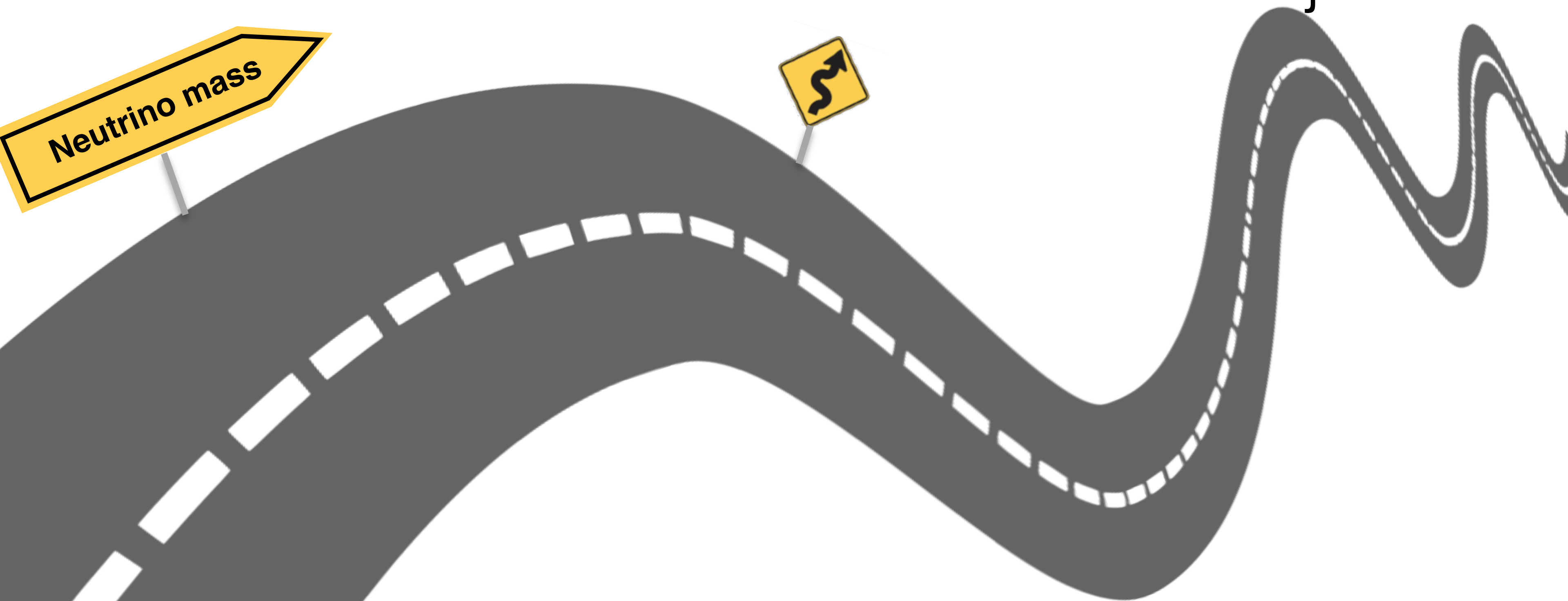
PROJECT 8

Massachusetts Institute of Technology

Towards the determination of the absolute neutrino mass scale with Project 8



DESY, 24.06.2022

Juliana Stachurska

Outline

Outline

The Neutrino: A brief history

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Neutrino mass measurements

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Neutrino mass measurements

Project 8: A concept for the future neutrino mass measurement

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Project 8: A concept for the future neutrino mass measurement

Phases I and II: Accomplishments

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Neutrino mass measurements

Project 8: A concept for the future neutrino mass measurement

Phases I and II: Accomplishments

Phases III and IV: R&D

The Neutrino Hypothesis

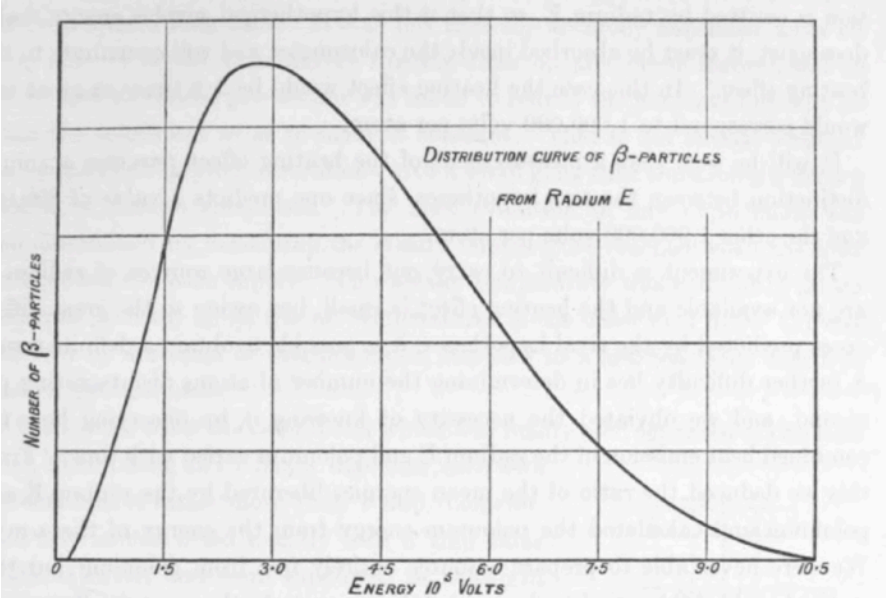


Fig. 1.

C. D. Ellis and W. A. Wooster, Royal Proc A 117 (1927)

The Neutrino Hypothesis

- 1930: Pauli postulates the existence of a new particle to save energy conservation in nuclear beta decay

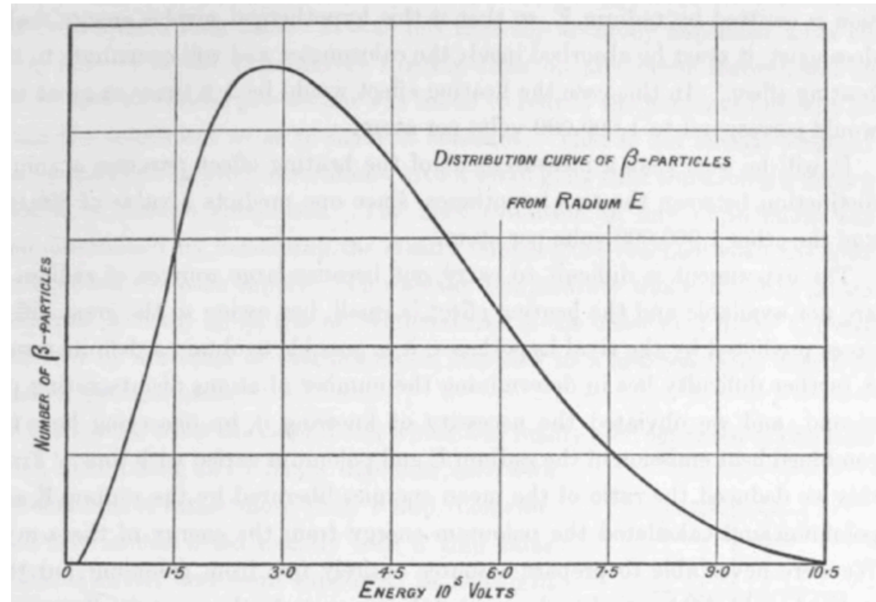


Fig. 1.

C. D. Ellis and W. A. Wooster, Royal Proc A 117 (1927)

> "The mass of the neutrons* should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass."

> "I have done a terrible thing, I have postulated a particle that cannot be detected"

*renamed "neutrino" by Fermi

Nuclear Beta Decay

- 1934: Fermi formulates beta decay theory
- Mass accessible via nuclear endpoint measurement

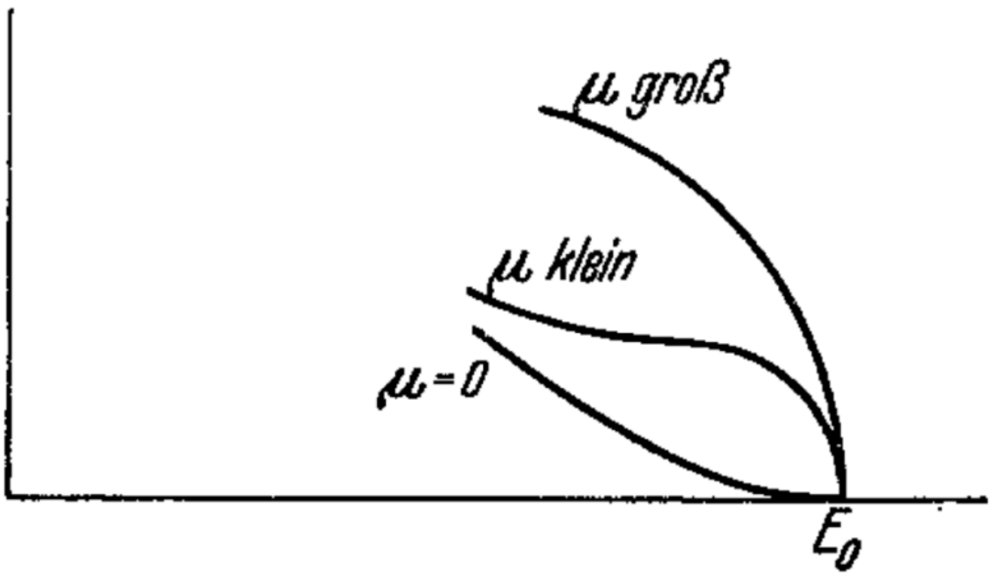
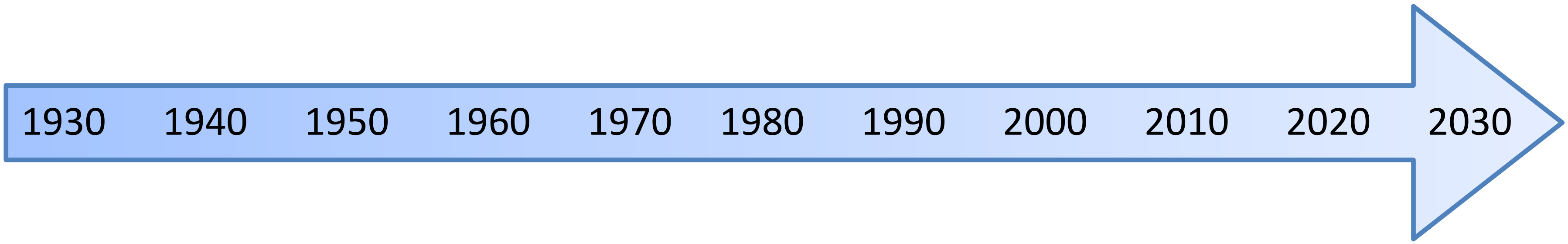


Fig. 1.

E. Fermi, ZS. f. Phys. 88, 3-4 (1934)

Neutrino Highlights



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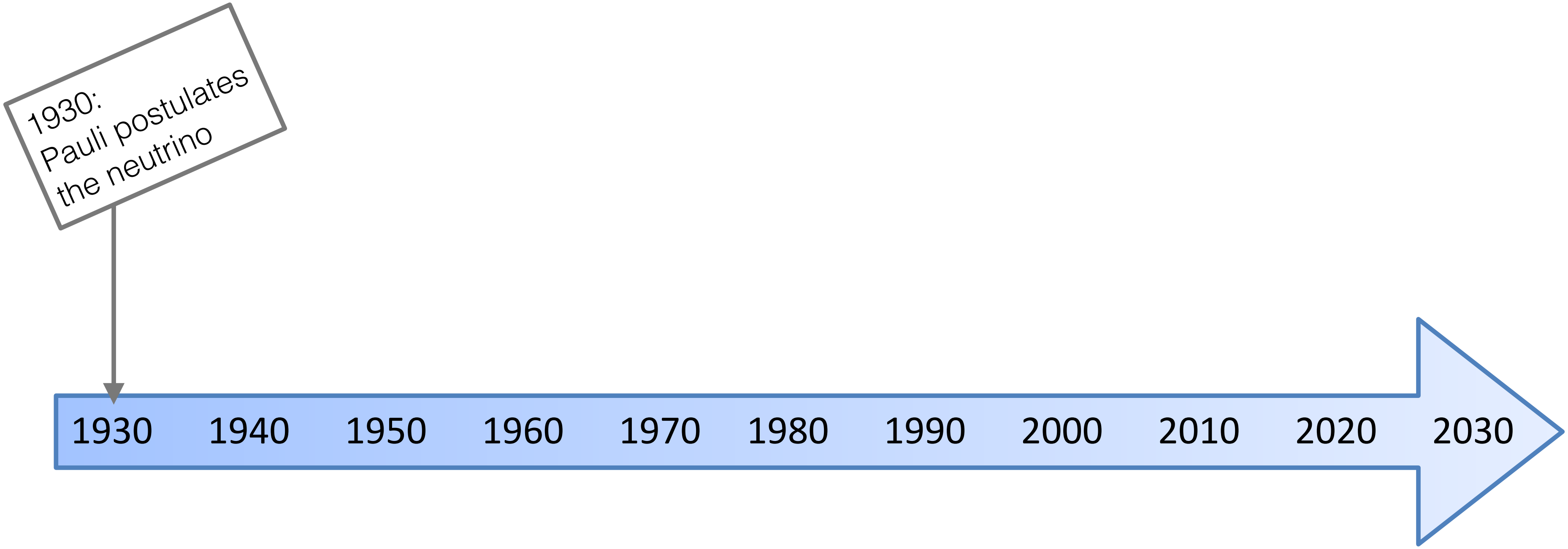

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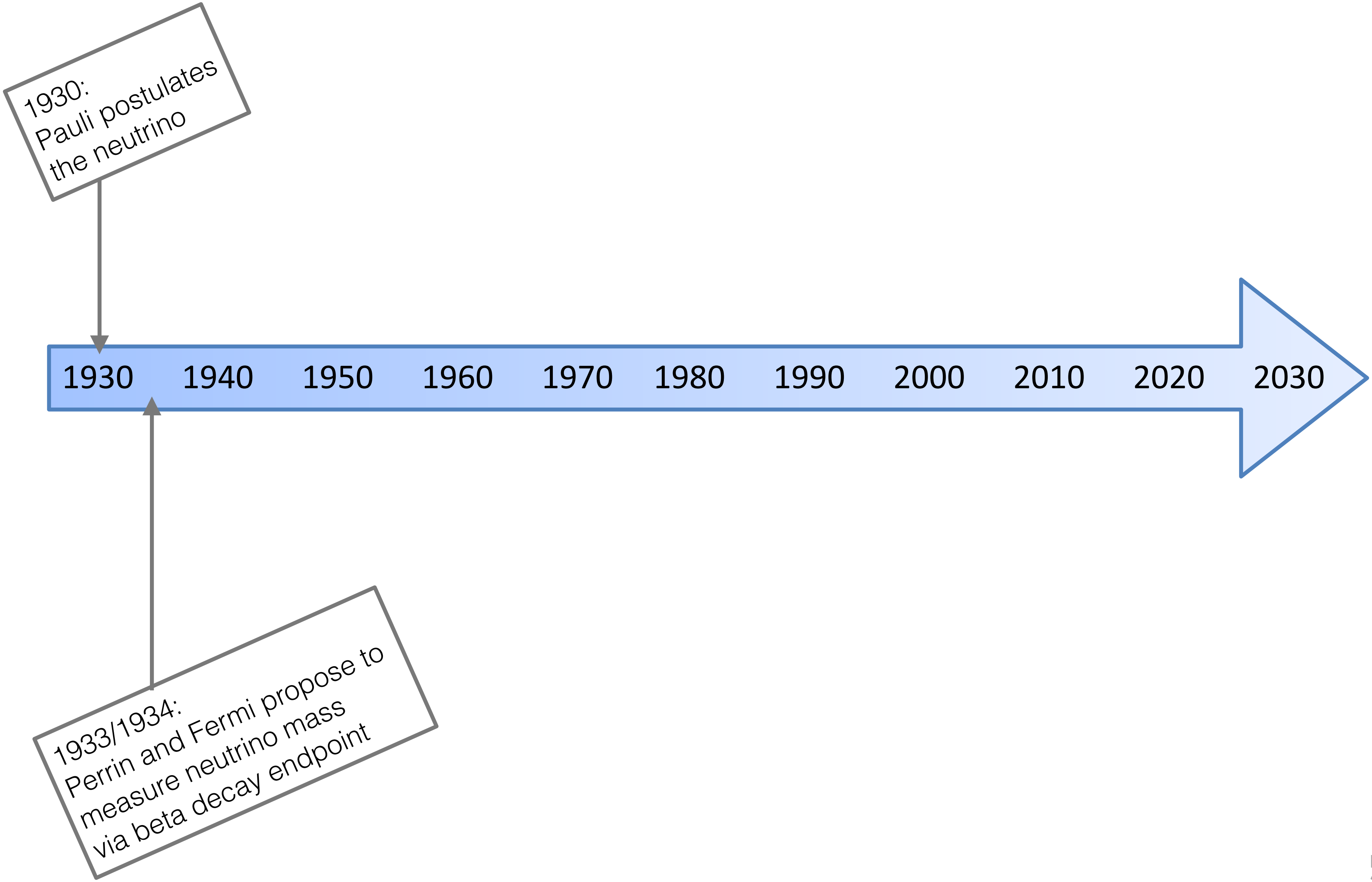
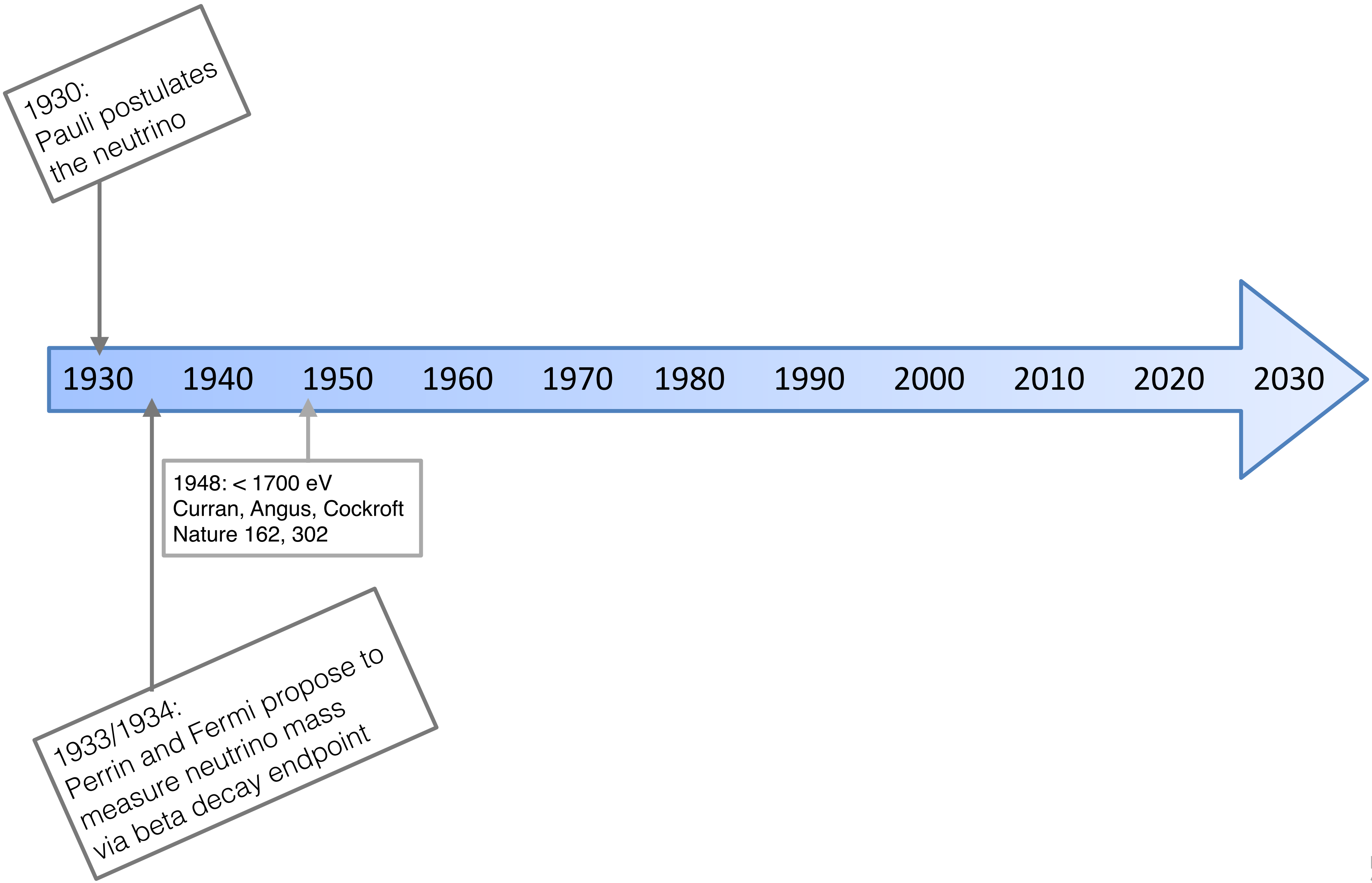


PROJECT 8

Neutrino Highlights



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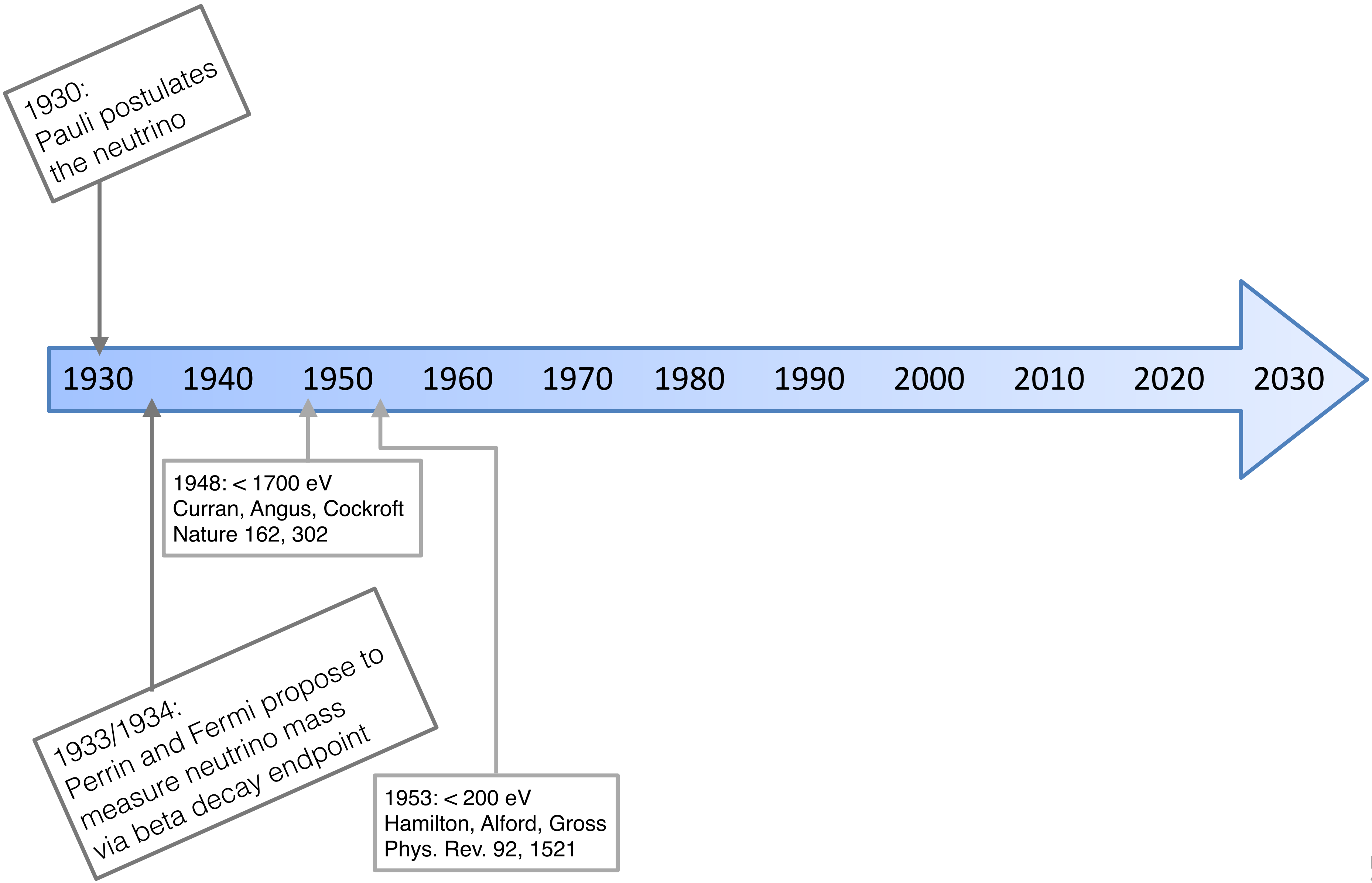

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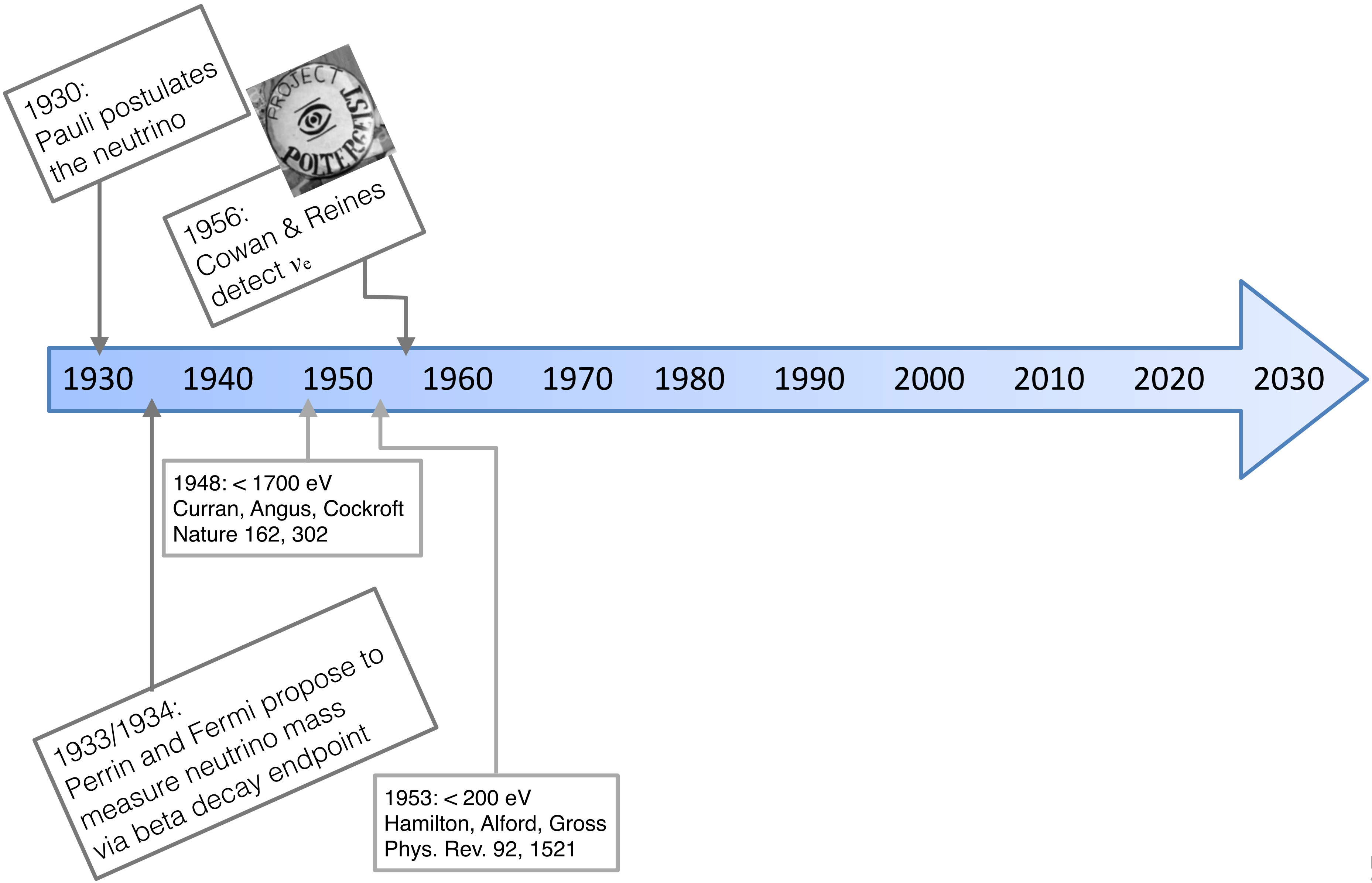
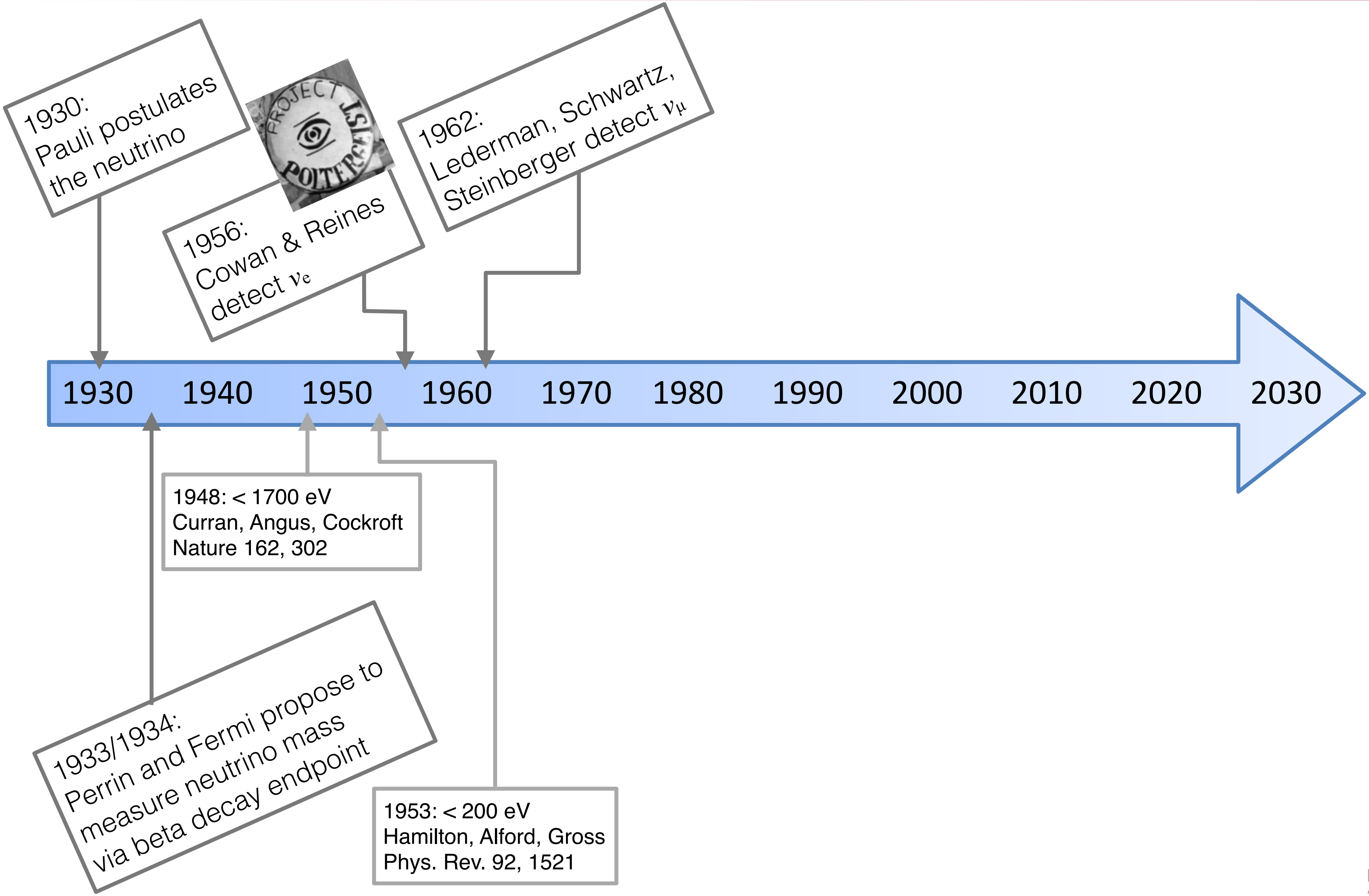


