet setup @ LNGS

Large Area Target Design

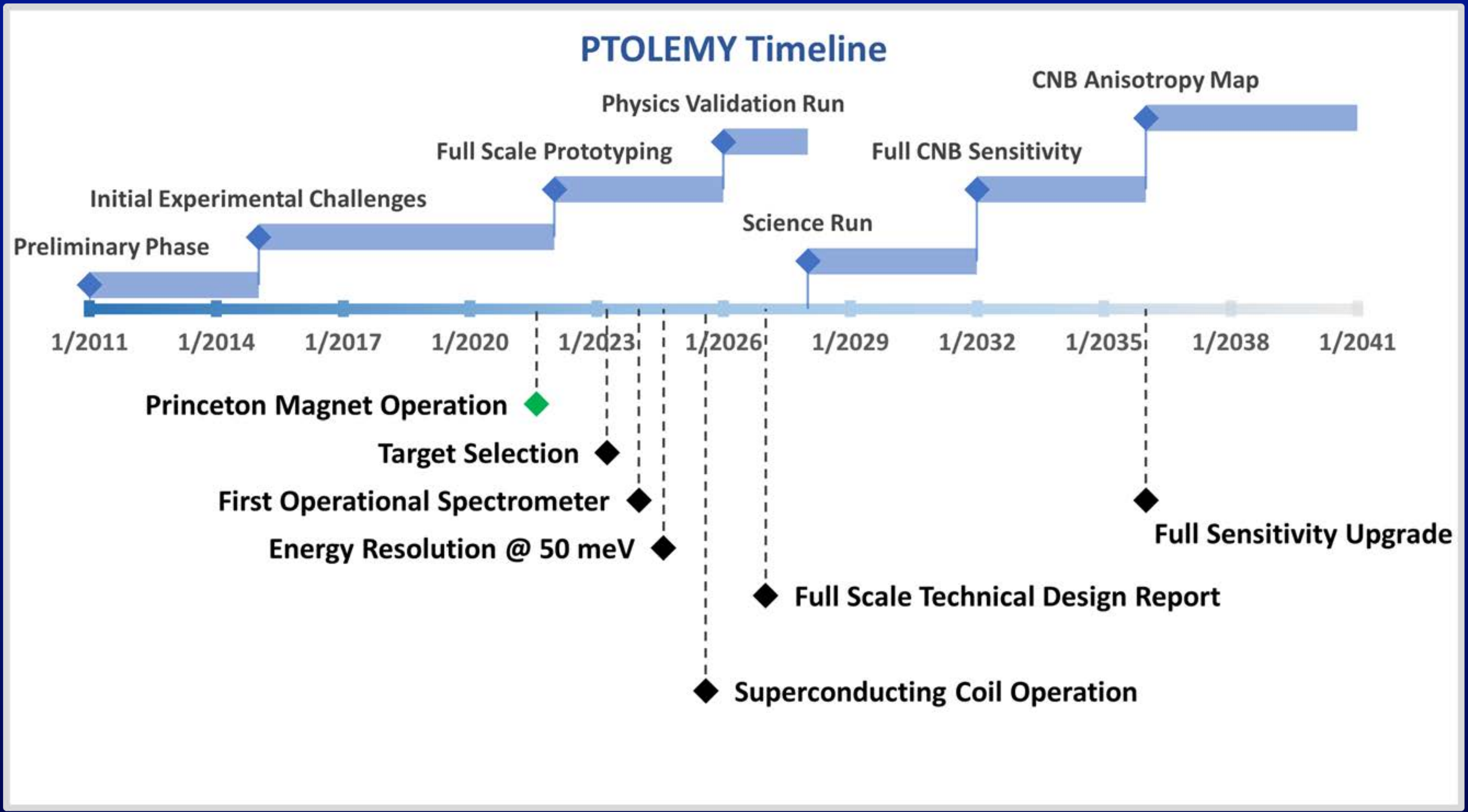


Order of magnitude
higher target mass
(as shown) than KATRIN



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:

