PTOLEMY

Precision Measurements with Tritium End Point Experiments

Reporting on behalf of Project 8 and PTOLEMY

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Princeton

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Chicago, IL, USA
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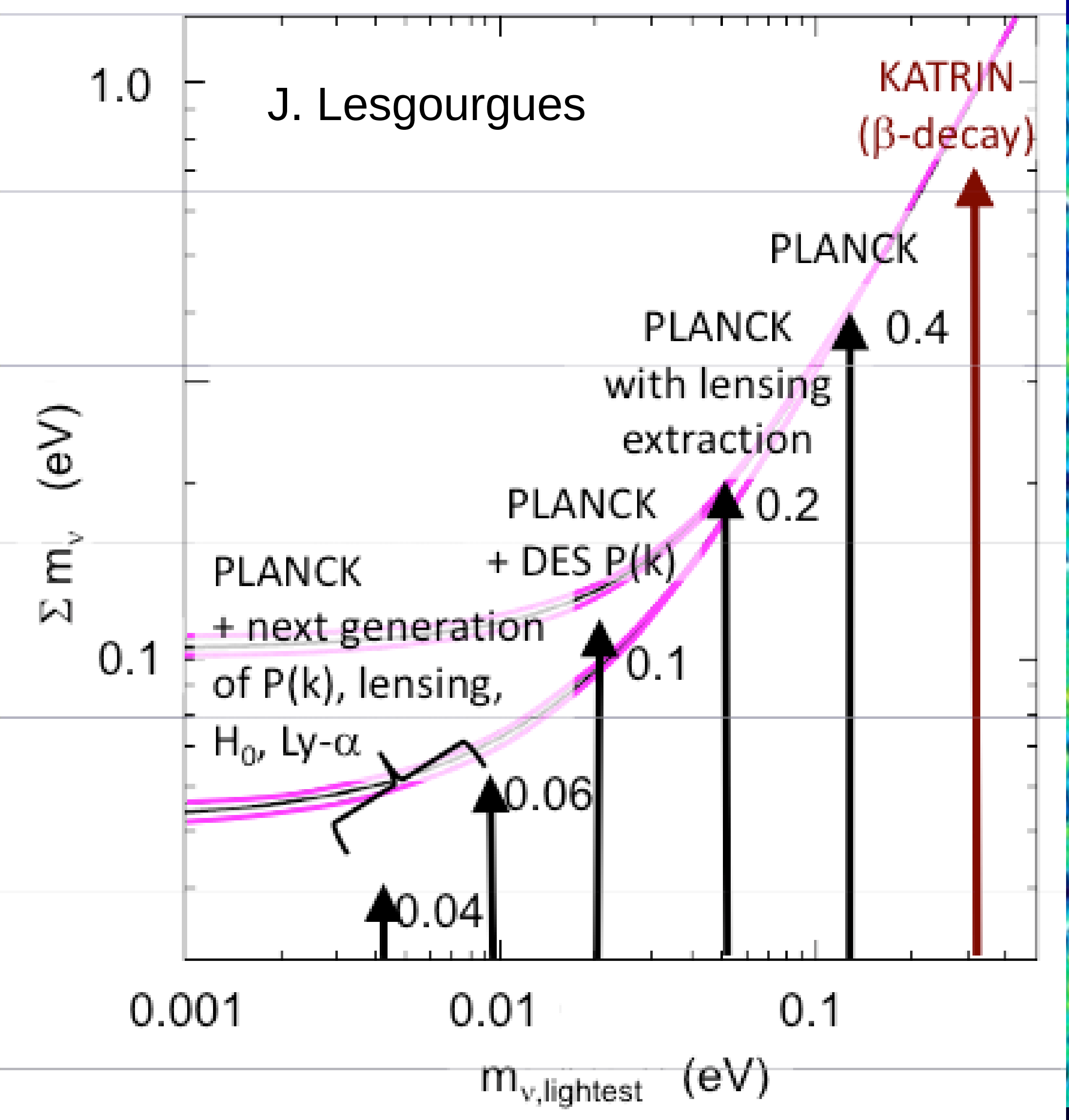
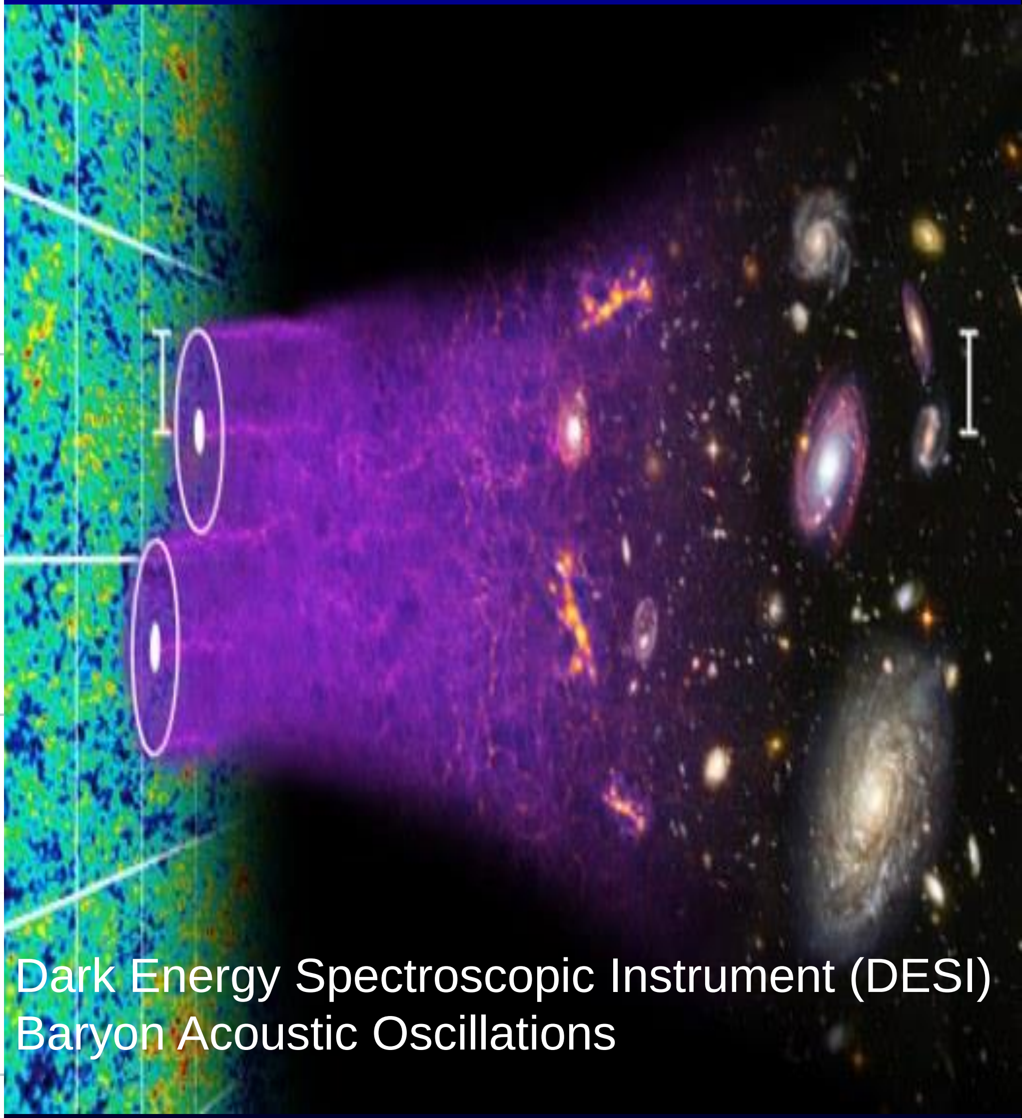
Sensitivity Frontier

- Next step in lab-based neutrino mass measurements will cross into new territory
  - 0.2eV KATRIN → 0.02eV New Approaches

In this era, neutrino mass will move from being an unknown to become a tool to separate out signals

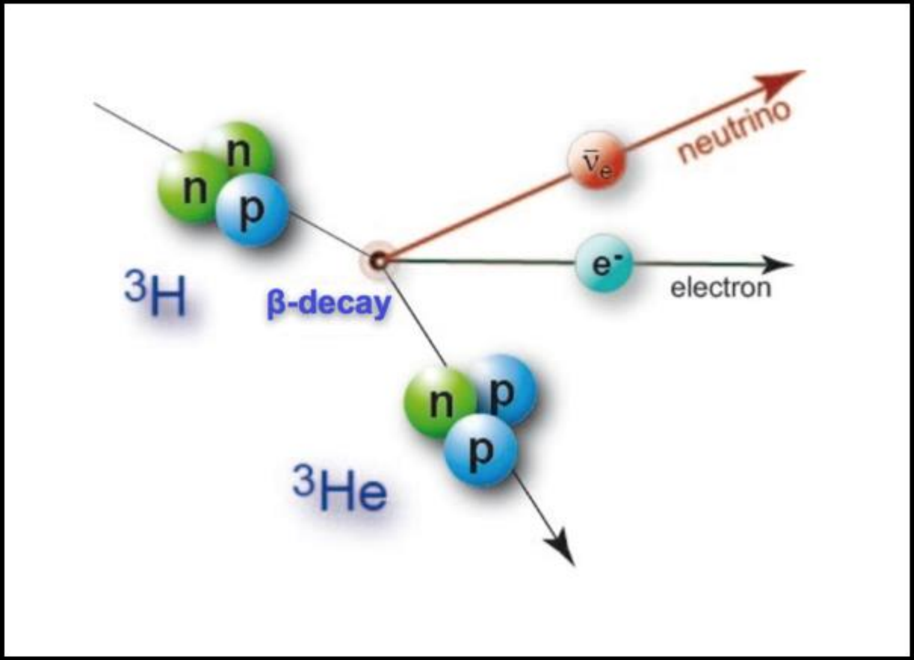
Precision Cosmology Projections





Dark Energy Spectroscopic Instrument (DESI)
Baryon Acoustic Oscillations

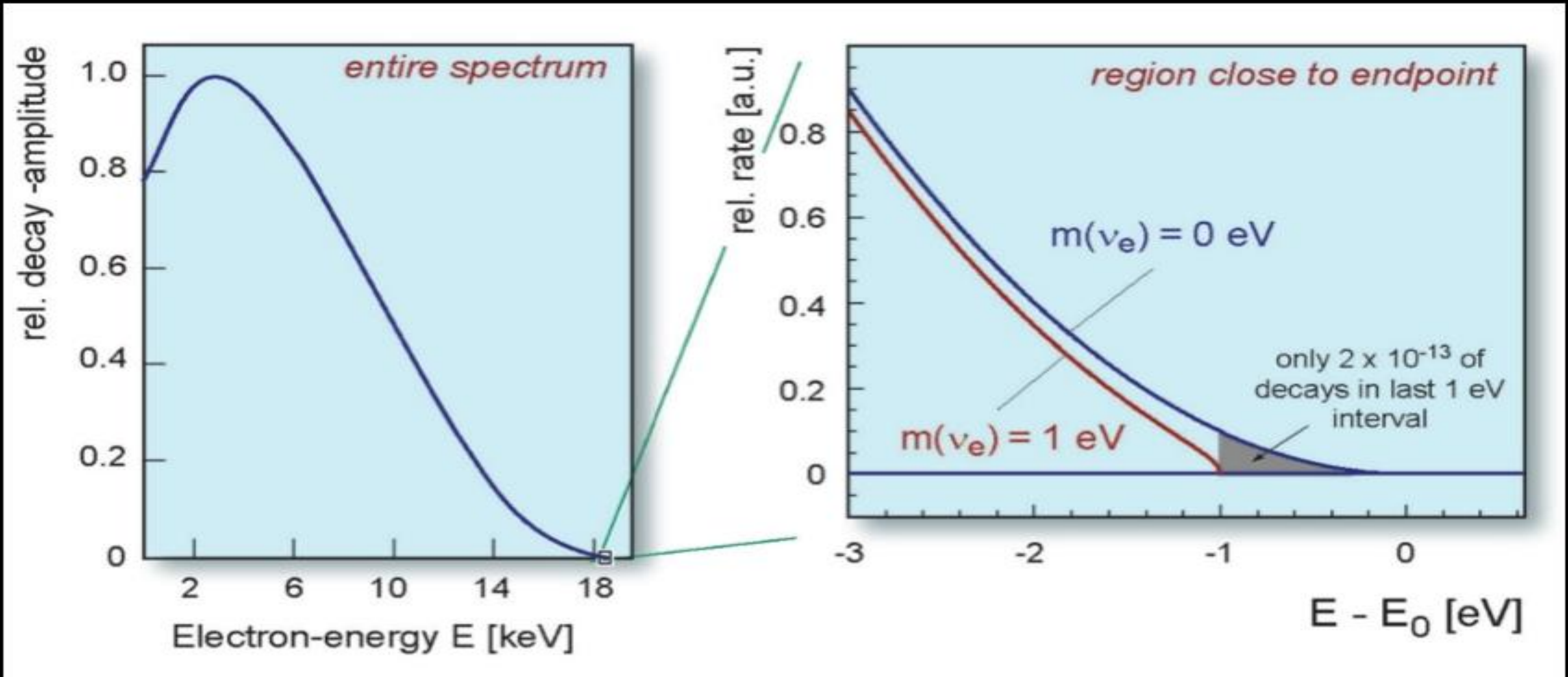
$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \overline{\nu}_e$$



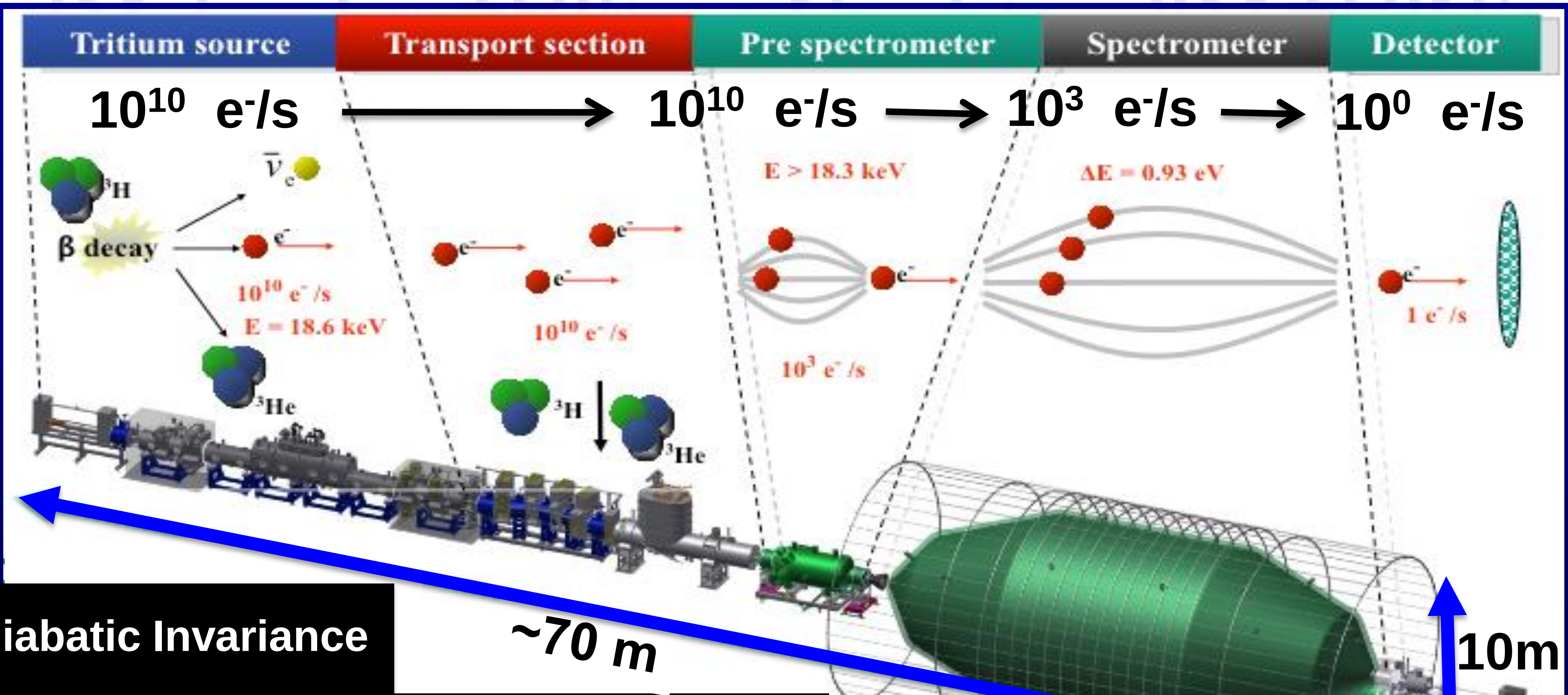
Sum of masses and kinetic energy must add up to mass of initial nucleus

