Credit: L. Thorne

Neutrino mass measurement with the Project 8 experiment

Larisa Thorne

Johannes Gutenberg University Mainz

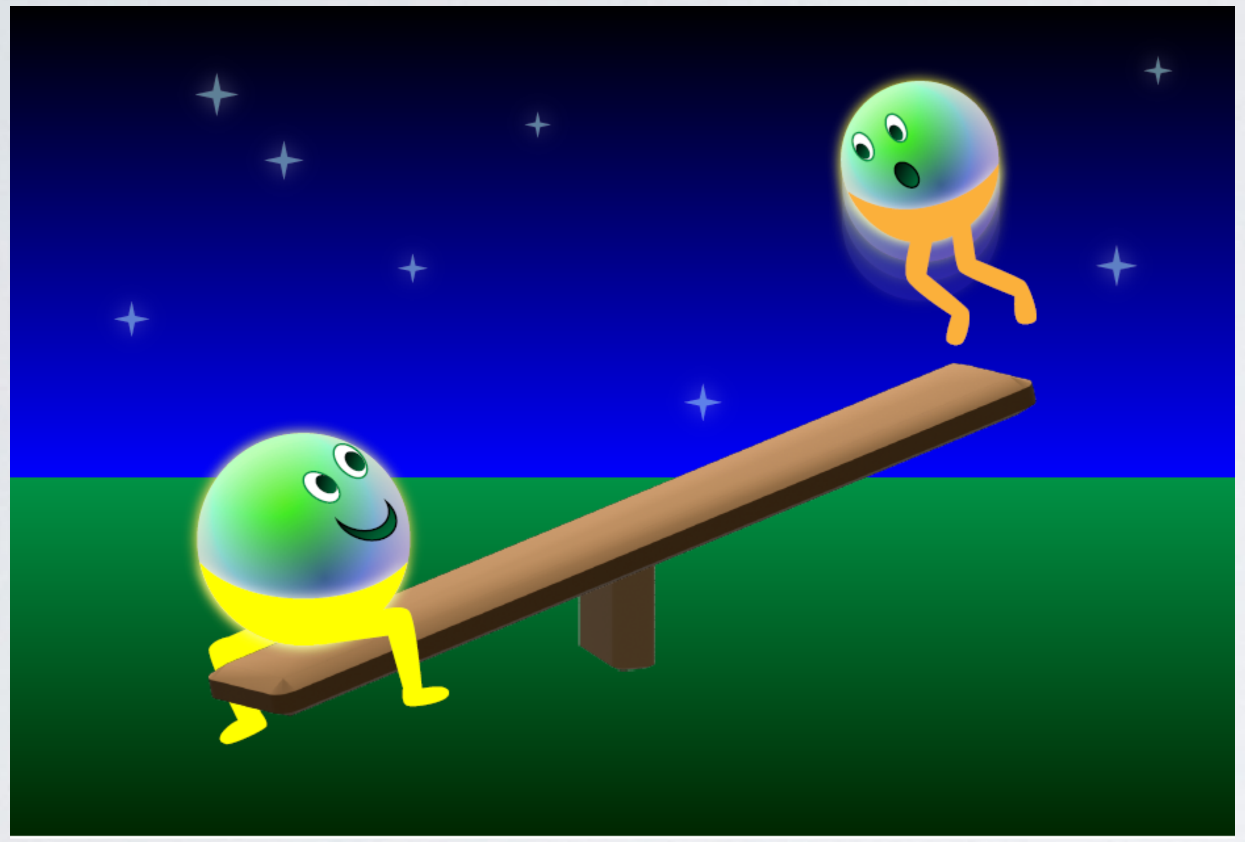
IRN 2023 (KIT) — 28 Nov 2023

PROJECT 8

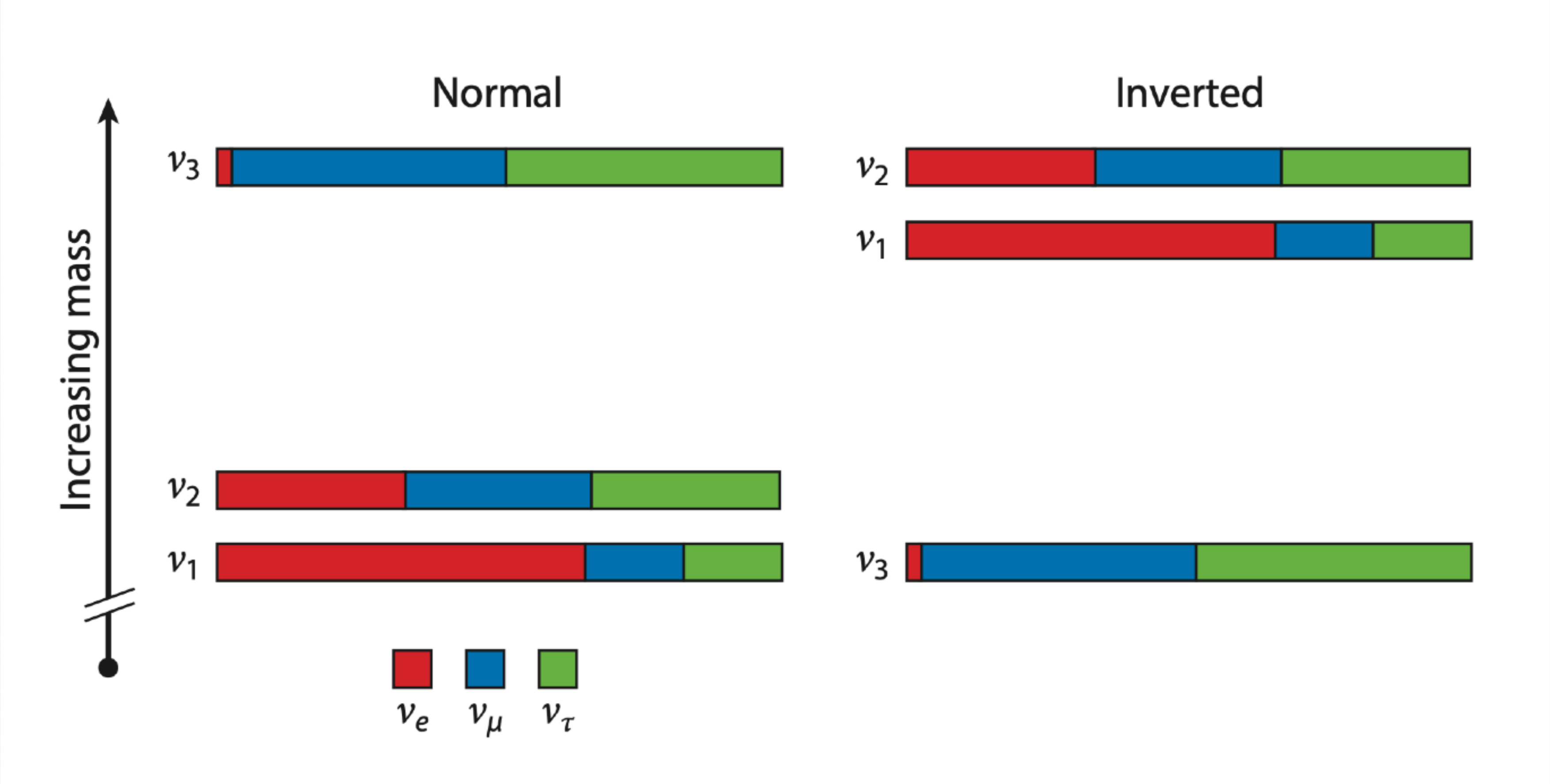
JG|U

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

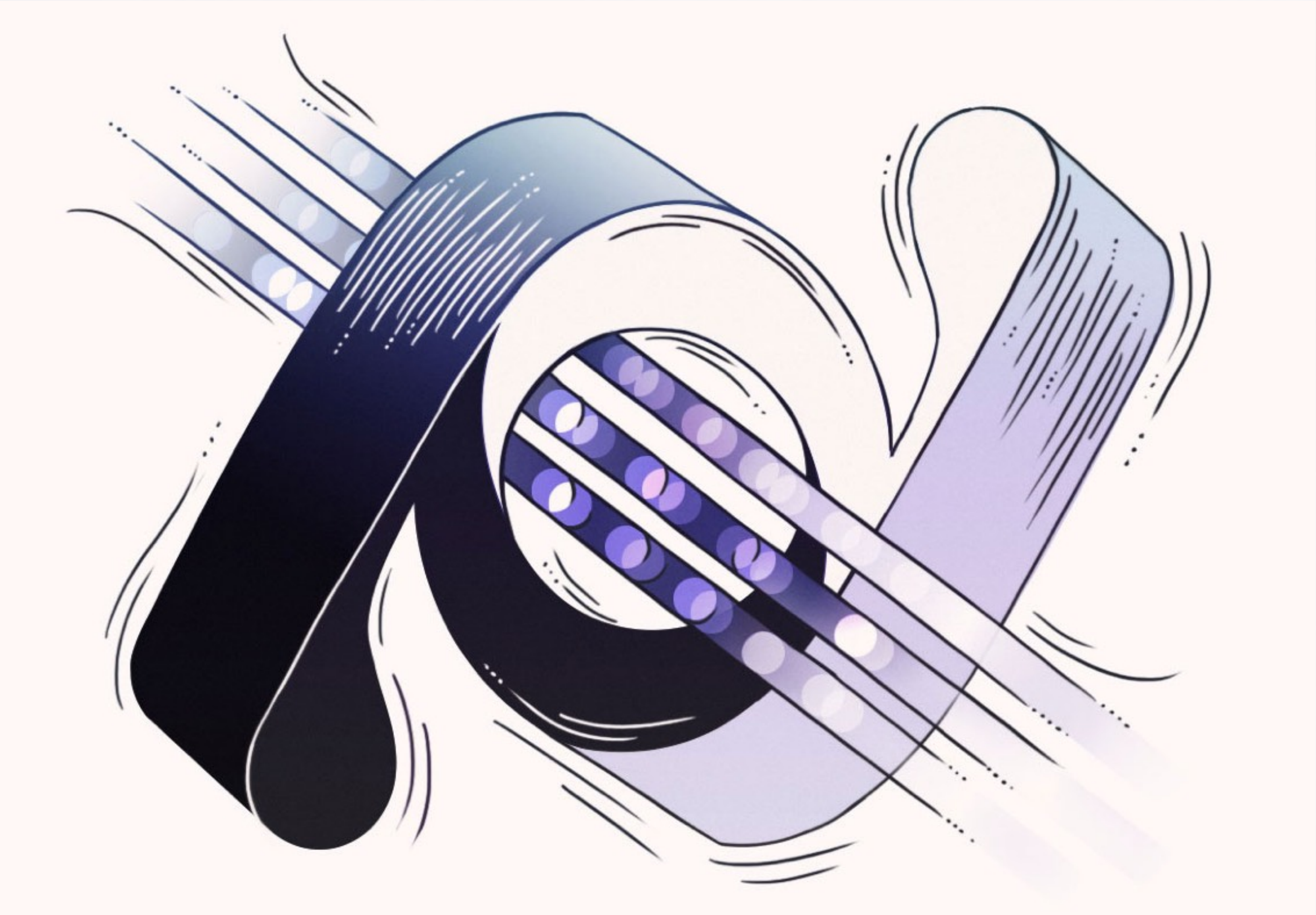
NEUTRINO MASS: WHY?



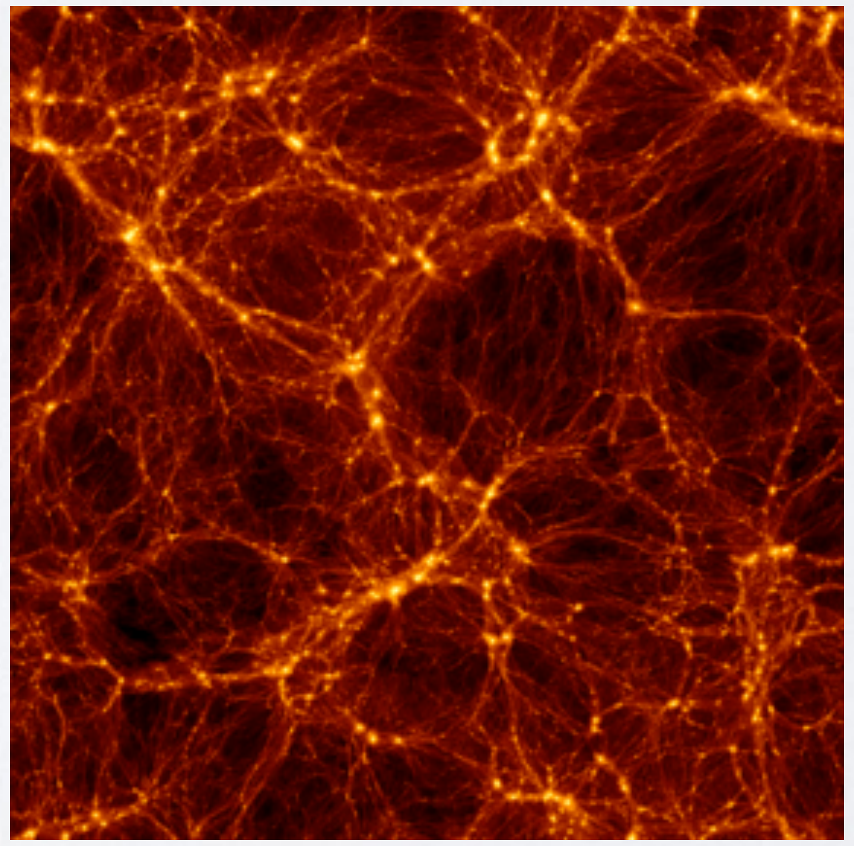
Source: https://physics.aps.org/articles/v16/20



Source: Formaggio et al, 2021



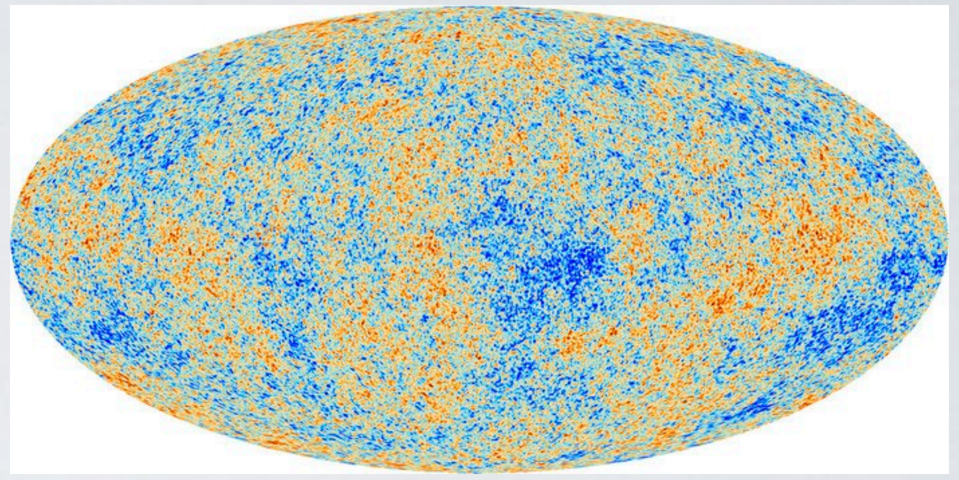
Source: Symmetry Magazine , 2016

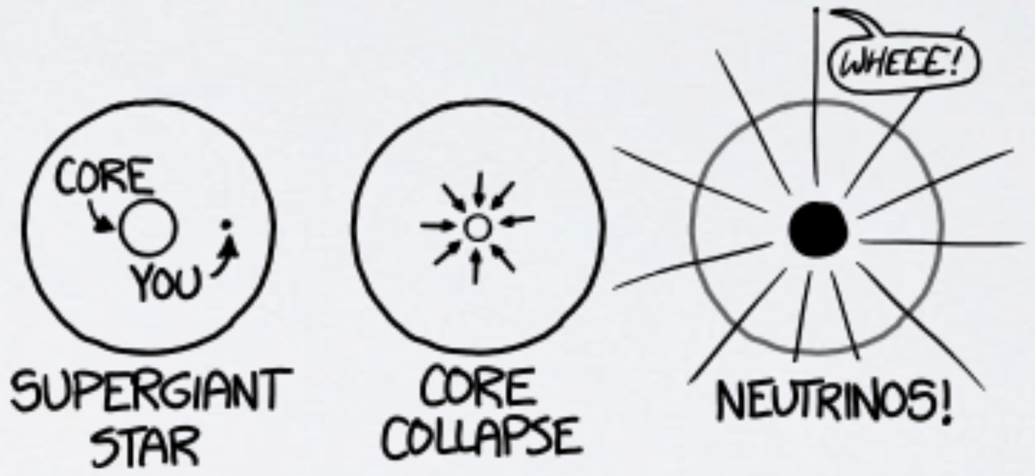


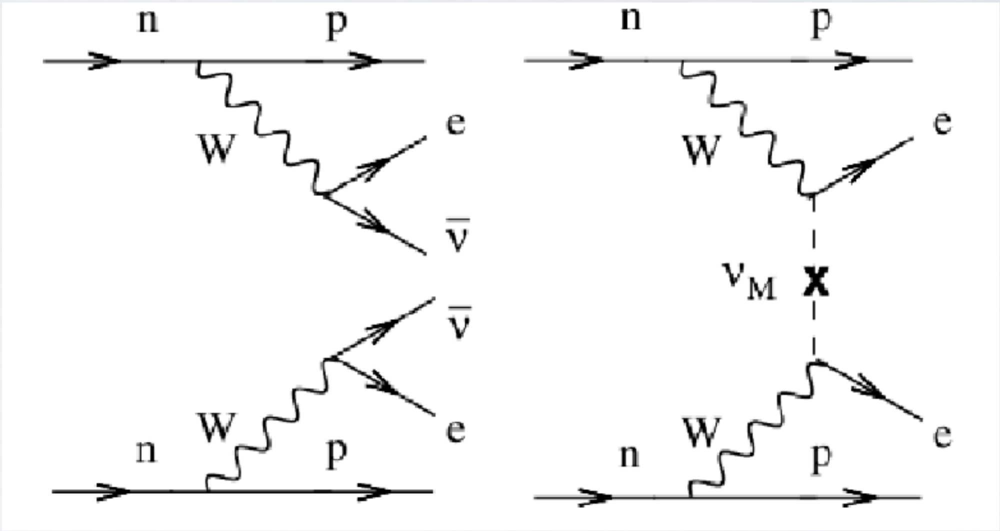
Source:https://arxiv.org/abs/1806.08395

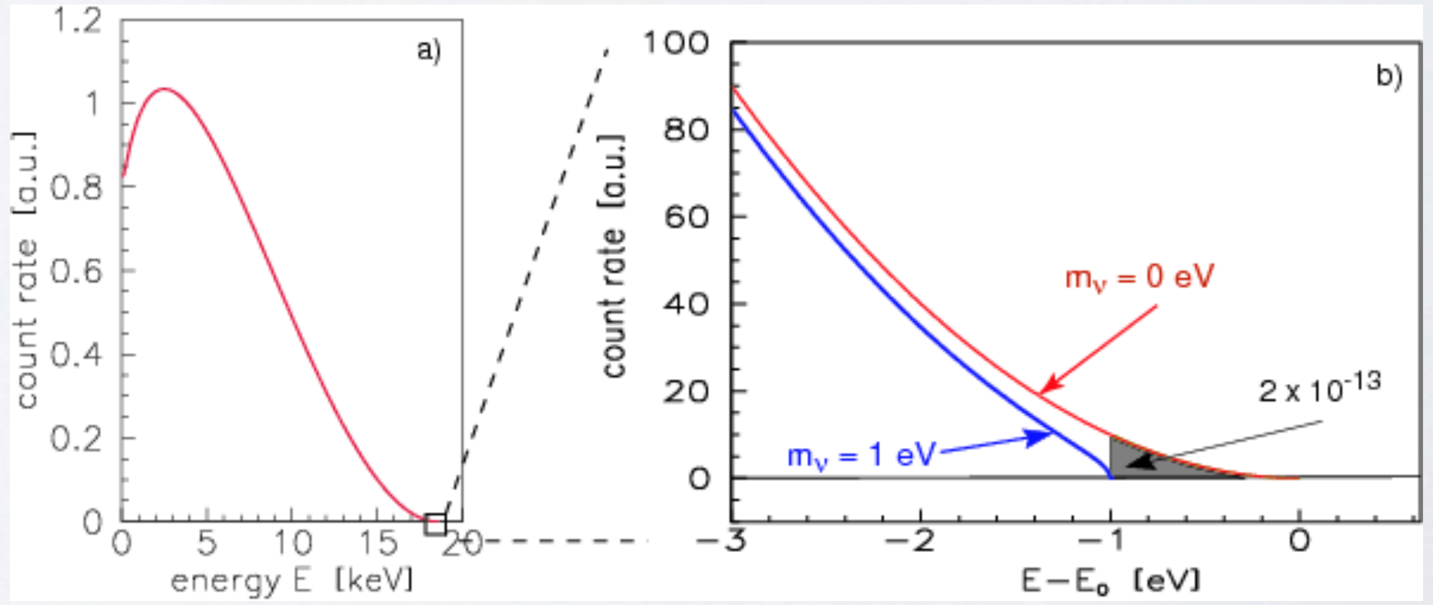
NEUTRINO MASS: HOW?

- 4 approaches to absolute neutrino mass measurement:
  1. Cosmic Microwave Background
  2. Supernova time-of-flight
  3. Search for neutrinoless double beta decay
  4. Kinematic methods



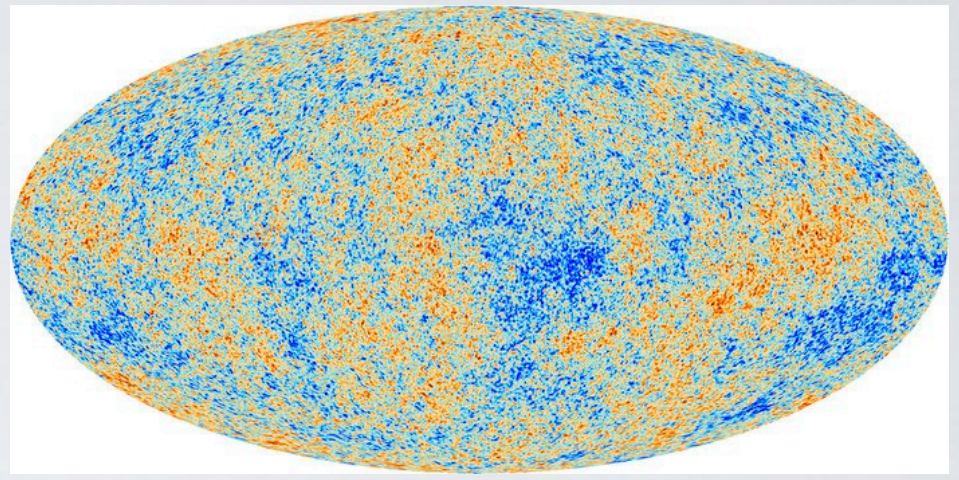


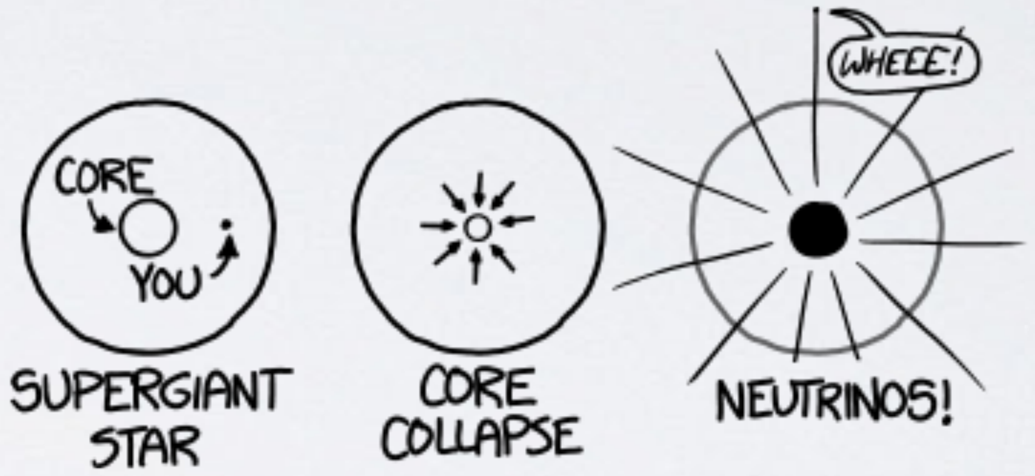


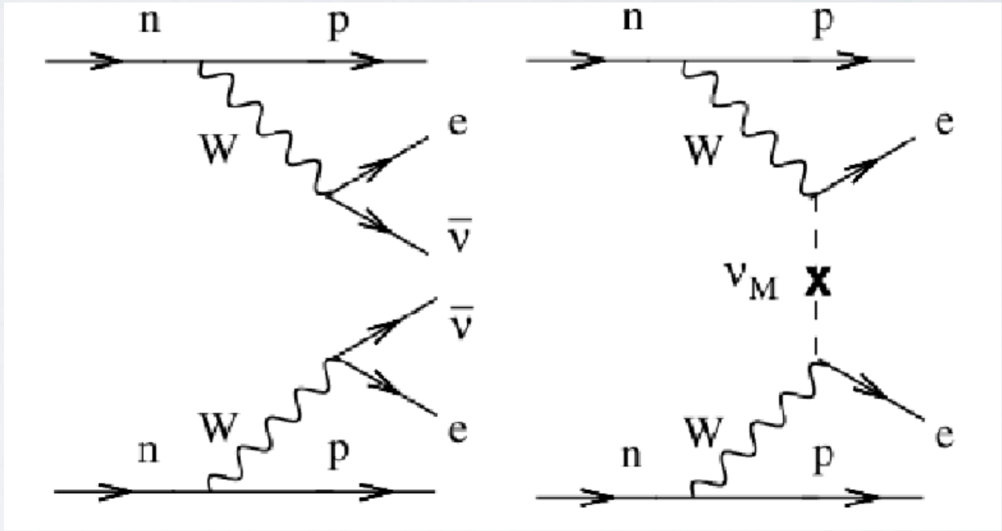


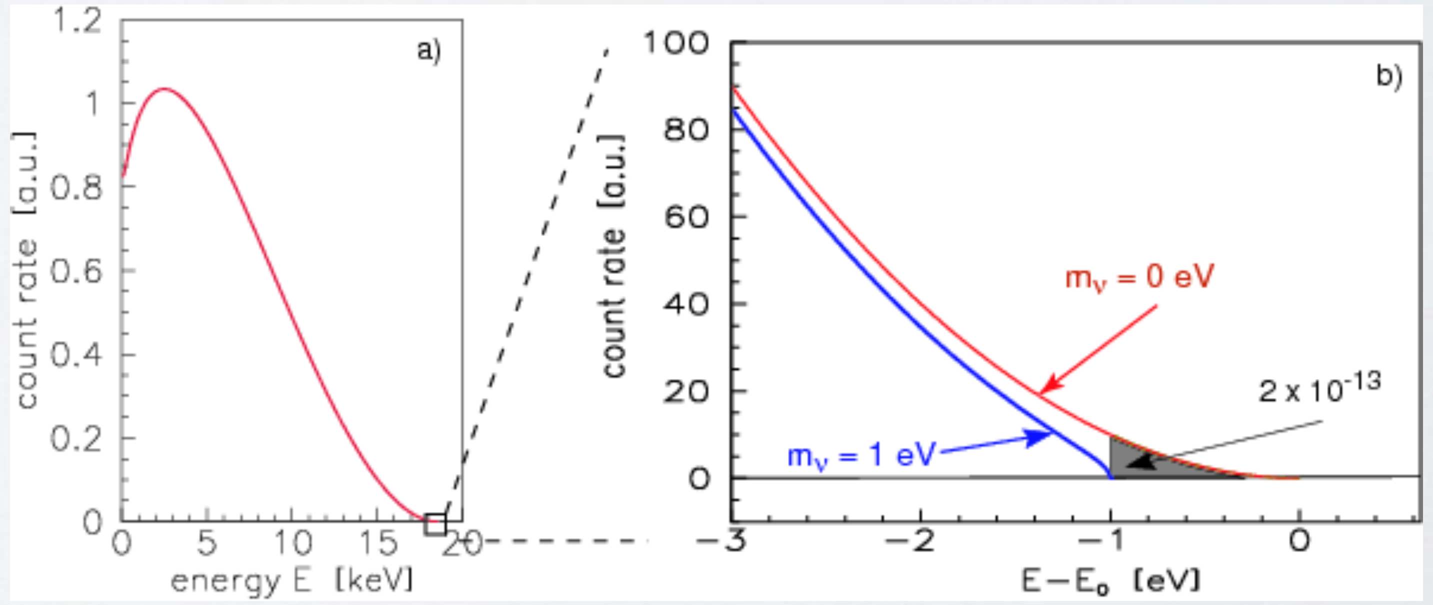
NEUTRINO MASS: HOW?

- 4 approaches to absolute neutrino mass measurement:
  1. Cosmic Microwave Background
  2. Supernova time-of-flight
  3. Search for neutrinoless double beta decay
  4. Kinematic methods
     - Via electromagnetic collimation
     - Via frequency-based measurement
     - Via calorimetric measurement



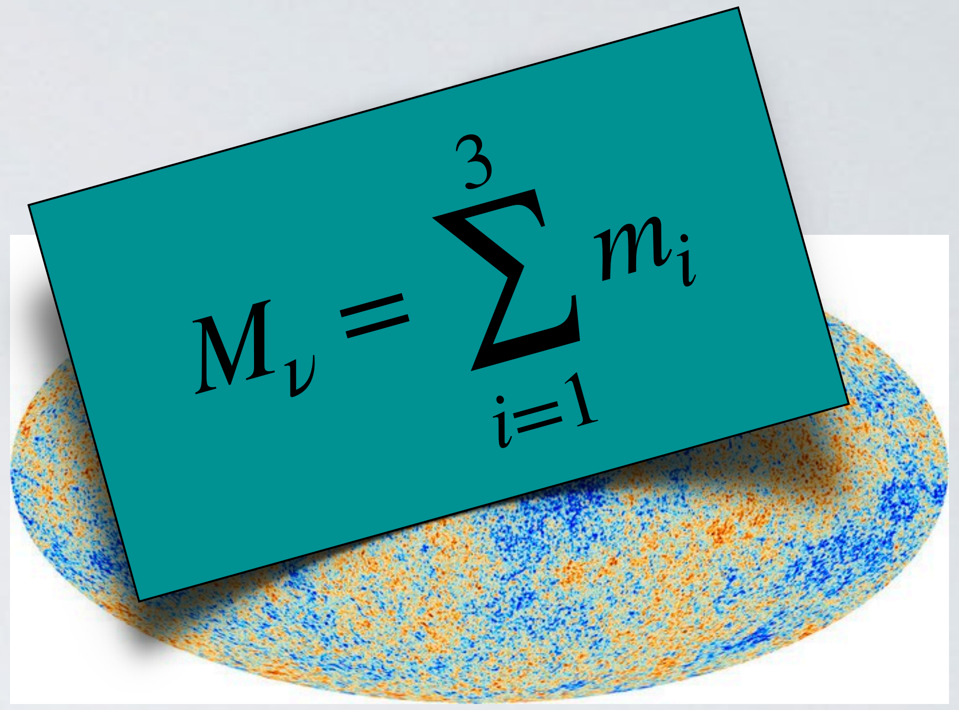




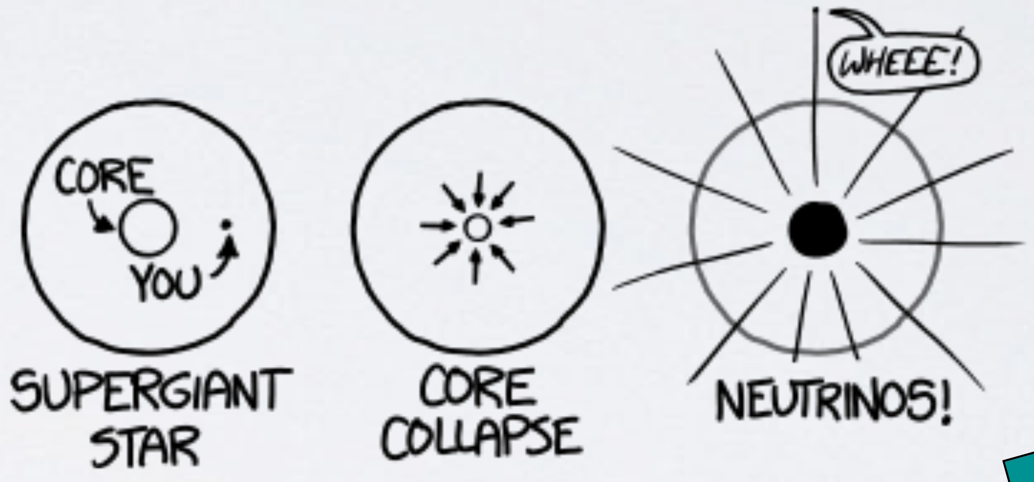


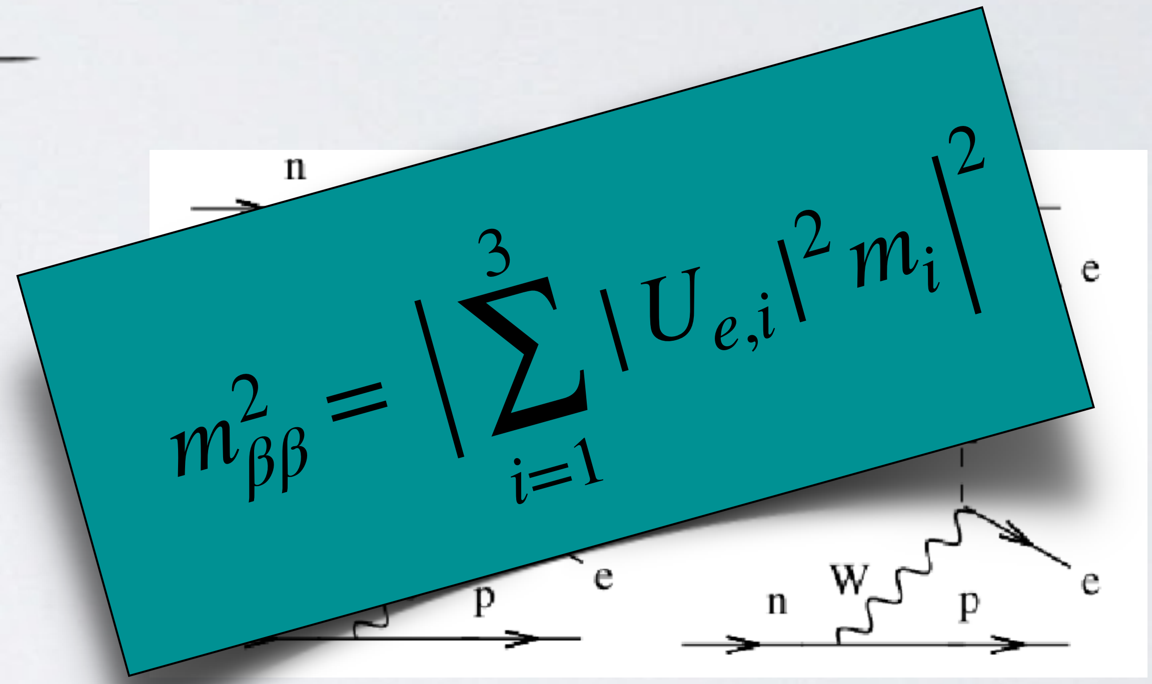
NEUTRINO MASS: HOW?