PROJECT 8

Neutrino Highlights



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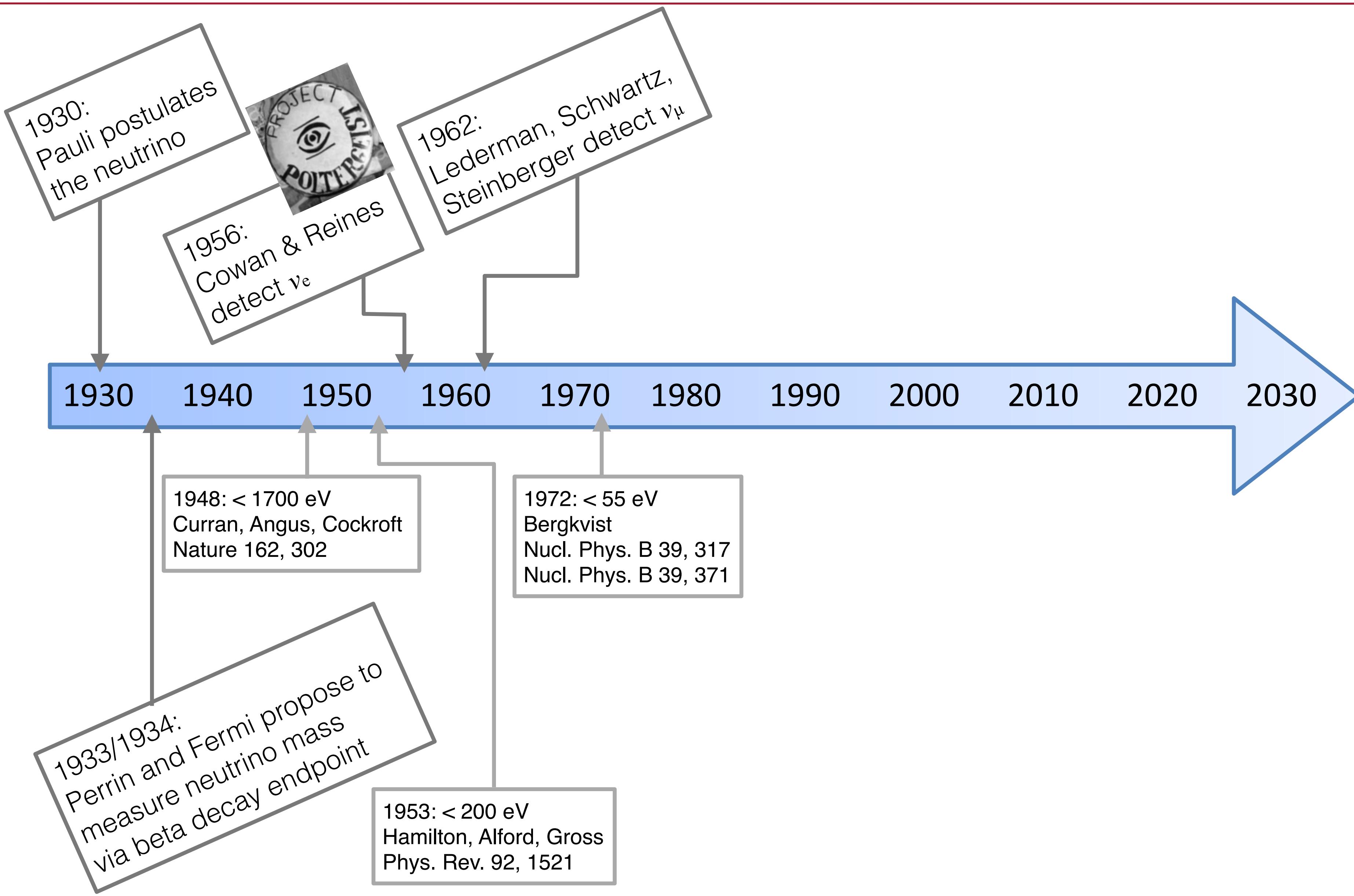
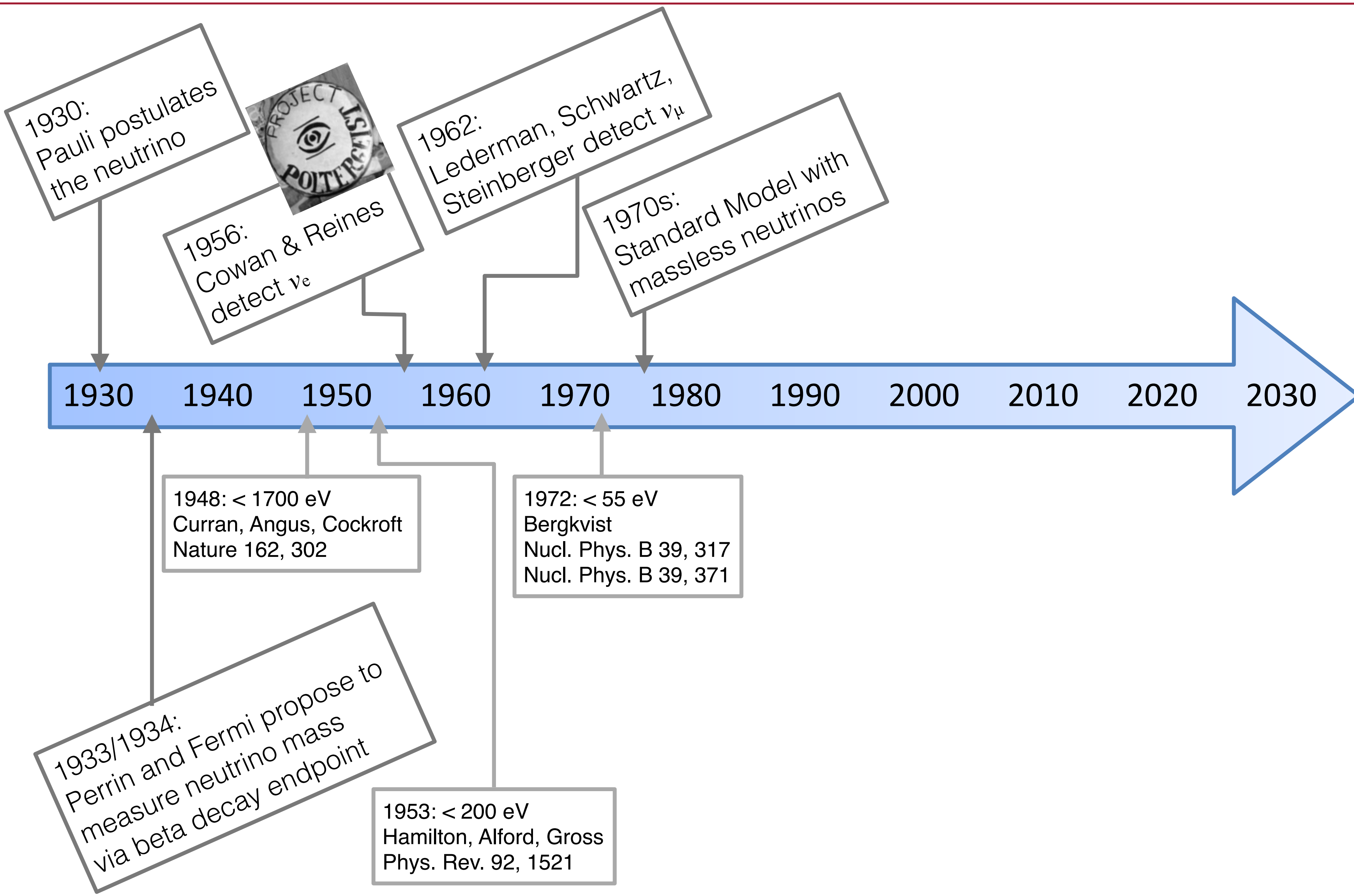


PROJECT 8

Neutrino Highlights



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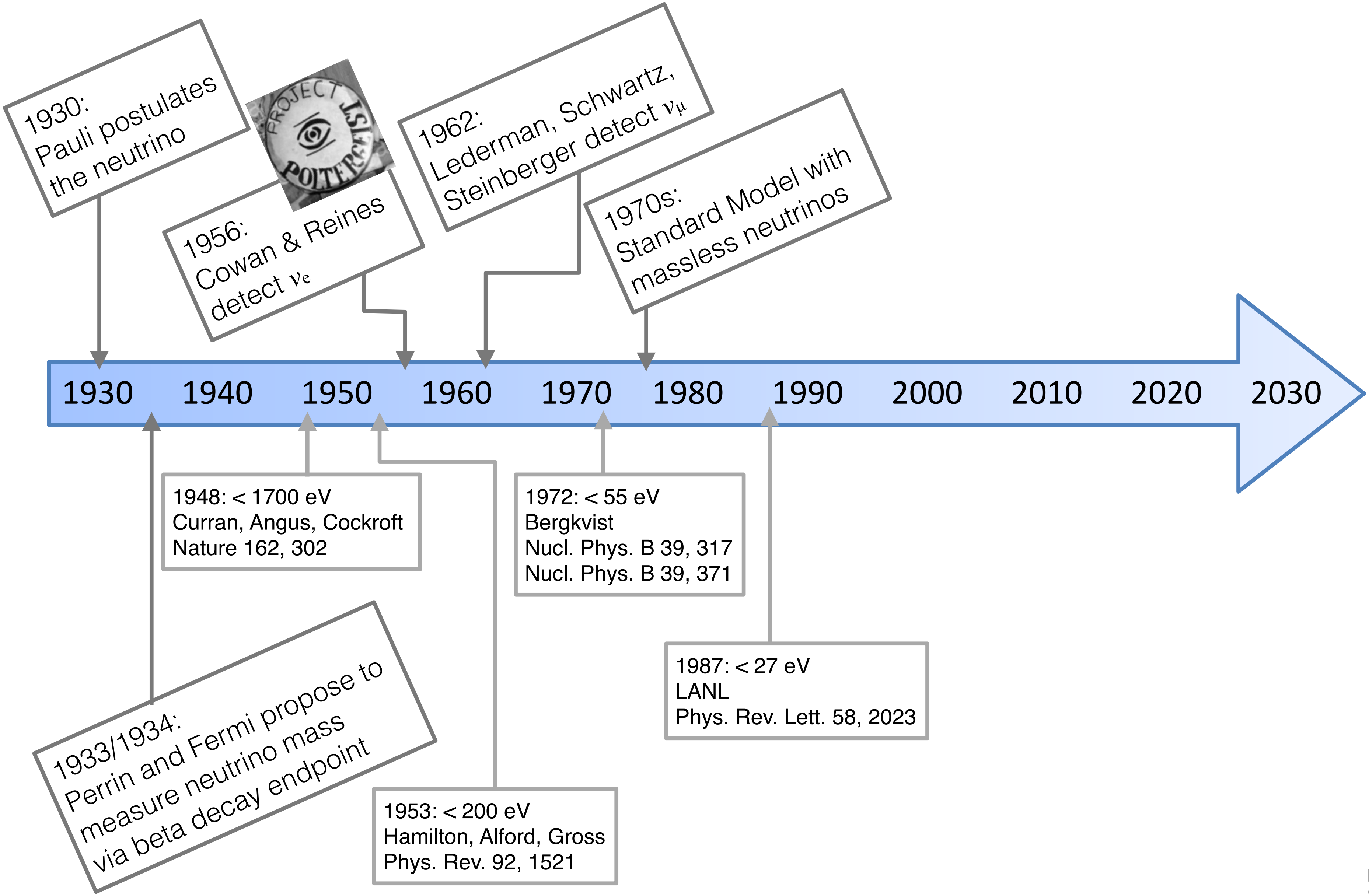

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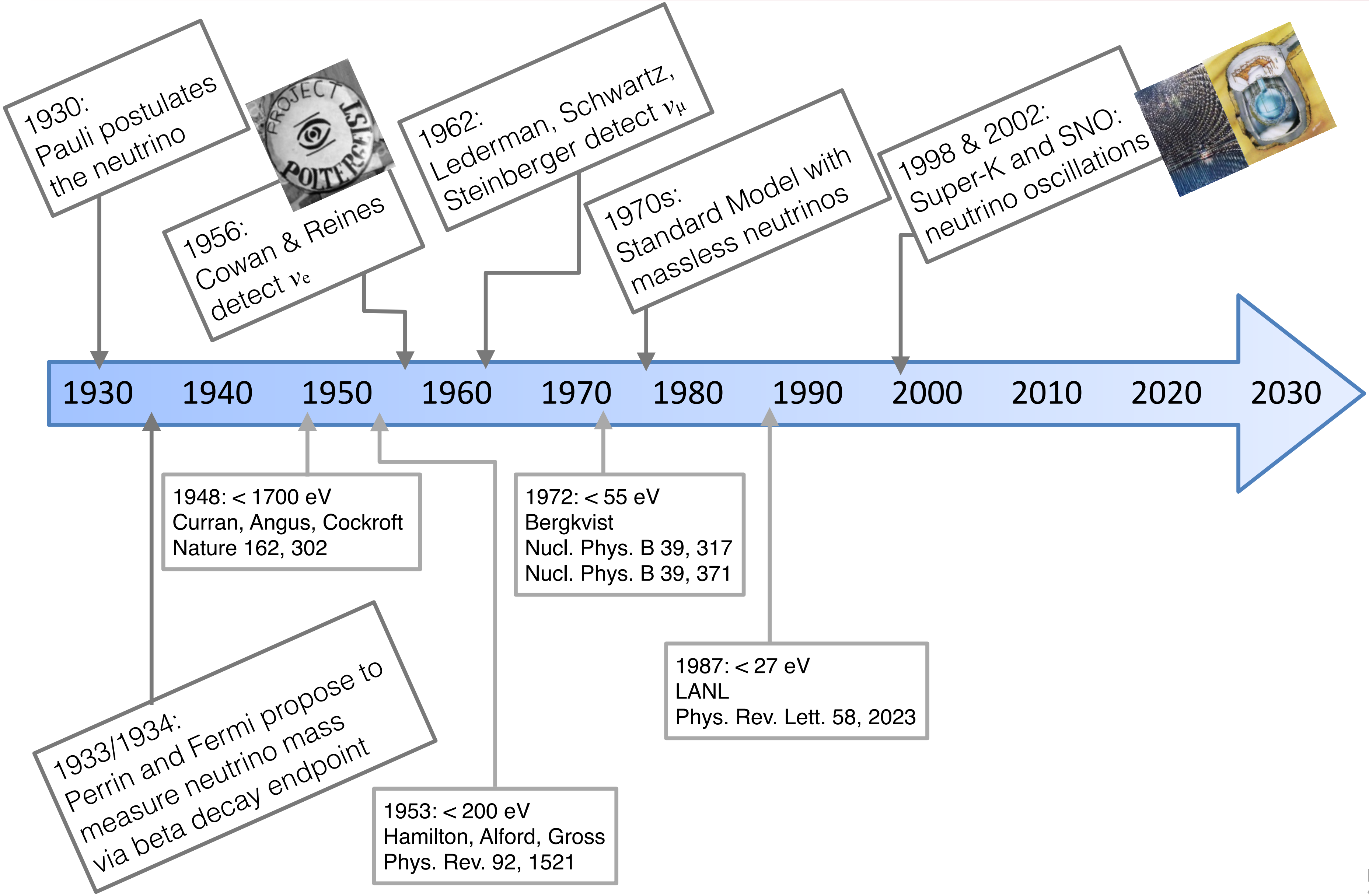

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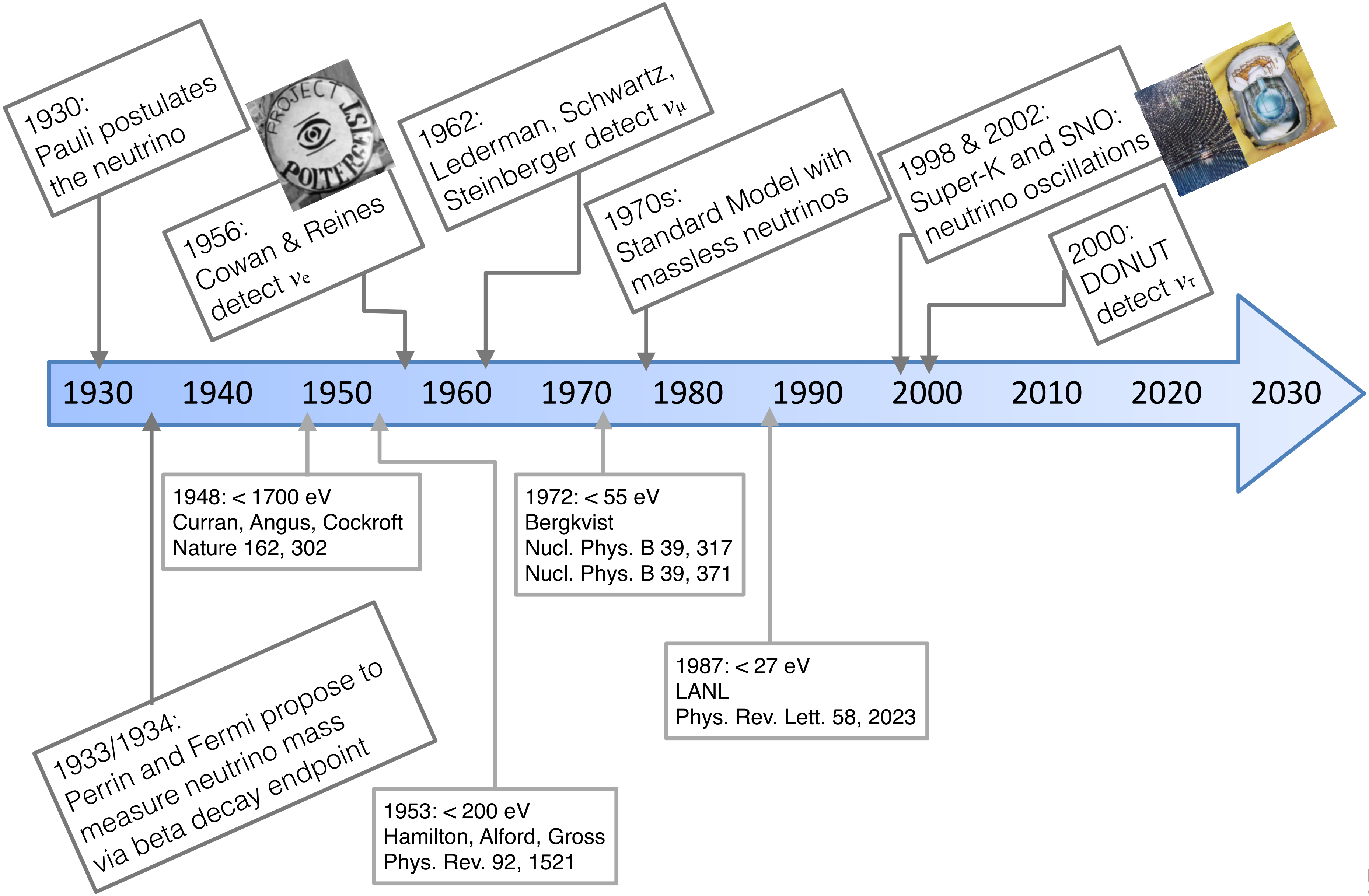

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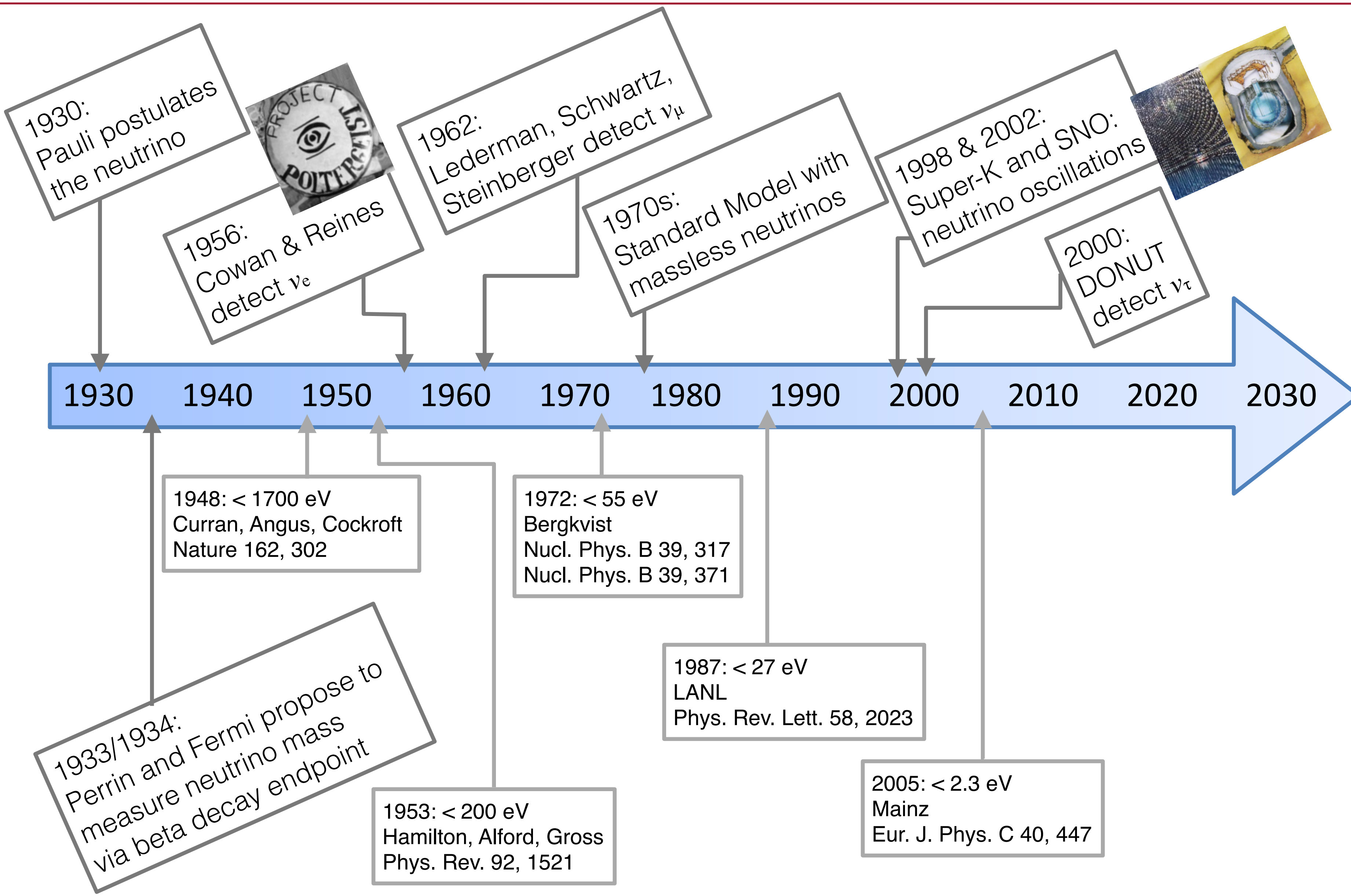

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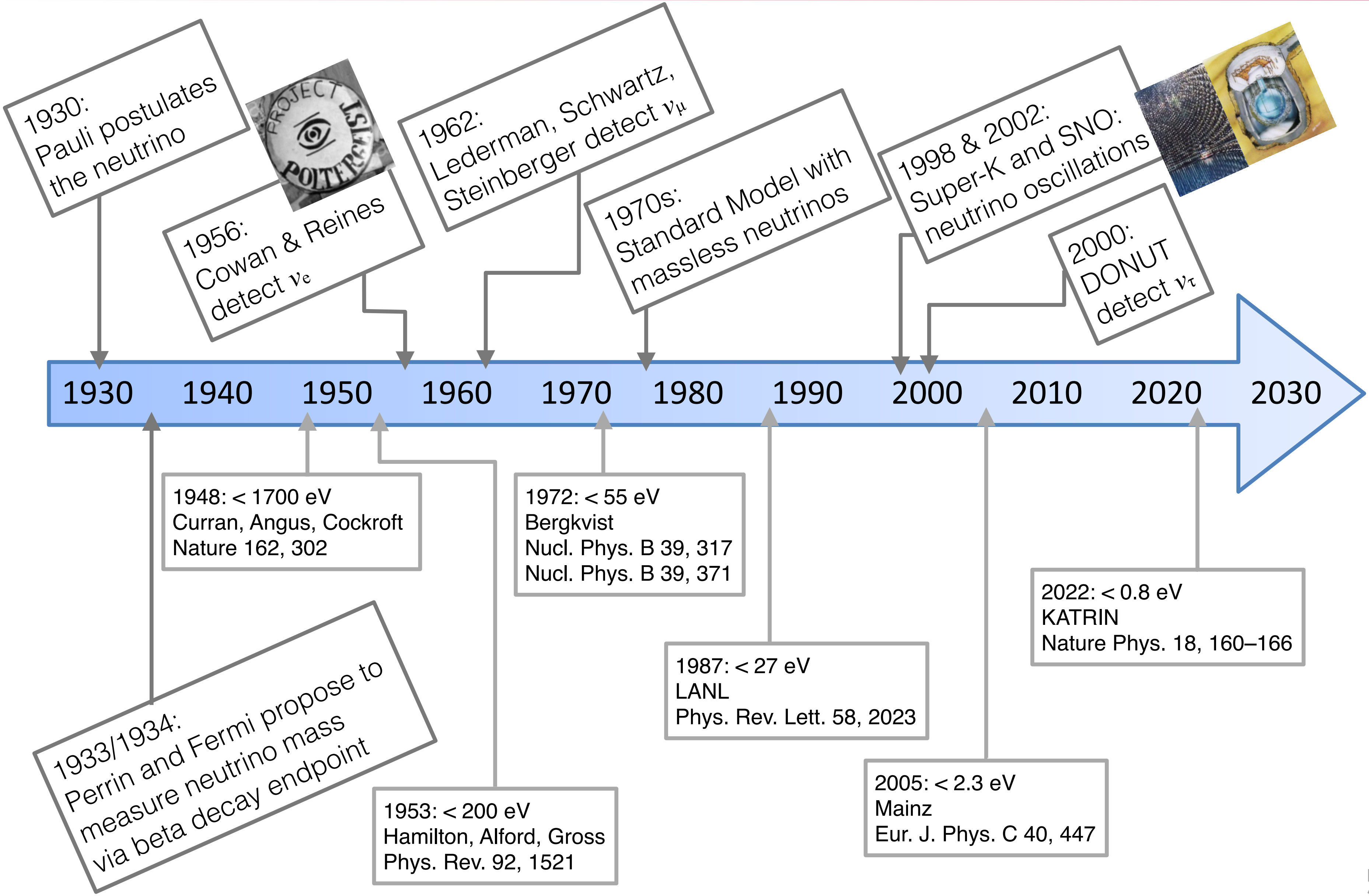
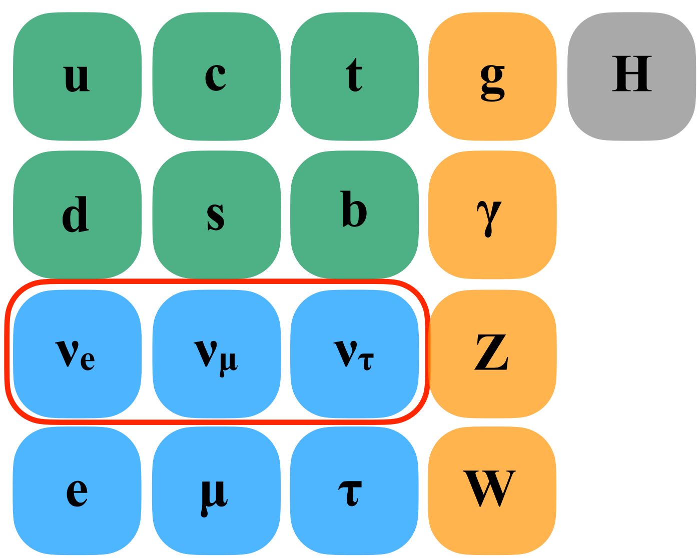
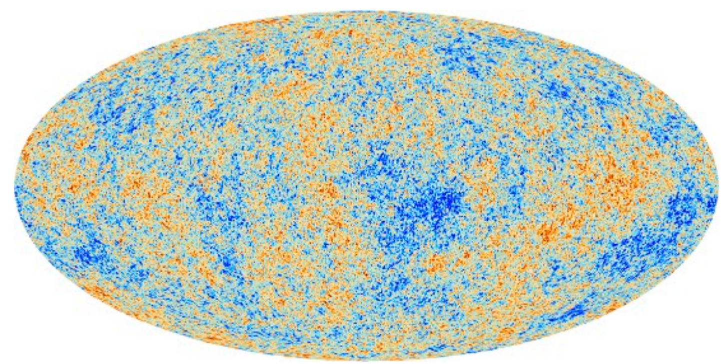


Neutrino Mass

- Neutrinos oscillate $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$ → mass eigenstates with non-zero mass differences
- Oscillations: only sensitive to mass differences Δm^2_{ij}
- Absolute neutrino mass?
- Mechanism generating neutrino masses most likely beyond the Standard Model
- Impact on cosmic evolution

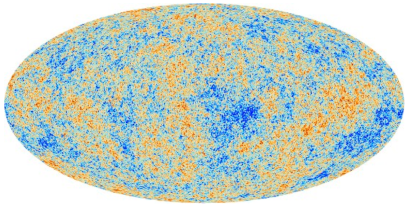


SM: massless neutrinos

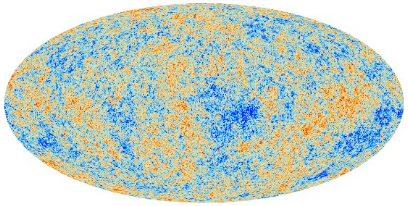


Cosmology: neutrino mass → structure formation

Neutrino Mass

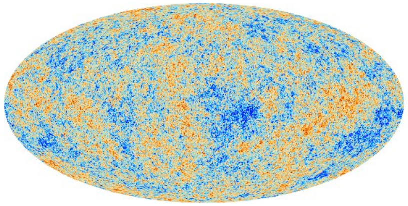


Neutrino Mass



- Cosmology: indirect, model-dependent, probing sum of masses
  — degeneracies between probed parameters
  - Planck + lensing + BAO: $\sum m_i < 0.12\,\mathrm{eV}$

Neutrino Mass



- Cosmology: indirect, model-dependent, probing sum of masses
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  - Planck + lensing + BAO: $\sum m_i < 0.12\,\mathrm{eV}$
- Laboratory nuclear measurement: direct, sensitive to electron-weighted neutrino mass
  - Beta decay (Tritium) $m_\beta^2 = \sum |U_{ei}|^2 m_i^2$
    - KATRIN: $m_\beta < 0.8\,\mathrm{eV}\,(90\,\%\,\mathrm{C.L.})$
    - Project 8
  - Electron capture (Holmium)
    - ECHo, HoLMES

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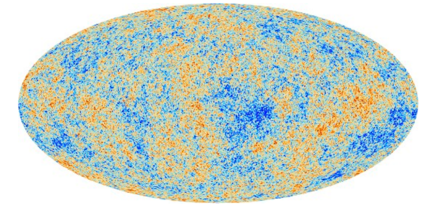

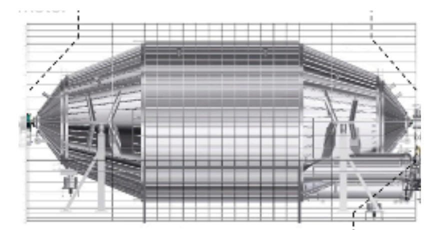

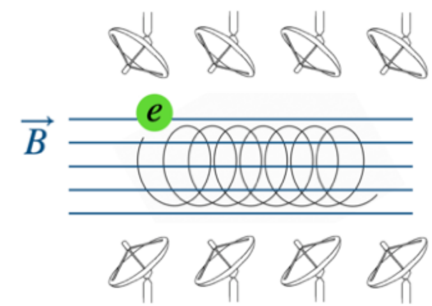

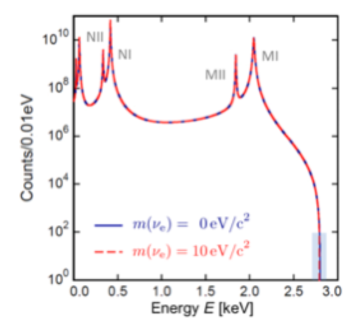

Neutrino Mass

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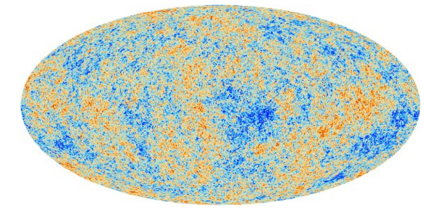
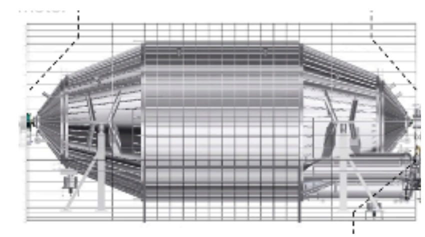
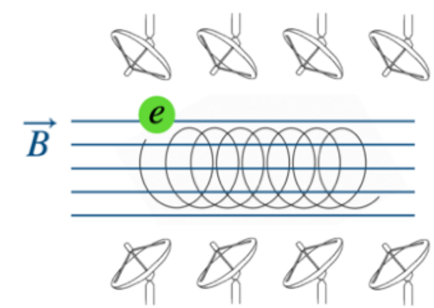
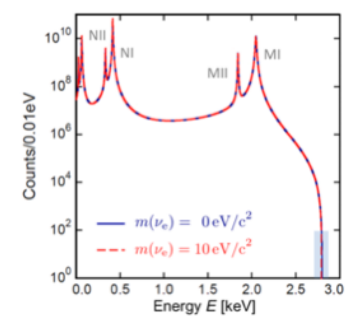
    - Project 8
  - Electron capture (Holmium)
    - ECHo, HoLMES
- Laboratory mass measurement: Input for cosmology!



