Prospects for Relic Neutrino Detection at PTOLEMY:

Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

Chris Tully

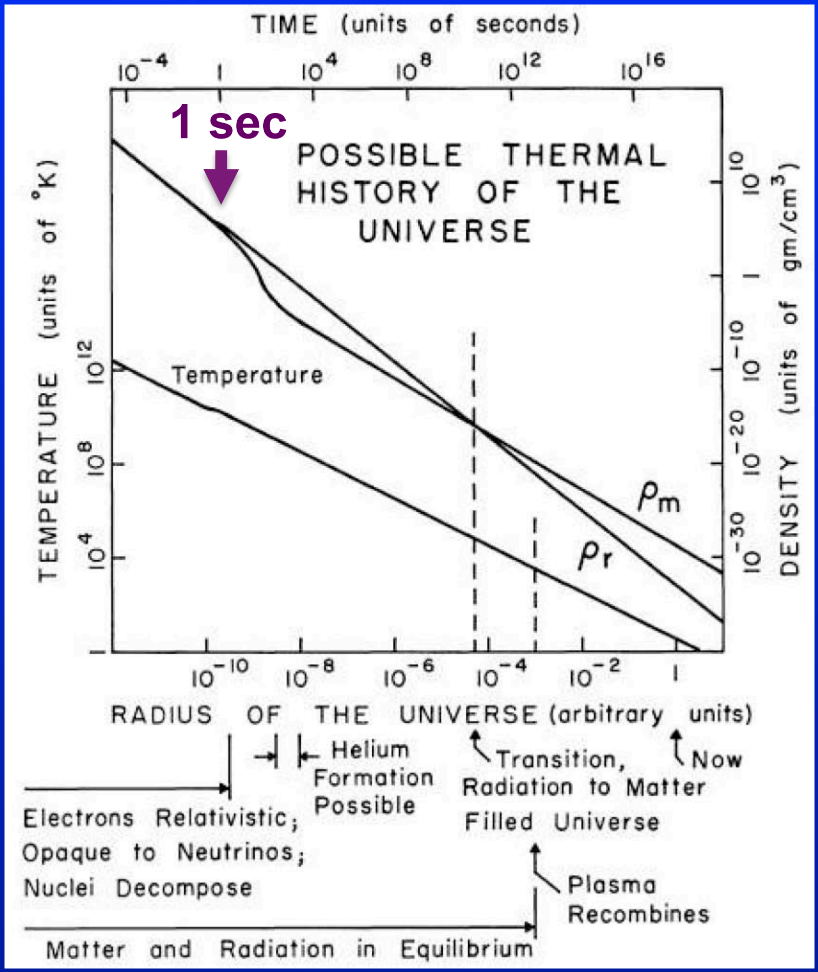
Princeton University

New Directions in Neutrino Physics

Aspen Winter Conference, February 6, 2013

Looking Back in Time

- The Universe was not always as cold and dark as it is today – there are a host of landmark measurements that track the history of the universe
- None of these measurements, however, reach back as far in time as ~1 second after the Big Bang
  - At ~1 second the hot, expanding universe is believed to have become transparent to neutrinos
  - In the present universe, relic neutrinos are predicted to be at a temperature of 1.9K ($1.7x10^{-4}$ eV) and to have an average number density of ~$56/cm^2$ per lepton flavor



Dicke, Peebles, Roll, Wilkinson (1965)

Relic Neutrino Detection

- Basic concepts for relic neutrino detection were laid out in a paper by Steven Weinberg in 1962 [*Phys. Rev.* 128:3, 1457]
  - Look for relic neutrino capture on tritium by measuring electrons at or above the endpoint spectrum of tritium beta-decay

$$\nu_e + A_Z \rightarrow e^- + A^*_{Z+1}$$

$$T_e = T_\nu + 2m_\nu + Q$$

What do we know?

Gap constrained to <0.6eV by WMAP

(some electron flavor expected above 0.05eV)

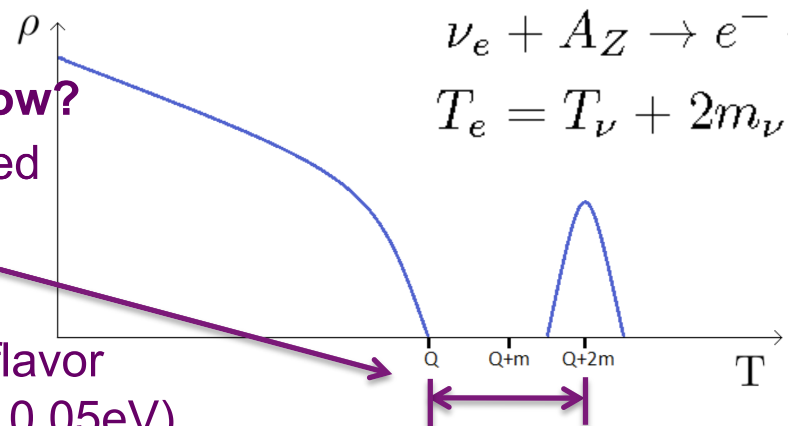
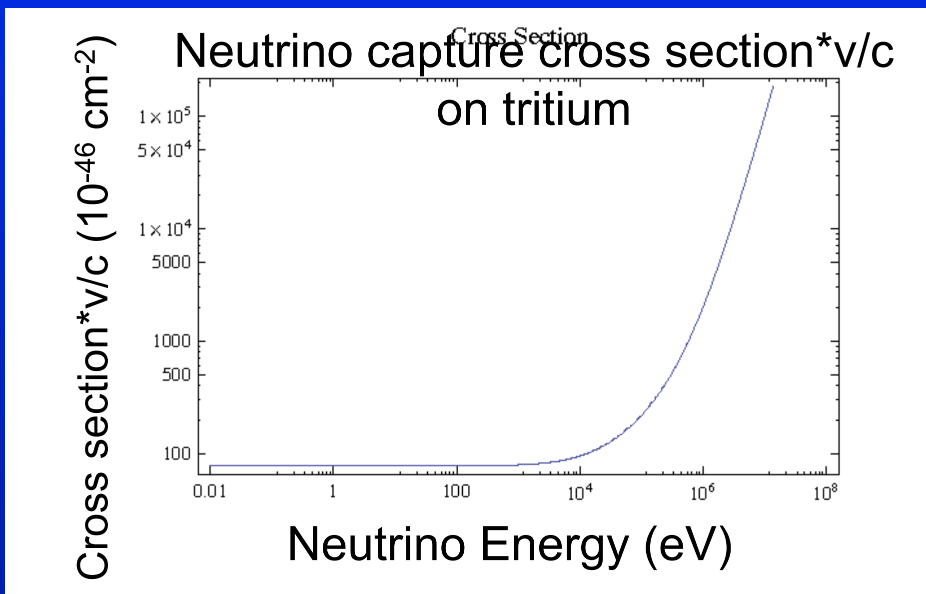
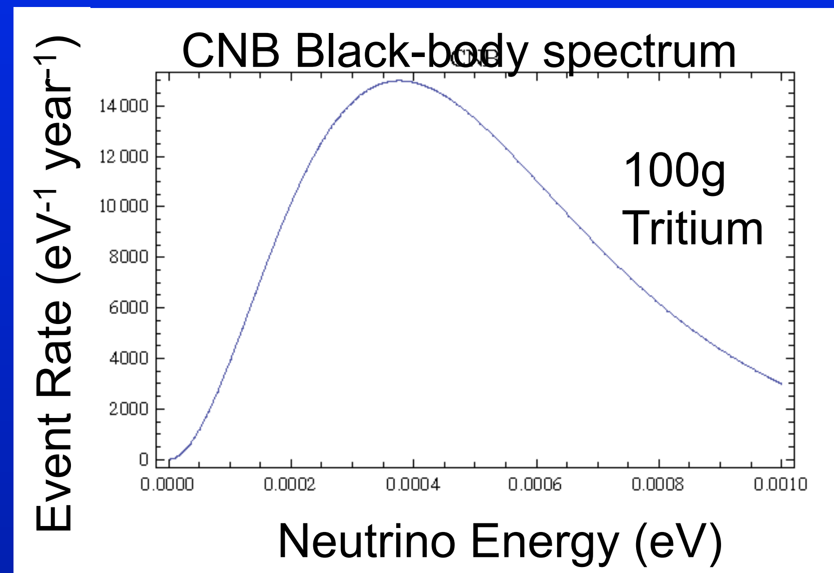


Figure 1: Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

Neutrino Interaction Rates

- 1 SNU = 1 neutrino interaction per second for 10^{36} target nuclei
- 100 grams of tritium (2.2×10^{25} nuclei)



