One Second After the Big Bang

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

Chris Tully
Princeton University

NIKHEF Colloquium
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ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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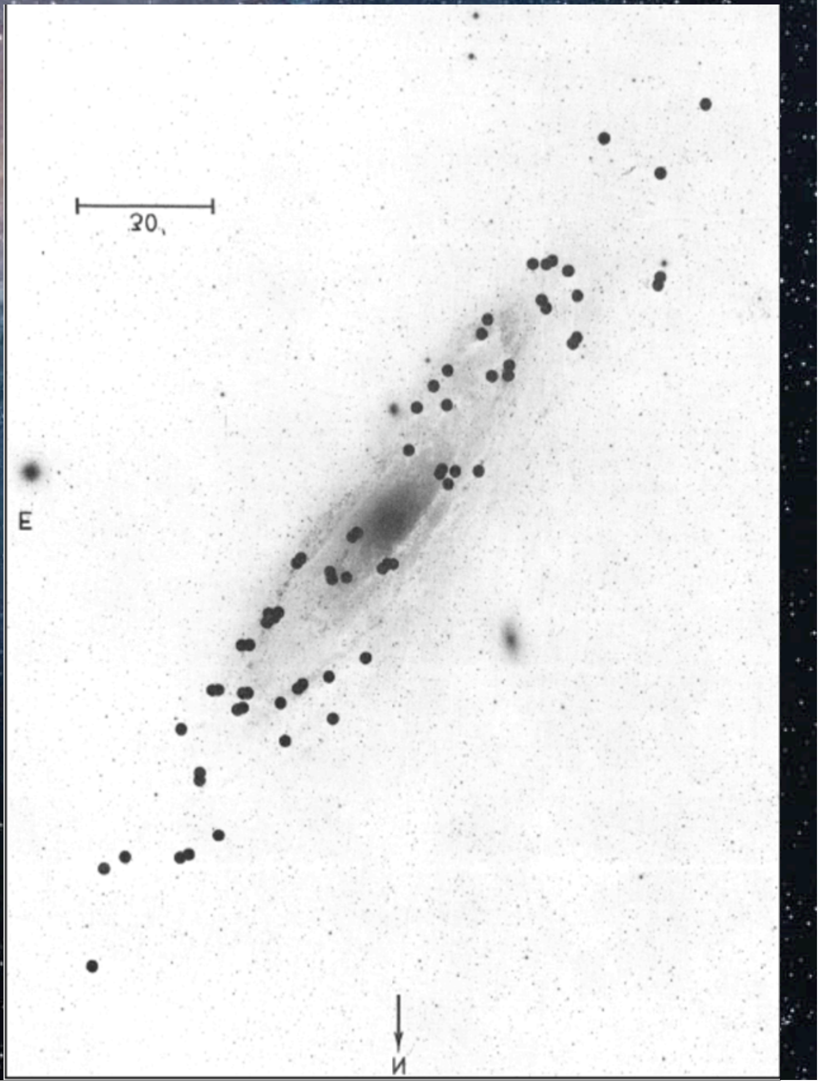
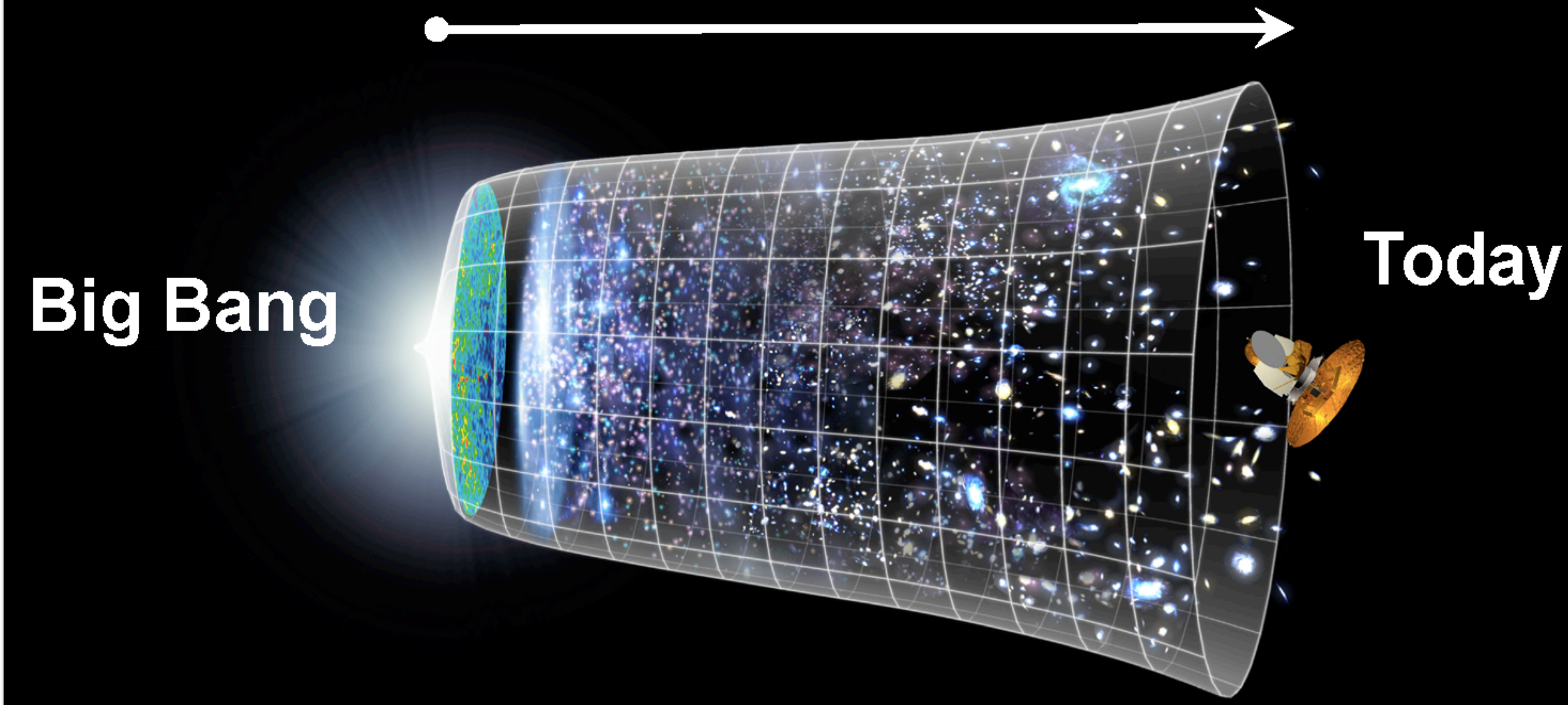
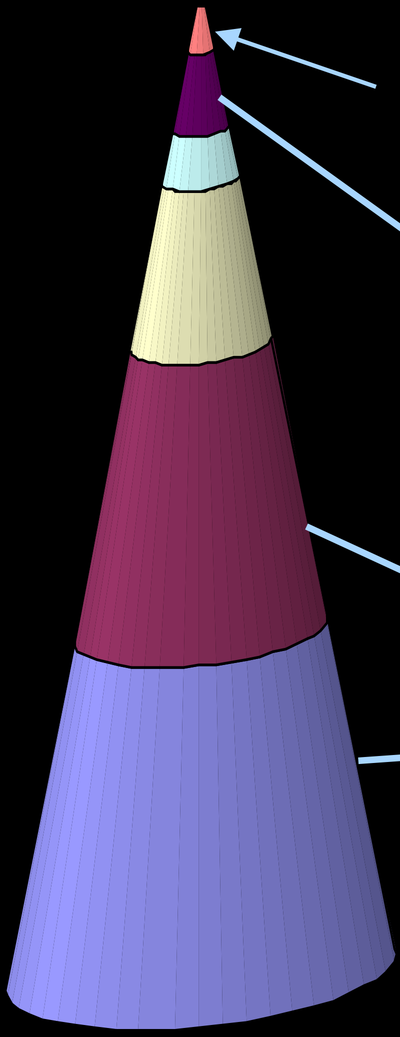
Lowell Observatory, and Kitt Peak National Observatory‡

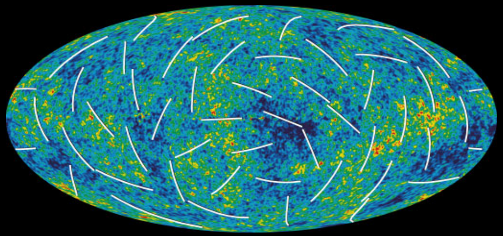


Timeline of the Universe





You Are Here.

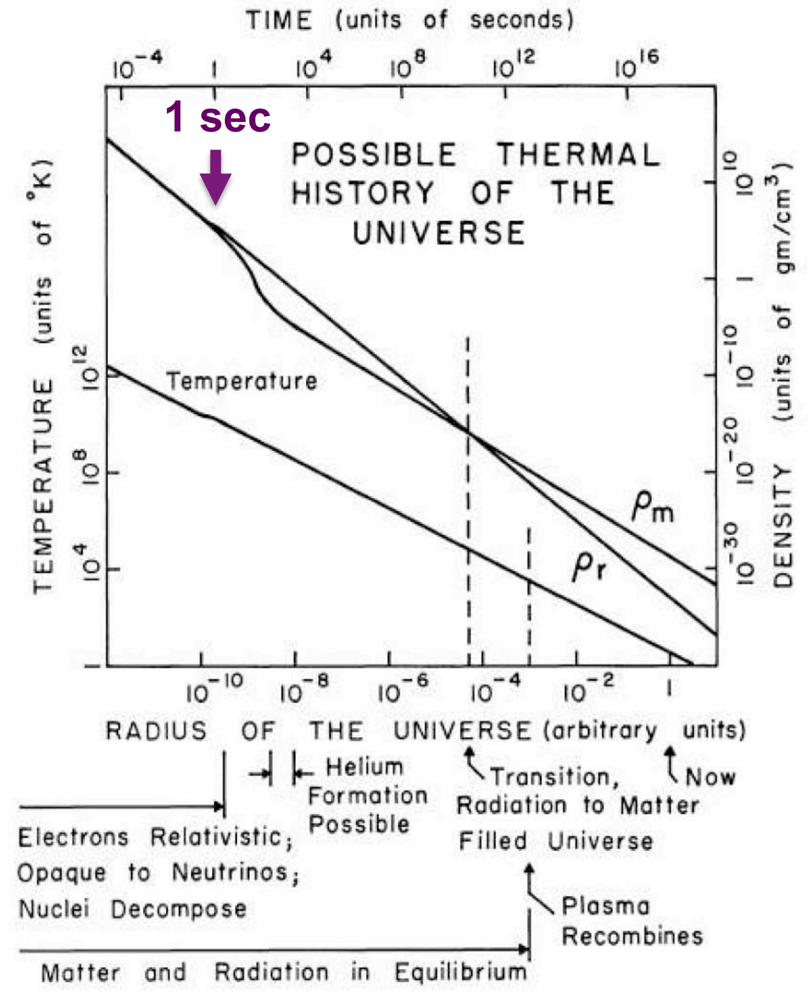


■	Other elements	0.03%
■	Neutrinos	0.3%
■	Stars	0.5%
■	Free H and He	3%
■	Dark matter	22%
■	Dark energy	74%

We do not know what makes up 96% of the universe.

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 (1.7x10^{-4} eV) and to have an average number density of ~56/cm^3 per lepton flavor



Dicke, Peebles, Roll, Wilkinson (1965)
CMB@50 conference in June 2015

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

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

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

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

Timing of Neutrino Decoupling

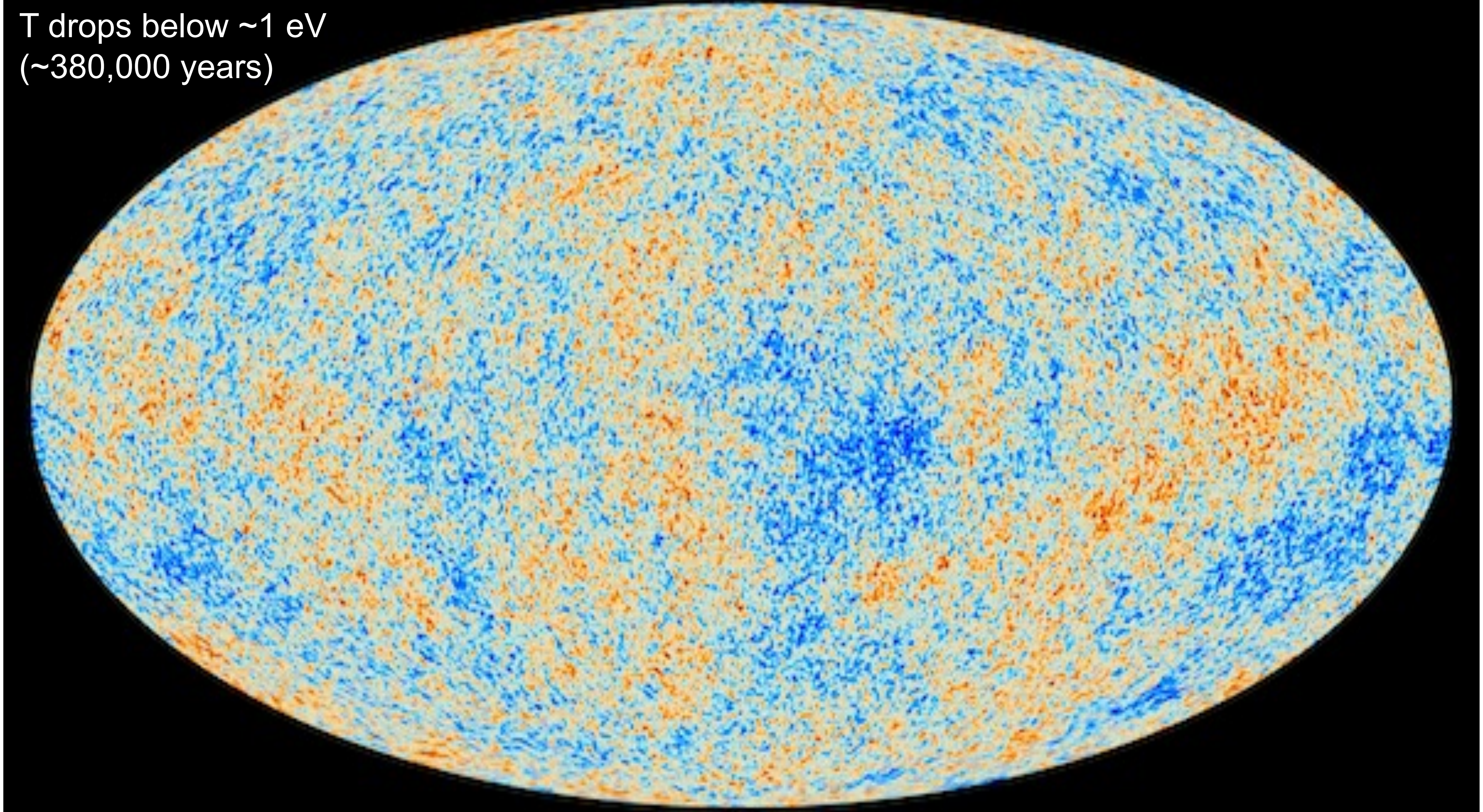
- Timing is essential to Big Bang predictions
  - – Neutrino decoupling at ~1 MeV (~1 sec)
    - Weak interactions constantly regenerate neutrons
  - – Neutron-Proton mass difference m_n-m_p~1.3 MeV
  - – Deuterium(→ Helium) at ~0.07 MeV (~132 sec) compared to neutron lifetime of ~886.7 sec
    - n/p~0.15*0.74~0.11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

$$\frac{\lambda(p \rightarrow n)}{\lambda(n \rightarrow p)} = e^{-Q/kT}$$

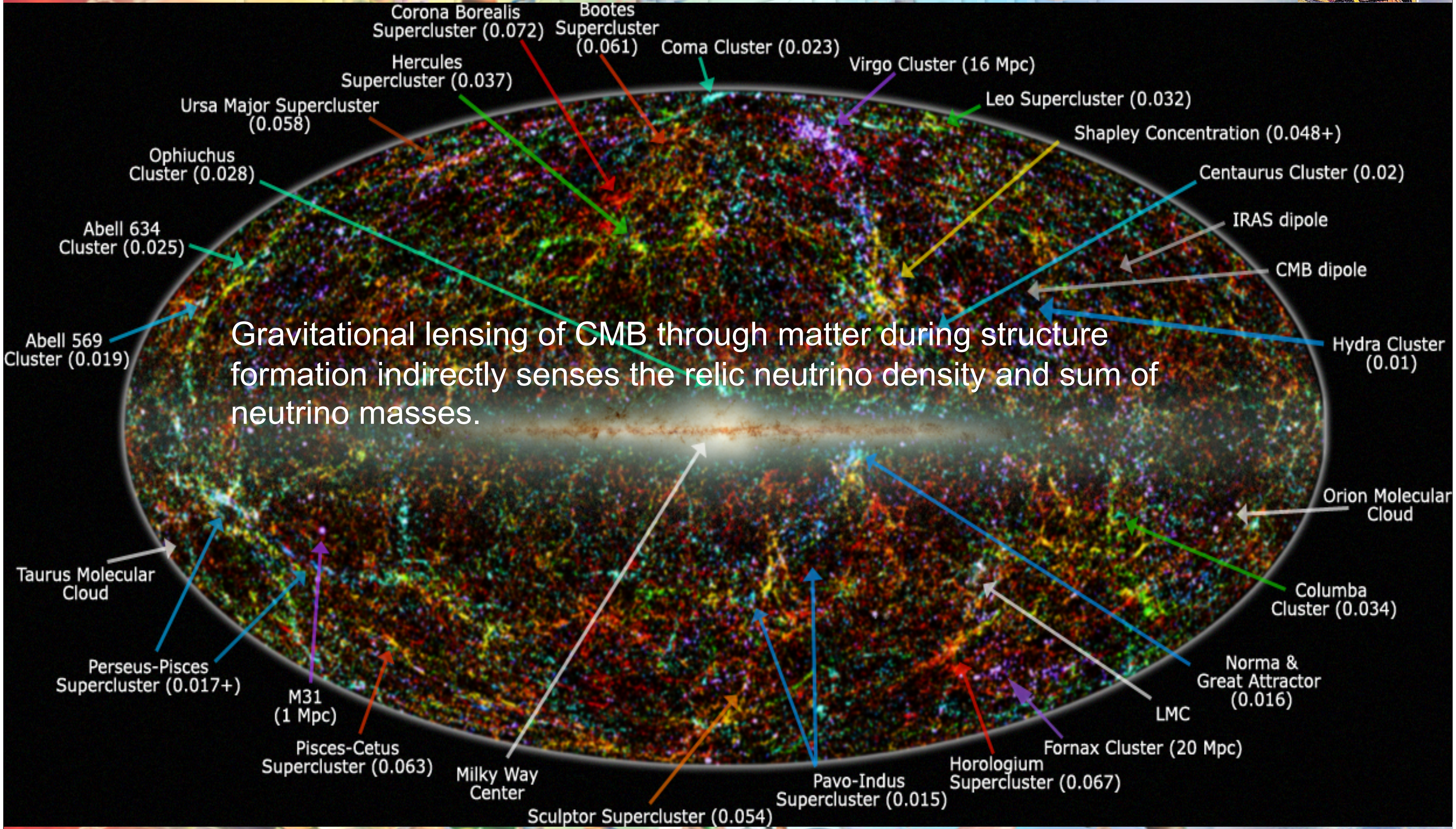
Not much wiggle room for the standard BBN prediction

Cosmic Background Radiation

T drops below ~1 eV
(~380,000 years)

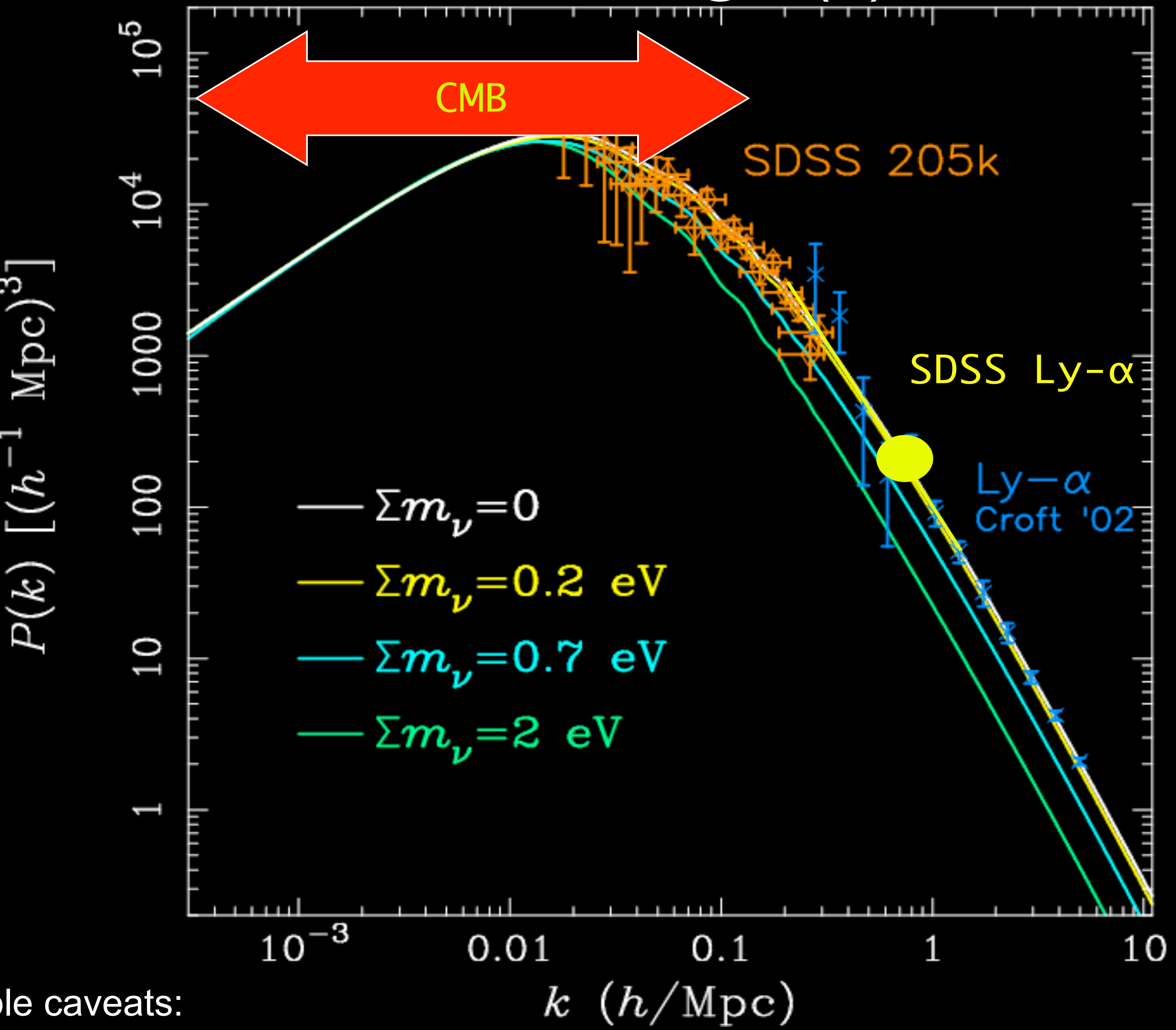


Large-Scale Structure



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

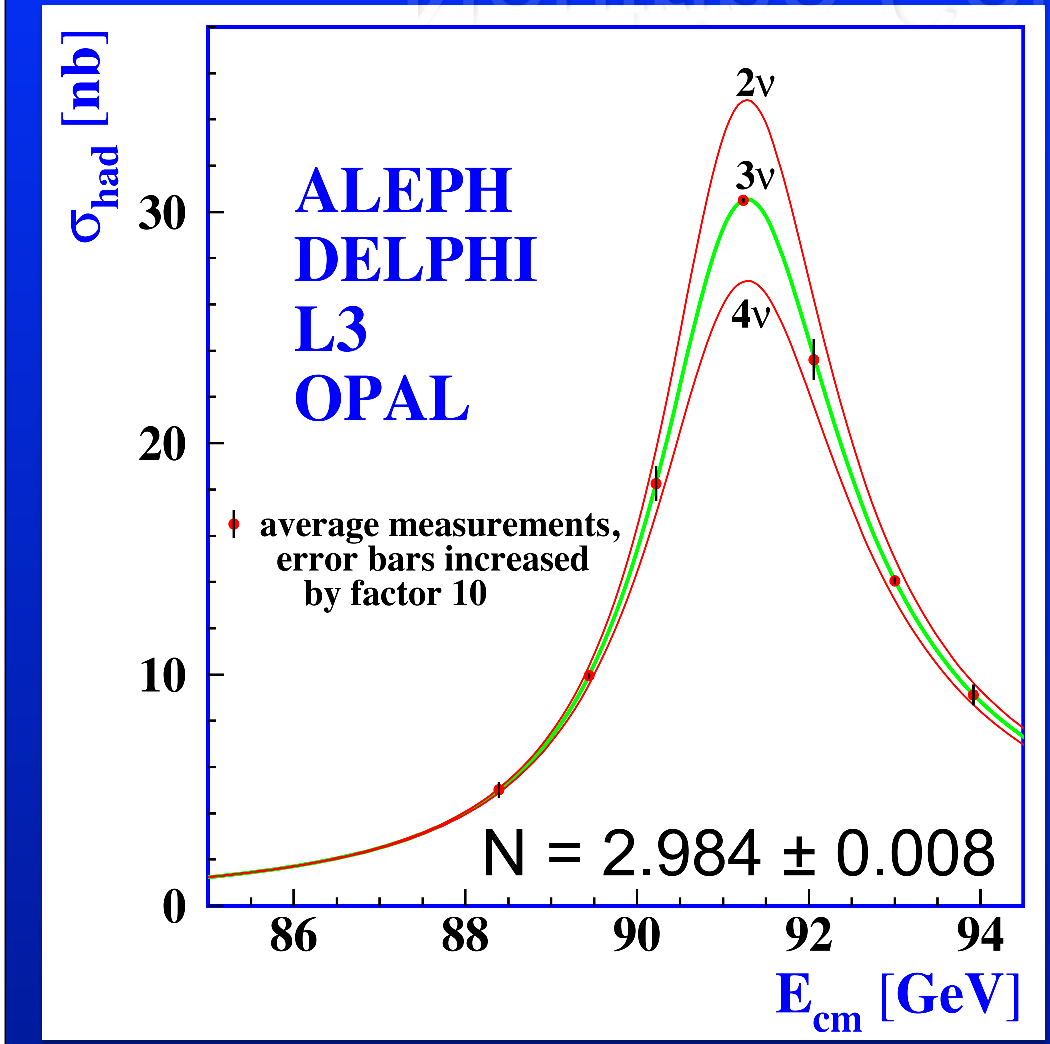
Measuring P(k)



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



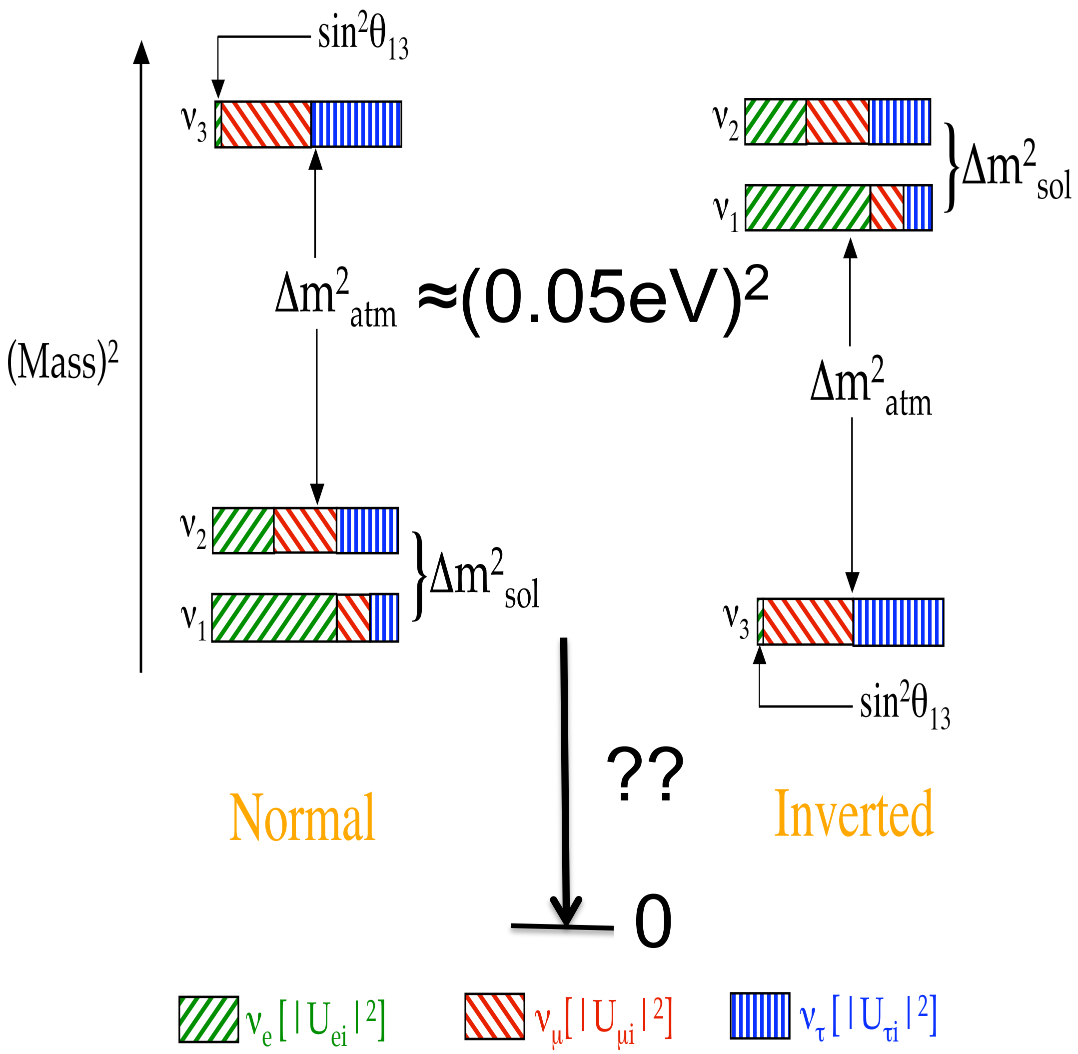
Produce ~1M Z bosons at an e^+e^- collider

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



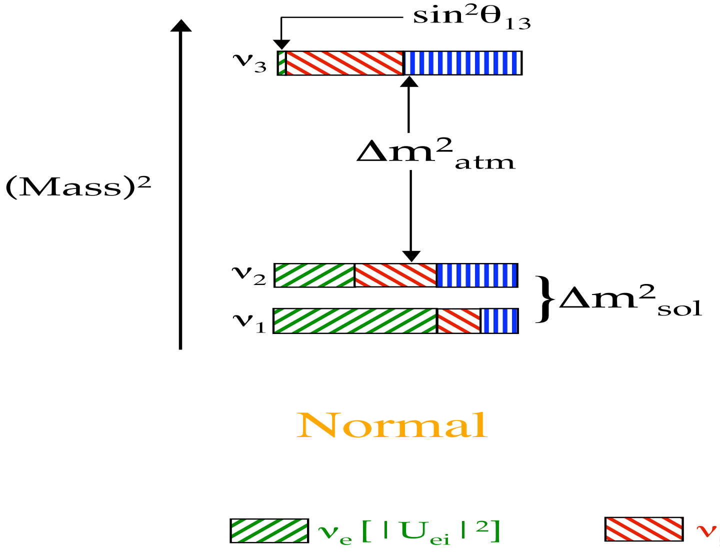
An incredible phenomenon appeared when neutrinos were measured from different sources: solar, atmospheric, reactor, accelerator.

