The challenges of relic neutrino direct detection and status of the **PTOLEMY experiment**

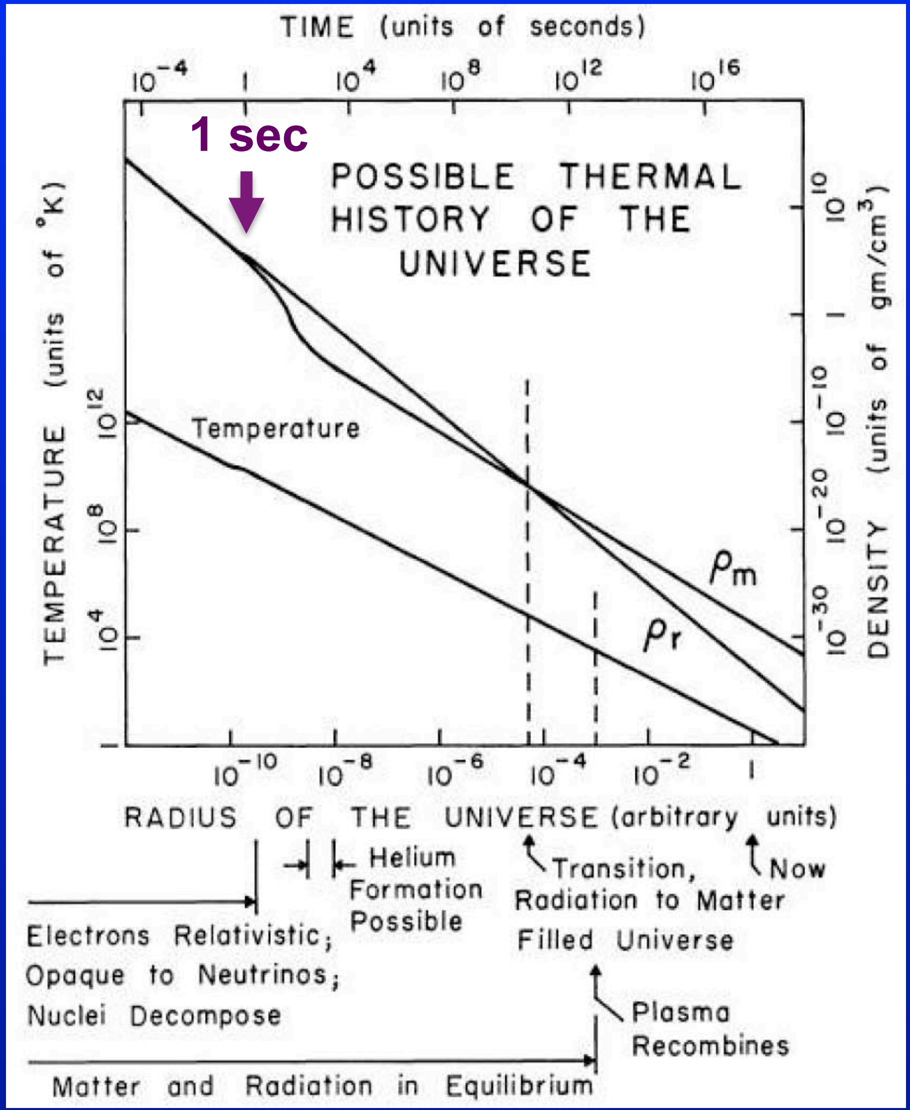
Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

Chris Tully
Princeton University

Chalonge Meudon Workshop 2014
5 June 2014

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 thermal history of the universe
- Few 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)

Big Bang Prediction I

When the mean free path exceeds the horizon size, the neutrinos decouple from matter

$$\lambda_\nu \sim \frac{1}{\sigma_\nu n_e} \sim \frac{1}{\left(G_F^2 T^2\right) T^3}$$

$$\lambda_h \sim \frac{1}{\sqrt{G\rho}} \sim \frac{M_{Pl}}{T^2}$$

$$\frac{\lambda_h}{\lambda_\nu} \sim \left(\frac{T}{T_{\nu d}}\right)^3 \sim M_{Pl} G_F^2 T^3$$

$$T_{\nu d} \sim M_{Pl}^{-1/3} G_F^{-2/3} \sim 1\ \mathrm{MeV}$$

Neutrinos decouple before e^+e^- annihilation, e^+e^- heats up photons

2 photon + 7/8(2 electron + 2 positron) → 2 photon

Relic neutrino temperature in lock step with photons and both drop at the same rate with the Hubble expansion

$$T_\nu(t) = T_\nu(t_{\nu d}) \frac{a(t_{\nu d})}{a(t)} = \left(\frac{4}{11}\right)^{1/3} T_{CMB}$$

$T_\nu \sim 1.95\mathrm{K}$

Big Bang Prediction II

Relic neutrino number density follows photon number density

$$n_\nu = \left(\frac{3}{4}\right)\left(\frac{4}{11}\right) n_\gamma = 112/\mathrm{cm}^3$$

per neutrino species
(neutrino+antineutrino)

Present-day relic neutrinos are distributed in velocity according to their original relativistic Fermi-Dirac distribution at one second after the Big Bang

$$g(p_\nu) = \frac{1}{1 + e^{p_\nu / T}}$$

in the relativistic limit

$$E \approx p_\nu + \frac{m^2}{2 p_\nu}$$

$$\langle \mathrm{v}_{rms} \rangle \propto T / m_\nu \text{ instead of } \propto \sqrt{T / m_\nu}$$

Relic velocity depends on mass $\langle \mathrm{v}_{rms} \rangle = 160 \text{ km/s } (1 \text{ eV} / m_\nu)$

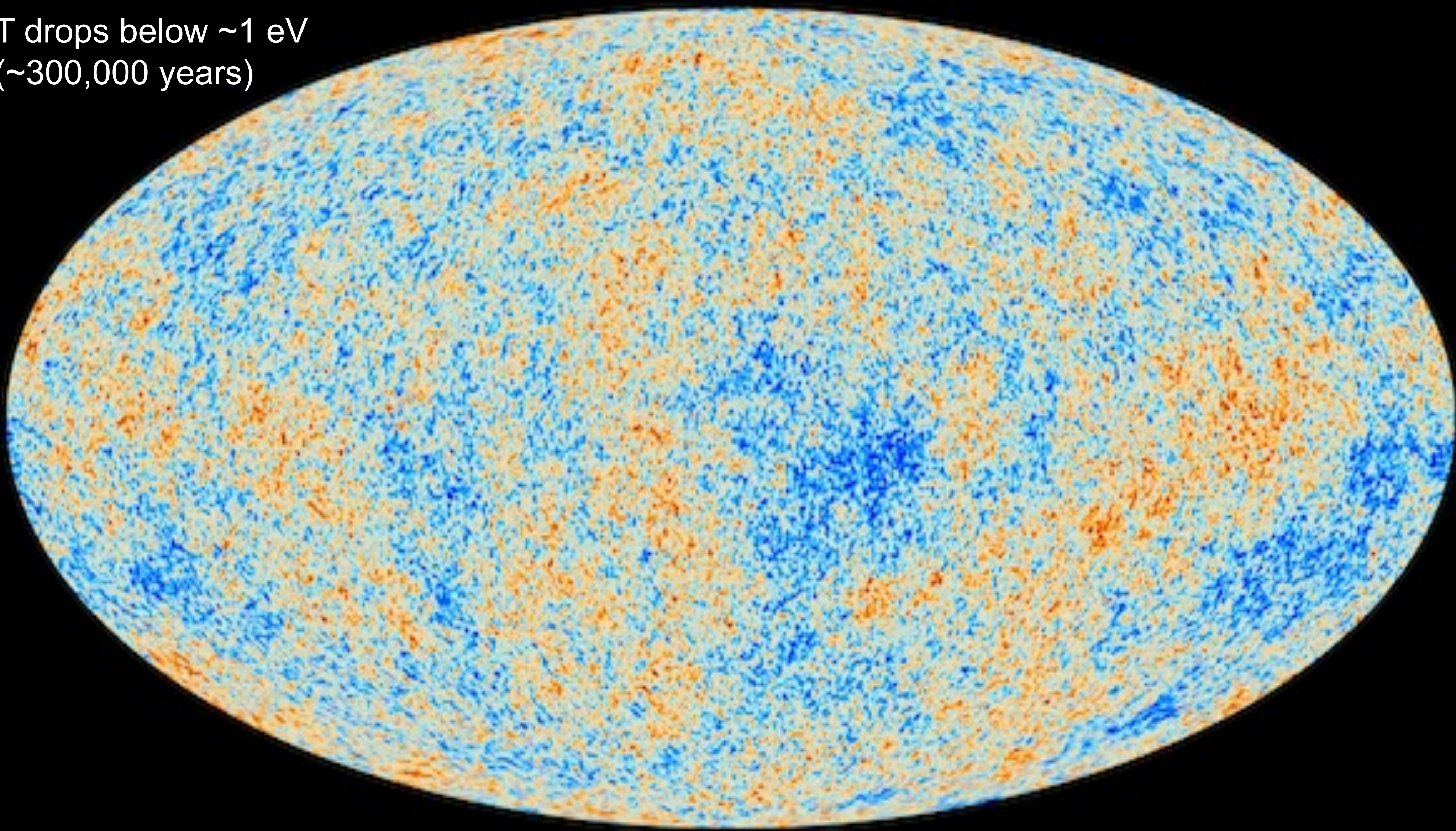
Timing of Neutrino Decoupling

- Timing is essential to Big Bang predictions
  - Neutrino decoupling at ~1 MeV (~1 sec)
    - Weak interactions constantly regenerate neutrons
  - Neutron-Proton mass difference m_n-m_p~1.3 MeV
  - Deuterium(→ Helium) at ~0.07 MeV (~132 sec) compared to neutron lifetime of ~886.7 sec
    - n/p~0.15*0.74~0.11 at the start of nucleosynthesis

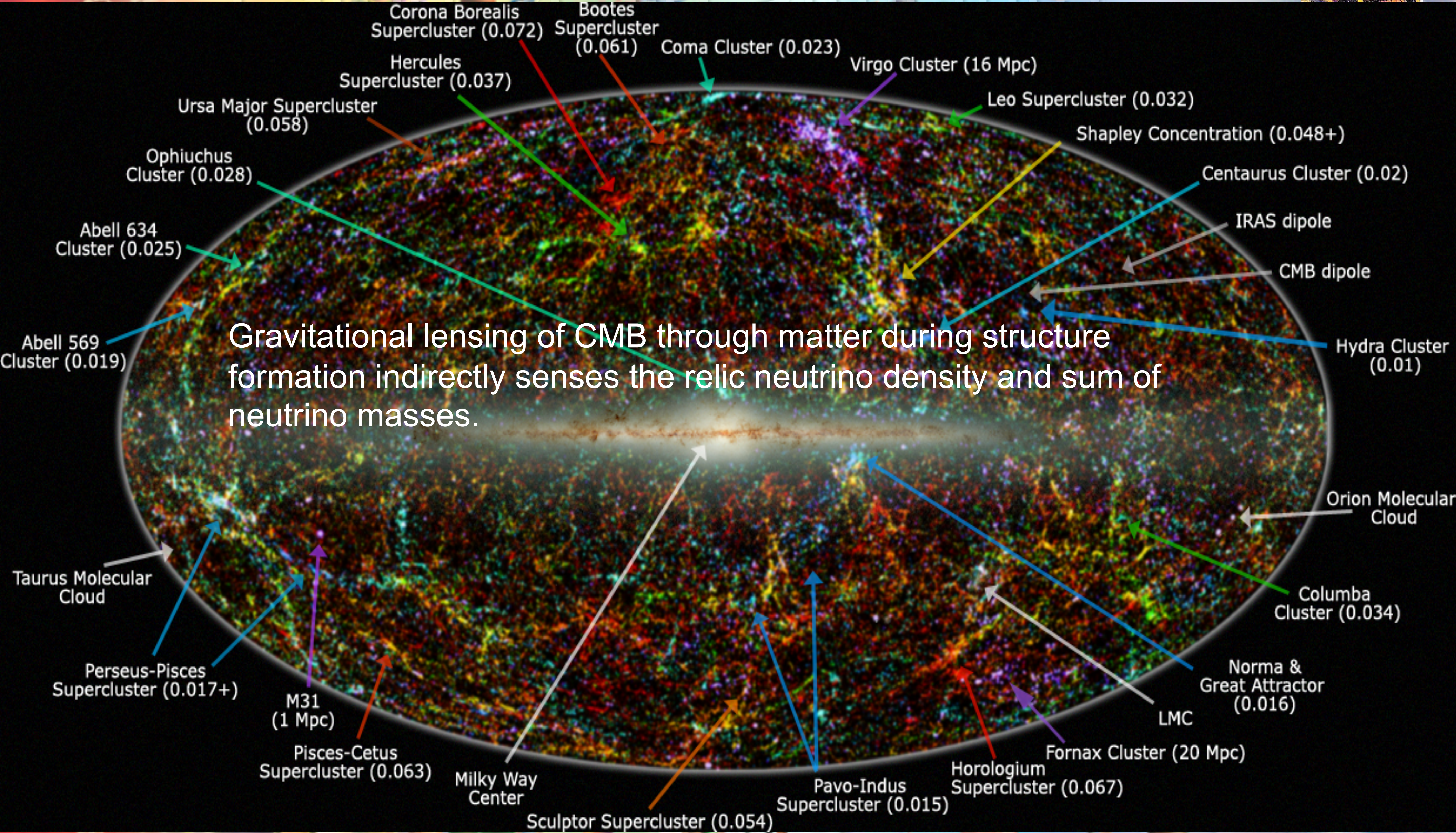
Not much wiggle room for the standard BBN prediction

Cosmic Background Radiation

T drops below ~1 eV
(~300,000 years)

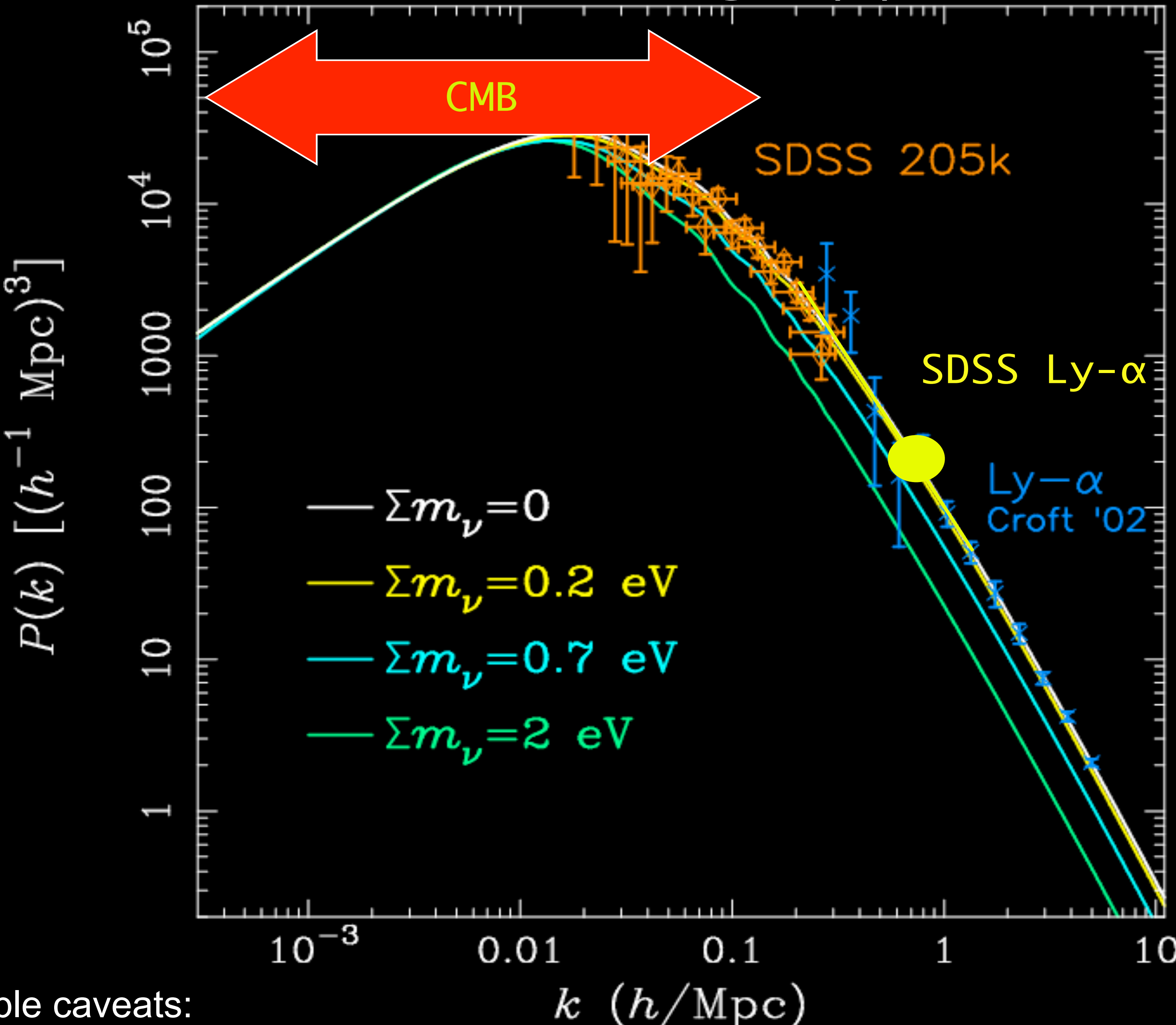


Large-Scale Structure



Gravitational lensing of CMB through matter during structure formation indirectly senses the relic neutrino density and sum of neutrino masses.

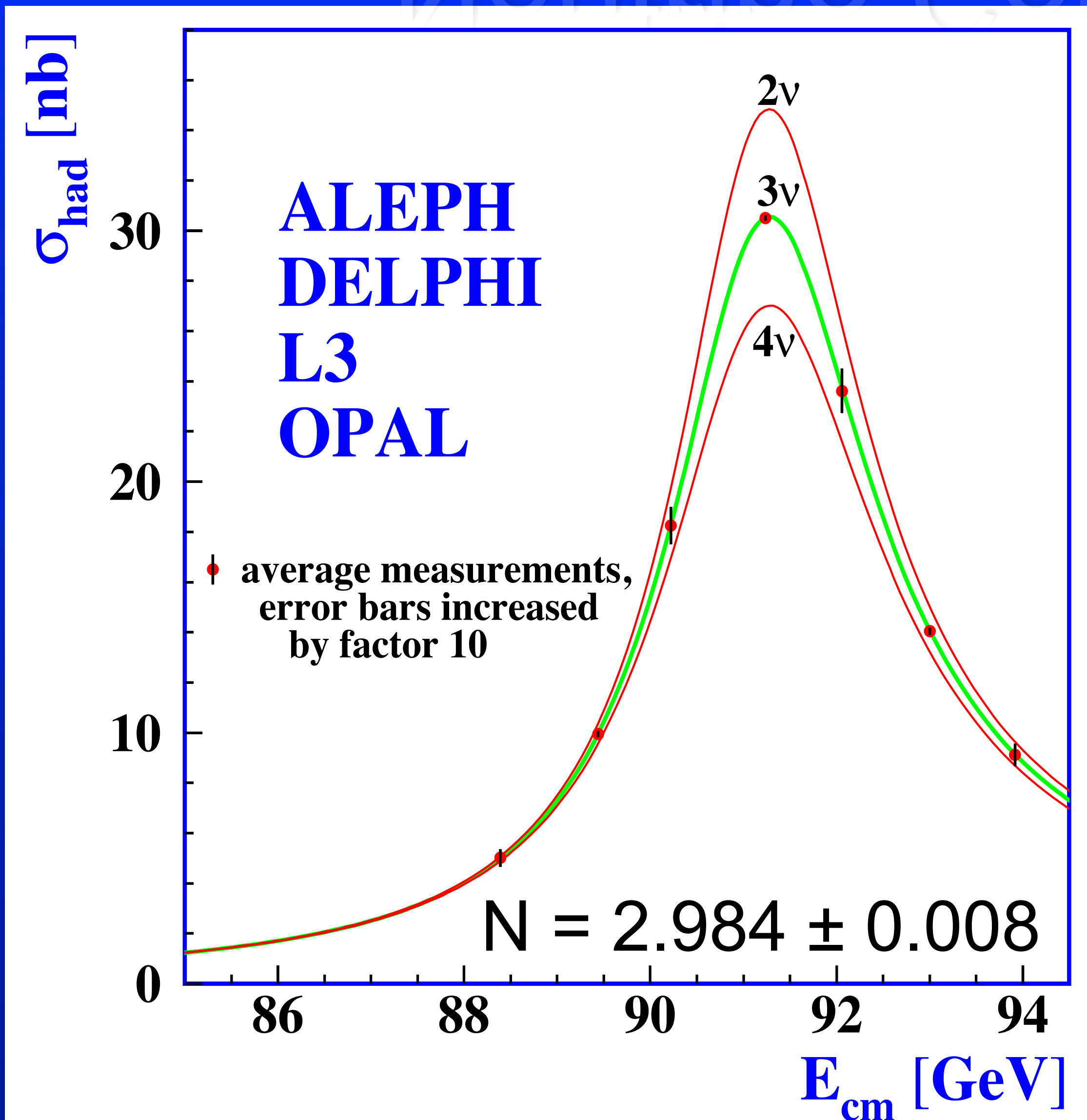
Measuring P(k)



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 degrees of freedom above N=3.04).

