Cosmological Relic neutrino detection
Only a dream?

Marcello Messina
Columbia University
on behalf of the PTOLEMY project

TAUP2015 Conference, Turin, September 9th, 2015

Facts about CNB

The cosmic neutrino background (CNB) is one of the most solid prediction of the standard cosmology. There are many indirect evidences for a background of neutrinos which decoupled from the electromagnetic radiation quite early during the Universe expansion, when the temperature was about 1 MeV (i.e. 1 sec after the big bang)

Number density today 112 cm^{-3} per flavor

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) = \frac{3}{11} n_\gamma = \frac{6\varsigma(3)}{11\pi^2} T_{CMB}^3 \approx$$

The largest astrophysical neutrino flux.

Mean kinetic energy: very small, of order T_ν 10^{-4} eV !

Energy density: $\Omega_\nu h^2 = 1.7 \times 10^{-5}$ relativistic ν, $T_\nu > m_\nu$

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{94.1\ \text{eV}}$$ for non relativistic ν, $T_\nu < m_\nu$

Hard to detect CNB directly

Very demanding if not impossible at all:

- they are only weakly interacting
- They have very low kinetic energy today

But

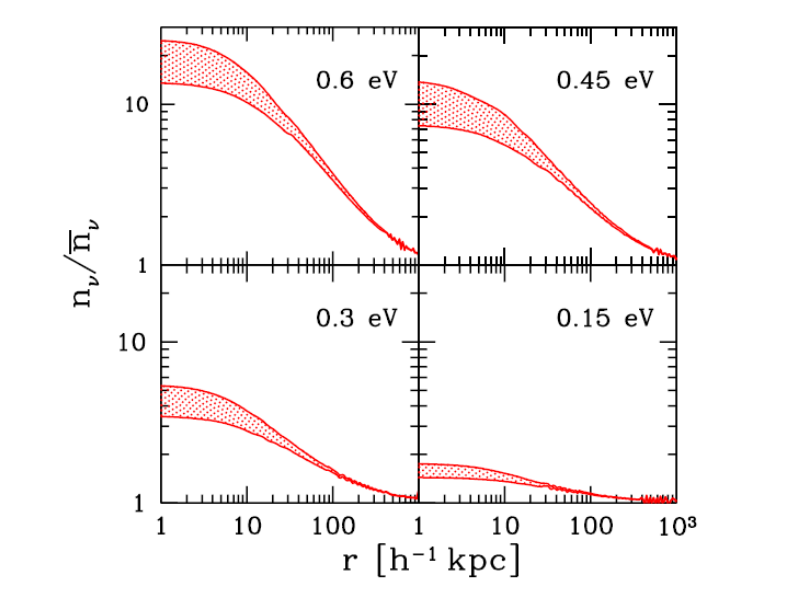
Neutrinos cluster if massive (eV) on large cluster scale

Escape velocity: Milky Way 600 Km/s

clusters 10^3 Km/s

$$v_\nu \approx c\sqrt{T_\nu / m_\nu} \approx 6 \cdot 10^3 Km/s(m_\nu / eV)$$

The local density normalized to the average cosmological value n_ν grows with neutrino mass



Ringwald and Wong '04

Detection idea

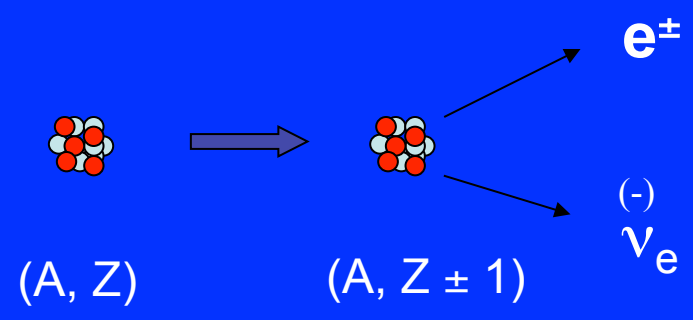
Massive neutrinos and neutrino capture on beta decaying nuclei

W. Weinberg, Phys. Rev. 128 1962

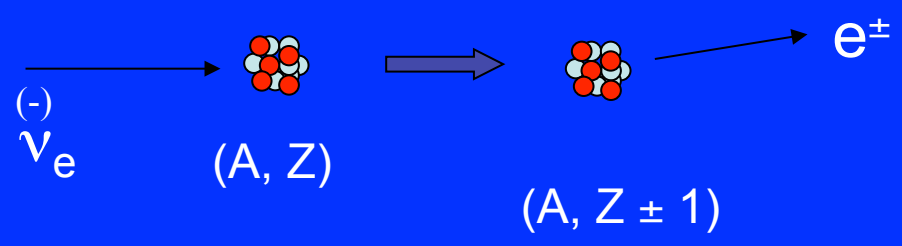
A.G.Cocco, G.Mangano and M.Messina JCAP 06(2007) 015

Luzauskas, P. Vogel, C. Volpe, J.Phys. G35 (2008) 025001

β decay



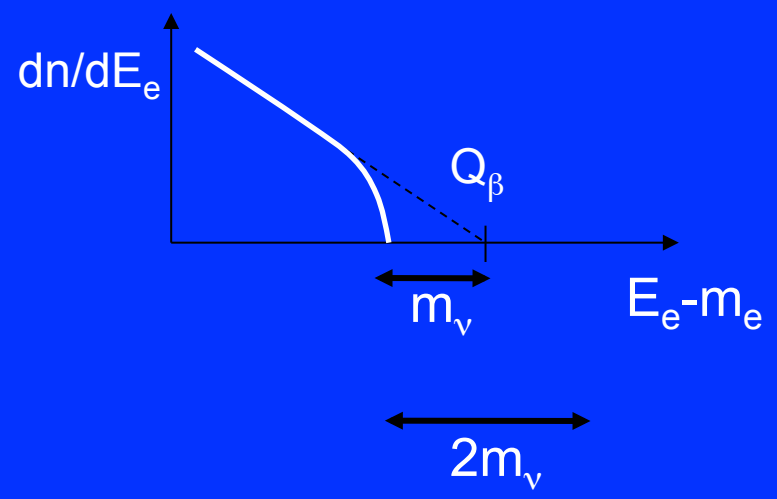
Neutrino Capture on a Beta Decaying Nucleus (NCB)



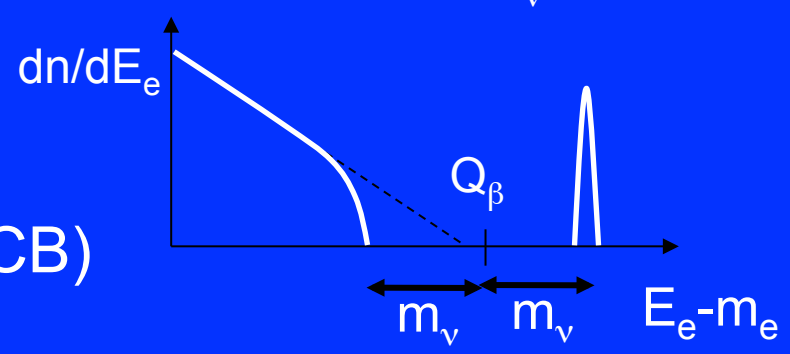
This process has no energy threshold !

Today we know that ν are non degenerate but they are massive

β decay



Neutrino Capture on a
Beta Decaying Nucleus (NCB)



A 2 m_ν gap in the electron spectrum centered around Q_β

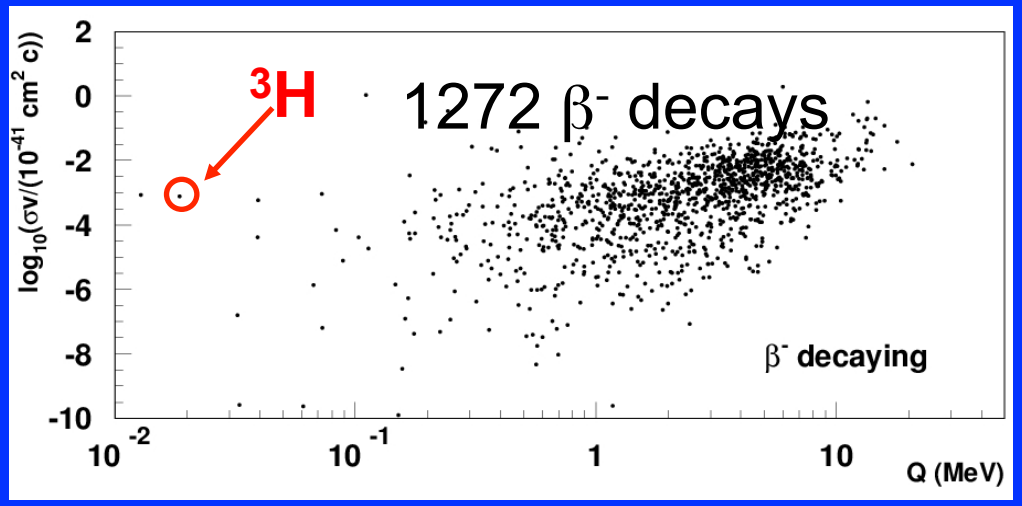
Two issues:

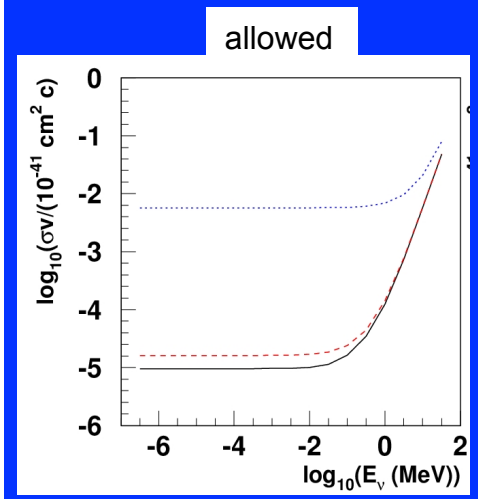
Rate

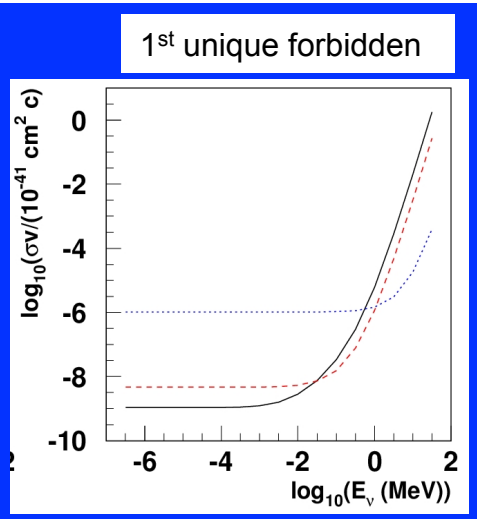
Background

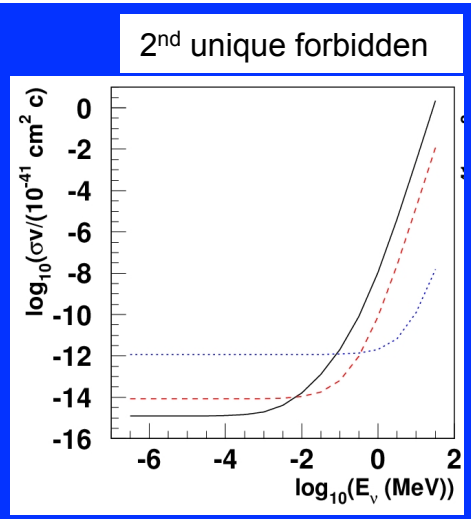
Rate

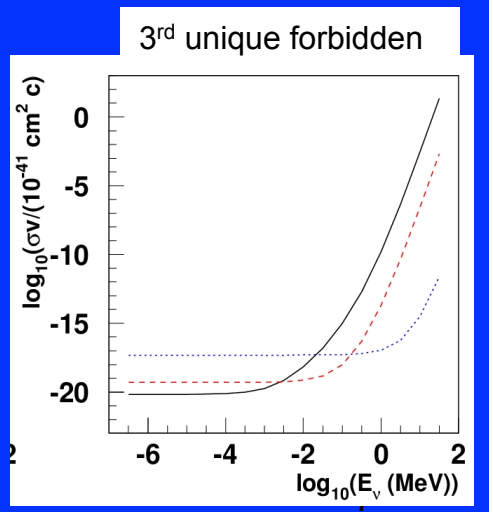
Beta decaying nuclei having BR($\beta^{\pm}$) > 5 % selected from 14543 decays listed in the ENSDF database











A.G.Cocco, G.Mangano and M.Messina JCAP 06(2007) 015

CNB capture rate

$$\lambda_\nu = \int \sigma_{\rm NCB} v_\nu \frac{1}{\exp(p_\nu/T_\nu)+1} \frac{d^3 p_\nu}{(2\pi)^3}$$

$T_\nu = 1.7 \cdot 10^{-4}$ eV

$$2.85 \cdot 10^{-2} \frac{\sigma_{\rm NCB} v_\nu / c}{10^{-45} {\rm cm}^2} \ {\rm yr}^{-1} \ {\rm mol}^{-1}$$

Event rate for a standard ν number density (FD) and also including gravitational clustering for different dark matter profiles and different neutrino masses:

A.G.Cocco, G.Mangano and M.Messina JCAP 06(2007) 015

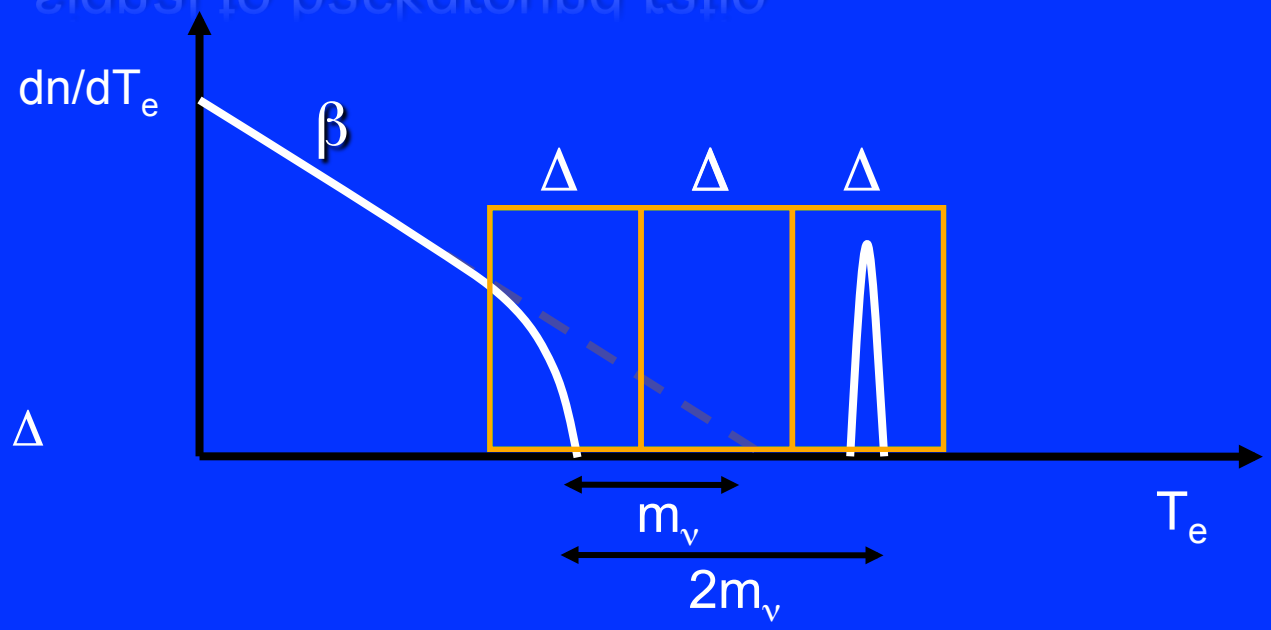
m_ν (eV)	FD (events yr^{-1})	NFW (events yr^{-1})	MW (events yr^{-1})
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

FD = Fermi-Dirac NFW= Navarro,Frenk and White
MW=Milky Way (Ringwald, Wong)

Relic Neutrino Detection

signal to background ratio

Observing the last energy bins of width Δ



$$\frac{S}{B} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}}\left[\frac{1}{\sqrt{2\pi}}\int_{\frac{2m_\nu}{\Delta}-\frac{1}{2}}^{\frac{2m_\nu}{\Delta}+\frac{1}{2}} e^{-x^2/2}dx\right]^{-1}$$

where the last term is the probability for a beta decay electron at the endpoint to be measured beyond the $2m_\nu$ gap

It works for $\Delta < m_\nu$

Relic Neutrino Detection

discovery potential

As an example, given a neutrino mass of 0.3 eV and an energy resolution at the beta decay end point of 0.1 eV a signal to background ratio of 3 is obtained

In the case of 100 g of Tritium it would takeone and a half year to observe a 5σ effect

In case of neutrino gravitational clustering we expect a significant signal enhancement

PTOLEMY project

started thanks to the effort of C. Tully at the Princeton University

Development of a Relic Neutrino Detection Experiment at PTOLEMY:
Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

S. Betts[1], W. R. Blanchard[1], R. H. Carnevale[1], C. Chang[2], C. Chen[3], S. Chidzik[3], L. Ciebiera[1], P. Cloessner[4], A. Cocco[5], A. Cohen[1], J. Dong[1], R. Klemmer[3], M. Komor[3], C. Gentile[1], B. Harrop[3], A. Hopkins[1], N. Jarosik[3], G. Mangano[5], M. Messina[6], B. Osherson[3], Y. Raitses[1], W. Sands[3], M. Schaefer[1], J. Taylor[1], C. G. Tully[3], R. Woolley[1], and A. Zwicker[1]

[1]Princeton Plasma Physics Laboratory
[2]Argonne National Laboratory and University of Chicago
[3]Department of Physics, Princeton University
[4]Savannah River National Laboratory
[5]Istituto Nazionale di Fisica Nucleare – Sezione di Napoli
[6]Department of Physics, Columbia University

