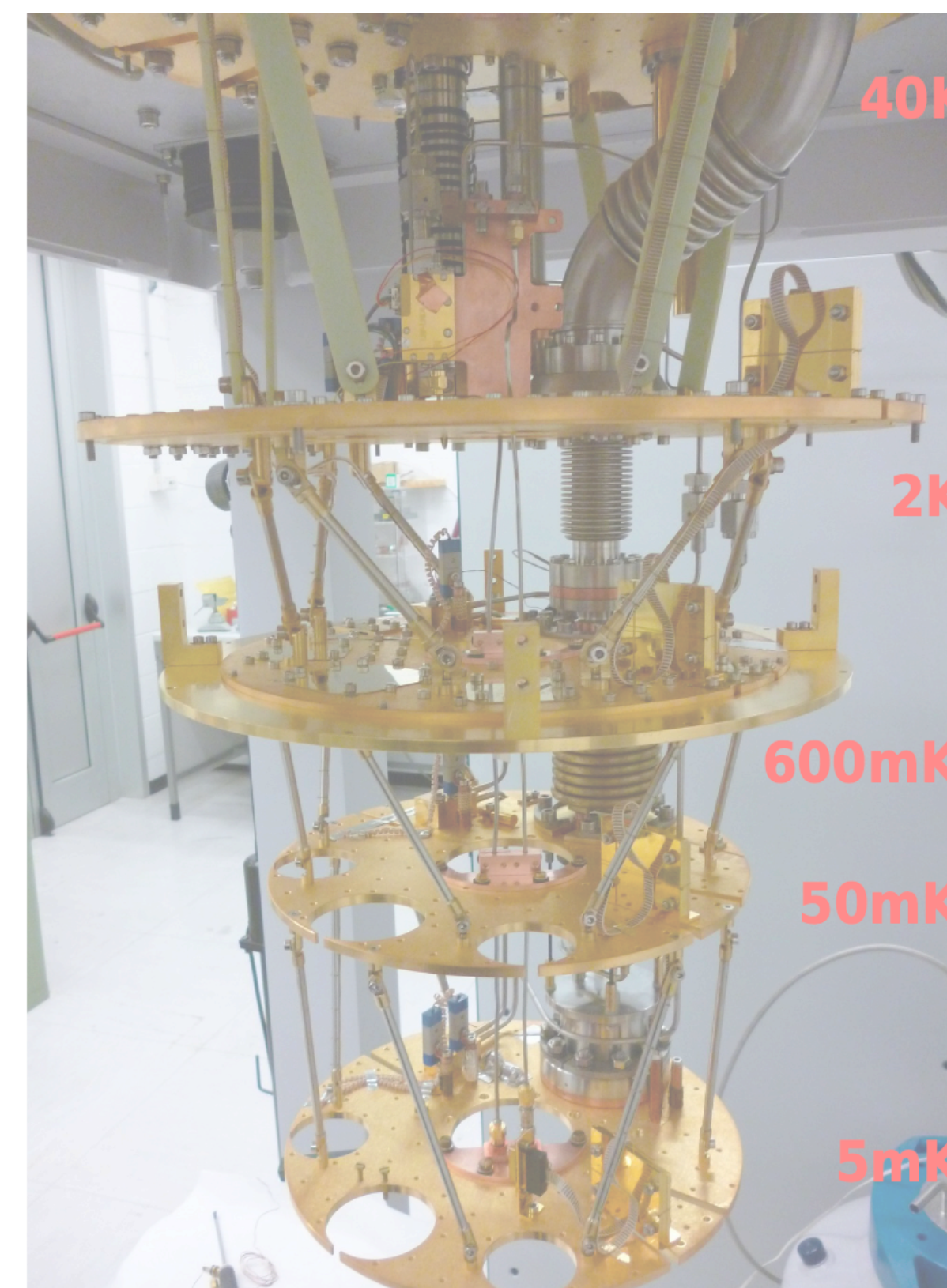
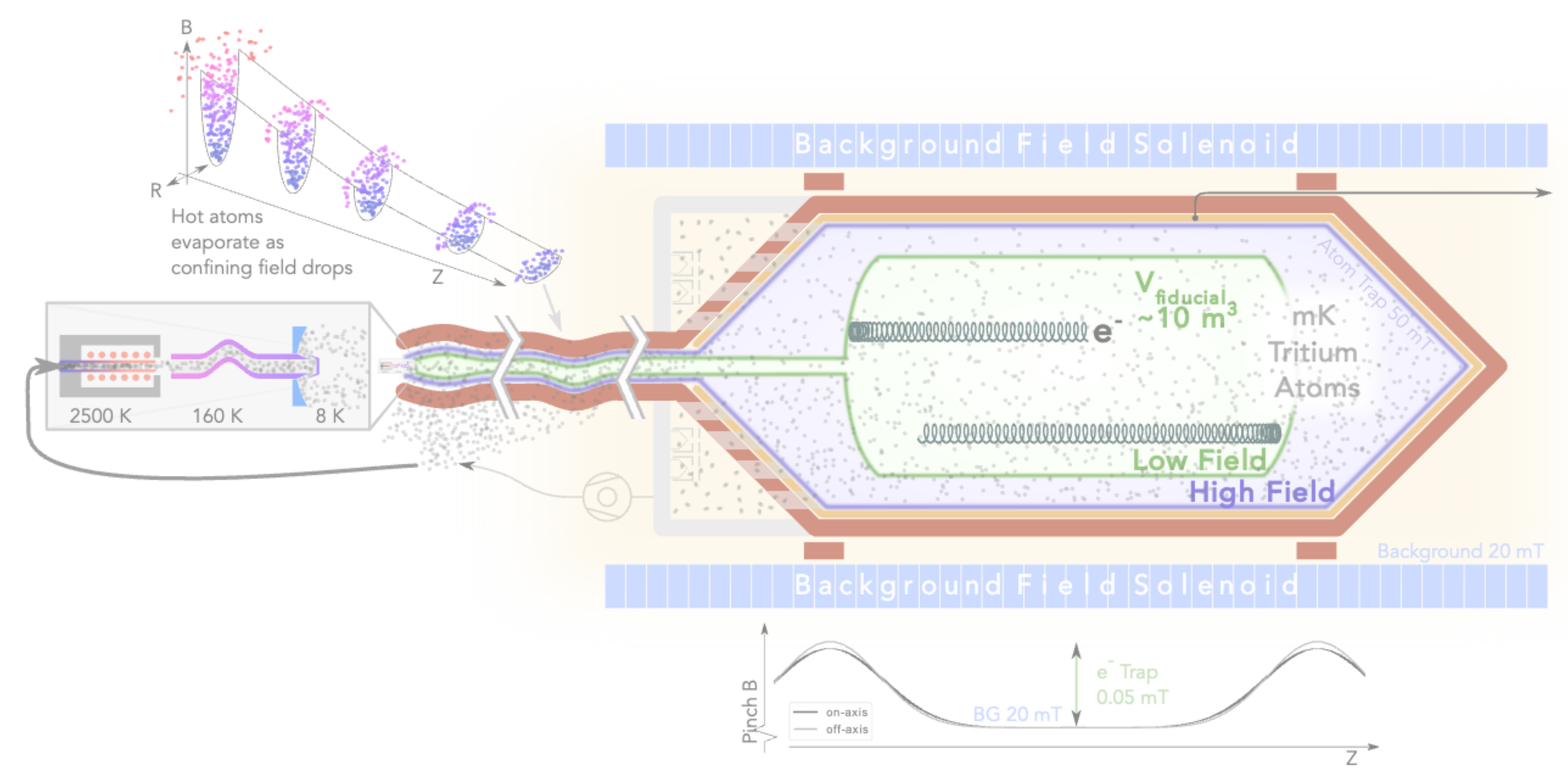


Feature Directions in Direct Neutrino Mass Measurements



Neutrino Mass

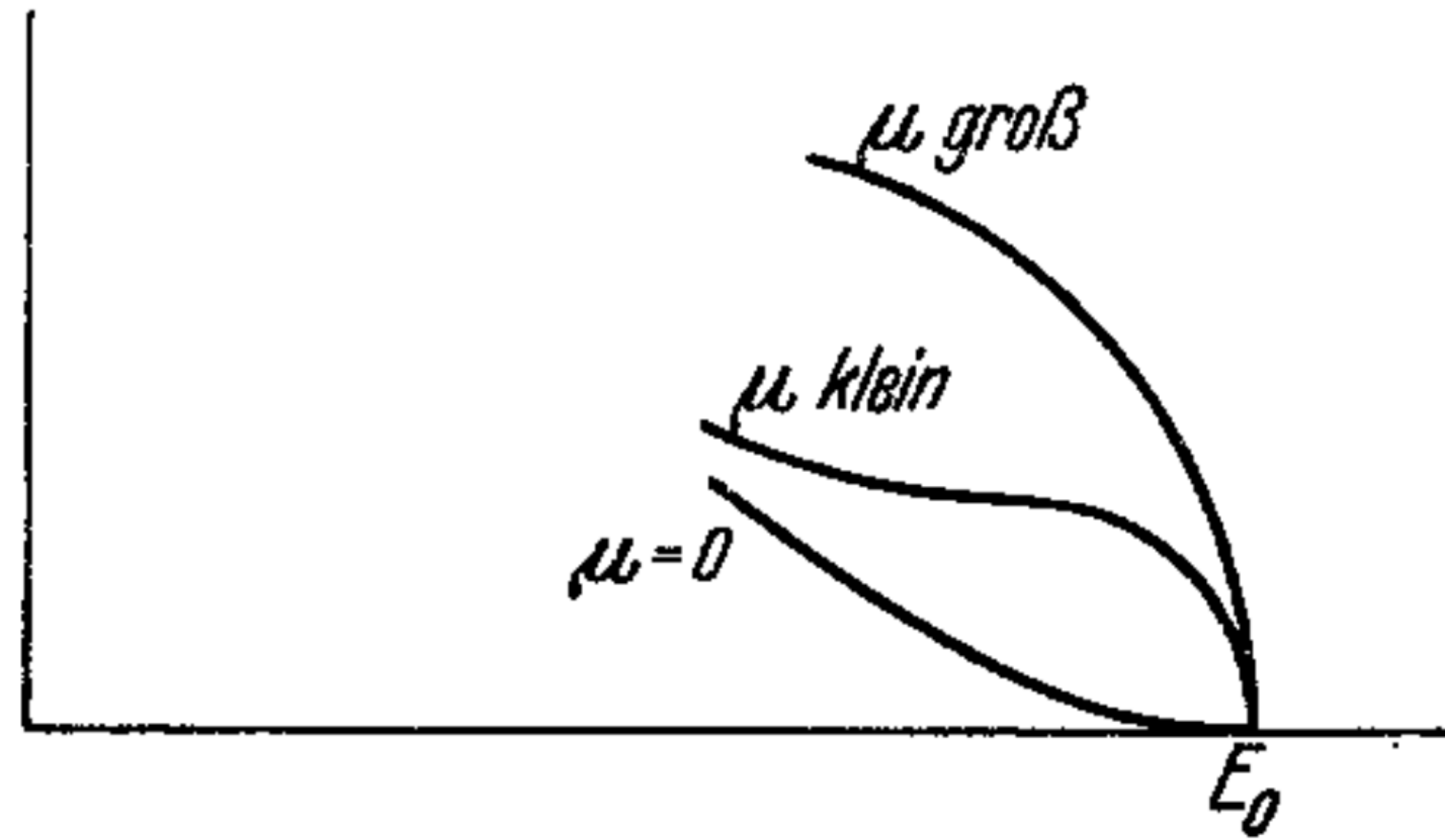
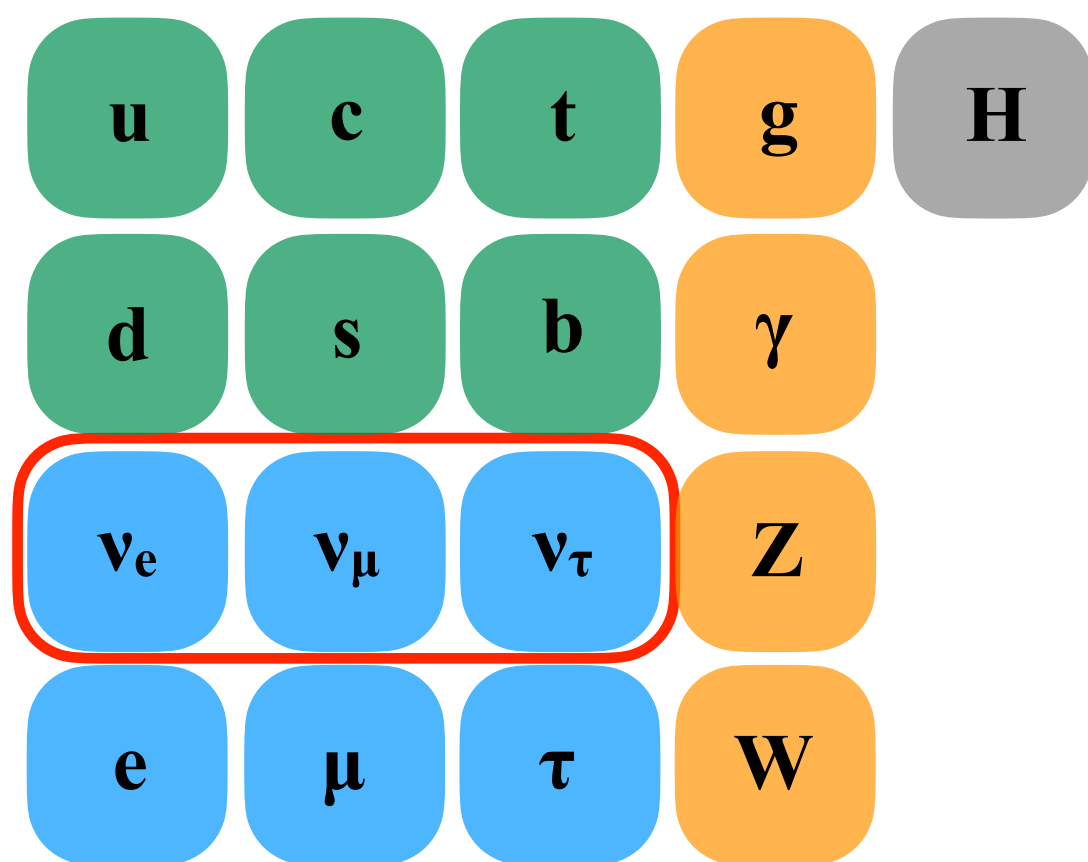
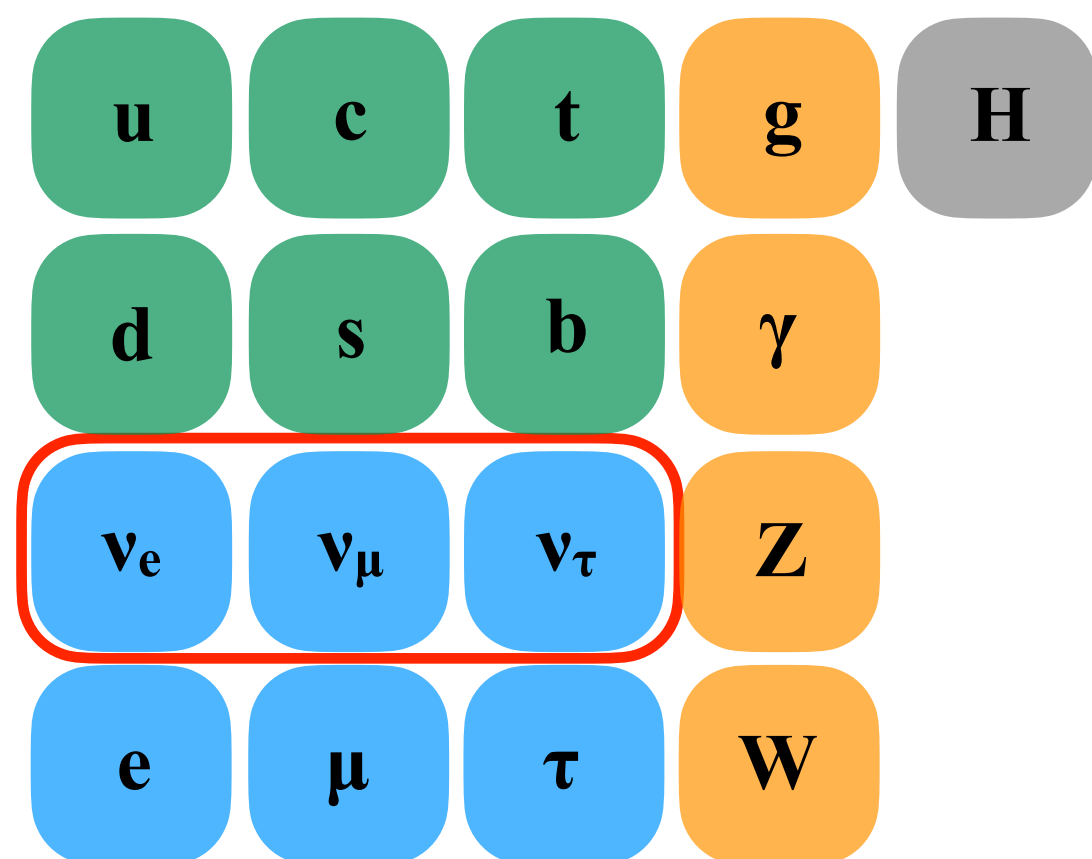


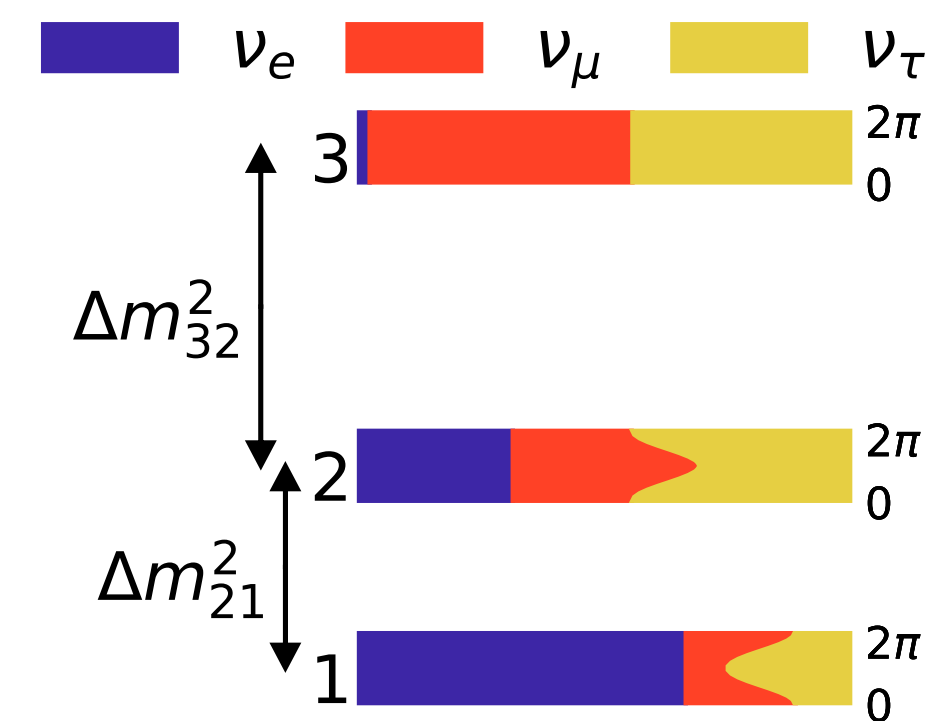
Fig. 1.



SM: massless neutrinos

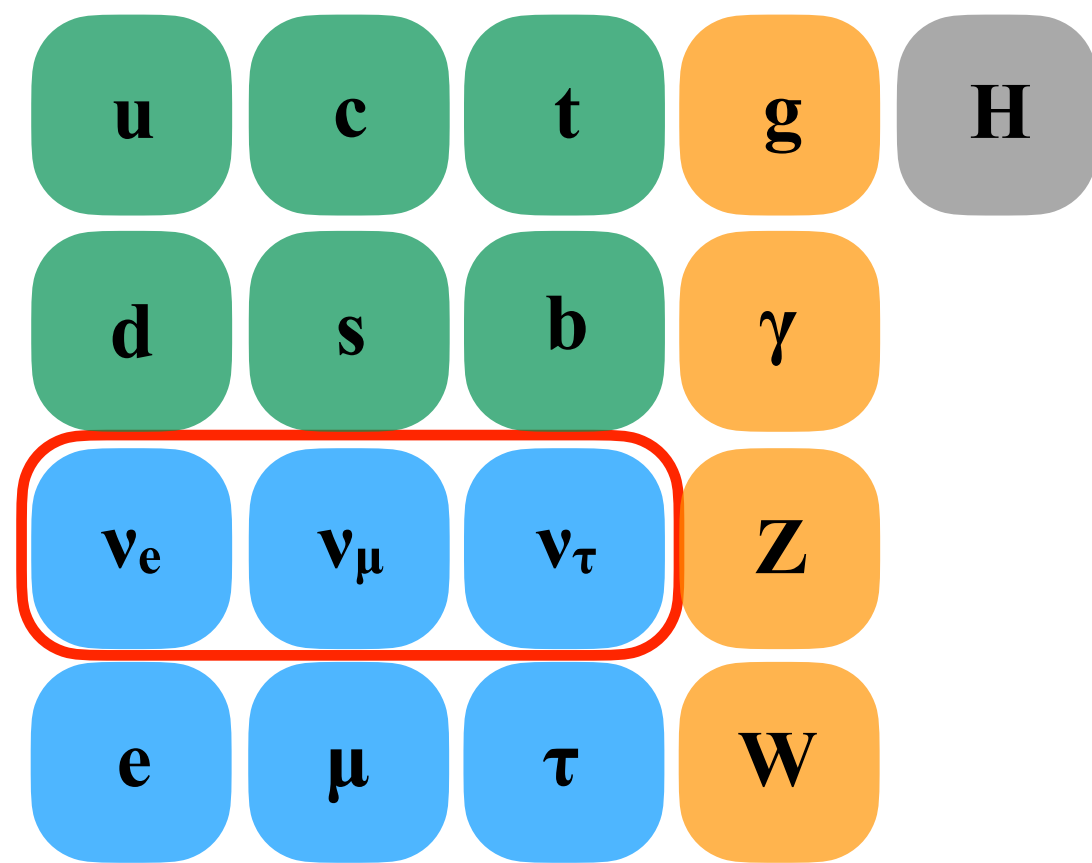


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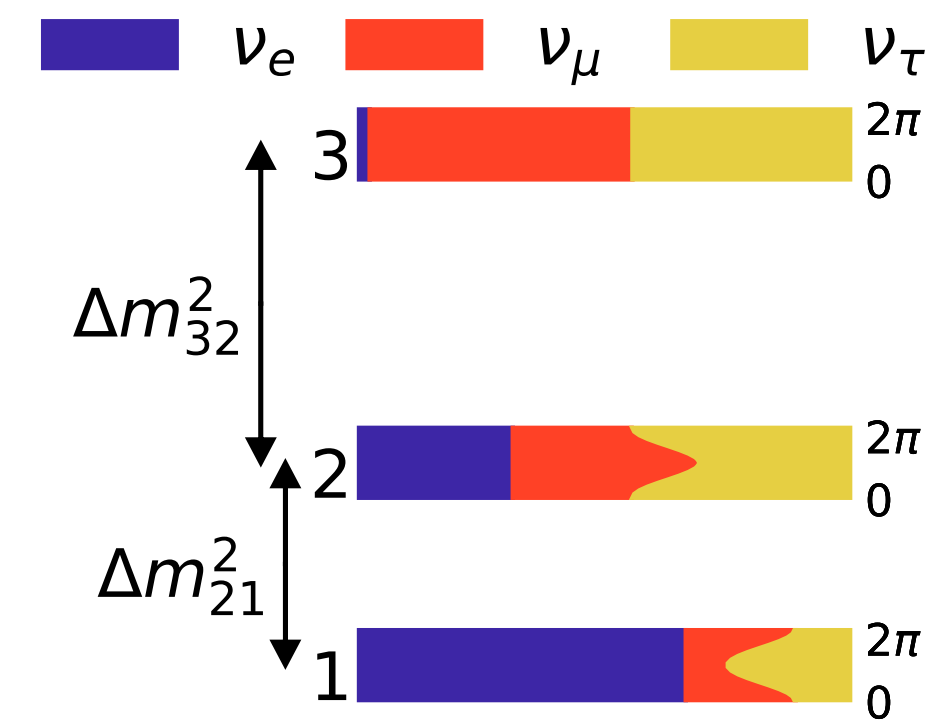
Neutrino oscillations
 $\rightarrow$ neutrino mass
 differences

$\Sigma m_i > 0.059 \text{ eV}$
[JHEP 12, 216 \(2024\)](#)



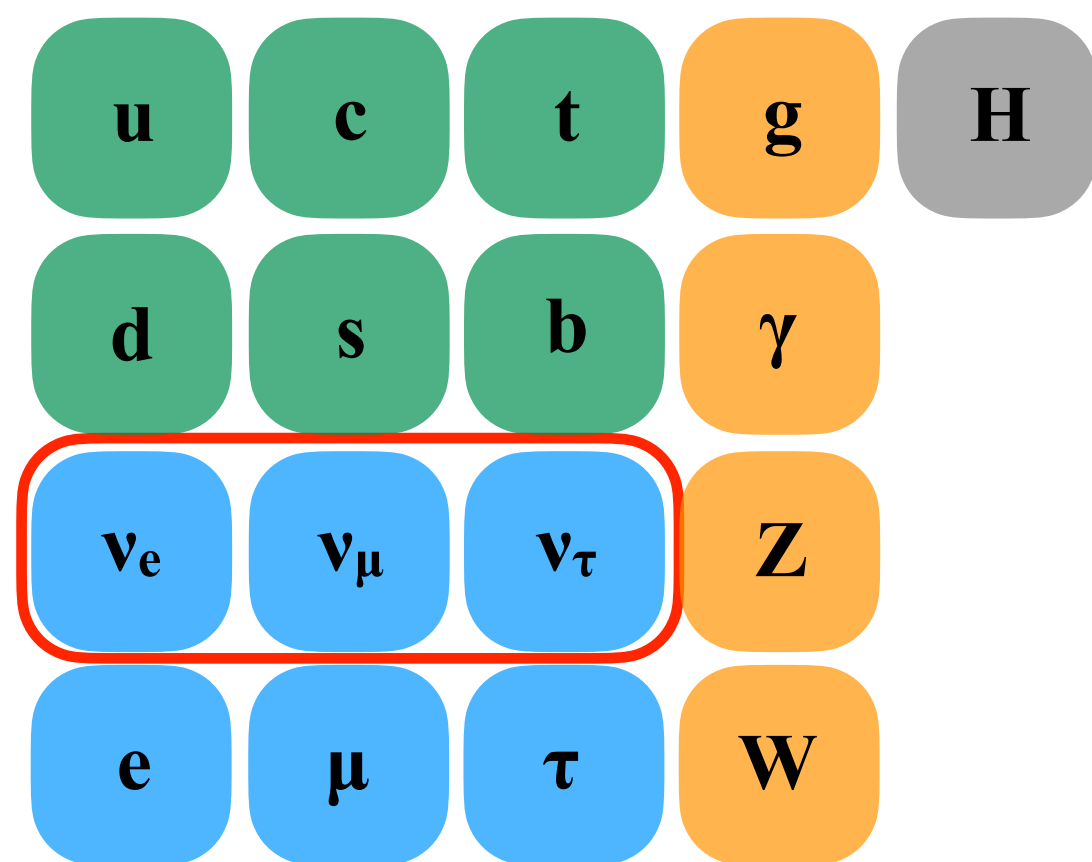
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Contradiction!



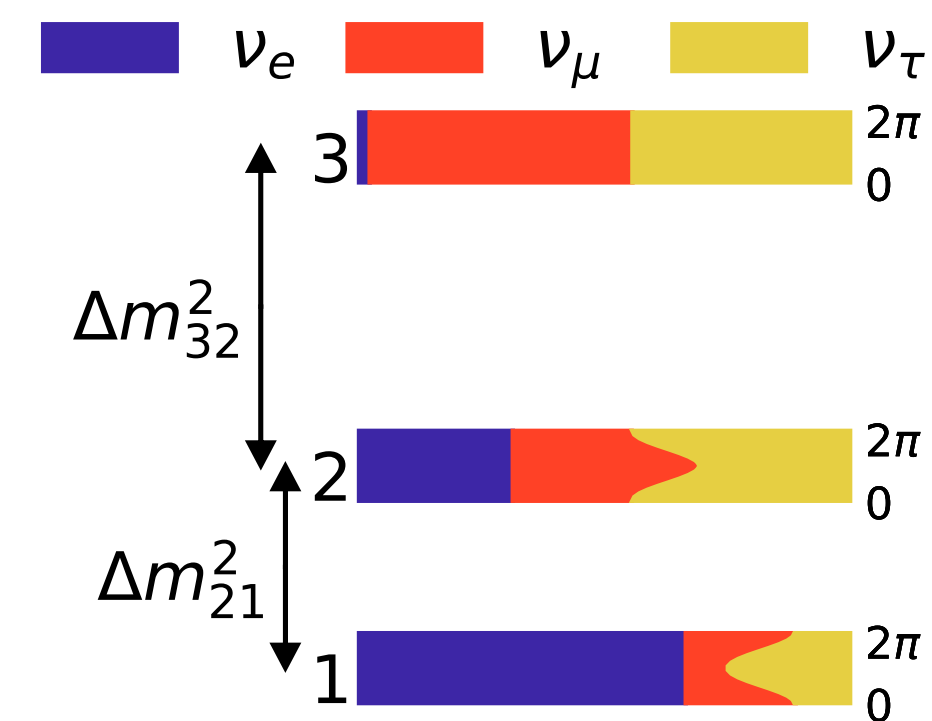
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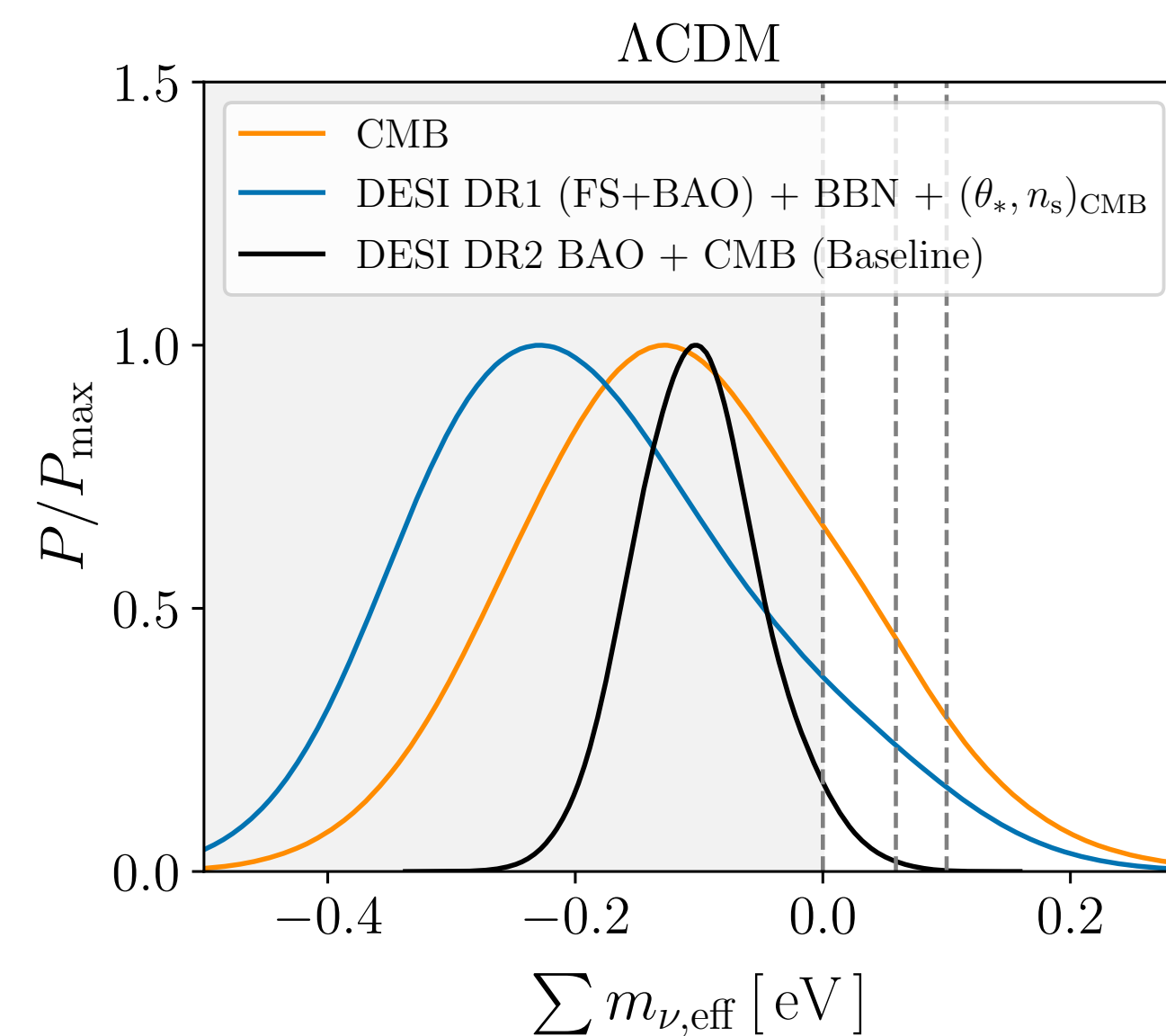
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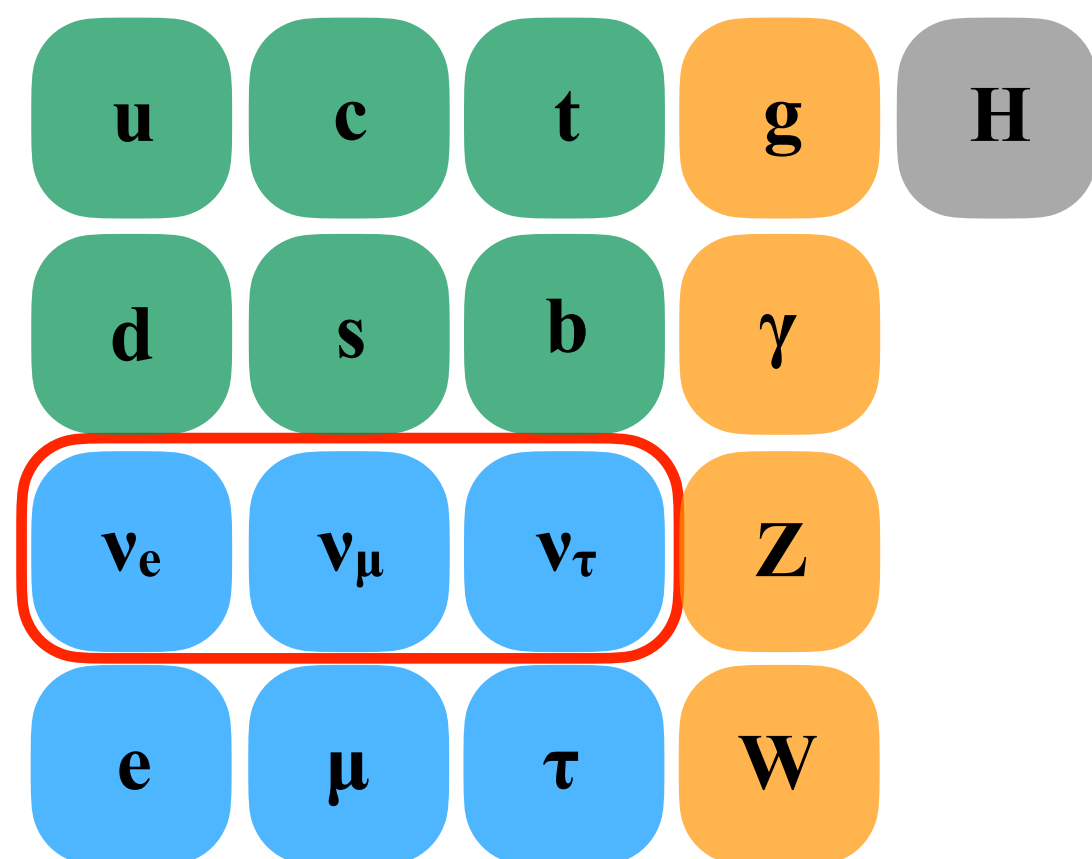
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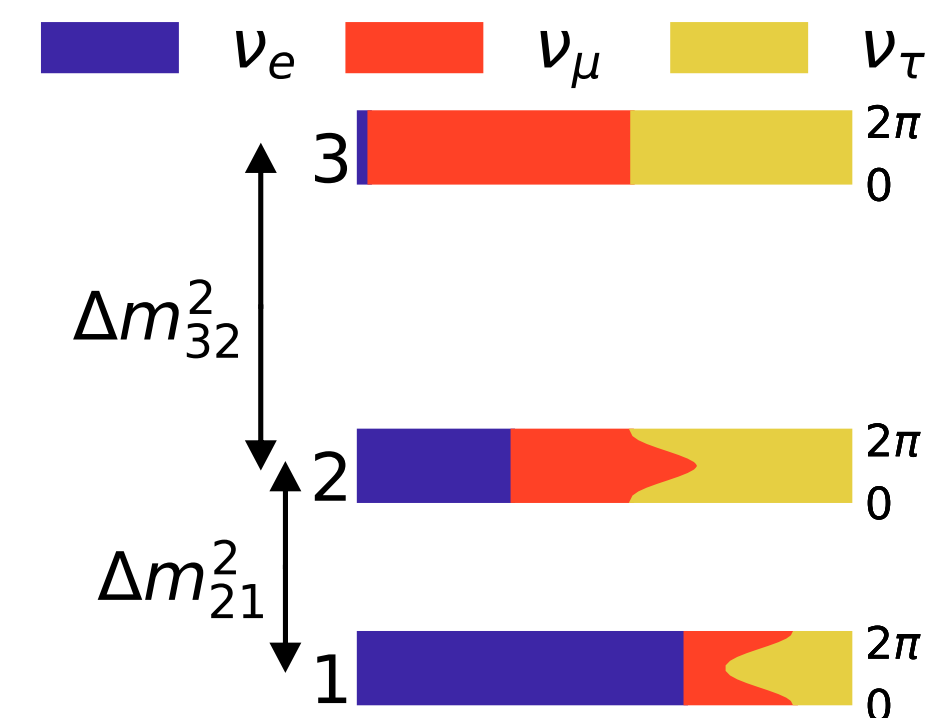
Cosmic surveys:
Indirect neutrino mass sensitivity

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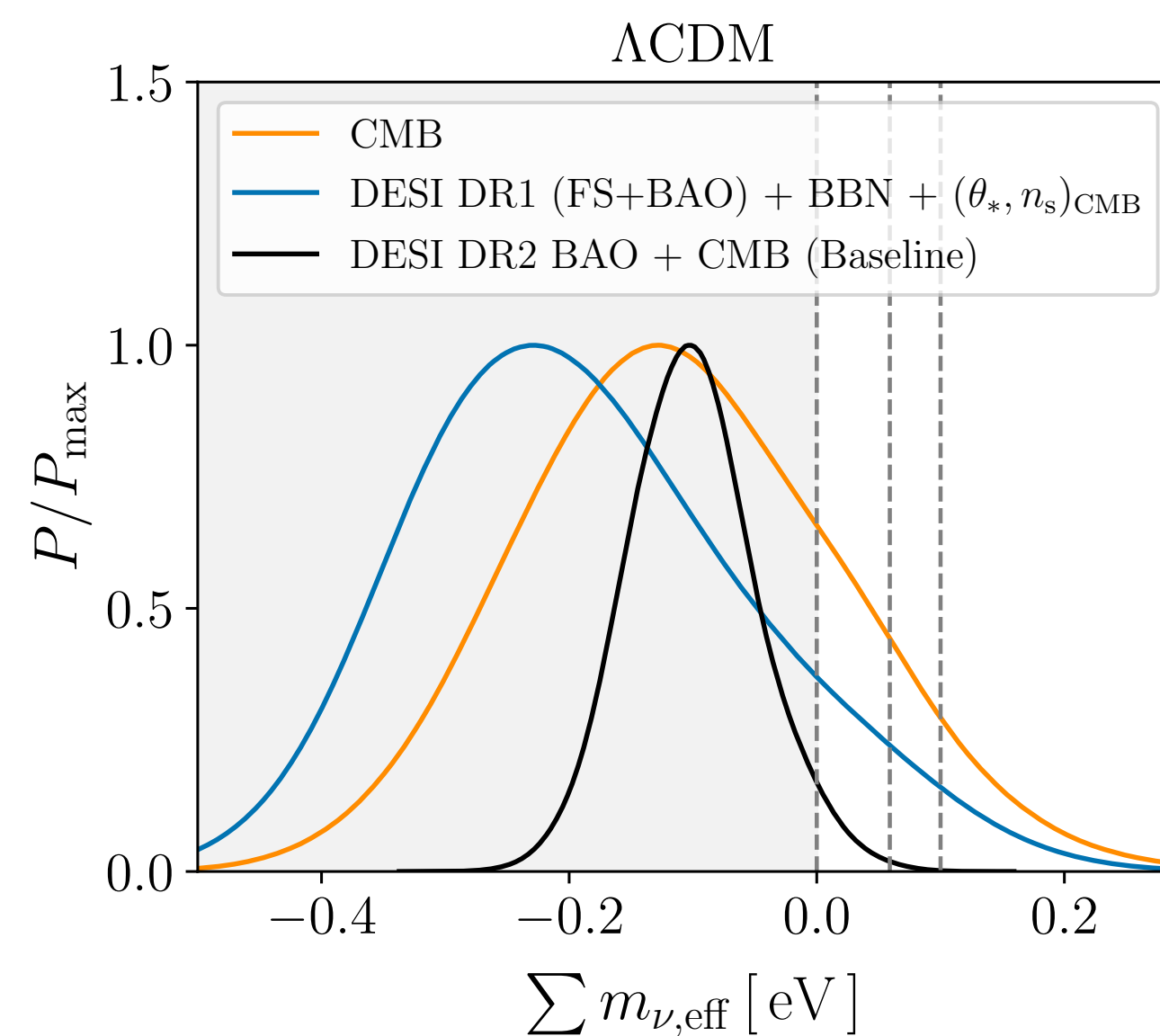
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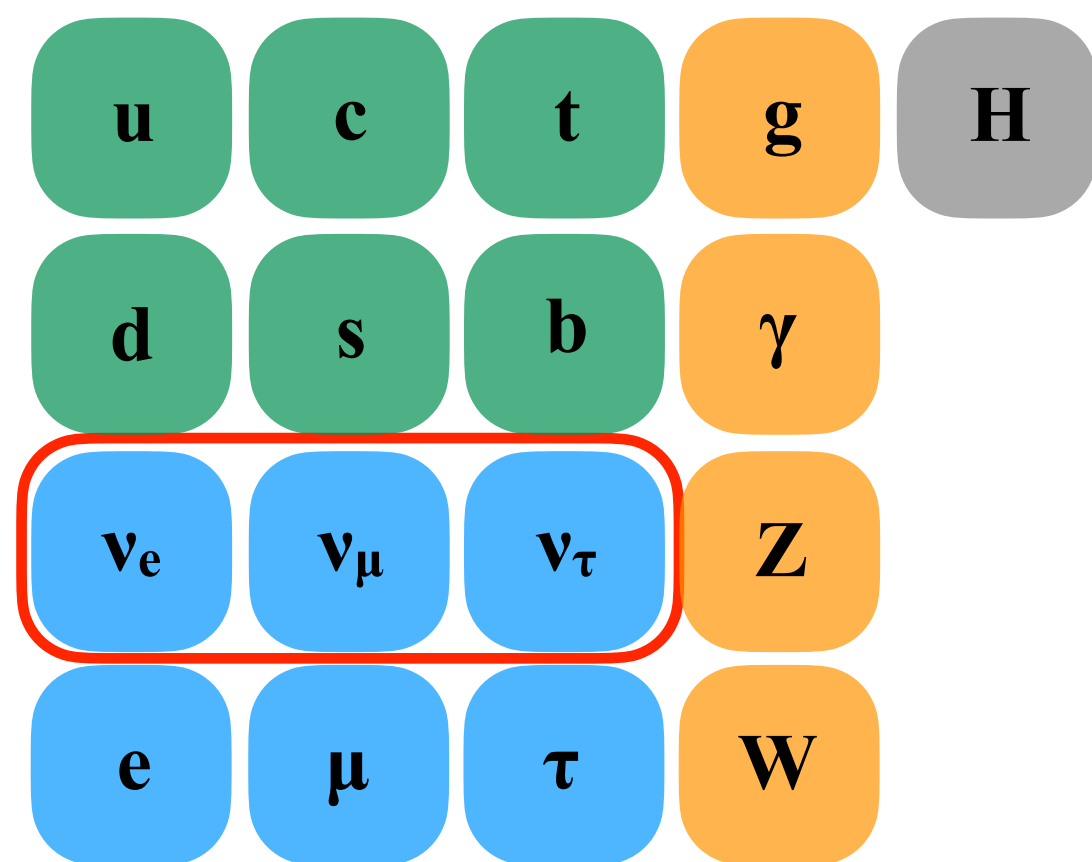
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3 σ tension!