- 4 approaches to absolute neutrino mass measurement:
  1. Cosmic Microwave Background
  2. Supernova time-of-flight
  3. Search for neutrinoless double beta decay
  4. Kinematic methods
     - Via electromagnetic collimation
     - Via frequency-based measurement
     - Via calorimetric measurement

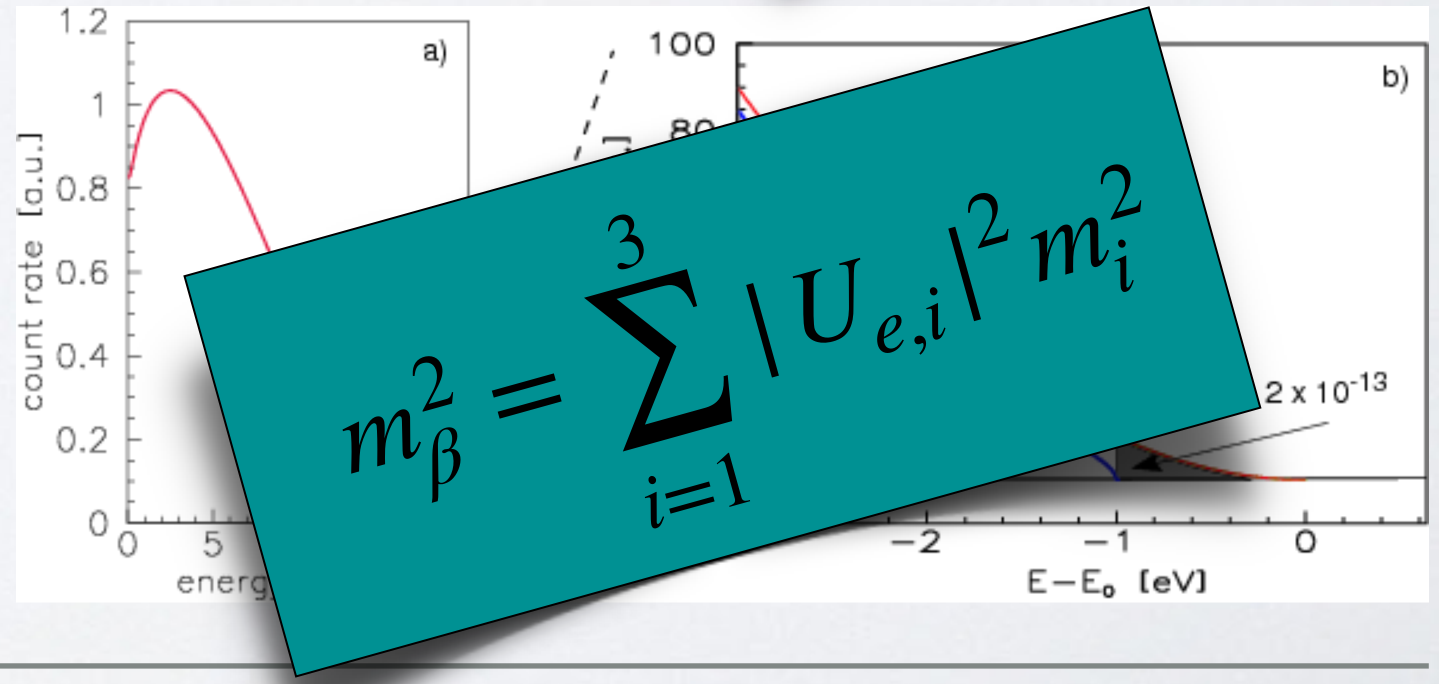


$$M_\nu = \sum_{i=1}^{3} m_i$$





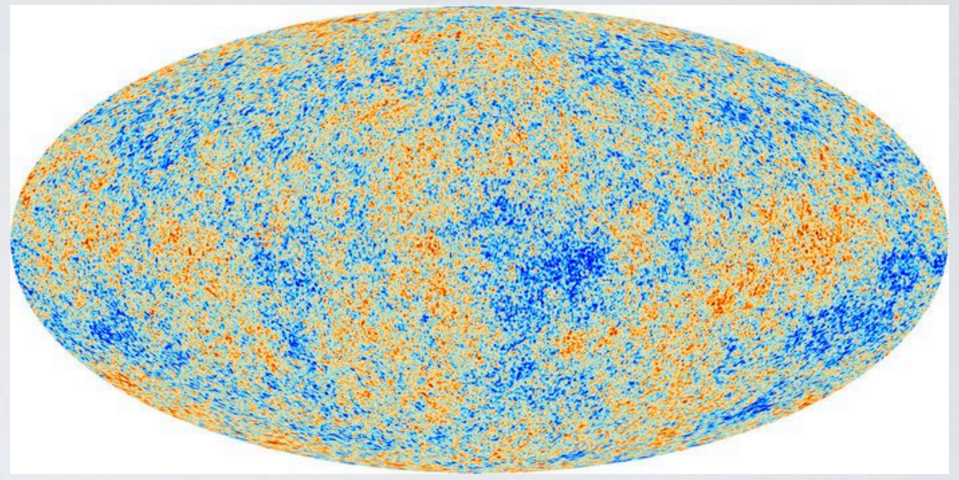
$$m_{\beta\beta}^2 = \left|\sum_{i=1}^{3} |U_{e,i}|^2 m_i\right|^2$$

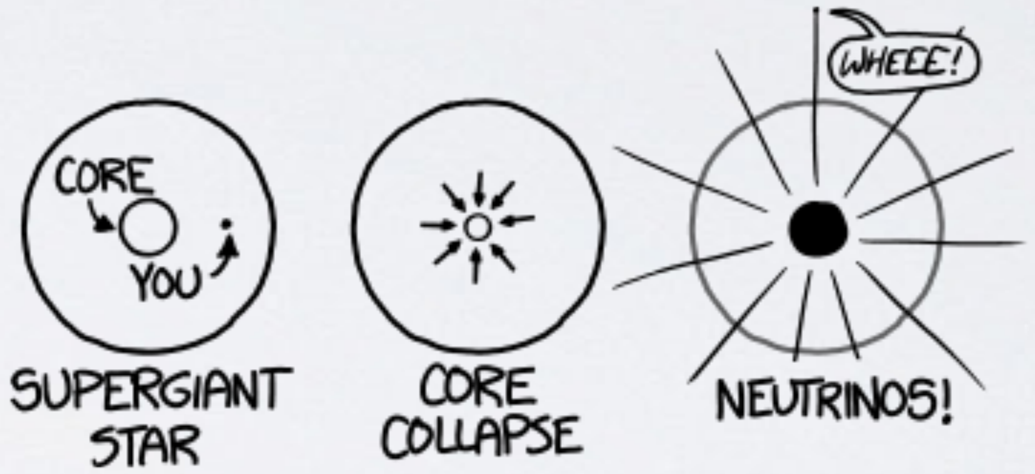


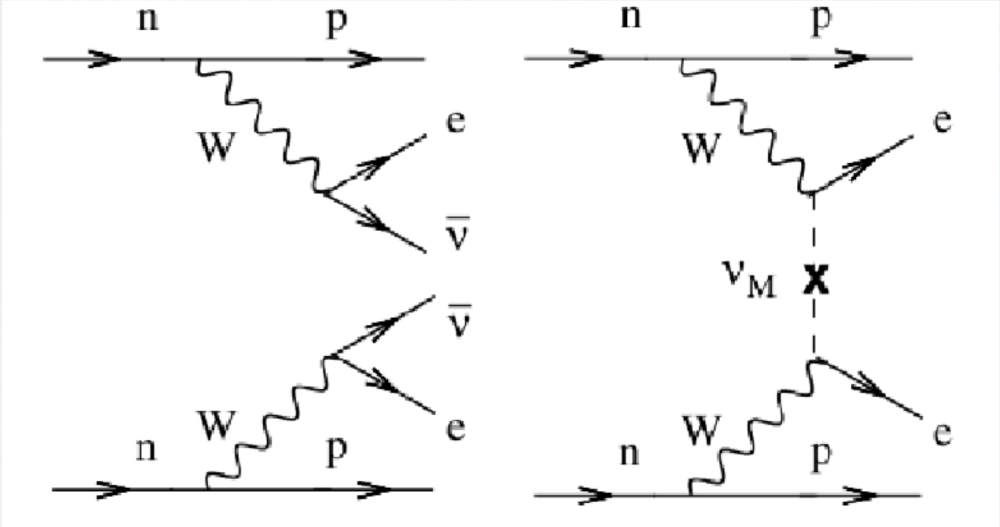
$$m_\beta^2 = \sum_{i=1}^{3} |U_{e,i}|^2 m_i^2$$

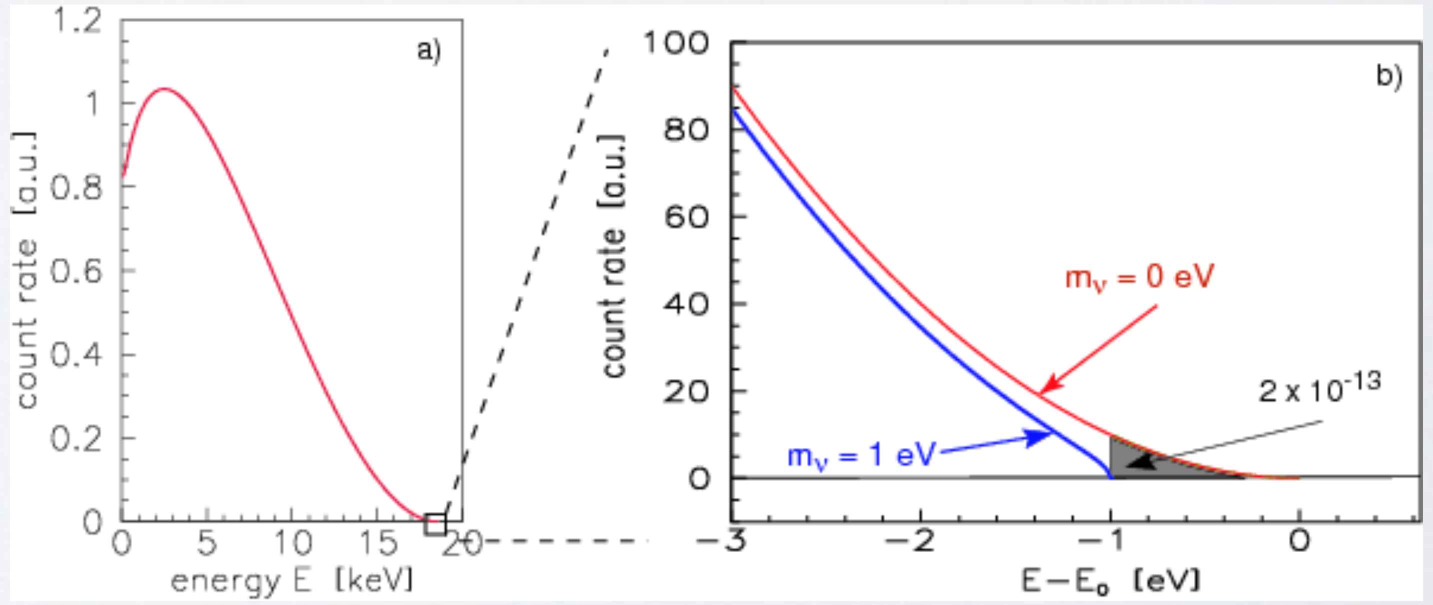
NEUTRINO MASS: HOW?

- 4 approaches to absolute neutrino mass measurement:
  1. Cosmic Microwave Background
  2. Supernova time-of-flight
  3. Search for neutrinoless double beta decay
  4. Kinematic methods
     - Via electromagnetic collimation
     - Via frequency-based measurement
     - Via calorimetric measurement

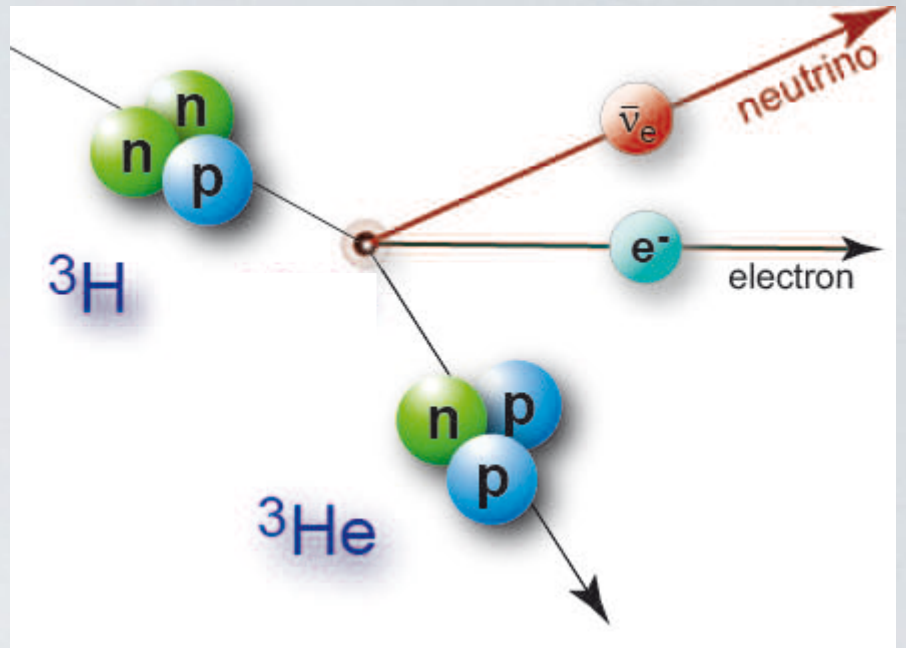




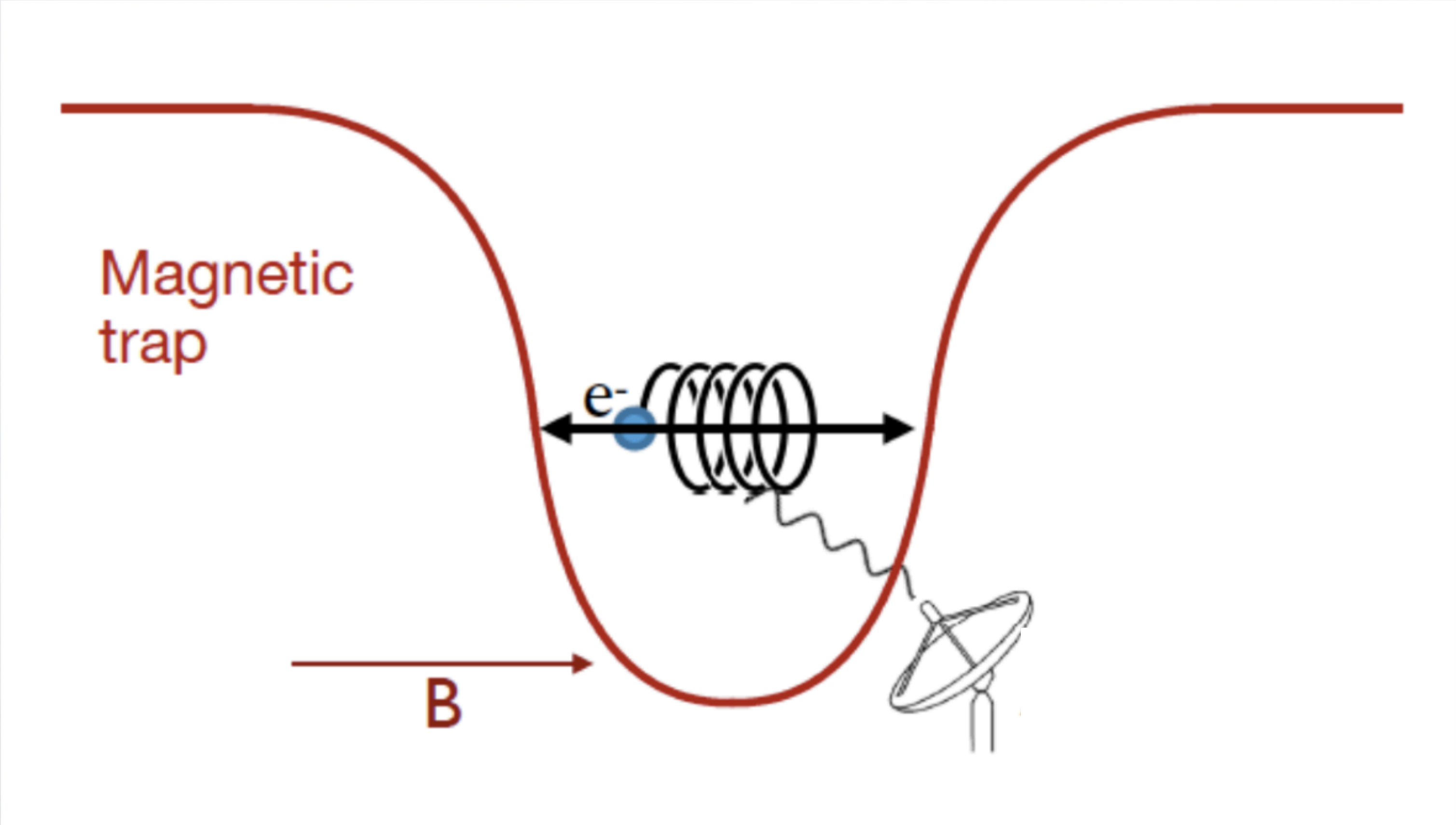




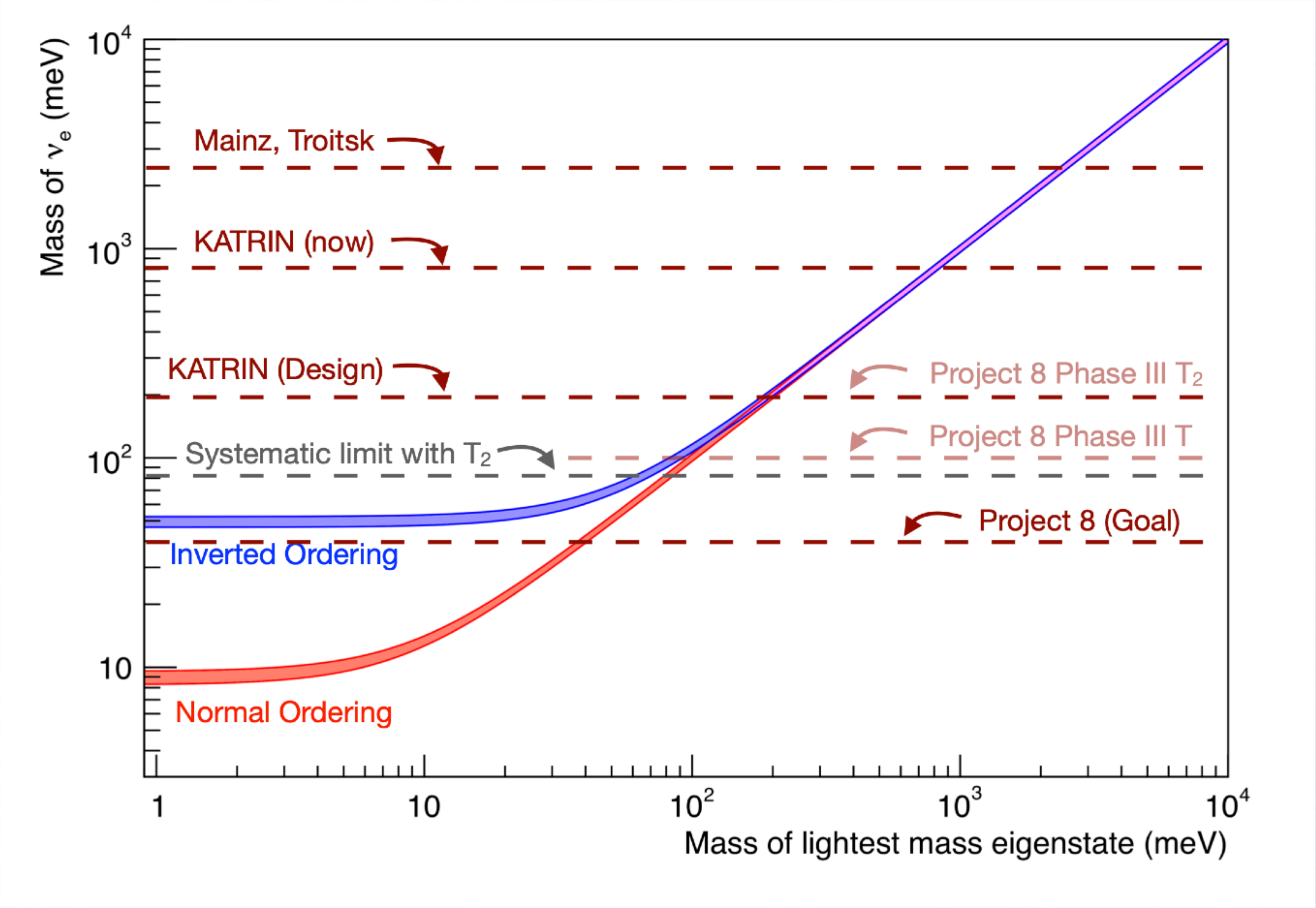
THE PROJECT 8 EXPERIMENT



- Goal: absolute neutrino mass measurement
- Technique: measure cyclotron radiation from trapped tritium beta decay electrons ("CRES": **c**yclotron **r**adiation **e**mission **s**pectroscopy)
- Design sensitivity: 40meV at 90% C.L.



https://www.project8.org

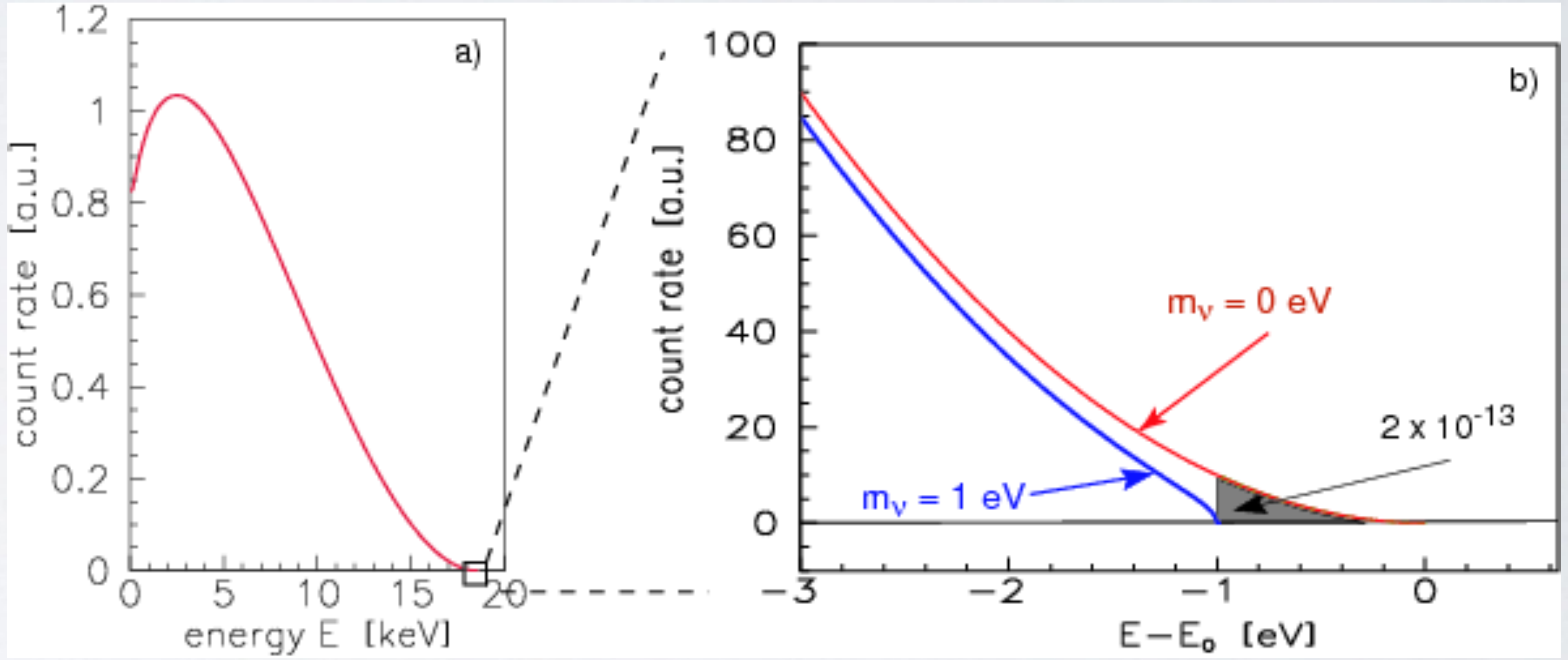


PROJECT 8: MEASUREMENT TECHNIQUE

CRES: cyclotron radiation emission spectroscopy

$$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$$

1. Trap decay electrons from tritium source gas within local minimum of a homogeneous B field
2. Beta decay electron undergoes cyclotron motion with frequency $\boldsymbol{f_{cyc}}$
3. Radiation detected



Tritium isotope has attractive beta decay properties: decay is **super-allowed**, practical **half-life** (~12.3yr), fairly low **endpoint energy** (~18.6keV)

PROJECT 8: MEASUREMENT TECHNIQUE

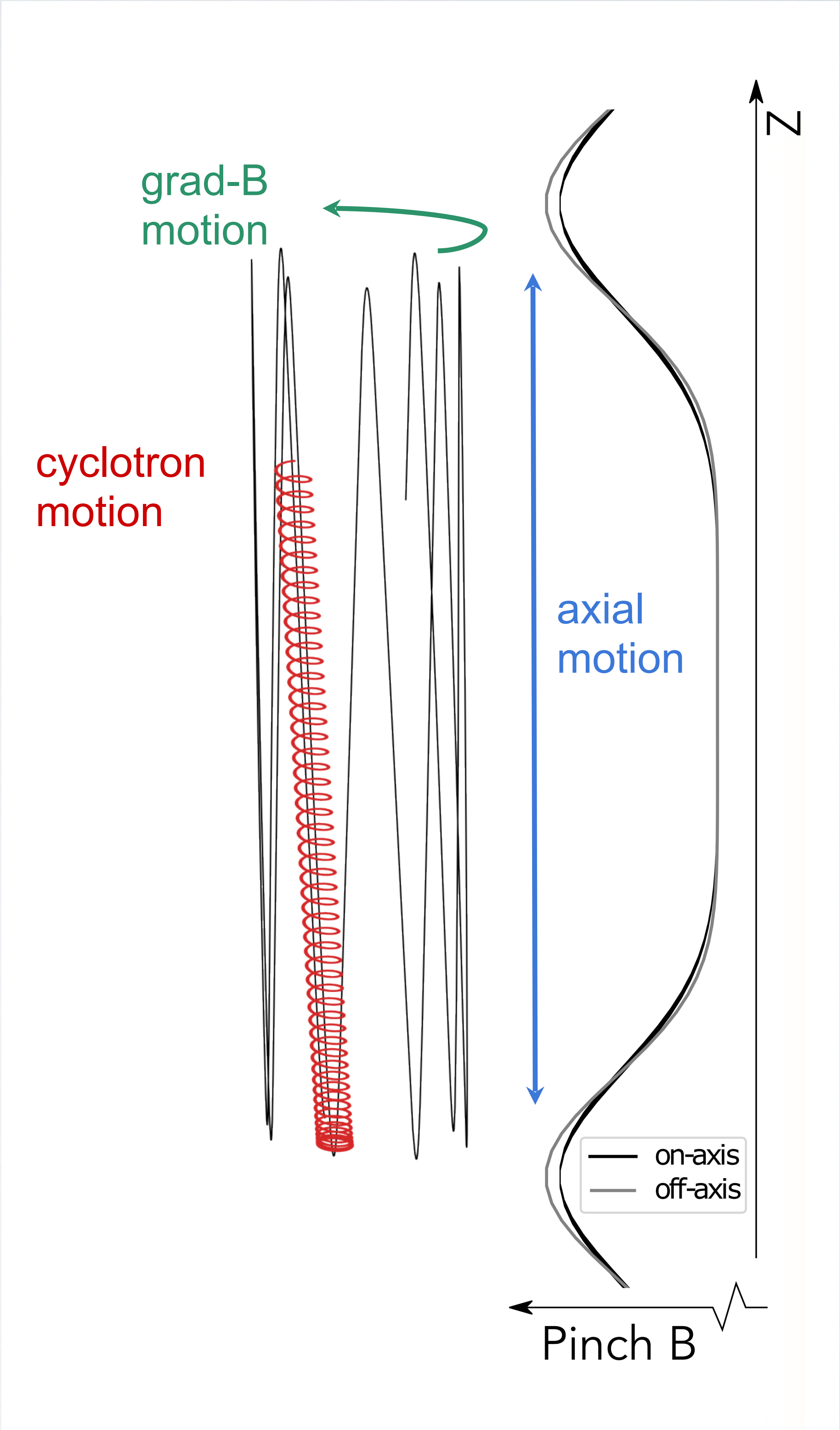
CRES: cyclotron radiation emission spectroscopy

1. Trap decay electrons from tritium source gas within local minimum of a homogeneous B field

2. Beta decay electron undergoes cyclotron motion with frequency $\boldsymbol{f_{cyc}}$

3. Radiation detected

$$f_{cyc} \propto \frac{q\langle B \rangle}{m_e + E_{kin}}$$



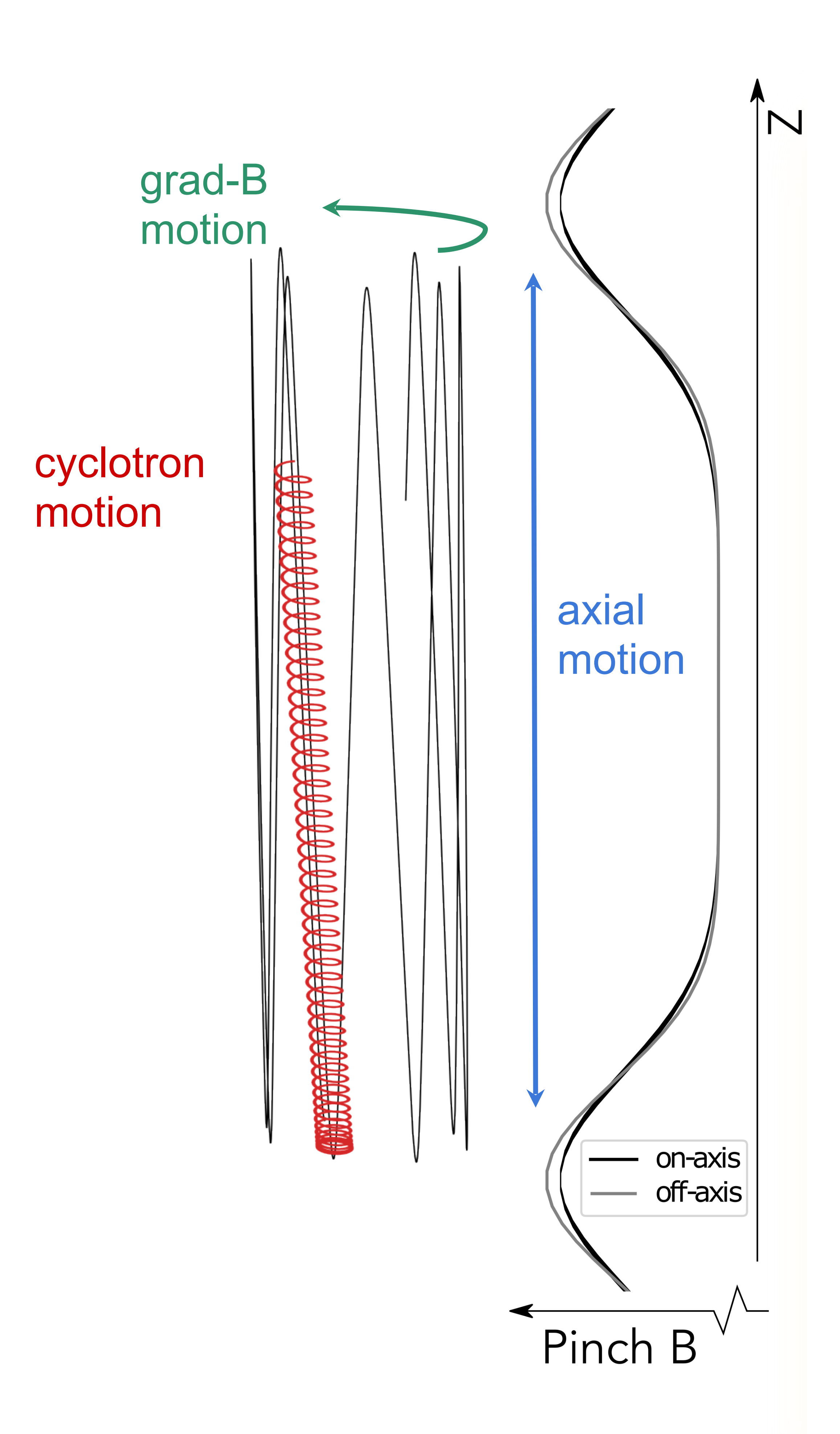
PROJECT 8: MEASUREMENT TECHNIQUE

CRES: cyclotron radiation emission spectroscopy

1. Trap decay electrons from tritium source gas within local minimum of a homogeneous B field

2. Beta decay electron undergoes cyclotron motion with frequency $\boldsymbol{f_{cyc}}$

3. Radiation detected



~325MHz ~0.01T

$$f_{cyc} \propto \frac{q\langle B\rangle}{m_e + E_{kin}}$$

~18.6keV

PROJECT 8: MEASUREMENT TECHNIQUE

CRES: cyclotron radiation emission spectroscopy

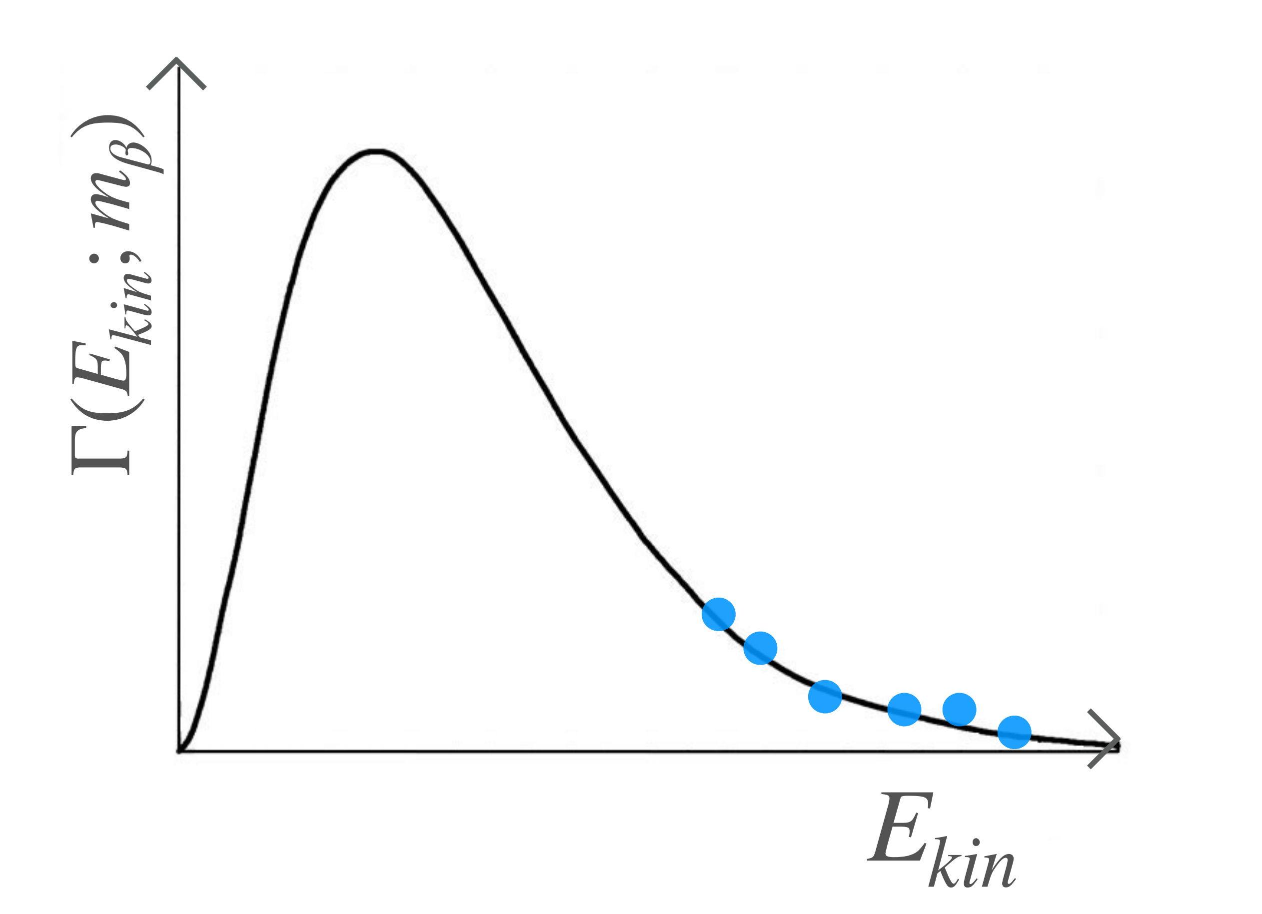
1. Trap decay electrons from tritium source gas within local minimum of a homogeneous B field

