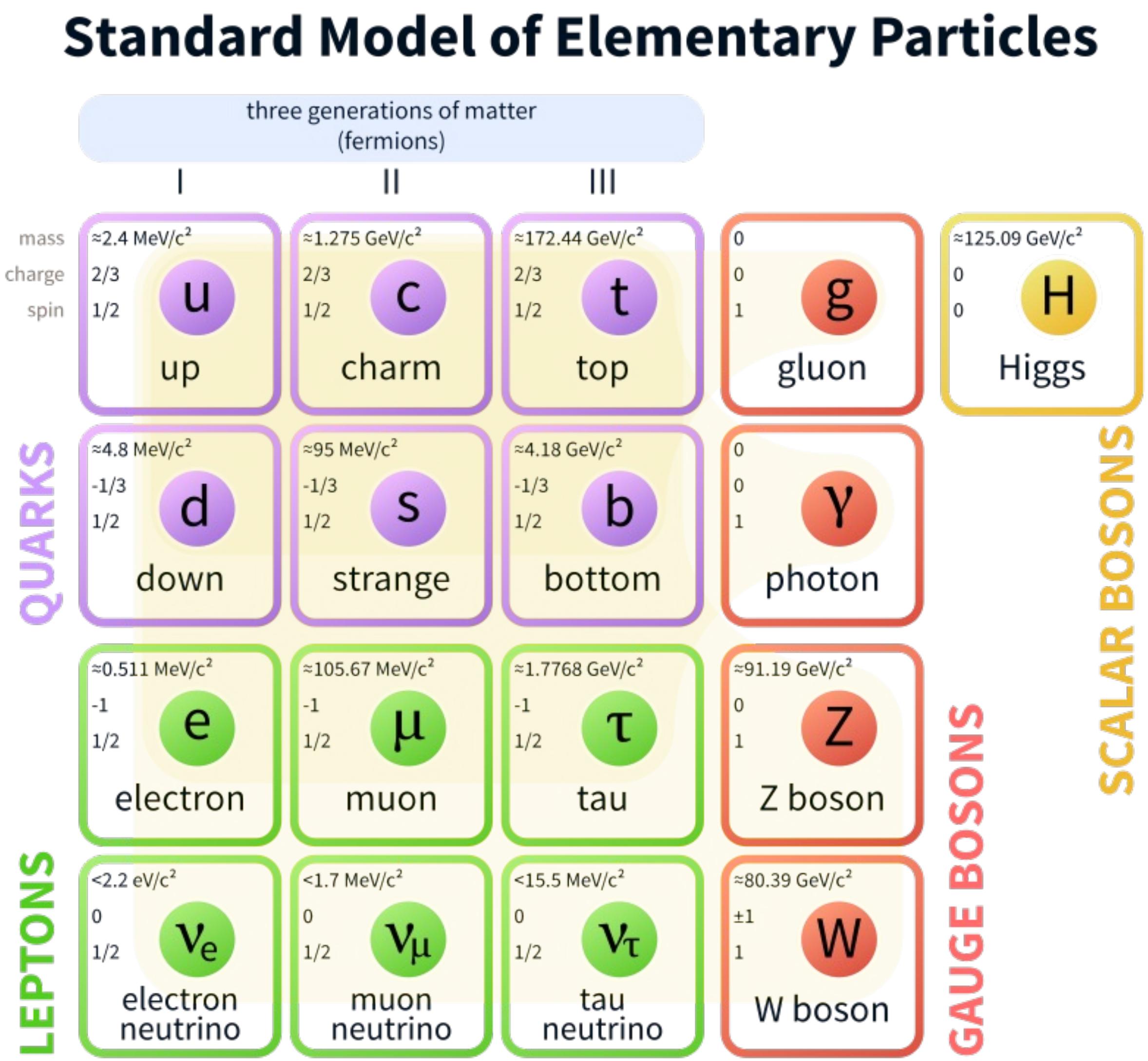
Project 8:
Neutrino Mass Measurement Using Cyclotron Radiation Emission Spectroscopy

Isfahan University of Technology

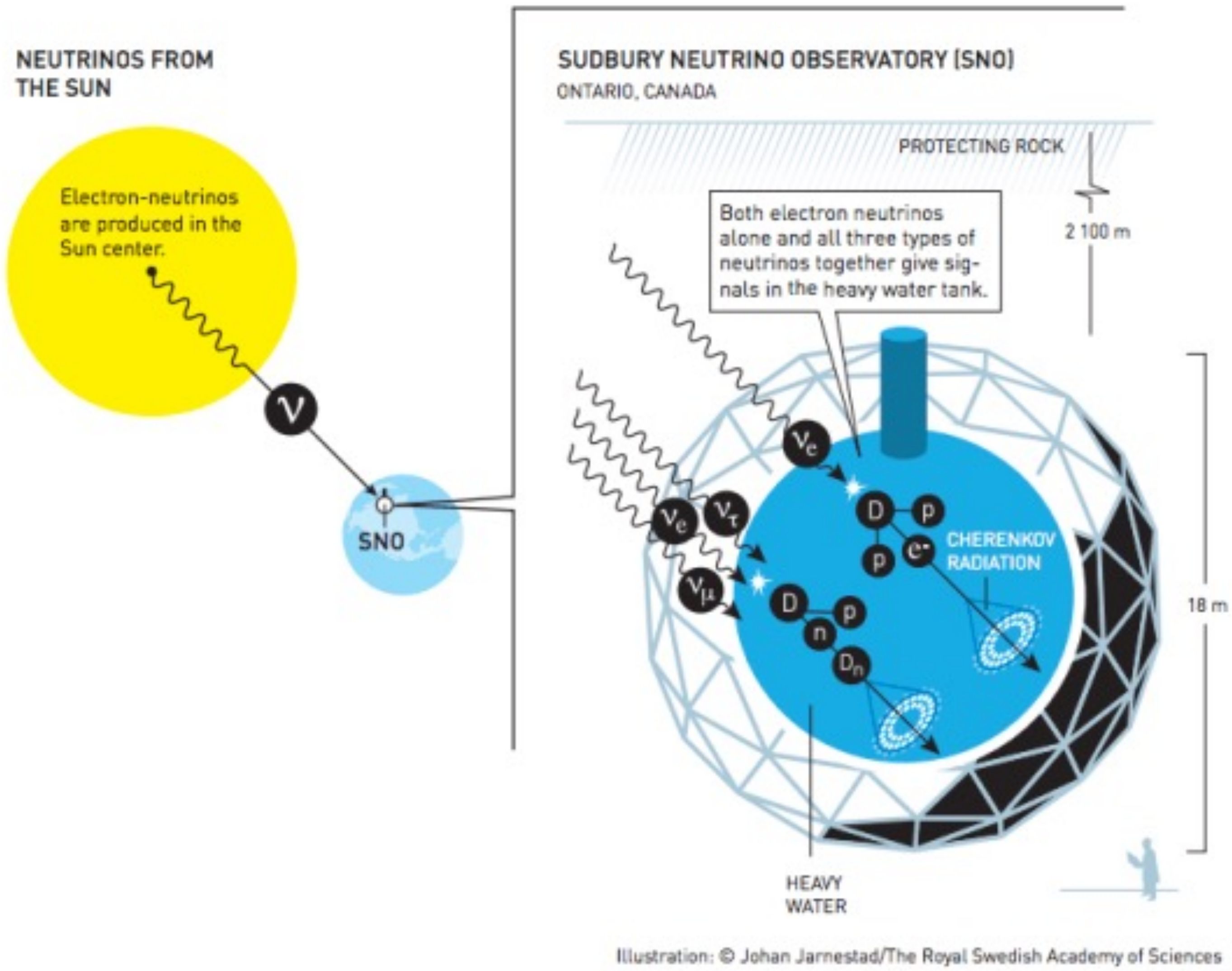
Ali Ashtari Esfahani

Khordad 1402

- Neutrino mass
- Cyclotron Radiation Emission Spectroscopy (CRES)
- Project 8 apparatus
- Analyzing the CRES spectrum
- Tritium spectrum and neutrino mass measurement

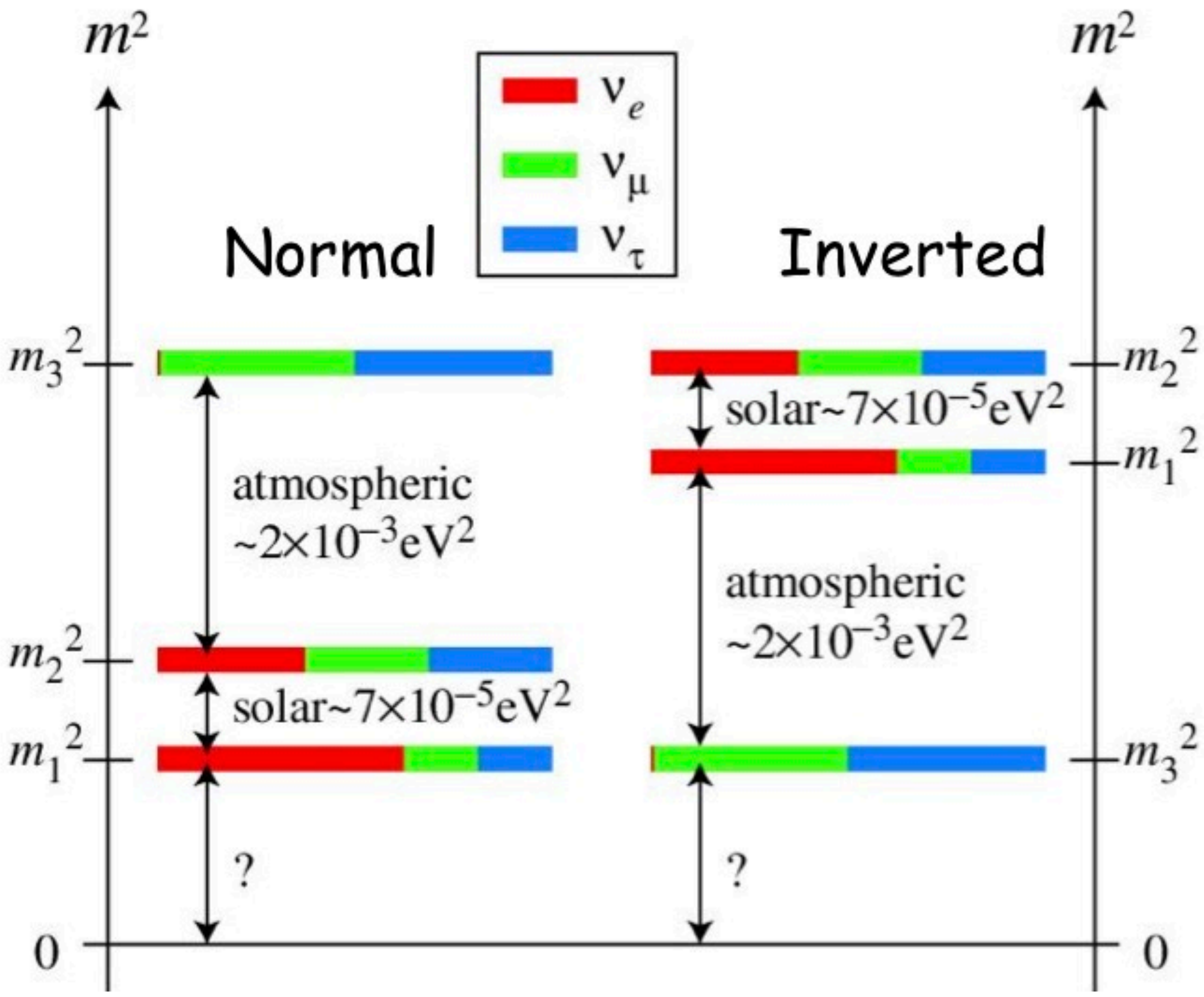


Three flavors of neutrinos as massless fermions in the standard model of particle physics.



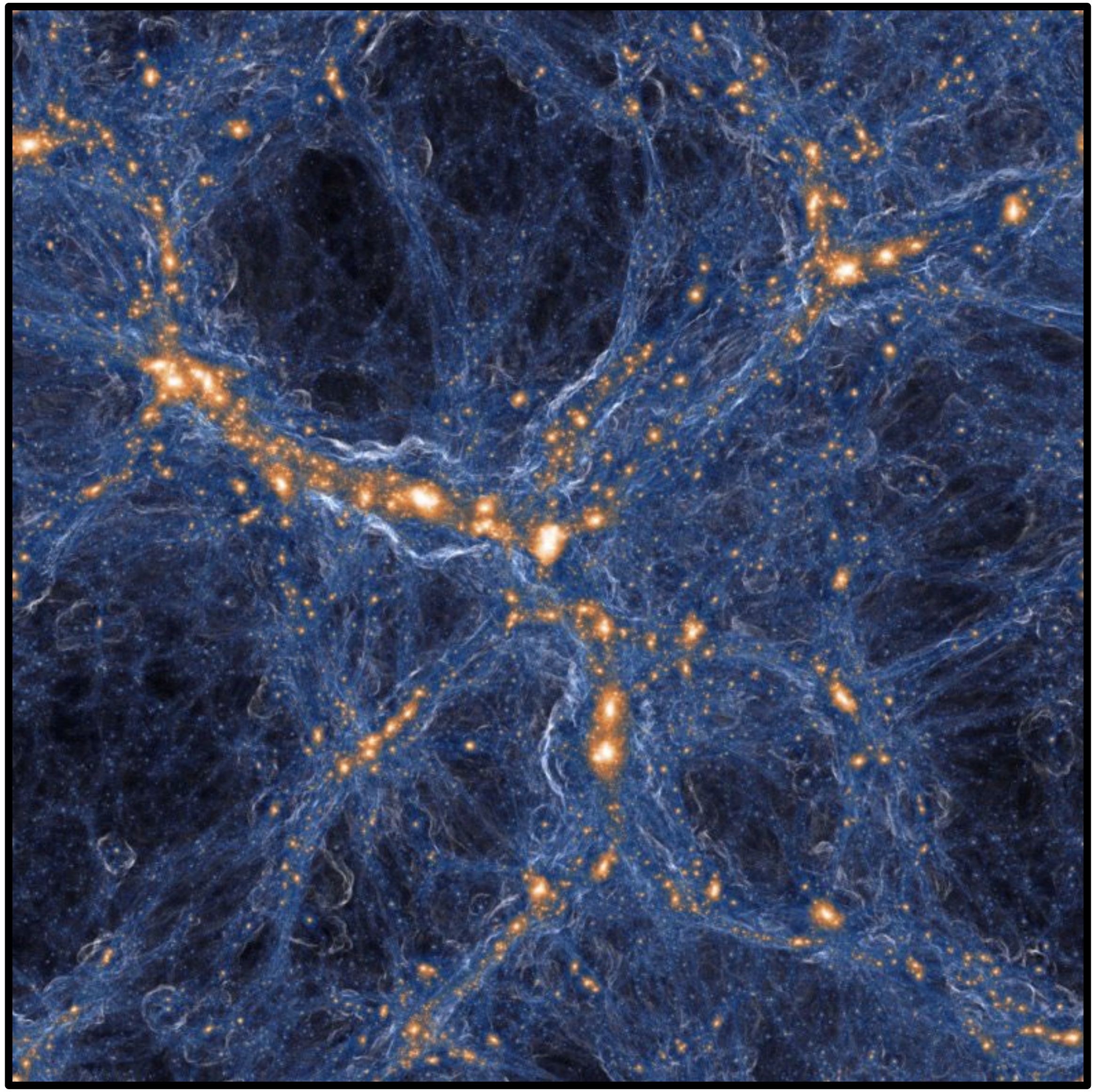
$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} PMNS \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Neutrinos cannot be massless!



The neutrino oscillation experiments left two questions unanswered:

- mass ordering ?
- absolute scale ?

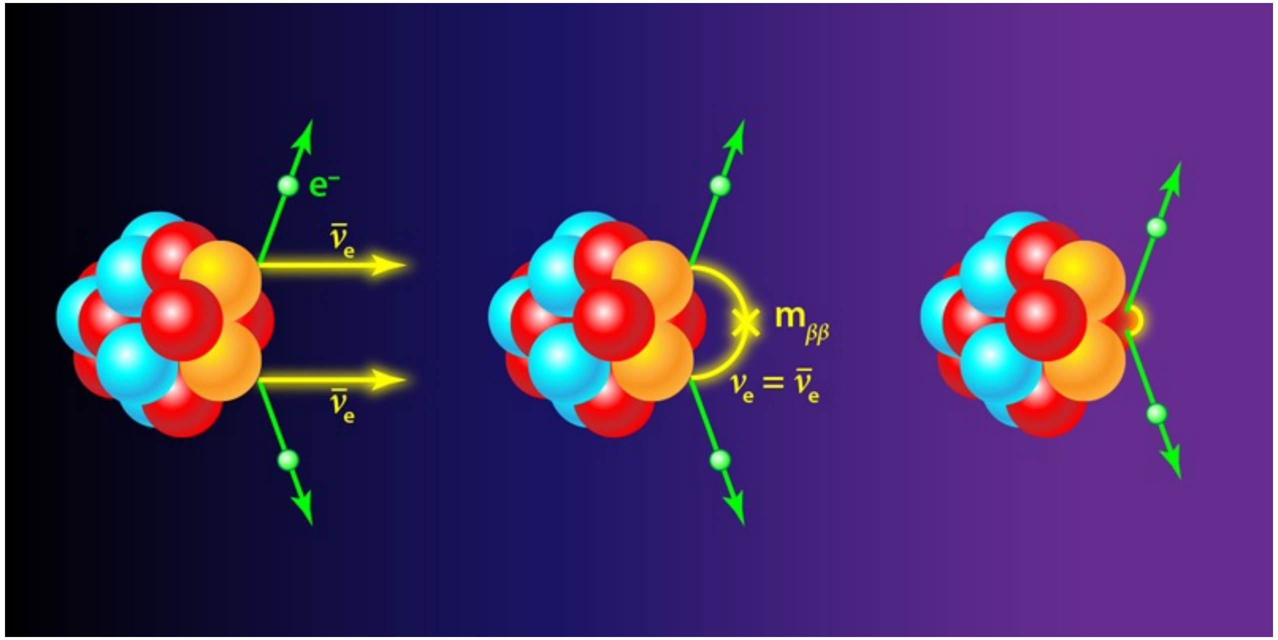


- Massive neutrinos play a role in the formation of the large structures in the universe.

- Data from CMB, large structure of galaxies, type Ia supernova, and big-bang nucleosynthesis can be used to look for the neutrino mass.

$$\sum m_\nu < 0.26\ eV/c^2\ (95\%\ C.L.)$$

A. Loureiro et al., Upper bound of neutrino masses from combined cosmological observations and particle physics experiments. Phys. Rev. Lett., 123:081301, Aug 2019.