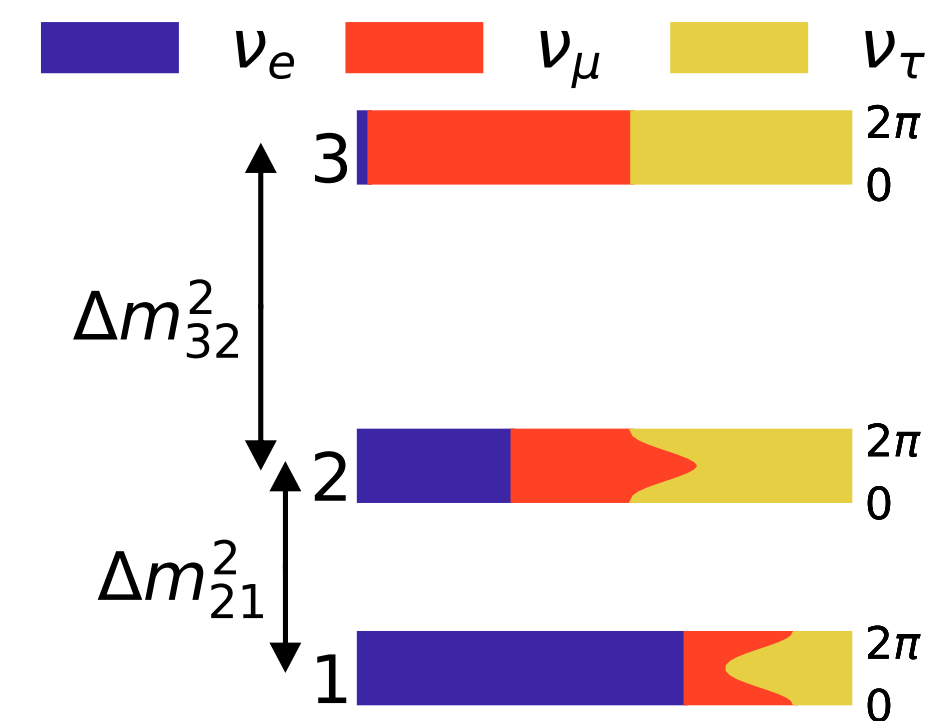
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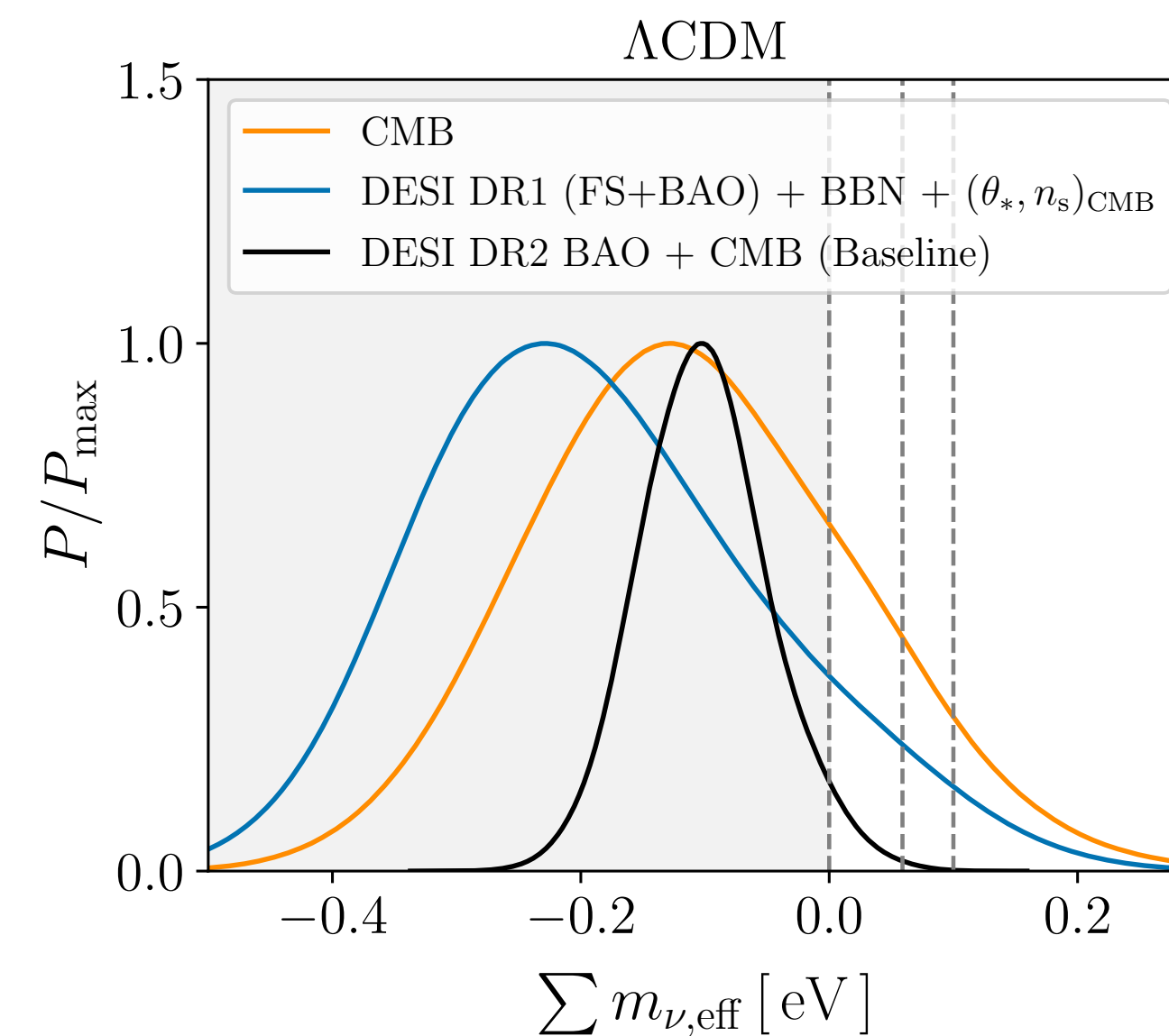


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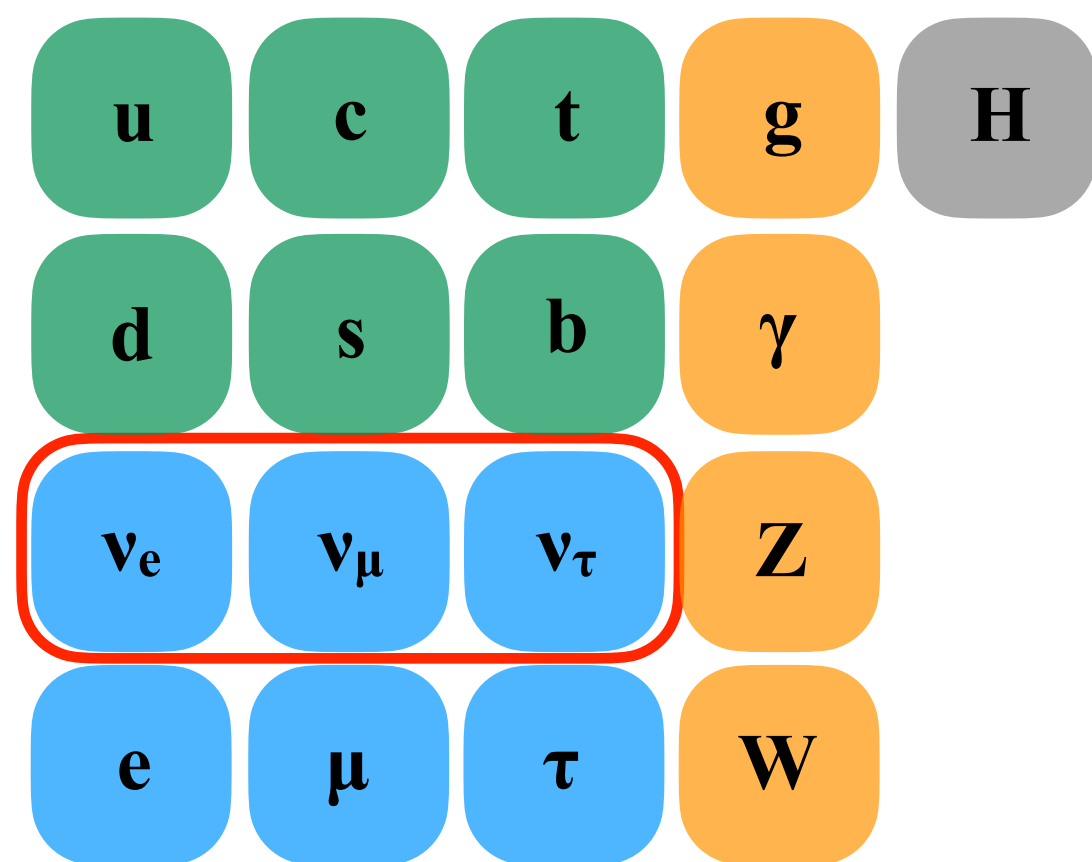
Neutrinos have mass, which is Beyond Standard Model. Not observable with oscillation experiments, elusive in cosmic surveys!

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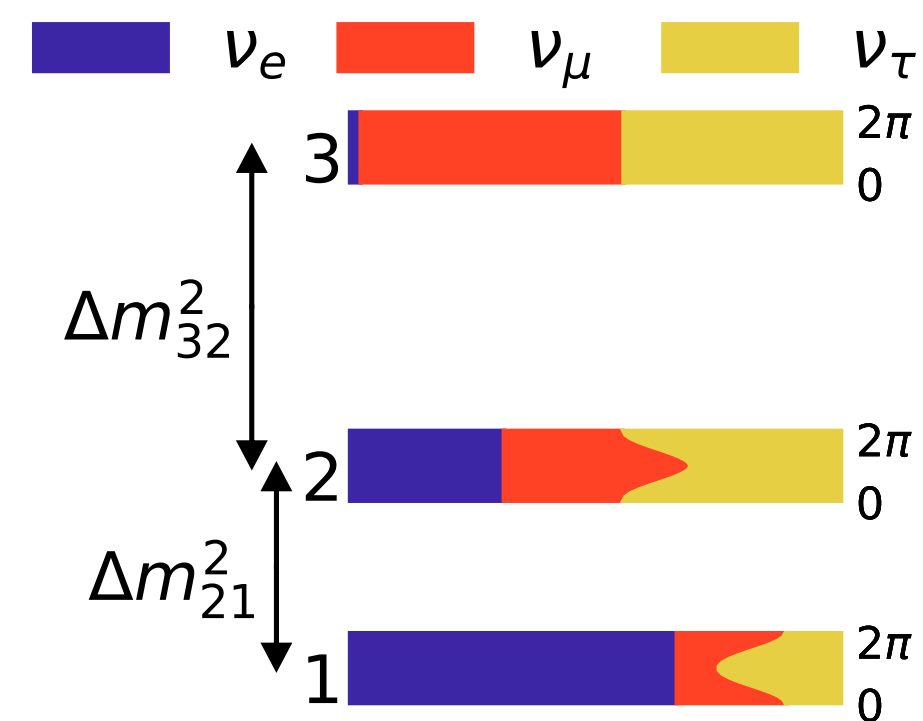
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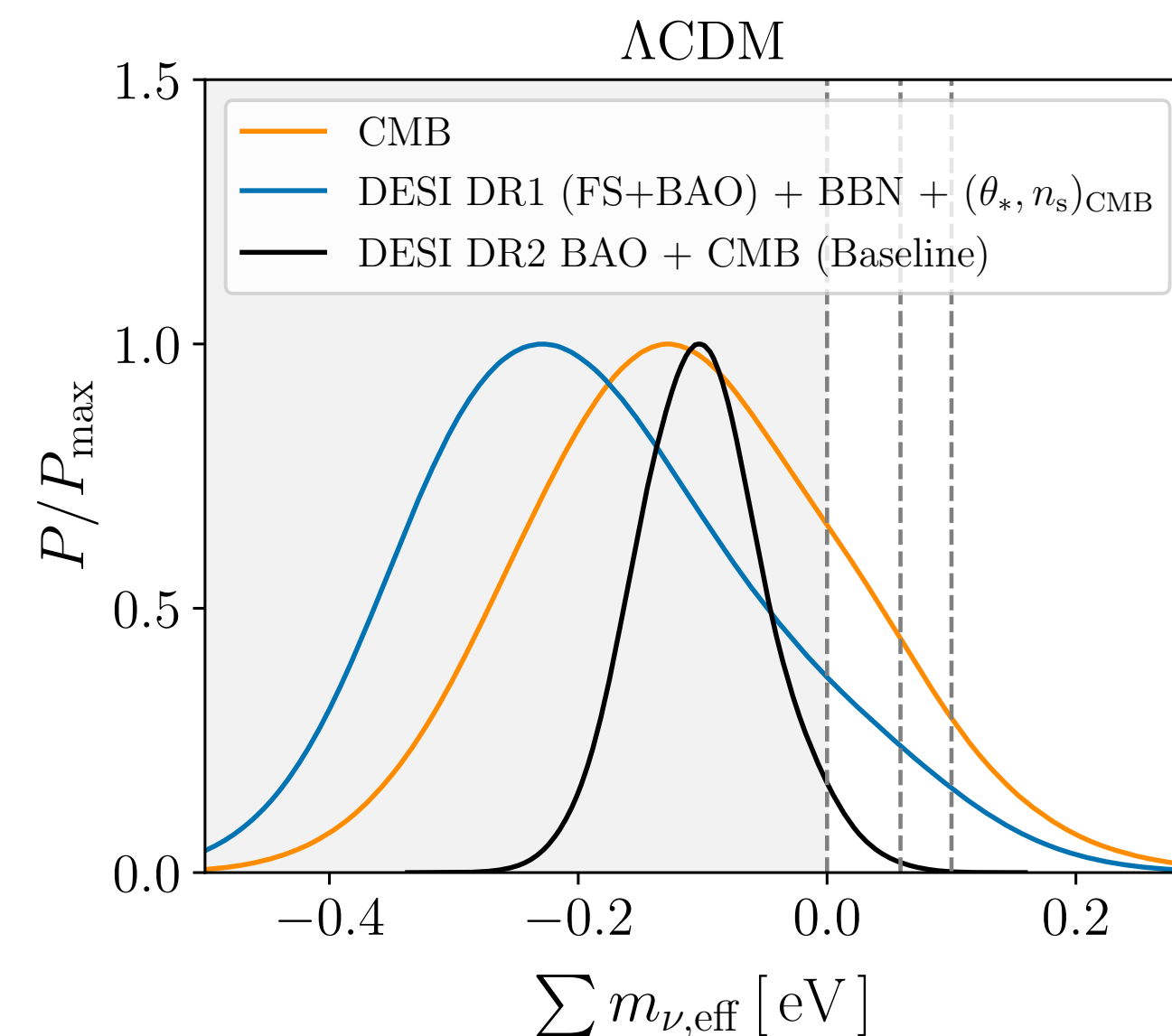
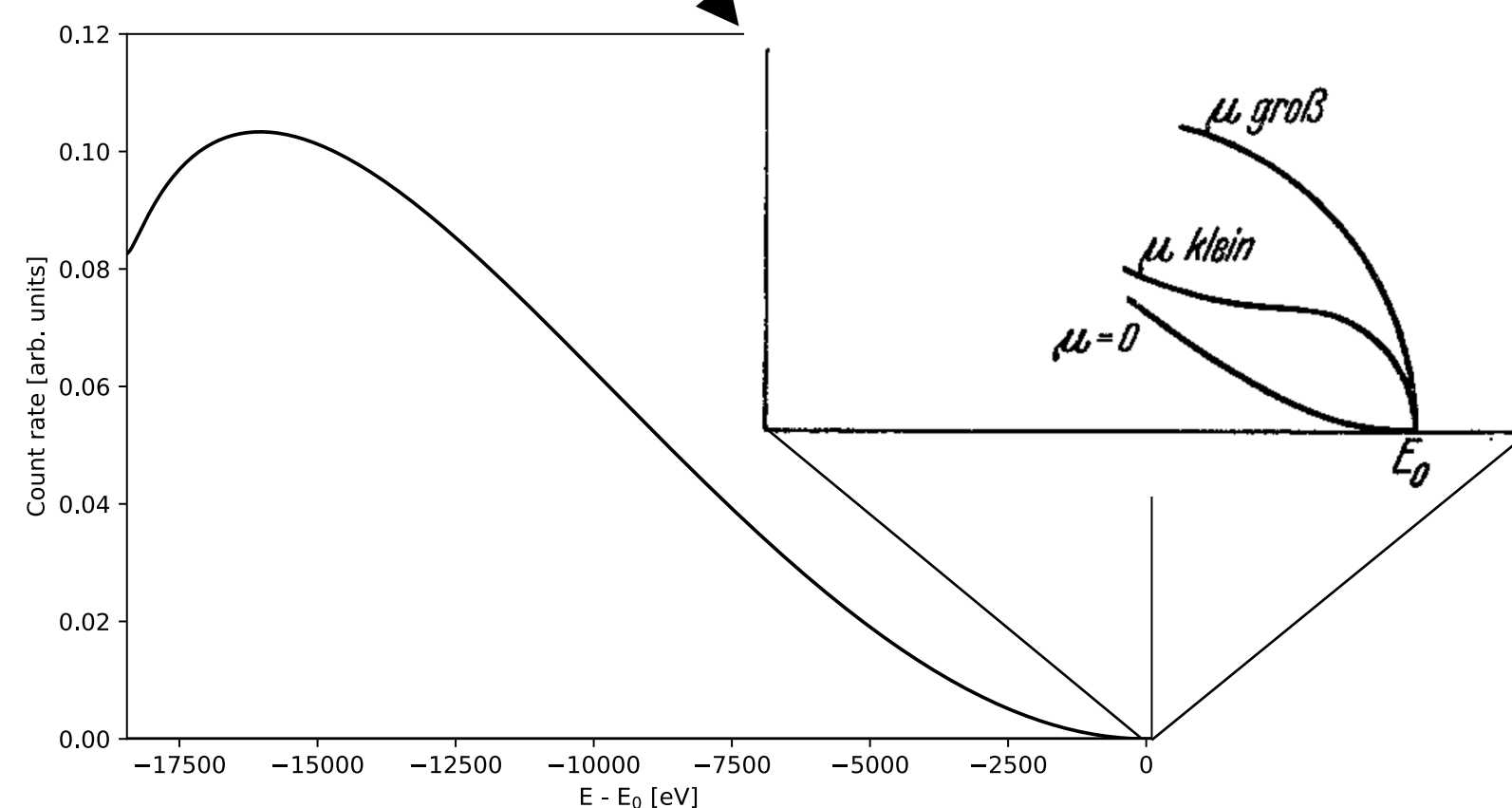
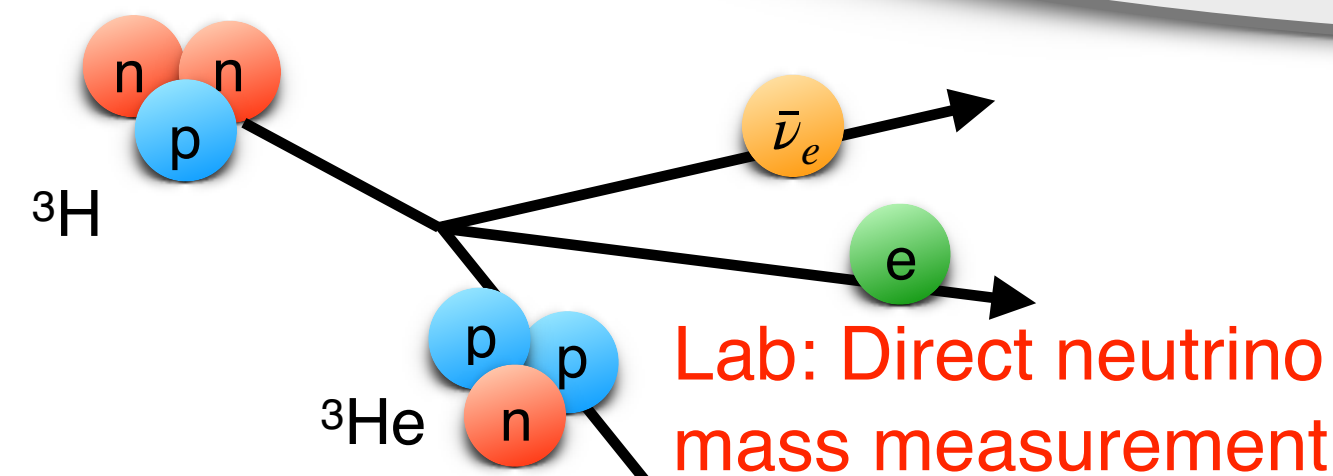
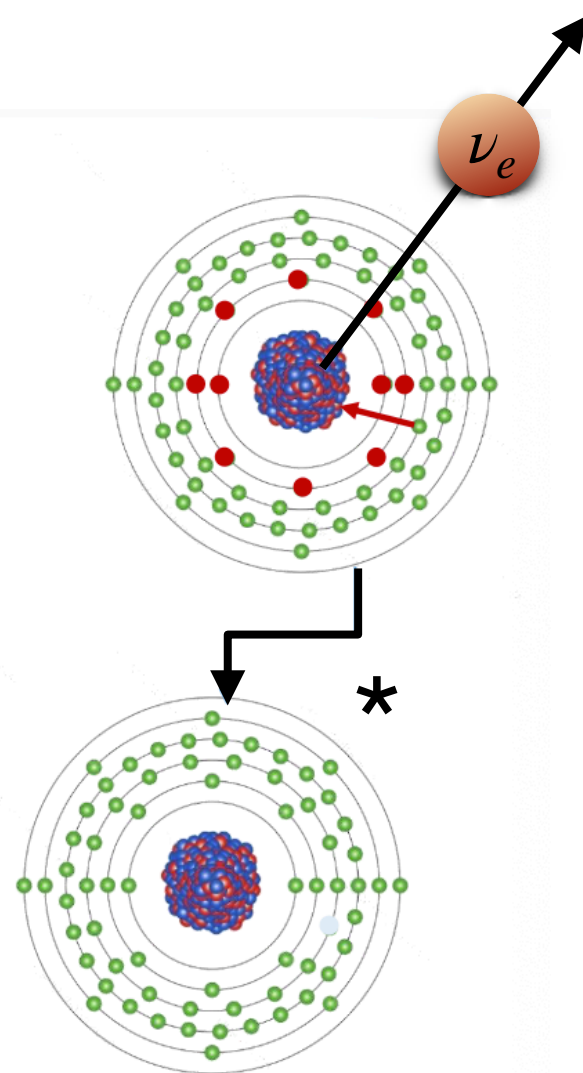


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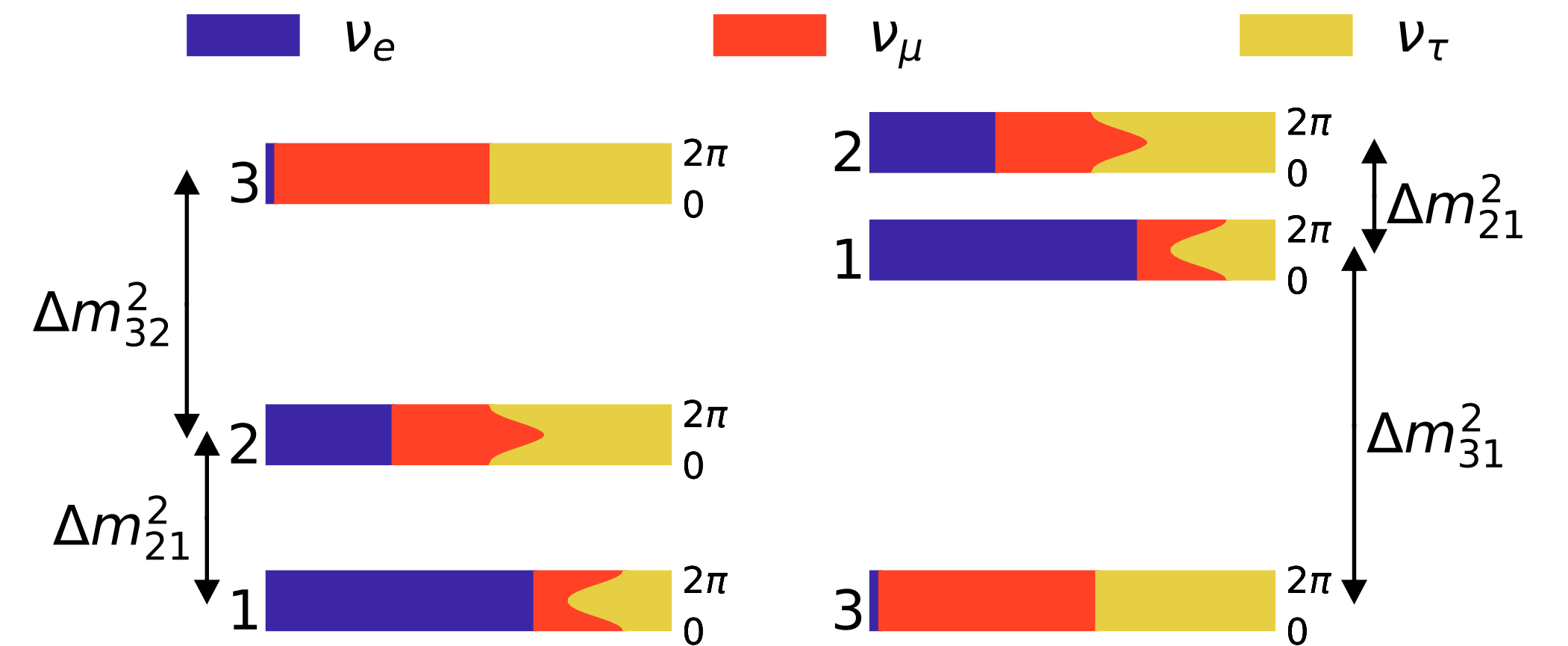
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Direct Neutrino Mass Measurement

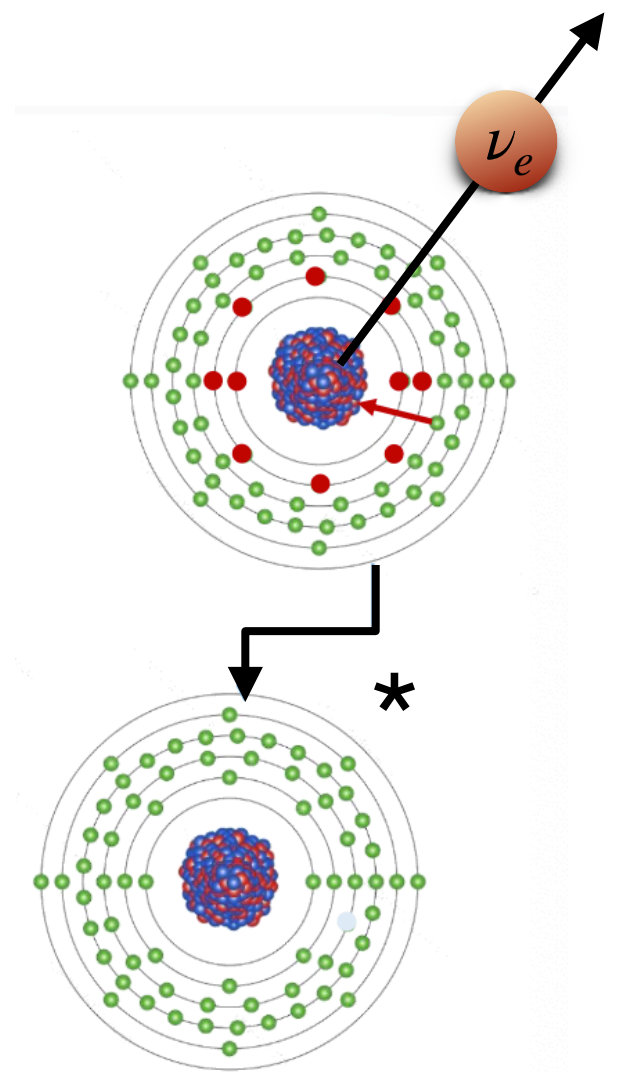
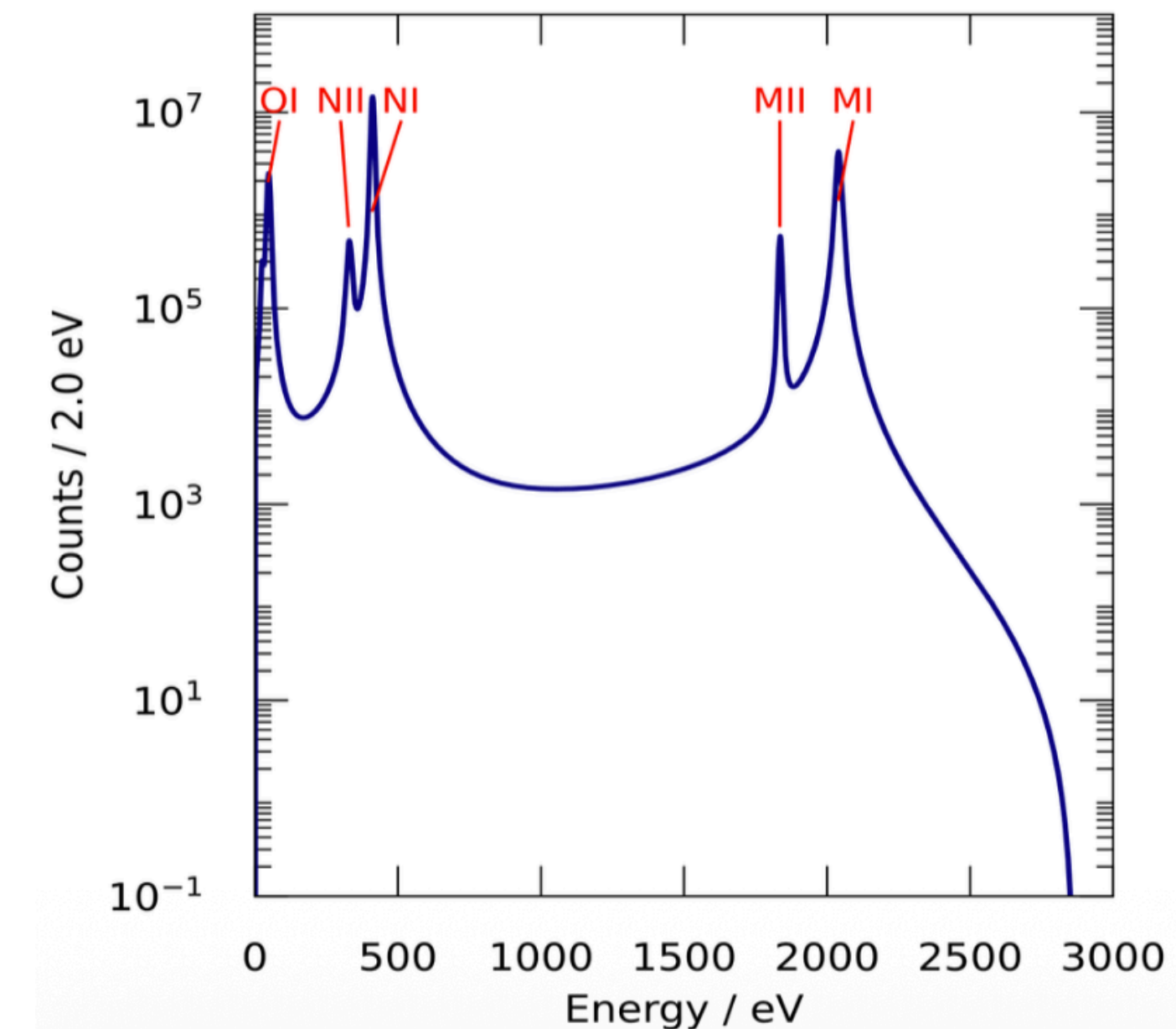


- Electron-weighted neutrino mass observable:

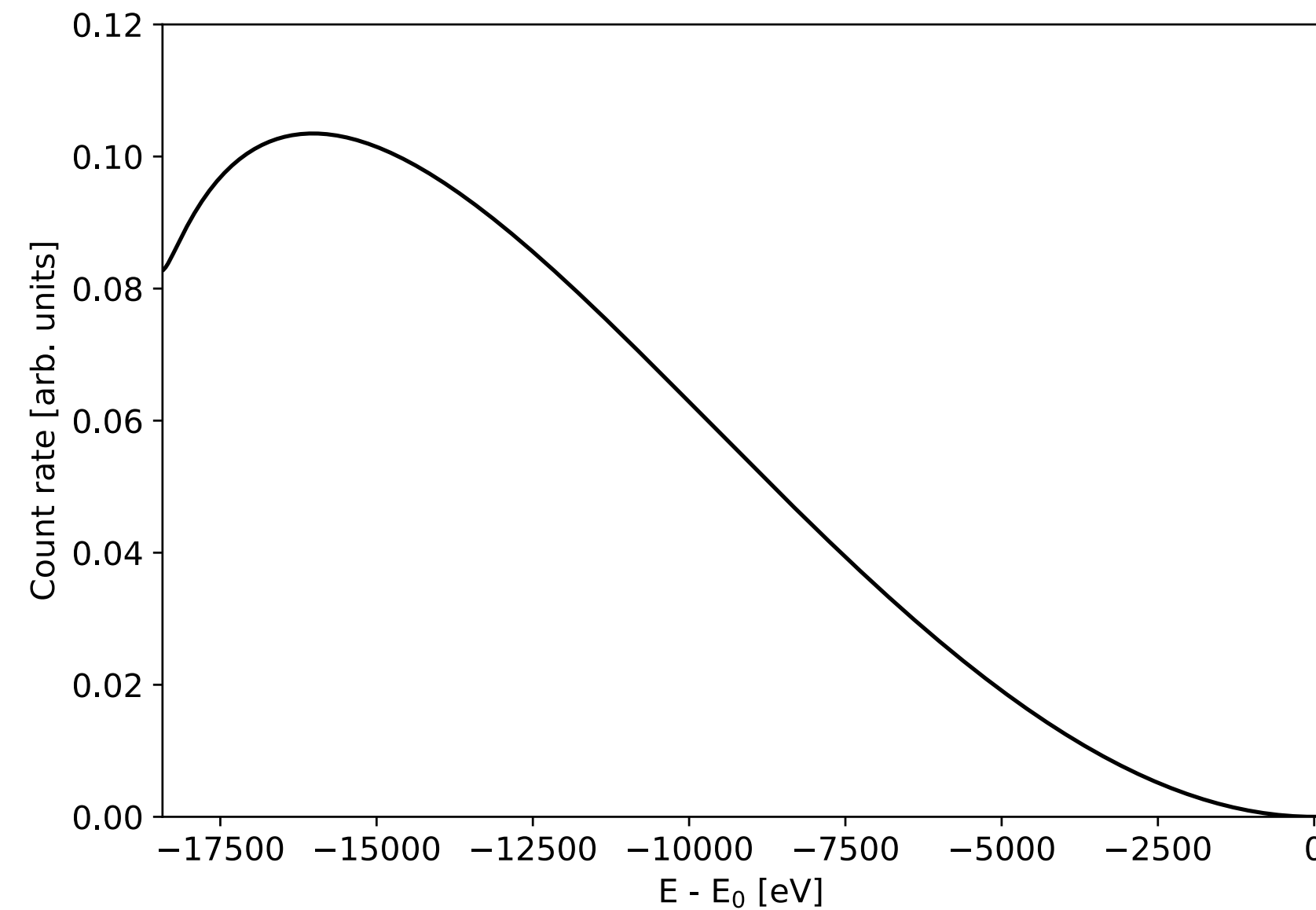
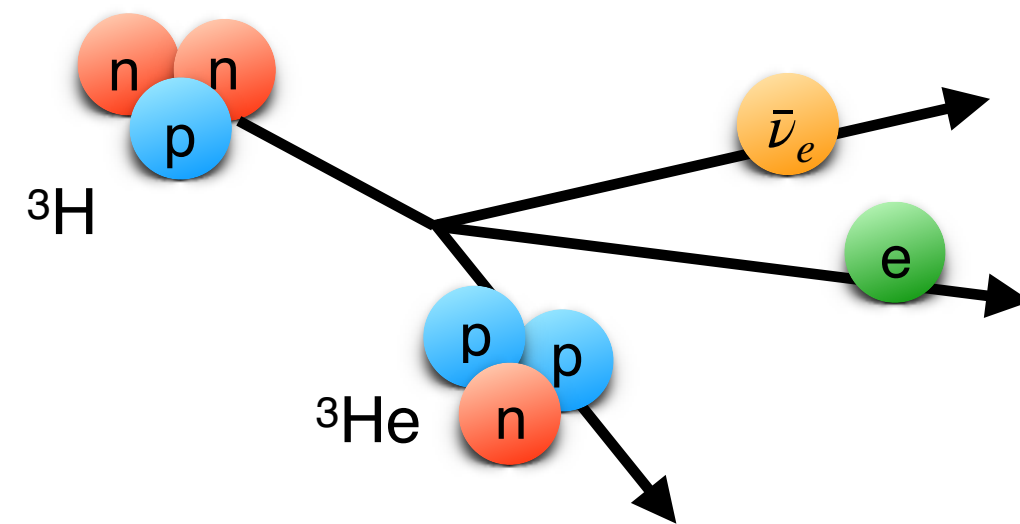
$$m_{\nu_e, \text{eff}}^2 = \sum |U_{ei}|^2 m_i^2$$

Direct Neutrino Mass Measurement

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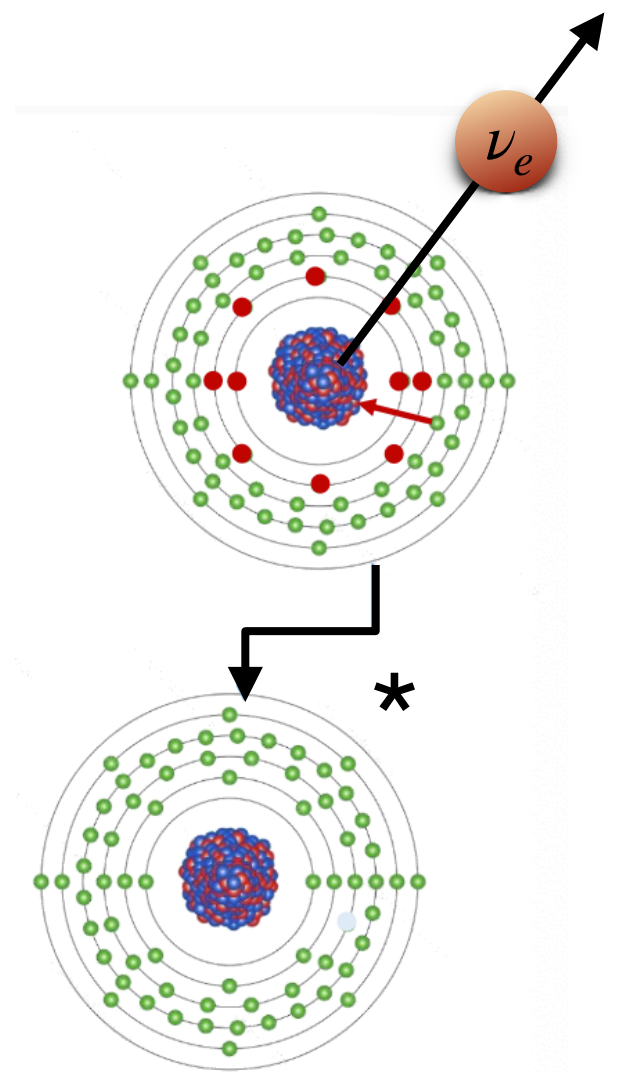
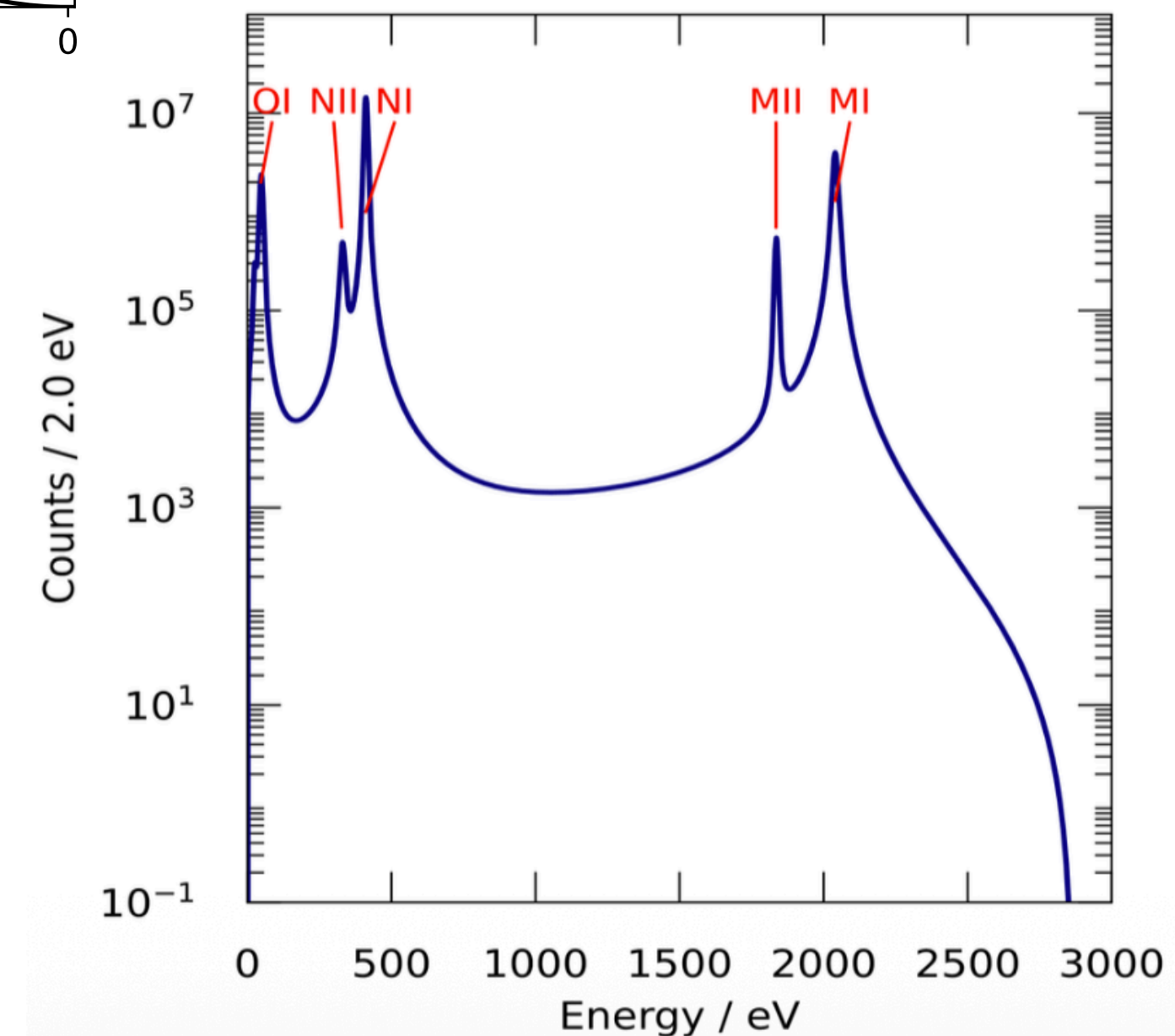