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)



Sensitivity on m(ν_e):

2 eV → 200 meV

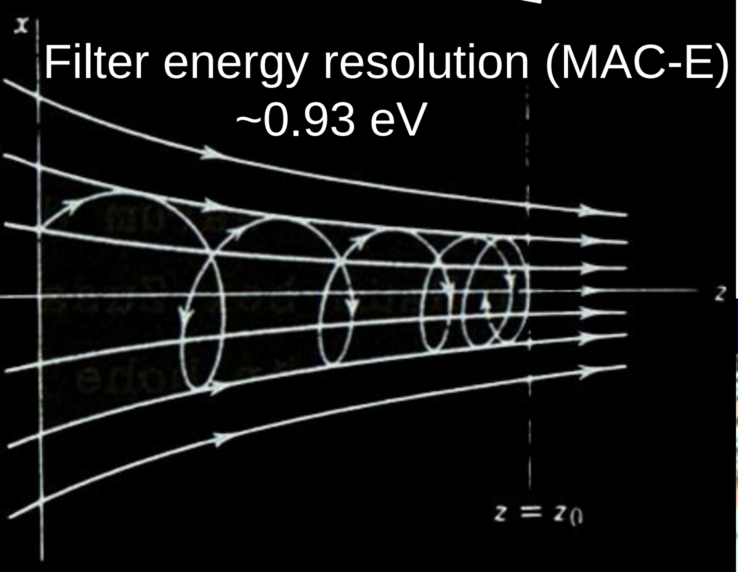
Adiabatic Invariance

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

$$p_\perp \to p_\parallel$$

Filter (E - Field)

$$p_\parallel \to p_\perp$$


Filter energy resolution (MAC-E)

~0.93 eV

New Approaches

- 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
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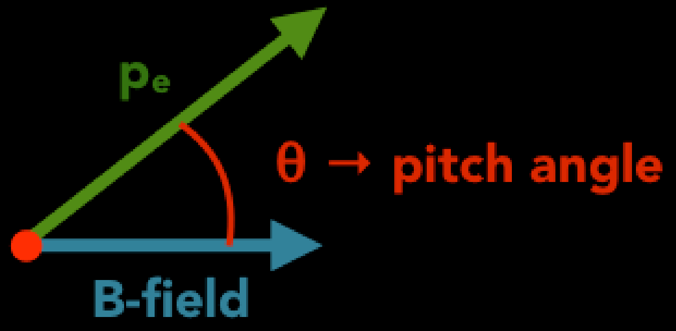
Cyclotron Radiation

Larmor formula

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



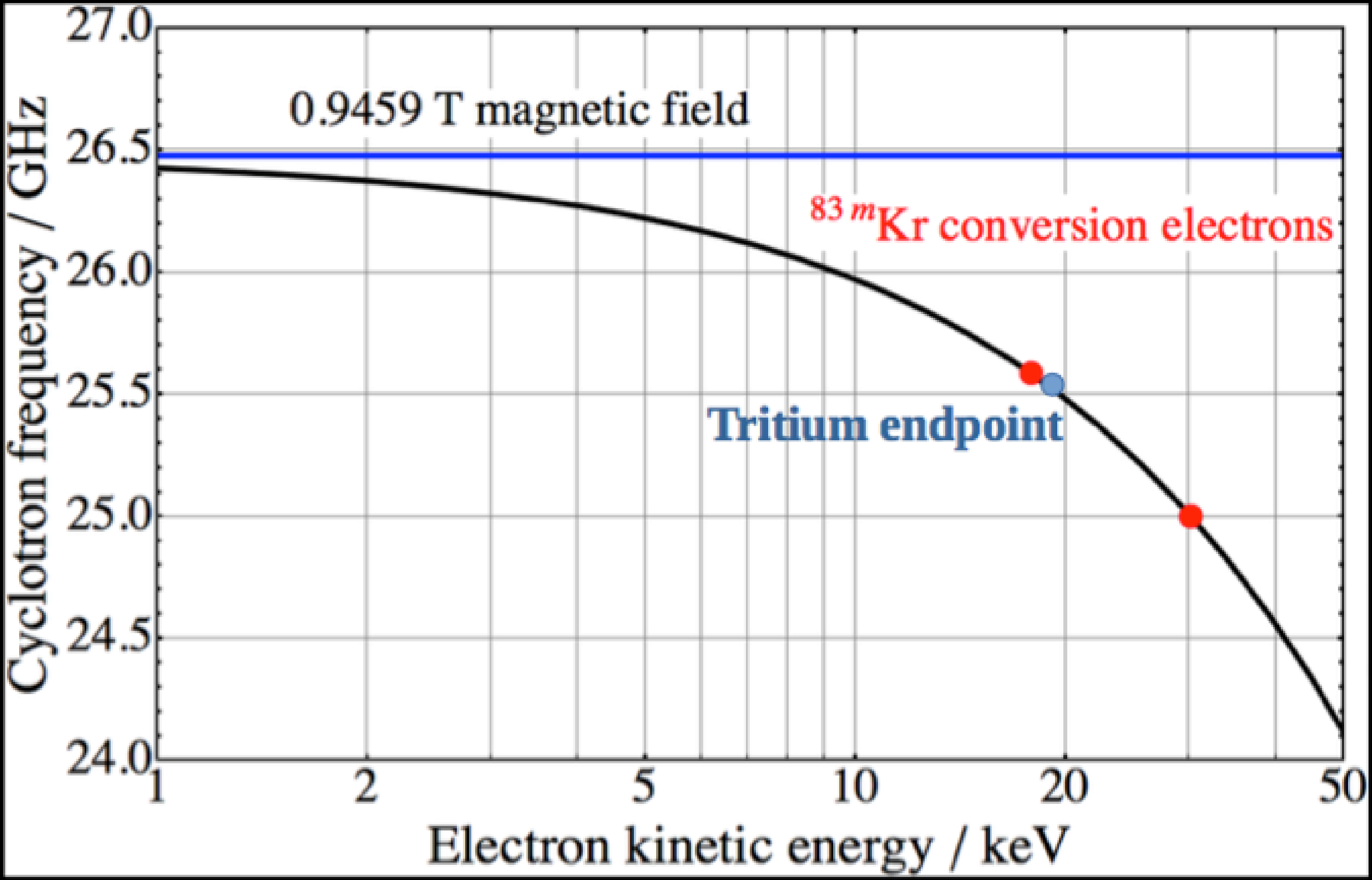
Emitted power

- 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!

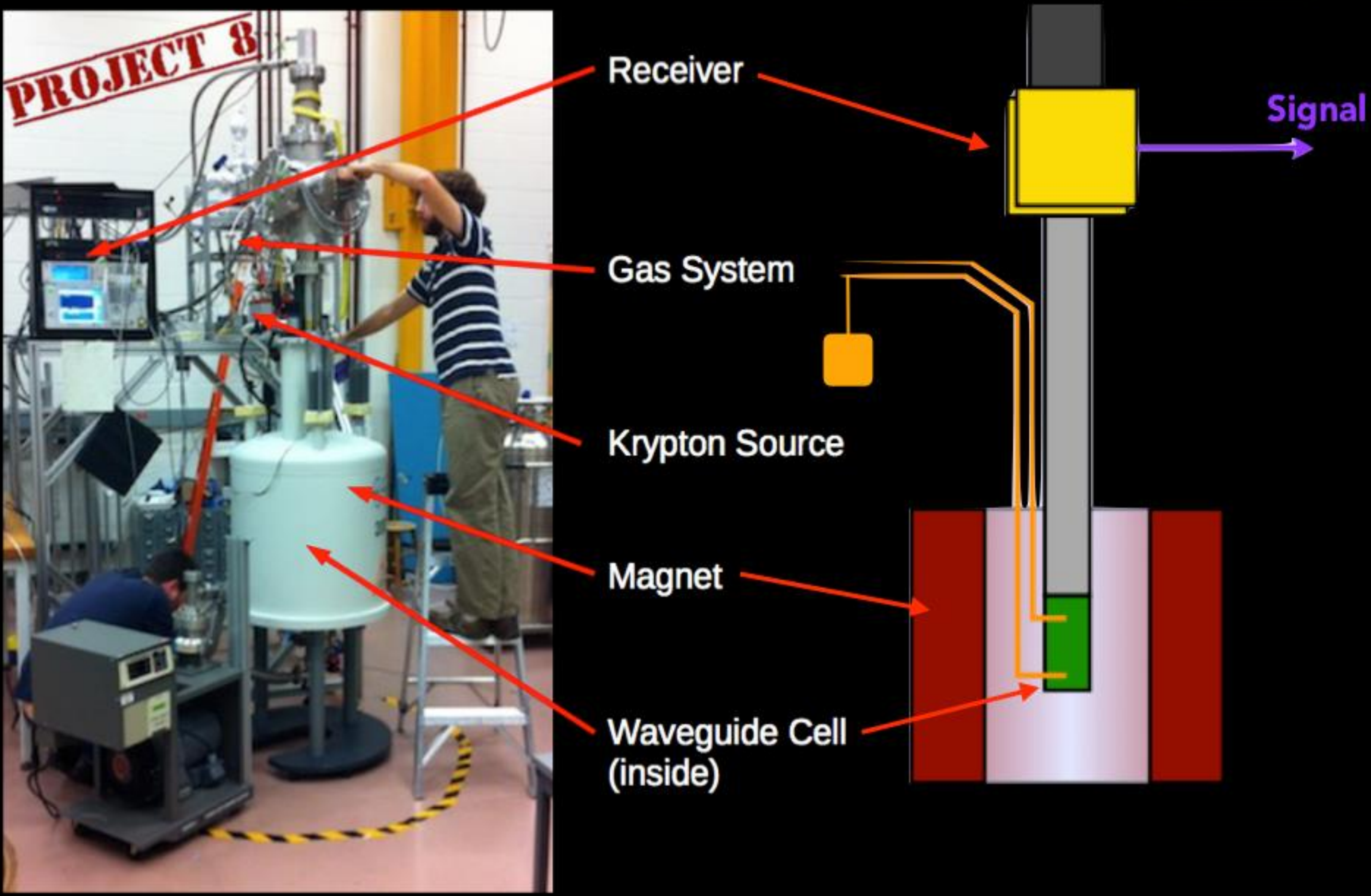
Relativistic Correction to Cyclotron Frequency

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



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

PROJECT8 PROTOTYPE



Receiver

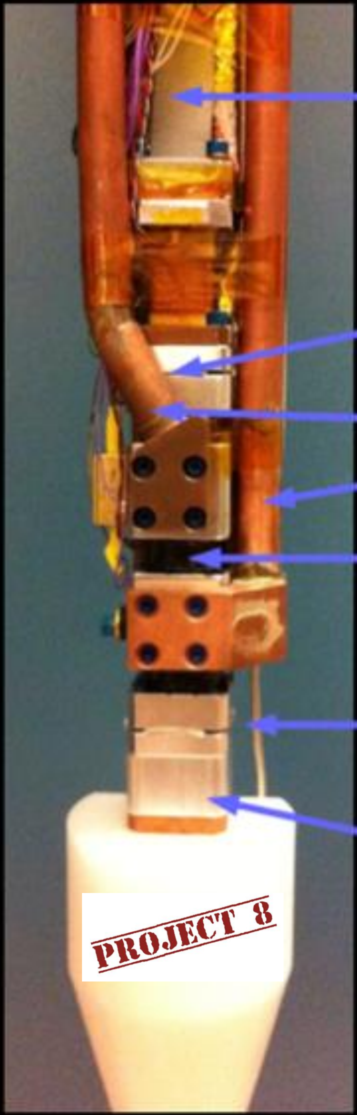
Gas System

Krypton Source

Magnet

Waveguide Cell
(inside)

