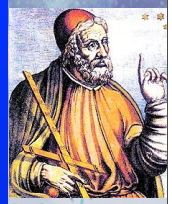
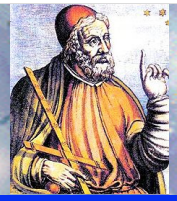


Challenges of Relic Neutrino Detection and the Status of PTOLEMY

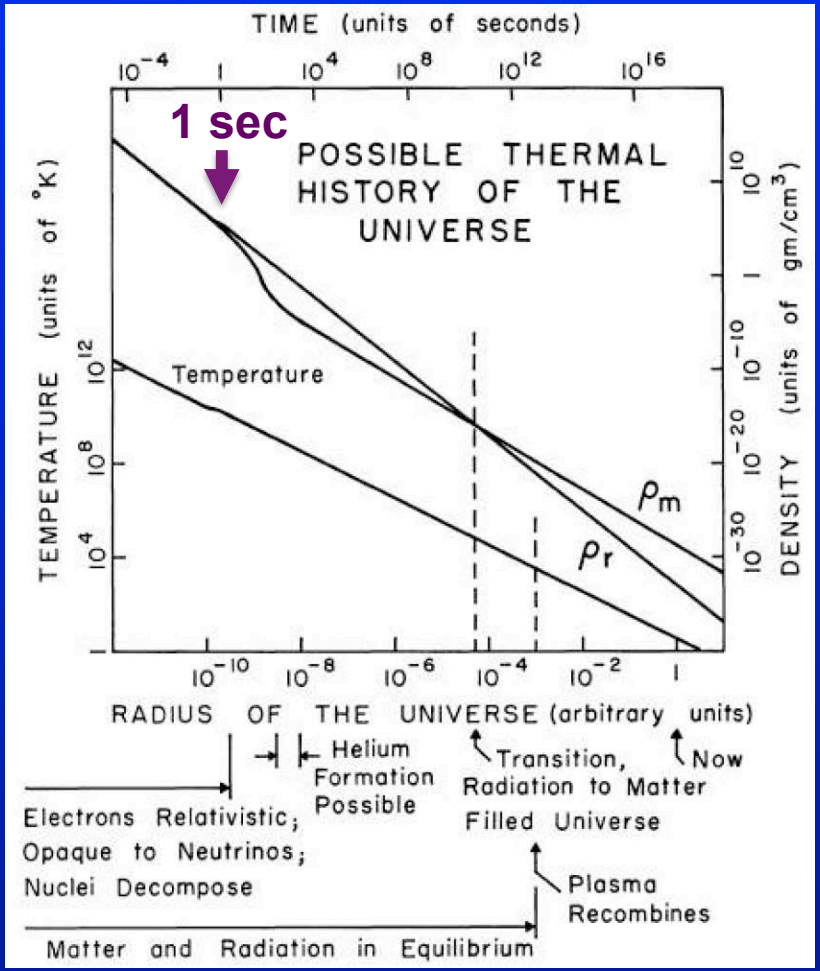
Chris Tully
Princeton University

Fermilab Astro Seminar
November 25, 2013

Looking Back in Time

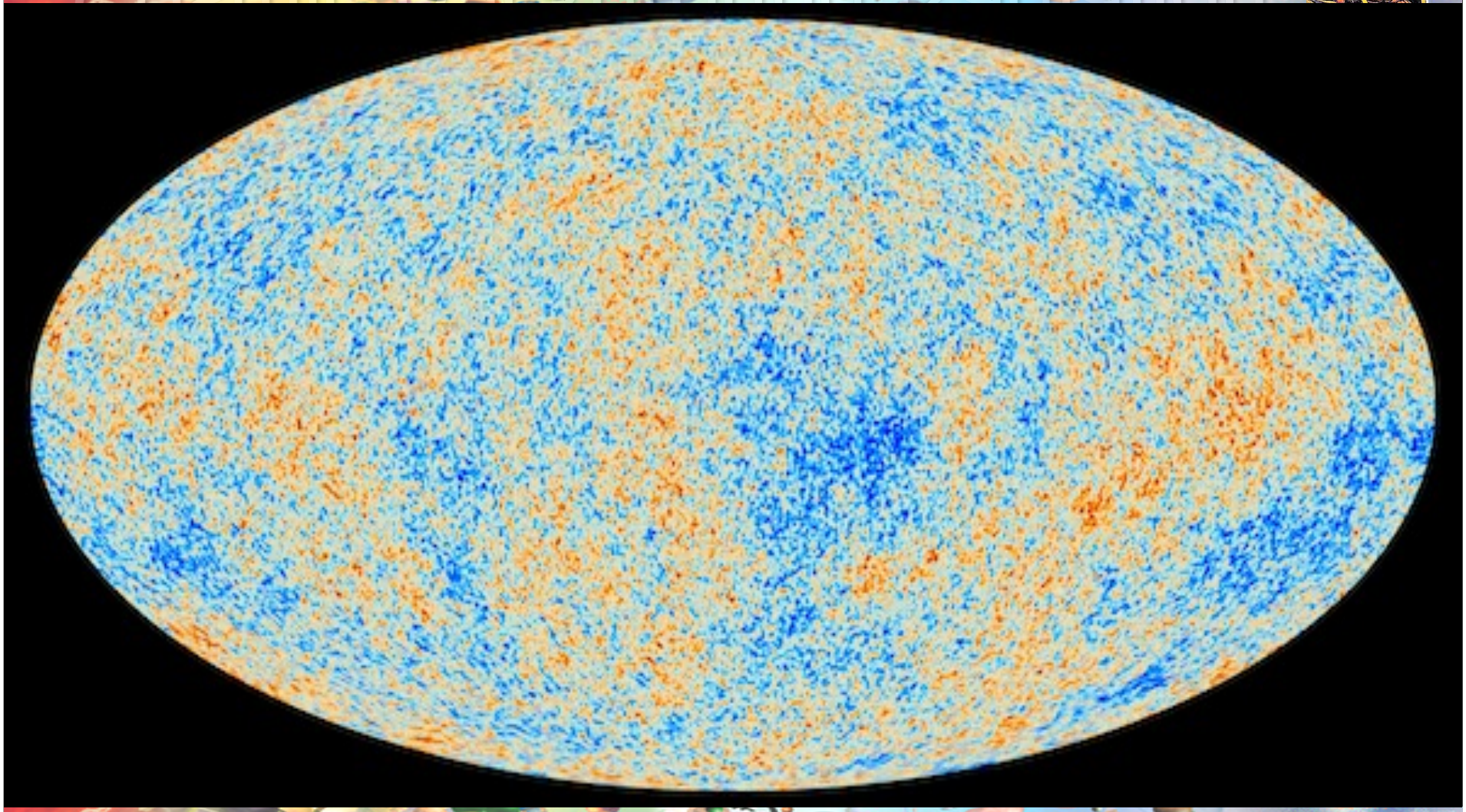


- The Universe was not always as cold and dark as it is today – there are a host of landmark measurements that track the history of the universe
- None of these measurements, however, reach back as far in time as ~1 second after the Big Bang
  - At ~1 second the hot, expanding universe is believed to have become transparent to neutrinos
  - In the present universe, relic neutrinos are predicted to be at a temperature of 1.9K (1.7×10^{-4} eV) and to have an average number density of ~56/cm^3 per lepton flavor

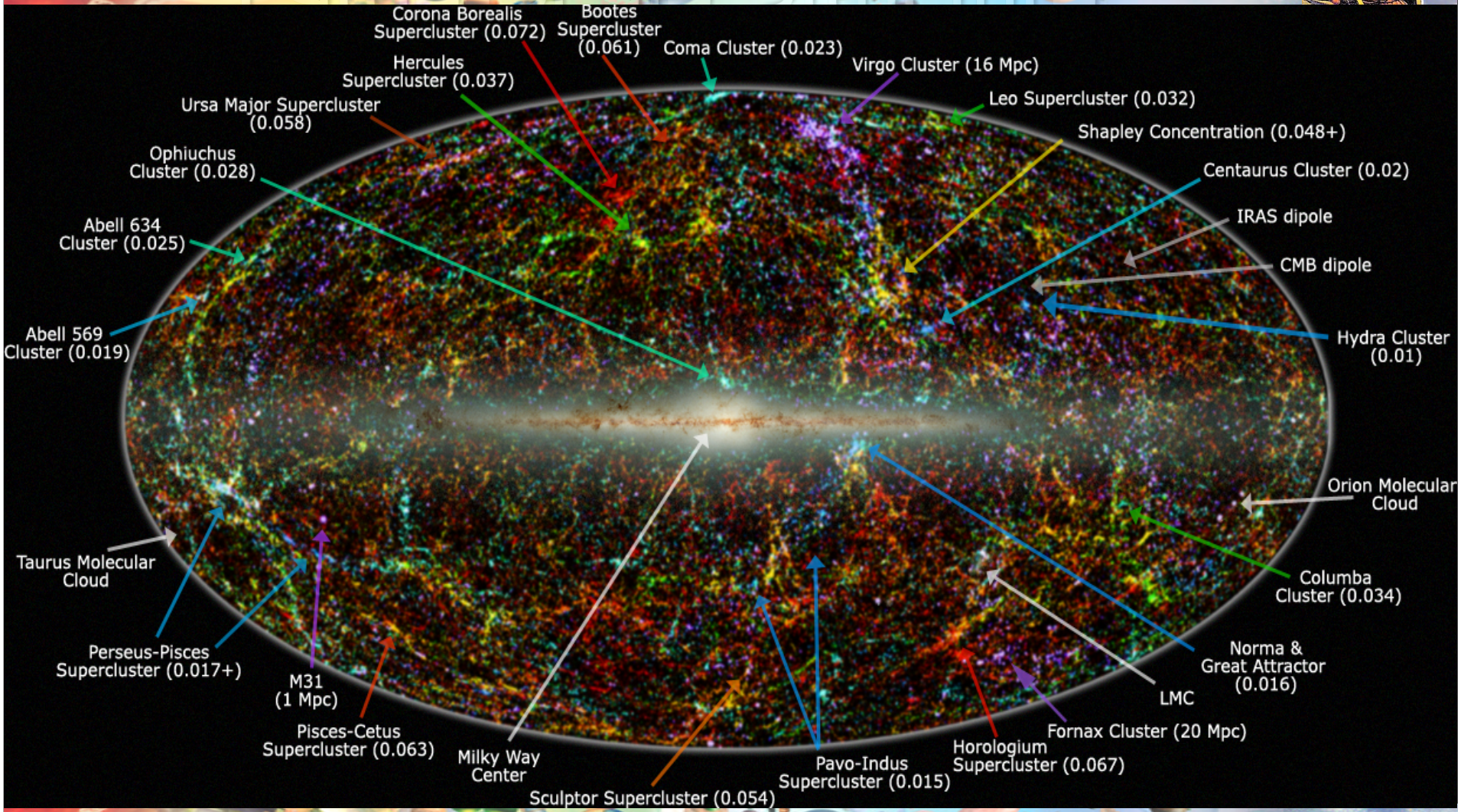


Dicke, Peebles, Roll, Wilkinson (1965)

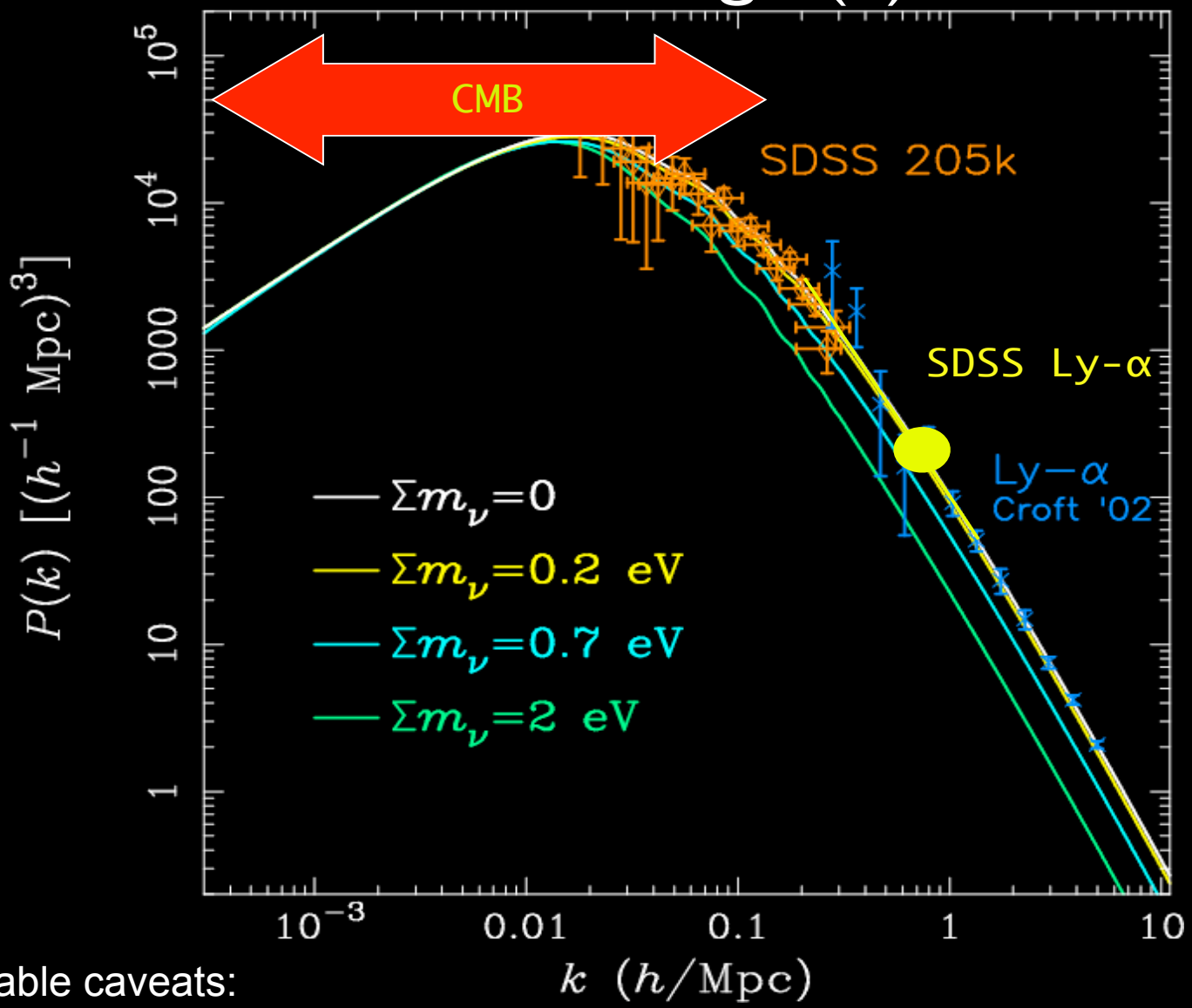
Cosmic Background Radiation



Large-Scale Structure



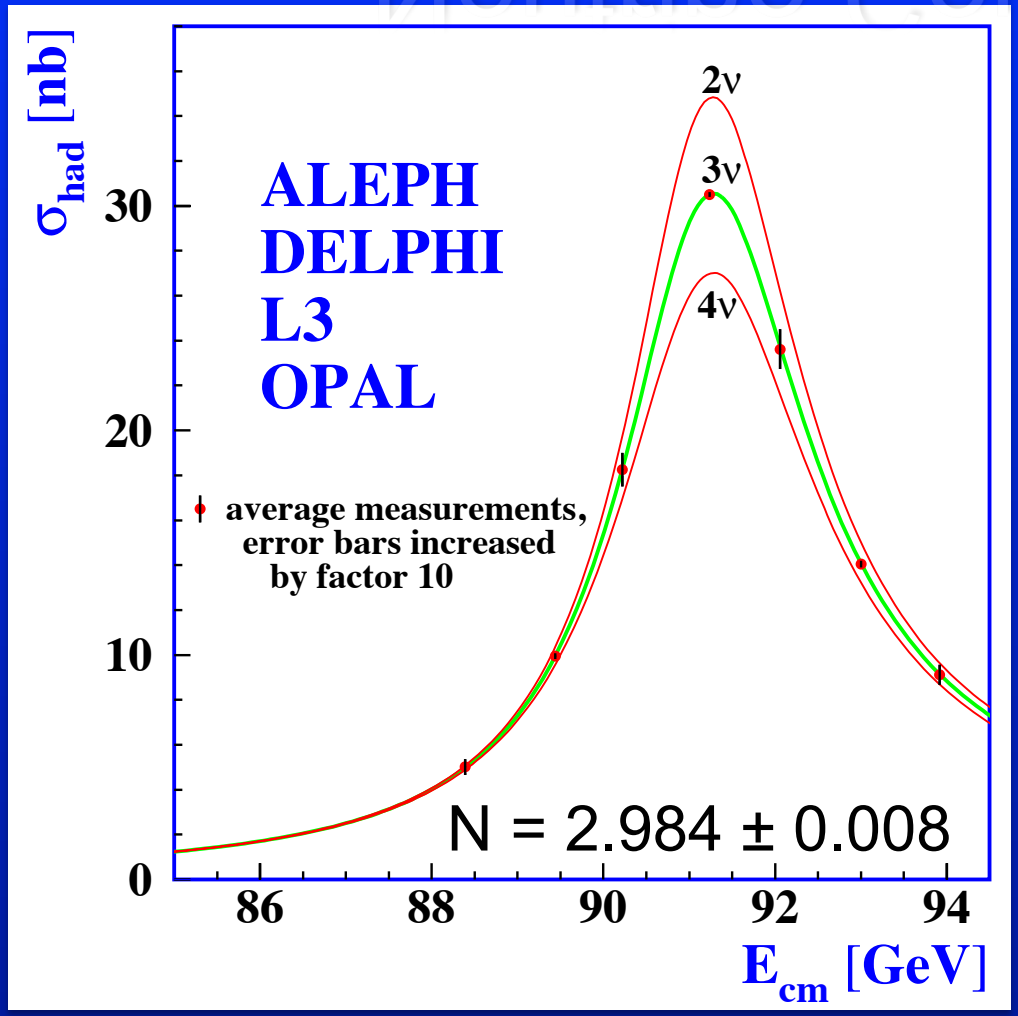
Measuring P(k)



Some notable caveats:

Bounds depend on cosmology assumptions, such as the dark energy contribution to the equation of state. One can also have a delay in the matter-radiation transition from dark radiation (the number of relativistic degree of freedoms above N=3.04).