Direct Neutrino Mass Measurement

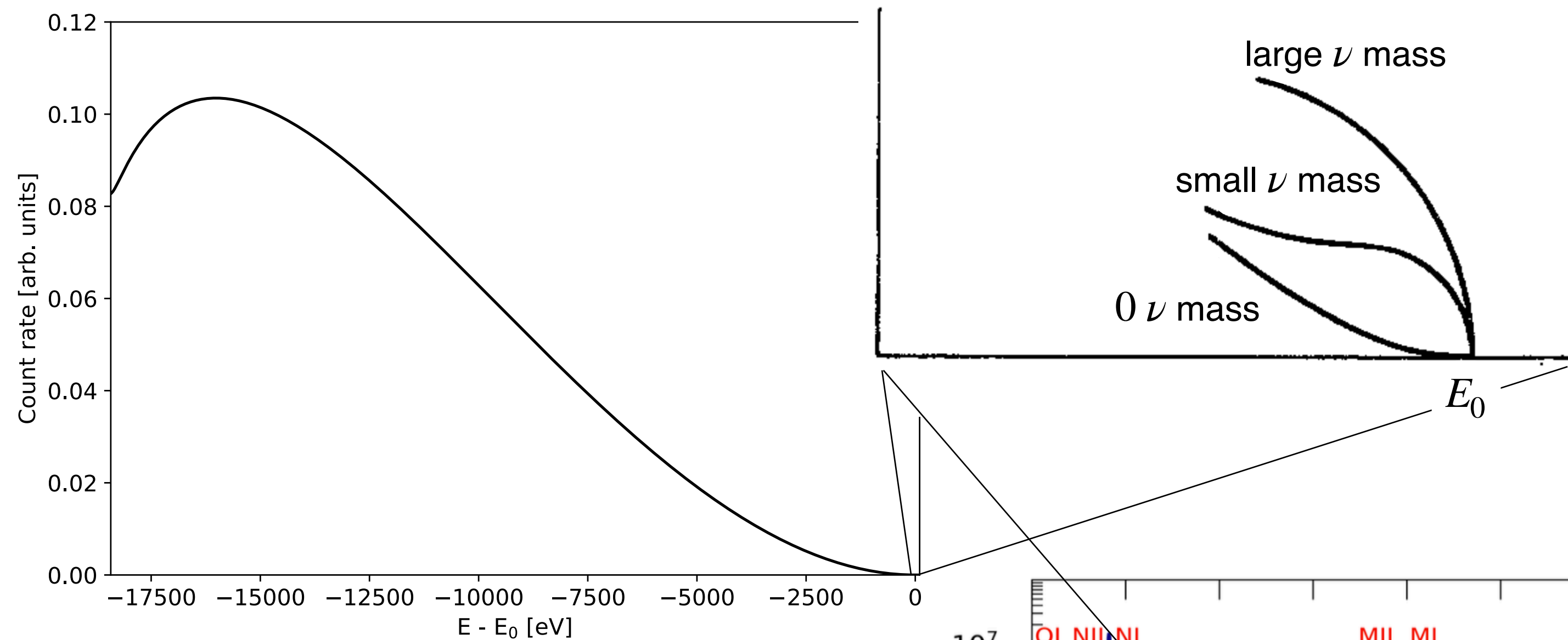
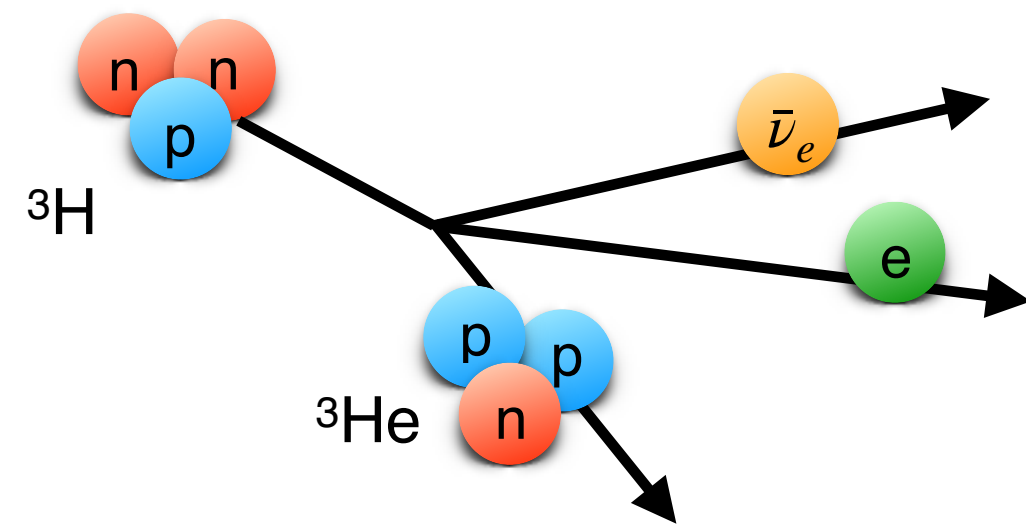


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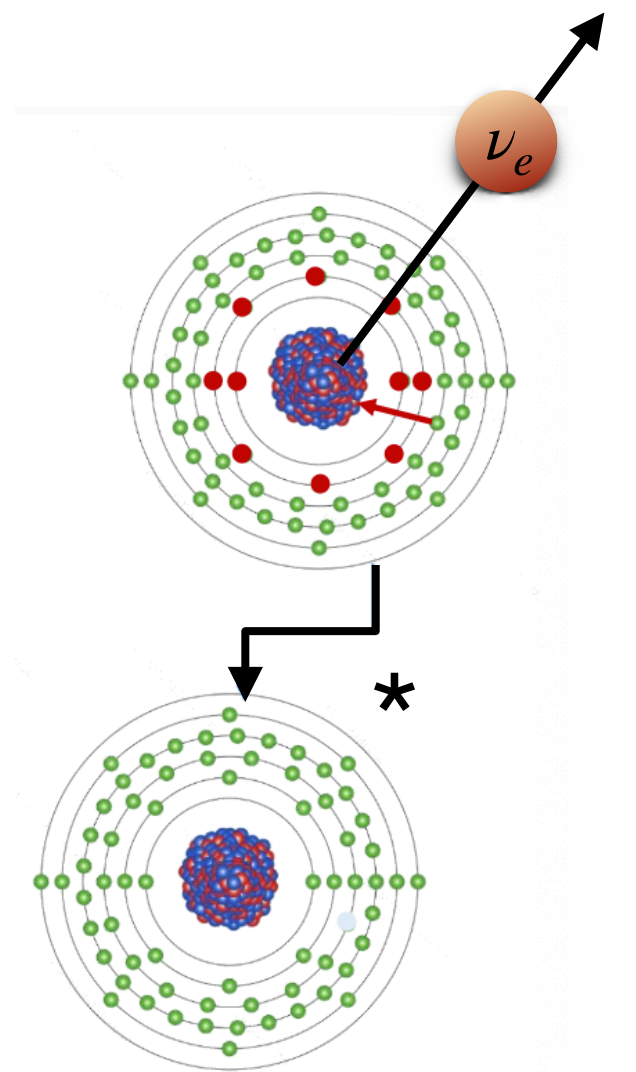
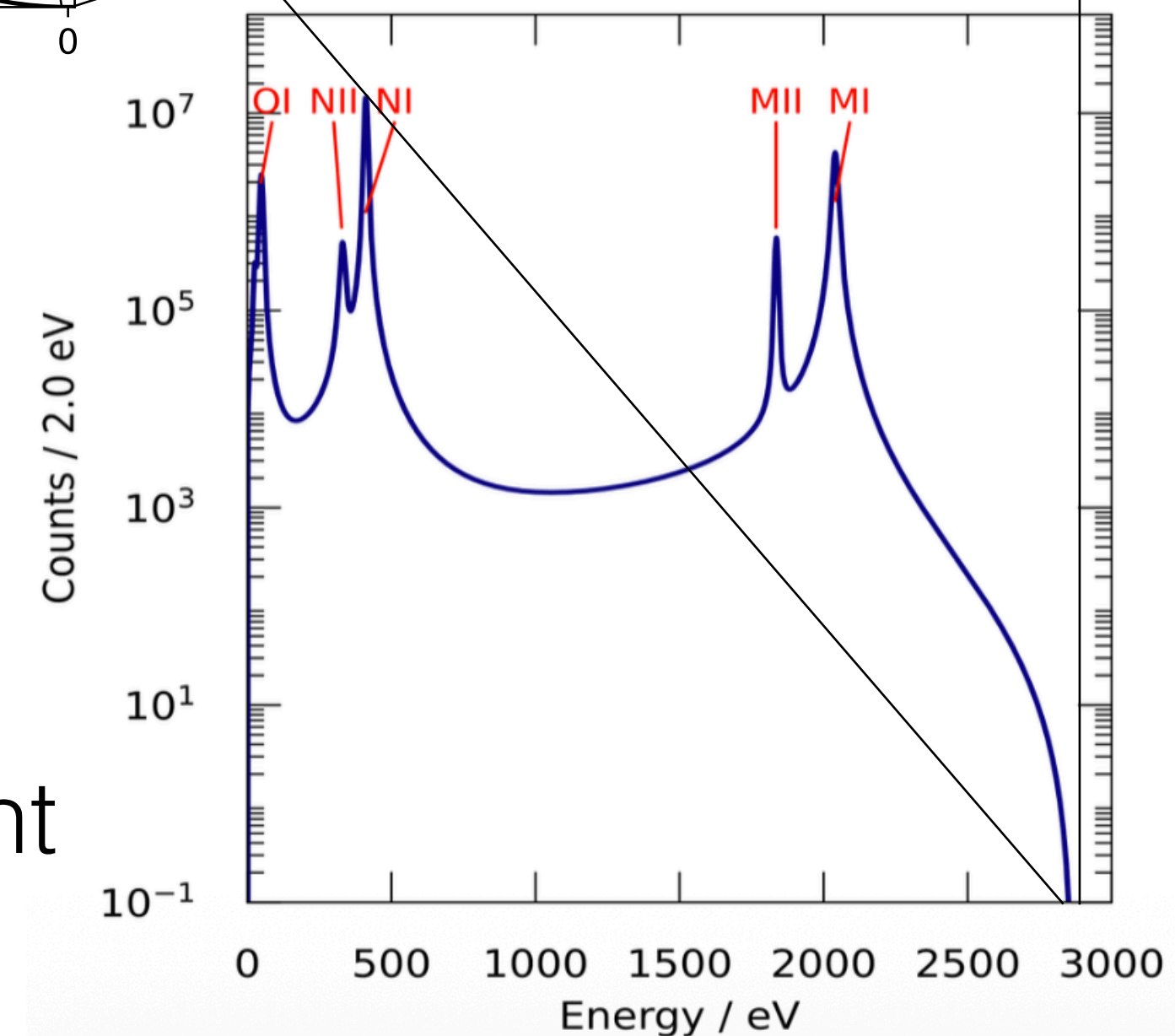


Direct Neutrino Mass Measurement



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- Electron capture on Holmium: ECHo, HoLMES
- Tritium beta decay: KATRIN, Project 8, QTNM
- Neutrino mass affects spectral shape at endpoint



Isotope(s) of Choice

- Low Q-value: higher activity close to endpoint
- Low half-life: smaller amount needed
- High Branching Ratio: smaller amount needed
- Source availability, handling

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Isotope	Q_A [eV]	$\tau_{1/2}$ [y]	Decay	BR	Limit [eV]	Active mass [g]*
^3H	18591.3(10)	12.3	β^-	1	0.45 [1]	10^{-7}
^{163}Ho	2863.2(6)	4570	EC	1	15 [2]	10^{-5}
^{187}Re	2470.9(13)	4.3×10^{10}		1	15 [3]	57
^{115}In	155(24)	4.4×10^{14}	β^-	$O(10^{-6})$	-	7.5×10^7
^{135}Cs	440(310)	$O(10^{10})$	β^-	$O(10^{-6})$	-	$O(10^{-1}..10^2)$

* to observe 1 count / eV / day
[1] KATRIN, [Science 388, 6743](#) (2025)
[2] ECHo, [PRL 136, 121801](#) (2026)
[3] [Phys.Rept. 914 1-54](#) (2021)



State-of-the-Art: KATRIN @ TLK

- Current best limit: $m_{\nu_e, \text{eff}} < 0.45 \text{ eV}$
- Design sensitivity: 0.2 eV

See talks by C. Weinheimer,
S. Schneidewind, K. Erhardt

KATRIN, [Science 388, 6743 \(2025\)](#)



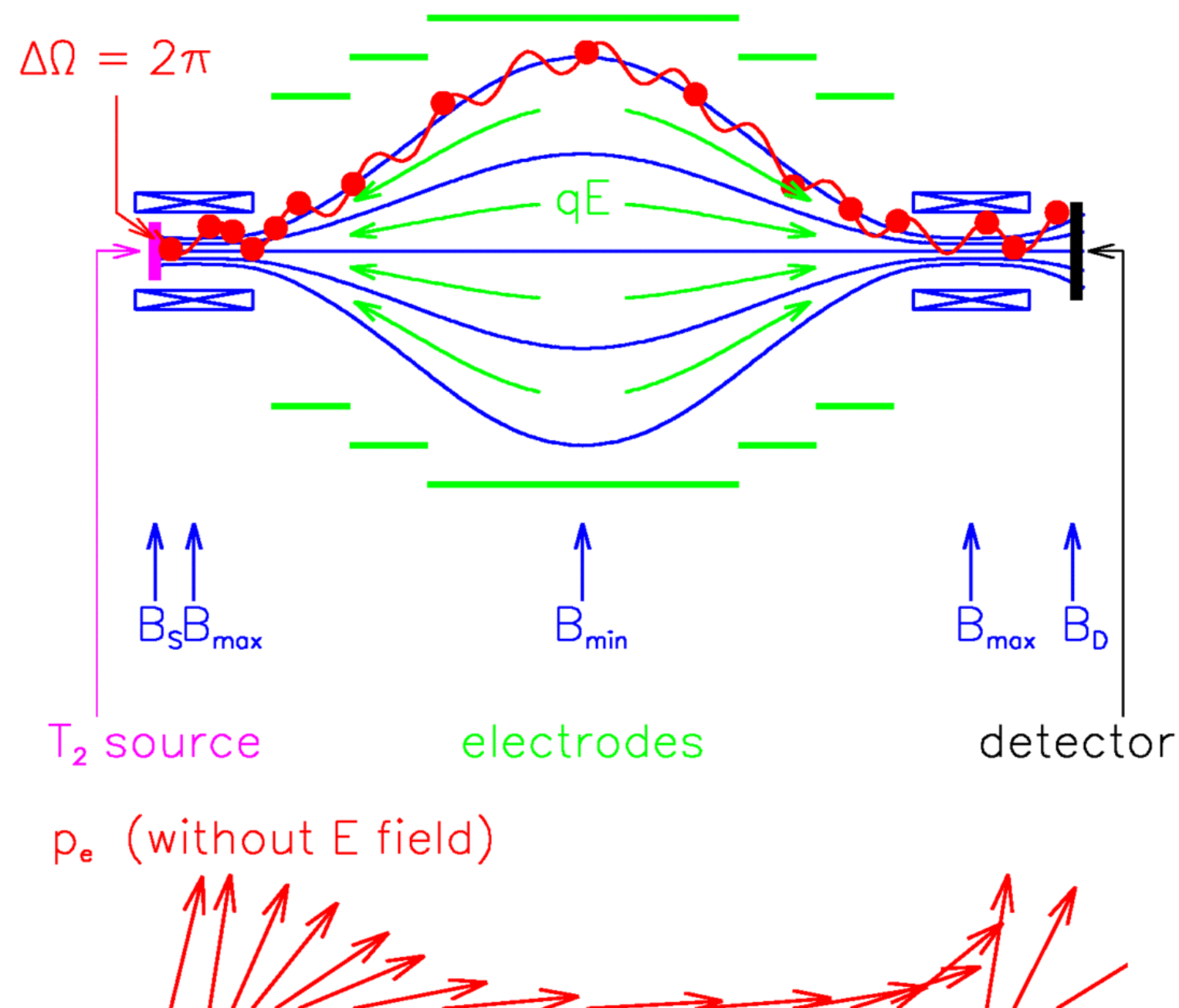
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- What if the mass is smaller?
- How to increase sensitivity?
- Strong T_2 source: strength limited by electrons scattering → energy loss
- MAC-E filter = high-pass filter:
→ integrated spectrum
filter resolution ~ spectrometer diameter
- Sensitivity scales as $\sigma(m_{\nu_e, \text{eff}}) \propto N^{-1/4}$

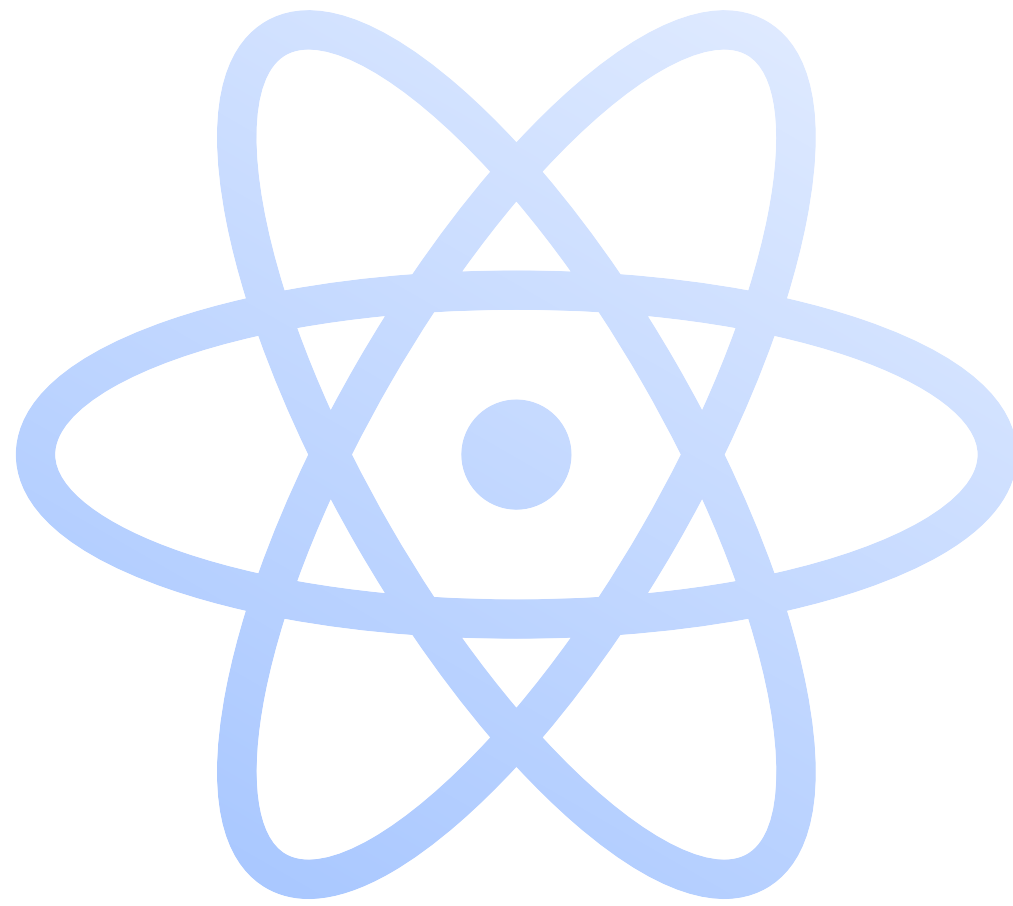


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KATRIN, [Science 388, 6743 \(2025\)](#)

KATRIN, <https://www.katrin.kit.edu/>

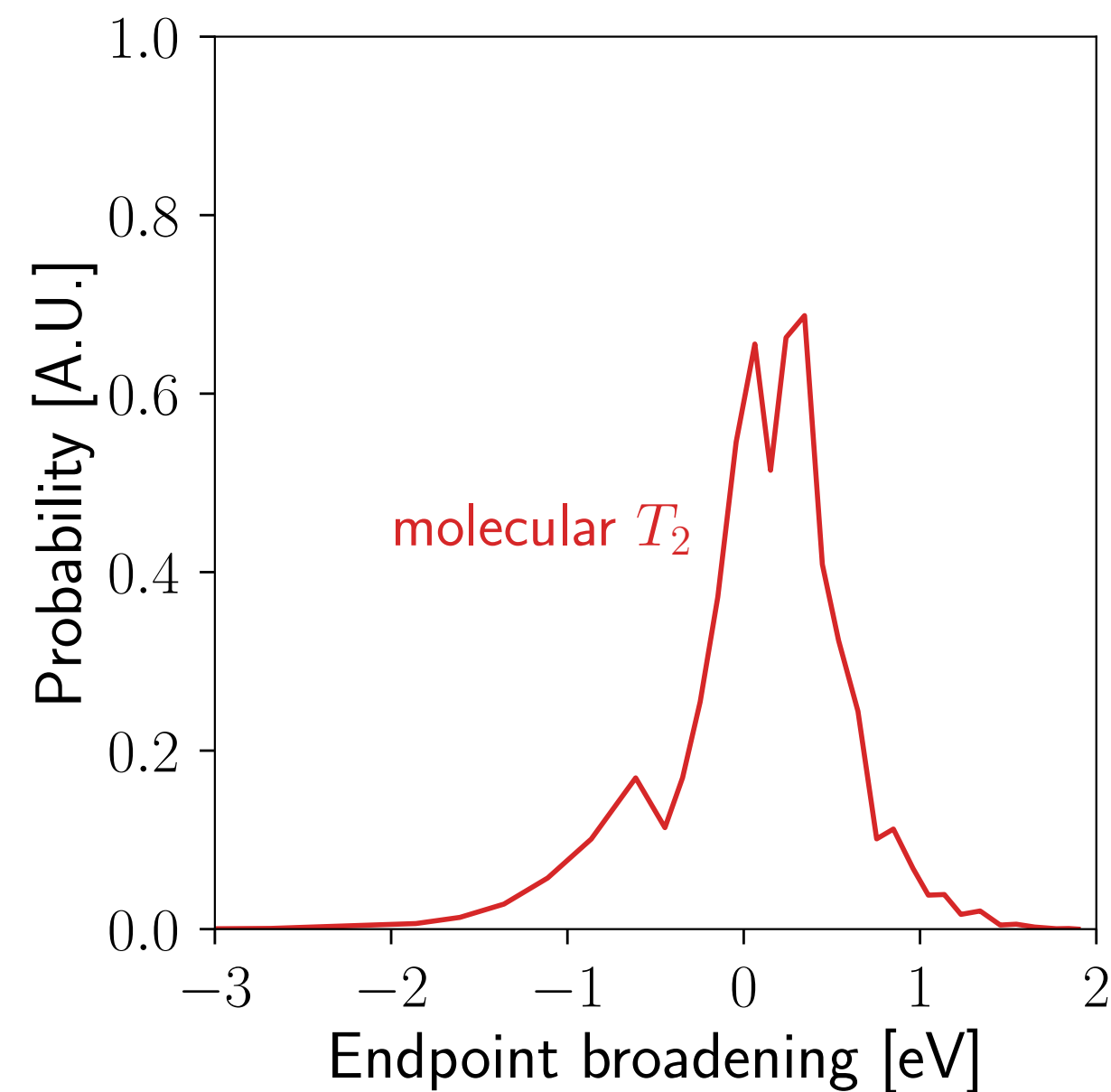
The Tritium Future



Next Tritium-Based Experiment

Necessary key technology developments:

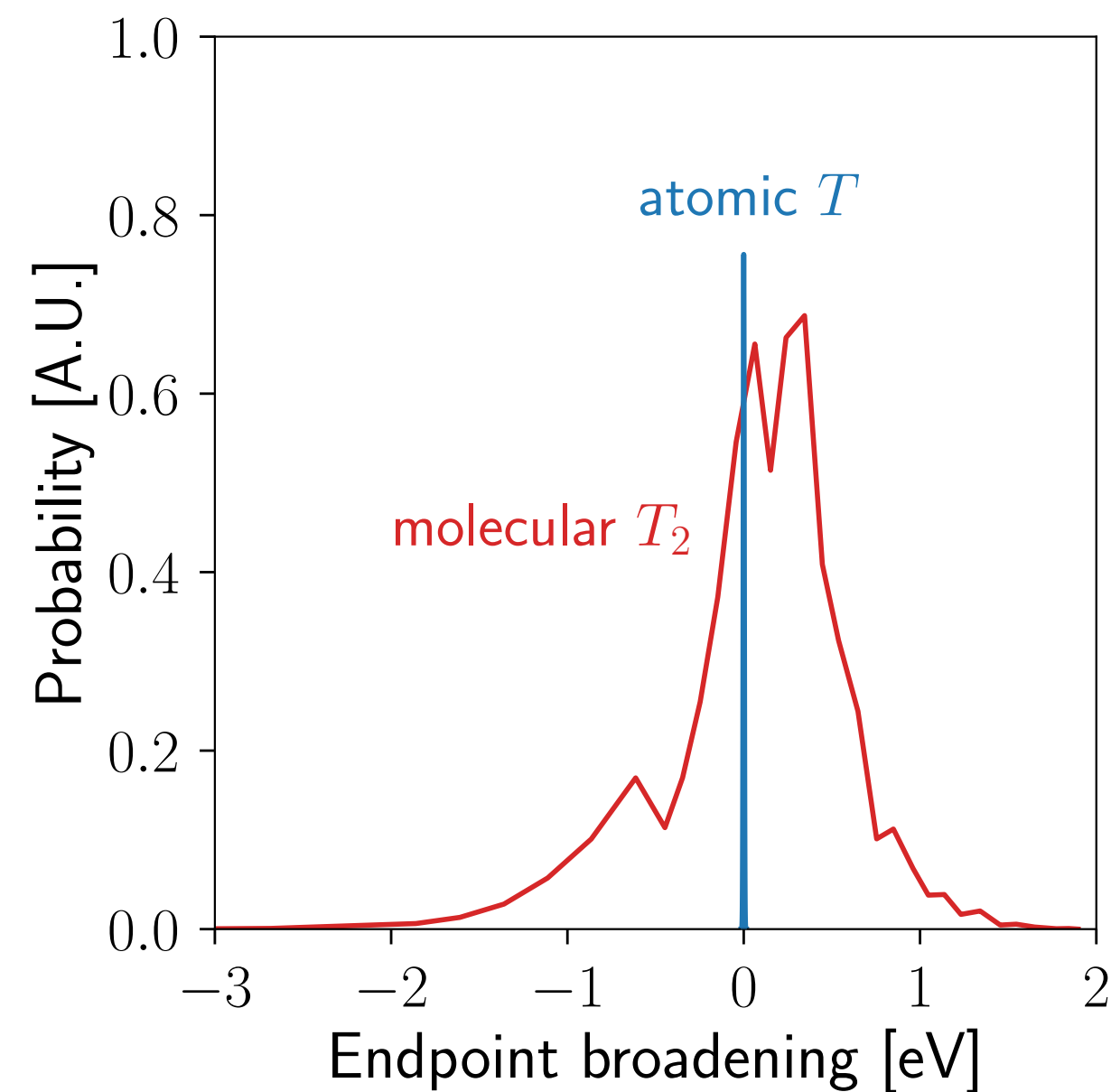
- Strong atomic tritium source



Next Tritium-Based Experiment

Necessary key technology developments:

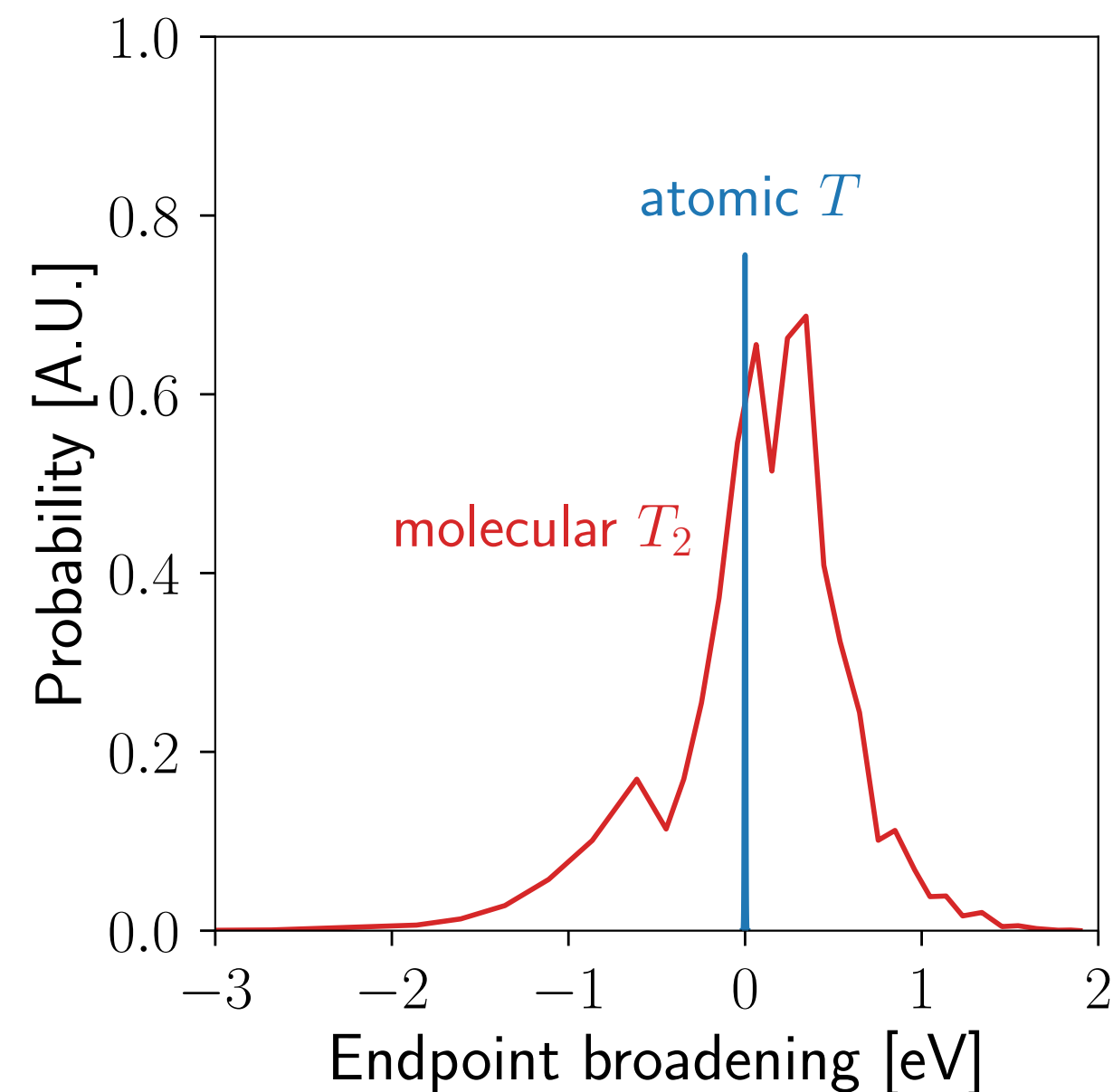
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Next Tritium-Based Experiment

Necessary key technology developments:

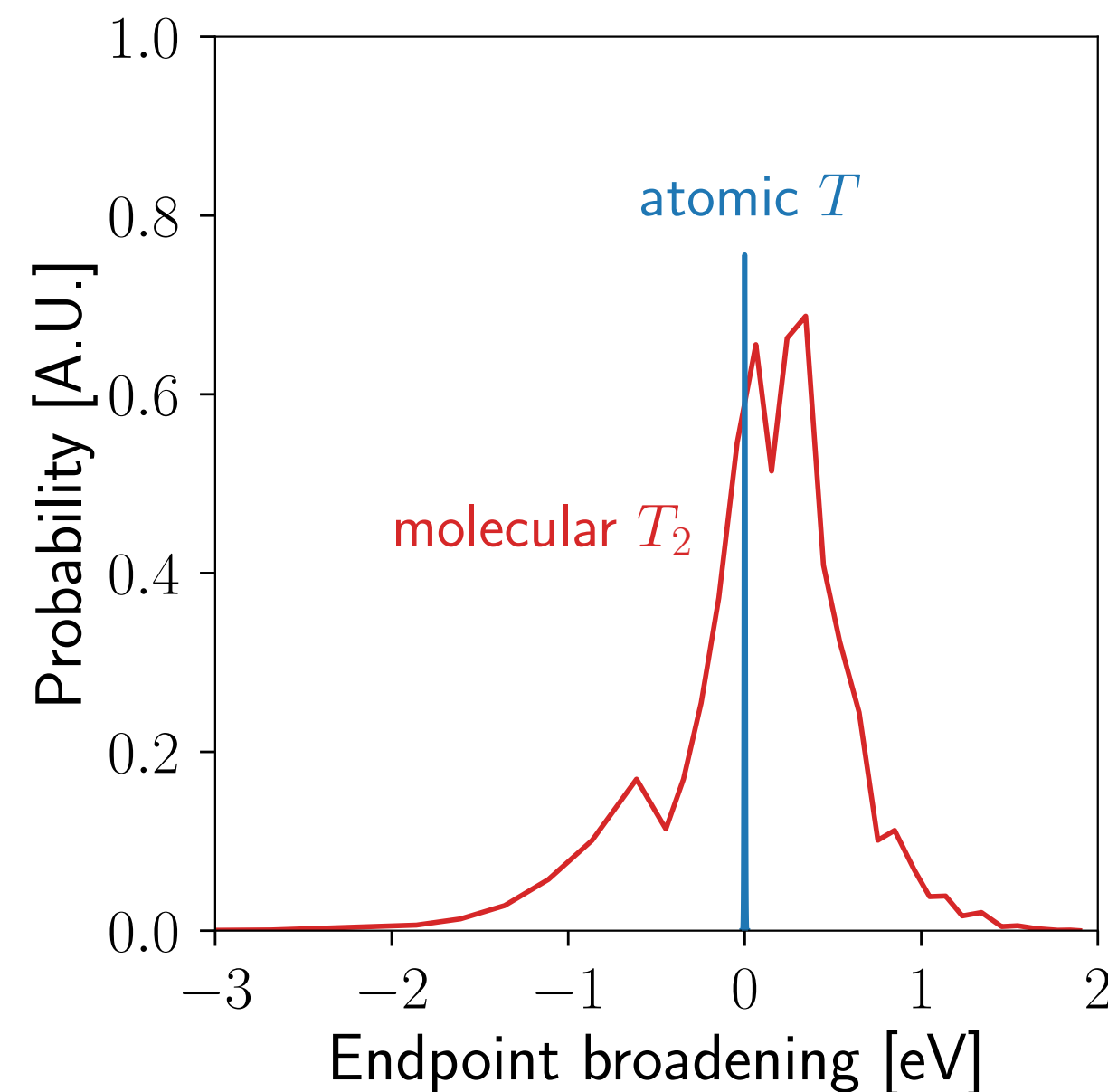
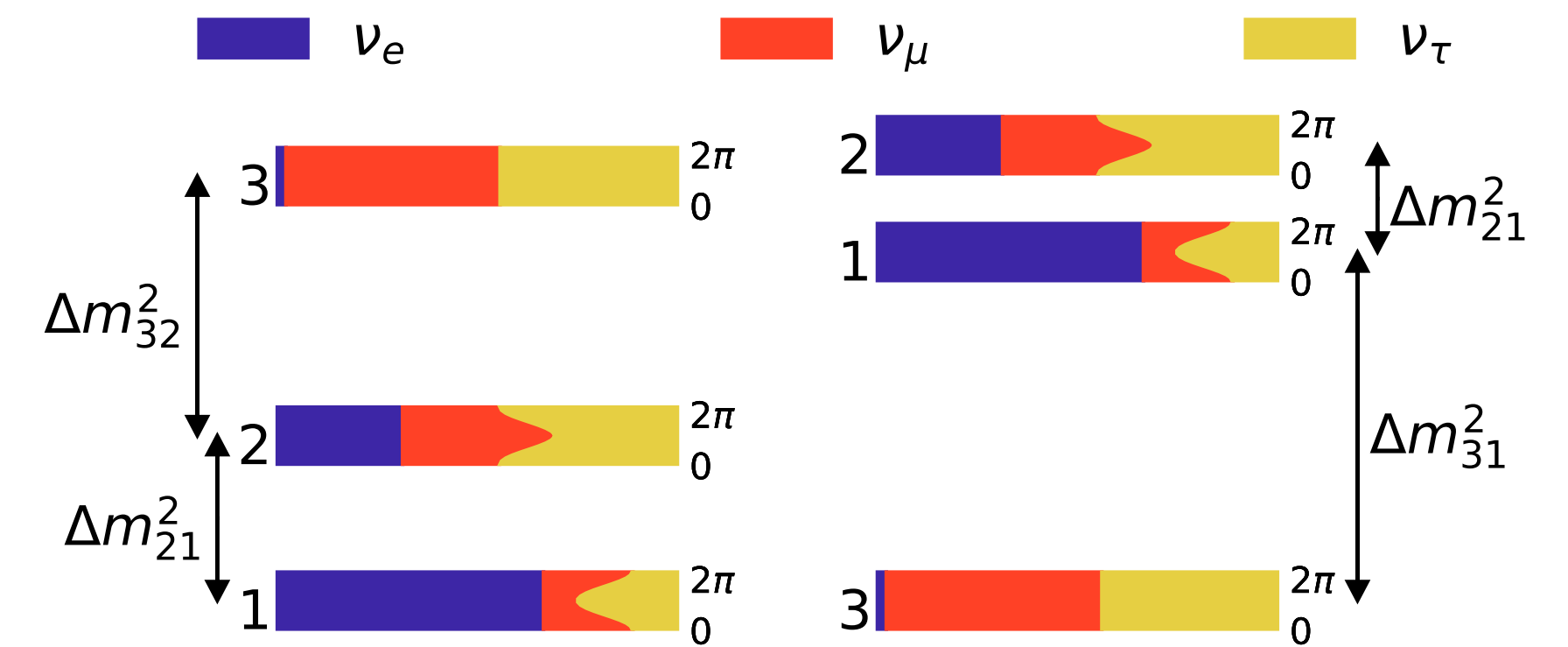
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- Ultra-precise, differential electron spectroscopy
- Compatibility of spectroscopy with atomic tritium



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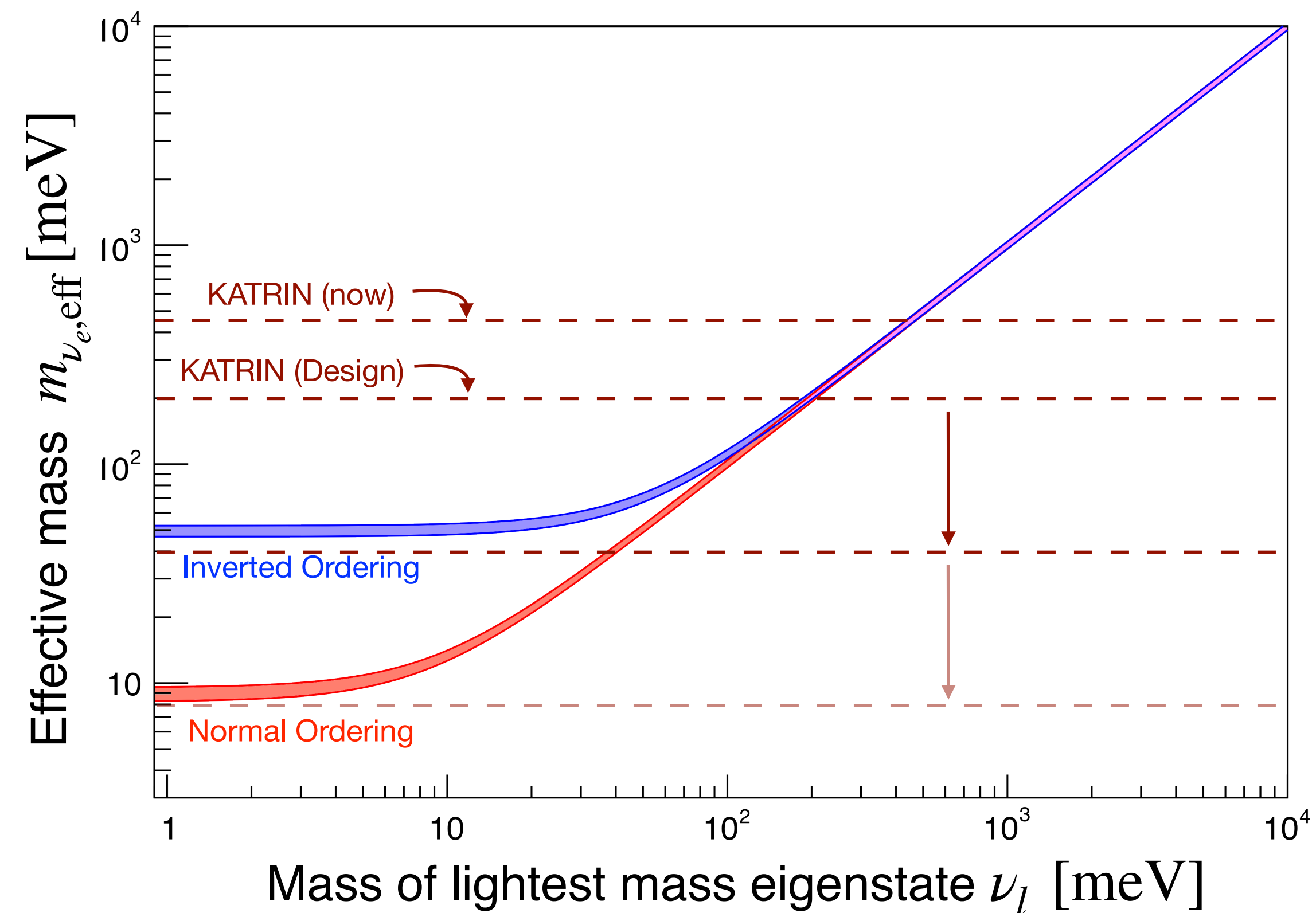
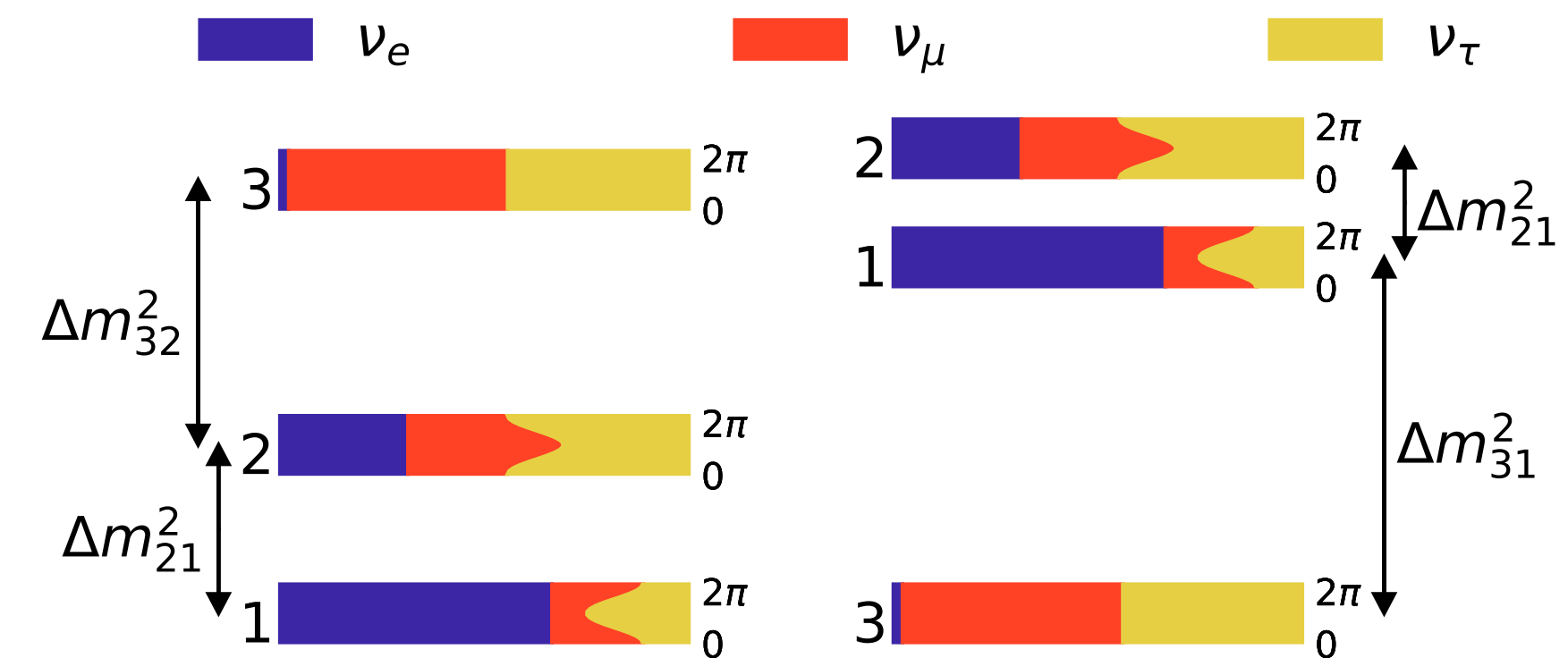
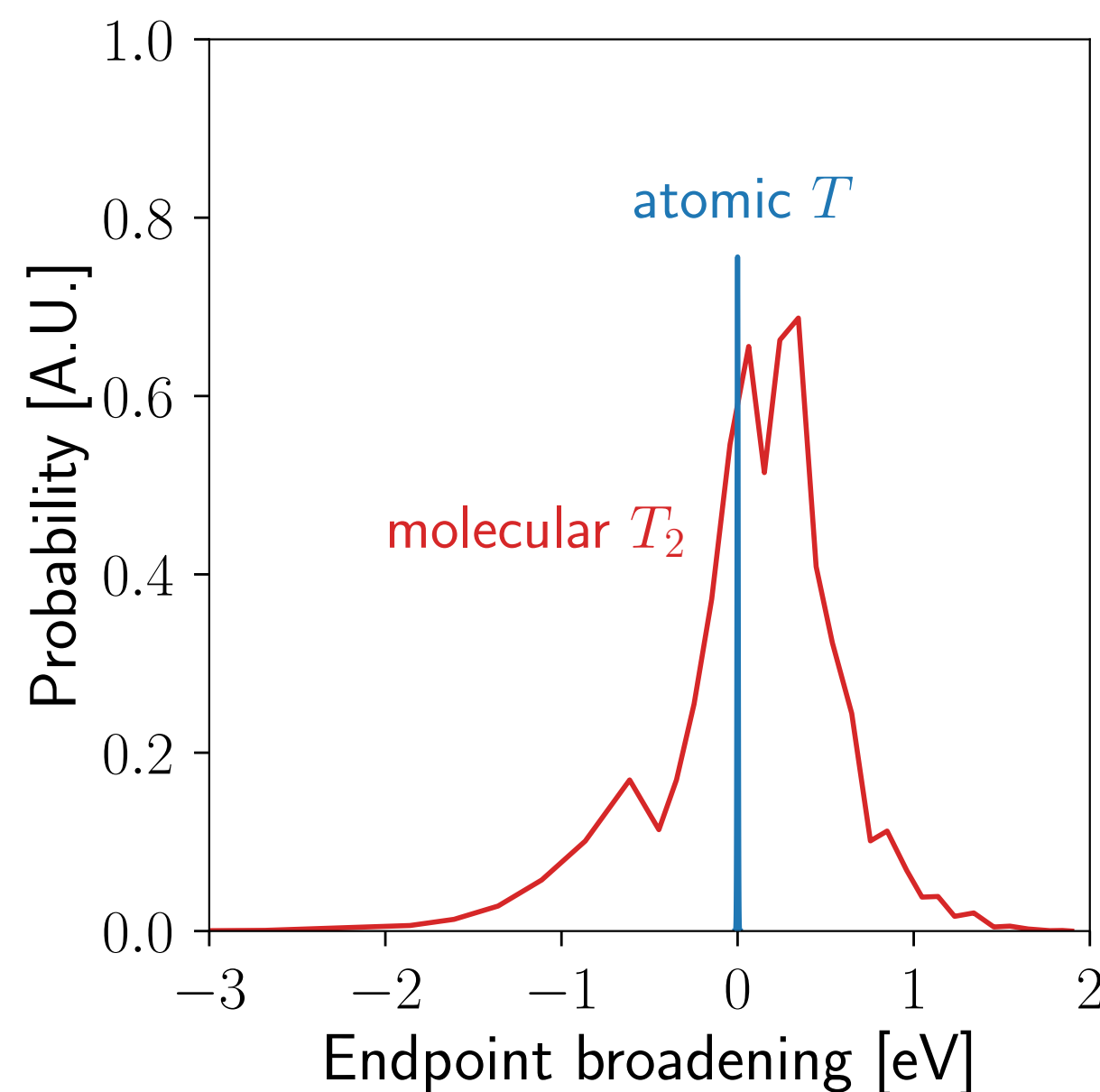
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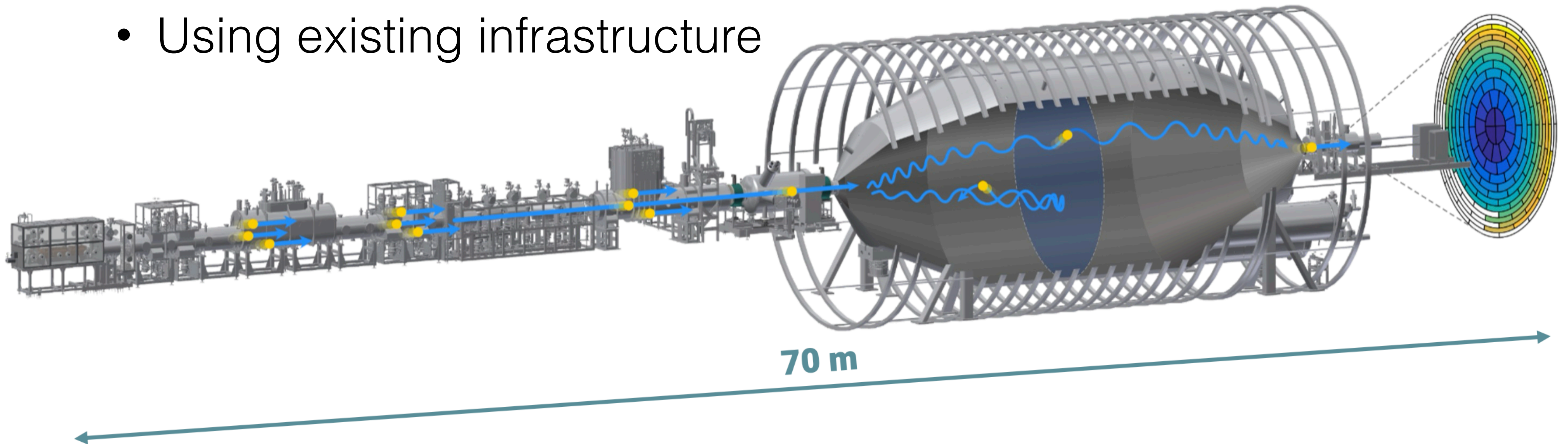
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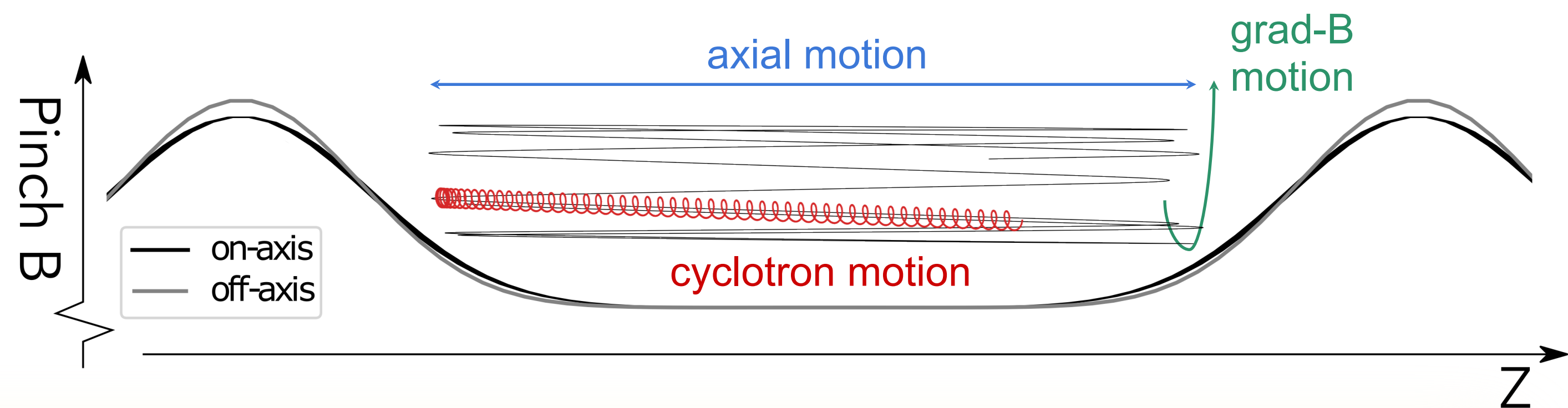
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- Typical next goal: 40 meV sensitivity to $m_{\nu_e, \text{eff}}$
- Final goal might be 10 meV



