Title: One Second After the Big Bang

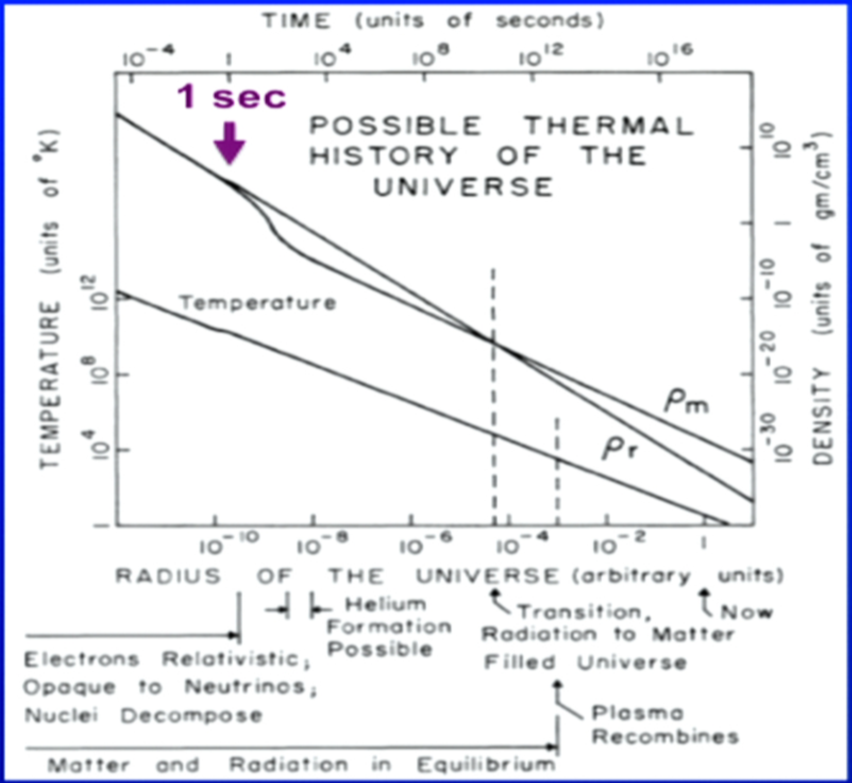
Date: Nov 25, 2014 01:00 PM

URL: http://pirsa.org/14110157

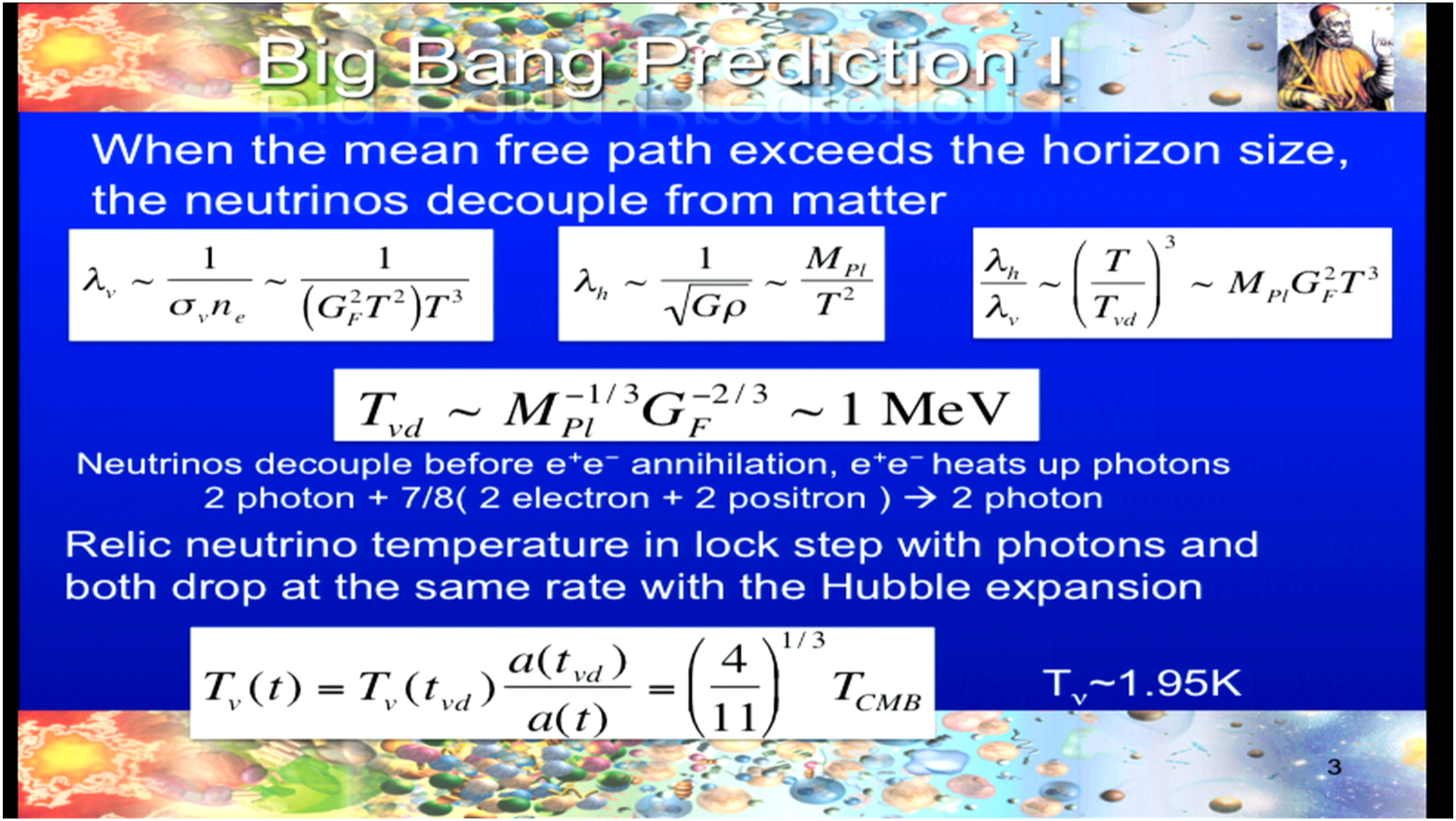
Abstract: <p>A new experiment called PTOLEMY (Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield) is under development at the Princeton Plasma Physics Laboratory with the goal of challenging one of the most fundamental predictions of the Big Bang â€“ the present-day existence of relic neutrinos produced less than one second after the Big Bang. Using a gigantic graphene surface to hold 100 grams of a single-atomic layer of tritium, low noise antennas that sense the radio waves of individual electrons undergoing cyclotron motion, and a massive array of cryogenic sensors that sit at the transition between normal and superconducting states, the PTOLEMY project has the potential to challenge one of the most fundamental predictions of the Big Bang, to potentially uncover new interactions and properties of the neutrinos, and to search for the existence of a species of light dark matter known as sterile neutrinos.</p>

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

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

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

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

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

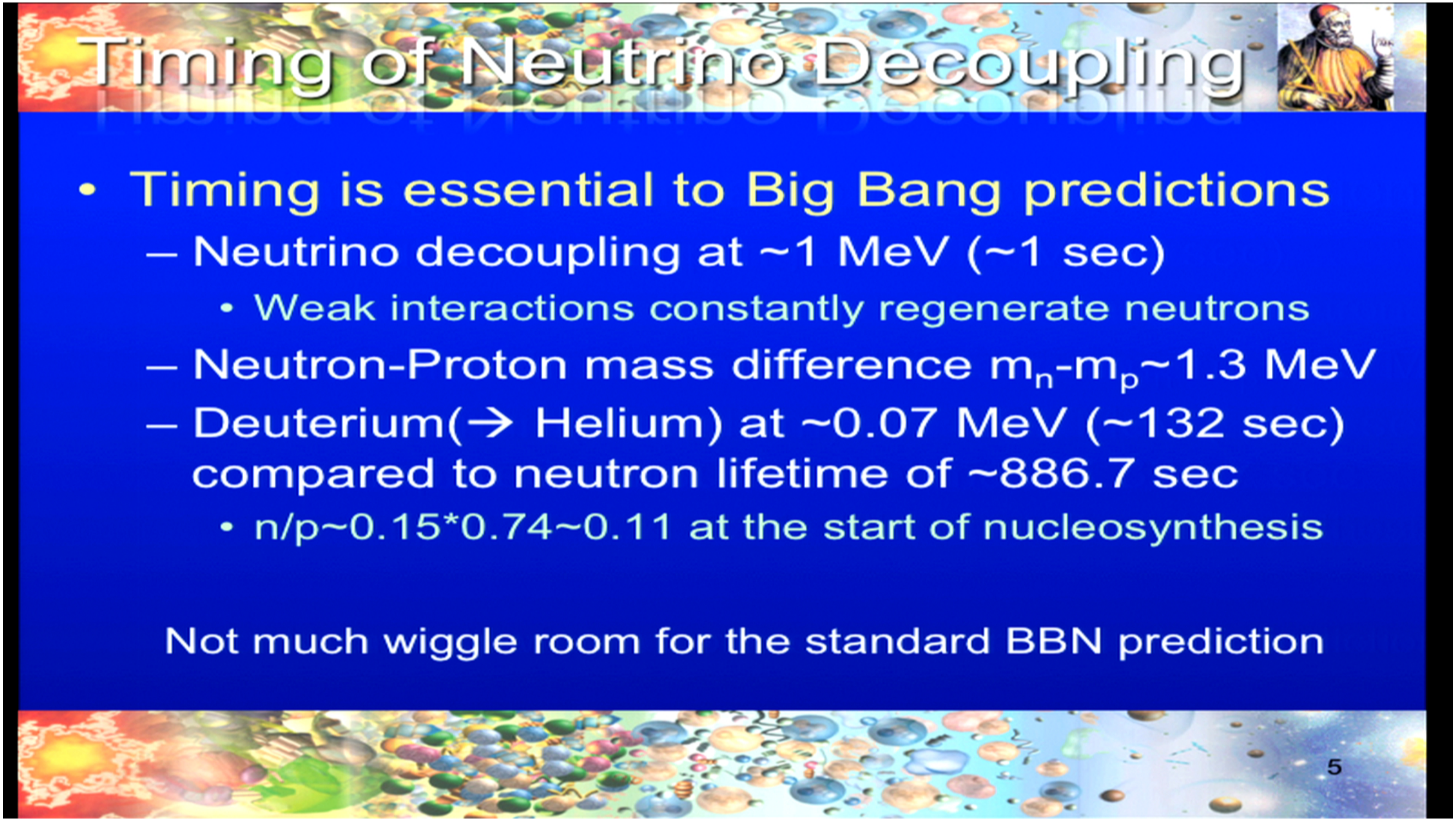
Neutrinos decouple before e^+e^- annihilation, e^+e^- heats up photons

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

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

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



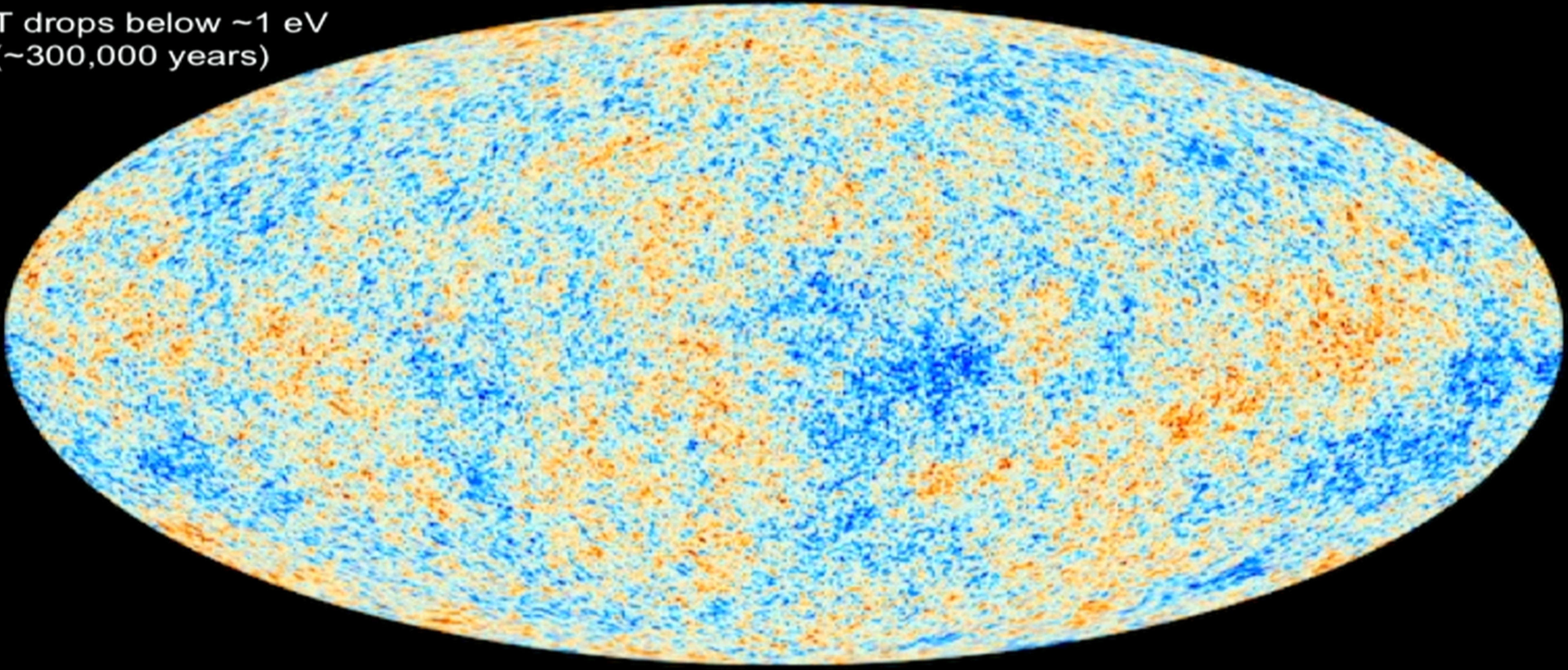
Timing of Neutrino Decoupling

- 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

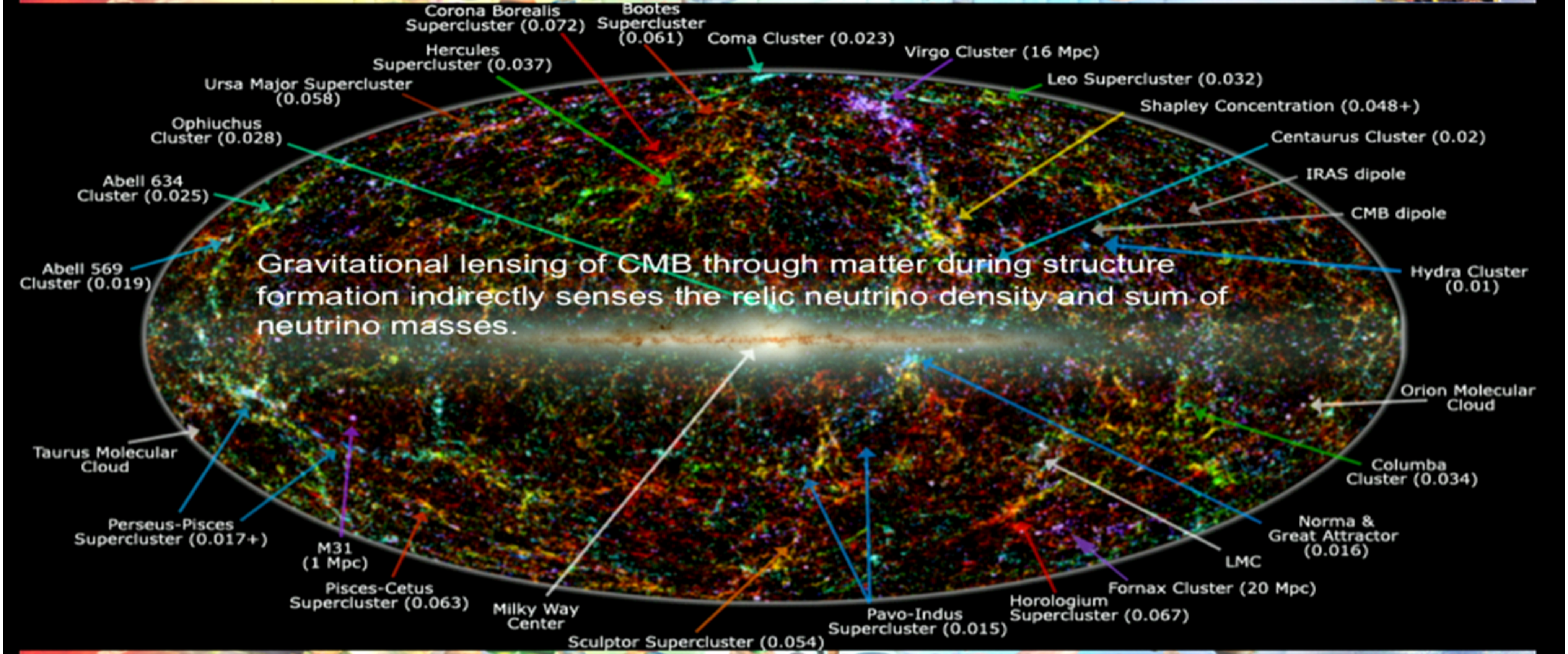
Not much wiggle room for the standard BBN prediction

Cosmic Background Radiation

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

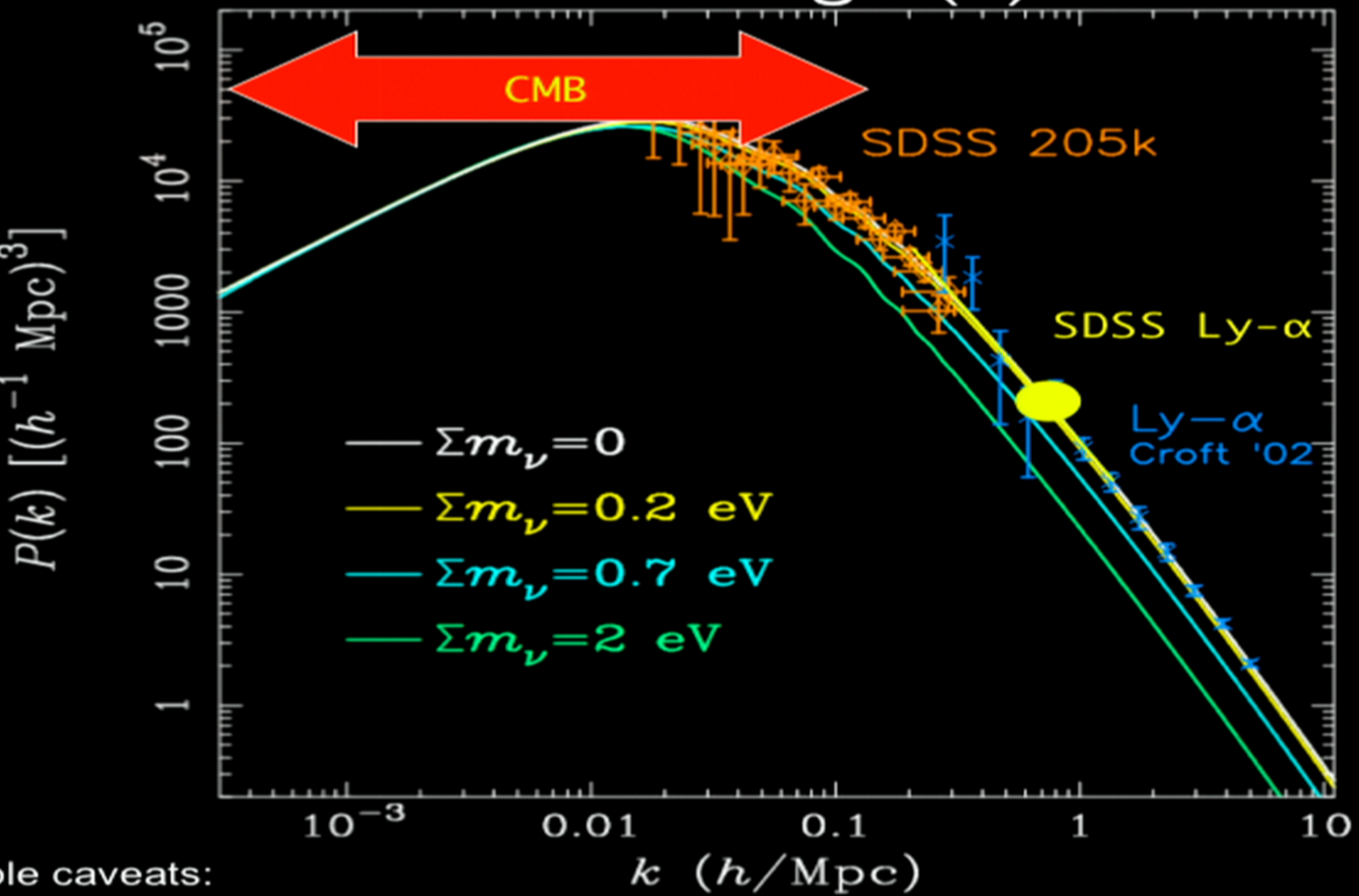


Large-Scale Structure



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

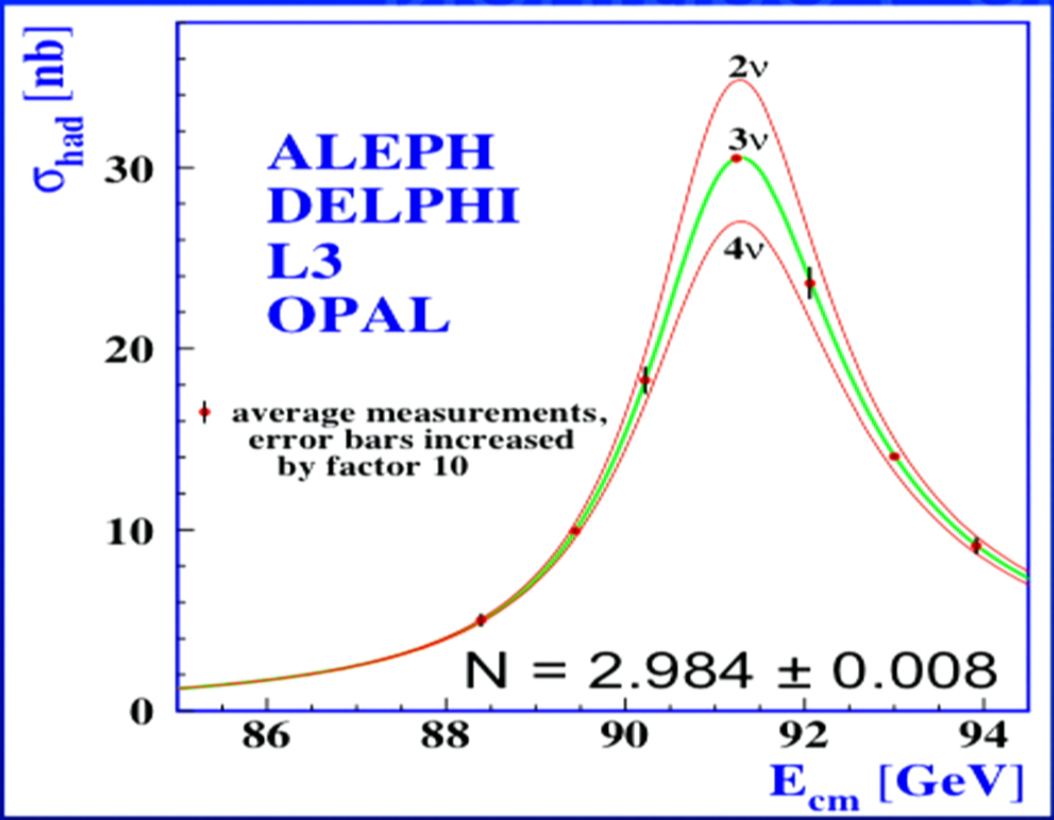
Measuring P(k)



