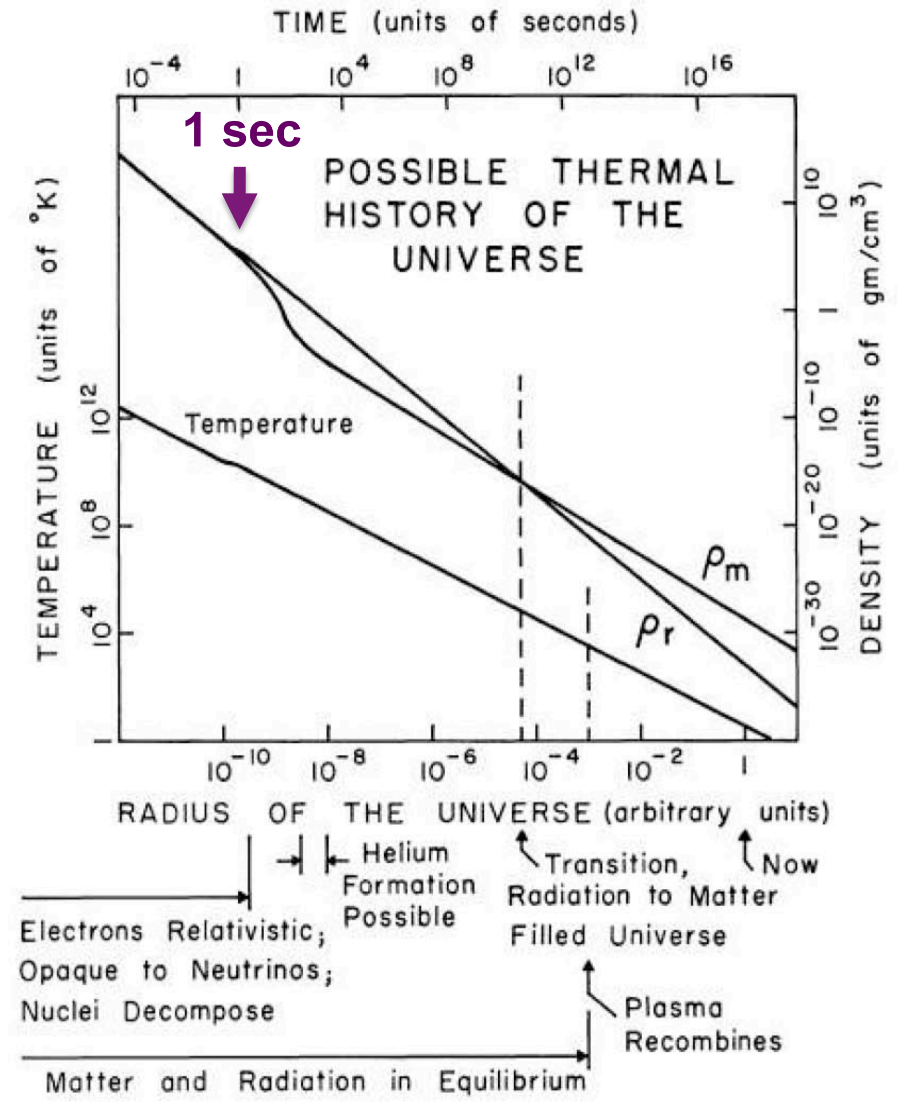
Searching for Sterile and Relic Neutrinos at PTOLEMY

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

Chris Tully
Princeton University

19th Paris Chalonge Colloquium
July 22-24, 2015

Looking Back in Time



Dicke, Peebles, Roll, Wilkinson (1965)

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

per neutrino species
(neutrino+antineutrino)

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

T_ν~1.95K

start of nucleosynthesis
n/p~0.15*0.74~0.11

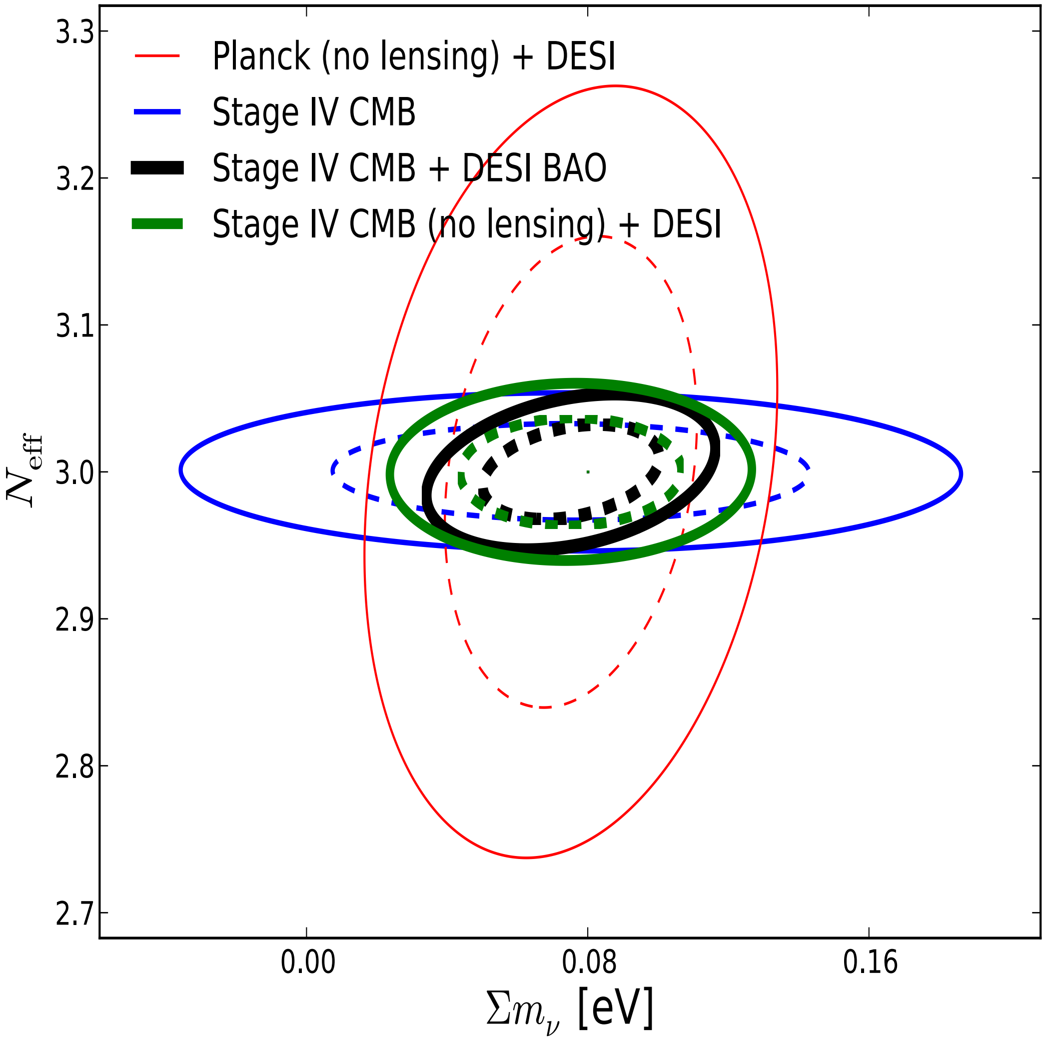
$$\frac{\lambda(p \rightarrow n)}{\lambda(n \rightarrow p)} = e^{-Q/kT}$$

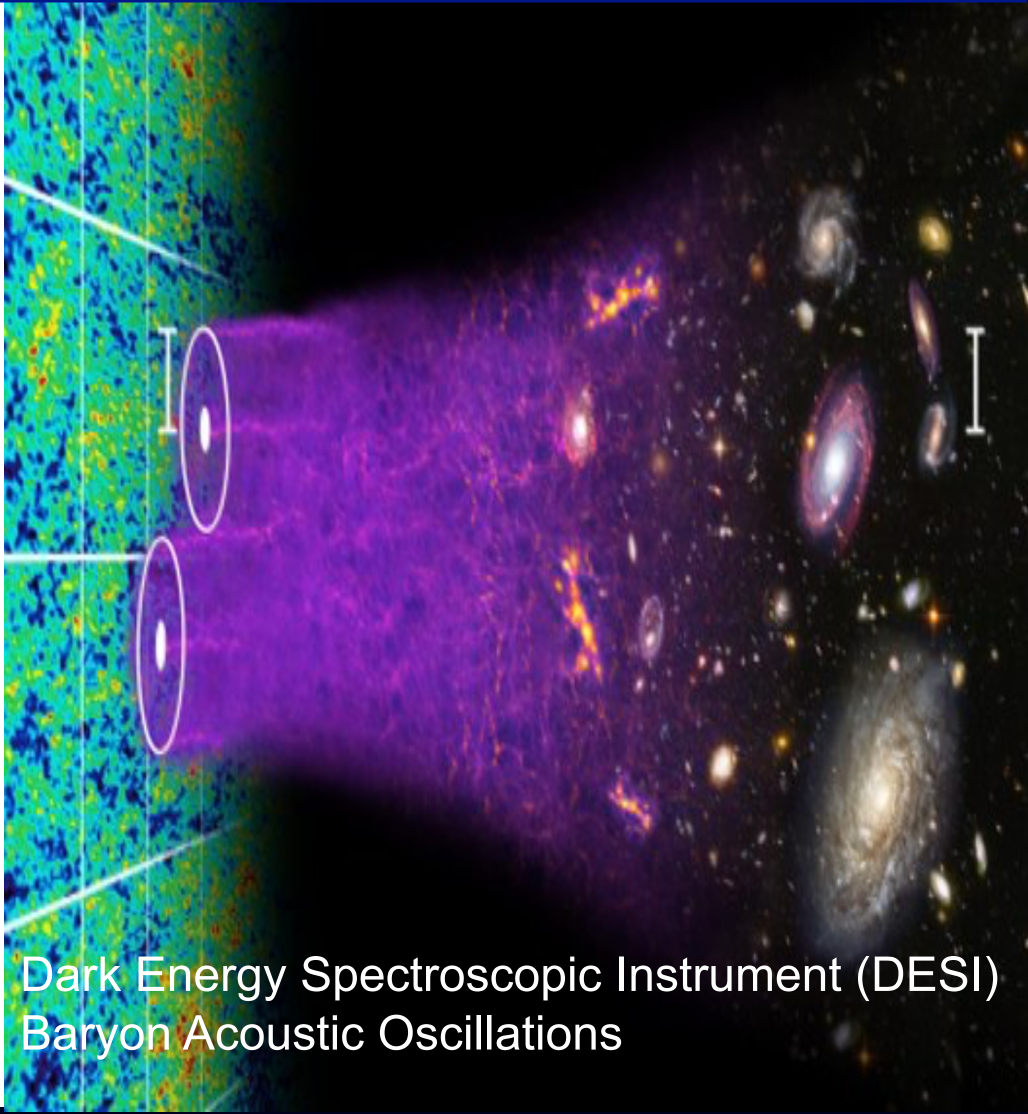
Relic velocity depends on mass

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

$$\langle \mathrm{v}_{rms} \rangle = 160\ \mathrm{km/s}\ \left(1\ \mathrm{eV}/m_\nu\right)$$

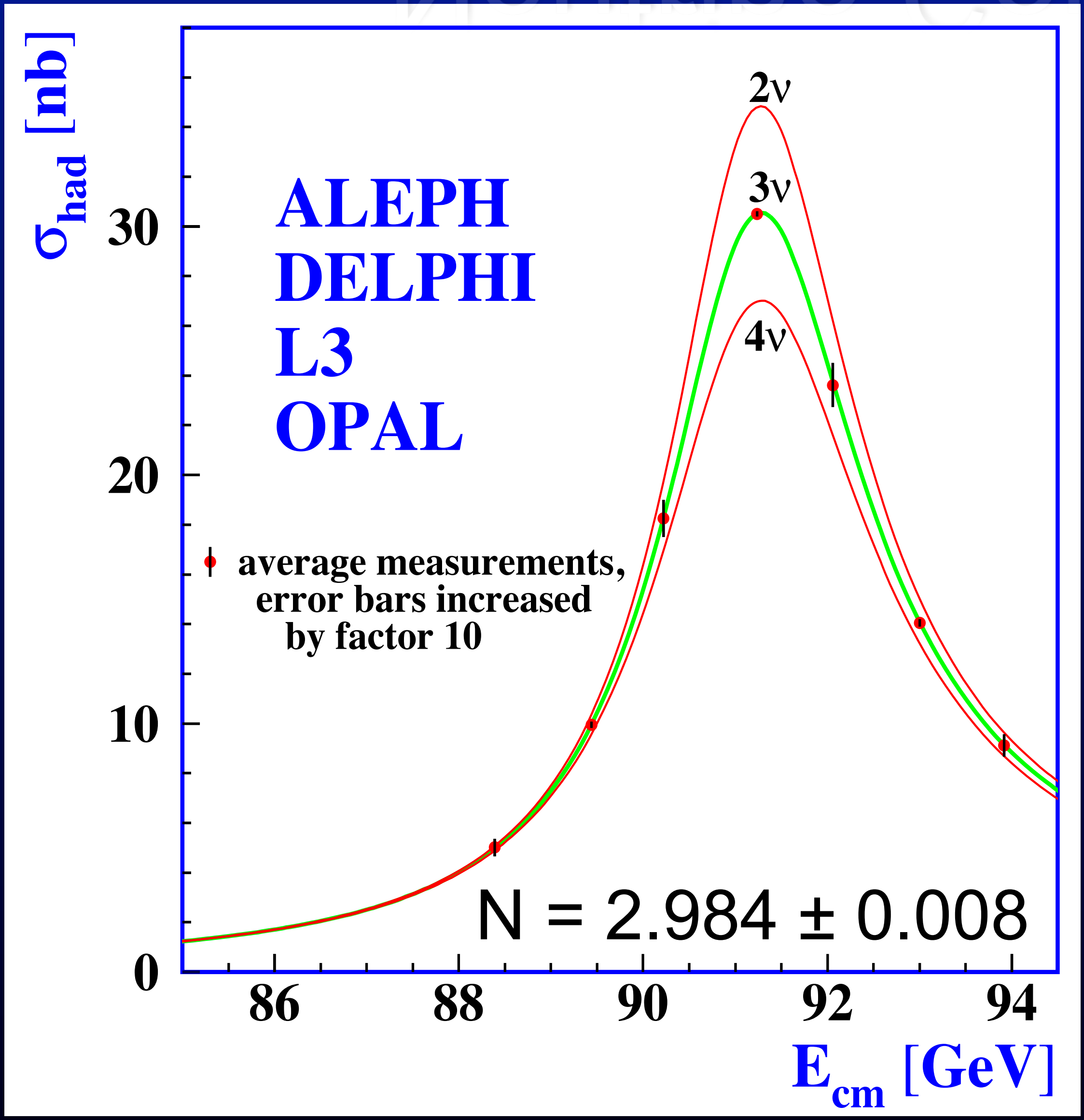
Precision Cosmology Projections





Dark Energy Spectroscopic Instrument (DESI)
Baryon Acoustic Oscillations

Neutrino Counting



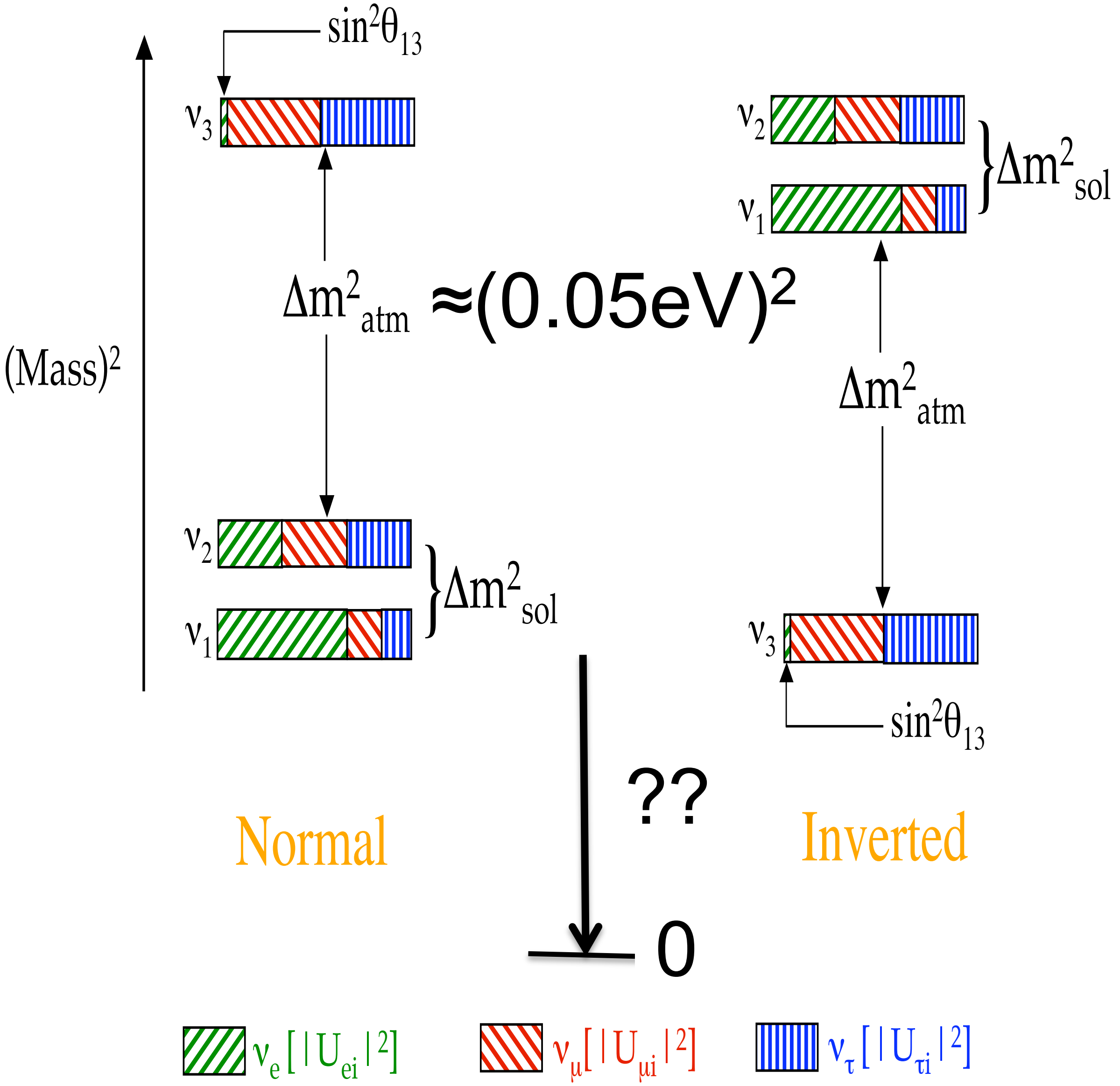
Produce ~1M Z bosons at an e^+e^- collider