Neutrino Counting



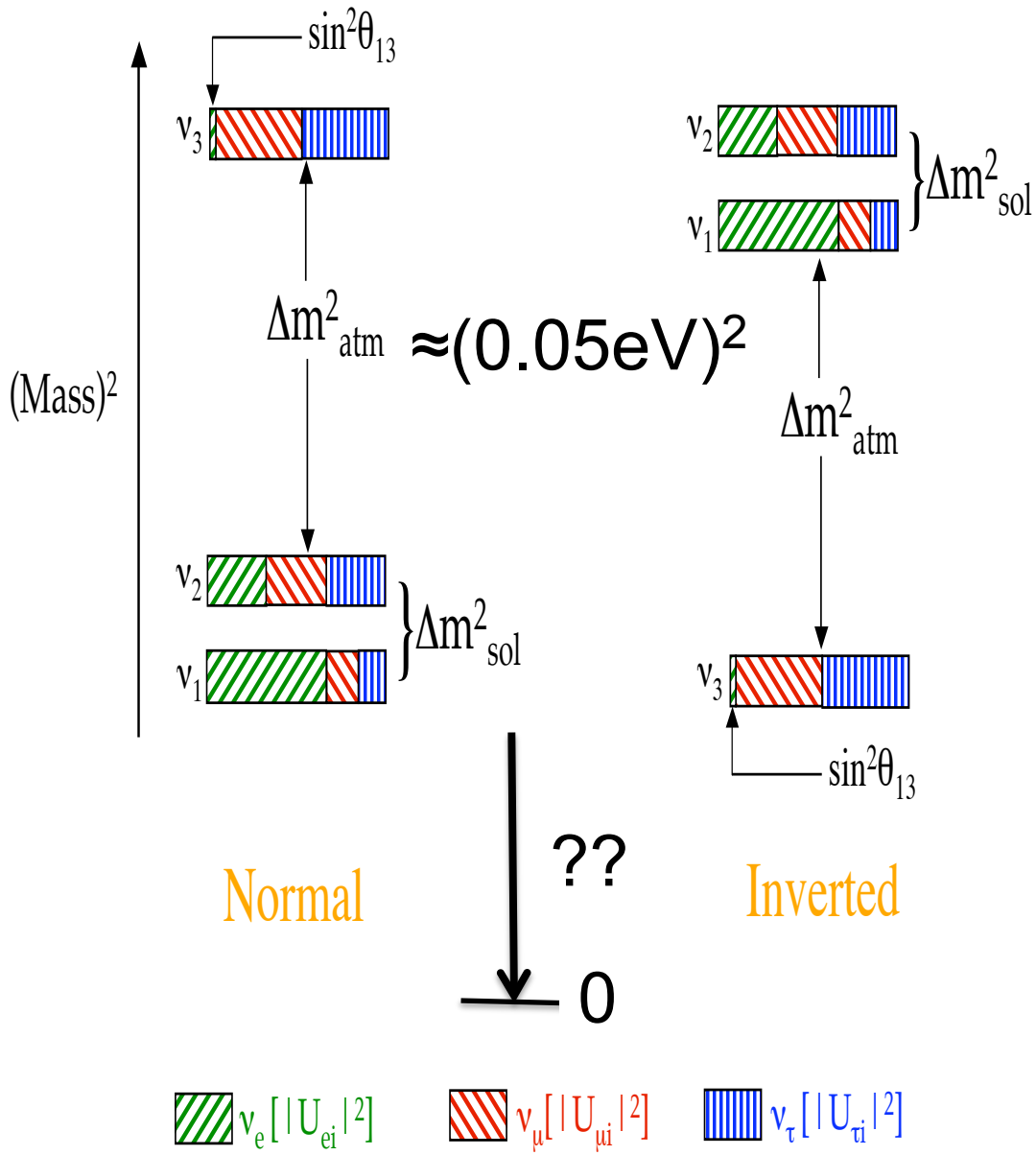
Produce ~1M Z bosons at an e^+e^- collider

Scan the line shape in center-of-mass energy

Count the number of hadronic Z decays

Compute the total width from visible decays and add an invisible width scaled by the SM couplings to neutrinos

Neutrino Masses from Oscillations



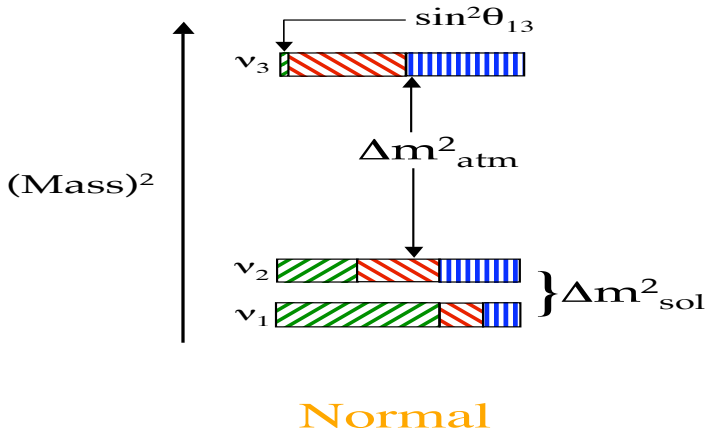
An incredible phenomenon appeared when neutrinos were measured from different sources: solar, atmospheric, reactor, accelerator.

A neutrino created with a definite lepton flavor (in this case, electron or muon) would arrive with a lower probability to be detected with the same flavor and a non-zero probability to have mixed into another flavor.

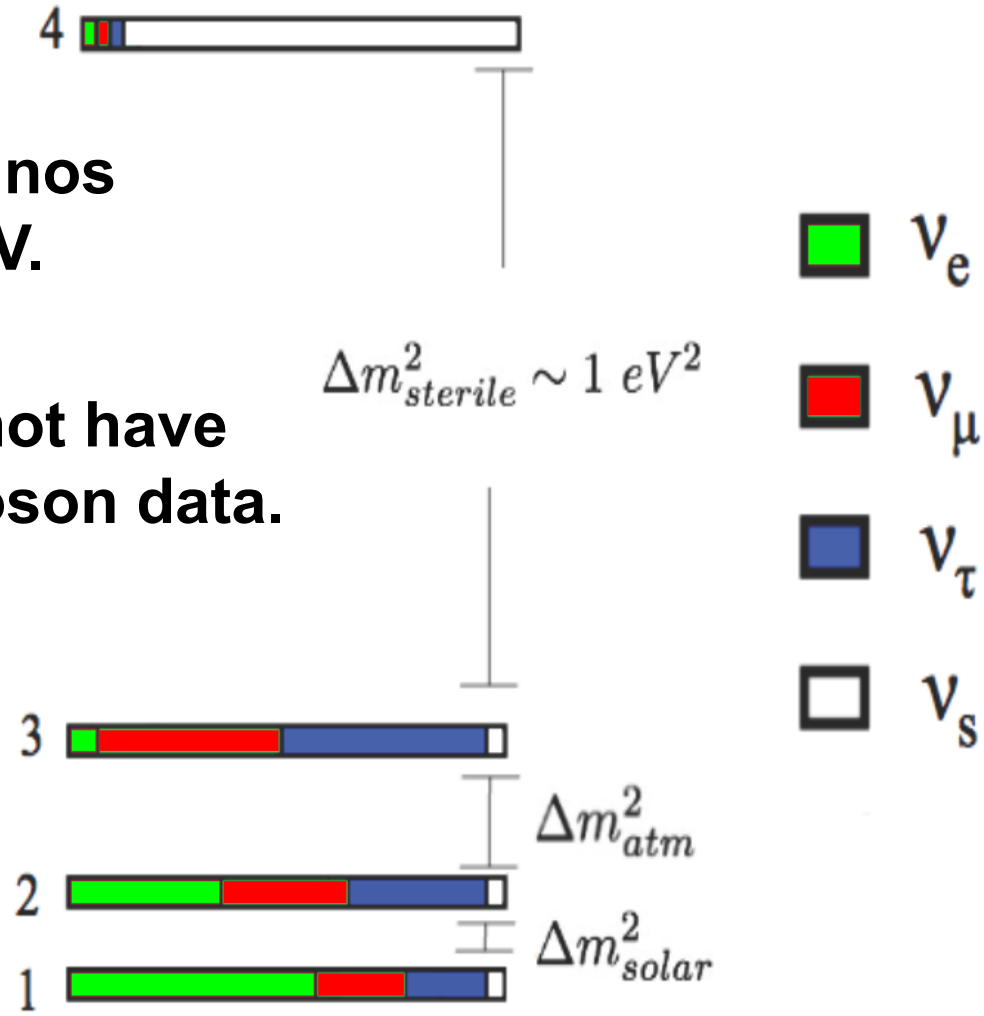
Sterile Neutrinos?

There may be heavier neutrinos in the mass range 1eV-10keV.

The sterile component cannot have weak interactions from Z boson data.

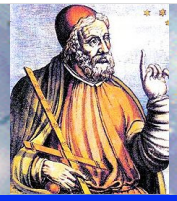


or



ν_e [| U_{ei} | ²] ν_μ[| $U_{\mu i}$ | ²] ν_τ [| $U_{\tau i}$ | ²]

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

What do we know?

Gap (2m) constrained to < ~0.6eV from Cosmology

(some electron flavor expected with 2m>0.1eV from neutrino oscillations)

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

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

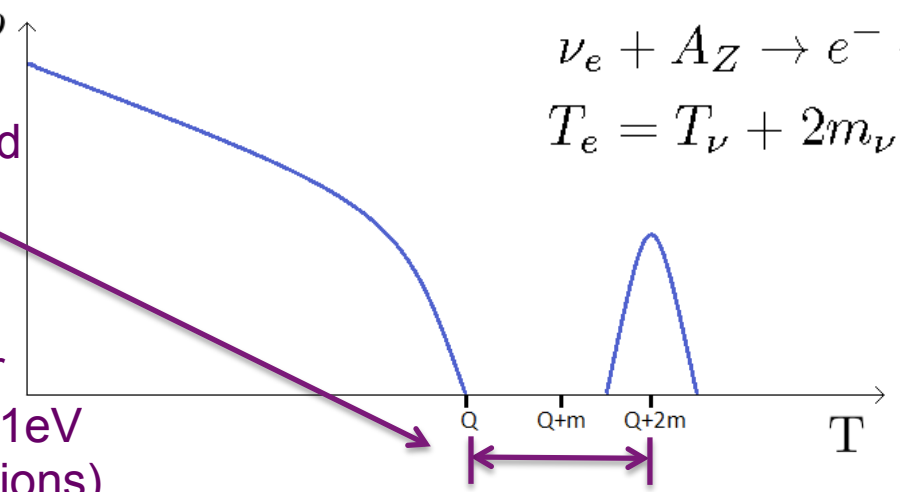
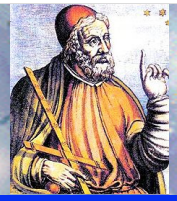


Figure 1: Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

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

Hydrogen (Isotope) Bonding



Tritium experiments typically use diatomic tritium T^2 where the bond strength is approximately 4eV.

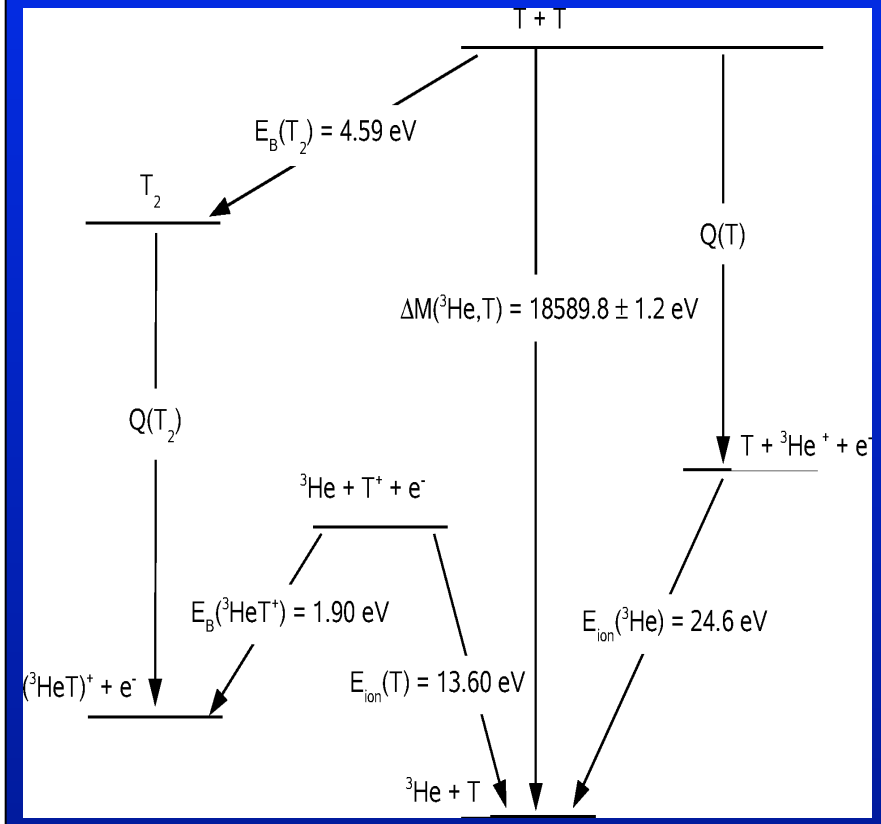
But what happens when one T atom decays?

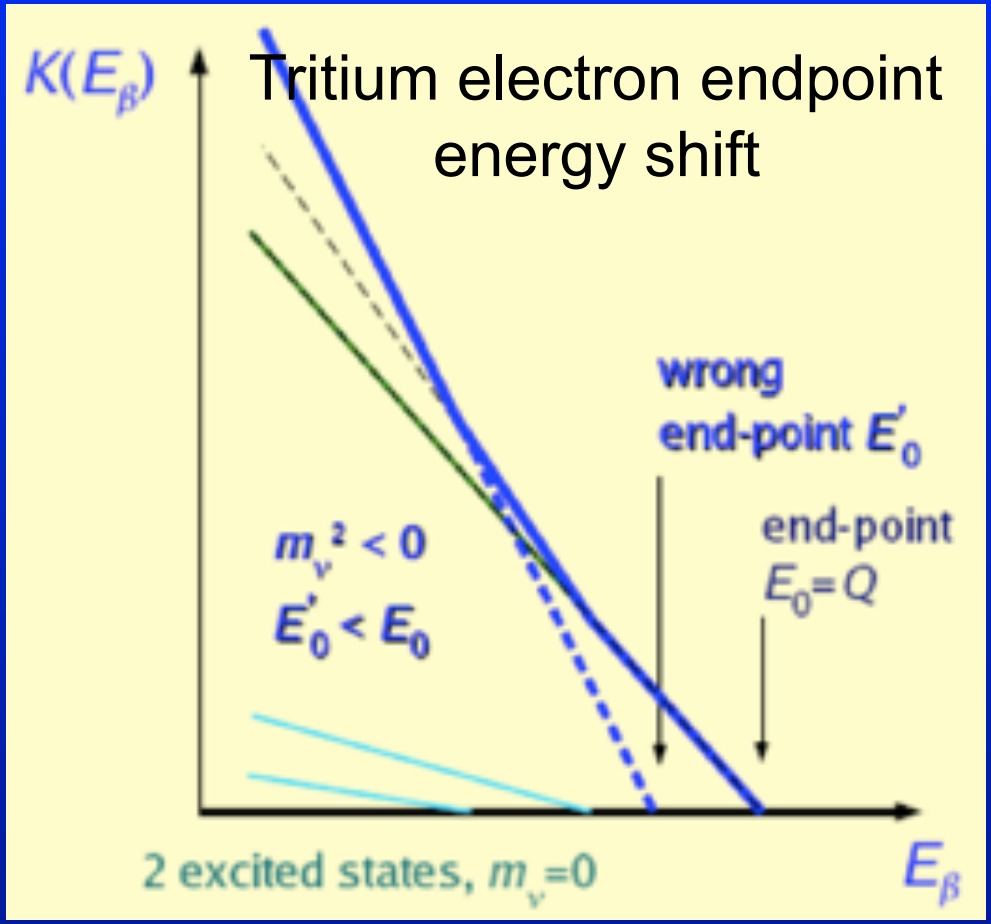
Answer: The maximum He^3 recoil energy is ~3eV. He^3 stays bound to the remaining T to form a T-He^3 molecule – and can fall into a number of closely spaced rotational and vibrational excited states

Quantum Mechanics tells us that the outgoing electron energy depends on the change in the binding energy of T^2 to $(THe^3)^*$

He^3 Binding Energy Shift

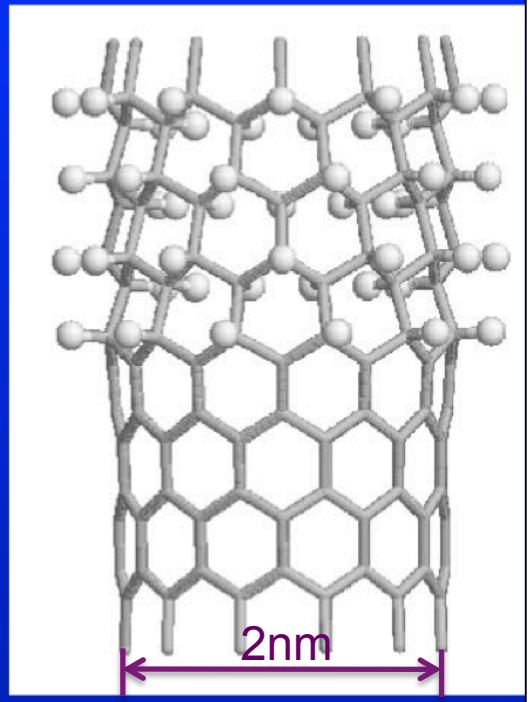
T-T → T-He^3 Level Diagram





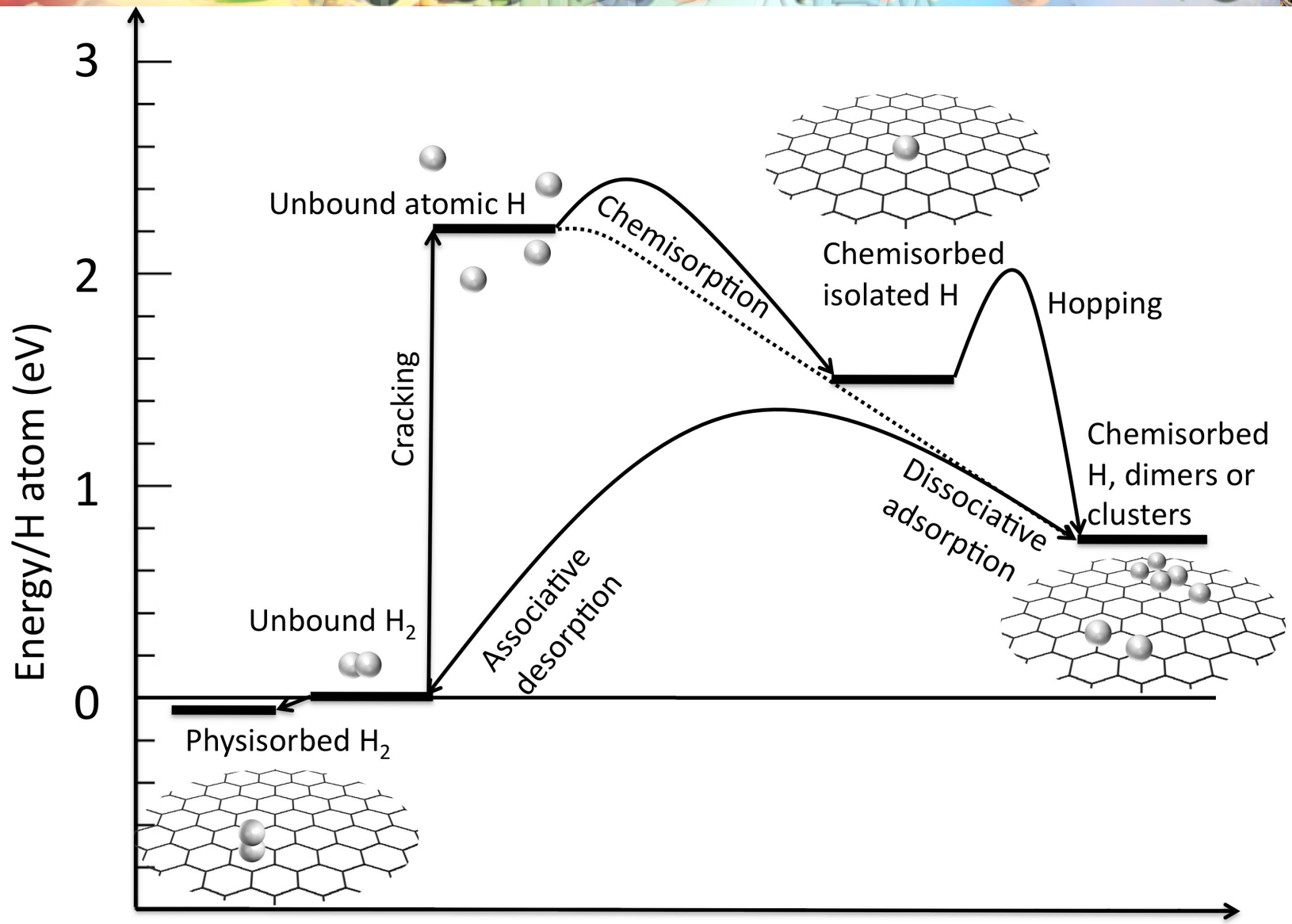
Tritium on Graphene

- In the hunt for alternative energies, there has been a great focus on the development of Hydrogen fuel cells
  - Here the advantage is to store hydrogen in a solid form (with 6%wt) at room temperature, but with a weak enough binding that the hydrogen can be released by heating or some other means



A Single-Walled Carbon Nanotube (SWNT) has the potential of having a hydrogen binding energy less than 3eV, and possibly as low as 1eV or less.