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



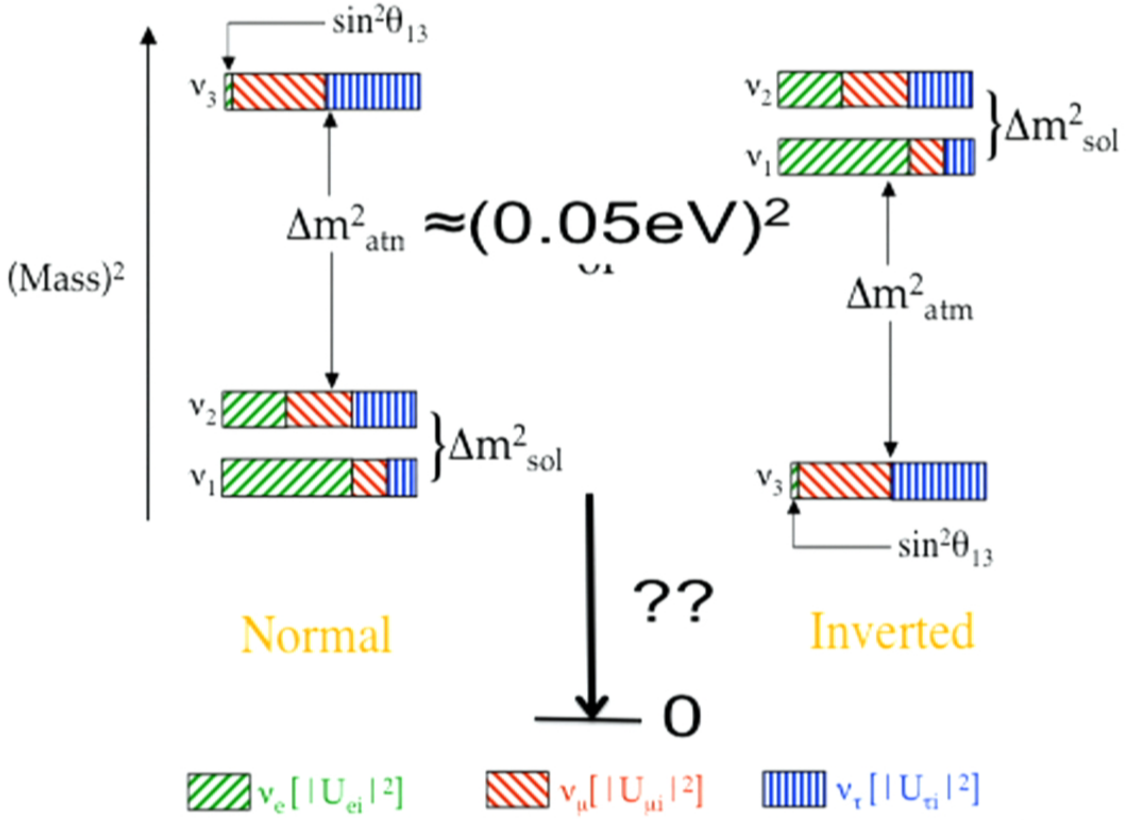
Produce ~1M Z bosons at an e^+e^- collider

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



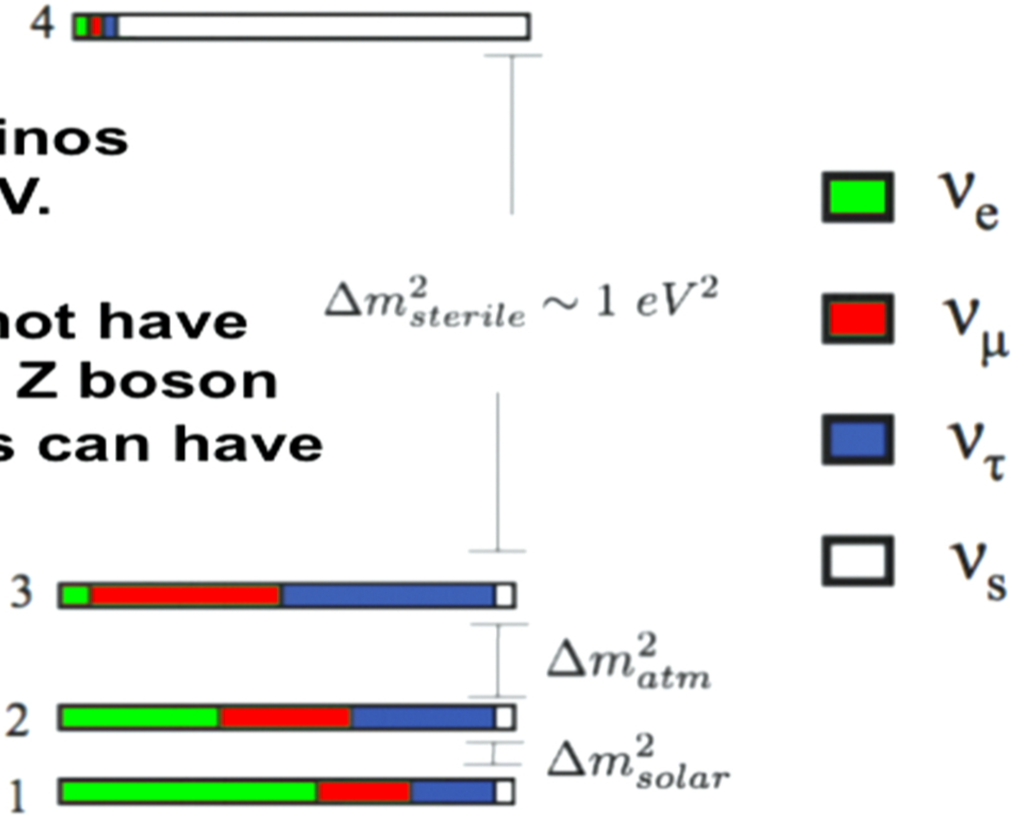
An incredible phenomenon appeared when neutrinos were measured from different sources: solar, atmospheric, reactor, accelerator.

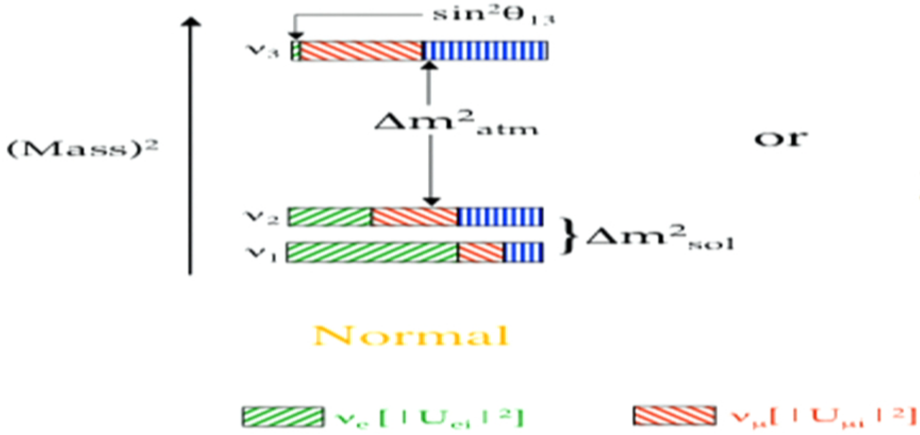
A neutrino created with a definite lepton flavor (in this case, electron or muon) would arrive with a lower probability to be detected with the same flavor and a non-zero probability to have mixed into another flavor.

Sterile Neutrinos?

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

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





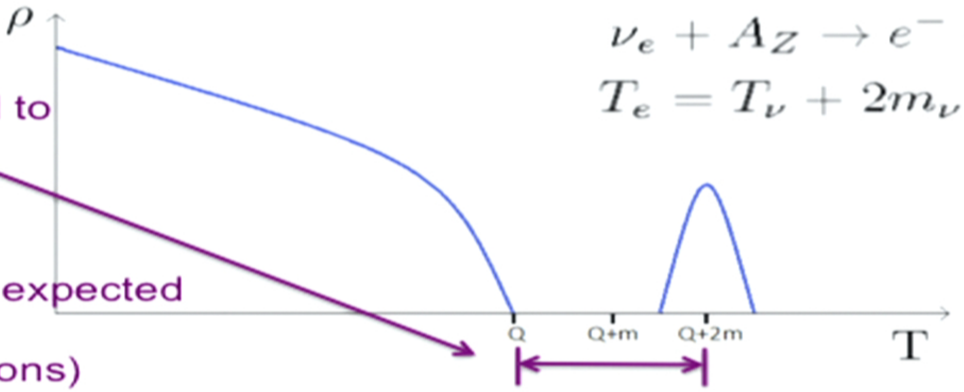
Relic Neutrino Detection

- 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)

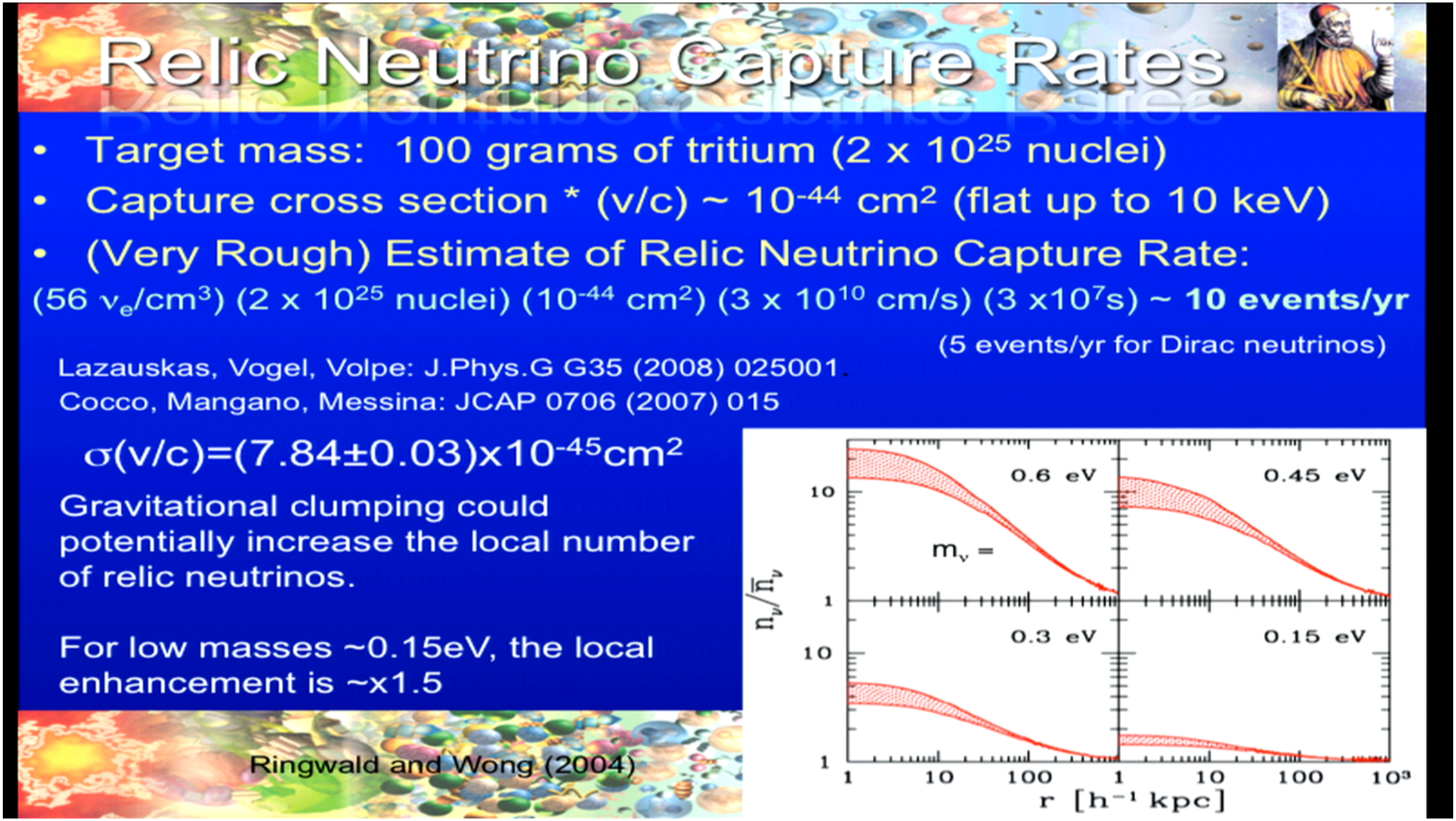


$$\nu_e + A_Z \to e^- + A^*_{Z+1}$$

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

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



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

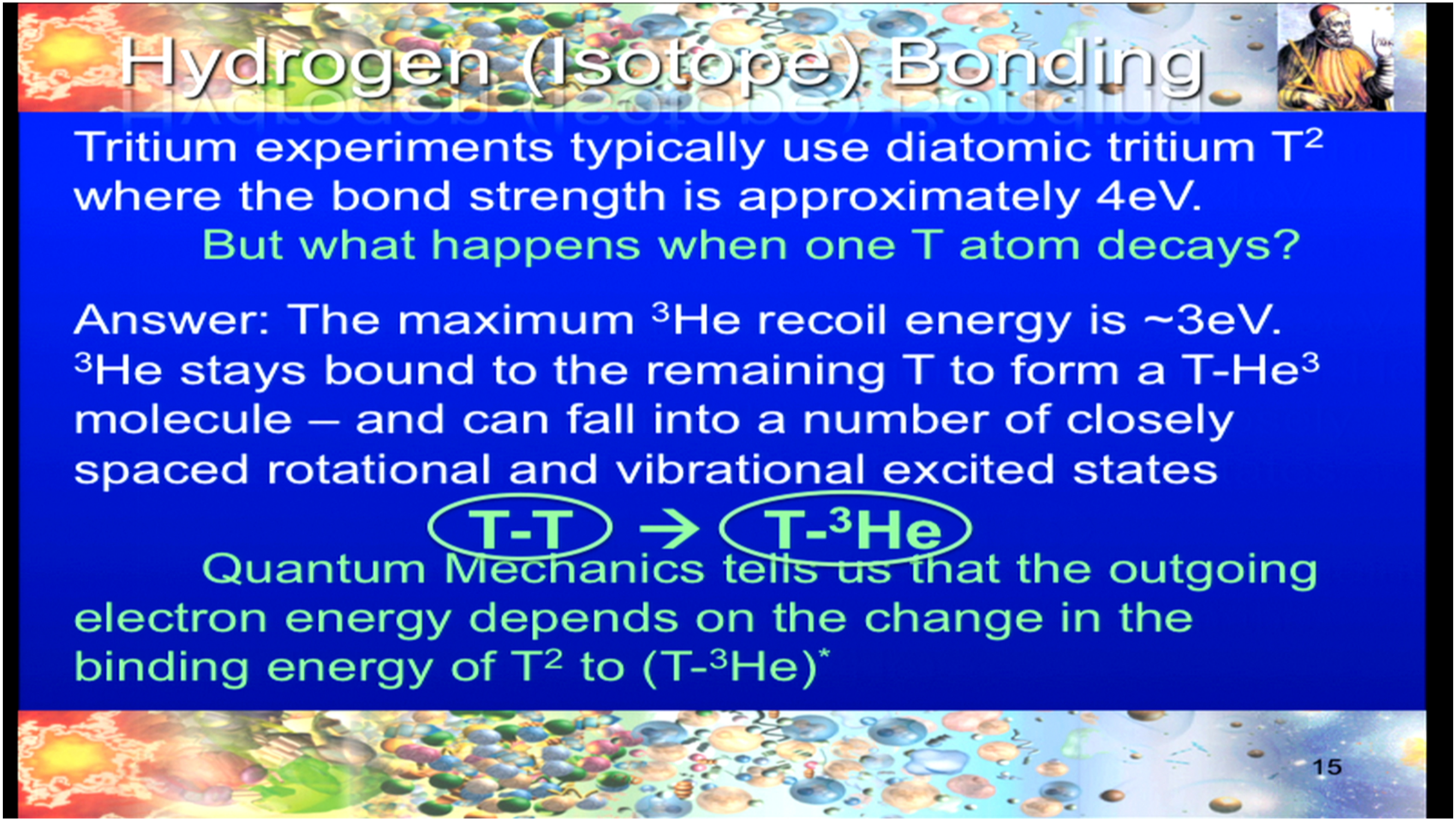
Long, Lunardini, Sabancilar: arXiv:1405.7654

"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?



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?

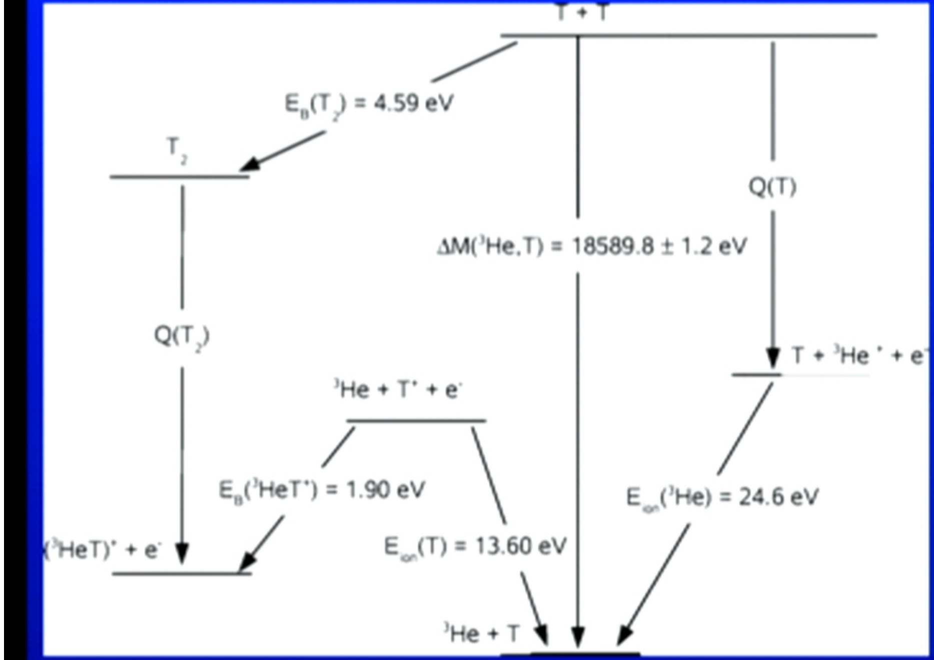
Answer: The maximum ^{3}He recoil energy is ~3eV. ^{3}He stays bound to the remaining T to form a T-He^3 molecule – and can fall into a number of closely spaced rotational and vibrational excited states

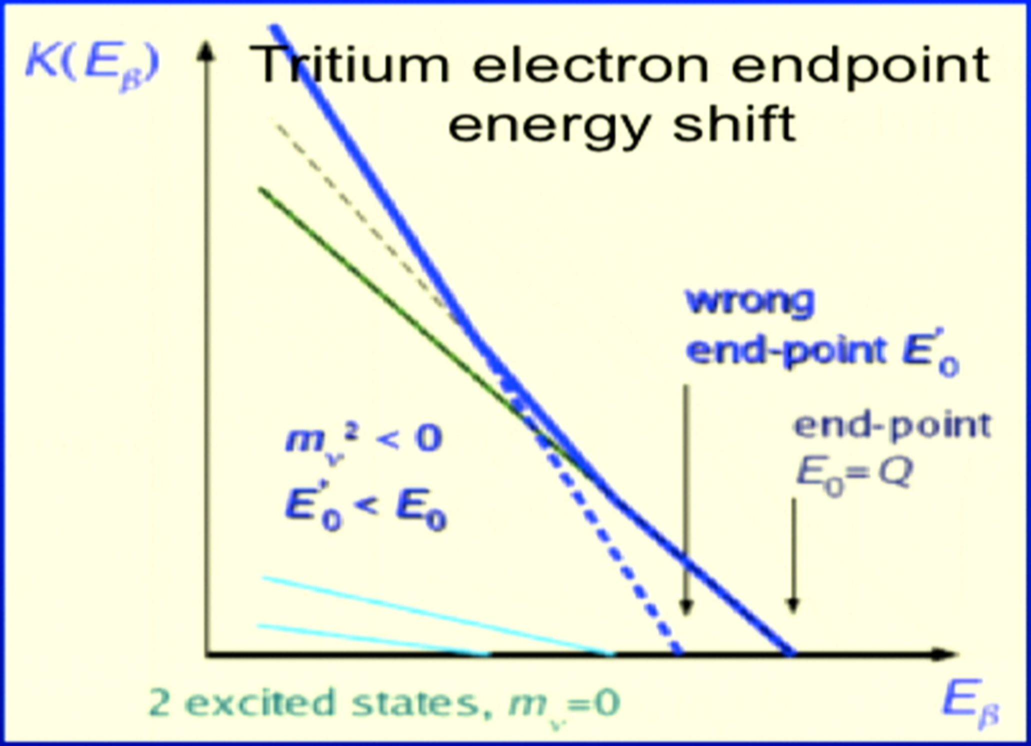
$$\boxed{T\text{-}T} \rightarrow \boxed{T\text{-}^3He}$$