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.

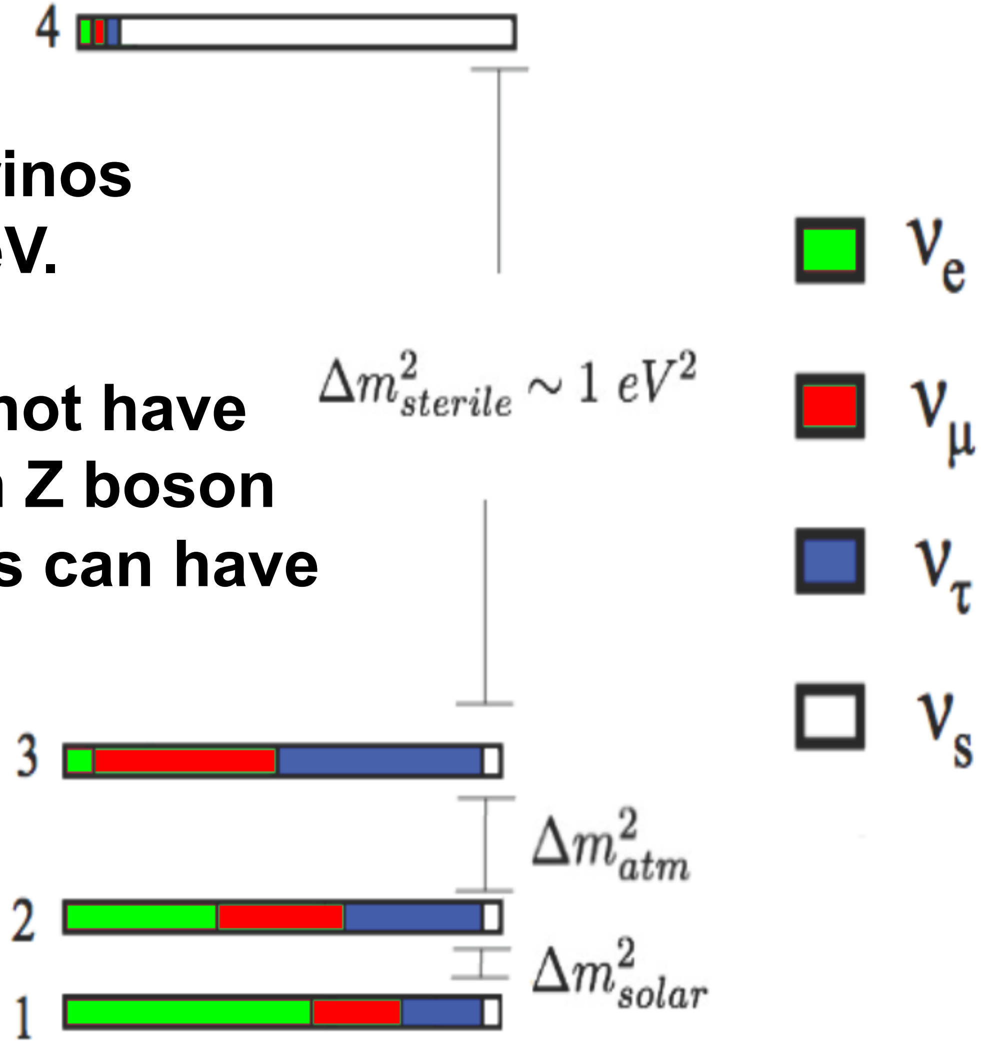
Sterile Neutrinos?

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

The sterile component cannot have weak interactions based on Z boson data – but mass eigenstates can have admixtures.

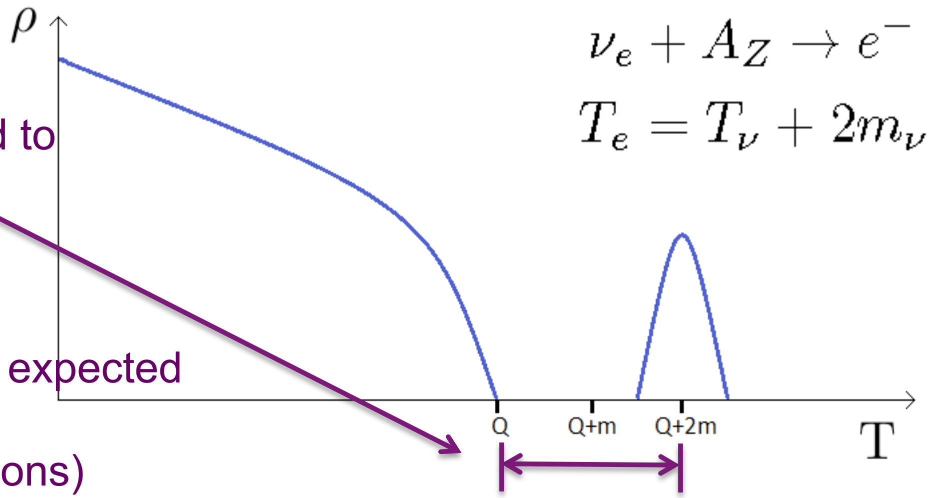


or



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)

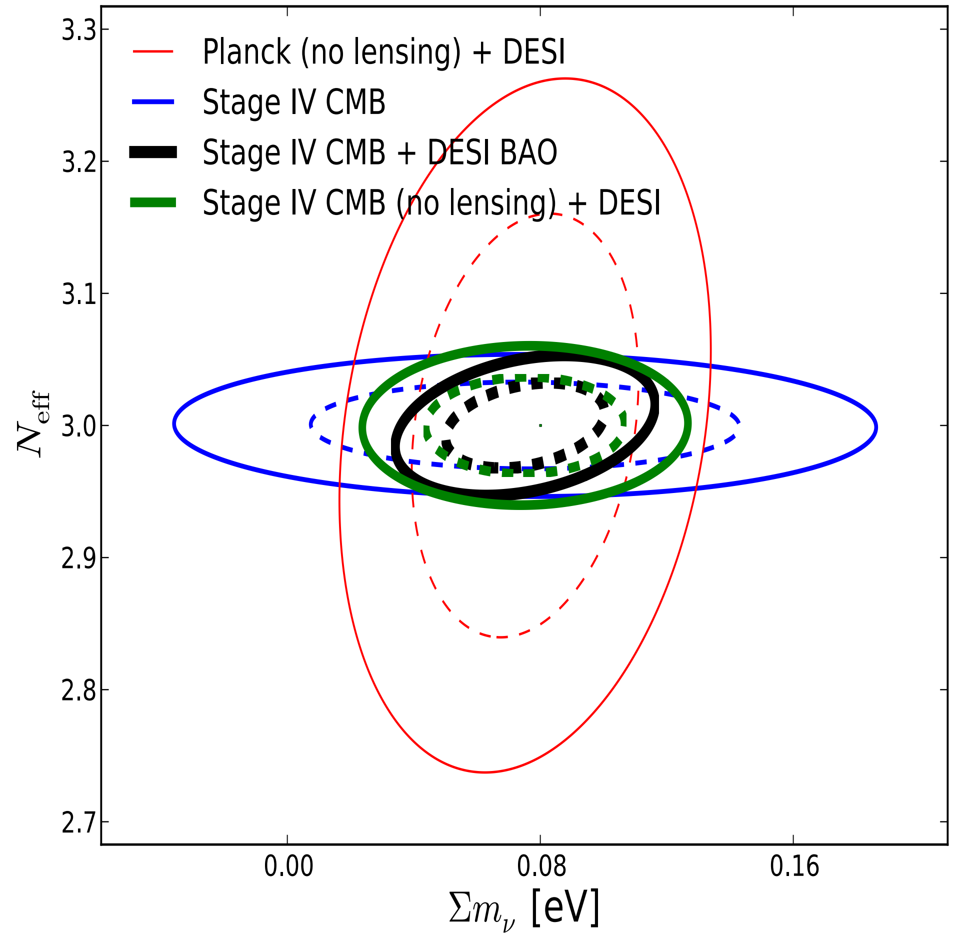
$$\nu_e + A_Z \to e^- + A^*_{Z+1}$$

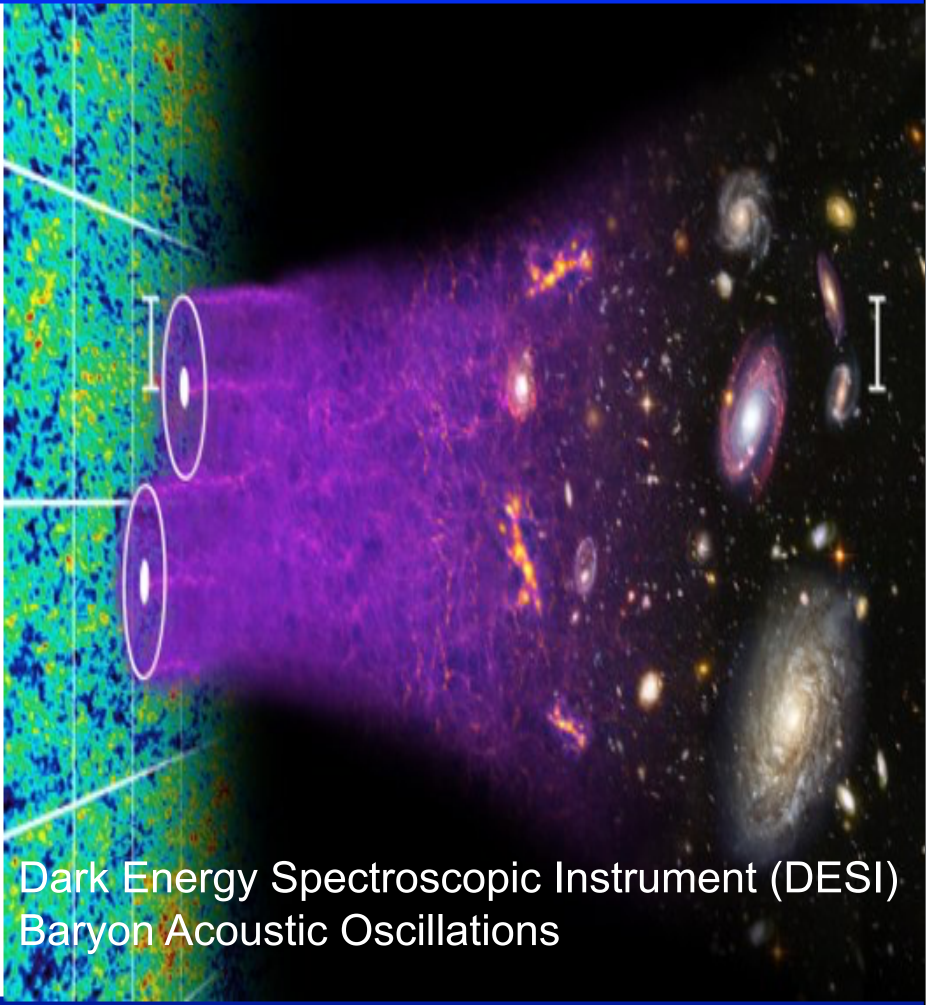
$$T_e = T_\nu + 2m_\nu + Q$$

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

Precision Cosmology Projections





Dark Energy Spectroscopic Instrument (DESI)
Baryon Acoustic Oscillations

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:

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

(5 events/yr for Dirac neutrinos)

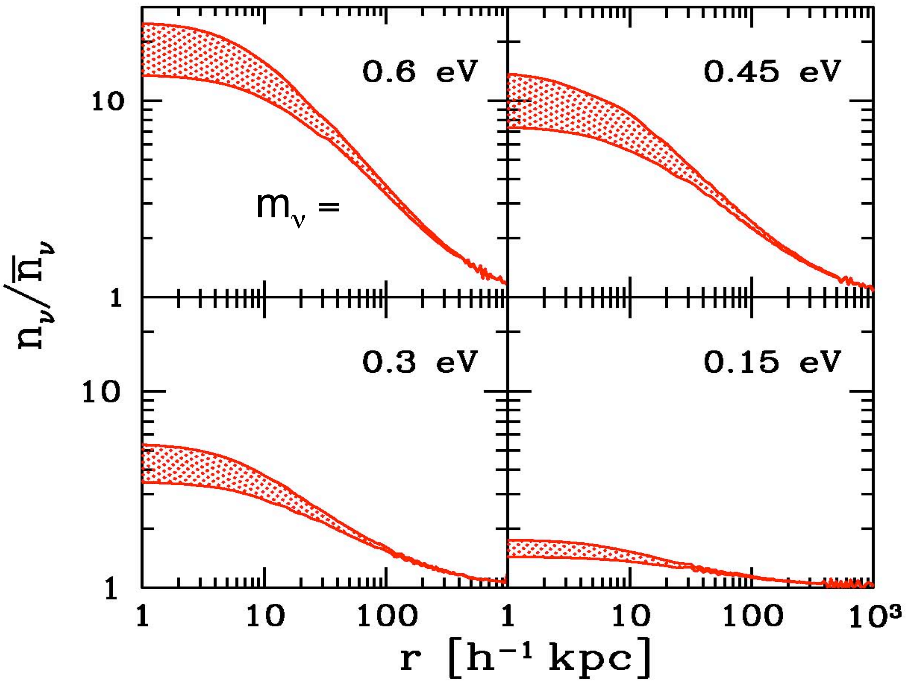
Lazauskas, Vogel, Volpe: J.Phys.G G35 (2008) 025001.

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



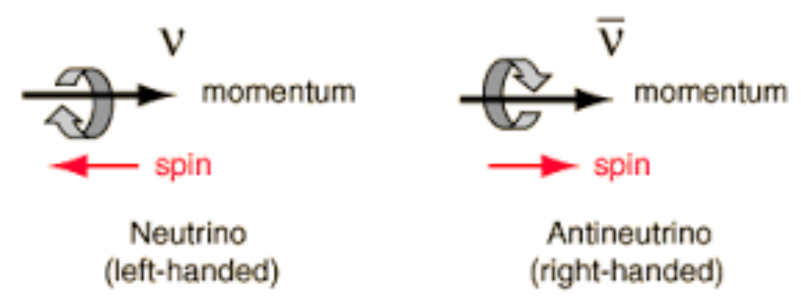
Ringwald and Wong (2004)

Dirac versus Majorana Neutrinos

Relic neutrinos are uniquely the largest source of non-relativistic neutrinos

Long, Lunardini, Sabancilar: arXiv:1405.7654

Factor of 2 difference in capture rate

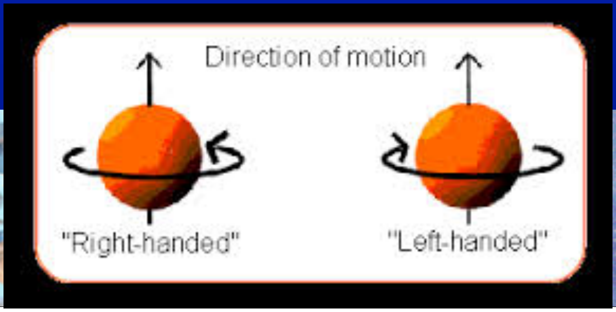


- Neutrinos decouple at relativistic energies
- Helicity (not chirality) is conserved as the universe expands and the relic neutrinos become non-relativistic

Dirac: after expansion, only ~half of left-handed helical Dirac neutrinos are left-handed chiral (active) and antineutrinos are not captured

Majorana: ~half of left-handed helical neutrinos are chiral left-handed and half of right-handed helical neutrinos are chiral left-handed (active)

Majorana/Dirac test outside of neutrinoless double-beta decay



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?

Bodine, Parno, Robertson: arXiv:1502.03497

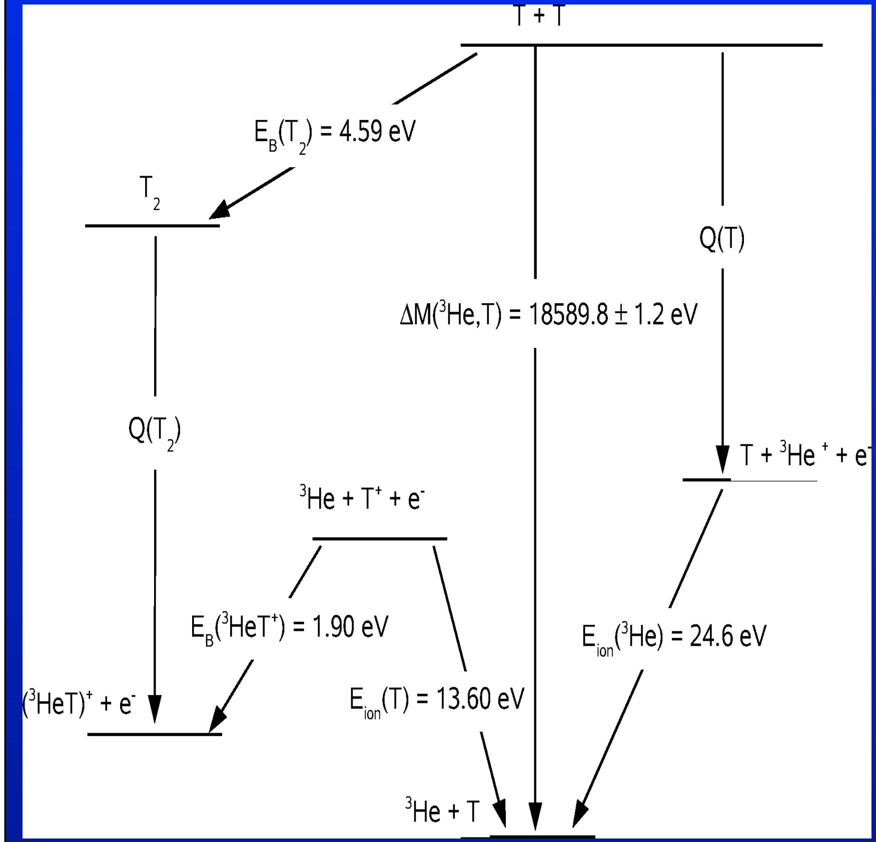
Answer: The maximum ^{3}He recoil energy is ~3eV. ^{3}He stays bound to the remaining T to form a T-He^3 molecule – and can fall into a number of closely spaced rotational and vibrational excited states

T-T → T-^{3}He

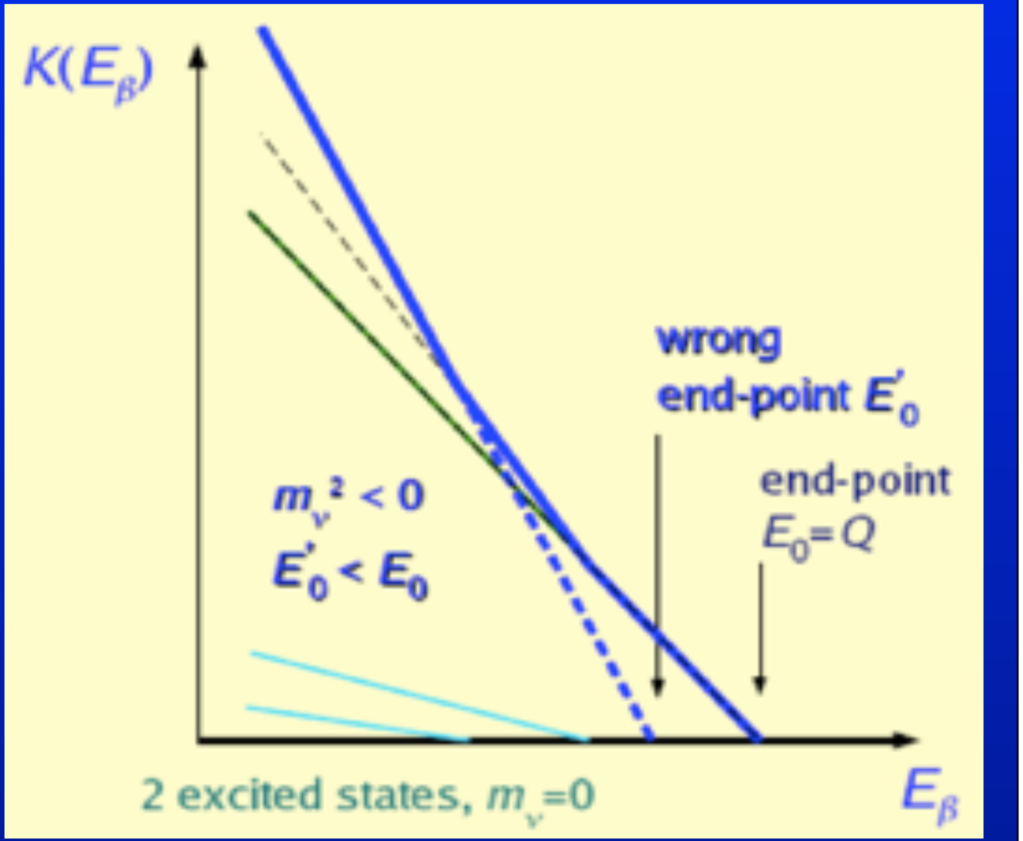
Quantum Mechanics tells us that the outgoing electron energy depends on the change in the binding energy of T^2 to (T-^{3}He)*

He^3 Binding Energy Shift

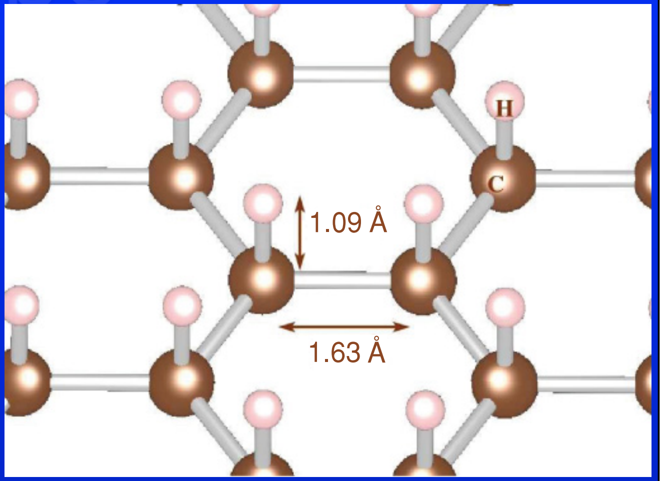
T-T → T-He^3 Level Diagram



Tritium endpoint shifts from excited states



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

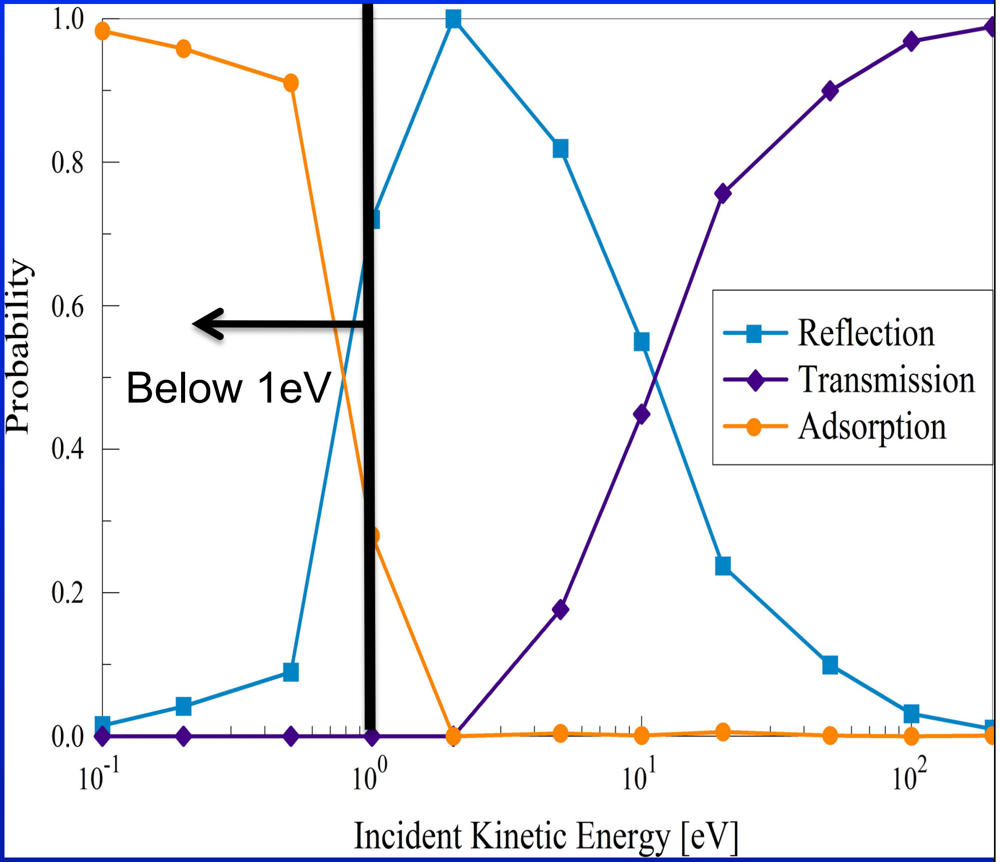
Single-sided-hydrogenated Graphene
- Planar (uniform bond length)
- Semiconductor (~Si gap)
- Polarized tritium(?)

