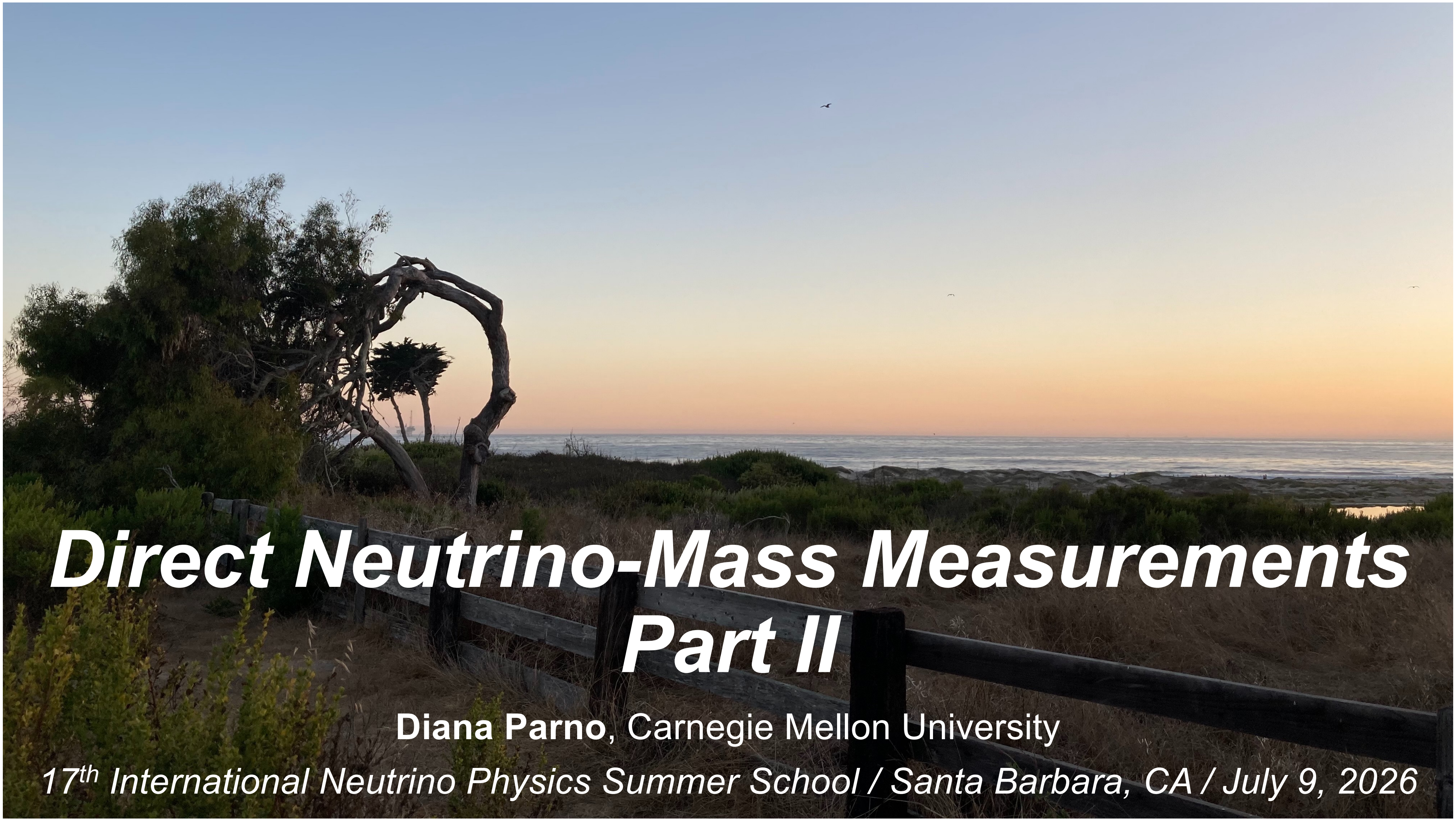
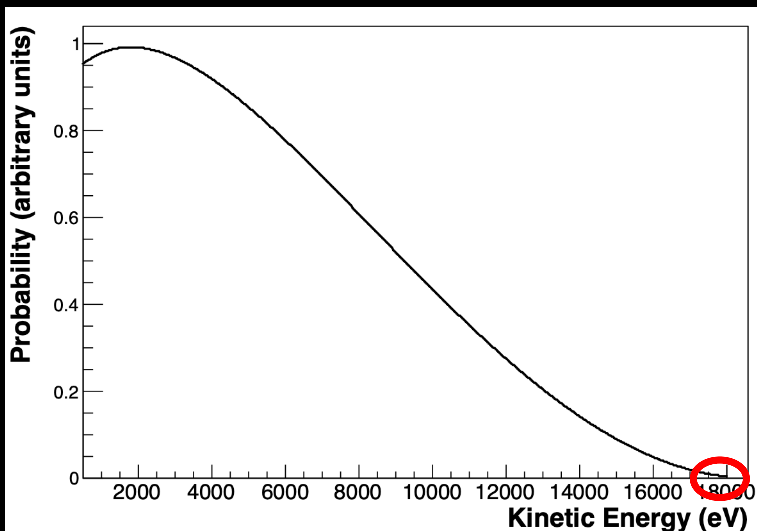


Direct Neutrino-Mass Measurements Part II

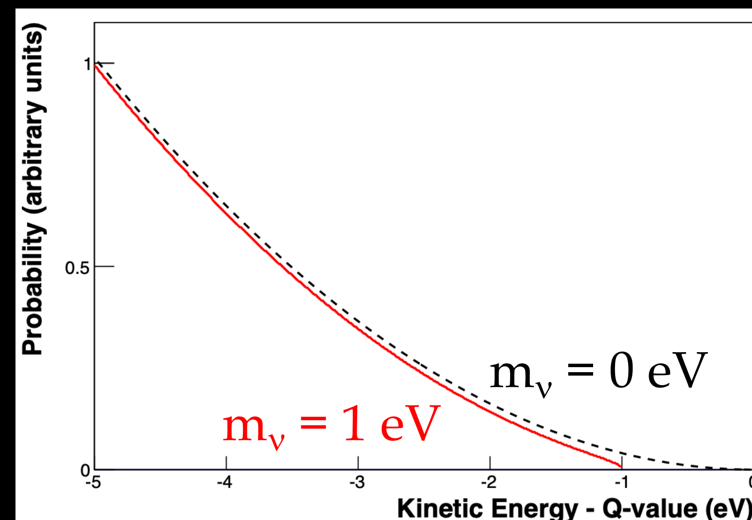
Diana Parno, Carnegie Mellon University

17^{th} International Neutrino Physics Summer School / Santa Barbara, CA / July 9, 2026

Reminder: The Challenge



$\sim 10^{-13}$



- Start with a huge number of decays
- Precisely measure energy, rate near endpoint
- Somehow ignore all the low-energy decays with no useful information

Tritium: Two Main Strategies

1. Transport β away from source to measure its kinetic energy
   - Electromagnetic spectrometer(s)
   - Standard particle-physics techniques (but at low energy)
2. Measure β kinetic energy in situ
   - No energy loss in transport
   - Need a way to "see" into source gas

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Never measure anything but frequency.

Arthur Schawlow

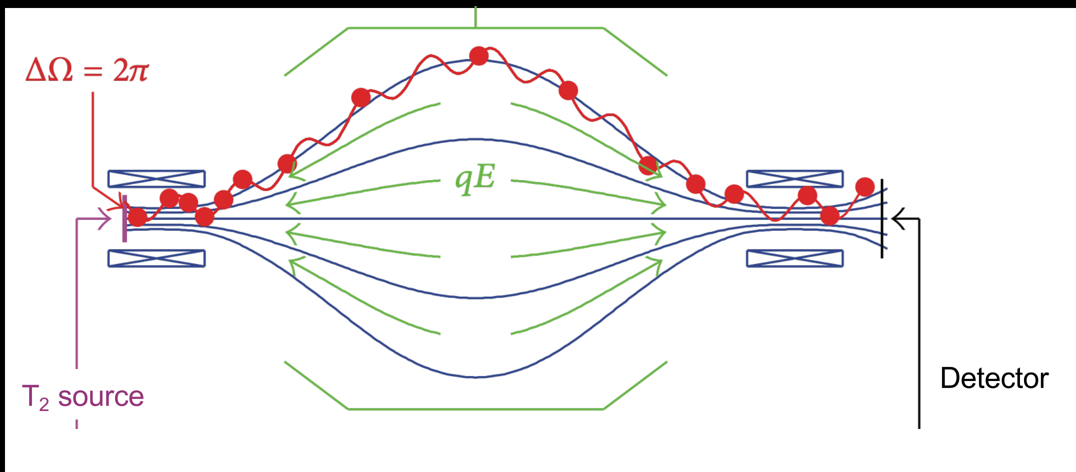
Photo: Chuck Painter for Stanford News Service

The Plan

- Accessing the neutrino-mass scale
- How to search for m_ν directly
- Nitty, gritty systematics
- Microcalorimetry basics (^{163}Ho)
- HOLMES
- ECHo
- Beta-spectroscopy basics (^{3}H)
- **KATRIN**
  - Working principle
  - Backgrounds
  - Neutrino-mass results
- Project 8
- Next-generation tritium R&D
- Sterile neutrinos and bonus physics
- Alternate measurement ideas

The KATRIN Approach

- Measure integral spectrum with moving threshold
- **M**agnetic **A**diabatic **C**ollimation + **E**lectrostatic filter



$$\mu = \frac{E_\perp}{B} = \mathrm{const}$$

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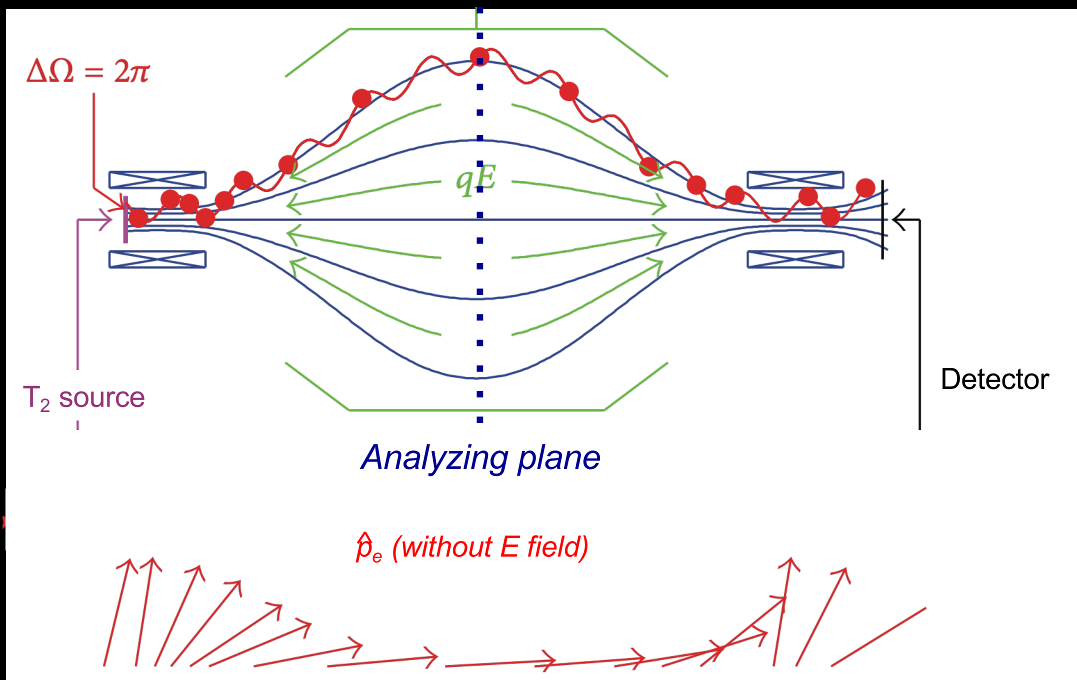

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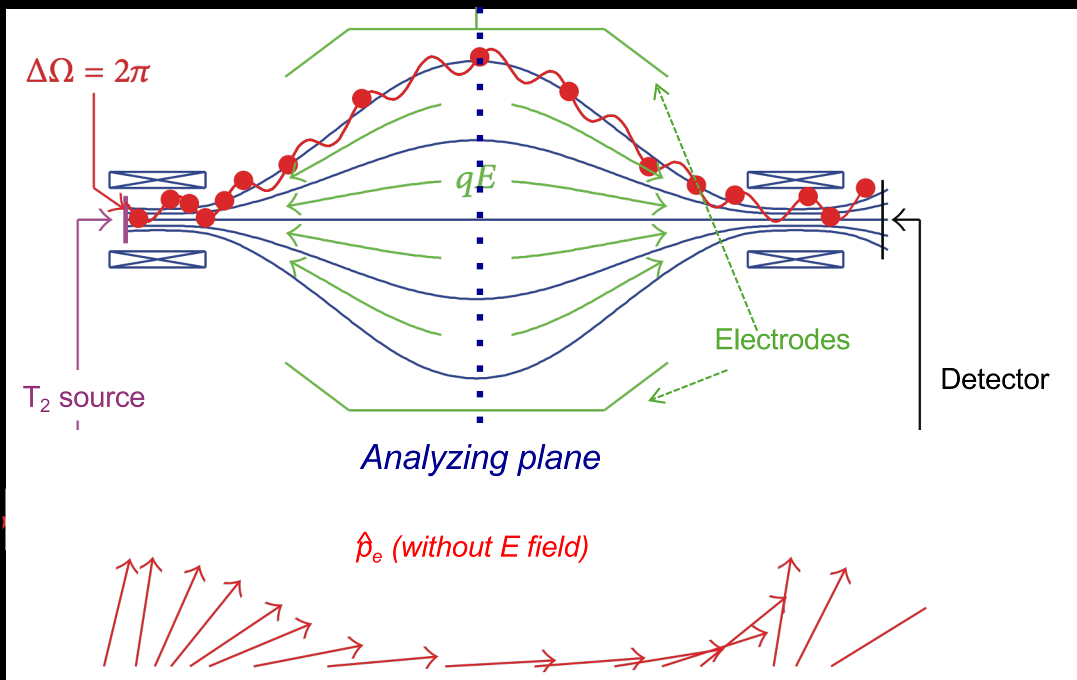

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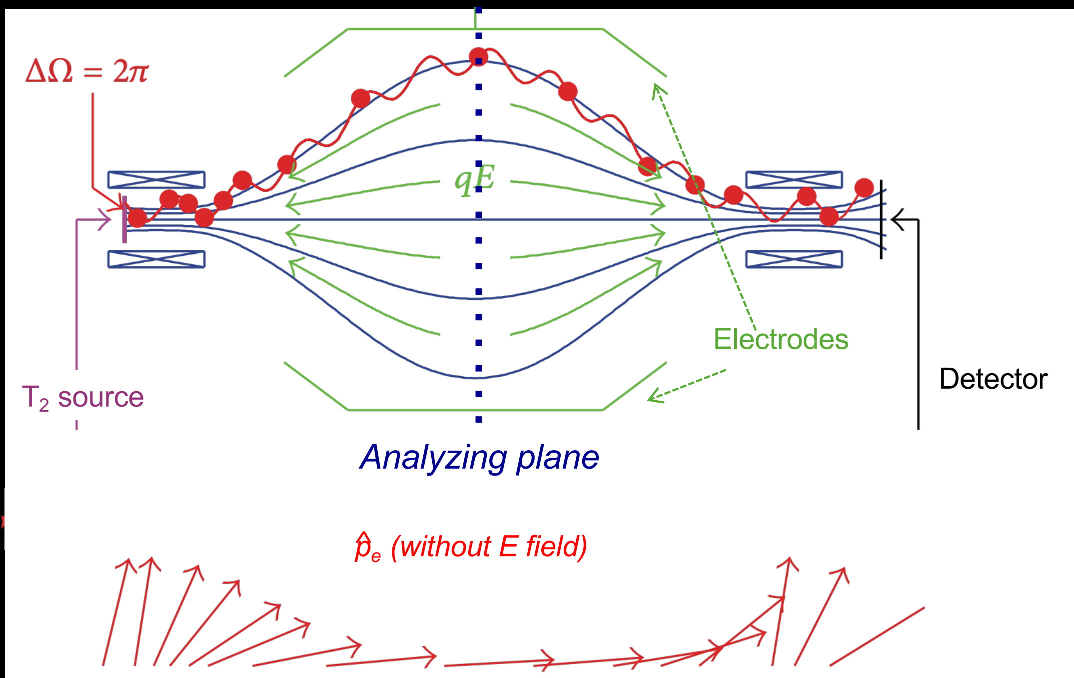


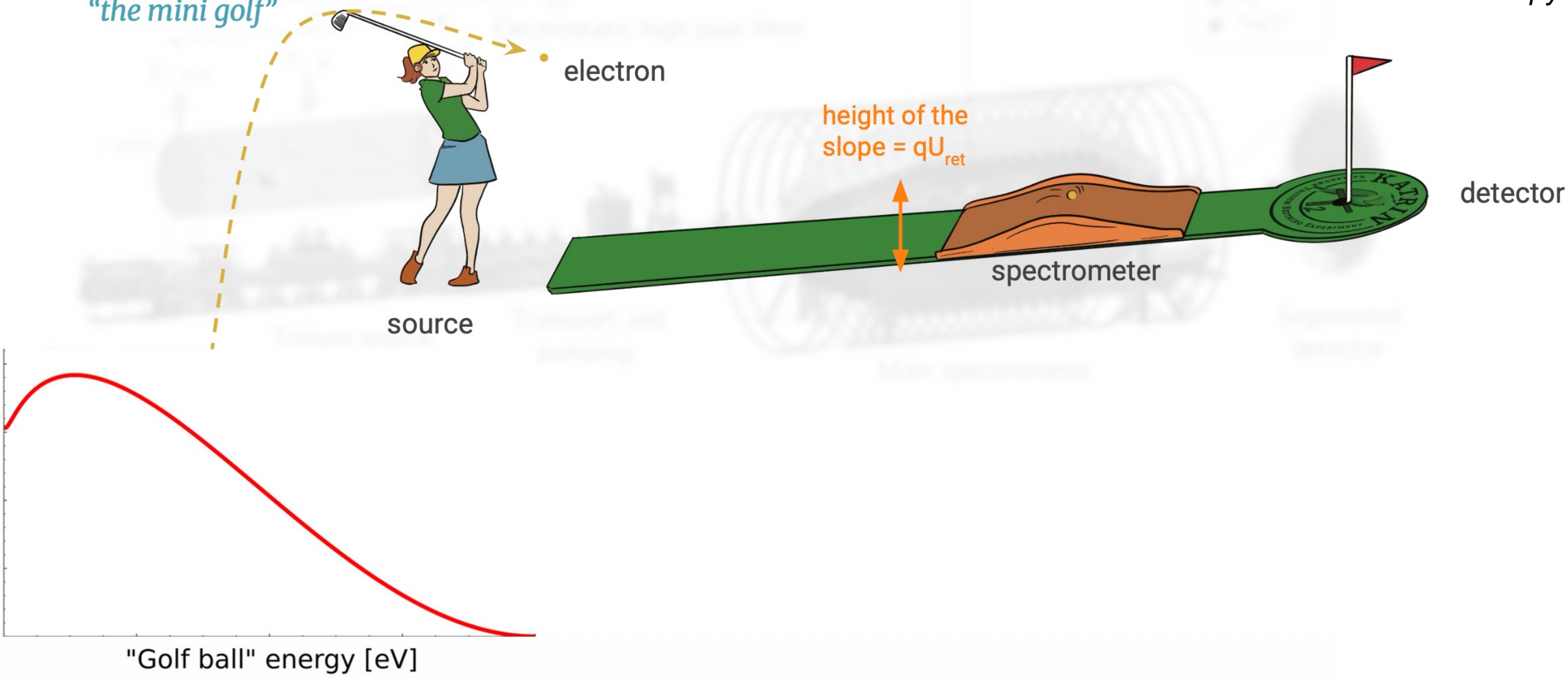
$$\mu = \frac{E_\perp}{B} = \text{const}$$

$$\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}}$$

An Analogy

Electrostatic filter principle:
"the mini golf"

Slide: Chloé Goupy



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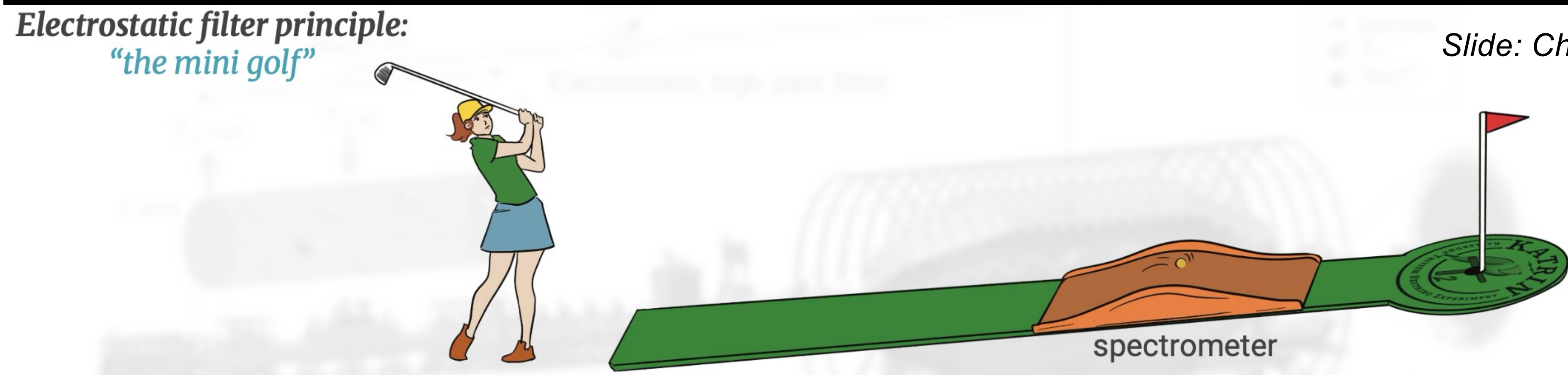

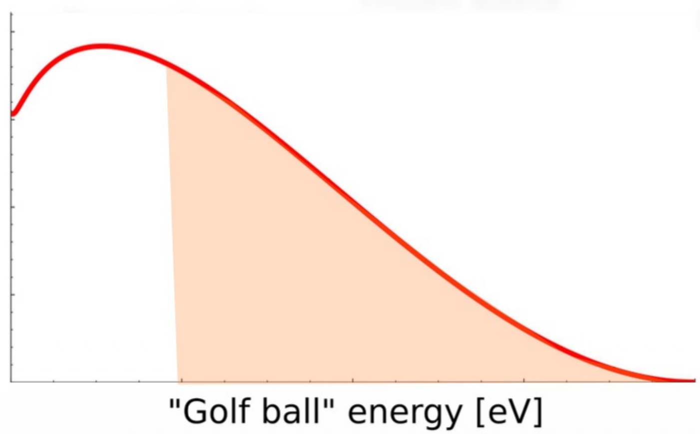

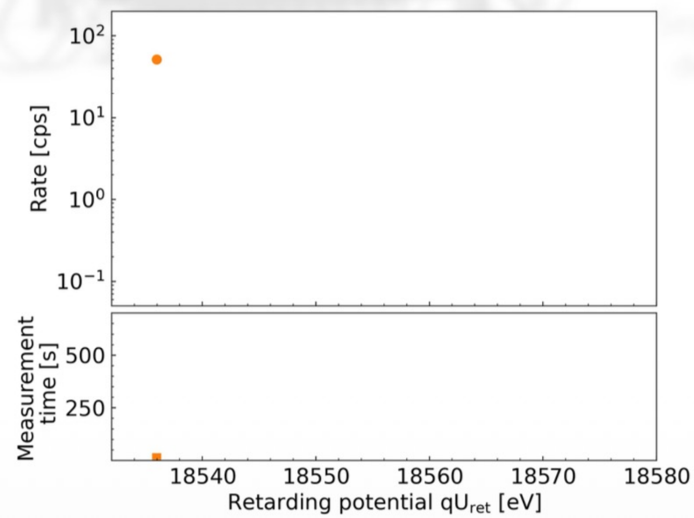

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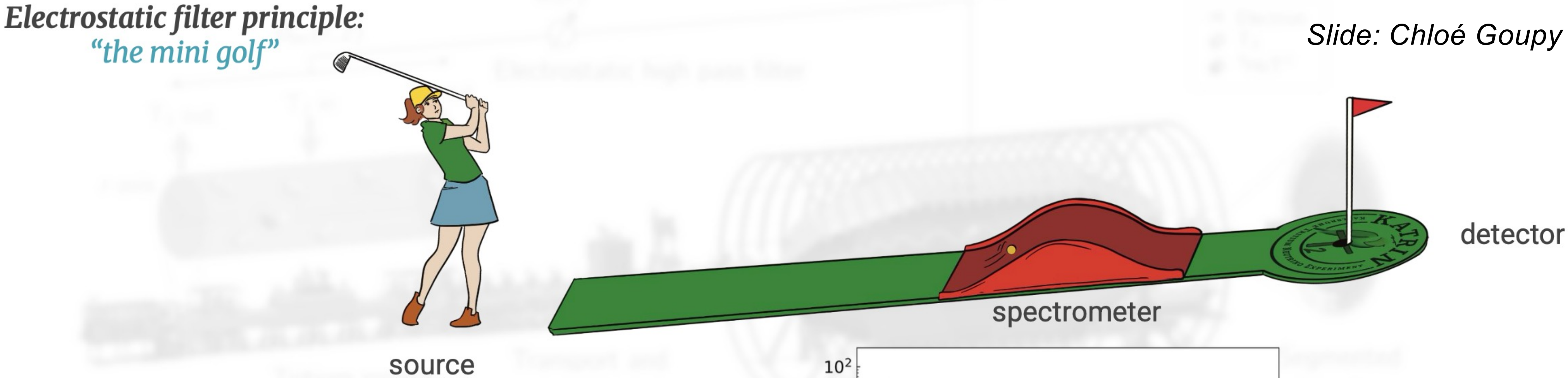

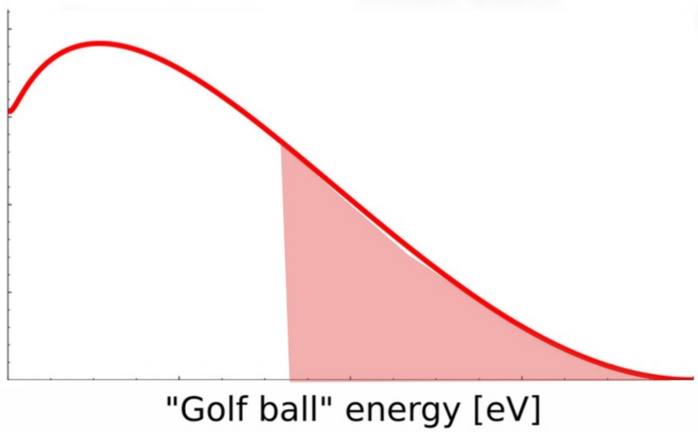

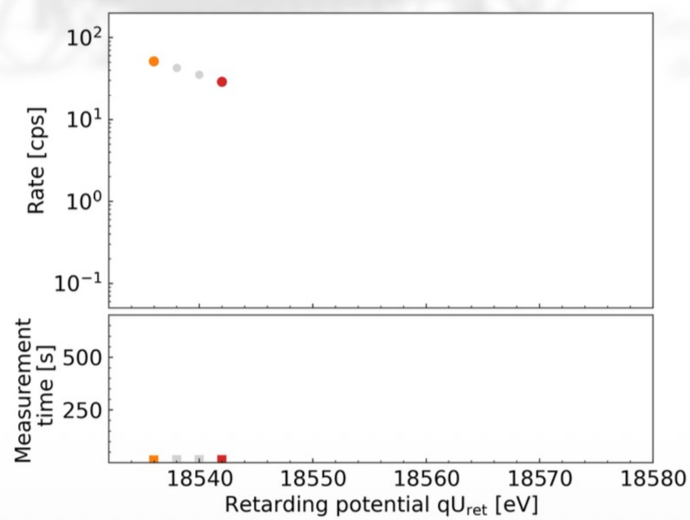

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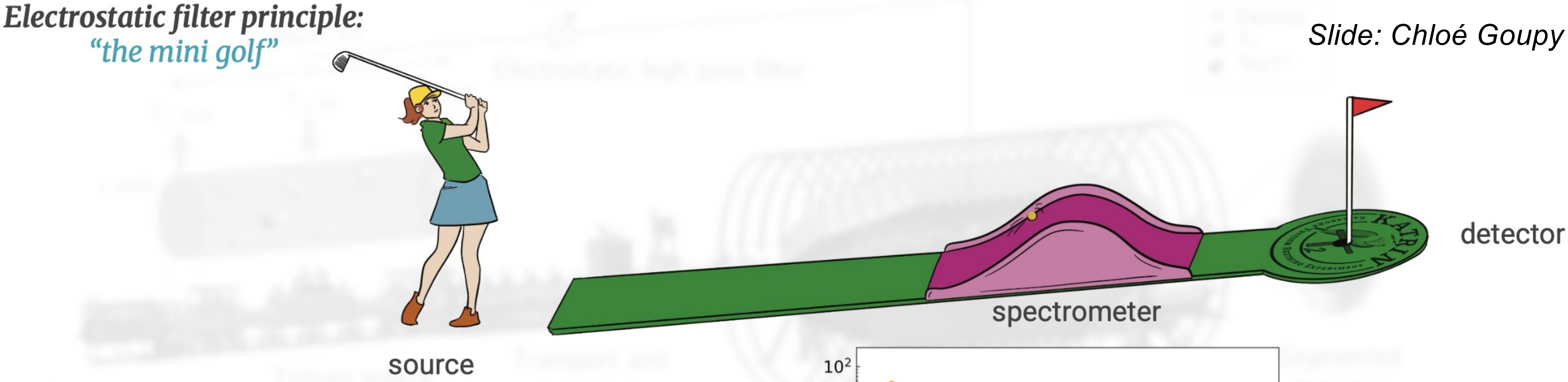

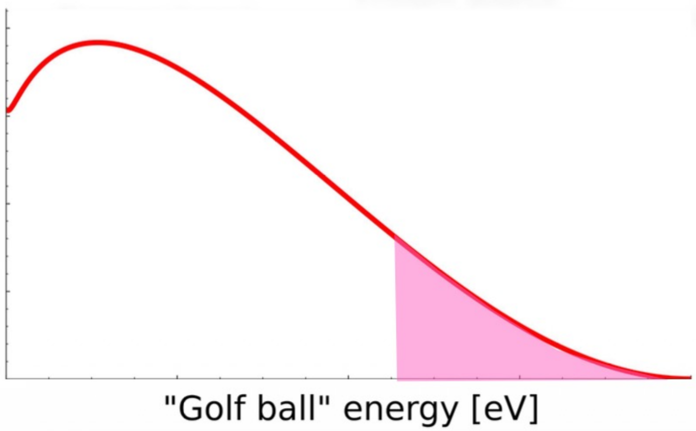

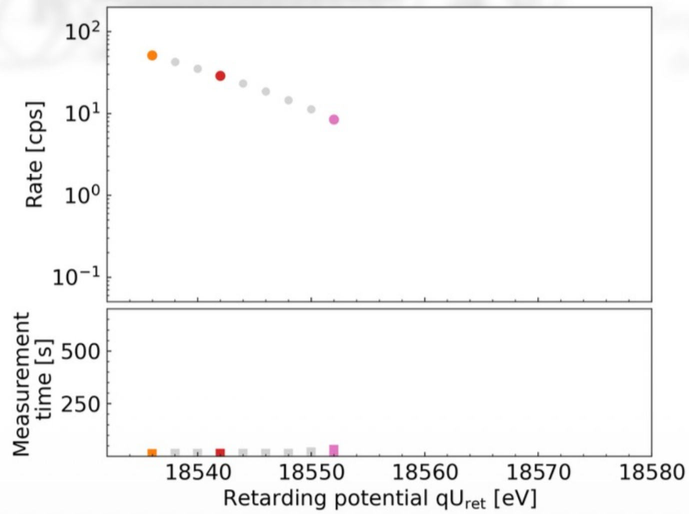

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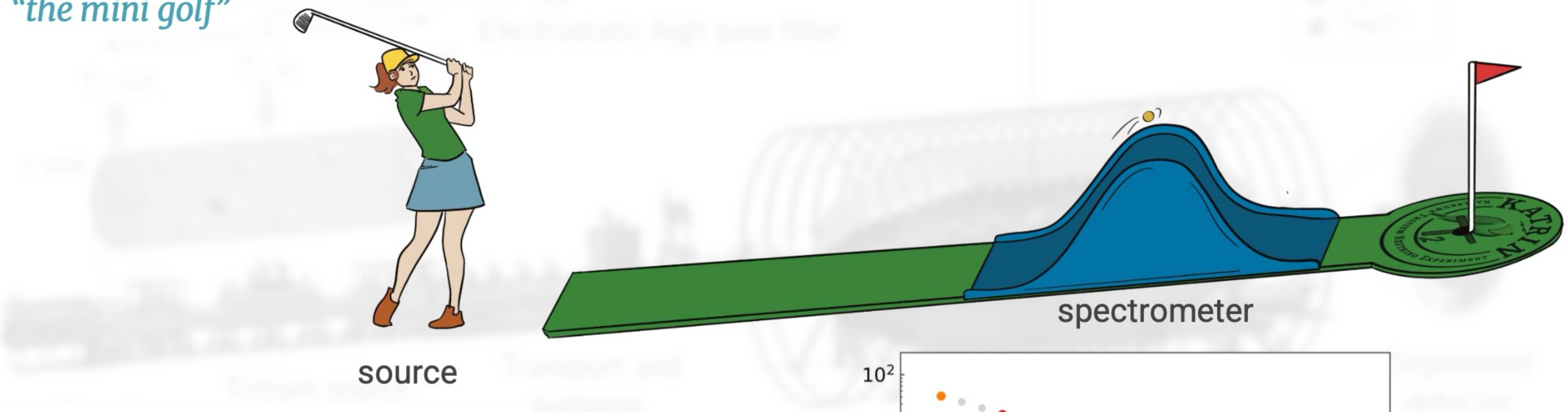

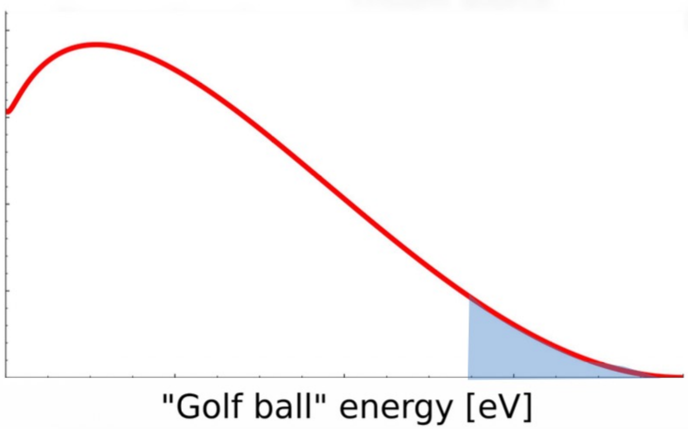

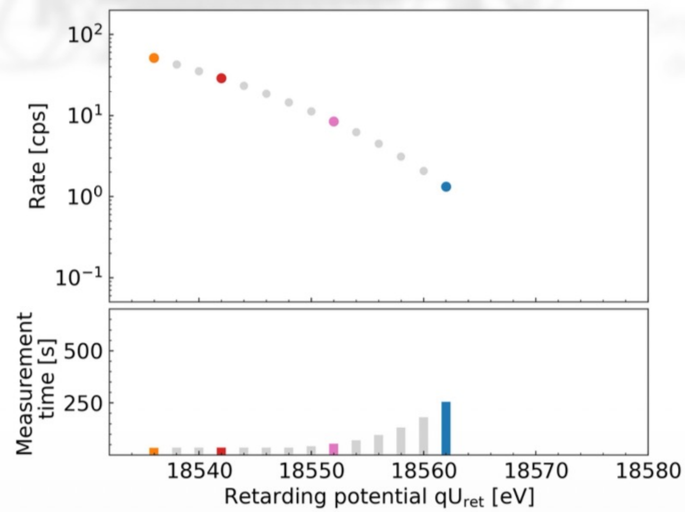

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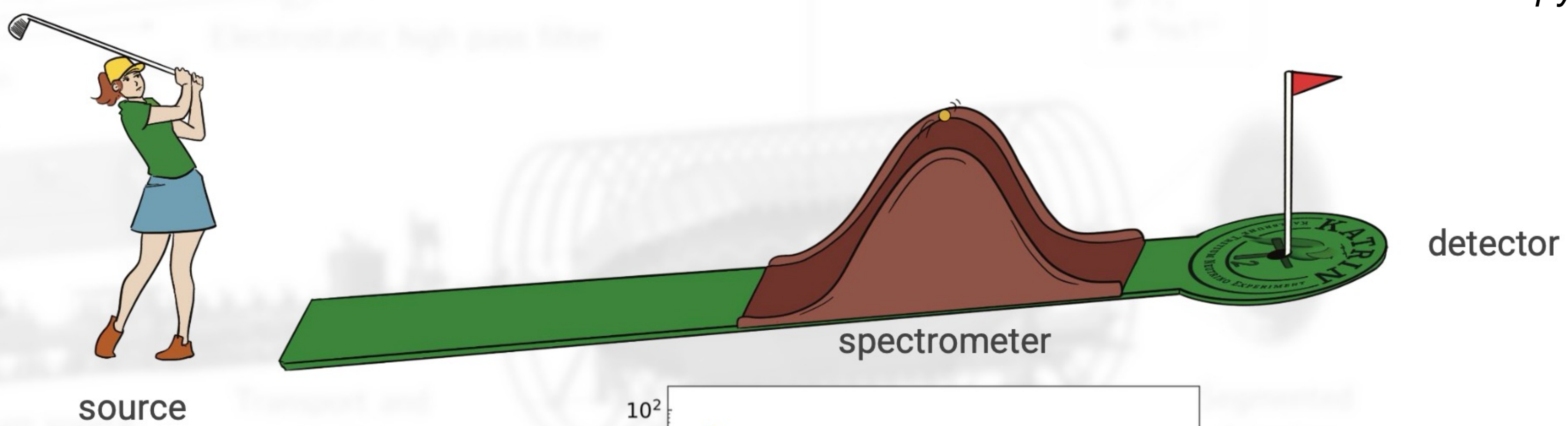

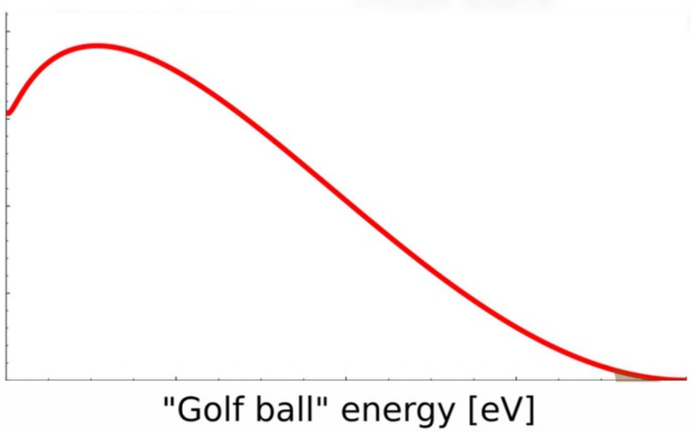

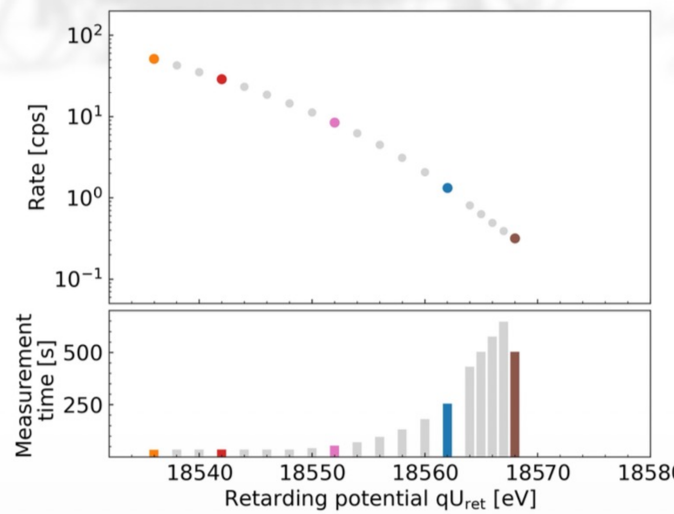

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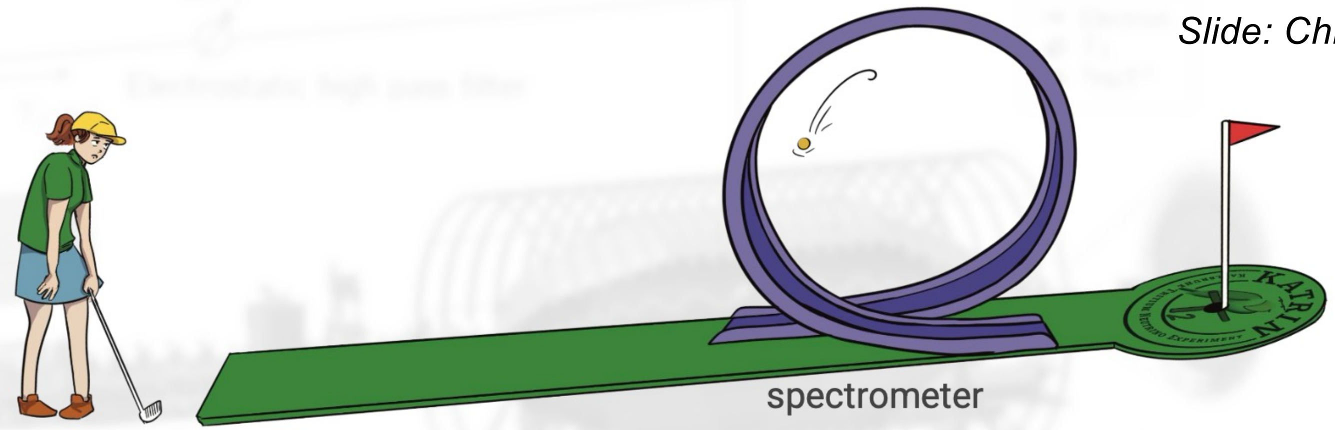
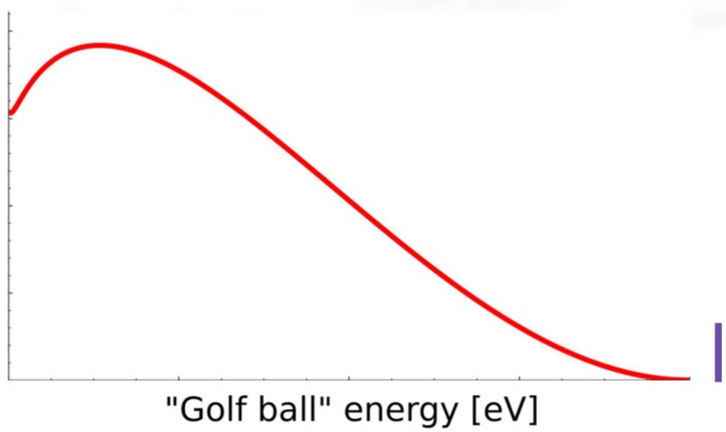
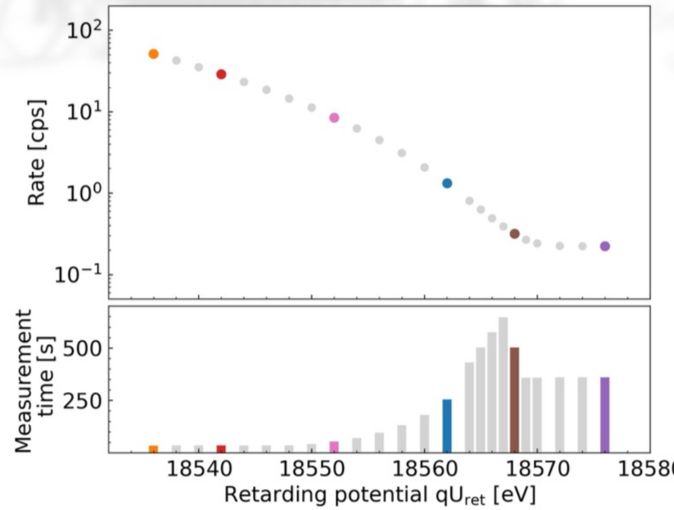
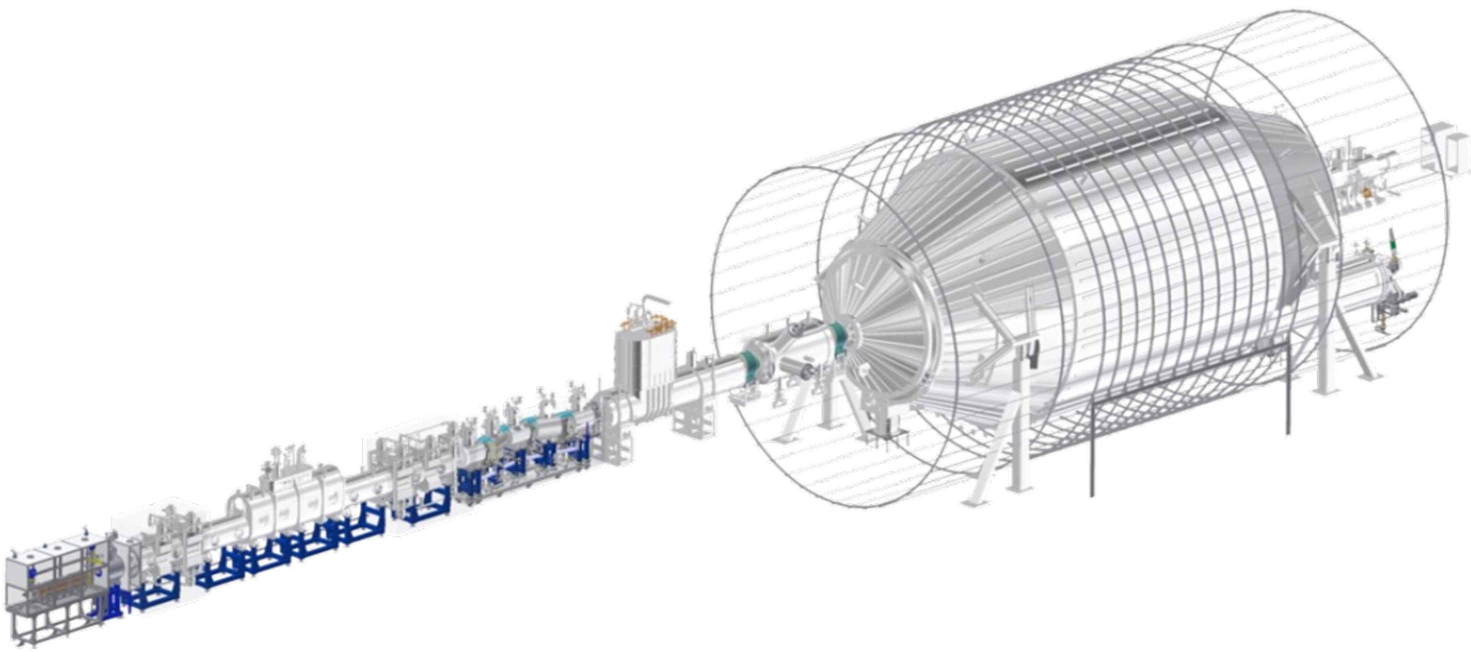