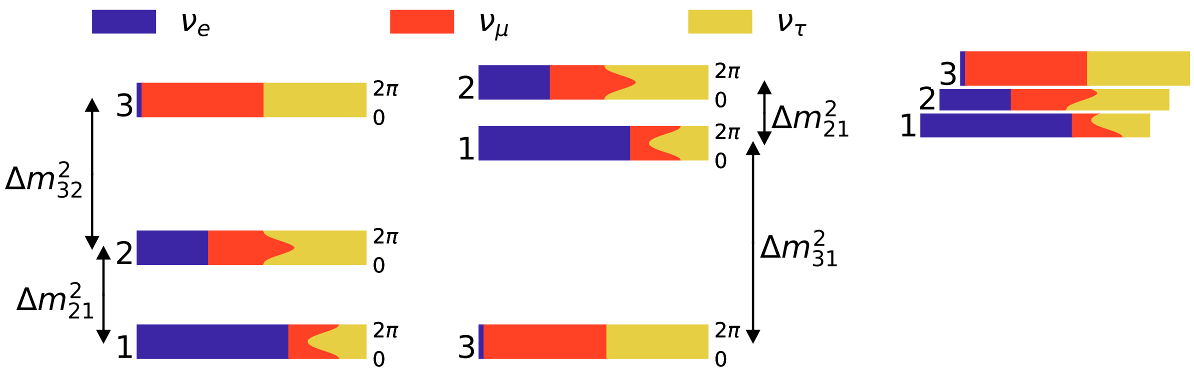






Neutrino Mass

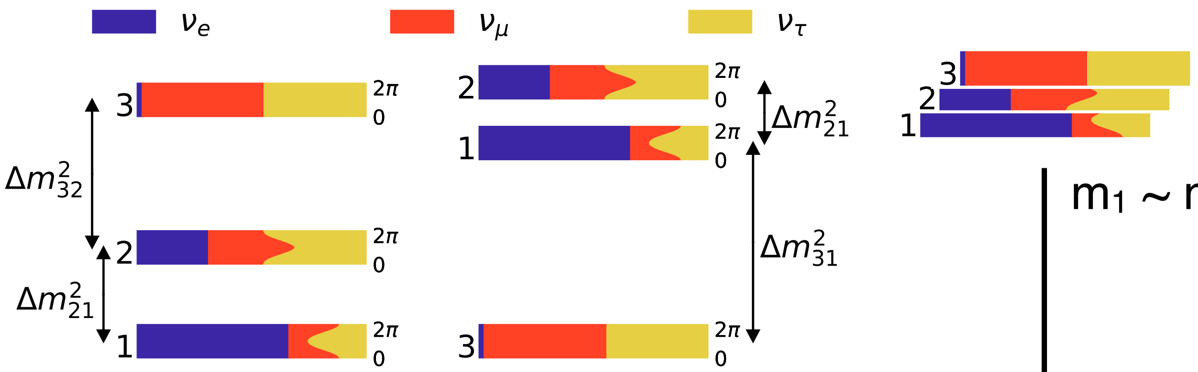
$$m_\beta^2 = \sum |U_{ei}|^2 m_i^2$$



Astron. Space Sci. **5**, 36

Neutrino Mass

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



$m_1 \sim m_2 \sim m_3 > 0$

Degenerate

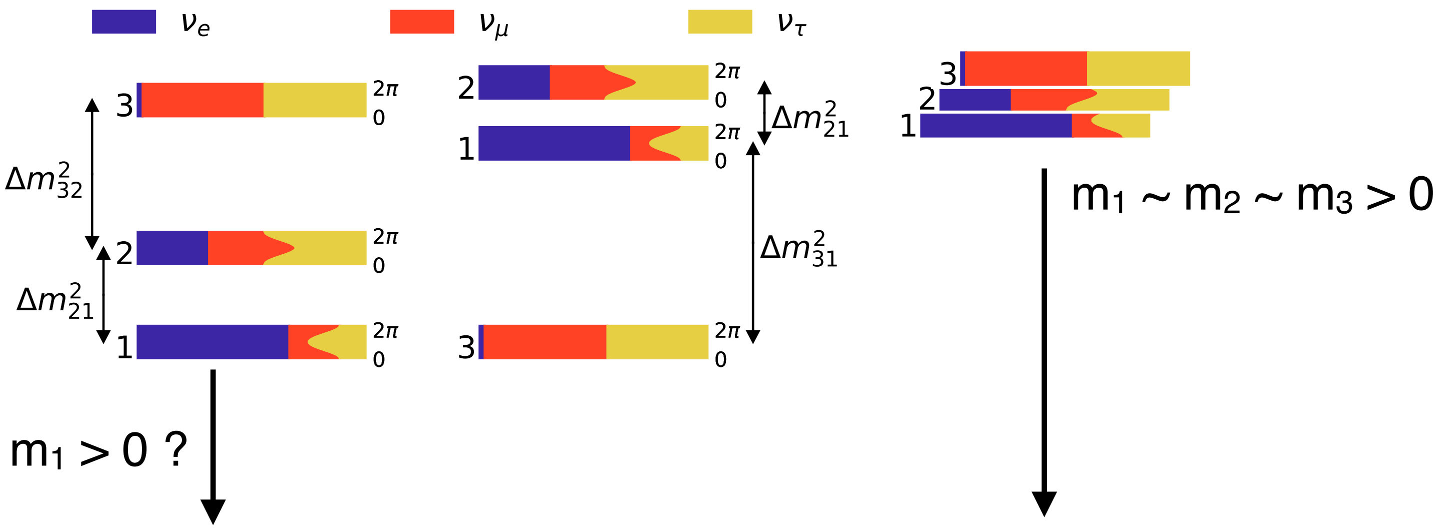
$$m_\beta^{\mathrm{Deg}} \gtrsim 200\,\mathrm{meV}$$

KATRIN:
running

Astron. Space Sci. **5**, 36

Neutrino Mass

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



Normal

$m_\beta^{NO} \gtrsim 8\,\mathrm{meV}$

TOUGH!!!

Degenerate

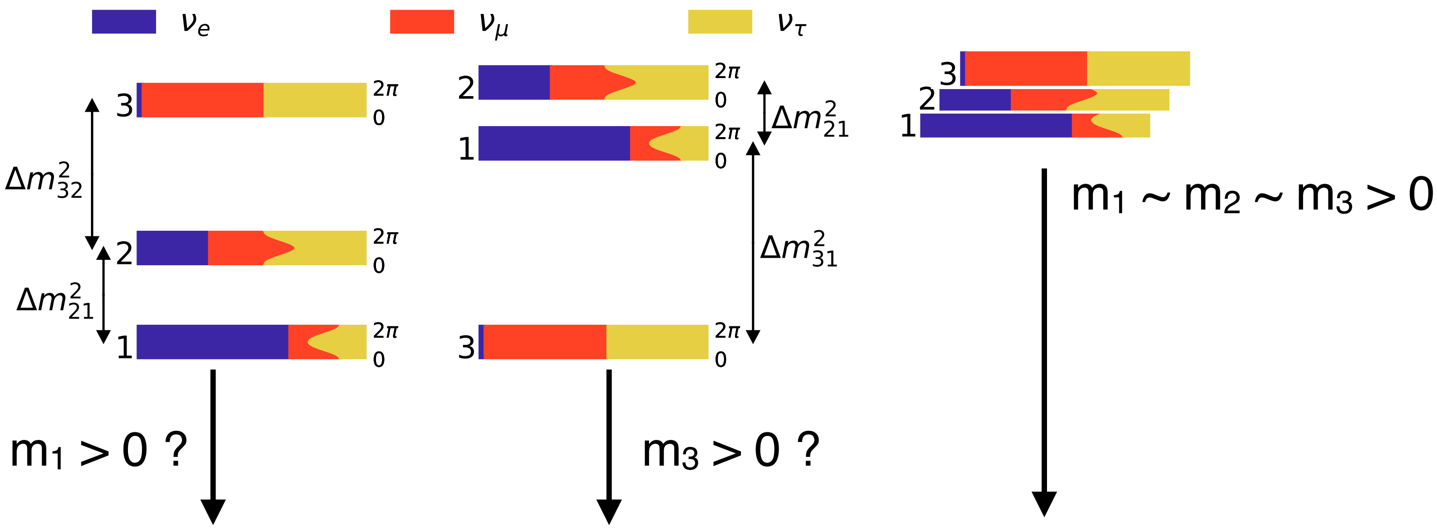
$m_\beta^{Deg} \gtrsim 200\,\mathrm{meV}$

KATRIN: running

Astron. Space Sci. **5**, 36

Neutrino Mass

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



Normal

$m_\beta^{NO} \gtrsim 8\,\text{meV}$

TOUGH!!!

Inverse

$m_\beta^{IO} \gtrsim 40\,\text{meV}$

Project 8:
proposed

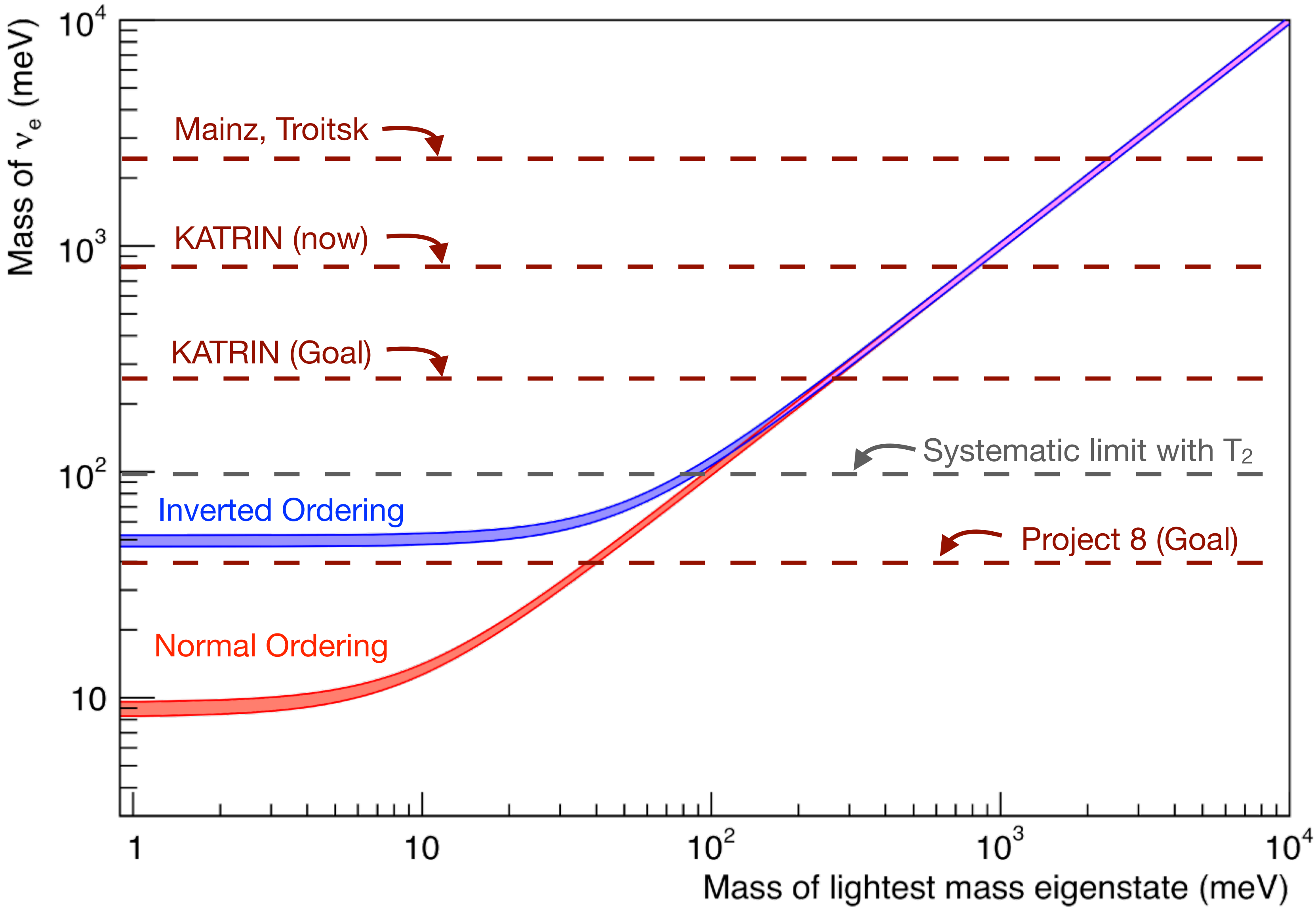
Degenerate

$m_\beta^{Deg} \gtrsim 200\,\text{meV}$

KATRIN:
running

Astron. Space Sci. **5**, 36

Project 8 Goal



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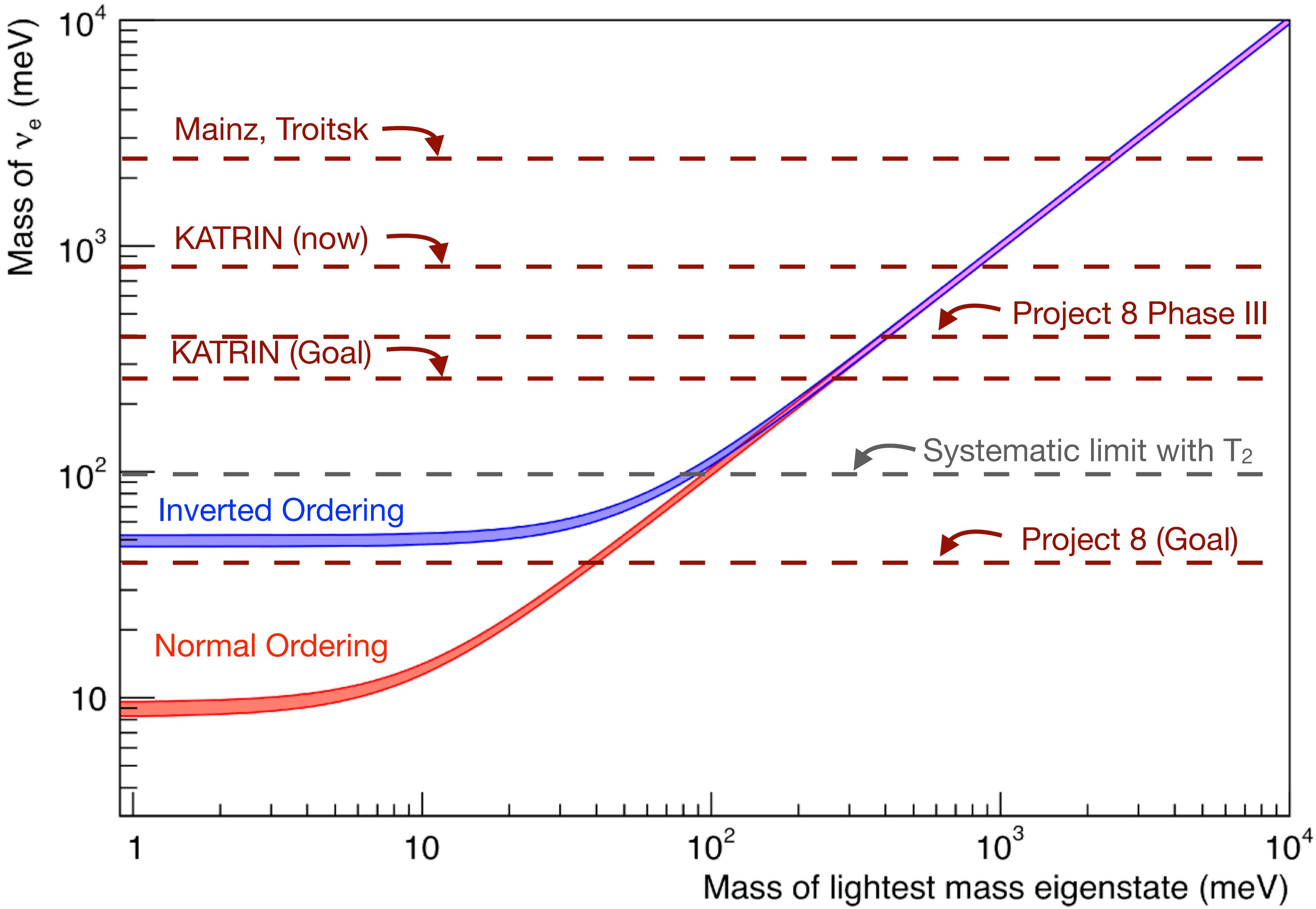
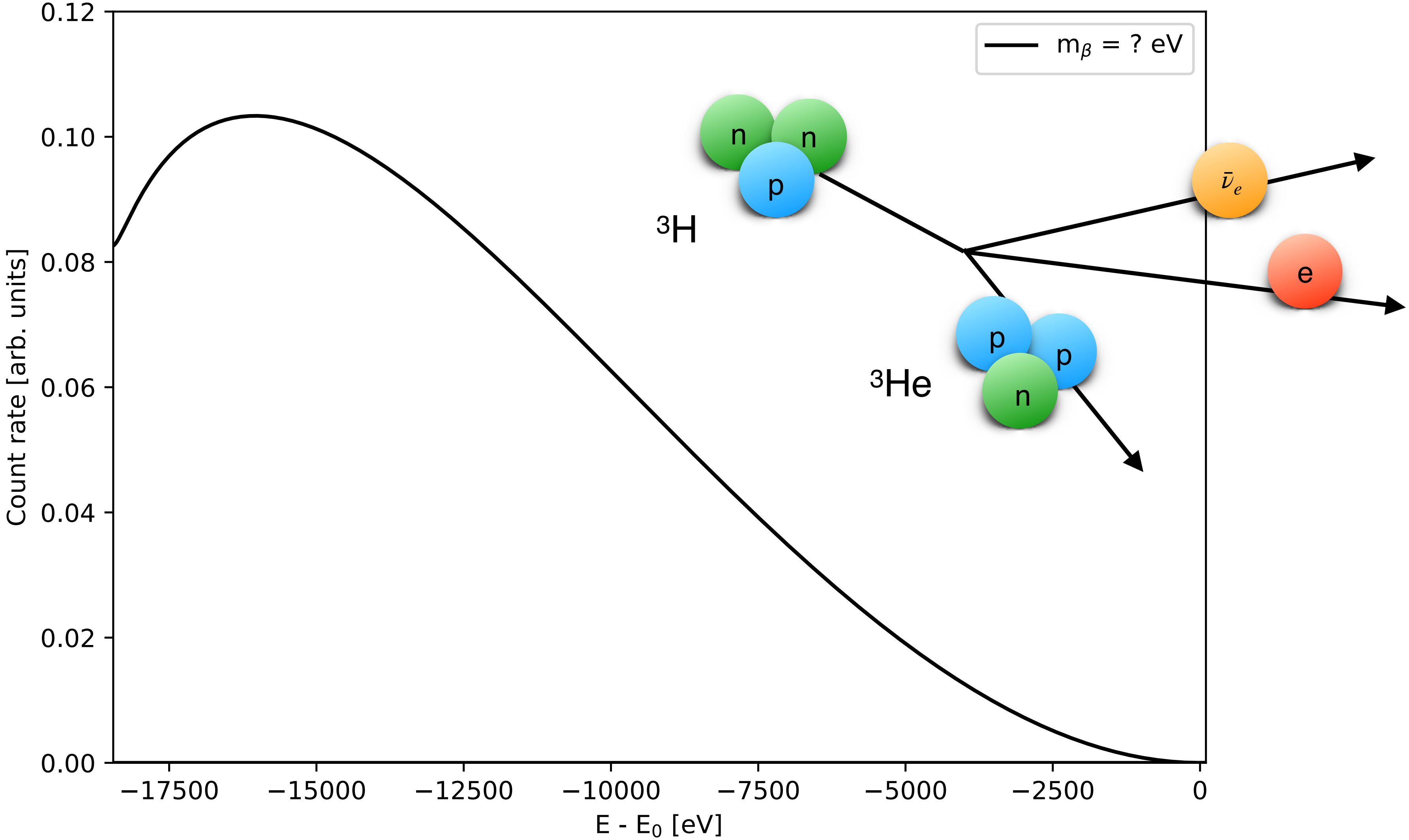


Beta Decay Spectrum



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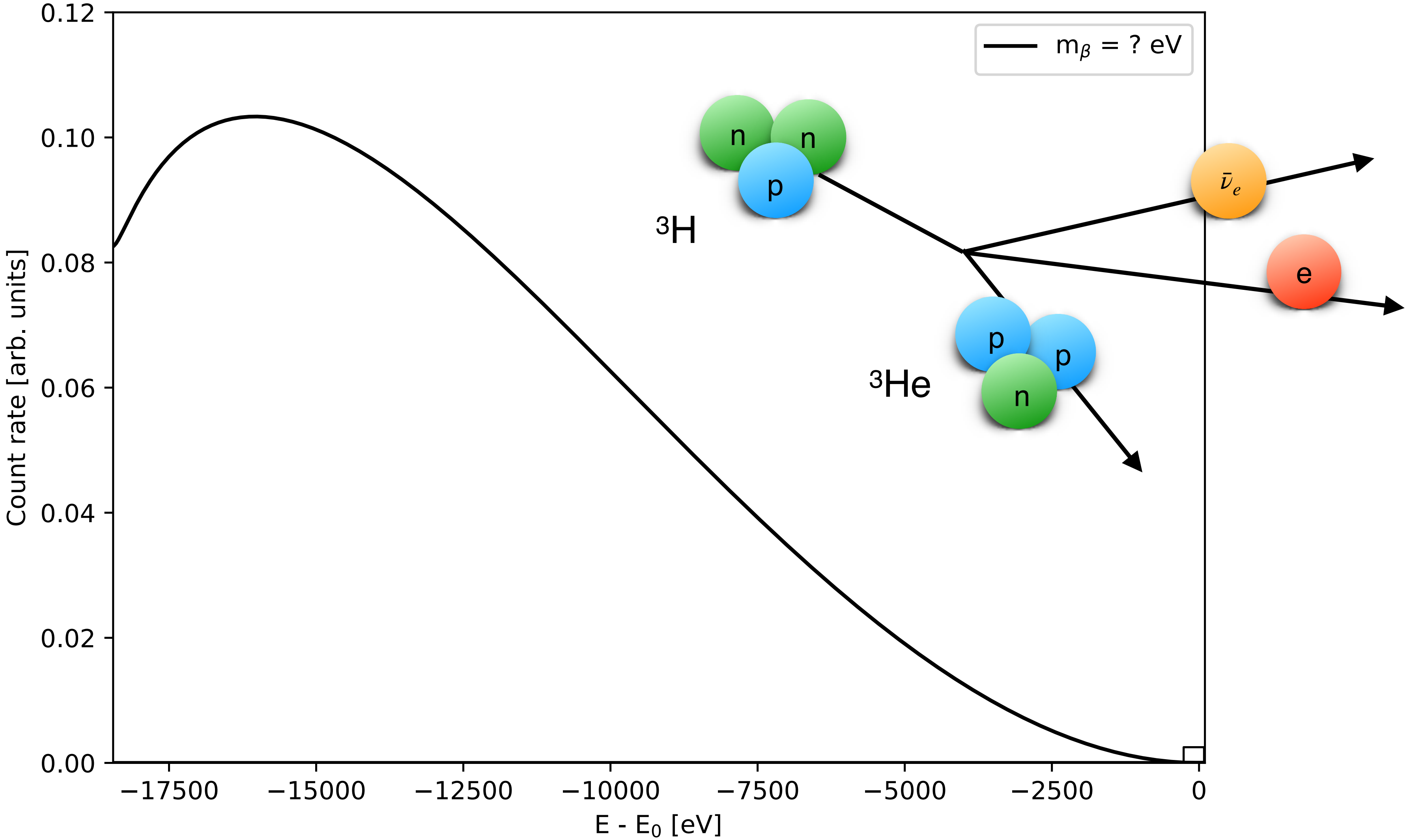

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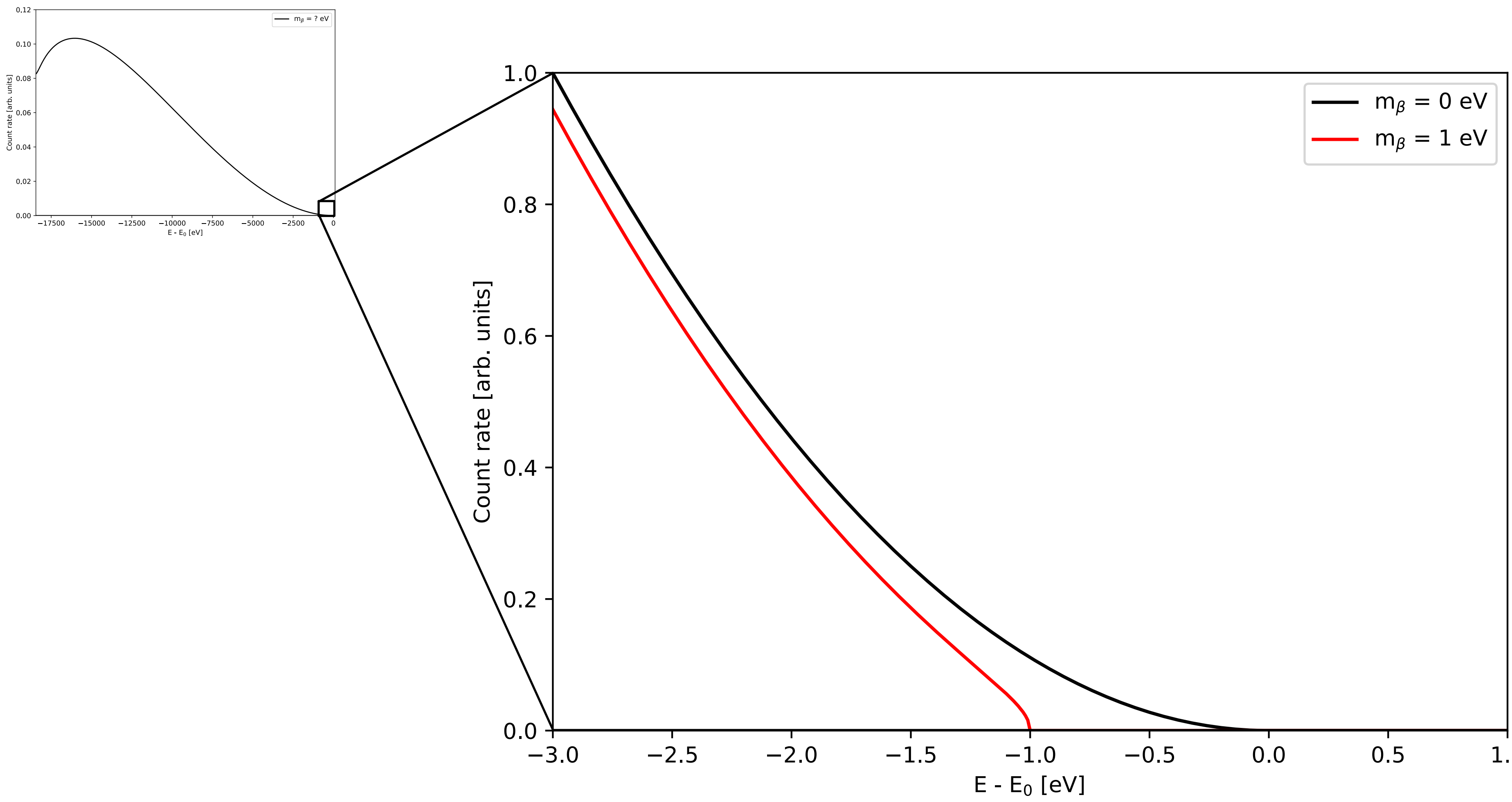
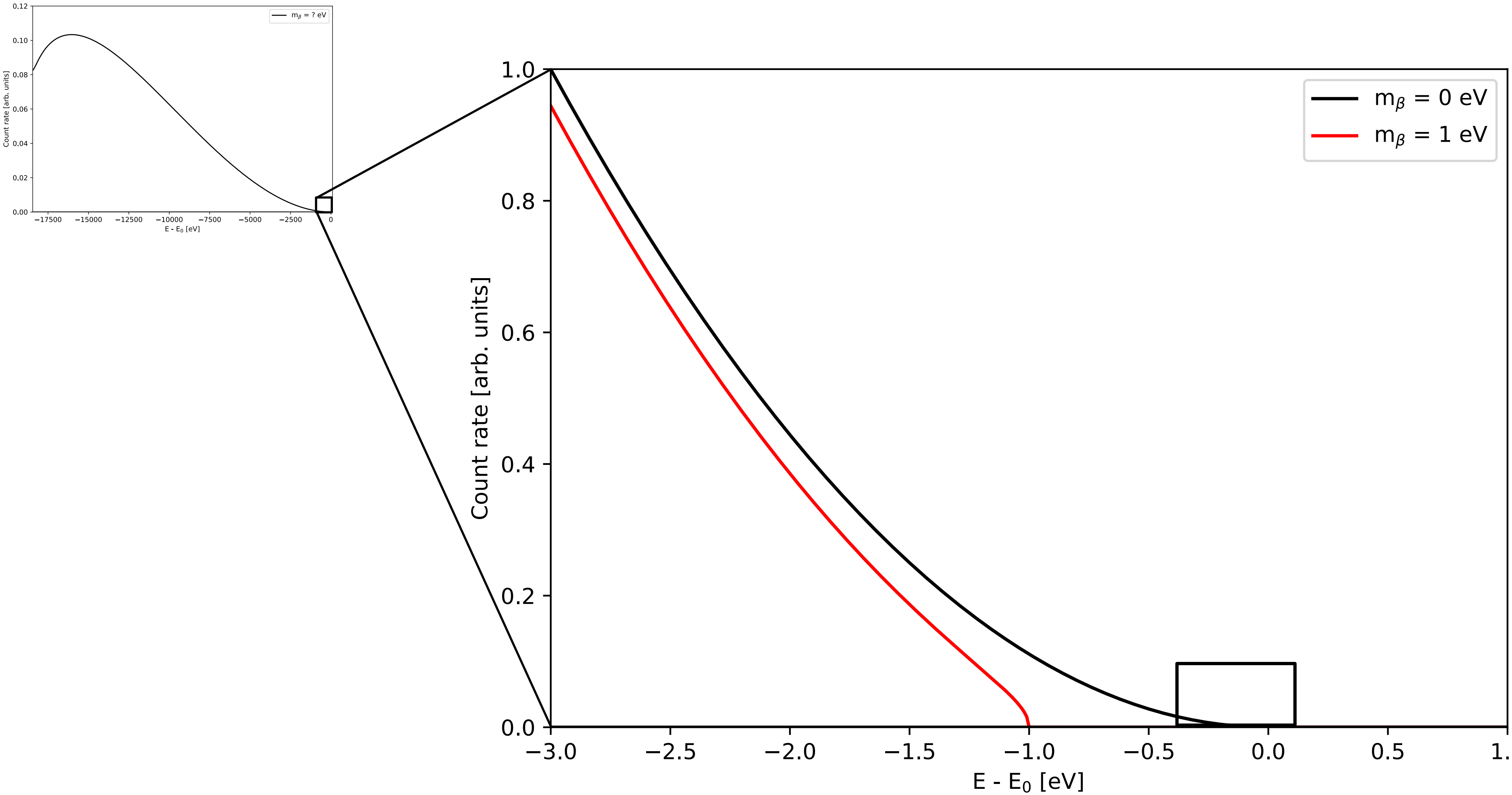


Beta Decay Spectrum



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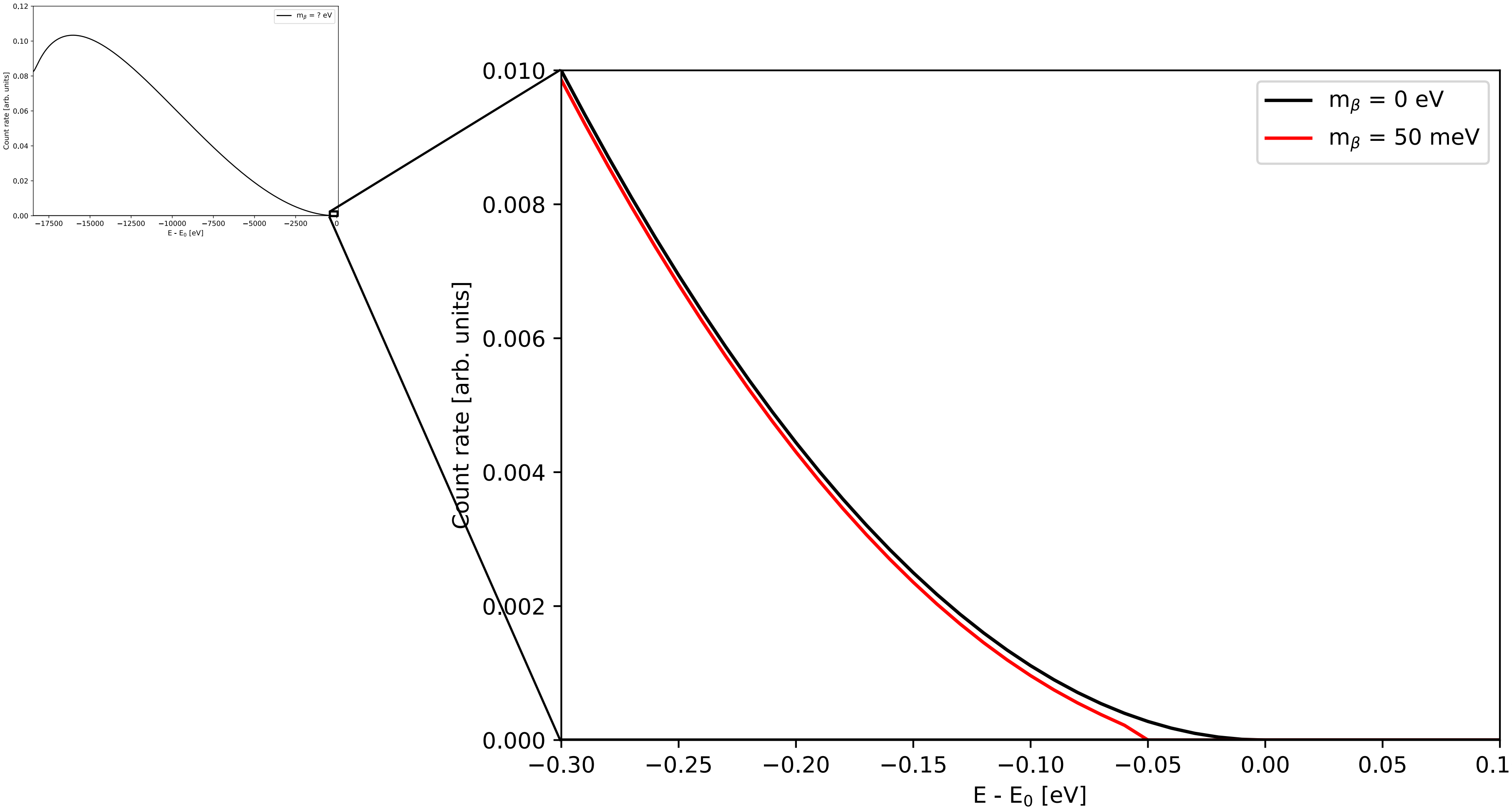