2. Beta decay electron undergoes cyclotron motion with frequency $\boldsymbol{f_{cyc}}$

3. Radiation detected →

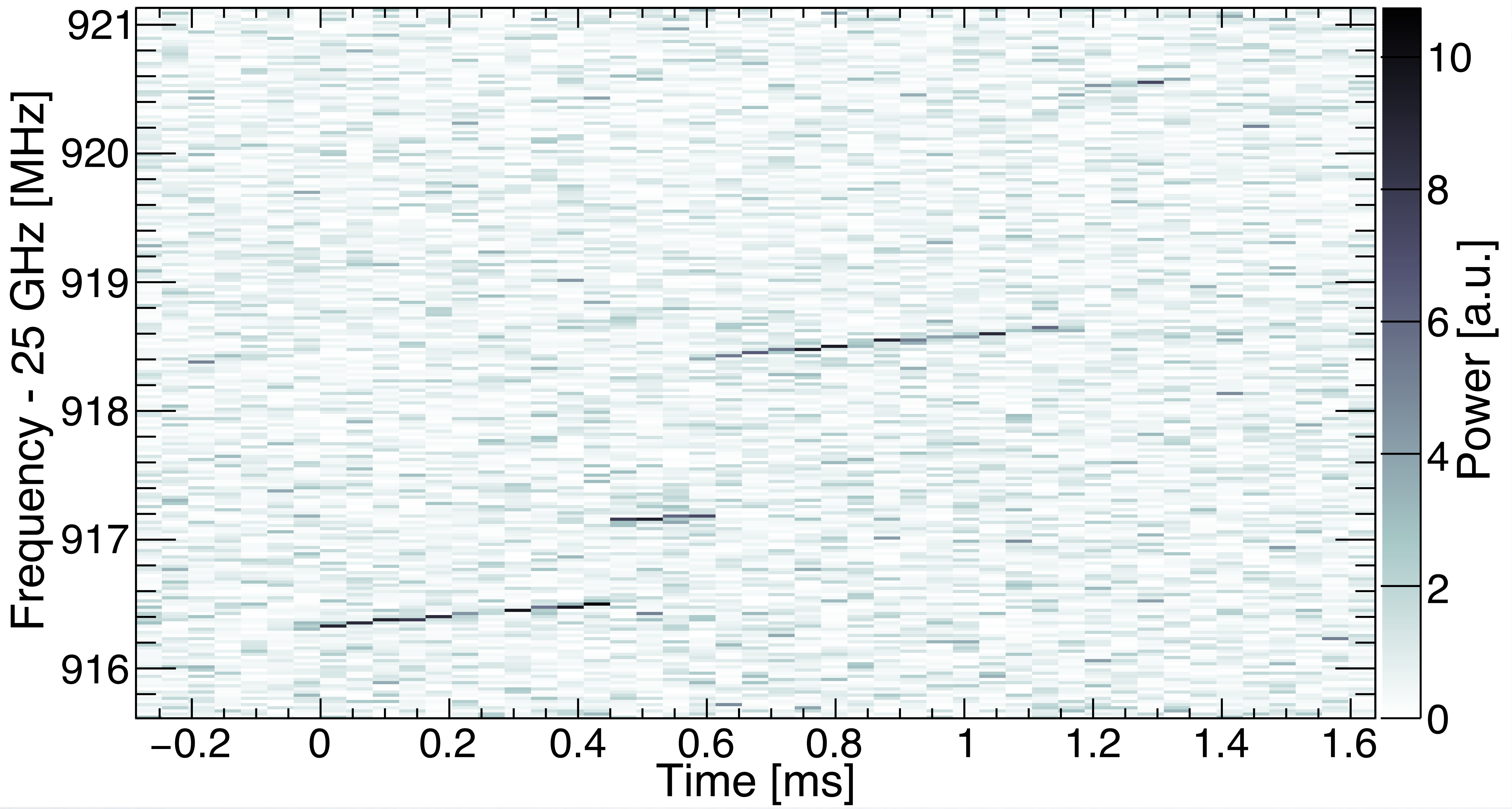
$$f_{cyc} \propto \frac{q\langle B\rangle}{m_e + E_{kin}}$$

Reconstruct differential spectrum:

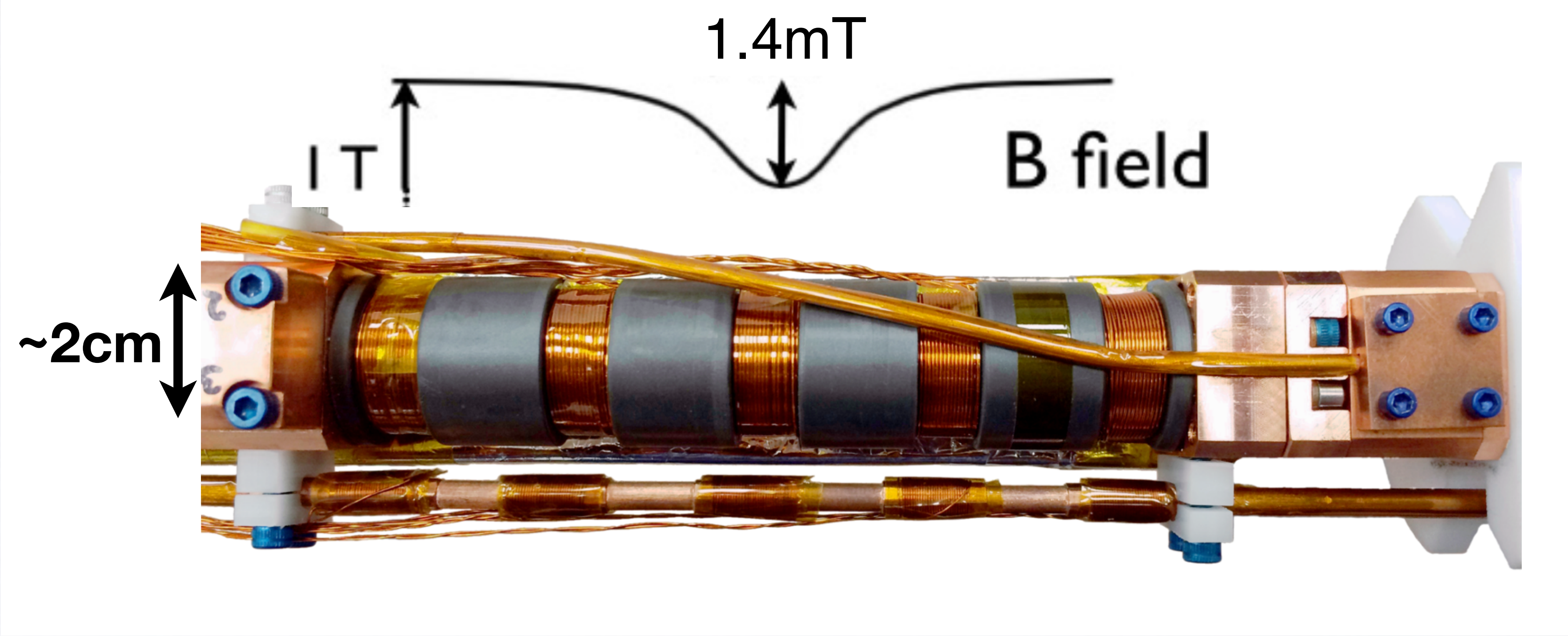


PROJECT 8: MEASUREMENT TECHNIQUE

Sample (tritium) CRES event:

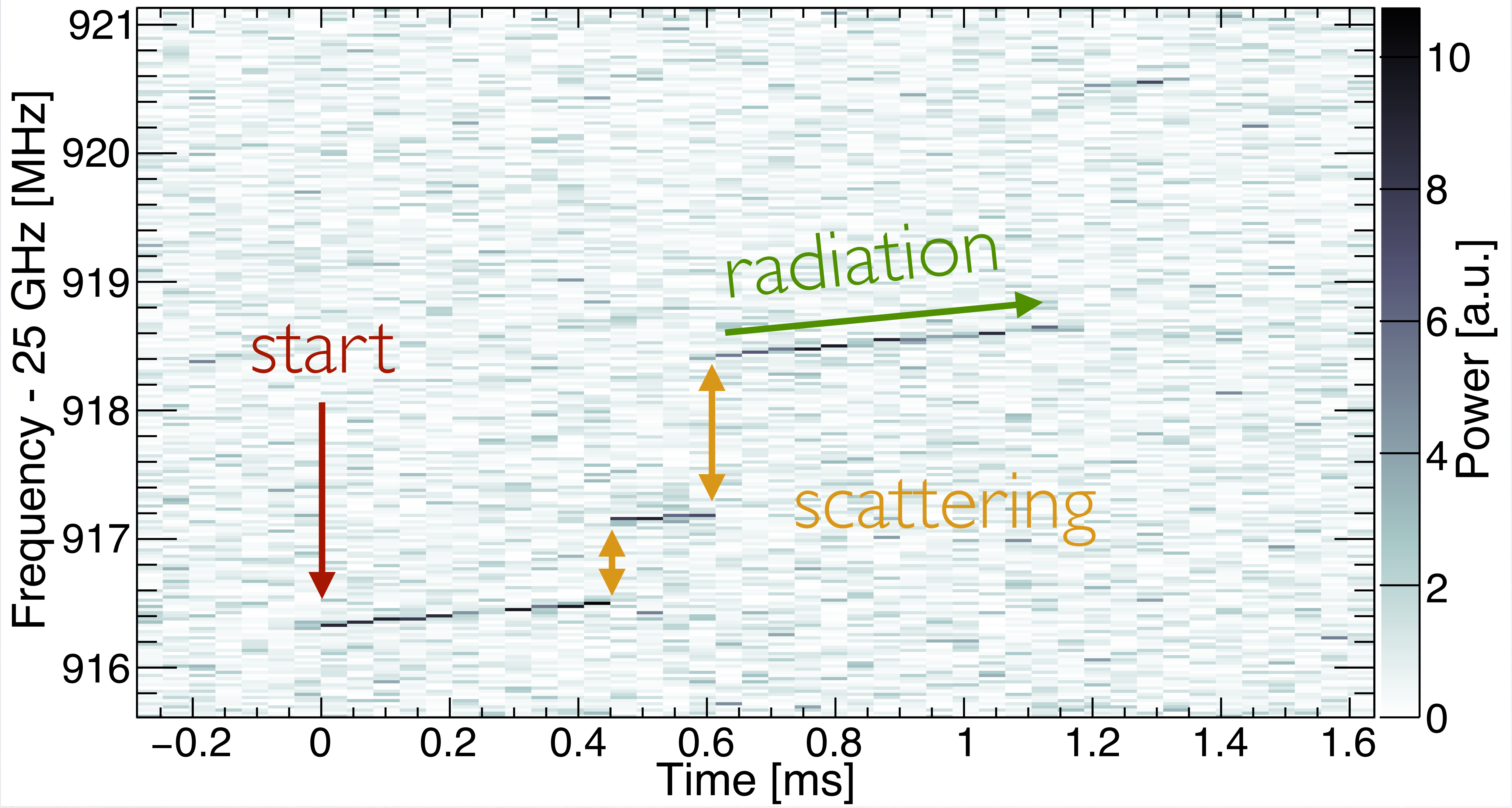


- First detection of single ^{83m}Kr electrons using CRES: *Phys. Rev. Lett. 114, 1162501 (2015)*
- First results with tritium (T_2), both Frequentist and Bayesian: Phys. Rev. Lett.131.102502



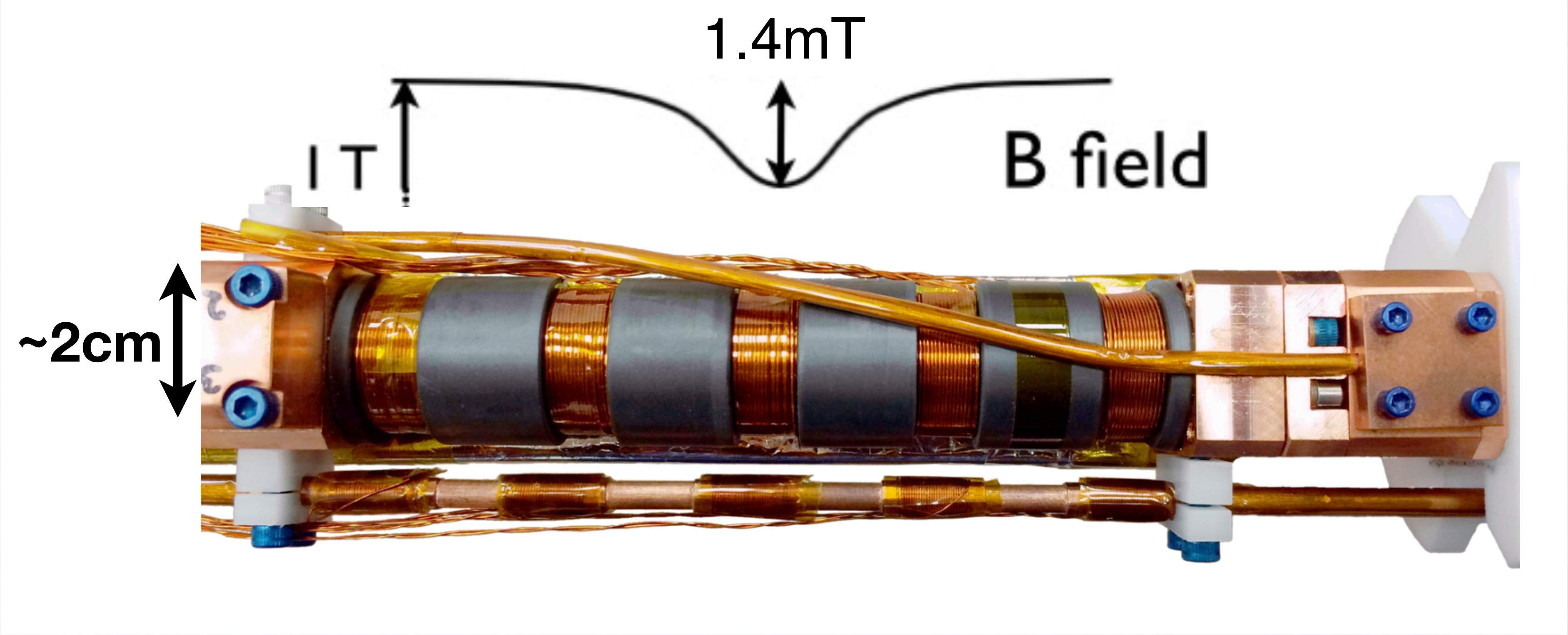
PROJECT 8: MEASUREMENT TECHNIQUE

Sample (tritium) CRES event:

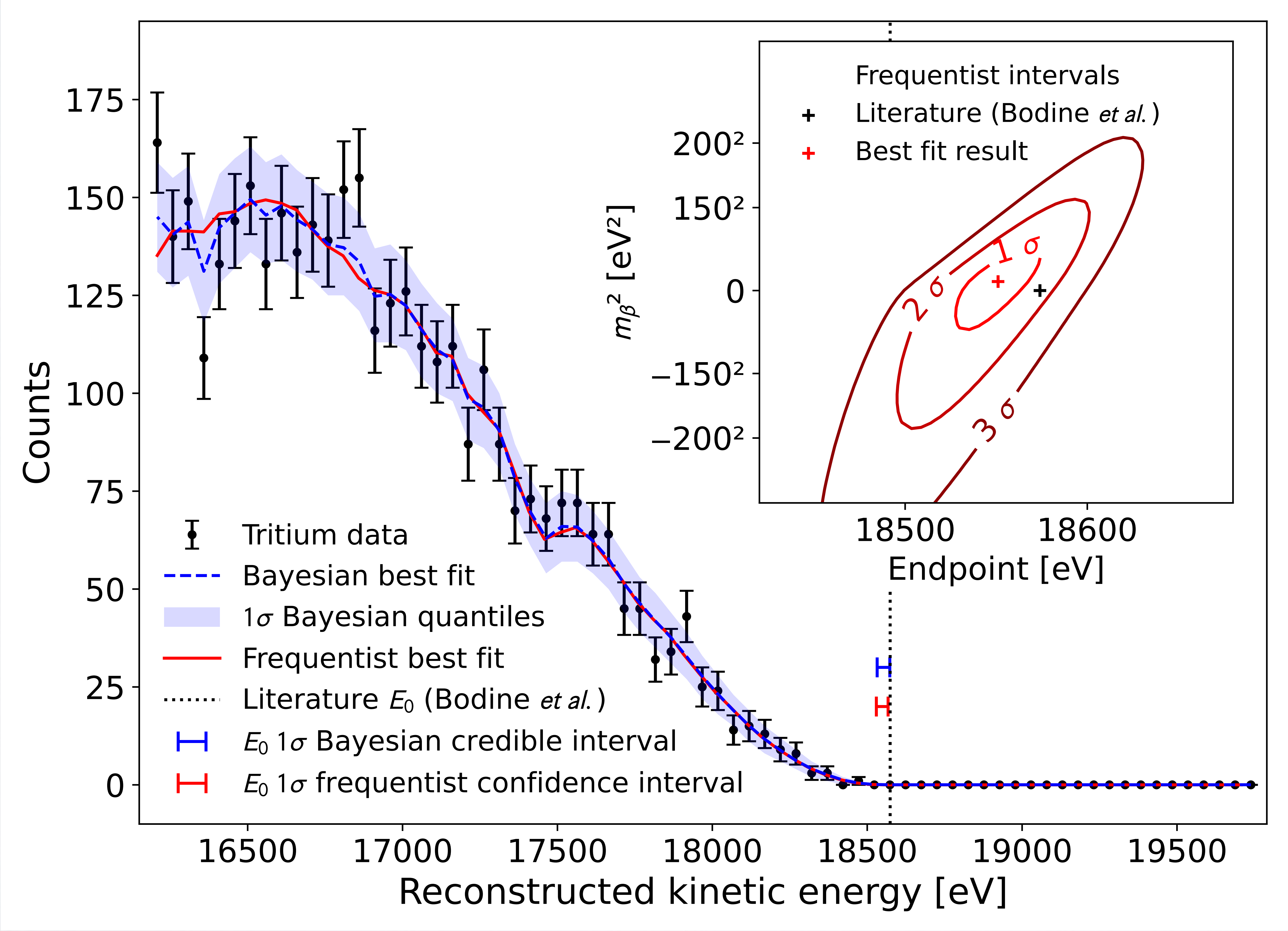


$$f_{cyc} \propto \frac{q\langle B\rangle}{m_e + E_{kin}}$$

- First detection of single ^{83m}Kr electrons using CRES: *Phys. Rev. Lett. 114, 1162501 (2015)*
- First results with tritium (T_2), both Frequentist and Bayesian: Phys. Rev. Lett.131.102502



PROJECT 8: FIRST RESULTS



Source: Phys.Rev.Lett. 131, 102502 (2023)

Tritium beta decay endpoint (90% C.L.):

- Frequentist: 18548^{+19}_{-19} eV
- Bayesian: 18553^{+18}_{-19} eV

Neutrino mass (90% C.L.):

- Frequentist: ≤ 152 eV/c²
- Bayesian: ≤ 155 eV/c²

Background count rate (90% C.L.):

- No events above endpoint!
- $\leq 3 \times 10^{-10}$cps/eV

Resolution:

- 54.3 eV (FWHM)

Effective volume:

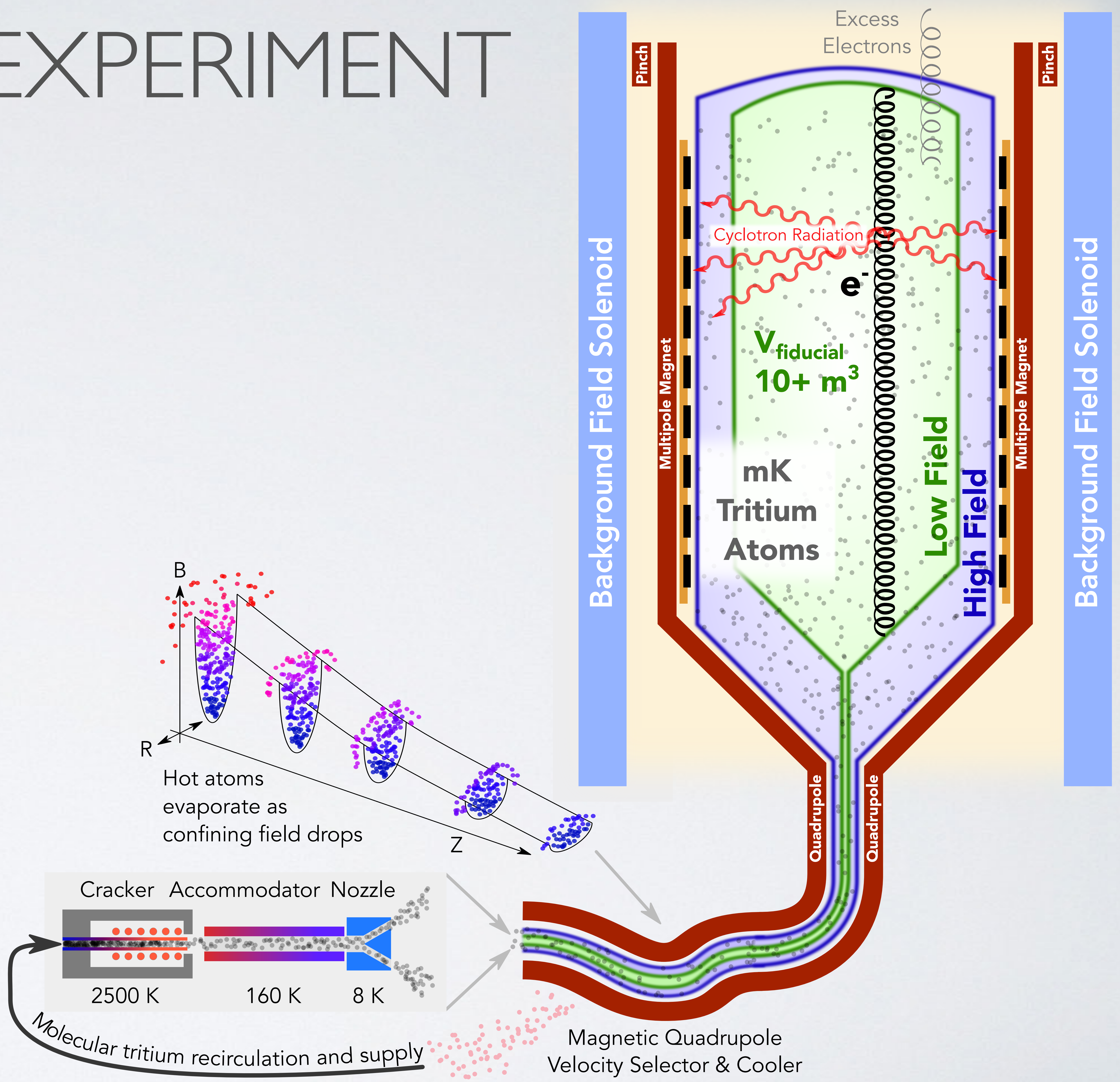
- 1.20 ± 0.09 mm³ eV

Statistics-limited (3 months' worth of data)

R&D FOR FULL-SCALE EXPERIMENT

Large sensitivity improvements achieved by:

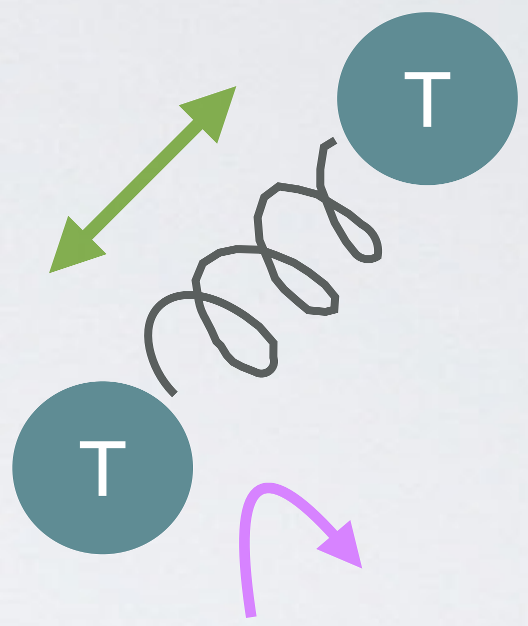
1. Switching from molecular → atomic tritium source
2. Scaling up CRES detection volume

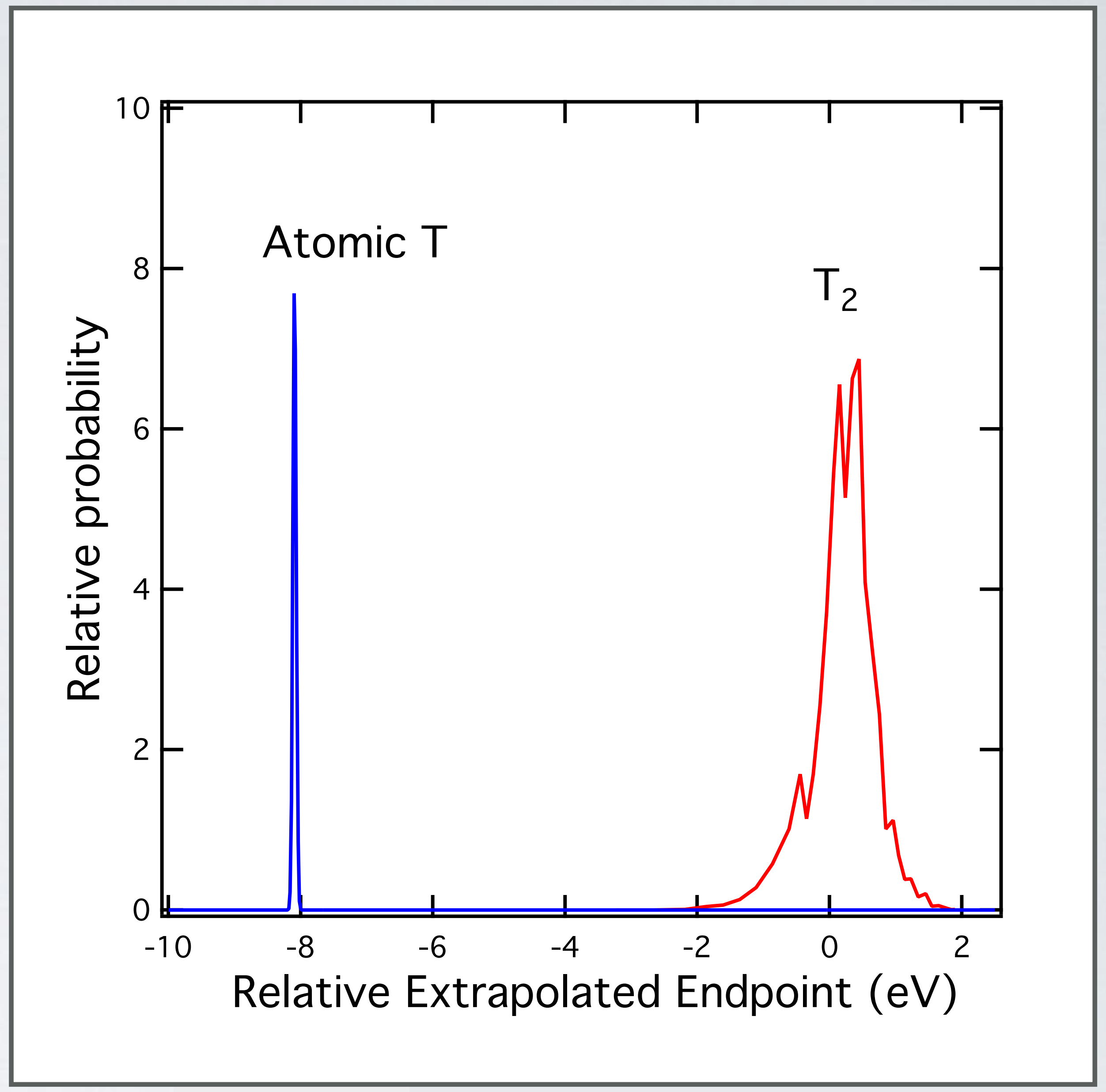


R&D FOR FULL-SCALE EXPERIMENT

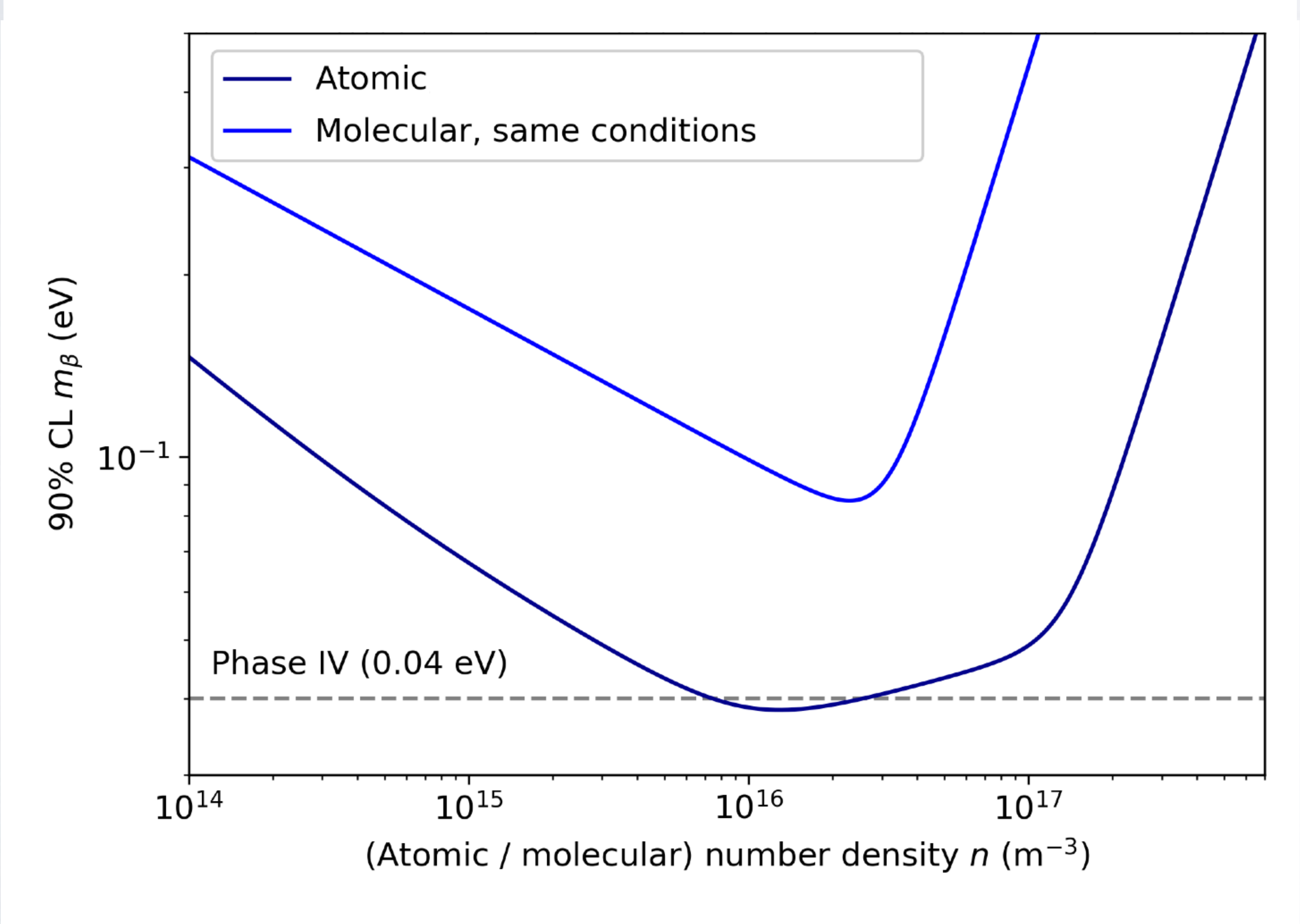
Large sensitivity improvements achieved by:

1. **Switching from molecular → atomic tritium source**
2. Scaling up CRES detection volume