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

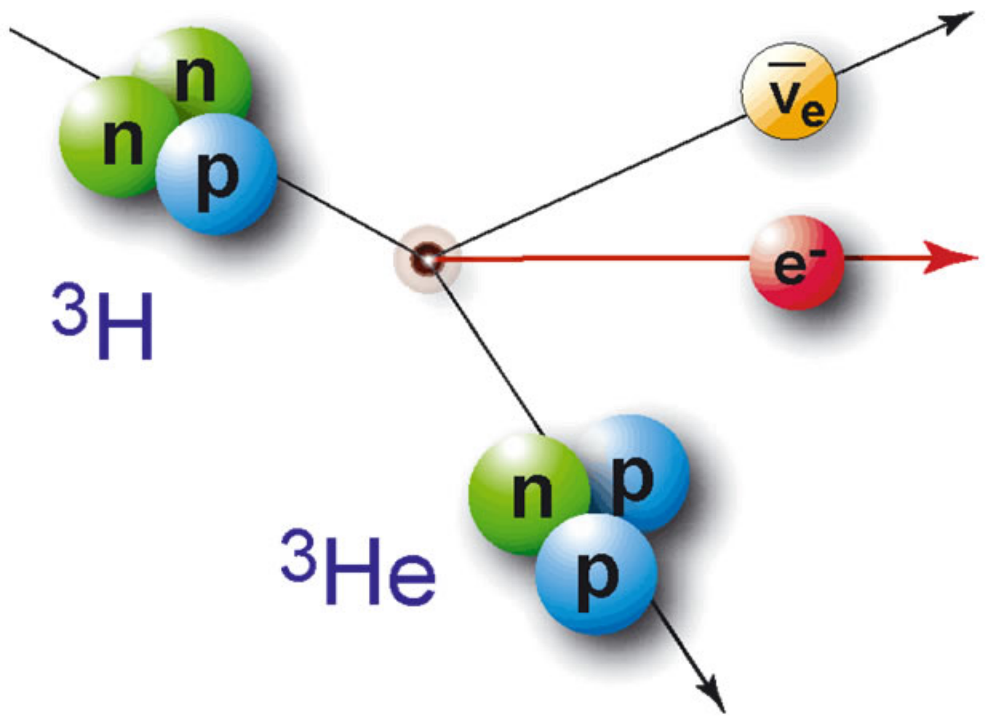
Neutrino Masses from Oscillations



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

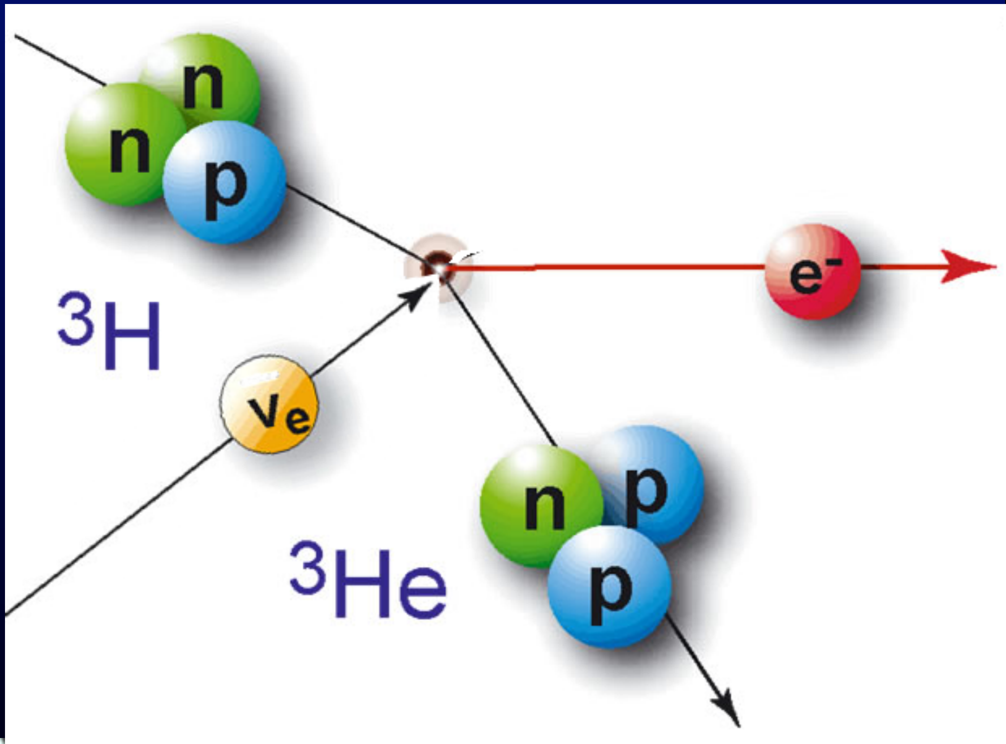
A neutrino created with a definite lepton flavor (in this case, electron or muon) would arrive with a lower probability to be detected with the same flavor and a non-zero probability to have mixed into another flavor.

Tritium



Tritium β-decay
(12.3 yr half-life)

Neutrino capture on Tritium



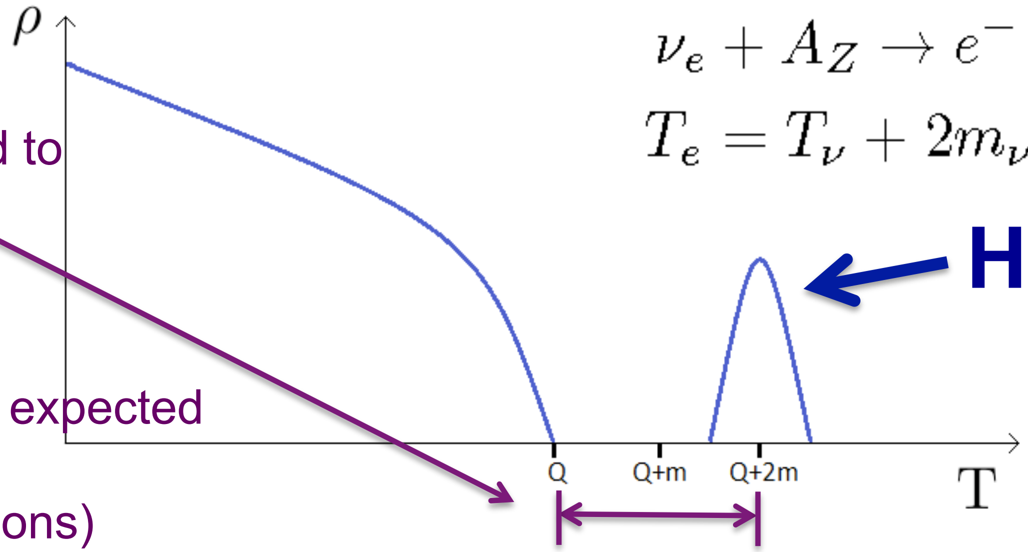
Relic Neutrino Detection

- 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)



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

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

How many?

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

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)

Lazauskas, Vogel, Volpe: J.Phys.G G35 (2008) 025001.
Cocco, Mangano, Messina: JCAP 0706 (2007) 015

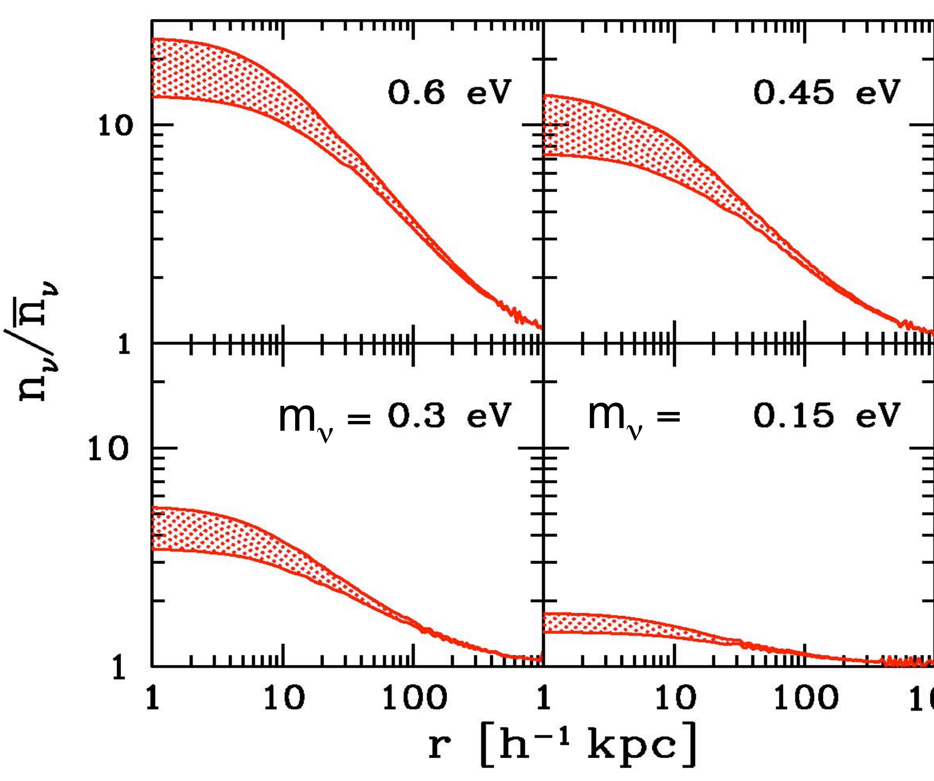
~ 10 events/yr

(5 events/yr for Dirac neutrinos)

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

Known to better than 0.5%

Gravitational clumping could potentially increase the local number of relic neutrinos.
For low masses ~0.15eV, the local enhancement is ~x1.5



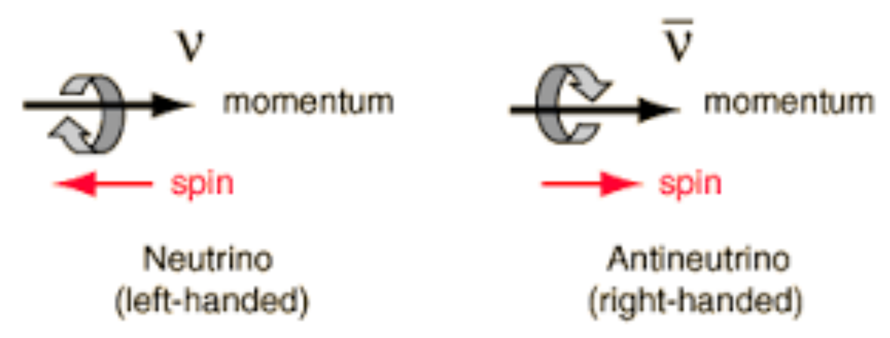
Ringwald and Wong (2004)

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

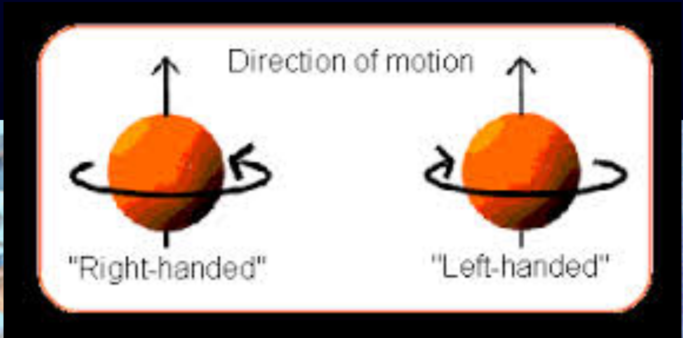


- Neutrinos decouple at relativistic energies
- Helicity (not chirality) is conserved as the universe expands and the relic neutrinos become non-relativistic

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

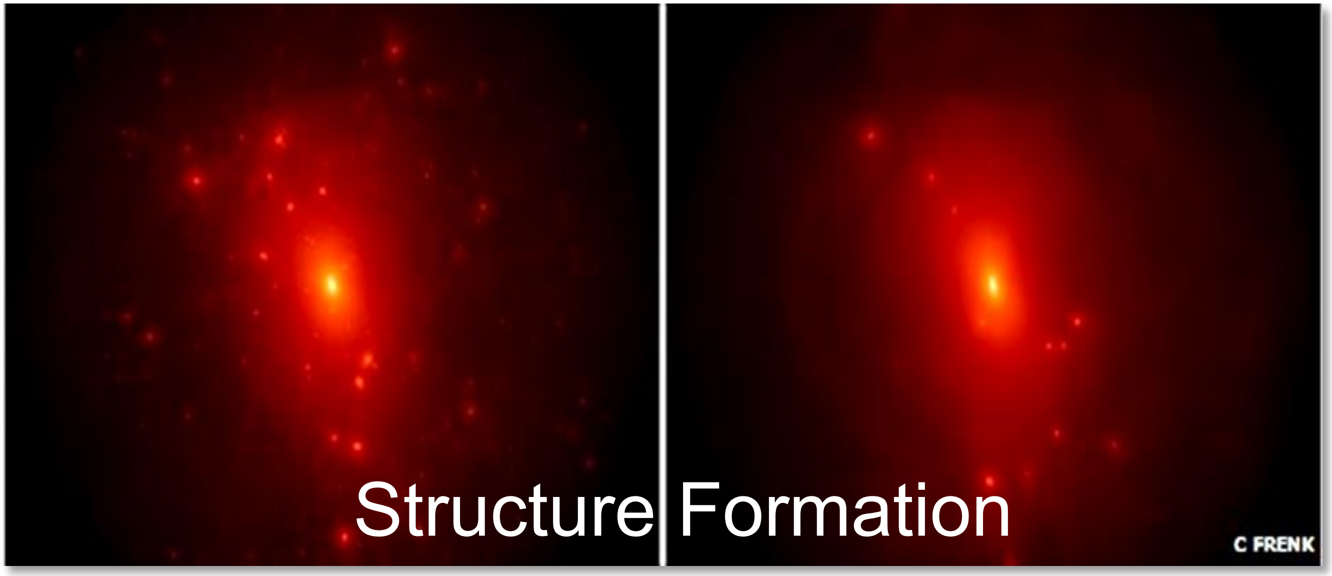
Majorana: ~half of left-handed helical neutrinos are chiral left-handed and half of right-handed helical neutrinos are chiral left-handed (active)