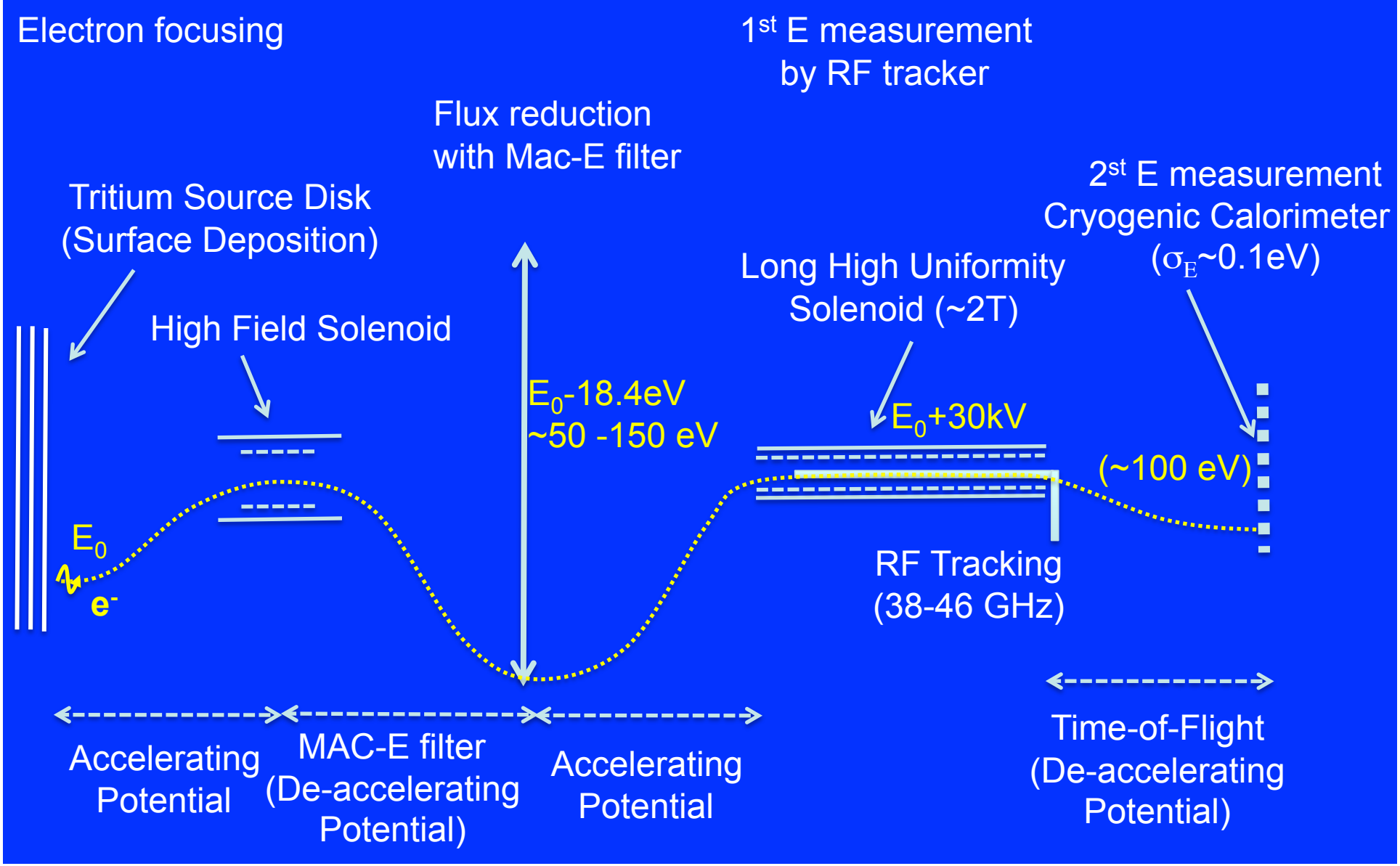
Project Summary

The direct detection of relic neutrinos from the Big Bang was proposed in a paper by Steven Weinberg in 1962 [*Phys. Rev.* 128:3 (1962) 1457]. The signal for relic neutrino capture on tritium is the observation of electron kinetic energies emitted from a tritium target that are above the β-decay endpoint. The requirements on the experimental energy resolution for relic neutrino identification are constrained by the thermal model for neutrino decoupling in the early universe that predicts a present-day average neutrino kinetic energy of 1.7×10^{-4}eV, neutrino mass mixing parameters that indicate mass eigenstates at least as massive as 0.05eV, and cosmological input from WMAP+SPT, and other sources, on the sum of the masses of the light neutrino species in thermal equilibrium in the early universe to be constrained to less than approximately 0.3eV. The parameters for a relic neutrino experiment require 100 grams of weakly-bound atomic tritium, sub-eV energy resolution commensurate with the most massive neutrinos with electron-flavor content, and below microHertz of background rate in a narrow energy window above the tritium endpoint. The PTOLEMY experiment (Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield) aims to

PTOLEMY Conceptual Design

- High precision on endpoint
  - Cryogenic calorimetry energy resolution
  - **Goal: 0.1eV resolution**
- Signal/Background suppression
  - RF tracking and time-of-flight system
  - **Goal: sub-microHertz background rates above endpoint**
- High resolution tritium source
  - Surface deposition (tenuously held) on conductor in vacuum
  - **Goal for CNB: maintains 0.1eV energy resolution with high efficiency**
  - **For sterile nu search: maintains 10eV energy resolution w/ high eff.**
- Scalable mass/area of tritium source and detector
  - **Goal: relic neutrino detection at 100g**
  - **Sterile neutrino (w/ % electron flavor) at ~1g and 10 eV resolution**

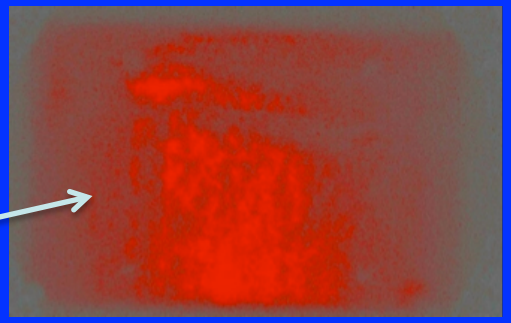
PTOLEMY Experimental Layout



Surface Deposition Sources

- At PPPL we are commissioning with samples of amorphous-Silicon:H:T plates
  - Experience with “tenuously held” tritium

Carbon tile image of tritium

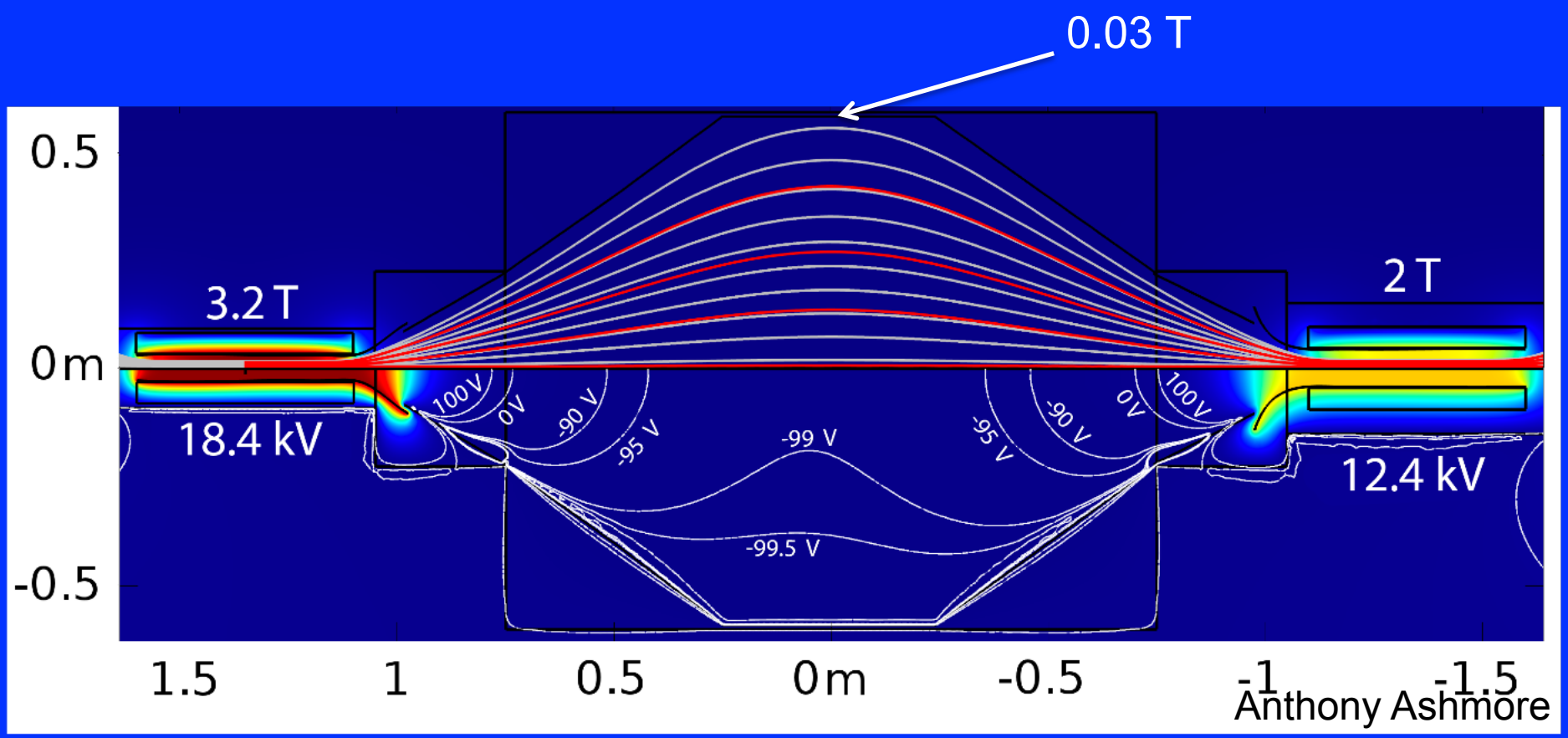


- Depositions on titanium, gold, diamond, and graphene are being investigated (done by Canadian firms and Savannah River National Lab in collaboration with PPPL)
  - Available titanium samples have been requested for testing

- Source strength with surface densities of ~1Ci/cm^2 (100micrograms/cm^2) are possible, but energy spread from source scattering needs to be measured

MAC-E filter

- MAC-E filter cutoff on electron energy at 10^{-2} to 10^{-3} precision level
  - If the threshold is set at ~1eV: Φ reduction~ $(\Delta E/Q)^3 = 1.55\ 10^{-13}$
    (for comparison the activity of 1 g of T is of $3.6\ 10^{+14}$ Hz)



Anthony Ashmore

The principle of the Mac-E filter

On their way from the source to the center of the spectrometer the magnetic field B drops by many orders of magnitude. Therefore, the magnetic gradient force transforms most of the cyclotron energy into longitudinal motion. Due to the slowly varying magnetic field B the momentum transforms adiabatically, thus the magnetic moment μ keeps constant.