Spotlight on the Beamline



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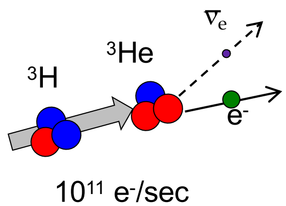
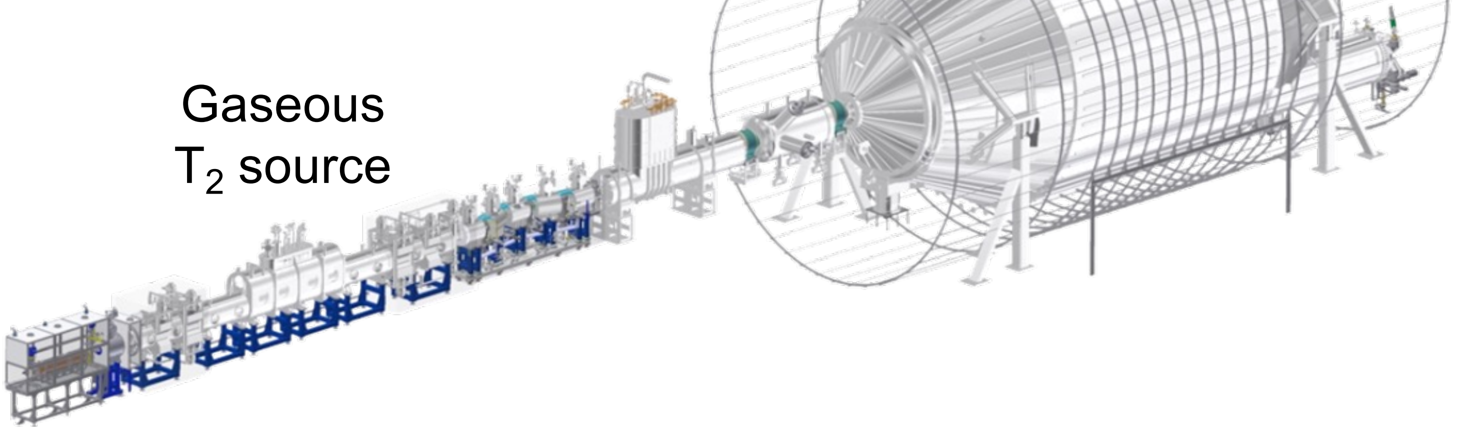


Gaseous
T_2 source



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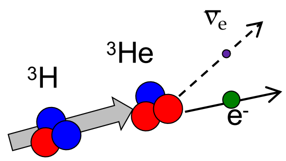
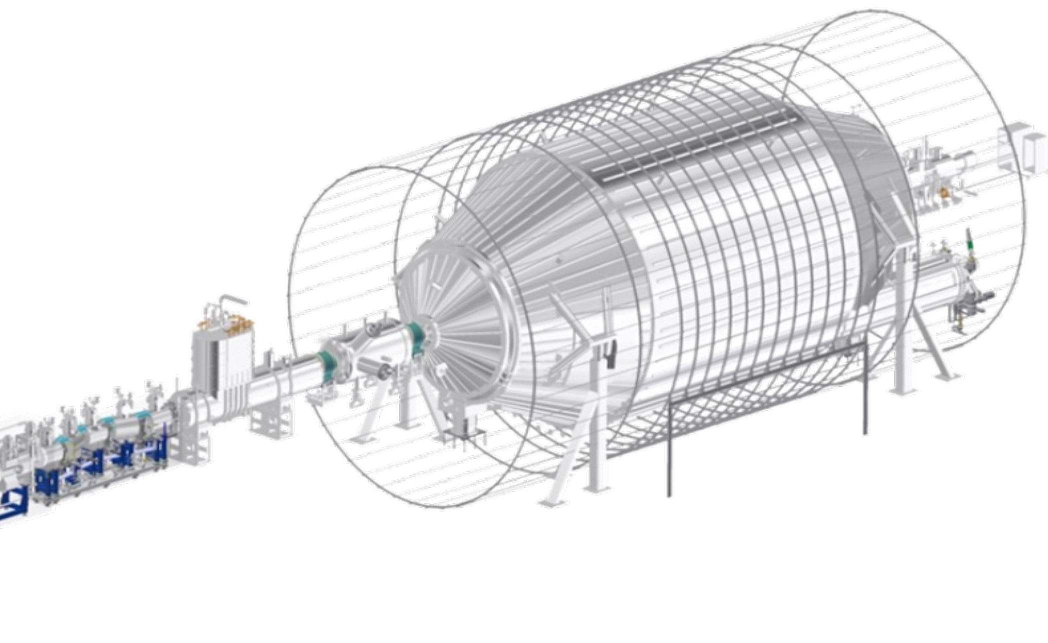


10^{11} e^-/sec



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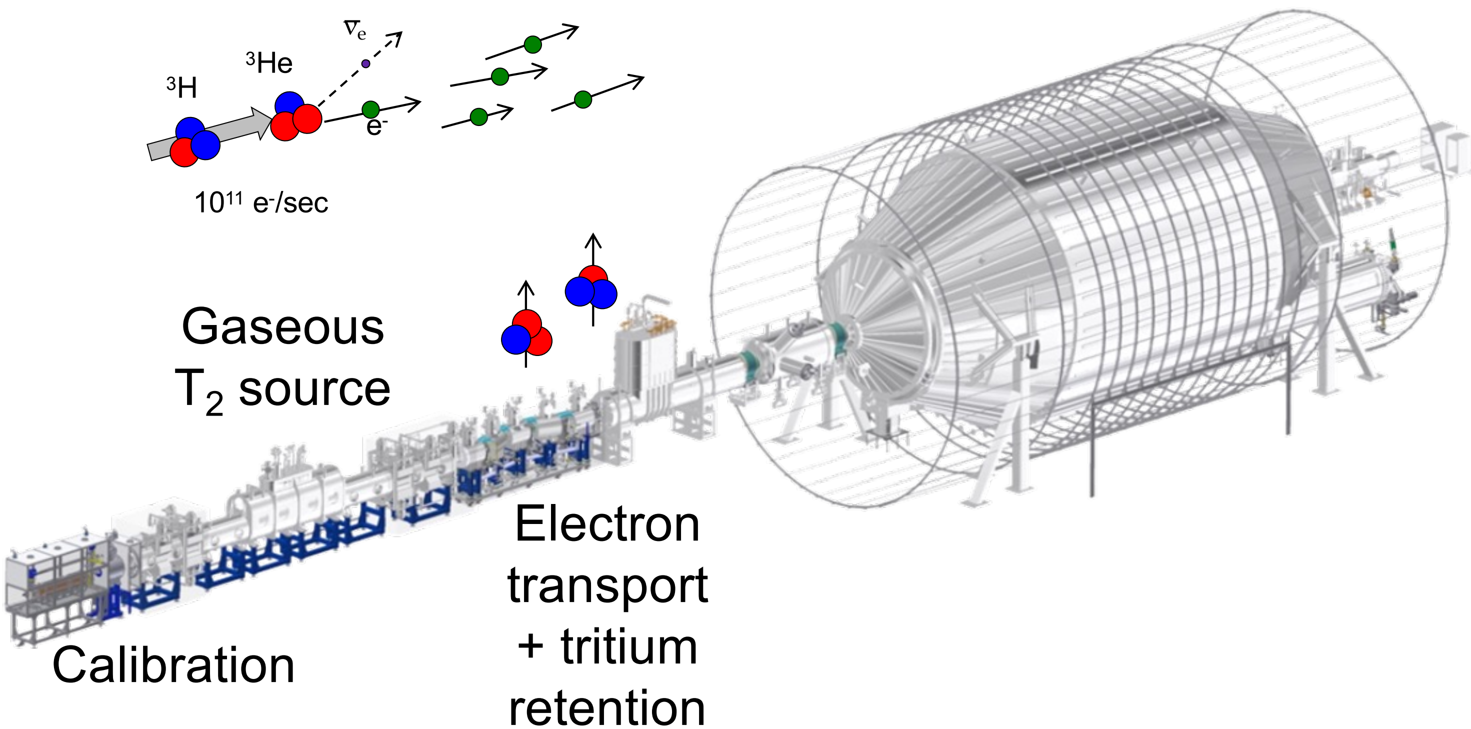
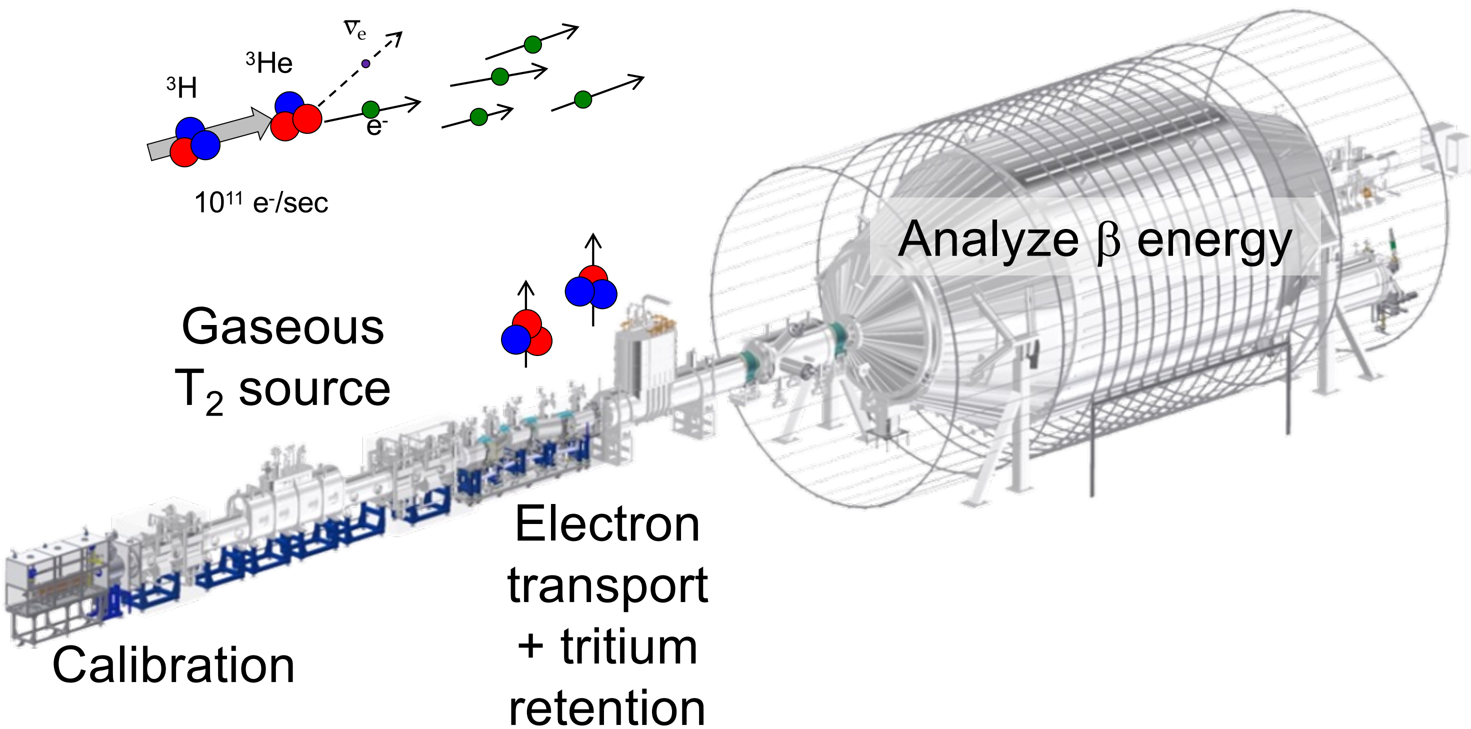


Spotlight on the Beamline



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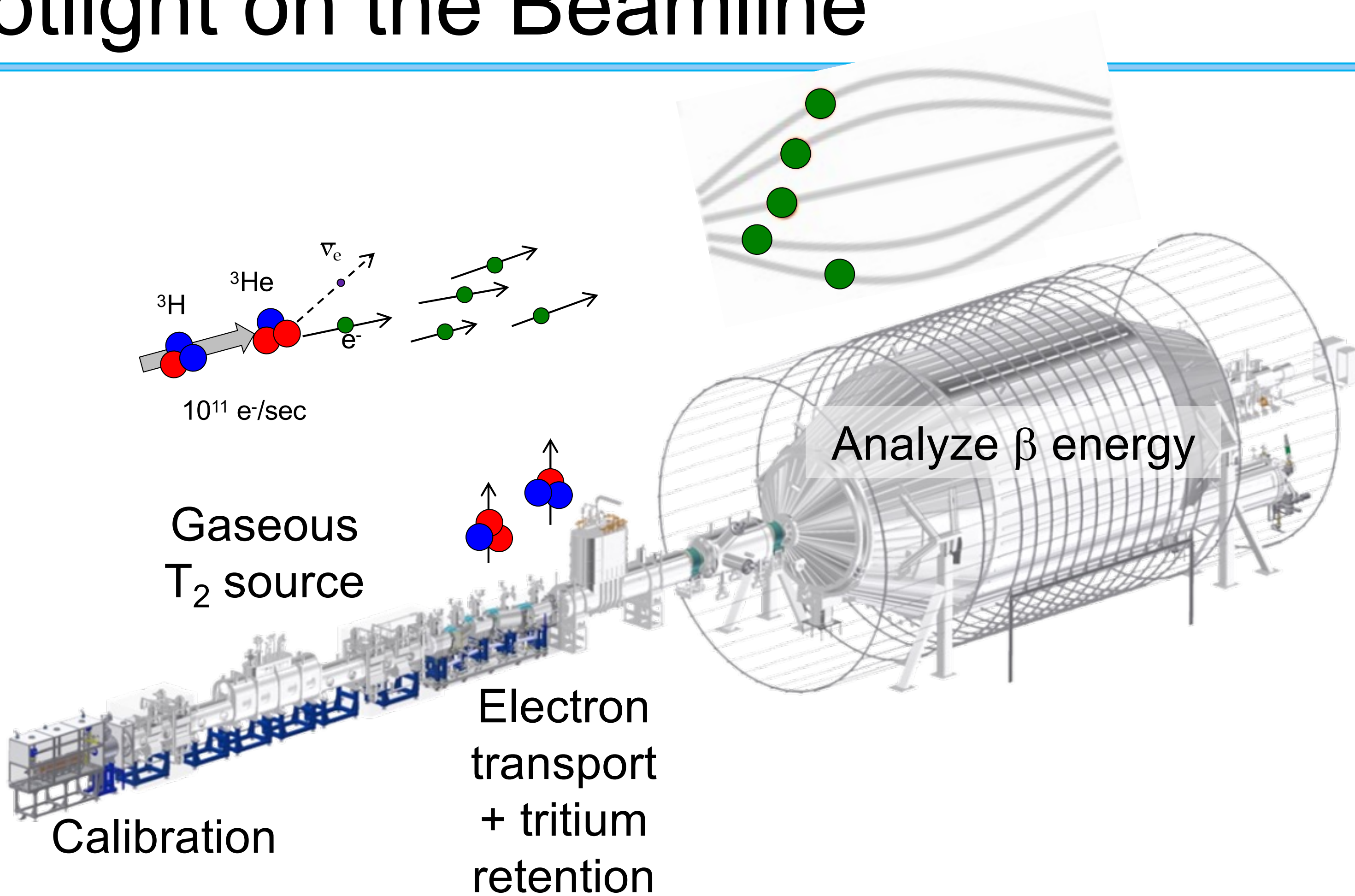

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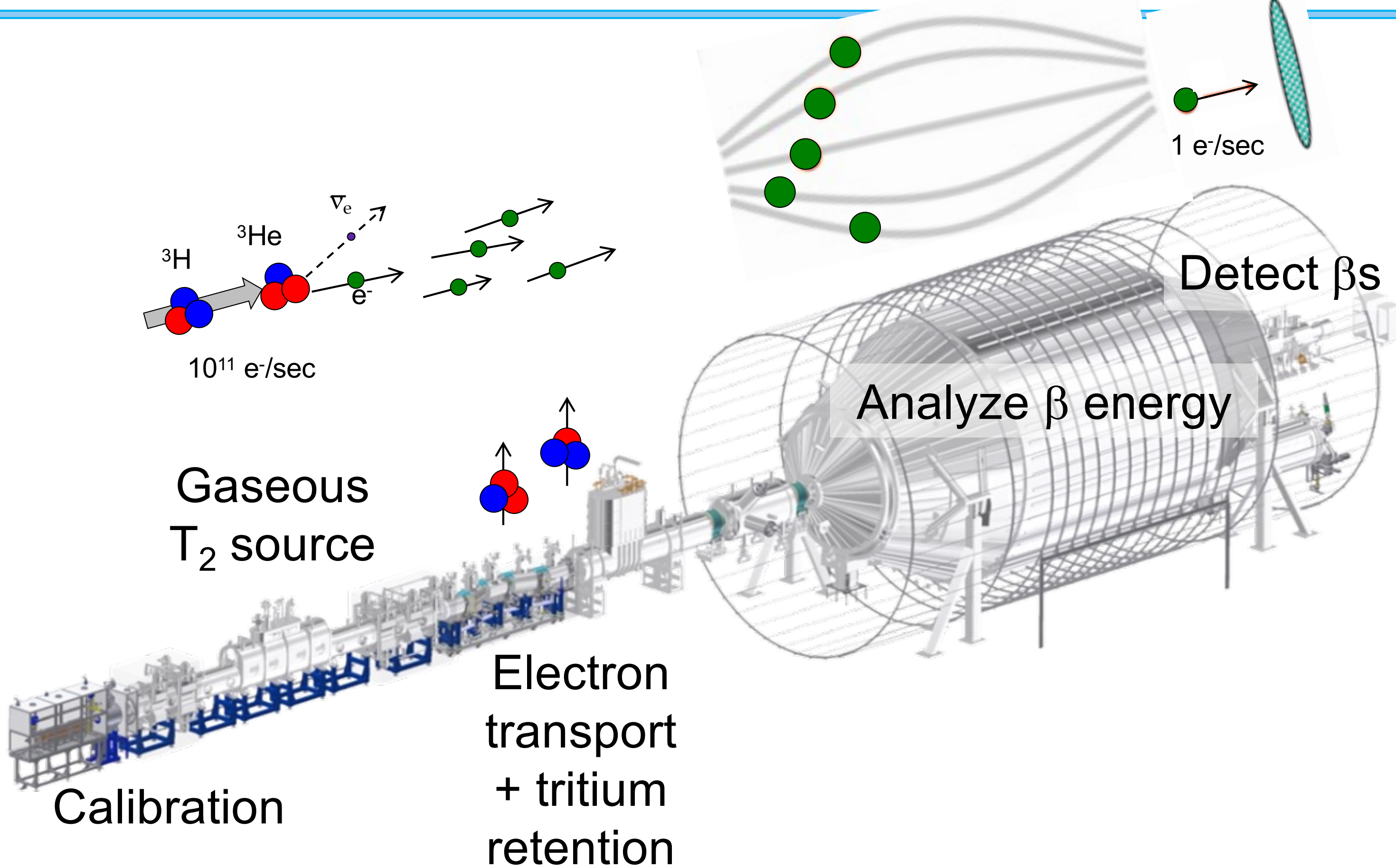

KATRIN by the Numbers

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- Target m_ν sensitivity in 5 calendar years:

  Better than 0.3 eV at 90% confidence

- Magnetic field range 3 G – 60,000 G
- Source activity: ~10^{11} decays every second
- 95% tritium purity
- Main spectrometer volume: 1240 m^3

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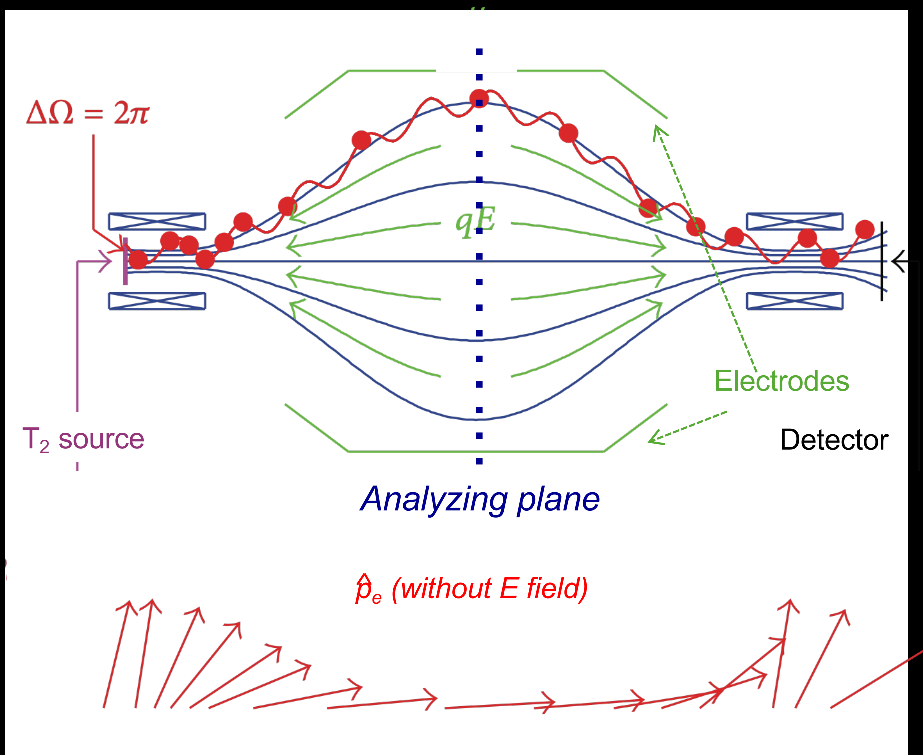
1240 m^3 in Real Life

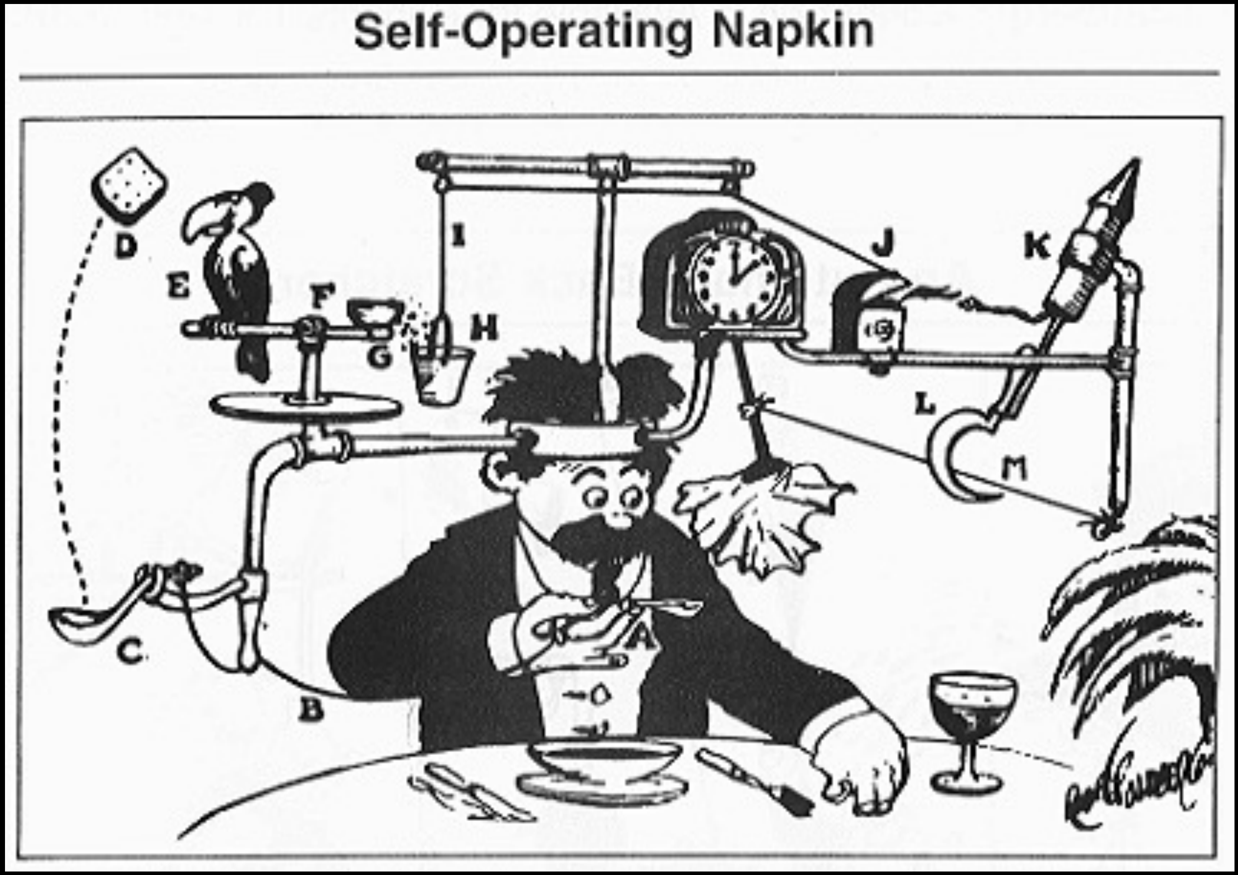
Leopoldshafen, Germany
November 2006
Photo: KIT

The Basic Background Problem



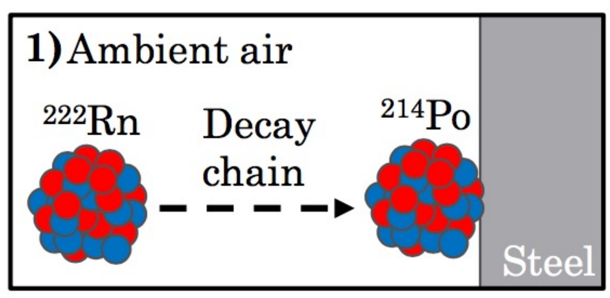
- Signal βs have very little kinetic energy in spectrometer center
- Low-energy secondary electrons can be indistinguishable from signal!

Rube Goldberg Backgrounds



Rube Goldberg, Collier's Magazine, 1931

The Rydberg Background



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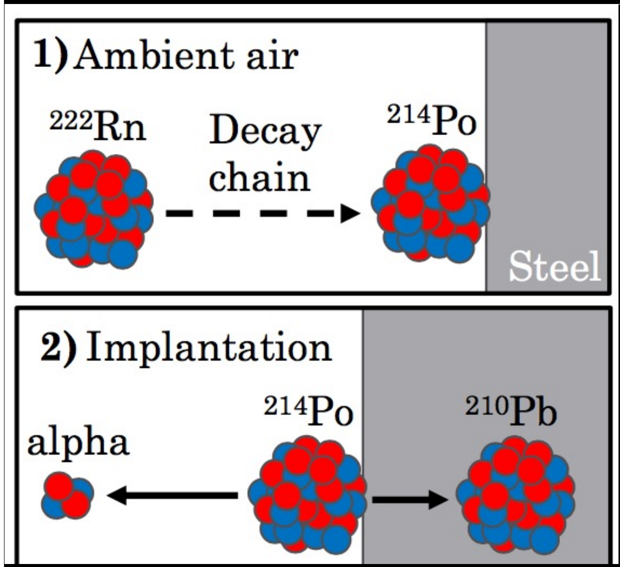

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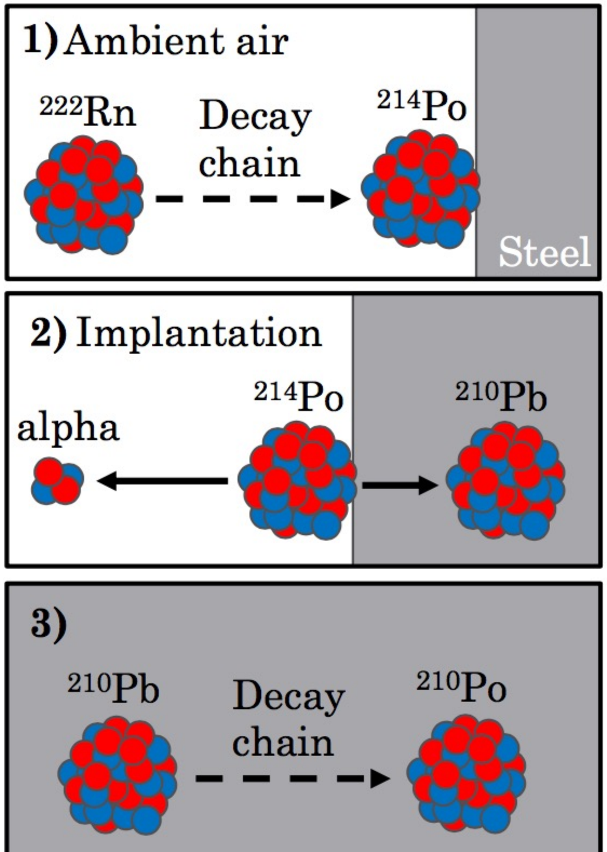

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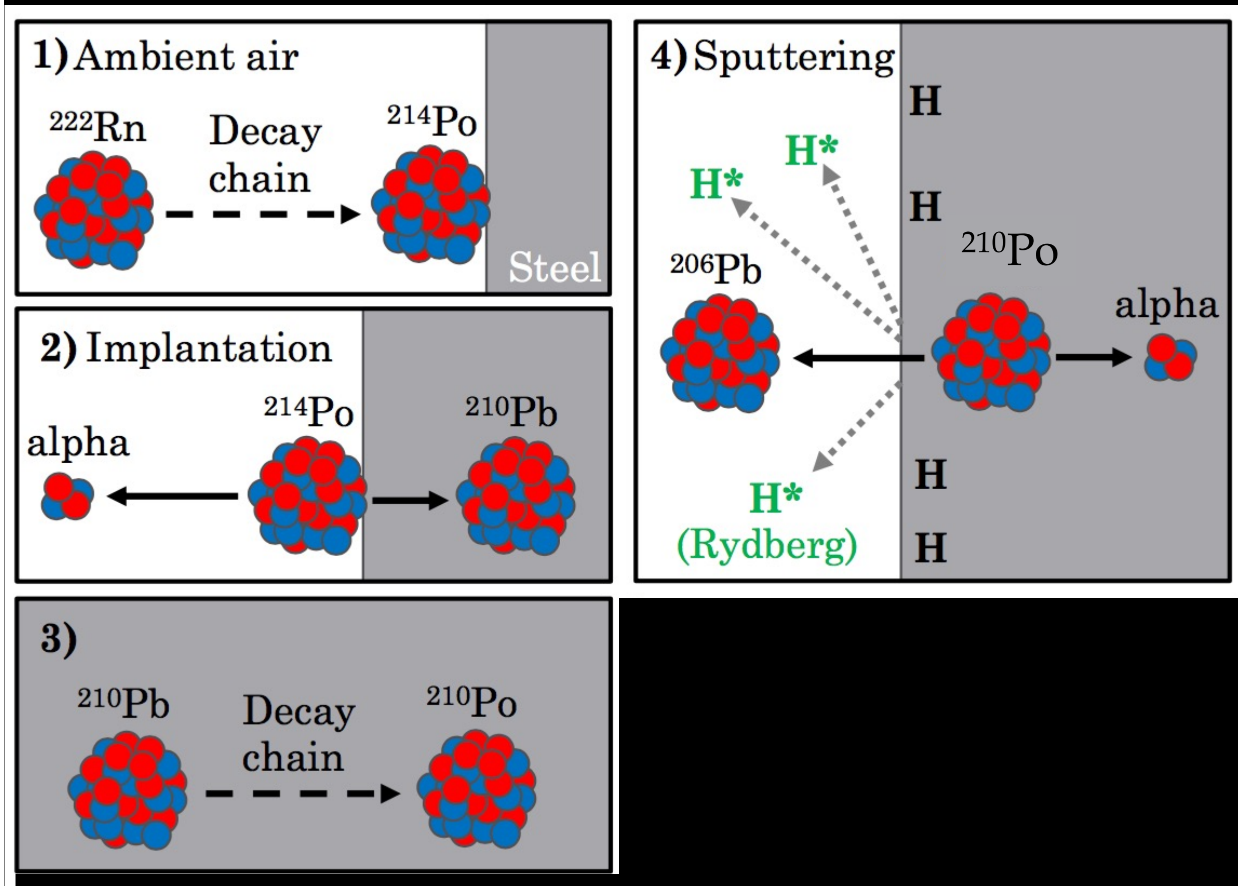

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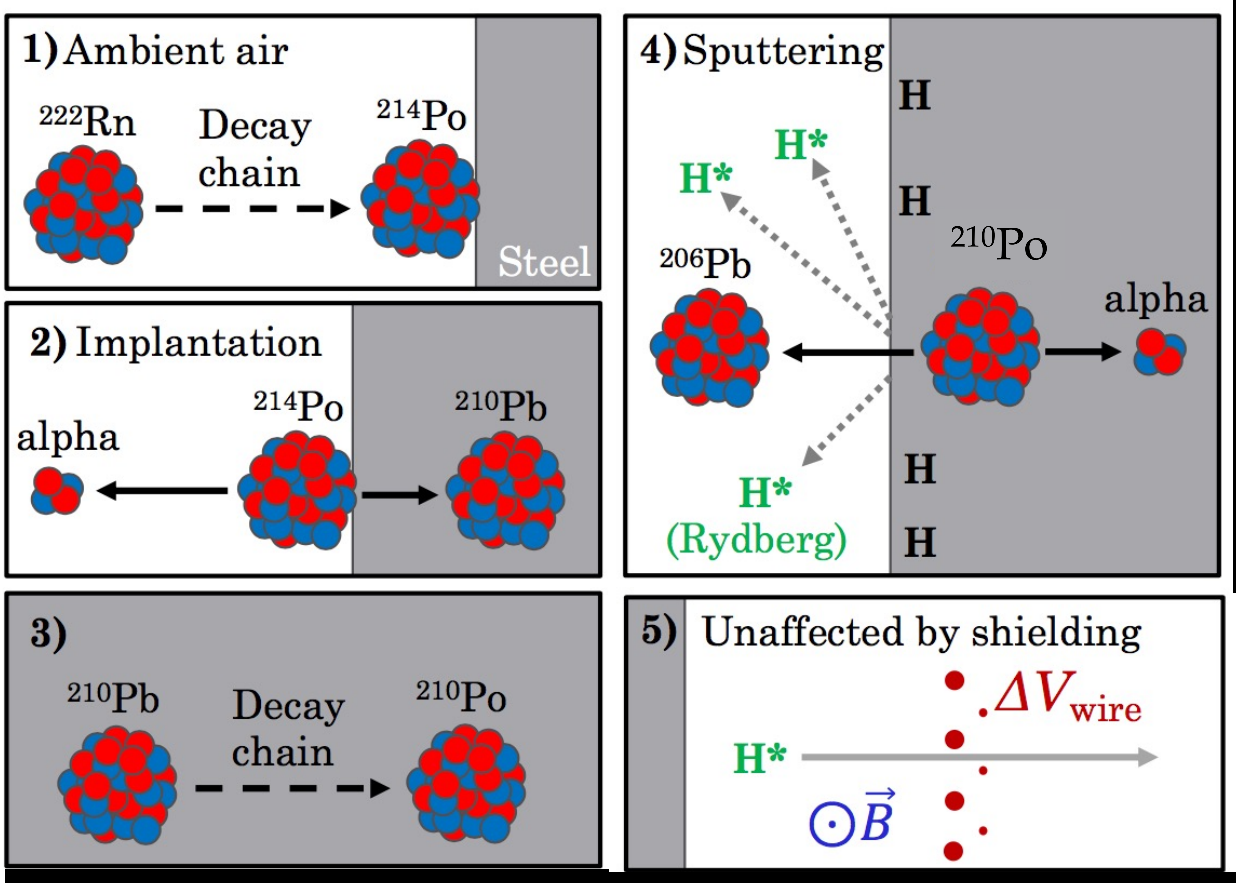

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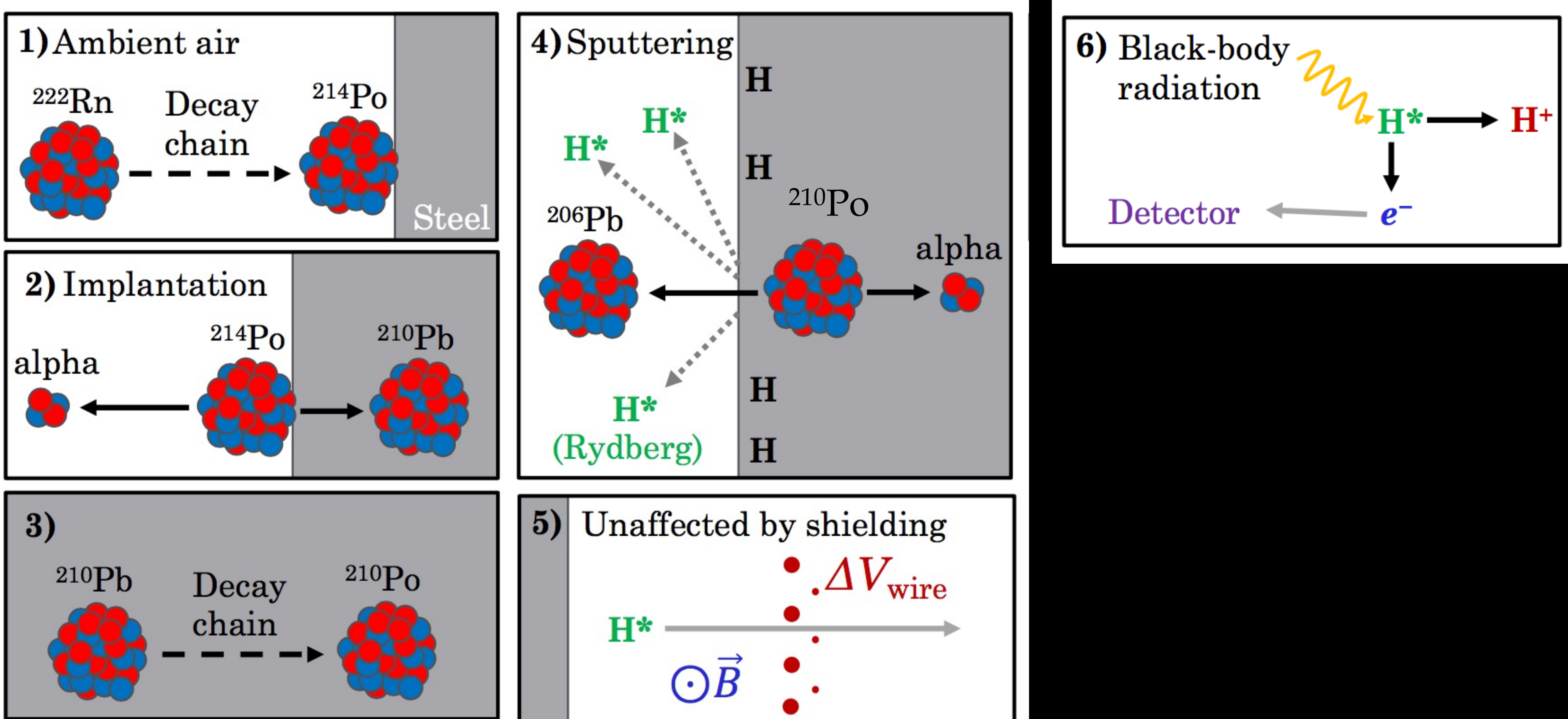

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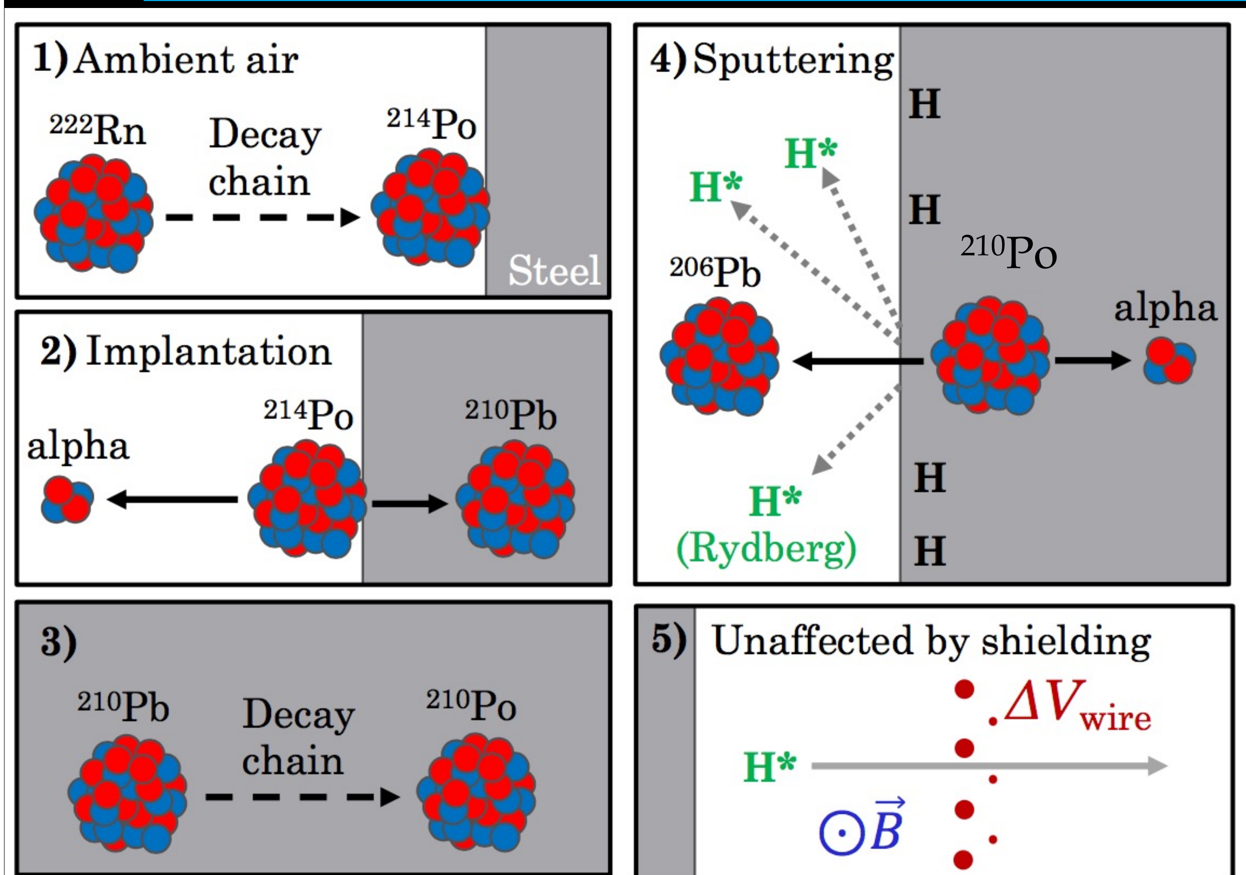
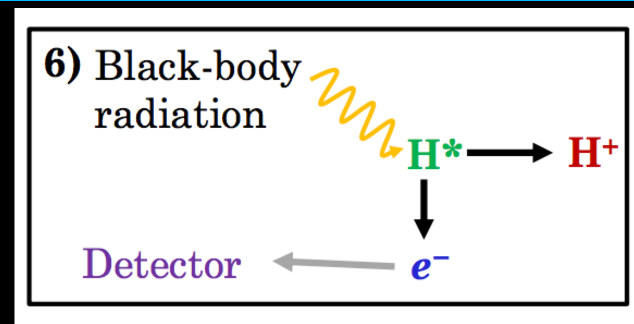
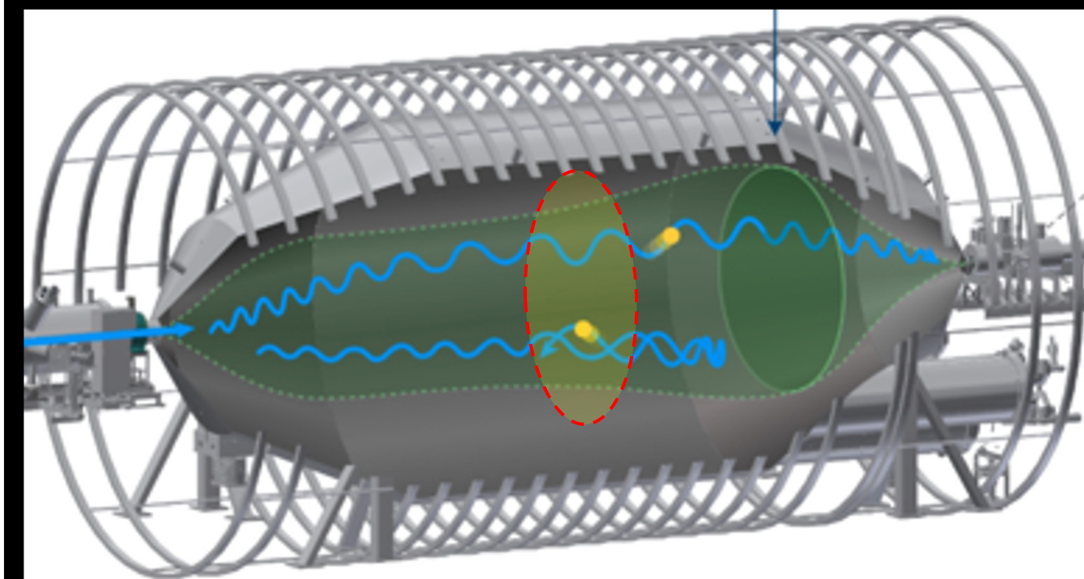




- Dominant background
- Tested with ^{220}Rn source
  - All daughters are short-lived
- Some component from heavier, autoionizing states

How Do You Solve a Background Like a Rydberg?