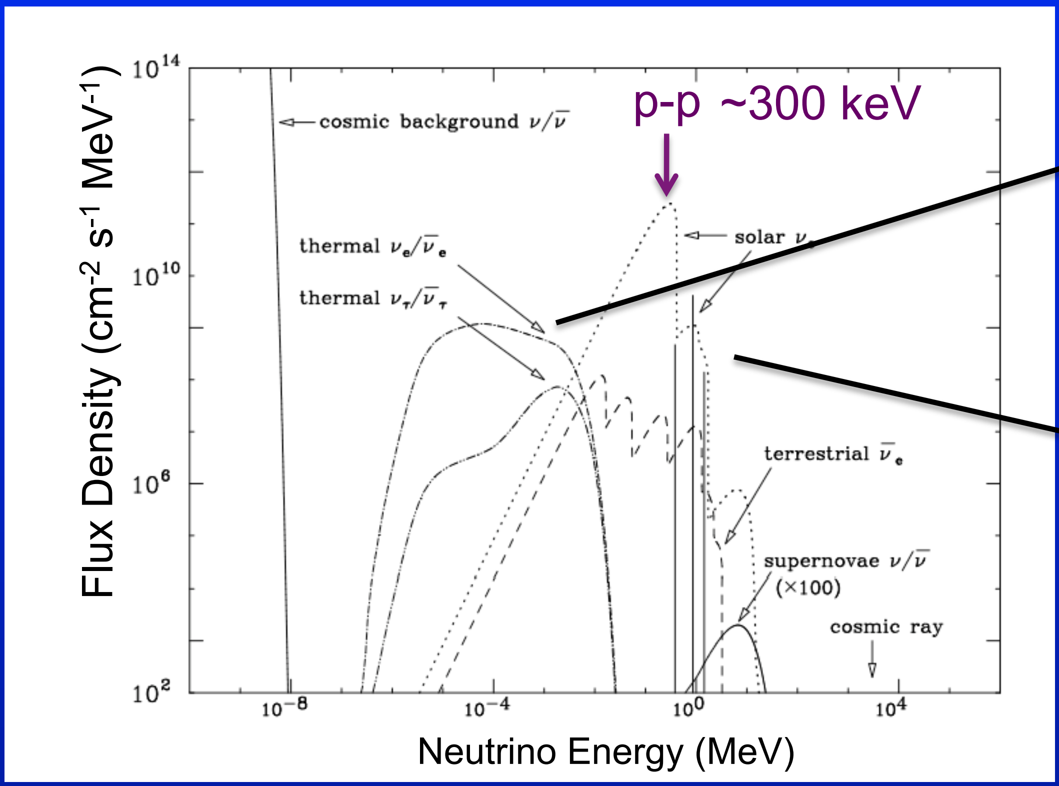


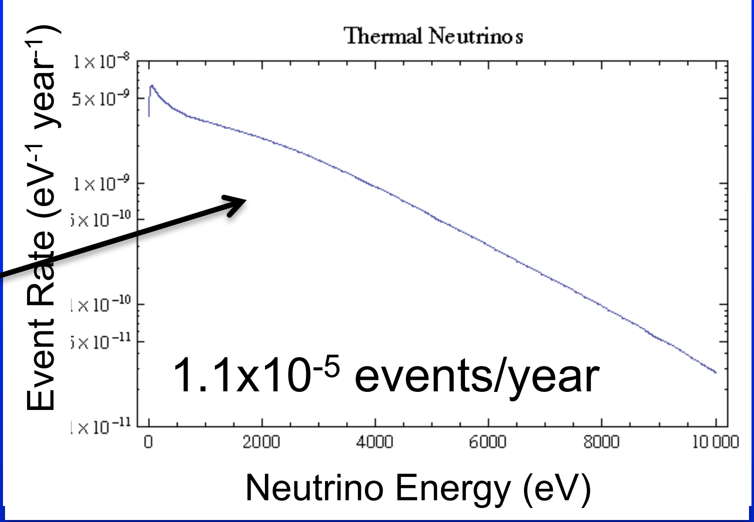
$$\int \sigma(p_\nu) v_\nu f_\nu(p_\nu) \frac{d^3 p_\nu}{(2\pi)^3}$$

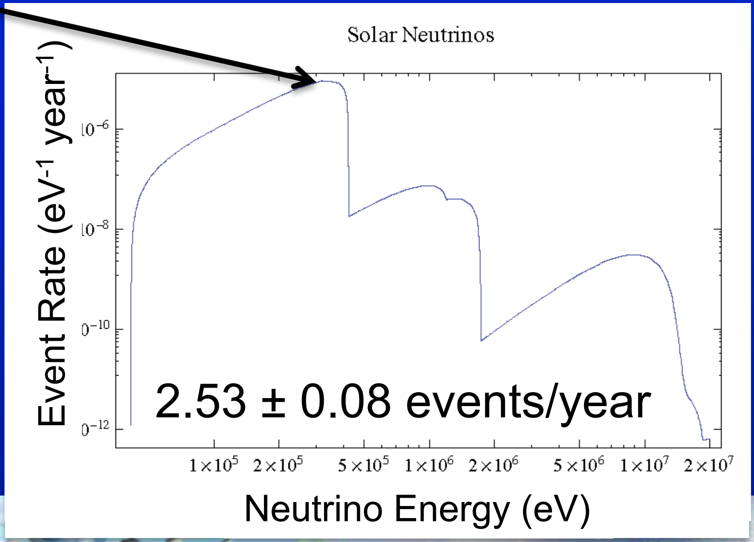
$$9.51 \pm 0.03 \text{ events/year } (13600 \pm 50 \text{ SNU})$$

Tritium and other isotopes studied for relic neutrino capture in this paper:
JCAP 0706 (2007)015, hep-ph/0703075 by Cocco, Mangano, Messina

Other Neutrinos?







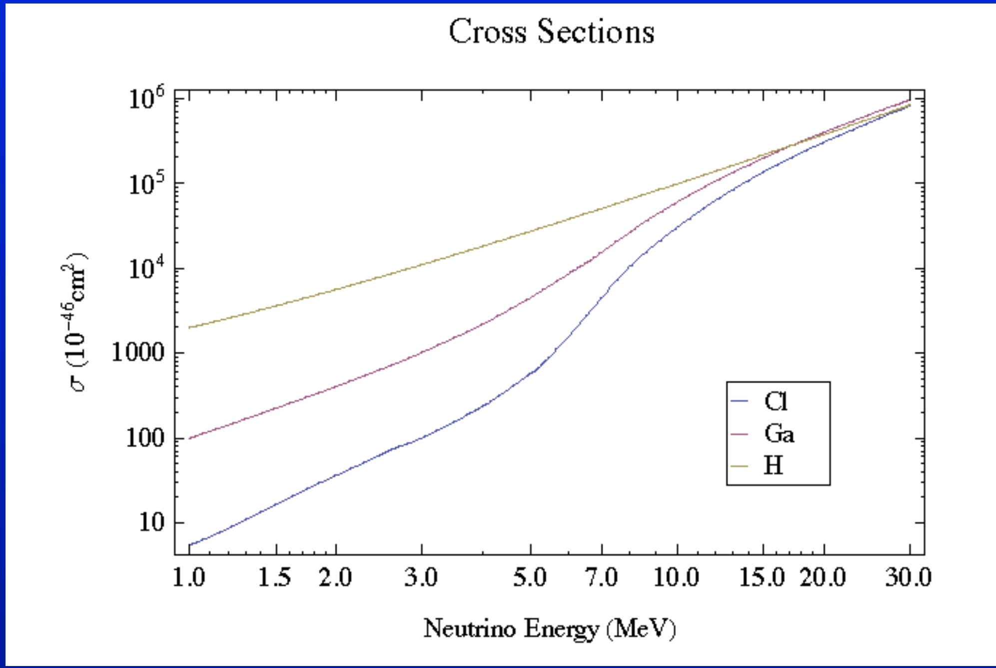
Solar Neutrino Capture Rates at PTOLEMY

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

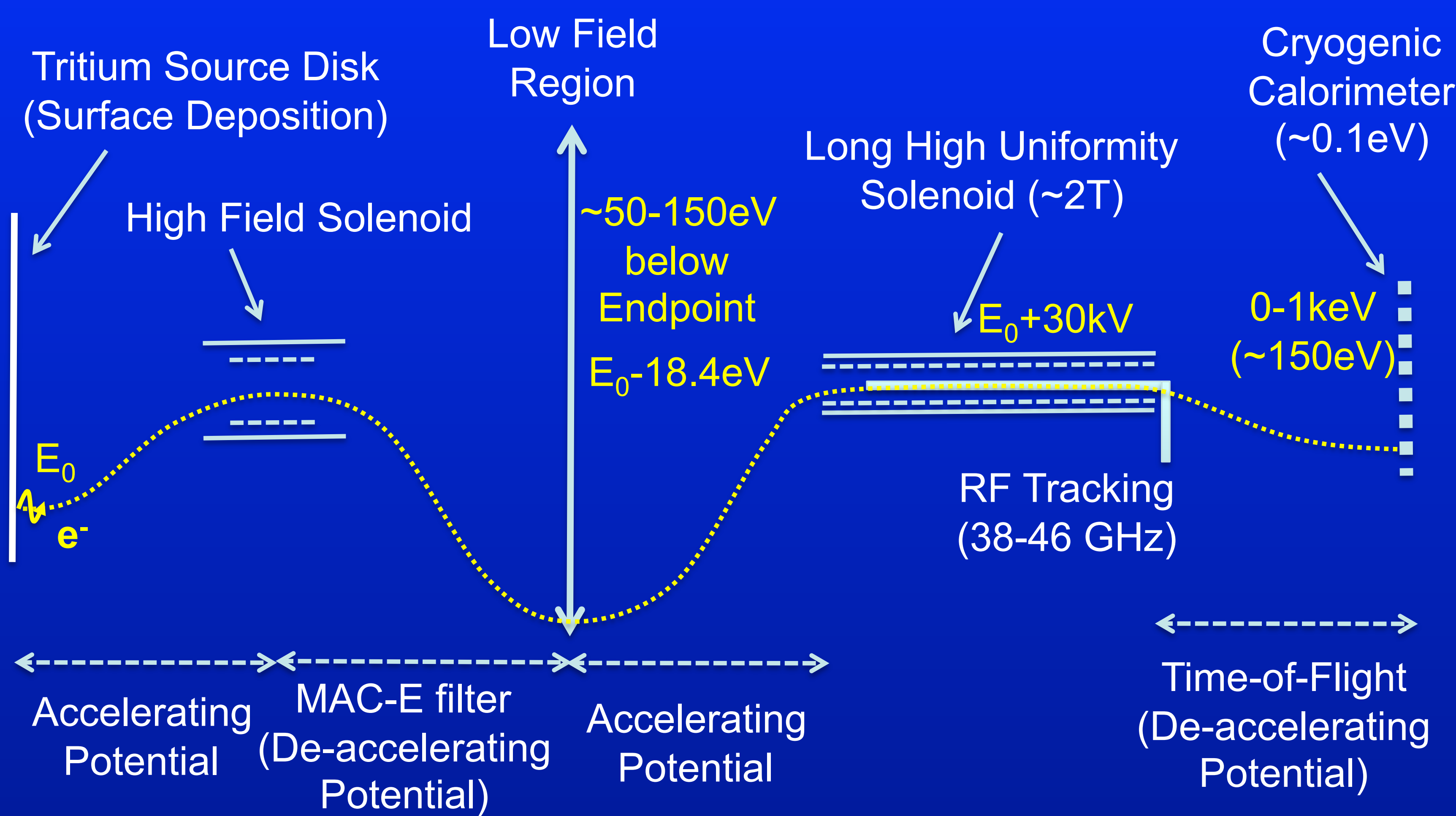
Hard to compete with Tritium for sub-MeV neutrino energies



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 signal features with high efficiency**
  - **For sterile nu search: maintains 10eV signal features w/ high eff.**
- Scalable mass/area of tritium source and detector
  - **Goal: relic neutrino detection at 100g**
  - **Sterile neutrino (w/ % electron flavor) at ~1g**