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

He^3 Binding Energy Shift

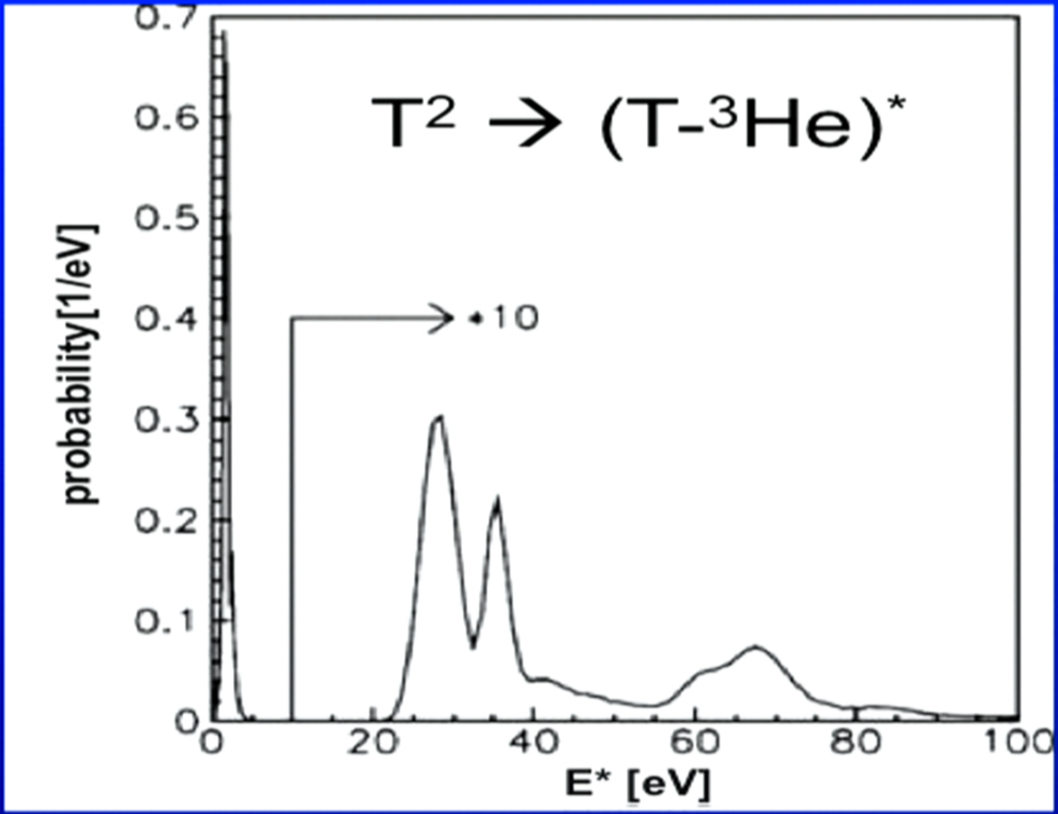
T-T → T-He^3 Level Diagram





Tritium electron endpoint energy shift

Energy Smearing from T-^{3}He Excitations

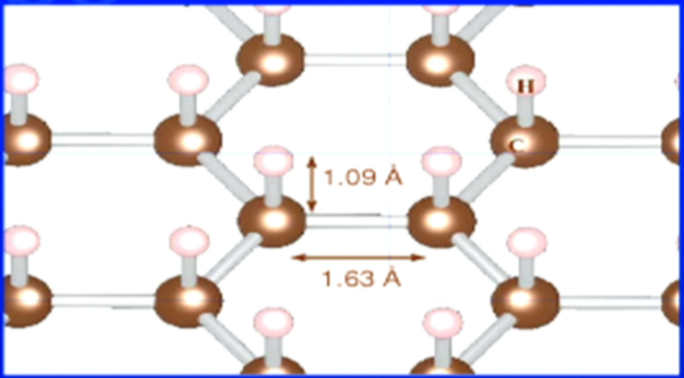


Diatomic T^2 excitation spectrum has ~3eV smearing for excited states below 10eV, making T^2 unsuitable for high resolution energy separation of beta-decays from relic neutrino capture.

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

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



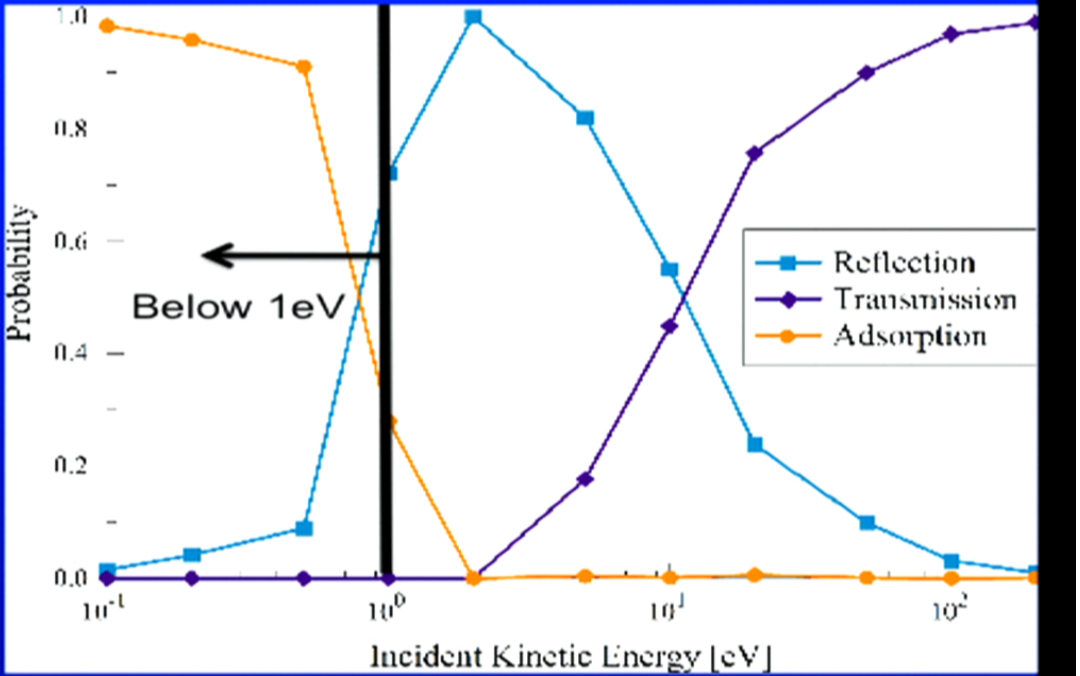
Single-sided-hydrogenated Graphene
- Planar (uniform bond length)
- Semiconductor (~Si gap)
- Polarized tritium(?)

~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

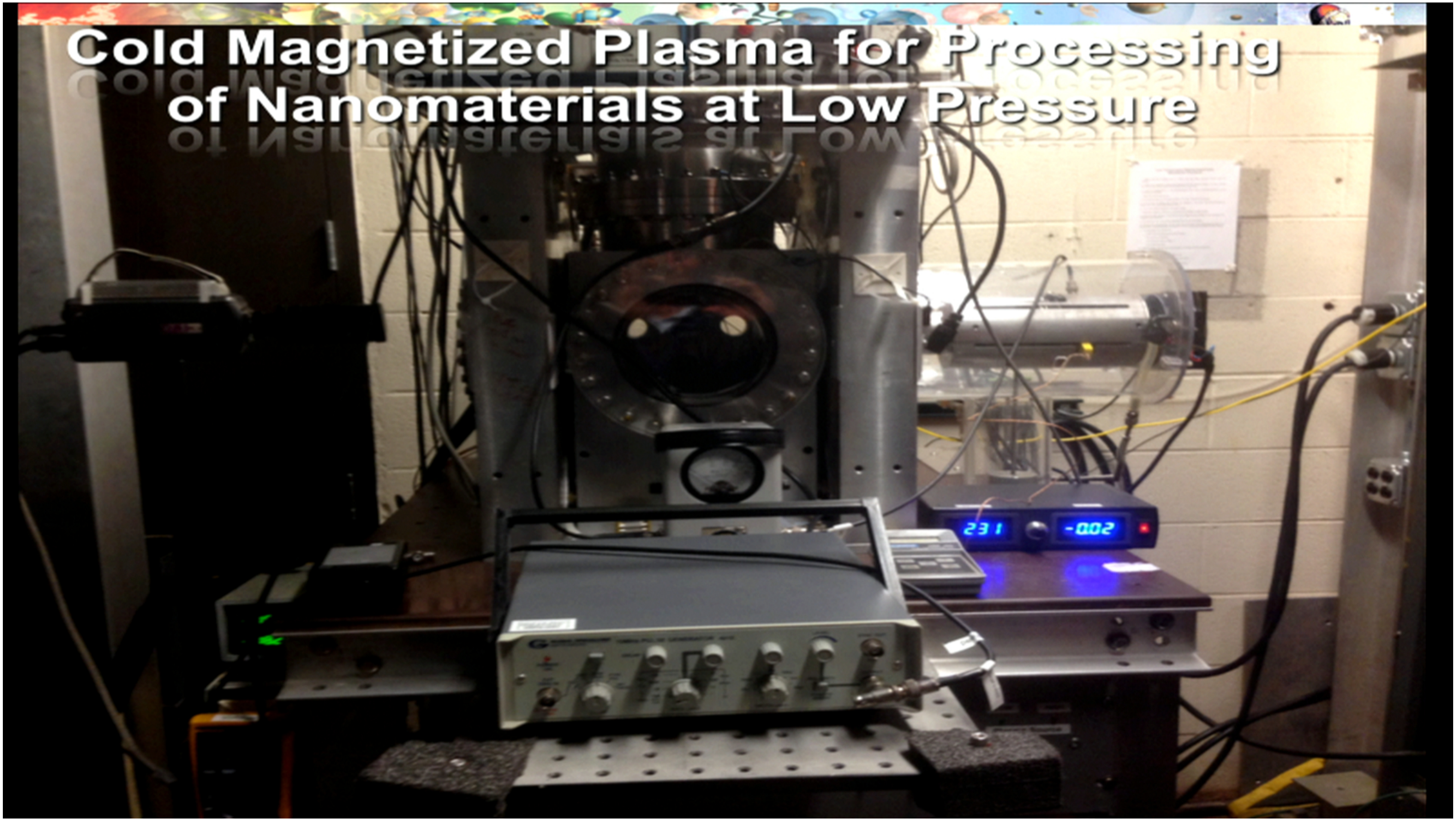
Tritium Loading

- 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



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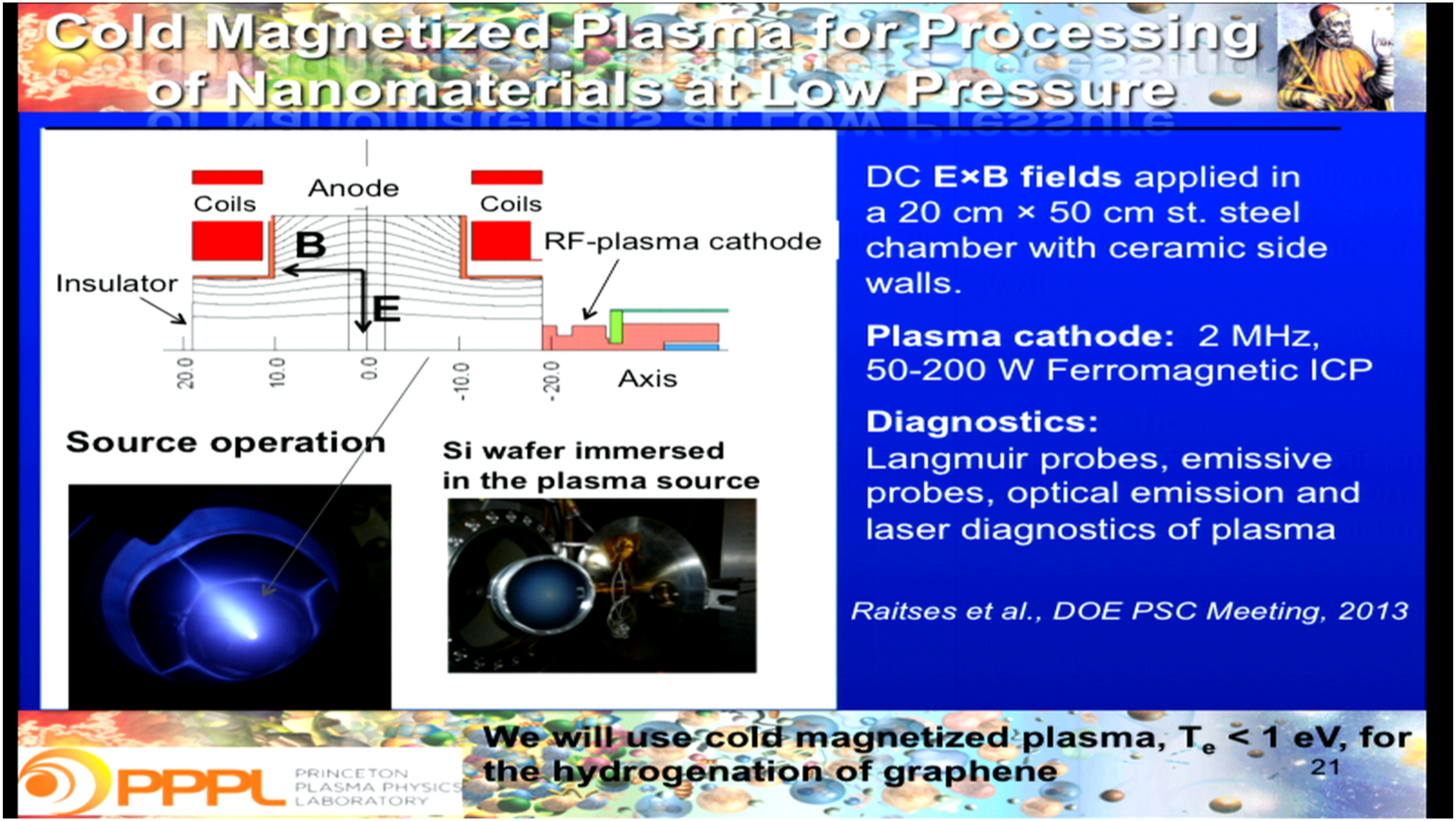

Source operation

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

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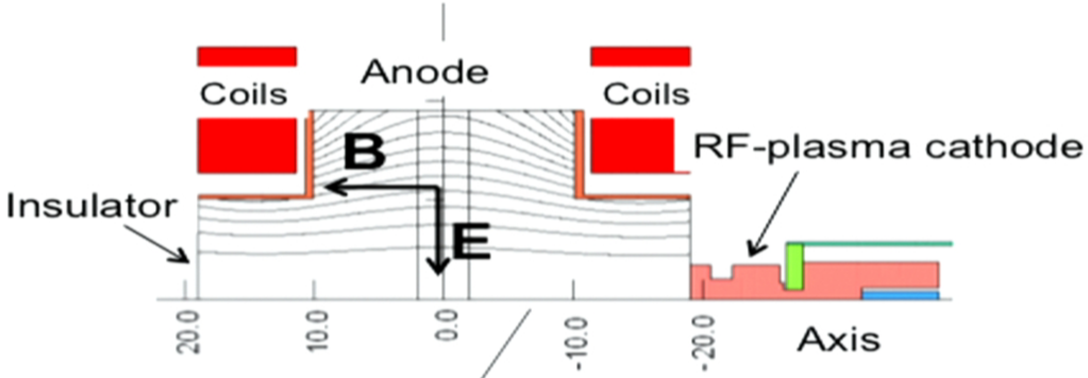
Cold Magnetized Plasma for Processing of Nanomaterials at Low Pressure



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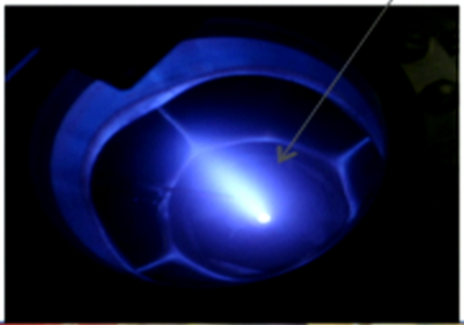

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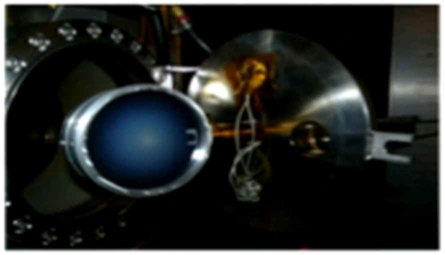

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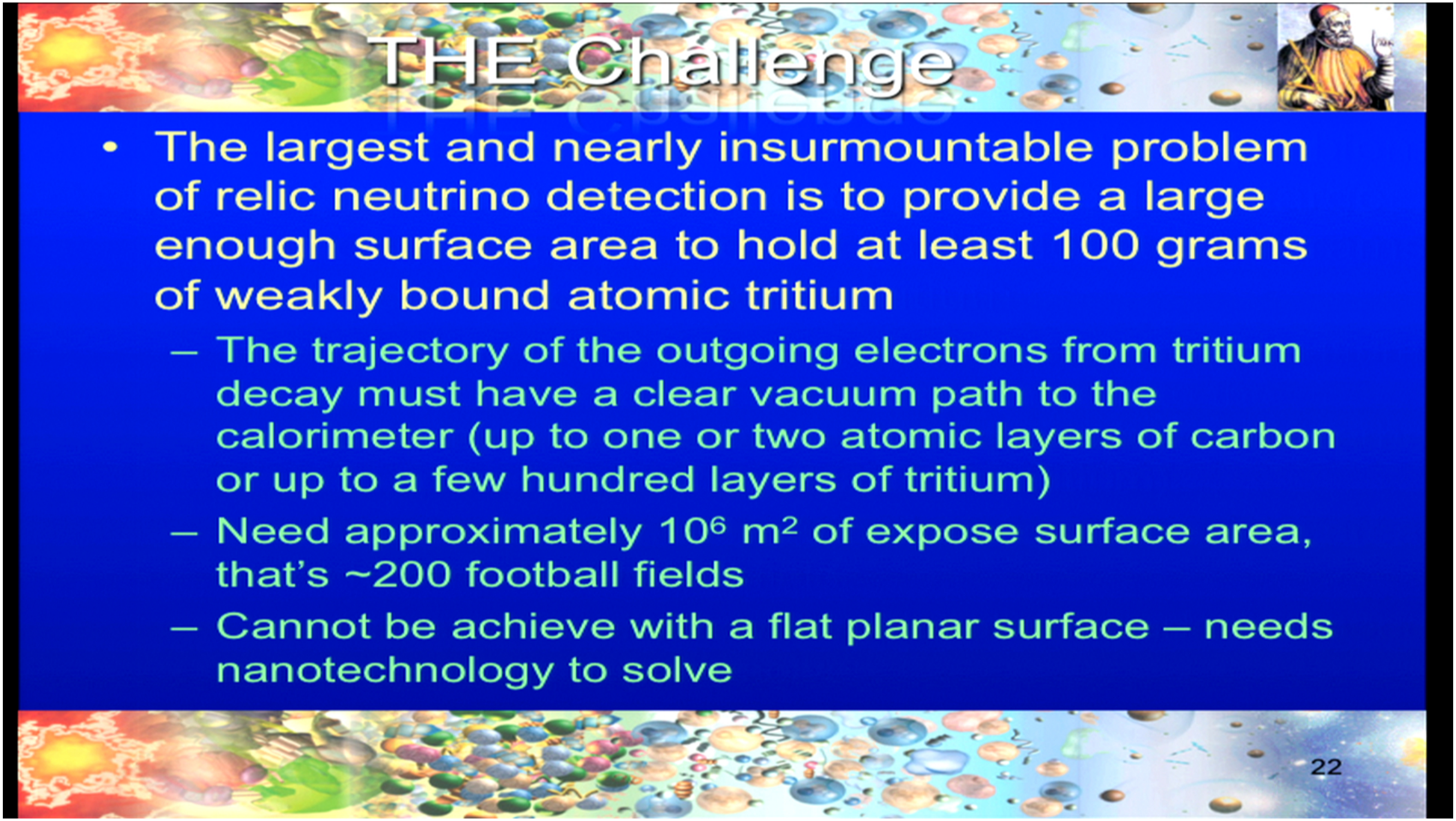
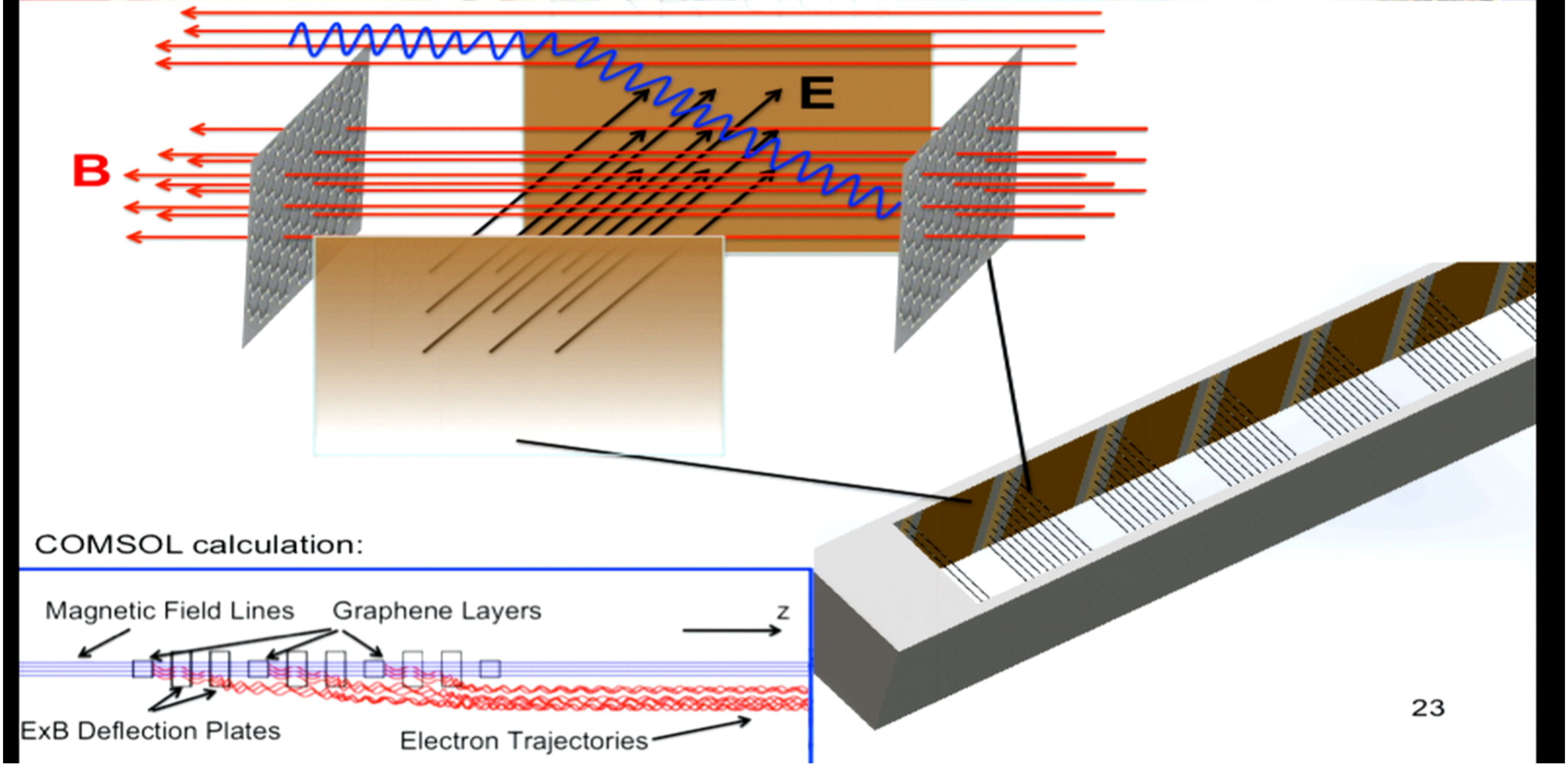