Neutrino Counting



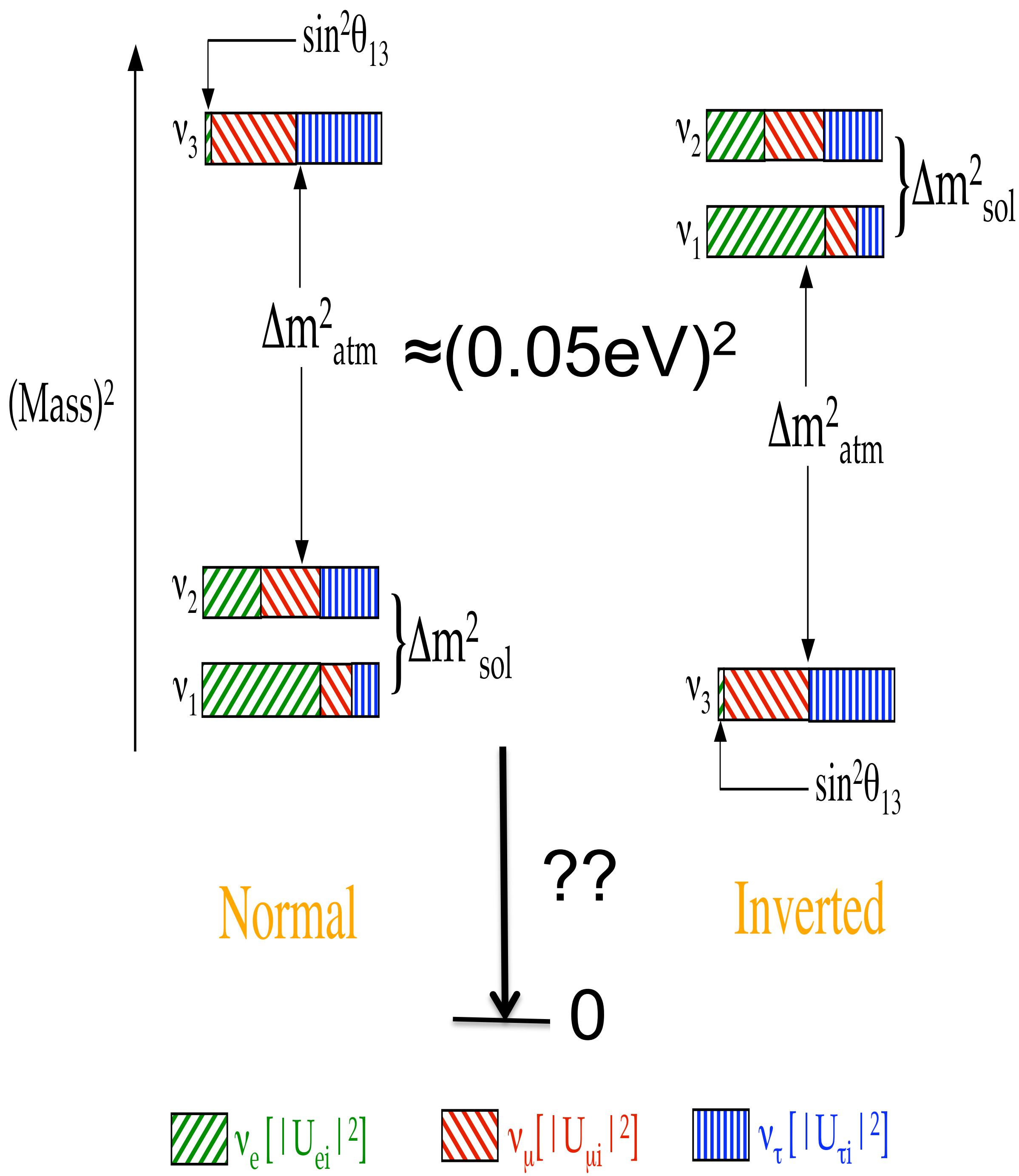
Produce ~1M Z bosons at an e^+e^- collider

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



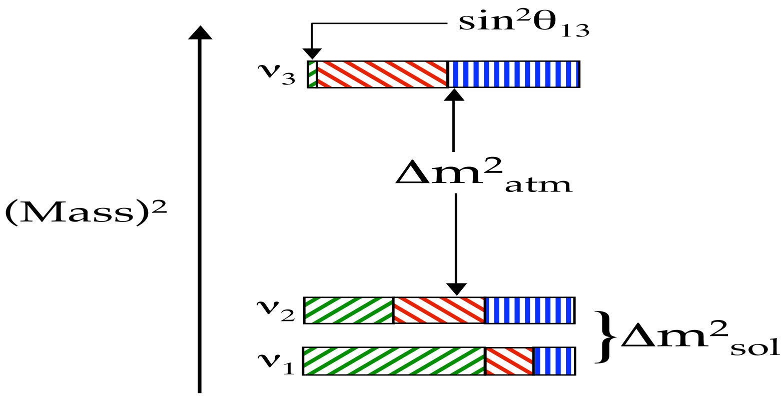
An incredible phenomenon appeared when neutrinos were measured from different sources: solar, atmospheric, reactor, accelerator.

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.

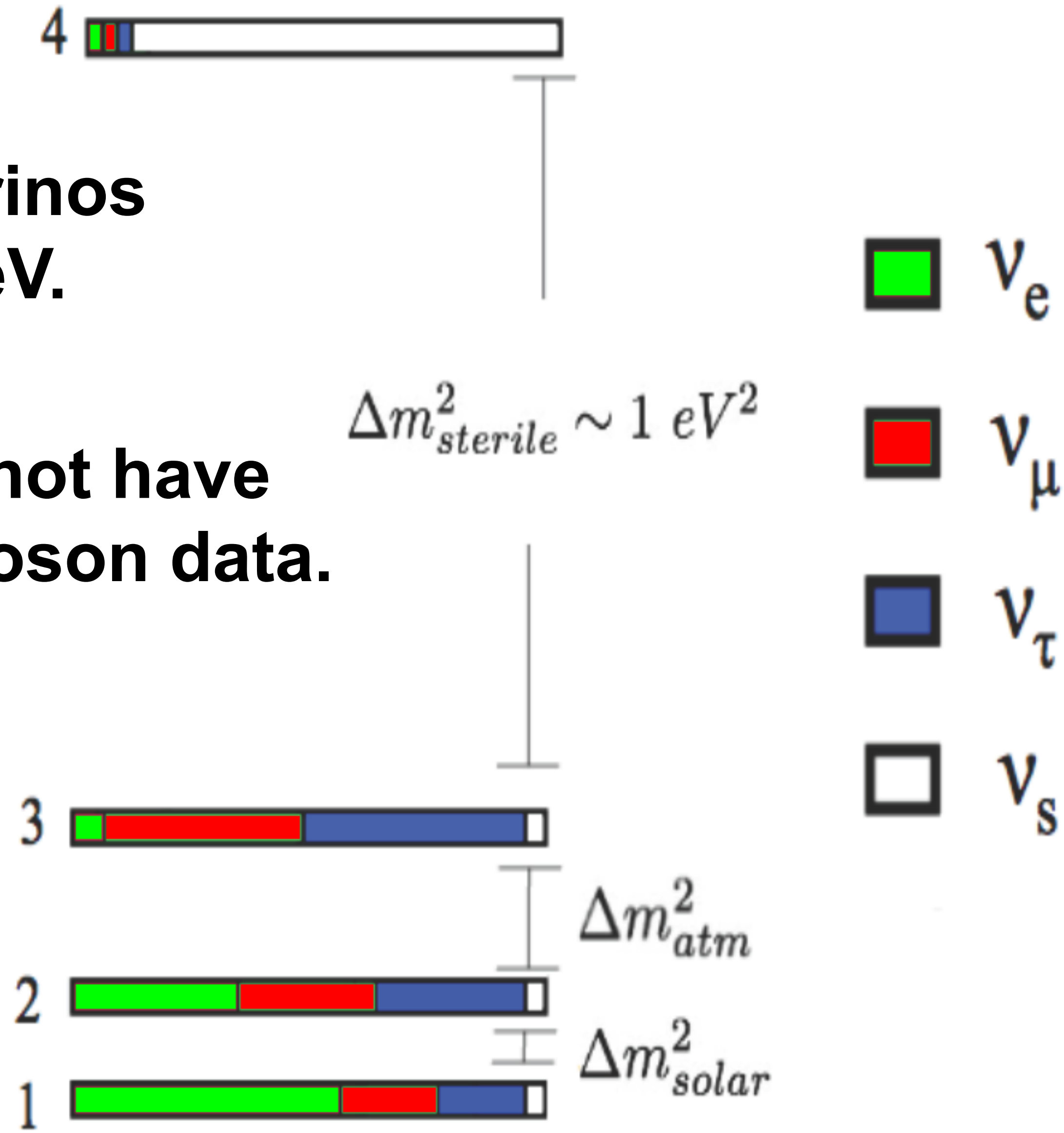
Sterile Neutrinos?

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

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



or



Normal

$\nu_e\ [\,|U_{ei}|^2]$ $\nu_\mu[\,|U_{\mu i}|^2]$ $\nu_\tau\ [\,|U_{\tau i}|^2]$

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

What do we know?

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

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

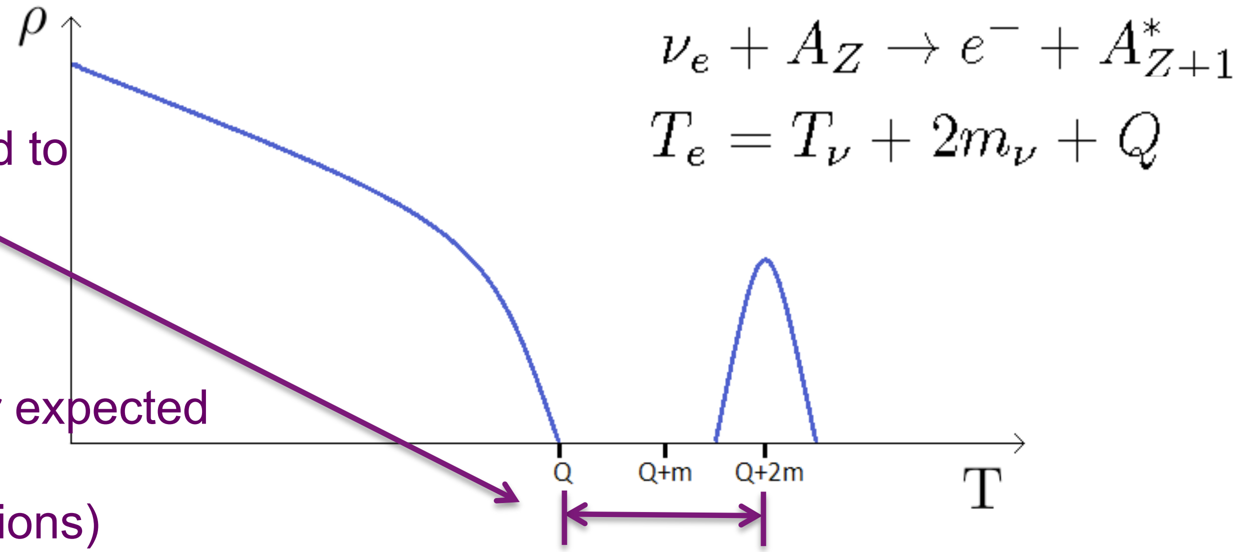


Figure 1: Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

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?

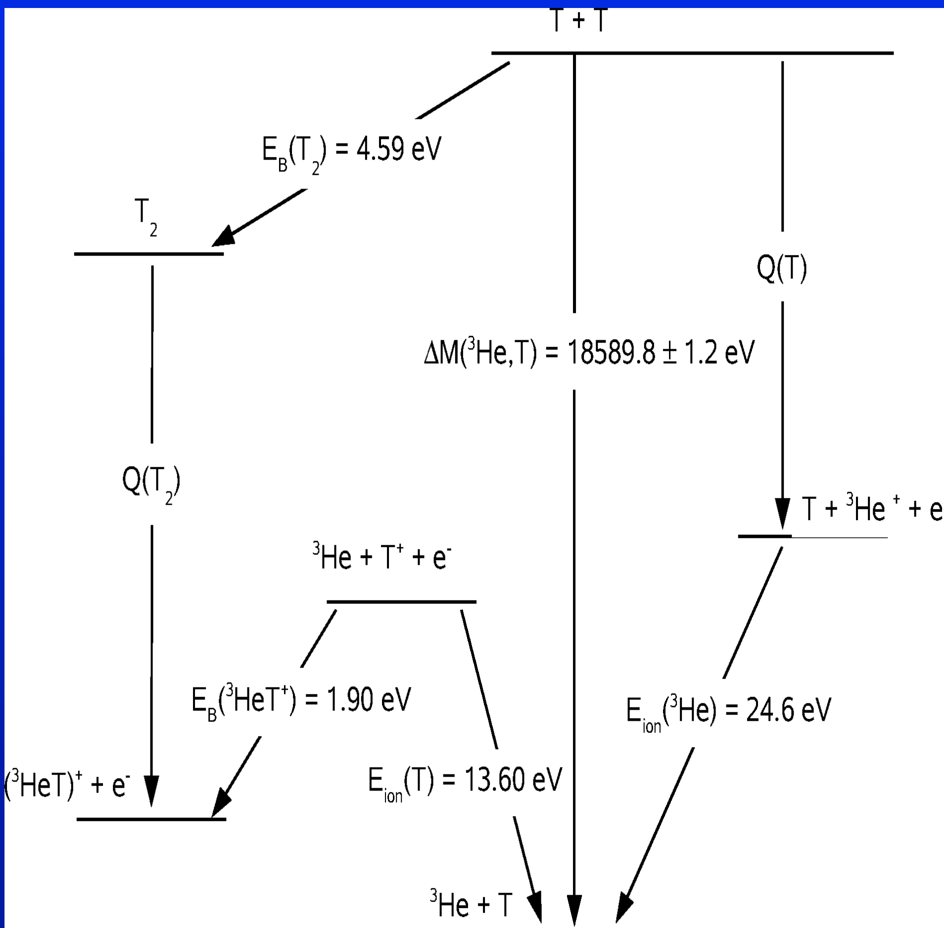
Answer: The maximum He^3 recoil energy is ~3eV. He^3 stays bound to the remaining T to form a T-He^3 molecule – and can fall into a number of closely spaced rotational and vibrational excited states

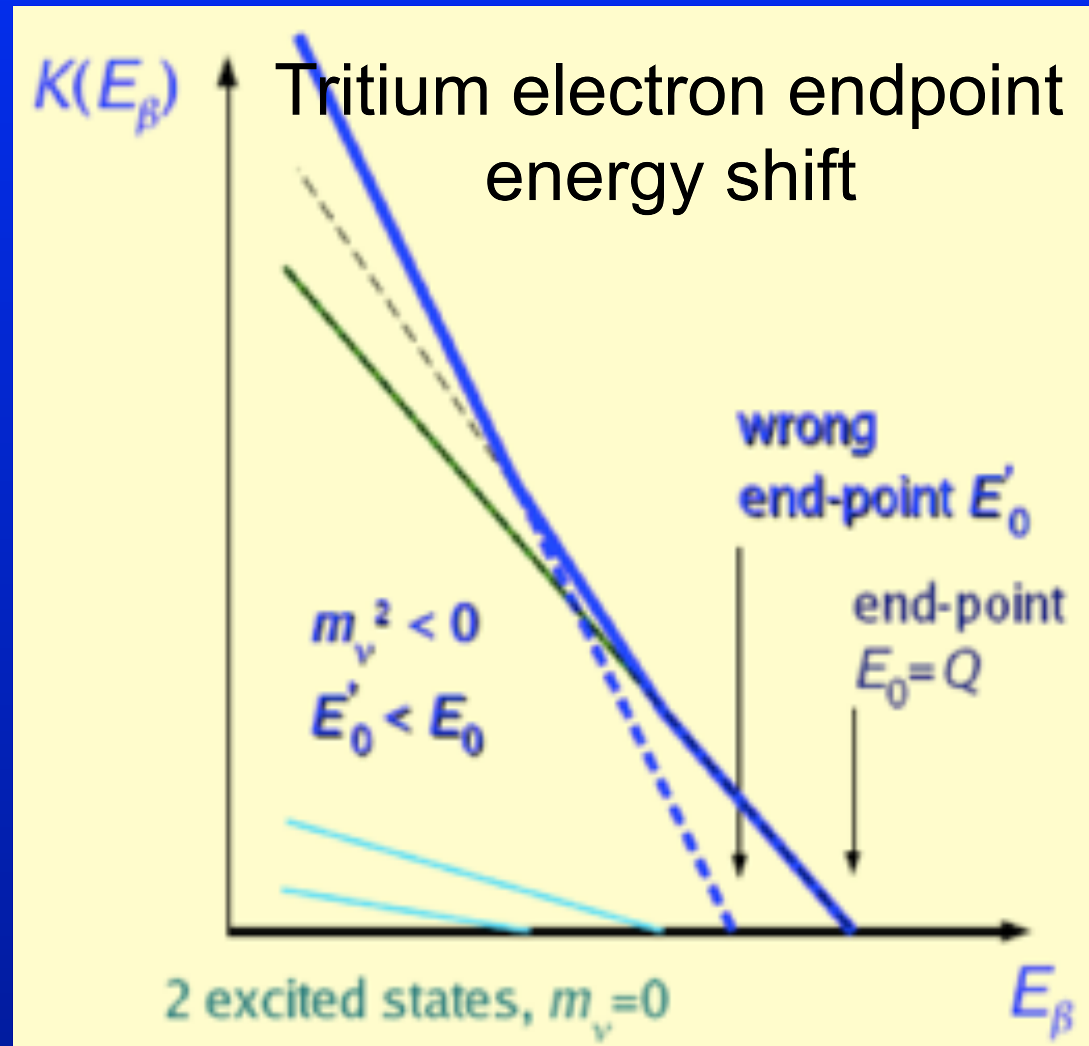
T-T → T-He^3

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

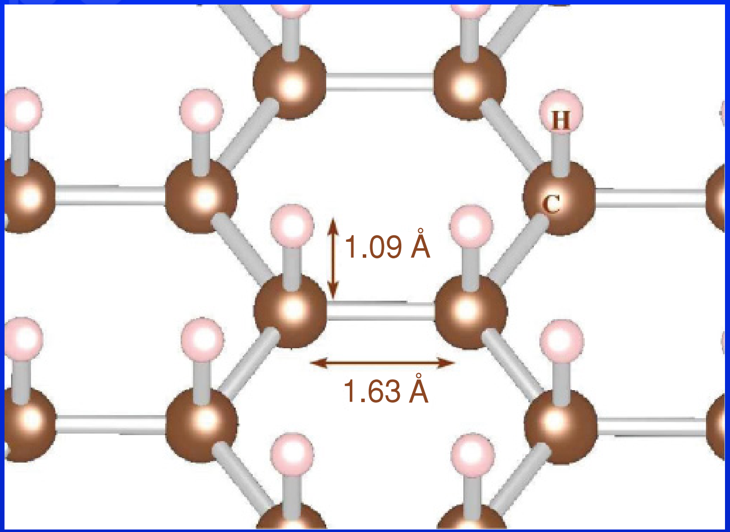
T-T → T-He^3 Level Diagram





Tritium on Graphene

- In the hunt for alternative energies, there has been a great focus on the development of Hydrogen storage systems
  – Hydrogen binds to the surface of graphene in a solid form (6%wt) at room temperature, but with a weak enough binding that the hydrogen can be readily released

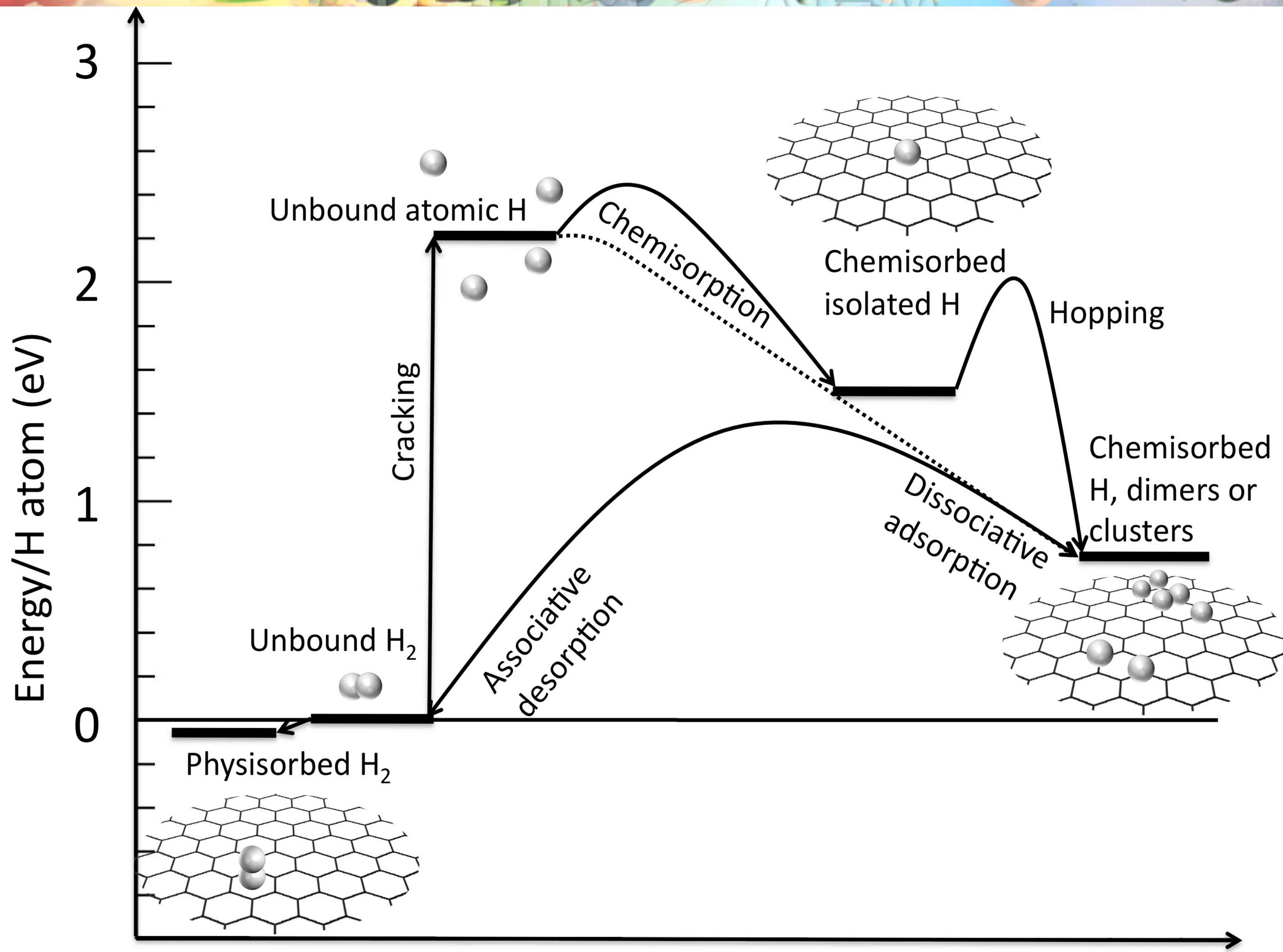


Single-sided-hydrogenated Graphene
- Planar (uniform bond length)
- Semiconductor (~Si gap)
- Polarized tritium(?)

~3×10^{13} T/mm^2 (~80kHz of decays/mm^2)

Different forms of hydrogenated graphene have a hydrogen binding energy less than 3eV – with no binding for He^3.