~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 potentially no binding for He^3

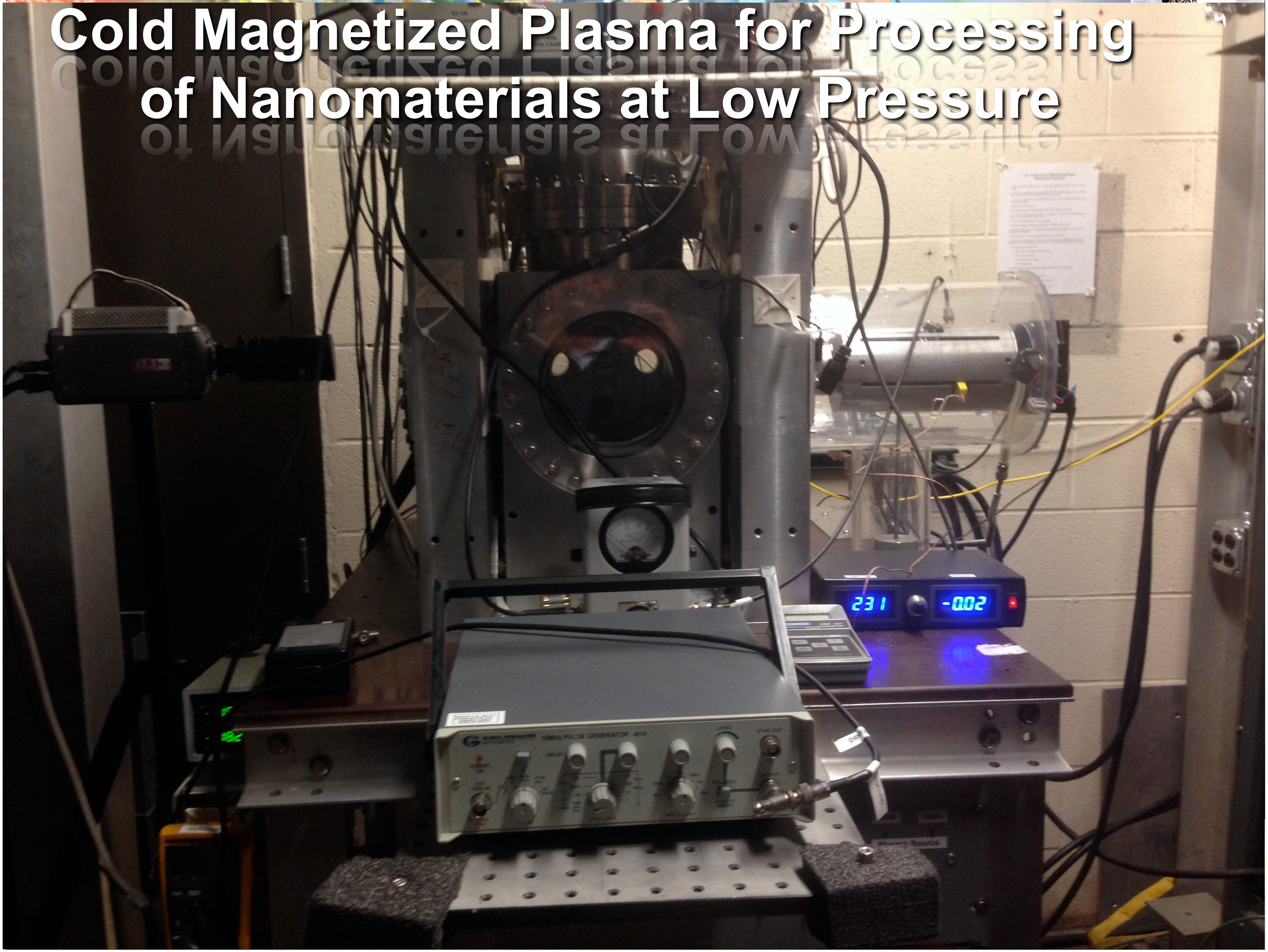
Tritium Loading

- 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

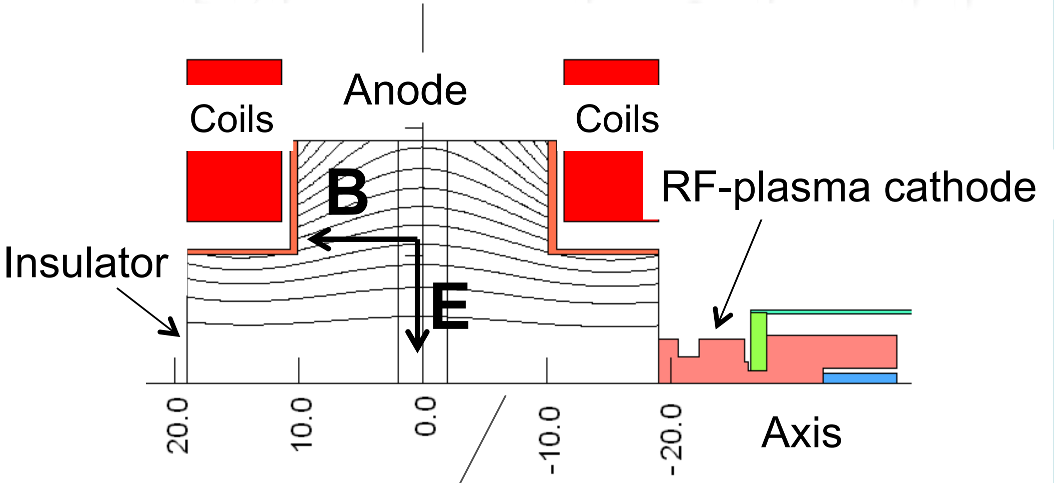


Ehemann et al. Nanoscale Research Letters 2012, 7:198

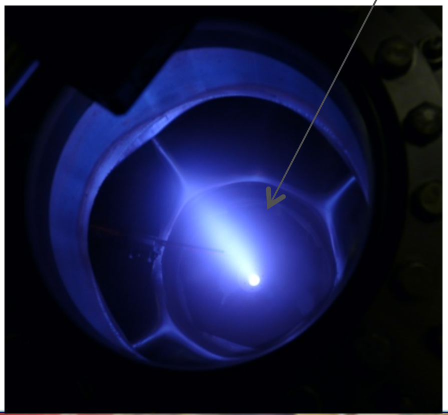
Cold Magnetized Plasma for Processing of Nanomaterials at Low Pressure



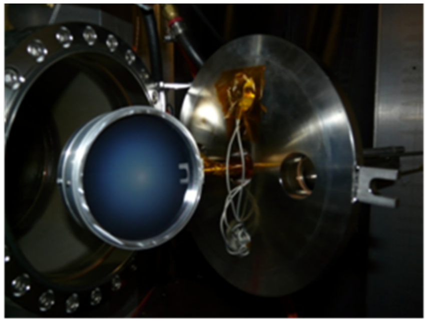
Cold Magnetized Plasma for Processing of Nanomaterials at Low Pressure



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

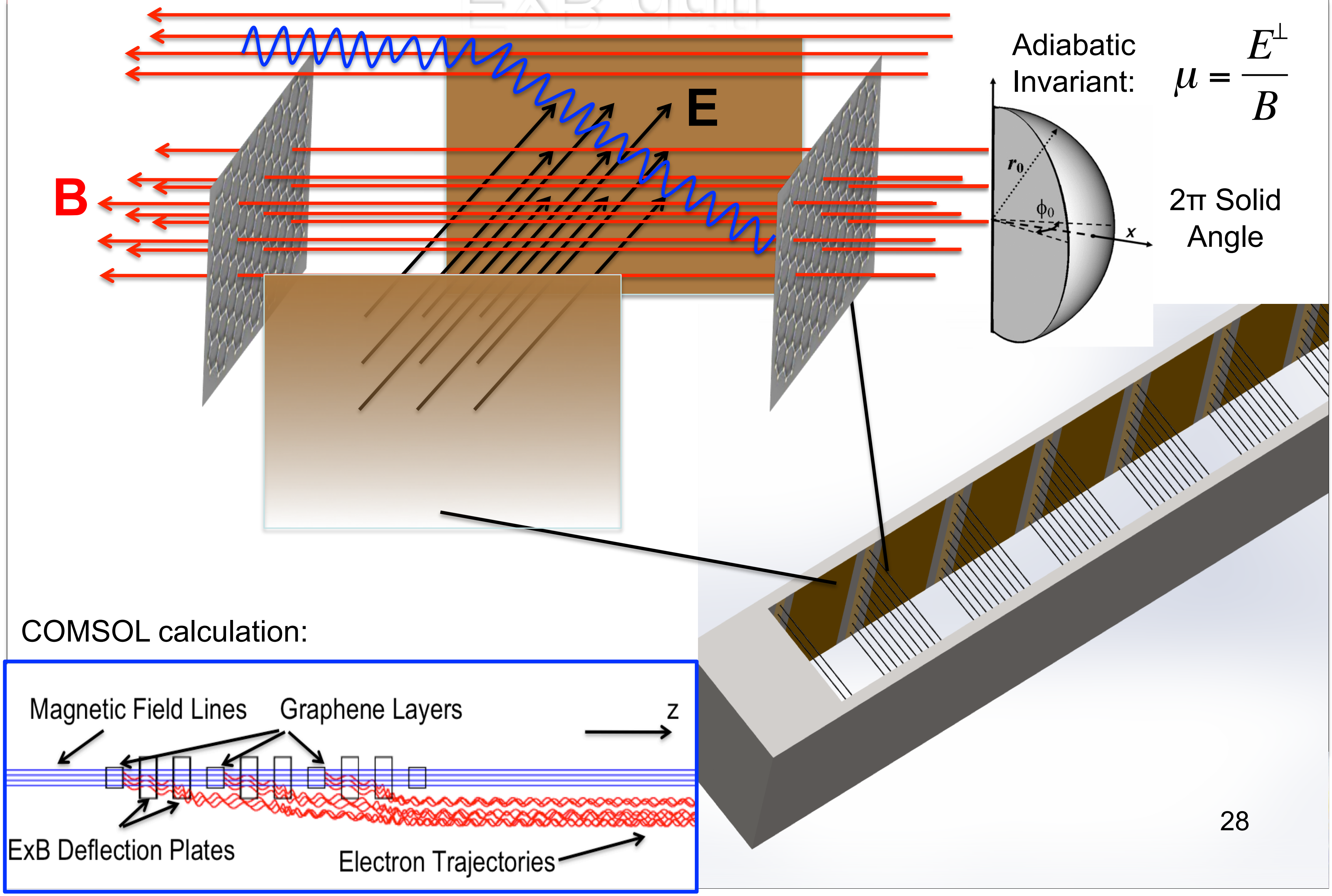
Raitses et al., DOE PSC Meeting, 2013

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

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 or up to a few hundred layers of tritium)
  - 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 and micro-pattern fabrication to solve

ExB drift

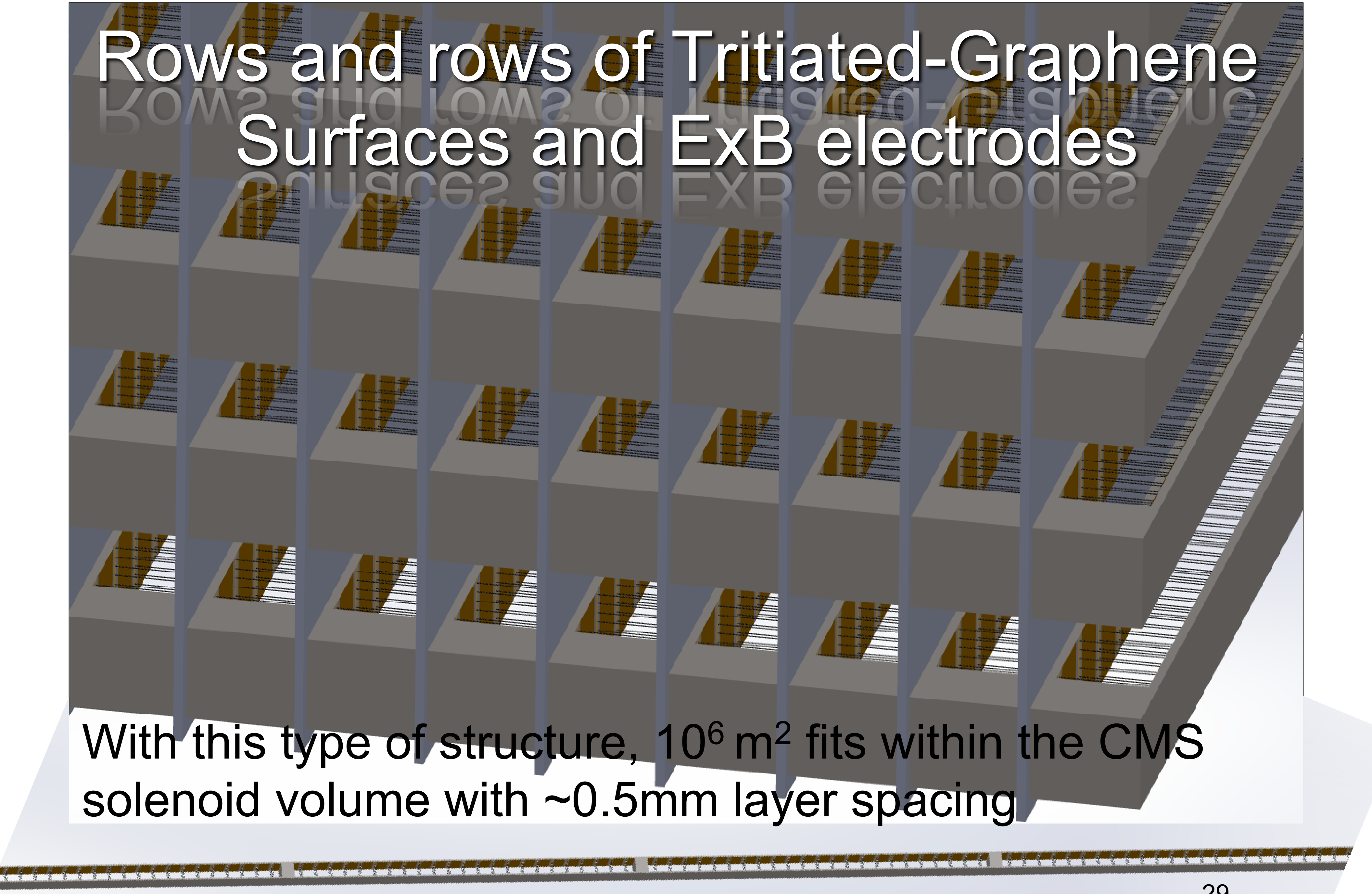


Adiabatic Invariant: $\mu = \frac{E^{\perp}}{B}$

2π Solid Angle

COMSOL calculation:

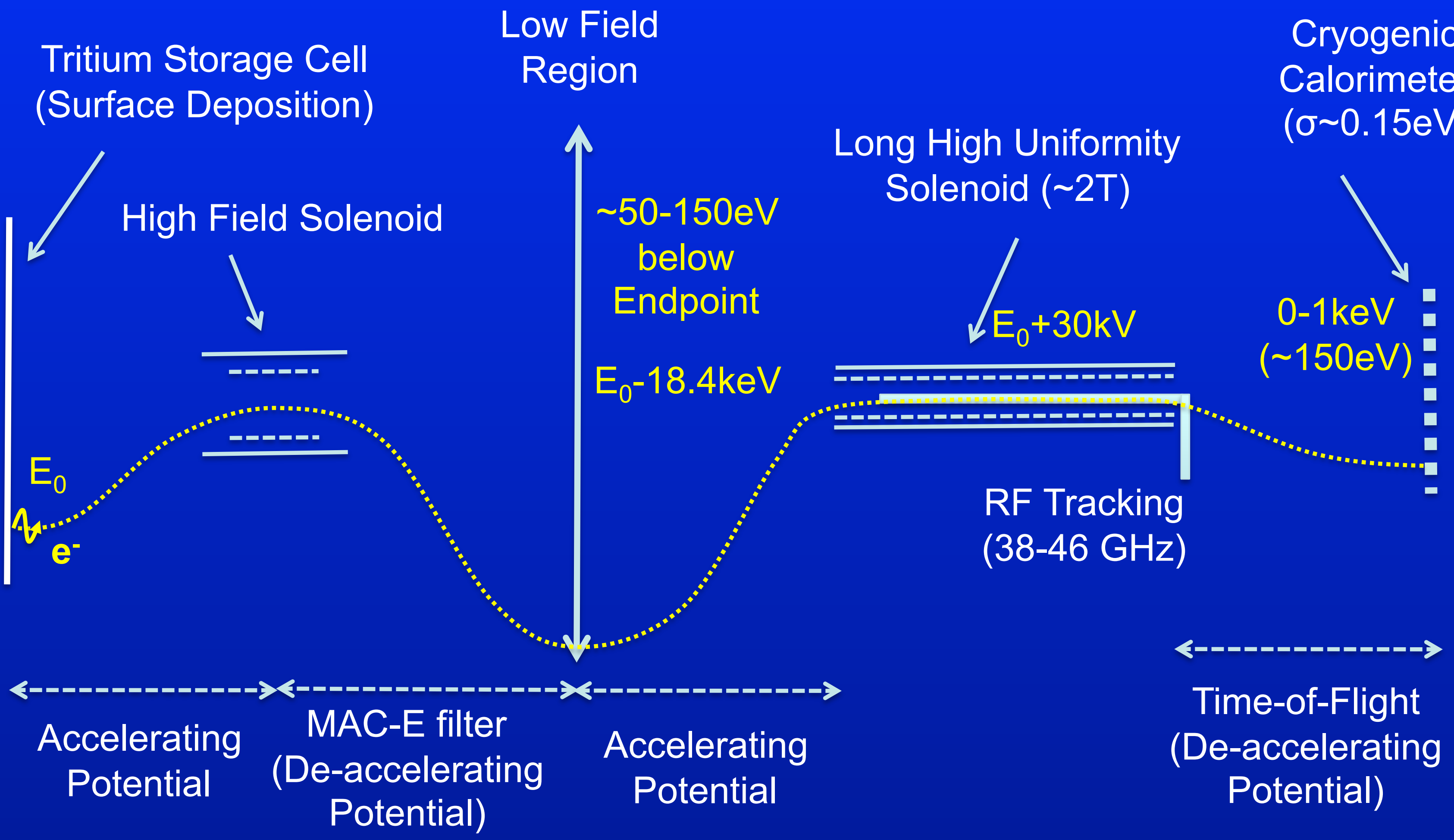
Rows and rows of Tritiated-Graphene Surfaces and ExB electrodes



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

PTOLEMY Experimental Layout

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



Tritium Storage Cell
(Surface Deposition)

High Field Solenoid

Low Field
Region

~50-150eV
below
Endpoint

E_0-18.4keV

Long High Uniformity
Solenoid (~2T)

E_0+30kV

Cryogenic
Calorimeter
(σ~0.15eV)

0-1keV
(~150eV)

E_0

e^-

RF Tracking
(38-46 GHz)

Accelerating
Potential

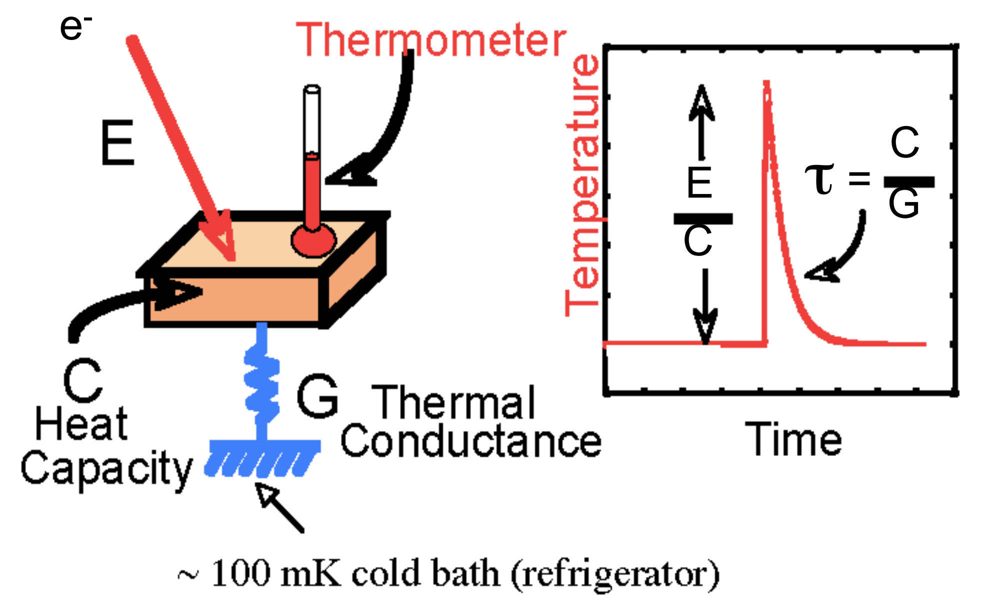
MAC-E filter
(De-accelerating
Potential)

Accelerating
Potential

Time-of-Flight
(De-accelerating
Potential)

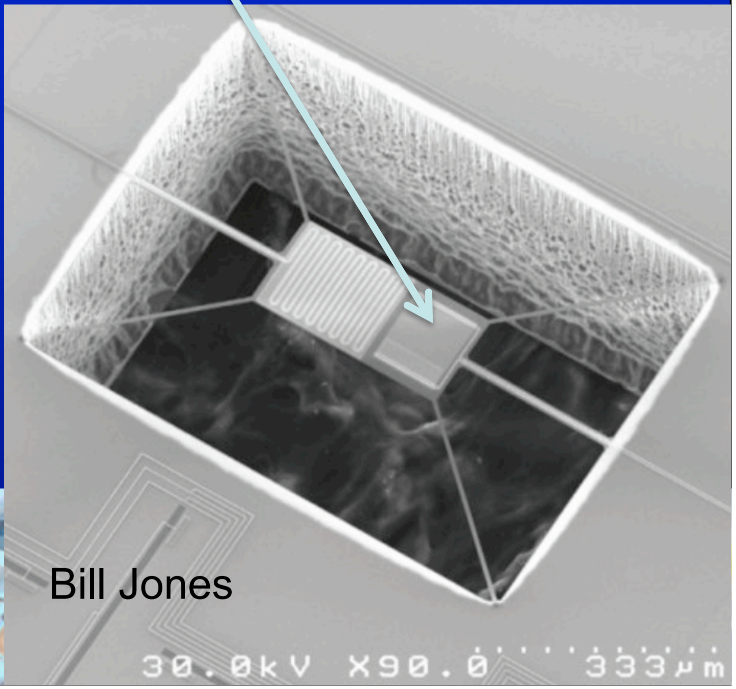
Transition-Edge Sensors for Calorimetry

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



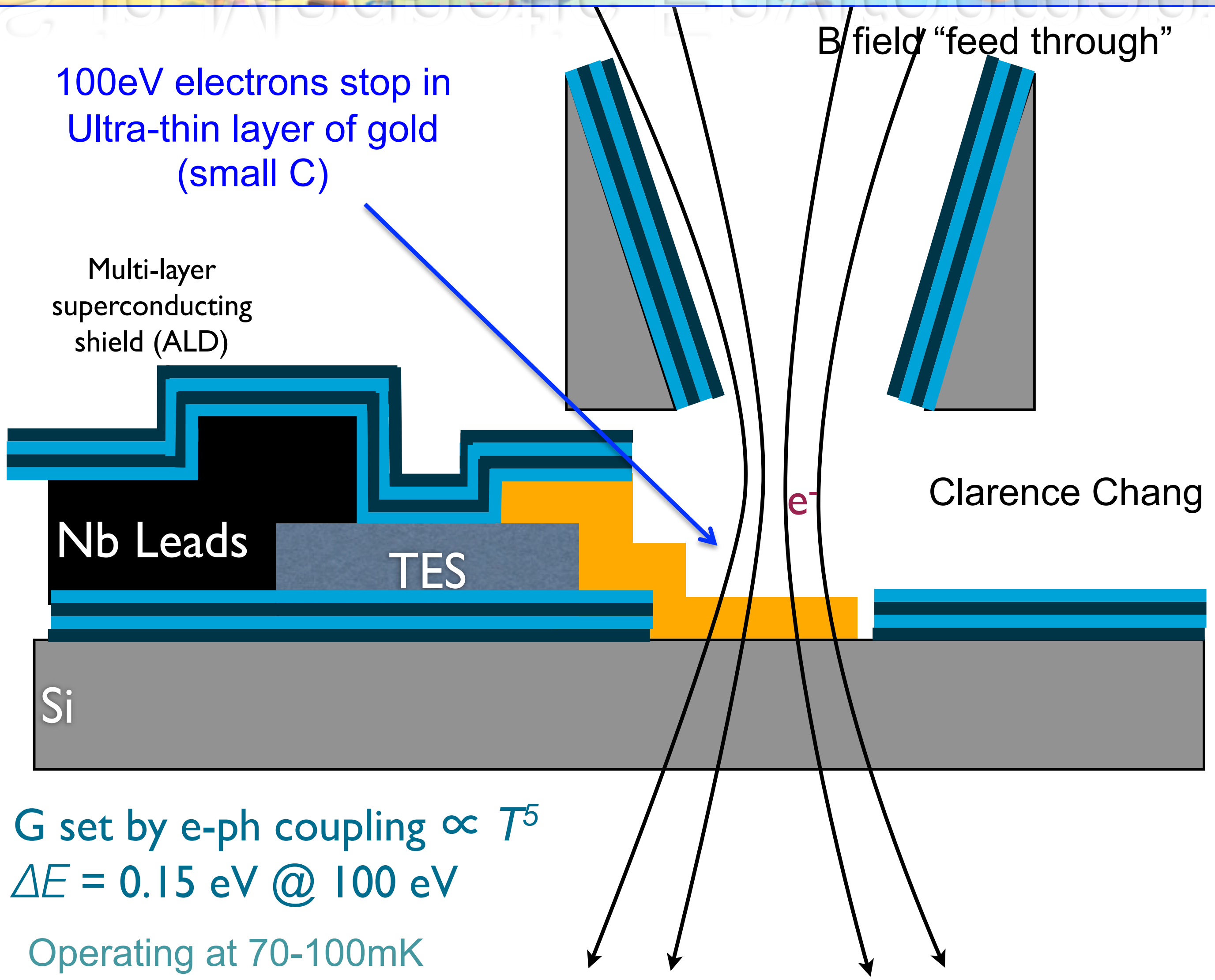
100eV electron can be stopped with very small C

(example) SPIDER Island TES



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

TES in Magnetic Environment



Clarence Chang

G set by e-ph coupling ∝ T^5

ΔE = 0.15 eV @ 100 eV

Operating at 70-100mK

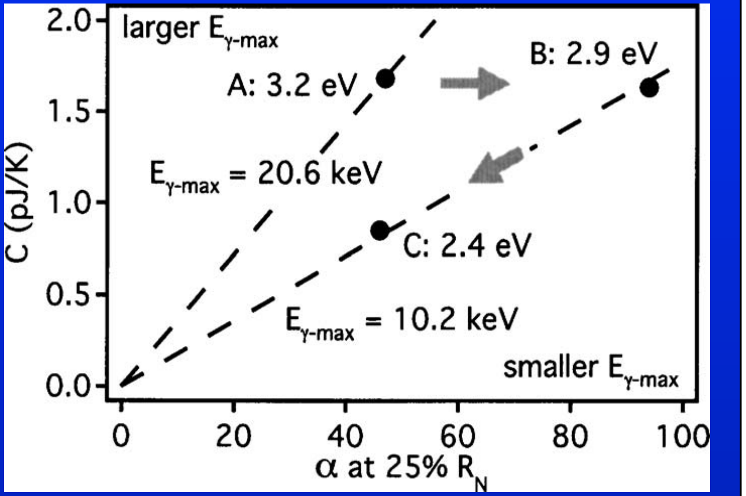
Calorimeter Energy Resolution

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

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



- 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/α) controlled by normal regions and magnetic field.