If neutrinos are Majorana, lepton number is not conserved → Leptogenesis



Sterile Neutrinos

CDM simulations WDM



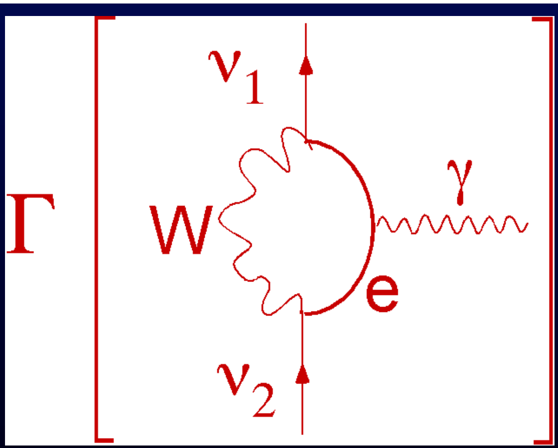
Structure Formation

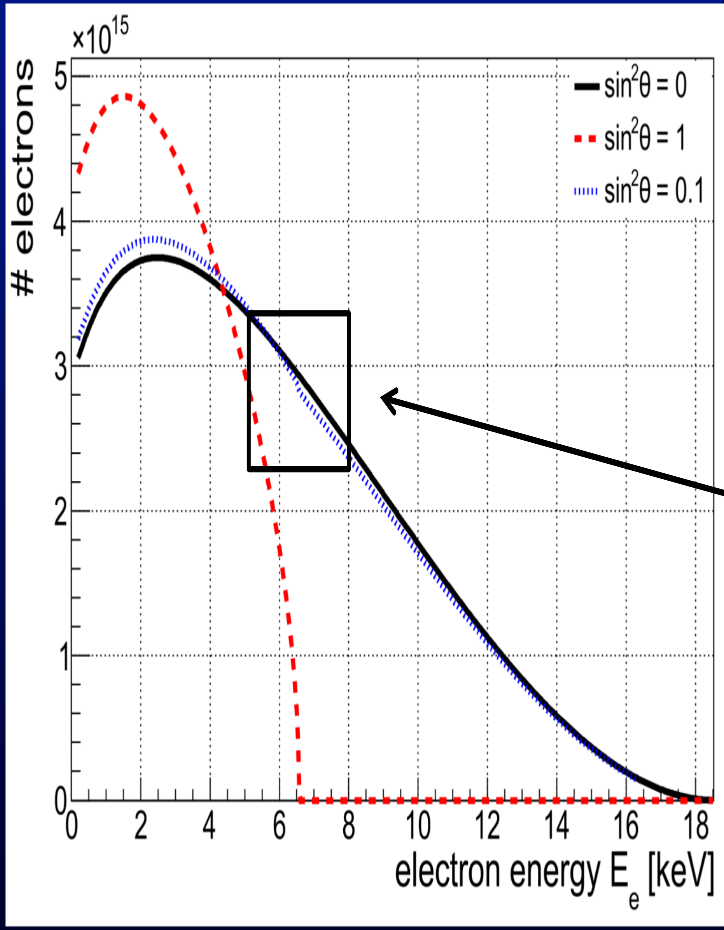
C FRENK

X-Ray Astronomy

$\nu_2 \rightarrow \nu_1 + \gamma$

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





Kai Dolde (Meudon 2014)
Susanne Meurtens (KATRIN)

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.

Relevant Parameter Space

Sterile neutrino (inverse) lifetime

$$\frac{1}{\tau} = \left(6 \times 10^{-33}\mathrm{s}^{-1}\right)\left[\frac{\sin^2(2\theta)}{10^{-10}}\right]\left[\frac{m_s}{\mathrm{keV}}\right]^5$$

10 keV: $\sin^2(2\theta) \sim 10^{-2}$ (~ age of universe) → WDM overdensity
$\sin^2(2\theta) \sim 10^{-5}$ → Too bright
$\sin^2(2\theta) < \sim 10^{-7}$ → Dim enough to be (yet) undiscovered

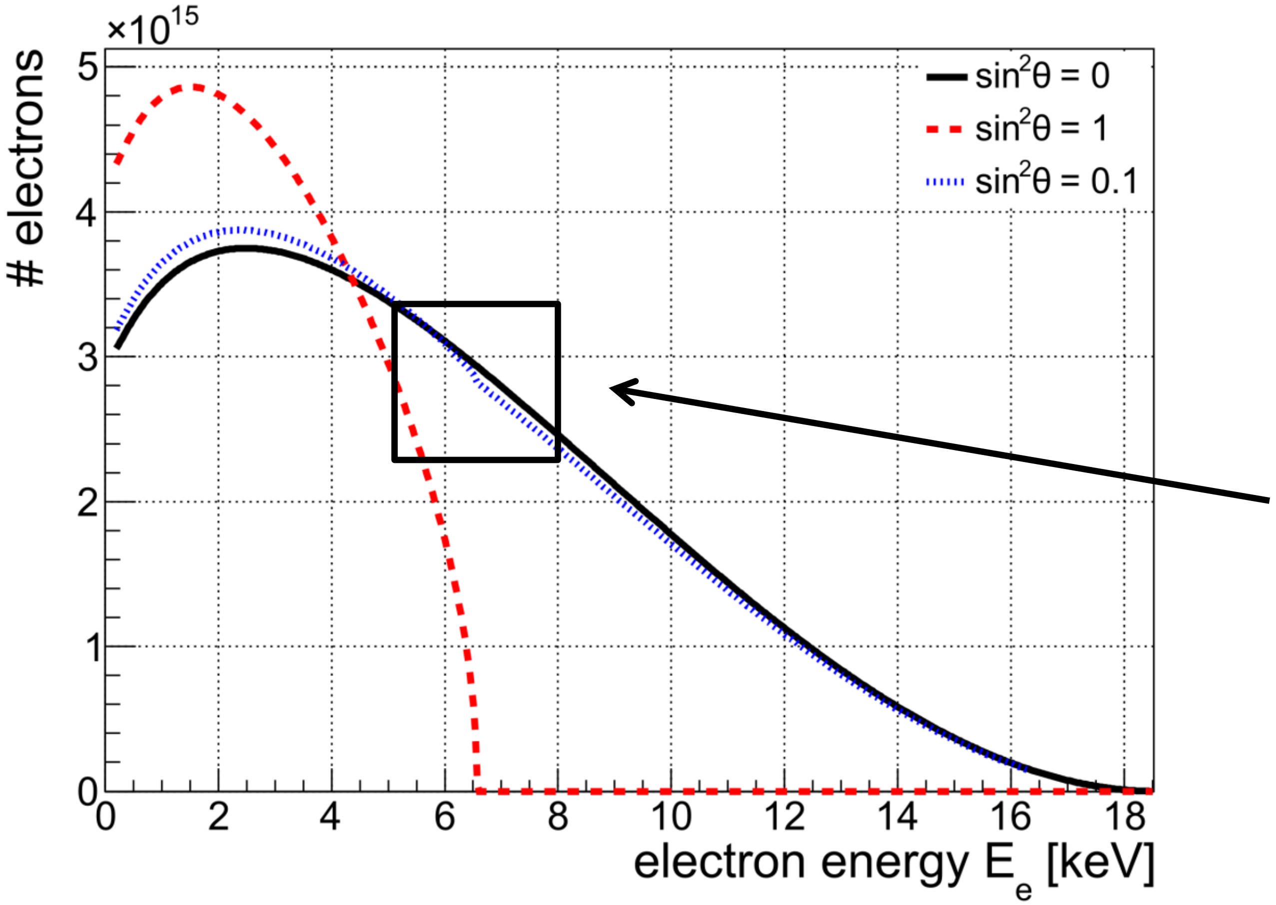
7 keV: $\sin^2(2\theta) < \sim 10^{-6}$
4 keV: $\sin^2(2\theta) < \sim 10^{-5}$
2.5 keV: $\sin^2(2\theta) < \sim 10^{-4}$

Rough estimates of current X-Ray observation sensitivities
(Please see other presentations)

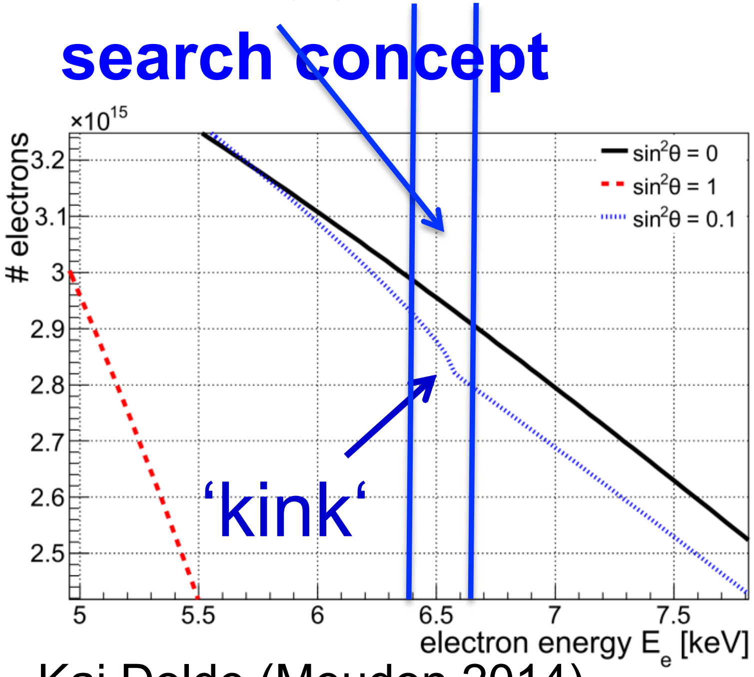
Sterile Neutrino Kink Finding

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

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



PTOLEMY "narrow window" search concept



Kai Dolde (Meudon 2014)
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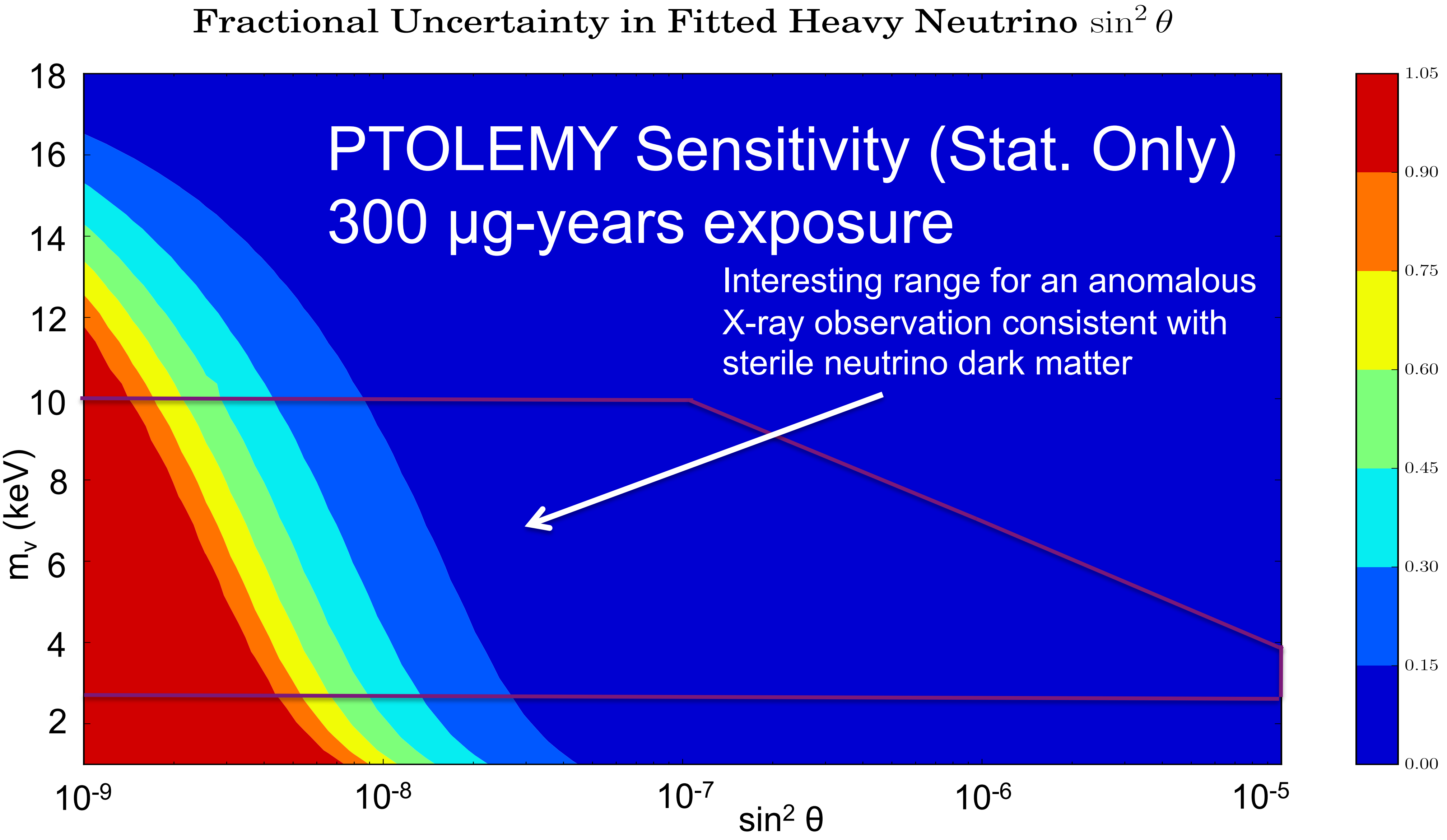
Sensitivity Scan



PTOLEMY Sensitivity (Stat. Only)
300 μg-years exposure

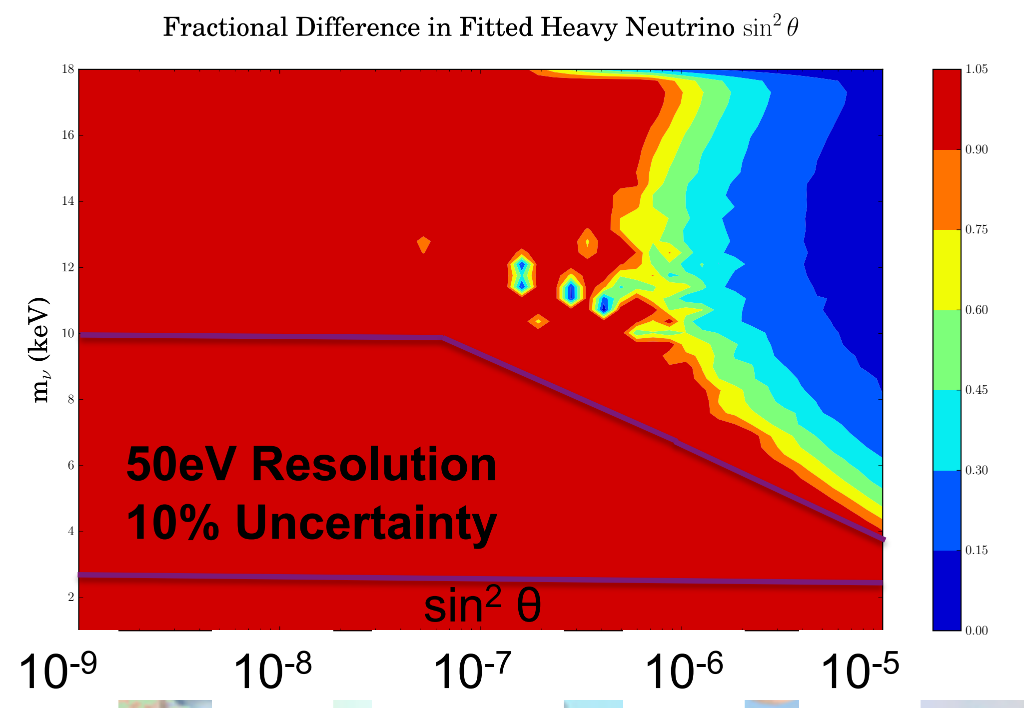
Interesting range for an anomalous X-ray observation consistent with sterile neutrino dark matter

Limiting Systematics

- Expected versus Observed Calorimeter Resolution
  - Single most important systematic:

    Energy Resolution Uncertainty
  - Scanning Base Calorimeter Resolution from 0.1eV to 50eV and fitting with the correct resolution had less effect than using 50eV resolution and applying a 10% shift up and down in the fit