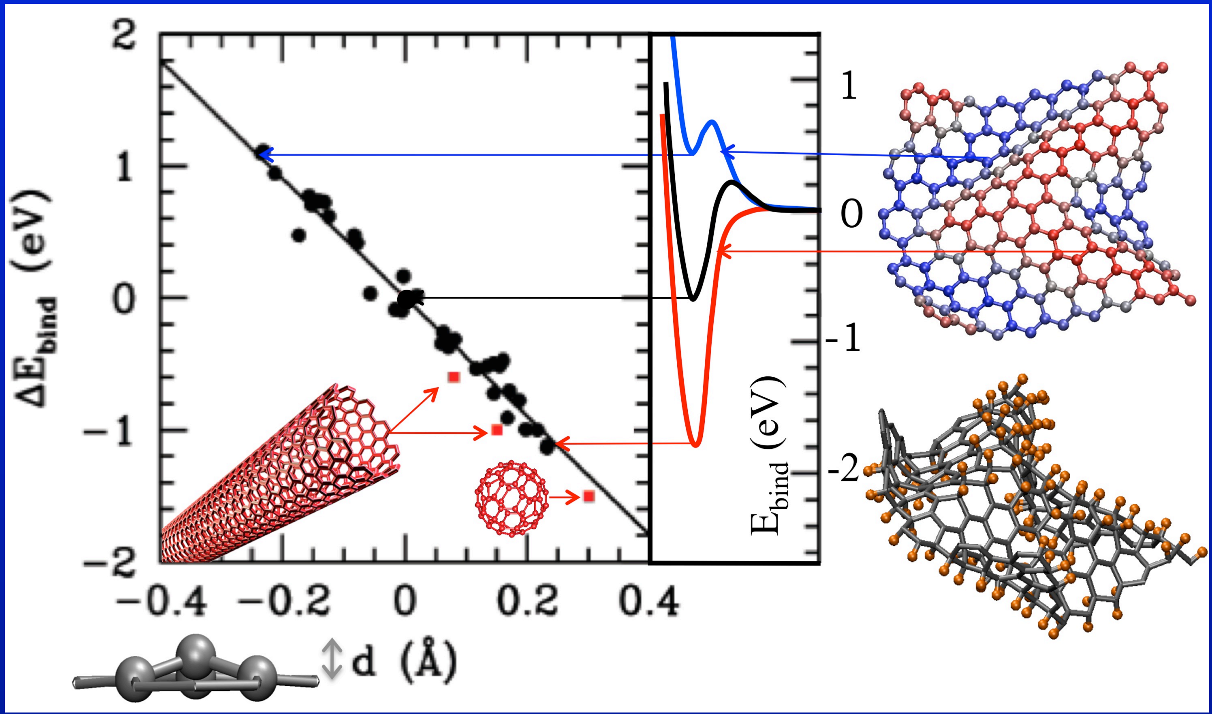
Chemist's View



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 and a high resolution microcalorimeter

New C-H bond measurement technique:
May help accelerate Hydrogen fuel cell/ storage research



Relic Neutrino Capture Rates

- Target mass: 100 grams of tritium (2 x 10^{25} nuclei)
- Capture cross section * (v/c) ~ 10^{-44} cm^2 (flat up to 10 keV)
- (Very Rough) Estimate of Relic Neutrino Capture Rate:

(56 ν_e/cm^3) (2 x 10^{25} nuclei) (10^{-44} cm^2) (3 x 10^{10} cm/s) (3 x10^7s) ~ **10 events/yr**

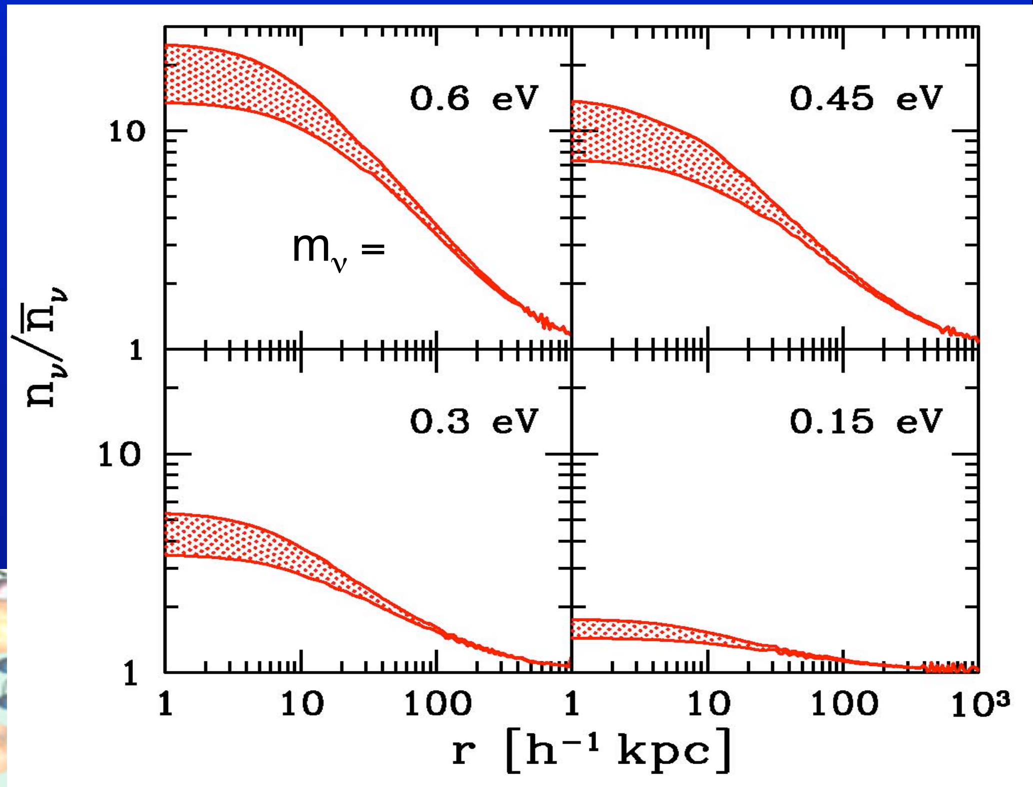
Lazauskas, Vogel, Volpe: J.Phys.G G35 (2008) 025001.

Cocco, Mangano, Messina: JCAP 0706 (2007) 015

$\sigma(v/c)=(7.84\pm0.03)\times10^{-45}cm^2$

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)

Dirac versus Majorana Neutrinos

Long, Lunardini, Sabancilar: arXiv:1405.7654

"Detecting non-relativistic cosmic neutrinos by capture on tritium: phenomenology and physics potential" →

Factor of 2 difference in capture rate

Relic neutrino capture rate on tritium depends on whether neutrinos are Dirac or Majorana:

Neutrinos decouple at relativistic energies

Helicity is conserved as the universe expands and the relic neutrinos become non-relativistic

Dirac: initially left-handed chiral=helical neutrinos and right-handed chiral=helical anti-neutrinos are active → cooldown →~half of left-handed helical Dirac neutrinos are right-handed chiral (non-active) → Factor of 2 drop in present-day capture rate on tritium for Dirac

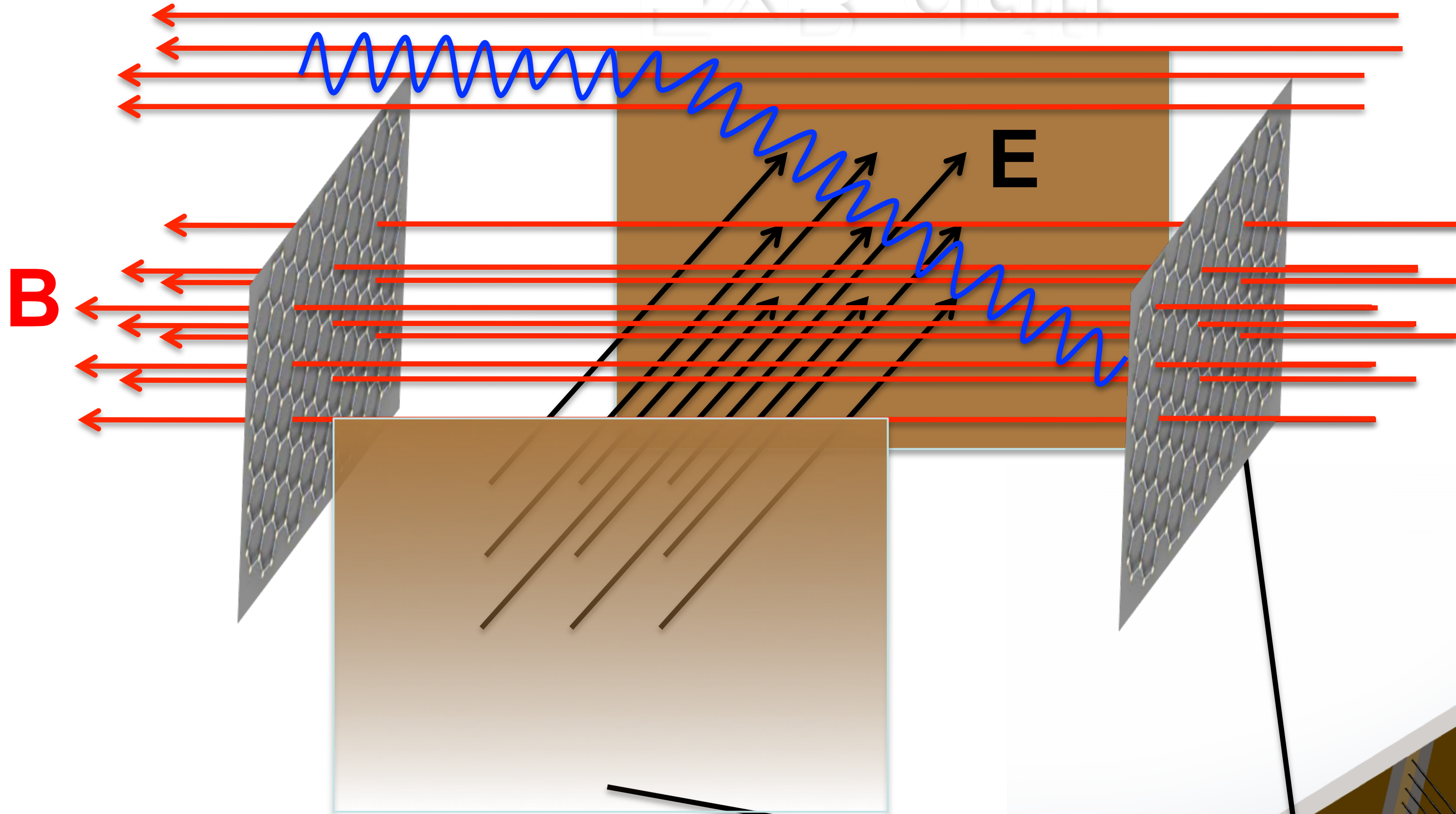
Majorana: initially left-handed chiral=helical neutrinos=antineutrinos and right-handed chiral=helical neutrinos=antineutrinos are active → cooldown → No change in present-day capture rate (heavy neutrino components are decoupled)

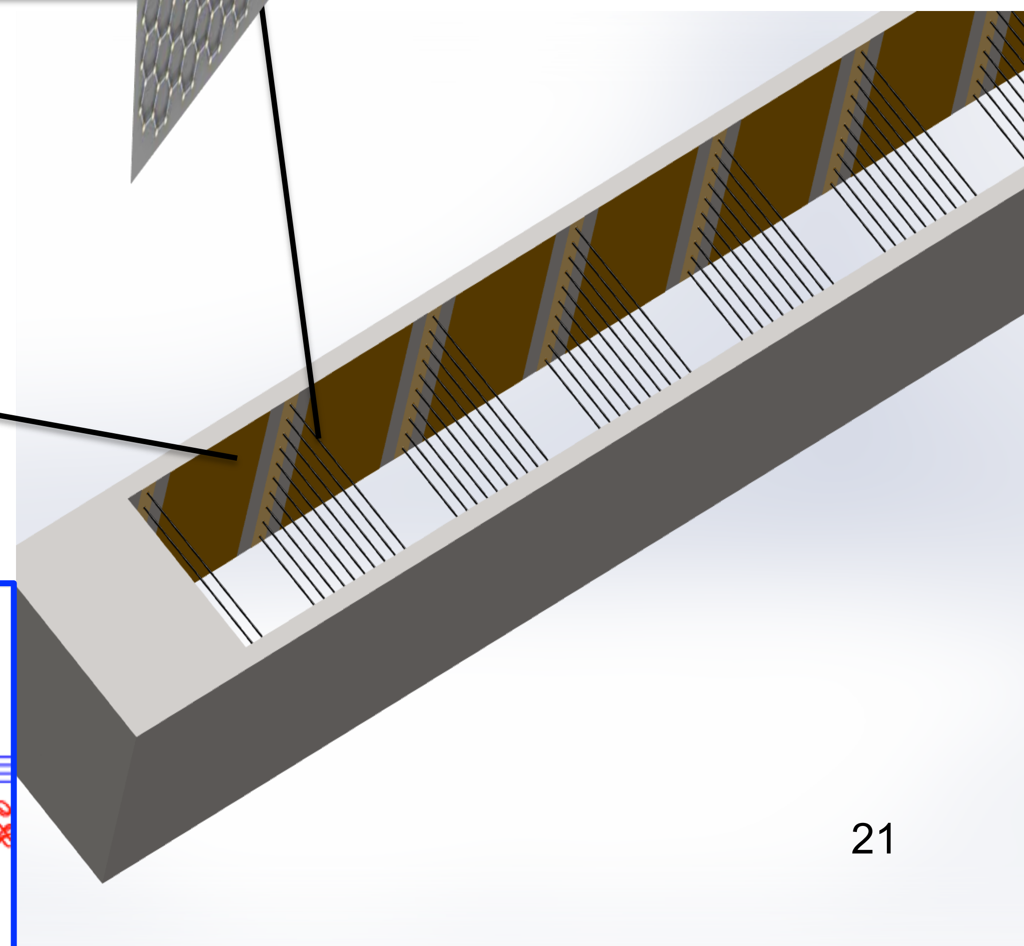
First Majorana/Dirac test outside of neutrinoless double-beta decay?

THE Challenge

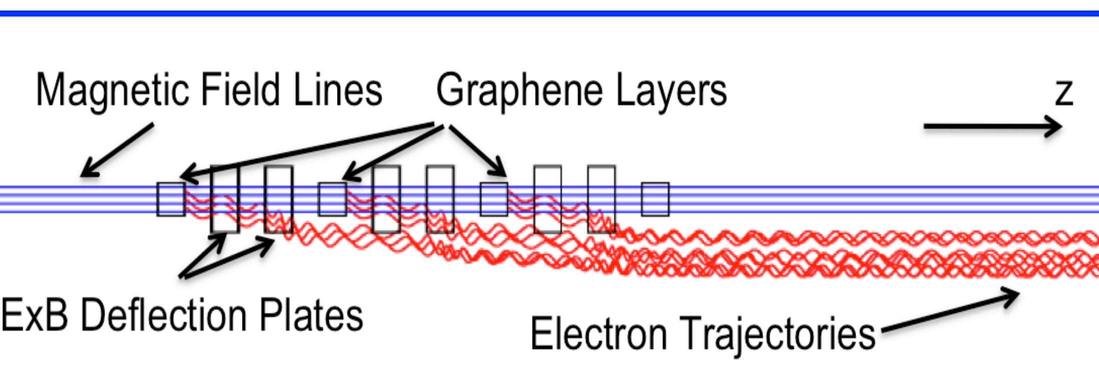
- The largest and nearly insurmountable problem of relic neutrino detection is to provide a large enough surface area to hold at least 100 grams of weakly bound atomic tritium
  - The trajectory of the outgoing electrons from tritium decay must have a clear vacuum path to the calorimeter (up to one or 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

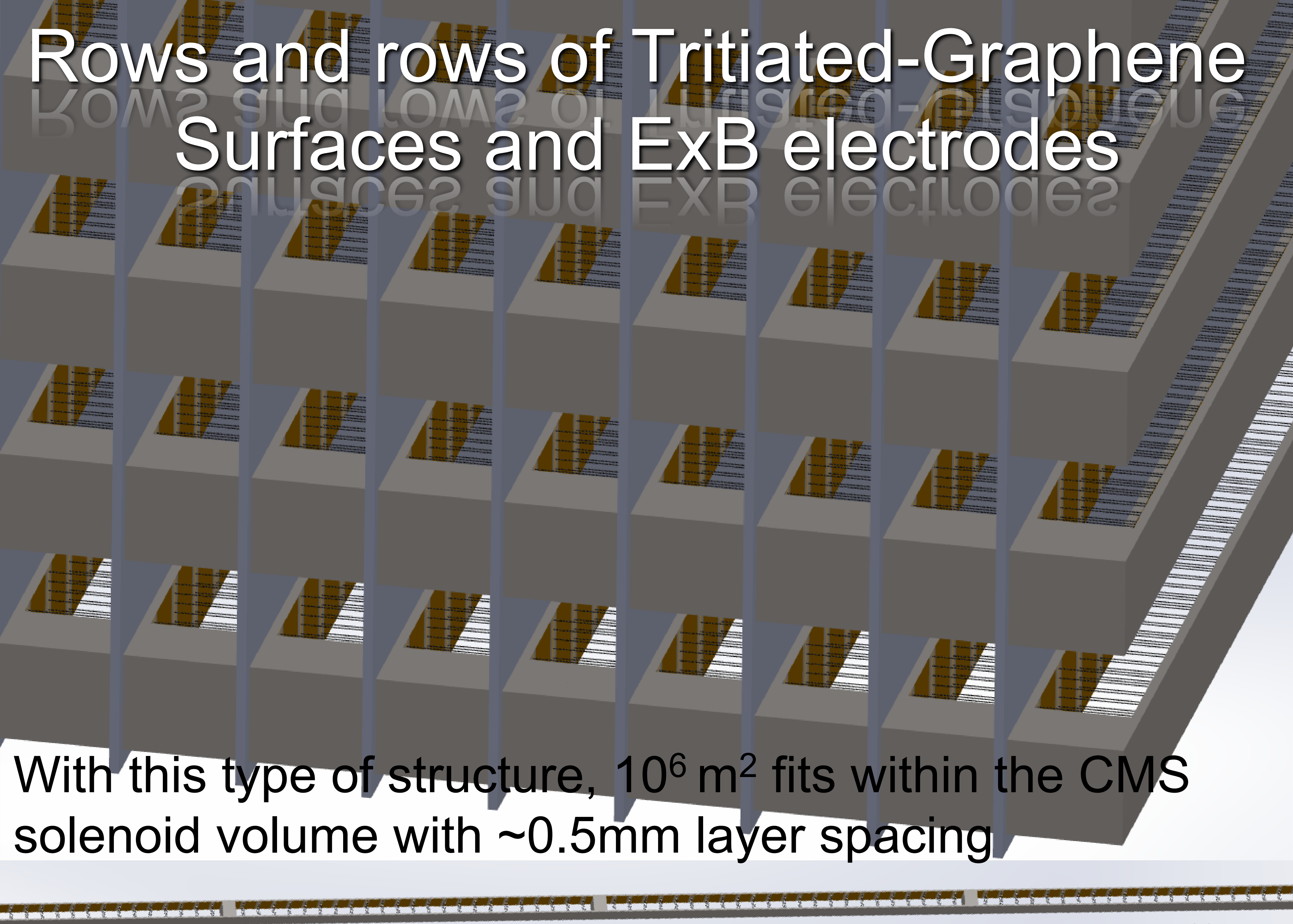




COMSOL calculation:



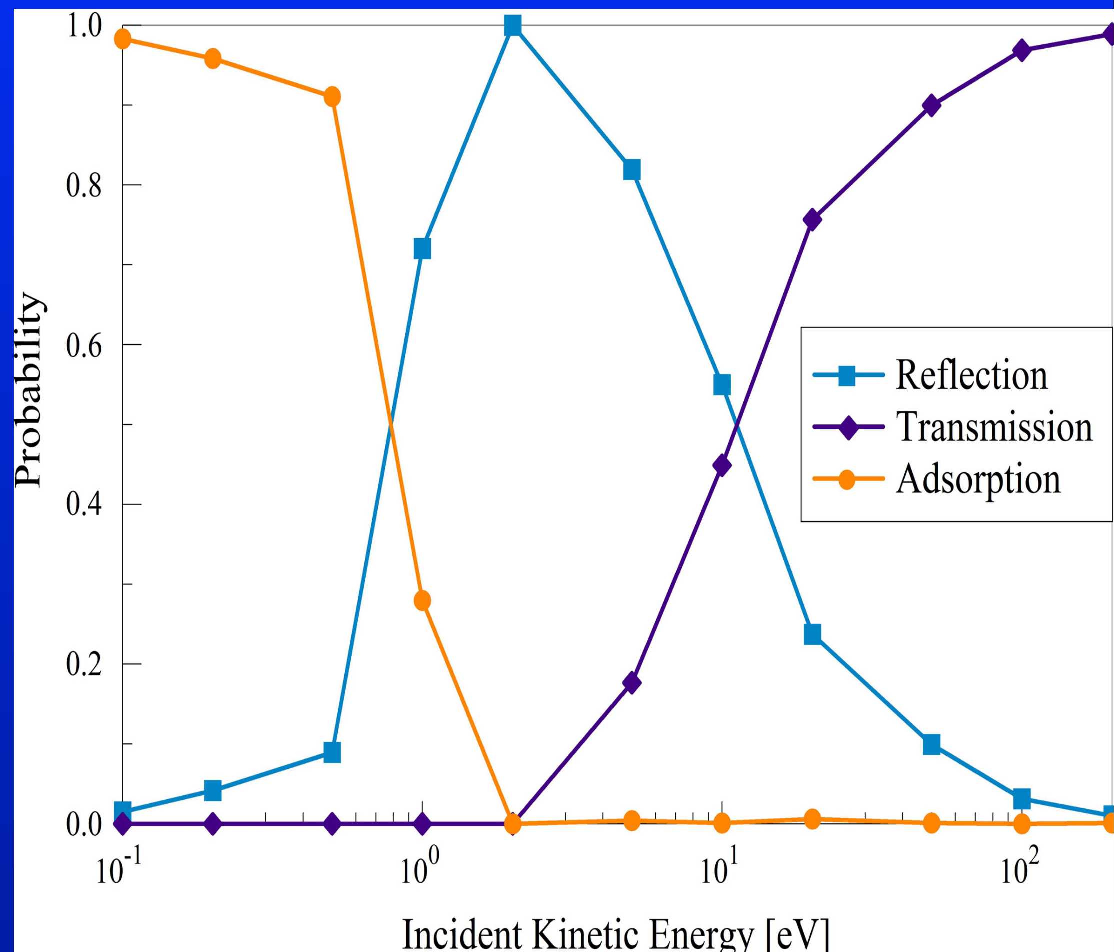
Rows and rows of Tritiated-Graphene Surfaces and ExB electrodes



With this type of structure, 10^6 m^2 fits within the CMS solenoid volume with ~0.5mm layer spacing