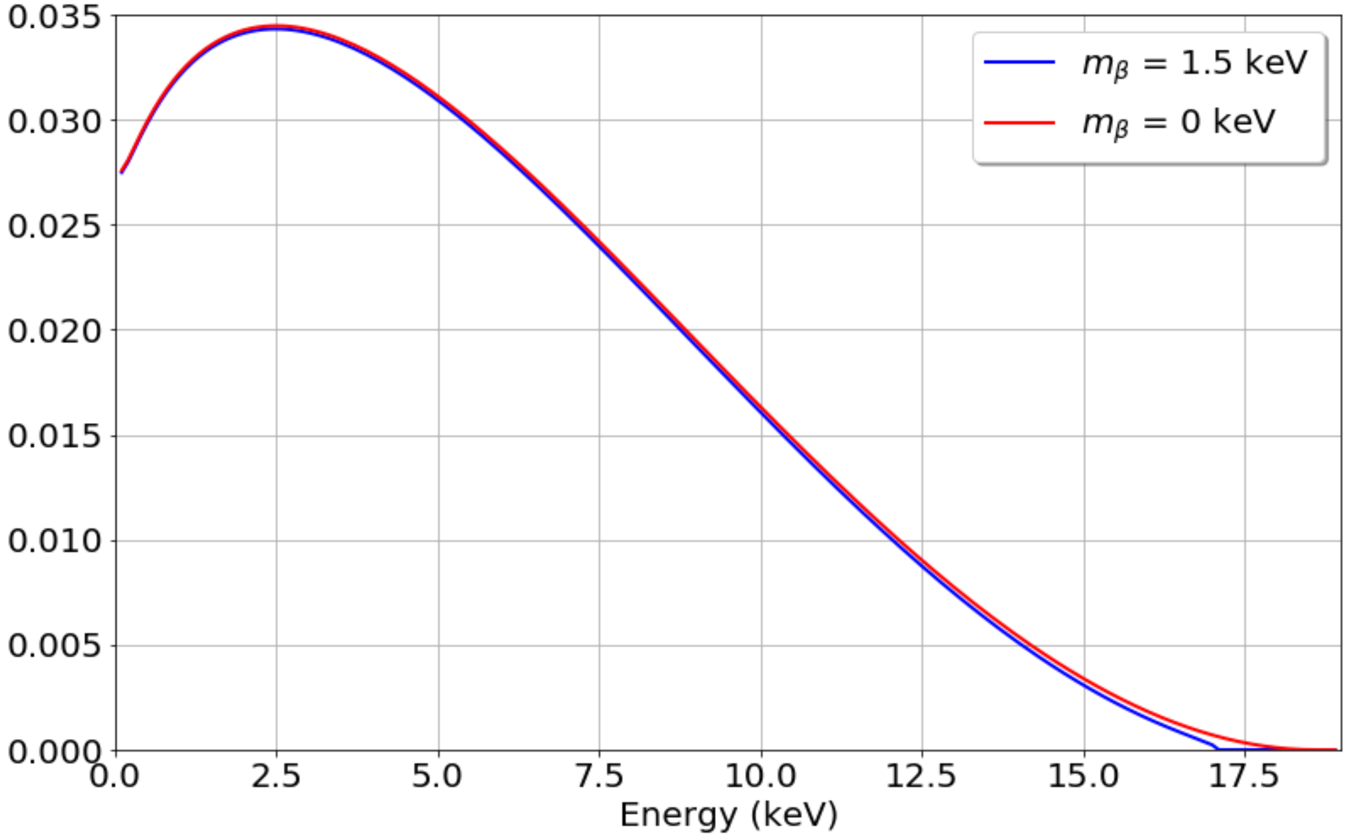


If neutrinos are Majorana fermions, detection of neutrino-less double beta decay can be used to find the neutrino mass.

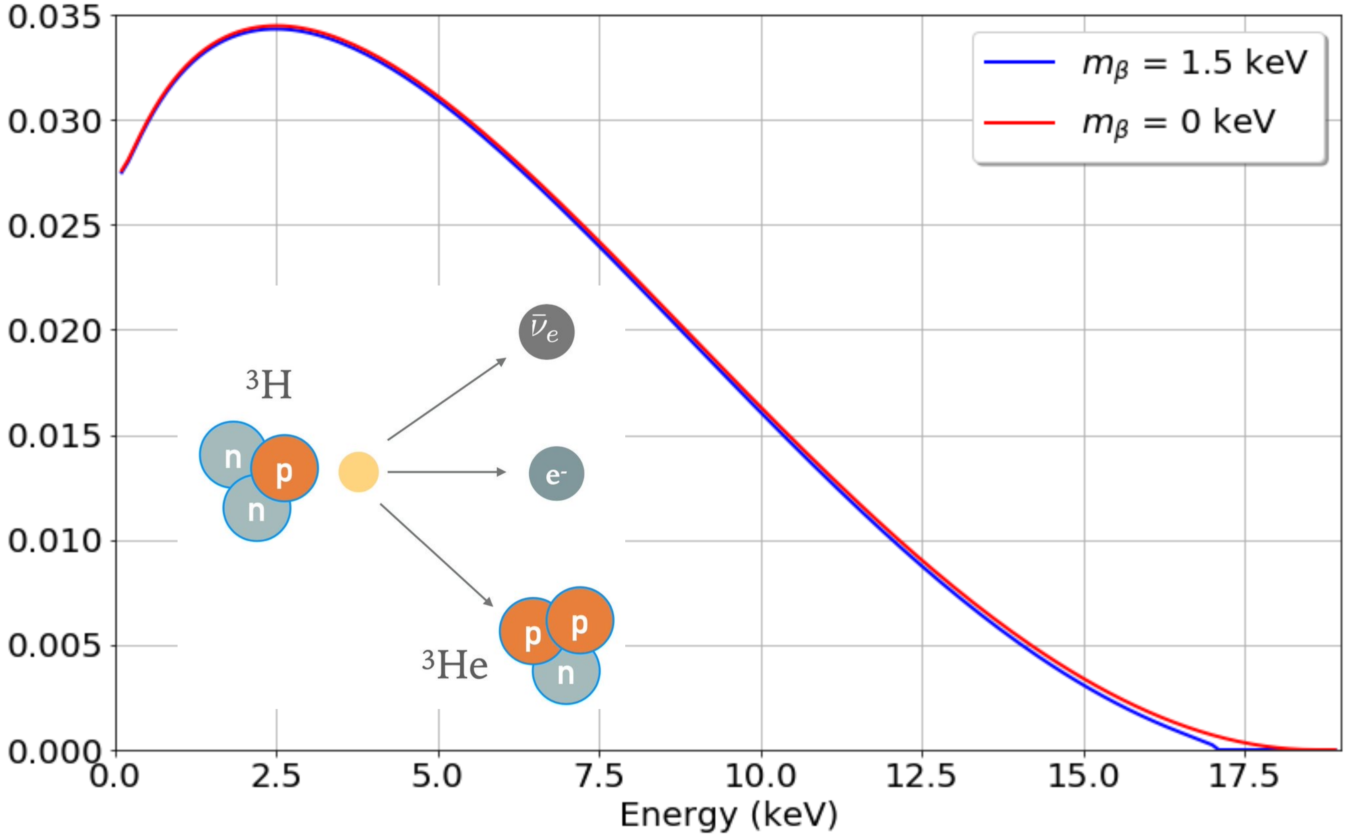
$$m_{\beta\beta}^2 = \left| \sum U_{ei}^2 \, m_i \right|^2$$

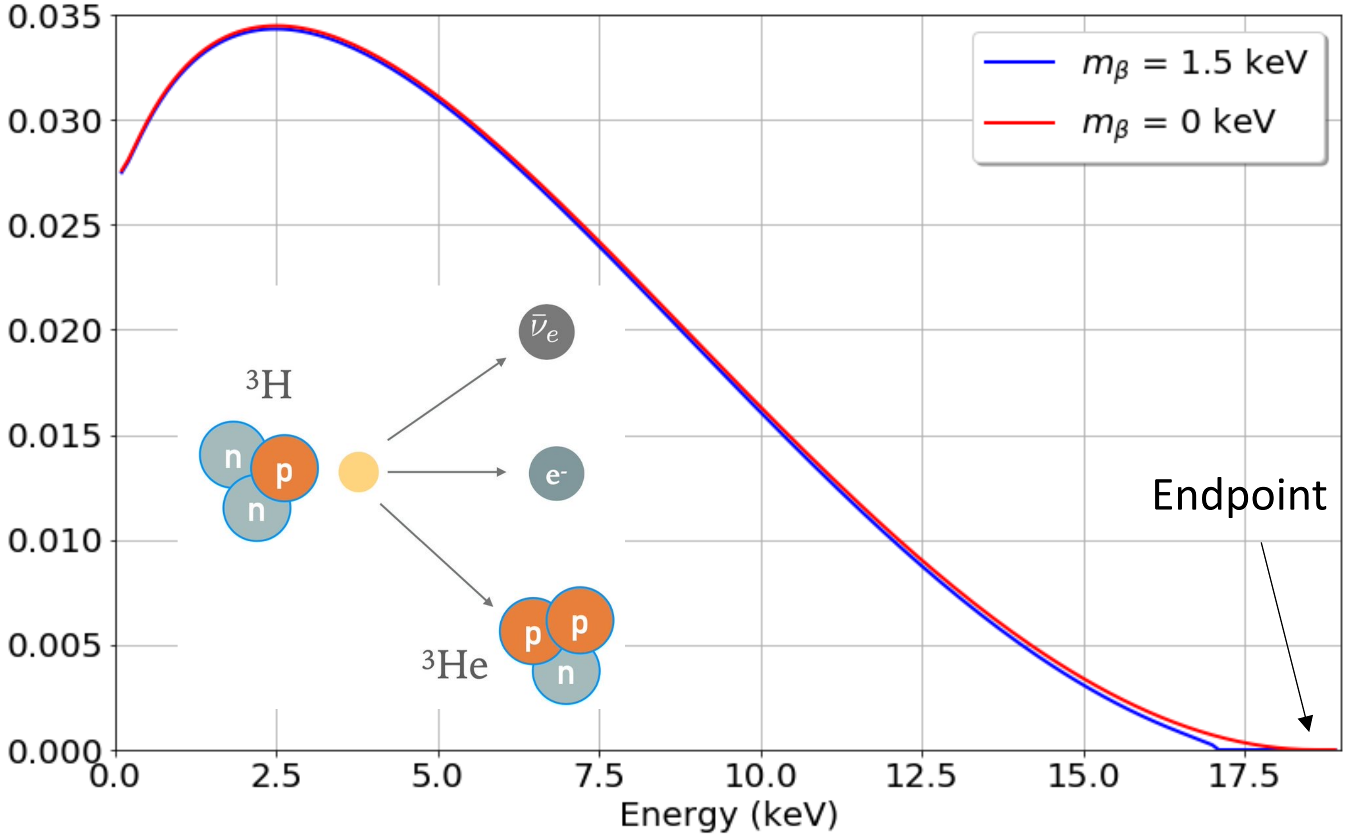
$$m_{\beta\beta} < 61 - 165 \; meV/c^2$$

- Neutrino mass has its mark on the beta decay spectrum.

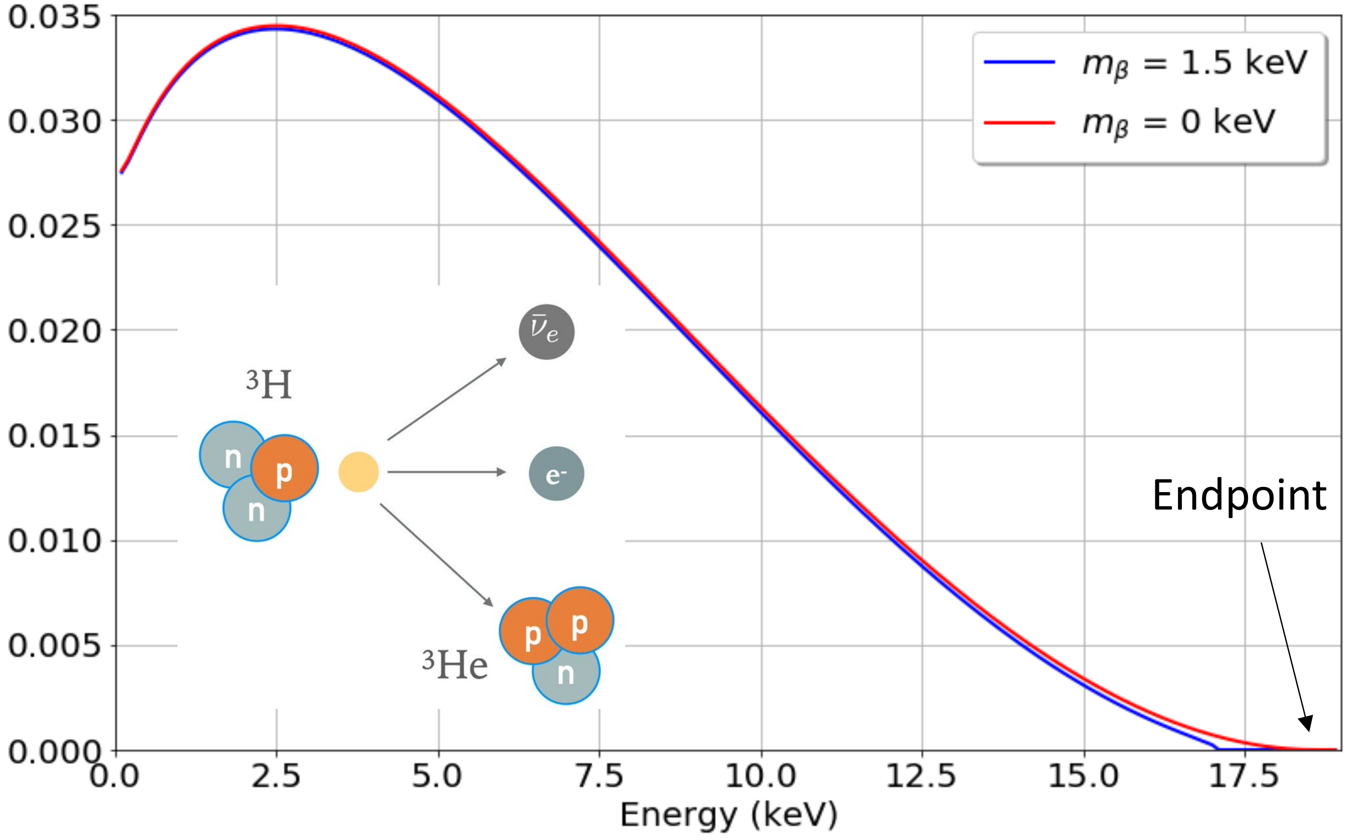


- Neutrino mass has its mark on the beta decay spectrum.
- Tritium beta decay is the most popular processes in the direct search.



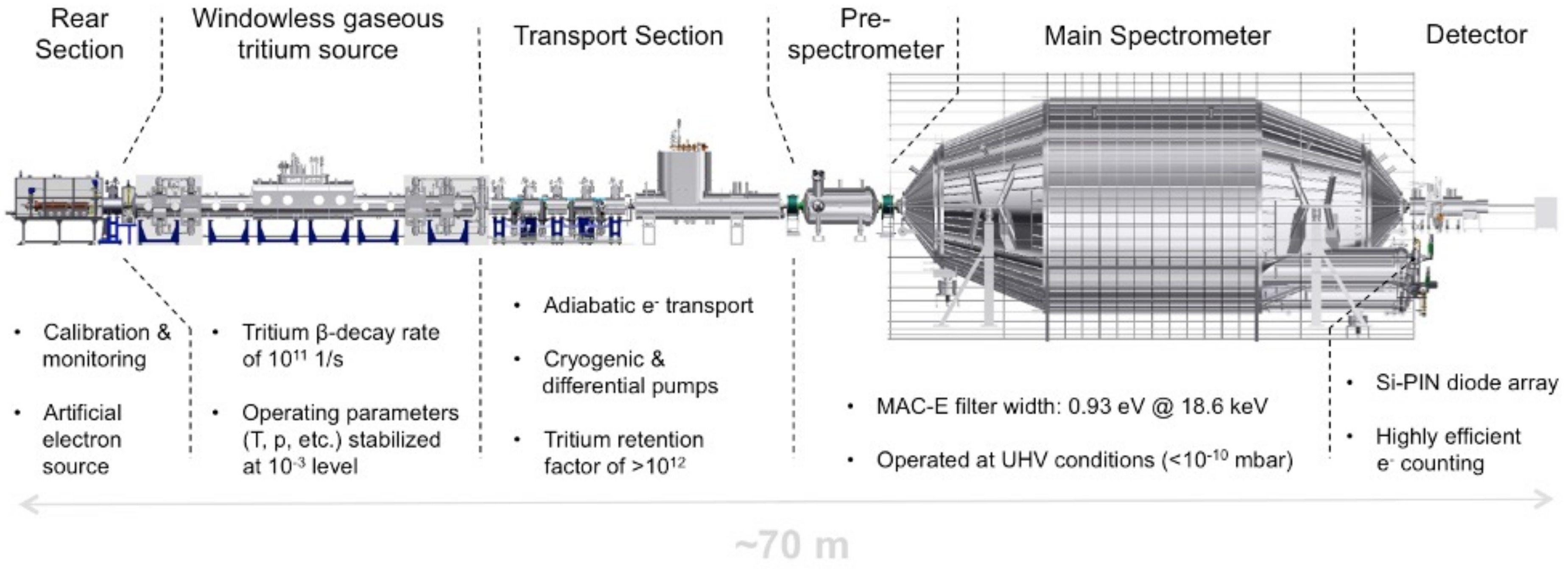


- Neutrino mass has its mark on the beta decay spectrum.
- Tritium beta decay is the most popular processes in the direct search.
  - Endpoint energy of 18.6 keV