THE Challenge

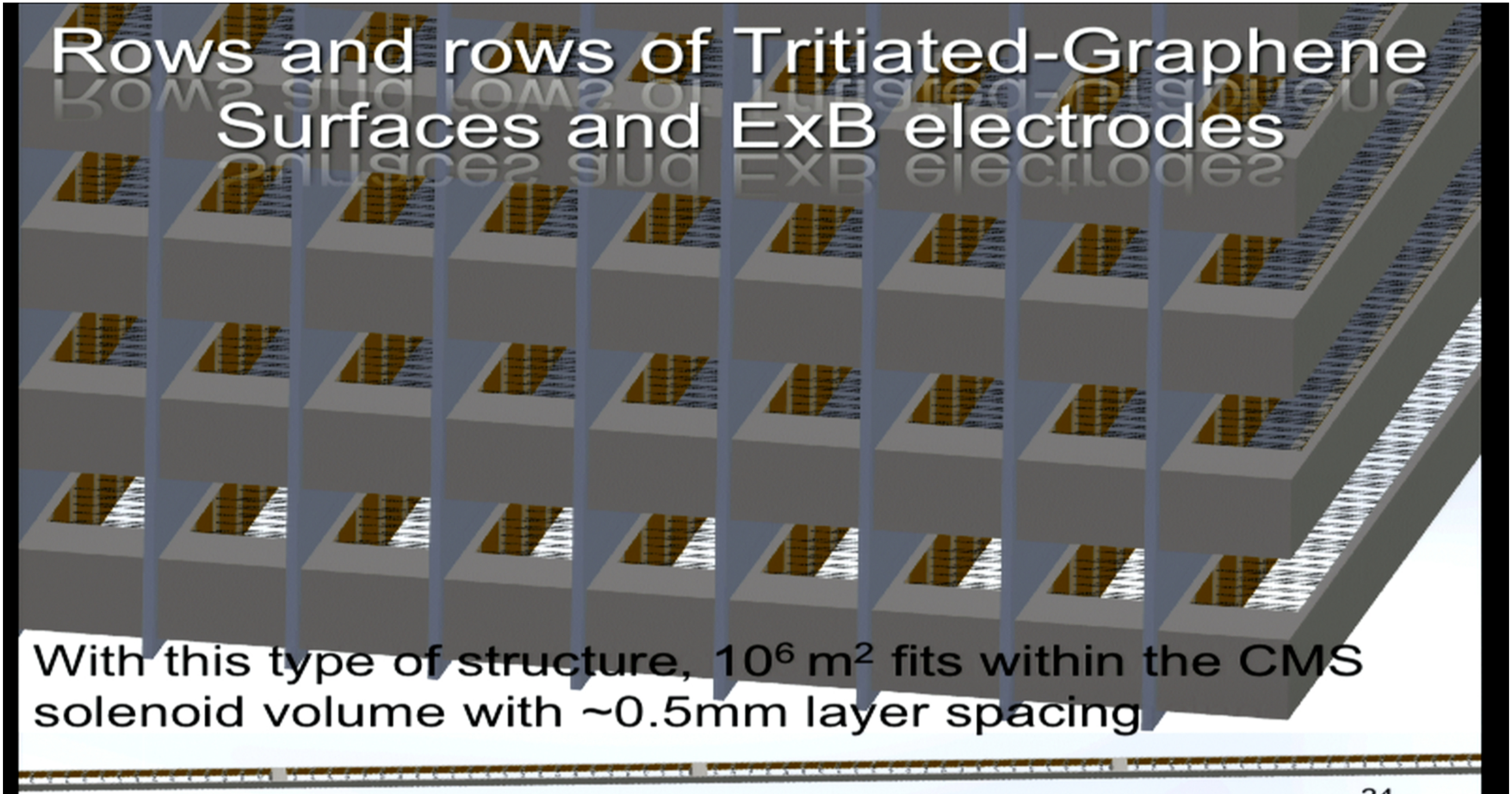
- The largest and nearly insurmountable problem of relic neutrino detection is to provide a large enough surface area to hold at least 100 grams of weakly bound atomic tritium
  - The trajectory of the outgoing electrons from tritium decay must have a clear vacuum path to the calorimeter (up to one or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

ExB drift

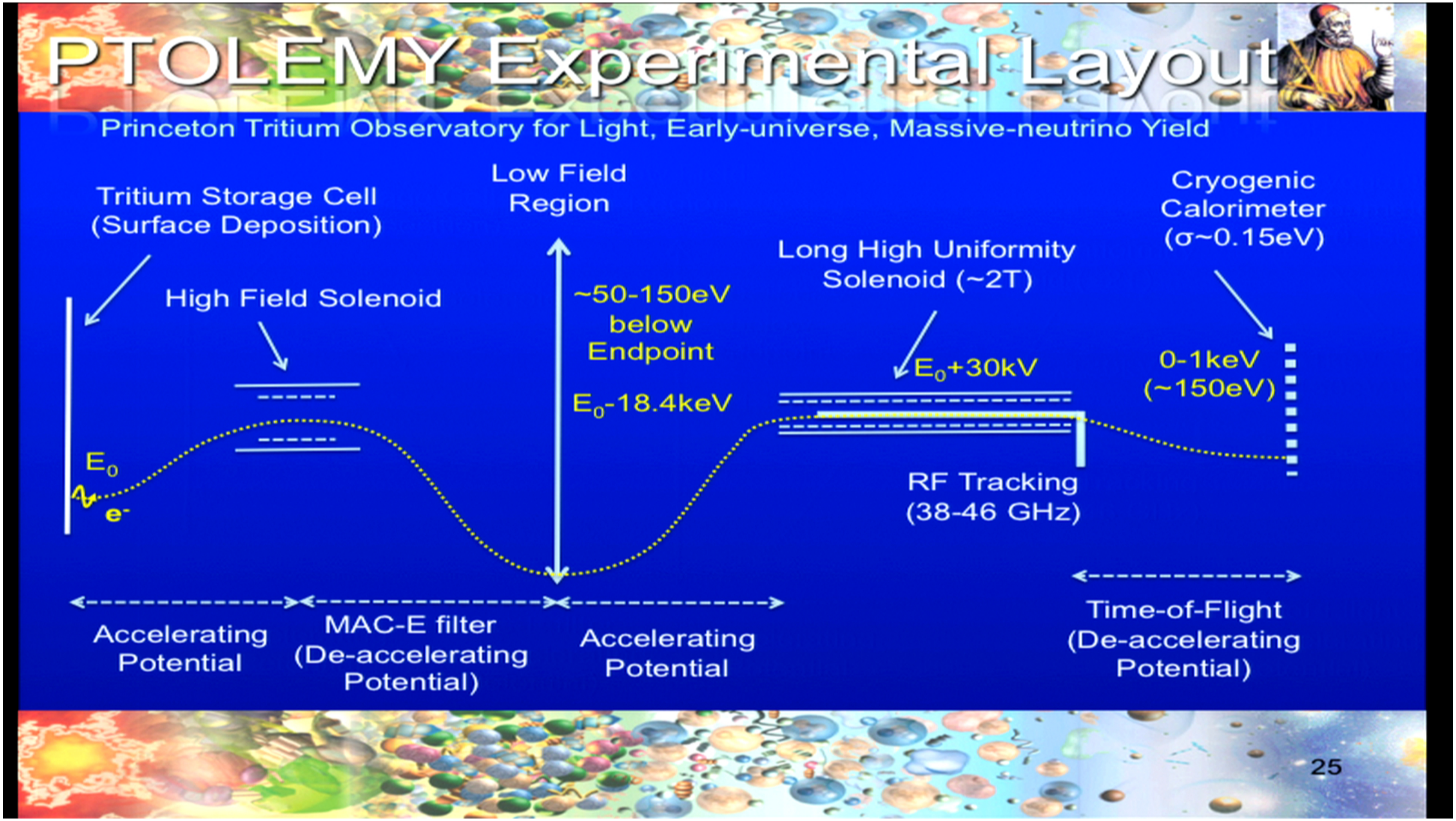


COMSOL calculation:

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



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

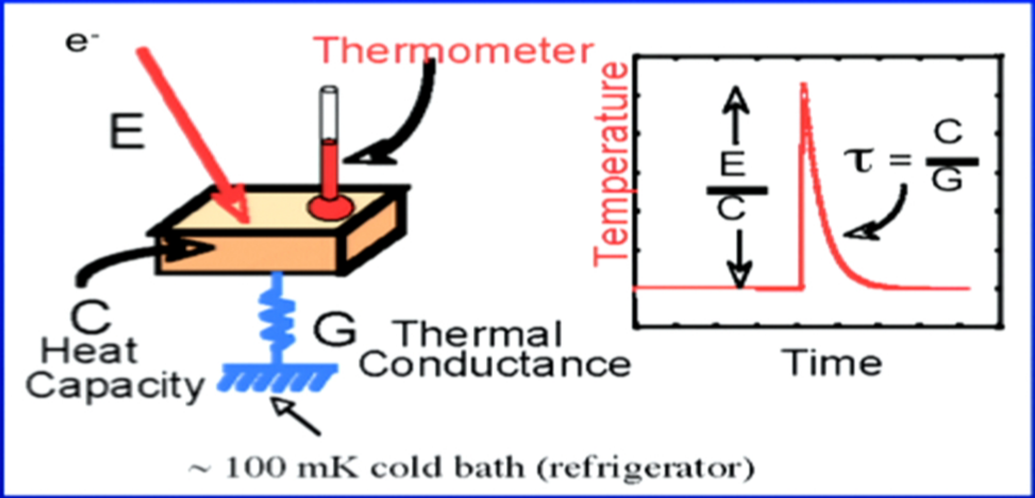
MAC-E filter
(De-accelerating
Potential)

Accelerating
Potential

Time-of-Flight
(De-accelerating
Potential)

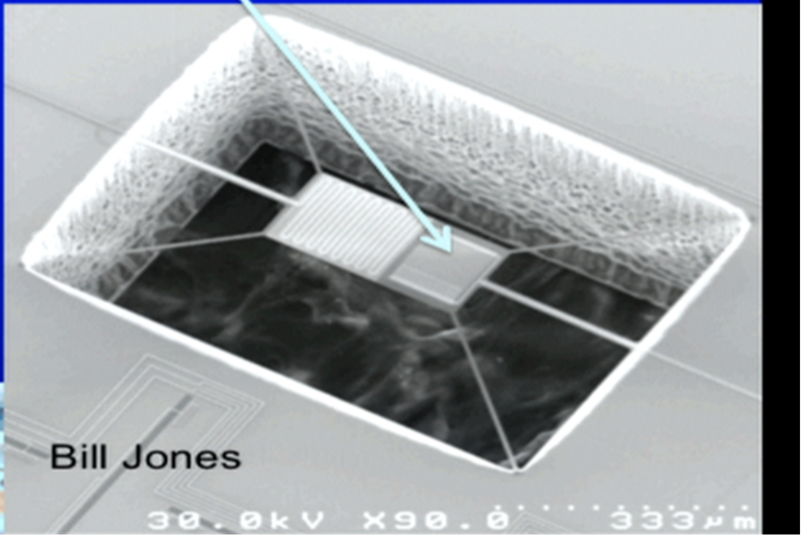
Transition-Edge Sensors for Calorimetry

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



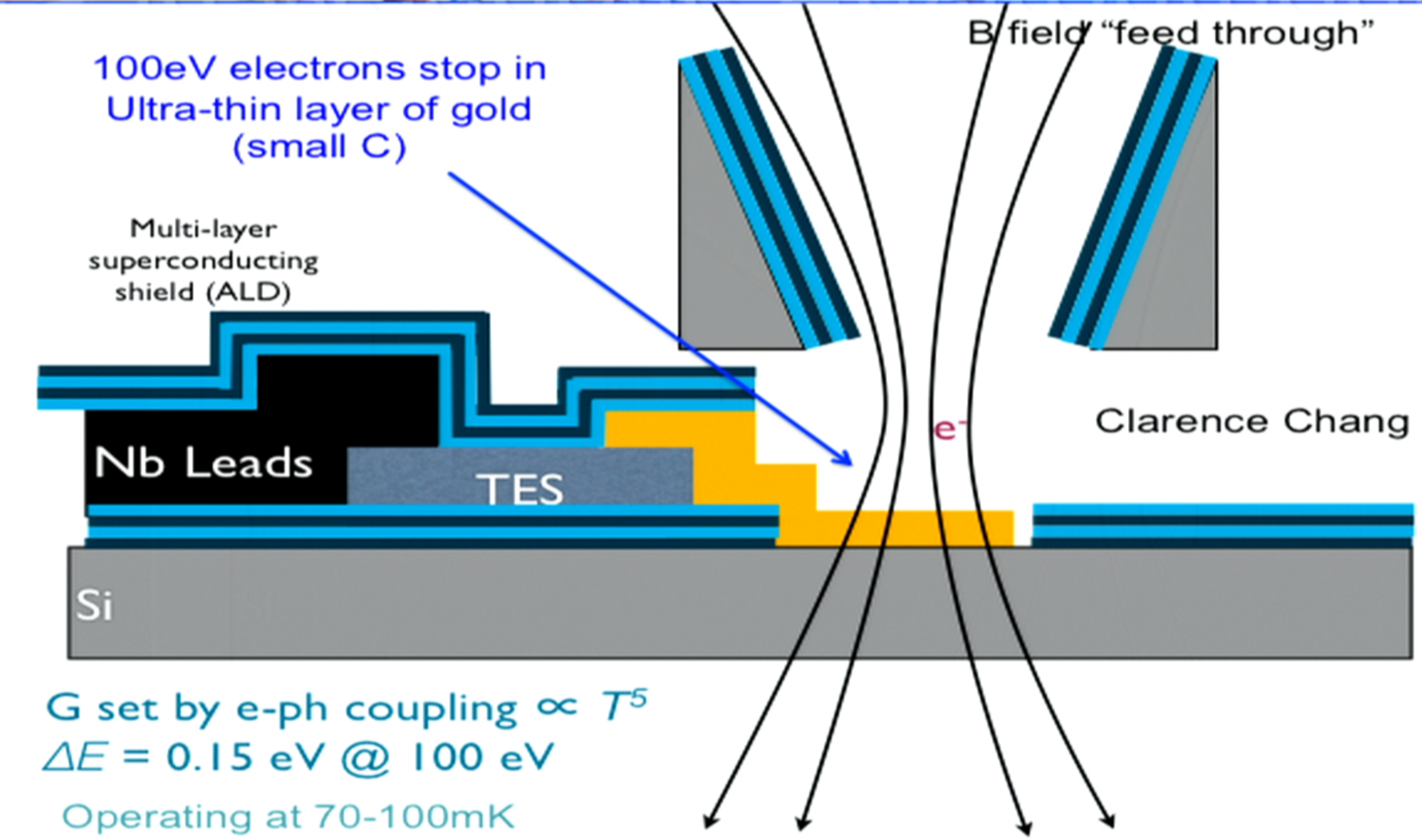
100eV electron can be stopped with very small C

(example) SPIDER Island TES



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

TES in Magnetic Environment



G set by e-ph coupling ∝ T^5

ΔE = 0.15 eV @ 100 eV

Operating at 70-100mK

Calorimeter Energy Resolution

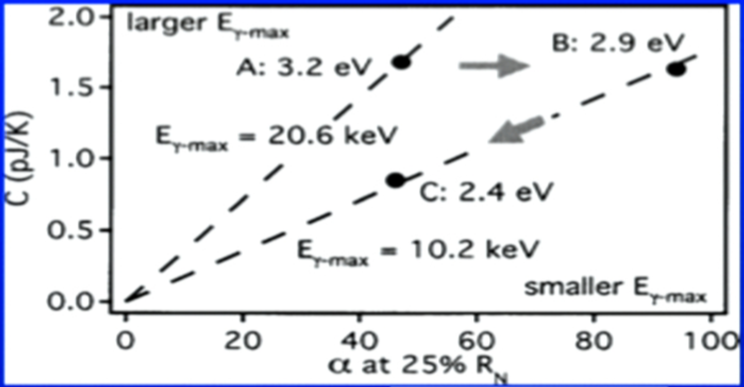
$$\Delta E_{\rm FWHM} = 2.355\sqrt{(4k_b T_c^2 C/\alpha)}\sqrt{(1+M^2)n/2}$$

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/α) controlled by normal regions and magnetic field.