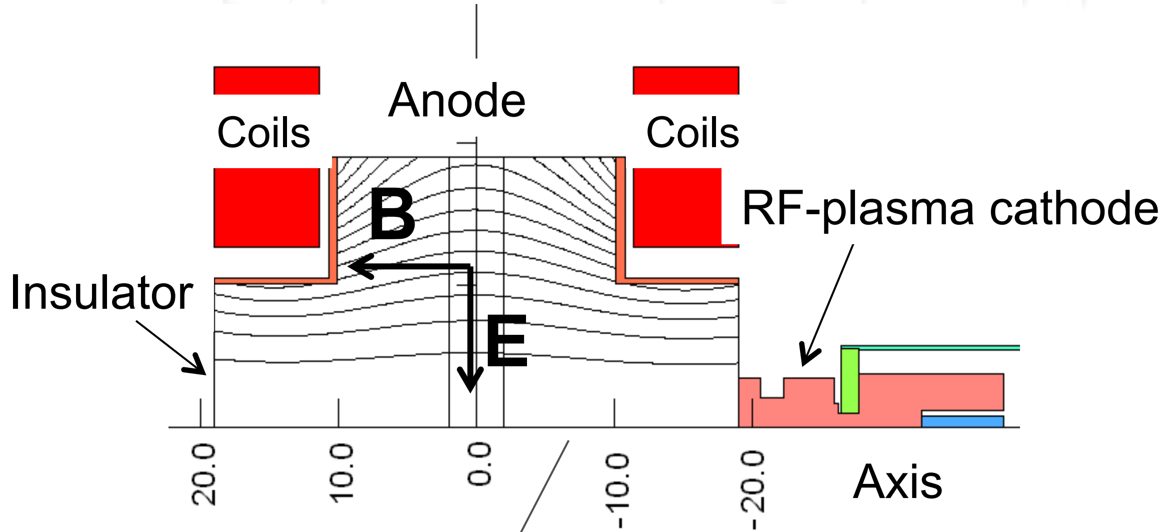
Tritium Loading

- The most common form of hydrogen loading is done at high pressure (~100atm) which is prohibitive for large surface areas.
- Ultra-low proton "beams" with T<1eV bombarding the graphene surface have near unity probability to be absorbed onto the surface
- Above 2eV, the adsorption probability drops off rapidly

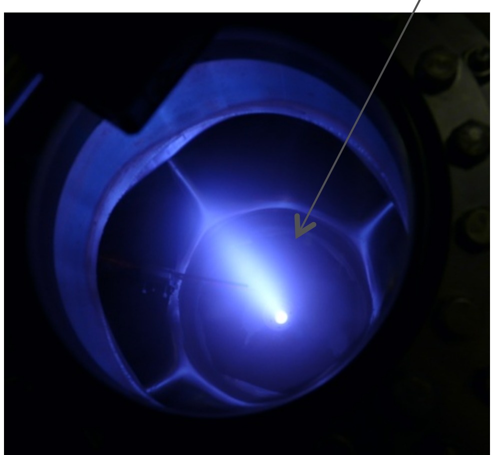


Ehemann et al. Nanoscale Research Letters 2012, 7:198

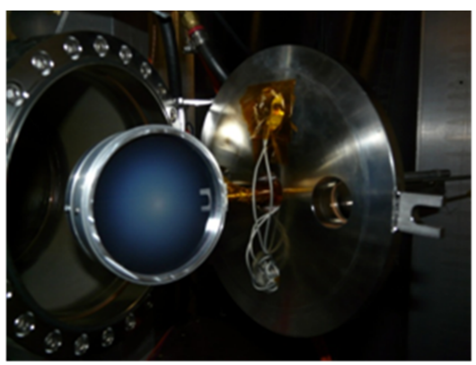
Cold Magnetized Plasma for Processing of Nanomaterials at Low Pressure



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

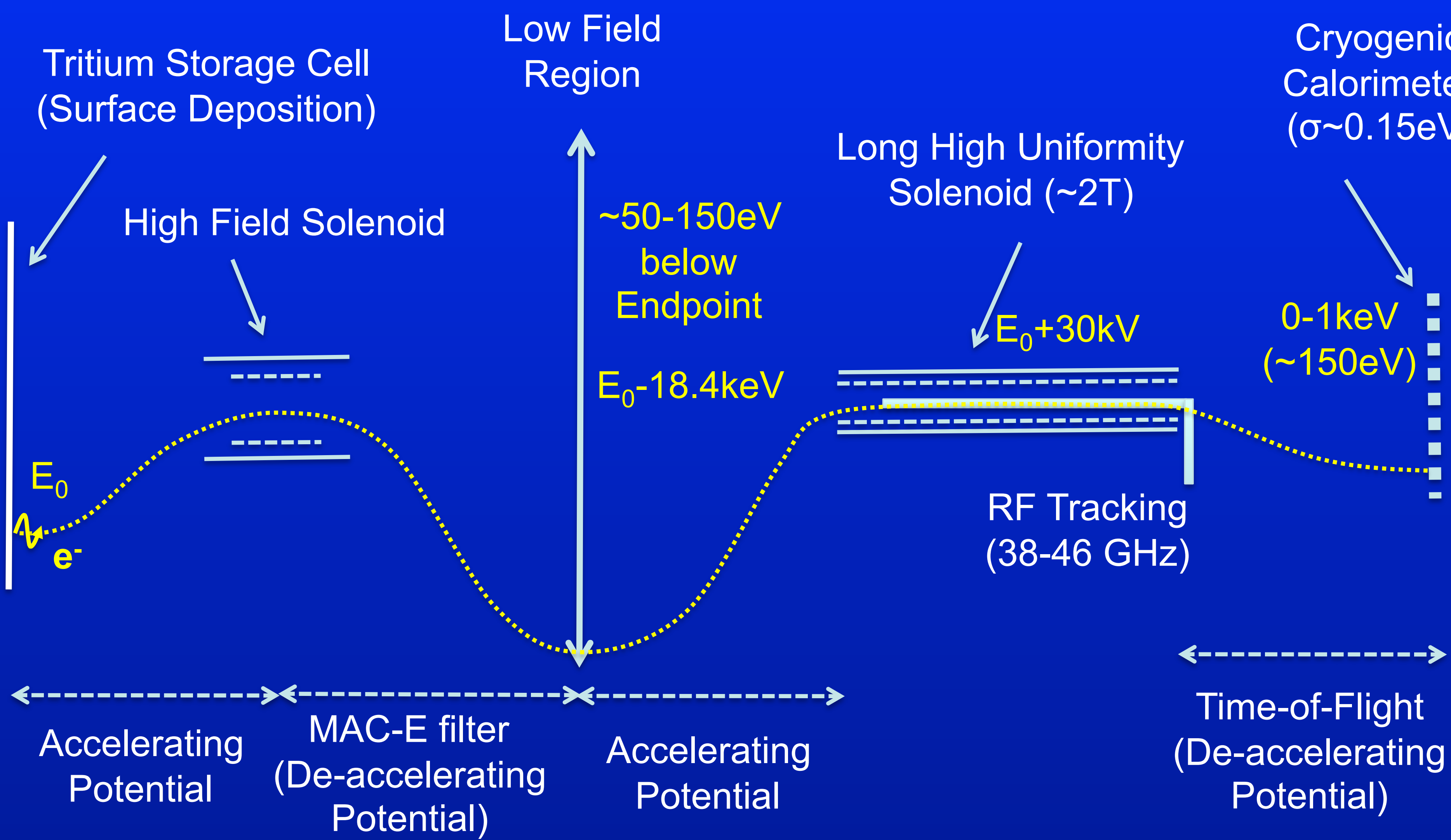
Raitses et al., DOE PSC Meeting, 2013

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

PRINCETON PLASMA PHYSICS LABORATORY

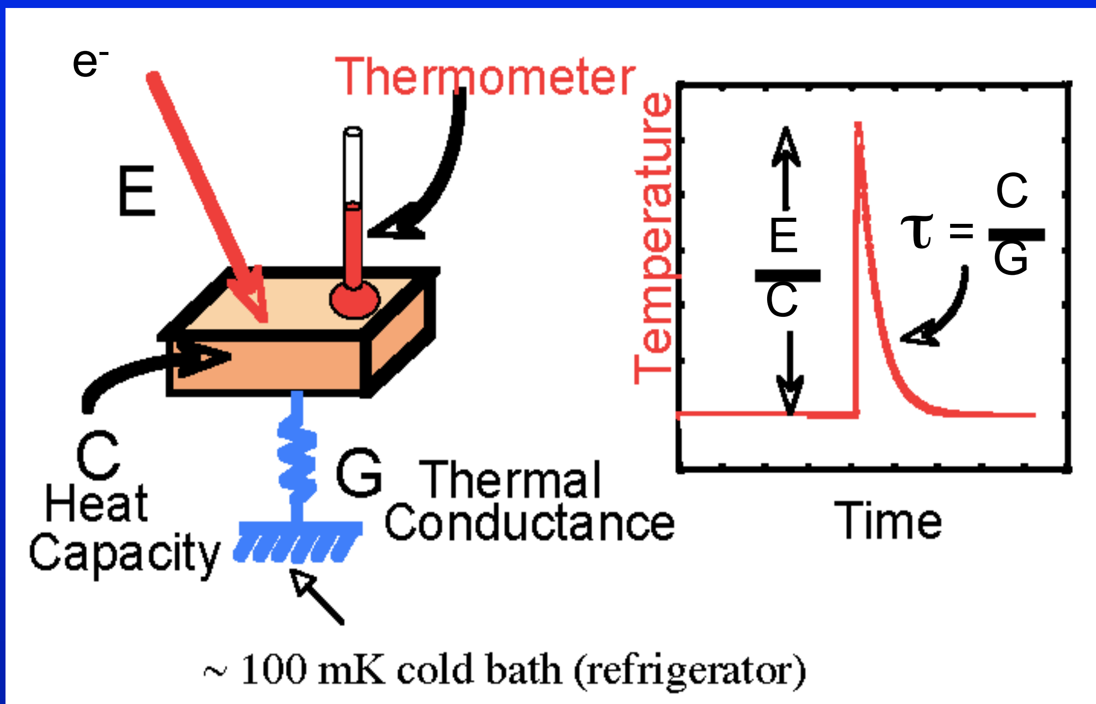
PTOLEMY Experimental Layout

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



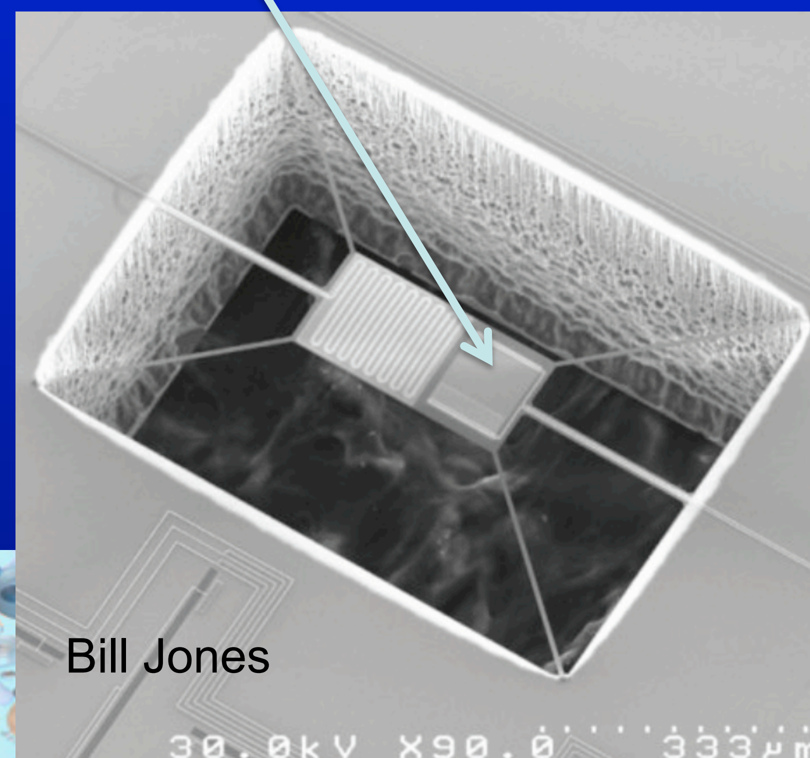
Transition-Edge Sensors for Calorimetry

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



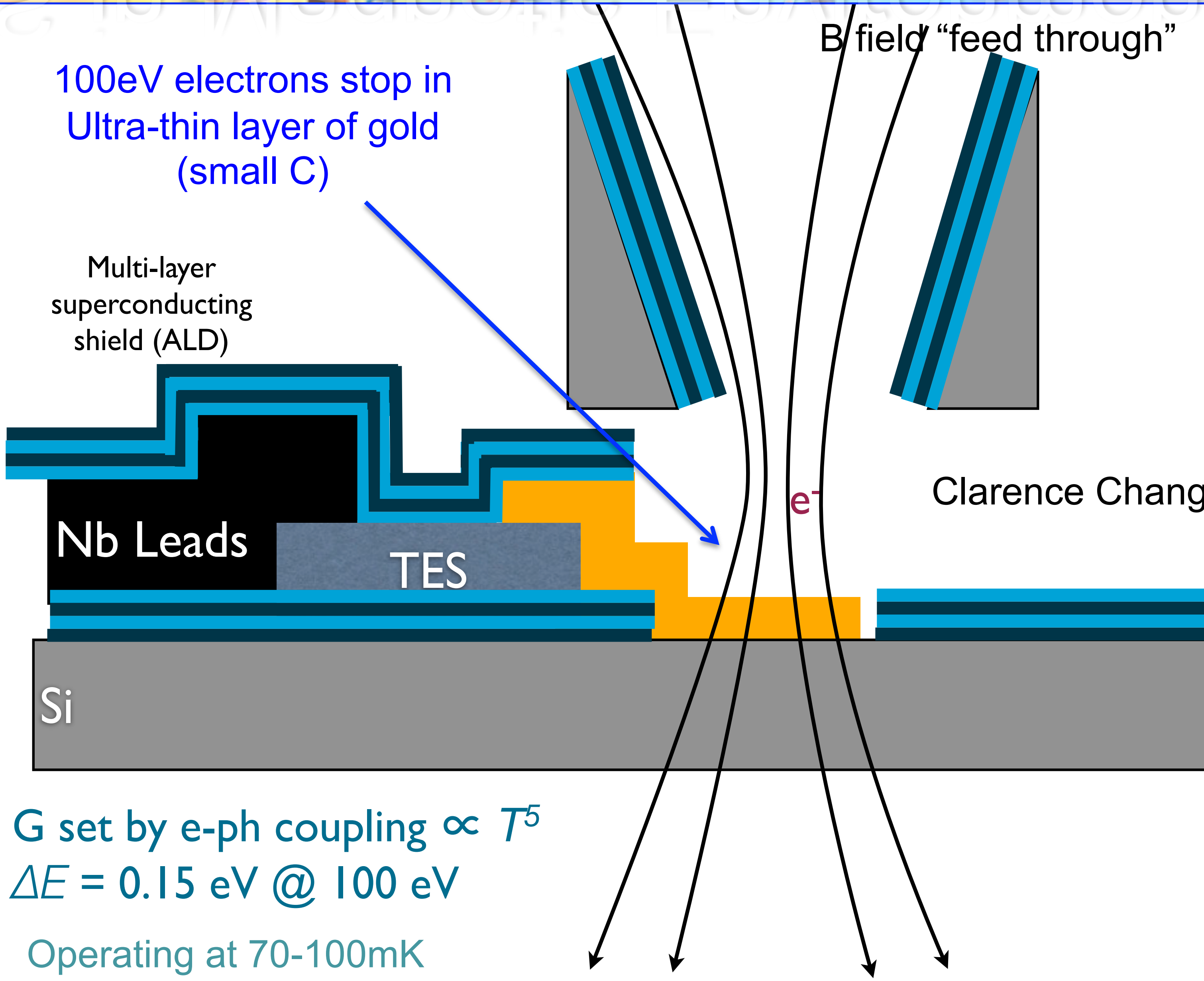
100eV electron can be stopped with very small C

(example) SPIDER Island TES



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

TES in Magnetic Environment



G set by e-ph coupling ∝ T^5

ΔE = 0.15 eV @ 100 eV

Operating at 70-100mK

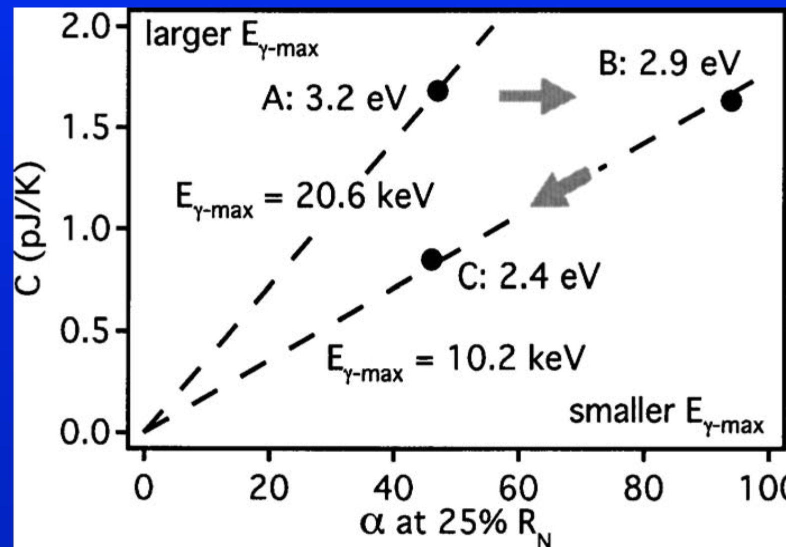
Calorimeter Energy Resolution

$$\Delta E_{\mathrm{FWHM}} = 2.355\sqrt{(4k_b T_c^2 C/\alpha)}\sqrt{(1+M^2)n/2}$$

Applied Physics Letters **87, 194103 (2005);**
doi: 10.1063/1.2061865

(C/α) scaled down by a factor of 100
Keep α large, but not too large to keep M small

Electron energy at calorimeter:	Thickness of Gold Absorber:
600 eV	9.64 nm
400 eV	6.63 nm
200 eV	3.82 nm
100 eV	2.39 nm
10 eV	0.68 nm



$$\alpha \propto \frac{1}{\Delta T_{width}}$$

- Thickness of Gold absorber can be 5 nm (~40 atomic layers), corresponding to C_p of approximately 0.04 pJ/K per mm^2
- Transition-edge steepness ($1/\alpha$) controlled by normal regions and magnetic field.

Au is not ideal as it doesn't stick well for thin layers,
Alternative materials would be studied (15nm of Bi)

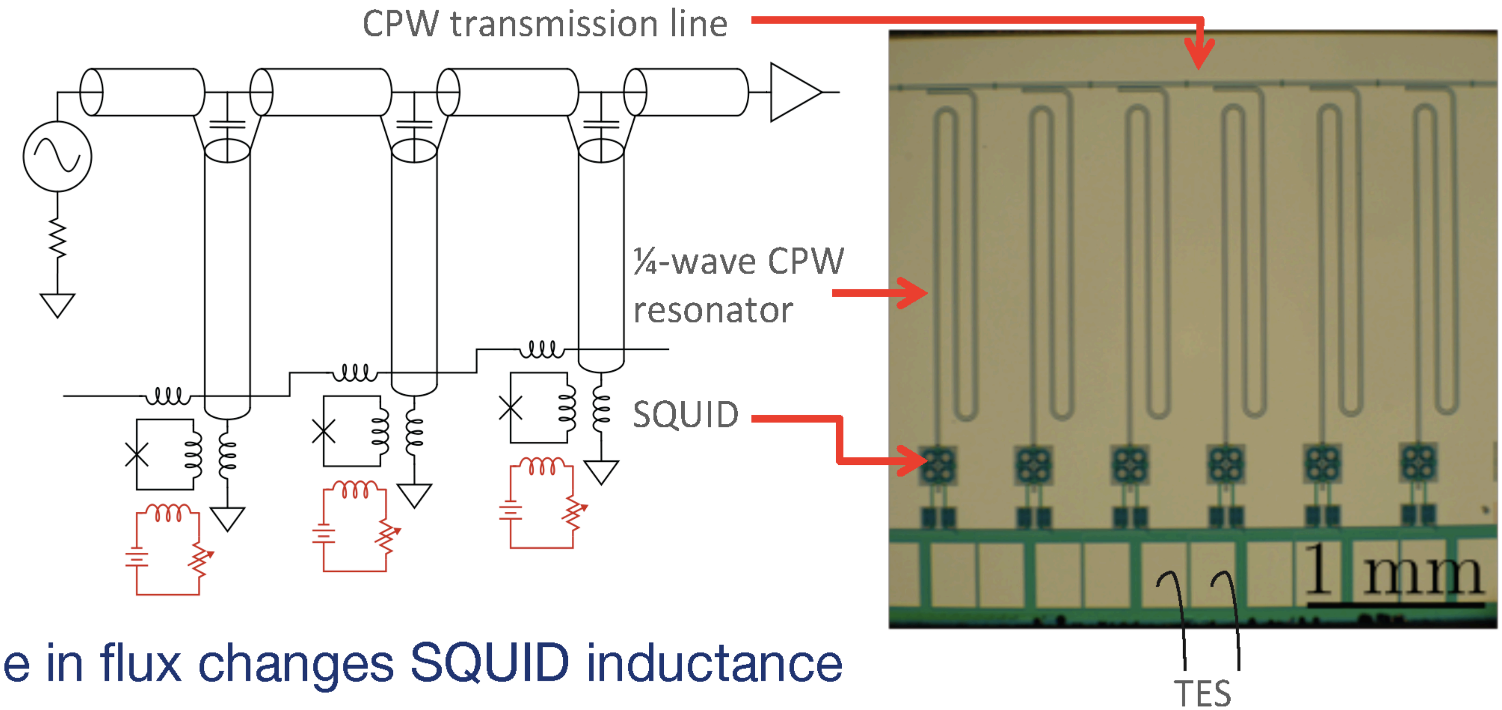
Clarence Chang

Backscatter from calorimeter can be efficiently collected by placing calorimeter surface at a +50V minimum (advantage of having only atomic electron backscatter)