- KATRIN finished data taking in 2025, data analysis ongoing
- Now running: TRISTAN - keV sterile neutrino search
- KATRIN++ program:
 - R&D on atomic tritium
 - R&D on differential methods
 - Using existing infrastructure

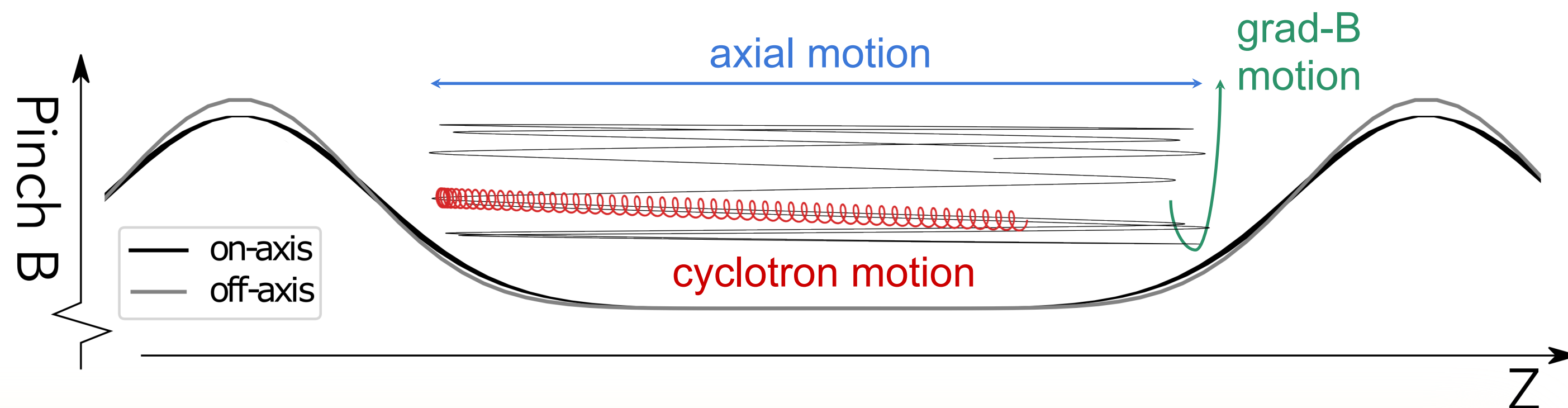
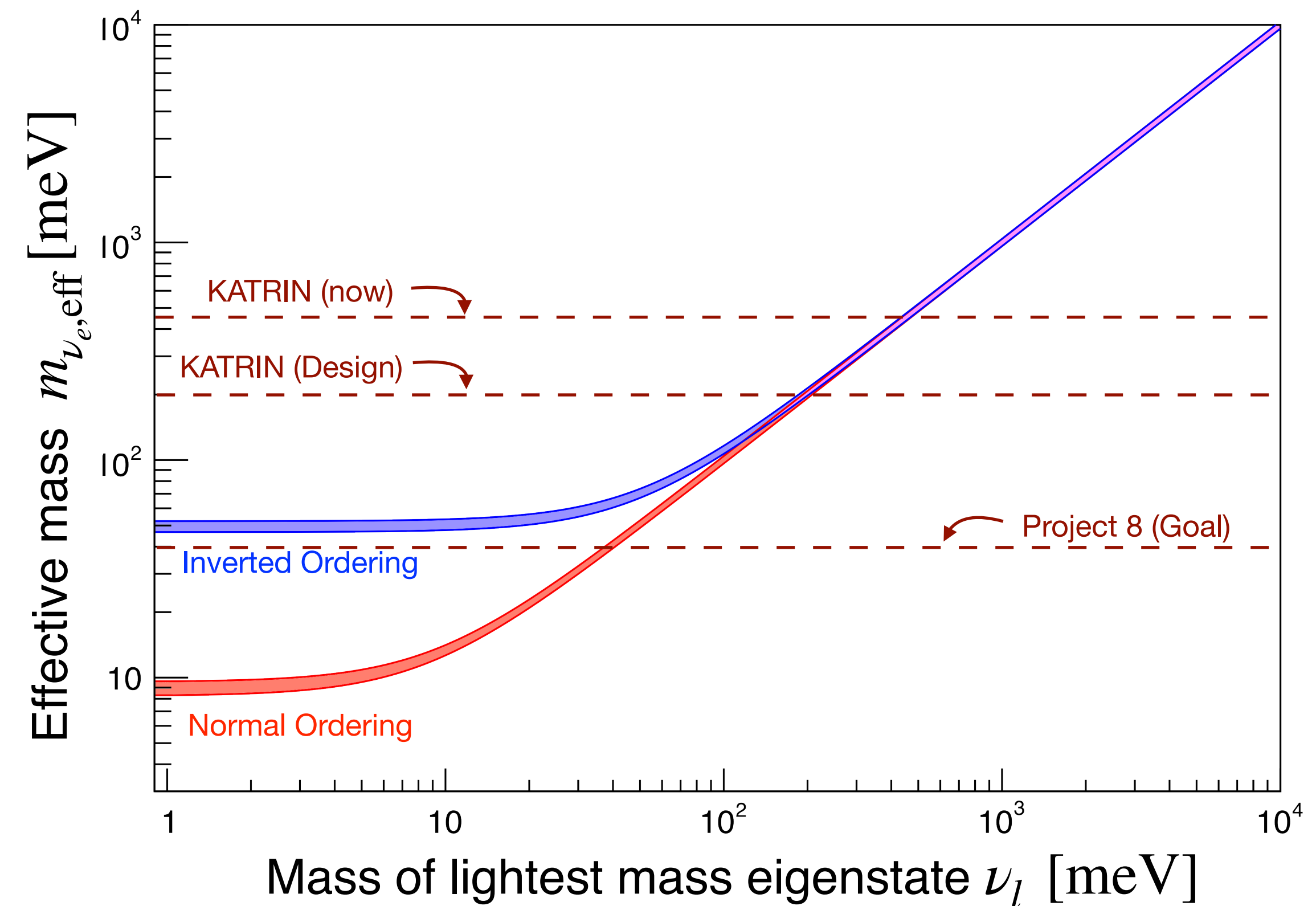


- Goal: reach the inverted mass ordering
- R&D on atomic tritium
- Demonstrated novel spectroscopy method: Cyclotron Radiation Emission Spectroscopy (CRES)

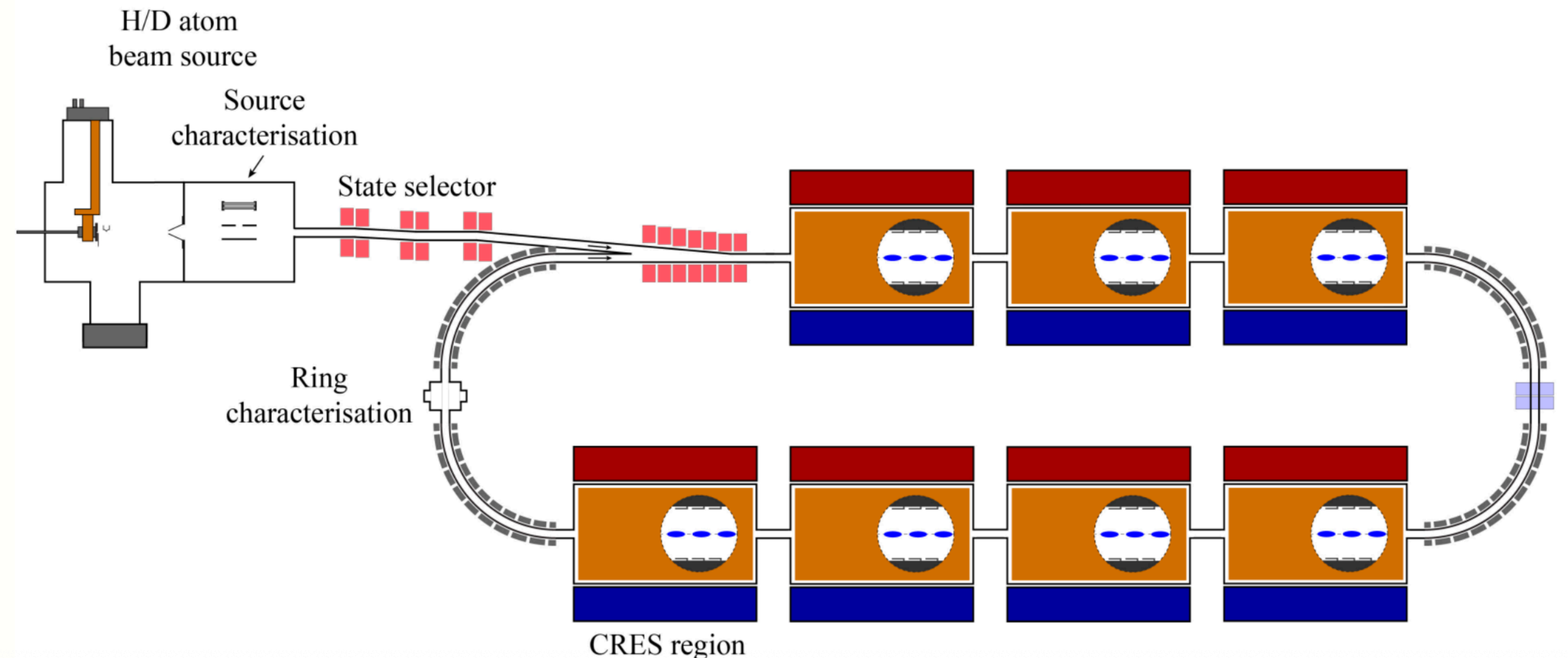
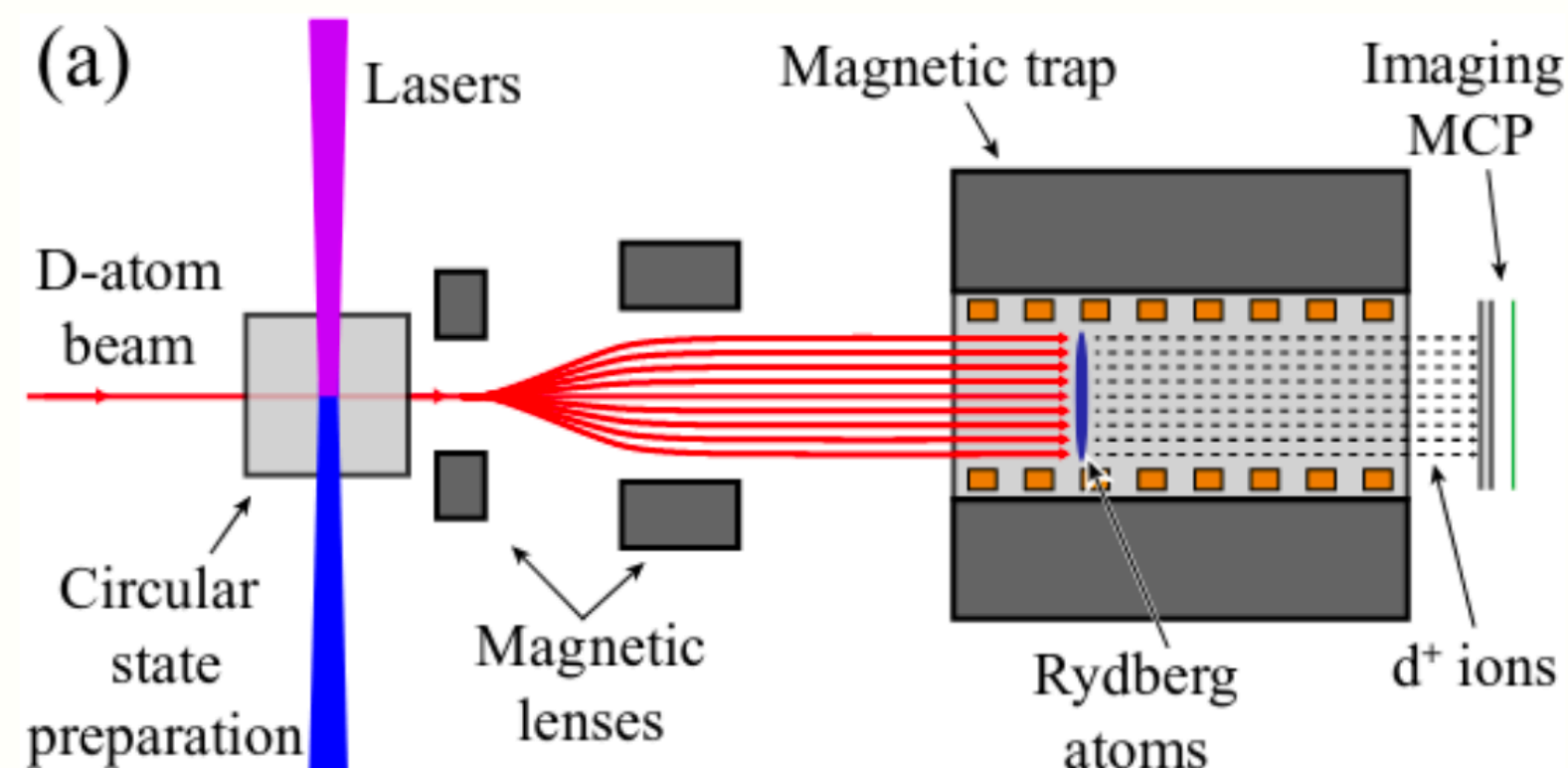


Project 8

- Goal: reach the inverted mass ordering
- R&D on atomic tritium
- Demonstrated novel spectroscopy method: Cyclotron Radiation Emission Spectroscopy (CRES)

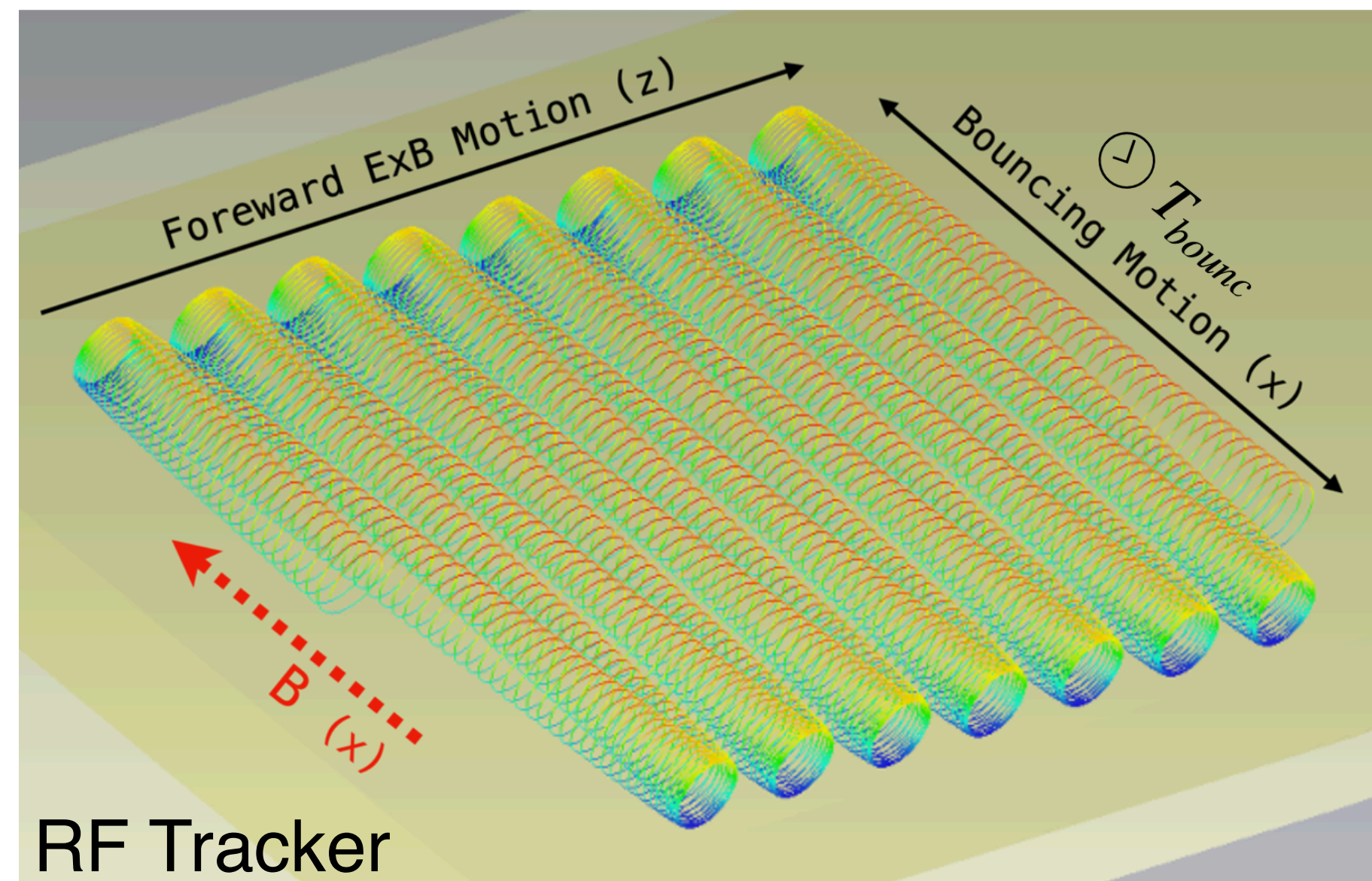
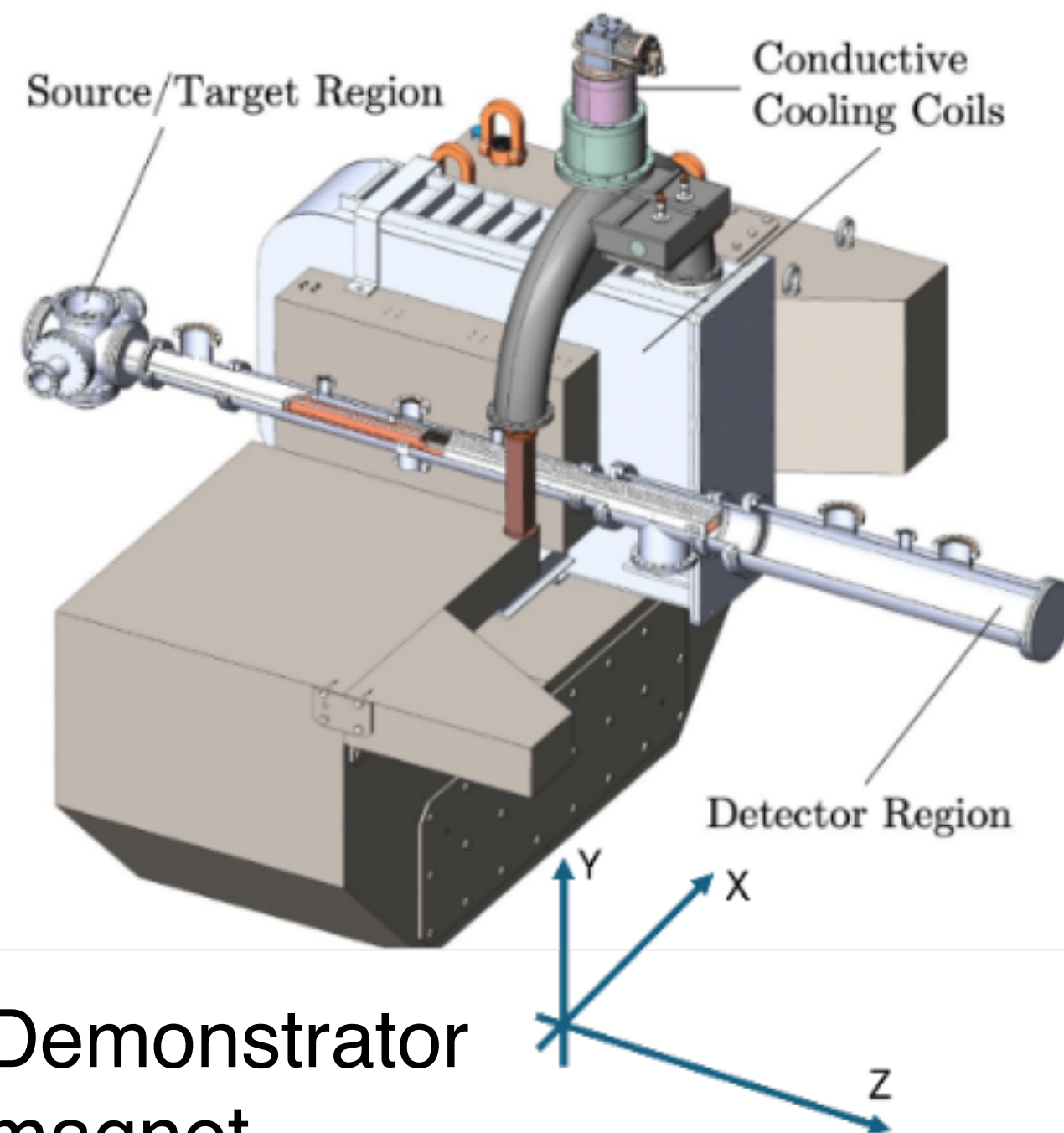
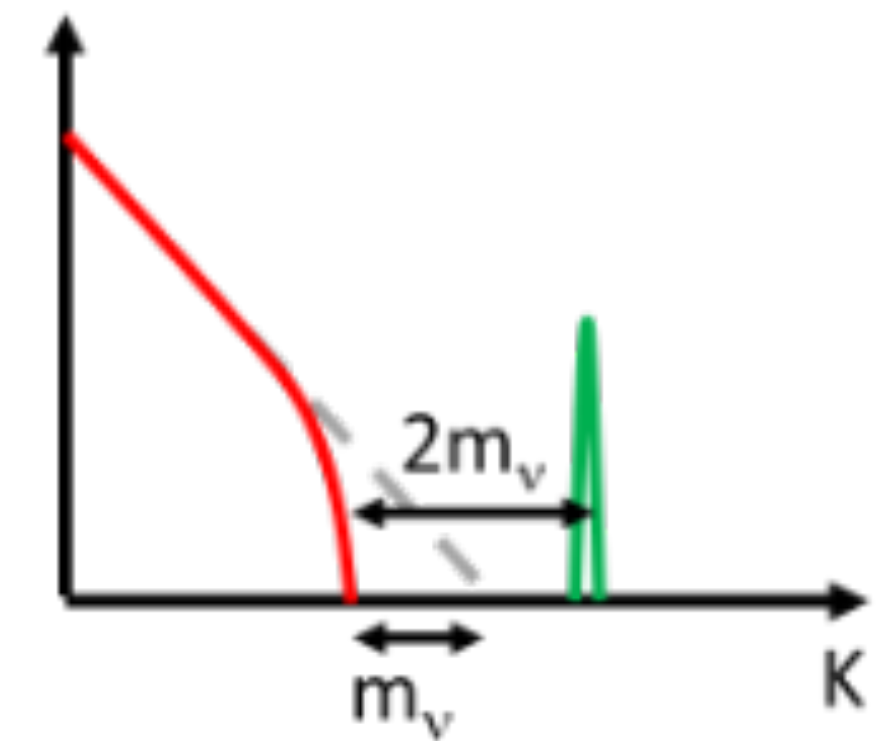


- Quantum Technologies for Neutrino Mass
- UK-based
- Similar to Project 8, but tackling quantum aspects first:
 - Magnetometry with Rydberg atoms
 - Quantum amplifiers
 - Atomic source

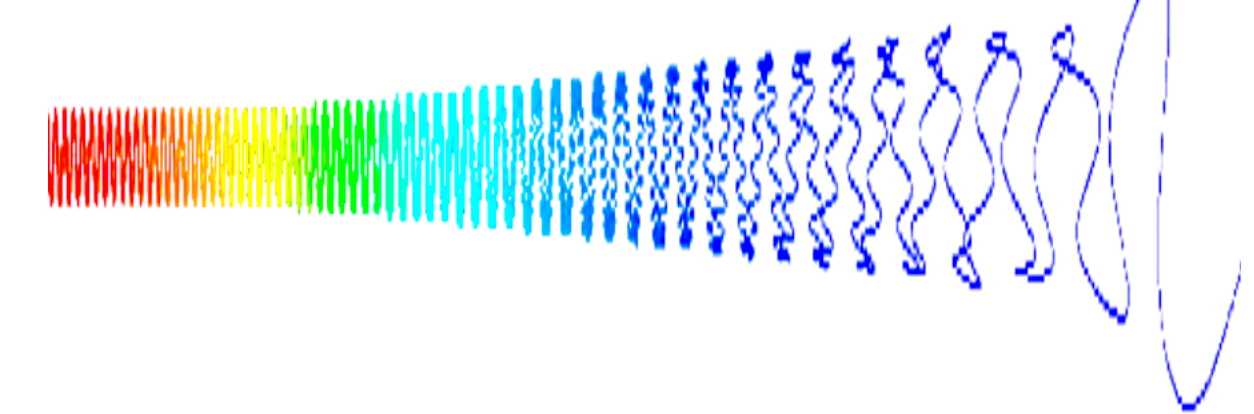


Based on S. Jones' NuMass 2026 presentation

- Main physics goal: discover the CNB via neutrino capture on tritium
- Neutrino mass measurement as intermediate step

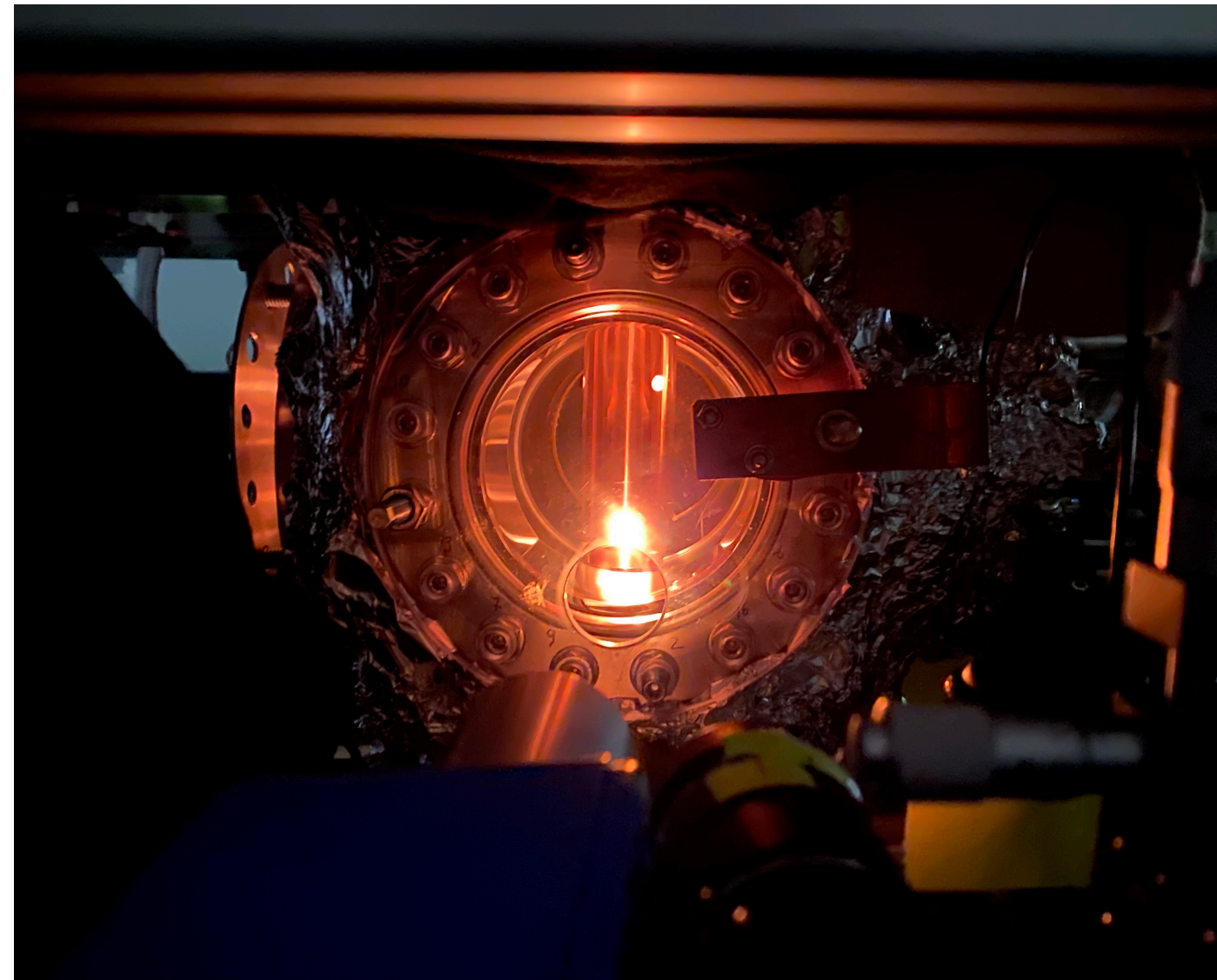


Electron filter

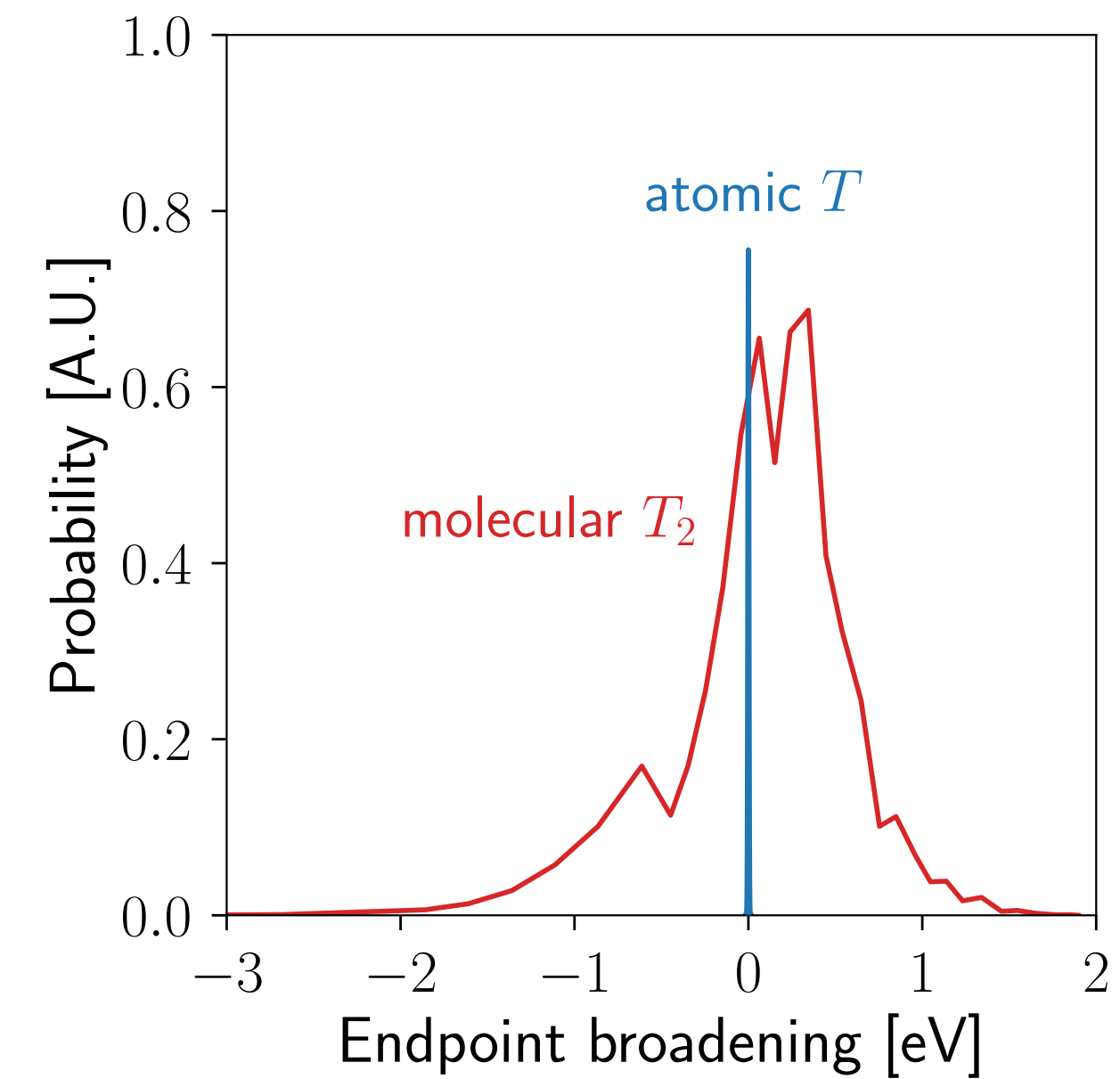
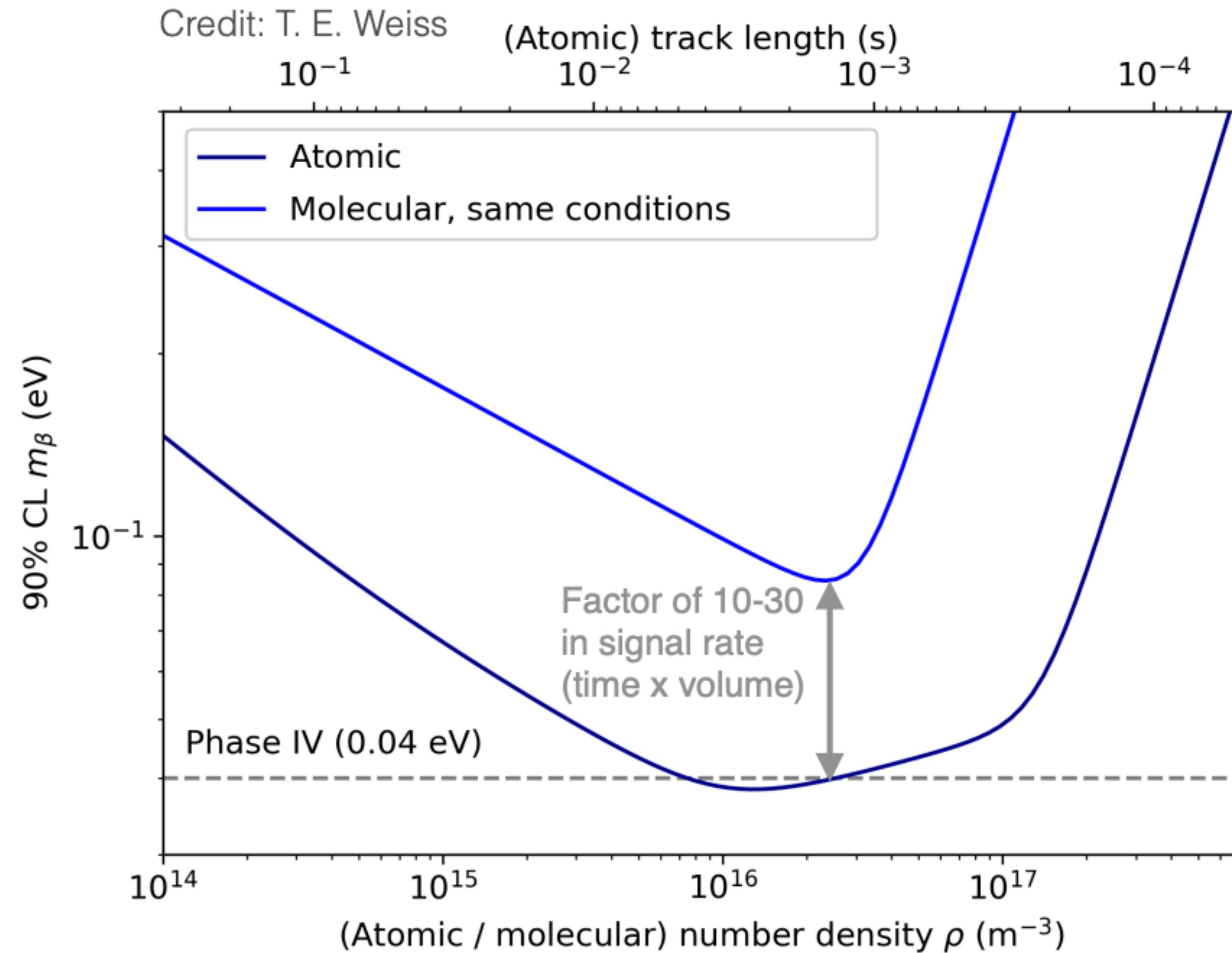


Based on F. Pofi's NuMass 2026 presentation

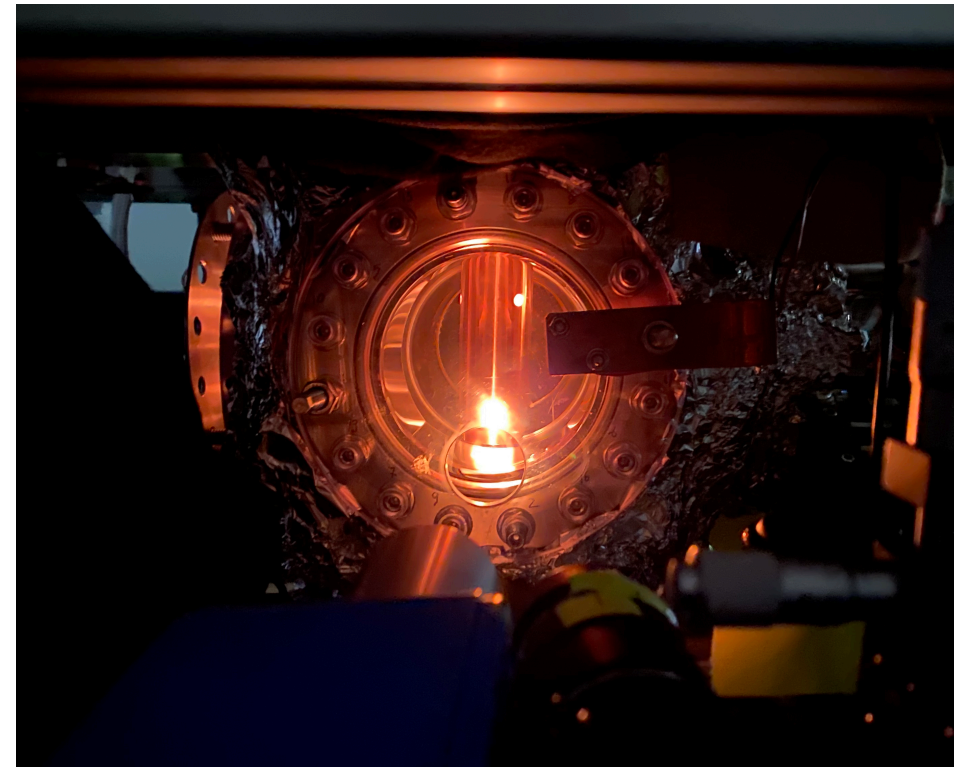
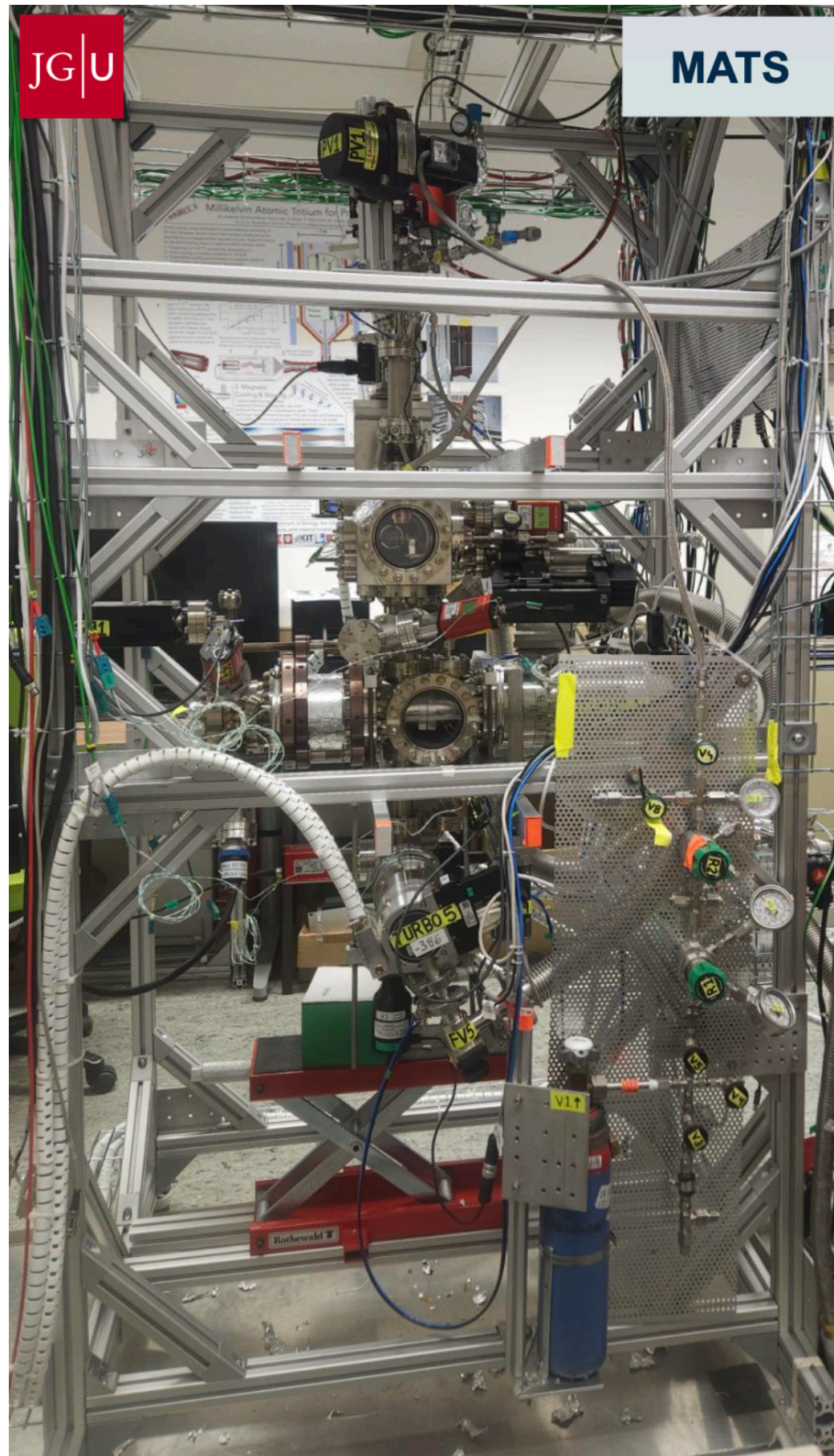
Atomic Source Development



Why Go Atomic?