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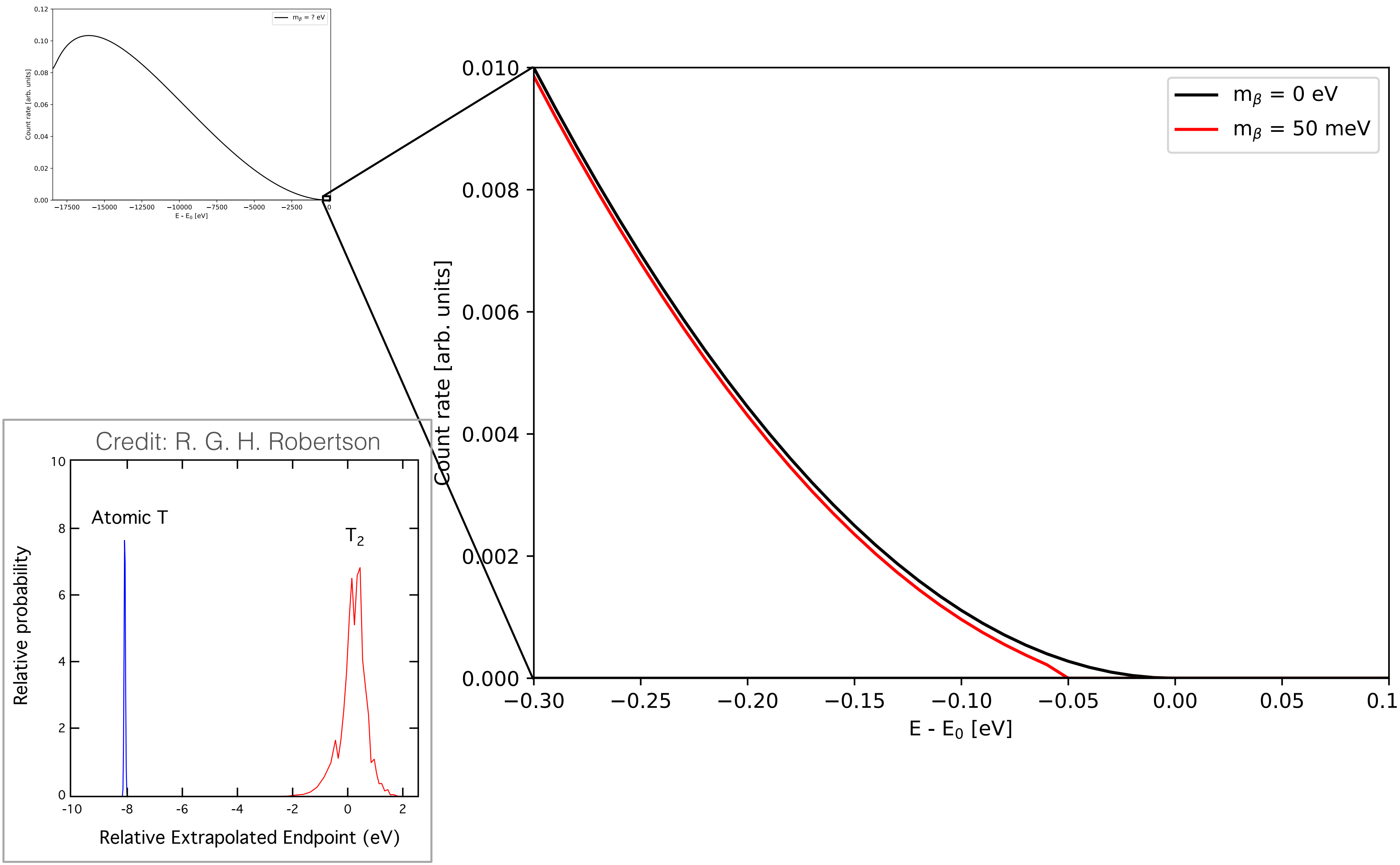
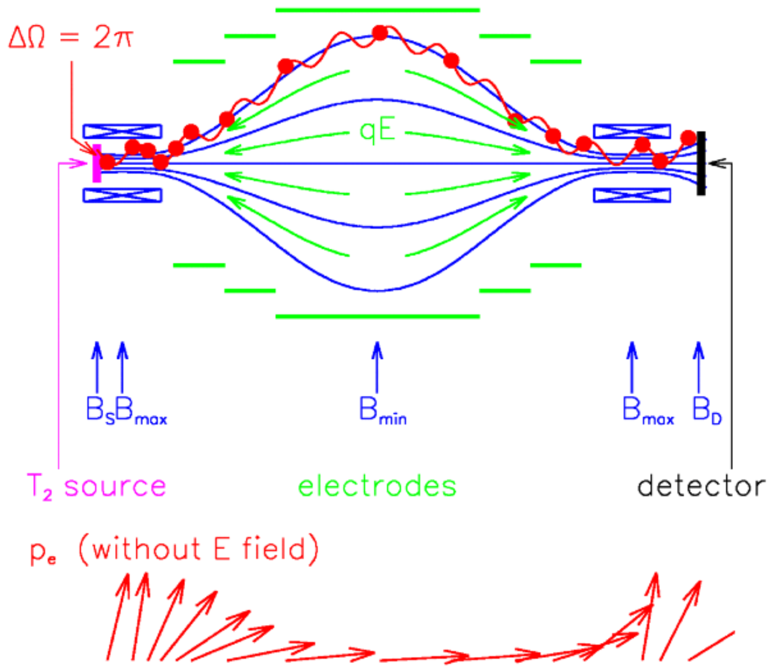


Measuring Neutrino Mass (Now)



- Energy resolution:

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

  defined by size of spectrometer
- Sensitivity to m_β scales as N^{-4}
- Irreducible systematics limit ~0.1 eV
- KATRIN sensitivity: 0.2 eV
  Current results:
  $m_\beta < 0.8\,\text{eV}\ (90\,\%\,\text{C.L.})$

Phys.Rev.Lett. 123 (2019) 22, 221802
https://www.katrin.kit.edu/

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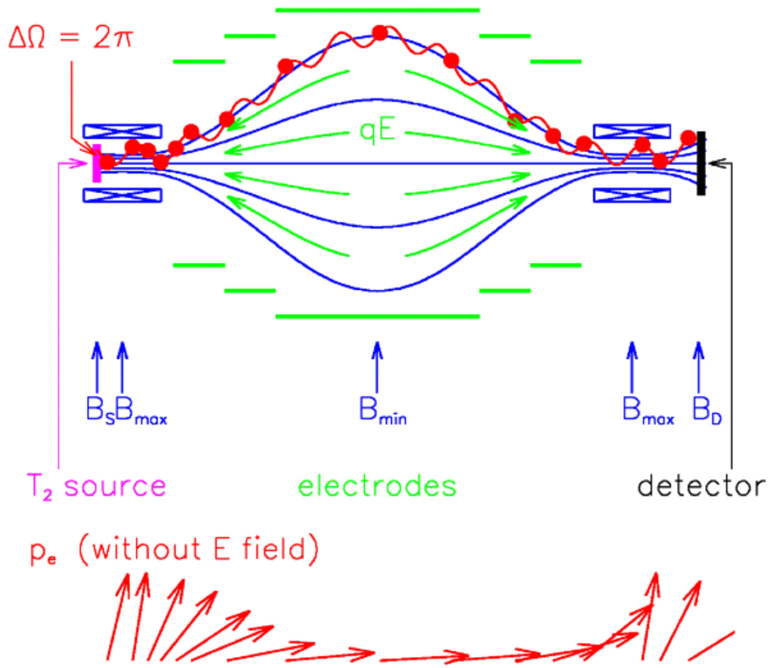

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- KATRIN sensitivity: 0.2 eV
  Current results:
  $m_\beta < 0.8\,\mathrm{eV}\ (90\,\%\ \mathrm{C.L.})$
- What if the mass is smaller than 0.2 eV?

Phys.Rev.Lett. 123 (2019) 22, 221802
https://www.katrin.kit.edu/

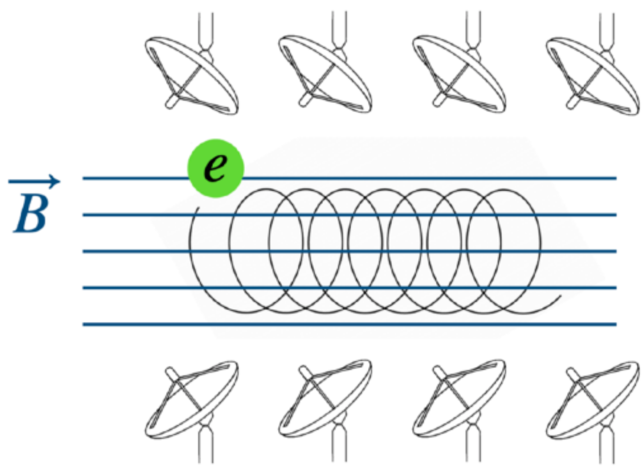
CRES

- Cyclotron Radiation Emission Spectroscopy
- Electron in B-field: cyclotron motion & radiation:

$$2\pi f = \frac{eB}{m_e + K_e/c^2} = \frac{eB}{\gamma m_e}$$

- Energy resolution:

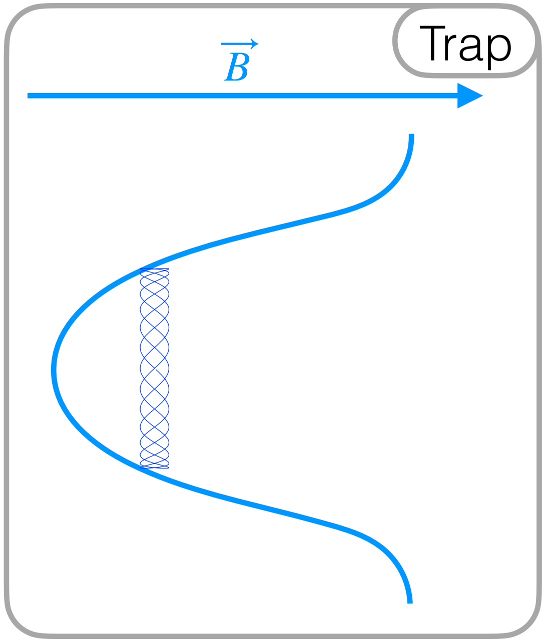
$$\frac{\Delta E}{m_e} = \frac{\Delta f}{f}$$



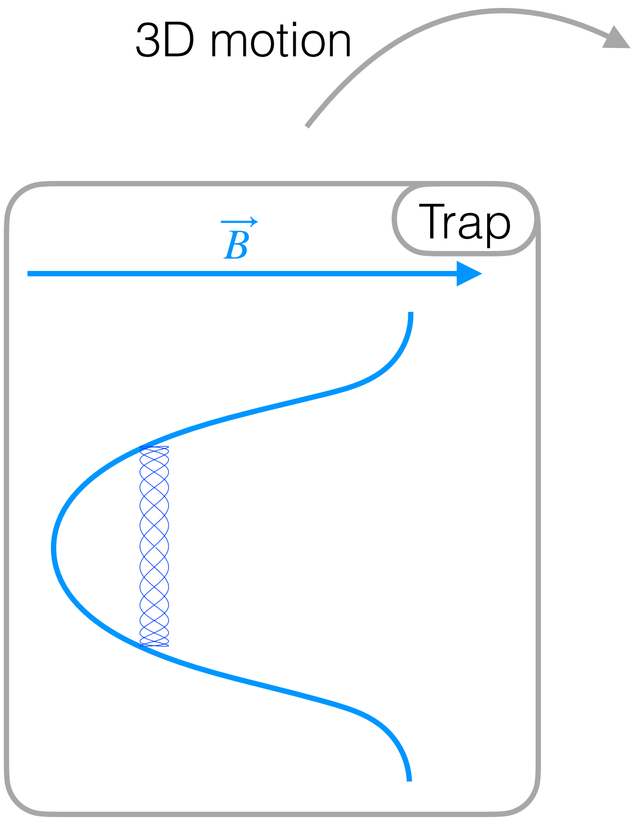
"Never measure anything but frequency!" — A. L. Schawlow

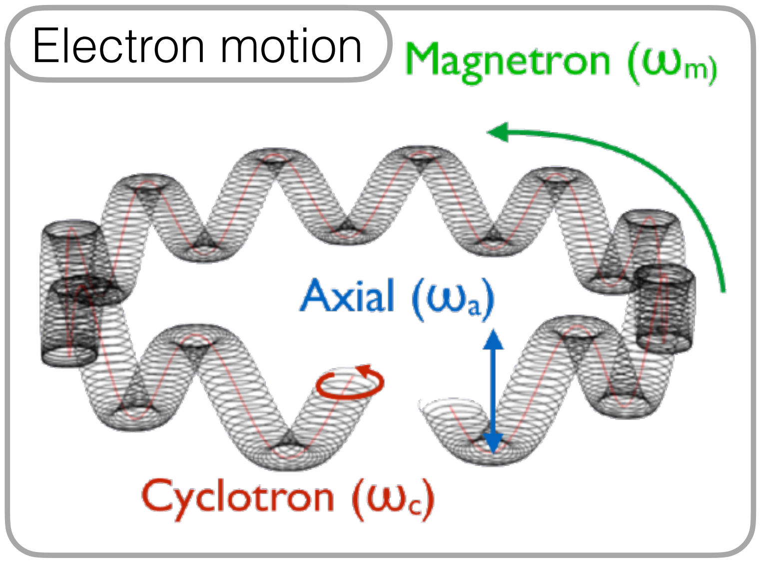
Phys.Rev.D 80 (2009) 051301

CRES



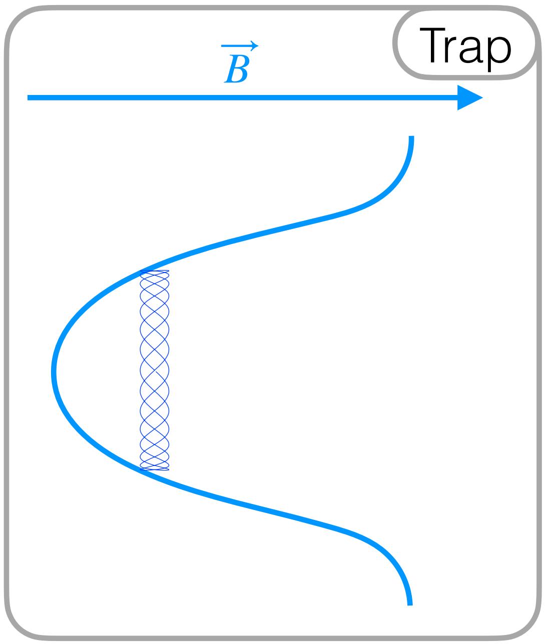
CRES

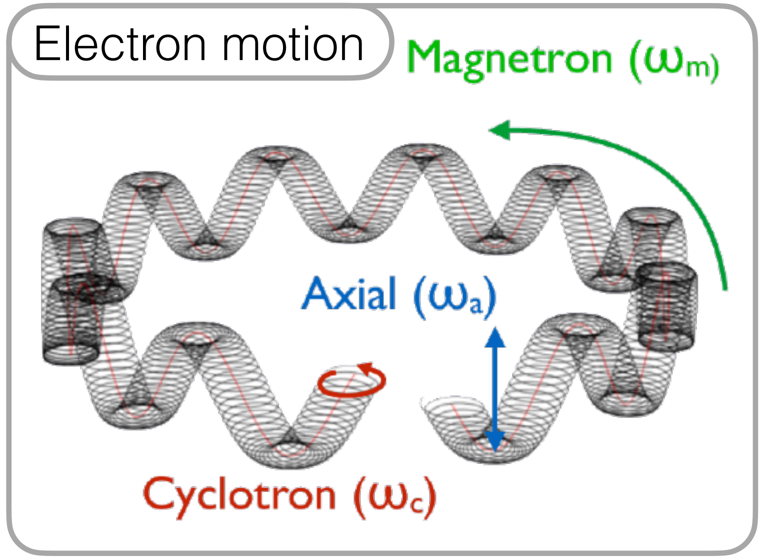

3D motion
Trap
$\vec{B}$


Electron motion
Magnetron (ω_m)
Axial (ω_a)
Cyclotron (ω_c)

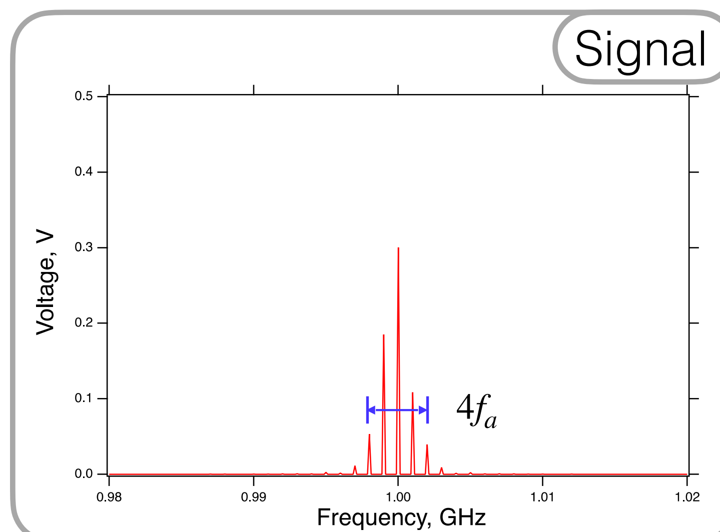
CRES

3D motion



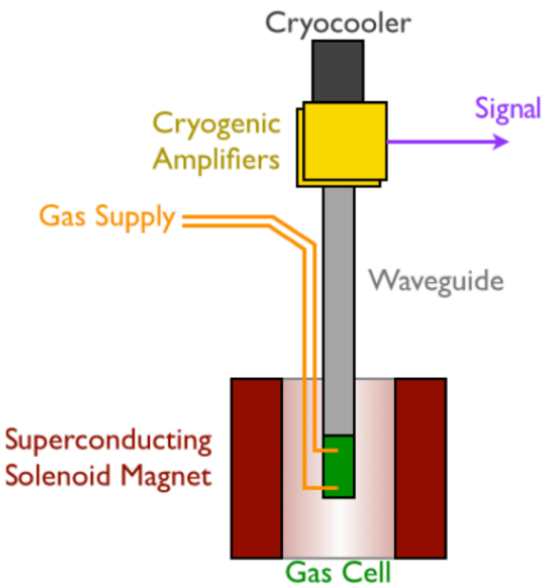


Sideband structure



Reconstruction & Analysis

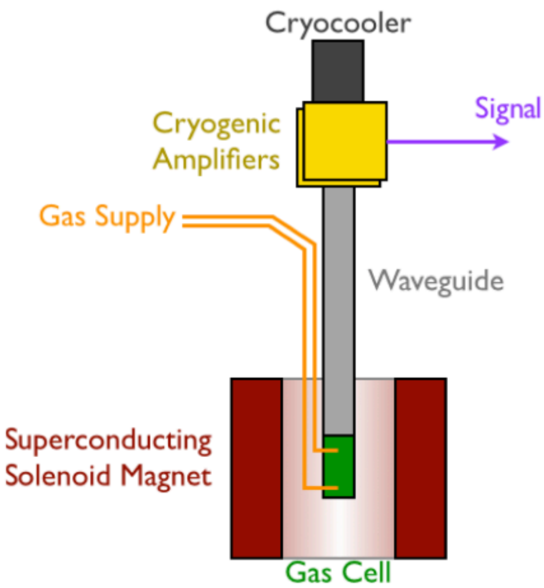
Phase I

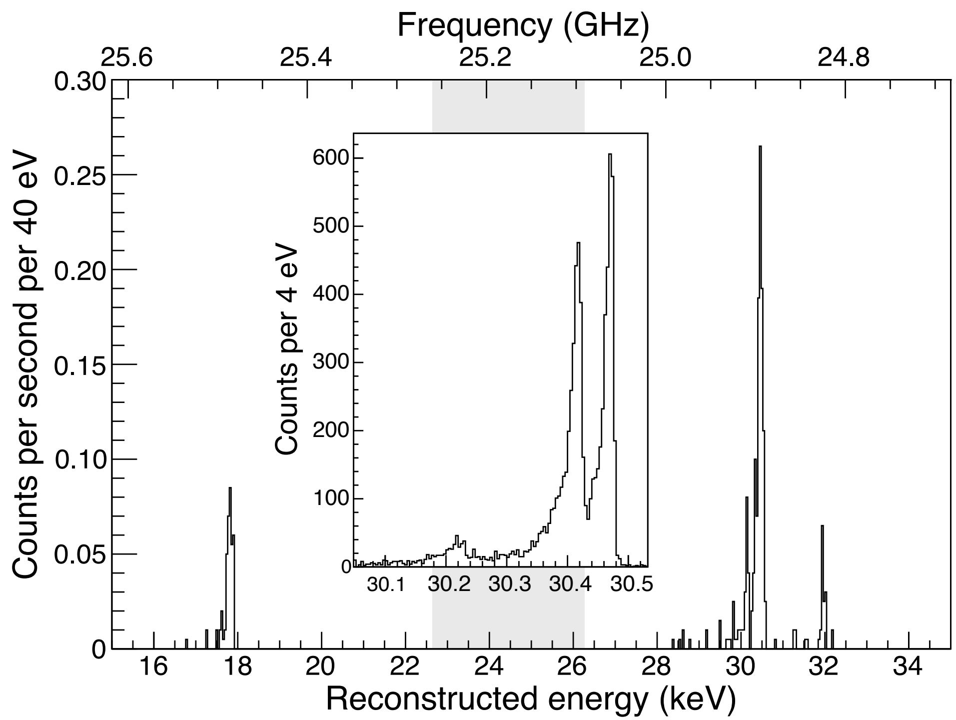


- ^{83m}Kr: electron conversion lines at 18 keV, 30 keV and a 32 keV
- Demonstrated energy measurement of single trapped electrons via CRES, resolution: 3.3 eV

Phys. Rev. Lett. 114 (2015) 162501

Phase I





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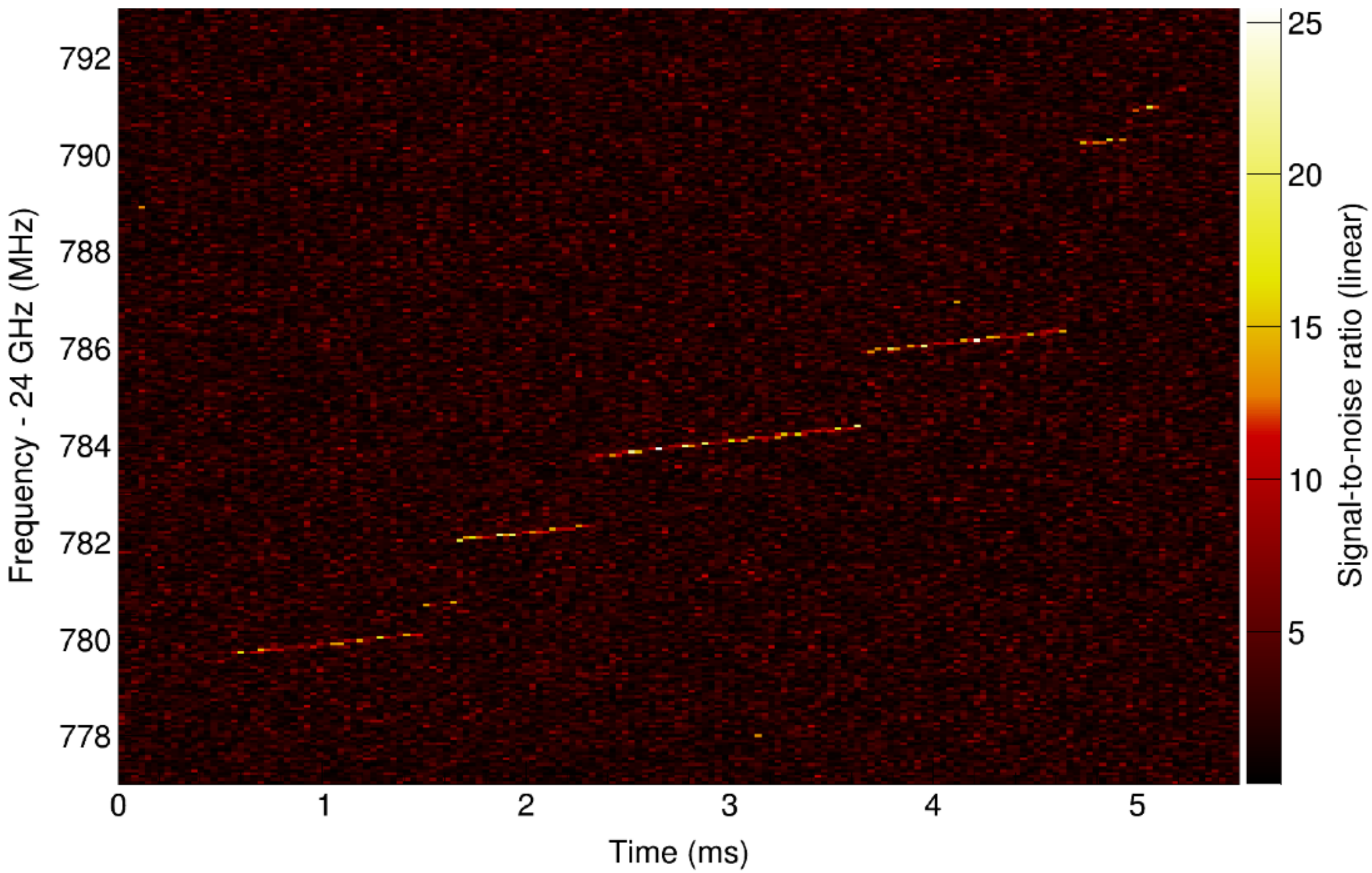
A Typical CRES Event



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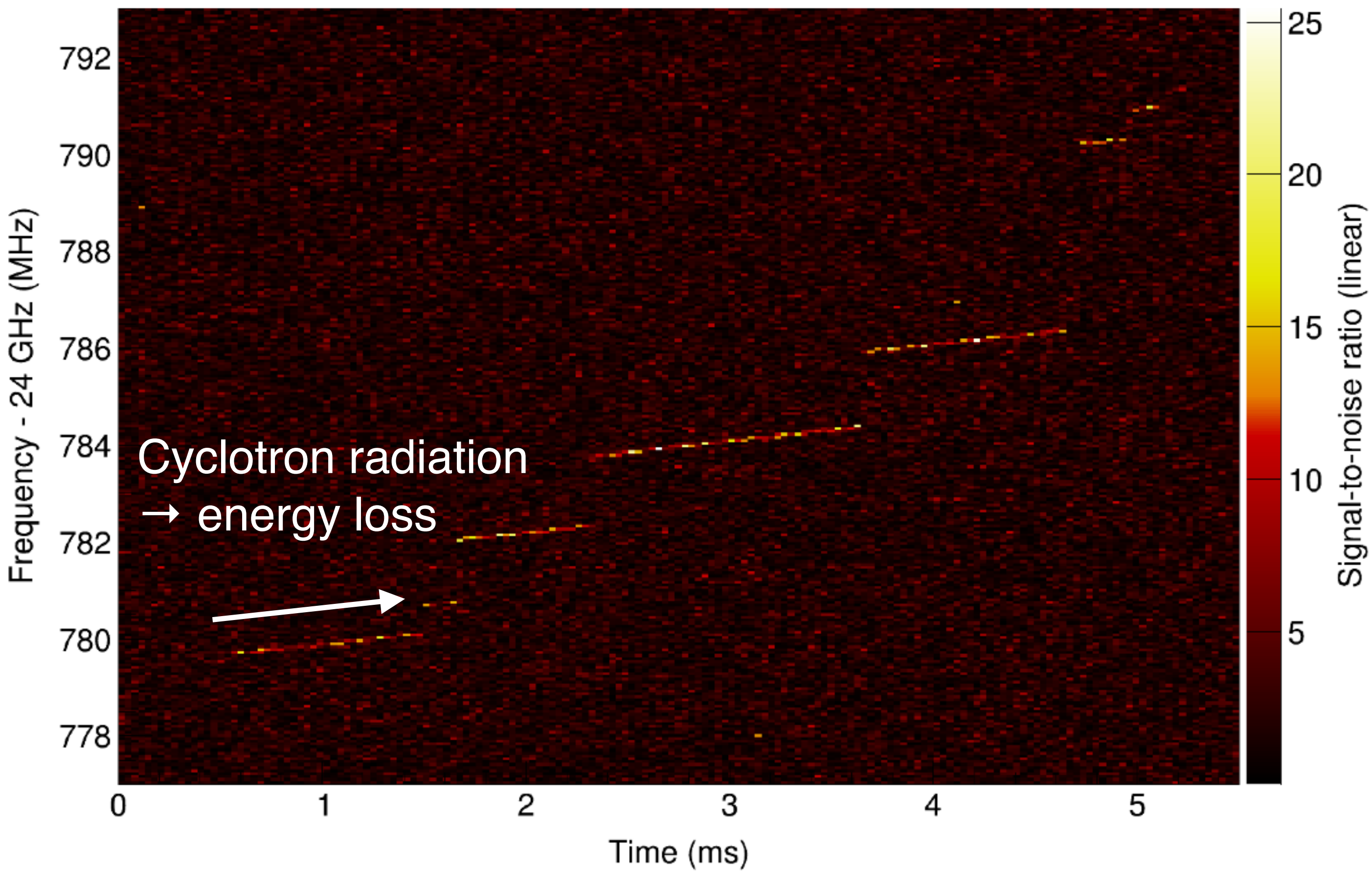
Phys. Rev. Lett. 114 (2015) 162501

A Typical CRES Event



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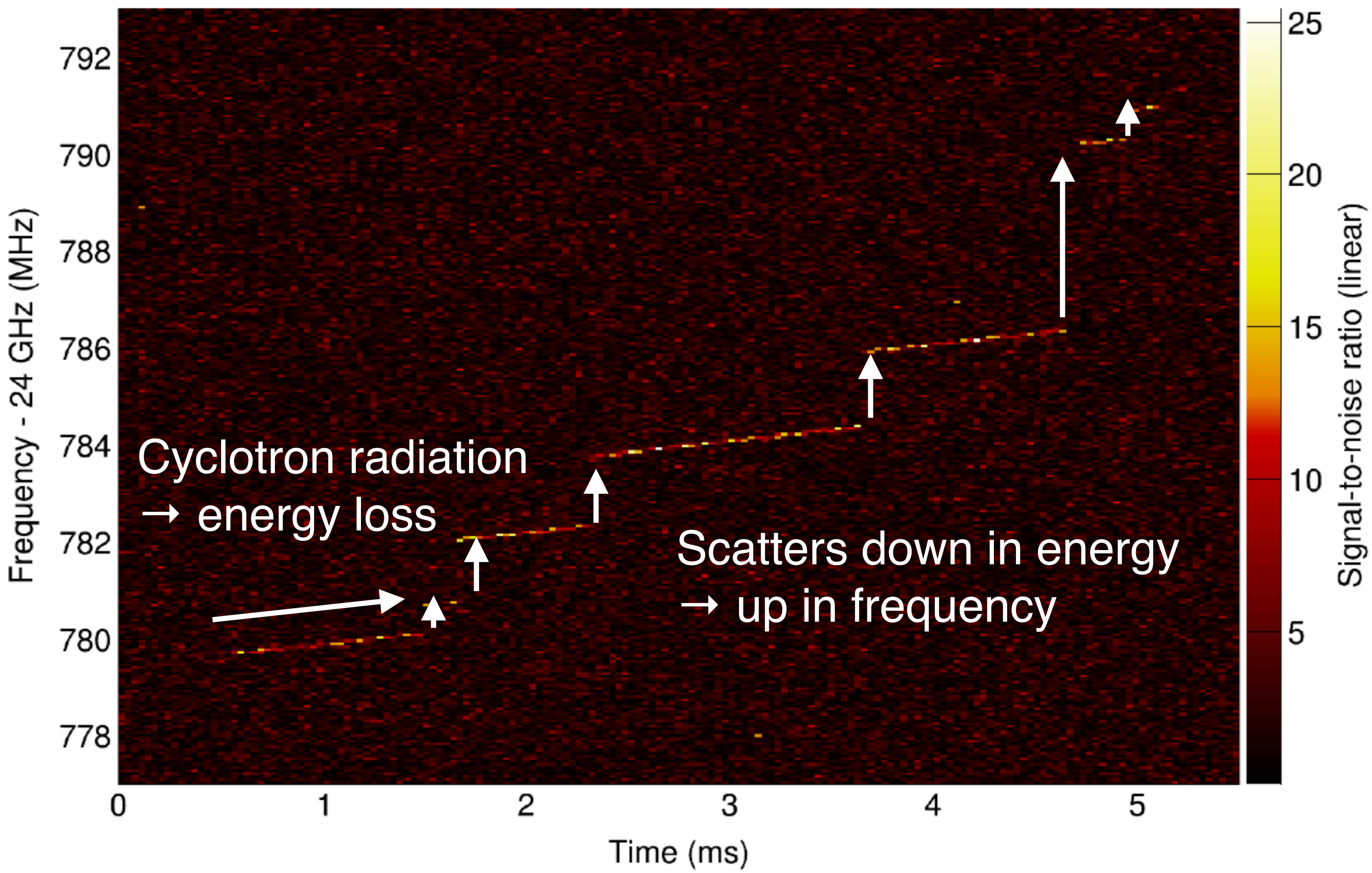