Sensitivity completely lost



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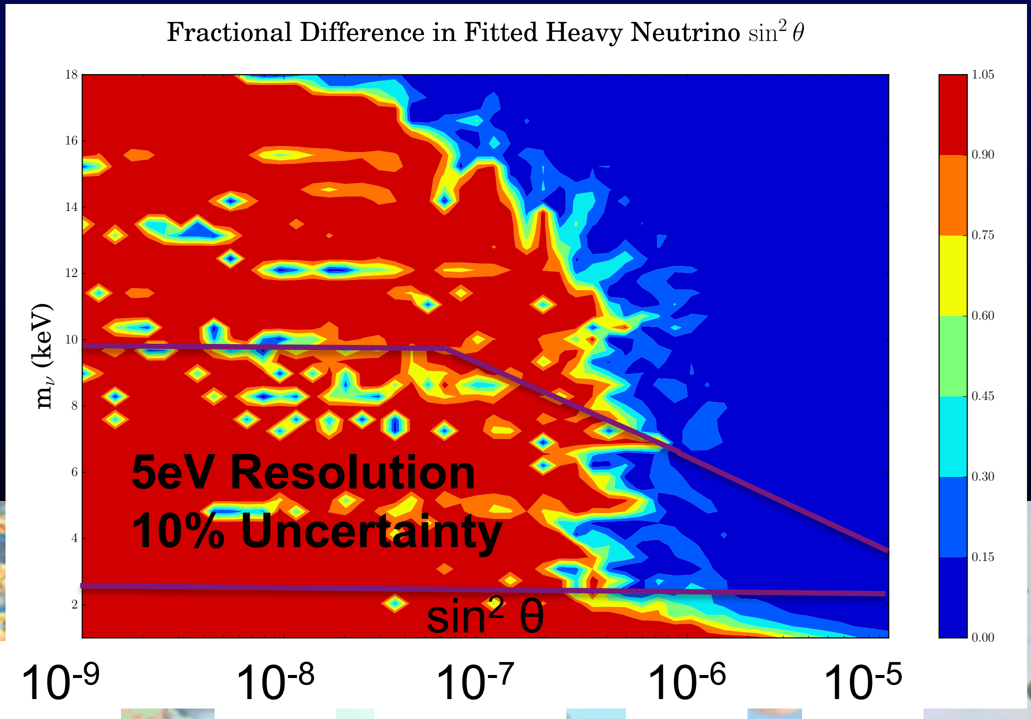
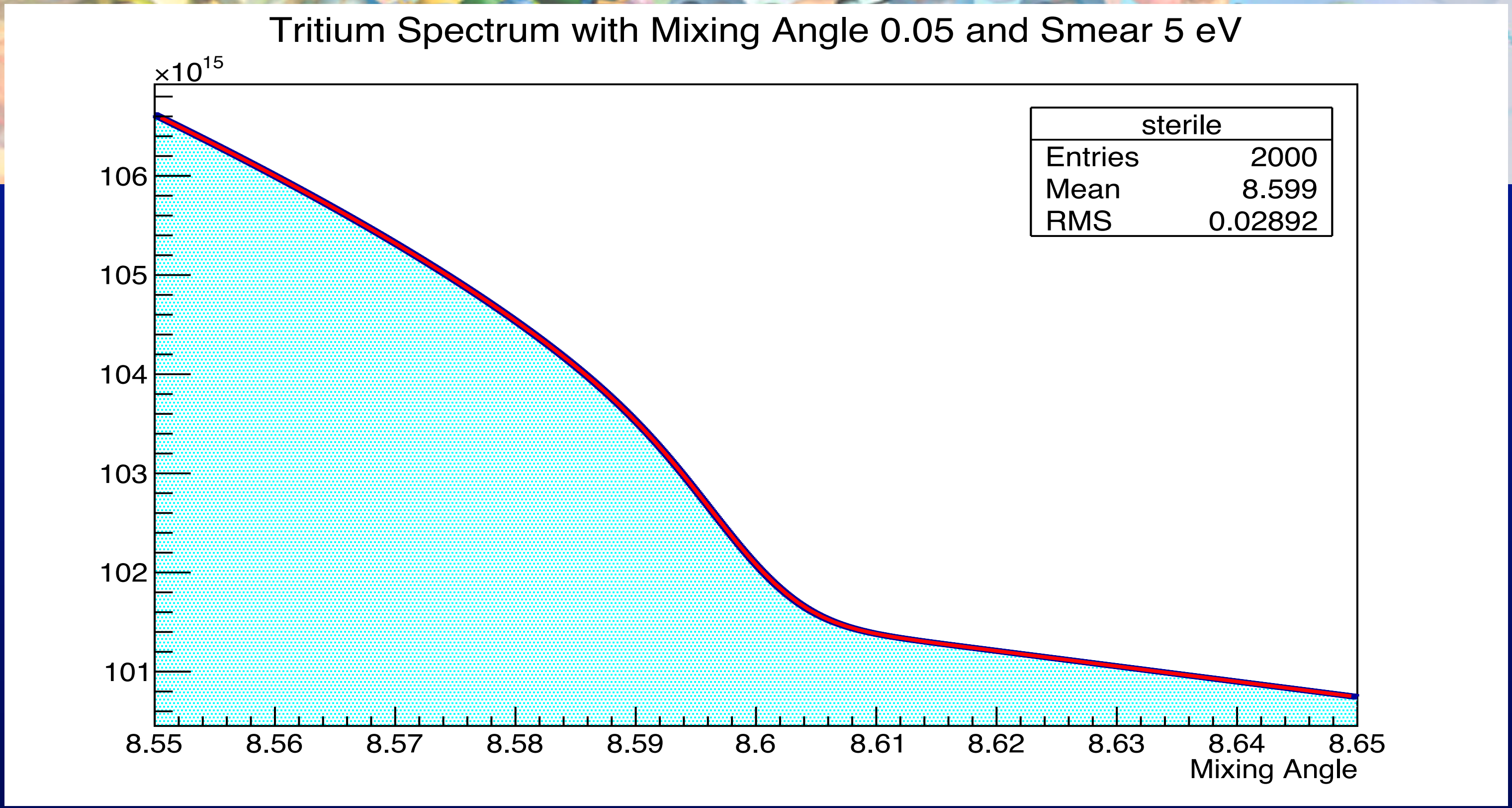
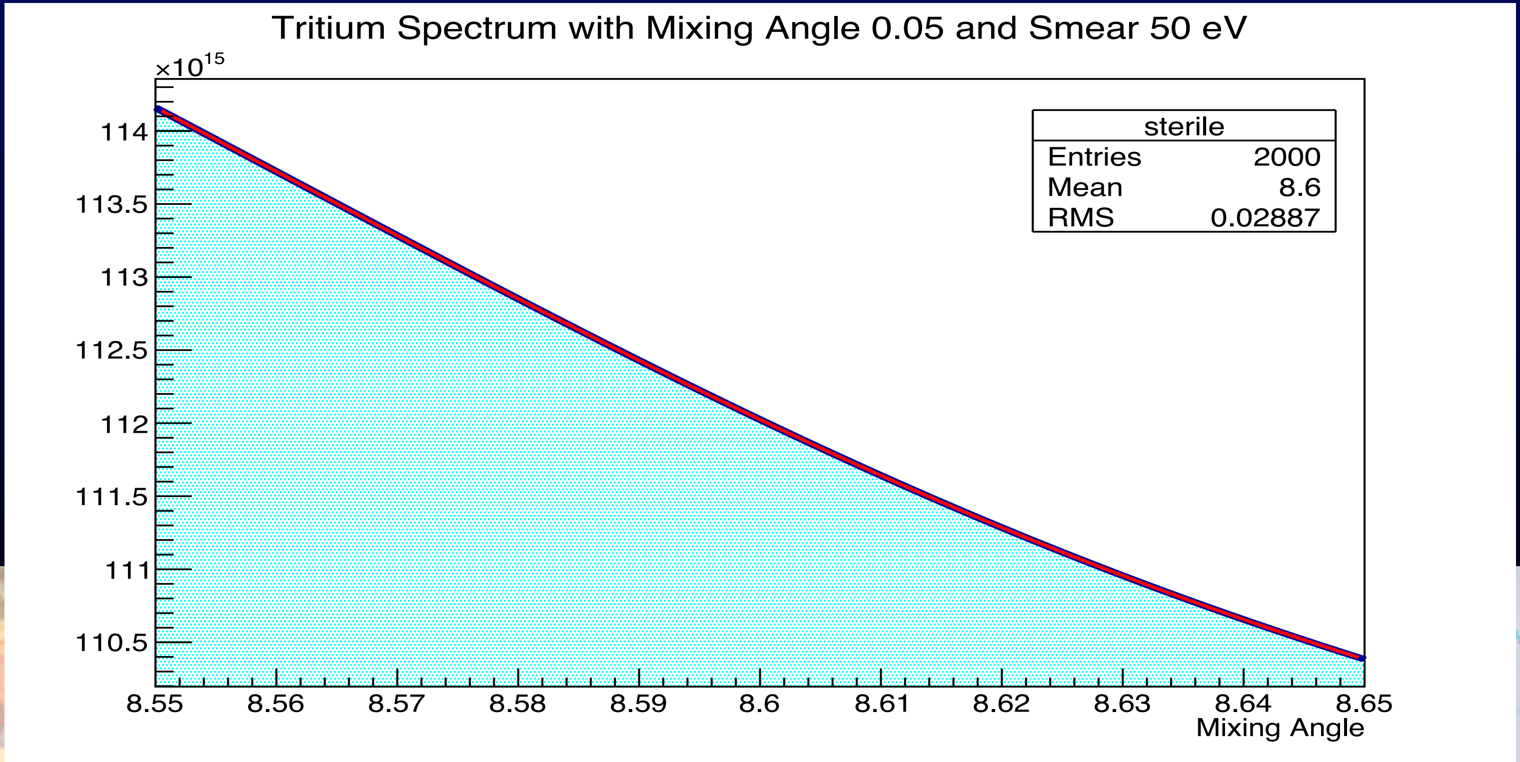
Higher absolute energy resolution visibly important




Tritium Spectrum with Mixing Angle 0.05 and Smear 5 eV


Tritium Spectrum with Mixing Angle 0.05 and Smear 50 eV

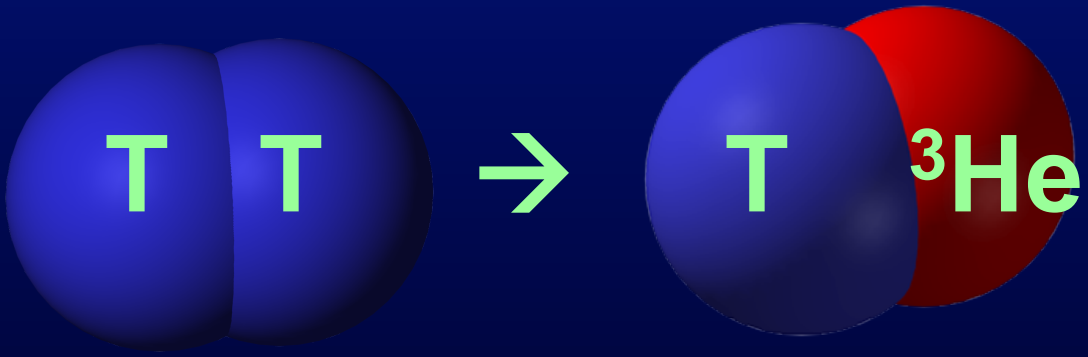
Hydrogen (Isotope) Bonding

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

But what happens when one T atom decays?

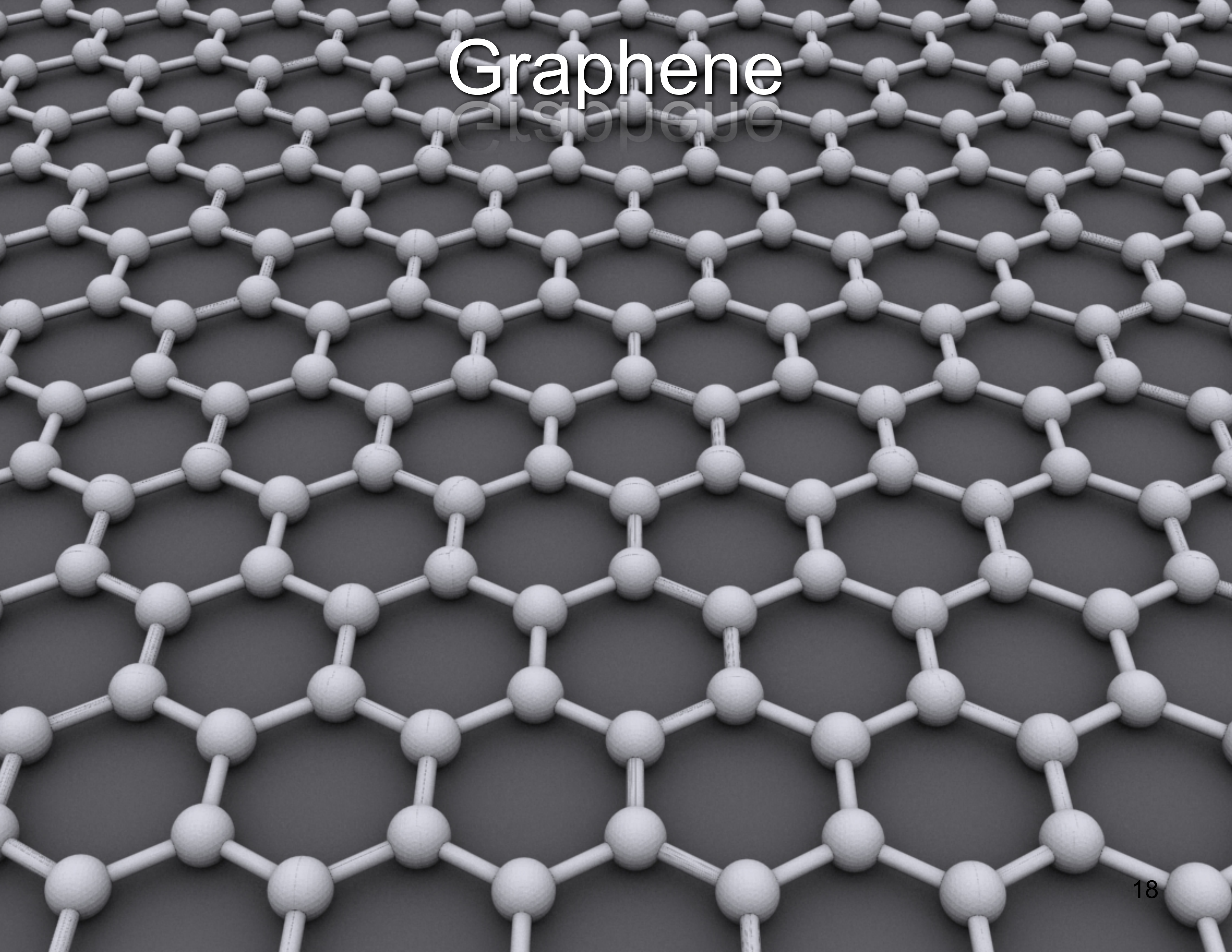
Bodine, Parno, Robertson: arXiv:1502.03497

Answer:



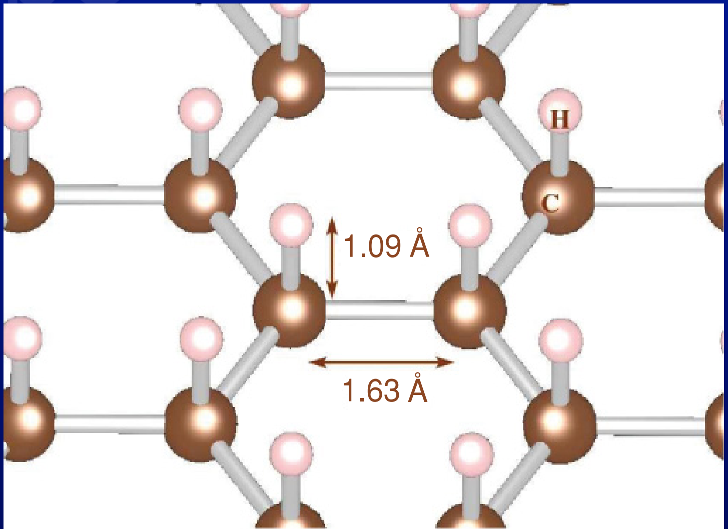
Quantum Mechanics tells us that the outgoing electron energy depends on the change in the binding energy of T^2 to $(T\text{-}^3He)^*$ - smearing >0.4eV

