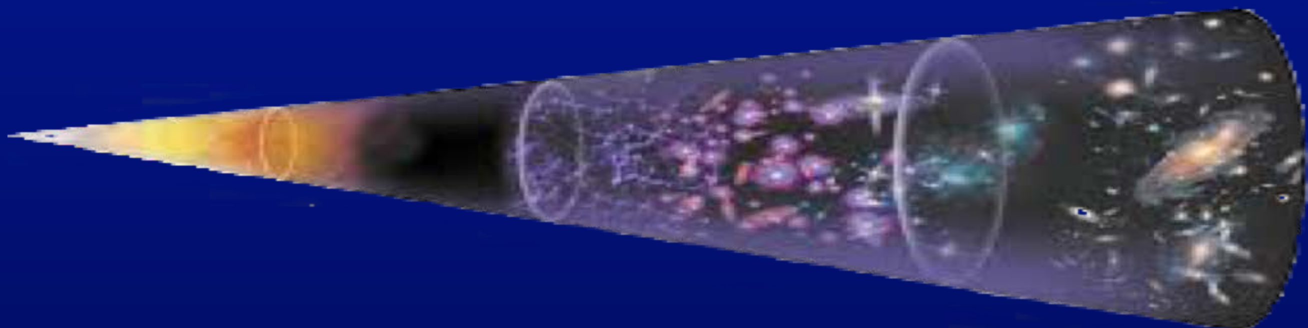
Observing the Big Bang with Relic Neutrinos (PTOLEMY)



Chris Tully

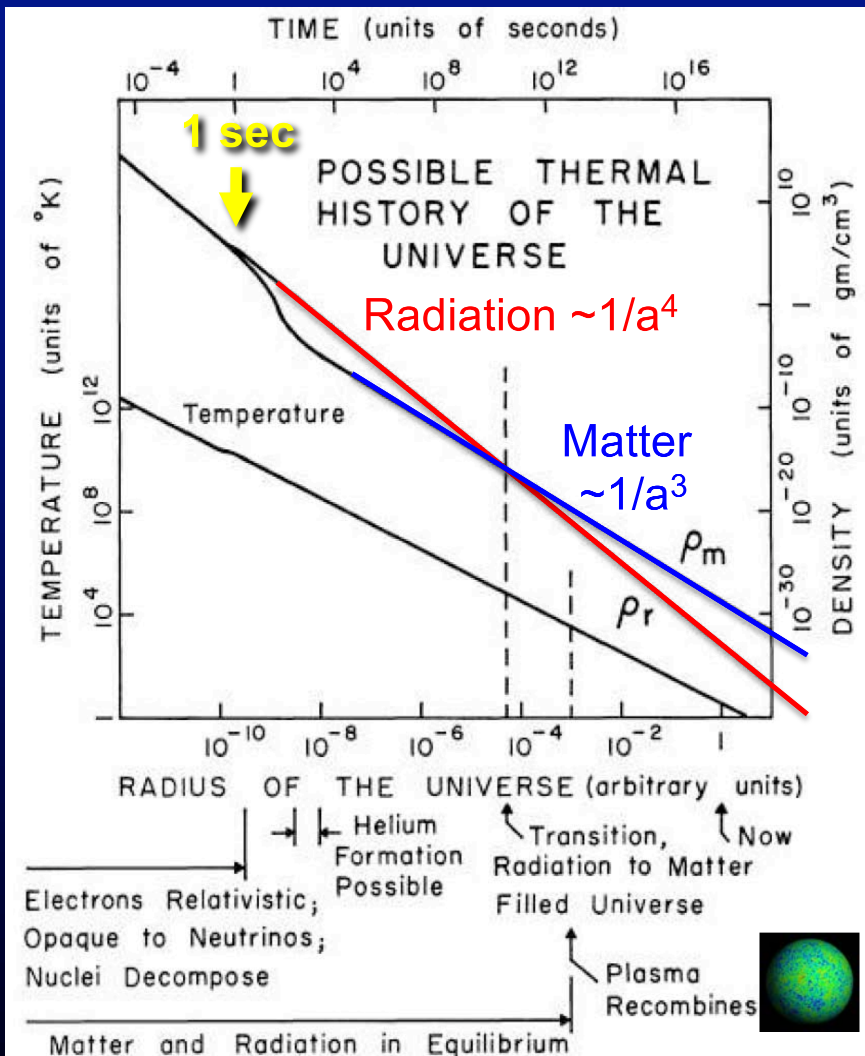
Princeton University

SNOWMASS NF04 SUPERNOVA & EARLY UNIVERSE NEUTRINO WORKSHOP

14 DECEMBER 2020

2015 Targeted Grant Award from the SIMONS FOUNDATION

Cosmic Neutrino Background



Number density:

$n_\nu = 112/cm^3$

Temperature:

$T_\nu \sim 1.95K$

Time of decoupling:

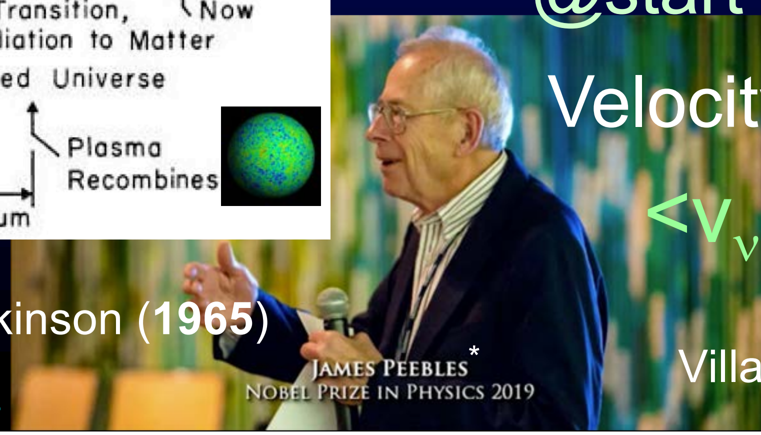
$t_\nu \sim 1$ second

~50% of the Total Energy Density of the Universe

neutron/proton ratio @start of nucleosynthesis

Velocity distribution:

$<v_\nu> \sim T_\nu / m_\nu$

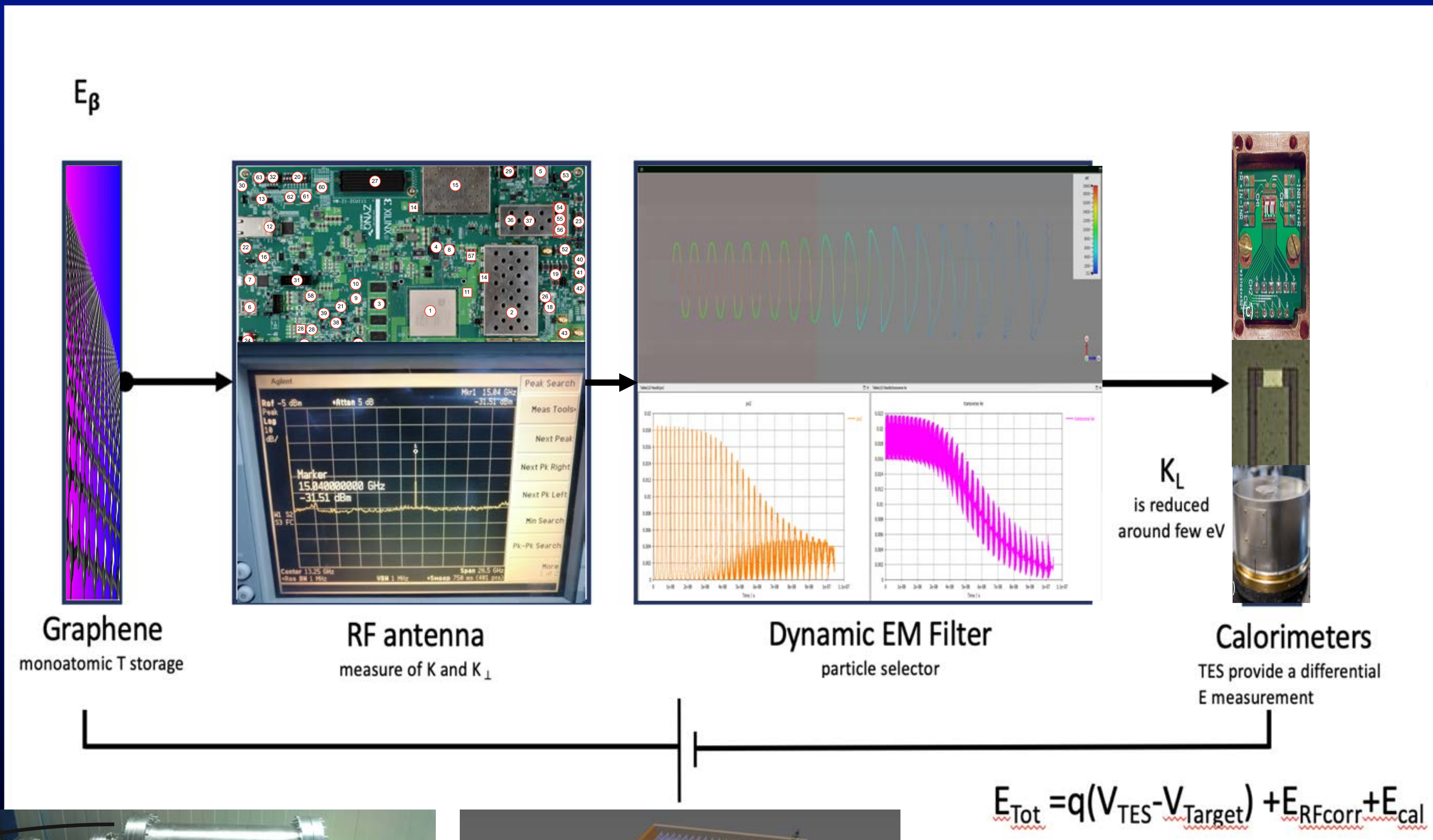


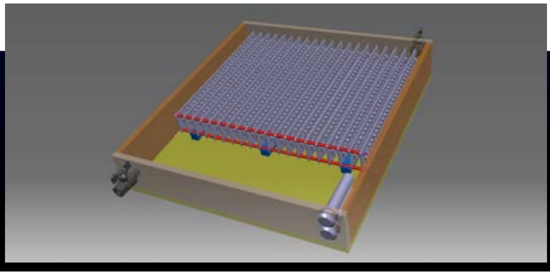
Dicke, Peebles*, Roll, Wilkinson (1965)

Cosmology's Century (2020)

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

PTOLEMY Conceptual Block Diagram





PTOLEMY Experiment Expertise

Areas of Technology/Expands Neutrino Experiment-Base

Material Science/Quantum Devices:
- Development of Target and related nano-fabrication projects (G-FET, CNT)

RF Sensing, Triggering and Readout:
- Single-Electron RF Momentum Measurements, Horns and equiv-5G Processing

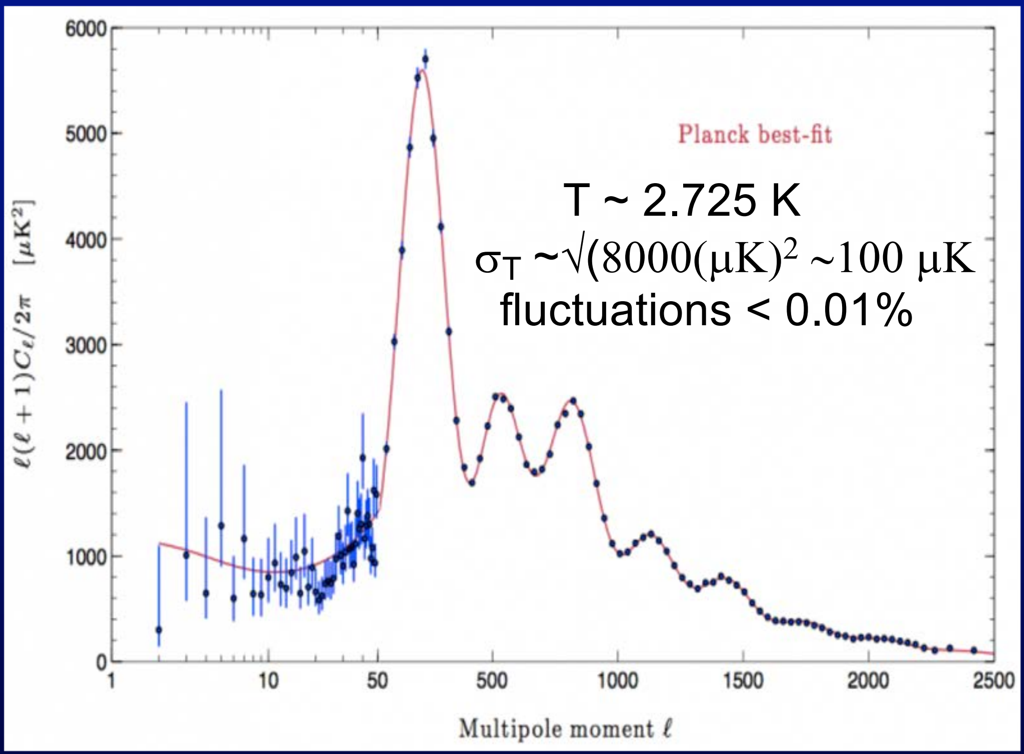
Novel Transverse Drift Filter Design:
- Most compact, high precision EM spectrometer
- Fast HV dynamical setting
- New method for e-Gun calibration source (filter run in reverse)

Magnet Design with Integrated Vacuum Cryostat:
- Compact design using custom iron poleface/return yoke

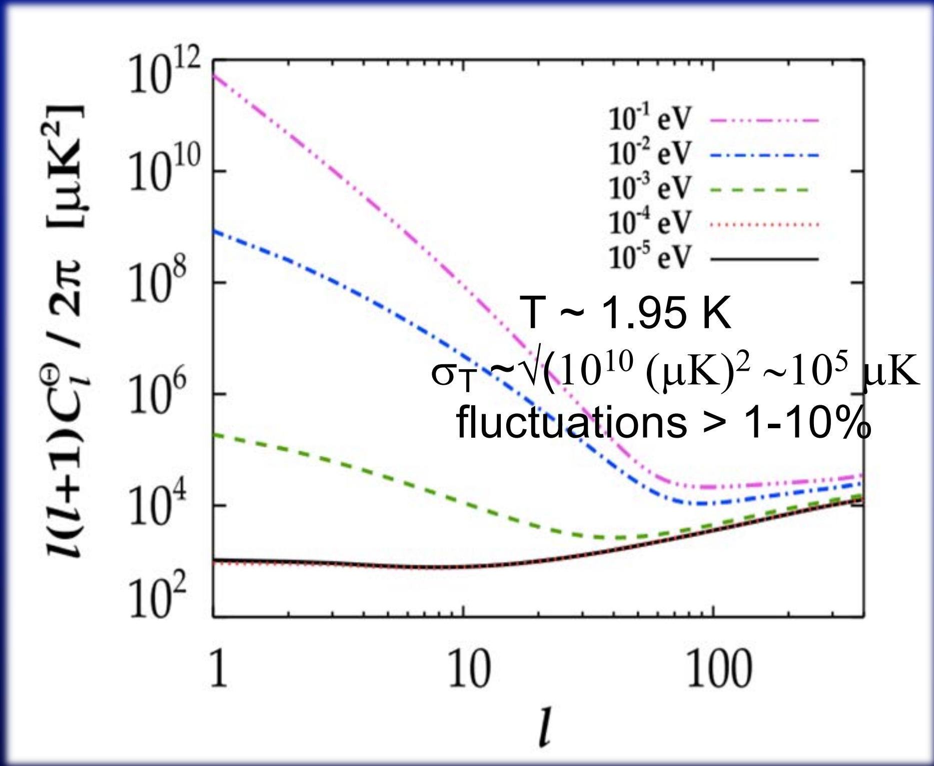
TES micro-calorimeter measurements on low energy electrons:
- Highest resolution IR photon detector recently redesigned for electrons

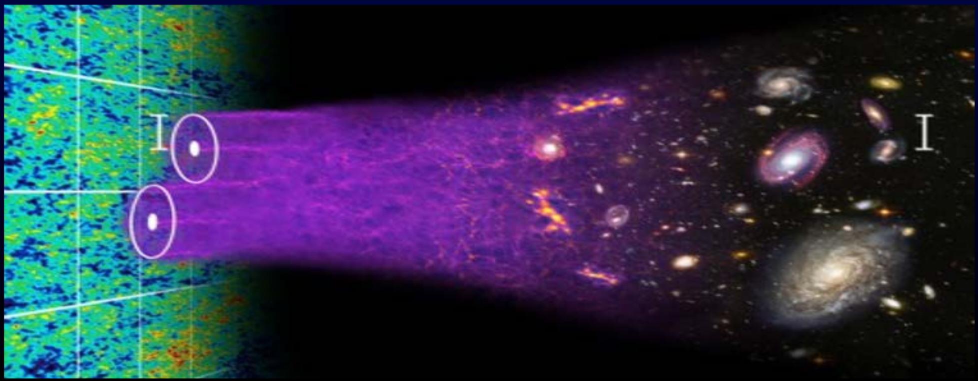
Neutrino Flux on the Sky

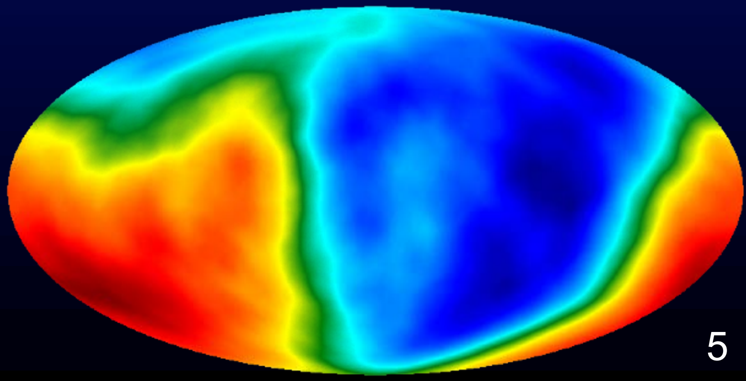
Cosmic Microwave Background (CMB)