- One simple idea: it's a *volume*-dependent background
  - So, squeeze the imaged volume*!*
  - Increase magnetic fields and shift analyzing plane downstream



A. Lokhov et al., Eur. Phys. J. C 82, 258 (2022)

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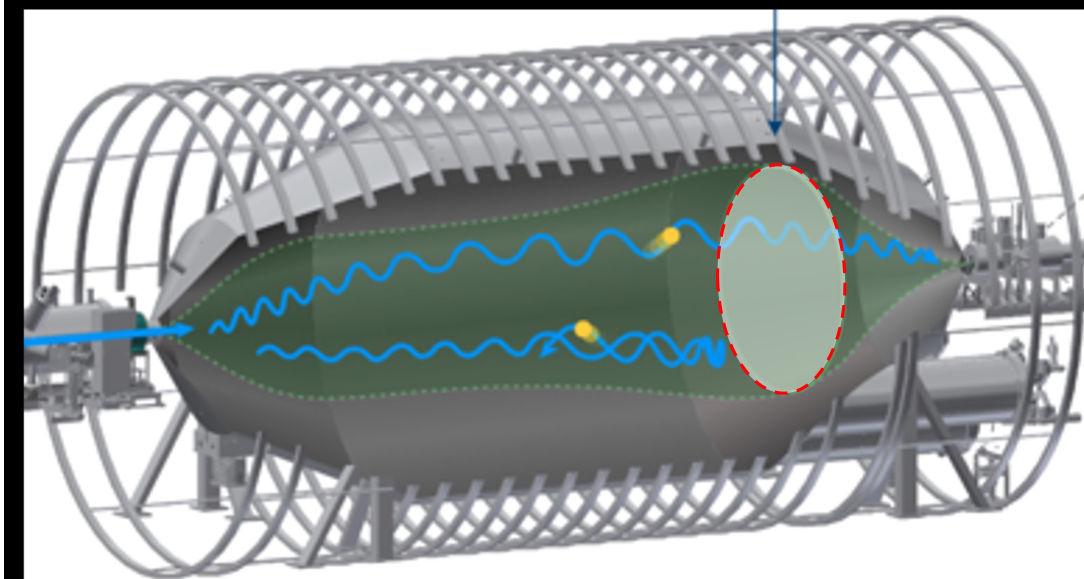

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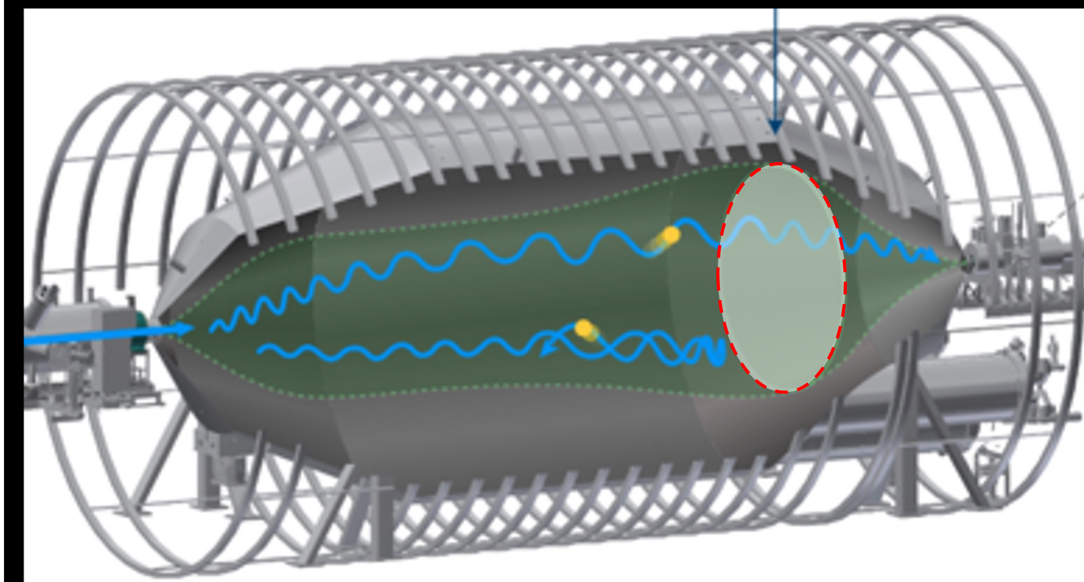
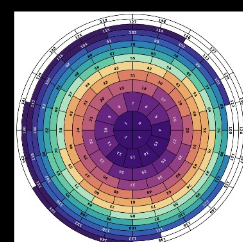
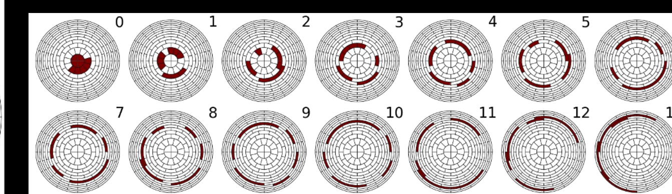


- Energy resolution is worsened
- Analysis is a little more complex



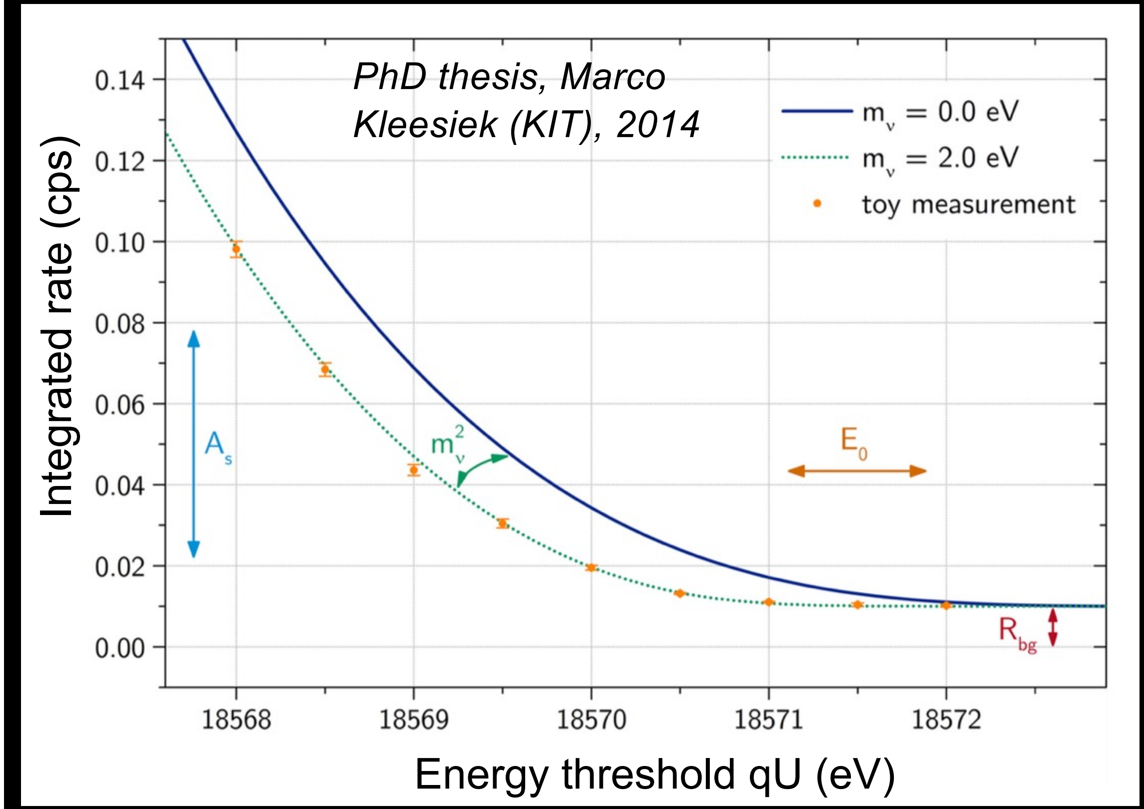


- But …2x background reduction!

A. Lokhov et al., Eur. Phys. J. C 82, 258 (2022)

Fitting the Data (in Principle)

- Fit modeled to measured spectrum with 4 free parameters



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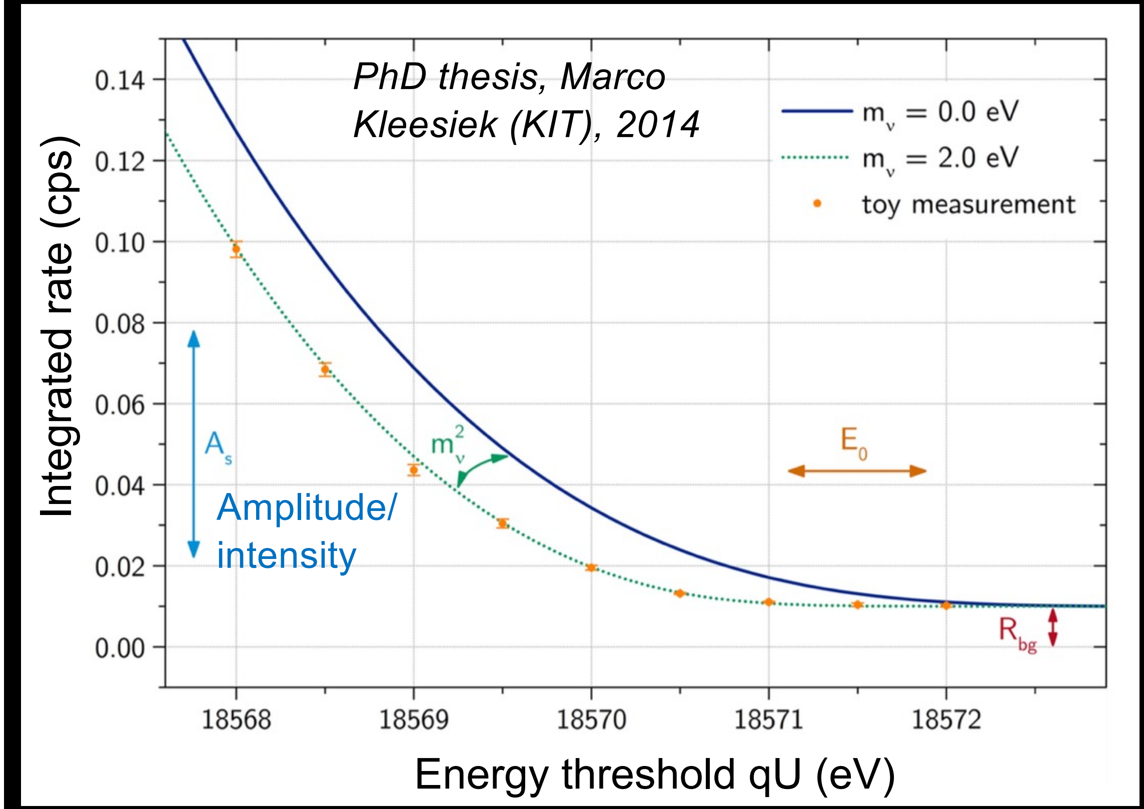

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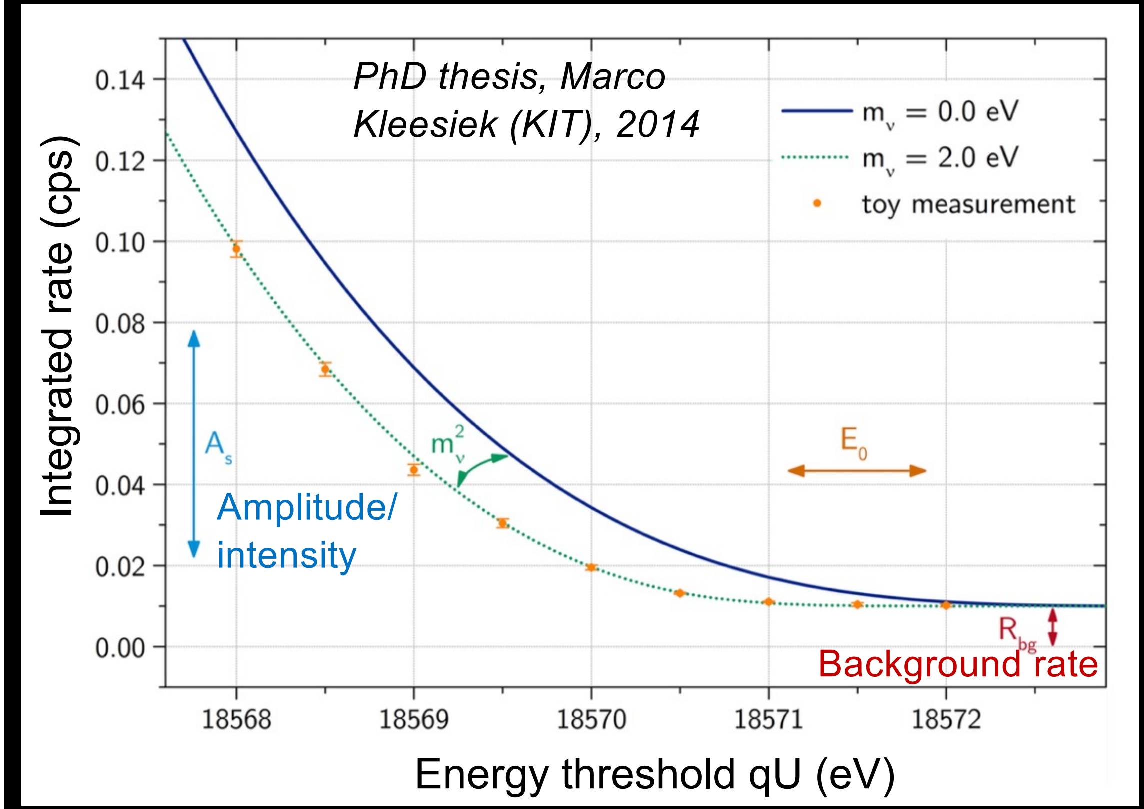

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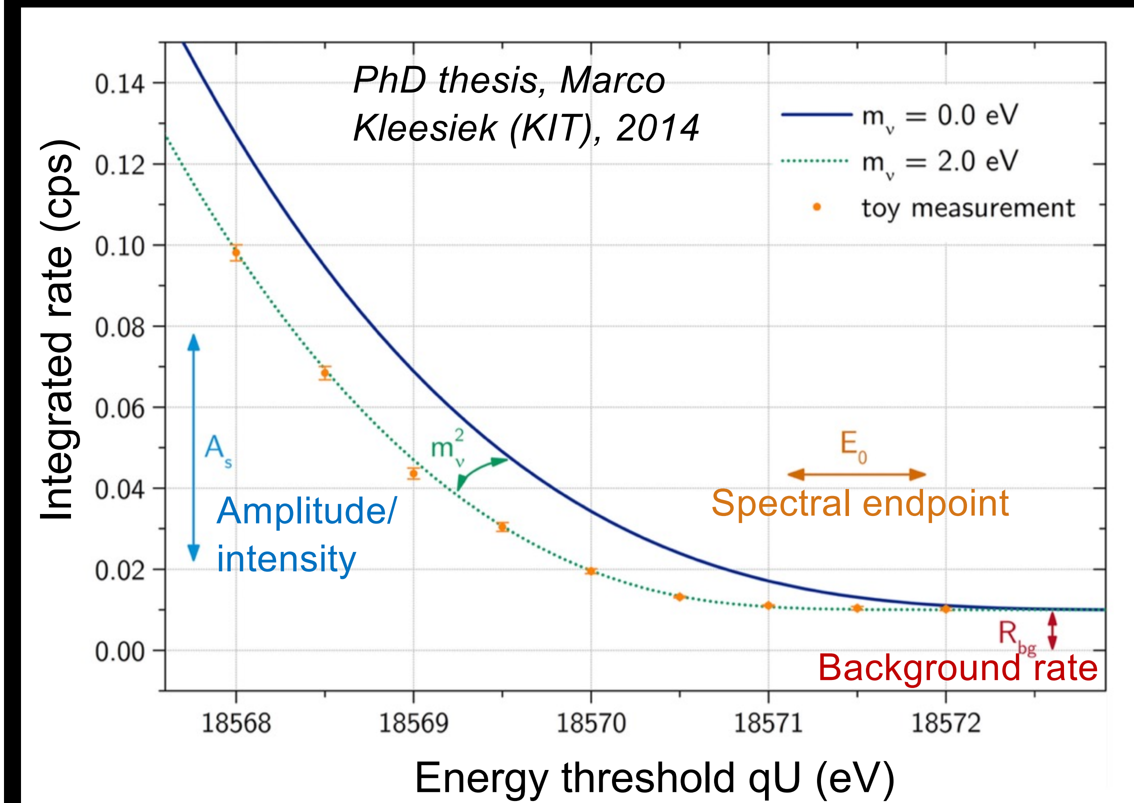

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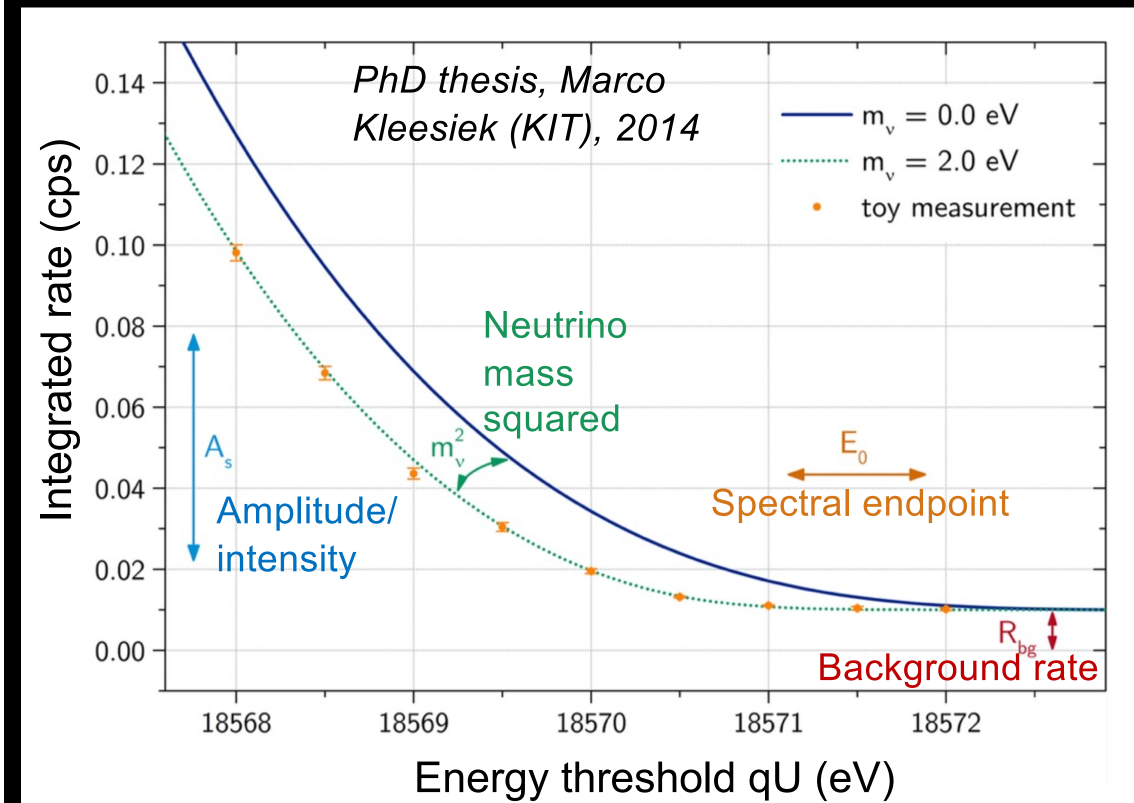

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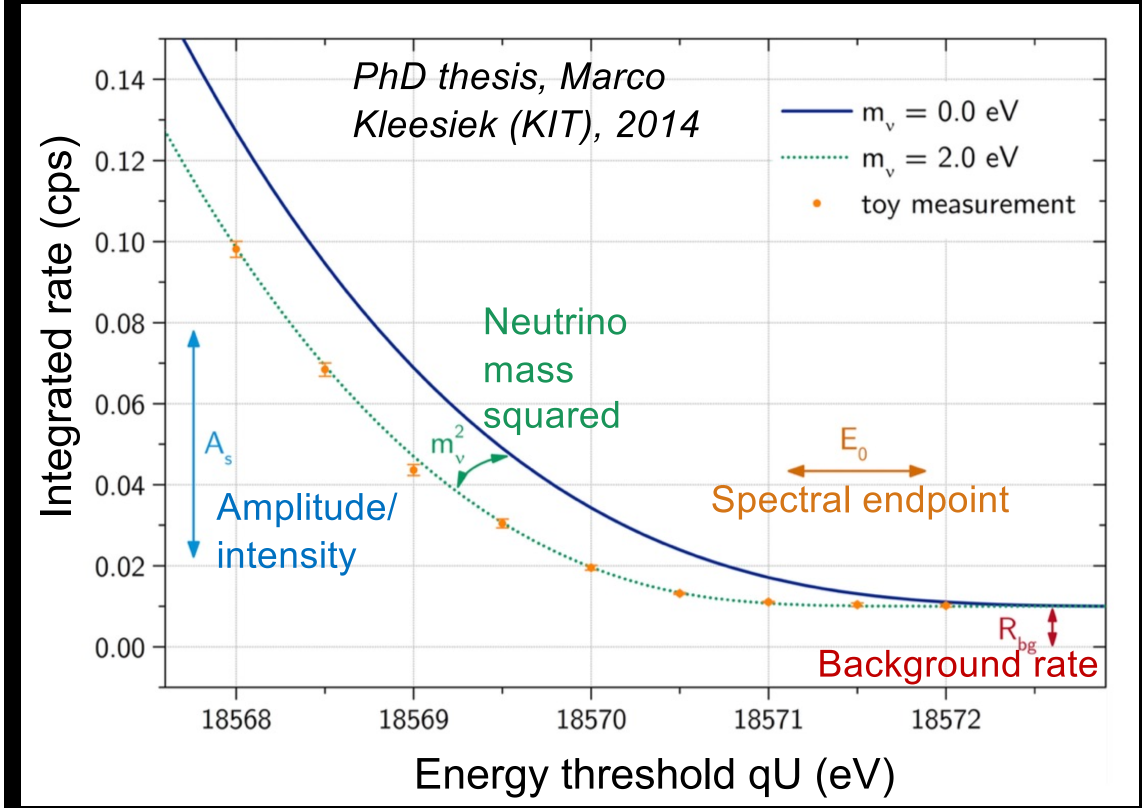

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- "Stack" similar high-voltage settings and combine runs
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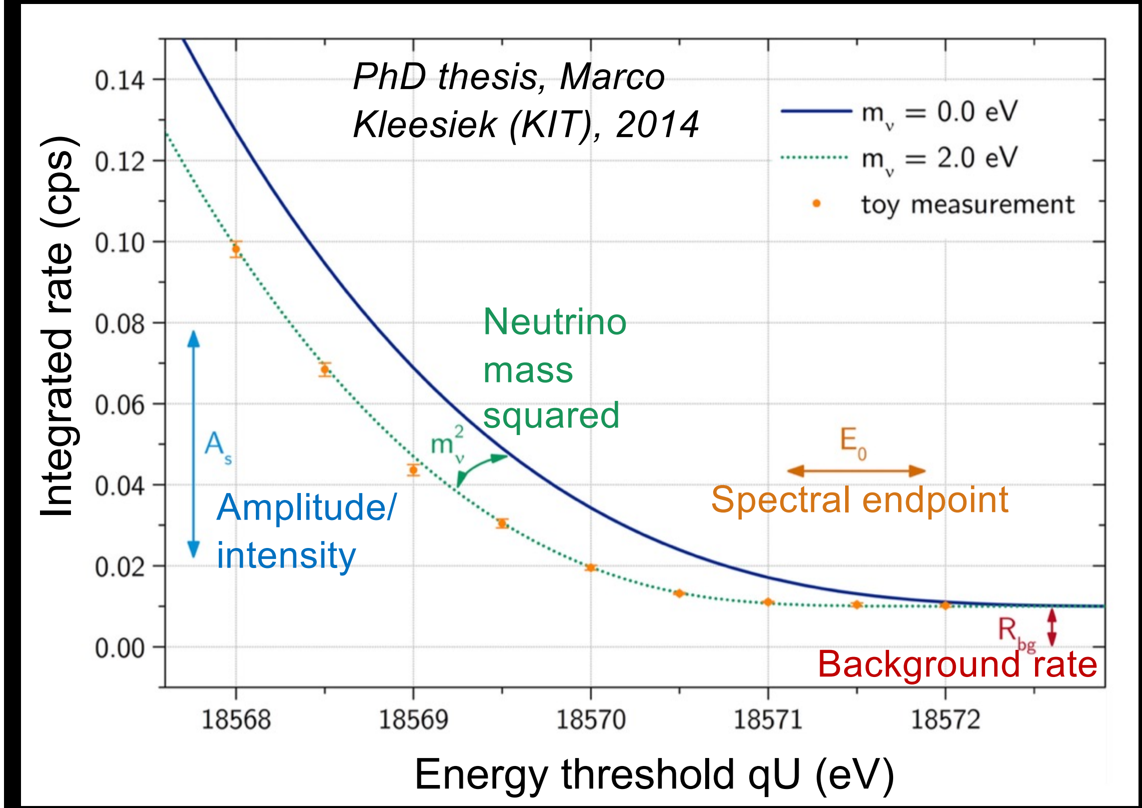

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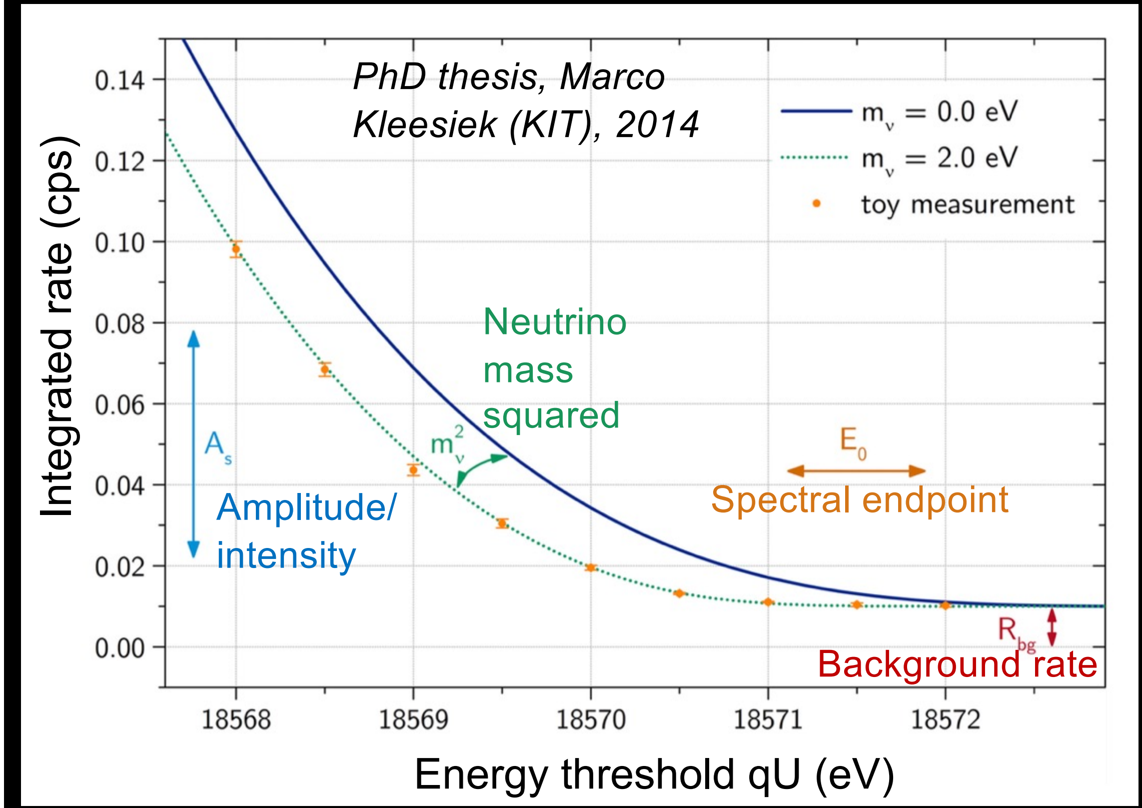


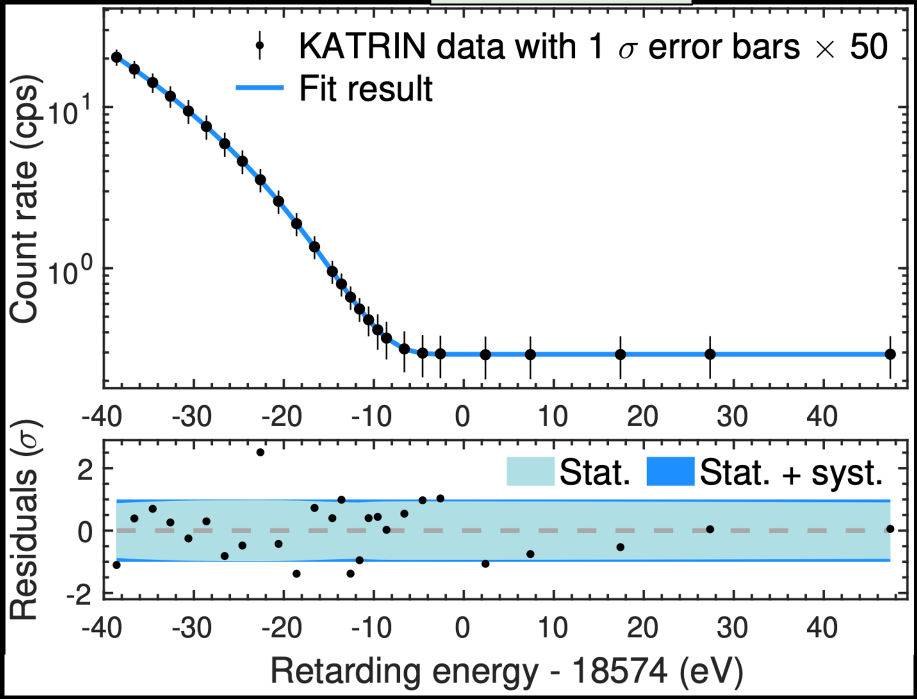
- Group detector pixels to reduce fit complexity
- "Stack" similar high-voltage settings and combine runs
- Cross-checks with multiple modeler/fitter packages

*More analysis details in Phys. Rev. D **104**, 012005 (2021)*

KNM1+2: KATRIN Takes Flight

- Spring 2019: 22 days at 2.5 x 10^{10} Bq

$$m_\nu^2 = (-1.0^{+0.9}_{-1.1})\ \mathrm{eV}^2$$
$$m_\nu < 1.1\ \mathrm{eV}\ (90\%\ \mathrm{C.L.})$$



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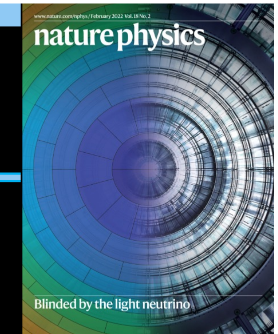

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- Autumn 2019: 31 days at 9.5 x 10^{10} Bq

$$m_\nu^2 = (0.26 \pm 0.34)\ \mathrm{eV}^2$$
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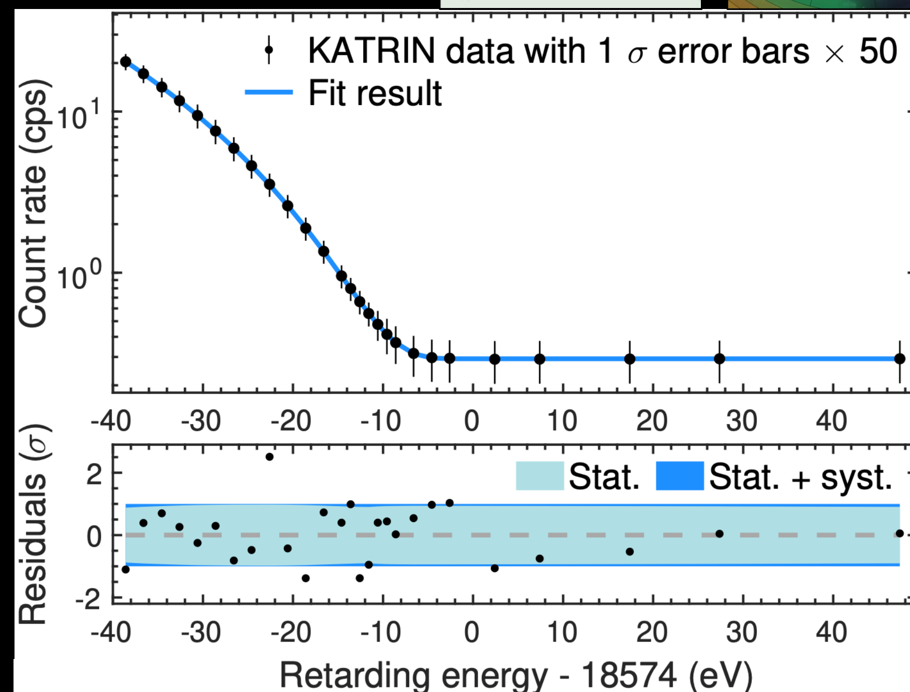
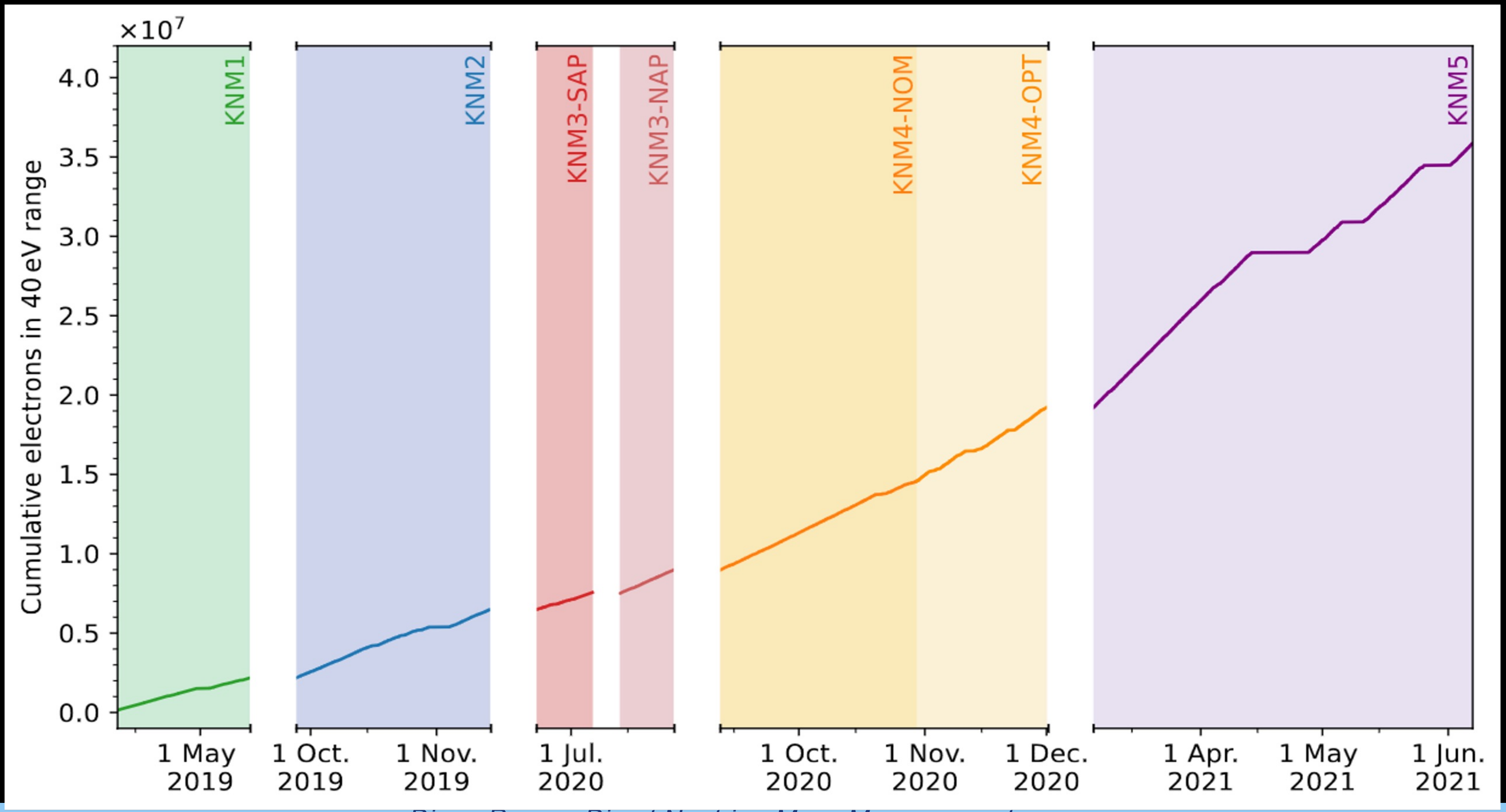
Nature Physics ***18*** *160 (2022)*



KNM1-5: Putting It Together

- How can we combine data taken under very different configurations?