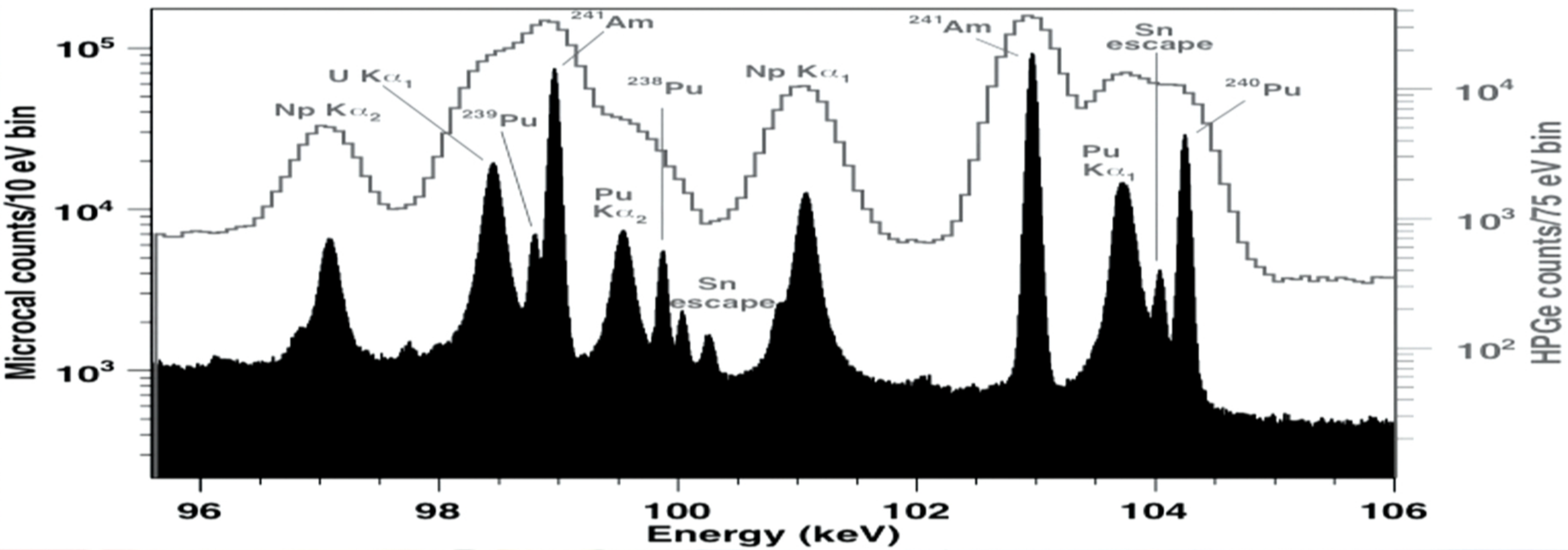
Au is not ideal as it doesn't stick well for thin layers,
Alternative materials would be studied (15nm of Bi)

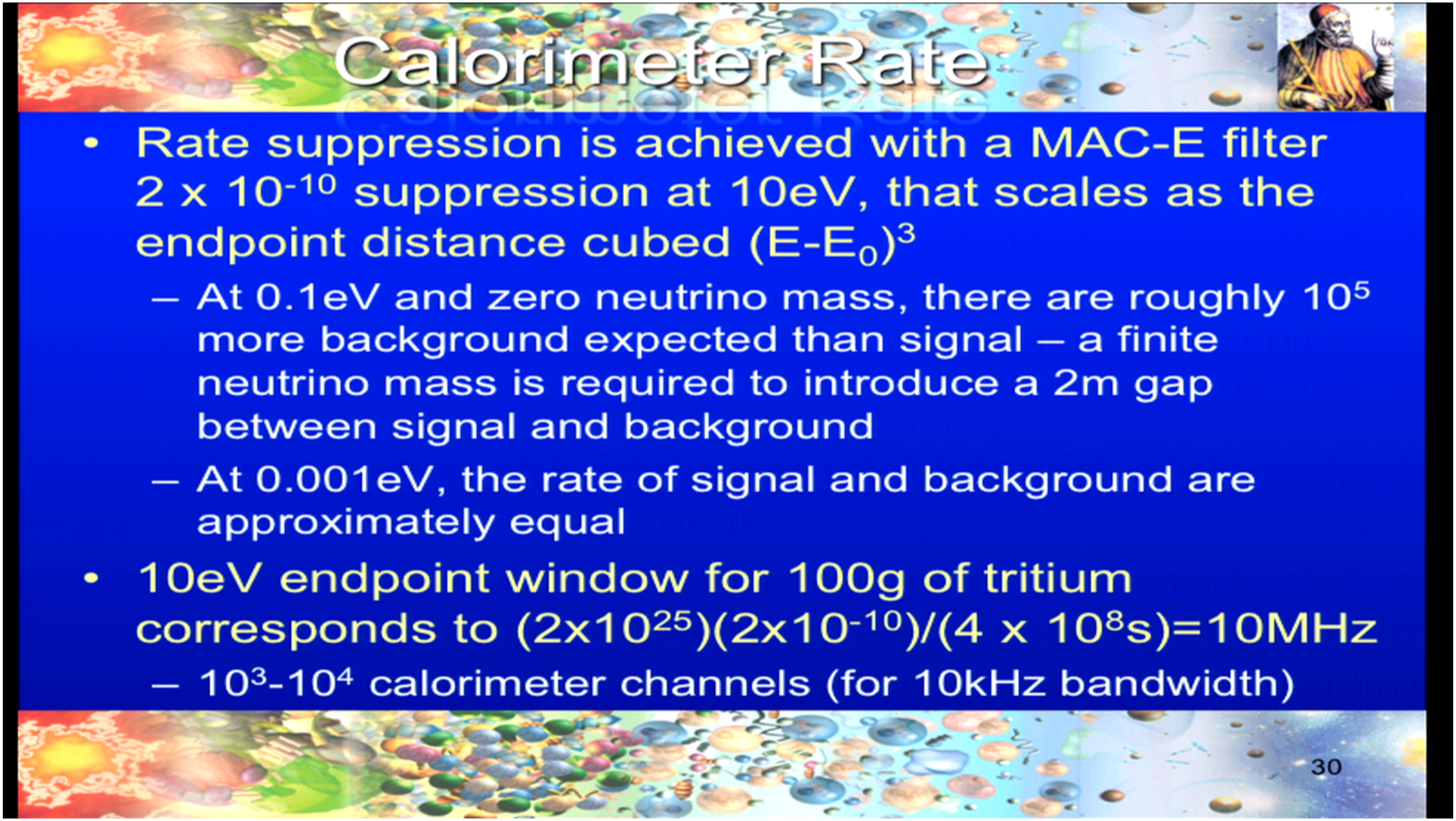
Clarence Chang

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

Microcalorimeter Resolution

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





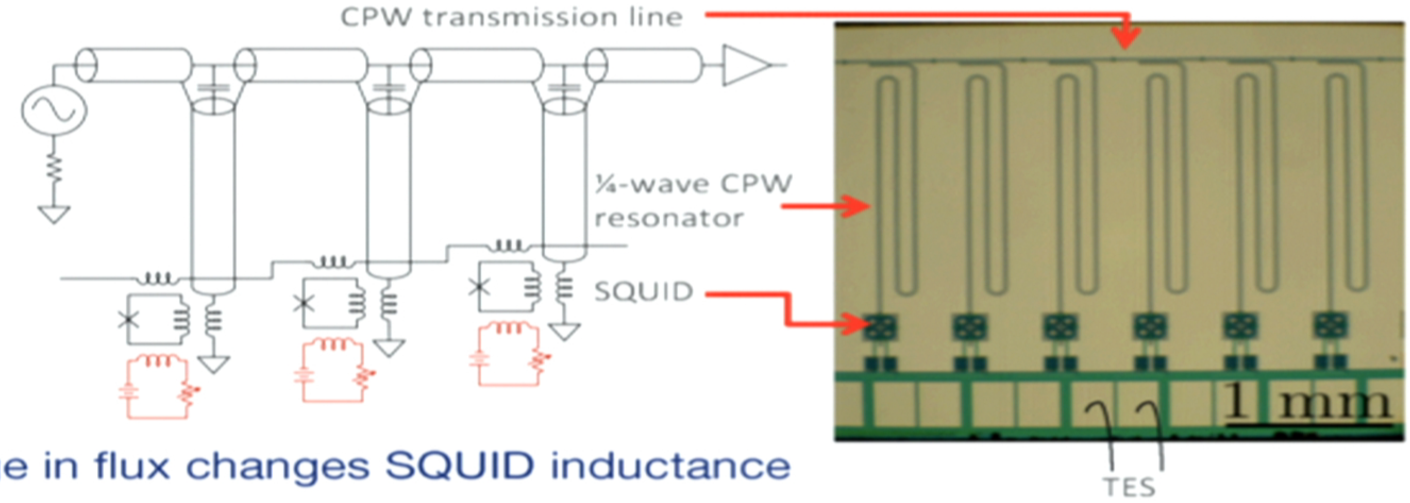
Calorimeter Rate

- 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)

Highly Multiplexed SQUID Readout

Microwave-readout Massive SQUID Multiplexer

Clarence Chang



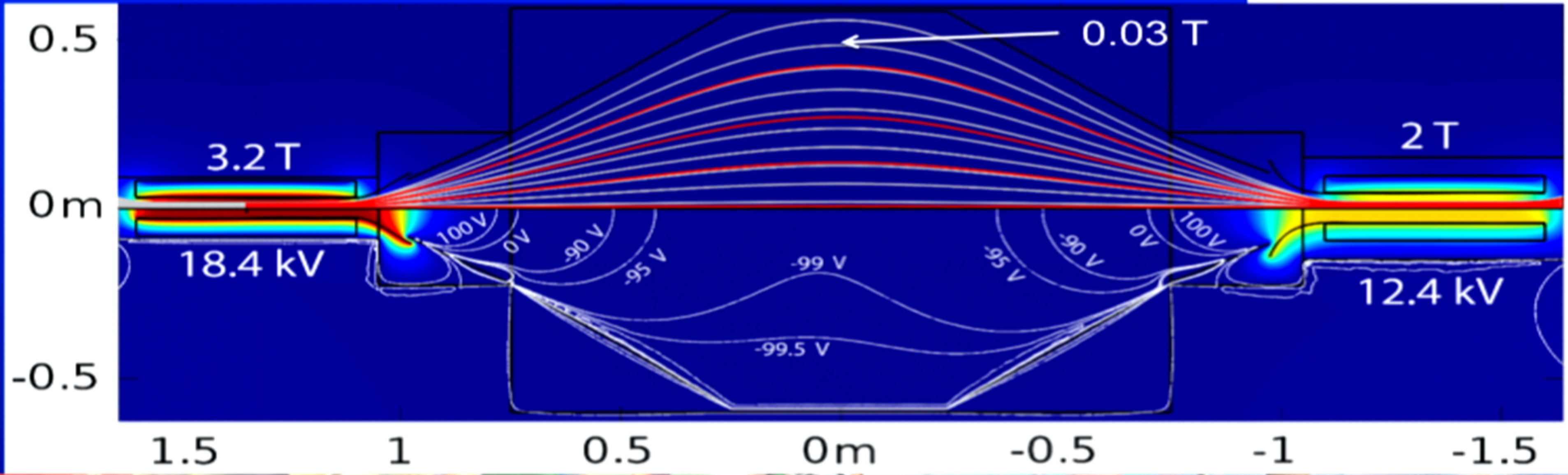
- Change in flux changes SQUID inductance
- at 1-10 GHz, can support ~1 MHz of bandwidth with ~1000 channels per line
- Originally developed for CMB measurements, recently demonstrated successful operation with X-ray u-cals

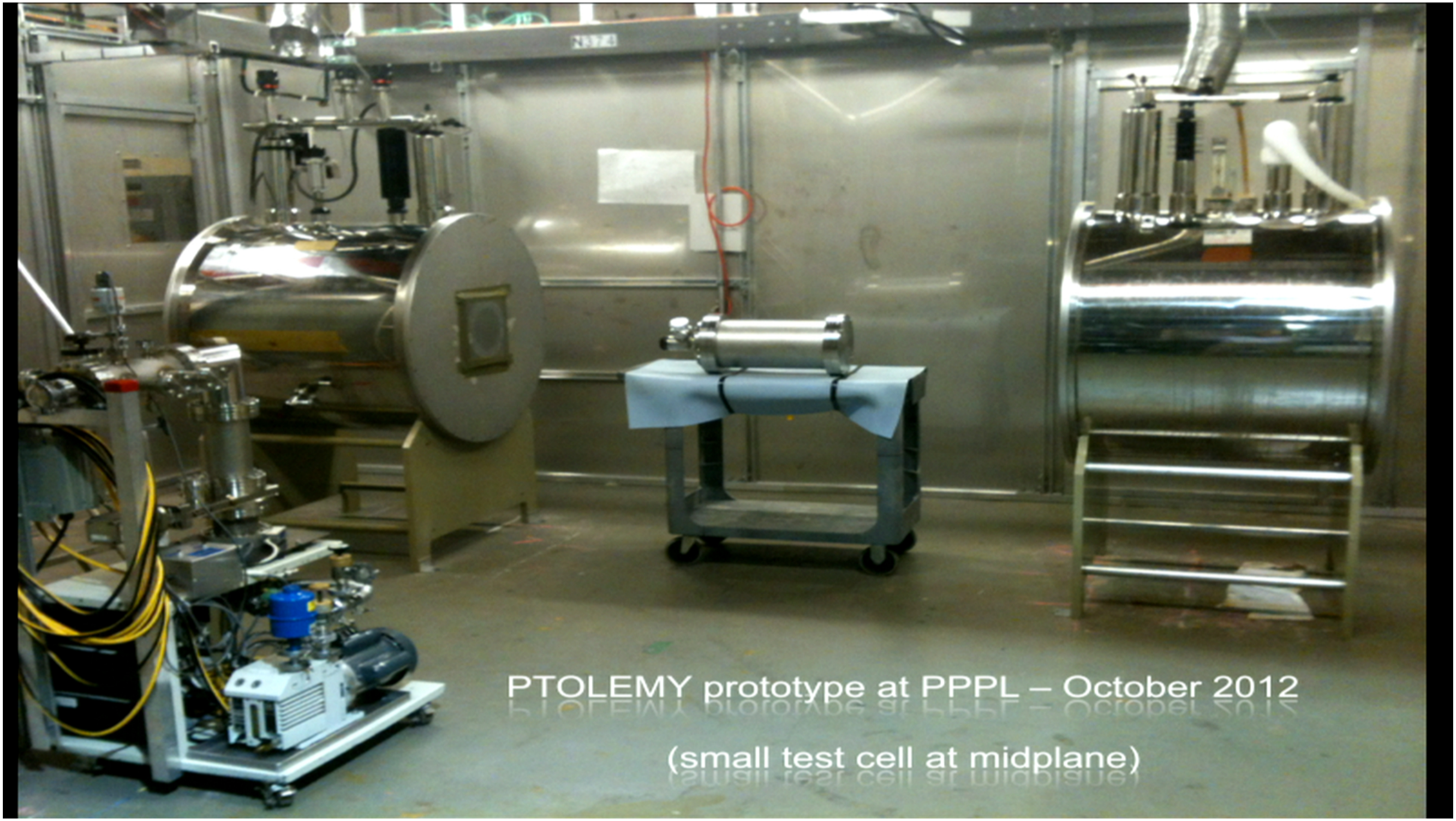
Kent Irwin

PTOLEMY MAC-E filter

- MAC-E filter cutoff of 10^{-2} to 10^{-3} precision on electron energy
  - Energy window below endpoint needed for 2π acceptance ~150eV
  - Voltage of filter cut-off accurate to ~1eV
  - Planar cell aperture of ~30cm² within 3.2T bore

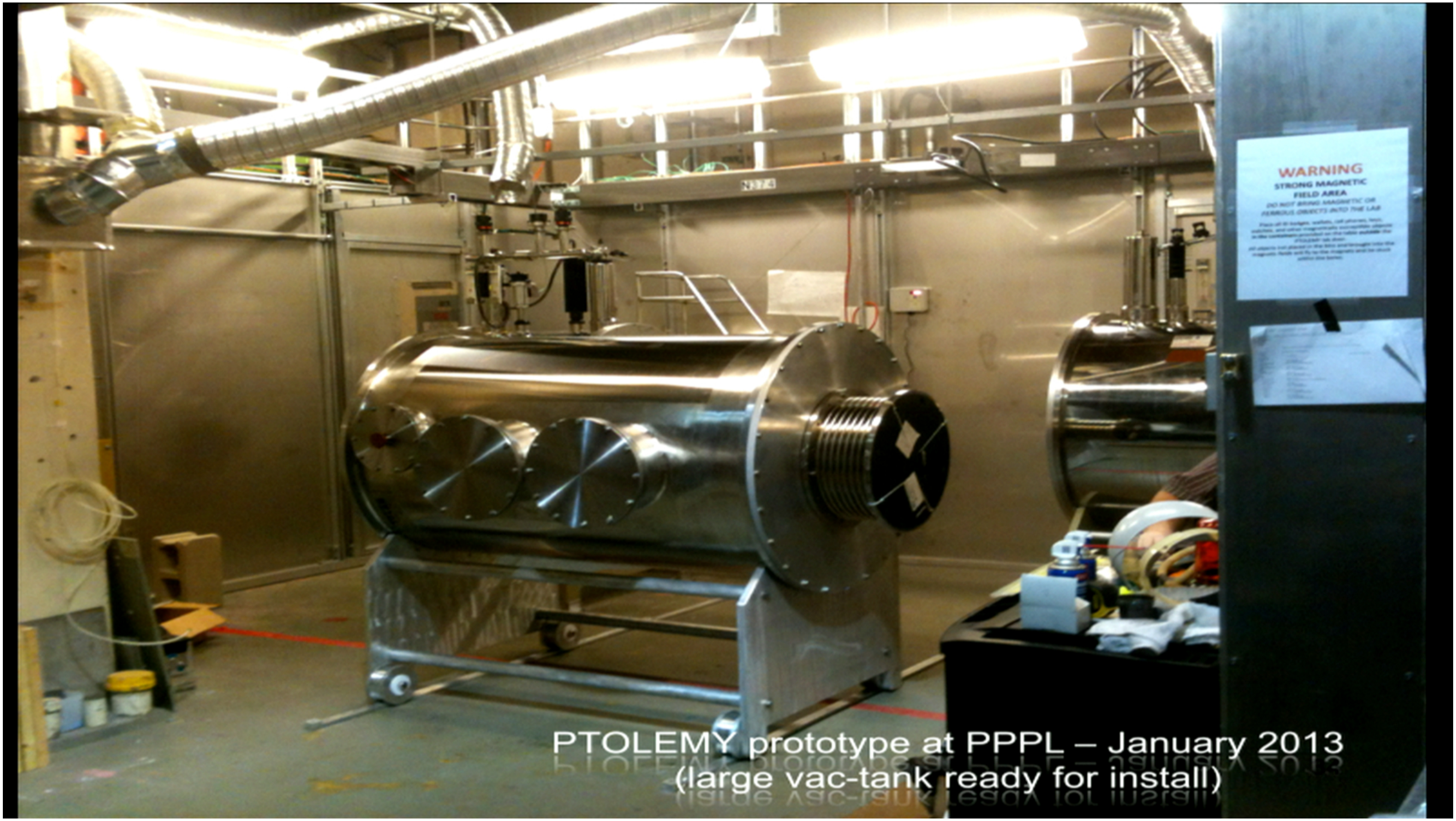
Adiabatic Invariant: $\mu = \frac{E^{\perp}}{B}$





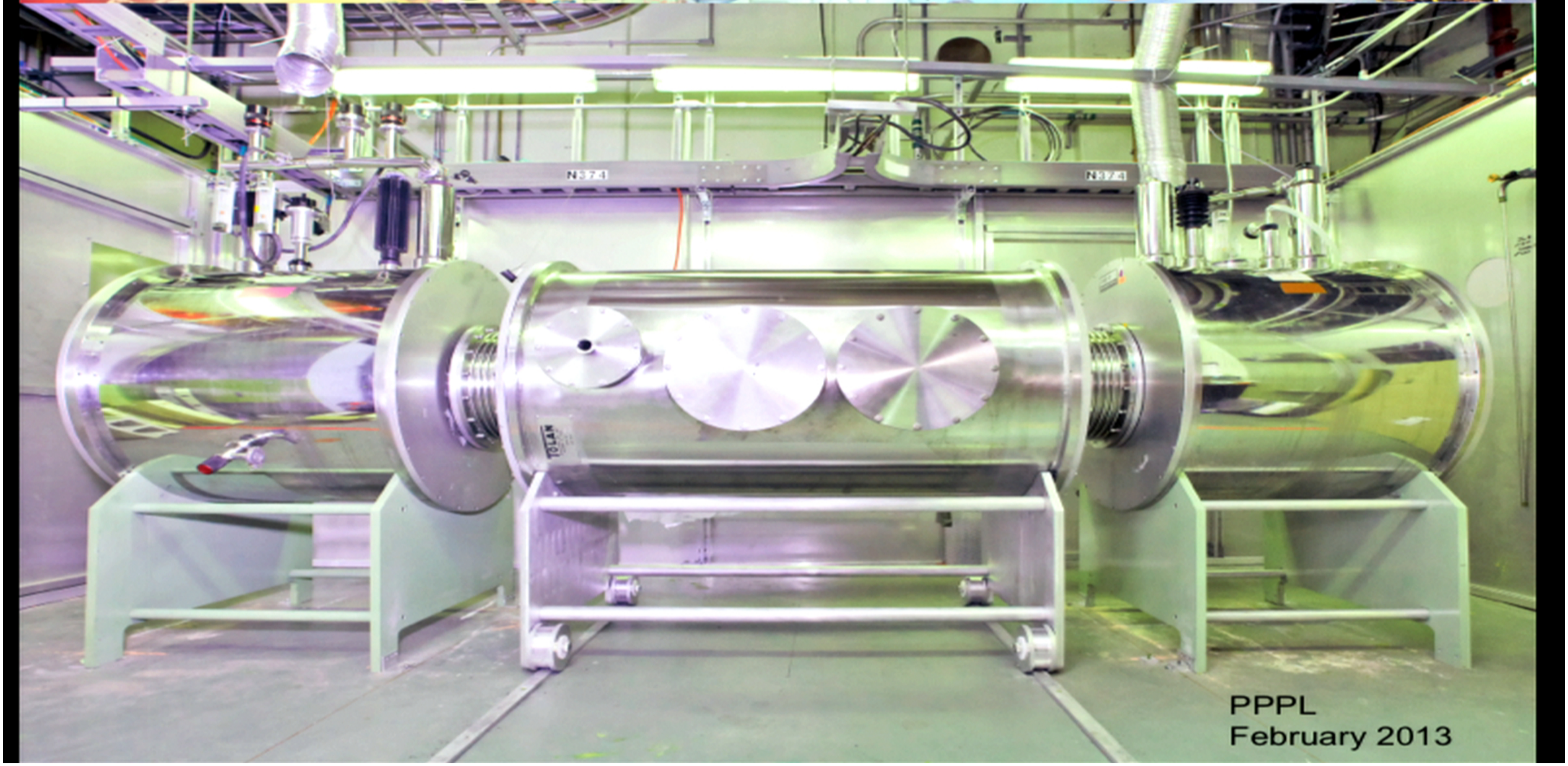
PTOLEMY prototype at PPPL – October 2012

(small test cell at midplane)