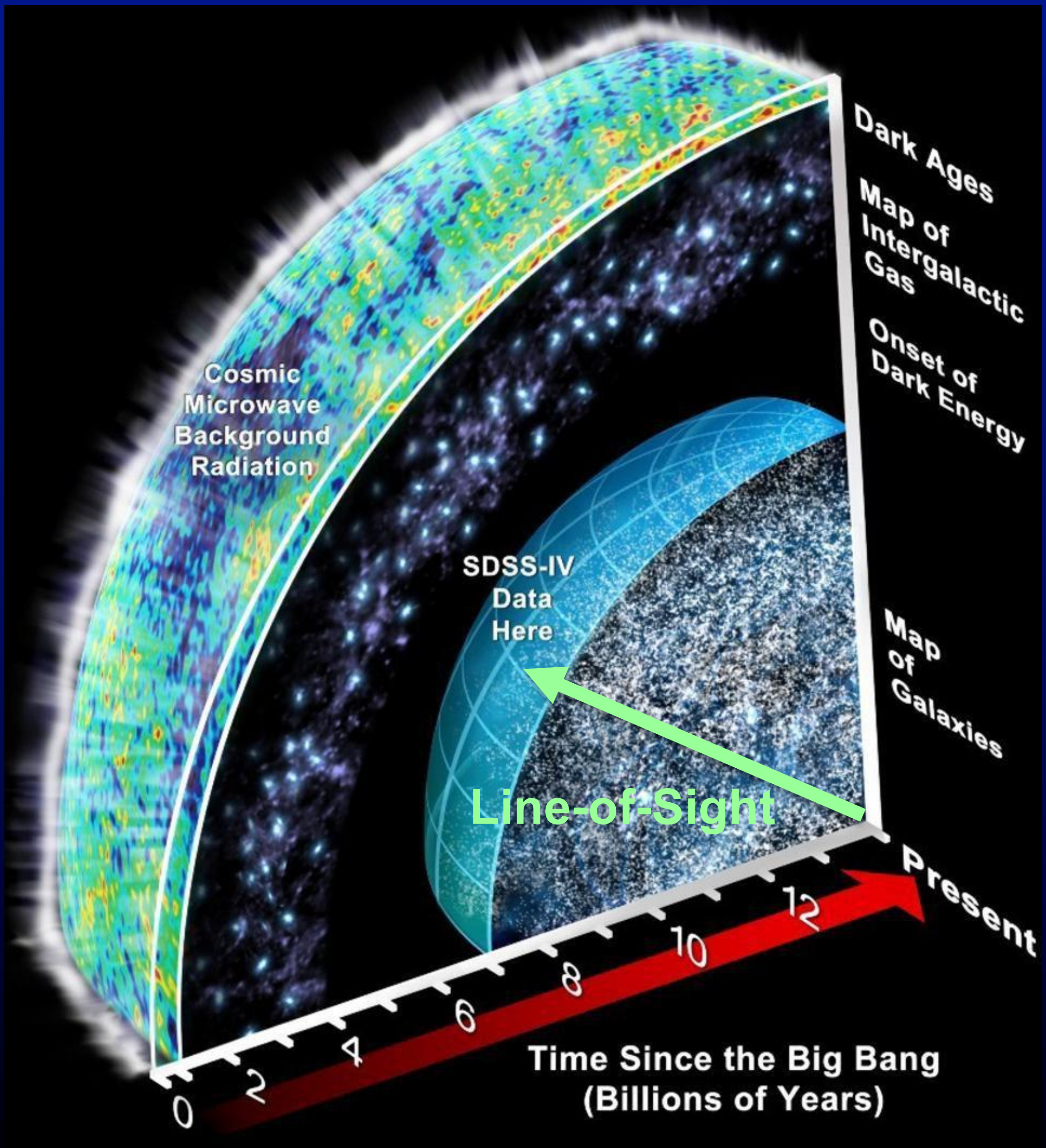
Cosmic Neutrino Background (CNB)

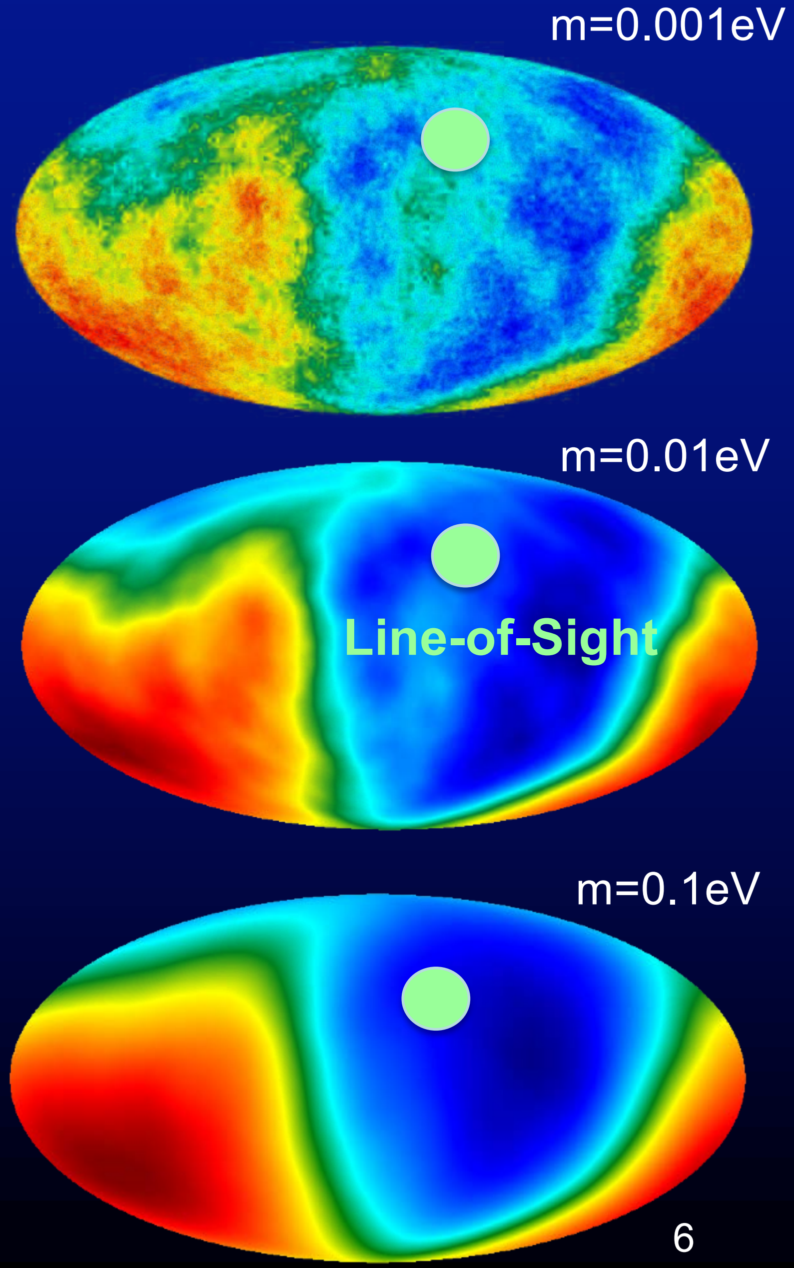




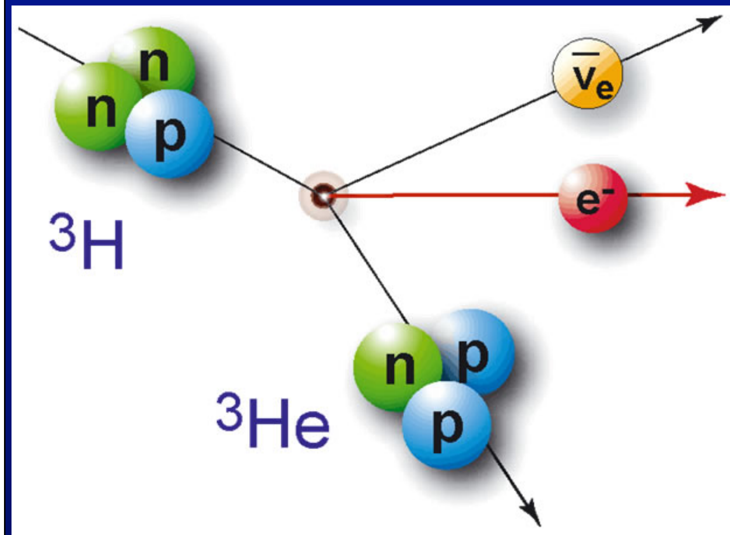


Multi-Messenger

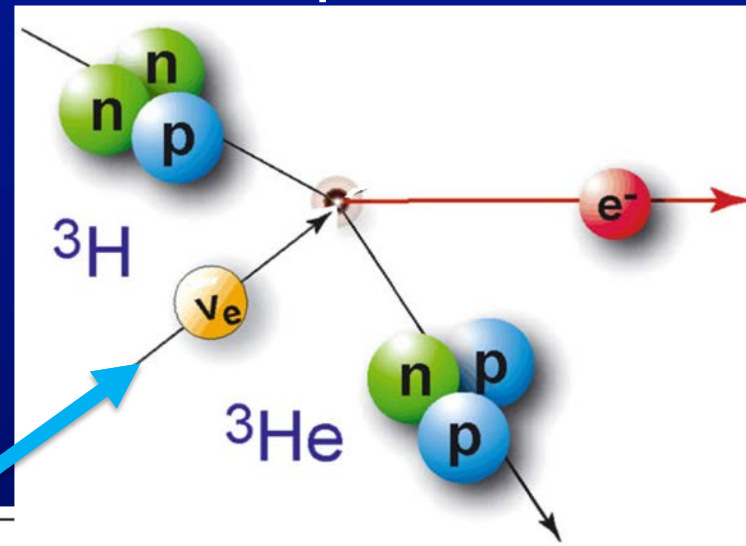


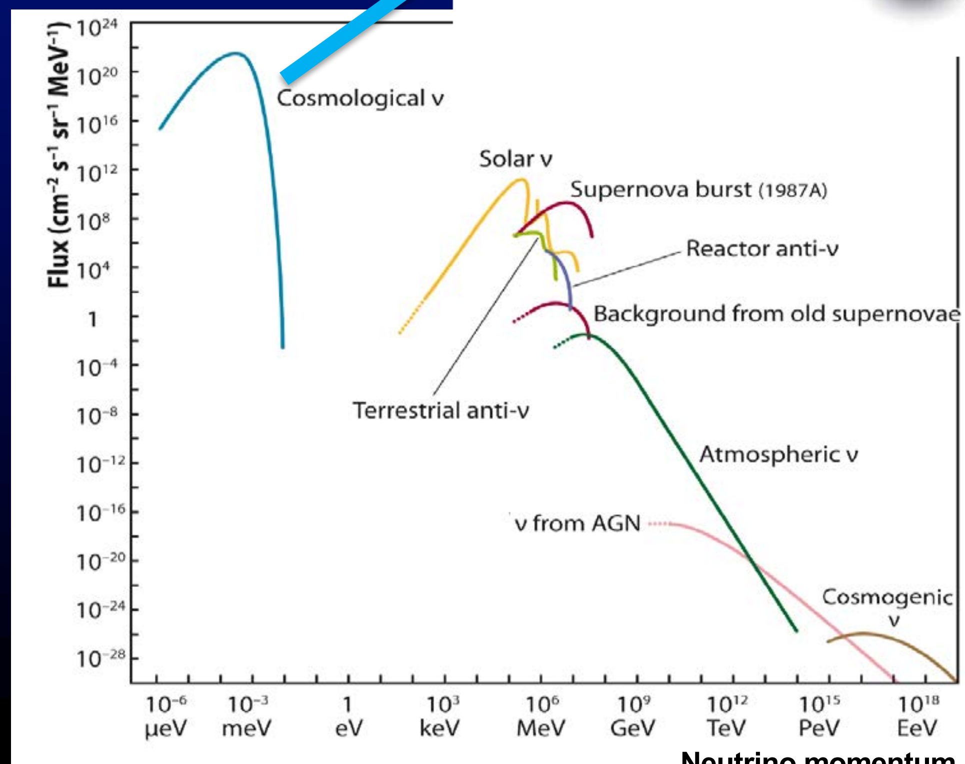


Neutrino capture on Tritium



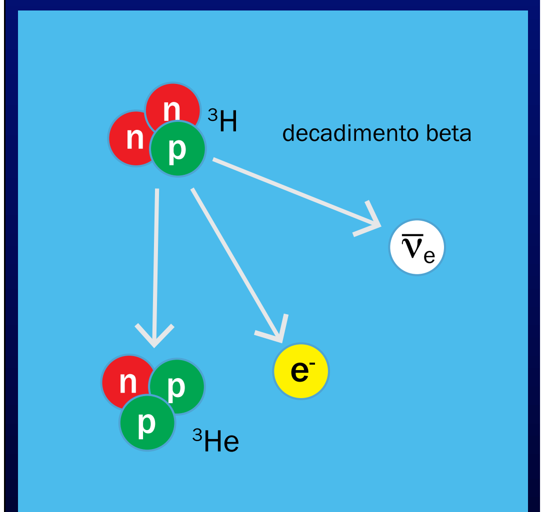
Tritium β-decay
(12.3 yr half-life)

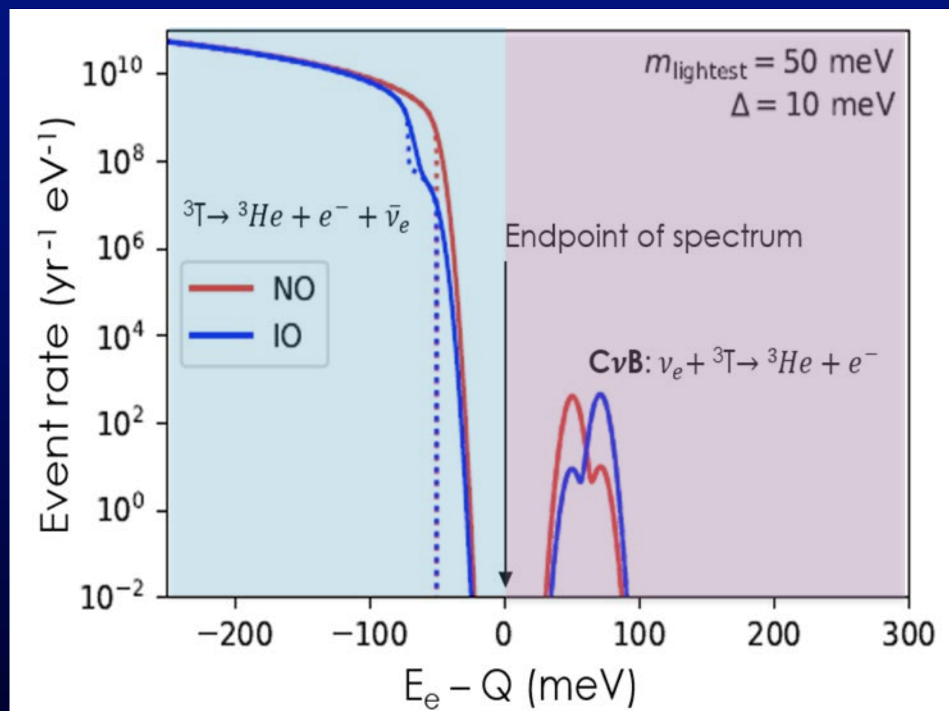


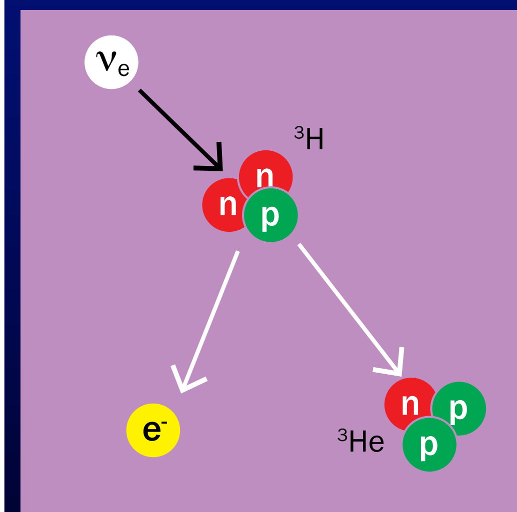


Detection Concept: Neutrino Capture

- 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]







What do we know?

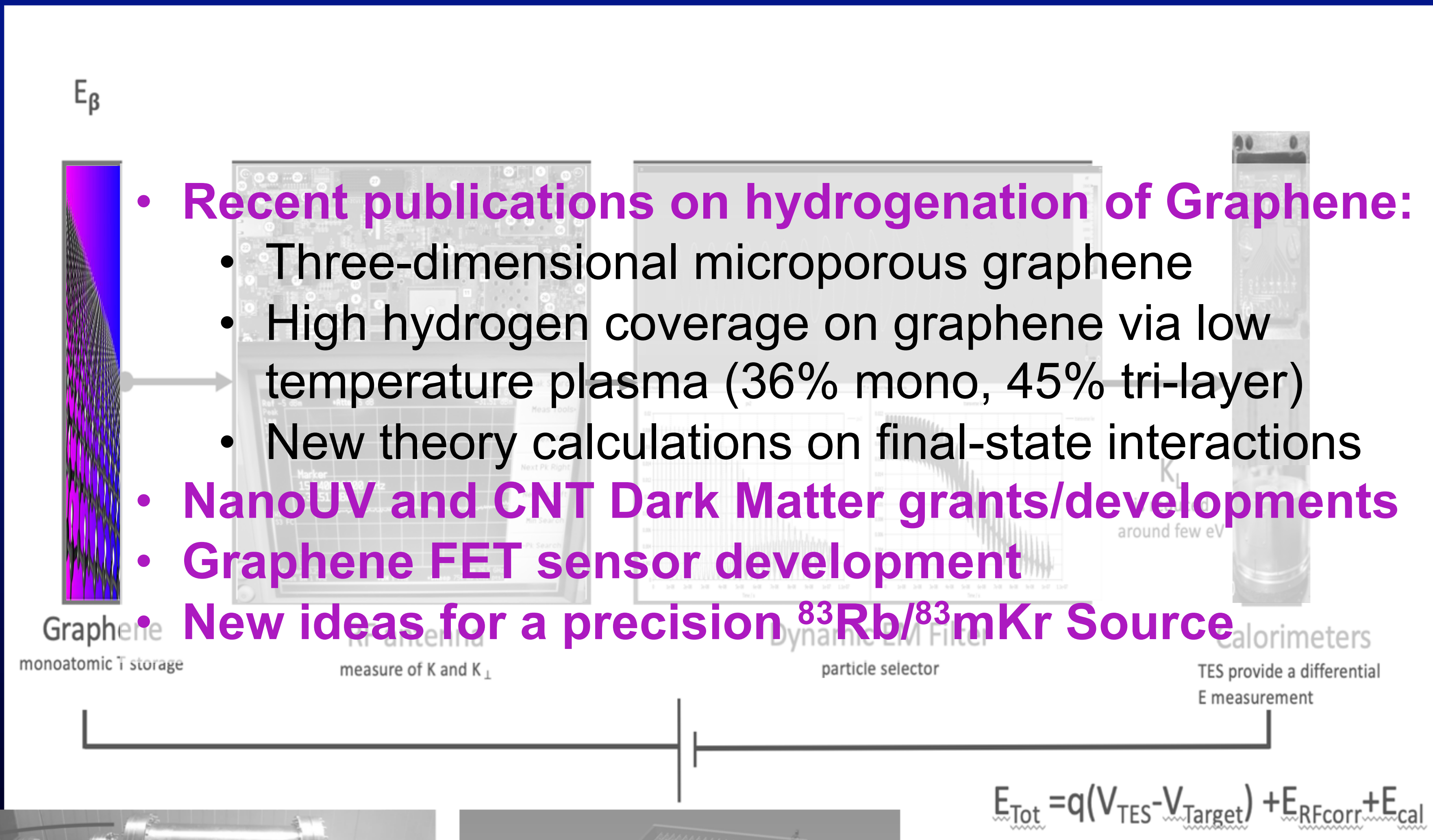
Electron flavor expected with
m > ~50meV
from neutrino oscillations