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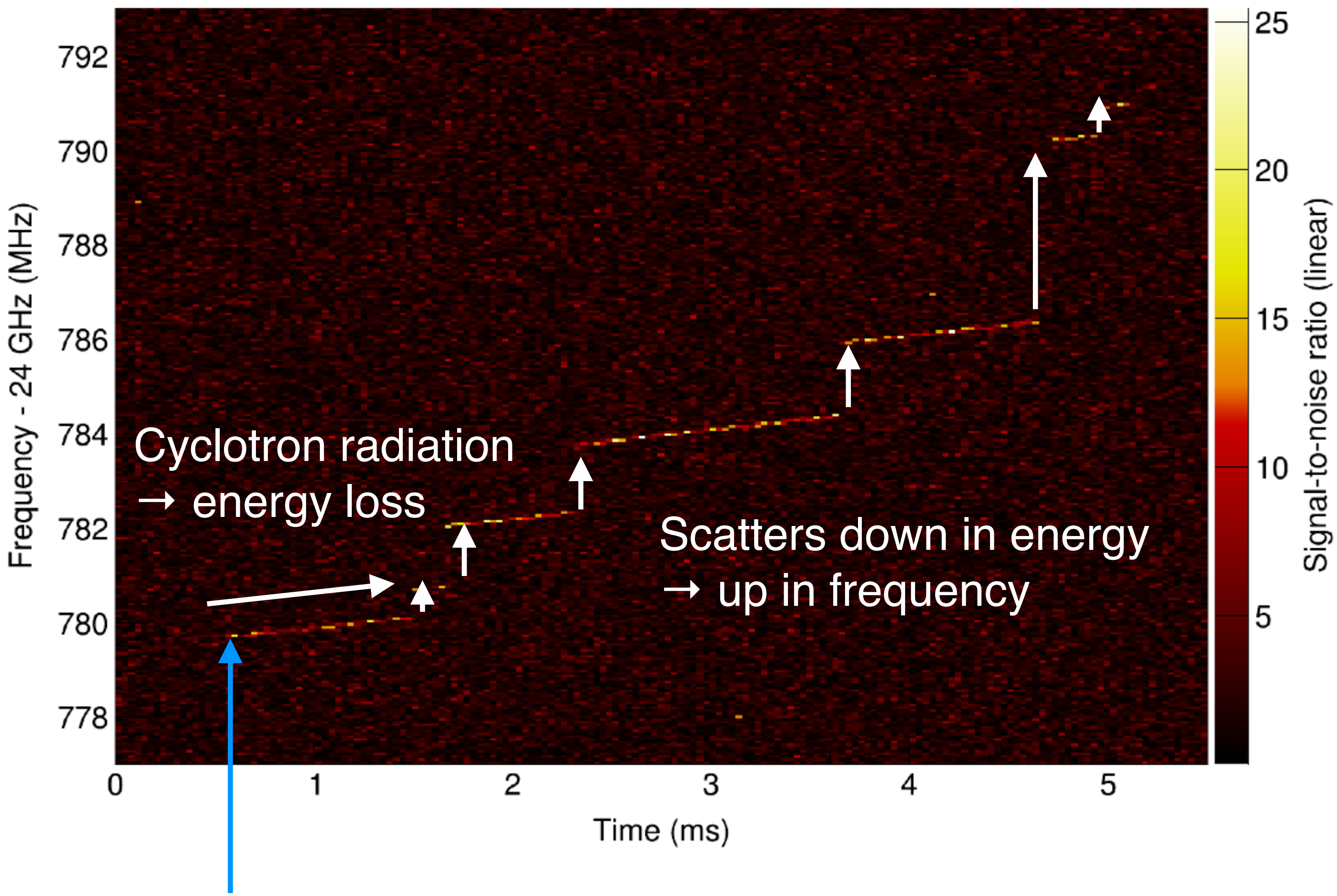
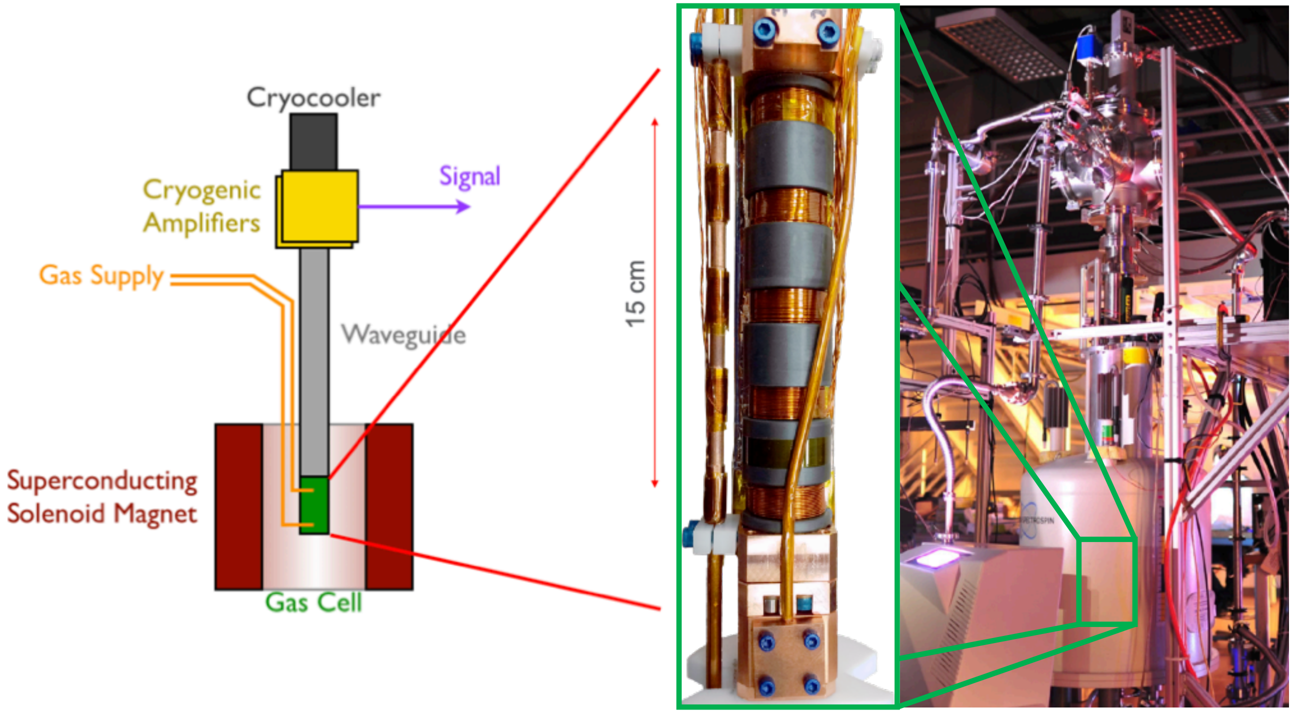


Start frequency: determines electron energy before losses

$$2\pi f = \frac{eB}{m_e + K_e/c^2} = \frac{eB}{\gamma m_e}$$

Phys. Rev. Lett. 114 (2015) 162501

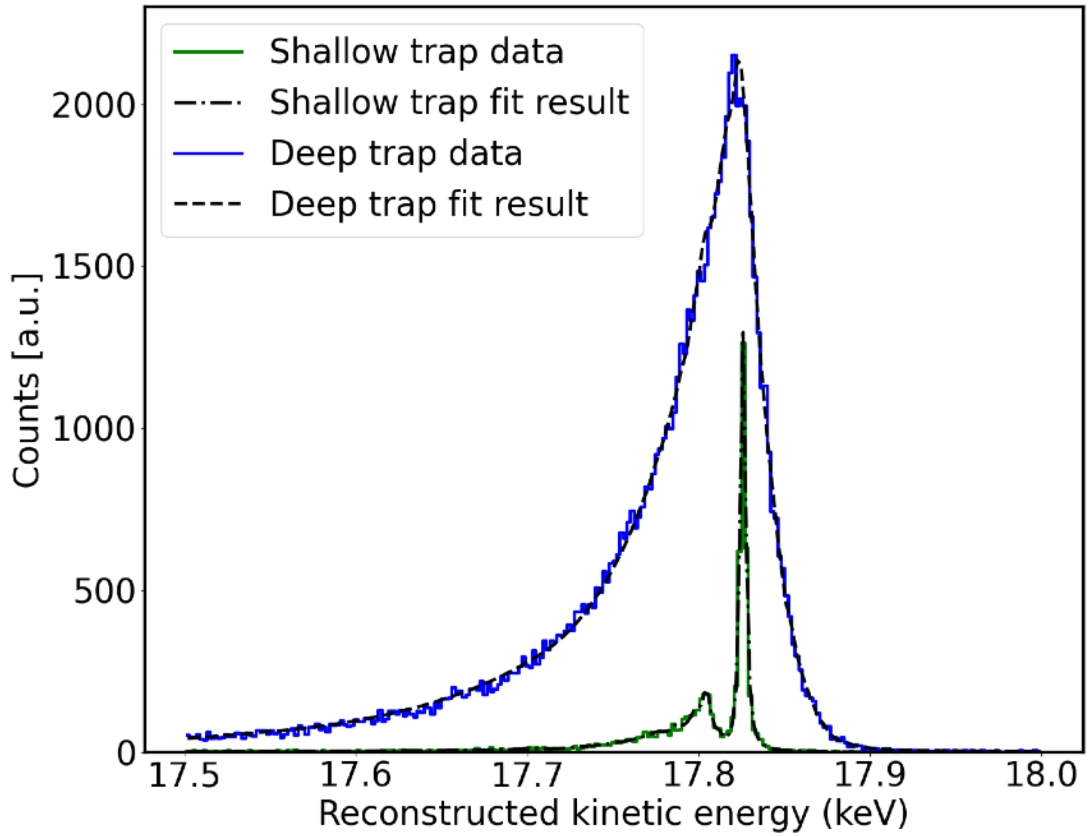
Phase II



- Effective volume: 1mm^3
- Demonstrated CRES on continuous spectrum
- First neutrino mass extraction

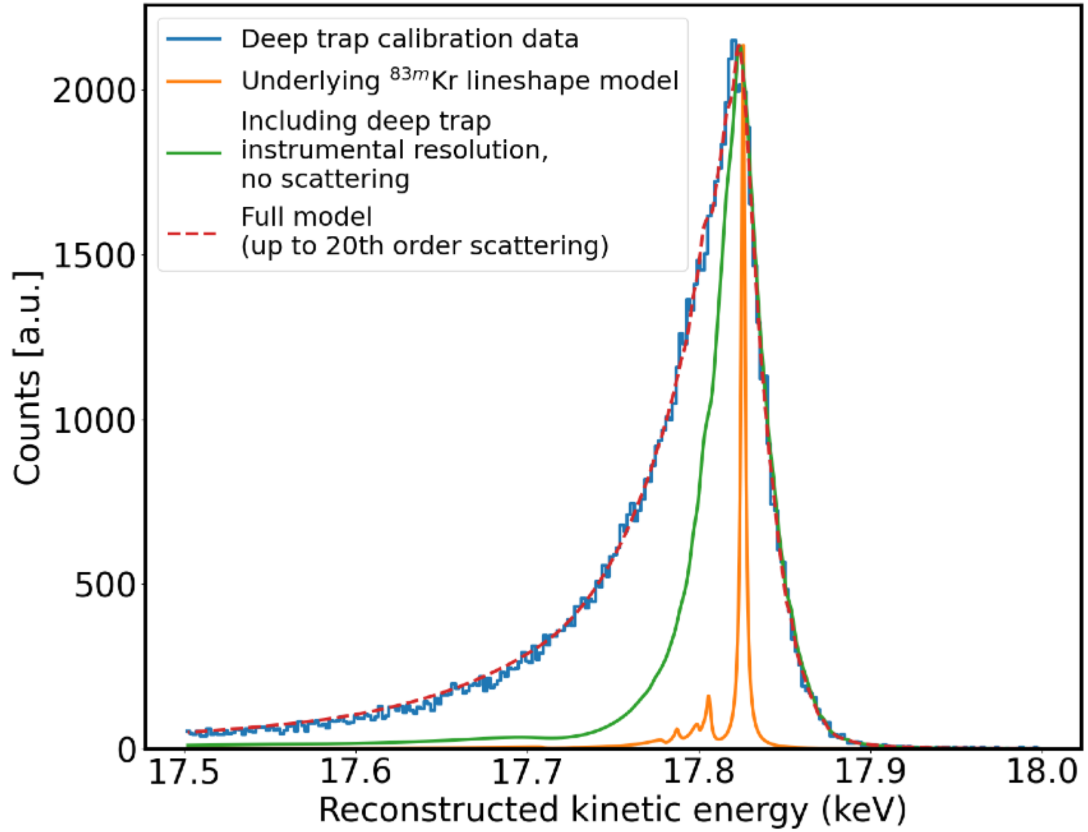
^{83m}Kr Measurements

- "Shallow" trap:
  - magnetic field calibration via Kr K-line
  - 1.7 ± 0.2 eV (FWHM) energy resolution (2.8 ± 0.1 eV natural linewidth)
- "Deep trap":
  - Increased statistics
  - Used for tritium run



Detector Response

- Broadening from magnetic field inhomogeneity, scattering, and missed tracks
- Well understood



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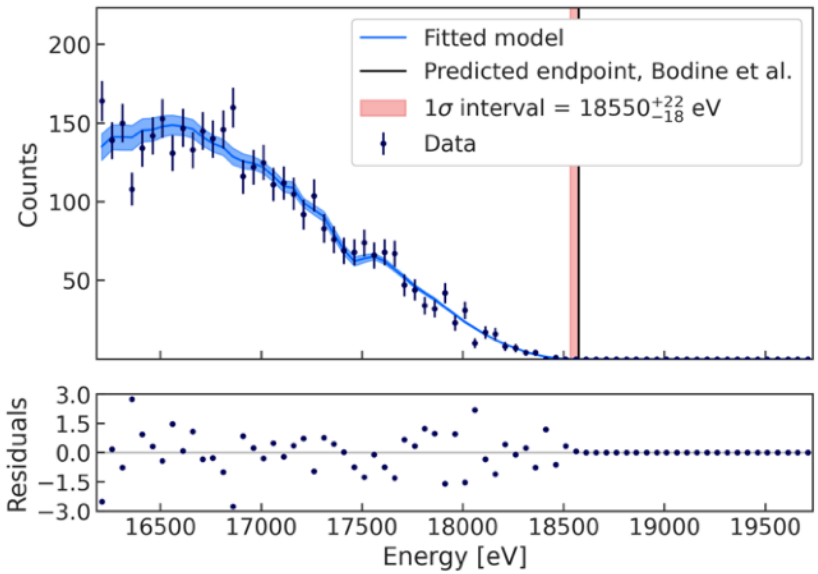

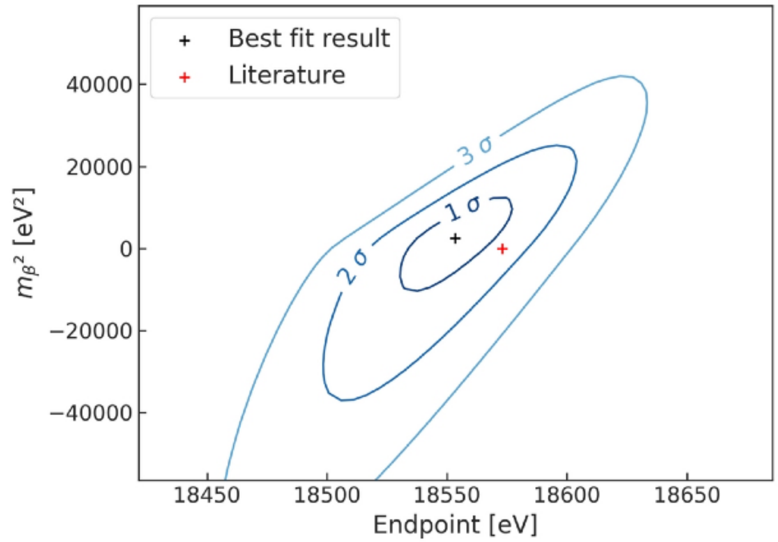

T_2 endpoint

Frequentist: $E_0 = \left(18550^{+22}_{-18}\right)$ eV (1σ)

Bayesian: $E_0 = \left(18553^{+17}_{-17}\right)$ eV (1σ)

Neutrino mass

Frequentist: $\leq 178\,\mathrm{eV}/c^2\,(90\,\%\,\mathrm{C.L.})$

Bayesian: $\leq 169\,\mathrm{eV}/c^2\,(90\,\%\,\mathrm{C.L.})$

Background rate

$\leq 3\times 10^{-10}\,\mathrm{eV}^{-1}s^{-1}\,(90\,\%\,\mathrm{C.L.})$

Project 8 Achievements

PROJECT 8

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

Phase I

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

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

Construction | Data-taking | Analysis

→ Systematic & background studies
→ T_2 spectrum and endpoint

- First **tritium spectroscopy** using CRES
- First **neutrino mass limit** using CRES
- Demonstration of **high resolution**
- Demonstration of a **zero background** experiment
- Demonstration of **control of systematic effects**

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- Demonstration of a **zero background** experiment ✓
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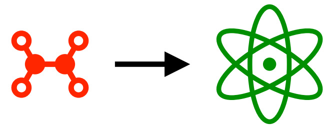
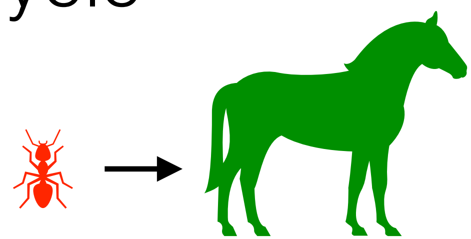
Phase III

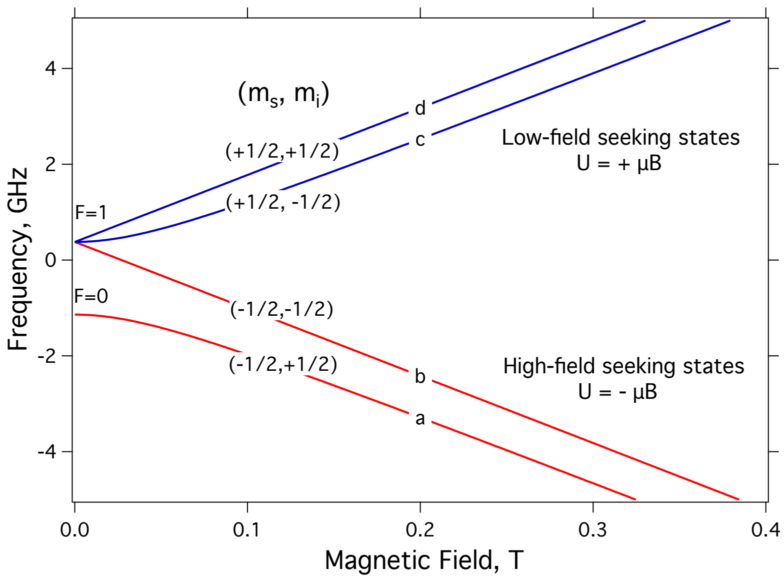
- Go atomic! 
  demonstrate atomic tritium trapping — crack, cool, trap, contain, recycle

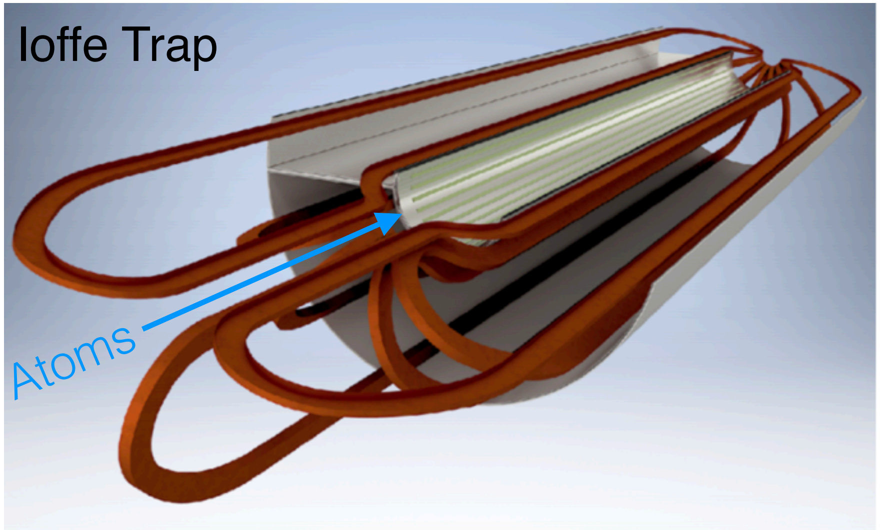


- Go bigger!
  demonstrate CRES on large source volume (free space or cavity)

- Merge both into atomic CRES experiment, obtain first neutrino mass limit using atomic tritium

Atomic Tritium Demonstrator

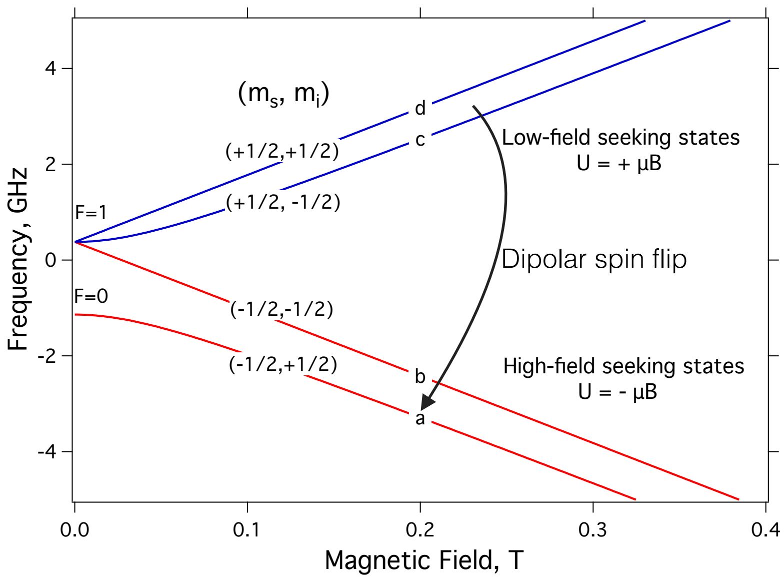


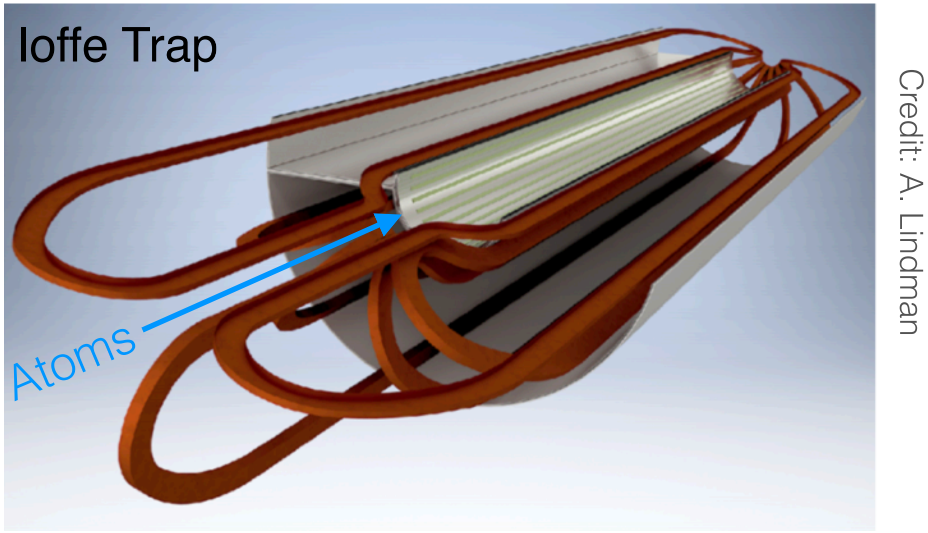


Credit: A. Lindman

- Ioffe trap: mature design, superconducting coils
- Alternative: Halbach array: permanent magnets

Atomic Tritium Demonstrator





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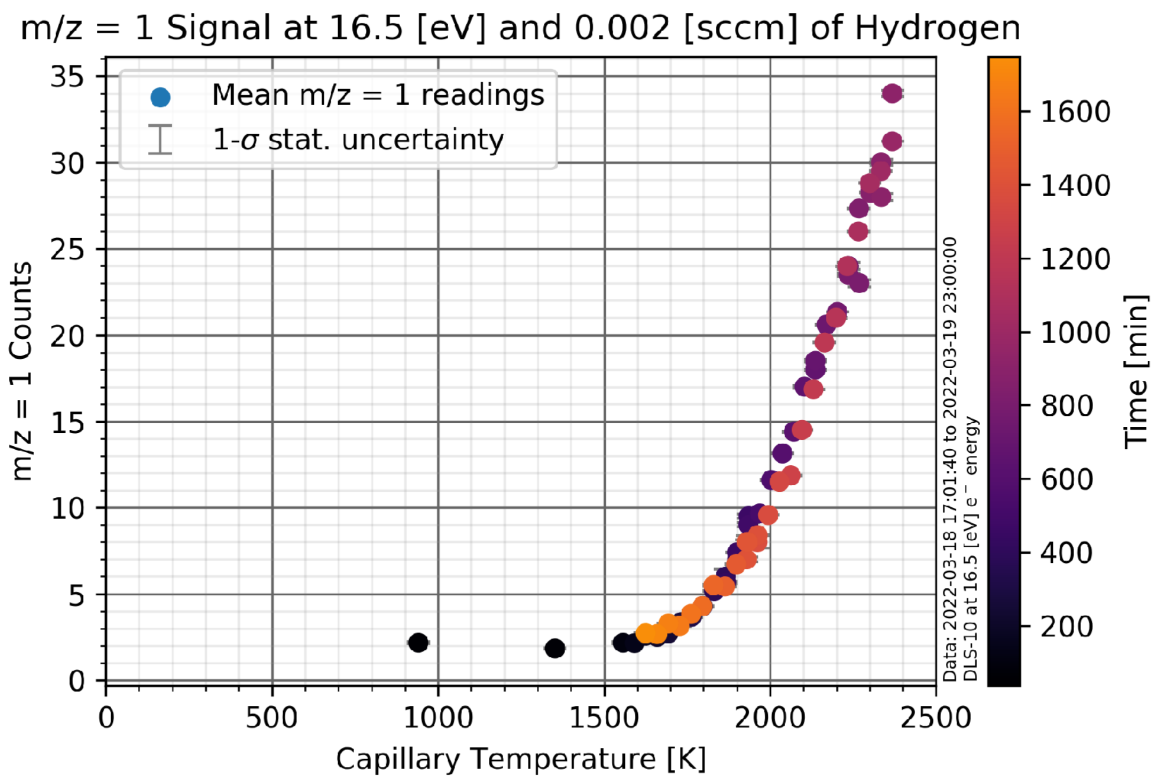
Hydrogen Atom Production

PROJECT 8



- Prove atom cracking using mass spectrometer

- Atom flux analysis in progress

Hydrogen Atom Production

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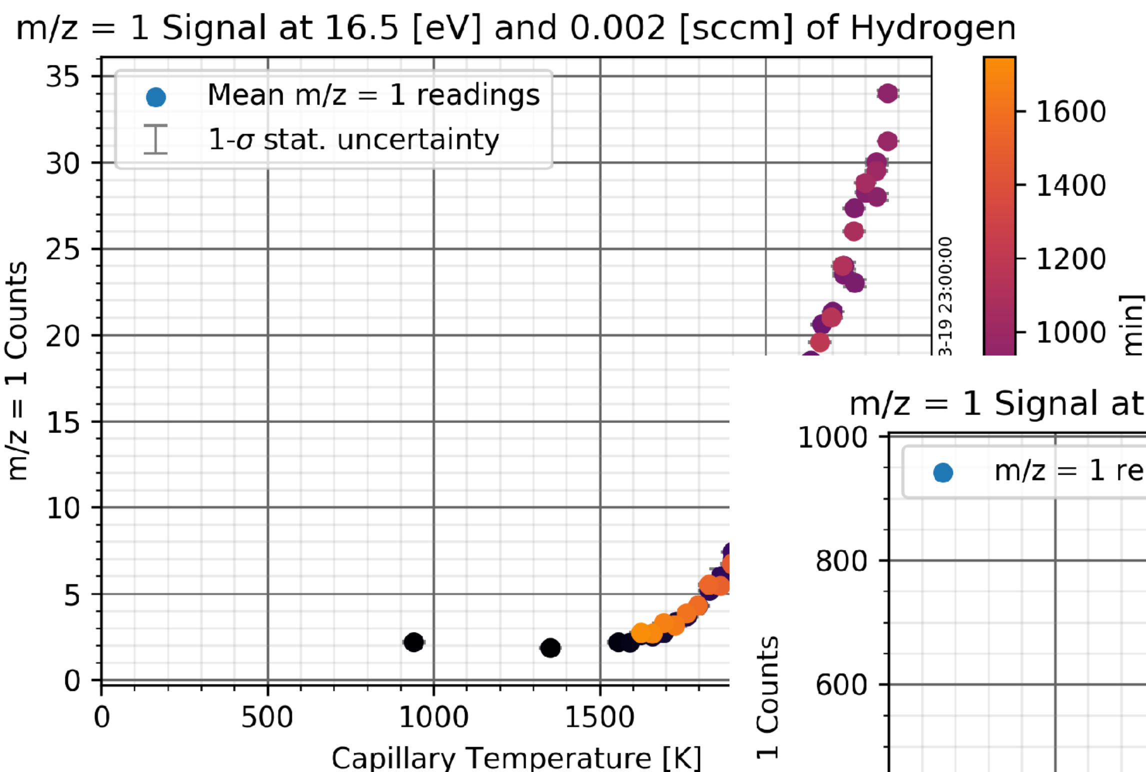

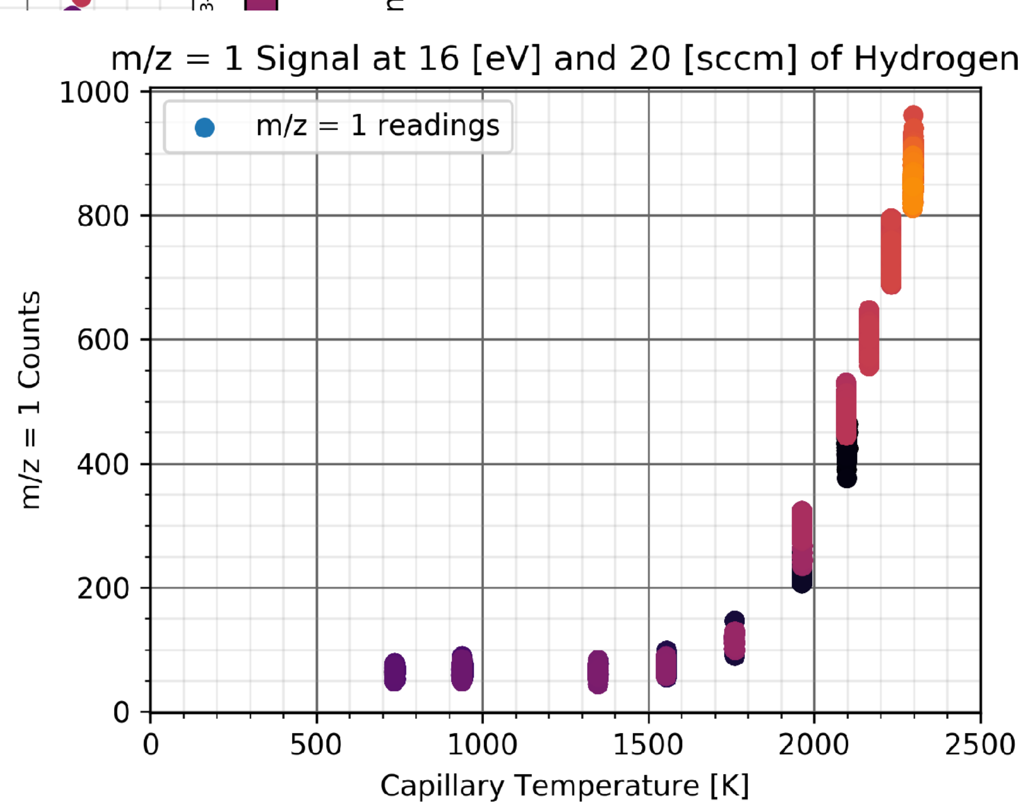

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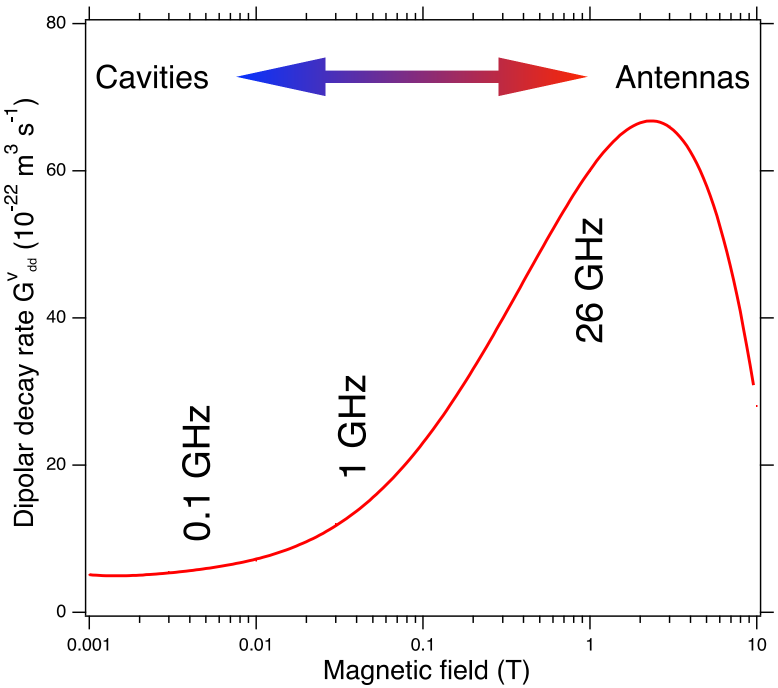
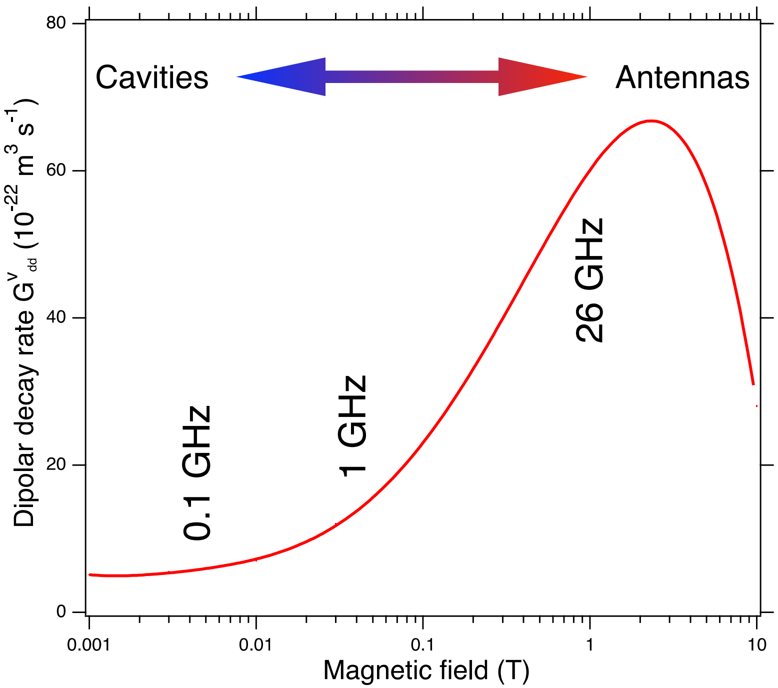
Cavity As CRES Volume