Graphene



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(?)**

~3x10^{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

THE Challenge

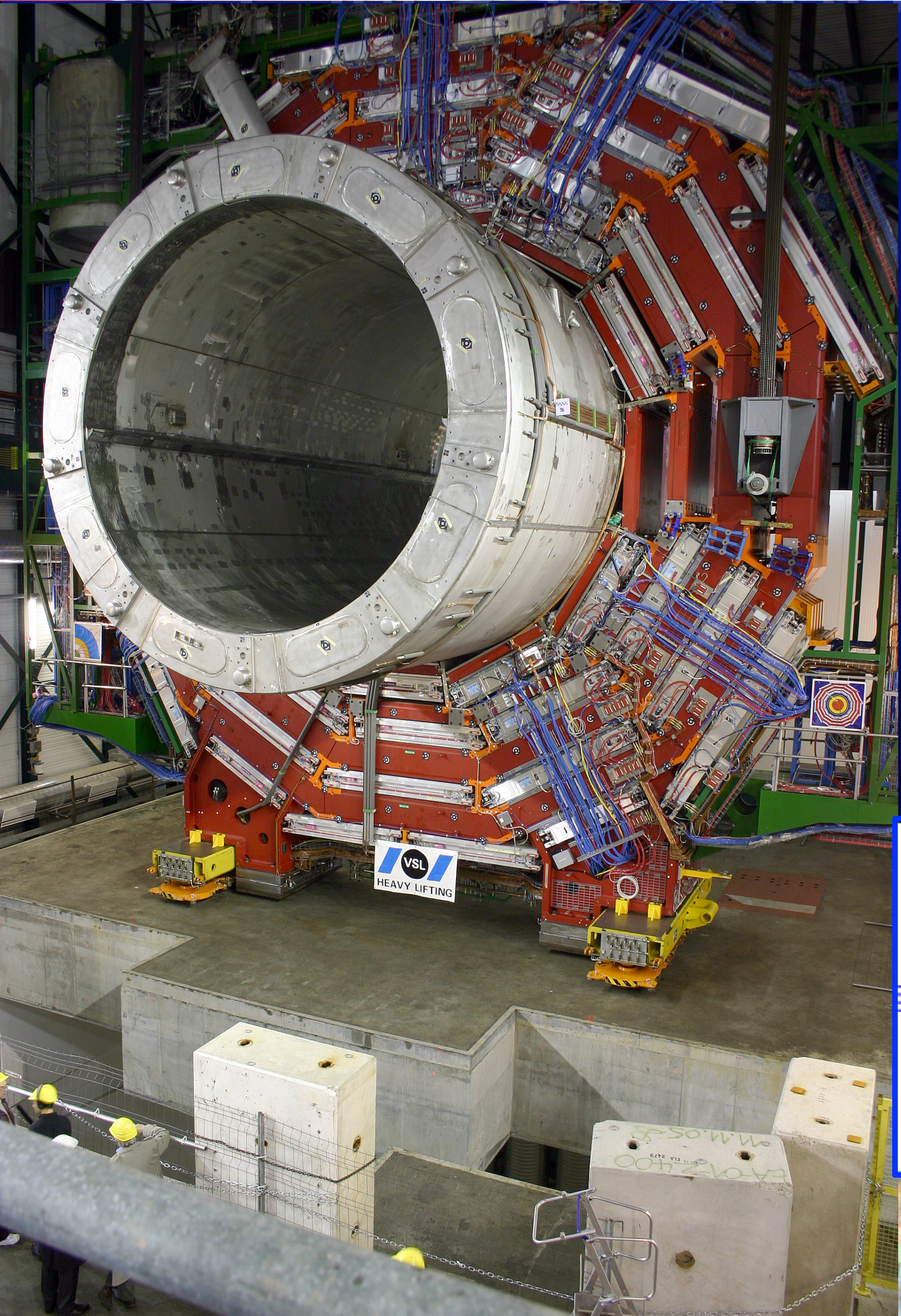
- The largest and nearly insurmountable problem of relic neutrino detection is to provide a large enough surface area to hold at least 100 grams of weakly bound atomic tritium
  - The trajectory of the outgoing electrons from tritium decay must have a clear vacuum path to the calorimeter (up to one or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

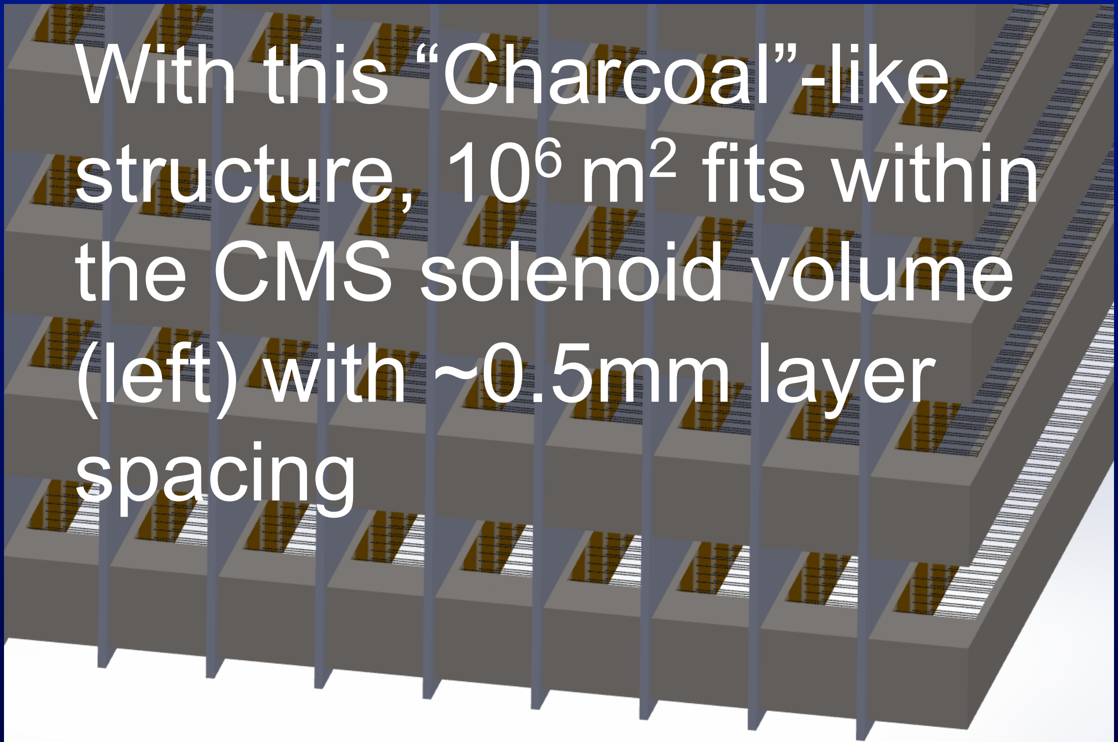
Charcoal

Charcoal

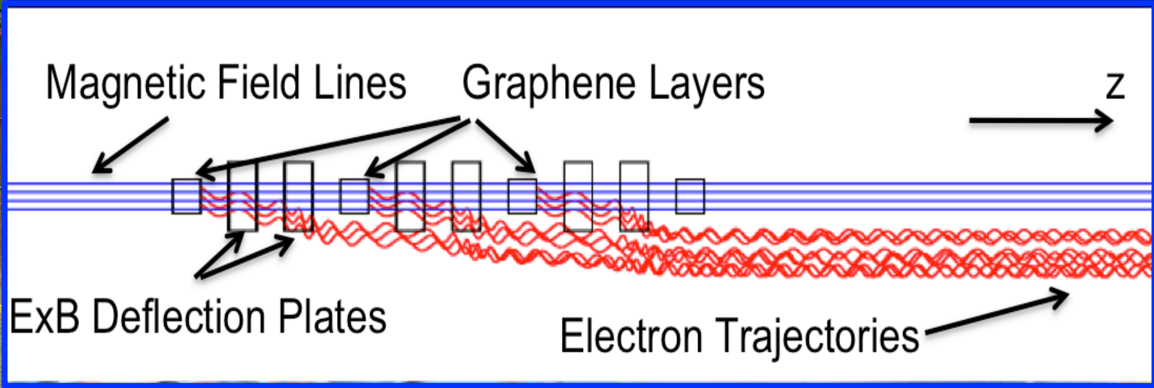
Surface Area ~7×10^5 m^2/kg

CMS Magnet at the LHC





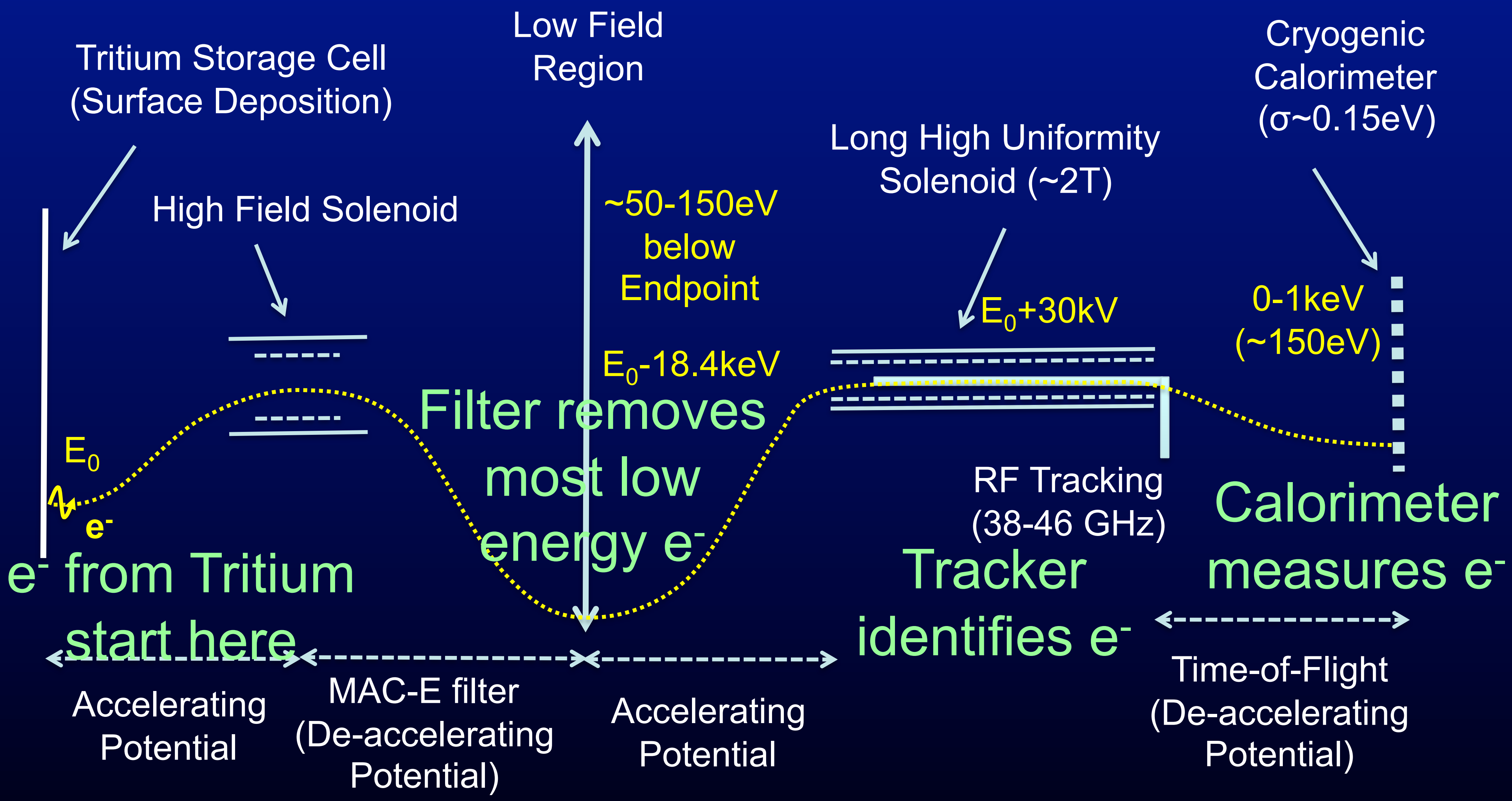
With this “Charcoal”-like structure, 10^6 m^2 fits within the CMS solenoid volume (left) with ~0.5mm layer spacing



Lyman Sptizer, Jr. (1950’s), Van Allen

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^-

e^- from Tritium start here

Filter removes most low energy e^-

RF Tracking (38-46 GHz)

Tracker identifies e^-

Calorimeter measures e^-

Accelerating Potential

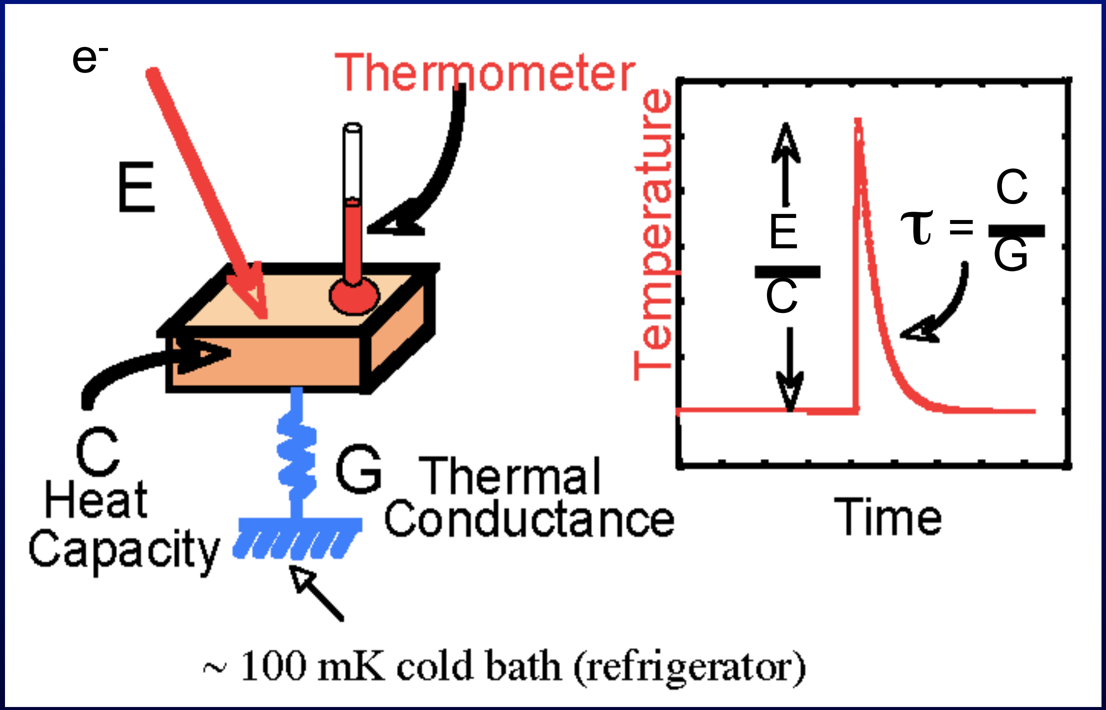
MAC-E filter (De-accelerating Potential)

Accelerating Potential

Time-of-Flight (De-accelerating Potential)

