PTOLEMY: A Method for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter

Princeton Tritium Observatory for Light, Early-Universe,
Massive-Neutrino Yield (PTOLEMY)

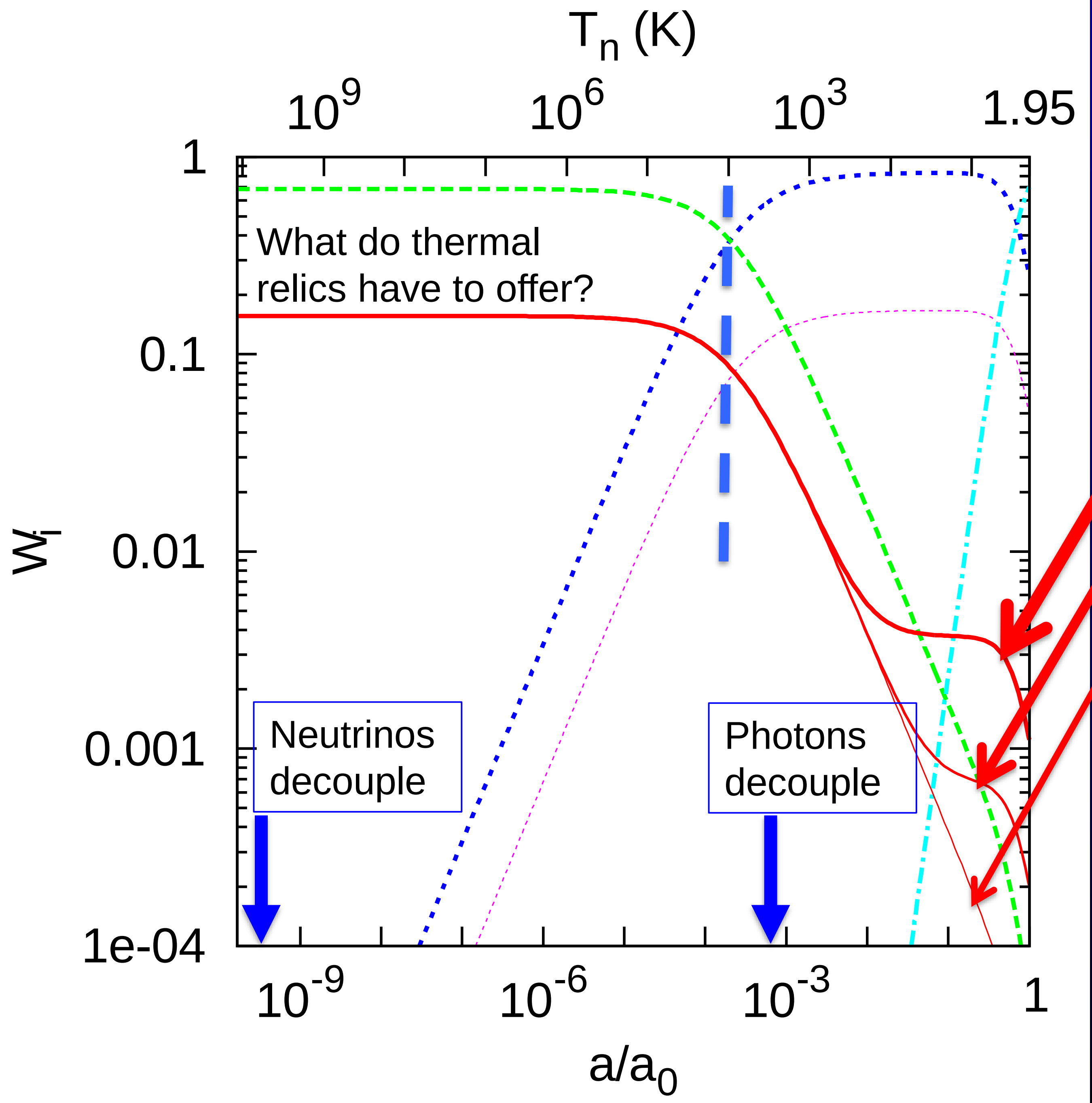
Chris Tully
Princeton

SNOLAB
17 August 2017

Overview

- Why is the physics of the thermal relics so important to our understanding of the early Universe?
- What are the main experimental challenges that need to be overcome to directly detect the Cosmic Neutrino Background with PTOLEMY?
  - Proposal for a concurrent physics program on the directional detection of MeV dark matter, complementary to high sensitivity non-directional detectors
- Synergies with SNOLAB?

Cosmic Coincidence



J. Lesgourgues

Individual neutrino contributions assuming Normal Hierarchy and

$m_3 = 0.05$ eV,

$m_2 = 0.009$ eV,

$m_1 = 0$

Coincidence?
Rise of Λ as fraction of Ω occurs roughly at the onset of non-relativistic era of relic neutrinos

Neutrinoless Universe

But isn’t the neutrino is stable because it’s the lowest mass state with spin-1/2 angular momentum?

Bahcall, Cabibbo, Yahil, 1972

Self-annihilation to scalar field?

Beacom, et. al,

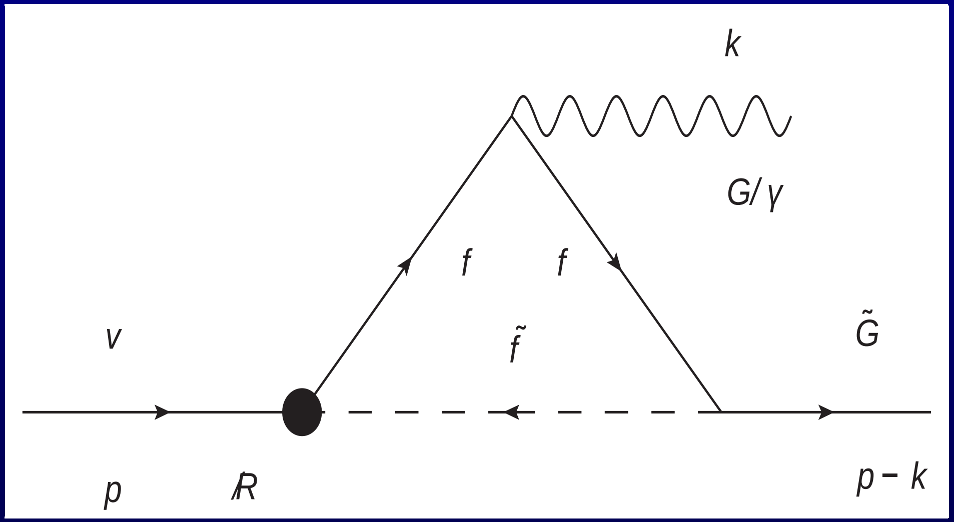
[10.1103/PhysRevLett.93.121302](https://doi.org/10.1103/PhysRevLett.93.121302)

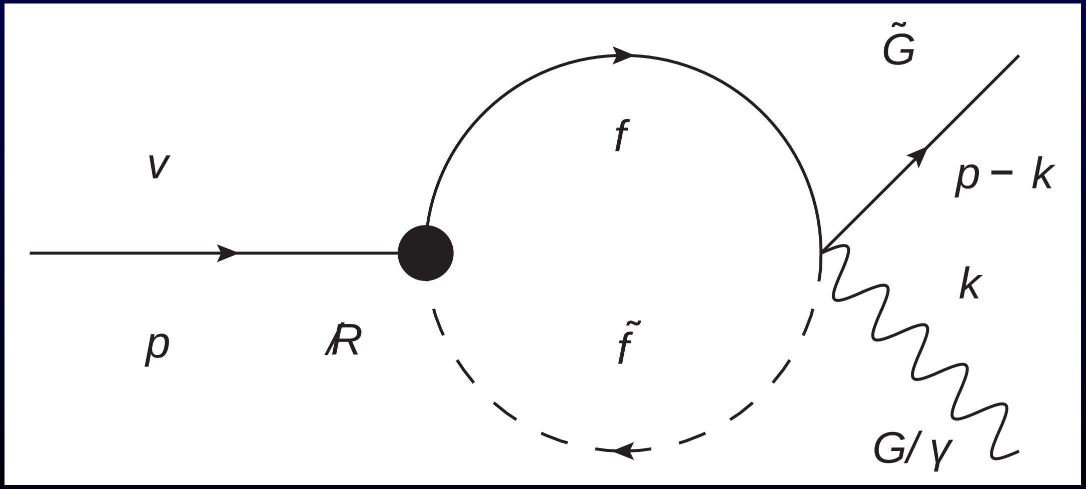
http://arxiv.org/abs/astro-ph/0404585

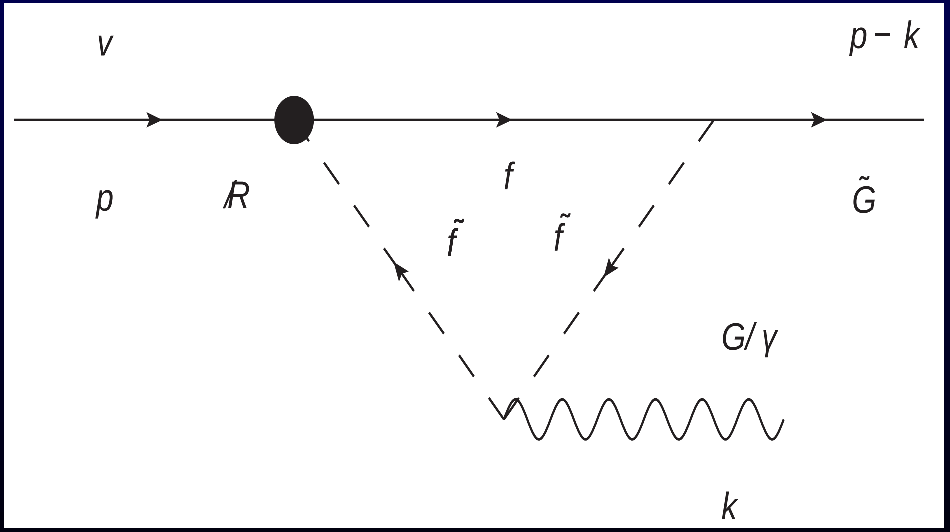
(Possible variant? Super-Higgs)

R-Parity violating decay into GR

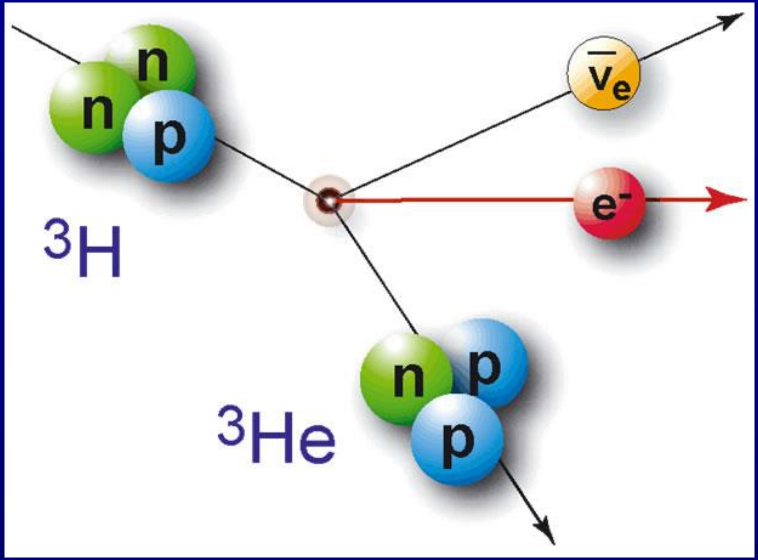
Gravitino spin-3/2





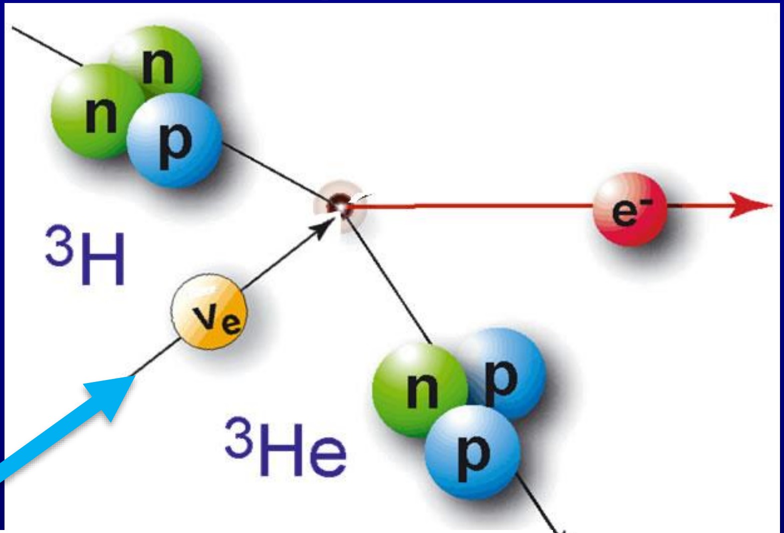


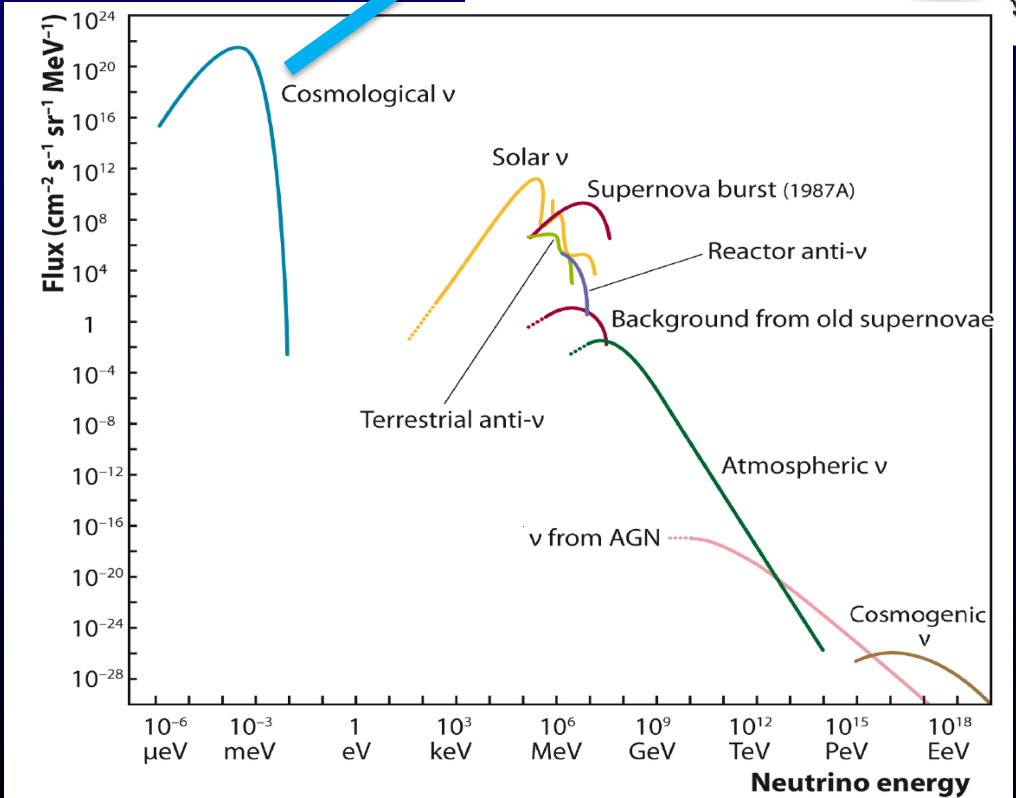
Tritium β-decay and Neutrino Capture



Tritium β-decay
(12.3 yr half-life)

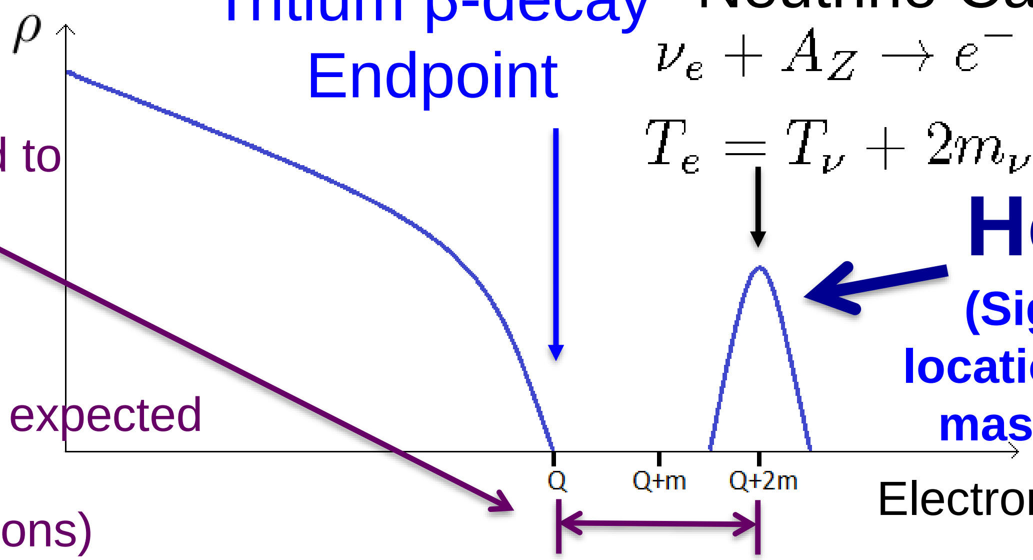
Neutrino capture on Tritium





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



Tritium β-decay Endpoint

Neutrino Capture

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

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

What do we know?

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

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

How many?

(Signal shape and location predicted from mass measurement)

Electron energy

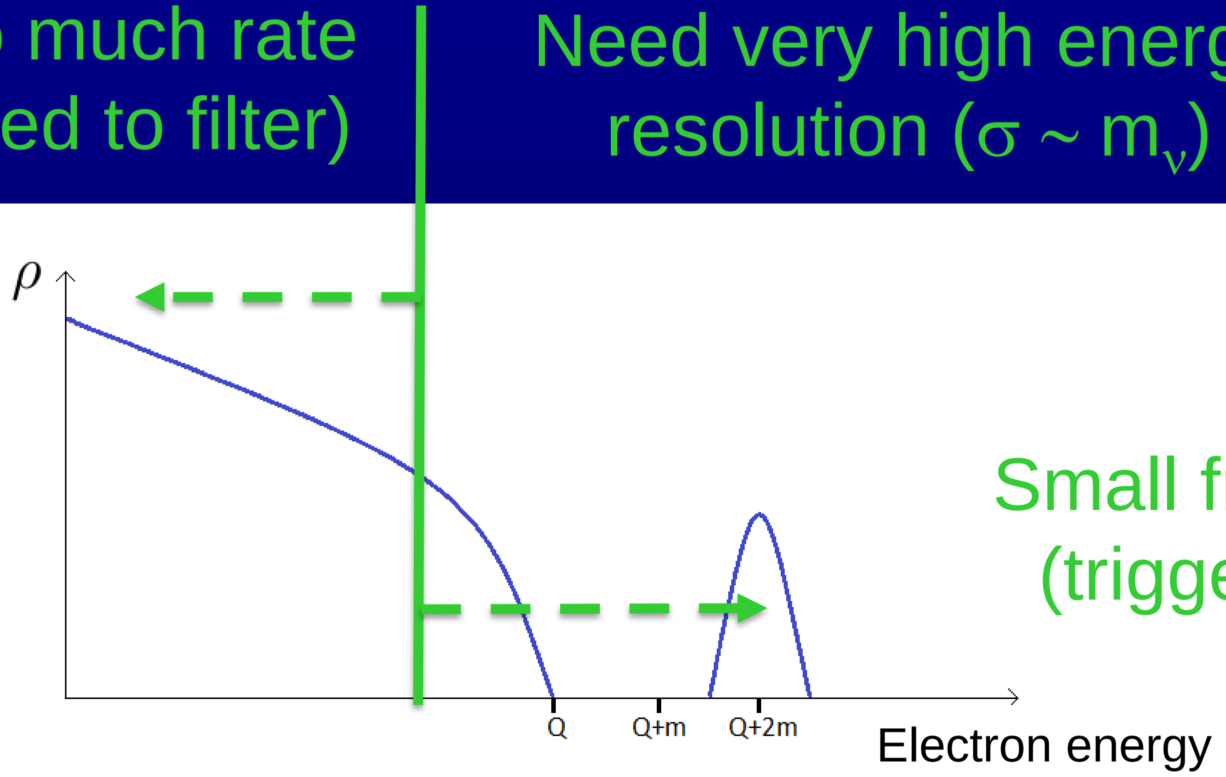
Figure 1: Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

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

Experimental Perspective

Too much rate
(need to filter)

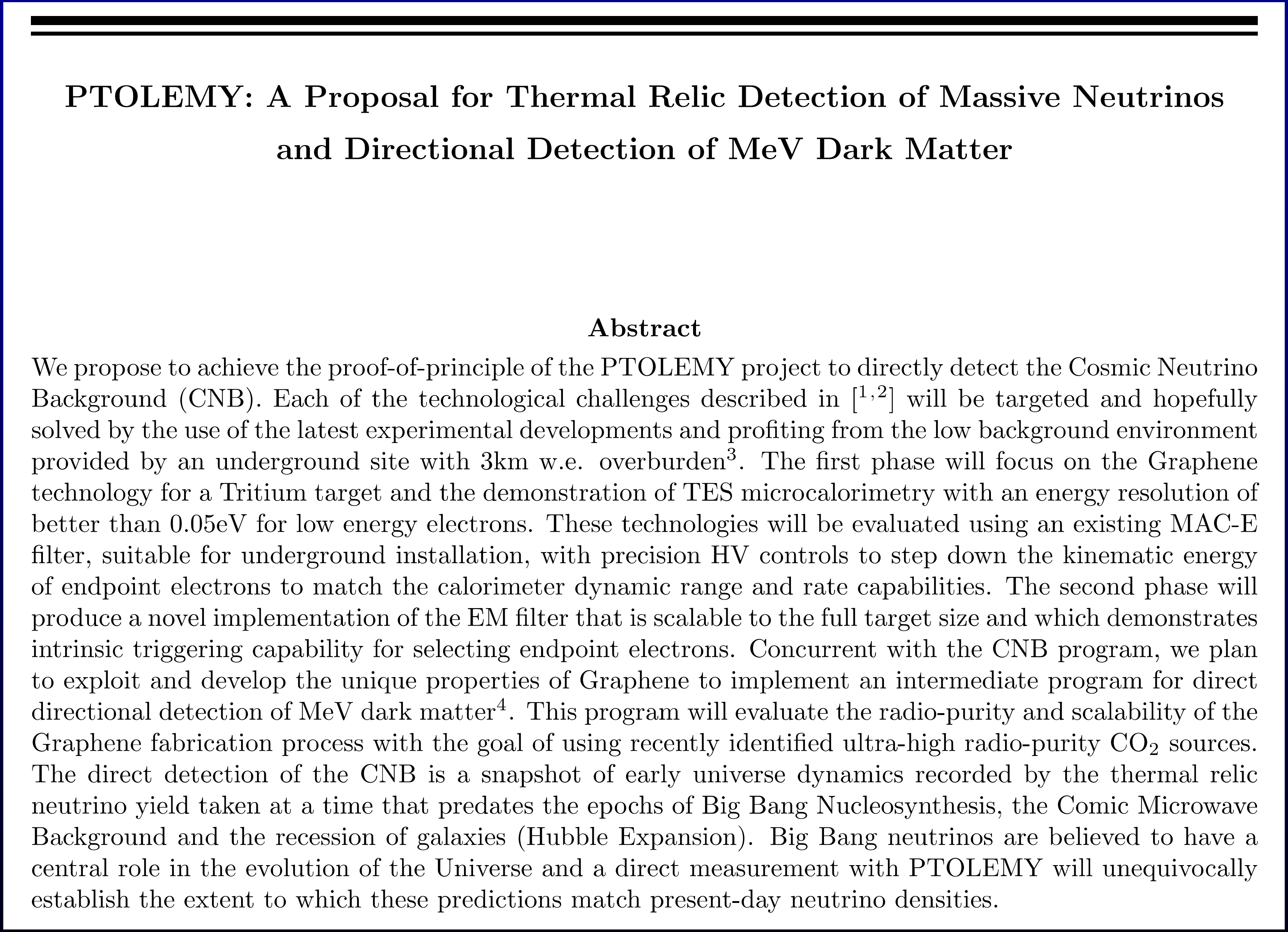
Need very high energy
resolution ($\sigma \sim m_\nu$)



Small fraction
(triggering)

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

Proposal



PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter

Abstract

We propose to achieve the proof-of-principle of the PTOLEMY project to directly detect the Cosmic Neutrino Background (CNB). Each of the technological challenges described in [1,2] will be targeted and hopefully solved by the use of the latest experimental developments and profiting from the low background environment provided by an underground site with 3km w.e. overburden[3]. The first phase will focus on the Graphene technology for a Tritium target and the demonstration of TES microcalorimetry with an energy resolution of better than 0.05eV for low energy electrons. These technologies will be evaluated using an existing MAC-E filter, suitable for underground installation, with precision HV controls to step down the kinematic energy of endpoint electrons to match the calorimeter dynamic range and rate capabilities. The second phase will produce a novel implementation of the EM filter that is scalable to the full target size and which demonstrates intrinsic triggering capability for selecting endpoint electrons. Concurrent with the CNB program, we plan to exploit and develop the unique properties of Graphene to implement an intermediate program for direct directional detection of MeV dark matter[4]. This program will evaluate the radio-purity and scalability of the Graphene fabrication process with the goal of using recently identified ultra-high radio-purity CO_2 sources. The direct detection of the CNB is a snapshot of early universe dynamics recorded by the thermal relic neutrino yield taken at a time that predates the epochs of Big Bang Nucleosynthesis, the Comic Microwave Background and the recession of galaxies (Hubble Expansion). Big Bang neutrinos are believed to have a central role in the evolution of the Universe and a direct measurement with PTOLEMY will unequivocally establish the extent to which these predictions match present-day neutrino densities.

Experimental Challenges

- Energy Resolution:
  - Molecular tritium source that exhibits minimal energy smearing on the outgoing electron
  - Measurement techniques that achieve ~0.05eV energy resolution at the tritium endpoint
- Low Background, High Radio-Purity Target
- Scalable Kinematic Energy Filtering with Triggering on endpoint electrons:
  - Remove the bulk of the β-decay electrons while preserving high acceptance for electrons from neutrino capture

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(10) events/yr for Dirac(Majorana) ν's

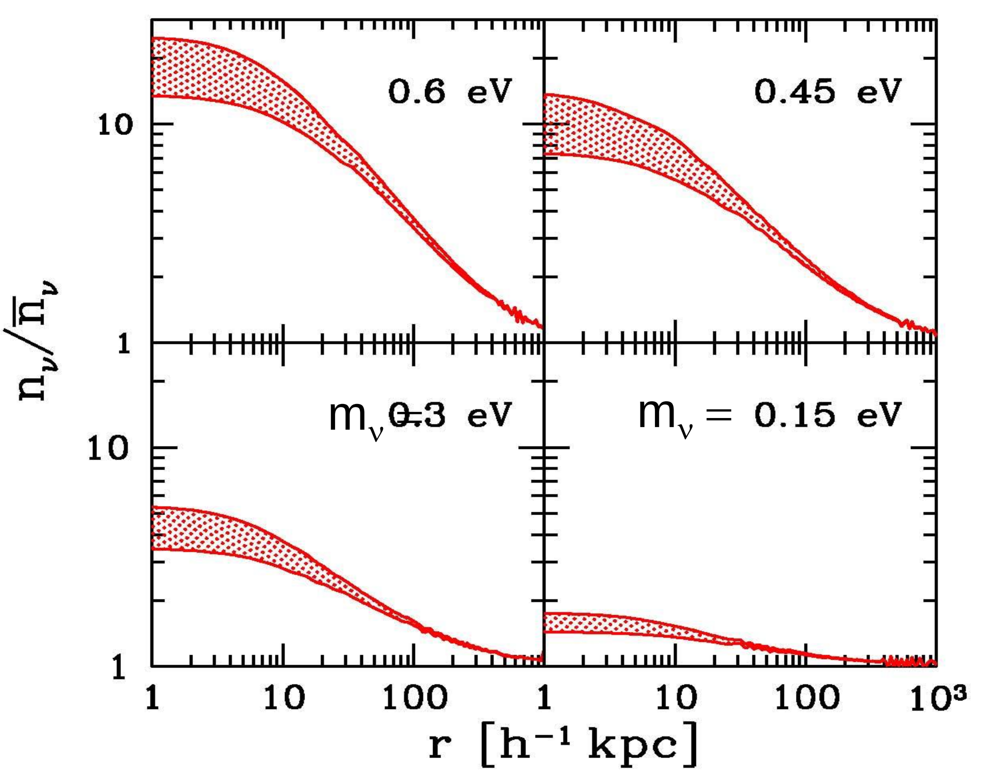
$\sigma(v/c)=(7.84\pm0.03)\times10^{-45}cm^2$

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 ~<10%

Ringwald and Wong (2004)

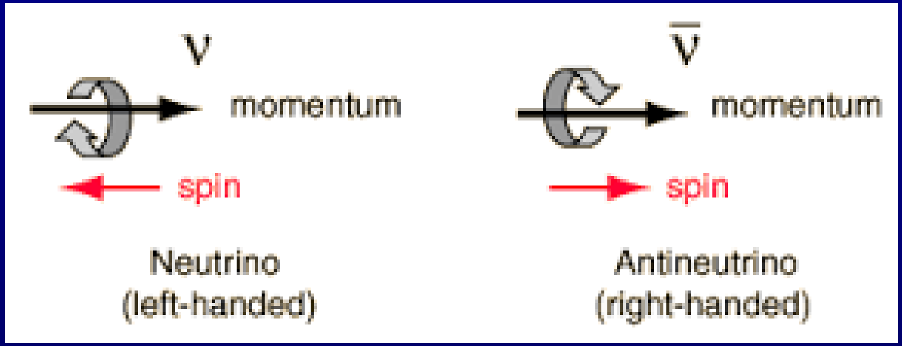
Villaescusa-Navarro et al (2011)



Dirac versus Majorana Neutrinos

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

Long, Lunardini, Sabancilar: arXiv:1405.7654



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

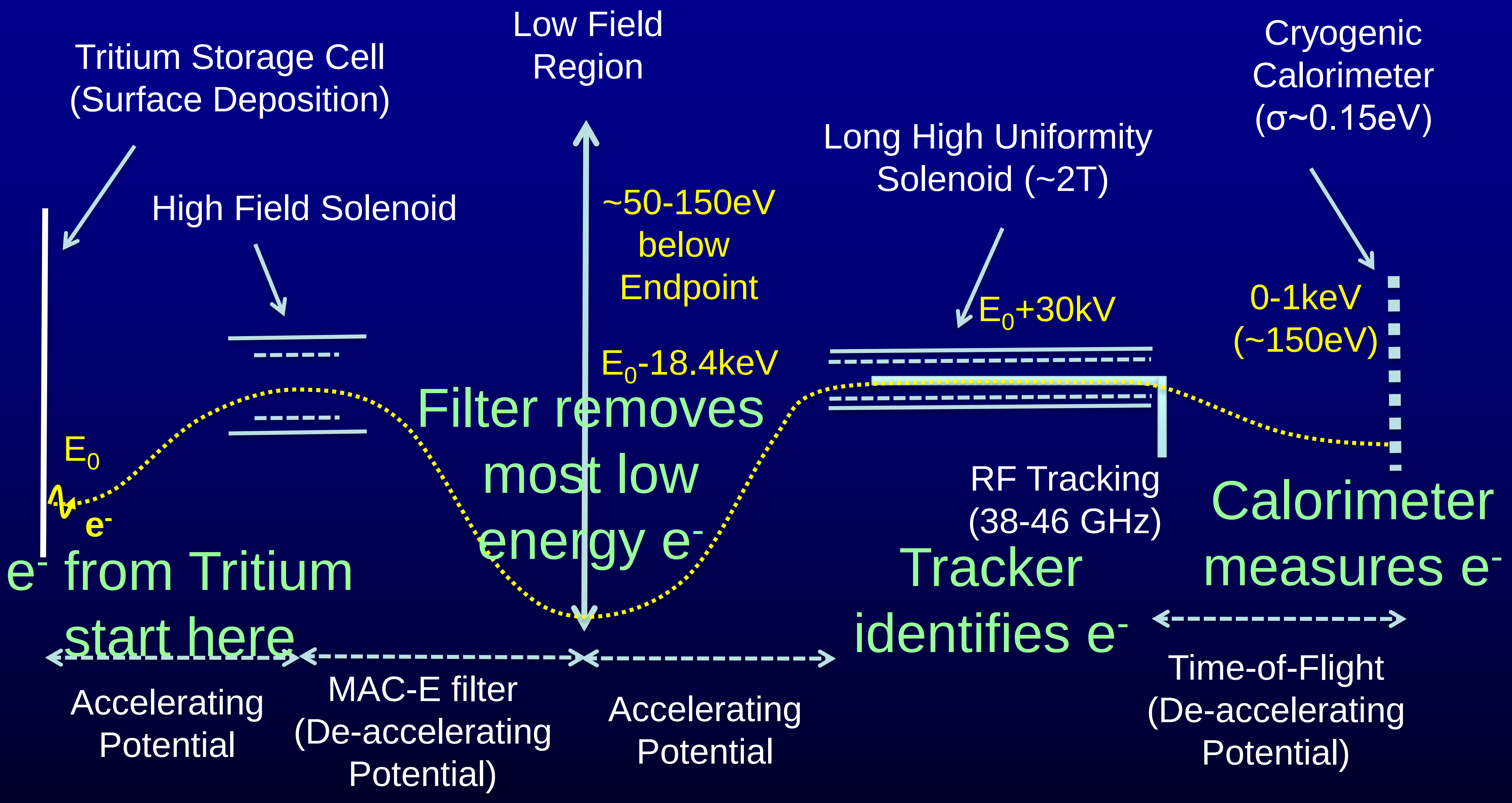
Dirac: after expansion, only ~half of left-handed helical Dirac neutrinos are left-handed chiral (active)
→ antineutrinos are not captured

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

Factor of 2 difference in capture rate

PTOLEMY Experimental Layout

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



Tritium Storage Cell
(Surface Deposition)

Low Field
Region

Cryogenic
Calorimeter
(σ~0.15eV)

Long High Uniformity
Solenoid (~2T)

High Field Solenoid

~50-150eV
below
Endpoint

E_0+30kV

0-1keV
(~150eV)

E_0-18.4keV

Filter removes most low energy e$^-$

E_0

e$^-$

RF Tracking
(38-46 GHz)

Calorimeter measures e$^-$

e$^-$ from Tritium start here

Tracker identifies e$^-$

Accelerating
Potential

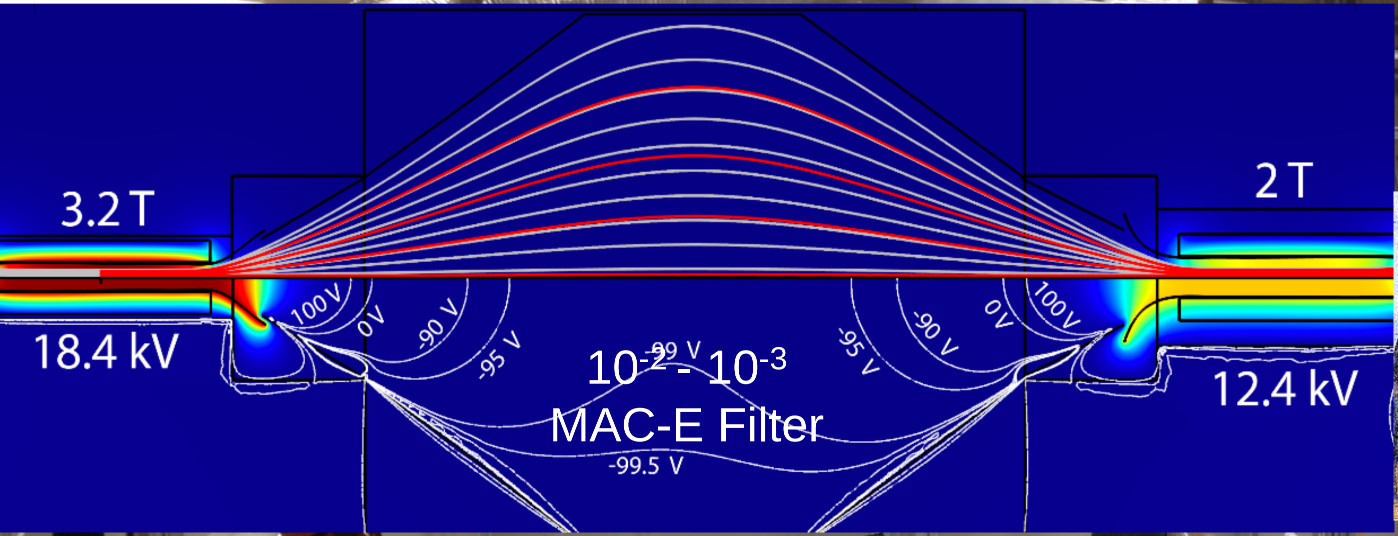
MAC-E filter
(De-accelerating
Potential)

Accelerating
Potential

Time-of-Flight
(De-accelerating
Potential)

R&D Prototype @ PPPL
(August 2, 2016)

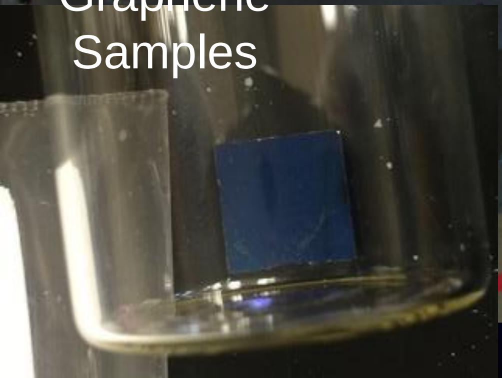
Supported by:
The Simons Foundation
The John Templeton Foundation



PTOLEMY

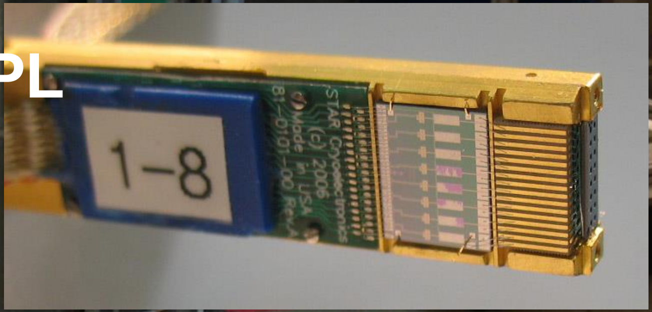
Dilution
Refrigerator
Kelvinox
MX400

Robot Arm
for Tritiated-
Graphene
Samples



R&D Prototype @ PPPL (August 2, 2016)

Supported by:
The Simons Foundation
The John Templeton Foundation



StarCryo
Microcalorimeter

PTOLEMY Prototype

R&D Prototype @ PU
(June 7, 2017)

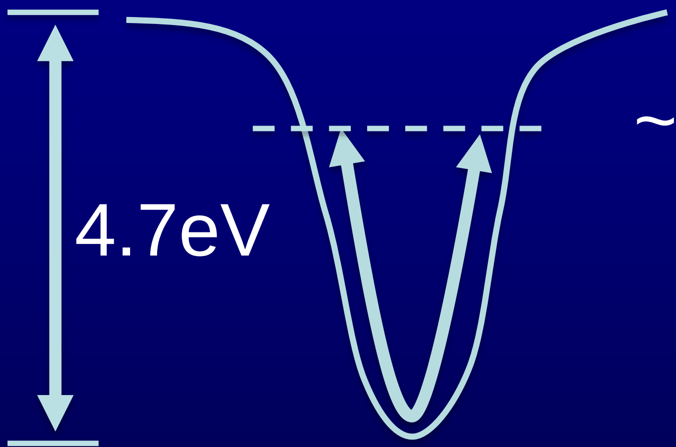
Supported by:
The Simons Foundation
The John Templeton Foundation

Equipment

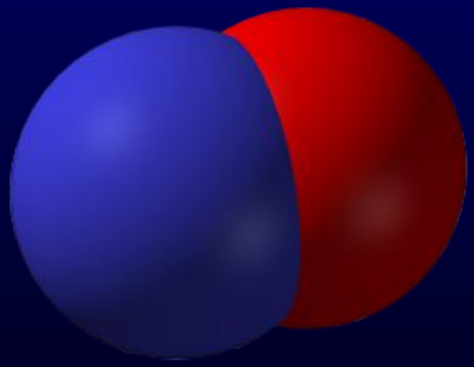
- Dilution Refrigerator (Kelvinox MX400 - Oxford Instruments). Lowest base temperature is 7mK and up to 400mW of cooling power is provided at 100mK. Custom cryostat with a sample space exceeding a volume of 10^3 cm^3 and with a vacuum path connecting to a horizontal port matching the vertical height of the horizontal bore magnets.
- StarCryo Precision X-Ray TES Calorimeter and SQUID readout system.
- 4.7T Oxford Instruments 200/330 horizontal bore superconducting magnet.
- 7.05T Oxford Instruments 300/183 horizontal bore superconducting magnet.
- Central vacuum tank hosting a 9-segment high precision HV electrostatic filter. The MAC-E filter achieves a 1% energy resolution and a novel HV reference system based on precision voltages held on capacitors with field mill sensing. Oerlikon Leybold TurboVAC 450 iX (160CF) and ScrollVAC SC15D pumping system.
- Robot arm (Genmark) for loading wafers in vacuum.

