PROJECT 8

R&D for a next-generation neutrino mass experiment

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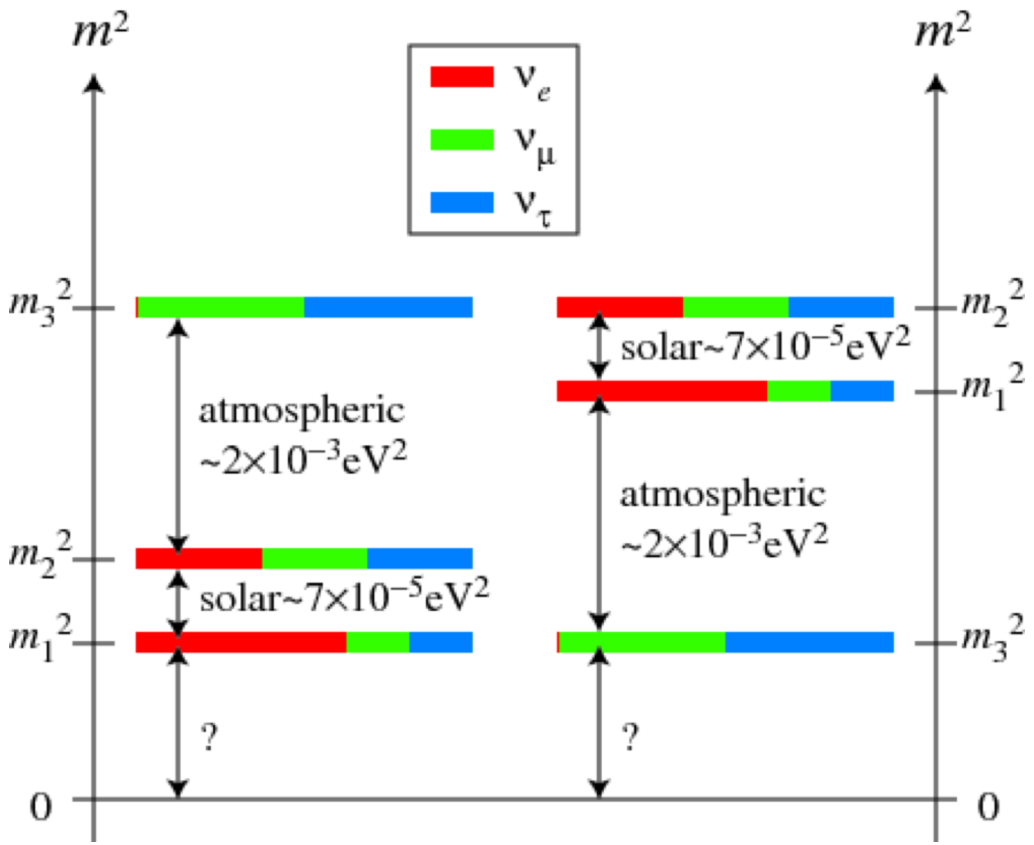
PRiSMA+ Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

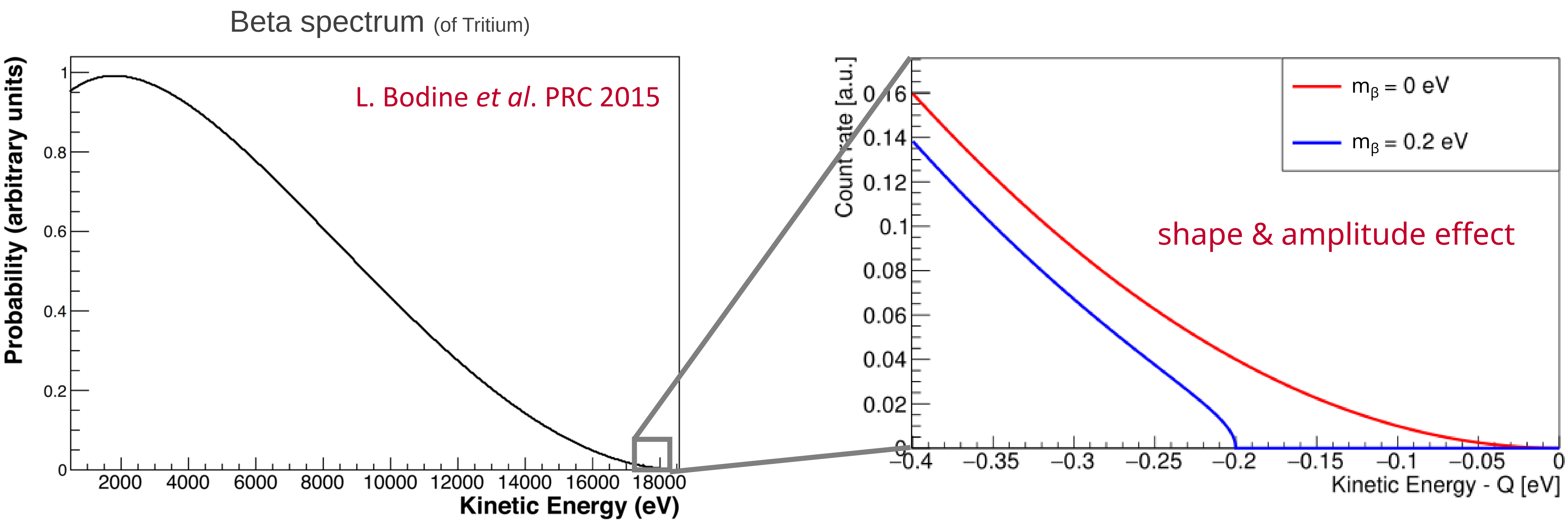
Measuring Neutrino Mass



- Neutrino oscillations provide clear evidence for neutrino mass
- Oscillation measurements only reveal the mass splitting

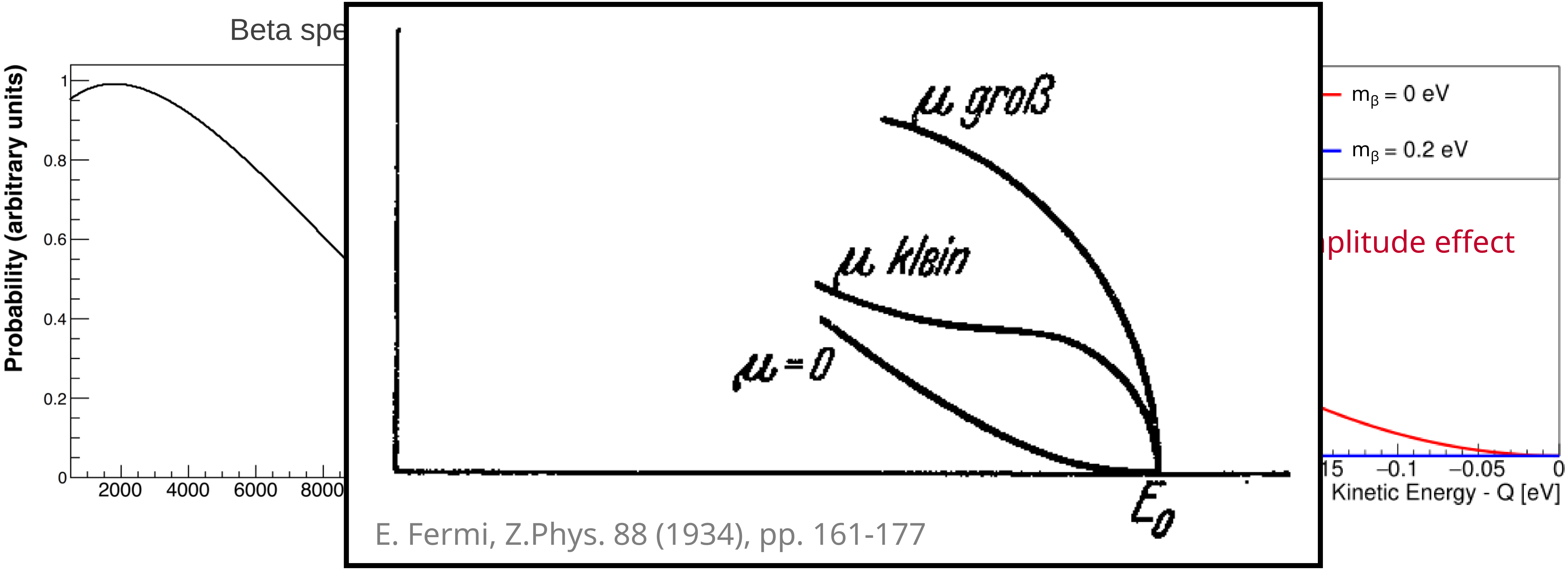
- Measuring the neutrino absolute mass scale requires a different probe
  - Cosmology: $\sum_{i=1}^{3} m_i$
  - 0νββ: $\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$
  - Endpoint measurements: $m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$

Direct Experiments – Endpoint Technique



Effect of neutrino mass alters beta (or electron capture) spectrum near endpoint
No model dependence, pure kinematic effect

Direct Experiments – Endpoint Technique

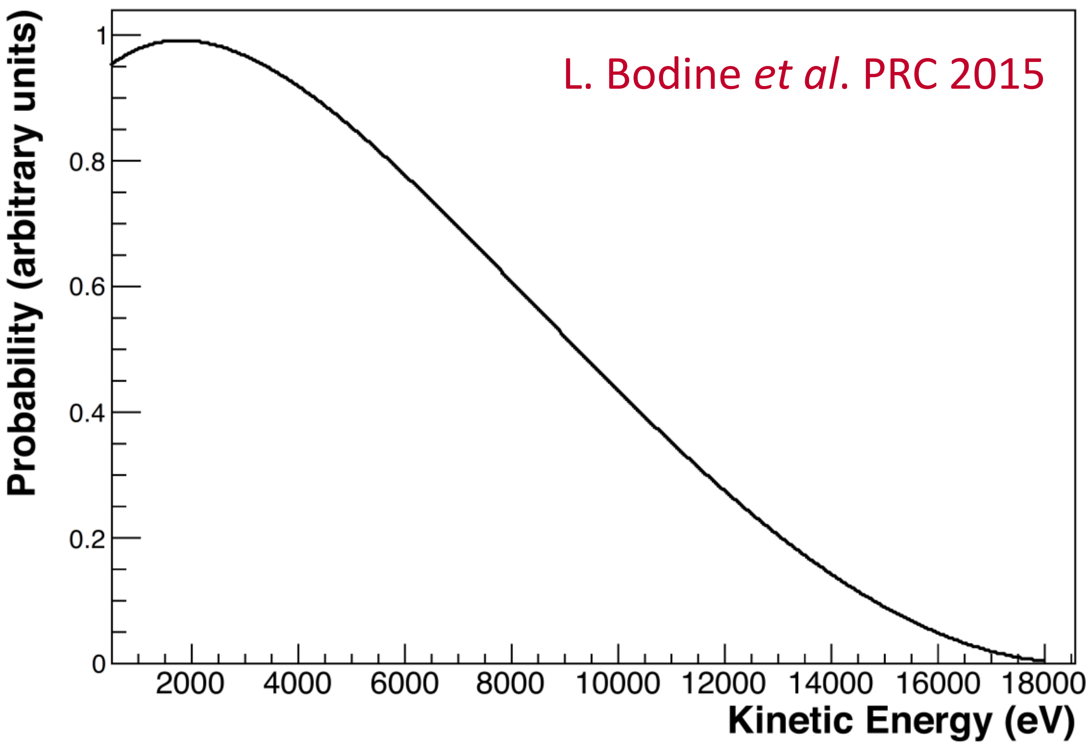


E. Fermi, Z.Phys. 88 (1934), pp. 161-177

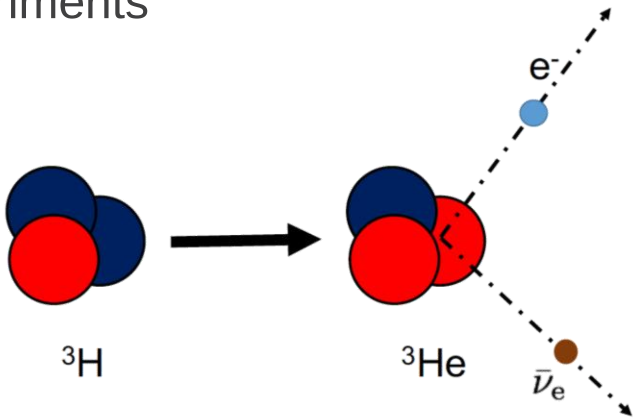
Effect of neutrino mass alters beta (or electron capture) spectrum near endpoint
No model dependence, pure kinematic effect