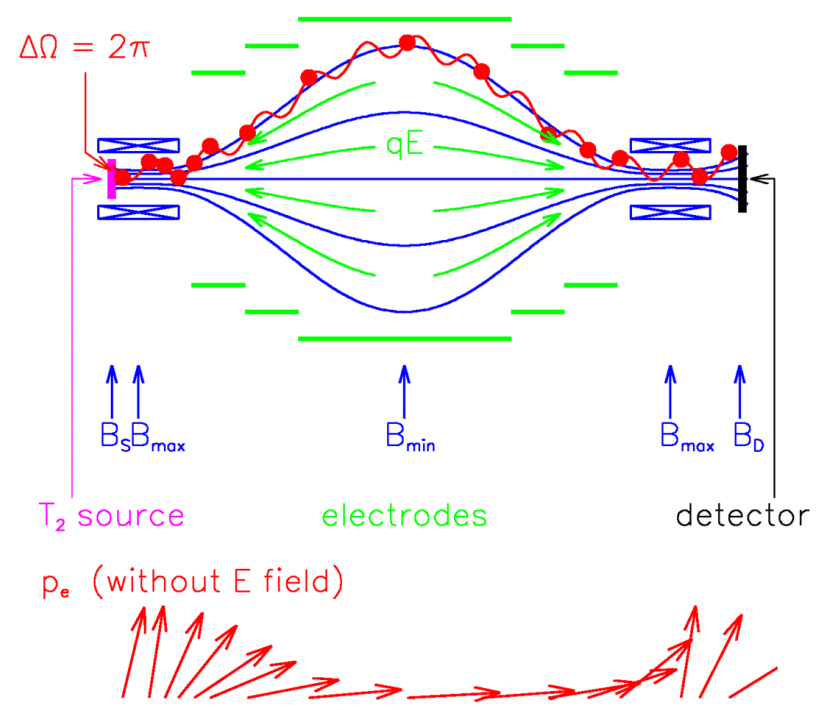
In non-relativistic approximation:

$$\mu = \frac{E_\perp}{B}$$

The relative sharpness of this filter is:

$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

In the case of PTOLEMY experiment this is further improved by the RF tracking and by the calorimetric measurement.



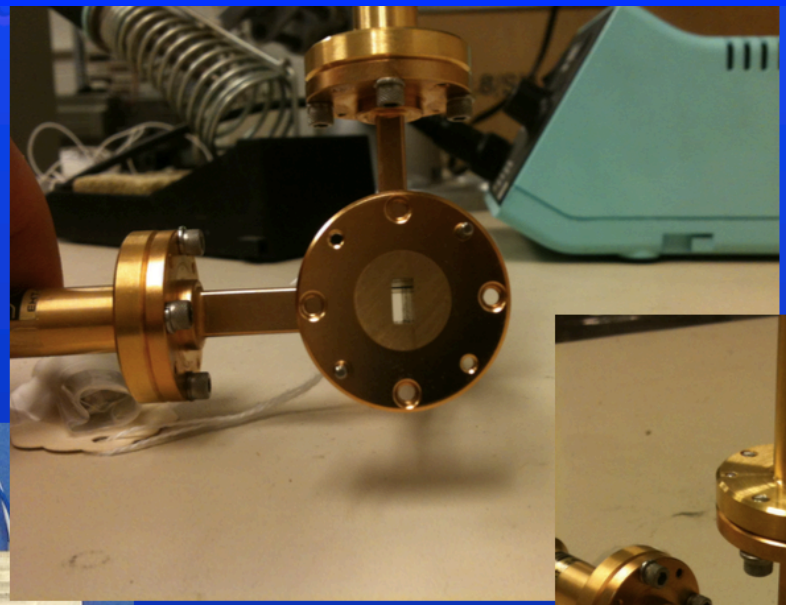
From KATRIN webpage

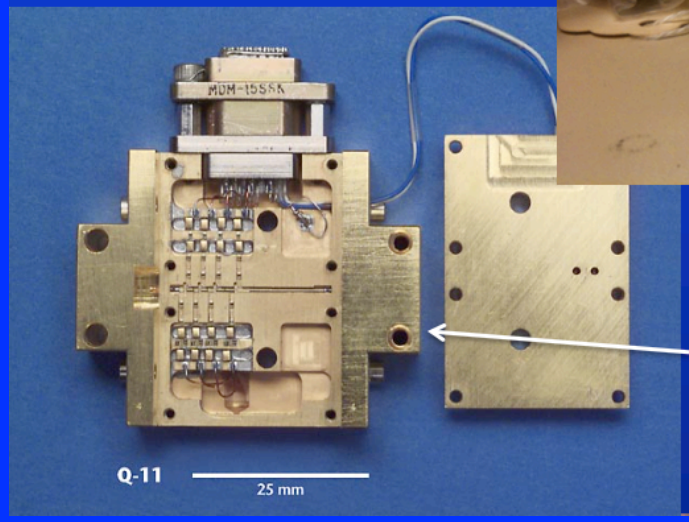
RF tracking and time-of-flight

Thread electron trajectories (magnetic field lines) through an array of Project-8 type antennas with wide bandwidth (few $x10^{-5}$) to identify cyclotron RF signal in transit times of order 0.2 msec. The timing resolution expected is ~10ns depending on micro-calorimeter response.

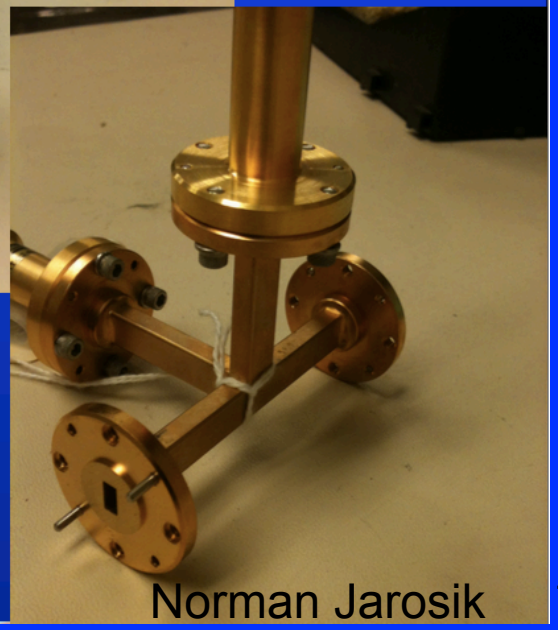
Readout Orthogonal to Electron Trajectory

Q-Band (38-46 GHz) Magic Tee Waveguide Junction





Q-Band (38-46 GHz) WMAP Amplifier



Norman Jarosik

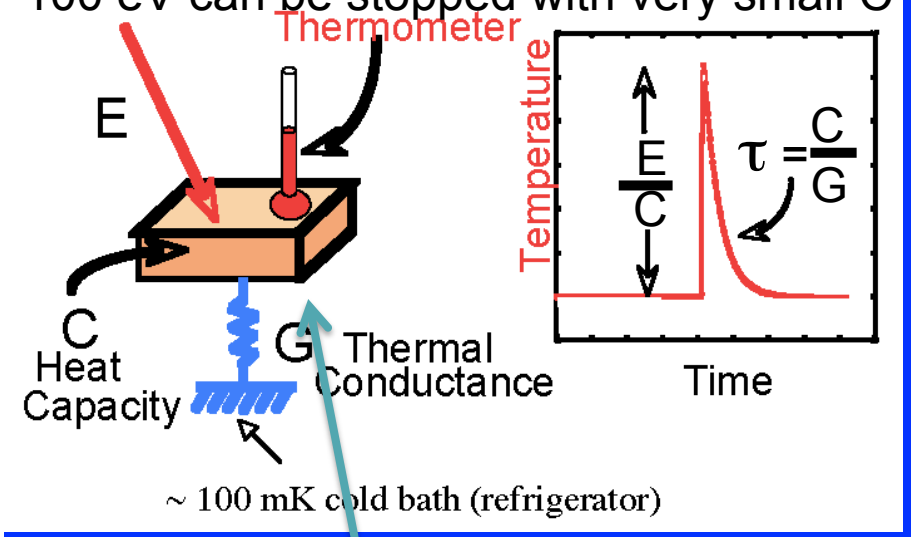
Calorimetric measurement

based on Transition Edges Sensors technology

Resolution of ~0.55eV at 1keV and ~0.15eV at 0.1keV operating at 70-100mK under investigation (Clarence Chang ANL, Moseley et. al. GSFC/NASA)