Harmonic e⁻ trap



Waveguide to amplifiers

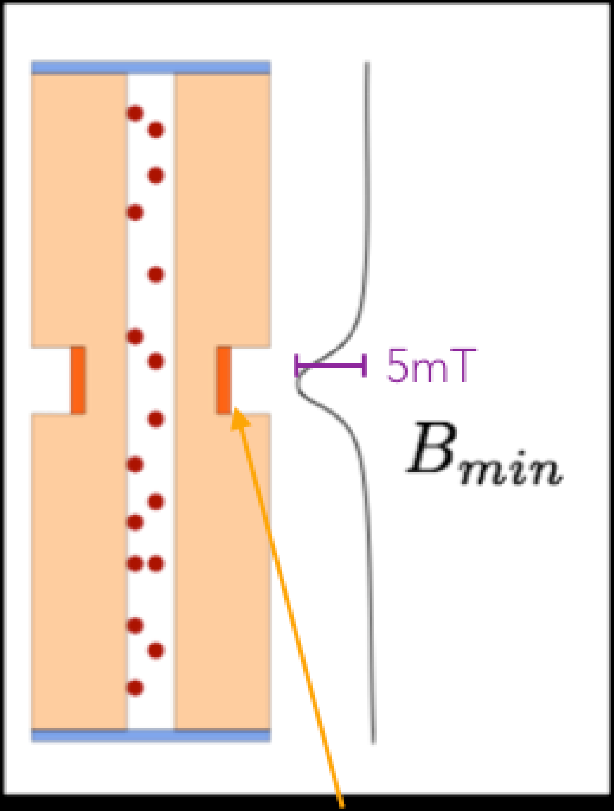
Cell upper window

Gas Lines

Magnetic Bottle Coil

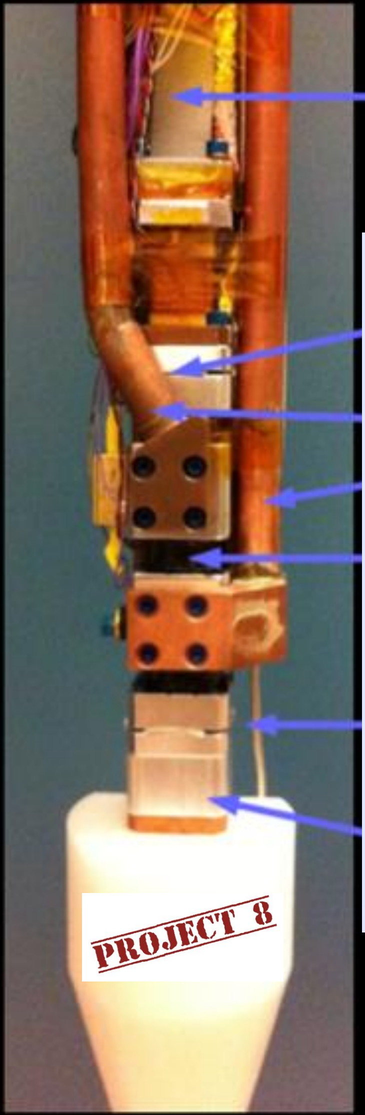
Cell lower window

Test signal injection port

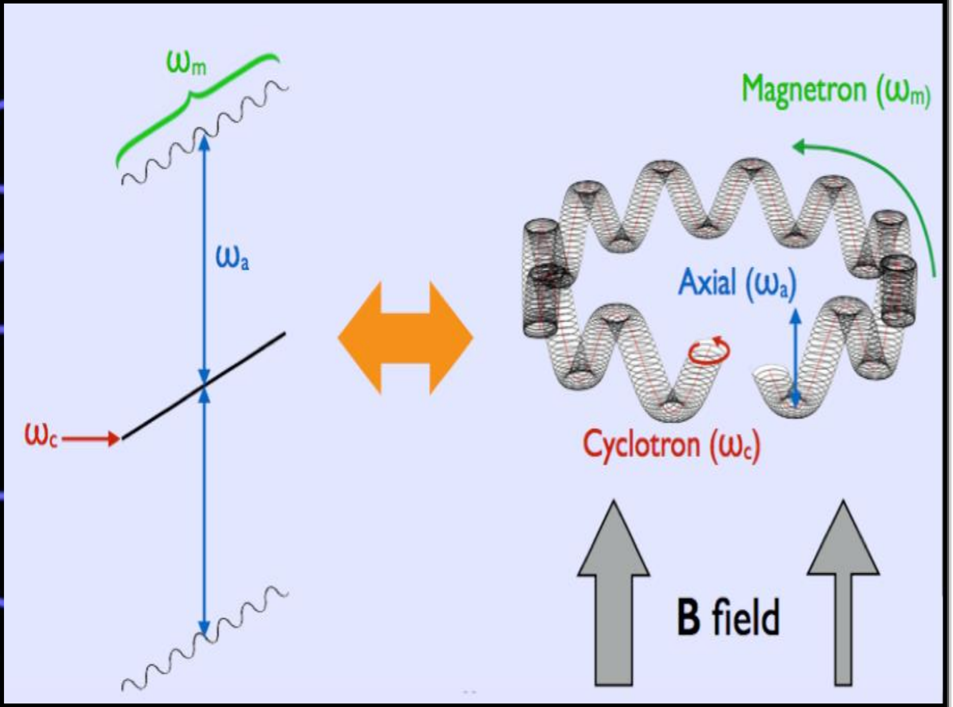


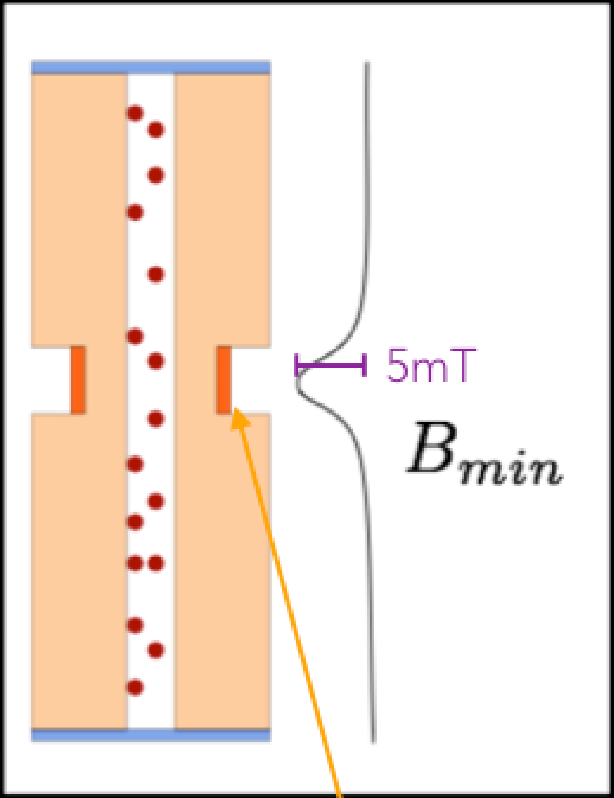
Magentic bottle coil

Harmonic e^- trap

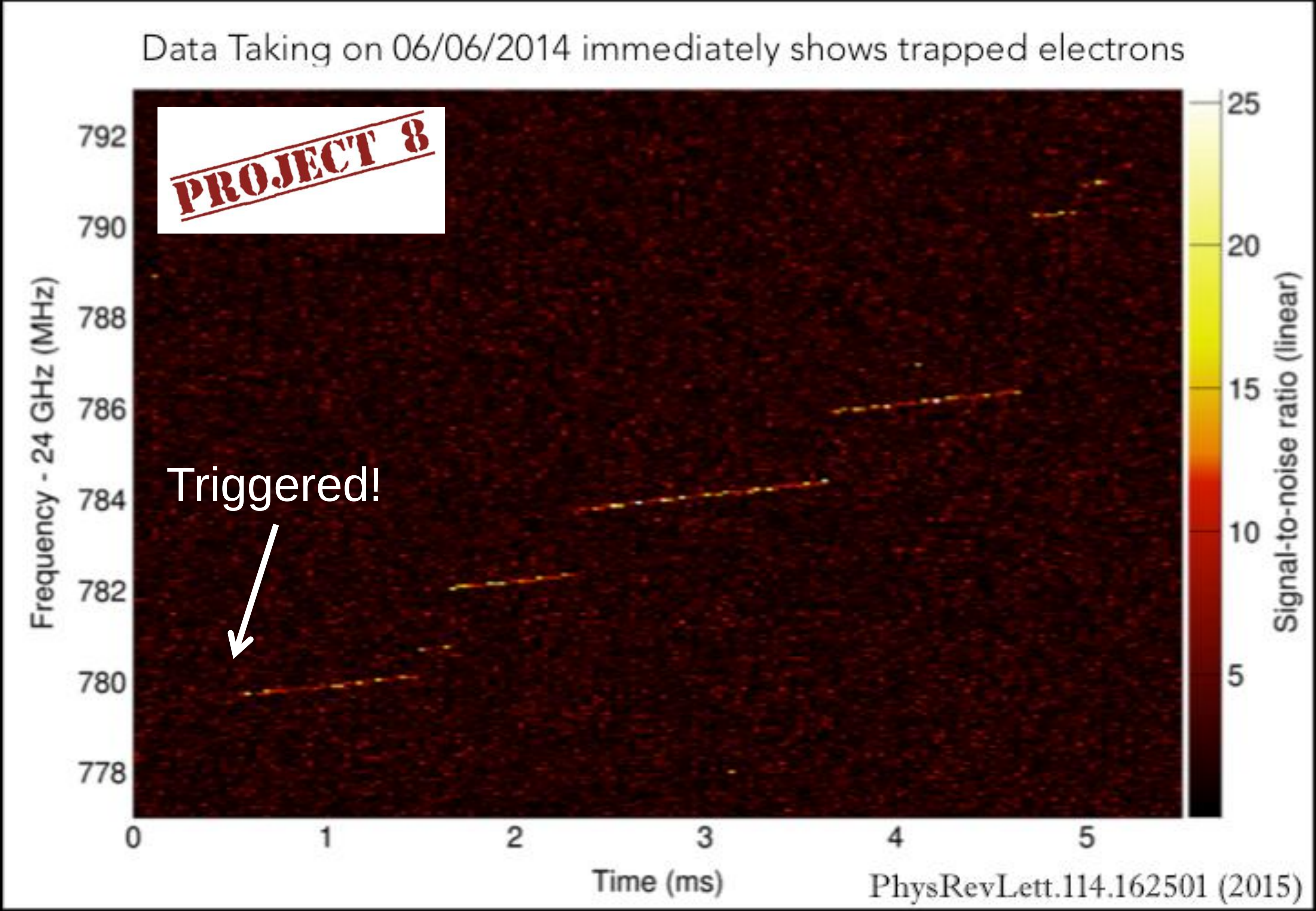


Waveguide to amplifiers





Magentic bottle coil

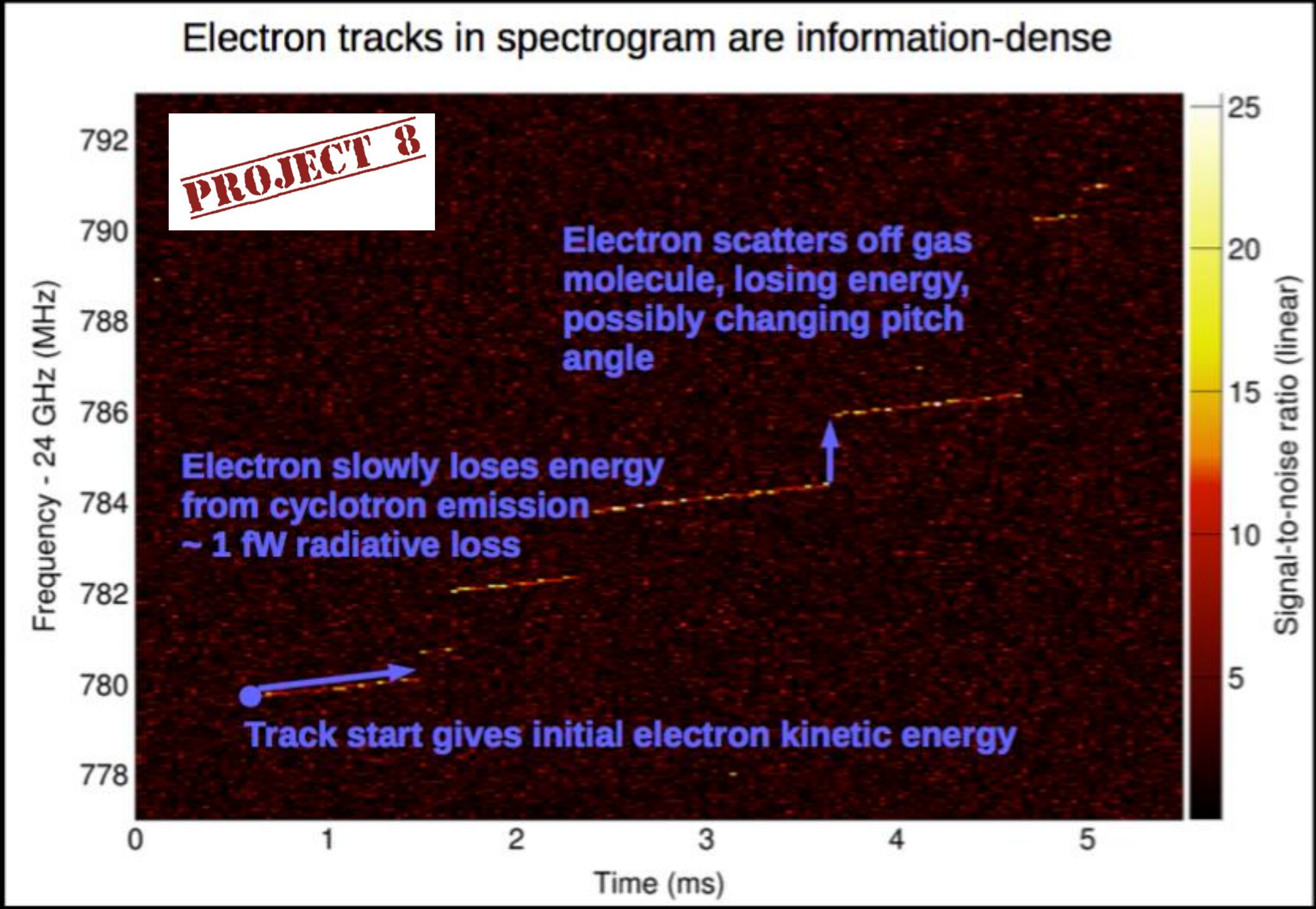


Data Taking on 06/06/2014 immediately shows trapped electrons

PhysRevLett.114.162501 (2015)

First detection of single-electron cyclotron radiation!