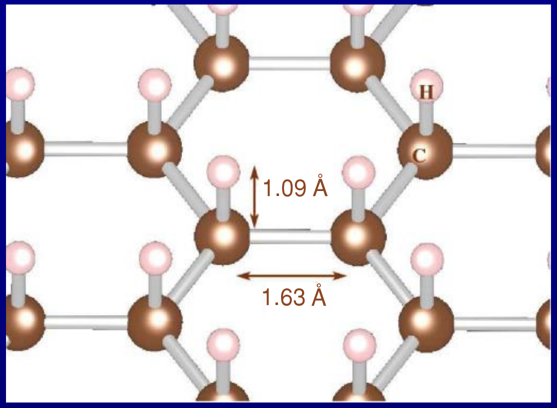
Molecular Broadening

T-T → $(T\text{-}He^3)^*$



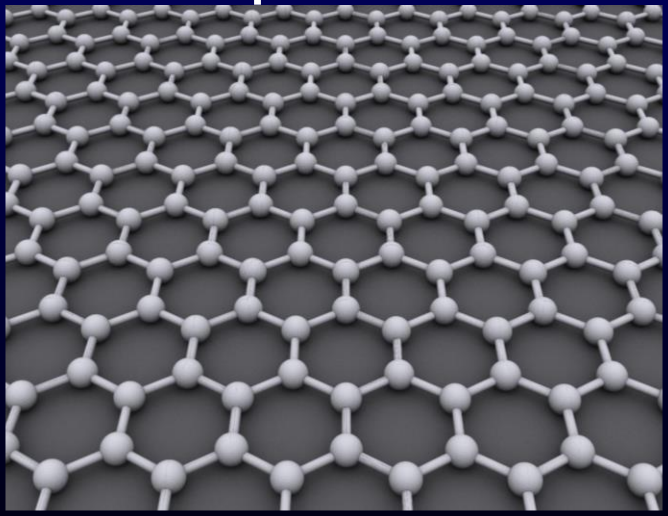
~3eV He^3 recoil
at endpoint



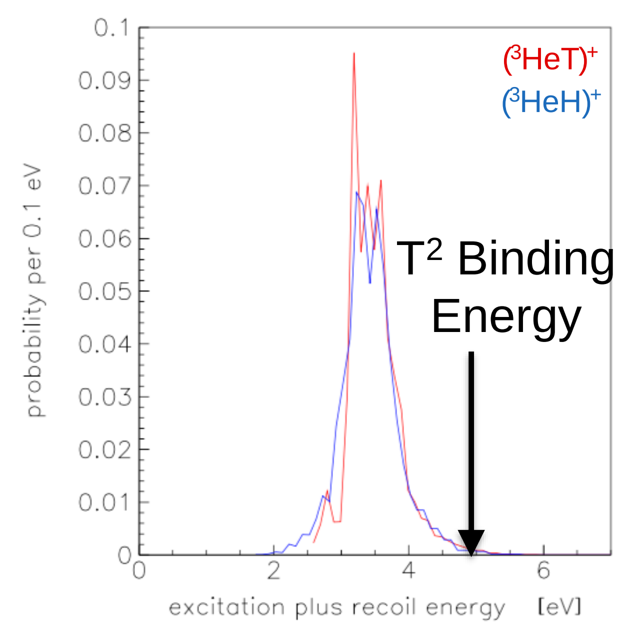


<3eV binding
energy

Graphene



Overcoming T^2 Molecular Broadening



Advances in High Energy Physics 2013 (2013) 39

Molecular excitations in daughter molecule

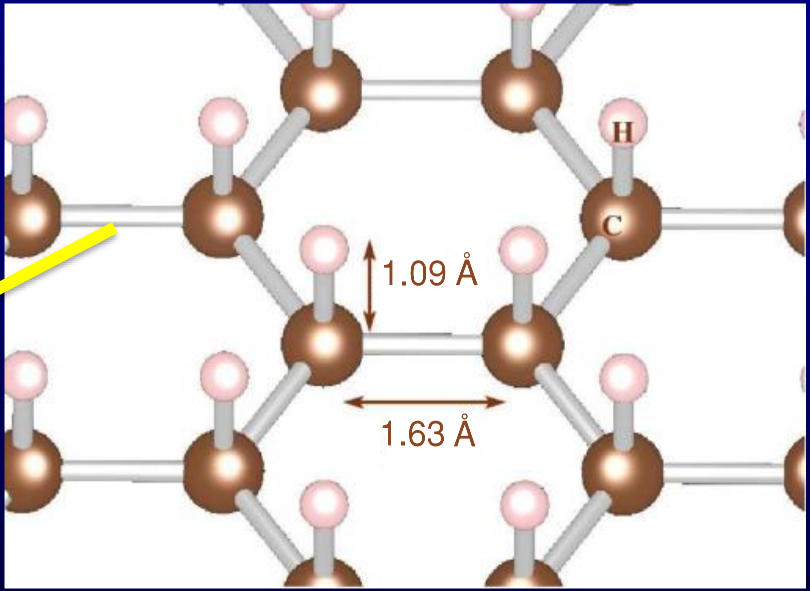
- blur tritium endpoint

→ fundamental limit to measurement of ! -mass

Need atomic tritium for ultimate experiment!

Tritiated-Graphene

- <3eV Binding Energy
- Single-sided (loaded on substrate)
- Planar (uniform bond length)
- Semiconductor (Voltage Reference)
- Polarized tritium(directionality?)

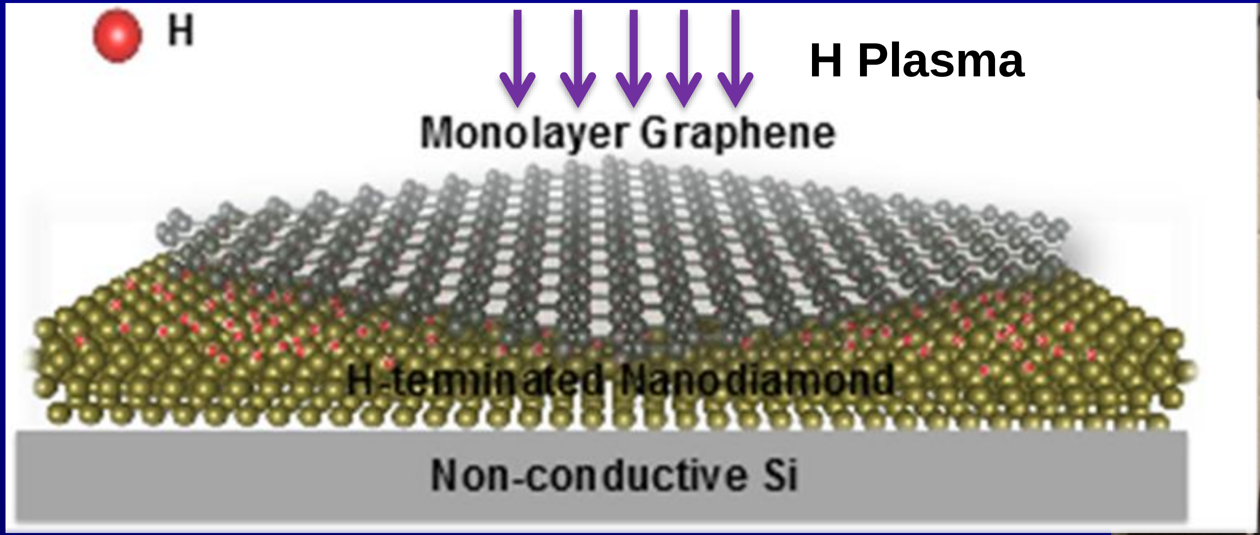


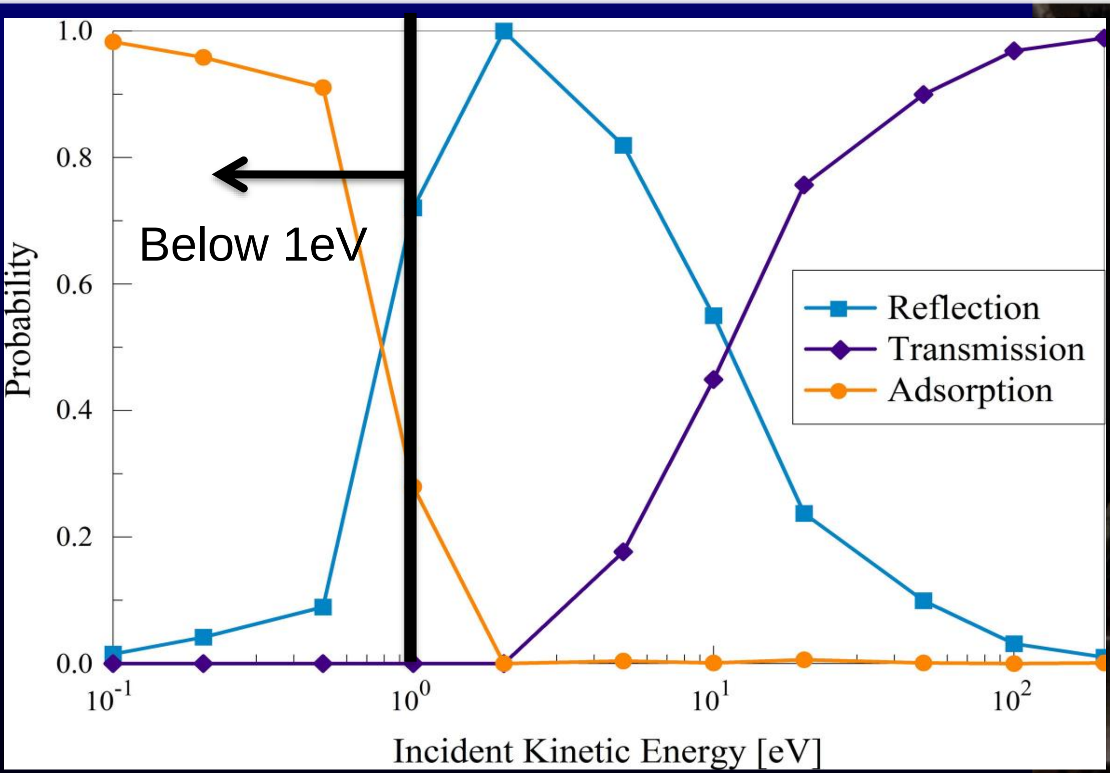
~3x10^{13} T/mm^2 (~80kHz of decays/mm^2)

First Samples Produced by SRNL

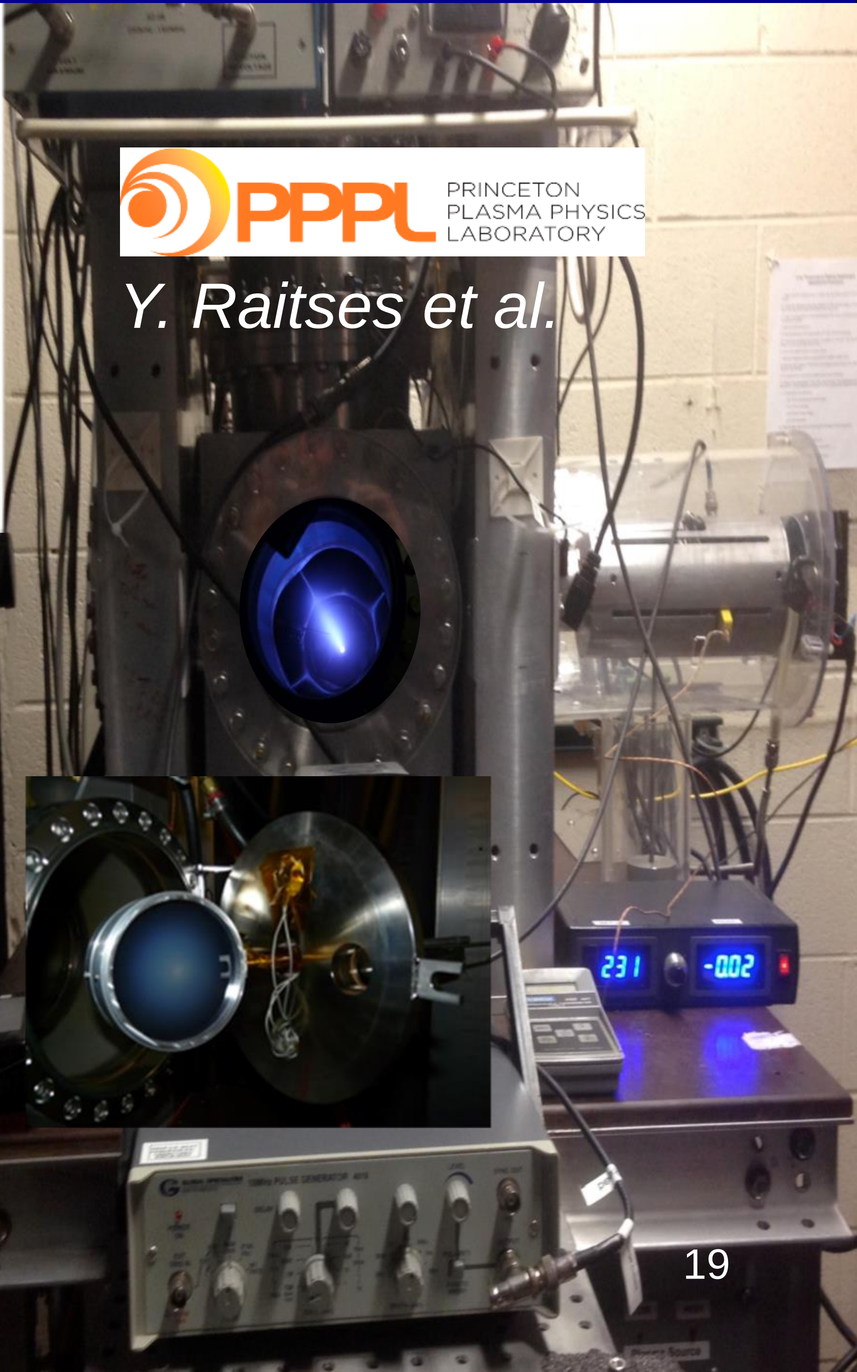
Cryogenic Au(111) also under investigation with Free Radical or Cold Plasma Loading

Cold Plasma Loading





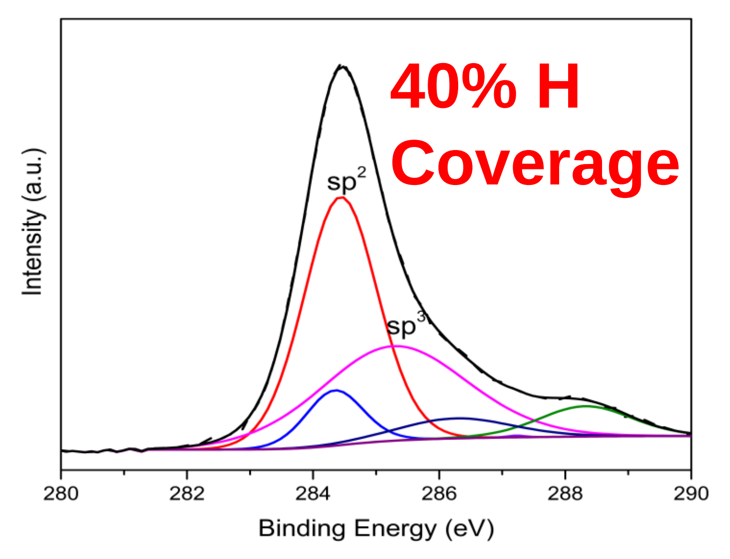
Ehemann et al. Nanoscale Research Letters 2012, 7:198



Y. Raitses et al.

Cold Plasma Loading at PPPL

XPS (X-Ray Photoelectron Spectroscopy) Analysis: sp^2 is from unhydrogenated C atoms. sp^3 is hydrogenated C atoms. The area ratio of sp^2 and sp^3 is used to calculate H coverage.



40% H Coverage

H coverage summary from the literature

2009 Science	DC plasma. H coverage 10%
2009 ACS Nano	Capacitive coupled RF plasma. H coverage 17%
2010 APL	RF hydrogen plasma. H coverage 9%
2011, Carbon	Oxford Plasmalab 1000. H coverage less than 10%
2011 Advance Material.	STM hydrogen dose, Hydrogen coverage max 25.6%
2014, Applied materials &interfaces	RIE system. H coverage 33%
2015, ACS nano	HPHT. H coverage 10%

Best results – aim to achieve saturation at 100% while preserving quality of Graphene

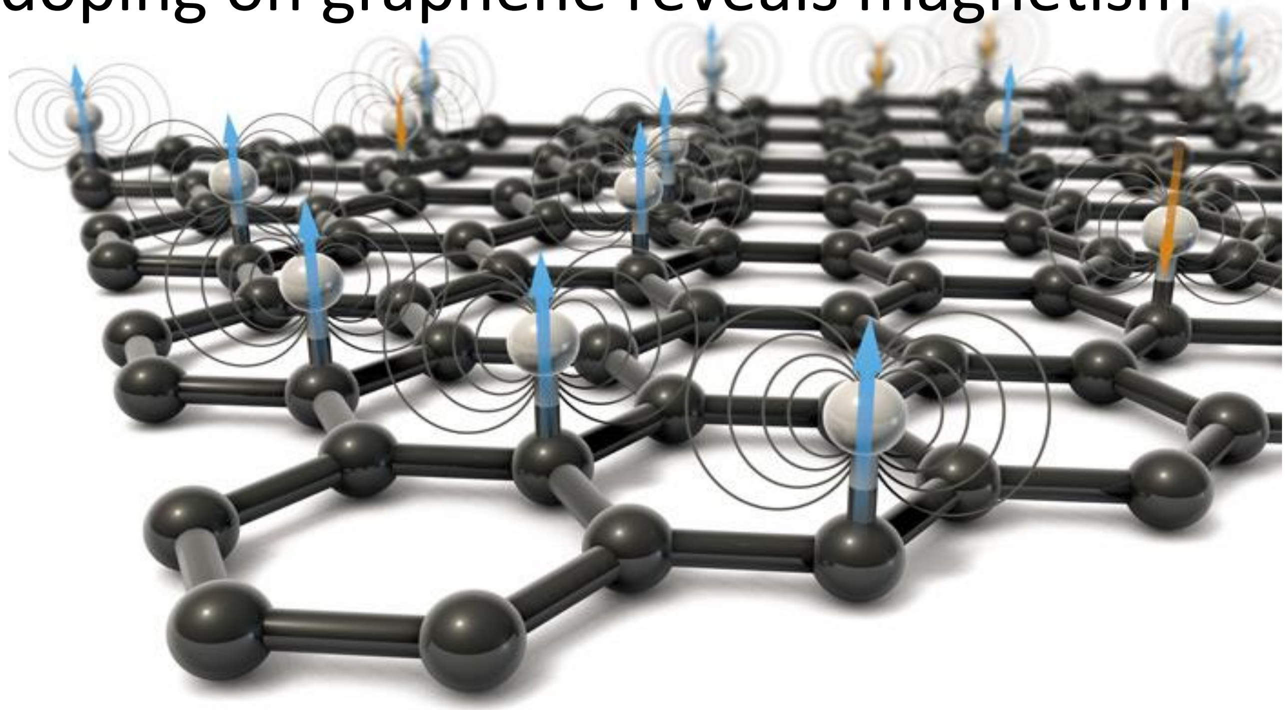
New Results!

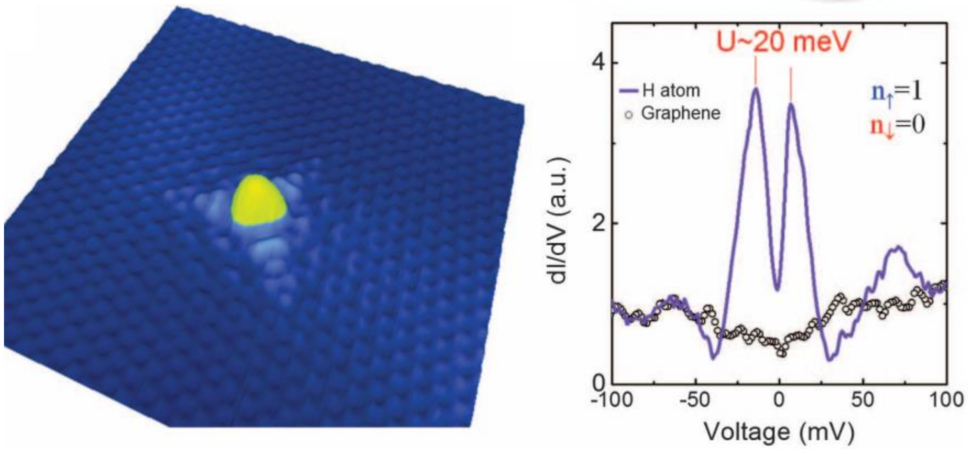
→ **BNL Center for Functional Nanomaterials**

→ **Cryogenic Hydrogen loading and STM Analysis**

Polarized Tritium Target

Hydrogen doping on graphene reveals magnetism



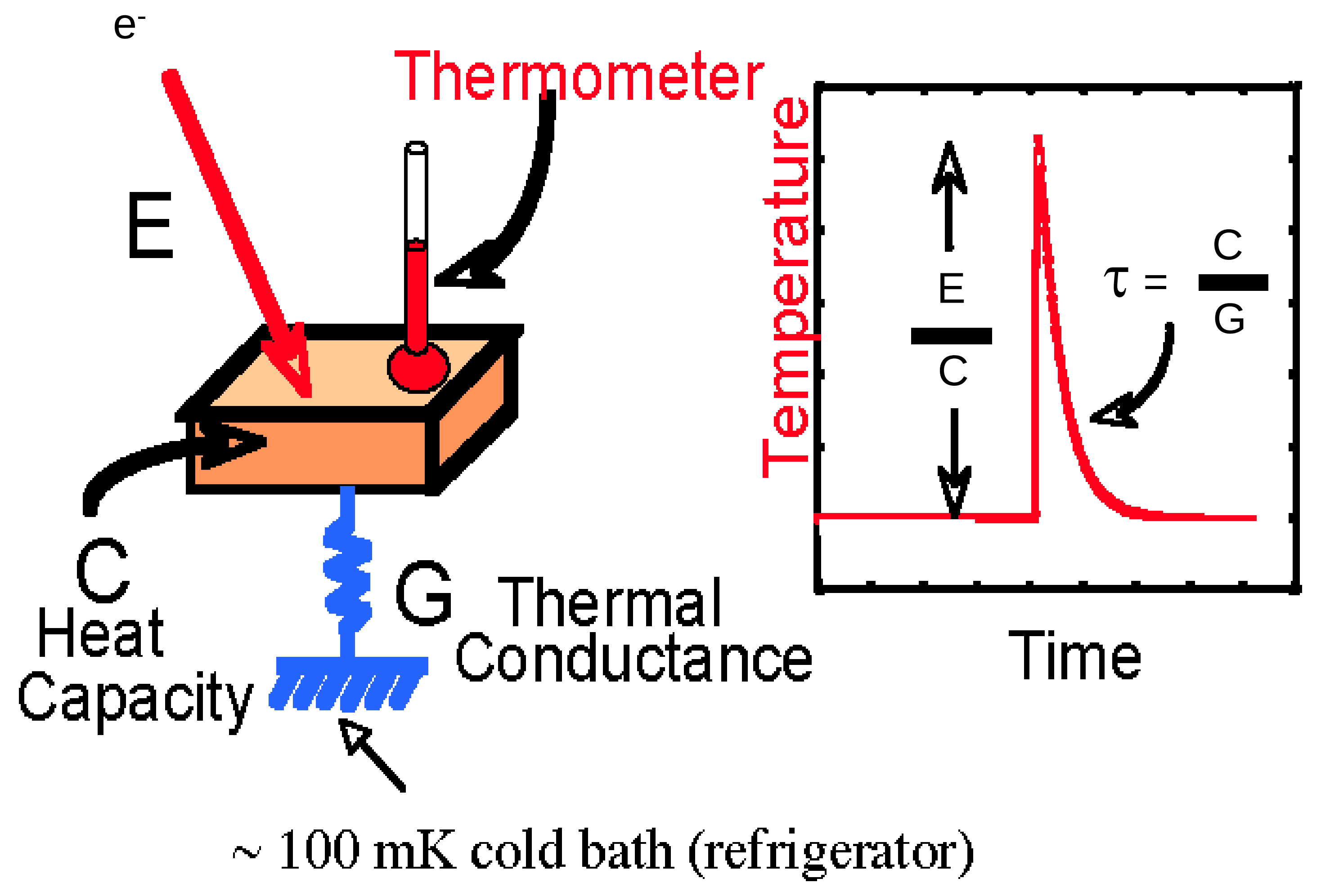


STM topography of a single H atom chemisorbed on neutral graphene. dI/dV spectrum measured on the H atom, showing a fully polarized peak at E_F, and measured on bare graphene far from the H atom.

Gonzalez-Herrero, H. *et al.* Atomic-scale control of graphene magnetism by using hydrogen atoms. *Science (80).* **352,** 437–441 (2016).

Microcalorimetry

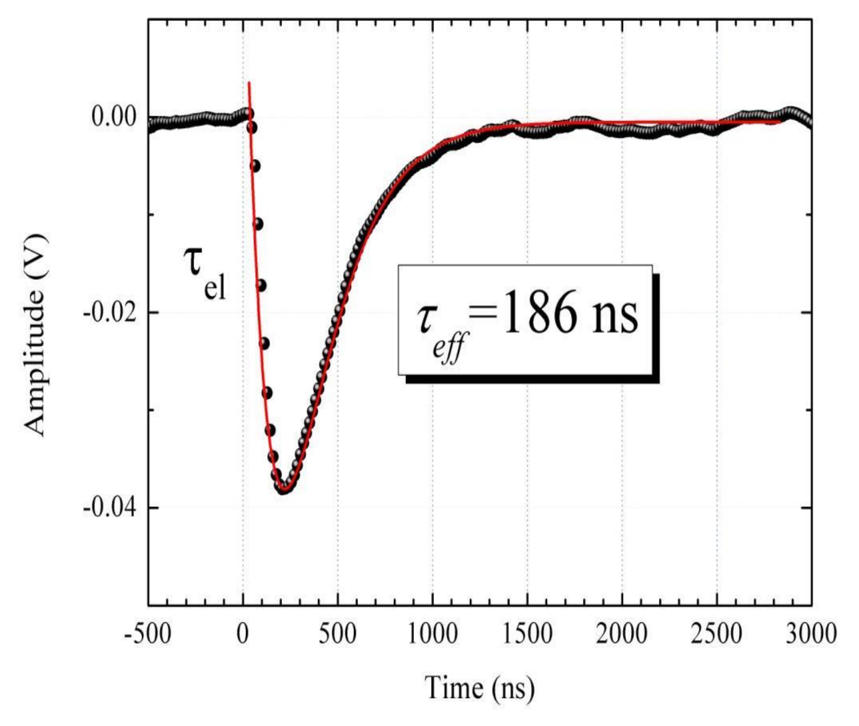
- Electron calorimetry with an energy resolution sufficient to resolve the neutrino mass



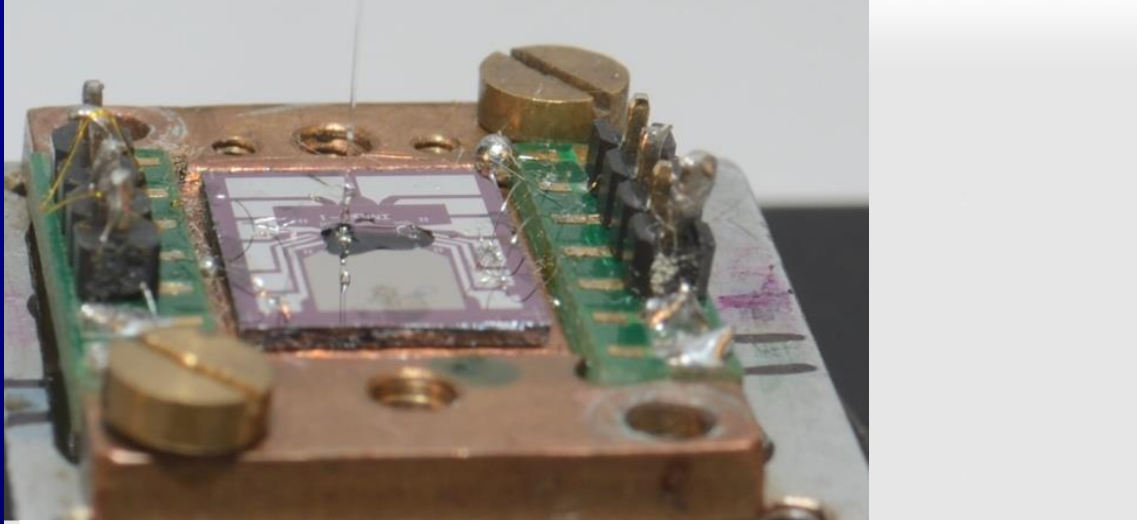
10eV electron can be stopped with very small C

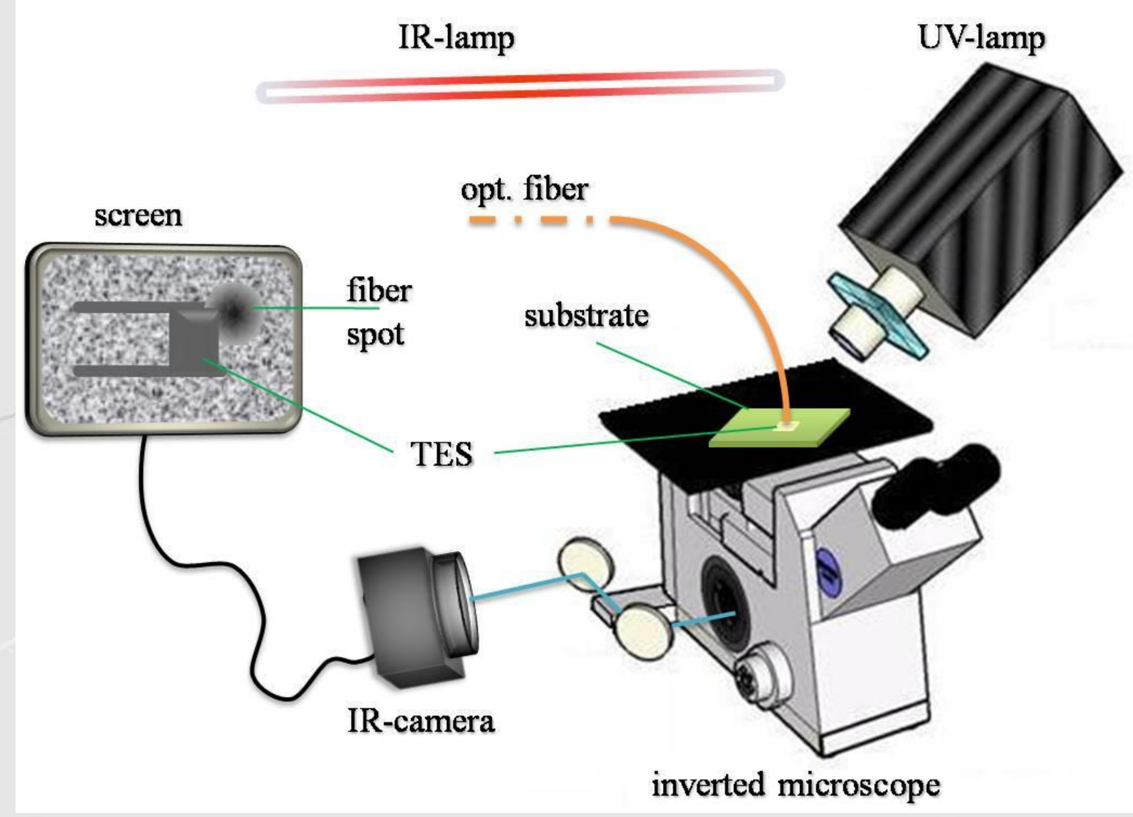
Time response (τ) also small (<μsec)

TES Single Photon IR Detectors



https://agenda.infn.it/getFile.py/access?contribId=12&sessionId=3&resId=0&materialId=slides&confId=12992





Microcal Energy Resolution

- Pushing down microcal resolution
  - – Most TES work is headed toward optical with extremely low heat capacitance
  - – 0.05eV@10eV (and further linear improvements from pushing down to 50mK)

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

(C/α) scaled down by a factor of ~1000

Keep α large, keep M small

Clarence Chang

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

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

Electron energy at calorimeter:	**Thickness of Gold Absorber:**
100 eV	**2.39 nm**
10 eV	**0.68 nm**

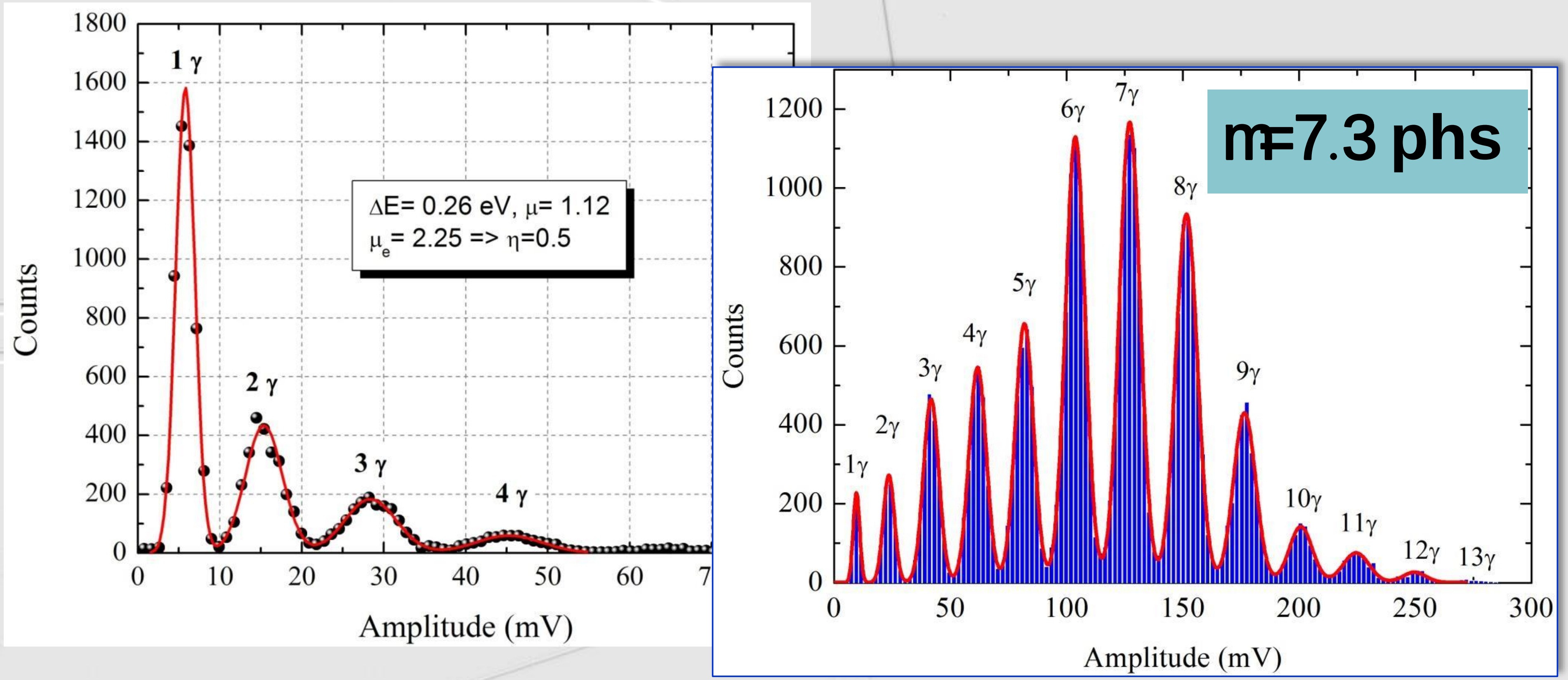
Also:

$$\Delta E_{FWHM} = 2.355\sqrt{4k_B T_c^3 \frac{\gamma V}{a}}\sqrt{\frac{n}{2}} \propto T_c^{3/2}$$