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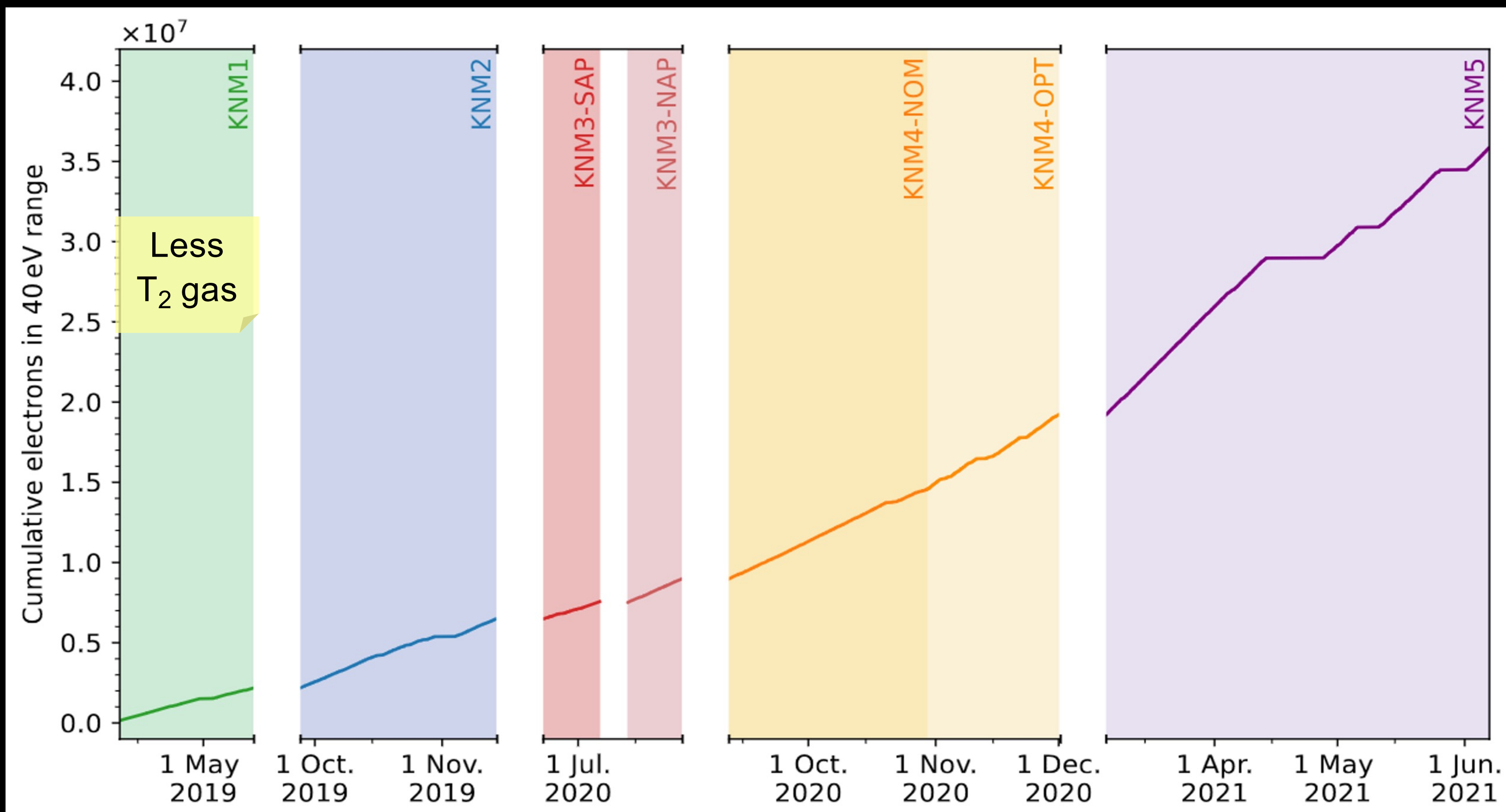

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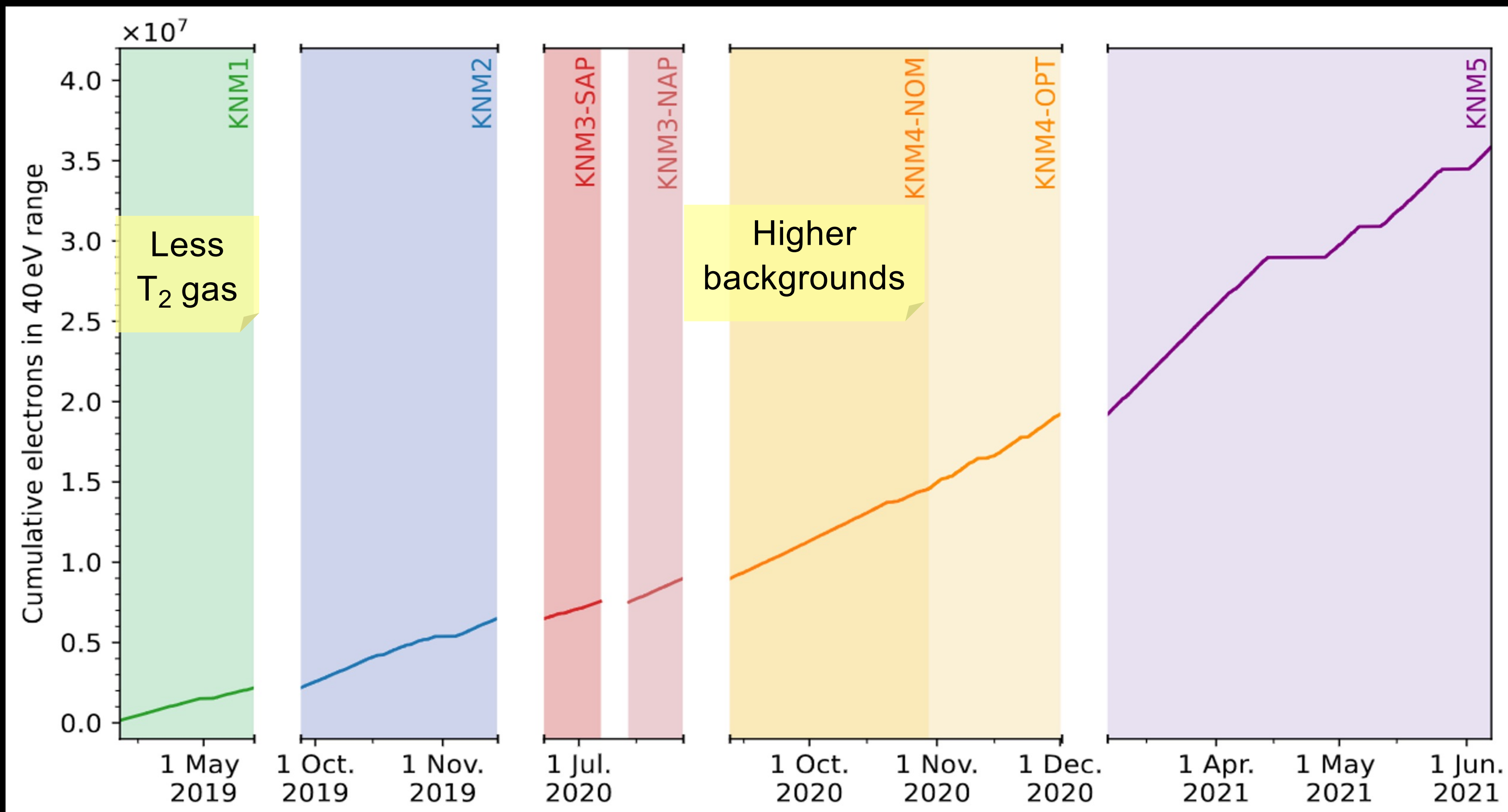

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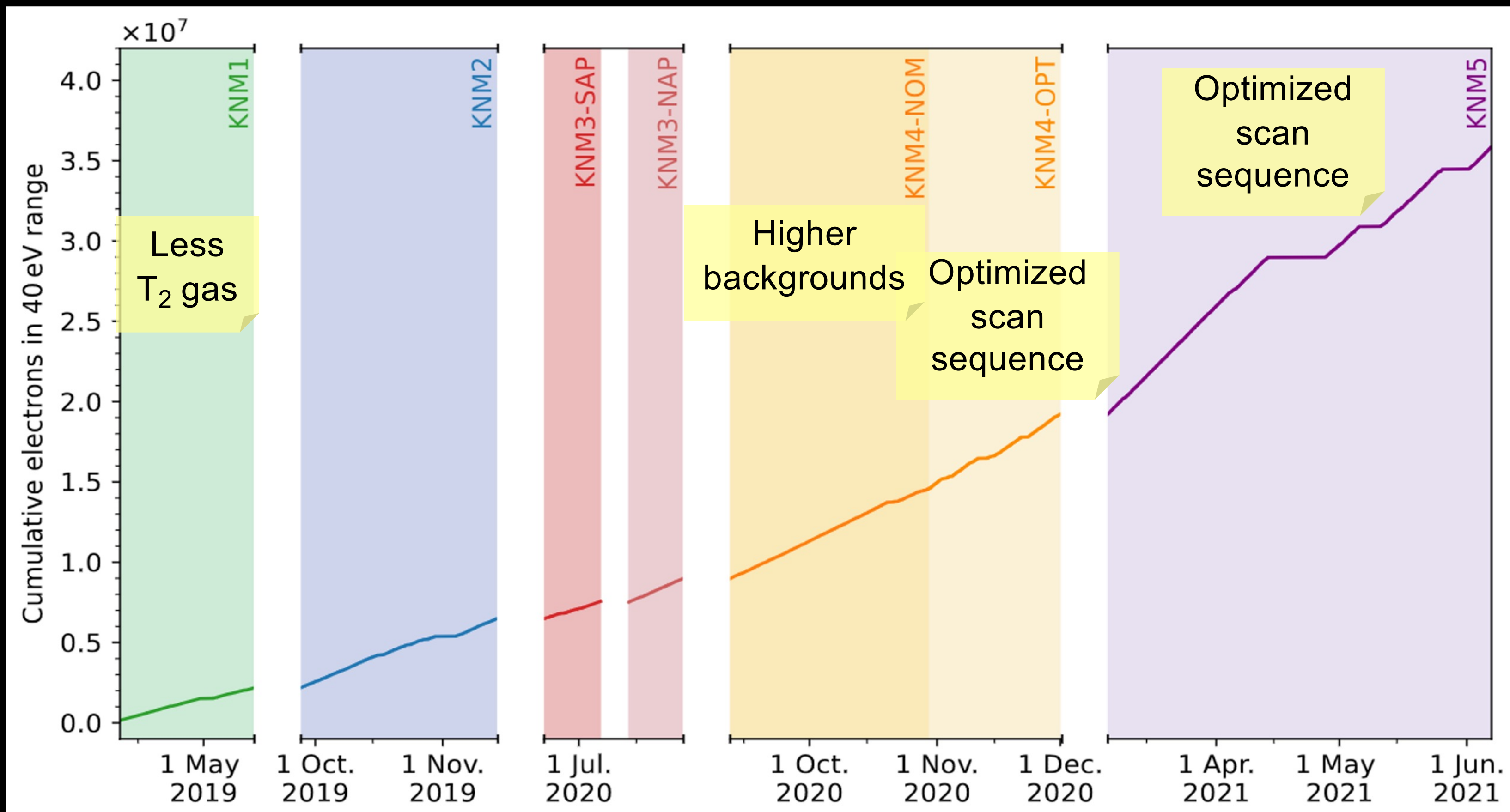

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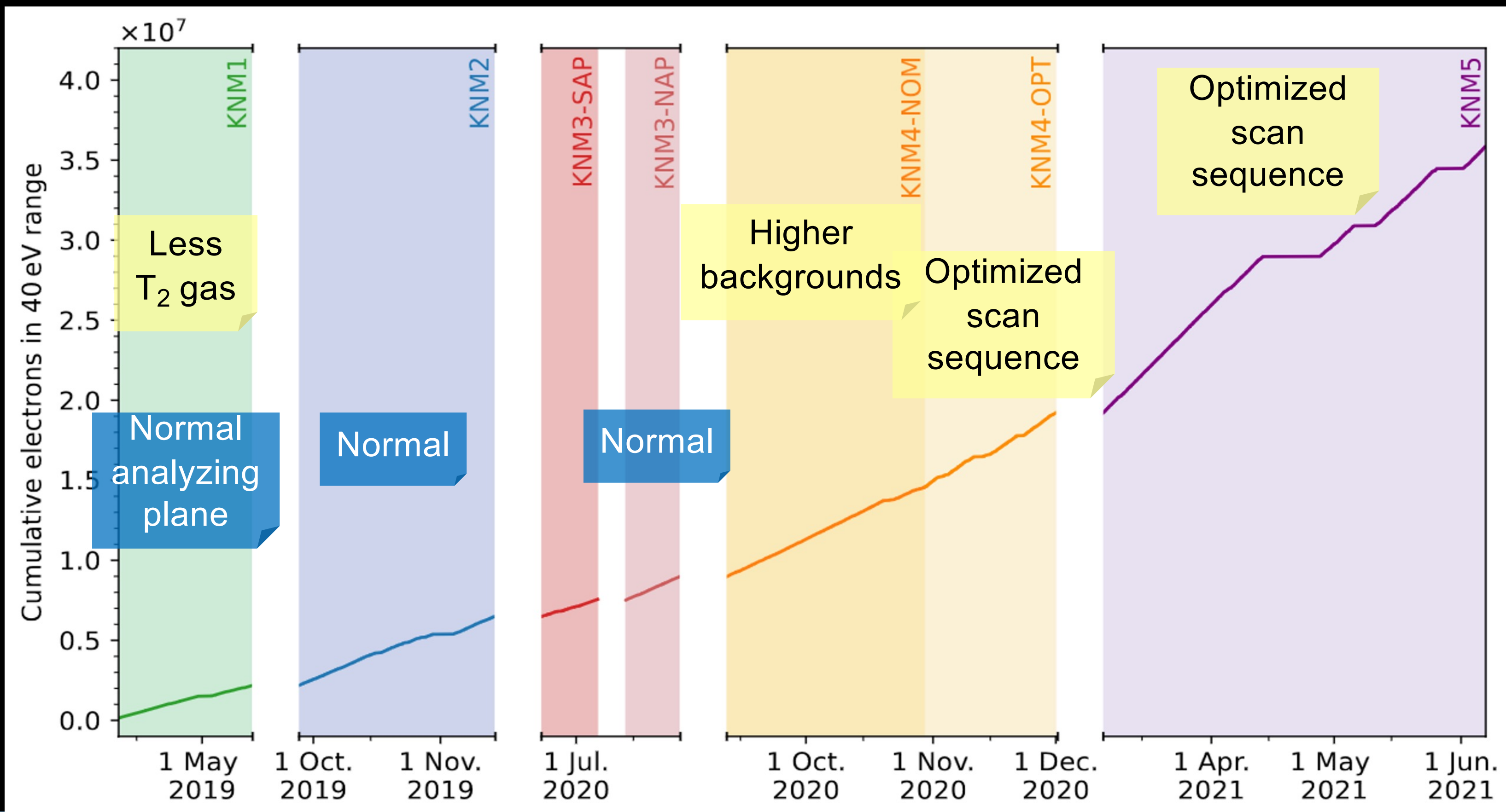

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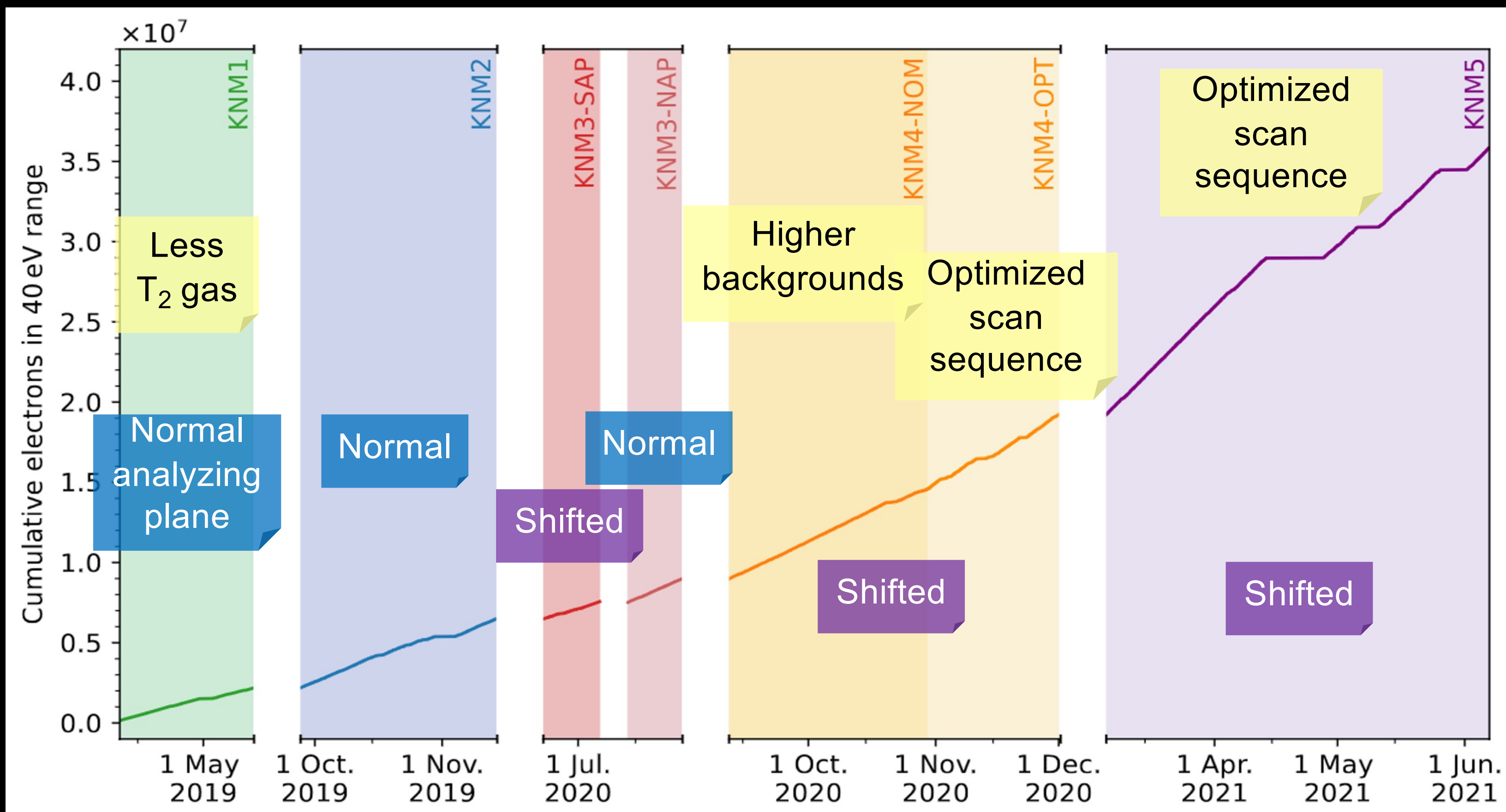

Joint Fit Across Campaigns and Patches

- Allow operating parameters to vary separately
- Neutrino-mass value is a common fit parameter across all spectra
- Model spectrum predicted for each campaign and patch

- 1609 data points across all spectra
- 144 correlated systematic parameters
- Two-level blindness scheme:
  1. Fix analysis methods using simulated data sets
  2. First look at data is model-blinded (smear molecular final states)

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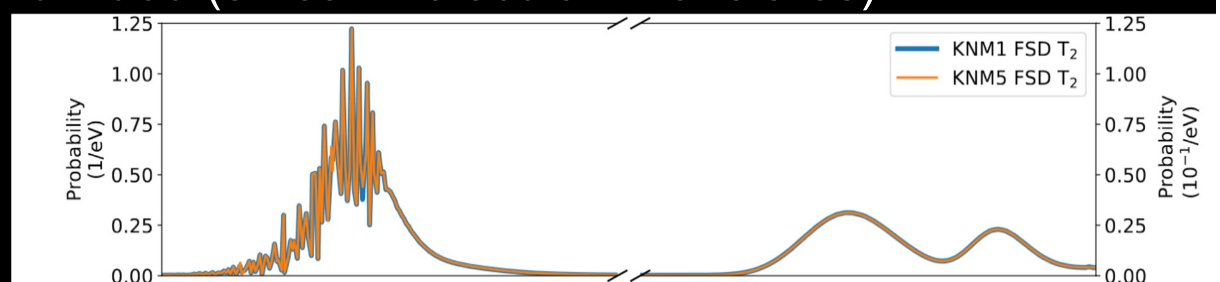

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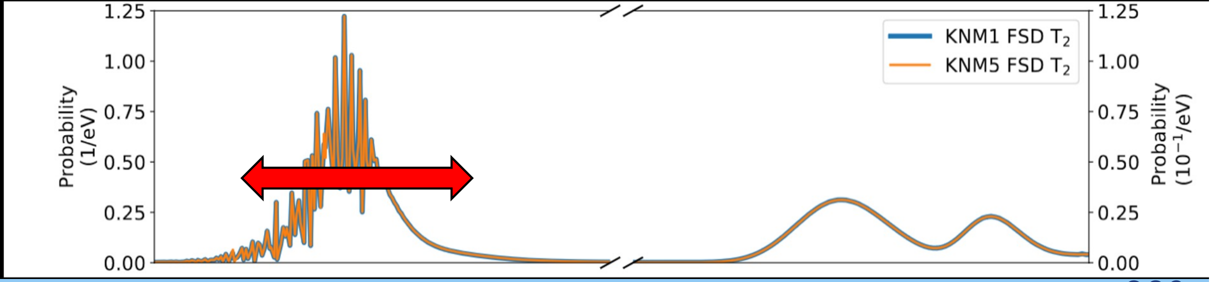
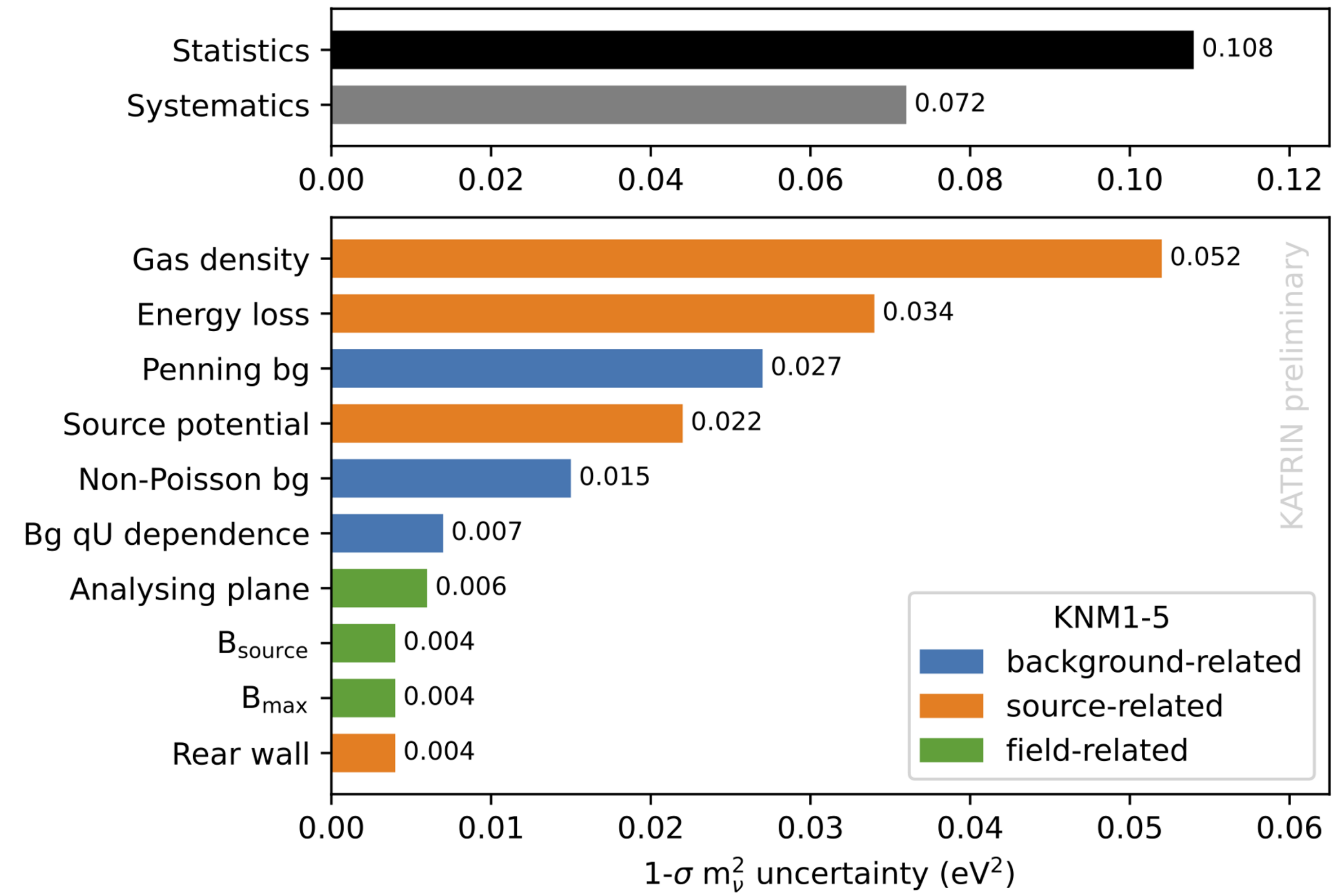


Uncertainty Budget



- Still dominated by statistics
- Background uncertainties substantially reduced
- Several systematics improvements (especially source scattering) on the way

Full Disclosure

- After unblinding, we discovered problems!
  - KNM4 included runs that were too different to combine into one spectrum
    - Split into KNM4-NOM and KNM4-OPT
  - Discovered inconsistency in energy-loss measurements
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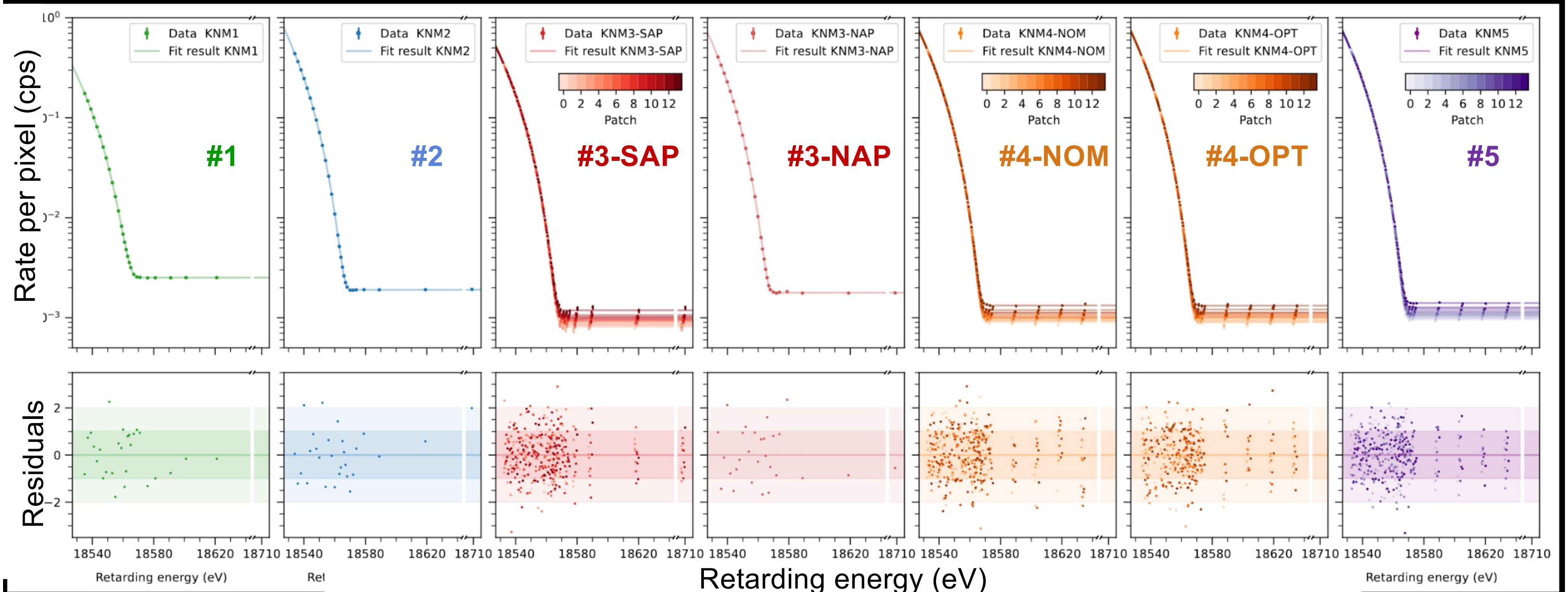
The Fits

- Maximum-likelihood fit with common m_ν^2 parameter
- $p = 0.84$



The Latest Result: 36M electrons

- Best fit is slightly negative, plausible within statistical fluctuations

$$m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$$

KATRIN, Science 388 180 (2025)

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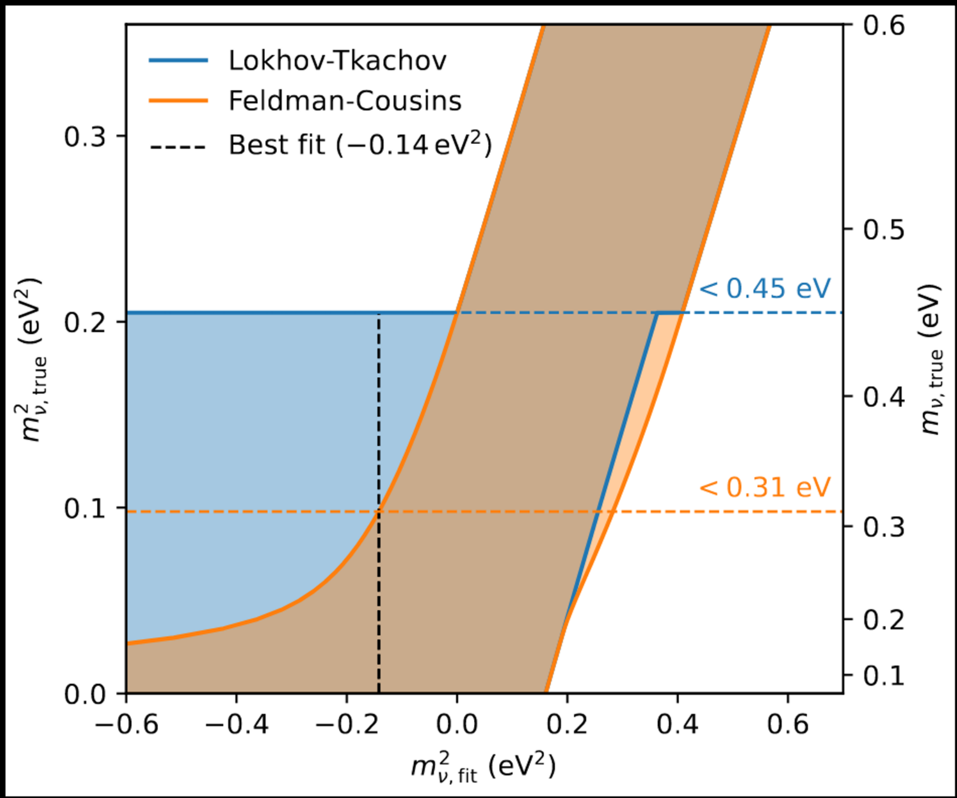

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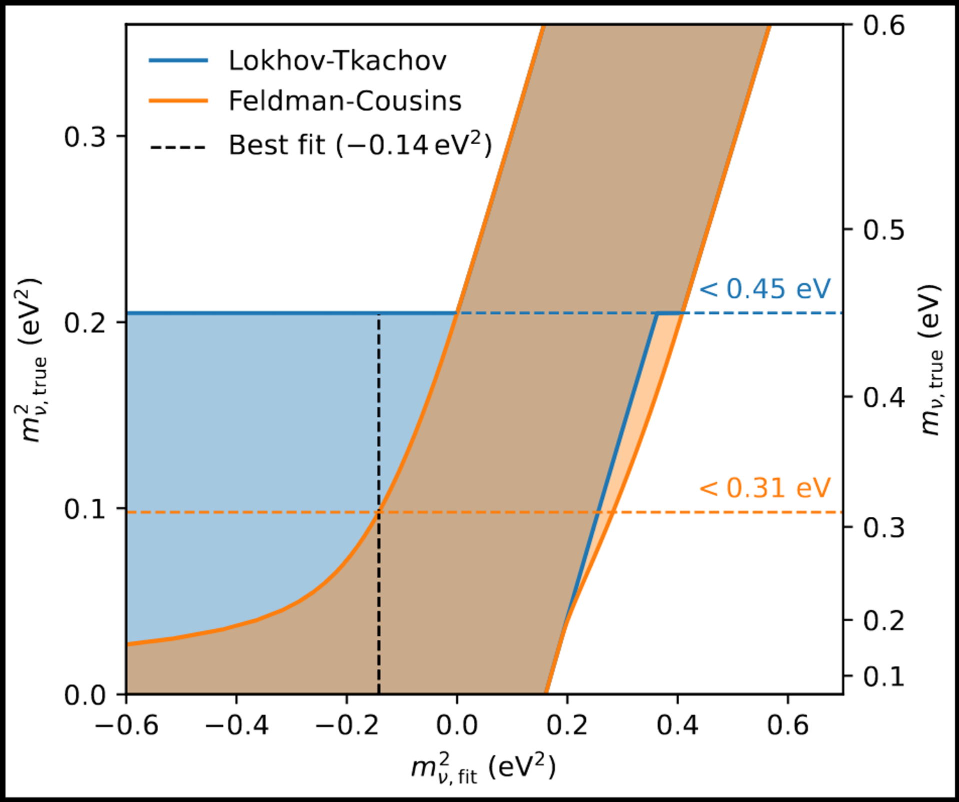

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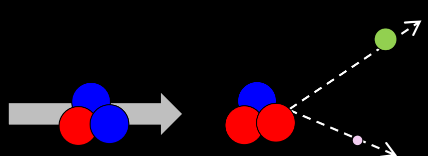
- KATRIN now has more than 230M electrons on disk

The Plan

- Accessing the neutrino-mass scale
- How to search for m_ν directly
- Nitty, gritty systematics
- Microcalorimetry basics (^{163}Ho)
- HOLMES
- ECHo
- Beta-spectroscopy basics (^{3}H)
- KATRIN
- **Project 8**
- Next-generation tritium R&D
- Sterile neutrinos and bonus physics
- Alternate measurement ideas

Cyclotron Radiation Emission Spectroscopy

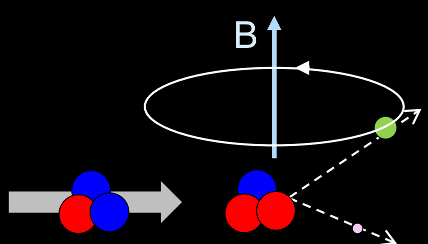


Electron produced in beta decay

First proposed: B. Monreal and J. Formaggio, PRD 80, 051301(R) (2009)

Cyclotron Radiation Emission Spectroscopy

Electron undergoes cyclotron motion in magnetic field



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PROJECT 8

QTNM
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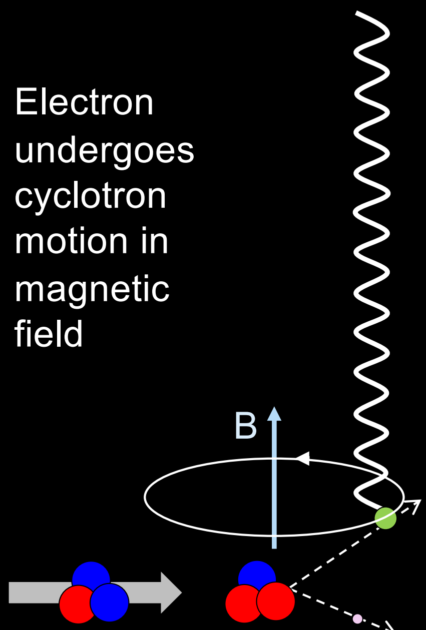

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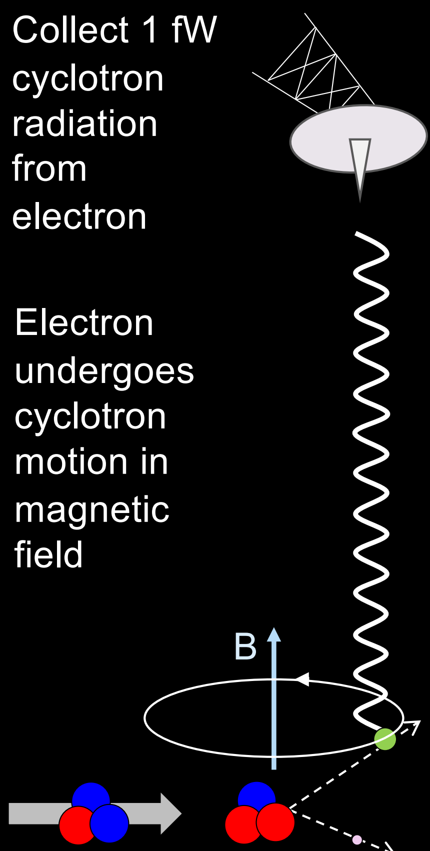

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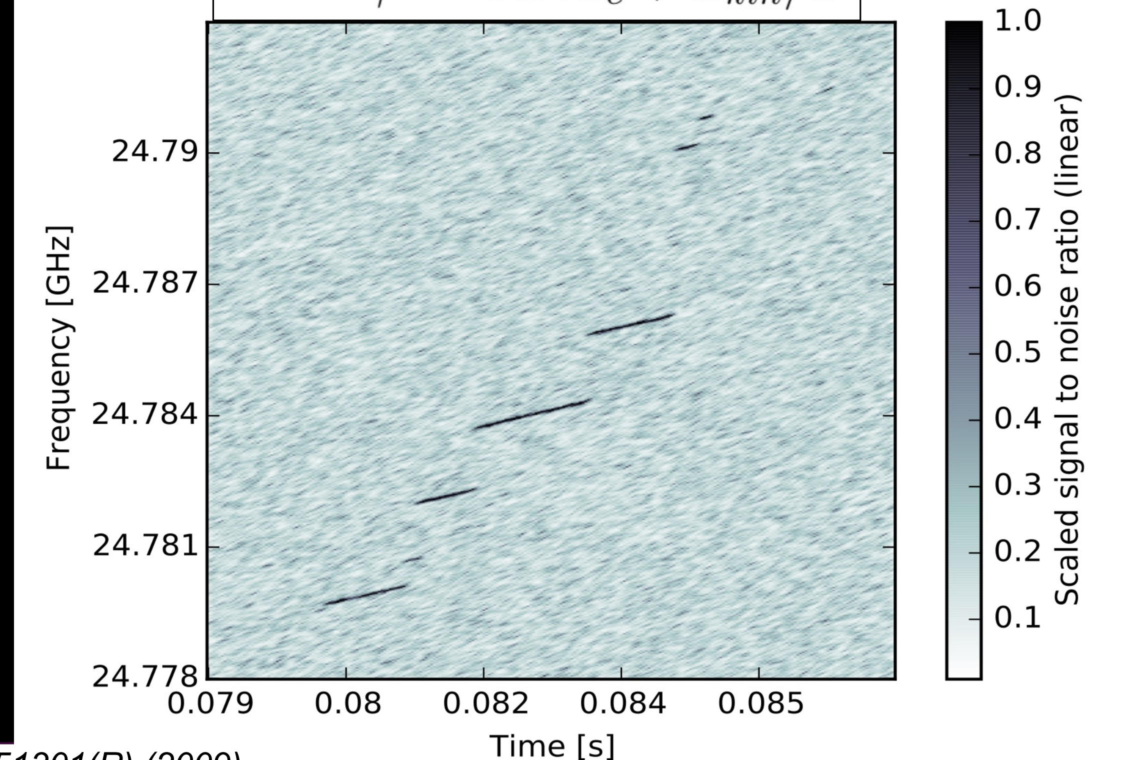

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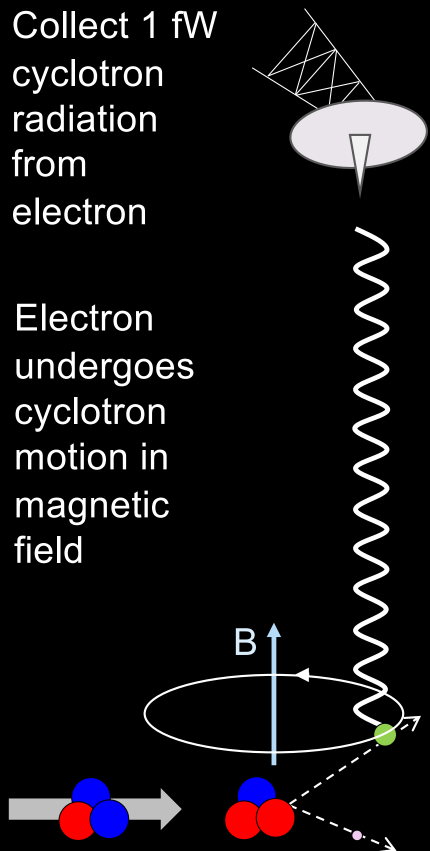

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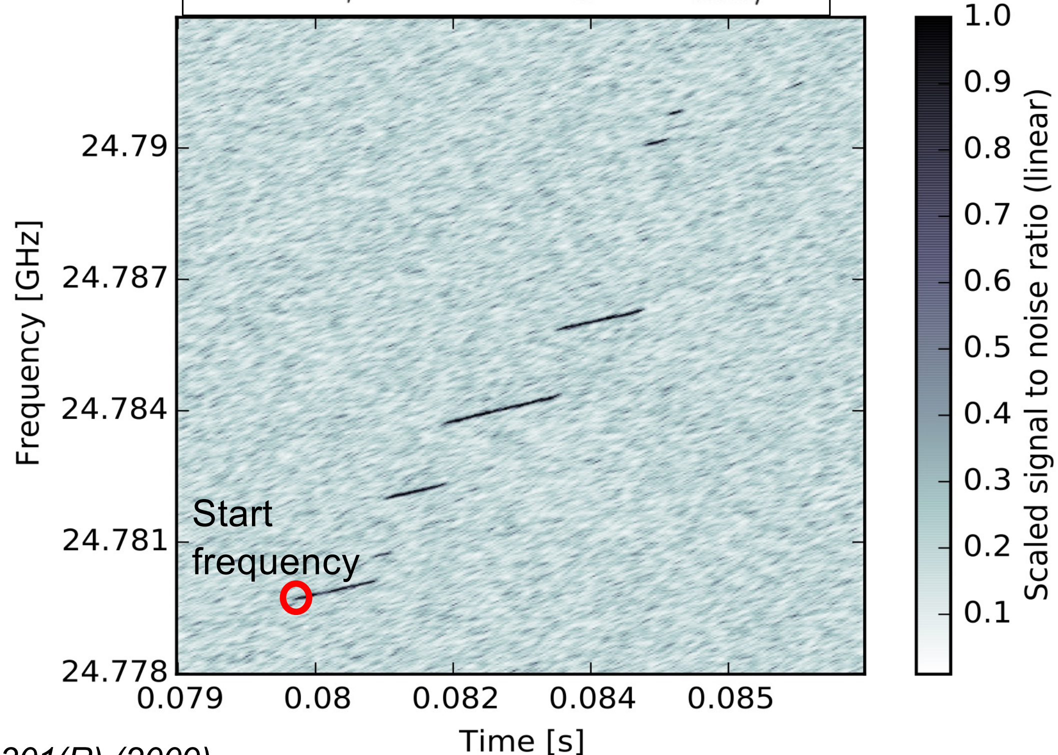

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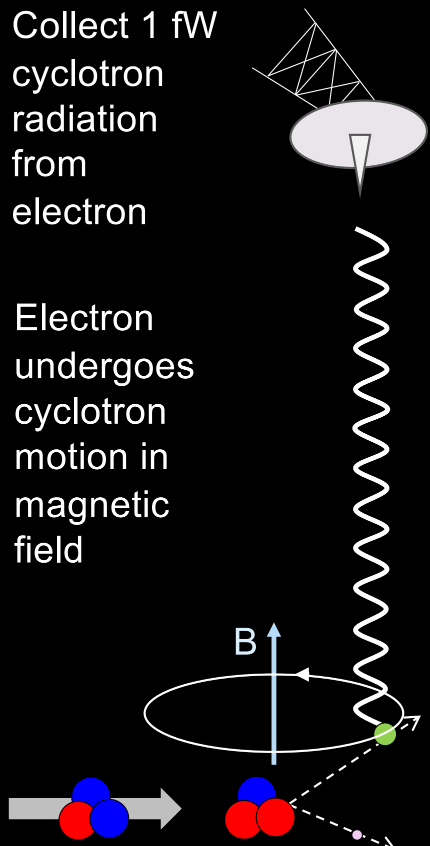

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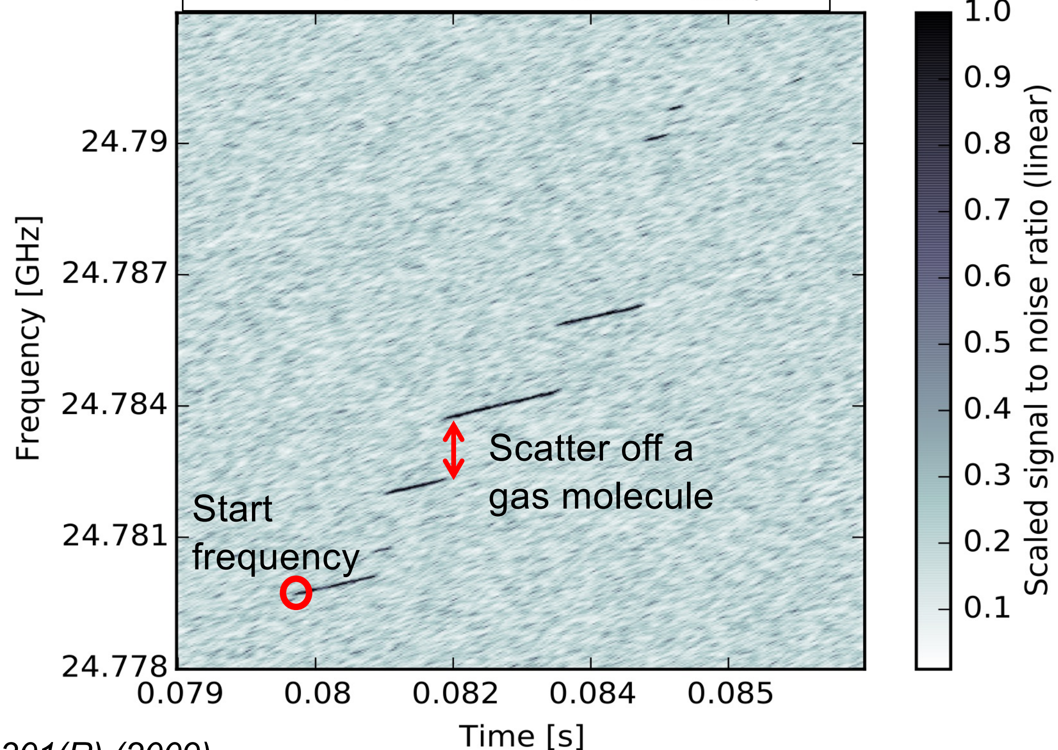