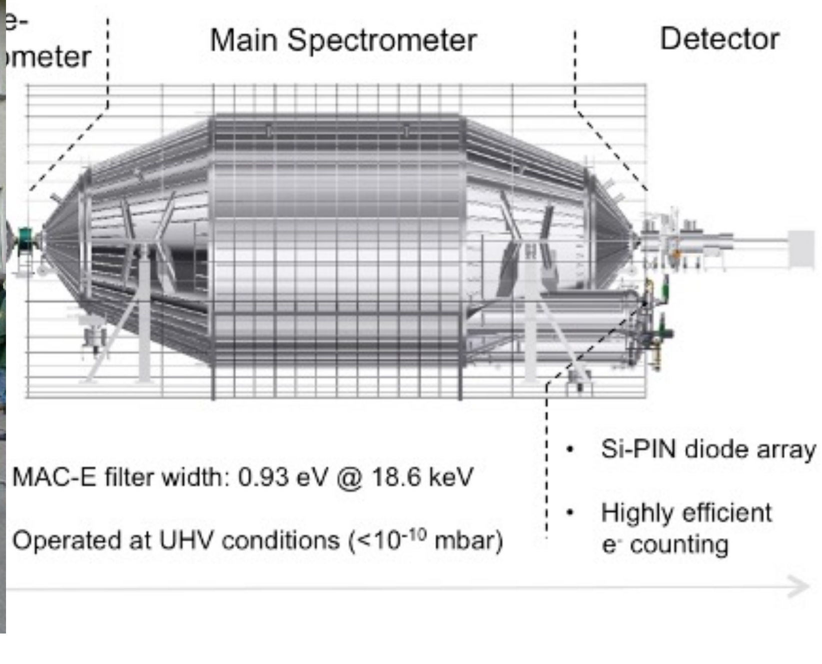


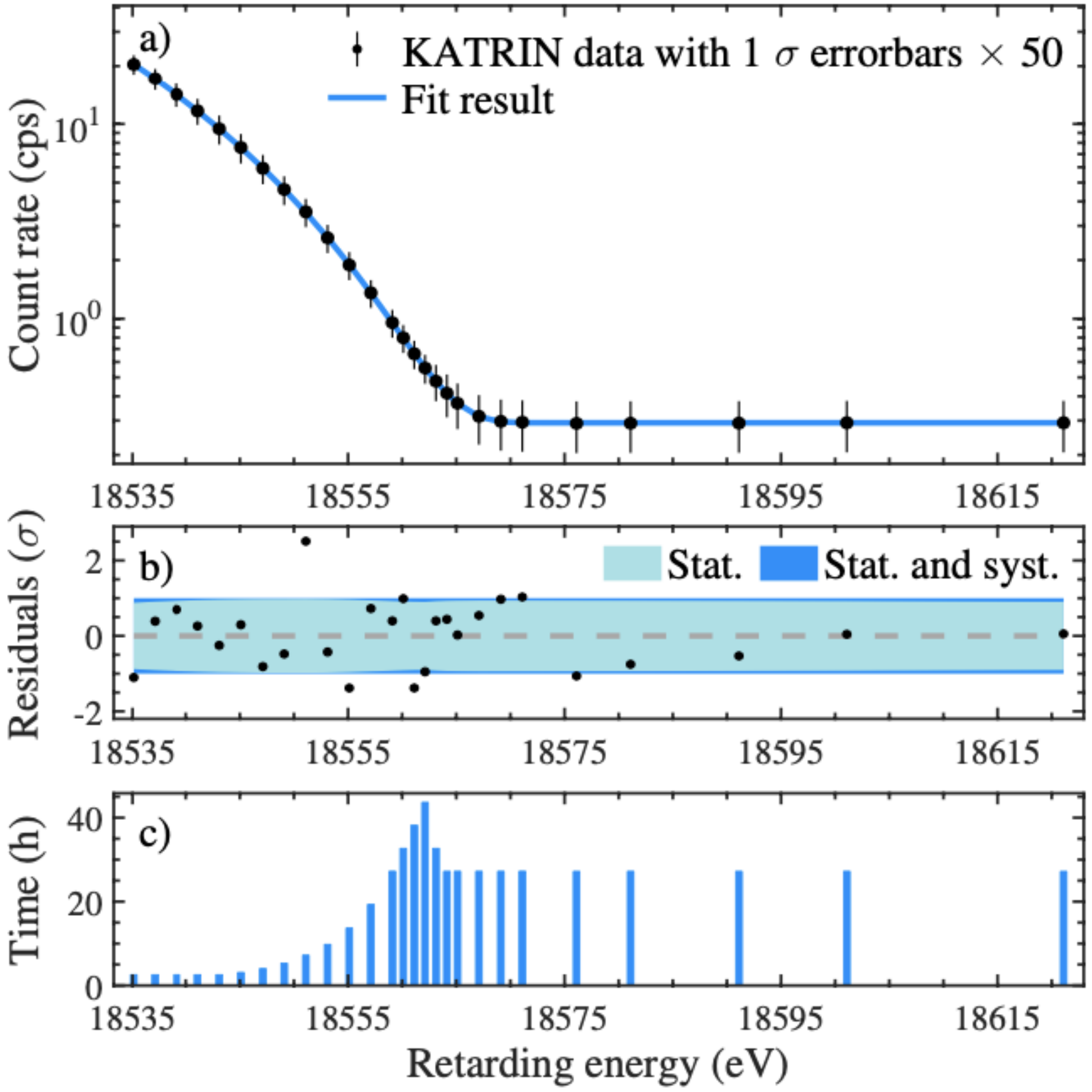
- Neutrino mass has its mark on the beta decay spectrum.
- Tritium beta decay is the most popular processes in the direct search.
  - Endpoint energy of 18.6 keV
  - Half life time of 12.3 y
  - Branching ratio of 2.10^{-13} to the last eV bin of the spectrum

- KATRIN main spectrometer uses the traditional MAC-E filter method for electron energy measurement.



- KATRIN main spectrometer uses the traditional MAC-E filter method for electron energy measurement.





- Currently the best limit is from KATRIN collaboration

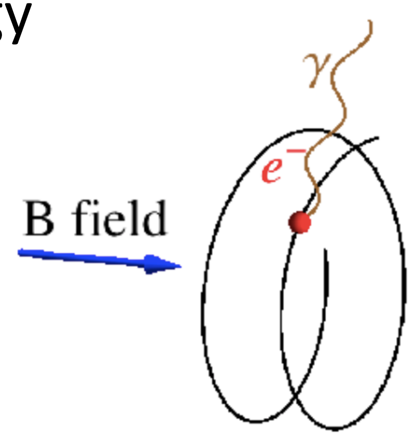
$$m_\beta = \sqrt{\sum |U_{ei}|^2 m_i^2}$$

$$< 0.8\ eV/c^2\ (90\%\ C.L.)$$

- Ultimate sensitivity of KATRIN to neutrino mass is 200 meV.

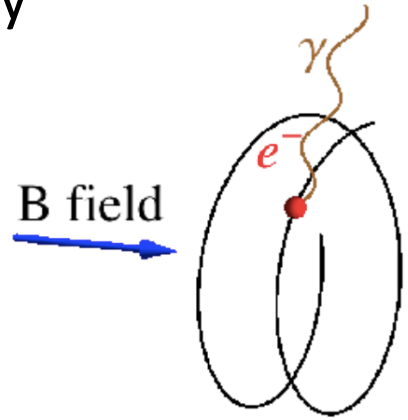
Cyclotron radiation from electron carries information about its energy

$$f_0 = \frac{1}{2\pi}\frac{eB}{m}$$



Cyclotron radiation from electron carries information about its energy

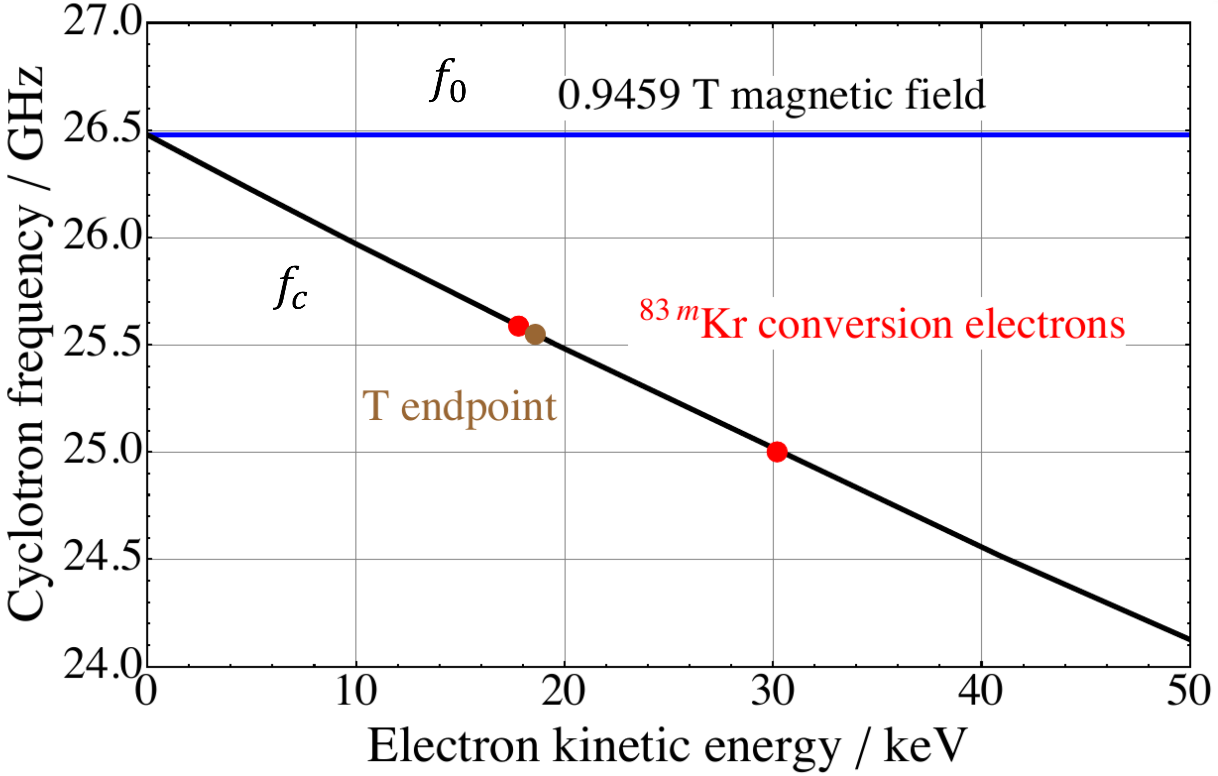
$$f_0 = \frac{1}{2\pi}\frac{eB}{m} \qquad f_c = \frac{f_0}{\gamma} = \frac{1}{2\pi}\frac{eB}{m + E_{kin}/c^2}$$

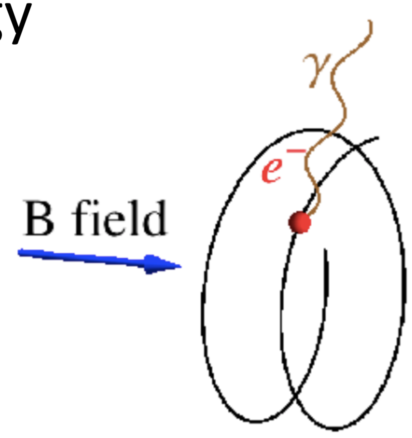


Cyclotron radiation from electron carries information about its energy

$$f_0 = \frac{1}{2\pi}\frac{eB}{m}$$

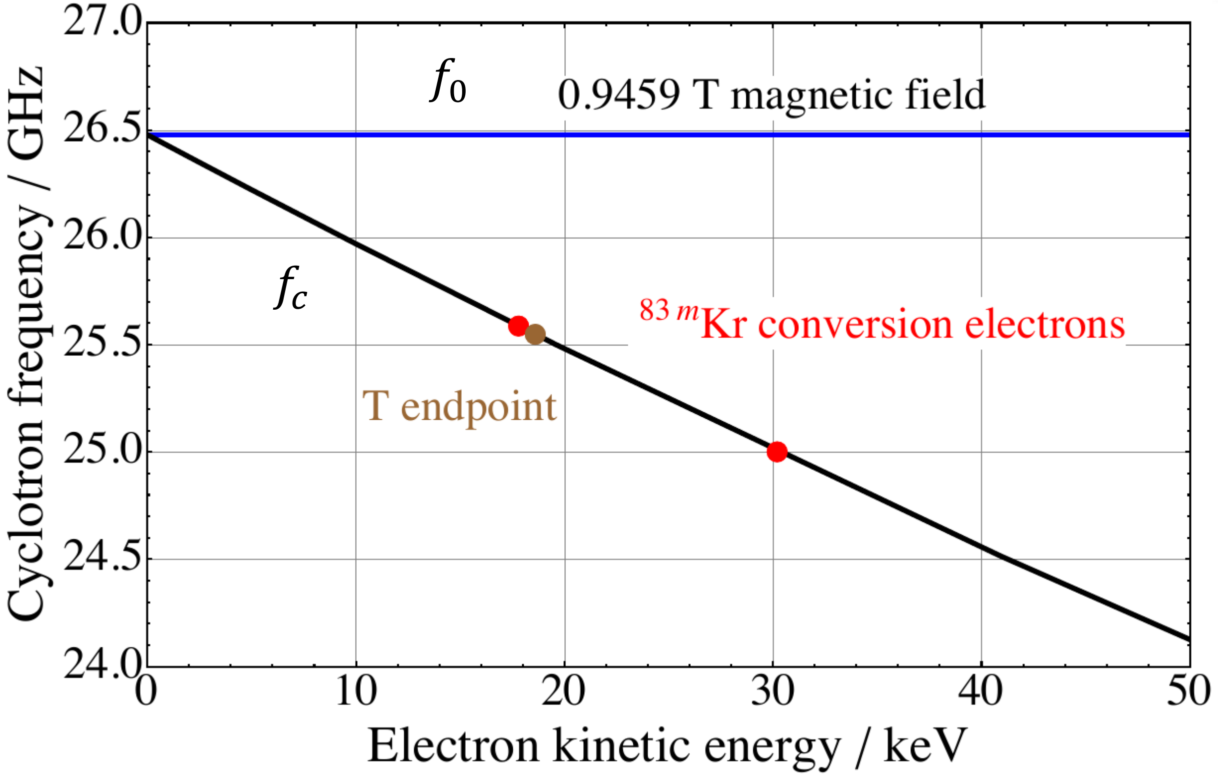
$$f_c = \frac{f_0}{\gamma} = \frac{1}{2\pi}\frac{eB}{m + E_{kin}/c^2}$$

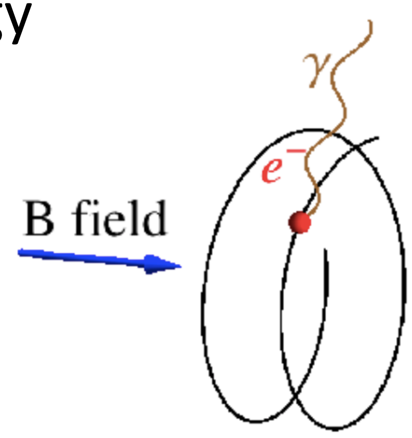




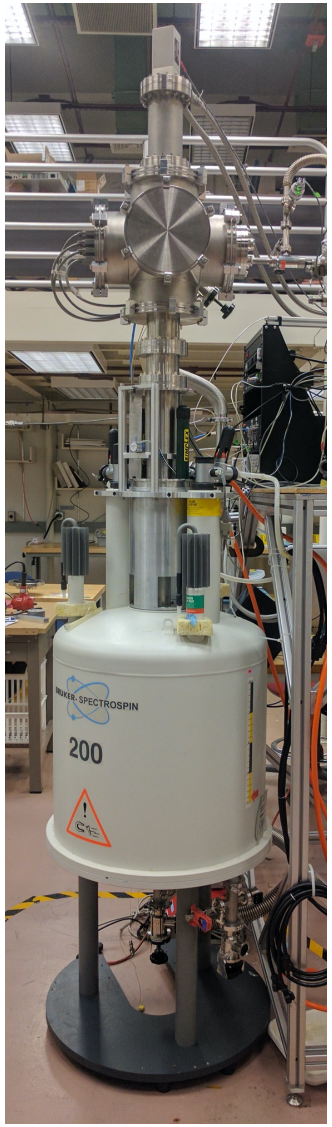
Cyclotron radiation from electron carries information about its energy

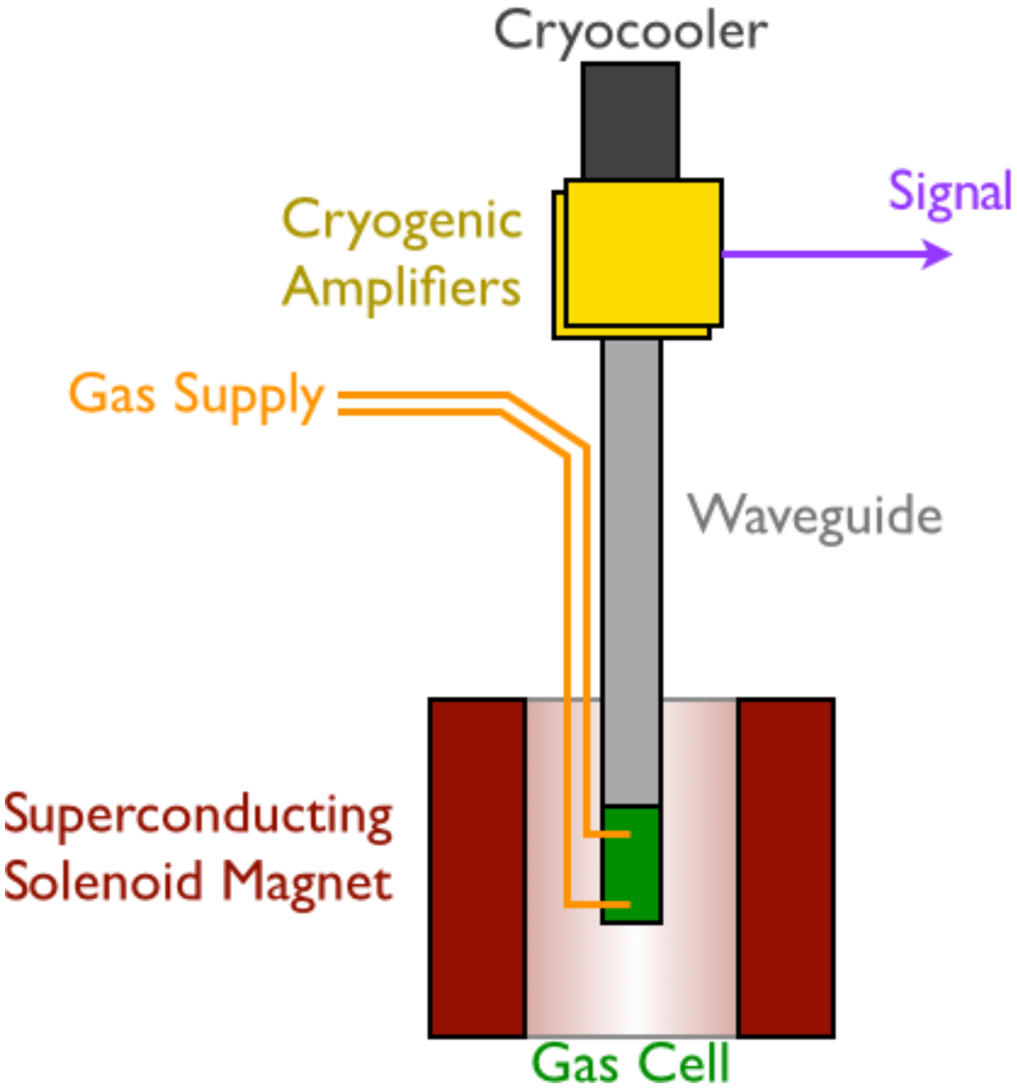
$$f_0 = \frac{1}{2\pi}\frac{eB}{m} \qquad f_c = \frac{f_0}{\gamma} = \frac{1}{2\pi}\frac{eB}{m + E_{kin}/c^2}$$