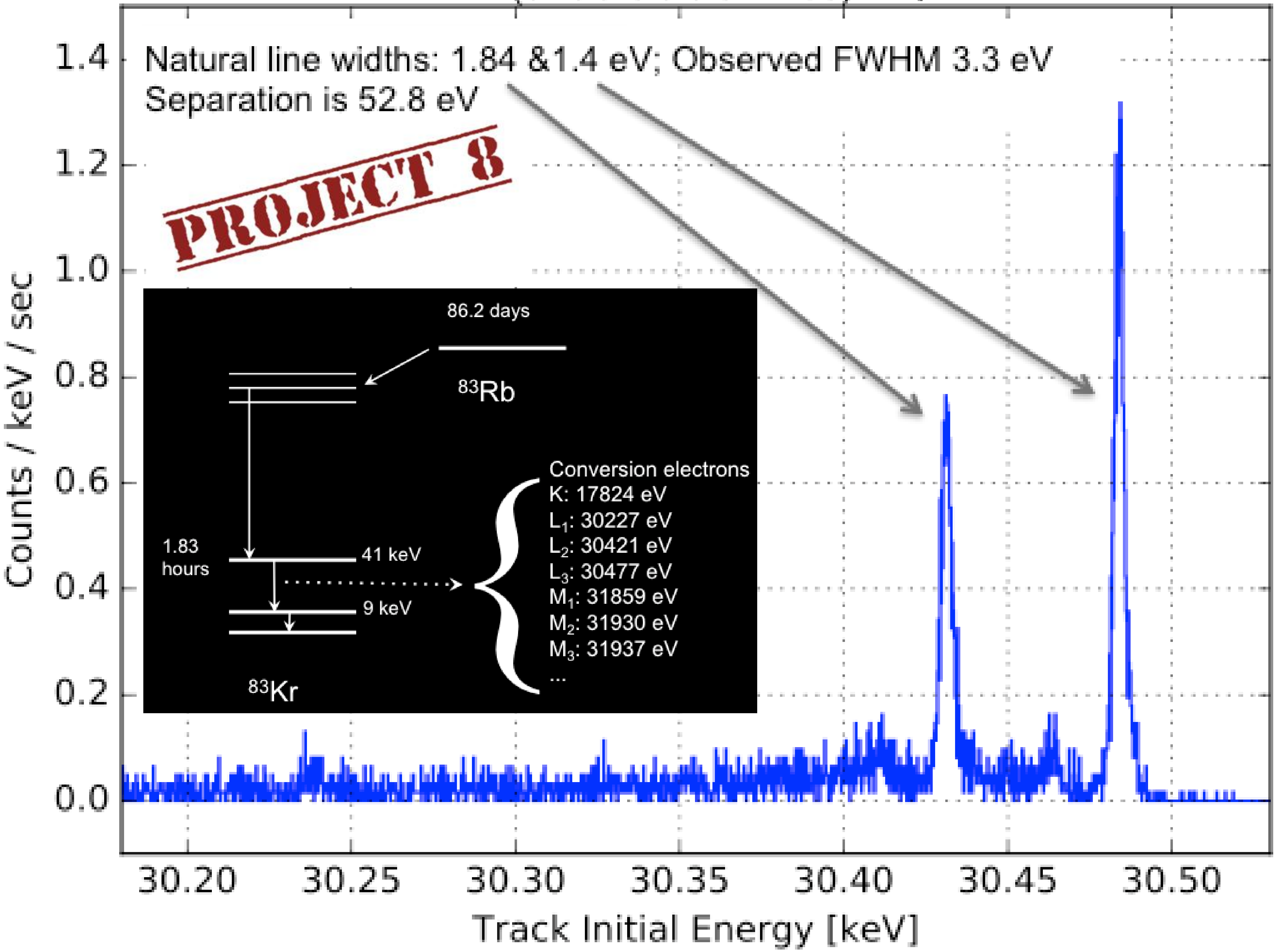
Scale:
100eV



Electron tracks in spectrogram are information-dense

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

PROJECT 8

Conversion electrons

K: 17824 eV

L_1: 30227 eV

L_2: 30421 eV

L_3: 30477 eV

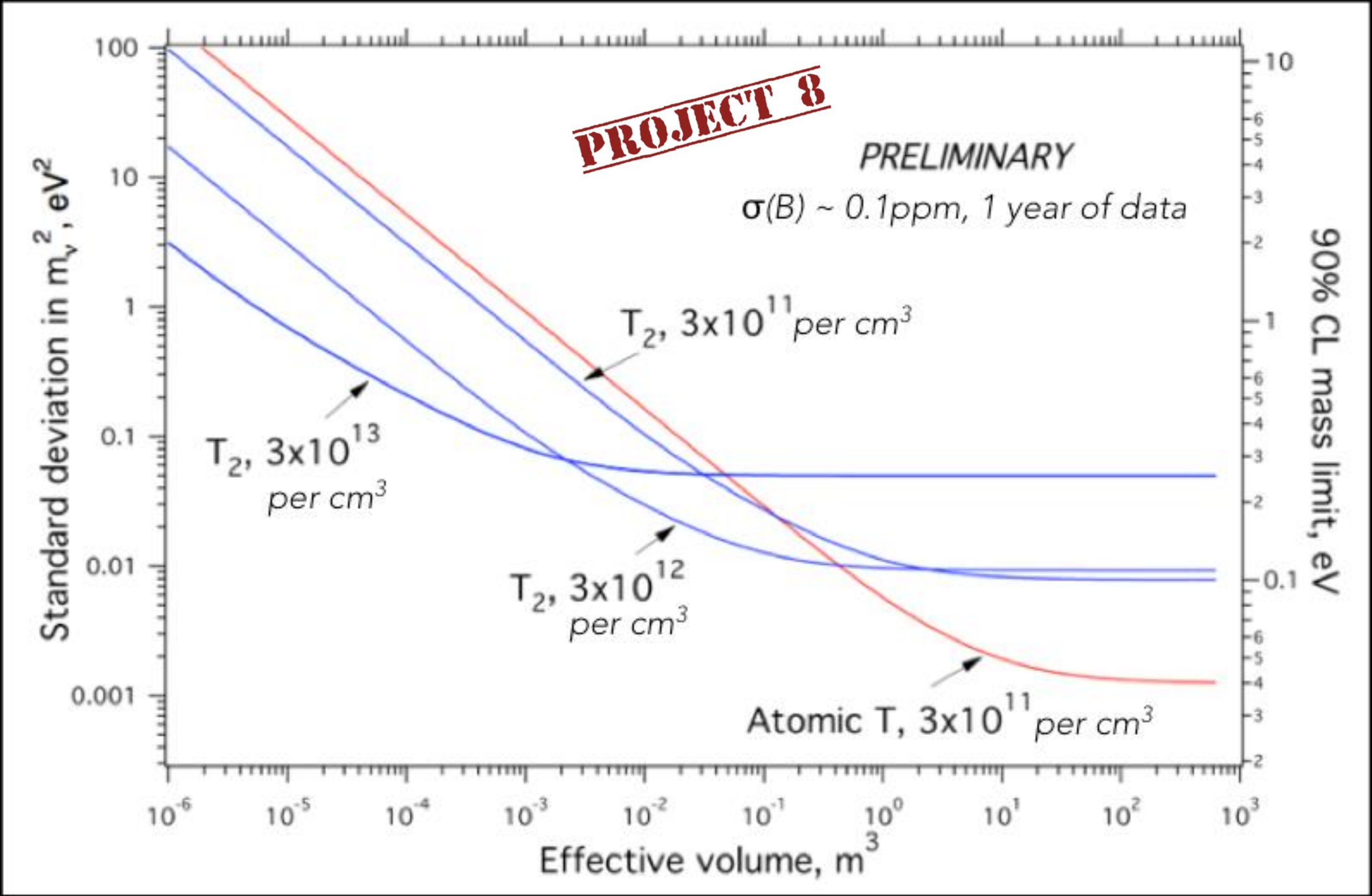
M_1: 31859 eV

M_2: 31930 eV

M_3: 31937 eV

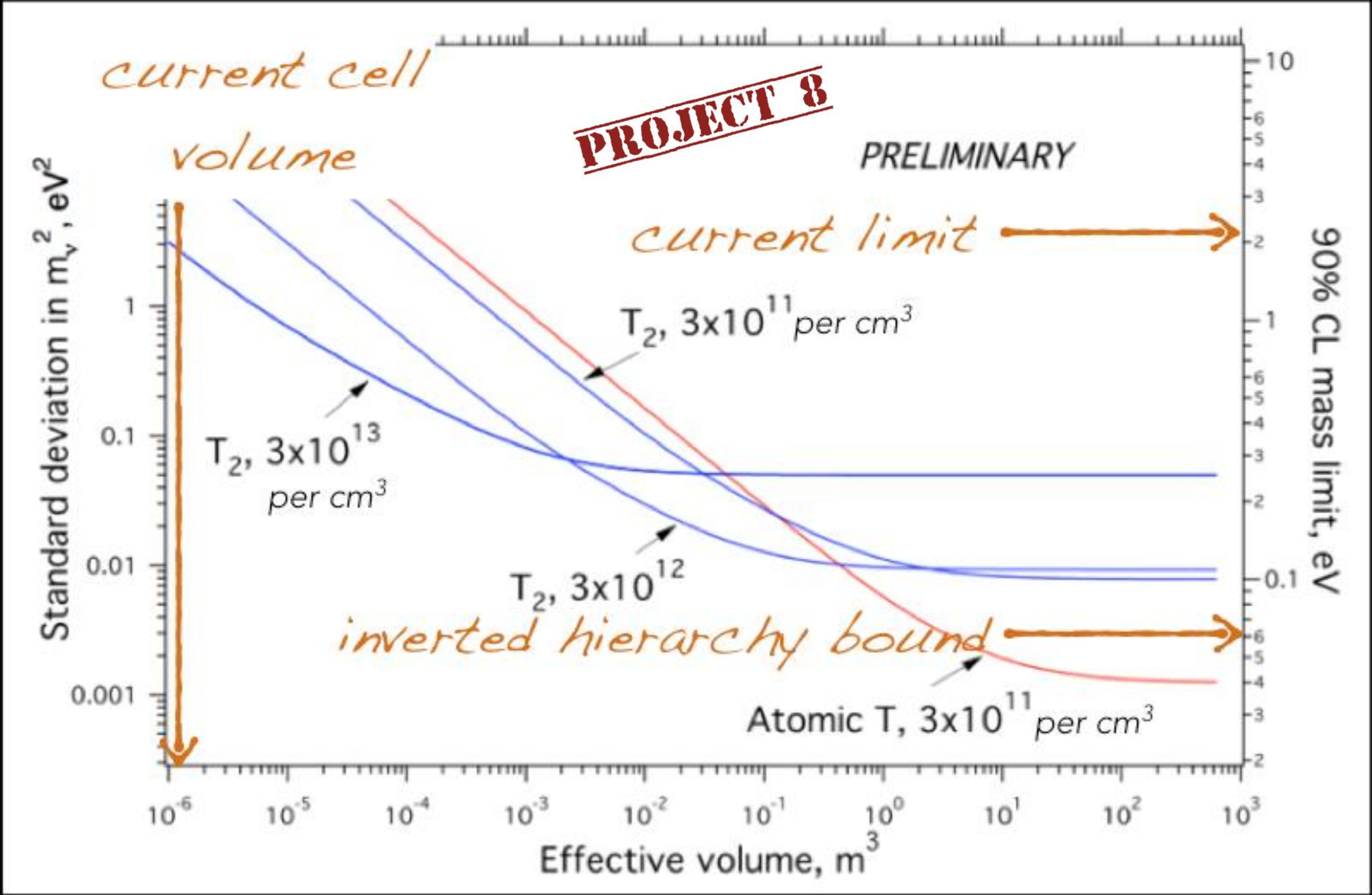
...

Mass Reach



Sensitivity limited by gas density!

Mass Reach



Inverted hierarchy limit in reach with atomic tritium!

PROJECT 8

Neutrino Mass as a Tool for Discovery

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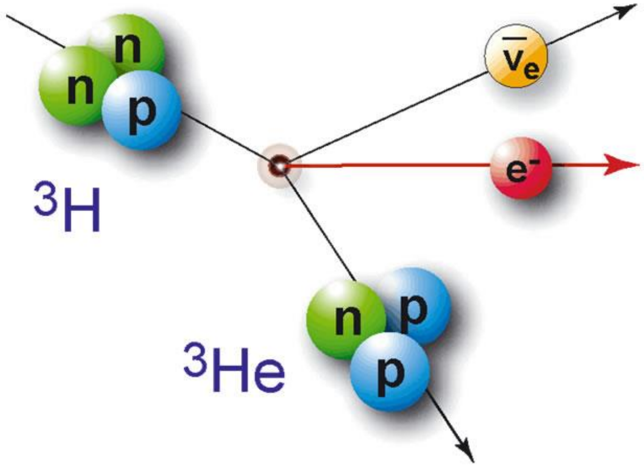
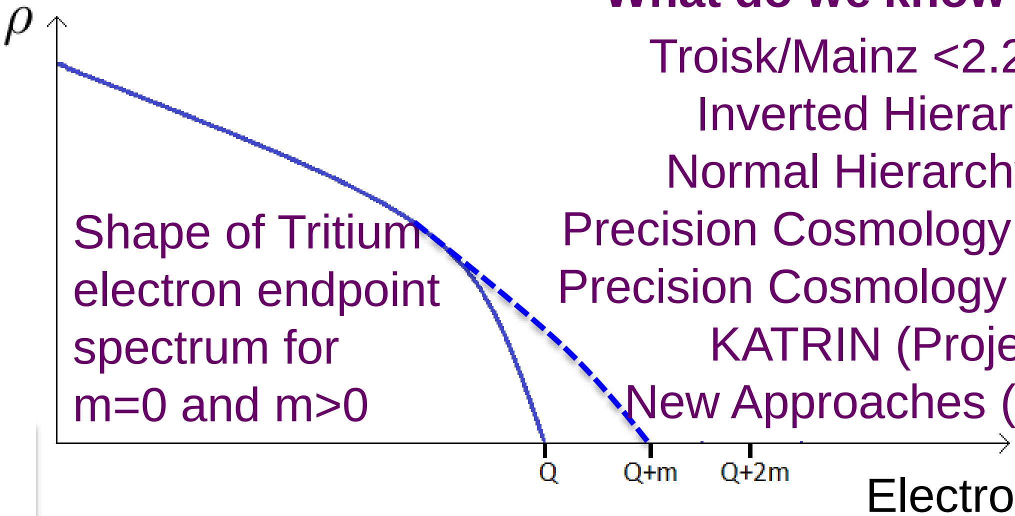


Tritium β-decay
(12.3 yr half-life)

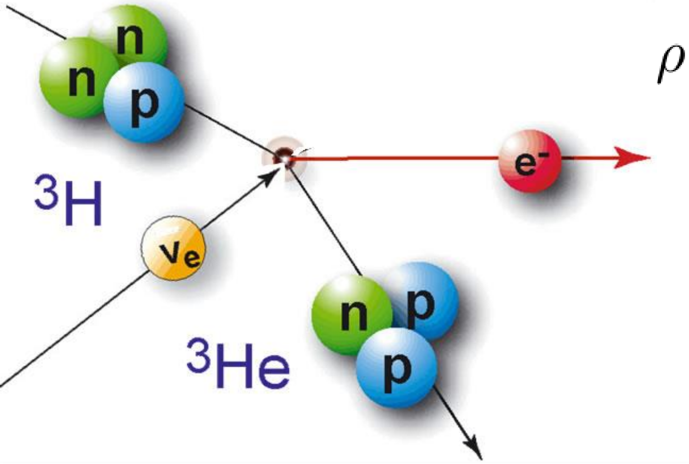


Shape of Tritium electron endpoint spectrum for m=0 and m>0

Electron energy

What do we know?

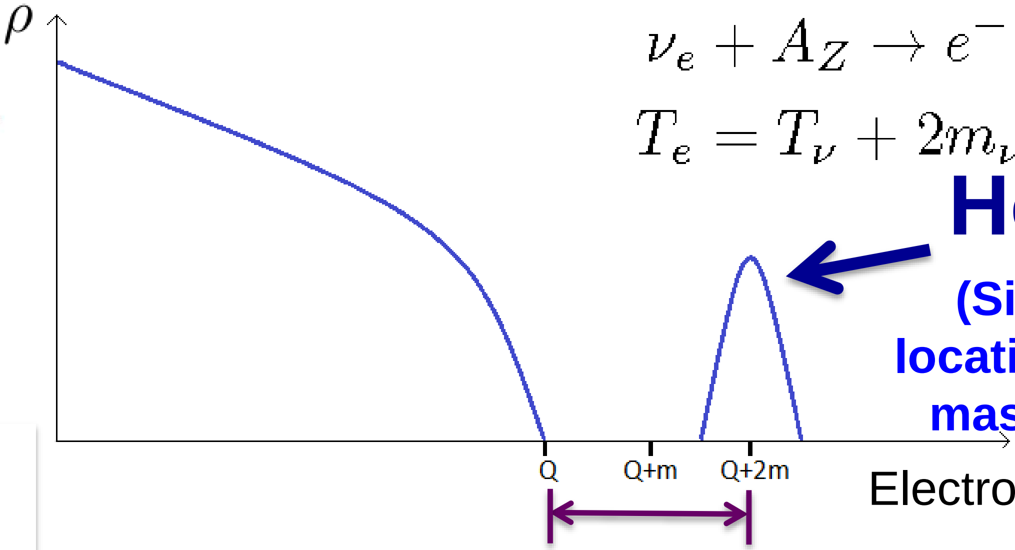
Troisk/Mainz <2.2eV (95% C.L.)
Inverted Hierarchy >0.05eV
Normal Hierarchy 0eV allowed
Precision Cosmology (Present) <0.23eV
Precision Cosmology (Projected) 0.04eV
KATRIN (Projected) 0.2eV
New Approaches (R&D) ~0.02eV?



Relic Neutrino
Capture on Tritium

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

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



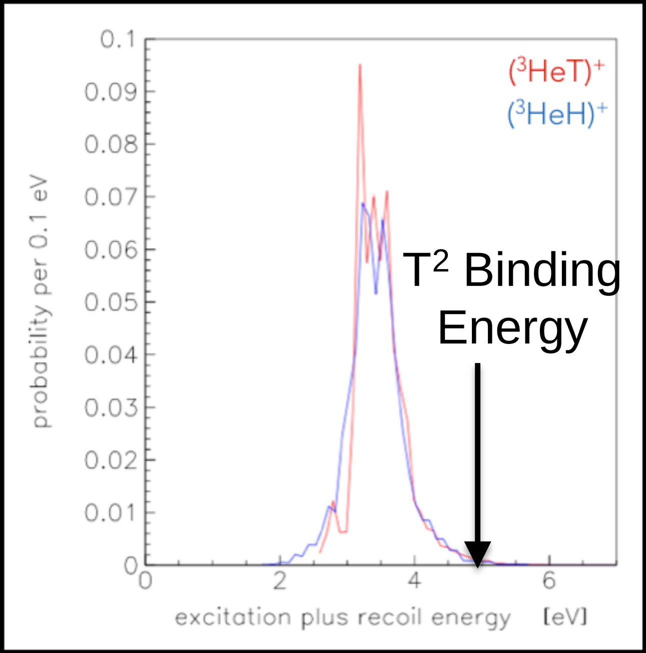
Electron energy

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

Overcoming T^2 Molecular Broadening



Advances in High Energy Physics 2013 (2013) 39

Molecular excitations in daughter molecule

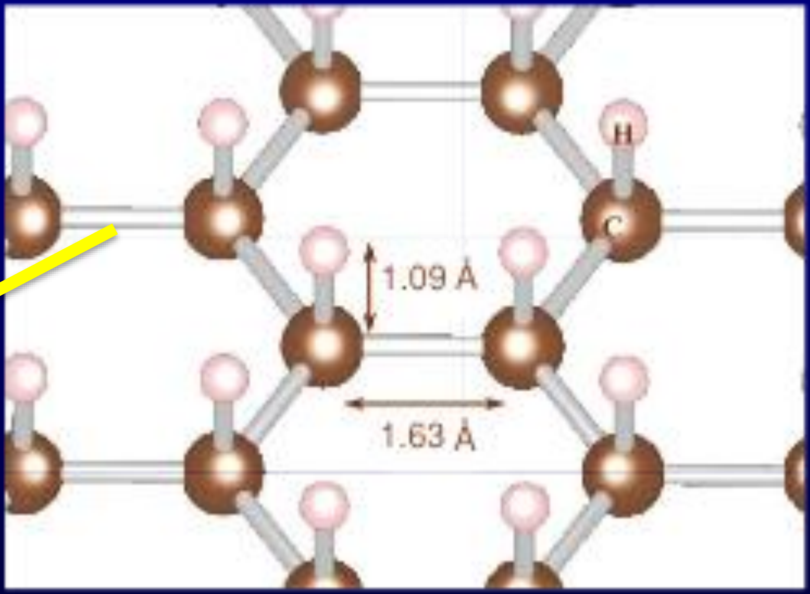
- blur tritium endpoint

→ fundamental limit to measurement of ν-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?)**