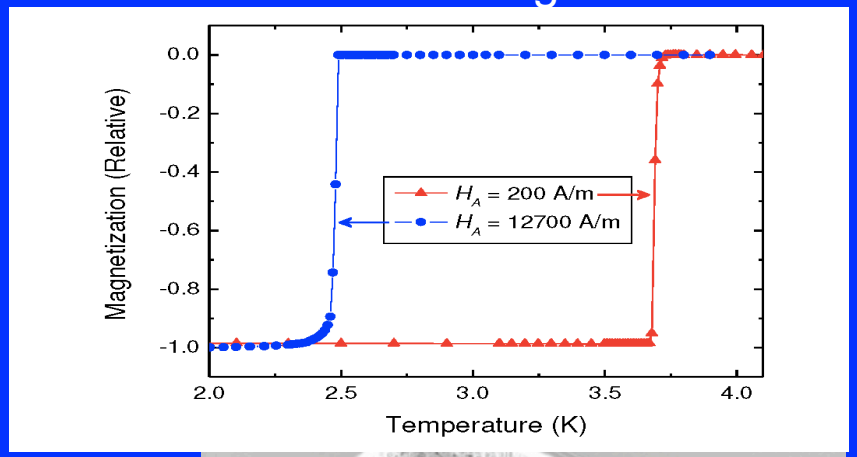
Magnetic fields of few hundred Gauss may be able to thread through normal regions