Direct Experiments – Tritium

Beta spectrum (of Tritium)

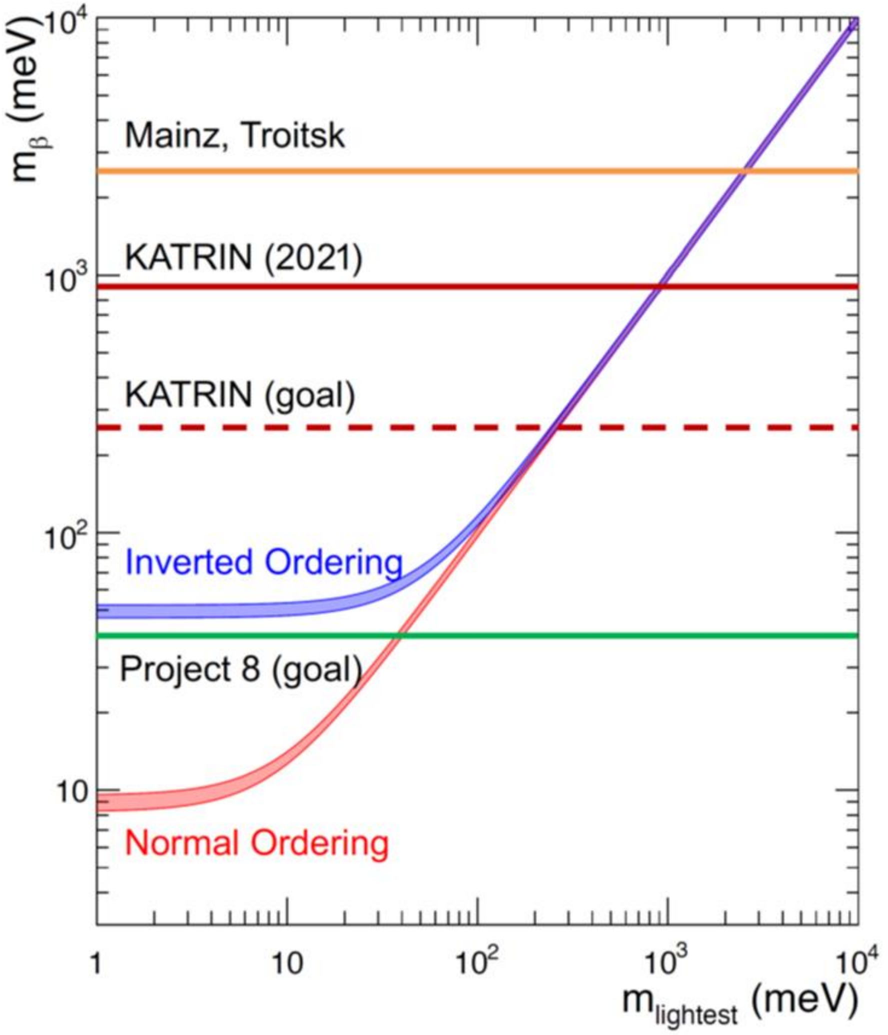


- Tritium is workhorse of direct mass experiments



- ${}^3_1H \rightarrow {}^3_2He^+ + e^- + \bar{\nu}_e$
  - Endpoint: 18.6 keV
  - Half-life: 12.3 yr
  - Superallowed decay

Direct Experiments – Sensitivity



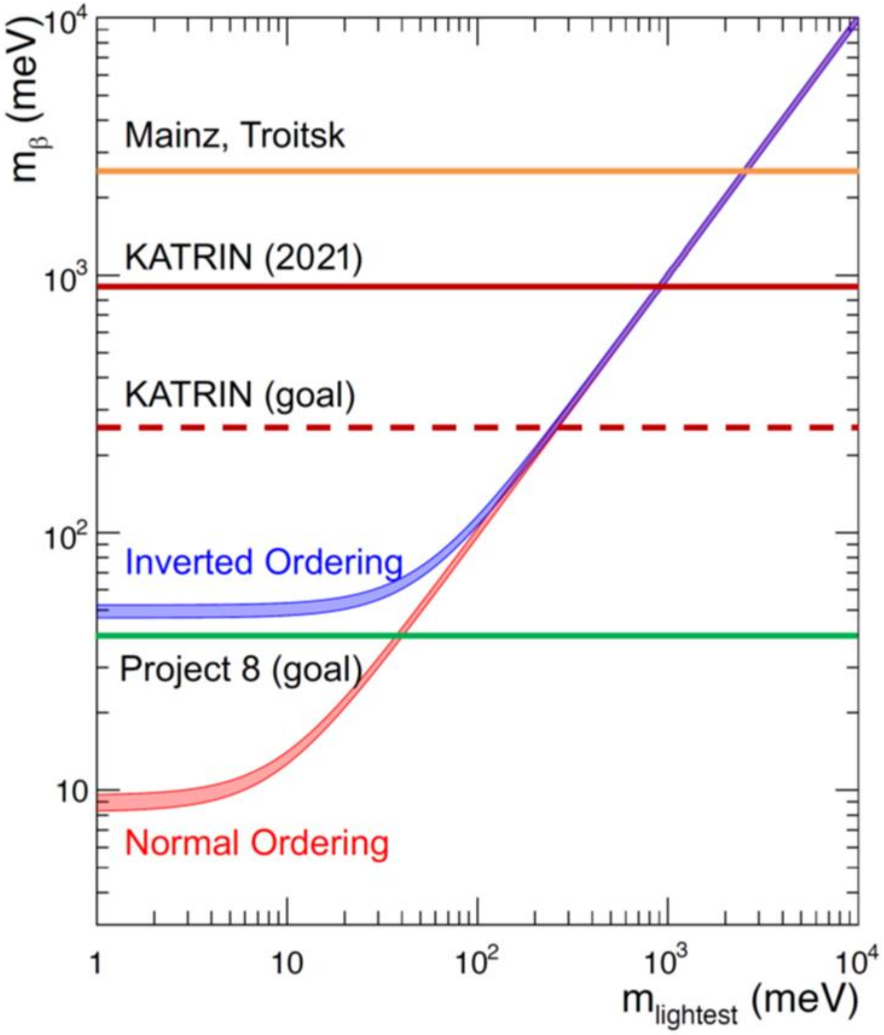
- Direct mass experiment "observable" has minimum possible value

$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

- KATRIN experiment places most stringent limit
  - will continue delivering world-leading sensitivity through its operation

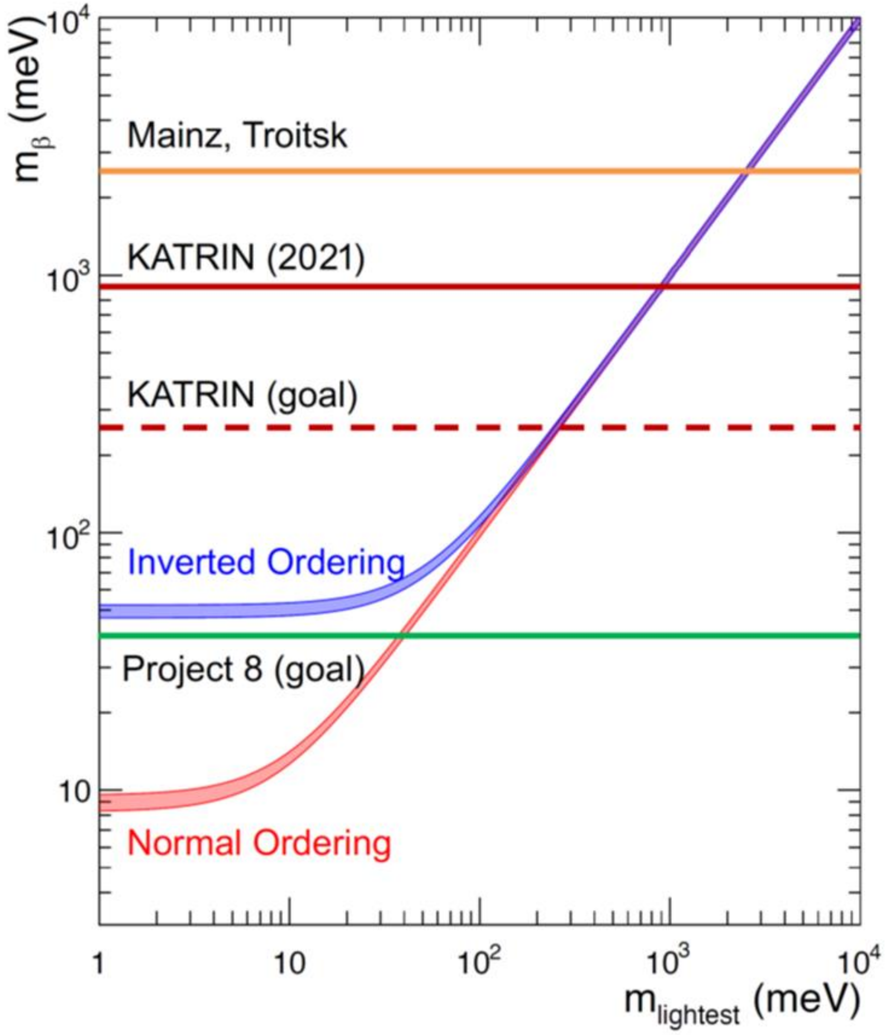
- Project 8 conceived as next-generation experiment to mass range allowed under inverted ordering