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

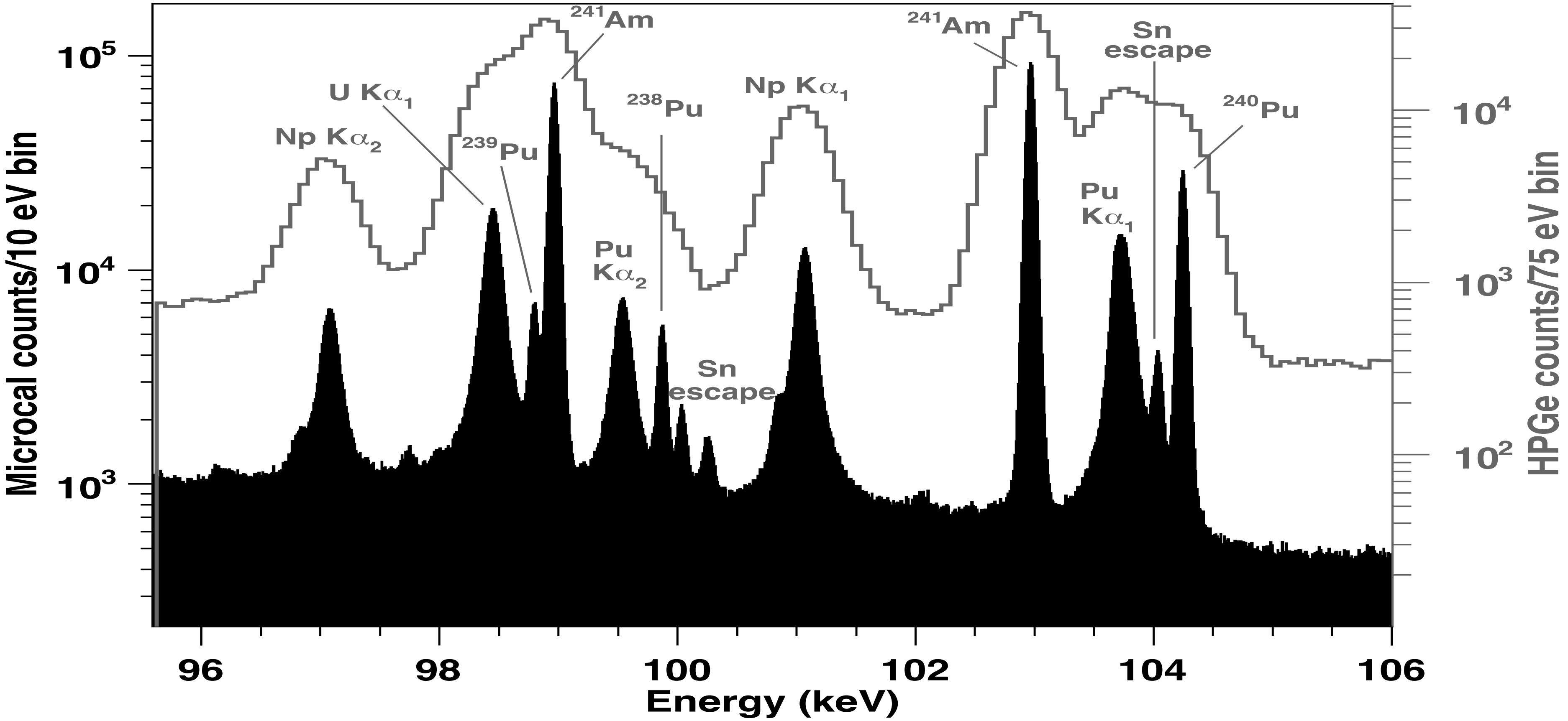
Au is not ideal as it doesn't stick well for thin layers.
Alternative materials will be studied (15nm of Bi)

Clarence Chang

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

Microcalorimeter Resolution

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



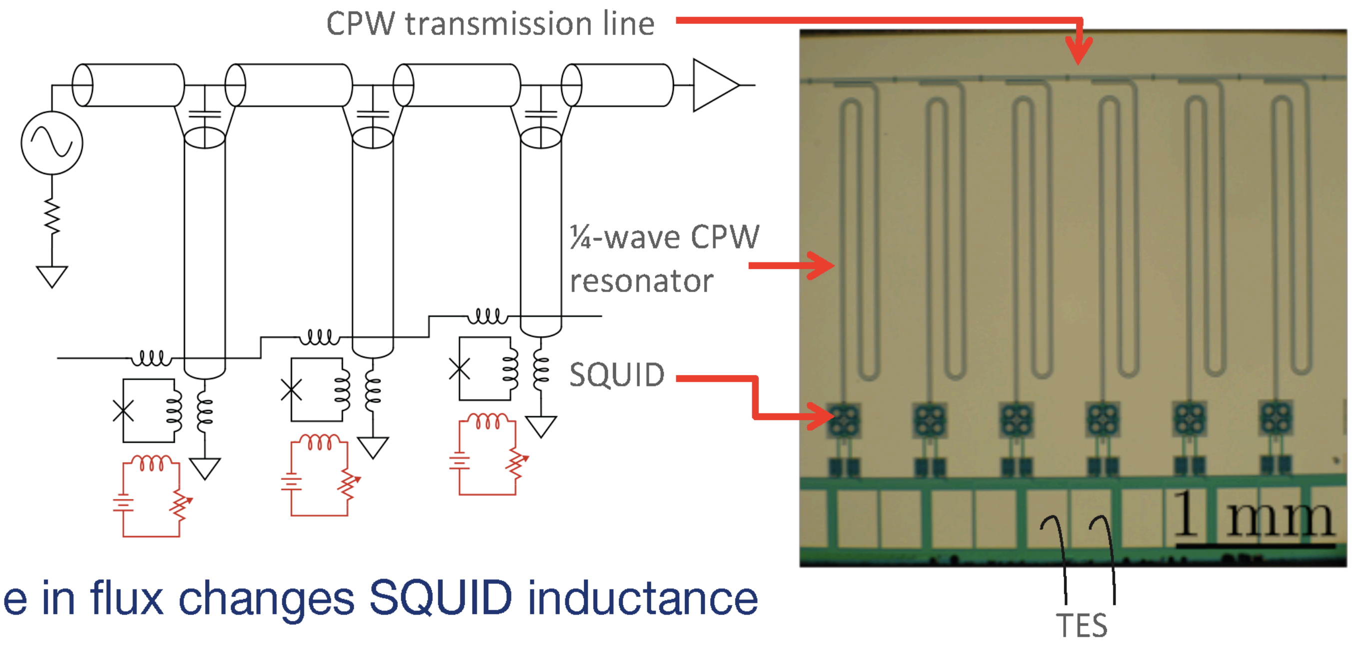
Calorimeter Rate

- 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 $(2\times10^{25})(2\times10^{-10})/(4 \times 10^{8}\text{s})=10\text{MHz}$
  - 10^3-10^4 calorimeter channels (for 10kHz bandwidth)

Highly Multiplexed SQUID Readout

Microwave-readout Massive SQUID Multiplexer

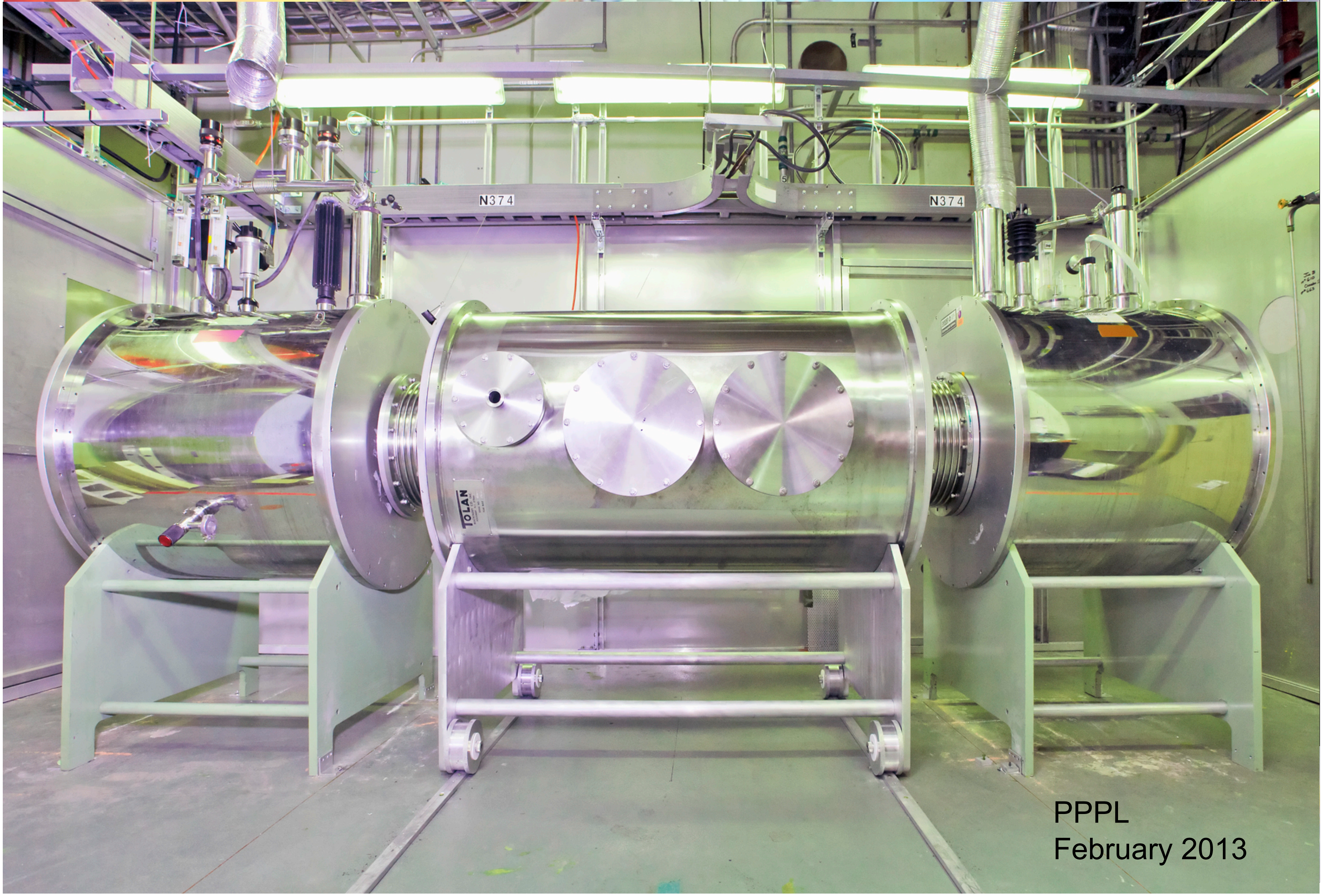
Clarence Chang



- 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

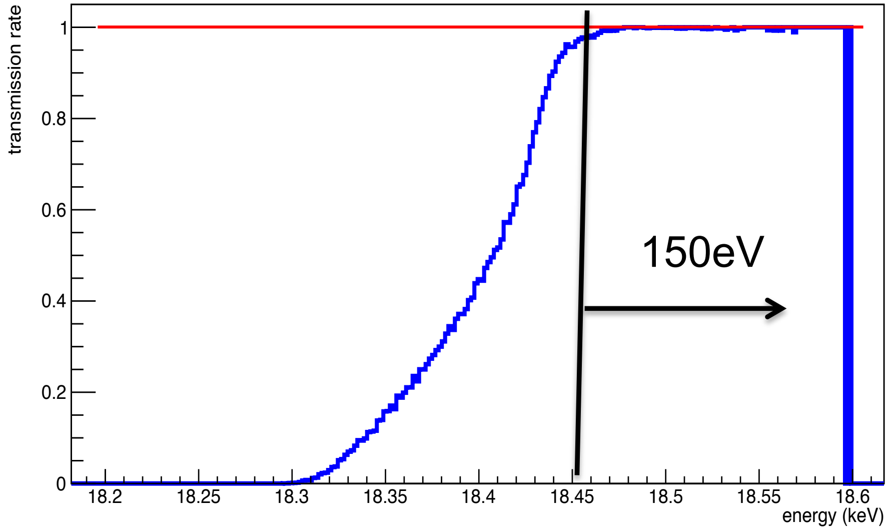
Kent Irwin

PTOLEMY

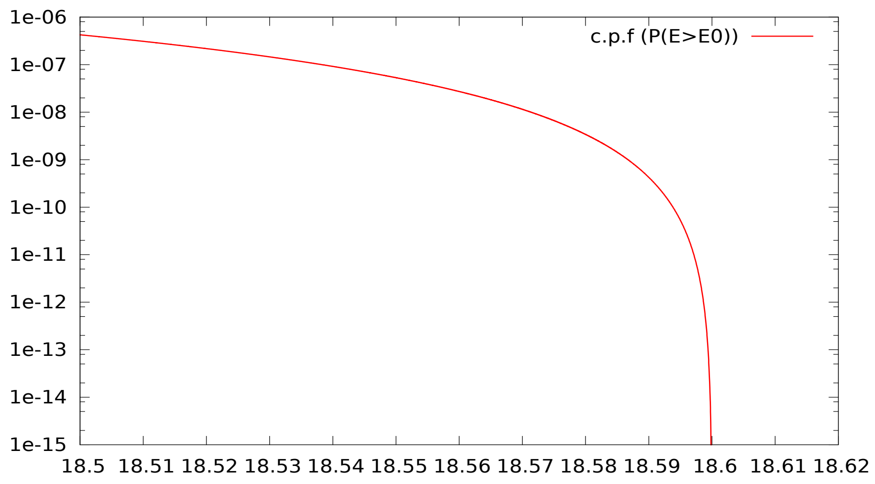


PPPL
February 2013

MAC-E Filter Transmission curve



~10^{-2} filter can be significantly improved when pre-sorted by longitudinal velocity

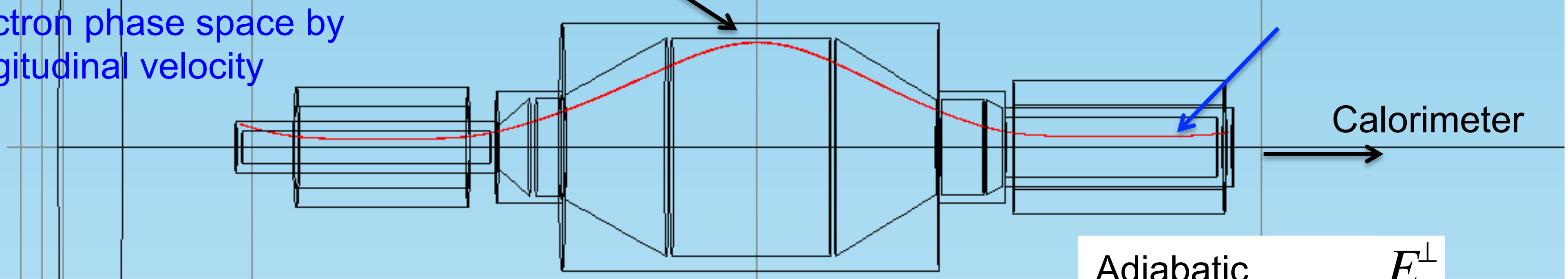


PTOLRMY MAC-E Filter

ExB drift before entering MAC-E filter
 - Can be used to differentiate electron phase space by longitudinal velocity

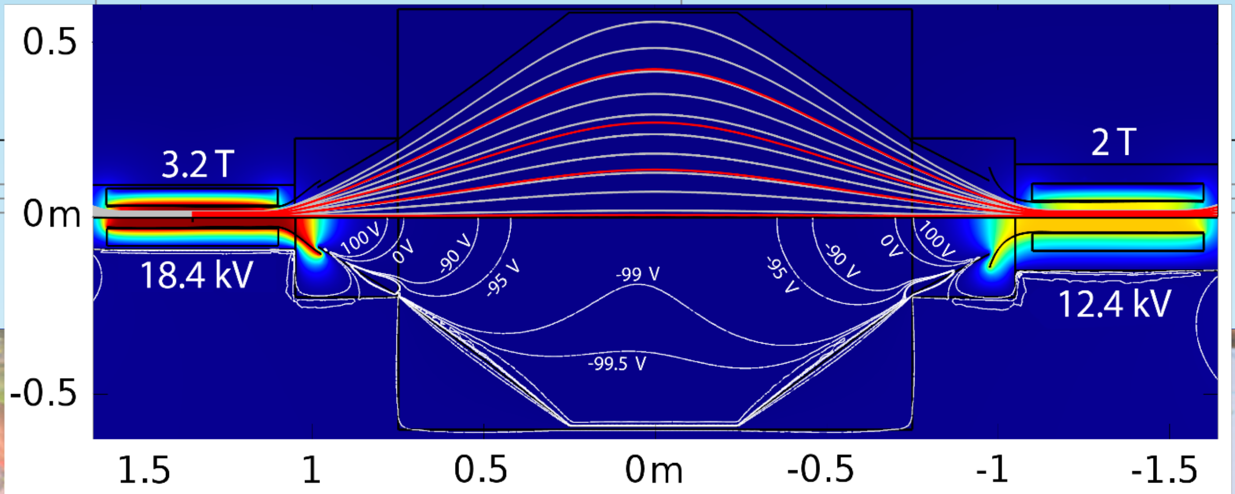
Limiting electron trajectory
(hits outer radius of filter)

Trajectories can be de-accelerated to have ~constant transit time through RF tracker

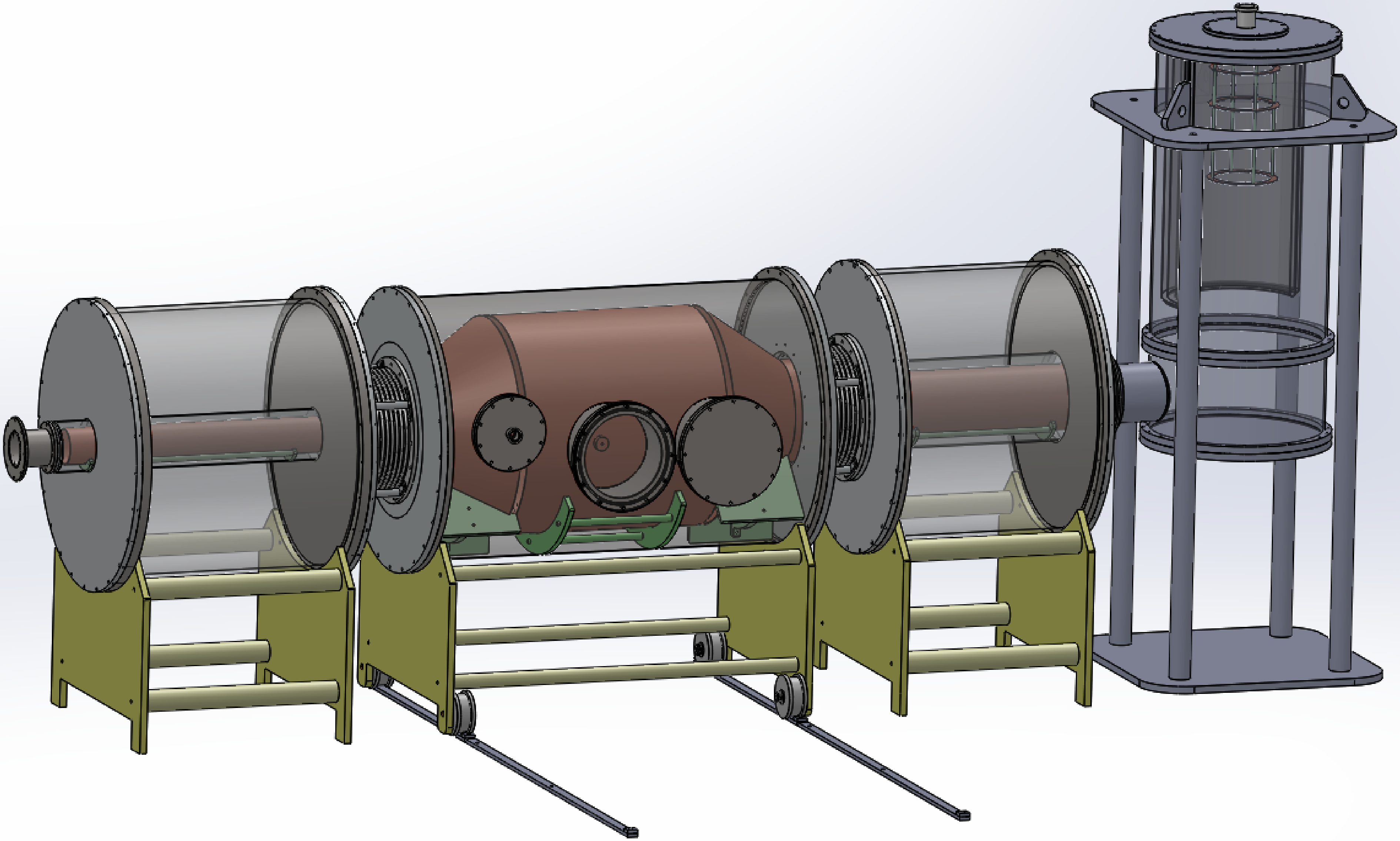


Planar cell aperture of ~30cm^2 within 3.2T bore

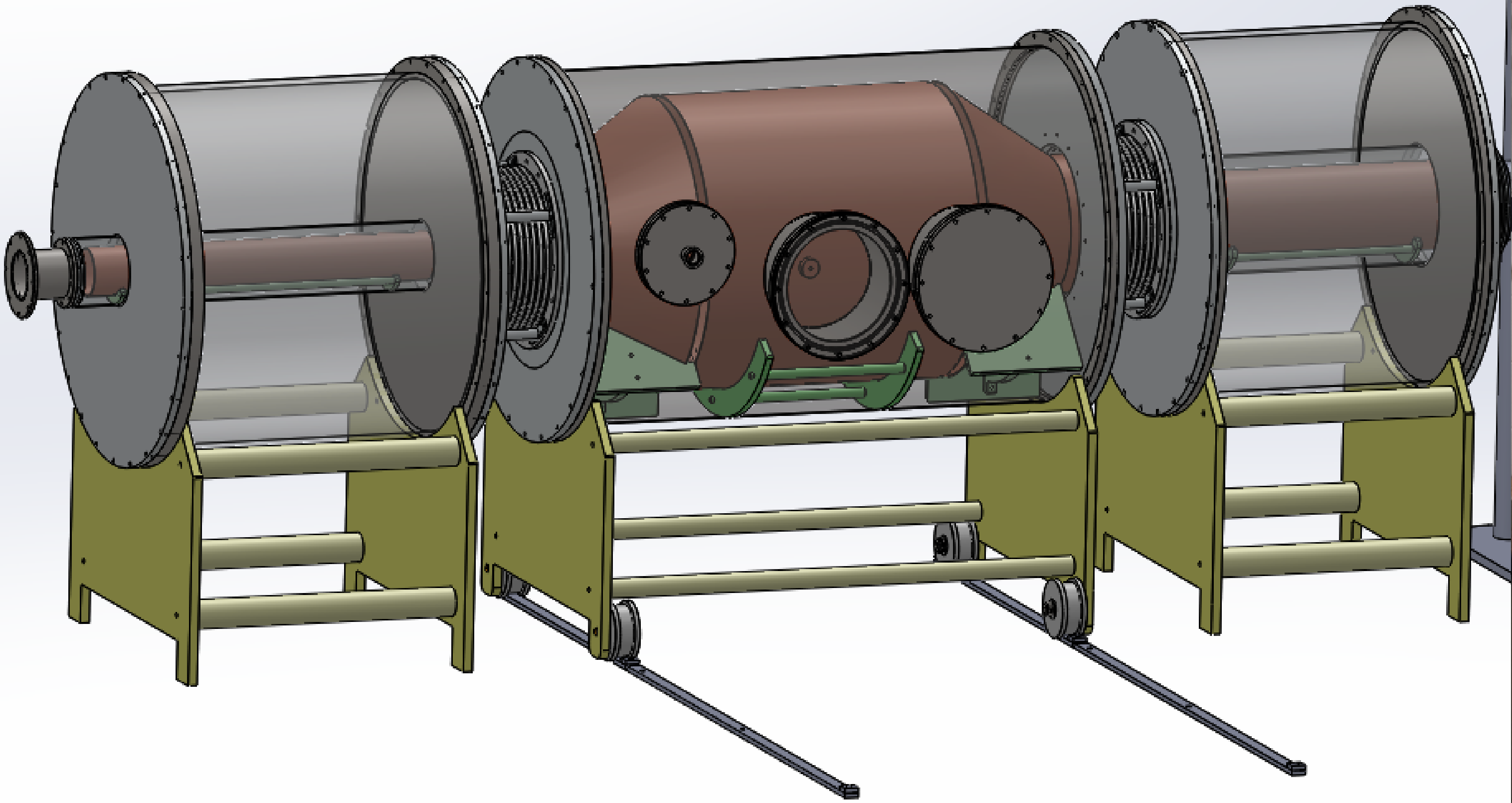
Adiabatic Invariant: $\mu = \frac{E^{\perp}}{B}$



Calorimeter Interface to MAC-E Filter



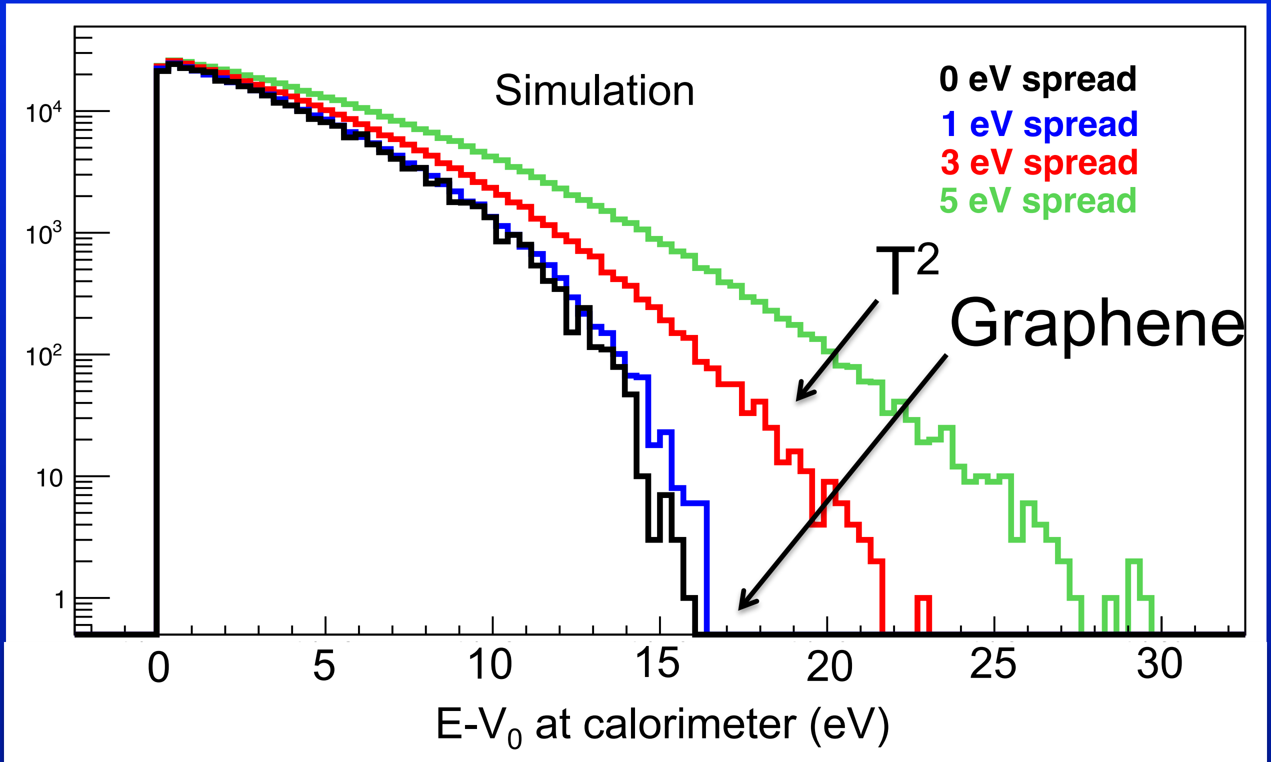
Calorimeter Interface to MAC-E Filter



Oxford Instruments Kelvinox MX400
(7mK base temp, 0.4mW@100mK)

Sensitivity to Shifts and Smearing

Direct measurement of systematic uncertainties from e^- energy smearing



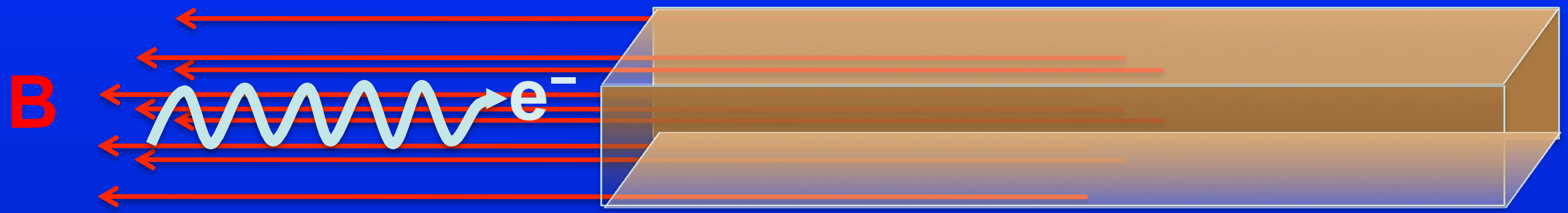
~10^{14} electrons from GEANT4 simulation (perfect resolution, ~1 month of data with 1µg ^{3}H)

Goals: Measure relative endpoint shifts of graphene compared to T^2 and determined relative energy smearing

Future: Ultra-weak surface binding below the room temperature stability limit.