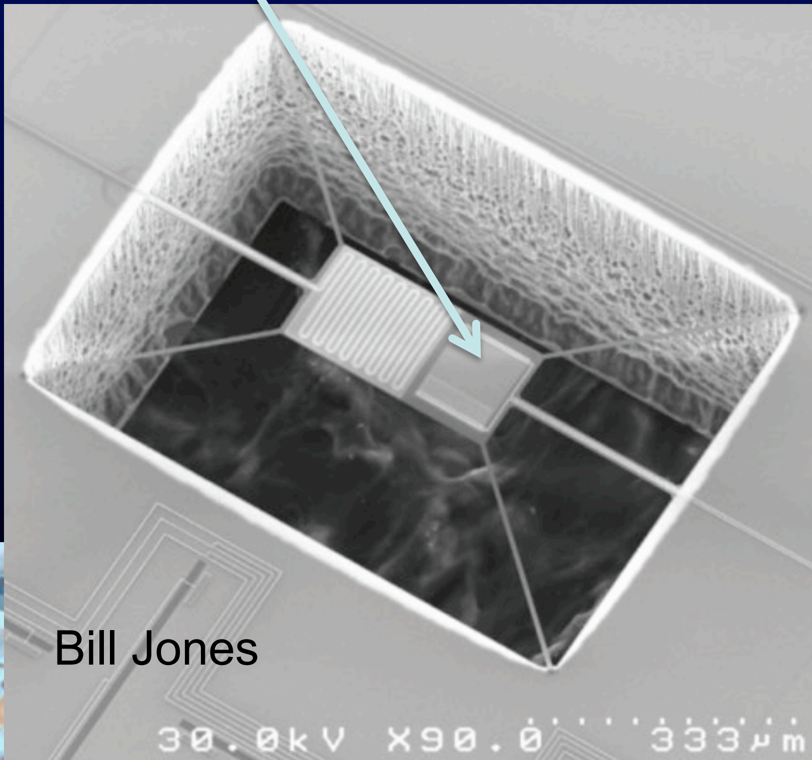
Transition-Edge Sensors for Calorimetry

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



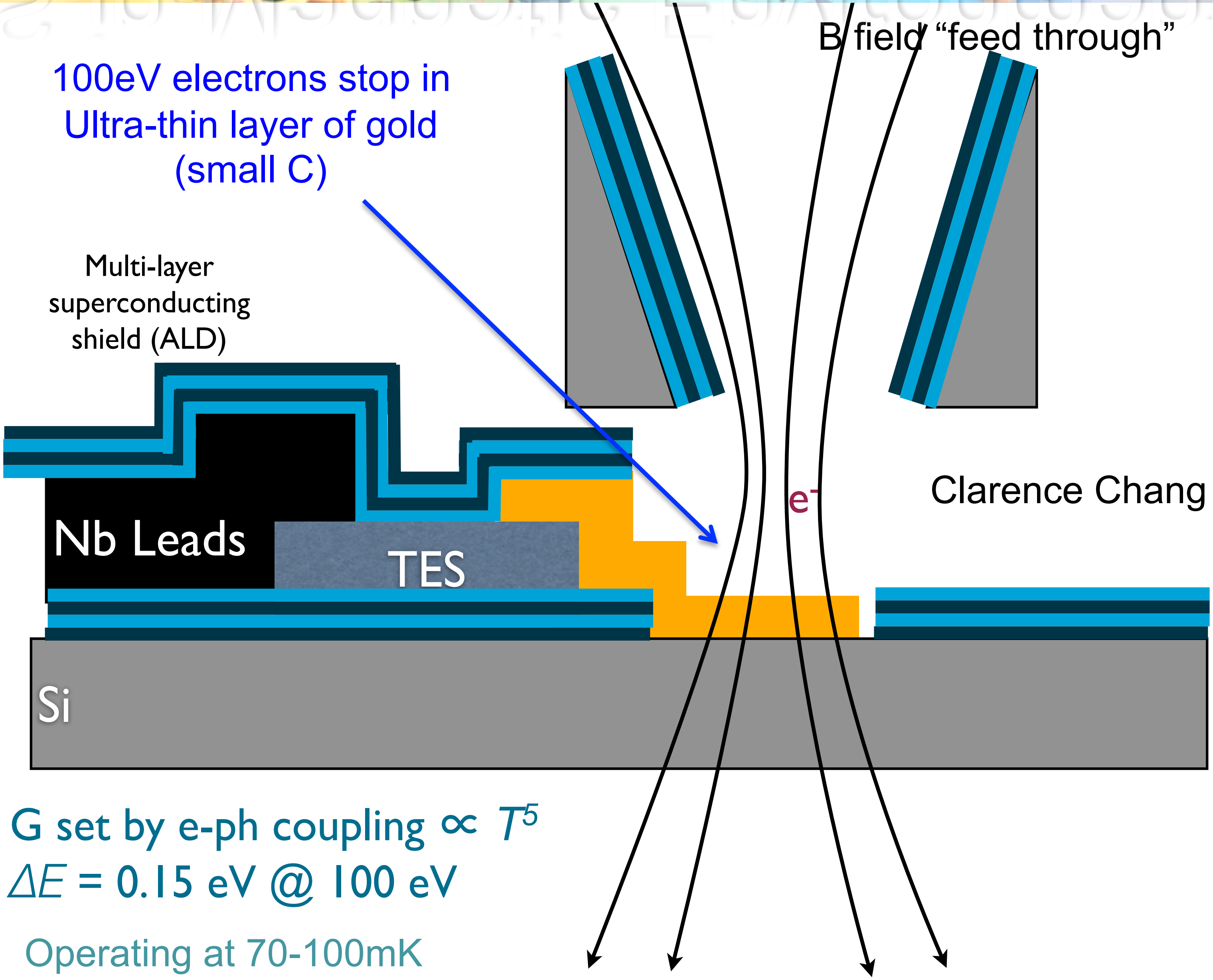
100eV electron can be stopped with very small C

(example) SPIDER Island TES



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

TES in Magnetic Environment



100eV electrons stop in Ultra-thin layer of gold (small C)

Clarence Chang

G set by e-ph coupling ∝ T^5

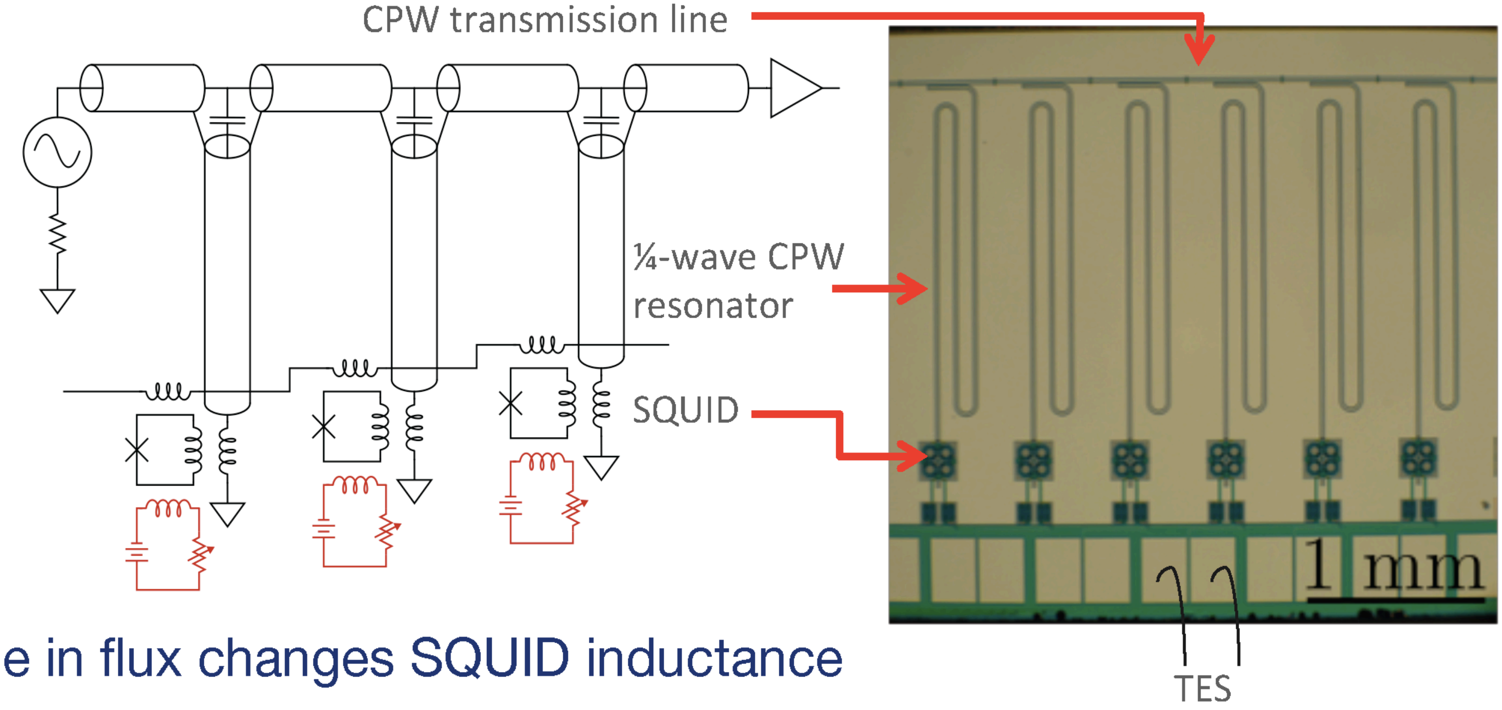
ΔE = 0.15 eV @ 100 eV

Operating at 70-100mK

R&D on Magnetic Shielding has important overlap with TES operational parameters for a wide number of land, balloon and space-based microwave and X-ray telescopes (working with Jack Sadleir, Harvey Moseley, Elmer Sharp and others at Goddard GSFC)

Highly Multiplexed SQUID Readout

Microwave-readout Massive SQUID Multiplexer



- 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

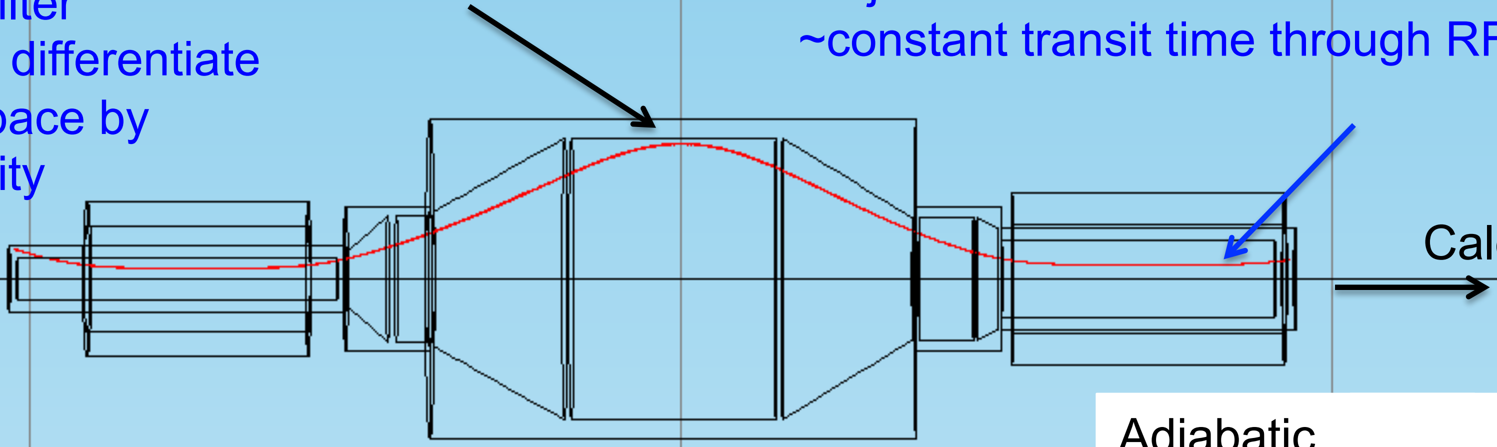
Kent Irwin

PTOLEMY MAC-E Filter

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

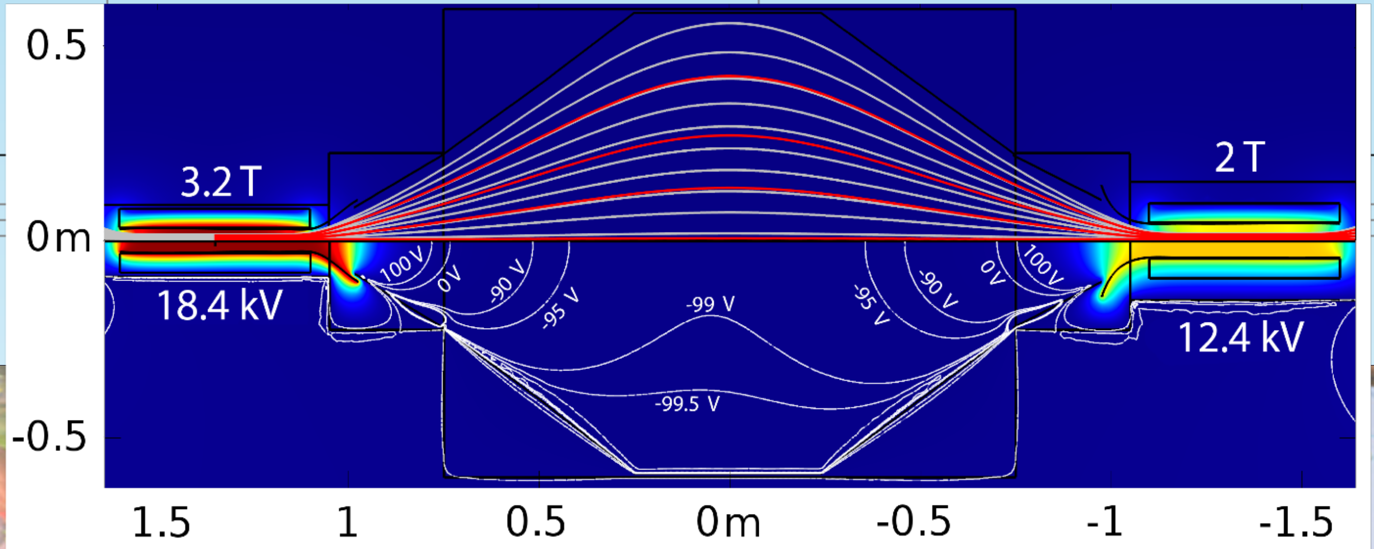
Limiting electron trajectory (hits outer radius of filter)