Highly Multiplexed SQUID Readout

Microwave-readout Massive SQUID Multiplexer

Clarence Chang

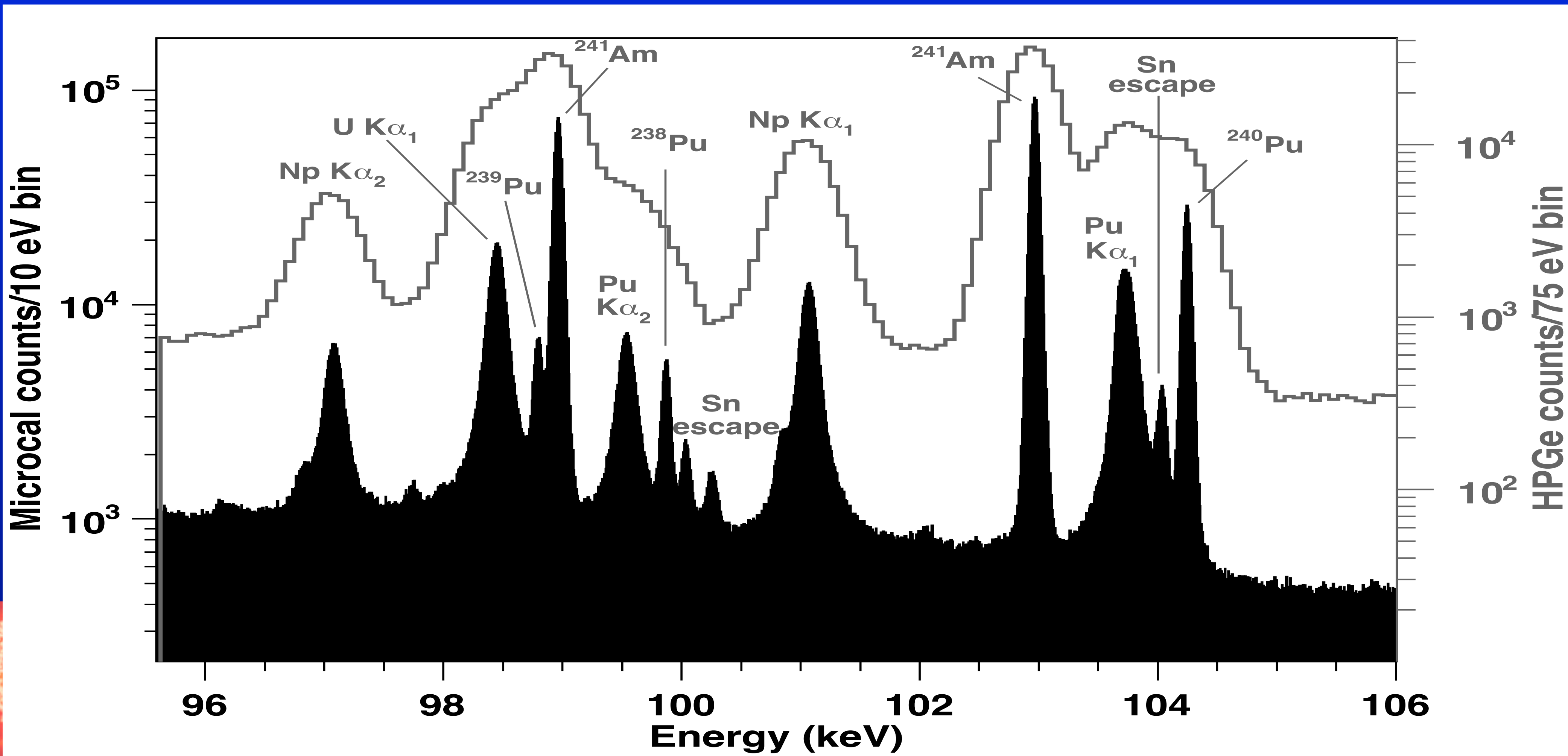


- Change in flux changes SQUID inductance
- at 1-10 GHz, can support ~1 MHz of bandwidth with ~1000 channels per line
- Originally developed for CMB measurements, recently demonstrated successful operation with X-ray u-cals

Kent Irwin

Microcalorimeter Resolution

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



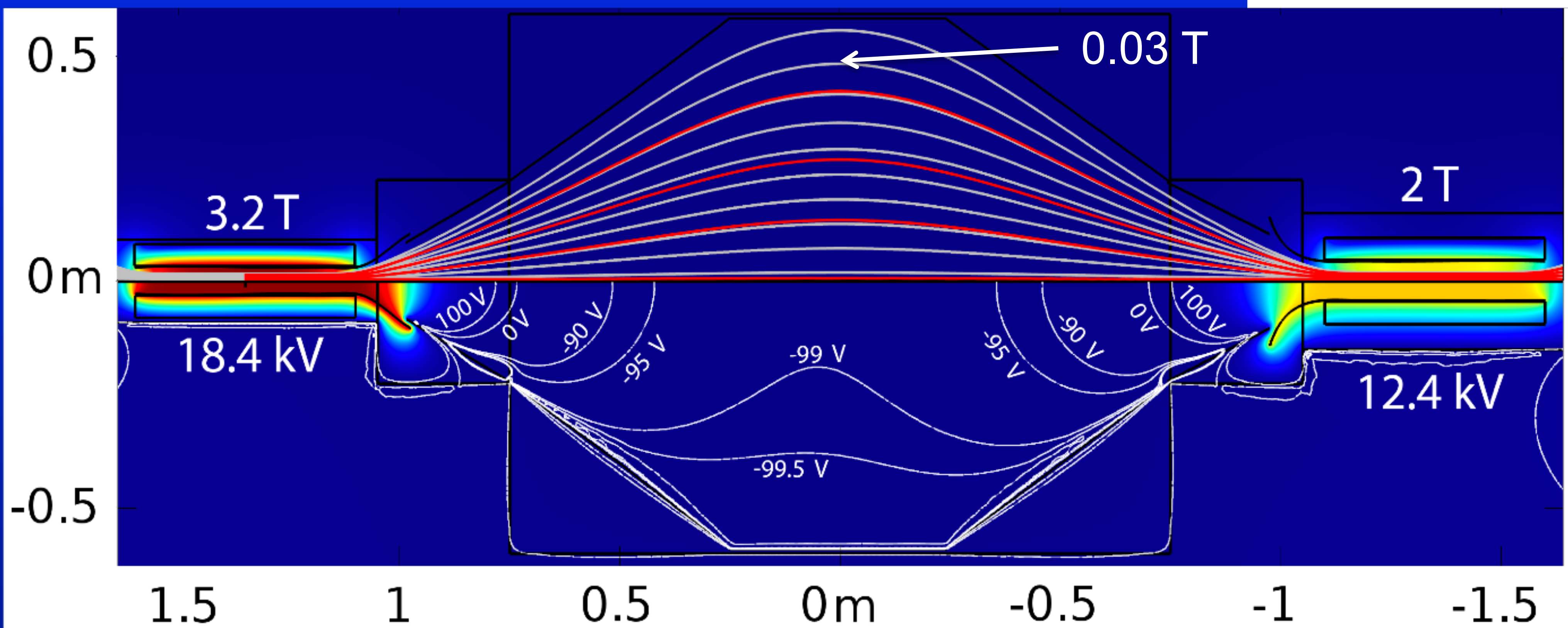
Calorimeter Rate

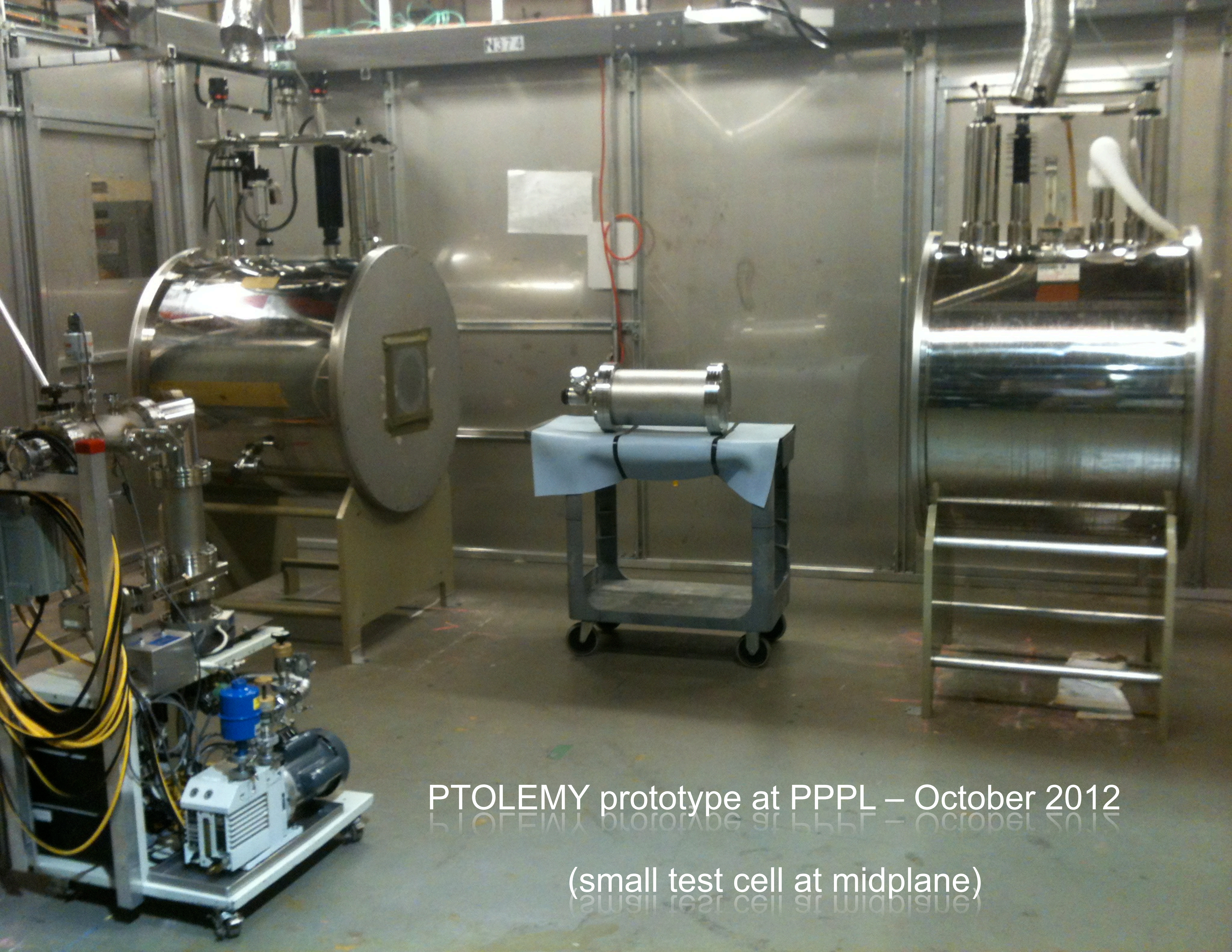
- Rate suppression is achieved with a MAC-E filter 2×10^{-10} suppression at 10eV, that scales as the endpoint distance cubed $(E-E_0)^3$
  - At 0.1eV and zero neutrino mass, there are roughly 10^5 more background expected than signal – a finite neutrino mass is required to introduce a 2m gap between signal and background
  - At 0.001eV, the rate of signal and background are approximately equal
- 10eV endpoint window for 100g of tritium corresponds to $(2\times10^{25})(2\times10^{-10})/(4 \times 10^8 s)=10MHz$
  - 10^3-10^4 calorimeter channels (for 10kHz bandwidth)

PTOLEMY MAC-E filter

- MAC-E filter cutoff of 10^{-2} to 10^{-3} precision on electron energy
  - Energy window below endpoint needed for 2π accepta
  - Voltage of filter cut-off accurate to ~1eV

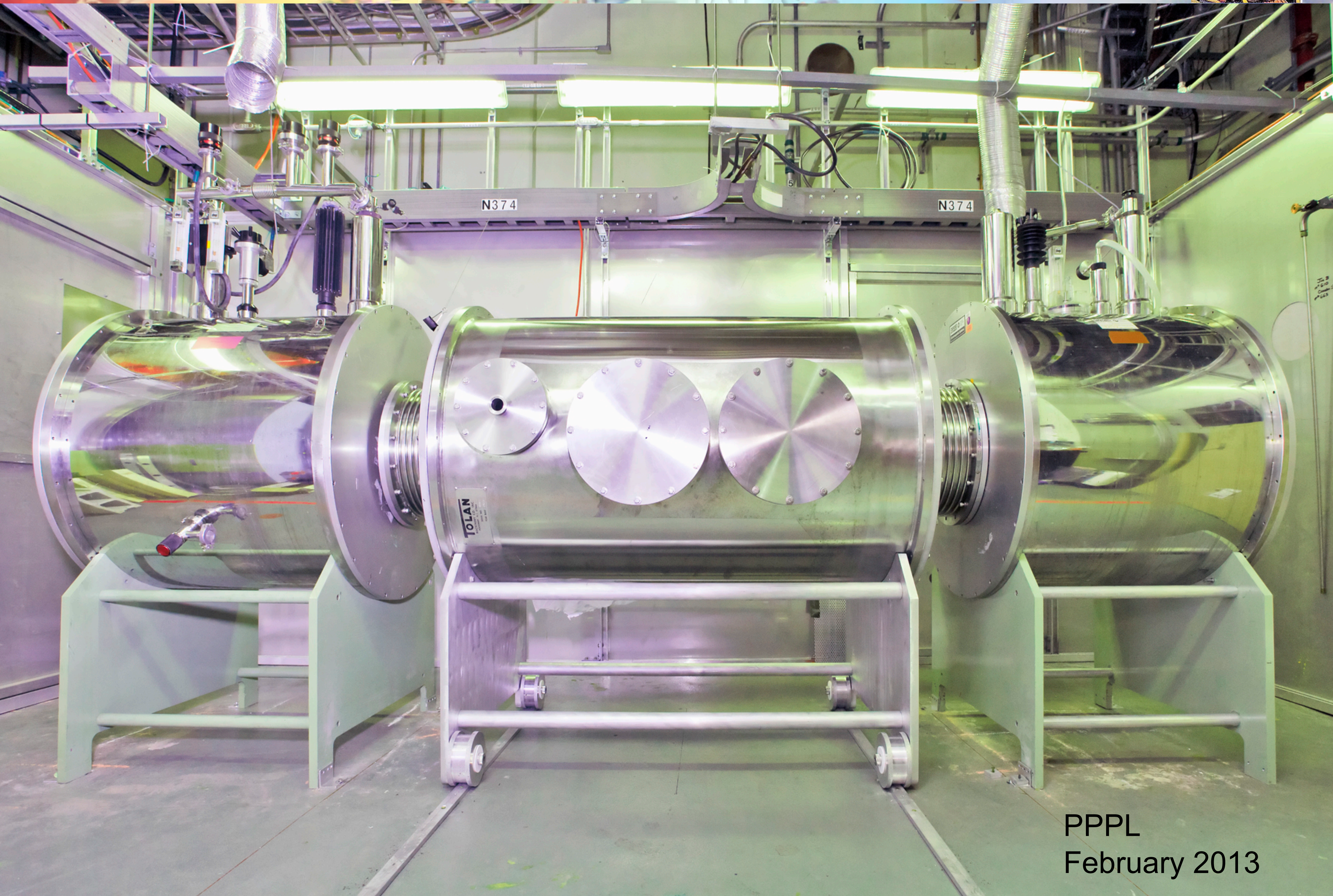
Adiabatic Invariant: $\mu = \frac{E^{\perp}}{B}$




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

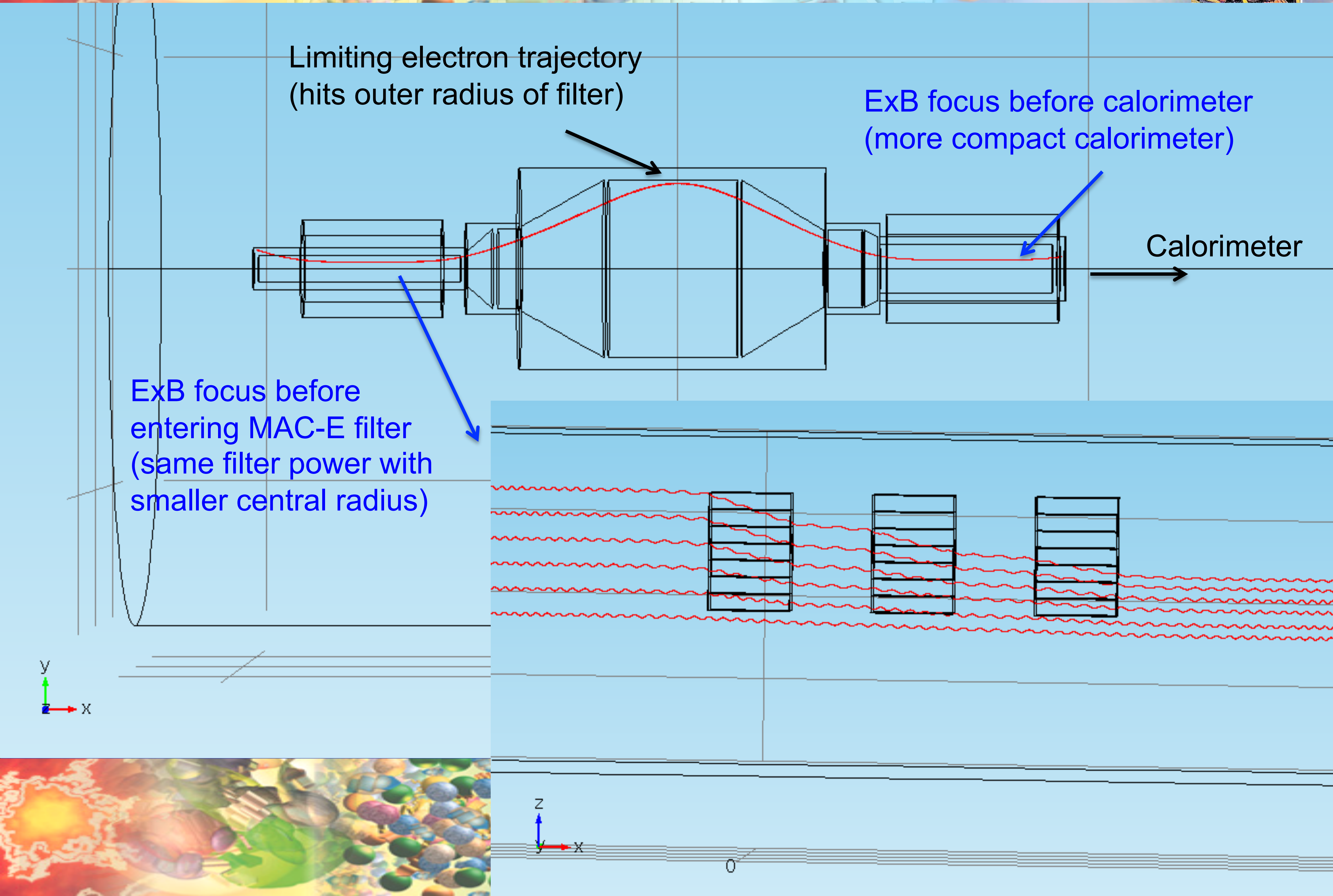
PTOLEMY prototype at PPPL – January 2013
(large vac-tank ready for install)