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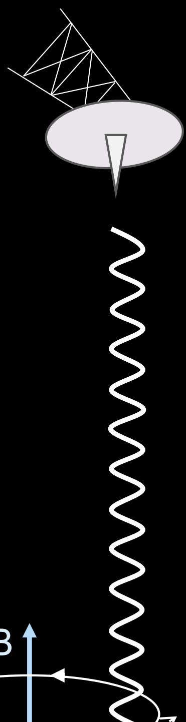

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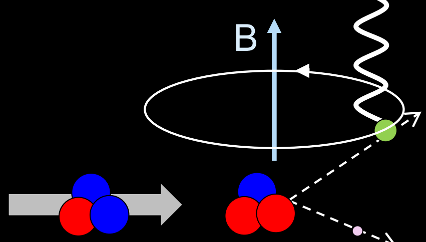

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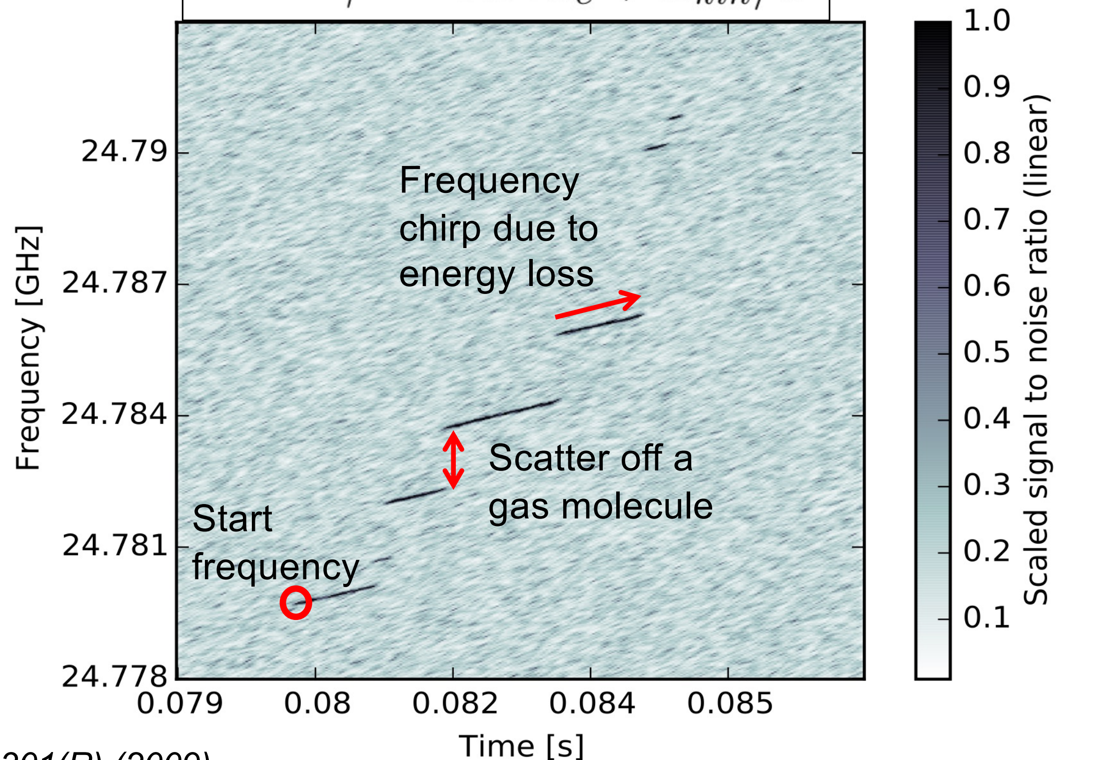

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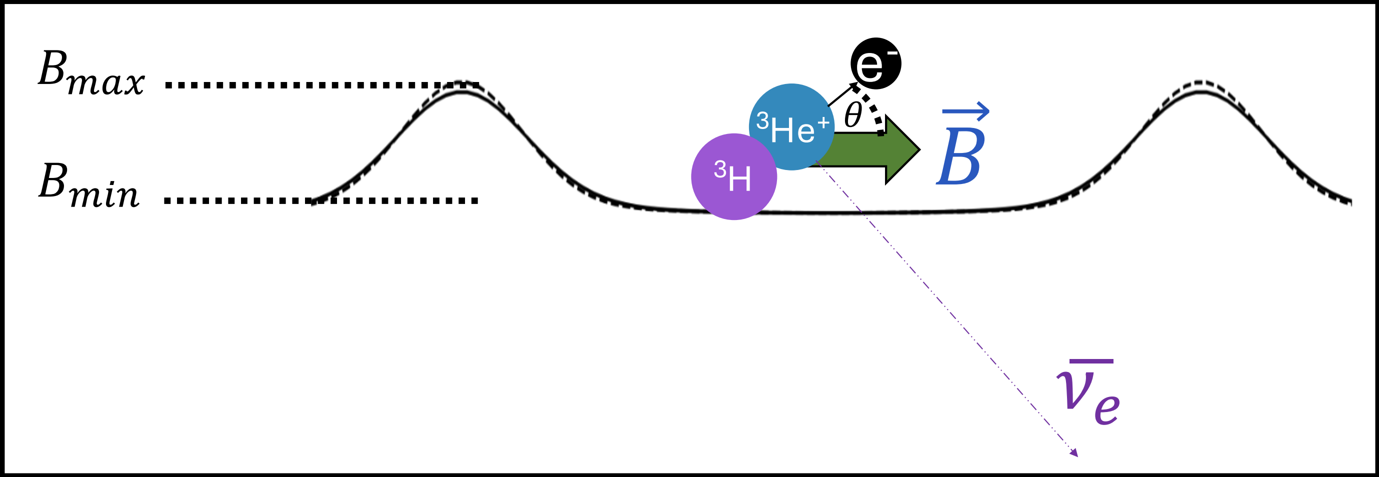
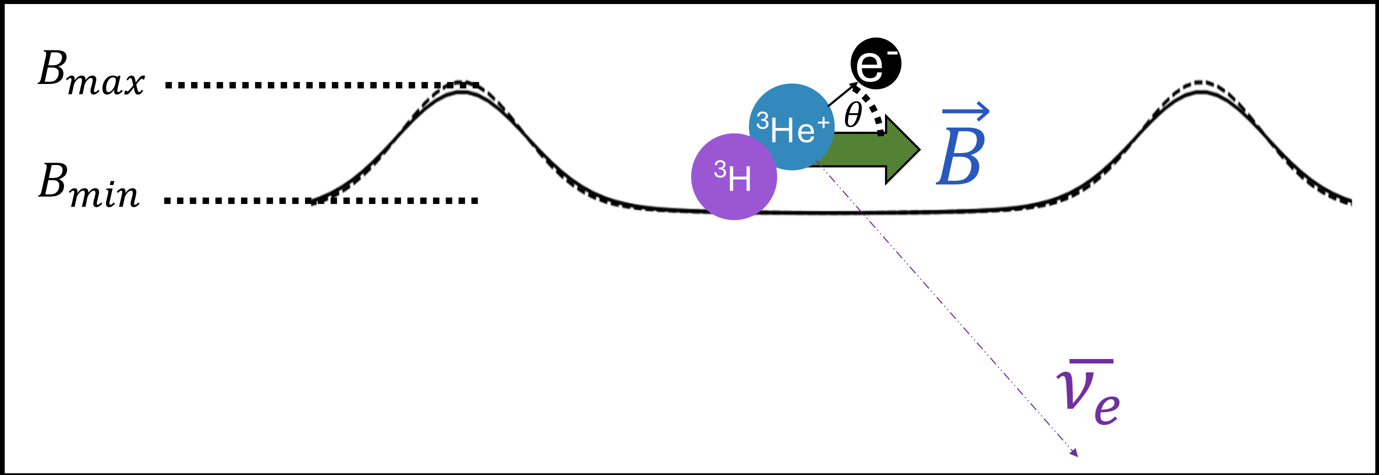
Electron dynamics in a magnetic trap



Slide: Hannah Binney

Electron dynamics in a magnetic trap

- Electron may be emitted in any direction
- Magnetic trap required to trap electrons long enough to be detected
- Pitch angle θ = angle between the electron momentum and the magnetic field
- Only electrons with $\theta > \sin^{-1}\left(\sqrt{B_{min}/B_{max}}\right)$ will be stored



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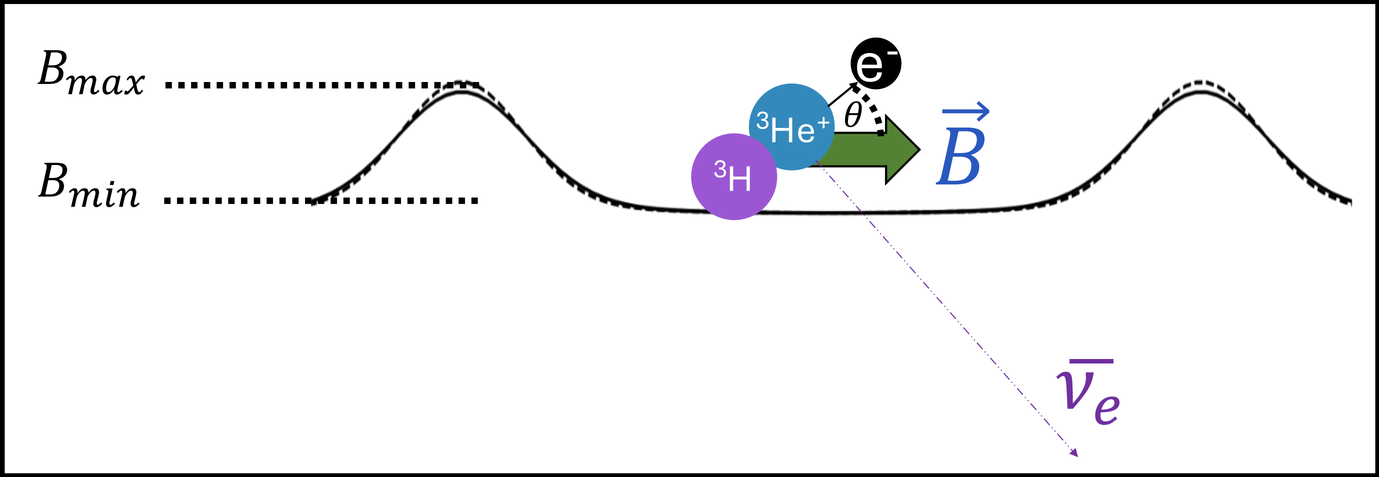

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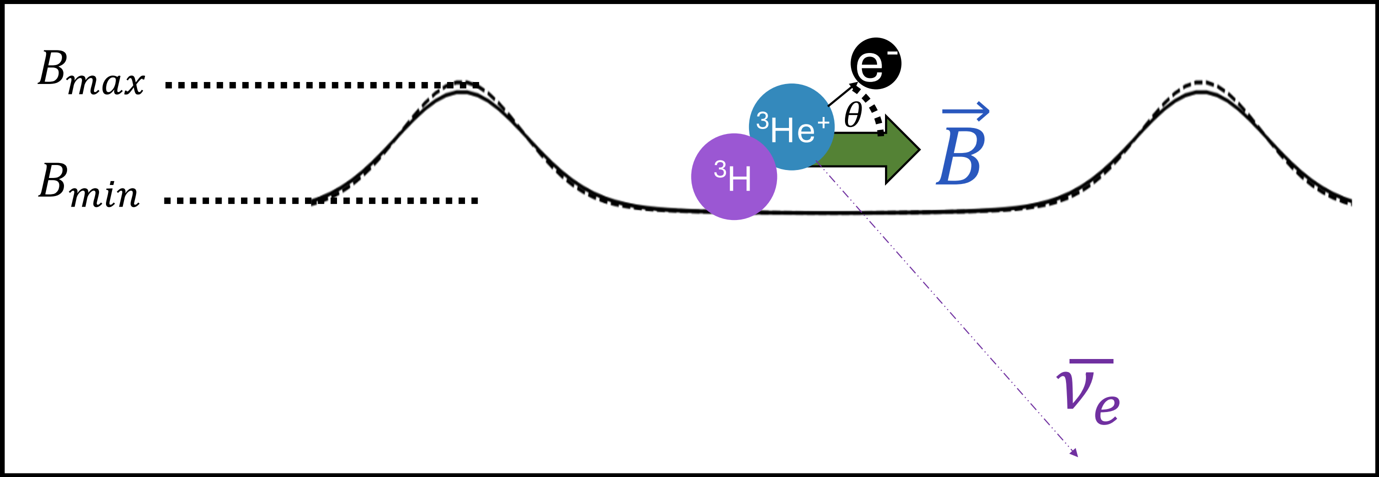

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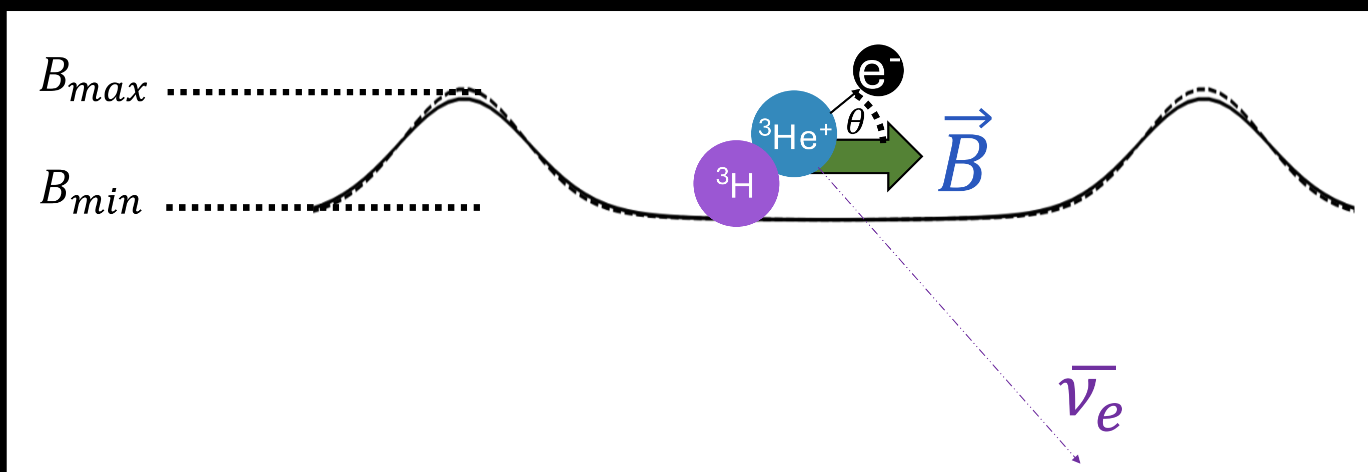

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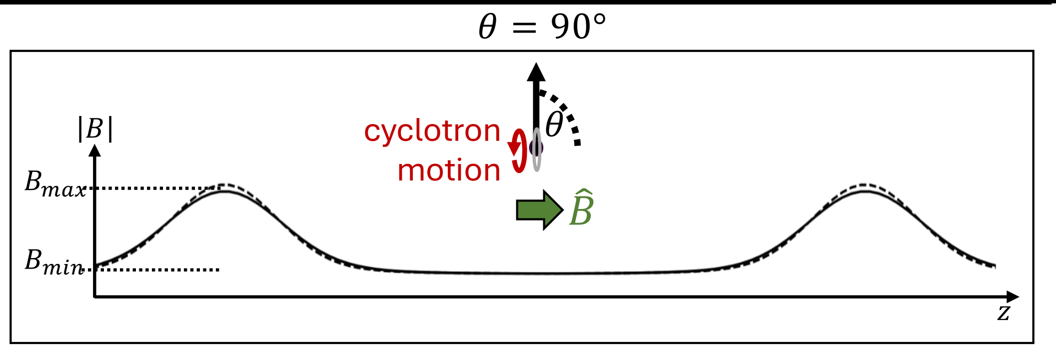

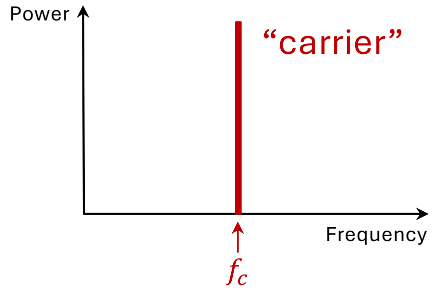

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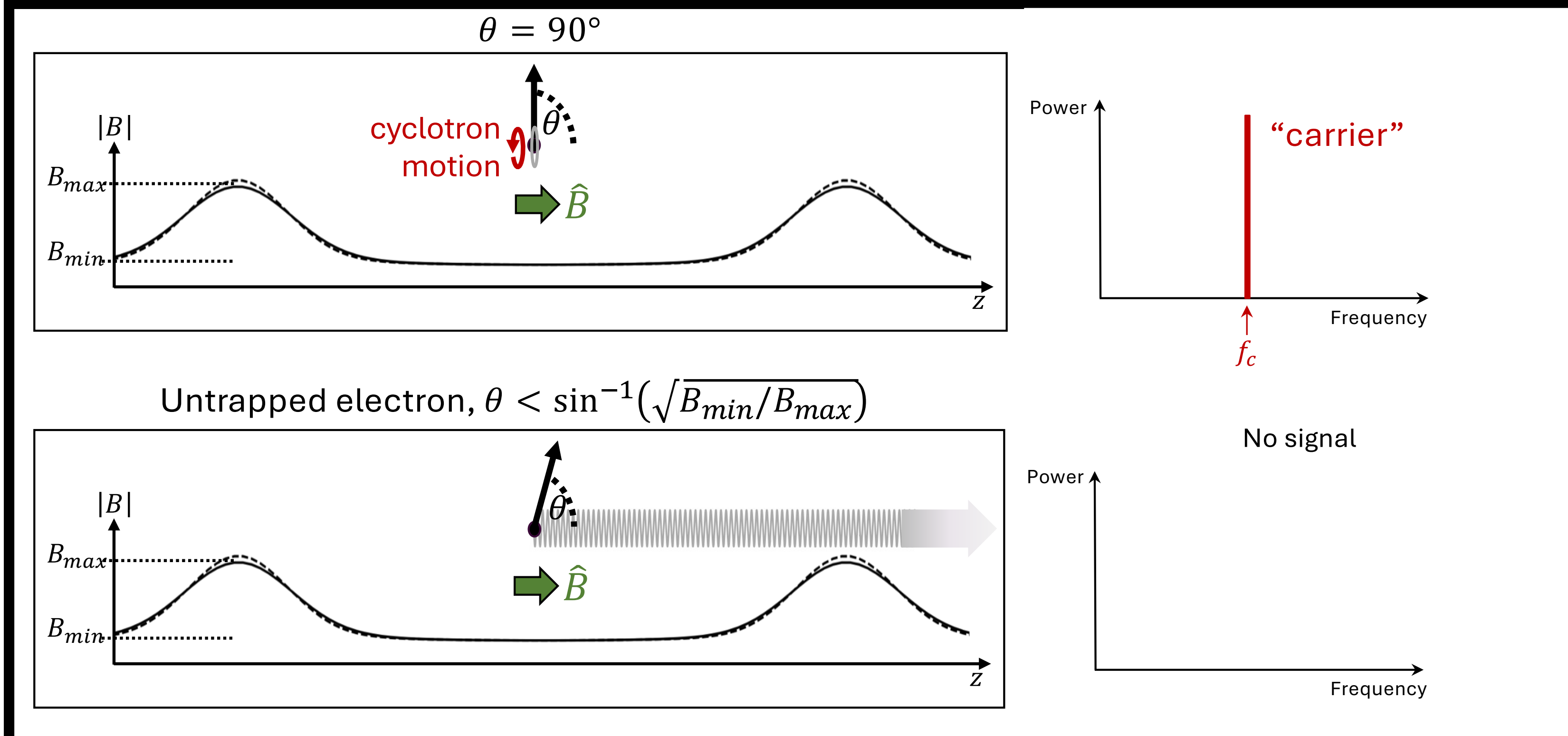

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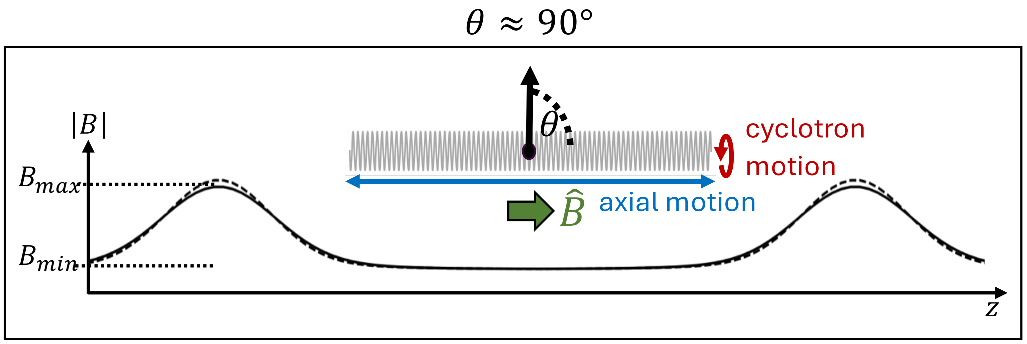

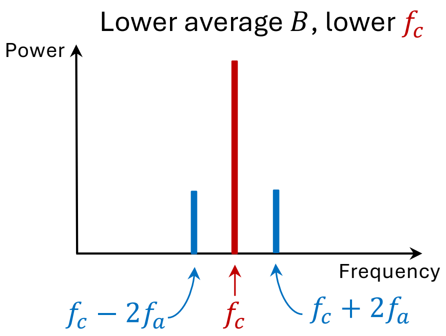

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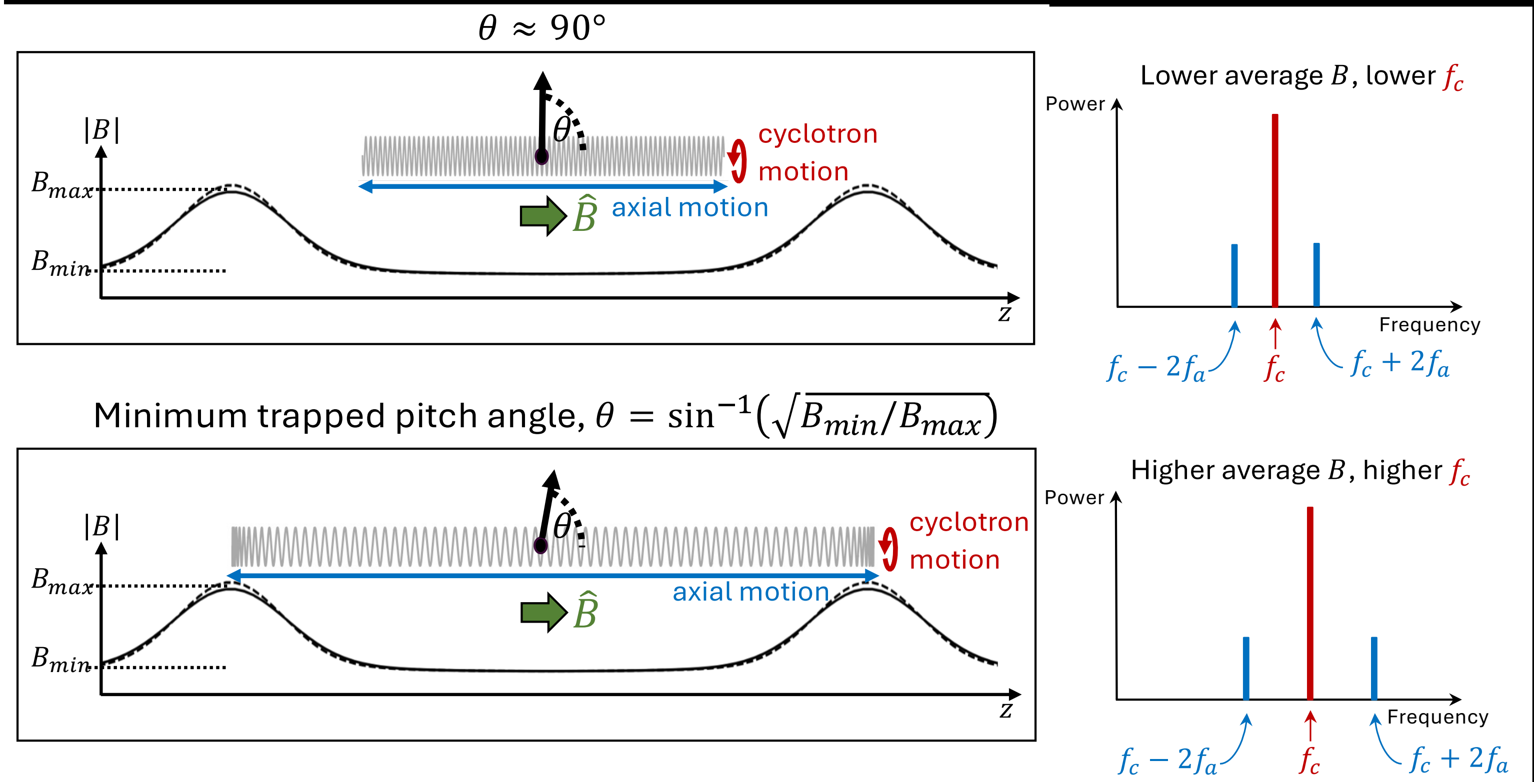

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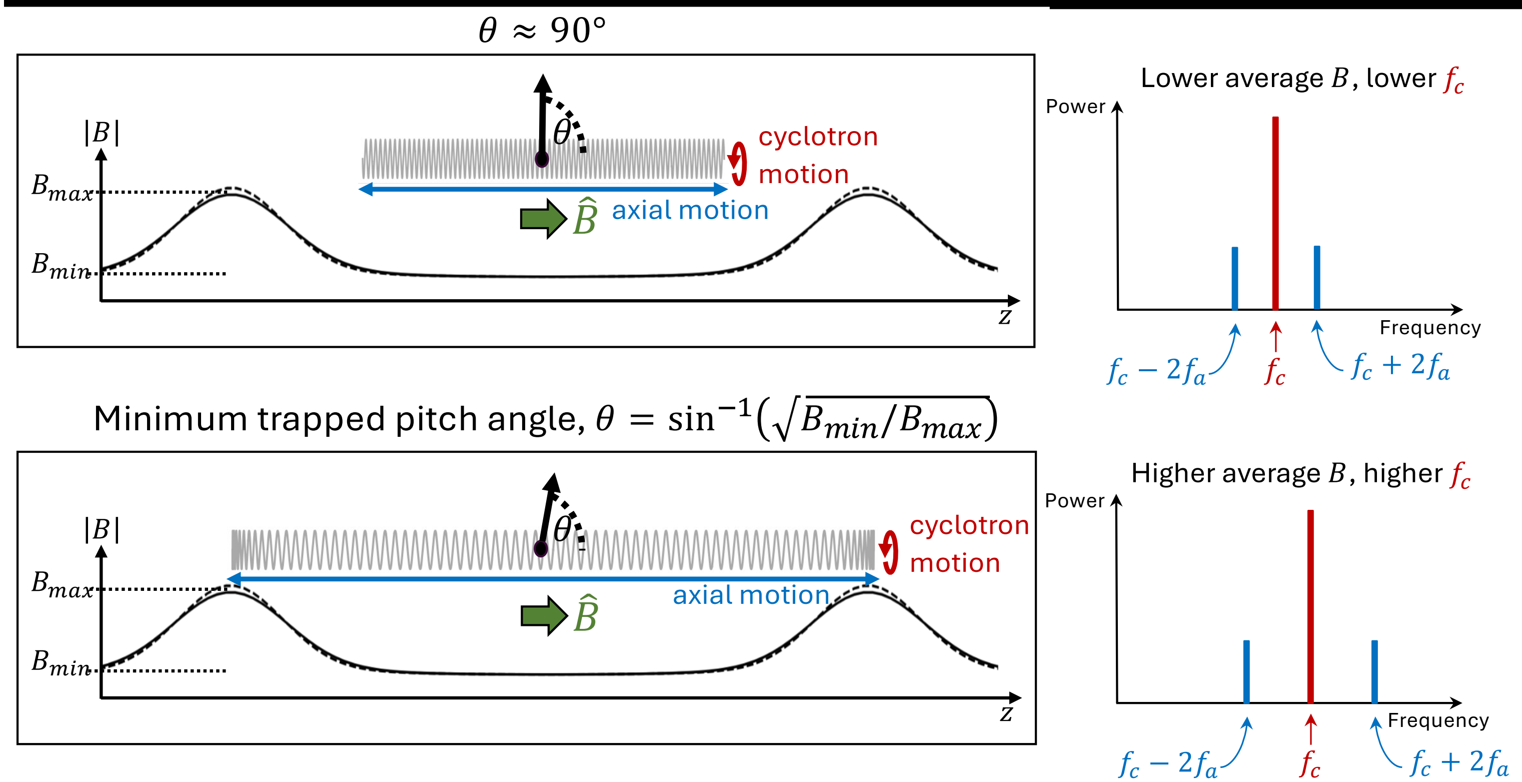

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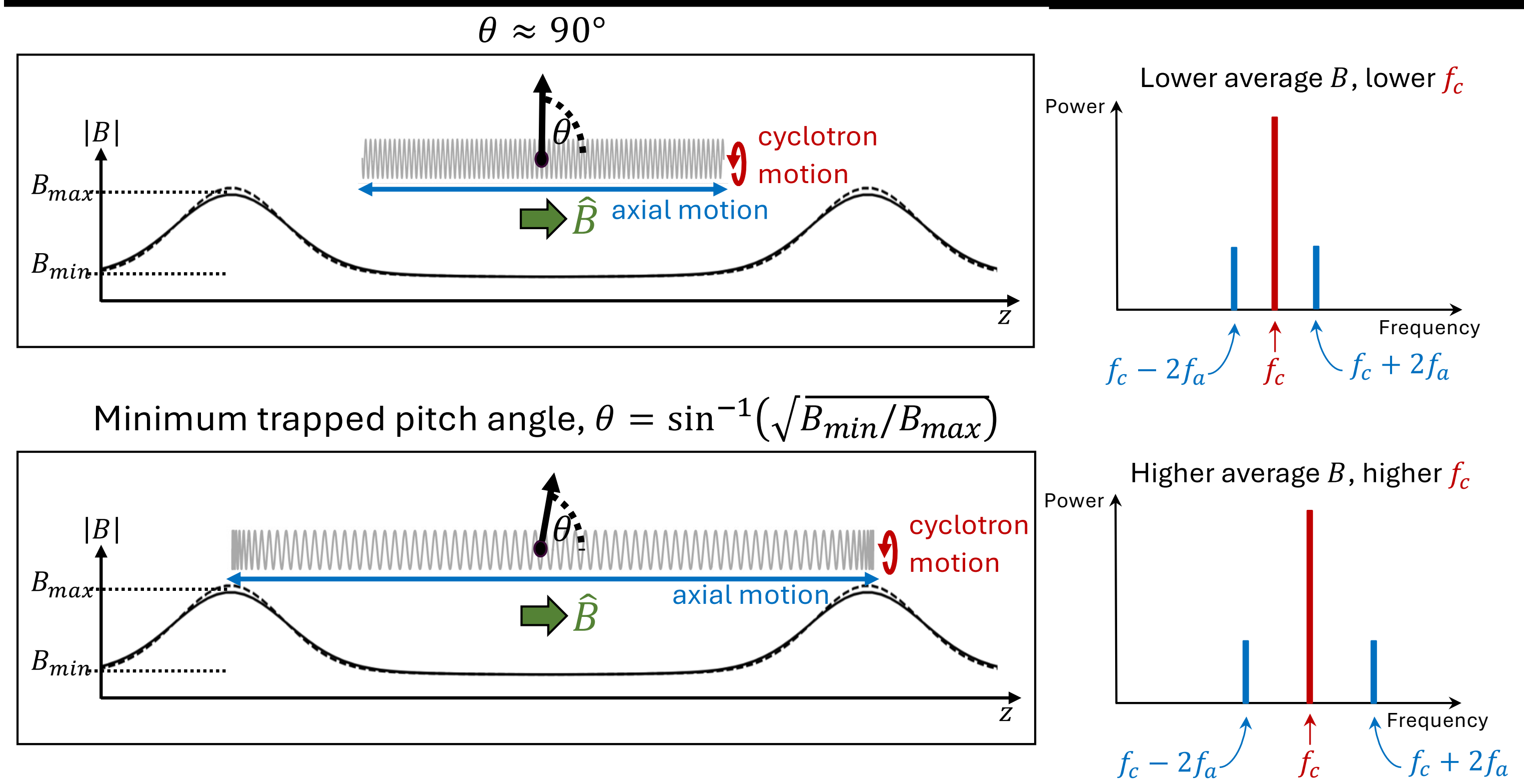

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Project 8 Phase II Apparatus

Located at CENPA at the University of Washington

Figures: A. Lindman, H. Harrington, A. Ashtari Esfahani, T. Wendler

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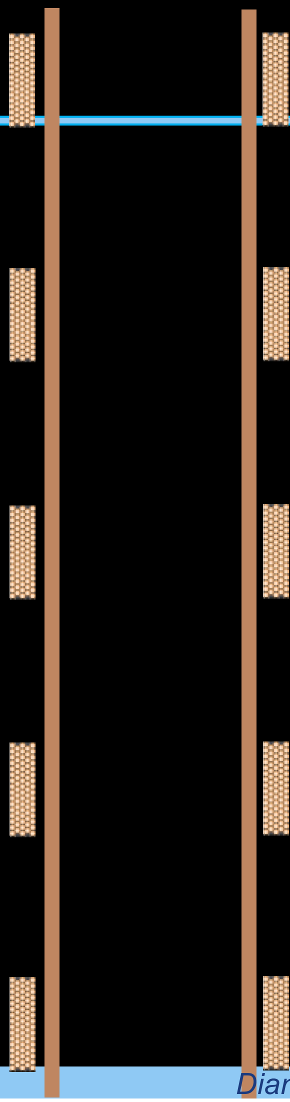

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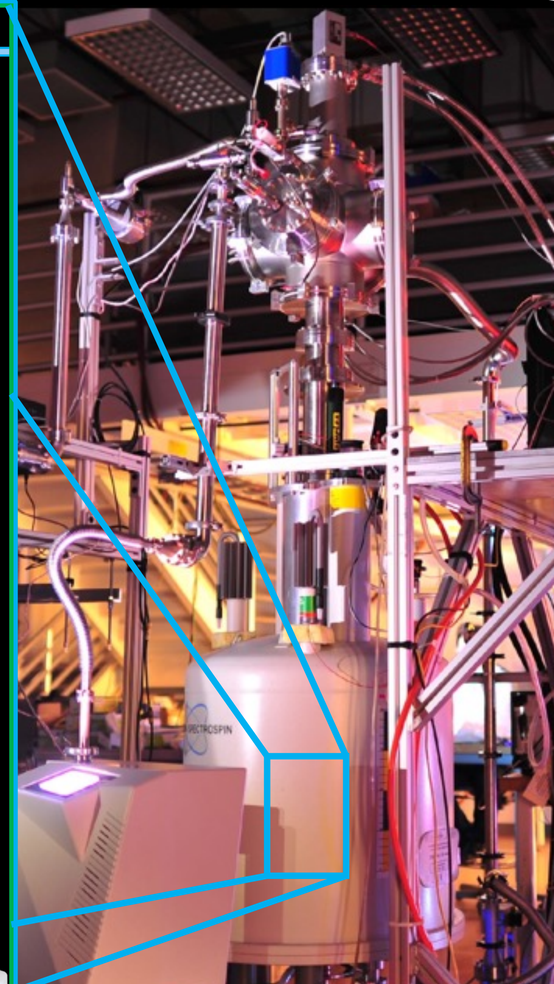

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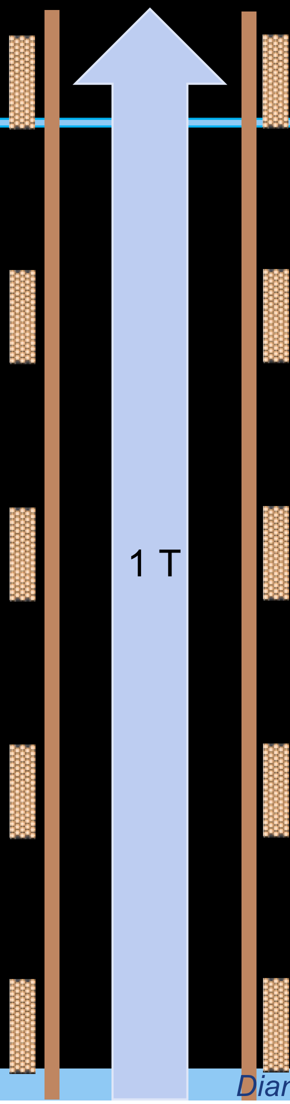

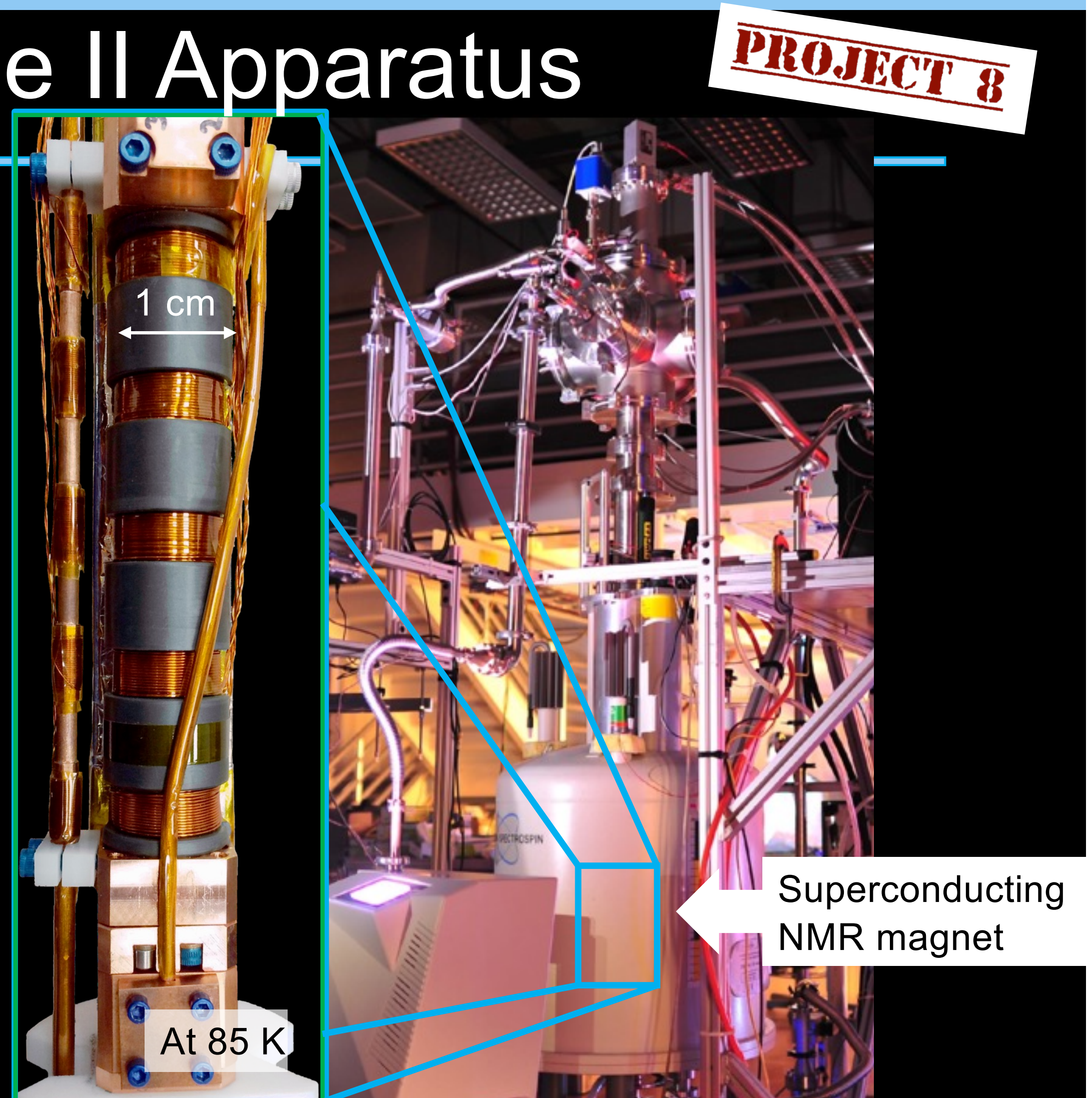

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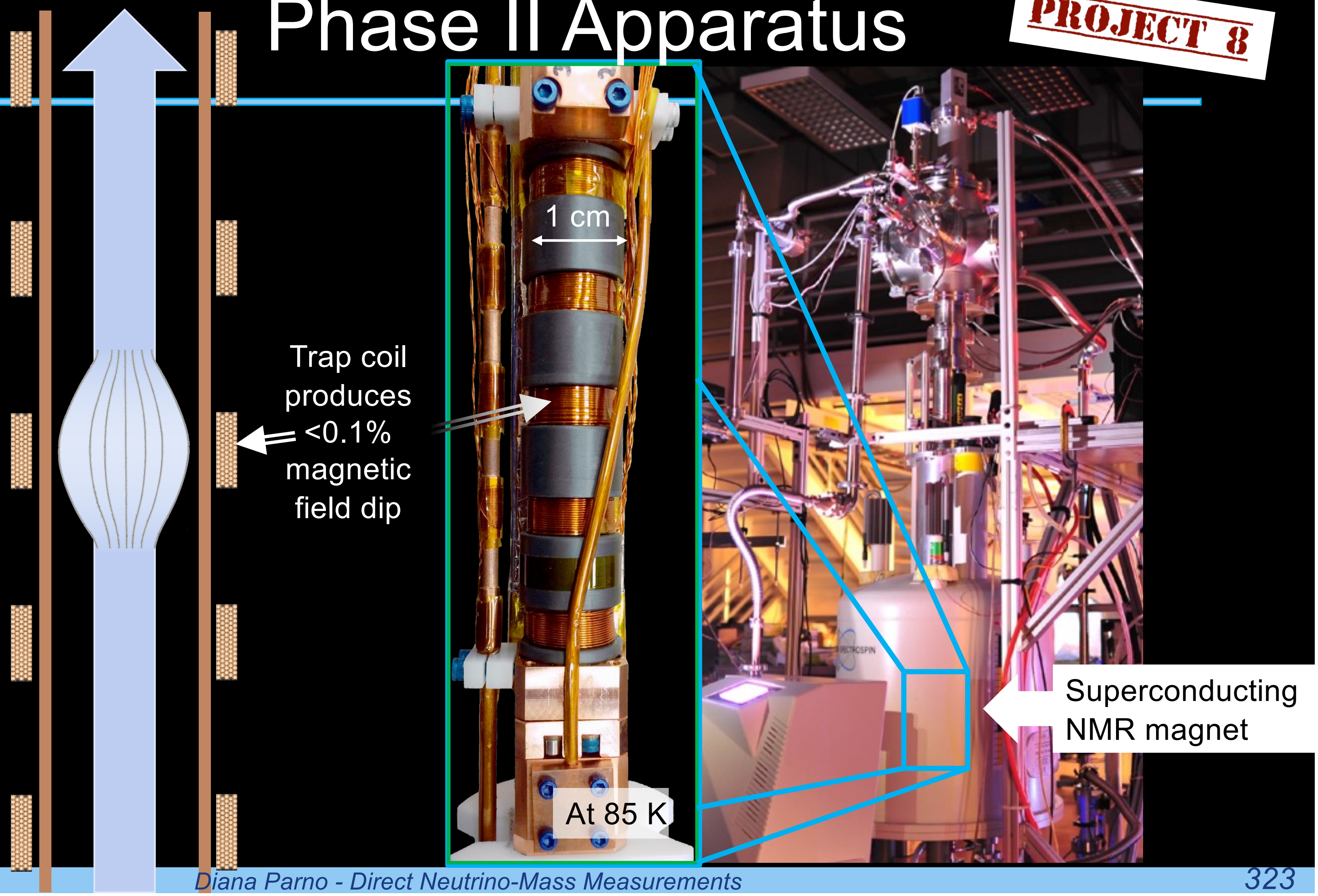
Project 8 Phase II Apparatus