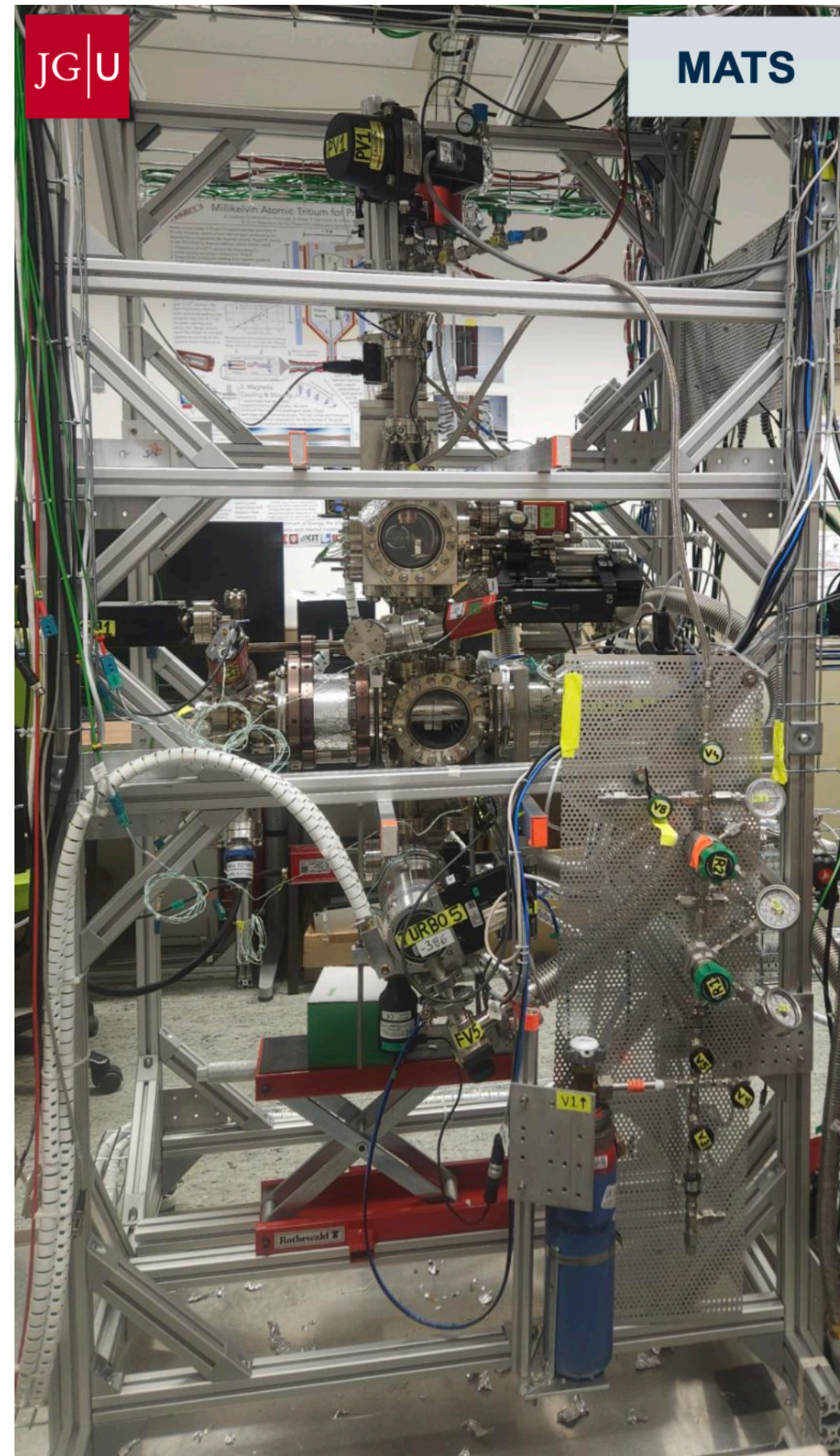
Atomic Source Development



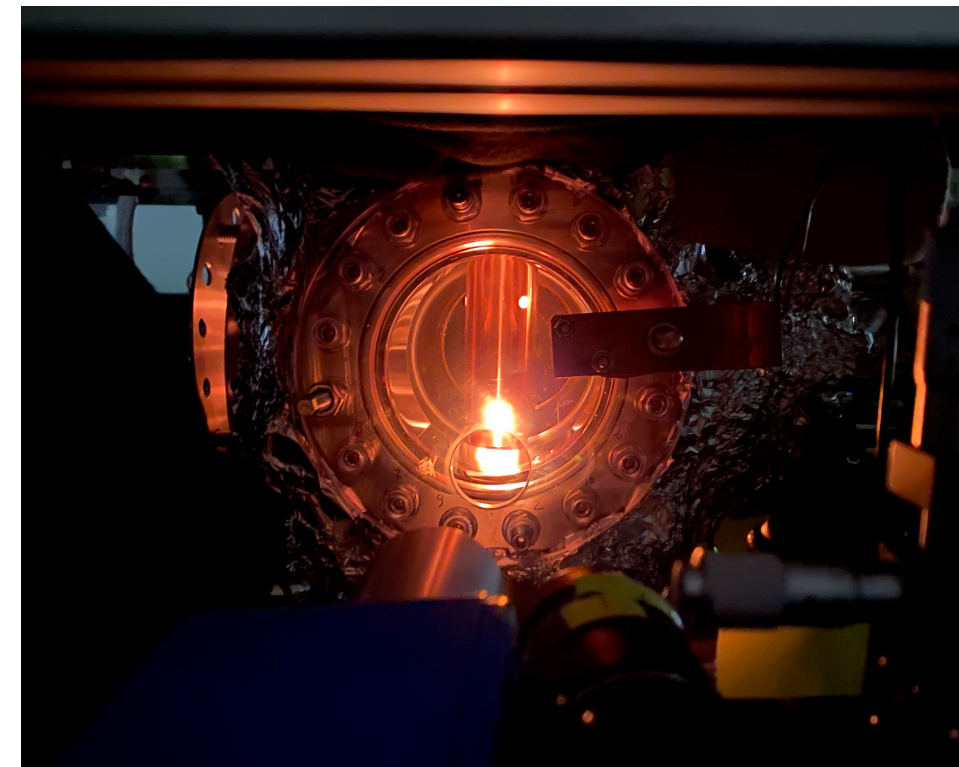
Credit: L. Thorne

1. Crack T_2 molecules at high temperatures using heated tungsten filament

Atomic Source Development

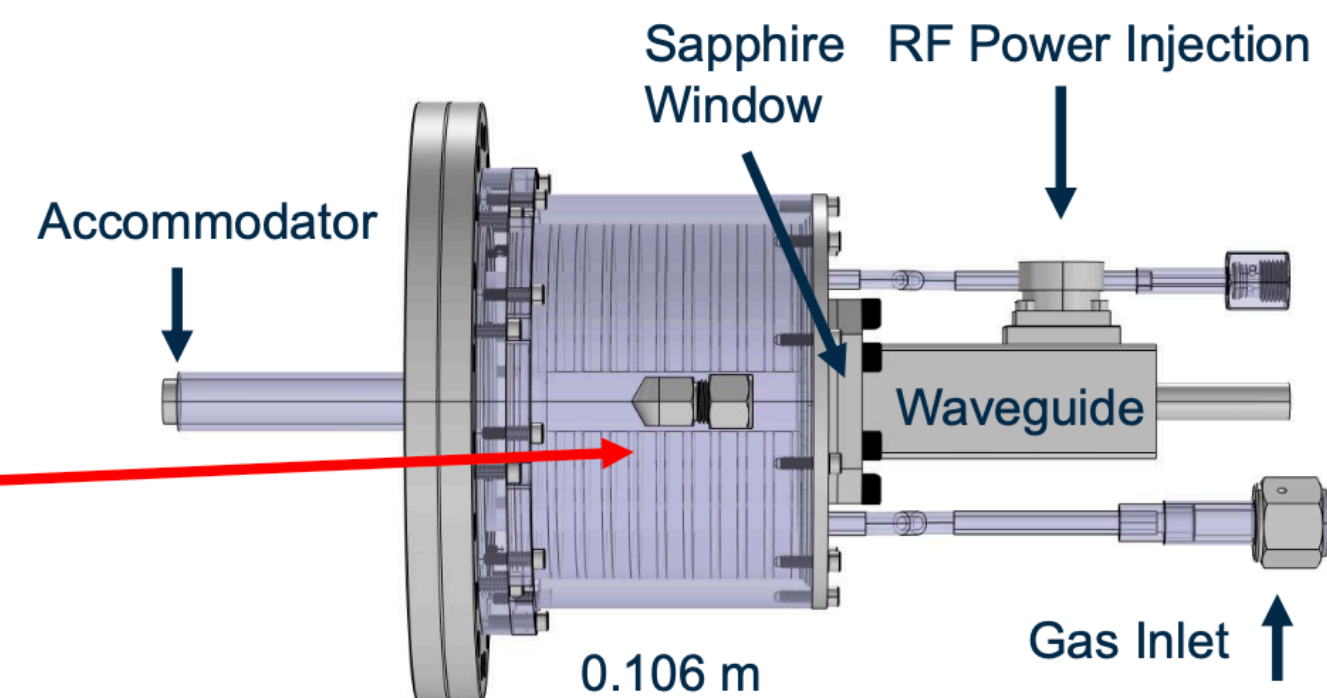
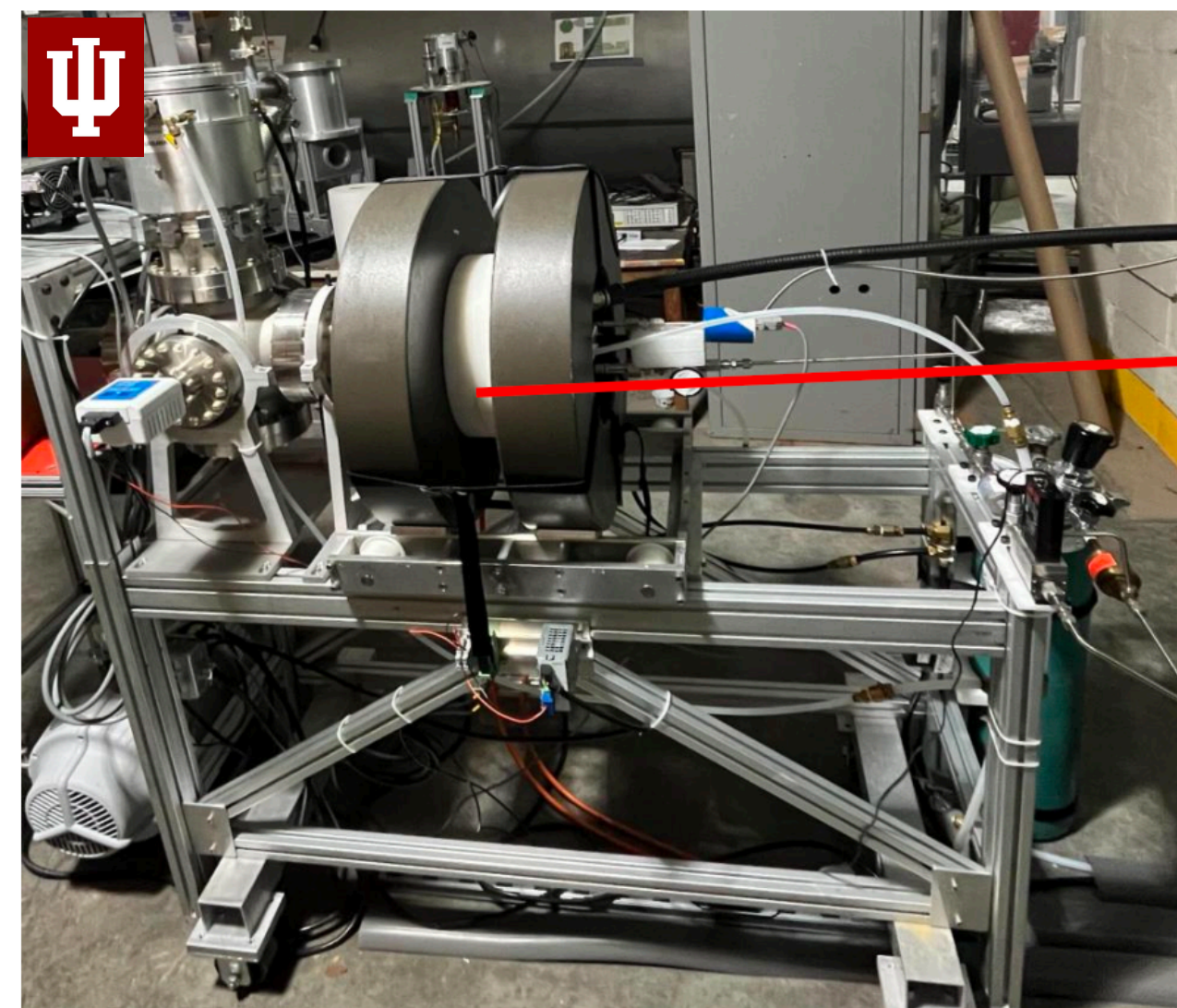


[Eur.Phys.J.D 79 5, 60 \(2025\)](#)

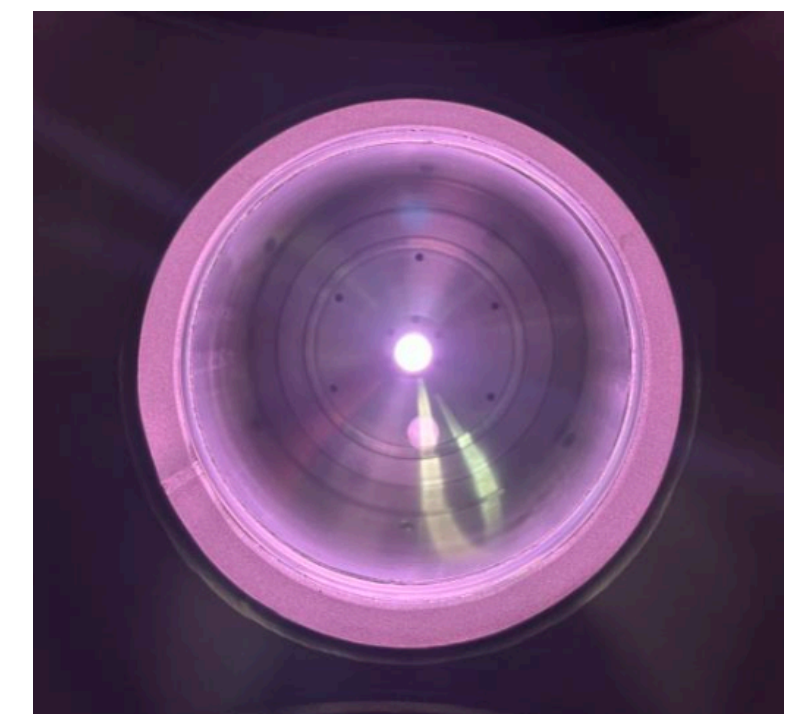


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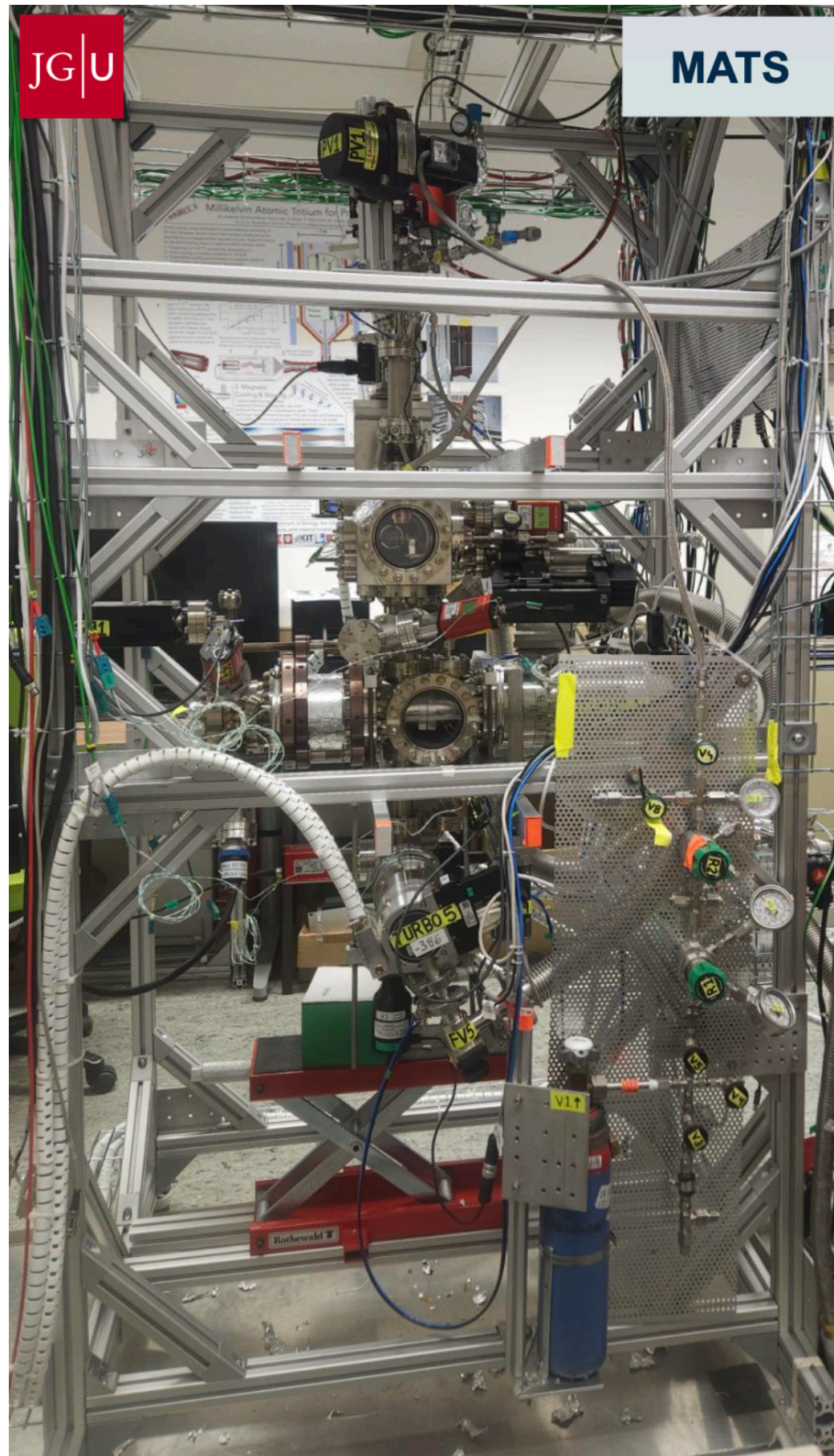
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2. Crack T_2 molecules with high-energy electrons
→ ECR plasma source



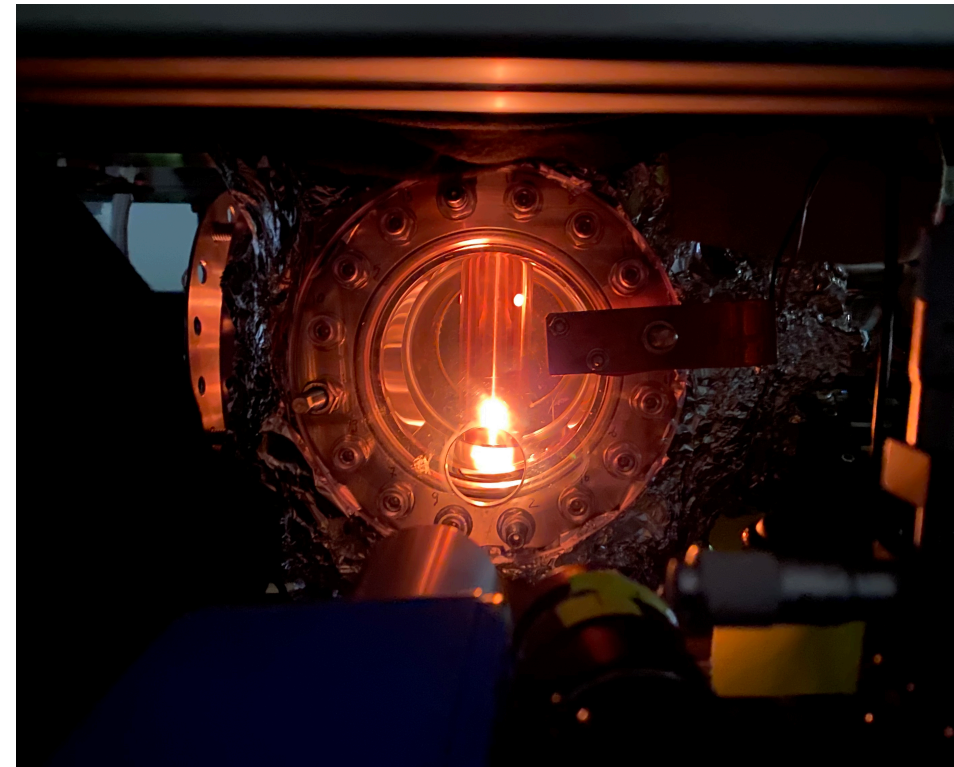
Credit: A. Reine



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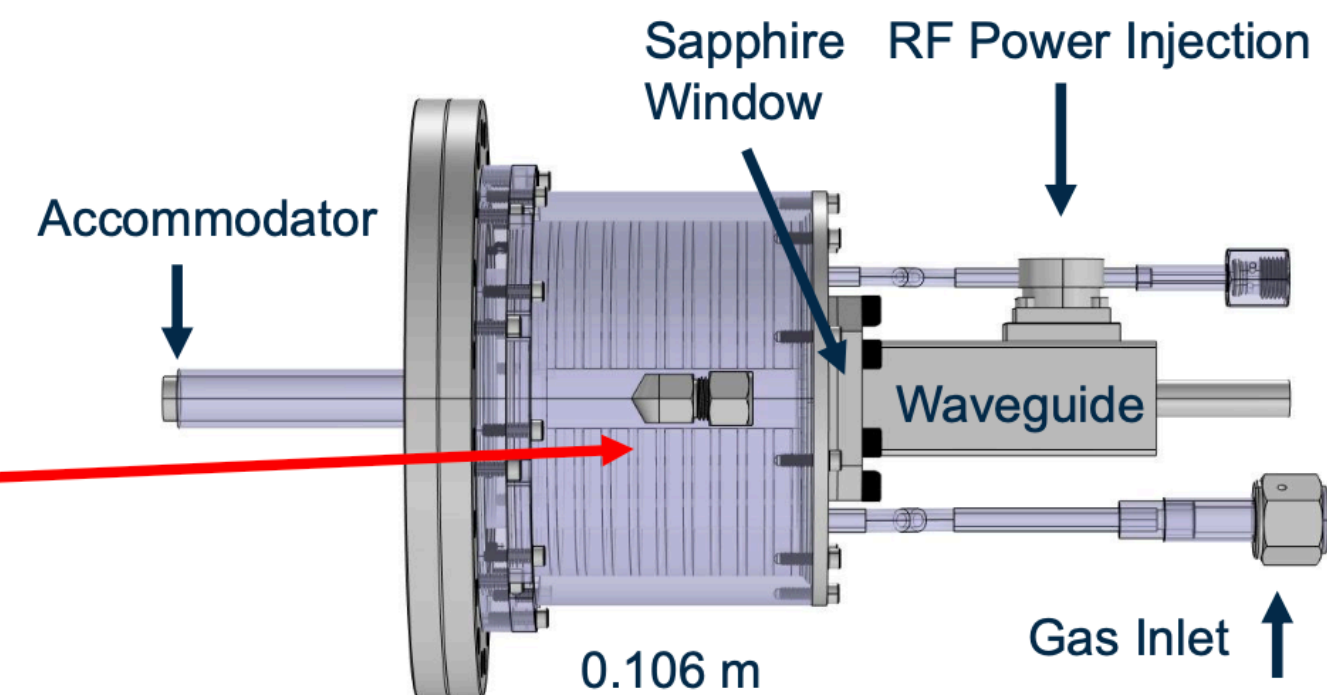
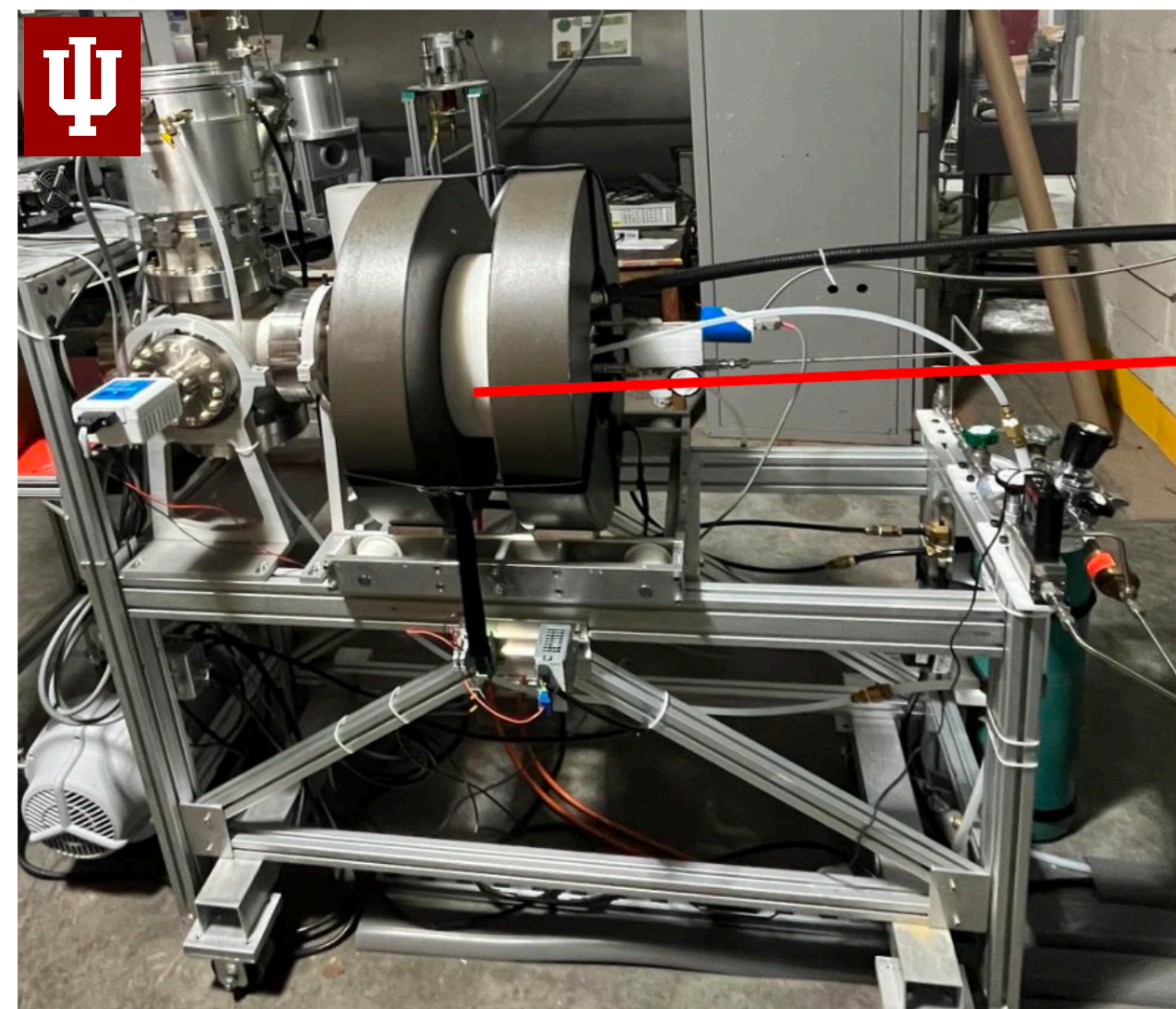
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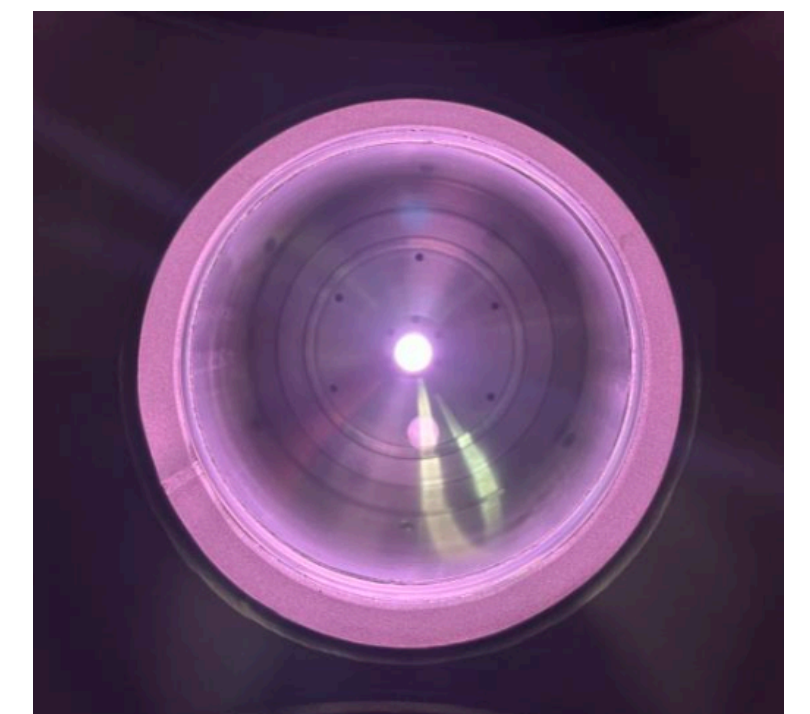
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→ ECR plasma source

Both developed on H_2 , now being investigated for T_2

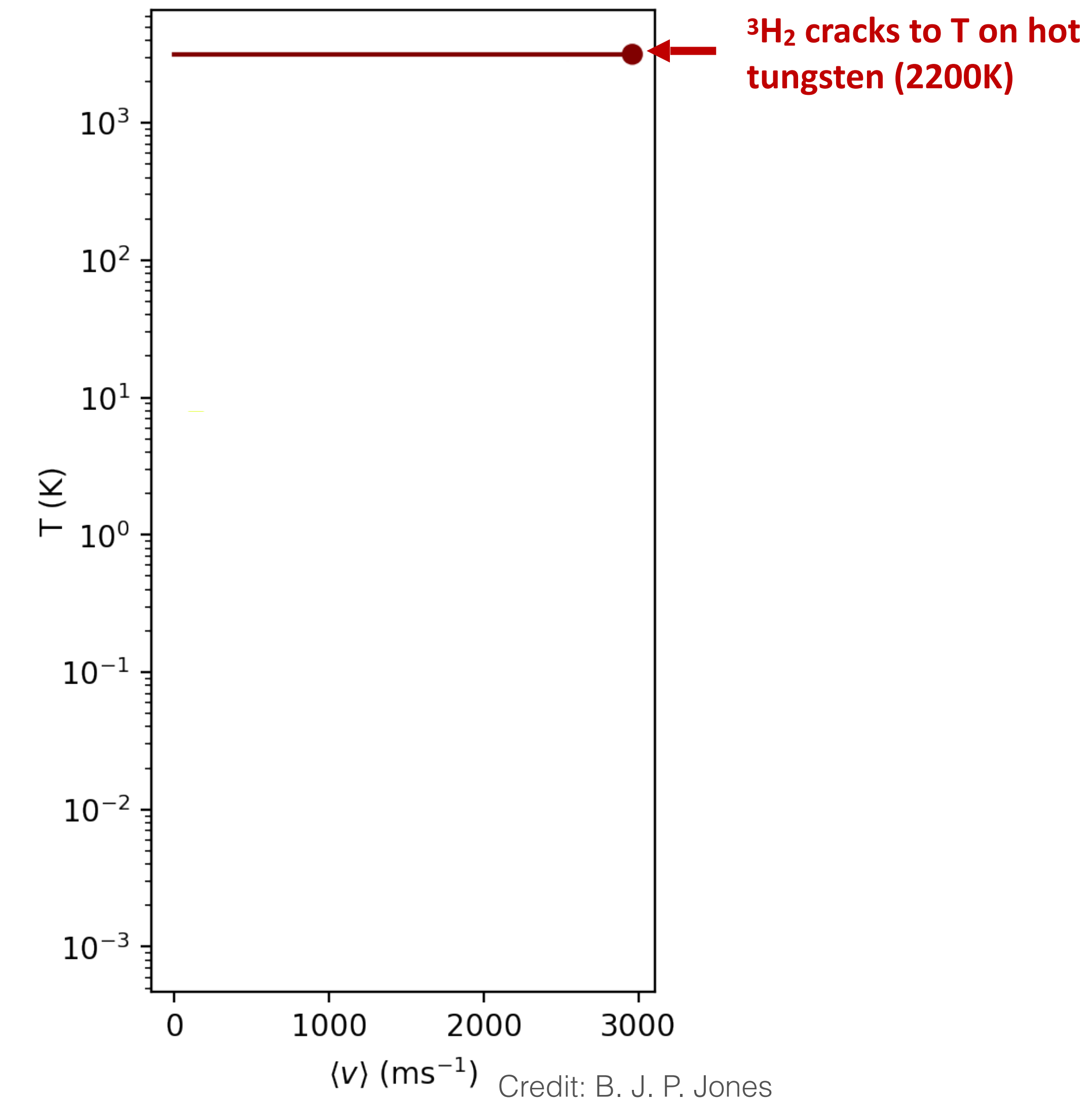


Credit: A. Reine



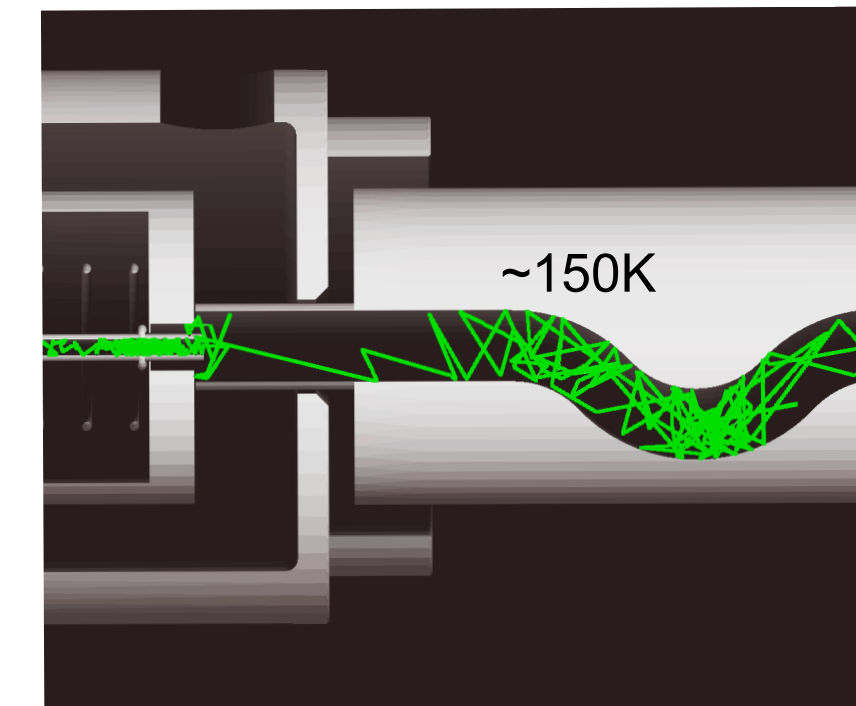
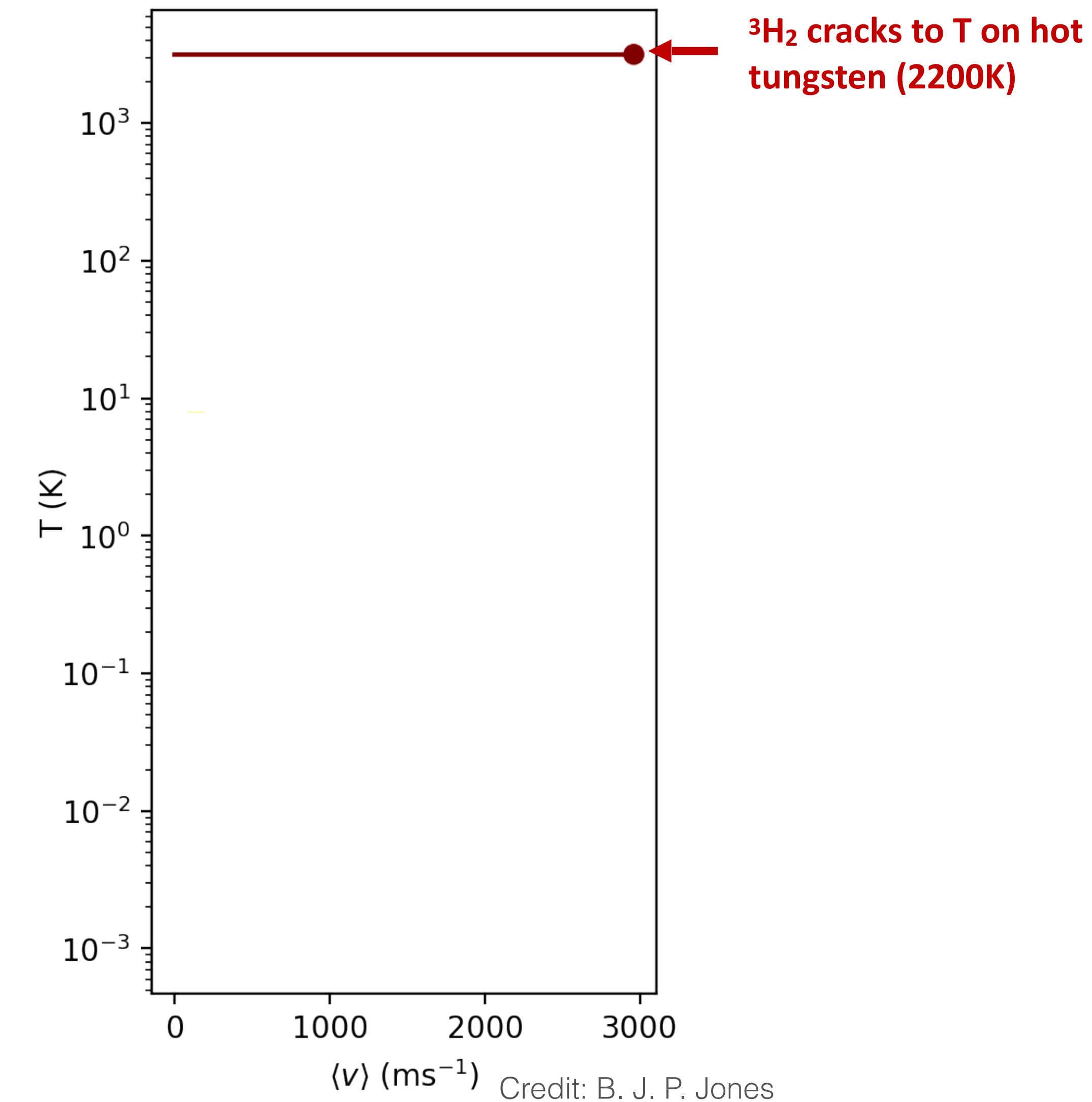
Atom Cooling & Slowing