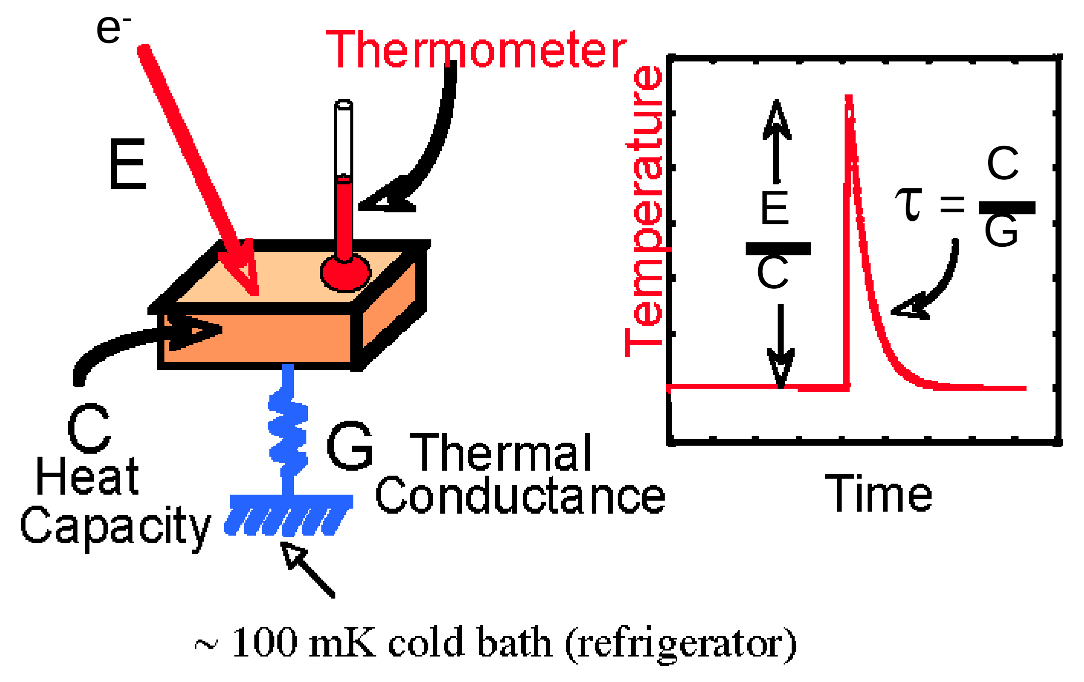
~3x10^{13} T/mm^2 (~80kHz of decays/mm^2)

First Samples Produced by SRNL

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

Microcalorimetry

- Electron calorimetry with an energy resolution sufficient to resolve the neutrino mass
  - Current TES calorimeter work (by ANL – Clarence Chang, by Goddard GSFC – Harvey Moseley, Jack Sadlier, by StarCryo) is on its way to reach 0.15eV @ 100eV (~70-100mK)
  - New focus on ~10eV energy scale may get down to 0.05eV (~50mK)



10eV electron can be stopped with very small C x10^{-4} smaller than for X-ray

τ (time response) also small Bandwidths of ~1 MHz to record ~10kHz of electrons hitting the individual sensors

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

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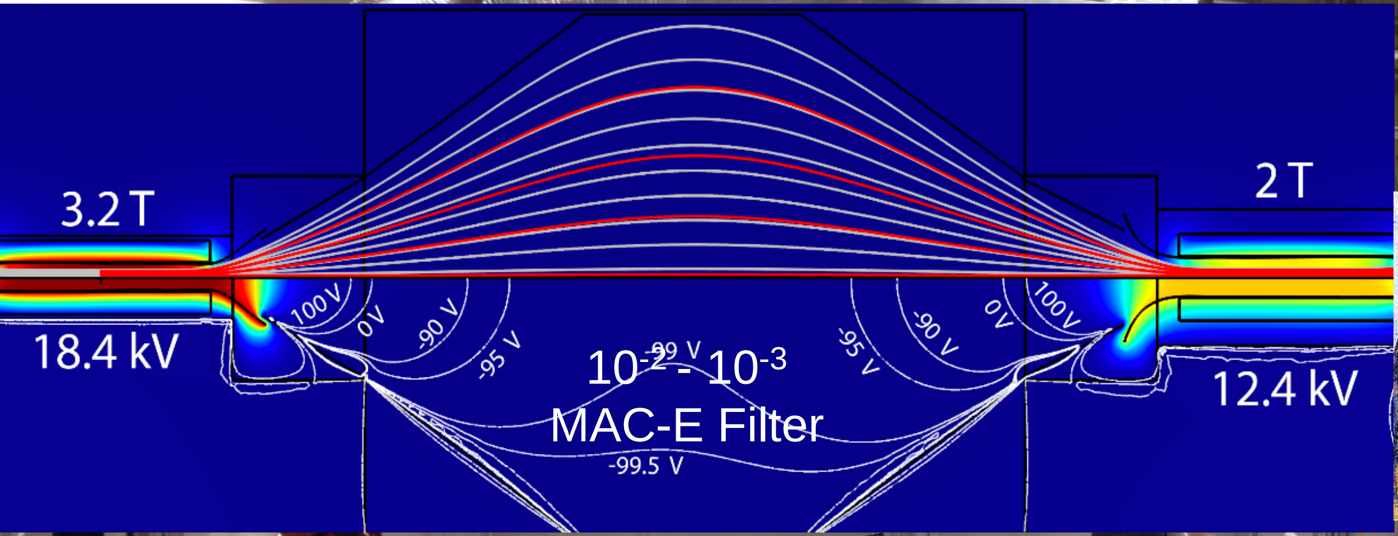

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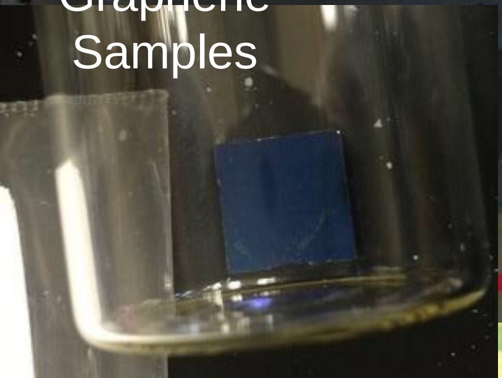
Dilution
Refrigerator
Kelvinox
MX400

Robot Arm
for Tritiated-
Graphene
Samples



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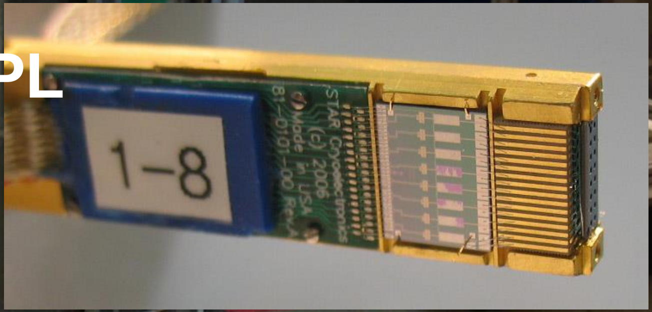


StarCryo
Microcalorimeter

PROJECT 8

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
Long, Lunardini, Sabancilar: JCAP 1408 (2014) 038

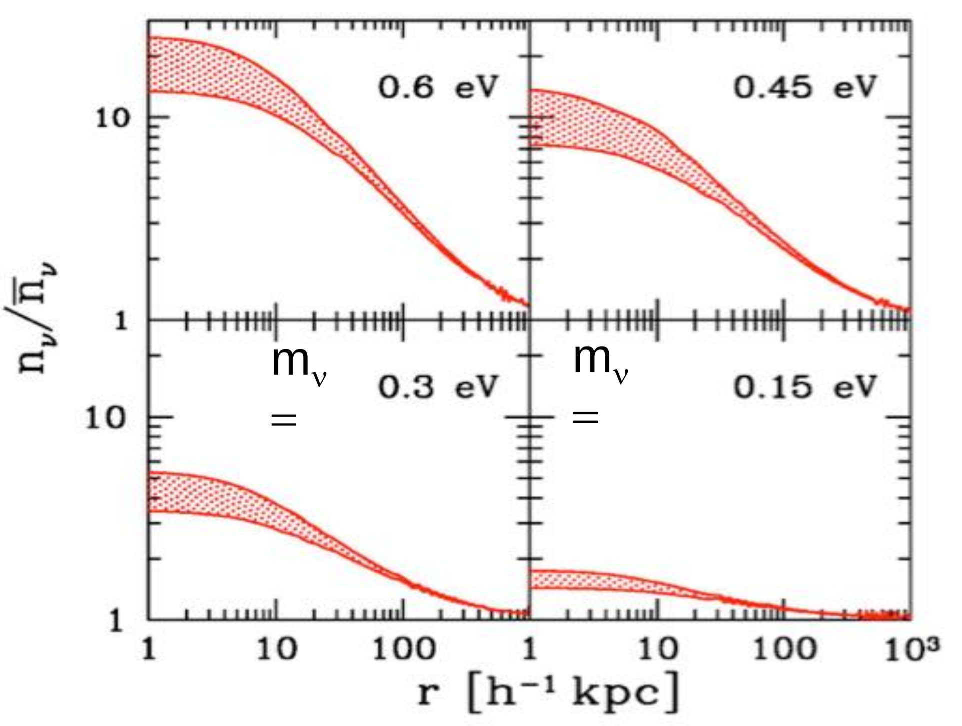
~ 10 events/yr

(5 events/yr for Dirac neutrinos)

σ*v/c=(7.84±0.03)x$10^{-45}$$cm^2$

Known to better than 0.5%

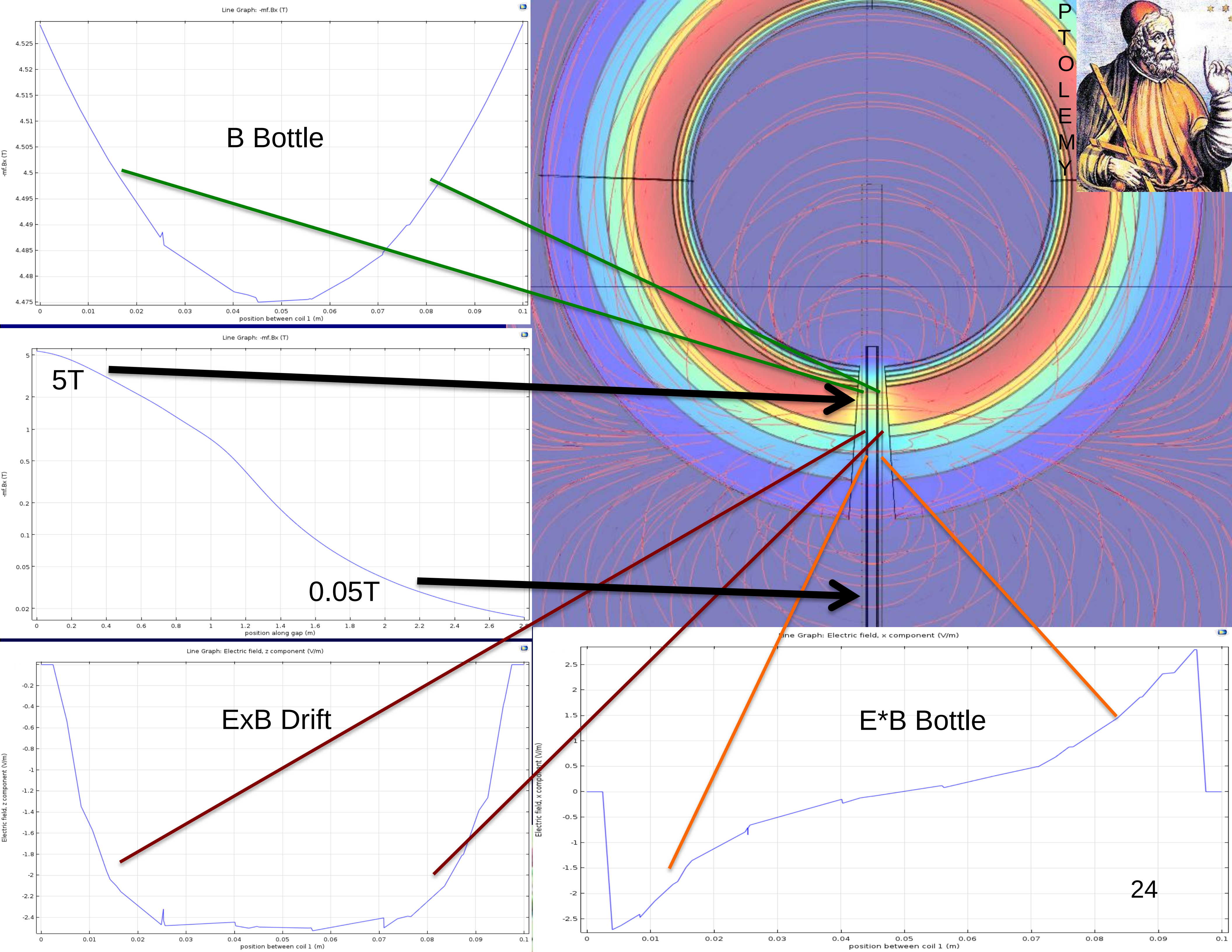
Gravitational clumping could potentially increase the local number of relic neutrinos.
For low masses ~0.15eV, the local enhancement is ~<10%

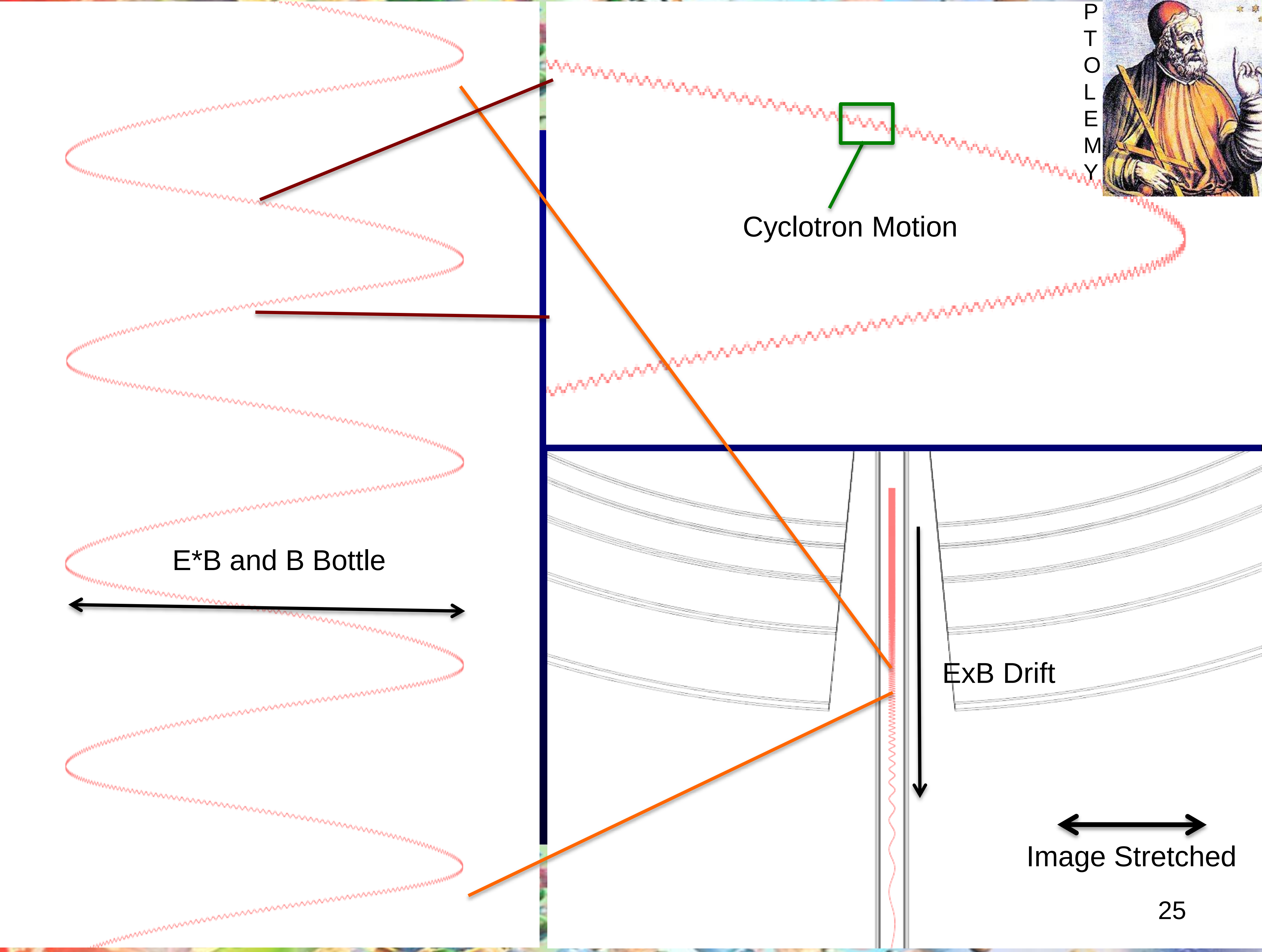


Ringwald and Wong (2004)
Villaescusa-Navarro et al (2011)

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
  - RF trigger system (Project 9?)