PTOLEMY

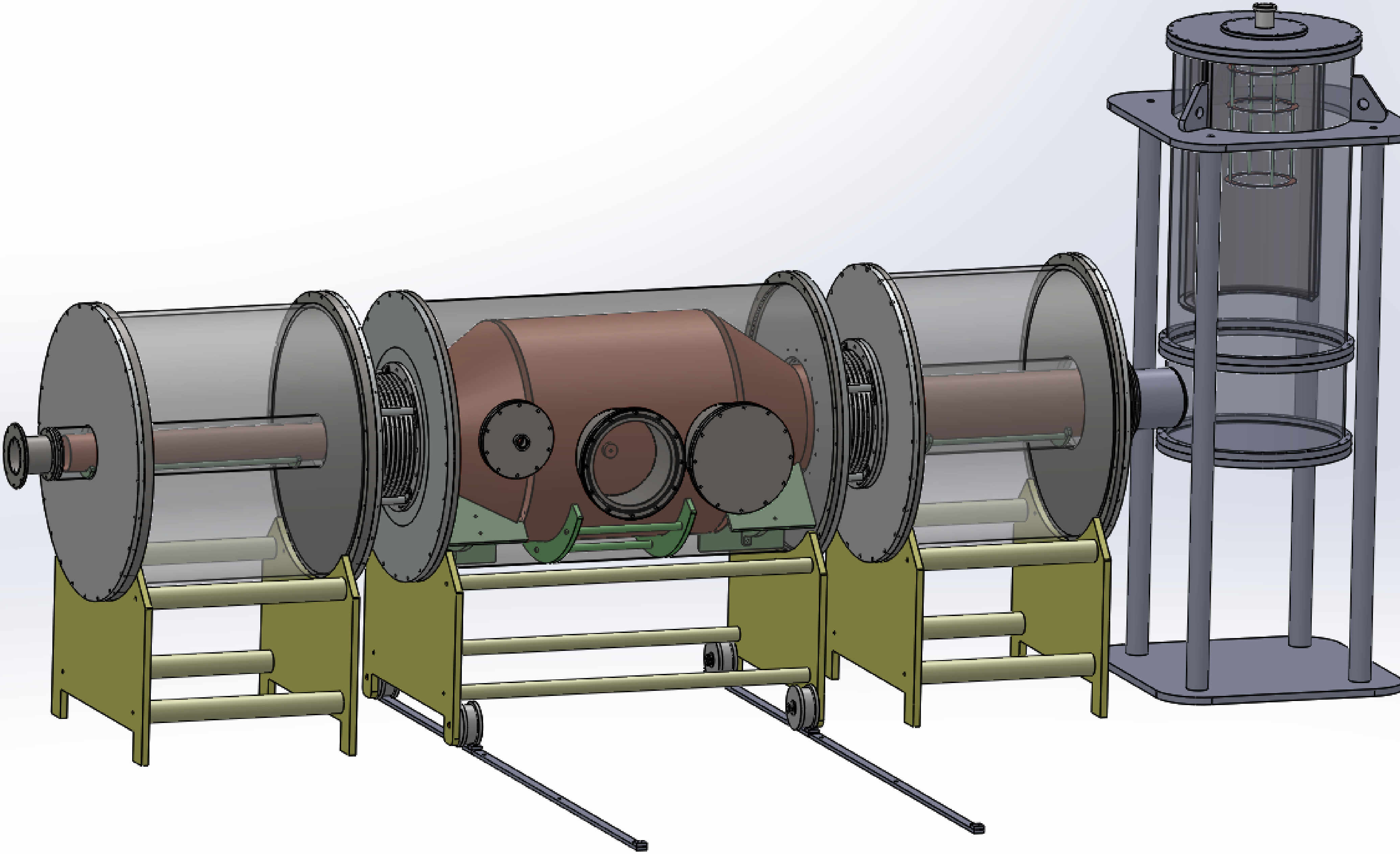


PPPL
February 2013

MAC-E Filter Size

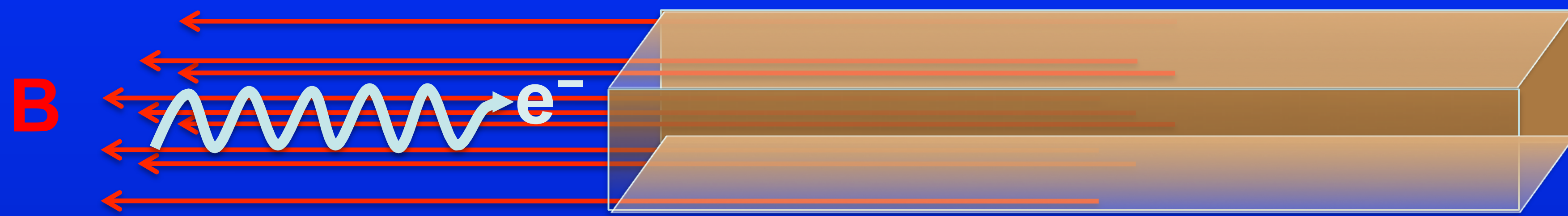


Calorimeter Interface to MAC-E Filter



Semi-relativistic Electron Identification

Concept Developed by Project 8

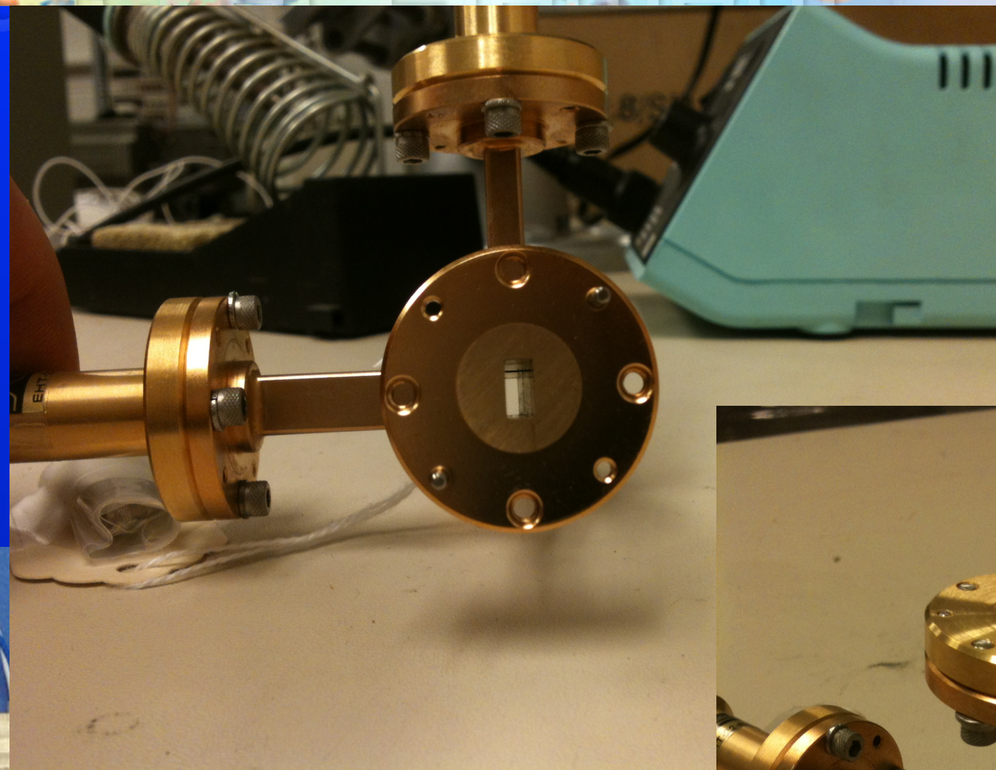


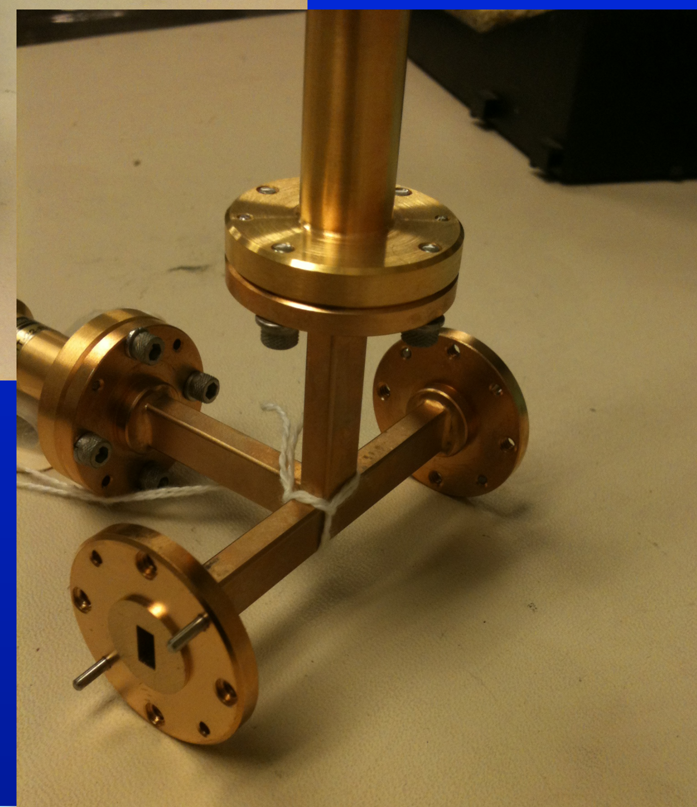
- RF tracking and time-of-flight
  - Thread electron trajectories (magnetic field guide lines) through a waveguide with ~wide bandwidth (few x10^{-5}) to identify cyclotron RF signal in transit times of order 0.2μsec
    - Currently using WMAP (Norm Jarosik) HEMT amplifiers with 1K/GHz noise and operating 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 x10^{-5})

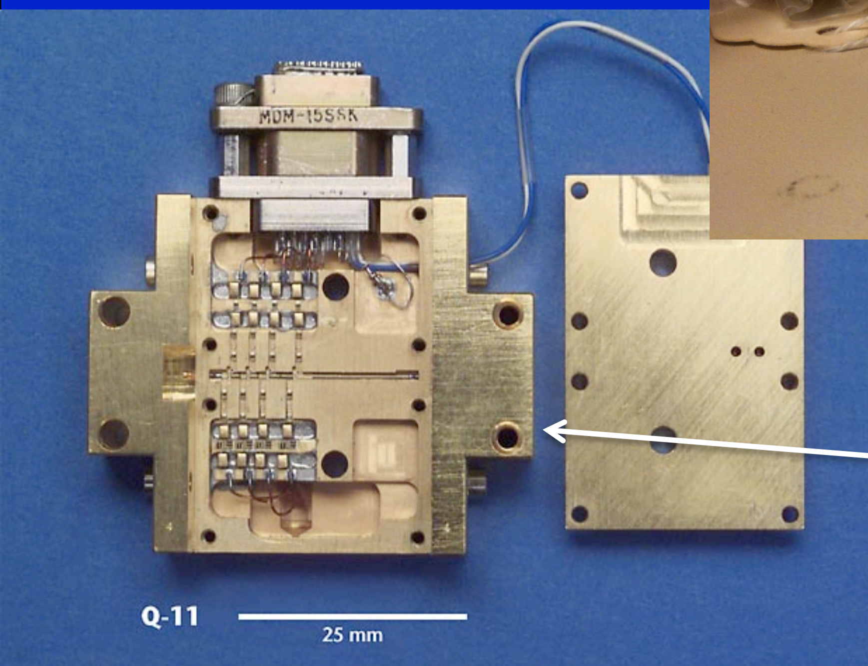
RF Tracker Element

Readout Orthogonal to Electron Trajectory

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



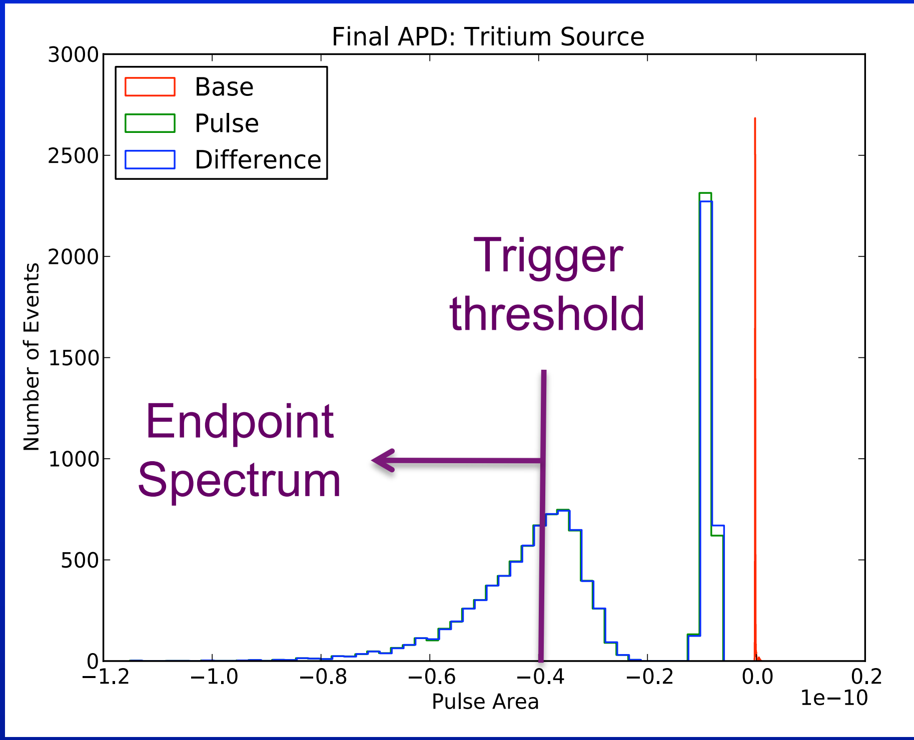


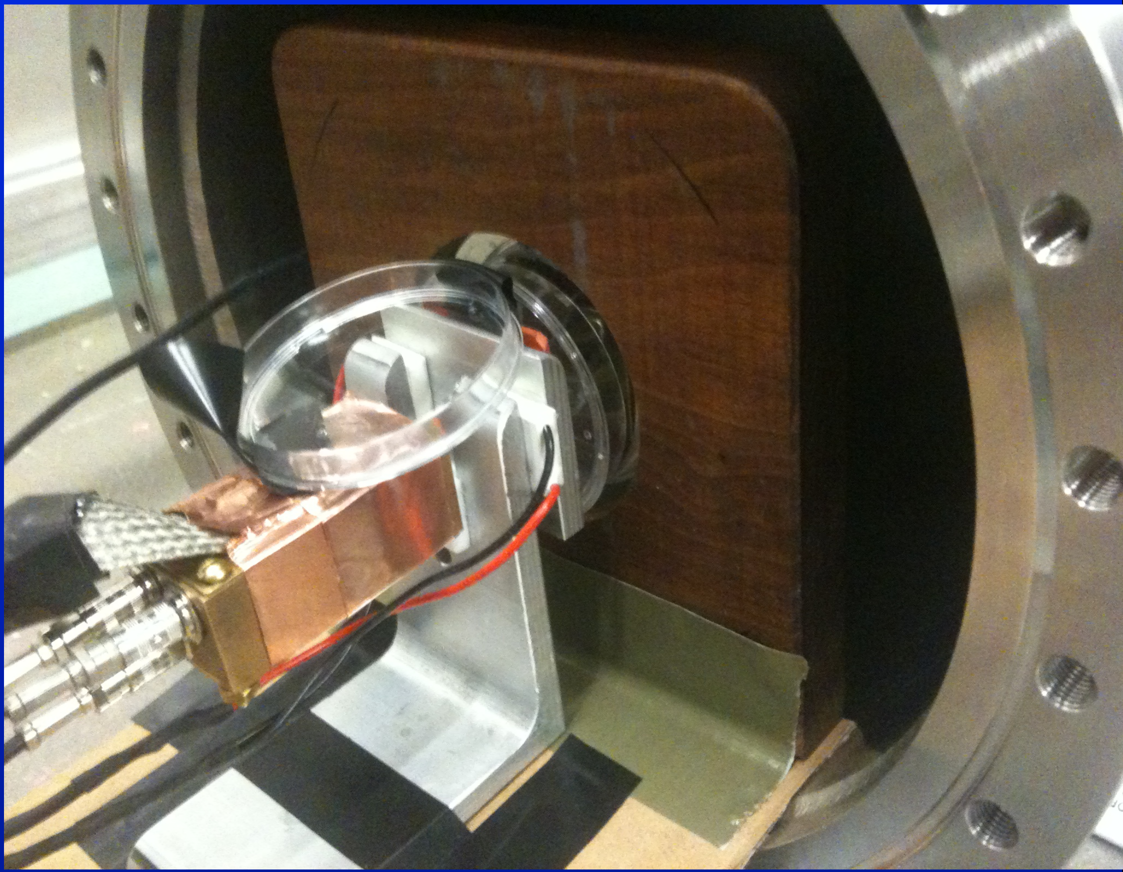


Q-Band (38-46 GHz)
WMAP Amplifier

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)





What about Carbon-14?

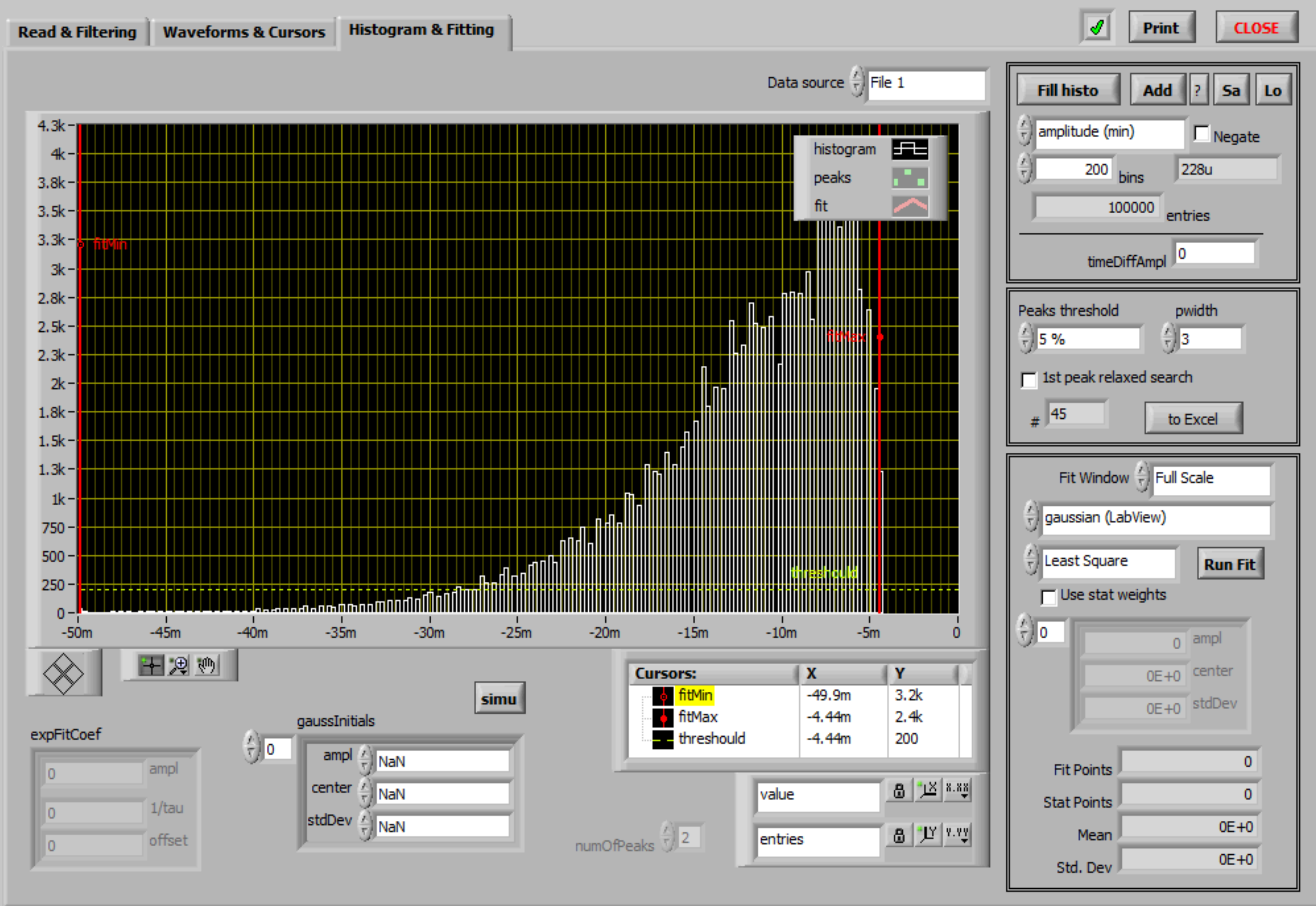
- Take a biological sample from centuries ago exposed to atmospheric carbon

→ 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

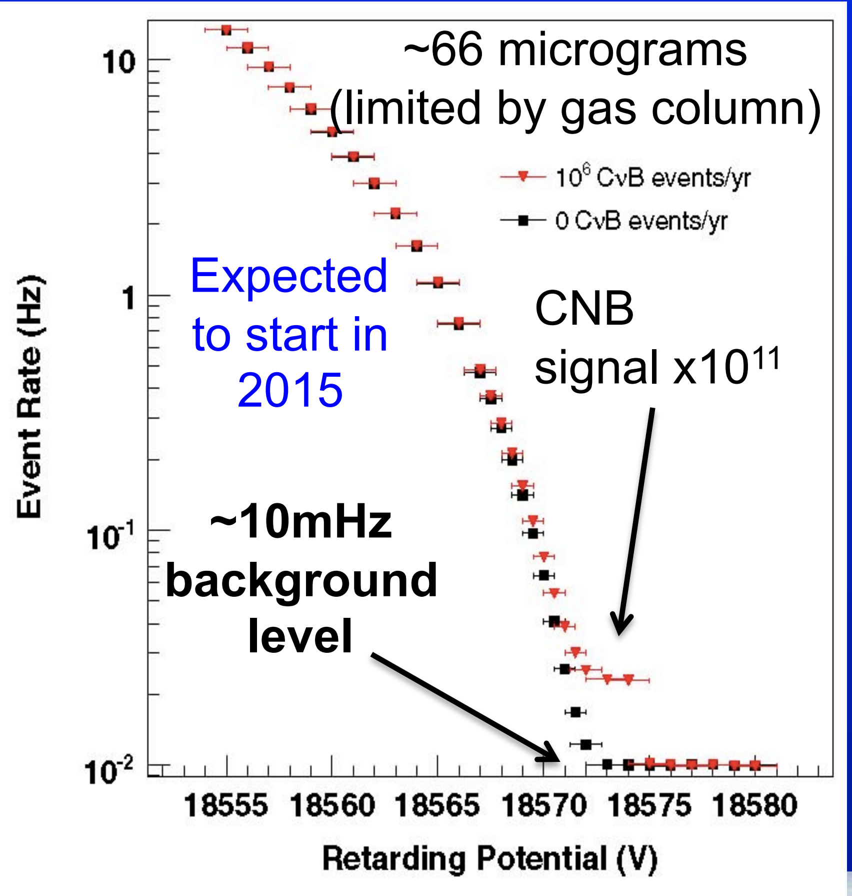
In a window of 0.5 eV (Q=156keV), biological levels of C^{14} are four orders of magnitude too much radiation for a relic neutrino experiment with a graphene substrate. Fortunately, underground carbon sources have 10^{-18} levels of C^{14} (achieved in Borexino).

Carbon-14 Spectrum



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**

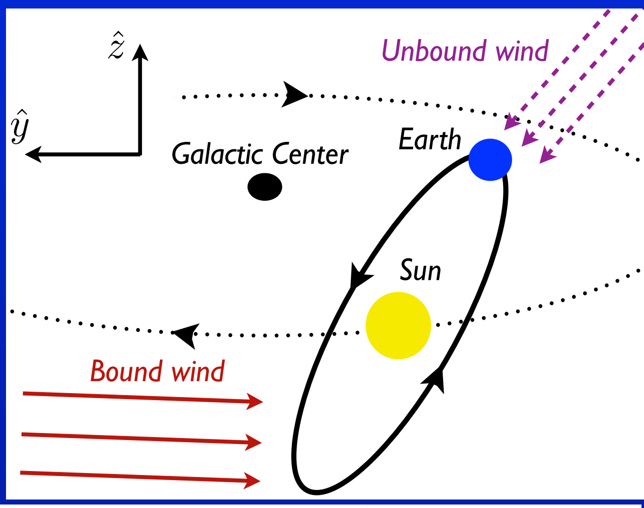


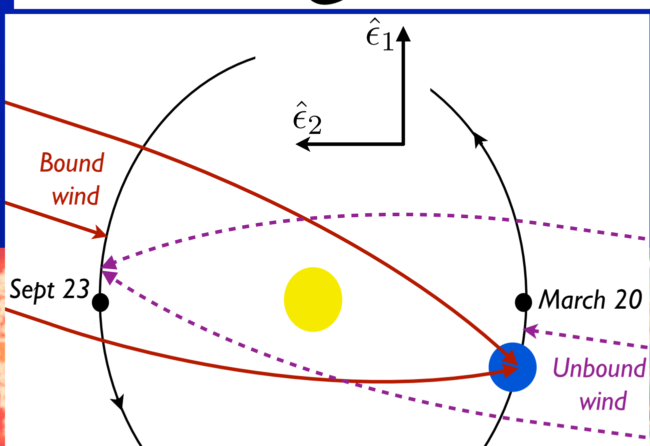
Annual Modulation of Cosmic Relic Neutrinos

B. Safdi, M. Lisanti, et al.
http://arxiv.org/pdf/1404.0680.pdf

If CMB rest frame = relic neutrino rest frame,
the direction and velocity of the Sun is known relative
to the rest frame (<v> ≈ 370 km/s)
represented by the unbound neutrino wind.

Sensitivity to relic neutrino velocity and direction through
annual **modulation** amplitude (0.1-1%) and phase





Additional sensitivity to neutrino velocity and direction for a polarized tritium

$$d\sigma_{\text{NCB}} \propto \left[1 + a\frac{\mathbf{p_e}\cdot\mathbf{p}_\nu}{E_e E_\nu} + A\frac{\hat{\mathbf{s}}\cdot\mathbf{p_e}}{E_e} + B\frac{\hat{\mathbf{s}}\cdot\mathbf{p}_\nu}{E_{\bar{\nu}}}\right]$$

Tritium polarization calibrated using beta decay electrons.

Velocity sensitivity provides possibility to measure:
Relic Neutrino **Rest Frame**, and potentially,
Relic Neutrino **Temperature** (from velocity and mass)

Neutrino Calibration Source

(quoted from work of) **V. Kornoukhov**

^{51}Cr decays to ^{51}V (Vanadium) through electron capture

$$e^{-} + (27,24) \rightarrow (28,23) + \nu_e$$

Neutrino lines are 746(81%), 751(9%), 426(9%), 431(1%) keV.

Direct neutrino detection at short distances considered for neutrino oscillation experiments into sterile neutrinos.

Capture rate calculation (B. Safdi)

$\sigma(^{51}Cr)$ / σ(relic neutrinos) ~ 19 (weighted)

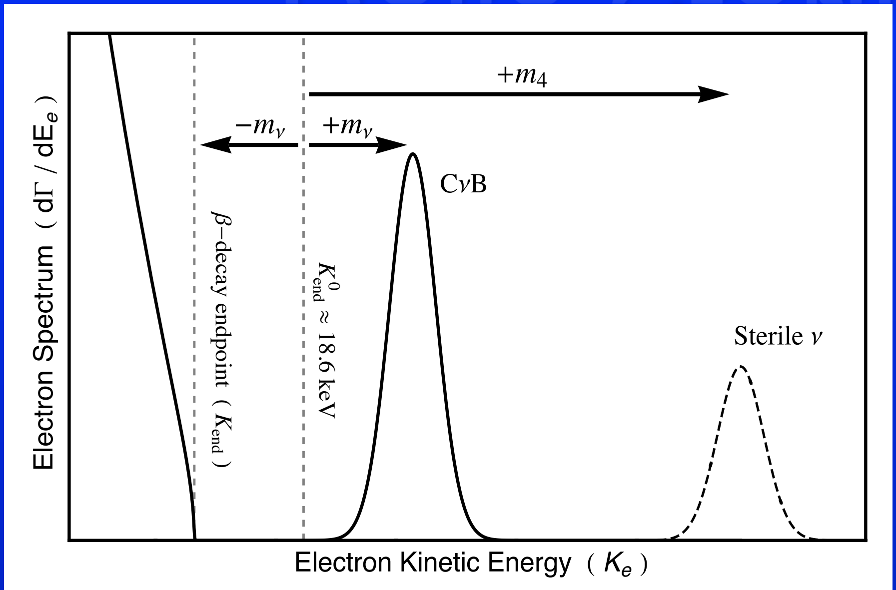
N_{events} ~ 40 events / 100g-years $(1 \text{ m} / R)^2$ $(M_{source}$ / MCi)

Relativistic neutrinos → clear angular dependence from tritium polarization

Neutrino scattering off of atomic electrons also a signal for the neutrino flux

Also considering Titanium thin films embedded with tritium to produce a high mass (kg), low resolution neutrino capture target for solar neutrinos and for a relic sterile neutrino search.