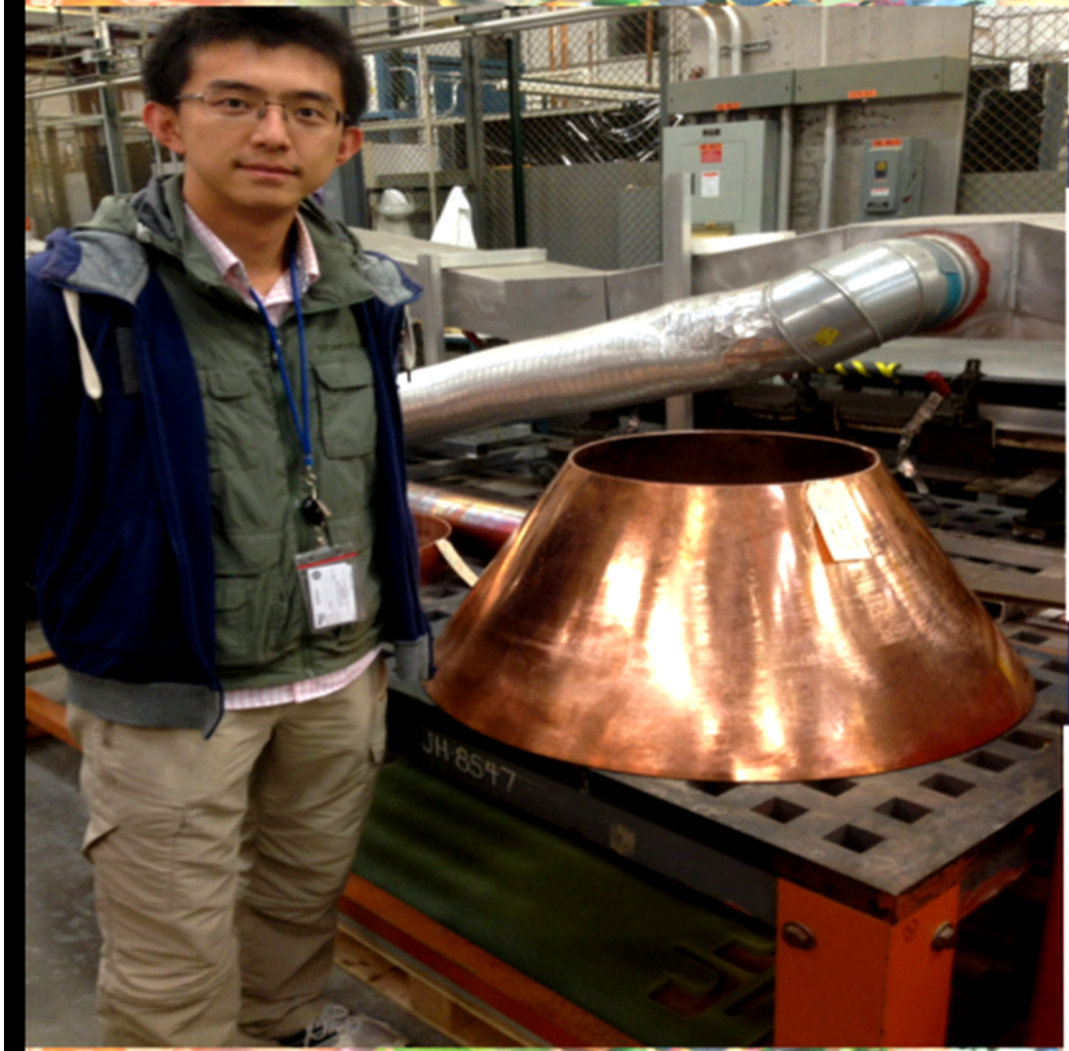


PTOLEMY prototype at PPPL – January 2013
(large vac-tank ready for install)

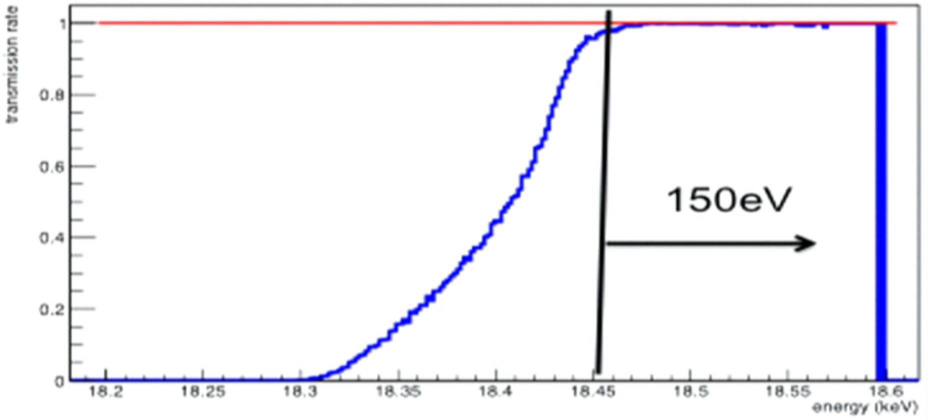
PTOLEMY



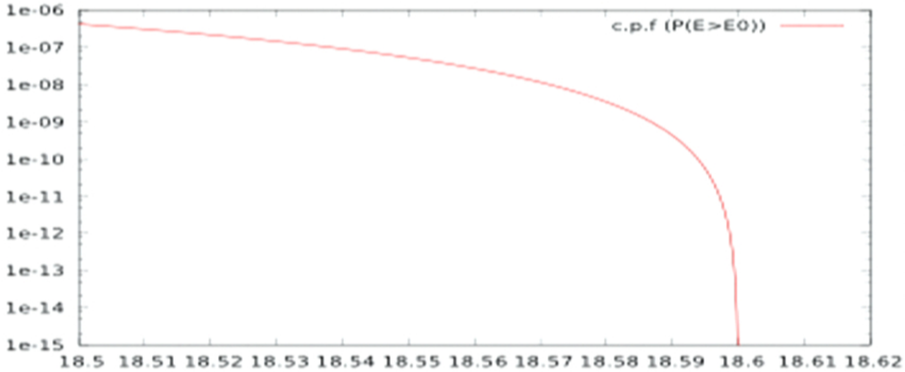
PPPL
February 2013



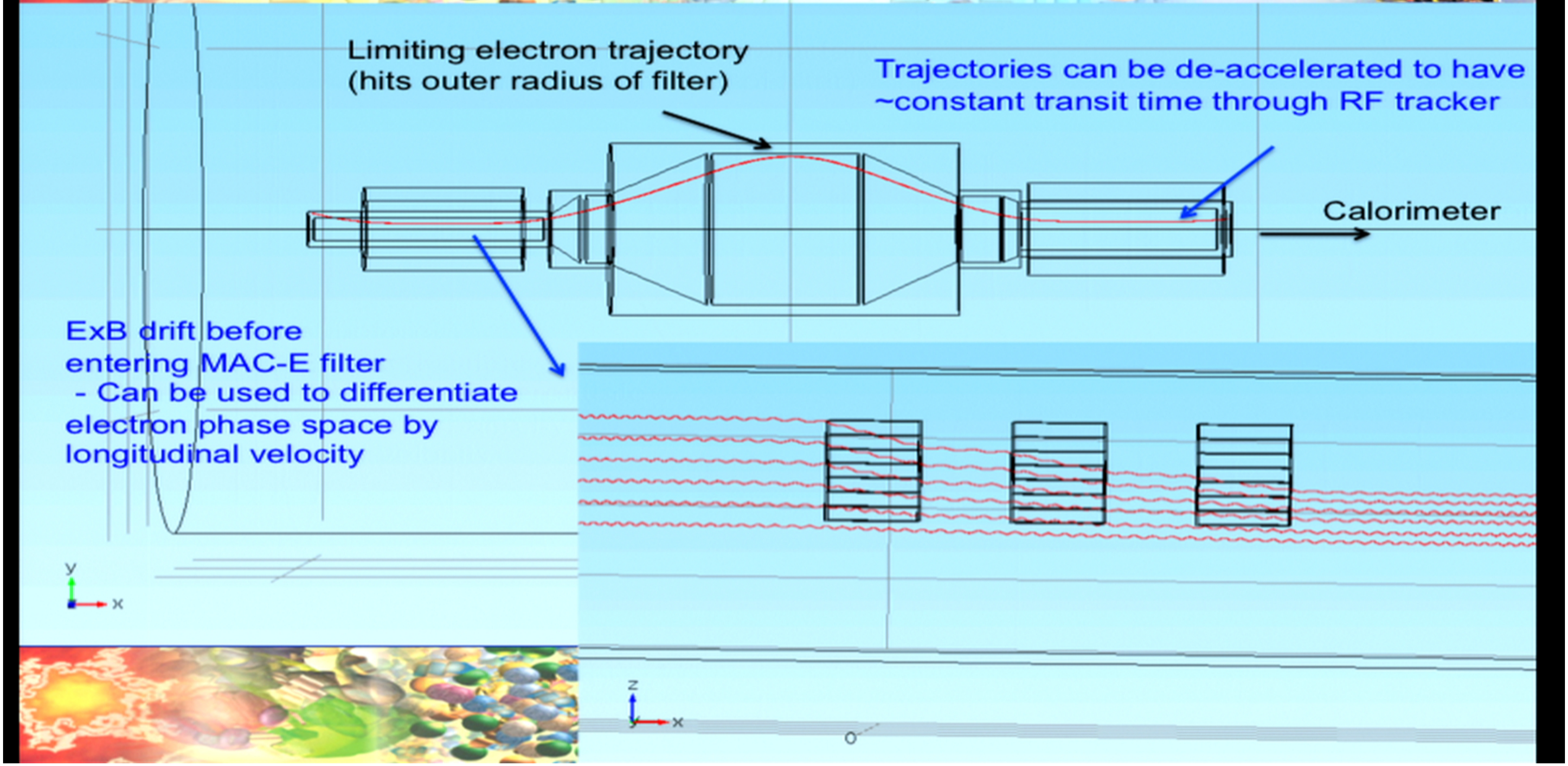
MAC-E Filter Transmission curve



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



ExB and MAC-E Filter



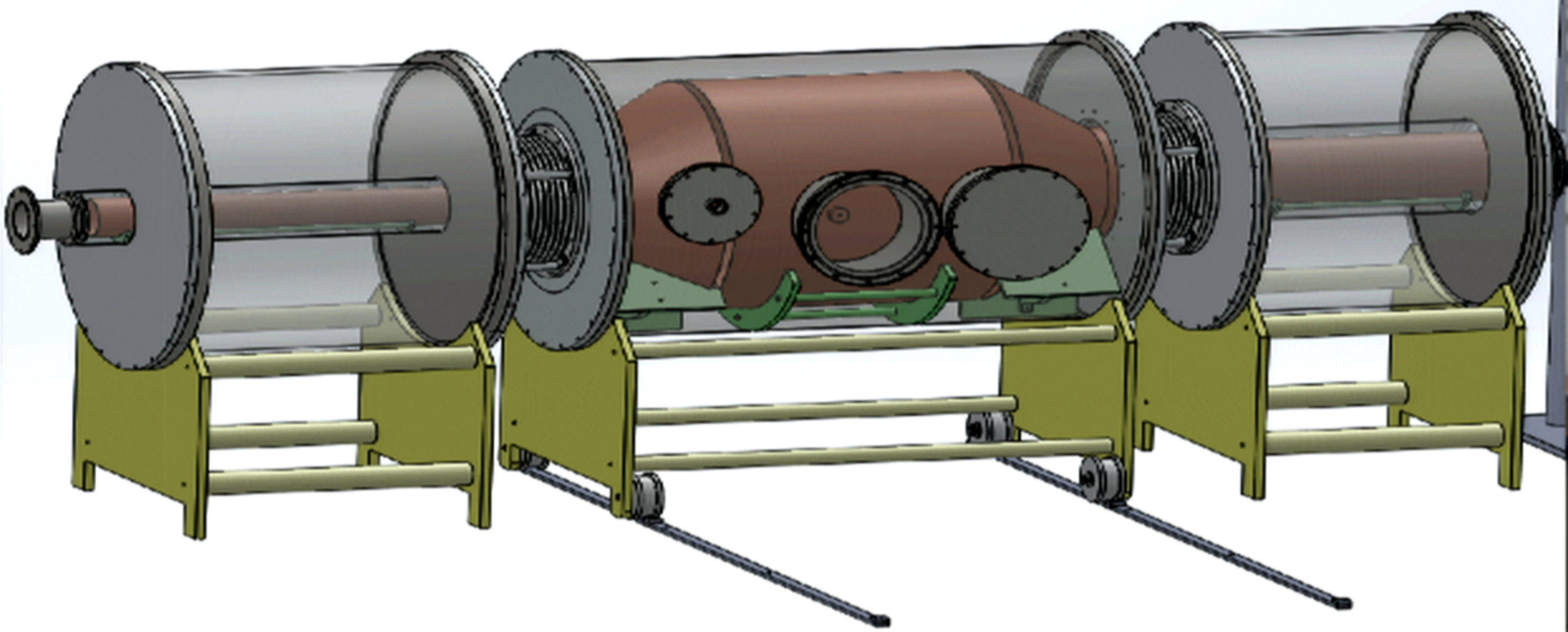
Limiting electron trajectory (hits outer radius of filter)

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

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

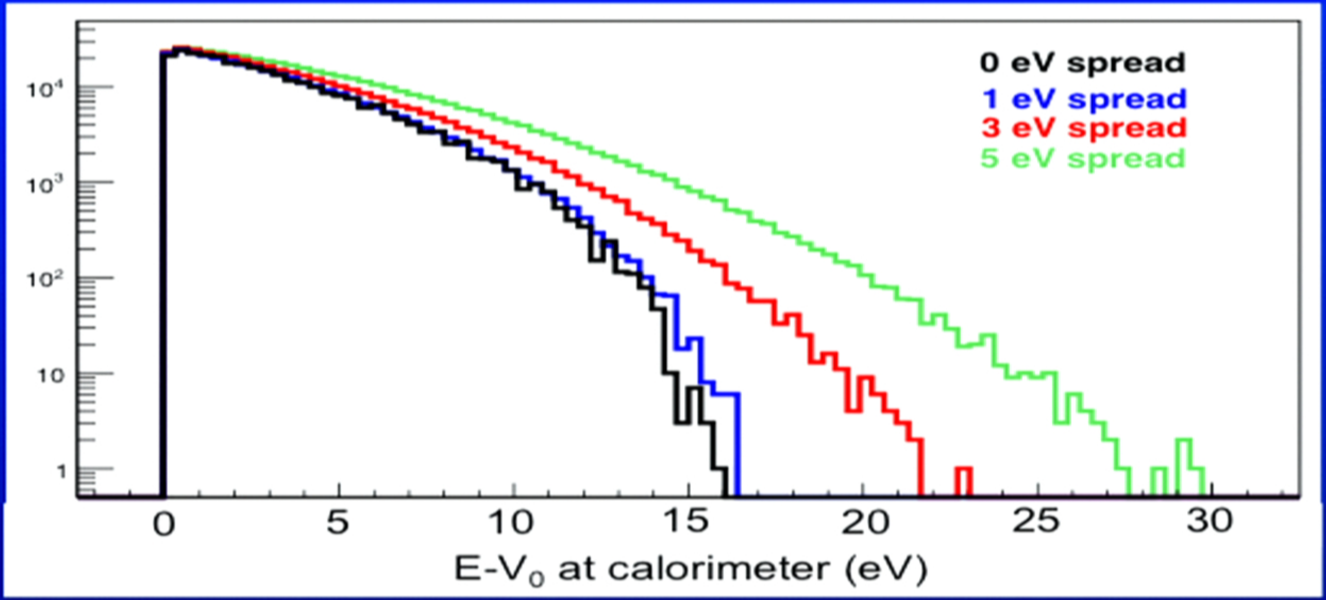
Calorimeter Interface to MAC-E Filter

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



Sensitivity to Shifts and Smearing

Energy Smearing (T^2 scales)

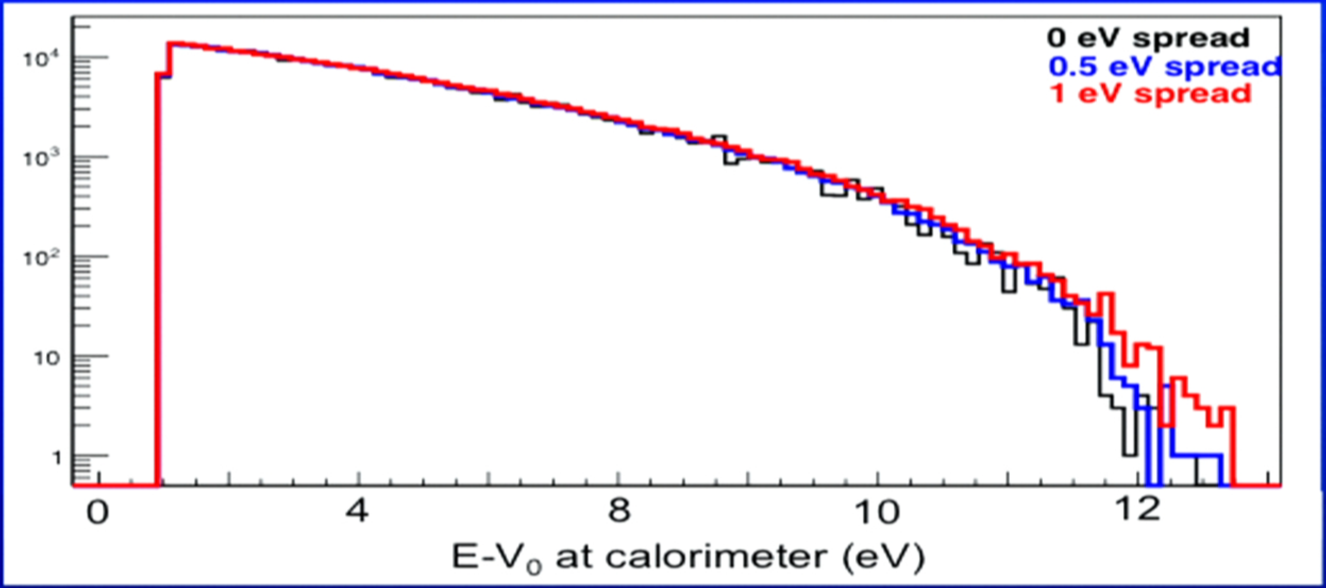


~10^{14} electrons from GEANT4 simulation (perfect resolution, ~1 month of data with 1μg ^3H)

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

Sensitivity to Shifts and Smearing

Sub-eV Energy Smearing



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

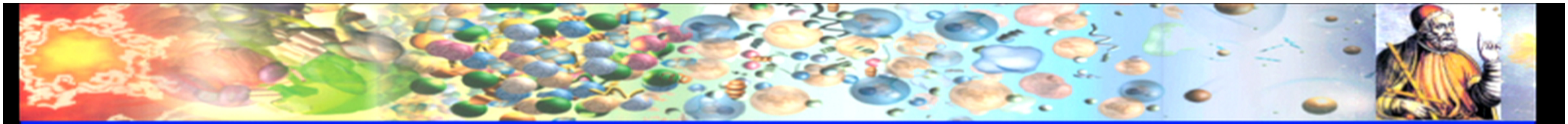
Goals: Measure relative endpoint shifts of graphene and T^2 and determined relative energy smearing

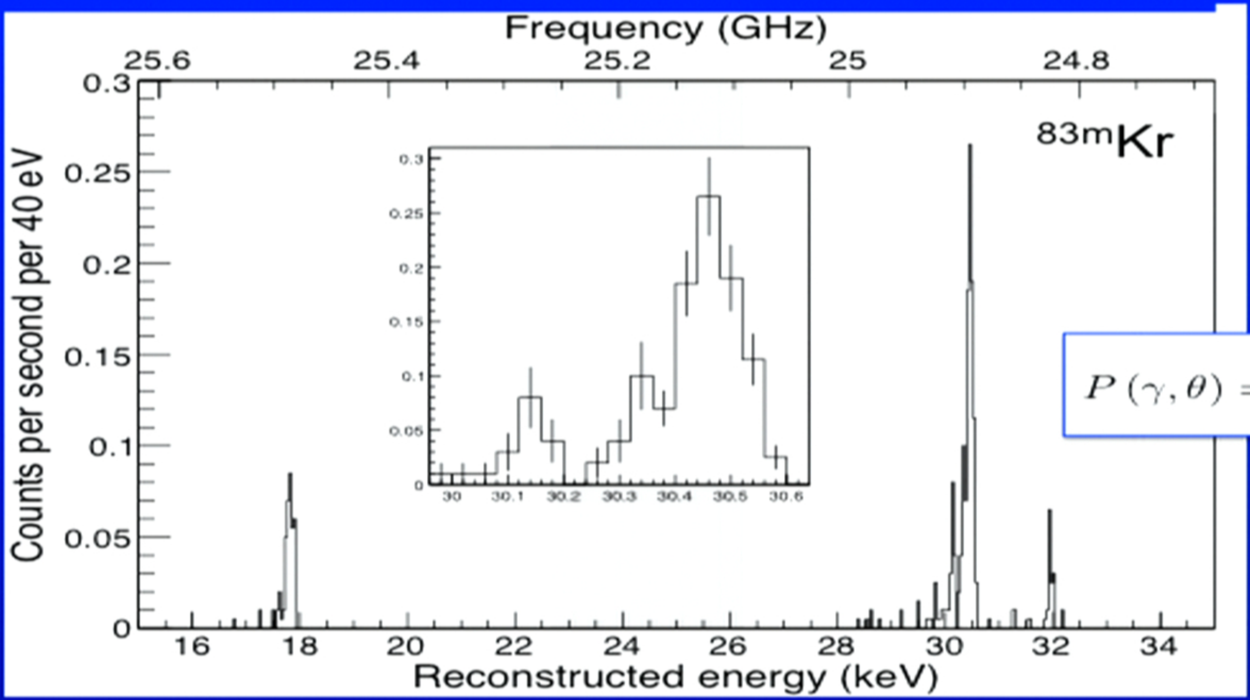
Semi-relativistic Electron Identification

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 $\times10^{-5}$ 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), working on integration with calorimeter dewar for 4K readout temperature