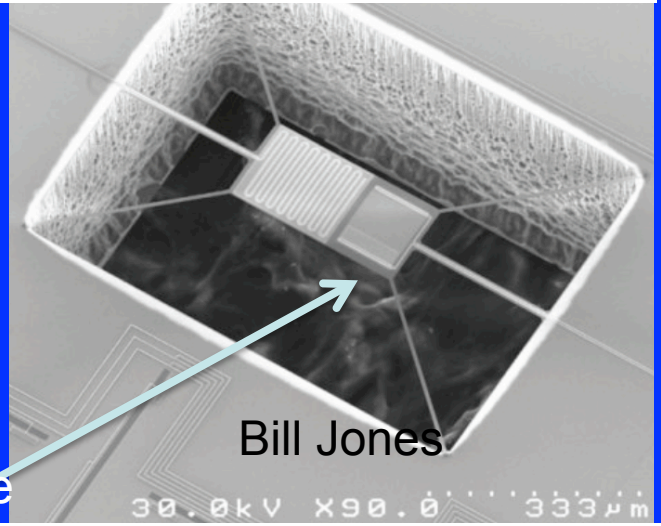
100 eV can be stopped with very small C



100 eV electron can be stopped in a very small absorber absorber i.e. small C

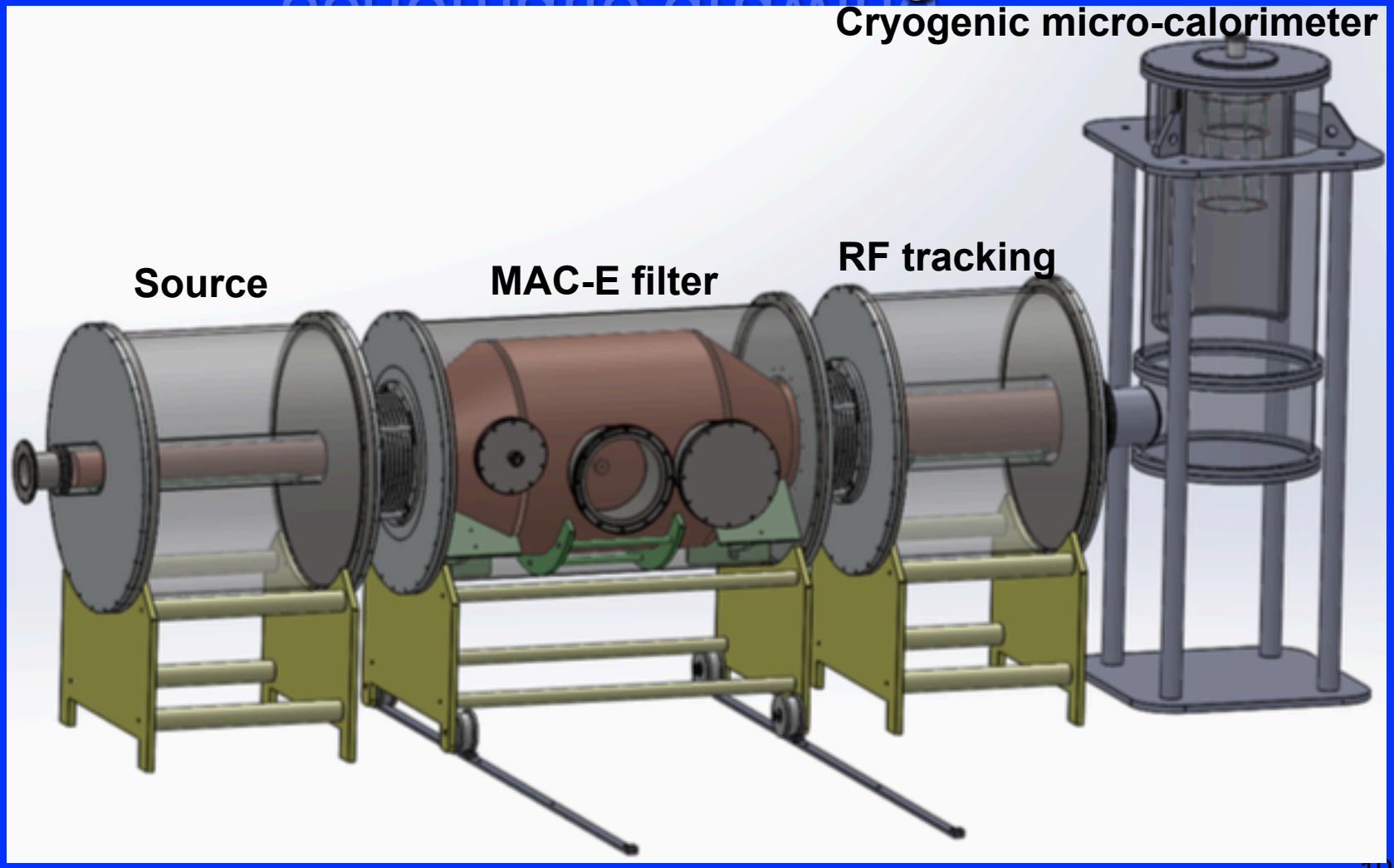
TES sensitive to magnetic field



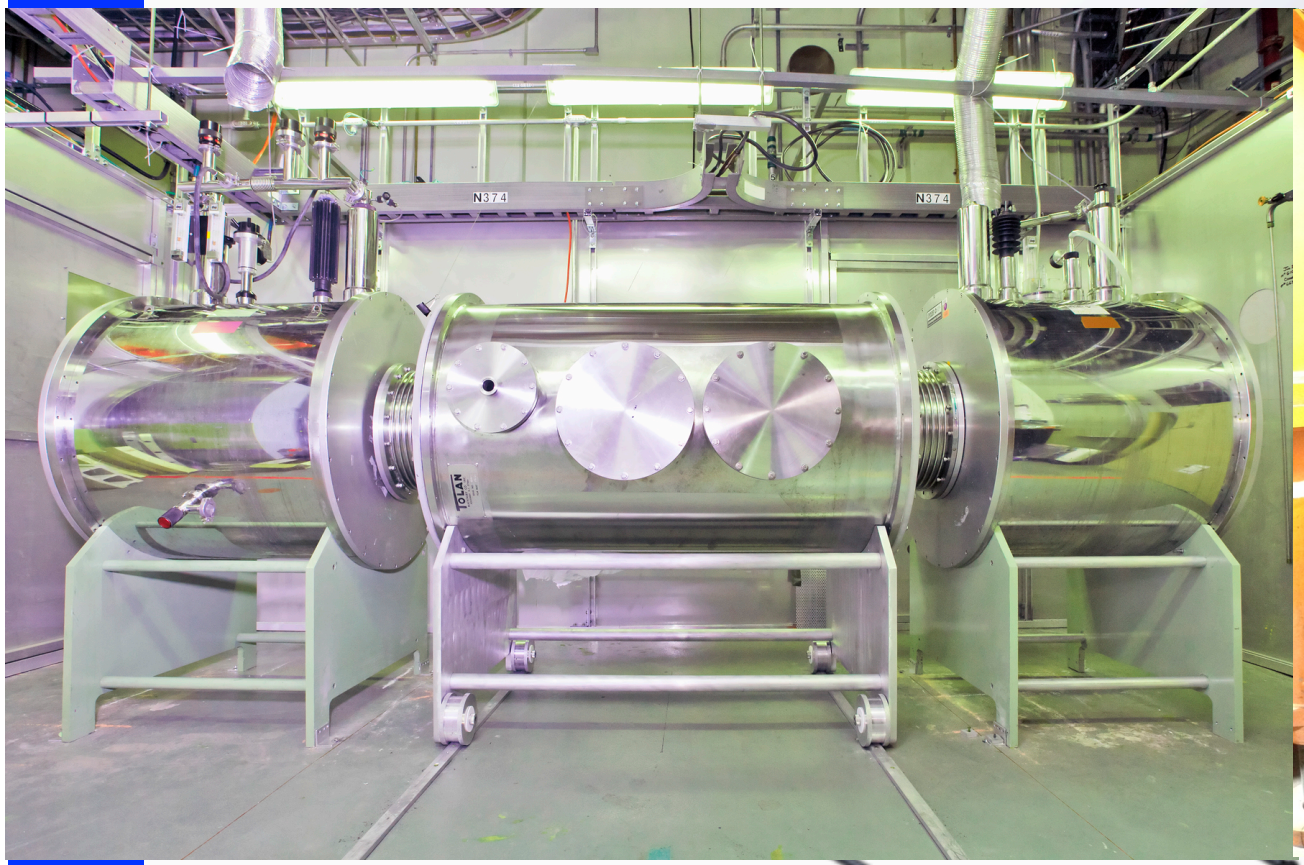


SPIDER island TES example

PTOLEMY
schematic drawing



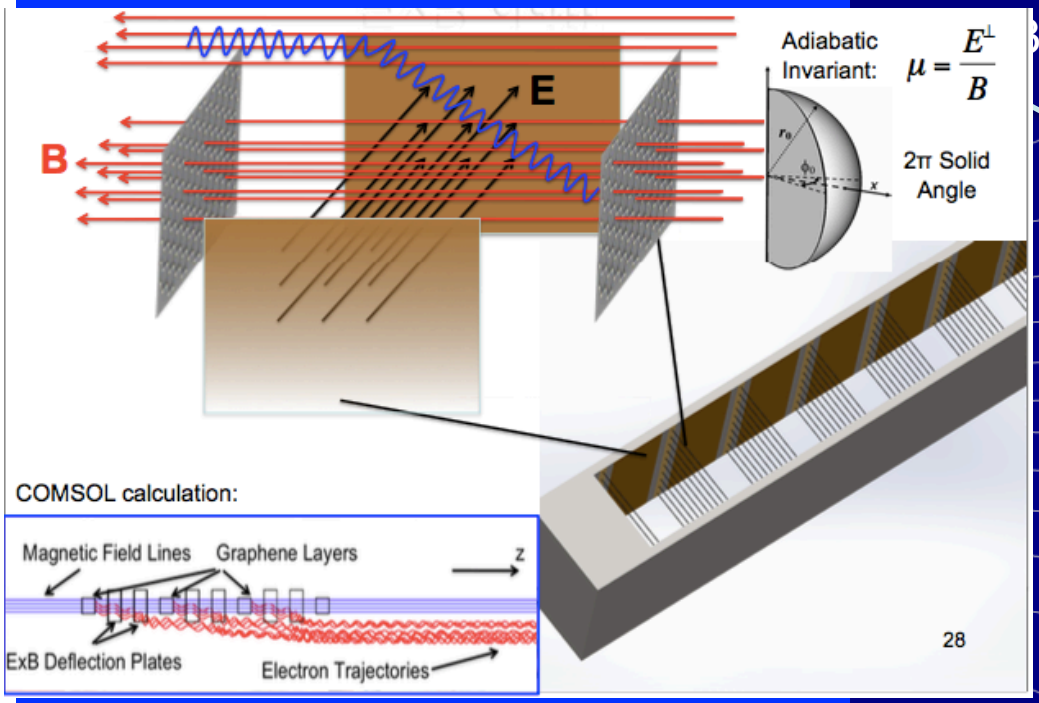
PTOLEMY
schematic drawing

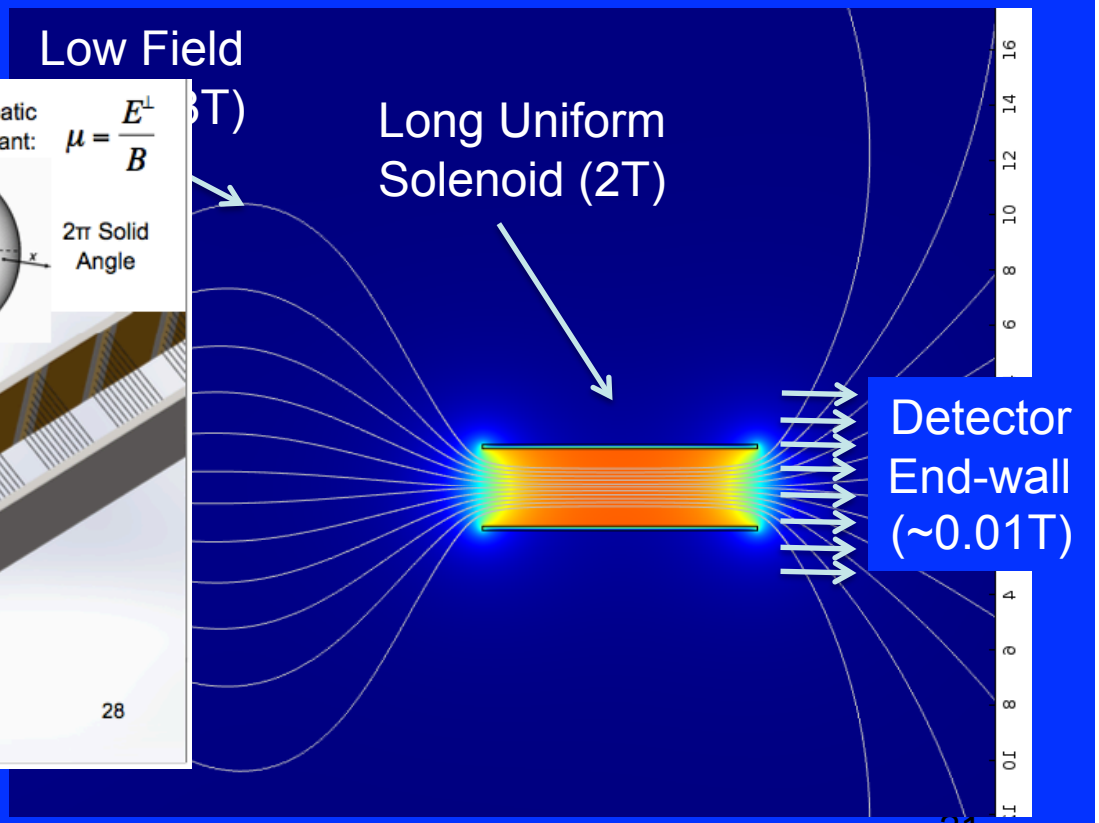


Will host an Oxford Instruments Kelvinox MX400 DR (100mK)

100g PTOLEMY

- Different geometries were investigated
  - Source disk will consist of 10^4-10^5 individual plates





Experimental Program for PTOLEMY Prototype

1st Milestone: **(done)** Commission small test vacuum chamber with APD readout of tritium spectrum in magnetic field
- Chamber arrived, Vacuum fittings completed.
-Electrical fittings, APD windowless from CERN.

-**2nd Milestone:** **(done)** Complete the construction of MAC-E filter.
- Installation of full-scale vacuum chamber.
- Install nine copper electrodes under HV

3rd Milestone: Install 100mK Oxford Instruments Dilution Refrigerator and commission TES calorimeter

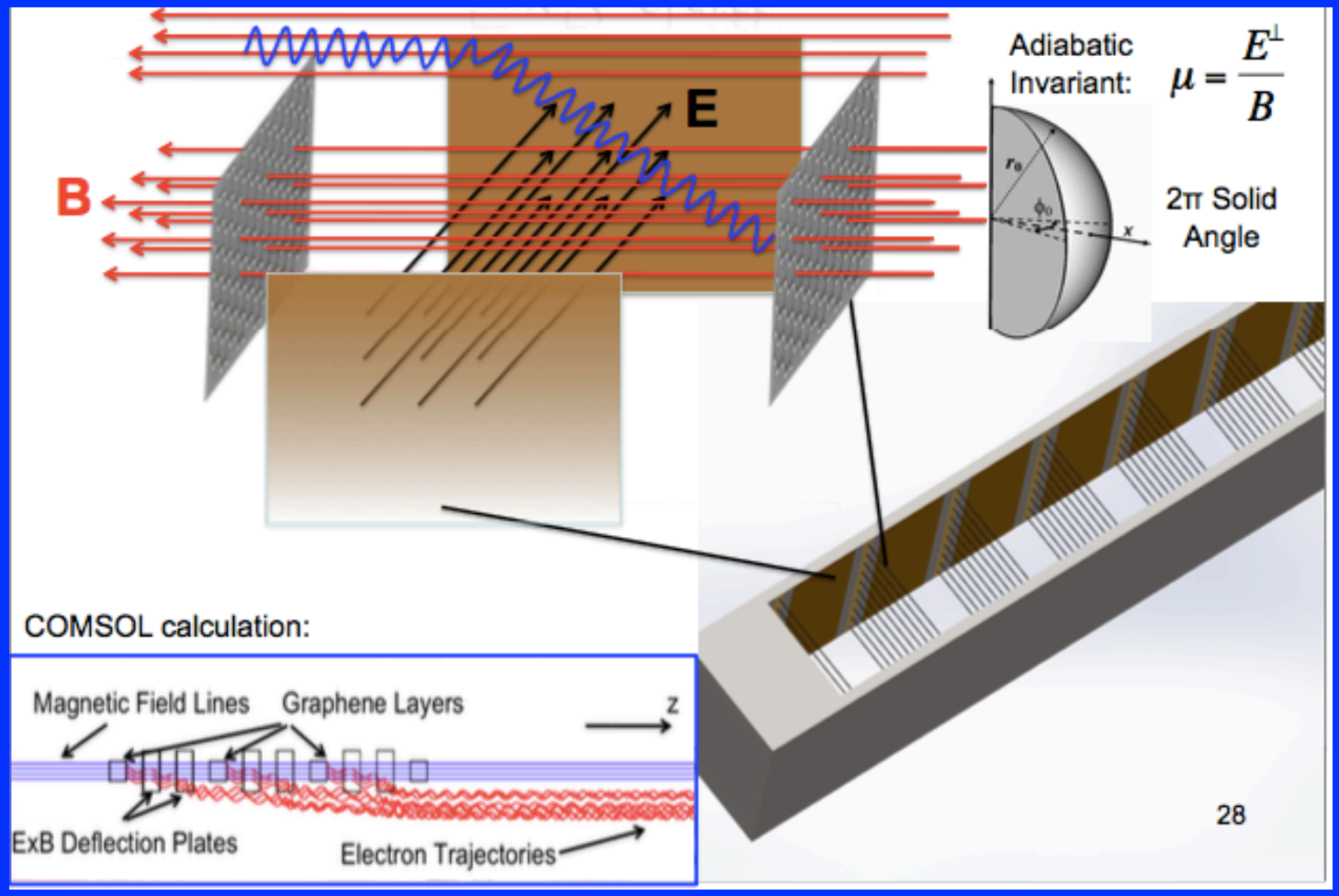
4th Milestone: Install Tritium-loaded Graphene Sample and commission MAC-E filter with APD readout