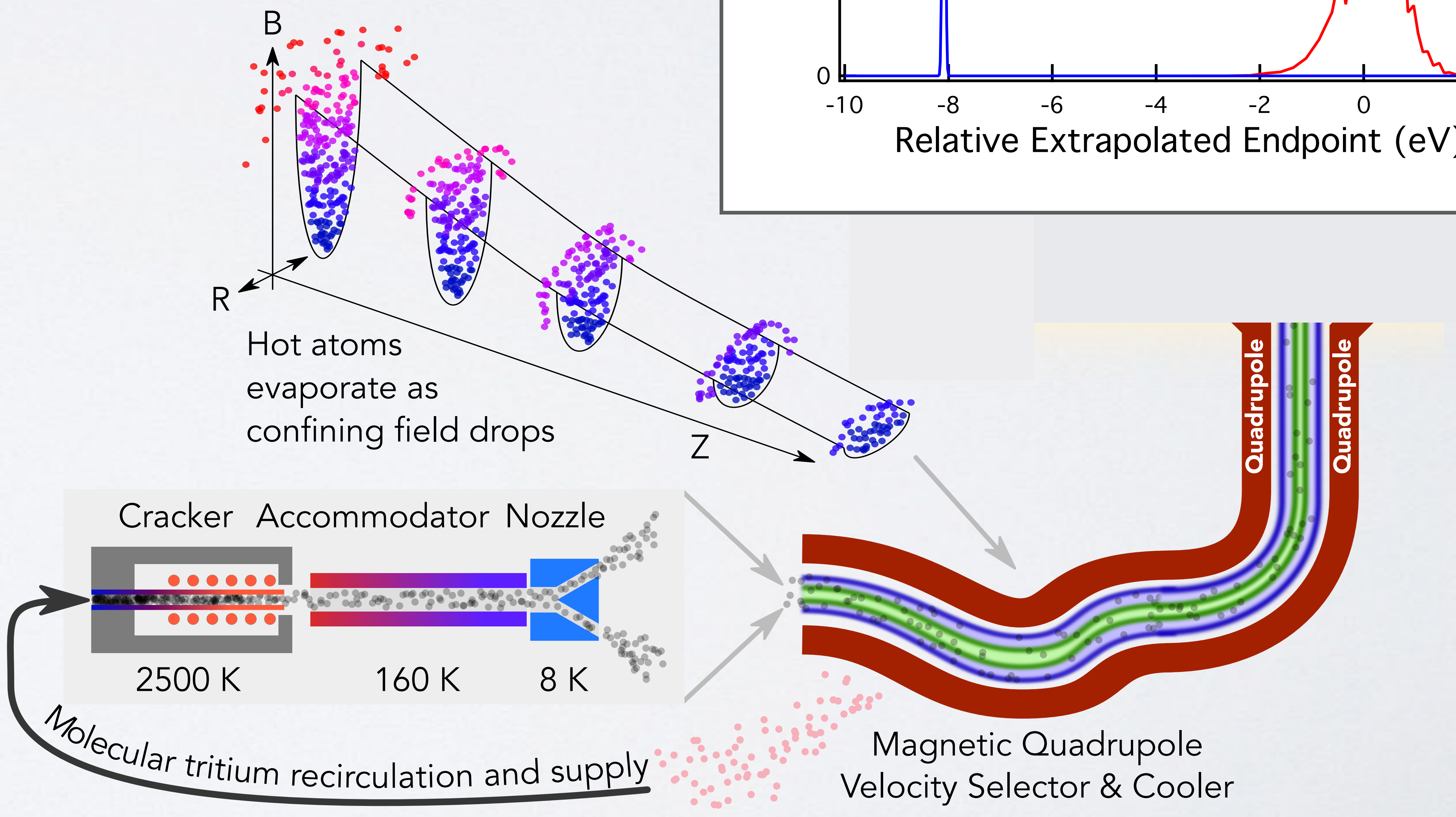




Adapted from L. Bodine



Adapted from T. Weiss

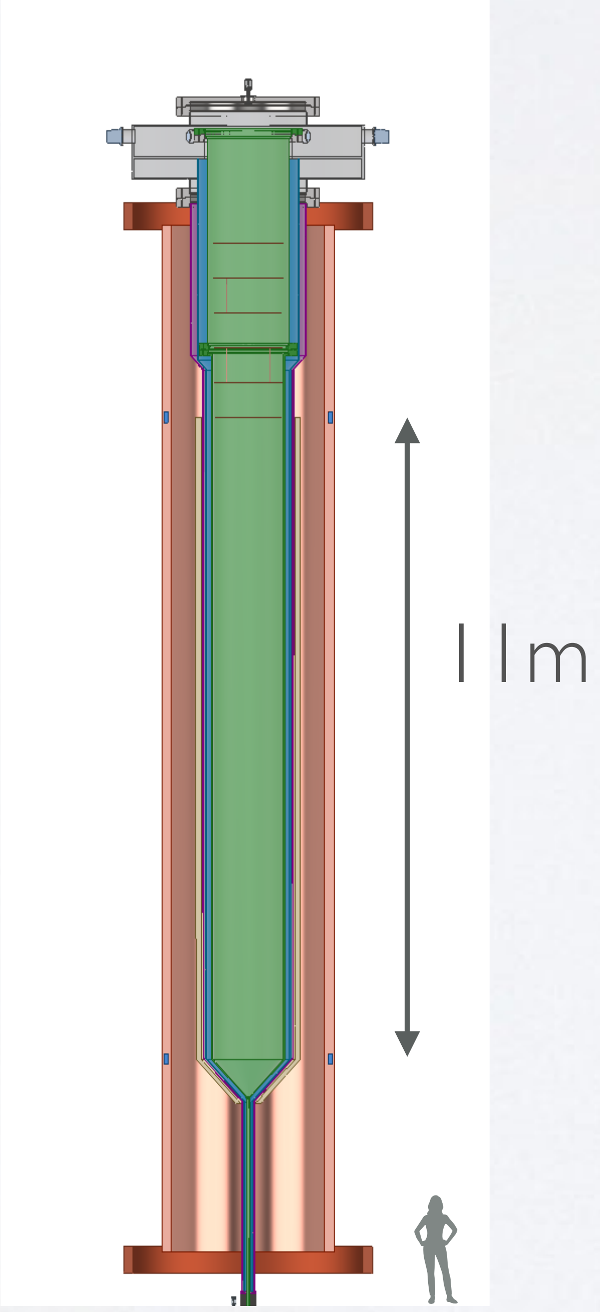


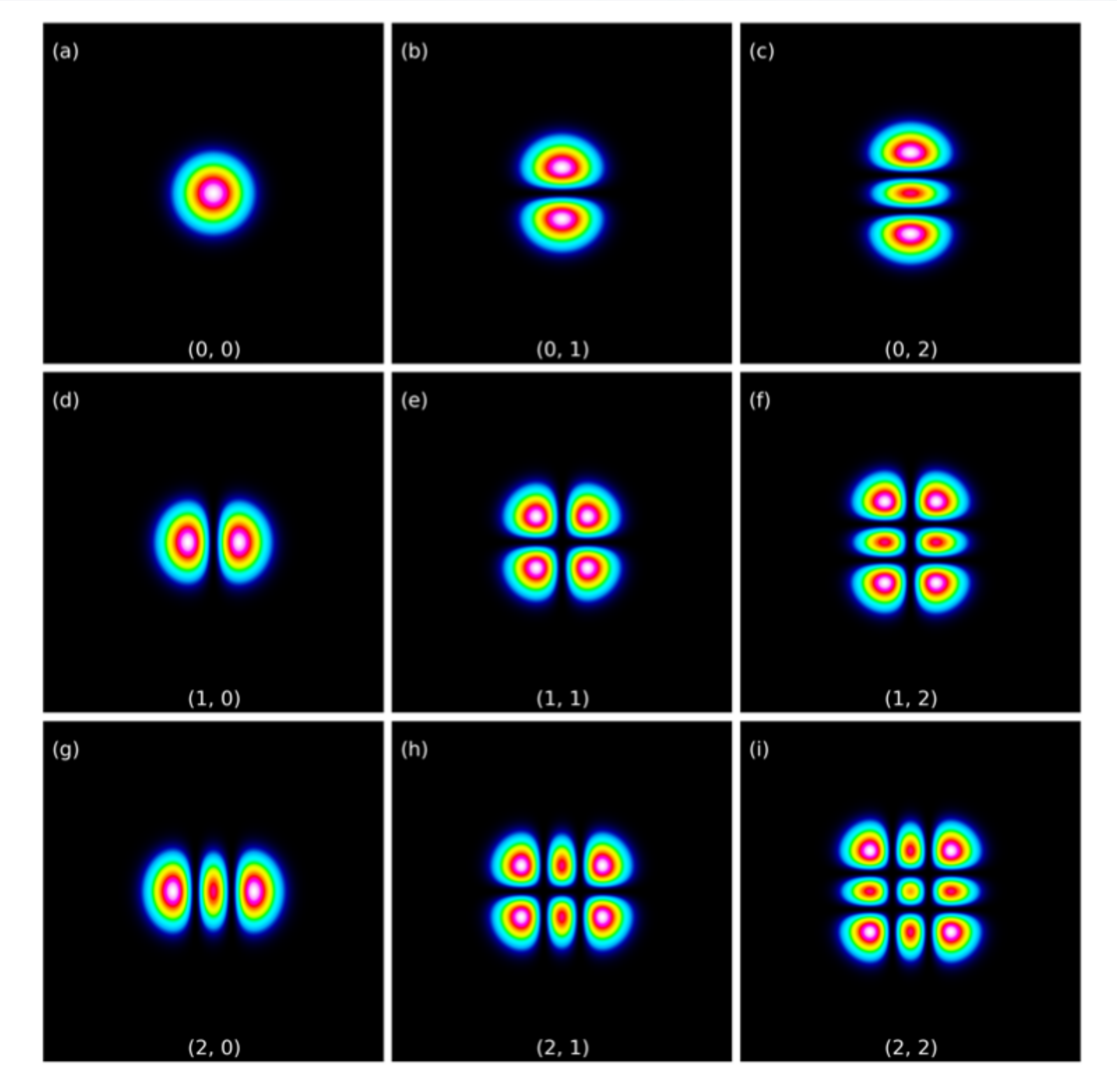
R&D FOR FULL-SCALE EXPERIMENT

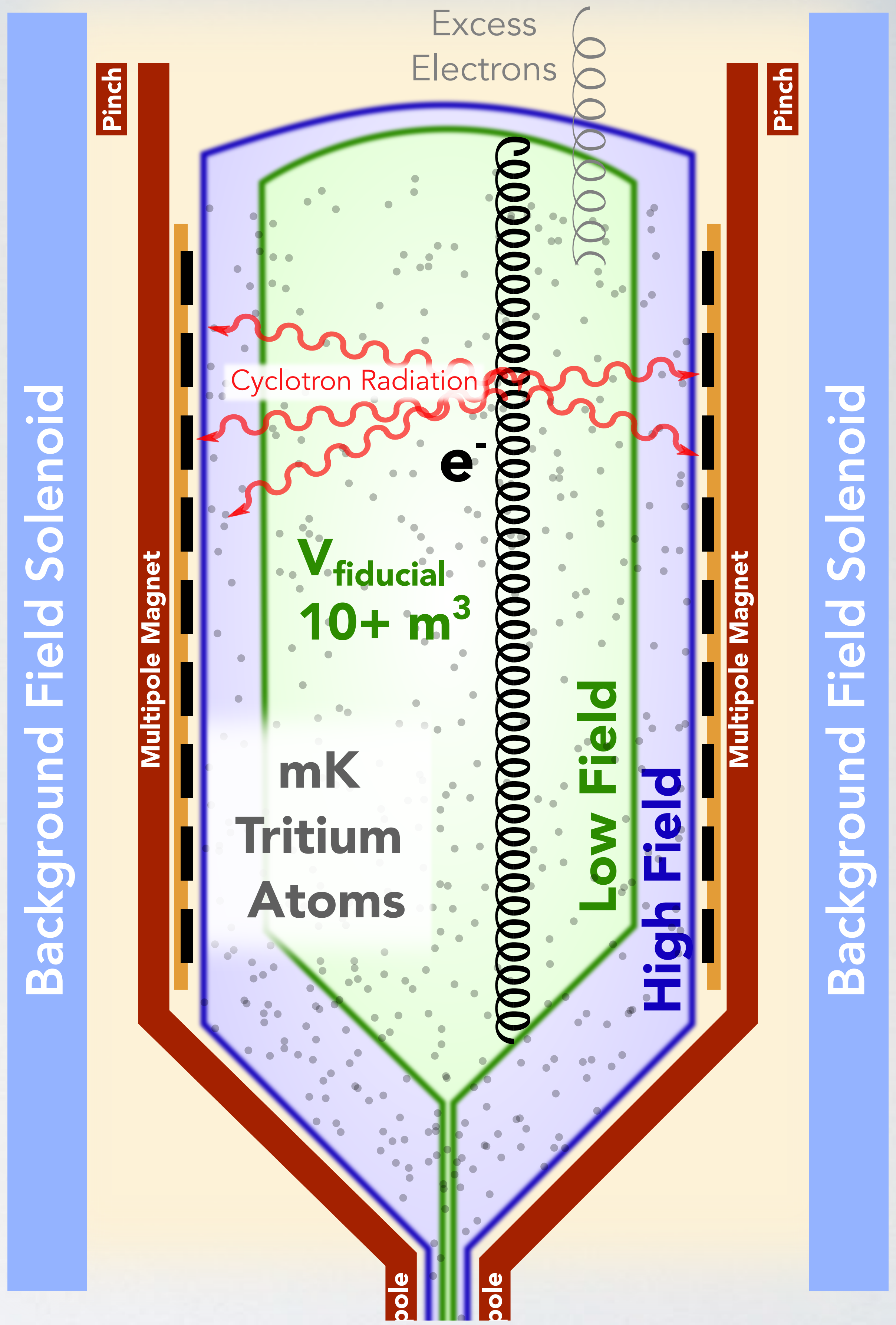
Large sensitivity improvements achieved by:

1. Switching from molecular → atomic tritium source

2. **Scaling up CRES detection volume**

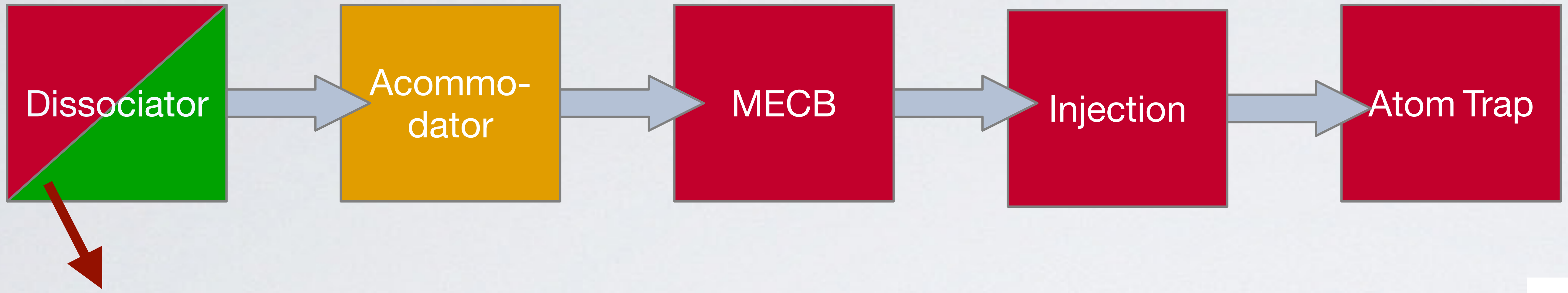




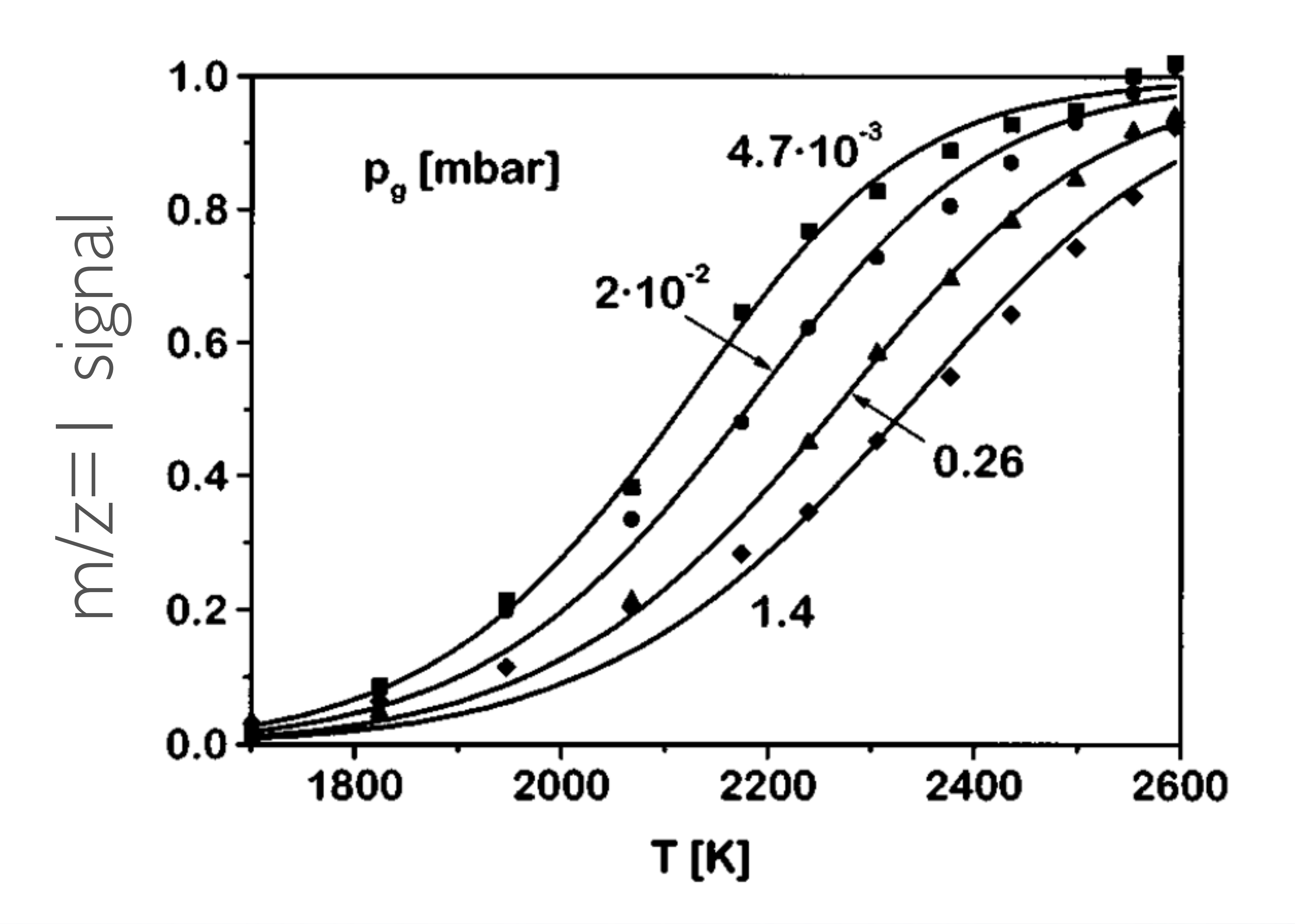


Fiducial volume: ~cm^3 → ~$10m^3$

SOURCE: ATOM PRODUCTION



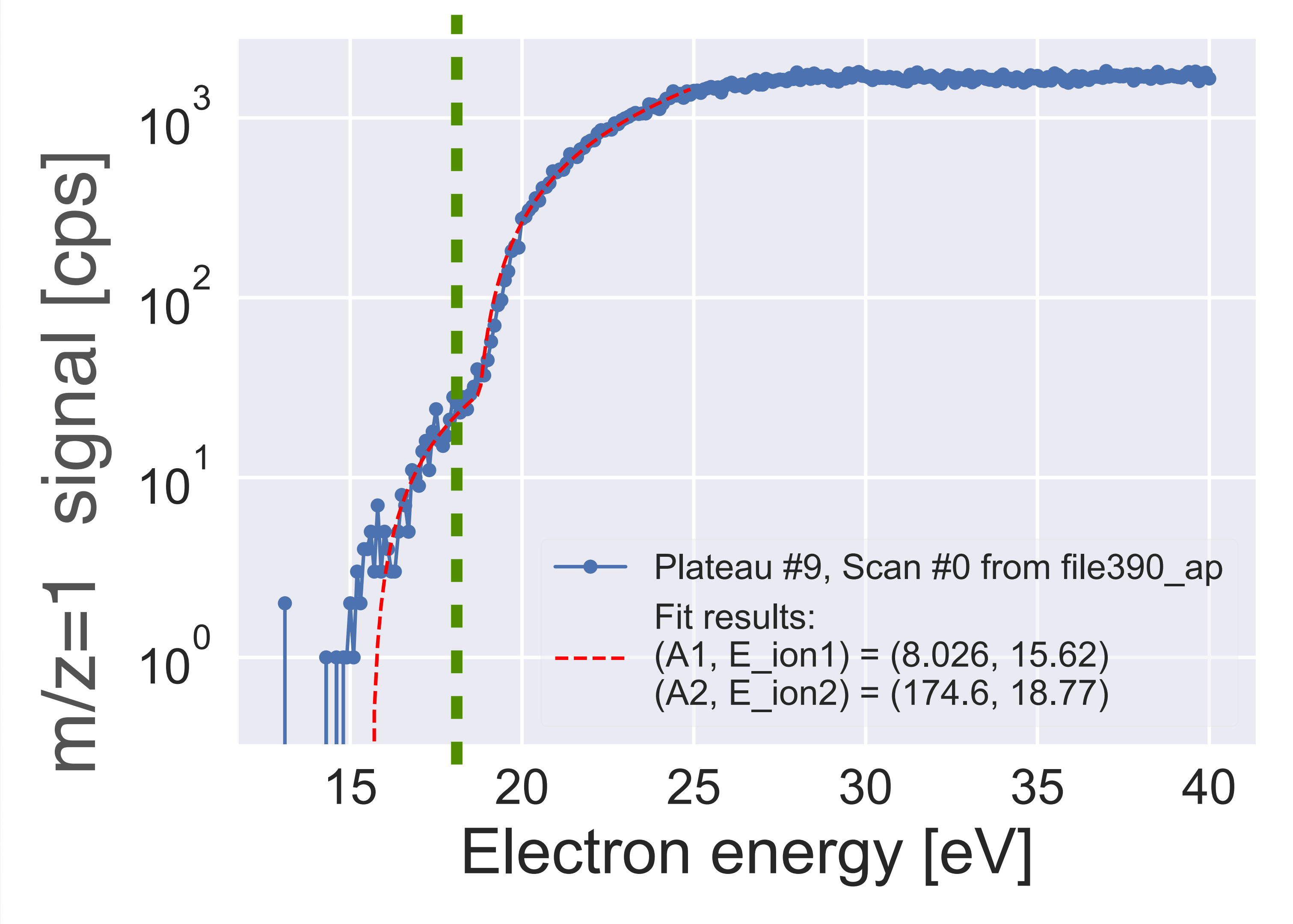
- Required atom flux: 10^{19} atoms/s
- Measure dissociation (test with $H_2 \rightarrow H$):
  - ➡ Two complementary techniques: mass spectrometry and recombination heating
  - ➡ Dissociation is dependent on gas flow, temperature, etc. → optimize
- Measure spatial distribution of atom beam



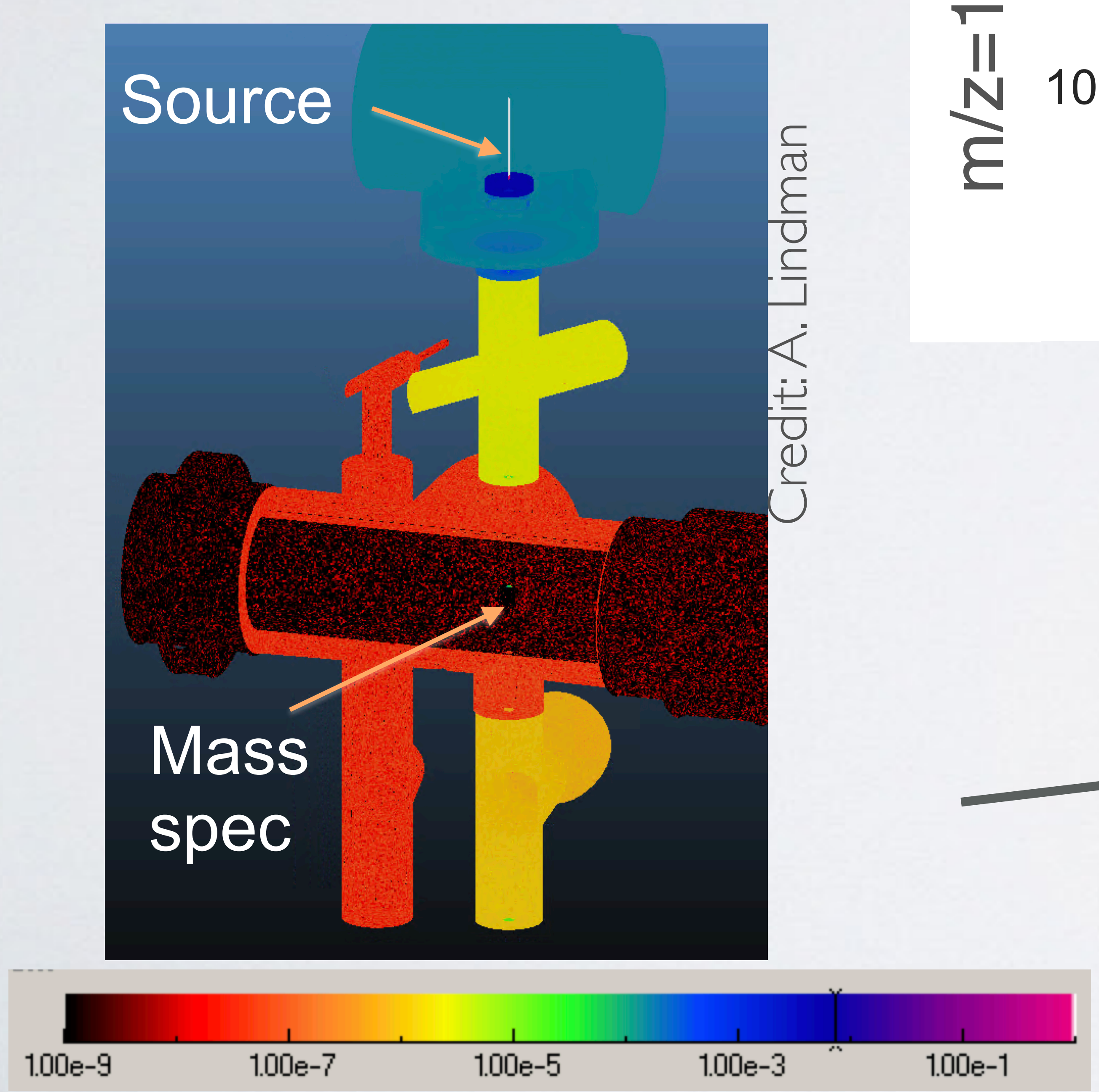
Source: Tschersich 2000

SOURCE: ATOM PRODUCTION

Hydrogen dissociation measurement at JGU Mainz:



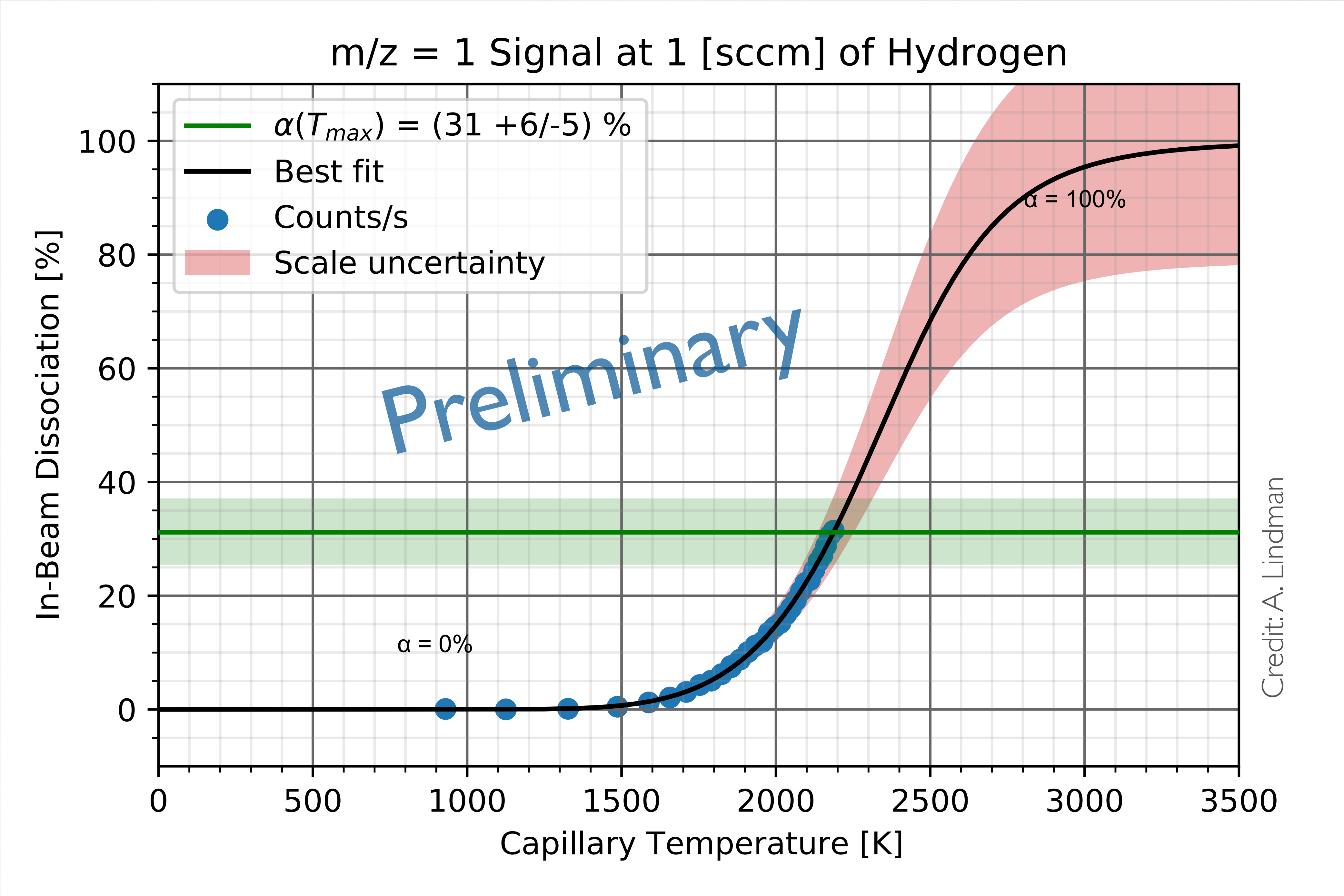
Credit: L. Thorne



Credit: A. Lindman

Optimize electron energy

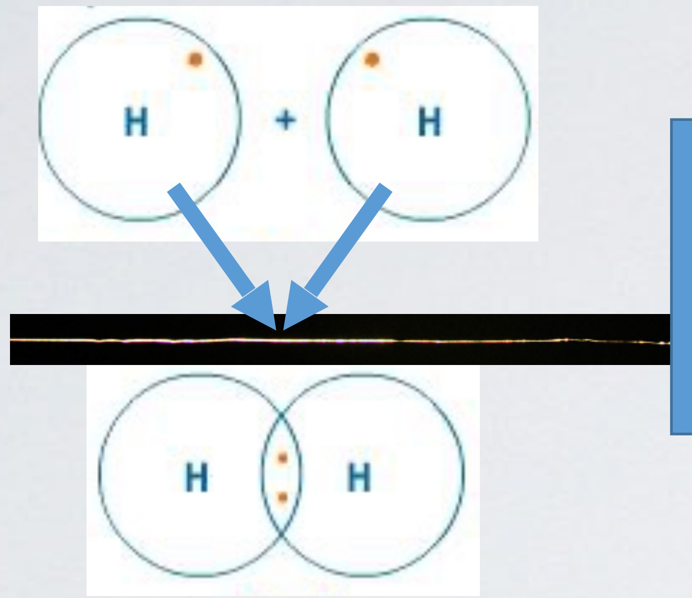
Optimize pump configuration



Credit: A. Lindman

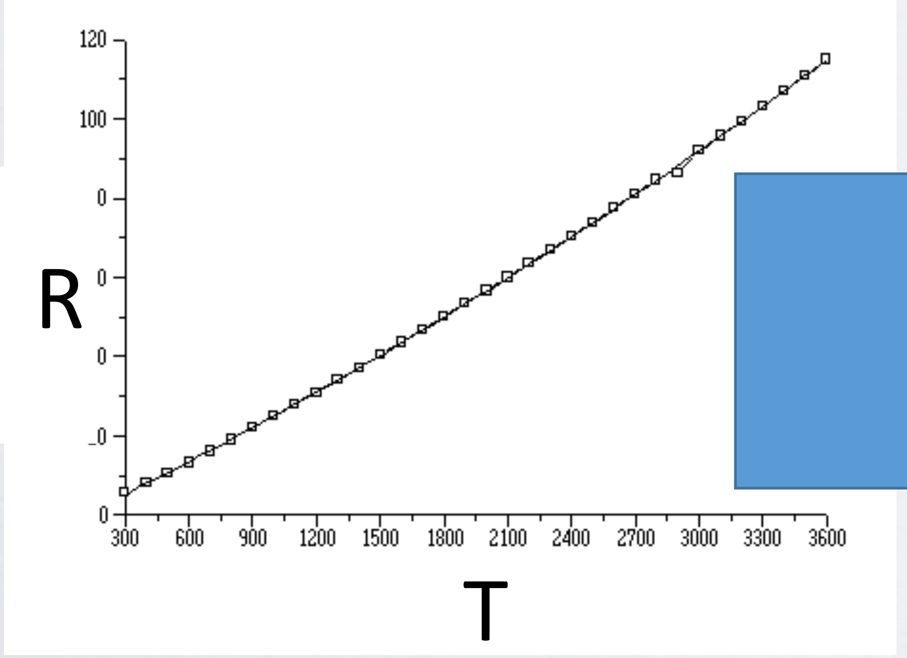
SOURCE: ATOM PRODUCTION

Beam profile measurement with wire detector at JGU Mainz:

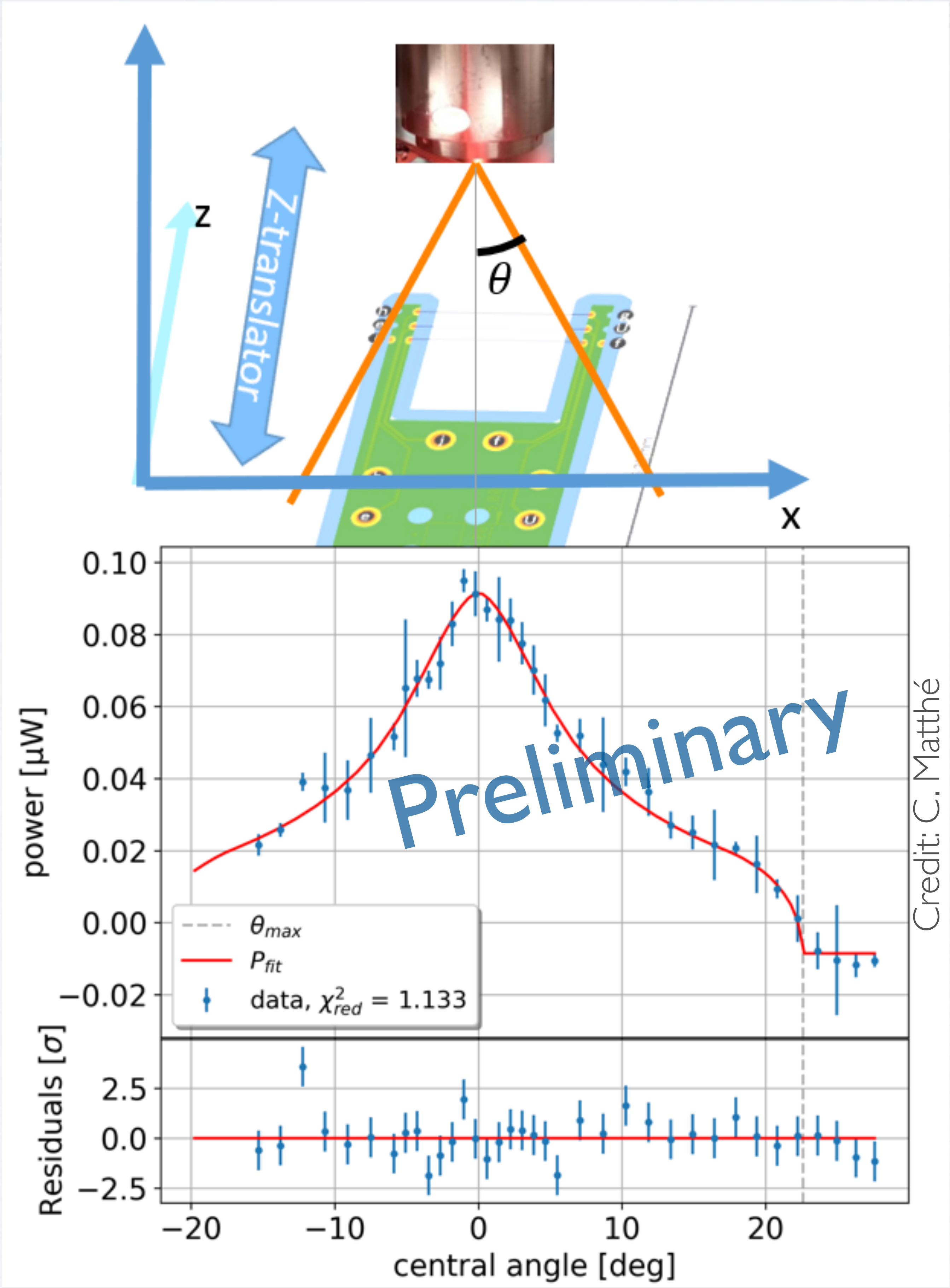


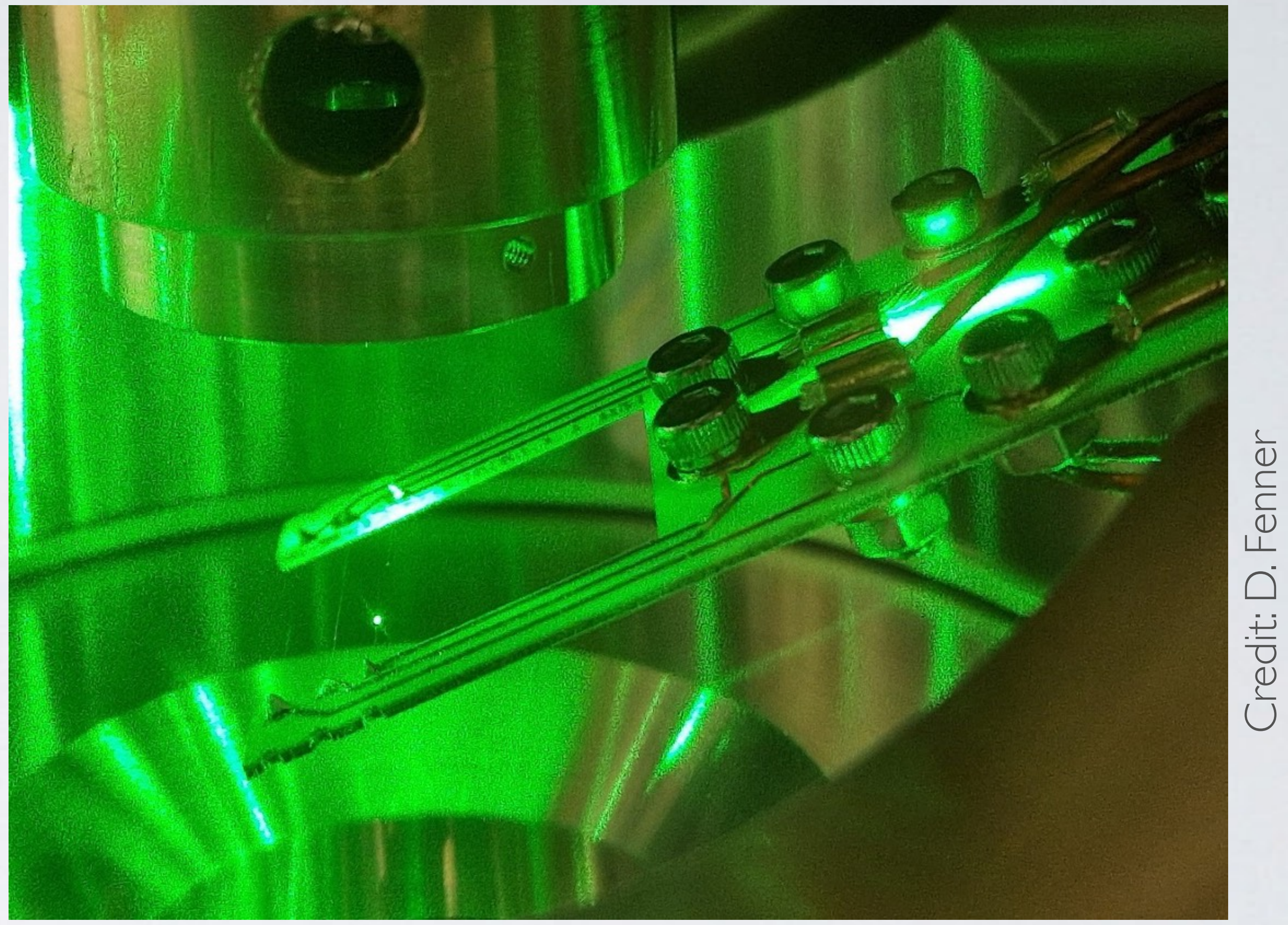
Recombination
$2H \rightarrow H_2$
($\approx$ 4.46 eV)

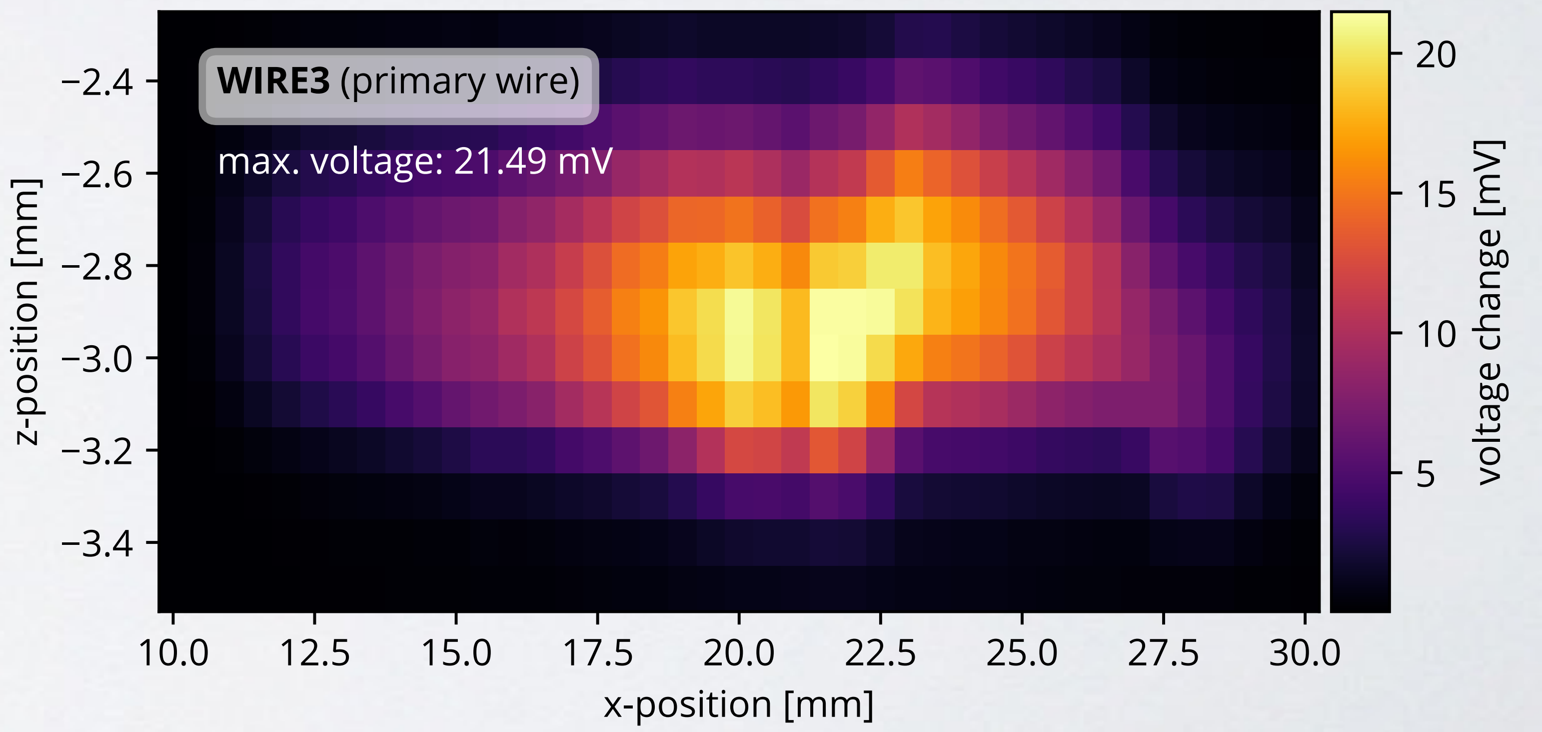
Wire heats up



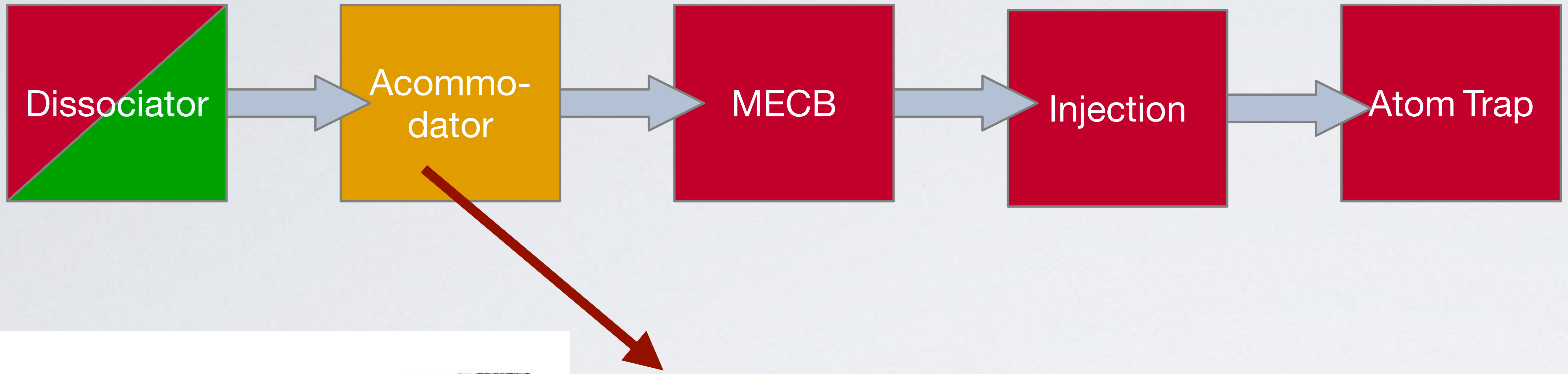
Higher

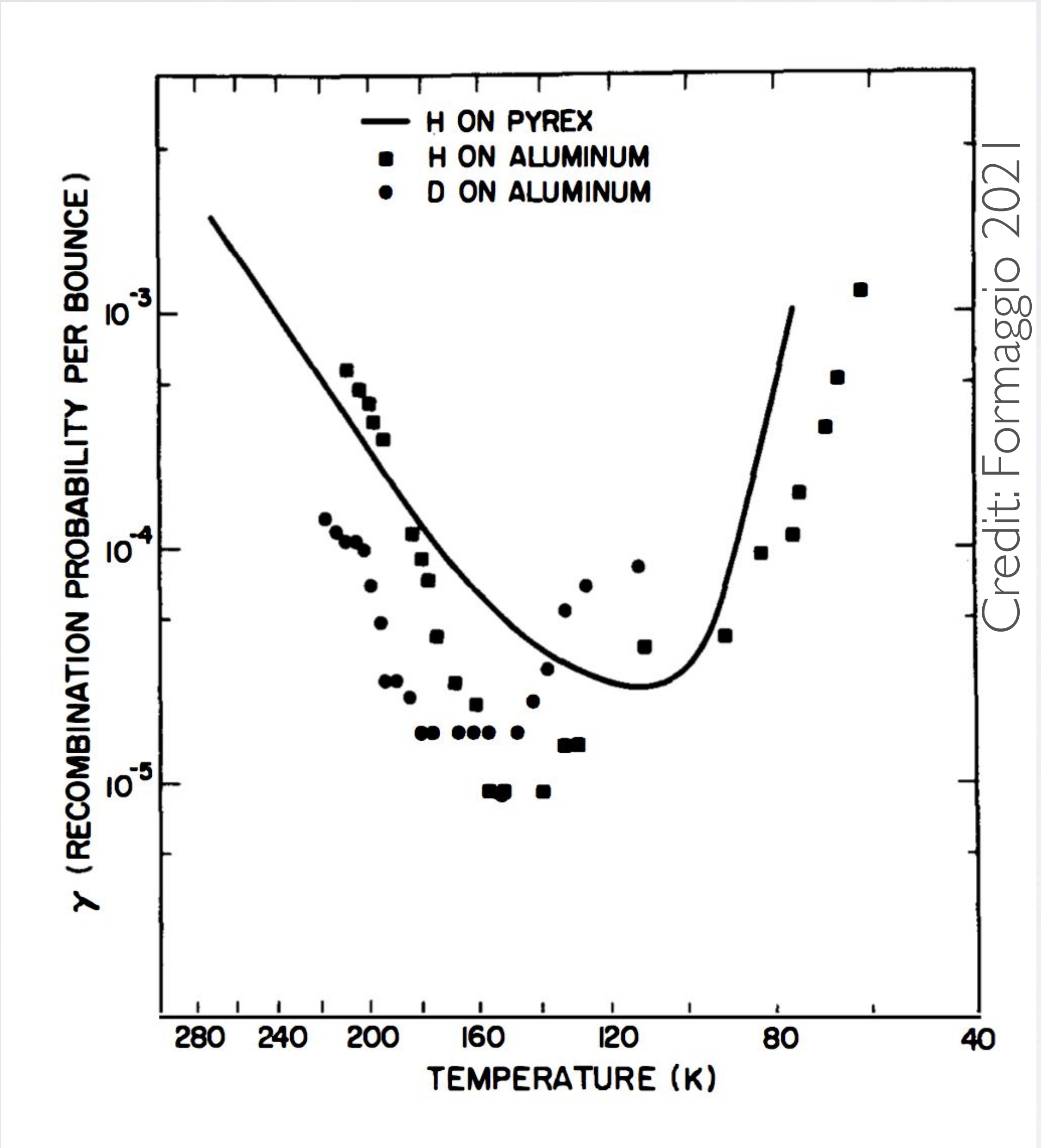




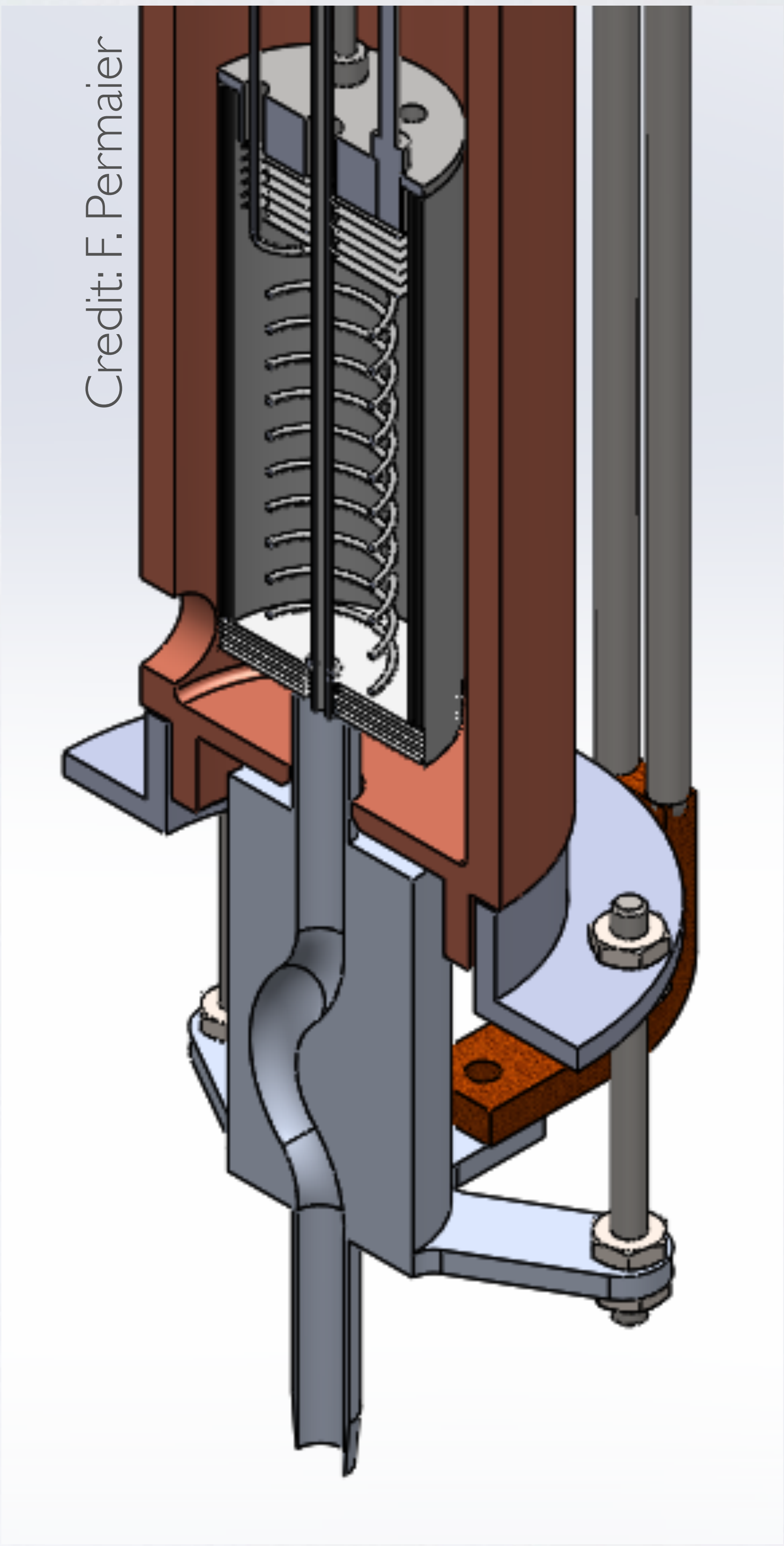


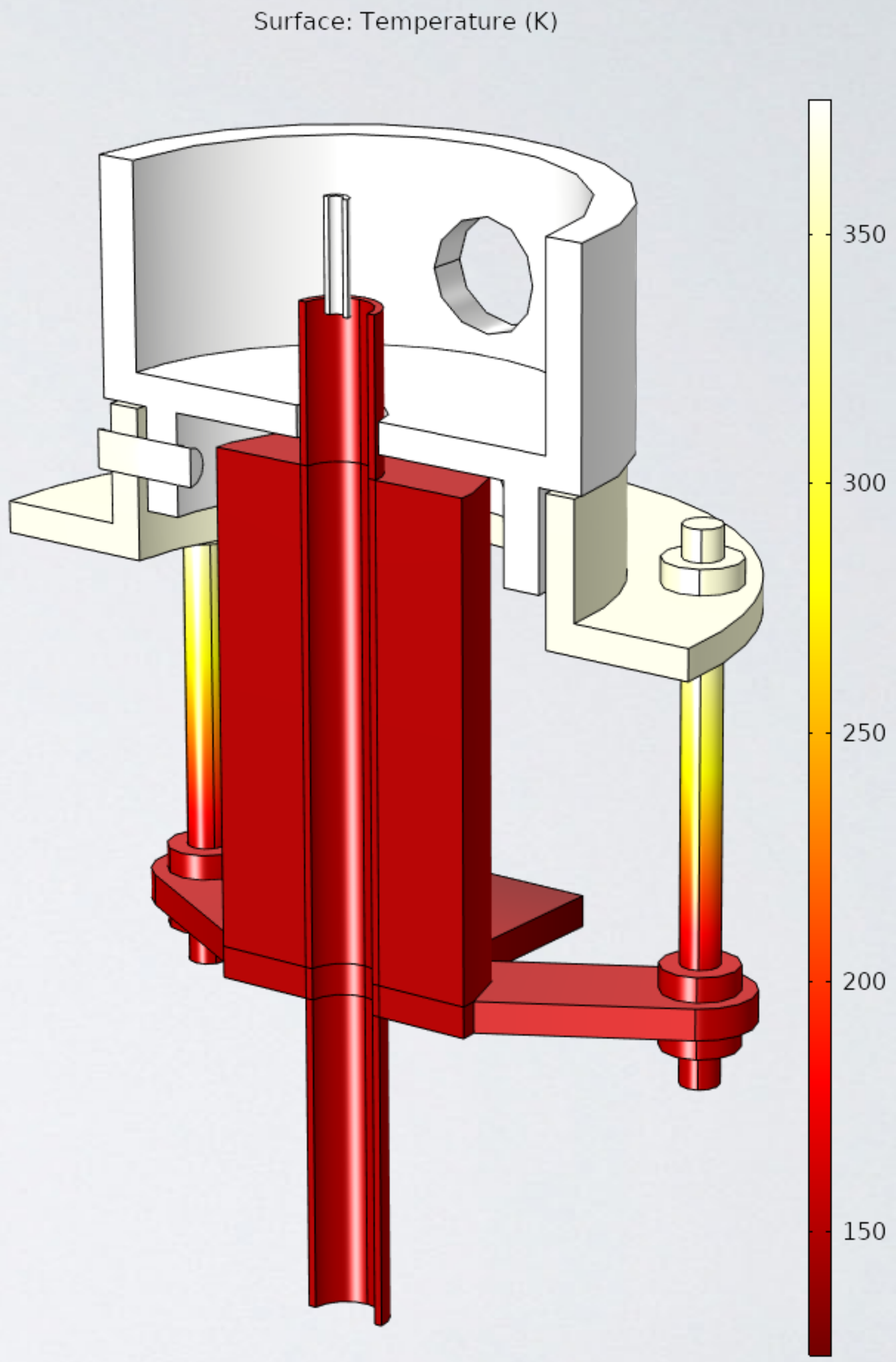
SOURCE: ATOM PRODUCTION





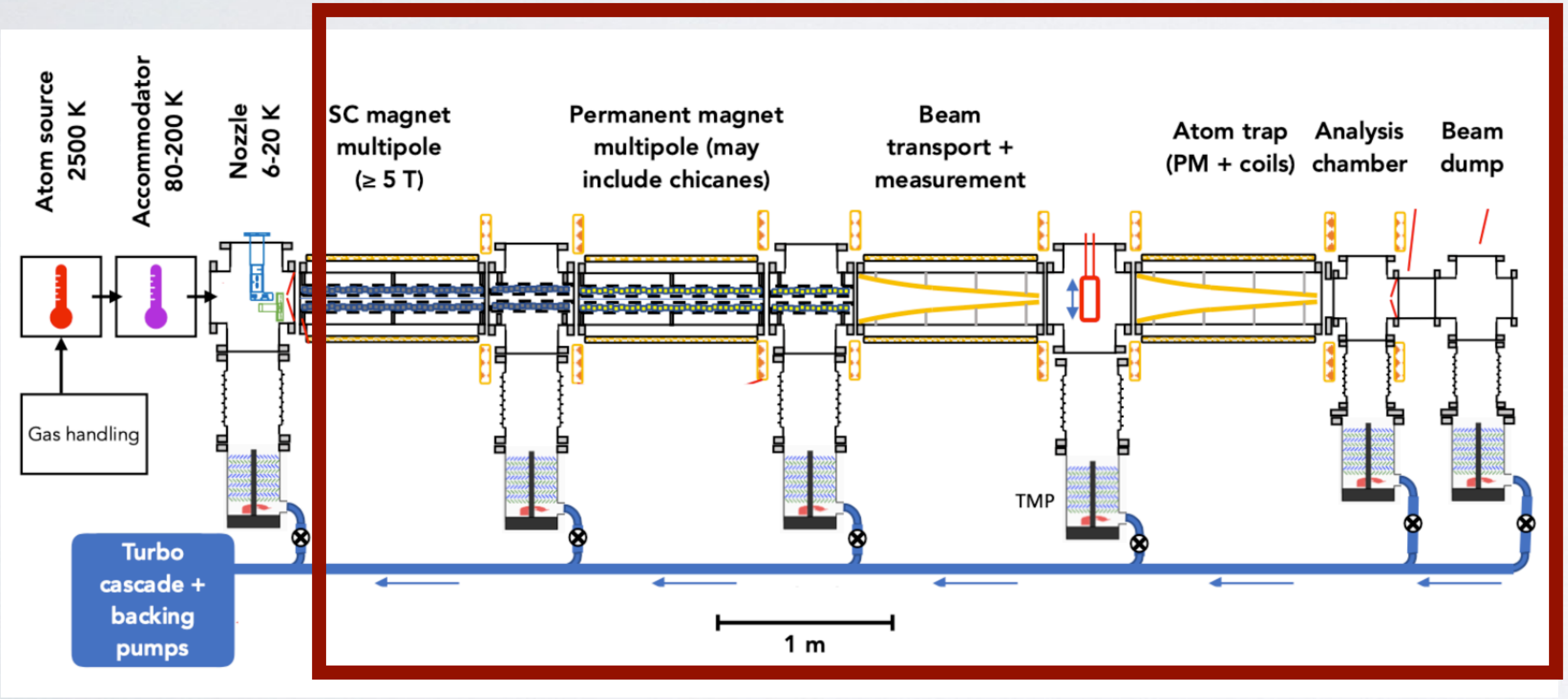
- Surface cooling at recombination minimum (~150K)
    - First thermal simulations to calculate required LN2 cooling power
- For cooling to ~10K: additional "nozzle" on downstream end with LHe



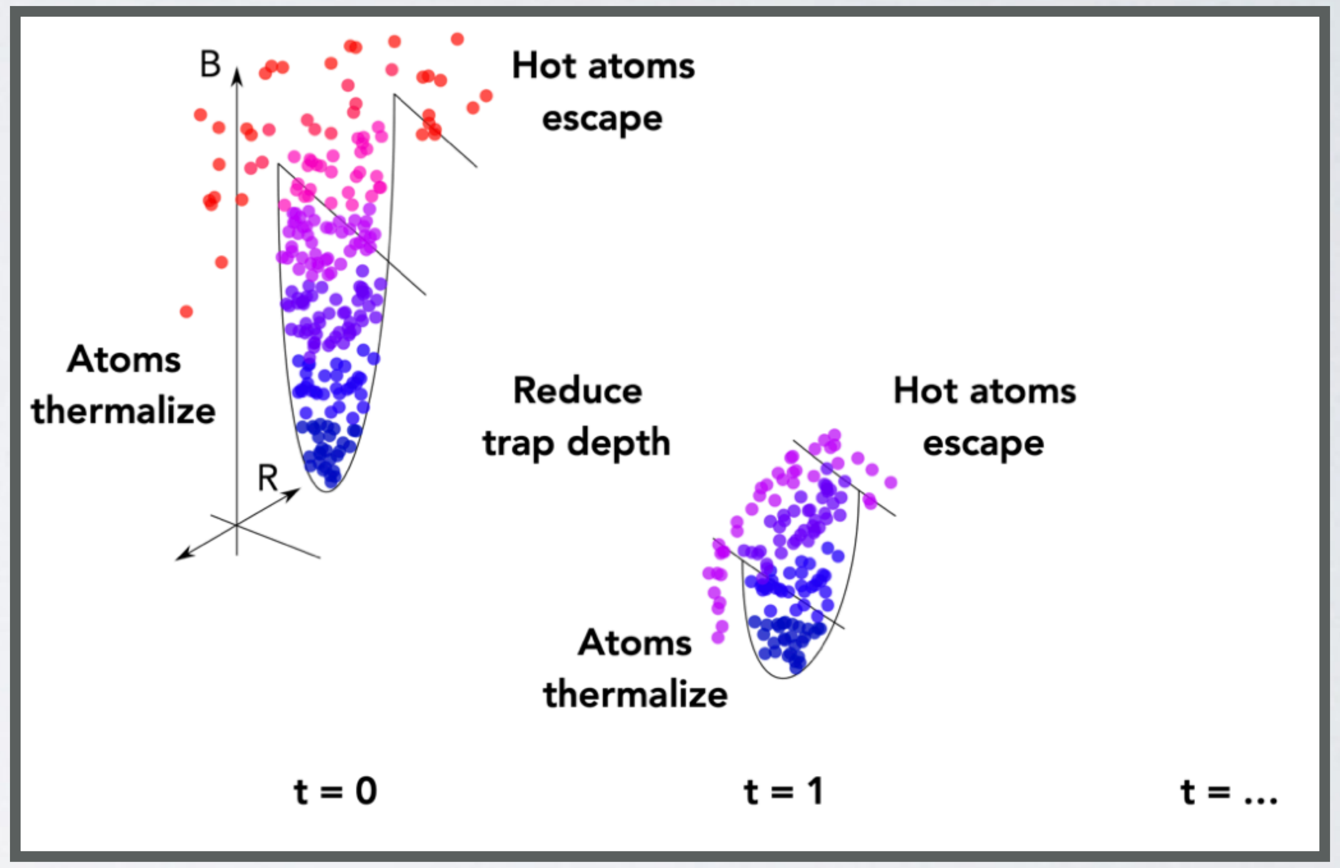


SOURCE: ATOM PRODUCTION

Magnetic Evaporative Cooling Beamline



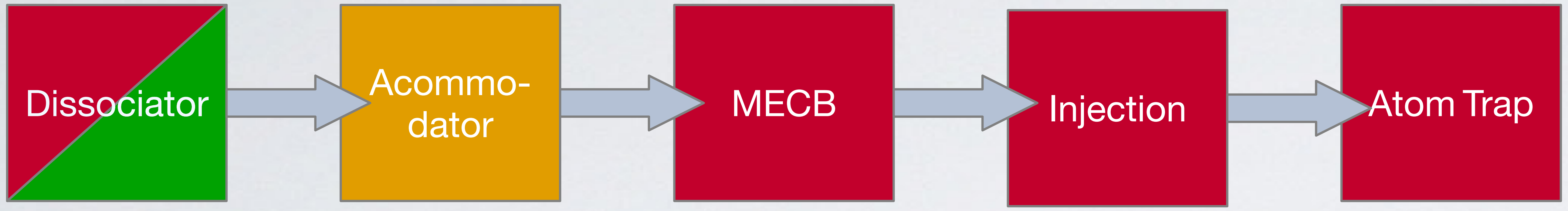
Credit: B. Jones

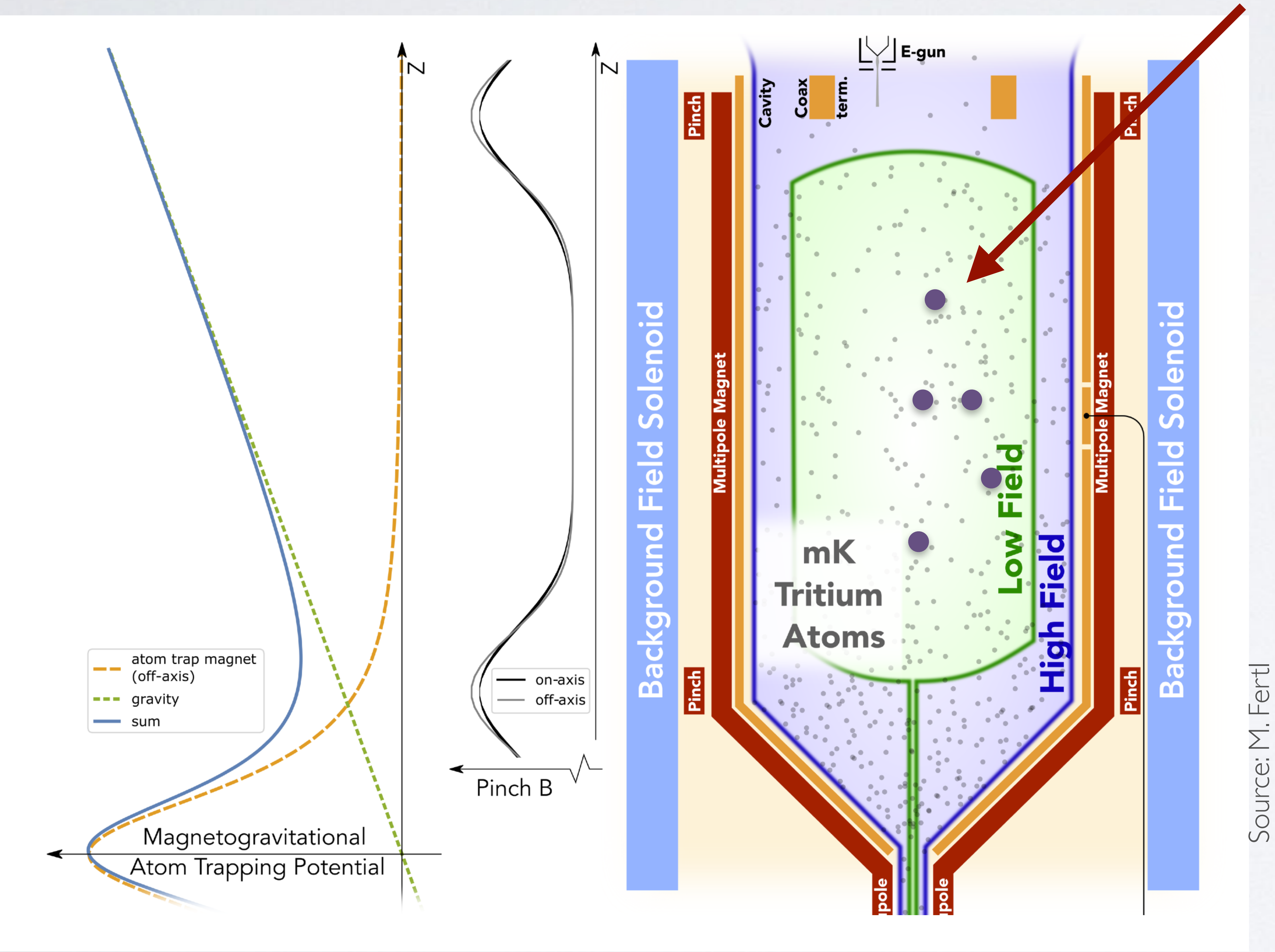


Credit: A. Lindman

- Hot atoms (higher transverse momentum) escape
- Test stand to validate MECB simulations, using ^{6}Li

