Measurement of Neutrino Mass with PROJECT 8

Pranava Teja Surukuchi

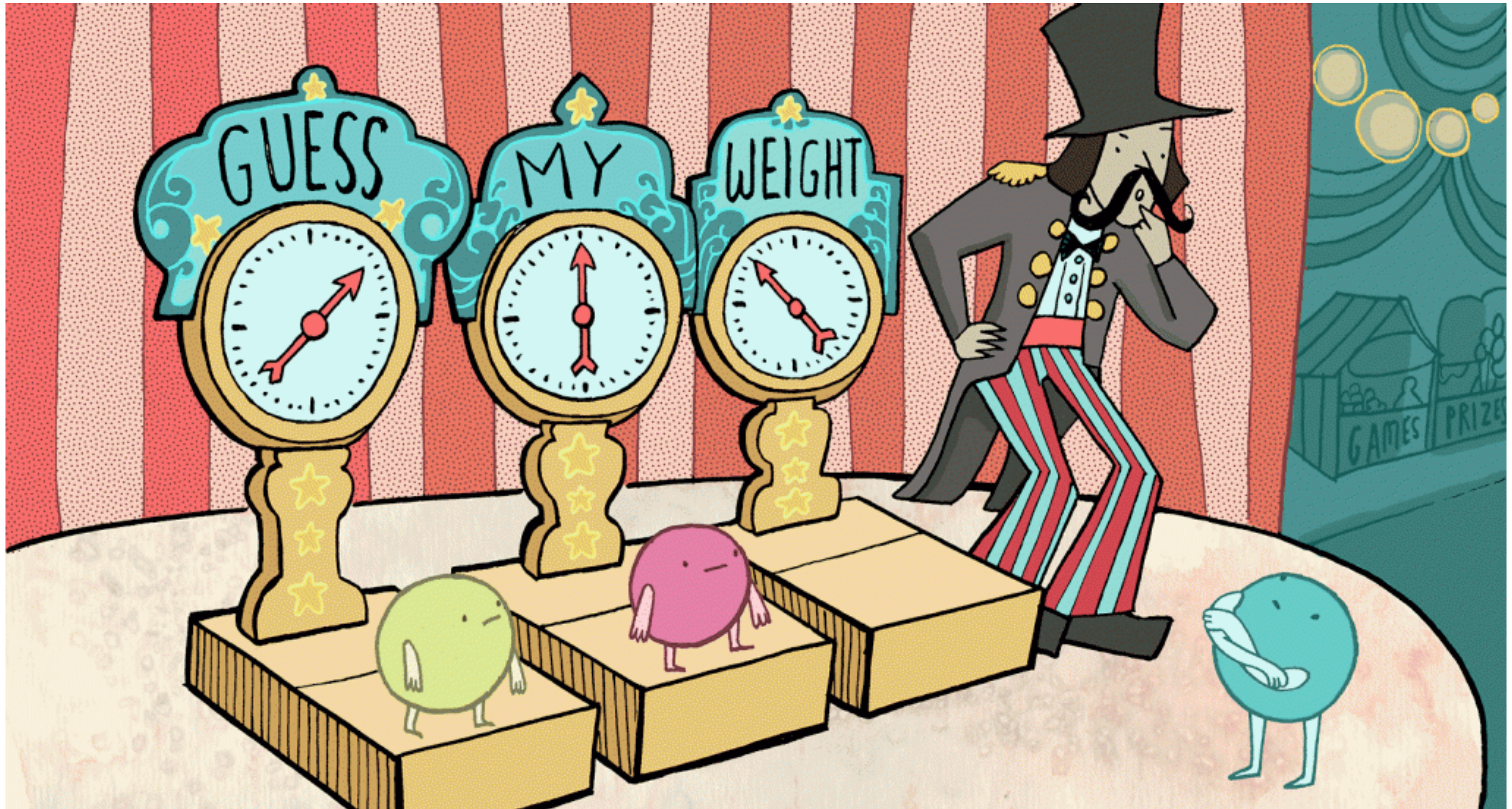
FNAL Neutrino Seminar

Yale
Wright Laboratory

Credit: Symmetry Magazine / Sandbox Studio, Chicago

Constraining Neutrino Mass

1. Neutrino oscillations
2. Cosmological
3. Astrophysical
4. Neutrinoless double beta decay
5. Direct measurements



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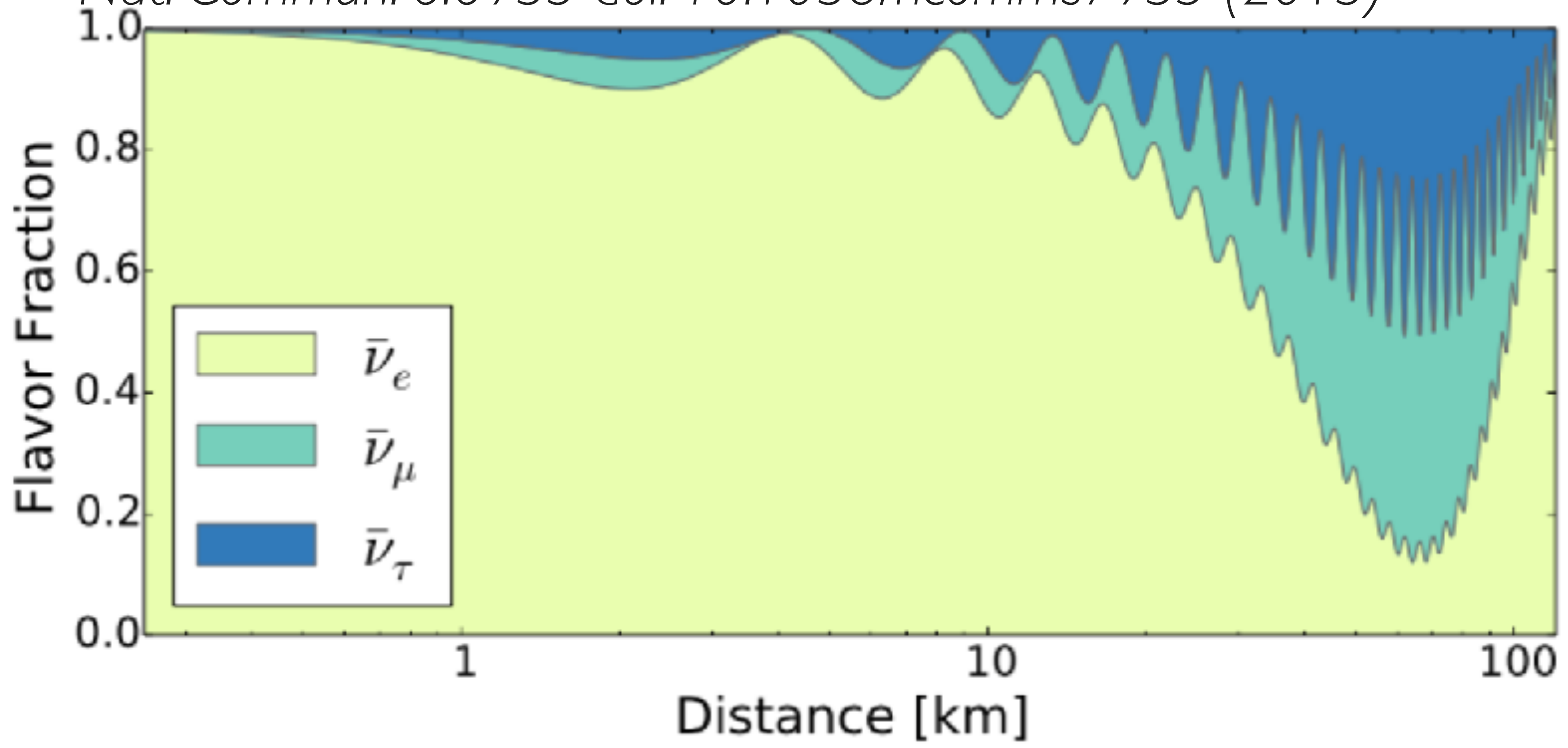
Oscillation Experiments

Experimental method	Measurable mass term
Neutrino oscillations	$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$
Cosmological	$\Sigma = \sum_i m_i$
Astrophysical	$m_{1,2,3}(\text{degenerate})$
Double beta decay	$\langle m_{\beta\beta}\rangle = \left\lvert \sum_j m_j U_{ej}^2 \right\rvert$
Direct Measurements	$m_\beta = \sqrt{\lvert U_{ei}\rvert^2 m_i^2}$

Nat. Commun. 6:6935 doi: 10.1038/ncomms7935 (2015)



$$P_{\alpha\beta} = \delta_{\alpha\beta} - \sin^2 2\theta \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

- Can be inferred based on the observed oscillation frequency
- Can't measure individual neutrino masses
- Places a lower limit

Cosmological

Experimental method	Measurable mass term
Neutrino oscillations	$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$
Cosmological	$\Sigma = \sum_i m_i$
Astrophysical	$m_{1,2,3}(\text{degenerate})$
Double beta decay	$\langle m_{\beta\beta} \rangle = \left\| \sum_j m_j U_{ej}^2 \right\|$
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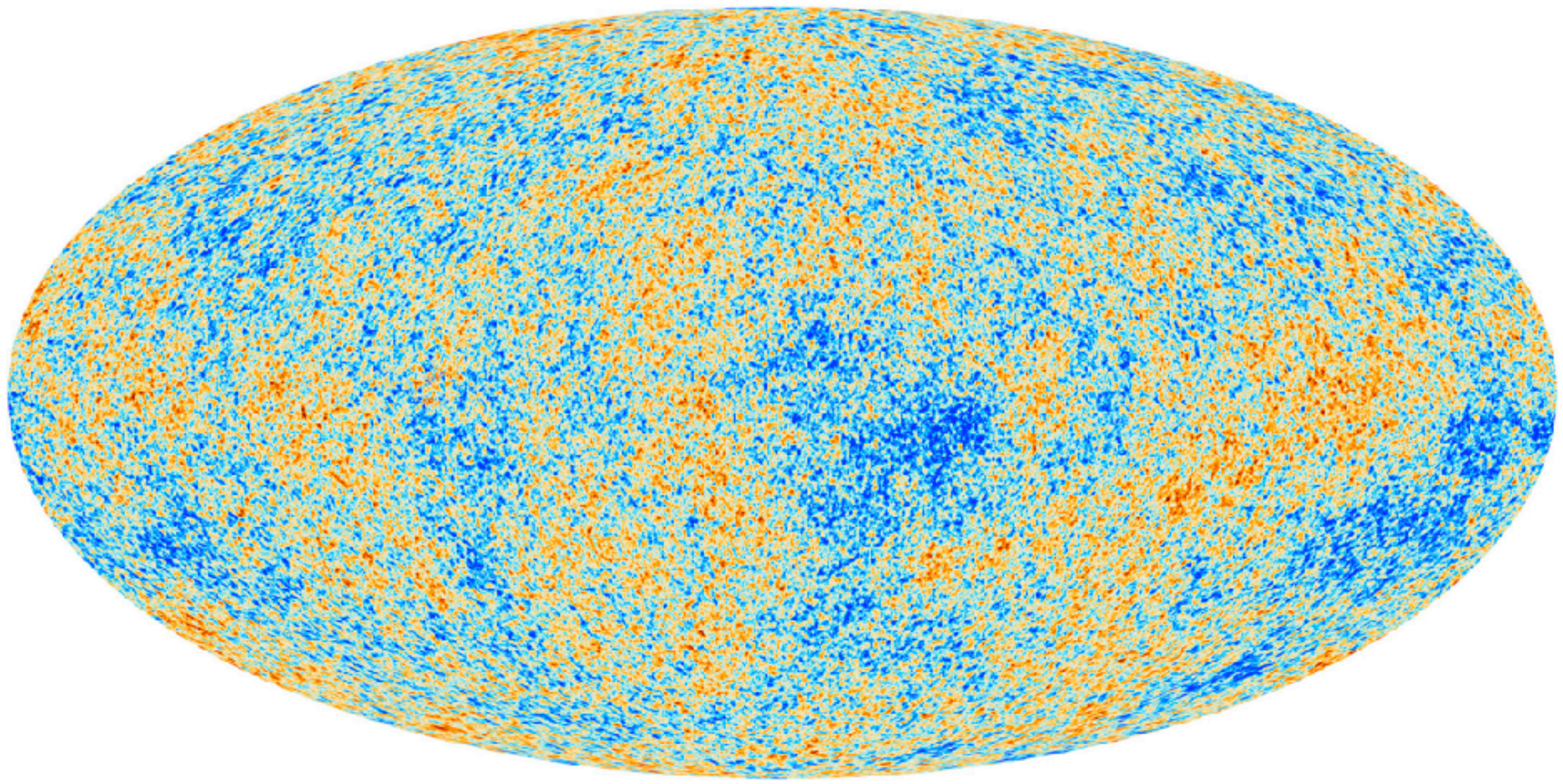

- Extract limits based on the large scale structures and CMB
- Most stringent limits
- Upcoming measurements to dramatically improve sensitivity
- Model-dependent

Astrophysical

Experimental method	Measurable mass term
Neutrino oscillations	$\Delta m^2_{ij} \equiv m^2_i - m^2_j$
Cosmological	$\Sigma = \sum_i m_i$
Astrophysical	$m_{1,2,3}(\text{degenerate})$
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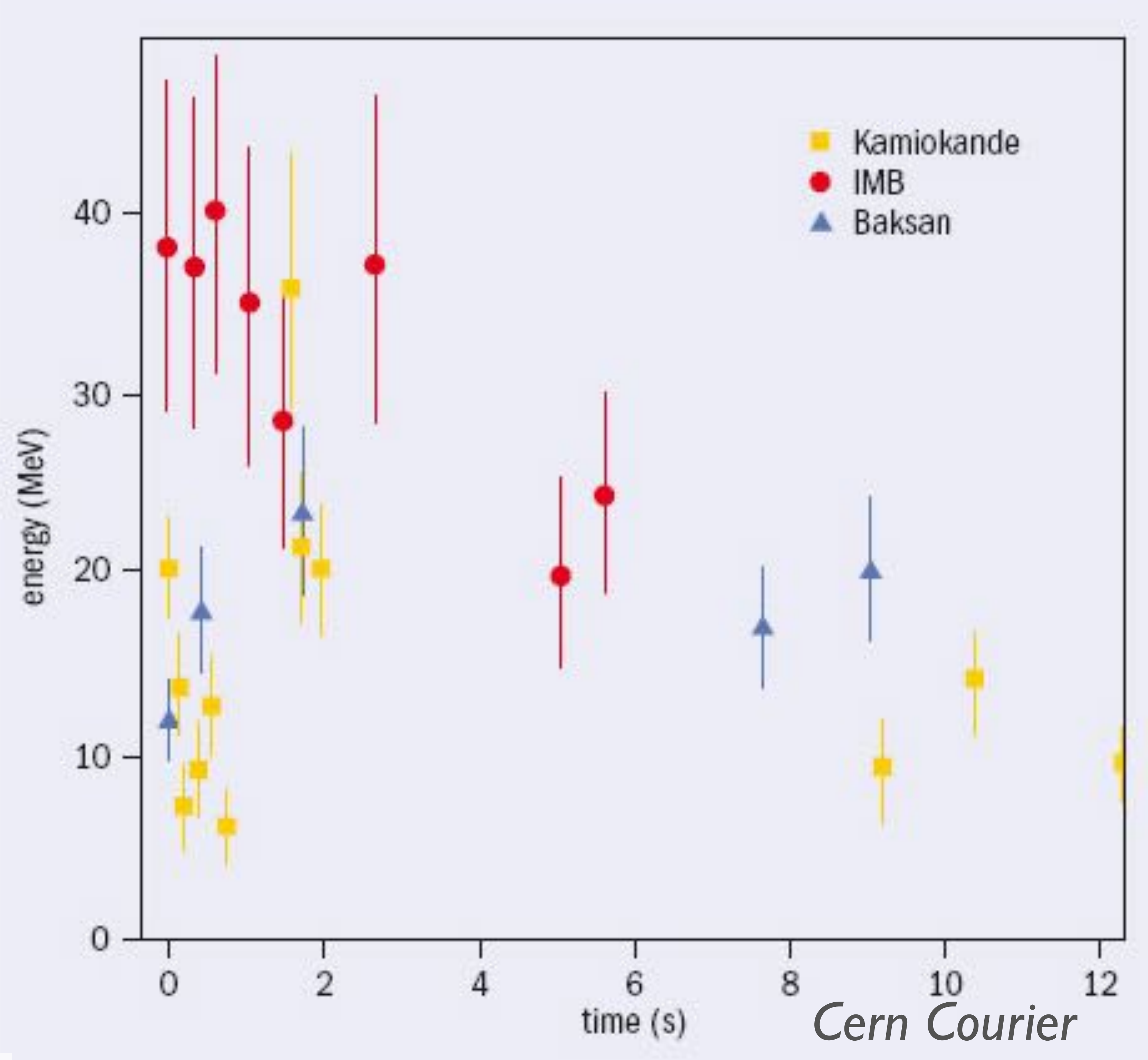

- Measured from time-of-flight of supernova neutrinos
- Don't know when the next supernova is going to be; last one was in 1987

Neutrinoless Double Beta Decay

Experimental method	Measurable mass term
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Cosmological	$\Sigma = \sum_i m_i$
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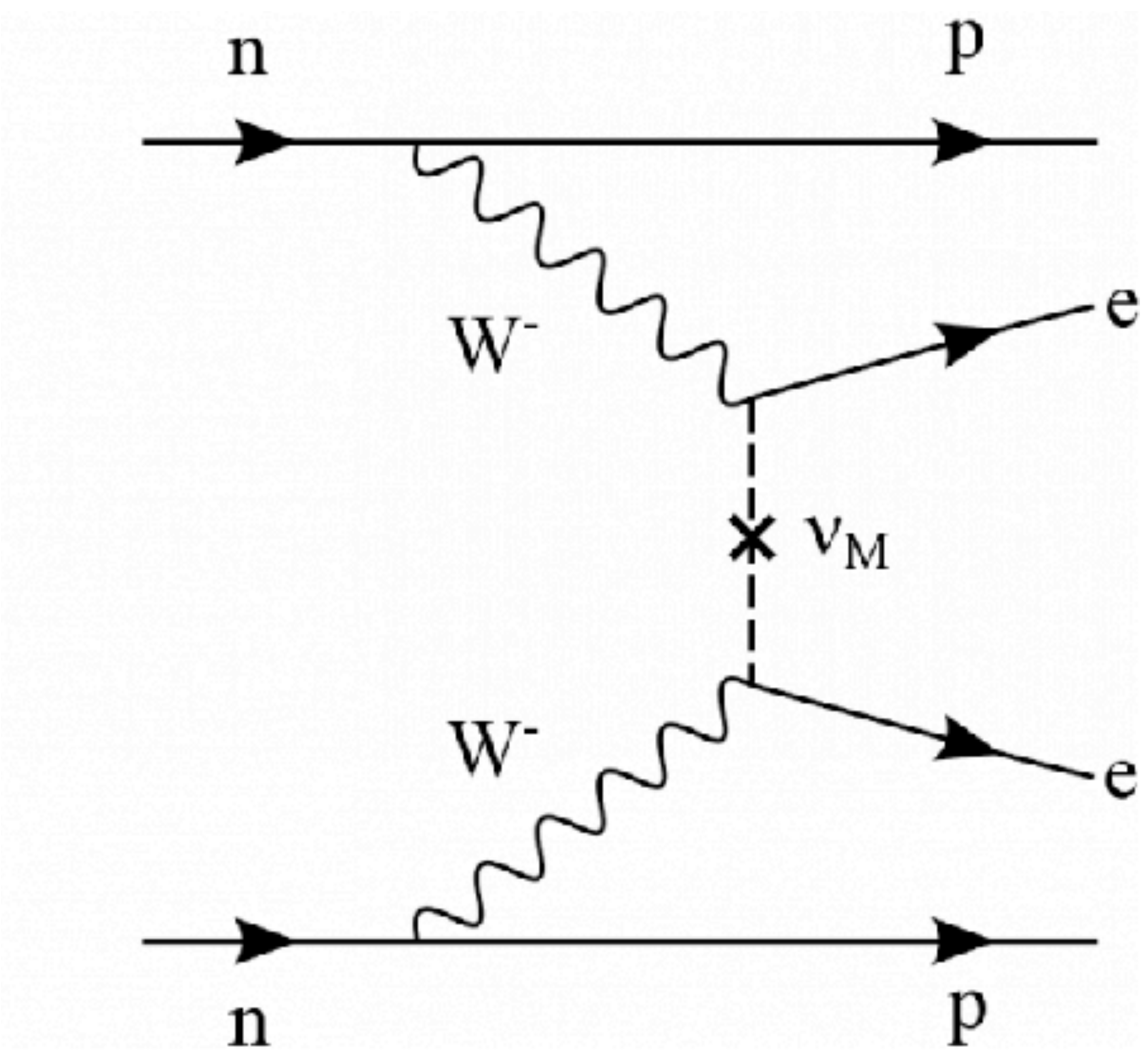

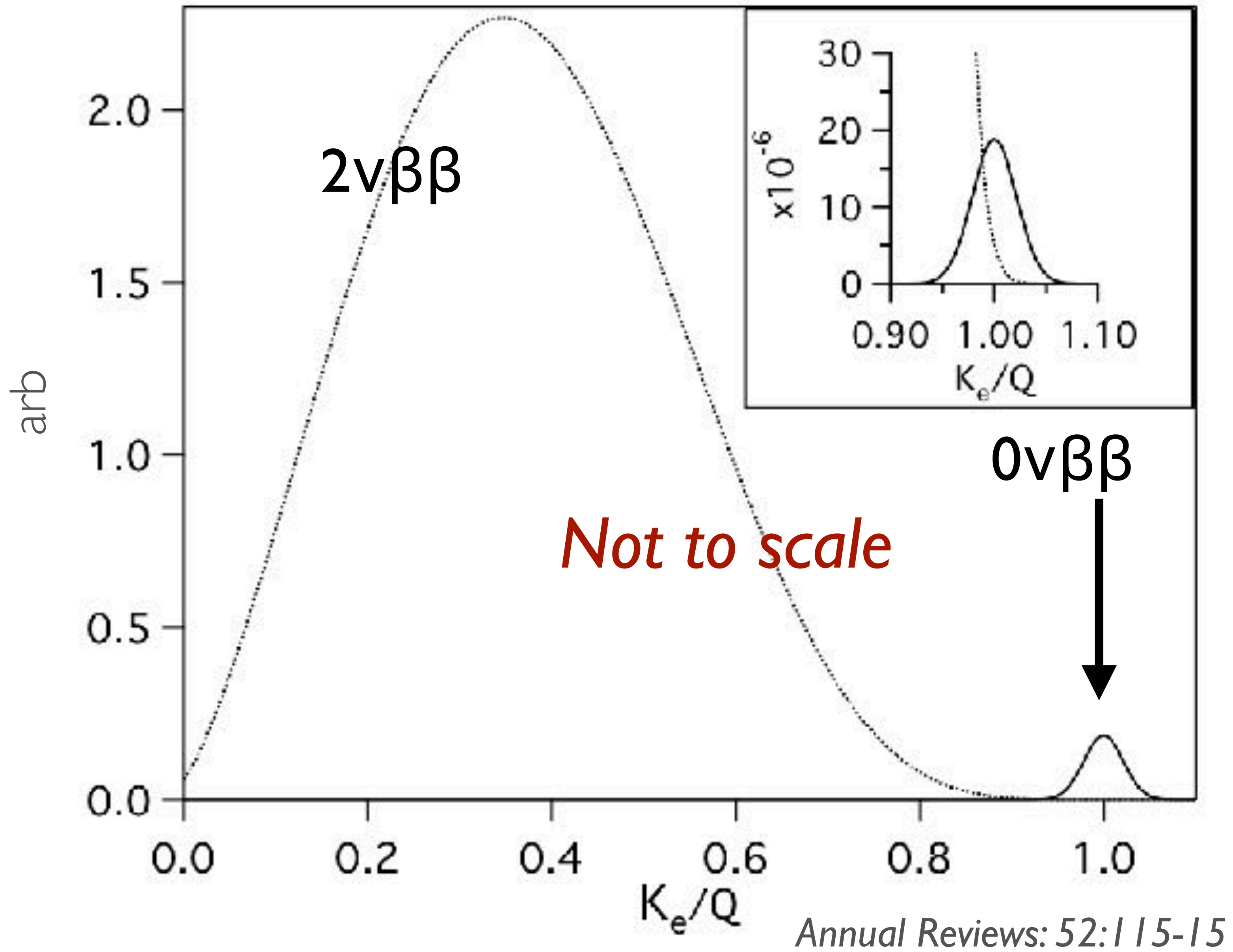

Annual Reviews: 52:115-151

- Infer from the rate of neutrinoless double beta decay
- Effective Majorana mass; only if neutrinos are Majorana type
- Model-dependent, nuclear matrix elements

Direct Measurements

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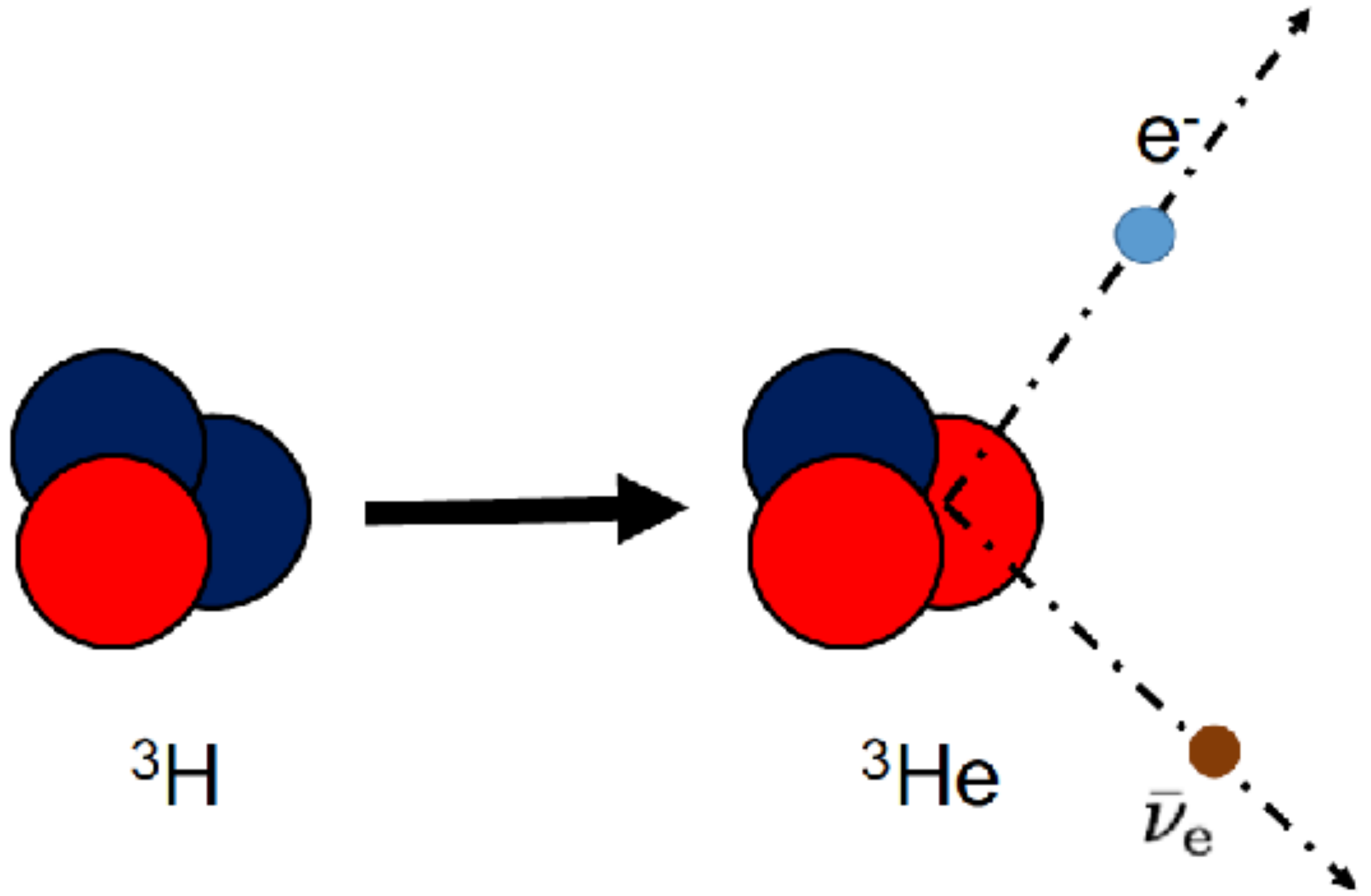

- Measure based on the distortion in shape of the end point spectrum
- Model-independent
- Quite challenging to measure

Mass Measurement Approaches: Limits

Experimental method	*Measurable mass term*
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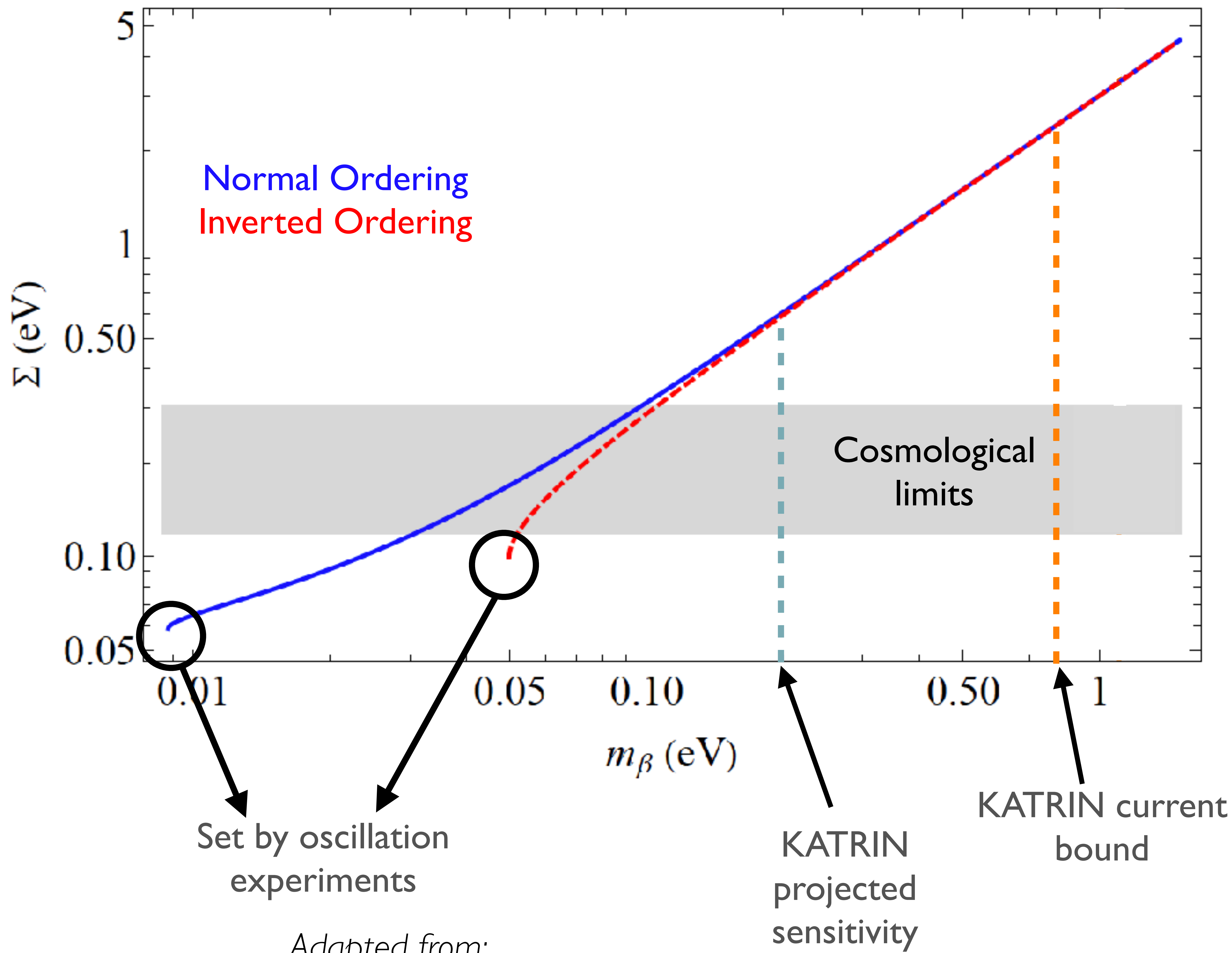
- Observables are different yet correlated

Mass Measurement Approaches: Complementarity

- Observables are different yet correlated
- Systematics are very different
- Measurement from one approach can constrain the model parameters in another
- Any inconsistencies between the approaches points to new physics



Adapted from:
Direct Measurements of Neutrino Mass: Physics Reports: 914, 1-54

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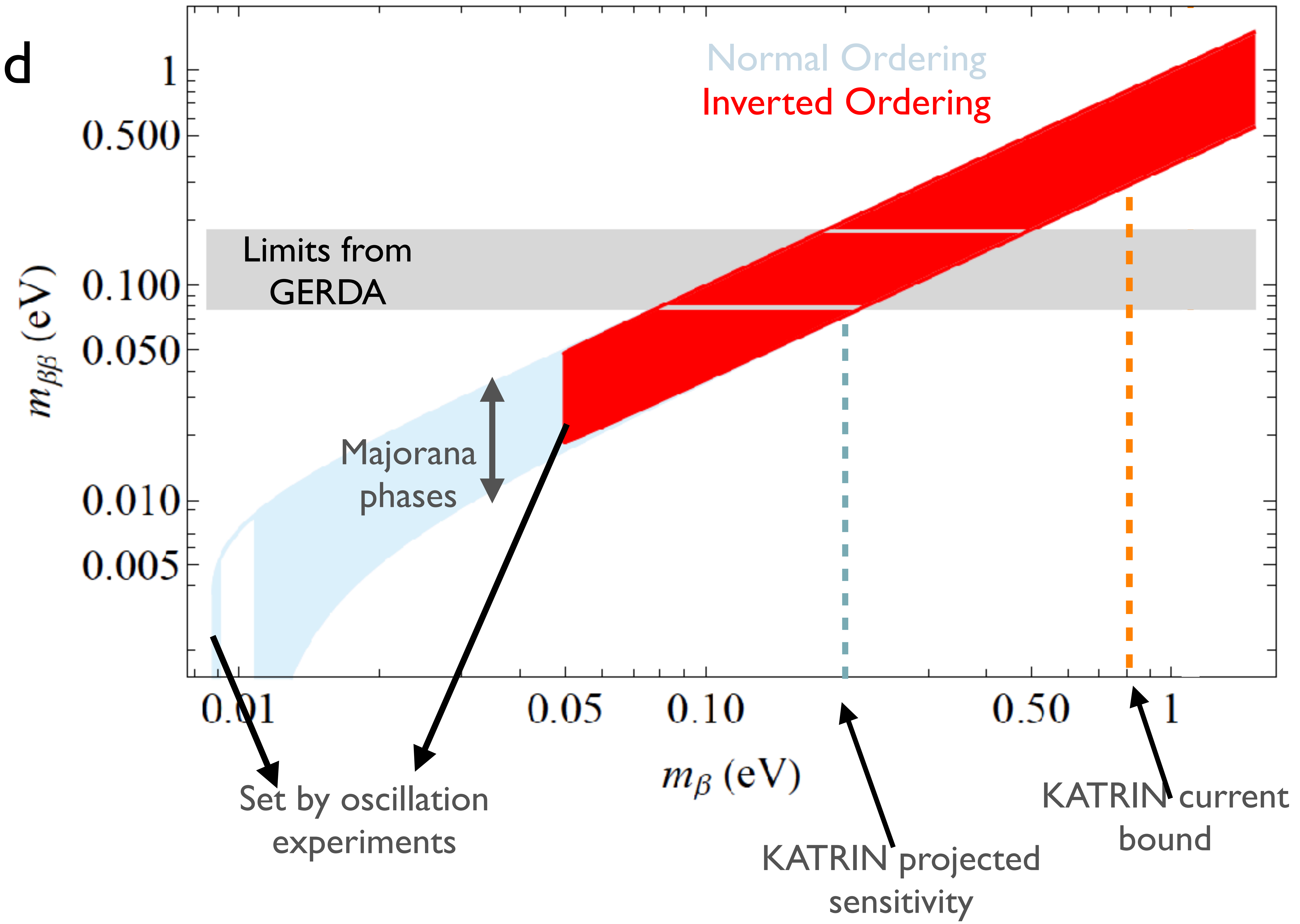

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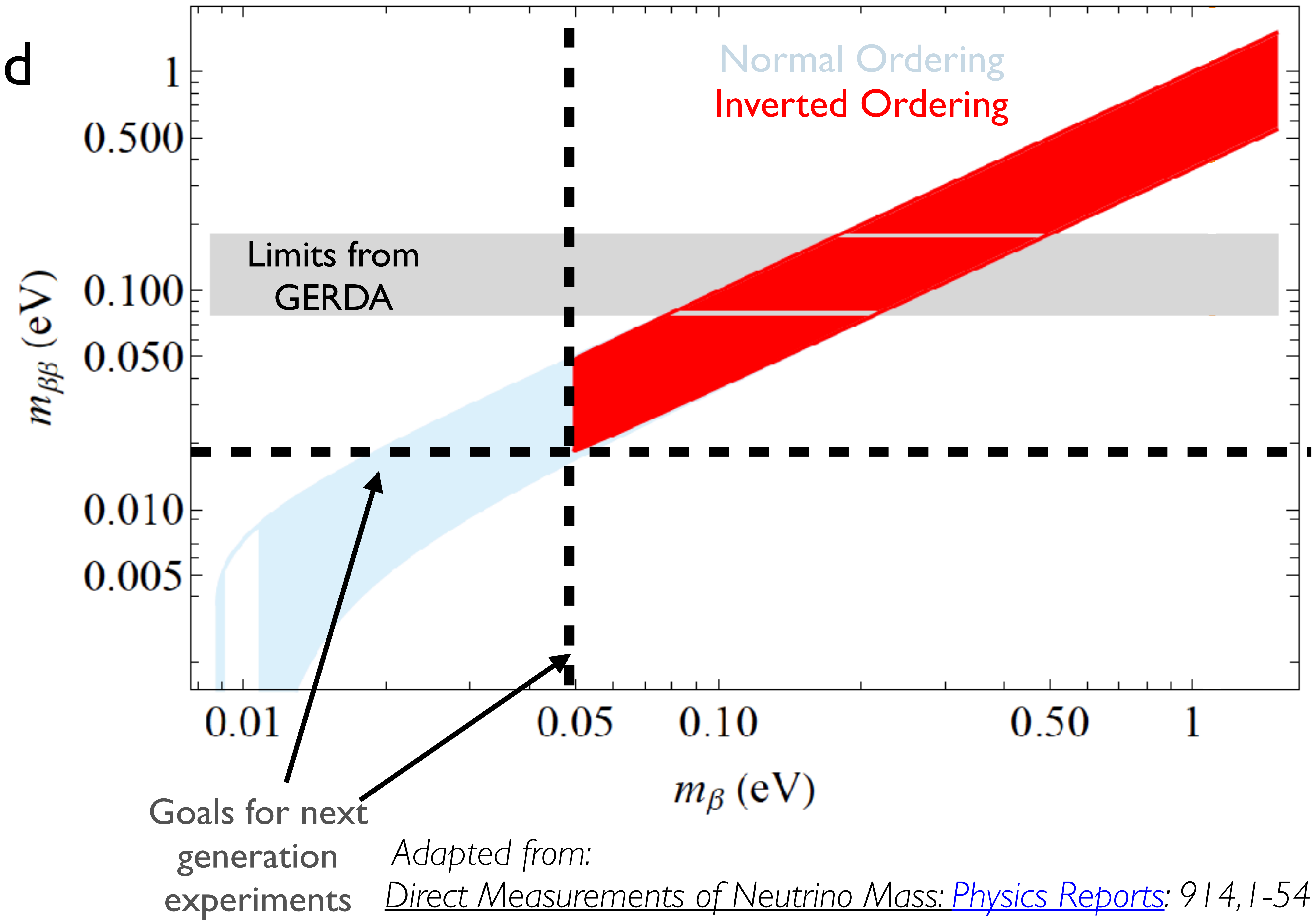

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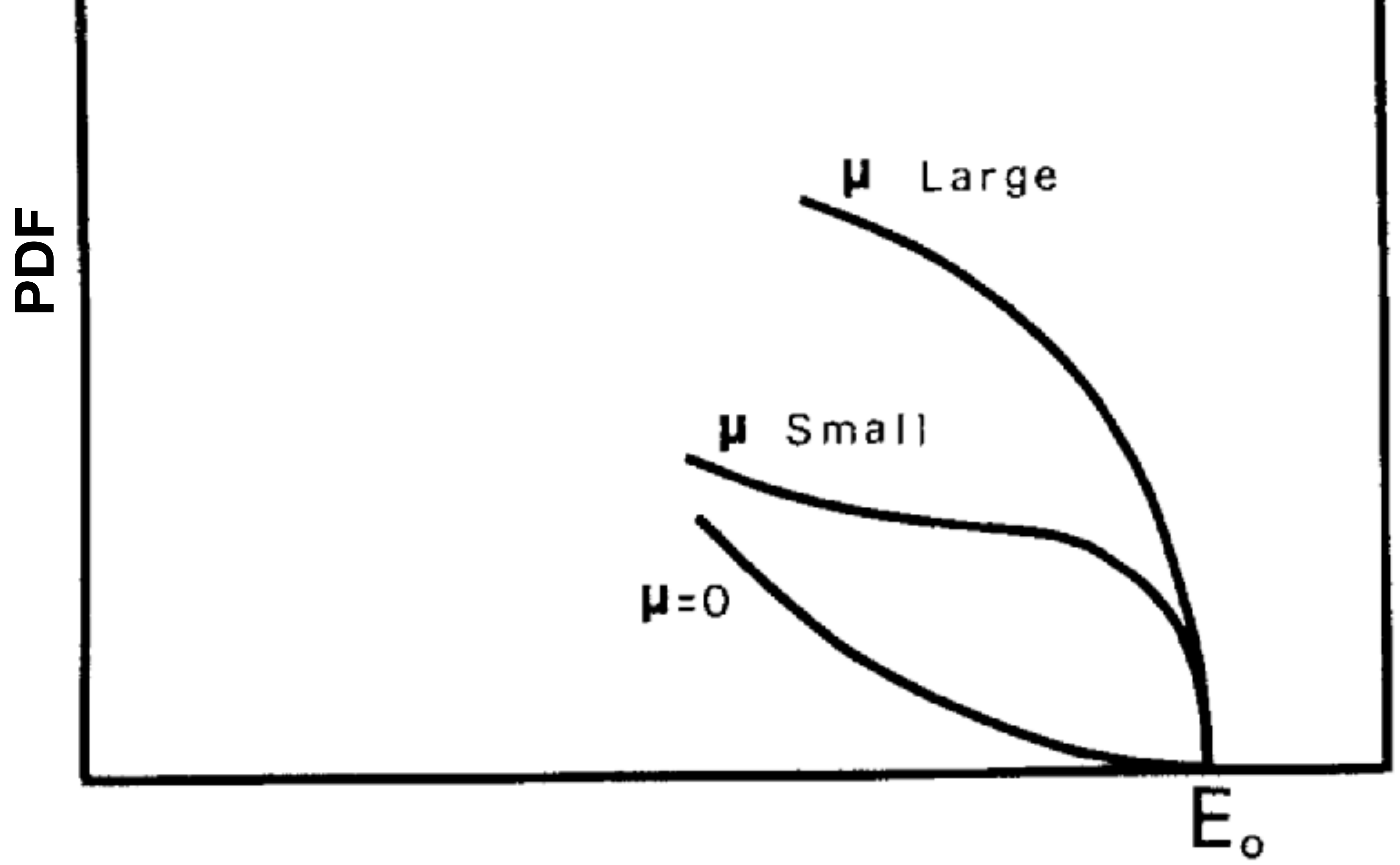
Next generation experiments aim to completely cover the Inverted Ordering

Direct Mass Measurements

- Idea: The shape near the end point can be used to infer neutrino mass
- Purely kinematic measurement
- No additional model building needed

E. Fermi, Z.Phys. 88 (1934), pp.161-177
Wilson, Fred L. AJP 36.12 (1968): 1150-1160.

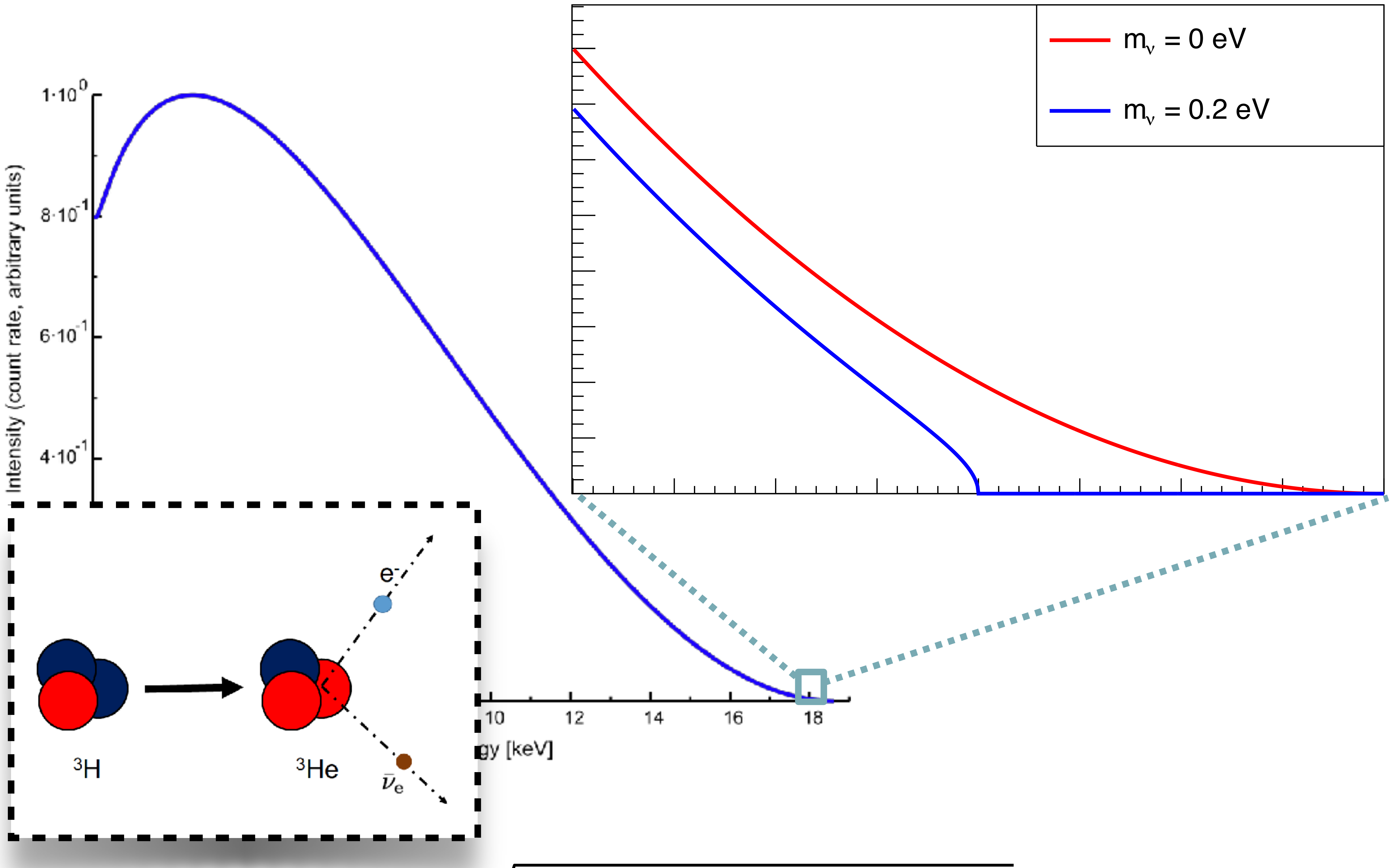


$$\frac{dN}{dE} = K\,|M|^2\,F(Z,R,E)\,p_e E\,(Q-E)\sqrt{(Q-E))^2 - m_\beta^2}$$

Matrix element — *Fermi function* — *Kinematic terms*

Direct Mass Measurements: Beta Decays

- Idea: The shape near the end point can be used to infer neutrino mass
- Purely kinematic measurement
- No additional model building needed
- Challenge: Small portion ($\sim 10^{-13}$) of decays in the last 1 eV



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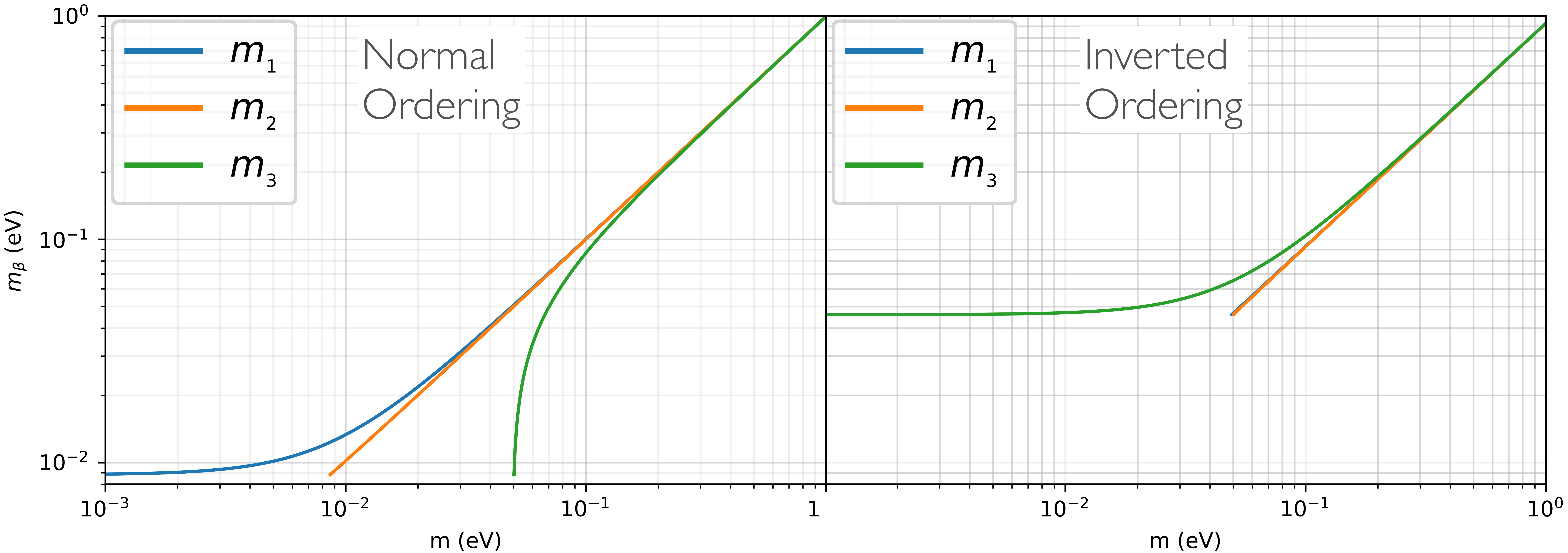
What is Measured in Beta Decay?