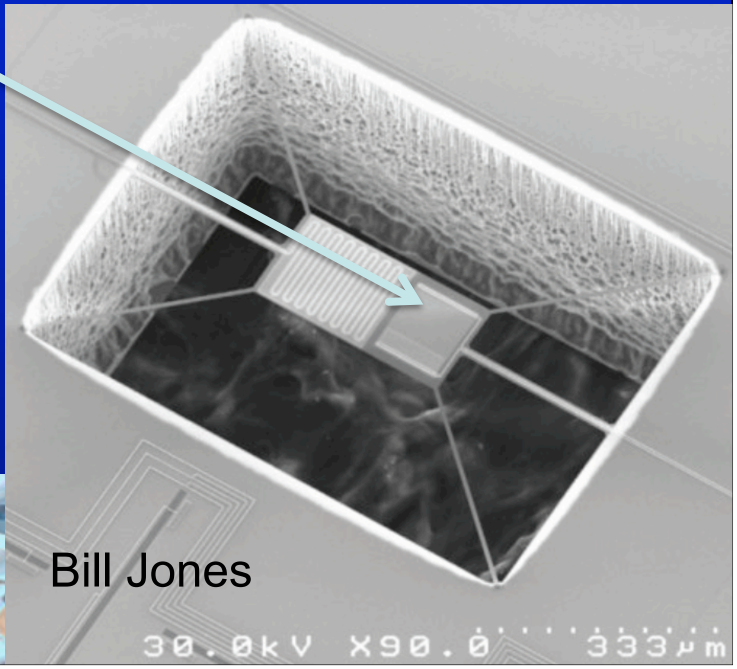
PTOLEMY Experimental Layout



High precision on Endpoint

- Transition-Edge Sensors for Calorimetry
  - ANL Group (Clarence Chang) estimates ~0.55eV at 1keV and ~0.15eV at 0.1keV operating at 70-100mK
  - New design introduces periodic pattern of normal regions in the TES to increase stability
    - **Magnetic fields of few hundred Gauss may be able to thread through normal regions**

(example) SPIDER Island TES



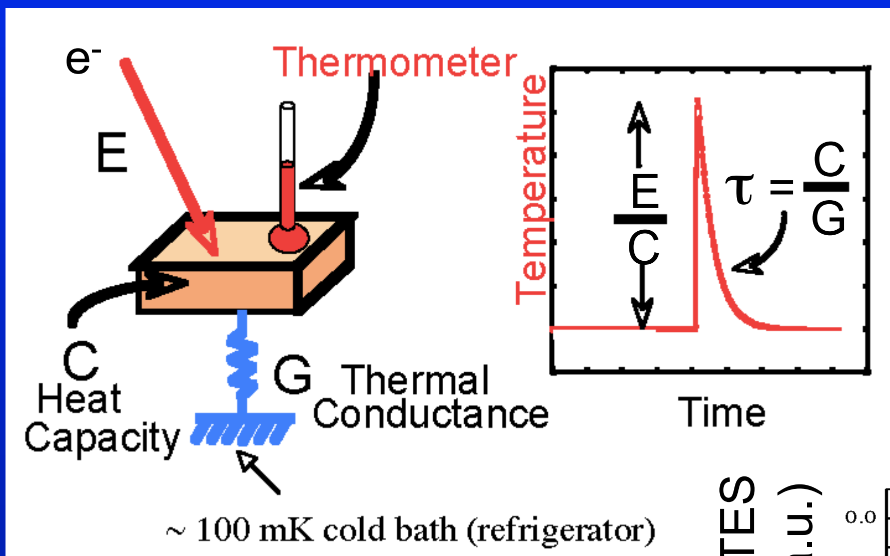
Important points for experiment:

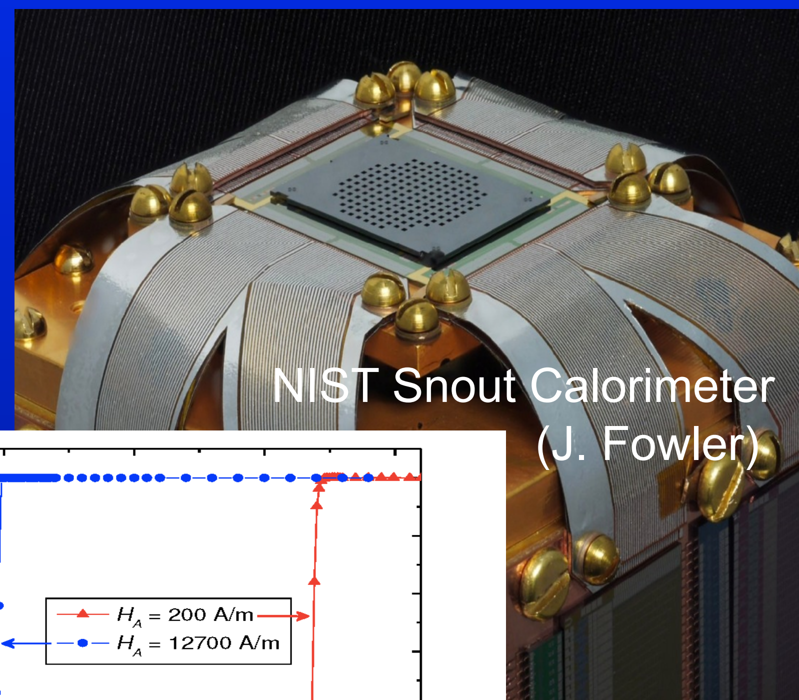
1) Need to truncate 18.570 keV energy spectrum and de-accelerate to within ~150eV of endpoint

2) Spatially segment source disks to map efficiently to finite TES sensor area (capacitance) of order ~1cm^2/channel

TES Calorimetry

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





TES sensitive to magnetic field

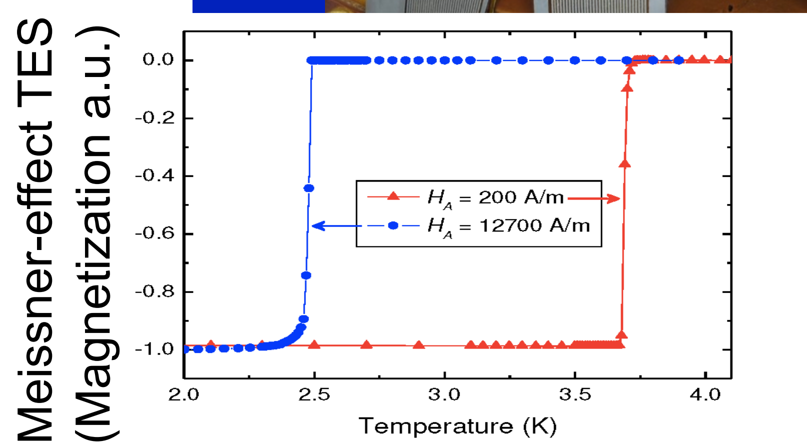
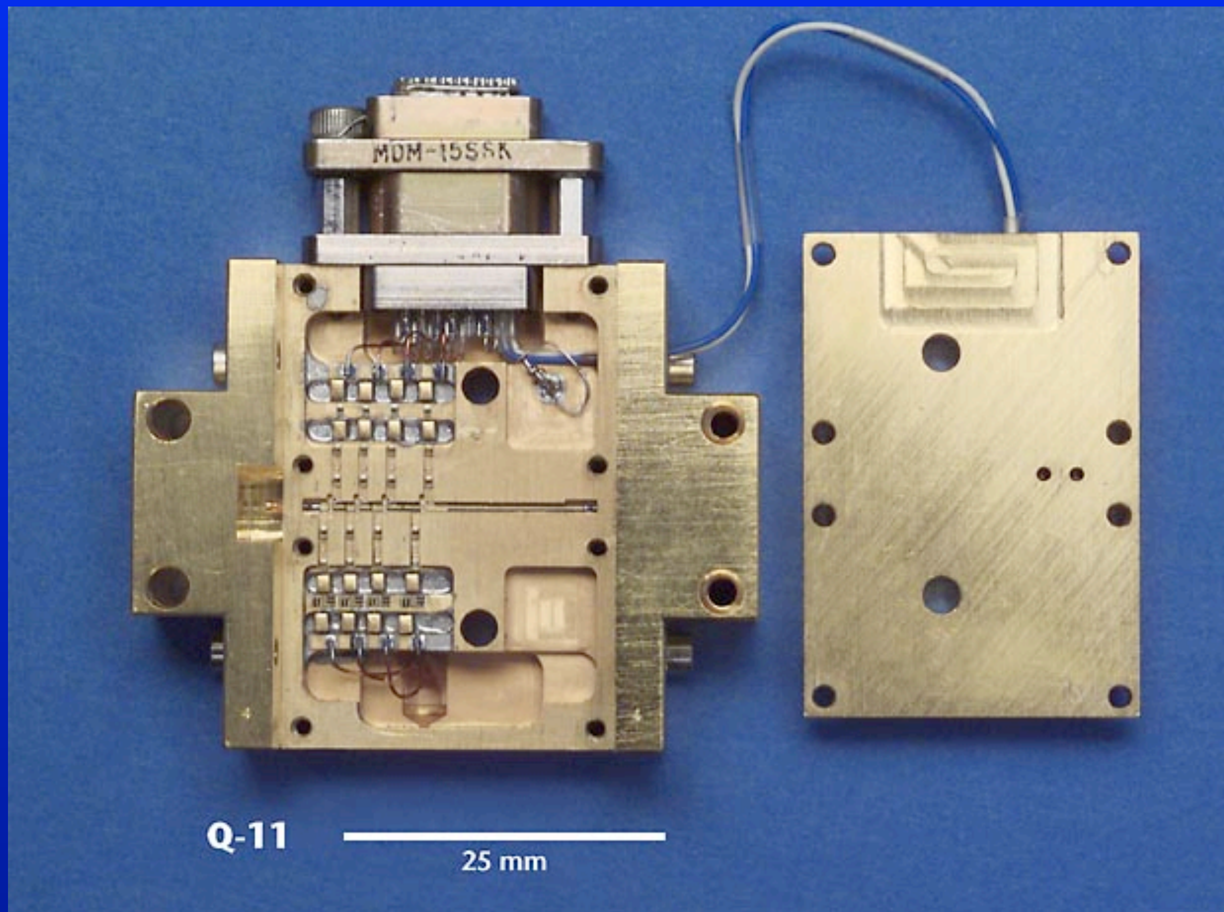


FIG. 1. (Color online) Magnetic superconducting transition for tin wire at two magnetic fields. For an applied field (H_A) of 1.3×10^4 A/m (160 Oe) applied parallel to the wire axis, the T_c is reduced from 3.7 to 2.5 K and the width of the transition remains below 30 mK.