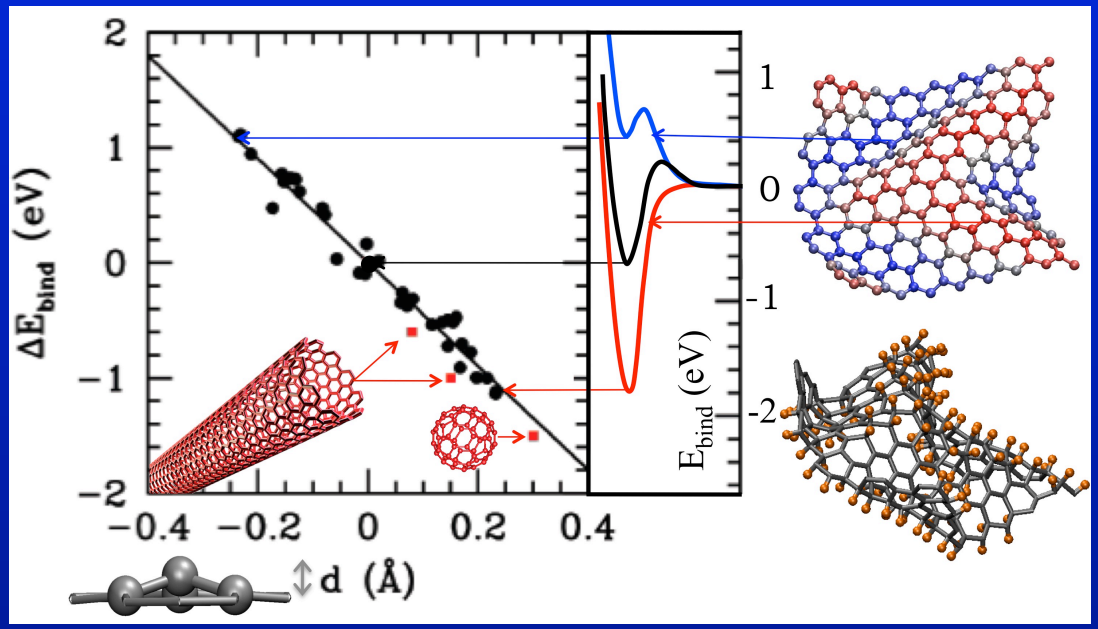
Chemist's View



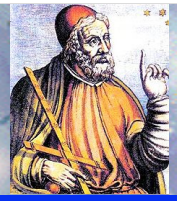
When in Doubt, Measure!

- 1st proposal of the PTOLEMY project is to use the setup to measure hydrogen bond strength differences using tritium beta decay energy measurements

New technique:
May help accelerate Hydrogen fuel cell research

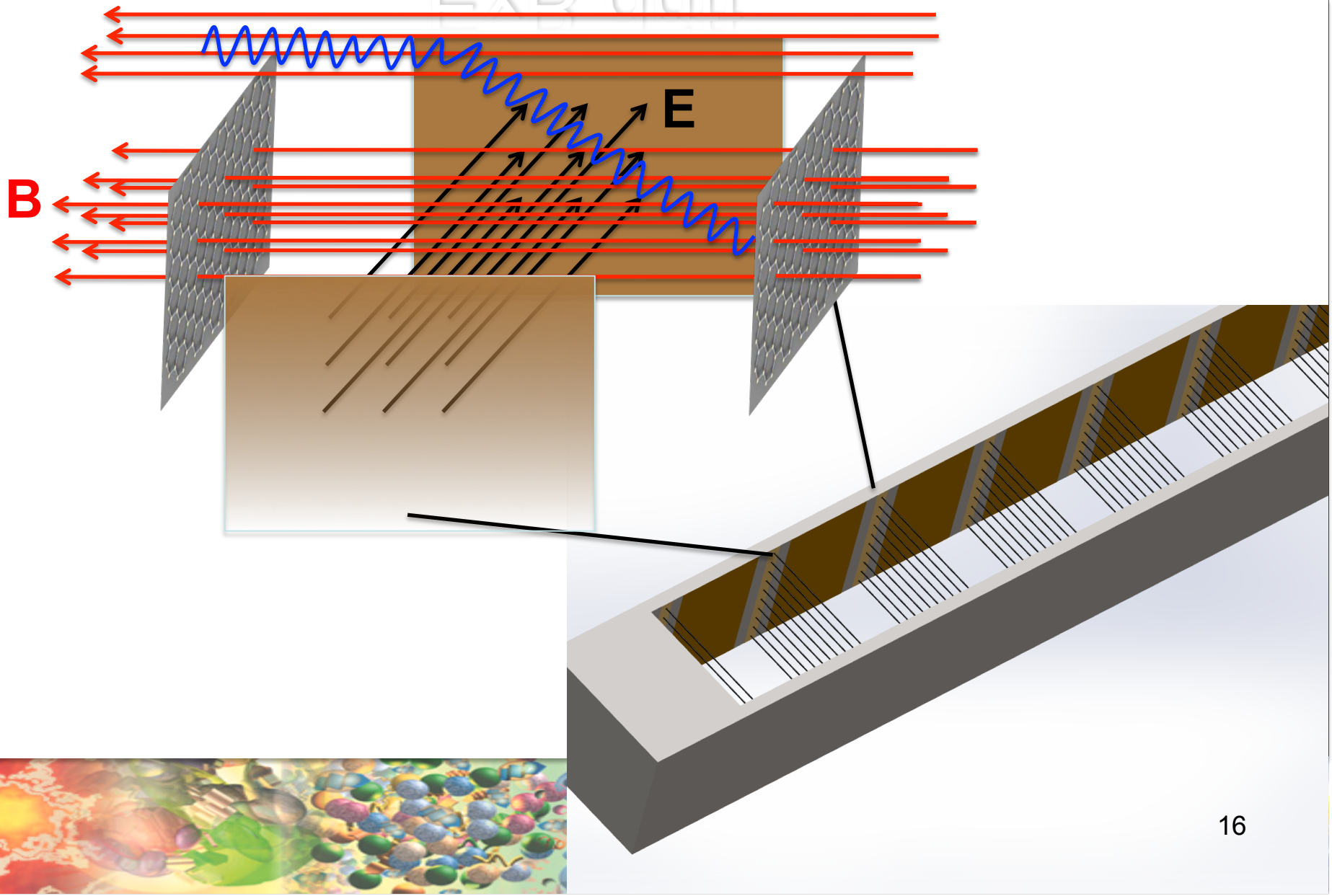


THE Challenge

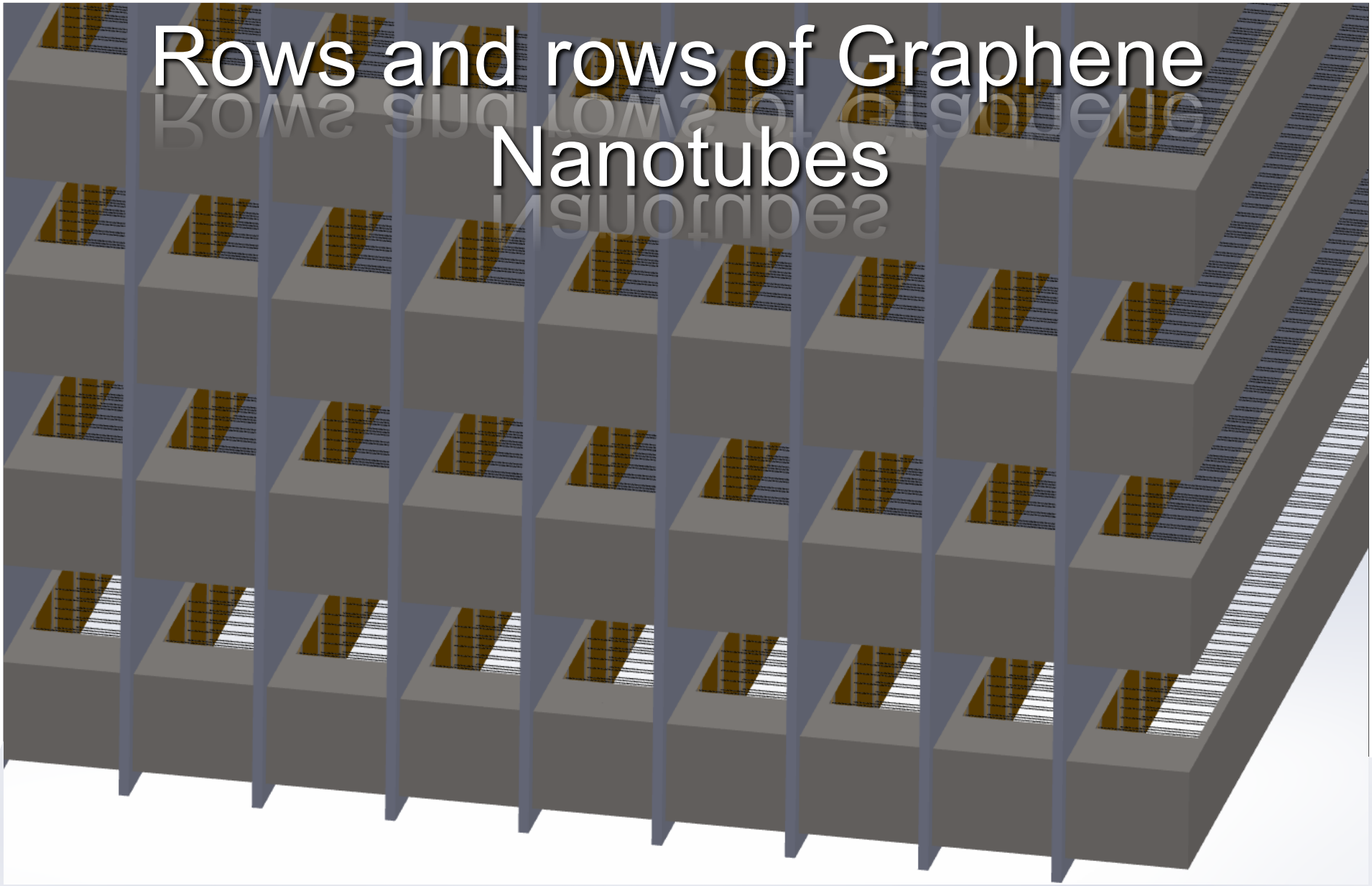


- The largest and nearly insurmountable problem of relic neutrino detection is to provide a large enough surface area to hold 100 grams of weakly bound atomic tritium
  - The trajectory of the outgoing electrons from tritium decay have to have a clear vacuum path to the calorimeter (up to one or two atomic layers of carbon)
  - Need approximately 10^6 m^2 of expose surface area, that's ~200 football fields
  - Cannot be achieve with a flat planar surface – needs nanotechnology to solve

ExB drift



Rows and rows of Graphene Nanotubes

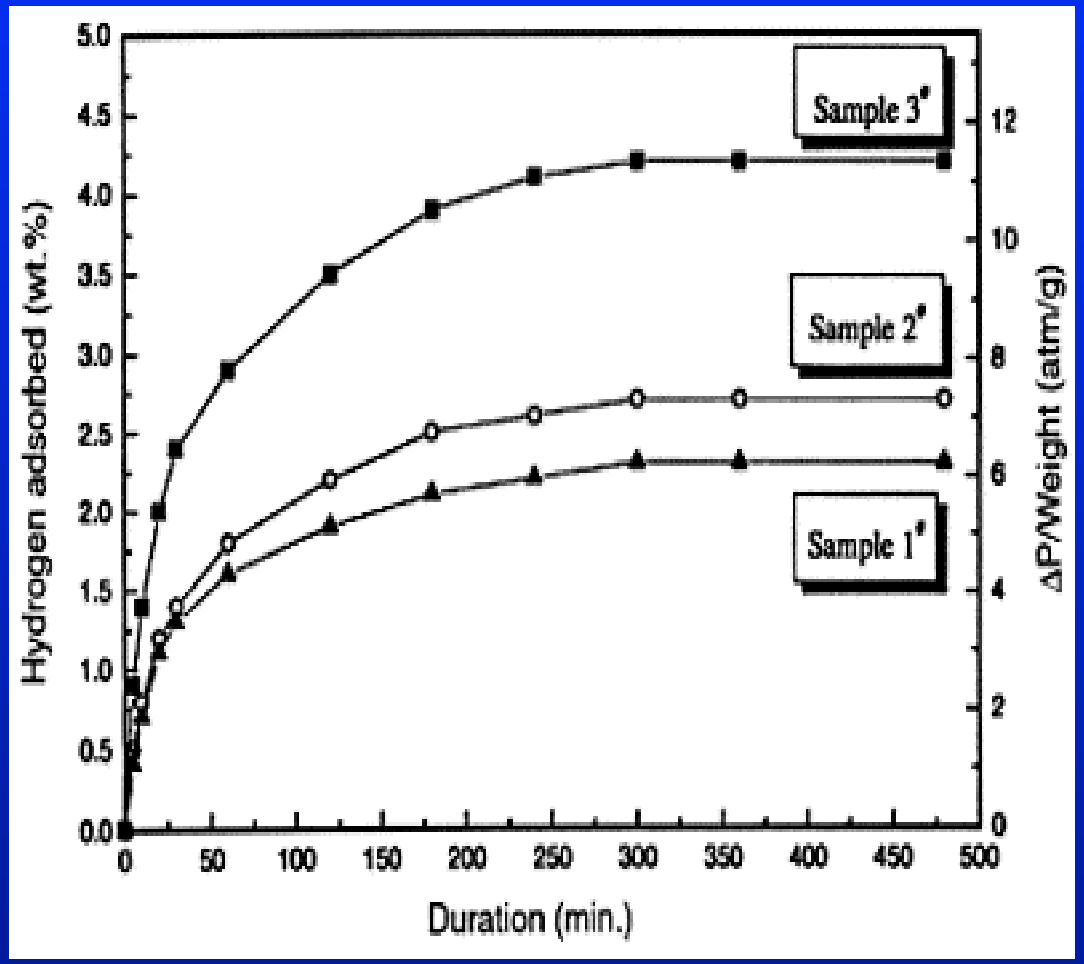


Cell Charging

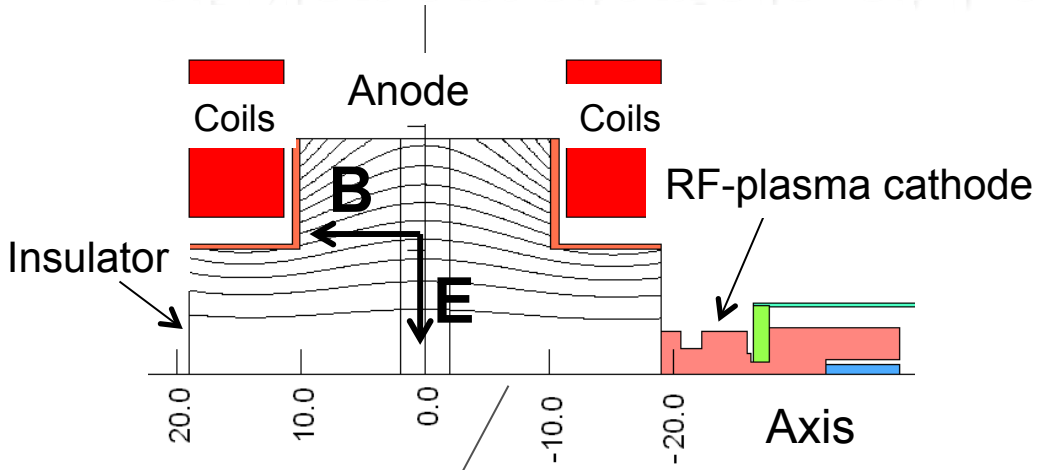
The charging time for Single-Walled Carbon Nanotubes (SWNT) is approximately 4 hours at 10MPa.

Monitoring:
Graphene transitions from a conductor to an insulator as tritium is absorbed.

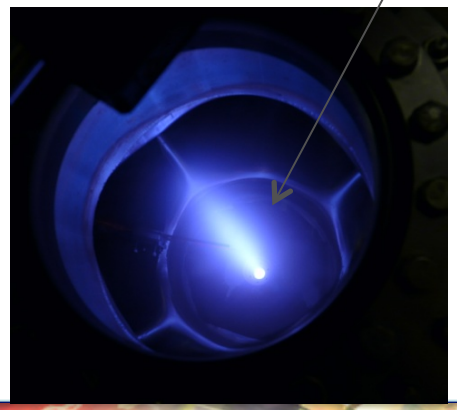
He^3 ions can be extracted out rear of cell.



Cold Magnetized Plasma for Processing of Nanomaterials at Low Pressure



Source operation



Si wafer immersed in the plasma source

DC **E×B fields** applied in a 20 cm × 50 cm st. steel chamber with ceramic side walls.

Plasma cathode: 2 MHz, 50-200 W Ferromagnetic ICP

Diagnostics:
Langmuir probes, emissive probes, optical emission and laser diagnostics of plasma

Raitses et al., DOE PSC Meeting, 2013

We will use cold magnetized plasma, T_e < 1 eV, for the hydrogenation of graphene

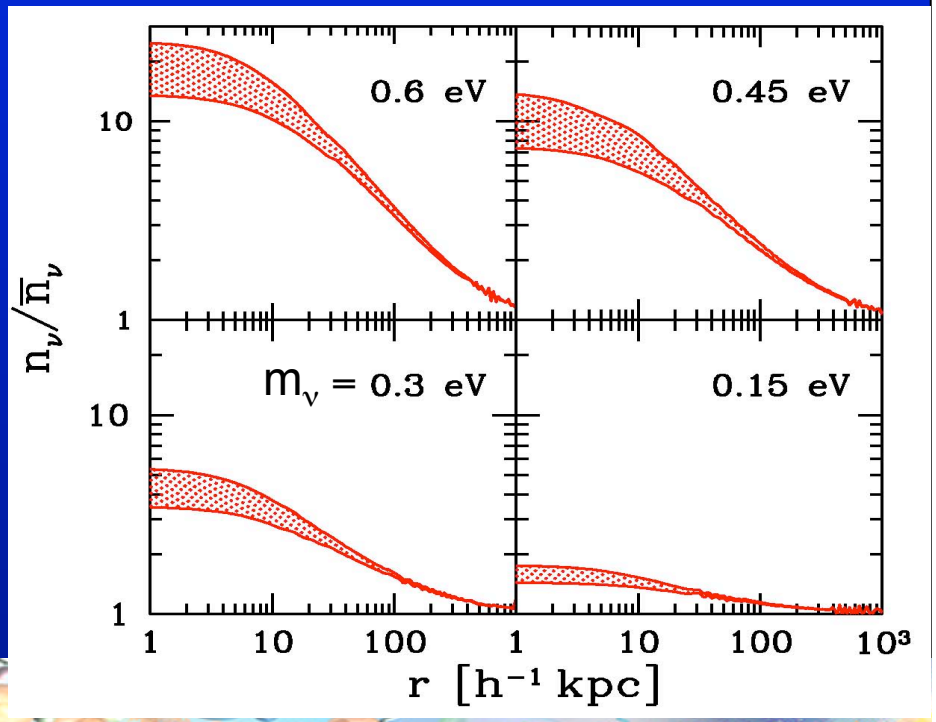
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Relic Neutrino Capture Rates

- Target mass: 100 grams of tritium (2×10^{25} nuclei)
- Capture cross section * (v/c) ~ 10^{-44} cm^{-2} (flat up to 10 keV)
- Rate ~ (56 electron neutrinos/cm^3)(2×10^{25} nuclei)(10^{-44} cm^{-2}) (3×10^{10} cm/s)(3×10^7s) ~ **10 events/year**

Gravitational clumping could potentially increase the local number of relic neutrinos.