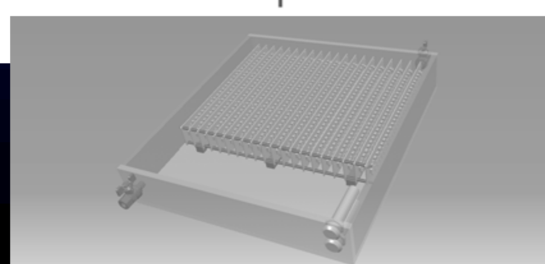
Gap (2m) constrained to
m < ~200meV
from Cosmology

Next

Conceptual Block Diagram

- **Recent publications on hydrogenation of Graphene:**
  - Three-dimensional microporous graphene
  - High hydrogen coverage on graphene via low temperature plasma (36% mono, 45% tri-layer)
  - New theory calculations on final-state interactions
- **NanoUV and CNT Dark Matter grants/developments**
- **Graphene FET sensor development**
- **New ideas for a precision $^{83}Rb/^{83m}Kr$ Source**

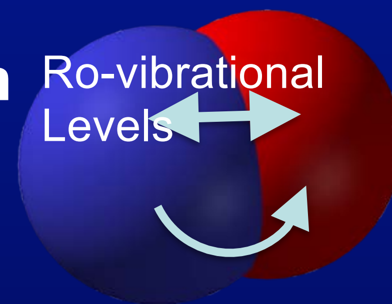




Tritium Target

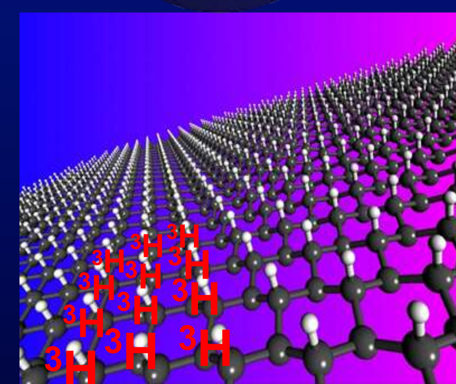
One of most severe challenges of probing ~50meV neutrino masses with nuclear processes is to control the initial-to-final state transitions of the target nuclei – tritium

Hierarchy of Quantum-limited Zero-Point Motion



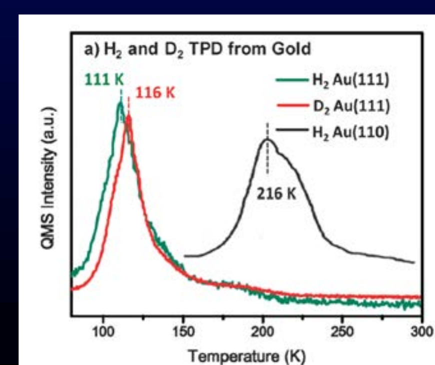
T-T molecule (4.7eV covalent bond) computed **ΔE ~ 340meV**

- ro-vibrational states w/ ~56.5% from (He^3-T)* (TRIMS)
- KATRIN cold gas windowless source



T-Graphene Monolayer (0.7-1.0eV covalent bond) **~x$\sqrt{1.0/4.7}$**

- vibrational and phonon excitations
- photon recoils with higher effective mass (Mossbauer)
- Tri-Layer / doped-Graphene (increased 2D diffusion)



T-Au(111) or Cu(111) mono-atomic surface cryogenic target

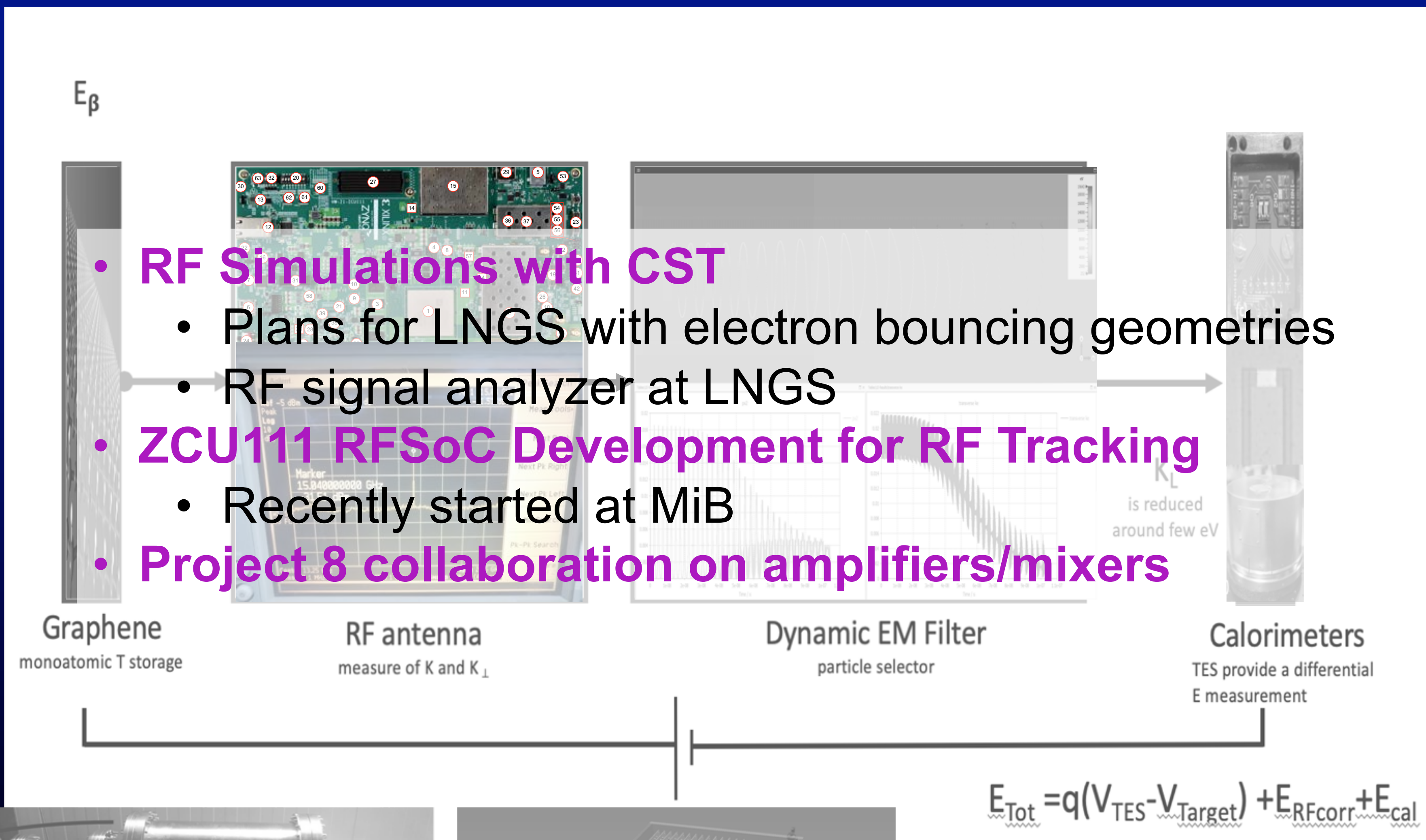
- diffusion barrier 0.15eV for 2D motion **~x$\sqrt{0.15/4.7}$** high pitch

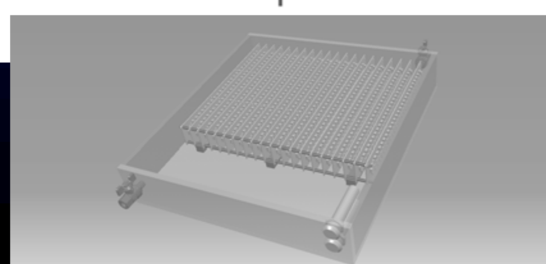
T-dissociated in superfluid ^{4}He (full 3D diffusion)

- Atomic T recombination ~0.5-6 months and circulated target
- (D. Lee) http://doi.org/10.1103/PhysRevLett.89.175301

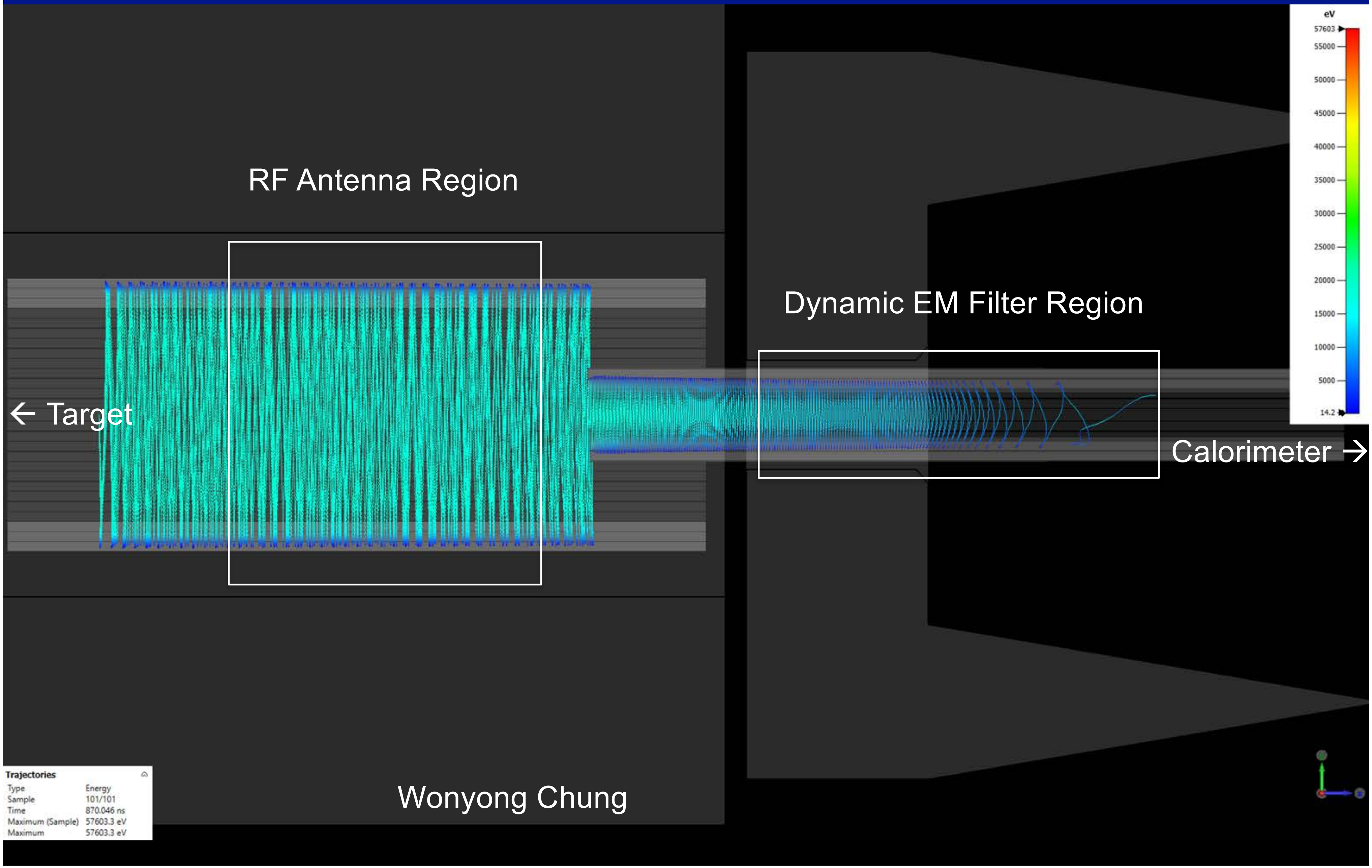
Conceptual Block Diagram

- **RF Simulations with CST**
  - Plans for LNGS with electron bouncing geometries
  - RF signal analyzer at LNGS
- **ZCU111 RFSoC Development for RF Tracking**
  - Recently started at MiB
- **Project 8 collaboration on amplifiers/mixers**

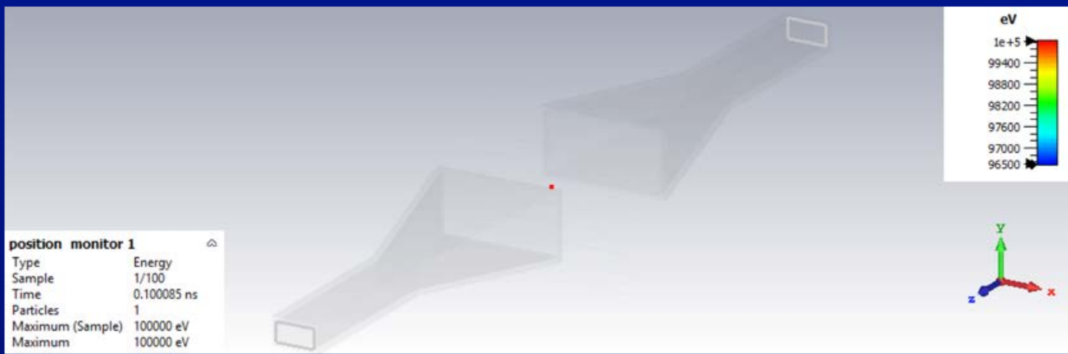


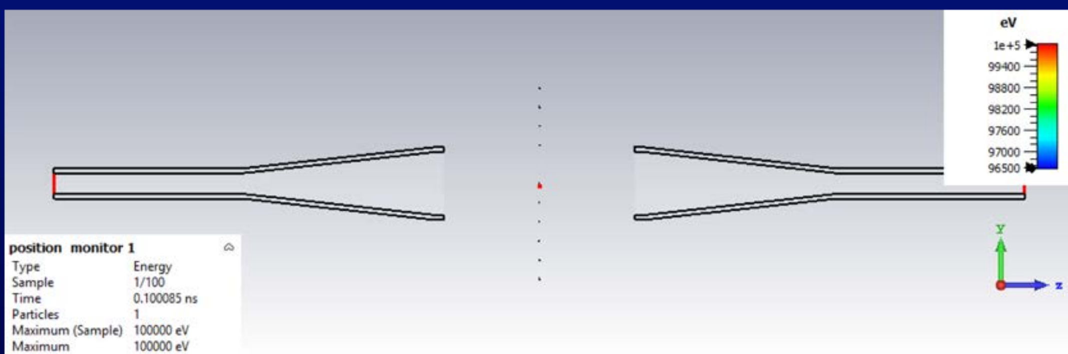


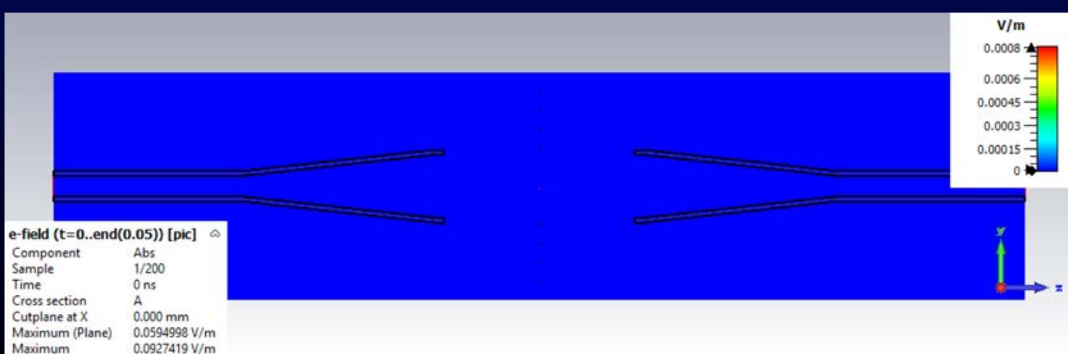
Electron Transport through RF antennas



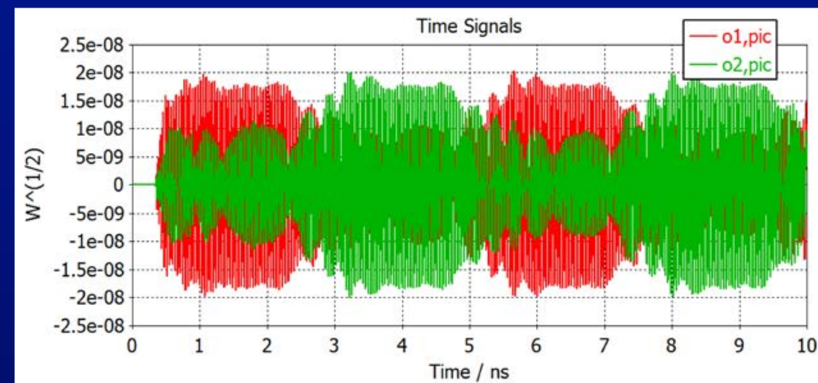
RF Sensing



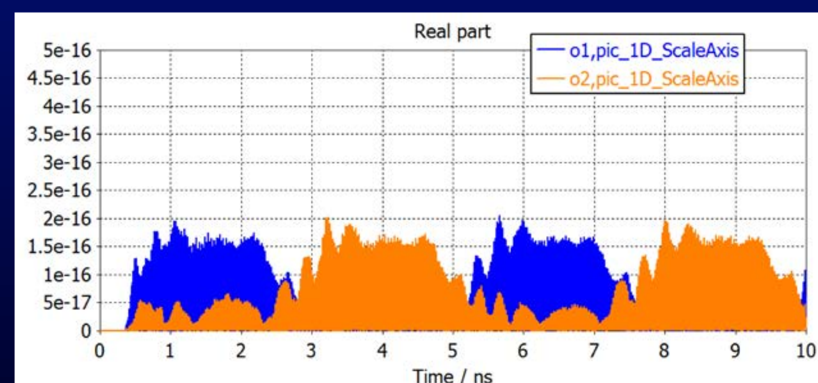


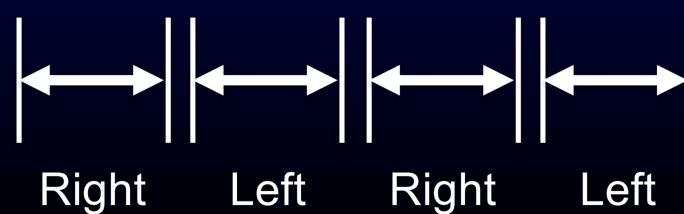


Time Series (~26 GHz)