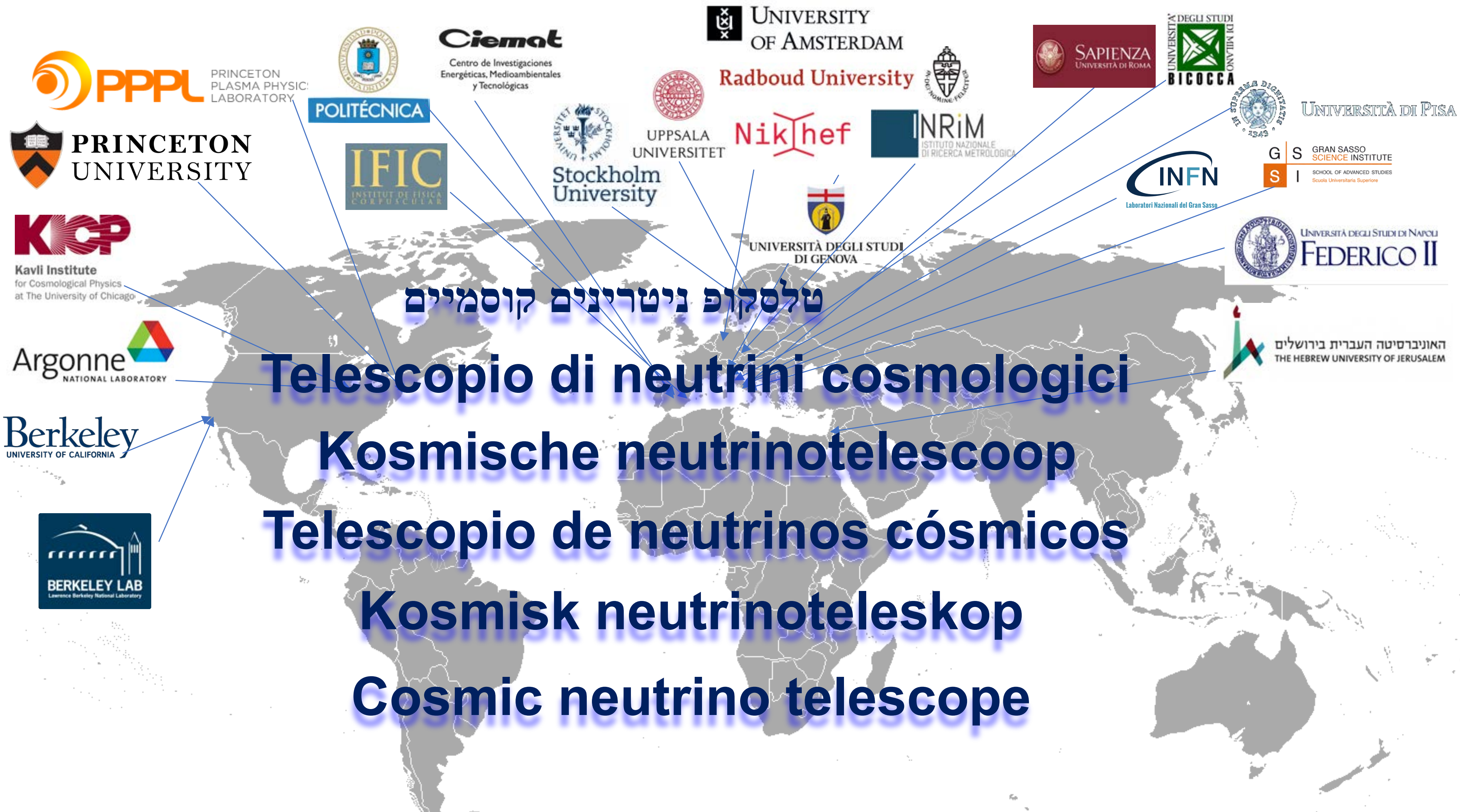
Measurement arm precision

Quantum smearing predictions

Scalability of technology

→ Leverage prototype system to explore new physics

PTOLEMY World-Wide Collaboration



טלסקופ ניטרינים קוסמיים

Telescopio di neutrini cosmologici

Kosmische neutrinotelescoop

Telescopio de neutrinos cósmicos

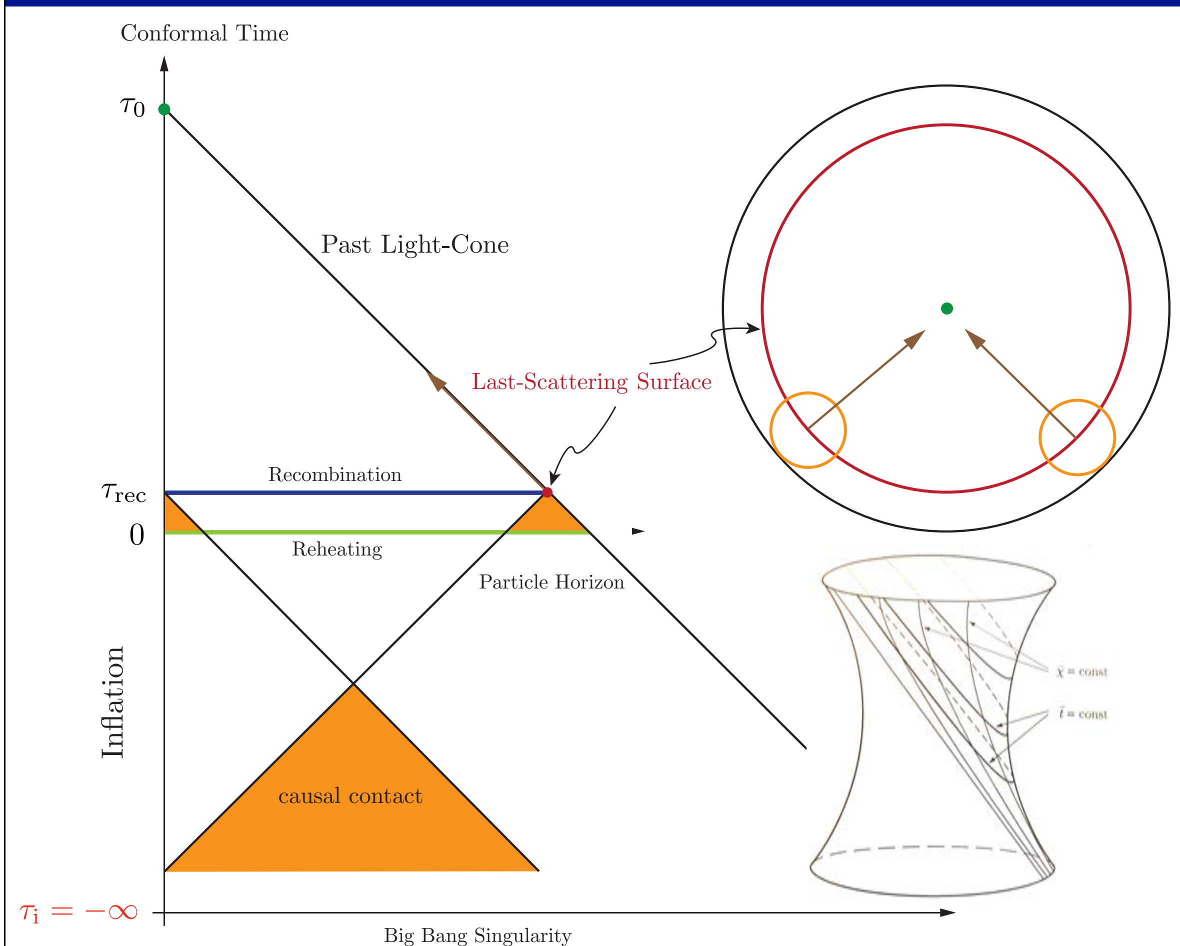