Line Graph: -mf.Bx (T)
-mf.Bx (T)
4.525
4.52
4.515
4.51
4.505
4.5
4.495
4.49
4.485
4.48
4.475
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
position between coil 1 (m)
B Bottle
Line Graph: -mf.Bx (T)
-mf.Bx (T)
5
2
1
0.5
0.2
0.1
0.05
0.02
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
position along gap (m)
5T
0.05T
P
T
O
L
E
M
Y
Line Graph: Electric field, z component (V/m)
Electric field, z component (V/m)
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
-2.2
-2.4
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
position between coil 1 (m)
ExB Drift
Line Graph: Electric field, x component (V/m)
Electric field, x component (V/m)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
position between coil 1 (m)
E*B Bottle



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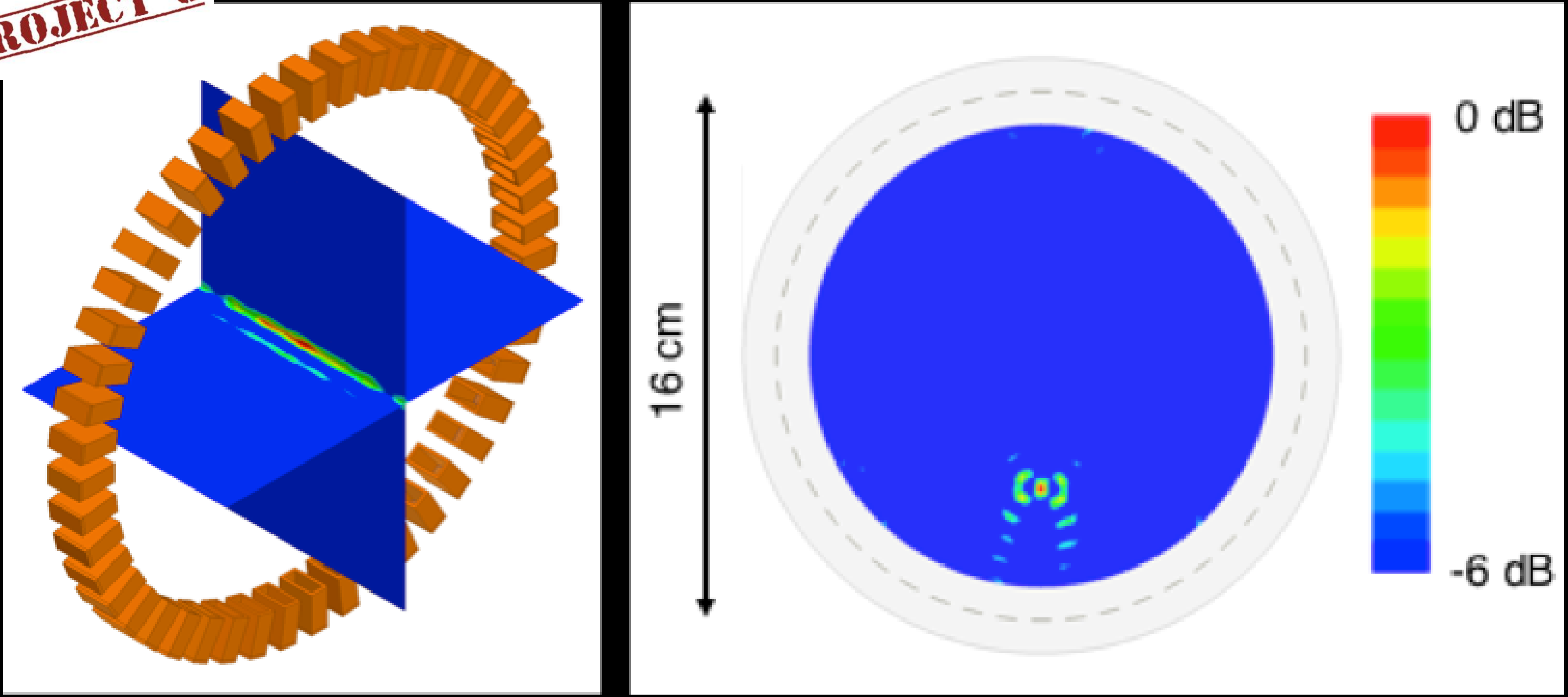
Cyclotron Motion

E*B and B Bottle

ExB Drift

Image Stretched



Example antenna configuration and vertex resolution being modeled

- Larger bore ~1T magnet → exists
- Phased array antenna configurations → under study

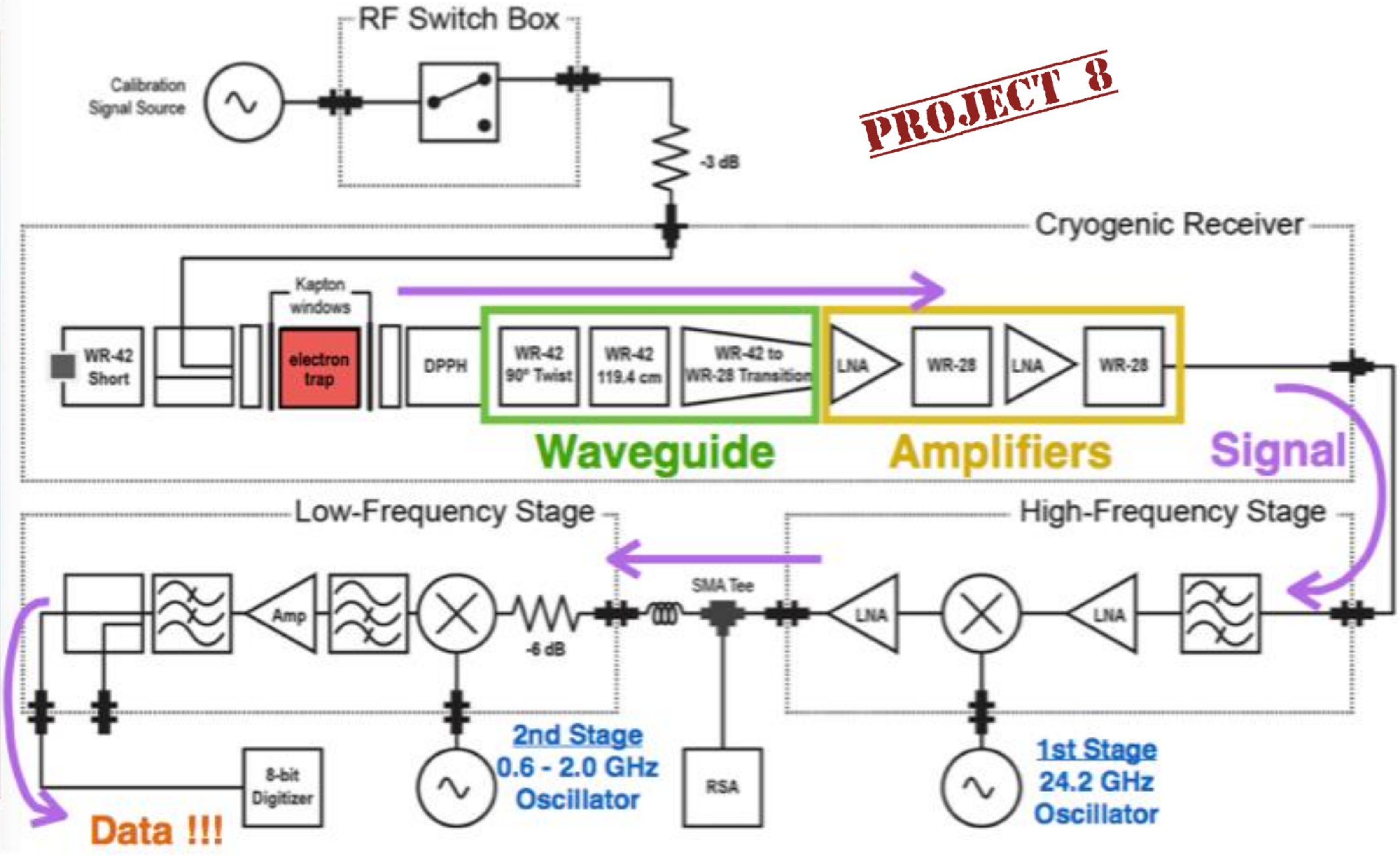
Summary

- Cyclotron Radiation Emission Spectroscopy
  - Great new reality for high precision spectroscopy
  - New Data! Tritium to be injected soon.
  - Large Volume, Phased-Array Concept in development
- Microcalorimetry
  - Potential for sub-eV resolution
    - First data soon!
  - Materials research on tritium substrates
  - New compact filter with RF trigger under design

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

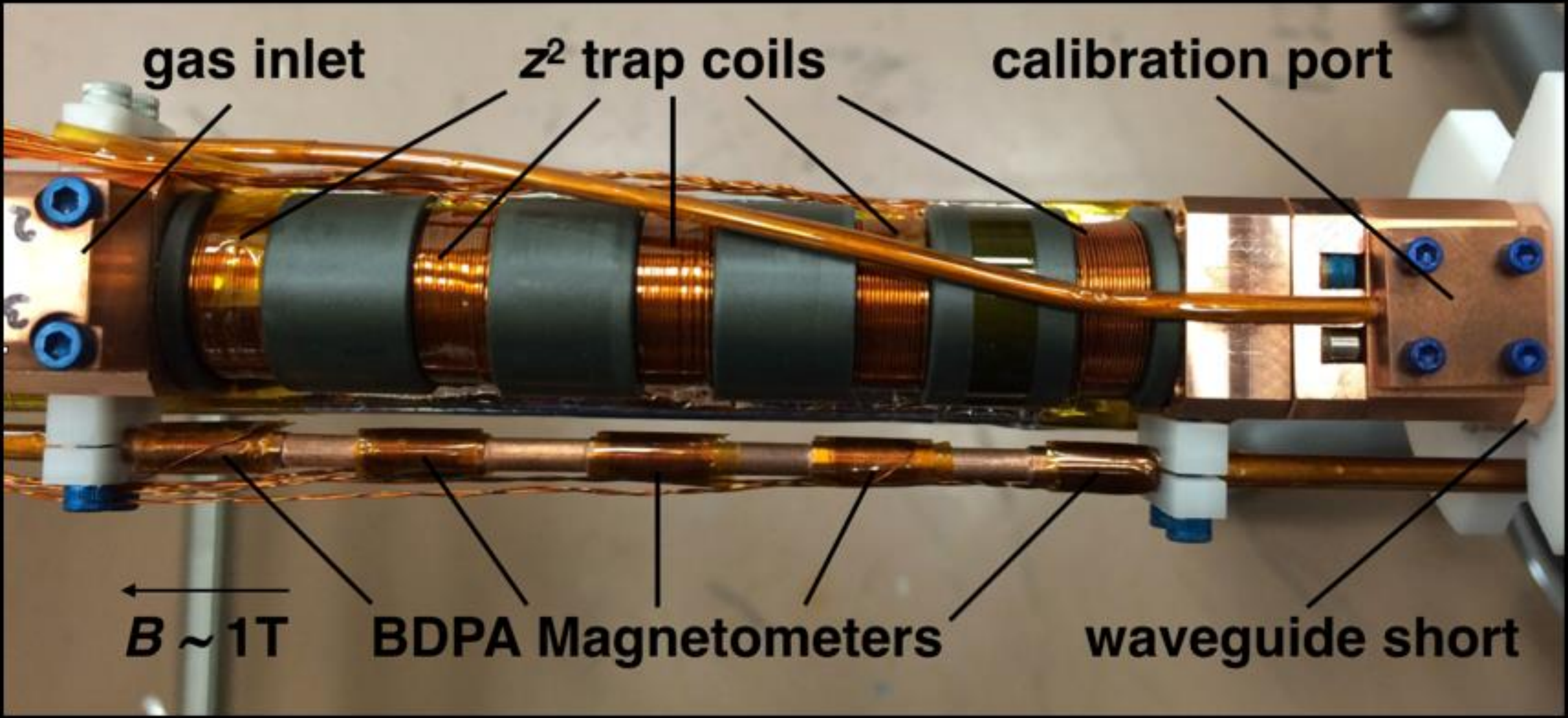
Backup
(Project 8)