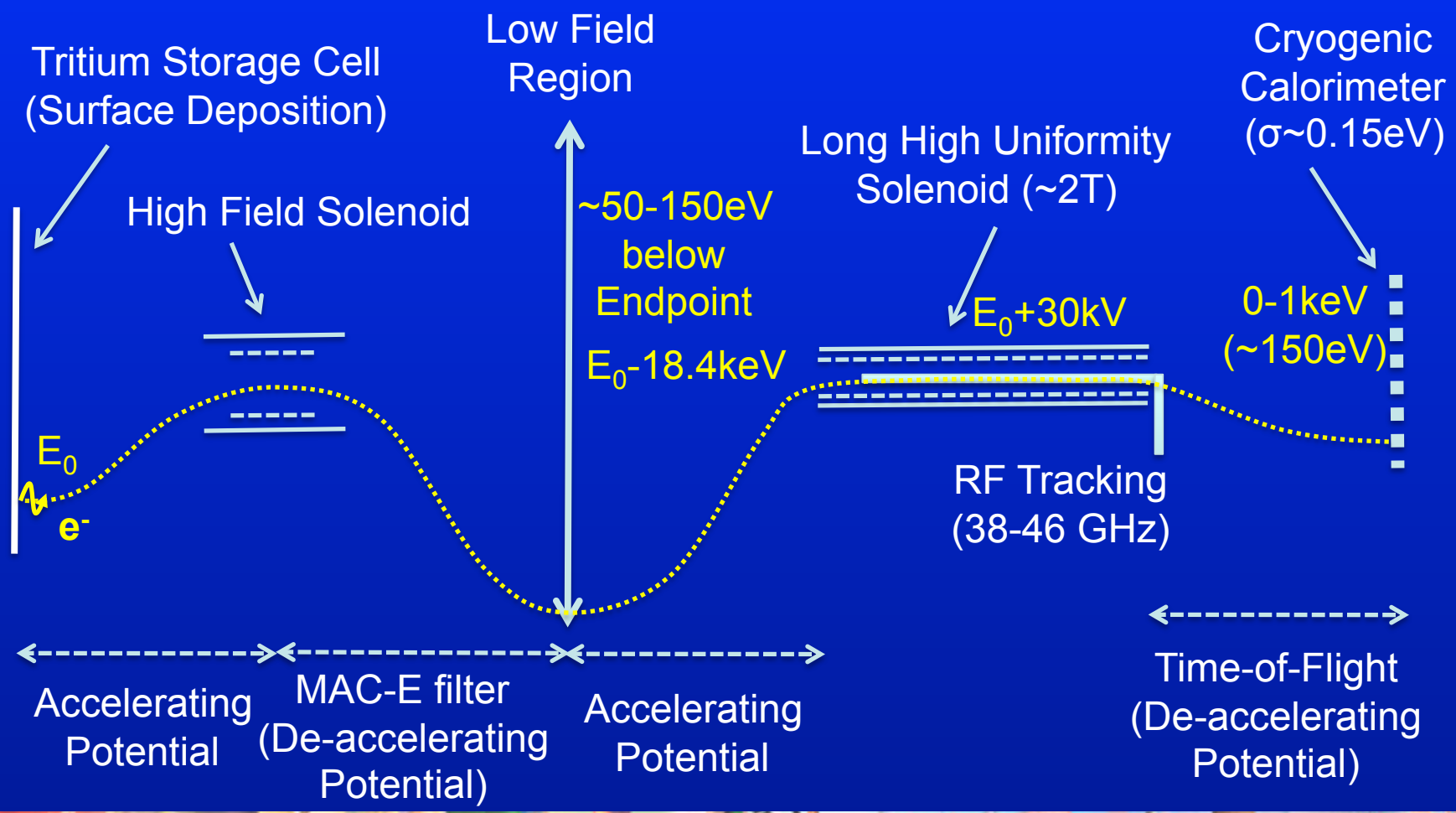
For low masses ~0.15eV, the local enhancement is ~x1.5



Ringwald and Wong (2004)

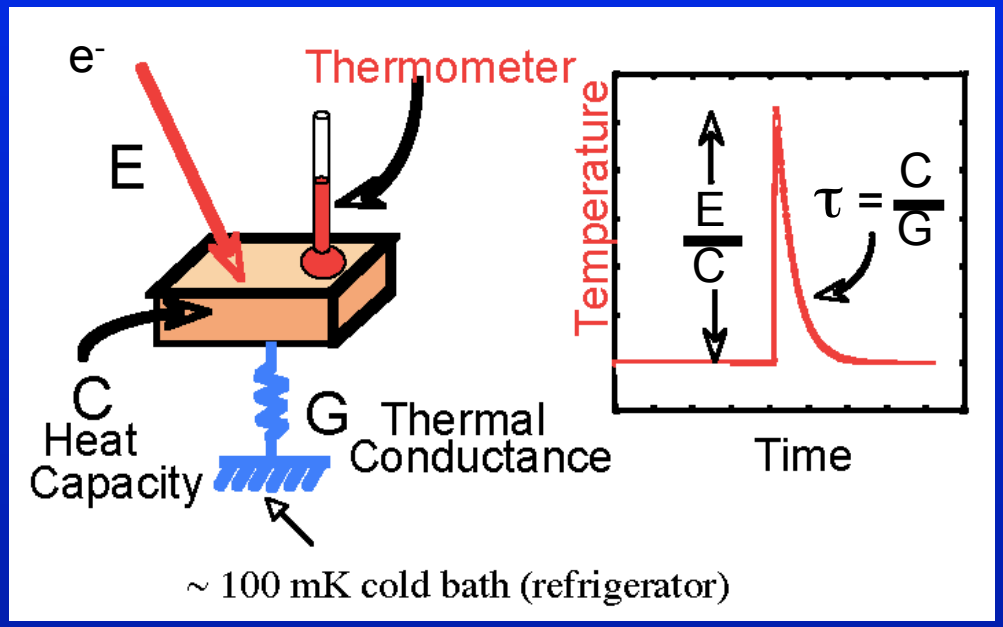
PTOLEMY Experimental Layout

Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield



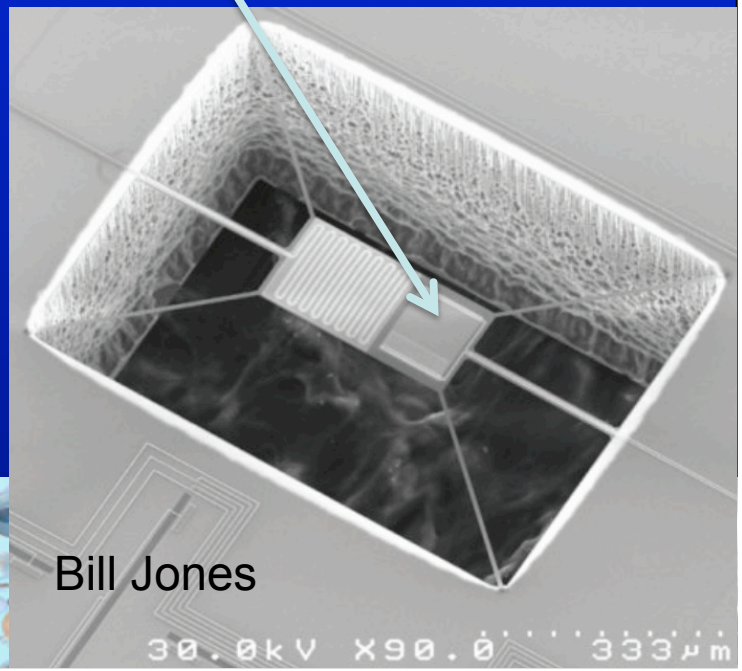
Transition-Edge Sensors for Calorimetry

– ANL Group (Clarence Chang) estimates ~0.55eV at 1keV and ~0.15eV at 0.1keV operating at 70-100mK



100eV electron can be stopped with very small C

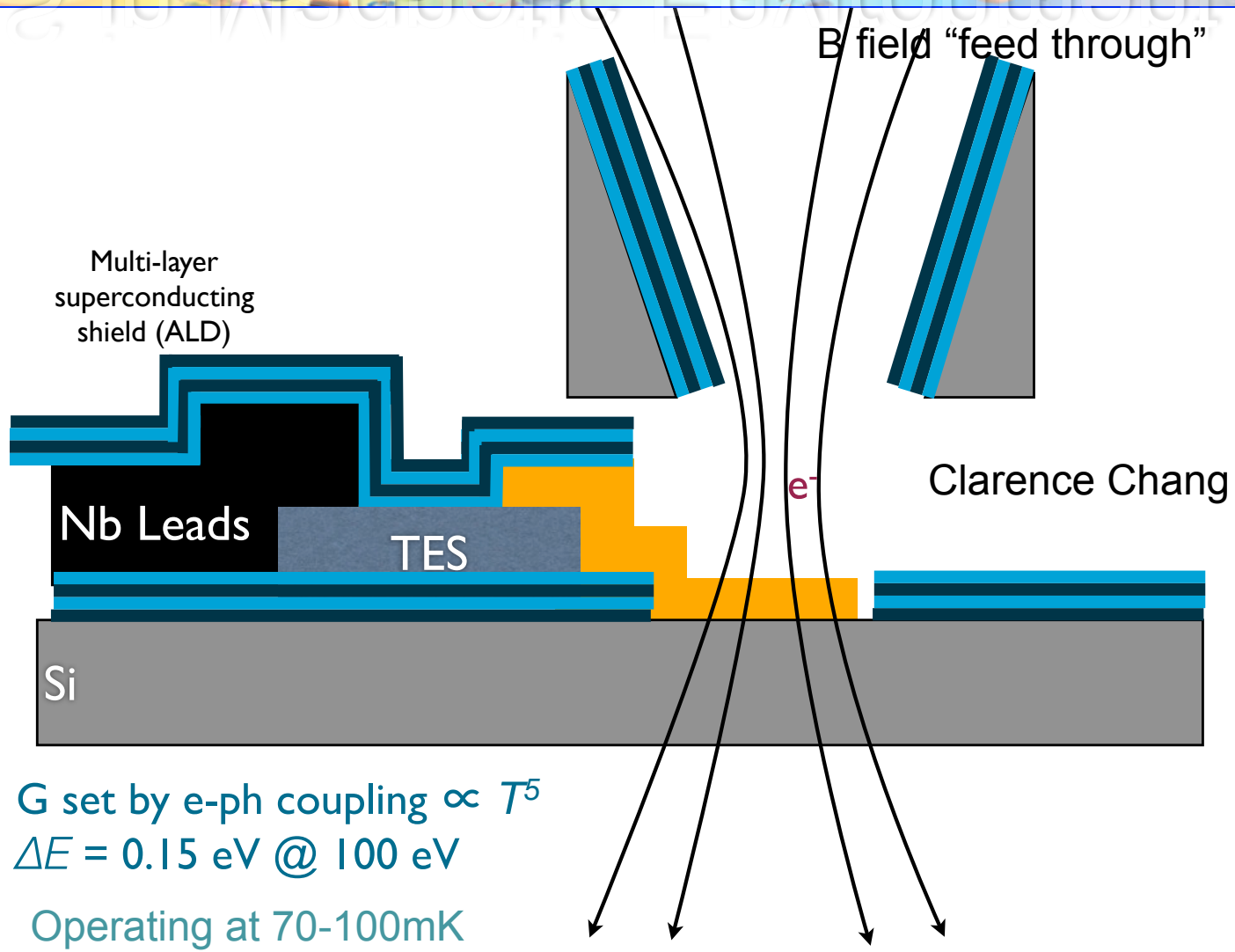
(example) SPIDER Island TES



Bill Jones

Bandwidths of ~1 MHz to record ~10kHz of electrons hitting the individual sensors

TES in Magnetic Environment



G set by e-ph coupling $\propto T^5$

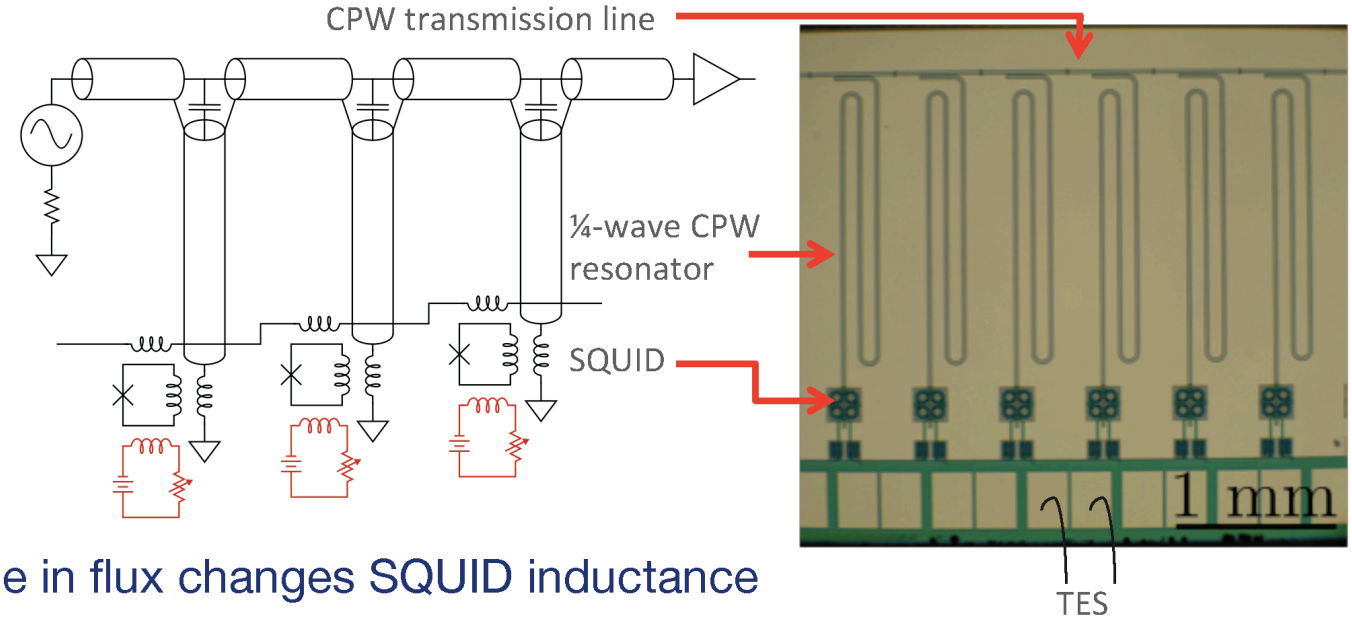
ΔE = 0.15 eV @ 100 eV

Operating at 70-100mK

Highly Multiplexed SQUID Readout

Microwave-readout Massive SQUID Multiplexer

Clarence Chang

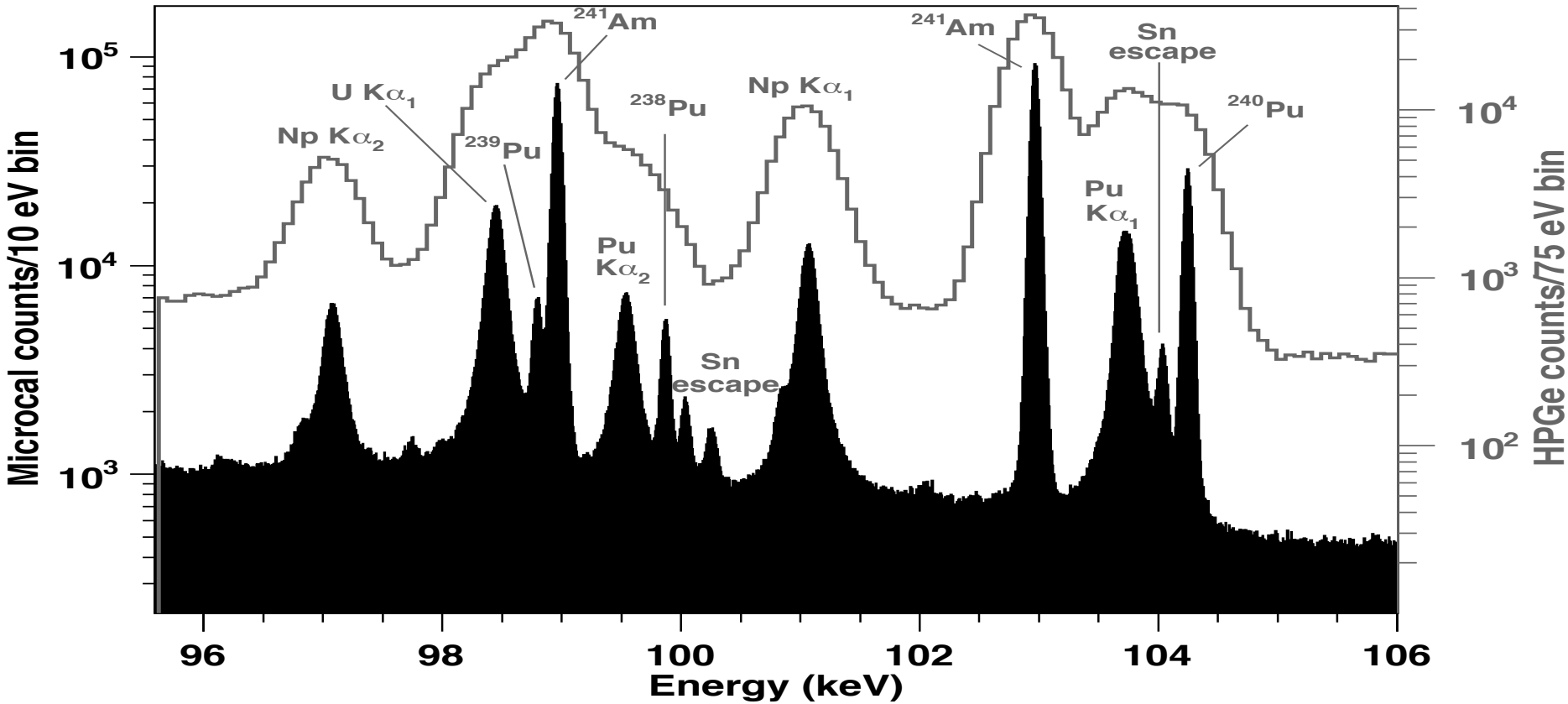


- Change in flux changes SQUID inductance
- at 1-10 GHz, can support ~1 MHz of bandwidth with ~1000 channels per line
- Originally developed for CMB measurements, recently demonstrated successful operation with X-ray u-cals

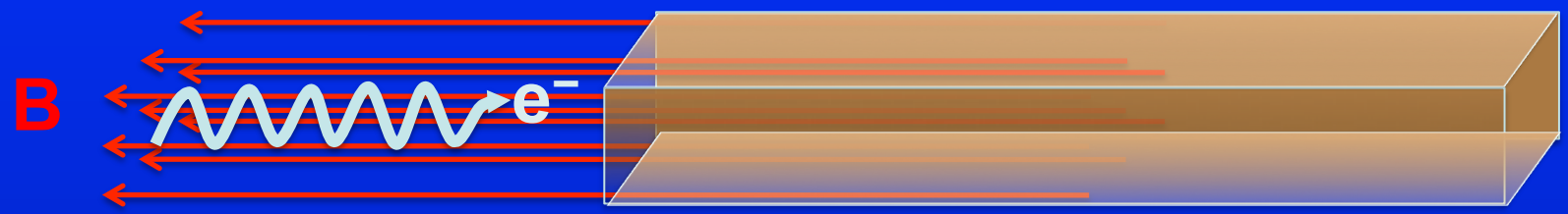
Kent Irwin

Microcalorimeter Resolution

- Cryogenic microcalorimeters promise to greatly improve many research areas with vastly higher precision and data collection speed