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



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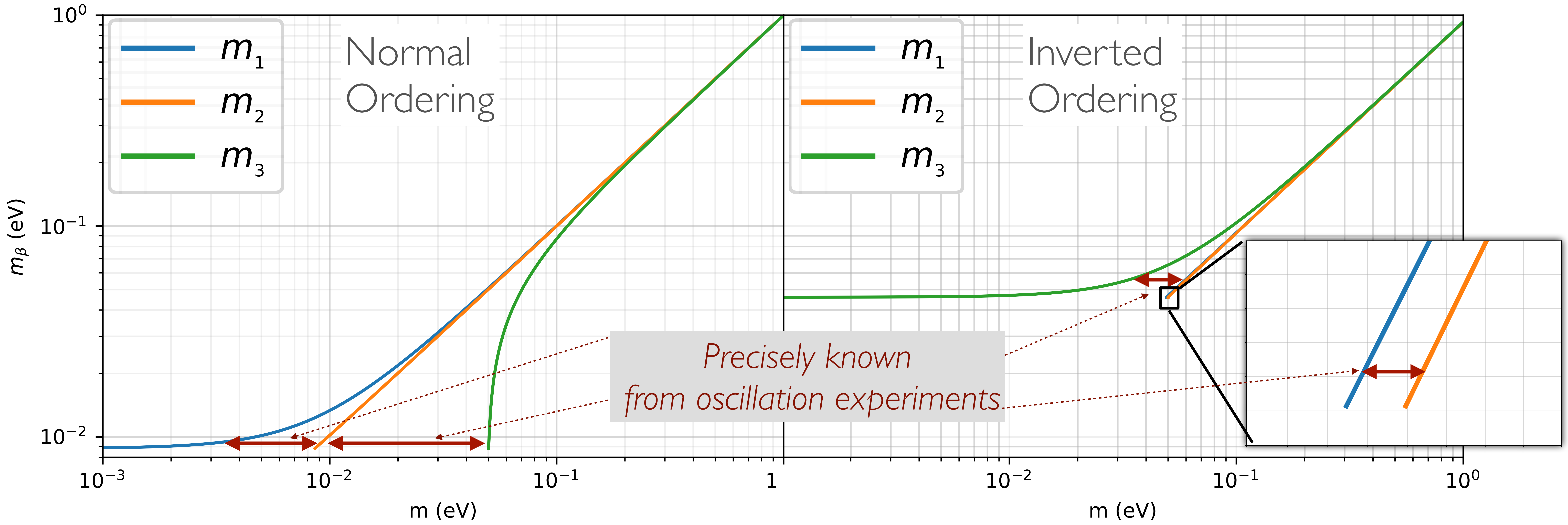
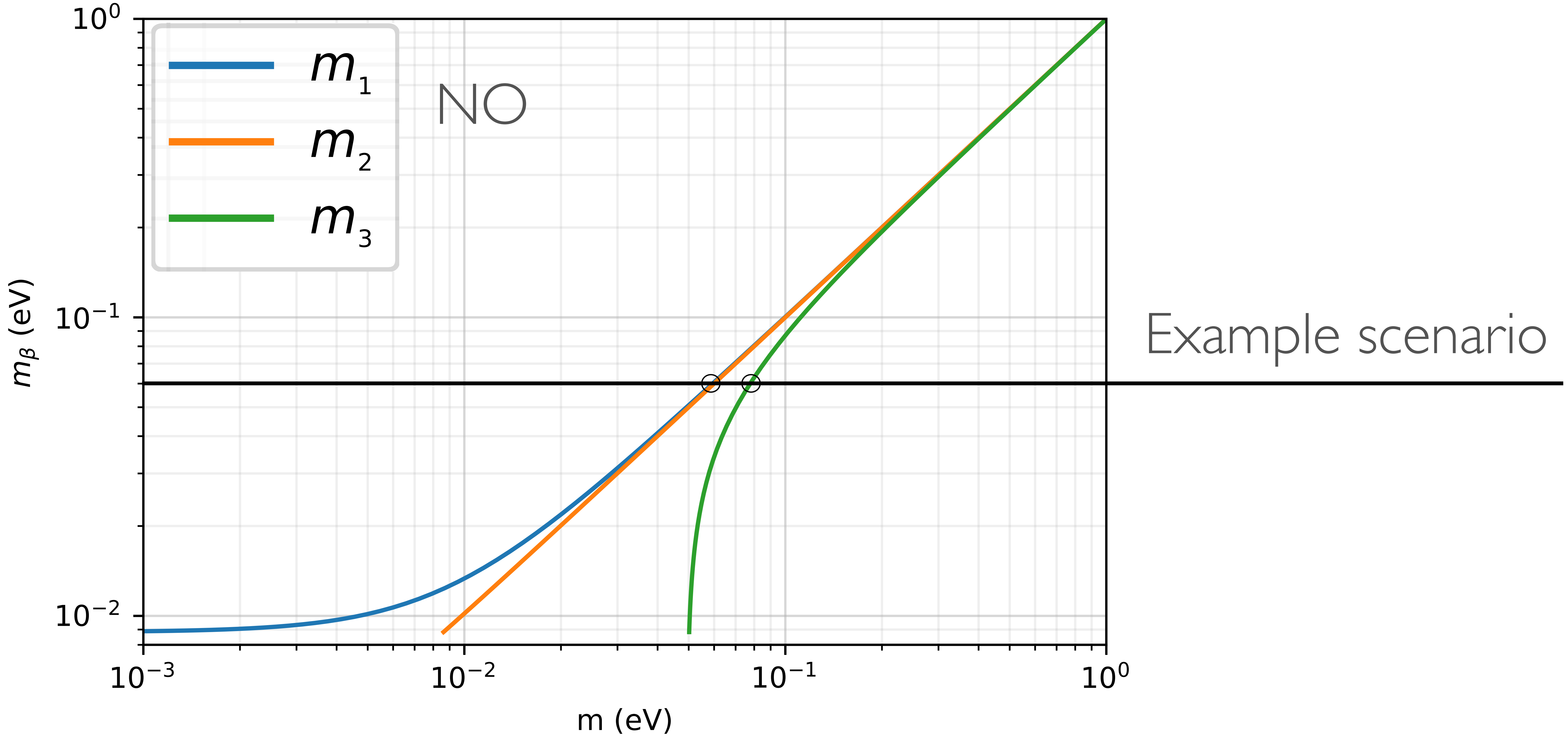


What is Measured in Beta Decay?

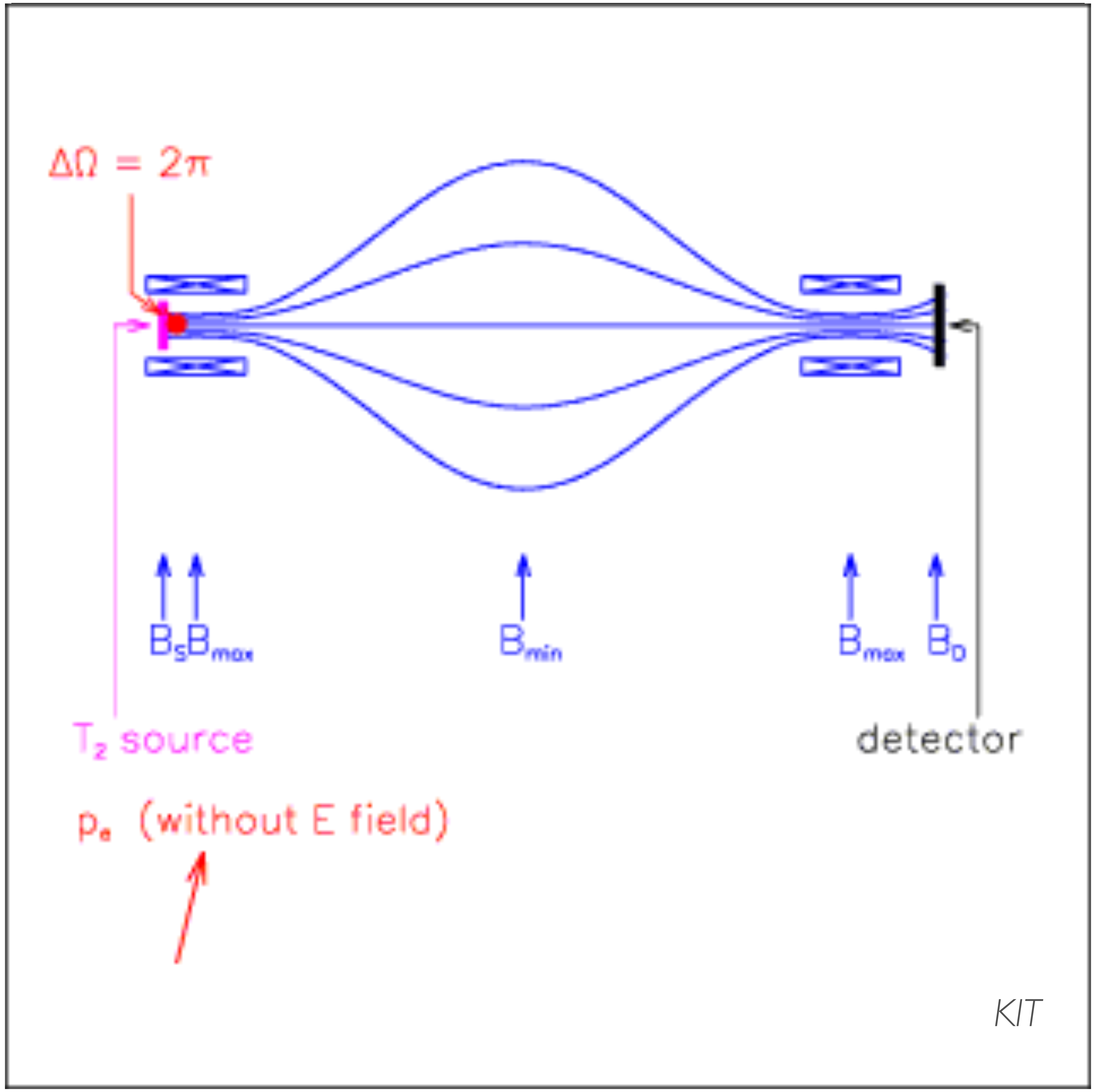
$$m_\beta^2 = \sum_{i=1,3} |U_{ei}|^2 m_i^2$$

- A measurement of neutrino mass from beta decay would provide all the three neutrino masses if the ordering is known



State of the Art Beta Decay Technique: MAC-E Filter

- Magnetic Adiabatic Collimation combined with Electrostatic Filter
- Beta decay electrons guided towards the center of the spectrometer
- MAC: Huge B-field gradient forces electrons to travel parallel to the field at the analyzing plane



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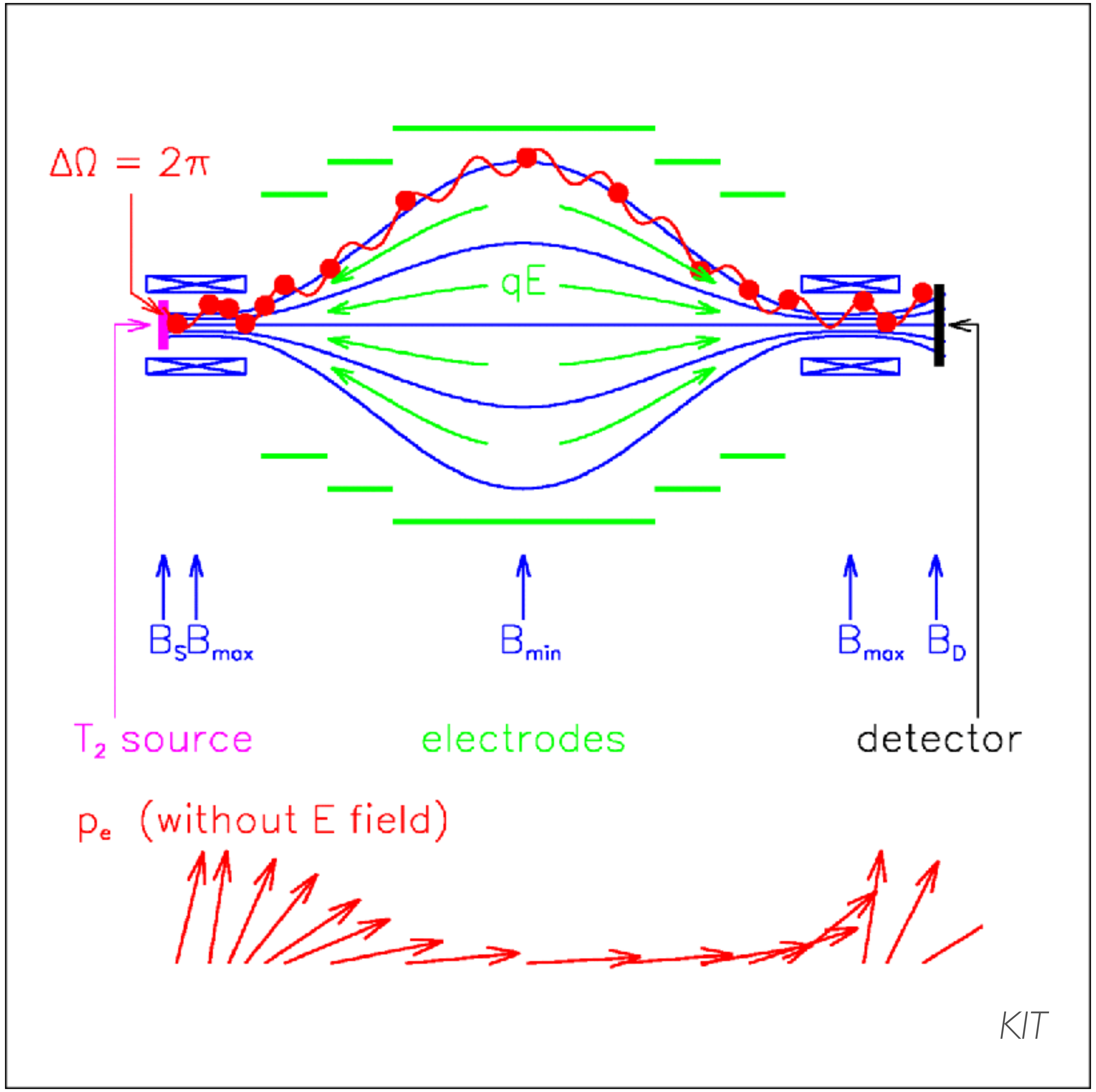
- Beta decay electrons guided towards the center of the spectrometer
- MAC: Huge B-field gradient forces electrons to travel parallel to the field at the analyzing plane
- E filter: Apply an electrostatic high-pass filter to count electrons above threshold
- Best direct neutrino mass limits for nearly 3 decades with this technique

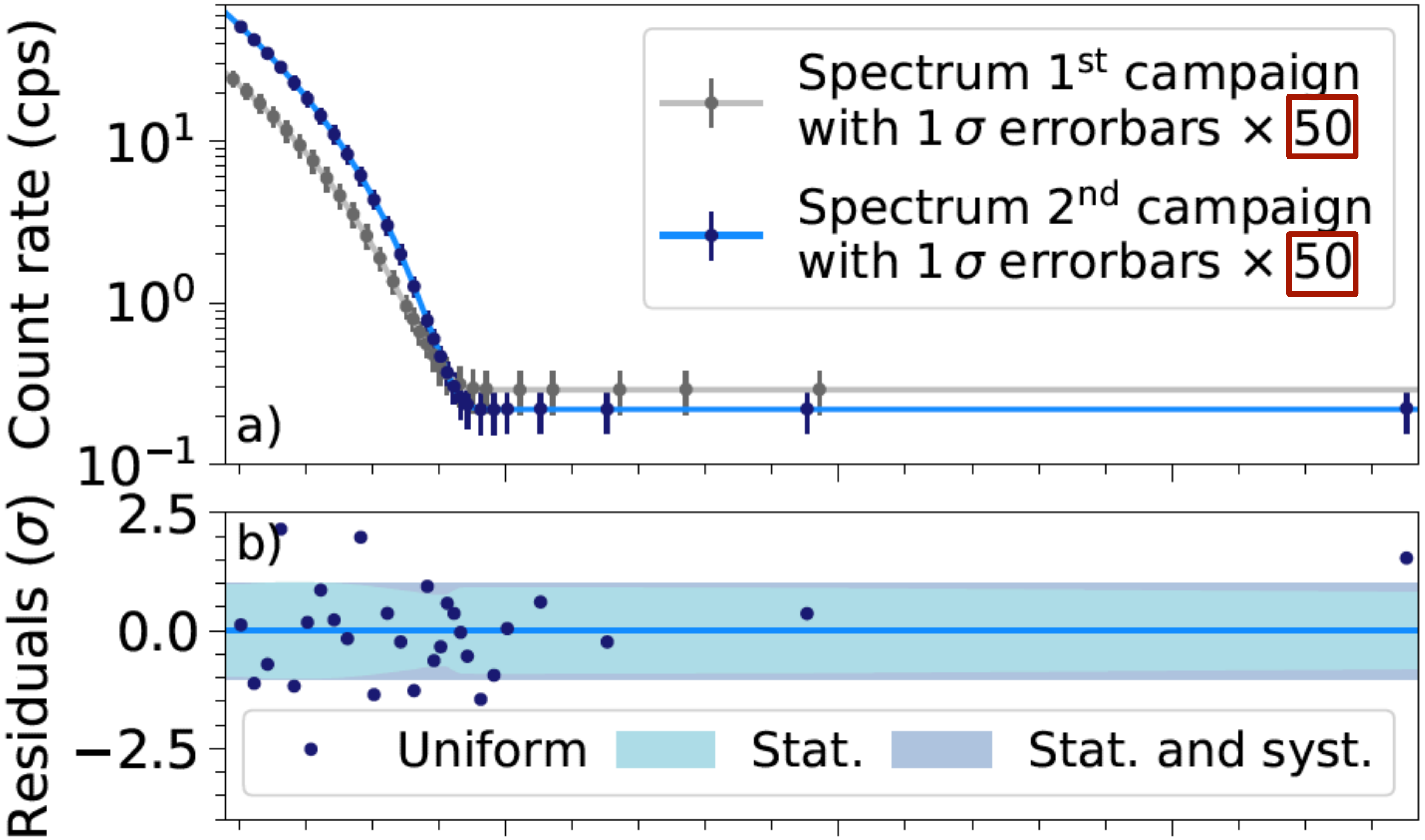


State of the Art Beta Decay Experiment: KATRIN

~10 m

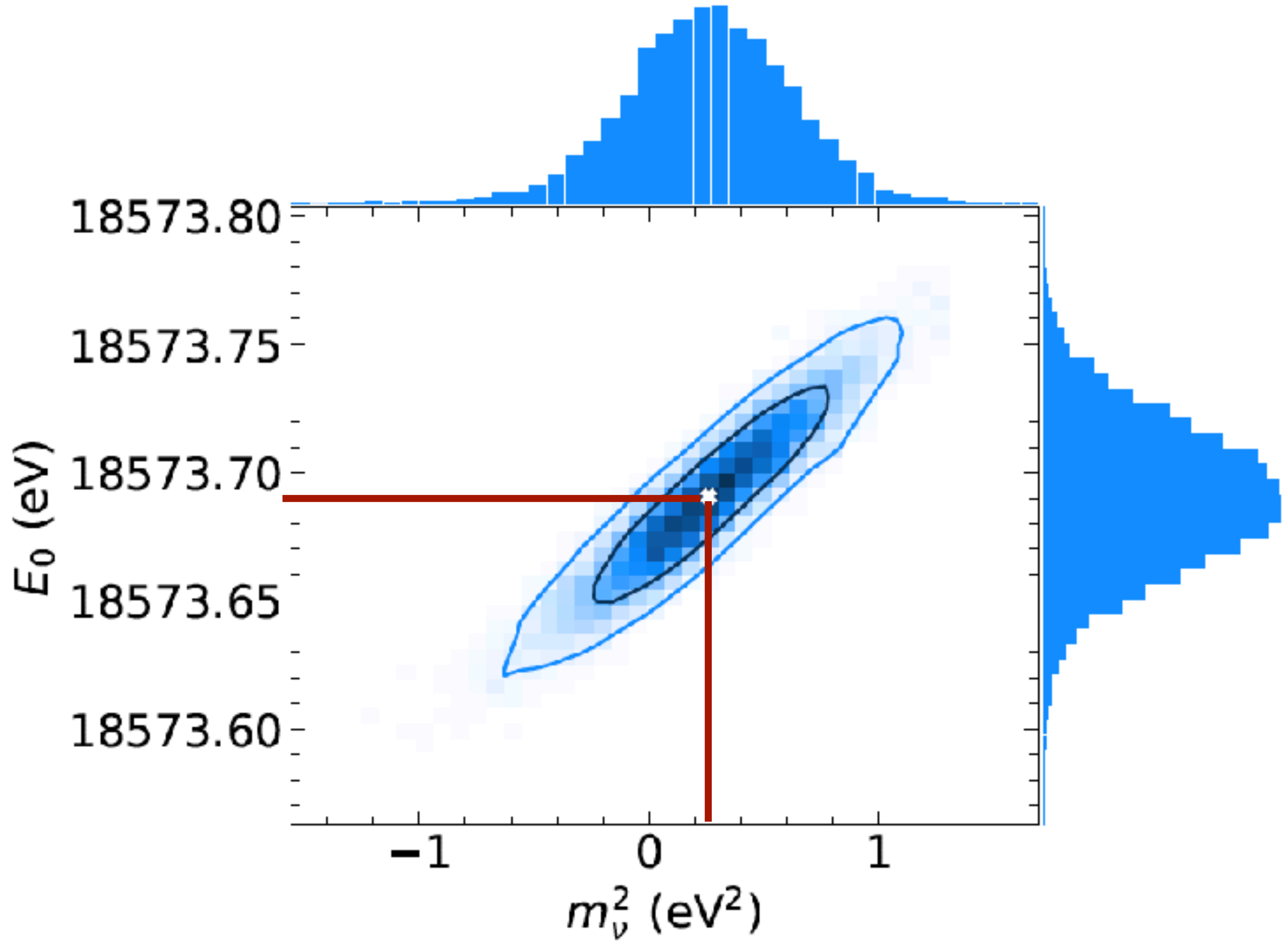
- 10 m diameter UHV vessel
- Tritium operation in June 2018
- First results in Sept 2019

State of the Art Beta Decay Experiment: KATRIN



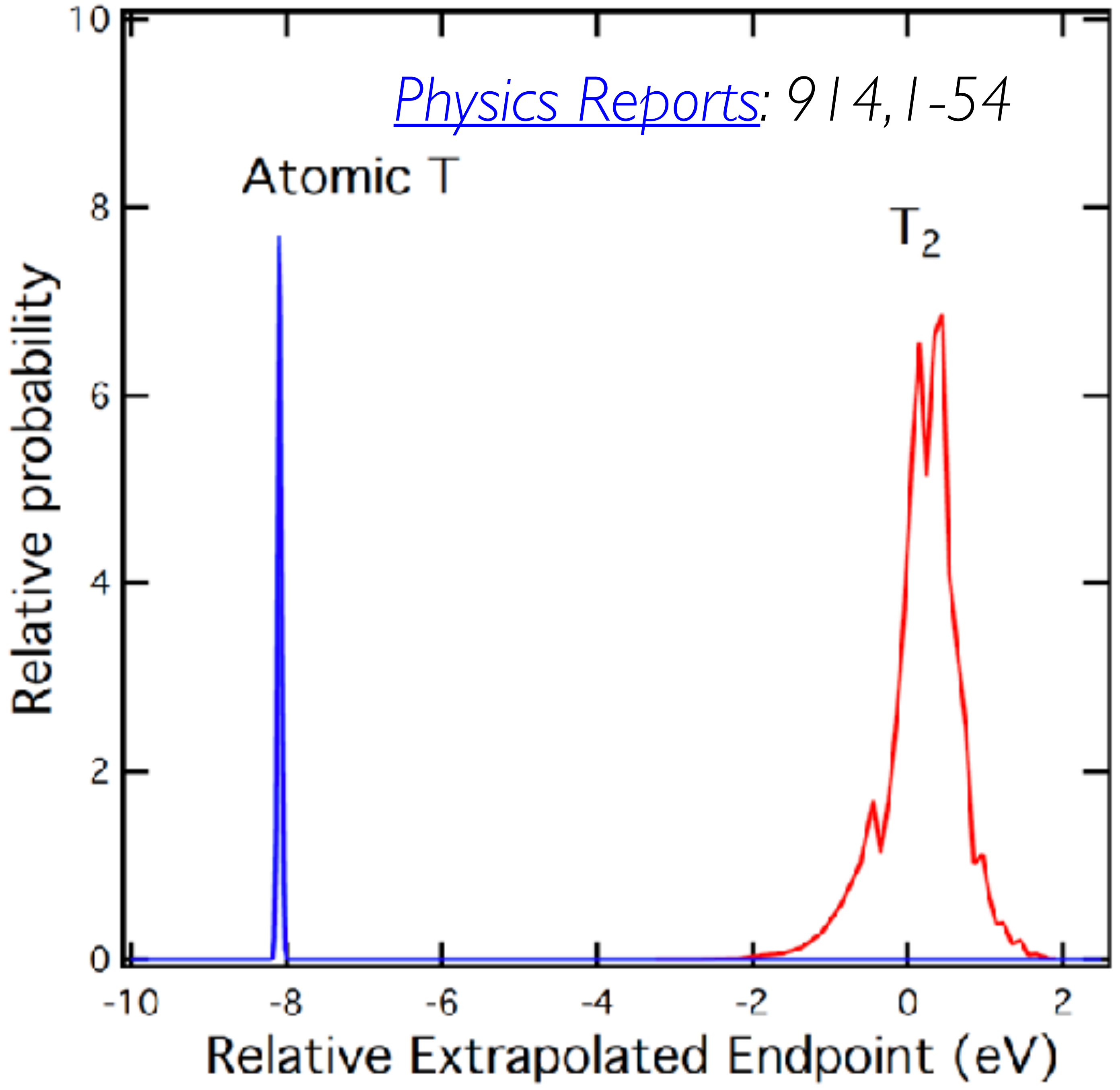
Nature Phys. 18 (2022) 2, 160-166

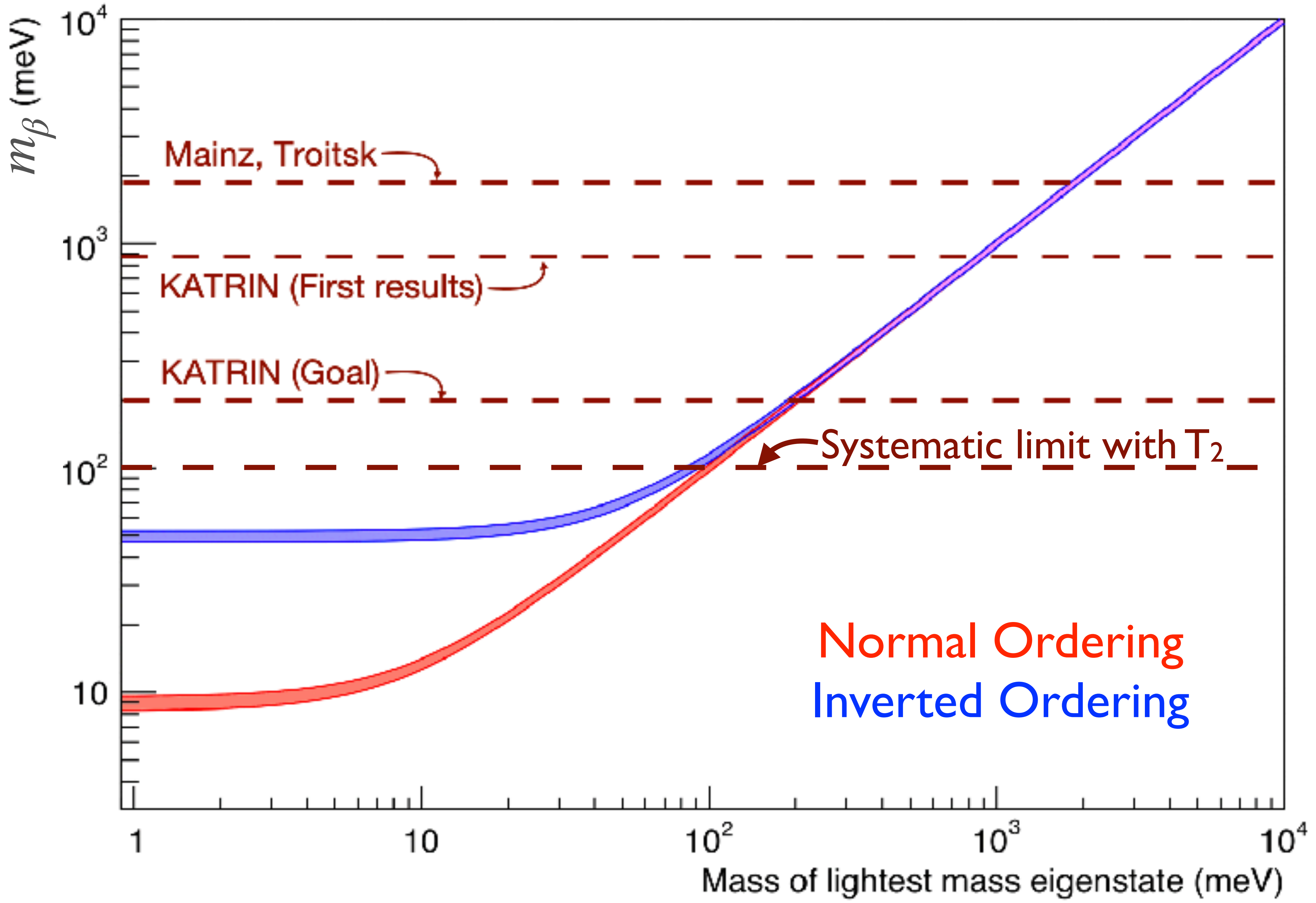
- Two measurement campaigns totaling ~53 days of data
- Upper limit: 0.8 eV/c² (90% CL)



State of the Art Beta Decay Limitations

- KATRIN's projected sensitivity is 200 meV (90% CL)
- Source column density in KATRIN is close to maximum: Limits number of decays
- Significant scaling of the spectrometer needed to improve sensitivity further
- Broadening of the final-state energy distribution of molecular tritium limits its sensitivity

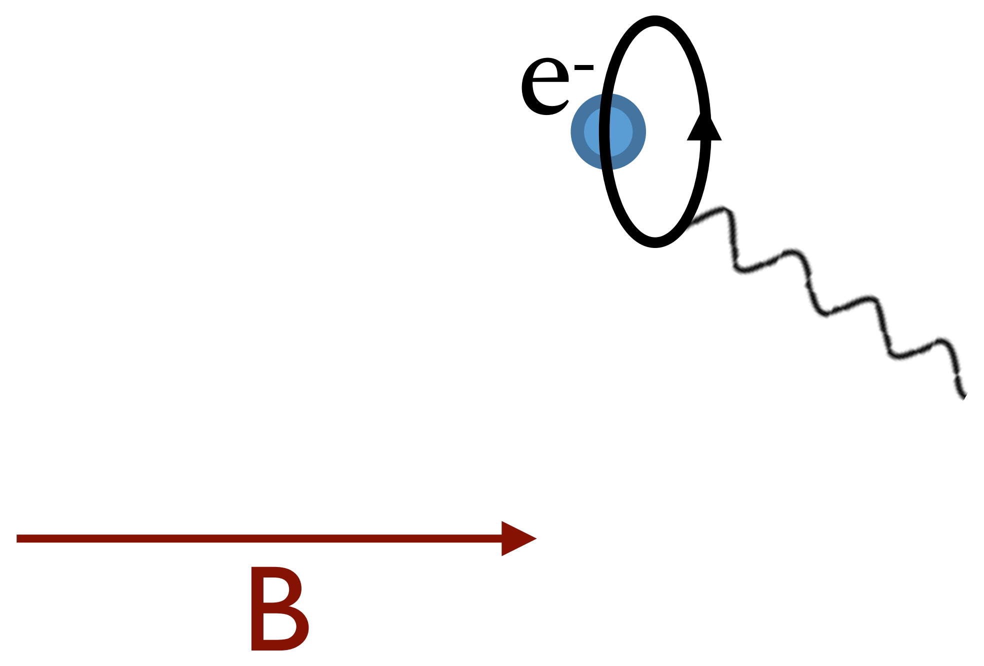




Need new technique and atomic tritium to improve sensitivity past KATRIN's limit

Cyclotron Radiation Emission Spectroscopy (CRES)

- Proposed by Monreal and Formaggio : *PRD* **80**, 051301 (2009)
  - Place beta decay (of tritium) electron in uniform magnetic field
  - It undergoes cyclotron motion and emits cyclotron radiation



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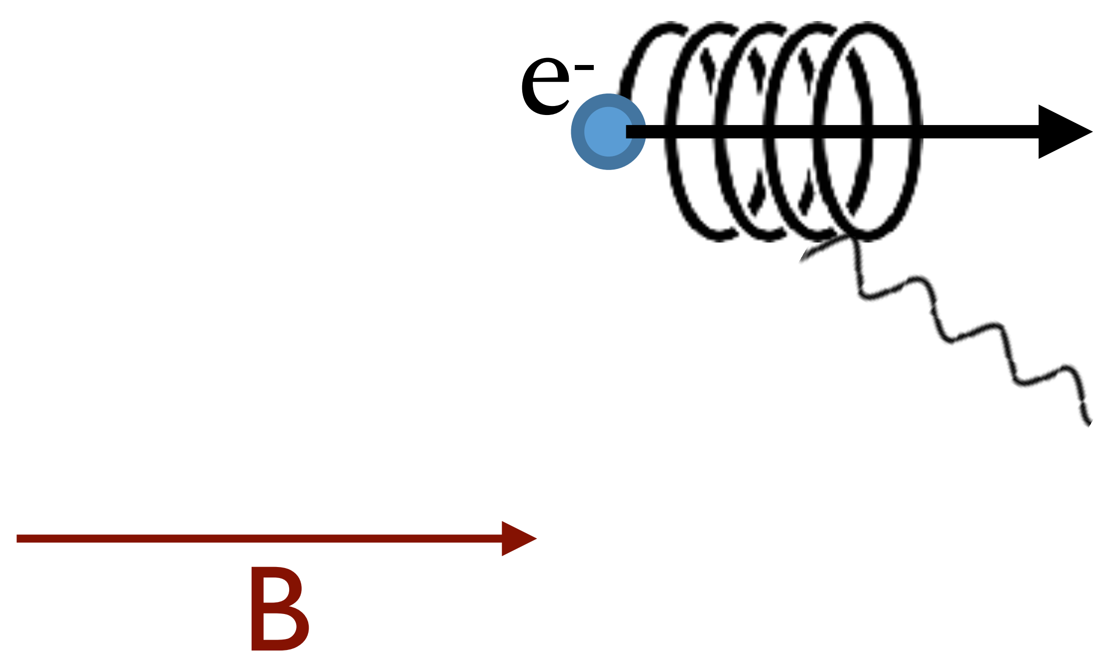

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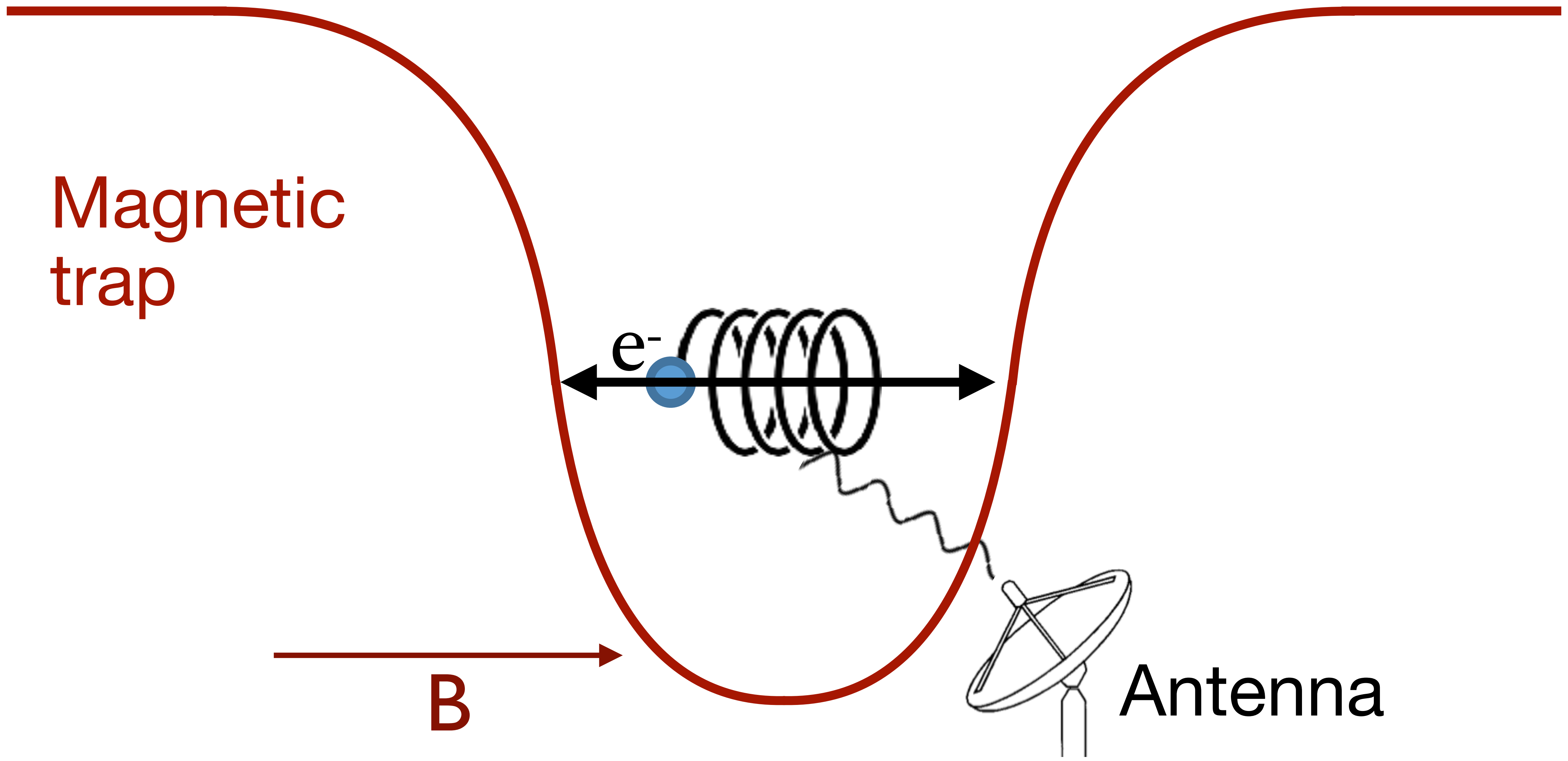

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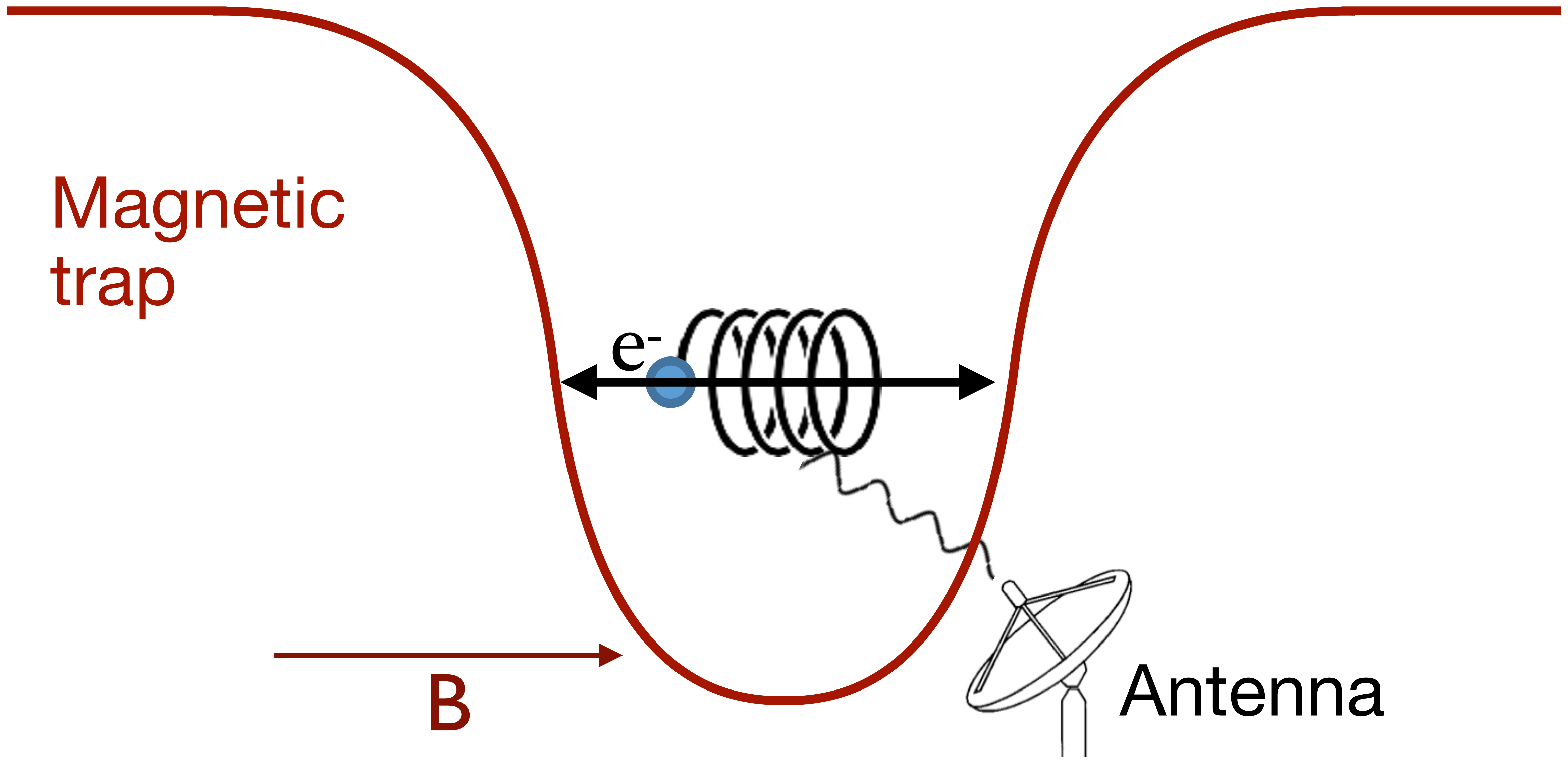
  - Keep the electron for long enough time to measure the cyclotron frequency
  - Cyclotron frequency has one-to-one relation with the electron kinetic energy
  - Extract electron spectrum by making sure there are enough of these electrons

$$\boxed{\omega} = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + \boxed{E}}$$

For 18.6 keV electrons
~26 GHz, 1 fW @ 1 T



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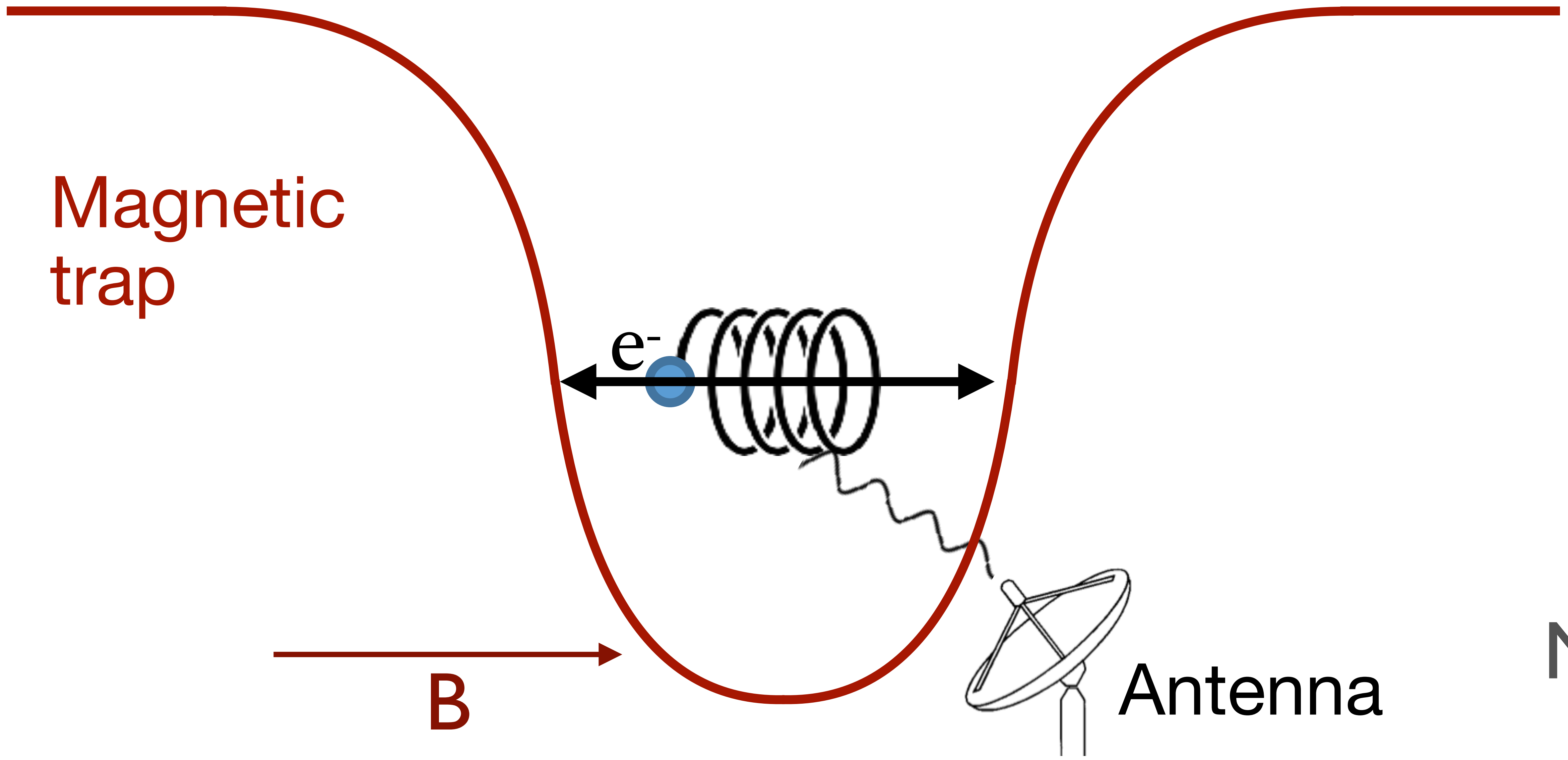


Major advantage: No electron transport needed

Project 8 Experiment

Case Western Reserve University
−Razu Mohiuddin, Benjamin Monreal, Yu-Hao Sun

Indiana University
−Walter Pettus

Harvard-Smithsonian Center for Astrophysics
−Sheperd Doeleman, Jonathan Weintroub, André Young

Johannes Gutenberg-Universität Mainz
−Sebastian Böser, Martin Fertl, Alec Lindman, Christian Matthé, Rene Reimann, Florian Thomas, Larisa Thorne

Karlsruher Institut für Technologie
−Thomas Thümmler

Lawrence Livermore National Laboratory
−Kareem Kazkaz

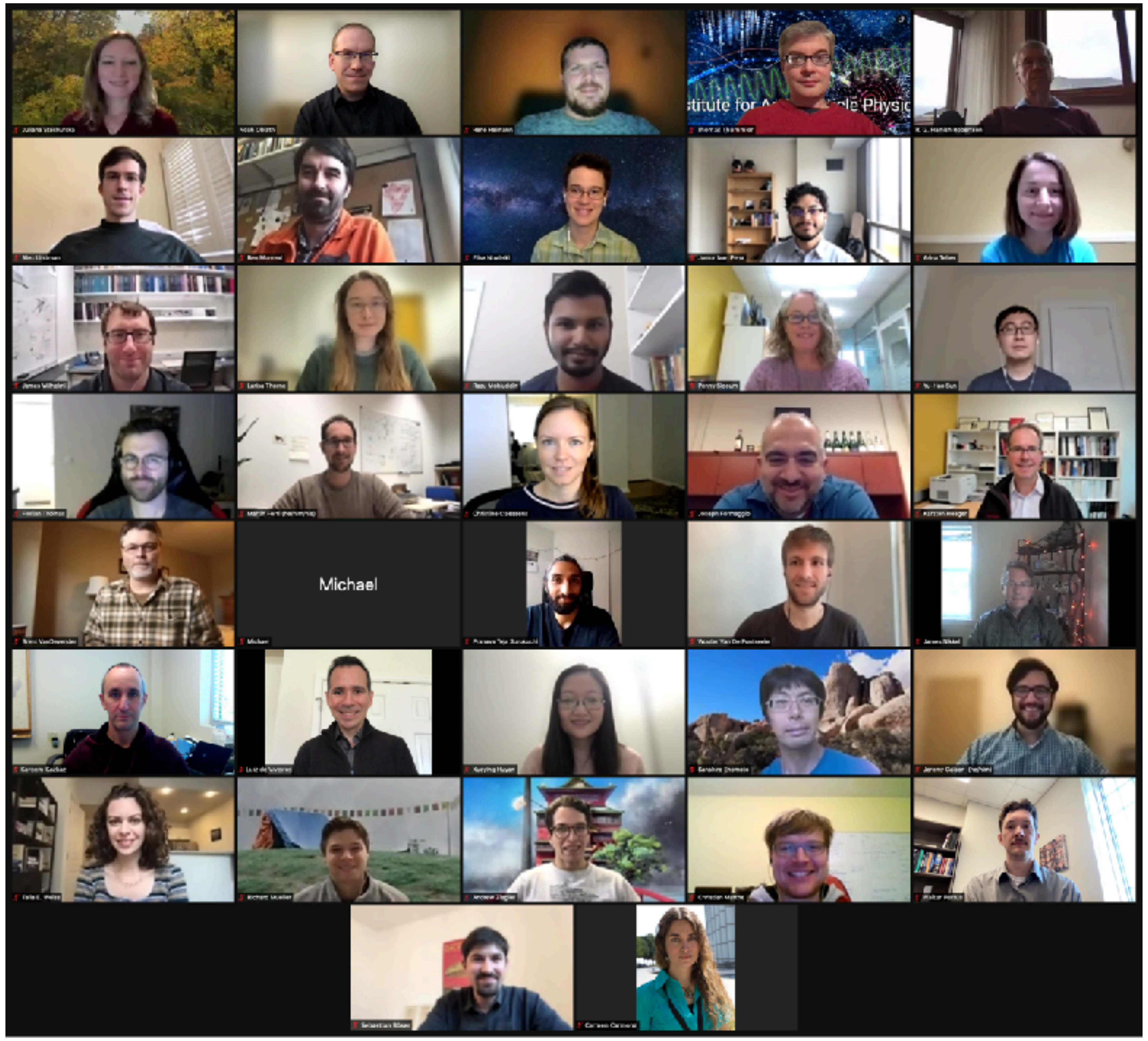
Massachusetts Institute of Technology
−Nicholas Buzinsky, Joseph Formaggio, MingyuLi, Junior Pena, Juliana Stachurska, WouterVan de Pontseele

Pacific Northwest National Laboratory
−Maurio Grando, Xueying Huyan, Mark Jones, Noah Oblath, Benjamin LaRoque, Malachi Schram, Jonathan Tedeschi, Mathew Thomas, Brent VanDevender

Pennsylvania State University
−Carmen Carmona-Benitez, Luiz de Viveiros, Andrew Ziegler

University of Washington
−Ali Ashtari Esfahani, Christine Claessens, Peter Doe, Sanshiro Enomoto, Elise Novitski, Hamish Robertson, Leslie Rosenberg, David Sweigart, Gray Rybka

Yale University
−Karsten Heeger, James Nikkel, Luis Saldaña, Penny Slocum, Pranava Teja Surukuchi, Arina Telles, Talia Weiss