RECEIVER STAGE



- Double-stage down-mixing
- Digitizer: 8-bit, 500Ms/s, 125MHz bandwidth

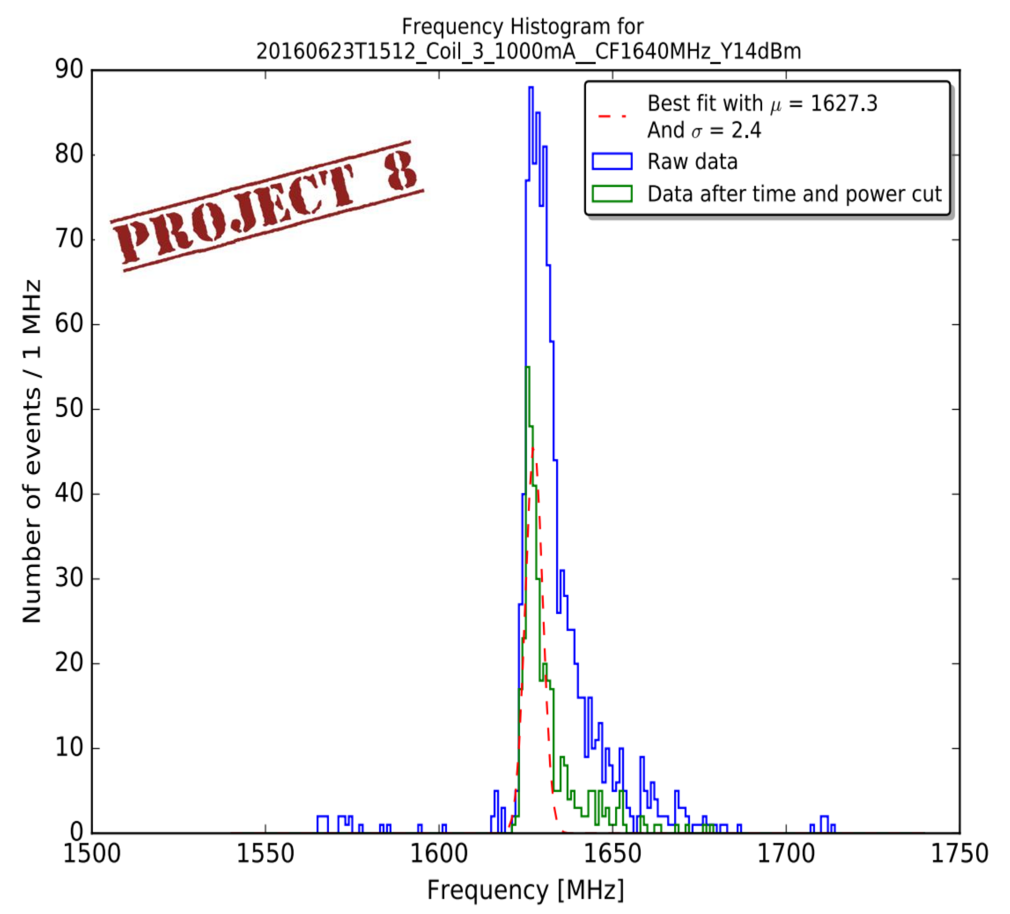
Project 8 Phase II Cell

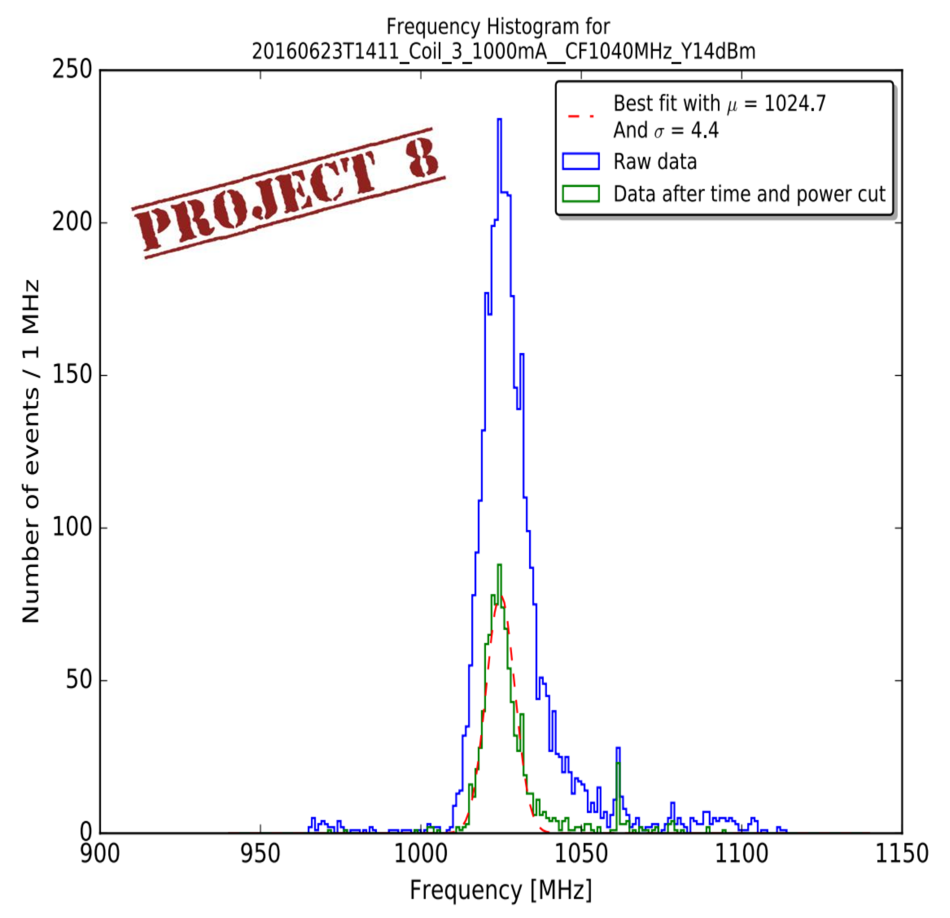


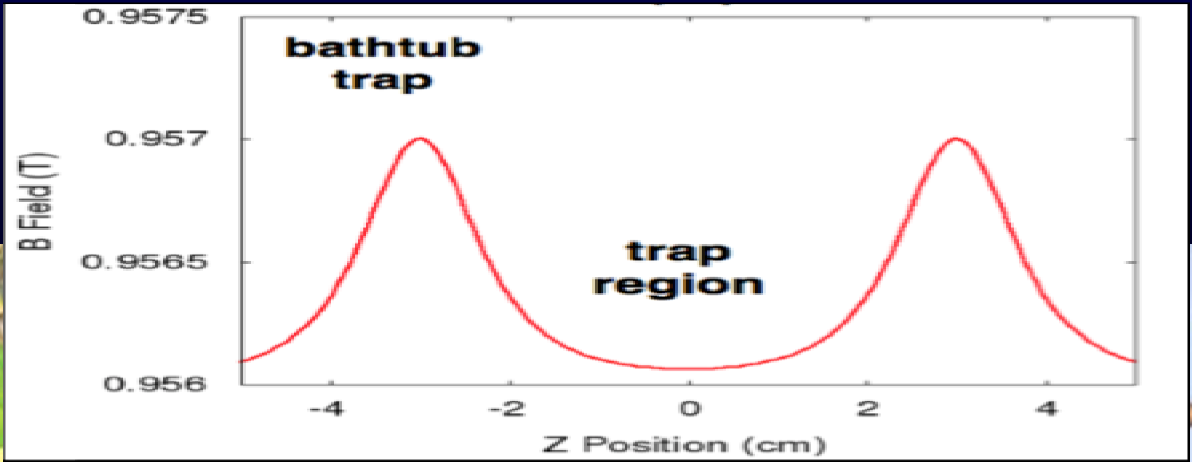
Improved insert installed

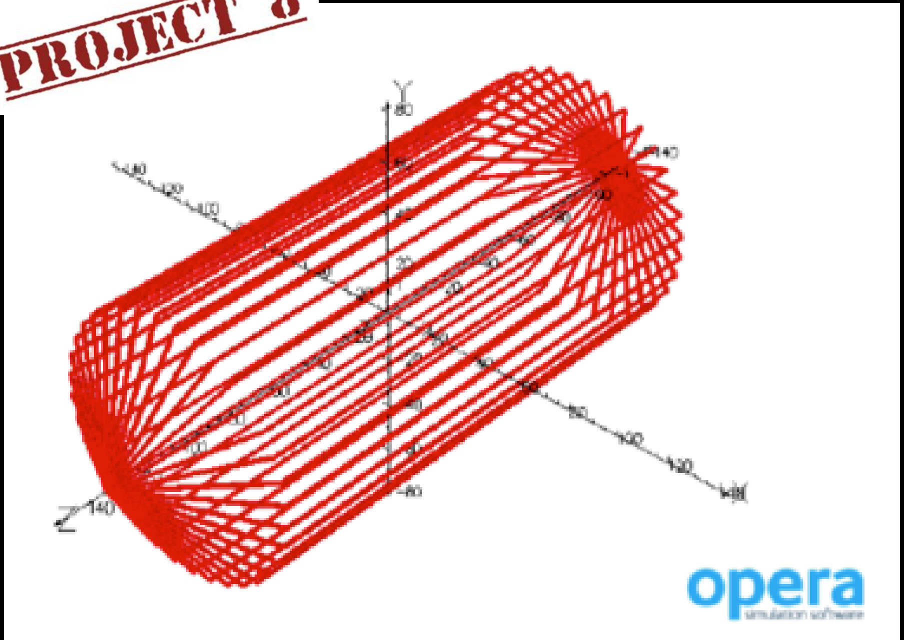
- first ^{83m}Kr data available → very promising
- T_2 - system ready to be installed

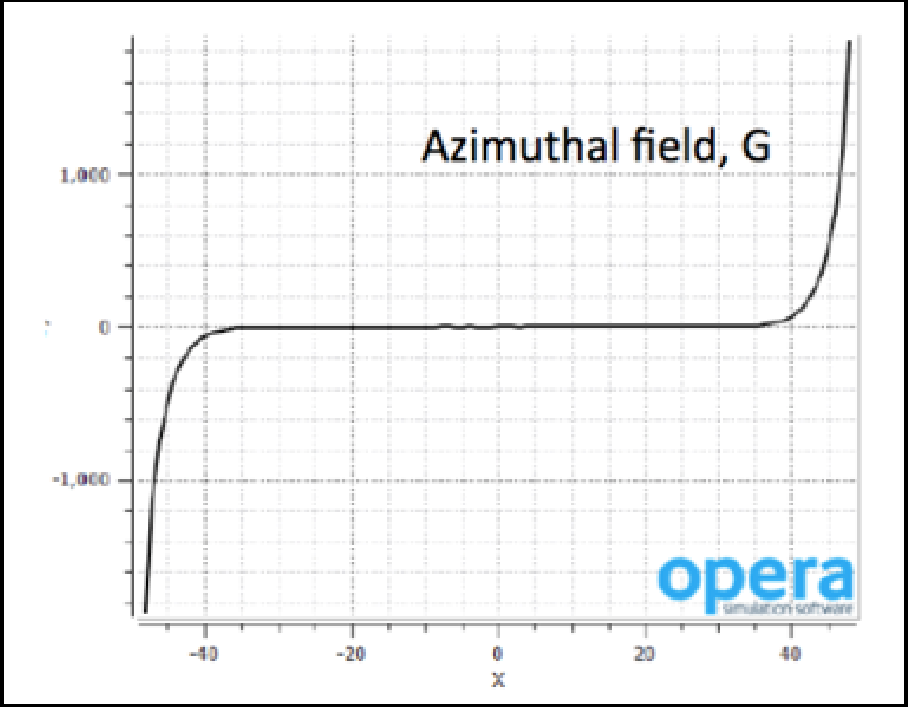
Bathtub Trap Data











Alexi Radovinsky, MIT Magnet Lab

Studying Ioffe-Pritchard trap

- couple to nuclear magnetic moment

$$\Delta E = -\vec{\mu} \cdot \vec{B}$$

- similar to BEC and anti-hydrogen traps (ALPHA)

Challenges

- cool atomic tritium to sub-Kelvin
- need high T/T_2 purity

Backup (PTOLEMY)

Rethinking Relic Neutrino Detection

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

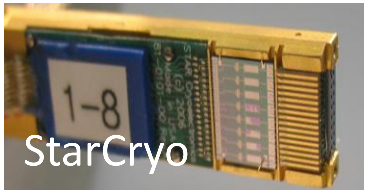
P rinceton
T ritium
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield

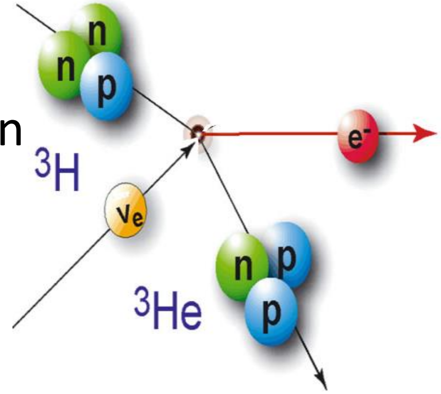
- Relic Neutrinos → Highest intensity DC neutrino flux in the Universe

- Massive neutrinos

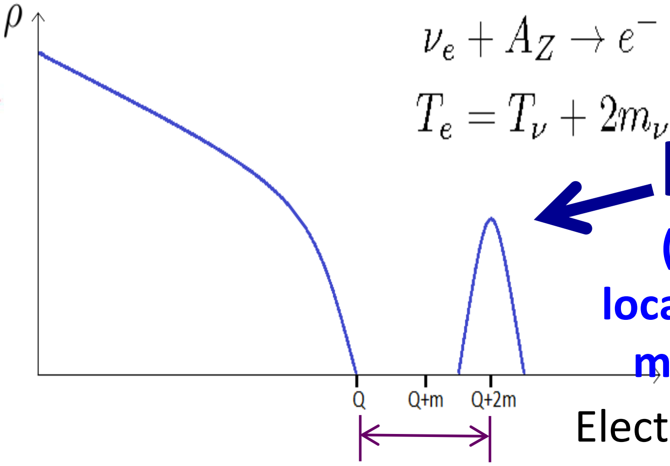
→High resolution electron microcalorimetry at 10eV

→~0.05eV sensitivity(?)





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)

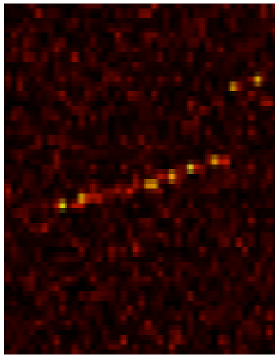
Electron energy

Original idea: Steven Weinberg in 1962 [*Phys. Rev*. 128:3, 1457]
JCAP 0706 (2007)015, hep-ph/0703075, Cocco, Mangano, Messina

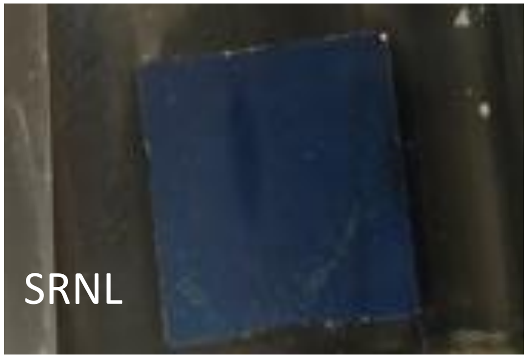
- RF triggering on single e⁻

→Large-scale tritium target and filtering of endpoint electrons

PROJECT 8



- Tritiated-Graphene target



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

PTOLEMY Supported by:
The Simons Foundation
The John Templeton Foundation

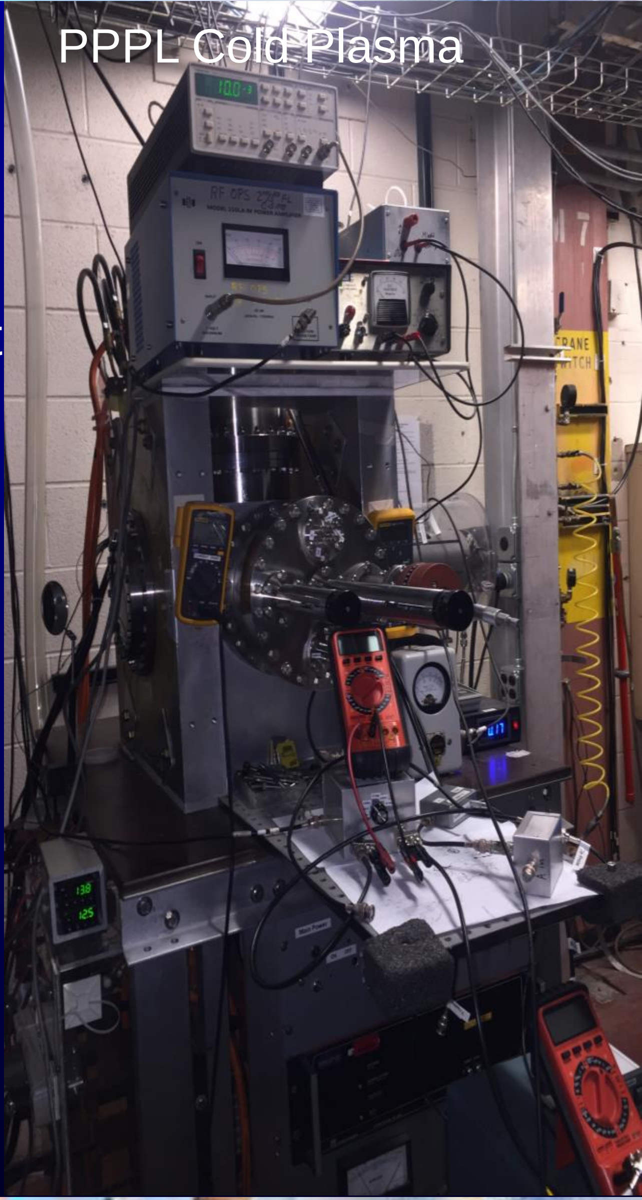
PROJECT 8

Hydrogenation Project

PTOLEMY

- Hydrogenation via Plasma
  - Cold Plasma in PPPL : The mixture of H atoms and ions treats samples under room temperature. The ratios of ions could be adjusted by plasma power.
  - Hydrogen atom Plasma in Chemical Engineering Dept (Princeton Univ): Ions are removed by the filter.