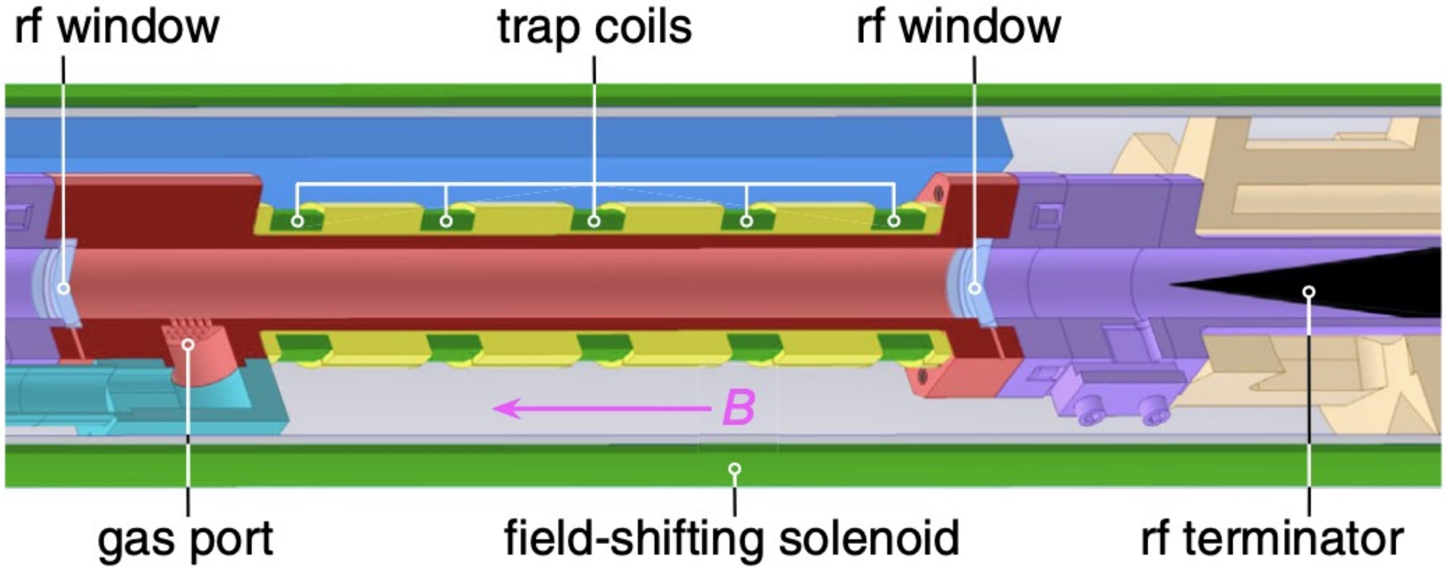
- No electron transport from source to detector
- Differential spectrum measurement
- Precise frequency measurement ⇒ Excellent energy resolution
- Low background

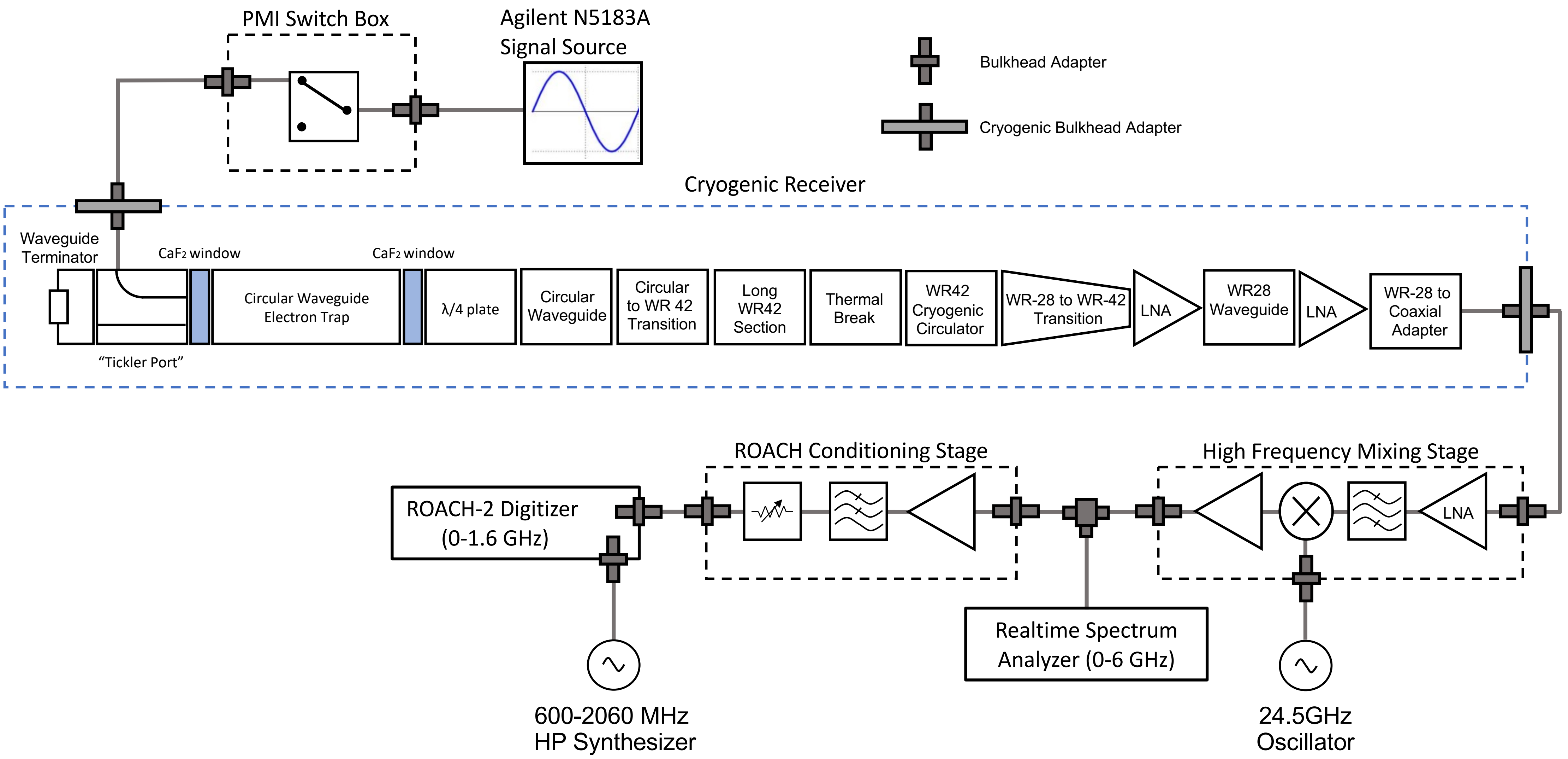


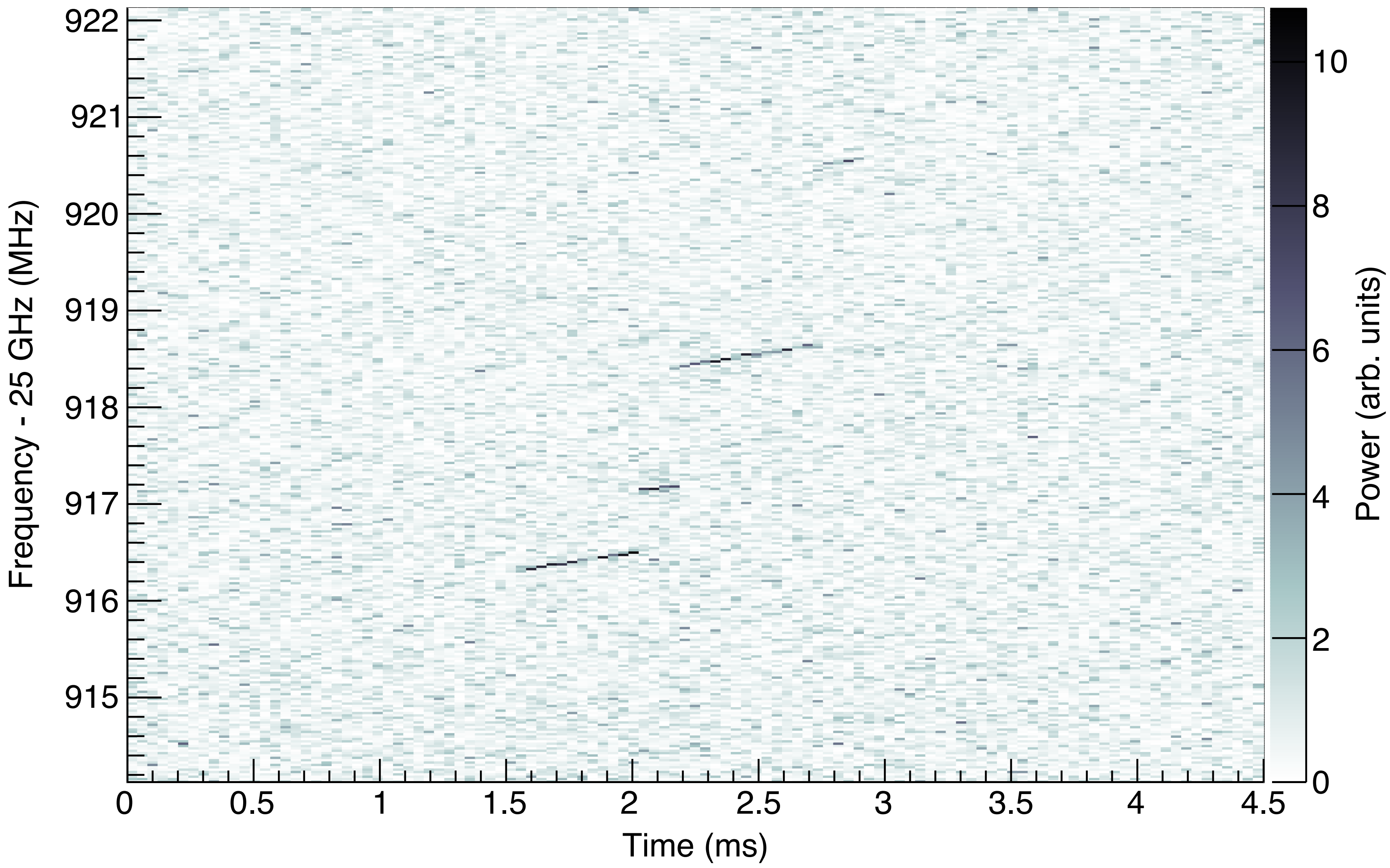


- NMR magnet produces the ~ 1 T background field
- Cyclotron frequency for 18 kev
  - ~26 GHz
  - ~ 1 fW
- Gas system feeds the gas cell with Kr/T_2
- Two stages of cryogenic amplifiers amplify the signal

- 5 coils act as the magnetic bottle trap to confine electrons
- TE_{11} mode of the circular waveguide couples to the electron's radiation
- 2 Caf_2 windows trap the gas inside the cell without disturbing the RF transparency
- RF terminator used to avoid interference of signals

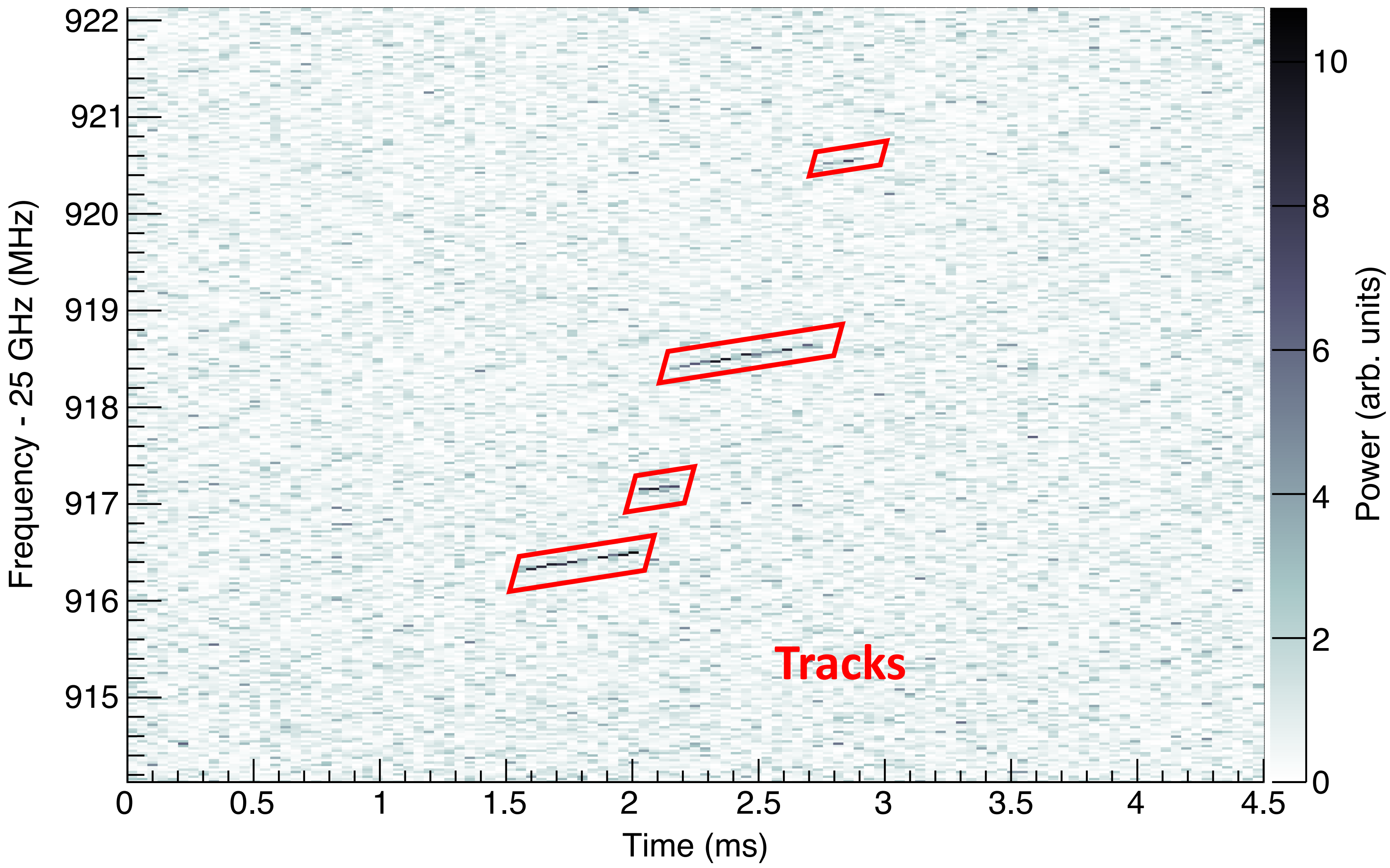


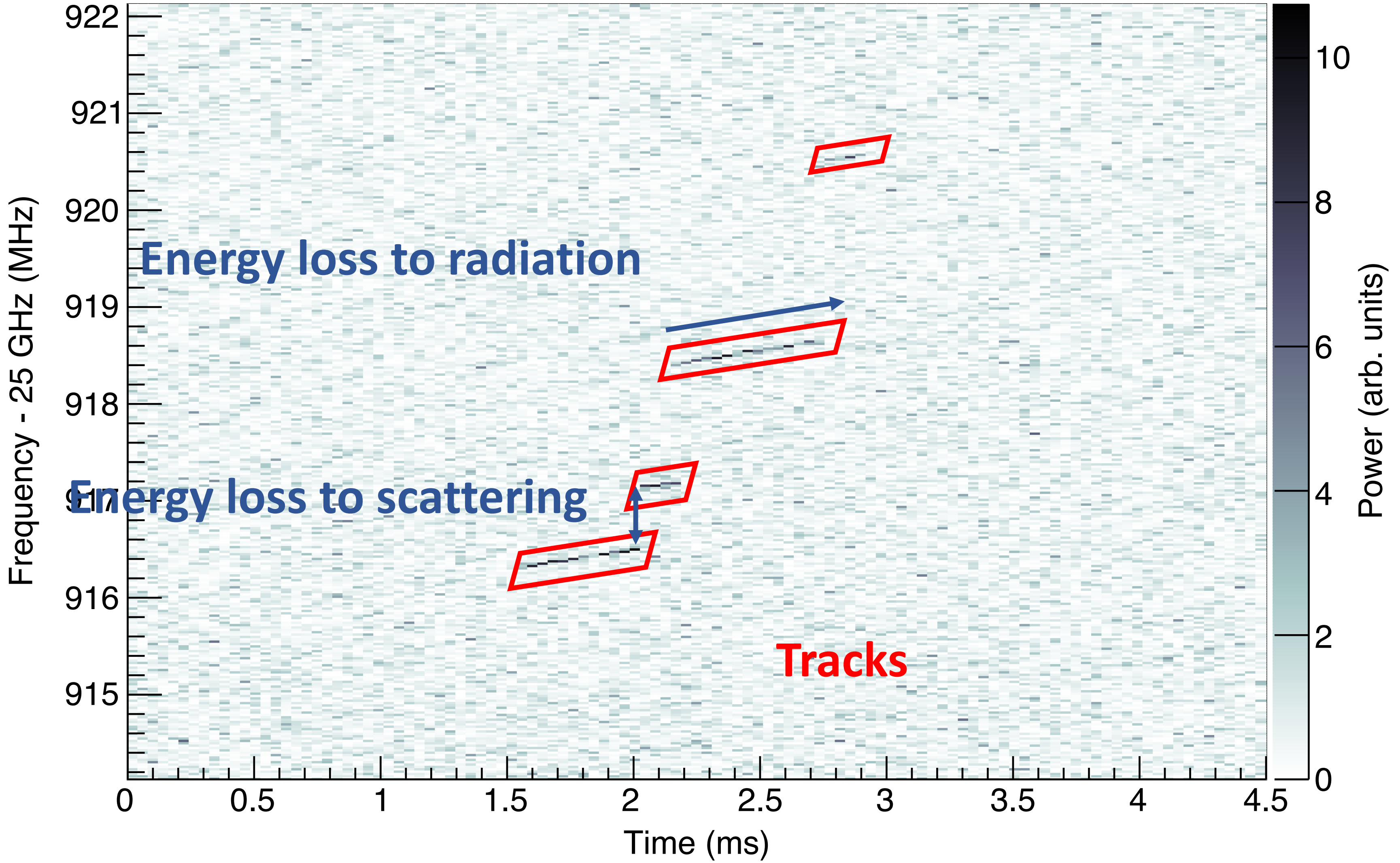

PMI Switch Box
Agilent N5183A
Signal Source
Bulkhead Adapter
Cryogenic Bulkhead Adapter
Cryogenic Receiver
Waveguide
Terminator
CaF2 window
CaF2 window
Circular Waveguide
Electron Trap
λ/4 plate
Circular
Waveguide
Circular
to WR 42
Transition
Long
WR42
Section
Thermal
Break
WR42
Cryogenic
Circulator
WR-28 to WR-42
Transition
LNA
WR28
Waveguide
LNA
WR-28 to
Coaxial
Adapter
"Tickler Port"
ROACH Conditioning Stage
High Frequency Mixing Stage
ROACH-2 Digitizer
(0-1.6 GHz)
LNA
Realtime Spectrum
Analyzer (0-6 GHz)
600-2060 MHz
HP Synthesizer
24.5GHz
Oscillator



922
921
920
919
918
917
916
915
Frequency - 25 GHz (MHz)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Time (ms)
10
8
6
4
2
0
Power (arb. units)