Direct Experiments – Challenges

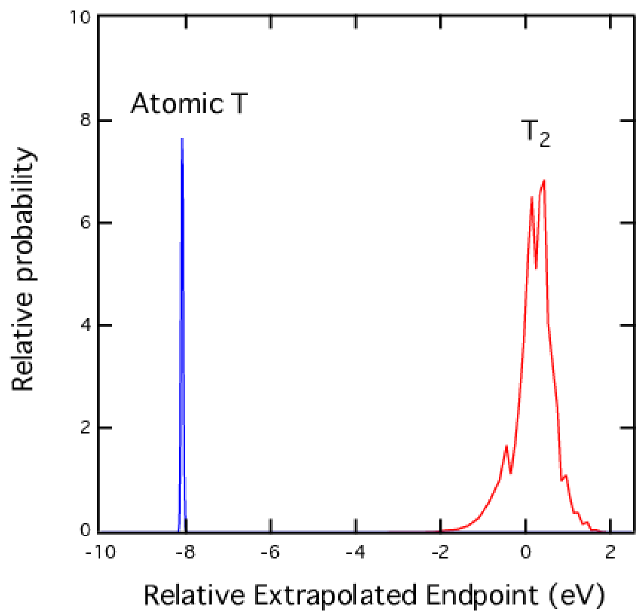


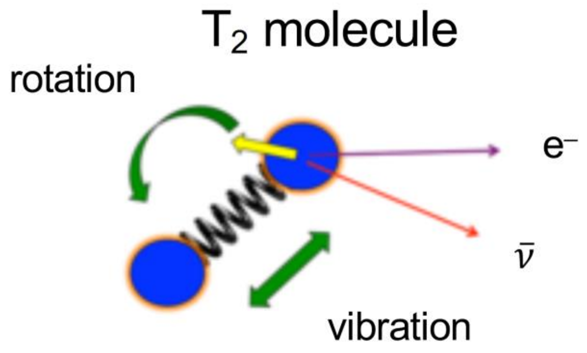
- Statistical sensitivity to m_β scales as $\sim 1/N^{1/4}$
- Existing detector technology reached limit of scalability

Direct Experiments – Challenges



- Statistical sensitivity to m_β scales as ~$1/N^{1/4}$
- Existing detector technology reached limit of scalability
- Irreducible systematics: molecular final states at ~100 meV



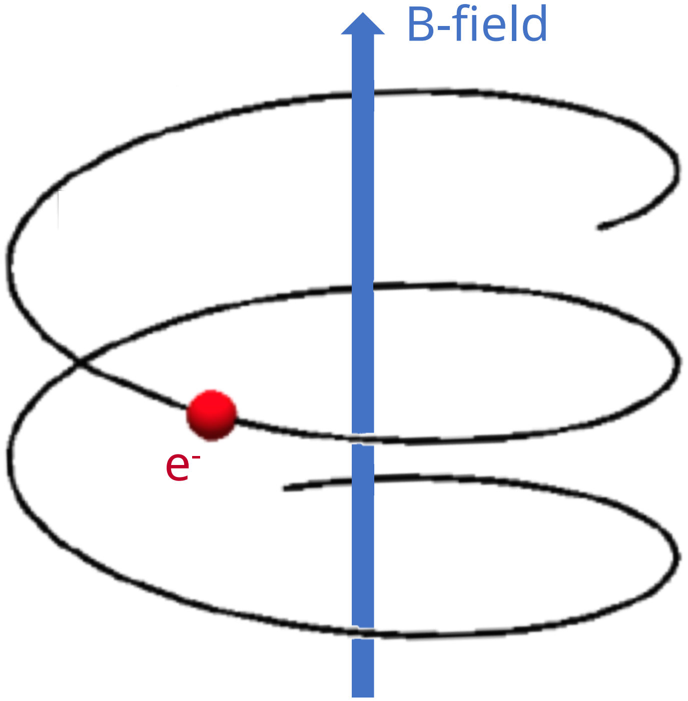


Cyclotron Radiation Emission Spectroscopy

- Using frequency-energy relation for relativistic electrons

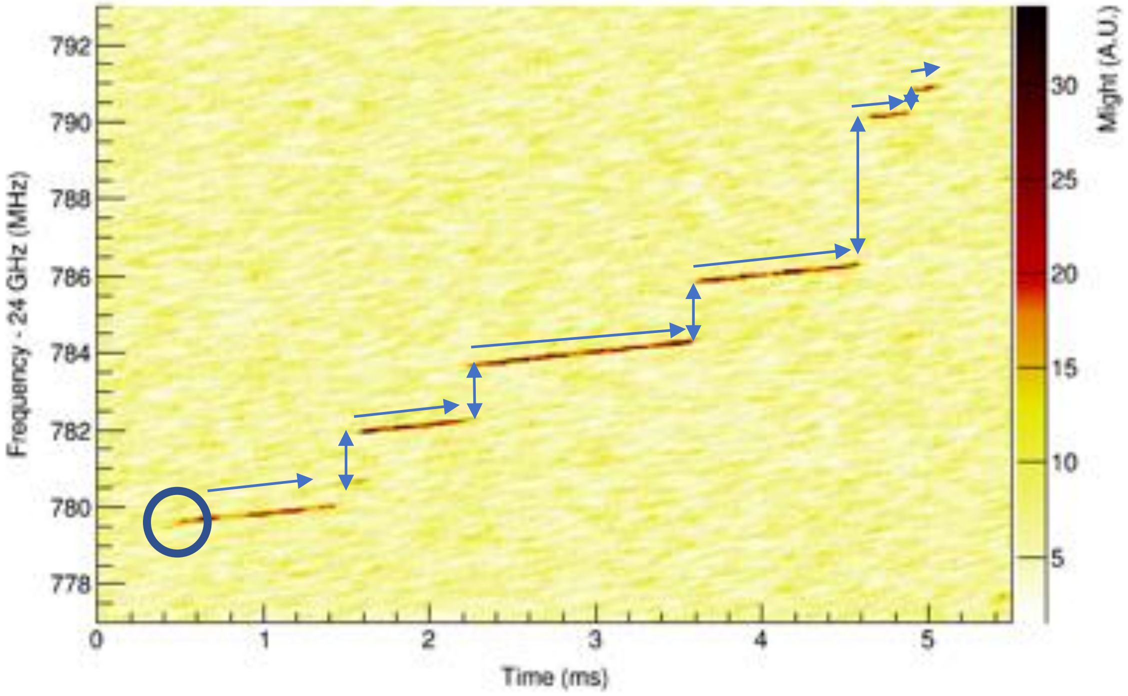
$$\underbrace{f_c}_{25.9\text{ GHz}} = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi}\frac{e\overbrace{B}^{1\text{ T}}}{m_e + \underbrace{E_{\text{kin}}/c^2}_{18.6\text{ keV}}}$$

- Frequency measurement
  → high precision
- Source volume is detector volume
  → transparent to own microwave radiation
  → no transport → volume scaling
- Differential spectrometer
  → increased statistical efficiency
- Compatible with atomic tritium
  → avoids final-state spectral broadening of T_2



radiated power: 1fW @ 25 GHz
→ challenging to detect

Observation of single CRES signal



- Spectrogram of detected RF power
- Single electron signal
  - High power bins
- Start frequency
  - Kinetic birth energy of electron
- Cyclotron radiation loss
  - Slow chirp
- Collisions off residual gas
  - Abrupt energy loss
  - Change of direction
- Electron trapped for long observation time

Project 8: Phased Approach

2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027

Phase I

→ Single-electron detection; spectroscopy
→ ^{83m}Kr conversion-electron spectrum

First CRES demonstration: PRL 114: 162501, 2015
~eV Resolution J. Phys. G. 44, 2017
Machine learning: New J. Phys. 22 (2020)

Phase II

→ Systematic & background studies
→ T_2 spectrum and endpoint measurement

Phenomenology: Phys. Rev. C. 99 (2019) 055501
RF simulation: New J. Phys. 21 (2019) 113051