Semi-relativistic Electron Identification

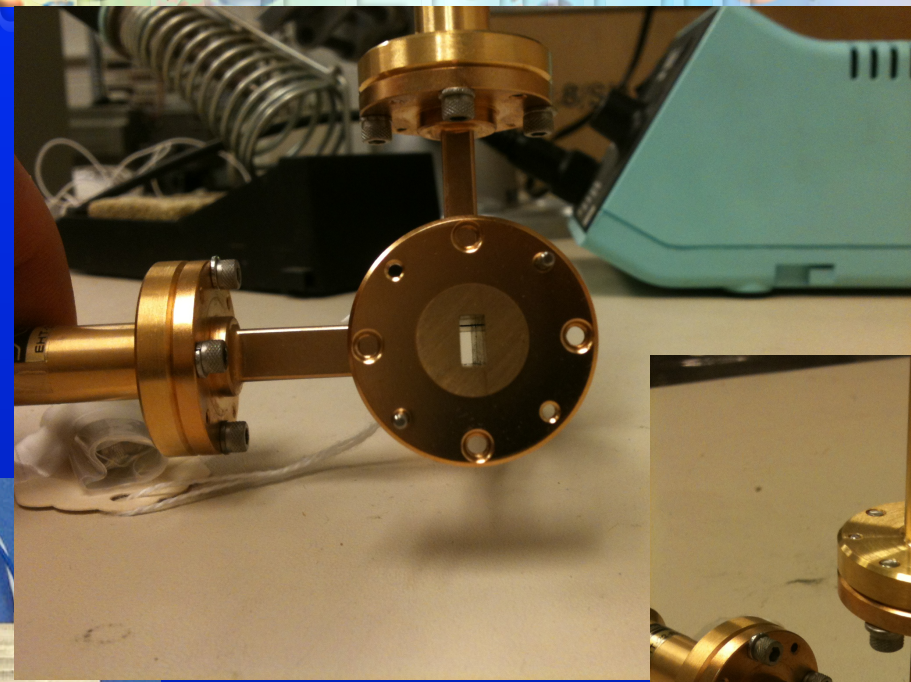


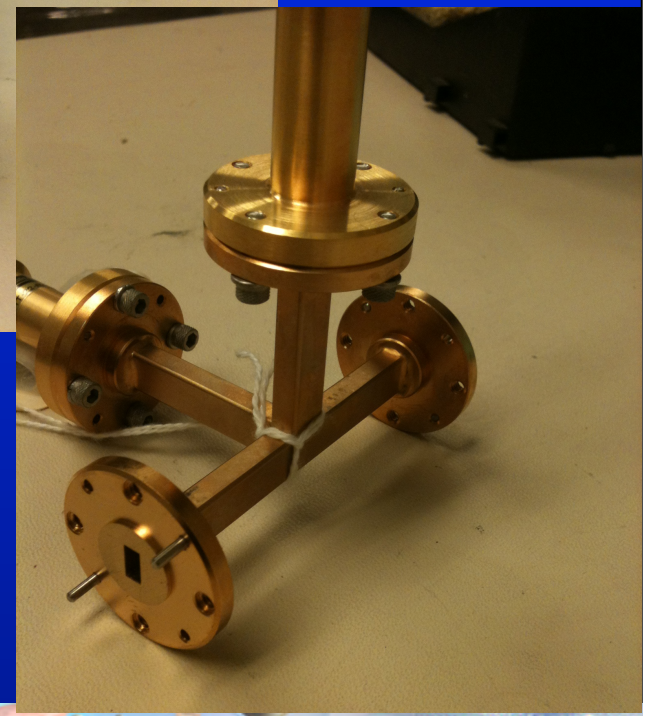
- RF tracking and time-of-flight
  - Thread electron trajectories (magnetic field guide lines) through a waveguide with ~wide bandwidth (few $\times 10^{-5}$) to identify cyclotron RF signal in transit times of order 0.2μsec
    - Currently using WMAP (Norm Jarosik) HEMT amplifiers with 1K/GHz noise and operating in the Q-Band 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 $\times 10^{-5}$)

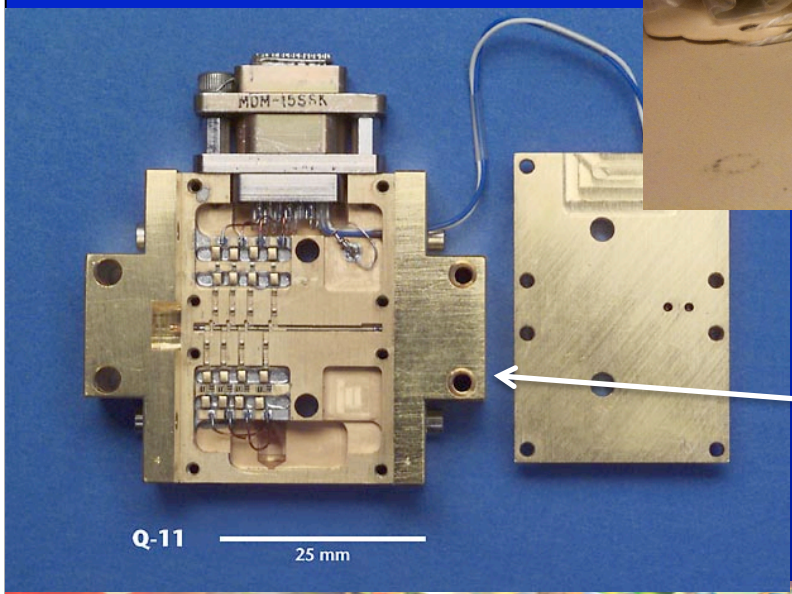
RF Tracker Element

Readout Orthogonal to Electron Trajectory

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



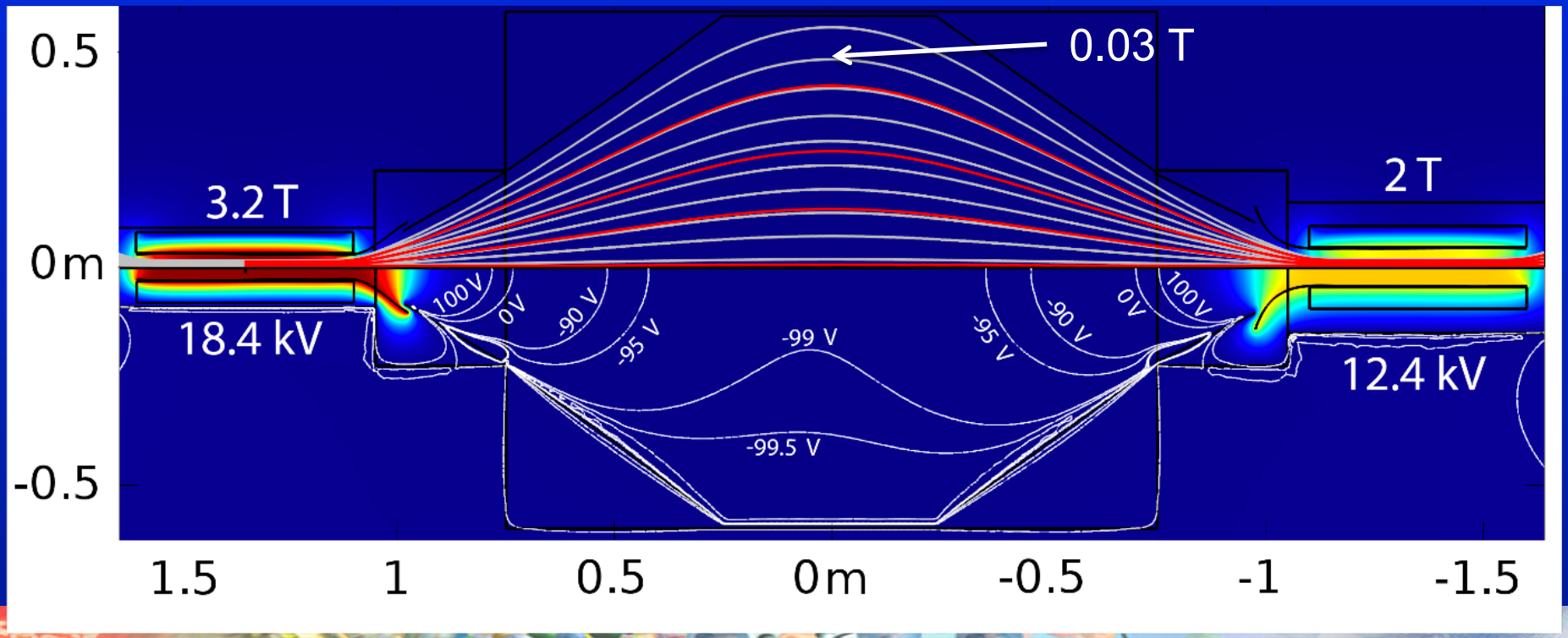


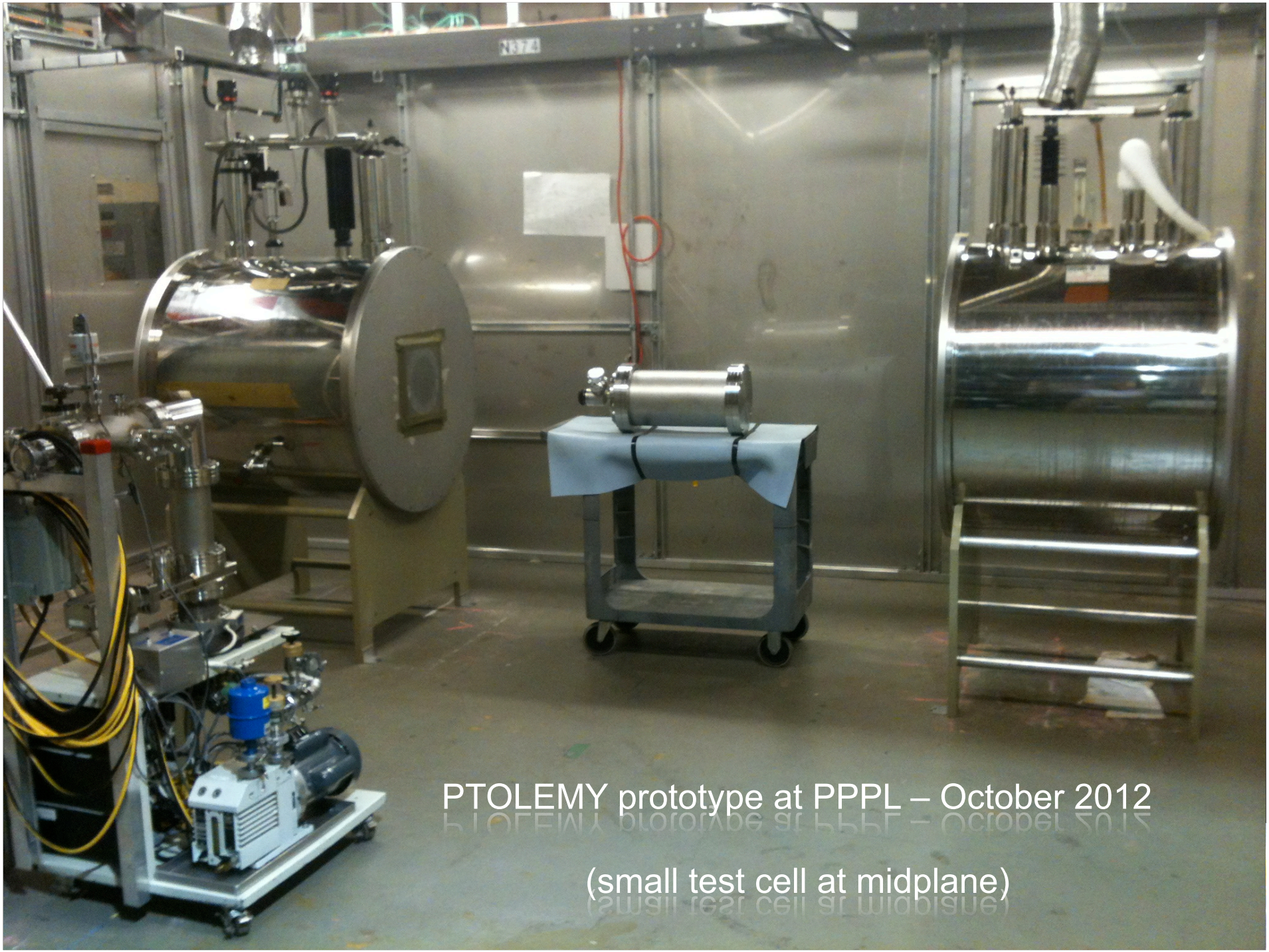


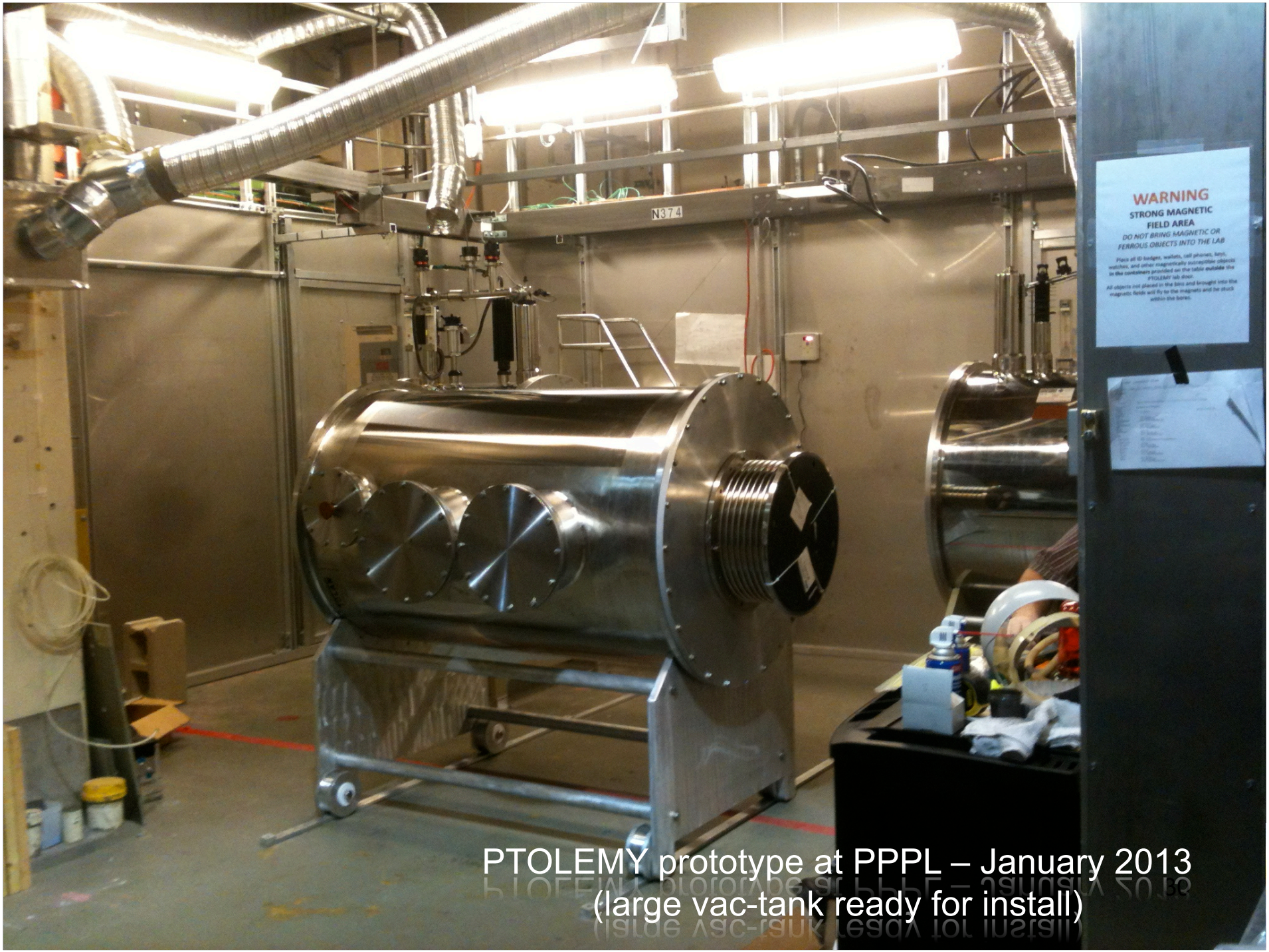
Q-Band (38-46 GHz)
WMAP Amplifier

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
  - Planar cell aperture of ~30cm^2 within 3.2T bore

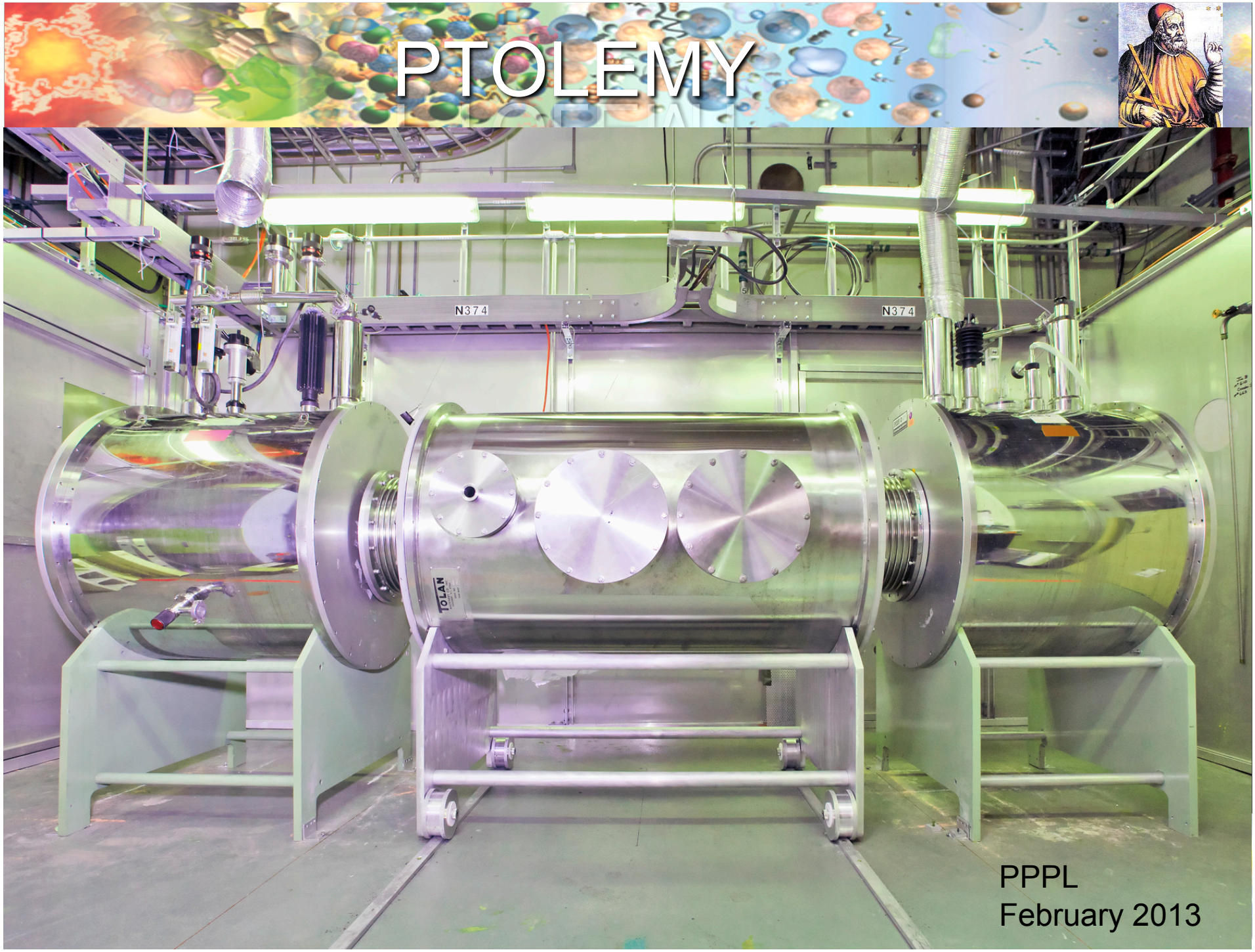



PTOLEMY prototype at PPPL – October 2012
(small test cell at midplane)