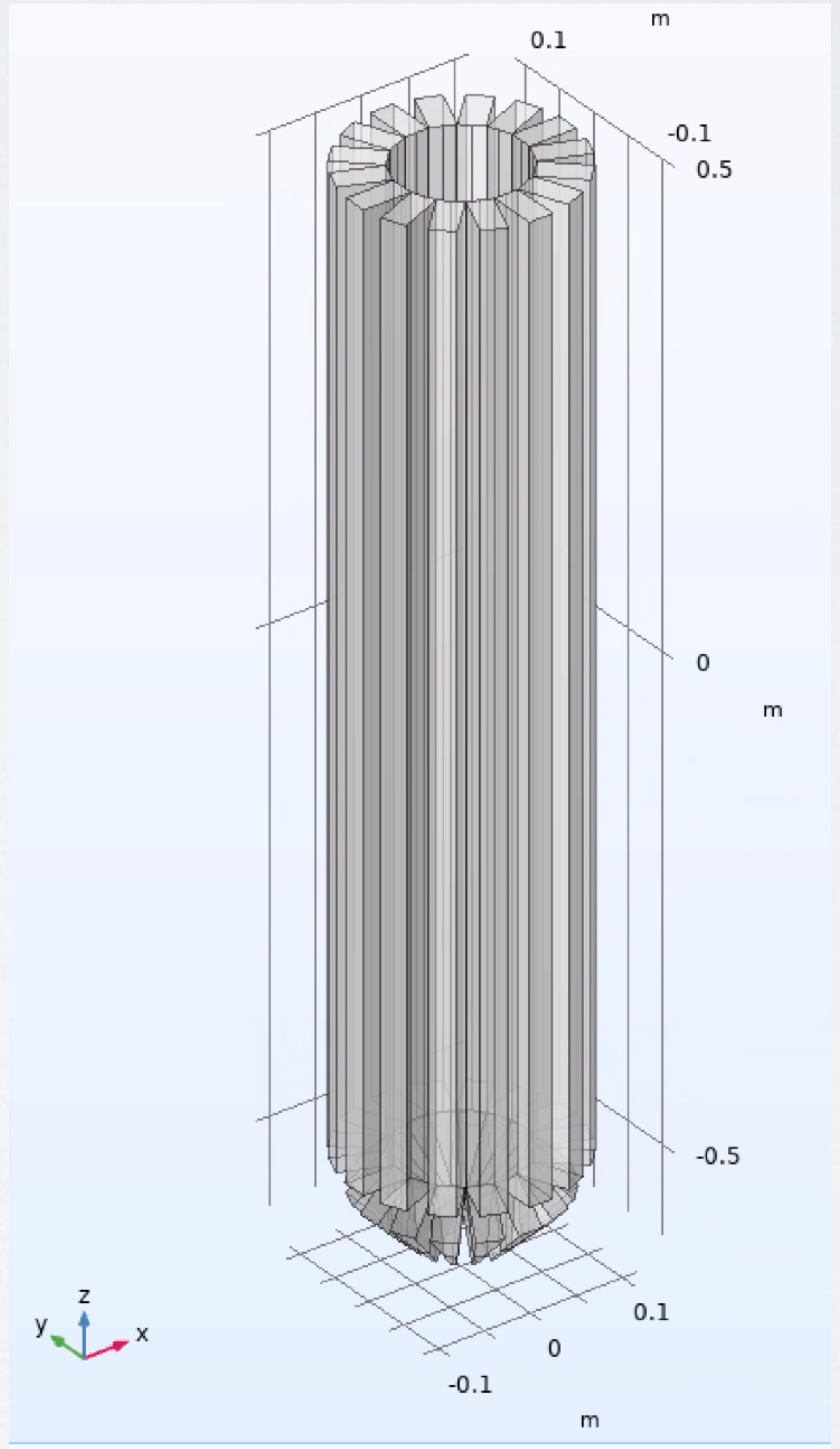
SOURCE: ATOM PRODUCTION

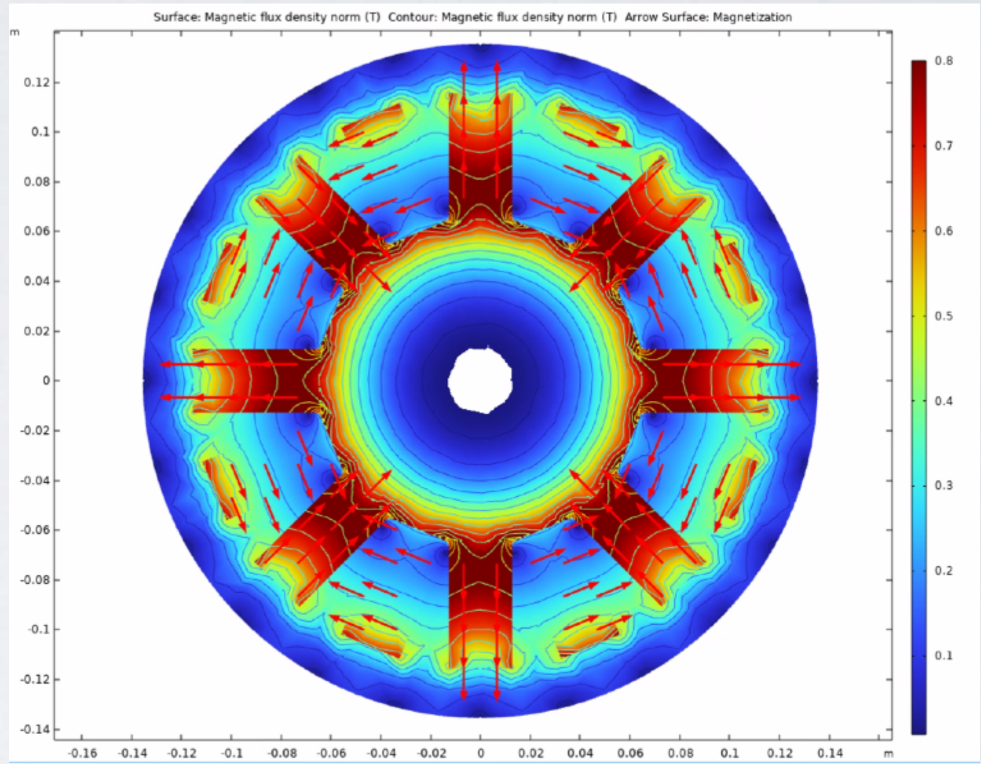


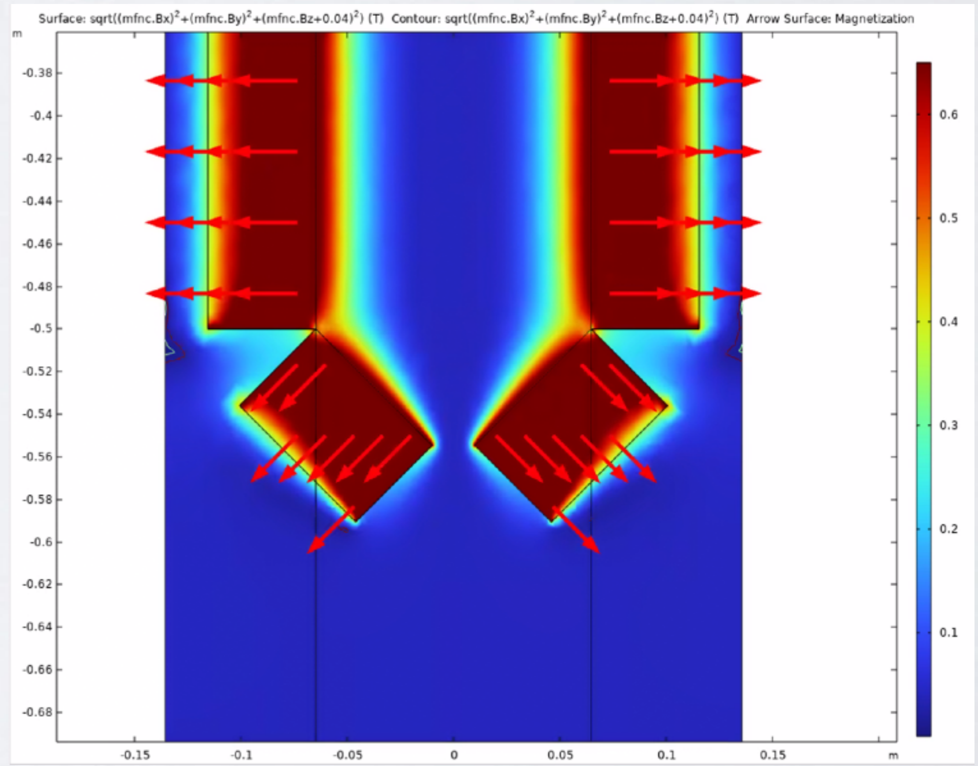


Source: M. Fertl

Magneto-gravitational trap, using Halbach array:







Source: C-Y. Liu

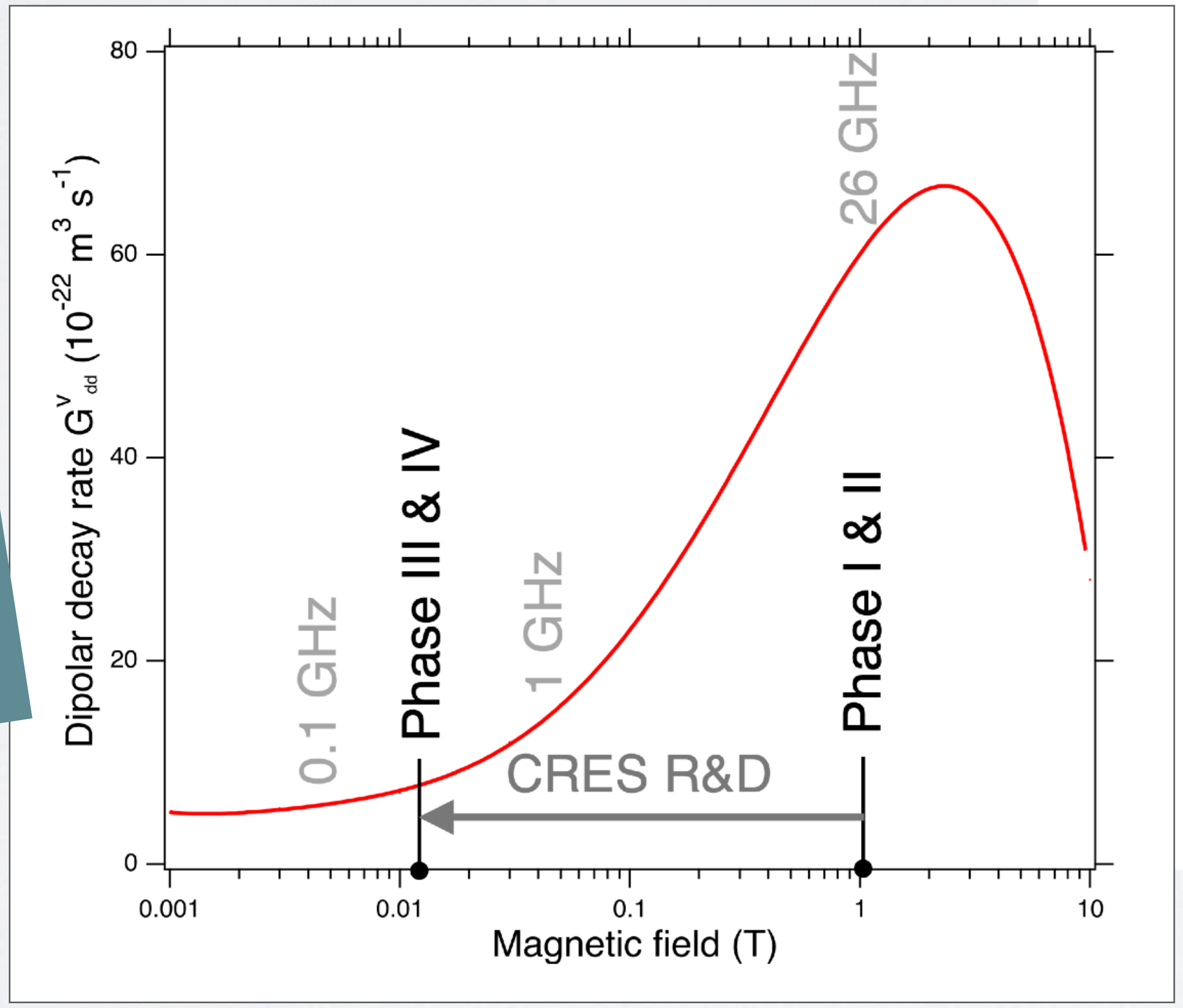
TRAP / DETECT: CAVITIES

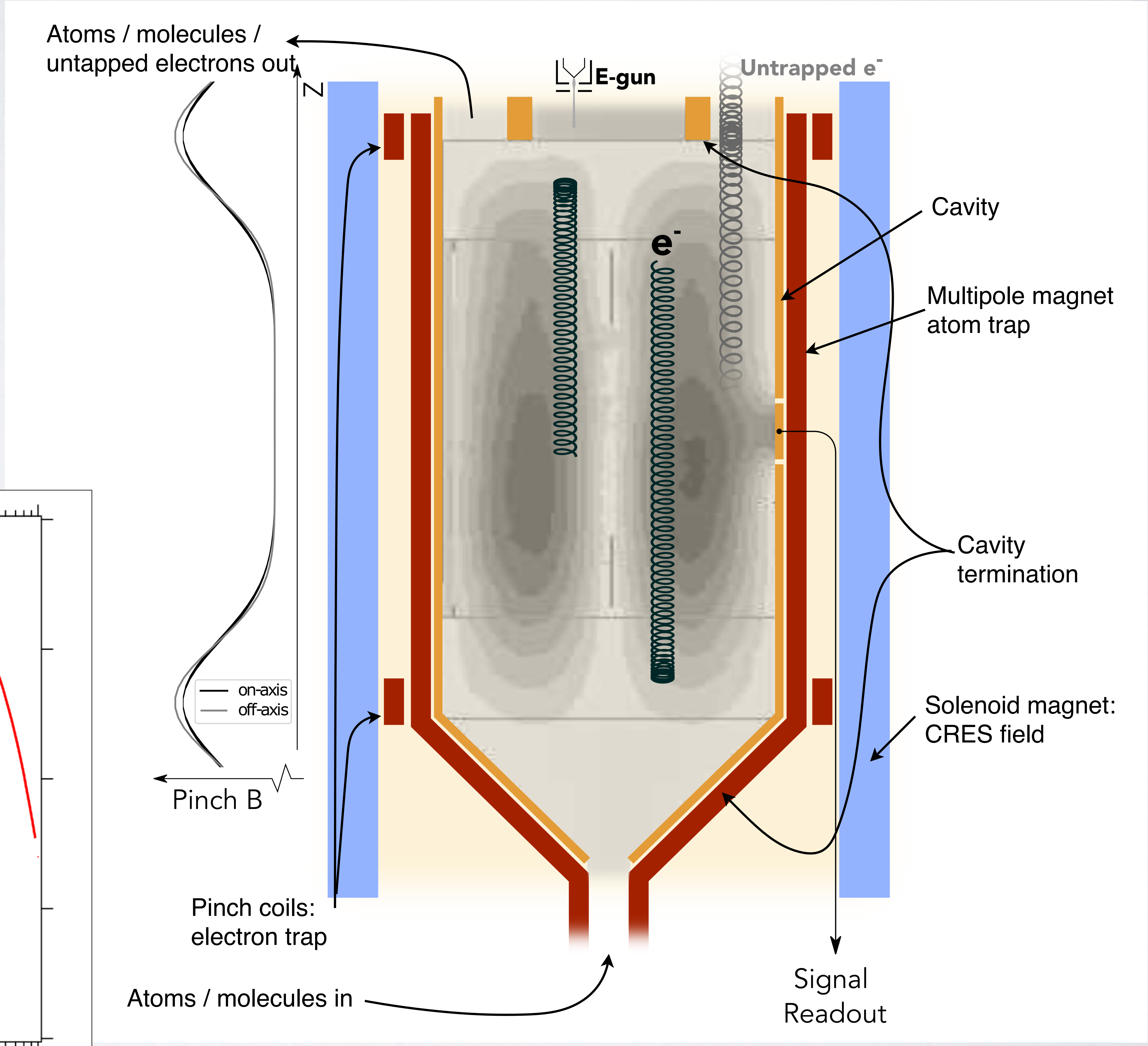
CRES in a cavity:

- Lower dipolar decay rate at lower B → lower *f* and longer trapping times
- Low *f* (≤ 1GHz) and scalable: ideal application for resonant cavities

With atomic T source, volume ~11m³, B~0.011 T, *f*=325 MHz, projected 1 year sensitivities:

- $m_\beta < 200$meV (T_2)
- $m_\beta < 200$meV (T)



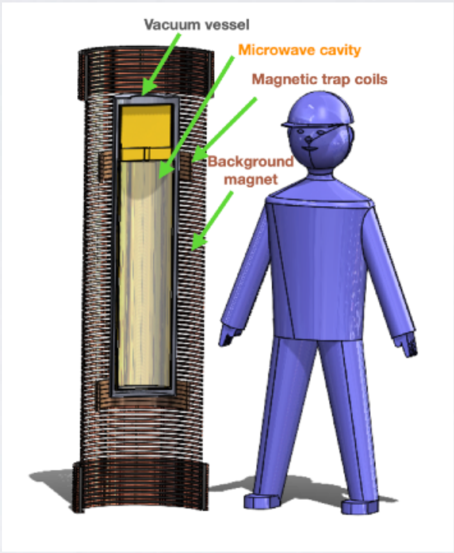


Source: J. Stachurska

TRAP / DETECT: CAVITIES

LFA (Low-Frequency Apparatus):

- Optimize for high E resolution, large volume
- Develops technology needed for tritium experiments
- Frequency: ~1GHz
- B: 0.035 T
- Volume: 0.3 m^3
- Status: *design phase*

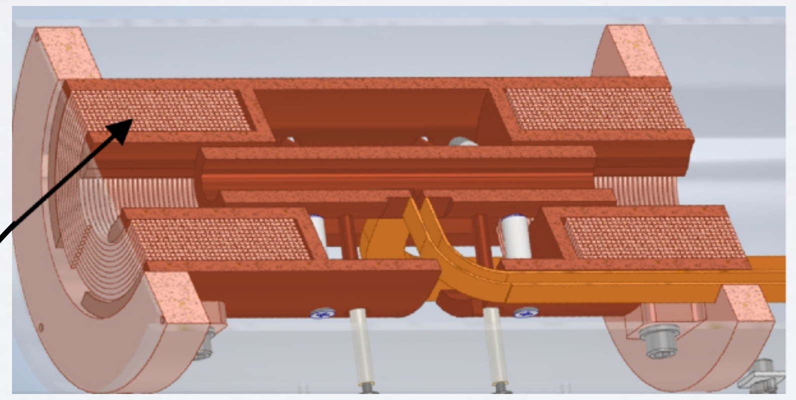


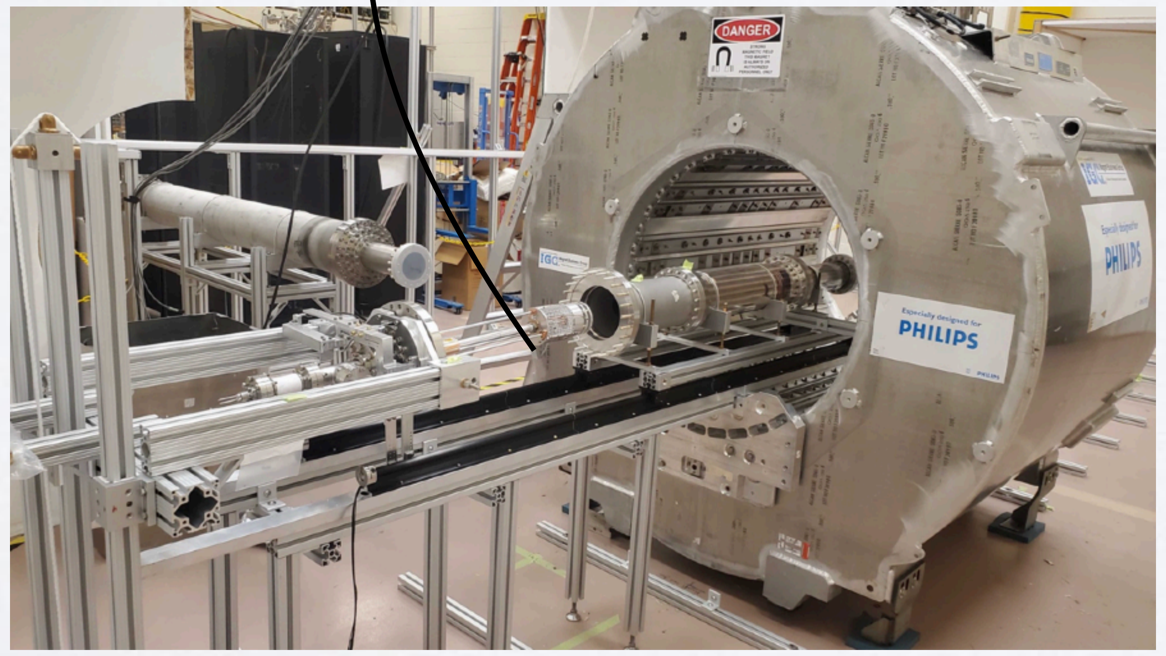
LUCKEY:

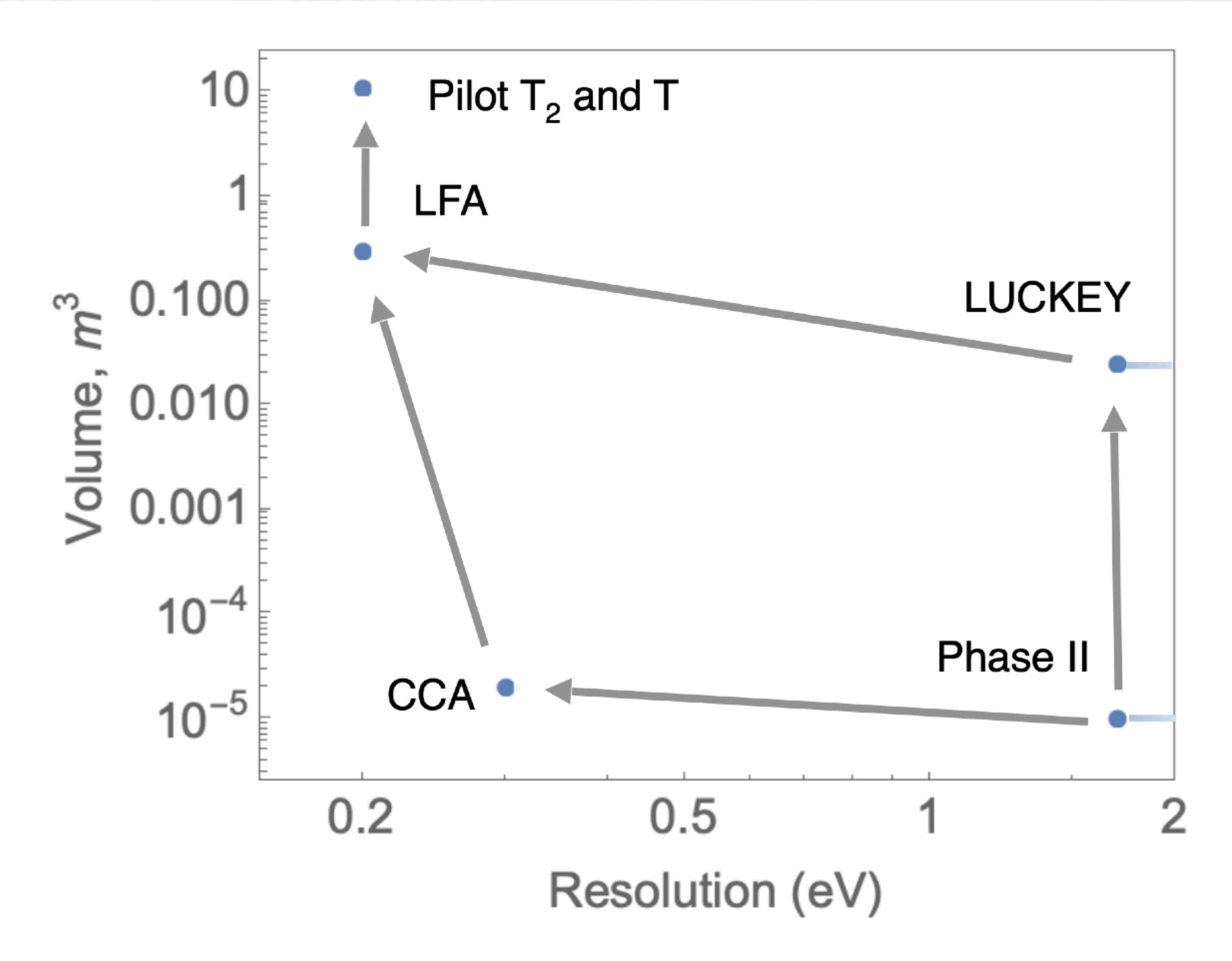
- Optimize for large volume
- Frequency: 1.5GHz
- B: 0.035 T
- Volume: 0.025 m^3
- Status: *developing magnet design*

CCA (Cavity CRES Apparatus):

- Optimize for high E resolution
- Frequency: 26GHz
- B: 1T
- Volume: 20 cm^3
- TE011 mode
- Test with e-gun, ^{83m}Kr
- Status: *under construction*







Source: E. Novitski

SUMMARY

- Final analysis results for demonstrator-scale experiment: $m_\beta \leq 155 \text{eV/c}^2$ at 90% C.L. [Phys. Rev. Lett.131.102502]

- Defined set of demonstrators needed to develop technology needed for final 40 meV-sensitivity experiment:

  - First steps to atomic tritium source via atomic hydrogen test stand at JGU Mainz complete

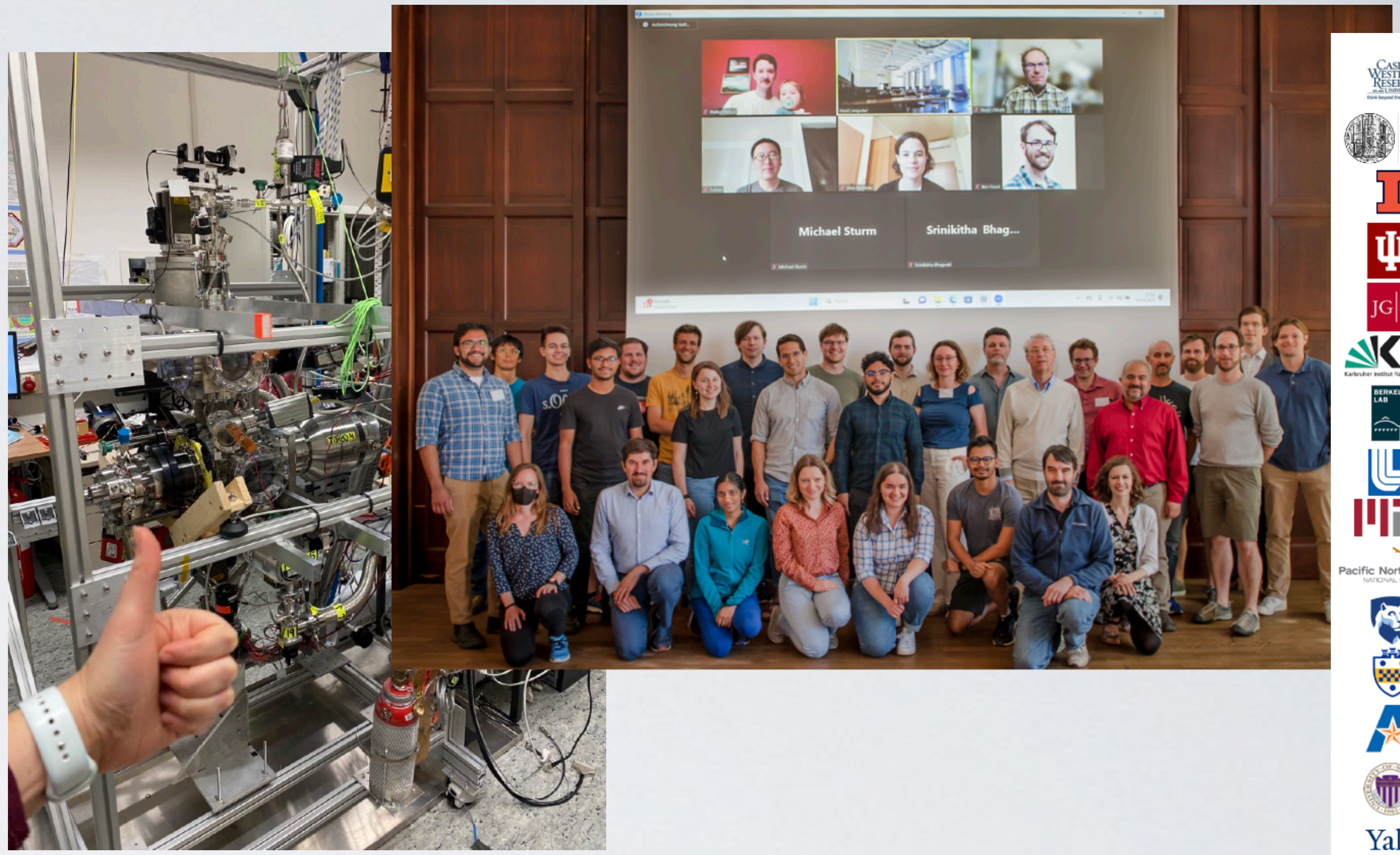
  - Resonant cavity development/testing ongoing

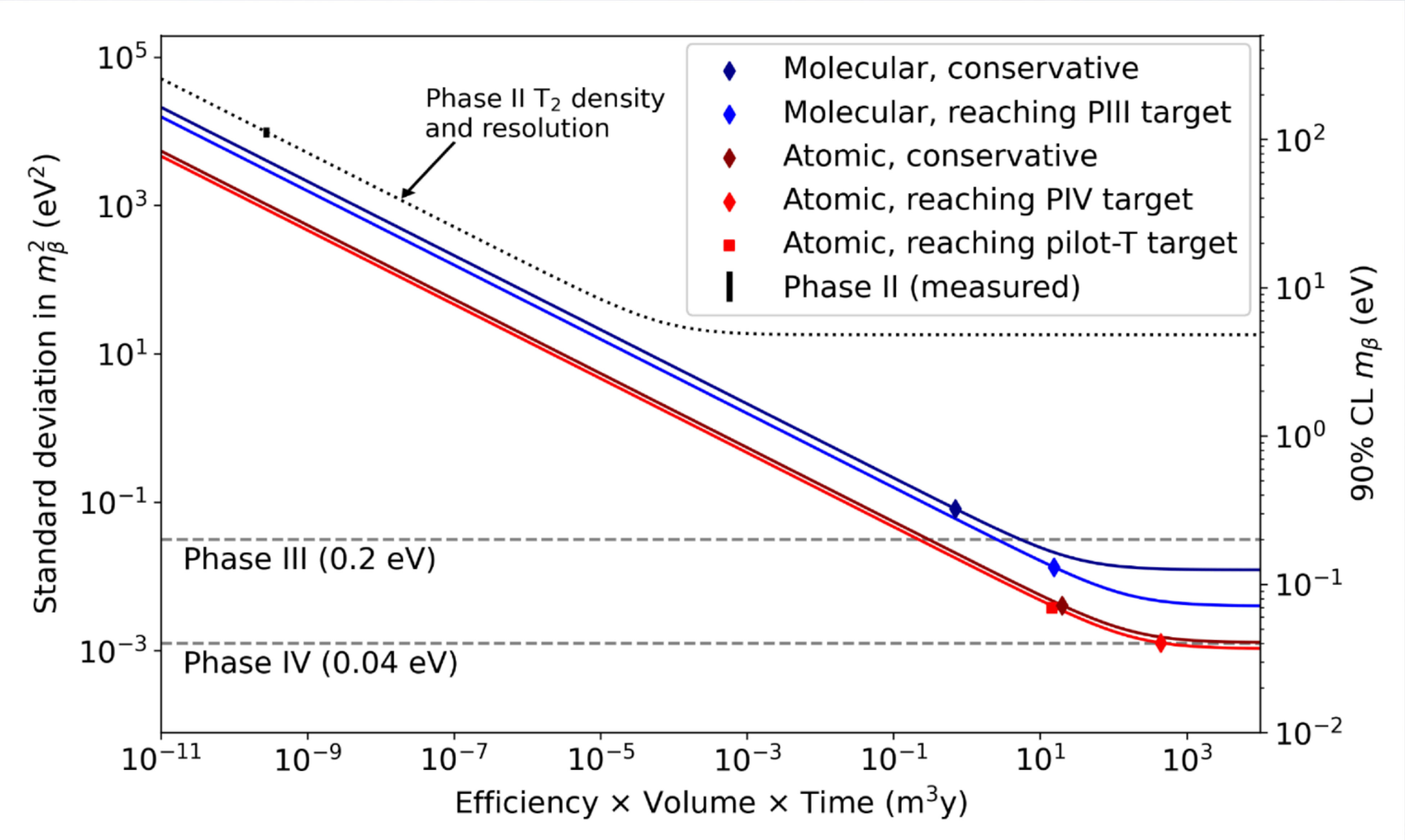
- Synergies with other experiments

KAMATE
KATRIN
He6
^{83m}Kr

Special thanks to:
JGU Mainz colleagues
Project 8 collaborators
Funding agencies (PRISMA+)

Thank you.