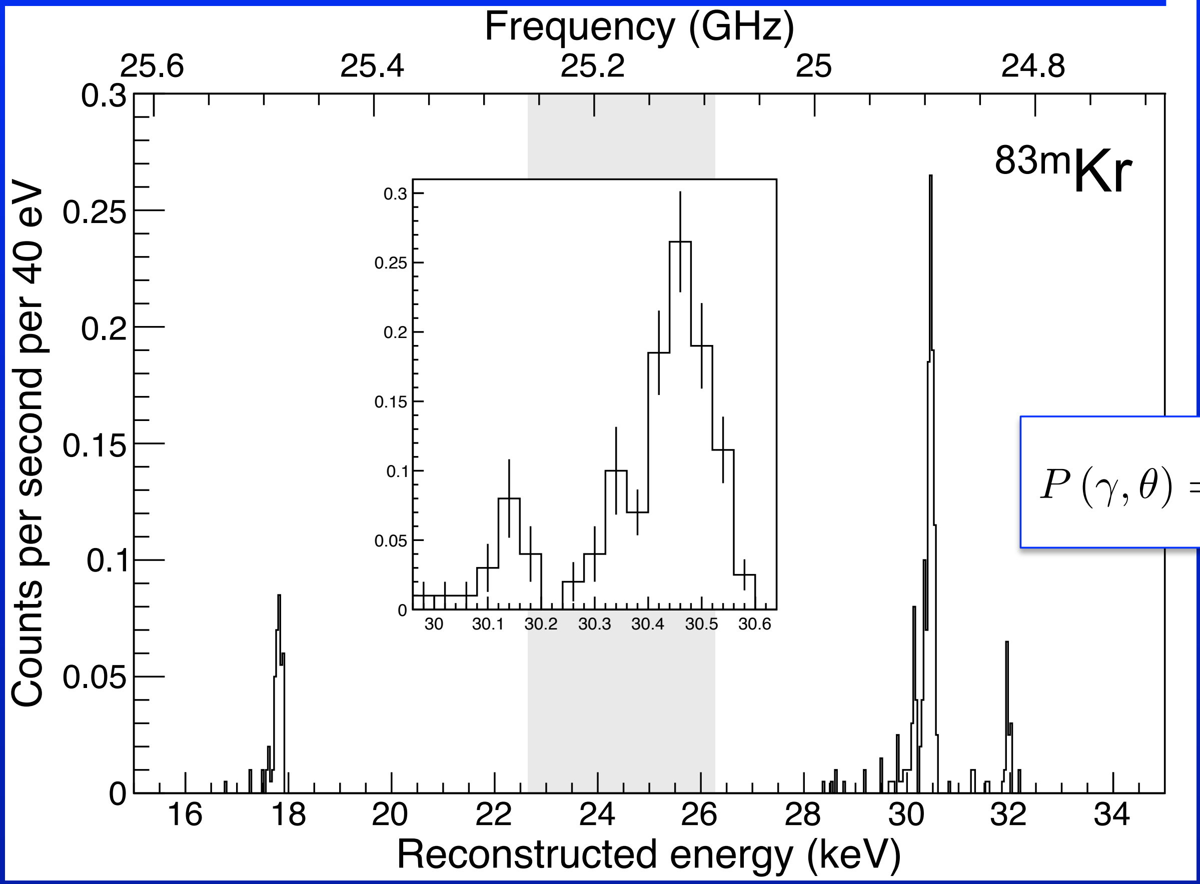
Semi-relativistic Electron Identification

Project 8 has first detection of single electron signal!



Asner et al., “Single electron detection and spectroscopy via relativistic cyclotron radiation”, arXiv:1408.5362

- RF tracking (p_T and transit time) and time-of-flight
  - Thread electron trajectories (magnetic field guide lines) through a coplanar waveguide with ~wide bandwidth (1GHz online → few x10^{-5} offline) to identify cyclotron RF signal in transit times of order 0.1 – 1μsec (with slow down)
    - Currently using WMAP (Norm Jarosik) HEMT amplifiers with 1K/GHz noise and operating in the Q-Band range 38-46 GHz (~1.9T)



$$f_\gamma \equiv \frac{f_\mathrm{c}}{\gamma} = \frac{eB}{2\pi\gamma m_\mathrm{e}}$$

$$P(\gamma,\theta) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{e^4}{m_\mathrm{e}^2 c}B^2\left(\gamma^2-1\right)\sin^2\theta$$

Asner et al., “Single electron detection and spectroscopy via relativistic cyclotron radiation”, arXiv:1408.5362

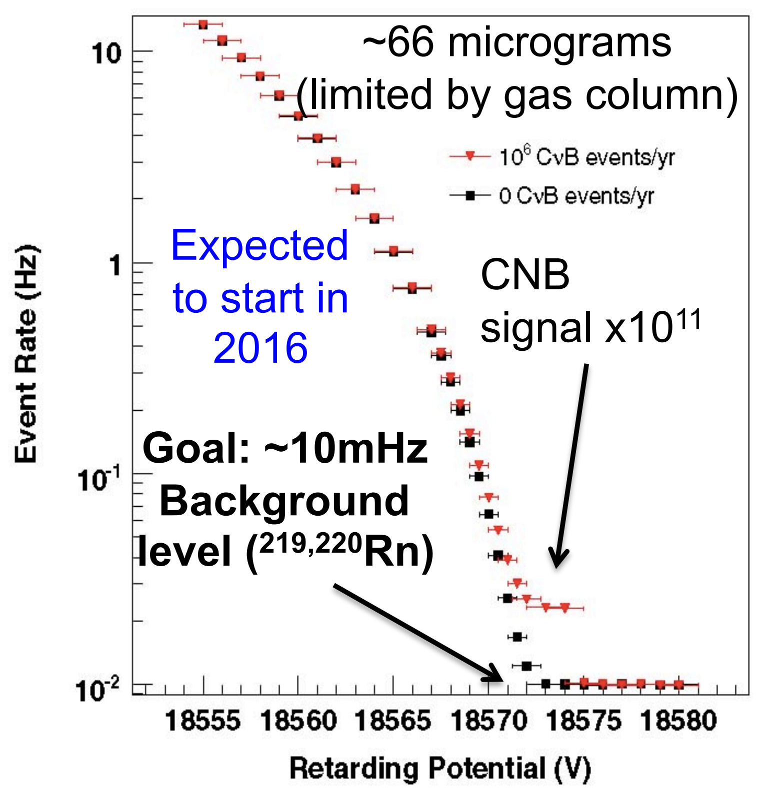
Trigger

Non-relativistic electrons in cyclotron motion can have their longitudinal velocity slowed down.

"Trigger" information from the RF tracker will introduce a time-dependence needed to reduce phase space coverage of the calorimeter.

Karlsruhe TRItium Neutrino (KATRIN)

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



~66 micrograms (limited by gas column)

Expected to start in 2016

CNB signal x10^{11}

Goal: ~10mHz Background level (^{219,220}Rn)

Wandkowsky, Drexlin, Frankle, Gluck ,Groh, and Mertens. ‘Modeling of electron emission processes accompanying radon-α-decays within electrostatic spectrometers’, doi:10.1088/1367-2630/15/8/083040

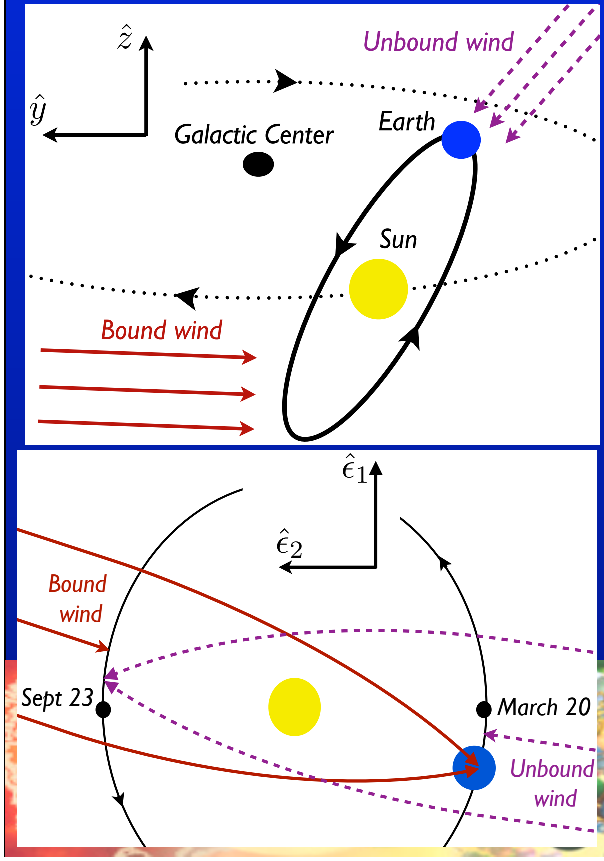
Low Carbon^{14} (Borexino) → Graphene

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

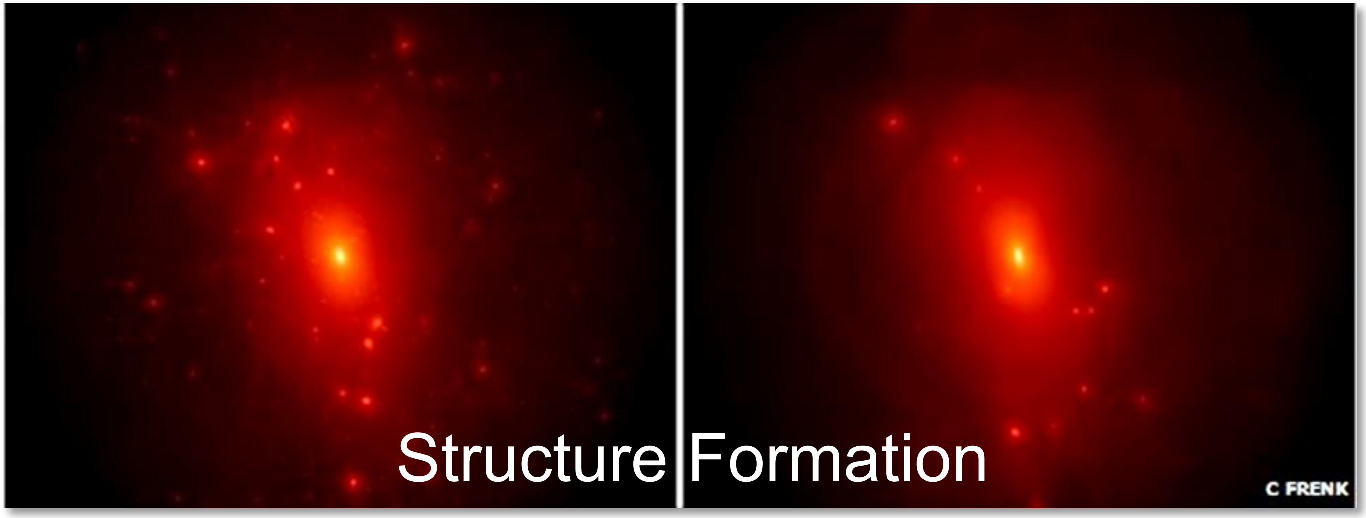
$$d\sigma_{\mathrm{NCB}} \propto \left[1 + a\frac{\mathbf{p_e}\cdot\mathbf{p}_\nu}{E_e E_\nu} + A\frac{\hat{\mathbf{s}}\cdot\mathbf{p_e}}{E_e} + B\frac{\hat{\mathbf{s}}\cdot\mathbf{p}_\nu}{E_{\bar{\nu}}}\right]$$

Tritium polarization calibrated using beta decay electrons.
http://arxiv.org/abs/1407.0393 **B. Safdi, M. Lisanti, CGT**

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

Sterile Neutrinos

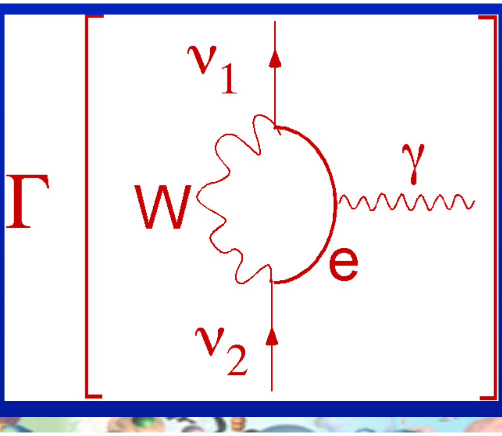
CDM simulations WDM



X-Ray Astronomy

$\nu_2 \rightarrow \nu_1 + \gamma$

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

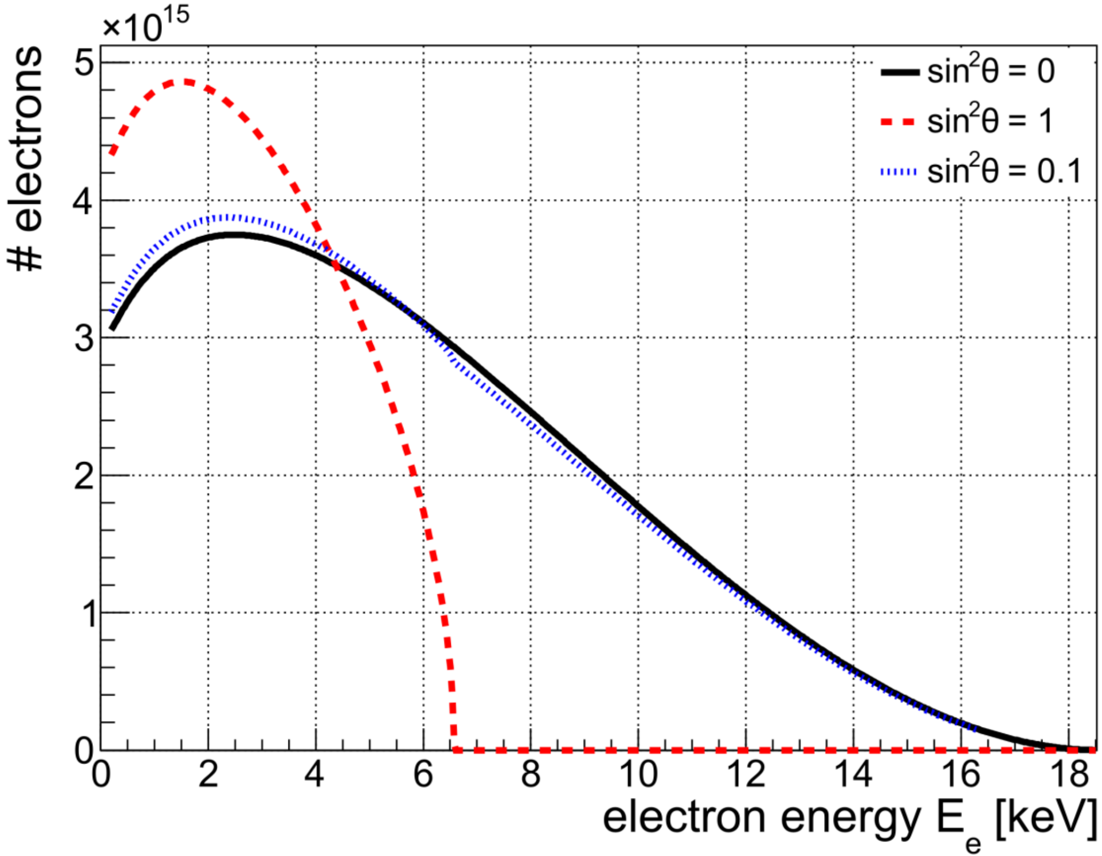


Sterile neutrinos will introduce a kink in the beta-decay spectrum at $K^0_{end} - m_4$ where sensitivities down to $|U_{e4}|^2 \sim 10^{-8}$ may be possible.

Sterile Neutrino Kink Finding

Mixing of keV-neutrinos and light neutrinos with mixing angle θ:

$$\frac{d\Gamma}{dE_\mathrm{e}} = \sin^2\theta \left(\frac{d\Gamma}{dE_\mathrm{e}}\right)_{\mathrm{m_{heavy}}} + \cos^2\theta \left(\frac{d\Gamma}{dE_\mathrm{e}}\right)_{\mathrm{m_{light}}}$$



m_heavy: mass eigenstate of sterile keV neutrino

m_light: effective mass of active neutrinos

$$m^2_\mathrm{light} = \sum_i |U_\mathrm{ei}|^2 m^2_\mathrm{i}$$

$$m_\mathrm{heavy} \gg m_\mathrm{light}$$

Kai Dolde (Meudon 2014)
Susanne Meurtens (KATRIN)

Sterile Neutrino Kink Finding

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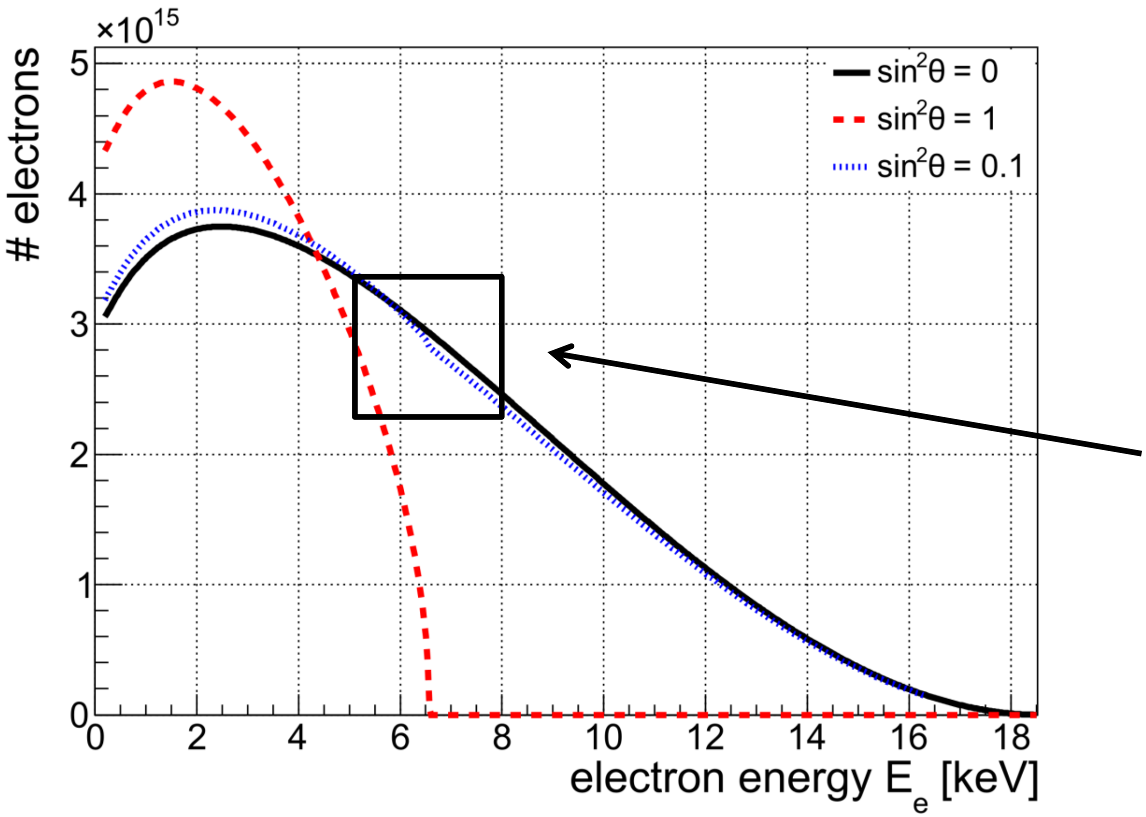

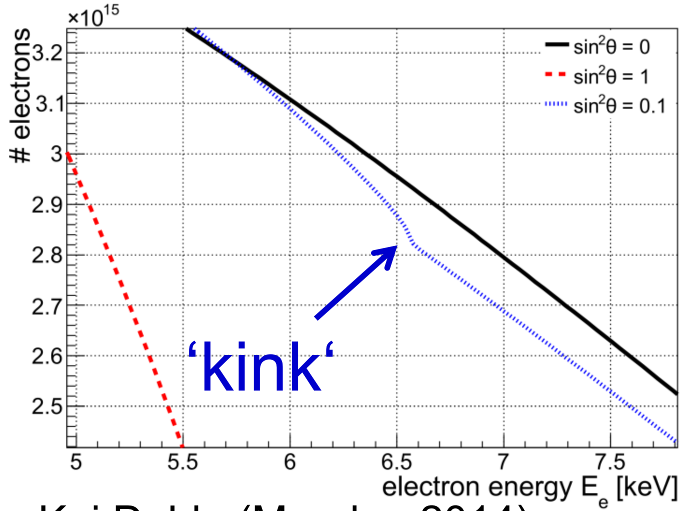

Kai Dolde (Meudon 2014)
Susanne Meurtens (KATRIN)

Sterile Neutrino Kink Finding

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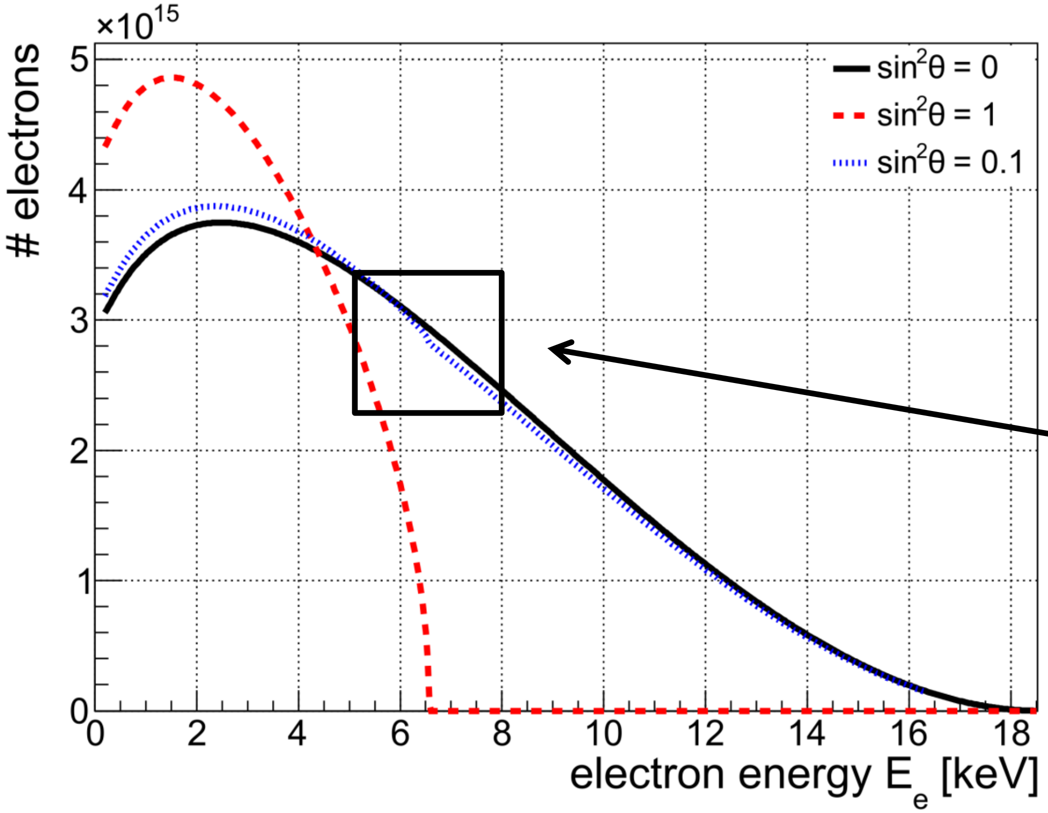
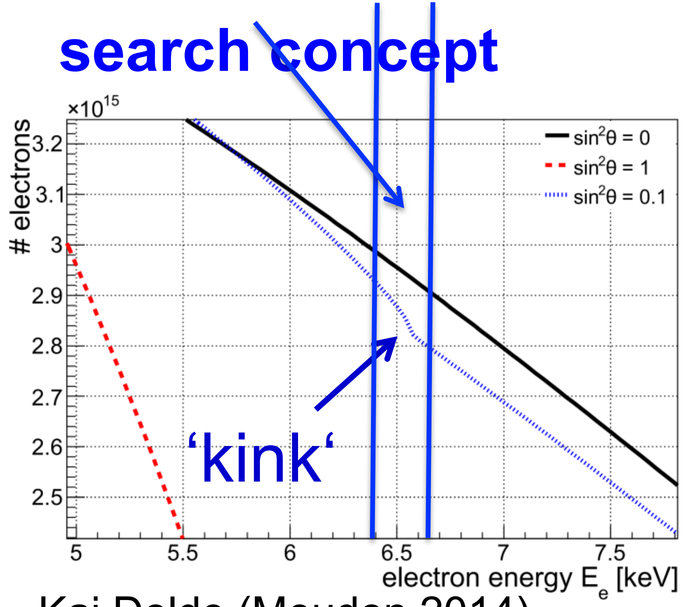
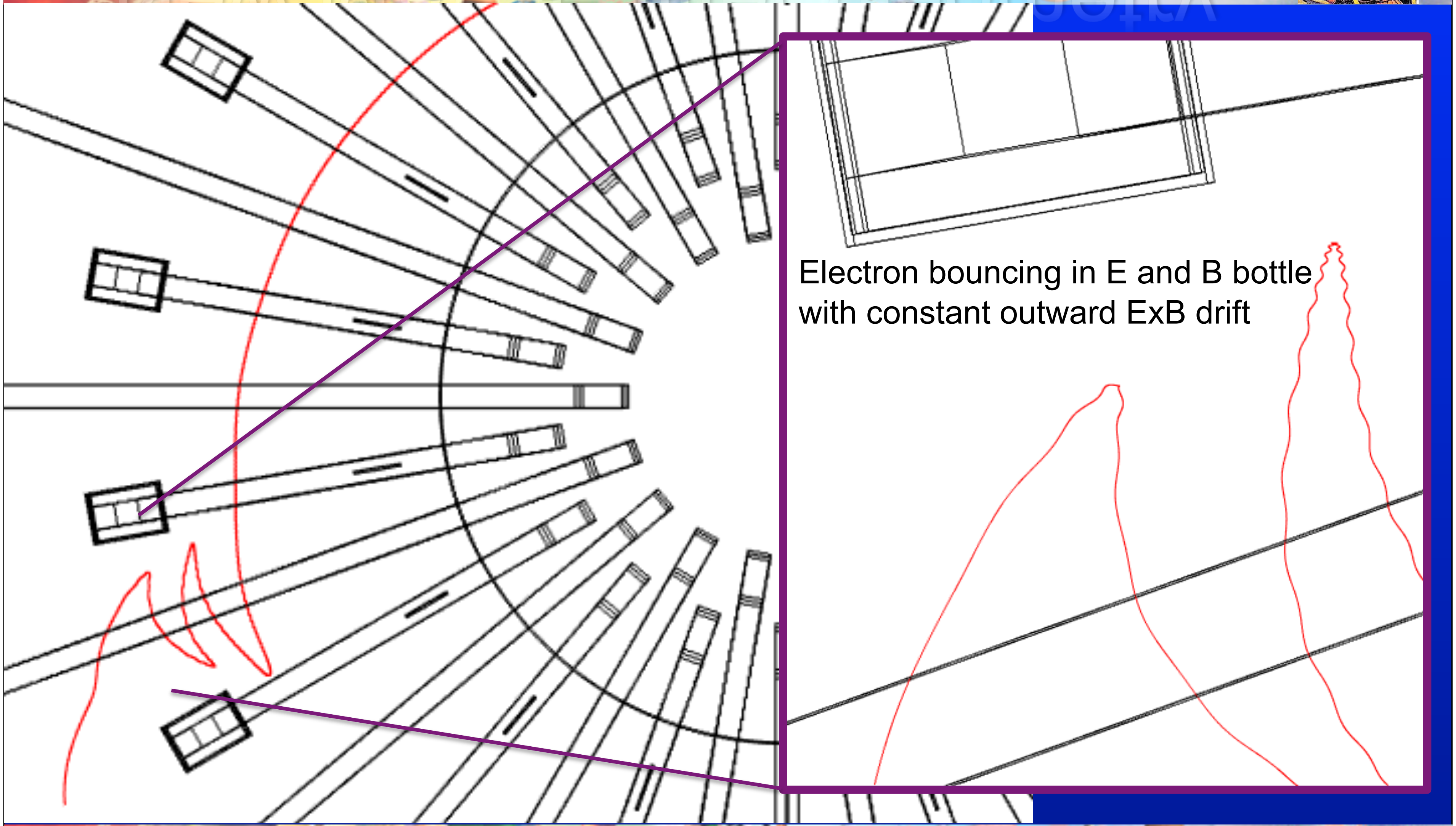