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

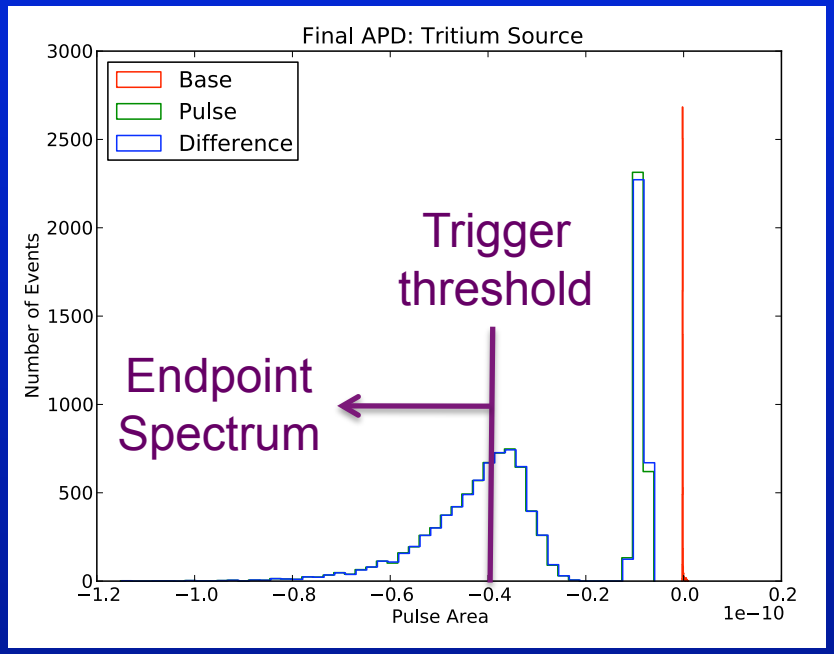
PTOLEMY

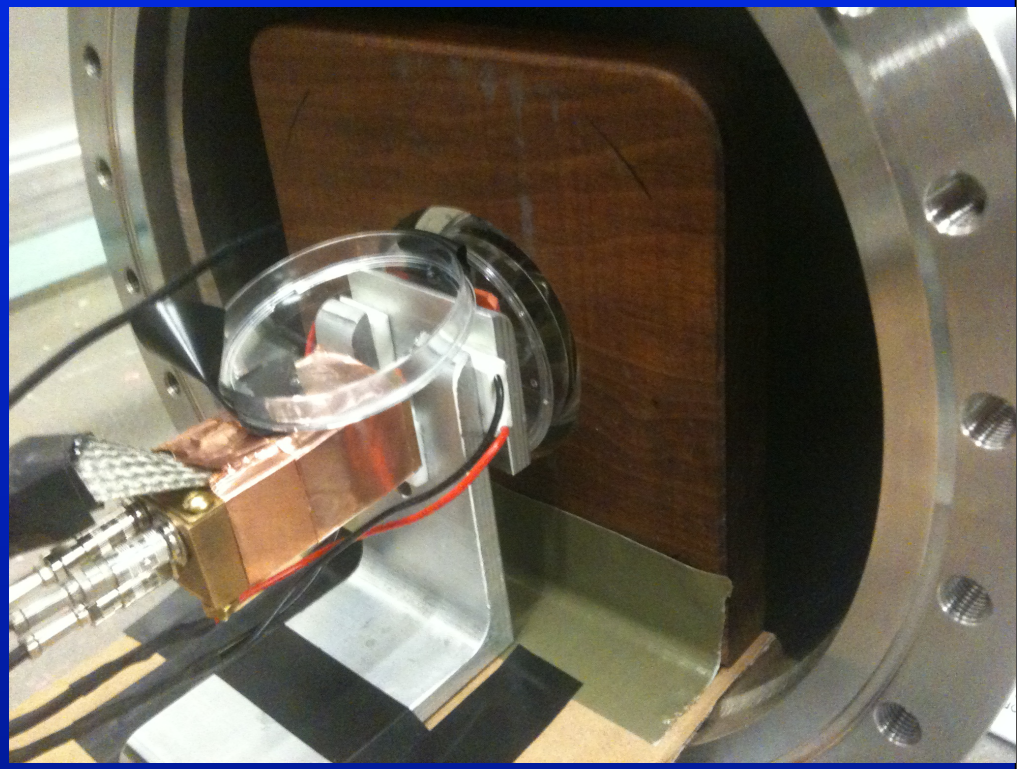


PPPL
February 2013

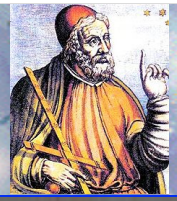
Tritium Tag Detector

- 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)



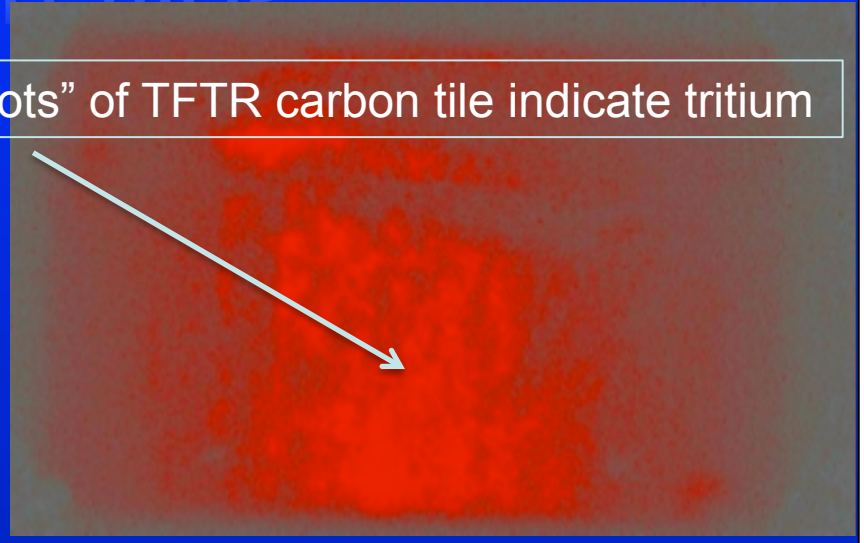


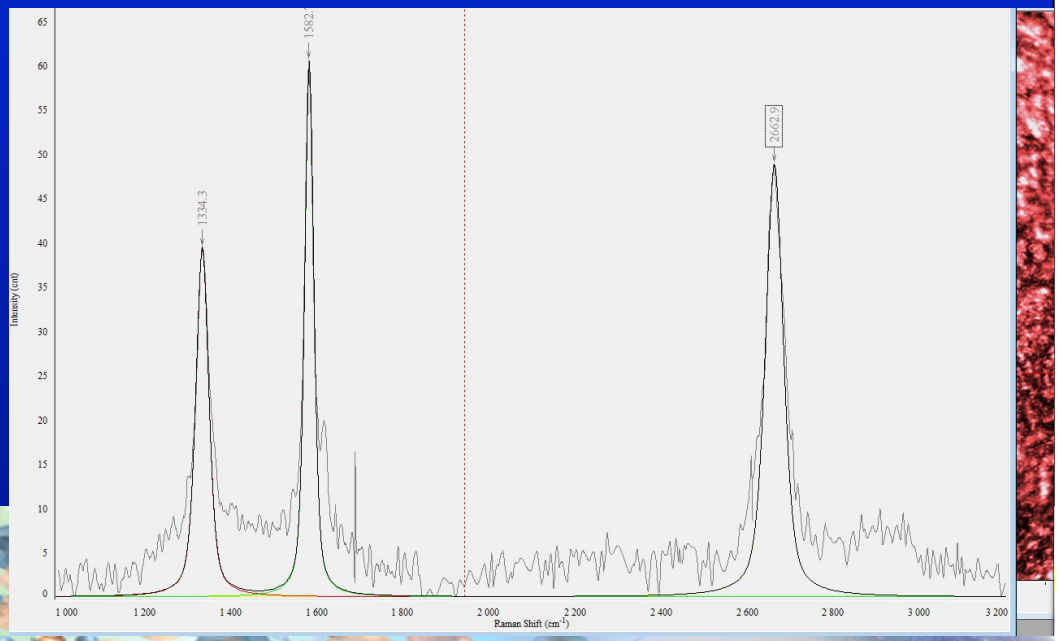
TFTR Carbon tiles



- PPPL already produced tritium-graphene samples in the 90's in TFTR
  - We are try to look at these are have started from Raman scattering analysis at PRISM
- We hope to get future sources from SRNL

"Hot spots" of TFTR carbon tile indicate tritium





What about Carbon-14?

- Take a biological sample from centuries ago exposed to atmospheric carbon

→ Now

With a half-life of ~5700 years
levels of C^{14} of 10^{-12} in $2x10^{25}$ nuclei
will produce 100 Hz of decays

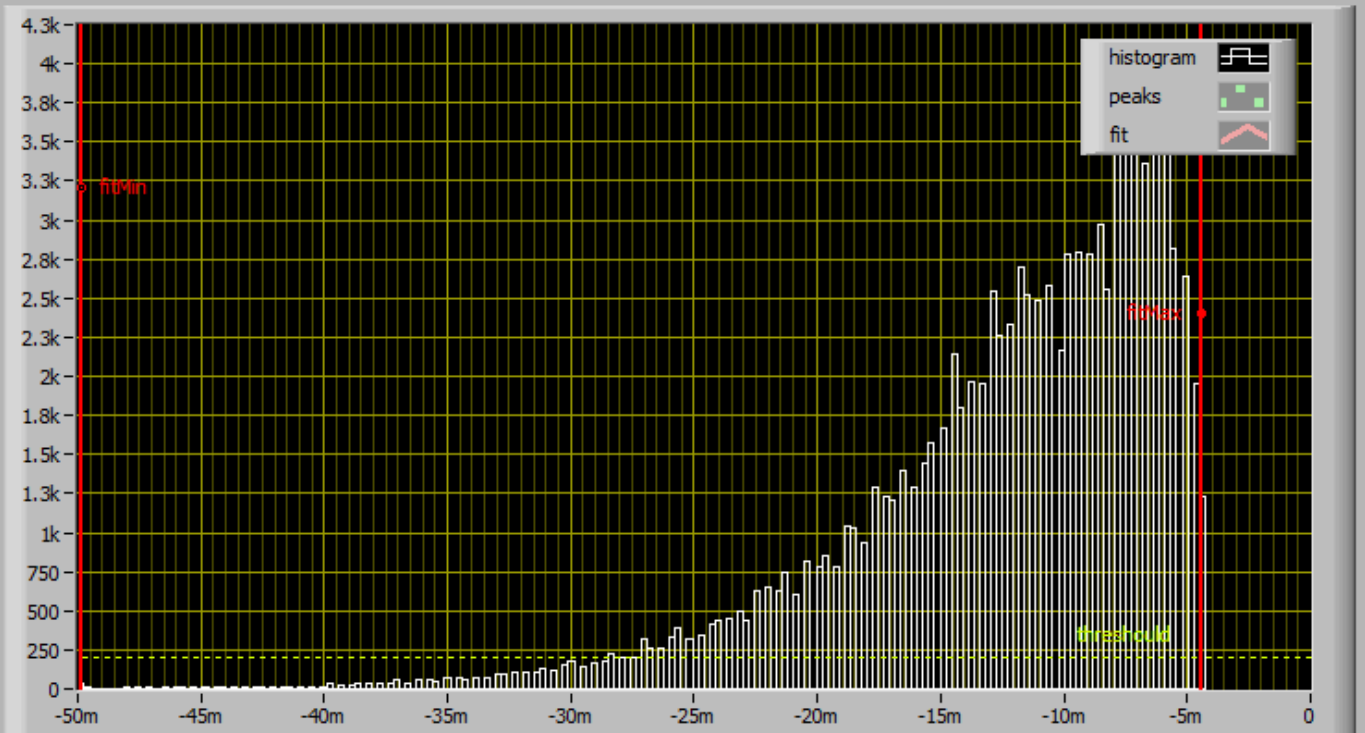
In a window of 0.5 eV (Q=156keV), biological levels of C^{14} are four orders of magnitude too much radiation for a relic neutrino experiment with a graphene substrate. Fortunately, underground carbon sources have 10^{-18} levels of C^{14} (achieved in Borexino).

Carbon-14 Spectrum

Read & Filtering | Waveforms & Cursors | Histogram & Fitting

Print | CLOSE

Data source: File 1



Fill histo | Add | ? | Sa | Lo

amplitude (min) — Negate

200 bins — 228u

100000 entries

timeDiffAmpl: 0

Peaks threshold: 5 % — pwidth: 3

1st peak relaxed search

45 — to Excel

Fit Window: Full Scale

gaussian (LabView)

Least Square — Run Fit

Use stat weights

0 — ampl: 0 — center: 0E+0 — stdDev: 0E+0

Fit Points: 0

Stat Points: 0

Mean: 0E+0

Std. Dev: 0E+0

simu

Cursors:	X	Y
fitMin	-49.9m	3.2k
fitMax	-4.44m	2.4k
threshould	-4.44m	200

expFitCoef: ampl 0 — 1/tau 0 — offset 0

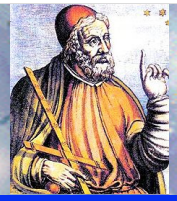
gaussInitials: 0 — ampl NaN — center NaN — stdDev NaN

numOfPeaks: 2

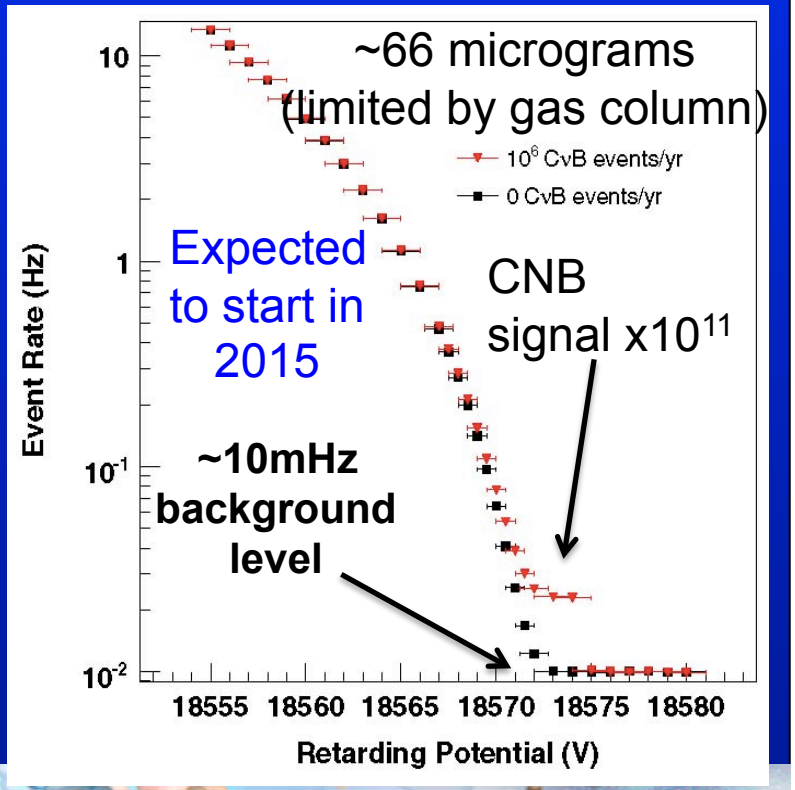
value

entries

Karlsruhe TRItium Neutrino (KATRIN)



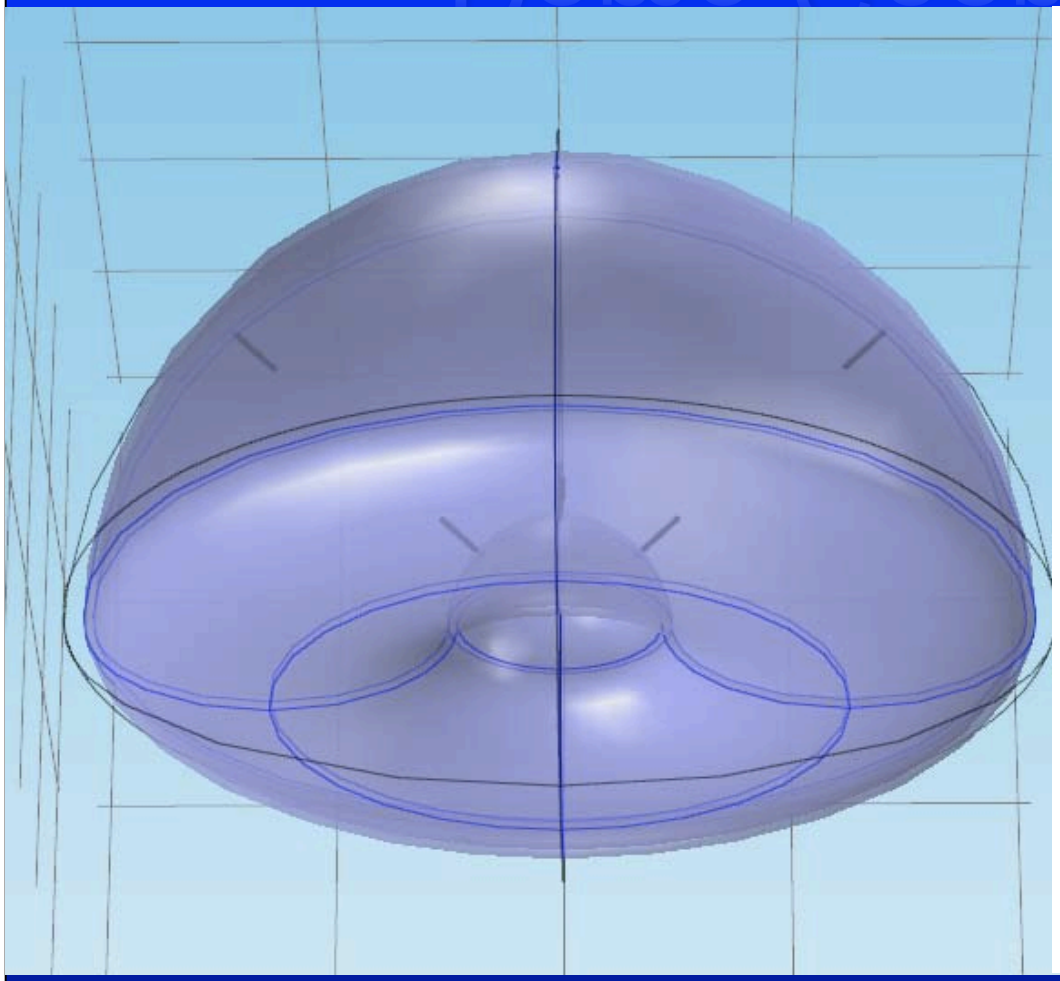
- Uses large uniform geometry to achieve ~0.2eV cut-off sensitivity – "Cut and Count" experiment
  - **PTOLEMY Goal: 10mHz →sub-μHz Background Rate**