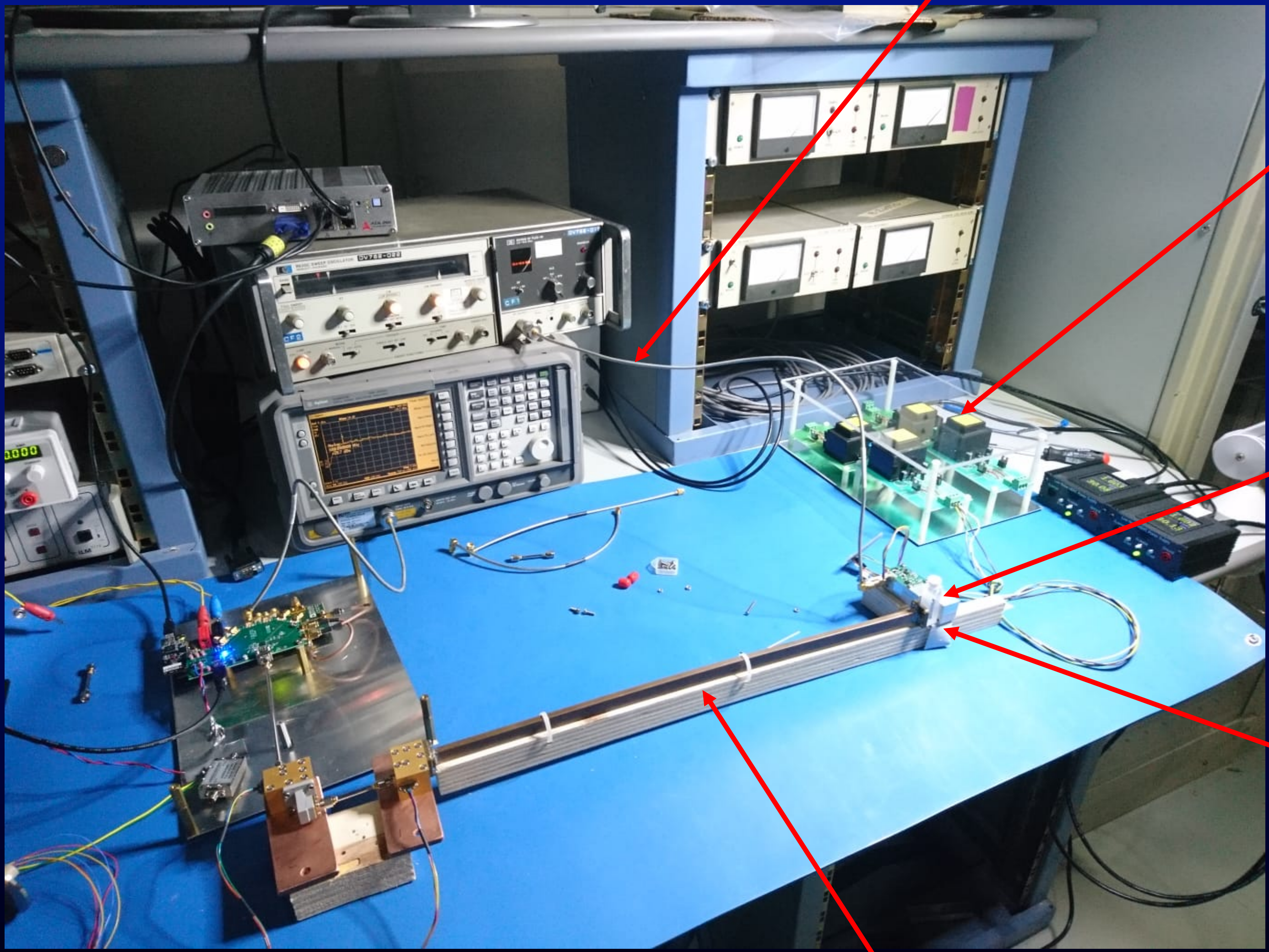


Power(~0.1 fW)





LNGS Setup



Signal injection: ~13 GHz

4 Low voltage channels

Frequency multiplier

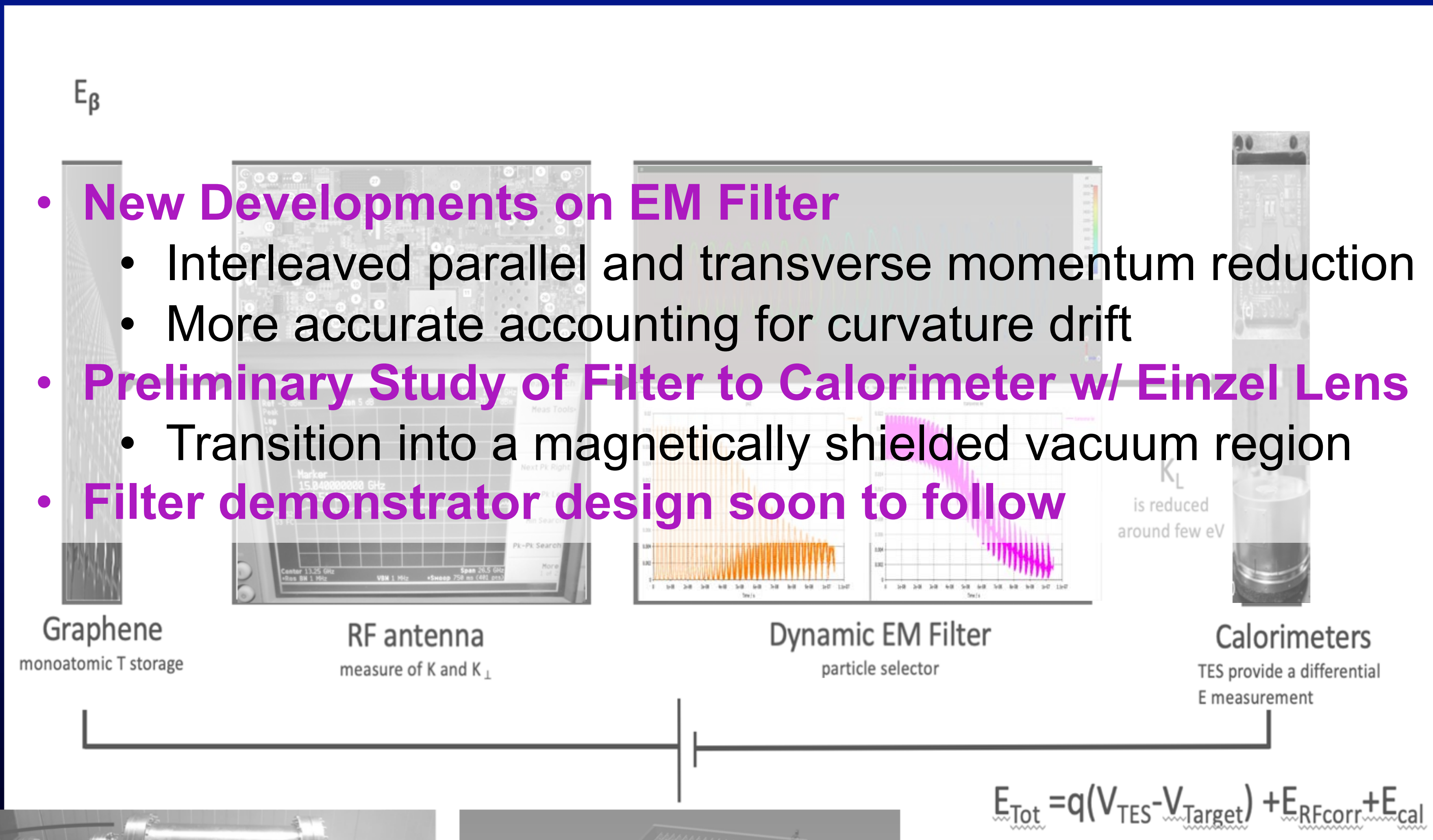
Calibrated 1 cm water absorber

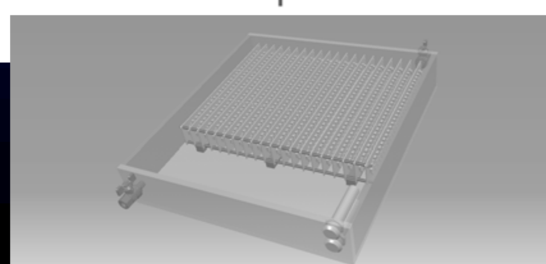
WR42 Waveguide from Princeton

Alfredo Cocco, George Korga, Marcello Messina

Conceptual Block Diagram

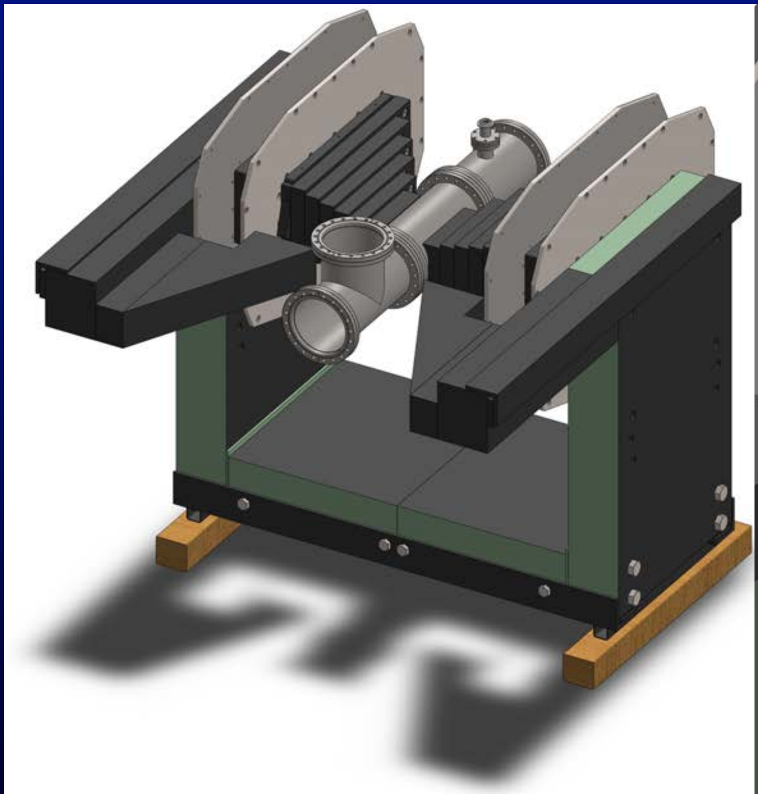
- **New Developments on EM Filter**
  - Interleaved parallel and transverse momentum reduction
  - More accurate accounting for curvature drift
- **Preliminary Study of Filter to Calorimeter w/ Einzel Lens**
  - Transition into a magnetically shielded vacuum region
- **Filter demonstrator design soon to follow**

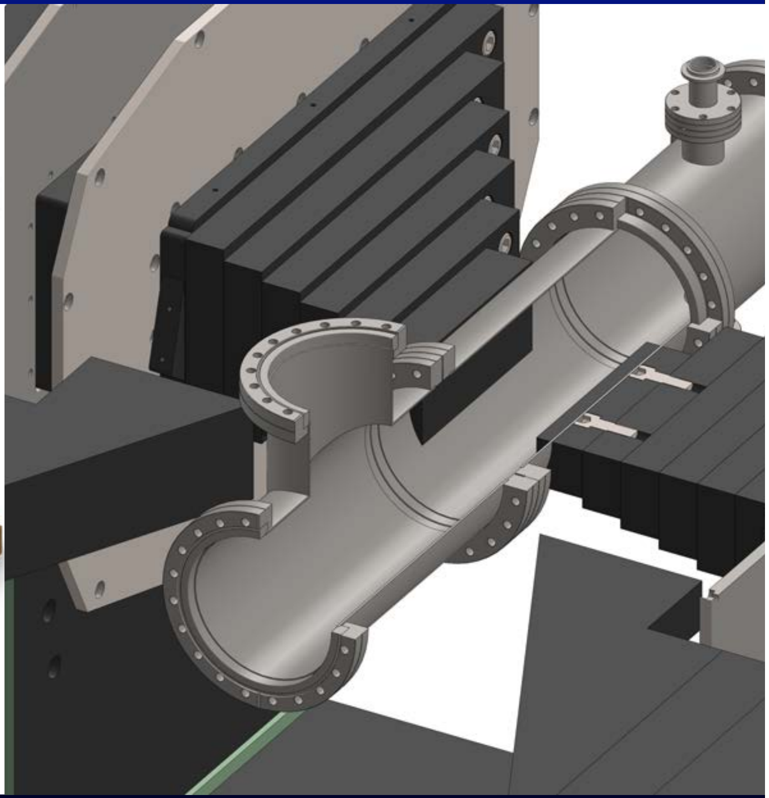




Magnet and Vacuum chamber

- Standard 6” tube with 8” CF flanges as the vacuum chamber.
- The iron poles were trimmed by the vacuum chamber.



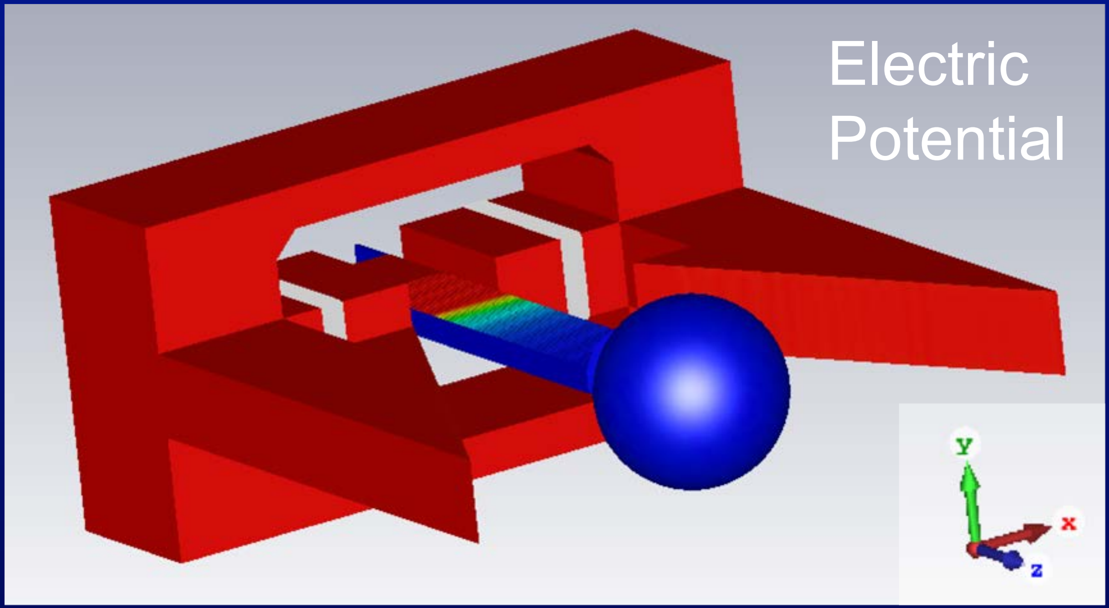


Andy Tan

Transverse Drift Filter

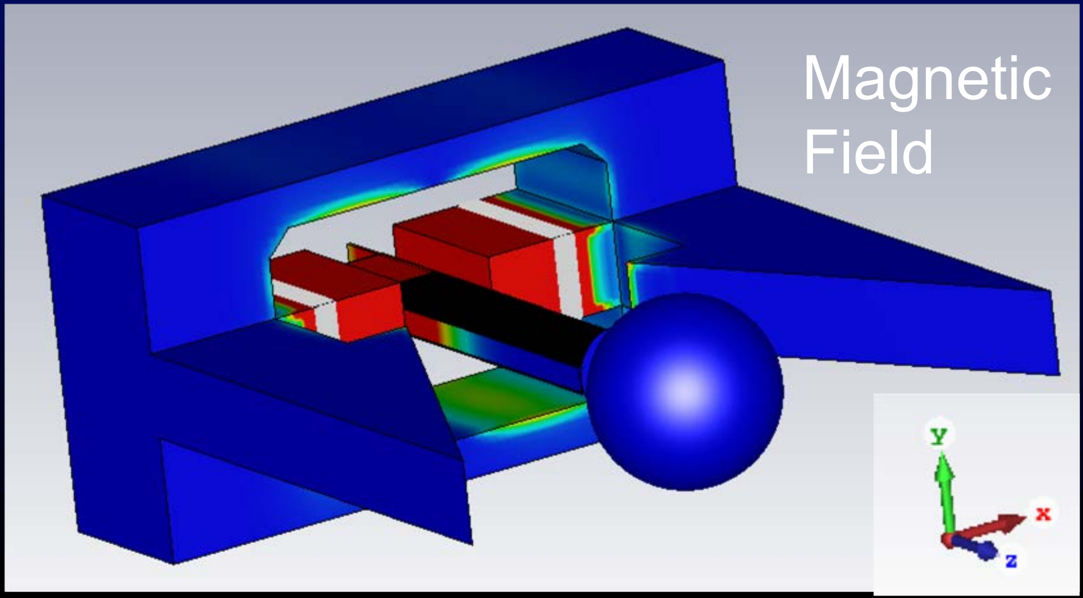
Principle of Operation:

Kinetic Energy of electron drained by climbing a voltage potential with second-order transverse drift



E Field drops exponentially

- E_x bounces electron in x
- E_y drifts in z ($B_x x E_y$)
- E_z counters grad-B y-drift



B Field drops exponentially

- B_x cyclotron motion in y-z
- grad-B drifts in y (work)

Next

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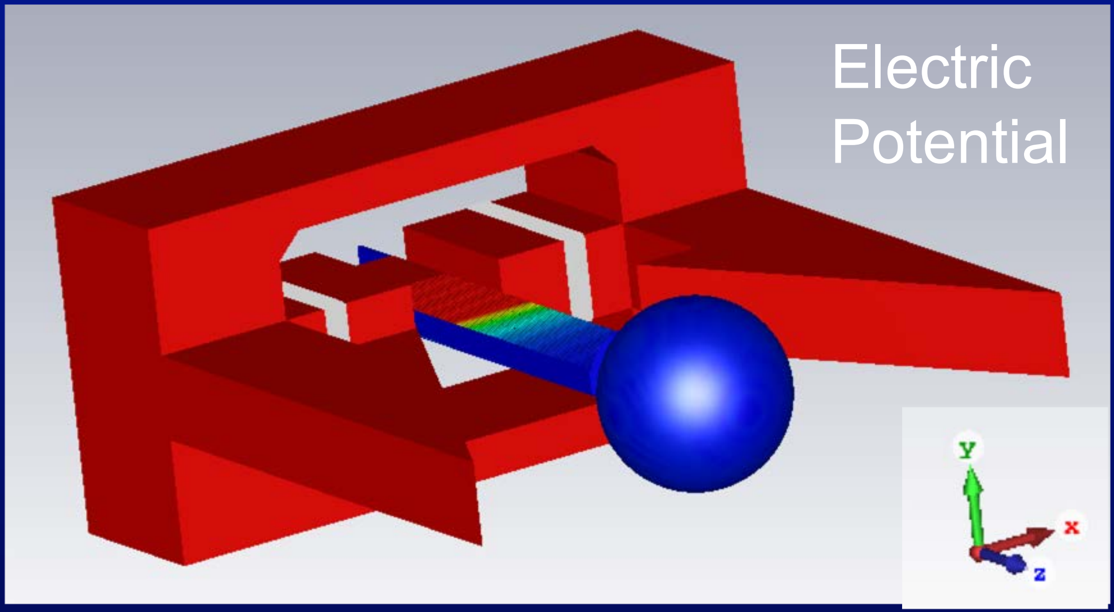