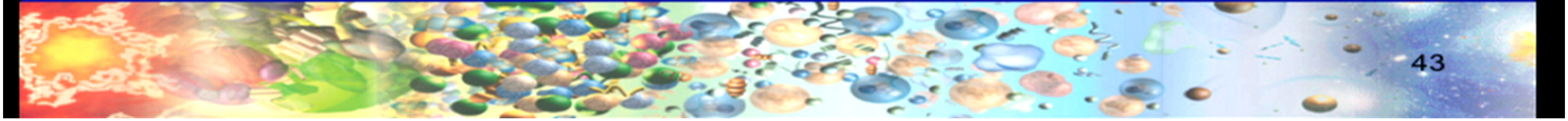




$$f_\gamma \equiv \frac{f_c}{\gamma} = \frac{eB}{2\pi\gamma m_e}$$

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

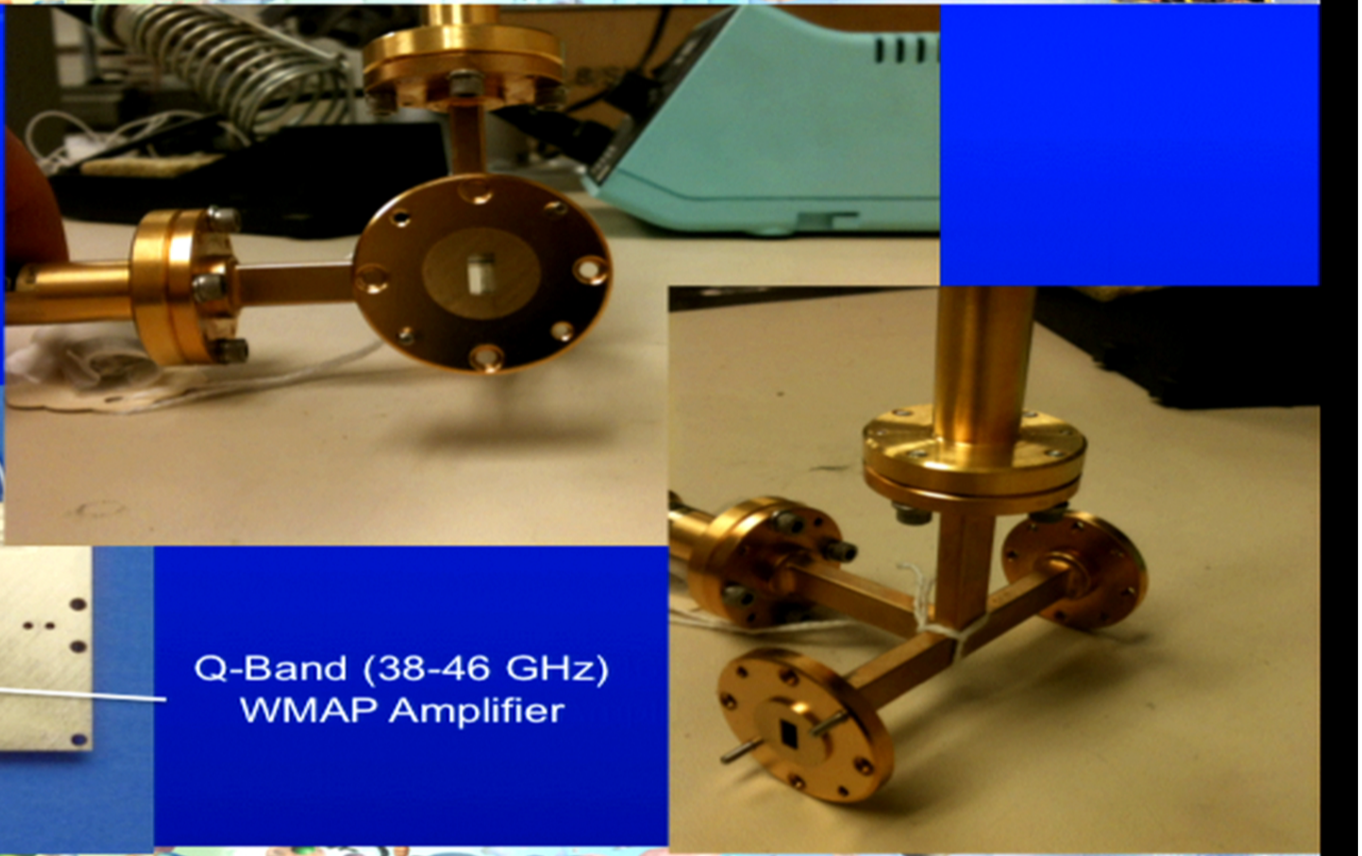
Asner et al., “Single electron detection and spectroscopy via relativistic cyclotron radiation”, arXiv:1408.5362

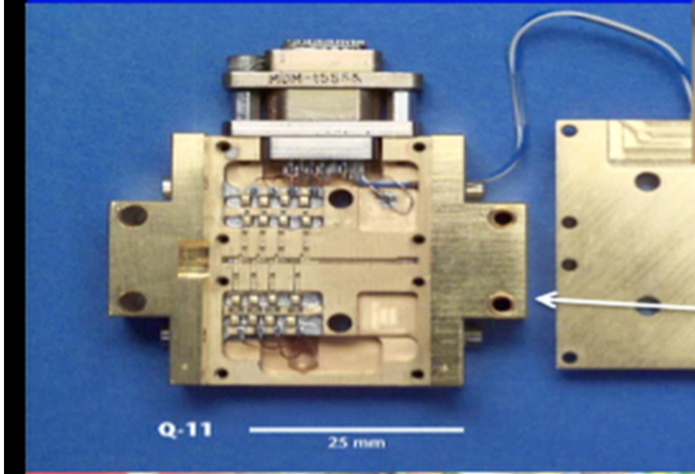


RF Tracker Element

Readout Orthogonal to Electron Trajectory

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

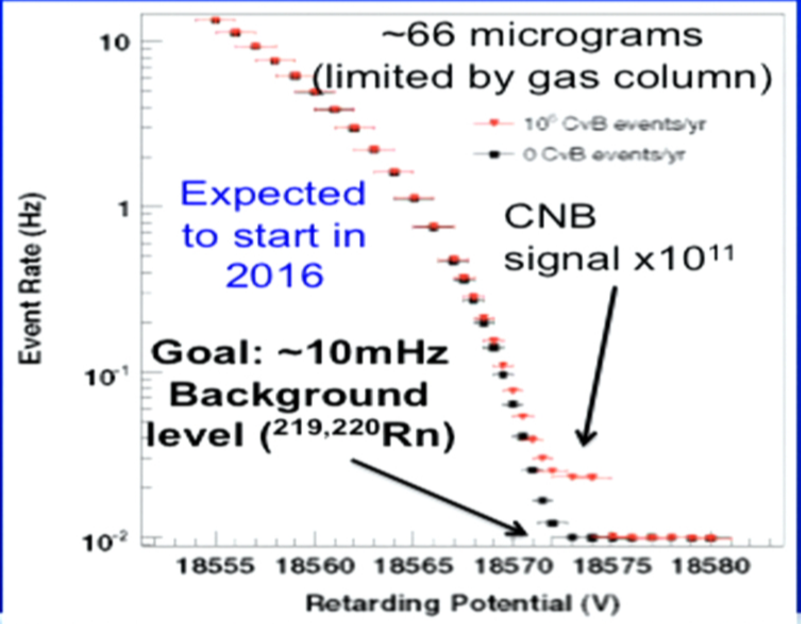




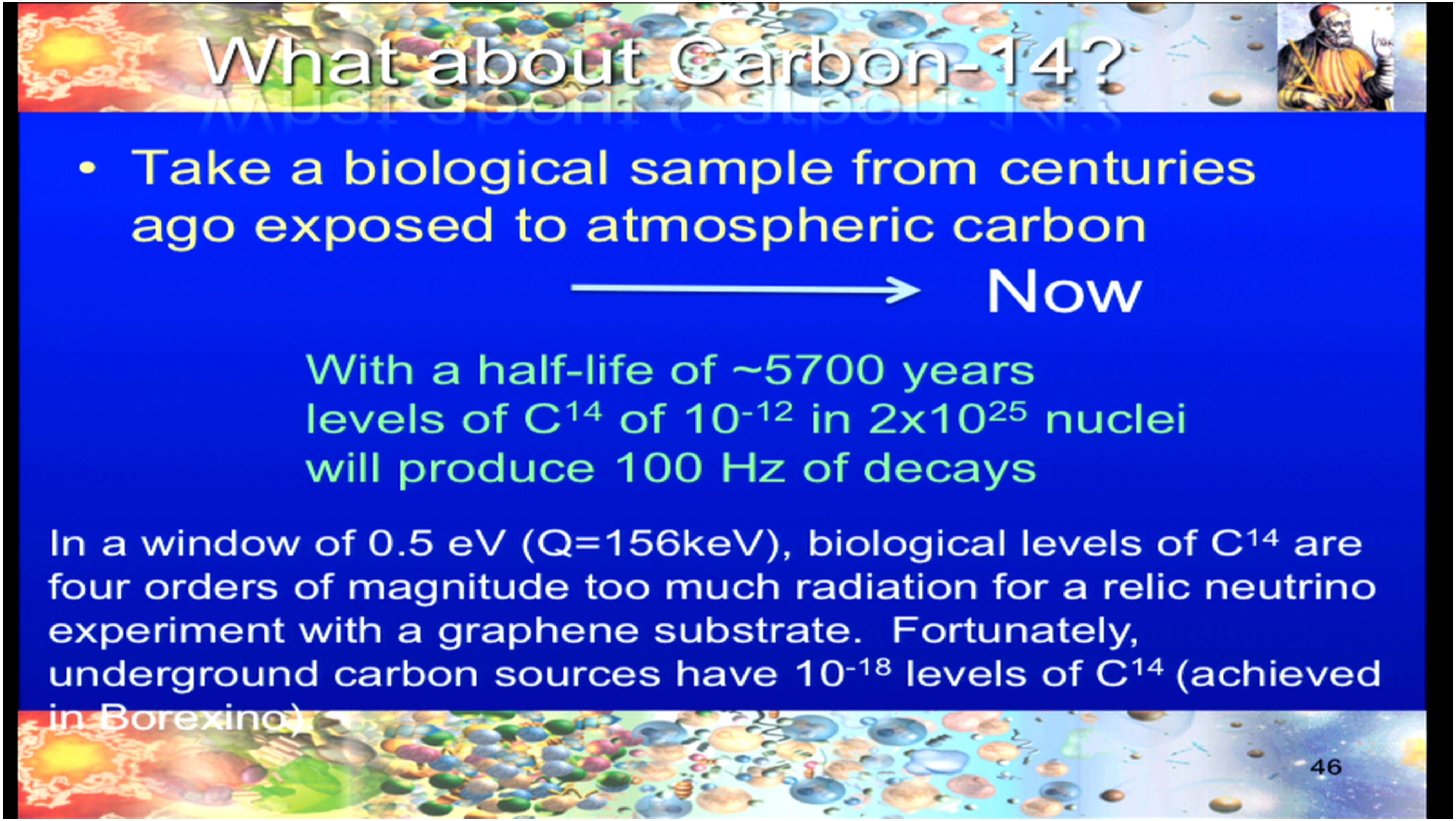
Q-Band (38-46 GHz)
WMAP Amplifier

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



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



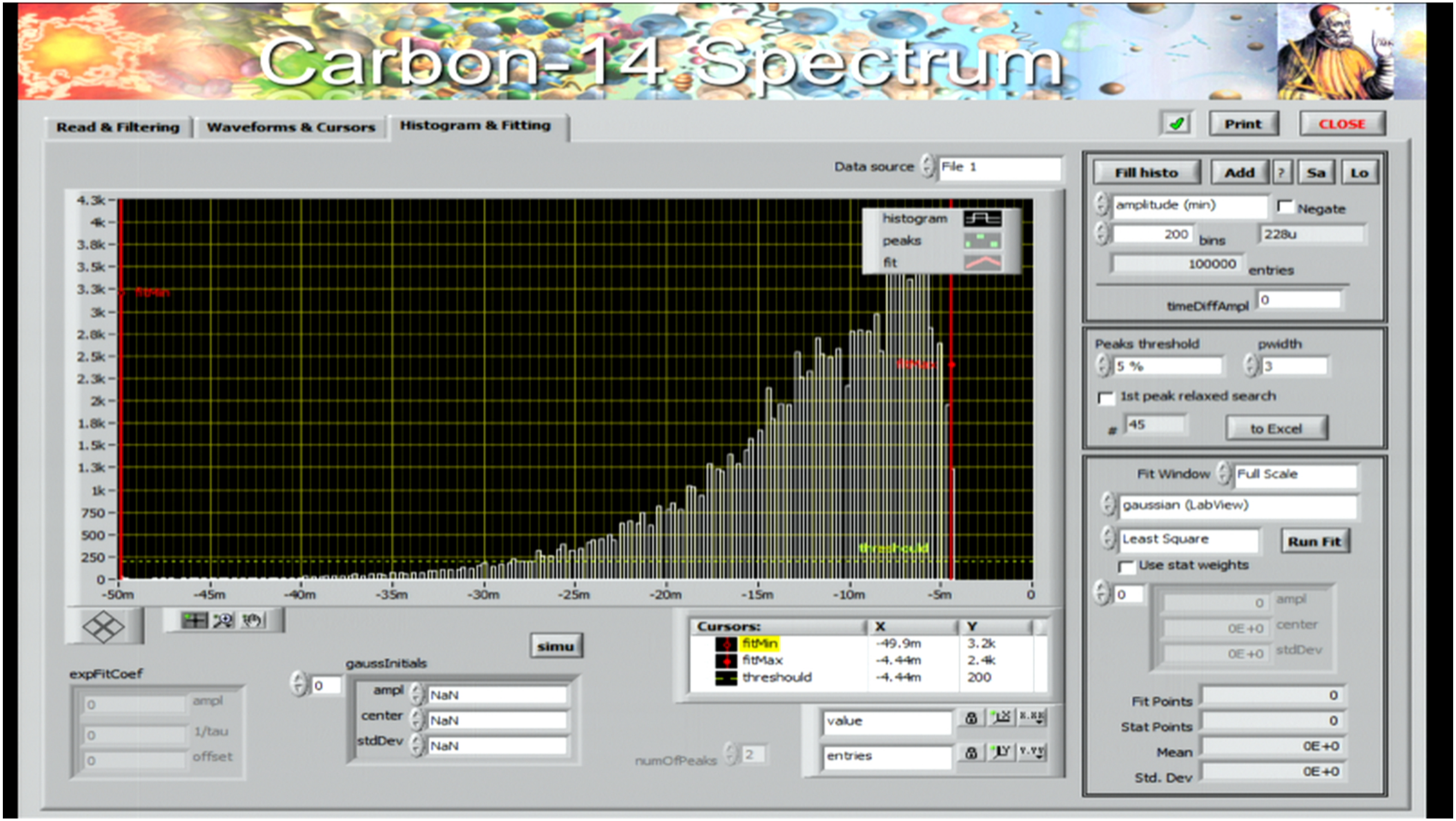
What about Carbon-14?

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

$\longrightarrow$ 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)



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

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

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

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

value

entries

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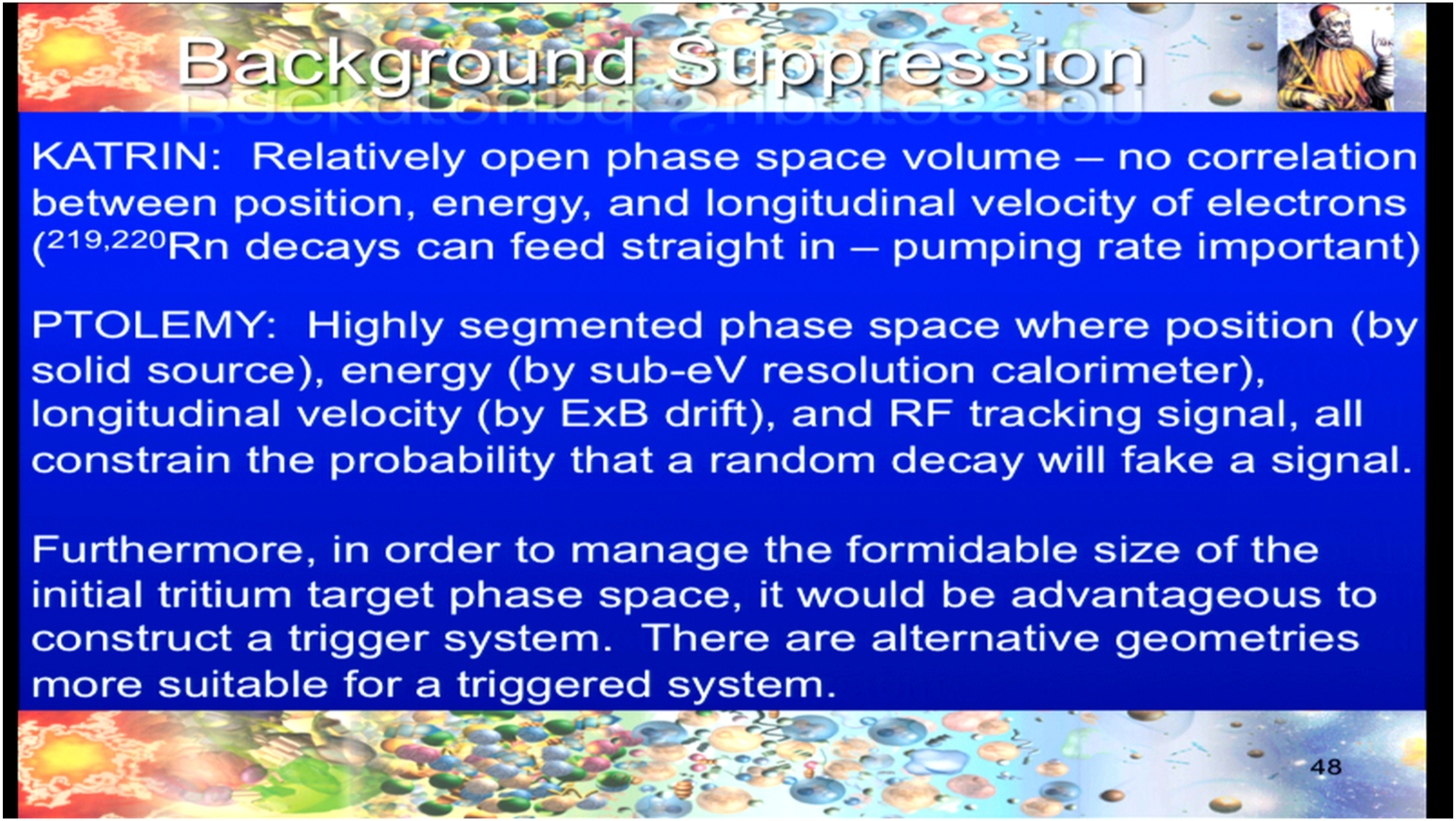
offset	0

gaussInitials 0

ampl	NaN
center	NaN
stdDev	NaN

numOfPeaks 2



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.

Trigger

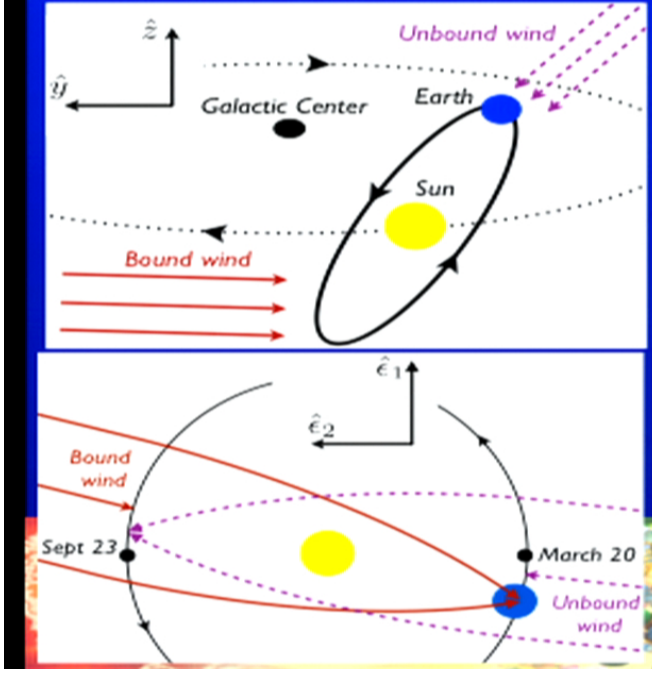
Non-relativistic electrons in cyclotron motion can have their longitudinal velocity slowed down – in an equal transit time configuration of the RF tracker, the trigger latency to decide whether to drift an electron to the calorimeter is constant and finite. The time-dependence of a trigger decision will reduce dramatically the effective phase space.

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

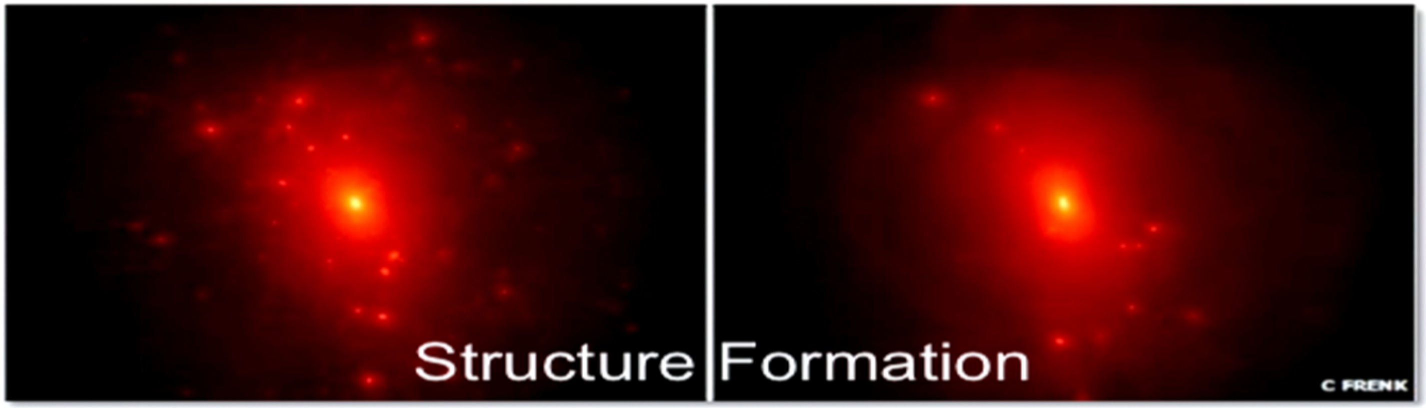
$$d\sigma_{\mathrm{NCB}} \propto \left[1 + a\frac{\mathbf{p_e}\cdot\mathbf{p}_\nu}{E_e E_\nu} + A\frac{\hat{\mathbf{s}}\cdot\mathbf{p_e}}{E_e} + B\frac{\hat{\mathbf{s}}\cdot\mathbf{p}_\nu}{E_{\bar{\nu}}}\right]$$

Tritium polarization calibrated using beta decay electrons.