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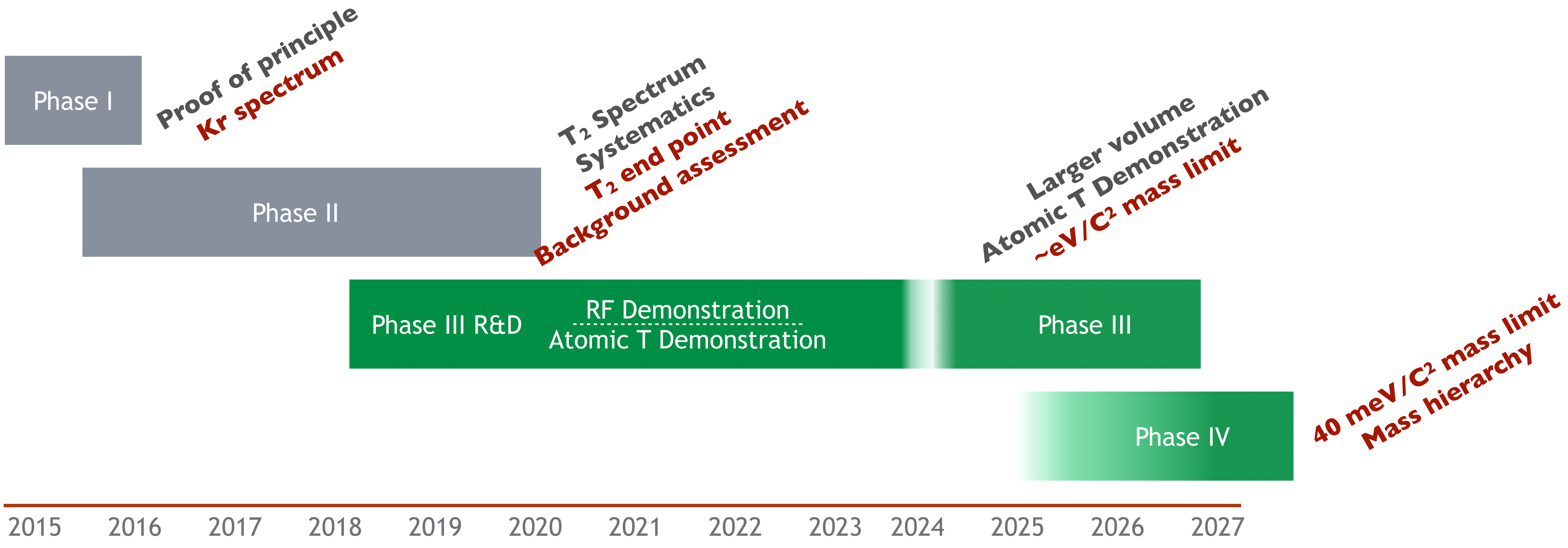
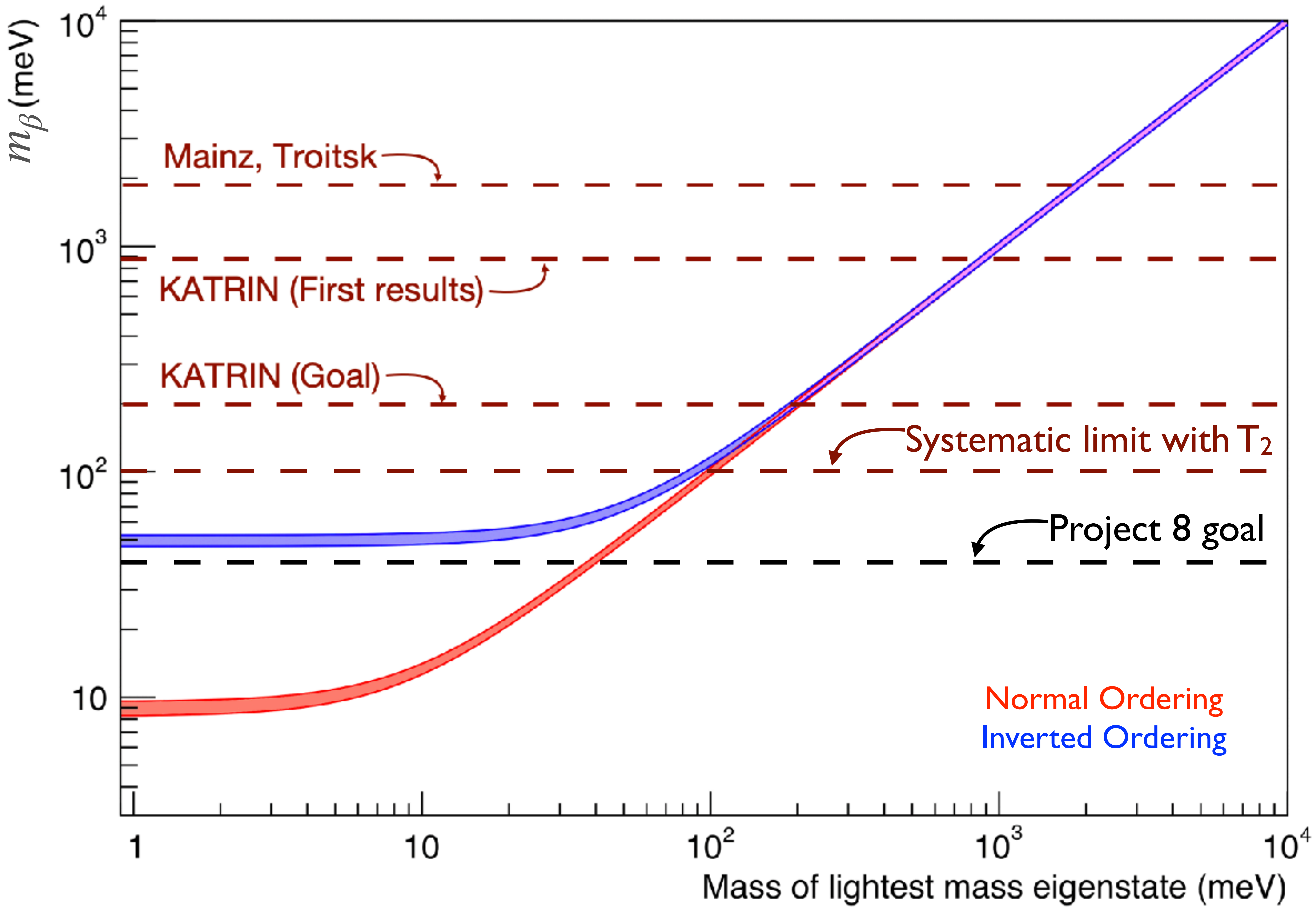
Project 8 Experiment

PROJECT 8

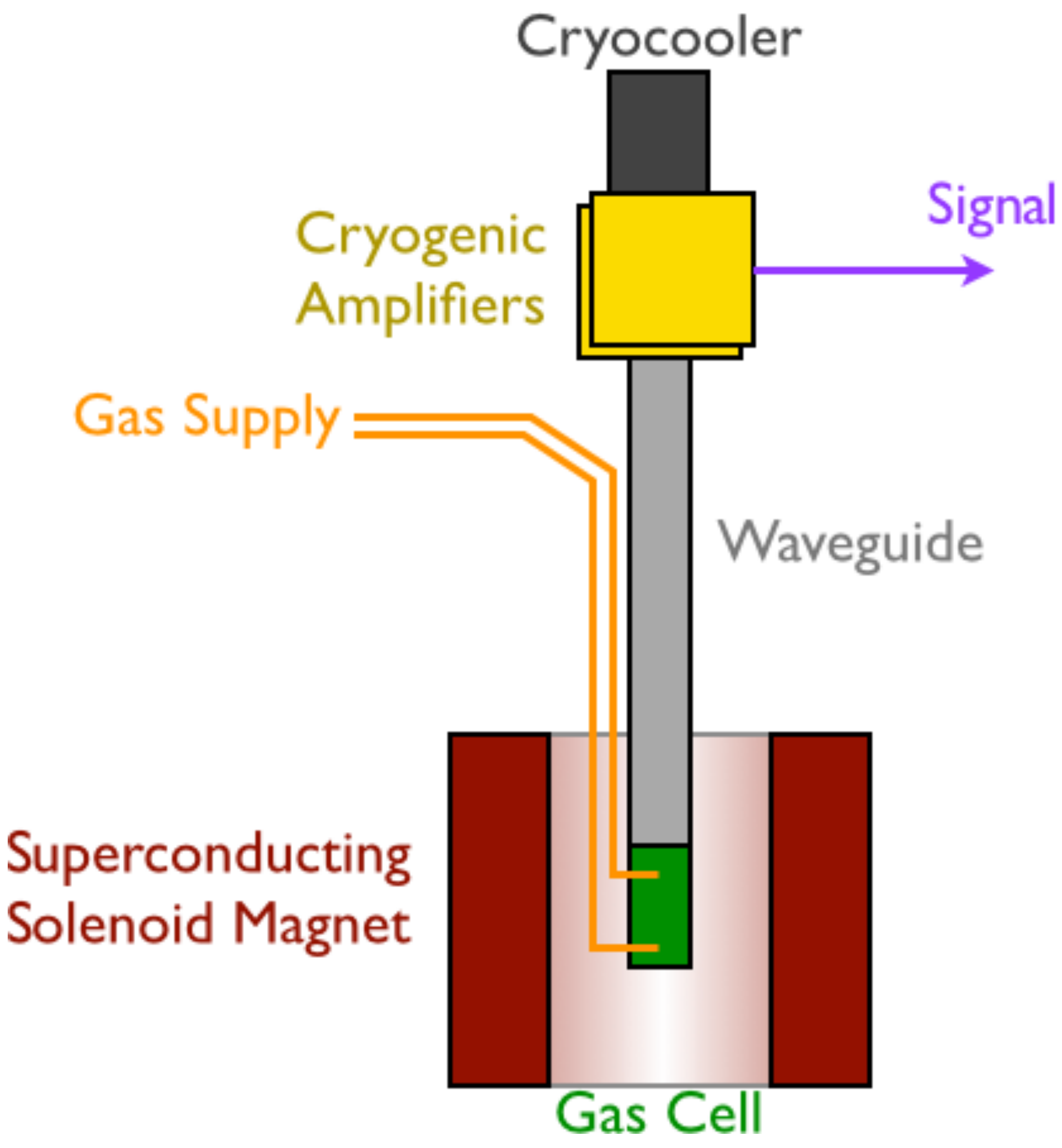
Phased approach to measure neutrino mass



Project 8 Goal

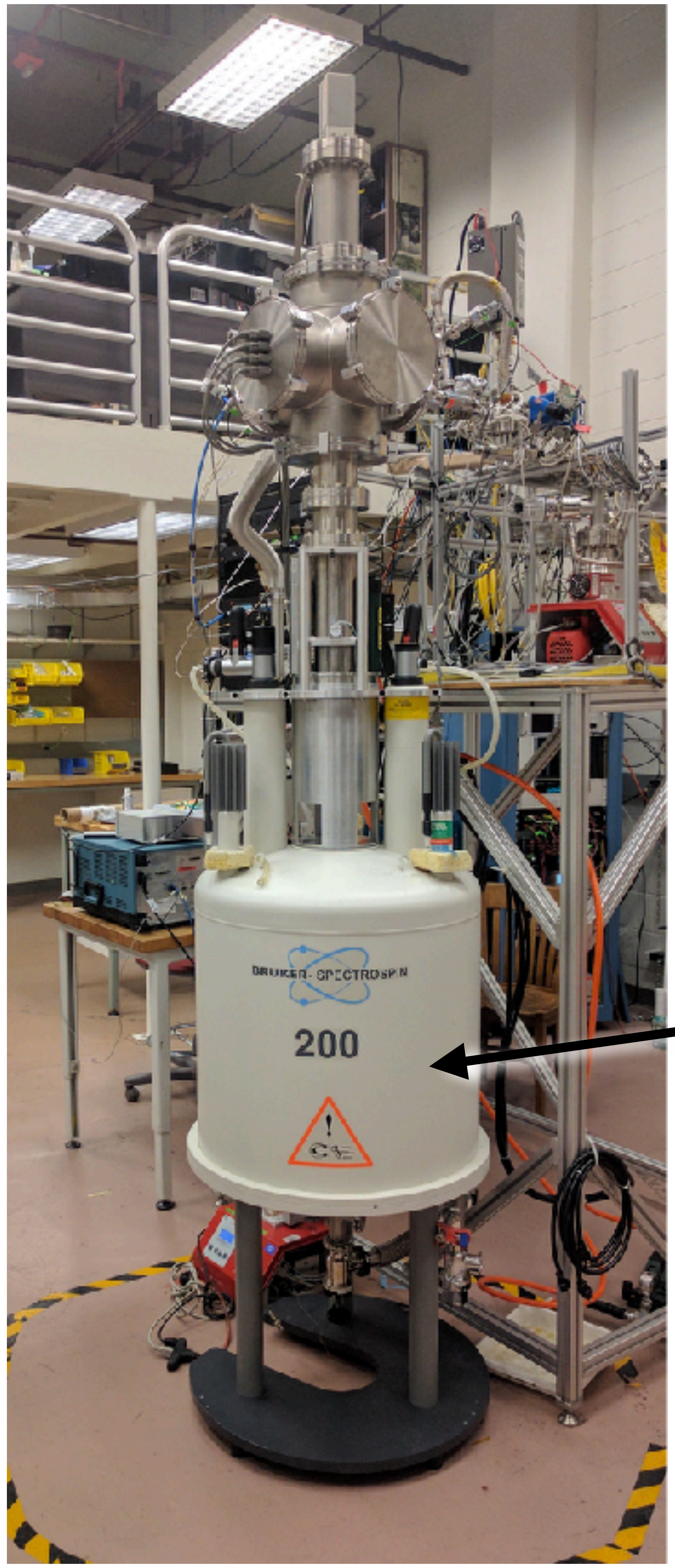


Experimental Setup: Phases I and II



- **Magnetic field:** *Provide background B field*
- **Insert:**
  - **Gas cell:** *Contains source gas*
  - **Trap:** *Traps the electrons*
  - **Waveguide:** *Transmits the RF signal*
  - **Amplifier:** *Amplifies the RF signal*
- **Gas system:** *Feed gas to the cell*

Phase I & II



NMR
magnet

- **Magnetic field:** *NMR superconducting magnet ~ 1T*
- Insert:
  - Gas cell
  - Trap
  - Waveguide
  - **Amplifier:** *Two-stage low noise cryogenic amplifiers*
- Gas system:

Phase II

Phase II

T_2 Spectrum Systematics
T_2 end point
Background assesment

- **Magnetic field:** *NMR superconducting magnet ~ 1 T*
- **Insert:**
  - **Gas cell:** *Circular Waveguide with CaF_2 windows*
  - **Trap:** *Five trap coils*
  - **Waveguide:** *Rectangular waveguide*
  - **Amplifier:** *Two-stage low noise cryogenic amplifiers*
- **Gas system:** *Supplies both T_2 and ^{83m}Kr*

CaF_2 window

Phase II

Phase II

T_2 Spectrum
Systematics
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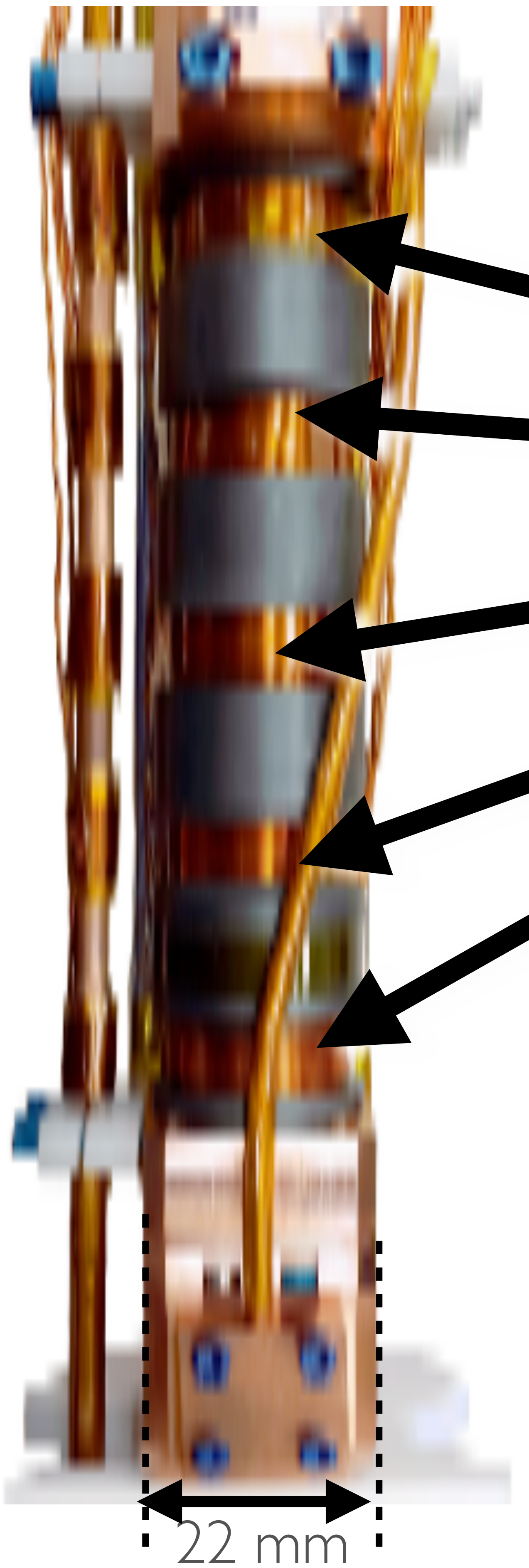

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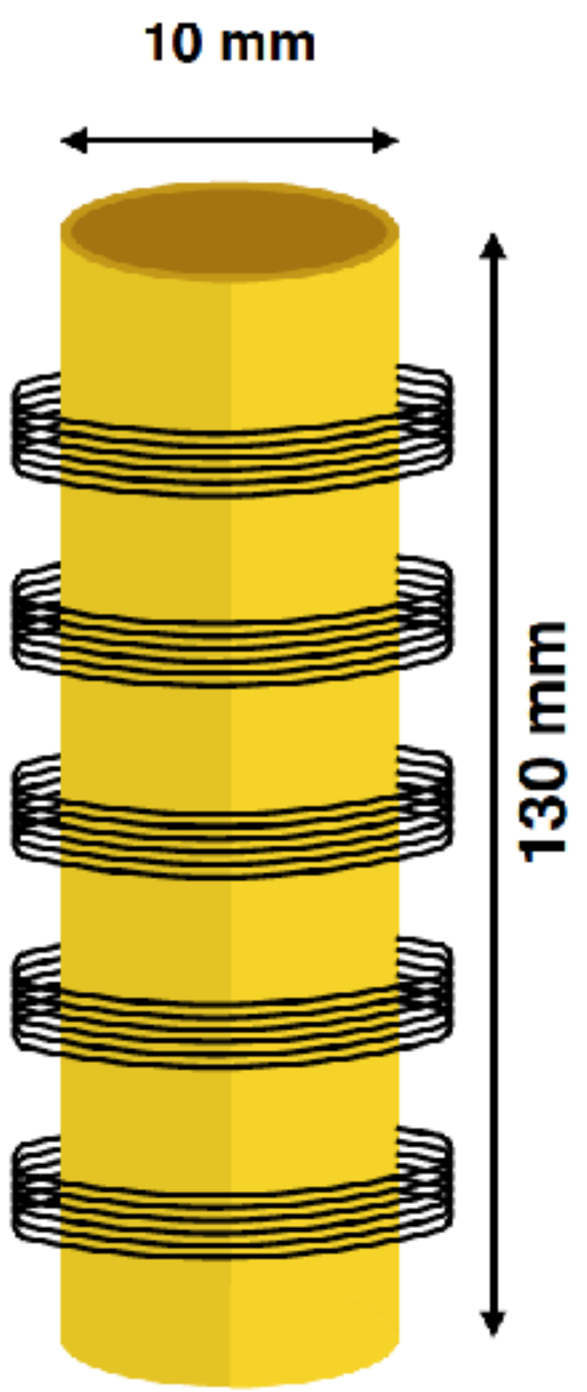

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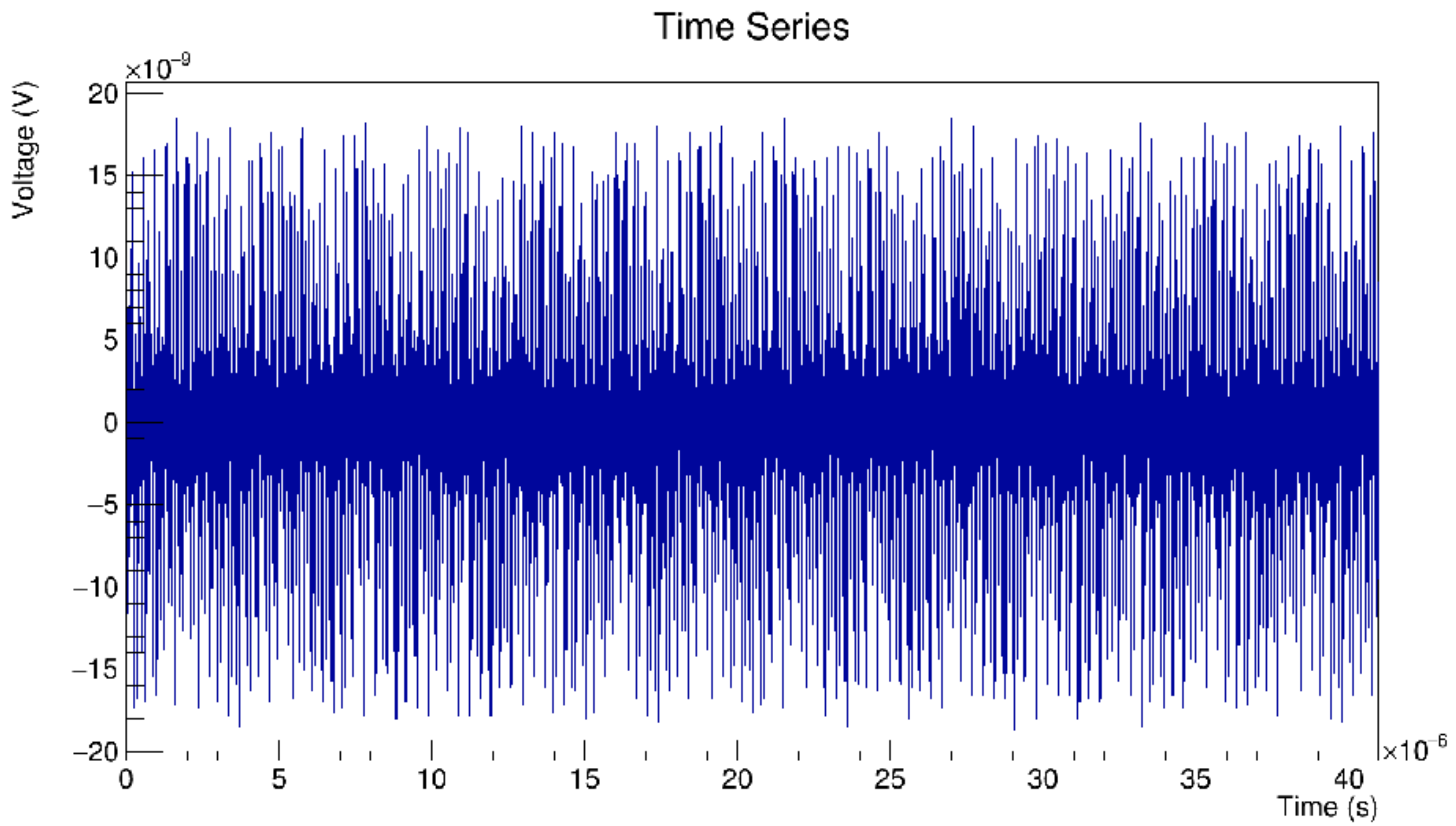
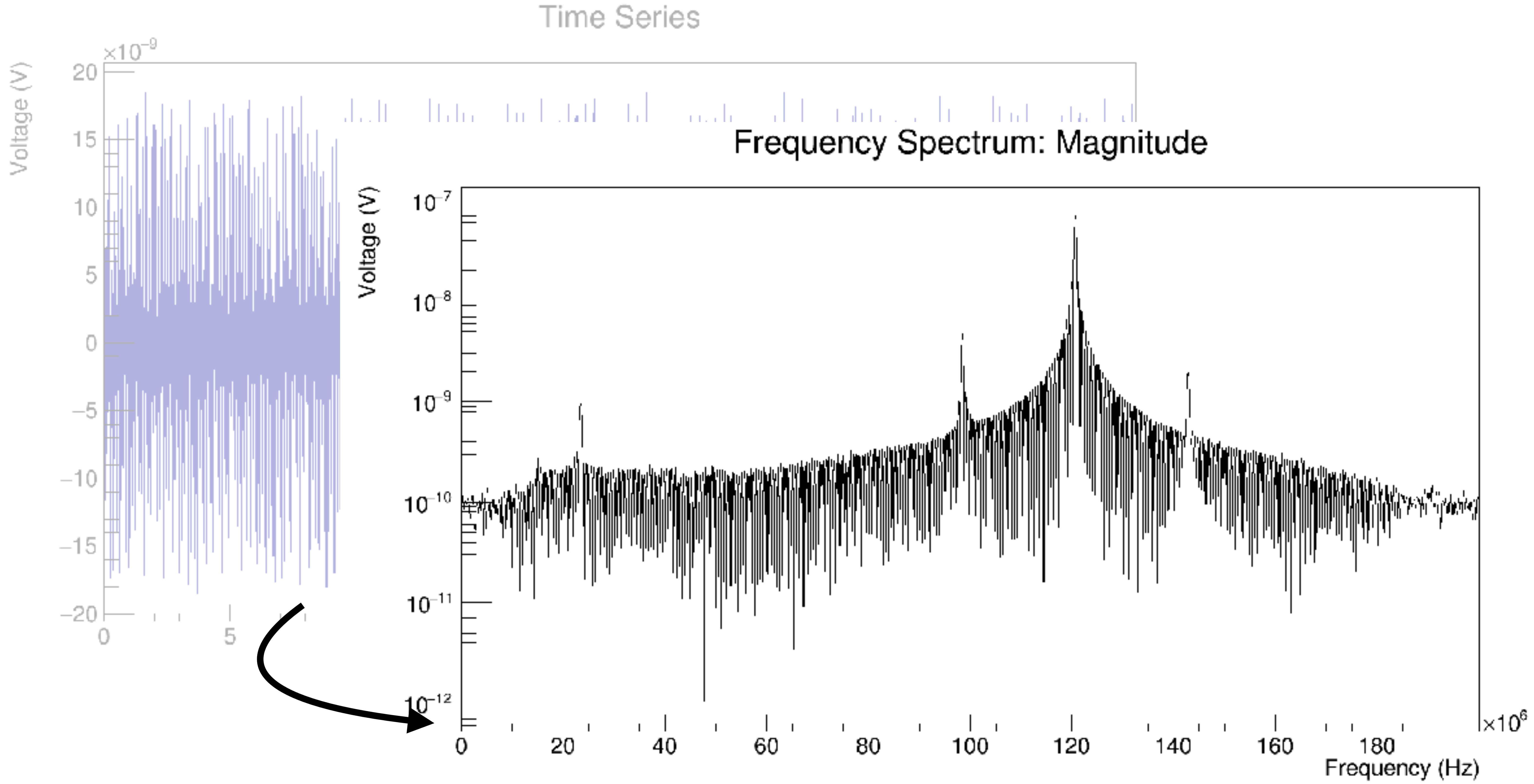
Phase II setup

Picture: Alec Lindman

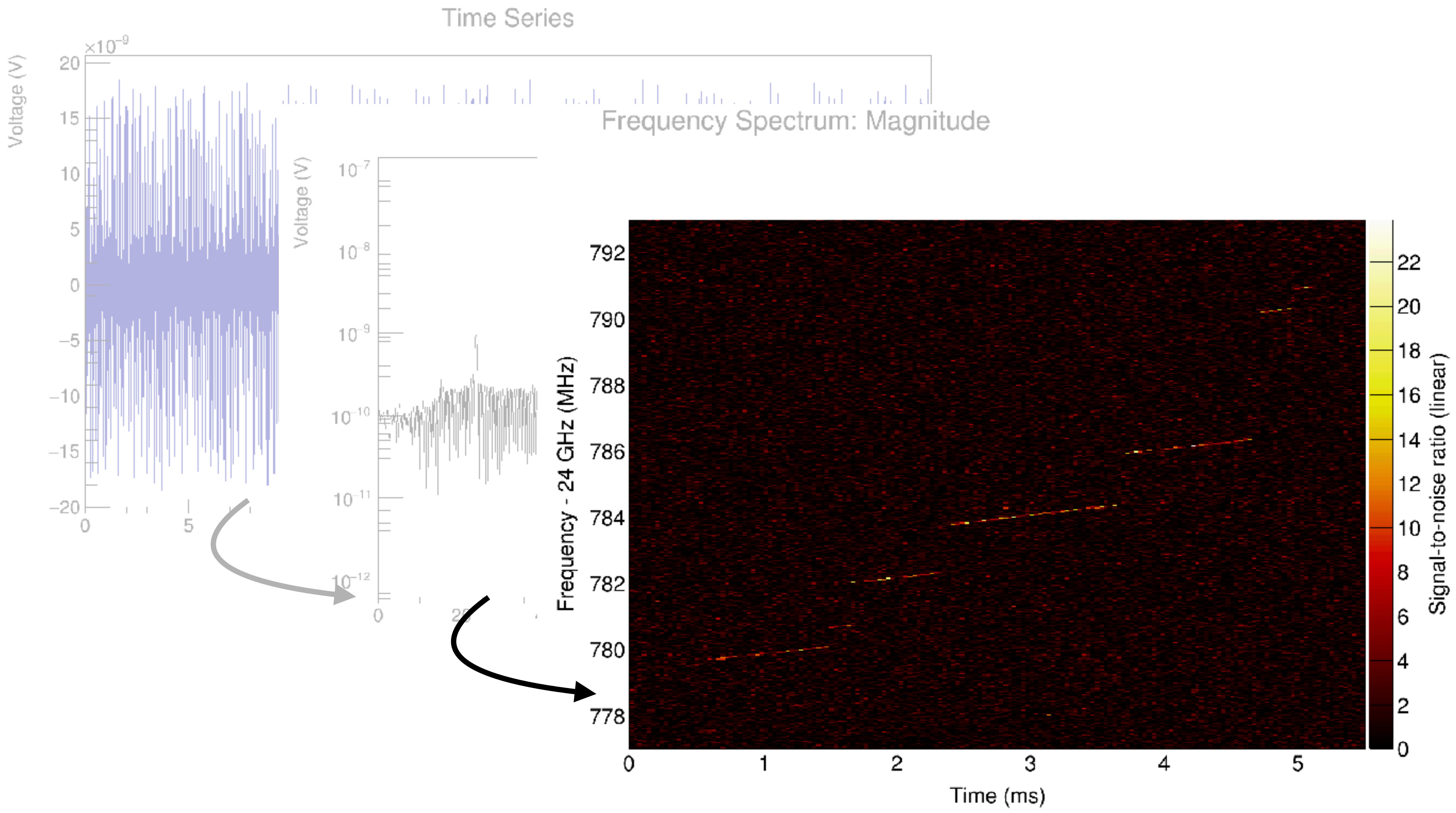
Data Analysis: Time series



Data Analysis: Frequency Spectrum



Data Analysis: Spectrogram



Asner et al., PRL 114, 162501 (2015)

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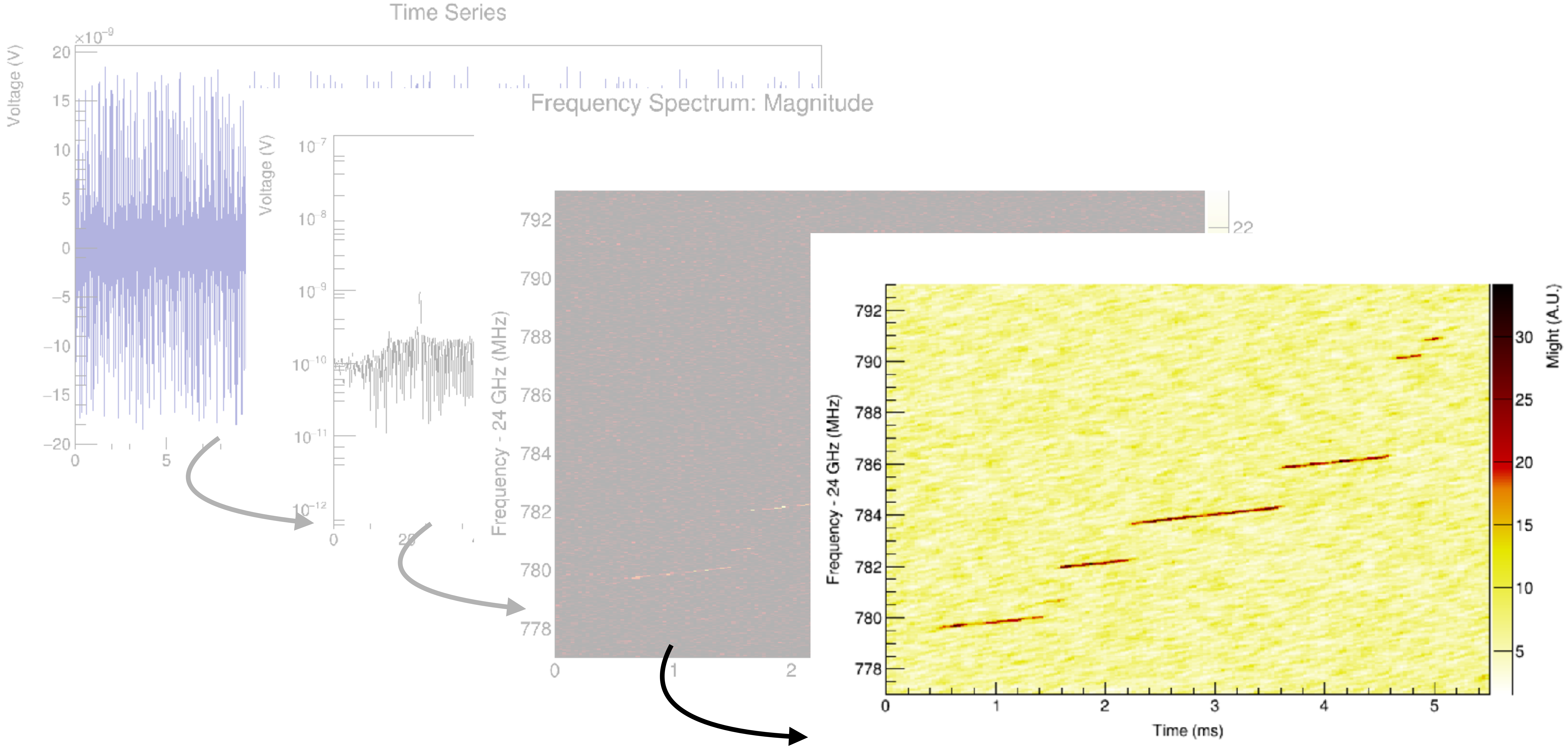

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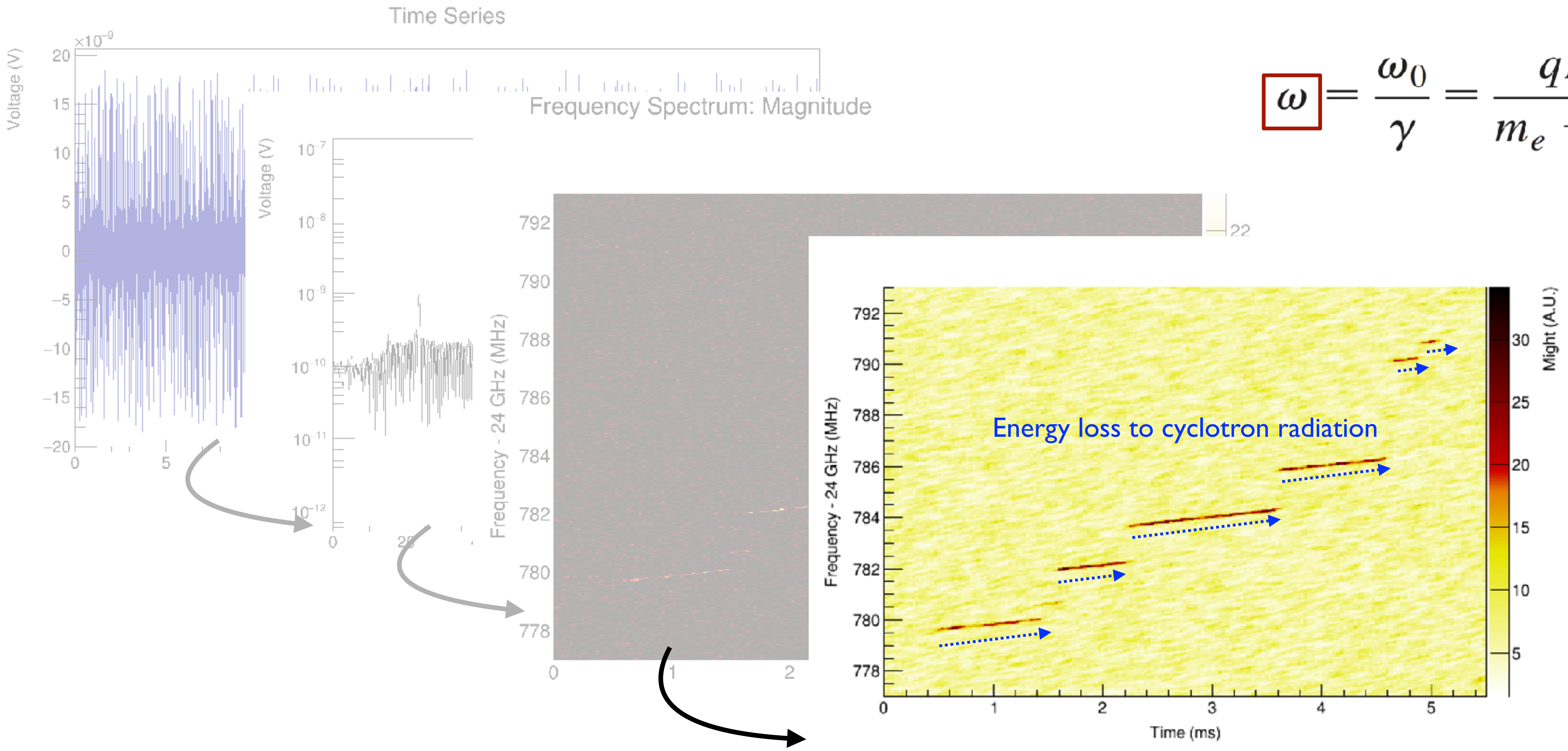
Data Analysis: Radiation Loss

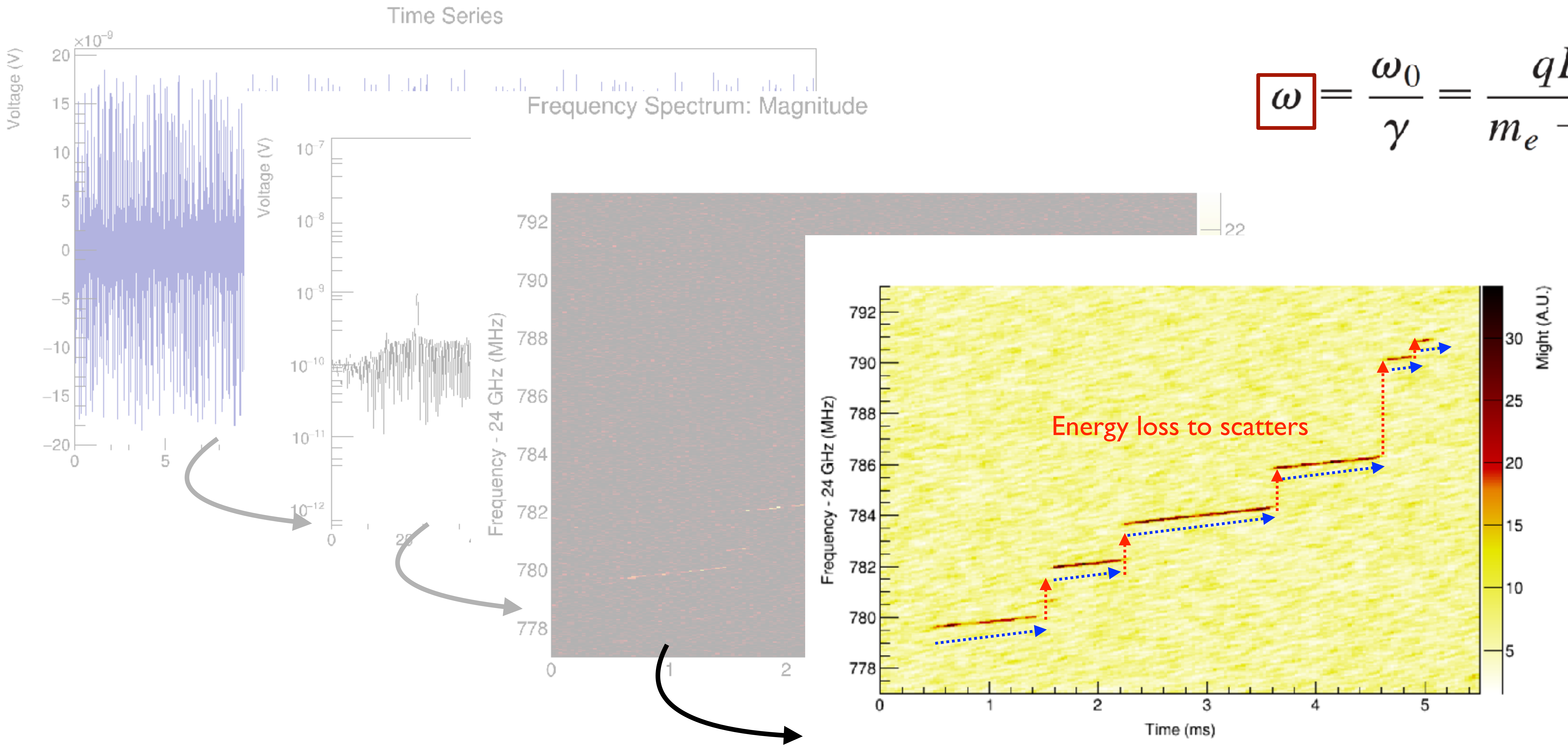
$$\boxed{\omega} = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + \boxed{E}}$$



Asner et al., PRL 114, 162501 (2015)

Data Analysis: Scattering Loss

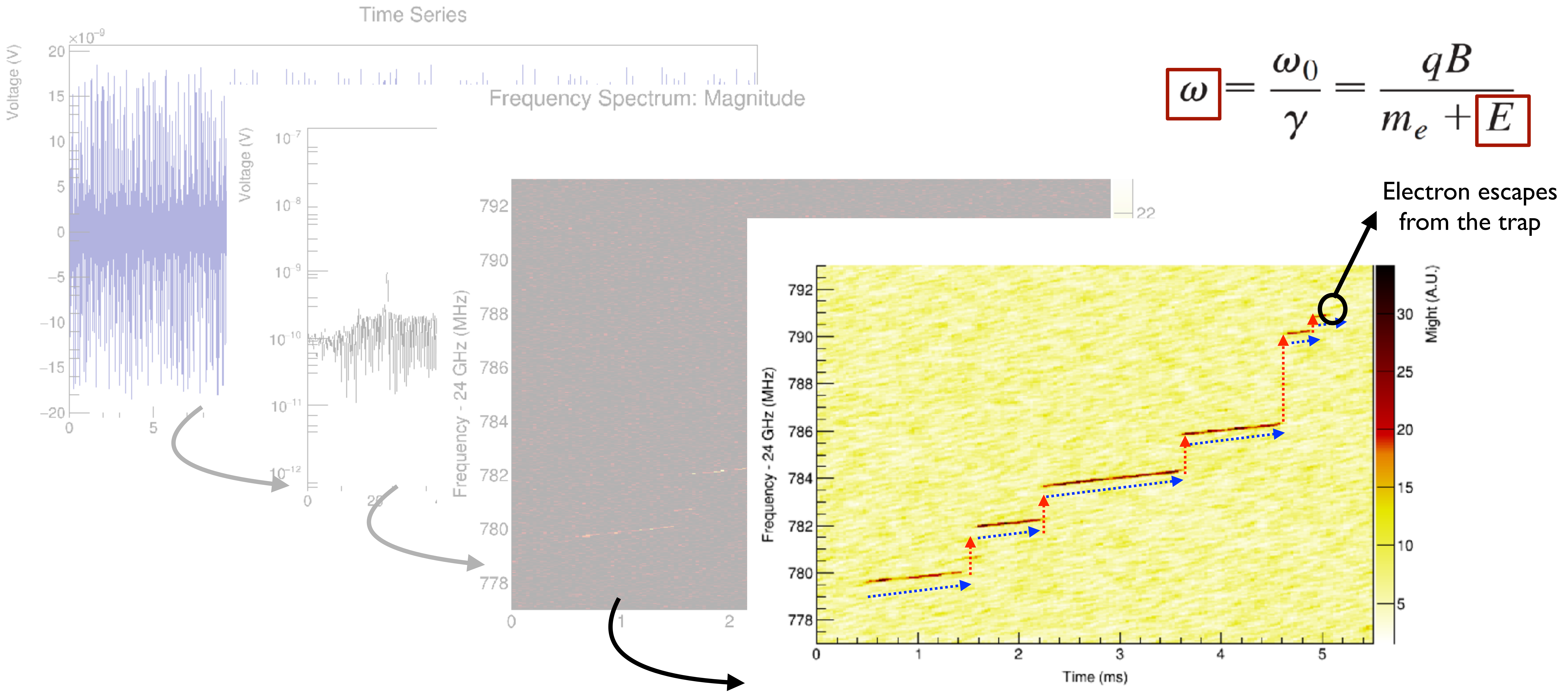
$$\boxed{\omega} = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + \boxed{E}}$$



Asner et al., PRL 114, 162501 (2015)

Data Analysis: Electron Escape

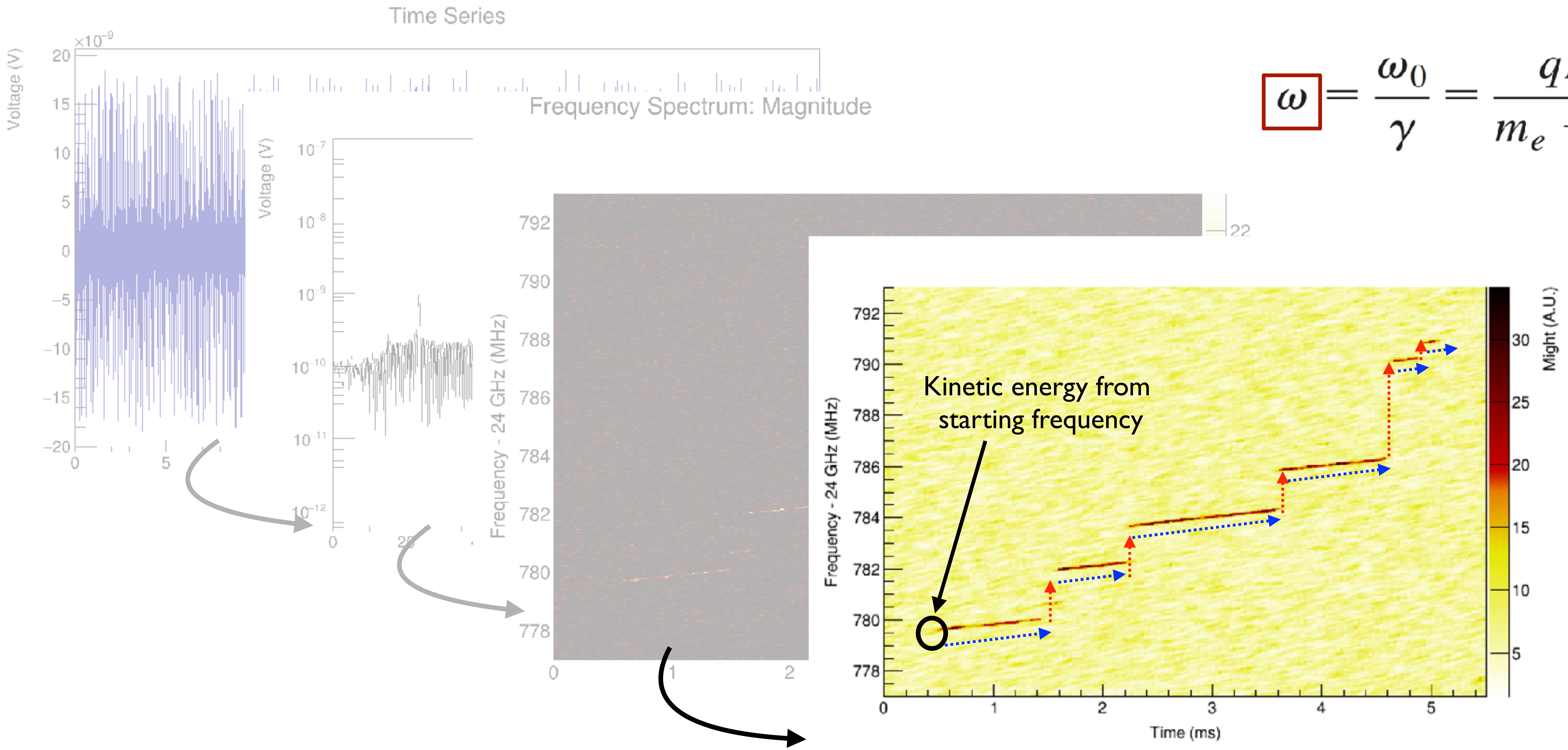
$$\boxed{\omega} = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + \boxed{E}}$$



Asner et al., PRL 114, 162501 (2015)

Data Analysis: Event

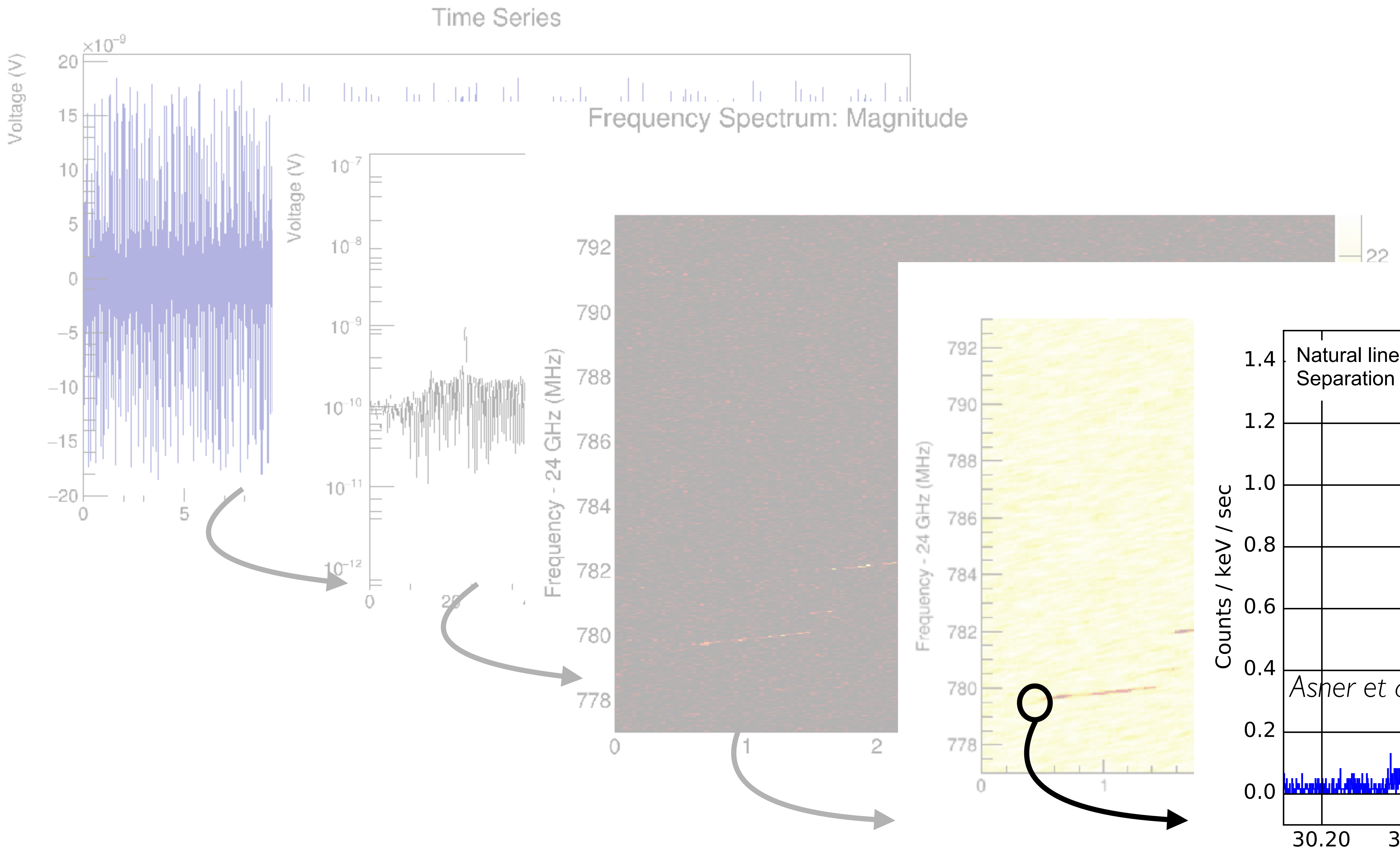
$$\boxed{\omega} = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + \boxed{E}}$$



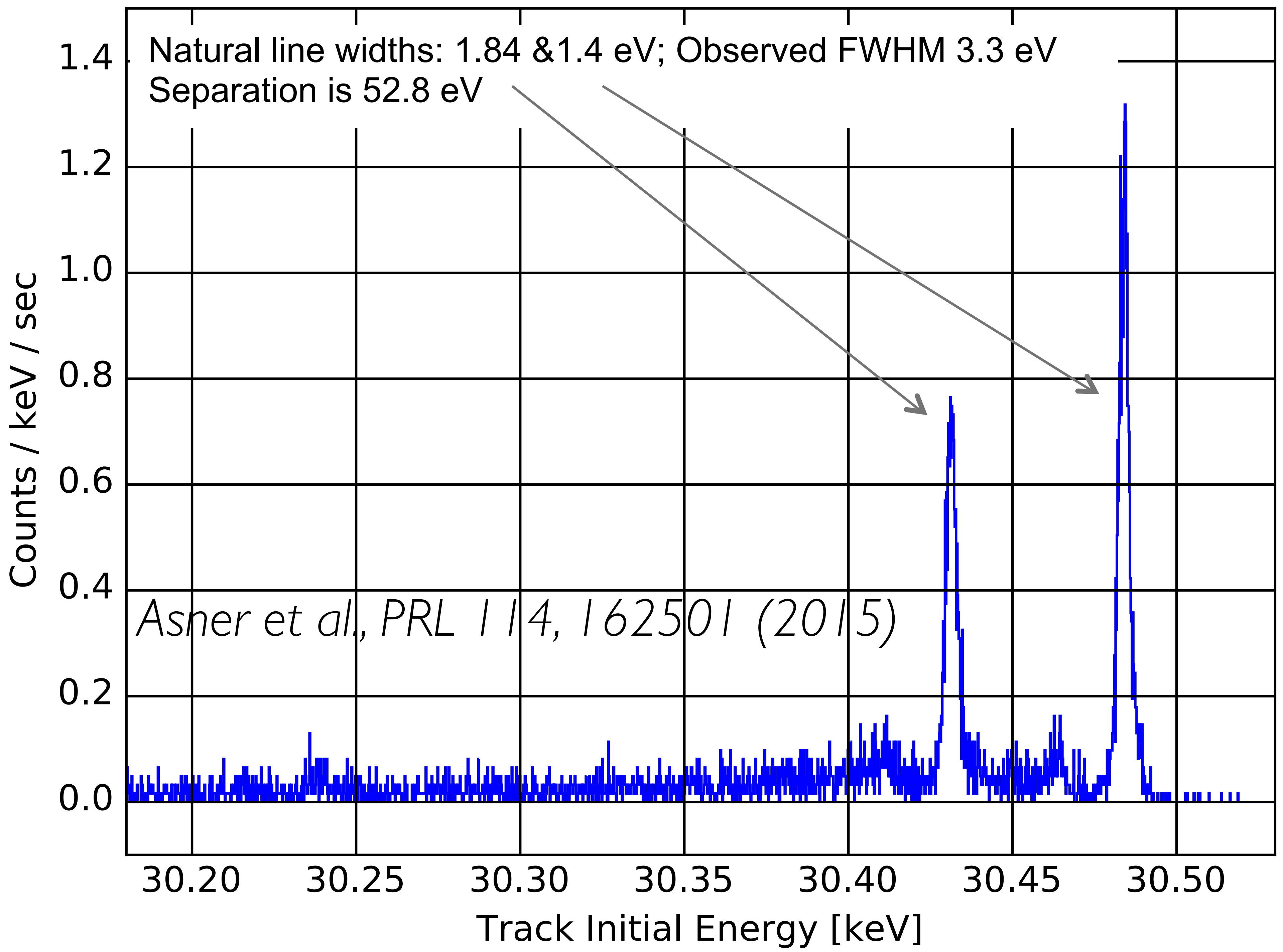
Asner et al., PRL 114, 162501 (2015)