Kosmisk neutrinoteleskop

Cosmic neutrino telescope

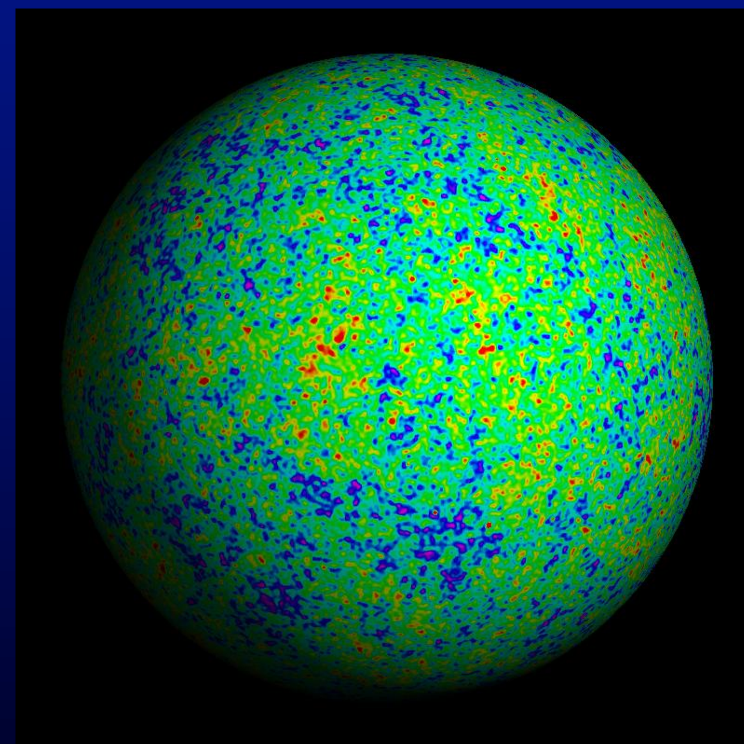
2015 Targeted Grant Award from the SIMONS FOUNDATION

Additional Slides

Big Bang Cosmology

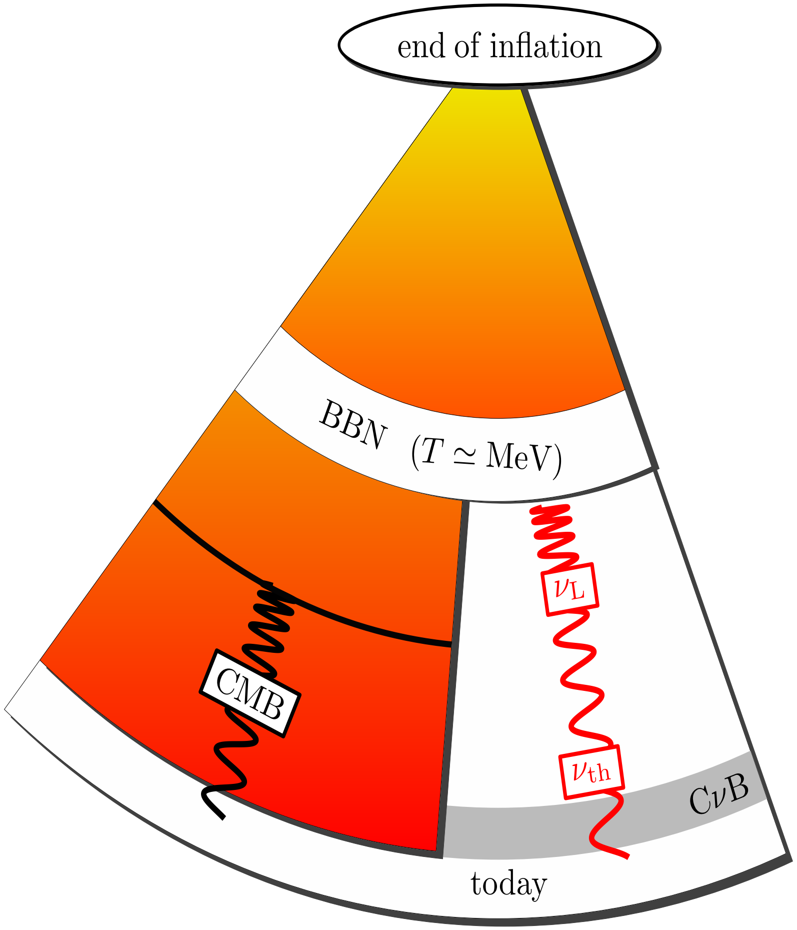


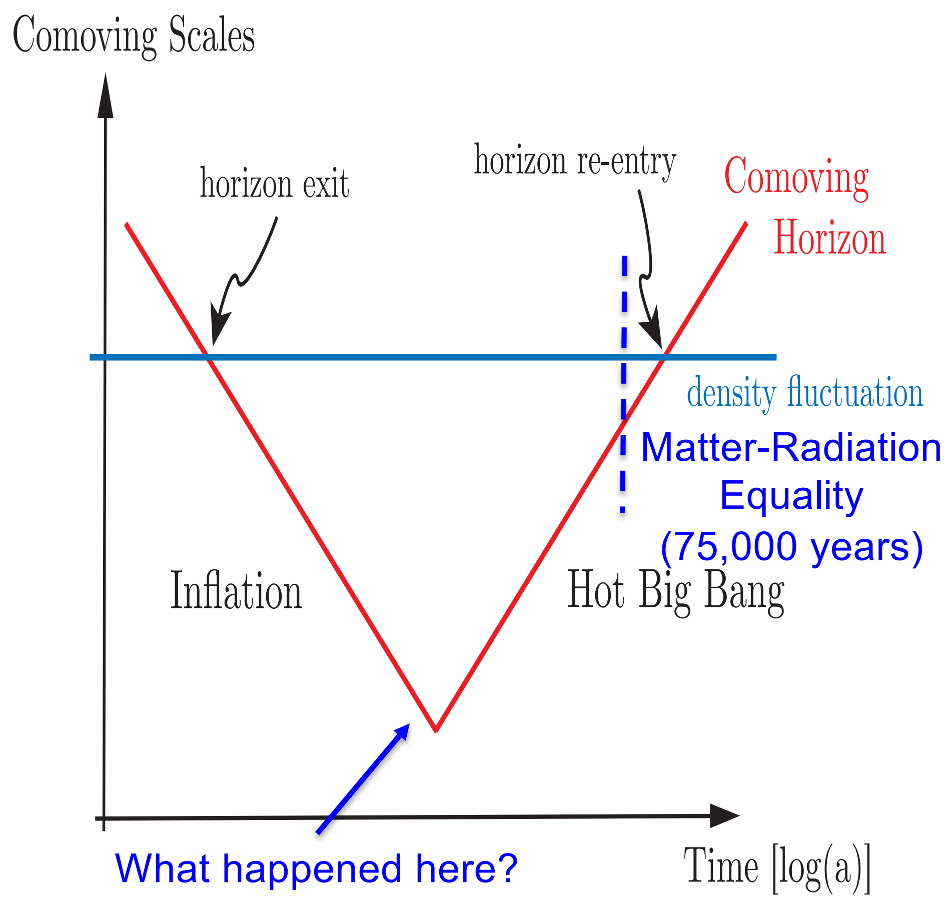
Adiabatic Density Anisotropies
$\delta \sim 10^{-5}$ at $z \sim 1100$