5th Milestone: Collect data at tritium endpoint with cryogenically cooled tritium and TES calorimeter and verify that the energy resolution is better than diatomic tritium. Most precise tritium endpoint spectrum!

6th Milestone: Validate technologies for 100g PTOLEMY.

Summary

- Relic neutrino detection has been promoted from “impossible” to “challenging”
- Important R&D still to be done on source, detector, background levels
- PPPL prototype is an excellent test bench for validating the technologies for a 100g PTOLEMY
- First grant from Simons Foundation started on Sep. 1st
- Kick-off meeting of the PTOLEMY collaboration will take place in November


E
B
Adiabatic Invariant:
$\mu = \frac{E^{\perp}}{B}$
2π Solid Angle
COMSOL calculation:
Magnetic Field Lines
Graphene Layers
z
ExB Deflection Plates
Electron Trajectories
28

Is there anything in the keV region ?
("what we see" vs "what we think it should be")

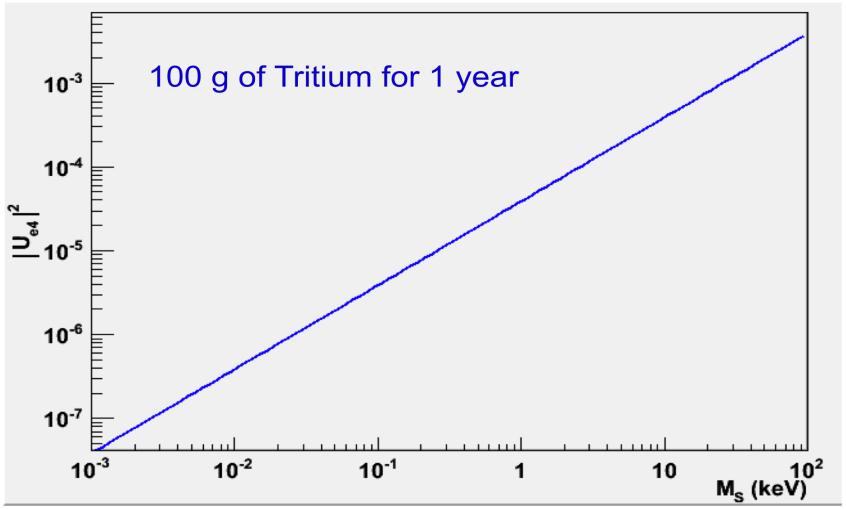
Everything "above" the endpoint is at zero background
(no need for sub-eV resolution ! Only E_x or $m_x > \Delta$)

Example:

Using ν capture...

If Dark Matter is made by sterile neutrino ➔ $\rho_S \sim \frac{0.4\times10^6}{M_S[\mathrm{keV}]}\ \mathrm{cm}^{-3}$

Looking beyond the beta decay endpoint energy (background free region)



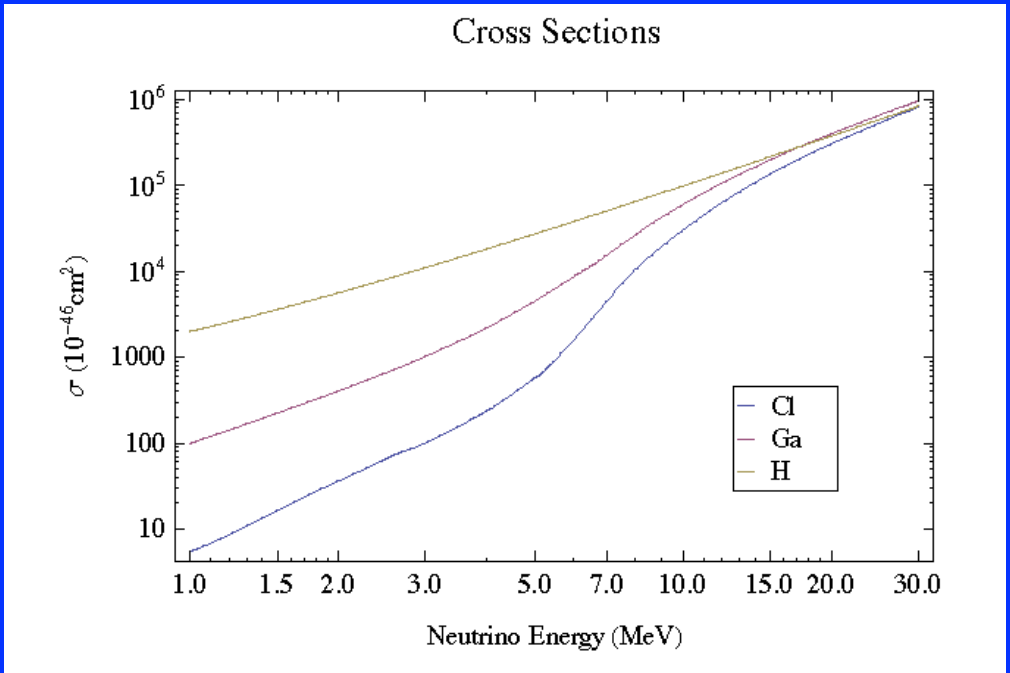
Solar Neutrino Capture Rates at PTOLEMY

Source	Integrated flux (cm^{-2} s^{-1})	$\overline{\sigma}$ (10^{-45} cm^2)	Events per year
p-p	5.90×10^{10}	4.56×10^{1}	1.87
^{8}B	5.50×10^{6}	5.33×10^{3}	0.02
^{13}N	2.98×10^{8}	1.30×10^{2}	0.02
^{15}O	2.25×10^{8}	2.08×10^{2}	0.03
^{17}F	5.69×10^{6}	2.09×10^{2}	0.0008
pep	1.51×10^{8}	3.38×10^{2}	0.03
^{7}Be	4.69×10^{8}	6.38×10^{1}	0.02
^{7}Be	4.54×10^{9}	1.63×10^{2}	0.51
hep	7.38×10^{3}	1.02×10^{4}	0.00005
All	6.46×10^{10}	5.60×10^{1}	2.53 ± 0.08

Solar Neutrino Capture Experiments

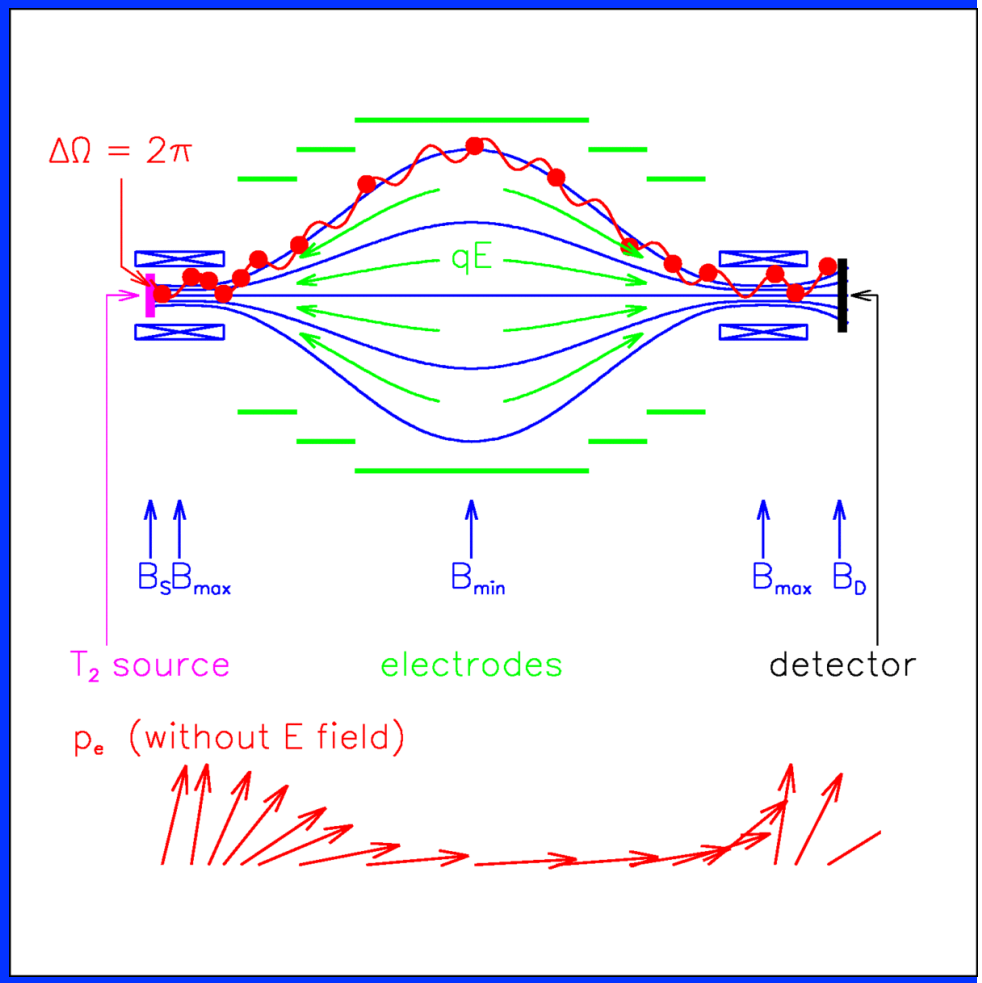
- PTOLEMY ~3618 SNU with 100g (10^{25} nuclei) 2.5 evts/year
- Gallex 70 SNU with 30 tons (10^{29} nuclei) 1200 evts/year
- Homestake (Chlorine) 8 SNU with 600 tons (10^{31} nuclei) 2500 evts/year