Data Analysis: Energy Spectrum

$$\boxed{\omega} = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + \boxed{E}}$$



Phase-I Spectrum

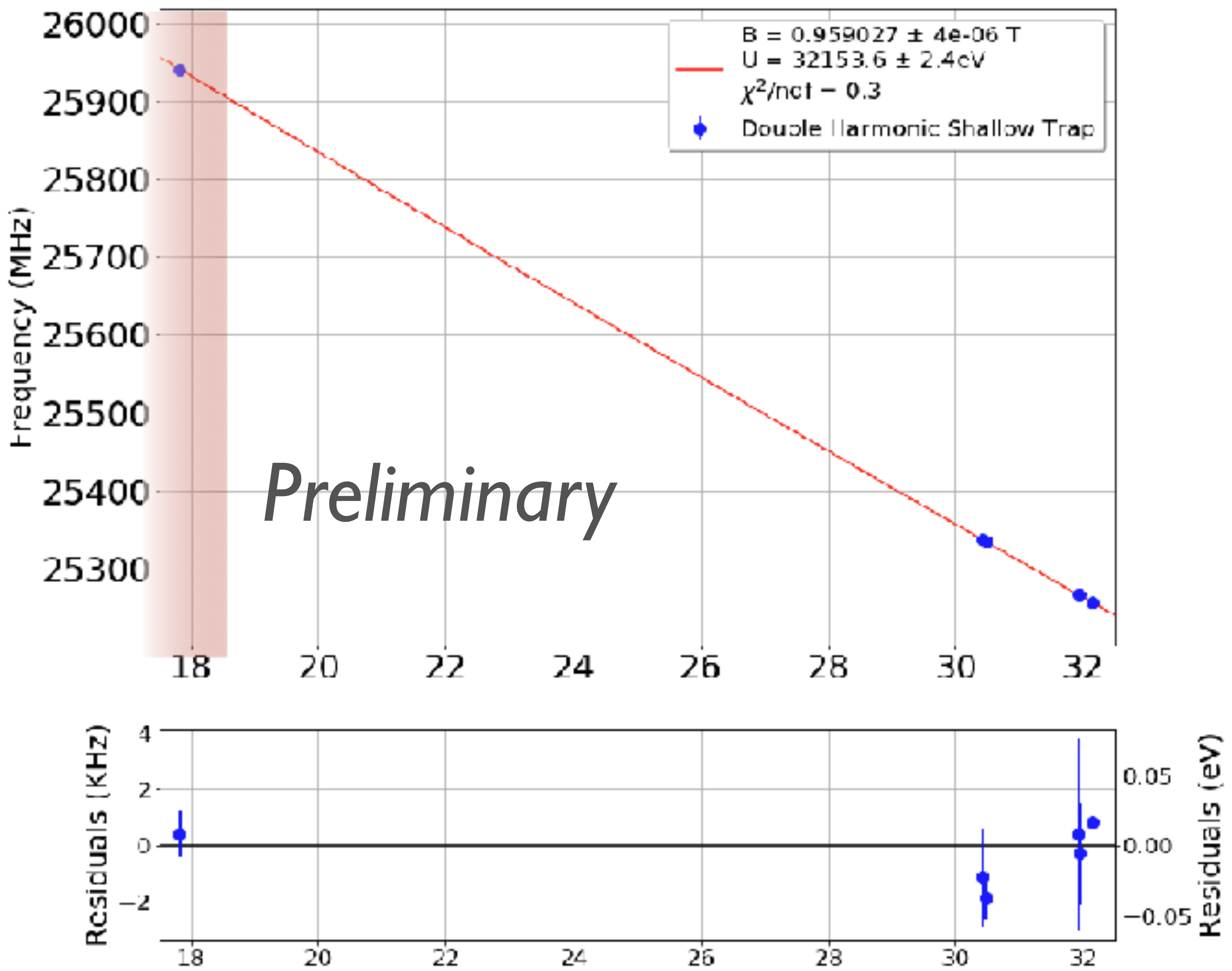


Phase II: Calibration

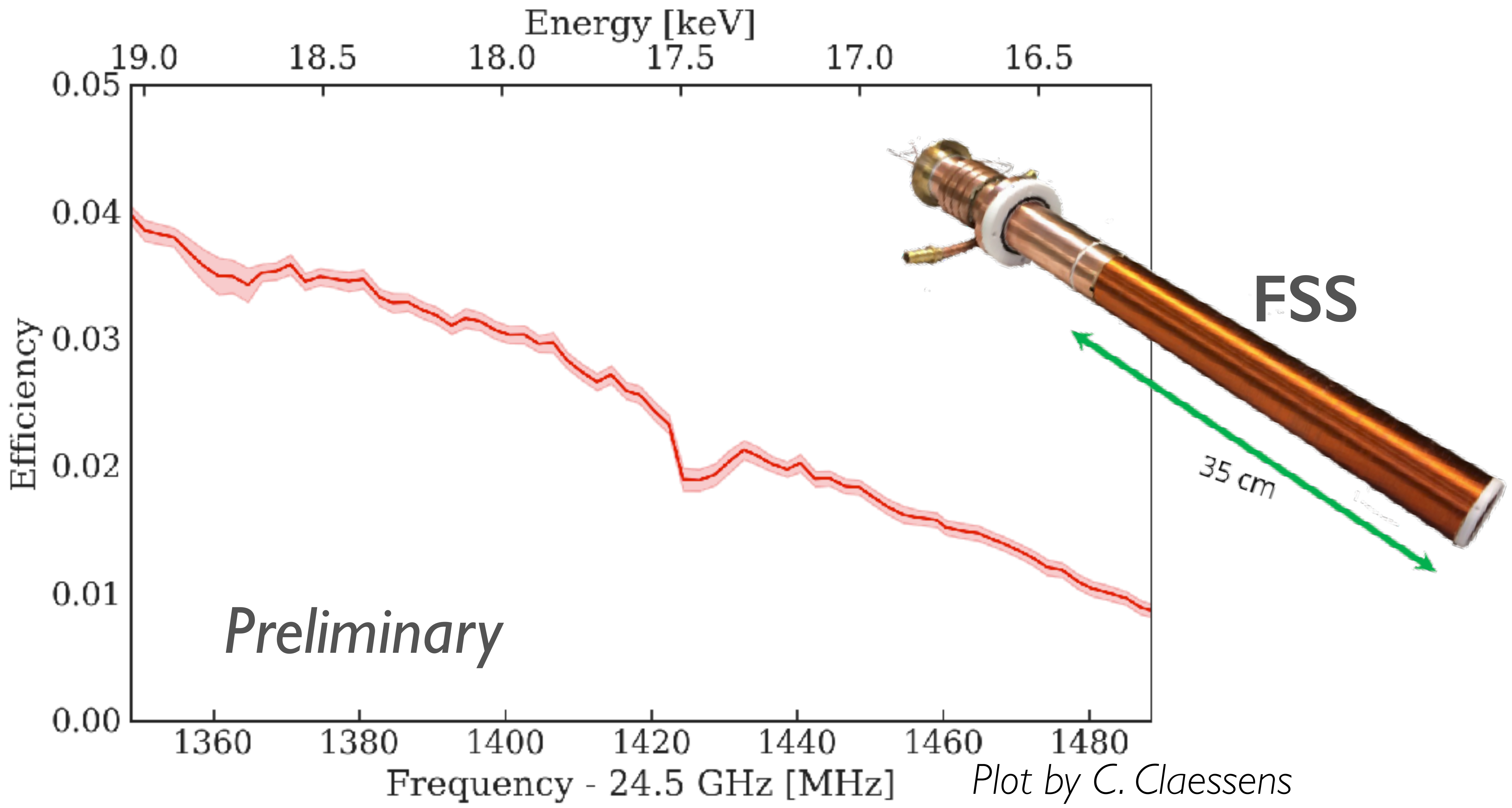
- Linearity of CRES demonstrated using ^{83m}Kr
- Energy-dependent efficiency extracted using Field Shifting Solenoid

T_2 Spectrum
Systematics
T_2 end point
Background assessment

$$\omega = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + E}$$

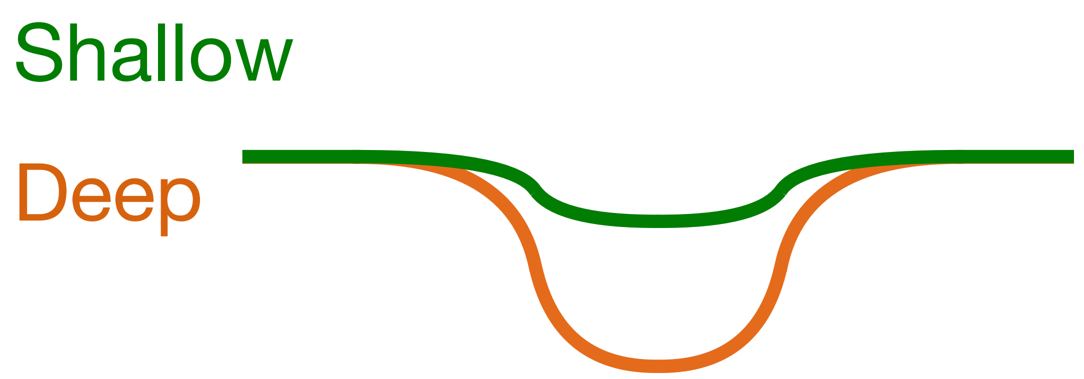


Plot by A. Ashtari Esfahani



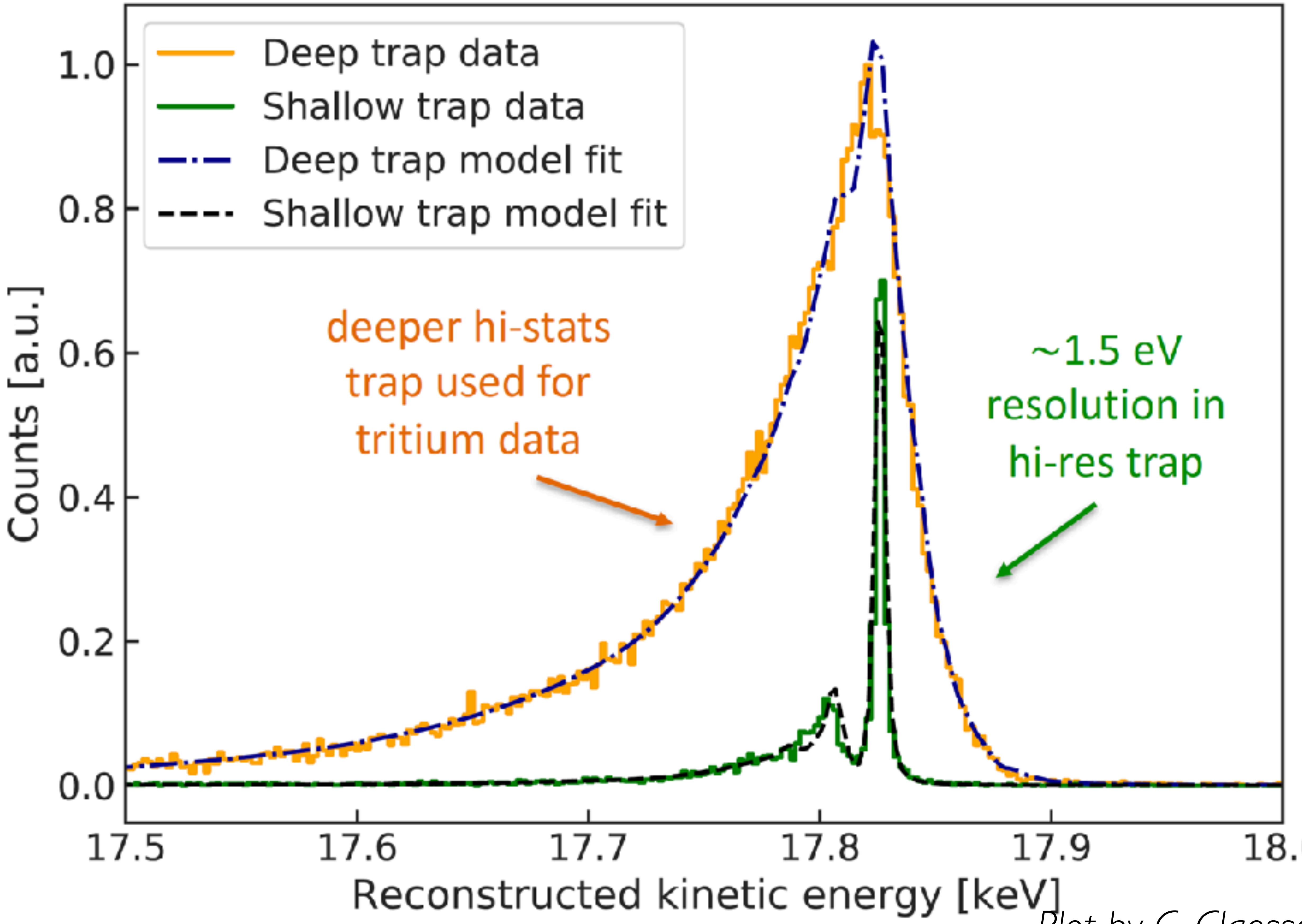
Plot by C. Claessens

Phase II: Trap Geometries



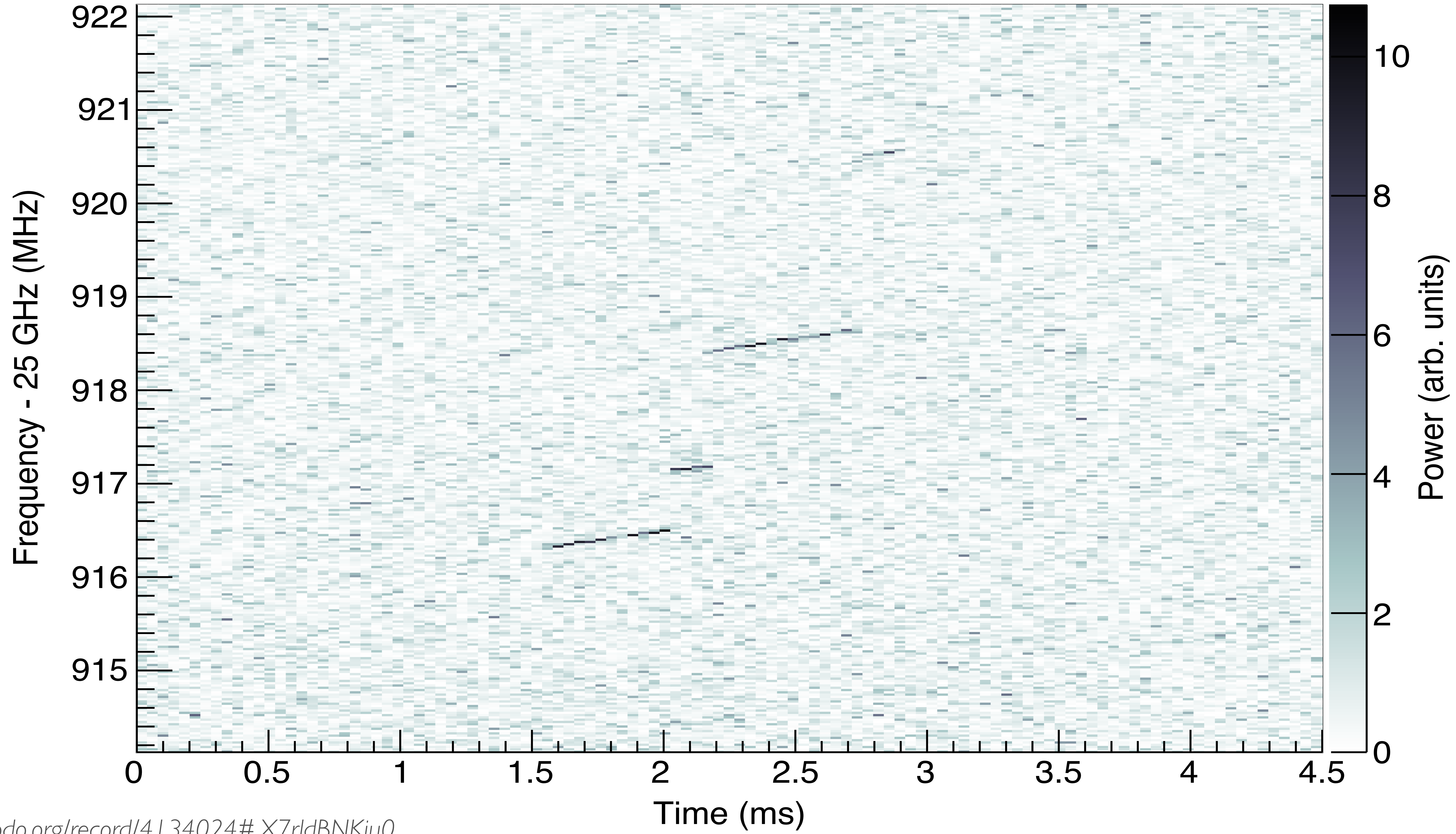
T_2 Spectrum
Systematics
T_2 end point
Background assessment

- Two configurations used in Phase II
  1. Shallow trap: High resolution, low event rate
  2. Deep trap: Low resolution, high event rate
- Tritium data taken with deep trap for better sensitivity



Plot by C. Claessens

First Tritium CRES Signal

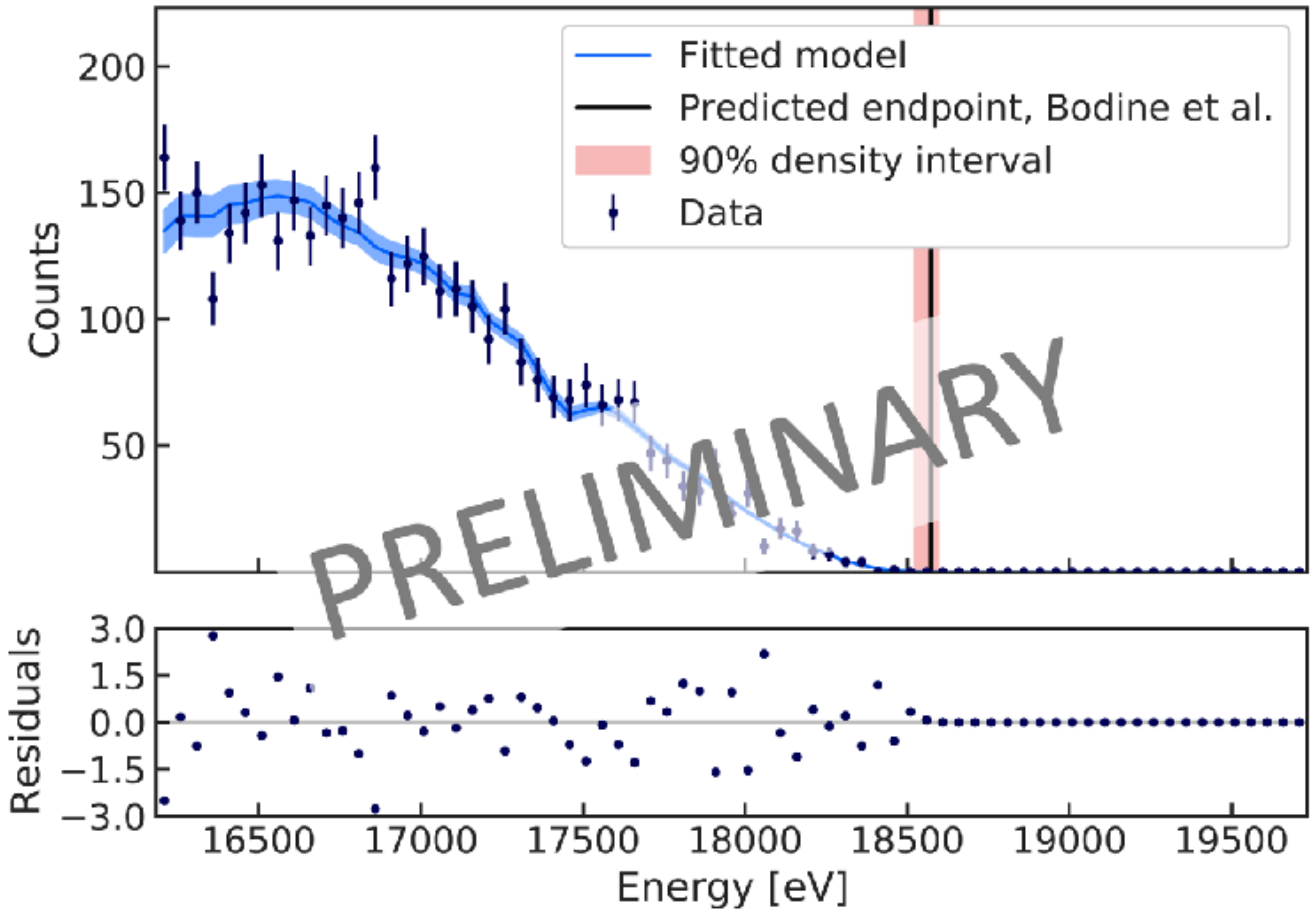


https://zenodo.org/record/4134024#.X7rldBNKju0

Phase II: Spectrum

- Measured T_2 beta decay spectrum with CRES

T_2 Spectrum
Systematics
T_2 end point
Background assessment



- Data taking in 2019/2020
- 82 days of livetime
- 3770 final event count

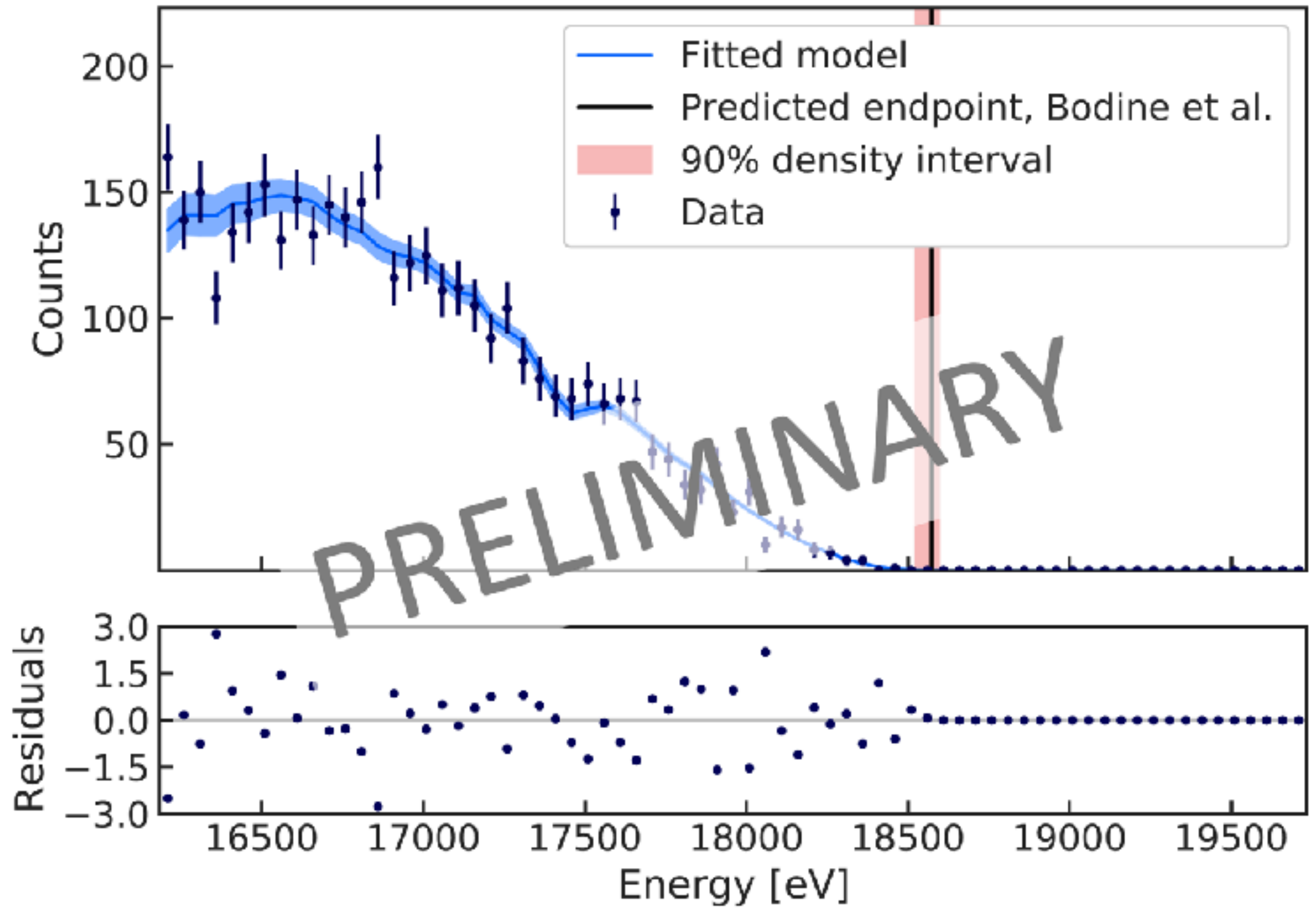
https://zenodo.org/record/4134024#.X7rldBNKju0

Plots by C. Claessans

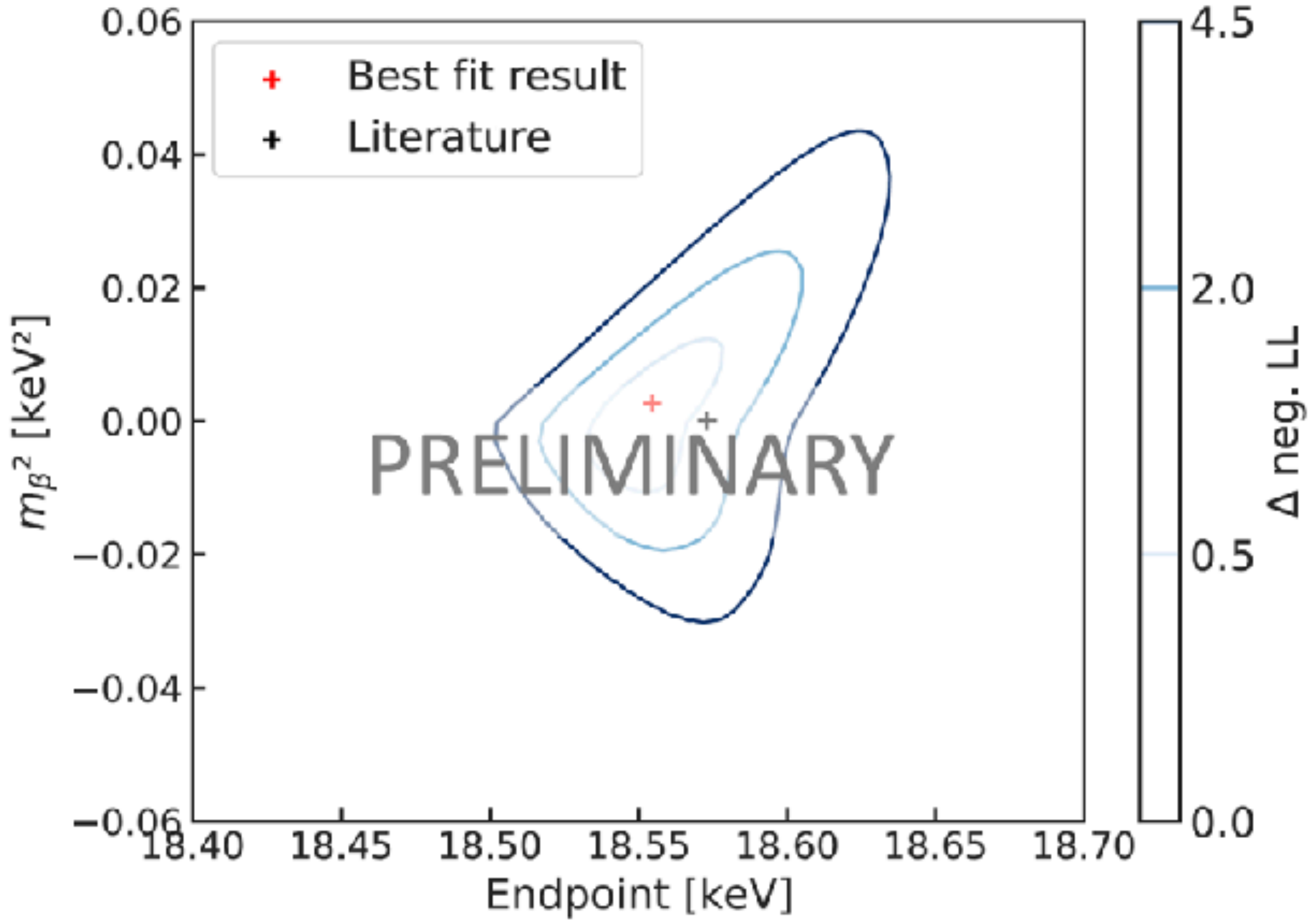
Phase II: Spectrum

- Measured T_2 beta decay spectrum with CRES
- Measured end point energy in agreement with predicted
- First measurement of neutrino mass $\leq$ **185** $\mathrm{eV/c^2}$ (90 % CL)

T_2 Spectrum
Systematics
T_2 end point
Background assessment



$E_0 = \mathbf{18550.6^{+46.1}_{-27.5}}$ eV (90 % CL)



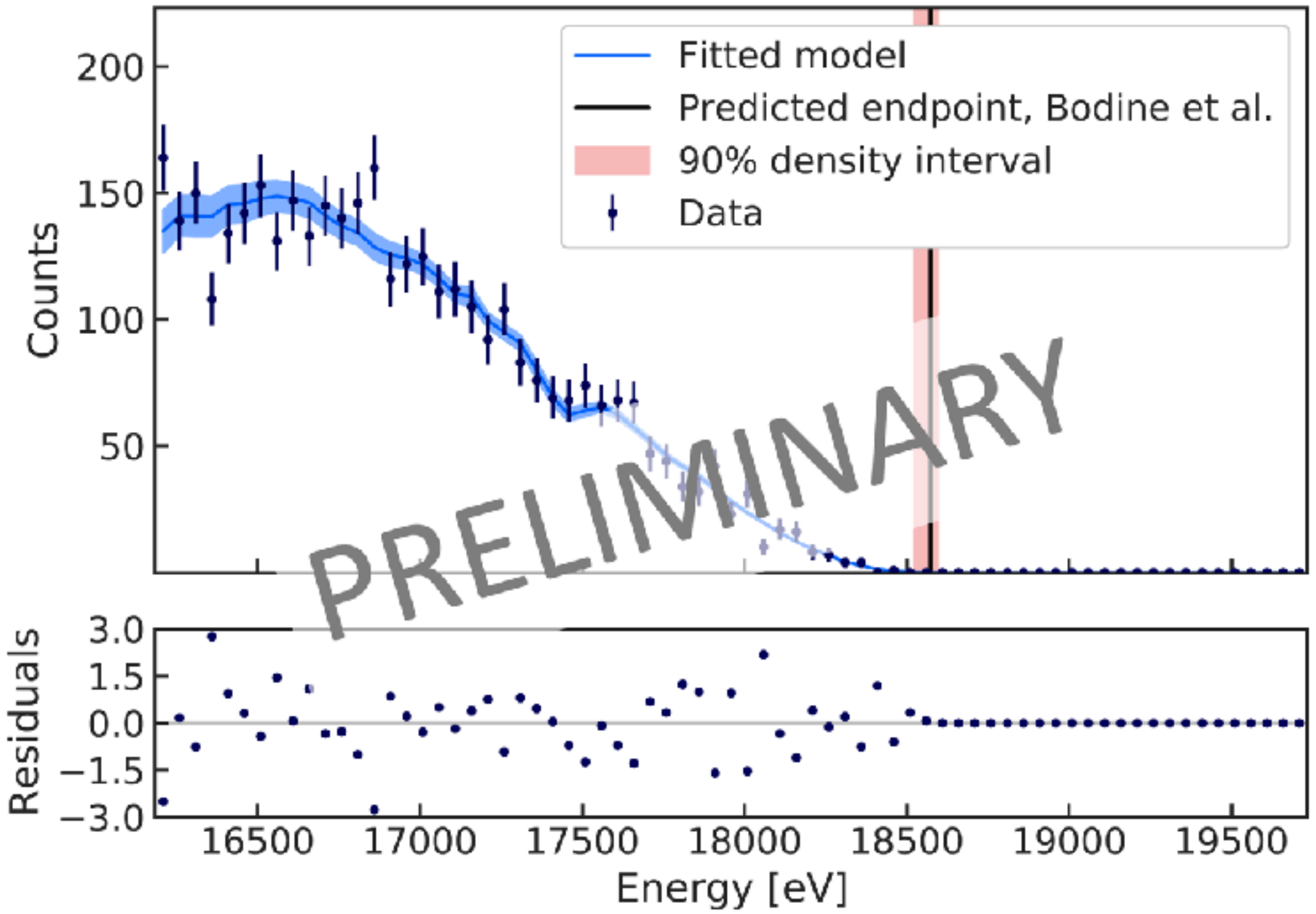
https://zenodo.org/record/4134024#.X7rldBNKju0

Plots by C. Claessans

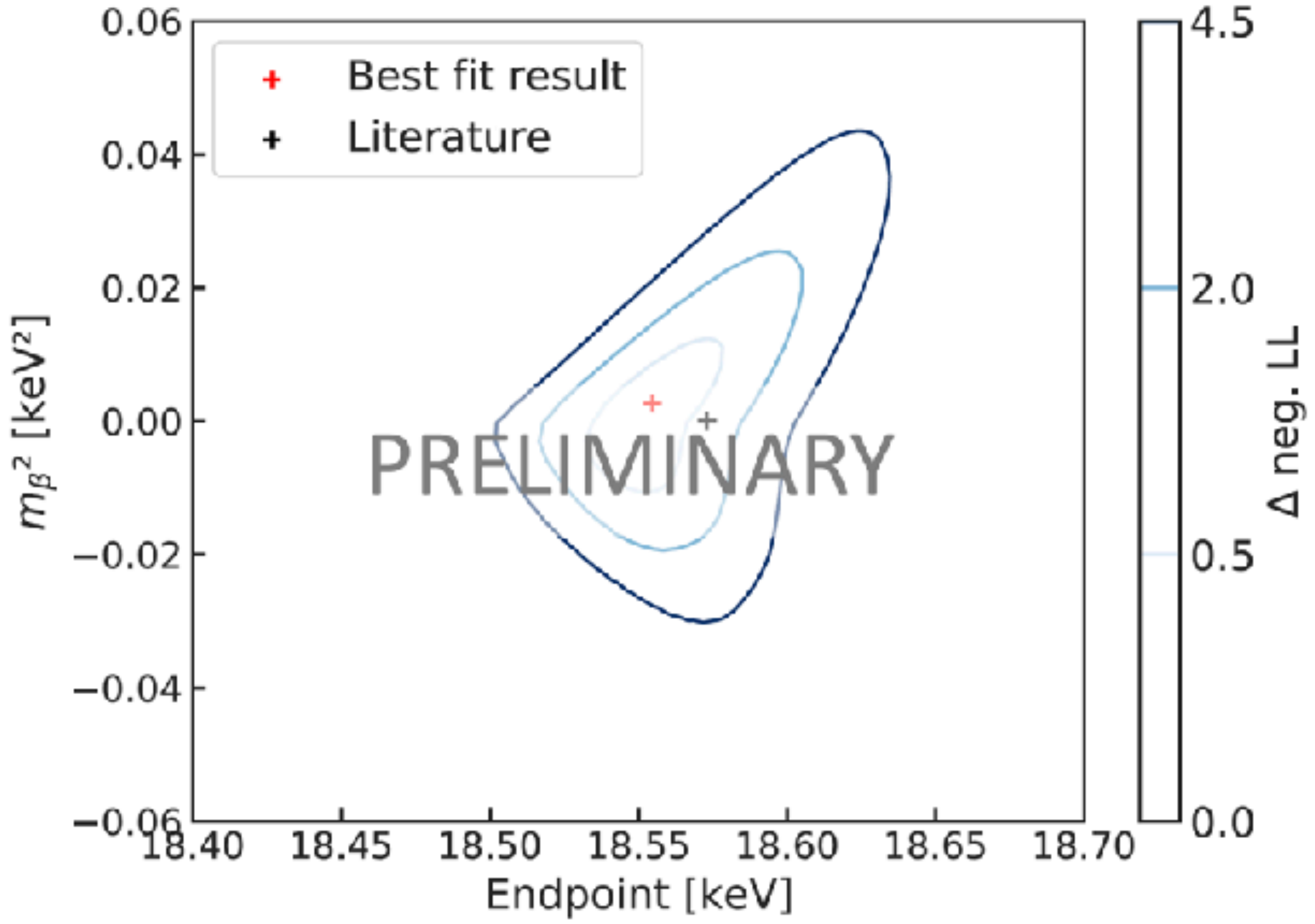
Phase II: Spectrum

T_2 Spectrum
Systematics
T_2 end point
Background assessment

- Measured T_2 beta decay spectrum with CRES
- Measured end point energy in agreement with predicted
- First measurement of neutrino mass $\leq \mathbf{185}\ \mathrm{eV/c^2}$ (90 % CL)
- No events past end point => Background rate $\leq \mathbf{3} \times \mathbf{10}^{-\mathbf{10}} \mathrm{eV^{-1}s^{-1}}$ (90 % CL)



$E_0 = \mathbf{18550.6}^{+\mathbf{46.1}}_{-\mathbf{27.5}}$ eV (90 % CL)



https://zenodo.org/record/4134024#.X7rldBNKju0

Plots by C. Claessans

Phase III

Larger volume
Atomic T Demonstration
eV-scale mass limit

- Two major R&D efforts needed to demonstrate CRES for neutrino mass measurement
    1. **Use of atomic tritium**
    2. **Scaling of the detection volume**

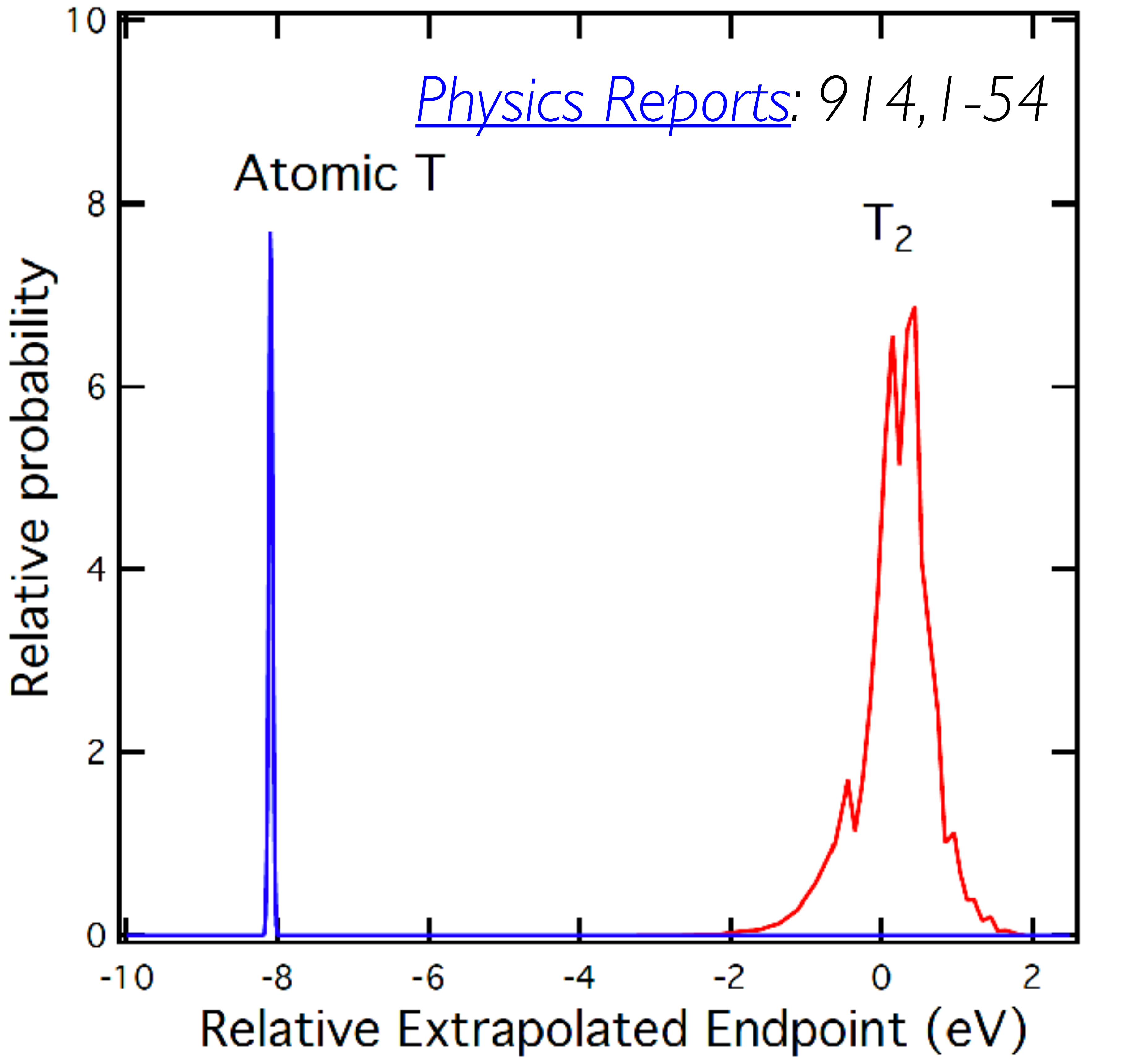
Phase III

Larger volume
Atomic T Demonstration
eV-scale mass limit

- Two major R&D efforts needed to demonstrate CRES for neutrino mass measurement
    1. **Use of atomic tritium**
    2. Scaling of the detection volume

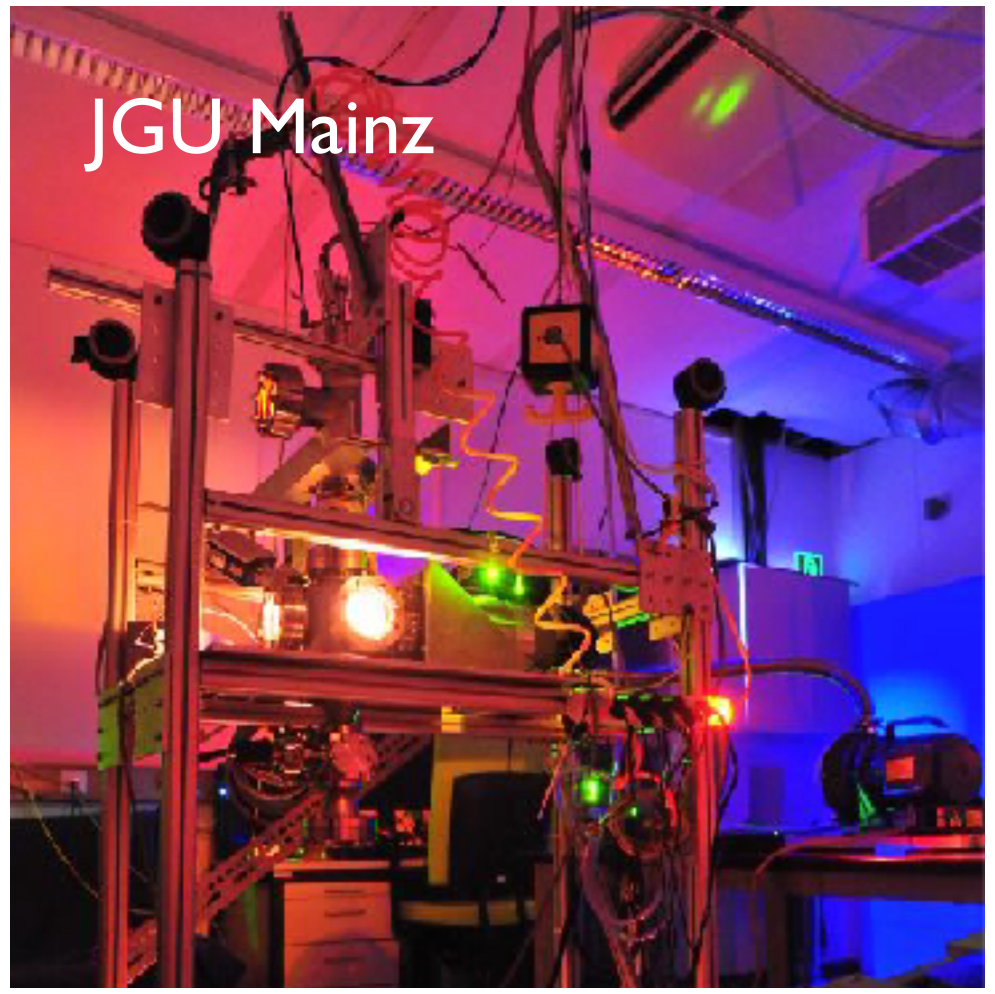
- Extraction of neutrino mass complicated by the irreducible final state energy distribution

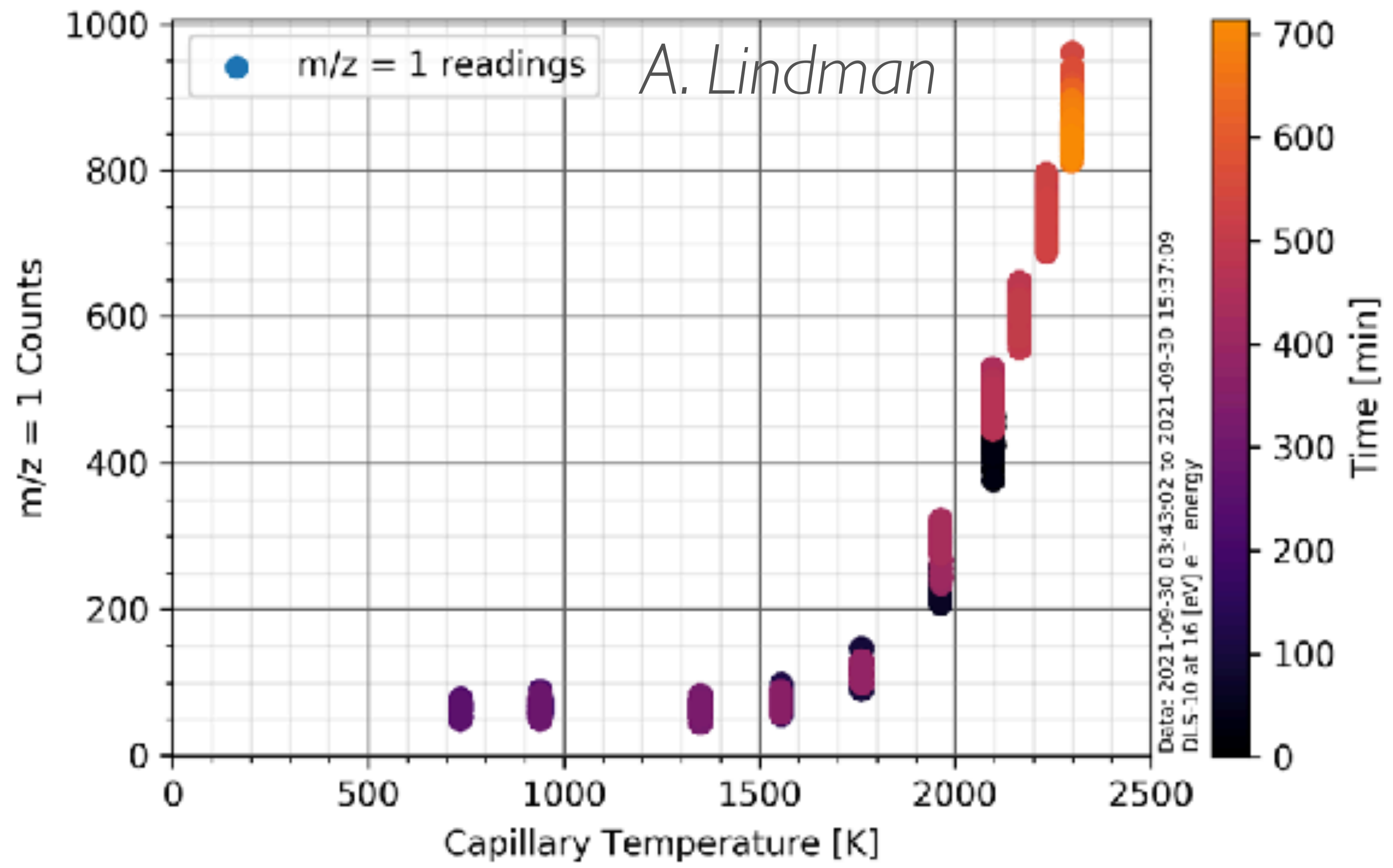
- Use atomic tritium to avoid relevant uncertainty



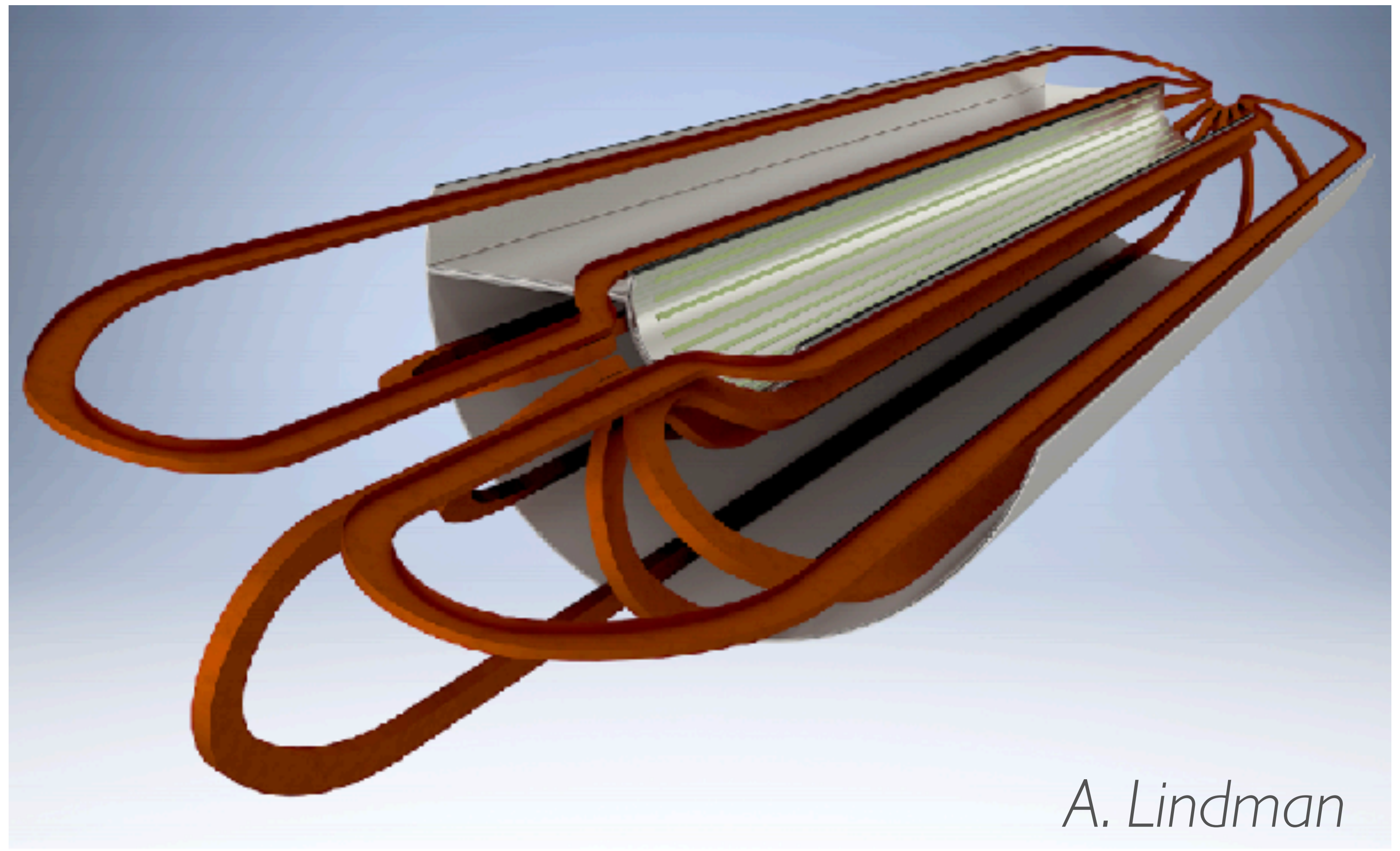
Atomic Tritium Demonstrator (ATD)