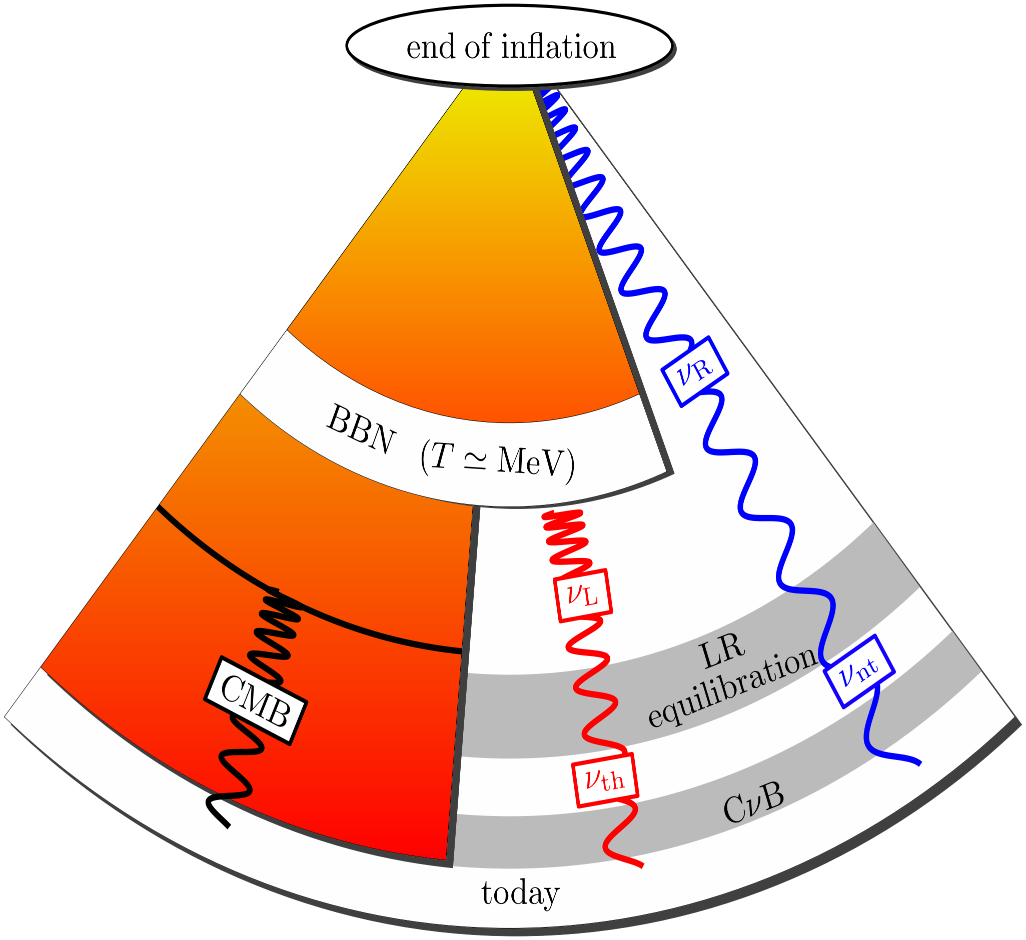
Where we think there is an initial $\tau_i=0$ Big Bang Singularity is believed to be the "end" of an inflation period that slowly pulled out (>60 e-folds $a(\tau) \sim e^{H\tau}$) of a "de Sitter"-like spacetime