Signal/Background suppression

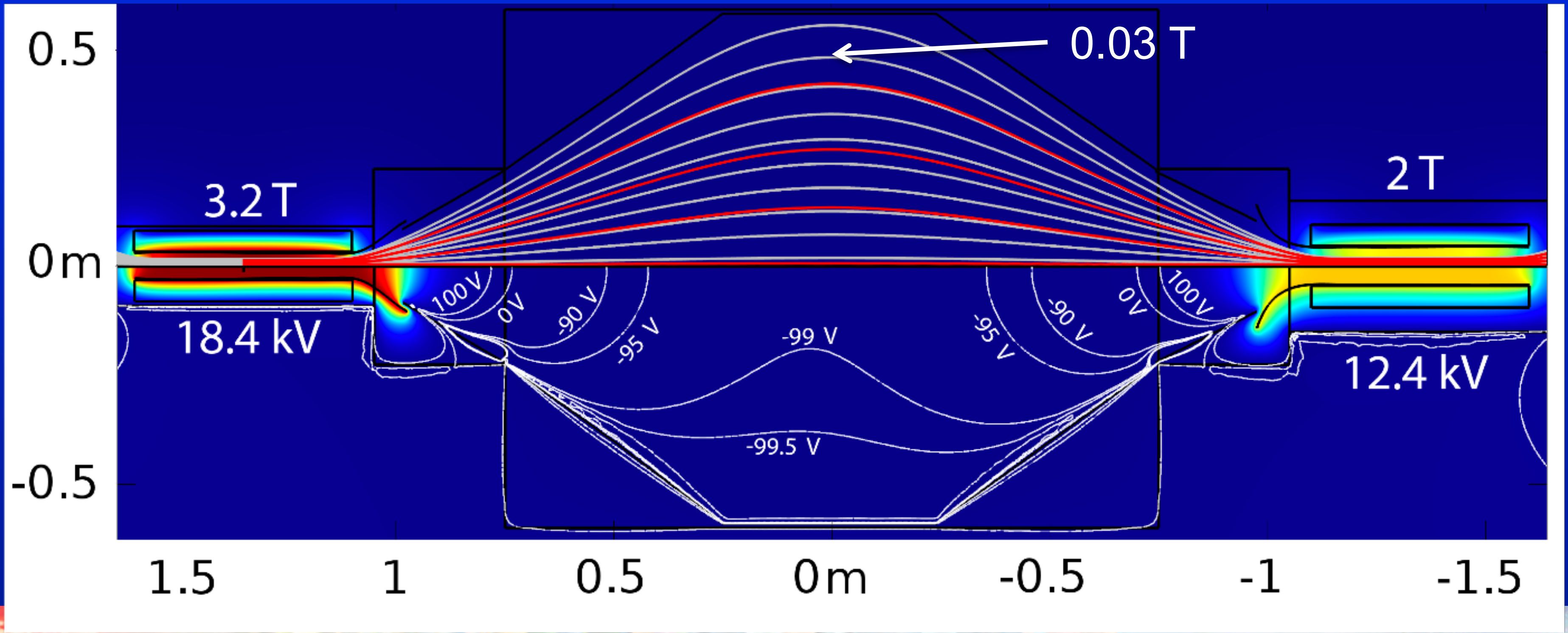
- RF tracking and time-of-flight
  - Thread electron trajectories (magnetic field lines) through an array of parallel plate Project-8 type antennas with wide bandwidth (few $\times 10^{-5}$) to identify cyclotron RF signal in transit times of order 0.2μsec
    - Currently using WMAP (Norm Jarosik) HEMT amplifiers with 1K/GHz noise and operating in the range 38-46 GHz (~1.9T)
    - Accelerate electrons to E_0+30keV in antenna region to increase electron cyclotron radiation – record in long uniform field (few $\times 10^{-5}$)
  - A requirement for an RF antenna "tracking" signal effectively introduces a transverse momentum cut on the signal electron in the bending plane
  - Timing resolution expected ~10ns depending on TES pulse

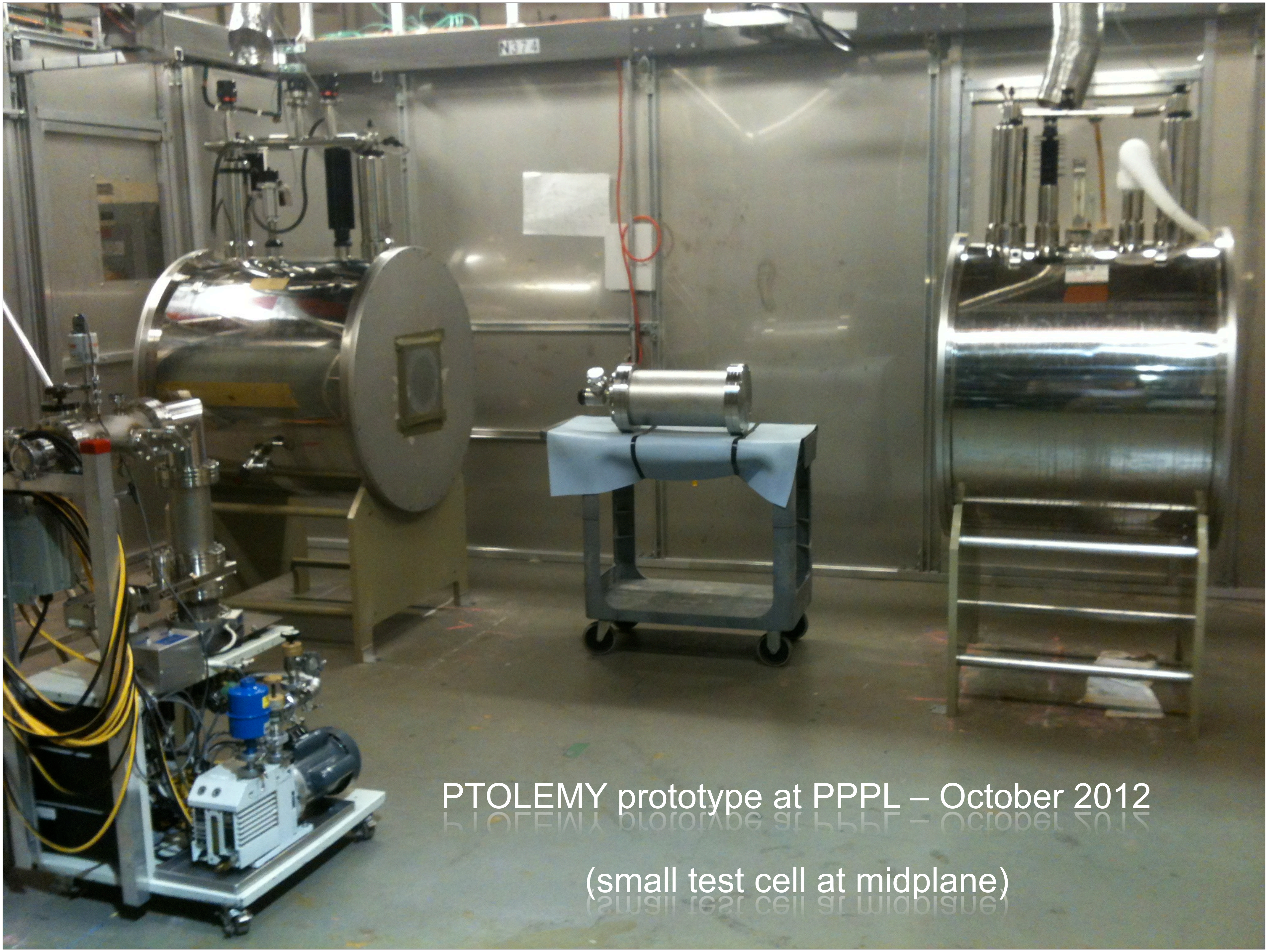
Q-Band (38-46 GHz) Amplifier



MAC-E filter

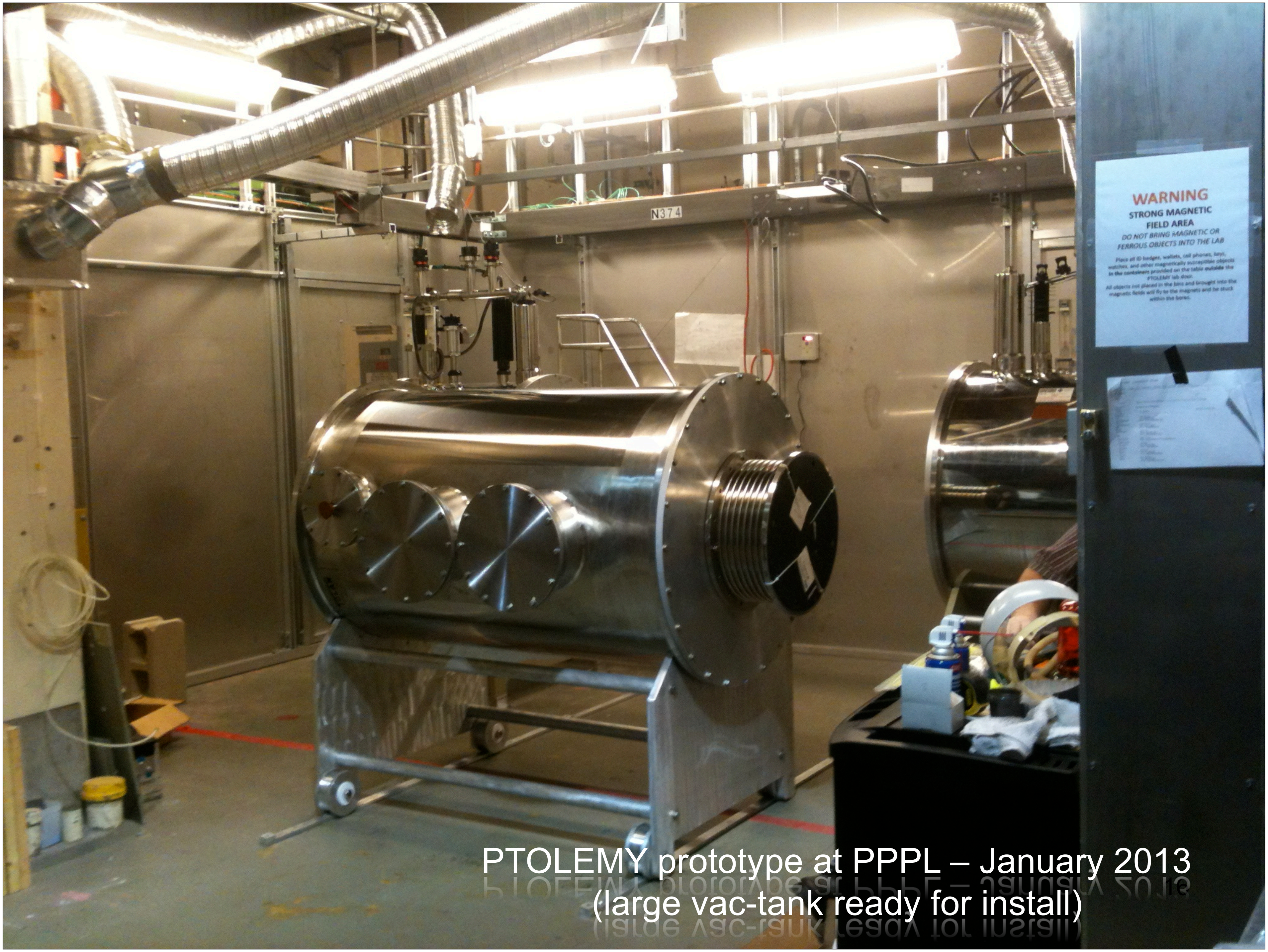
- MAC-E filter cutoff of 10^{-2} to 10^{-3} precision on electron energy
  - Energy window below endpoint needed for 2π acceptance ~150eV
  - Voltage of filter cut-off accurate to ~1eV
  - Source aperture of ~30cm^2 within 3.2T bore