X-Ray microcals are typically 15 µm

TES: IR Photon Counting

TiAu TES T_c=301 mK



λ=1535 nm

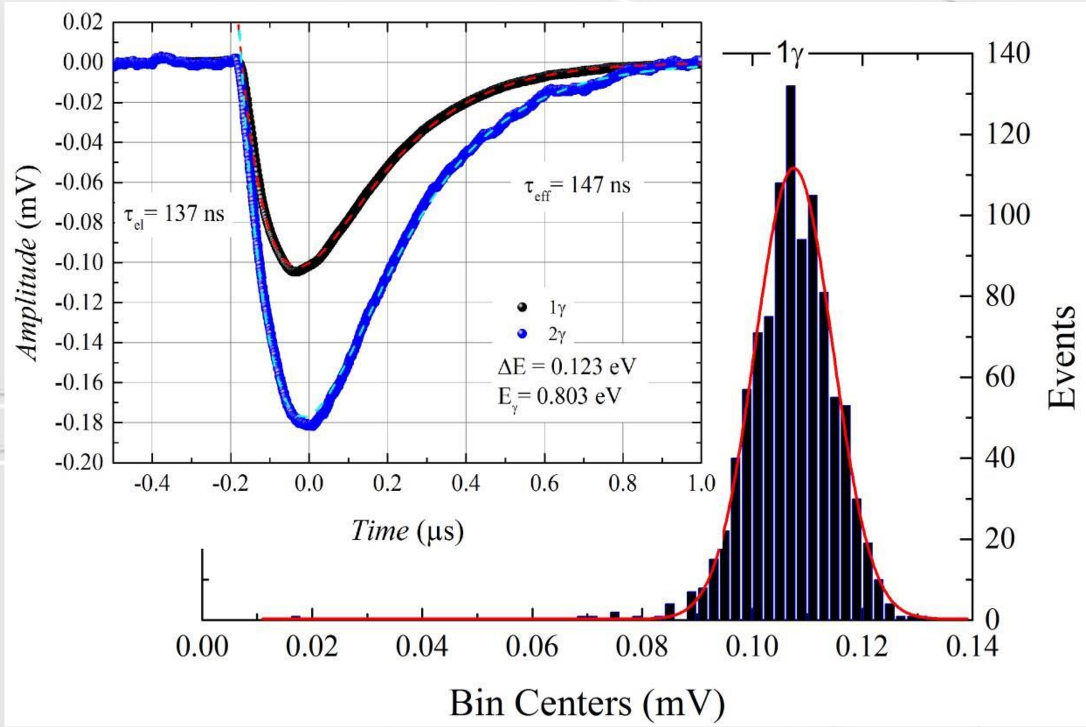
QE ~ 50 %

@ 500 kHz means
3.65x10^6 photons/s (473 fW)

Microcal for IR Photons

Example:

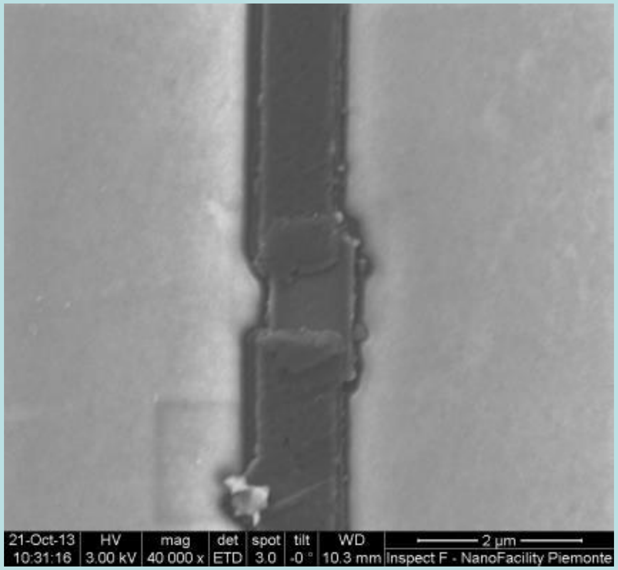
IR TES cameras also very active 0.12 eV resolution achieved at 0.8 eV for single IR photons



t_{etf} = 147ns

ΔE_{FWHM}= 0.12 eV
@ 1545nm

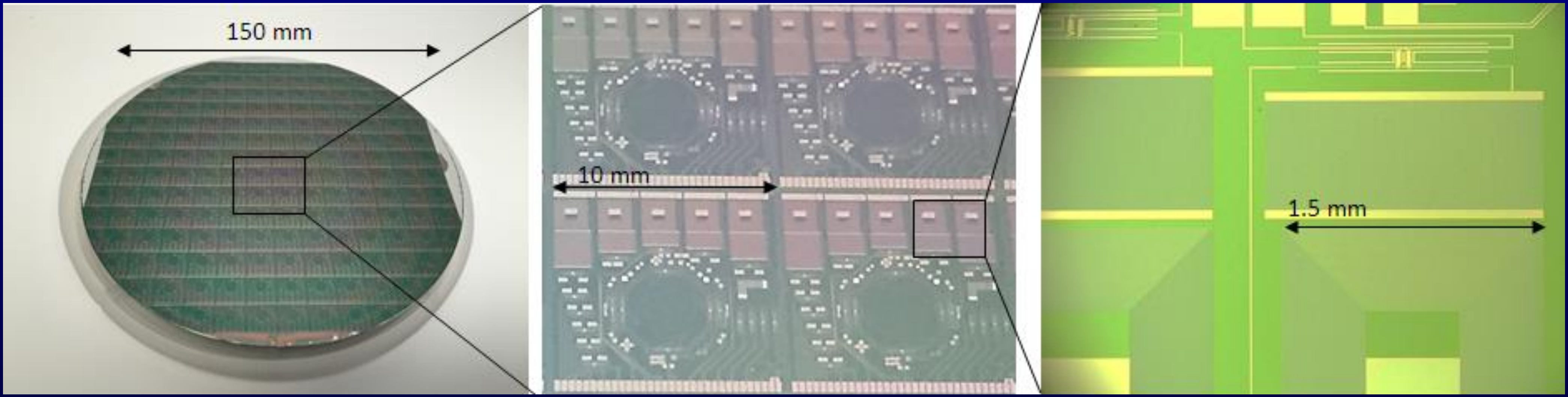
1 mm × 1 mm



C. Portesi *et al*, IEEE Trans App Supercond, 25, 3, (2015)

Synergies with CMB-S4

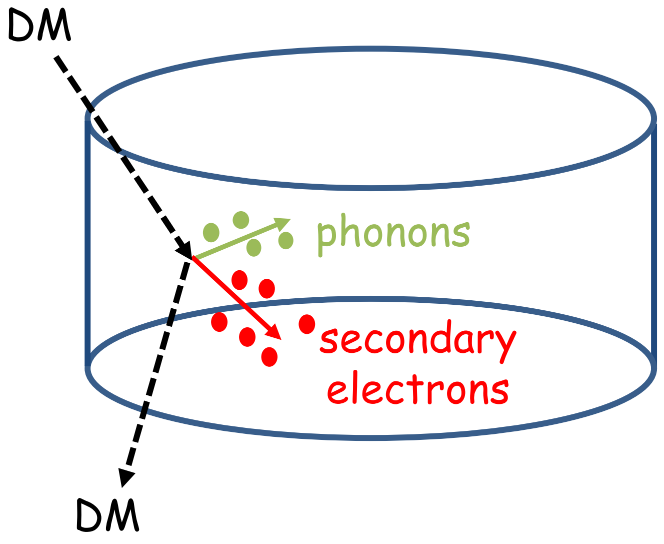
Microcalorimeter development work for PTOLEMY builds off of S4 TES designs from Clarence Chang (ANL)
Microwave multiplexing developments for CMB-S4 are directly relevant for PTOLEMY



~100 MHz Lumped Element Resonators → ~1 GHz
Integrated onto wafer (compact, eliminates wire bonding)

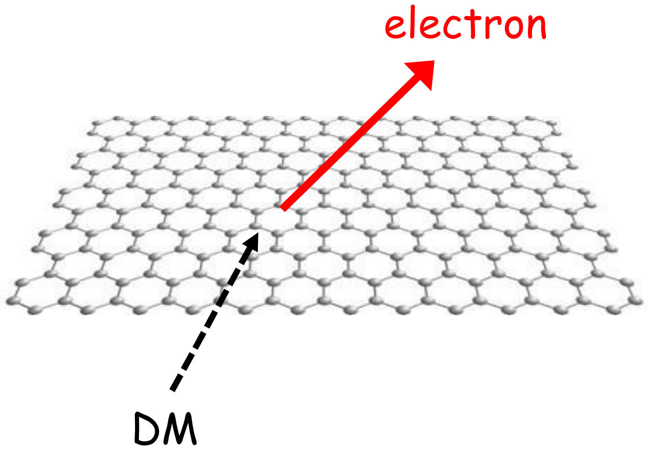
Photocathode-type e$^-$ Emission

Lose directional information
if detecting secondaries



e.g. SuperCDMS, superconductors

Retain directional information
if observe primary!



2D targets; Graphene

- To eject electron: $E_{\text{eject}} = E_b + \Phi \sim \text{eV}$

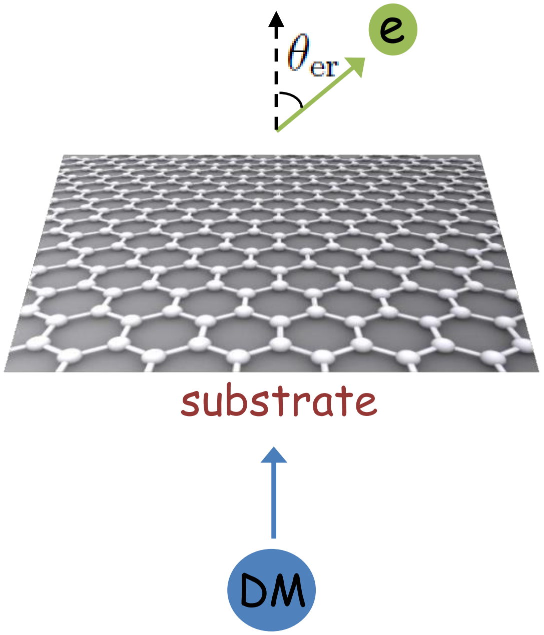
Binding energy

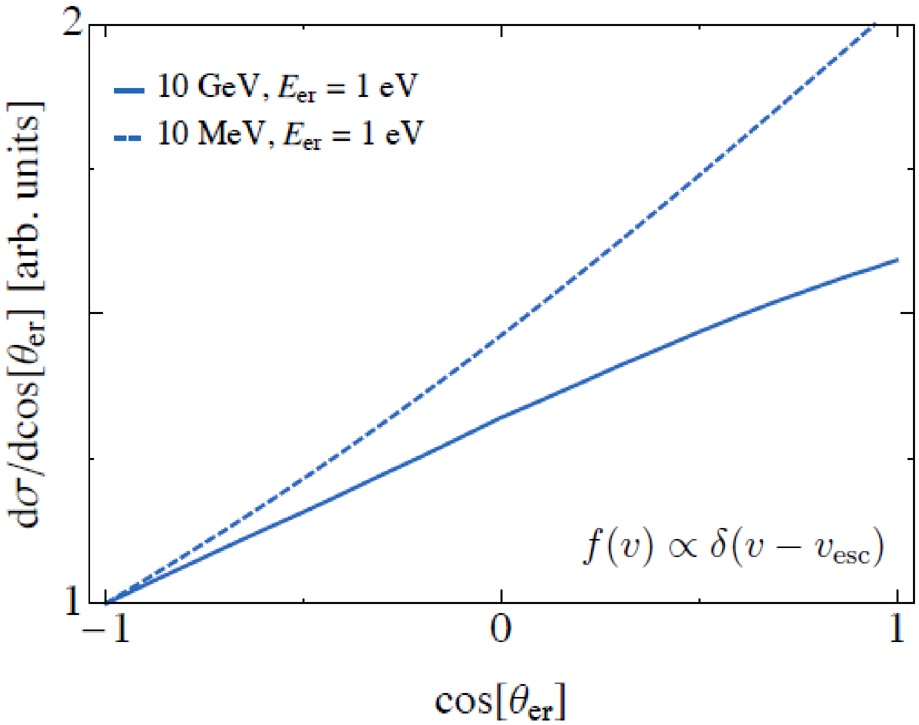
Work function ~4 eV,
tunable

Forward-Backward Asymmetry

Dark matter stream perpendicular to the sheet:

Forward scattering persists.





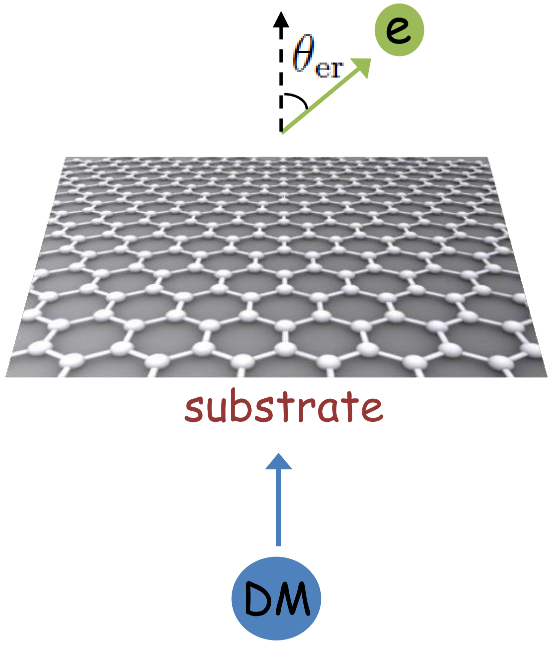
Daily Modulation

Dark matter stream perpendicular to the sheet:

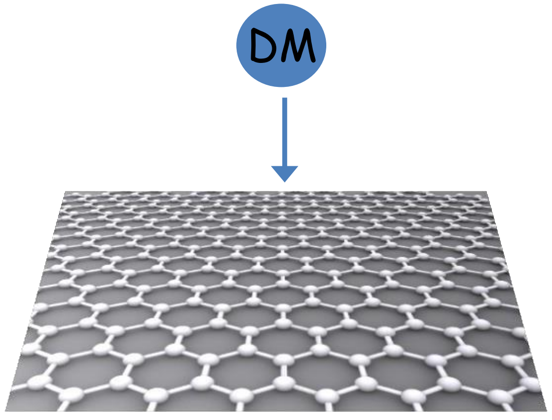
Forward scattering persists.

Naturally gives forward-backward discrimination

Electron detected

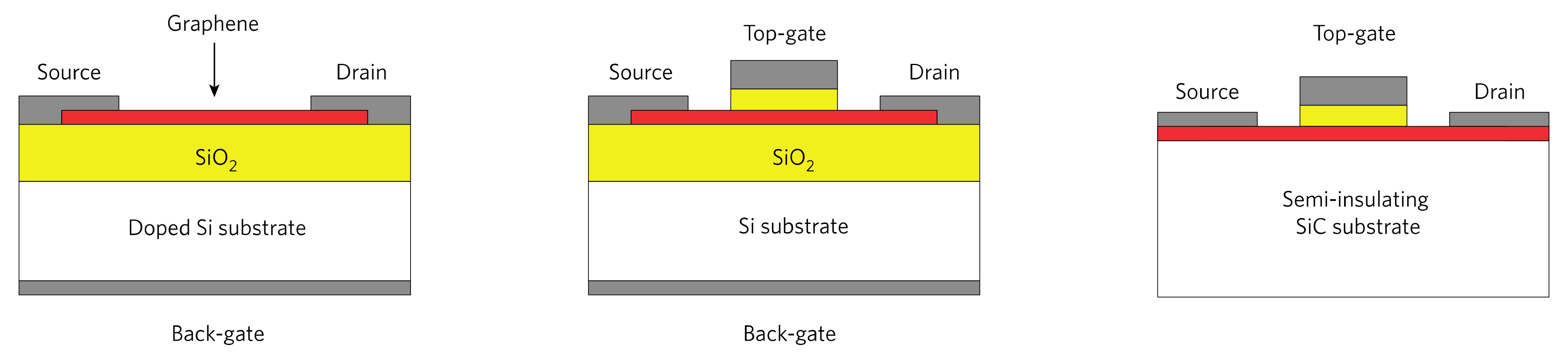


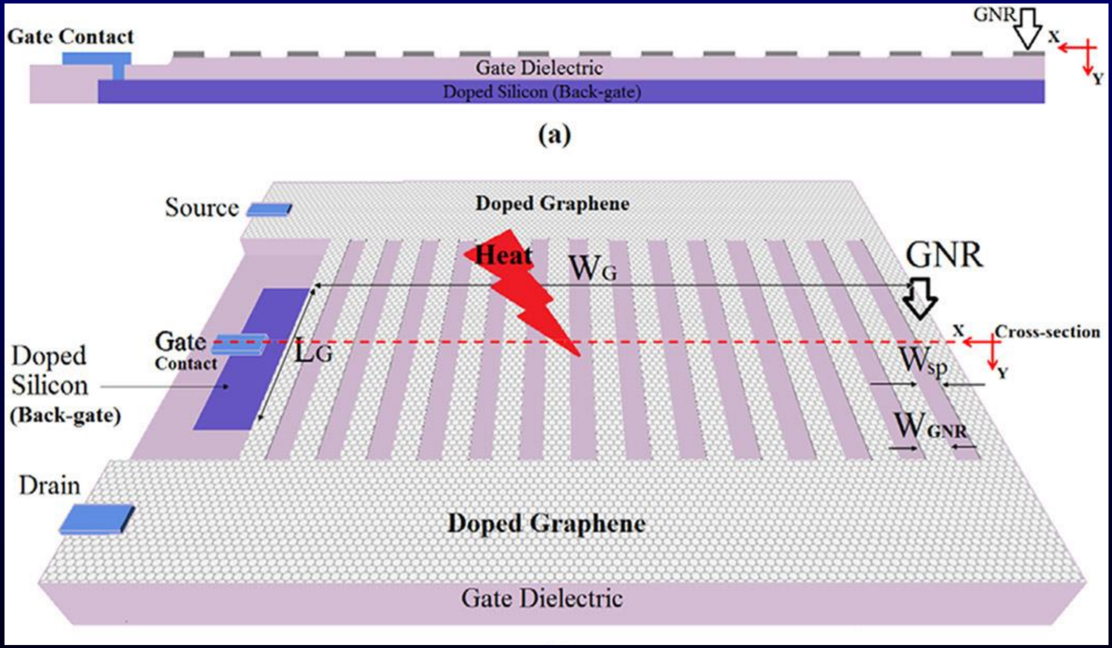
electron not detected



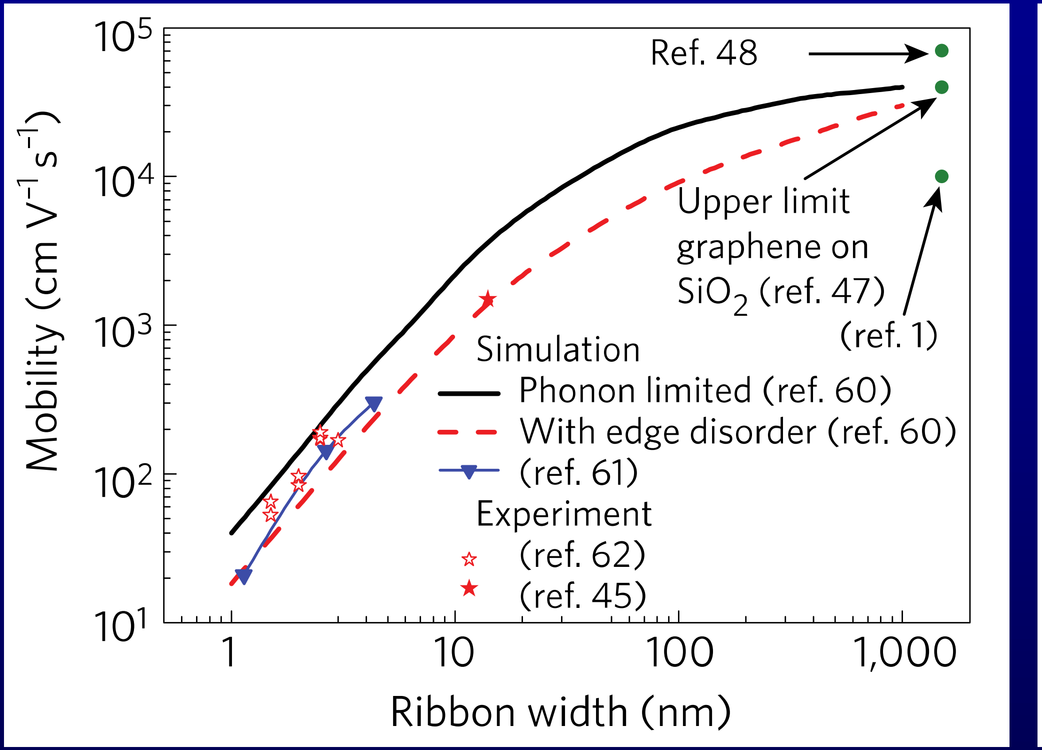
12 hours later

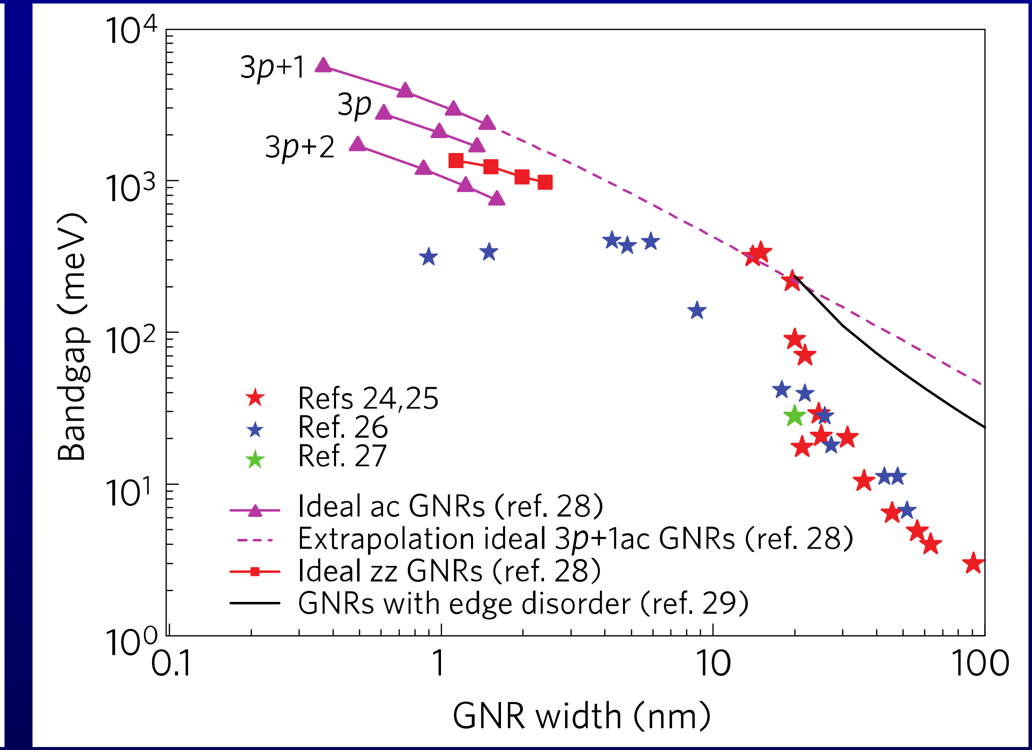
Graphene FET Structures

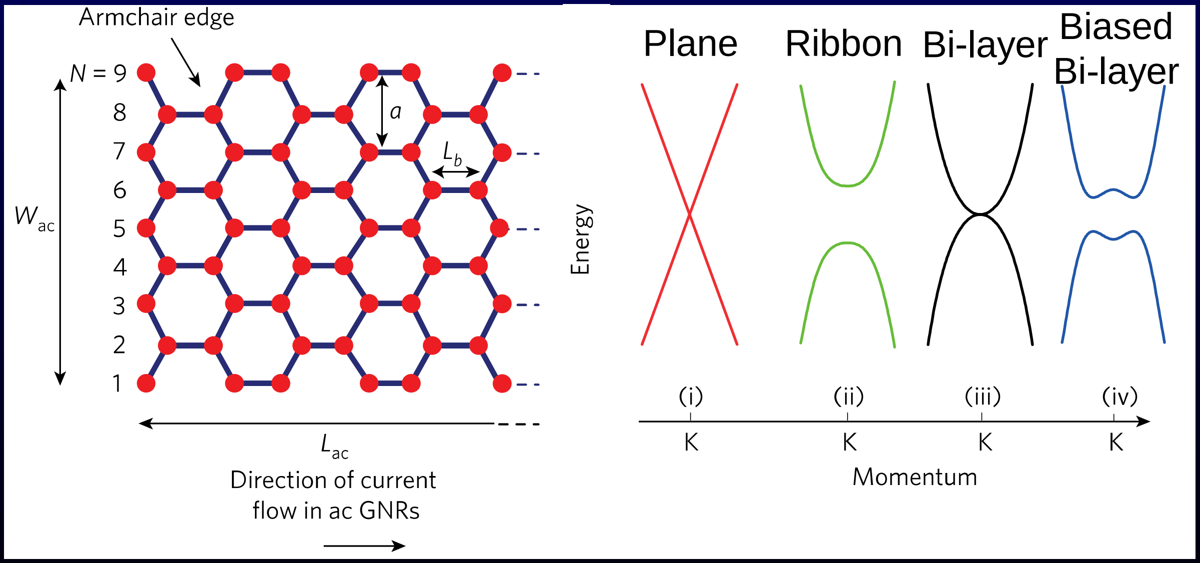




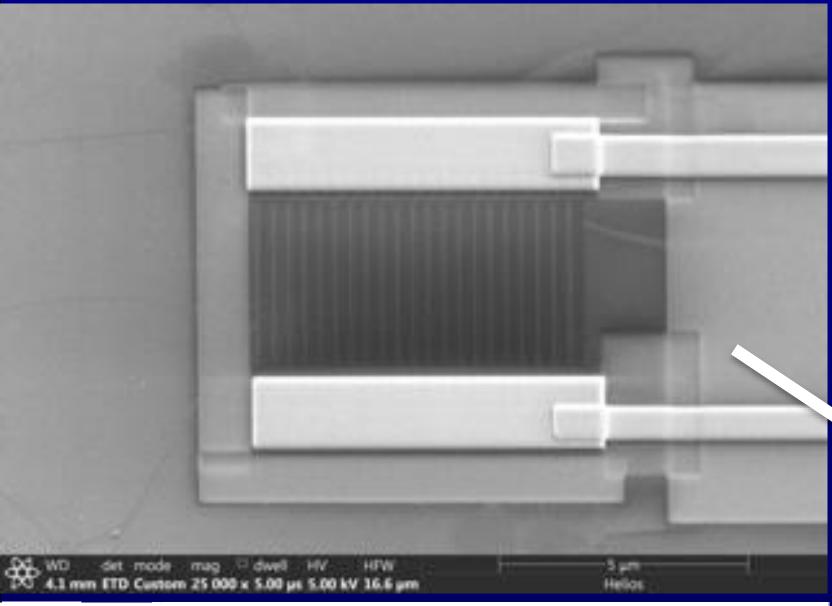
Graphene Nanoribbons (GNR)





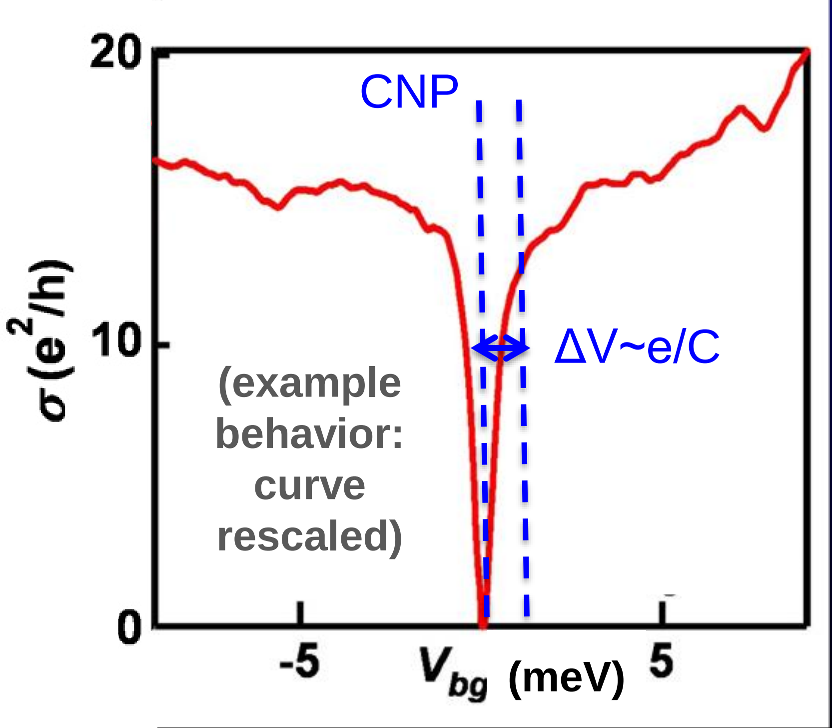


G-FET

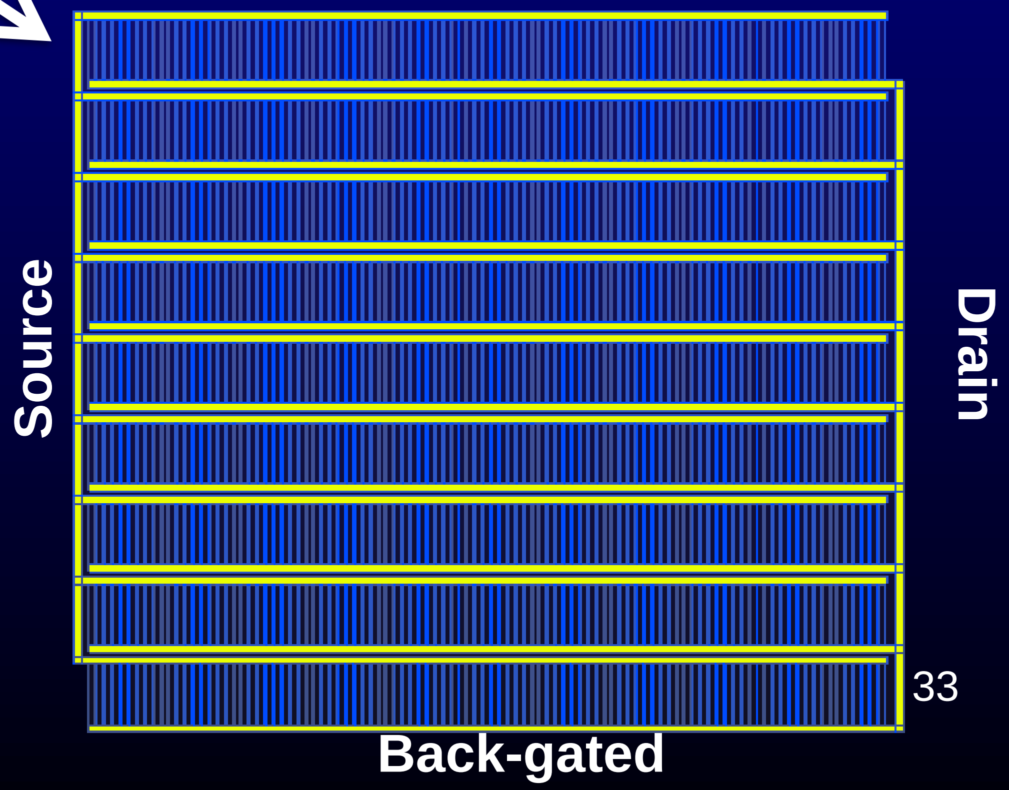


Principles of Operation:

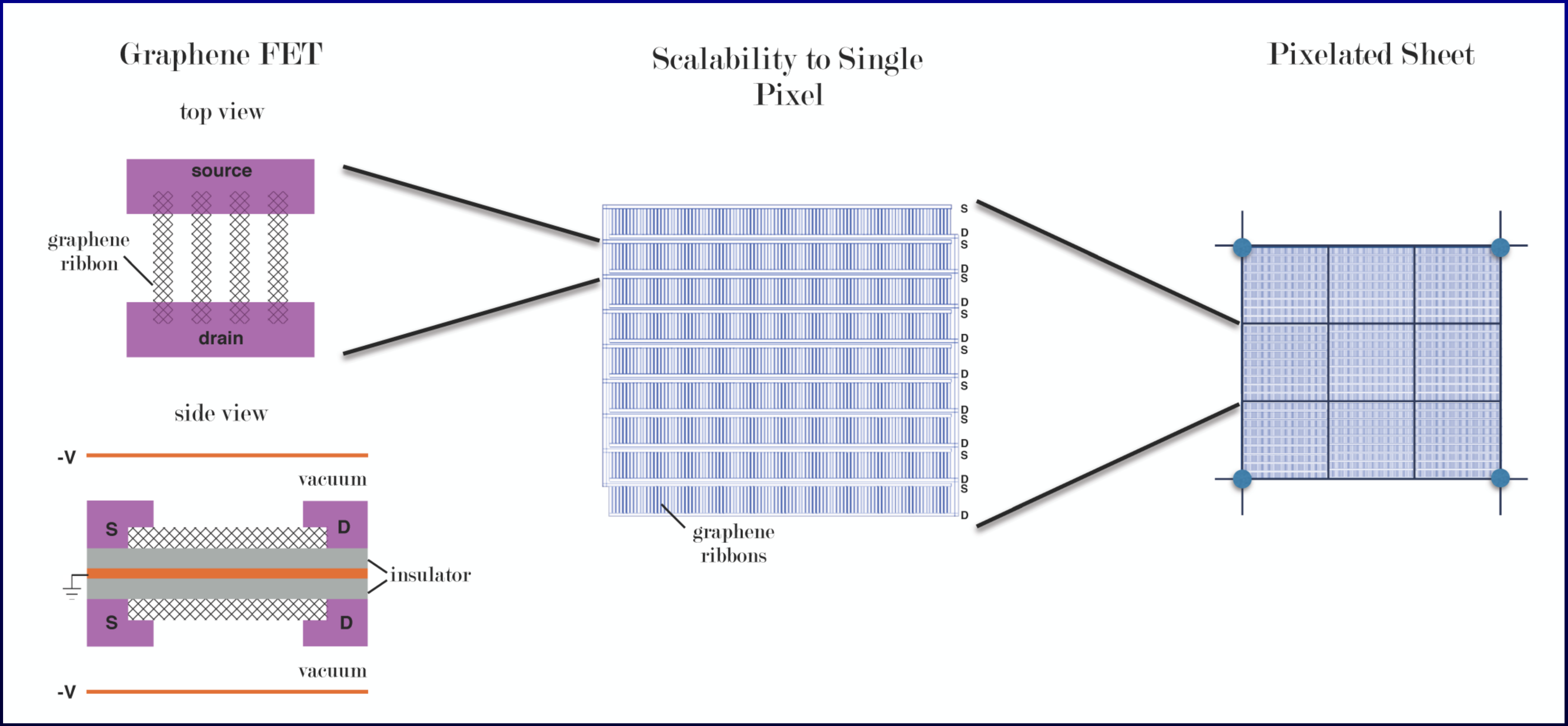
- Tunable meV band gap set by nanoribbon width (E_{gap} ~ 0.8eV/width[nm])
- Large jump in conductivity (~10^{10} charge carriers) relative to charge neutrality point under the field-effect from a single electron scatter



Scalability to Interdigitated Capacitor



Scaling up ~μm to ~cm



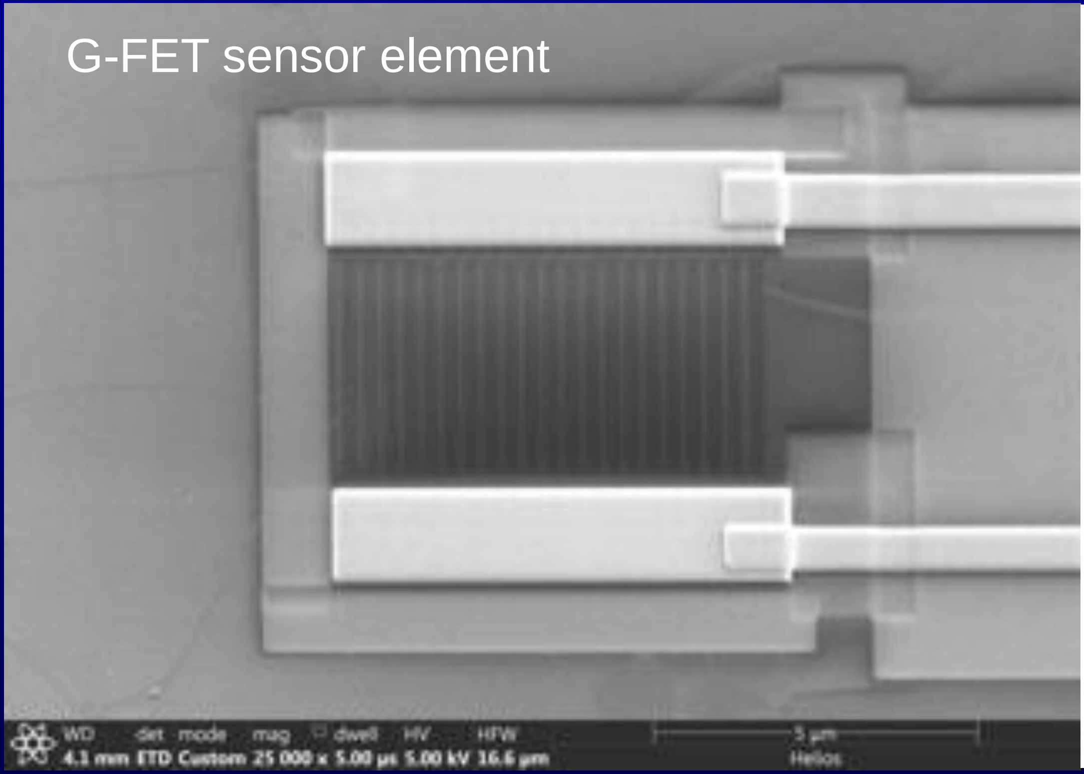
PTOLEMY-G^3

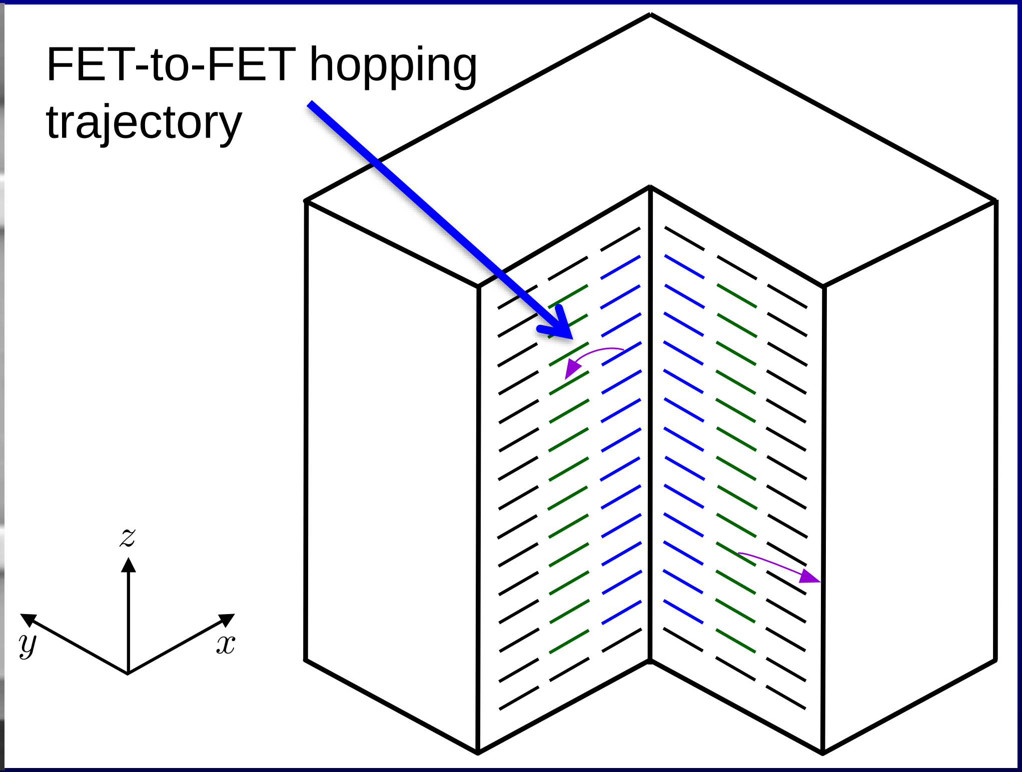
- 2D Targets for Direct Directional Detection of MeV Dark Matter
  - Hochberg, et. al, 2016. “Directional Detection of Dark Matter with 2D Targets", http://doi.org/10.1016/j.physletb.2017.06.051
  - Graphene field-effect transistors (G-FETs) arranged into a fiducialized volume of stacked planar arrays – Graphene cube (G^3)
  - Unprecedented sensitivity to electron recoil, at the level of single charge detection
- G-FETs provide tunable meV band gaps and provide high-granularity particle tracking when configured into arrays
  - A narrow, vacuum-separated front-gate of the G-FET imposes a kinematic discrimination on the maximum electron recoil energy, and the FET-to-FET hopping trajectory of an ejected electron indicates the scattering direction, shown to be correlated to the dark matter wind

Importance for Relic Neutrinos:

Provides an opportunity to “null” experiment with a large “bare” Graphene target (no tritium) to qualify the radiopurity and backgrounds are at the level for relic neutrino detection.