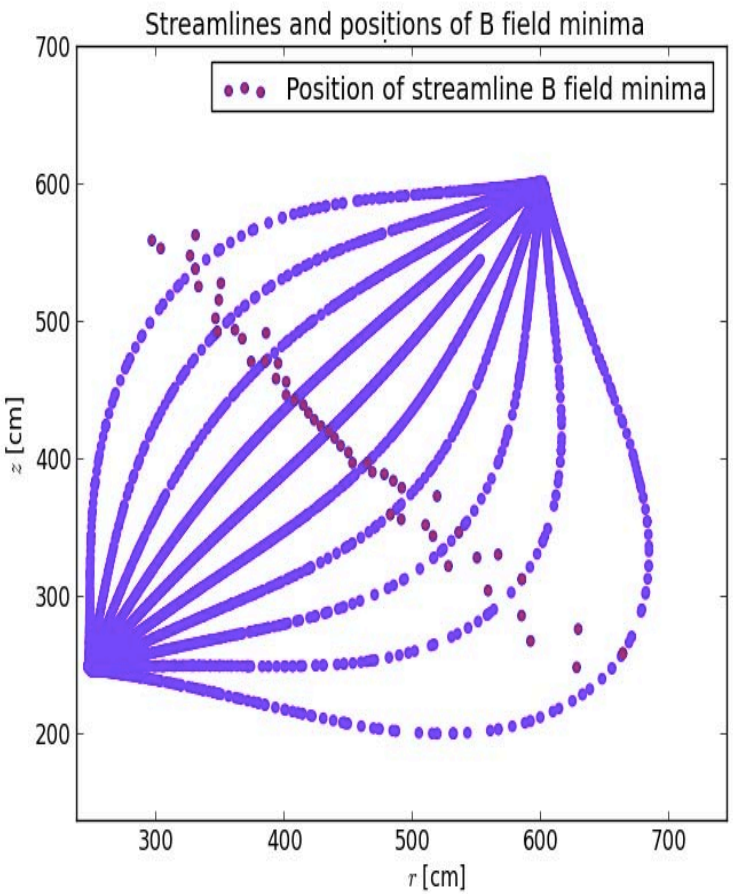


Outlook 2-3 years

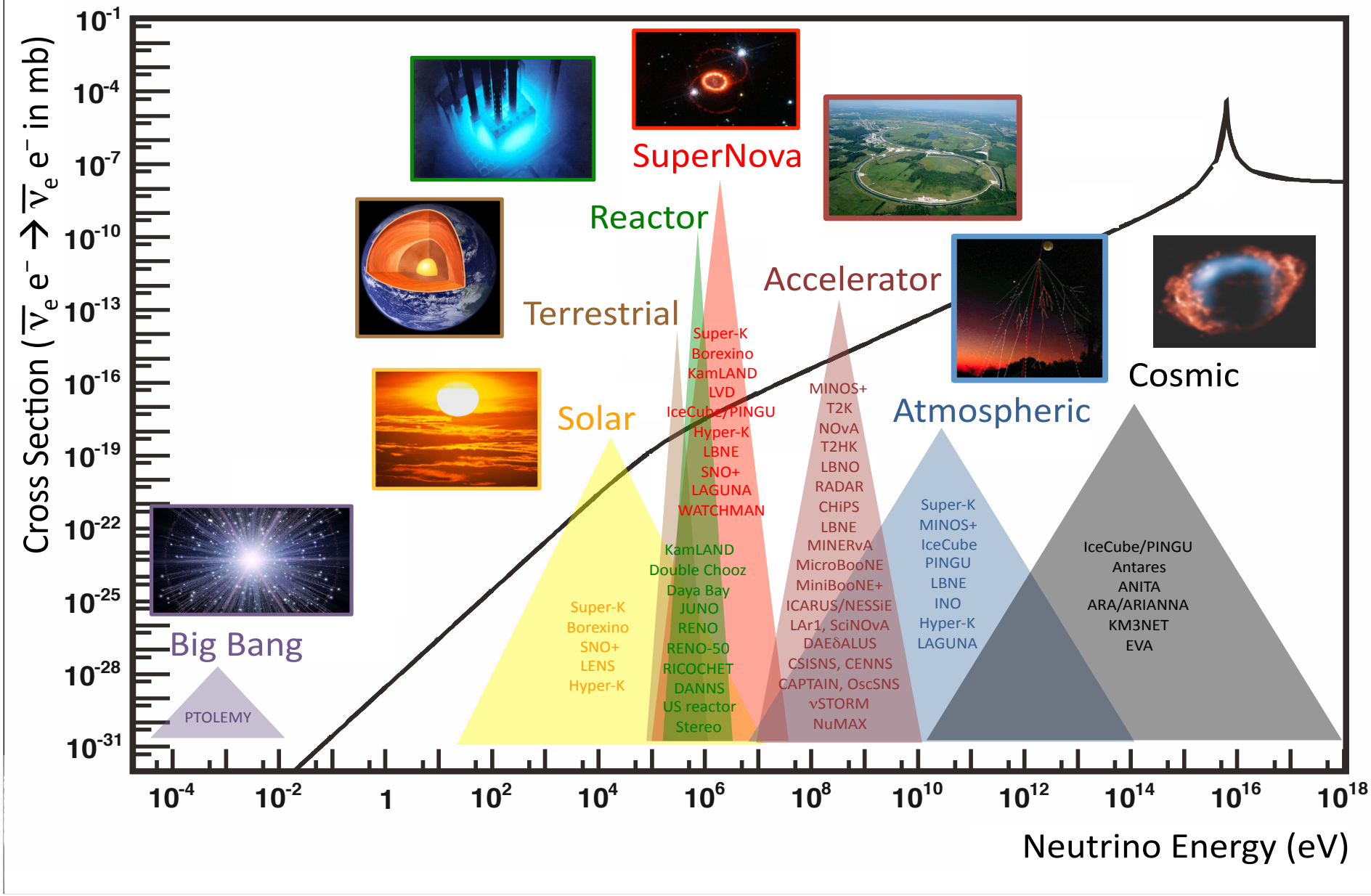
- PTOLEMY will operate with:
  - Completed MAC-E filter (1% cut-off)
  - Collect tritium spectra in 50-150eV of endpoint
  - 100 micrograms (1 Cu) of tritium with $1m^2$ area (~300 layer cell)
  - 0.15eV energy resolution at 100eV
  - Demonstrate RF-tagged electron identification
  - Measure tritium cell systematics to sub-eV
- Physics
  - 1st direct constraint on relic neutrino density (10^6 above nominal)
  - Comparable resolution performance on neutrino mass (systematics will be measured)
  - Early universe relic sterile neutrino limits (up to ~10keV)

Dome Geometry

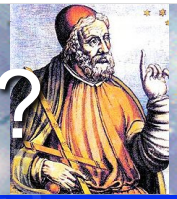




Overview of Neutrino Experiments

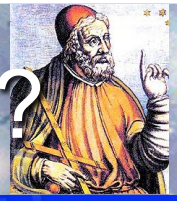


What can Relic Neutrino Density tell us?



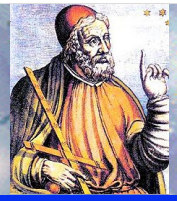
- Are there experimental outcomes that are inconsistent with Big Bang cosmology? Yes!
  - Too many cold neutrinos with no visible mass separation from the end-point (no galactic clumping factor) would contradict the initial conditions of Big Bang nucleosynthesis (present day H, D, He, Li abundances)
- 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

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

Summary

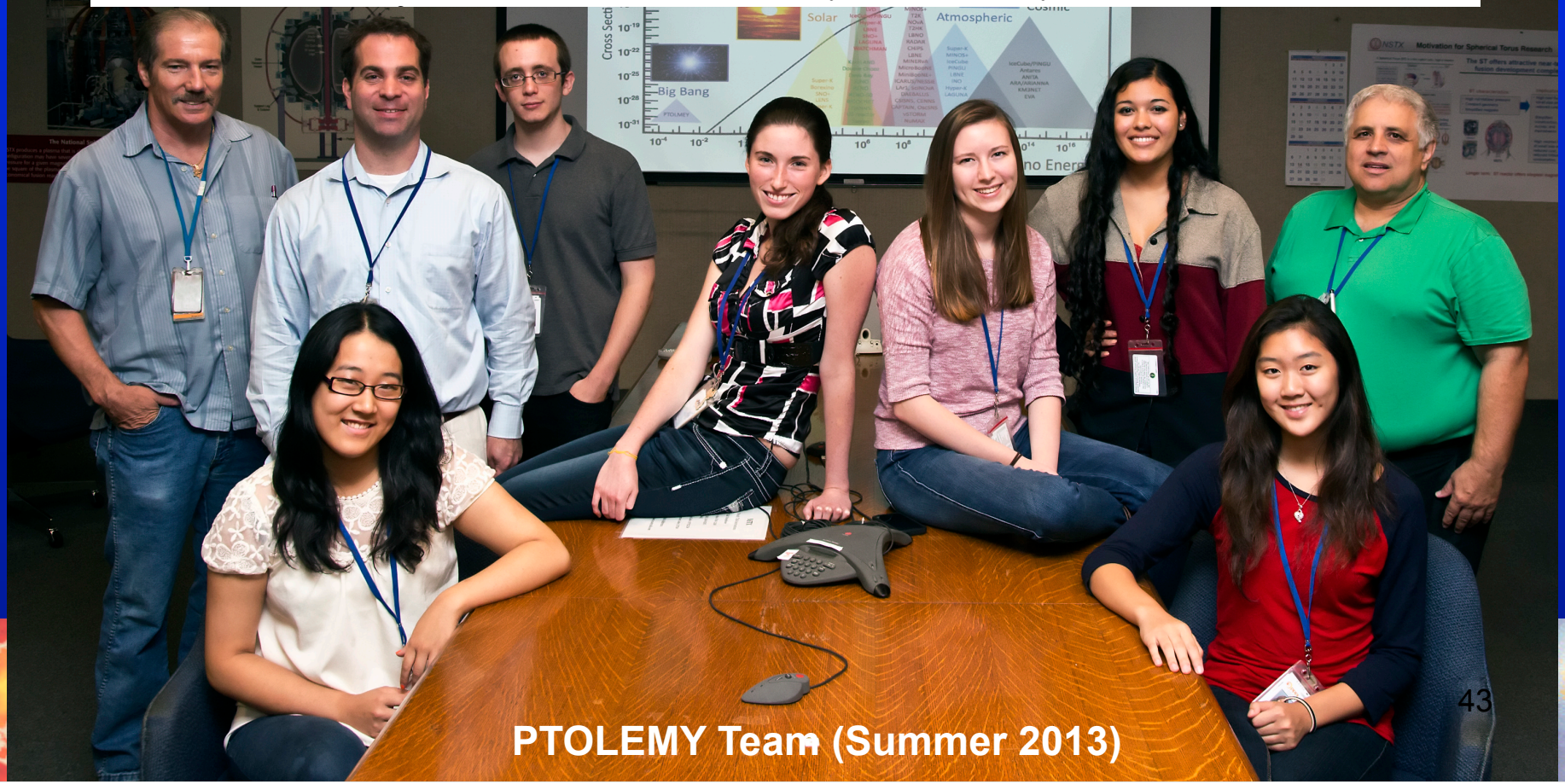


- Princeton University committed $1.2M in cost-sharing for January 2014 NSF MRI submission
  - PTOLEMY won internal Princeton competition (top 3)
  - Intermediate funding for next 9 months for He^3 system
- Important R&D still to be done on the tritium storage cell, the detector, and background levels
- PPPL prototype is an excellent test bed for validating the technologies for a 100g PTOLEMY
  - We will continue to develop the high mass capacity system for the next phase of the experiment in 2-3 years

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



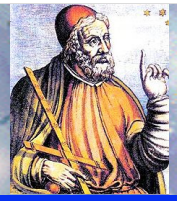
PTOLEMY Team (Summer 2013)

Backup Slides

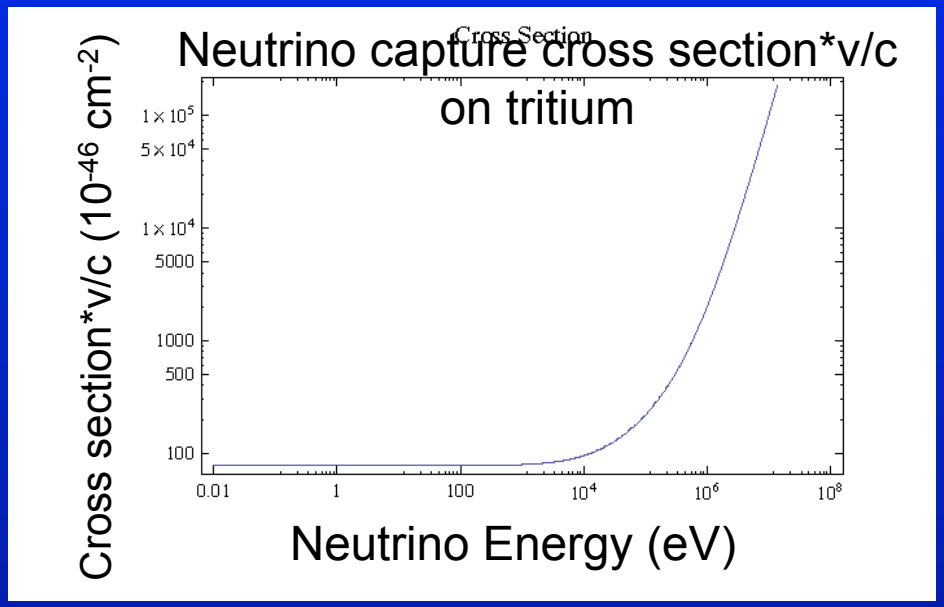
- Previous solid sources were limited at approximately 100 atomic layers from electron scattering
  - With an ExB source, if we consider individual graphene nanotubes and a 100:1 ratio of source size to separation – then we could have 1 million nanotubes strung with 1 micron spacing over a distance of 1 meter. With a 1 m^2 total transverse area of tubes per layer, we would achieved 100 grams of tritium

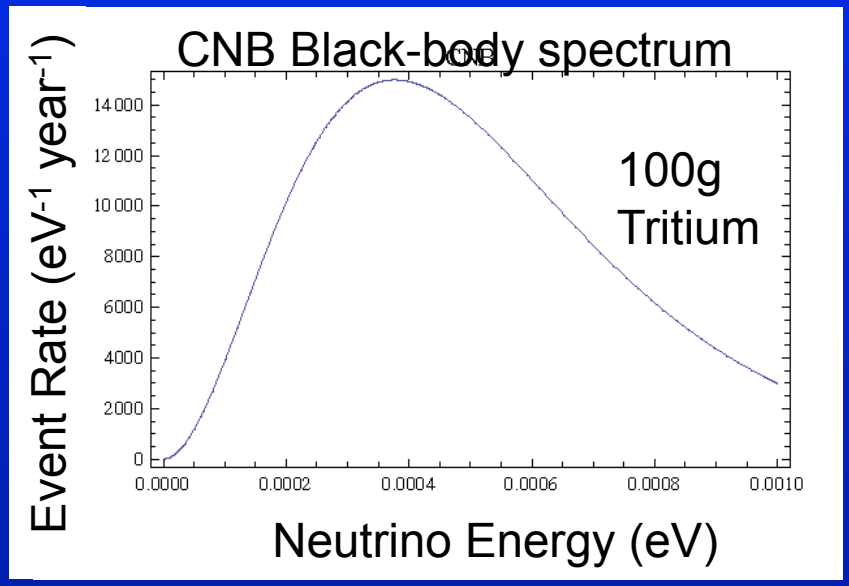
- Sub-K tritium
  - Insulator/conductor transition using flux-lock loop and SQUID readout
  - Potential to drift He3 ions in the opposite path for coincident collection (or to sell them!)
  - New tritium storage tank – could liberate atoms either by heating or with RF and the free ions could be collected to act as a source cell for an injector or a controlled reaction

Neutrino Interaction Rates



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





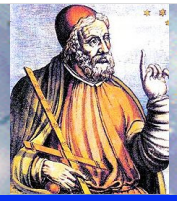
$$\int \sigma(p_\nu) v_\nu f_\nu(p_\nu) \frac{d^3 p_\nu}{(2\pi)^3}$$

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

Laurentiu Rodina

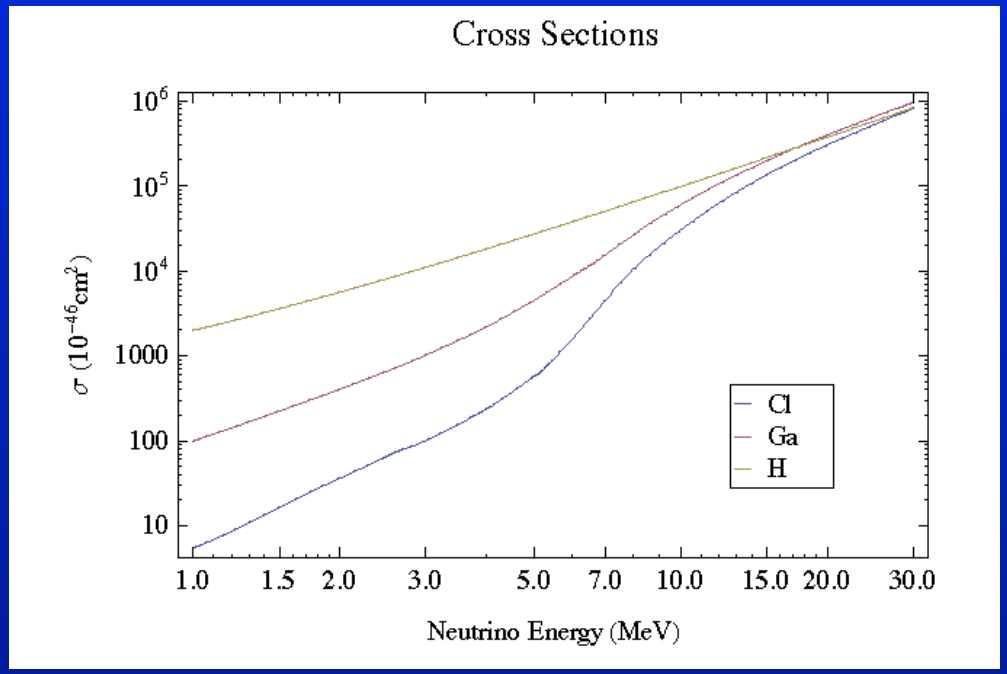
Tritium and other isotopes studied for relic neutrino capture in this paper:
JCAP 0706 (2007)015, hep-ph/0703075 by Cocco, Mangano, Messina

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

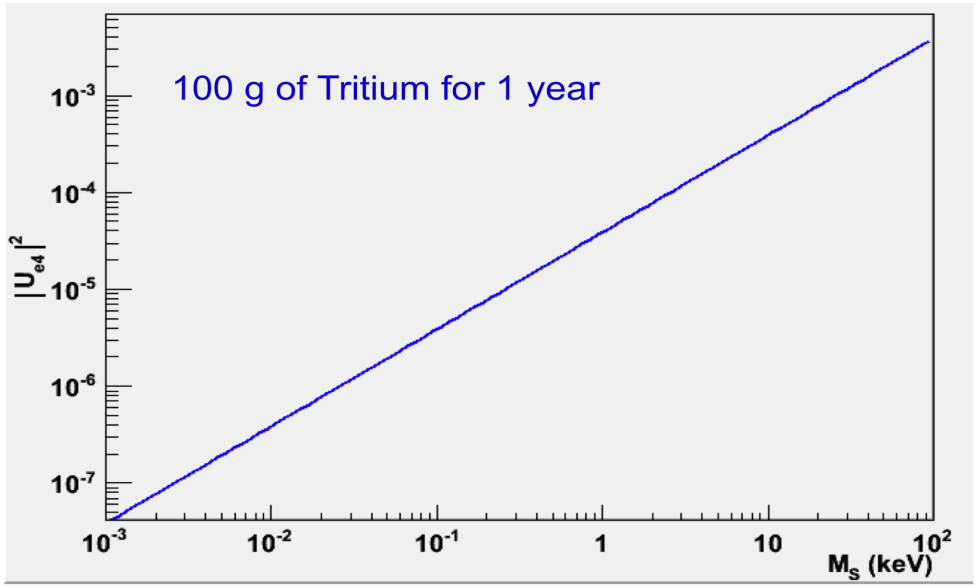


Sterile Neutrino Search

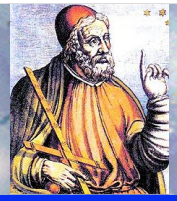
Using ν capture...