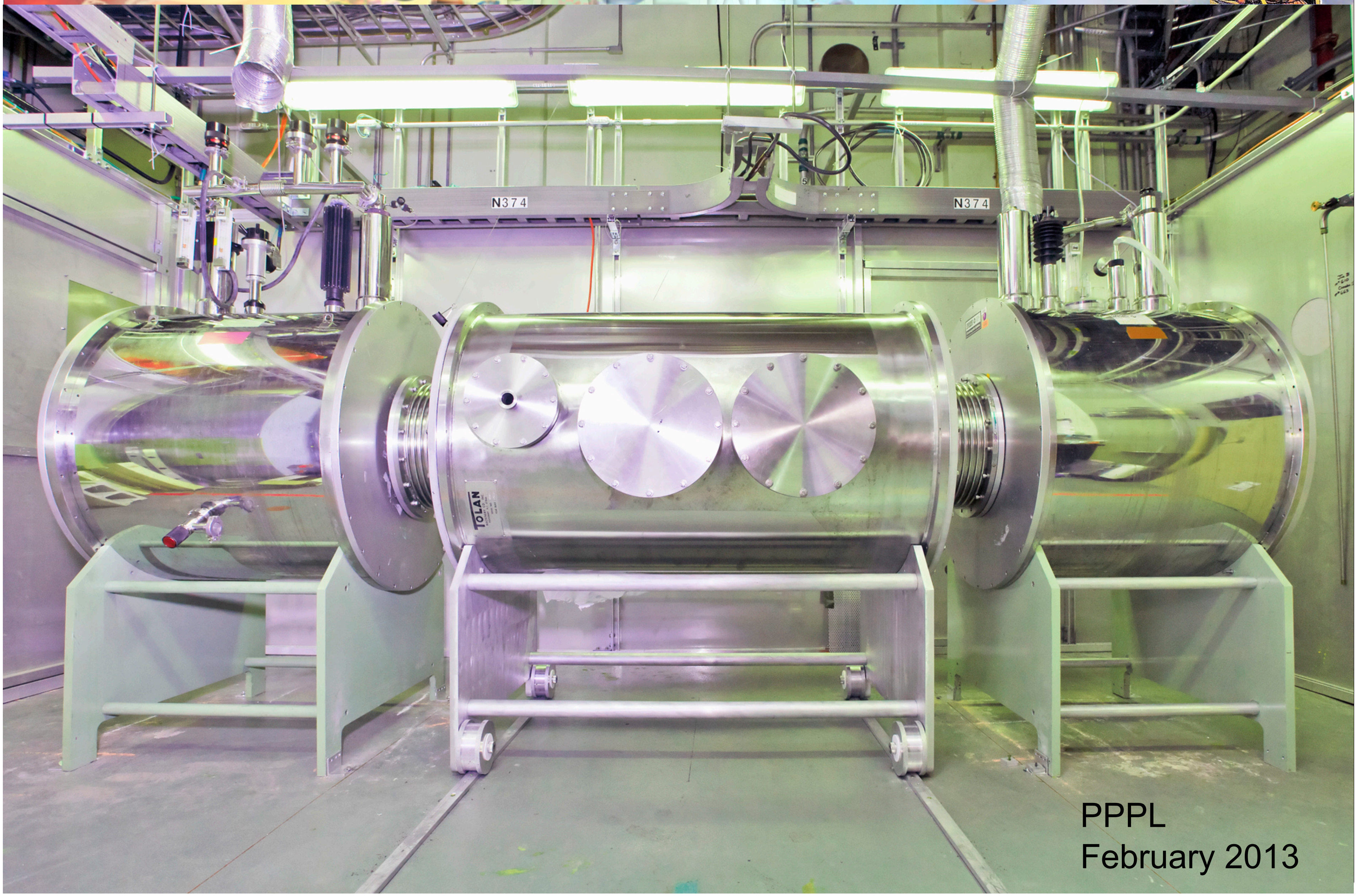
PTOLEMY prototype at PPPL – October 2012

(small test cell at midplane)



PTOLEMY prototype at PPPL – January 2013
(large vac-tank ready for install)