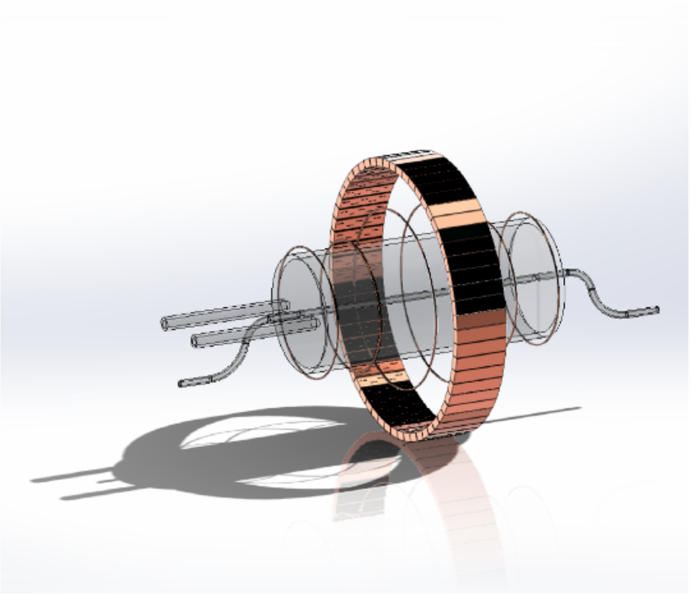


- Dipolar decay rate can be greatly reduced by lowering magnetic field for longer trapping life times

Data from Phys. Rev. B, 33:626–628,1986

Cavity As CRES Volume



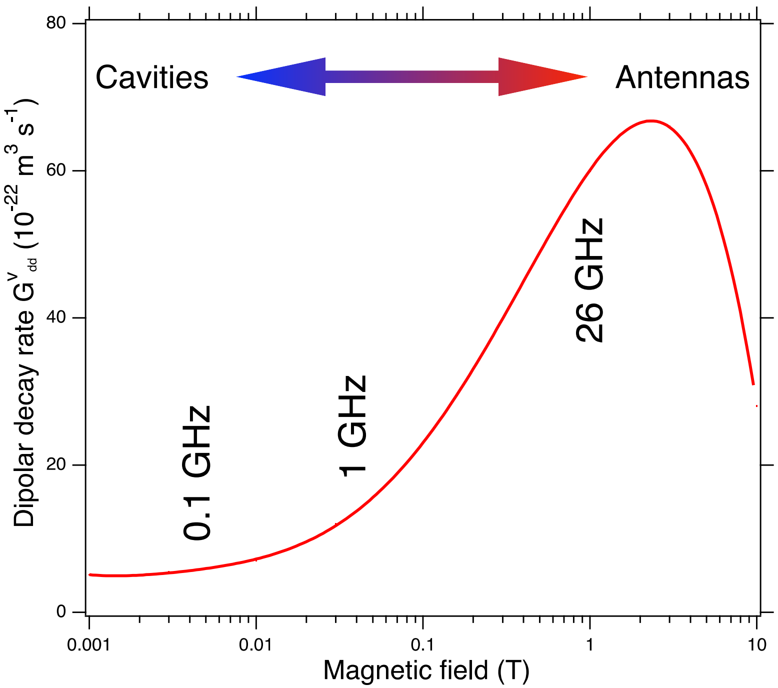


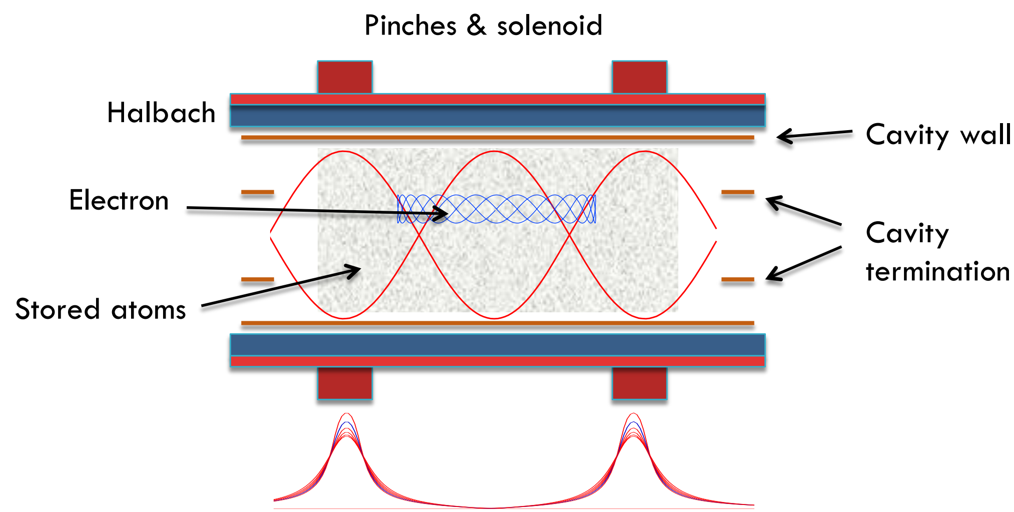
- Dipolar decay rate can be greatly reduced by lowering magnetic field for longer trapping life times

- Ring of patch antennas views central volume
- Beamforming for position reconstruction

Data from Phys. Rev. B, 33:626–628,1986

Cavity As CRES Volume





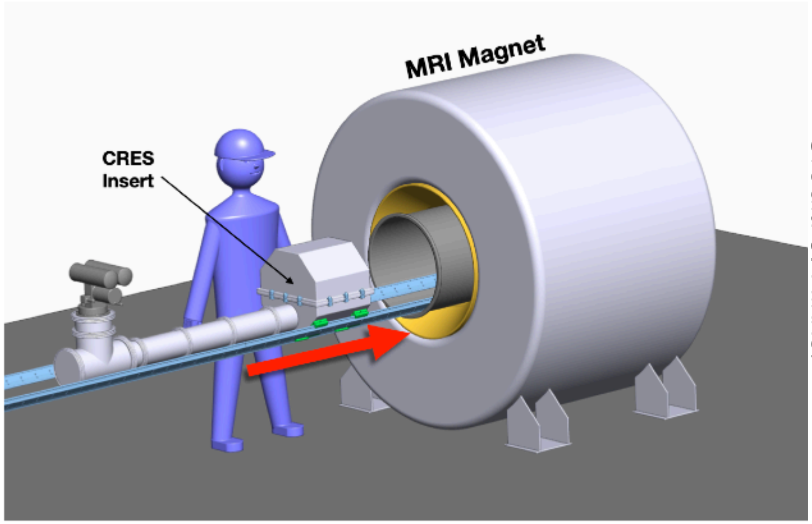
- Dipolar decay rate can be greatly reduced by lowering magnetic field for longer trapping life times

- Cavity volume scales as $1/f^3$
- Lower frequency makes resonant cavity desirable
- Mode-filtered, open-ended

Data from Phys. Rev. B, 33:626–628,1986

MRI Calibration

- Need to know the magnetic field and electron trajectories precisely
- Insert electron gun into MRI
- Map field in center



Credit: J. Nikkel

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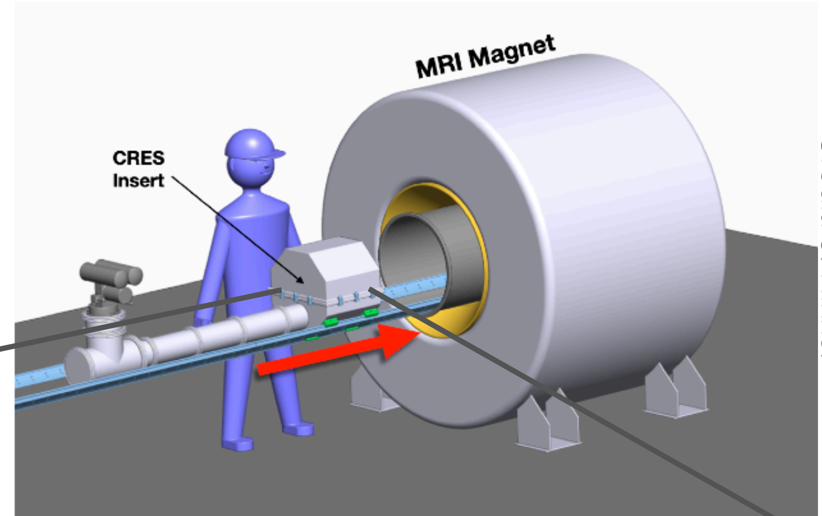

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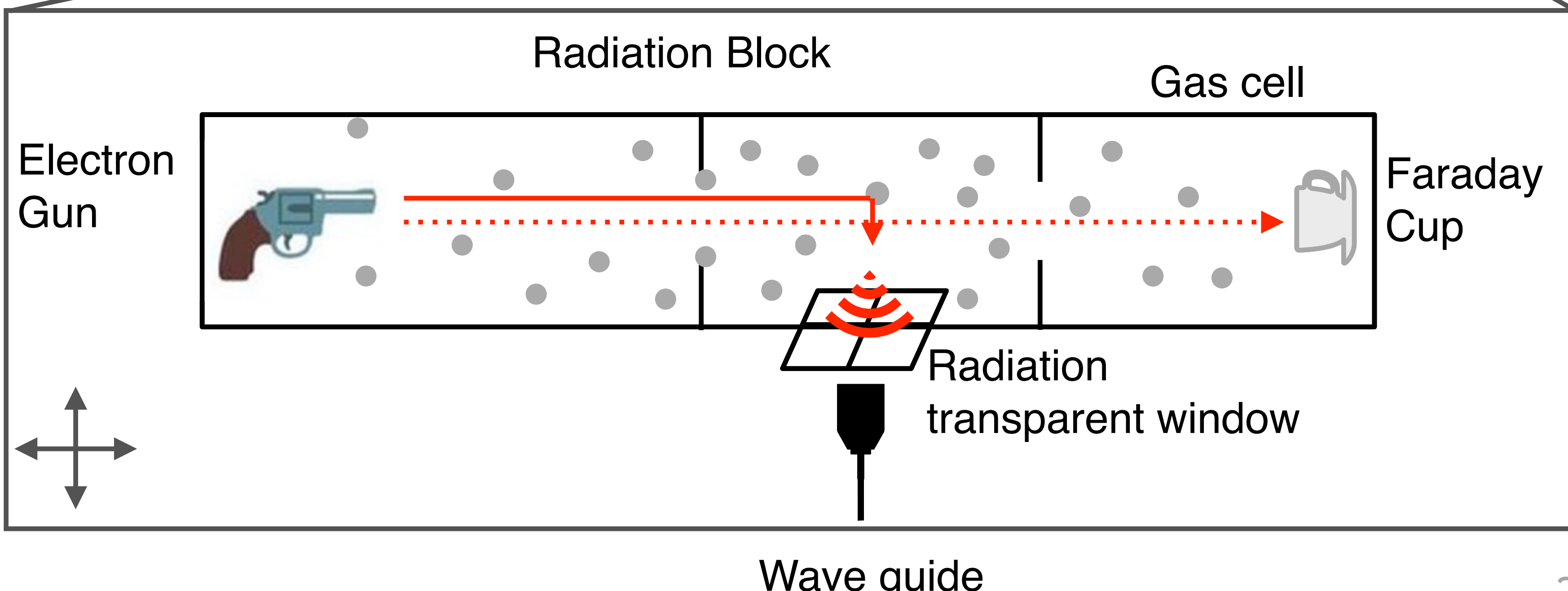

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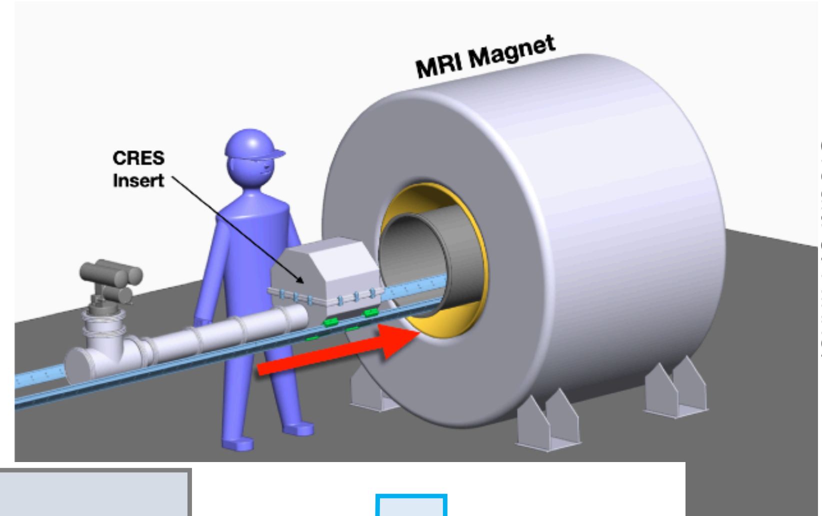

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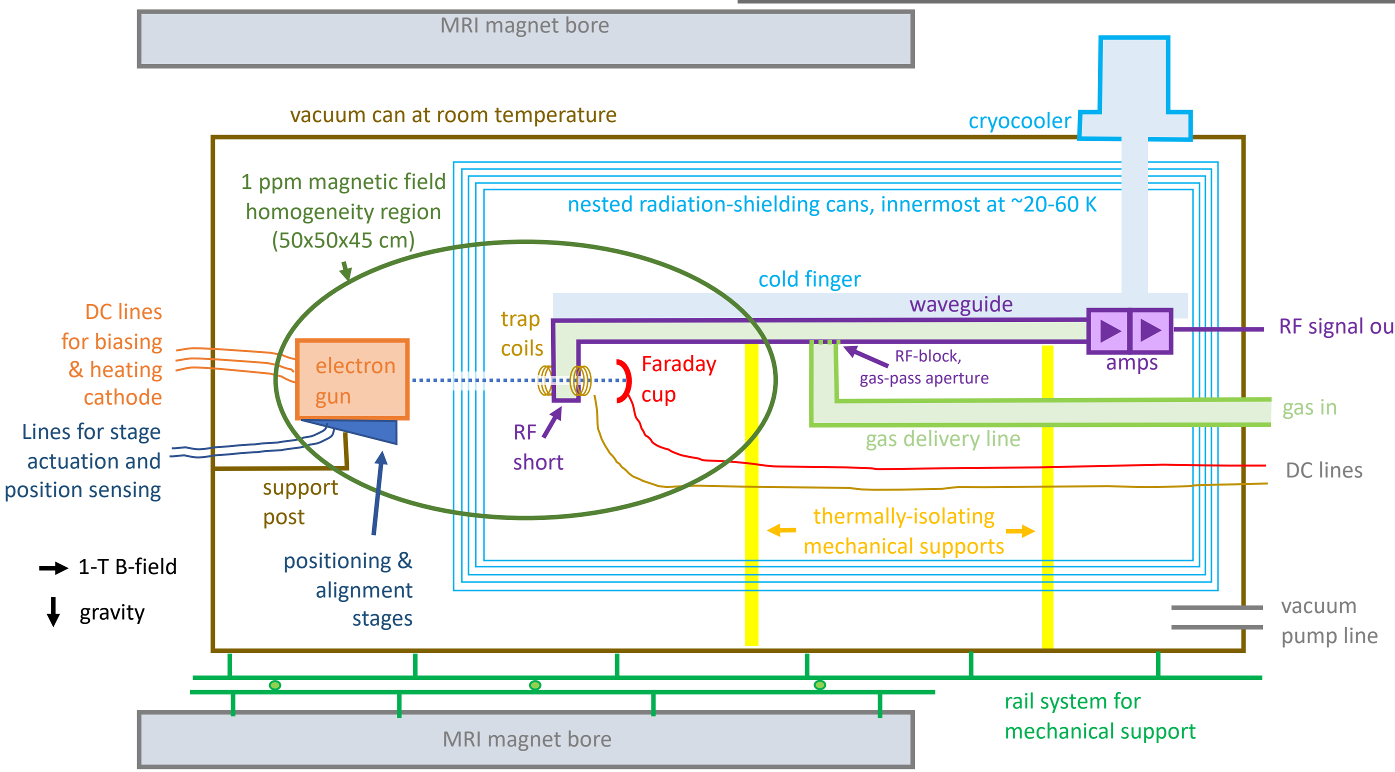

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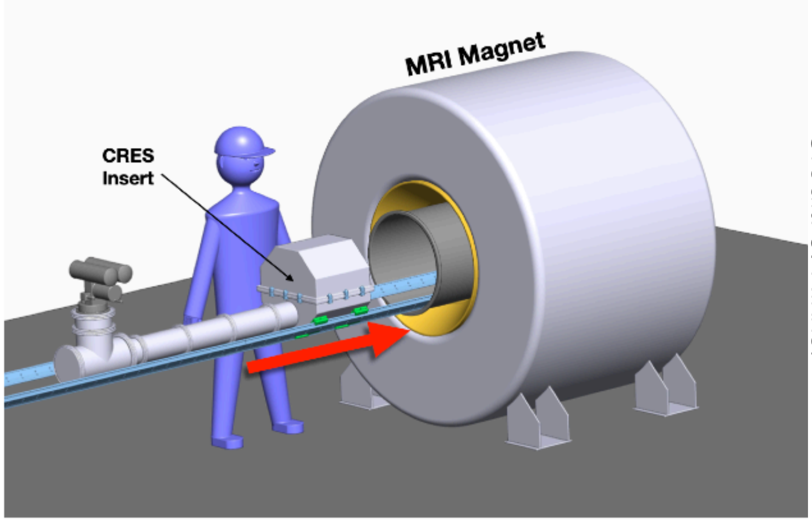

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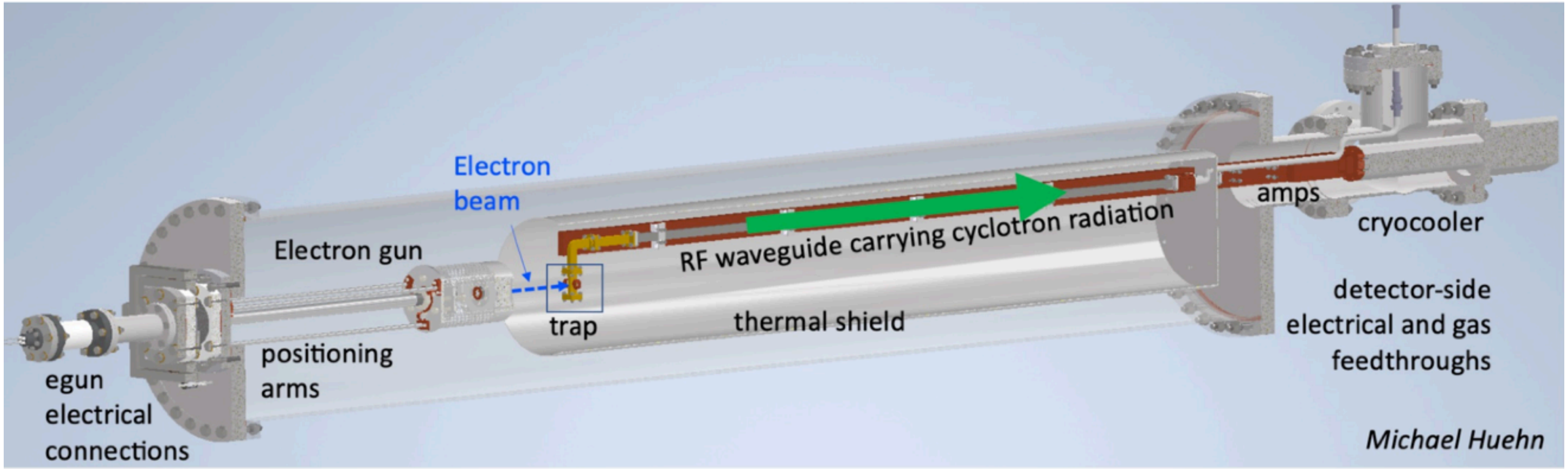
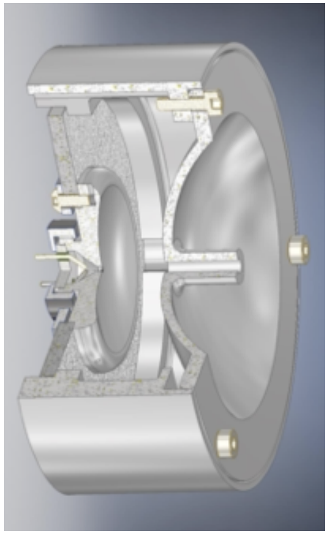
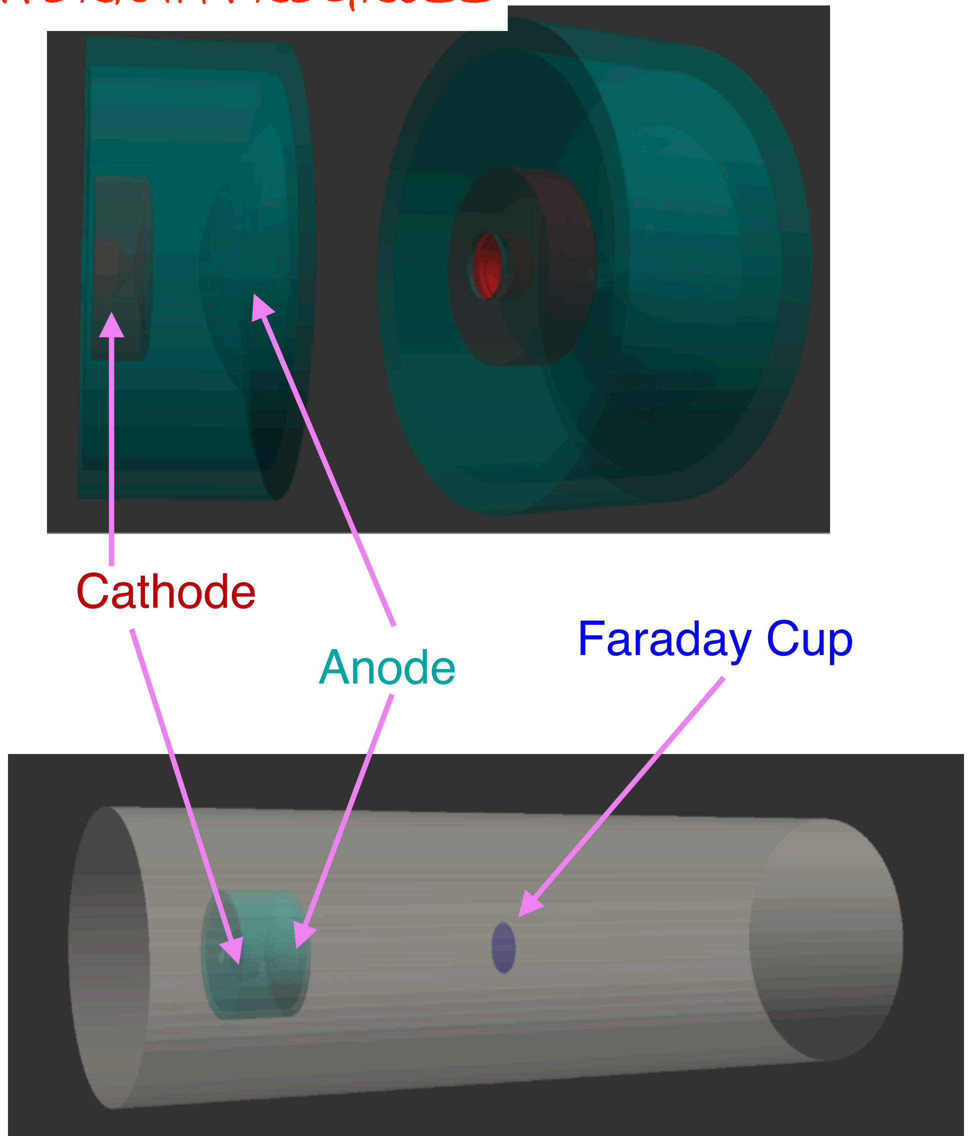


Electron Source



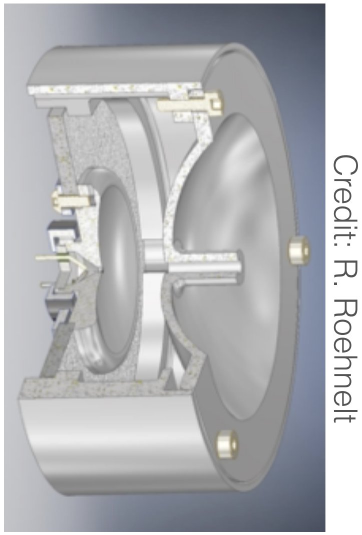
Credit: R. Roehnelt

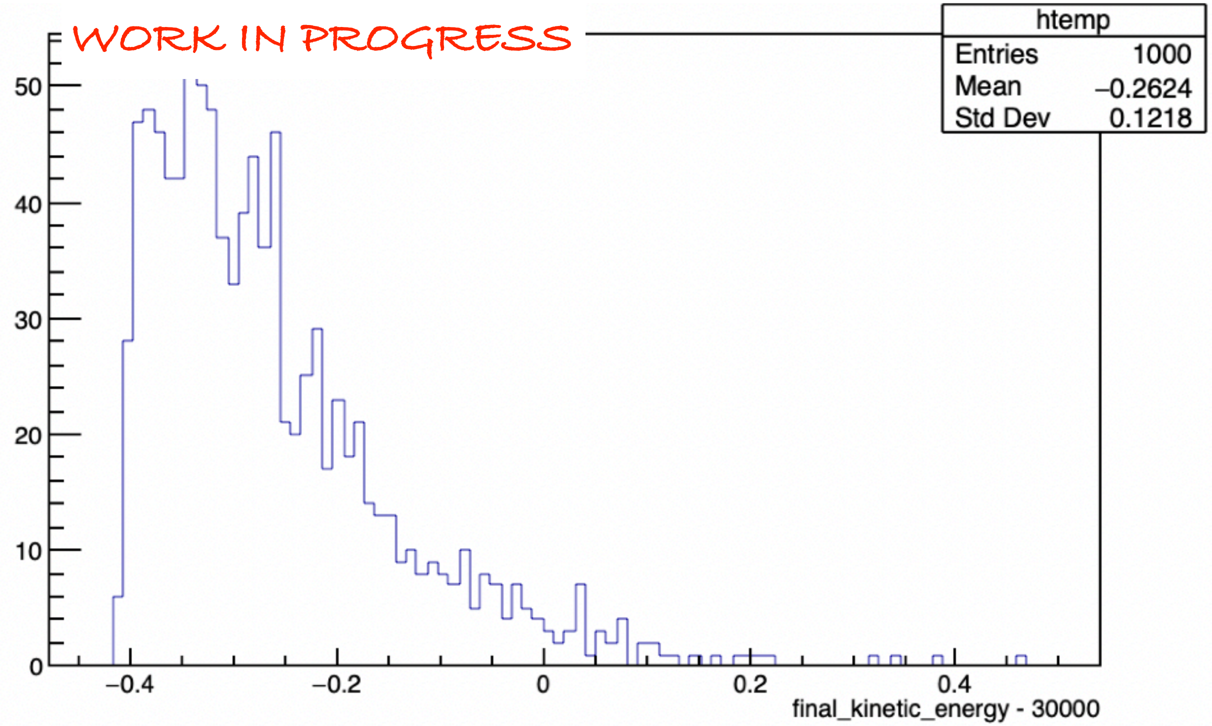
WORK IN PROGRESS



- Pierce design
- Excellent energy spread (simulated)
- Test stand at UW

Electron Source





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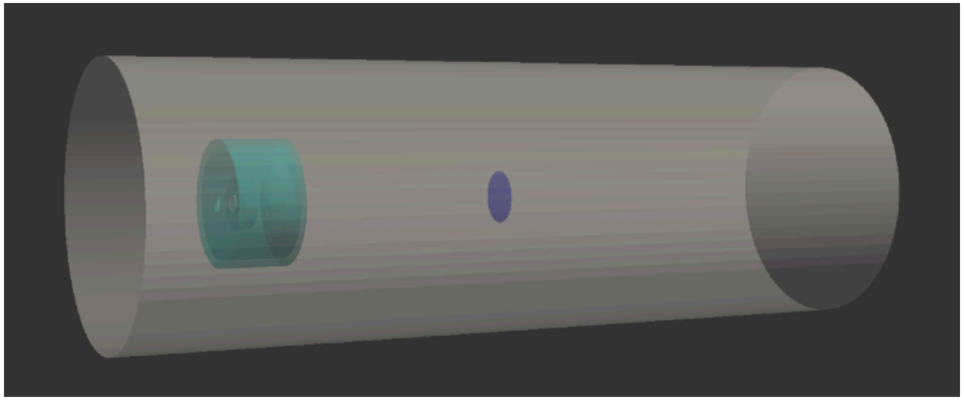
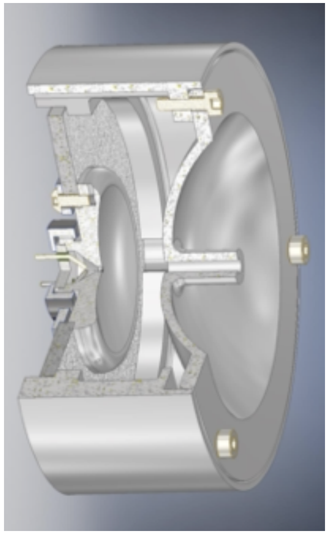
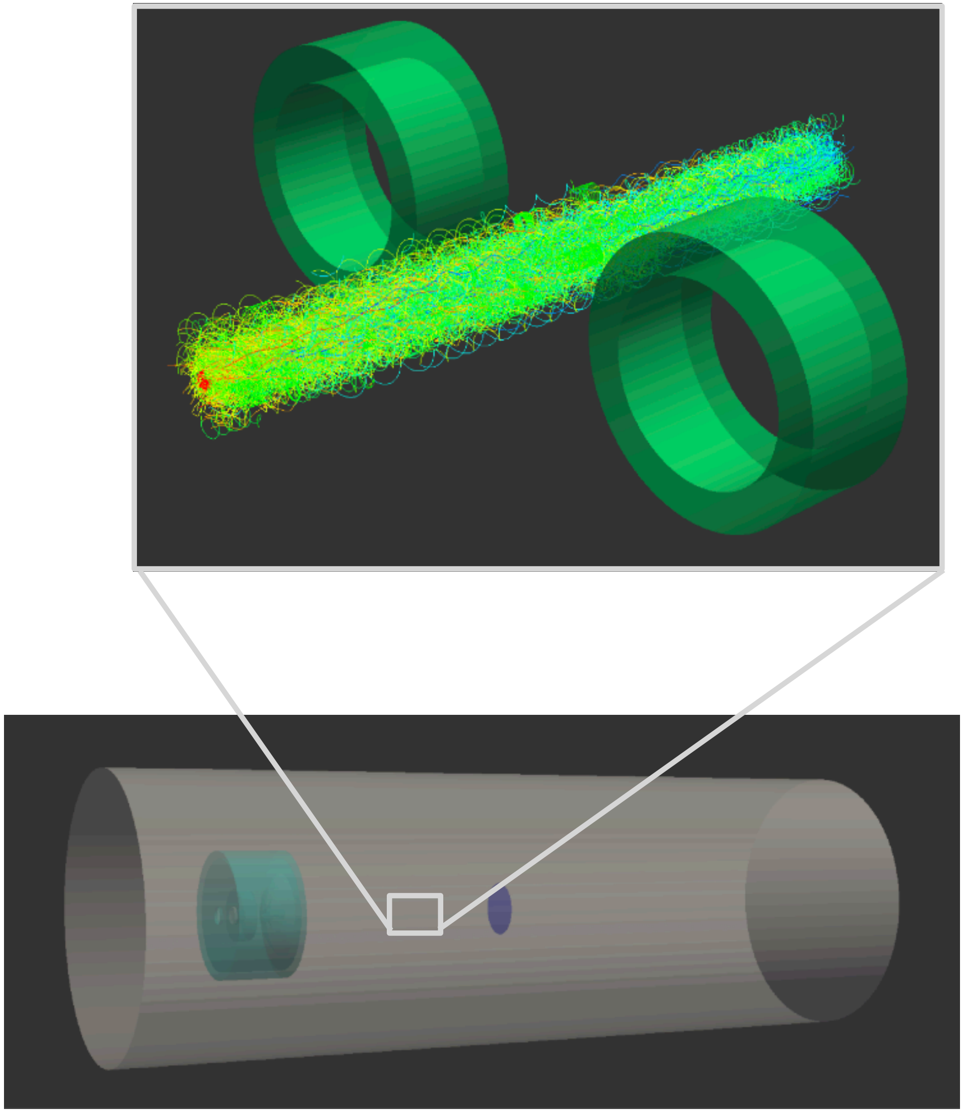