PROJECT 8

Located at CENPA at the University of Washington



Figures: A. Lindman, H. Harrington, A. Ashtari Esfahani, T. Wendler

Slide: Elise Novitski

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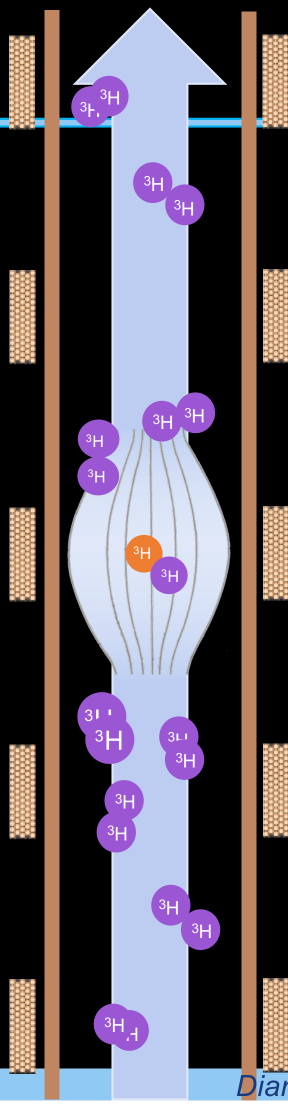

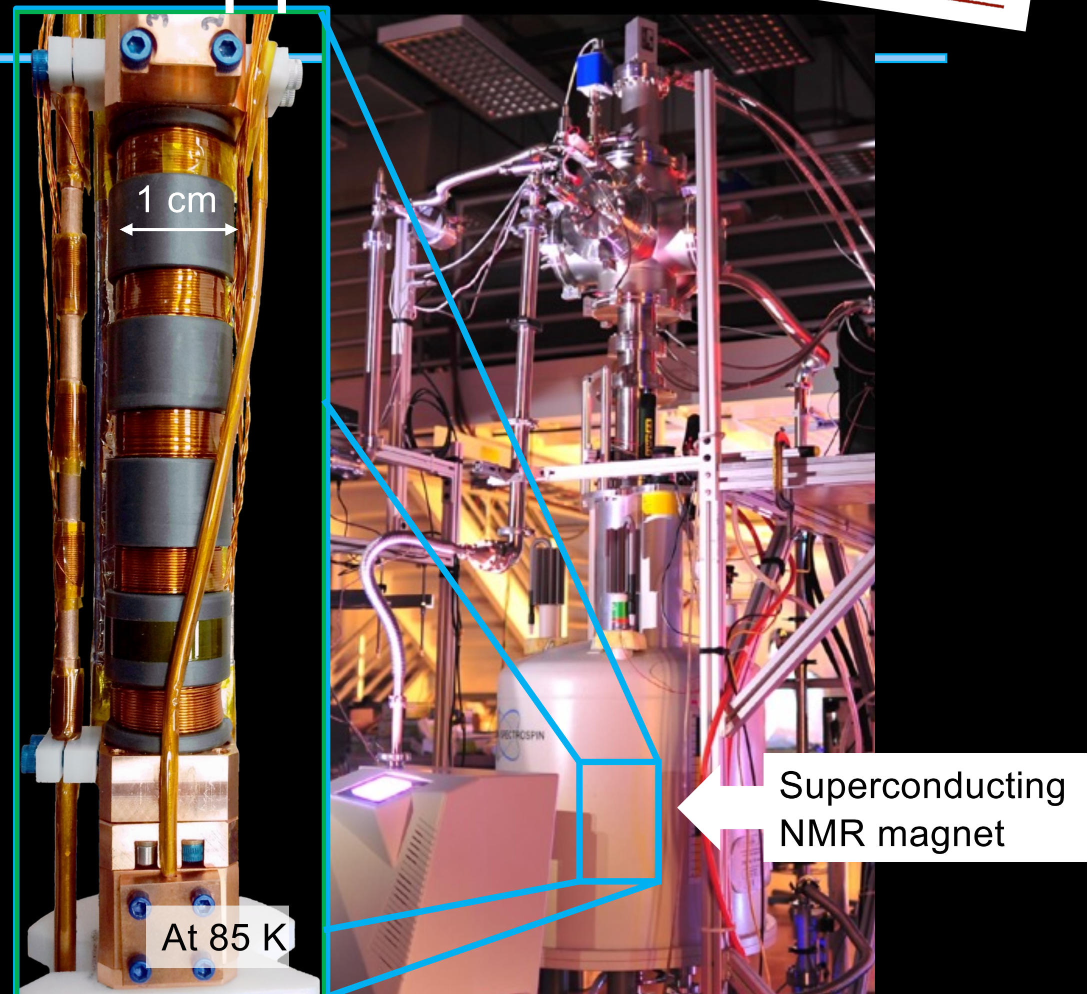

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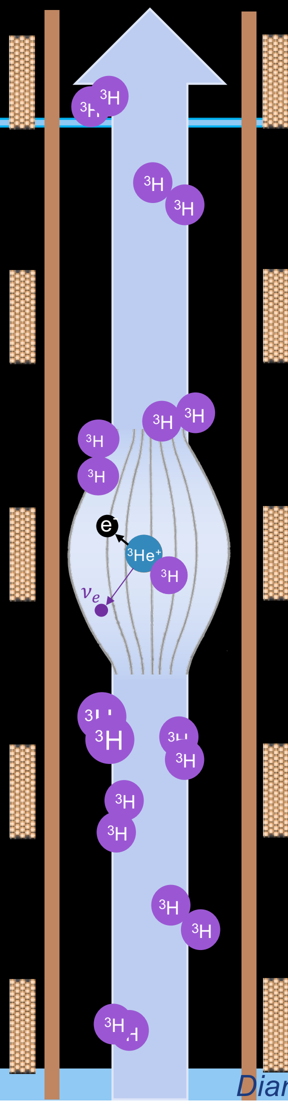

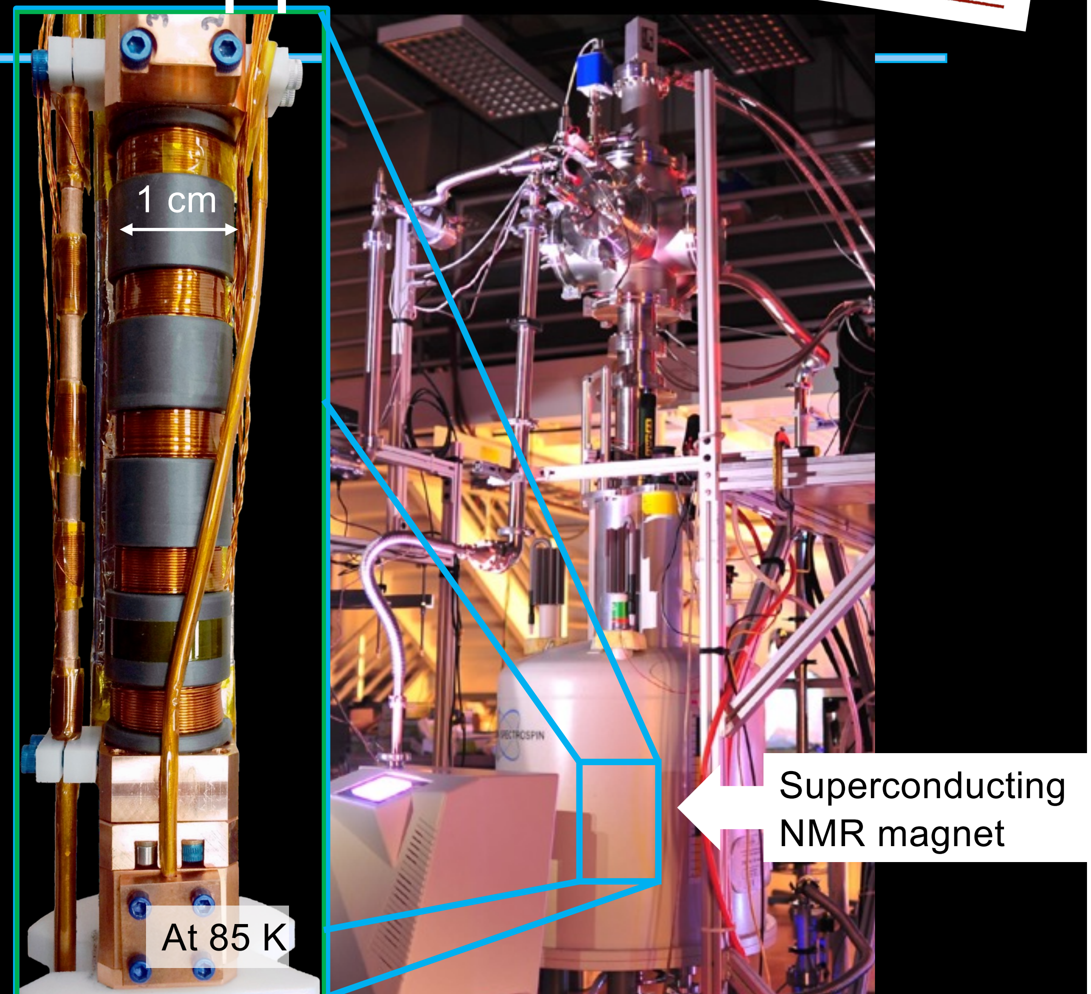

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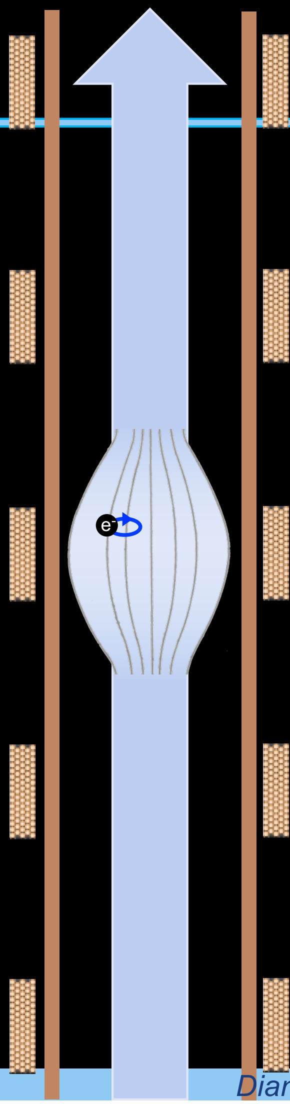

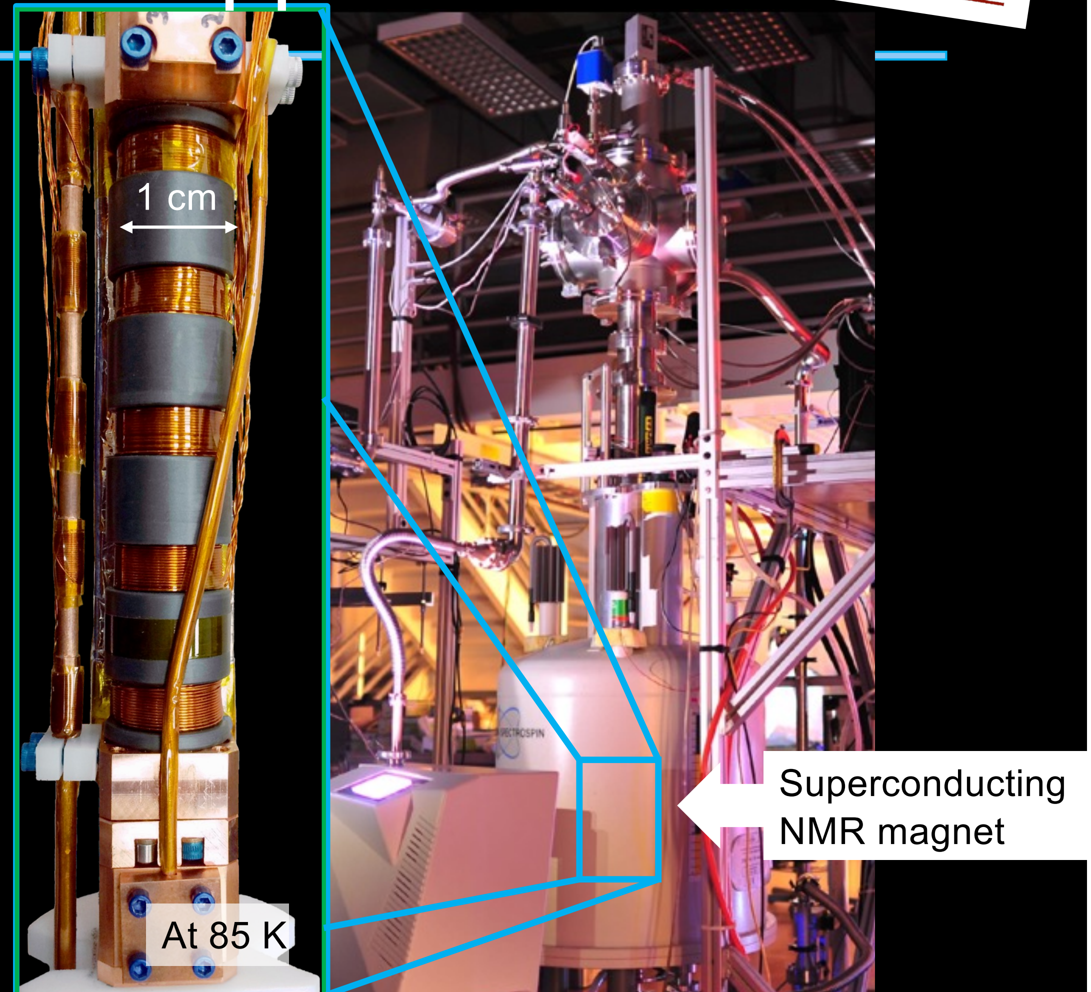

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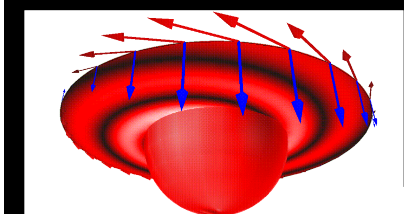

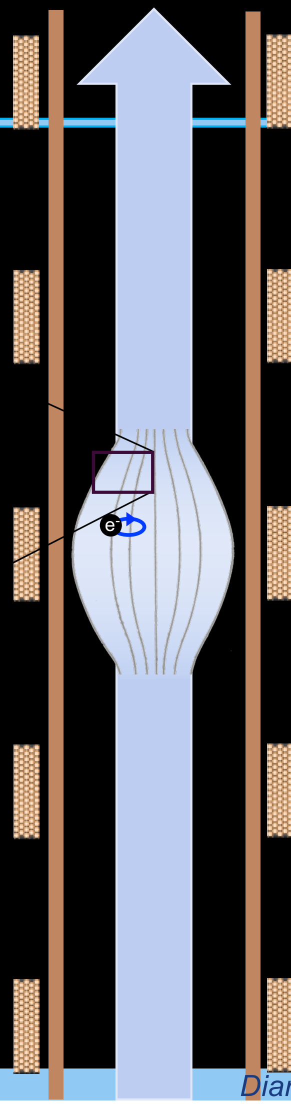

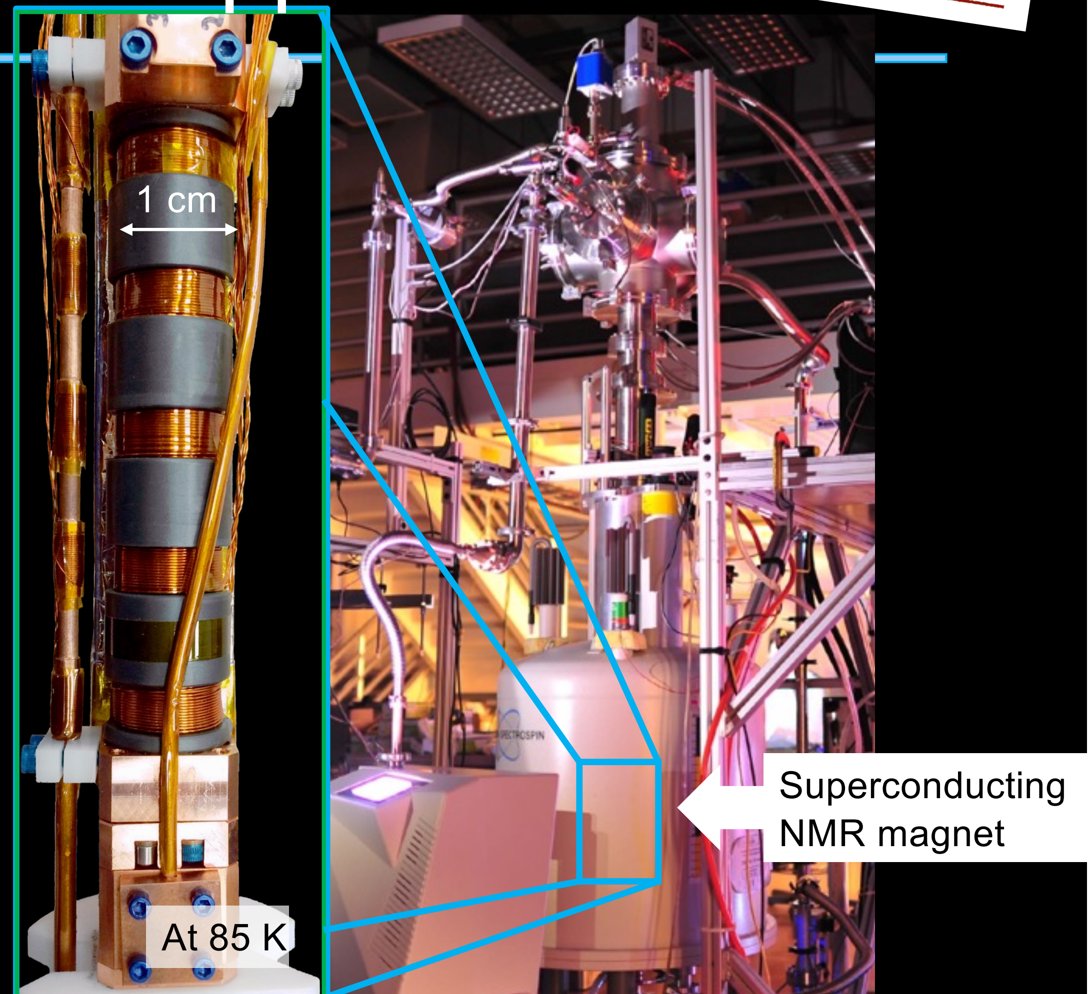

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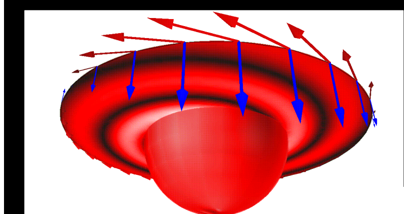

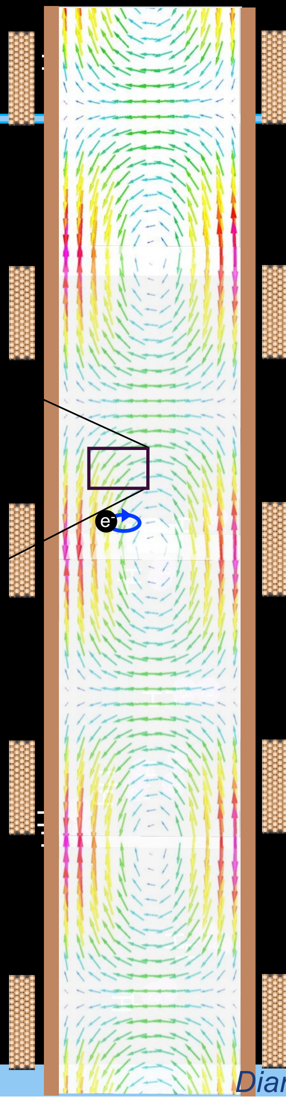

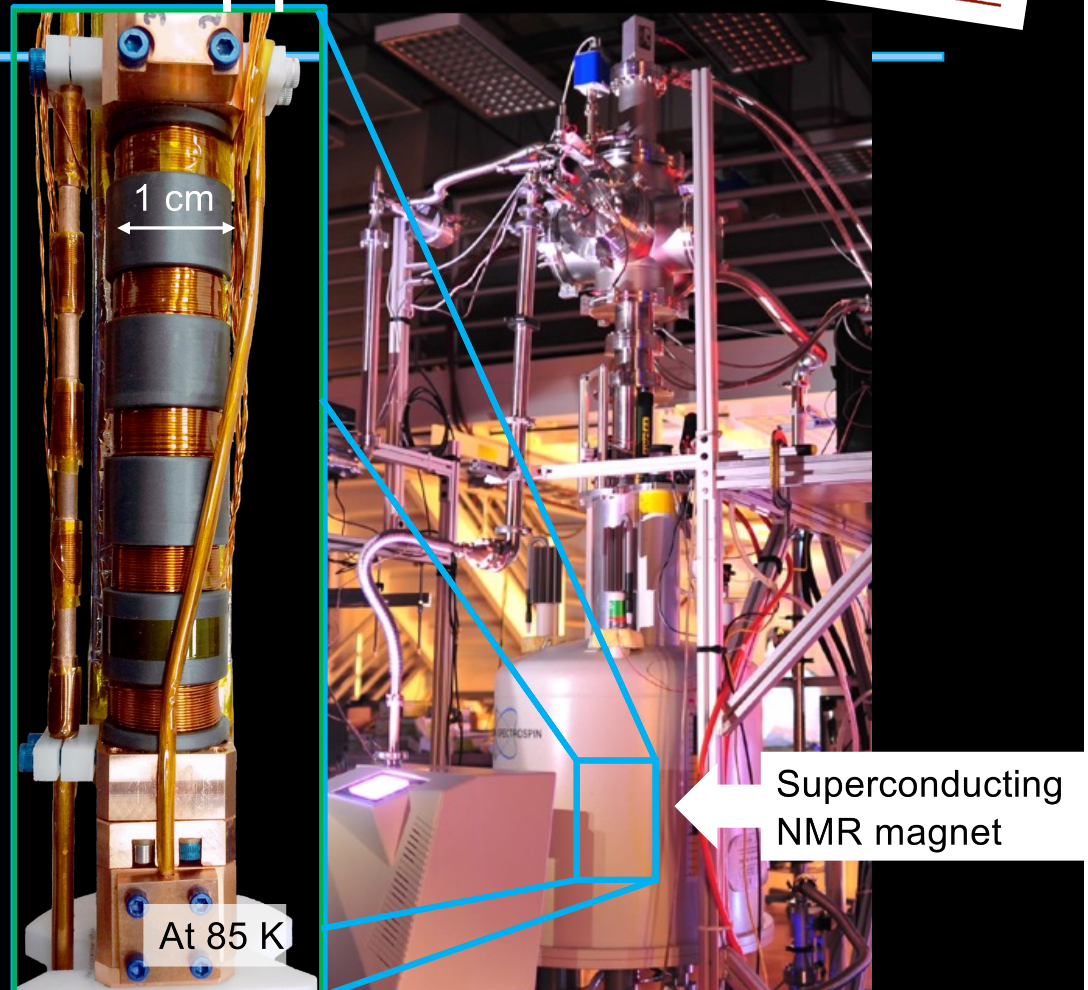

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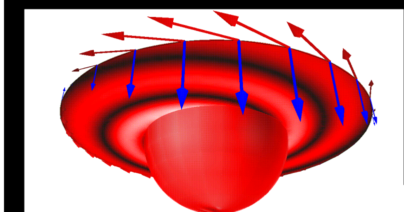

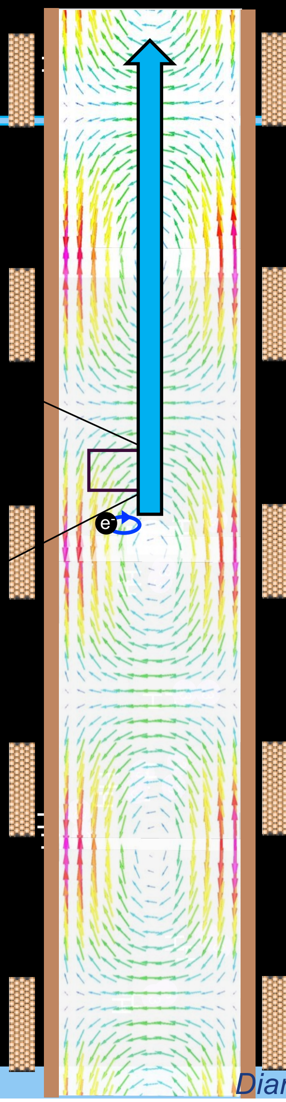

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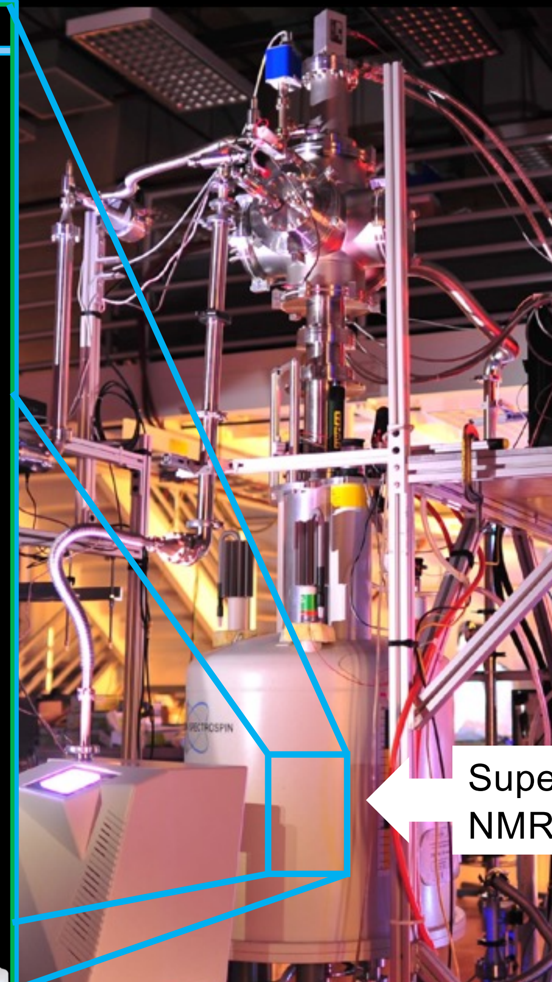

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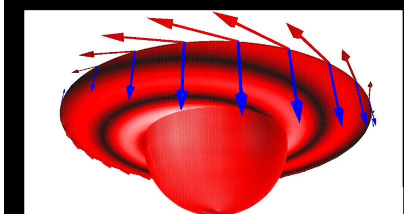

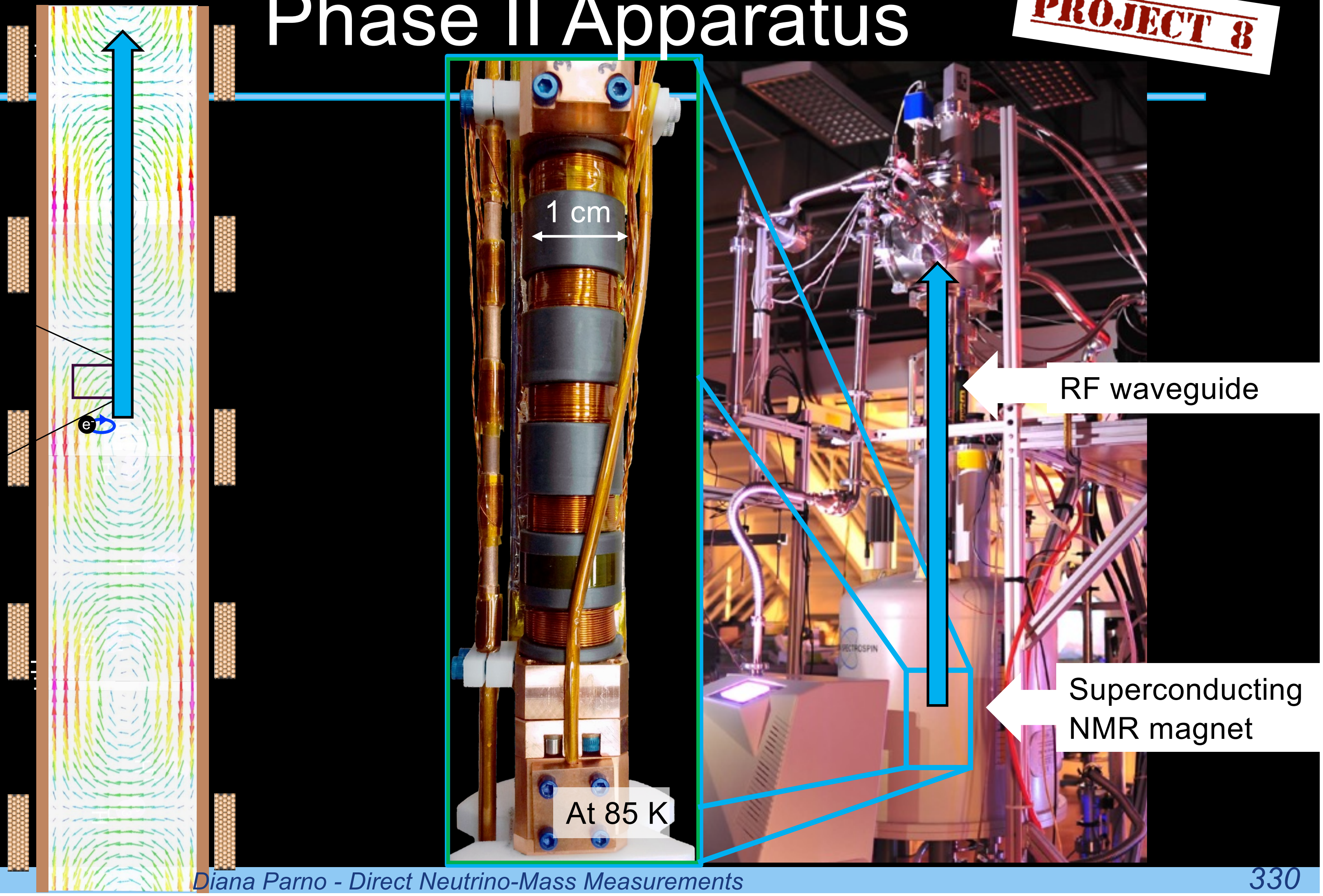

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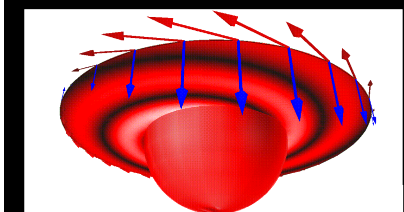

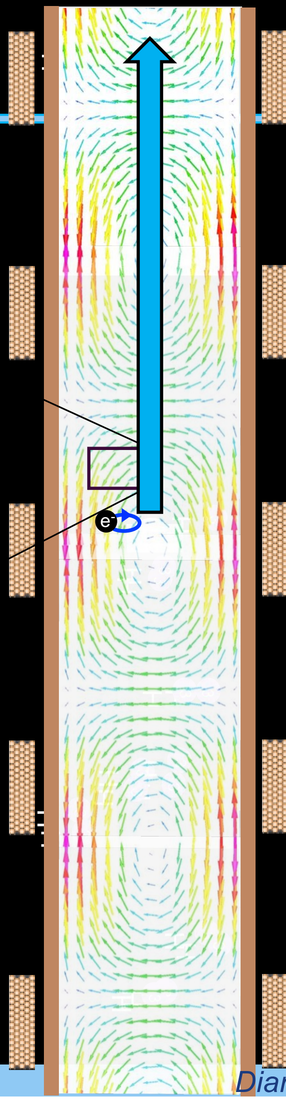

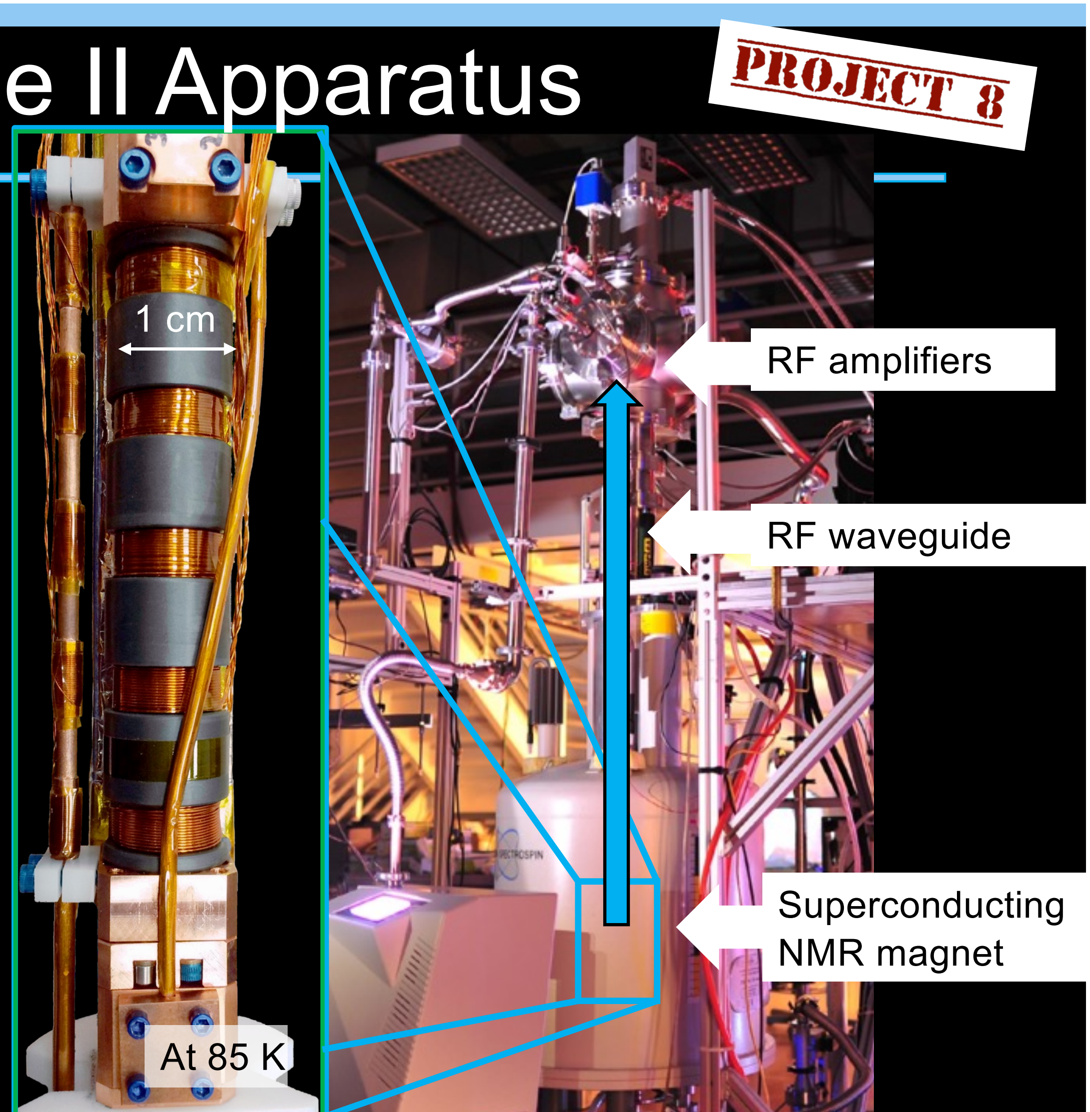

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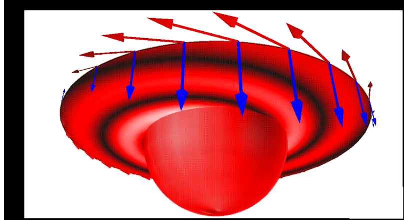
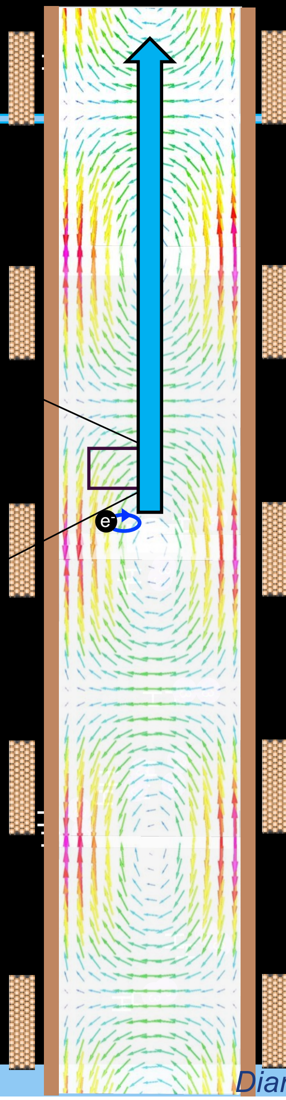
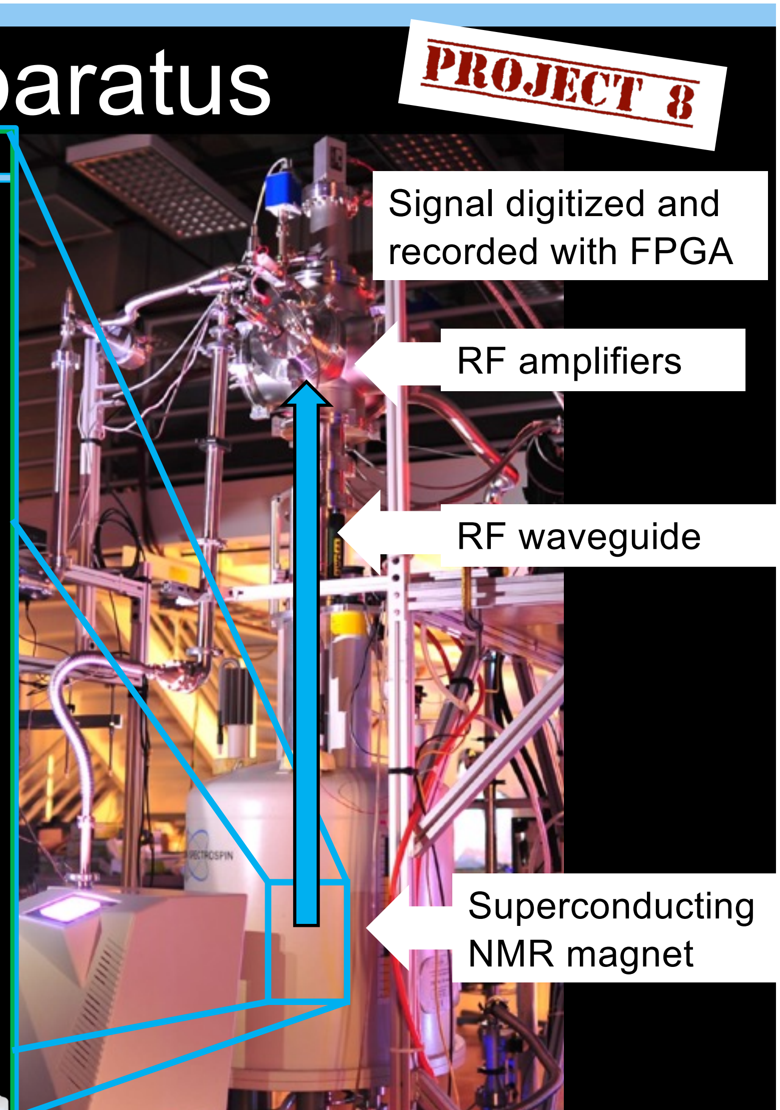




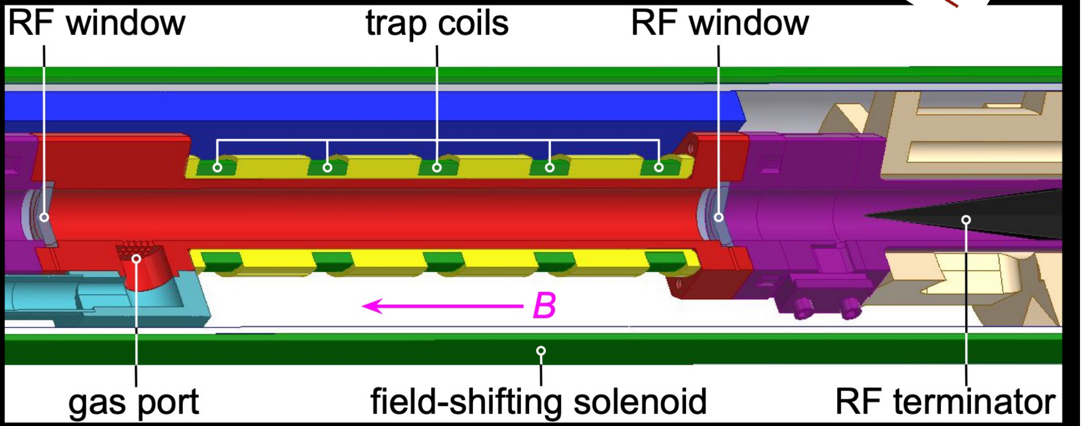


Figures: A. Lindman, H. Harrington, A. Ashtari Esfahani, T. Wendler

Slide: Elise Novitski

First CRES Neutrino-Mass Limit!