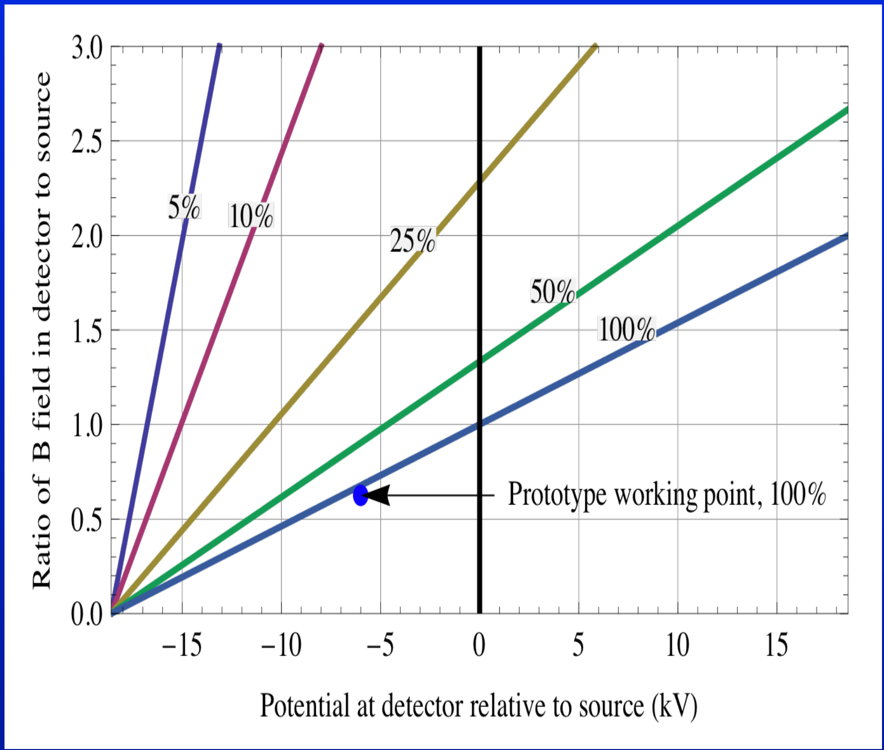
PTOLEMY

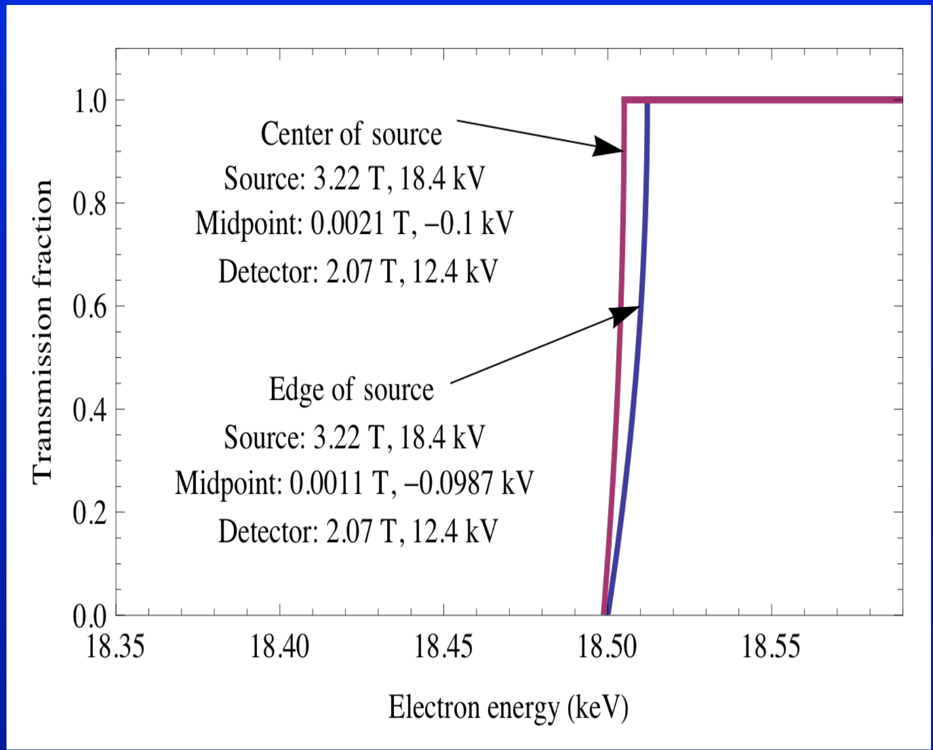


PPPL
February 2013

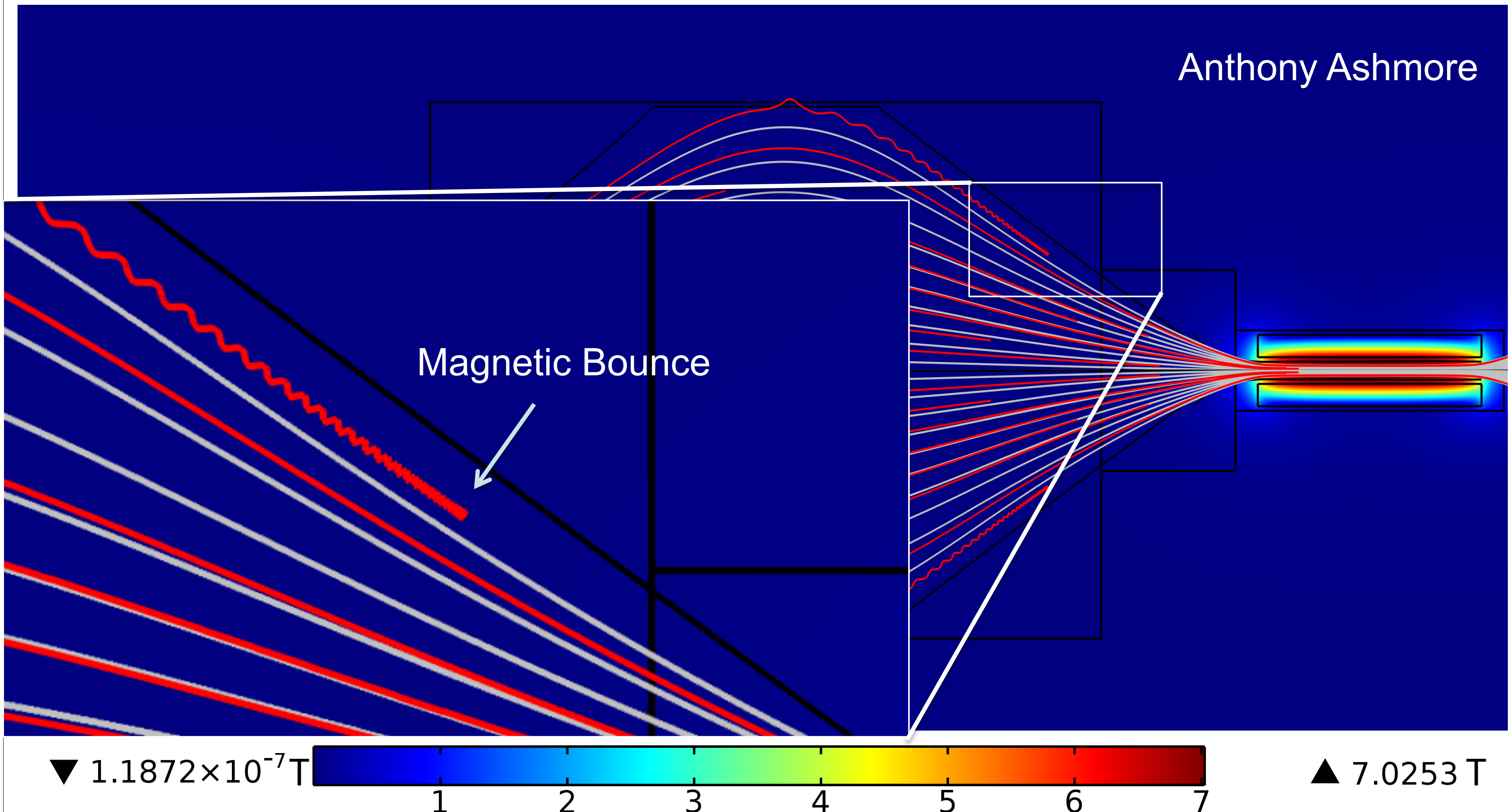
Cut-off Uniformity and Decay Acceptance

- In order to avoid magnetic bounce, electrons must be accelerated back up in going from mid-plane to detector
- Different trajectories have different cut-off precisions



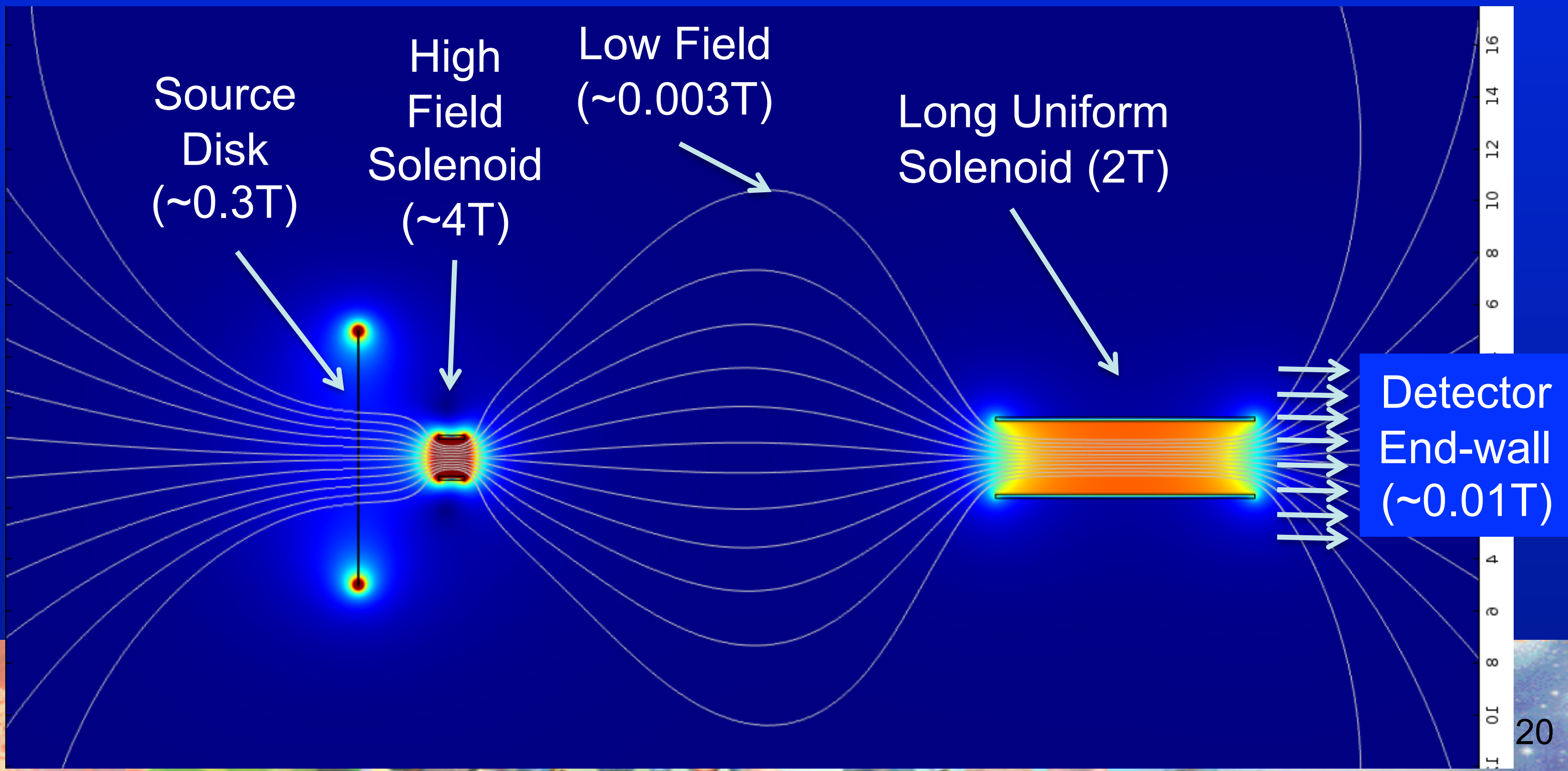


Trajectory Calculations



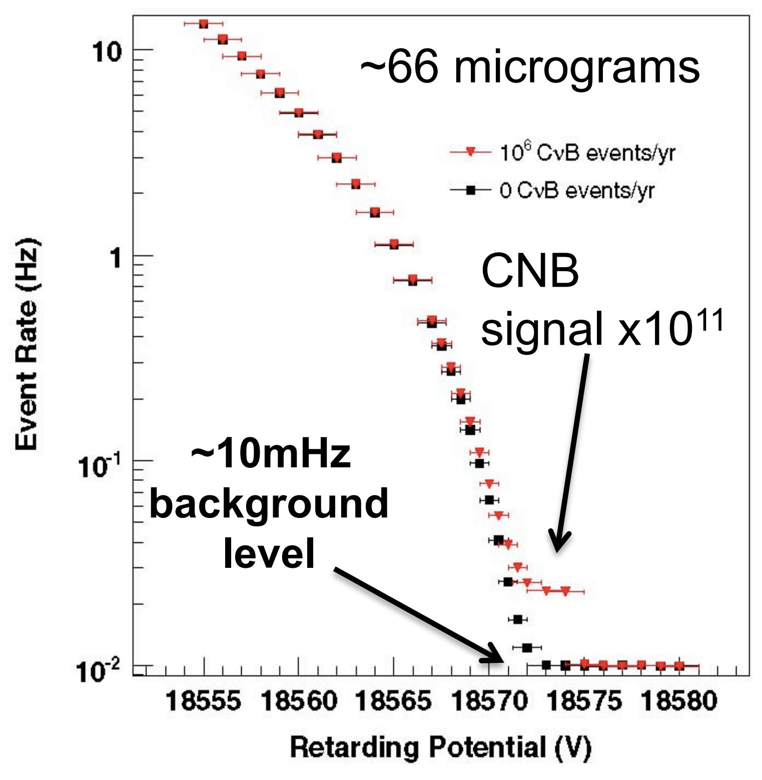
100g PTOLEMY

- Different geometries were investigated
  - Example configuration places a 12m diameter disk at the input to the 1st MAC-E magnet (accelerated to ~90keV)
  - Source disk will consist of 10^4-10^5 individual plates



Karlsruhe TRItium Neutrino (KATRIN)

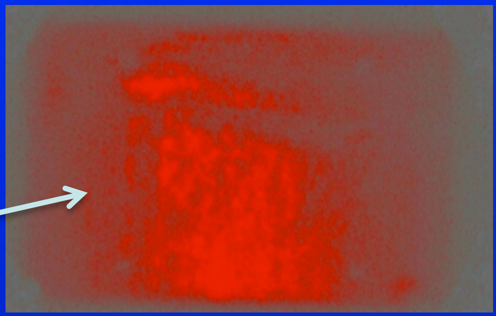
- Uses large uniform geometry to achieve ~0.2eV cut-off sensitivity – "Cut and Count" experiment
  - **PTOLEMY Goal: 10mHz →sub-μHz Background Rate**