1. Create T atoms at high temperatures



Atom Cooling & Slowing

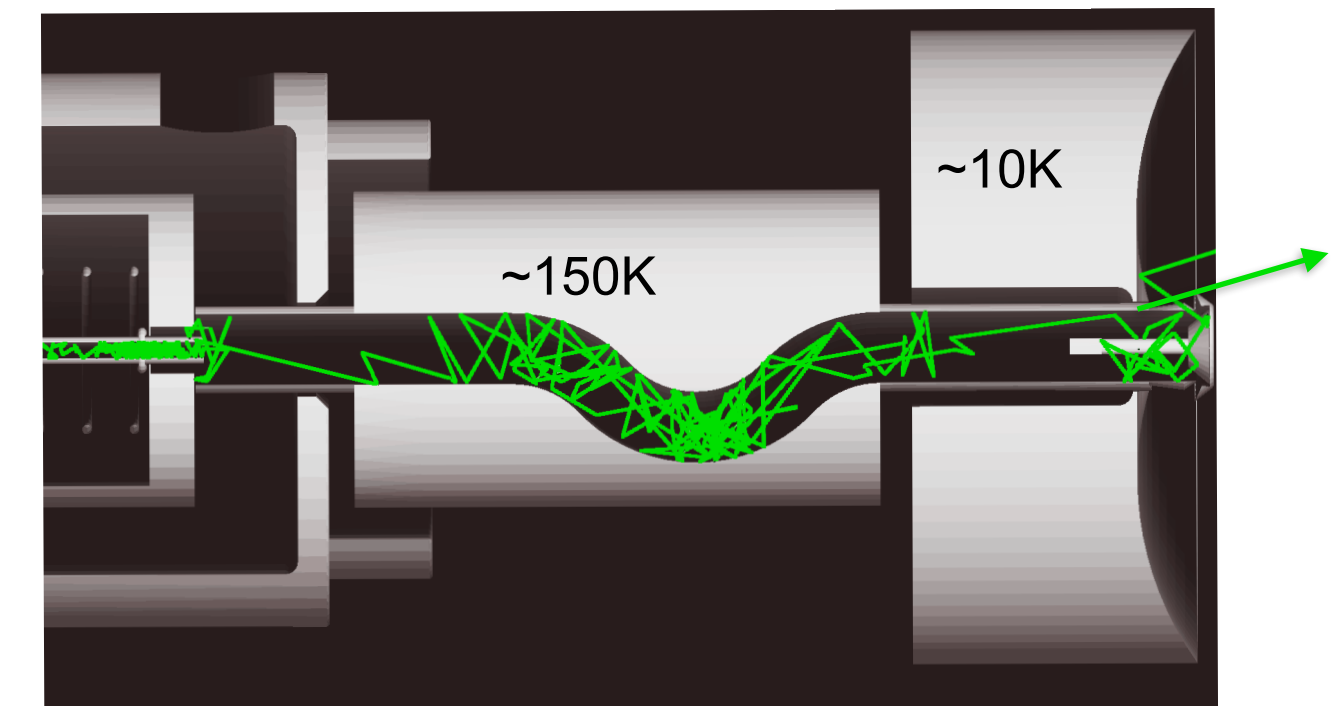
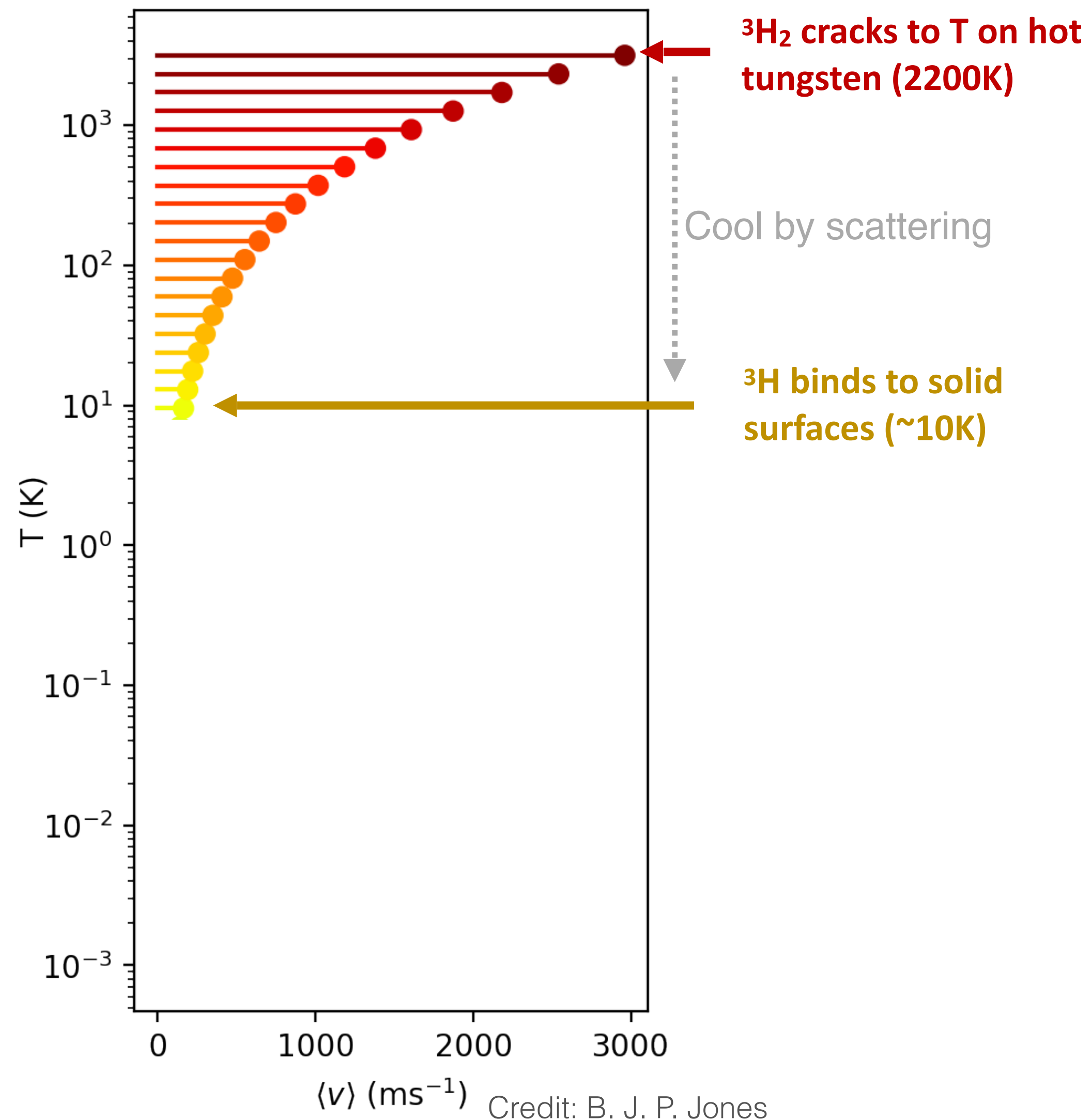
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2. Accommodator: cool to 150K with multiple bounces at low recombination rate



Credit: A. Lindman

Atom Cooling & Slowing

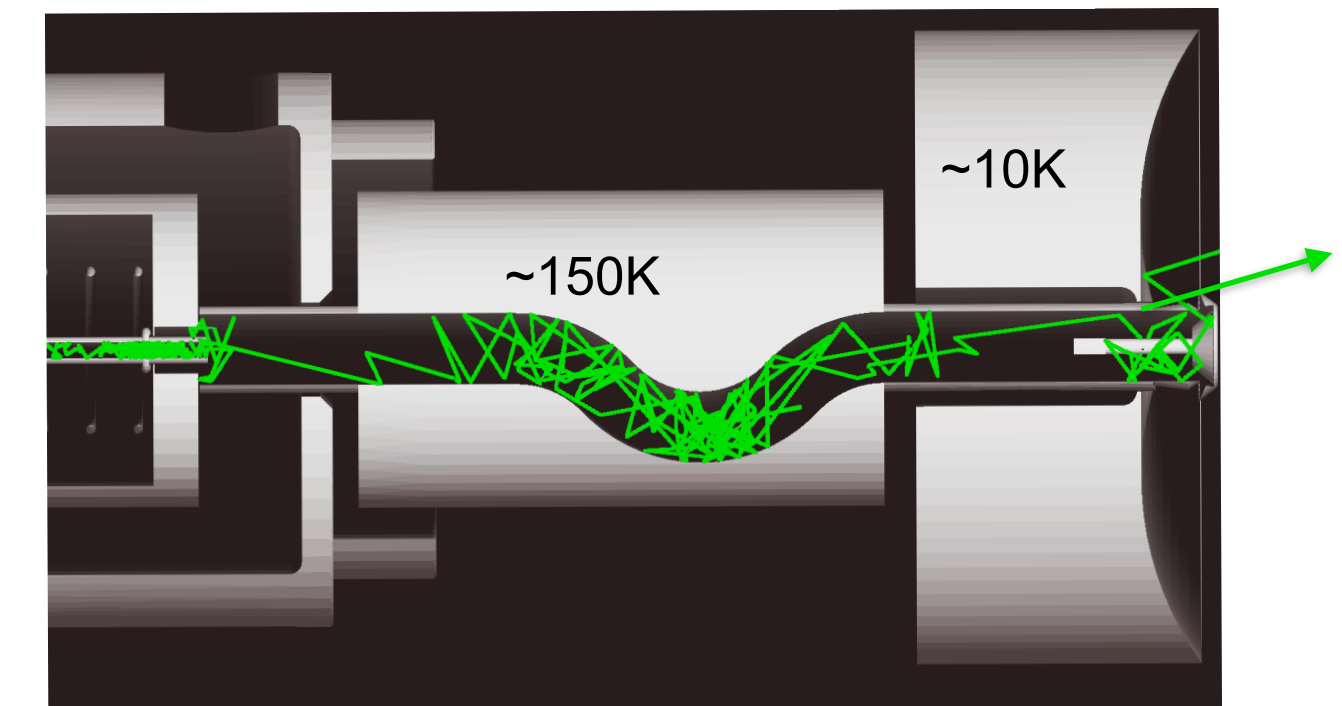
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3. One-bounce nozzle to cool to 10K



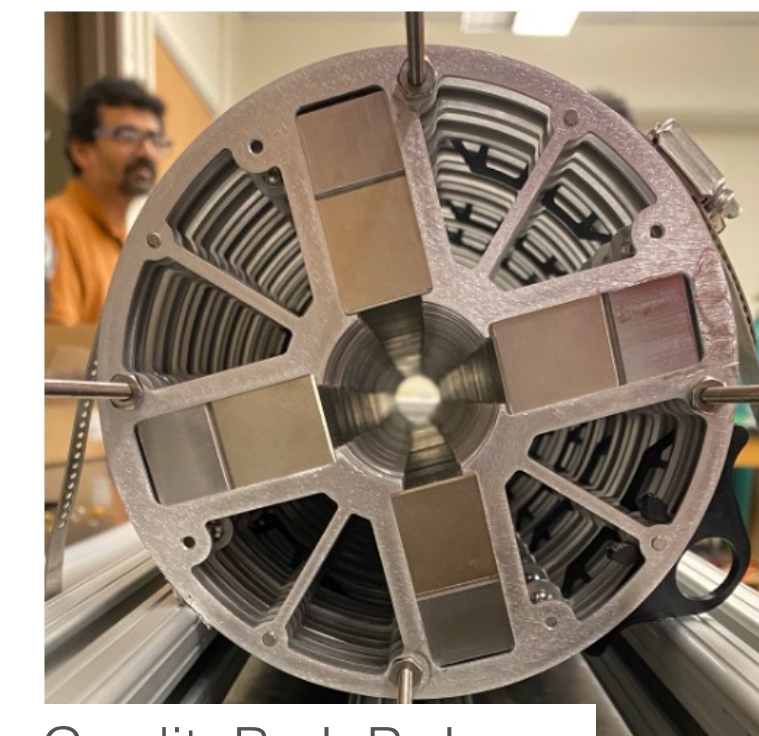
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Atom Cooling & Slowing

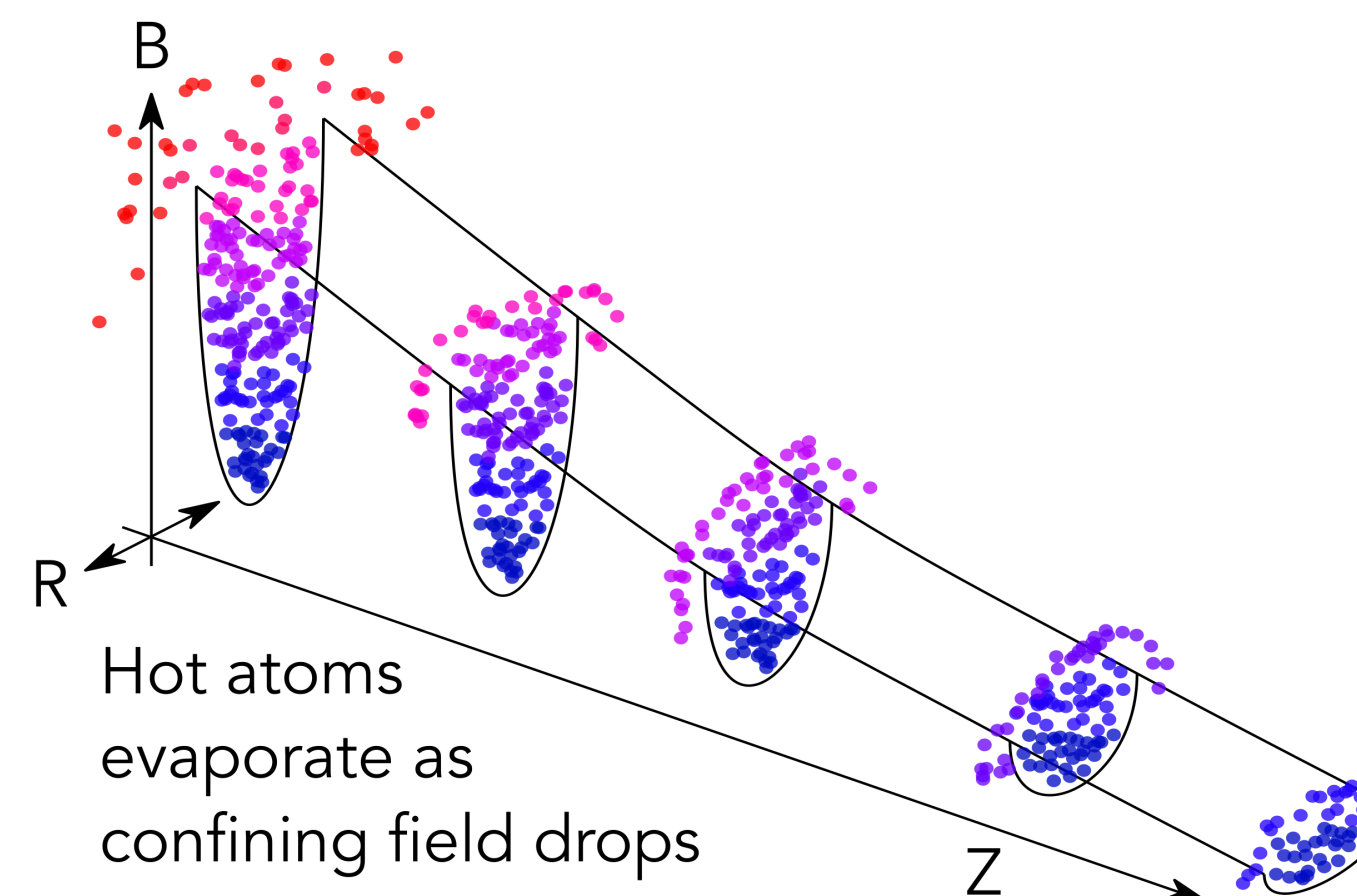
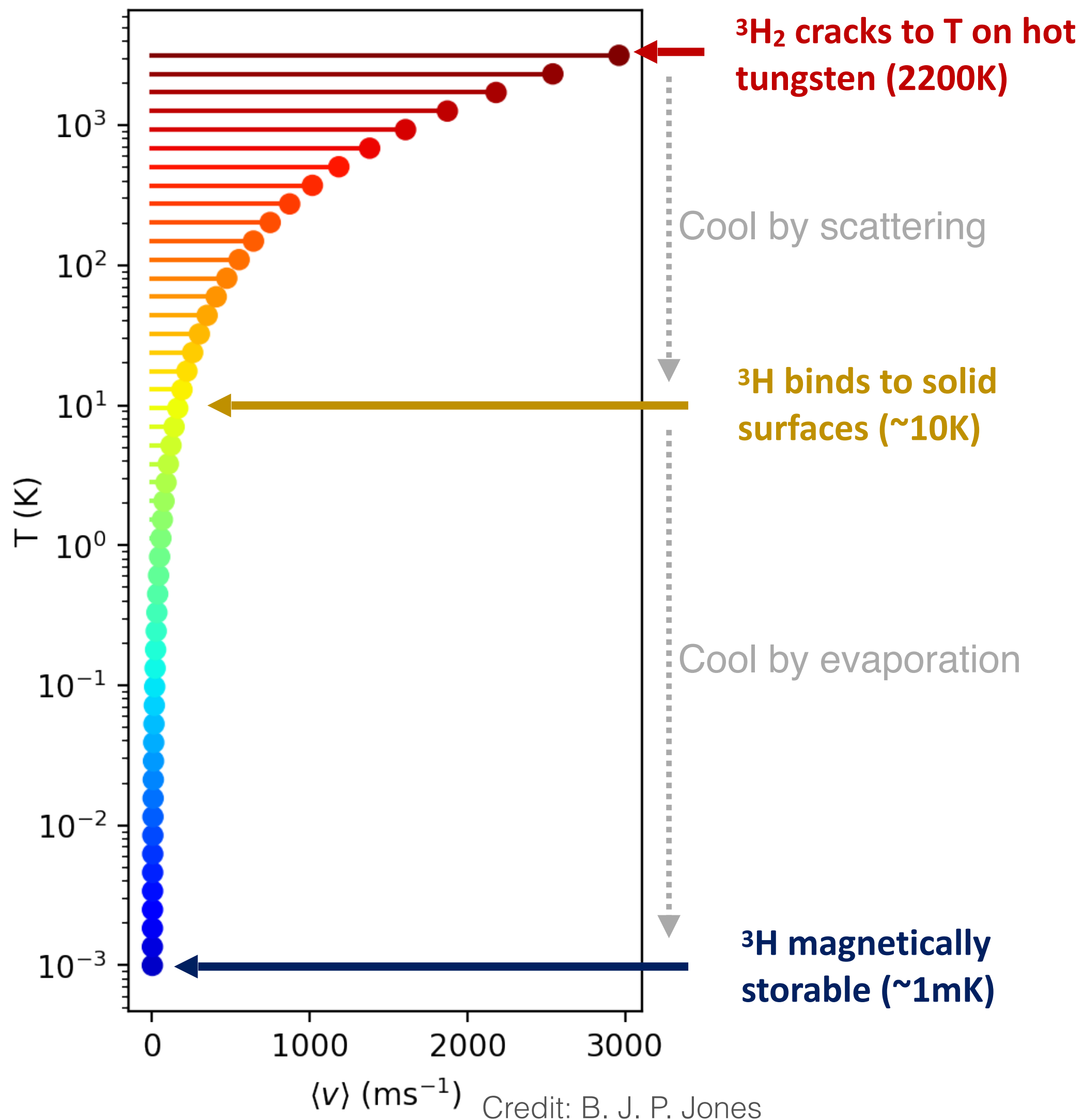
1. Create T atoms at high temperatures
2. Accommodator: cool to 150K with multiple bounces at low recombination rate
3. One-bounce nozzle to cool to 10K
4. Cool by evaporation of hottest atoms



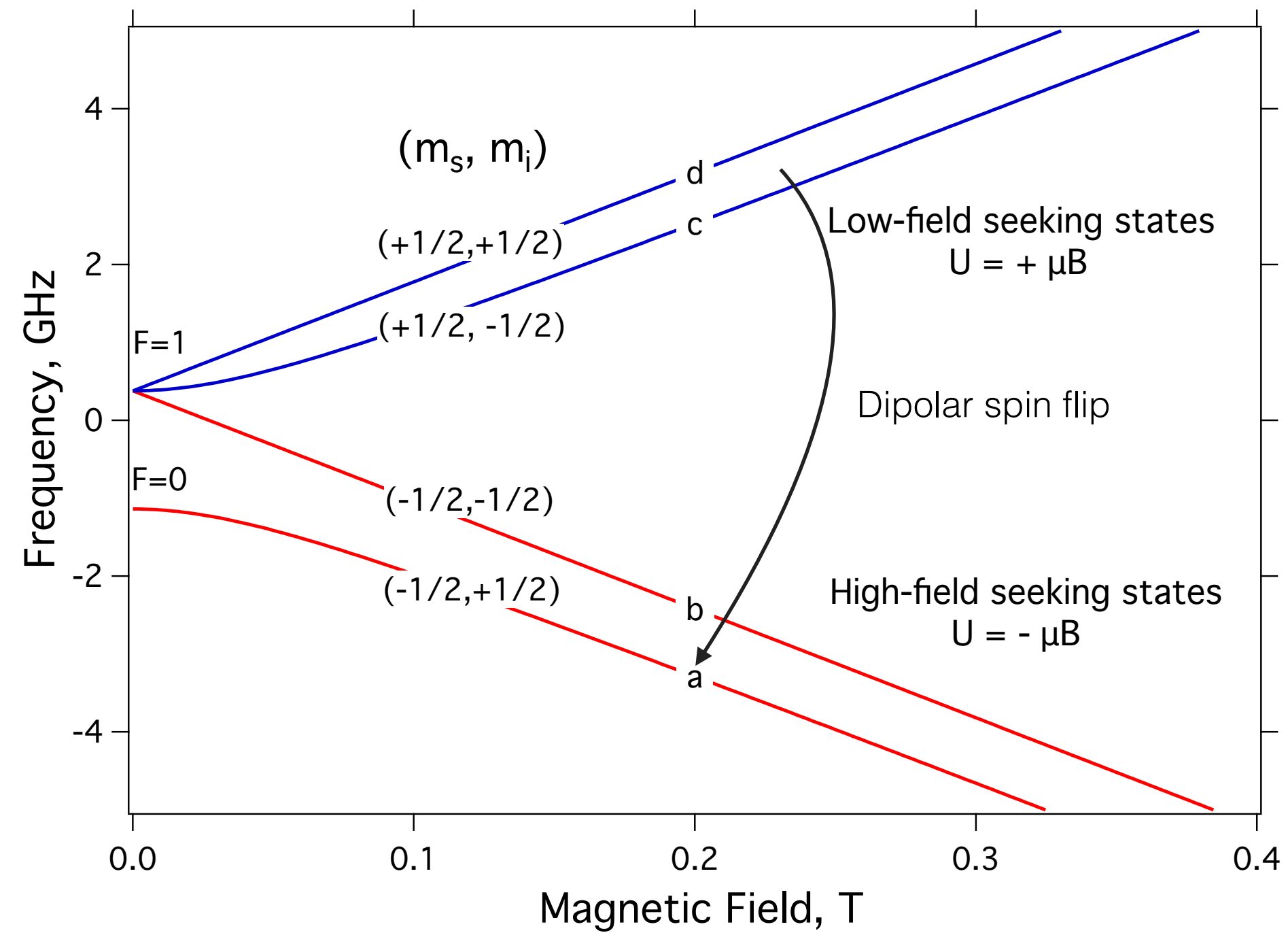
Credit: A. Lindman



Credit: B. J. P. Jones

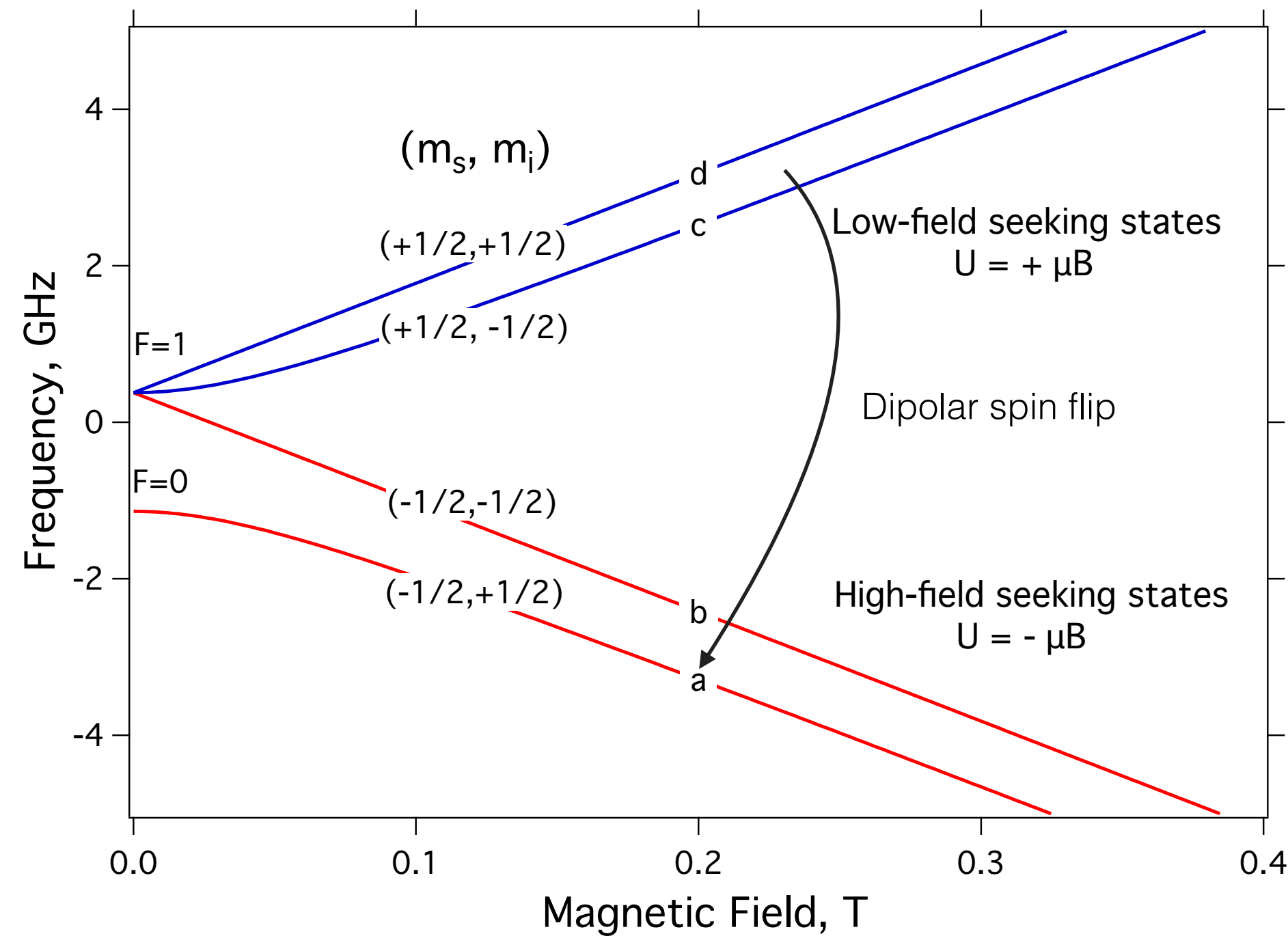


[PRA 112, 033311](#) (2025)

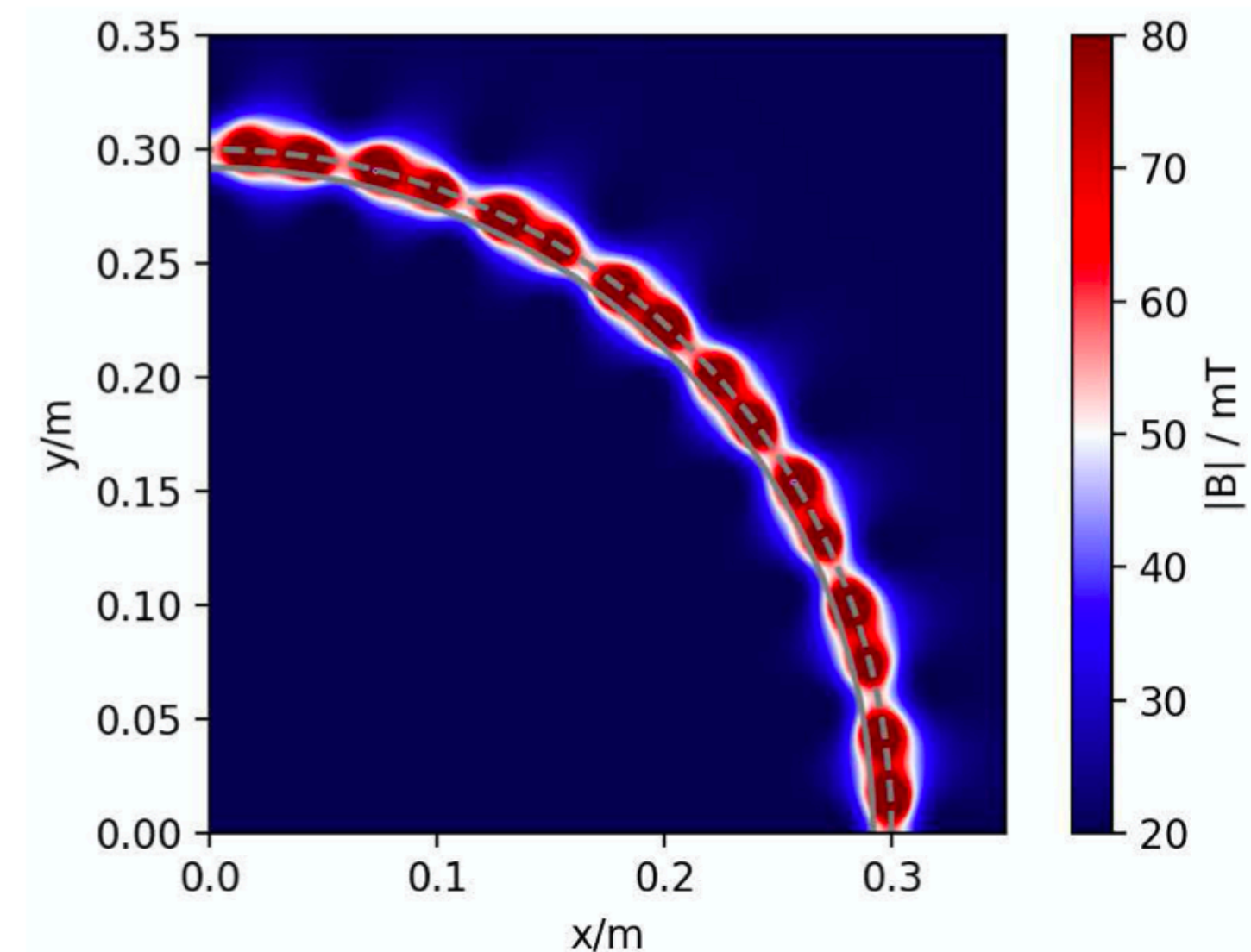
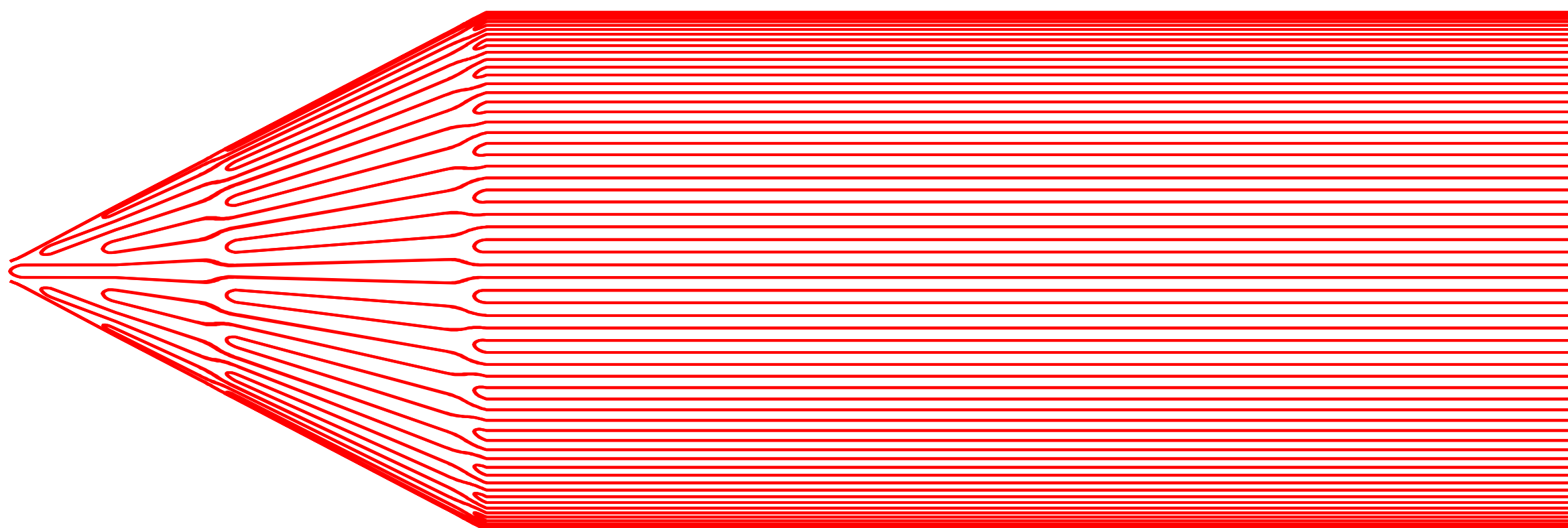


- Cannot let atoms touch walls!

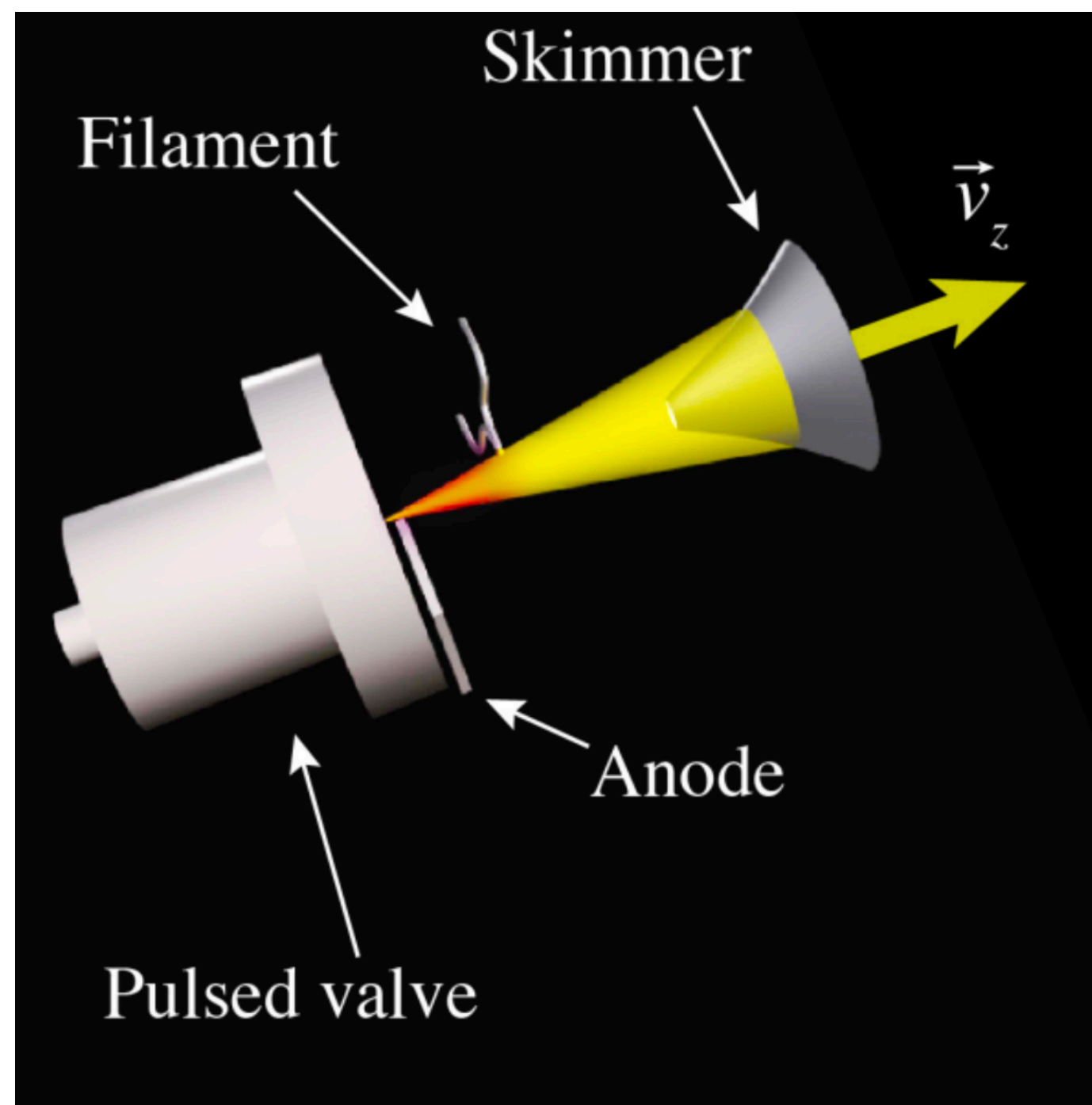
Magnetic Atom Trapping



- Cannot let atoms touch walls!
- Confine atoms in low-field seeking state magnetically
- Ioffe trap creates magnetic wall
- Central part free of field variations for CRES



Cryogenic Pulsed Atomic Source

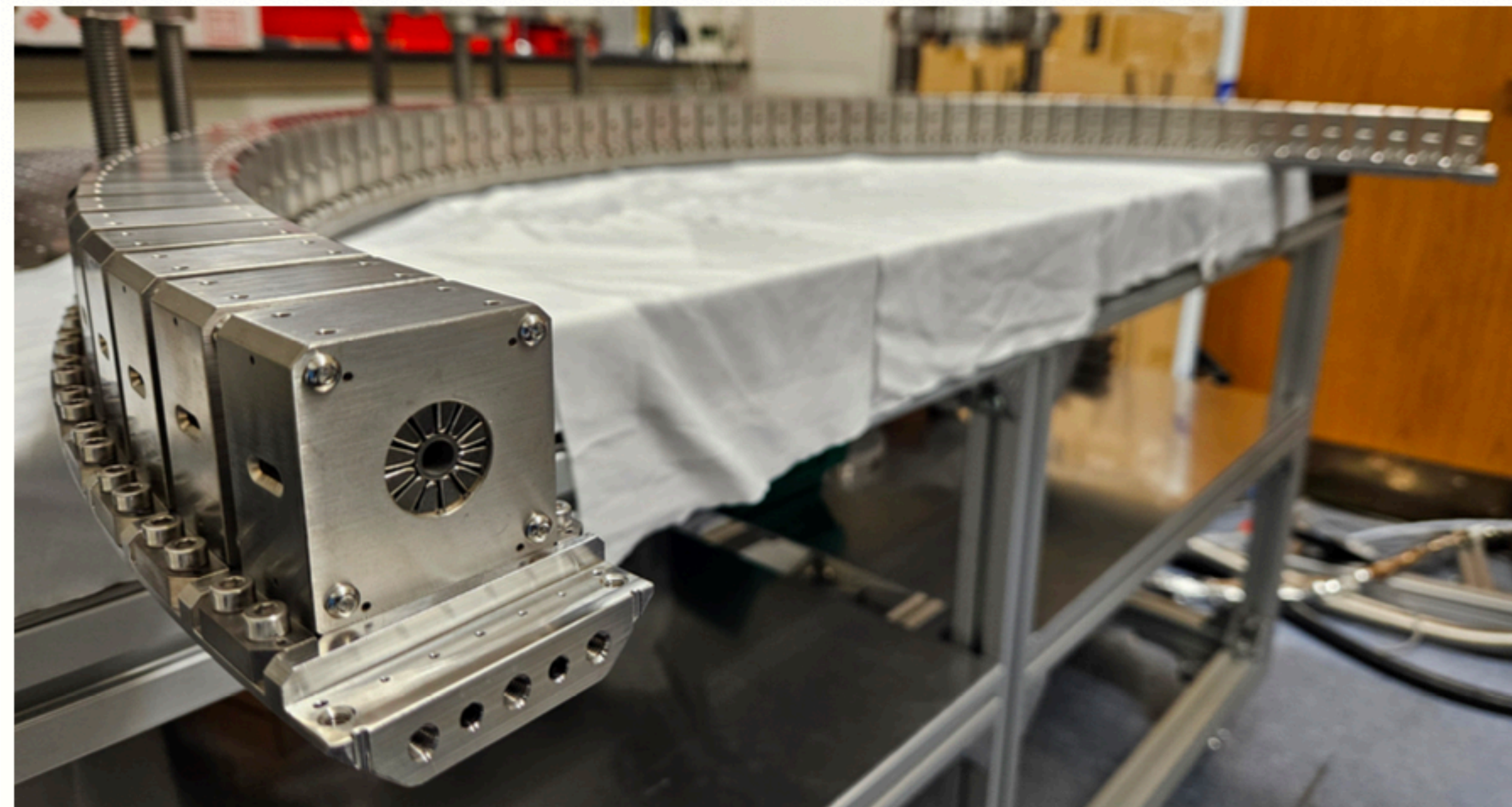
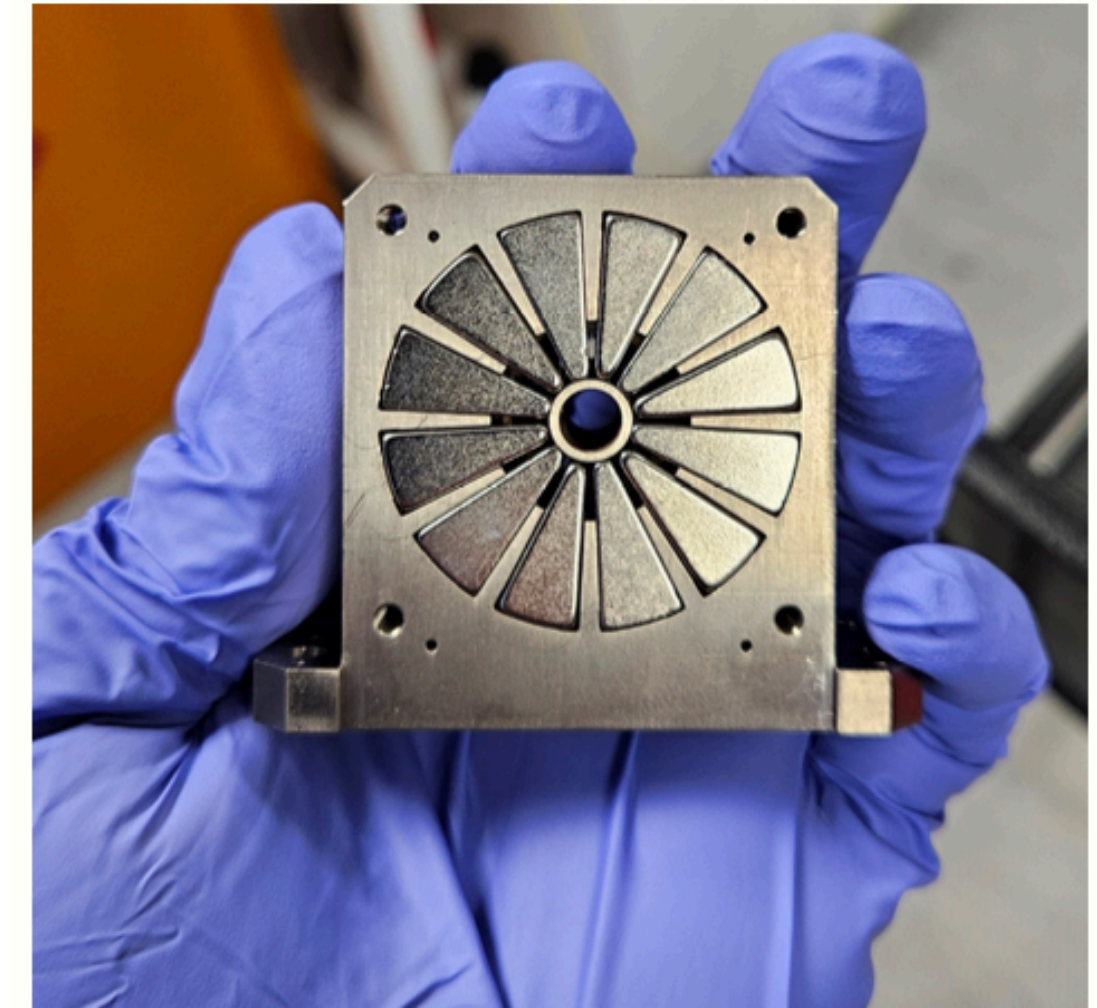


Credit: S. Hogan, Habilitation

- 30K pulsed supersonic source
- $\text{H}_2/\text{D}_2/\text{T}_2$ dissociation using DC discharge seeded with electrons from Tungsten filament
- High-purity, cold atomic beams

Atom Trapping

- Magnetically confine atoms in low-field seeking state
- Use Halbach array of hexapole magnets to create a storage ring
- No longitudinal slowing necessary