- T_2 gas in waveguide, ~1mm^3 volume
- Calibrate with gaseous ^{83m}Kr



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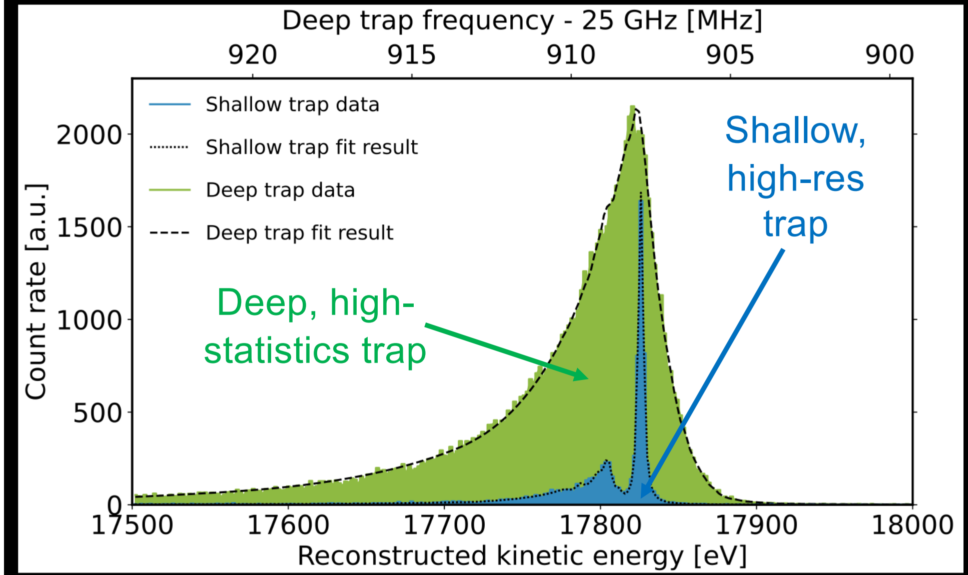
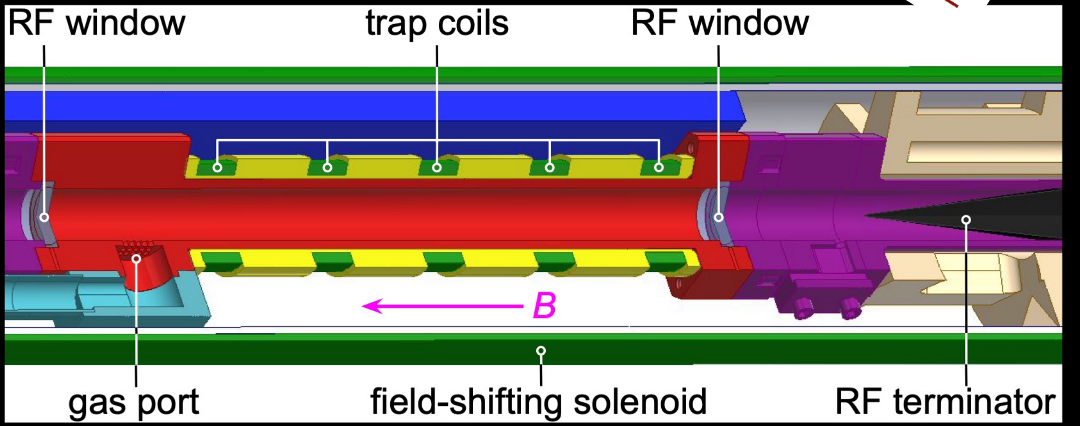


Calibration spectrum



*Project 8, PRL **131** (2023) 102502*

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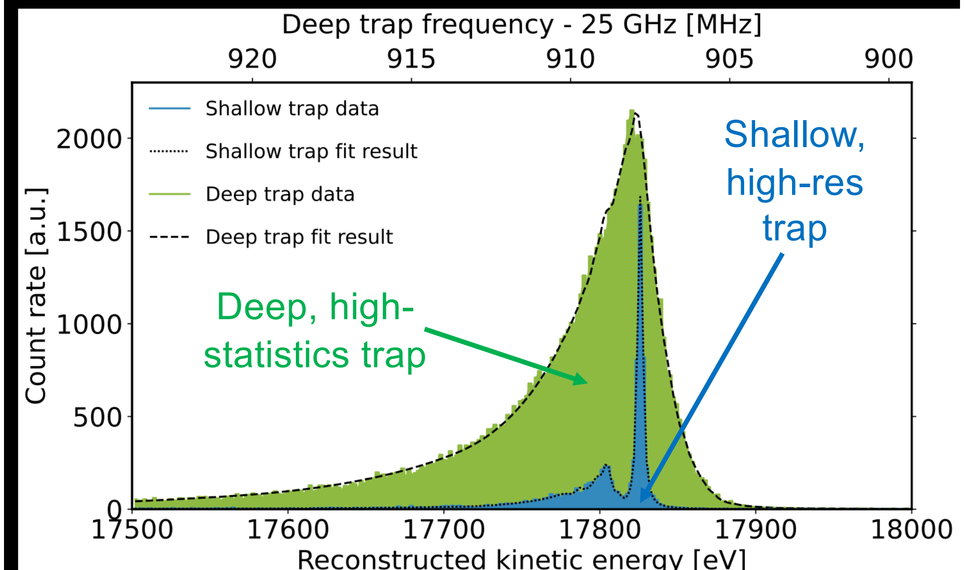
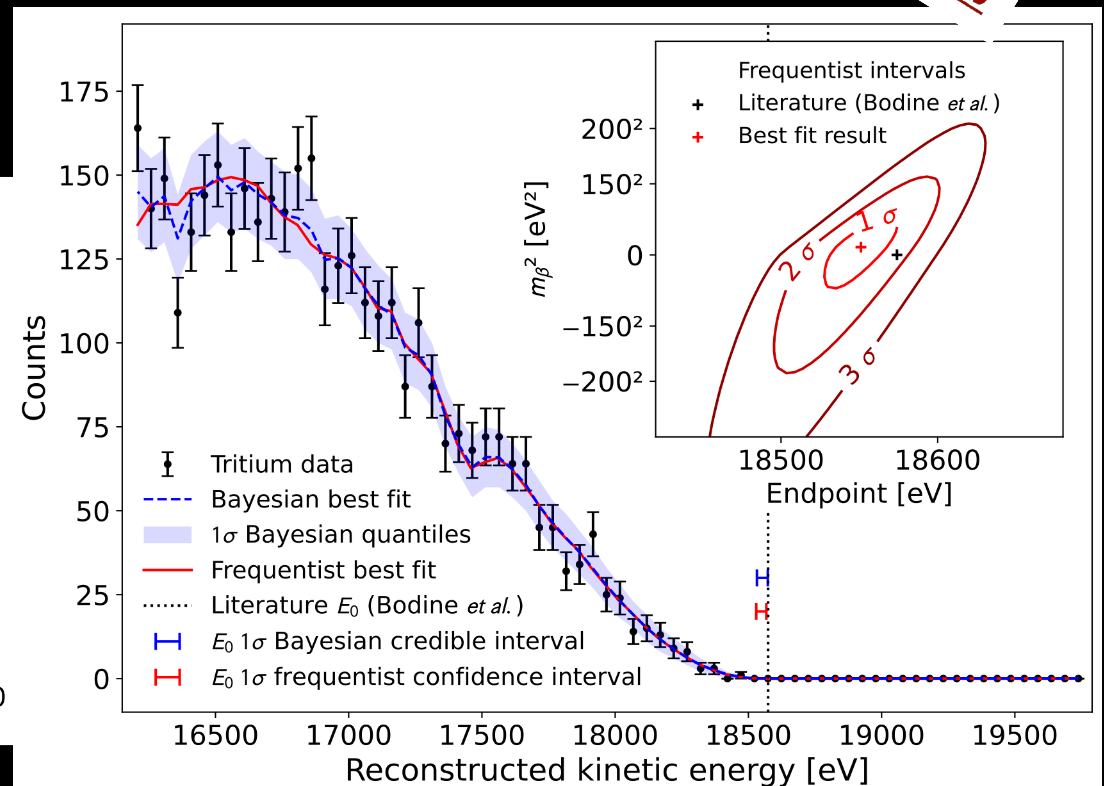


Calibration spectrum



Tritium spectrum

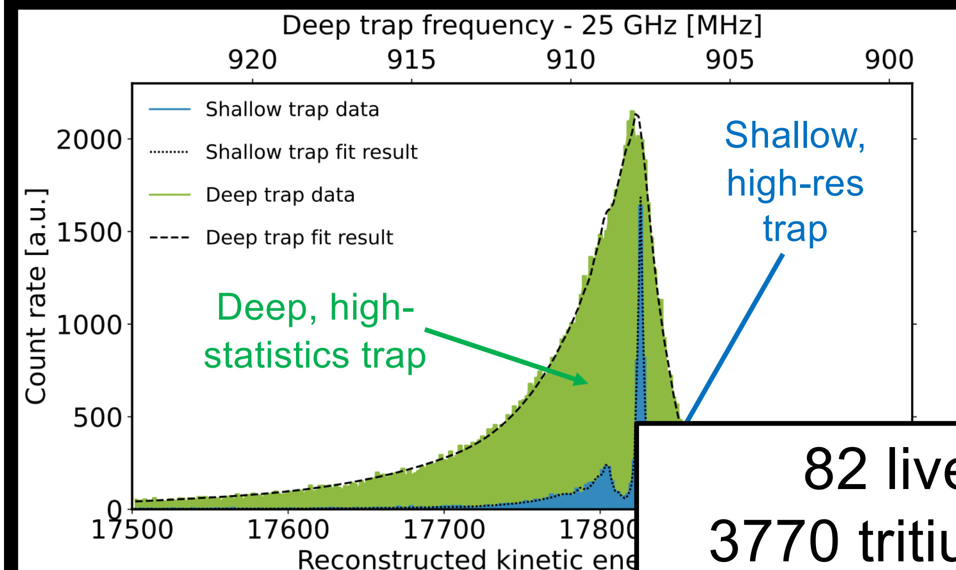
PROJECT 8

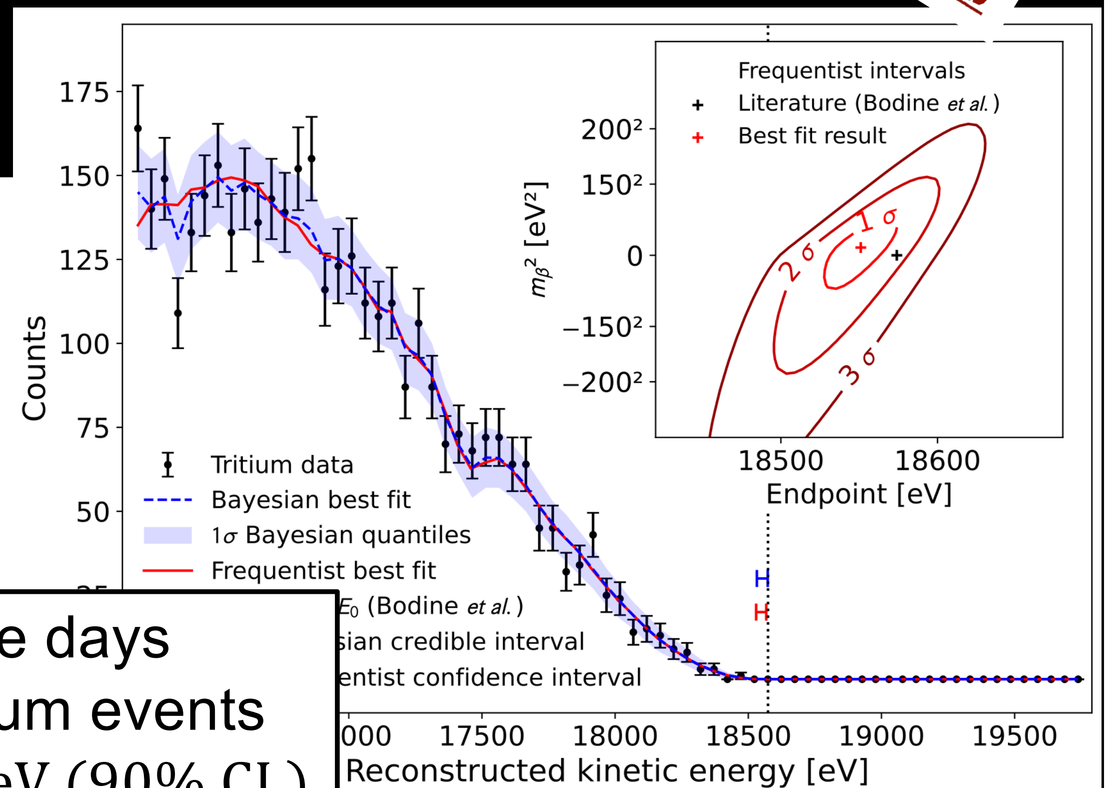
*Project 8, PRL **131** (2023) 102502*

First CRES Neutrino-Mass Limit!

PROJECT 8

- T_2 gas in waveguide, ~1cm^3 volume
- Calibrate with gaseous ^{83m}Kr





82 live days

3770 tritium events

$m_\nu < 180$ eV (90% CL)

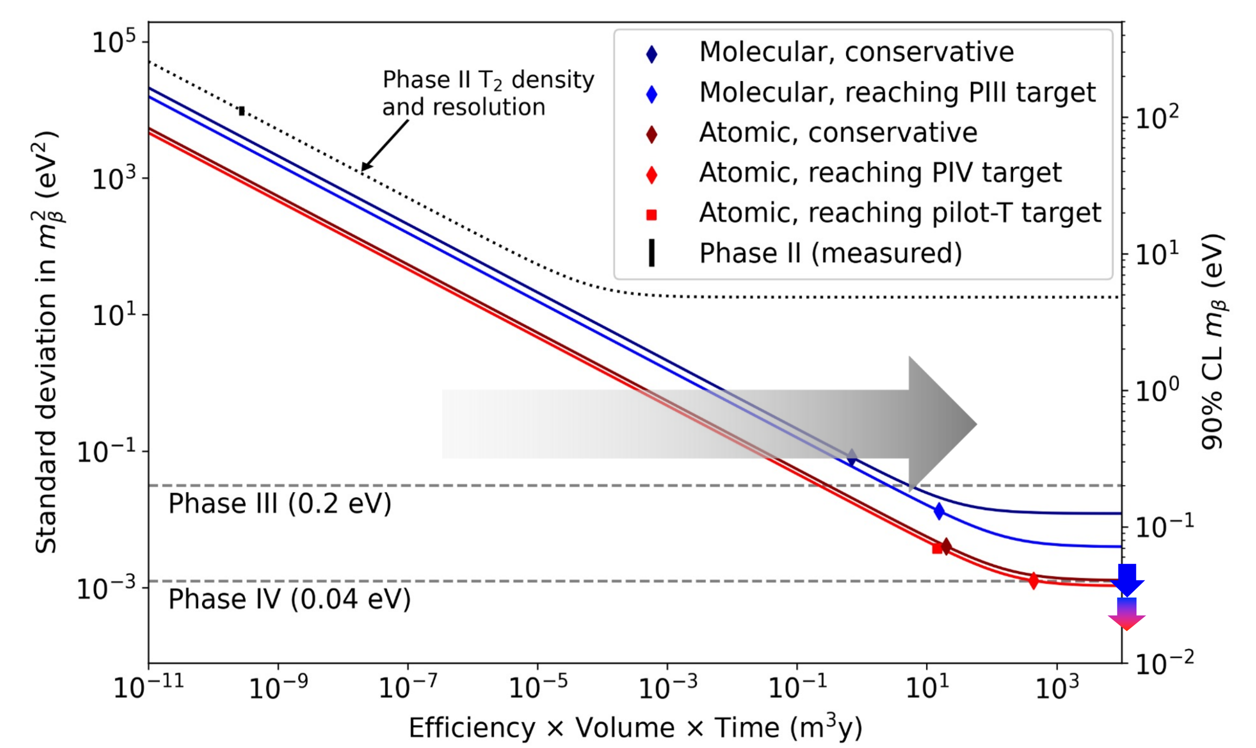
Tritium spectrum

Project 8, PRL ***131*** *(2023) 102502*

The Plan

- Accessing the neutrino-mass scale
- How to search for m_ν directly
- Nitty, gritty systematics
- Microcalorimetry basics (^{163}Ho)
- HOLMES
- ECHo
- Beta-spectroscopy basics (^{3}H)
- Project 8
- KATRIN
- **Next-generation tritium R&D**
- Sterile neutrinos and bonus physics
- Alternate measurement ideas

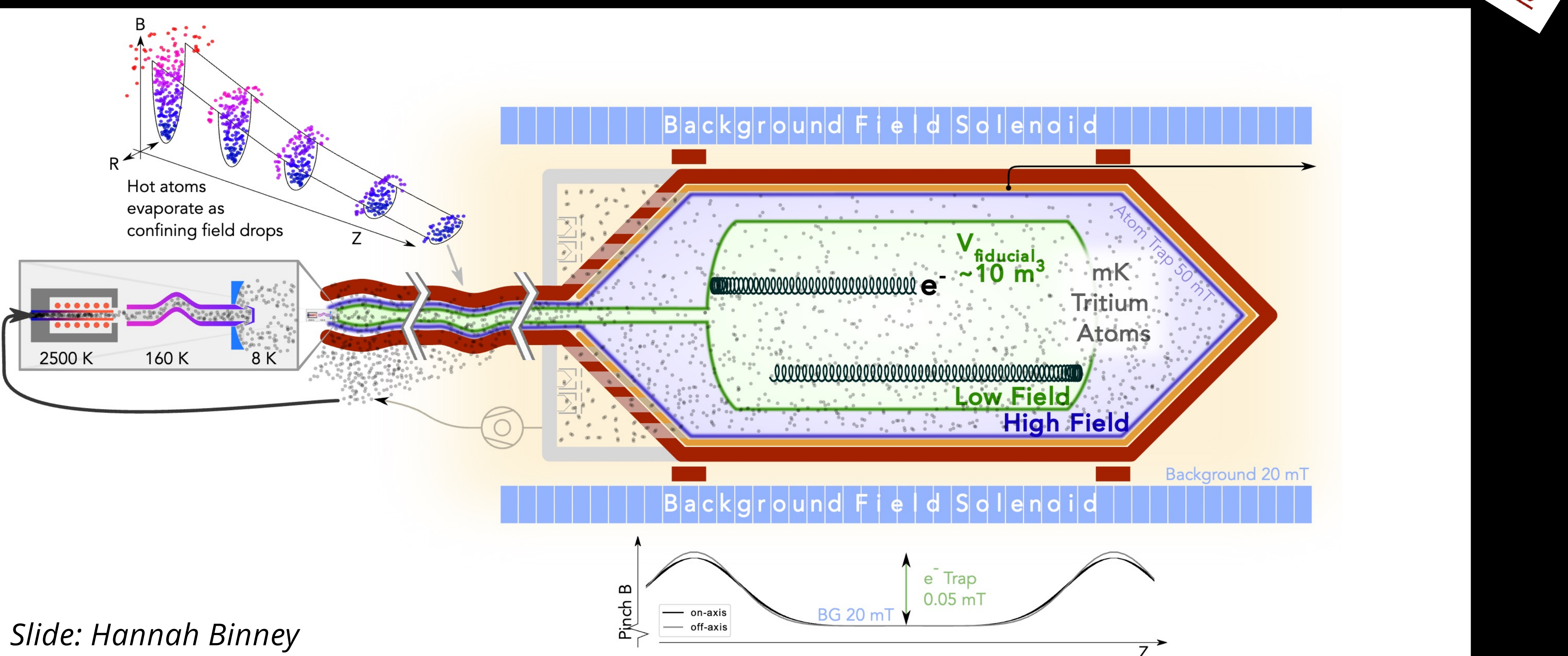
Project 8's Path to 40-meV Sensitivity



- Increase event rate
  - Larger volume
  - Higher efficiency
- Improve resolution, control of systematics, field homogeneity, scattering effects
- Develop atomic tritium source
  - Overcome systematic of molecular final states

Slide: Elise Novitski

The Project 8 Dream



Slide: Hannah Binney
Images: Alec Lindman

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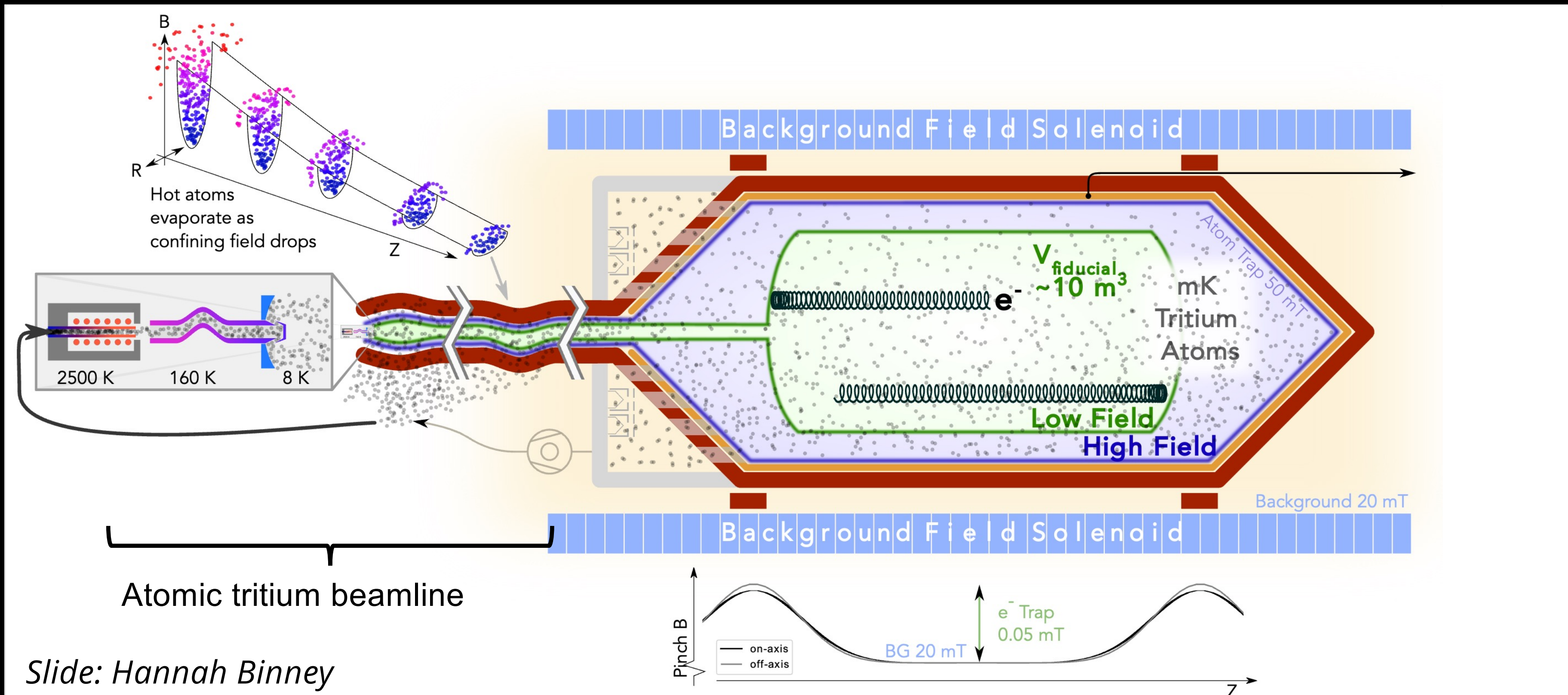

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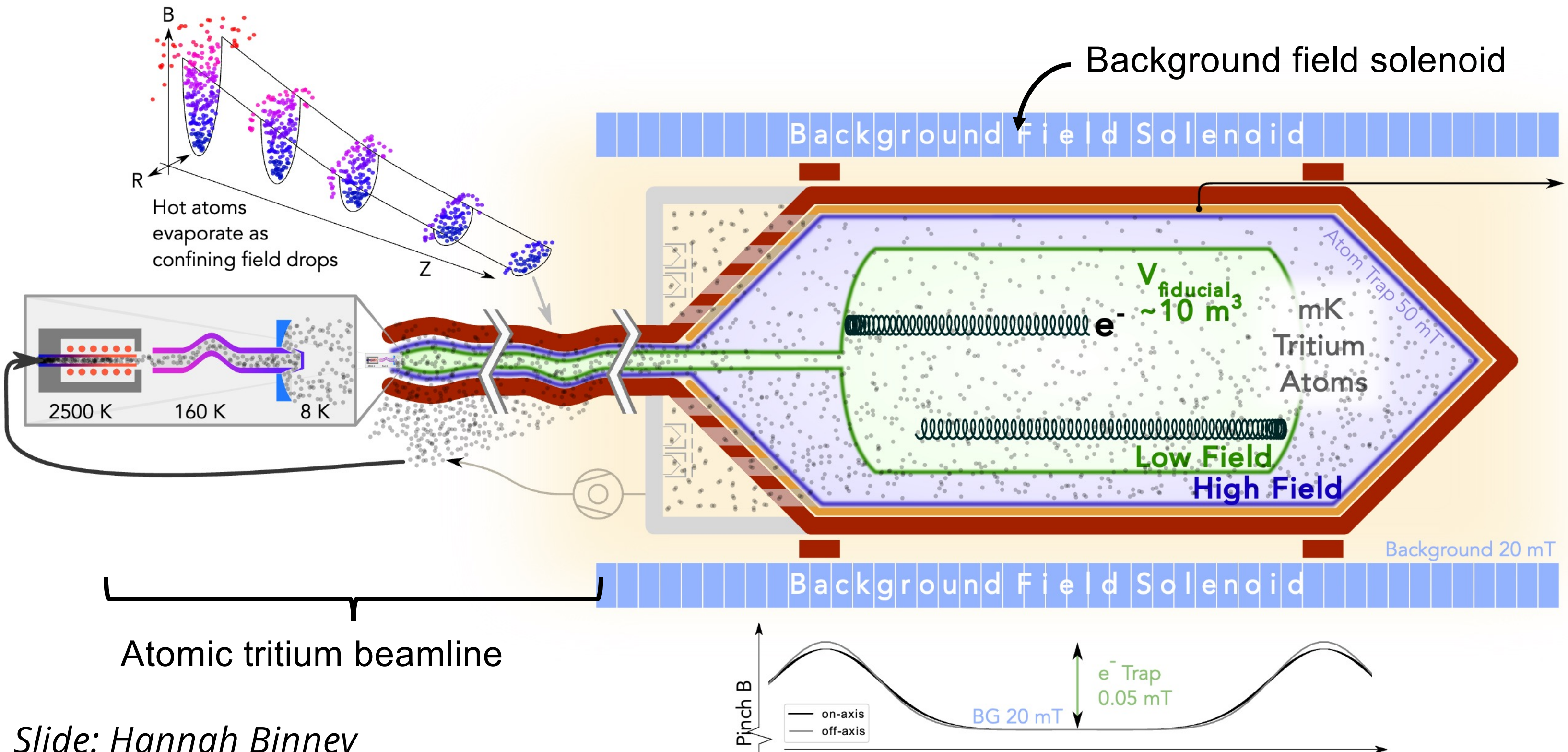

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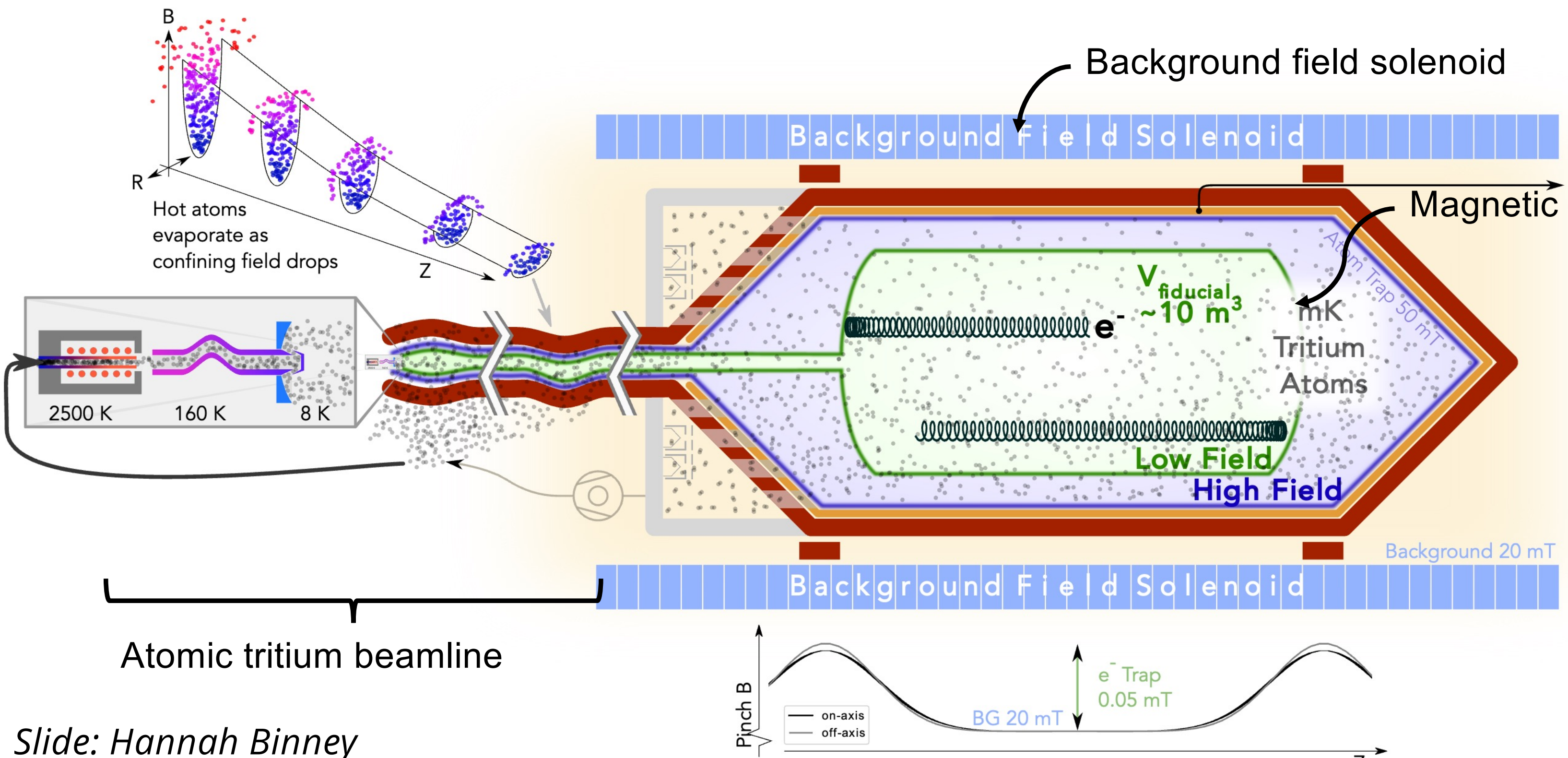

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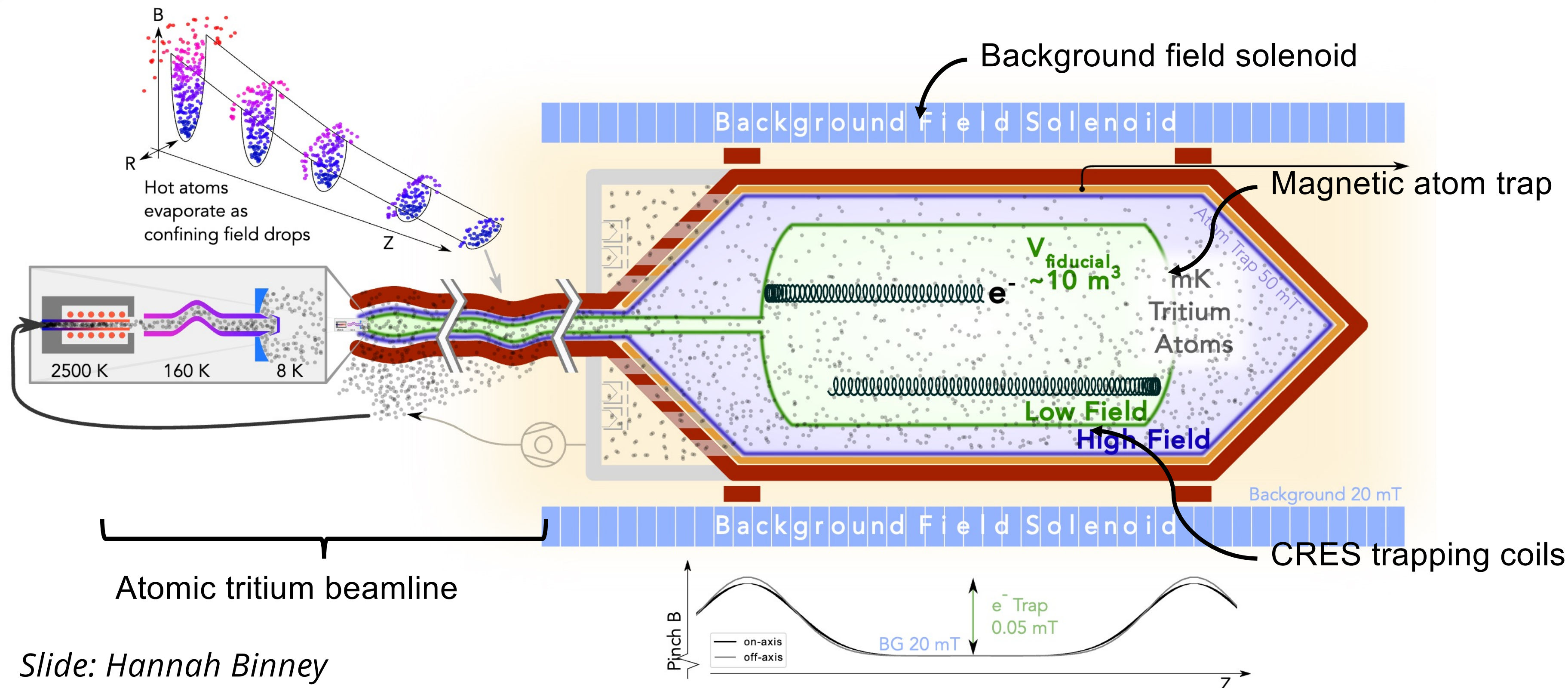

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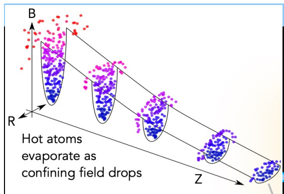
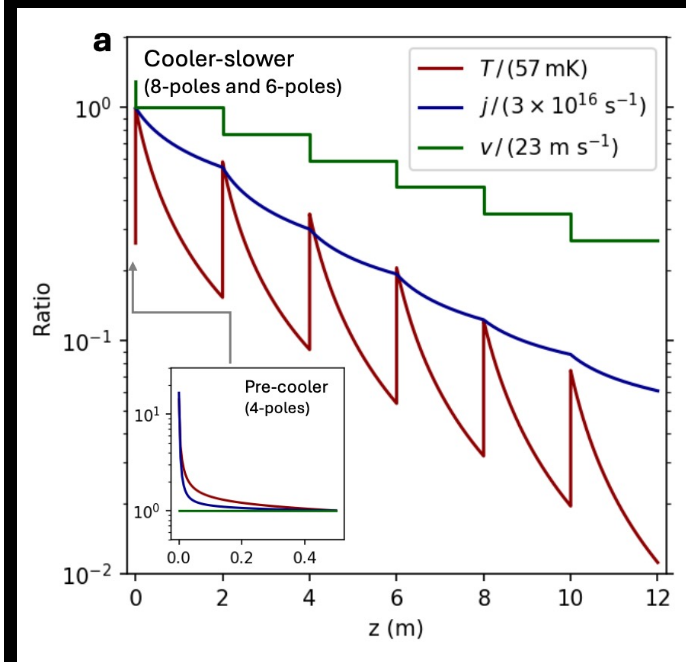


Atomic Tritium Highlight: Hot to Cold

- Atom beam must be both cooled and slowed to trap low-field-seeking states

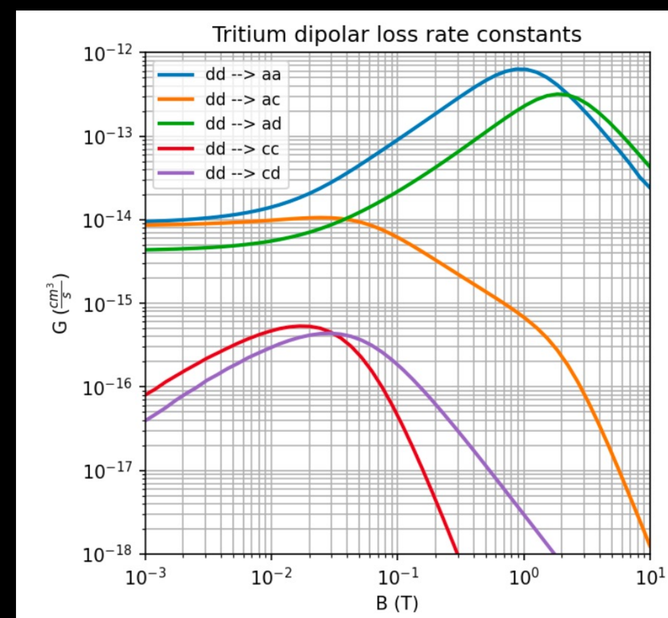


Project 8, PRA ***112*** *(2025) 033311*

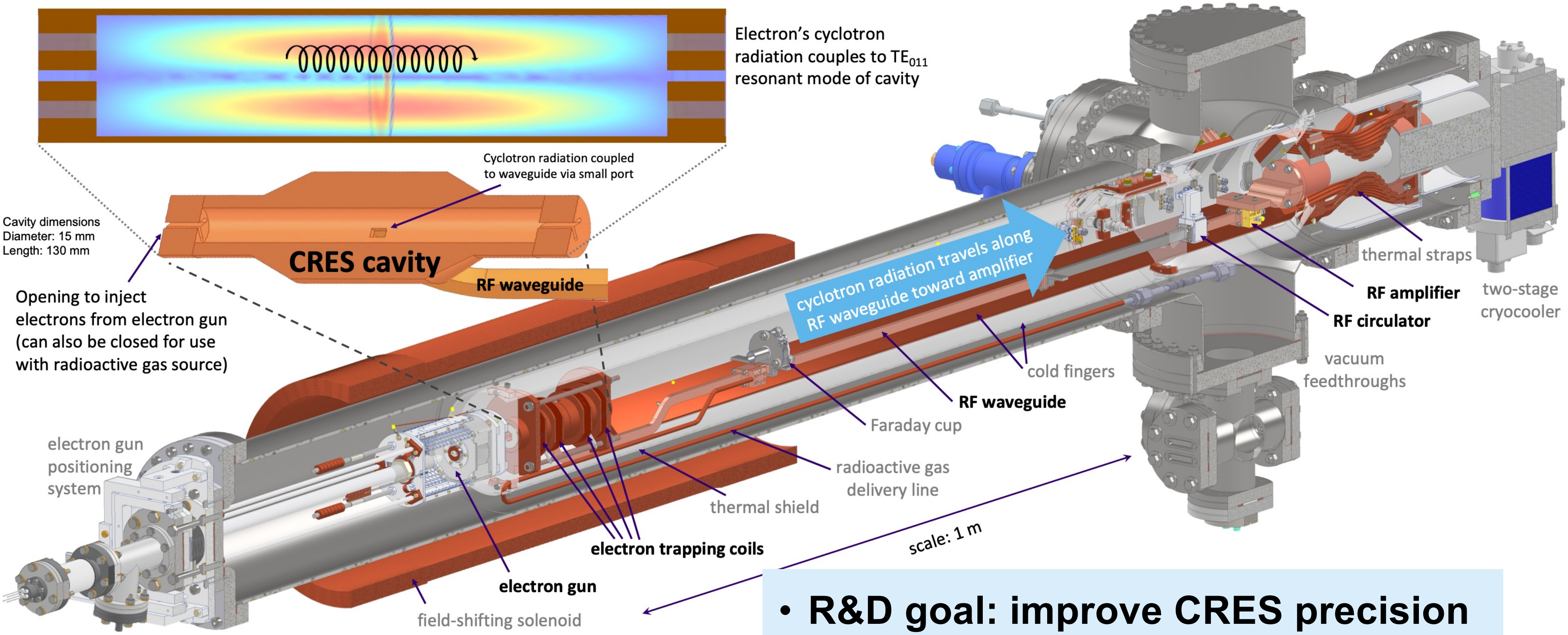
- Magnetic Evaporative Cooling Beamline facilitated by enhanced elastic T-T scattering at low temperature
- But enhanced inelastic cross section makes T atoms harder to trap

Elliott and Jones, PRA ***112*** *(2025) 062818*

PROJECT 8



Cavity CRES Apparatus (CCA)

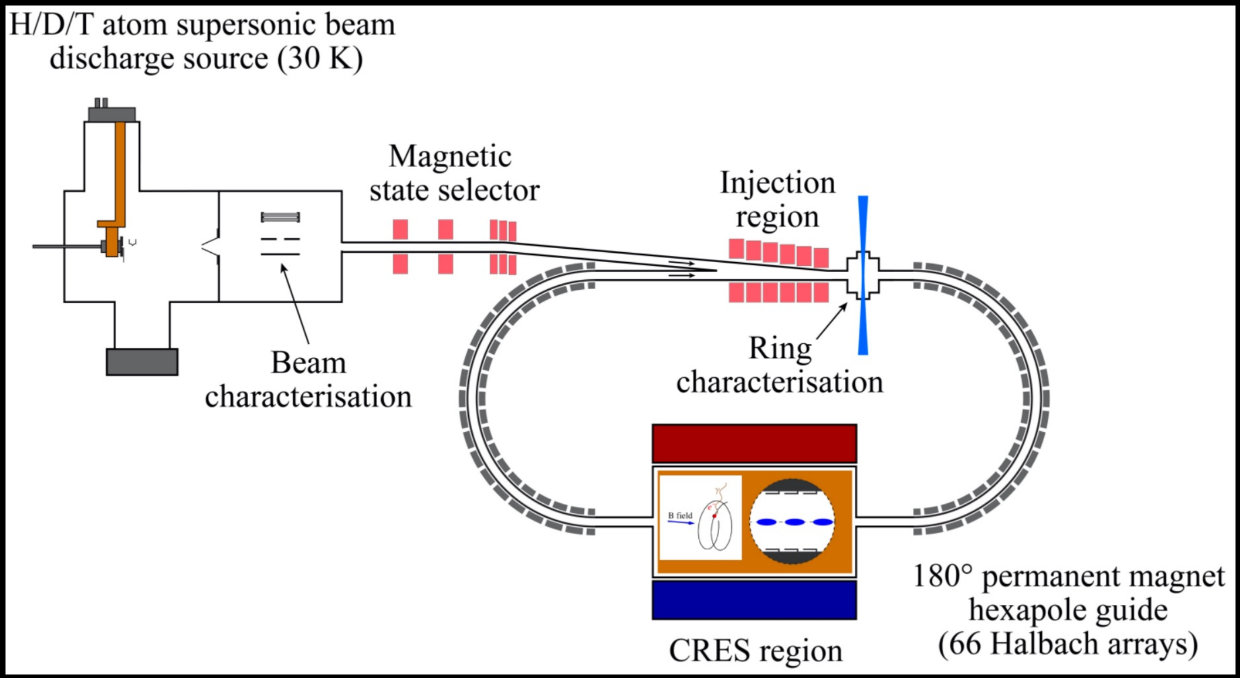


- **R&D goal: improve CRES precision**
- **Science goal: do ultra-precise spectroscopy of ^{83m}Kr**

Slide: Elise Novitski

Another Way to Do CRES

- Use a storage ring instead
  - Higher efficiency
  - Optimize B field for CRES detection, not for trapping
- Demonstrator in progress



*QTNM, New J Phys **27** (2025) 105006*

Credit: Seb Jones

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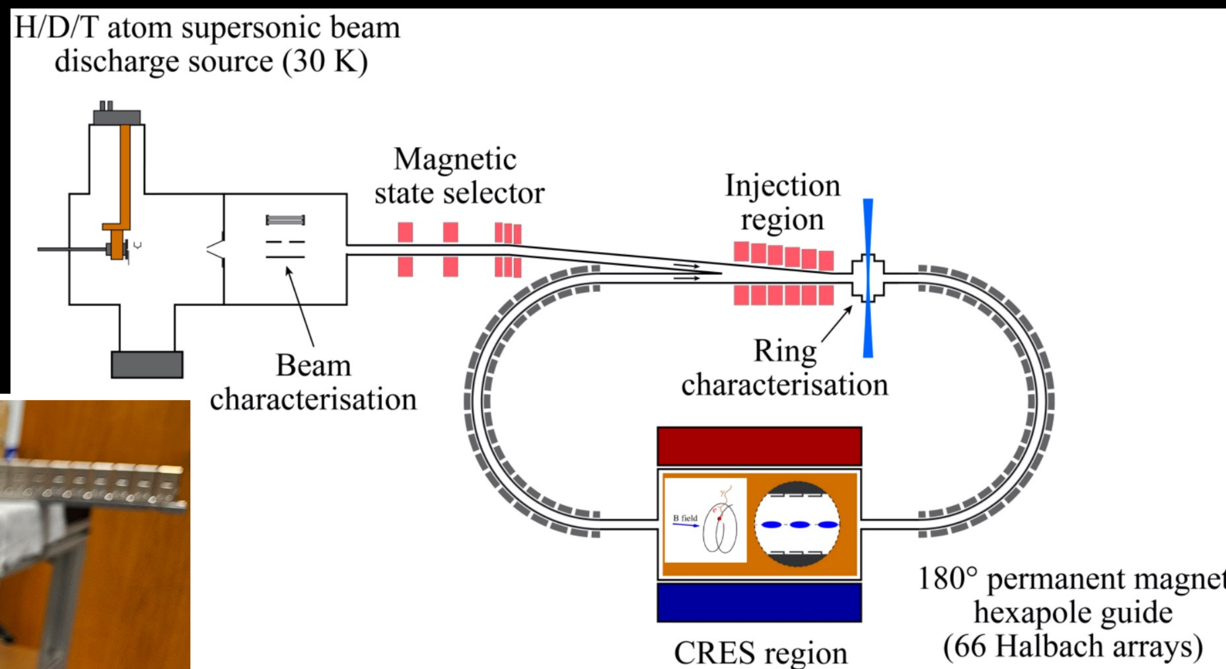