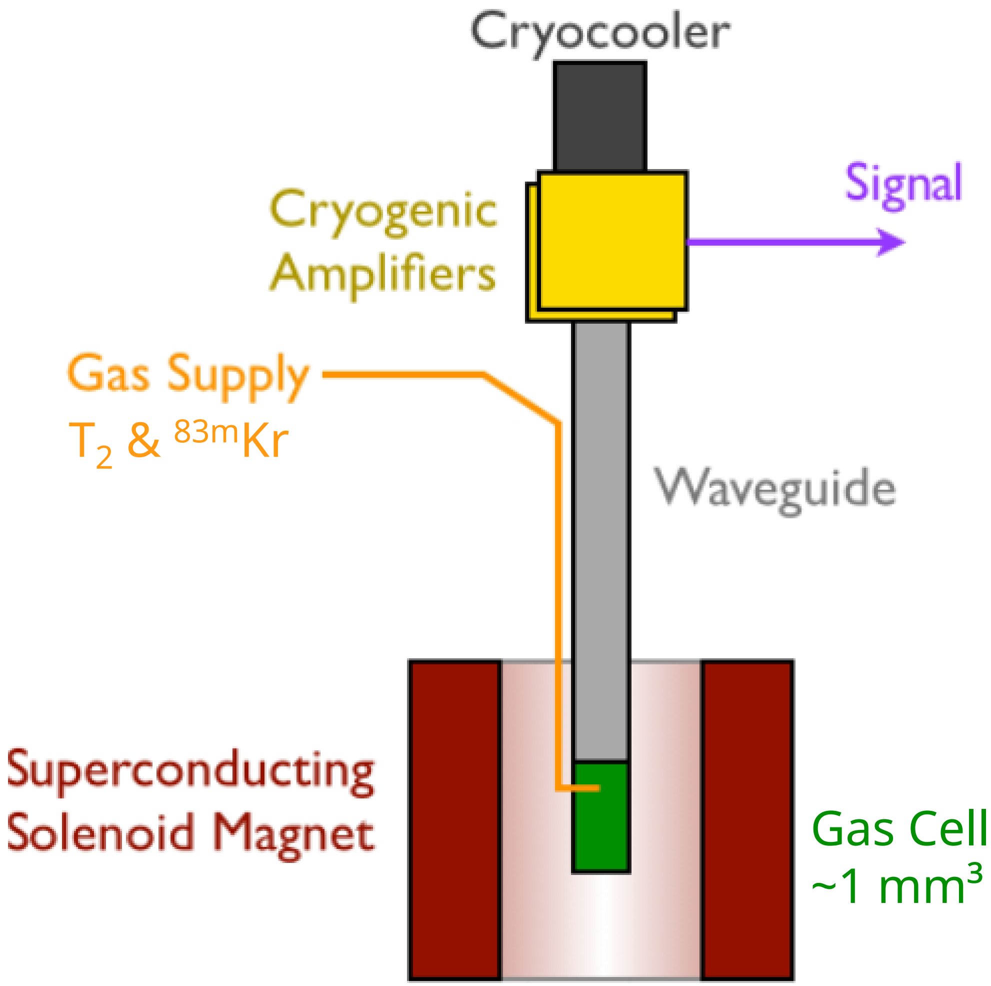
Phase III R&D **Phase III**

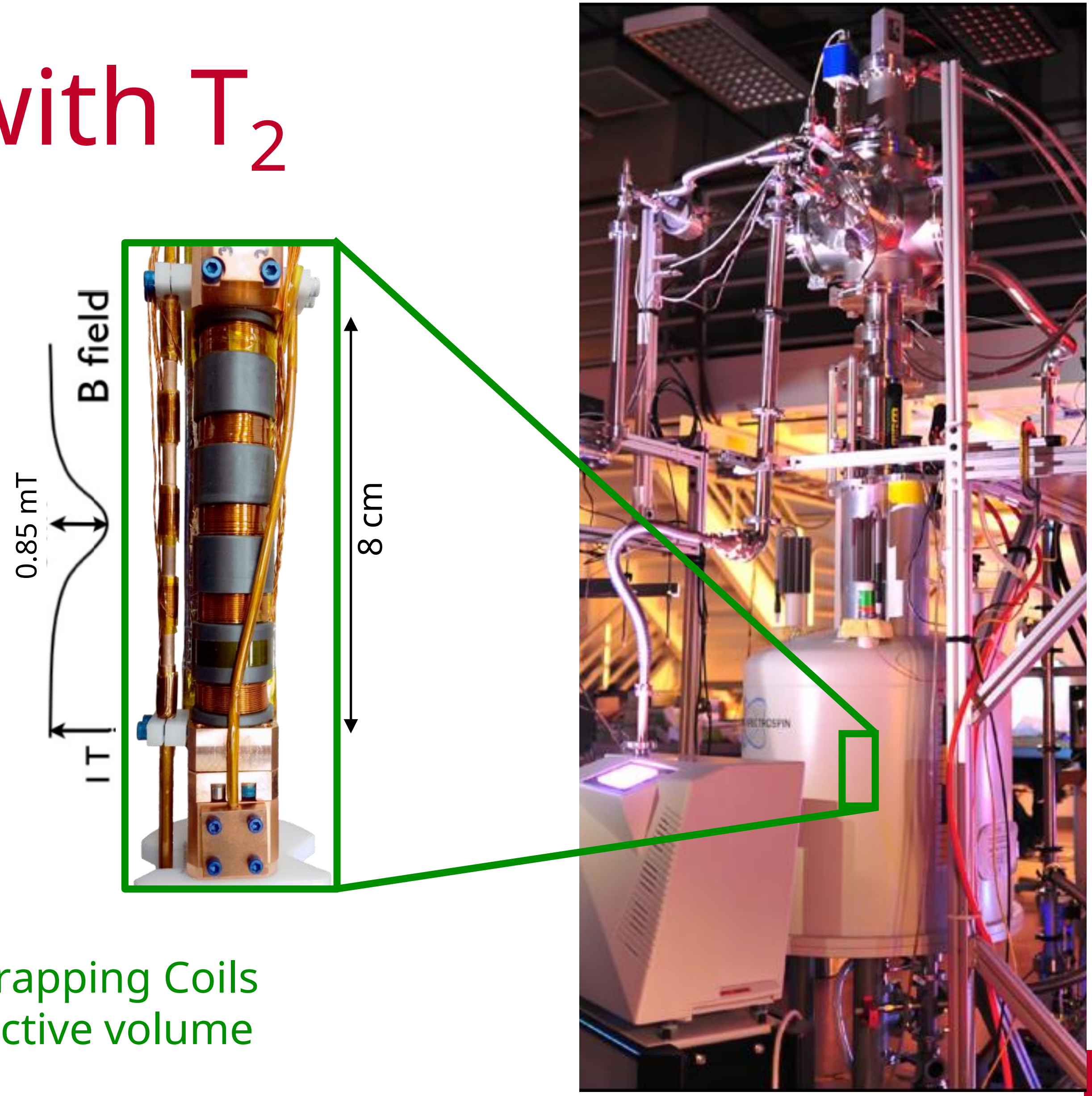
→ ≈10-100s cm^3 volume; free-space detection with antenna array; m_β < 5 eV/c^2
→ Demonstration of atomic tritium production, cooling, and trapping

Phase IV

→ m_β < 40 meV/c^2
→ Mass hierarchy

First CRES setup with T_2





Gas Cell & Trapping Coils
~1 mm^3 effective volume

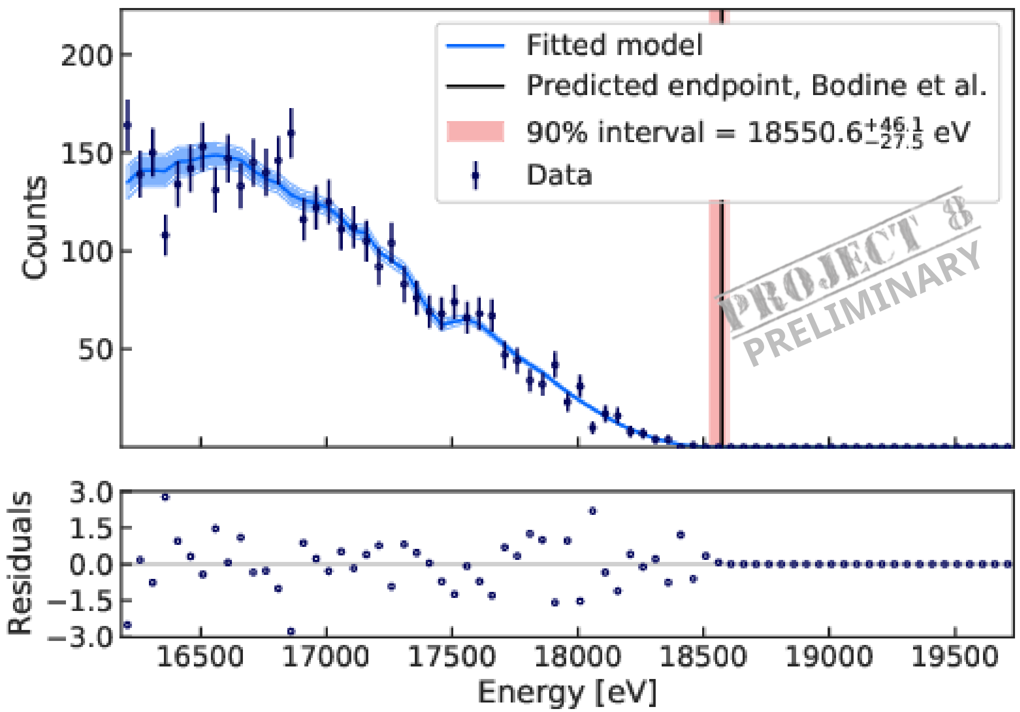
Preliminary T_2 results

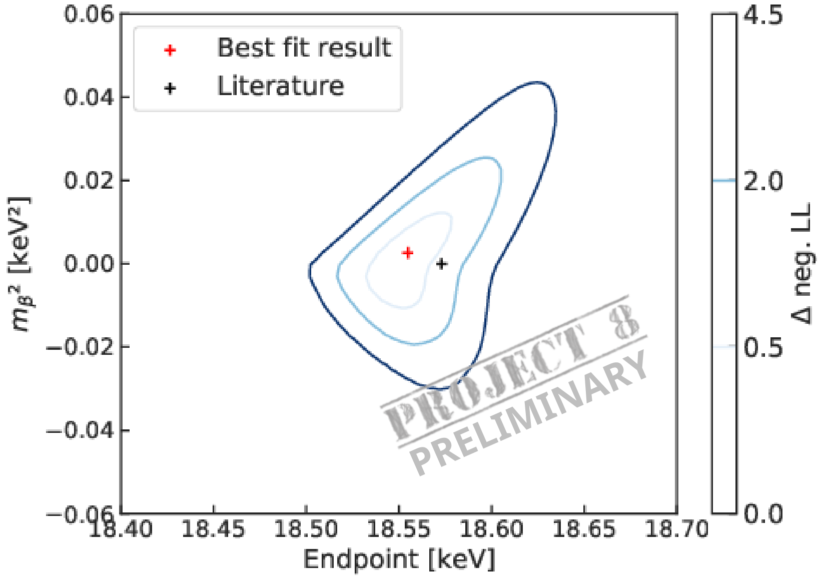
Frequentist and Bayesian analysis

Instrumental resolution
Scattering effects
Detection efficiency (frequency)
Calibrated using ^{83m}Kr

Analysis is being finalized

T_2 endpoint	$18550.6^{+46.1}_{-27.5}$ eV	(90% CL)
Background rate	≤ 3×10^{-10} $eV^{-1}s^{-1}$	(90% CL)
Neutrino mass	≤ 185 eV/c^2	(90% CL)





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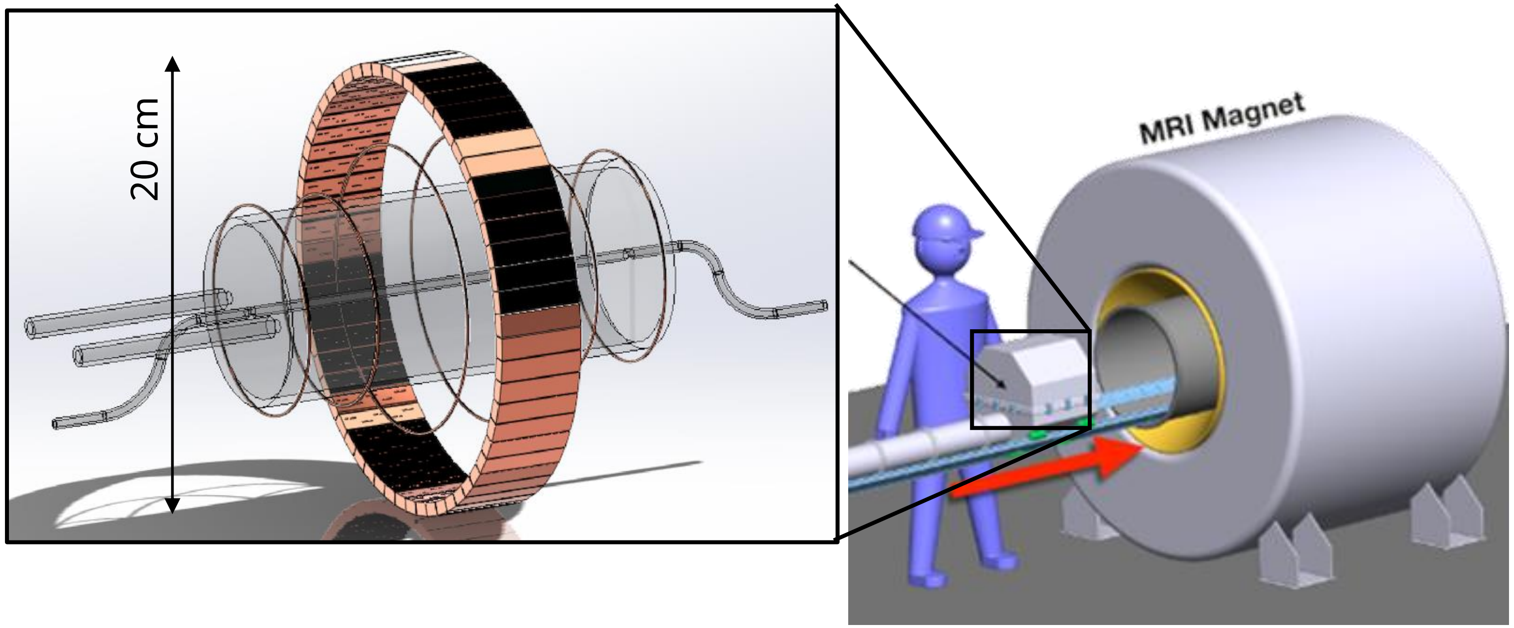
→ Mass hierarchy