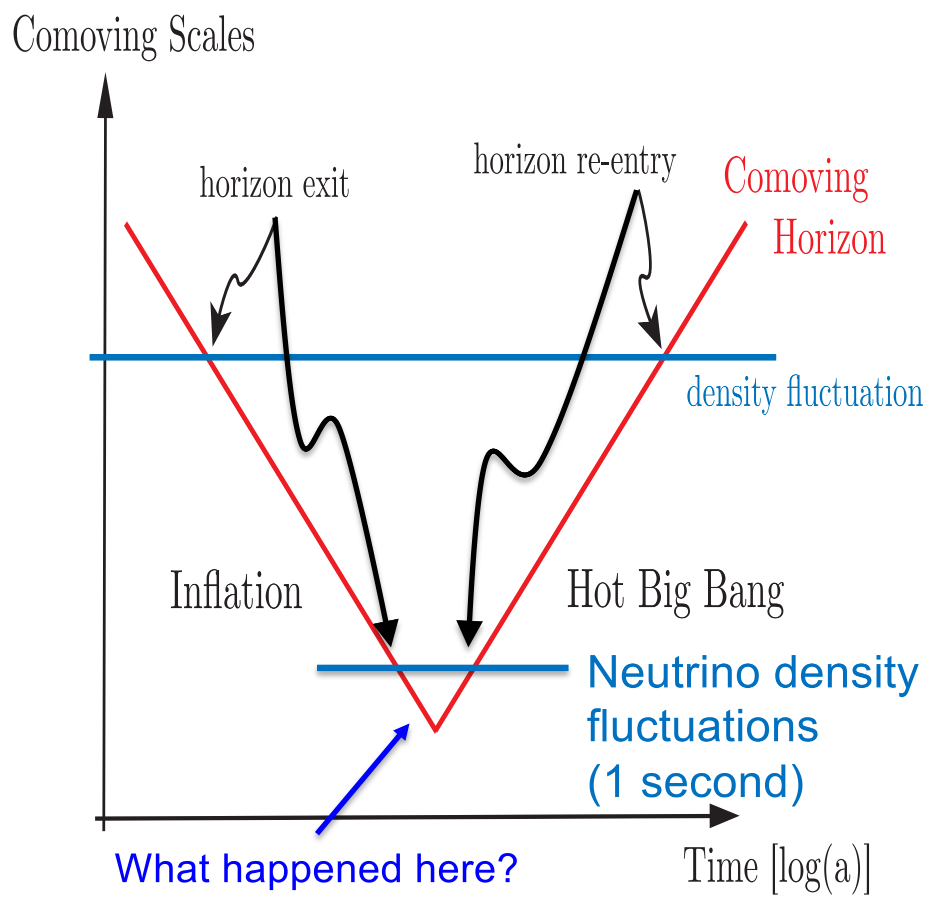
Inflation → Hot Big Bang





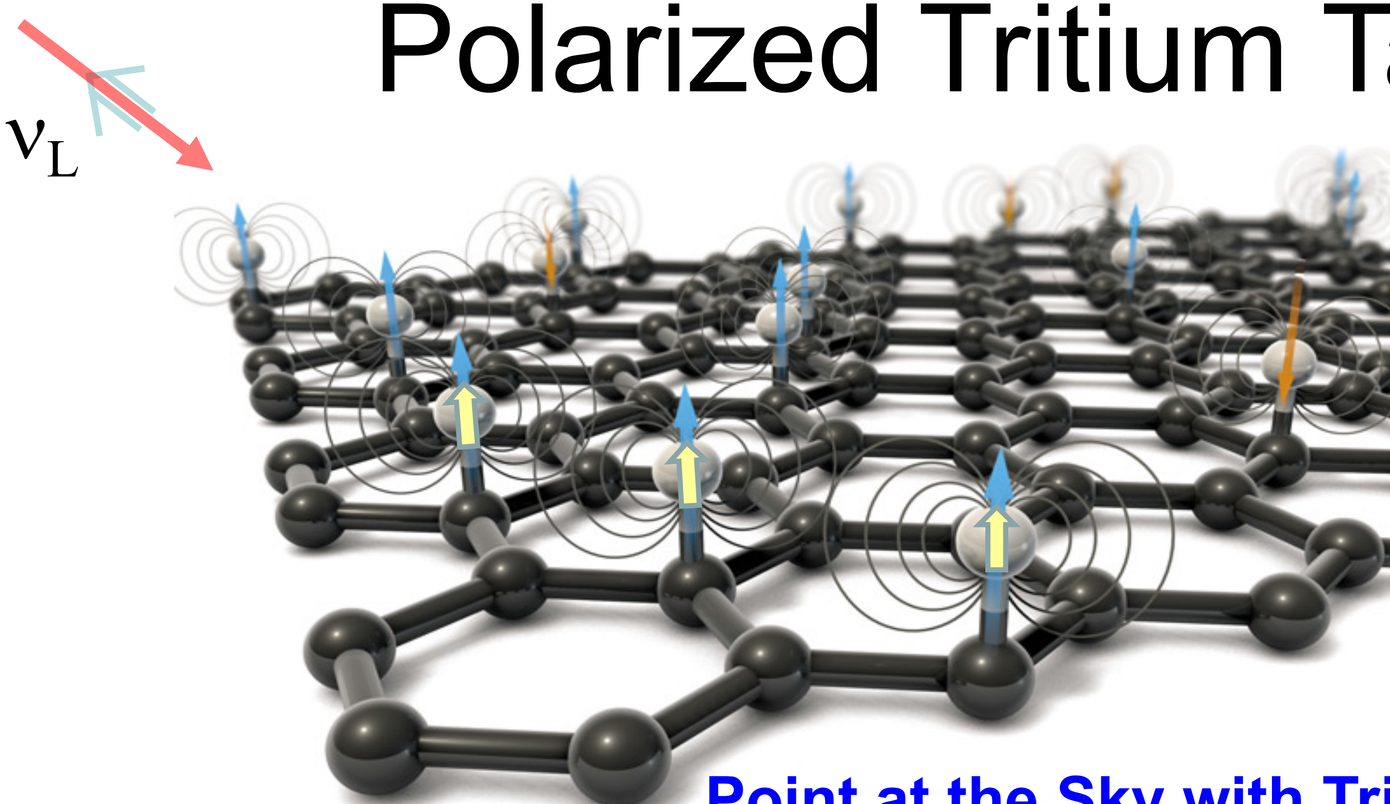
Inflation → Hot Big Bang





Ratz
(Erice 2017)

Polarized Tritium Target



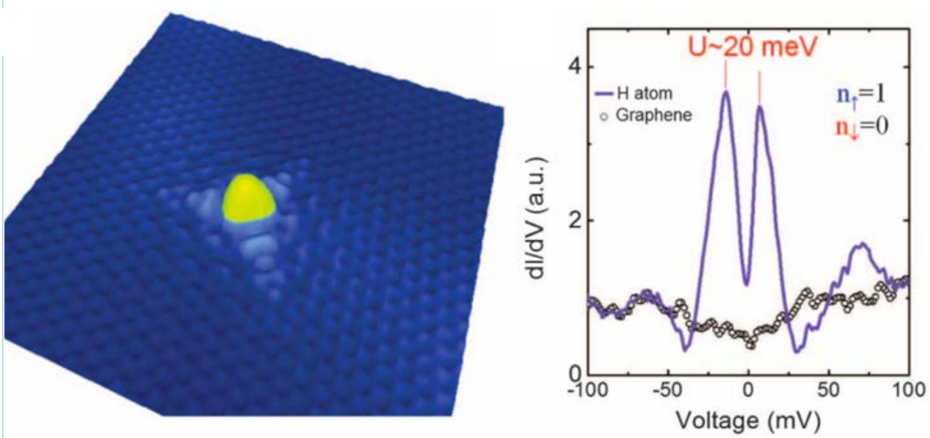
Lisanti, Safdi, CGT, 2014.
10.1103/PhysRevD.90.073006

Akhmedov, 2019.
10.1088/1475-7516/2019/09/031

Point at the Sky with Tritium Nuclear Spin ⇧

Detection (capture) of cold neutrinos:

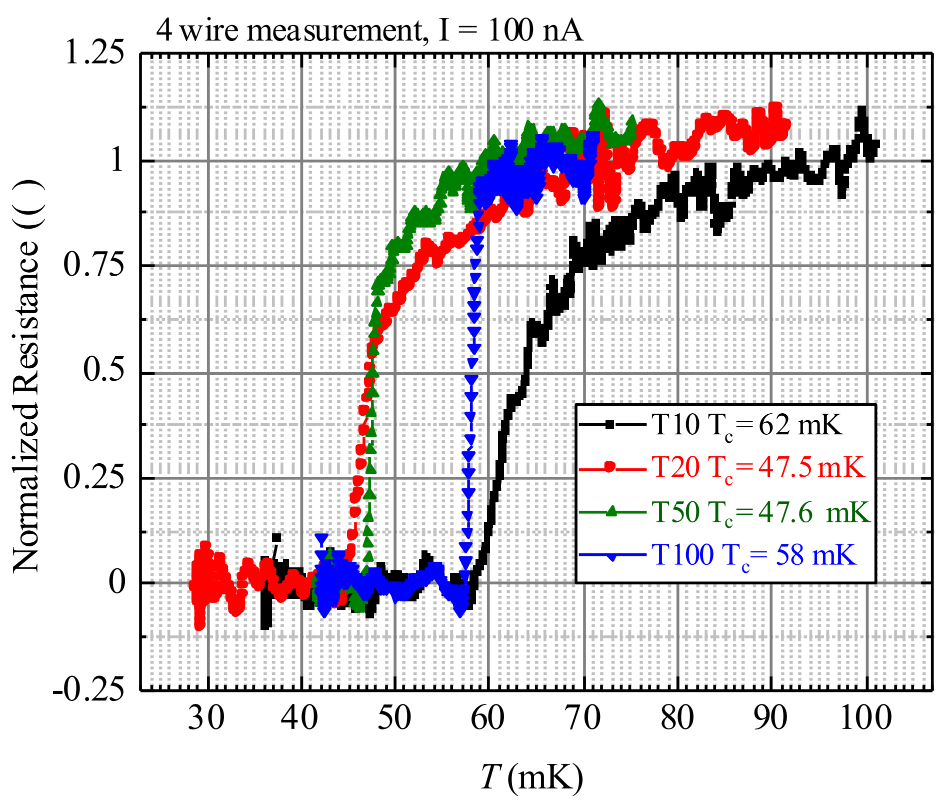
$d\sigma/d\cos\theta\ (v/c) \sim (1+\cos\theta)$

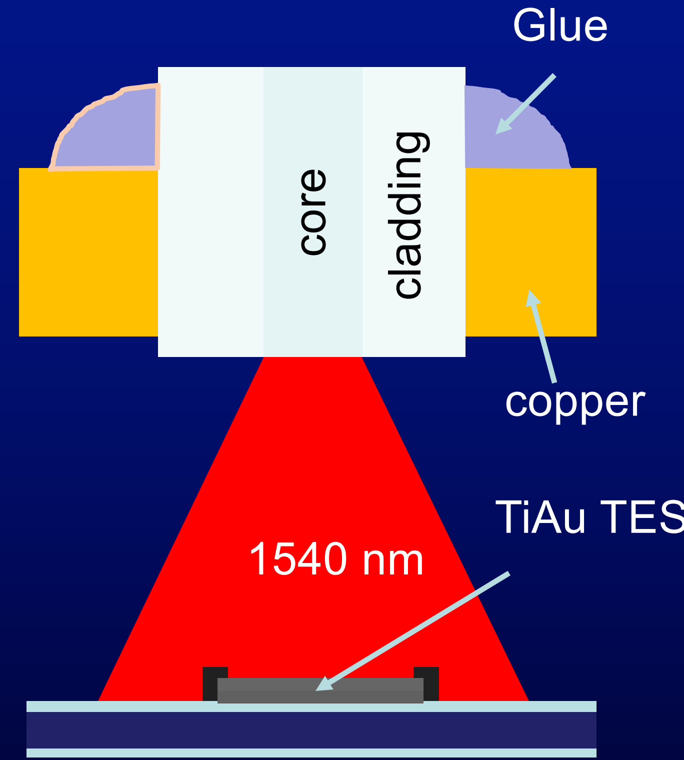


Hydrogen doping on graphene reveals magnetism

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



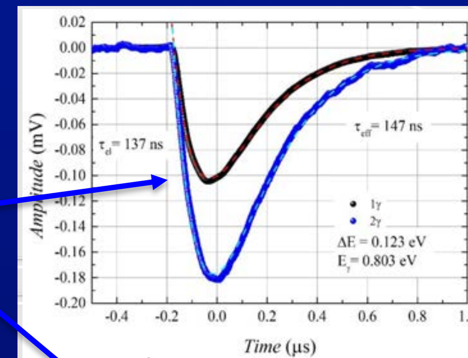


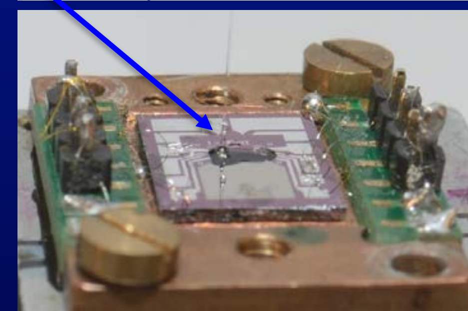
Fiber-TES distance ~ 2mm
(Not in scale)

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)