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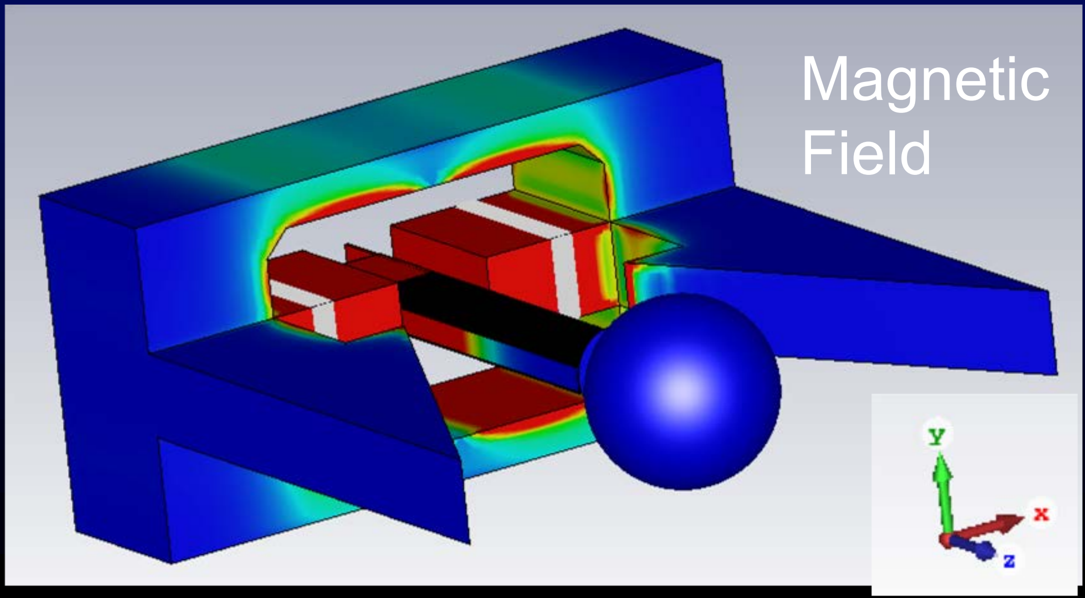

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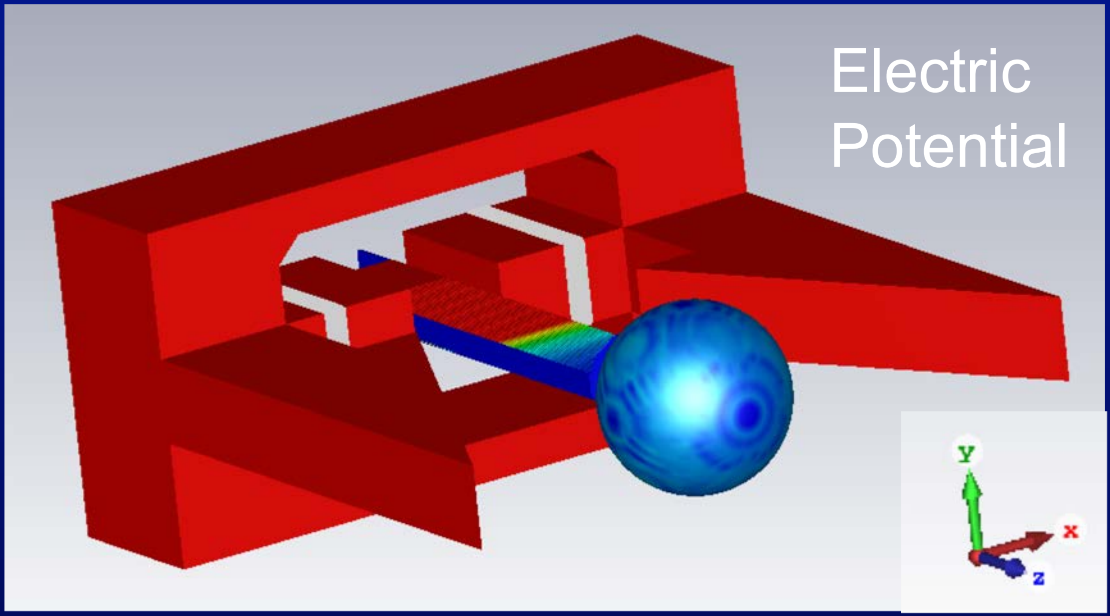

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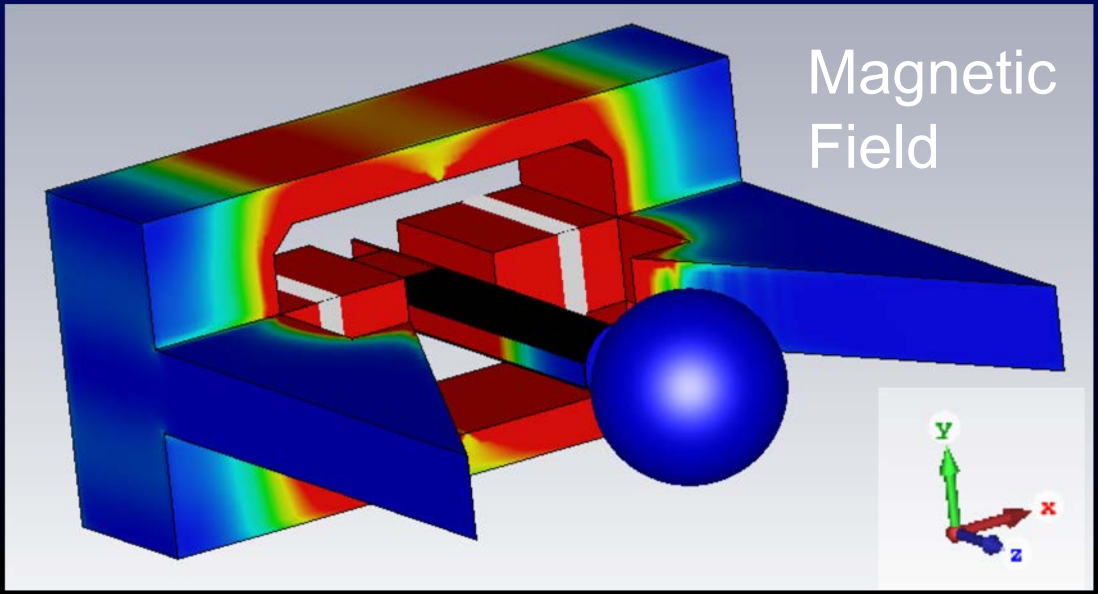

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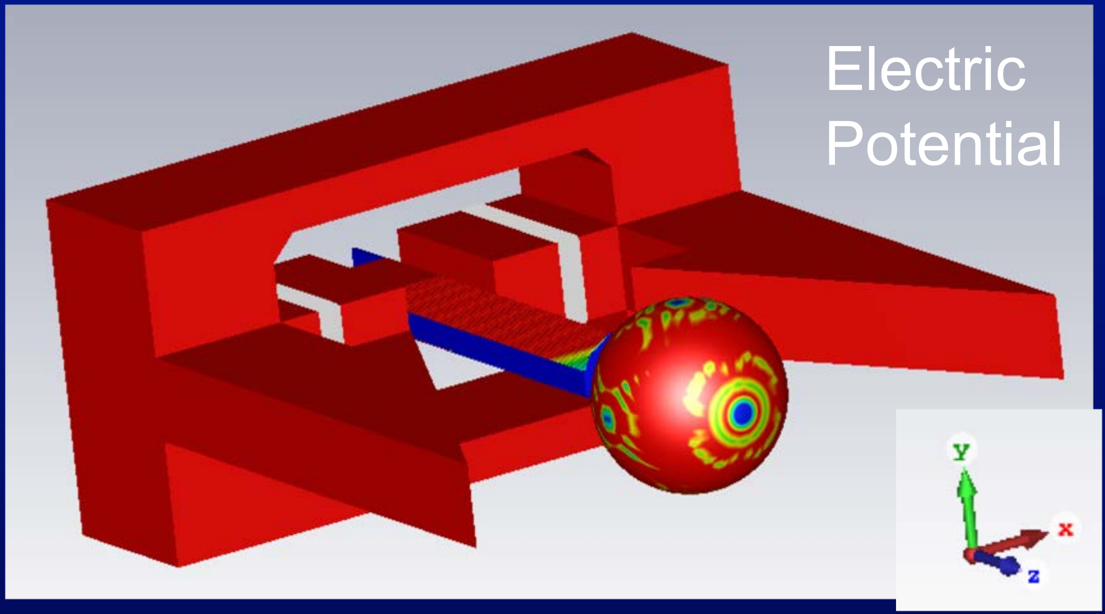

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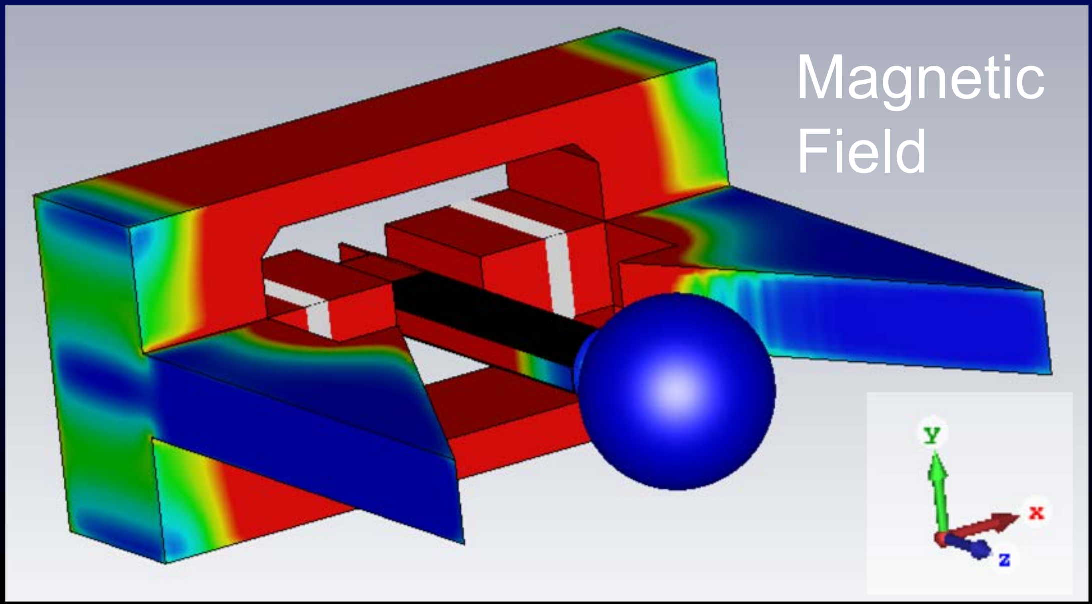

B Field drops exponentially

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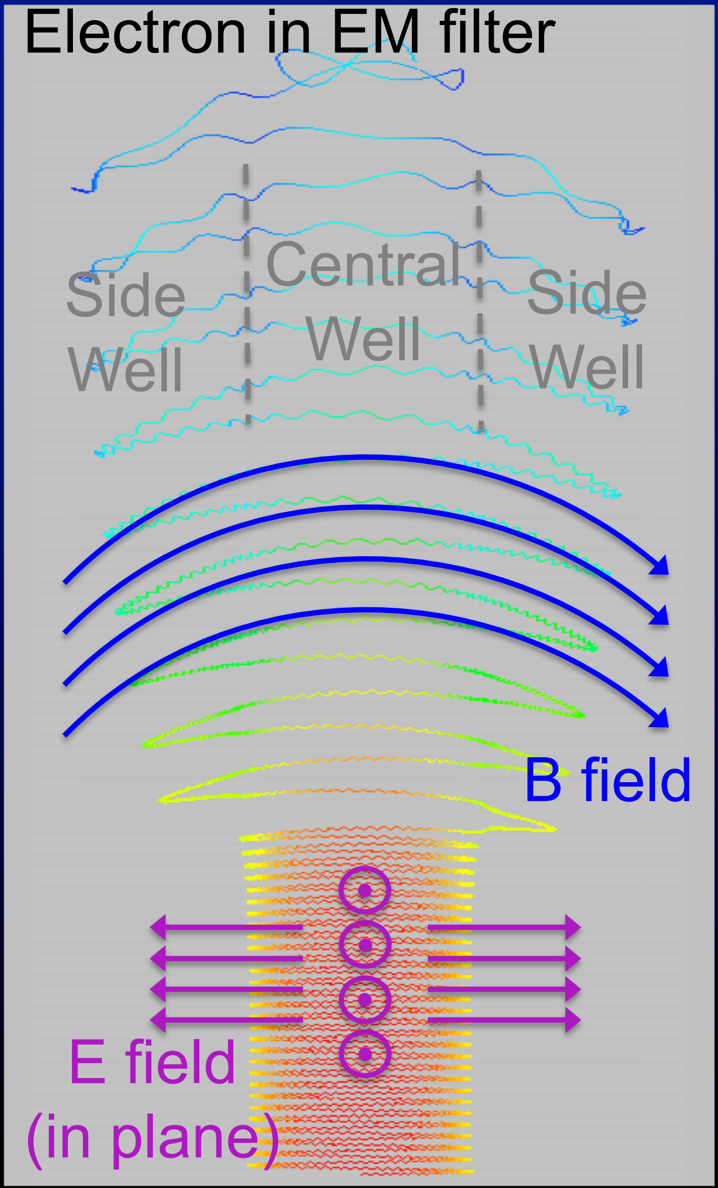
- grad-B drifts in y (work)

Parallel/Transverse Kinetic Energy → Electric Potential



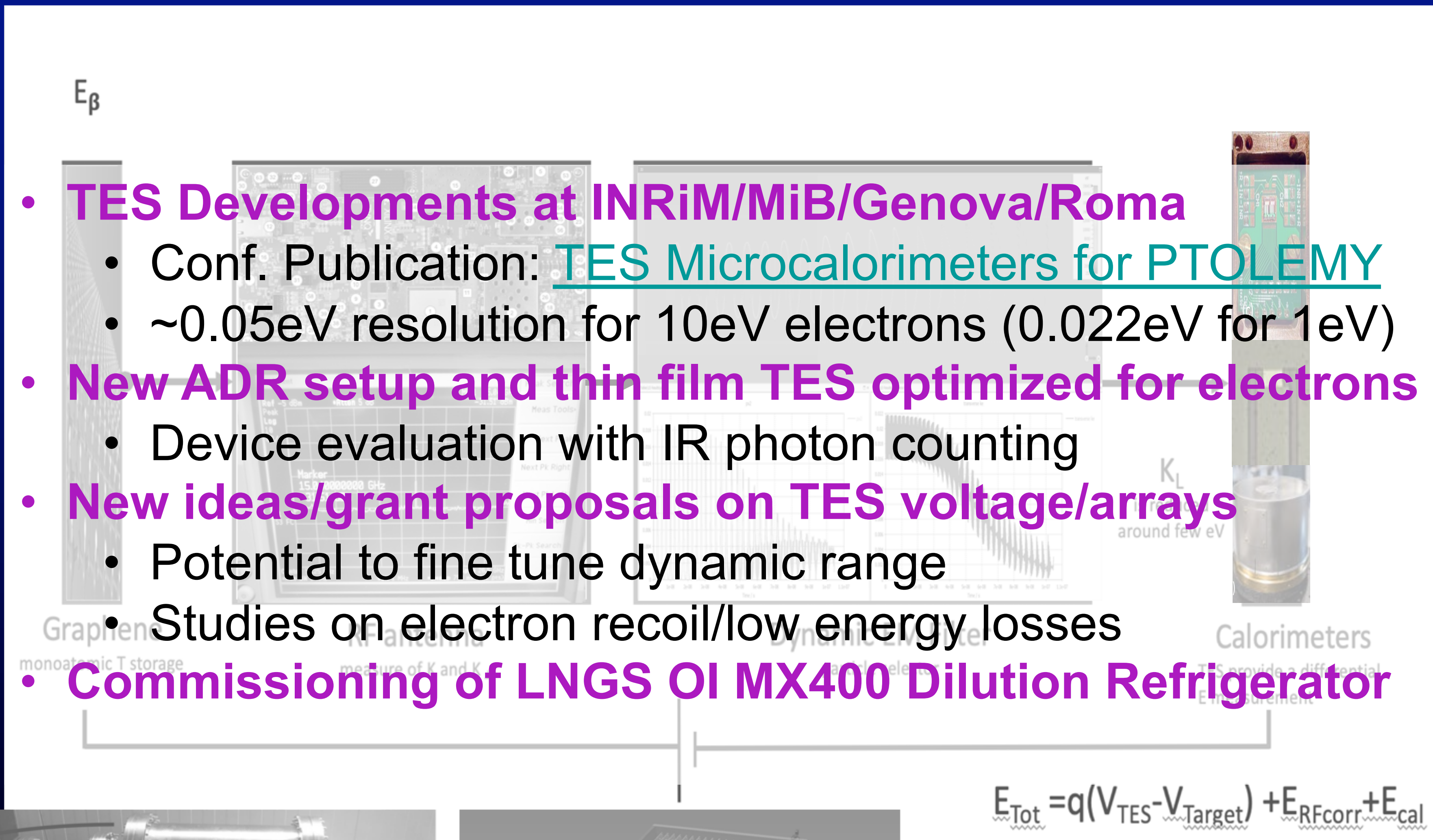
Blue = ~ 100 eV KE

~ 25 cm

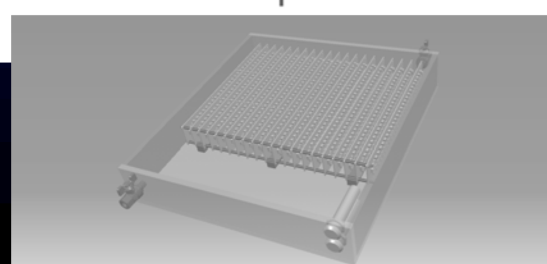
"Herringbone Technique"

Red = 18,600 eV KE

Conceptual Block Diagram



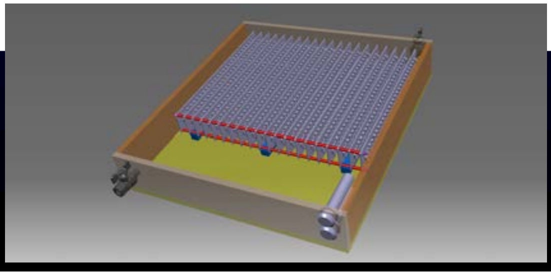
- **TES Developments at INRiM/MiB/Genova/Roma**
  - Conf. Publication: TES Microcalorimeters for PTOLEMY
  - ~0.05eV resolution for 10eV electrons (0.022eV for 1eV)
- **New ADR setup and thin film TES optimized for electrons**
  - Device evaluation with IR photon counting
- **New ideas/grant proposals on TES voltage/arrays**
  - Potential to fine tune dynamic range
  - Studies on electron recoil/low energy losses
- **Commissioning of LNGS OI MX400 Dilution Refrigerator**