Scale up CRES technique

Phase II Setup

- Waveguide
- ~ 1 mm^3 effective volume

Free Space CRES Demonstrator



- Antenna array → CRES in free space
- 10-100 cm^3 effective volume

R&D for Free Space CRES Demonstrator

Antenna design

Low noise amplifiers

Magnetic field / trap design

Simulation of CRES

Triggering and reconstruction

Calibration concepts

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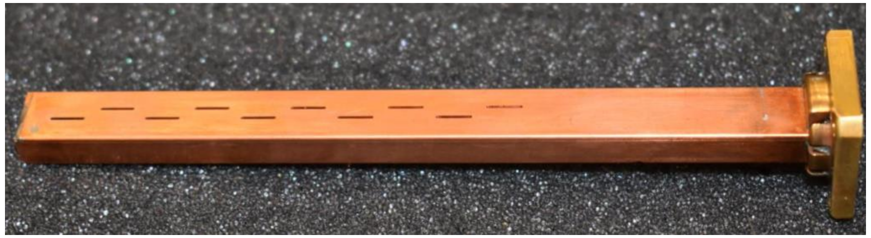
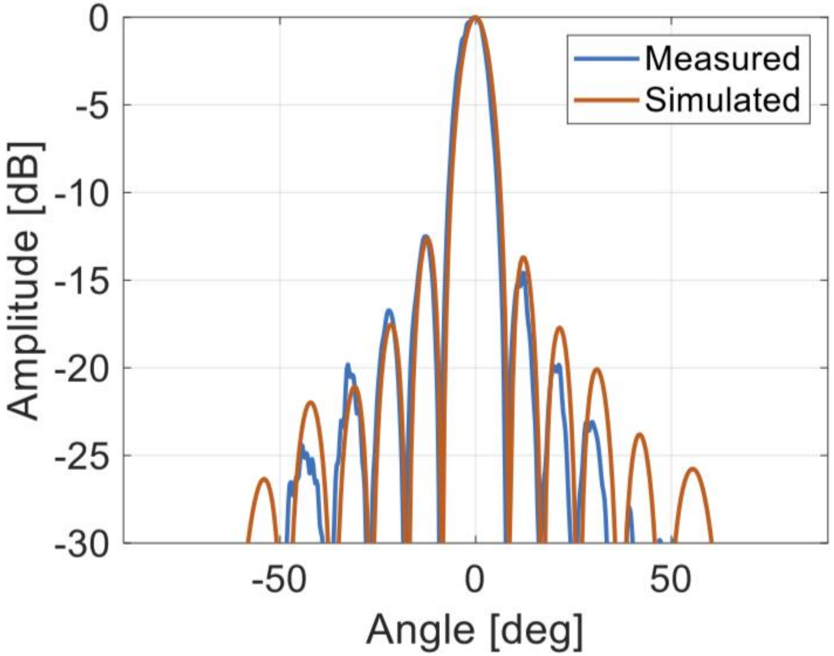
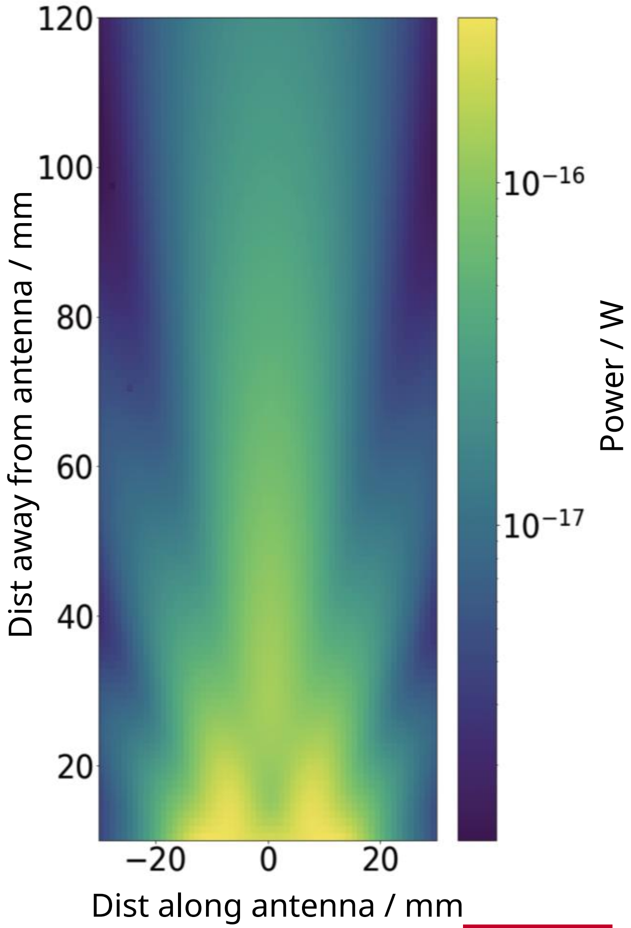






R&D for Free Space CRES Demonstrator

Antenna design

Low noise amplifiers

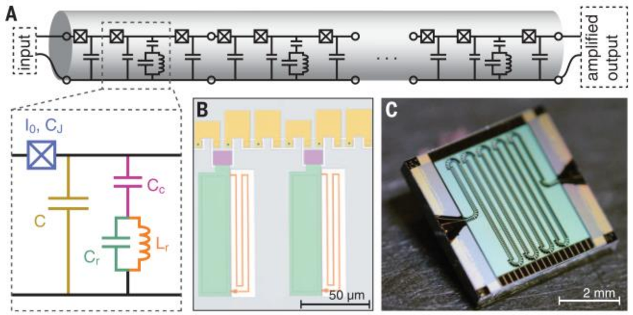
Magnetic field / trap design

Simulation of CRES

Triggering and reconstruction

Calibration concepts

- Josephson Traveling Wave Parametric Amplifier
- Superconducting
- Near quantum-noise limited
- High gain over broad frequency range (~20 dB over ~2 GHz)



Science 350,6258(2015)

- JTWPA for Project 8
  - Performance of 26 GHz JTWPA unknown
  - Multiplexing (not validated >10 GHz)
  - Magnetic fields
  - Operating temperatures

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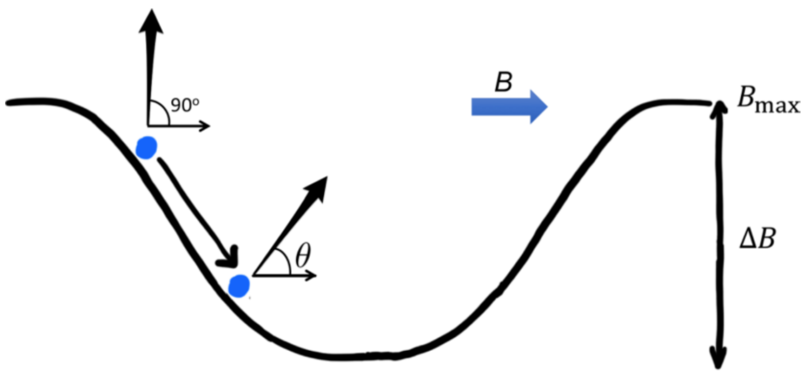
Calibration concepts



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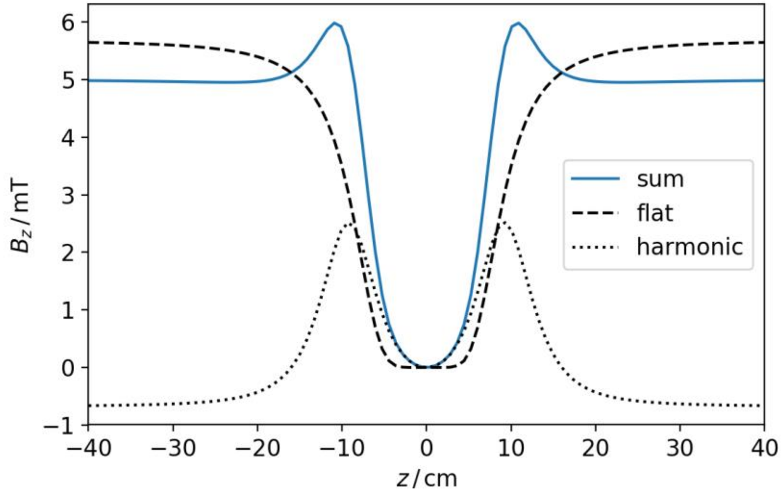

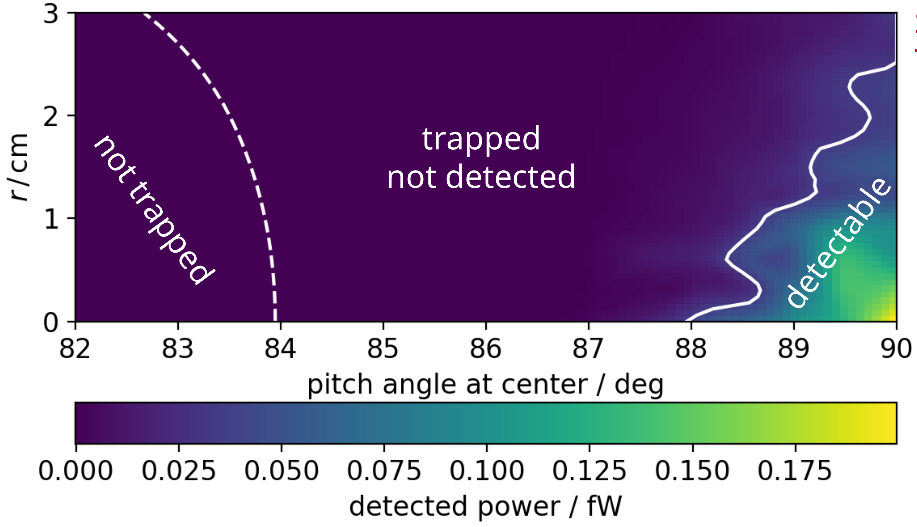

SNR=10 dB
T_{noise}=10 K

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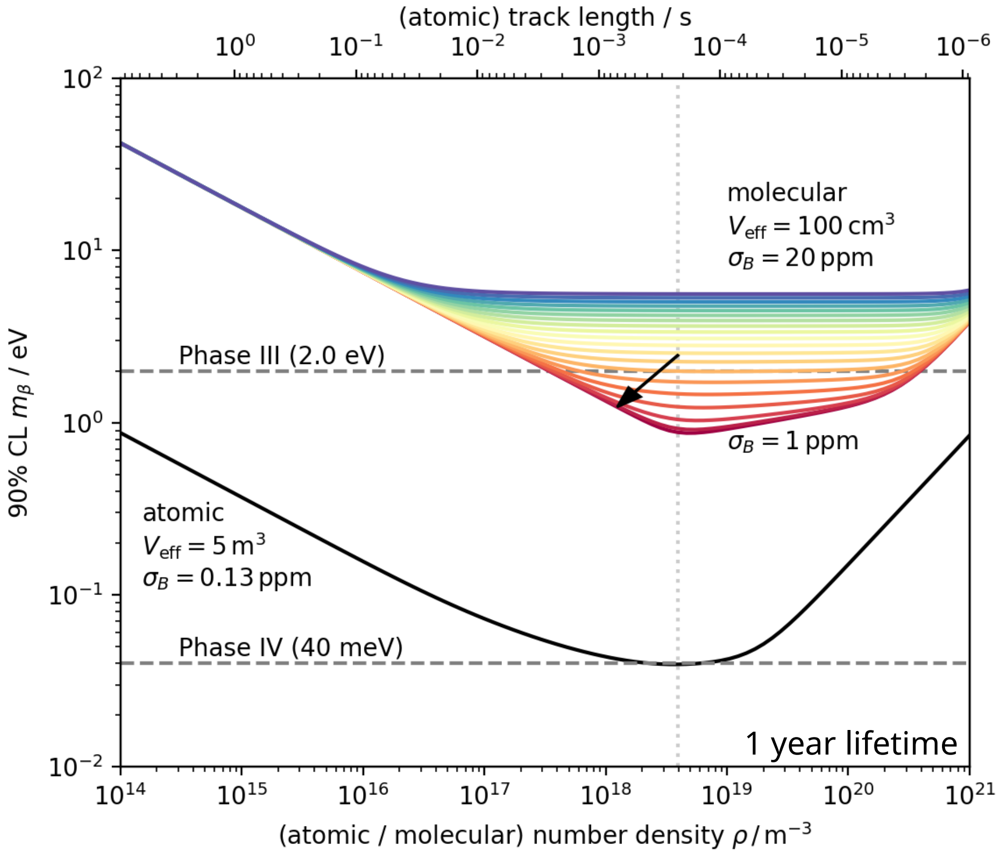