Fiducialized Volume (G^3)





20 Graphene Nanoribbon Array
(produced at Princeton University)
Resistance-Temperature (RT) and Current-Voltage (IV) curves in progress
Scalability to interdigitated capacitor with pixel areas of 1mm^2 or larger

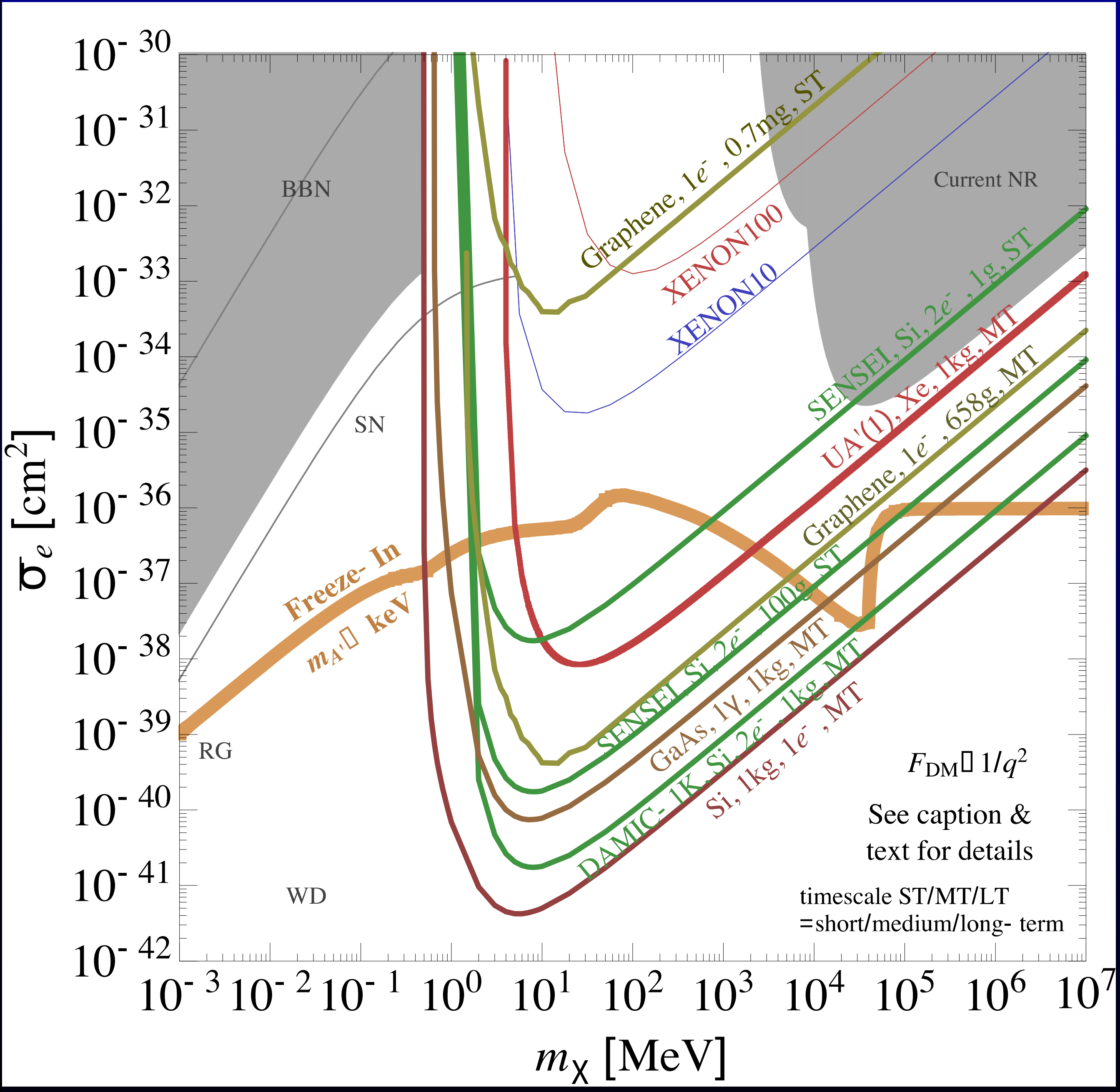
Stacked planar arrays of G-FETs
1kg ~ 10^{10}cm^2 ~ 10^9cm^3
Individually vacuum-sealed wafers
Cryogenically cooled (4.2K)
Cryopumping of gas contaminants on G^3 surface - no line-of-sight trajectories
Low mass substrates with ALD dielectric

Graphene Target: Important Step for PTOLEMY

Projected Low Backgrounds

- High radio-purity wafer-level fabrication
  - Low background contamination lithography has been demonstrated, see for example ``Cryogenic Dark Matter Search detector fabrication process and recent improvements'' by Jastram et. al, 2015. NIM A: 772:14-25.
- Ultra-low ratio $^{14}C/C$ graphene growth → Push forward on the landmark work done for Borexino (source identified)
  - Litherland et. al, 2005. ``Low-level 14C measurements and Accelerator Mass Spectrometry'' in AIP Conference Proceedings, vol. 785, p. 48. http://dx.doi.org/10.1063/1.2060452
  - A. E. Lalonde AMS Laboratory in Ottawa interested in restarting program to measure $^{14}C/C$ at level of 10^{-21}
- Cosmic Ray Overburden
  - Pursing possibility of relocating PTOLEMY prototype in an underground laboratory
  - An overburden of 3km w.e. would reduce dead-time from self-veto to a reasonable level (estimated to be sub-percent)

Comparing MeV Direct Detection



New Proposal: PTOLEMY-G^3
Hochberg, et. al, 2016.
"Directional Detection of Dark Matter with 2D Targets",
http://doi.org/10.1016/j.physletb.2017.06.051

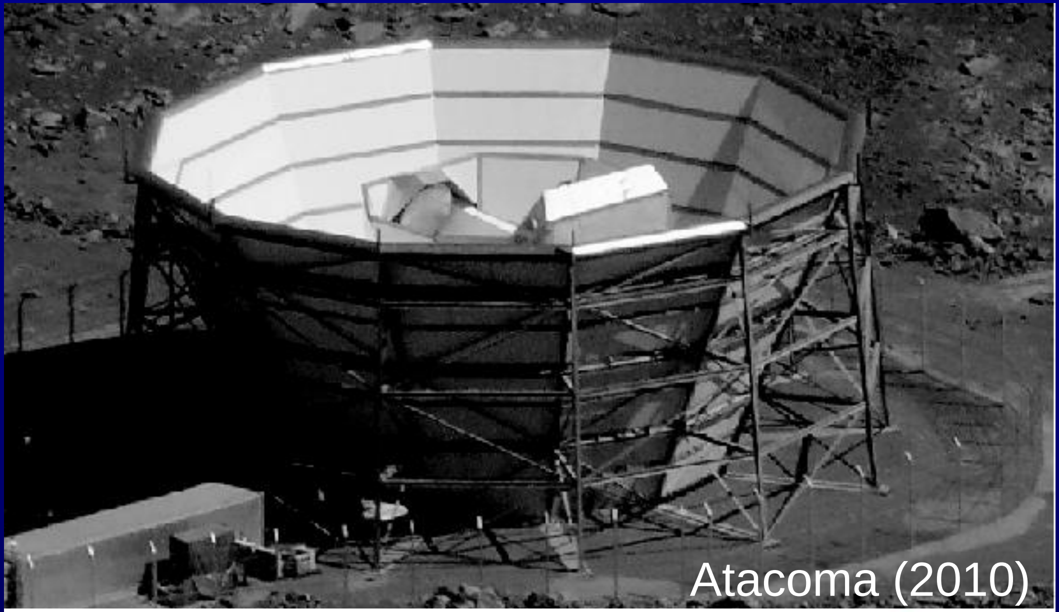
Near-term results for MeV Dark Matter expected with 2e$^-$ thresholds in Si (DAMIC/SENSEI/SuperCDMS)

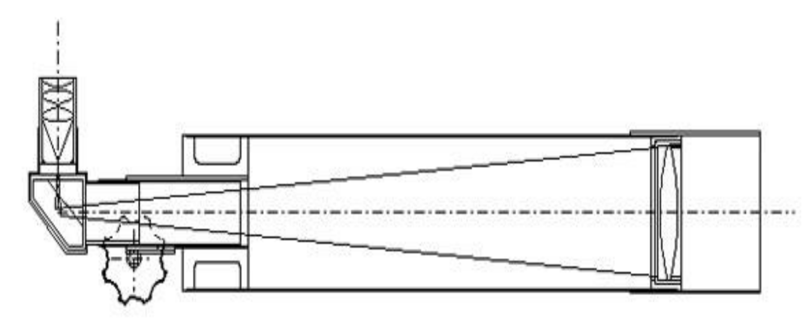
→ Significant overlap in sensitivity to follow up with **Directional Detection (PTOLEMY-G^3)**

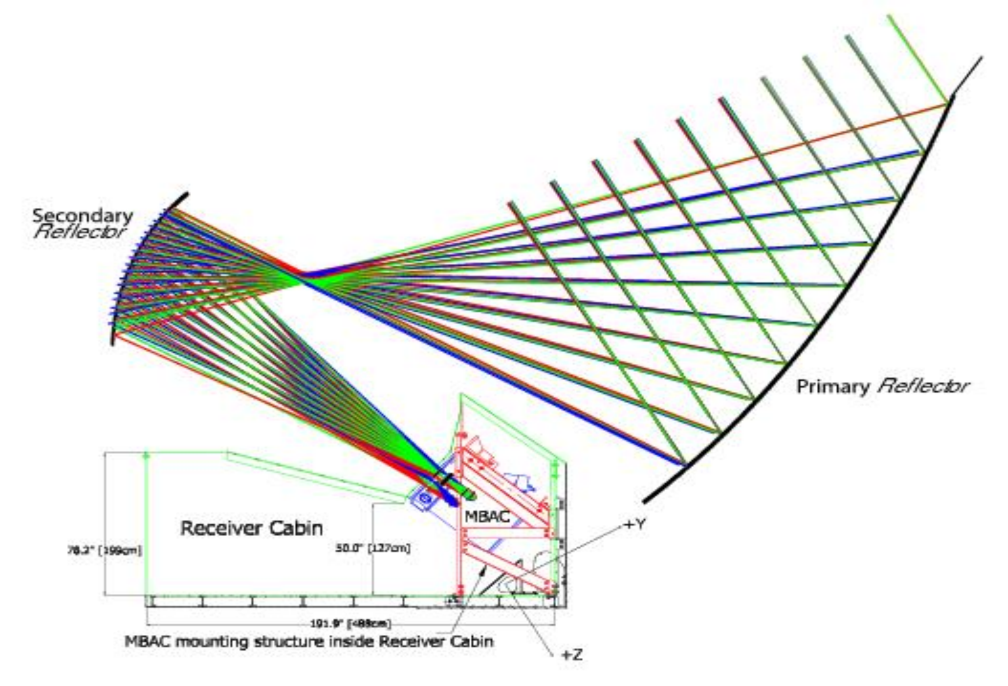
U.S. Cosmic Vision
New Ideas in Dark Matter
http://arxiv.org/abs/1707.04591

End of the Line for Refractor Telescopes


Yerkes (1895)


Atacoma (2010)

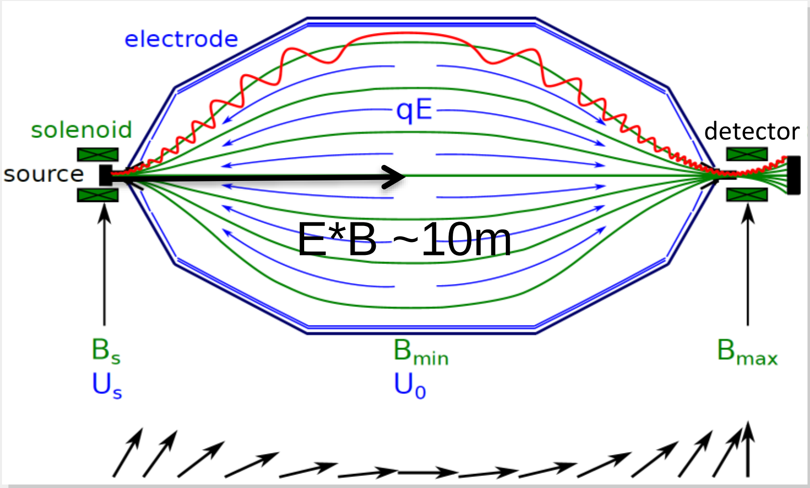




MAC-E “Telescope”

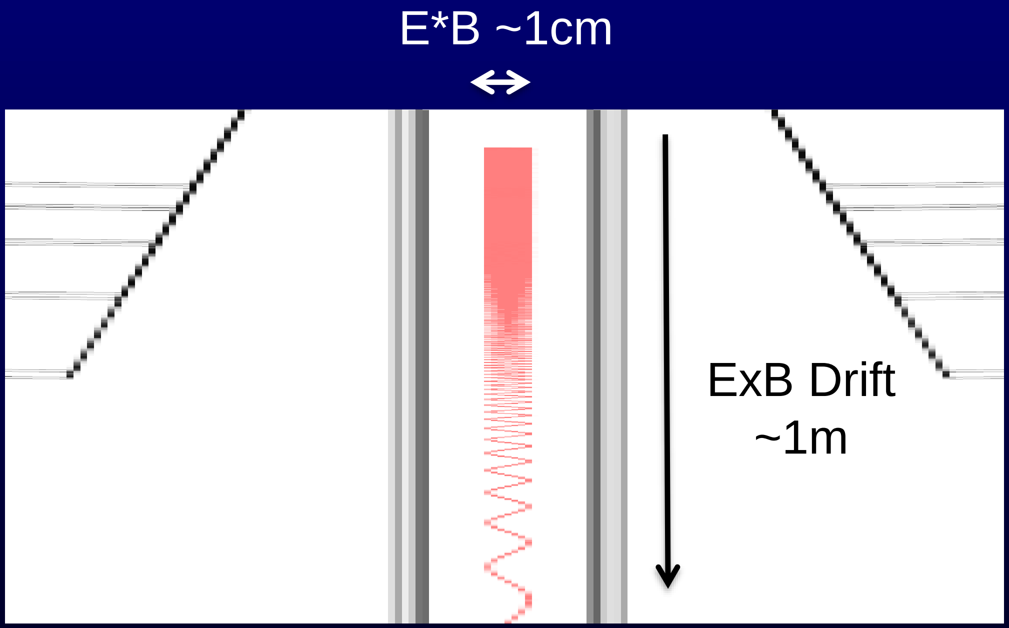
MAC-E filter technique

Magnetic Adiabatic Collimation with Electrostatic filter
Picard et al., NIM B63 (1992) 345



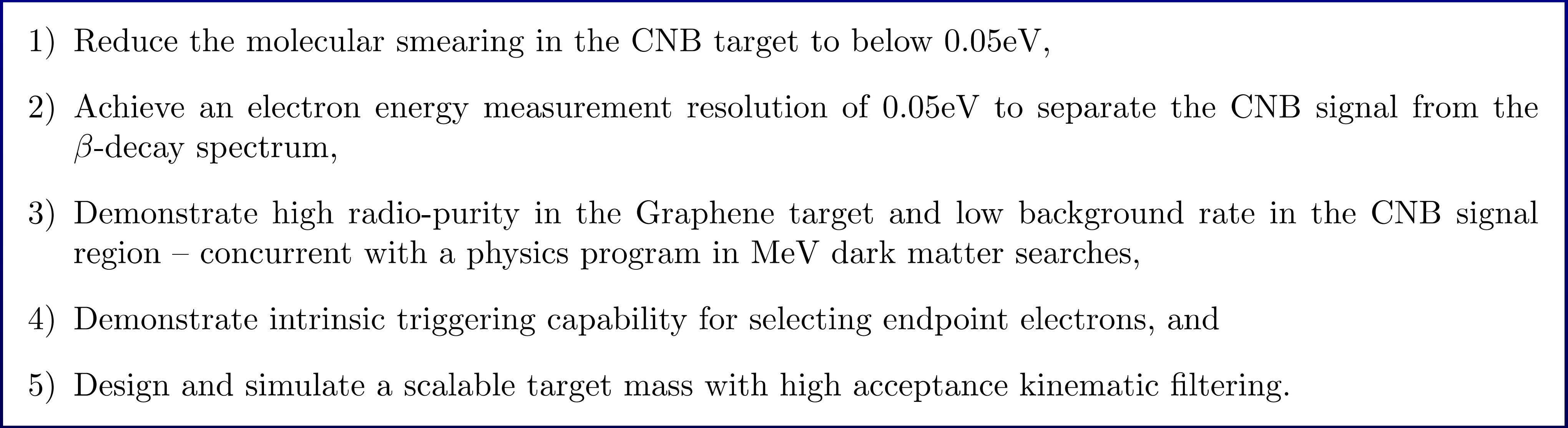
$$\mu = \frac{E_\perp}{B} = \text{const.}$$

PTOLEMY implements a “reflector” method that is four orders of magnitude more compact along the direction of the B field



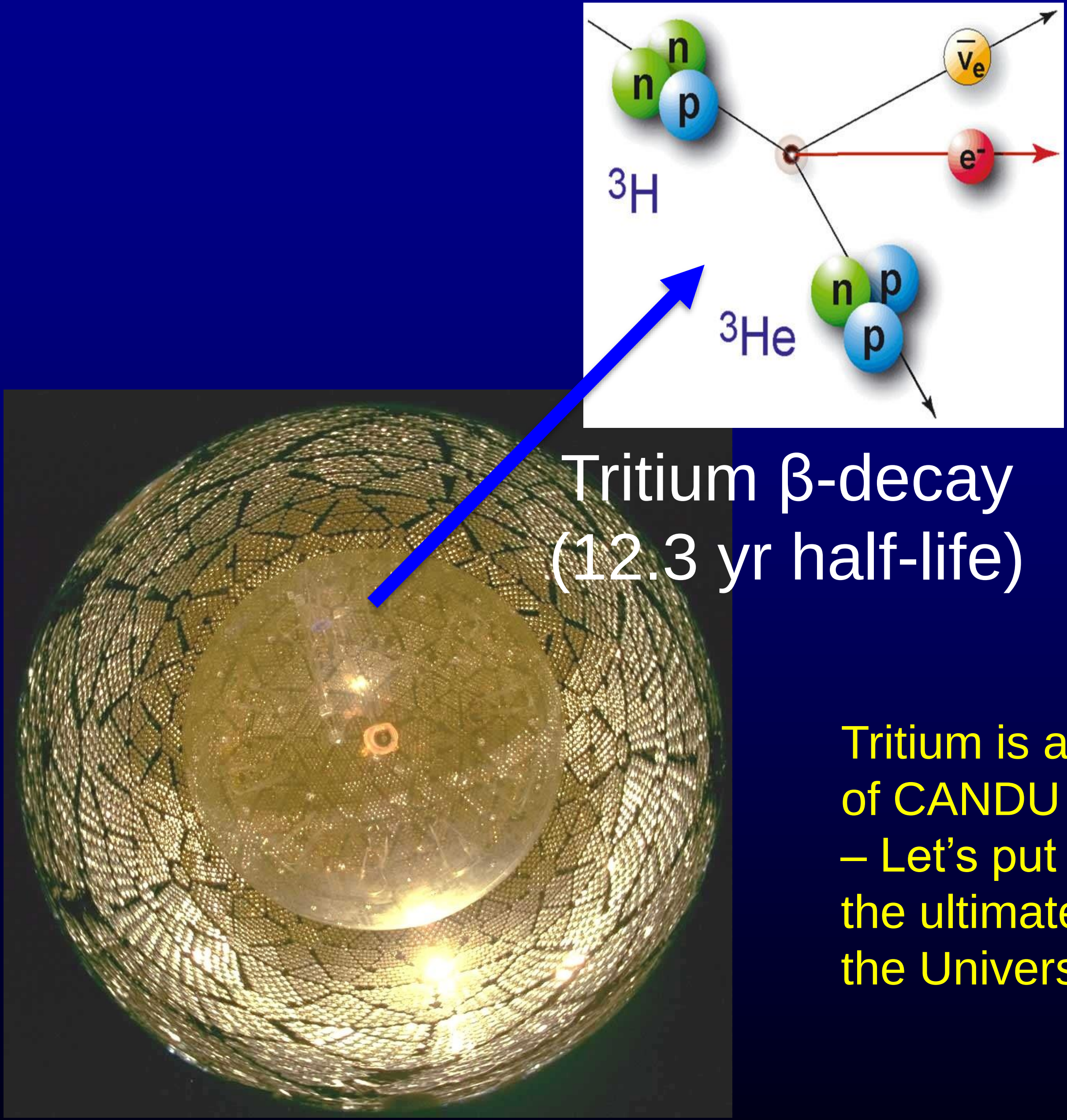
Filtering of the energy is in the vertical direction

Program of Work



1) Reduce the molecular smearing in the CNB target to below 0.05eV,
2) Achieve an electron energy measurement resolution of 0.05eV to separate the CNB signal from the β-decay spectrum,
3) Demonstrate high radio-purity in the Graphene target and low background rate in the CNB signal region – concurrent with a physics program in MeV dark matter searches,
4) Demonstrate intrinsic triggering capability for selecting endpoint electrons, and
5) Design and simulate a scalable target mass with high acceptance kinematic filtering.

Synergy with SNOLAB



Tritium β-decay
(12.3 yr half-life)

No kinematic threshold to this process
→ Target material for ultra-cold neutrino detection

Tritium is a natural bi-product of CANDU reactors
– Let's put it to use to solve the ultimate questions about the Universe!

Now the problem…

Princeton Tritium Observatory → PTOLEMY

“P” is silent??

Partnership of Tritium Observatories

Canada (SNOLAB)

Italy (LNGS)

P.J.E. Peebles

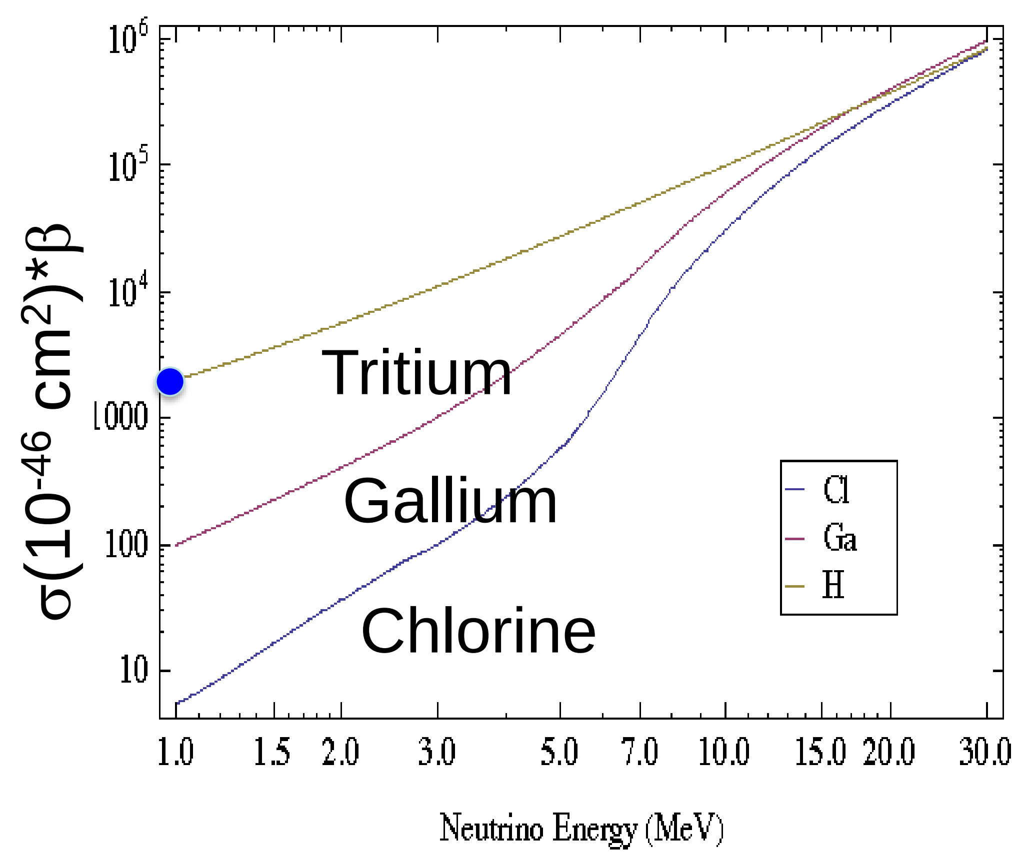
Pontecorvo

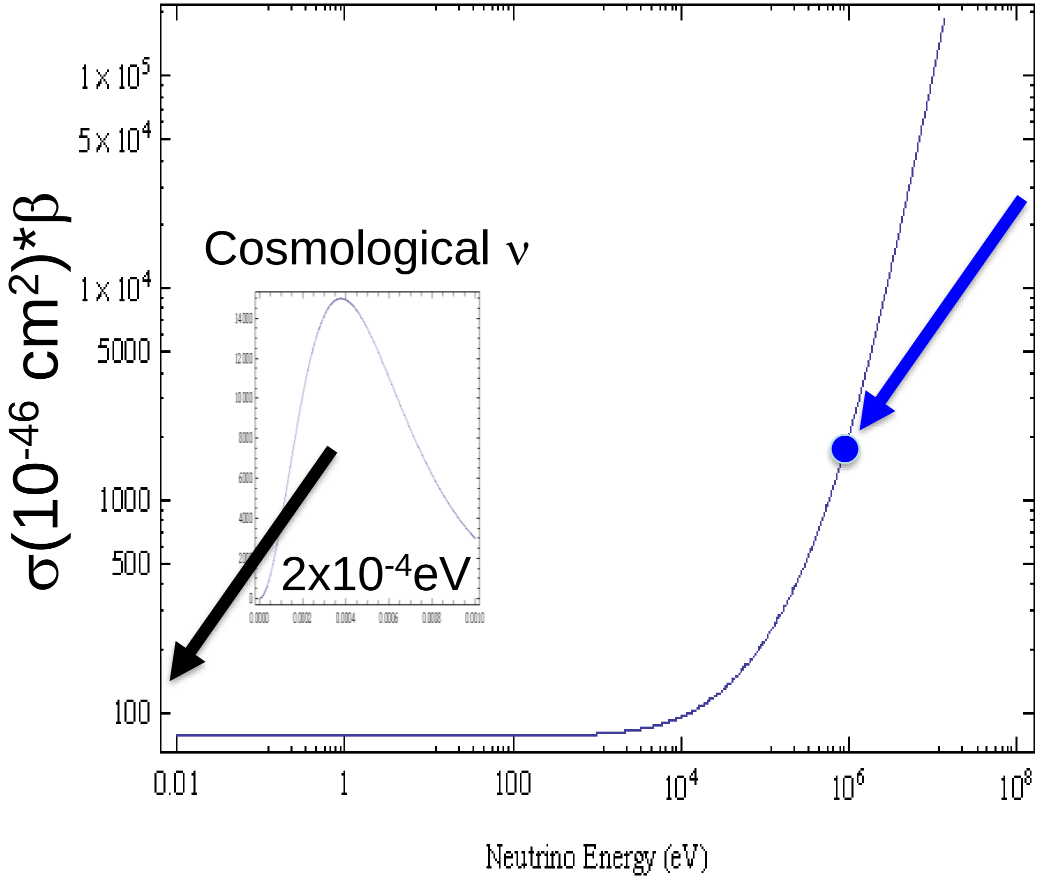
China (JinPing)??

Backup

Neutrino Capture σ*β

Tritium compares well with Gallium and Chlorine (and has no threshold)





Flattens out at low energy:

$\sigma^*\beta=(7.84\pm0.03)\times10^{-45}\text{cm}^2$

Neutrino Love Affair

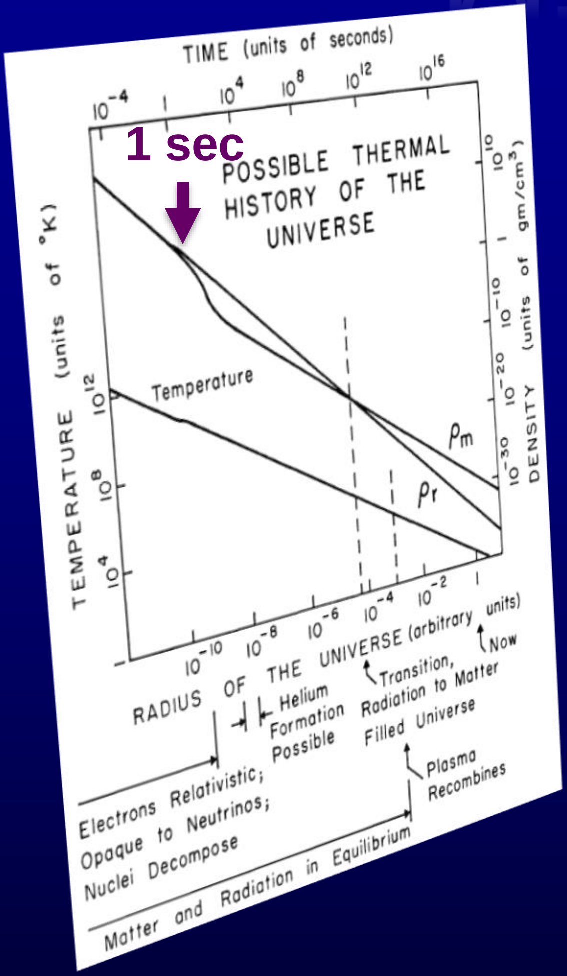
- Neutrino Portal
  - Mirror Universe → Restore exact L-R symmetry under Mirror Parity by introducing a Dark Sector mirror copy of the visible sector Gauge Group with SU(5)^{VS} x SU(5)^{DS}

$$f = \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad u_R \quad d_R \quad e_R$$

$$f' = \begin{pmatrix} u' \\ d' \end{pmatrix}_R \quad \begin{pmatrix} \nu' \\ e' \end{pmatrix}_R \quad u'_L \quad d'_L \quad e'_L$$

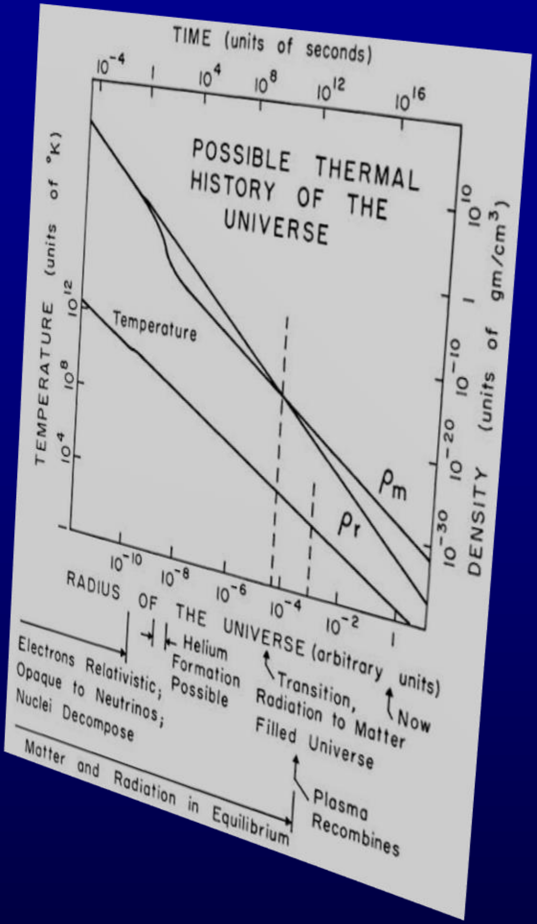
- Neutrino mass terms (half dark?)
  - LH ν coupled to any SM singlet and scalar vev – why not a Mirror RH ν charged under a Dark R and coupled with a Higgs bi-doublet with vev? $\mathcal{L} \sim y \Phi_{GUT} L R$
  - Weinberg 5th Operator $\mathcal{L} \sim \Lambda^{-1} (\Phi_{VS} L)(\Phi_{DS} R)$
- Small mass from Seesaw mechanism (heavy Majorana neutrino or slow roll scalar potential?)

Mirror thermal relics



Visible
Relativistic ν's through recombination

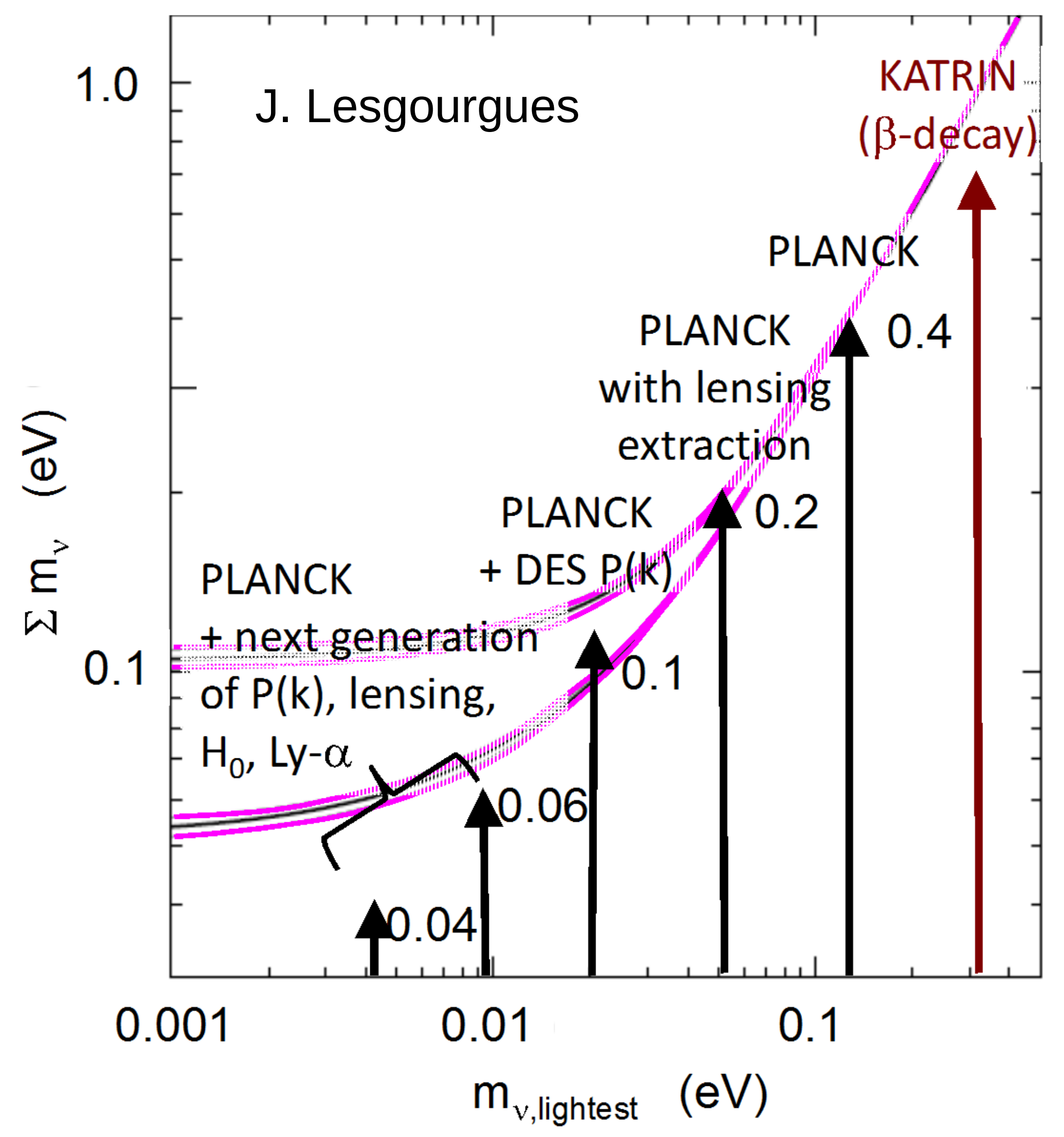
Mirror
Non-relativistic ν's at the point of (visible) recombination ?