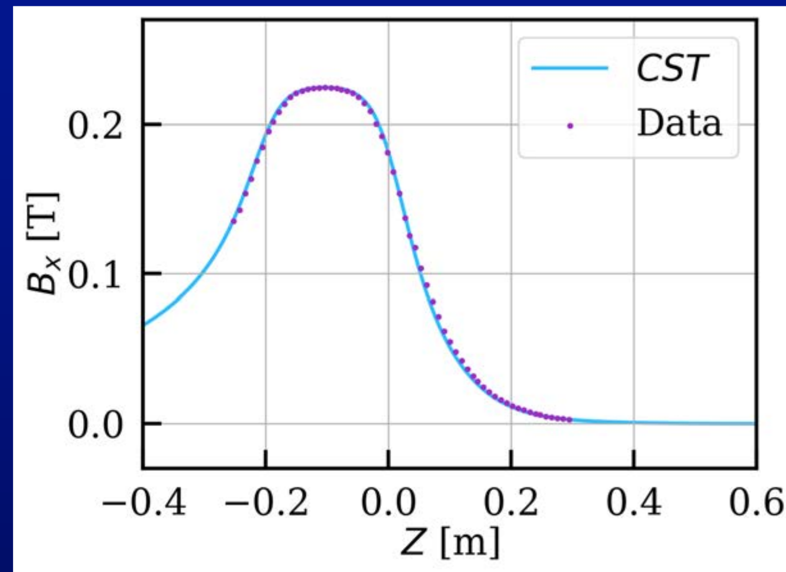


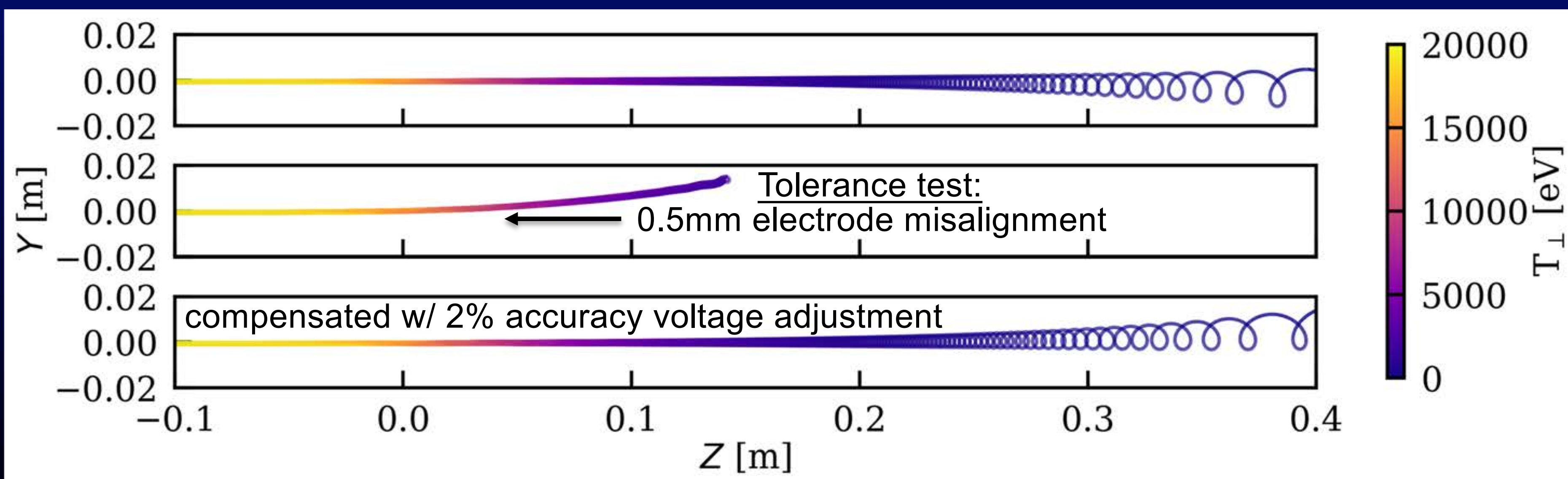
Design Goal (PTOLEMY): ΔE_{FWHM} = 0.05 eV @ 10 eV
translates to $\Delta E \propto E^{\alpha}$ $(\alpha \leq 1/3)$
ΔE_{FWHM} = 0.022 eV @ 0.8eV

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

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

Achieves Required Magnetic Field Map





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

Graphene Hydrogenation

PRINCETON UNIVERSITY

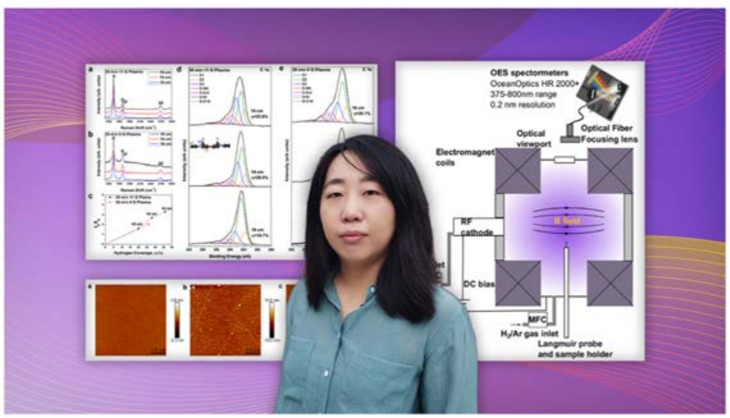
MENU

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Home » News

QUEST Research Magazine

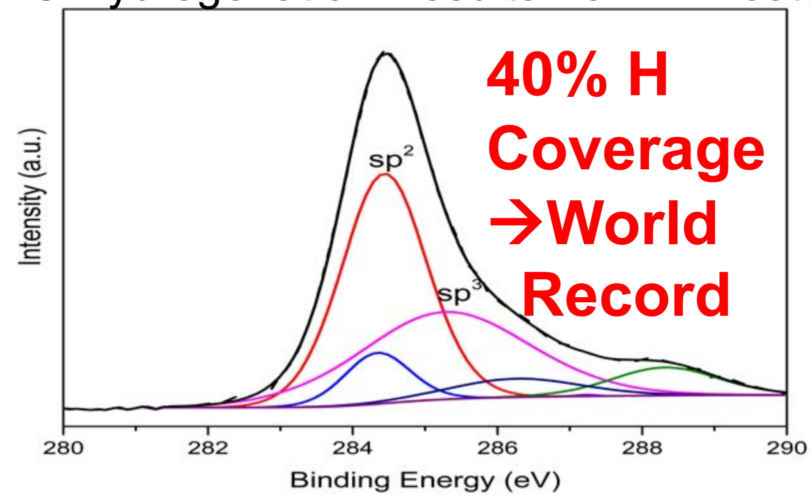
Plasma to the rescue: Scientists develop a path-setting method to enable vast applications for a promising nanomaterial