Conceptual Block Diagram

- **New Design of HV System**
  - Layout and components available at LNGS
  - Preliminary simulations show that the design specifications can be met with this system
- **E-gun Developments at LNGS**
  - Helmholtz canceling coils tests and working
  - MCP detectors for single electron detection
- **New E-gun Design under development**
  - Running PTOLEMY filter “in reverse”

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



Karolina Rozwadowska

PTOLEMY R&D at LNGS

PonTecorvo Observatory for Light, Early-universe, Massive-neutrino Yield

R&D effort hosted at the Gran Sasso National Laboratory

Exploring possible future sites that can host telescope operation with a 10mg tritium target (expertise from TLK group)

Recent Publications and Funding

The Simons Foundation:
https://www.simonsfoundation.org/grant/targeted-grants-in-mps/?tab=awardees

European Funding (NWO – The Netherlands):
https://www.nwo.nl/en/researchprogrammes/toekenningen-nwa-orc/awards-nwa-orc-2019

INFN Detector R&D at LNGS:
https://ptolemy.lngs.infn.it

Neutrino Physics Program (CNB, Mass, Sterile,..):
Neutrino physics with the PTOLEMY project, M.G. Betti et al.,
JCAP **07** (2019) 047,
DOI: 10.1088/1475-7516/2019/07/047,
e-Print: arXiv:1902.05508

Transverse Filter Design:
A design for an electromagnetic filter for precision energy measurements at the tritium endpoint,
M.G. Betti et al.,
Prog.Part.Nucl.Phys. **106** (2019) 120-131,
DOI: 10.1016/j.ppnp.2019.02.004,
e-Print: arXiv:1810.06703

Papers in Progress (and many others in R&D):
- *Experimental Design of the PTOLEMY Concept*
- *Low Field Optimization of PTOLEMY Electromagnetic Filter*
- *Multi-Messenger Astrophysics with the Cosmic Neutrino Background*

PTOLEMY World-Wide Collaboration

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 FÍSICA CORPUSCULAR

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Stockholm University

UPPSALA UNIVERSITET

UNIVERSITY OF AMSTERDAM

Radboud University

Nikhef

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

UNIVERSITÀ DEGLI STUDI DI GENOVA

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEGLI STUDI DI MILANO 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

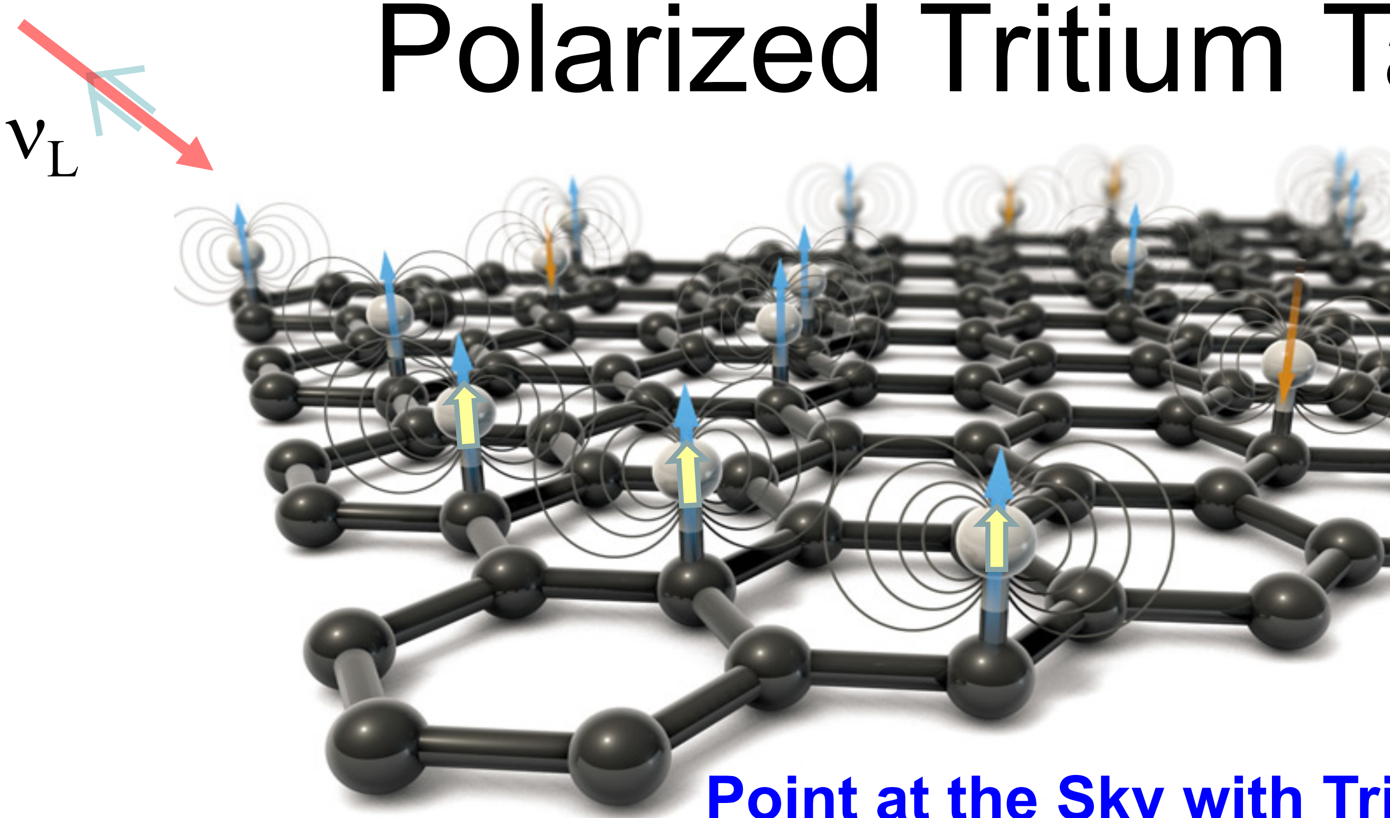
Kosmisk neutrinoteleskop

Cosmic neutrino telescope

2015 Targeted Grant Award from the SIMONS FOUNDATION

ADDITIONAL SLIDES

Polarized Tritium Target

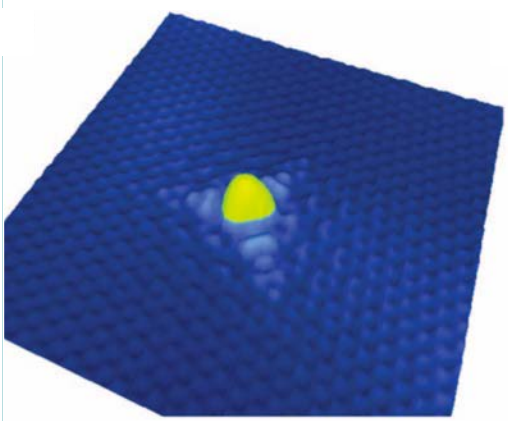


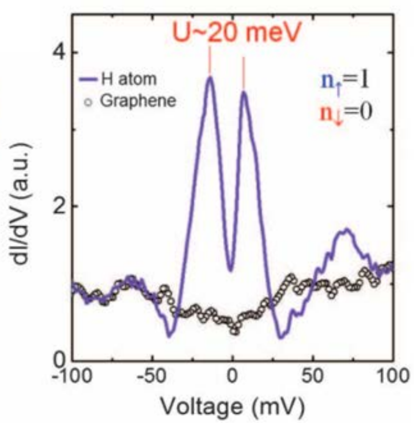
Lisanti, Safdi, CGT, 2014.
10.1103/PhysRevD.90.073006
Akhmedov, 2019.
10.1088/1475-7516/2019/09/031

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).

2.6 Cosmological Neutrinos (C. Tully)

2.6.1 Introduction

At a red-shift of roughly 10 billion, nearly half of the total energy density of the Universe was in the form of neutrino kinetic energy, according to the Standard Cosmology Model. After decoupling from the thermal bath of the hot Big Bang at under 1 second, Big Bang neutrinos, also known as the Cosmic Neutrino Background (CνB) or relic neutrinos, have continued to influence the Hubble expansion and rates of large-scale structure formation during over 13.7 billion years to the present day. Due to the finite mass splittings measured through flavor oscillations, an important transition from relativistic to non-relativistic energies is believed to have already transpired for at least two massive states of the neutrinos. As a result, the CνB is the largest known source of non-relativistic neutrinos.

Despite the unequivocal importance of neutrinos in shaping the expansion of the Universe, there is no present-day evidence that the CνB neutrinos continue to pervade all of space with a predicted average number density of 336 particles per cubic centimeter, assuming three flavors of light neutrinos and making no assumptions on whether the neutrino is distinct from the anti-neutrino. The experimental effort on detecting the cosmic neutrino background is being advanced on two fronts. One is through a new generation of precision cosmology measurements to detect the sub-percent fraction of the critical energy density from massive neutrinos, and the second is through the development of direct detection methods based on neutrino capture on β-decaying nuclei.

2.6.2 Direct Detection Experiments

Several methods to detect relic neutrinos have been proposed. Most of them have estimated sensitivities many orders of magnitude too low to detect relic neutrinos. However, one of them – neutrino capture on β-decaying nuclei, looks conceivable with major improvements in the detection techniques. The idea was suggested by Weinberg [205] for massless neutrinos. Cocco *et al.* [98] have noticed that for massive neutrinos the energy of the electrons from the neutrino capture process exceeds the maximum energy in the β-decay by about two neutrino masses. Therefore, the separation of the neutrino capture process from the overwhelming background from usual β-decays would be feasible with an extremely good energy resolution of about 50 meV or even better. The PTOLEMY collaboration [89] performs active R&D [77] in order to demonstrate the feasibility of such a goal. The possibility to detect the neutrino capture on β-decaying nuclei using correlations between the neutrino direction and the spin of the β-decaying nucleus was discussed recently [158, 41].

Snowmass LOI

PTOLEMY: Towards Direct Detection of the Cosmic Neutrino Background

Snowmass 2021 Letter of Intent

LOI Supporters and the PTOLEMY Collaboration

M.G. Betti[10,11], M. Biasotti[4], A. Boscá[16], F. Calle[16], J. Carabe-Lopez[14], G. Cavoto[10,11], C. Chang[24,25], W. Chung[28], A.G. Cocco[6], A.P. Colijn[13], J. Conrad[19], N. D'Ambrosio[2], P.F. de Salas[17,19], M. Faverzani[5], A. Ferella[19], E. Ferri[5], L. Ficcadenti[10,11], P. Garcia-Abia[14], G. Garcia Gomez-Tejedor[15], S. Gariazzo[17], F. Gatti[4], C. Gentile[27], A. Giachero[5], J.E. Gudmundsson[19], Y. Hochberg[1], Y. Kahn[25,26], M. Lisanti[28], C. Mancini-Terracciano[10,11], G. Mangano[6], L.E. Marcucci[8,9], C. Mariani[11], J. Martínez[16], M. Messina[2], A. Molinero-Vela[14], E. Monticone[12], A. Nucciotti[5], F. Pandolfi[10], S. Pastor[17], J. Pedrós[16], C. Pérez de los Heros[20], O. Pisanti[6,7], A.D. Polosa[10,11], A. Puiu[5], I. Rago[10,11], Y. Raitses[27], M. Rajteri[12], N. Rossi[10], A. Ruocco[29], R. Santorelli[14], K. Schaeffner[3], C.F. Strid[18,19], A. Tan[28], C.G. Tully[28], F. Zhao[28], K.M. Zurek[22,23]

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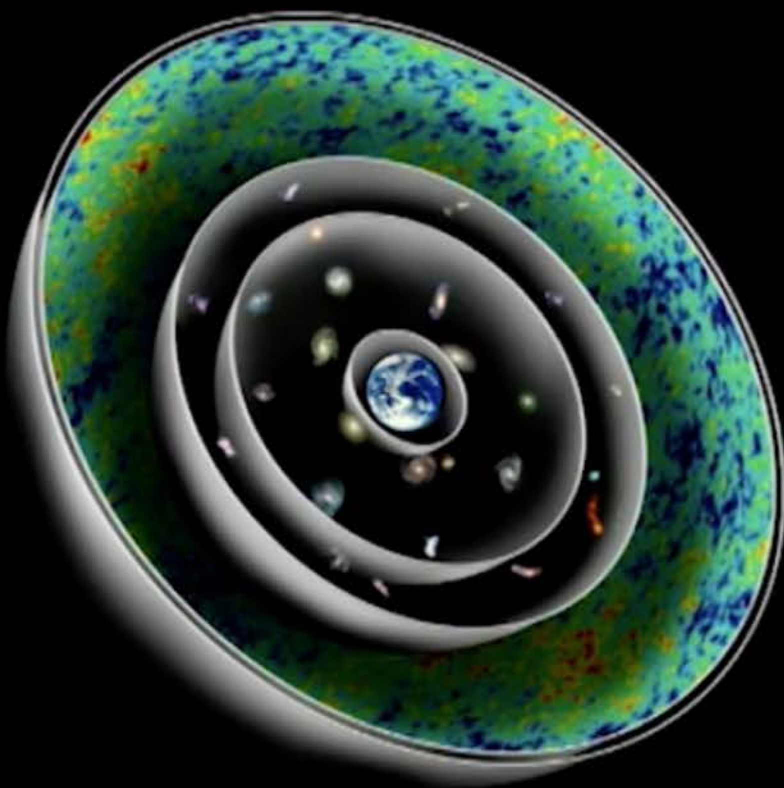
Looking Back in Time



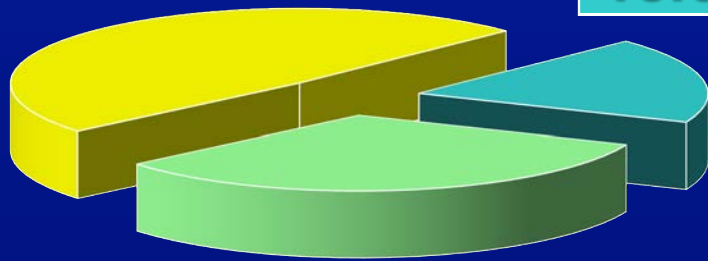
Le Sphere du Monde (1549)

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

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

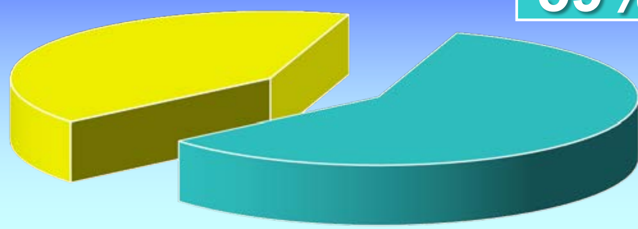
Elementary Particle (MeV)

Neutrino Decoupling (t=1 second)



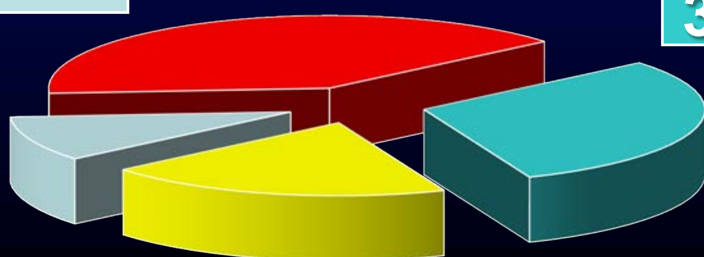
Nuclear (keV)

Big Bang Nucleosynthesis (1 minute)

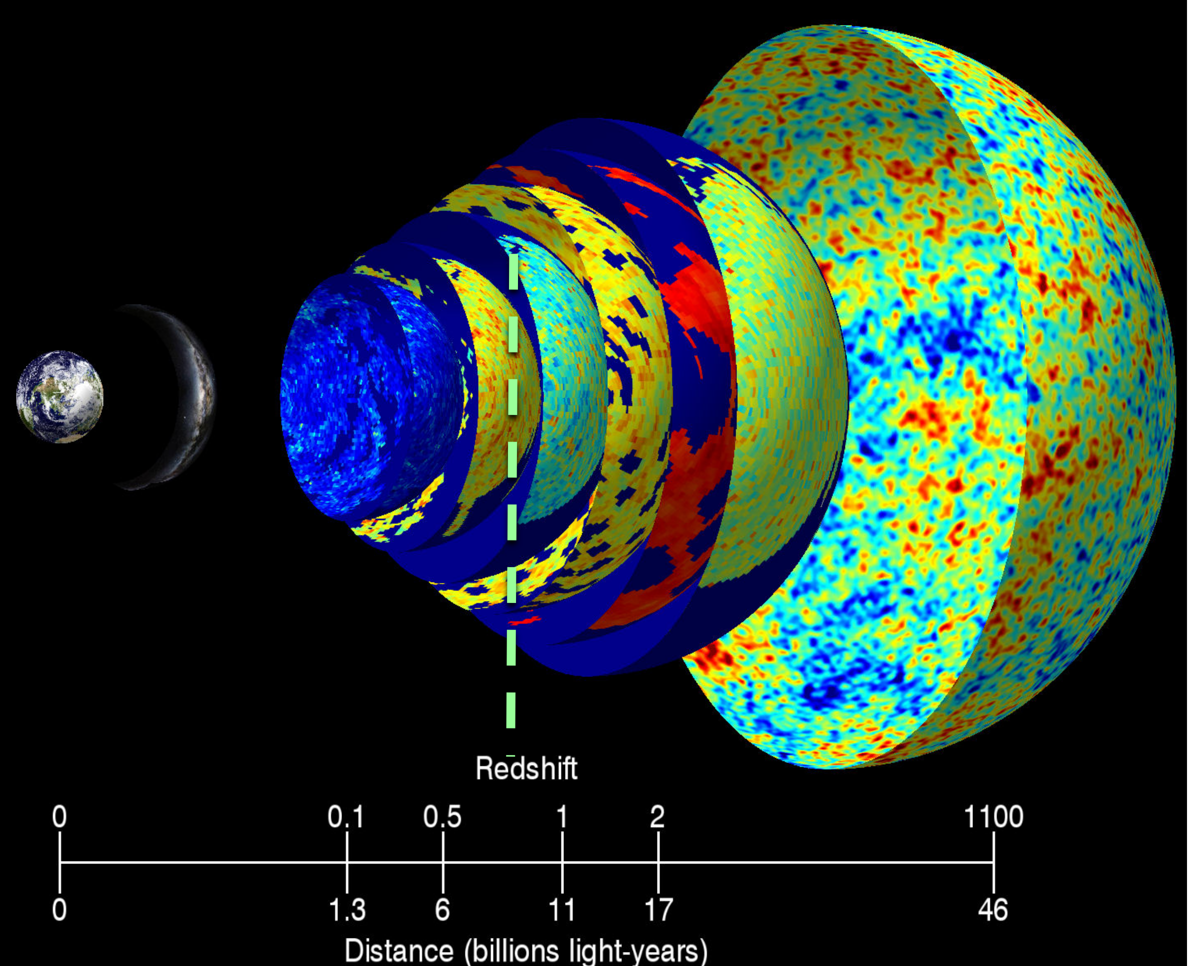


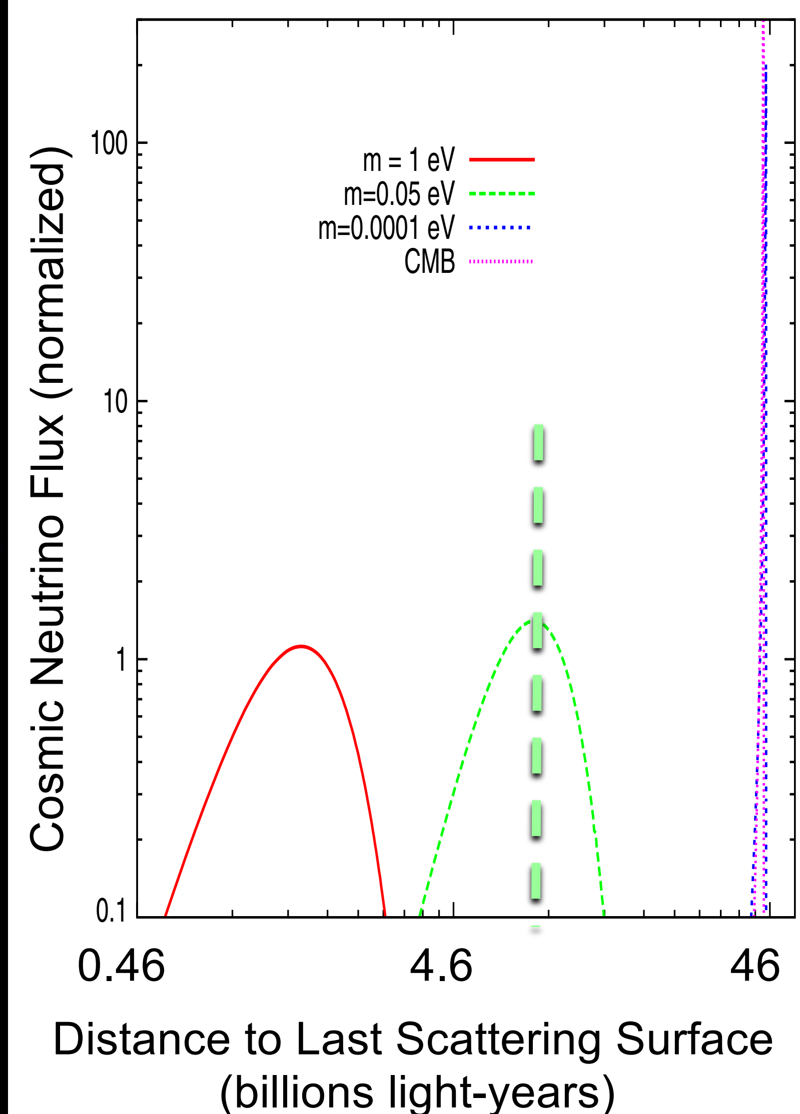
Atomic (eV)