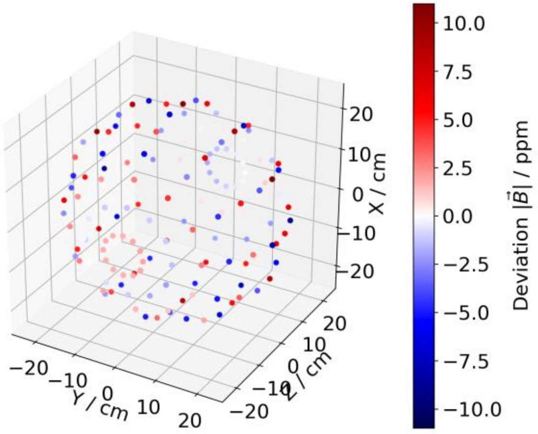

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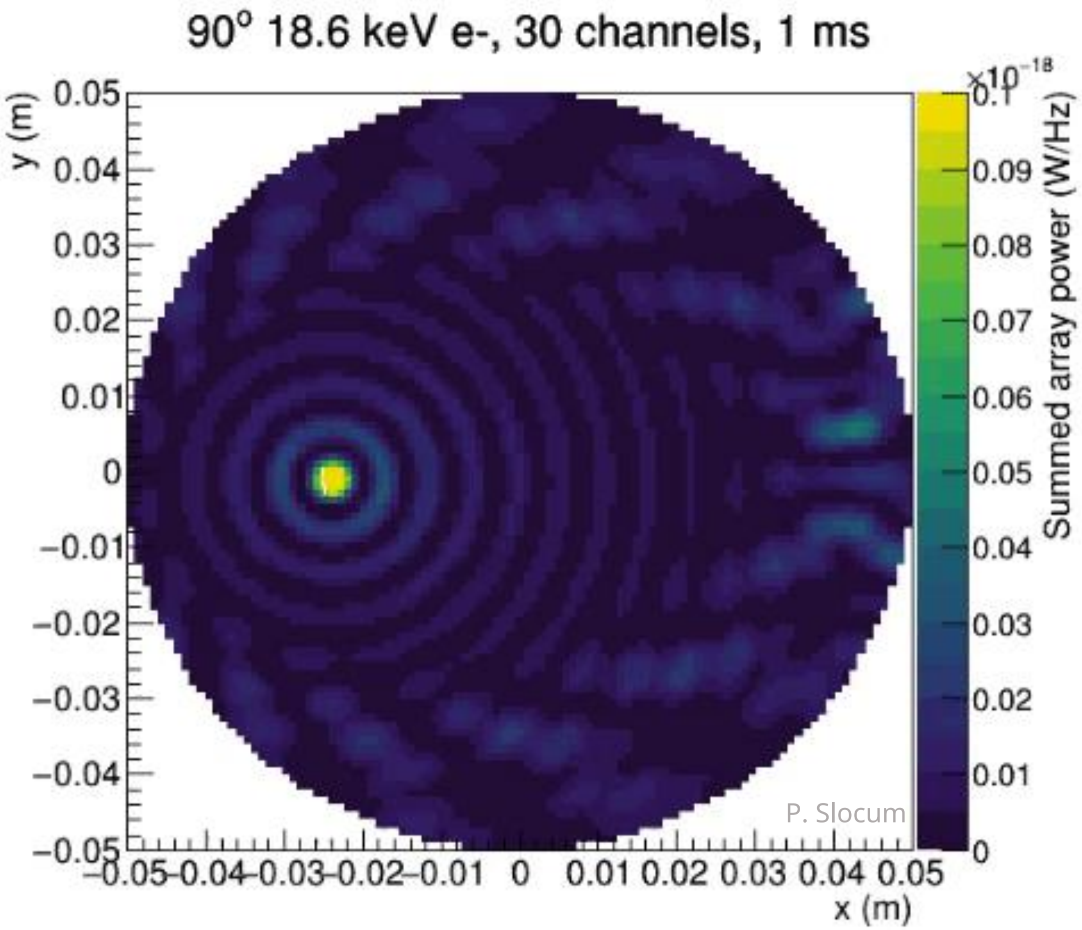

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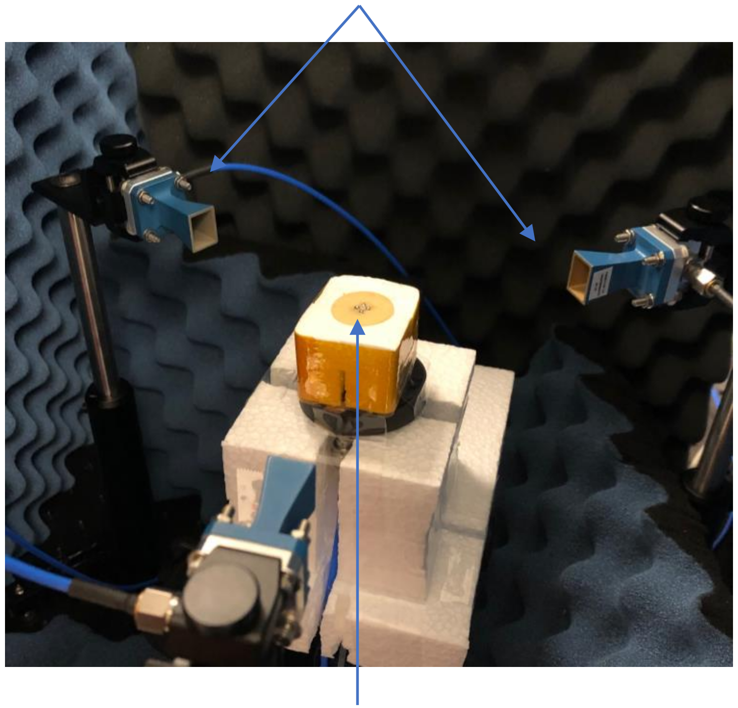

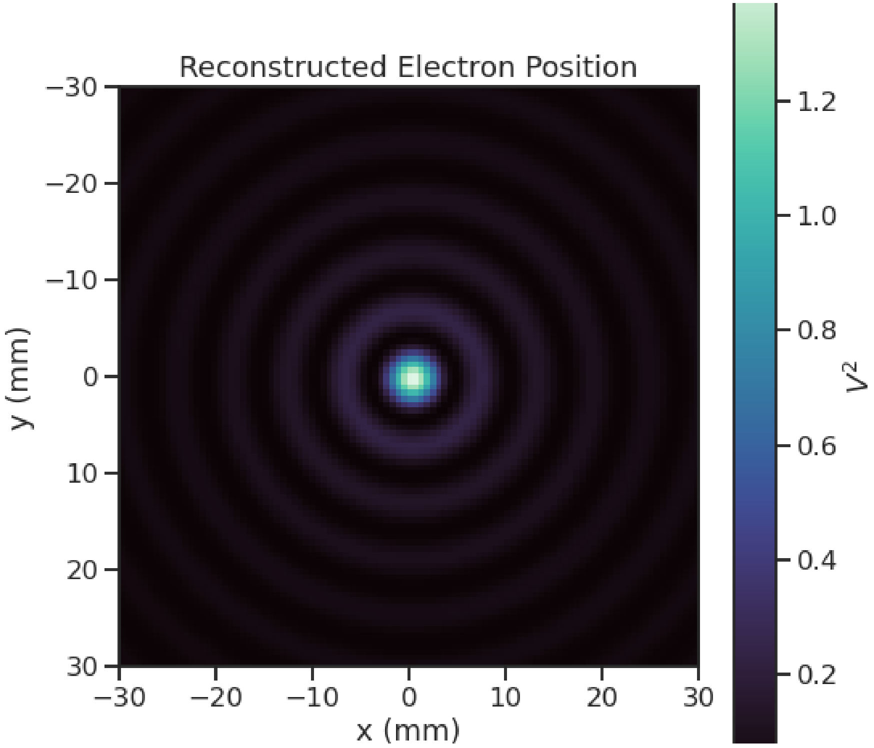

see also poster by A. Ziegler

R&D for Free Space CRES Demonstrator

Antenna design

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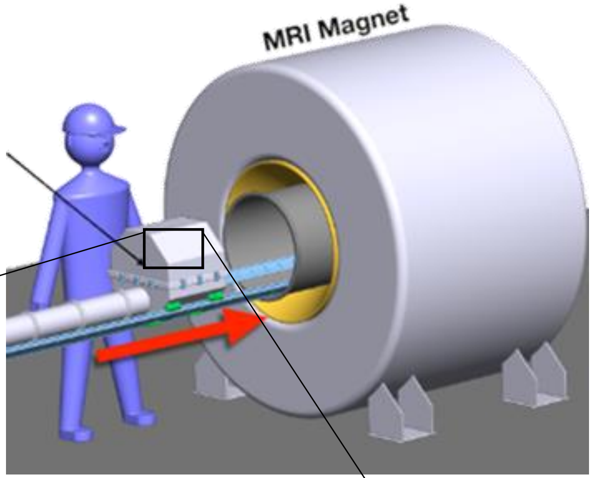
Magnetic field / trap design