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

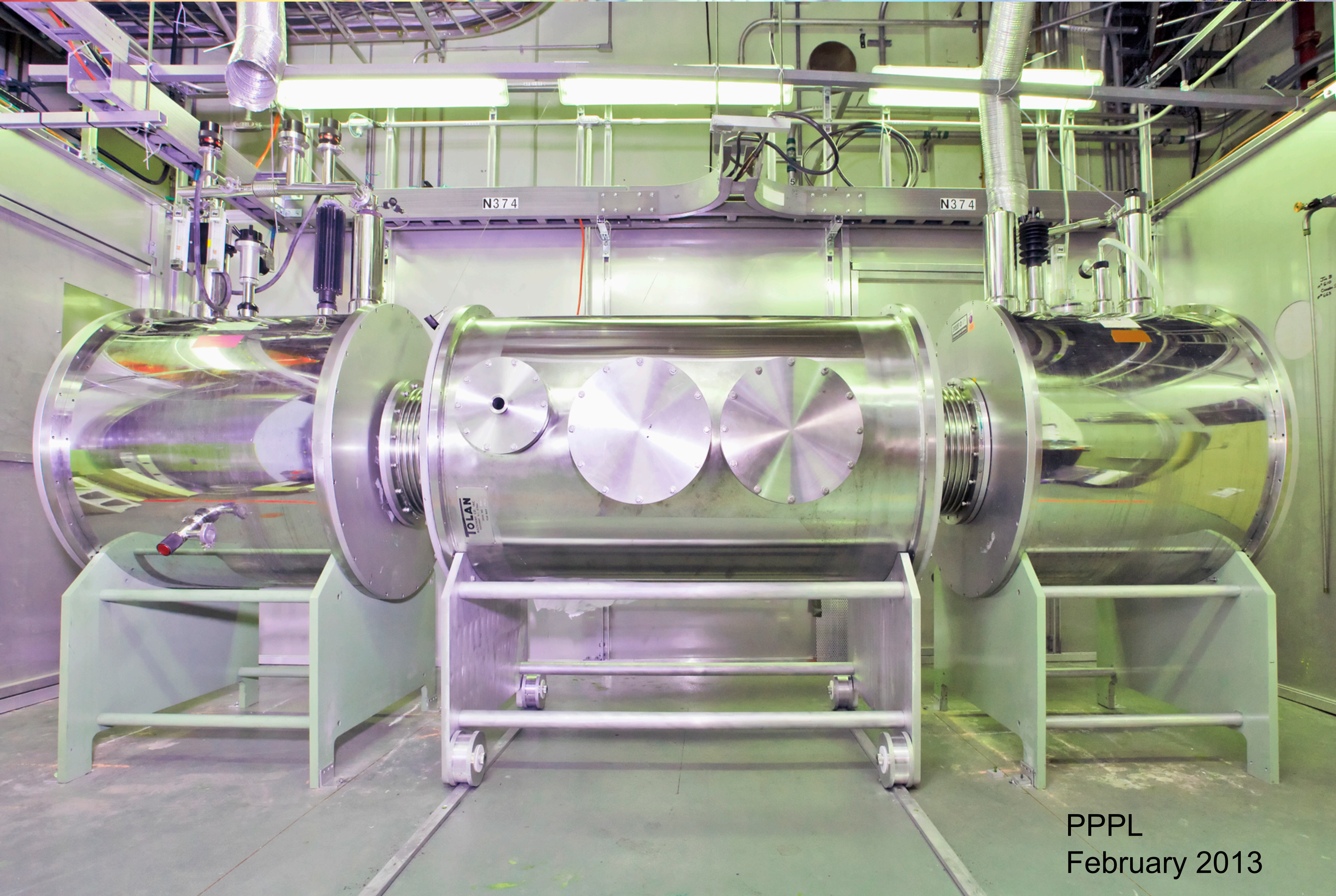


Planar cell aperture of ~30cm^2 within 3.2T bore

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

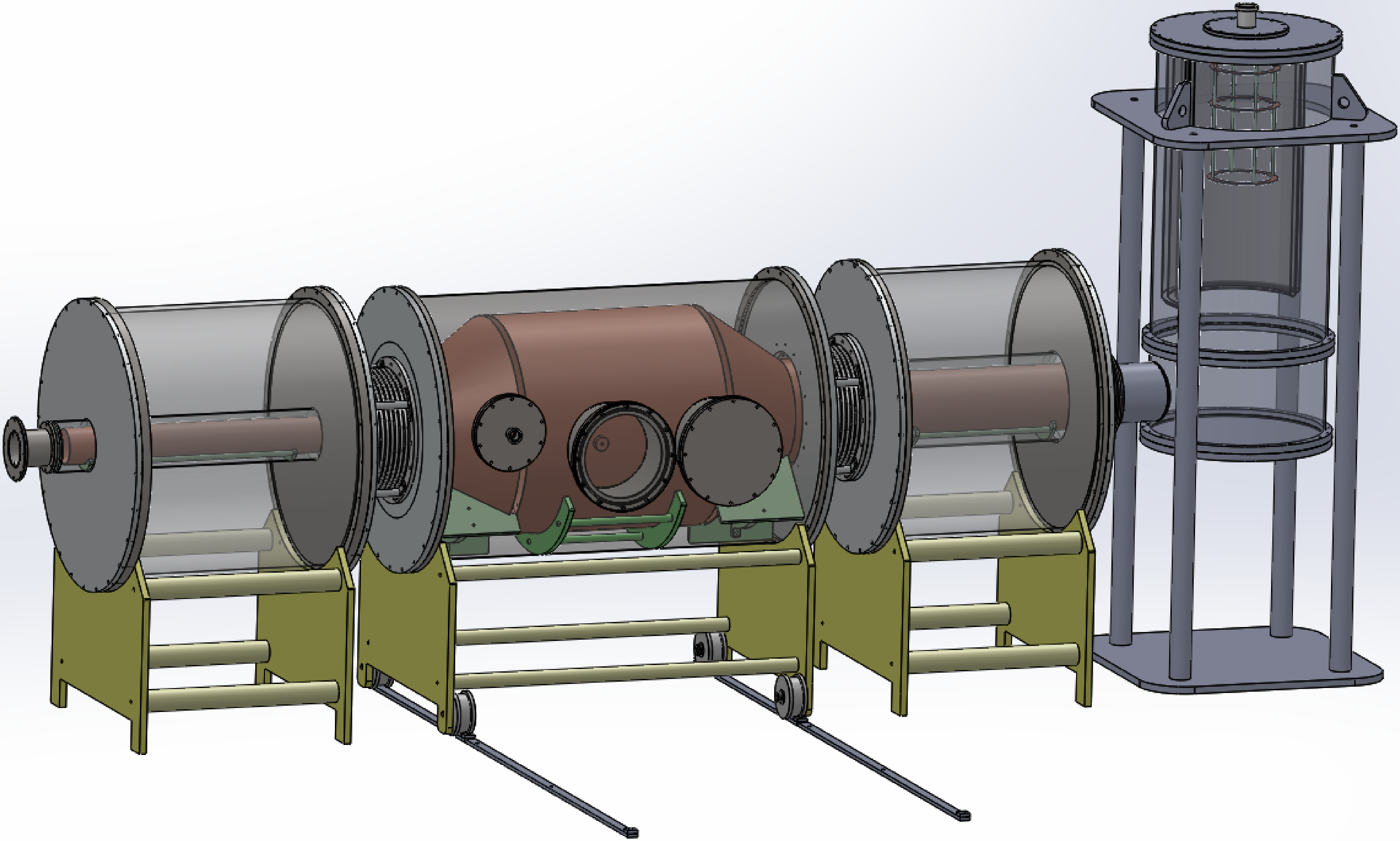


PTOLEMY



PPPL
February 2013

Calorimeter Interface to MAC-E Filter



Recent Progress

Side View (PPPL)

Supported by:
The Simons Foundation

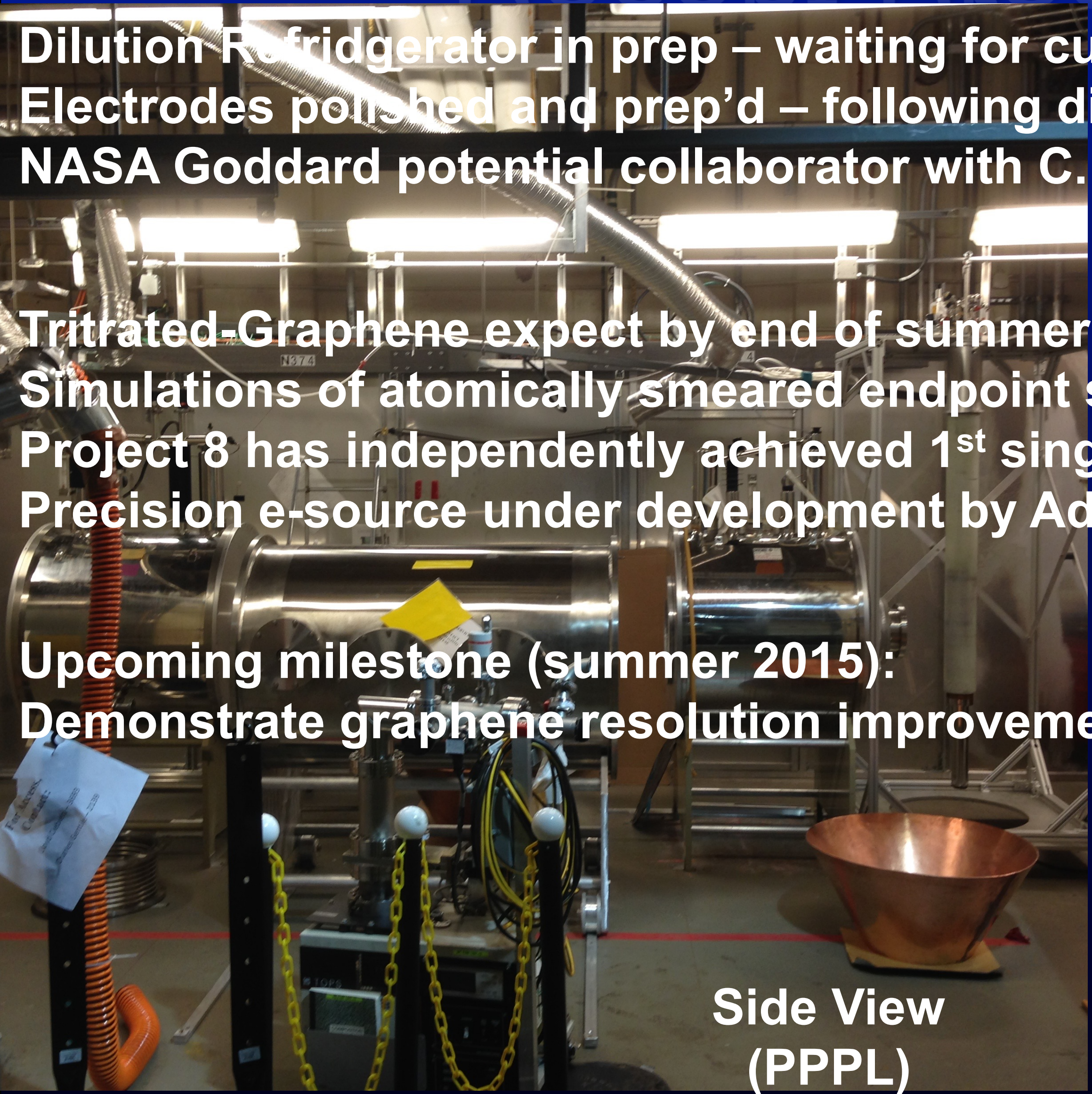
End on View (May 11, 2015)

Recent Progress

Dilution Refridgerator in prep – waiting for custom dewar from KADEL
Electrodes polished and prep'd – following discussions with V. Pantuyev (Troisk)
NASA Goddard potential collaborator with C. Chang (ANL) on calorimeter

Tritrated-Graphene expect by end of summer from P. Cloessner (SRNL)
Simulations of atomically smeared endpoint spectra show graphene improvement
Project 8 has independently achieved 1st single electron RF detection
Precision e-source under development by AdvEnergySystems (Forrestal campus)

Upcoming milestone (summer 2015):
Demonstrate graphene resolution improvements on tritium endpoint



Side View
(PPPL)

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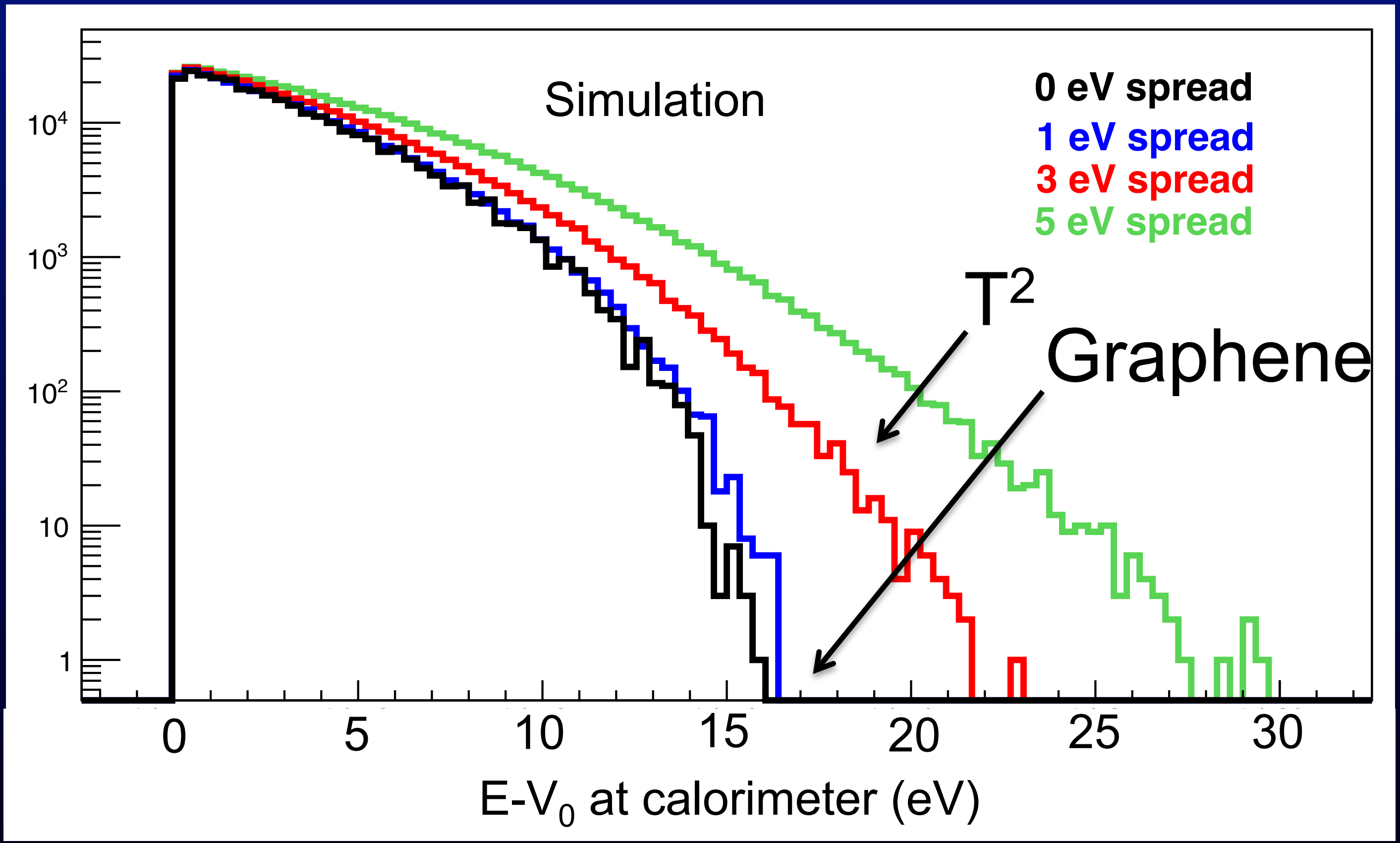
End on View (May 11, 2015)

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)

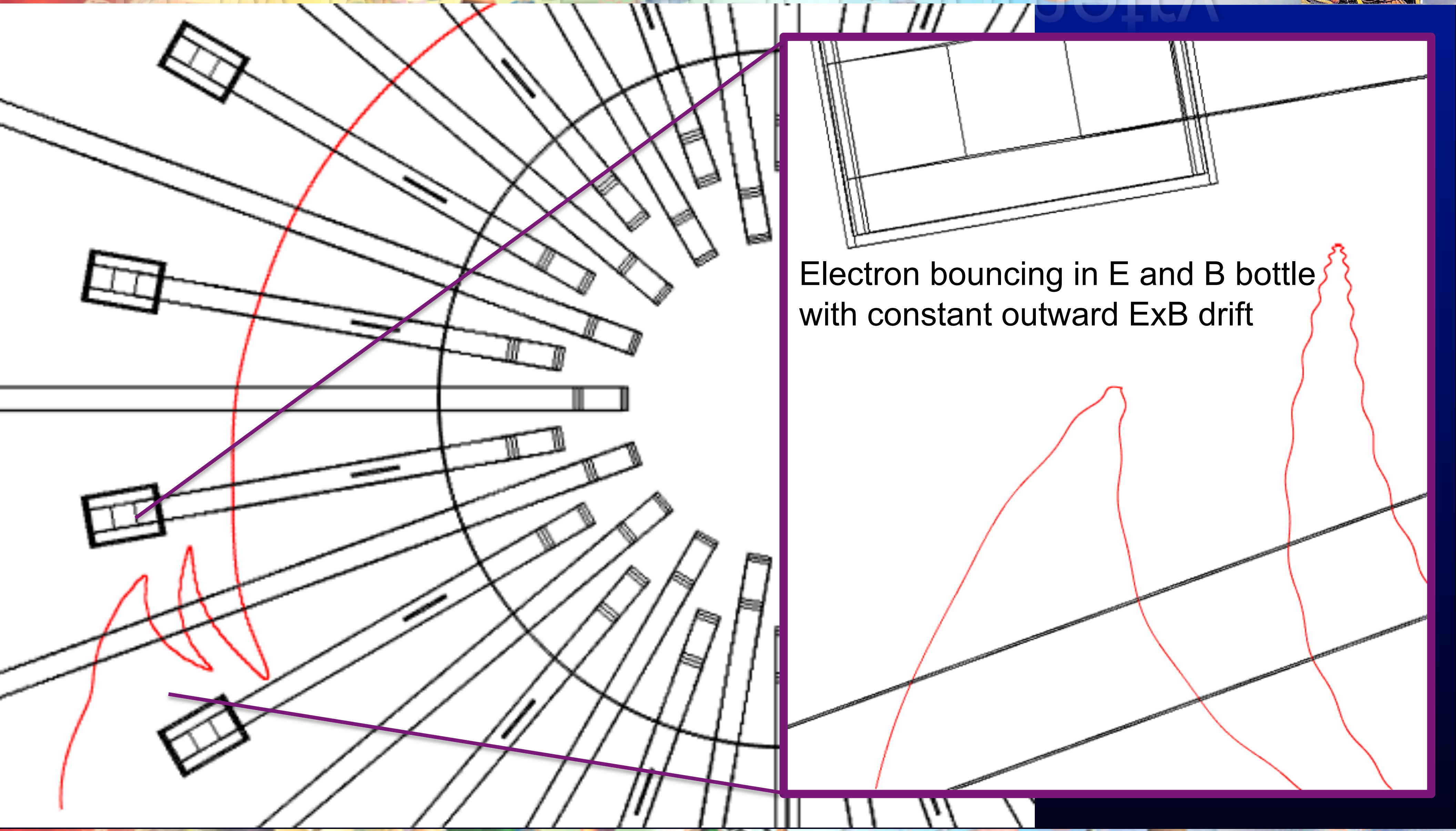
Goals: Measure relative endpoint shifts of graphene compared to T^2 and determined relative energy smearing