- Demonstrate atomic tritium:
    1. Production
    2. Cooling and purification
    3. Trapping and transportation
- Multi-institutional effort for tritium cracking
- High flow hydrogen cracking demonstrated





Ioffe trap design concept for trapping

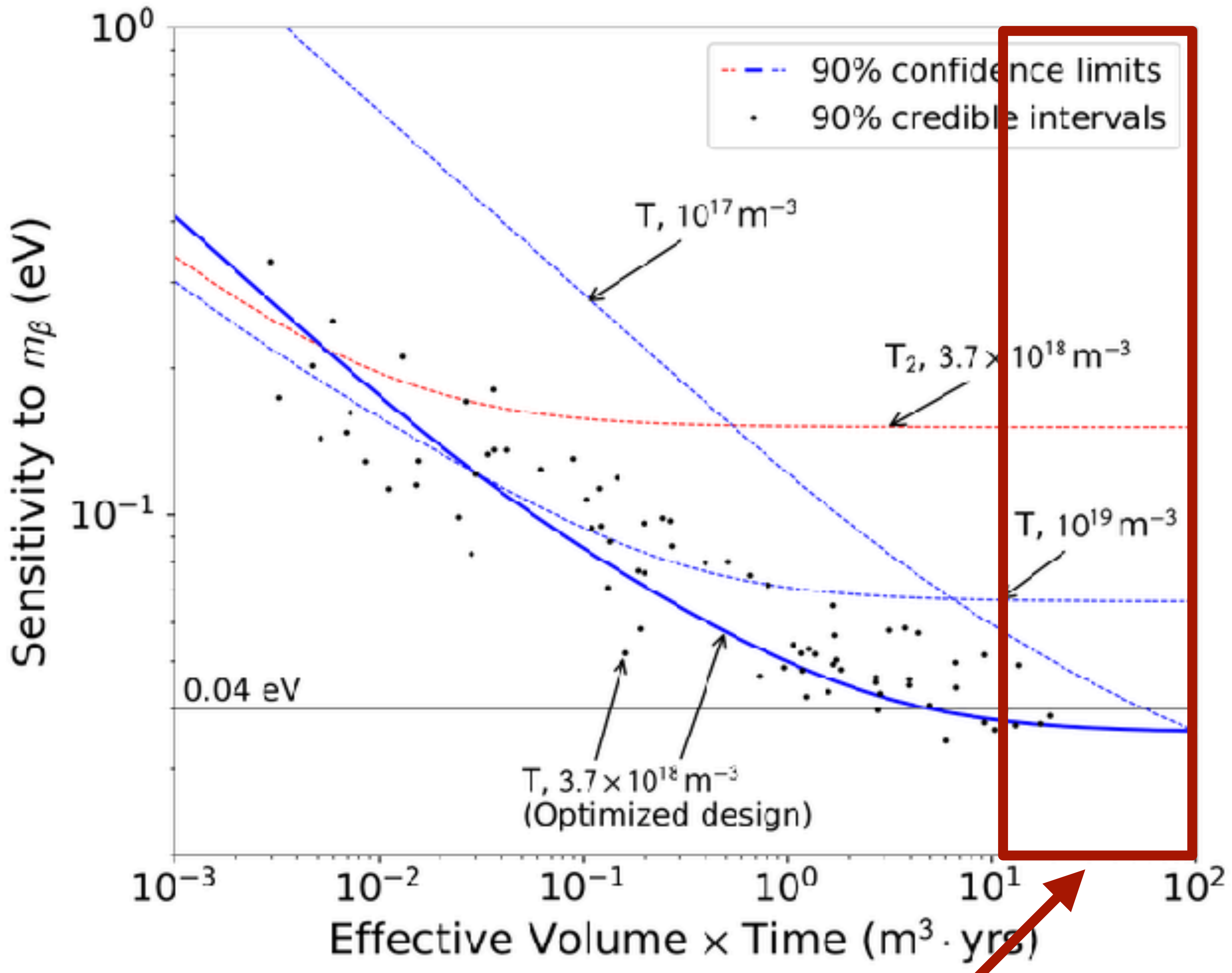


Phase III

Larger volume
Atomic T Demonstration
eV-scale mass limit

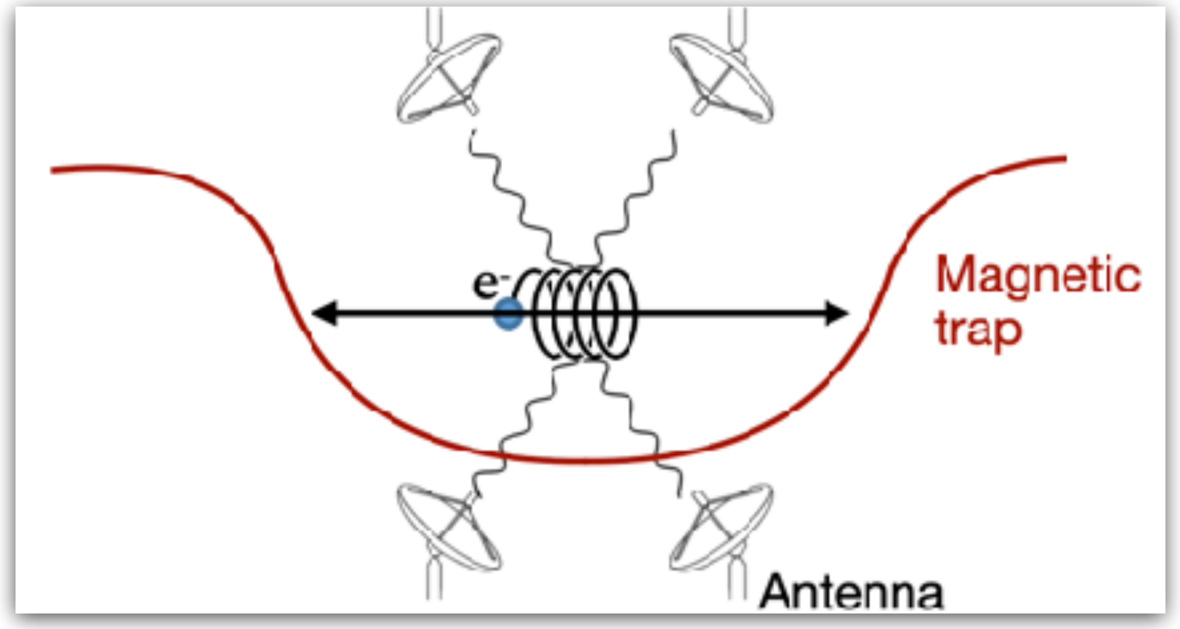
- Two major R&D efforts needed to demonstrate CRES for neutrino mass measurement
  1. Use of atomic tritium
  2. Scaling of the detection volume

- Phase - II had ~1 mm³ effective volume
- Require ~10 m³ scale for Phase-IV
- Two options under consideration:
  1. Array of antennas
  2. Microwave cavity

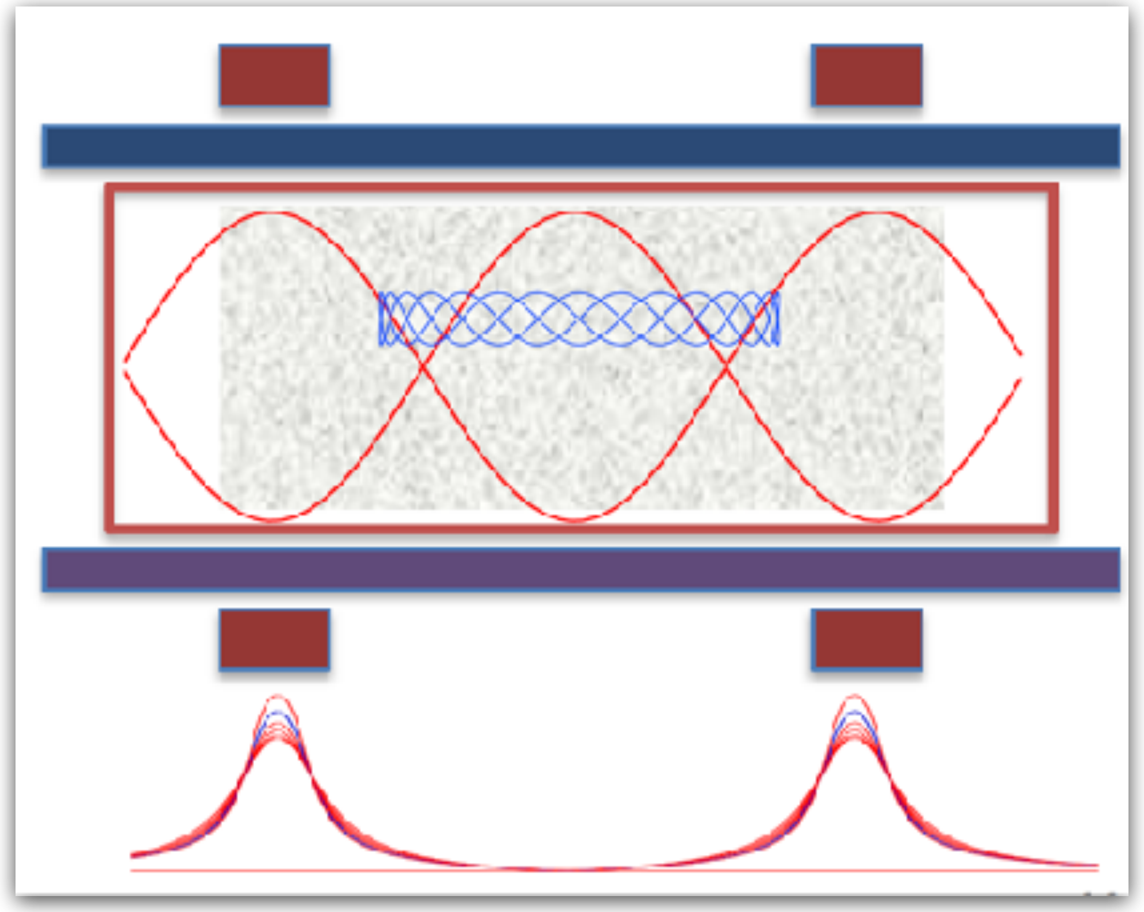


Need >10 m3 volume to reach P-IV sensitivity

Antenna array



Resonant cavity

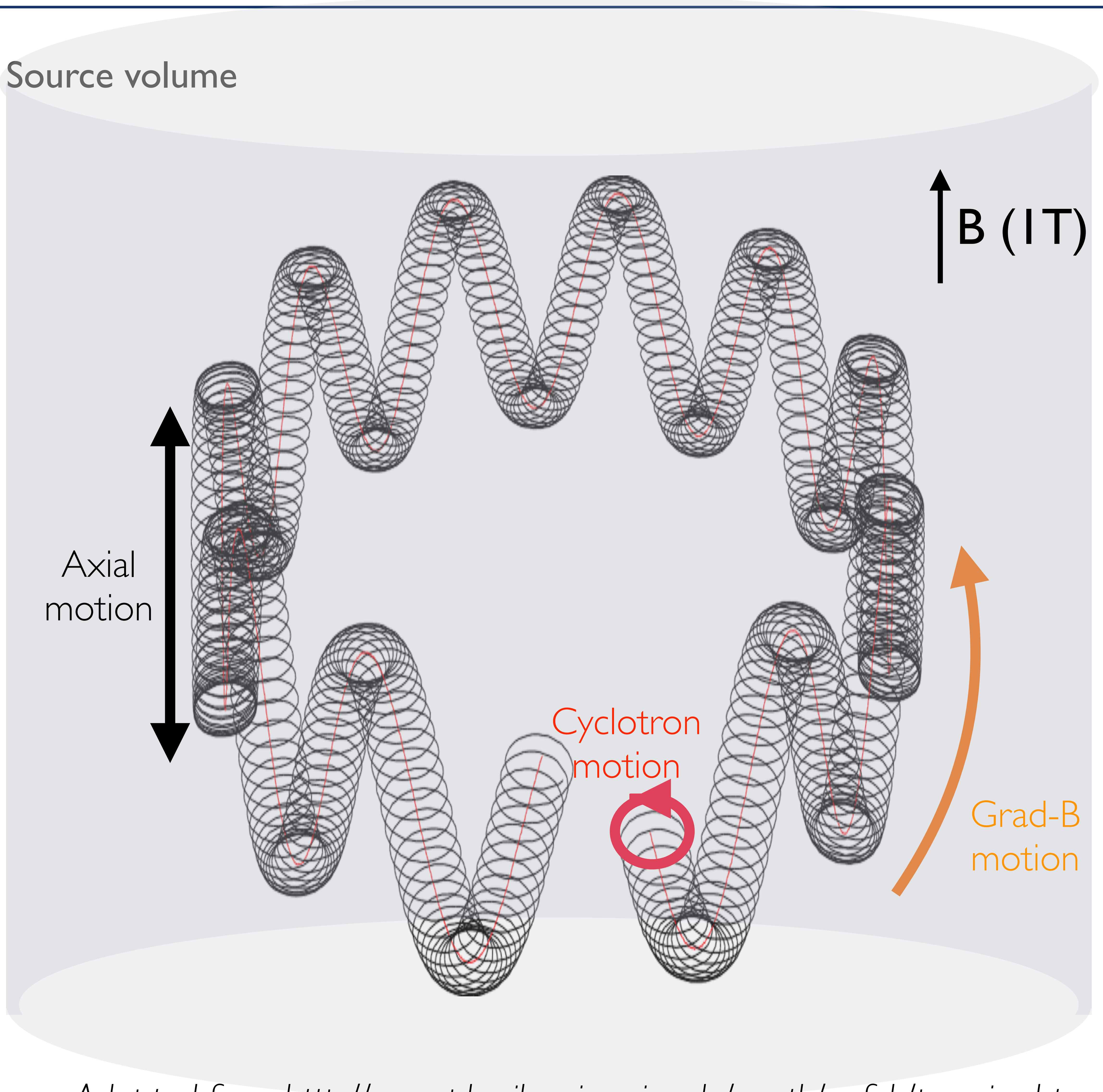


Demonstration of larger volume CRES a key R&D requirement

Electron Motion In Magnetic Field

- Electron undergoes three different motions:
  1. Cyclotron motion (~26 GHz)
  2. Axial motion (~10s MHz)
  3. Grad-B motion (~ kHz)
- Cyclotron motion is the relevant motion
- Axial motion and Grad-B motion
  - Power loss
  - Induce amplitude and frequency modulations (AM and FM)
  - Complicates the position reconstruction

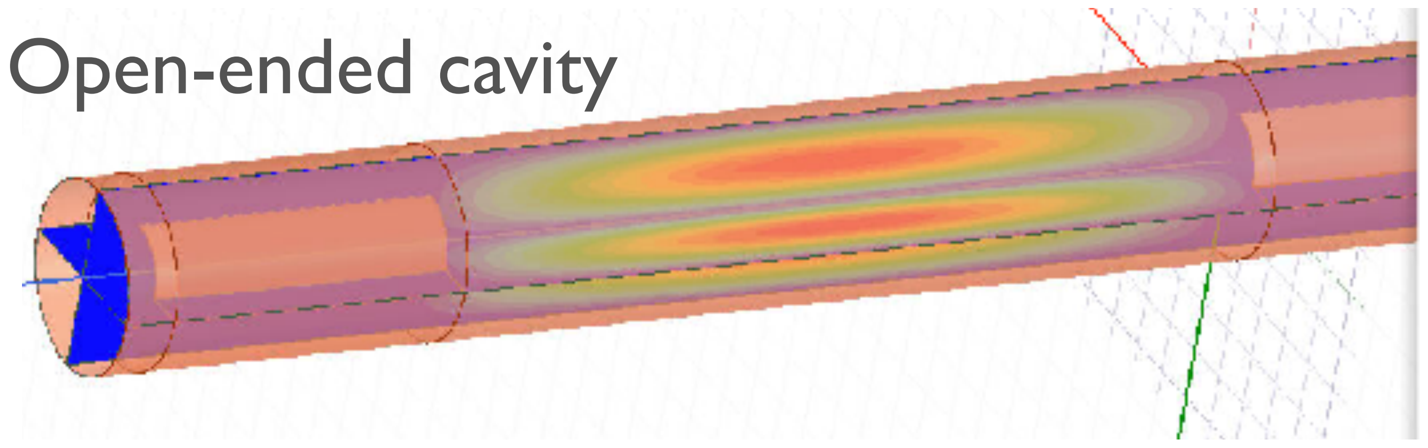
- Crucial to:
  - Design trap to optimize electron motion
  - Develop optimal reconstruction techniques to extract full power



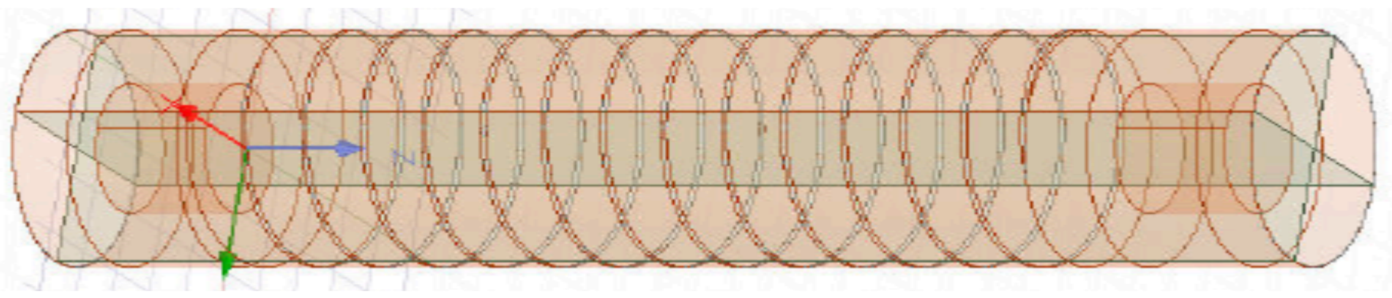
Adapted from http://www.physik.uni-mainz.de/werth/g_fak/penning.htm

Resonant Cavity

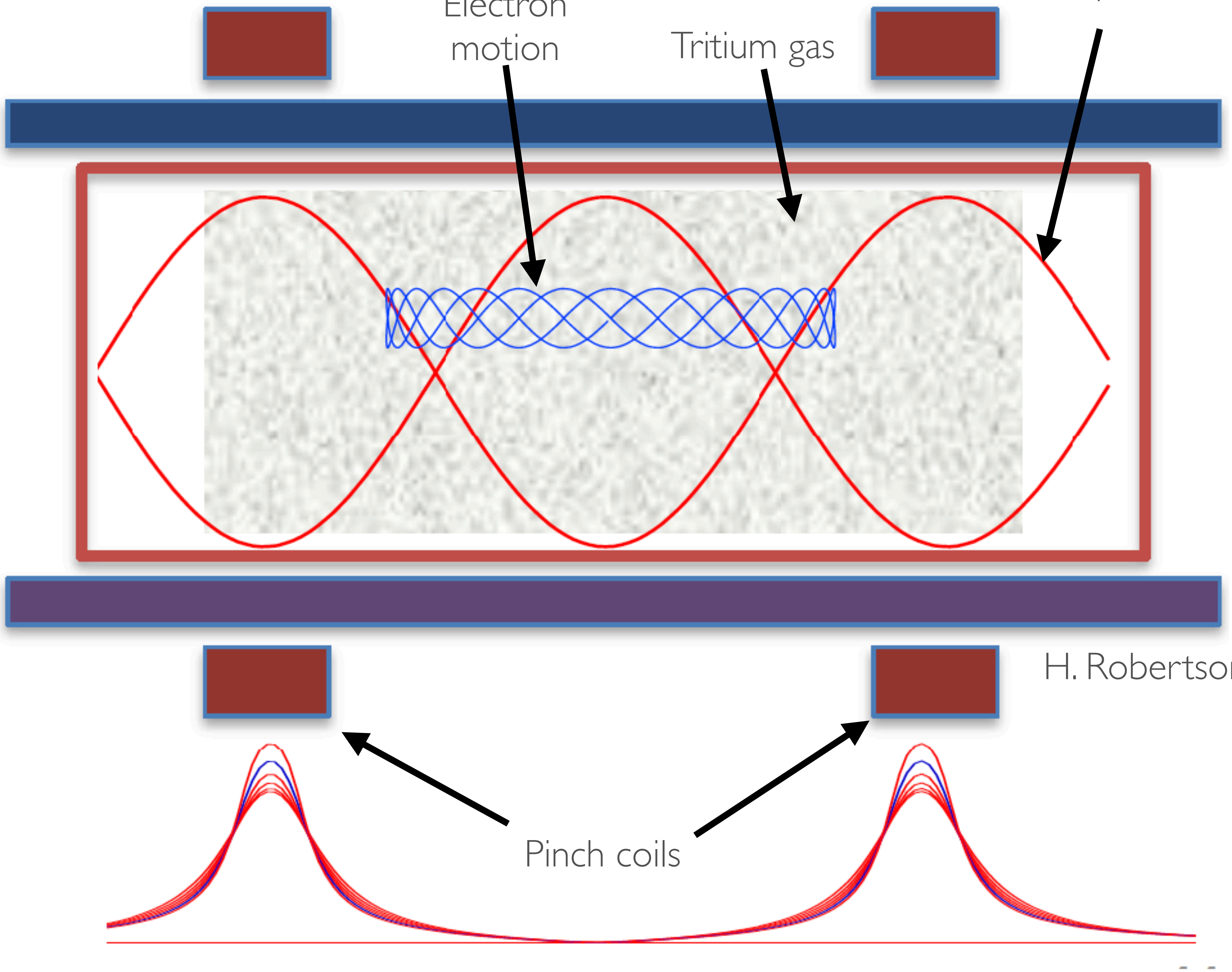
- Perform CRES inside a cavity
- Could have high efficiency
- Need a detailed understanding of mode couplings
- Need an entry for radioactive gas
- Preliminary lab measurements underway



A. Ziegler



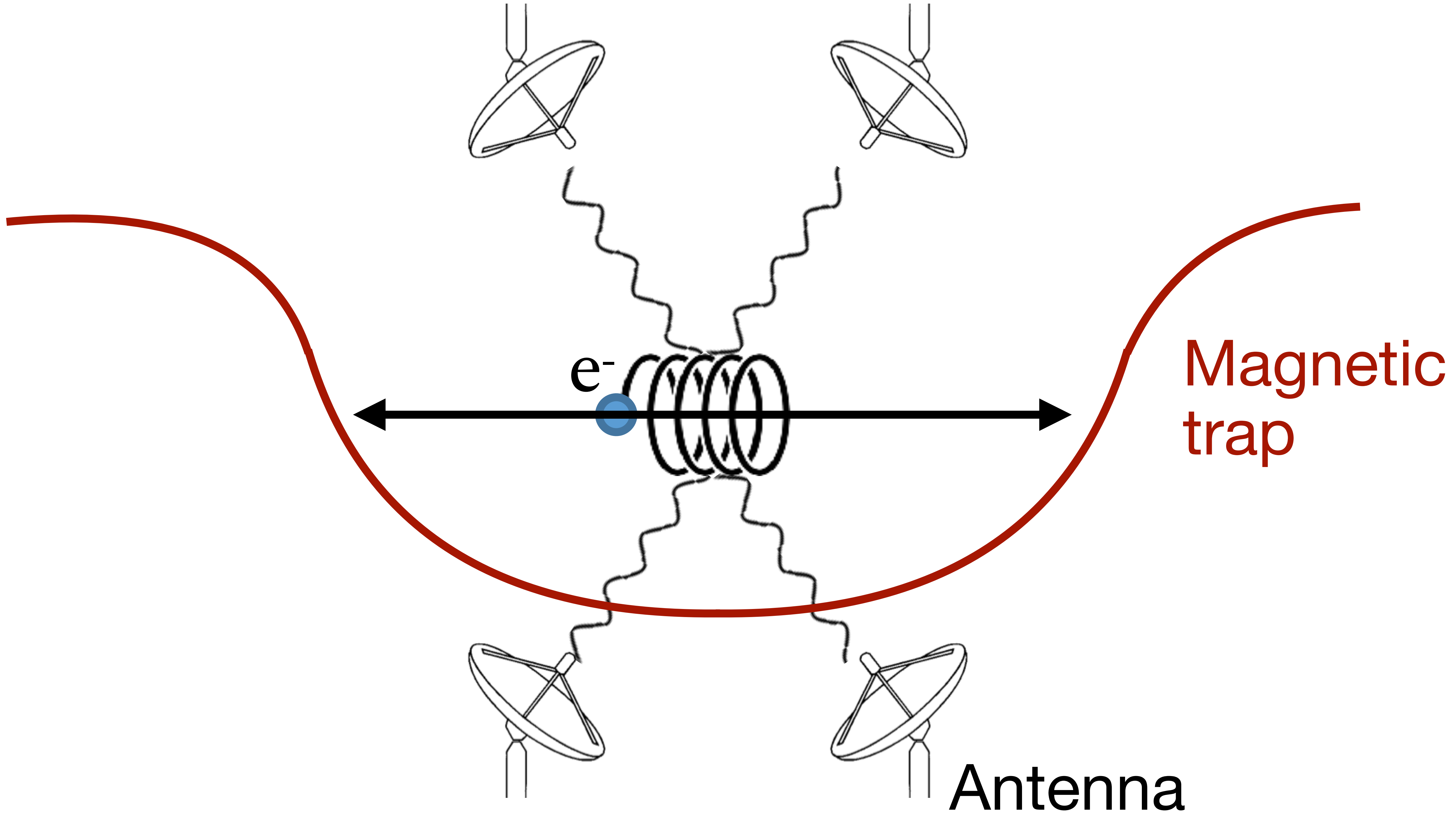
Mode-filtered cavity



H. Robertson

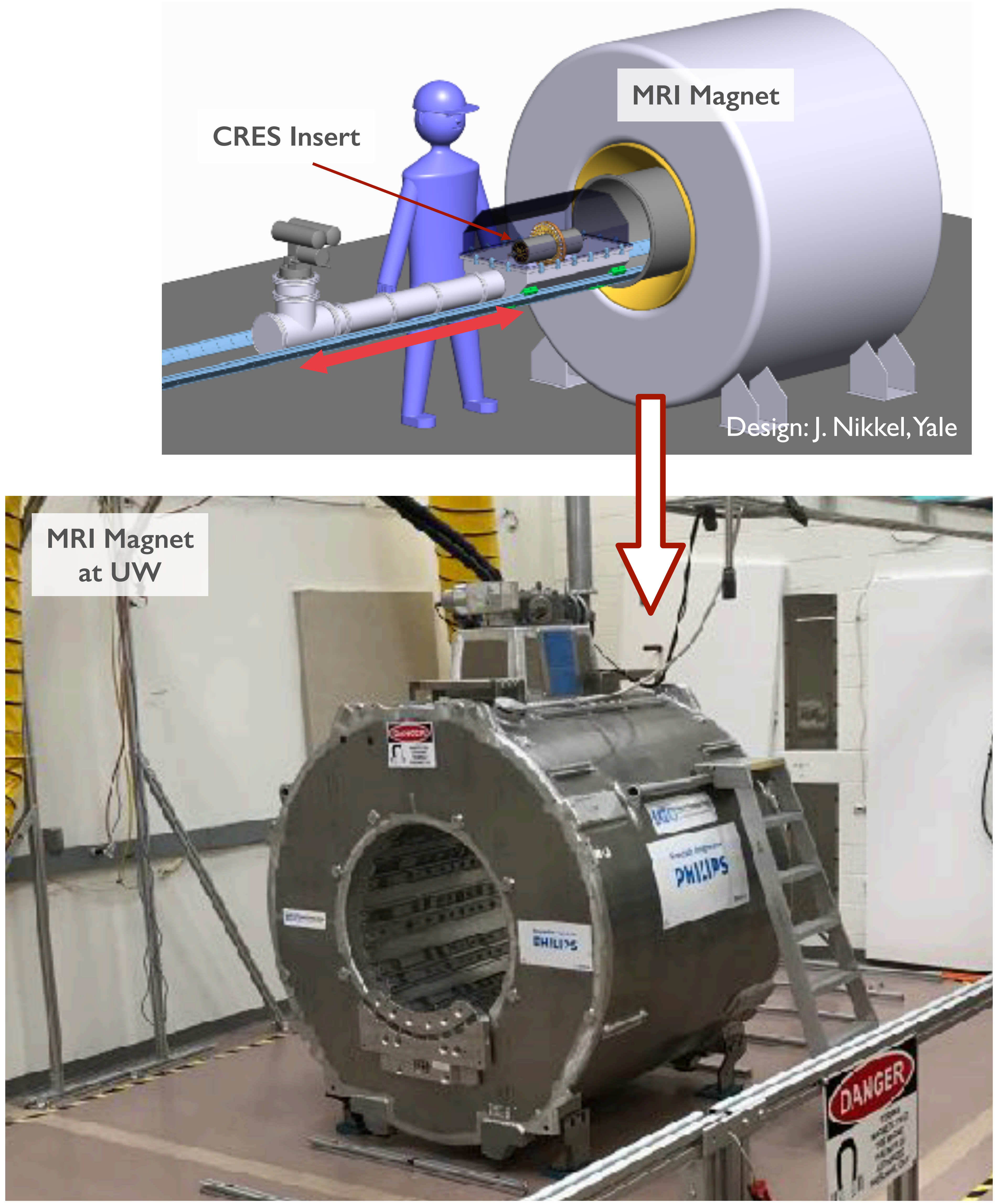
Antenna Array

- Perform CRES in free space to increase effective volume
- Detect CRES using RF antennas
- Flexibility in detector dimensions
- Need to detect 1 fW above noise



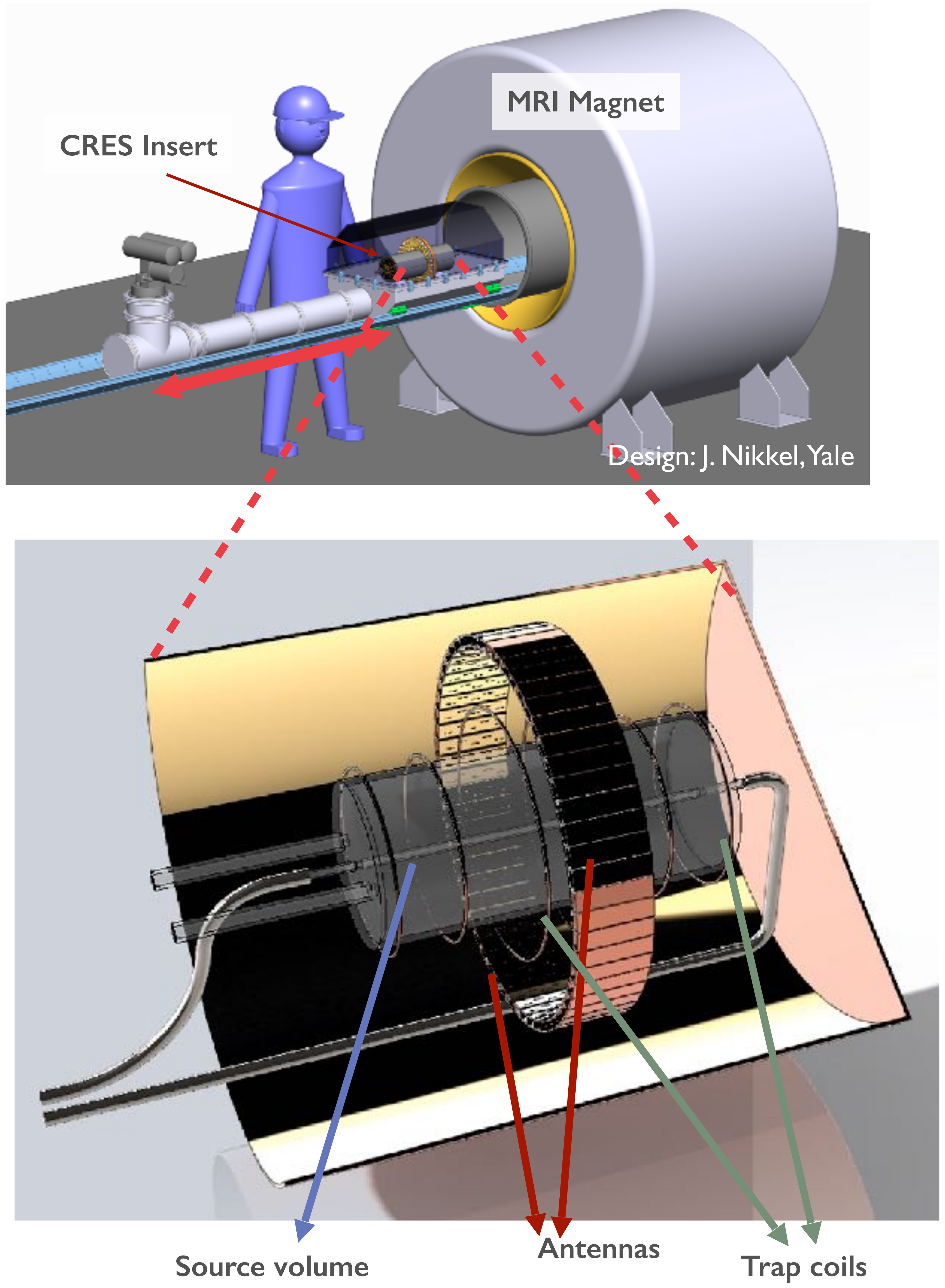
Antenna Array: Strategy

- Source volume will be placed in ~1T uniform field
- MRI magnet already at UW



Antenna Array: Strategy

- Source volume will be placed in ~1T uniform field
- MRI magnet already at UW
- Array of antennas in free space for detecting cyclotron radiation
- Power received by each antenna too small
- Collect power using a cylindrical ring of antennas



Antenna Design

- Antenna requirements:
  - Strong coupling to electron
  - Polarization along the azimuth
  - Working frequency: 26 GHz
  - Low profile: Fits in the physical volume
  - Low losses

Project 8 Software Tools

Simulations tools guide the design of the detector

ANSYS HFSS

- Industry standard RF software
- Optimized for steady state solutions
- **For Project 8: Model frequency response of antenna**

Kassiopeia

github.com/KATRIN-Experiment/Kassiopeia

NJoP, vol 19, May 2017

- EM and particle tracking software developed by KATRIN collaboration
- **For Project 8: Simulate trap and track EM fields and motion of CRES electrons**

Locust

github.com/project8/locust_mc

NJoP, vol 21,Nov 2019

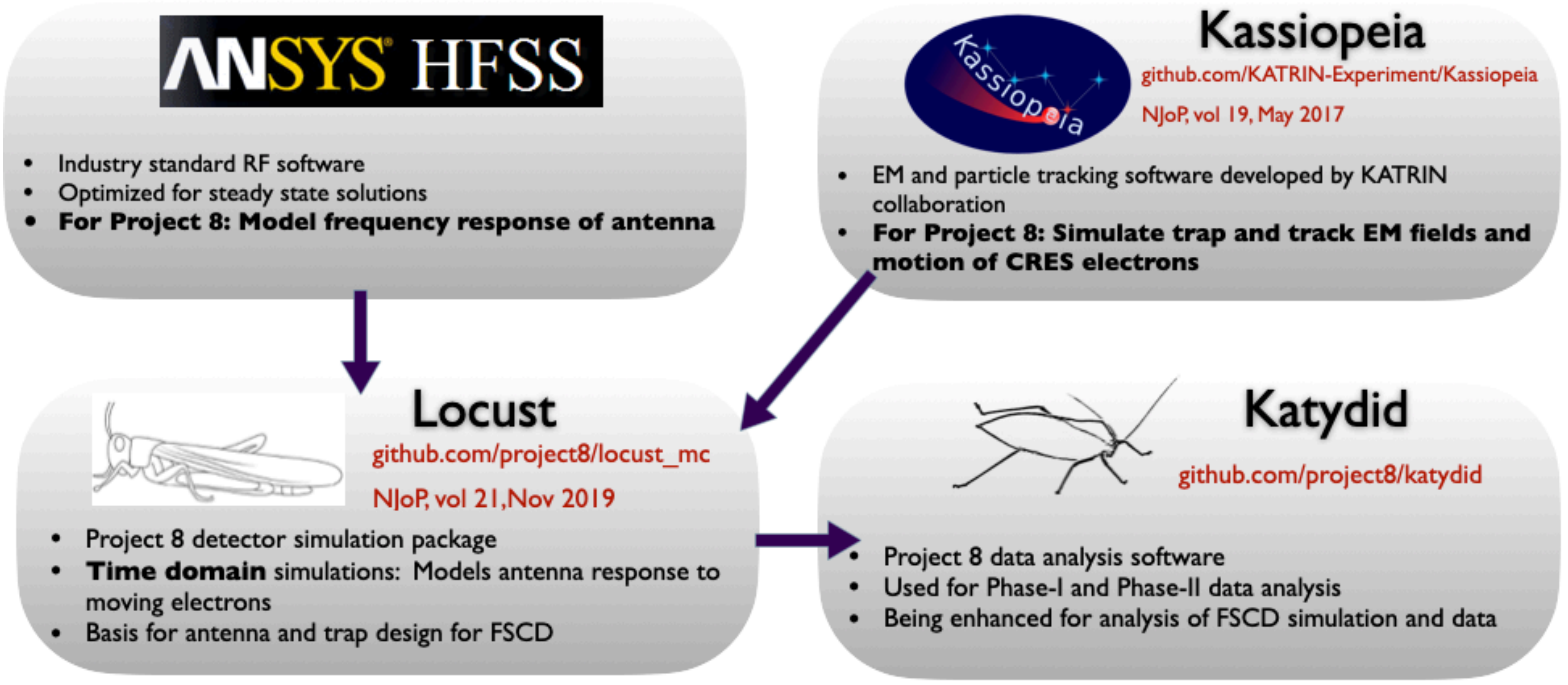
- Project 8 detector simulation package
- **Time domain** simulations: Models detector response to moving electrons
- Basis for antenna and trap design for FSCD

Katydid

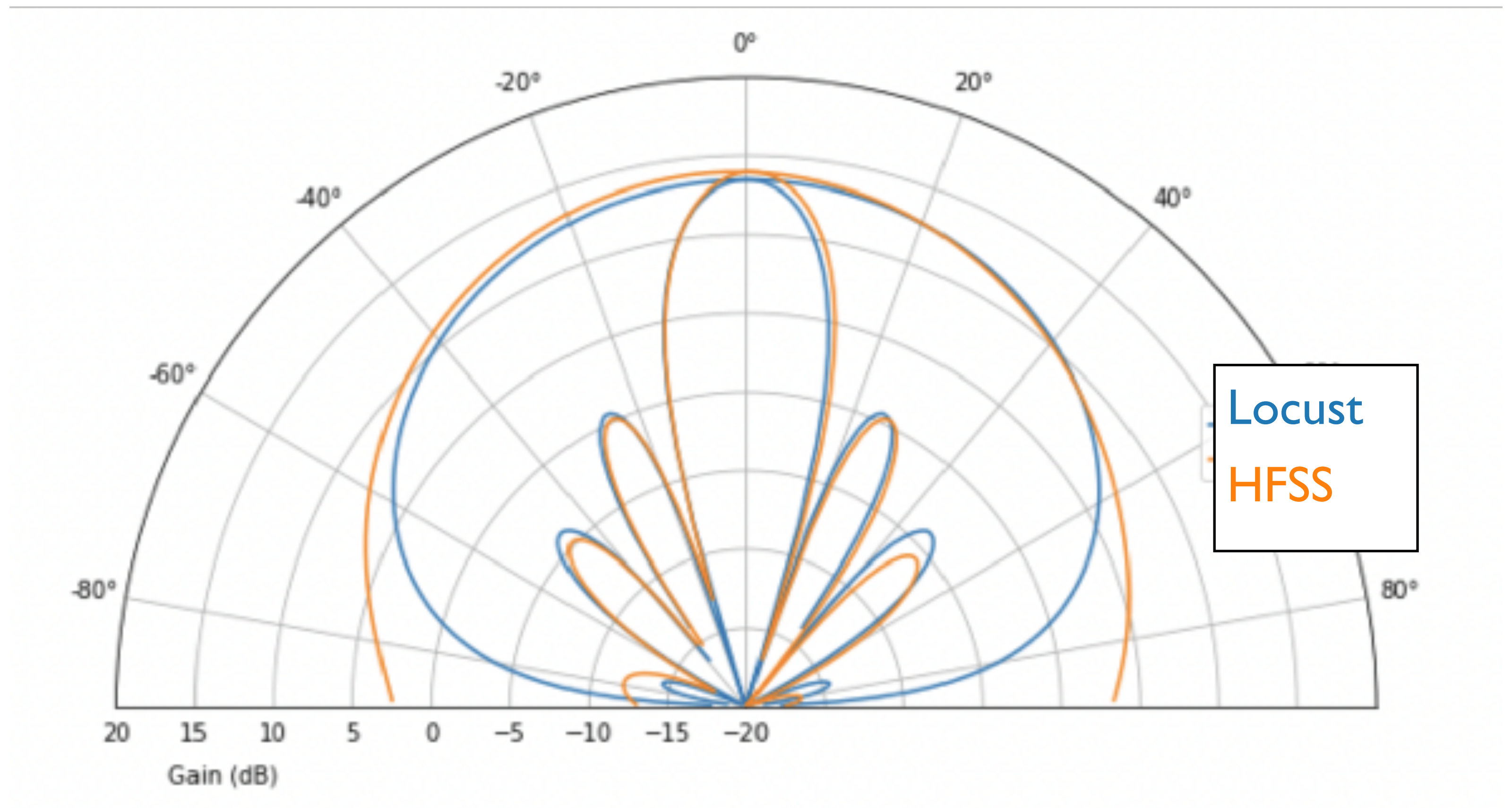
github.com/project8/katydid

- Project 8 data analysis software
- Used for Phase-I and Phase-II data analysis
- Being enhanced for analysis of FSCD simulation and data

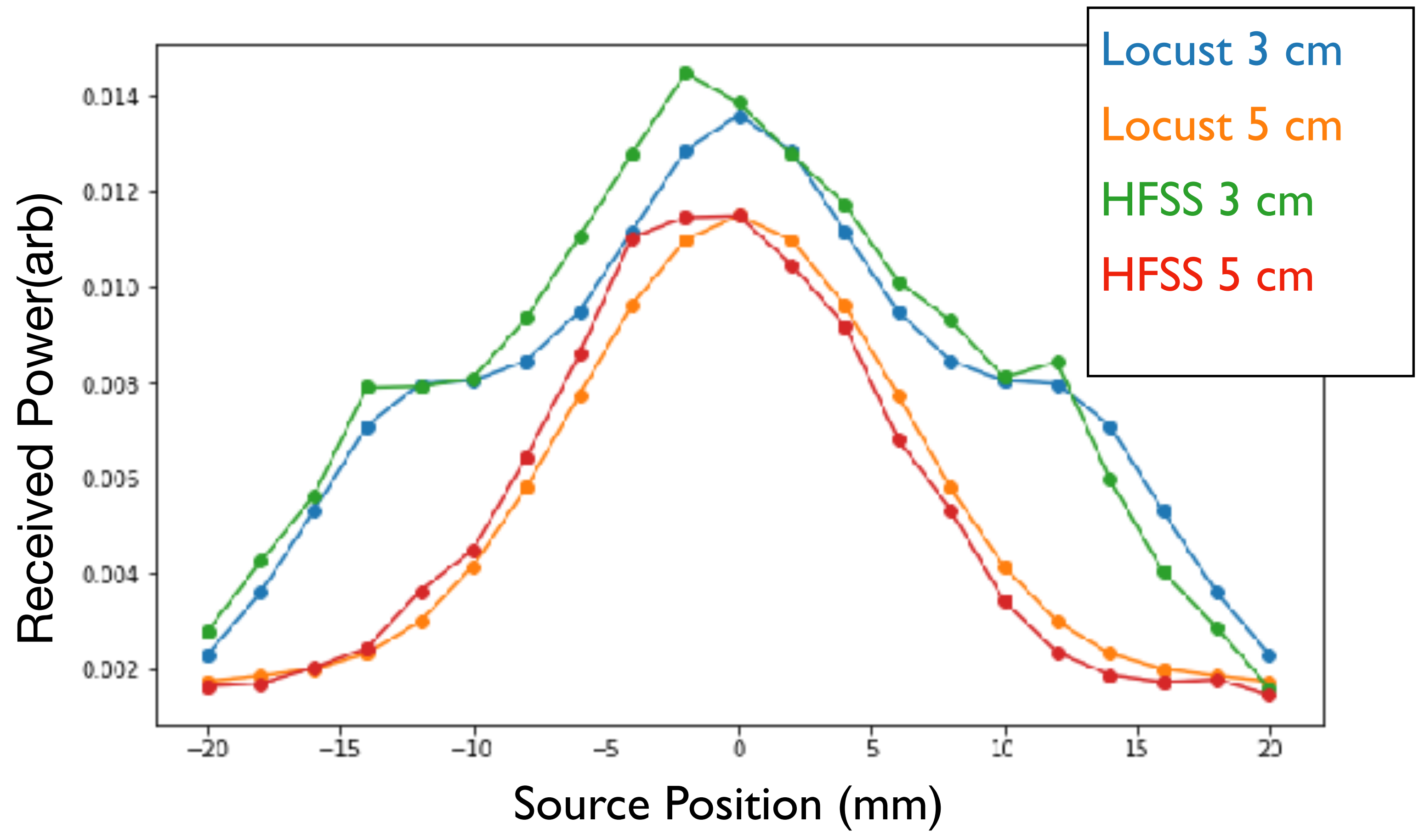
Simulation Efforts



- Dedicated simulation campaign to model antennas in Locust
- Demonstrated that Locust models antenna response well
- Locust used for the development of antenna and trap



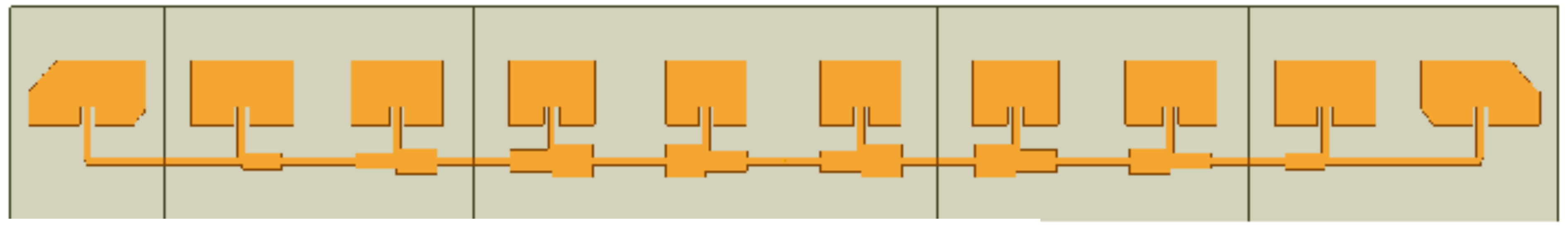
A. Telles

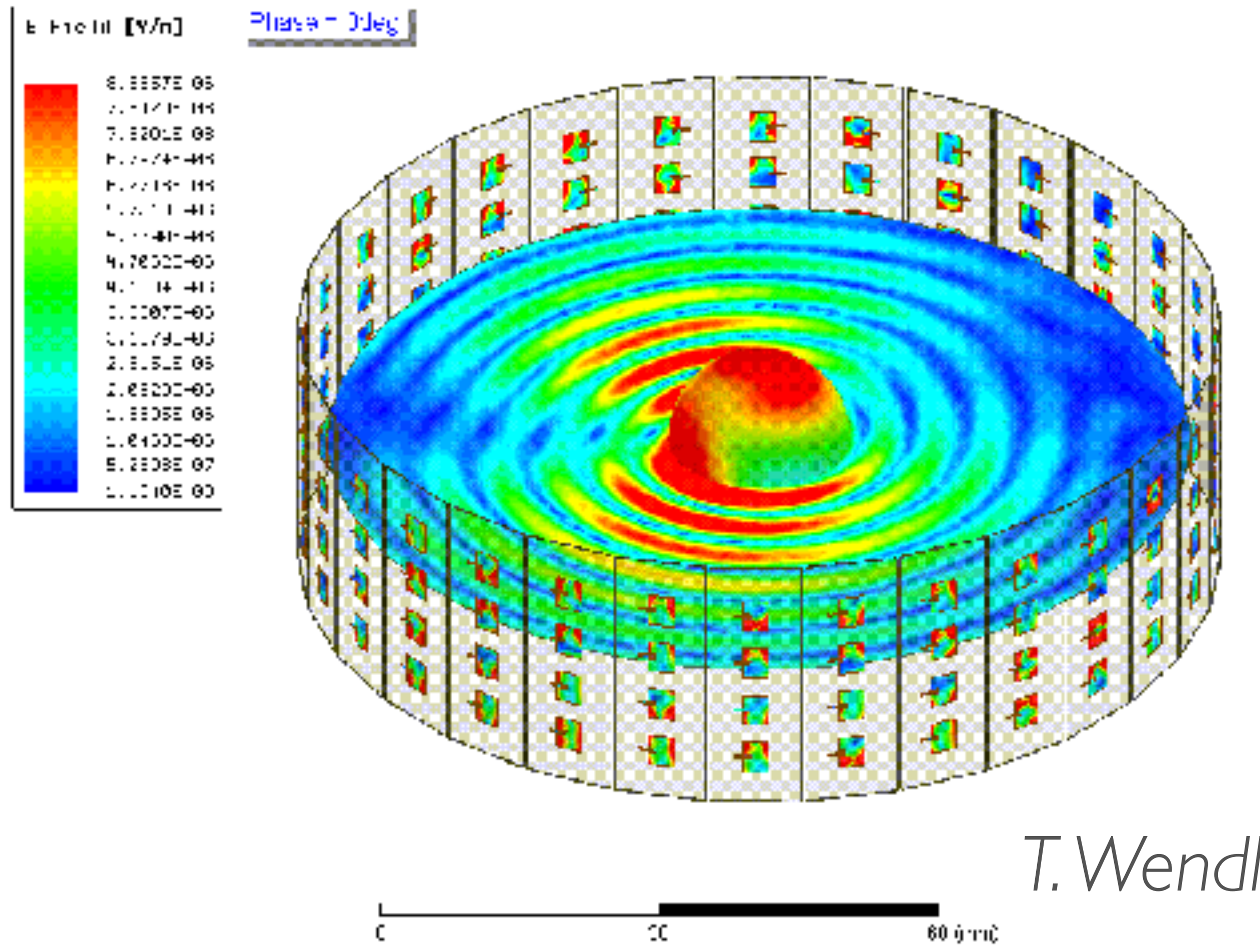


Antenna Design

Patch Antennas:

- Cheap
- Easy to fabricate and assemble
- High insertion losses
- Complicated divider network