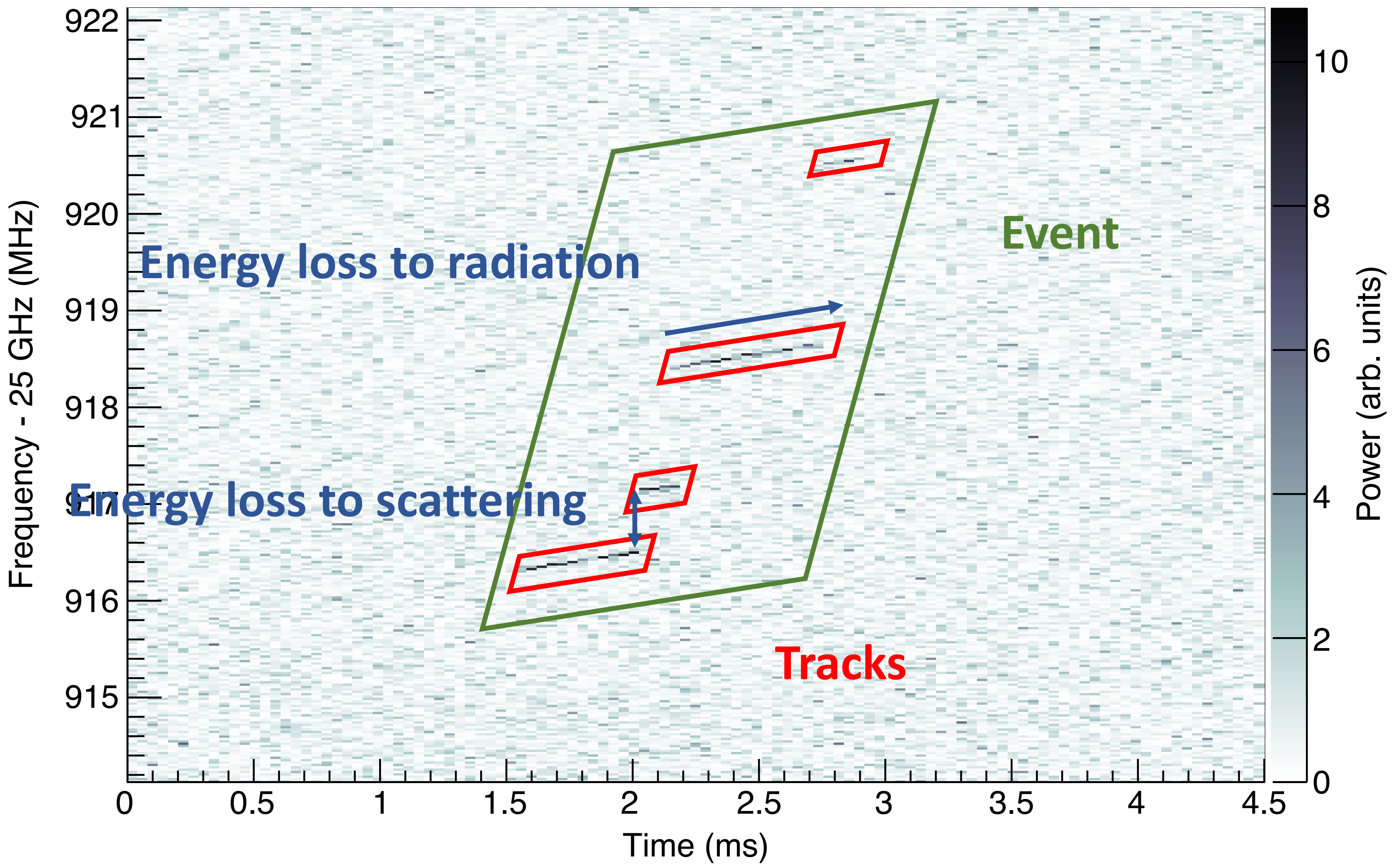
Waterfall plot

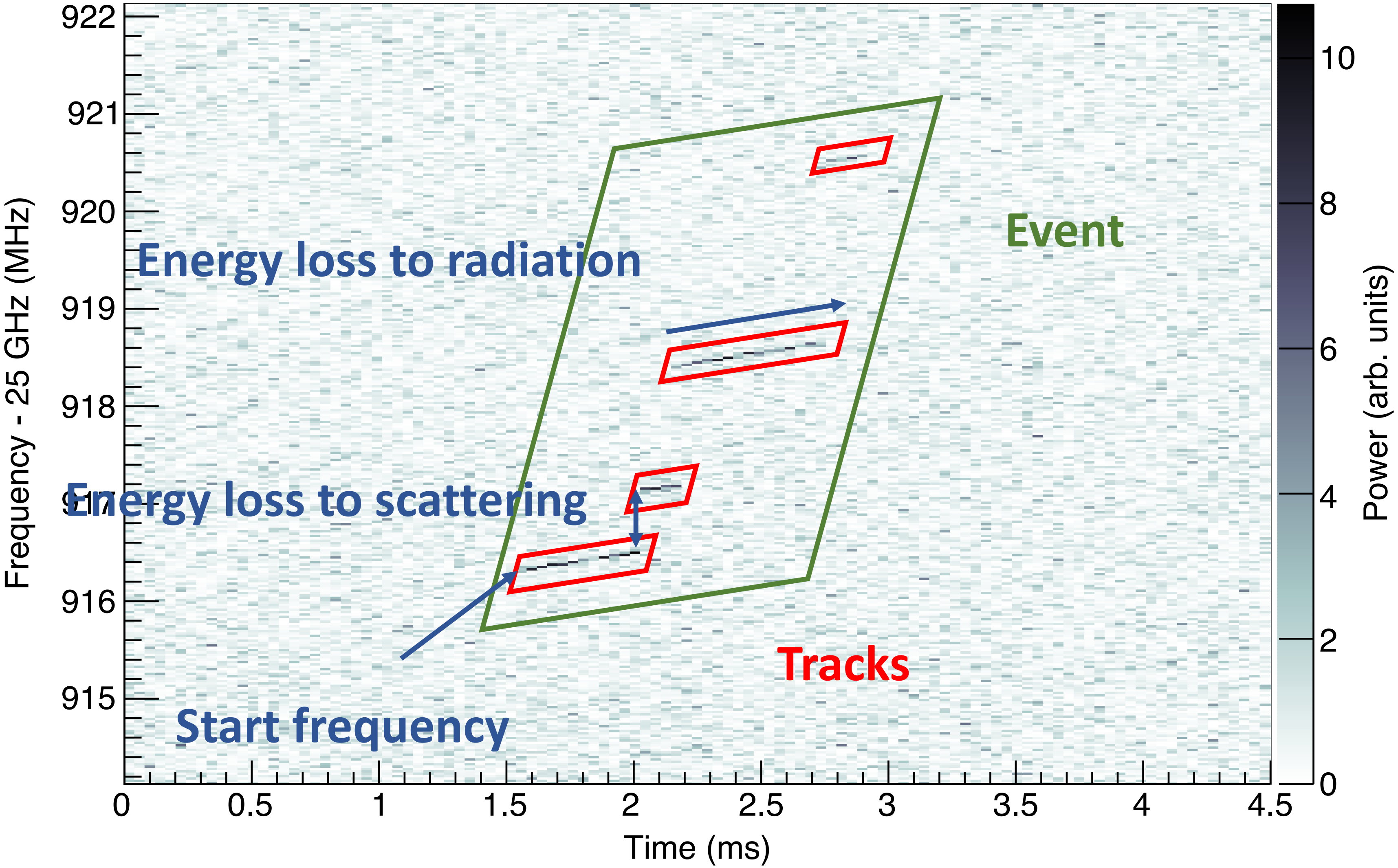




922
921
920
919
918
917
916
915
Frequency - 25 GHz (MHz)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Time (ms)
10
8
6
4
2
0
Power (arb. units)
Energy loss to radiation
Energy loss to scattering
Tracks

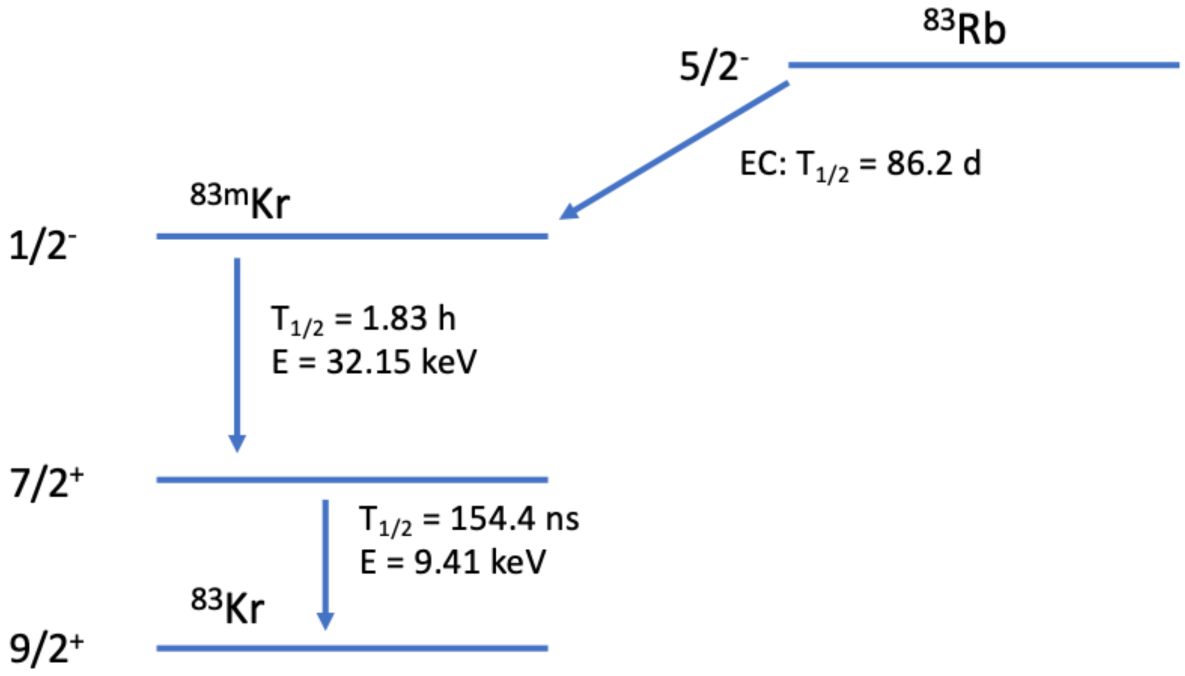
Waterfall plot





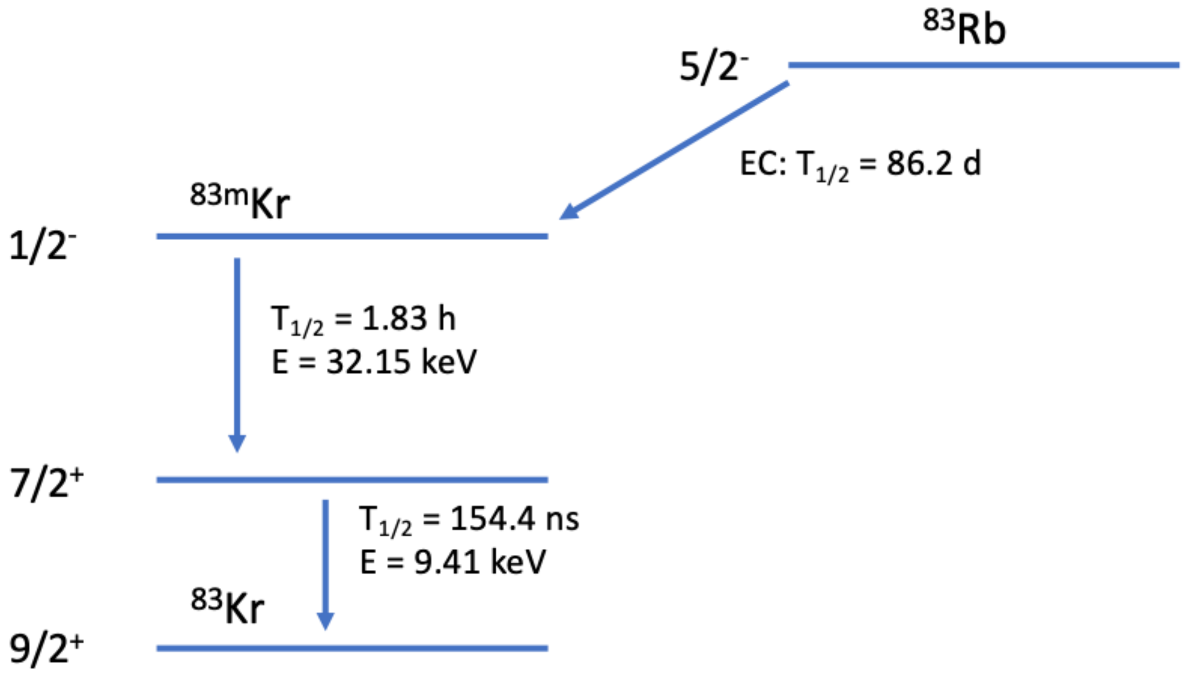
922
921
920
919
918
917
916
915
Frequency - 25 GHz (MHz)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Time (ms)
10
8
6
4
2
0
Power (arb. units)
Energy loss to radiation
Energy loss to scattering
Start frequency
Event
Tracks

- ^{83m}Kr is the decay product of ^{83}Rb
- ^{83m}Kr decays to its ground state in a cascade of two internal conversions which release conversion electrons

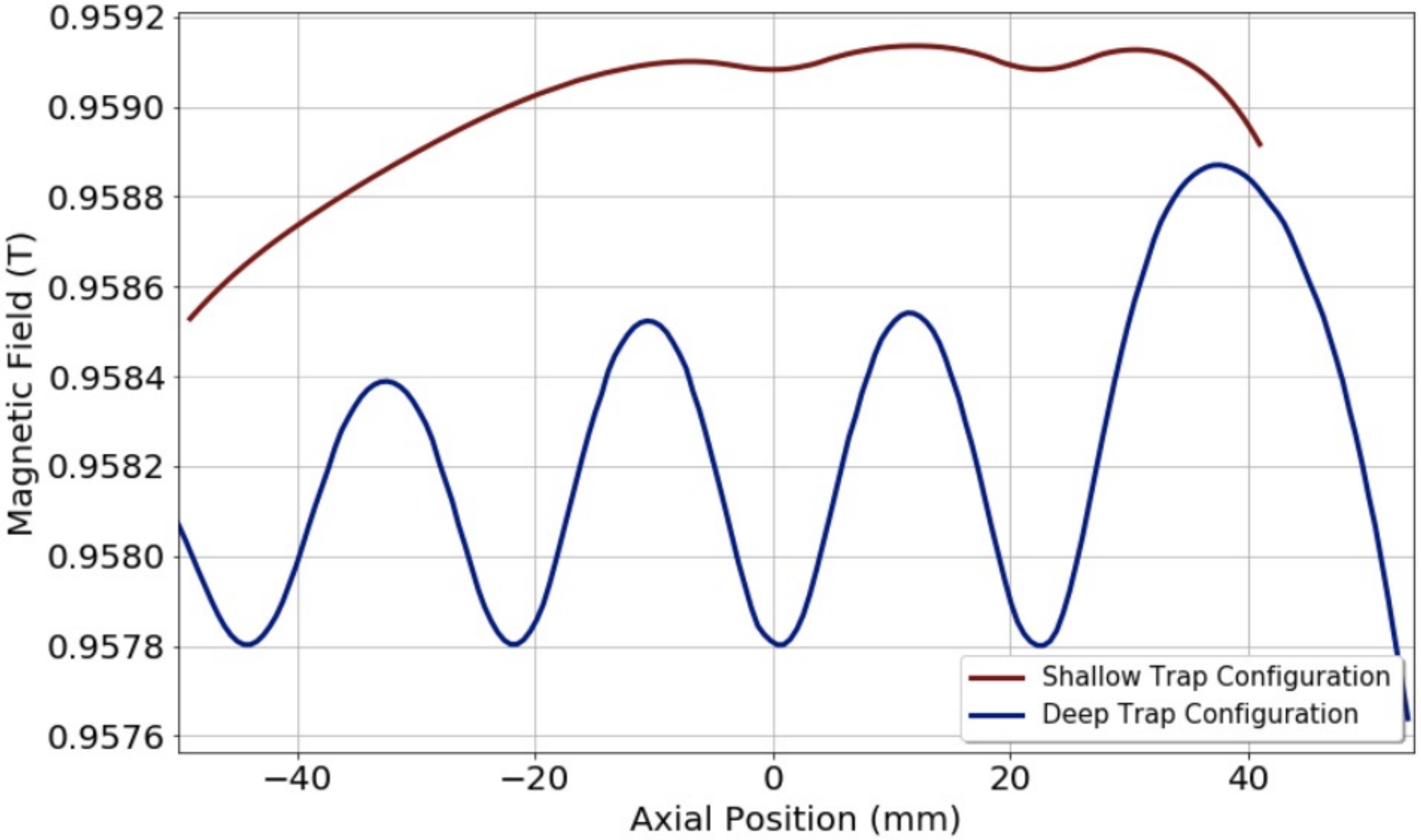


- ^{83m}Kr is the decay product of ^{83}Rb
- ^{83m}Kr decays to its ground state in a cascade of two internal conversions which release conversion electrons

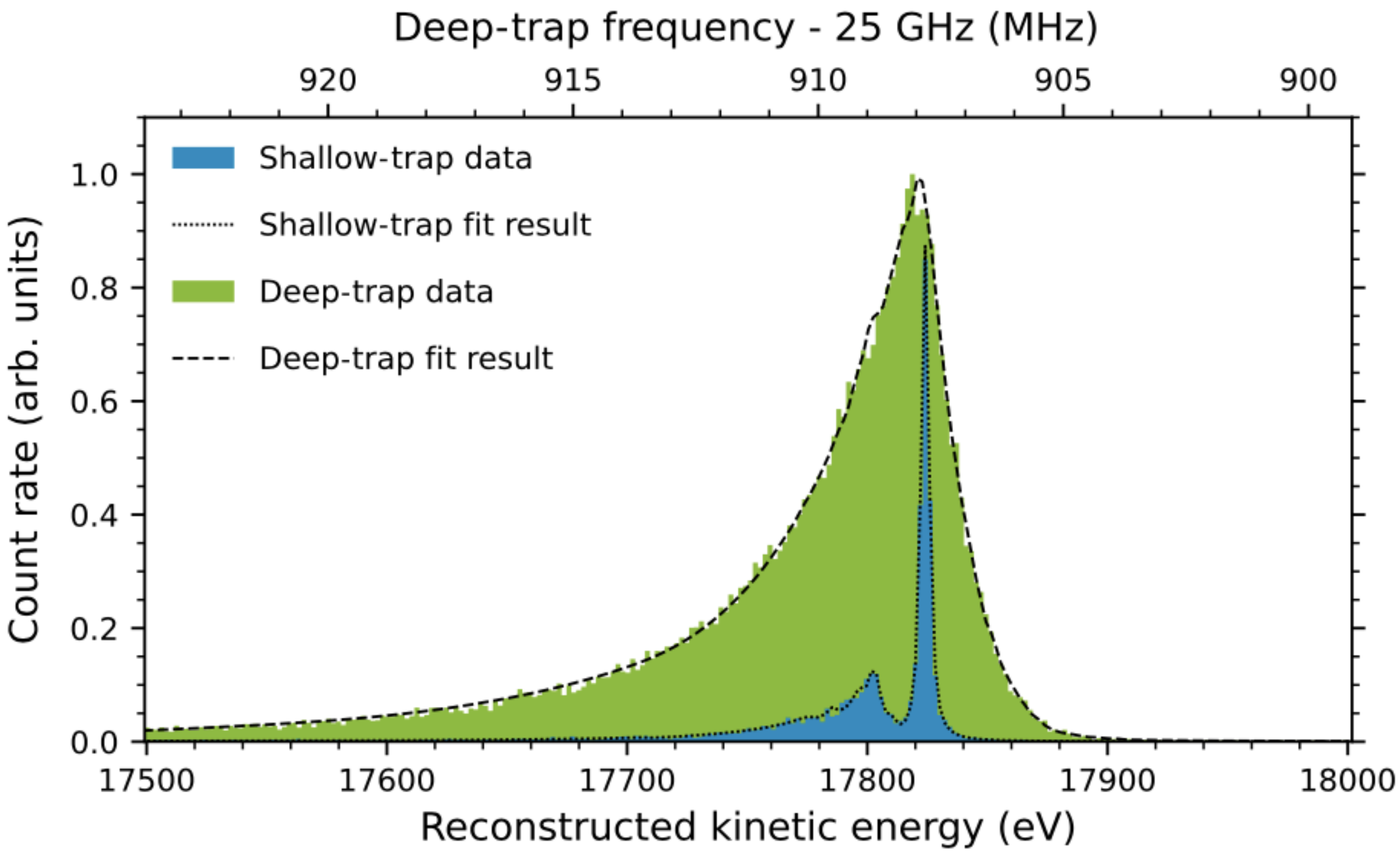
Line	Energy (keV)
K	17.824
L2	30.419
L3	30.472
M2	31.929
M3	31.936
N2	32.136
N3	32.137