Matter-Radiation Equality (75,000 years)



Distance to Last Scattering Surface for Massive Neutrinos





http://doi.org/10.1103/PhysRevLett.103.171301

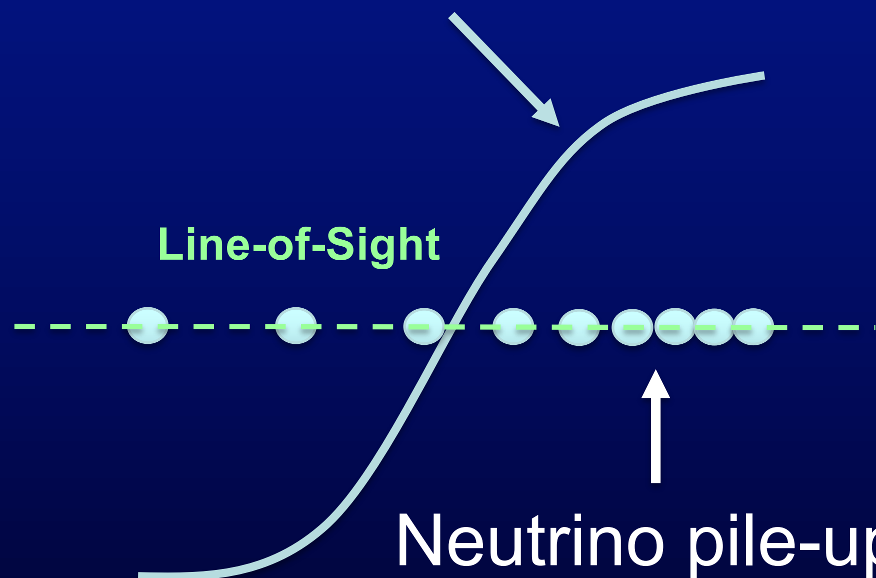
Line-of-Sight Calculations

Primordial power spectrum coverage: $\sim A_s\,(k/k_{pivot})^{ns-1}$

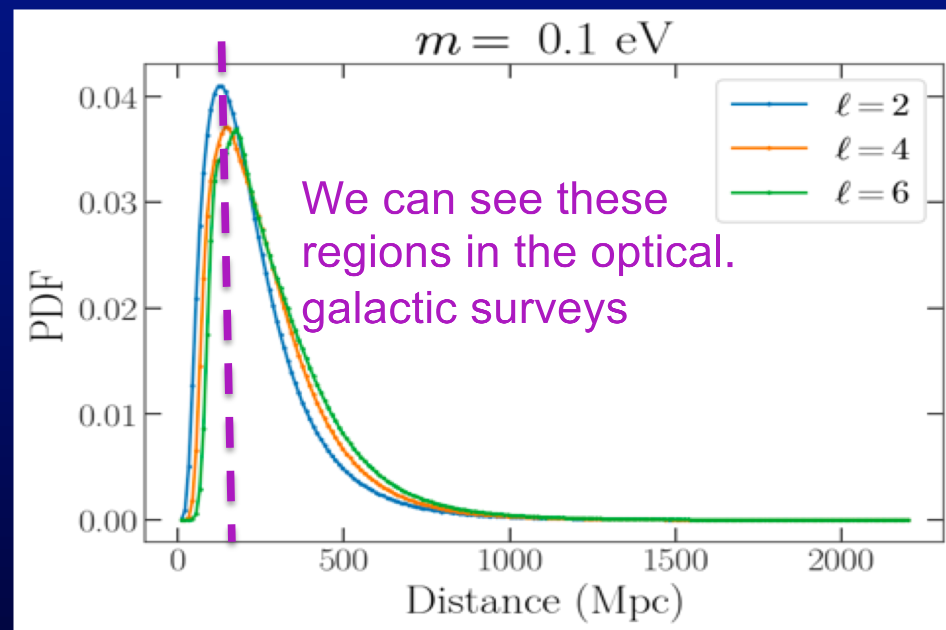
CMB: LSS ~ 10^4 Mpc/h, k ~ 5 x 10^{-3}

CNB: LSS ~ 10^3 Mpc/h, k ~ 5 x 10^{-2}

(linear) k-mode in gravity potential



Neutrino pile-up
from non-rel. velocities

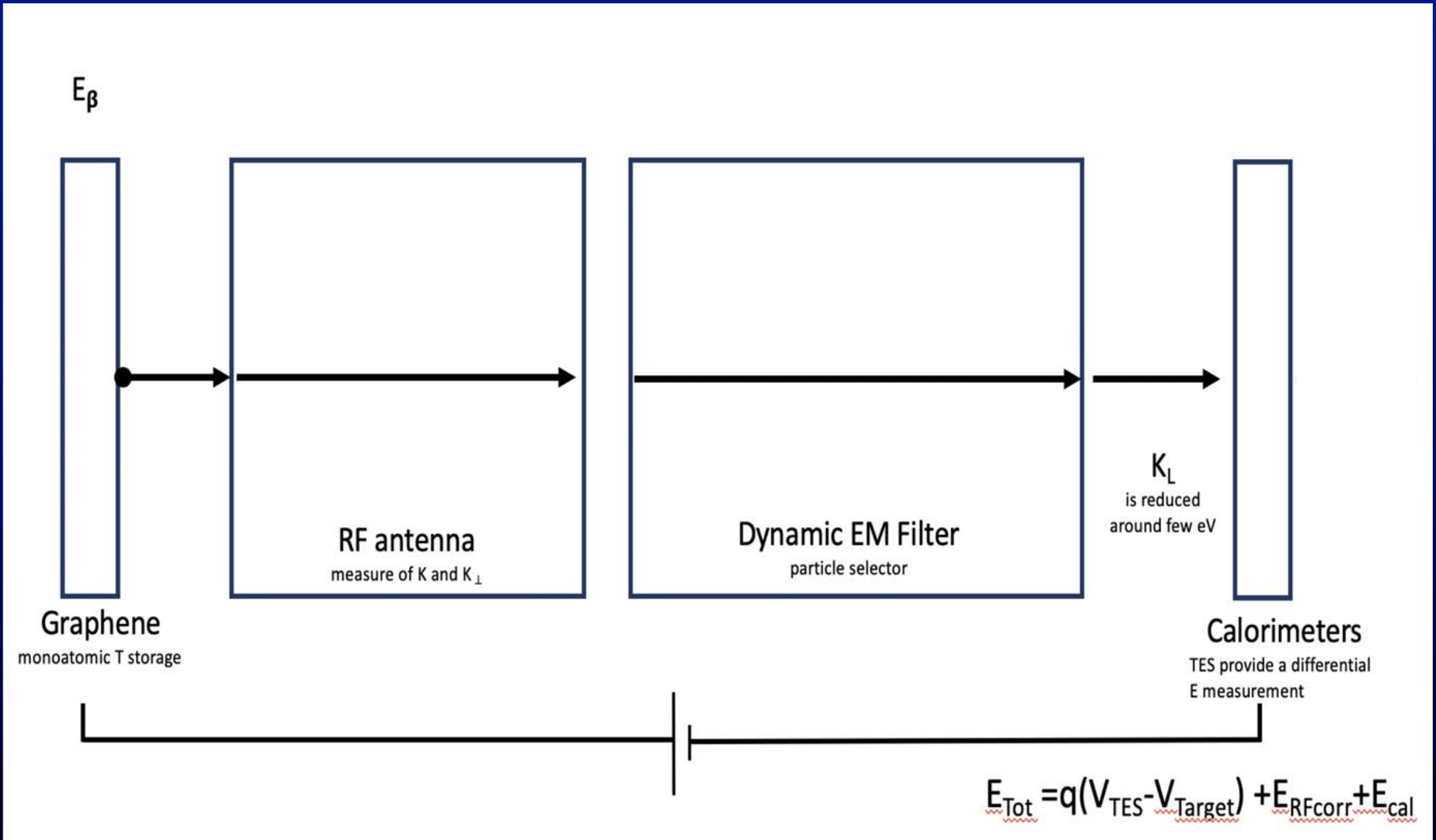


neutrino velocity ~ 2% c at peak

Detection (capture) of cold neutrinos:
$\sigma(v/c)$ ~ constant ~ 10^{-44} cm^2

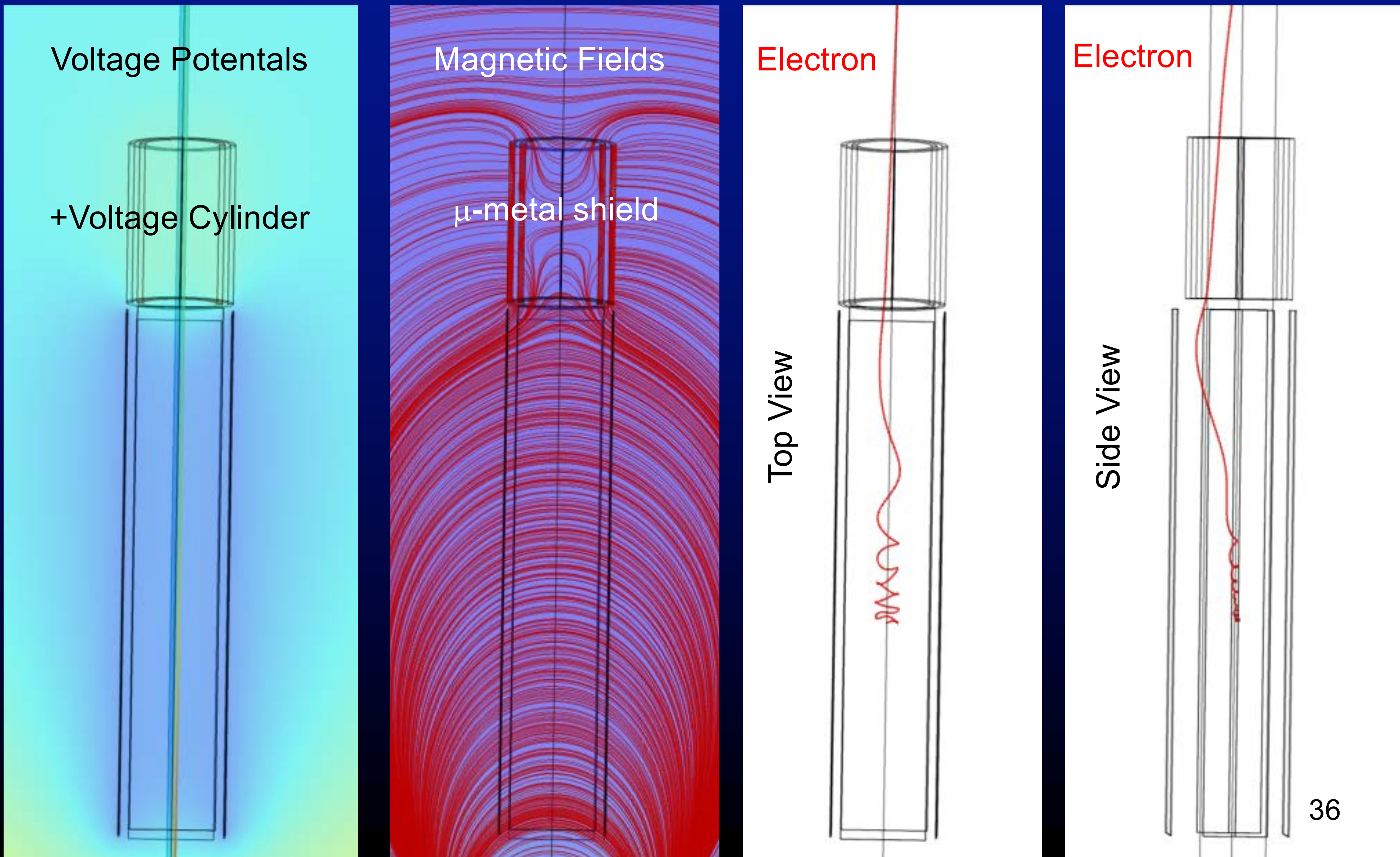
CNB angular power spectrum:
k-modes get highly amplified from
$1/v^2$ term, roughly $[(1/0.02)^2]^2$ ~ x10^7