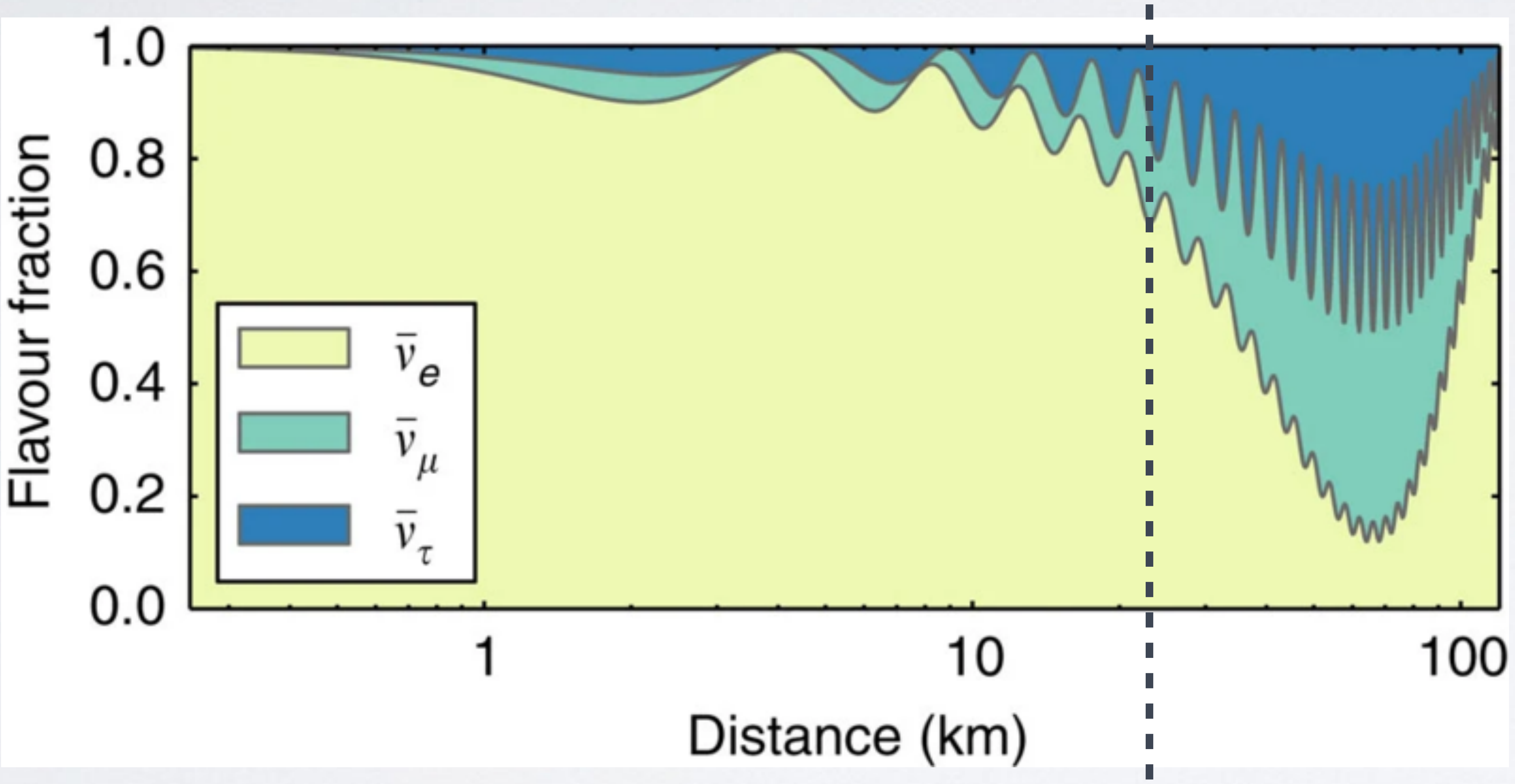


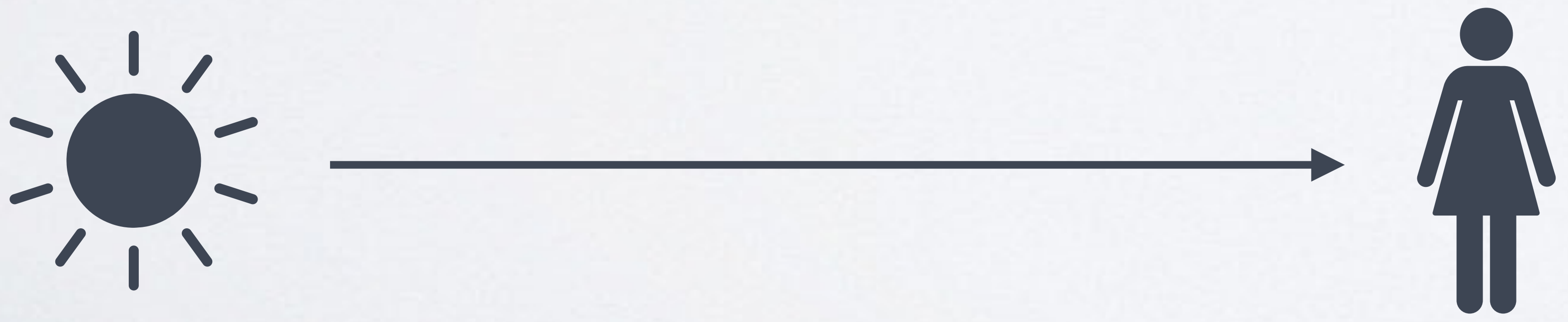
Credit: T. Weiss

Supplemental slides

PRIMER ON NEUTRINOS

- Neutrino oscillation:





PMNS mixing matrix

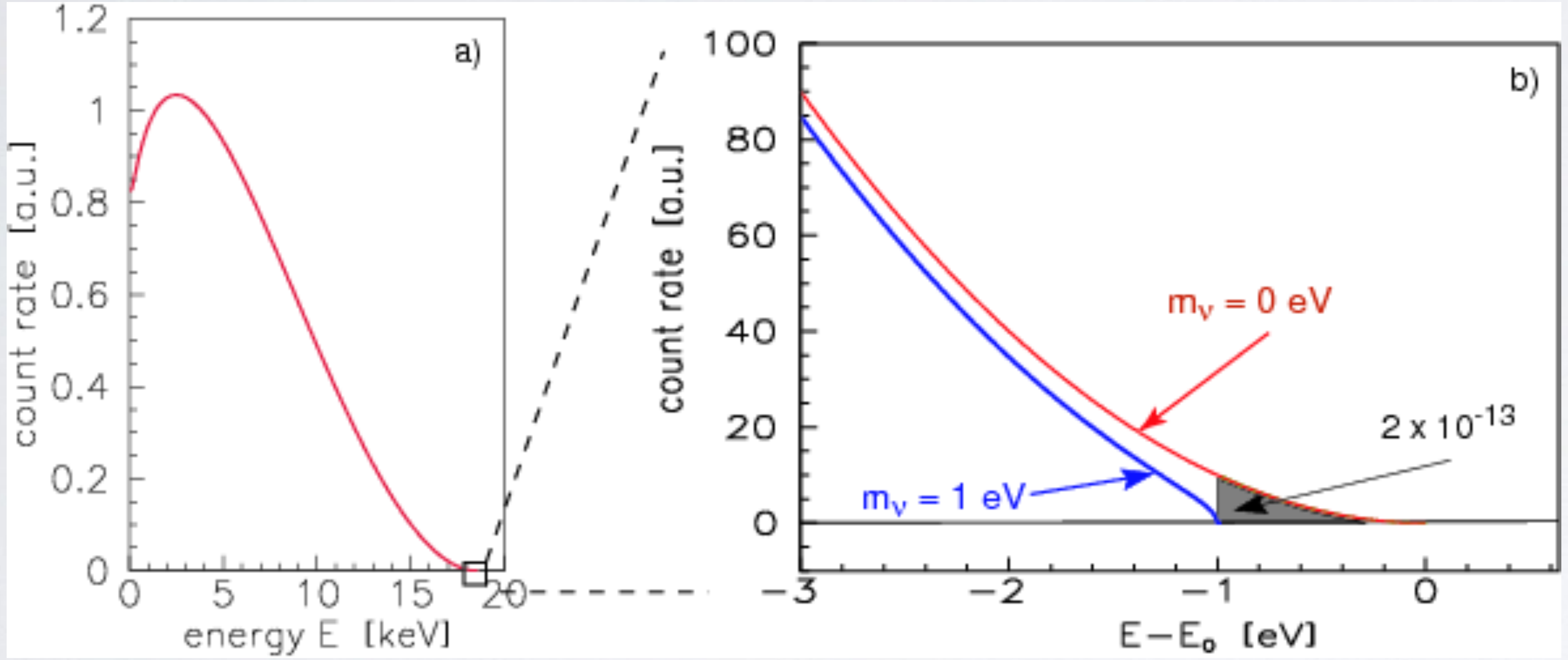
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Flavor eigenstates $|\nu_l>$

Mass eigenstates $|\nu_i>$

PROJECT 8: DESIGN PRINCIPLE

$$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$$



Select tritium because its beta decay is **super-allowed**, has appropriate **half-life** (~12.3yr), **endpoint energy** fairly low (~18.6keV)

Via Fermi's Golden Rule:

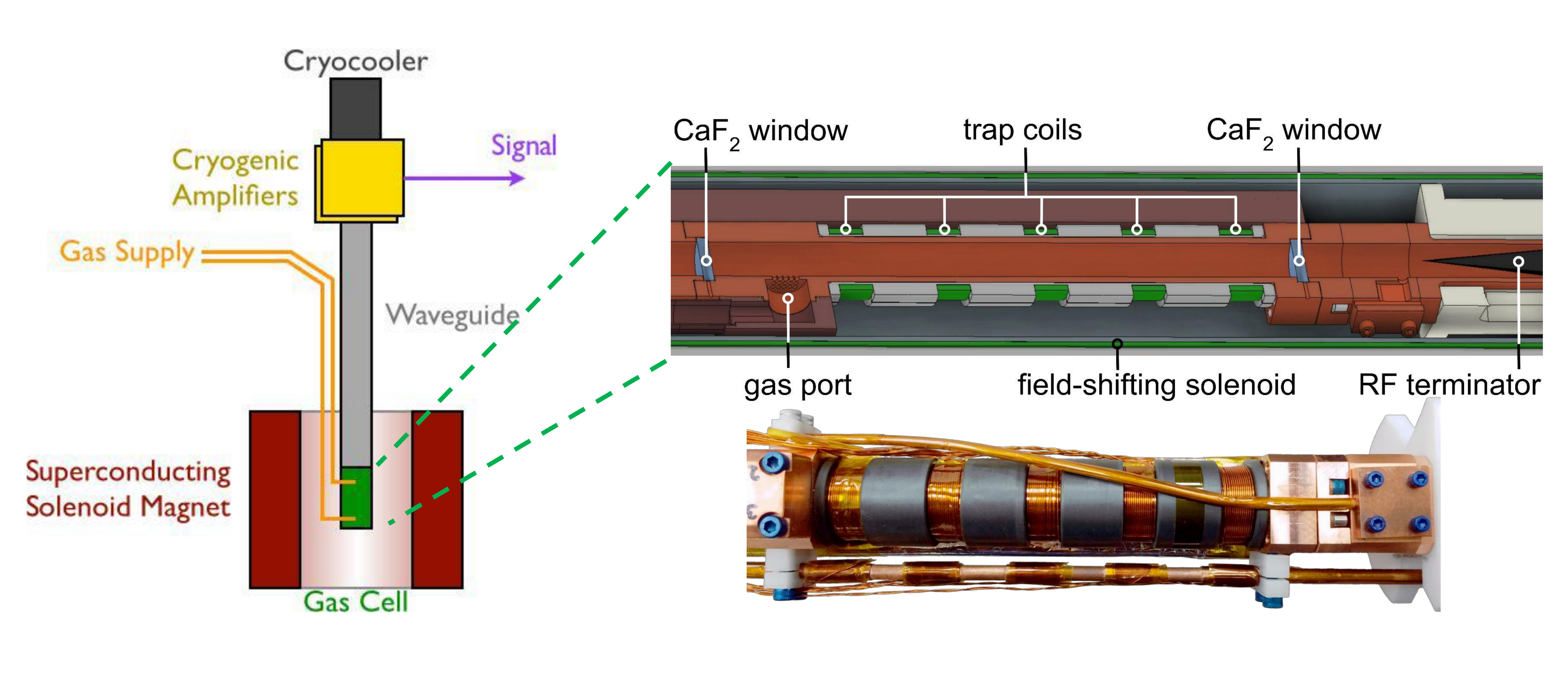
$$\frac{d^2N}{dEdt} = \frac{G_F |V_{ud}|^2}{2\pi^3} |M_{nucl}|^2 F(Z,E) p_e (E + m_e)$$

$$\cdot \sum_f G_f P_f \epsilon_f \sqrt{\epsilon_f^2 - m_\beta^2}\, \Theta(\epsilon_f - m_\beta)$$

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

$$\approx m_\beta^2$$

PHASE II SETUP:



Credit: R. Reimann

PROJECT 8: SPECTRUM ANALYSIS

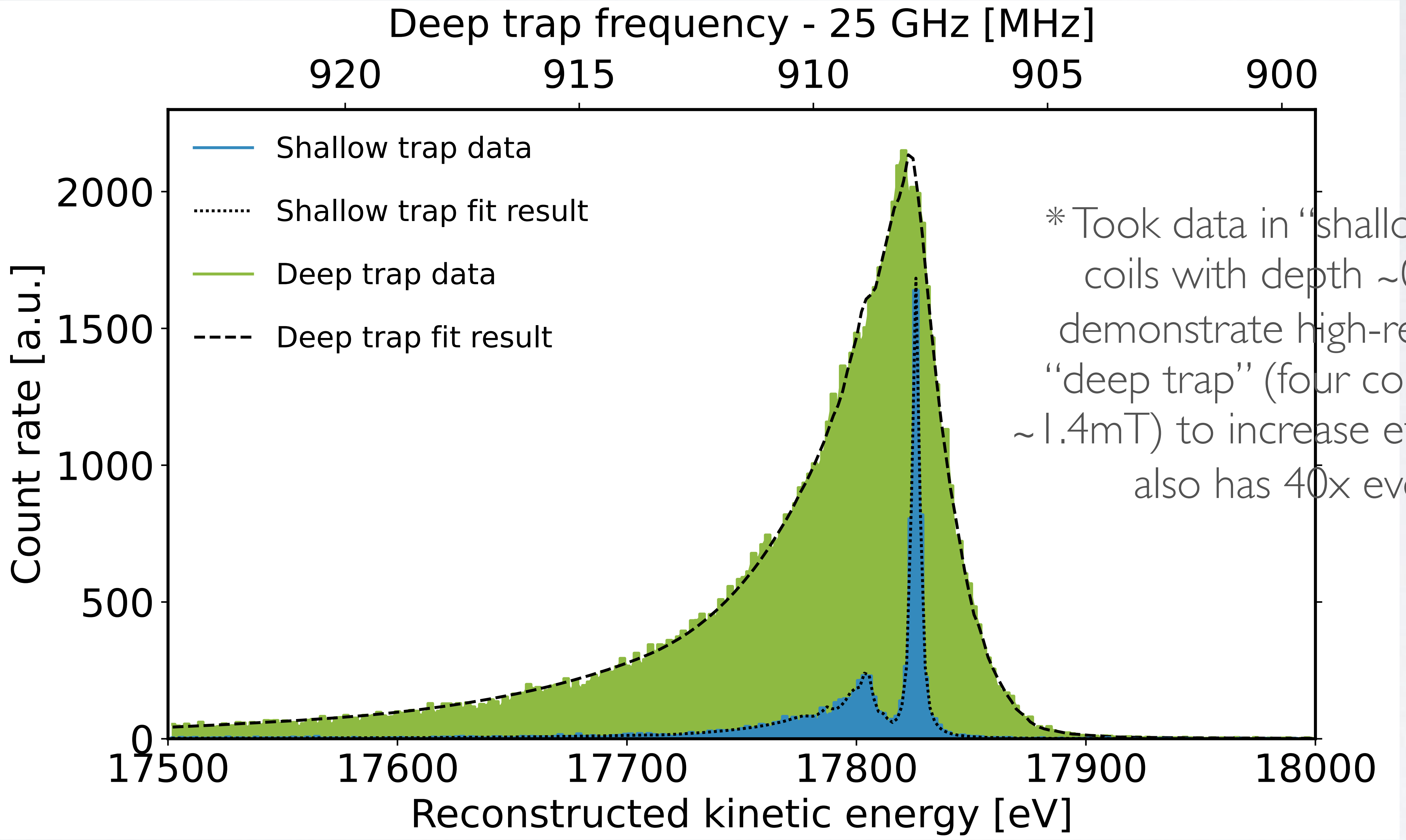


FIG. 3. Data and fits of the 17.8 keV ^{83m}Kr conversion electron K-line, as measured in the shallow (high-resolution) and the deep (high-statistics) electron trapping configurations. The shallow trap exhibits an instrumental resolution of 1.66±0.16 eV (FWHM), while the deep trap provides direct calibration of the tritium data-taking conditions.

* Took data in "shallow trap" (two coils with depth ~0.08mT) to demonstrate high-res CRES, and "deep trap" (four coils with depth ~1.4mT) to increase effective volume; also has 40x event rate.

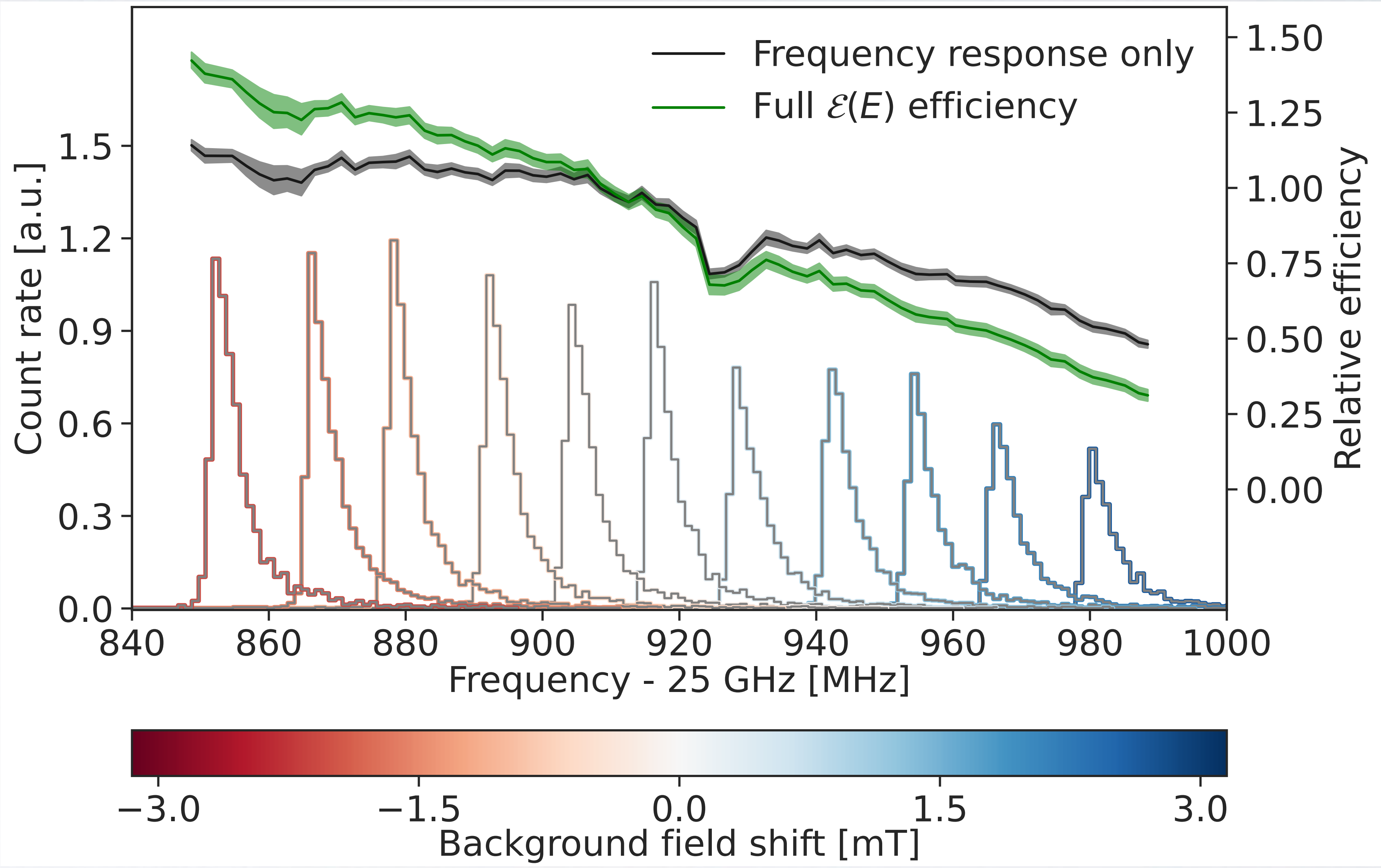


FIG. 4. The 17.8 keV ^{83m}Kr conversion electron line recorded in the deep trap with varying magnetic background fields (red to blue). The gray curve shows the efficiency response to frequency variation, extrapolated from single trap data. The green curve is corrected for energy dependence and shows the relative efficiency predicted for tritium data.

* Use 17.8 keV Kr line and sweep magnetic field (0.07mT steps, over a ±3.2mT range)

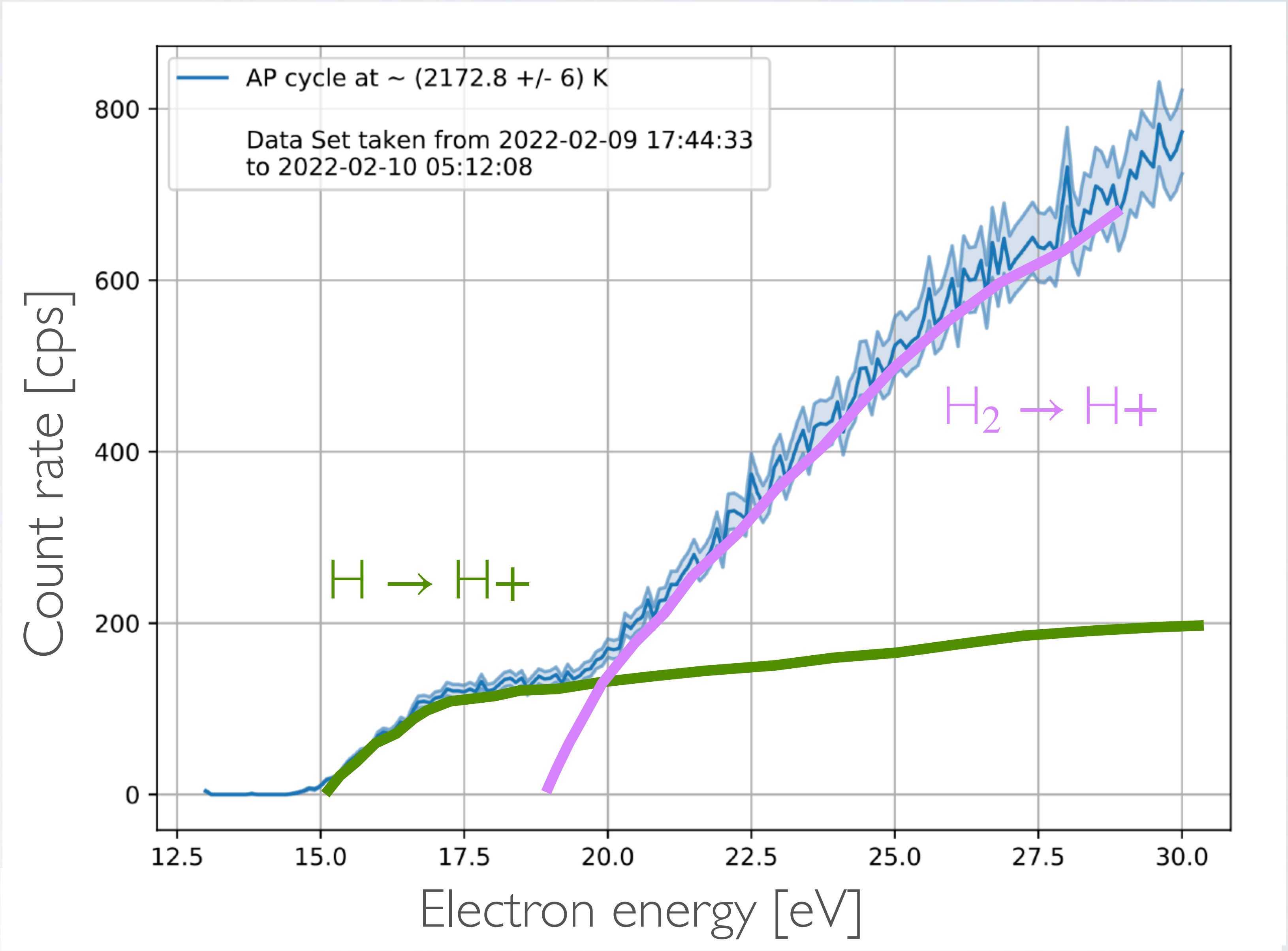
* Notch in efficiency is caused by the interaction with TM01 mode of detection cavity

Resolution: $\frac{\Delta f}{f} \approx \frac{\Delta E}{m_e}$

SOURCE: ATOM BEAM CHARACTERIZATION

- Proof of hydrogen cracking is only the first step
- Atomic hydrogen beam characterization in progress:
  - Current measurements give us a handle on composition, absolute number density, and background due to non-beam molecular hydrogen
  - Address backgrounds via dedicated measurement campaigns
  - First results from measurements with newly upgraded setup show much promise

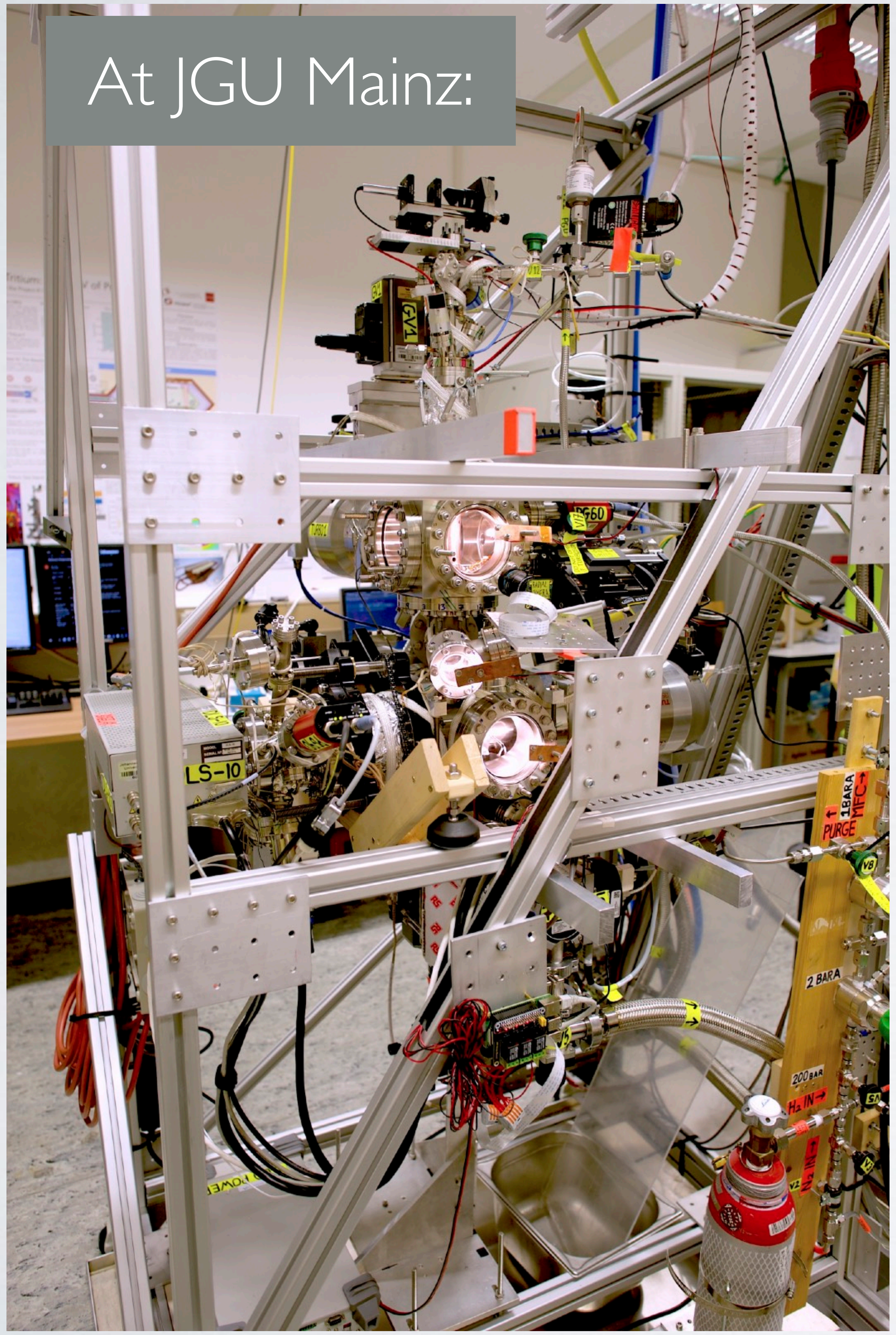
m/z=1 at 0.1sccm flow:

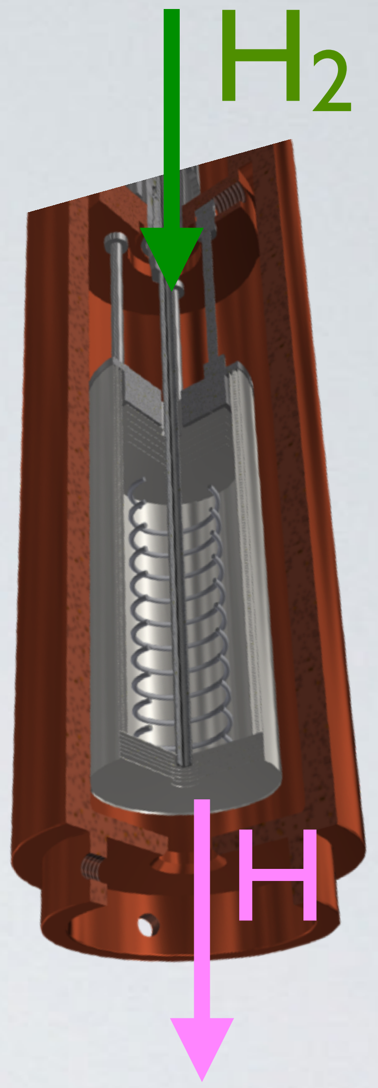


Source: M. Heyer

$$n = \frac{P}{RT} = \frac{1.36 \times 10^{-6}\ \text{hPa}}{1.38 \times 10^{-23} \frac{\text{J}}{\text{K}} \times 300\ \text{K}} = 3.29 \times 10^{16} \frac{\text{H2 molecules}}{\text{m}^3}$$

SOURCE: ATOM PRODUCTION





Cracker } Converts H_2 to H by thermal dissociation

Mass spectrometer

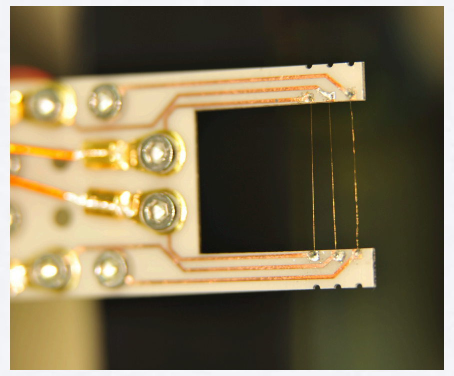
Symmetric differential pumping

} Measure atom signal (approach #1)

→ Beam dissociation measurement

→ Differentiate between beam, background atoms

Wire detector

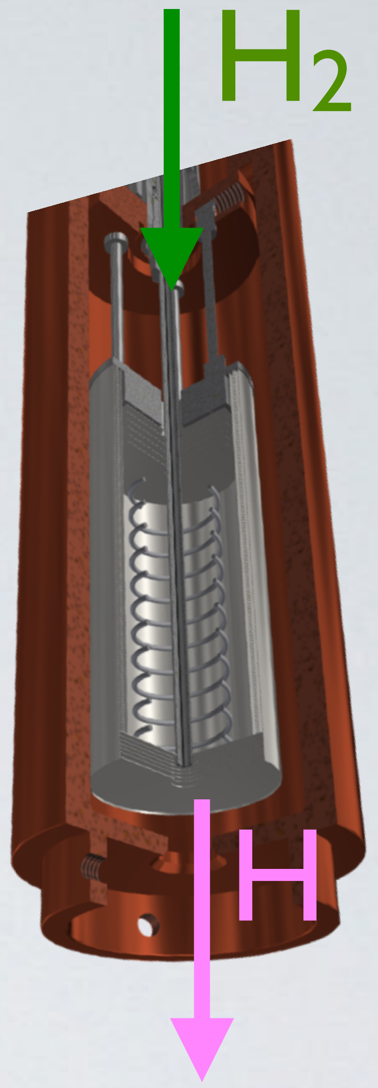


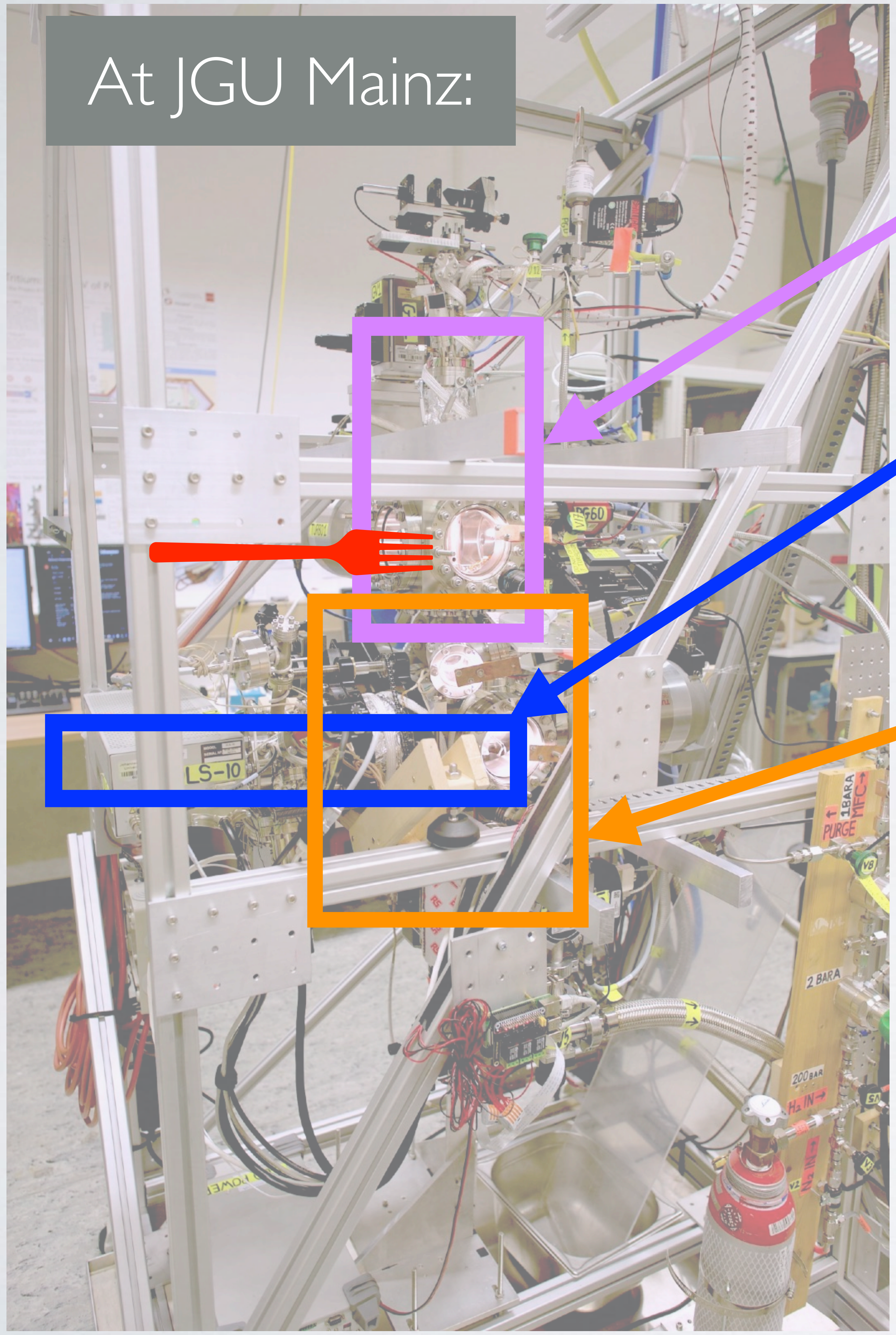
} Measure atom signal (approach #2)

→ Fits in tight spaces

→ Beam profile measurement

SOURCE: ATOM PRODUCTION





Cracker } Converts H_2 to H by thermal dissociation

Mass spectrometer

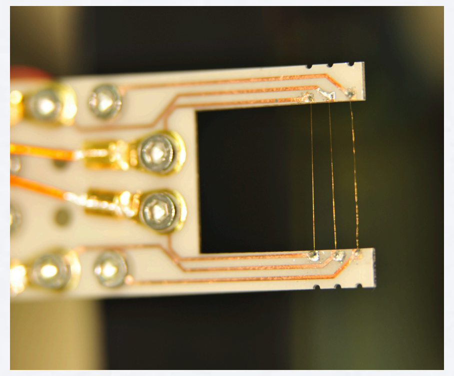
Symmetric differential pumping

} Measure atom signal (approach #1)

→ Beam dissociation measurement

→ Differentiate between beam, background atoms

Wire detector



} Measure atom signal (approach #2)