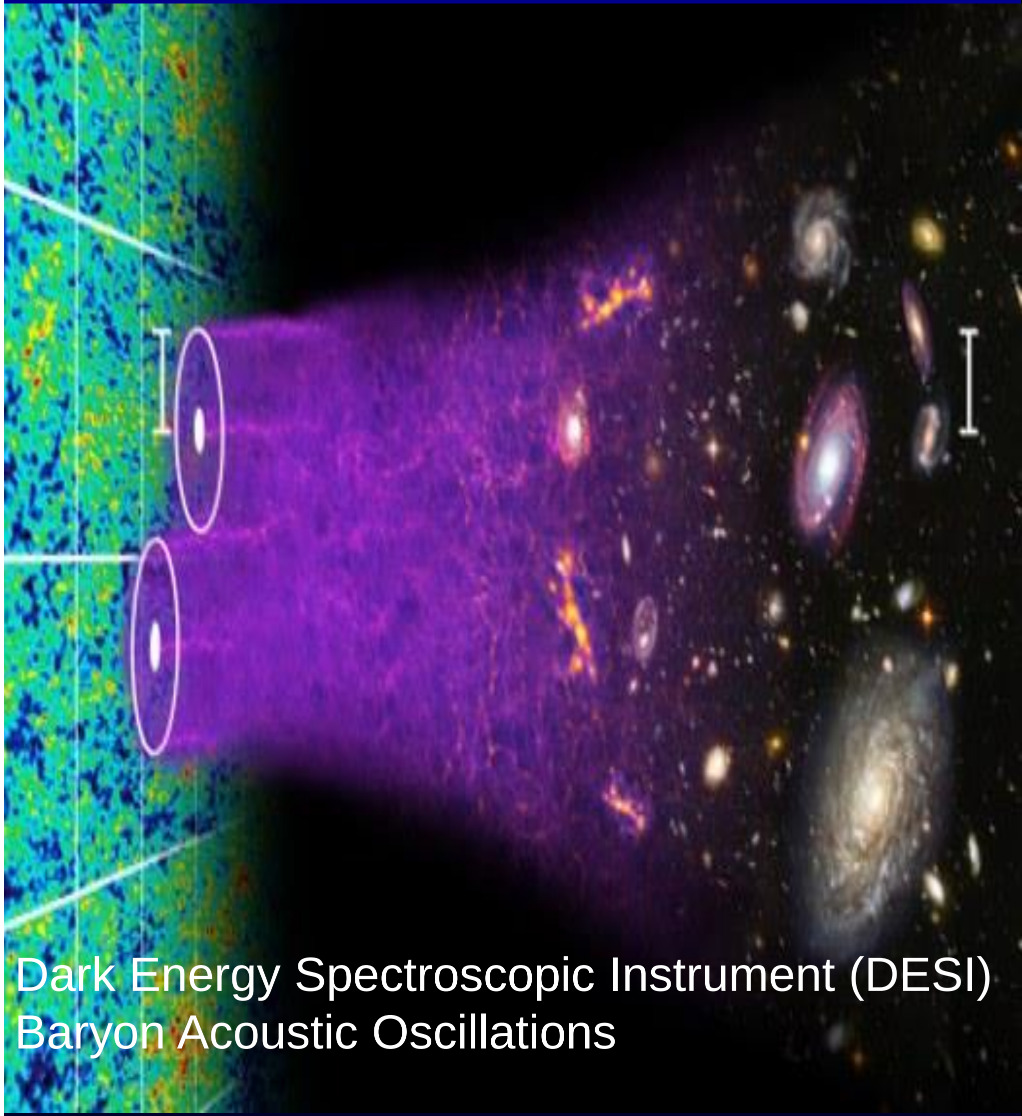


Would a weak (scalar L-R) interaction between relic ν's and mirror relic ν's alter the local number density of CNB?

Similar Ideas:
(Solar) "Dark MSW" https://arxiv.org/abs/1702.08464
(Cosmic Rays) "High-Energy DM Neutrino" https://arxiv.org/abs/1612.08472
(DM Direct Detection) "Exotic Neutrino Interactions" https://arxiv.org/abs/1701.07443
(CMB and LSS) "Constraining DM-Neutrino Interactions" https://arxiv.org/abs/1401.7597
→ Limit $\sigma_{DM\text{-}\nu} < 10^{-33}\ (m_{DM}/\mathrm{GeV})\ \mathrm{cm}^2$ (for constant cross section, Early Universe MSW)

Precision Cosmology Projections





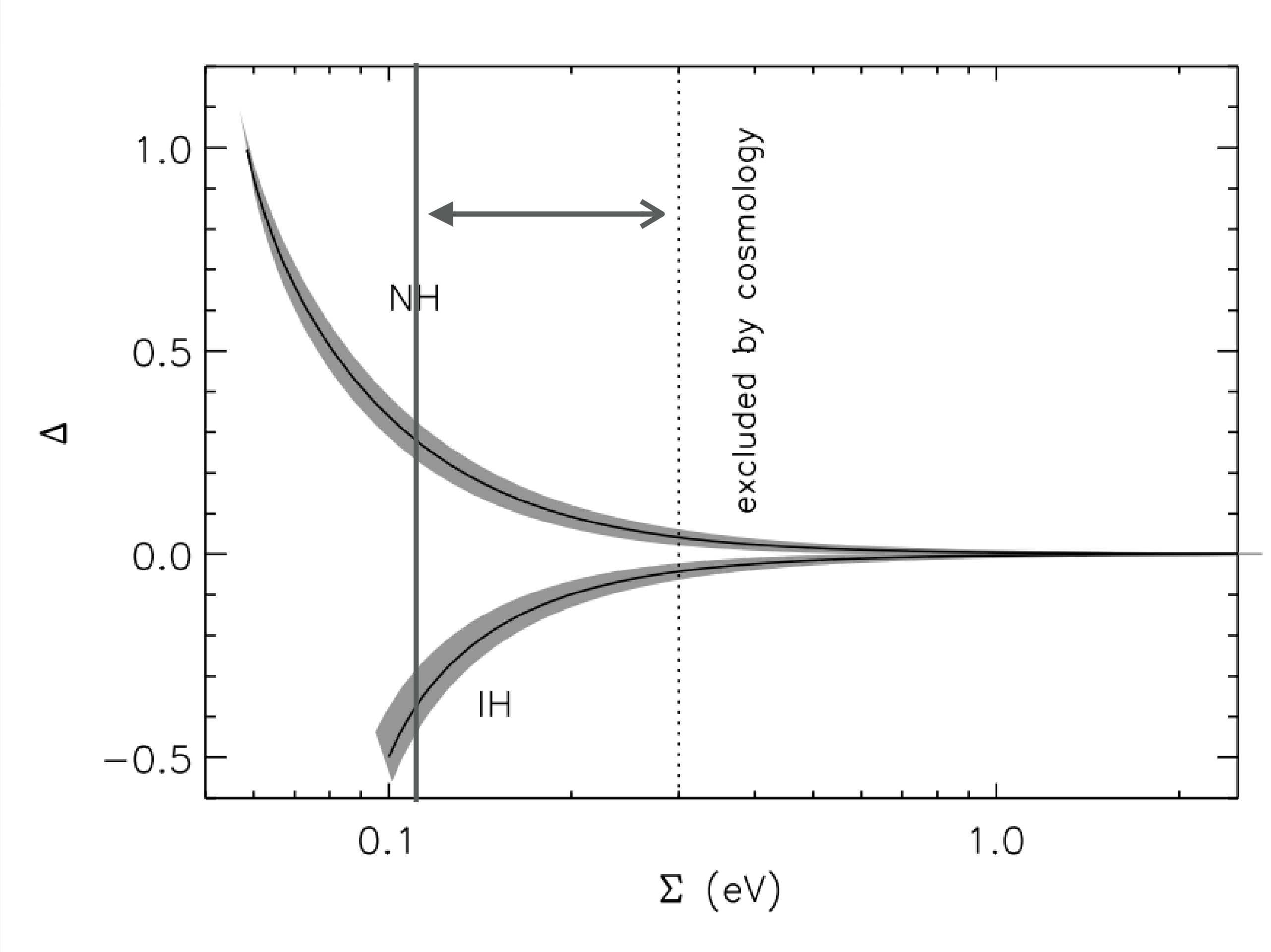
Dark Energy Spectroscopic Instrument (DESI)
Baryon Acoustic Oscillations

ΛCDM Fits for Σ and Δ

Carlos Peña Garay

$$\mathrm{NH}: \quad \Sigma = 2m + M \quad \Delta = (M - m)/\Sigma$$

$$\mathrm{IH}: \quad \Sigma = m + 2M \quad \Delta = (m - M)/\Sigma$$

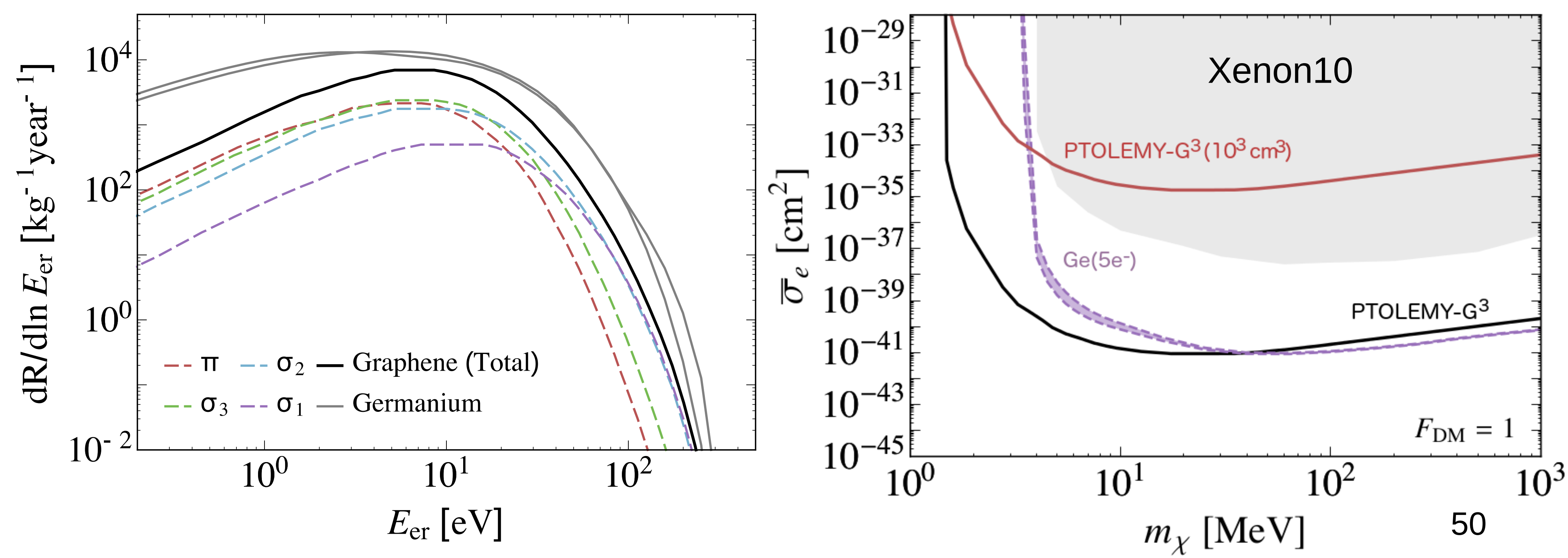


Jimenez, Peña Garay & Verde, 2010, 2016

Projected Sensitivity

- Projected detection sensitivity exceeds an equivalent mass target of low noise (5 e- threshold) germanium cryogenic detectors
- With a modest, small-scale deployment of PTOLEMY-G^3, a fiducialized volume of 10^3 cm^3 will search down to $\sigma \sim 10^{-33}$ cm^2 at 4 MeV in one year, uncovering a diffcult blind spot inaccessible to current experiments

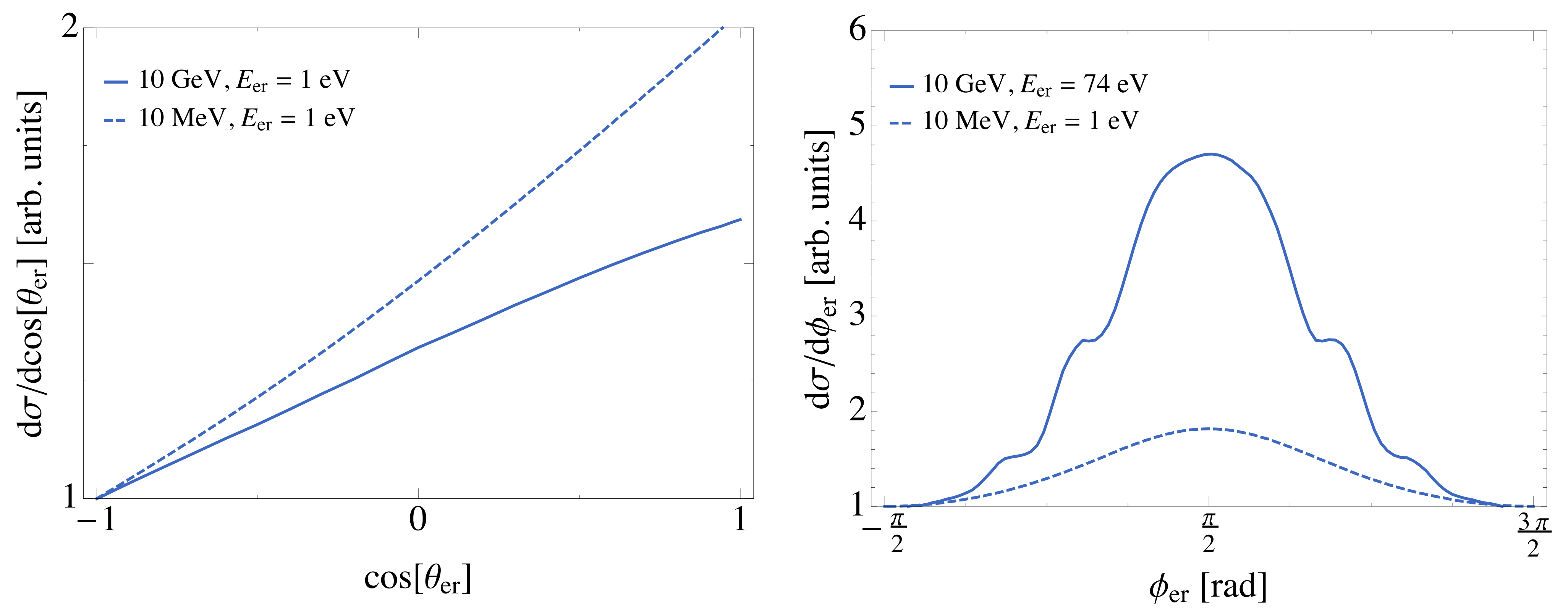
Figure 1-1. (left) *Differential rate for a 100 MeV DM particle scattering off an electron in graphene is shown with the solid black line with $\overline{\sigma}_e = 10^{-37}$ cm^2 and $F_{DM}(q) = 1$.* (right) *Expected background-free 95% C.L. sensitivity for a graphene target with a 1-kg-year exposure (black). A first experiment with a G^3 volume of 10^3 cm^3 (target surface of 10^4 cm^2) will search down to approximately $\overline{\sigma}_e = 10^{-33}$ cm^2 at 4 MeV.*



Directional Detection Sensitivity

- The new approach of 2D targets opens up for the first time direct directional detection of MeV dark matter

Figure 1-2. *Predicted angular distributions for DM masses 10 MeV (dashed) and 10 GeV (solid) in a DM stream with* v_{stream} = 550 *km/s in the lab frame.* (left) *Polar distribution of the final-state electron when the stream is oriented perpendicular to the graphene plane and points along* cos ✓= 1*.* (right) *Azimuthal distribution of the final-state electron when the stream is oriented parallel to the graphene plane and points along φ = ⇡/2. The outgoing electron direction is highly correlated with the initial DM direction.*



Summary

- A rich outlook on the importance of Massive Neutrinos in cosmology is vital to the pursuit of the experimental program
- There are many tough challenges for the experimental program, but the recent development of a path forward with a low background “null” experiment for directional light dark matter is a convincing case to pursue large-area instrumented Graphene and a logical step on the path to PTOLEMY relic neutrino detection

These breakthroughs would not have been possible without the Simons Foundation and John Templeton Foundation support for PTOLEMY

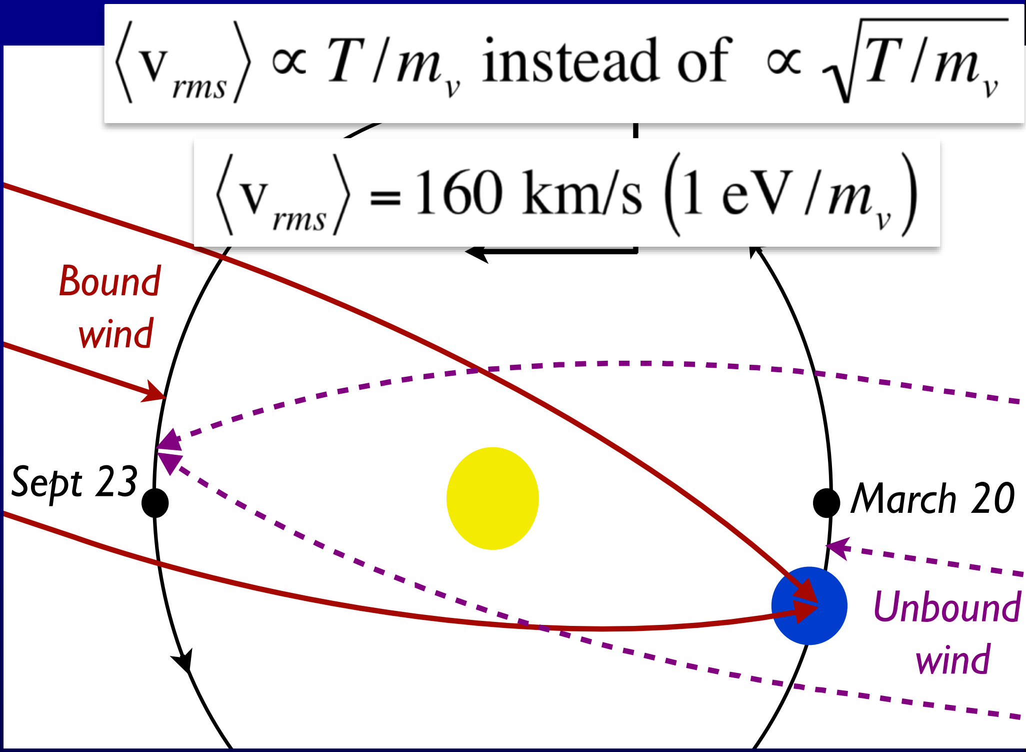
Three Major Challenges

- Reduce molecular smearing
  - New source (Tritiated-Graphene or Cryogenic Au(111))
- Measure the energy spectrum directly with a resolution comparable to the neutrino mass
  - High-resolution electron microcalorimeter
- Compress a 70m spectrometer length – KATRIN's length – down to ~cm scale and replicate it ~x10^4-10^6 at lower precision – final measurement from microcalorimeter
  - New ExB filter concept (Newtonian vs. Galilean)
  - RF trigger system (Project 8 development)
  - G-FET as a potential trigger system

Annual Modulation of Cosmic Relic Neutrinos

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

Sensitivity to relic neutrino velocity and direction through annual **modulation** amplitude (0.1-1%) and phase
-- Not anytime soon



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

$$\langle v_{rms} \rangle = 160 \text{ km/s } (1 \text{ eV}/m_\nu)$$

Possible Sensitivity Enhancement:
Polarized Tritium Nucleus

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

CMB rest frame = Relic Neutrino Rest Frame?

Velocity sensitivity provides possibility to measure:

Relic Neutrino **Rest Frame**, and potentially,
Relic Neutrino **Temperature** (from velocity and mass)
m_ν (lightest) = 0? contribution to Unbound fraction?

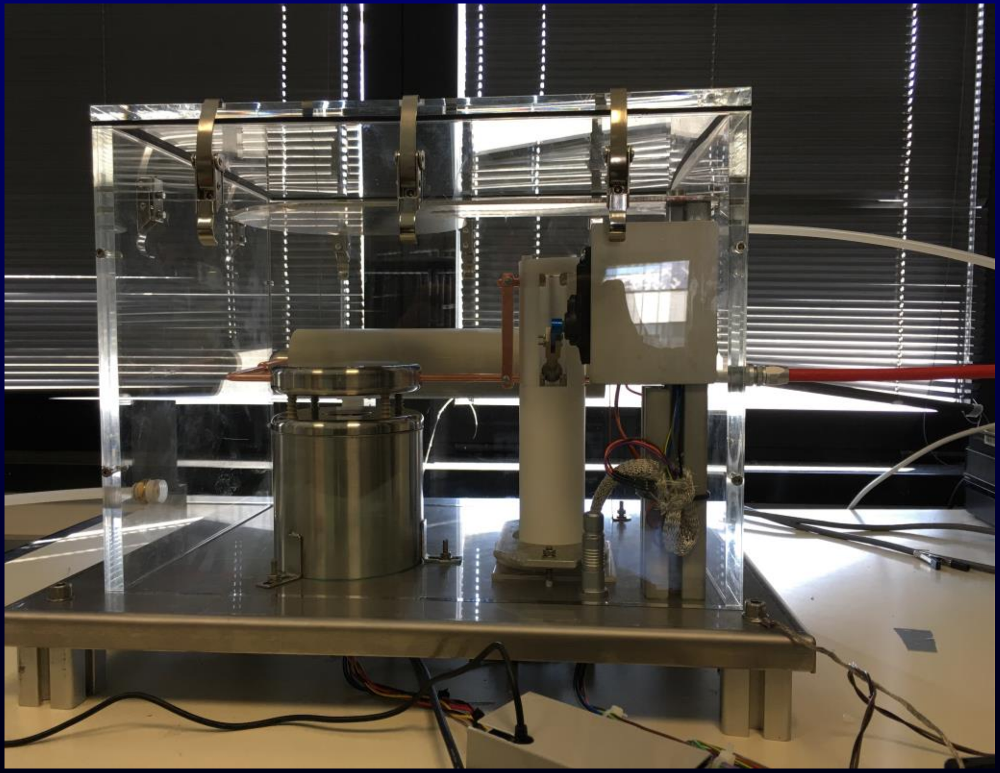
HV biasing and monitoring system of the PTOLEMY detector electrodes

Voltage provided on a locking capacitor

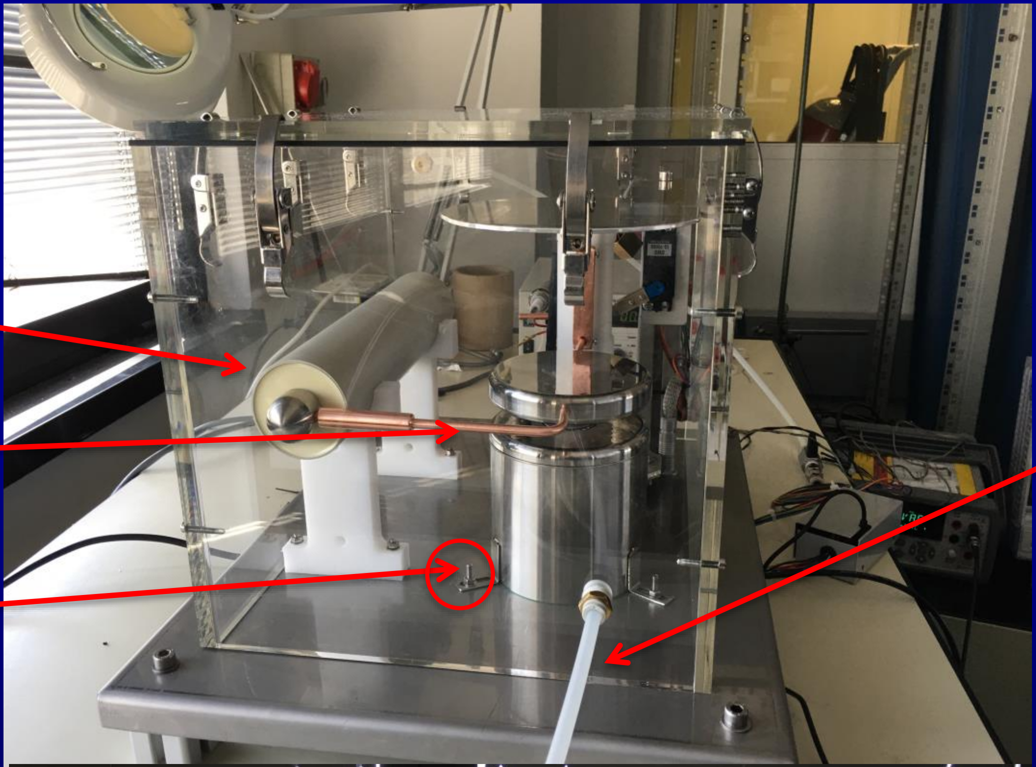
→ not a resistive divider

Field Mill voltage monitoring

→ On path to supersede all precision voltage systems



LNGS (recent photo)
INFN
Cocco, Messina

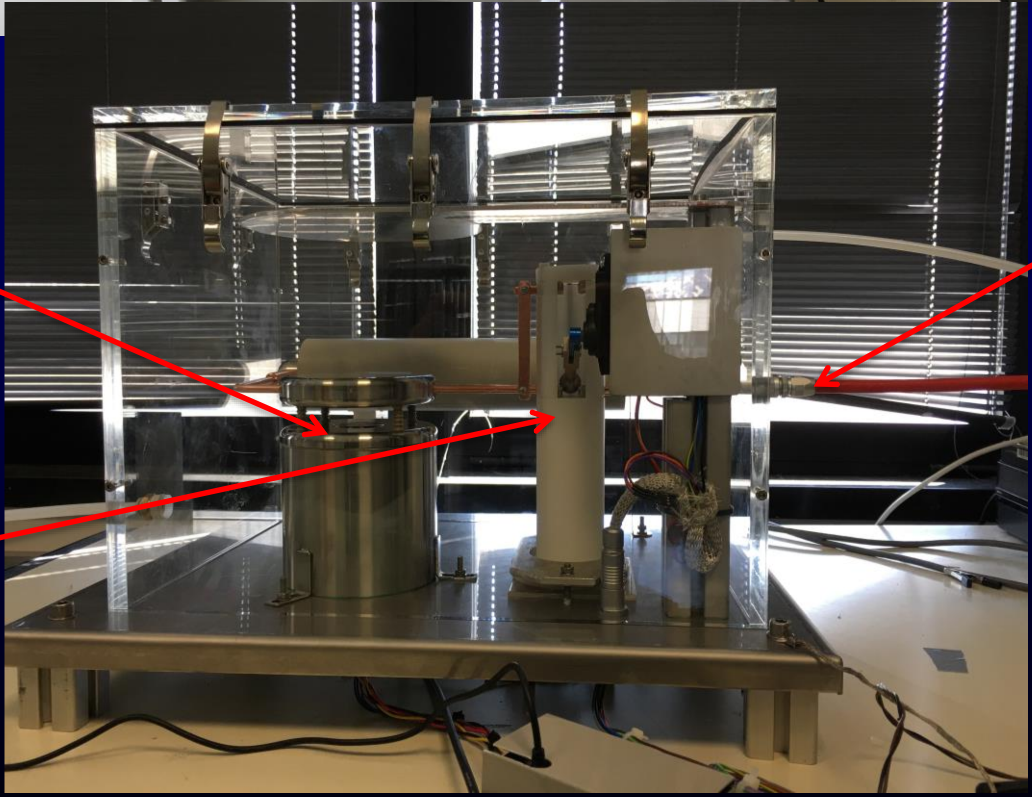


Locking capacitor 200 nF

Connection to the Field Mill

Detector/electrode side. The HV connection is still missing.

Dry N pipe.
In future also SF6 to prevent discharge in air.
The plexi-box is also important for safety.



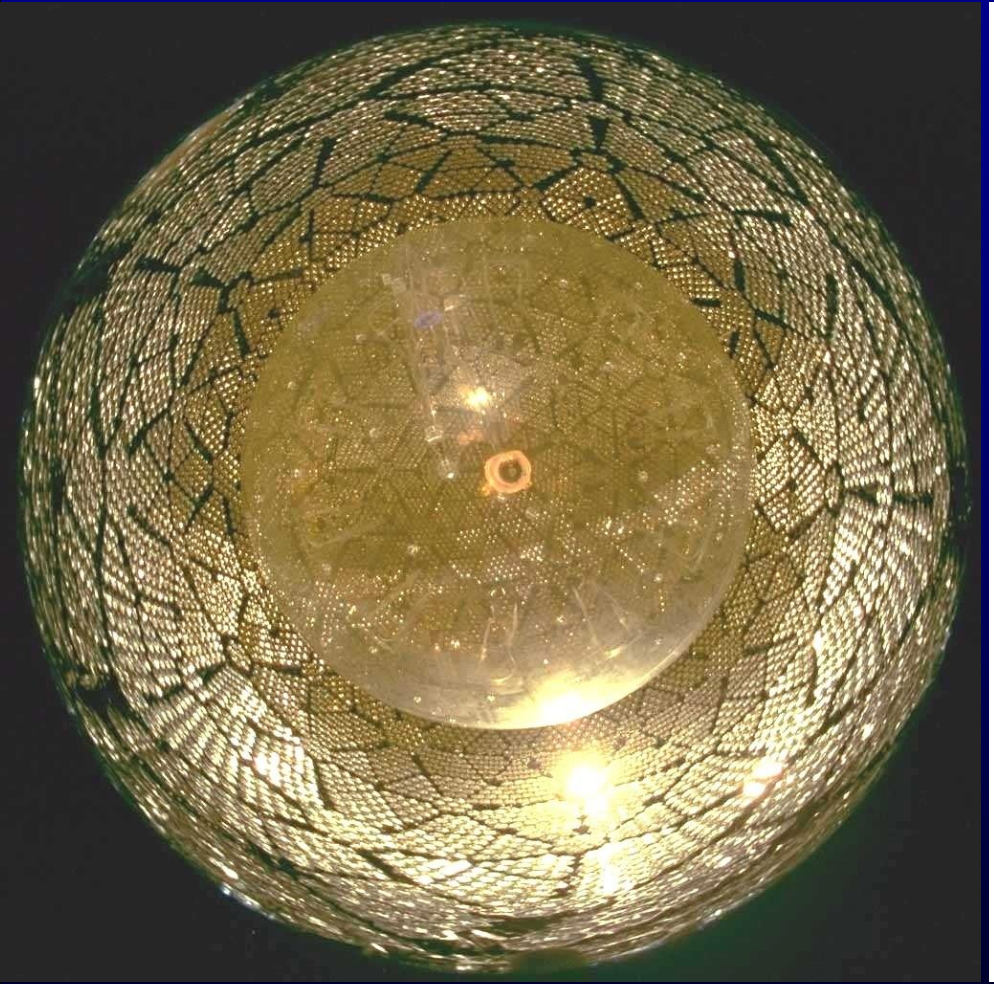
Side view of the Field Mill

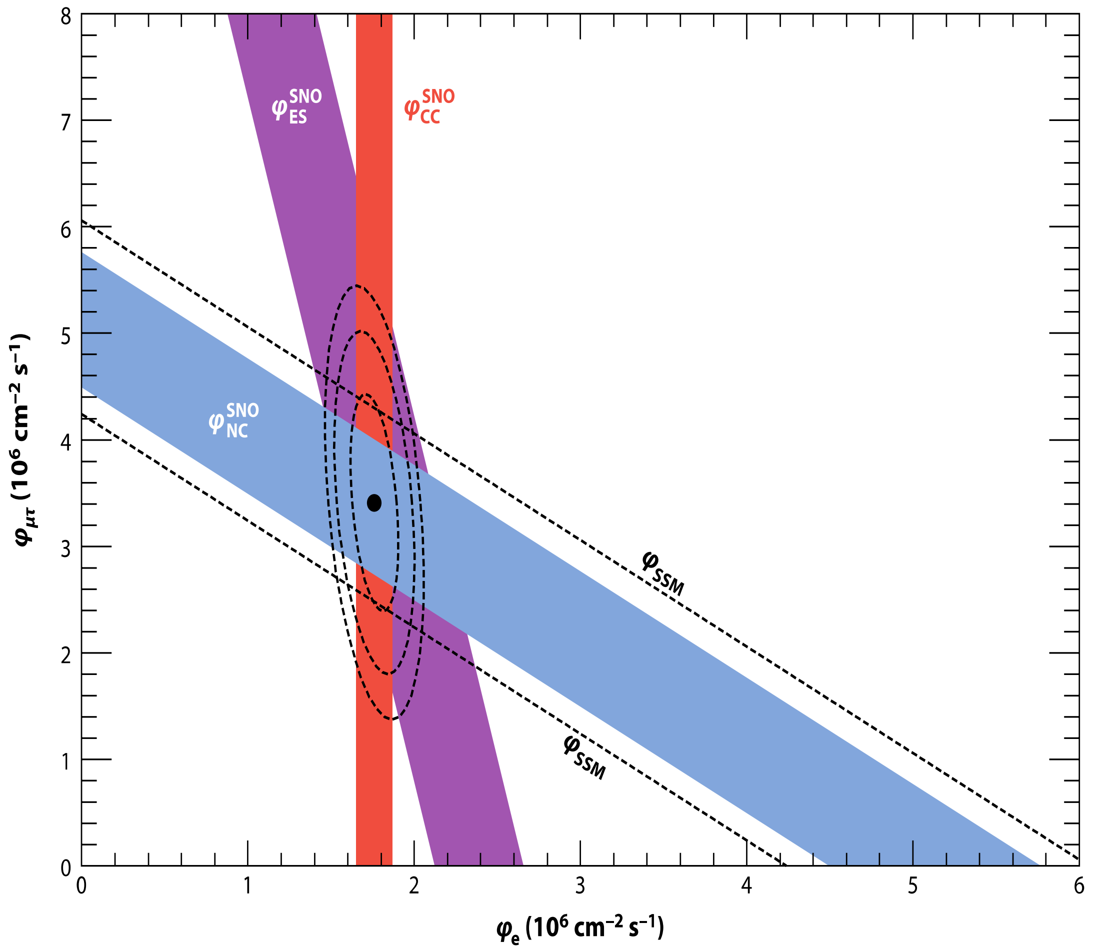
HV switch to charge up the capacitor (top position), to discharge (bottom). Normal position (middle) while measuring.

Connection to DC power supply

Solar Neutrino Problem

GALLEX → SNO





Schedule of Activities

Re-commission Kelvinox MX400 following electrical work
- resize tubing, check indium bottom plate seals, setup PC
- schedule OI (July)

Schedule installation of StarCryo calorimeter (July/August)

Re-commission magnets following connector repair and new support
- electrical for power supply, schedule Davidson (July/August)
- field mapping for magnets, He recovery system hookup

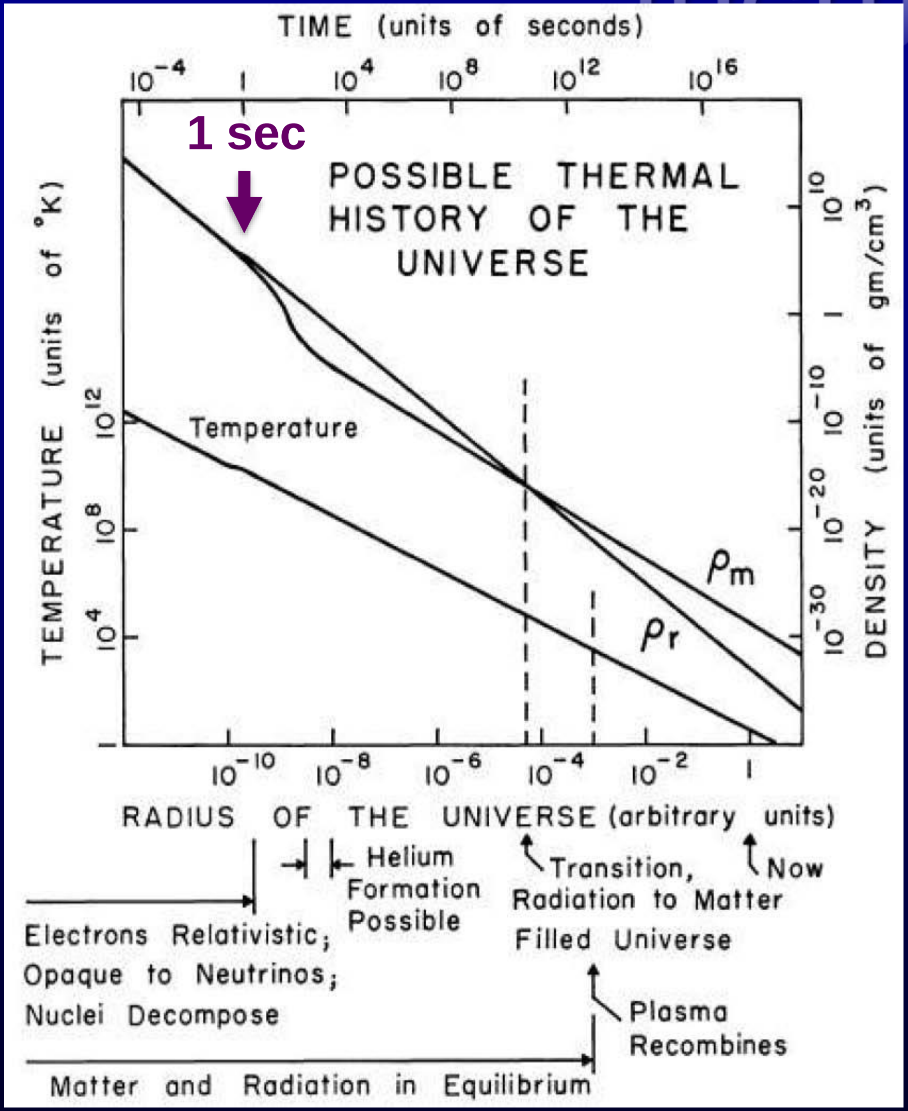
Install central vacuum tank (August)
- electrical for pump station, routing of tubes, pumpdown

HV system for MAC-E filter (September)
- install contacts and feed-throughs
- setup HV power supply and monitoring with HV divider

Install test sample in source magnet (September)
- line sources, beta-decay sample, robot arm controller

Data-taking with Samples, MAC-E filter and Calorimeter
- Scheduled for September/October

CNB is the classic fermionic thermal relic



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

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

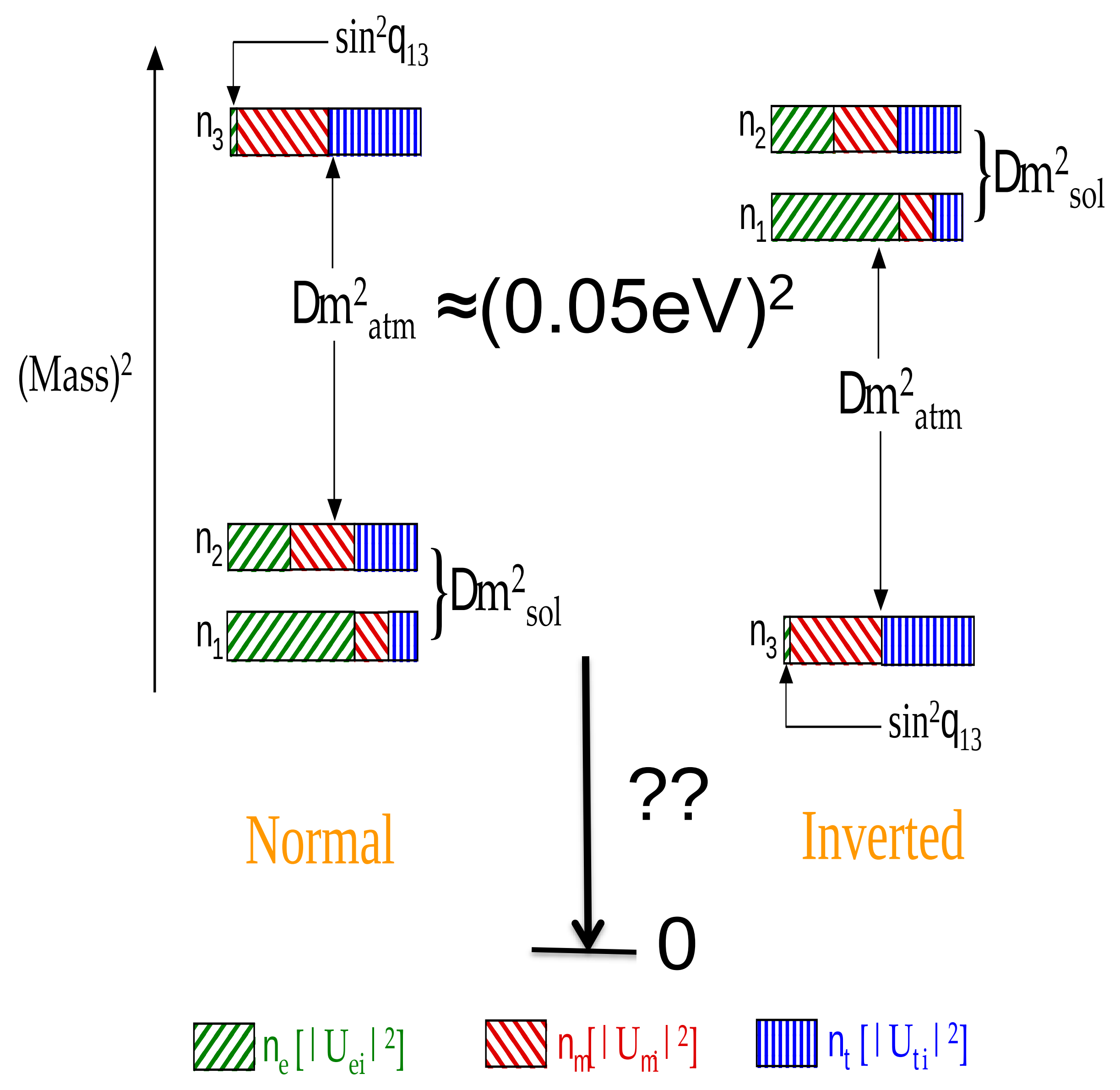
Relic velocity depends on mass

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

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

Non-linear distortions Villaescusa-Navarro et al (2013)

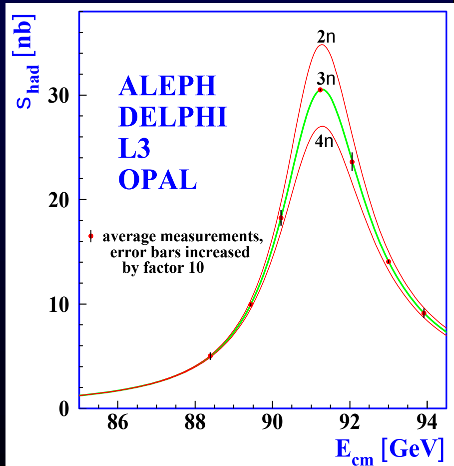
Neutrino Masses from Oscillations



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.