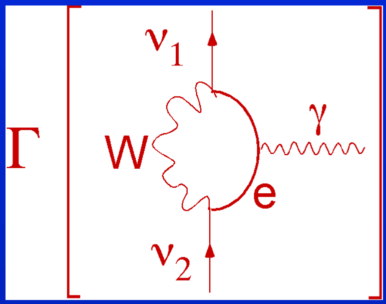
Relic Sterile Neutrinos



Long, Lunardini, Sabancilar: arXiv:1405.7654

Either a Majorana or a Dirac neutrino can decay radiatively:

$$\nu_2 \to \nu_1 + \gamma$$



$\propto G_F^2[m(\nu_2)]^5$

For $m(\nu_2) \sim 0.5$ eV,

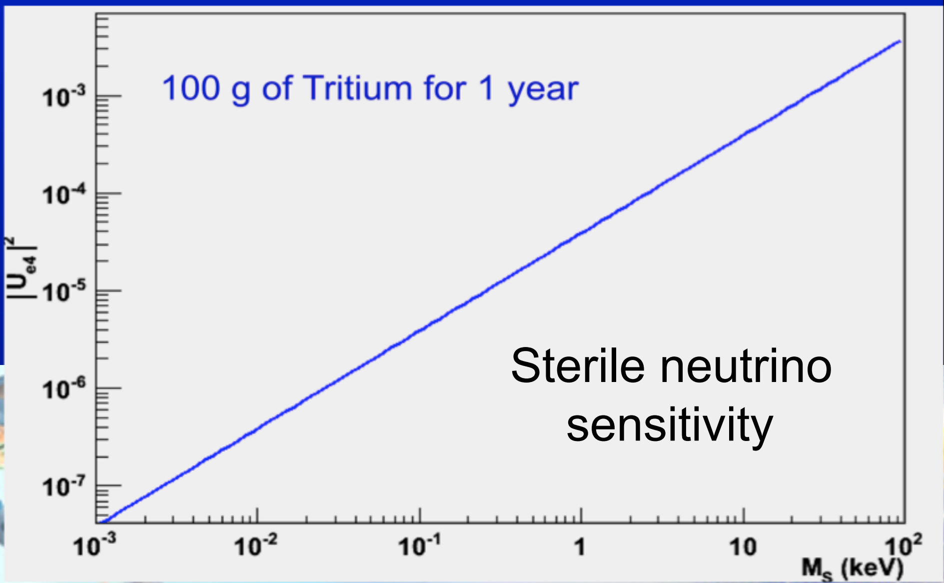
$|U_{e4}|^2 \sim 0.03$, $f_c \sim 20$, $\Delta N_{eff} = 1$

$N_{capture}$ ~5 events/100g-year

For $m(\nu_2) \sim 1$ keV,

$|U_{e4}|^2 \sim 10^{-4}$, $f_c \sim 5000$ ($\rho_{DM} \sim 0.3$ GeV/cm^3),

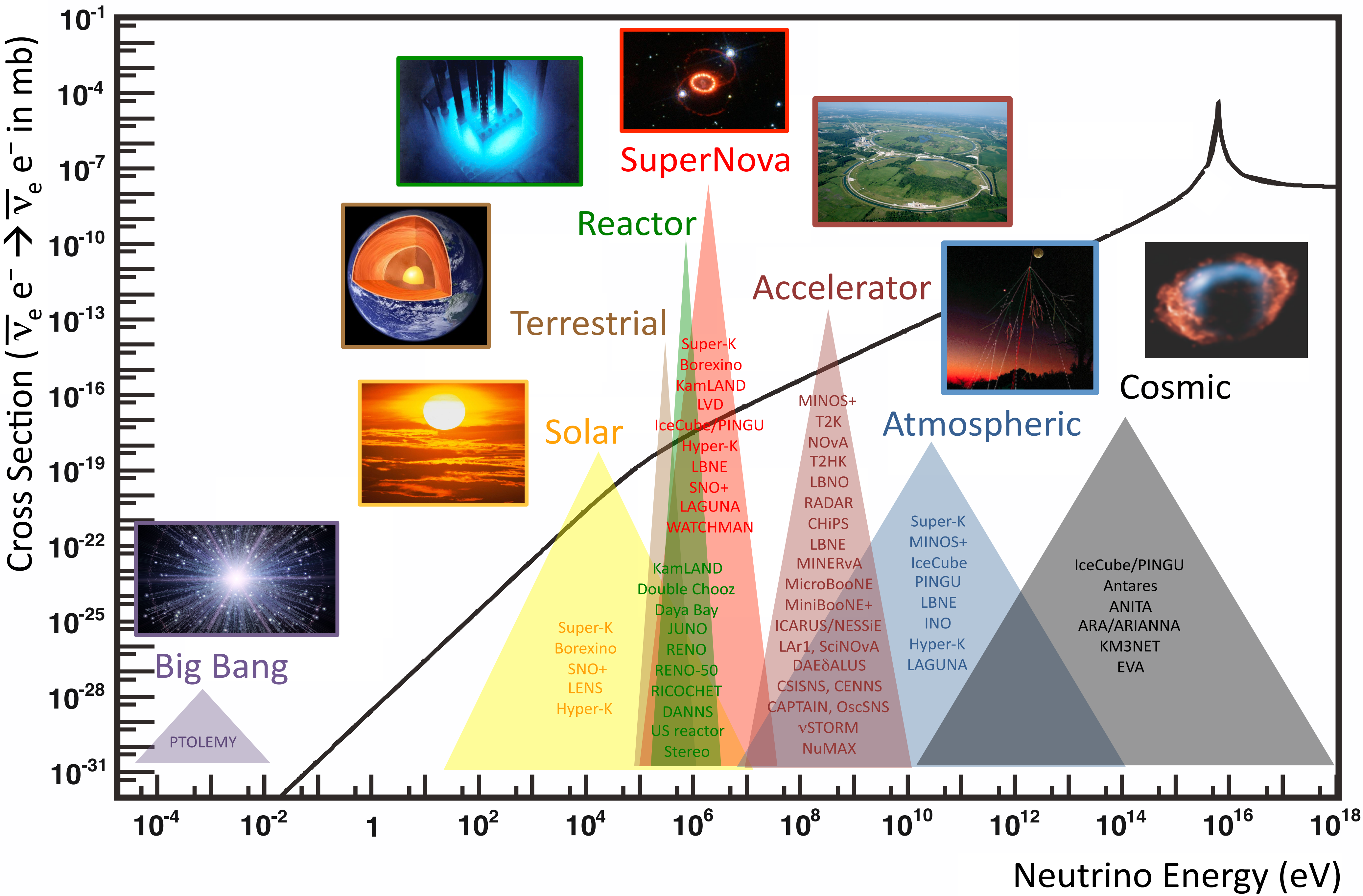
$N_{capture}$ ~4 events/100g-year (10kg?)



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)
  - Competitive resolution performance on neutrino mass (systematics will be measured)
  - Early universe relic sterile neutrino limits (up to ~10keV) for a range ($|U_{e4}|^2 \sim 10^{-4}$-10^{-6}) of sterile neutrino electron flavor content

Overview of Neutrino Experiments



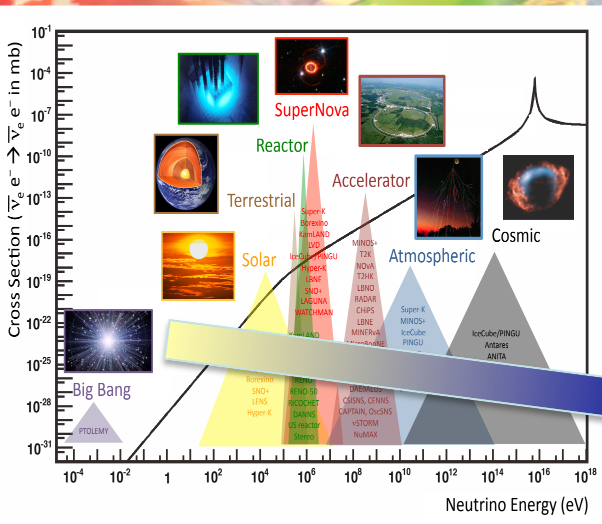
What can Relic Neutrino Density tell us?

- 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

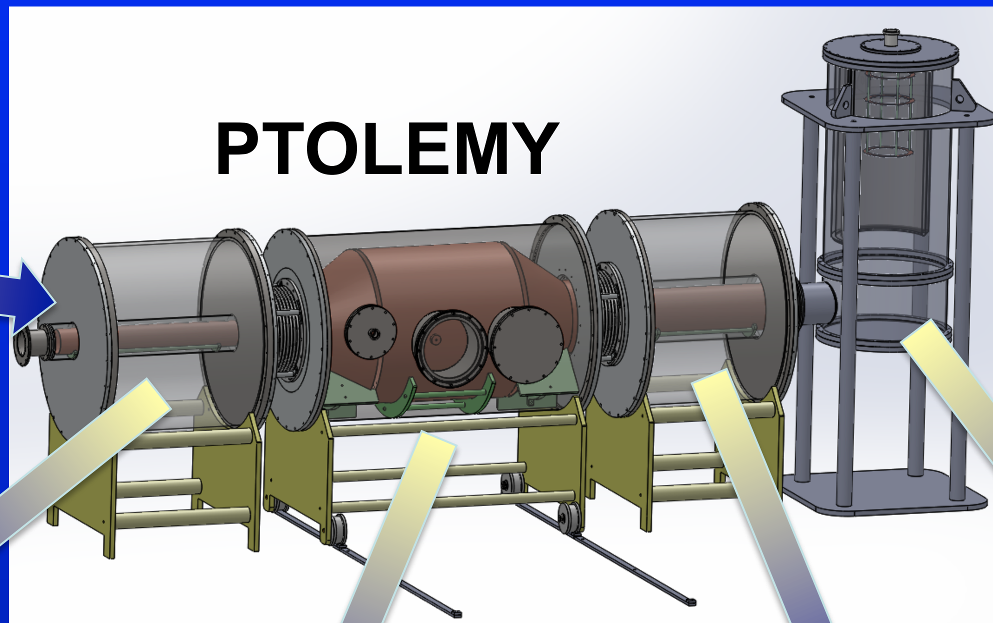
What can Relic Neutrino Density tell us?

- 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

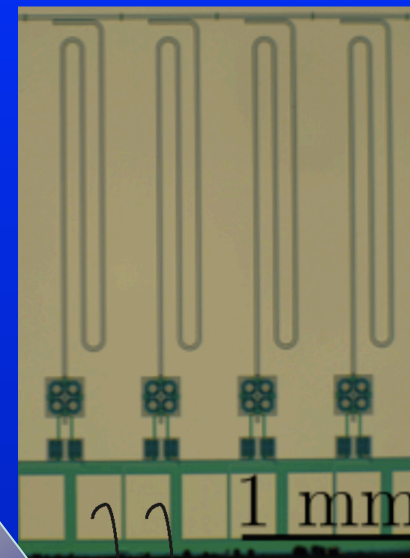
Summary



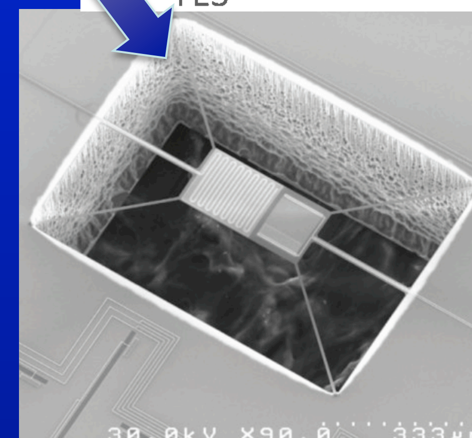
SuperNova
Reactor
Terrestrial
Accelerator
Solar
Atmospheric
Cosmic
Big Bang
PTOLEMY
Cross Section ($\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$ in mb)
Neutrino Energy (eV)



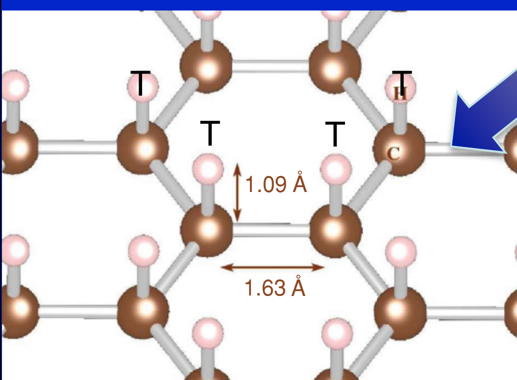
PTOLEMY



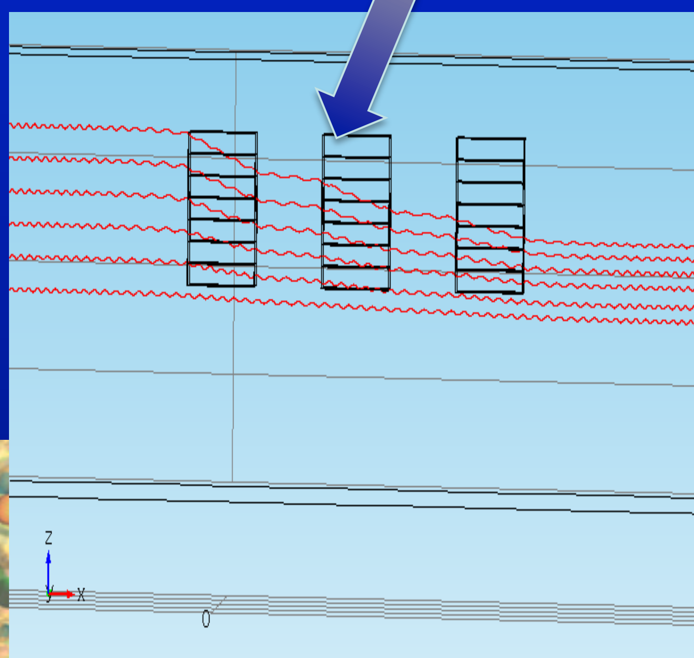
1 mm
TES



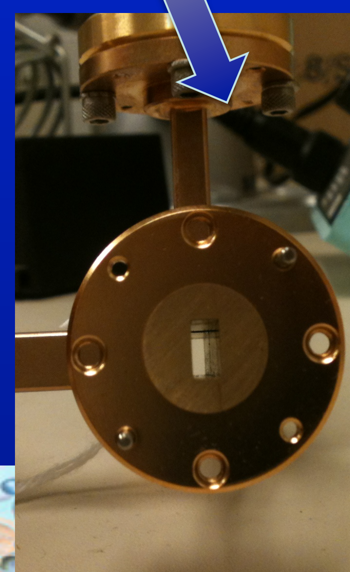
30.0kV X90.0 333µm



T
T
T
T
1.09 Å
1.63 Å
C



Z
X



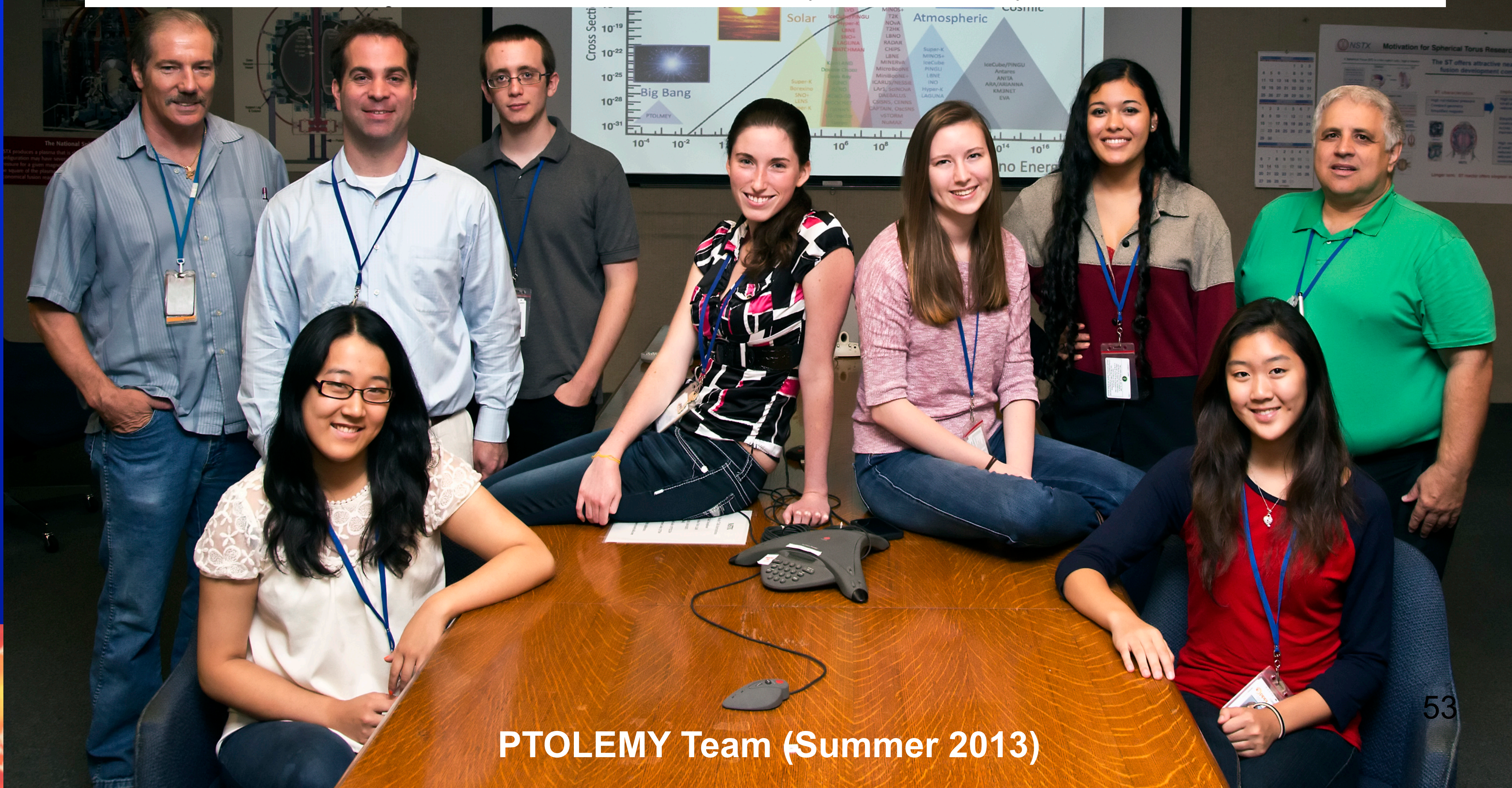
Backup Slides

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

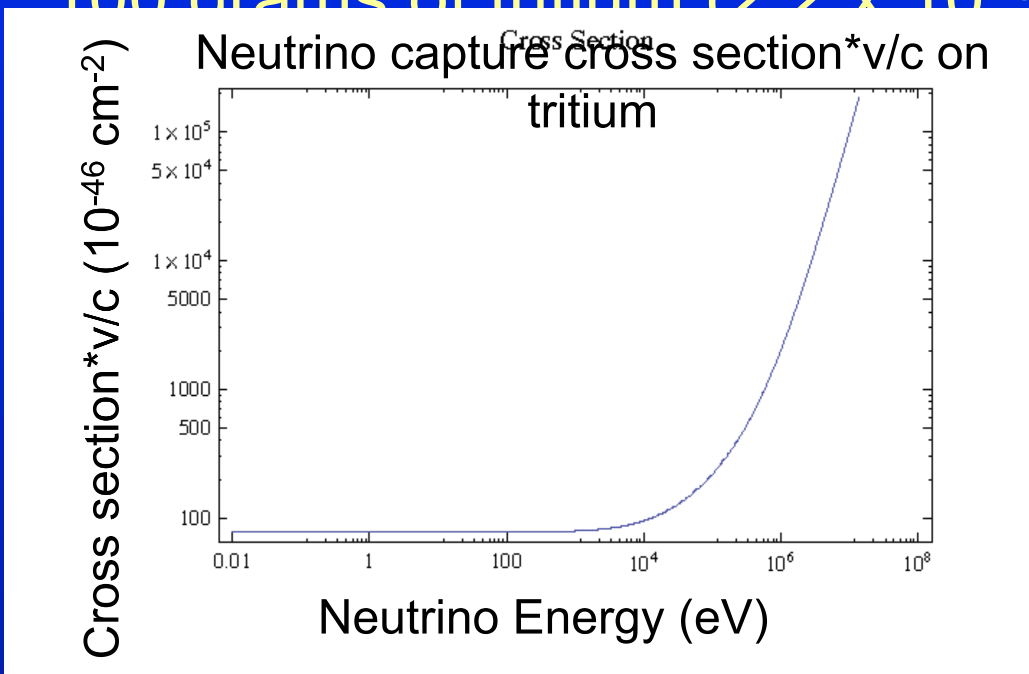
arXiv: 1307.4738

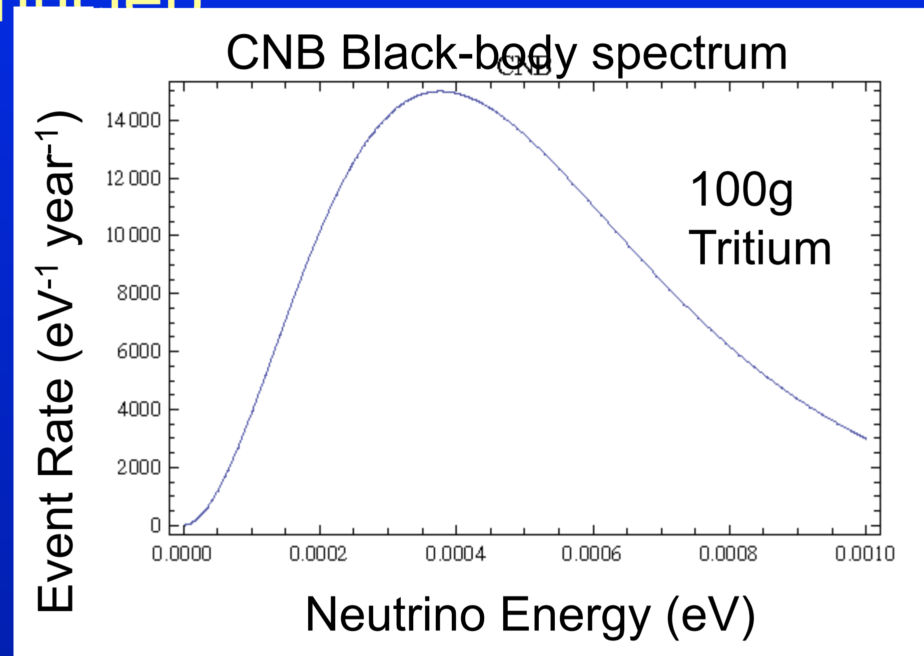


PTOLEMY Team (Summer 2013)