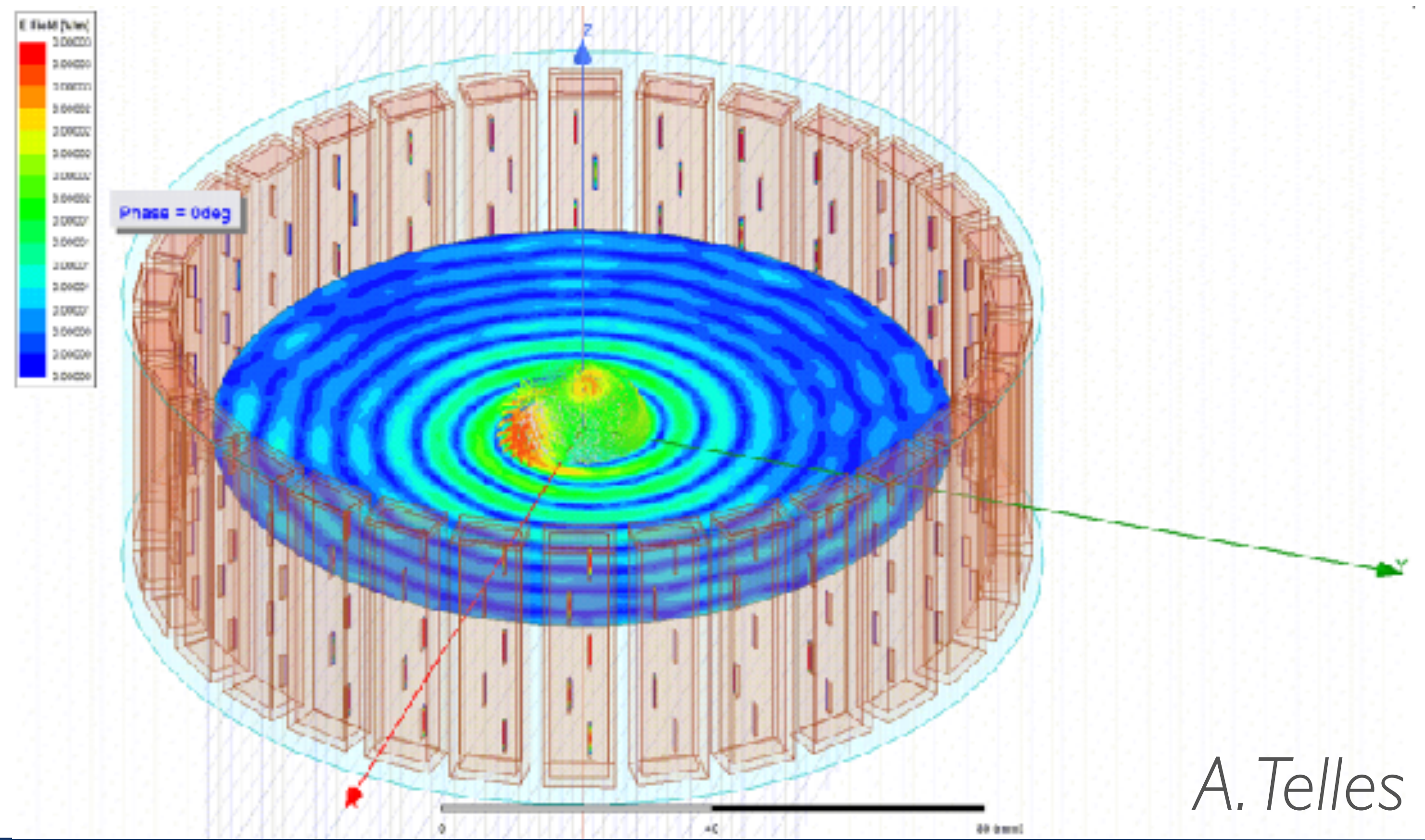


T. Wendler

Slotted Waveguide:

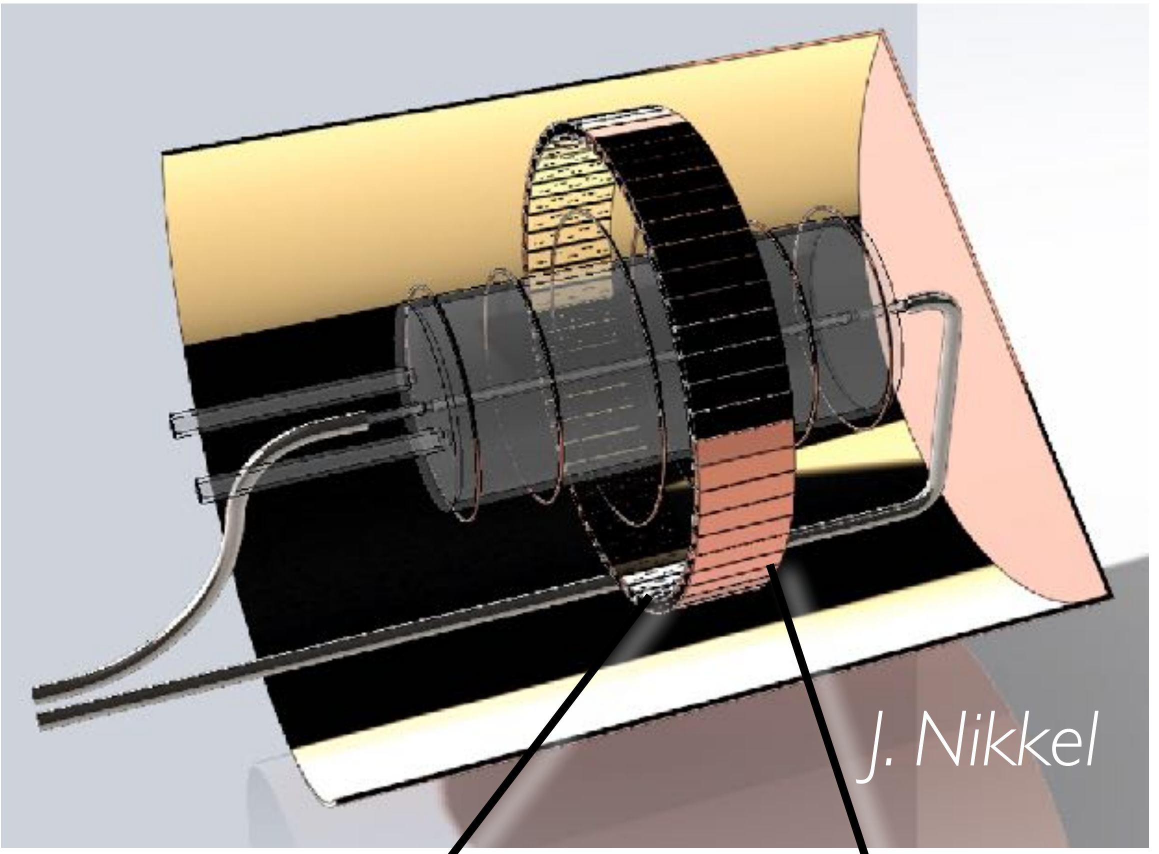
- Low losses
- Access to low noise amplifiers
- Relatively expensive
- Complicated to machine and assemble

M. Grande



A. Telles

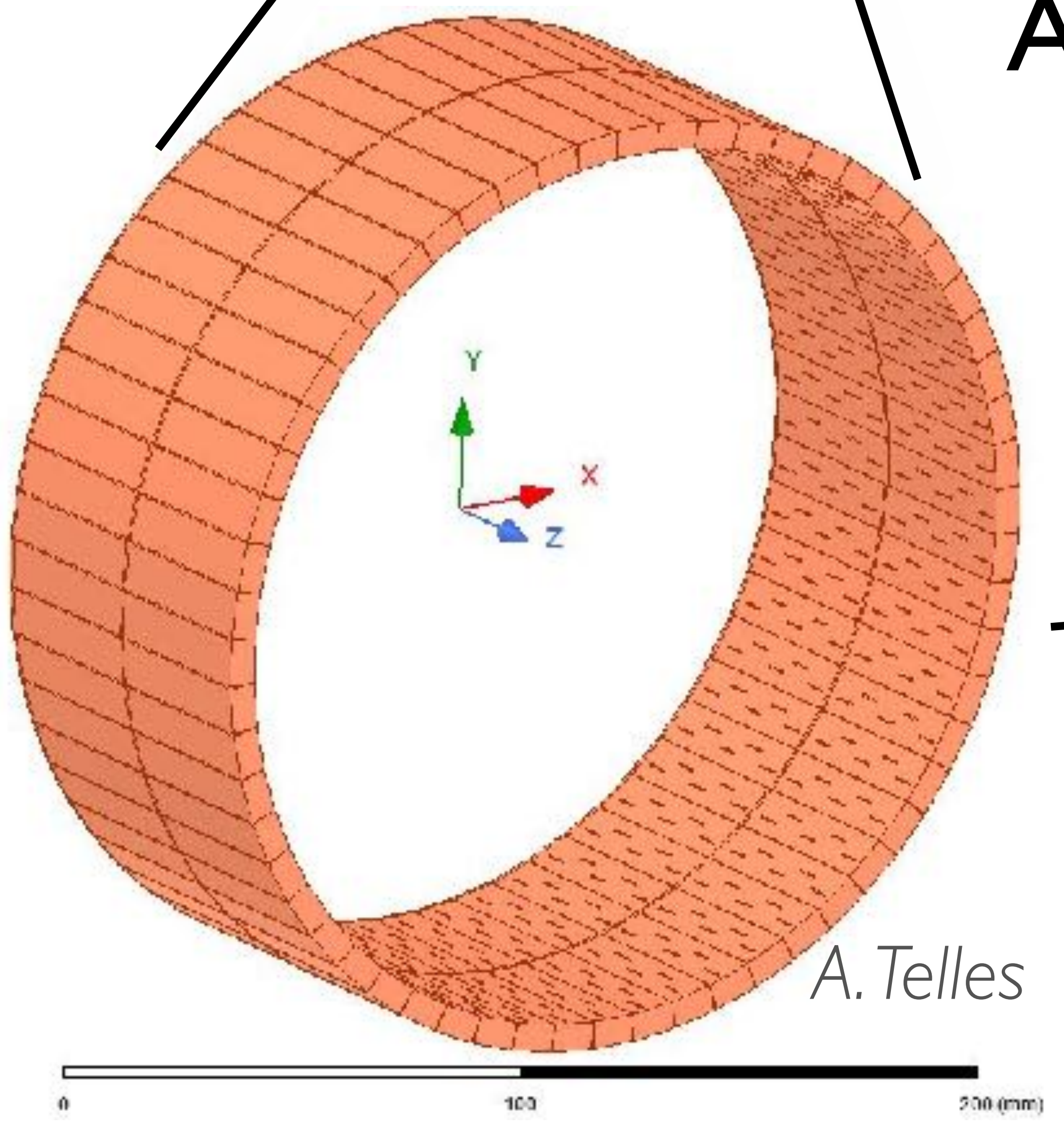
Antenna Design

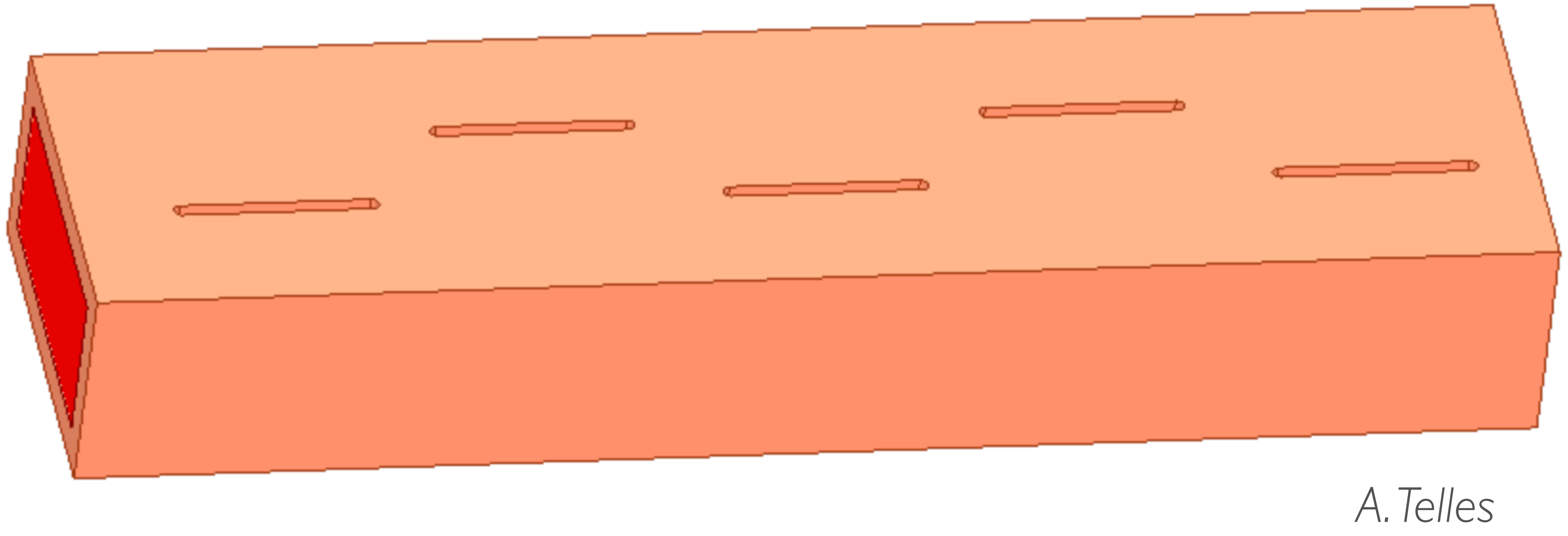


Slotted Waveguide:

- Low losses
- Access to low noise amplifiers
- Relatively expensive
- Complicated to machine and assemble

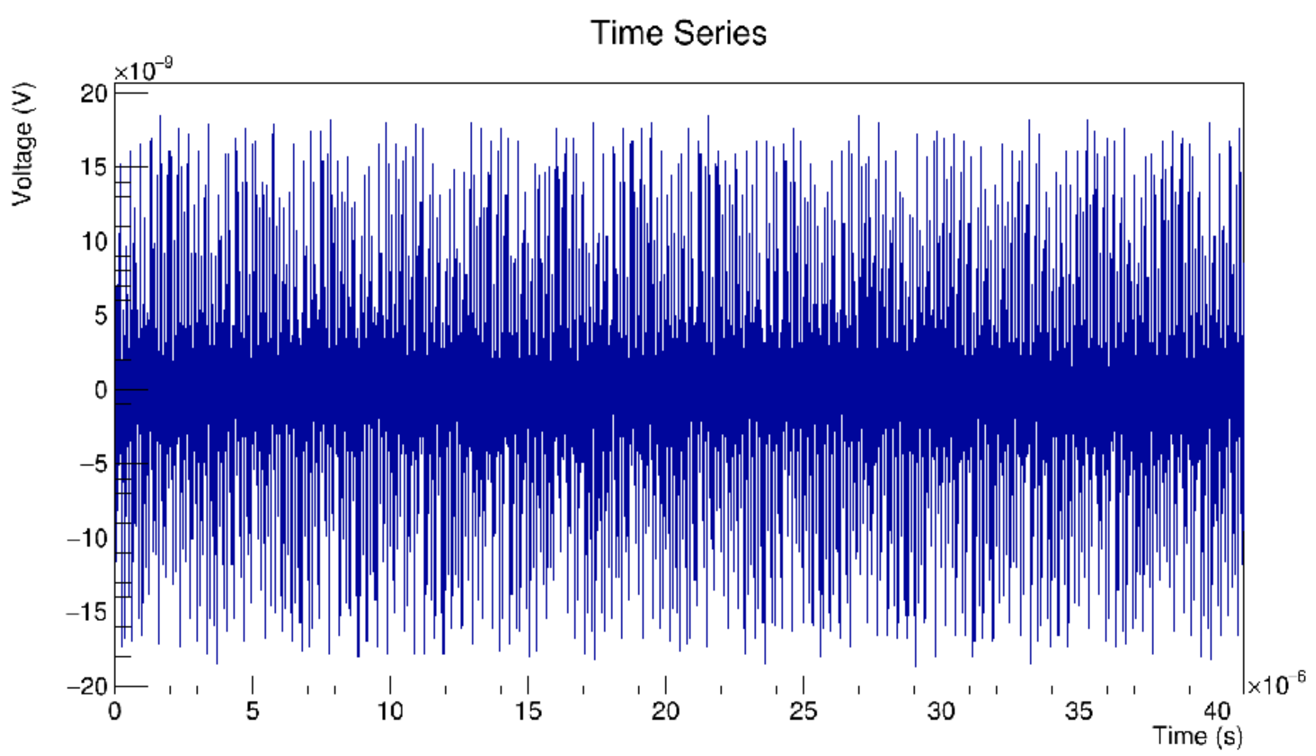
After extensive simulation campaign, down selected to slotted waveguides



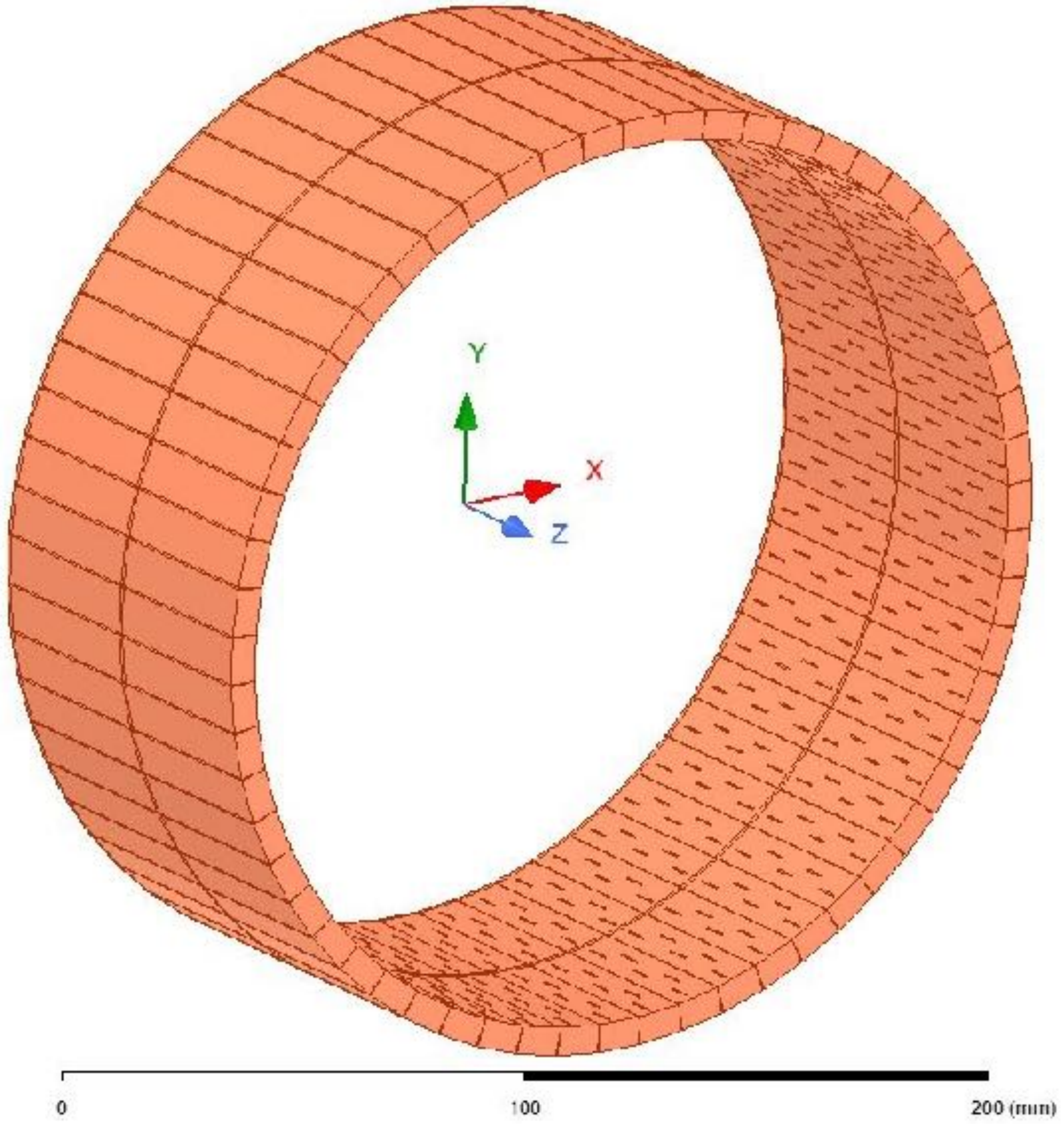


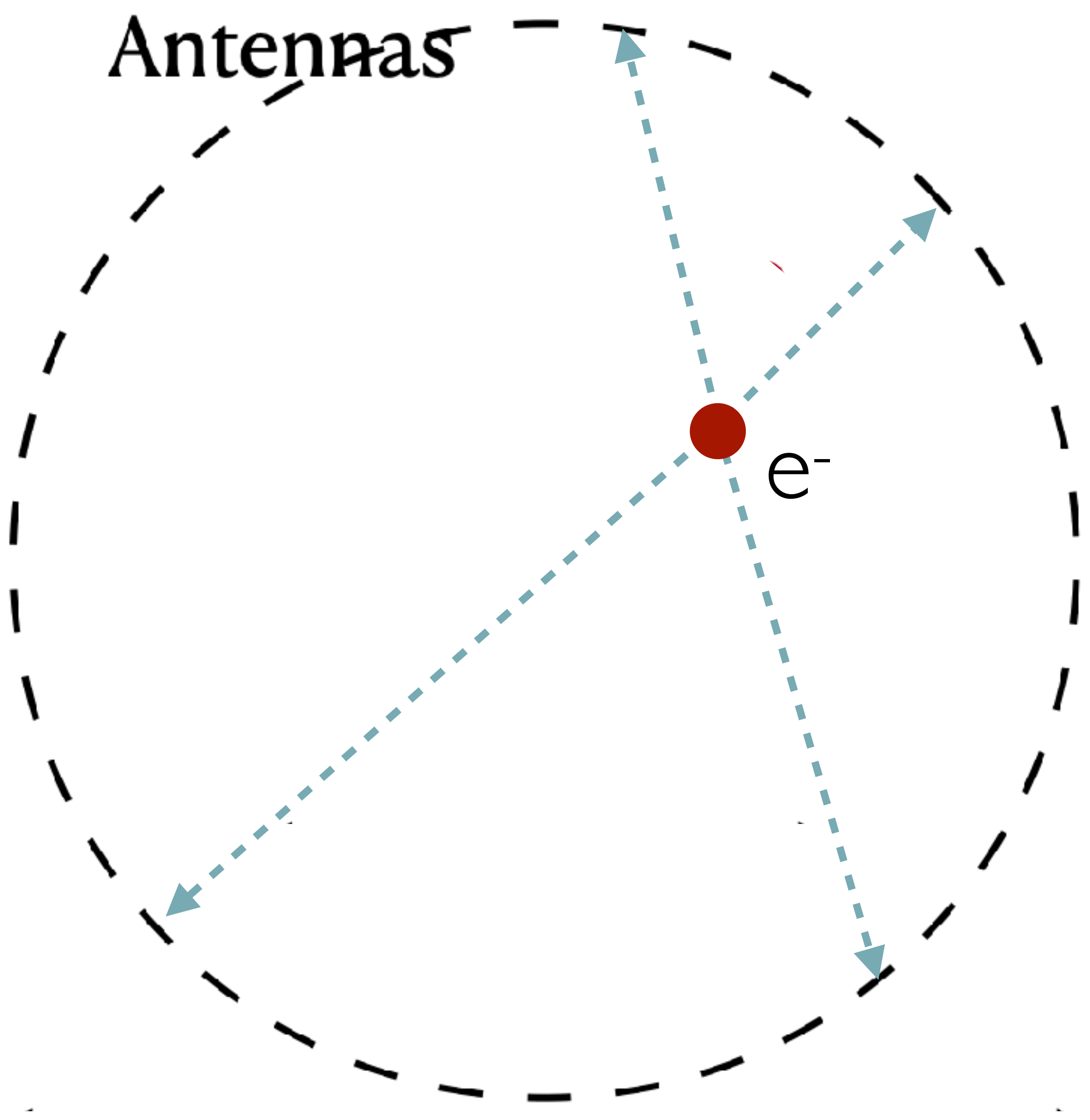
Reconstructing CRES Electrons

- Array of antennas arranged cylindrically
- The signal received will have a relative phase based on the position of the electron



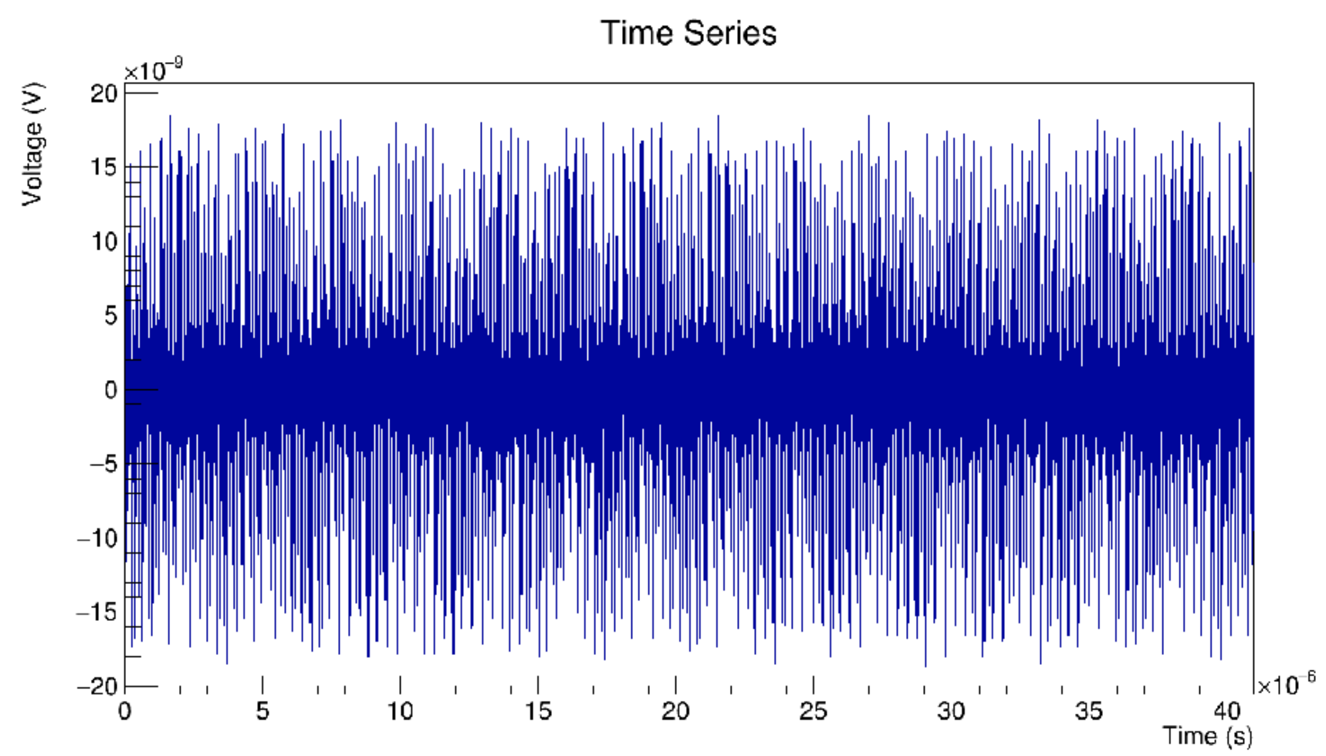
X N channels



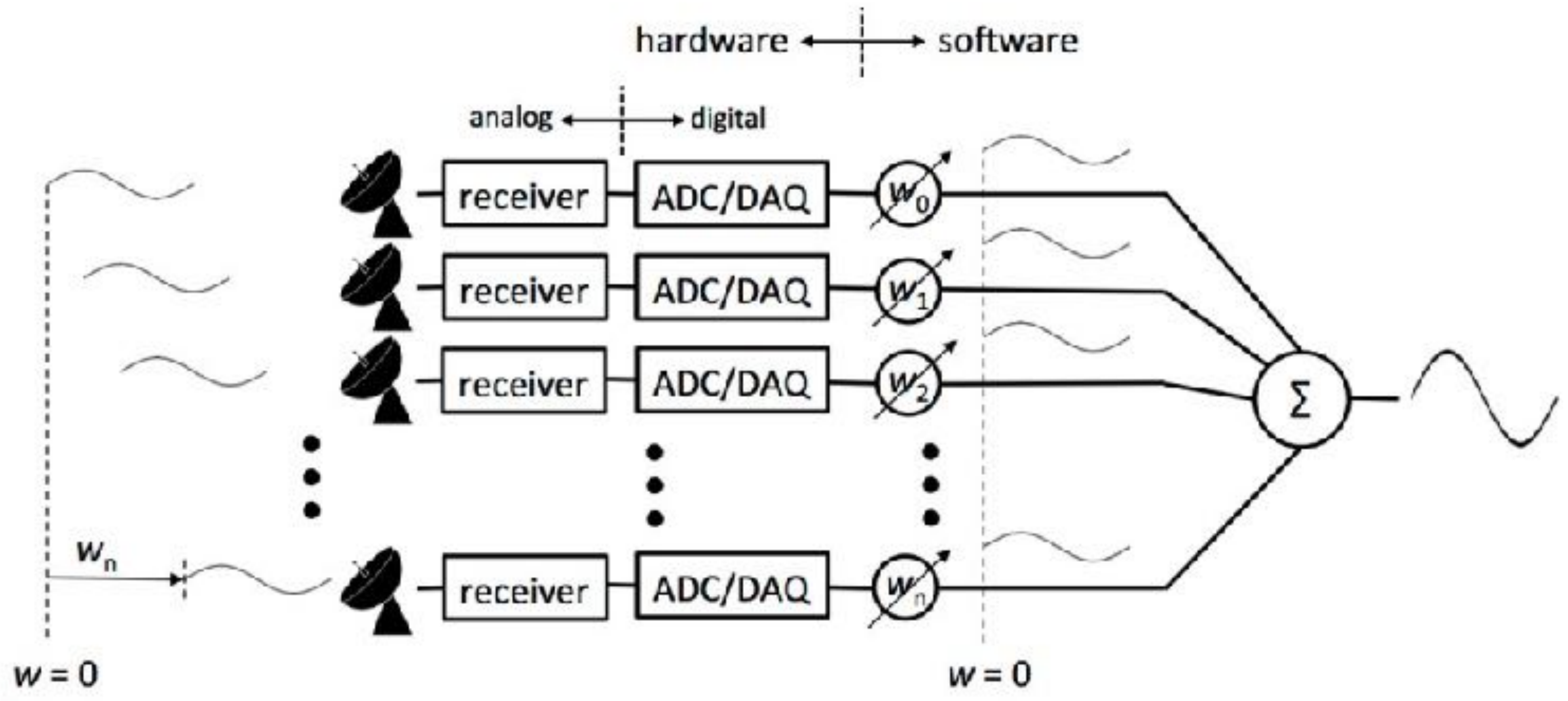


Reconstructing CRES Electrons

- Array of antennas arranged cylindrically
- The signal received will have a relative phase based on the position of the electron
- Digitally apply phase shifts to reconstruct the electron position (Digital Beamforming)

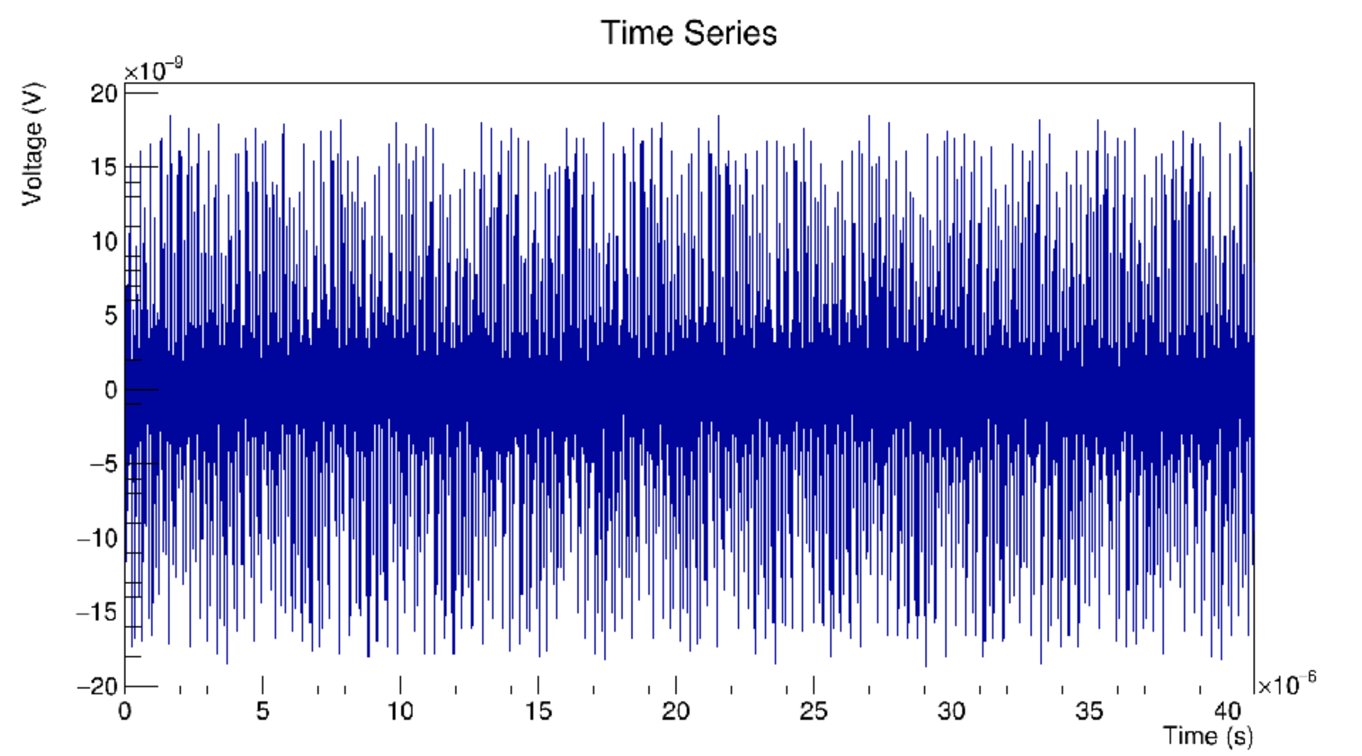


X N channels



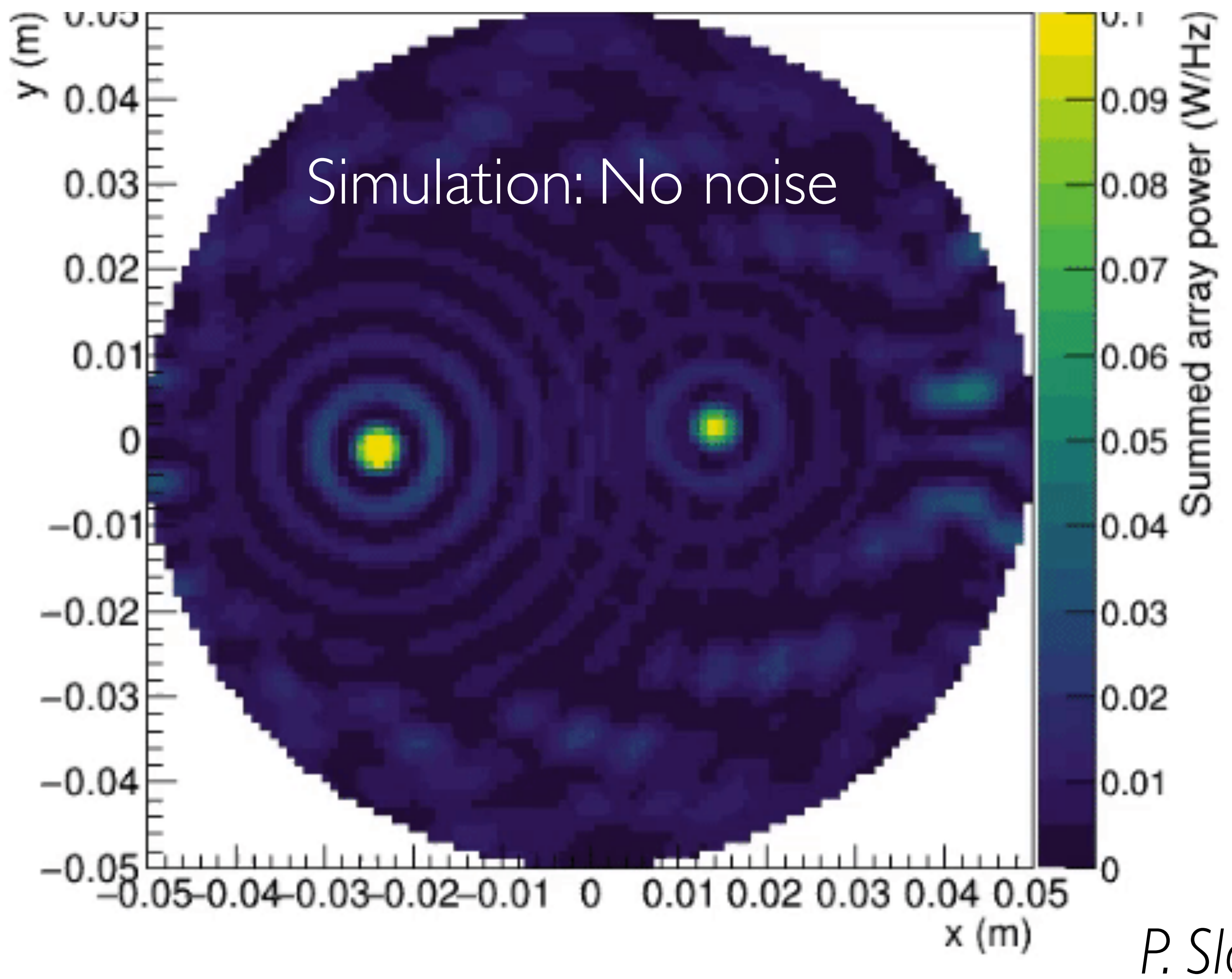
Reconstructing CRES Electrons

- Array of antennas arranged cylindrically
- The signal received will have a relative phase based on the position of the electron
- Digitally apply phase shifts to reconstruct the electron position (Digital Beamforming)
- The reconstructed power is maximized for the true position
- Beamforming enables the observation of CRES electron in free space without pileup



X N channels

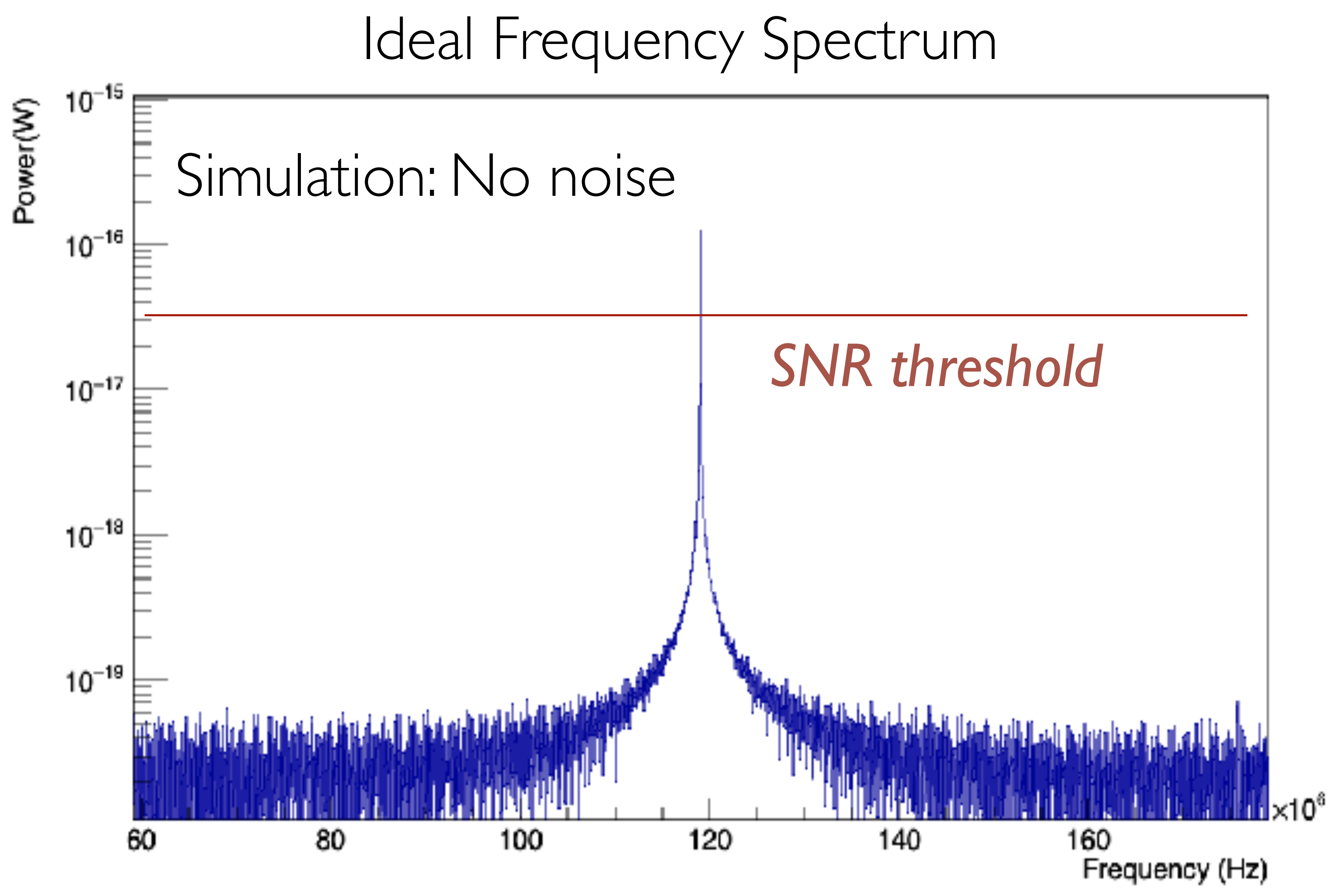
Reconstruction of two simultaneous electrons

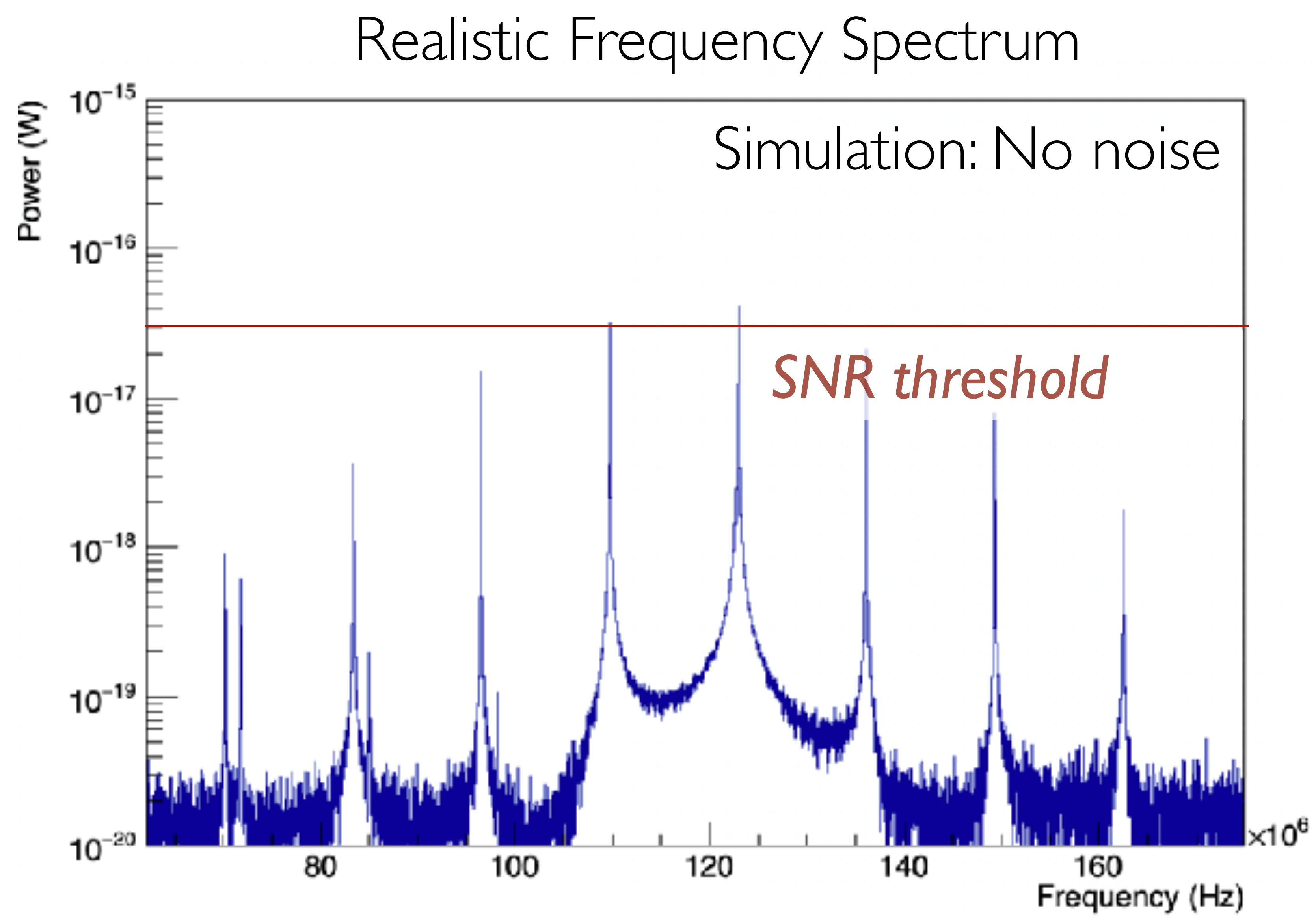


P. Slocum

Advanced Reconstruction Techniques

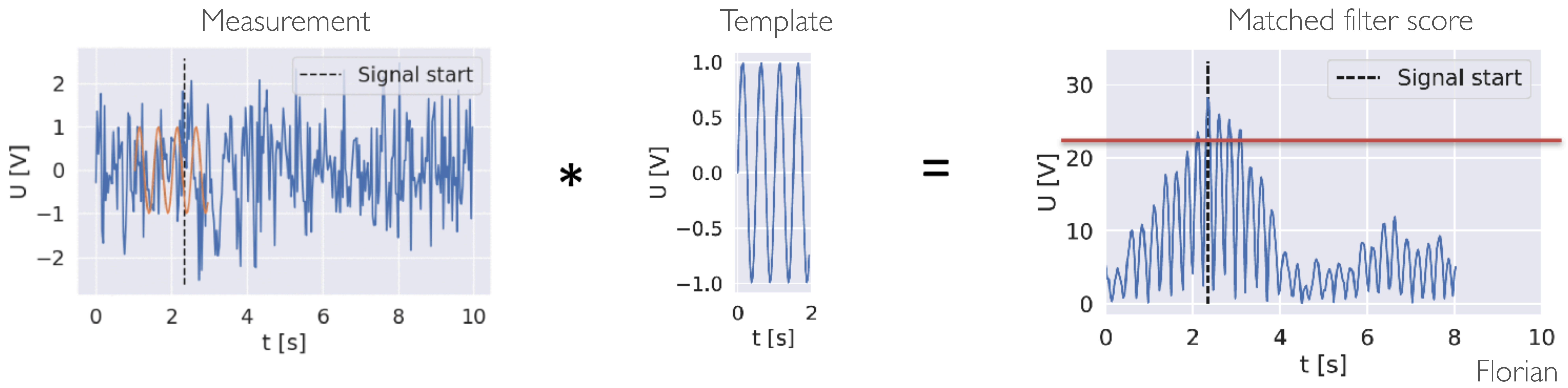
- Complicated signal based on electron's kinematics
- Low SNR limits electron detection
- Investigating advanced reconstruction techniques to leverage full signal structure





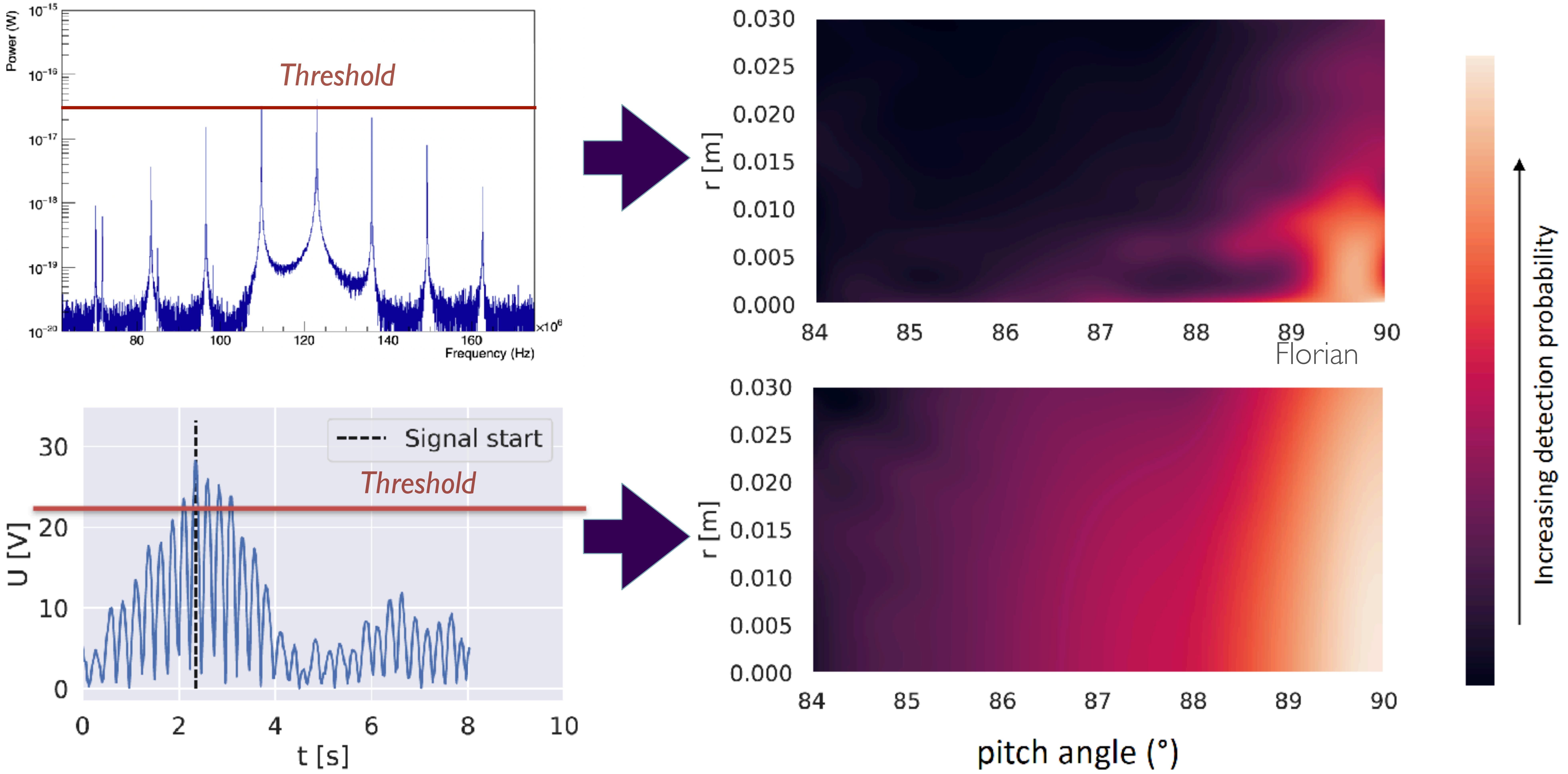
Advanced Reconstruction Techniques: Matched Filter

- Matched filter: Optimal linear filter that maximizes the signal to noise ratio



- Search for the signal by applying matched filter over a template bank
- Used widely in radar and digital communications
  - Notably used for gravitational wave detection by LIGO

Advanced Reconstruction Techniques: Matched Filter



- Matched filter improves efficiency by taking full advantage of the signal structure
- Template bank development and demonstration of Matched Filtering feasibility underway

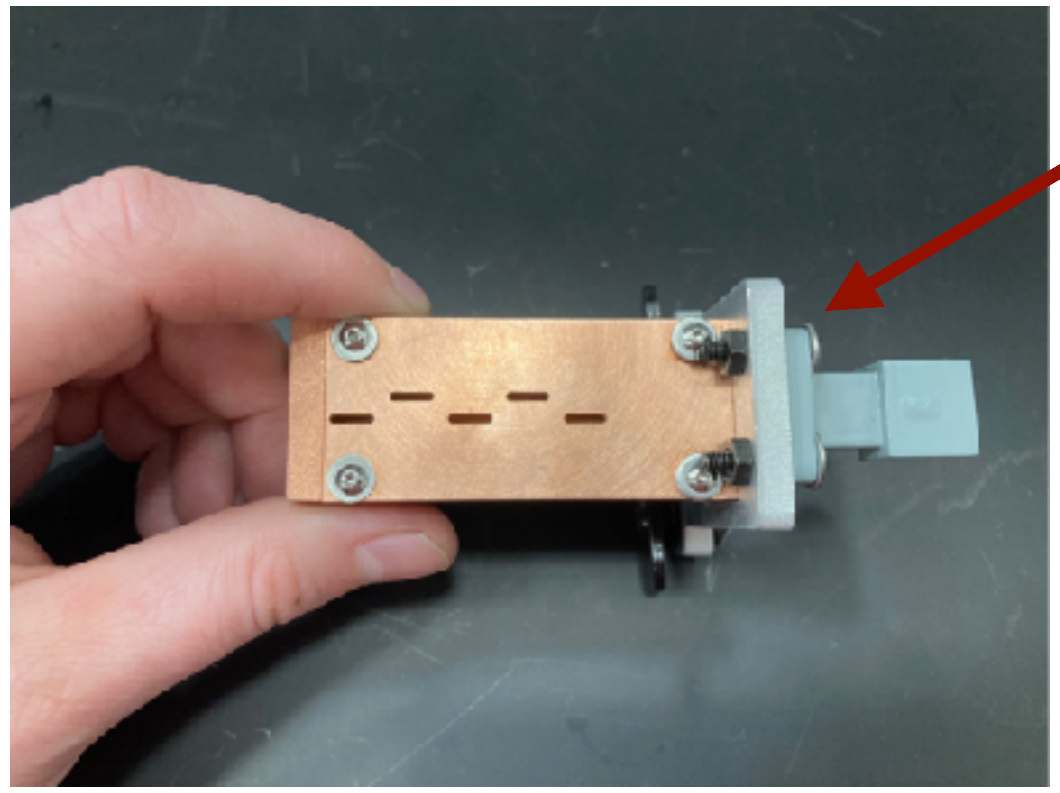
R&D for Demonstrators

- Before the assembly of full antenna array at cryogenic temperature plan to:
  - Characterize detector components
  - Study analysis techniques
  - Validate simulations