$N_\nu = 2.984 \pm 0.008$



Calorimeter Energy Resolution

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

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

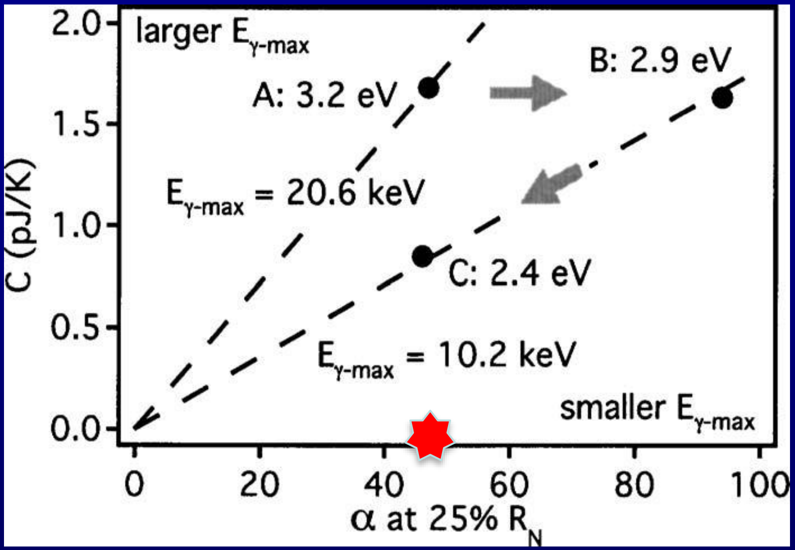
(C/α) scaled down by a factor of ~1000

Keep α large, keep M small

Clarence Chang

Electron energy at calorimeter:	**Thickness of Gold Absorber:**
100 eV	**2.39 nm**
10 eV	**0.68 nm**

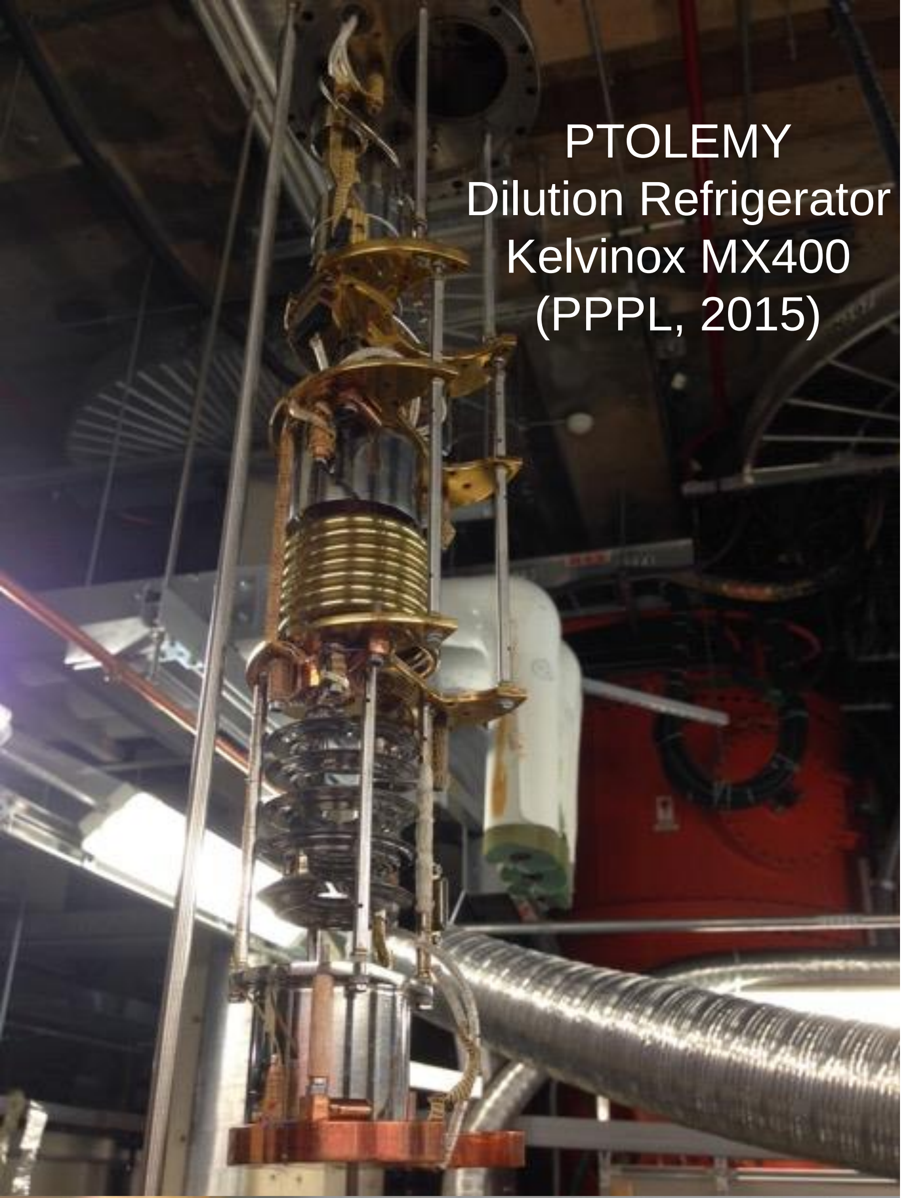
X-Ray microcals are typically 15 μm



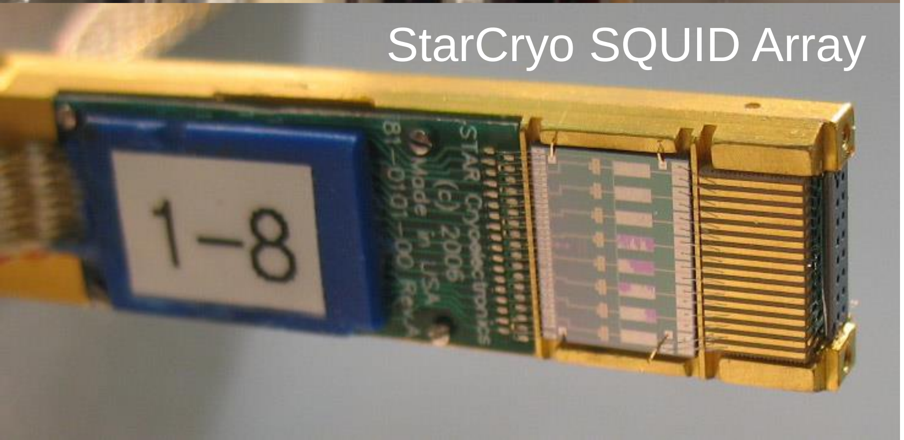
$$\alpha \propto \frac{1}{\Delta T_{width}}$$

- Thickness of Gold absorber can be 2 nm (~20 atomic layers), corresponding to C_p of approximately 0.02 pJ/K per mm^2
- Stacked Graphene layers also possible (recent work on proximity induced SC)
- Transition-edge steepness (1/α) controlled by normal regions and magnetic field.

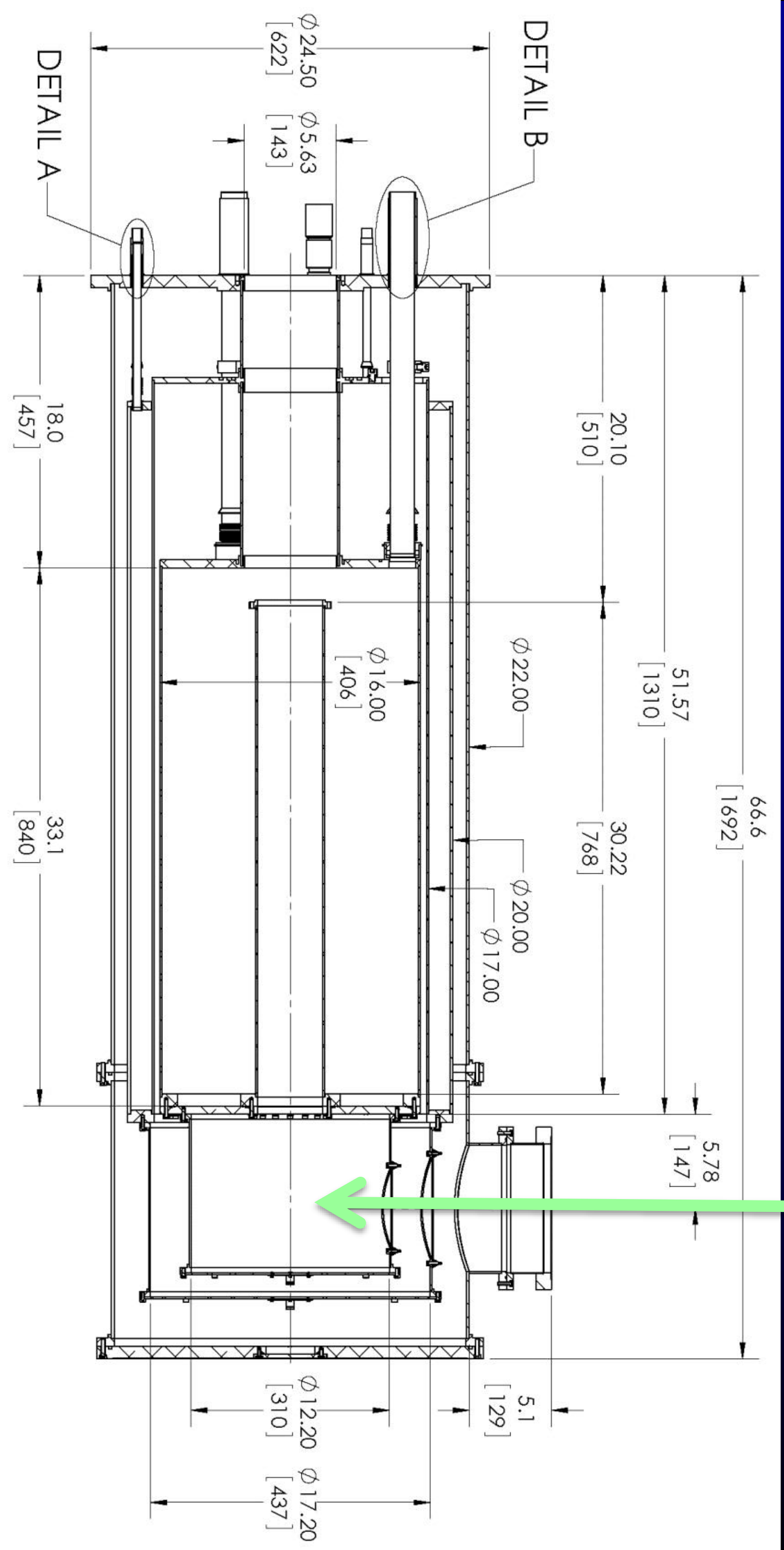
Important collaboration with balloon and space-based TES that want to develop more effective/active magnetic shielding/compensation (Goddard GFSC – Jack Sadleir, Harvey Moseley, and others)



PTOLEMY
Dilution Refrigerator
Kelvinox MX400
(PPPL, 2015)



StarCryo SQUID Array



PTOLEMY
Custom Dewar
w/ Vacuum Path
to MAC-E filter

Neutrino Seesaw with Scalar Field

Neutrino Masses vary as A^{-1}

Fardon, Nelson, Weiner
arXiv:astro-ph/0309800

Neutrino mass matrix
$$\begin{array}{cc} & \begin{array}{cc} \nu & \quad n \end{array} \\ \begin{array}{c} \nu \\ n \end{array} & \begin{pmatrix} 0 & yH \\ yH & A \end{pmatrix} \end{array}$$

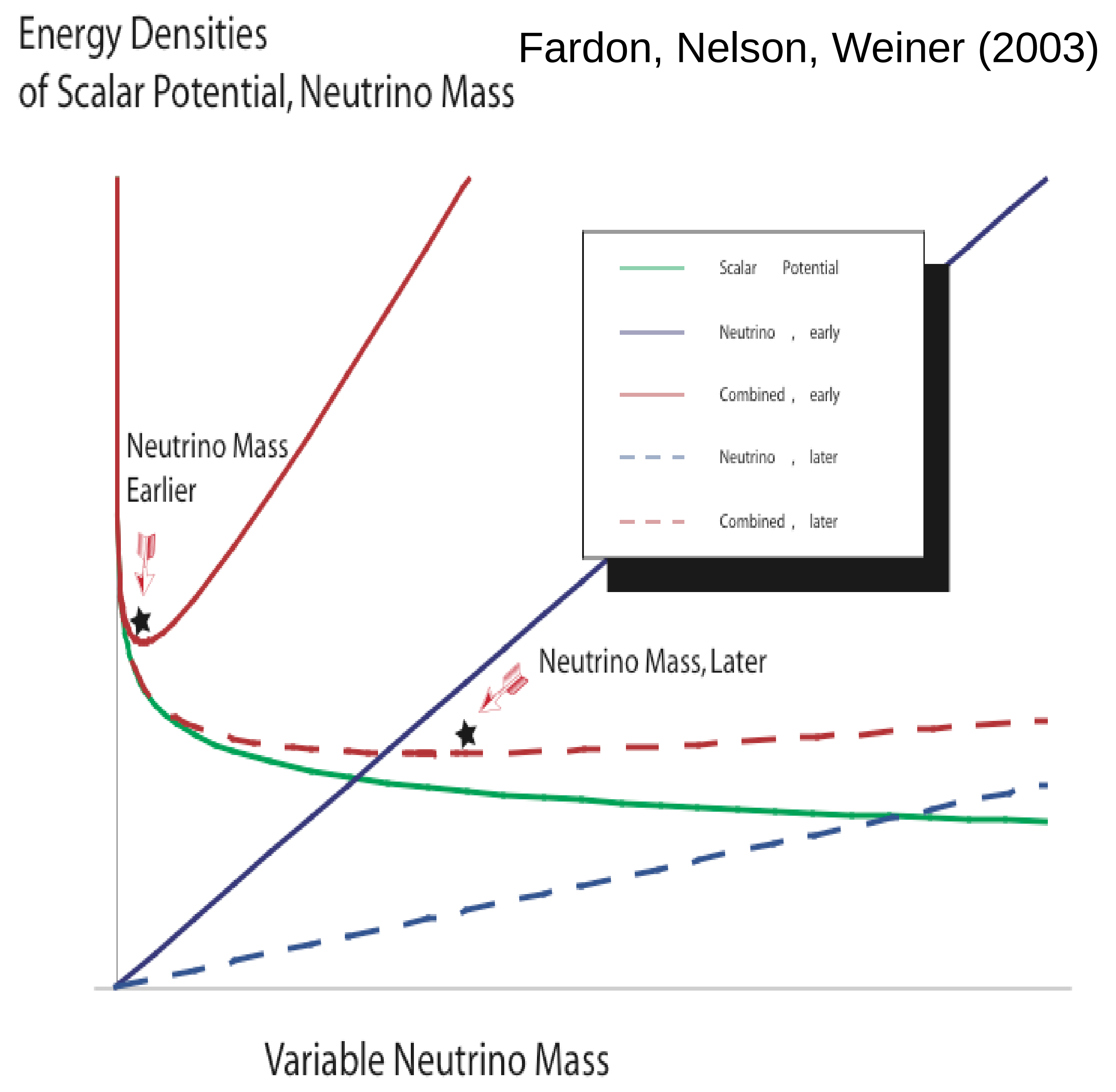
For large $\langle A \rangle$ light neutrino mass is $(yH)^2/A$

Assume $V(A)$ slowly increasing function of A.

V is then slowly decreasing function of the light neutrino mass

$$V(A(m_\nu)) \sim m_\nu^{(1+w)/w}$$

Mass Varying Neutrinos (MaVaN)

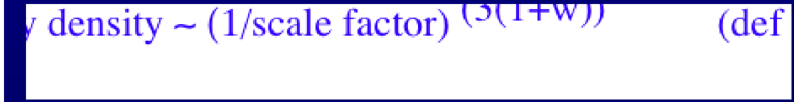


Energy Densities
of Scalar Potential, Neutrino Mass

Fardon, Nelson, Weiner (2003)

Neutrino mass increases adiabatically as neutrino density dilutes (w ~ -1)

Nonrelativistic:



density ~ (1/scale factor)$^{(3(1+w))}$ (def

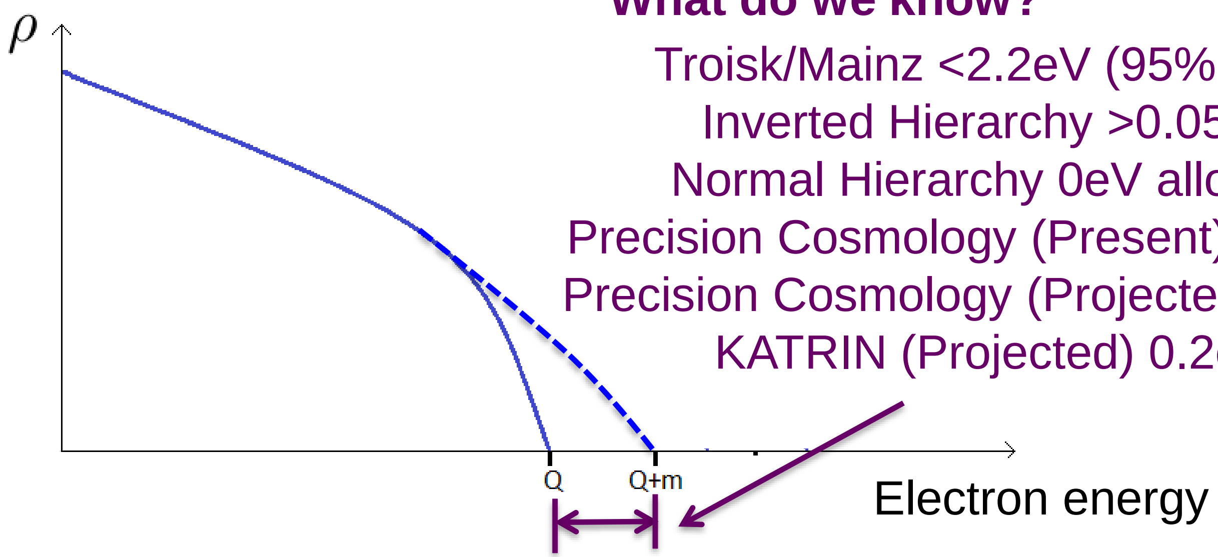
Combined neutrino + scalar potential energy decreases slowly

A. Nelson

Neutrino Mass

- Tritium endpoint measurement of neutrino mass sensitive to mass eigenstates with electron flavor
  - Look for kinematic endpoint or “knee” by measuring electrons near the endpoint spectrum of tritium beta-decay

Shape of Tritium electron endpoint spectrum for m=0 and m>0

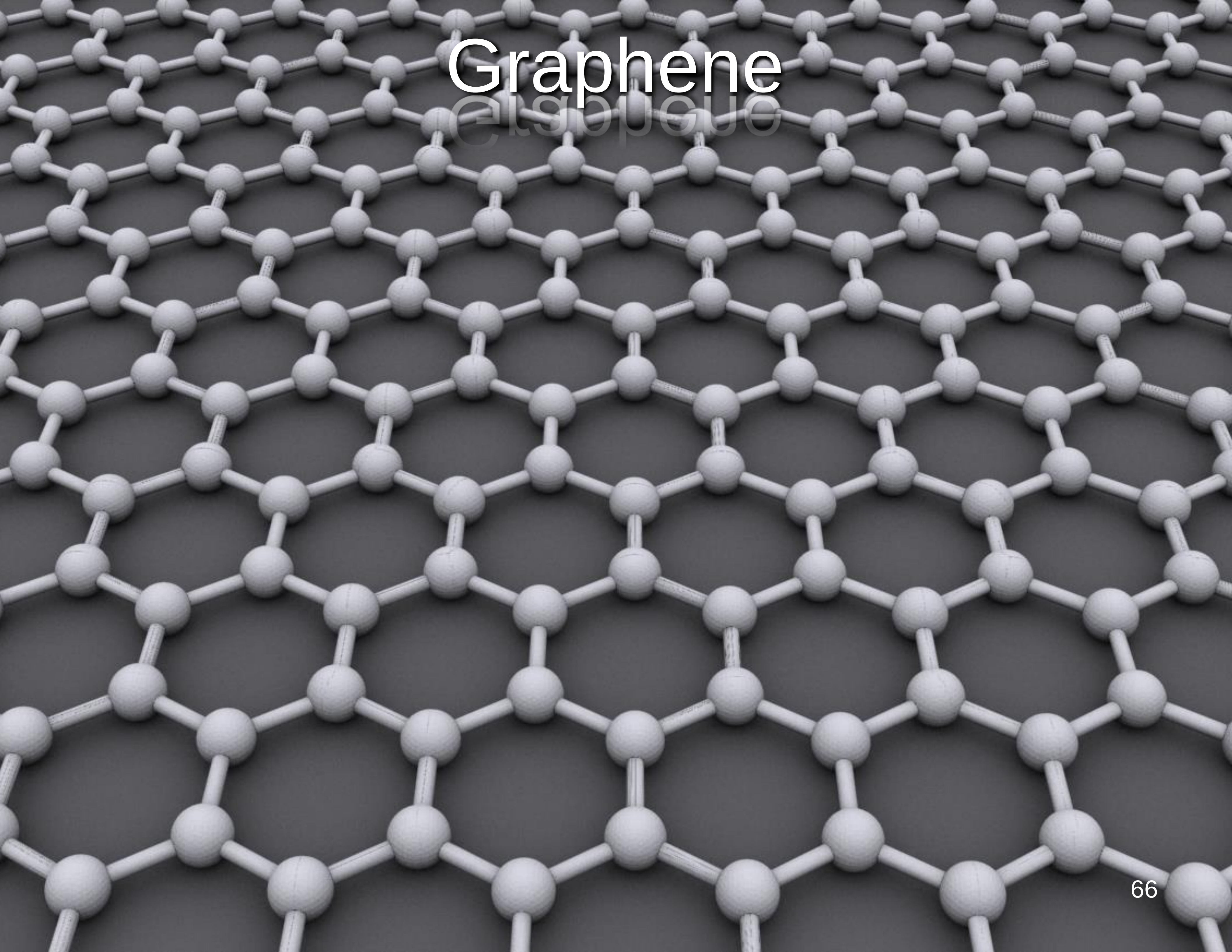


What do we know?

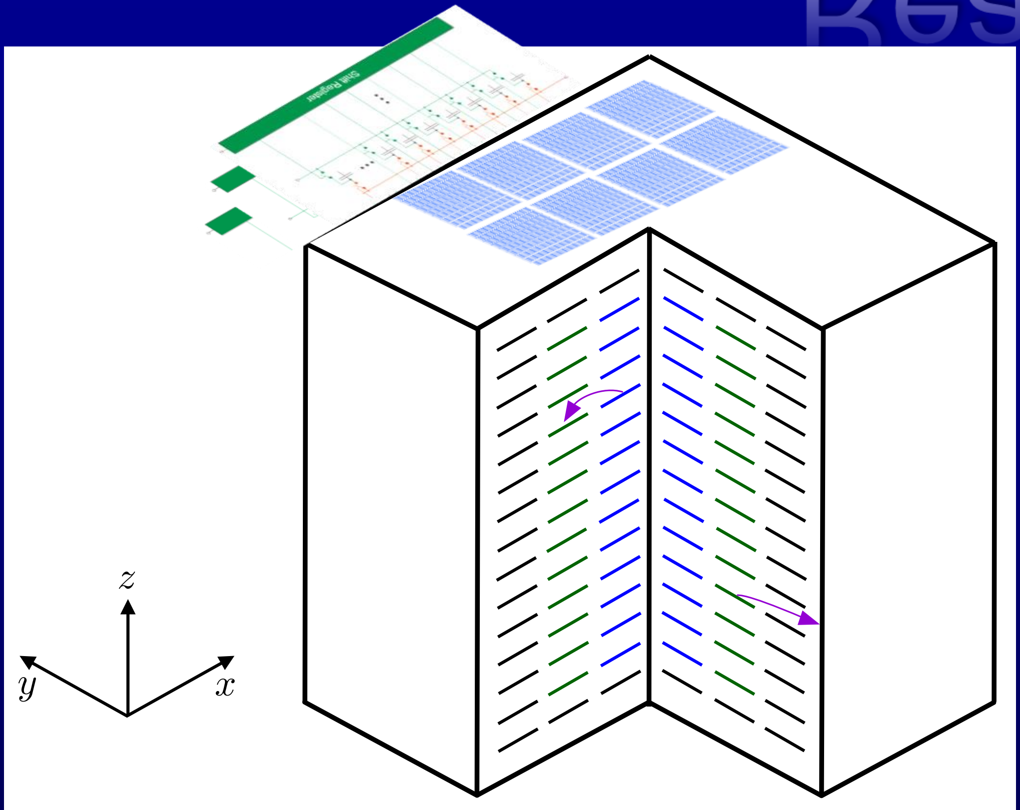
Troisk/Mainz <2.2eV (95% C.L.)
Inverted Hierarchy >0.05eV
Normal Hierarchy 0eV allowed
Precision Cosmology (Present) <0.23eV
Precision Cosmology (Projected) 0.04eV
KATRIN (Projected) 0.2eV

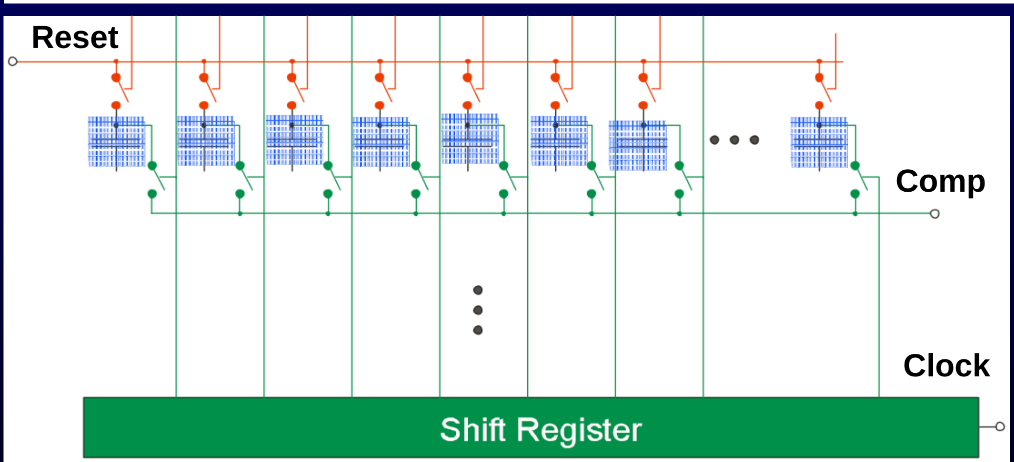
What limits KATRIN?

Graphene



Readout





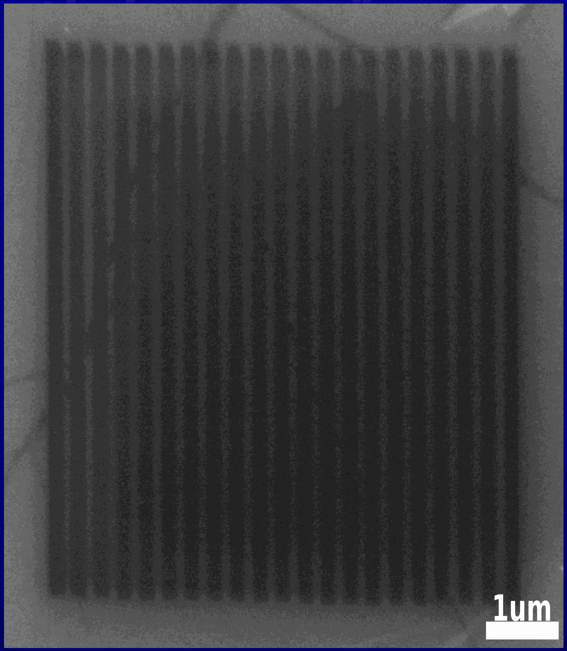
- Switched Capacitor Array Readout (DRS-style)
  - G-FET “capacitors” compared against threshold, time-multiplexed in a token ring and digital output barrel shifted out
  - Caps are reset following each read
- Number of transistors in PTOLEMY-G^3 comparable to a single Intel G4 processor
  - Expected to exceed the number of neurons in the human brain by 2026 (~300 billion @ 1kHz)

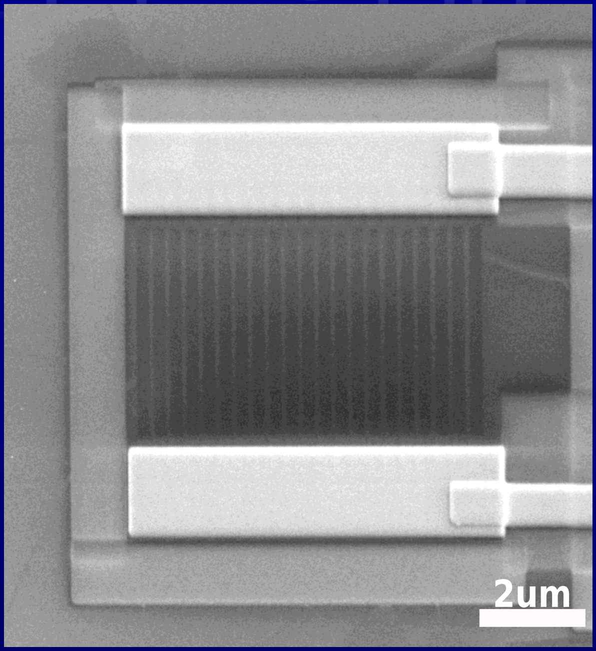
PTOLEMY-G^3

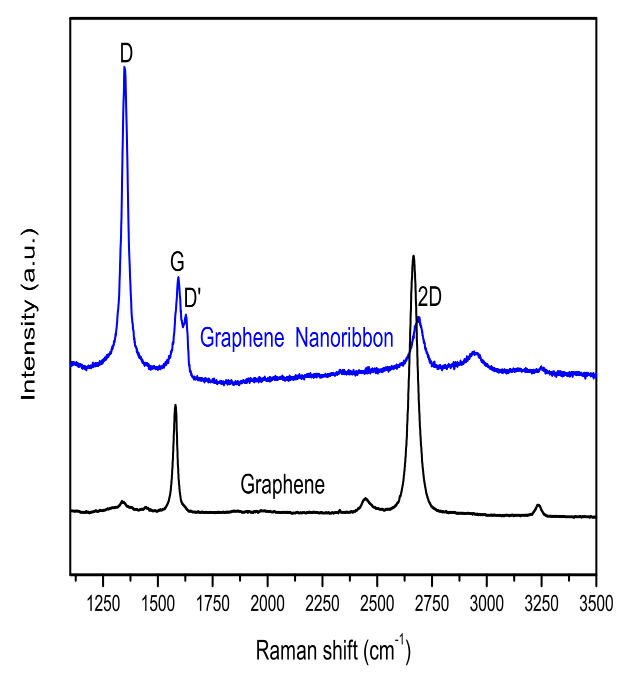
- The only experiment with direct directional detection capability for MeV dark matter
- Has a projected detection sensitivity that exceeds an equivalent mass target of low noise (5 e^- threshold) germanium cryogenic detectors
- With a modest, small-scale deployment with a fiducialized volume of 10^3 cm^3 (target surface of 10^4 cm^2) will search down to $\sigma \sim 10^{-33}$ cm^2 at 4 MeV in one year, uncovering a diffcult blind spot inaccessible to current experiments.
- Graphene sensor results are reported at this workshop and the existing PTOLEMY setup at Princeton University has the volume and cooling capacity to host PTOLEMY-G^3 with a fiducialized volume of 10^3 cm^3
- PTOLEMY-G^3 is ready for a first phase experiment.

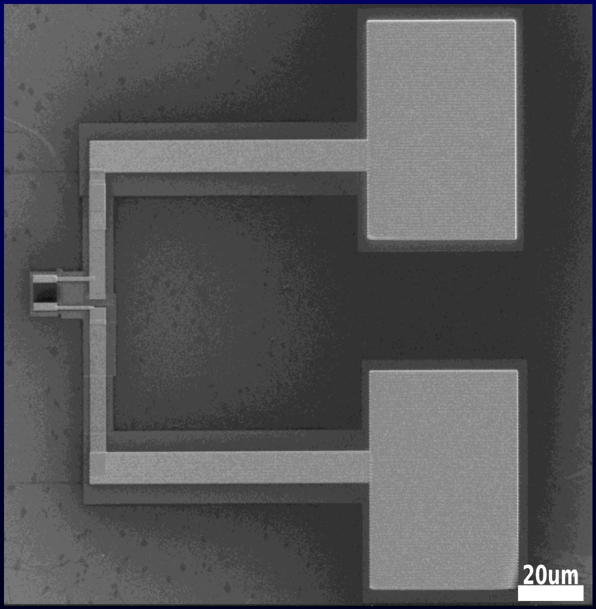
Graphene Nanoribbon Array FET via FIB

- GNs array: 20 GNs with 40nm width on SiO_2/Si substrate
- Bottom gate FET: Pt contacts and channels are deposited with 100nm thick by FIB direct deposition
- Before metal deposition, mill the graphene around GNS and on the area for contacts and channels
- Raman results for GNs: only G and 2D peaks for pristine graphene. D and D' peaks appear on GNs









PTOLEMY

- Next generation of tritium endpoint experiments focus on:
  - High sub-eV resolution calorimeter/spectrometer-based measurements in the ~10eV region of the endpoint
  - Reduced molecular smearing from tritium decay within a molecular bond
  - Higher mass capacity (~100 micrograms → grams)
  - Low backgrounds and background rejection coincidence methods
- High sensitivity at the endpoint is important for neutrino mass measurement and also provides an R&D program for relic neutrino capture experiments (PTOLEMY)

Rethinking Relic Neutrino Detection

PTOLEMY Collaboration, S. Betts *et al.*, arXiv:1307.4738 (astro-ph)

P rinceton
T ritium
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield

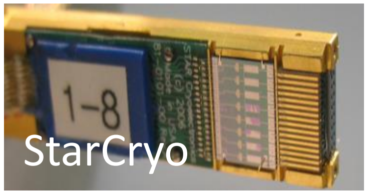
- Relic Neutrinos → Highest intensity DC neutrino flux in the Universe

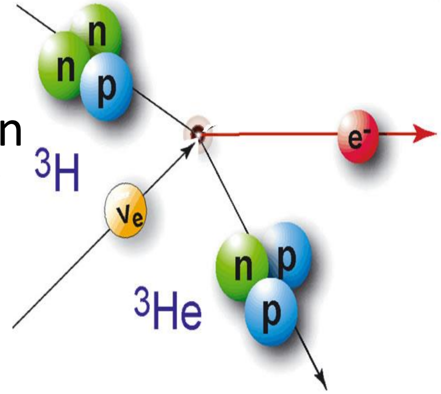
- Massive neutrinos

→High resolution electron microcalorimetry at 10eV

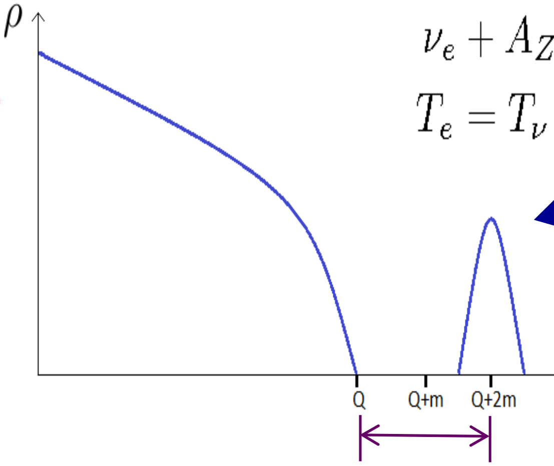
→~0.05eV sensitivity(?)

R&D with ANL


StarCryo



Relic Neutrino Capture on Tritium



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

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

How many?