Neutrino Interaction Rates

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





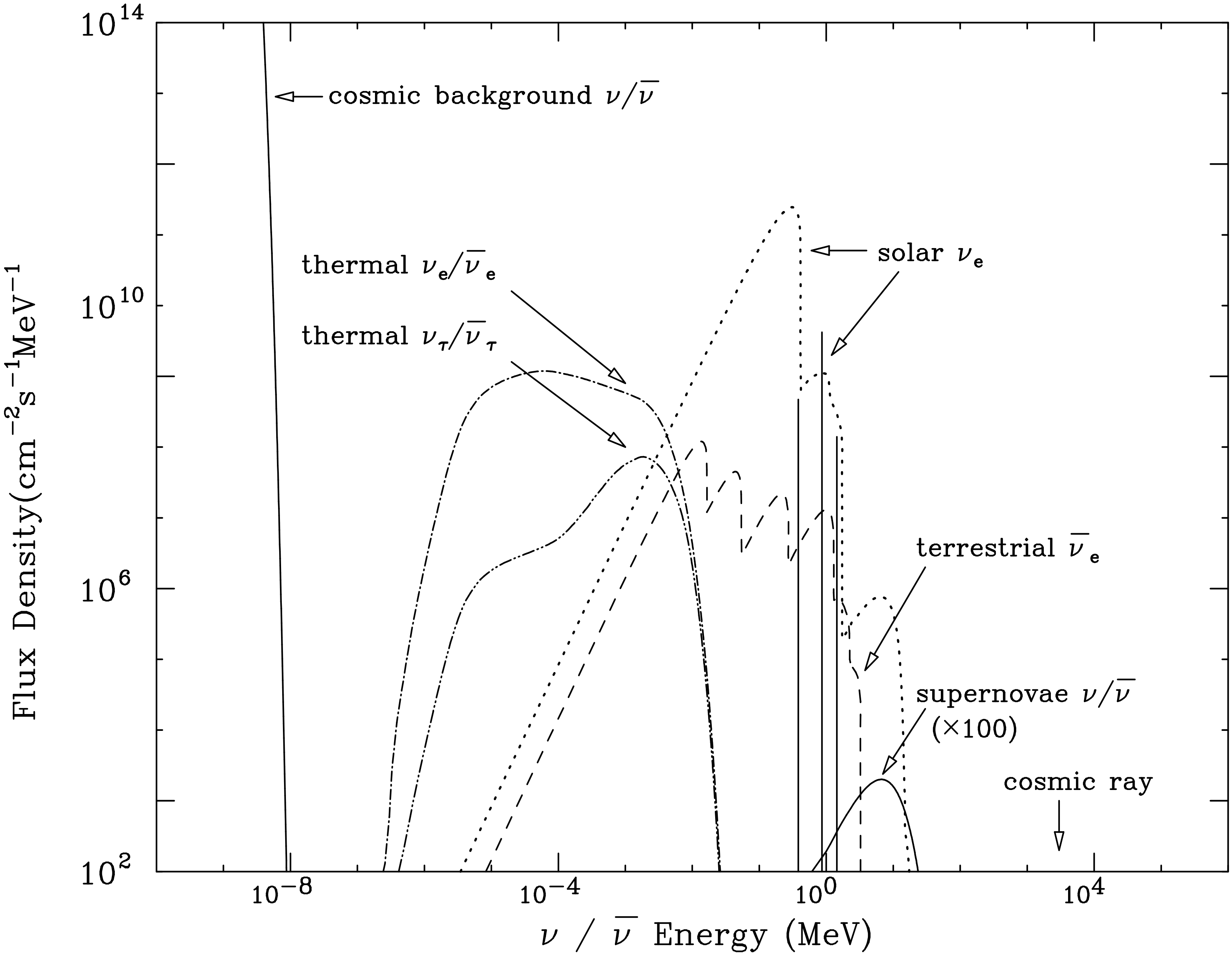
$$\int \sigma(p_\nu) v_\nu f_\nu(p_\nu) \frac{d^3 p_\nu}{(2\pi)^3}$$

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

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

Neutrino Flux

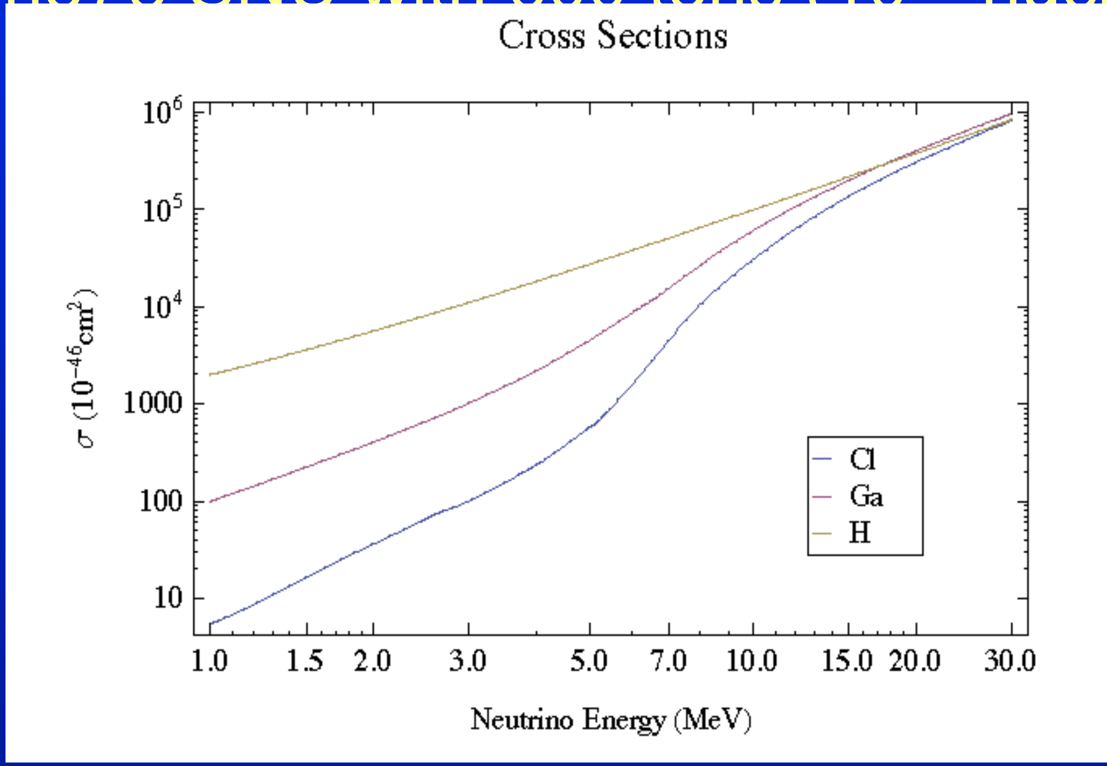
Haxton, Lin: Phys.Lett. B486 (2000) 263-271



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

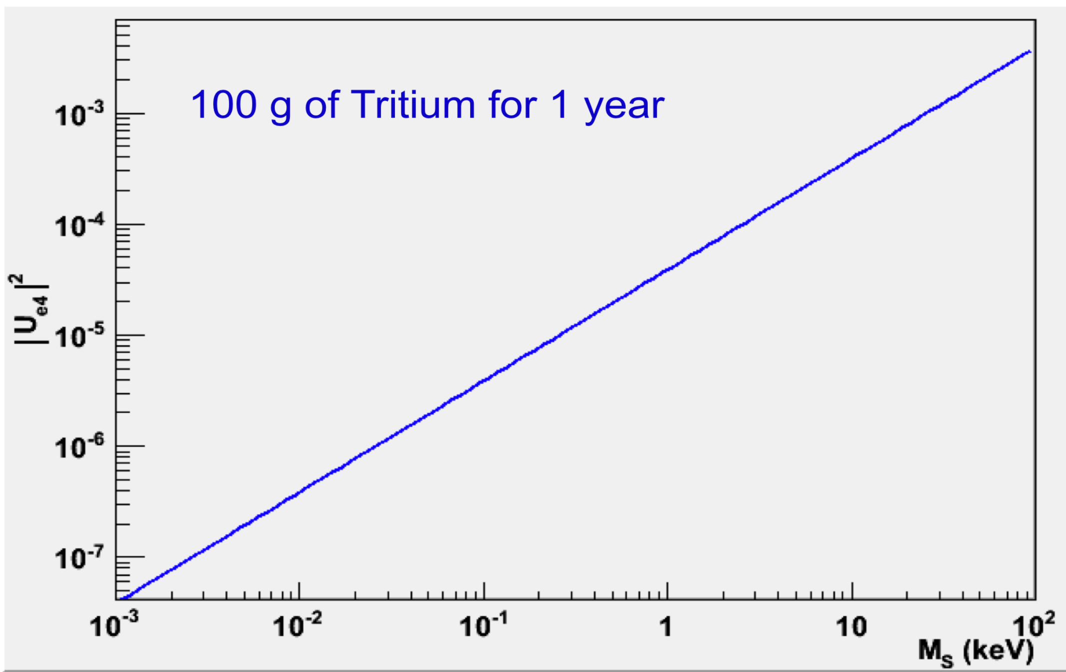


Sterile Neutrino Search

Using ν capture...

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

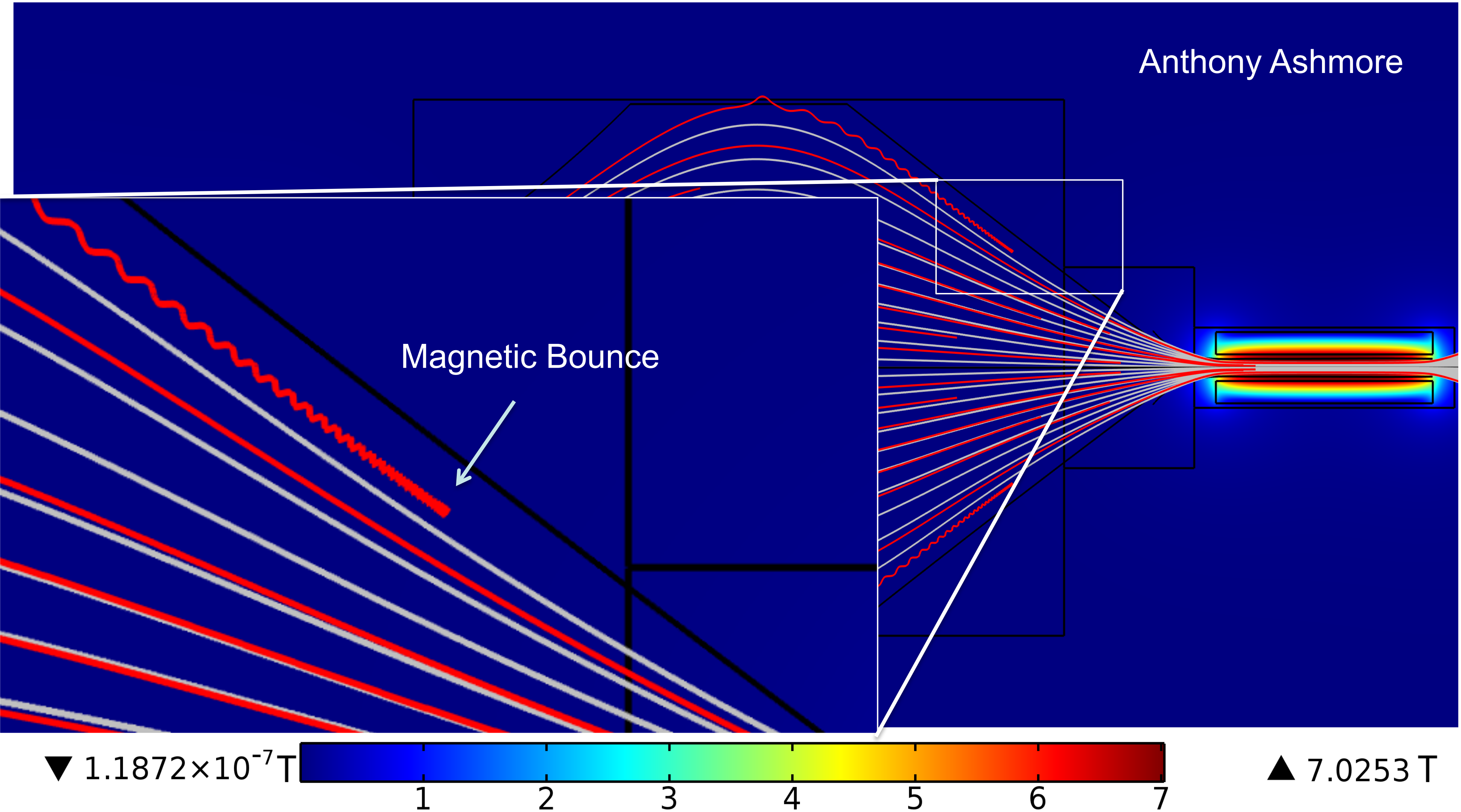
Looking beyond the beta decay endpoint energy (background free region)



PTOLEMY Conceptual Design

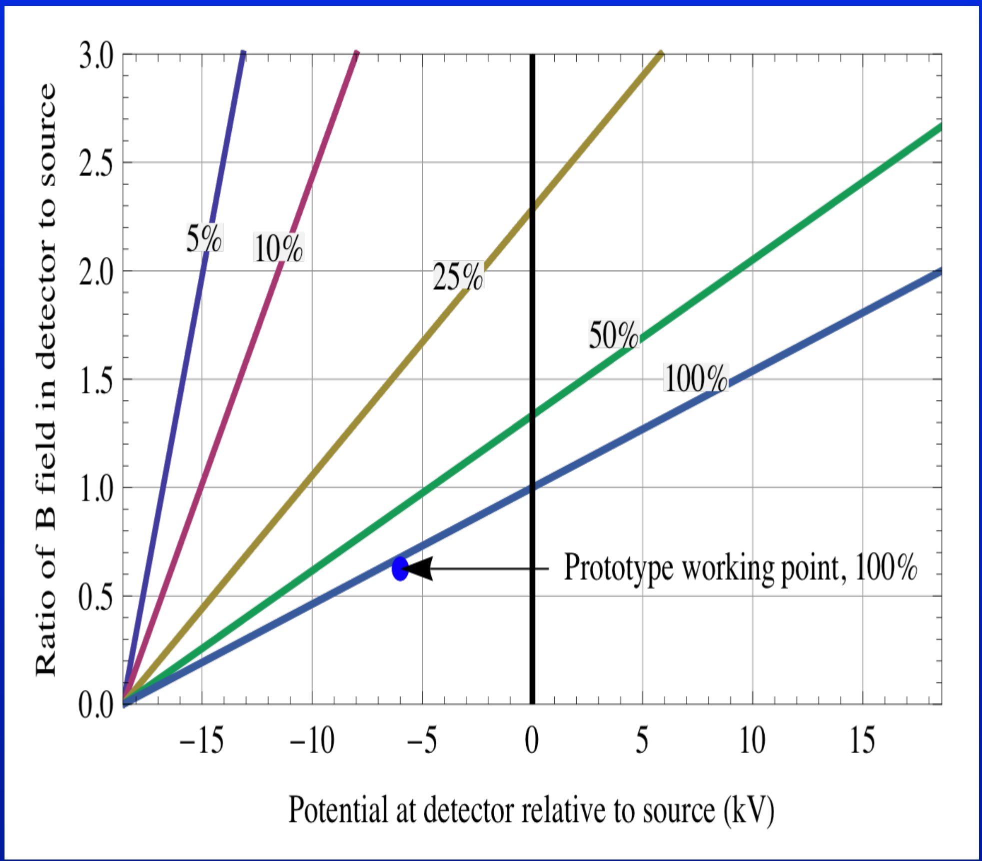
- High precision on endpoint
  - Cryogenic calorimetry energy resolution
  - **Goal: 0.1eV resolution**
- Signal/Background suppression
  - RF tracking and time-of-flight system
  - **Goal: sub-microHertz background rates above endpoint**
- High mass, high resolution tritium target
  - Surface deposition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

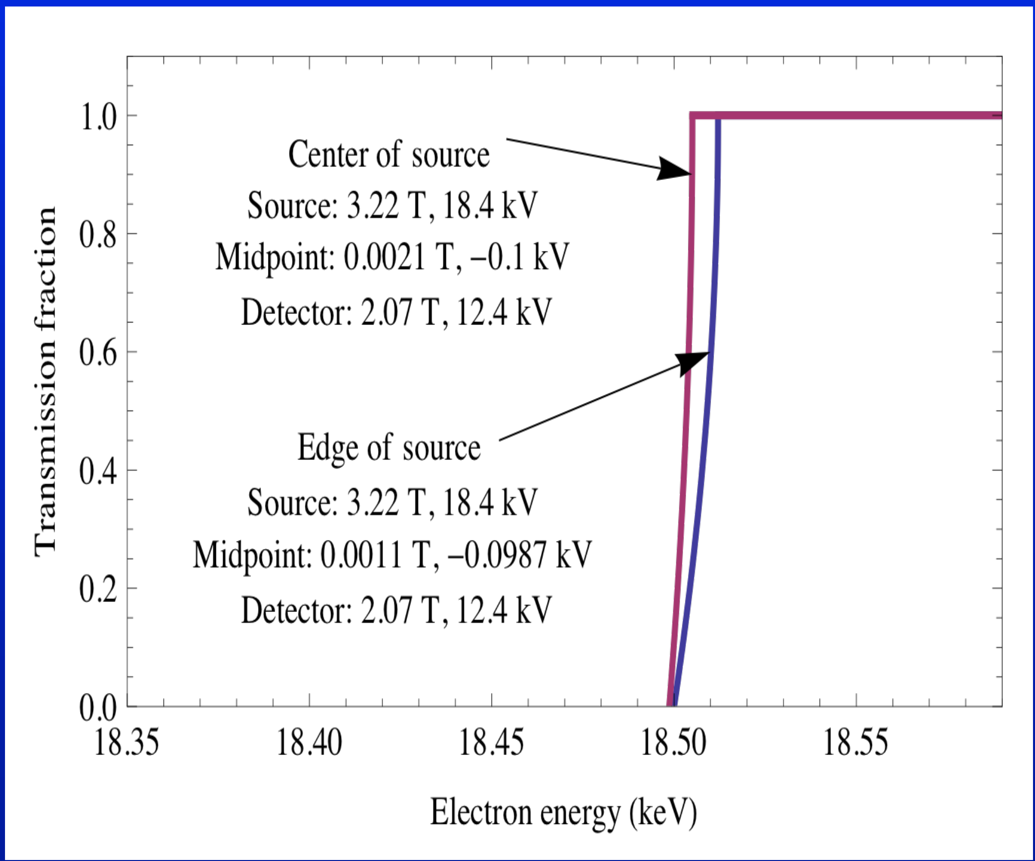
Trajectory Calculations



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



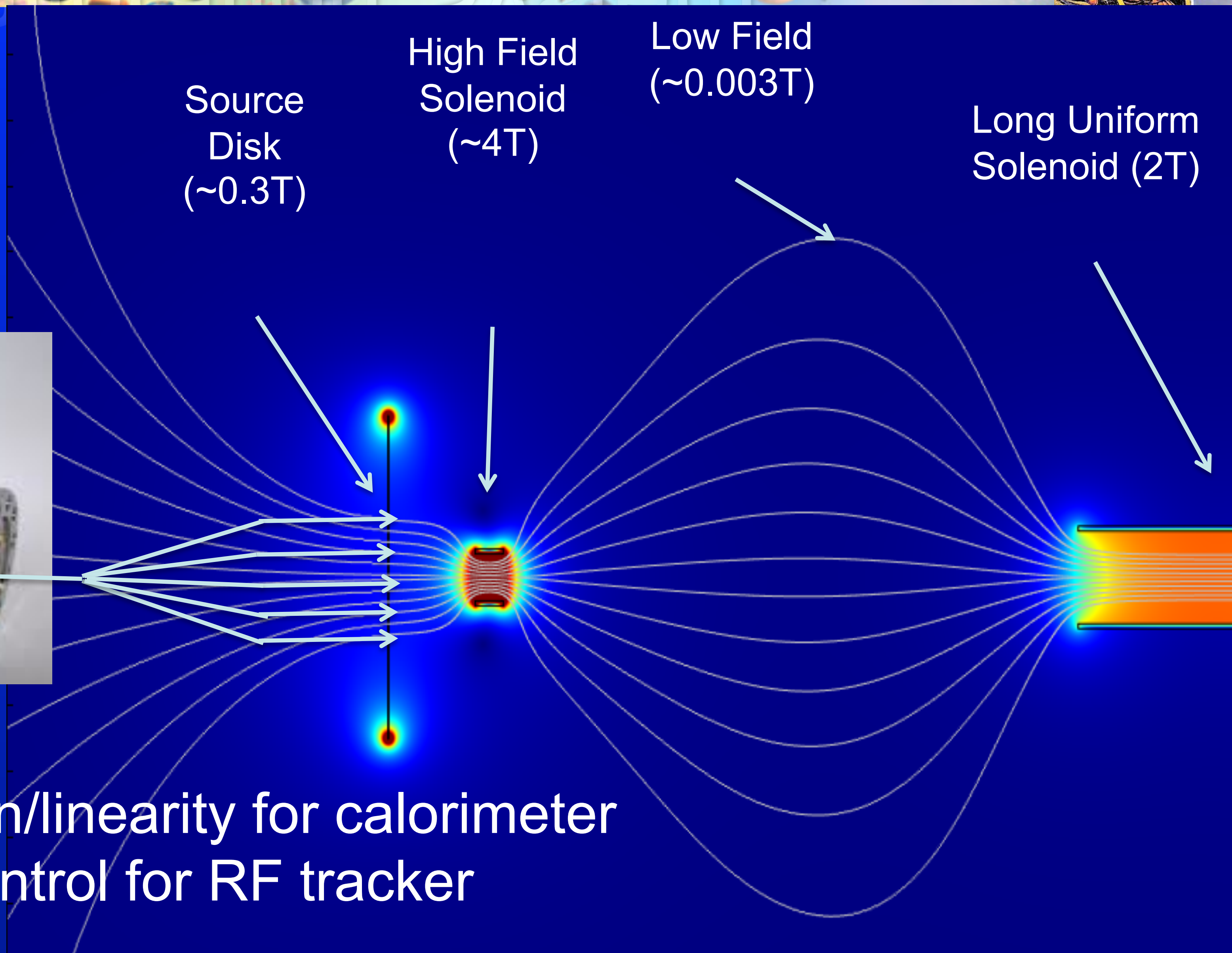


Calibration and Backgrounds

- 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

TFTR Carbon tiles

- PPPL already produced tritium-graphene samples in the 90's in TFTR
  - These have been analyzed with Raman scattering
- SRNL are providing tritium loaded graphene samples
  - Loaded at 100 atm