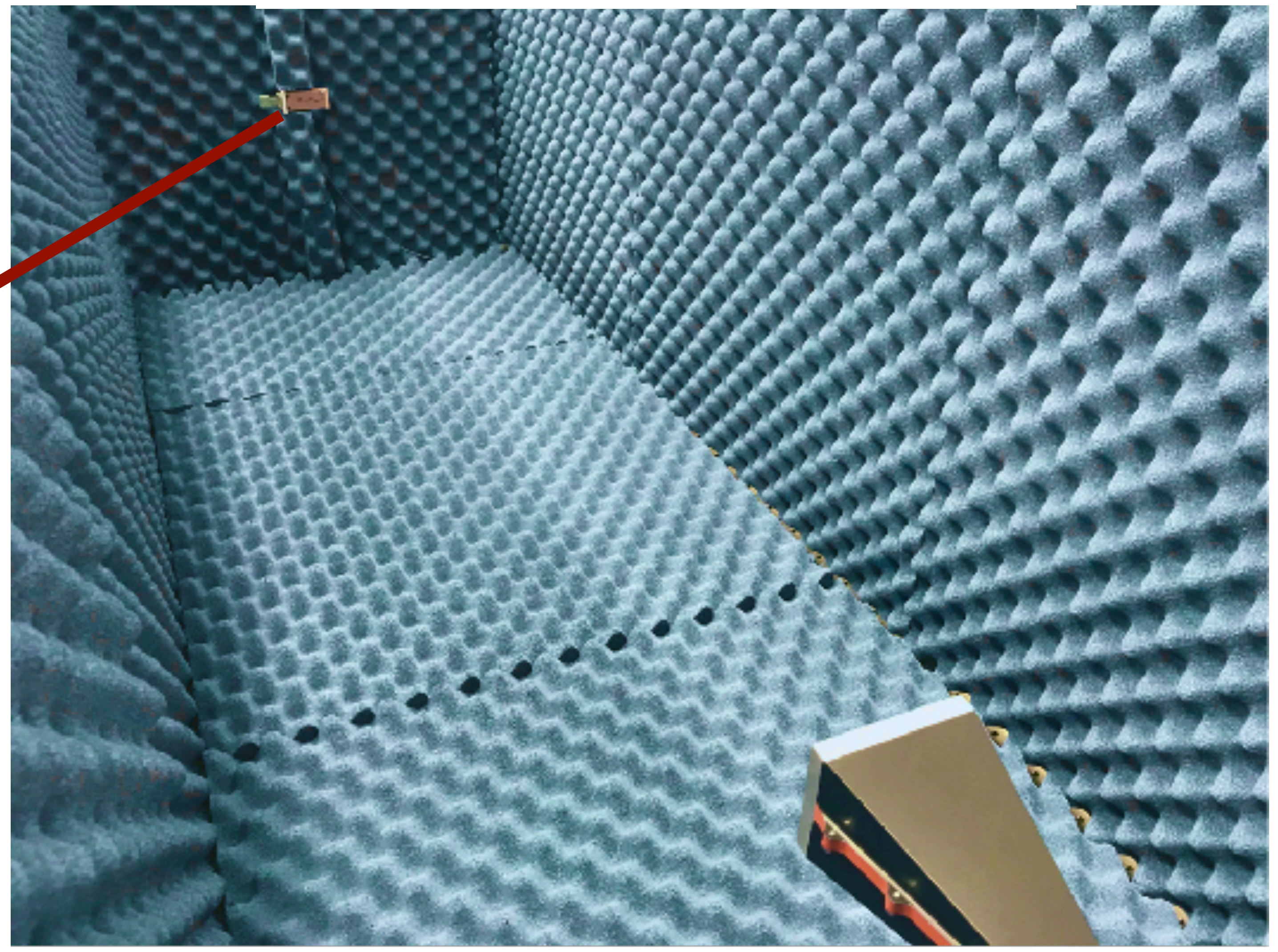
R&D for Demonstrators: Antennas

- Testbed at Yale for antenna R&D
- Custom-built antennas at Yale for room temperature antenna measurements
- Modular design allows for quick prototyping

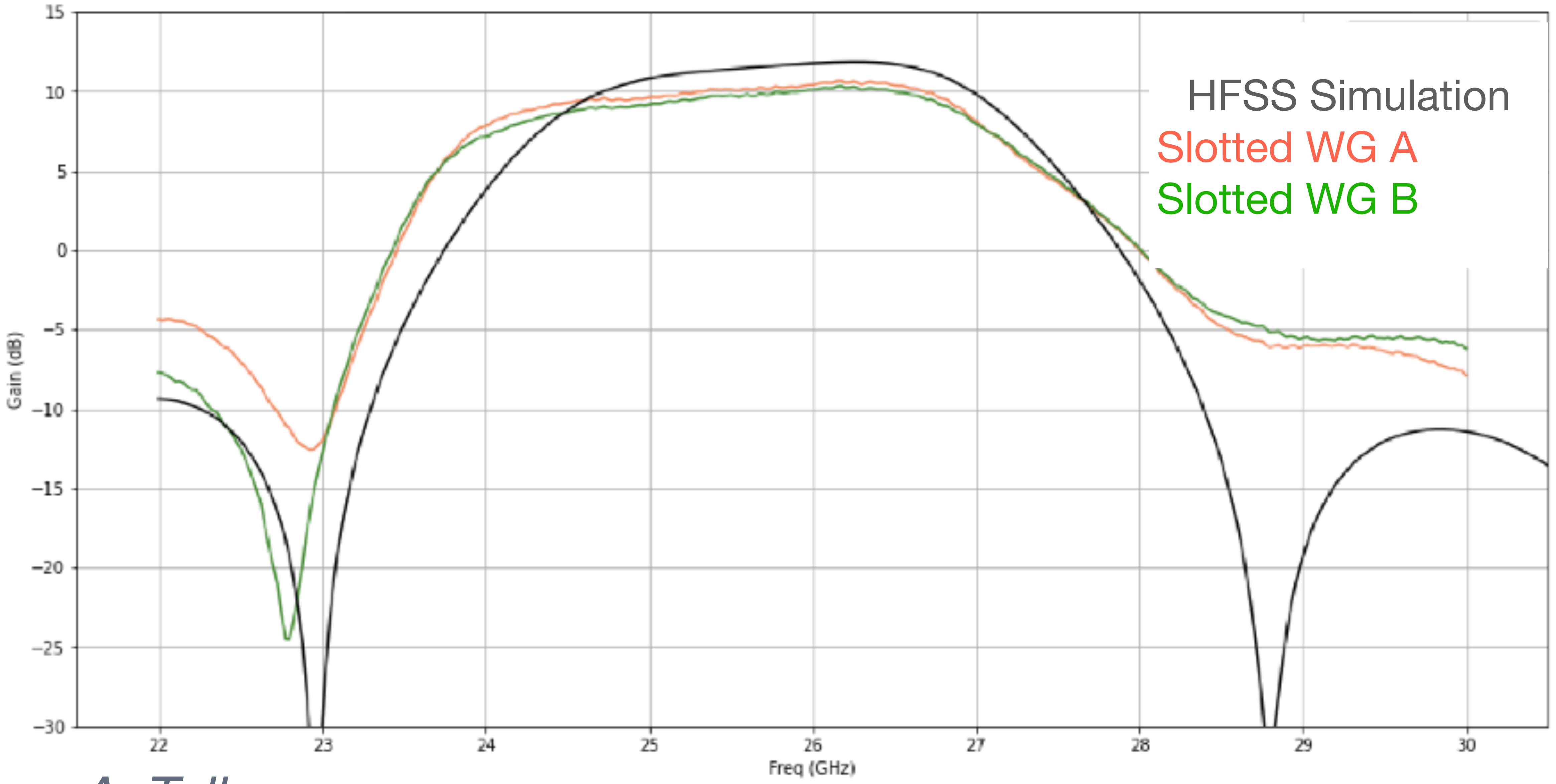
Custom-built modular antenna design



Antenna characterization setup

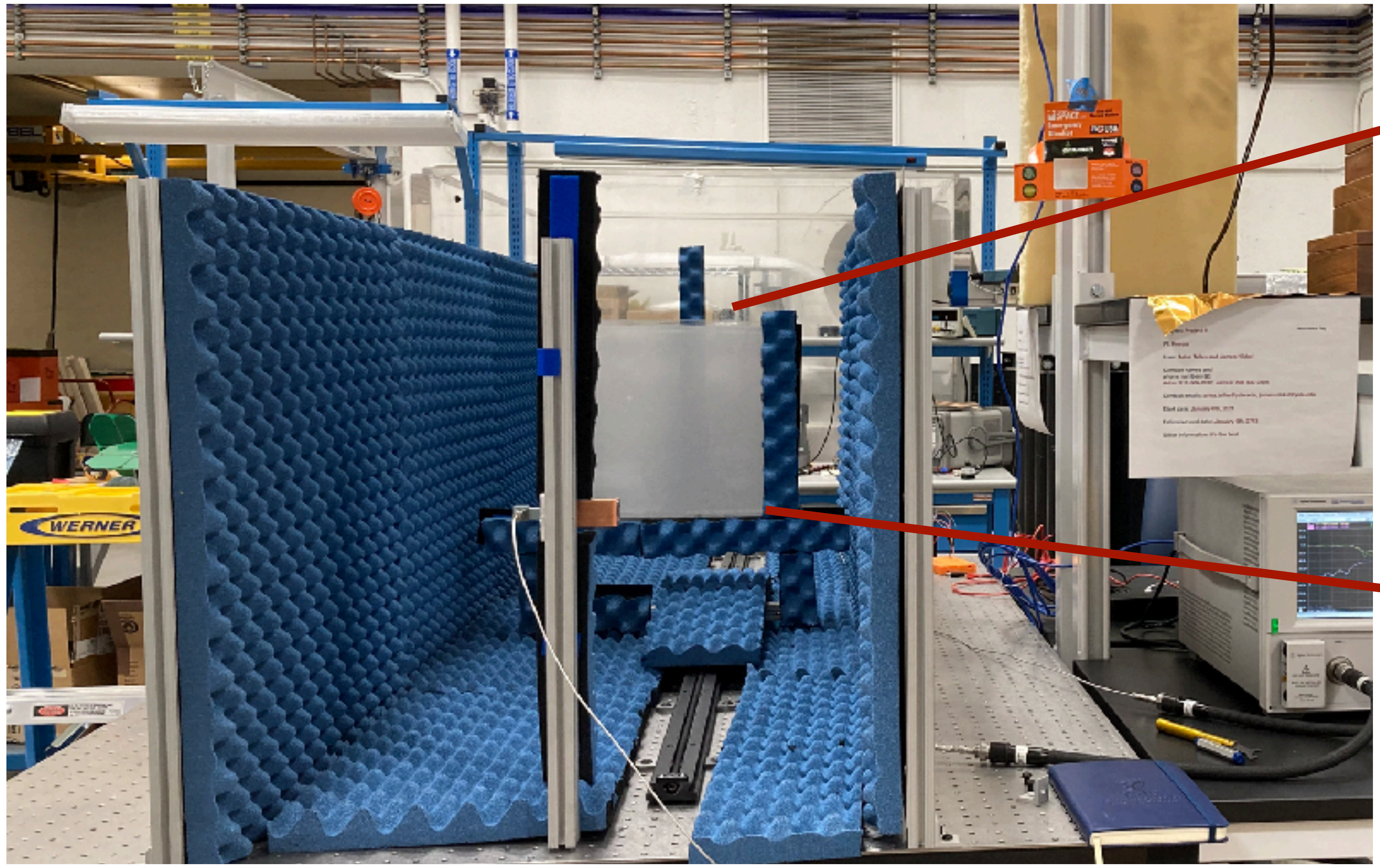


Boresight Gain of Slotted Waveguide

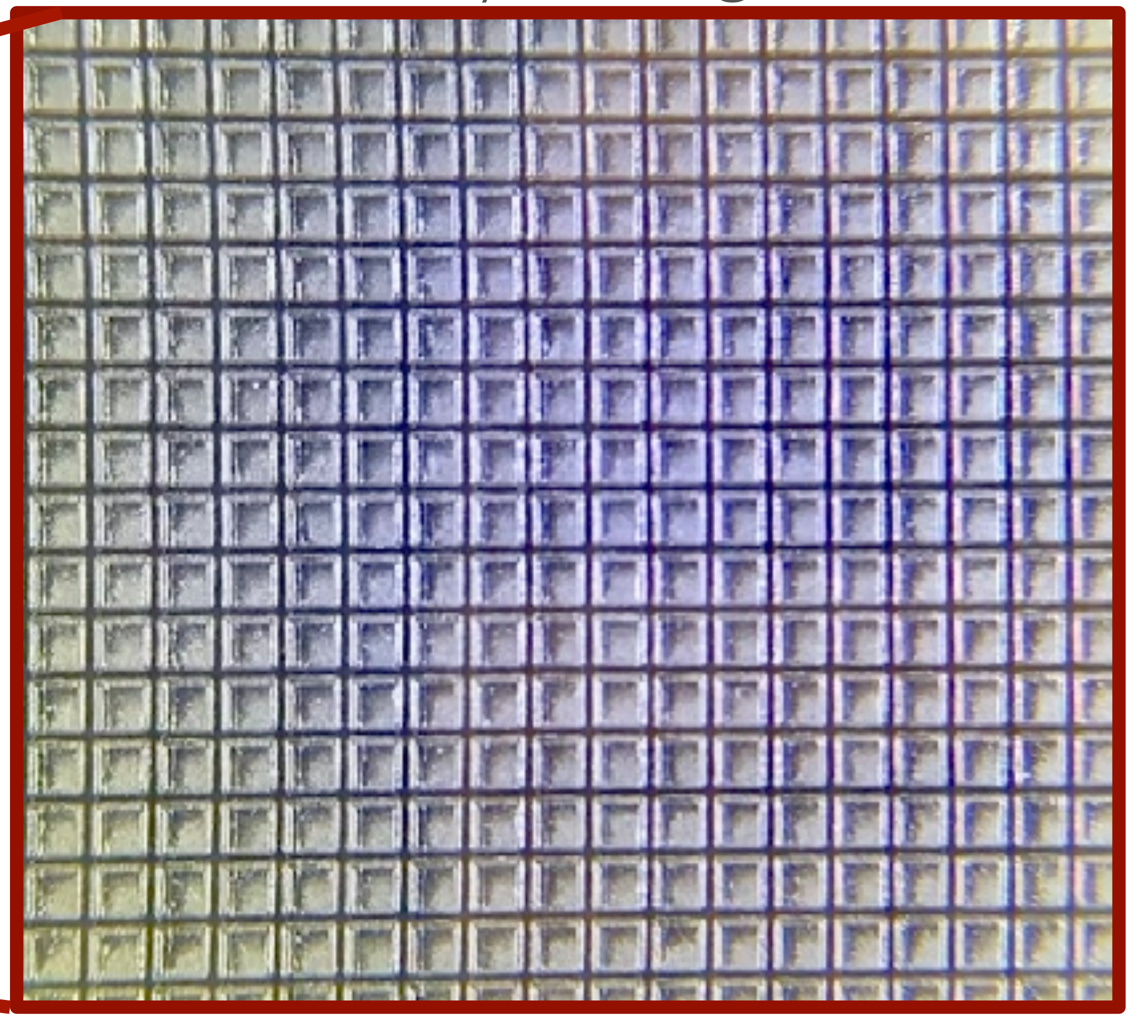


A. Telles

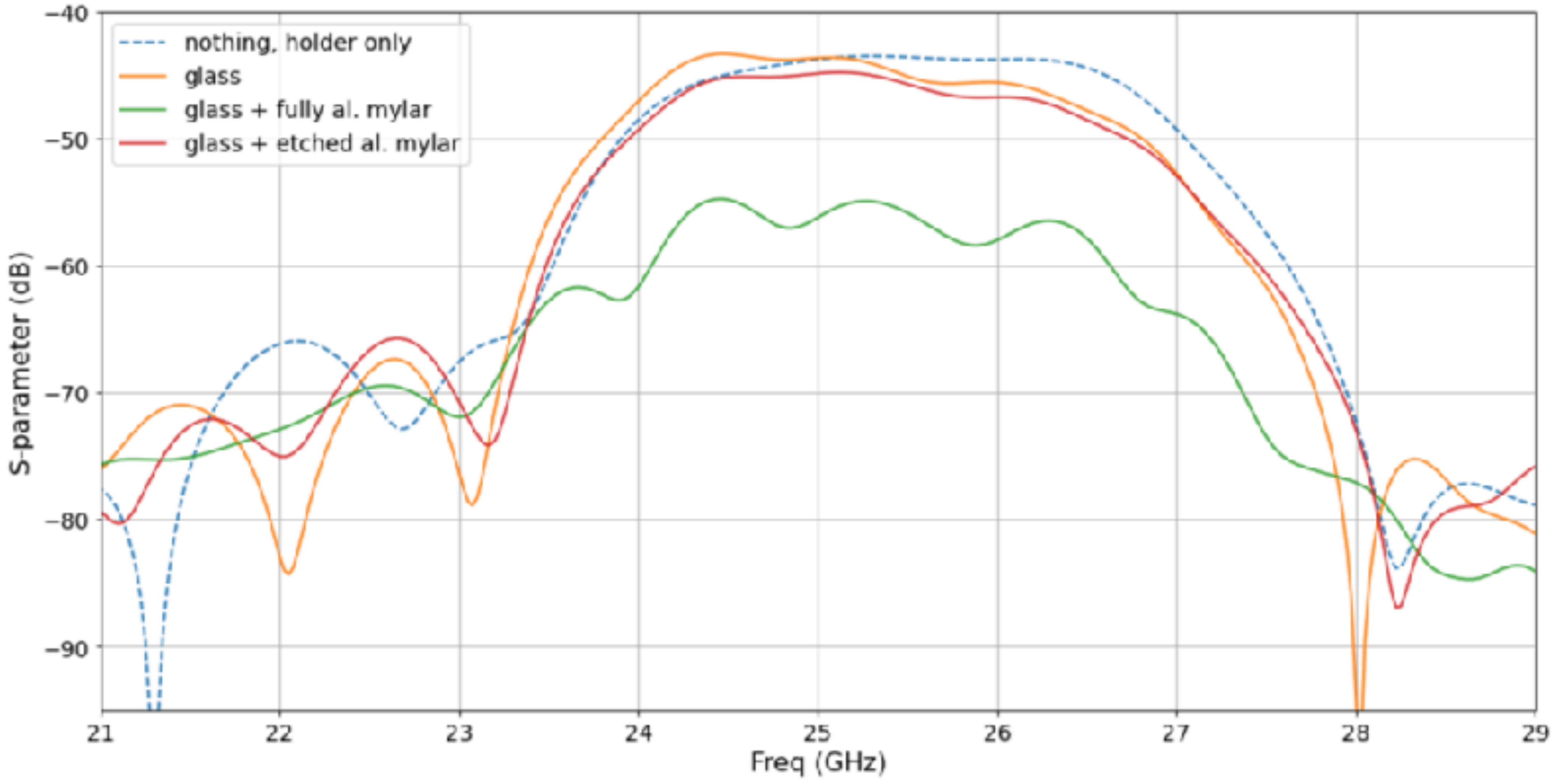
R&D for Demonstrators: Component Characterization



Etched mylar on glass



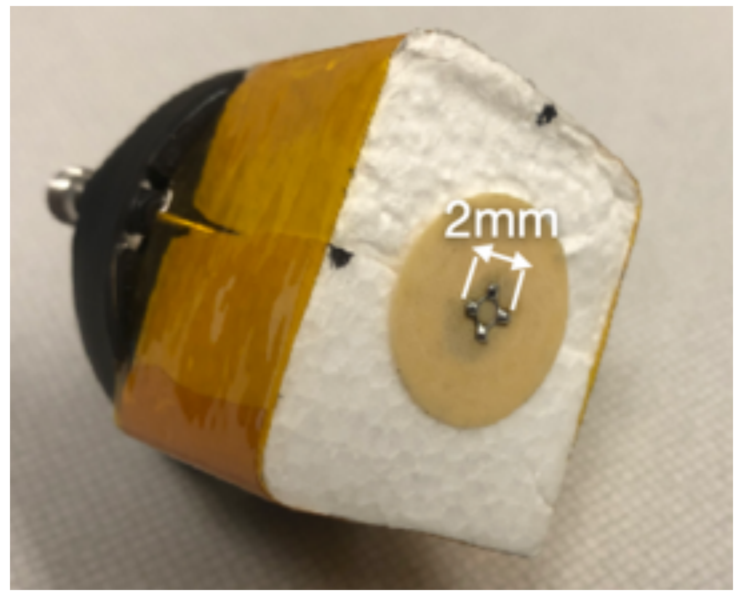
A. Telles

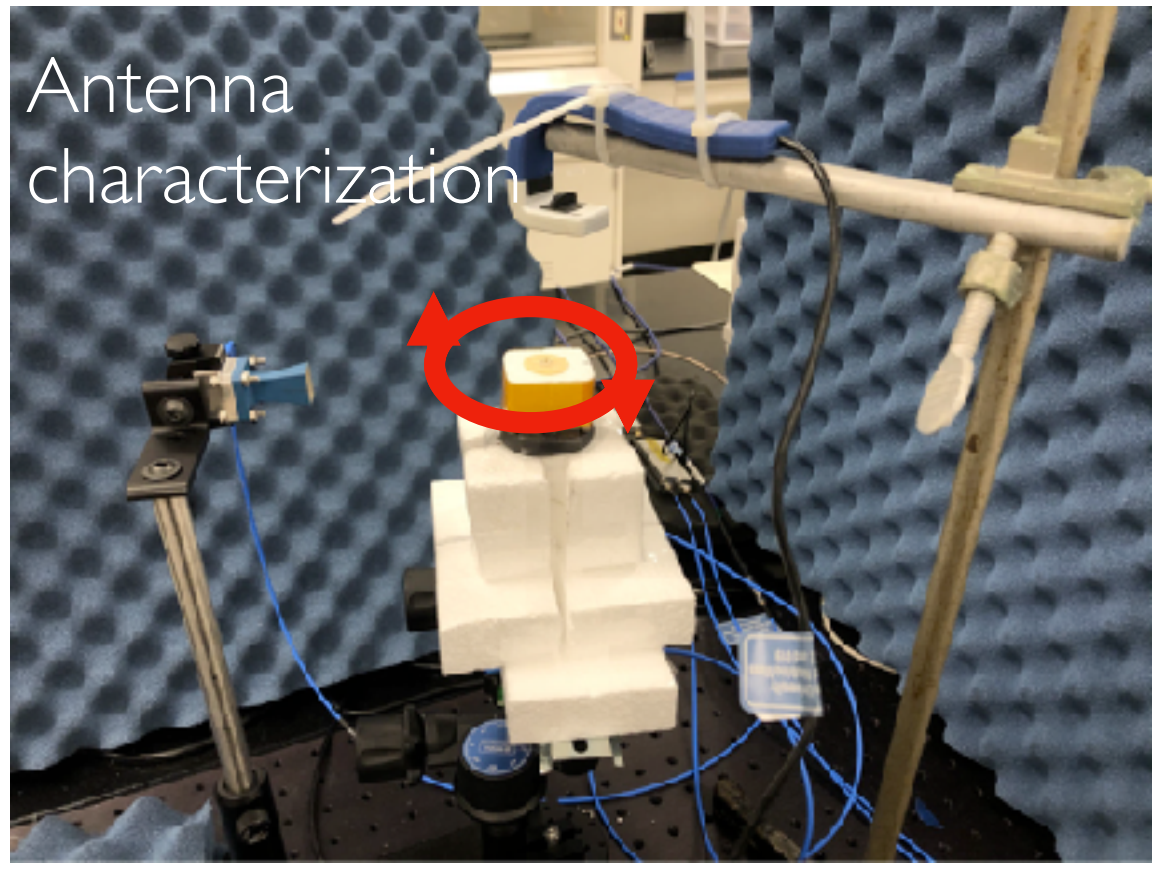


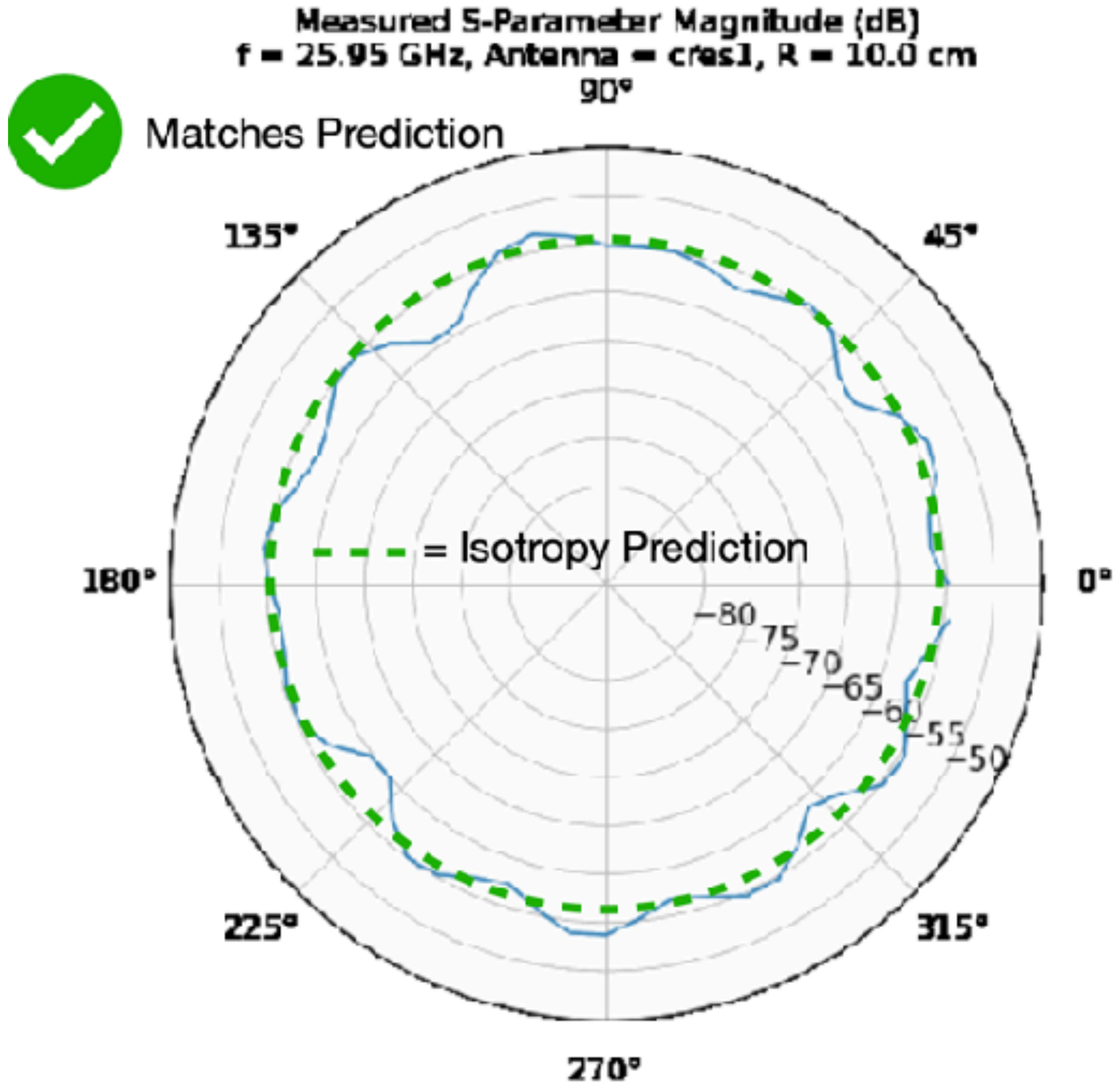
- Testbed at Yale to perform
  - Attenuation measurements of detector components
  - Development of RF-transparent thermal insulation

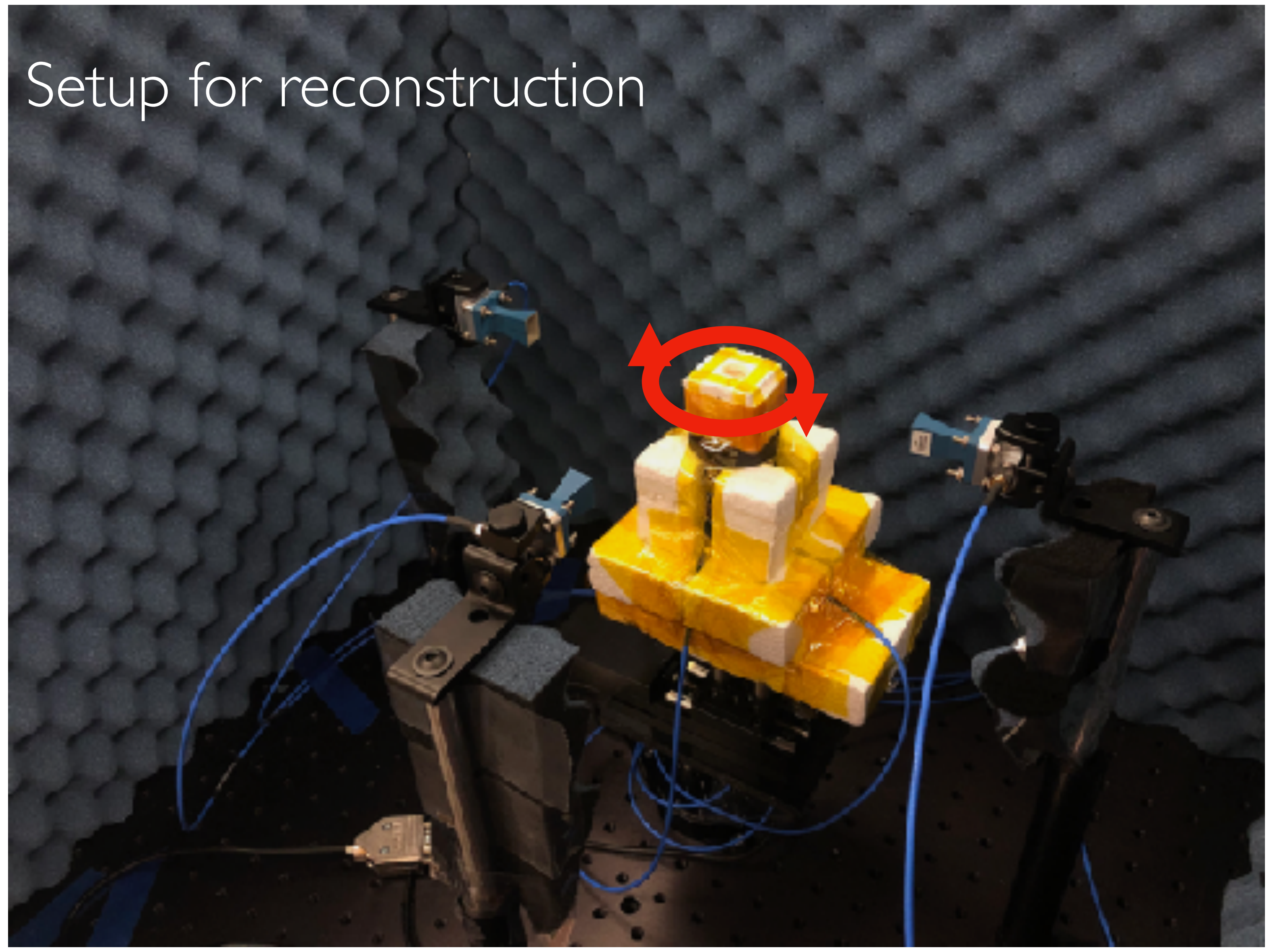
R&D for Demonstrators: Reconstruction

- Testbed at Penn state for studying reconstruction
  - CRES-like antenna developed and characterized
  - Initial reconstruction tests
  - Will be used for commissioning of phase-III antenna array

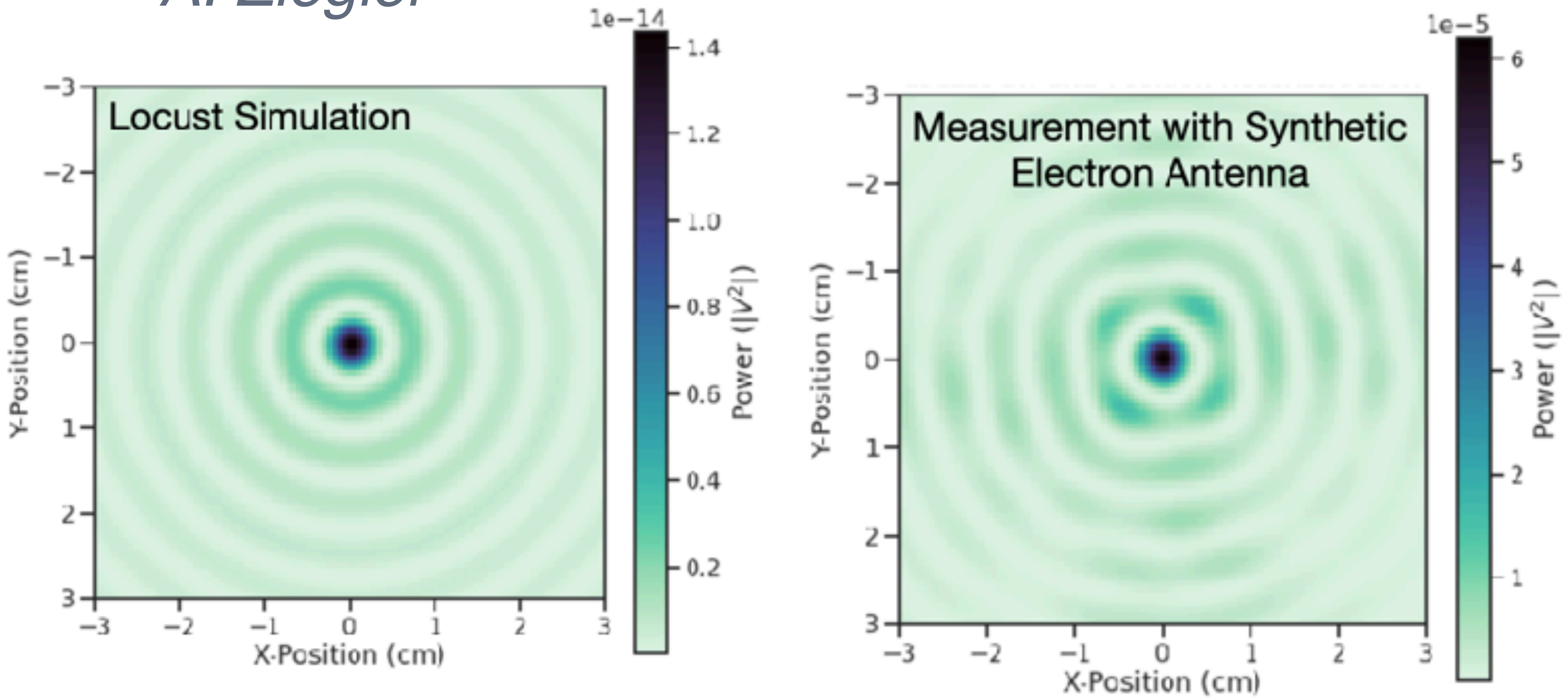






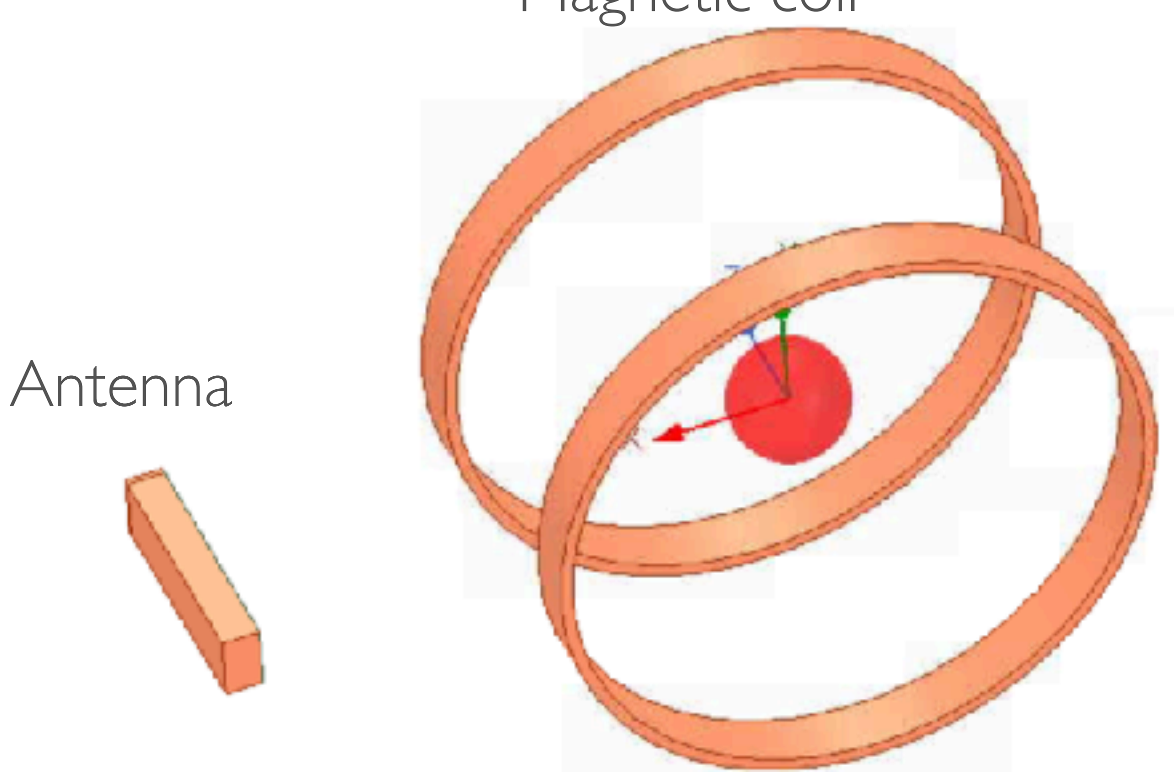


A. Ziegler

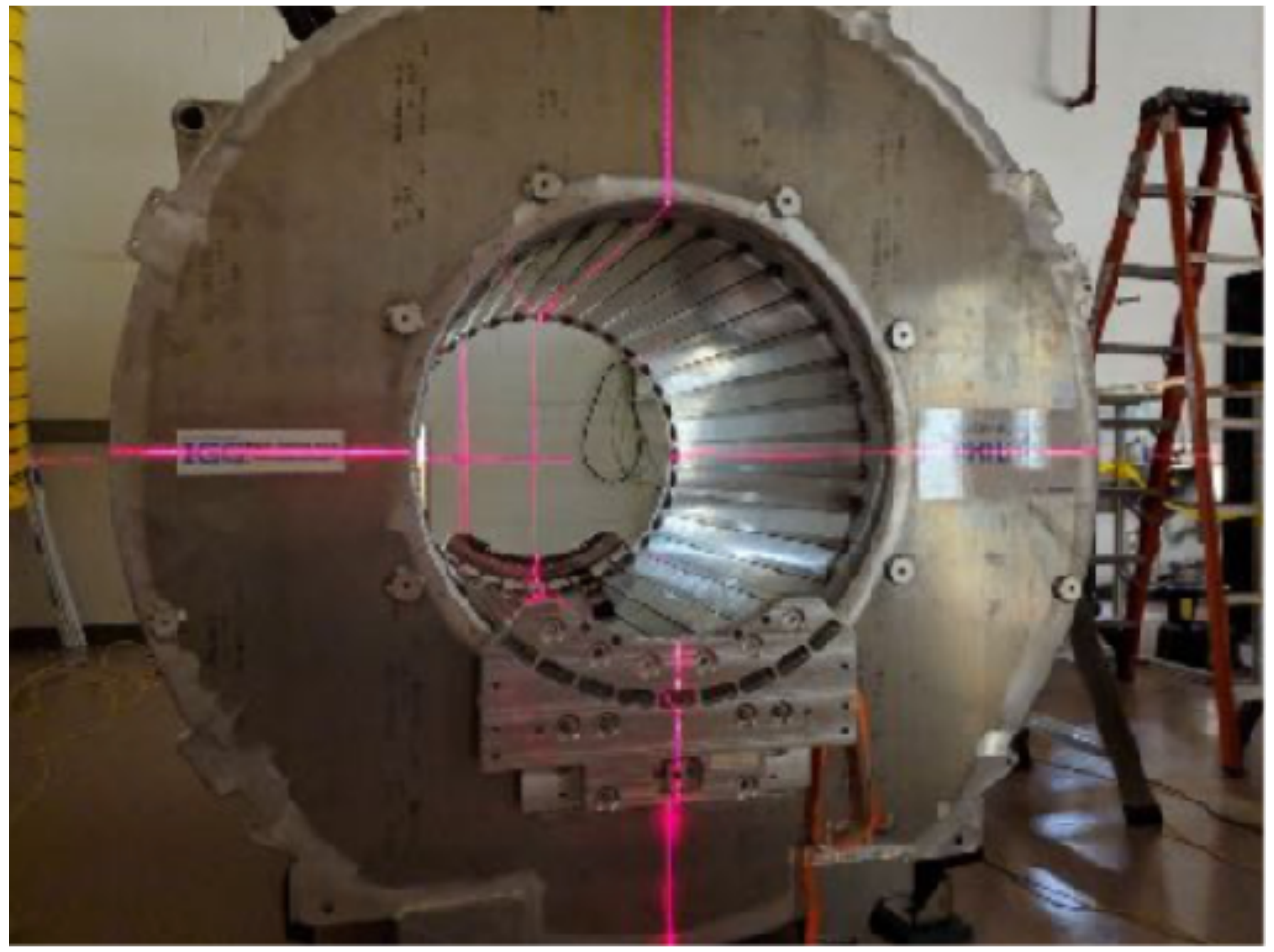


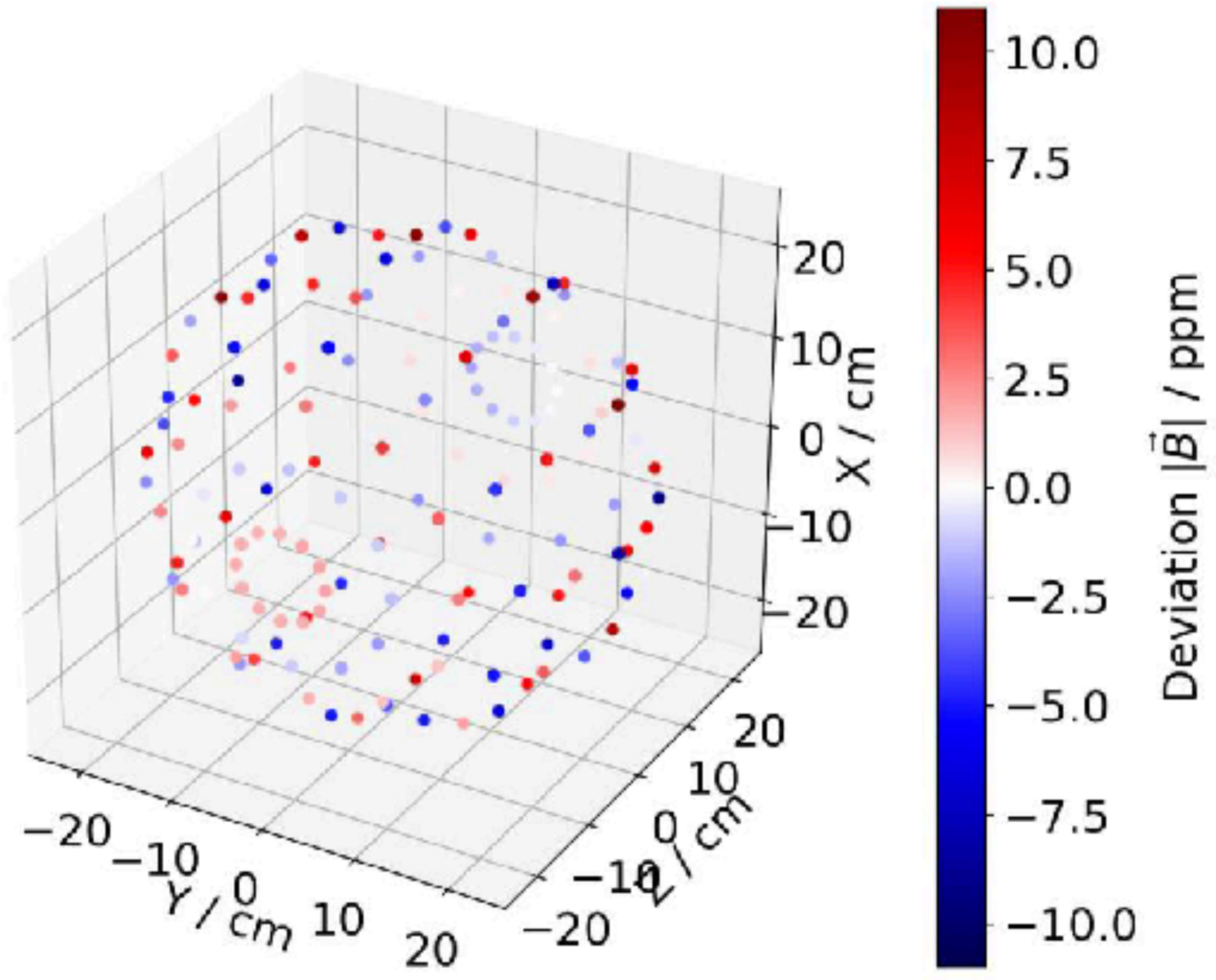
R&D for Demonstrators: Magnetic Field and Trapping

- Mapping of the commercial MRI magnet performed
- ~ppm-level homogeneity over 200 cm^3 volume
- Iterative antenna-trap design