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

Sterile Neutrinos

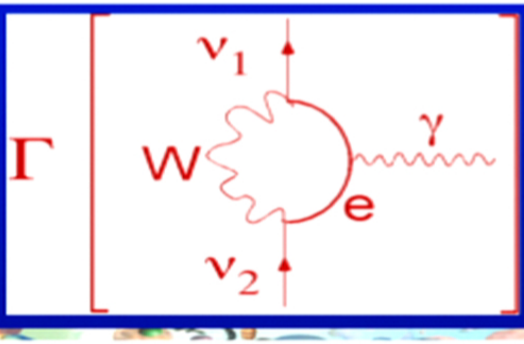
CDM simulations WDM



X-Ray Astronomy

$\nu_2 \rightarrow \nu_1 + \gamma$

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

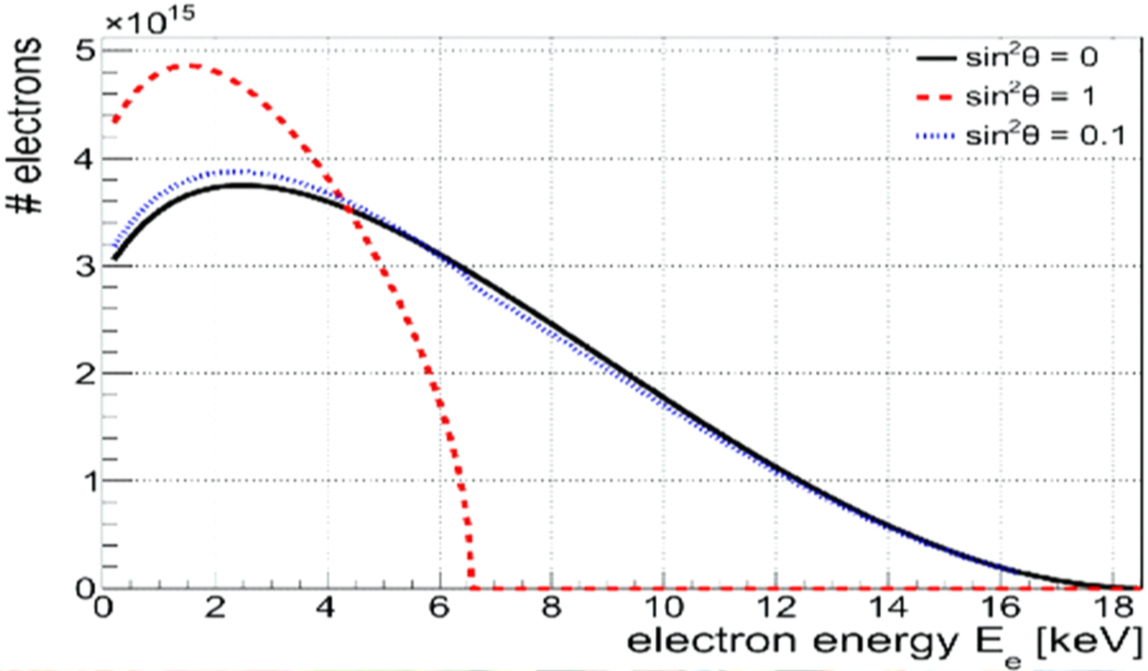


Sterile neutrinos will introduce a kink in the beta-decay spectrum at $K^0_{end} - m_4$ where sensitivity to $|U_{e4}|^2 \sim 10^{-7}$ may be possible with a fast response detector

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

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

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

Kai Dolde (Meudon 2014)
Susanne Meurtens (KATRIN)

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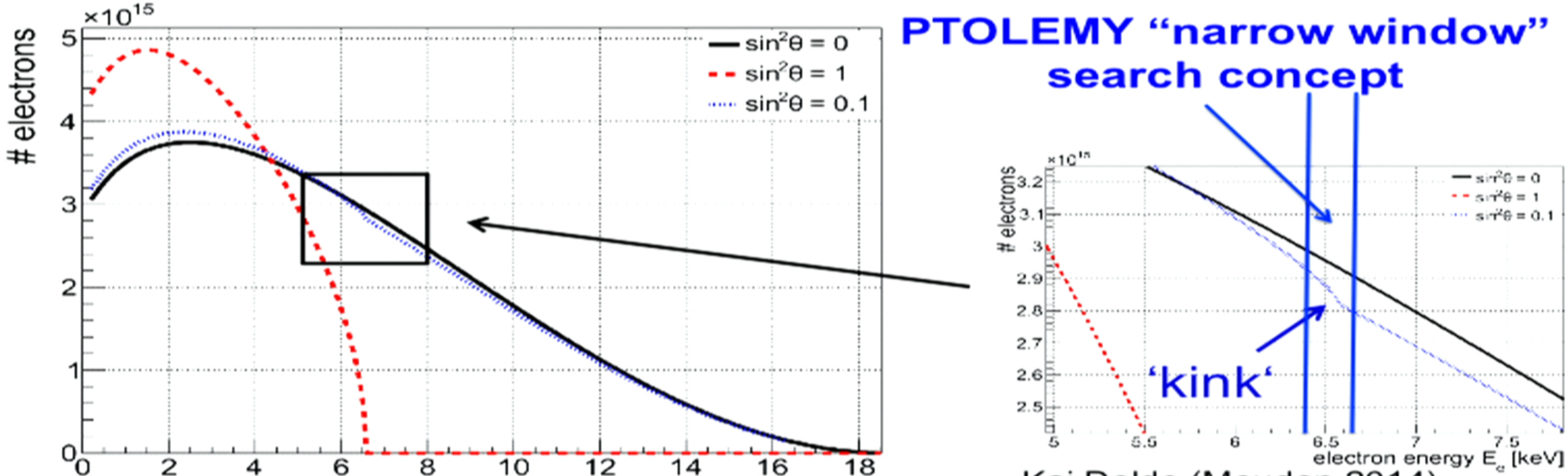
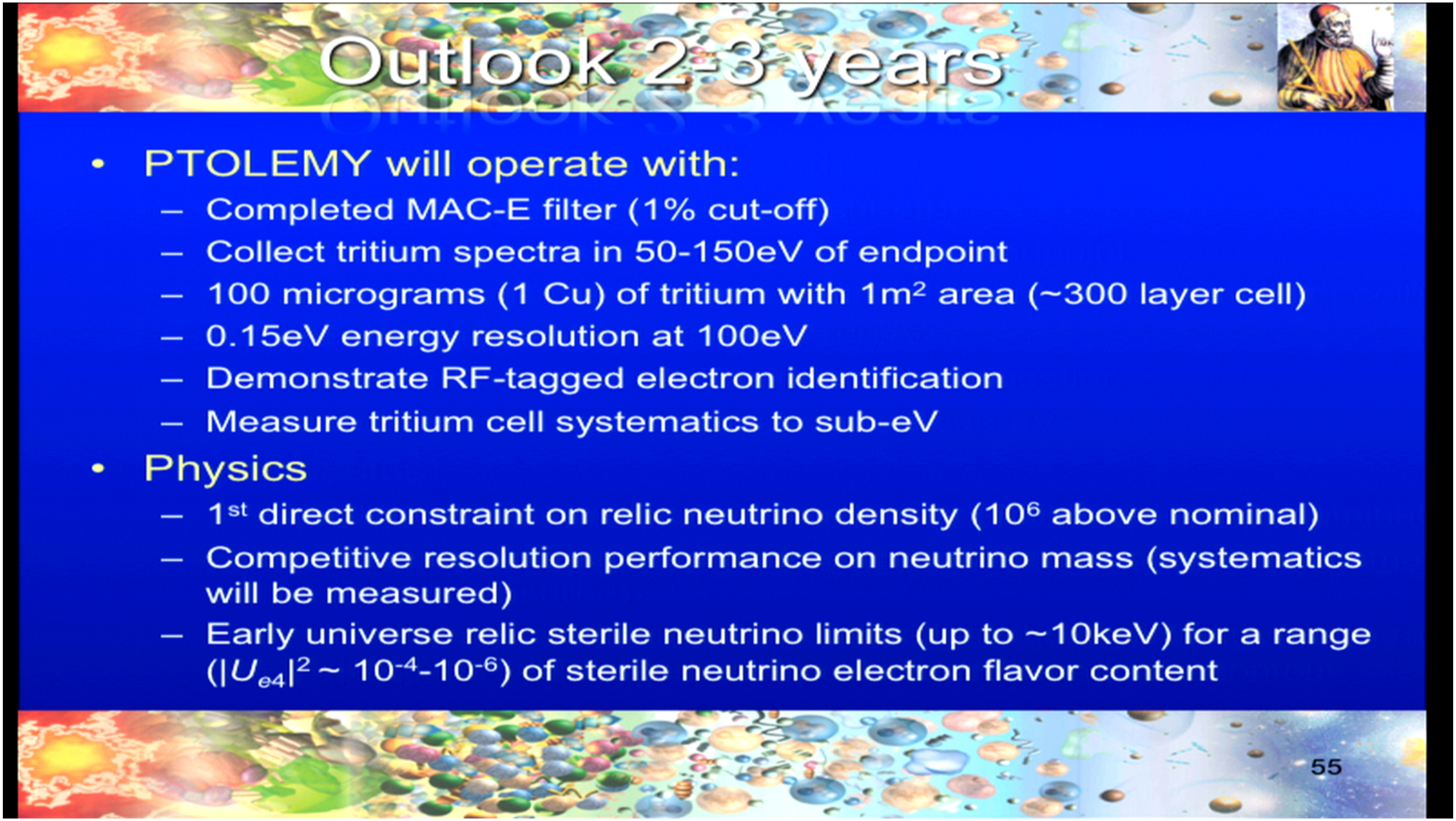


PTOLEMY "narrow window" search concept

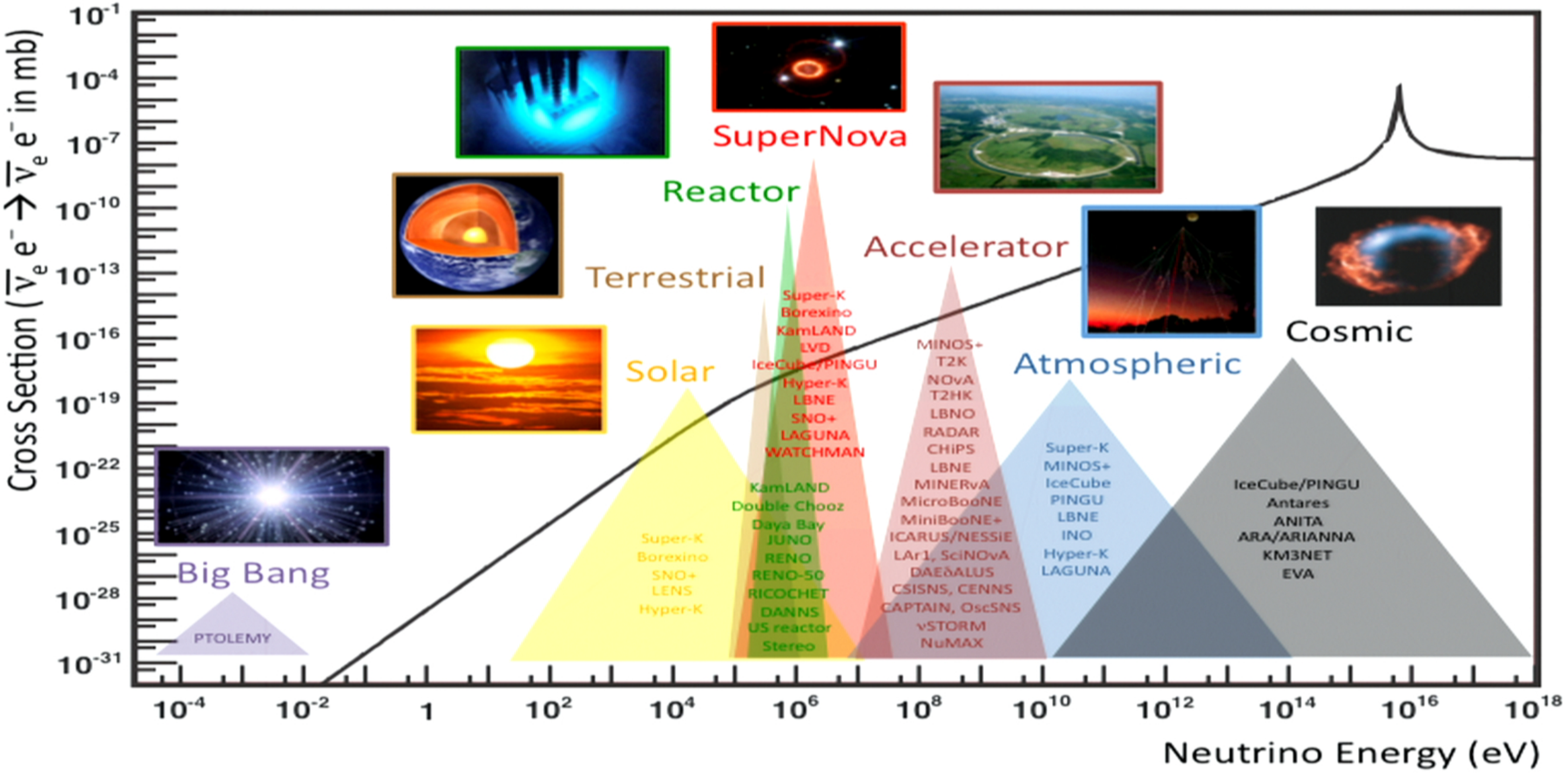
Kai Dolde (Meudon 2014)
Susanne Meurtens (KATRIN)

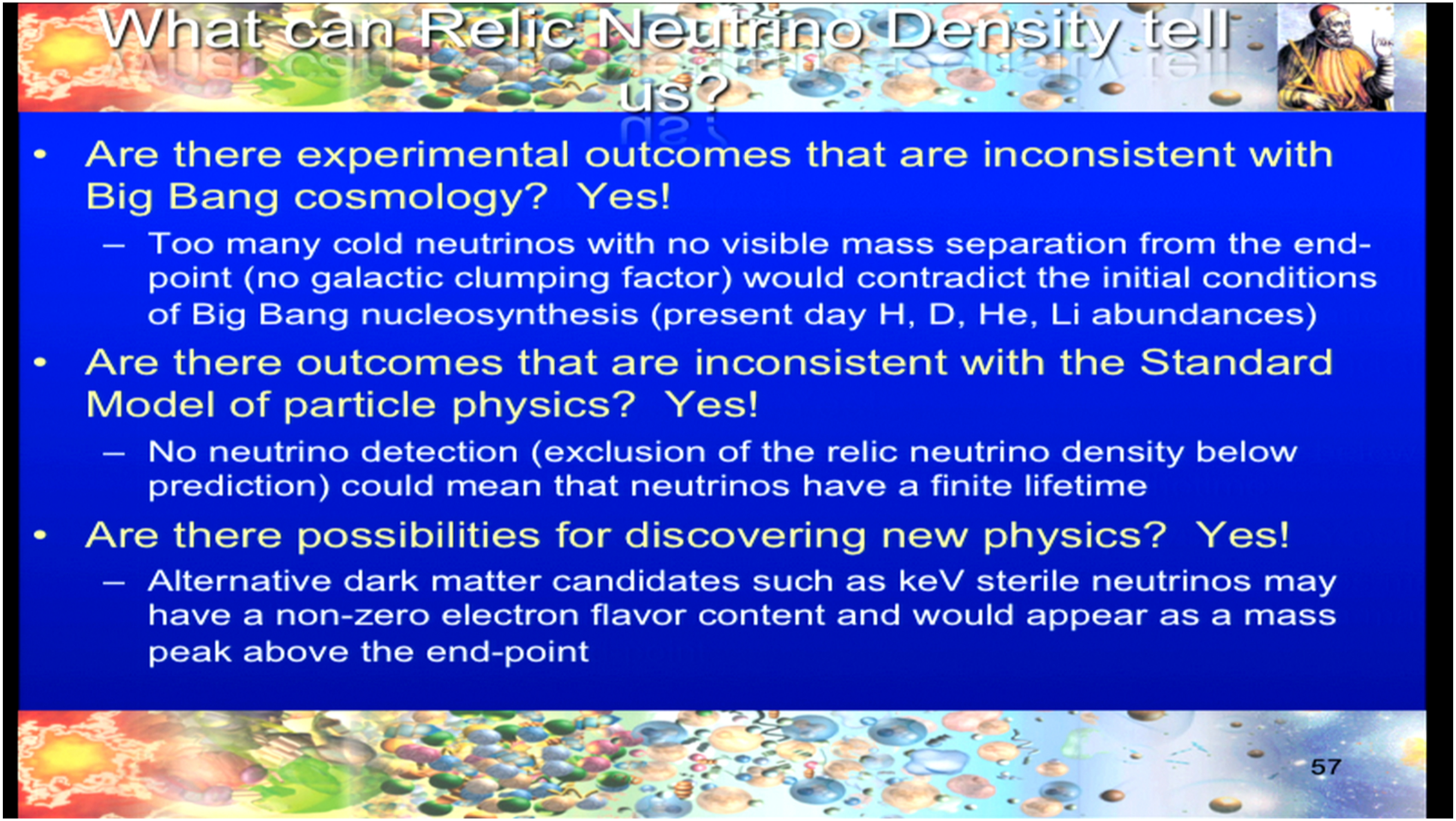


Outlook 2-3 years

- 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





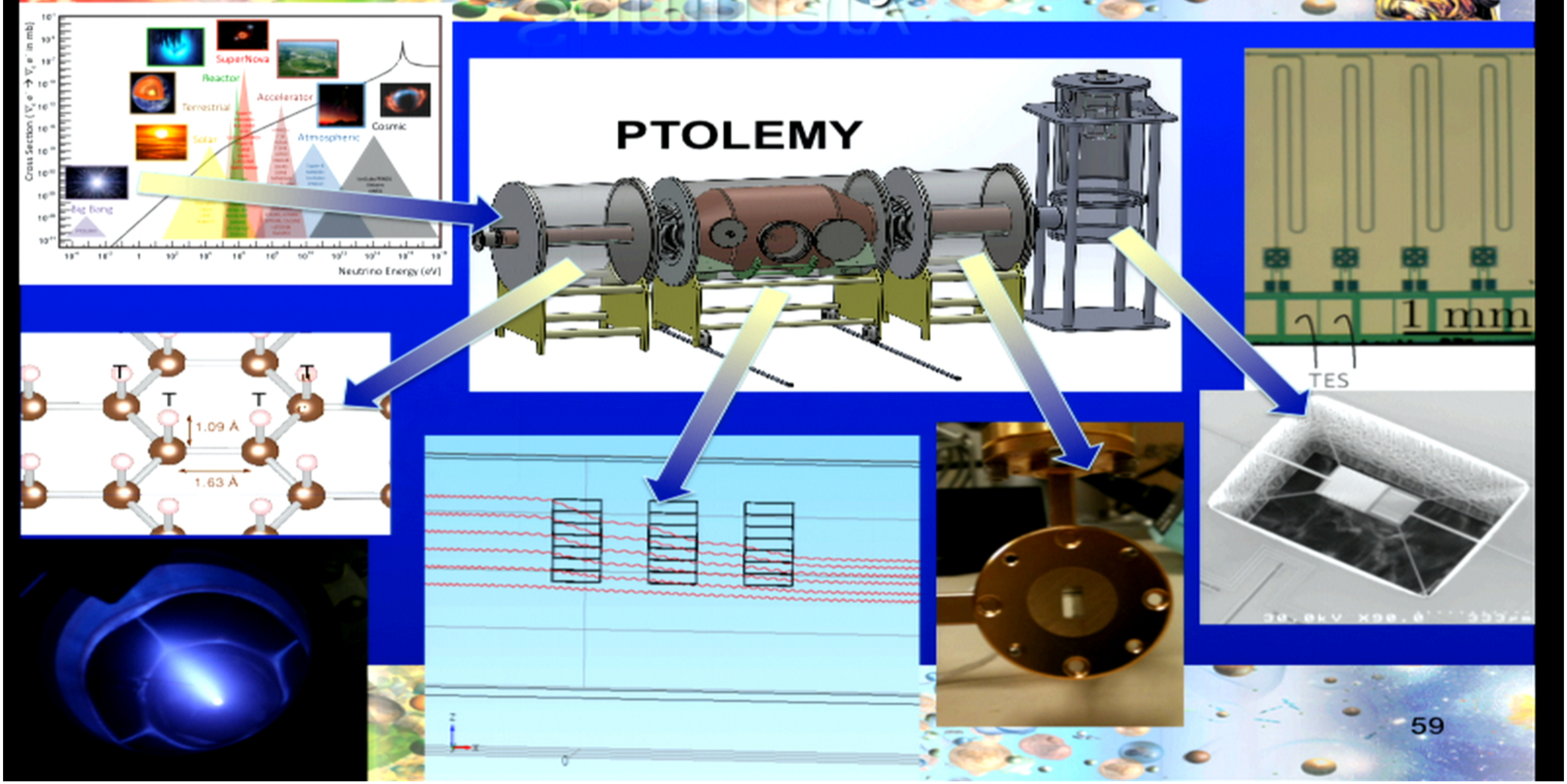
What can Relic Neutrino Density tell us?

- 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


Cross Section ($\bar{\nu}_e e^- \to \bar{\nu}_e e^-$ in mb)
SuperNova
Reactor
Terrestrial
Accelerator
Solar
Atmospheric
Cosmic
Big Bang
Neutrino Energy (eV)
PTOLEMY
T
1.09 Å
1.63 Å
1 mm
TES