(Signal shape and location predicted from mass measurement)

Electron energy

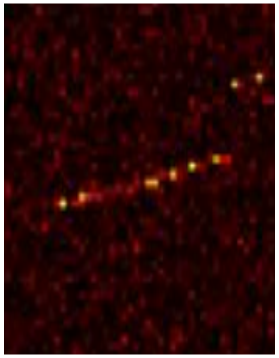
Original idea: Steven Weinberg in 1962 [*Phys. Rev*. 128:3, 1457]

JCAP 0706 (2007)015, hep-ph/0703075, Cocco, Mangano, Messina

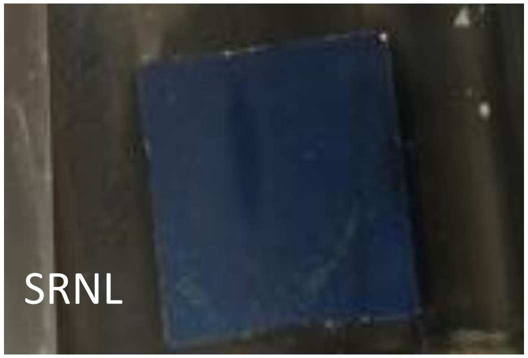
- RF triggering on single e$^-$

→Large-scale tritium target and filtering of endpoint electrons

PROJECT 8



- Tritiated-Graphene target


SRNL

- ExB filter ~x10^{-4} length of KATRIN for microcalorimeter

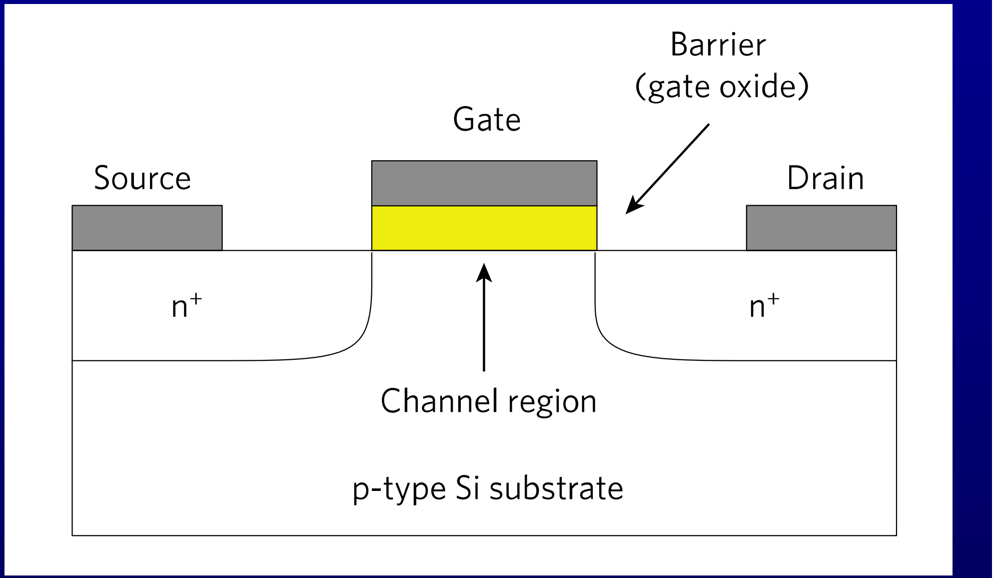
PTOLEMY Supported by:
The Simons Foundation
The John Templeton Foundation

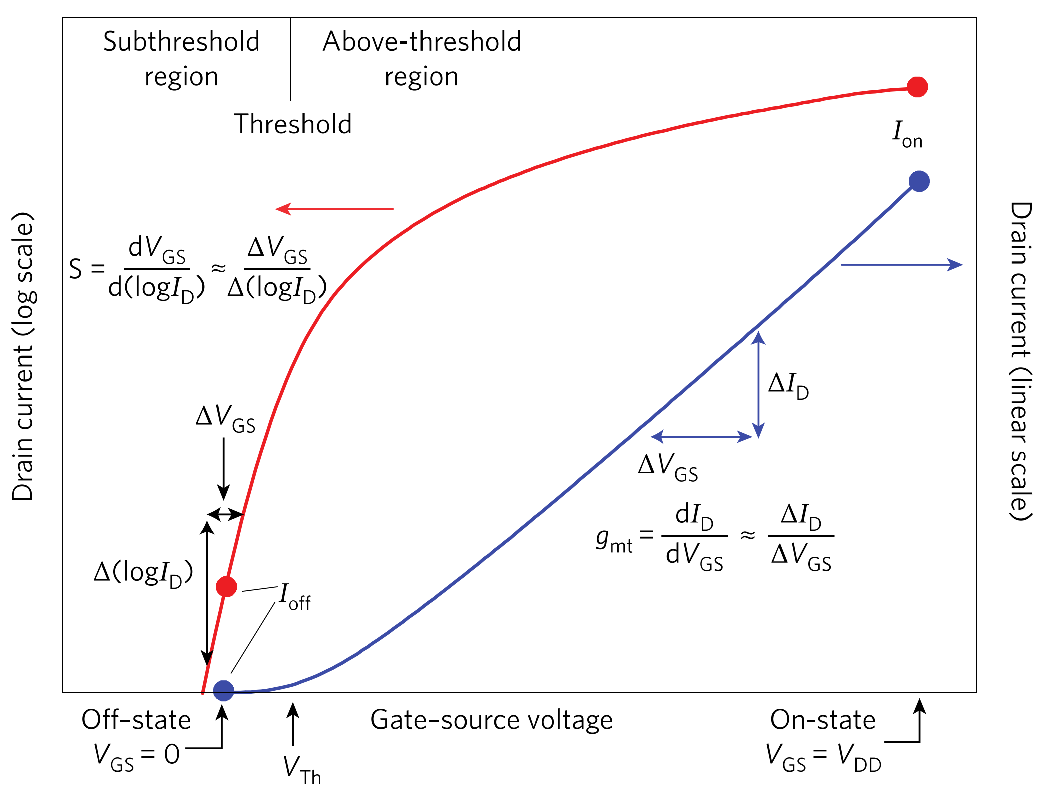
MeV DM

- The scattering of light DM off of electrons produces an electron recoil energy spectrum out to ~10-100eV
  - This energy range is similar to the region of interest for a calorimeter/spectrometer-based analysis of the tritium endpoint
  - By analogy, the process of single photon detection is a process where a single electron is ejected from a photocathode into vacuum and then manipulated with electric fields (Ex. HPD)
  - In the study of directionality information retained in the DM-electron scattering process for DM on atomic electrons some news ideas were developed to make use of a “null” PTOLEMY experiment with pure Graphene and Electric fields.

Y. Hochberg, Y. Kahn, M. Lisanti, C. Tully, K. Zurek, **arXiv:1606.08849**

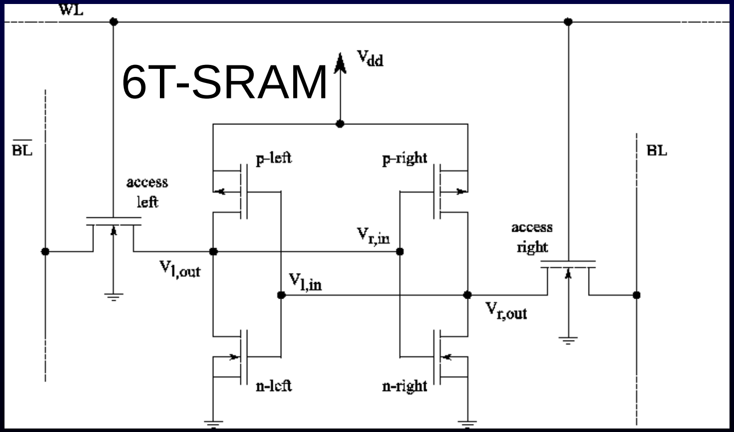
n-channel MOSFET





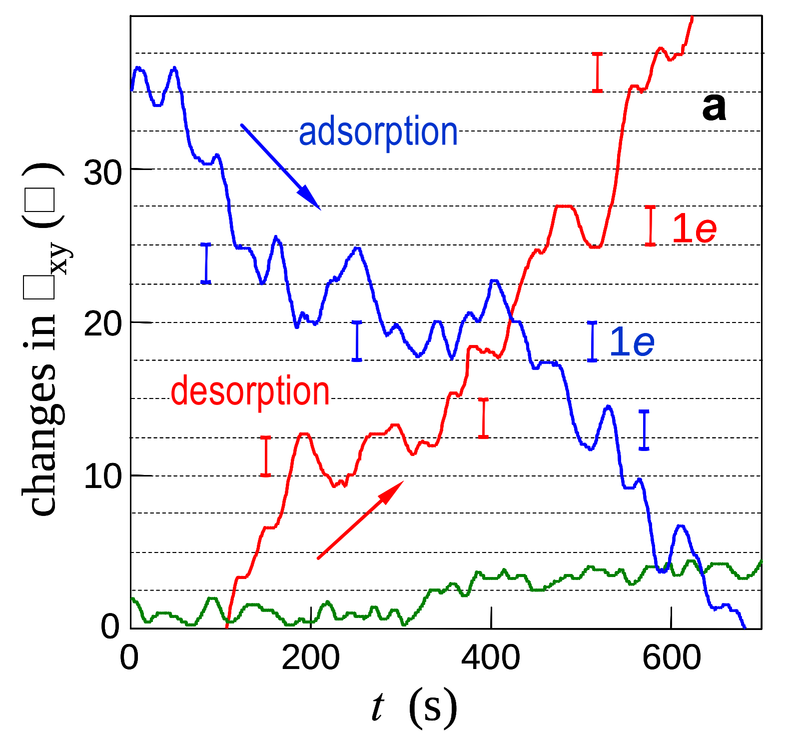
Operates in “enhancement” mode when conduction opens up in channel region for $V_{GS}>V_{Th}$

SEU from neutron interactions in the depletion region – also contribute charge carriers → basis for SRAM neutron detectors



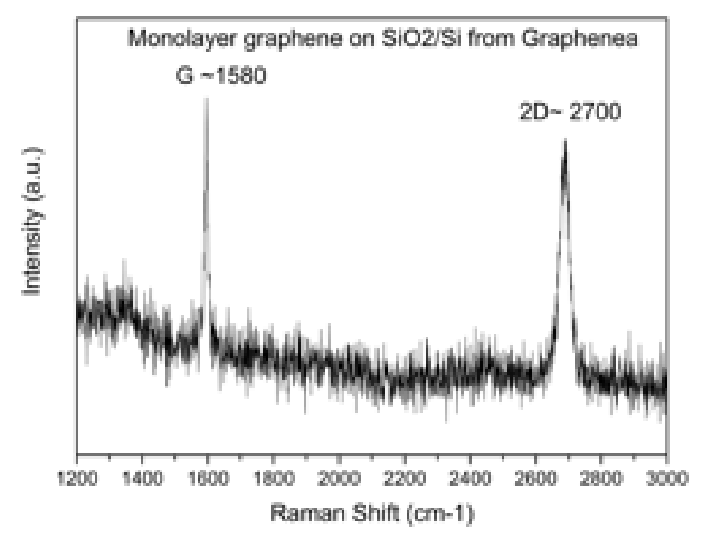
Graphene FET

- One of the most interesting properties of Graphene (noted by Geim et al.) is the sensitivity to a single electric charge (added or removed) in a Field-Effect Transistor configuration – shown here at room temperature
- What are the limitations to this sensitivity and will it create new opportunities for light DM exps?



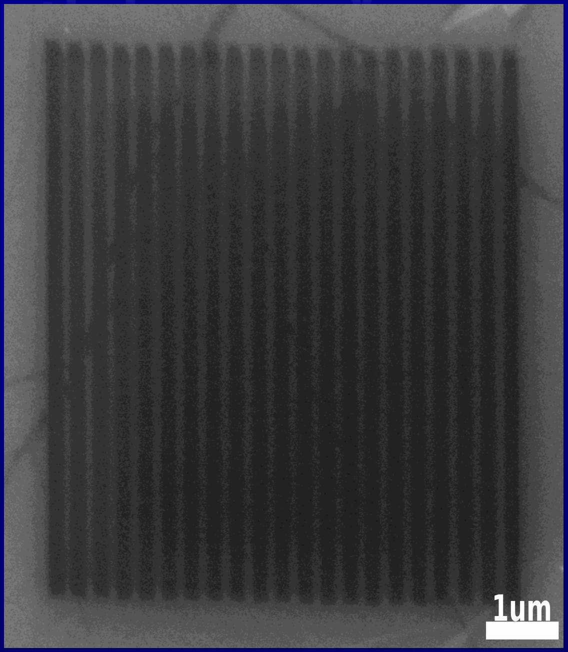
Commercial Monolayer Graphene

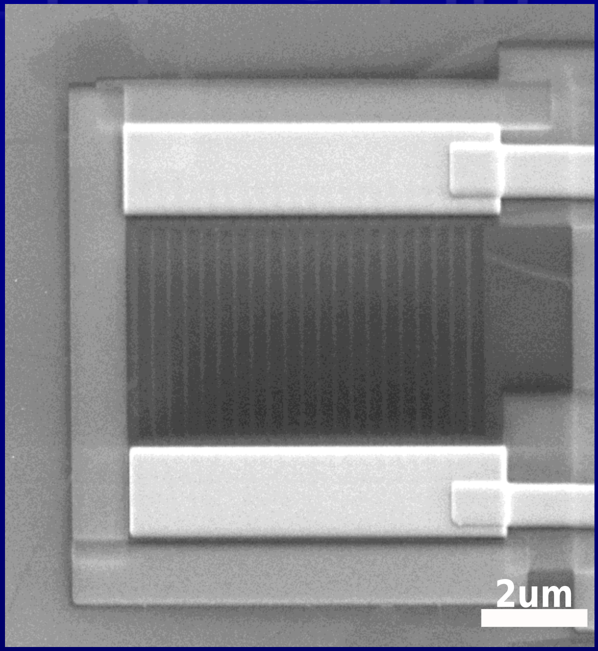
- High quality 1 cm^2 samples readily available (free samples)
  - Common substrates for transport: Copper, Si/SiO$_2$
- Single crystals are less common (discussed later)

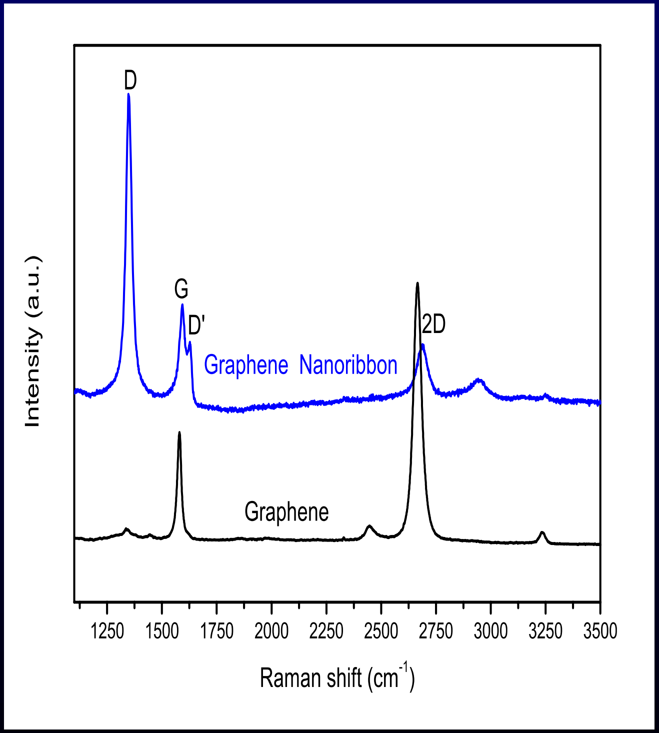


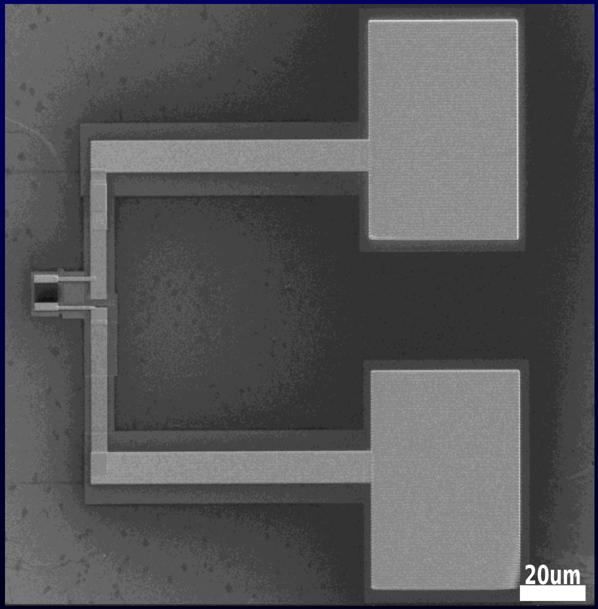
Graphene Nanoribbon Array FET via FIB

- GNs array: 20 GNs with 40nm width on SiO_2/Si substrate
- Bottom gate FET: Pt contacts and channels are deposited with 100nm thick by FIB direct deposition
- Before metal deposition, mill the graphene around GNS and on the area for contacts and channels
- Raman results for GNs: only G and 2D peaks for pristine graphene. D and D' peaks appear on GNs









Graphene nanoribbon growth on SiC (in process)

- GNs are grown from lithographically patterned trenches in SiC.
- When a trench in SiC is oriented perpendicular to the $\langle \bar{1}100 \rangle$ direction, the graphene that grows has its AC edge parallel with the step edge [Figure1 c,e].
- When a SiC trench is oriented parallel to the $\langle 1\bar{1}00 \rangle$ direction, the graphene that grows has its ZZ edge parallel with the step edge(Figure1 d,f)
- We use two type of SiC: semi-insulating and n-type semiconducting.

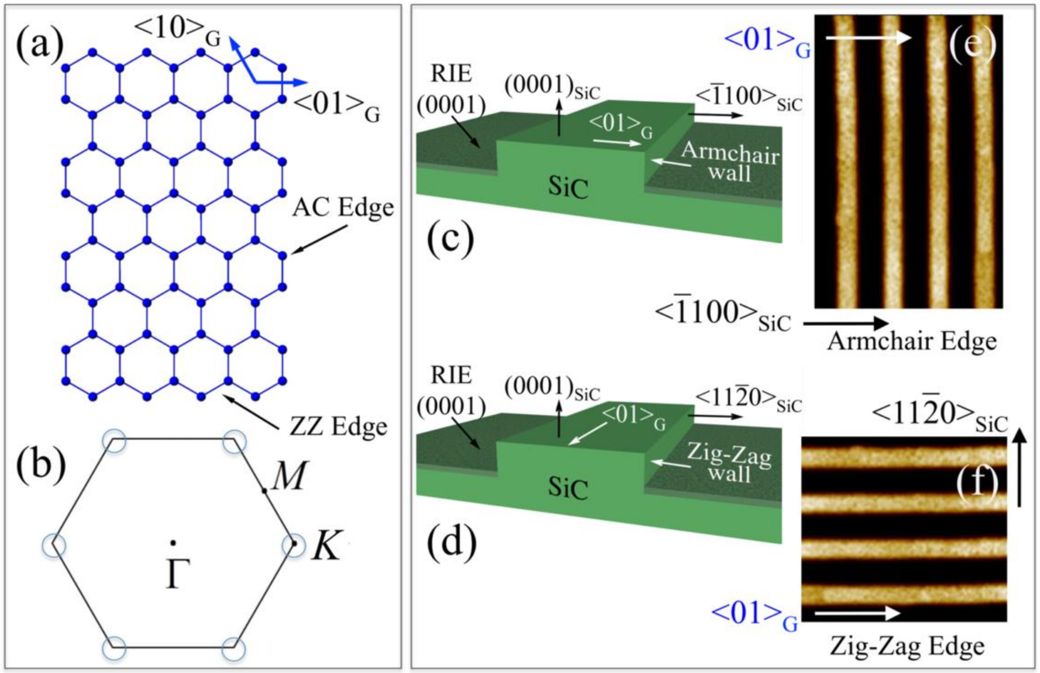


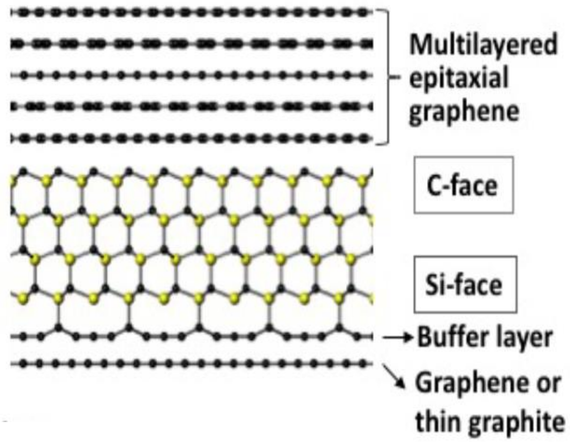
Figure 1. Orientation of the SiC trenches relative to the graphene. (a) The graphene lattice relative to the Brillouin zone in (b). (c,d) Schematic of a pregraphene growth trenches with (c) AC and (d) ZZ sidewalls. AFM images of graphitized SiC trenches with (e) AC edge graphene and (f) ZZ edge graphene. Dark areas are the trench bottoms. [1]

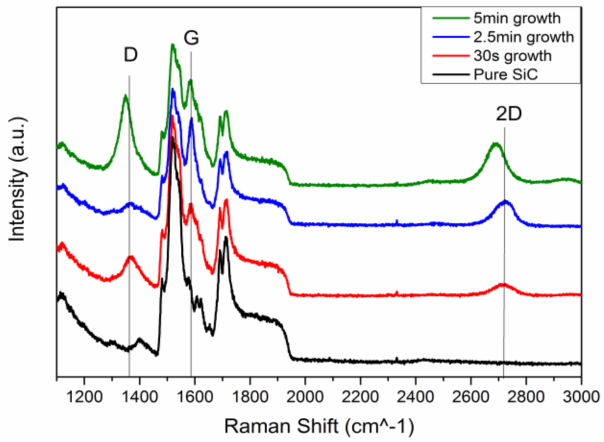
---

1. Conrad, E. H. The Bottom-up Growth of Edge Specific Graphene Nanoribbons. *Nano lett.*(2014).

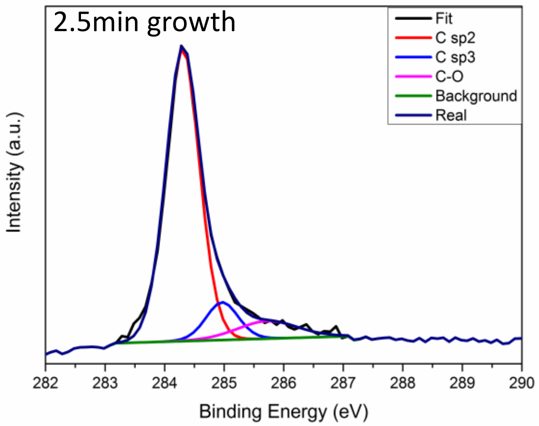
Graphene Growth on SiC (our results)

- Graphene are grown by thermal decomposition of SiC. Currently, we grow graphene on 4H-SiC with Si top face with different pressure and temperature.
- Graphene or thin graphite prefer to grow on Si-face 4H-SiC.
- Raman and XPS analysis support to understand graphene thickness.
- Room Temperature STM analyze graphene surface.





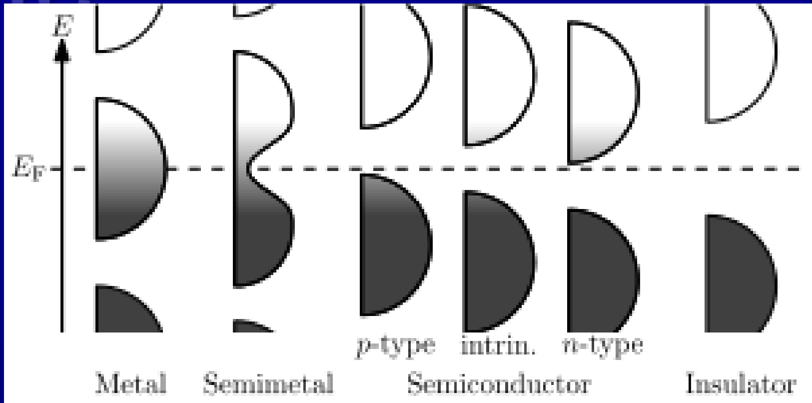
Raman result: Graphene fingerprints Raman peaks G and 2D peaks appear after growth.

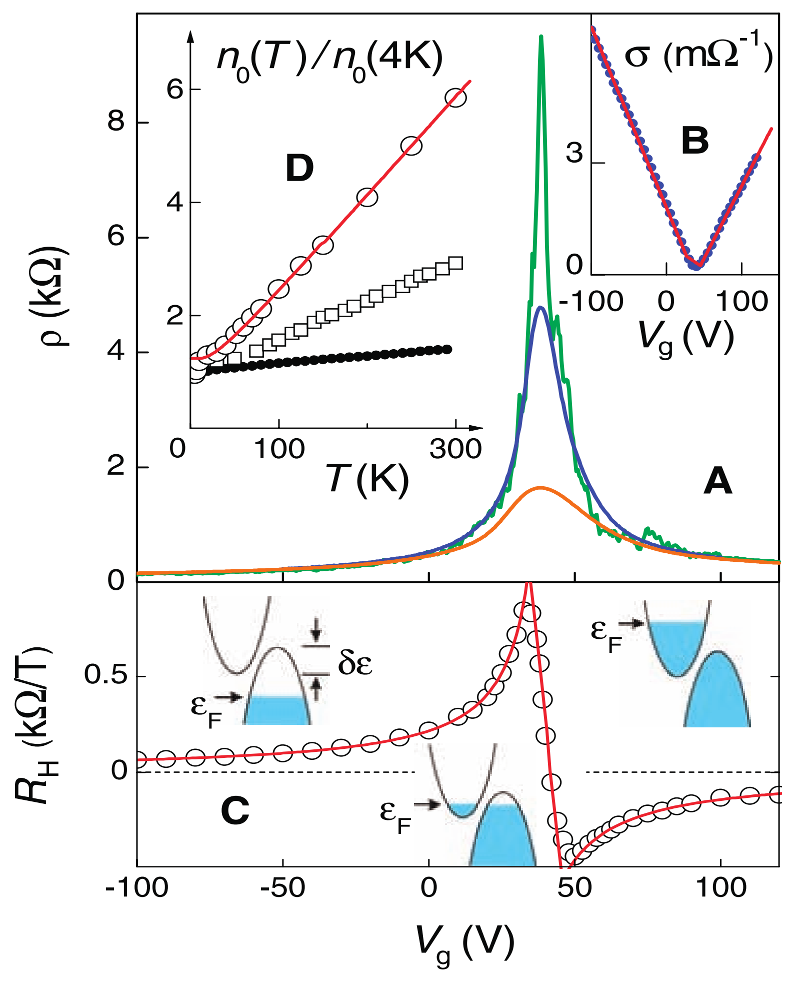


XPS result: after 2.5min UHV annealing, epitaxial graphene is grown on SiC. Sp2 peak is from graphene.

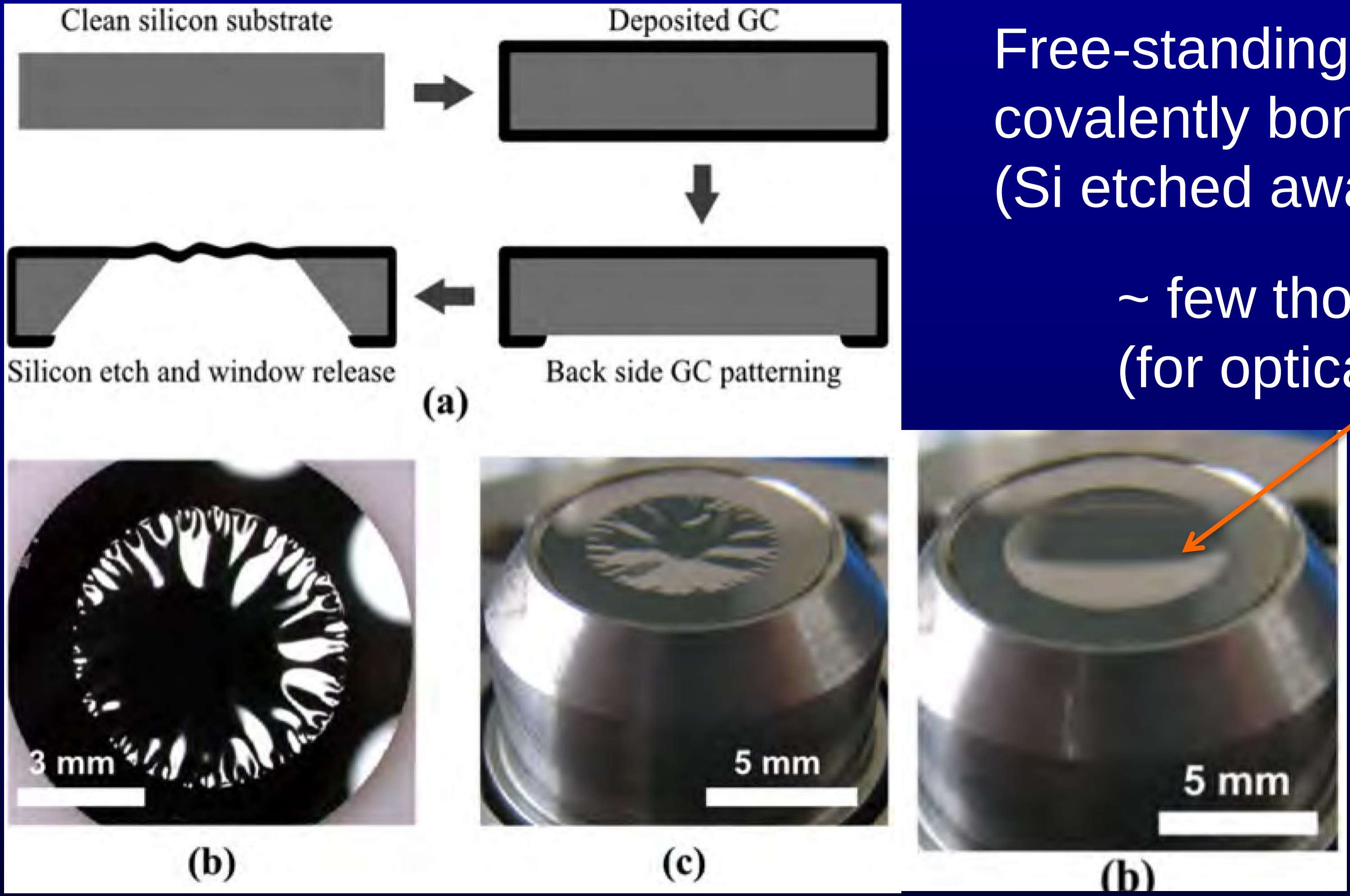
Semimetals

- Properties of semimetals:
  - Dirac point provides a resistivity spike at a single gate voltage and the height is set by the inverse of the mobility
  - Mobility increases by an order of magnitude at cryogenic temperatures
  - Small band gap (~meV) induced in Graphene could provide clean on/off transitions





Graphene UHV Vacuum Window



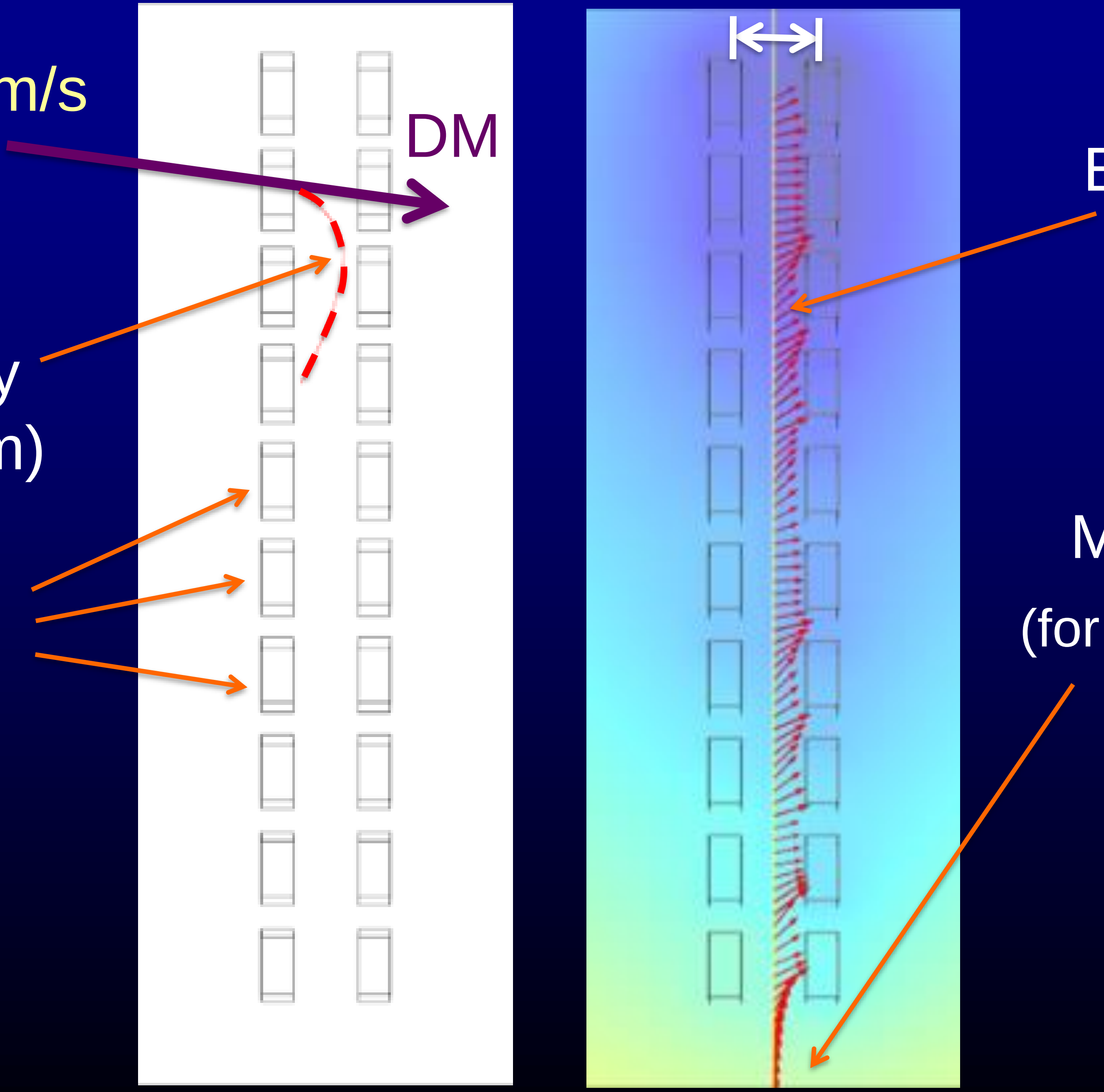
Free-standing Graphene covalently bonded to Si (Si etched away)

~ few thousand layers (for optical opacity)

Single-electron FET

- Voltage step ($\Delta V=e/C$) needed to get sufficient mobility to turn on/off will determine dimensions of FET
  - How many transistors (per unit area) are too many?
- If Dirac point is symmetric (and preferably there is a ~meV gap) with sensitivity to adding or subtracting a charge, then an electron trajectory can register a FET if DM scatters an electron off the FET, and register again on a 2nd FET if the electron follows a “hopping” trajectory between two FETs

Hopping Trajectory



v_{DM} ~220 km/s

Electron
Trajectory
(in vacuum)

Graphene
FETs

~100 V

E-Field

Microcal

(for big hops)

Trajectories from FET hits

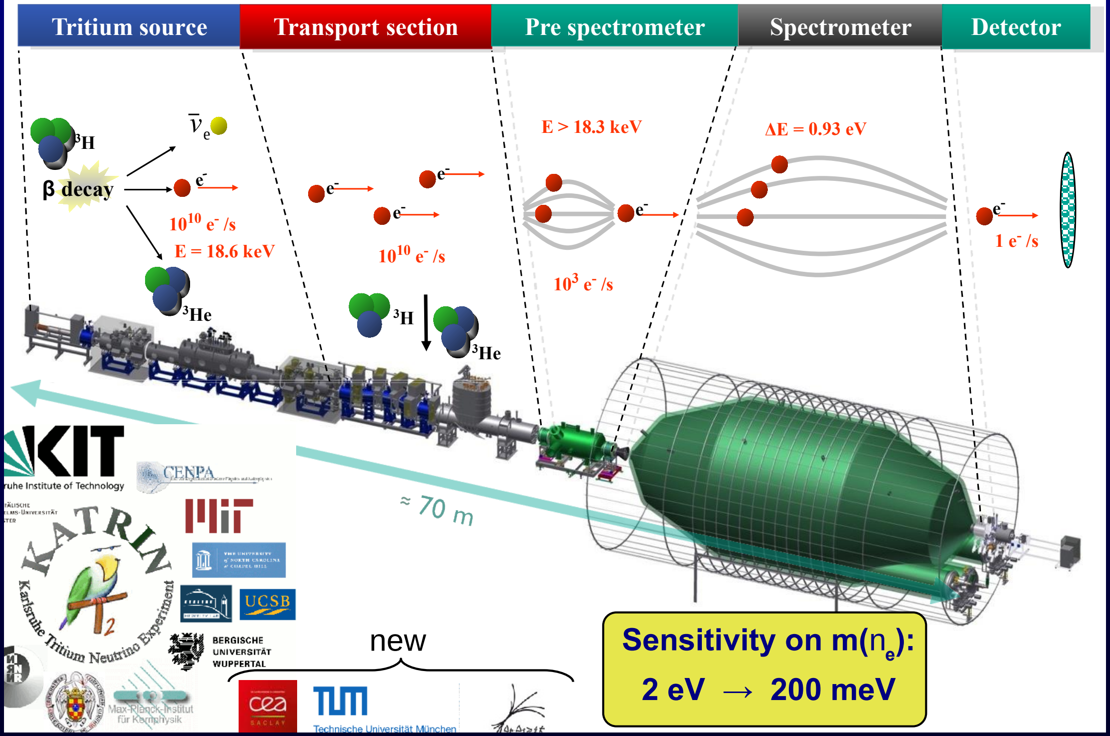
- Up to a maximum recoil energy set by the voltage (~100 V) across two neighboring layers, electrons ejected into the vacuum will follow a vacuum trajectory until they hit another FET or exit the layers
  - Spatial coordinates of the starting and ending FET (assuming low hit density and common bus lines in x- and y-) are recorded
  - For non-relativistic trajectories over ~cm distances, the possibility for time-of-flight consistency may be possible (rise time/ signal-to-noise ~ 3ns/10 ? for 30+ns TOF?)
  - Monitoring of the energy spectrum at ends could be achieved by microcal (limited area coverage - at perimeter)
  - Level of angular precision and energy degeneracy will depend on spatial size FET and velocity information from TOF or microcal

Silicon → Graphene Valley

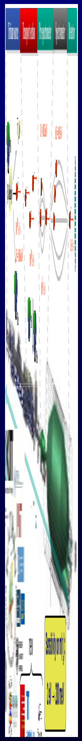
- Initial work with Graphene R&D companies (in this case Graphena) indicate that at the research level at this time, roughly 2-3 grams of Graphene could be produced in ~1-2 years for ~$10M
  - One full wafer (4”-6” dia.) Graphene production is achieved, it’s believed that two orders of magnitude high production could be done for ~an order of magnitude higher total cost in a small fraction of the time
  - Example: SiPM development 10 years ago led to $2M (SiPM device cost) upgrade of CMS HCAL for ~$2M/0.1m^2 (under installation now) – which was an orer of magnitude below original R&D cost. Current production FBK→LFoundry of 14 sq. meters in one week will cost roughly the same (~$2M).