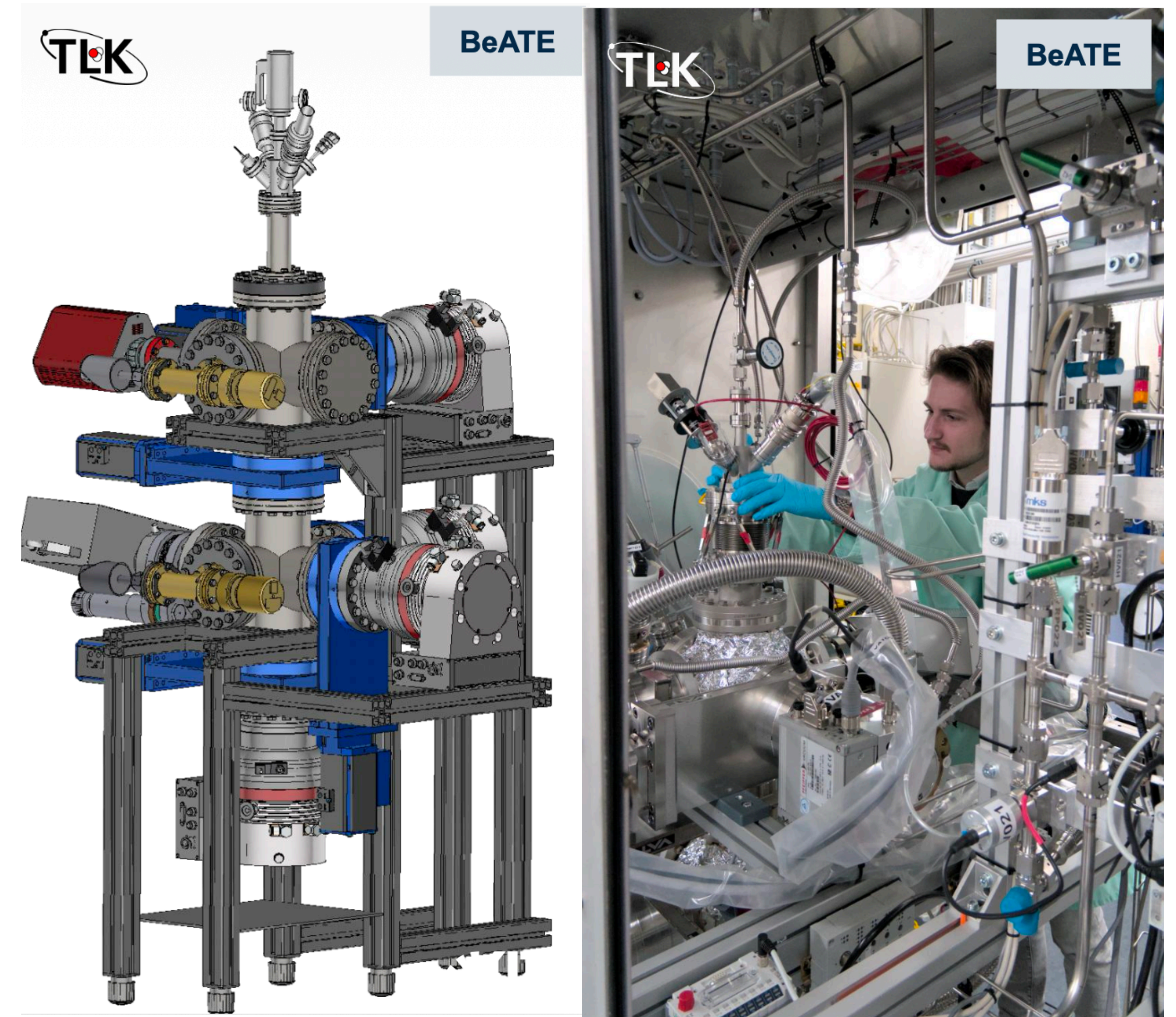


Based on S. Jones NuMass 2026 presentation

From Hydrogen to Tritium Sources

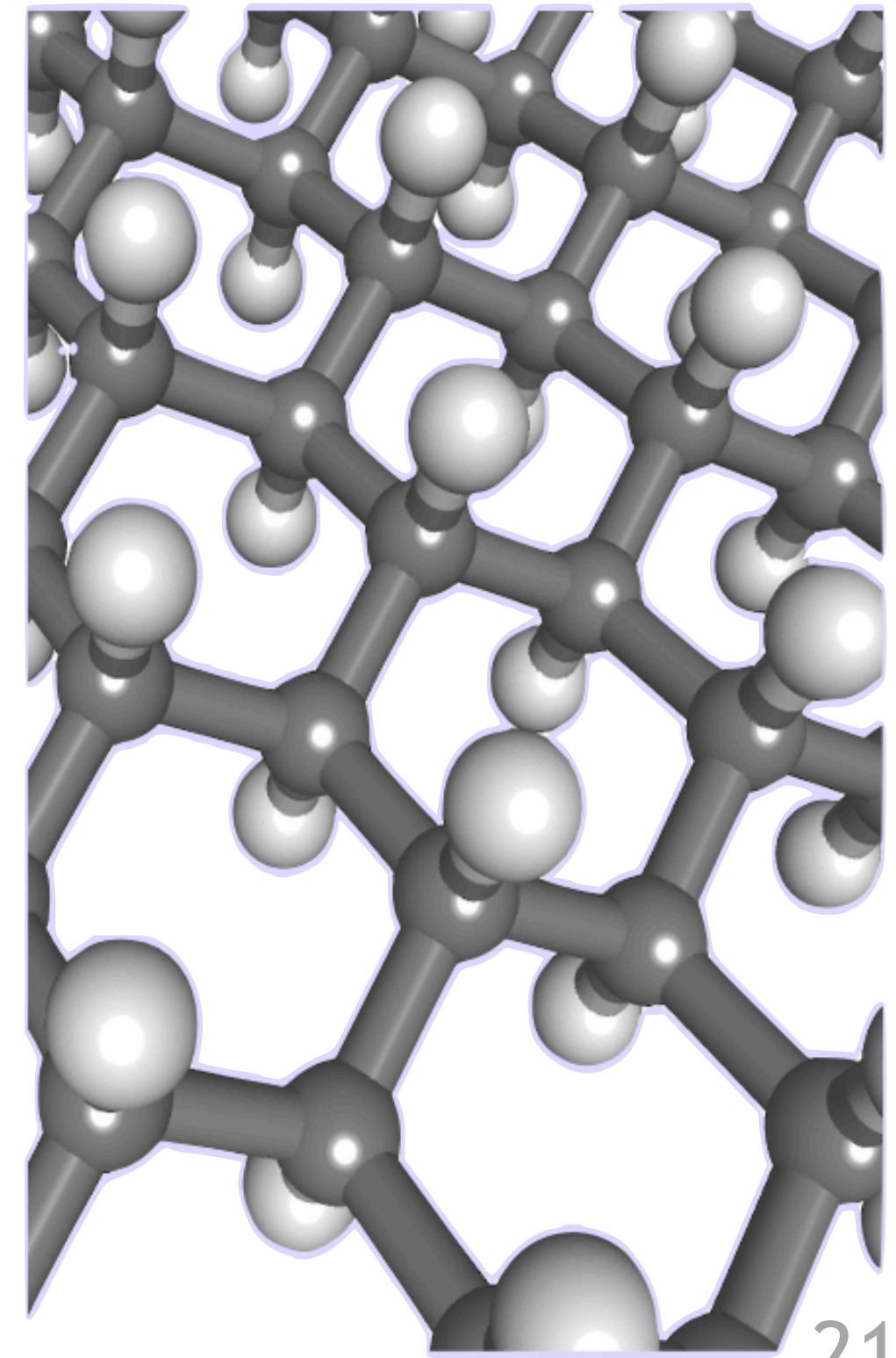
- TLK: Core facility with 30 years of tritium experience
- KArlsruhe MAInz Tritium Experiment
- Aim: generate high-intensity, atomic, mK cold atomic T source
- Combine atomic H source developments by Project 8 with T know-how at TLK

See D. Frese's talk



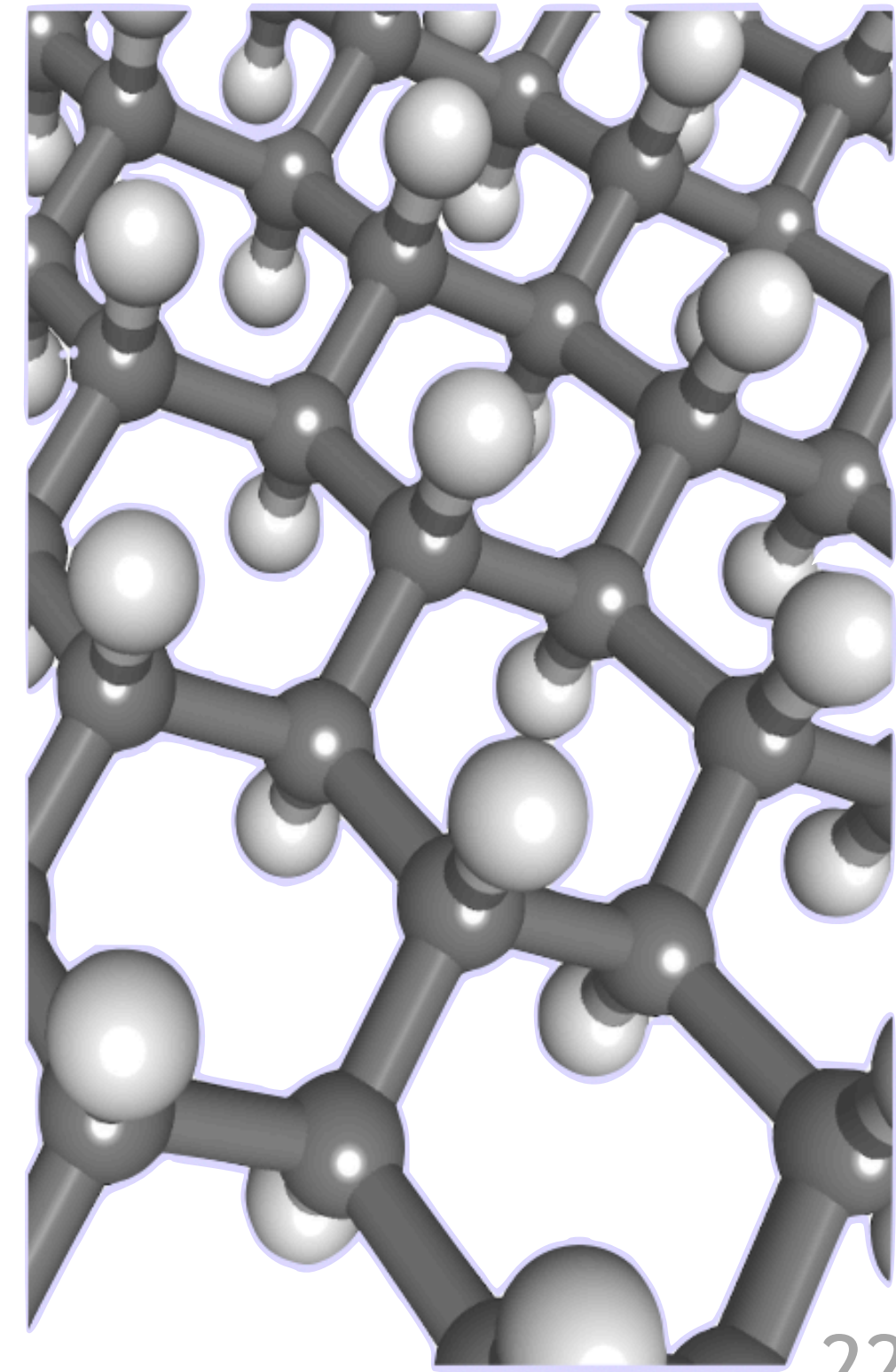
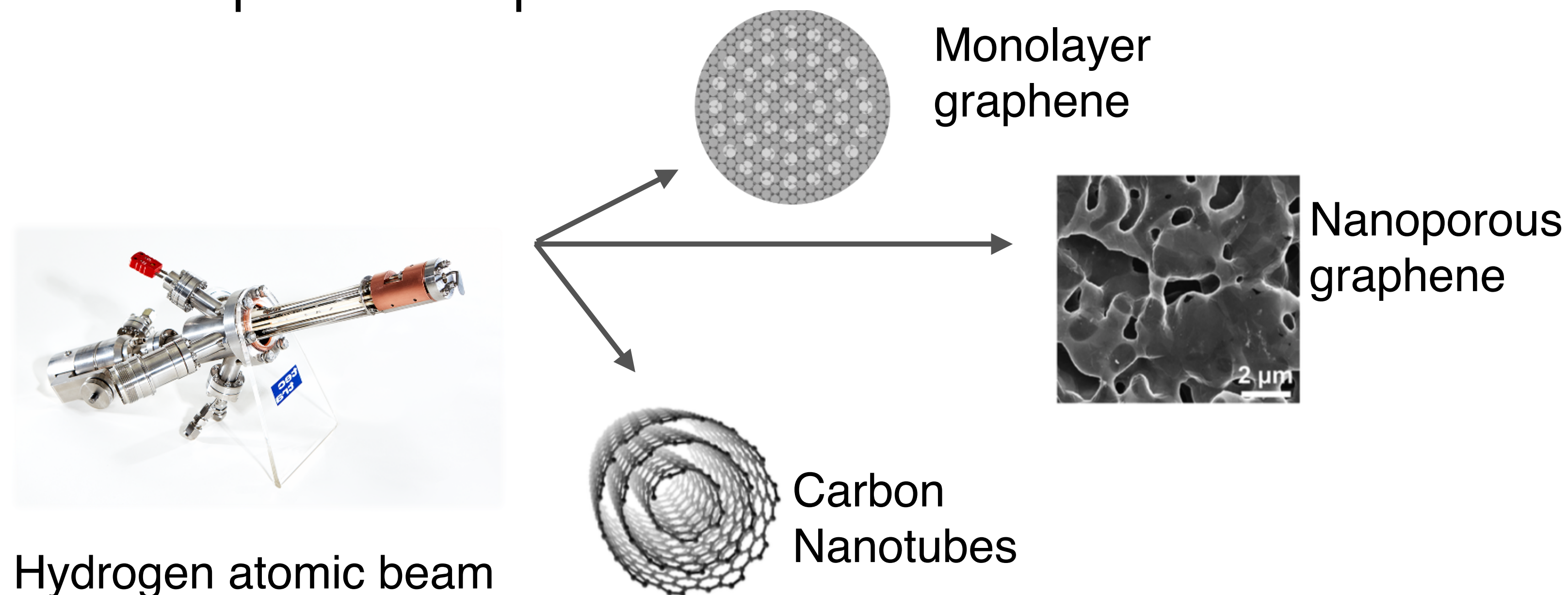
A Different Tritium Approach

- If we need higher T exposure, maybe denser is the way to go?
- For CNB, need $\mathcal{O}(g)$ of effective tritium mass
- Idea: tritiated graphene should be
 - Very compact
 - Stable
 - Engineered to (de)localize captured tritium



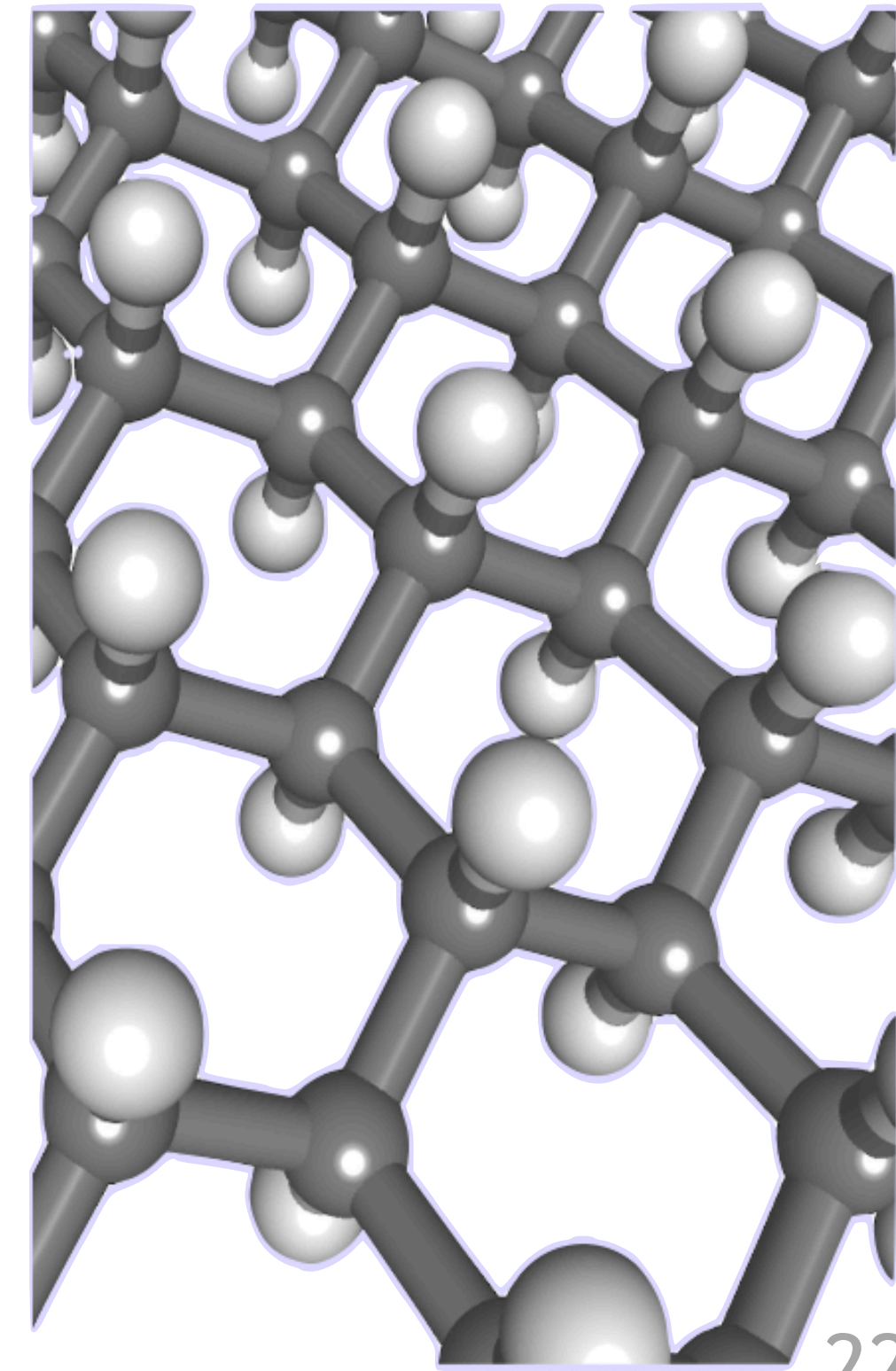
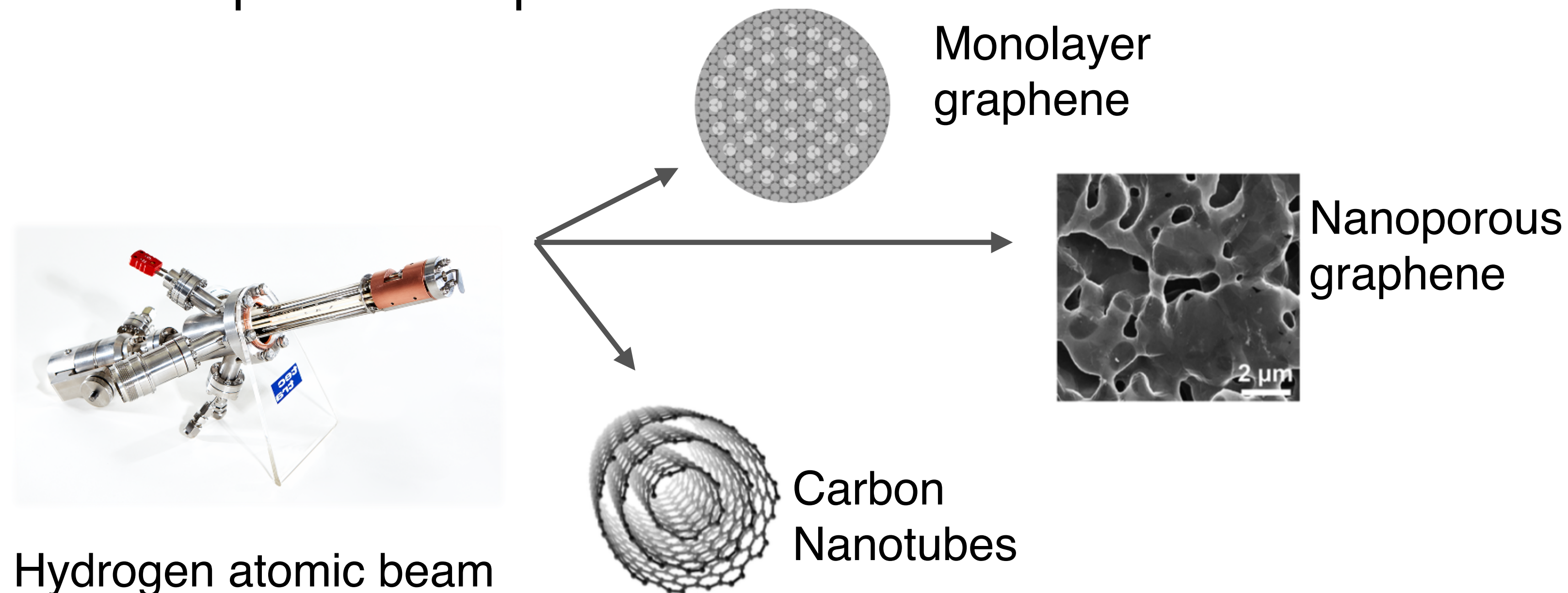
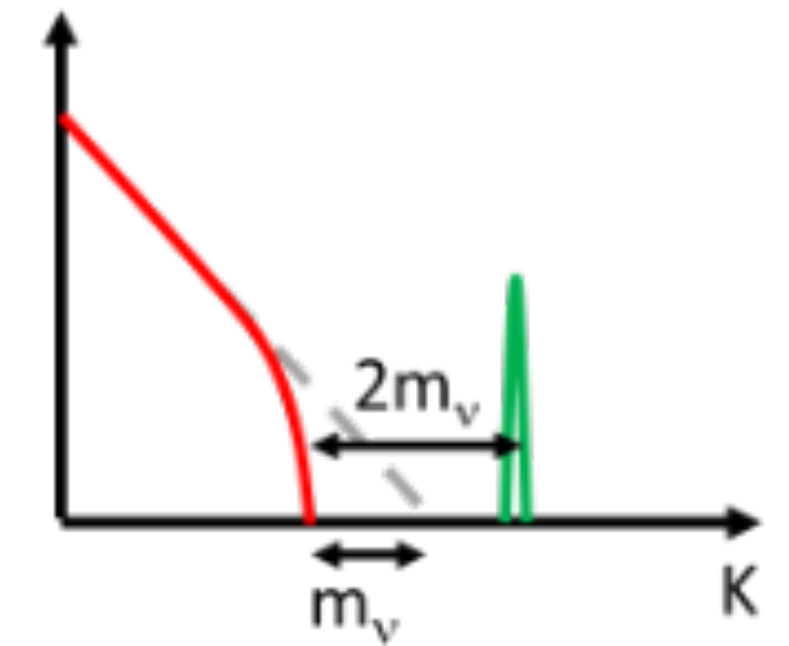
A Different Tritium Approach

- Nanoporous graphene loaded to 90% with H
- Stable after 4 months in UHV
- But it's not atomic: still have to deal with multiple endpoints



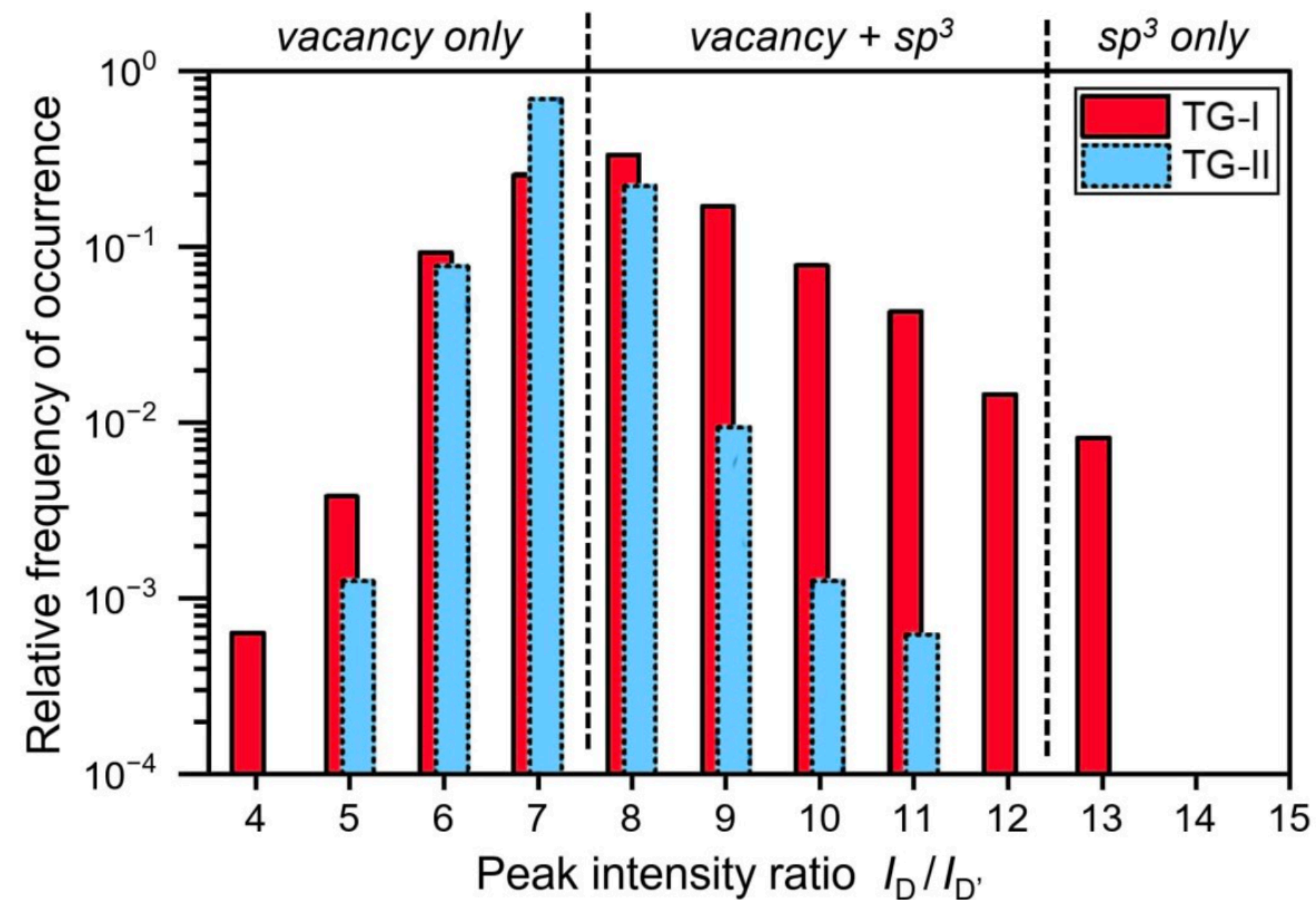
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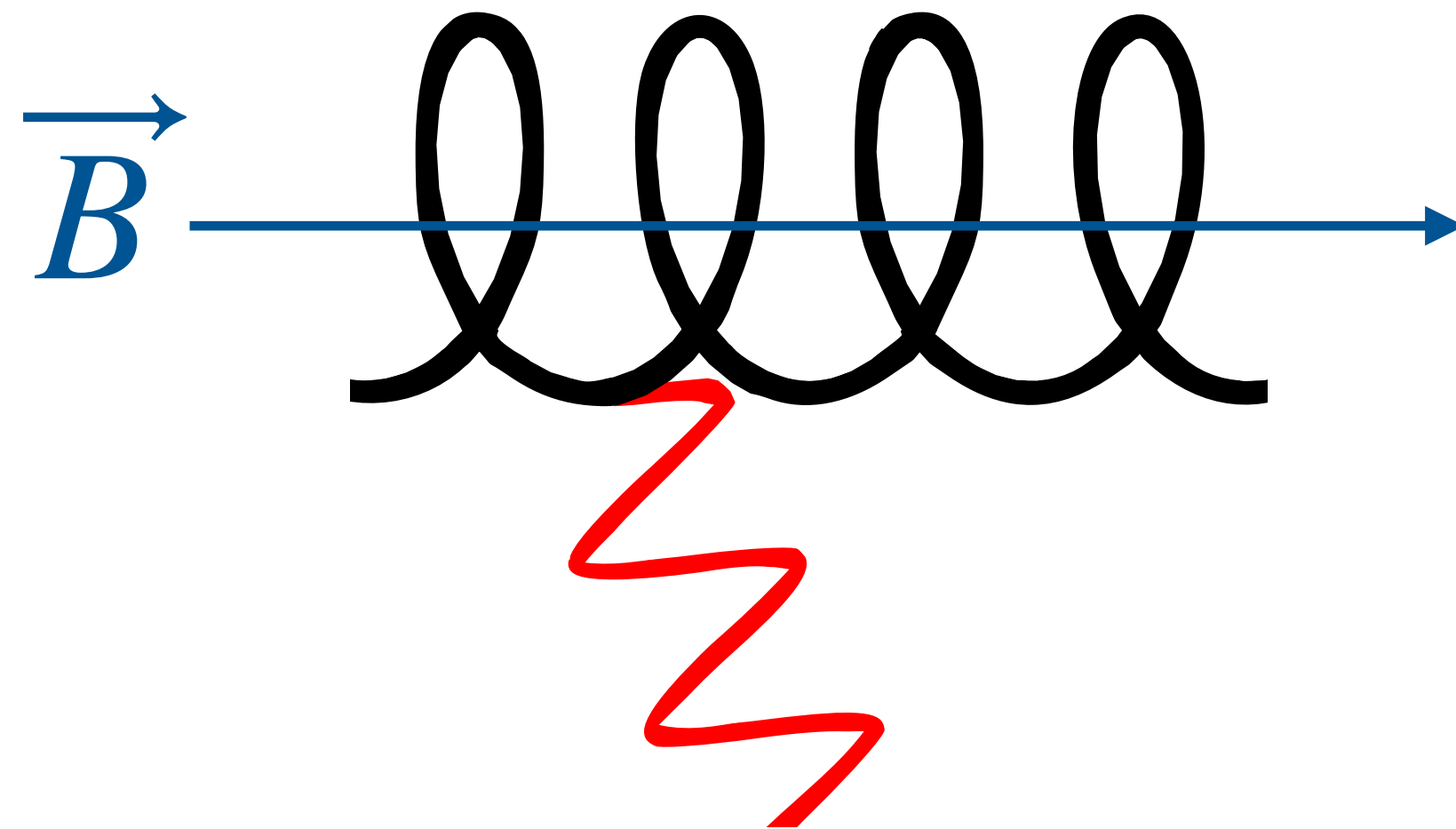
Tritiated Graphene

- Tritiated graphene sample created at TLK by exposing graphene to tritium
- Many defects that “heal” over time
- Stability and outgassing studies ongoing



Based on G. Zeller's NuMass 2026 presentation

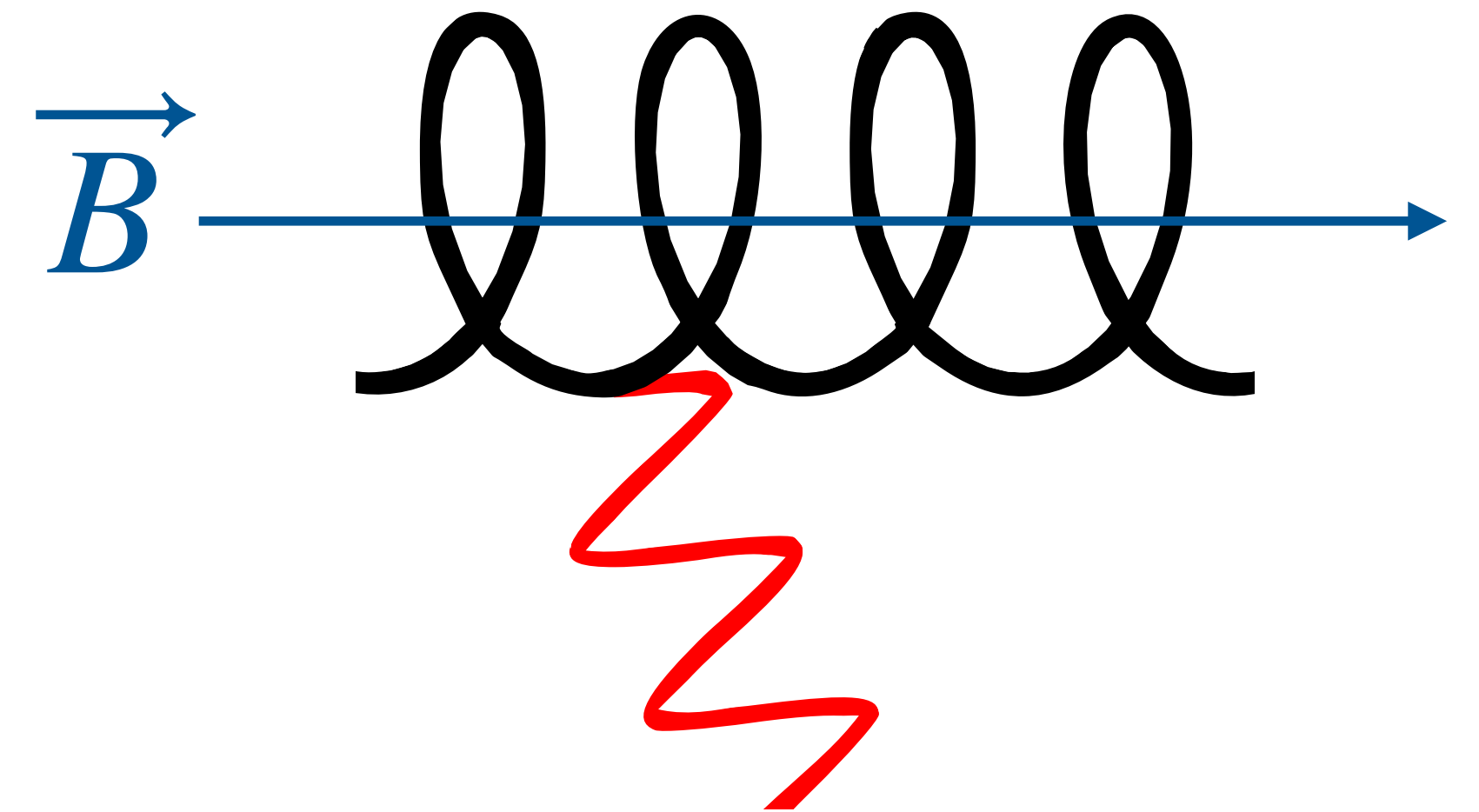
Electron Detection



PROJECT 8 Cyclotron Radiation Emission Spectroscopy (CRES)

- Electron in B-field: cyclotron motion & radiation

$$2\pi f = \frac{e\langle B \rangle}{m_e + K_e/c^2}$$



“Never measure anything but frequency!” — A. L. Schawlow

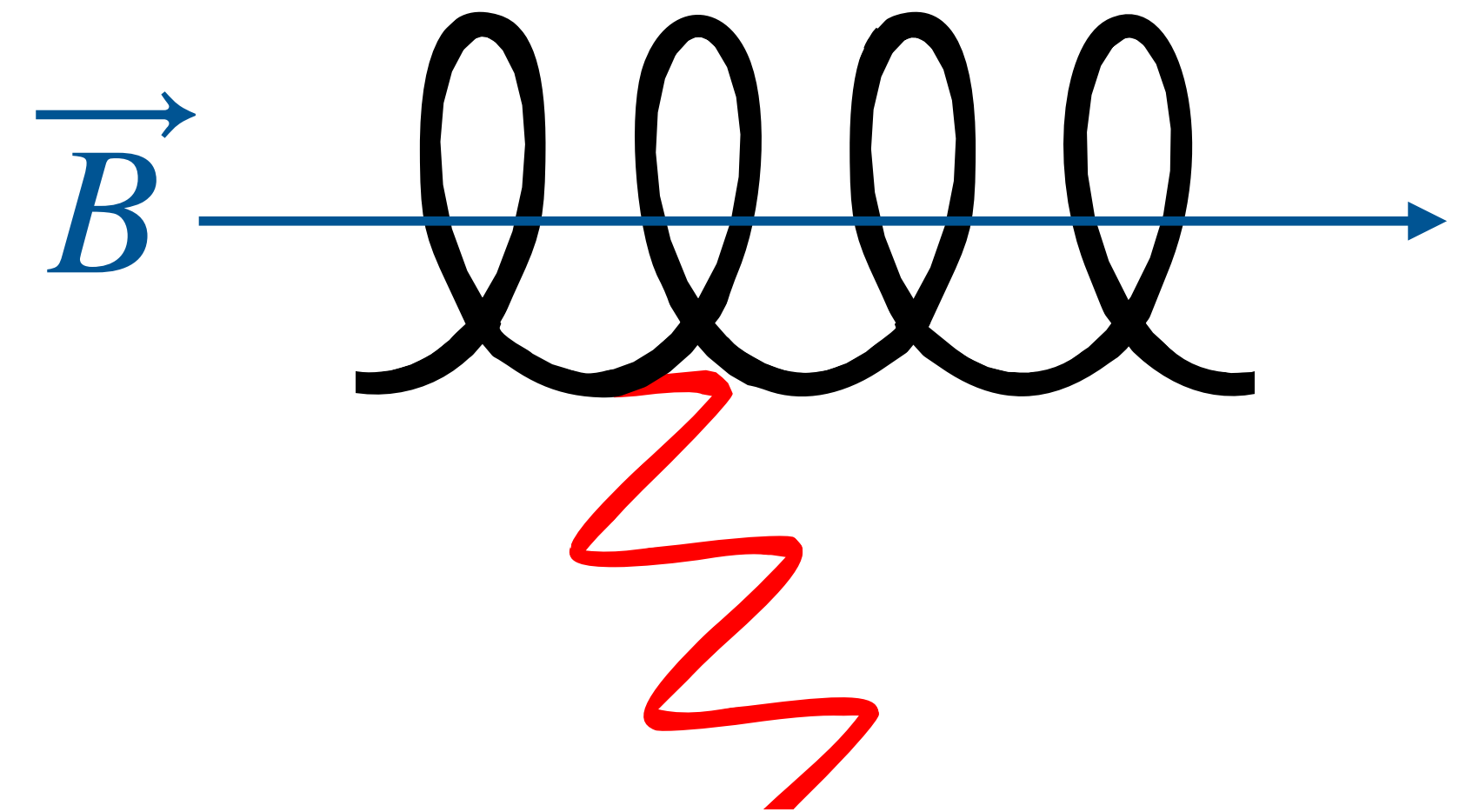
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$$\frac{\Delta E}{m_e} = \frac{\Delta f}{f}$$



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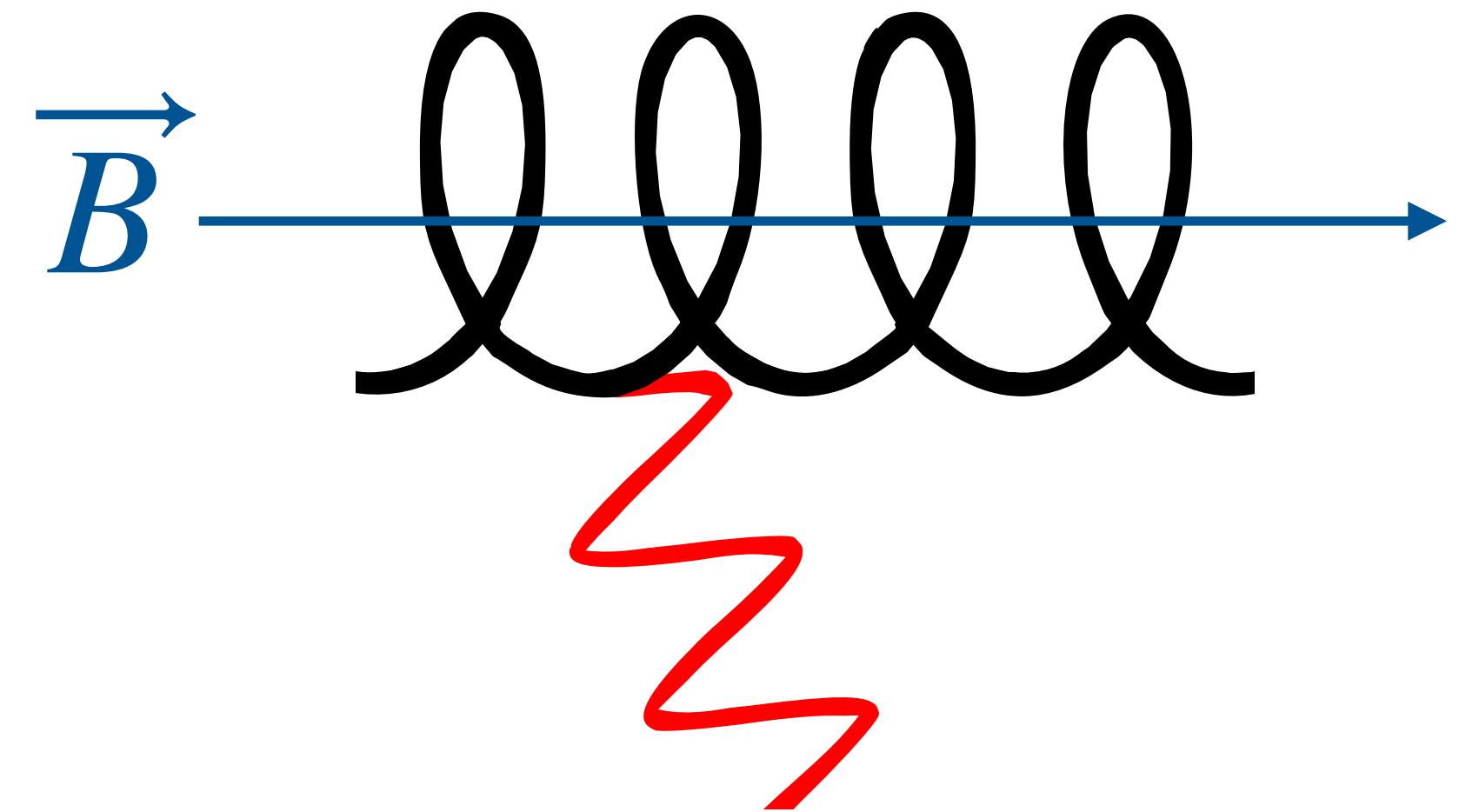
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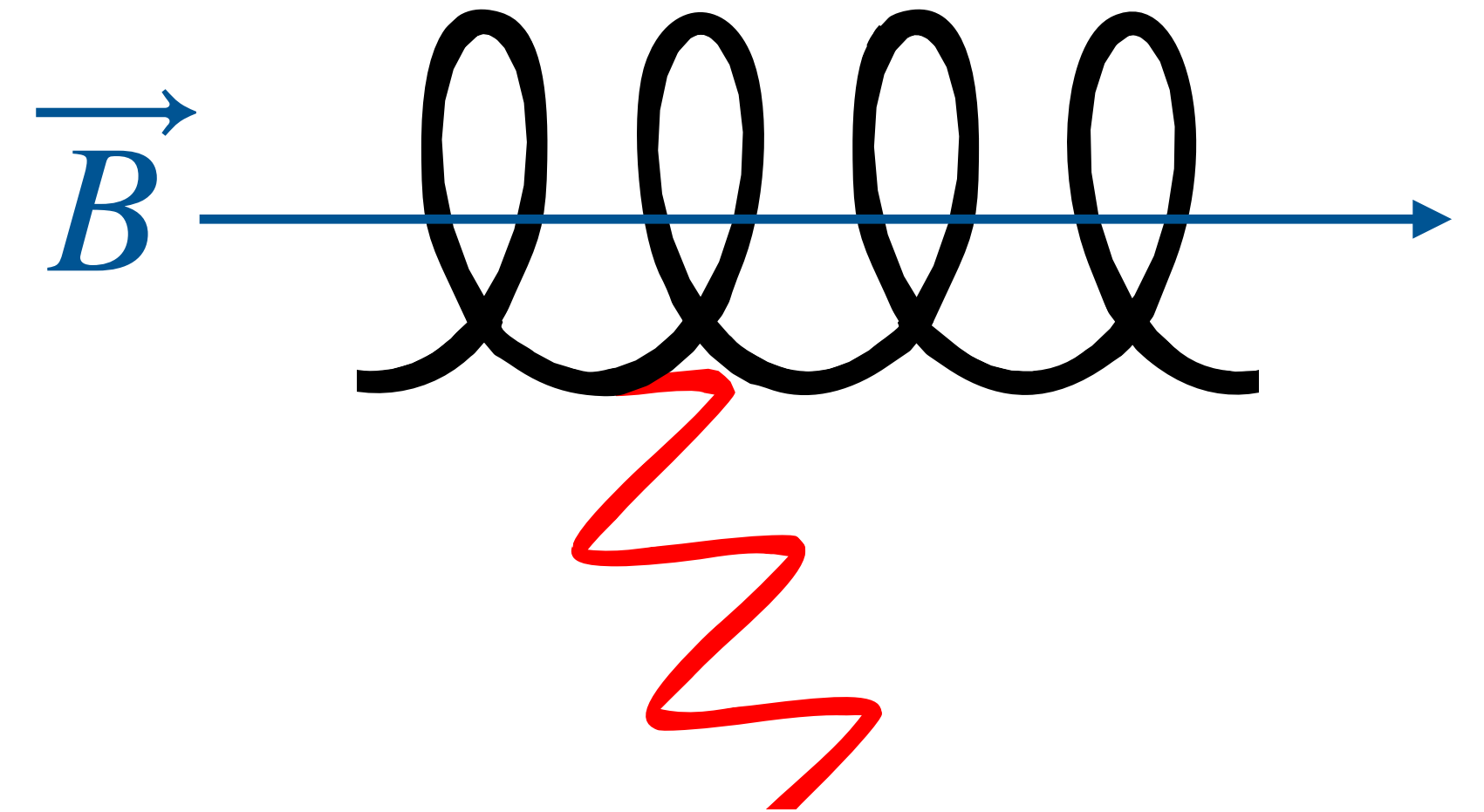
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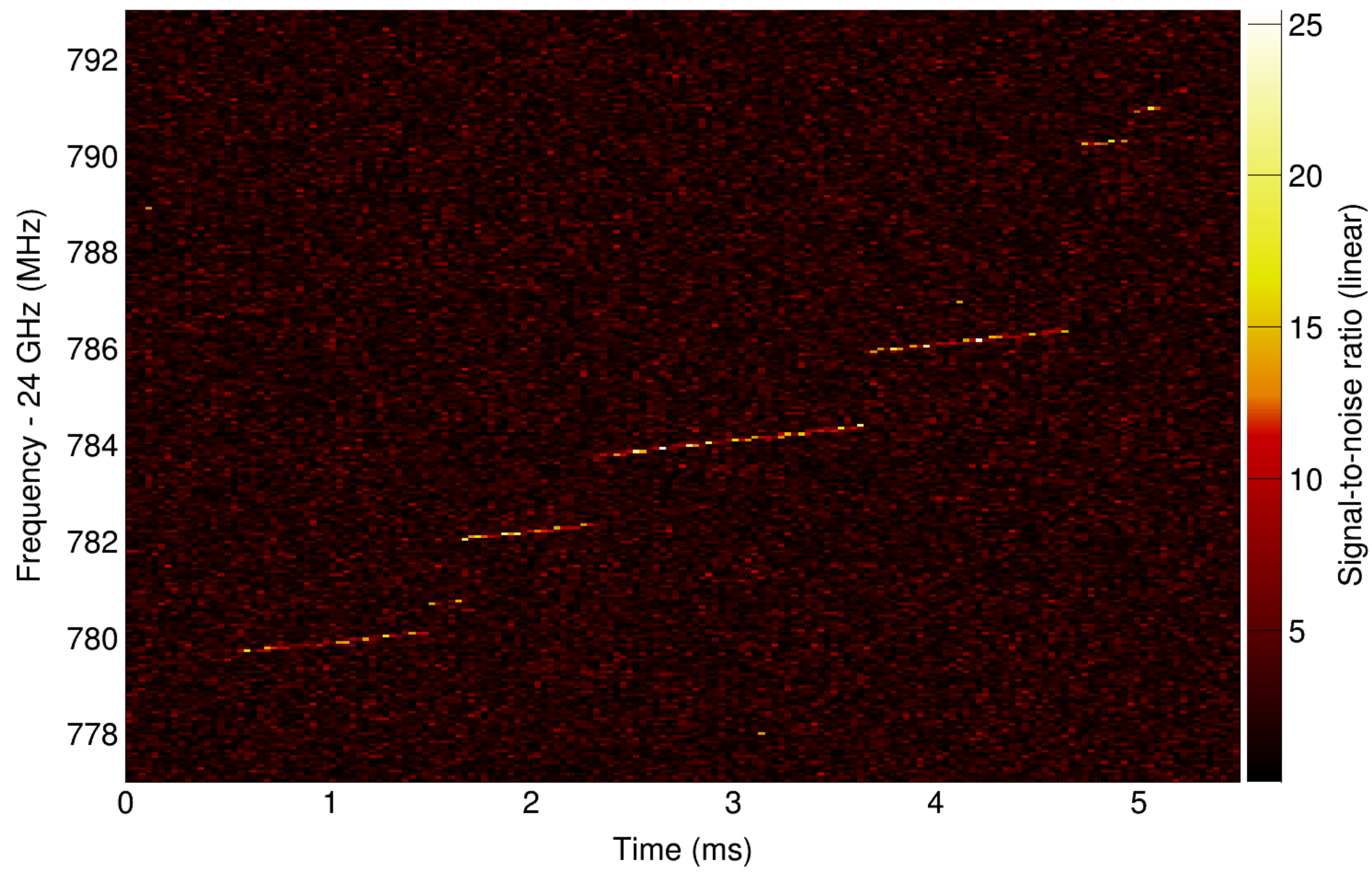
“Never measure anything but frequency!” — A. L. Schawlow