Conceptual Block Diagram



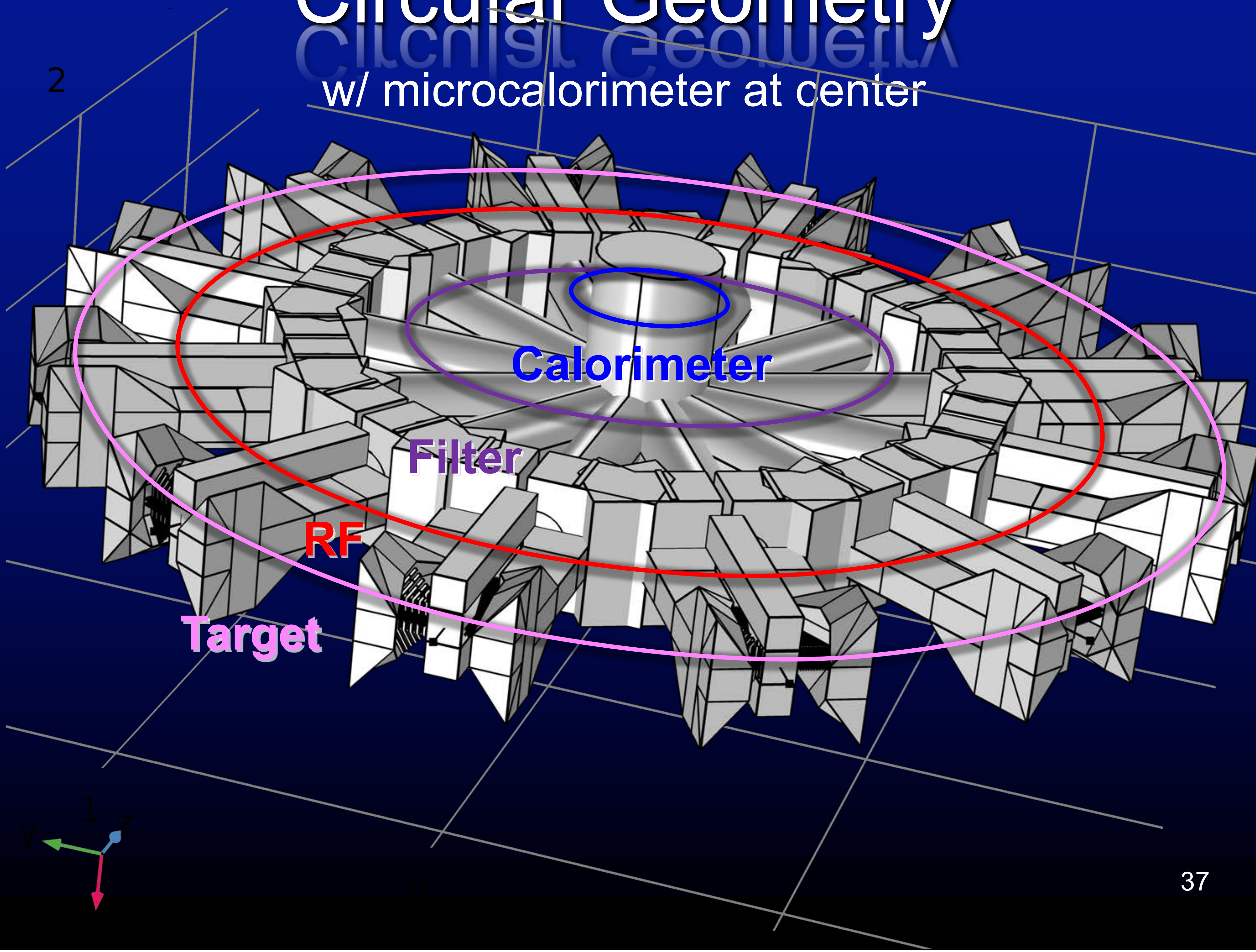
Transport from Filter to Calorimeter

Einzel Lens Approach

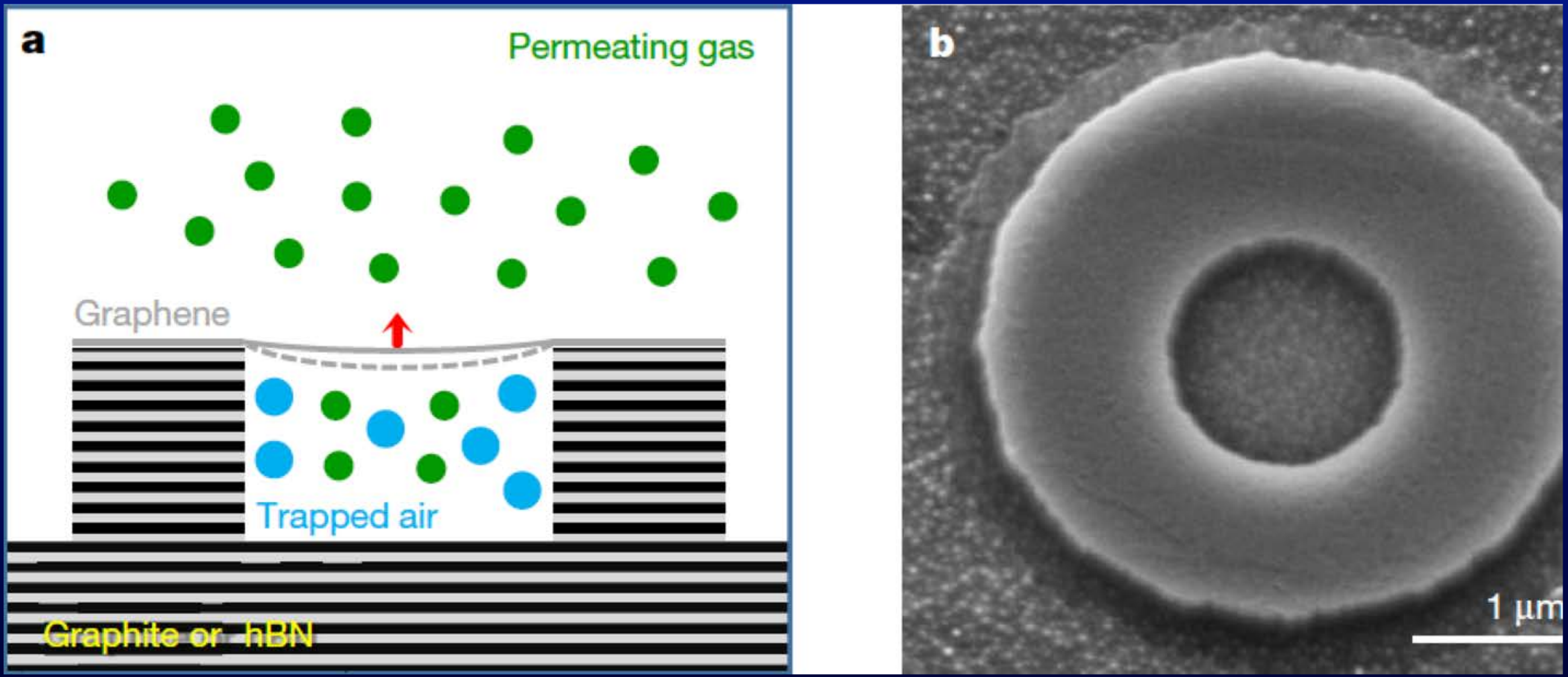


Circular Geometry

w/ microcalorimeter at center

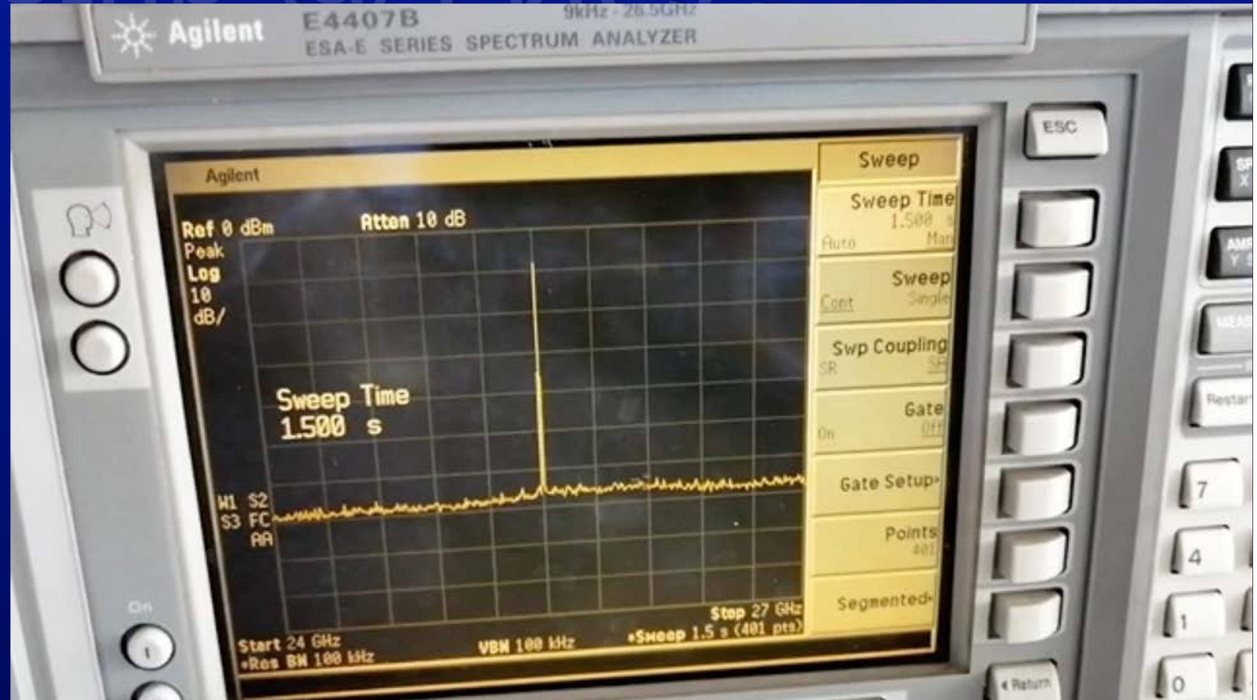


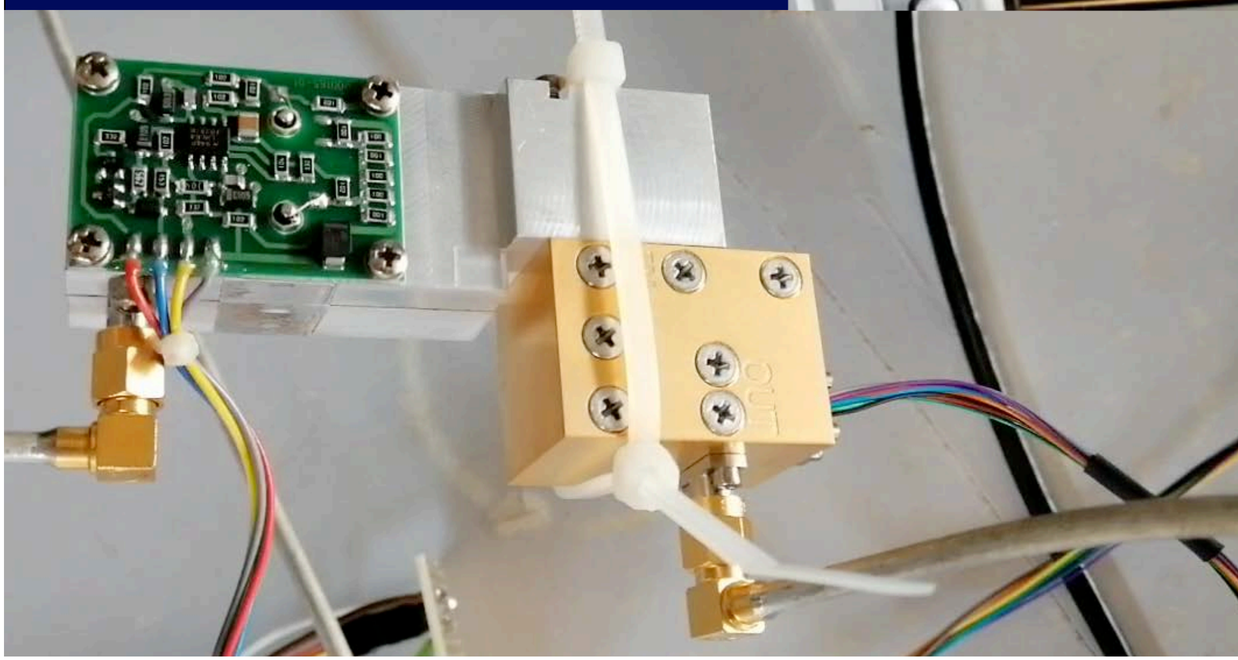
^{83}Rb/^{83m}Kr Graphene Trap

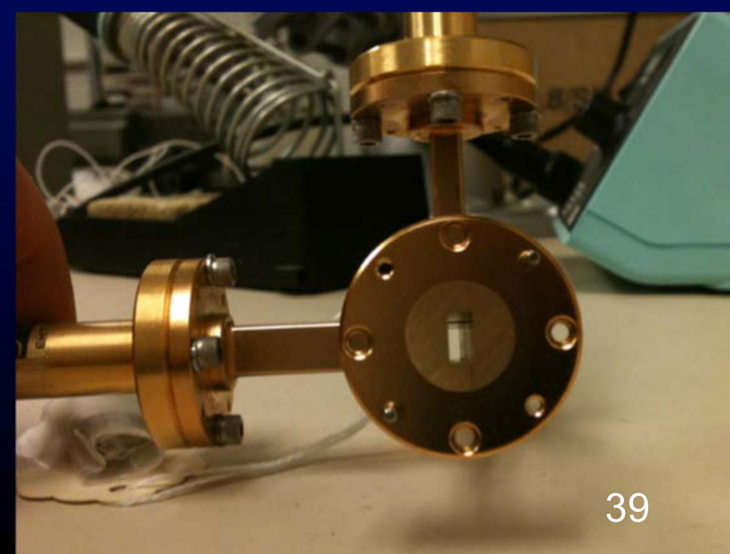


https://www.nature.com/articles/s41586-020-2070-x
https://doi.org/10.1038/s41586-020-2070-x

RF Setup @ LNGS







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)

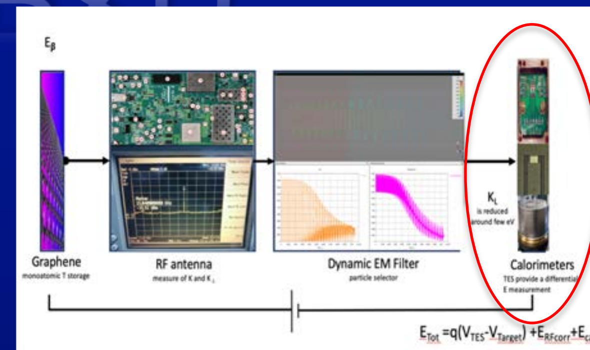
Design Goal (PTOLEMY): ΔE_{FWHM} = 0.05 eV @ 10 eV

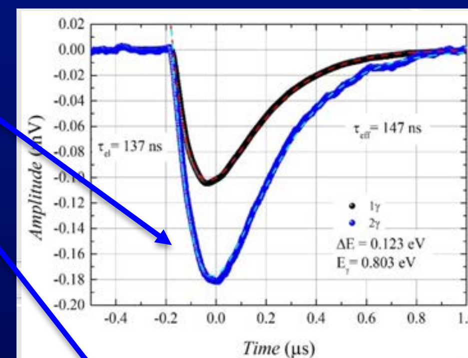
translates to $\boldsymbol{\Delta E \propto E^{\alpha}\ (\alpha \leq 1/3)}$

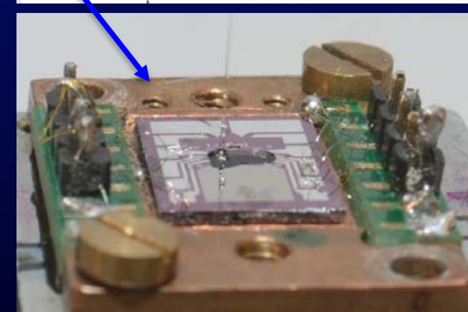
ΔE_{FWHM} = 0.022 eV @ 0.8eV

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

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







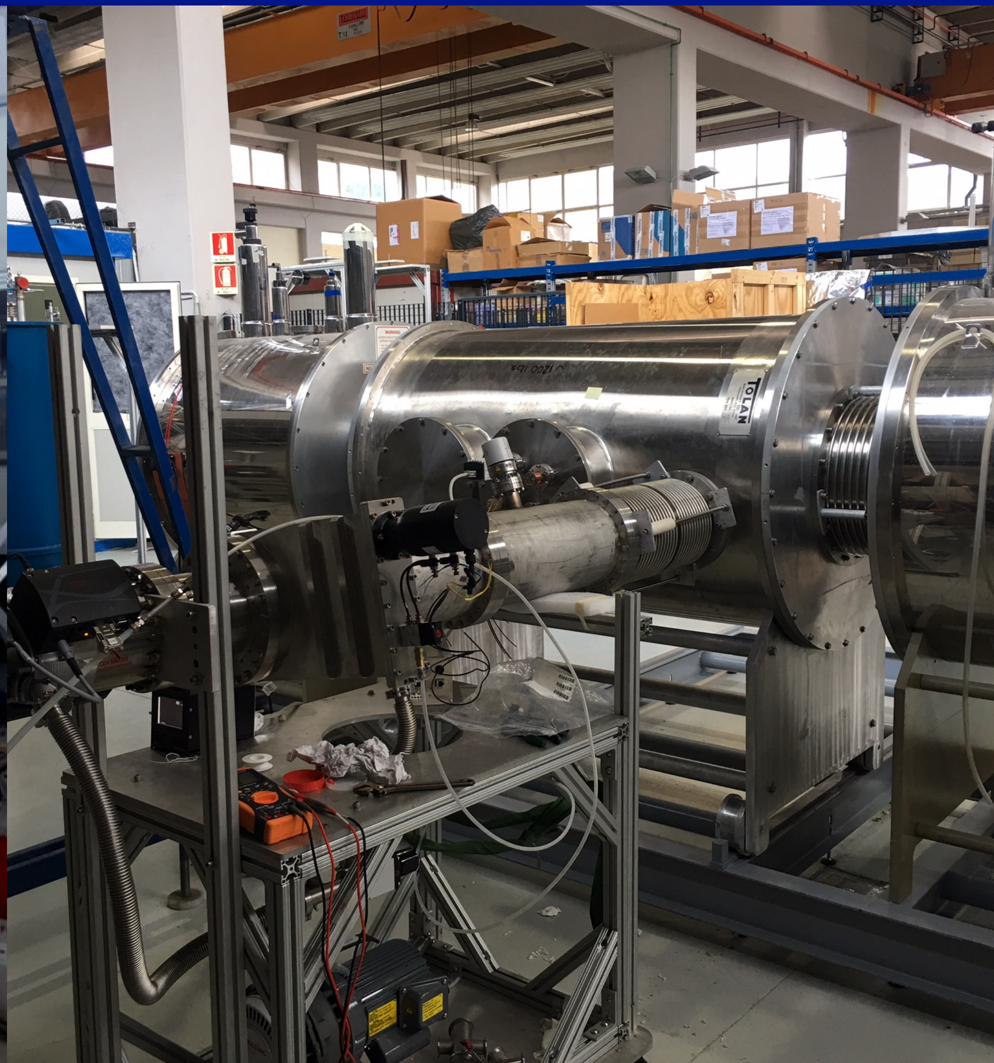
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

ROMA TRE UNIVERSITÀ DEGLI STUDI

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

PTOLEMY R&D at LNGS

PonTecorvo Observatory for Light, Early-universe, Massive-neutrino Yield



R&D effort hosted at the Gran Sasso National Laboratory

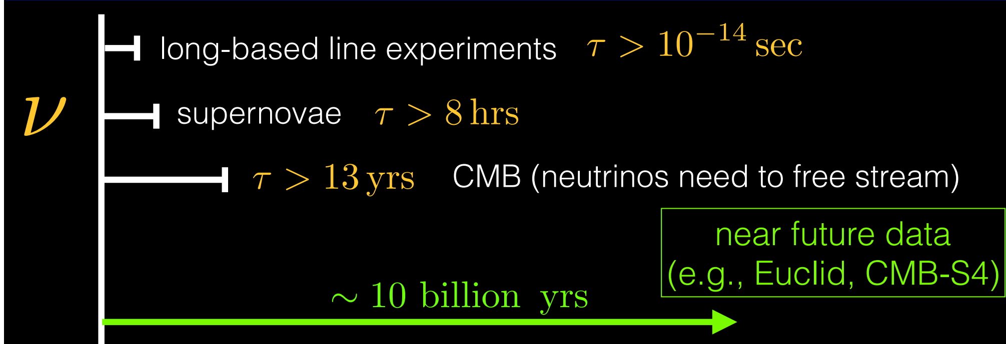
Exploring possible future sites that can host telescope operation with a 10mg tritium target

Neutrino Lifetime

Large Scale Structure Signals of Neutrino Decay

Yuhsin Tsai
University of Maryland

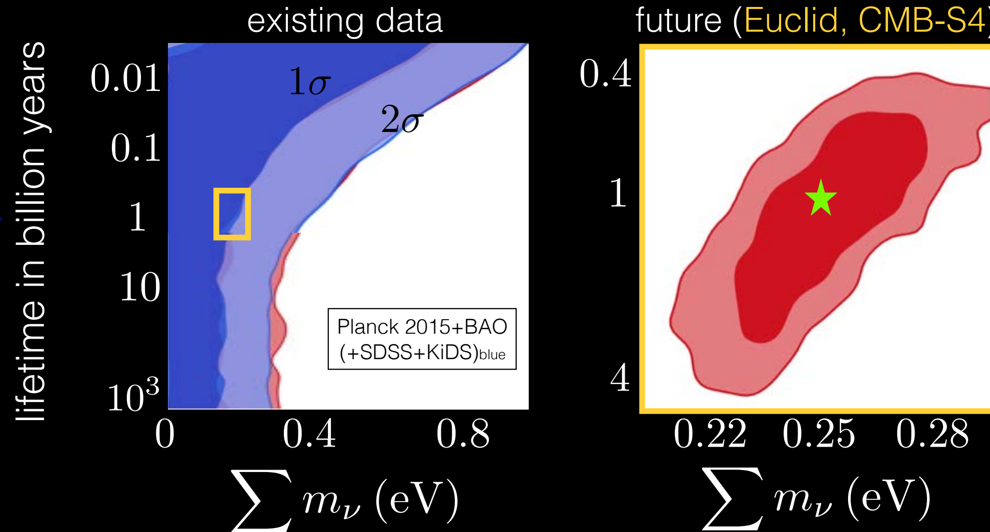
with Zackaria Chacko, Abhish Dev, Peizhi Du, Vivian Poulin
1909.05275, 19XX….



Chacko, Dev, Du, Poulin, **YT** (in preparation)
see also Serpico (2007)

Measure neutrino mass & lifetime

Chacko, Dev, Du, Poulin, **YT** (in preparation, preliminary)



Something not expected??

→ **CNB Direct Detection would need to resolve this**