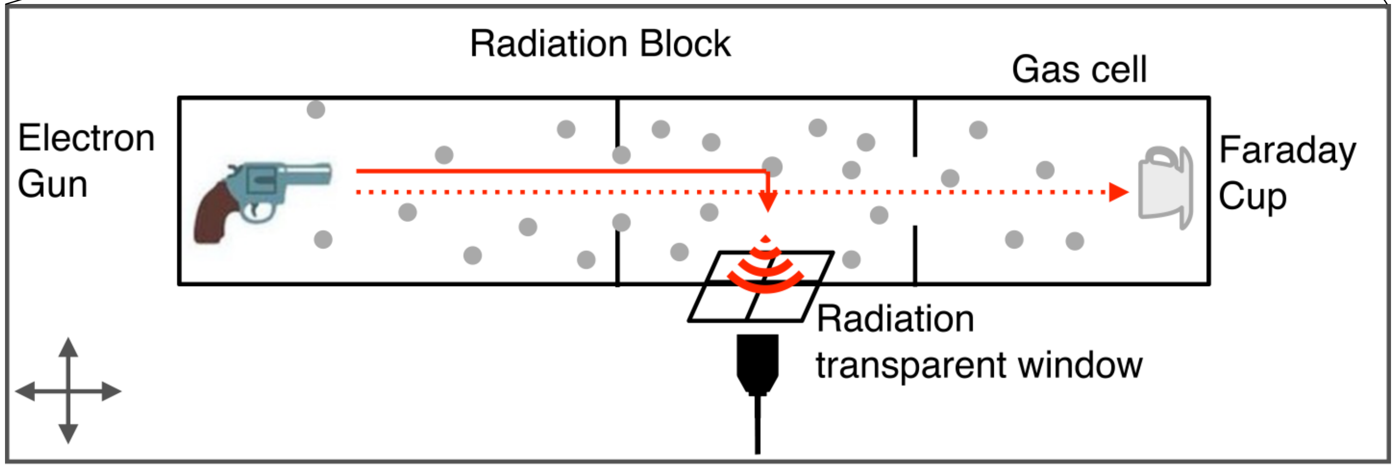
Simulation of CRES

Triggering and reconstruction

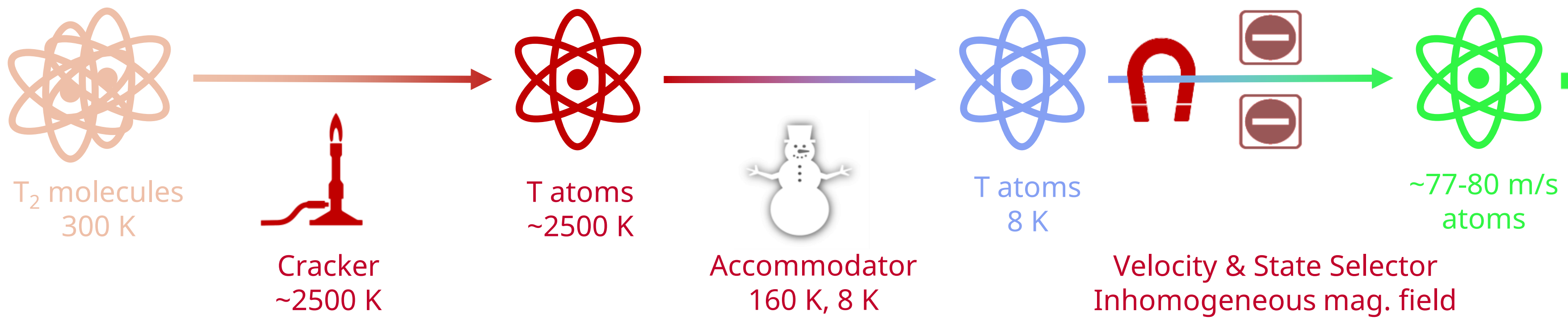
Calibration concepts

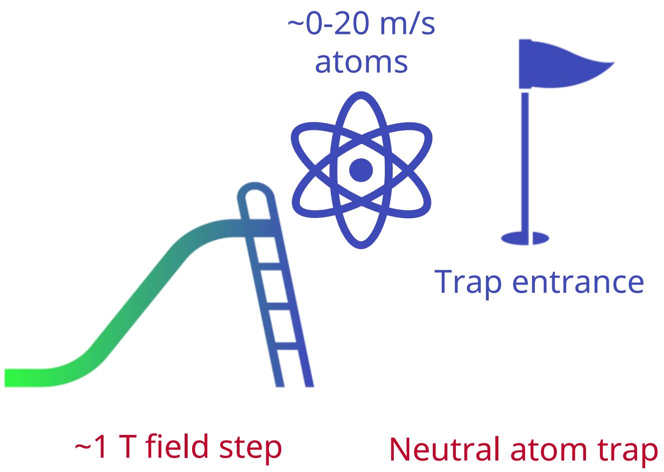
- Precise calibration of magnetic field
- Accelerate electrons by electric field
- Well defined electron energy & position
- Map field in center of MRI

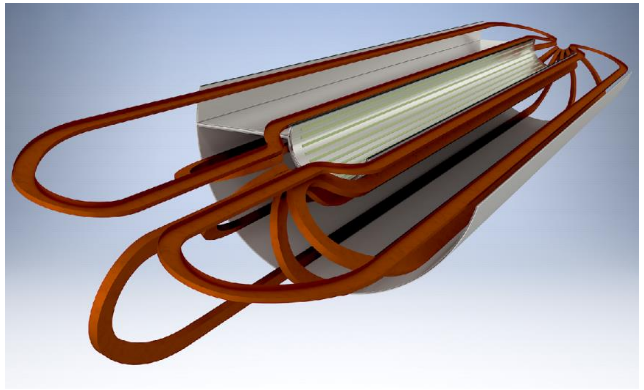




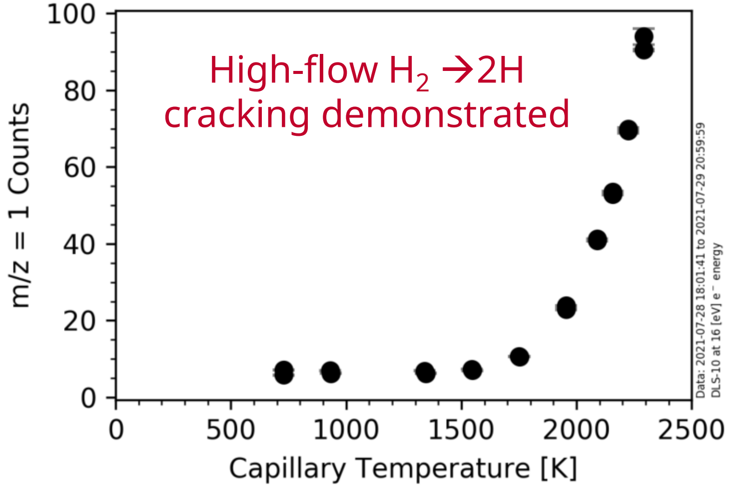
Atomic Tritium Demonstrator







Ioffe trap: superconducting coils
Halbach array: permanent magnets



Develop
- atomic tritium production
- cooling to <50 mK
- trapping of neutral atoms

Developed using hydrogen and deuterium

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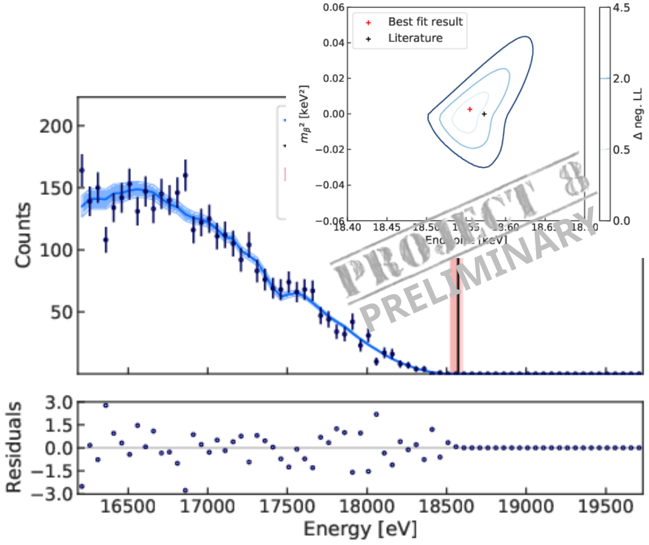

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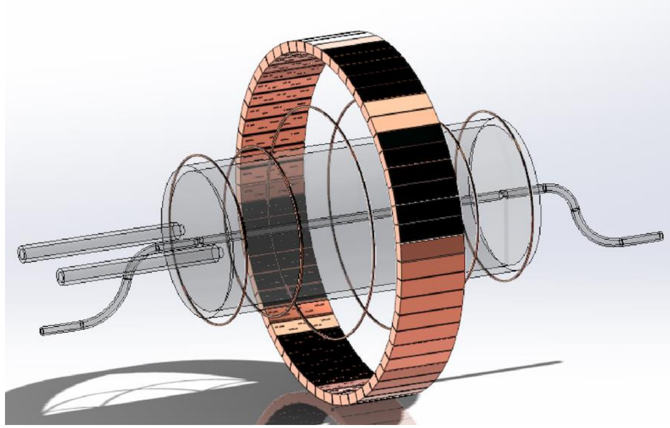
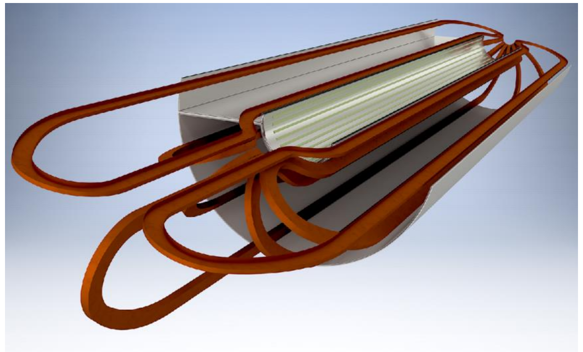
→ Mass hierarchy



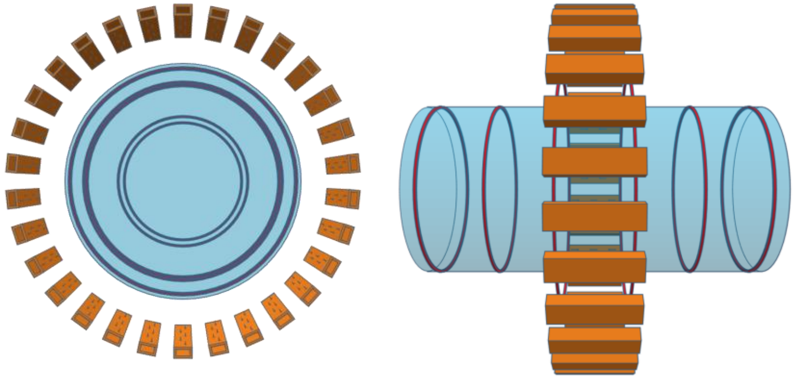


Thank you!