Electron Source

WORK IN PROGRESS





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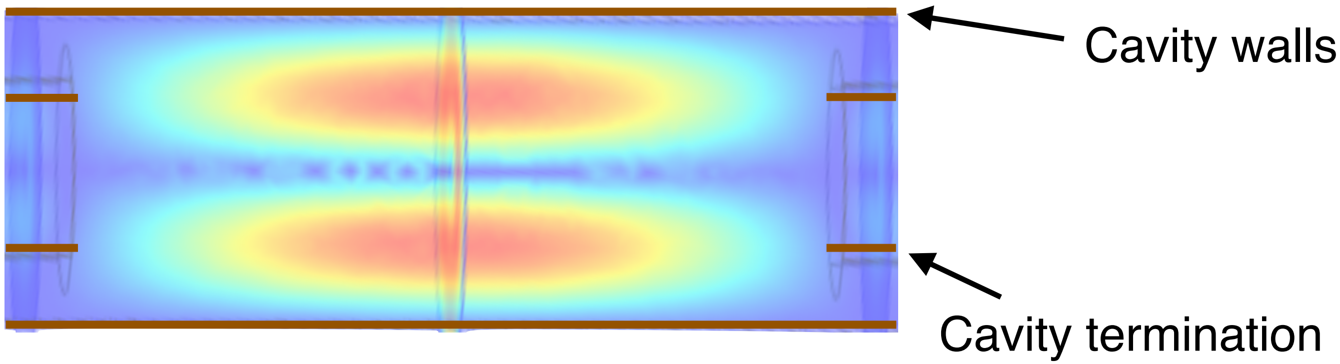
CRES in Cavity

CRES in Cavity



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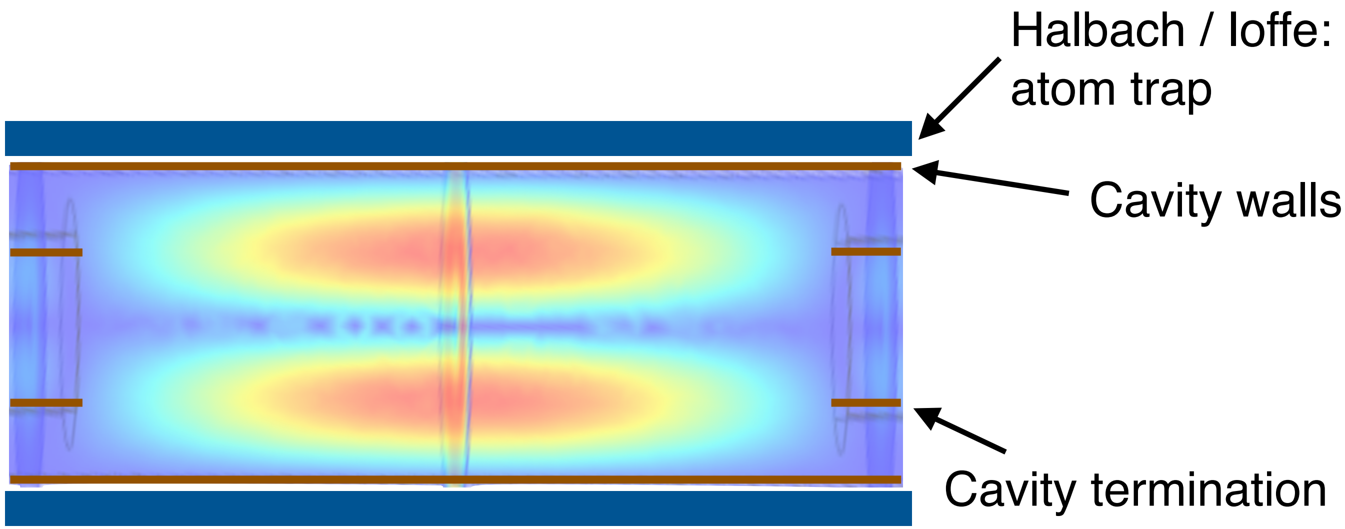

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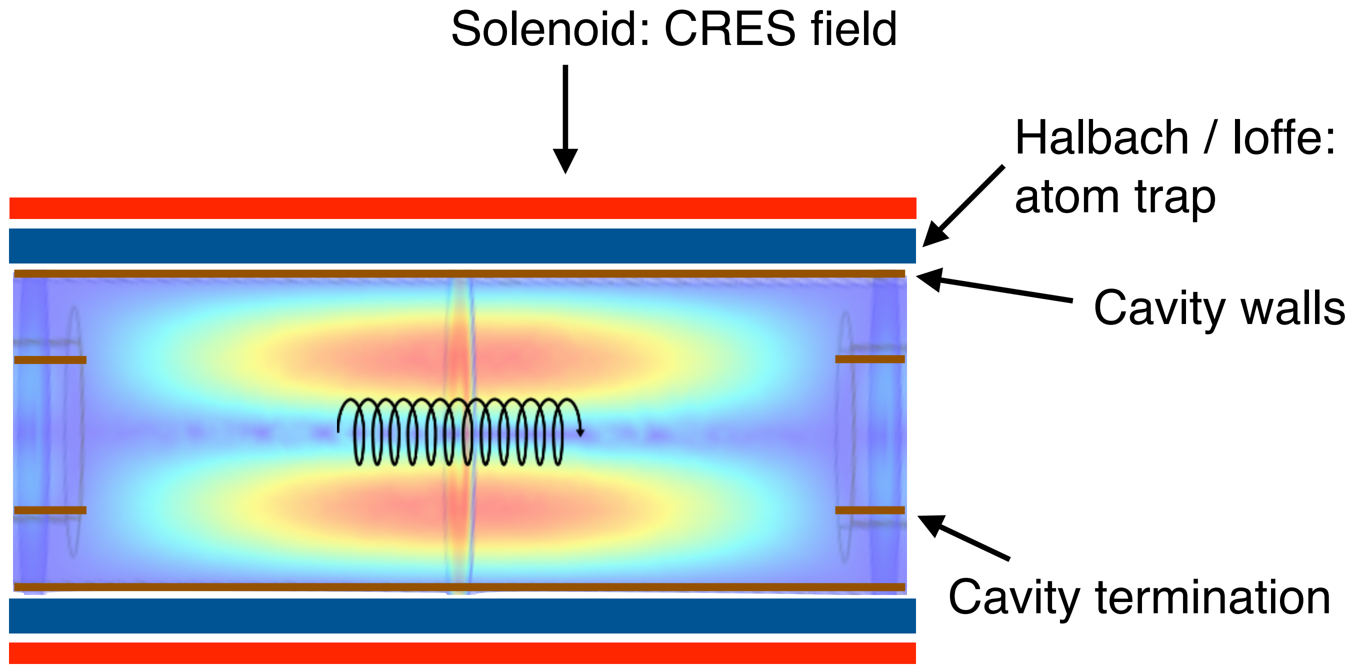
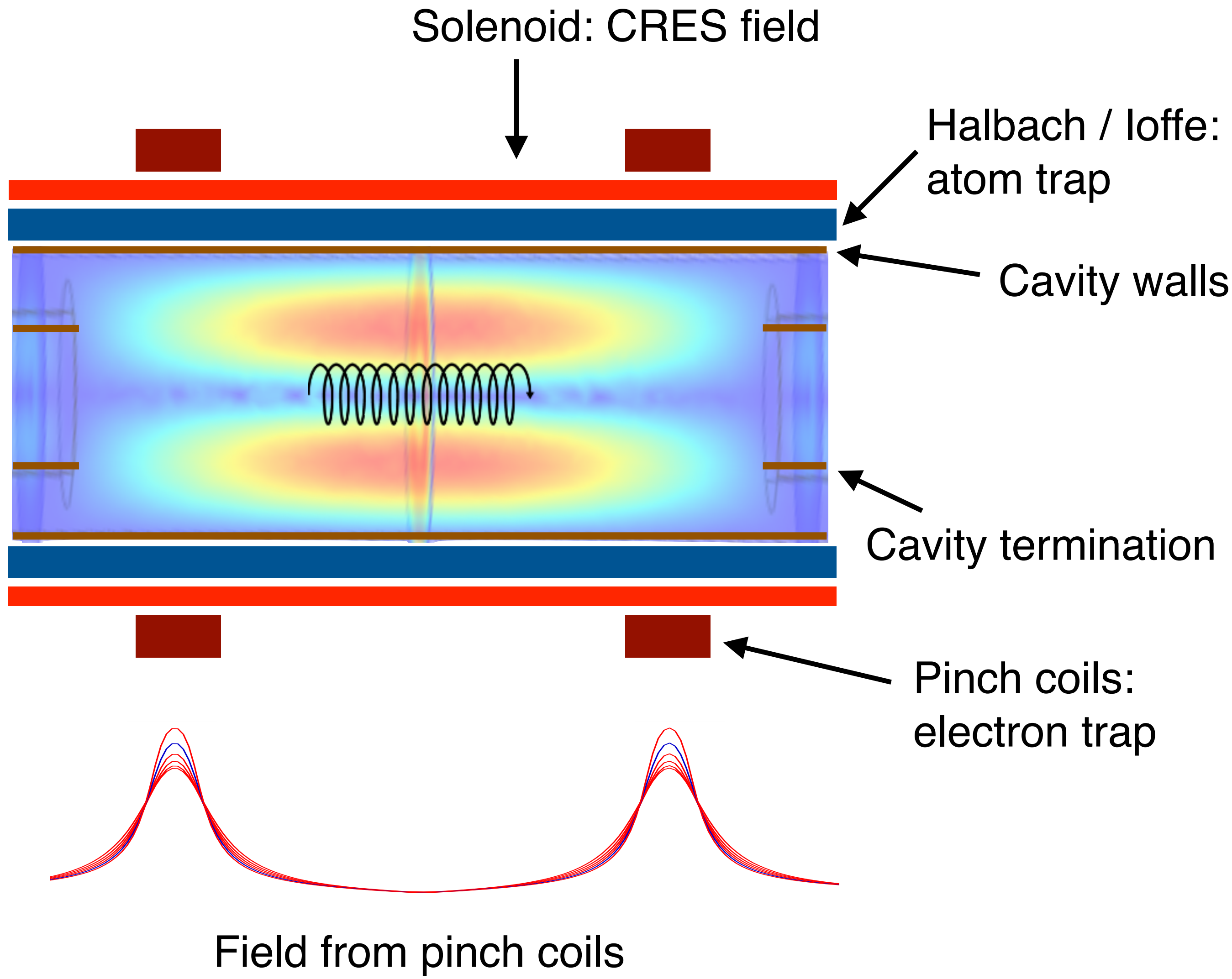


PROJECT 8

CRES in Cavity



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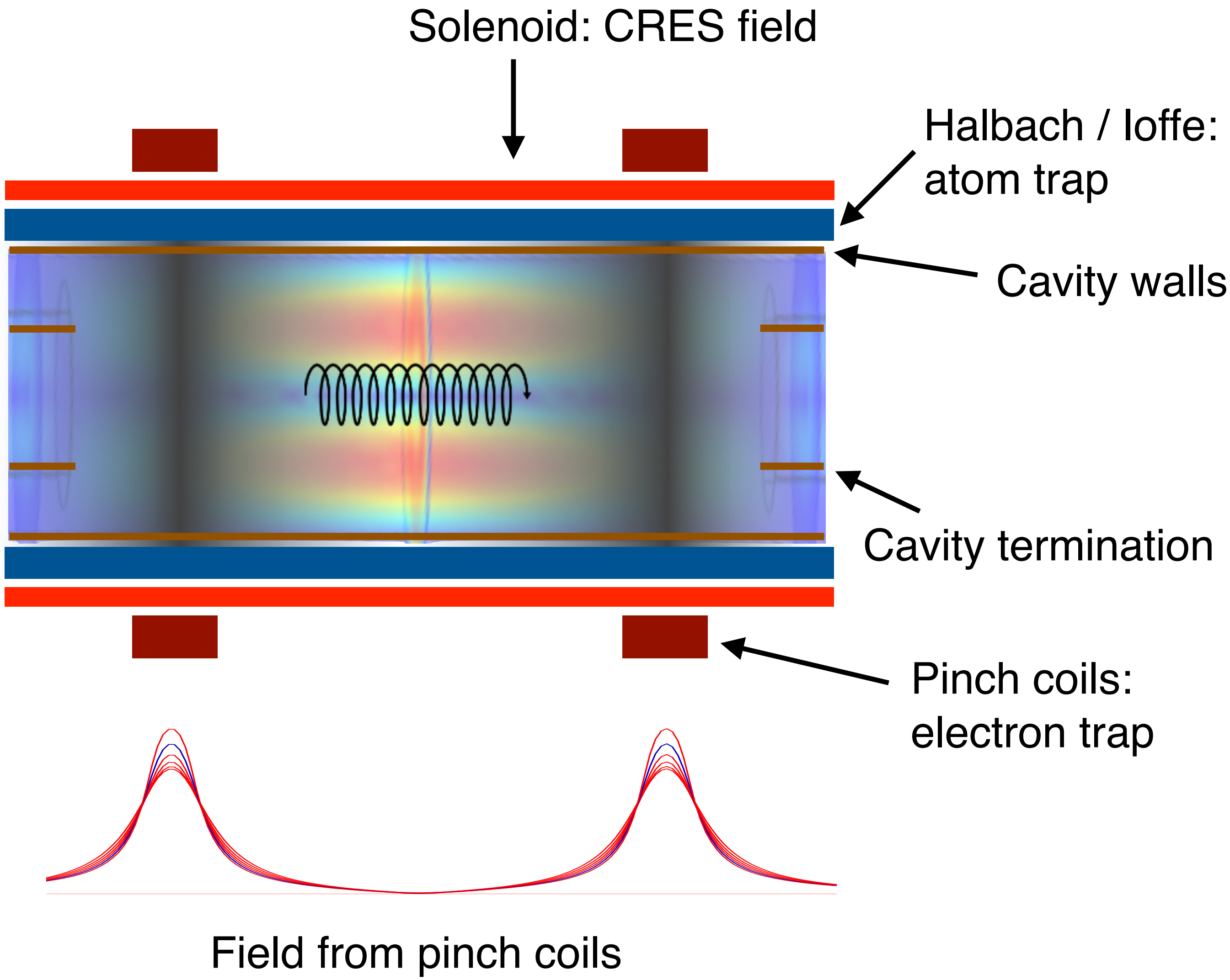
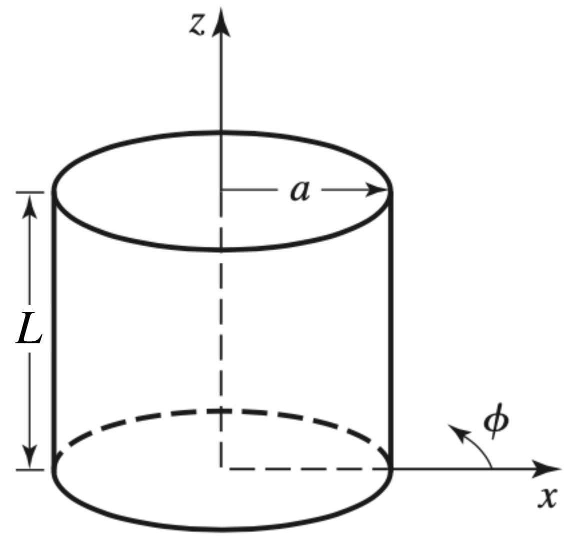
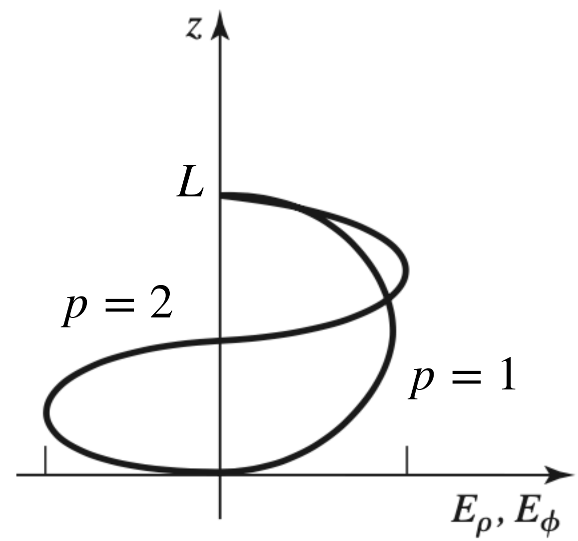


PROJECT 8

Cylindrical Cavities

- Transverse electric (TE) & transverse magnetic (TM) modes, TE_{mnp} and TM_{mnp} where $m, n, p =$ # of antinodes in $\vec{E}, \vec{H}$ in ϕ, ρ, z directions
- Wave propagates in z direction, reflected at ends of cavity
- Largest wavelength supported: $\lambda/2 = L$ (length)
- $f_{TE,nmp} \propto \sqrt{\left(\frac{X'_{nm}}{R}\right)^2 + \left(\frac{p\pi}{L}\right)^2}$, X'_{nm}: *n*-th zero of *m*-th derivative of Bessel function
- Can manipulate mode structure by e.g. pickup antennas, other features

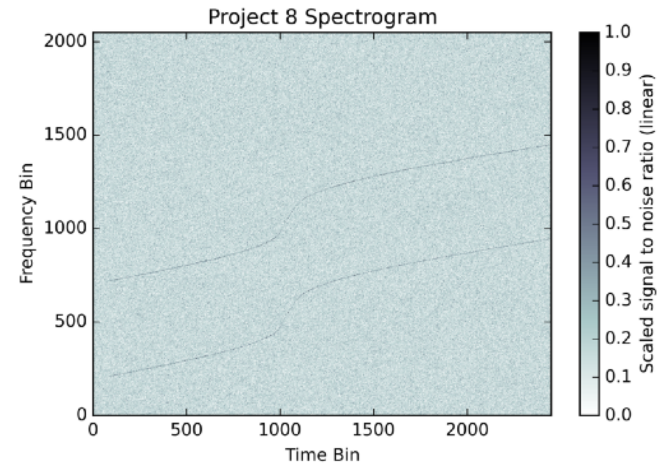




D. M. Pozar: Microwave Engineering

Multi-mode Challenges

- Cavities have infinite modes
- Complex signal & complex readout
- Intruder modes
  - Electrons' frequency chirps up more before turn-around points in trap
  - May lose energy to invisible modes
- Solution: Mode-filtered cavities!
- But: position reconstruction is a challenge!
  - Magnetic field uniformity constraints
- Modulation index: $h = \frac{\Delta f}{f_m} = p$
- Sideband structure compact for TE_{011}



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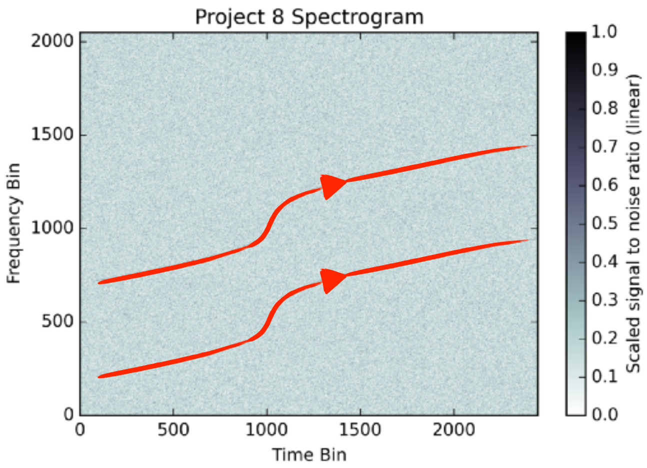

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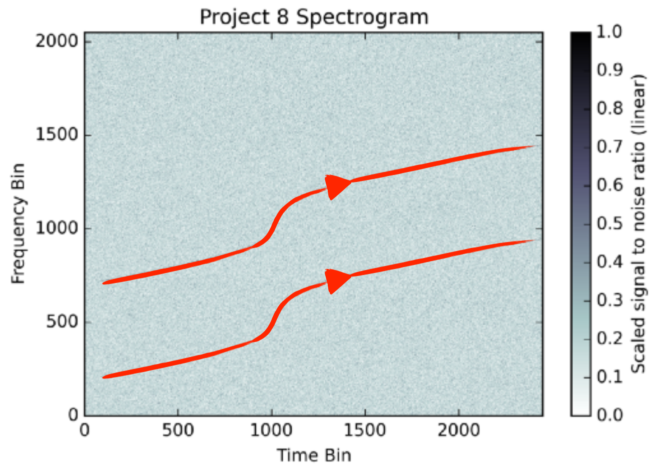
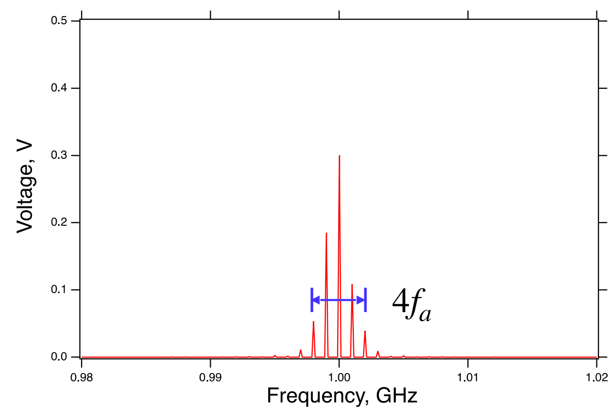




Mode-filtered Cavities

- Open-ended cavity to allow for atom flow
- Also shifts & suppresses TM modes relative to TE modes
- Allowing only circumferential currents suppresses all but TE_{0np} modes
- Either by helical grooves or insulating rings
- Long cavity: electrons can only excite first (few) TE_{01p}

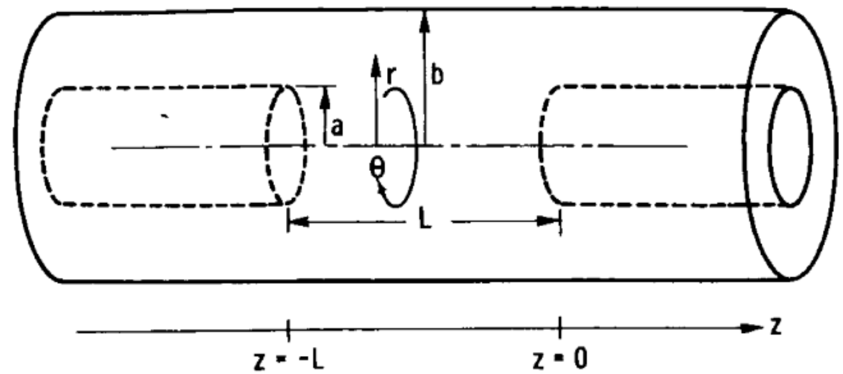
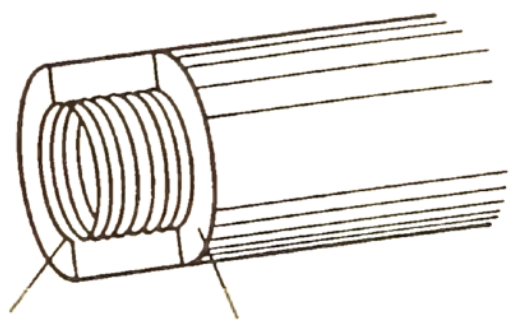


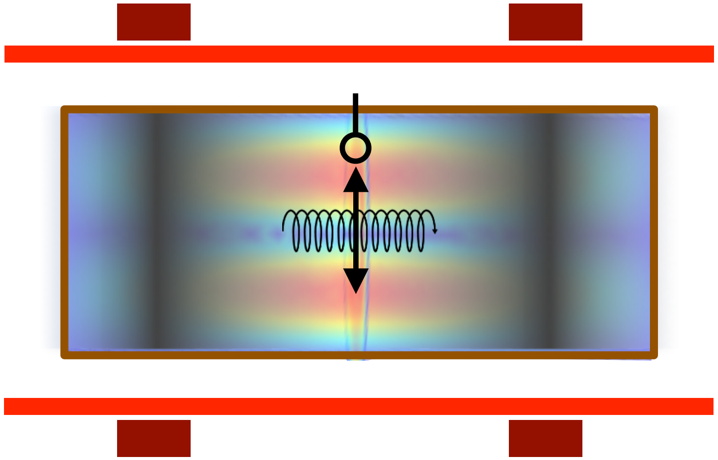
Figure 6. - Model of open-ended cavity.

N. C. Wenger, NASA Technical Note (1966)



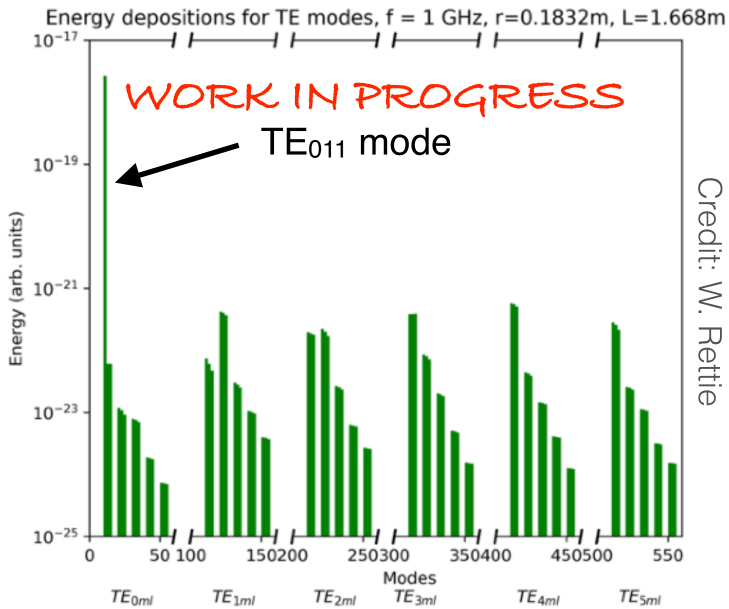
E. Venzura et al., NIST Technical Note (1993)

Simulation Development



- **Locust**: simple cylindrical cavity
- Mode-filtering imposed by Q setting
- Simulate electron coupling to mode
- Idealized readout in center & off-center

Simulation Development



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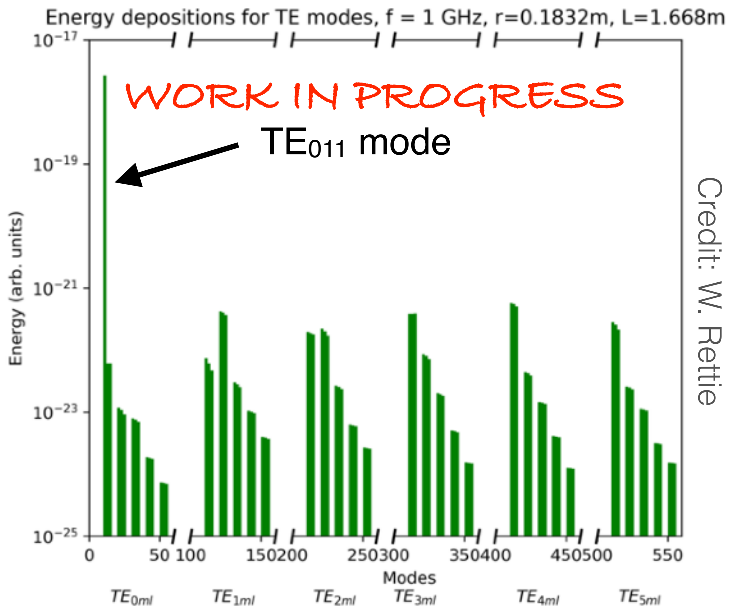

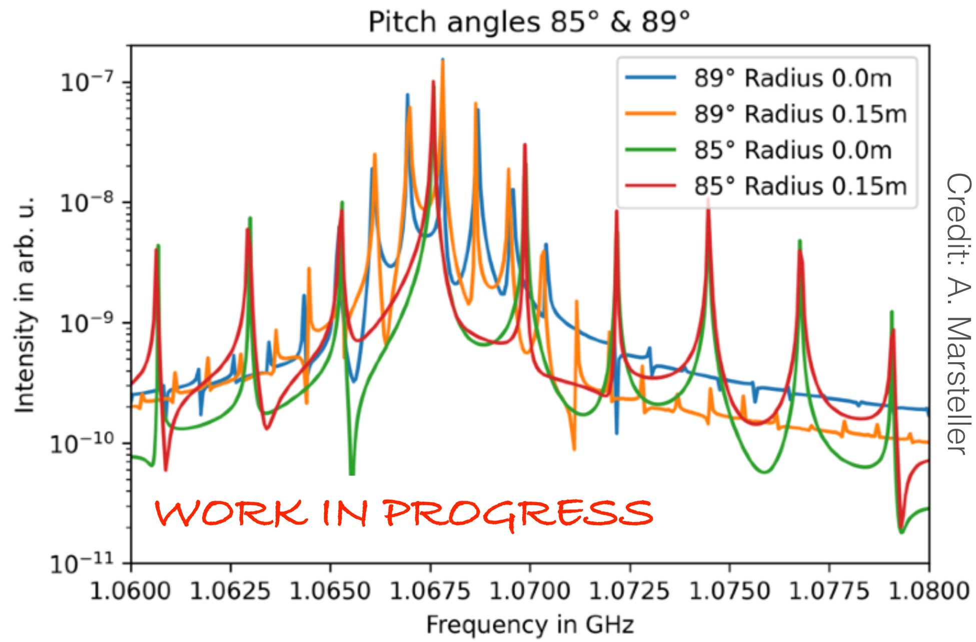

- **Locust**: simple cylindrical cavity
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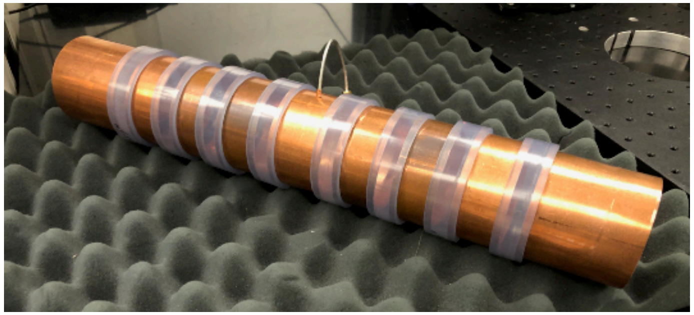
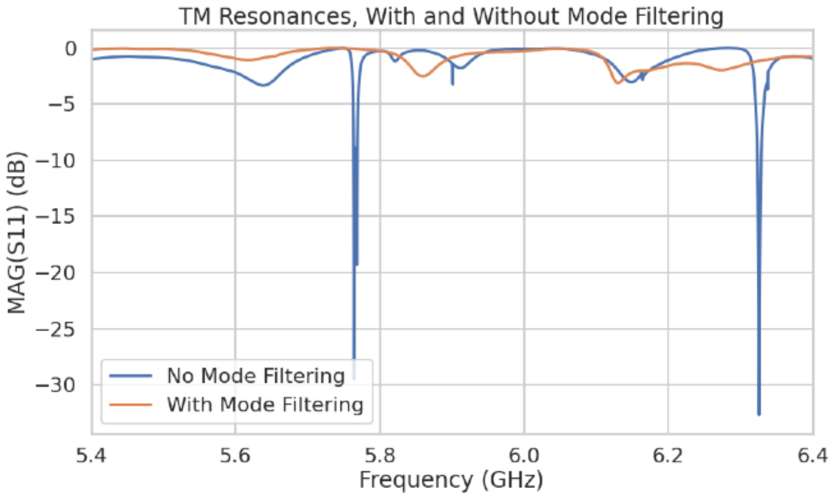
- Simulate electron coupling to mode
- Idealized readout in center & off-center

- **Kassiopeia**: cylindrical cavity with idealized magnetic fields
- Electron drives cavity response
- Time series of trapped electrons for pitch angle range, on- and off-radius