Surface Deposition Sources

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

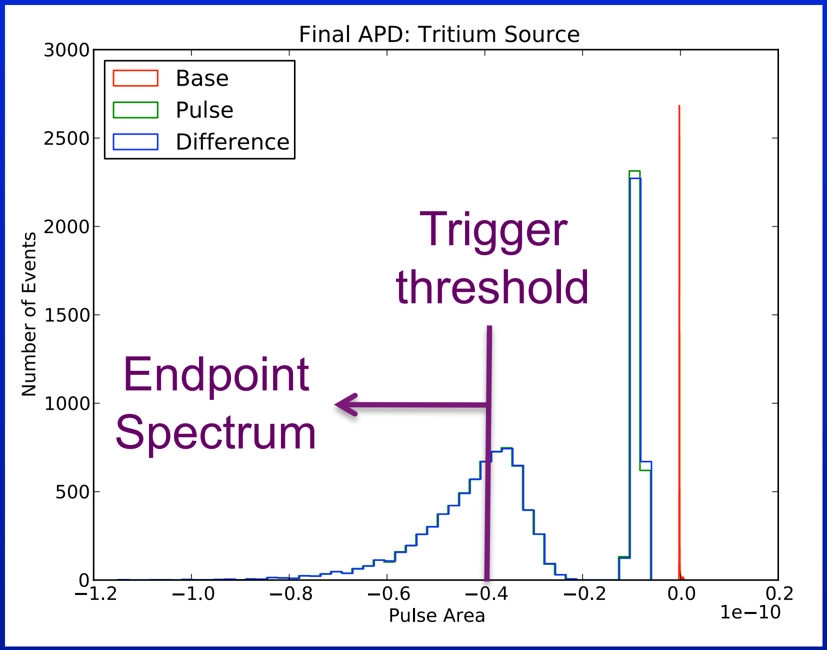
Carbon tile image of tritium

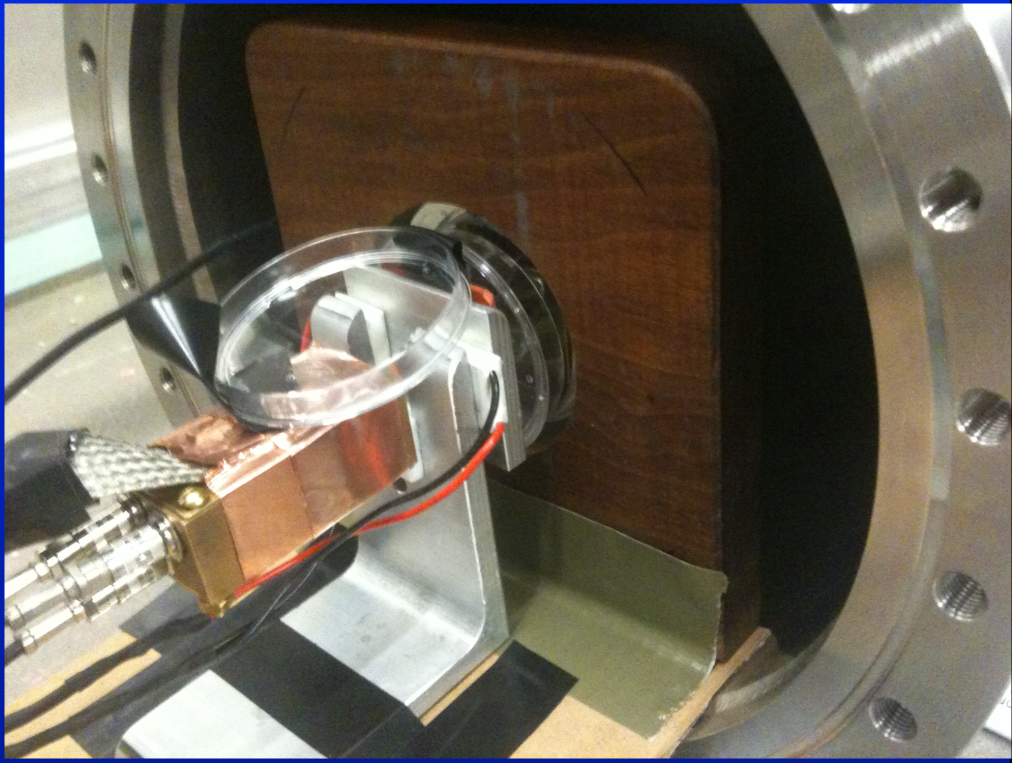


- Depositions on titanium, gold, diamond, and graphene are being investigated (done by Canadian firms and Savannah River National Lab (SRNL) in collaboration with PPPL)
  - SRNL has titanium samples that we have requested for testing
- Source strength surface densities of ~1Ci/cm^2 (100micrograms/cm^2) are possible, but energy spread from source scattering needs to be measured
  - Required resolution ~0.1eV for CNB and ~10eV for sterile nu search

Tritium Tag Detector

- For studying antenna data, a windowless APD is used to tag the tritium decay from a tritium disk source
  - Trigger on APD and record antenna (50 GHz mixed down to ~10 MHz bandwidth)





Calibration and Backgrounds

- High precision (0.1eV) electron gun
  - Off-axis directionality needed for RF antenna calibration
  - Investigating fabrication of non-magnetic models
- Vacuum studied with residual gas analyzer (RGA)
- Several possibilities for background estimation
  - sideband data-driven background estimation below MAC-E filter cutoff
  - out-of-time tracking-calorimeter coincidence
  - varying source strength tiles (null sources)
- NMR calibration for magnetic field uniformity in RF tracker

Experimental Program for 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 Prototype

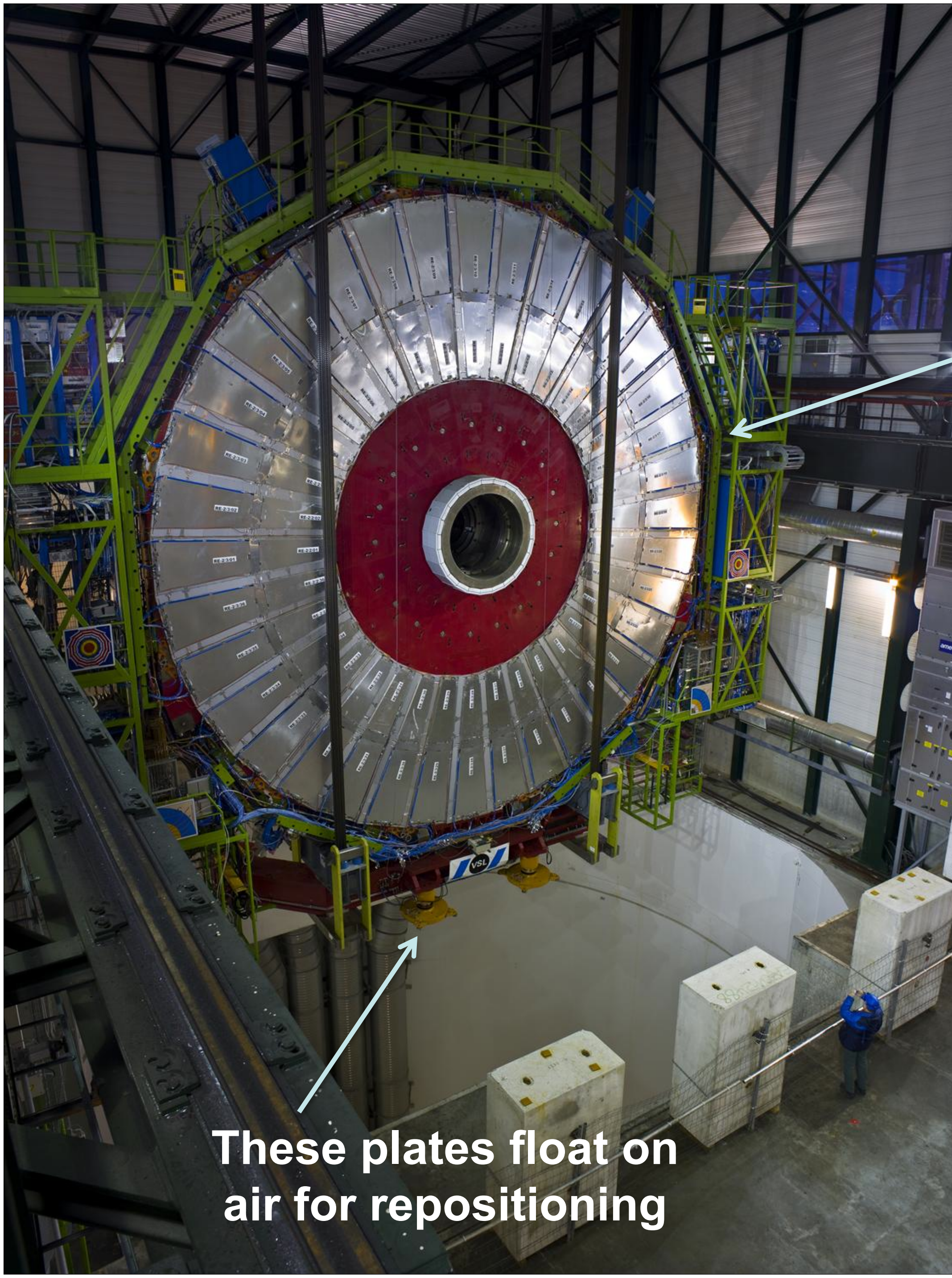
4th Milestone: Commission MAC-E filter.
- Finish fabrication of copper tubes
- Install in Vac-tank with HV stand-offs and 50kV cable/connectors.
- Evaluate performance of filter cut-off with APD data in vacuum.

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

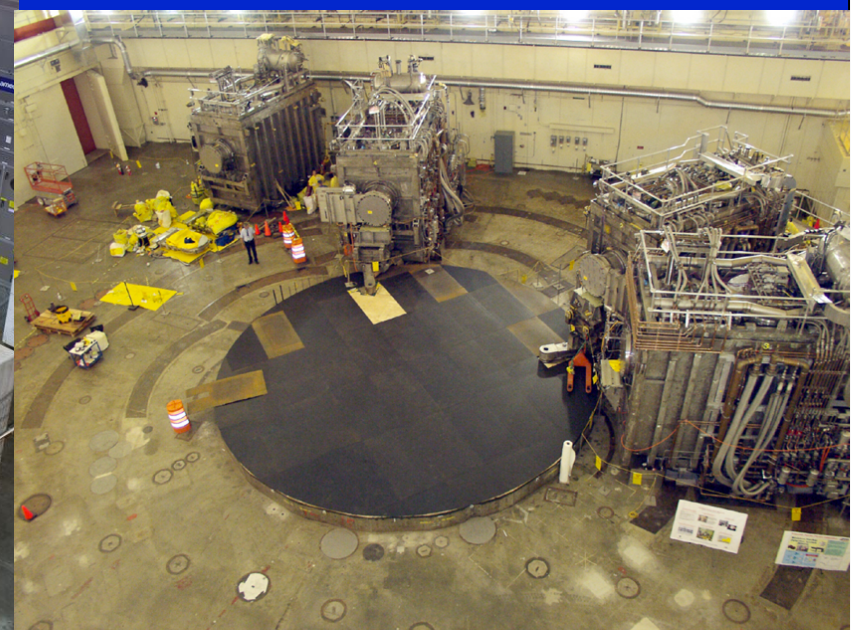
6th Milestone: Validate technologies for 100g PTOLEMY.
- Introduce disk source feeding source magnet aperture.
- Introduce TES micro-calorimeter with sub-eV resolution.
- Benchmark system performance.