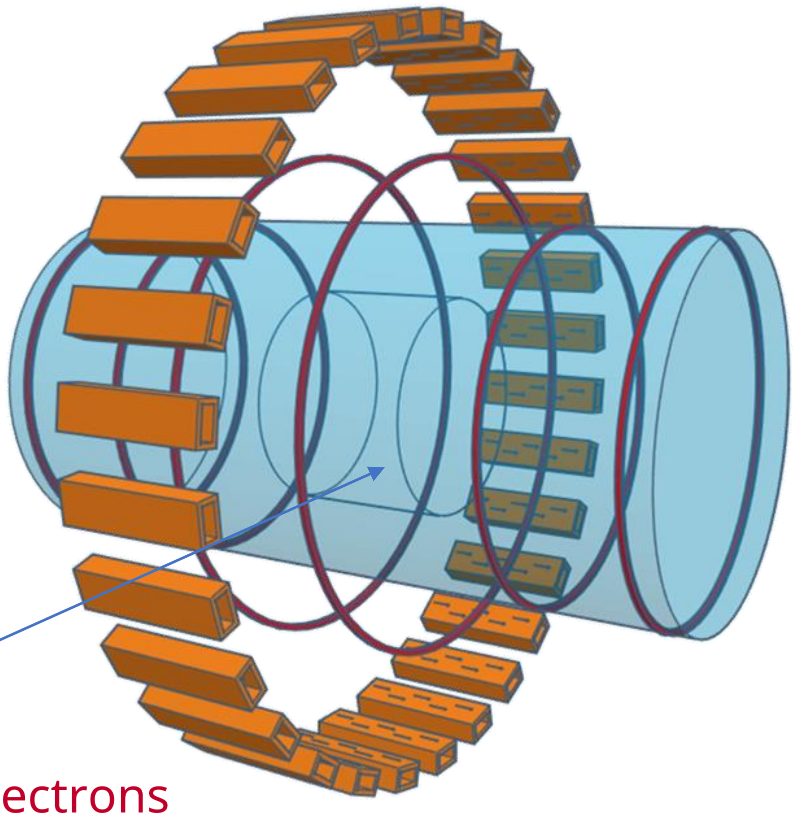
Acknowledgment: This work is supported by the US DOE Office of Nuclear Physics, the US NSF, the PRISMA+ Cluster of Excellence at the University of Mainz, and internal investments at all institutions.

Backup

Present Conceptual Design



- Antenna array
    - One ring with 60 antennas
    - Antenna radius 10 cm
    - Slotted waveguides with 5 slots
- Gas cell
    - Radius of 5 cm
- Magnetic trap
    - Harmonic trap of two coils
    - Flat trap of four coils
- Coils are idealized as their spatial extent is tiny

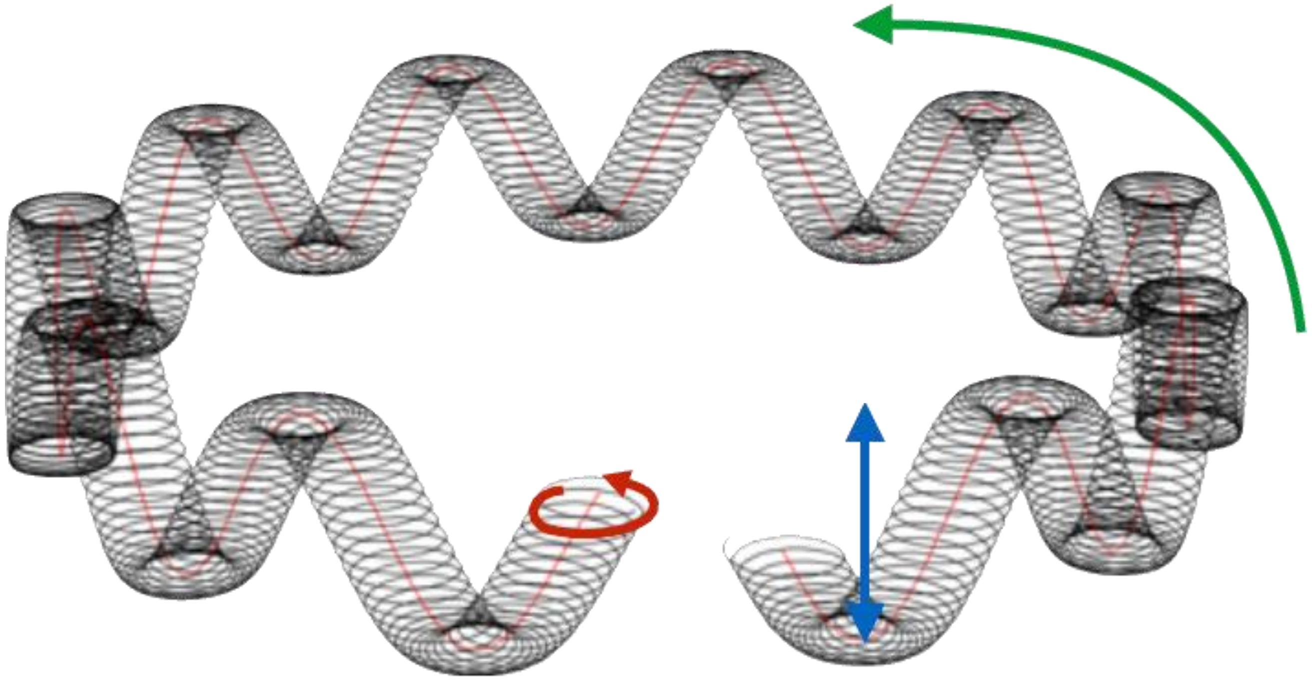


Volume where we trap $\theta \geq 89°$ electrons

A CRES Electron’s Motion

- Cyclotron motion (~26 GHz)
  - Mainly determined by background field
  - Typical cyclotron radius 0.5mm
- Axial motion (~10 MHz)
  - Depends on pitch angle
  - Depends on trap shape
- Grad-B motion (~10 kHz)
  - Component for off-axis electrons
  - Proportional to $\vec{B} \times \nabla\vec{B}$

$$\omega_c = \frac{eB}{m_e + E_{kin}/c^2}$$



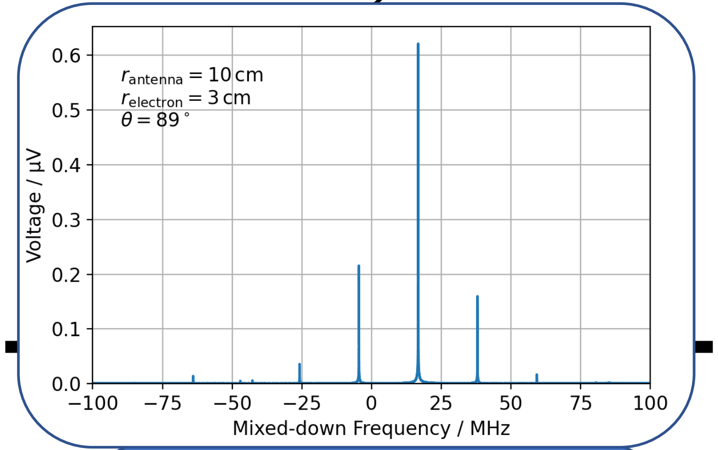
Antenna
gain

Trap
radiated frequency
trajectory

$$V(t) \propto A\left(\omega(\vec{r}(t)), \vec{r}(t)\right) \exp\left(i\, \omega(\vec{r}(t))t + \phi_0\right)$$

Amplitude Modulation

Frequency Modulation

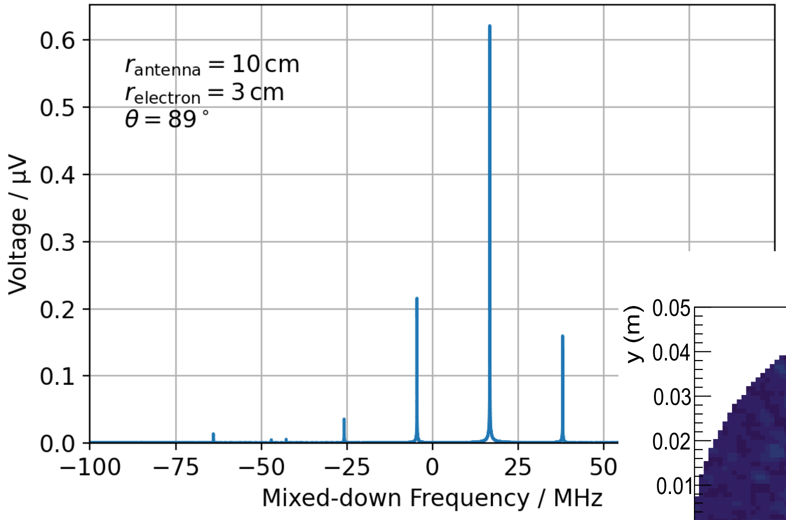


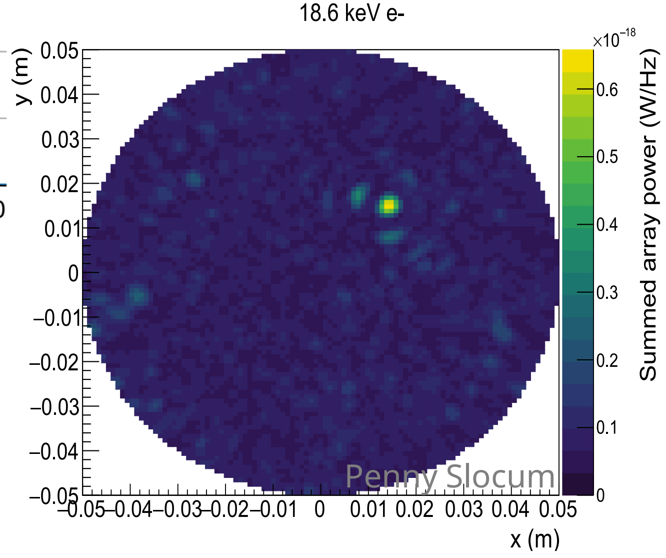
Defines signal

Makes use of signal

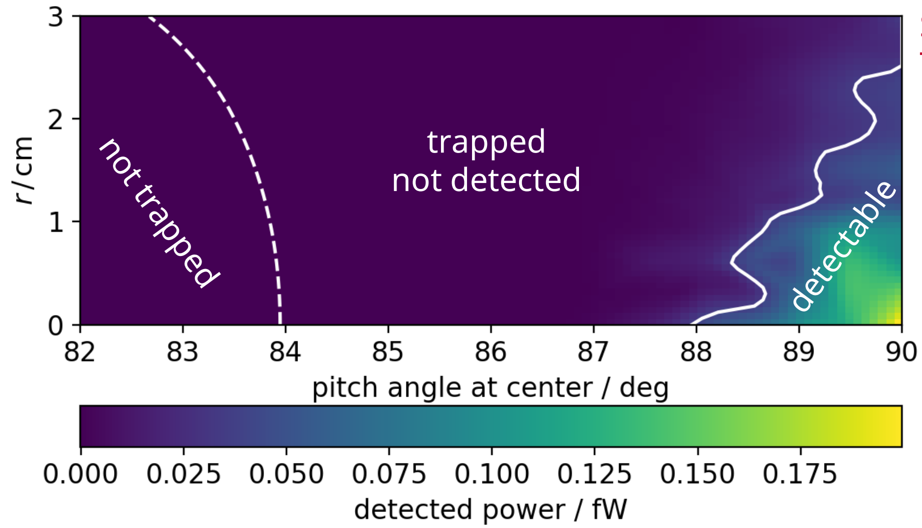
Trigger
FFT, beamforming,
decision

Simulated Signals





- Measure complex voltage in each antenna
- Determine energy using carrier of spectrum
- Use interference of antennas to locate electron position
- Simple trigger algorithm enables detection of electrons with θ > 88° and r < 2-3 cm
- Effective volume ε·V on cm³ scale



SNR=10 dB
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