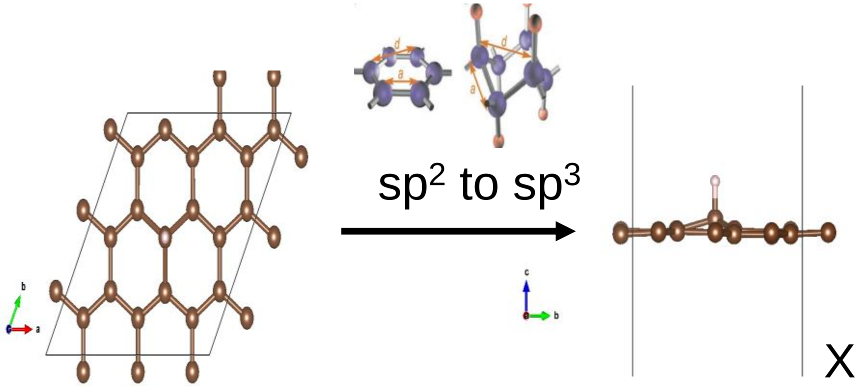
  Cold plasma and hydrogen atom plasma reduces the damage in thin film surfaces from high energy plasma and provide a long duration treatment to increase hydrogen coverage.
- Surface Characterization for hydrogen doping
  - Raman Spectroscopy
  - High resolution X-ray Spectroscopy (XPS)
  - Photoluminescence (PL)
  - Low T Scanning Tunneling Microscopy (STM)
  - Scanning Transmission Electron Microscope (STEM)
- DFT Calculation via Vasp



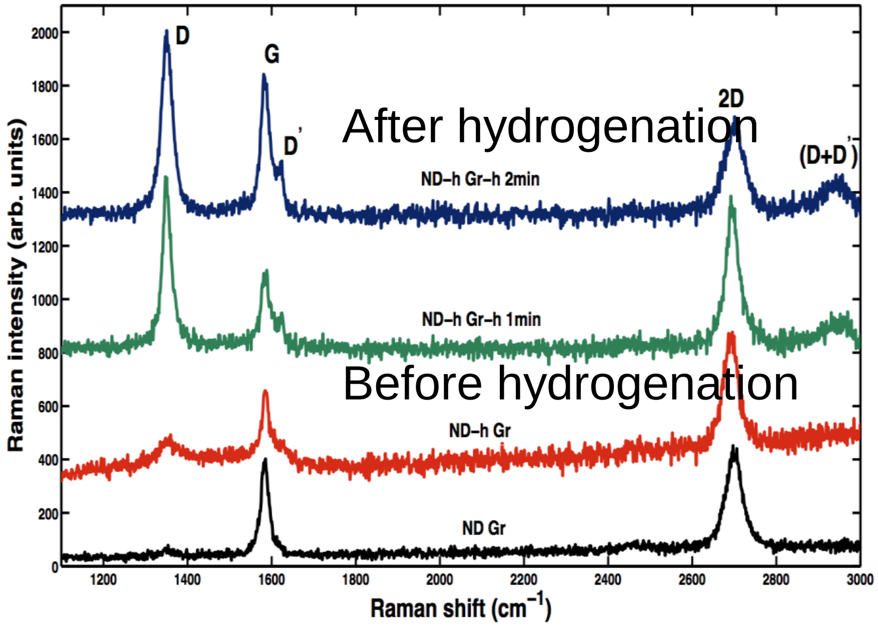
PPPL Cold Plasma

Hydrogenation on Graphene

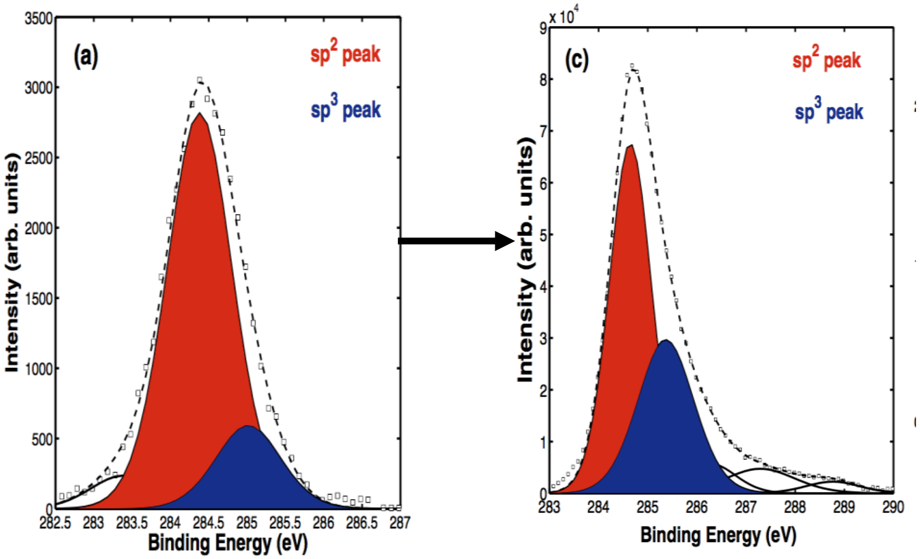
After hydrogenation, graphene sp^2 structures are twisted to sp^3 hybrid structures. It could be detected by Raman, XPS and low T STM.



Raman results



XPS results

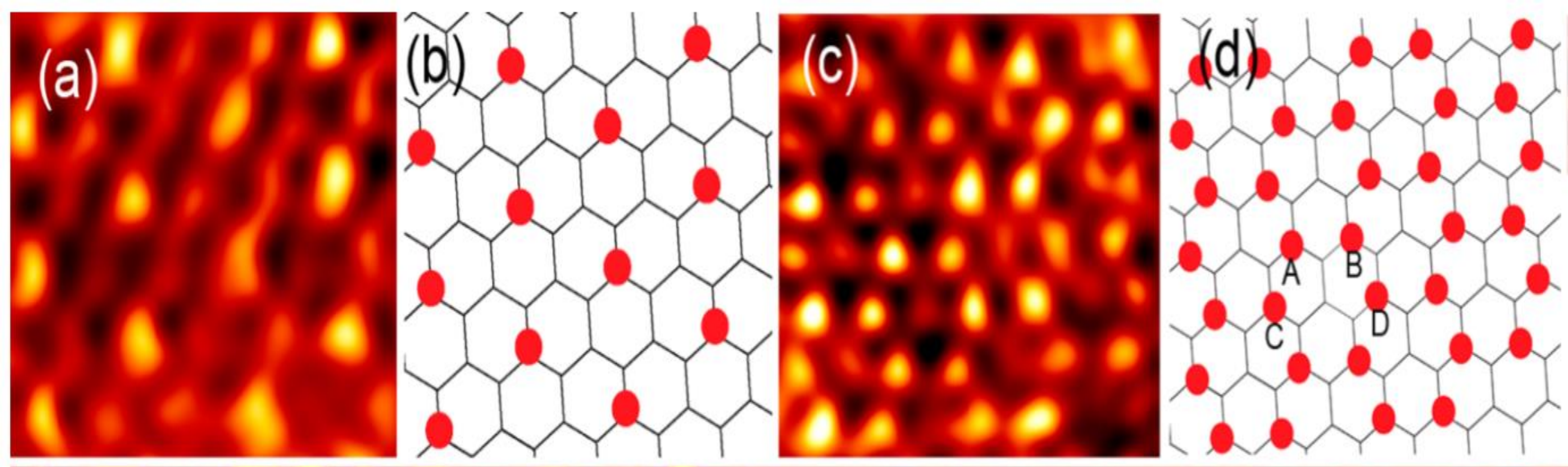


Before hydrogenation

After hydrogenation

Low Temperature STM

STM images showing ordered configurations of H atoms



DFT Calculation for H binding energies

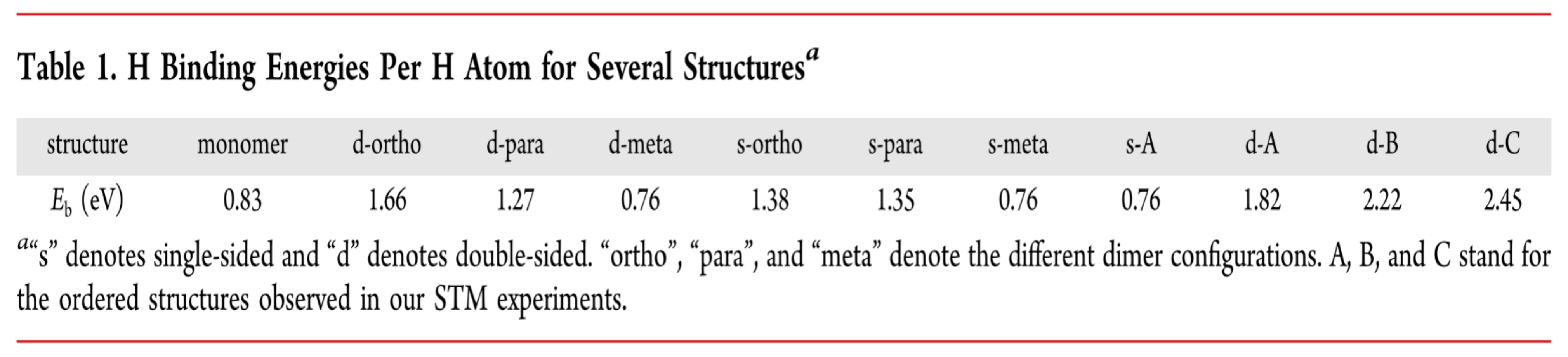


Table 1. H Binding Energies Per H Atom for Several Structures[a]

structure	monomer	d-ortho	d-para	d-meta	s-ortho	s-para	s-meta	s-A	d-A	d-B	d-C
E_b (eV)	0.83	1.66	1.27	0.76	1.38	1.35	0.76	0.76	1.82	2.22	2.45

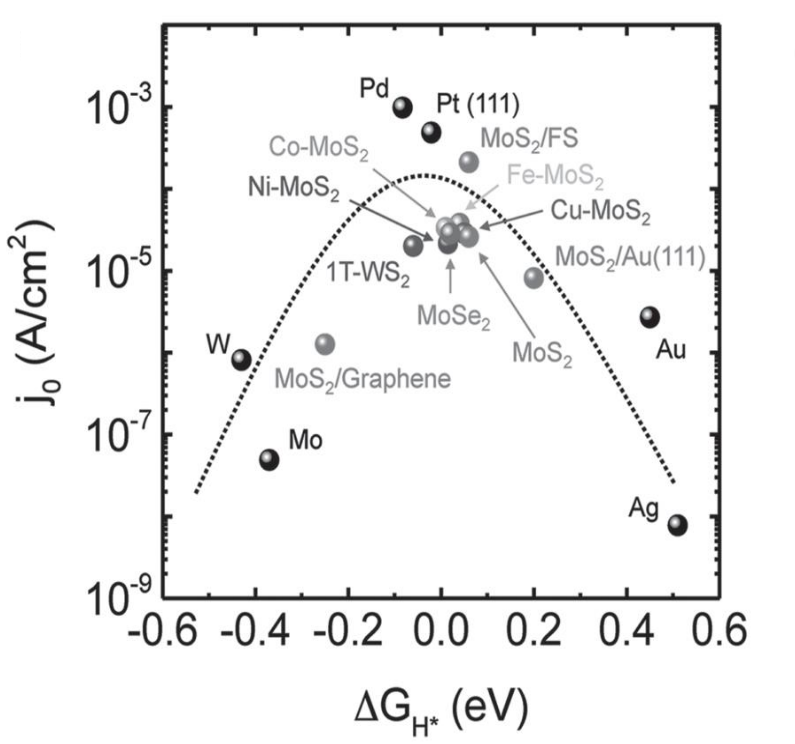
[a] "s" denotes single-sided and "d" denotes double-sided. "ortho", "para", and "meta" denote the different dimer configurations. A, B, and C stand for the ordered structures observed in our STM experiments.

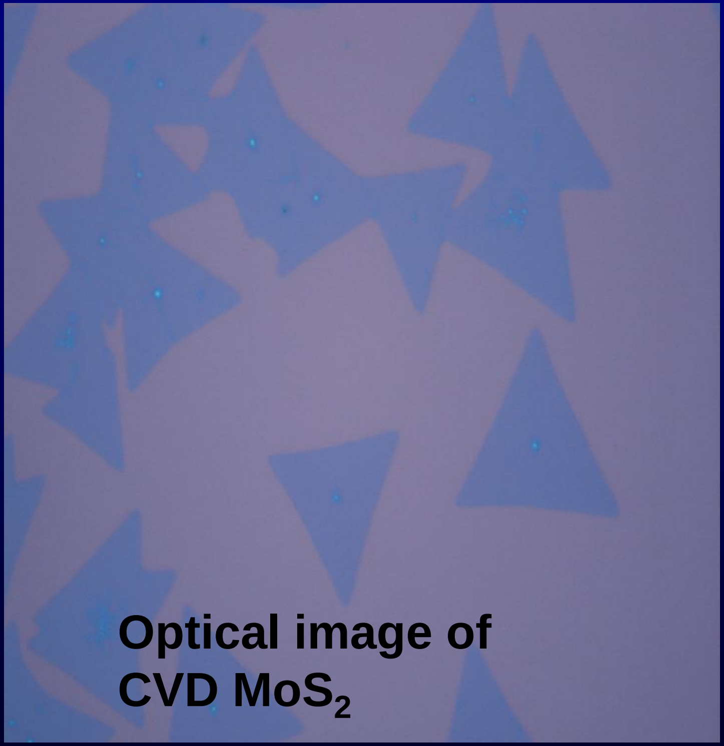
Ref: Lin, C. *et al. Nano Lett.* **15,** 903–908 (2015).

Other Substrates

From the research of hydrogen evolution reaction, metals and Transition metal dichalcogenides (TMDs) show weak H binding energies and high hydrogen absorption.

- TMDs monolayers: MoS_2 and NbS_2(CVD growth)
- Single crystal metals: Cu (111) and Au (111)





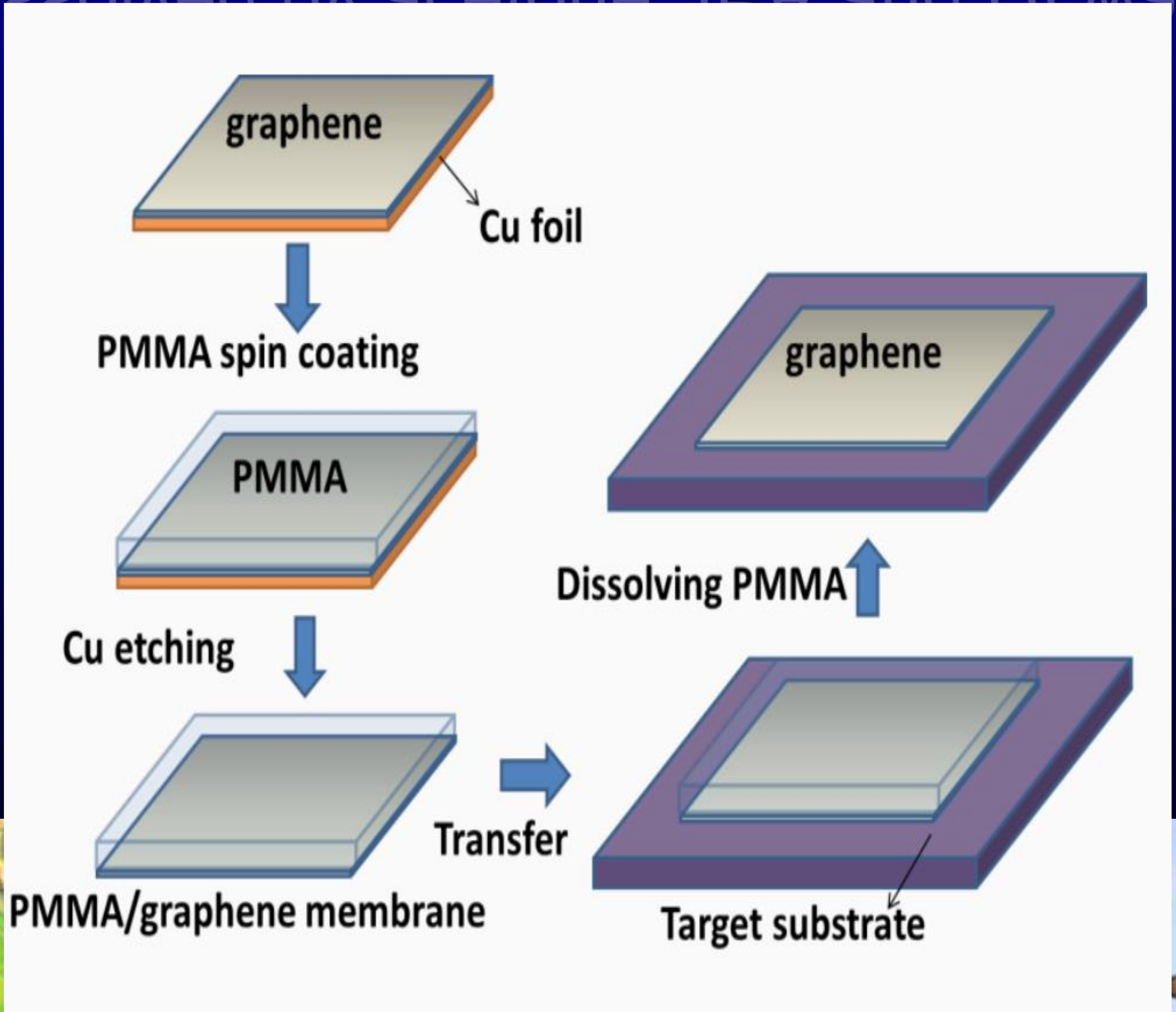
Optical image of CVD MoS_2

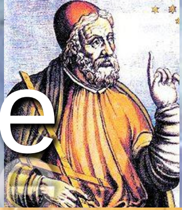
Exchange current density against hydrogen binding energy

Ref: 1. Voiry, D., Yang, J. & Chhowalla, M. *Adv. Mater.* (2016).

Graphene Transfer

Graphene transfer (standard simple transfer process): PMMA works as a supporting layer for transparent graphene. After transferring to substrates, PMMA is dissolved by acetone, IPA and DI water.





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)