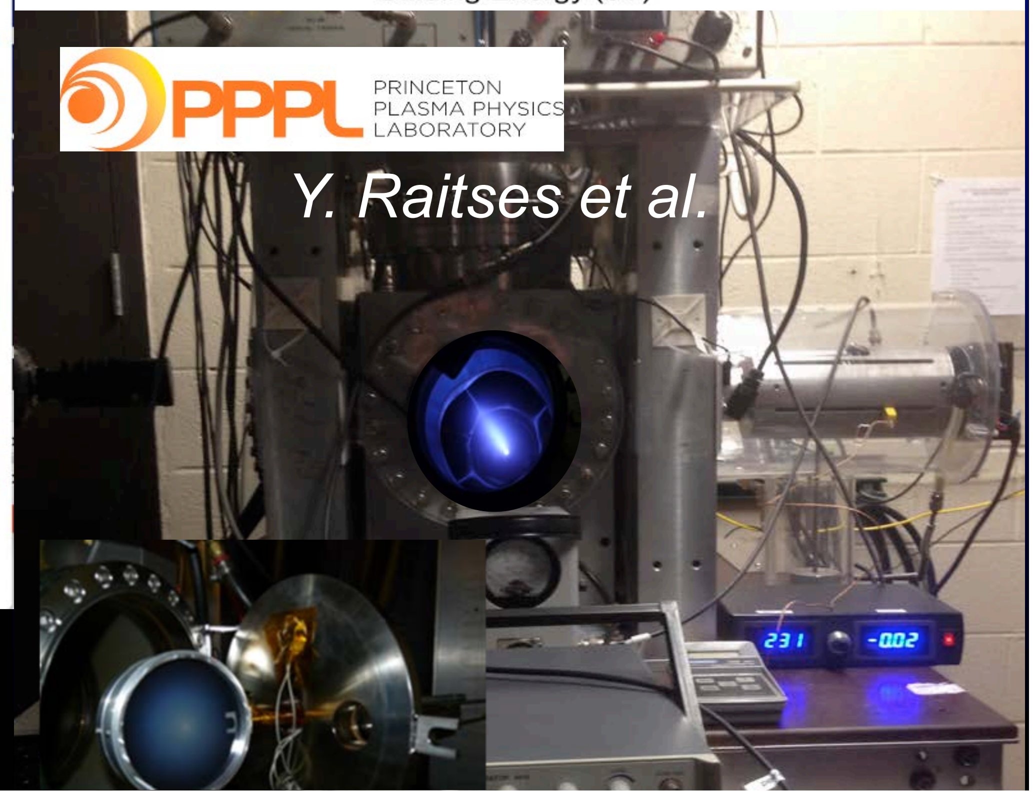


Physicist Fang Zhao with figure from her paper. (Photo courtesy of Fang Zhao.)

John Greenwald

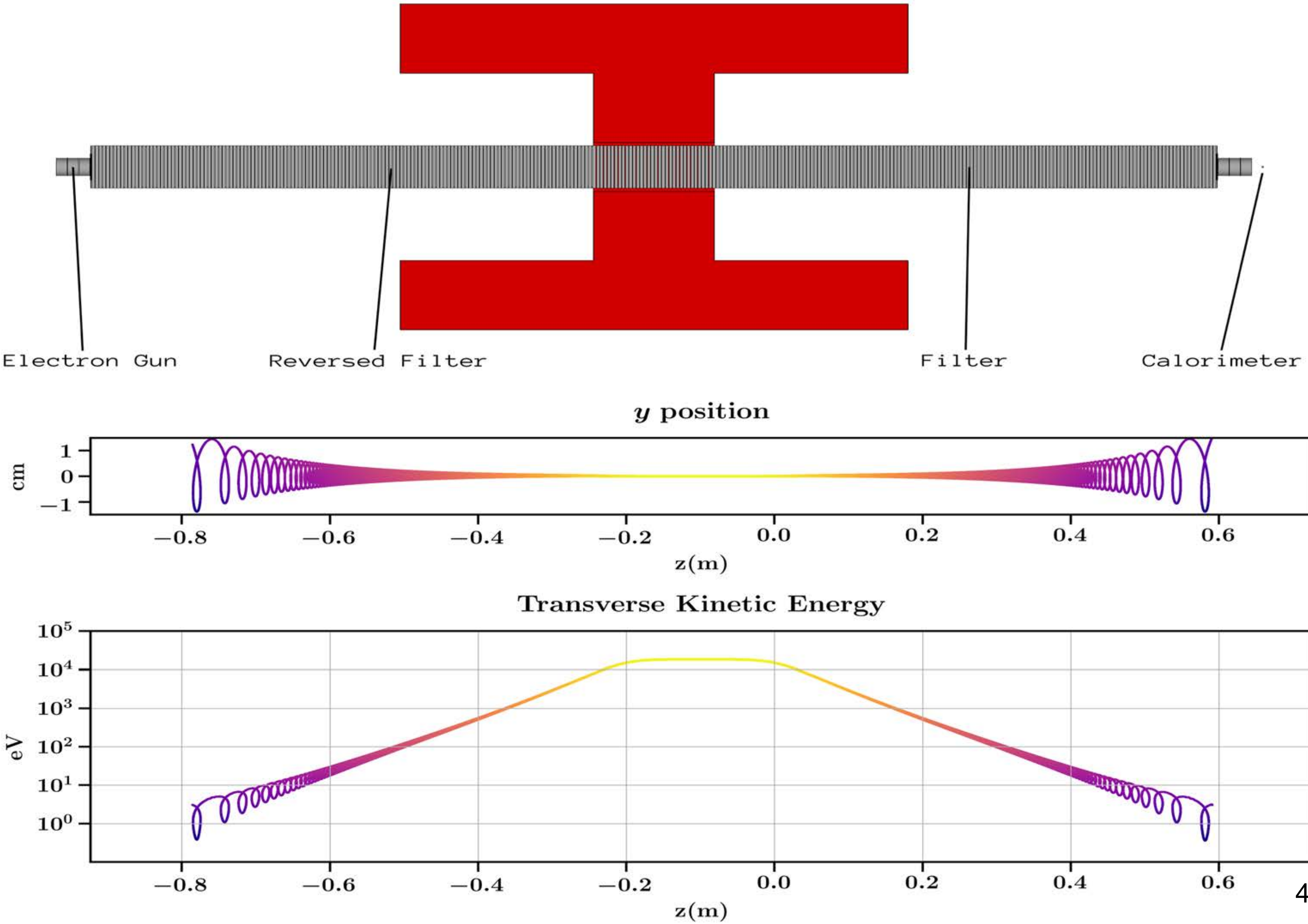
XPS Hydrogenation Results from Princeton





Research support from the John Templeton Foundation

Reverse Filter



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