PTOLEMY "narrow window" search concept



Kai Dolde (Meudon 2014)
Susanne Meurtens (KATRIN)

New MAC-E filter Geometry

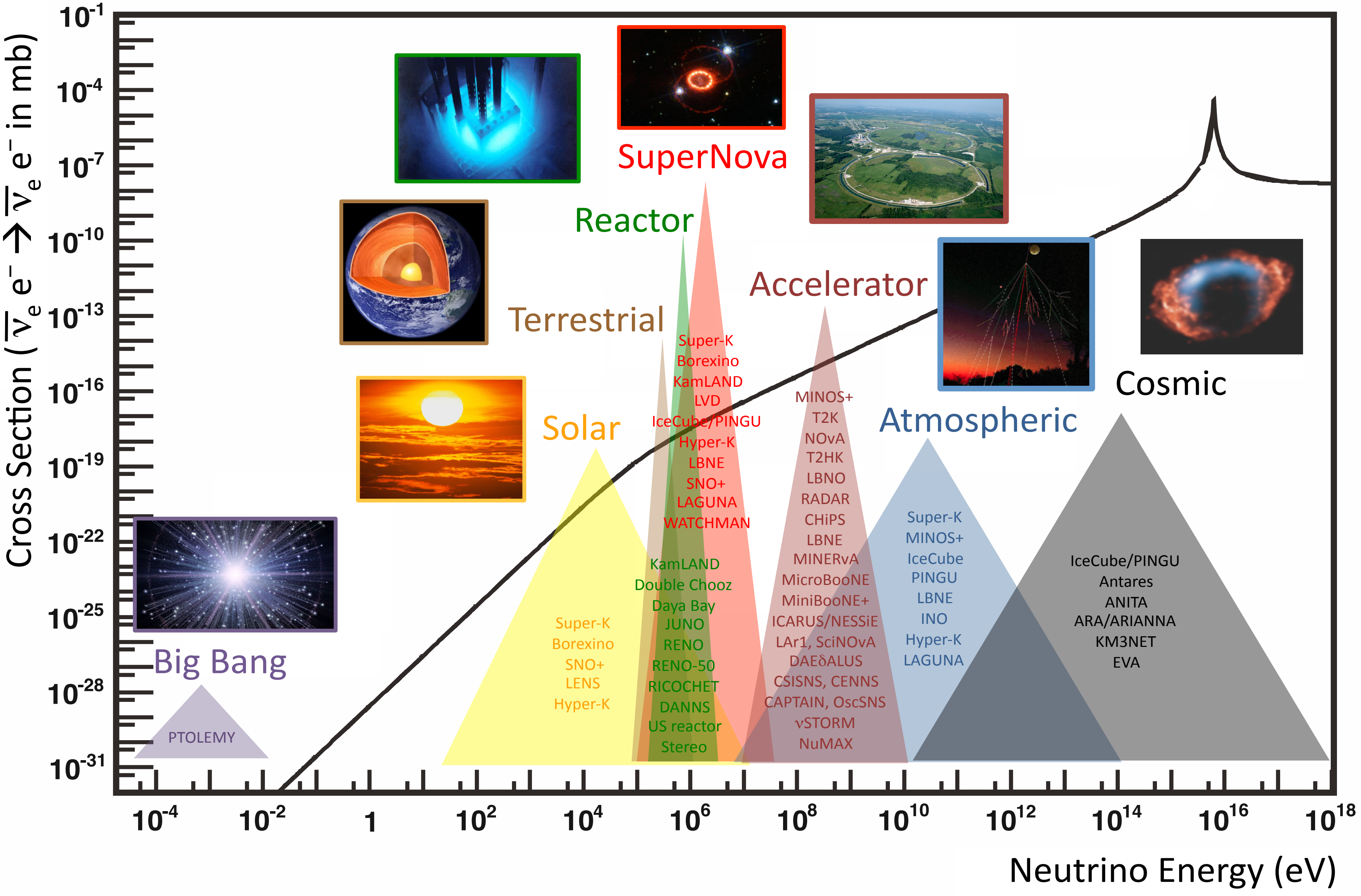


Electron bouncing in E and B bottle with constant outward ExB drift

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 (highest resolution e$^-$ calorimeter)
  - 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

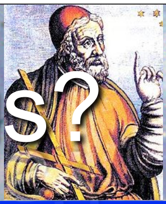
Overview of Neutrino Experiments



What can Relic Neutrino Density tell us?

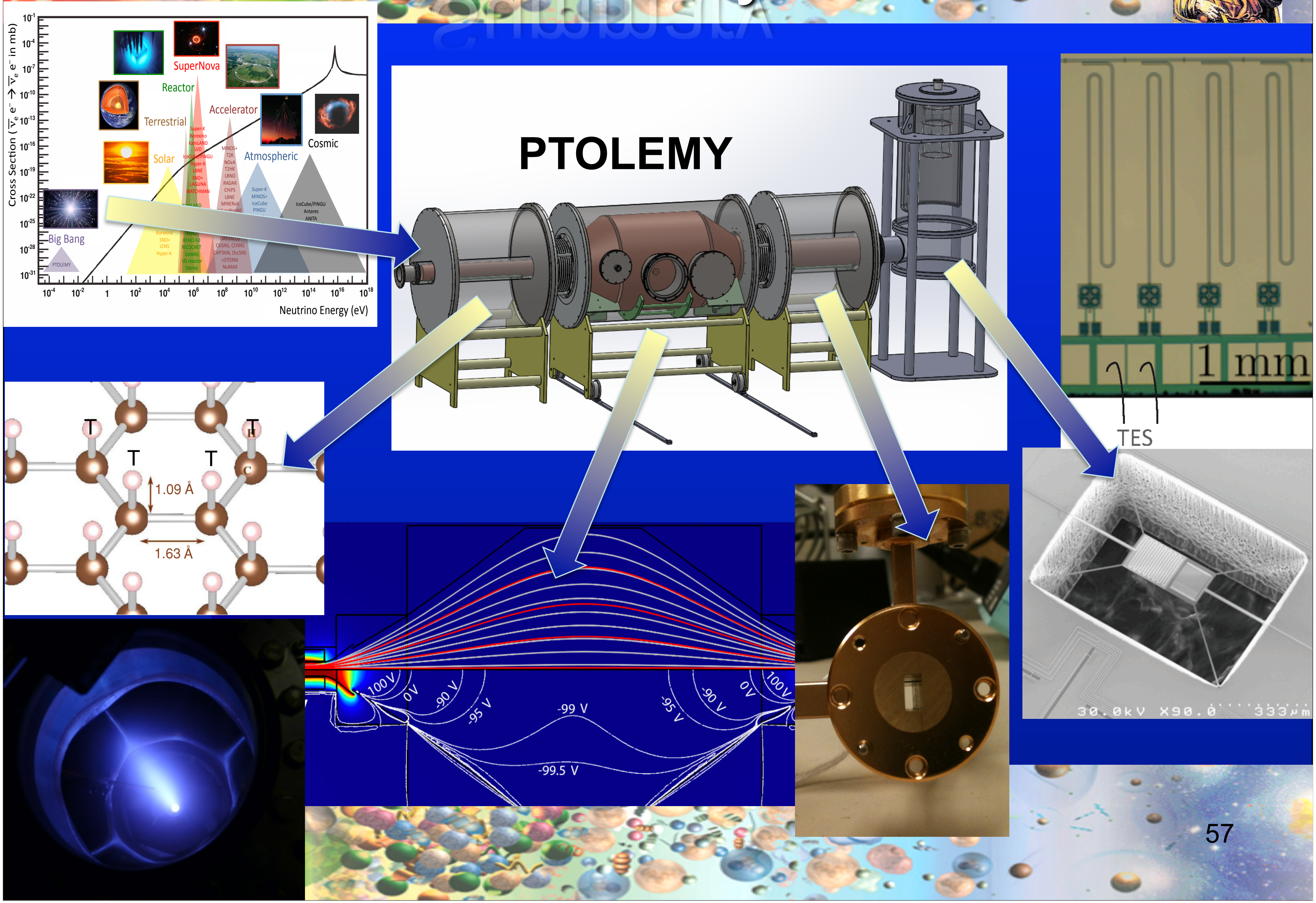
- Are there experimental outcomes that are inconsistent with precision Big Bang cosmology? Yes!
  - Observed neutrino mass and number density point to a different and perhaps non-thermal component to history of the universe
- Are there outcomes that are inconsistent with the Standard Model of particle 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 distort the tritium spectrum

What can Relic Neutrino Density tell us?



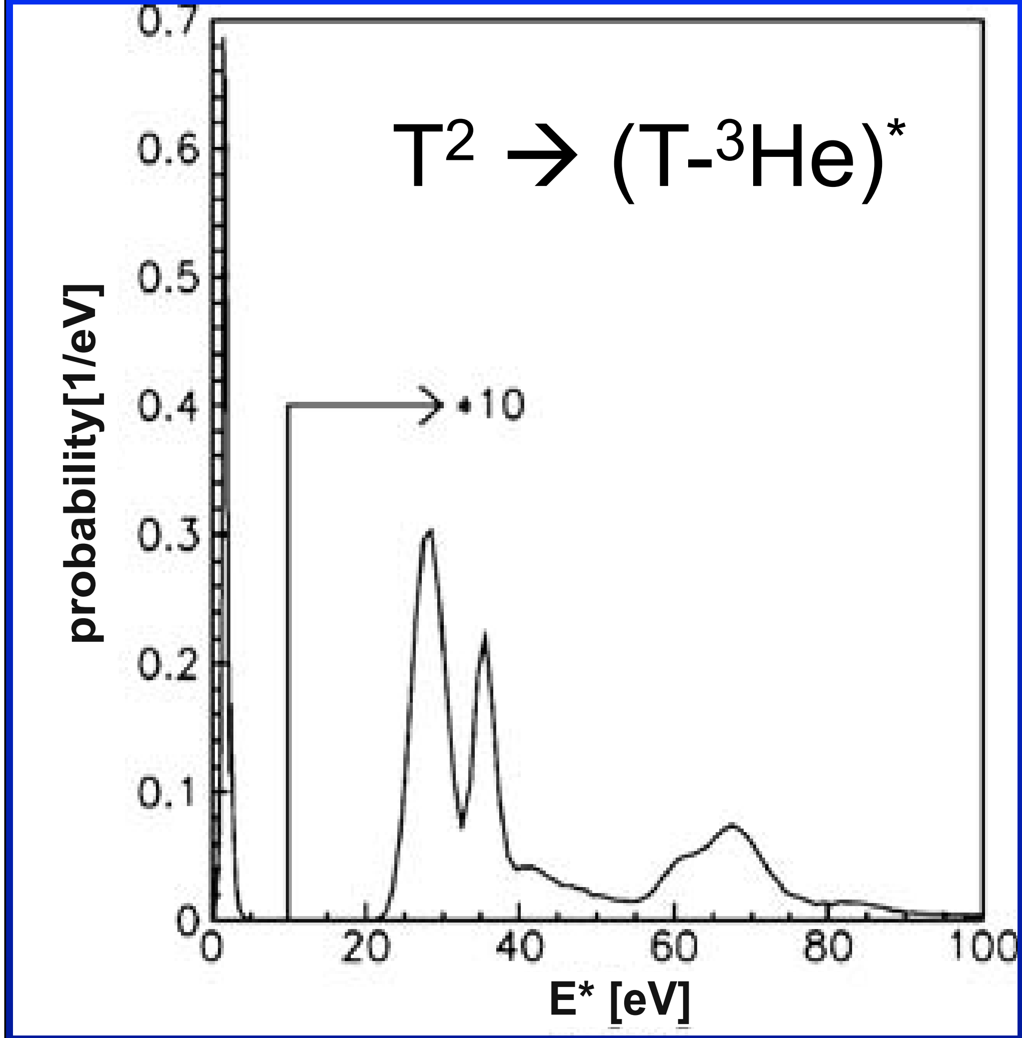
- Is there a possibility to make long-term contributions to the understanding of the Universe?
  - Absolutely! We believe that we live in a sea of 14 billion year old neutrinos all around us (the oldest relics in the Universe) – is it true?
  - When one opens a new frontier of exploration, there is no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

Summary


Cross Section ($\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$ in mb)
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^{-31}
SuperNova
Reactor
Terrestrial
Accelerator
Cosmic
Solar
Atmospheric
Big Bang
PTOLEMY
Super-K
Borexino
KamLAND
LVD
IceCube/PINGU
Hyper-K
LBNE
SNO+
LAGUNA
WATCHMAN
MINOS+
T2K
NOvA
T2HK
LBNO
RADAR
CHiPS
LBNE
MINERvA
Super-K
MINOS+
IceCube
PINGU
IceCube/PINGU
Antares
ANITA
Borexino
SNO+
LENS
Hyper-K
RENO
RENO-50
RICOCHET
DANNS
US reactor
Stereo
DAEδALUS
CSISNS, CENNS
CAPTAIN, OscSNS
νSTORM
NuMAX
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
Neutrino Energy (eV)
PTOLEMY
1 mm
TES
T
T
T
T
T
C
1.09 Å
1.63 Å
100 V
0 V
-90 V
-95 V
-99 V
-95 V
-90 V
0 V
100 V
-99.5 V
30.0kV X90.0 333μm

Backup Slides

Energy Smearing from T-^{3}He Excitations



Diatomic T^2 excitation spectrum has ~3eV smearing for excited states below 10eV, making T^2 unsuitable for high resolution energy separation of beta-decays from relic neutrino capture.

Note that a cold gas (~20K) column depth of T^2 is also limited to avoid scattering (~30eV per inelastic scatter)

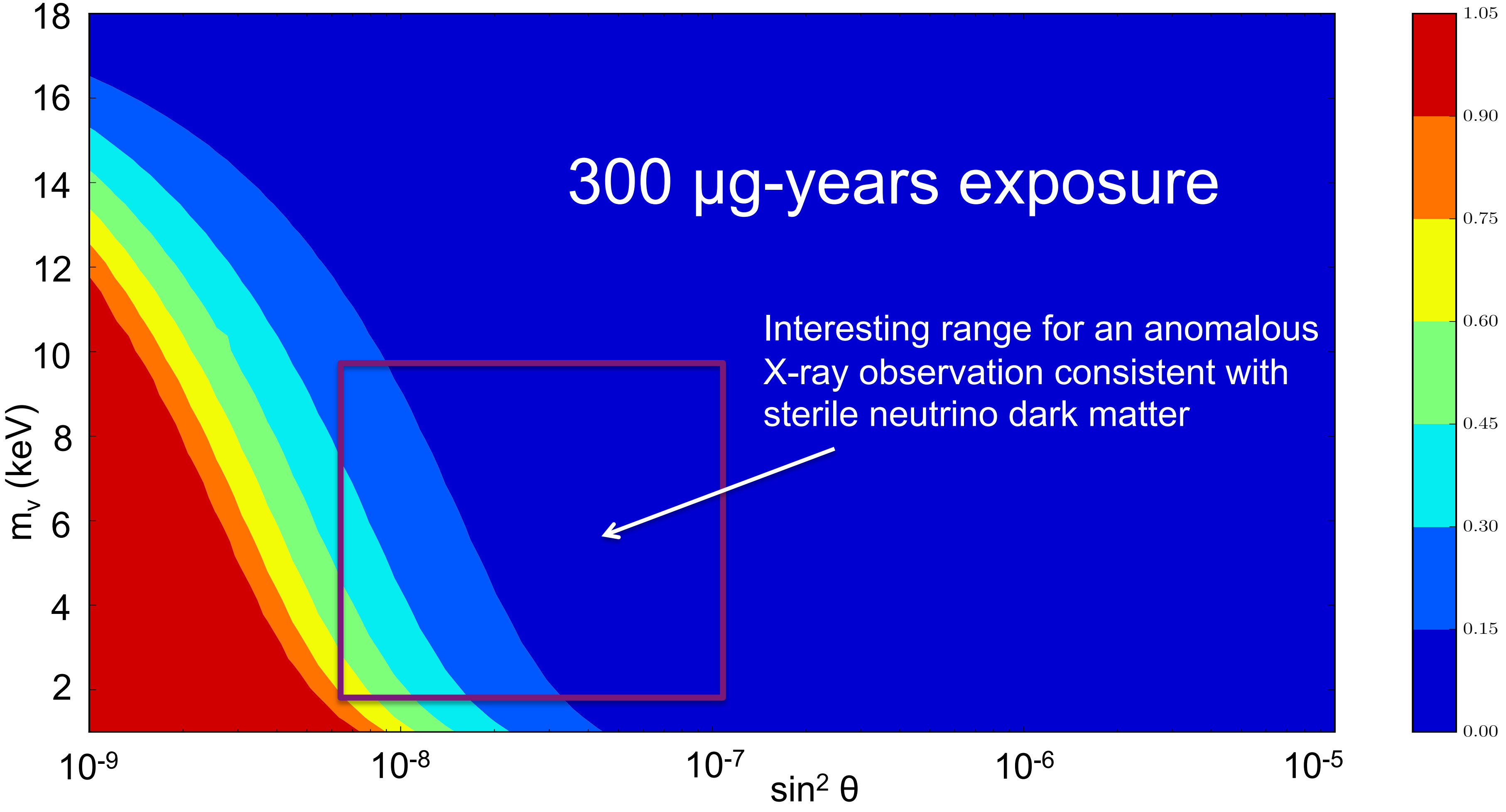
Background Suppression

KATRIN: Relatively open phase space volume – no correlation between position, energy, and longitudinal velocity of electrons (^{219,220}Rn decays can feed straight in – pumping rate important)

PTOLEMY: Highly segmented phase space where position (by solid source), energy (by sub-eV resolution calorimeter), longitudinal velocity (by ExB drift), and RF tracking signal, all constrain the probability that a random decay will fake a signal.

Furthermore, in order to manage the formidable size of the initial tritium target phase space, it would be advantageous to construct a trigger system. There are alternative geometries more suitable for a triggered system.

Fractional Uncertainty in Fitted Heavy Neutrino $\sin^2\theta$



300 μg-years exposure

Interesting range for an anomalous X-ray observation consistent with sterile neutrino dark matter

PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Upper Limits on the Neutrino Mass from the Tritium Beta Spectrum*

DONALD R. HAMILTON, W. PARKER ALFORD,† AND LEONARD GROSS‡
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received August 25, 1953)

The shape of the tritium beta spectrum near the end point has been investigated in a spherical electrostatic integral spectrograph with particular reference to the possible effects of a nonzero neutrino mass. It is shown that the source thickness of 100 micrograms/cm² may be satisfactorily taken into account in the last kilovolt of the spectrum, upon which the results are based. An upper limit to the neutrino mass of 500, 250, and 150 electron volts is found for the Dirac, Majorana, and Fermi forms, respectively, of the beta interaction.

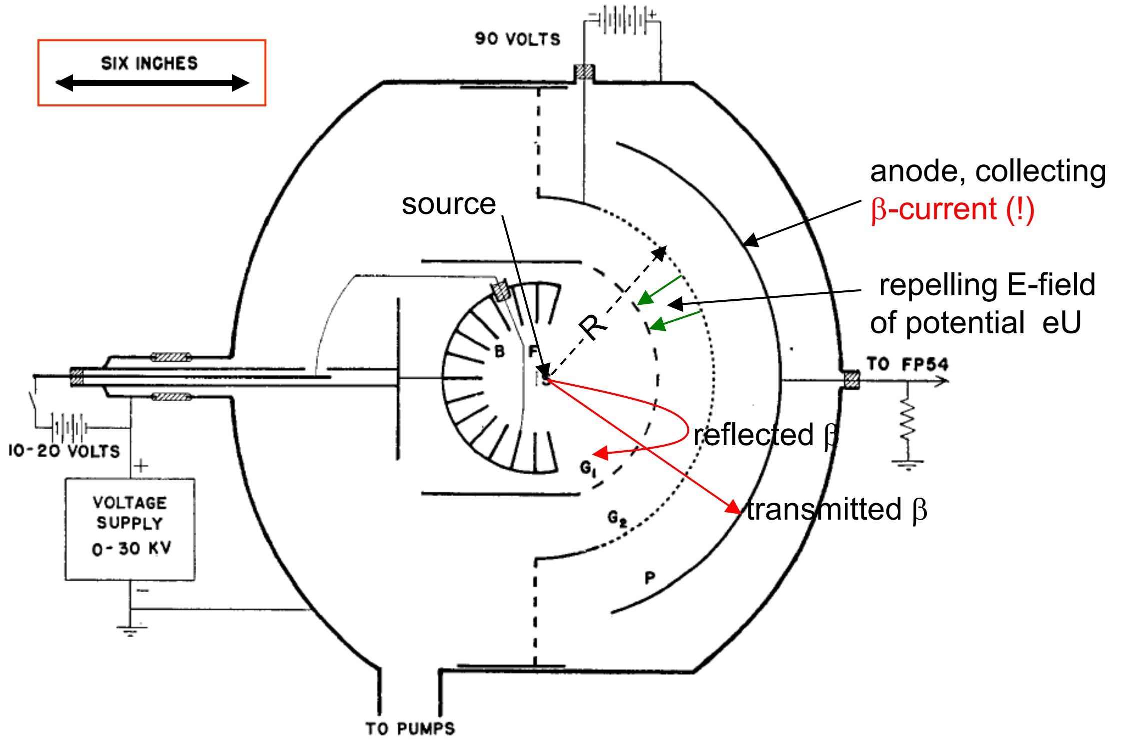


FIG. 1. Schematic diagram of electrostatic beta-spectrograph showing collector P, grids G_1 and G_2, source S, decharging filament F, and electron backstop B.