12m Disk

A 12m diameter Source Disk is comparable to the size of a CMS YE-2 end-plate at CERN



These plates float on air for repositioning



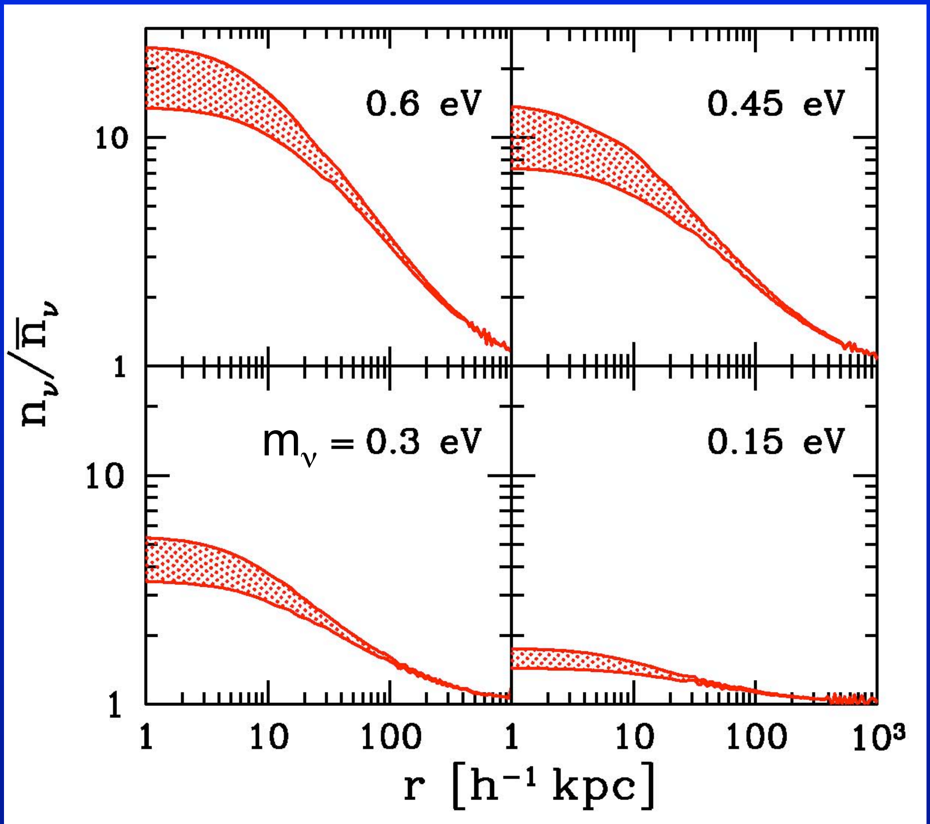
PPPL Test Cell Area

Clumping Factor Enhancement

- T_ν = 1.9K = ~1.7 x 10^{-4} eV is small compared to at least 2 of the neutrino mass eigenstates

The local neutrino number density (with electron flavor content) may be enhanced in clusters by factors that typically range from 1-100 depending on the neutrino mass(es)

This would translate directly in 1-100 times more CNB signal events.



Ringwald and Wong (2004)

What can Relic Neutrino Density tell us?

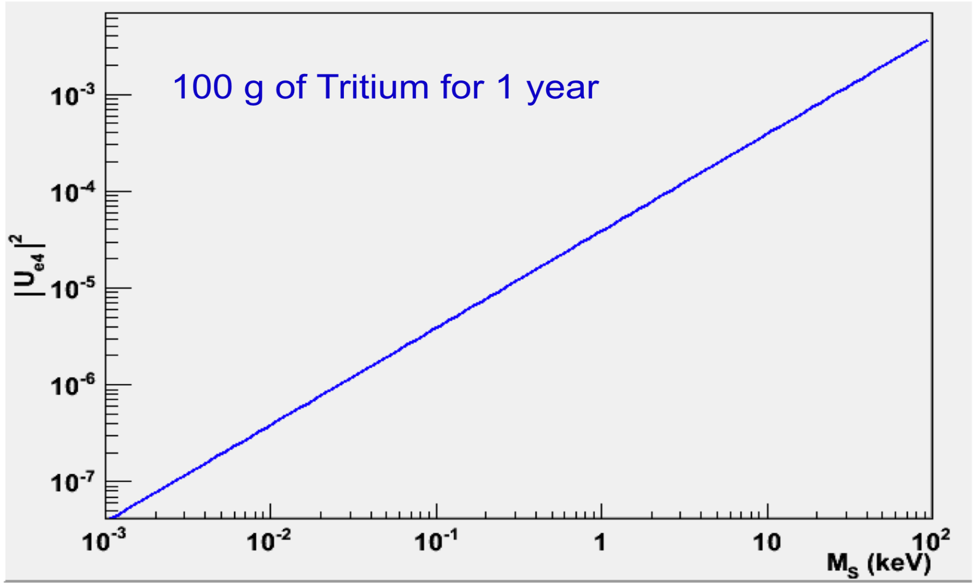
- Are there experimental outcomes that are inconsistent with Big Bang cosmology? Yes!
  - Too many cold neutrinos with no visible mass separation from the end-point (no galactic clumping factor) would contradict the initial conditions of Big Bang nucleosynthesis (present day H, D, He, Li abundances)
- Are there outcomes that are inconsistent with the Standard Model of particle physics? Yes!
  - No neutrino detection (exclusion of the relic neutrino density below prediction) could mean that neutrinos have a finite lifetime
- Are there possibilities for discovering new physics? Yes!
  - Alternative dark matter candidates such as keV sterile neutrinos may have a non-zero electron flavor content and would appear as a mass peak above the end-point

Sterile Neutrino Search

Using ν capture...

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

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



What can Relic Neutrino Density tell us?

- Is there a possibility to make long-term contributions to the understanding of the Universe?
  - Absolutely! We believe that we live in a sea of 14 billion year old neutrinos all around us (the oldest relics in the Universe) – is it true?
  - When one opens a new frontier of exploration, there is no telling what will be found and learned

Outlook

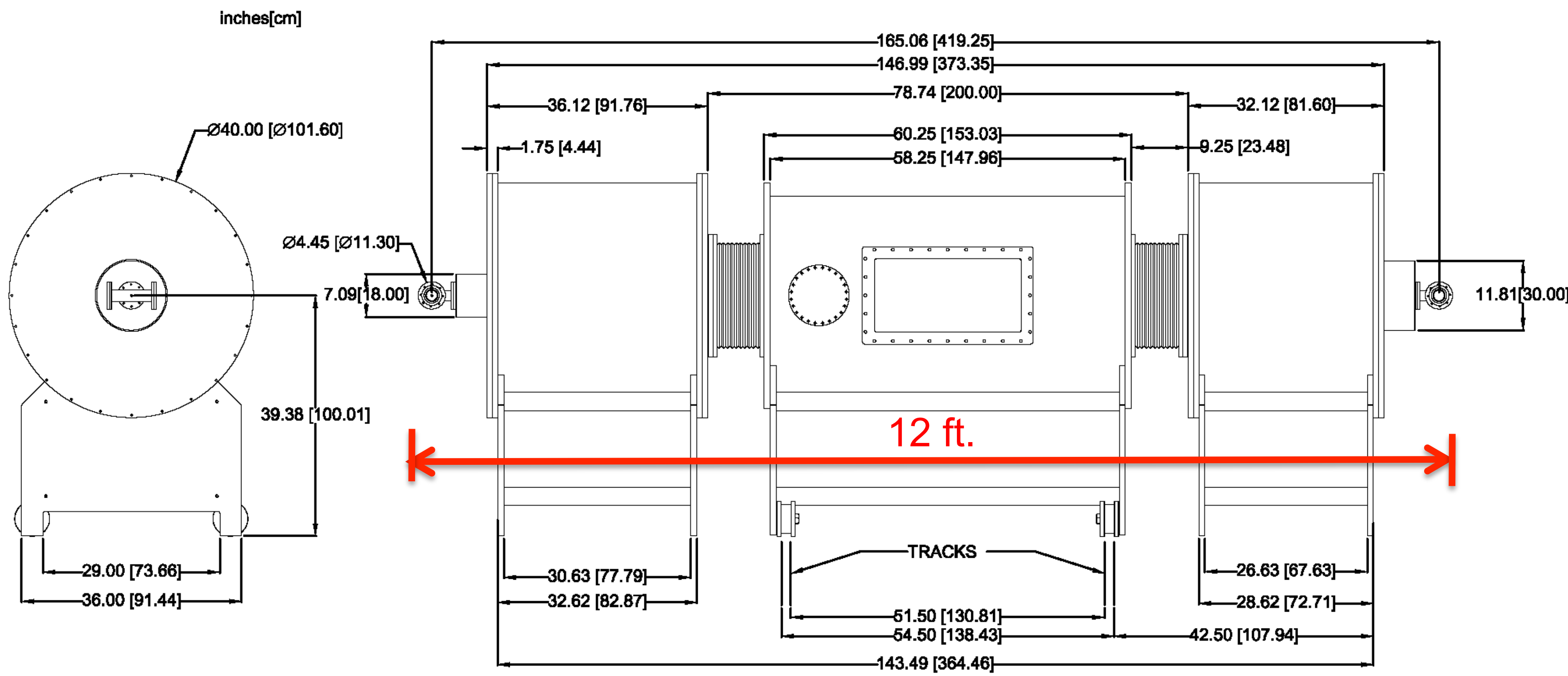
- Important R&D still to be done on source, detector, background levels
- PPPL prototype is an excellent test bed for validating the technologies for a 100g PTOLEMY
- KATRIN will hopefully provide more input on the neutrino mass(es)
- Planning to do some interesting experimental work at Princeton during the LHC shutdown

Collaborators are very welcome

Backup Slides

Vacuum Chamber Design

- Central vacuum chamber on rails to provide access to source and detector areas during install



Adam Cohen, Bill Blanchard, Lloyd Ciebiera, John Dong, Charlie Gentile, Bill Sands, Jim Taylor, Chris Tully