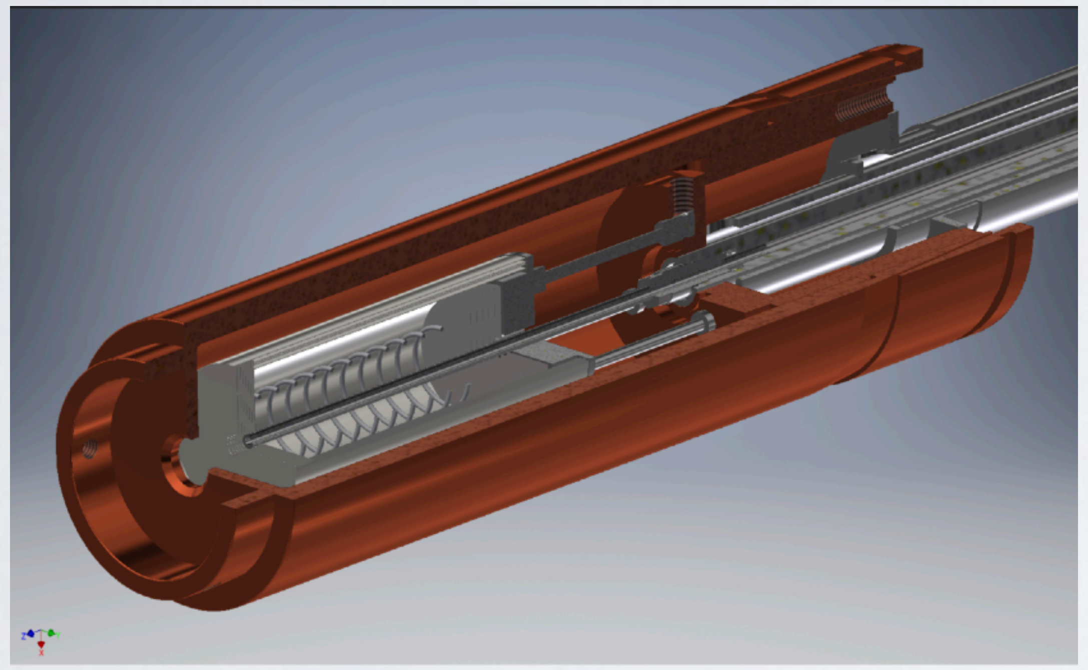
→ Fits in tight spaces

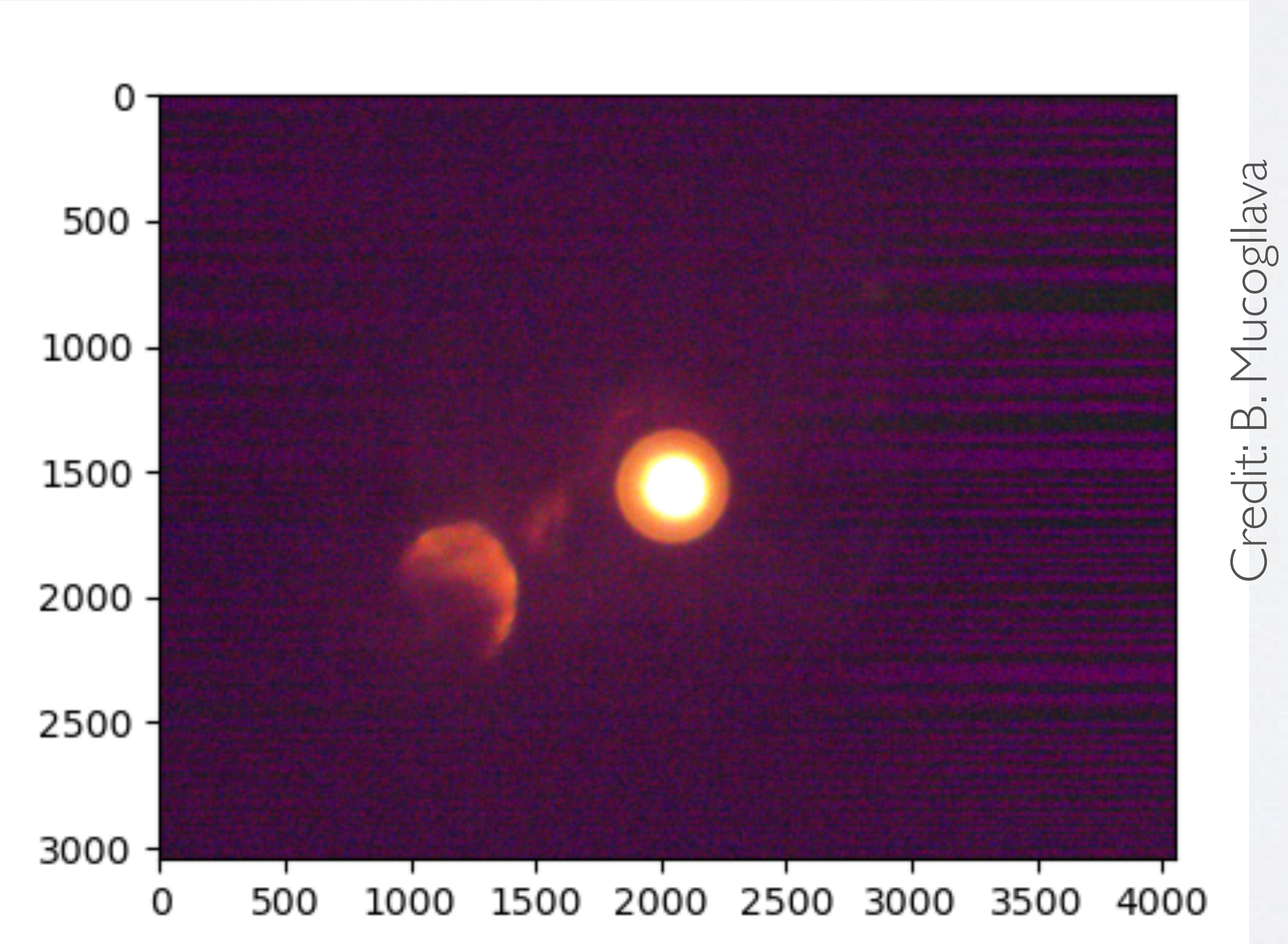
→ Beam profile measurement

SOURCE: ATOM PRODUCTION

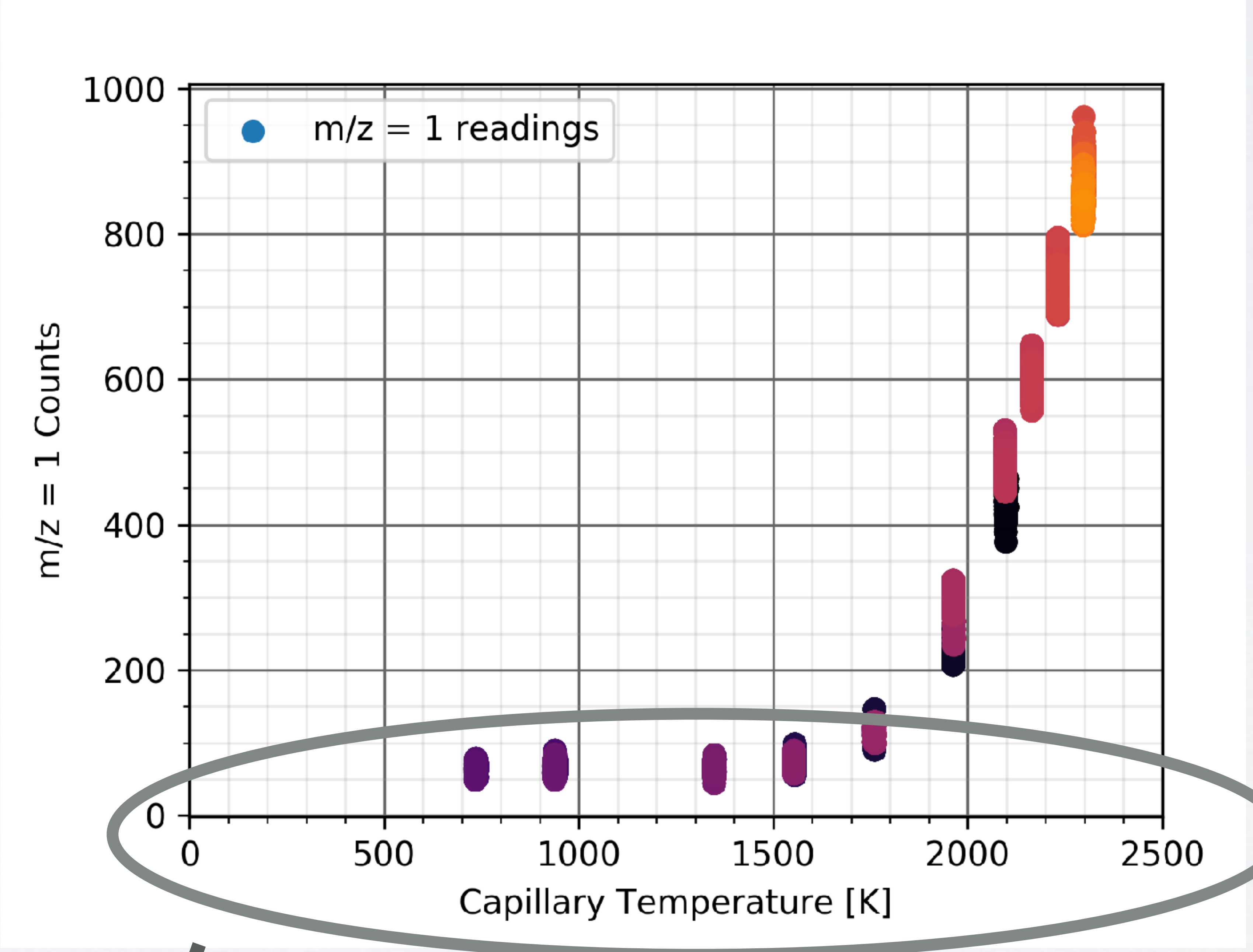
Challenges in characterizing the hydrogen atom beam:

Inside the source:

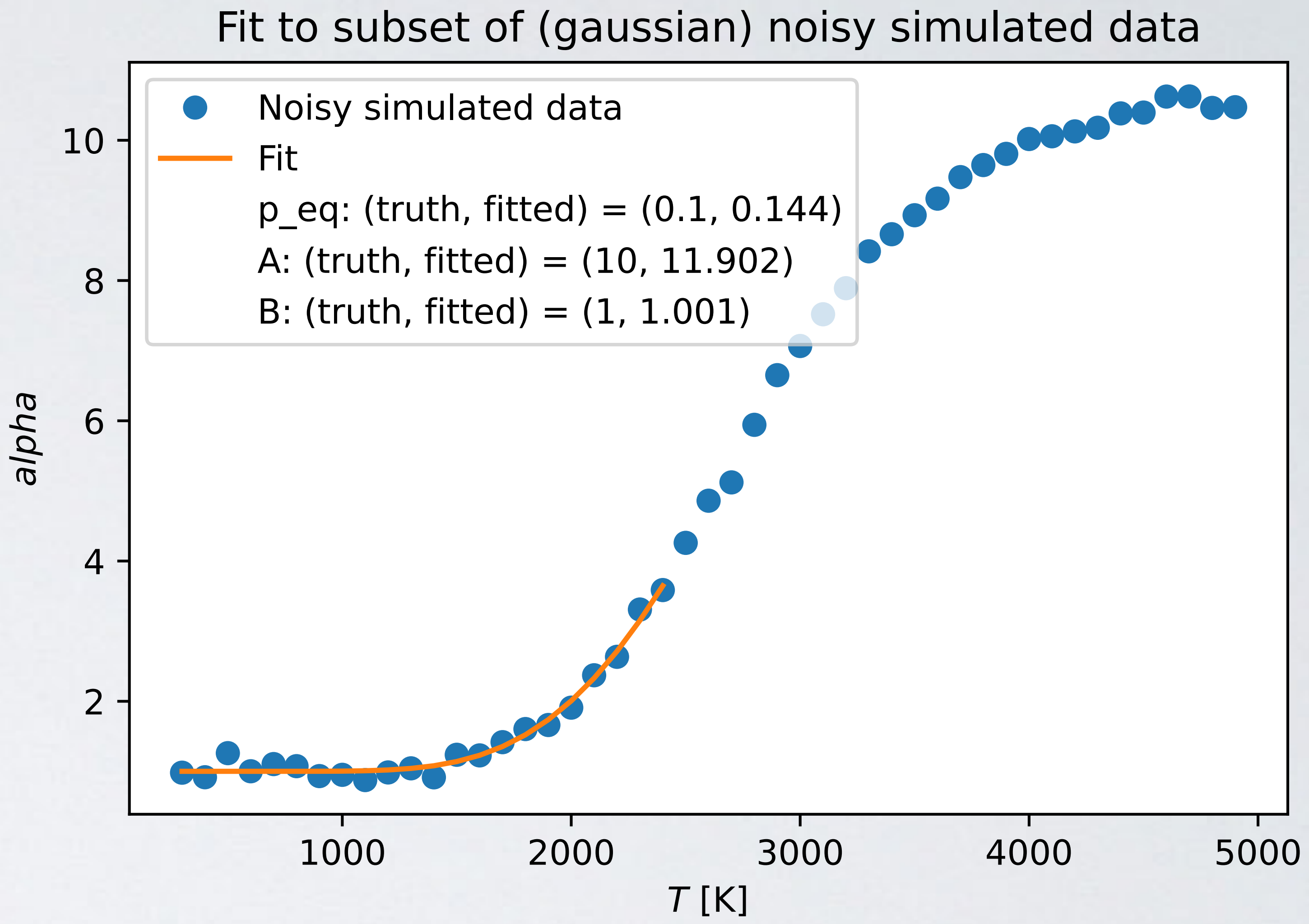




Credit: B. Mucogllava

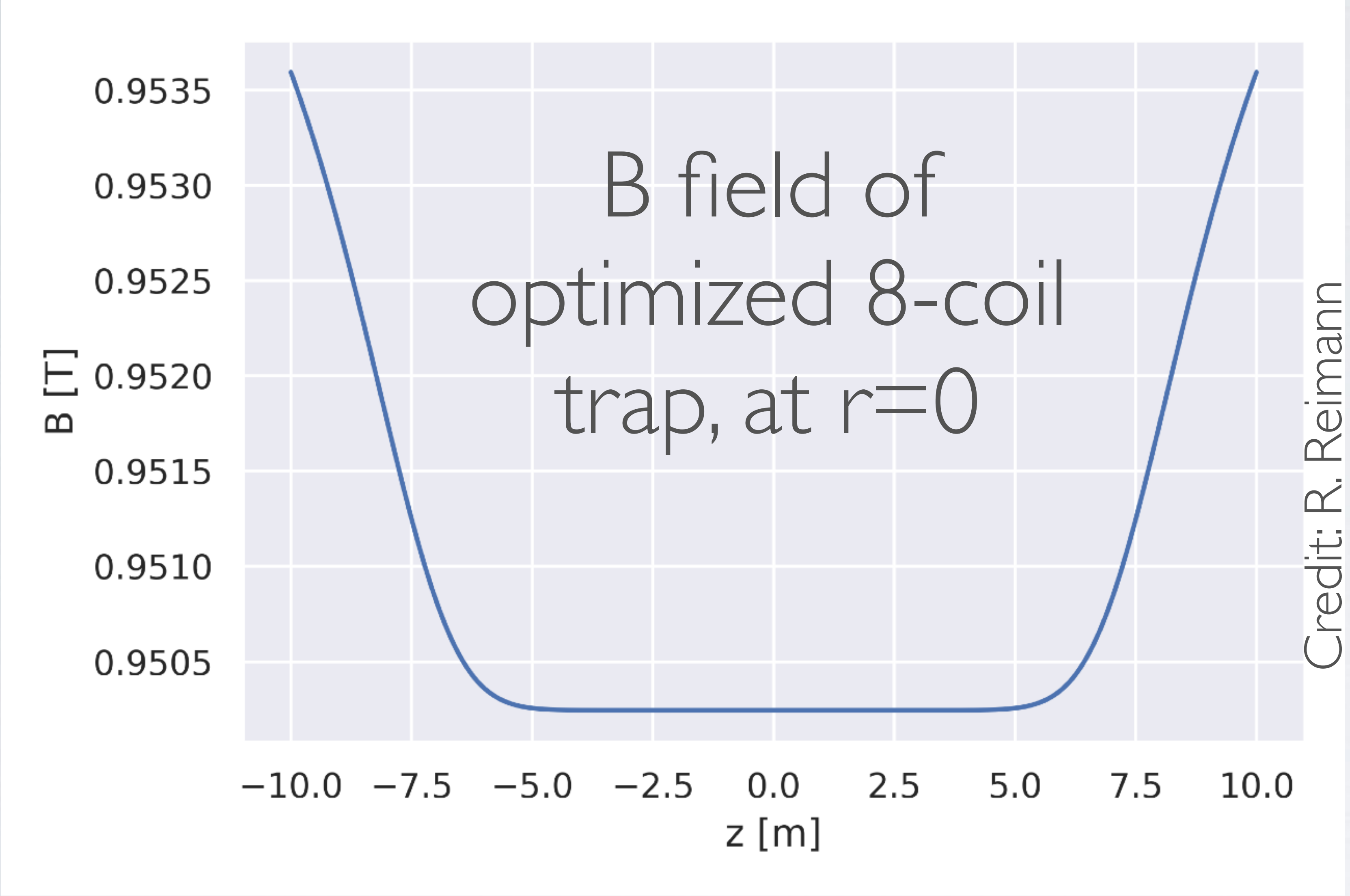


Credit: A. Lindman

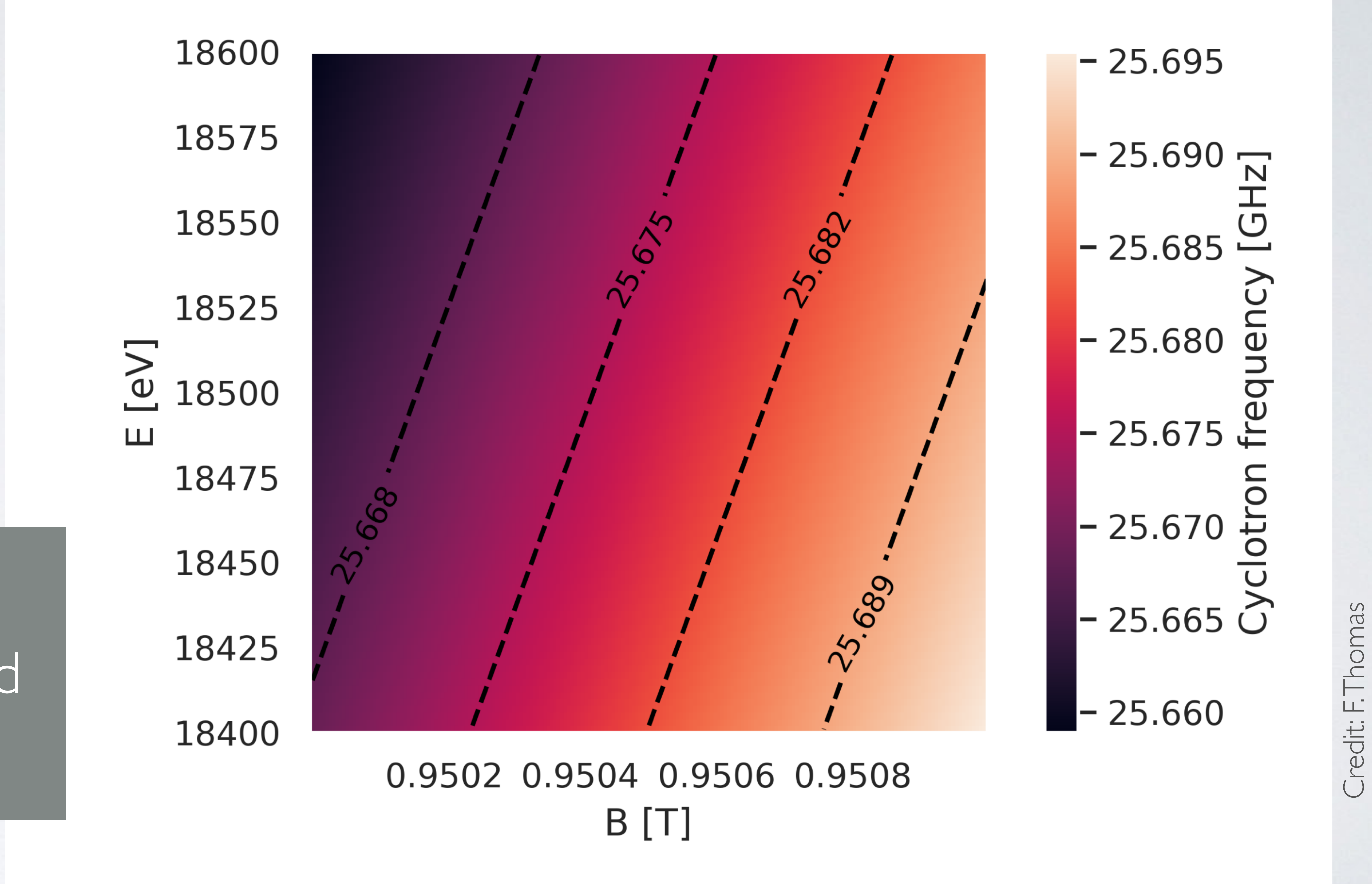


Credit: L. Thorne

SIMULATIONS

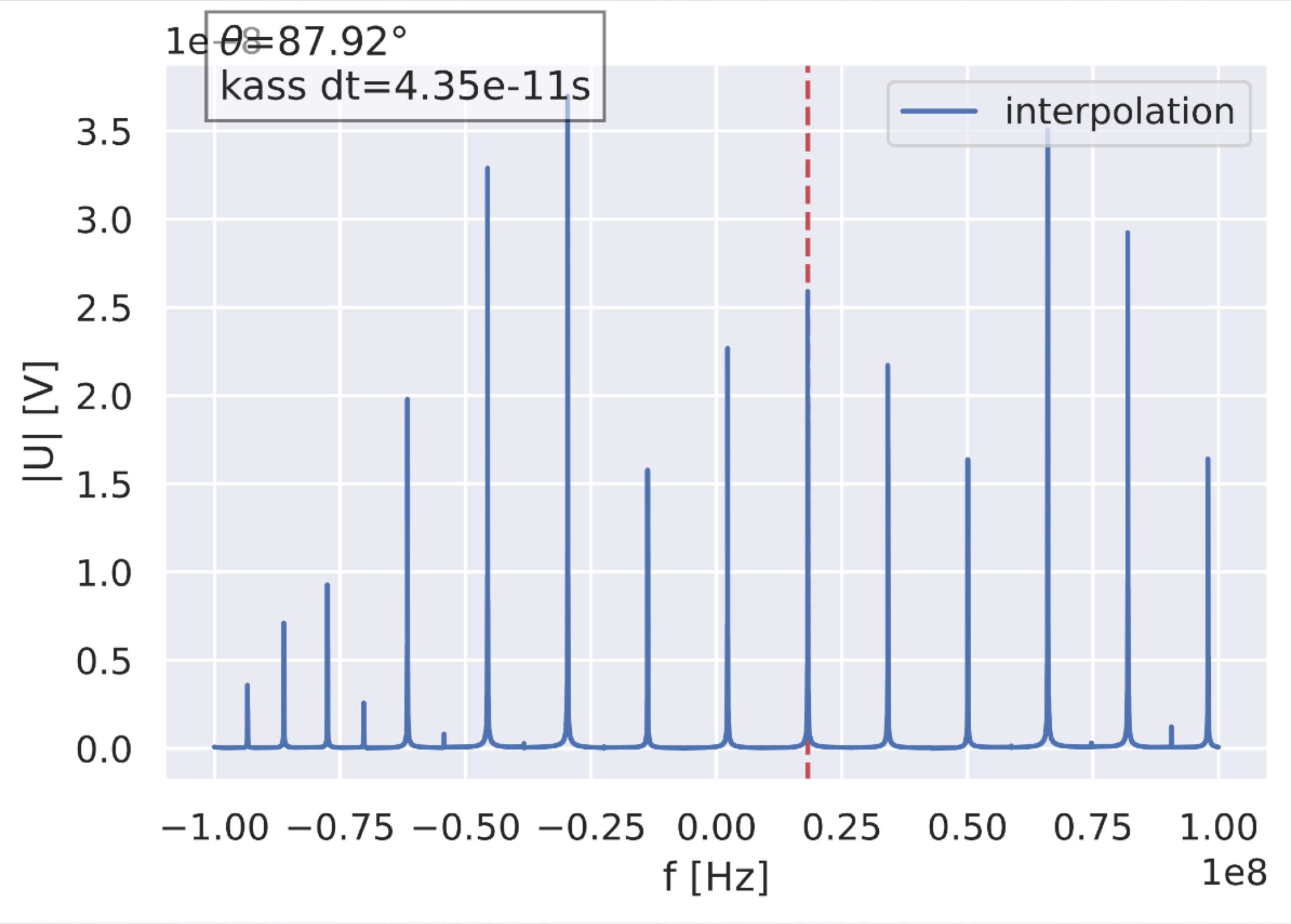


Degeneracy in energy and pitch angle, if B field isn't flat at center!



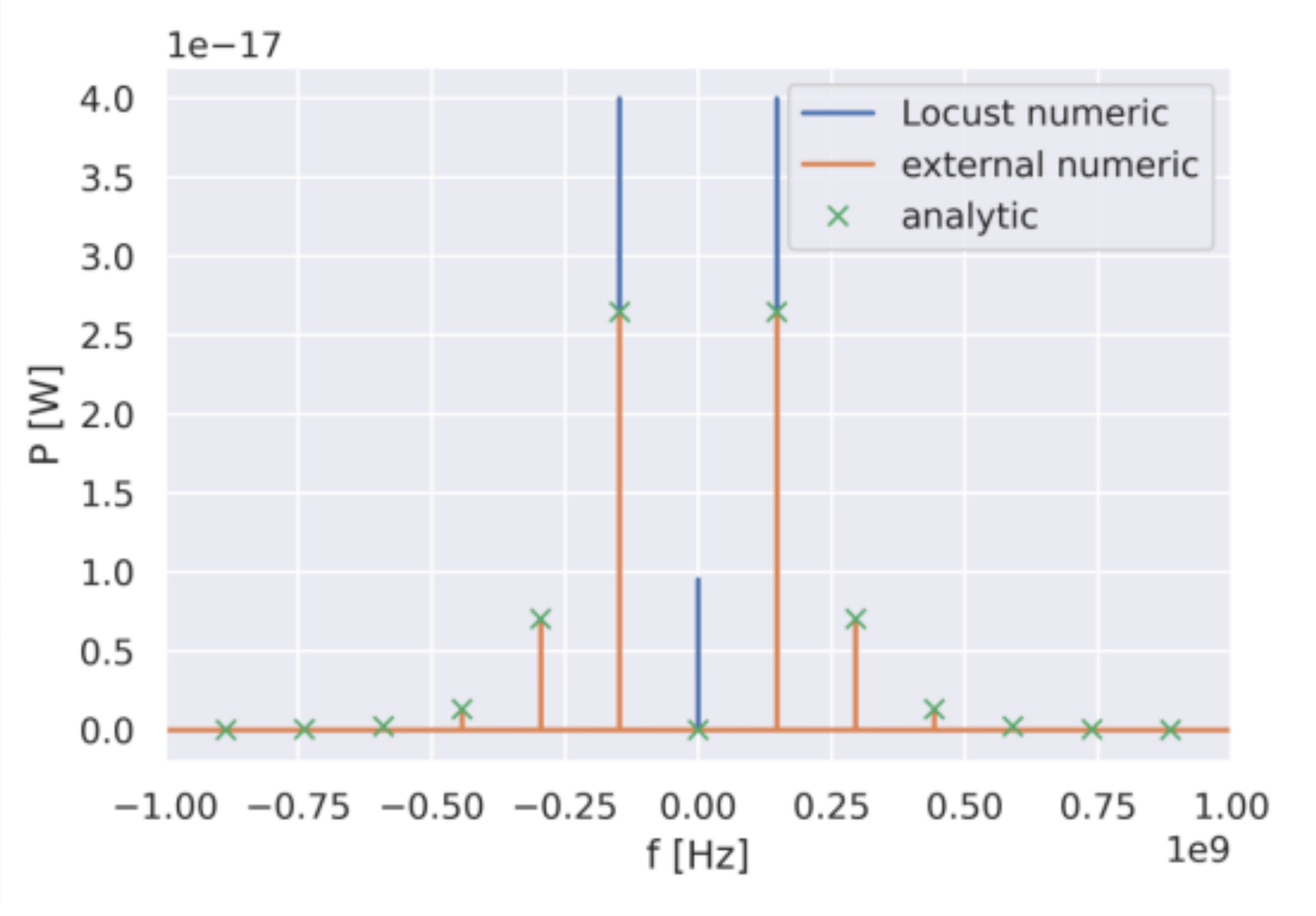
SIMULATIONS

Sample spectrum (Kassiopeia, CRESana):



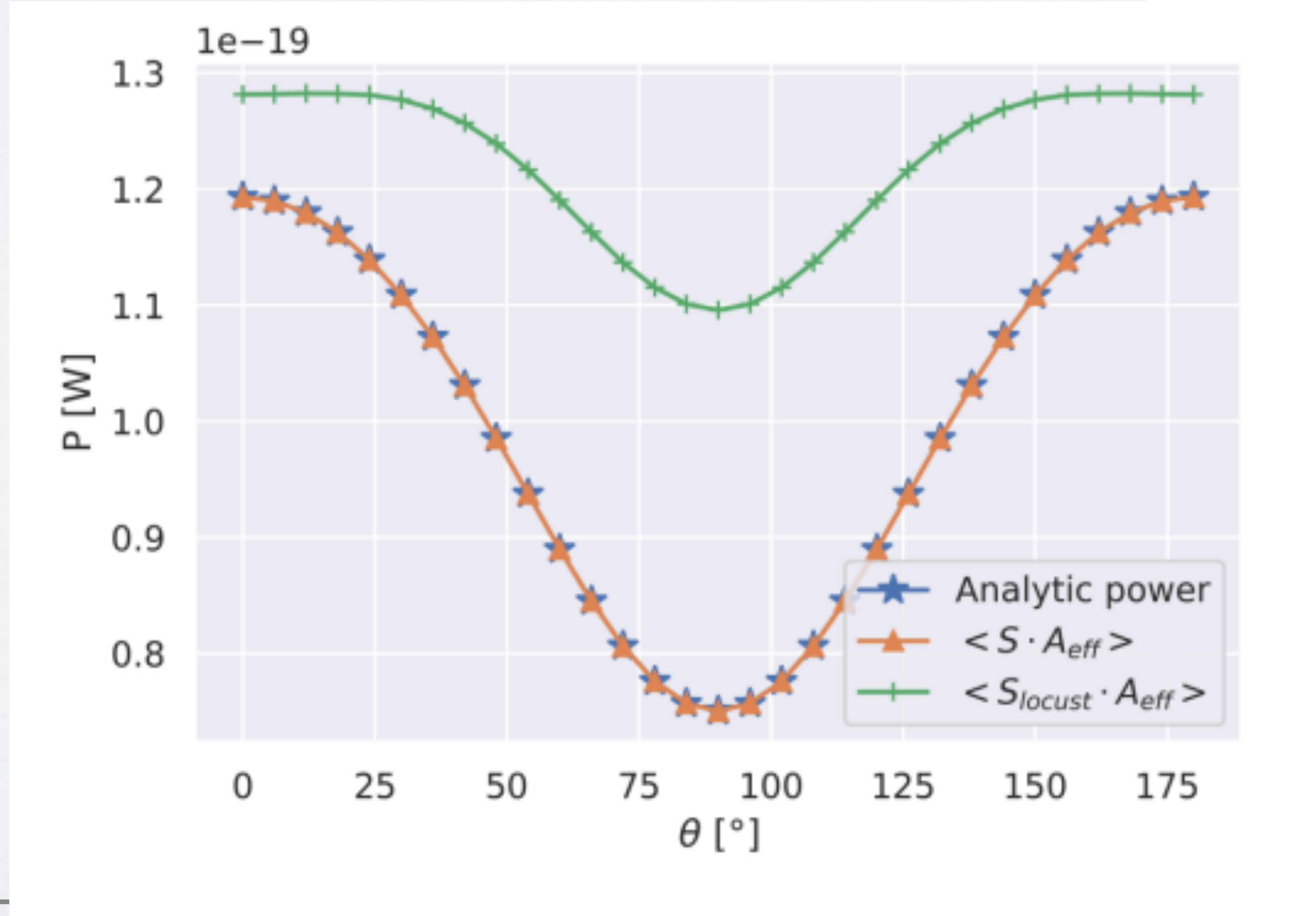
Credit: F. Thomas

Power spectrum of $\theta = 90^o$ electron (CRESana, Locust):



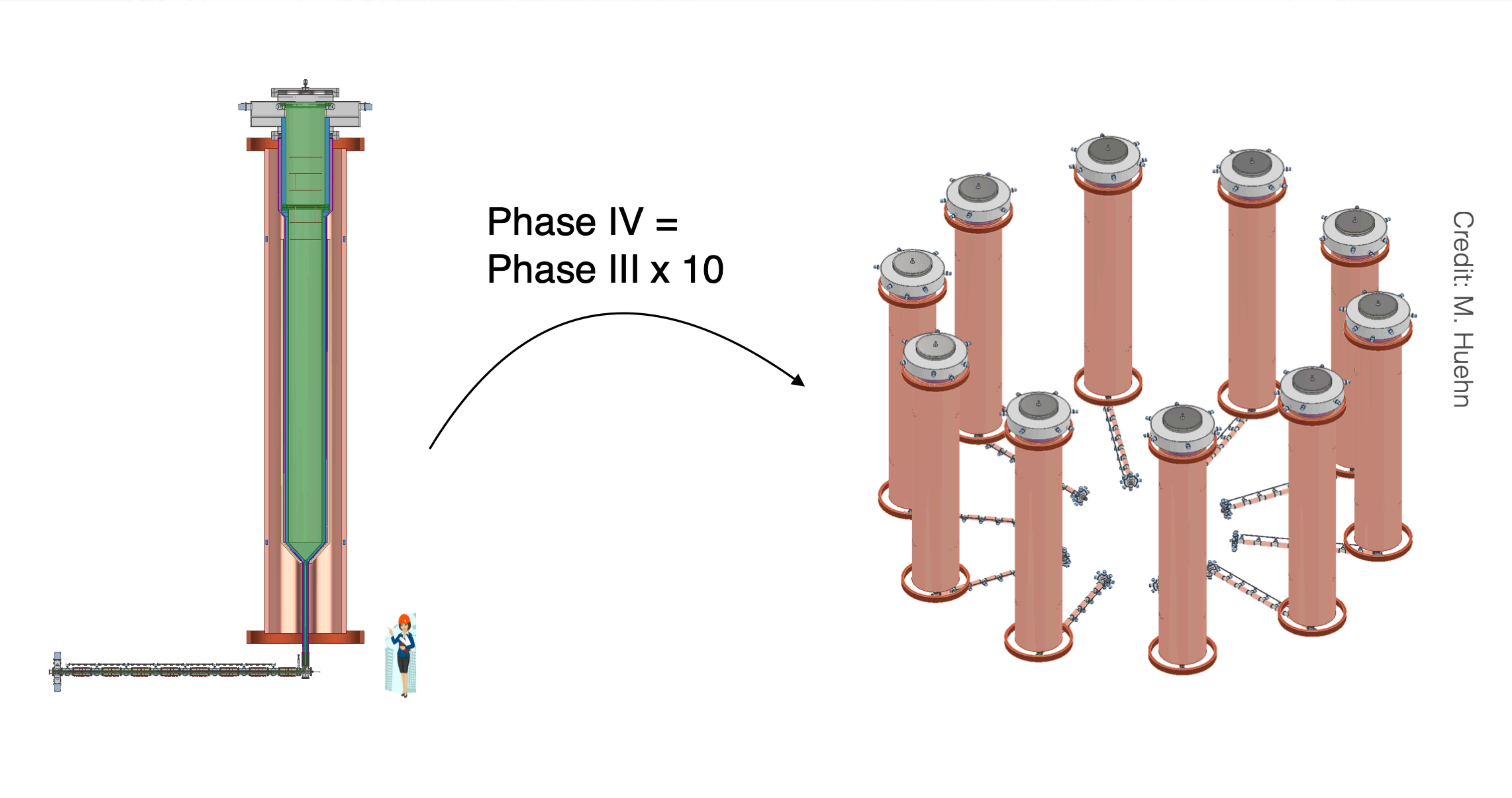
Credit: F. Thomas

Detected signal power as function of observation angle (CRESana):



Credit: F. Thomas

Validation campaign improved analytic modeling and understanding of signal


Phase IV =
Phase III x 10
Credit: M. Huehn