- Deep trap Configuration for high event rate
- Shallow trap configuration for better energy resolution



- Shallow trap configuration
    - Peak width 1.66 eV (FWHM)
- Deep trap Configuration
    - Peak width 54.3 eV (FWHM)
    - 40× higher event rate



$$\mathcal{S} = \epsilon\left(\mathcal{Y} * \mathcal{R}_{PSF}\right)$$

Efficiency

$$\mathcal{S} = \epsilon\,(\mathcal{Y} * \mathcal{R}_{PSF})$$

Efficiency

$$\mathcal{S} = \epsilon\,(\mathcal{Y} * \mathcal{R}_{PSF})$$

Underlying true energy spectrum of the electrons

Efficiency

$$\mathcal{S} = \epsilon\,(\mathcal{Y} * \mathcal{R}_{PSF})$$

Underlying true energy spectrum of the electrons

Point spread function

$$\mathcal{S} = \epsilon\,(\mathcal{Y} * \mathcal{R}_{PSF})$$

Efficiency

Underlying true energy spectrum of the electrons

Point spread function

- Lorentzian with fixed width for Krypton data (2.8 eV for K-line)
- Shake up and shake off electrons

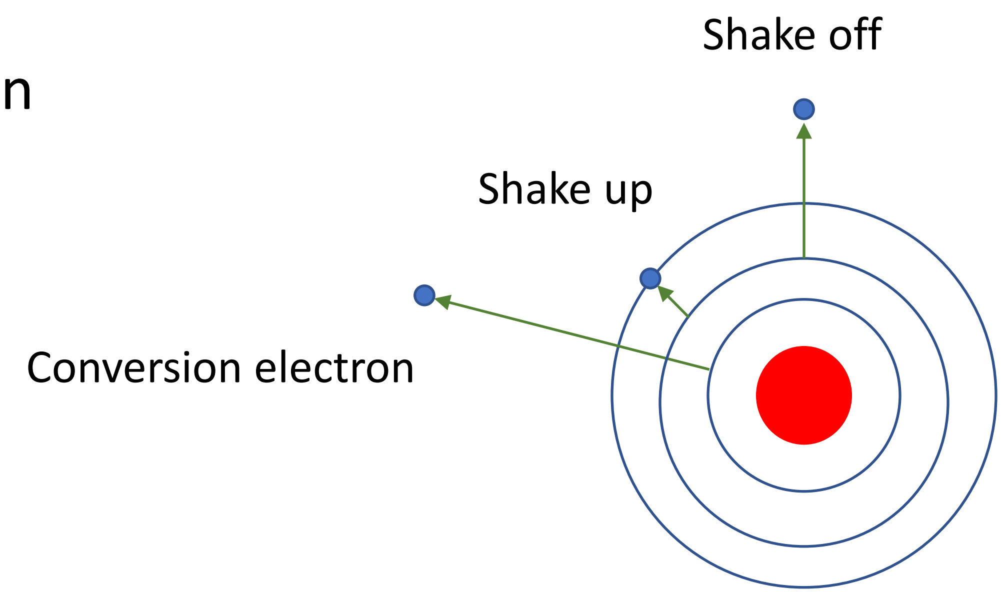
Efficiency

$$\mathcal{S} = \epsilon\,(\mathcal{Y} * \mathcal{R}_{PSF})$$

Underlying true energy spectrum of the electrons

Point spread function

- Lorentzian with fixed width for Krypton data (2.8 eV for K-line)
- Shake up and shake off electrons



$$\mathcal{R}_{PSF} = \sum_{j=0} \mathcal{A}_j \left(\mathcal{I} * \mathcal{L}^{*j} \right)$$

Scatter peak amplitude

Proportional to the probability that electron is first detected after j scatters

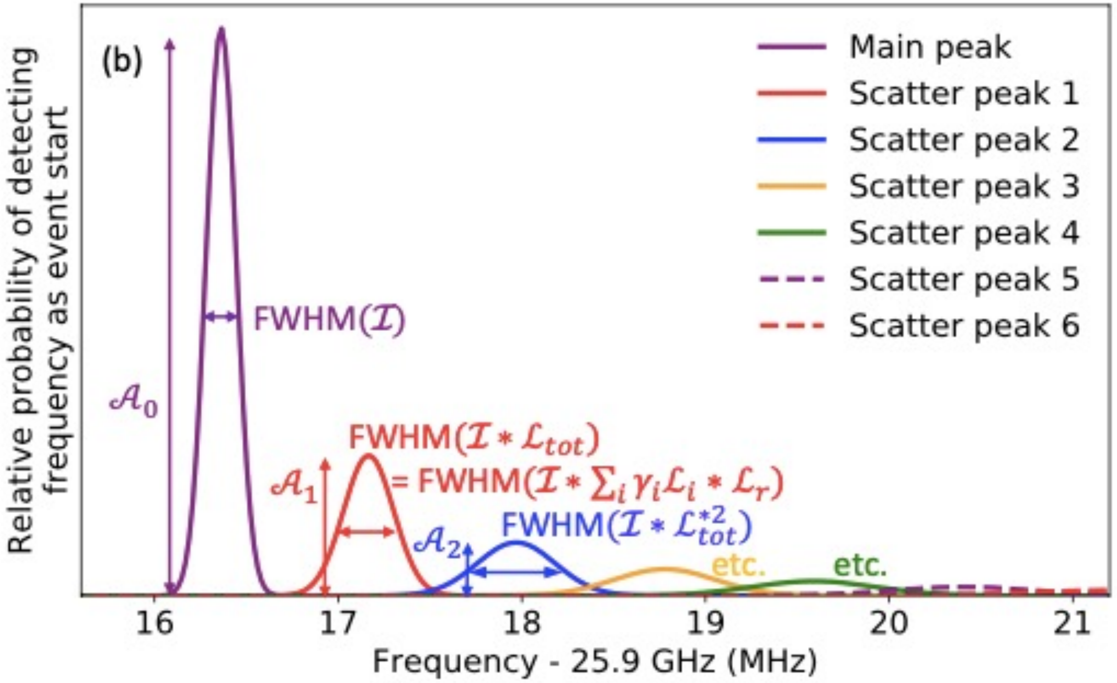
Instrumental resolution

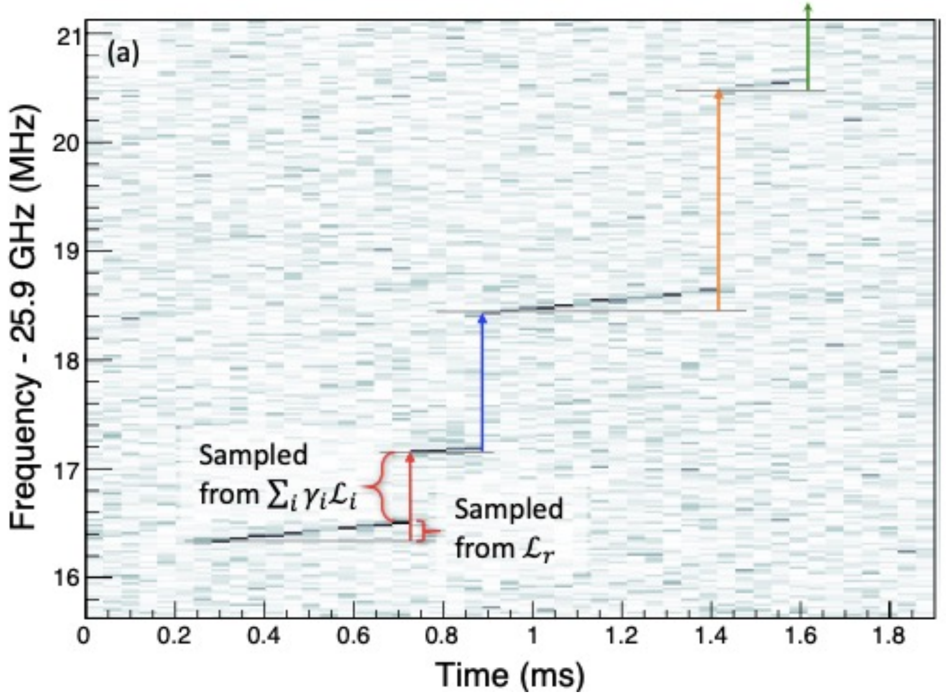
Caused by the difference in the magnetic field experienced by different electrons

Energy loss distribution after j scatters

Depends on the cross section, fraction of each gases, and

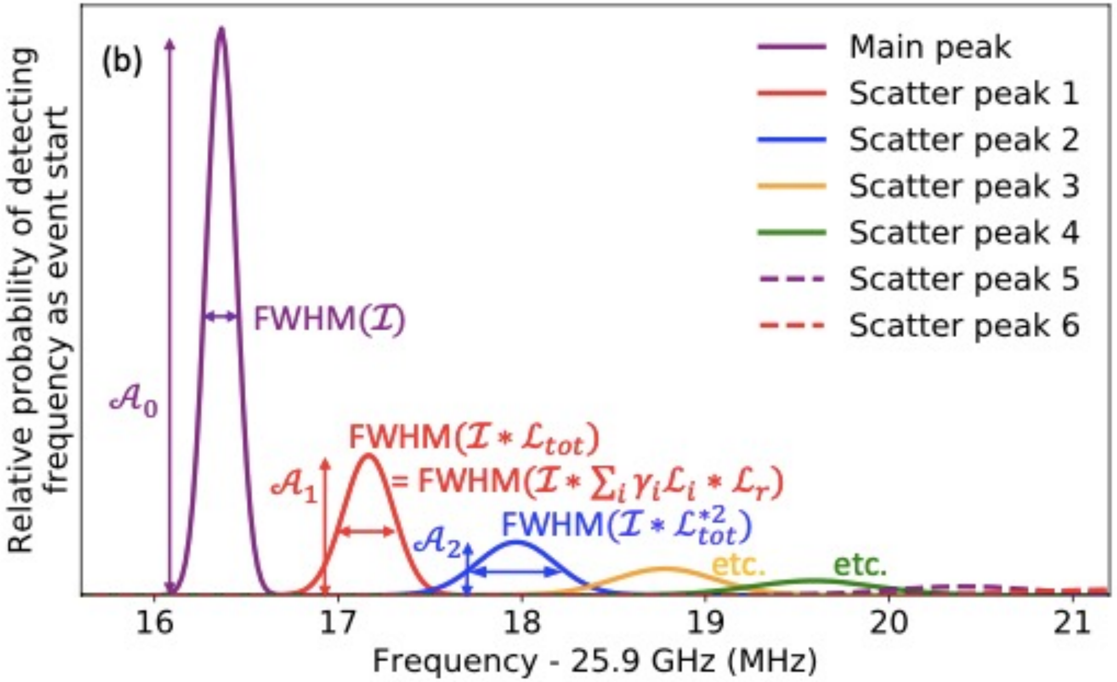
$$\mathcal{R}_{PSF} = \sum_{j=0} \mathcal{A}_j \left(\mathcal{I} * \mathcal{L}^{*j} \right)$$

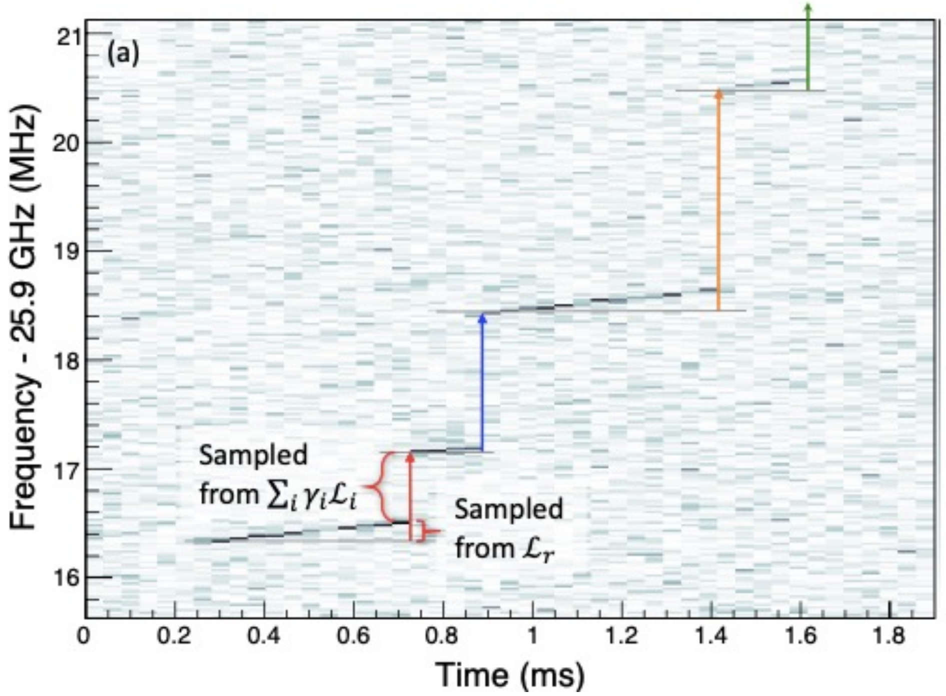




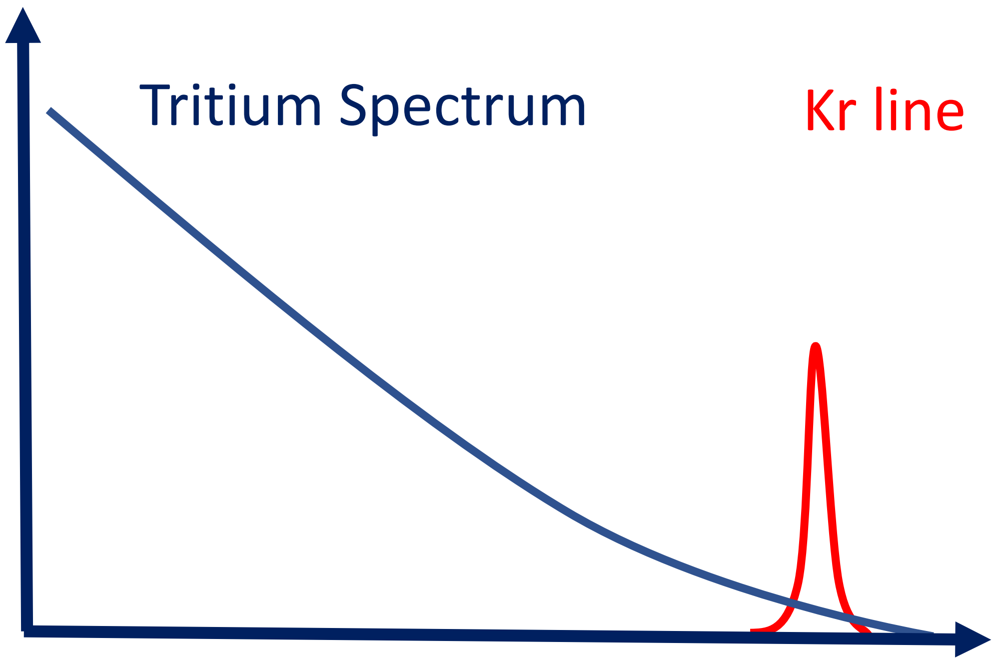
$$\mathcal{R}_{PSF} = \sum_{j=0} \mathcal{A}_j\left(\mathcal{I} * \mathcal{L}^{*j}\right)$$

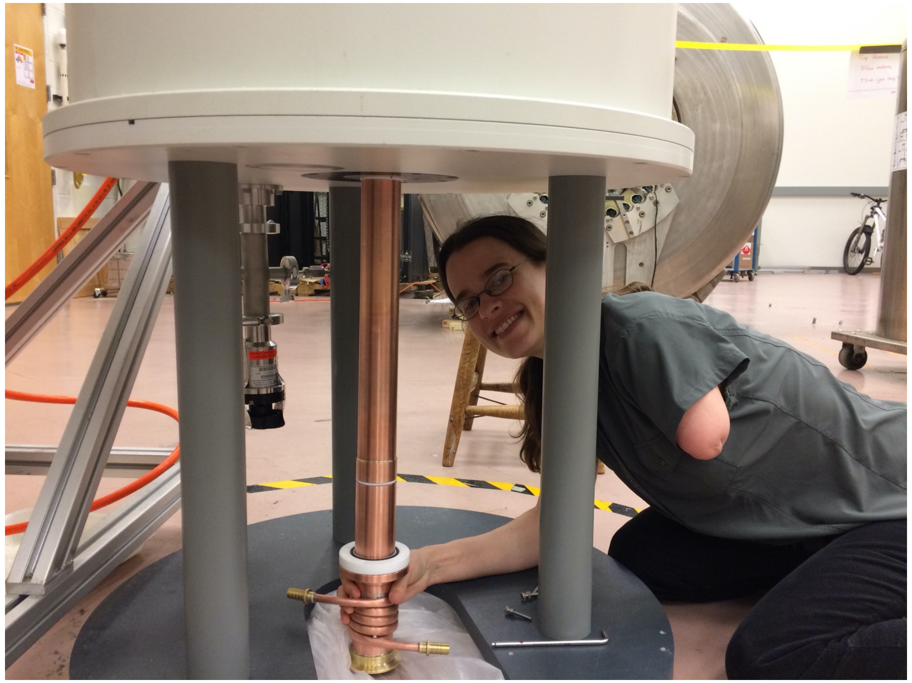
$$\mathcal{L} = (\gamma_1\mathcal{L}_1 + \gamma_2\mathcal{L}_2 + \cdots + \gamma_n\mathcal{L}_n) * \mathcal{L}_r$$