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

Liouville's Theorem

- "Parallel" and "Orthogonal" MAC-E Filters
  - KATRIN $\nabla\vec{B} \parallel \vec{B}$
    - Magnetic flux expands in fringe field between pair of solenoids
    - All electrons pass through one Area aperture
  - PTOLEMY $\nabla\vec{B} \perp \vec{B}$
    - Adiabatic invariant conserved under transverse drift
    - Electrons drift orthogonal to B field under ExB
    - Equivalent Area aperture is replicated many-fold

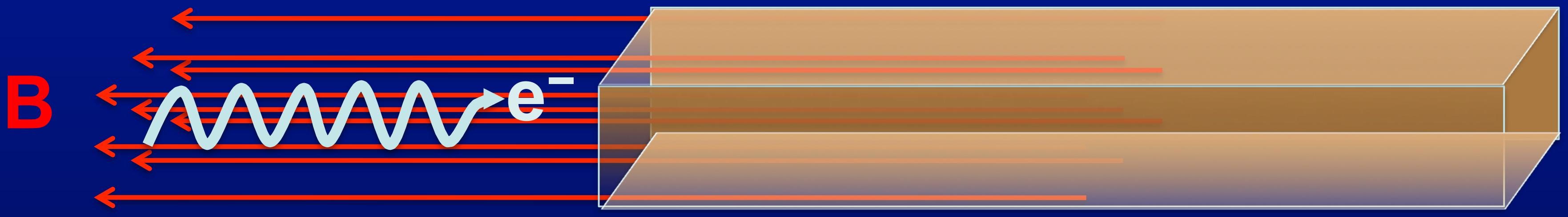
New MAC-E filter Geometry



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

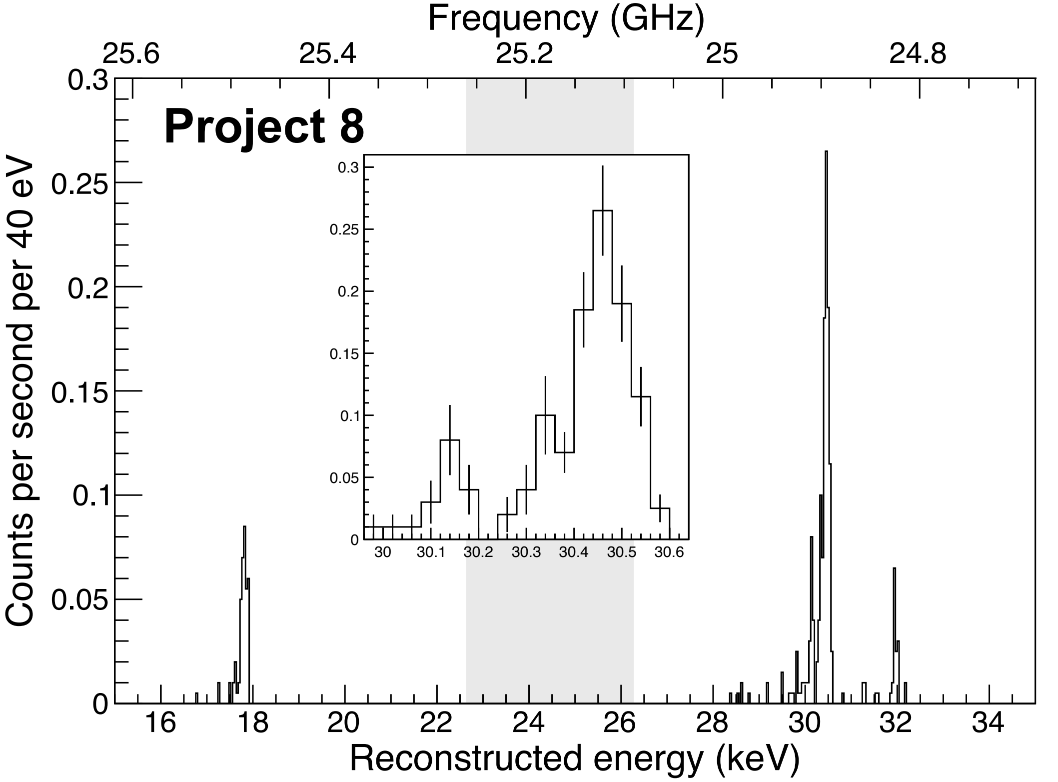
Semi-relativistic Electron Identification

Project 8 has first detection of ~18keV 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

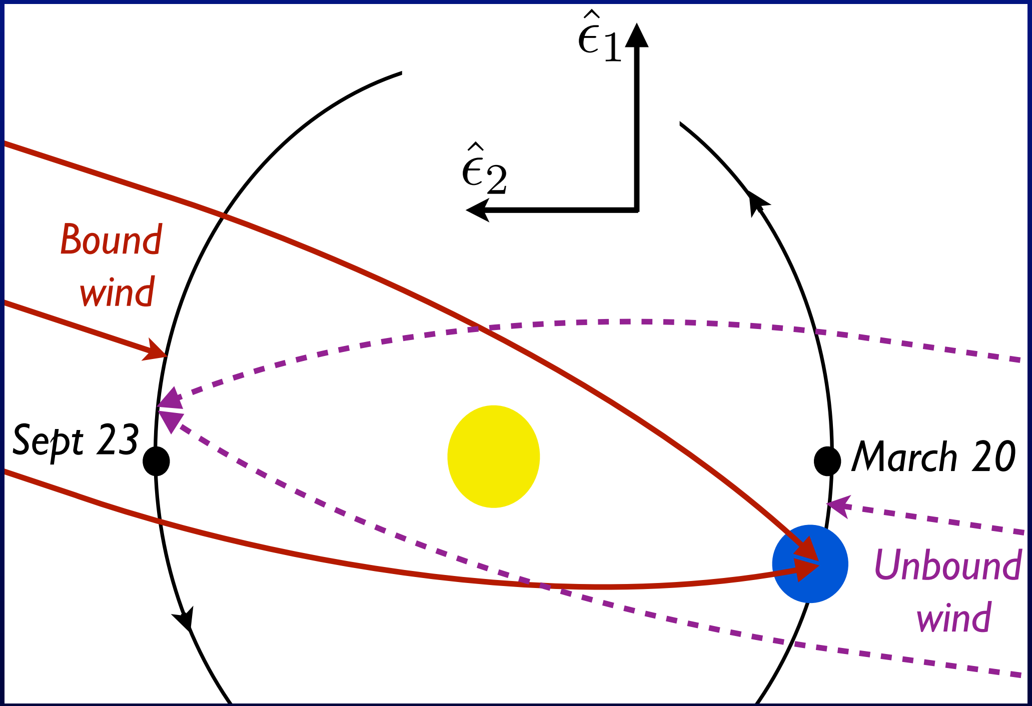


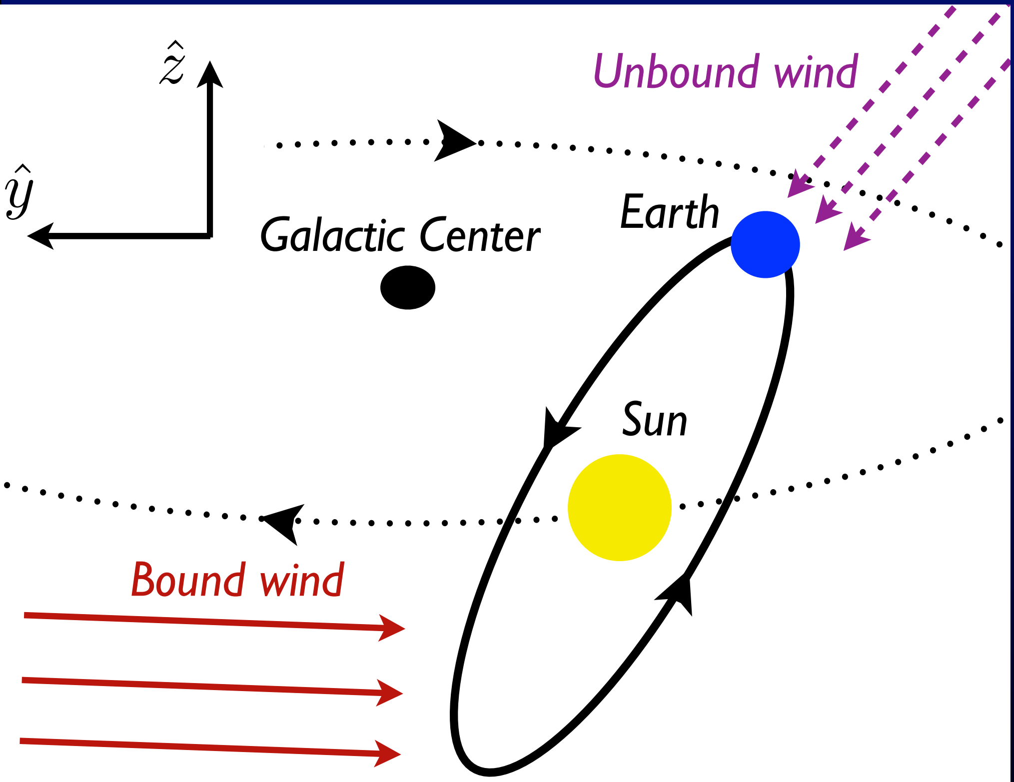
Q-Band Waveguide
“Magic Tee”
WMAP HEMT

Annual Modulation of Cosmic Relic Neutrinos

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

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



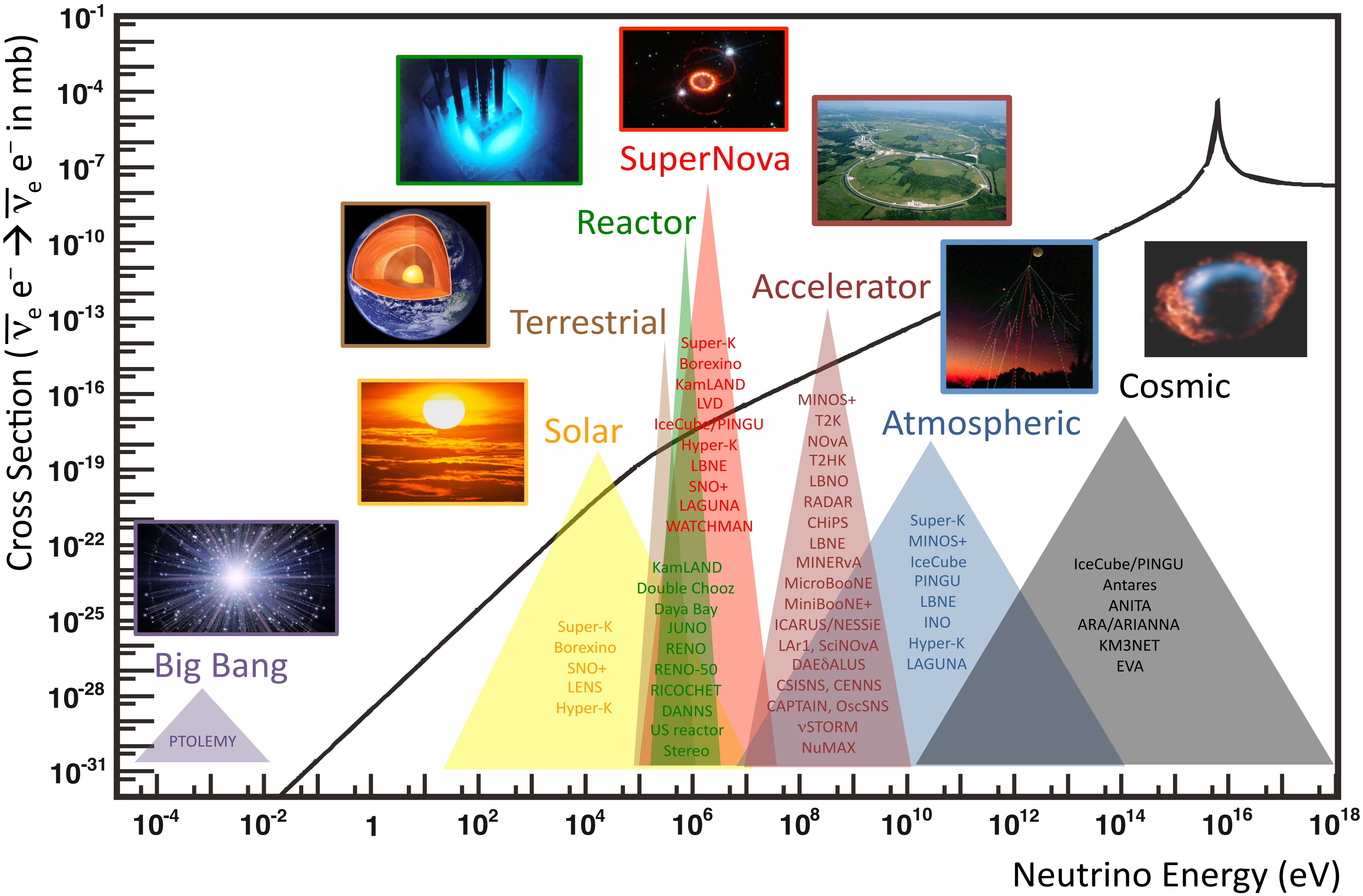


CMB rest frame = Relic Neutrino Rest Frame?

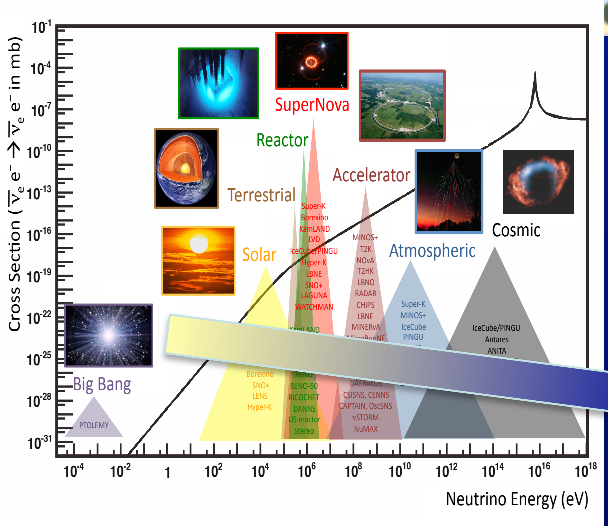
Polarized Tritium Nucleus
http://arxiv.org/abs/1407.0393 **Safdi, Lisanti, CGT**

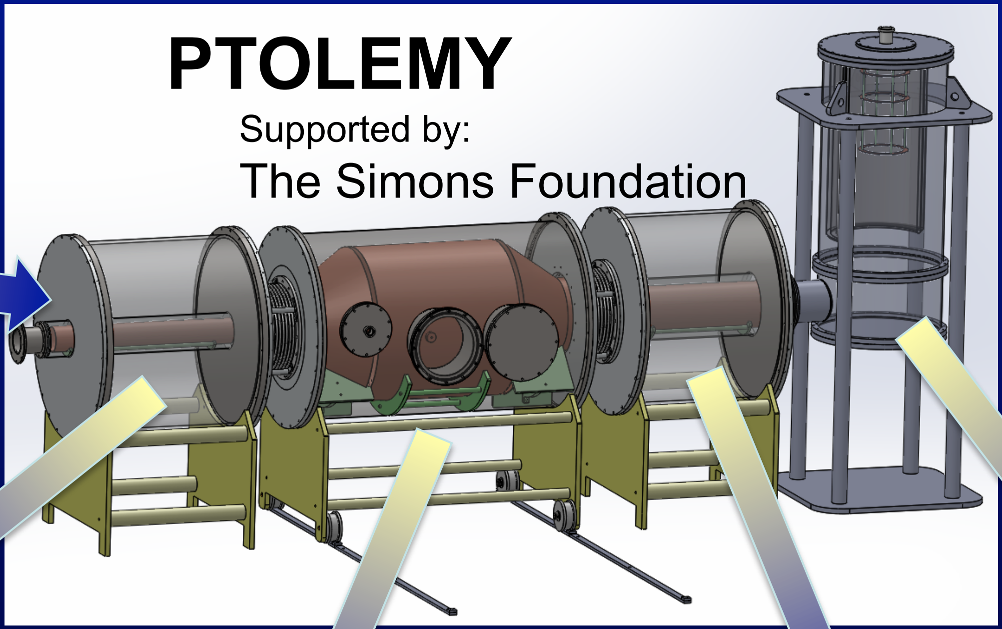
Velocity sensitivity provides possibility to measure:
Relic Neutrino **Rest Frame**, and potentially,
Relic Neutrino **Temperature** (from velocity and mass)

Overview of Neutrino Experiments



Summary





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