Cavity Prototype Development

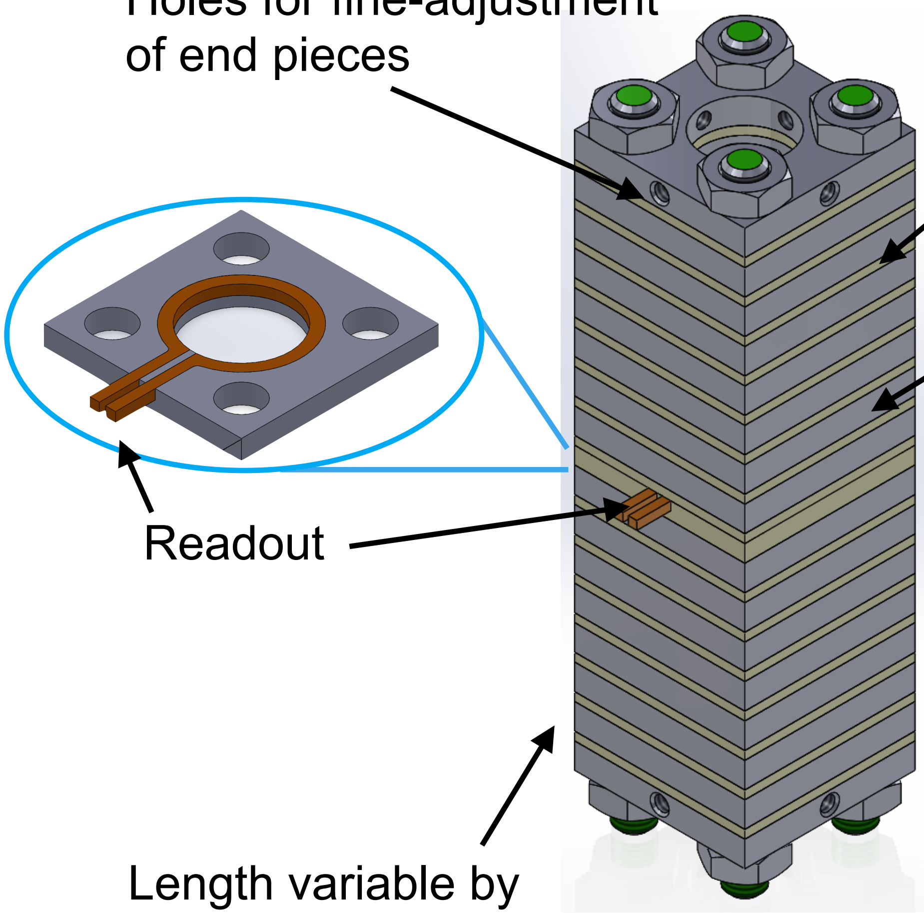
- Copper tubes connected by PVC rings permit only circumferential currents
- Allows only TE_{01p} modes to propagate
- Verified mode-filtering
- Readout via rotatable coax loop

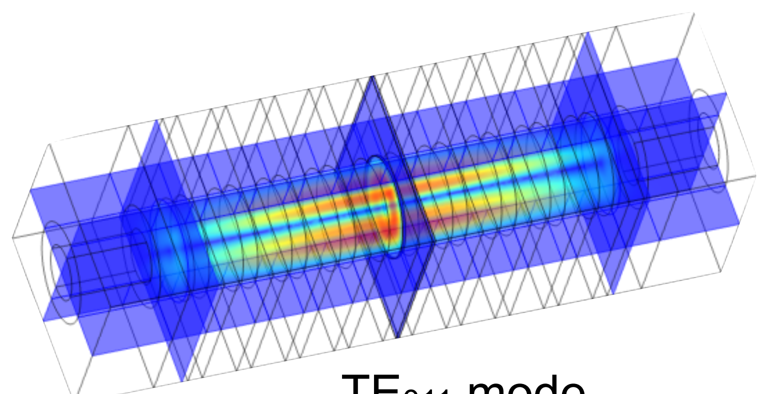




Credit: A. Ziegler

Cavity Prototype Development

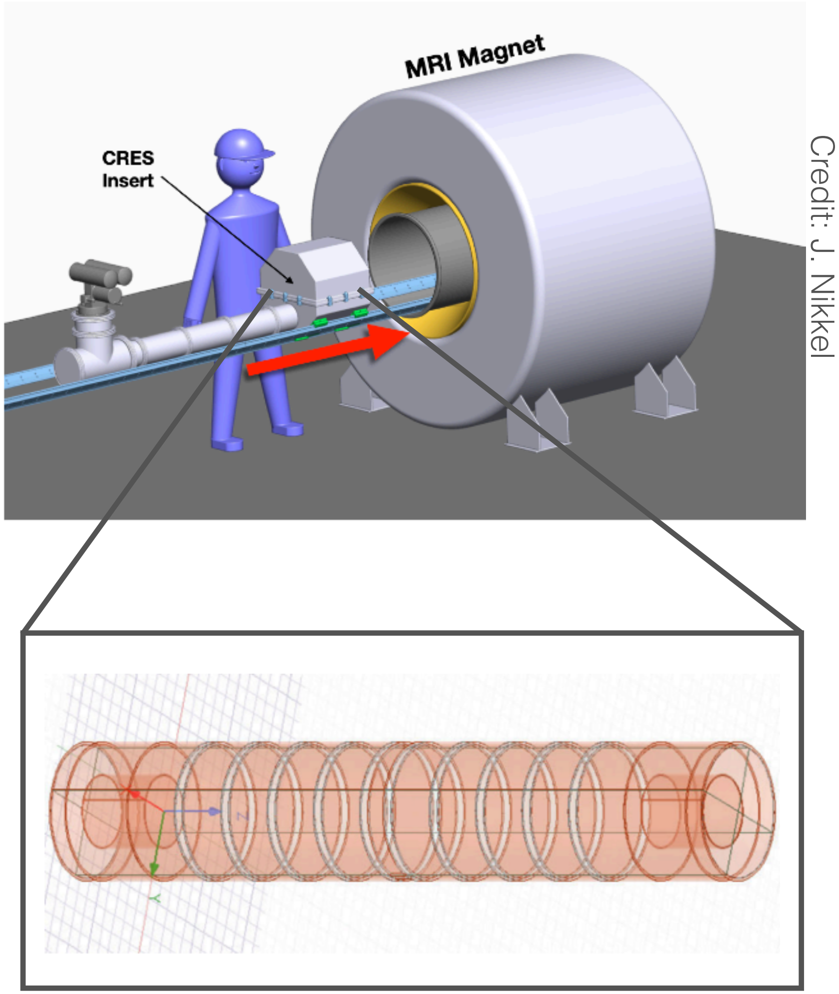




TE_{011} mode

Cavity CRES Demonstrator

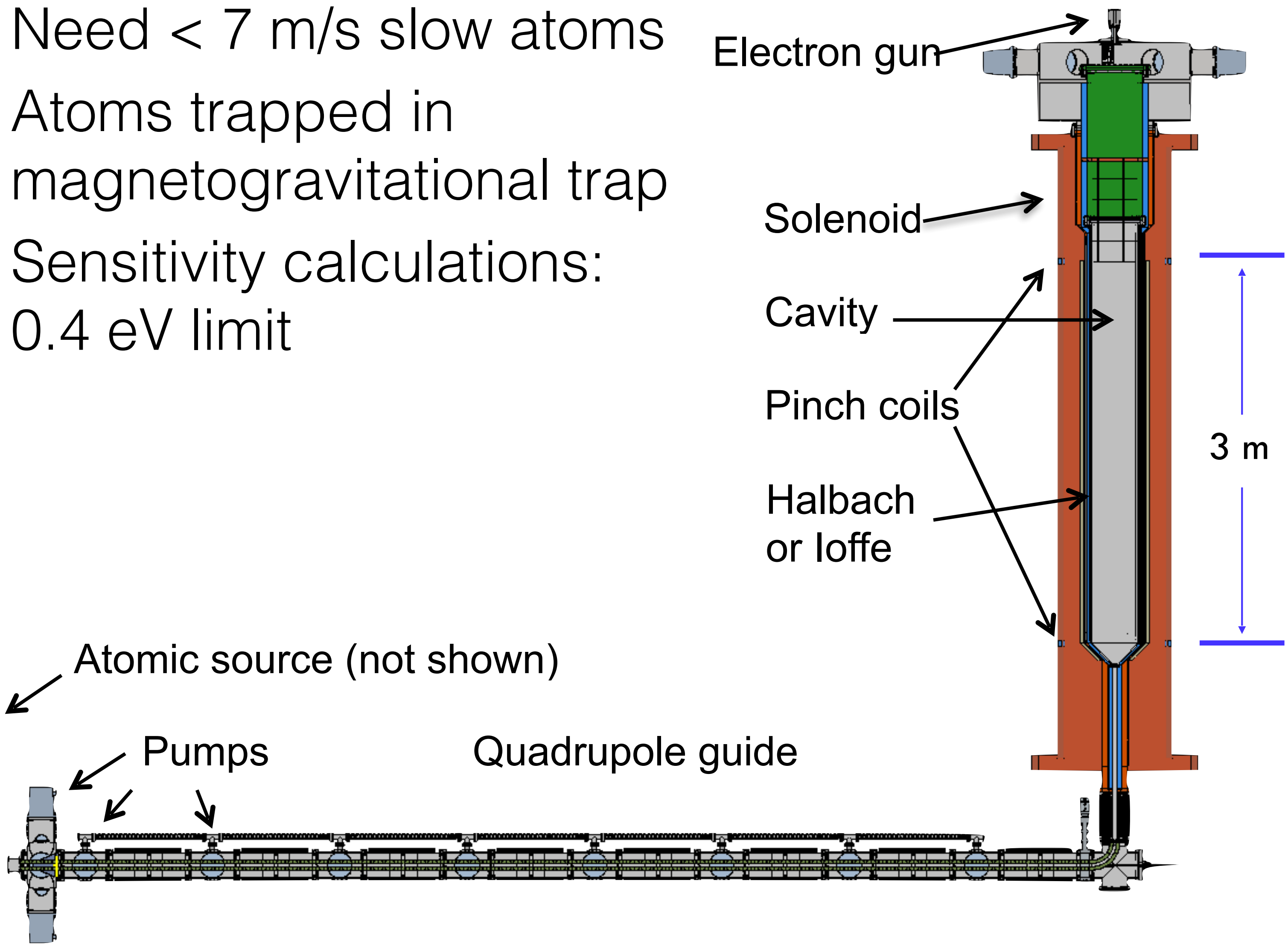
- Cavity at 26 GHz:
- Small:
  $L = 6\,\text{cm}, R < 1\,\text{cm}, V \sim 10\,\text{cm}^3$
- Characterize on bench and in dilution fridge
- Then insert into 1 T MRI magnet
  - Electron gun to inject electrons
  - Verify readout
  - Demonstrate CRES in cavity
  - Verify high volume & pitch angle efficiency



Insert: electron gun + Helium gas cell + cavity

Cavity-based Phase III

- Need < 7 m/s slow atoms
- Atoms trapped in magnetogravitational trap
- Sensitivity calculations: 0.4 eV limit



Credit: H. G. R. Robertson

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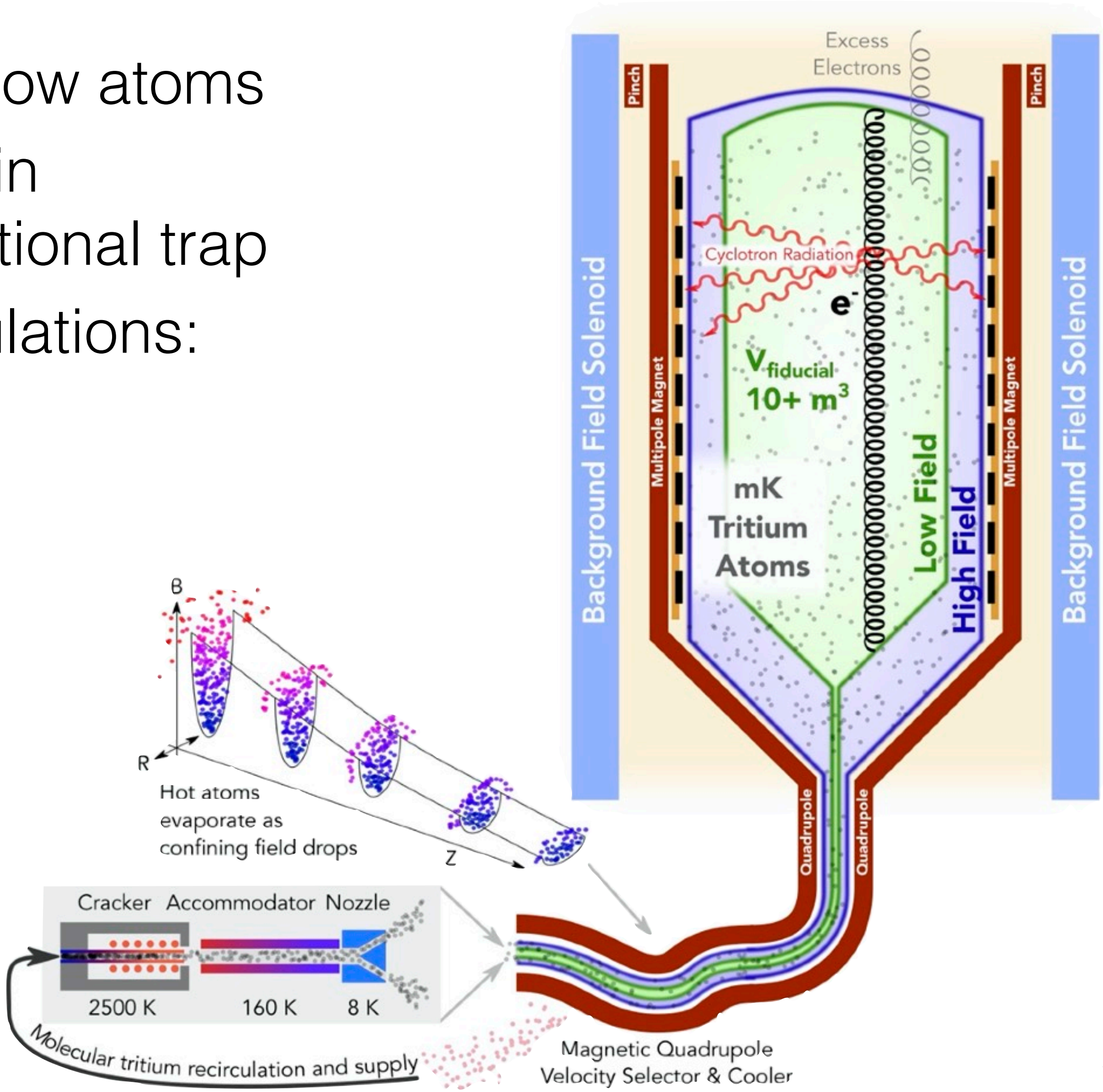
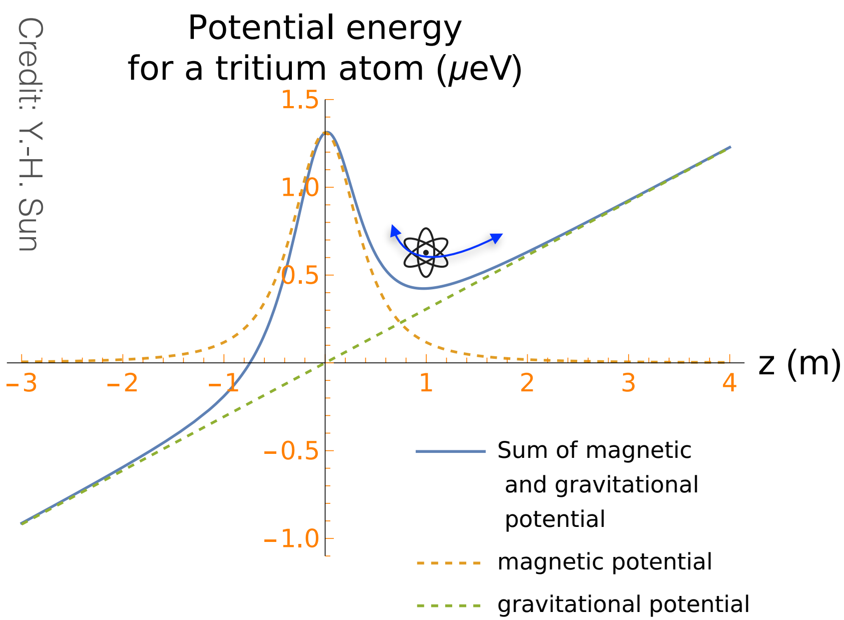
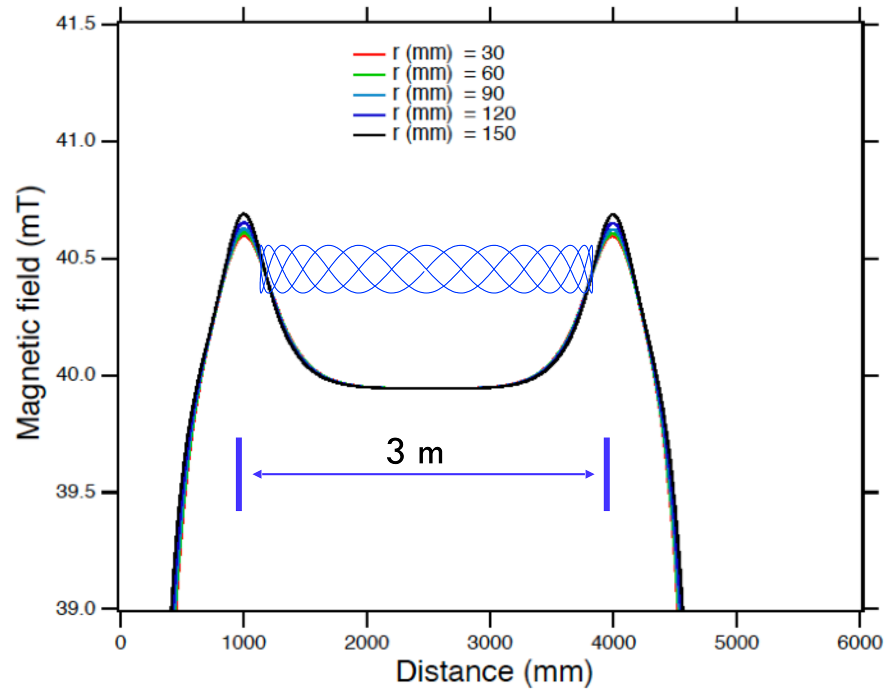


Credit: A. Lindman

Trapping Potentials

Credit: Y.-H. Sun



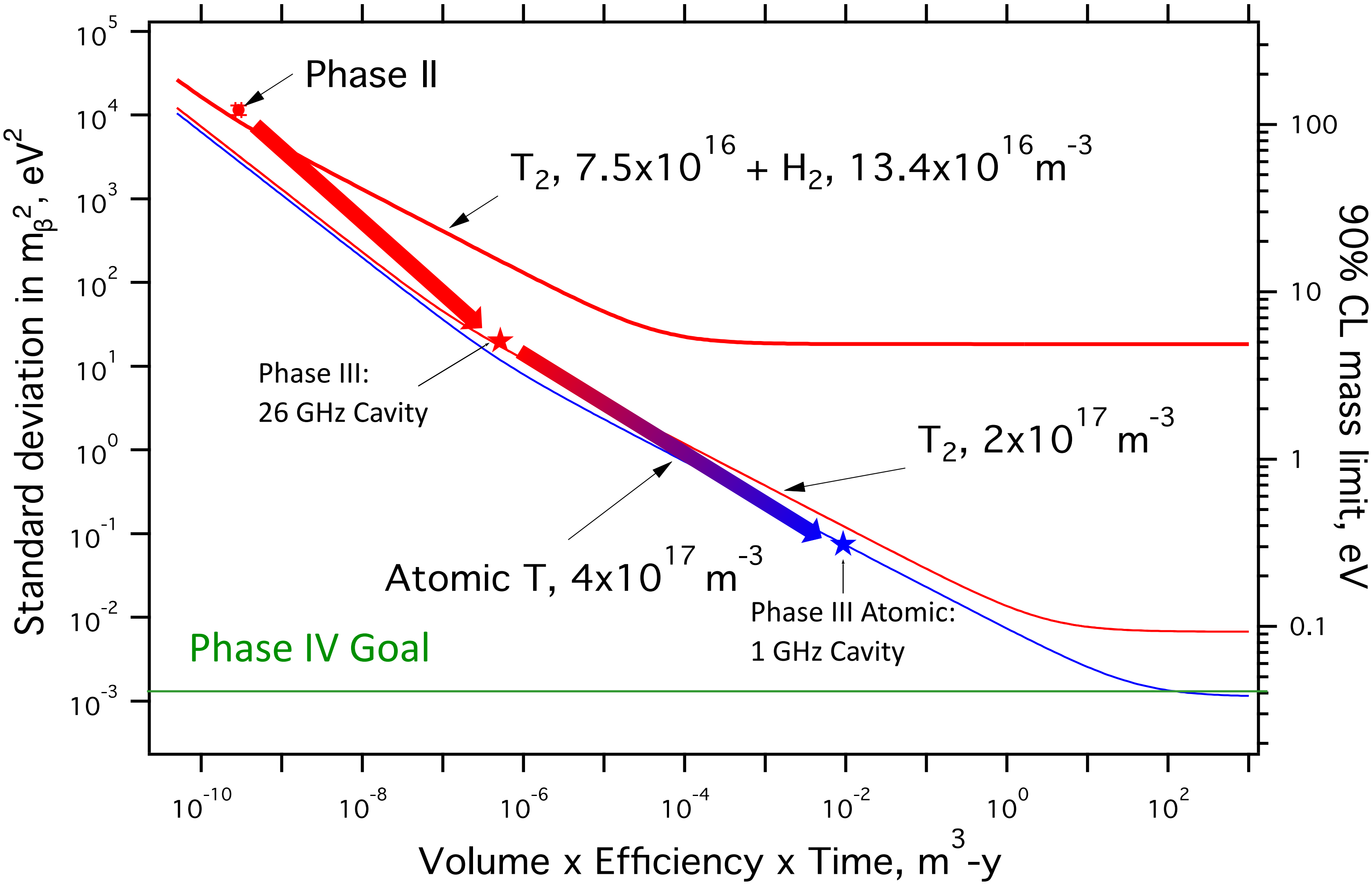


Credit: H. G. R. Robertson

Magnetic and gravitational potentials trap atoms

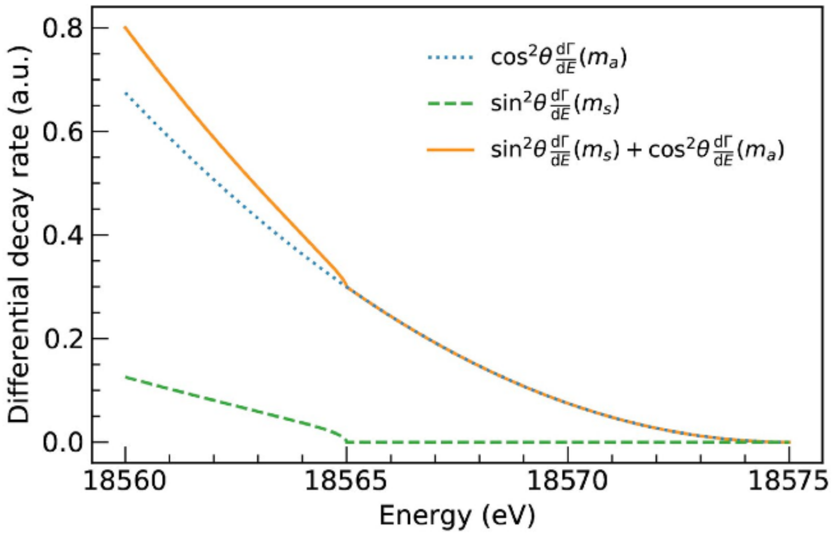
Magnetic field with pinch coils traps electrons

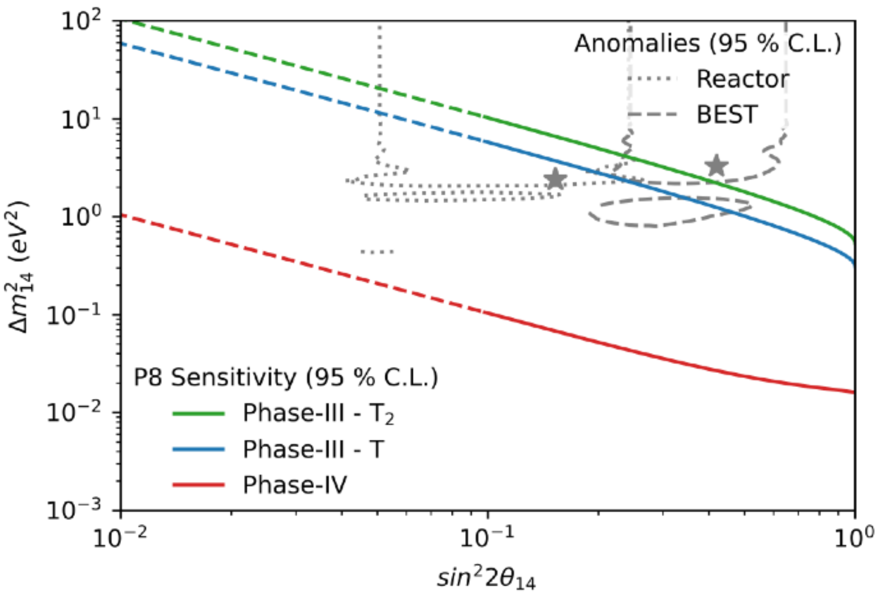
Cavity Experiments' Sensitivities



Sterile Neutrino Sensitivity

- Simultaneous active and sterile mass measurements possible
- eV-scale sterile search planned
- Higher mass sterile sensitivity under investigation





Take Away

- Neutrino mass is one of the outstanding problems of particle physics & cosmology
- The Project 8 approach:
  - High precision frequency measurement
  - Source = detector
  - Differential spectrum measurement for high statistics
  - Low background
- Next challenges:
  - Atomic tritium handling
  - Large source volumes
- “Next”: cavity CRES demonstration with electron source
- “Next-to-next”: First atomic tritium neutrino mass extraction
- Final experiment: 40 meV neutrino mass sensitivity

The Collaboration

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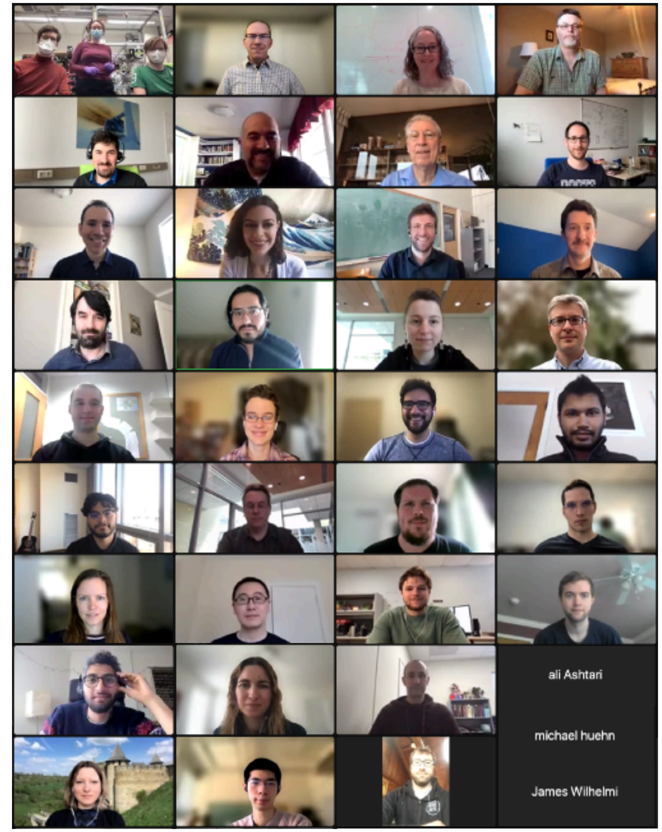
Yale University: K. Heeger, J. Nikkel, L. Saldaña, P. Slocum, P. Surukuchi, A. Telles, J. Wilhelmi, T. Weiss



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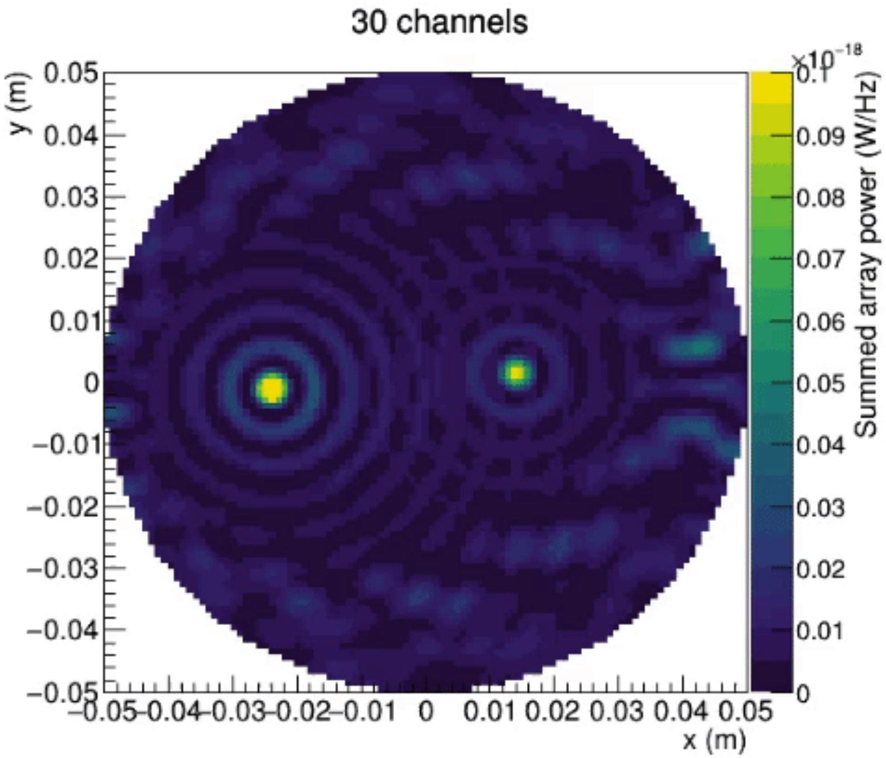
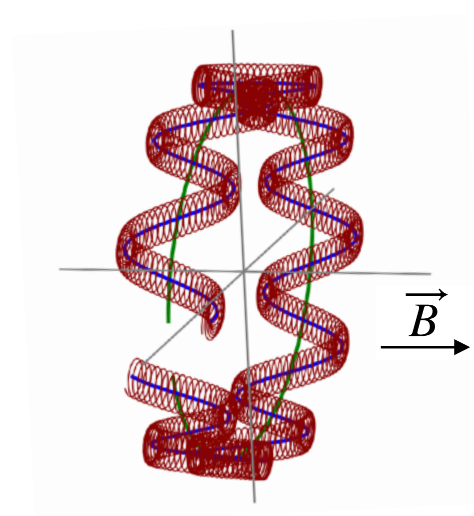
Free-space CRES demonstrator



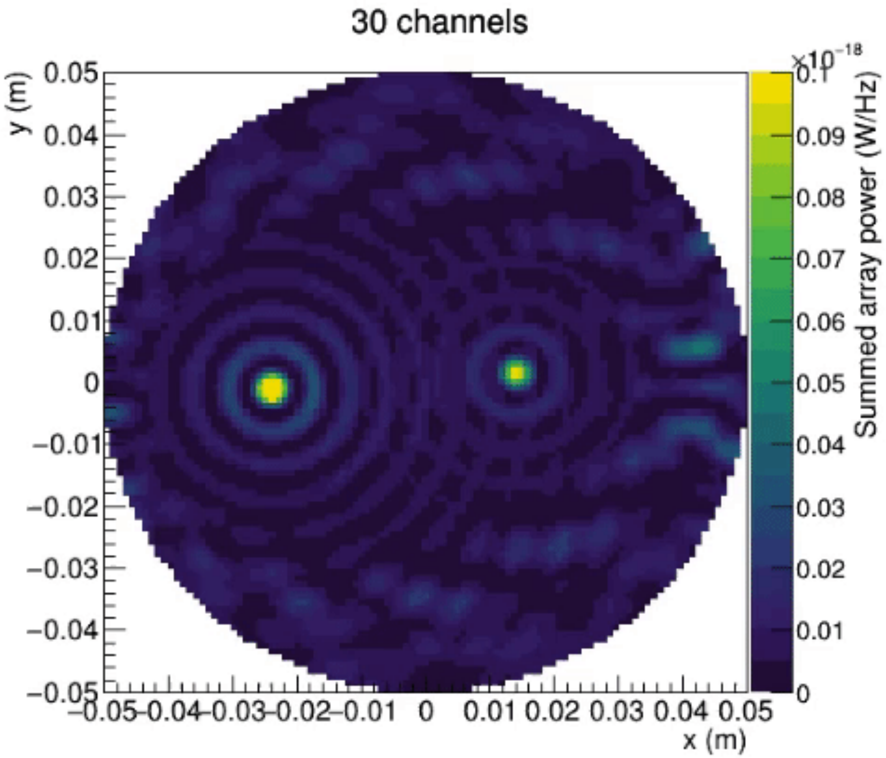
- Every antenna sees part of signal
  → sum coherently (beamforming)
- Challenges: Doppler shift, $\nabla \vec{B}$ -motion
  → antennas see slightly different frequency

- Position reconstruction
  → multiple events in one trigger window



Credit: R. Reimann

Free-space CRES demonstrator



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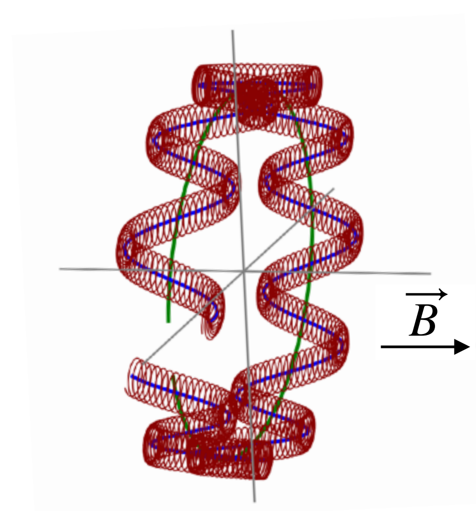

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