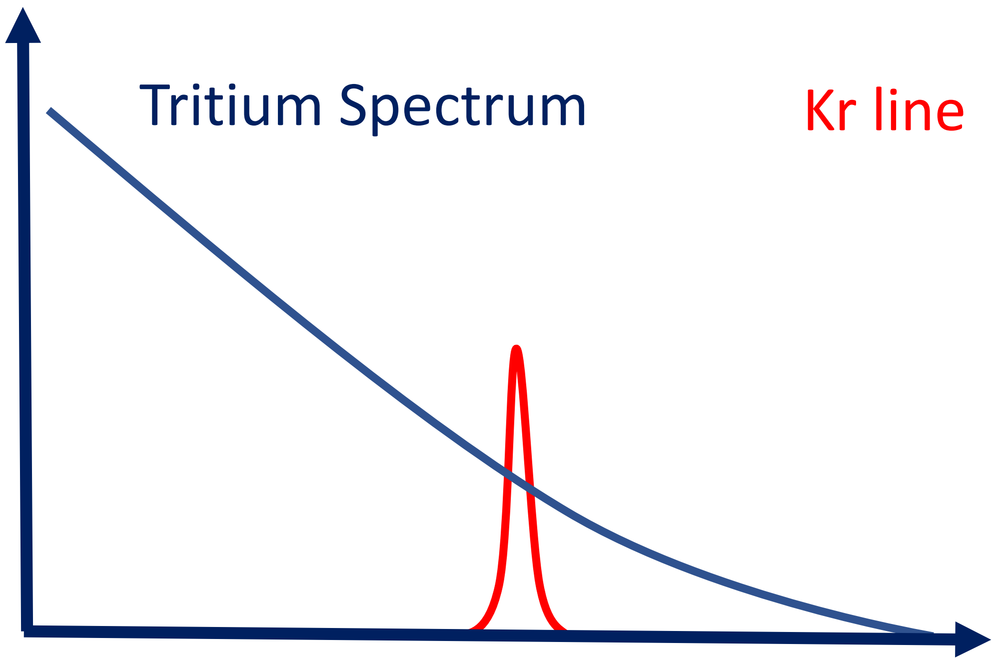


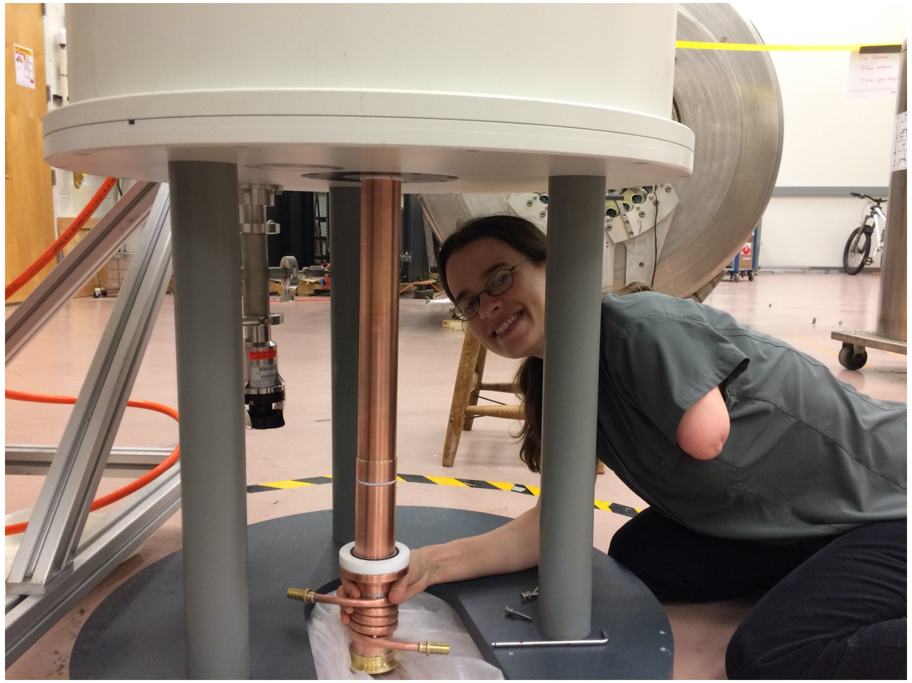
Field shifting solenoid is installed inside the NMR magnet bore to change the field inside the bore and move the krypton K line in the frequency region of interest



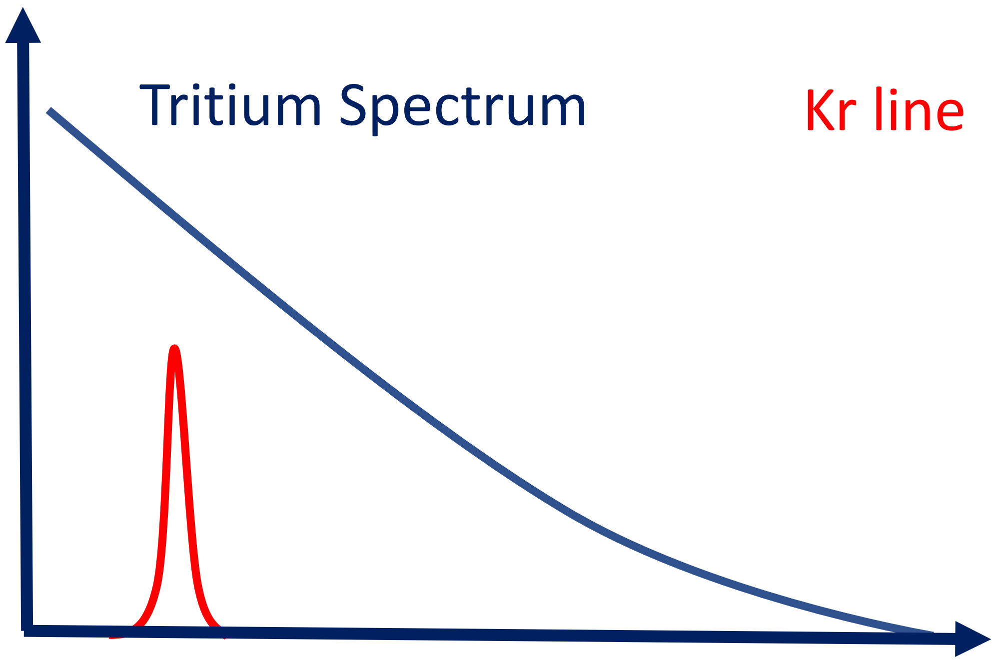


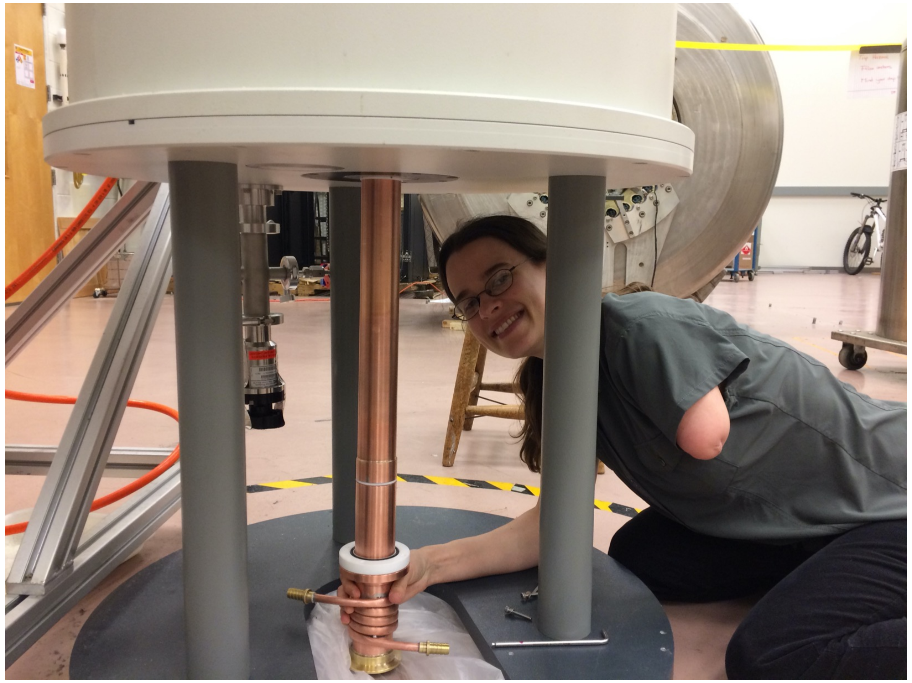
Field shifting solenoid is installed inside the NMR magnet bore to change the field inside the bore and move the krypton K line in the frequency region of interest

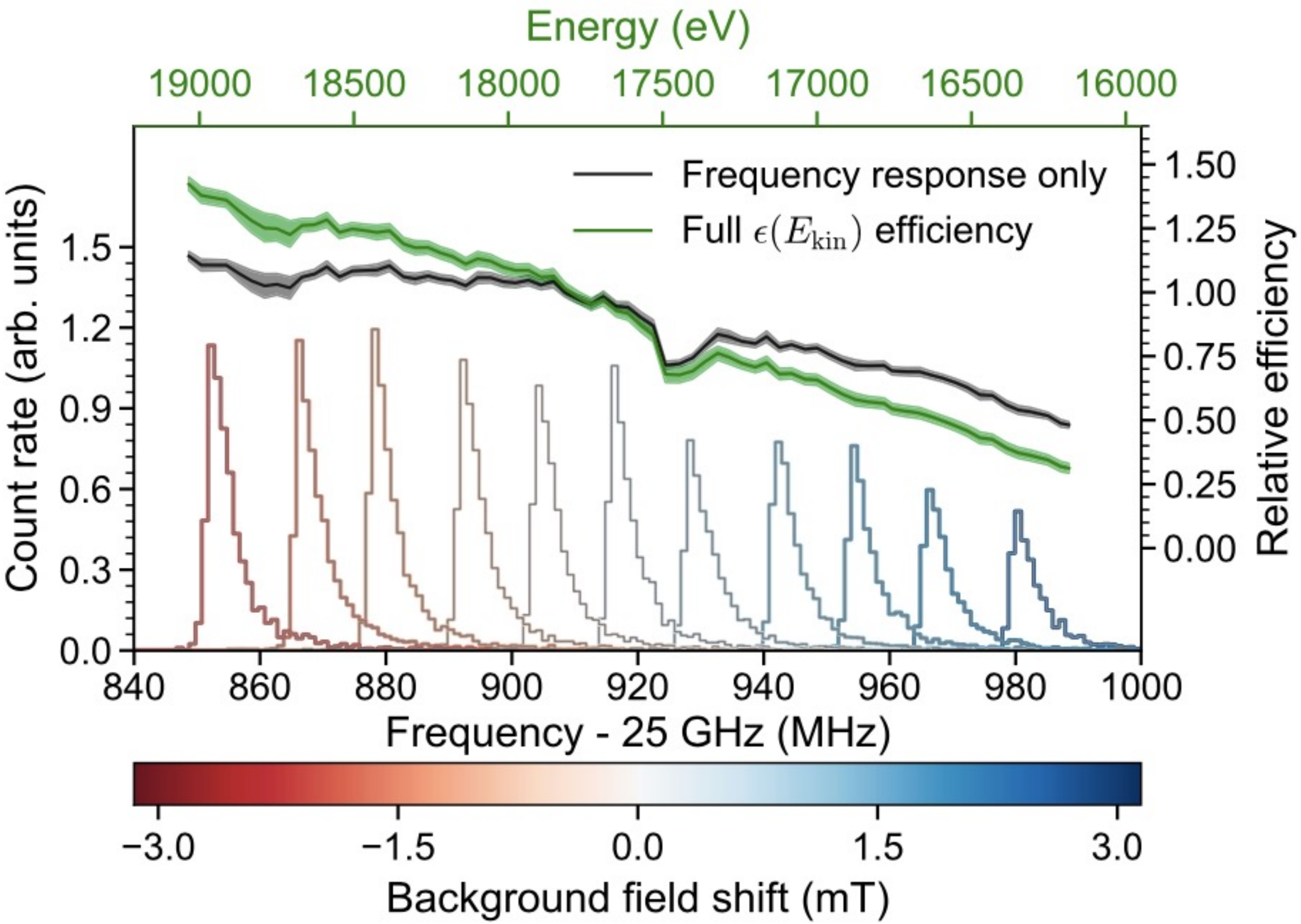




Field shifting solenoid is installed inside the NMR magnet bore to change the field inside the bore and move the krypton K line in the frequency region of interest

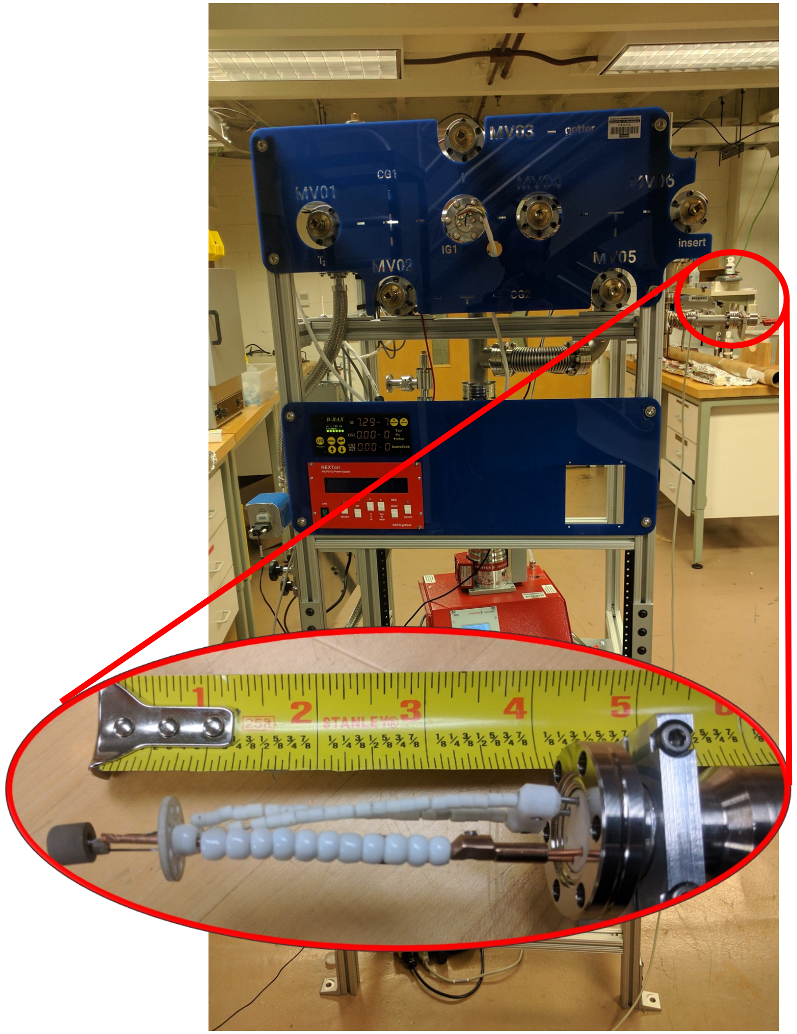





Energy (eV)
19000
18500
18000
17500
17000
16500
16000
Frequency response only
Full $\epsilon(E_{\mathrm{kin}})$ efficiency
Count rate (arb. units)
1.5
1.2
0.9
0.6
0.3
0.0
Relative efficiency
1.50
1.25
1.00
0.75
0.50
0.25
0.00
840
860
880
900
920
940
960
980
1000
Frequency - 25 GHz (MHz)
−3.0
−1.5
0.0
1.5
3.0
Background field shift (mT)

Tritium pressure inside the cell was controlled using a non-evaporable getter

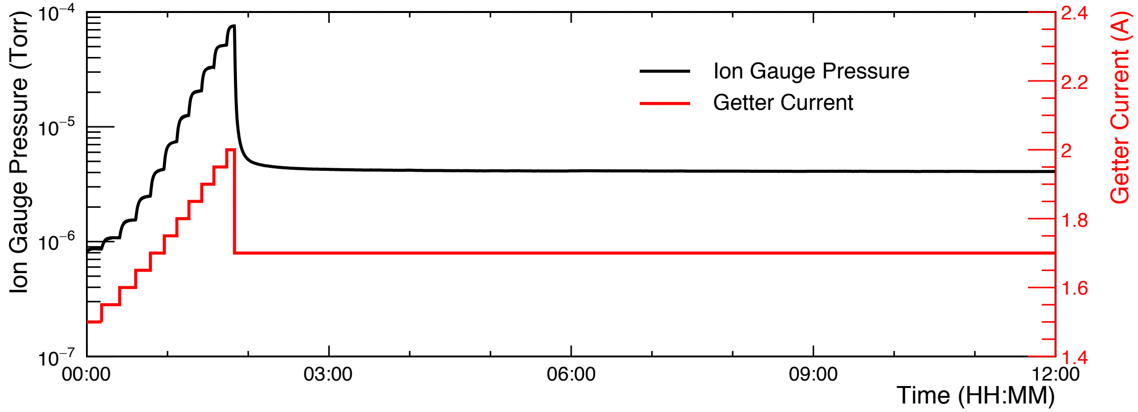
$$H_2 + 2ZrAl \underset{desorption}{\overset{absorption}{\rightleftharpoons}} 2(ZrAl - H)$$