Hard to compete with Tritium for sub-MeV neutrino energies



The principle of the Mac-E filter*

The main features of the MAC-E-Filter are illustrated here. Two superconducting solenoids are producing a magnetic guiding field B. The beta electrons, which are starting from the tritium source in the left solenoid into the forward hemisphere, are guided magnetically on a cyclotron motion around the magnetic field lines into the spectrometer, thus resulting in an accepted solid angle of up to 2π.



*from Katrin webpage

Experimental Program for PTOLEMY Prototype

1st Milestone: ✓ **(done)** Commission small test vacuum chamber with APD readout of tritium spectrum in magnetic field

- Chamber arrived, Vacuum fittings completed.
- Electrical fittings, APD windowless from CERN cleaned at PRISM.
- First spectrum taken.

2nd Milestone: (in progress) Tritium spectrum taken under full magnetic transport

- Installation of full-scale vacuum chamber.
- Commissioning of vacuum for 2 weeks, Electrical fittings for vacuum with installation of detector.
- Tritium spectrum taken with magnetic transport in full-scale vacuum chamber.

3rd Milestone: Detect RF signal in coincidence with APD trigger in vacuum.

- Re-energize 1.9T magnet with few $x10^{-5}$ field uniformity
- Install WMAP 40-50 GHz amplifier with parallel-plate/BalUn and 100 MHz mixer
- Install APD trigger system and APD/antenna digital readout in vacuum
- Observe 3-5 Sigma RF signals

Experimental Program for PTOLEMY Prototype

4th Milestone: Commission MAC-E filter.
- Finish fabrication of copper tubes
- Install in Vac-tank with HV stand-offs and 50kV cable/connectors.
- Evaluate performance of filter cut-off with APD data in vacuum.

5th Milestone: First physics dataset analyzed for sterile nu search.
- Measure magnetic aperture of source to detector with MAC-E filter applied
- Scan EM cutoff and measure sharpness of low energy cutoff across aperture
- Optimize readout system and DAQ for 24/7 operation
- Upgrade source strength in to 1 Curie or as large as possible
- Take calibration data and background runs interspersed with data runs

6th Milestone: Validate technologies for 100g PTOLEMY.
- Introduce disk source feeding source magnet aperture.
- Introduce TES micro-calorimeter with sub-eV resolution.
- Benchmark system performance.

The principle of the Mac-E filter

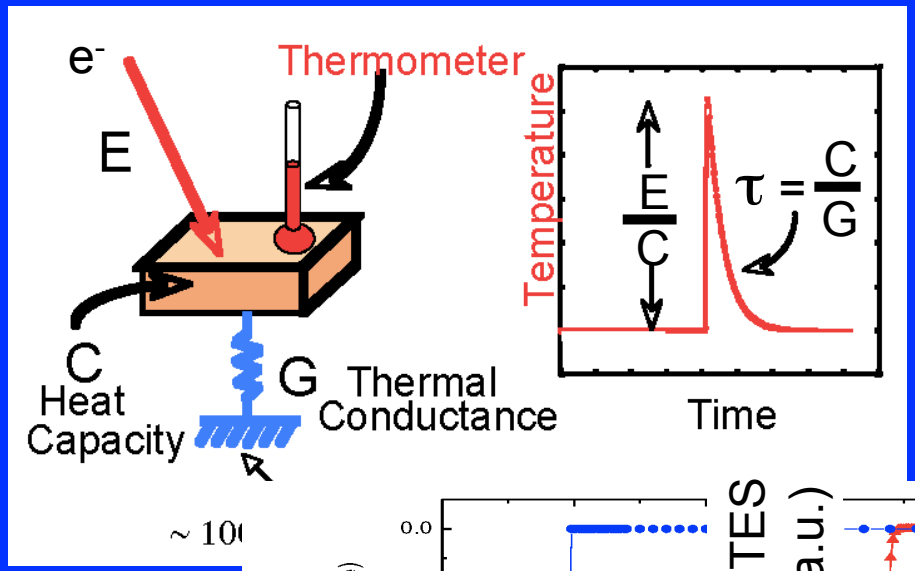
This transformation can be summarized as follows: The beta electrons, isotropically emitted at the source, are transformed into a broad beam of electrons flying almost parallel to the magnetic field lines. This parallel beam of electrons is running against an electrostatic potential formed by a system of cylindrical electrodes. All electrons with enough energy to pass the electrostatic barrier are reaccelerated and collimated onto a detector, all others are reflected. Therefore the spectrometer acts as an integrating high-energy pass filter. The relative sharpness of this filter is given by the ratio of the minimum magnetic field B_{min} in the center plane and the maximum magnetic field B_{max} between beta electron source and spectrometer :

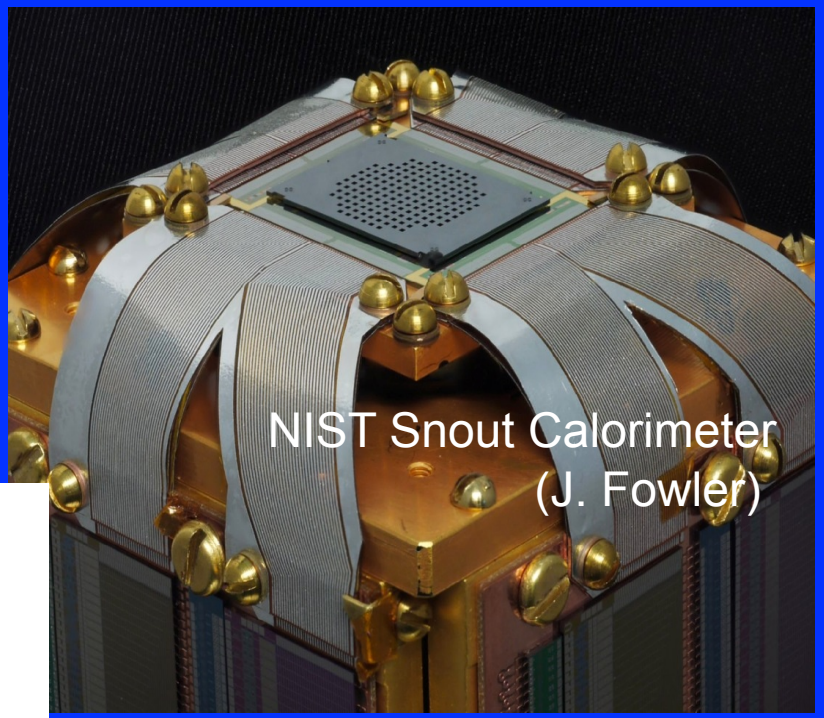
$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

In the case of PTOLEMY experiment this is is further improved by the RF tracking and by the calorimetric measurement.

TES Calorimetry

- NIST and ANL are leaders in the development of these sensors (driven by X-ray source astrophysics)





TES sensitive to magnetic field

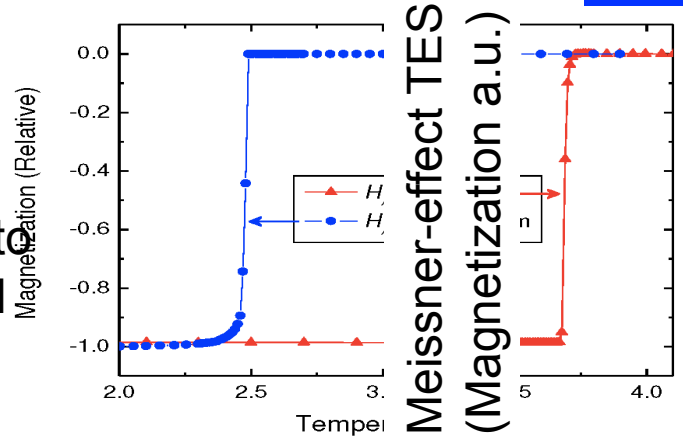


FIG. 1. (Color online) Magnetic superconducting transition for tin wire at two magnetic fields. For an applied field (H_A) of 1.3×10^4 A/m (160 Oe) applied parallel to the wire axis, the T_c is reduced from 3.7 to 2.5 K and the width of the transition remains below 30 mK.