Progress on PTOLEMY

- Simulations of compact filtering
  - Phase space transformation in KATRIN (2π momentum directions for KE~18.6keV → ~1-D for KE~1eV) comes from the transverse size expansion, not from the length dimension
  - Length is from a specific solution for adiabatic EM transport



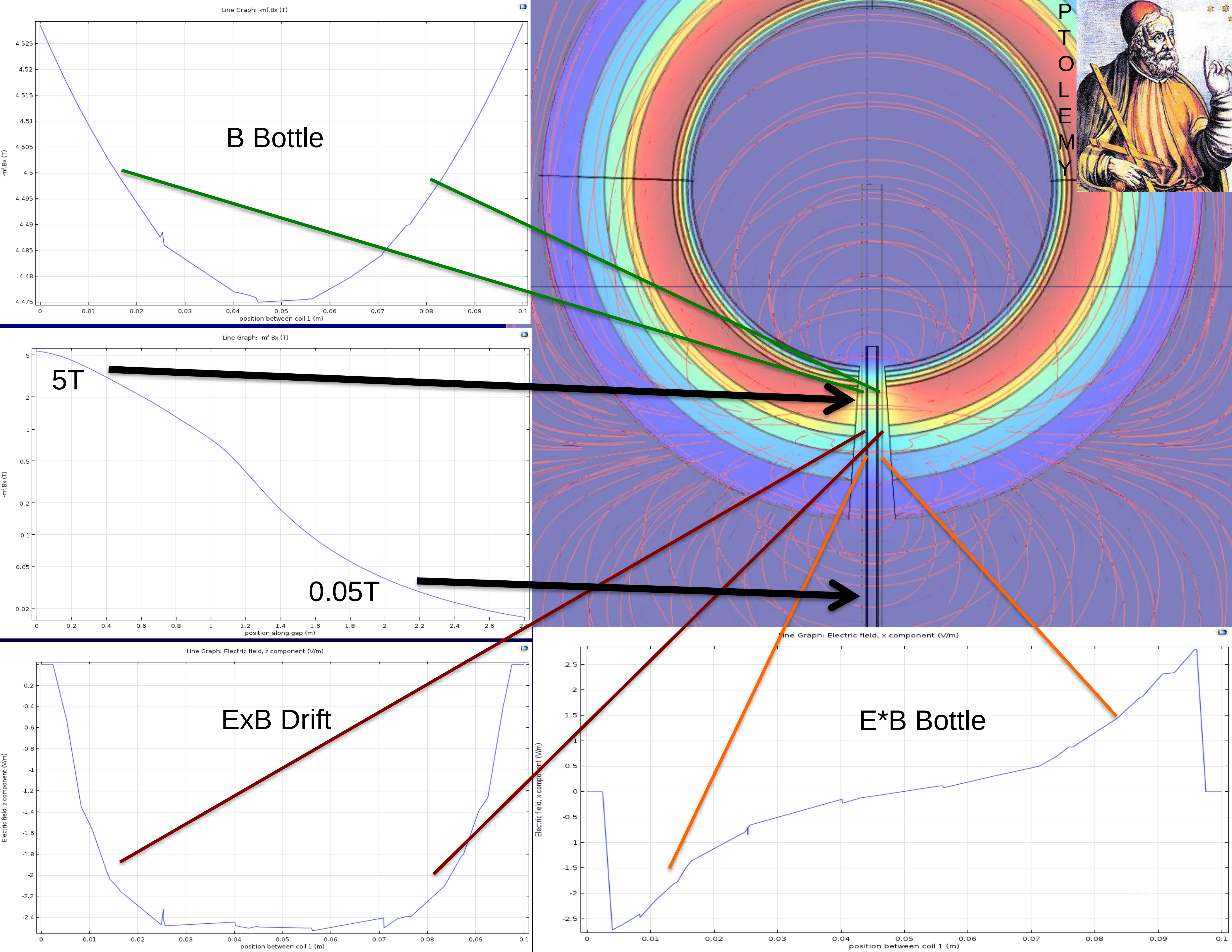
Goal: Reduce this length by x10^{-4}



Alternative Filtering

- KATRIN: As B drops along longitudinal KE of electron, transverse KE → longitudinal and E*B term trades total KE with potential energy – electrons below filter cut-off bounce (reverse longitudinal momentum) due to E*B
- PTOLEMY: Electrons enter at a fixed reference voltage into one end of an E*B bottle, as they bounce back and forth, they trade KE for potential energy as they slowly ExB drift vertically in the voltage potential and also drift into lower B field from transverse ExB drift where they exchange transverse KE → longitudinal

Primary difference: KATRIN electrons travel a longitudinal distance of 10’s of meters, PTOLEMY electrons travel ~ 1cm
Commonality: Transverse area connecting ~1eV electrons uniquely to the 2π in momentum at KE=18.6keV is equally large



B Bottle

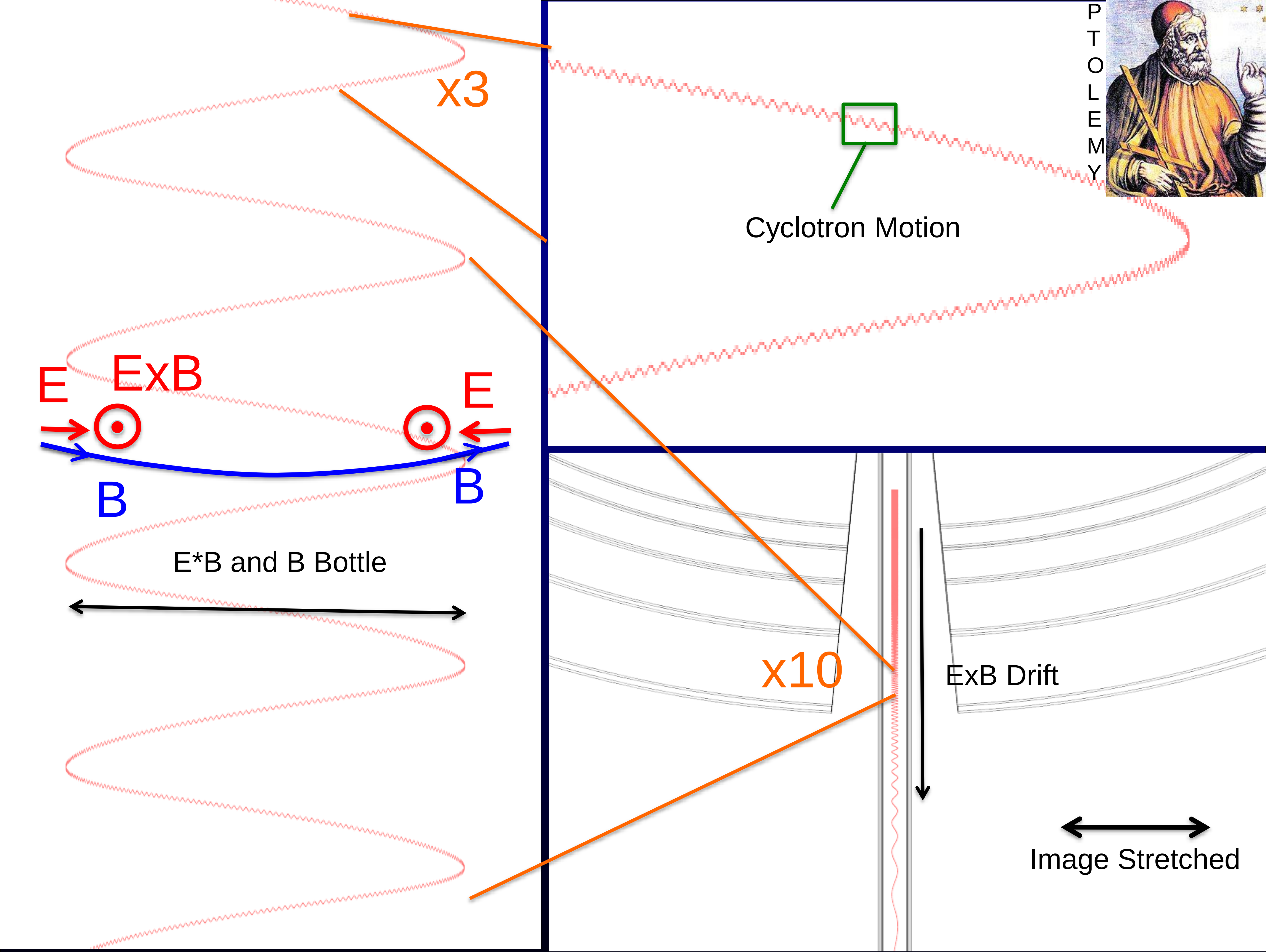
5T

0.05T

ExB Drift

E*B Bottle

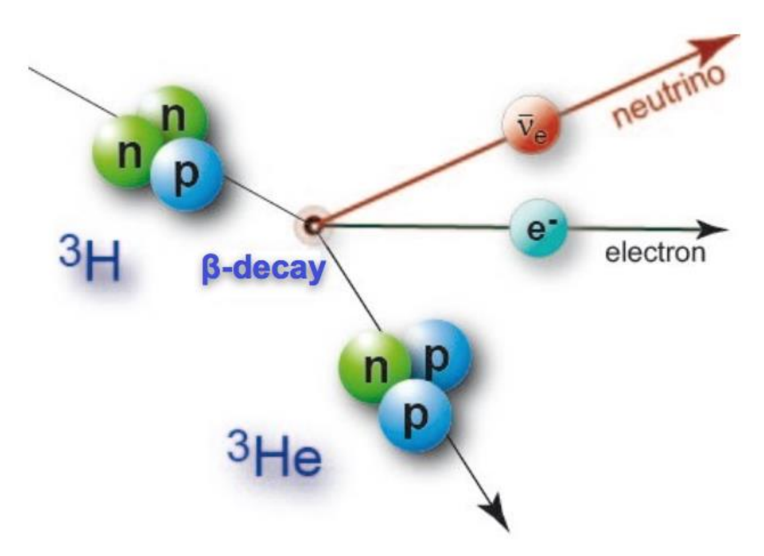
PTOLEMY


x3
E
ExB
E
B
B
E*B and B Bottle
Cyclotron Motion
PTOLEMY
x10
ExB Drift
Image Stretched

Molecular Smearing

- Progress much faster than originally foreseen
  - Cold plasma loading of hydrogen on Graphene is very efficient, though maximum surface loading and uniformity still under study
  - Graphene is one of several possibilities for holding atomic tritium with ~1eV dissociation energy
  - Cryogenic(<100K) Au(111) produces high density coverage (1T per Au atom on surface) and can be loaded using <0.5% single atom catalysts
    - Analysis underway at BNL cryogenic STM (waiting for STM time)
  - Final tests will be done with tritium and microcal measurements

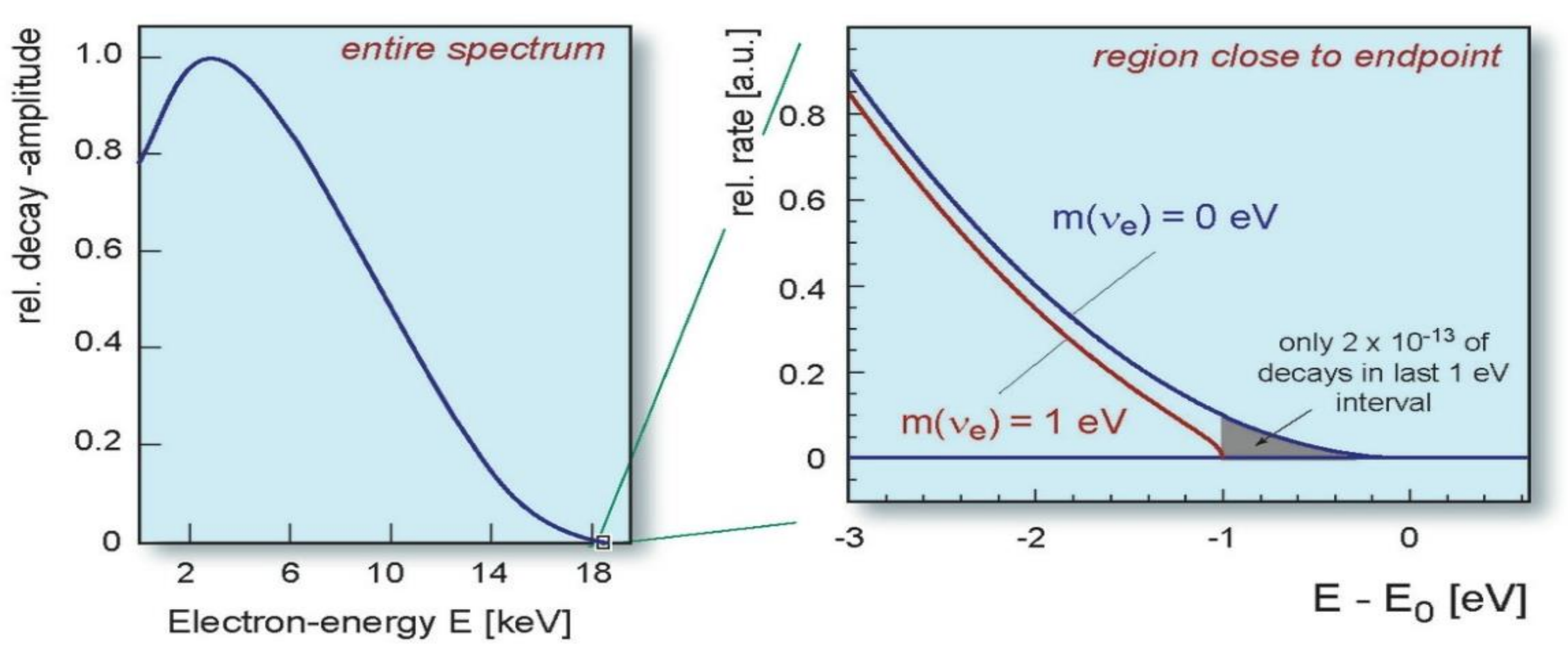
$^{3}H \rightarrow {}^{3}He^{+} + e^{-} + \bar{!}_{e}$



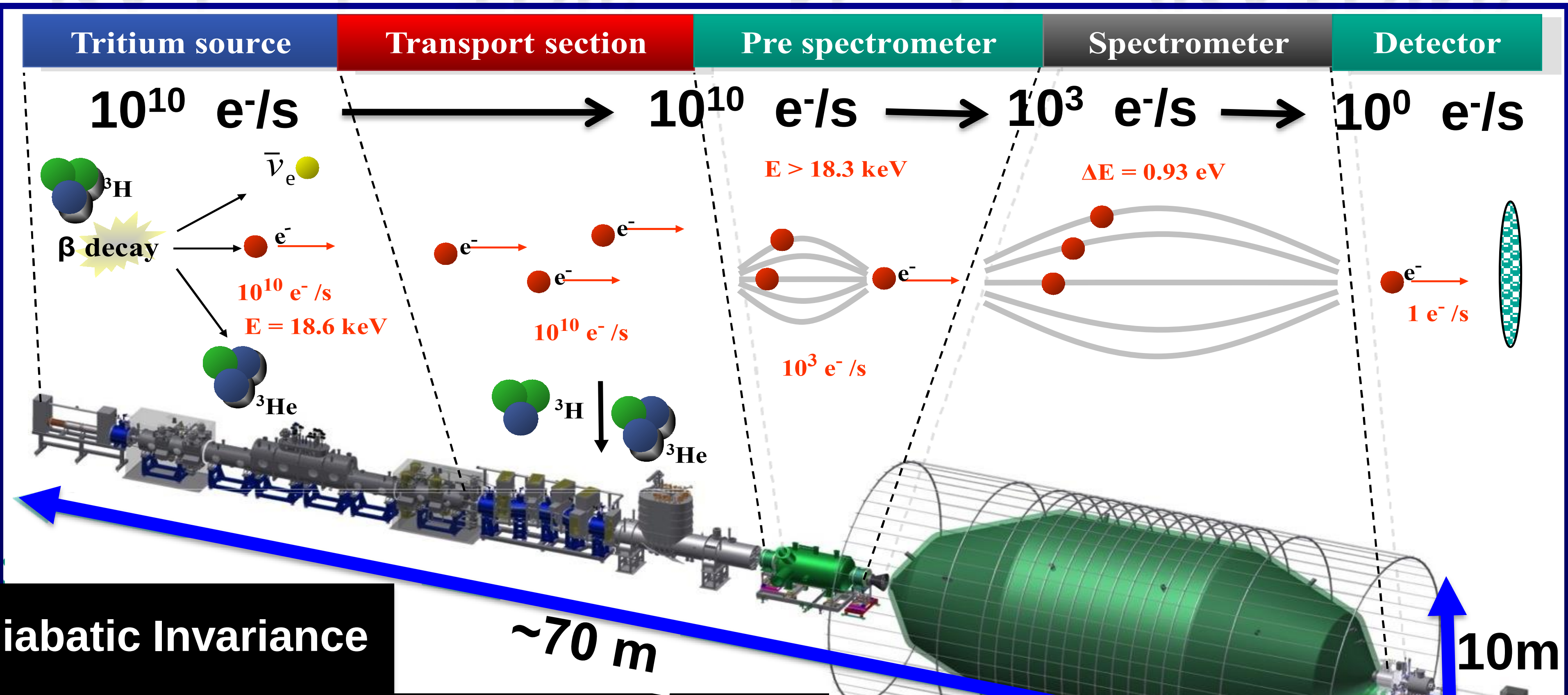
Sum of masses and kinetic energy must add up to mass of initial nucleus

Electron Endpoint Spectrum

$$\frac{dN}{dE} \sim \sqrt{\left(E - E_0\right)^2 - \sum_{i}^{n_\nu} \left|U_{ei}\right|^2 m_{\nu,i}^2}$$



KArlsruhe TRItium Neutrino (KATRIN)



Adiabatic Invariance

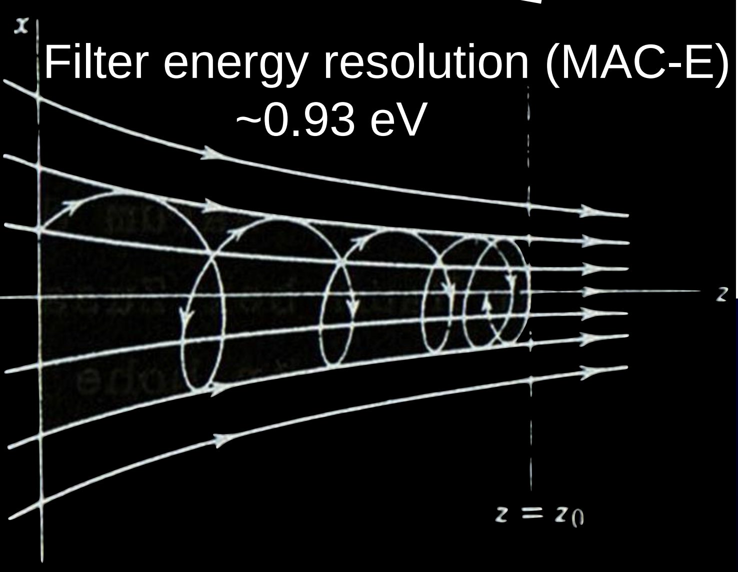
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

$p_\perp \to p_\parallel$

Filter (E - Field)

$p_\parallel \to p_\perp$

Filter energy resolution (MAC-E)
~0.93 eV



Sensitivity on $m(n_e)$:

2 eV → 200 meV

New Approaches

PROJECT 8

- Cyclotron Radiation Emission Spectroscopy B. Monreal and J. Formaggio, Phys. Rev. D80:051301
  - – Relativistic correction to cyclotron frequency
  - – Low density cold T^2 gas → Atomic traps
- Microcalorimetry S. Betts *et al.*, arXiv:1307.4738 (astro-ph)
  - – Transition-Edge-Sensor Electron Calorimetry
  - – RF tracking/triggering
  - – Cryogenic Tritiated Graphene/Au Surfaces

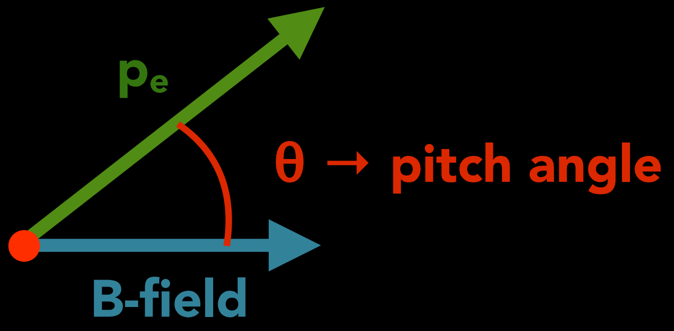
P rinceton
T ritium
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield

PTOLEMY Supported by:
The Simons Foundation
The John Templeton Foundation

Cyclotron Radiation

Larmor formula

$$P(\gamma,\theta) = \frac{1}{4\pi\varepsilon_0}\frac{2}{3}\frac{q^4B^2}{m_e^2}(\gamma^2-1)\sin^2\theta$$



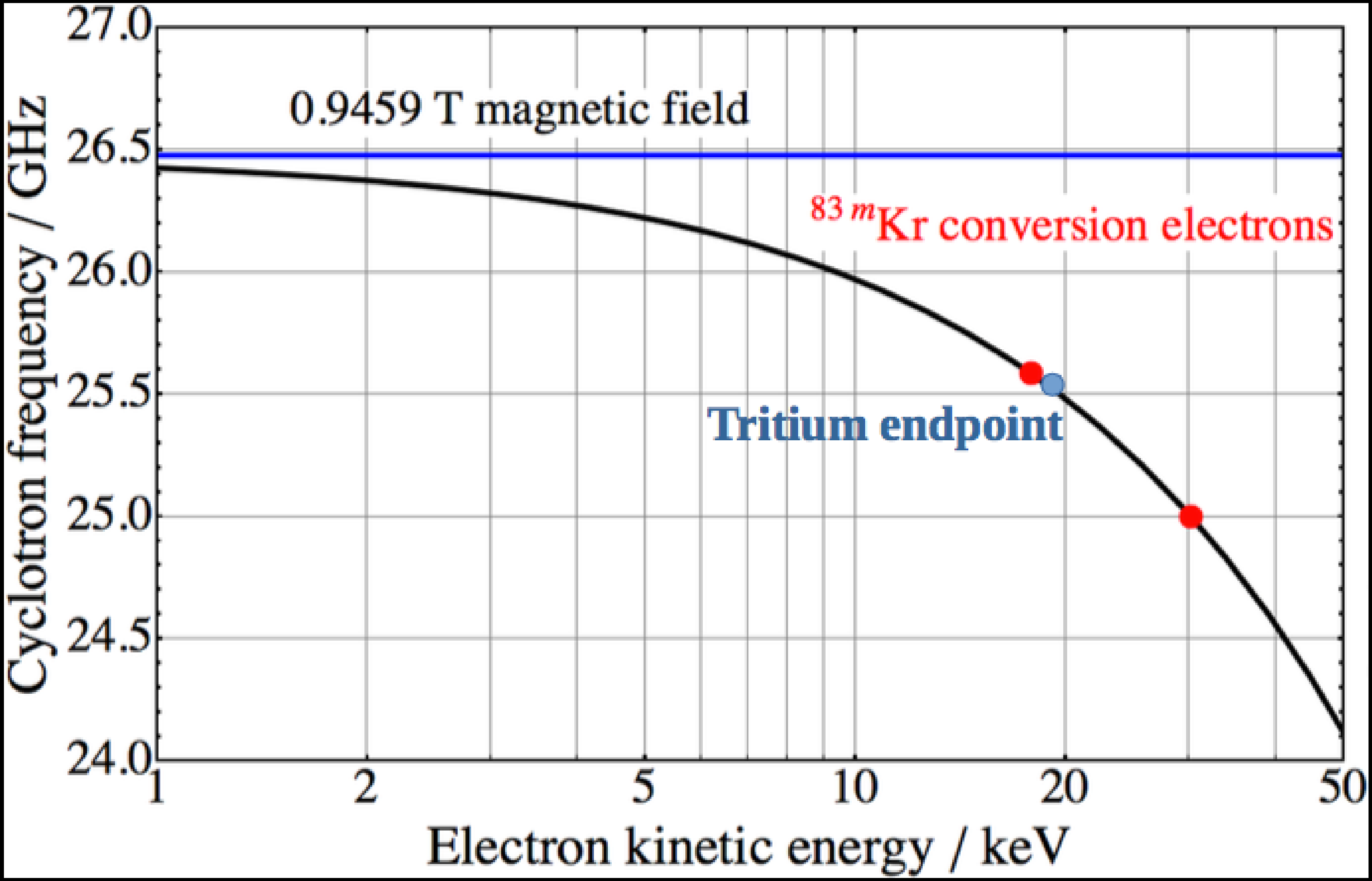
Emitted power

- 1.1 fW for 18 keV e^- at 90°
- 1.7 fW for 30.4 keV e^- at 90°

→ Low-noise cryogenic RF-system needed!

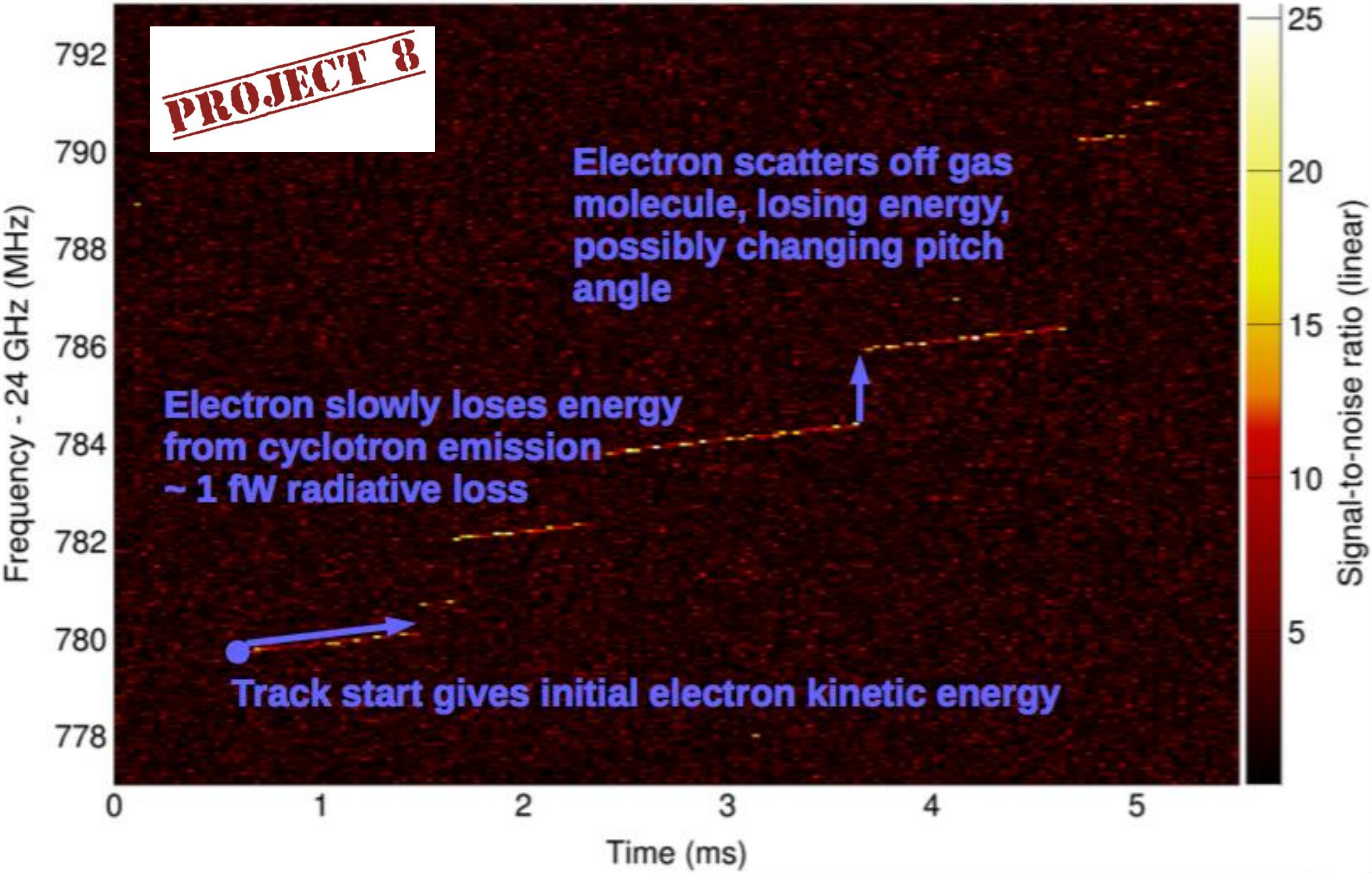
Relativistic Correction to Cyclotron Frequency

magnetic field of 1T → cyclotron frequency in K-Band



^{83m}Kr provides electrons close to tritium endpoint

Electron tracks in spectrogram are information-dense



Electron scatters off gas molecule, losing energy, possibly changing pitch angle

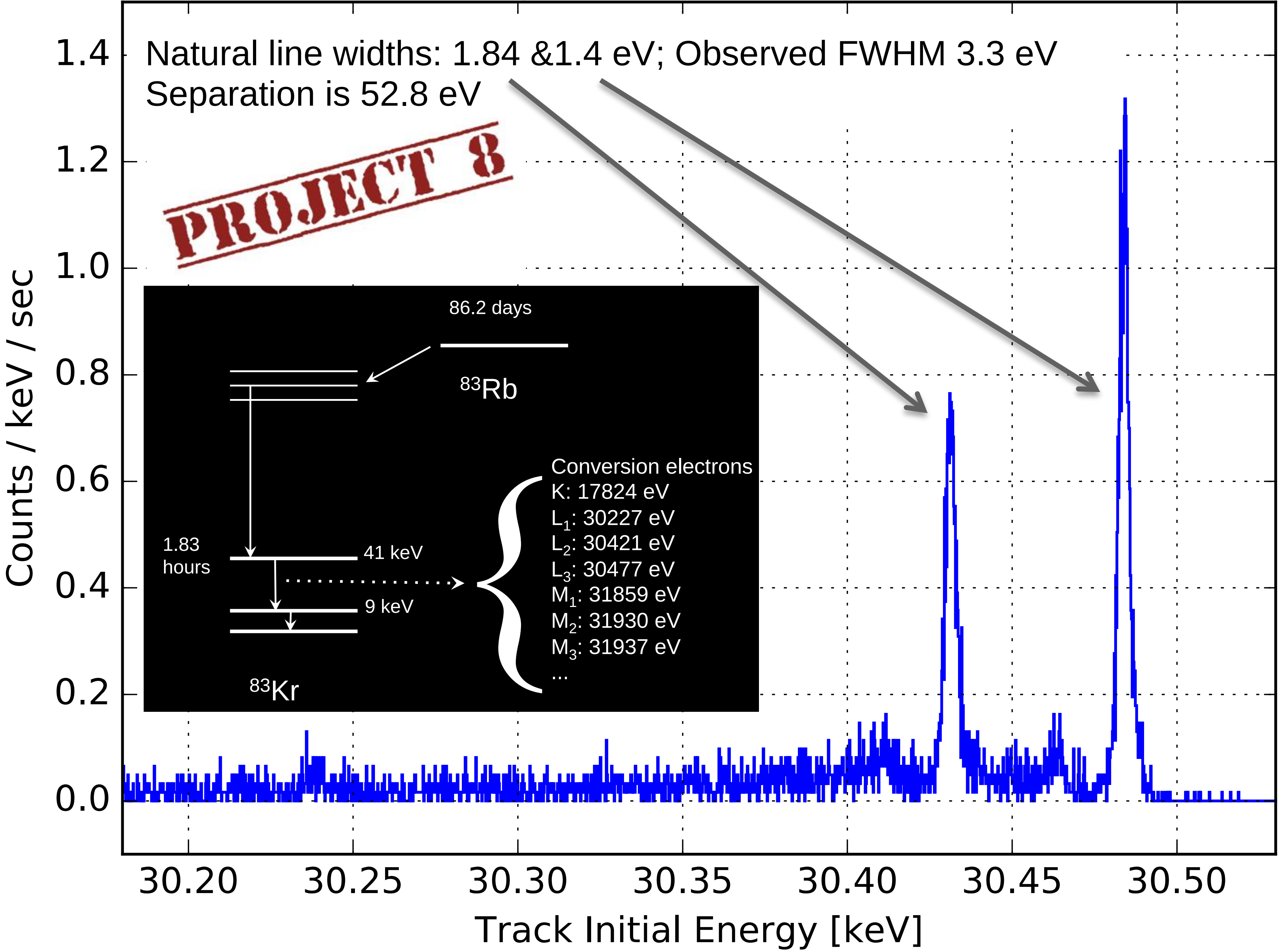
Electron slowly loses energy from cyclotron emission
~ 1 fW radiative loss

Track start gives initial electron kinetic energy

Scale:
100eV

Region of interest near the 30.4 keV lines

(bins are 0.5 eV wide)



Natural line widths: 1.84 &1.4 eV; Observed FWHM 3.3 eV

Separation is 52.8 eV

Conversion electrons

K: 17824 eV

L_1: 30227 eV

L_2: 30421 eV

L_3: 30477 eV

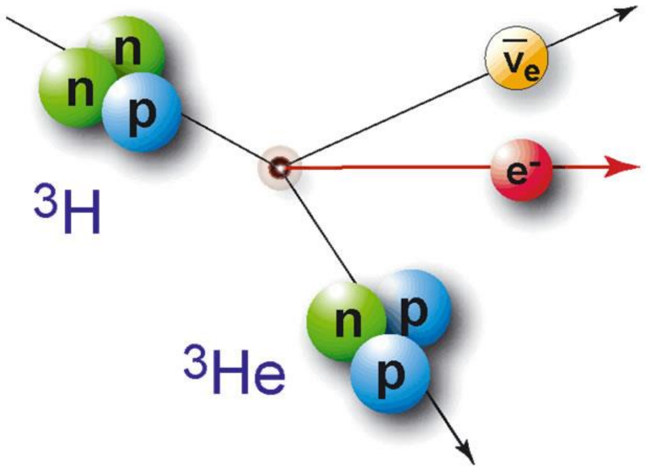
M_1: 31859 eV

M_2: 31930 eV

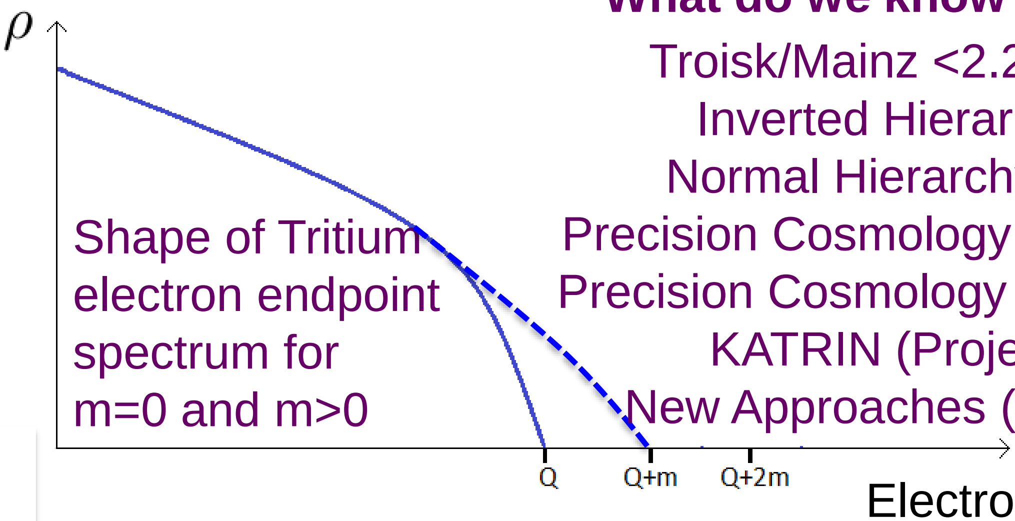
M_3: 31937 eV

...

Neutrino Mass as a Tool for Discovery



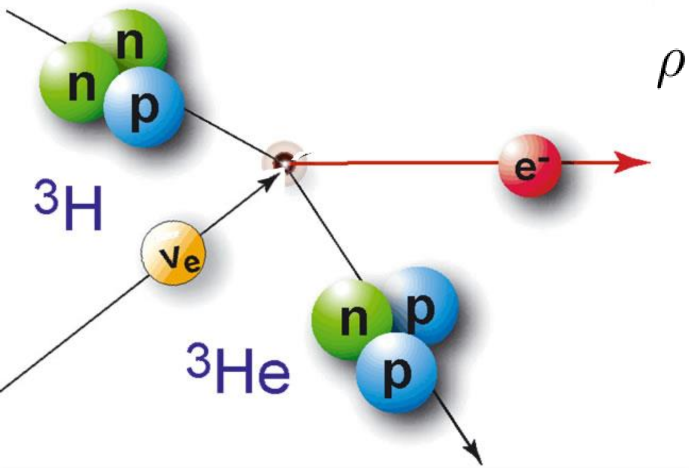
Tritium β-decay
(12.3 yr half-life)



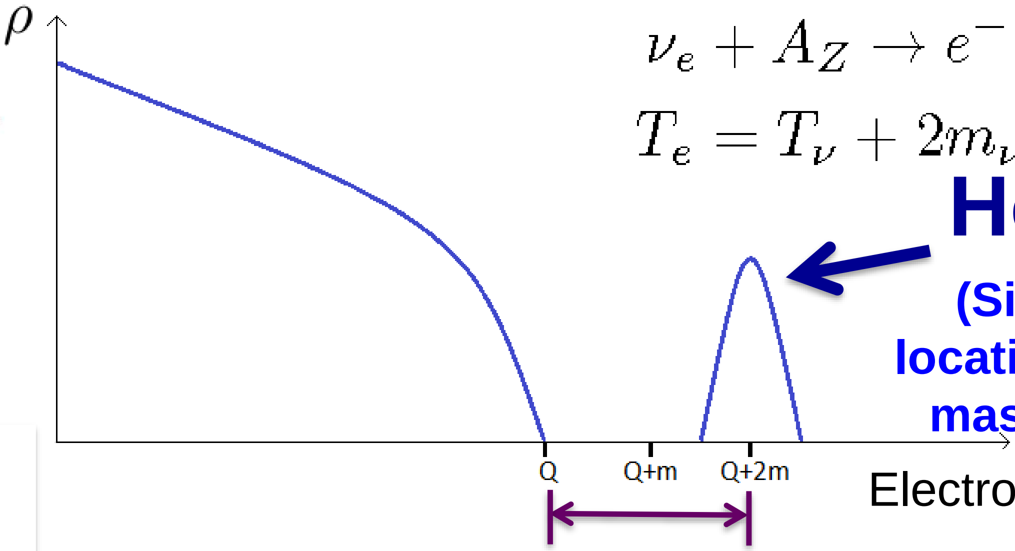
Shape of Tritium electron endpoint spectrum for m=0 and m>0

What do we know?

Troisk/Mainz <2.2eV (95% C.L.)
Inverted Hierarchy >0.05eV
Normal Hierarchy 0eV allowed
Precision Cosmology (Present) <0.23eV
Precision Cosmology (Projected) 0.04eV
KATRIN (Projected) 0.2eV
New Approaches (R&D) ~0.02eV?



Relic Neutrino
Capture on Tritium



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

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

How many?

(Signal shape and location predicted from mass measurement)

Original idea: Steven Weinberg in 1962 [*Phys. Rev.* 128:3, 1457]

Relic Neutrino Signal/Noise: JCAP 0706 (2007)015, hep-ph/0703075 by Cocco, Mangano, Messina