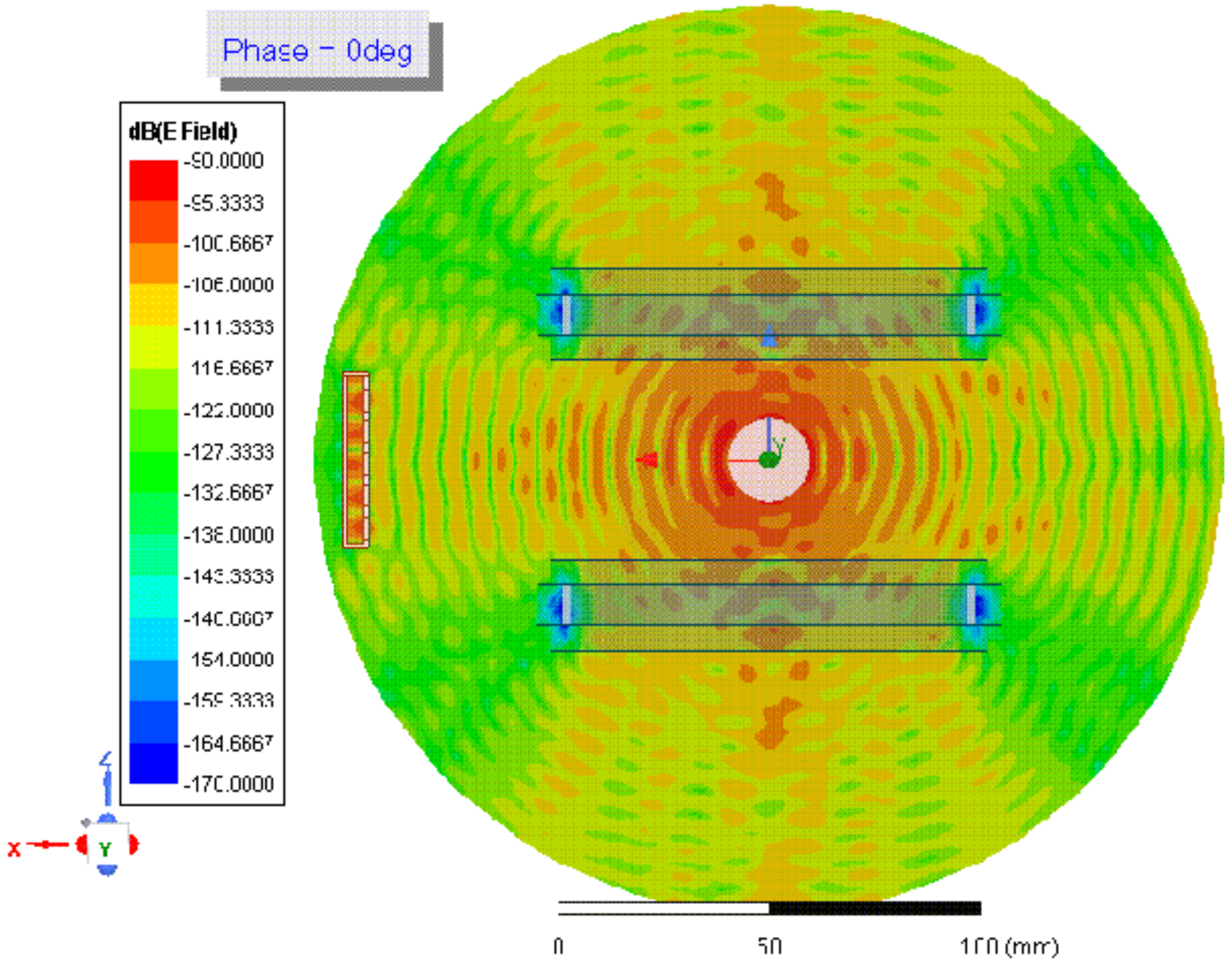


A. Telles

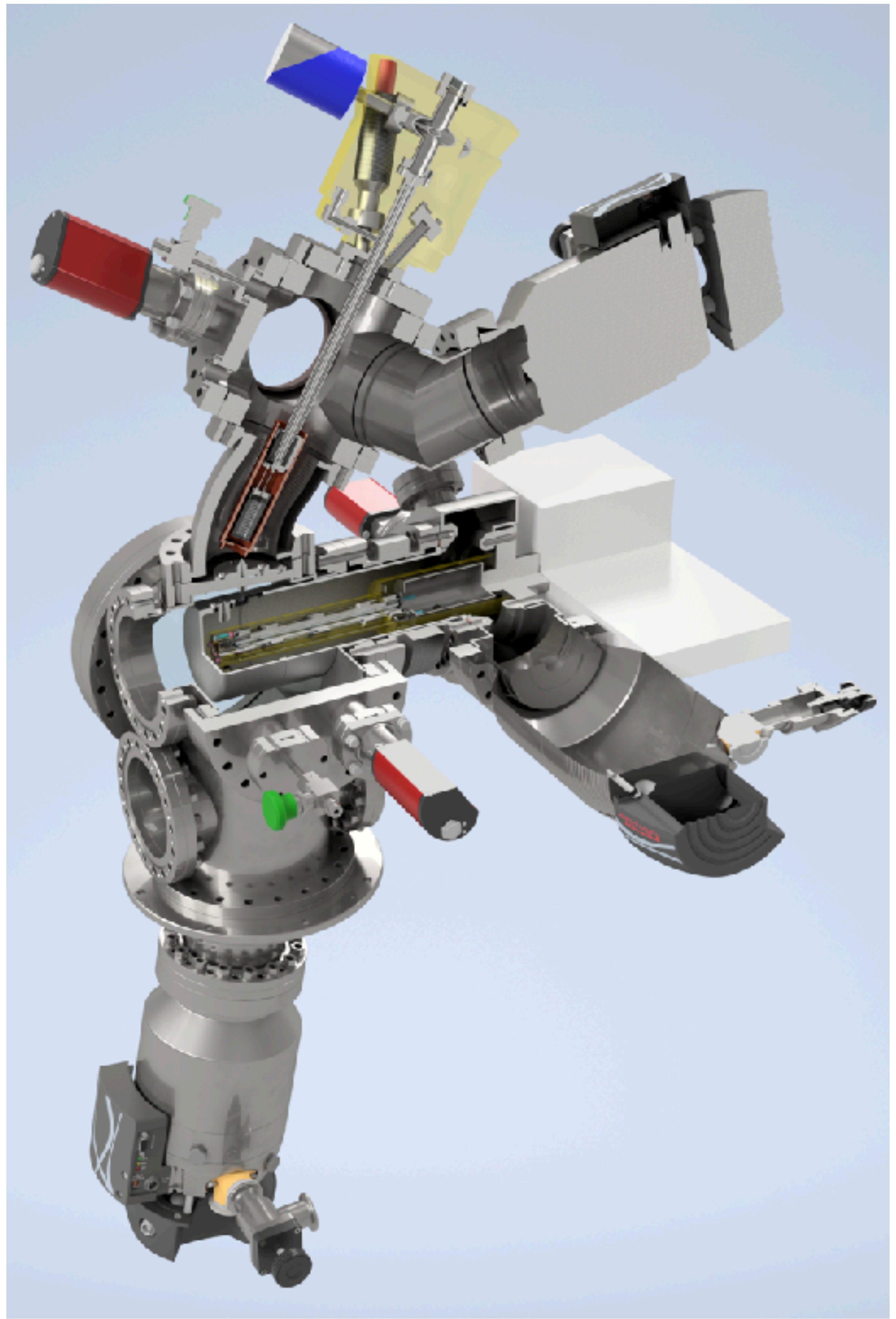




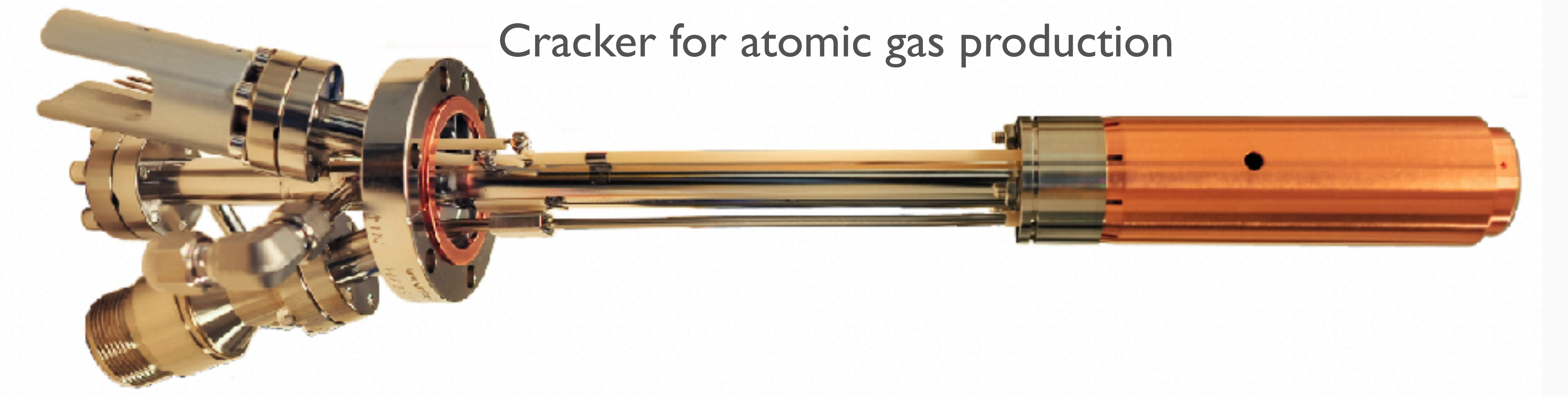
R. Reimann



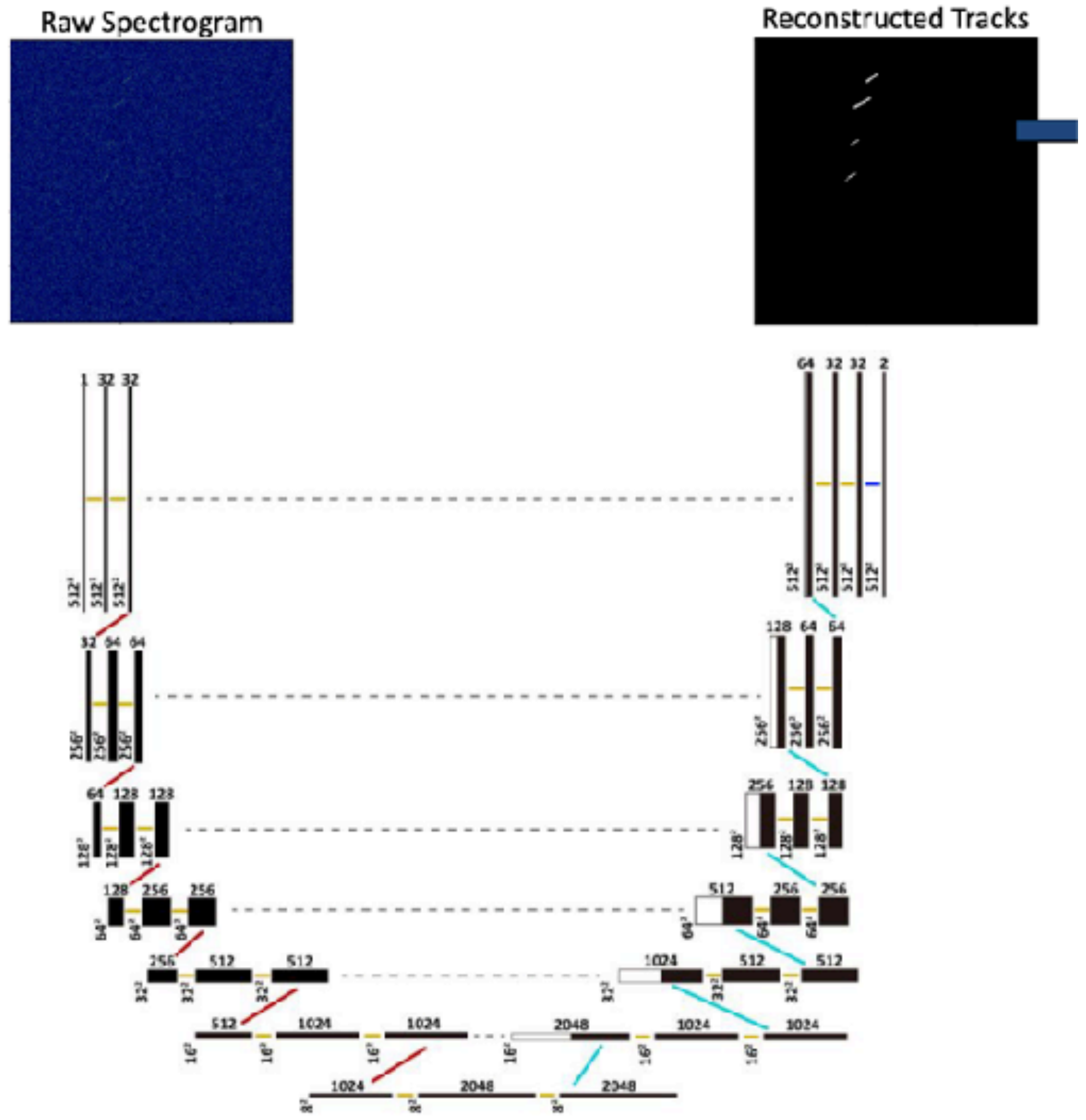
A Lot More Active Projects



Setup for atomic hydrogen production

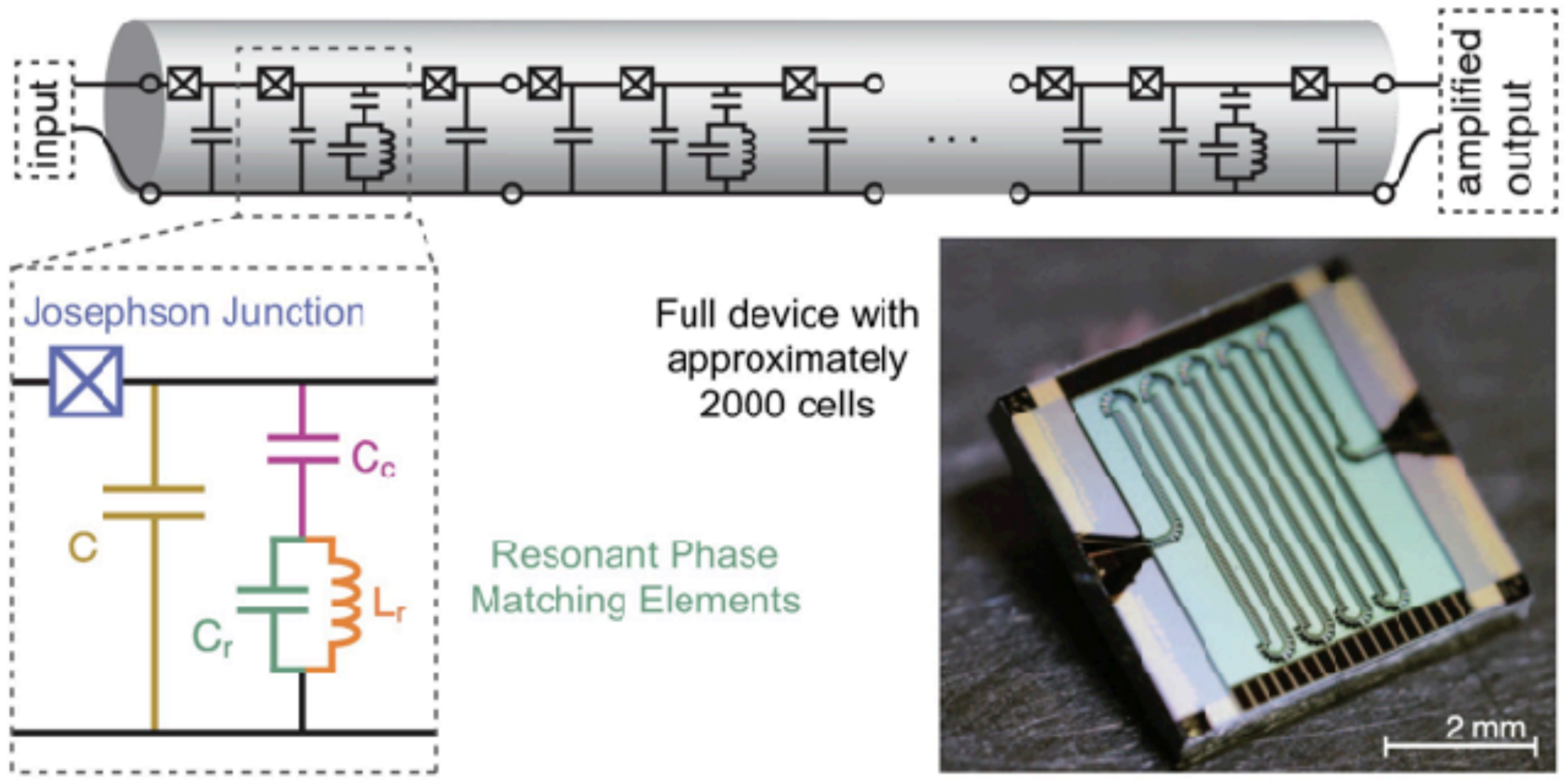


Cracker for atomic gas production



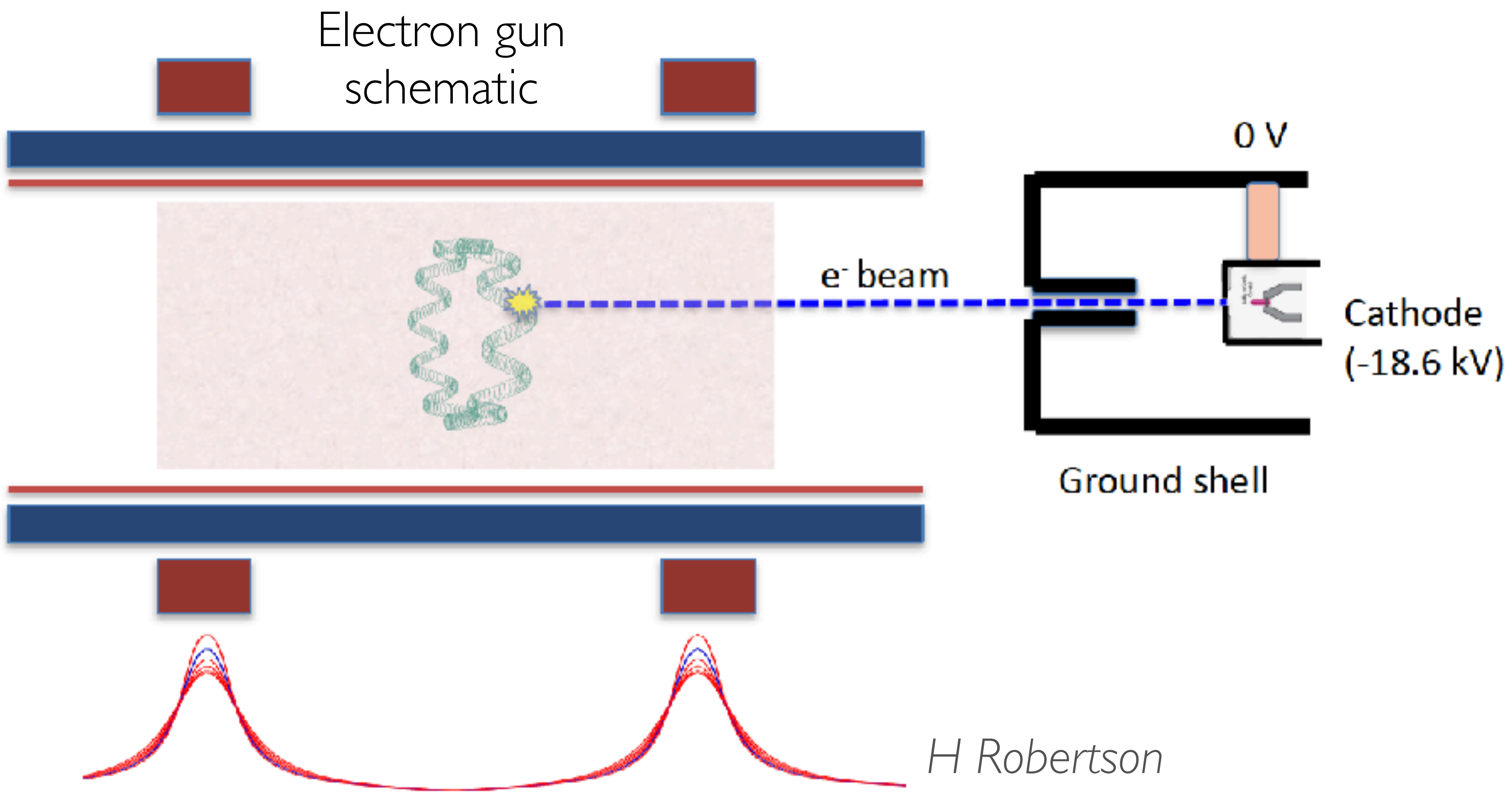
U-Net for track reconstruction

Quantum amplifiers

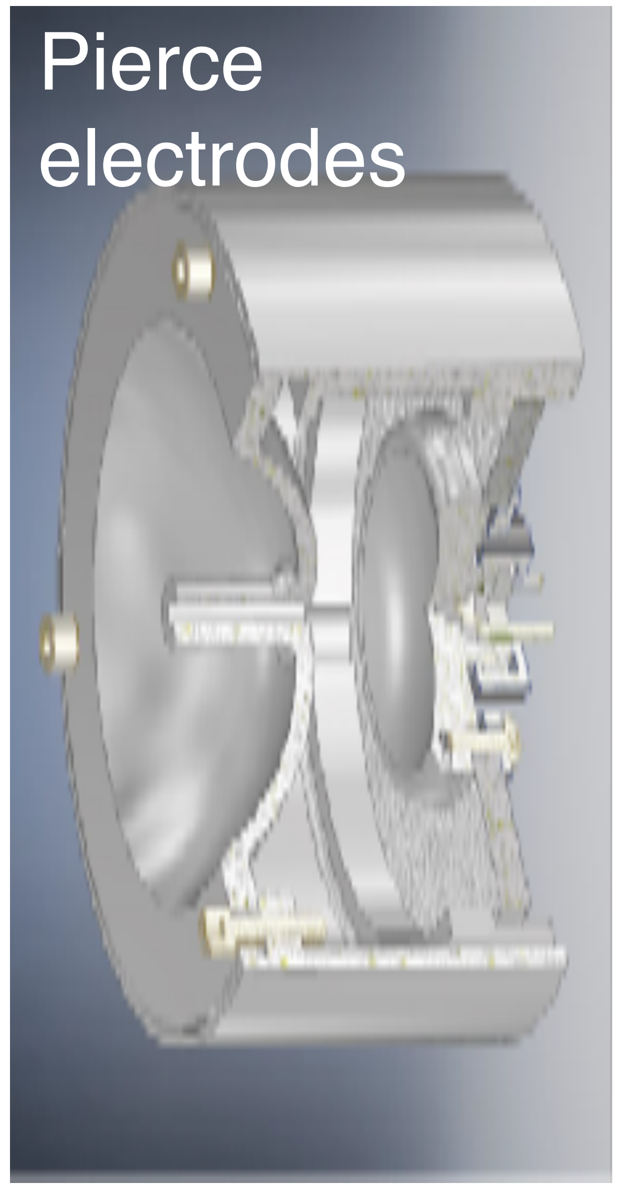


and more…

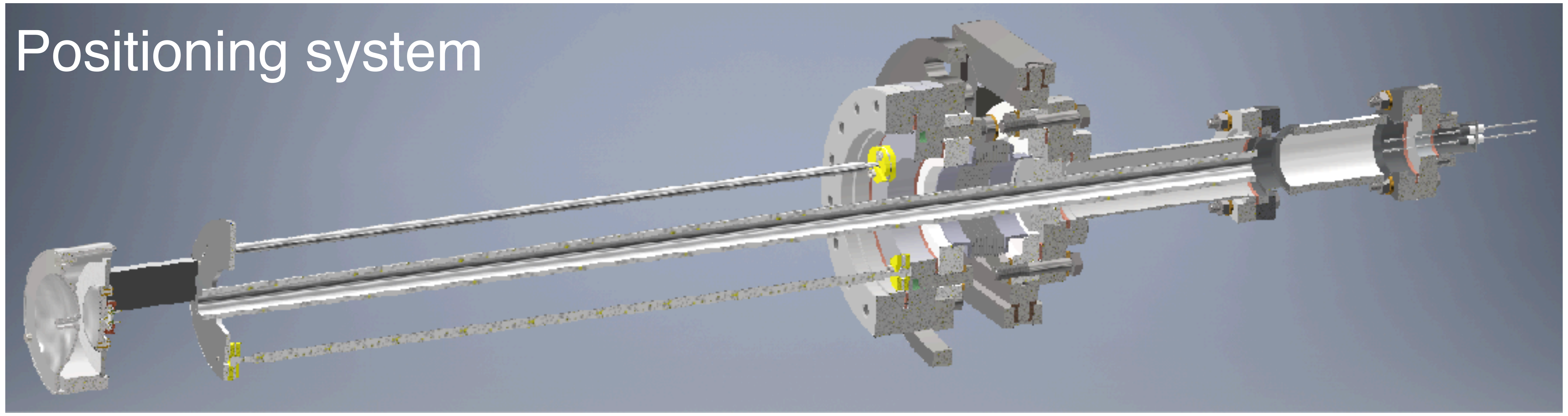
Phase-III Calibration



H Robertson



R Roenhelt



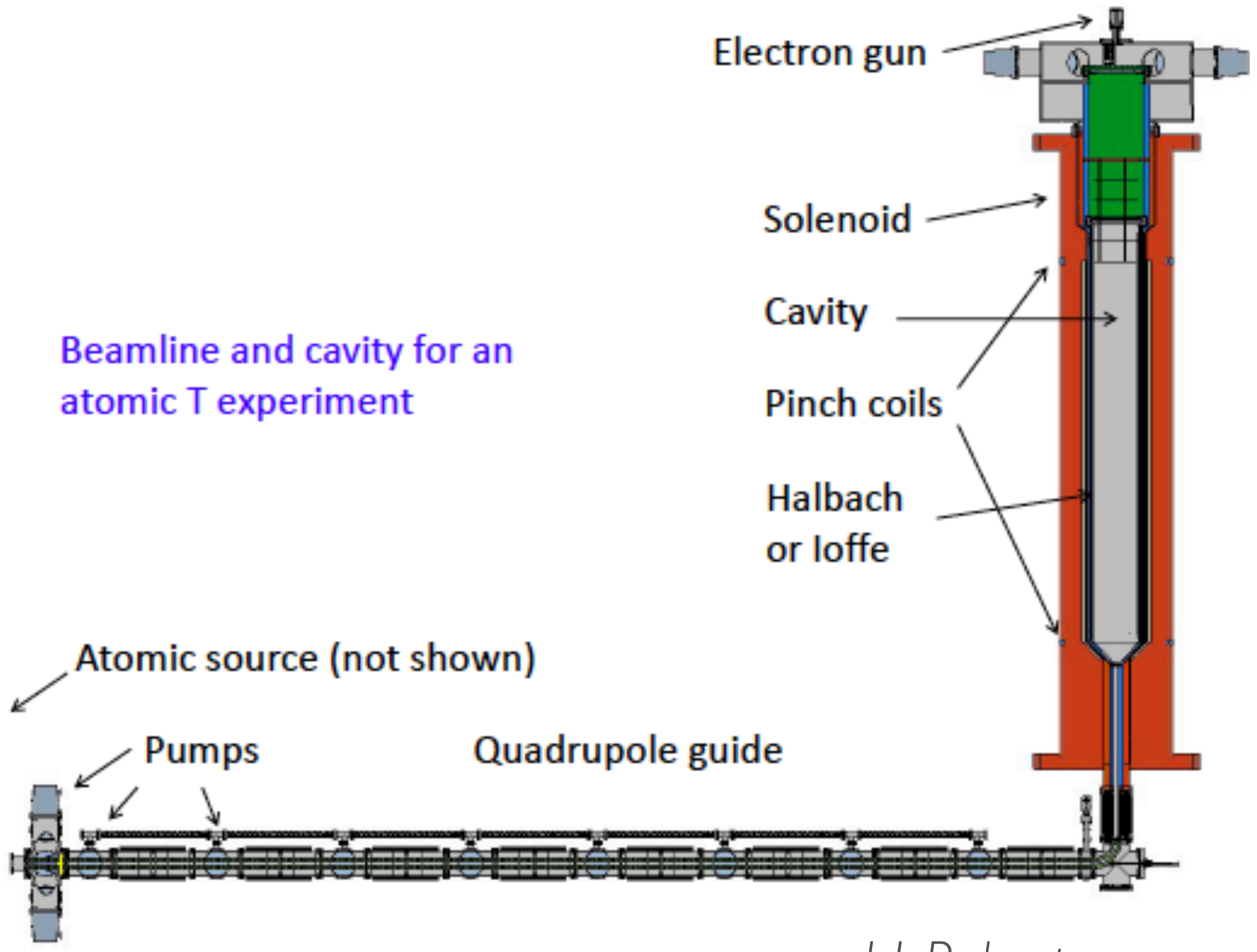
- Electron gun being built at UW for calibration
  - Portion of electrons mott scatter off of gas and get trapped
  - Narrow energy spread (~0.3 eV)
  - Energy-tunable radius-specific calibration

Phase III Science

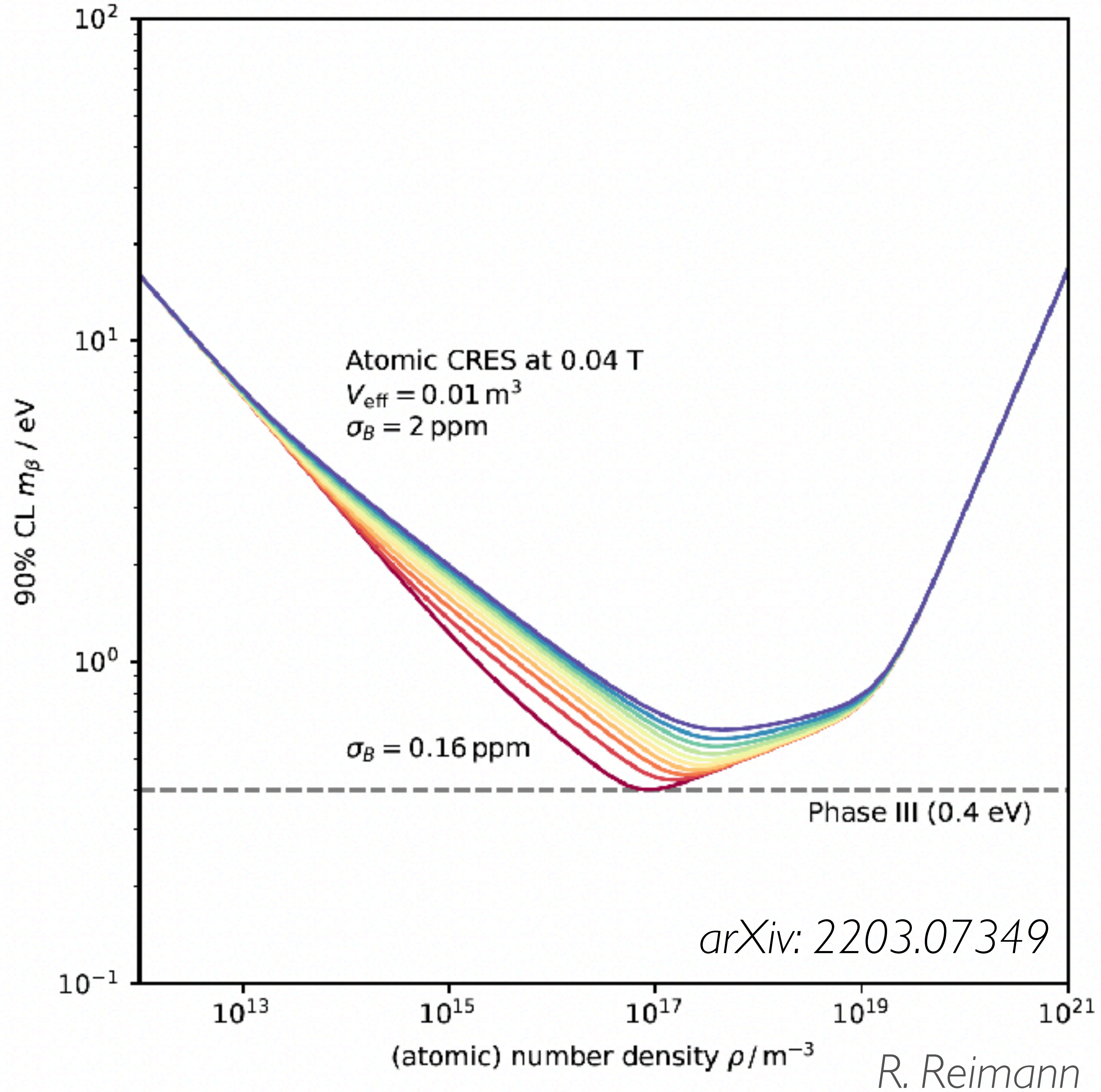
Phase III R&D	RF Demonstration / Atomic T Demonstration	Phase III

Larger volume
Atomic T Demonstration
eV-scale mass limit

- Goal:
  - Large volume atomic T CRES neutrino mass experiment at sub-eV m_β



H. Robertson

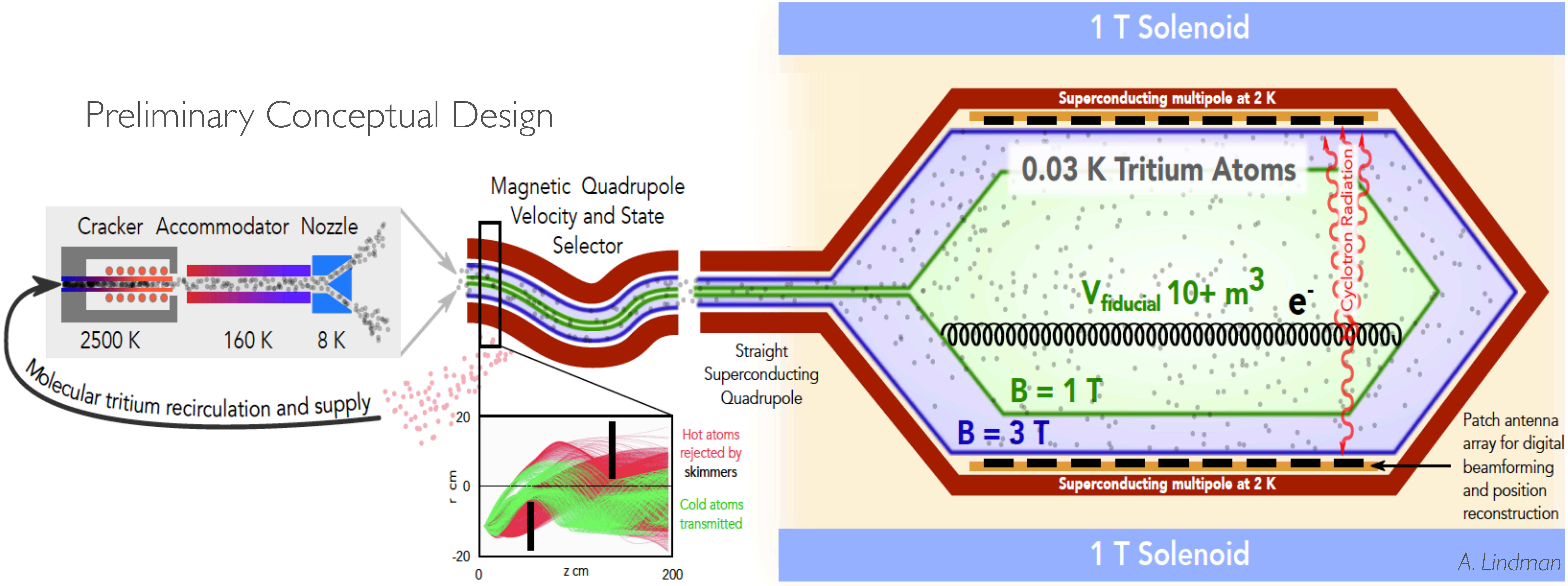


R. Reimann

Phase IV: Combining Everything

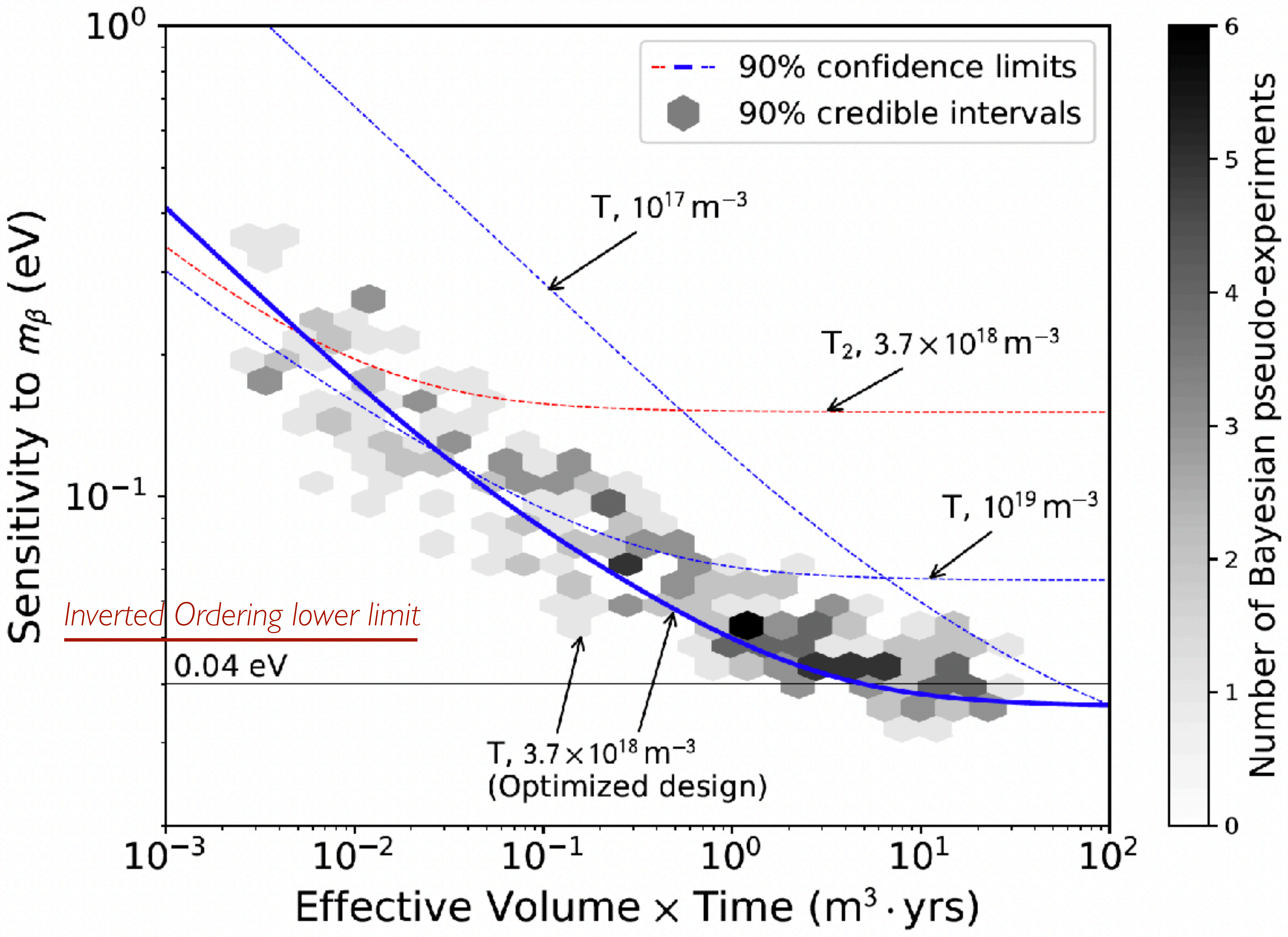
- Large volume atomic tritium experiment with an effective volume of >10 m³

Preliminary Conceptual Design



Phase IV: Mass Sensitivity

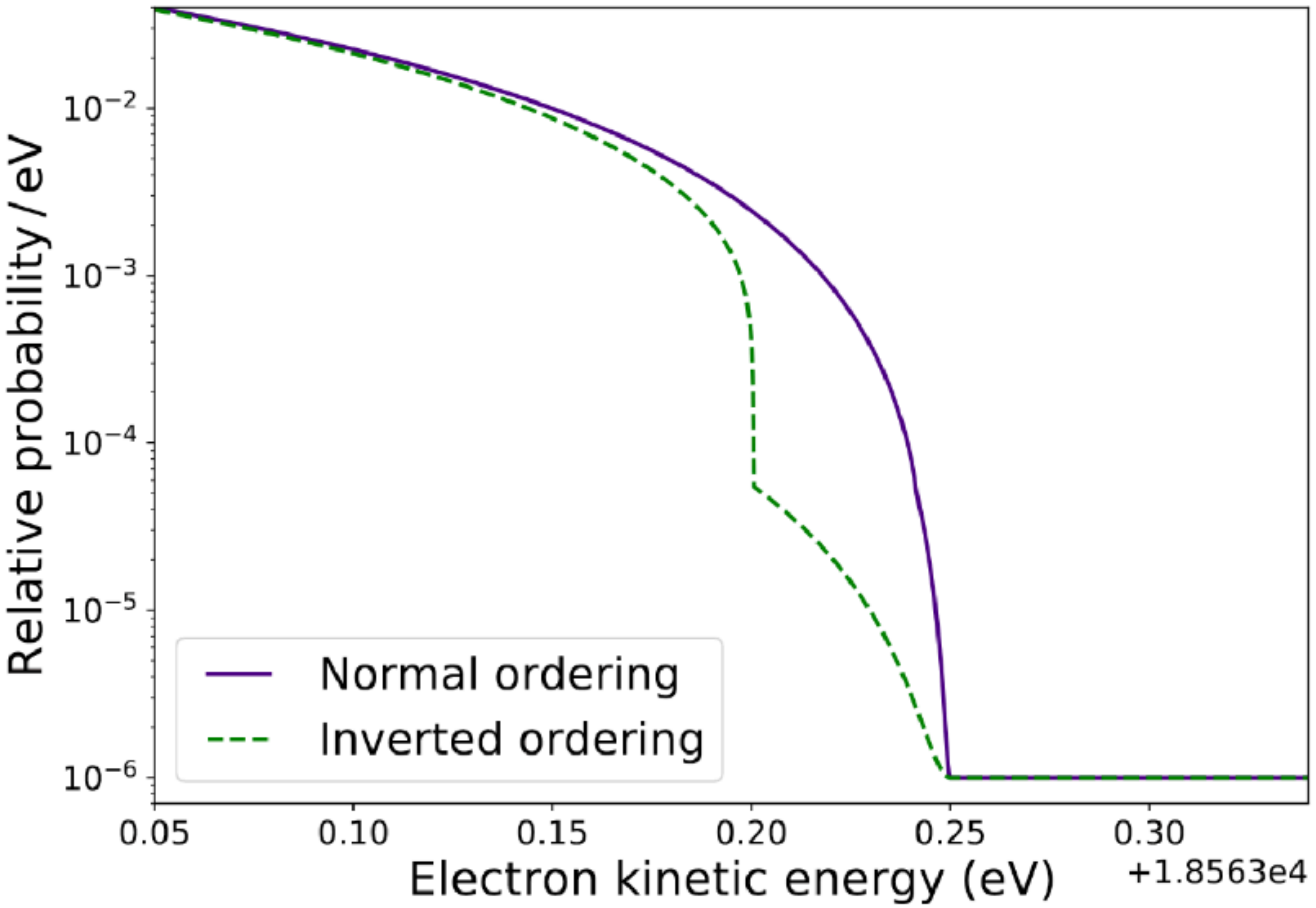
- Phase IV aims to reach mass sensitivity of m_β ~ 40 meV
- Fully cover inverted ordering



Sensitivity to Additional Physics

- Tritium β-decay spectrum can be thought of as sum of spectra from the mass eigenstates
- Has the potential to identify mass ordering from 'kinks' in the spectrum

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

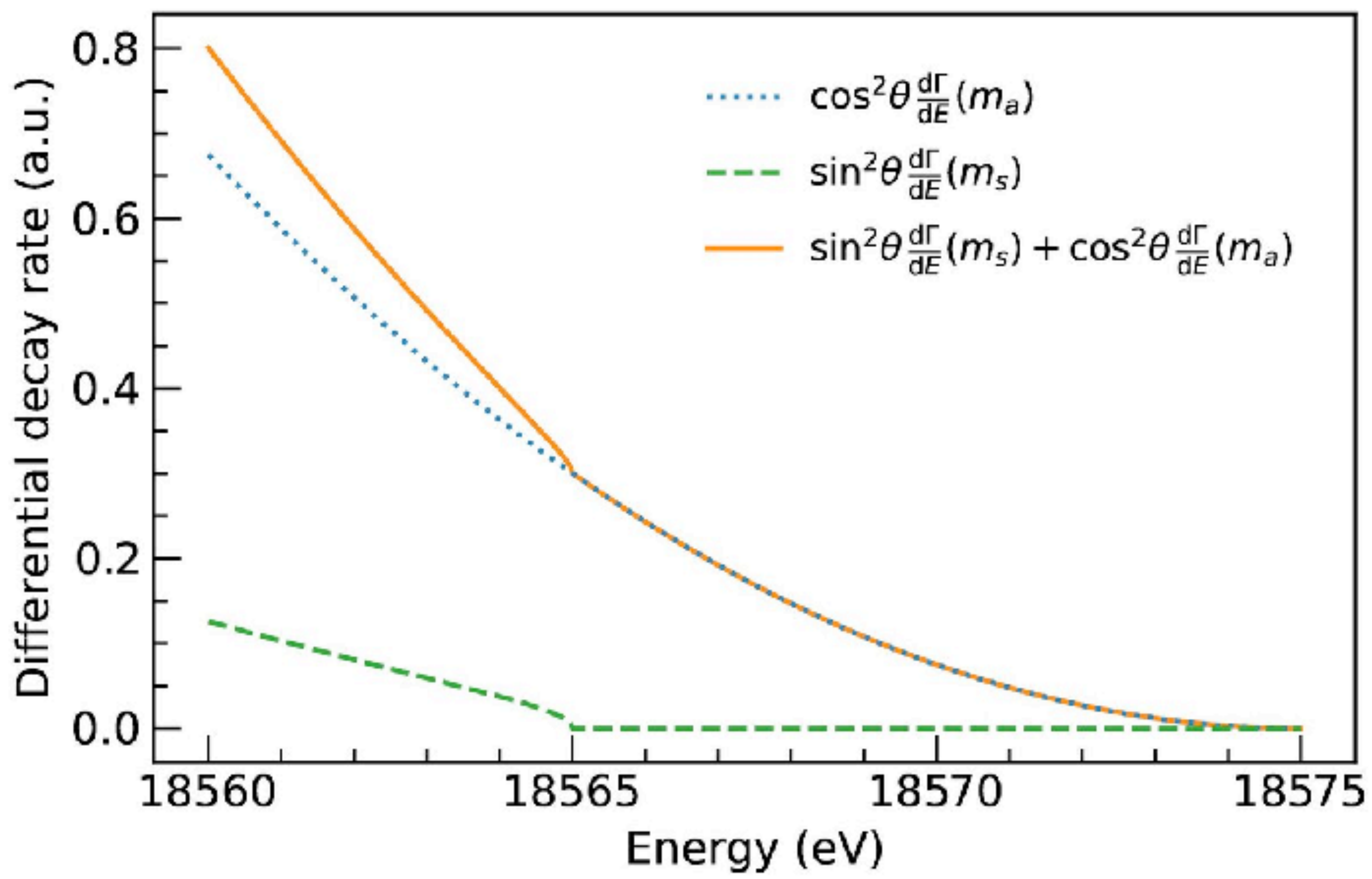


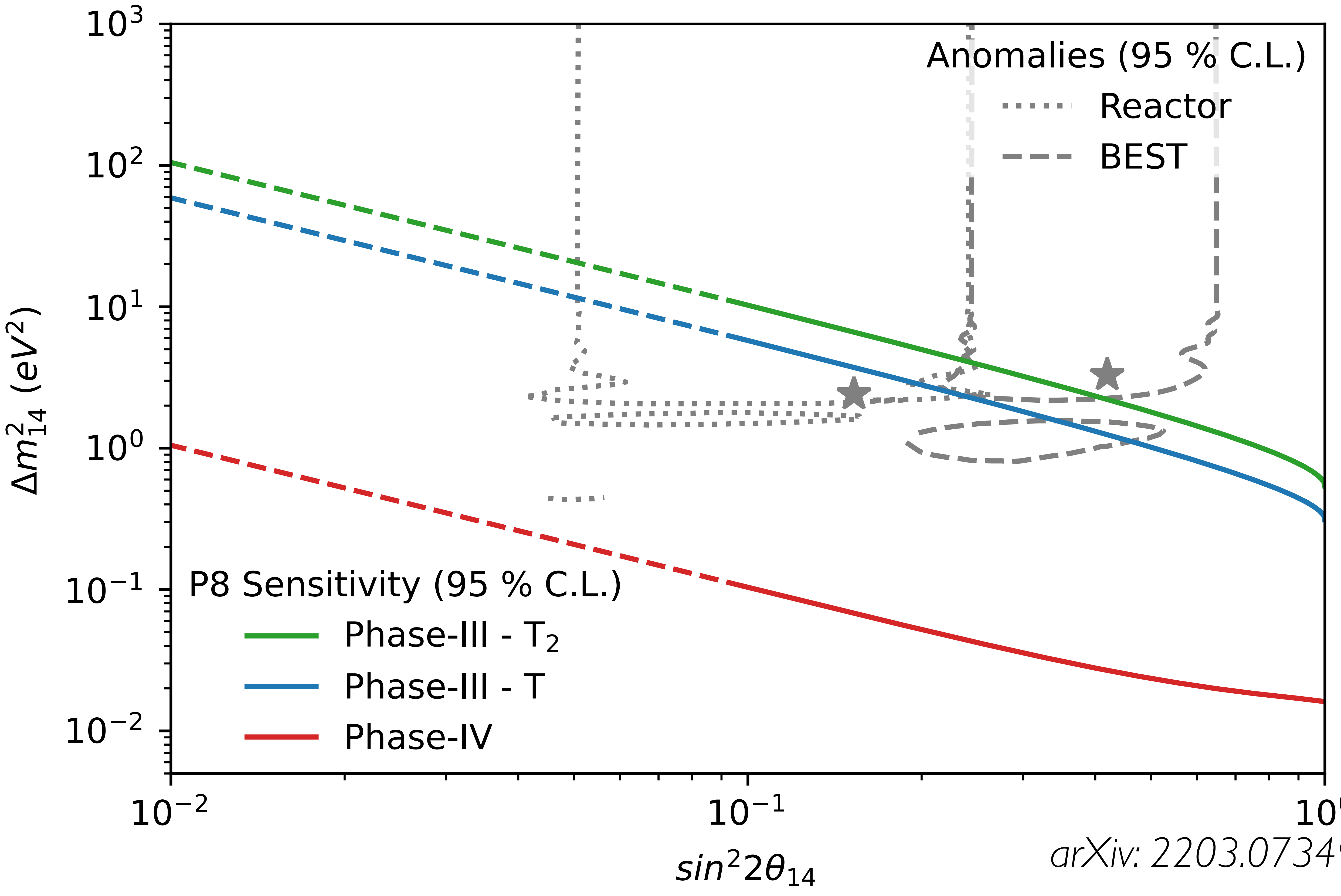
T. Weiss *PRC.103.065501*

Sensitivity to Additional Physics

- Tritium β-decay spectrum can be thought of as sum of spectra from the mass eigenstates
- Has the potential to identify mass ordering from 'kinks' in the spectrum
- Relaxing the spectral range also provides sensitivity to sterile neutrinos over several generations

$$\frac{dN}{dE} = \cos^2\theta \frac{dN}{dE}(m_\beta) + \sin^2\theta \frac{dN}{dE}(m_s)$$

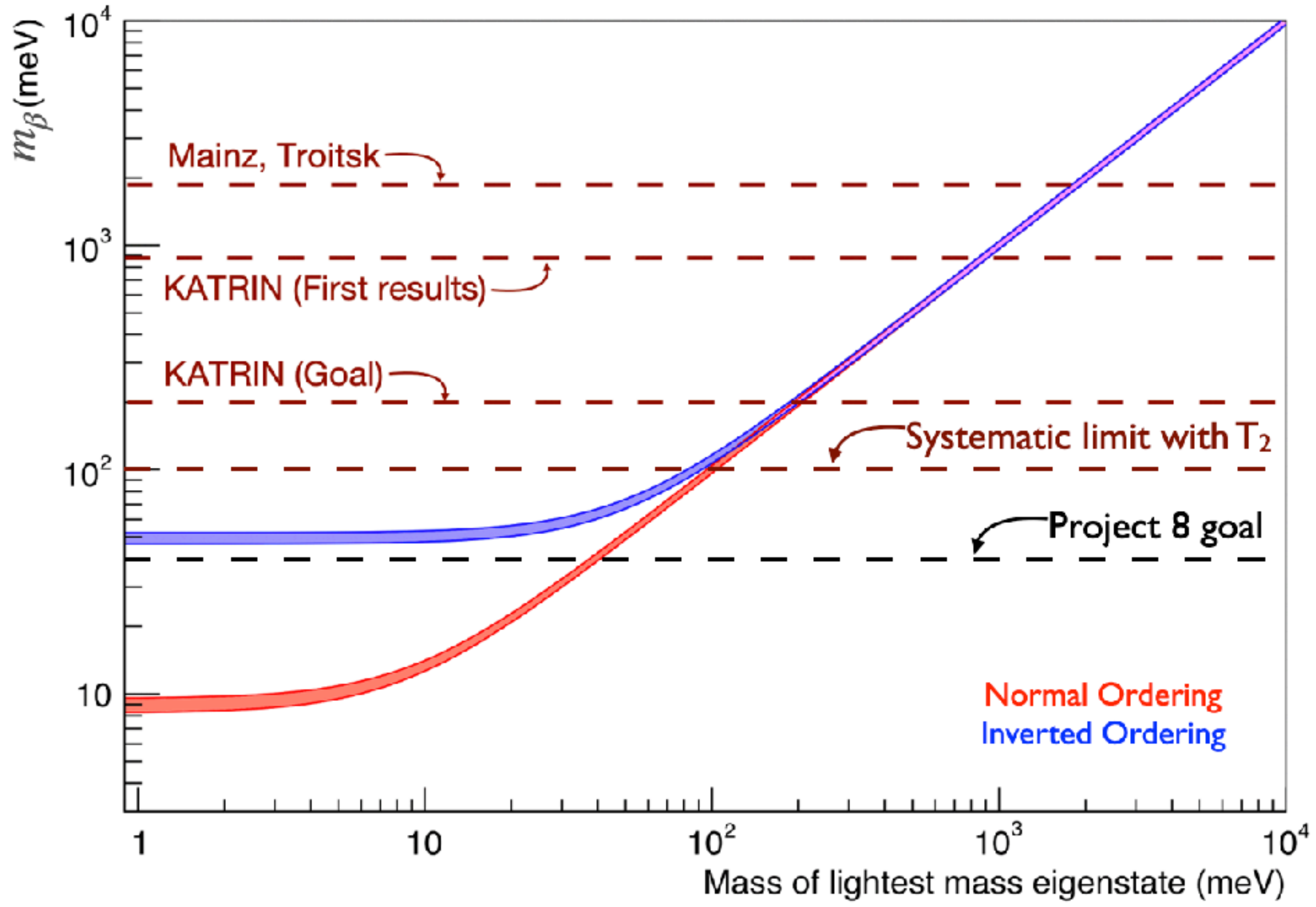




arXiv: 2203.07349

Summary

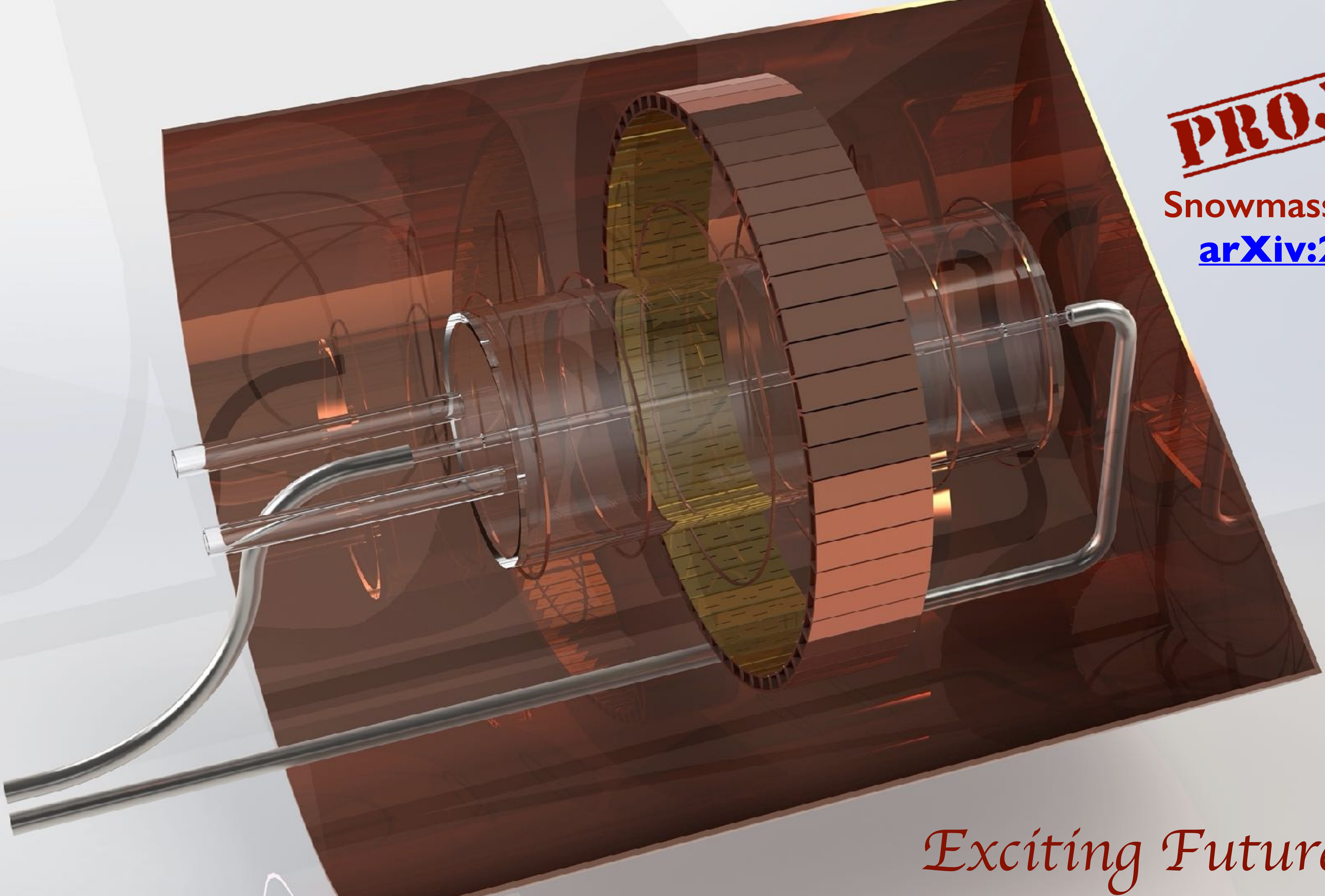
- Absolute mass of neutrino still unknown
- CRES with atomic tritium has the potential for precision neutrino mass measurement
- Project 8:
  - Demonstrated CRES using ^{83m}Kr and T_2
  - Performed the first neutrino mass measurement using CRES
- Critical R&D underway to demonstrate CRES in large volumes with atomic tritium
- Phase IV aims to reach mass sensitivity of $m_\beta \sim 40$ meV to cover inverted ordering



PROJECT 8

Snowmass White Paper

[arXiv:2203.07349]



Exciting Future Awaits!

Backup