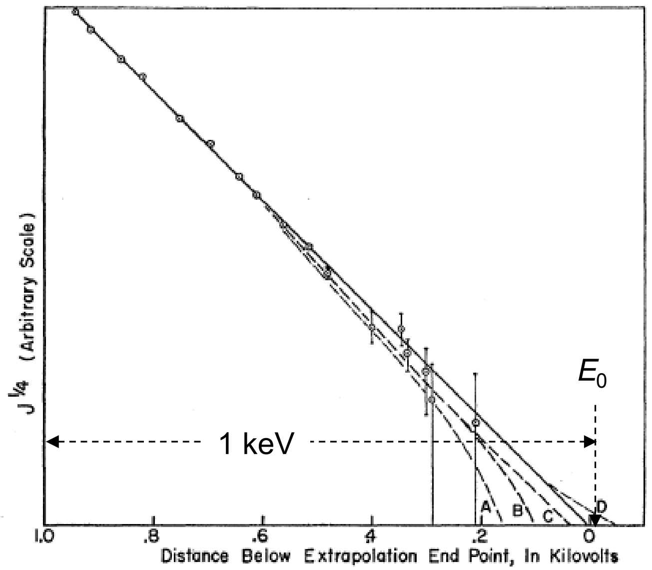
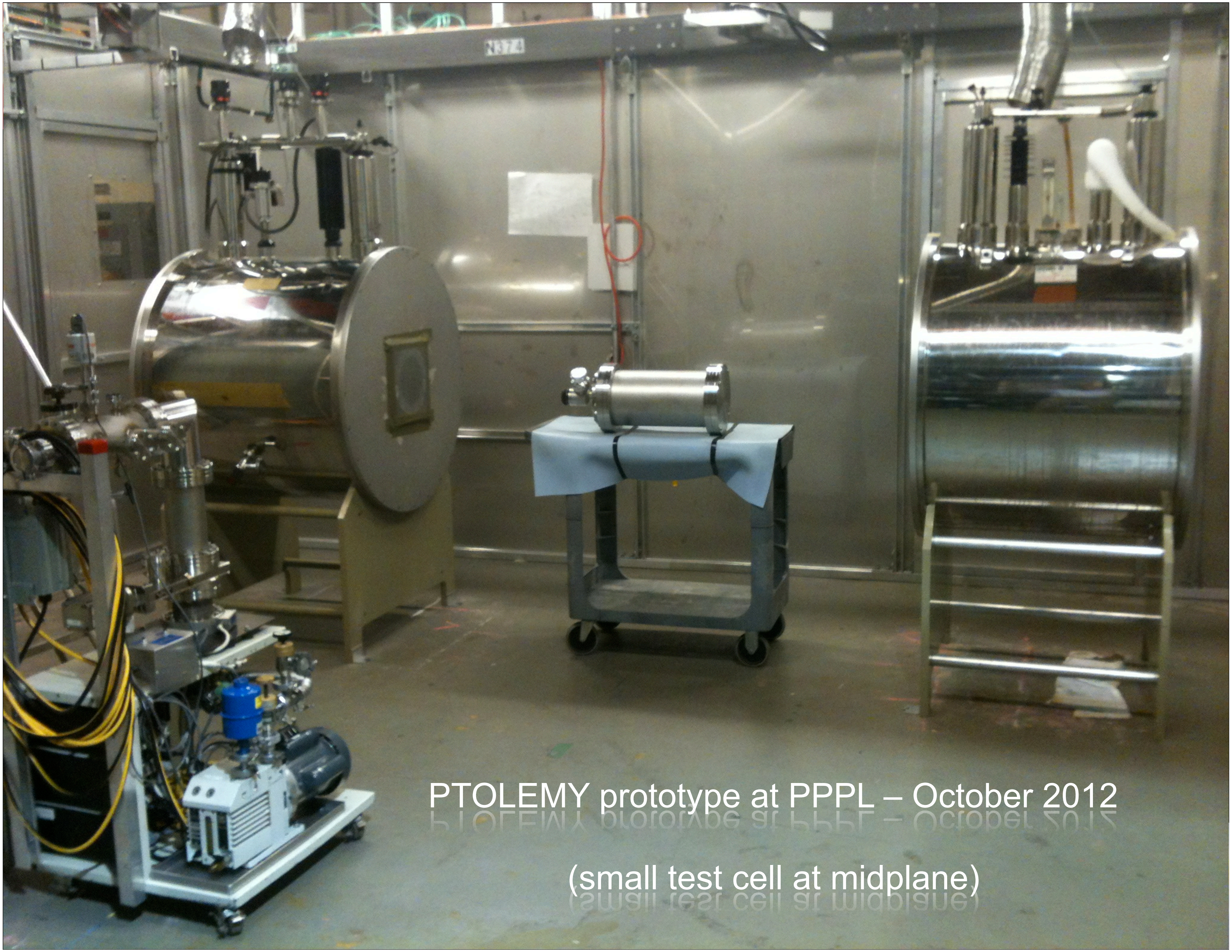


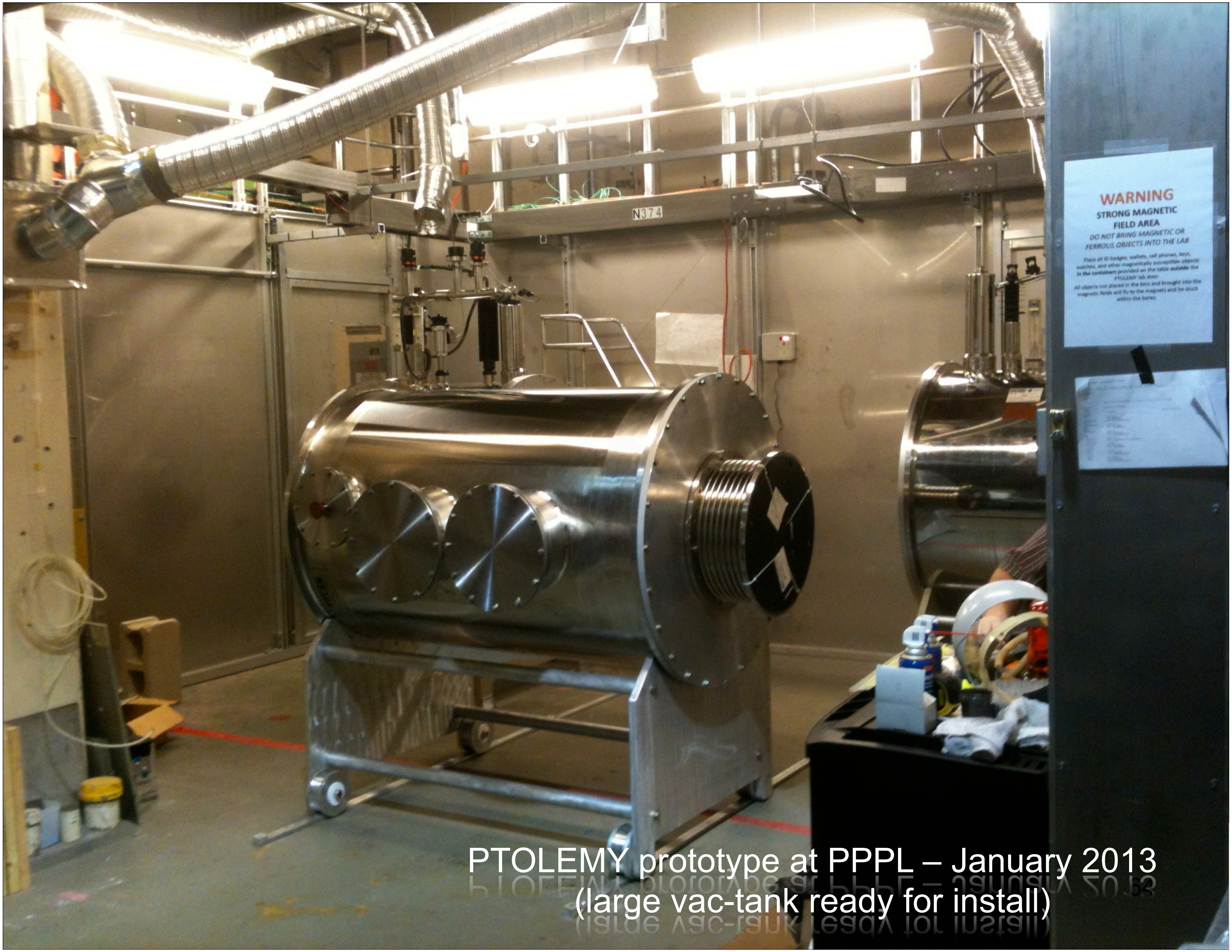
FIG. 3. Fourth root of tritium current plotted against kilovolts below end point. Dotted curves represent curves predicted on the basis of measured resolution and for various neutrino masses and interactions. Majorana, Fermi, and Dirac interactions indicated by (0) (+) (−), respectively. Neutrino mass μ in electron volts.

Curve A: $\mu=250$ (+), 350 (0).
Curve B: $\mu=150$ (+), 200 (0).
Curve C: $\mu=500$ (−).
Curve D: $\mu=0$ (0, +, −).



PTOLEMY prototype at PPPL – October 2012

(small test cell at midplane)

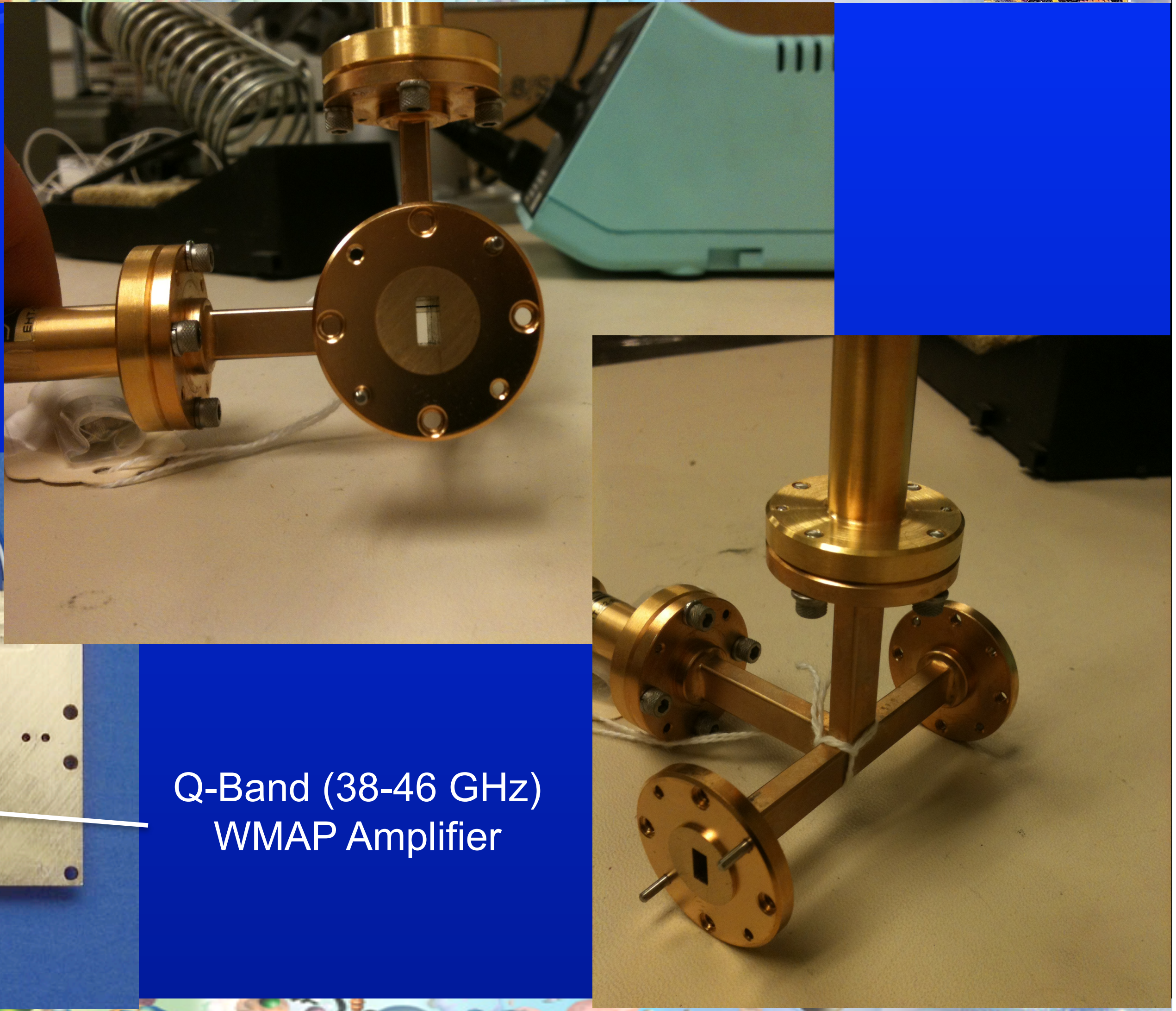


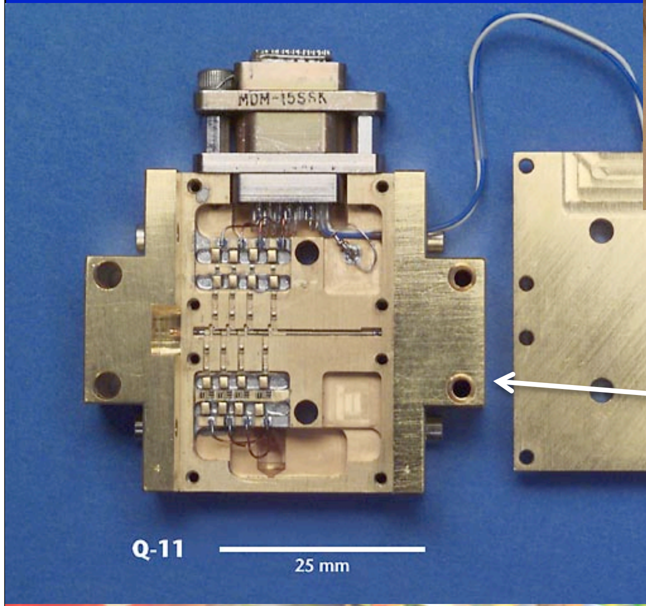
PTOLEMY prototype at PPPL – January 2013
(large vac-tank ready for install)

RF Tracker Element

Readout Orthogonal to Electron Trajectory

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





Q-Band (38-46 GHz)
WMAP Amplifier

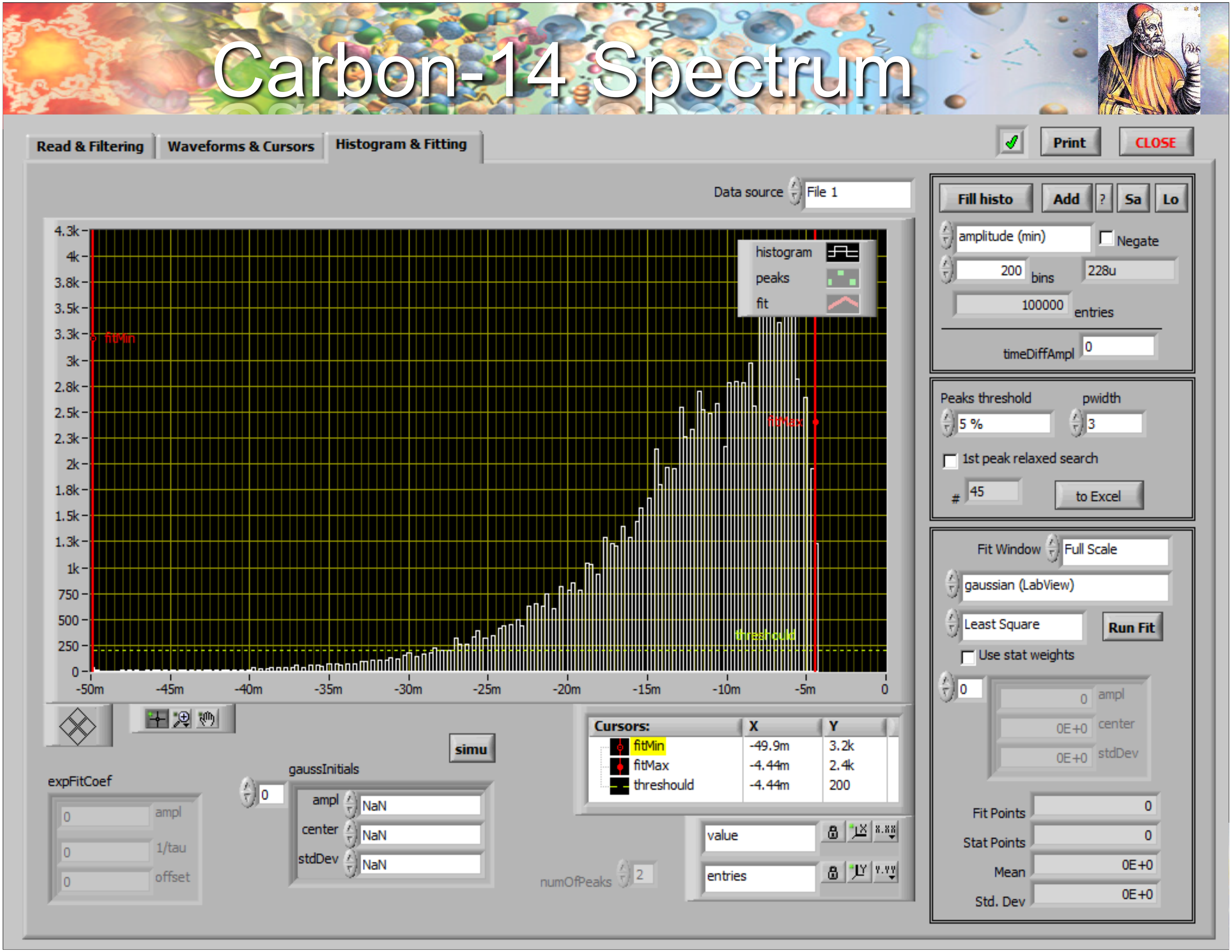
What about Carbon-14?

- 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 2×10^{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

Data source: File 1

amplitude (min) ☐ Negate

200 bins 228u

100000 entries

timeDiffAmpl 0

Peaks threshold 5 %

pwidth 3

☐ 1st peak relaxed search

45

Fit Window: Full Scale

gaussian (LabView)

Least Square

☐ Use stat weights

0

0	ampl
0E+0	center
0E+0	stdDev

Fit Points	0
Stat Points	0
Mean	0E+0
Std. Dev	0E+0

expFitCoef

0	ampl
0	1/tau
0	offset

gaussInitials 0

ampl	NaN
center	NaN
stdDev	NaN

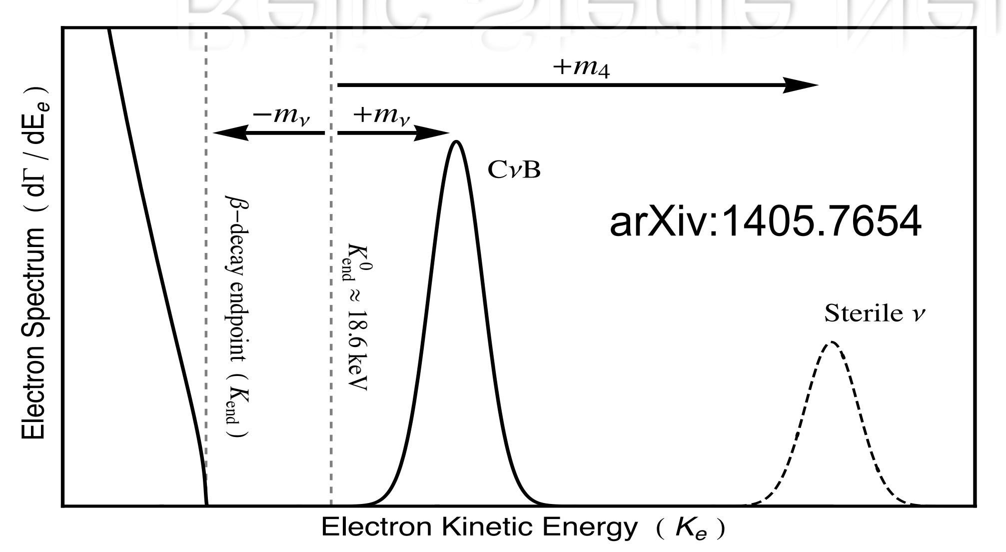
numOfPeaks 2

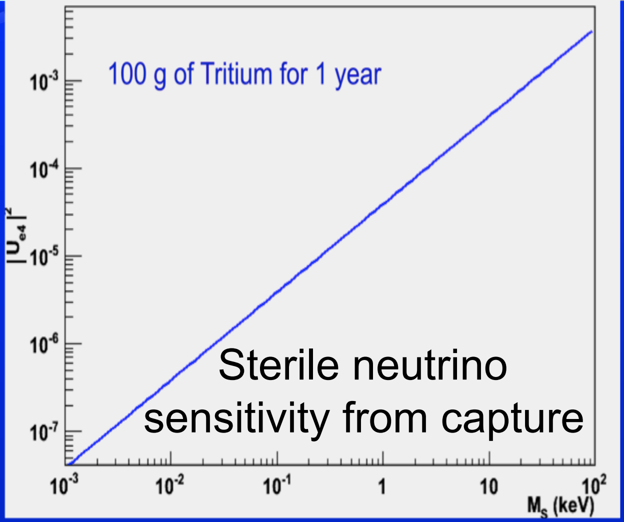
Cursors:	X	Y
fitMin	-49.9m	3.2k
fitMax	-4.44m	2.4k
threshould	-4.44m	200

value

entries

Relic Sterile Neutrinos





For m(ν_2) ~ 0.5 eV,

$|U_{e4}|^2$ ~ 0.03, ΔN_{eff} = 1, f_c ~ 20,

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

% of Dark Matter limited by Structure formation

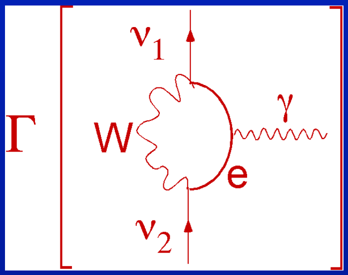
For m(ν_2) ~ 1 keV,

$|U_{e4}|^2$ ~ 10^{-4}, ΔN_{eff} = 0, f_c ~ 5000 (ρ_{DM} ~ 0.3 GeV/cm^3),

$N_{capture}$ ~4 events/100g-year

X-ray constraints for 100% Dark Matter are more stringent on $|U_{e4}|^2$

Either a Majorana or a Dirac neutrino can decay radiatively:



$\nu_2 \rightarrow \nu_1 + \gamma$

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

Sterile neutrinos will introduce a kink in the beta-decay spectrum at $K^0_{end} - m_4$ where sensitivity to $|U_{e4}|^2$ ~ 10^{-7} may be possible with a fast response detector

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)

$\sigma(^{51}\mathrm{Cr}) / \sigma(\text{relic neutrinos}) \sim 19$ (weighted)

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

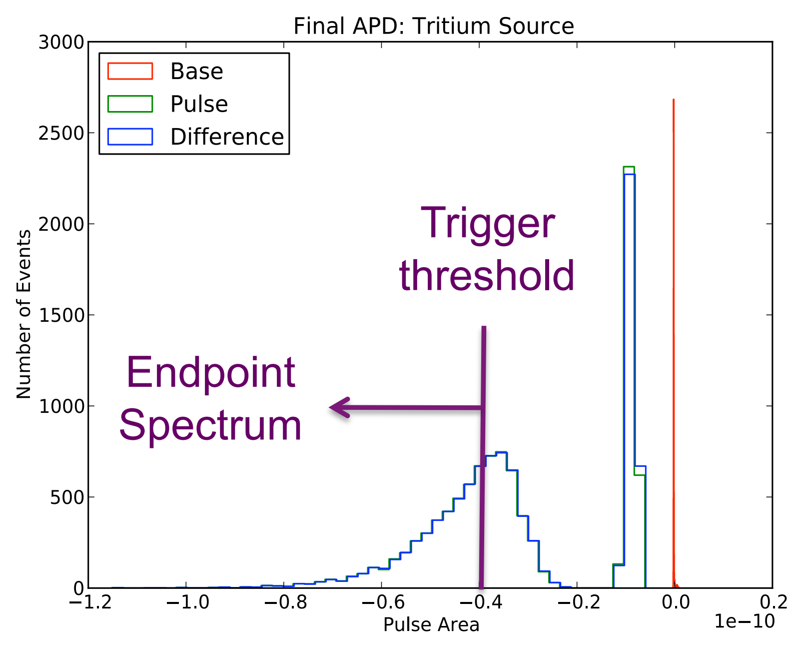
Relativistic neutrinos → clear angular dependence from tritium polarization

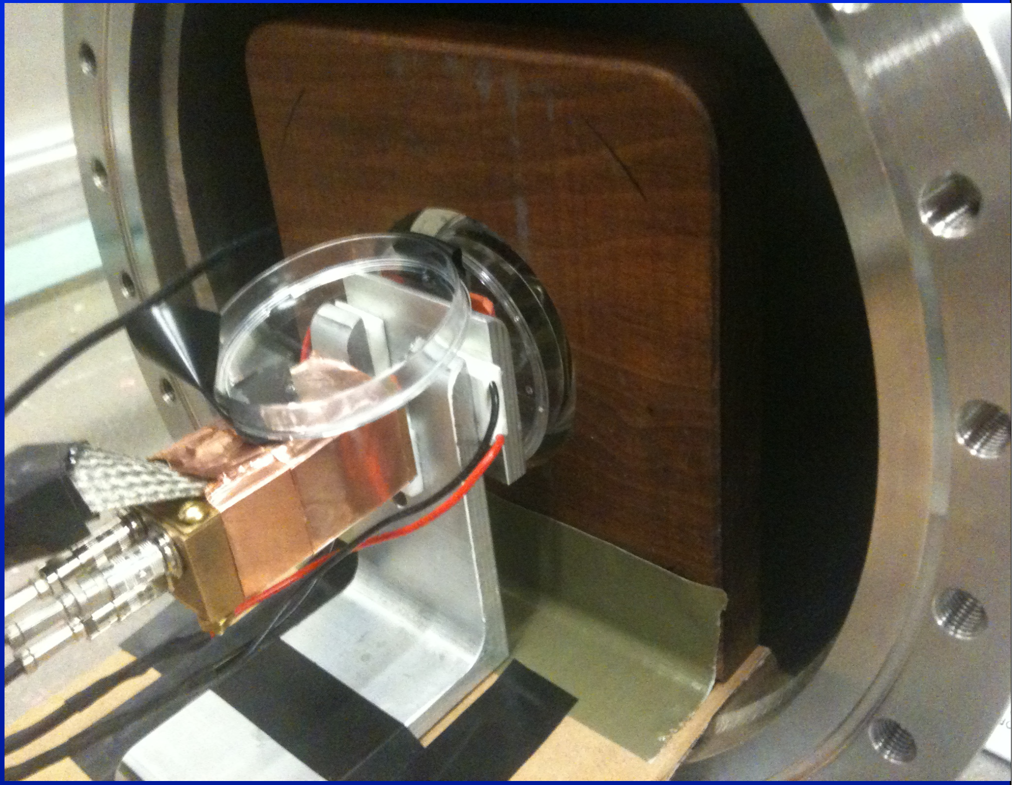
Neutrino scattering off of atomic electrons also a signal for the neutrino flux

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.