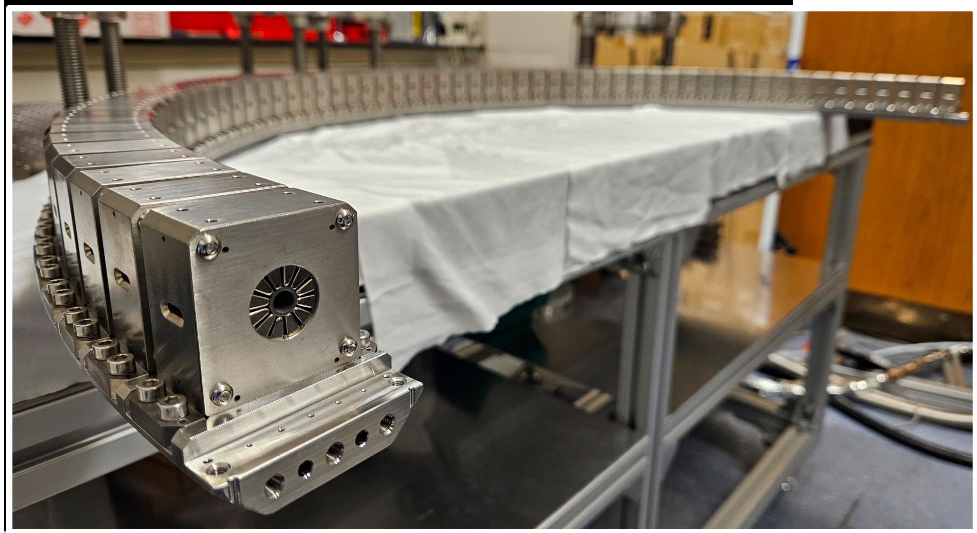

*QTNM, New J Phys **27** (2025) 105006*

Credit: Seb Jones

Coming Together for the Future

- 10-year (5-iteration) workshop series on direct neutrino-mass measurements
- Existing inter-experiment cooperation structures on shared challenges
- Parallel R&D paths help us figure out the best strategies

NuMass workshop, Karlsruhe, Germany, April 2026

The Plan

- Accessing the neutrino-mass scale
- How to search for m_ν directly
- Nitty, gritty systematics
- Microcalorimetry basics (^{163}Ho)
- HOLMES
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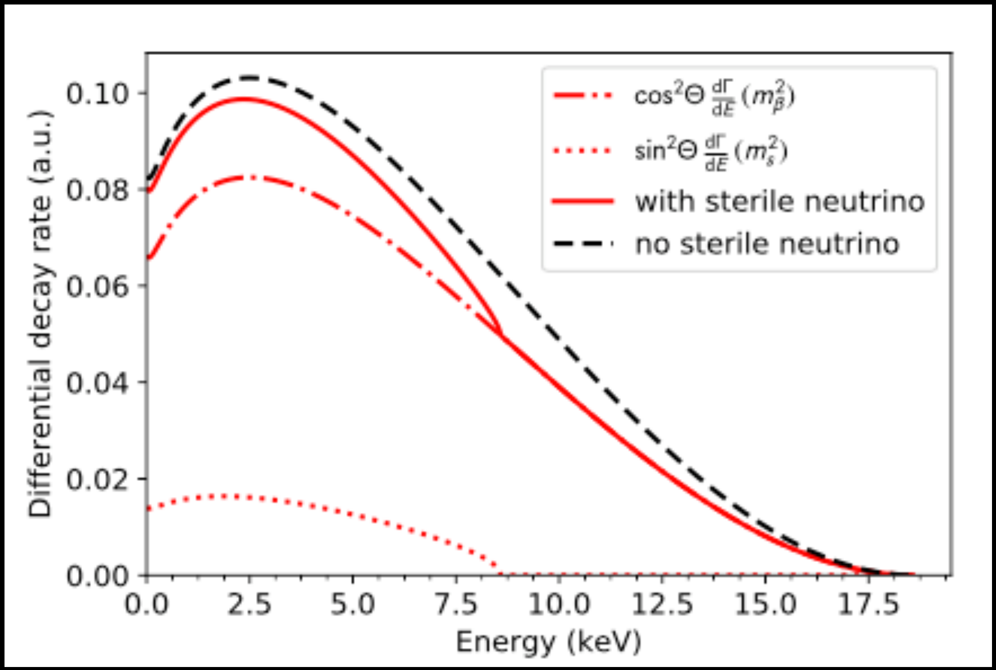
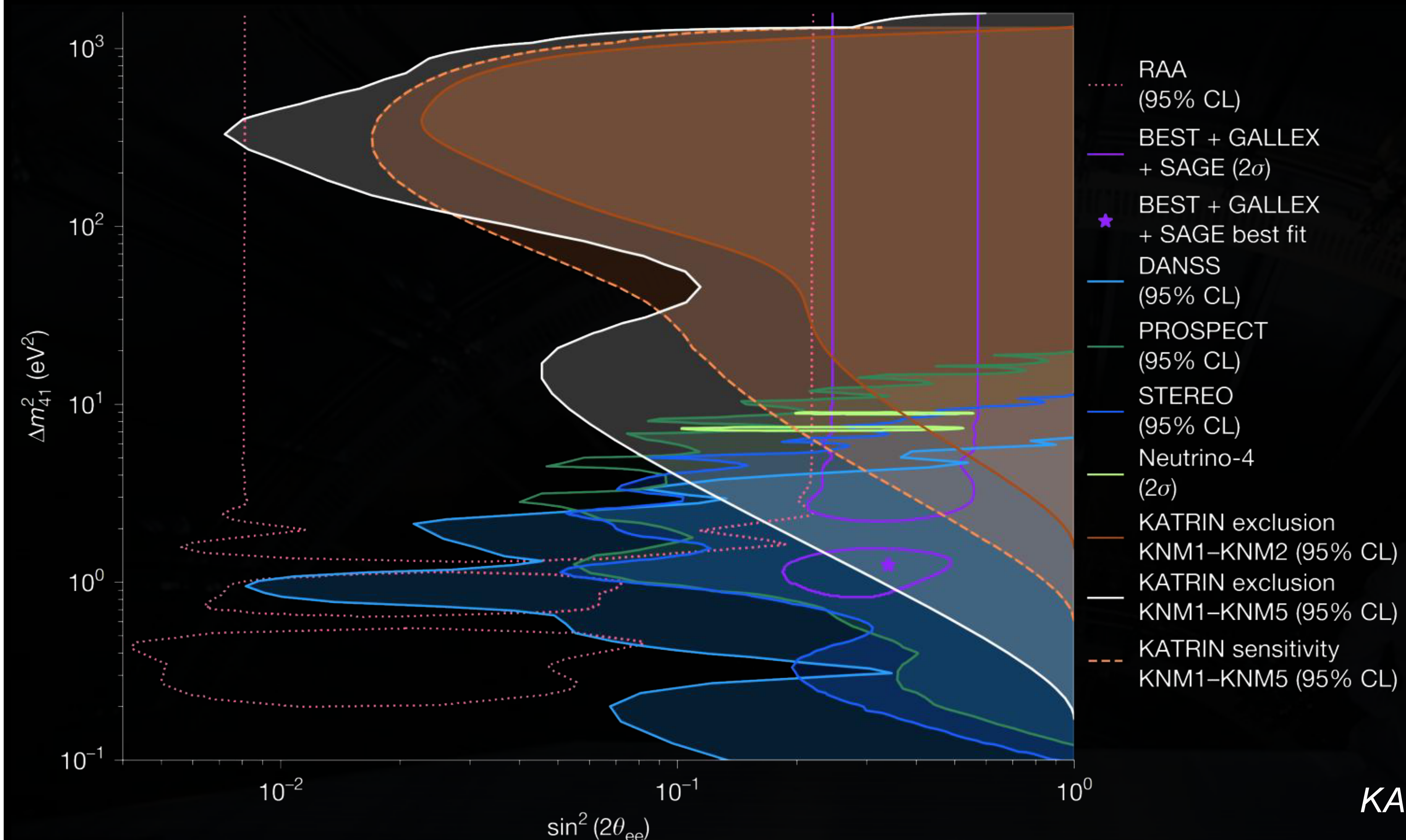
- KATRIN
- Project 8
- Next-generation tritium R&D
- **Sterile neutrinos and bonus physics**
- Alternate measurement ideas

Bonus Physics: Sterile Neutrinos!

- What if there's a 4th neutrino flavor that *doesn't* couple to the weak force?
  - This *sterile* neutrino would still mix with active flavors
  - Kink in spectrum at $E_0 - m_4$



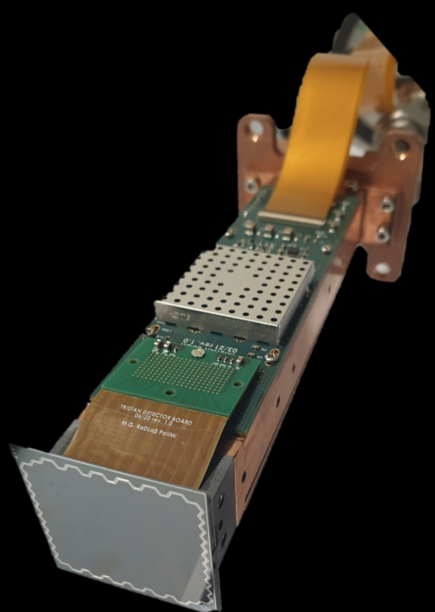
Search in KNM1-5 Data



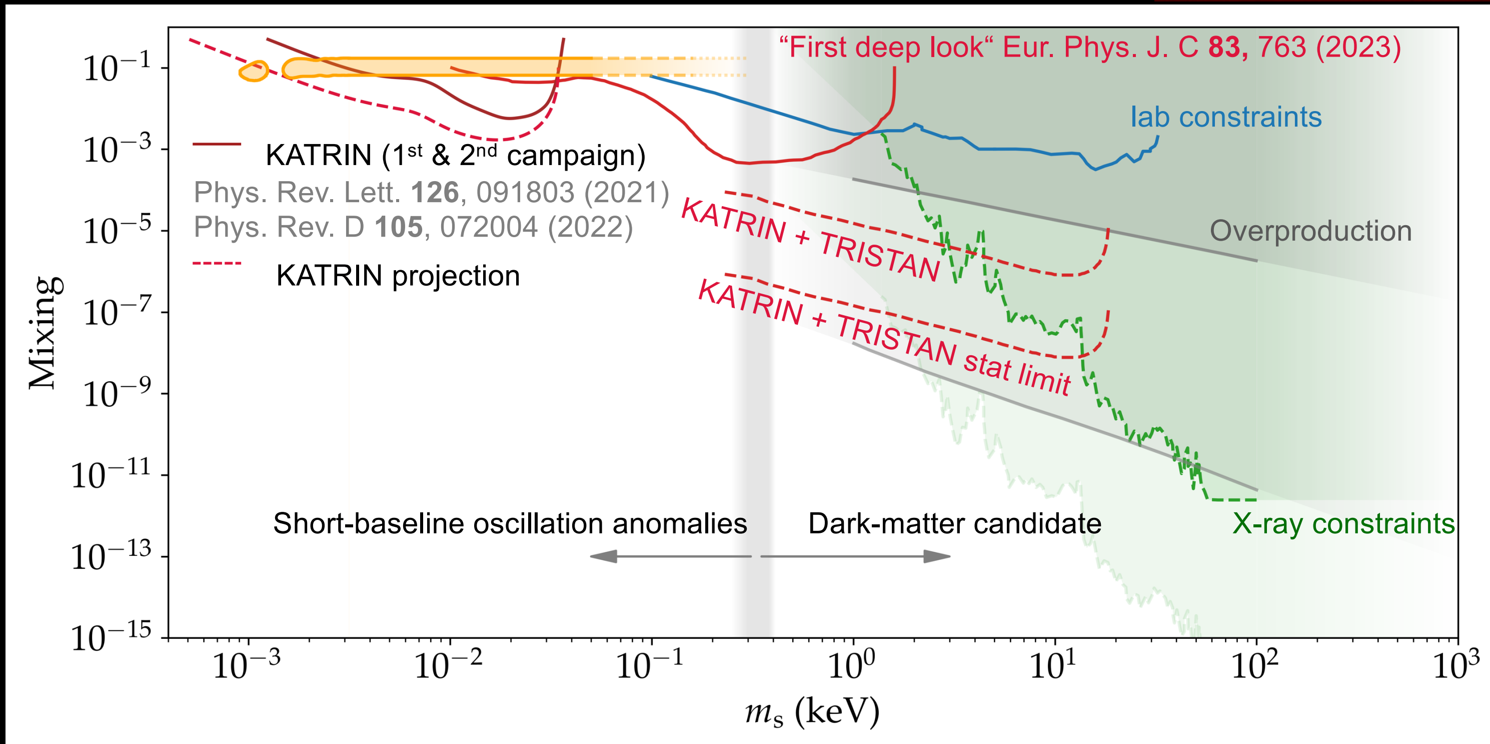
*KATRIN, Nature **648** 70 (2025)*

KATRIN Phase II

- Low-energy search for keV-scale sterile neutrinos
- 2026-7: Install 1500-pixel, high-rate “TRISTAN” silicon drift detector



KATRIN, arXiv:2603.23256



More Bonus Physics

- Cosmic relic neutrions decoupled at 1s after Big Bang!
- Proposal by Weinberg in 1962: detect by capture on tritium

$$\nu_e + {}^3H \longrightarrow e^- + {}^3He$$

Slide: Elise Novitski

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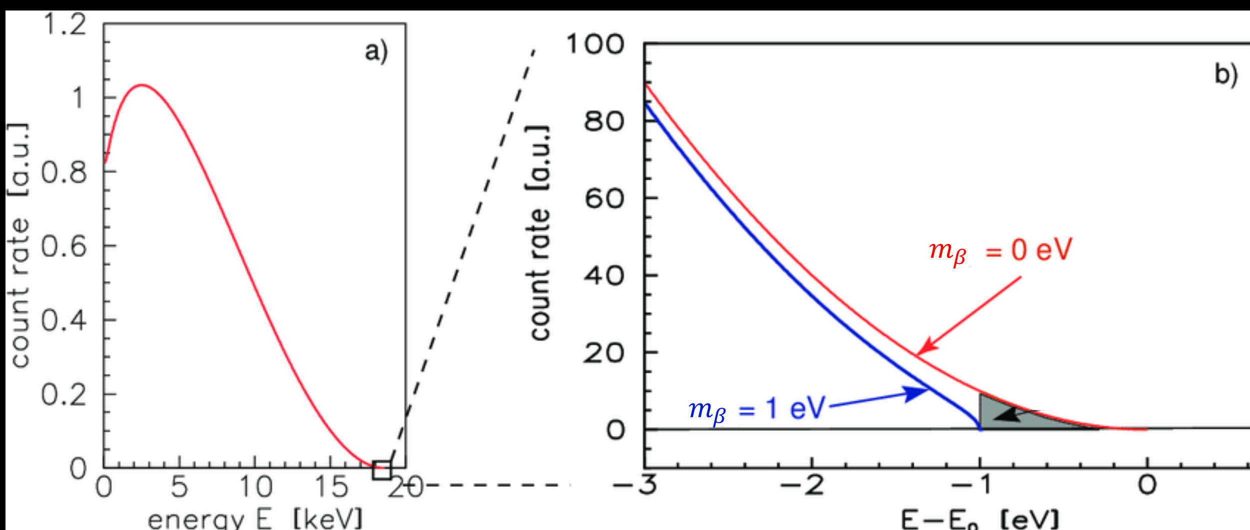

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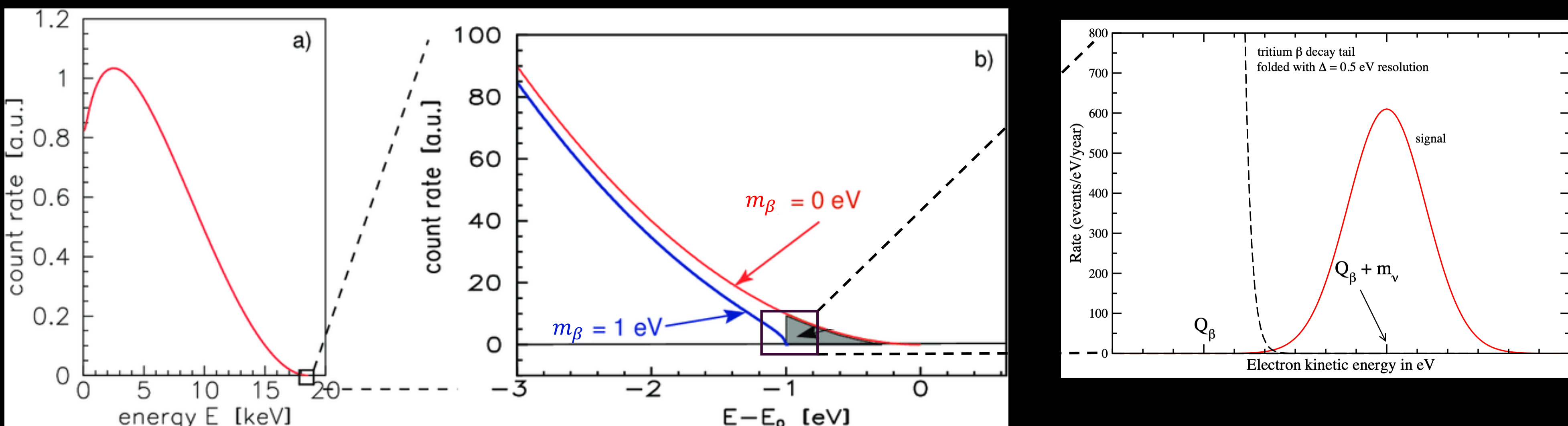
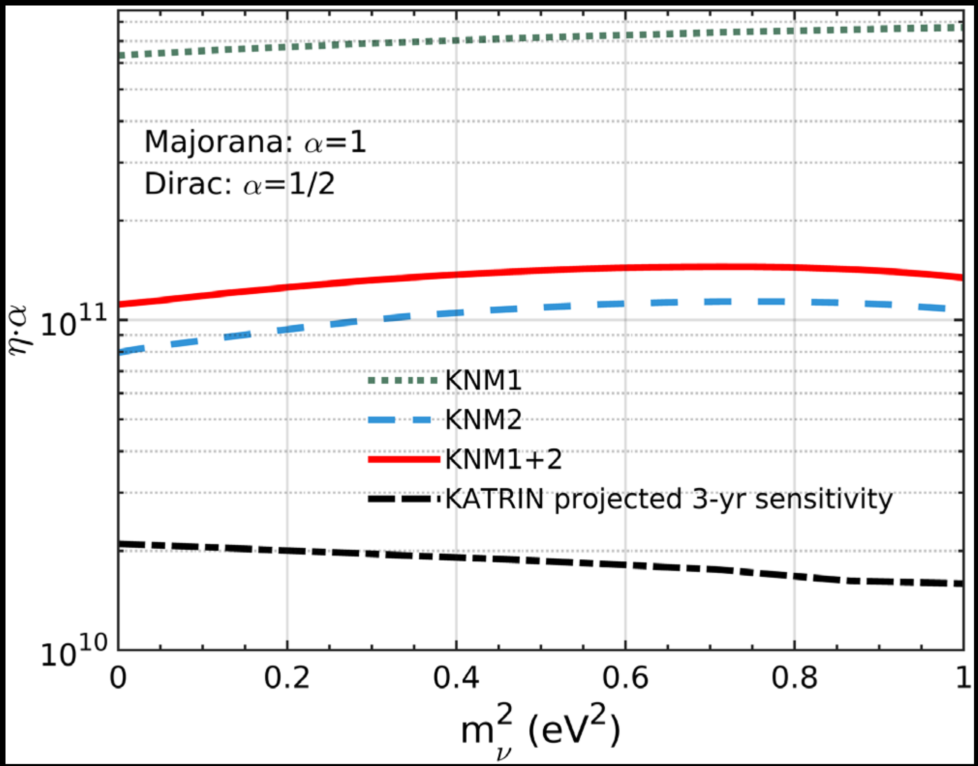


Slide: Elise Novitski

KATRIN Looked For this!

- Not enough tritium to detect predicted CνB abundance
- Instead, set limit on local CνB overdensity η



*KATRIN , PRL **129** (2022) 011806*

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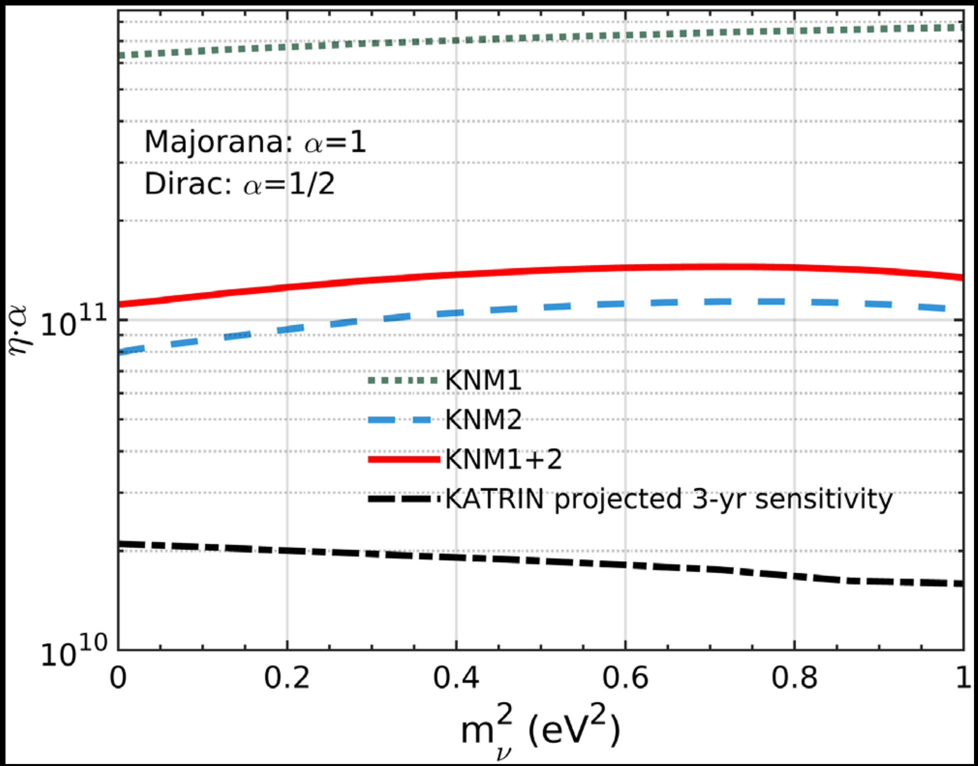
- Other searches:
  - Lorentz-invariance violation
  - Generalized neutrino interactions
  - Light-boson emission



*KATRIN , PRL **129** (2022) 011806*

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    *KATRIN, PRD **107 (2023)** 082005*
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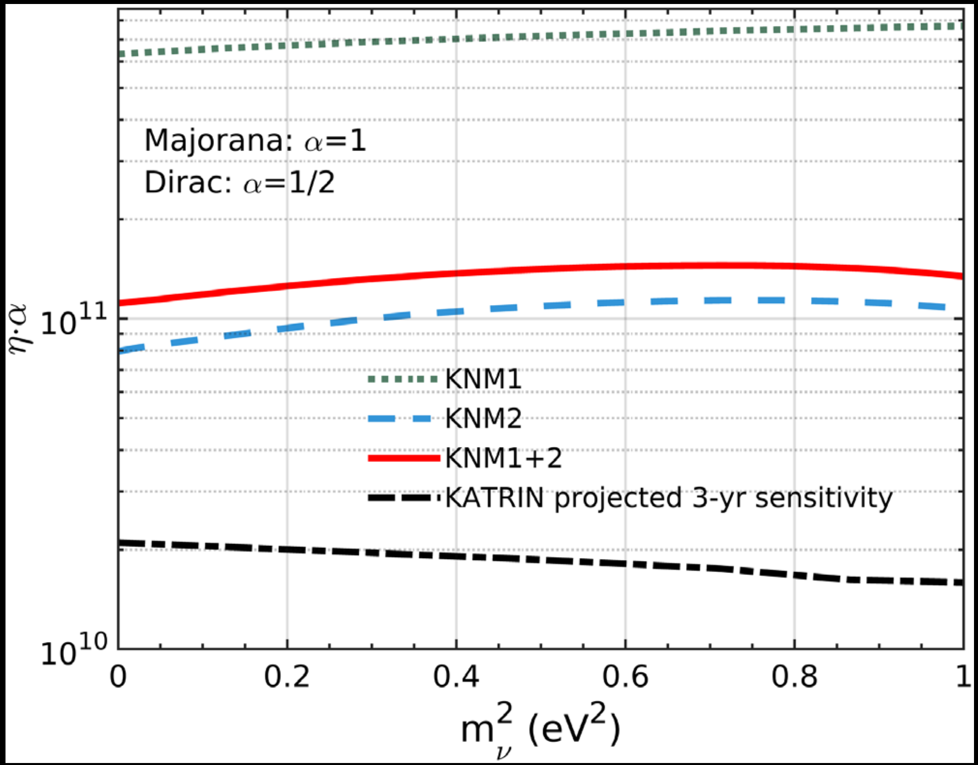

*KATRIN , PRL **129** (2022) 011806*

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    *KATRIN, PRD **107 (2023)** 082005*
  - Generalized neutrino interactions

    *KATRIN, PRL **134** (2025) 251801*
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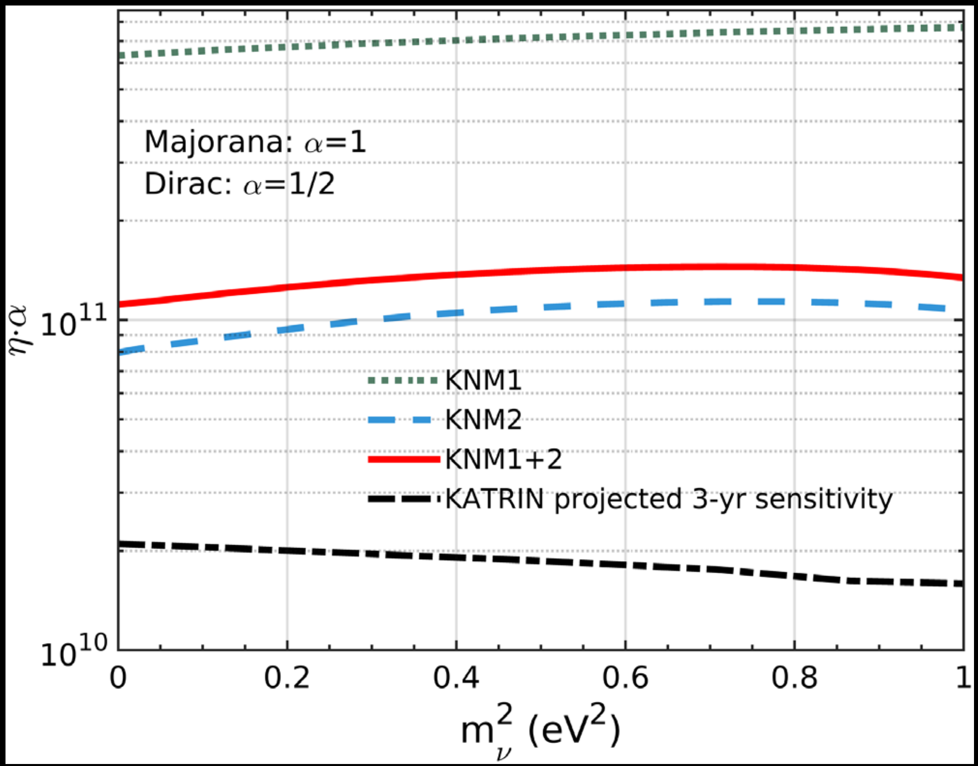

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KATRIN Looked For this!

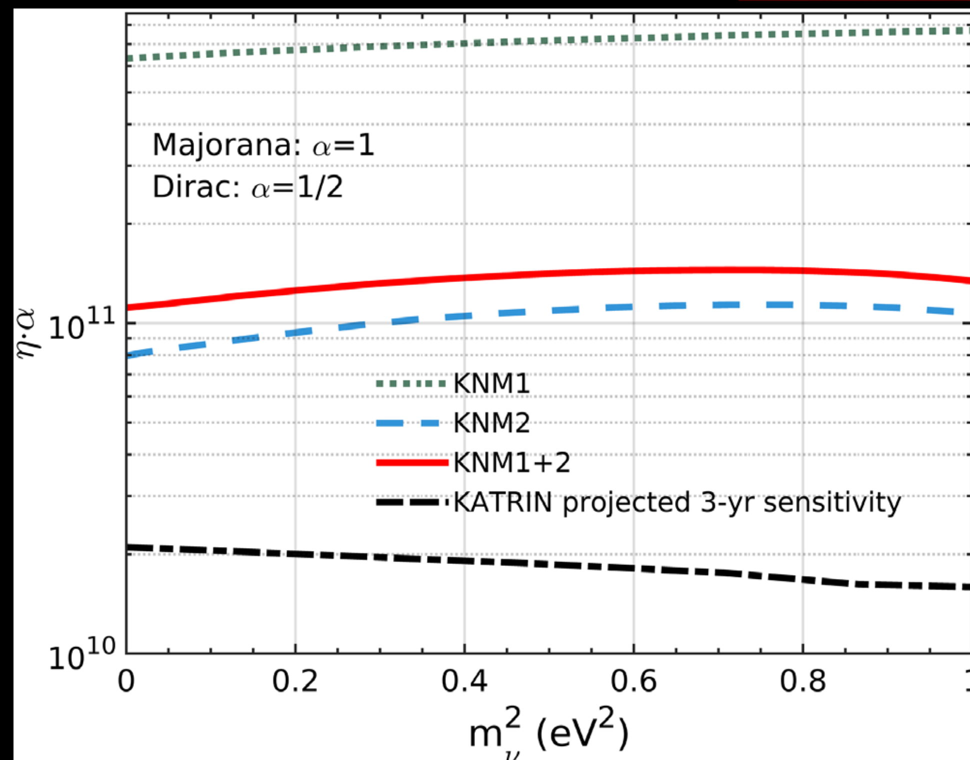
- Not enough tritium to detect predicted CνB abundance
- Instead, set limit on local CνB overdensity η

- Other searches:
  - Lorentz-invariance violation

    *KATRIN, PRD **107 (2023)** 082005*
  - Generalized neutrino interactions

    *KATRIN, PRL **134** (2025) 251801*
  - Light-boson emission

    Lauer, PoS ICHEP2024 (2024), 326



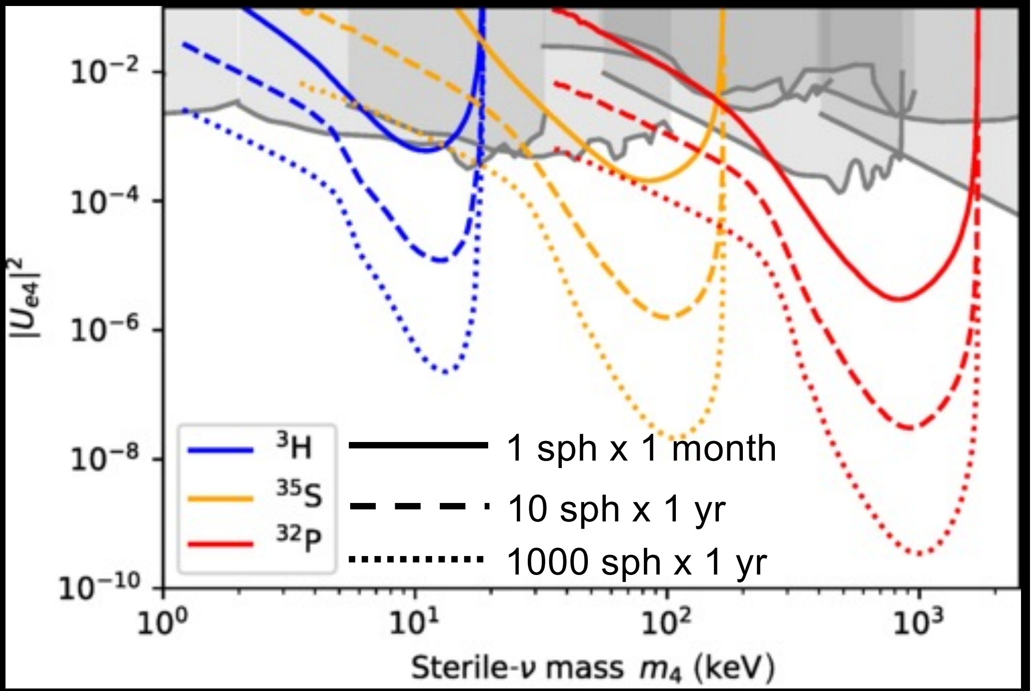
*KATRIN , PRL **129** (2022) 011806*

The Plan

- Accessing the neutrino-mass scale
- How to search for m_ν directly
- Nitty, gritty systematics
- Microcalorimetry basics (^{163}Ho)
- HOLMES
- ECHo
- Beta-spectroscopy basics (^{3}H)
- KATRIN
- Project 8
- Next-generation tritium R&D
- Sterile neutrinos and bonus physics
- **Alternate measurement ideas**

Optomechanical Systems

- Load a microsphere with β-decaying isotope
- Optically levitate the microsphere
- Measure recoil from nuclear decay

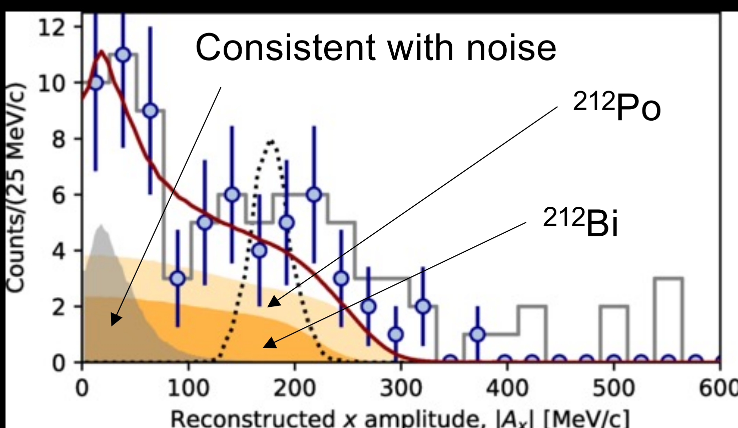


*Carney, Leach, and Moore, PRX Quantum **4** (2023) 010315*

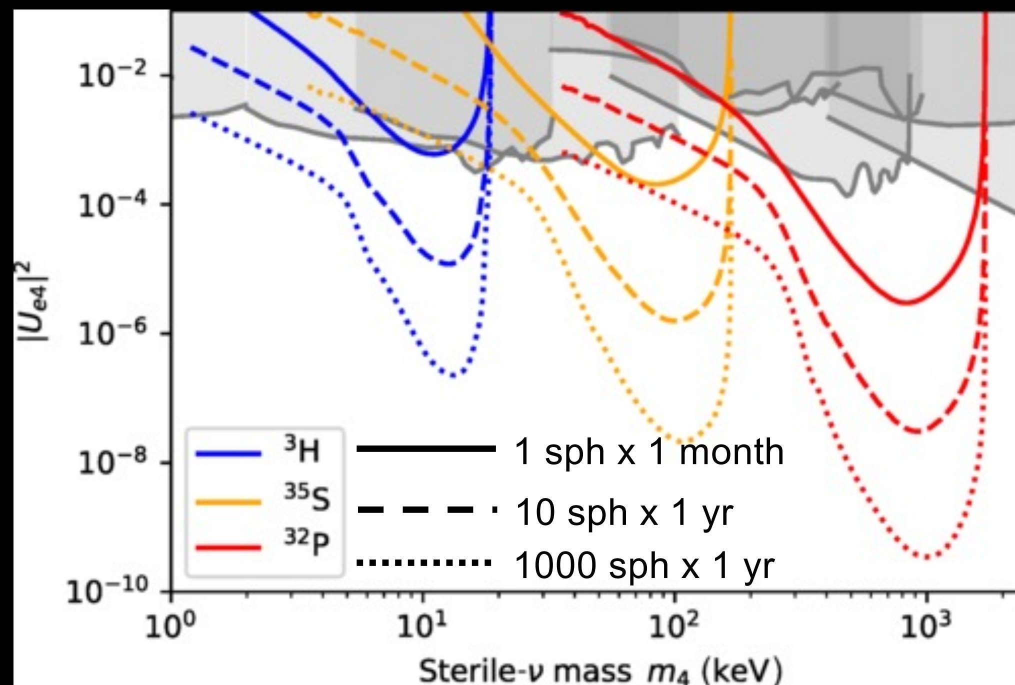
Optomechanical Systems

- Load a microsphere with β-decaying isotope
- Optically levitate the microsphere
- Measure recoil from nuclear decay

α decays have been measured this way!



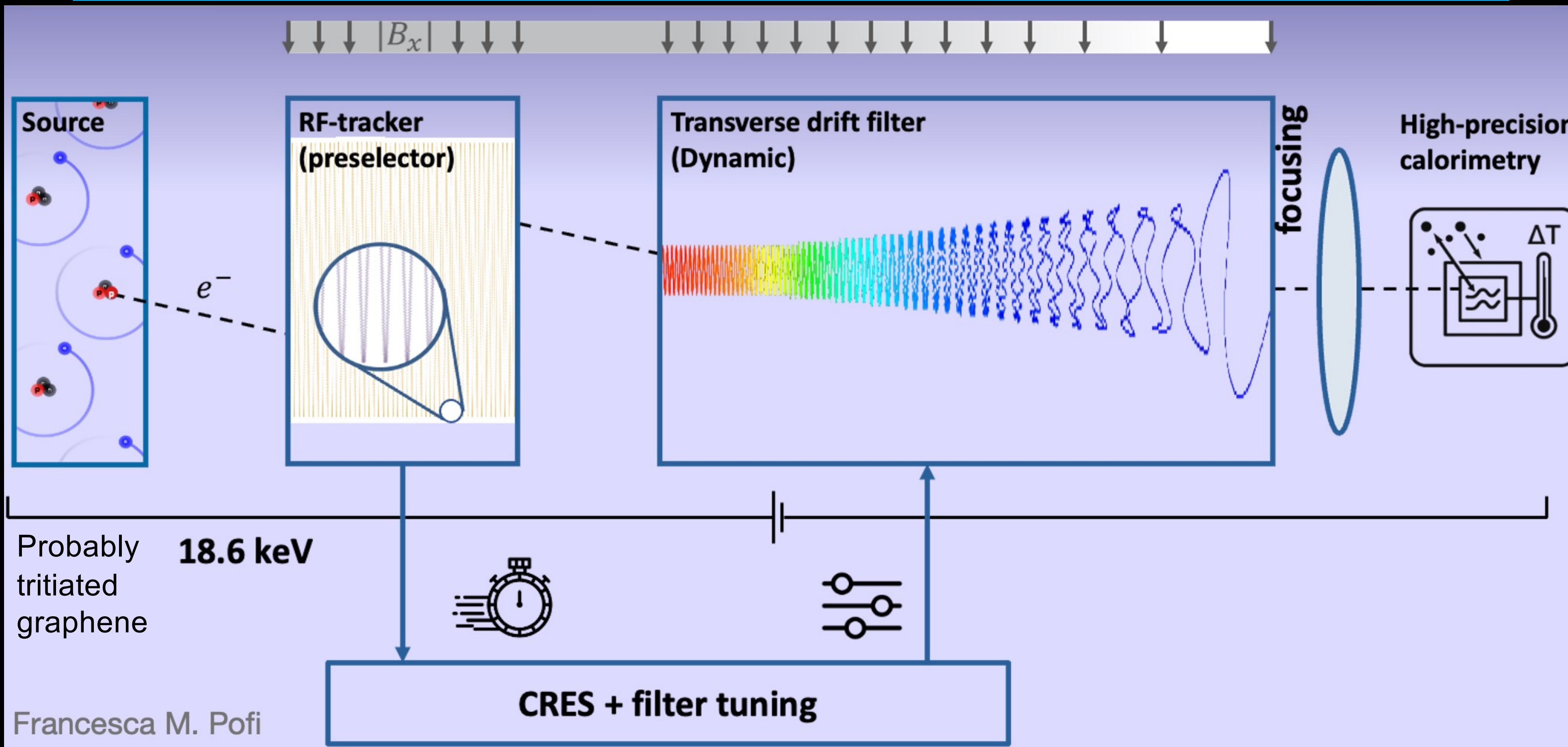
Wang et al, PRL ***133*** *(2024) 023602*



Carney, Leach, and Moore, PRX Quantum ***4*** *(2023) 010315*

Combining Lots of Ideas

*PTOLEMY, Nuovo Cim.C **49** (2026) 20*

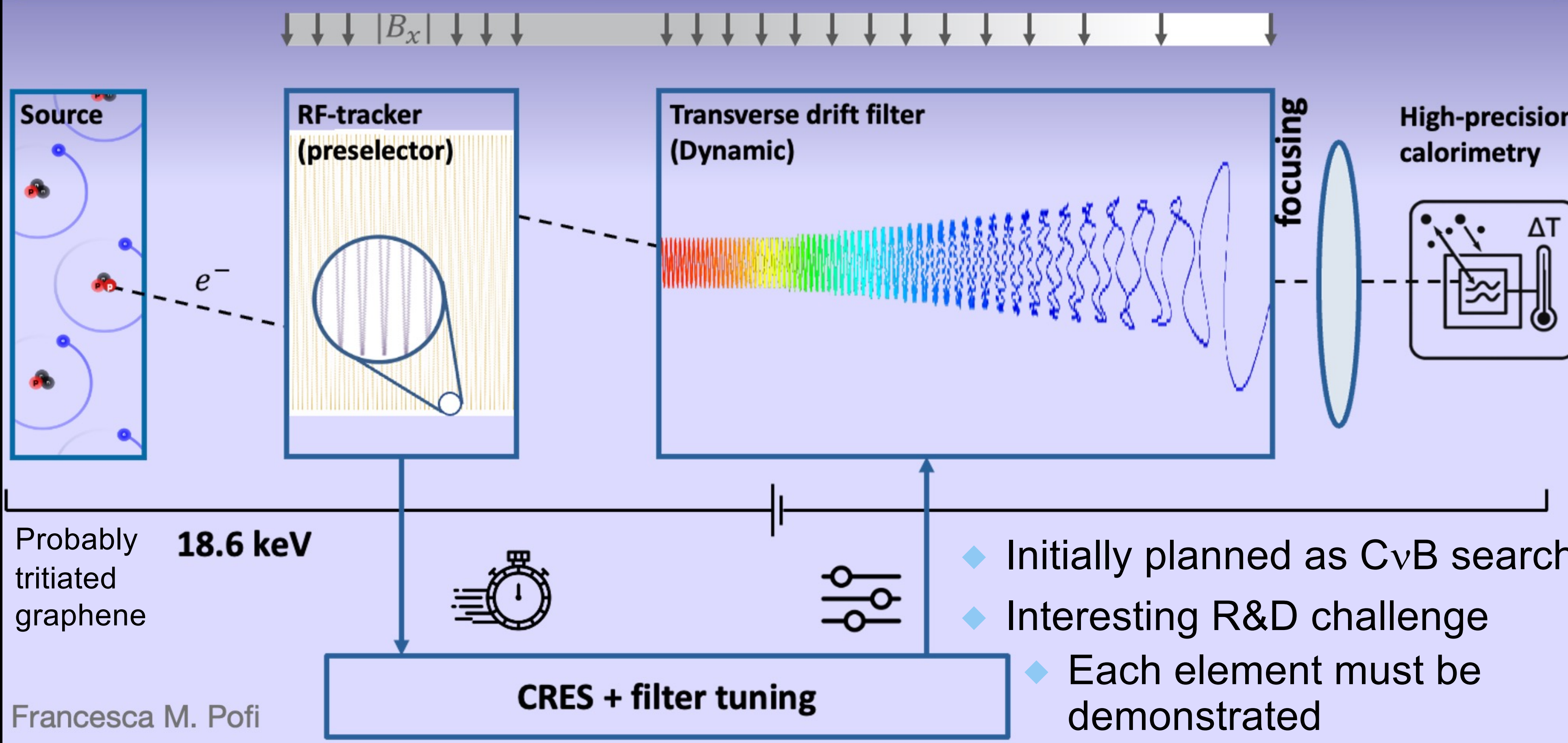


Francesca M. Pofi

Combining Lots of Ideas

PTOLEMY, Nuovo Cim.C ***49*** *(2026) 20*

PTOLEMY



- Initially planned as CνB search
- Interesting R&D challenge
  - Each element must be demonstrated

Francesca M. Pofi

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- Thanks to DOE Nuclear Physics for supporting neutrino-mass work in the US (including mine)
- Thanks to my collaborators on KATRIN and Project 8, and my colleagues on all experiments, for all the cool progress
- Thanks to the organizers!

Conclusions

- The neutrino mass scale remains both fascinating and challenging
- Direct, kinematic measurements are a critical piece of the puzzle
- Decades of work and creativity to improve precision for ^{3}H and ^{163}Ho

- This is an exciting time for the field!

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Thank you!