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)

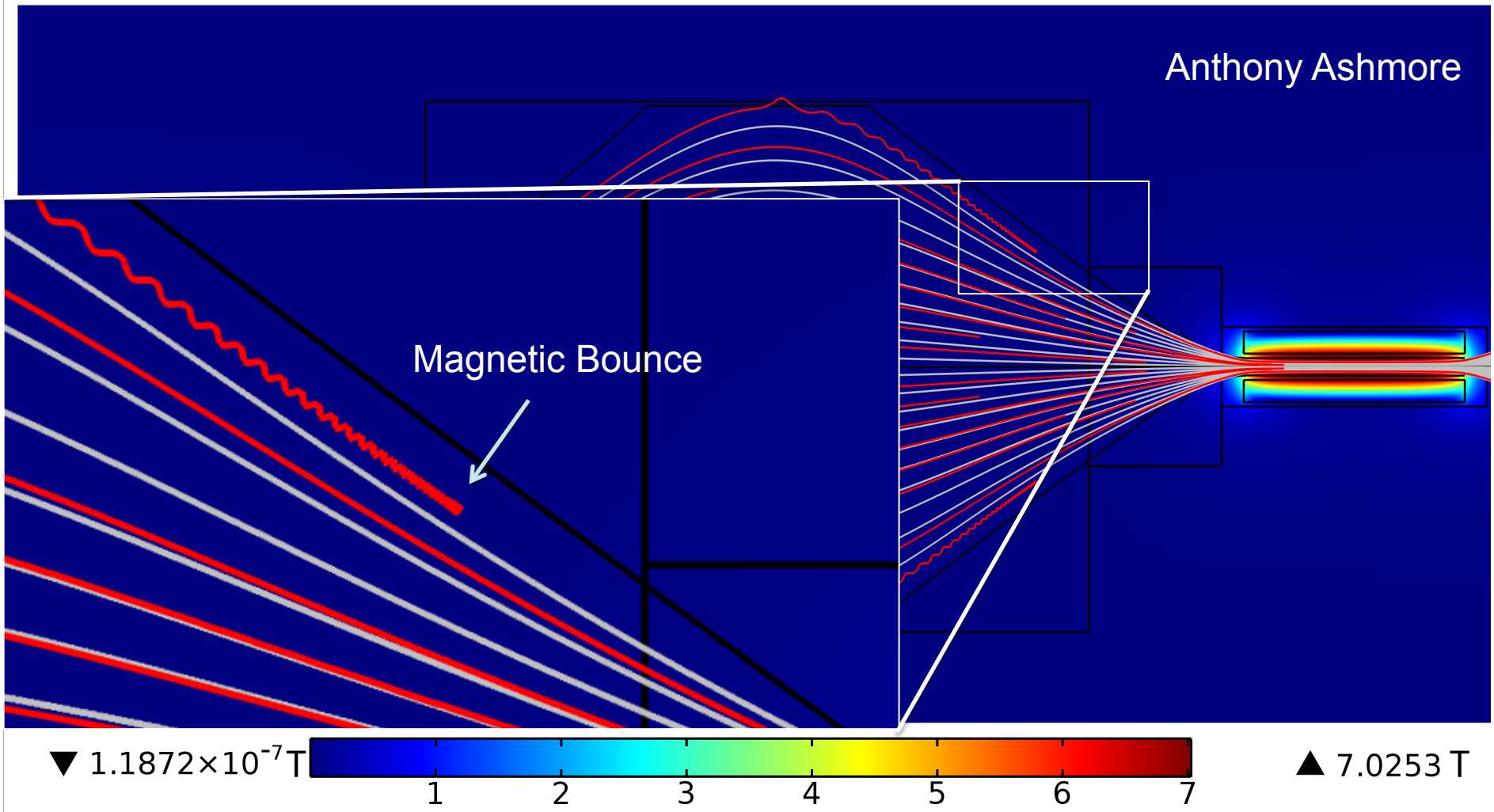


PTOLEMY Conceptual Design



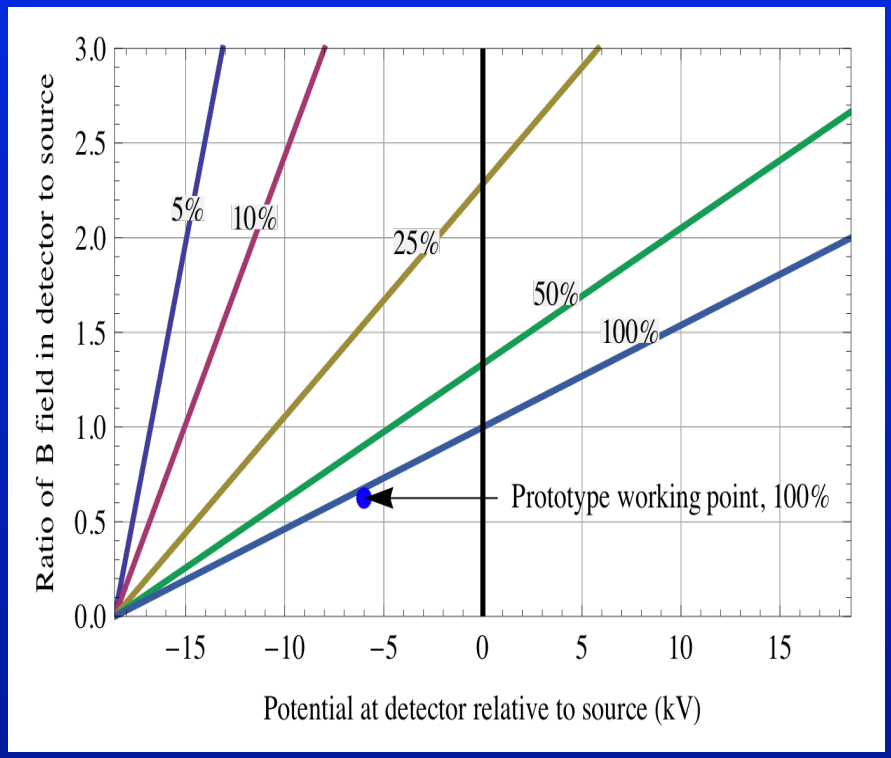
- High precision on endpoint
  - Cryogenic calorimetry energy resolution
  - **Goal: 0.1eV resolution**
- Signal/Background suppression
  - RF tracking and time-of-flight system
  - **Goal: sub-microHertz background rates above endpoint**
- High mass, high resolution tritium target
  - Surface deposition (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**

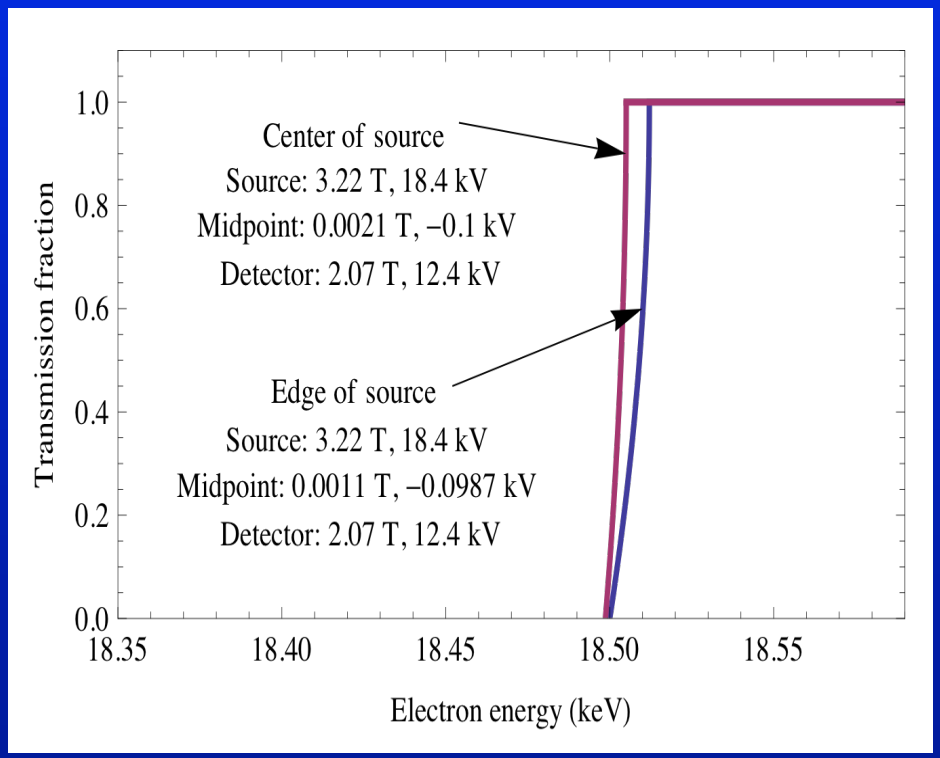
Trajectory Calculations



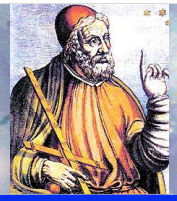
Cut-off Uniformity and Decay Acceptance

- 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





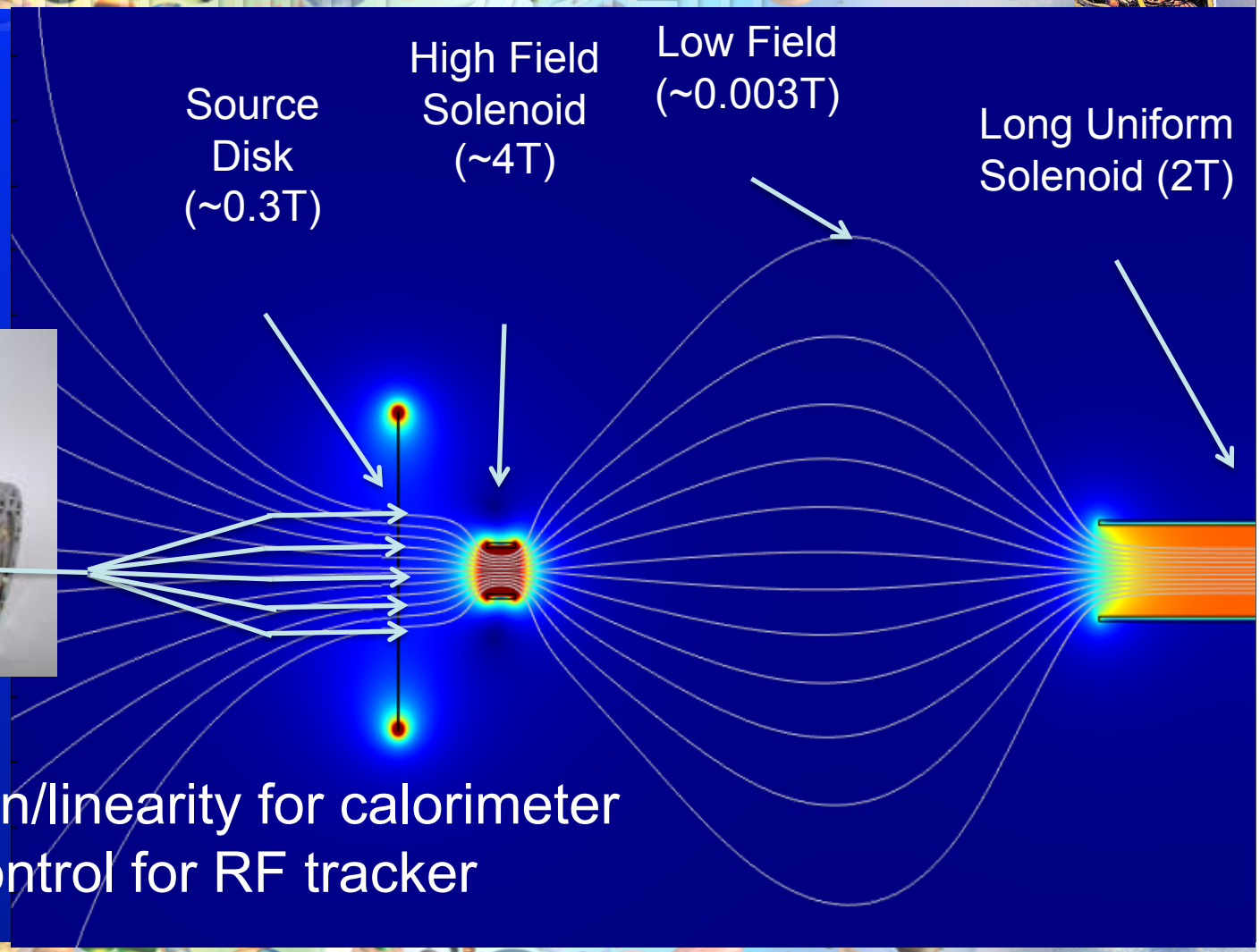
Calibration and Backgrounds



- High precision (0.1eV) electron gun
  - Off-axis directionality needed for RF antenna calibration
  - Investigating possibility of a single or multiple high precision guns situated outside of the magnetic field of the tritium target plate with a “switch yard” of input spigots to provide in situ calibration peaks for every calorimeter channel and electron trajectory
- 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
  - (vacuum-)scattered electron trajectory analysis
  - varying source strength tiles (null sources)
- NMR calibration for magnetic field uniformity in RF tracker

Calibration System

Precision e-gun
"switchyard"



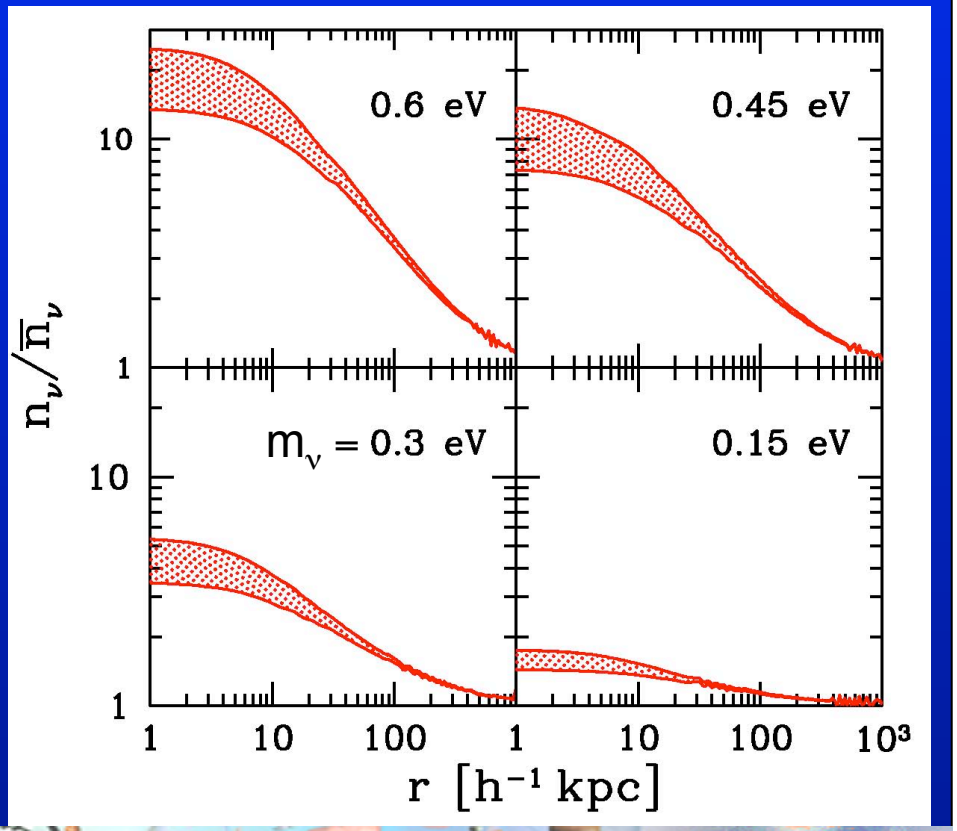
Energy resolution/linearity for calorimeter
Angular control for RF tracker

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)

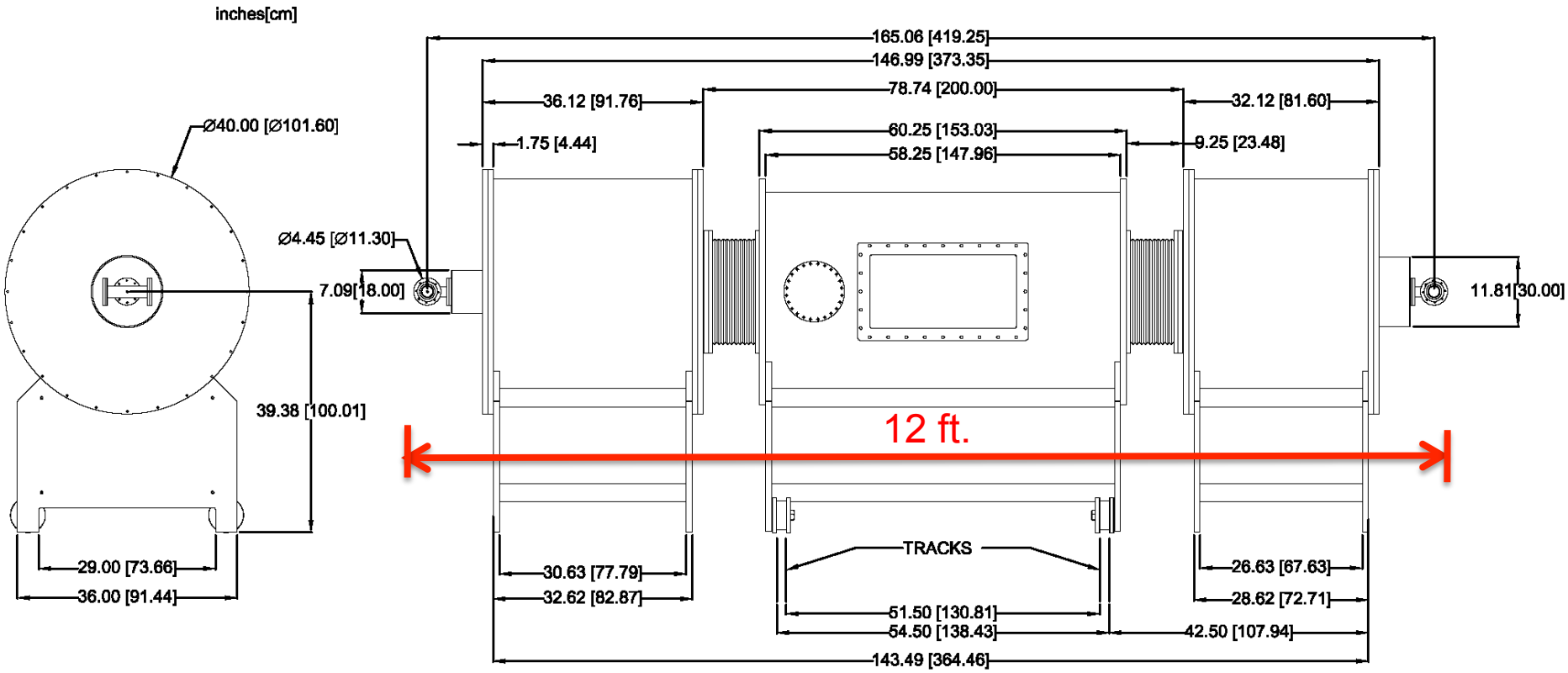
This would translate directly in 1-100 times more CNB signal events.



Ringwald and Wong (2004)

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