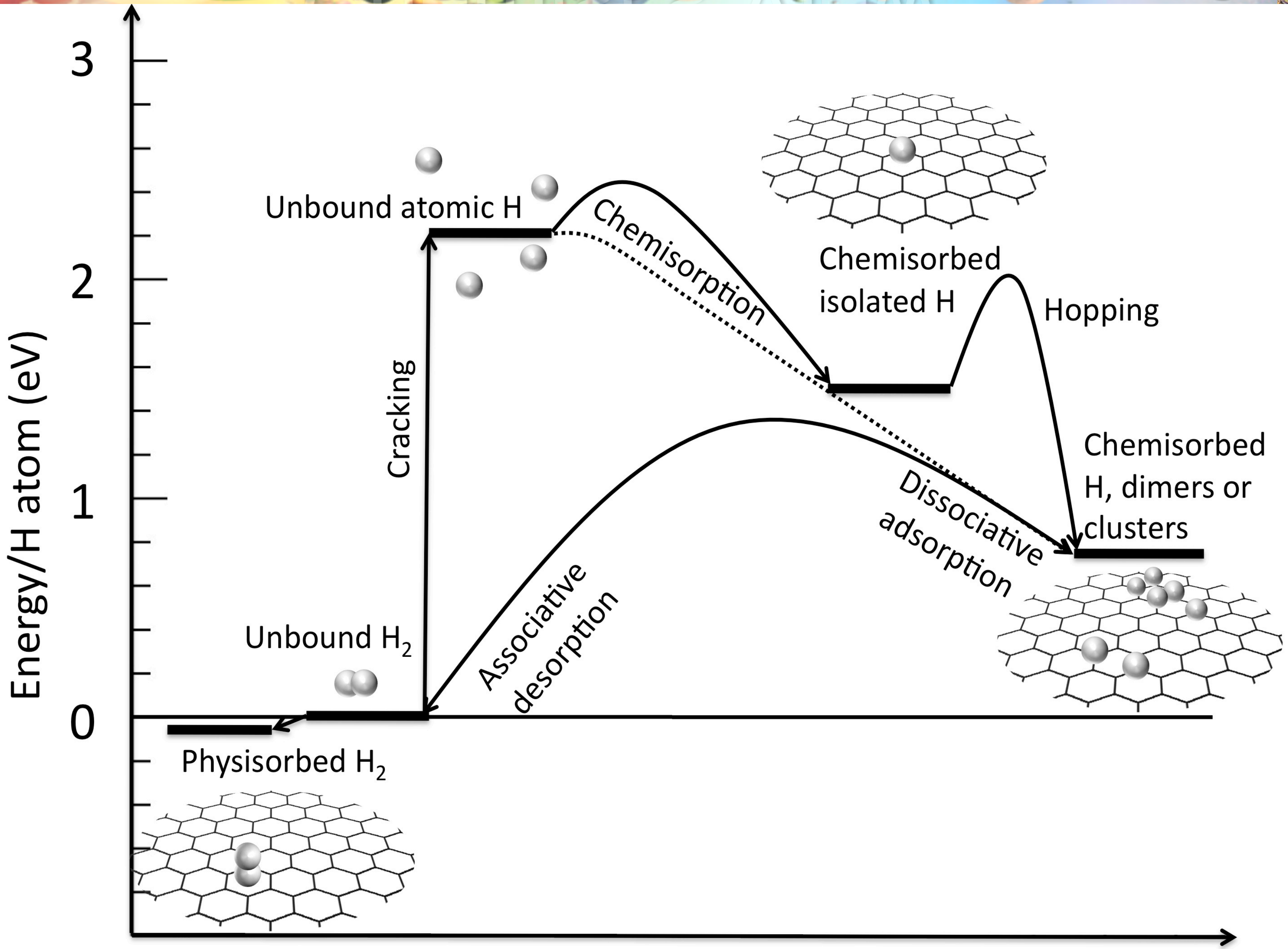
Tritium Tag Detector

- 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)





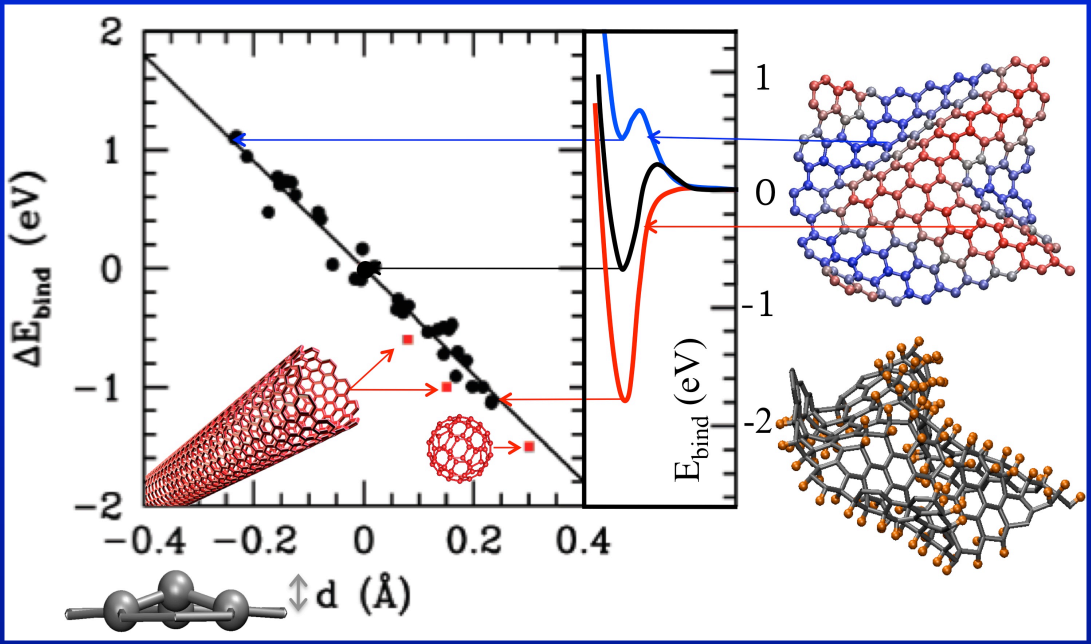
Chemist's View



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



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]

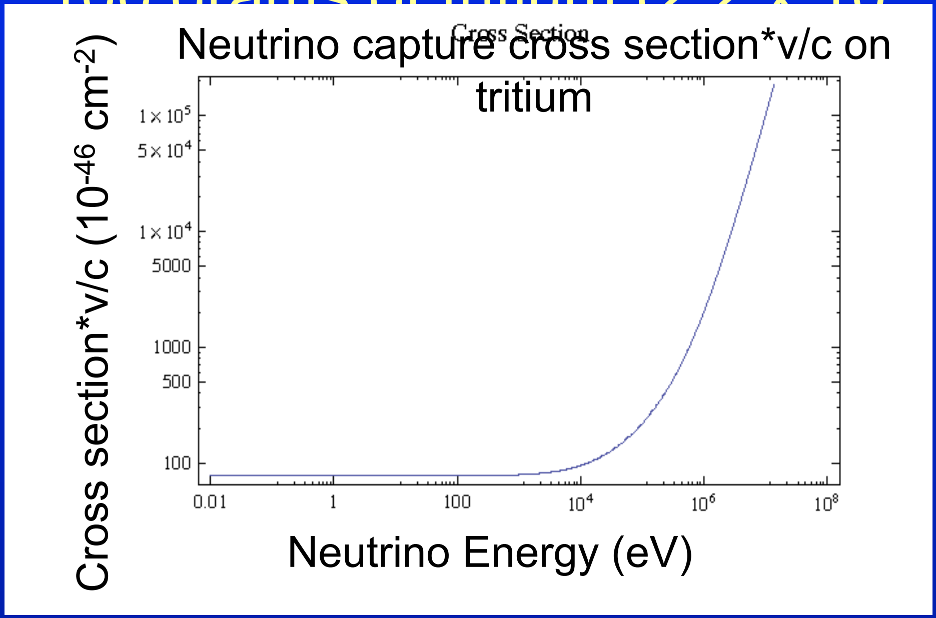
[1]Princeton Plasma Physics Laboratory

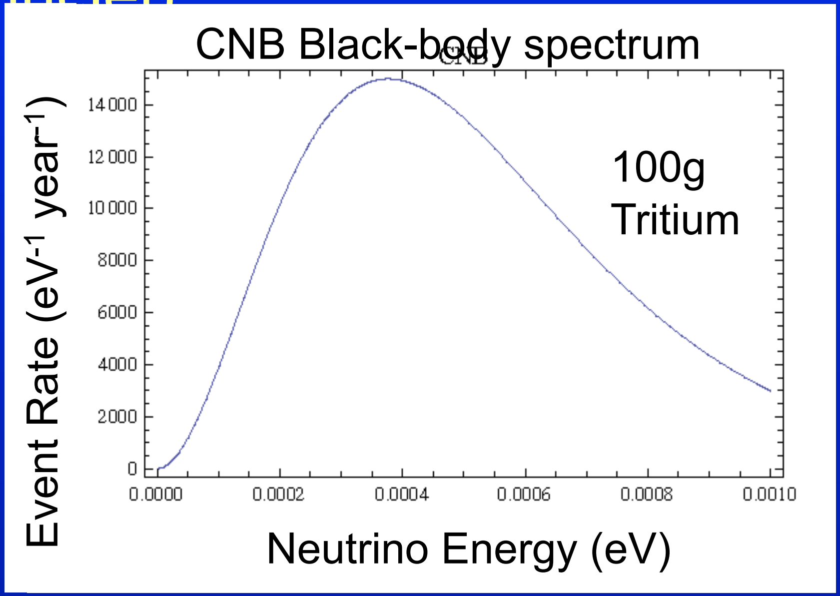
arXiv: 1307.4738

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)





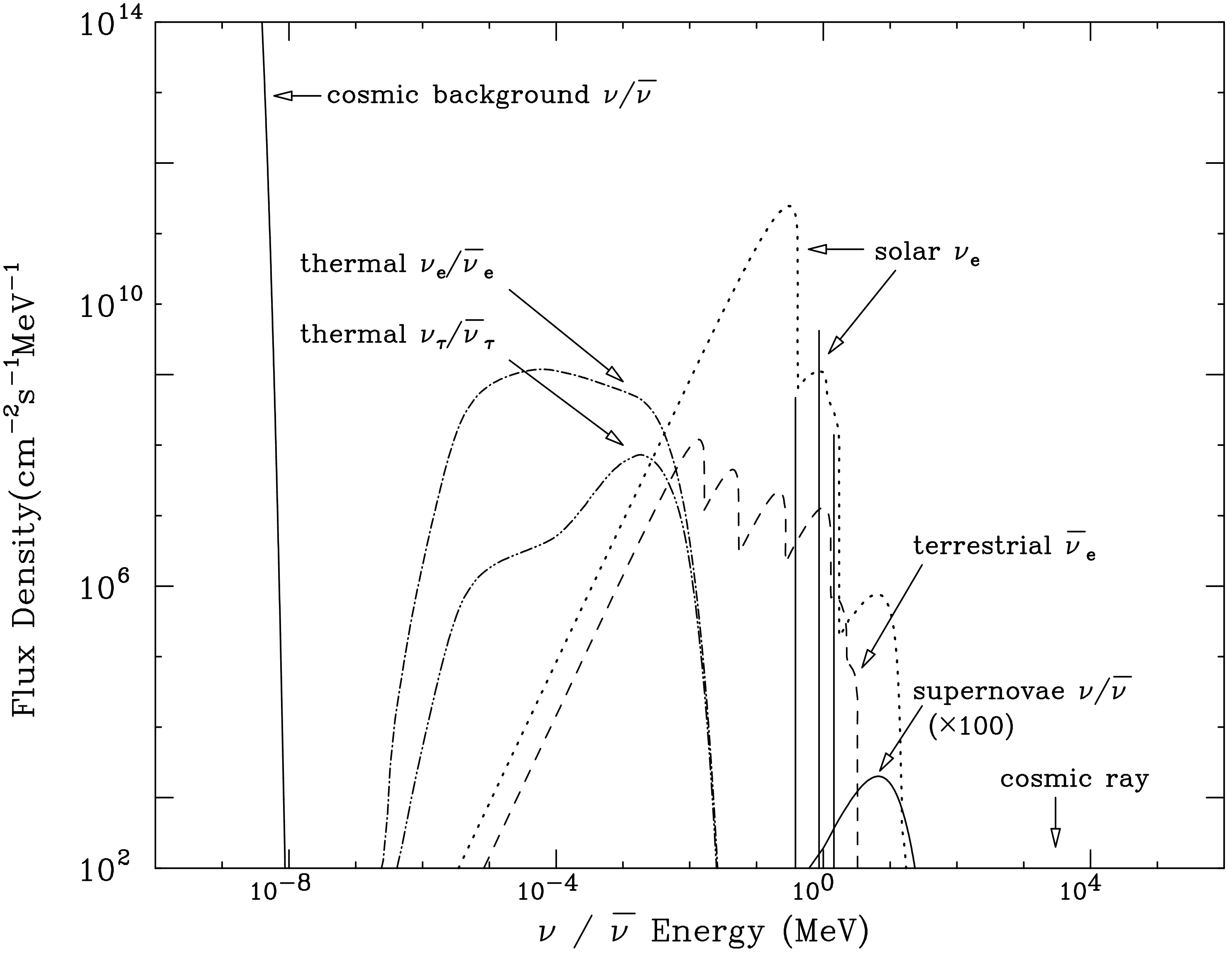
$$\int \sigma(p_\nu) v_\nu f_\nu(p_\nu) \frac{d^3 p_\nu}{(2\pi)^3}$$

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

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

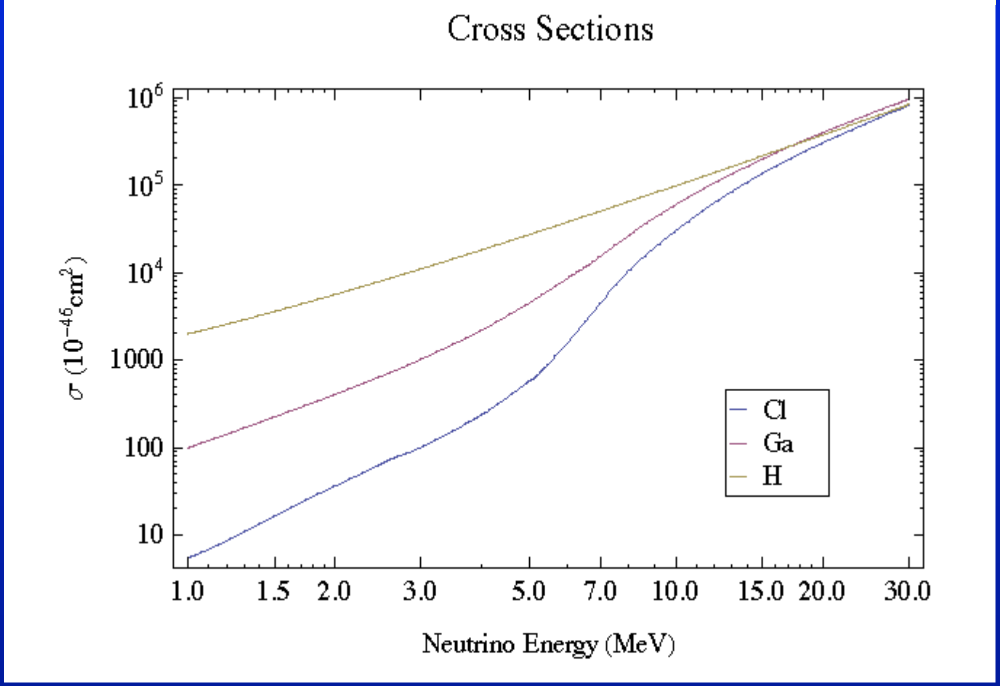
Haxton, Lin: Phys.Lett. B486 (2000) 263-271



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

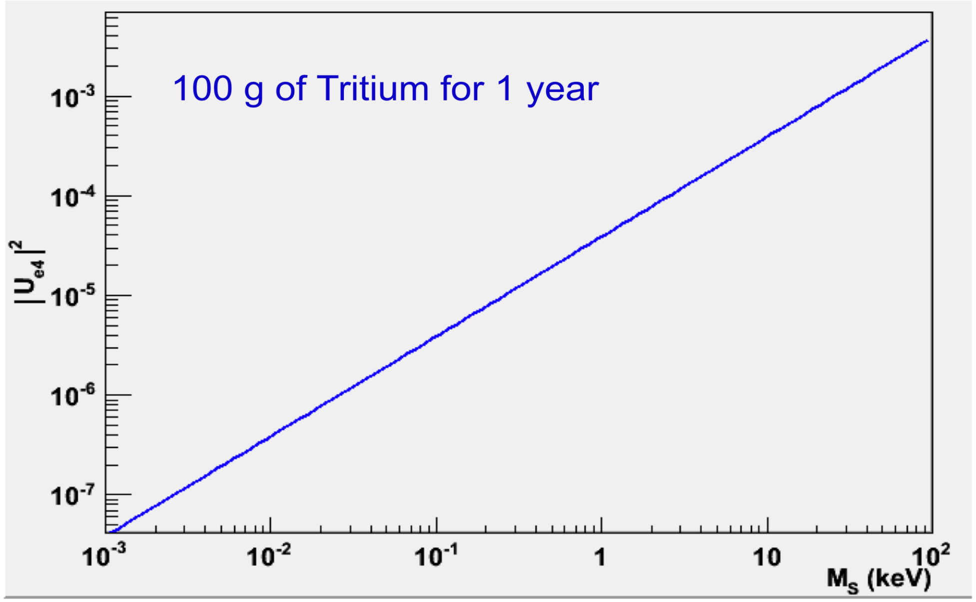


Sterile Neutrino Search

Using ν capture...

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

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

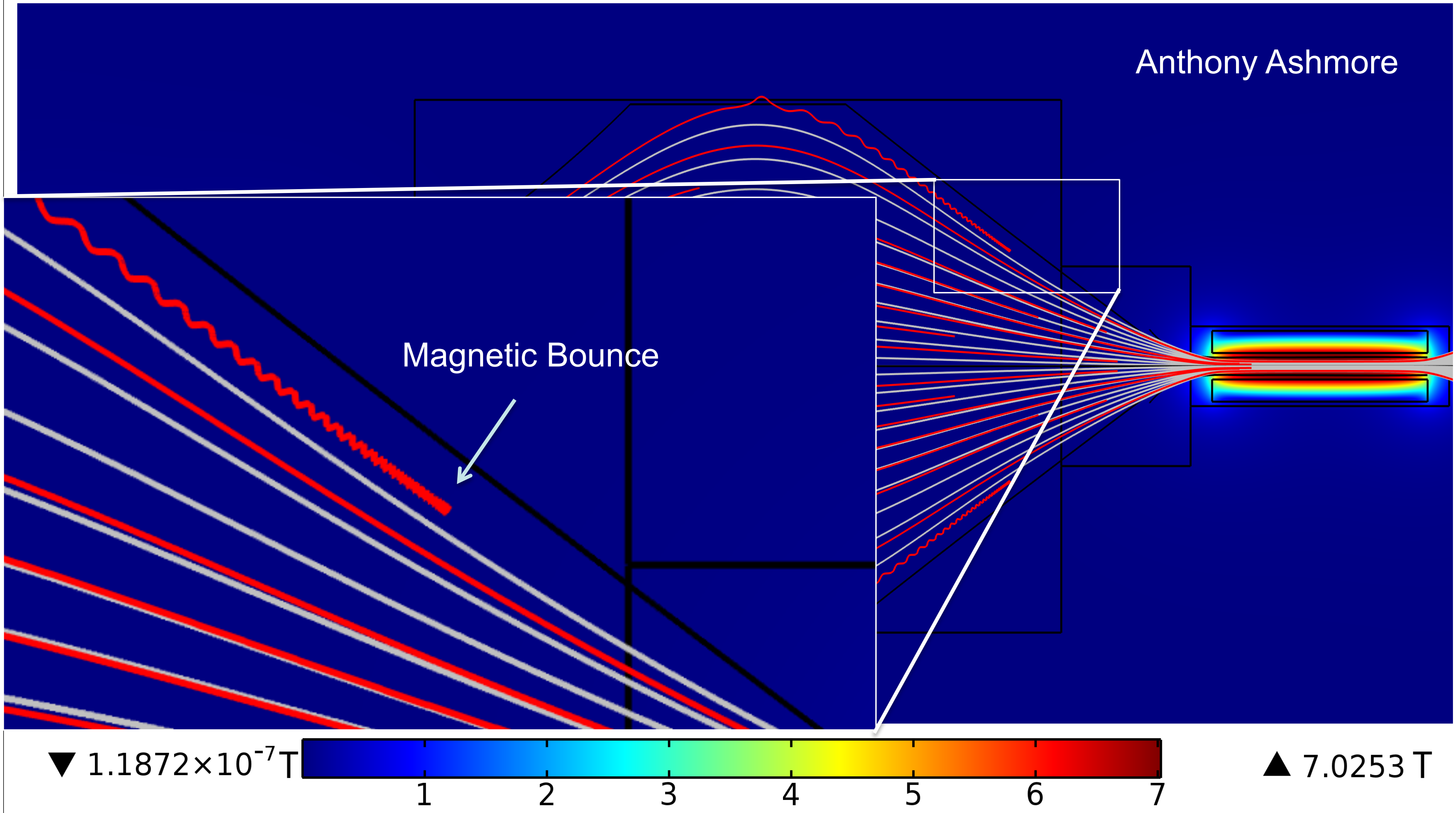


Alfredo Cocco

PTOLEMY Conceptual Design

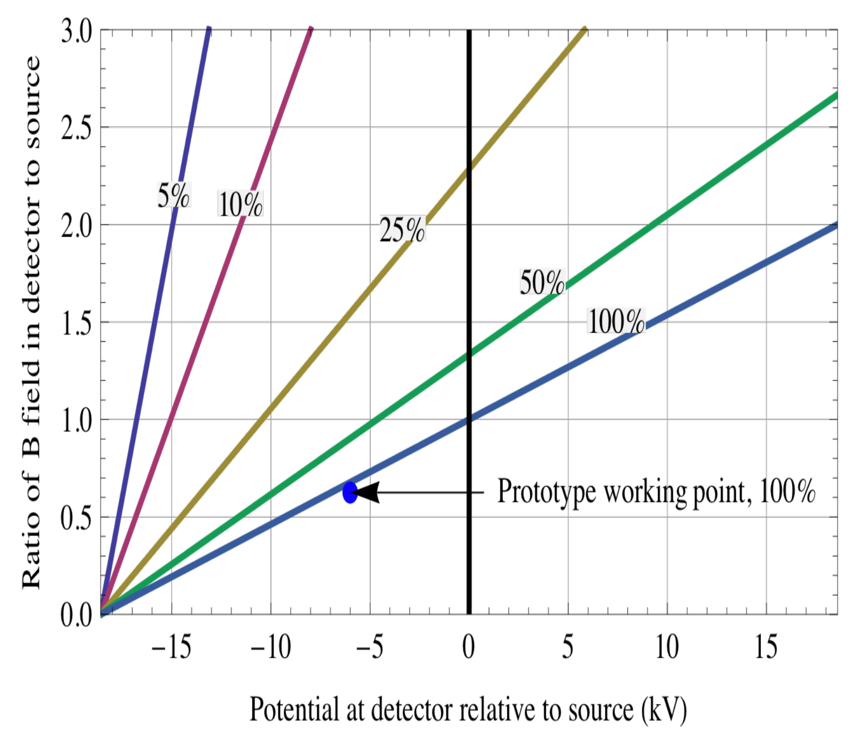
- High precision on endpoint
  - Cryogenic calorimetry energy resolution
  - **Goal: 0.1eV resolution**
- Signal/Background suppression
  - RF tracking and time-of-flight system
  - **Goal: sub-microHertz background rates above endpoint**
- High mass, high resolution tritium target
  - Surface deposition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

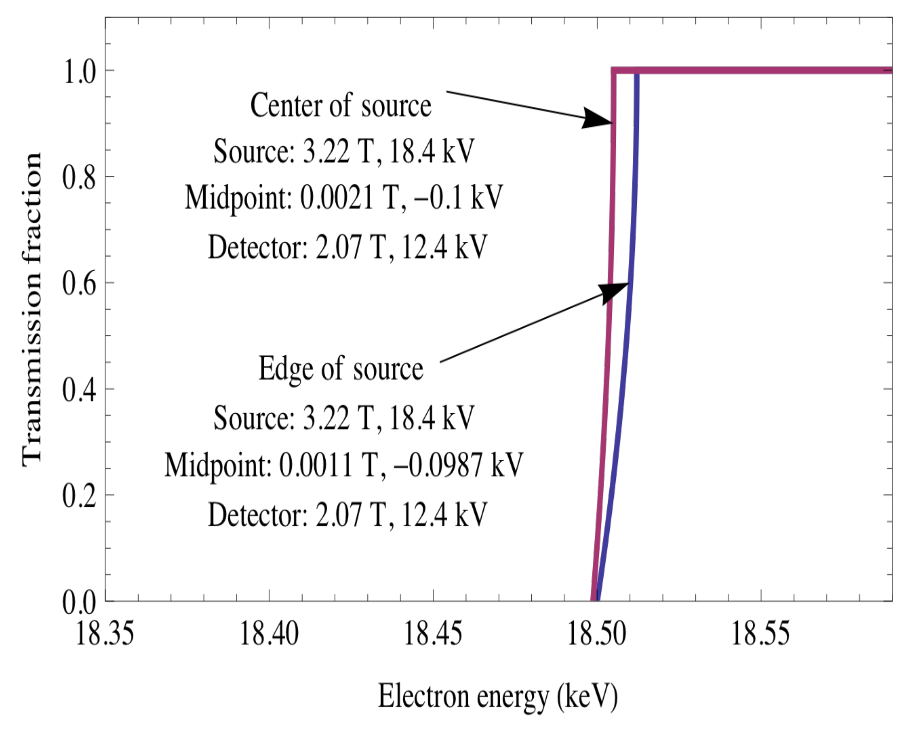


Cut-off Uniformity and Decay Acceptance

- 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



Prototype working point, 100%



Center of source
Source: 3.22 T, 18.4 kV
Midpoint: 0.0021 T, −0.1 kV
Detector: 2.07 T, 12.4 kV

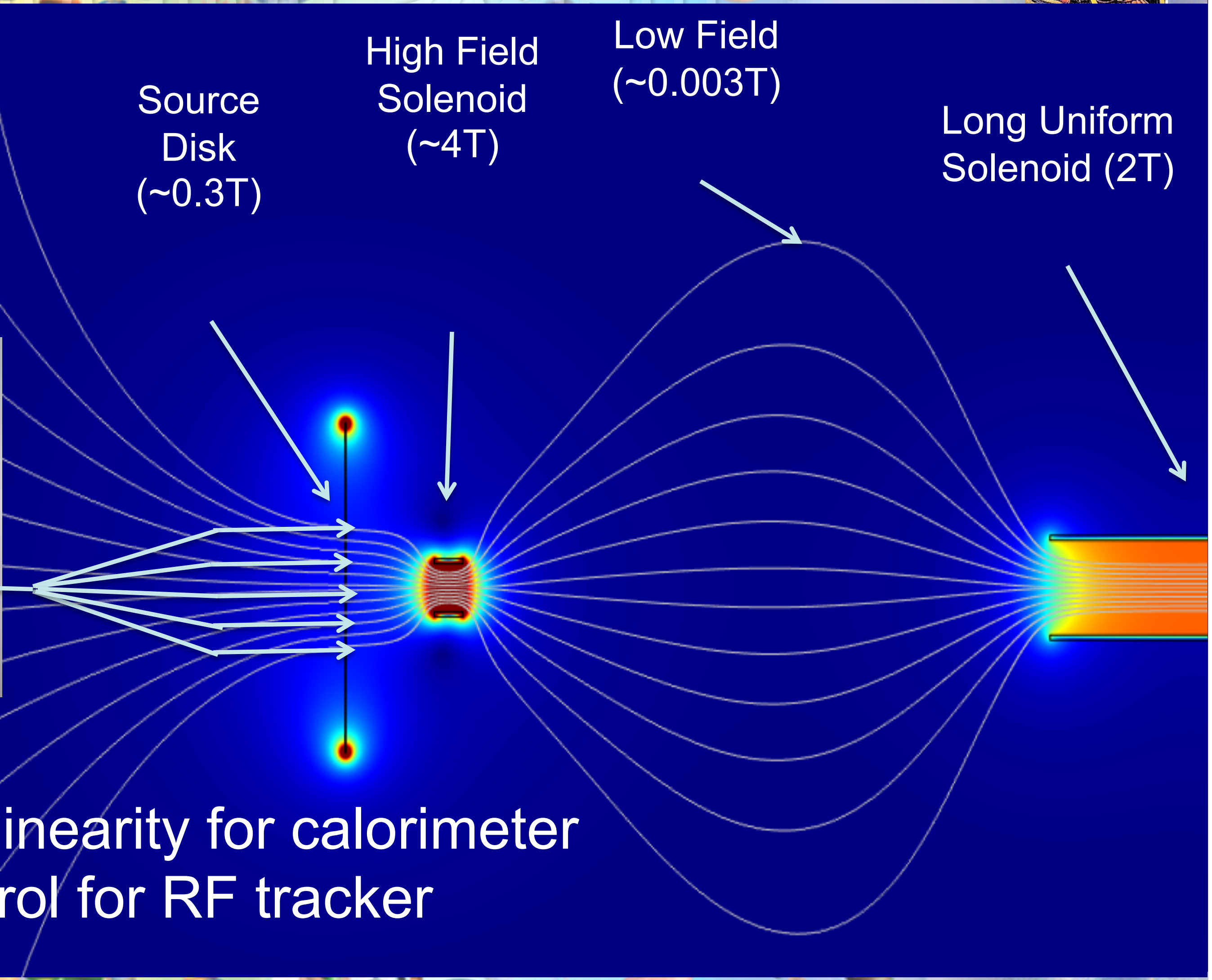
Edge of source
Source: 3.22 T, 18.4 kV
Midpoint: 0.0011 T, −0.0987 kV
Detector: 2.07 T, 12.4 kV

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

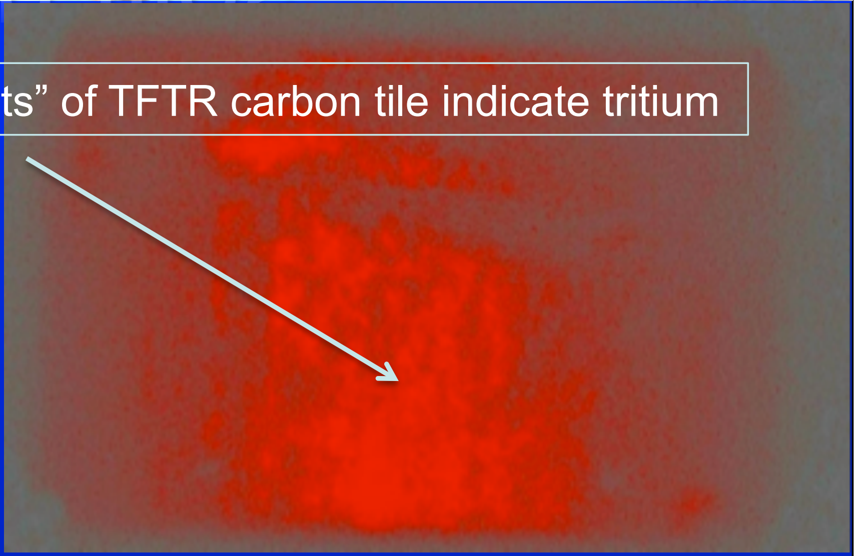
Precision e-gun
“switchyard”



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



“Hot spots” of TFTR carbon tile indicate tritium