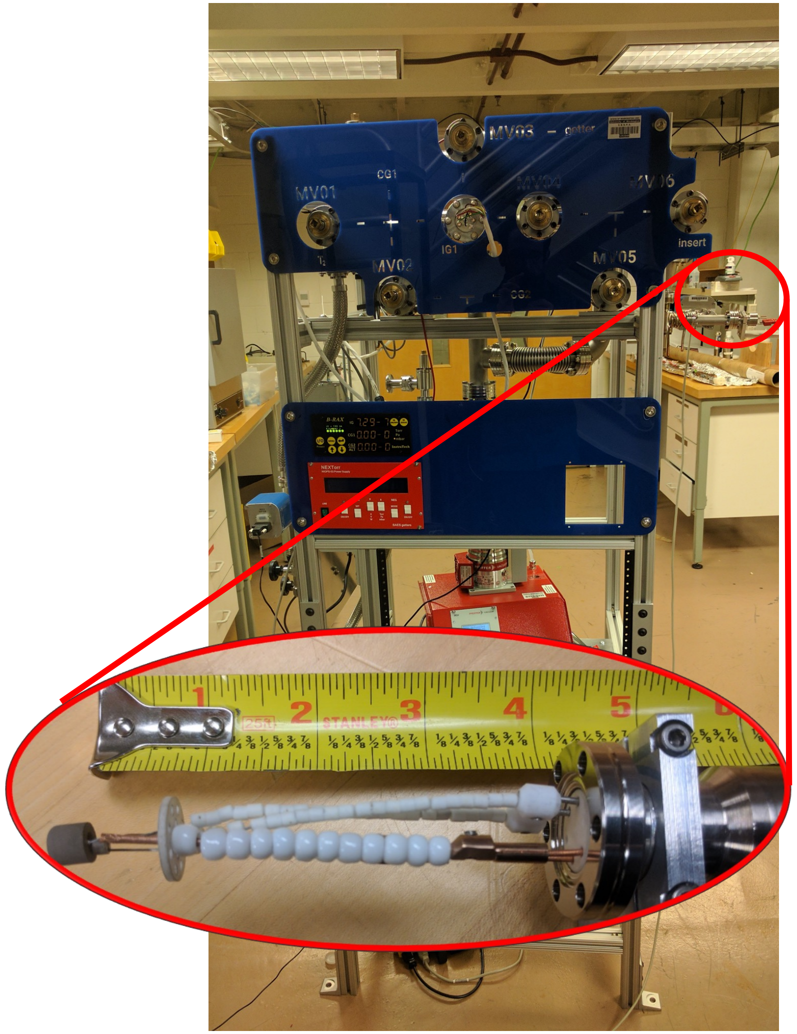


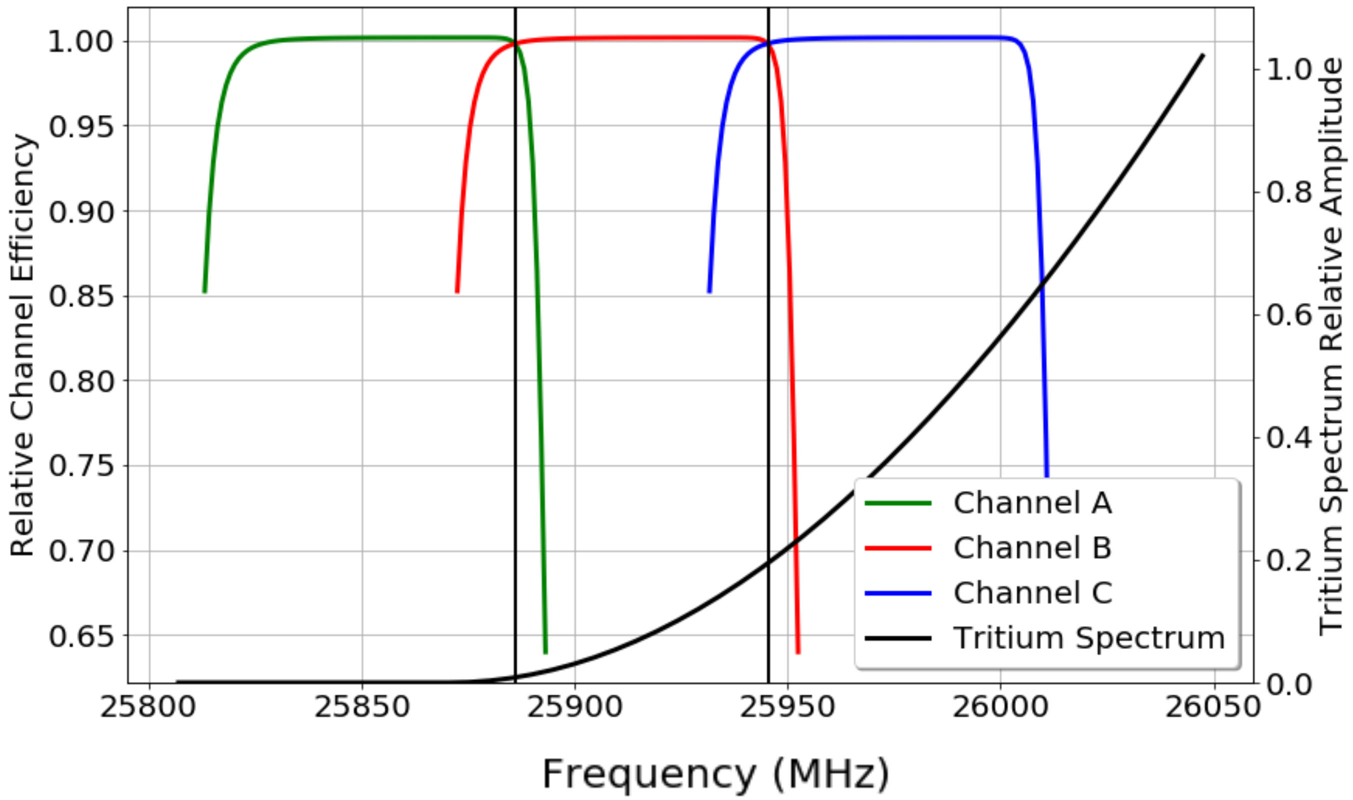
Tritium pressure inside the cell was controlled using a non-evaporable getter

$$H_2 + 2ZrAl \underset{desorption}{\overset{absorption}{\rightleftharpoons}} 2(ZrAl - H)$$

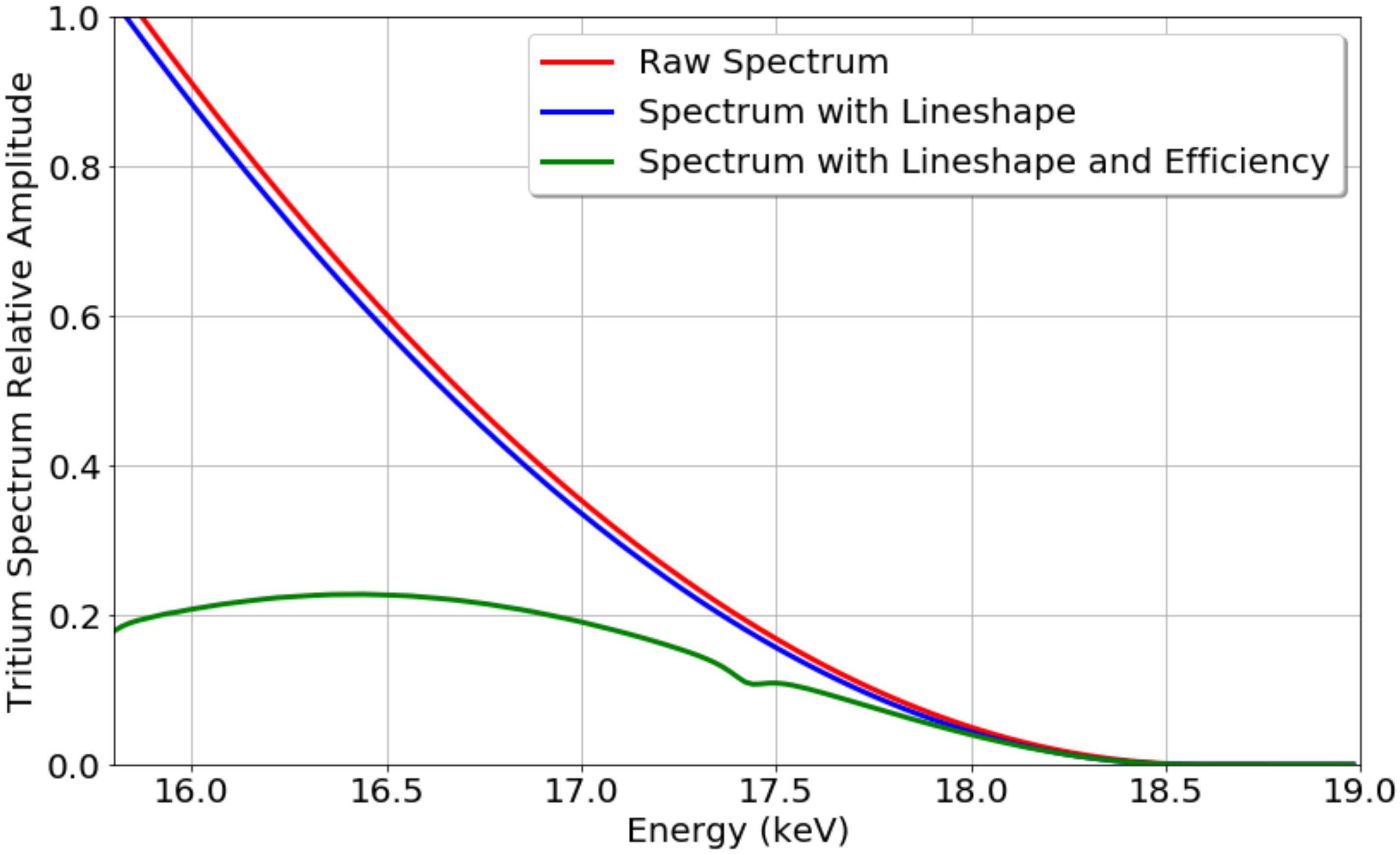
- Continuous pumping of H2, CO, CO2, H2O, CH4
- Pressure Regulation
- Successful test with D_2





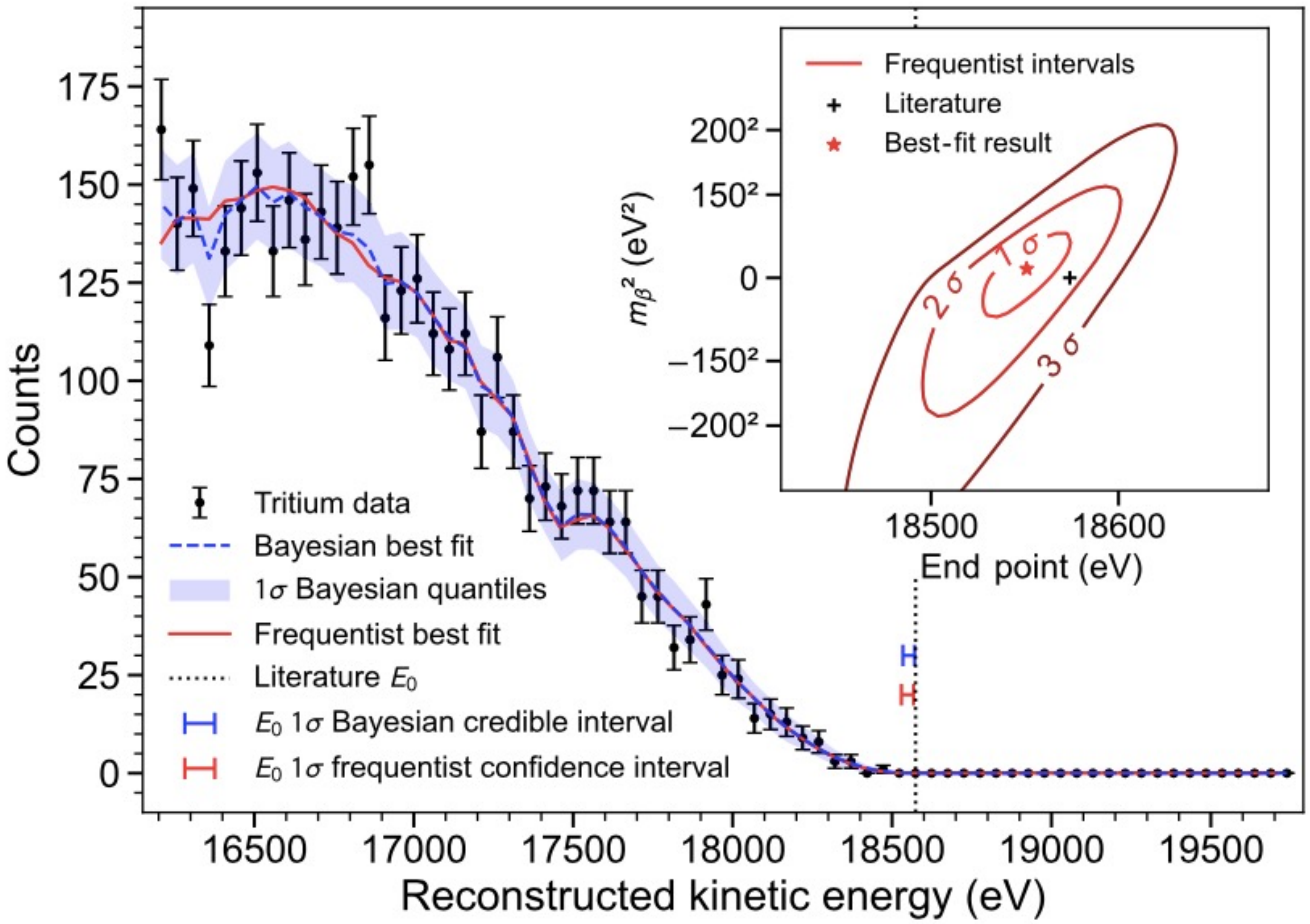


3 DAQ channels were arranged to cover 25810 – 25990 MHz corresponding to 16.2 - 19.8 keV



Expected spectral shape is calculated

$$\mathcal{S} = \epsilon\,(\mathcal{Y} * \mathcal{R}_{PSF})$$



- 3770 distinct tritium events were recorded in 82 days
- No event beyond the endpoint energy
- Frequentist and Bayesian analysis were performed

Endpoint energies agree with the literature value E_0 = 18574 eV

	End point [eV]	m_β limit [eV/c^2]
Bayesian	$18\,553^{+18}_{-19}$	<155
Frequentist	$18\,548^{+19}_{-19}$	<152

Endpoint energies agree with the literature value E_0 = 18574 eV

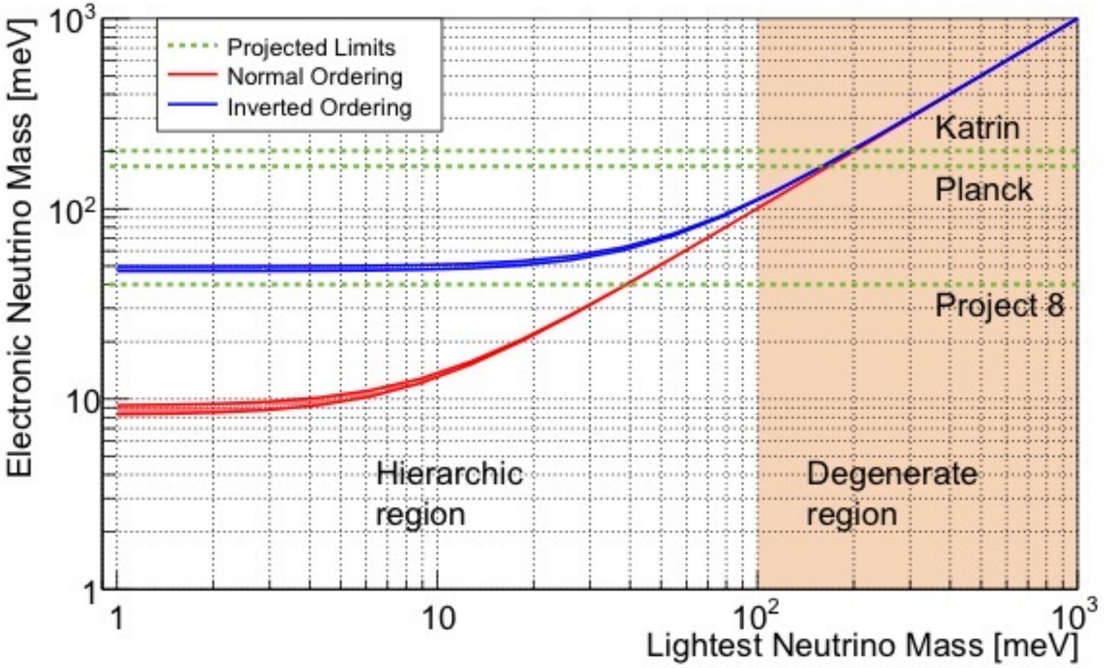
	End point [eV]	m_β limit [eV/c^2]
Bayesian	$18\,553^{+18}_{-19}$	<155
Frequentist	$18\,548^{+19}_{-19}$	<152

Contributions to uncertainty in endpoint energy uncertainty

Uncertainty	Parameters	$\sigma(E_0)$ [eV]
Magnetic field	B	4
Magnetic field broadening	σ	4
Scattering	γ_{H_2}, $\mathcal{A}_j$	6
Efficiency variation	ϵ	4
Other freq. dependence	$\sigma(f_c)$, $\mathcal{A}_j(f_c)$	6
Systematics total		9
Statistical		17

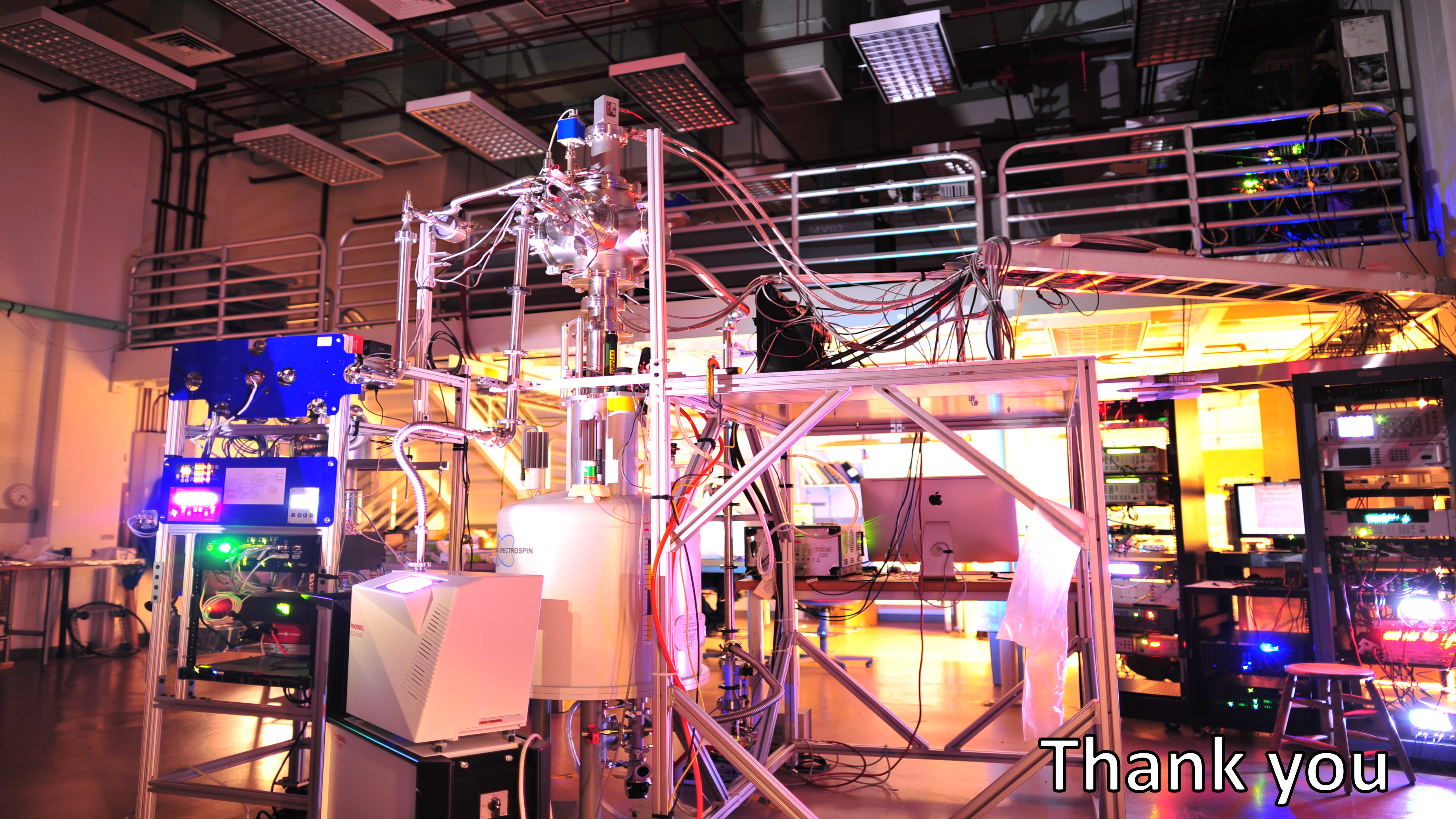
- Phase I
  - First detection of CRES with ^{83m}Kr
- Phase II
  - First continuous spectrum measurement with T_2
- Phase III
  - Atomic source development
  - Large-volume CRES
  - Expected sensitivity $m_\beta \sim 100\ meV$
- Phase IV
  - Neutrino mass measurement if

$$m_\beta < 40\ meV$$



- First frequency-based measurement of tritium beta spectrum were performed

- Cyclotron Radiation Emission Spectroscopy was proved to be a viable technique as the next step in direct neutrino mass measurement with high resolution and low background


SPECTROSPIN
Thank you