CRES advantages

- + high precision
- + ^3H transparent to radiation
- + no electron transport: no losses, no backgrounds
- + differential - high statistics

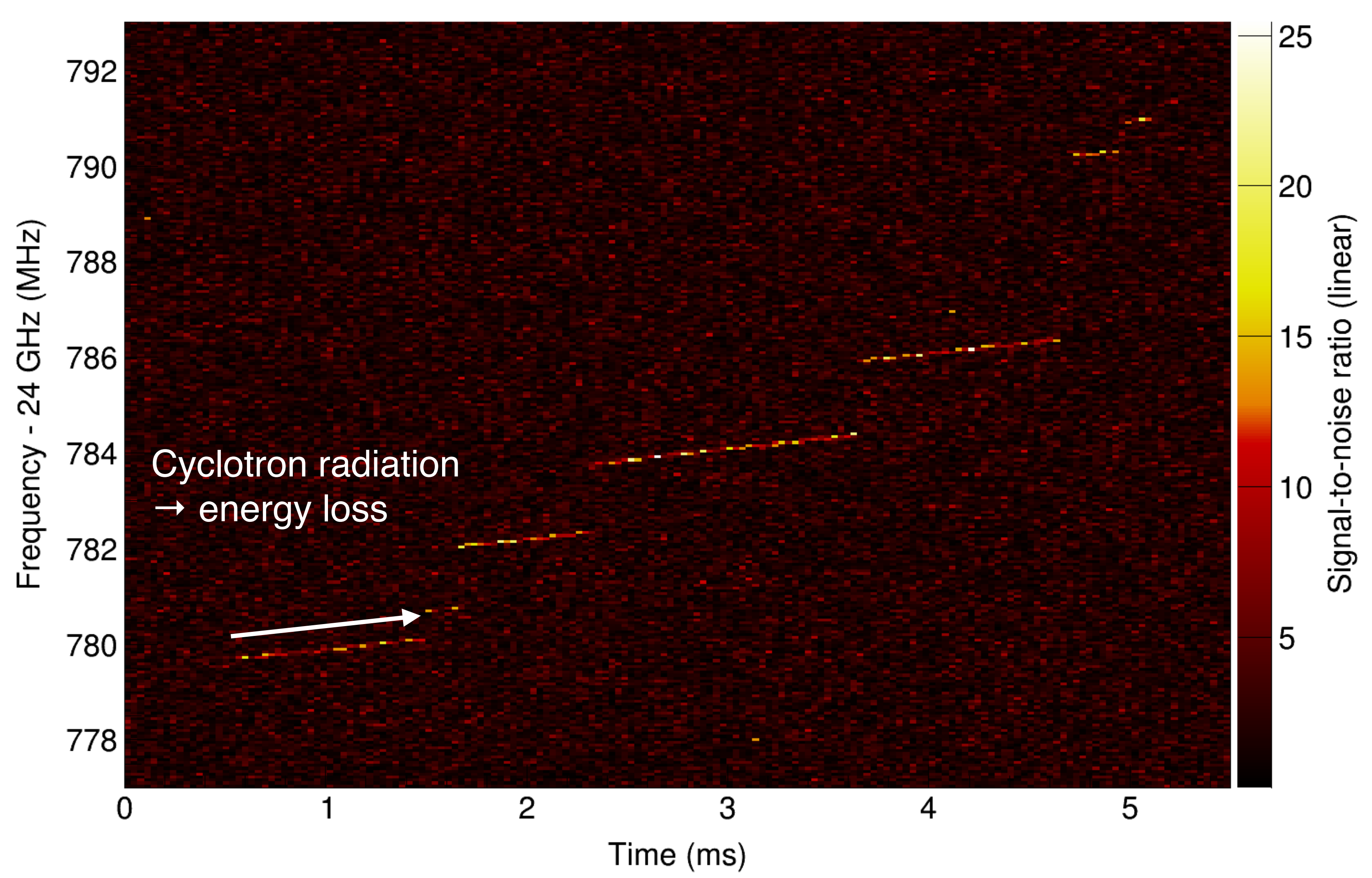
A Typical* CRES Event & Spectrum



* so far

$$2\pi f = \frac{e\langle B \rangle}{m_e + K_e/c^2}$$

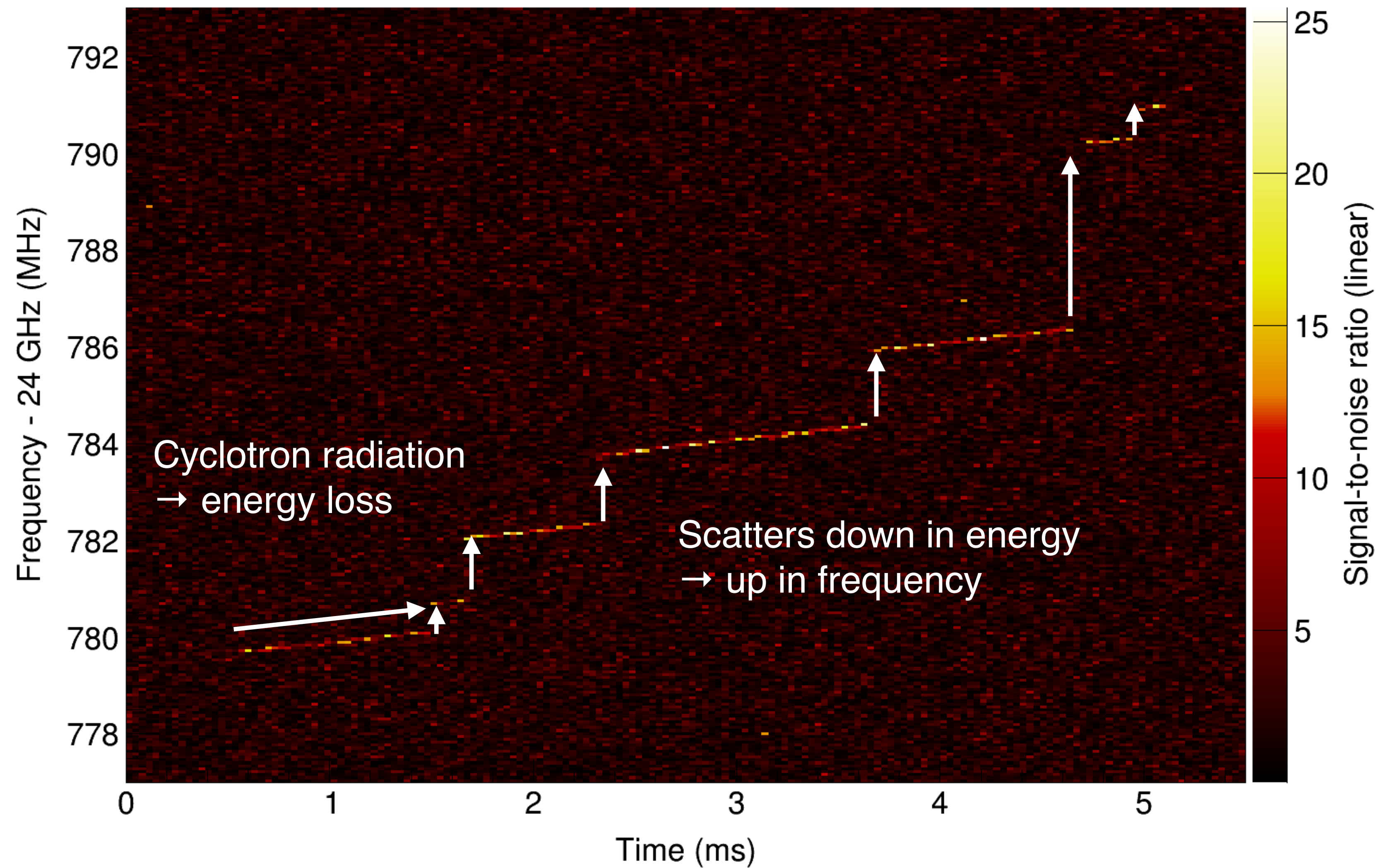
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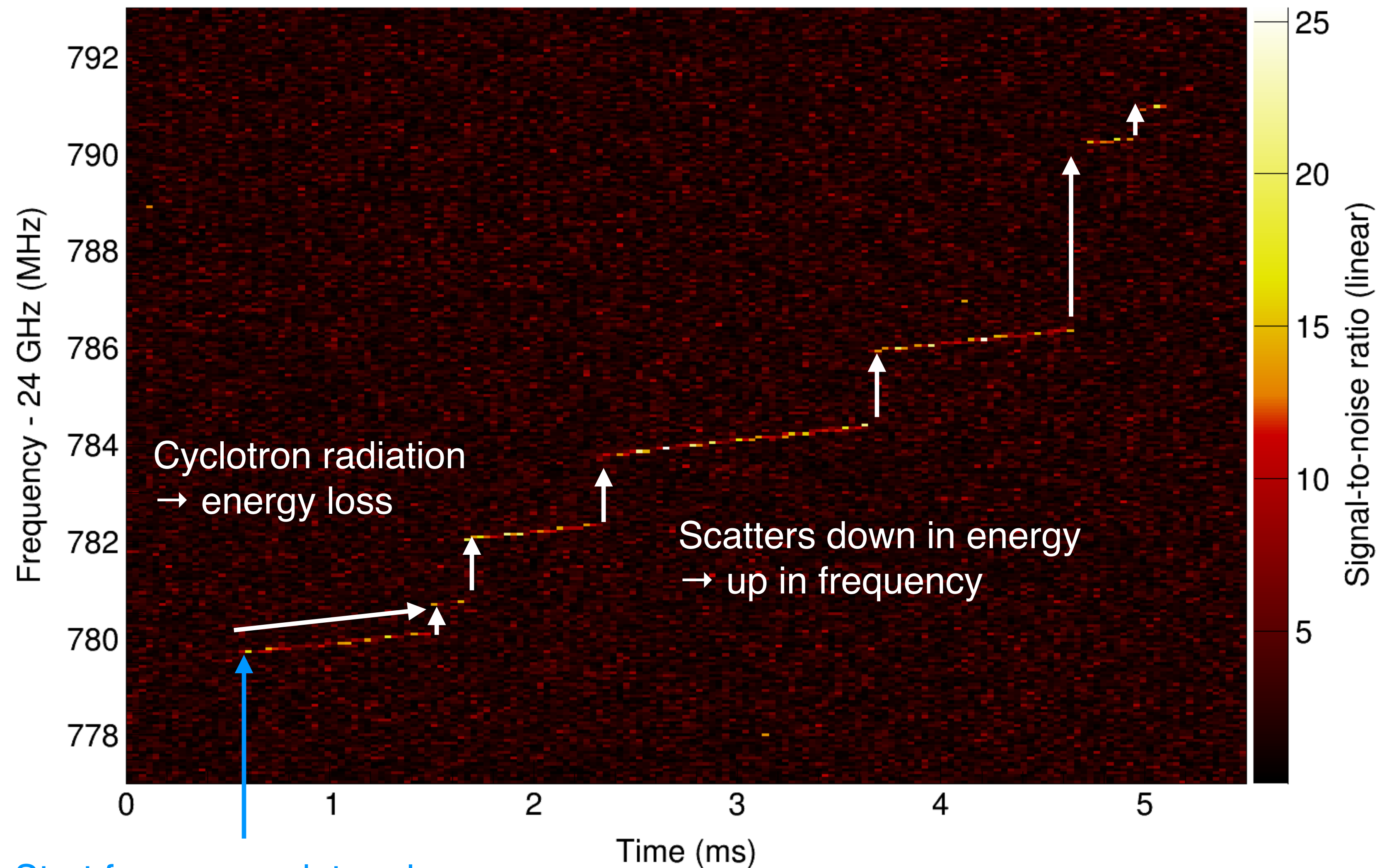
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A Typical* CRES Event & Spectrum



Start frequency: determines
electron energy before losses

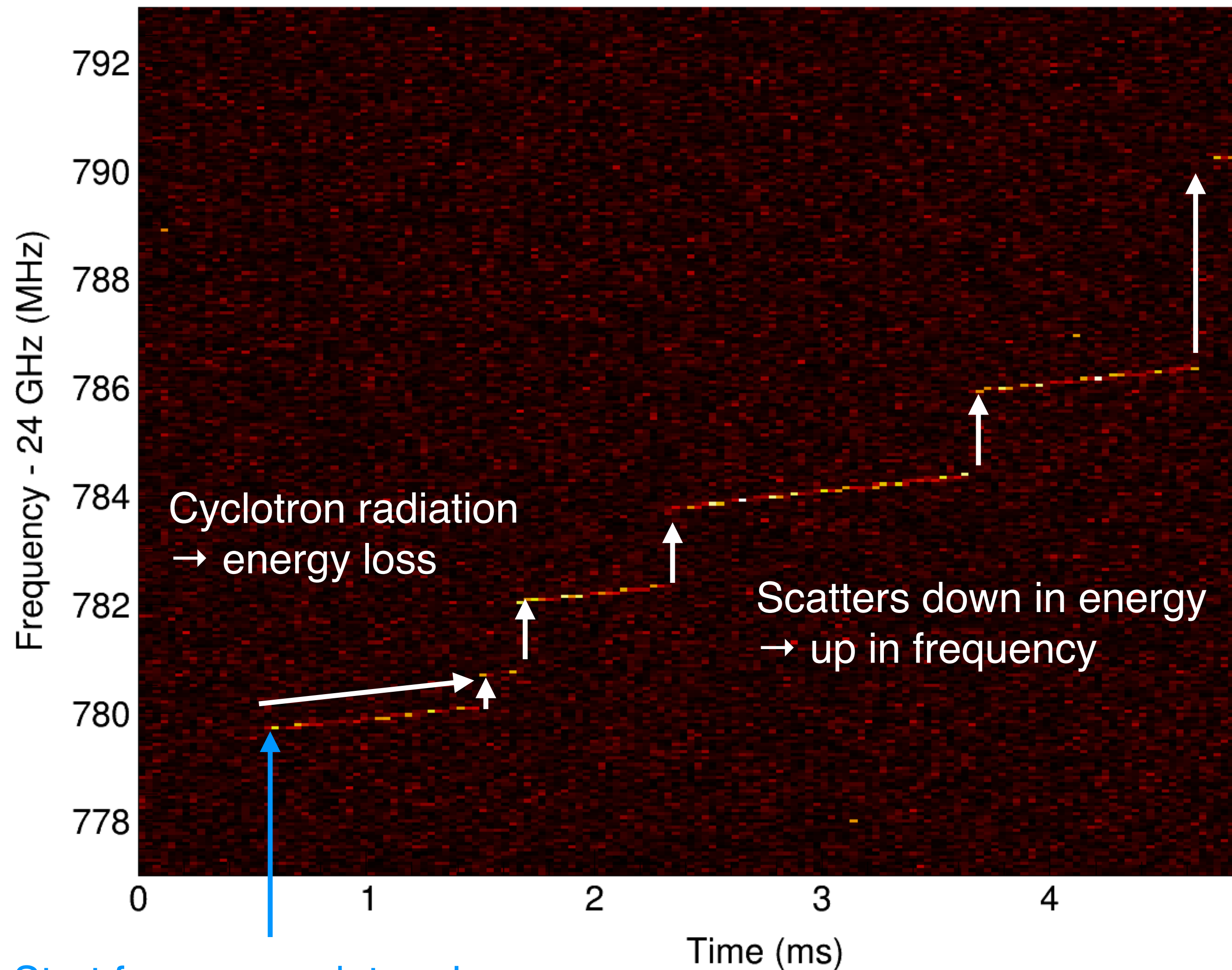
[PRL 114, 162501](#) (2015)

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[PRL 131, 102502](#) (2023)

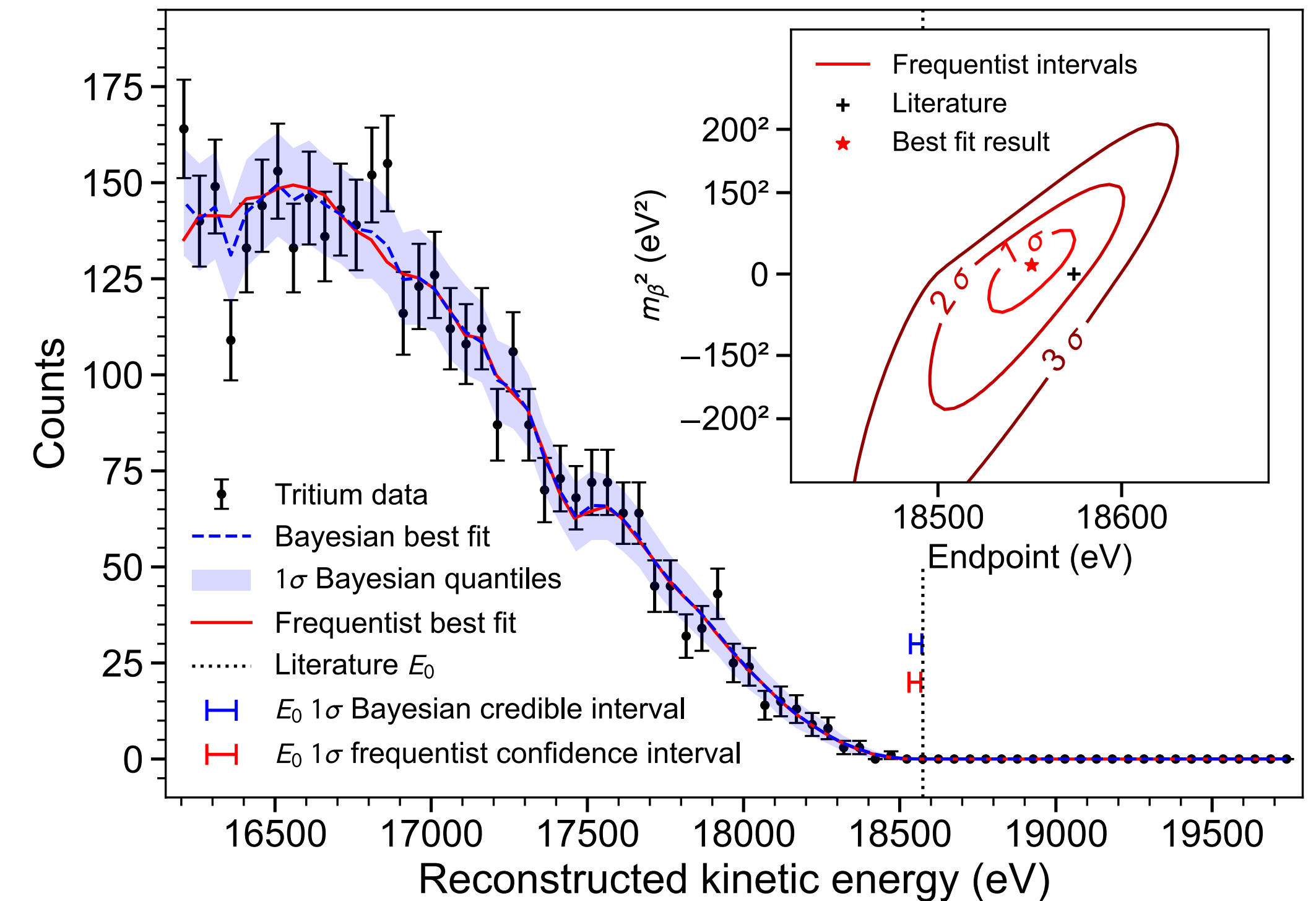
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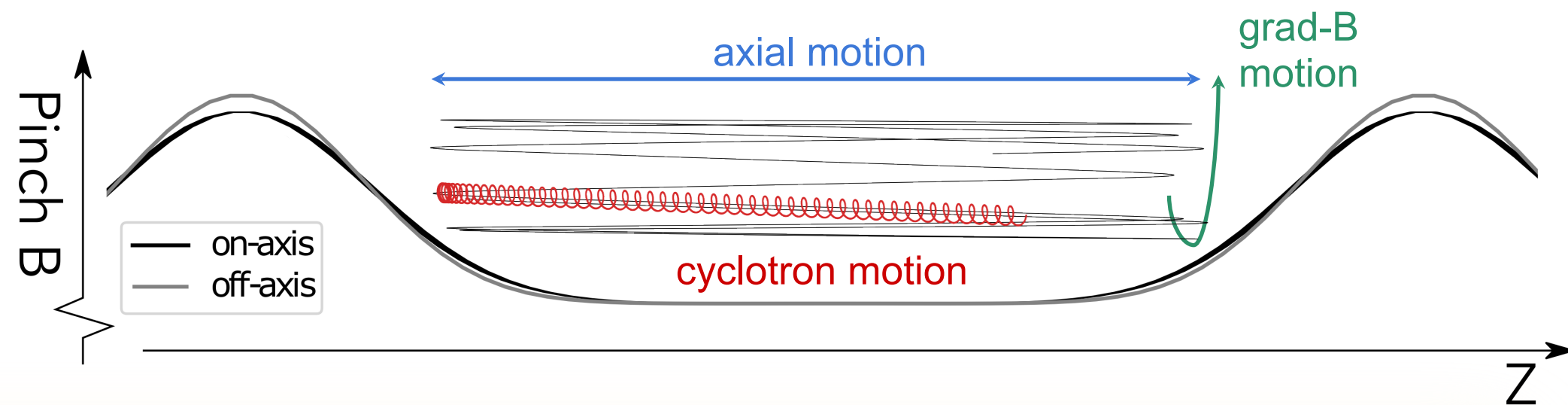
[PRL 114, 162501](#) (2015)

- First neutrino mass upper limit with CRES:
 $m_{\nu_e, \text{eff}} \leq 155 \text{ eV}/c^2$ (90 % C.L.)
- Zero background observed
- High energy resolution: $1.7 \pm 0.2 \text{ eV}$ (FWHM)



[PRL 131, 102502](#) (2023)

CRES Electron Motion

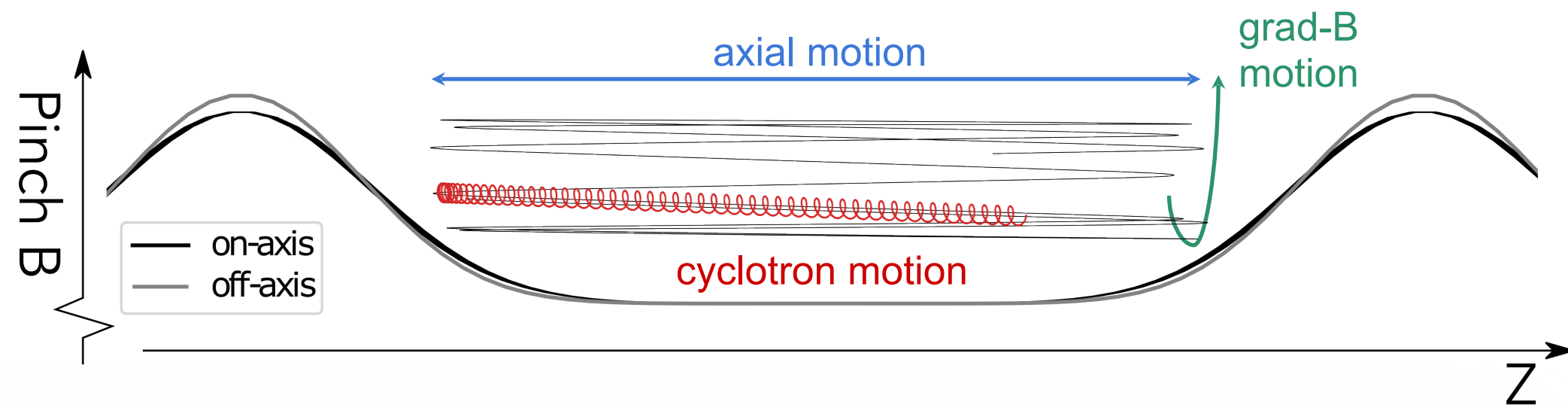


- Electron trapped in magnetic field
- Three superimposed motions:
 - Cyclotron motion with frequency

$$f_c = \frac{1}{2\pi} \frac{e \langle B \rangle}{m_e + E/c^2}$$

average magnetic field
along electron trajectory

- Axial motion with frequency f_a that depends on trap design and electron's pitch angle
- Grad-B motion $f_{\nabla B}$ from magnetic trapping field gradient



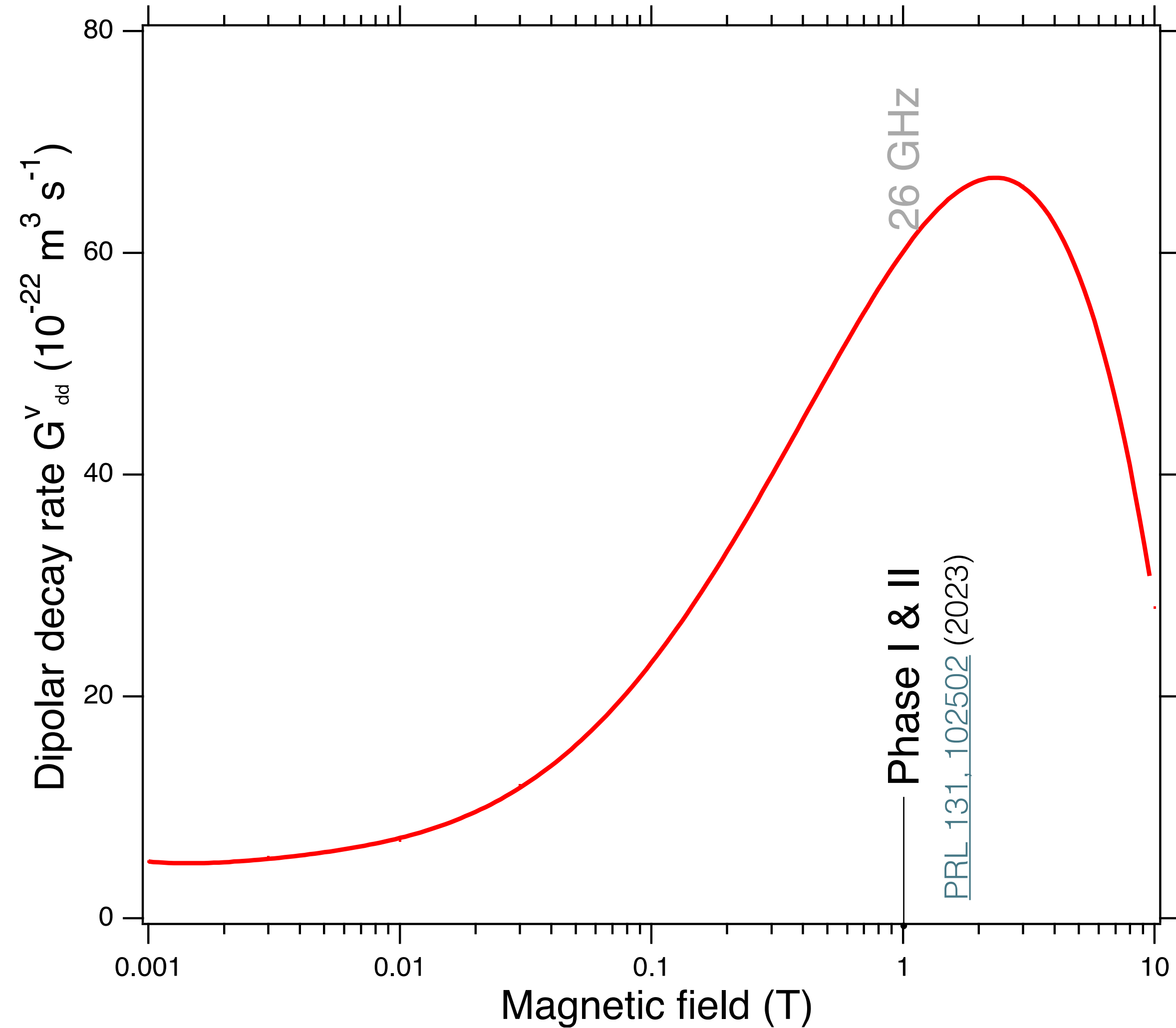
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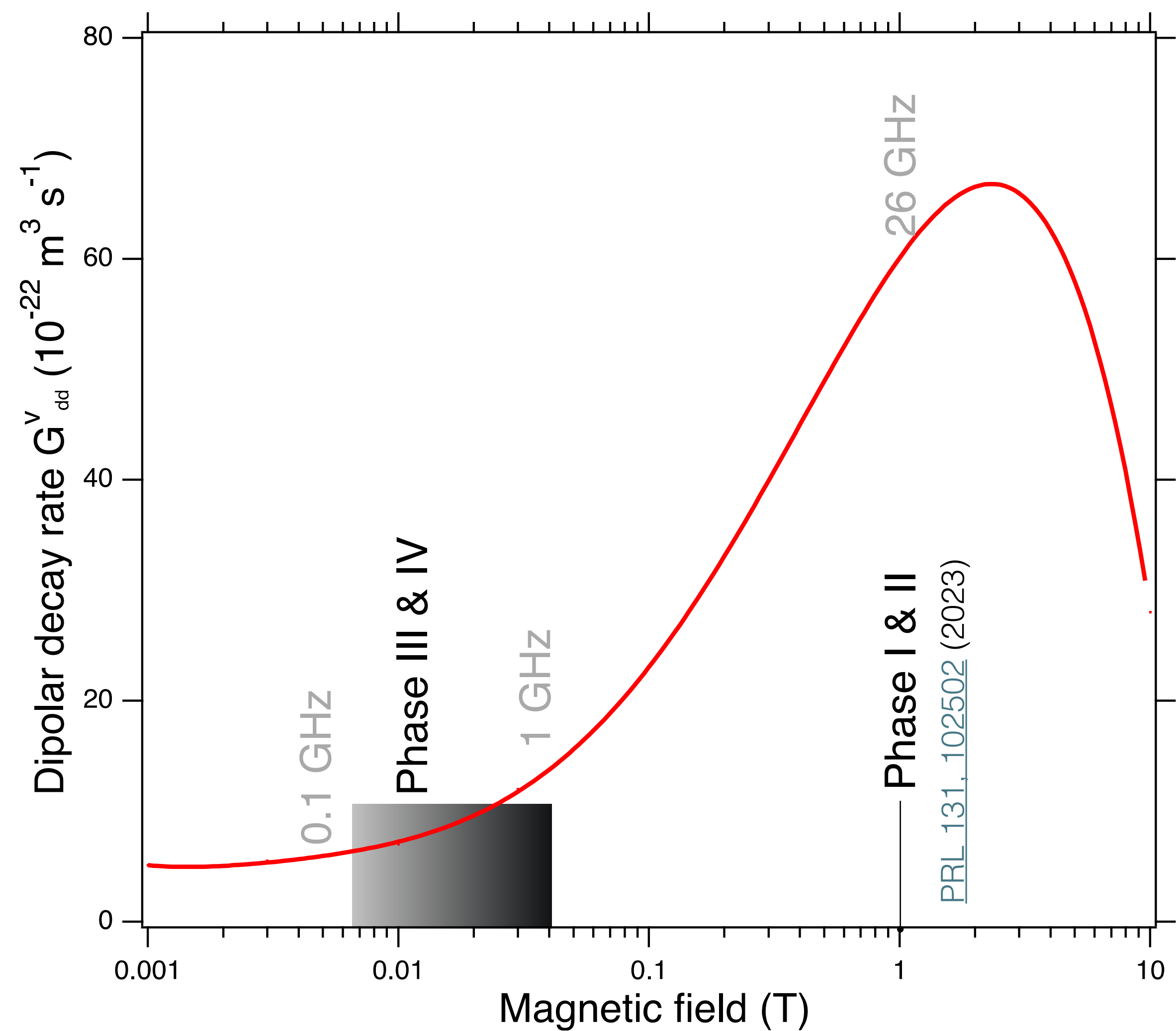
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- Low CRES fields for atomic tritium trapping
→ low emitted powers



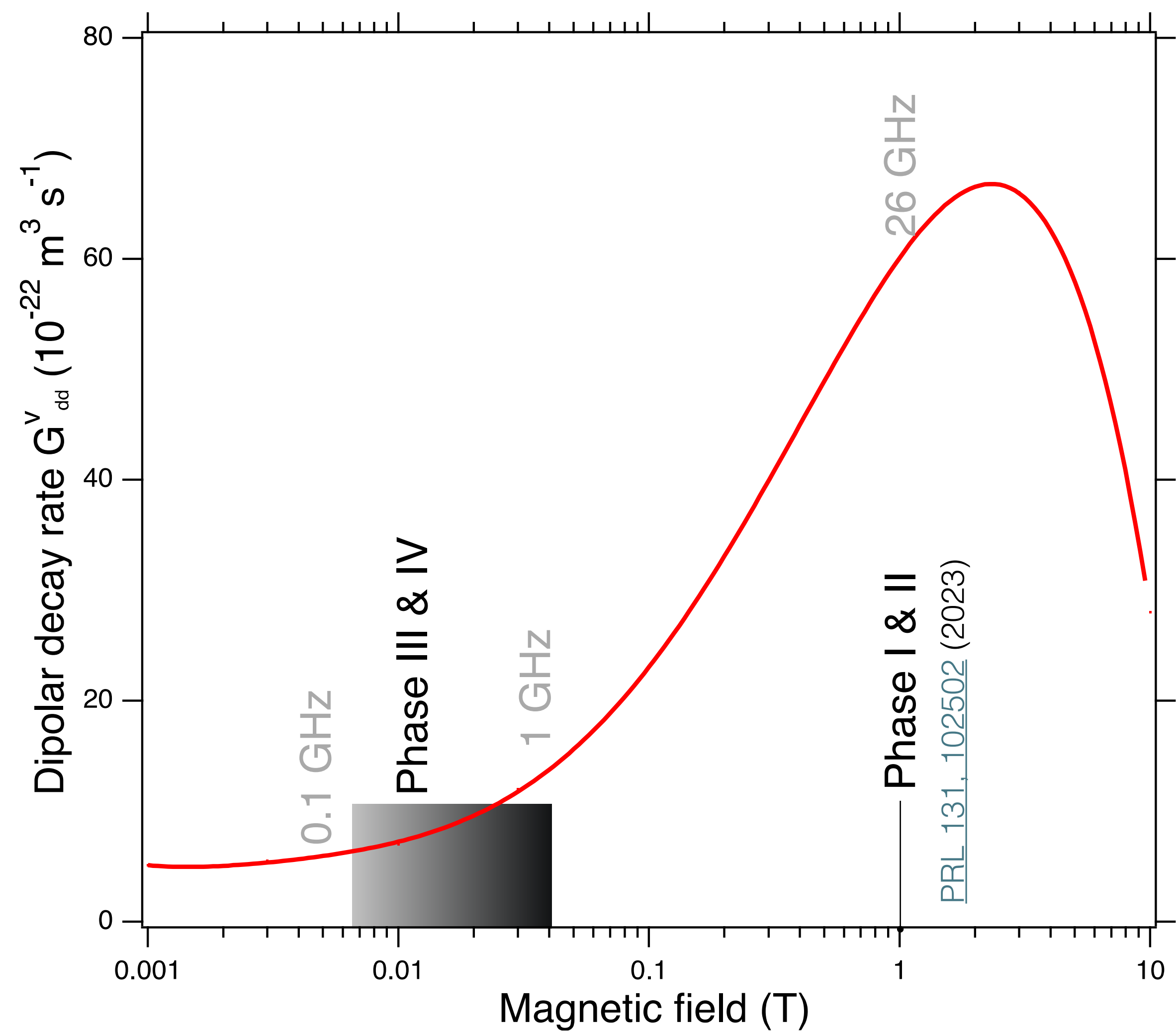
Challenge: Large-Volume CRES

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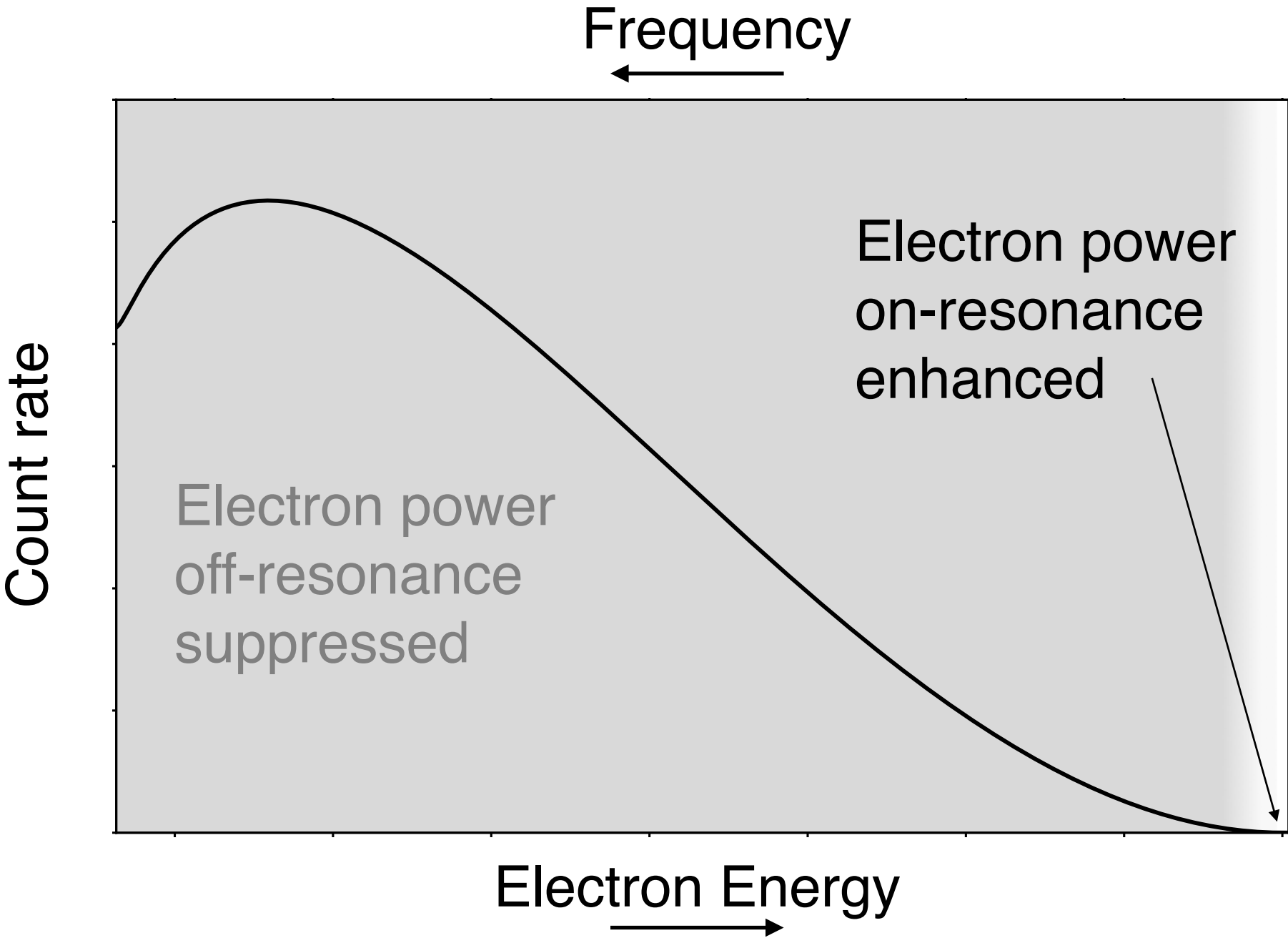


Challenge: Large-Volume CRES

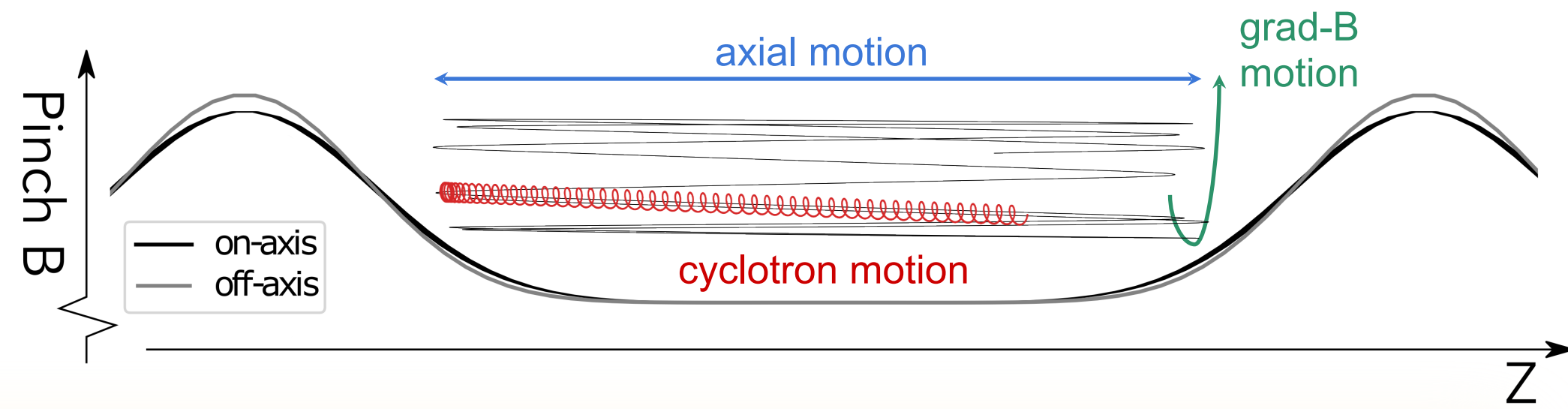
- Low CRES fields for atomic tritium trapping
→ low emitted powers
- Large volumes for high statistics



- Low CRES fields for atomic tritium trapping
→ low emitted powers
- Large volumes for high statistics
- Solution are large resonant cavities:
 - Large volumes at low frequencies
 - Resonant enhancement of electron signal
 - Compatible with atomic tritium

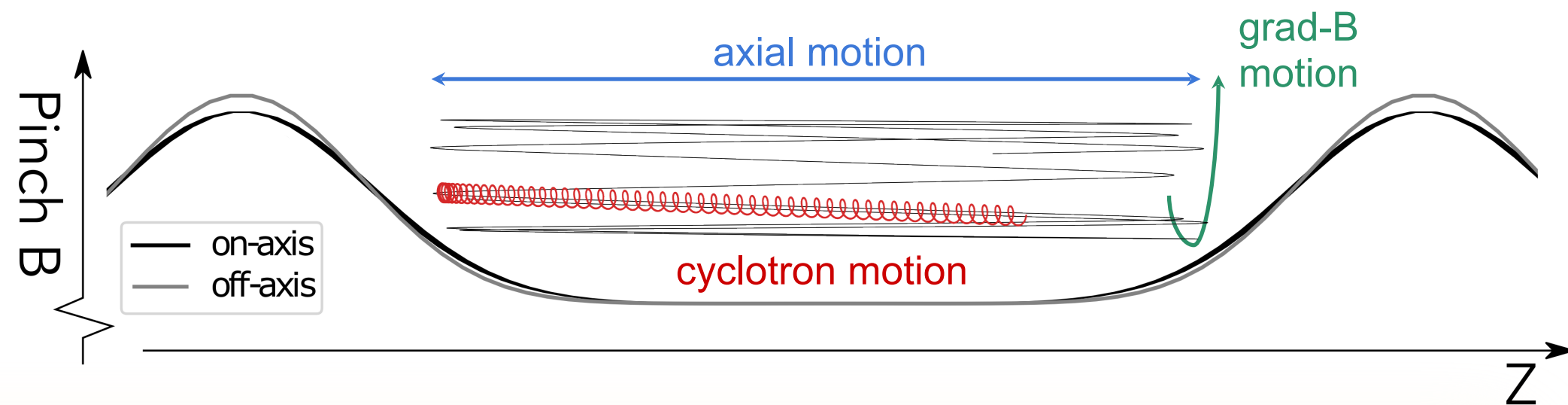


CRES in Cavities

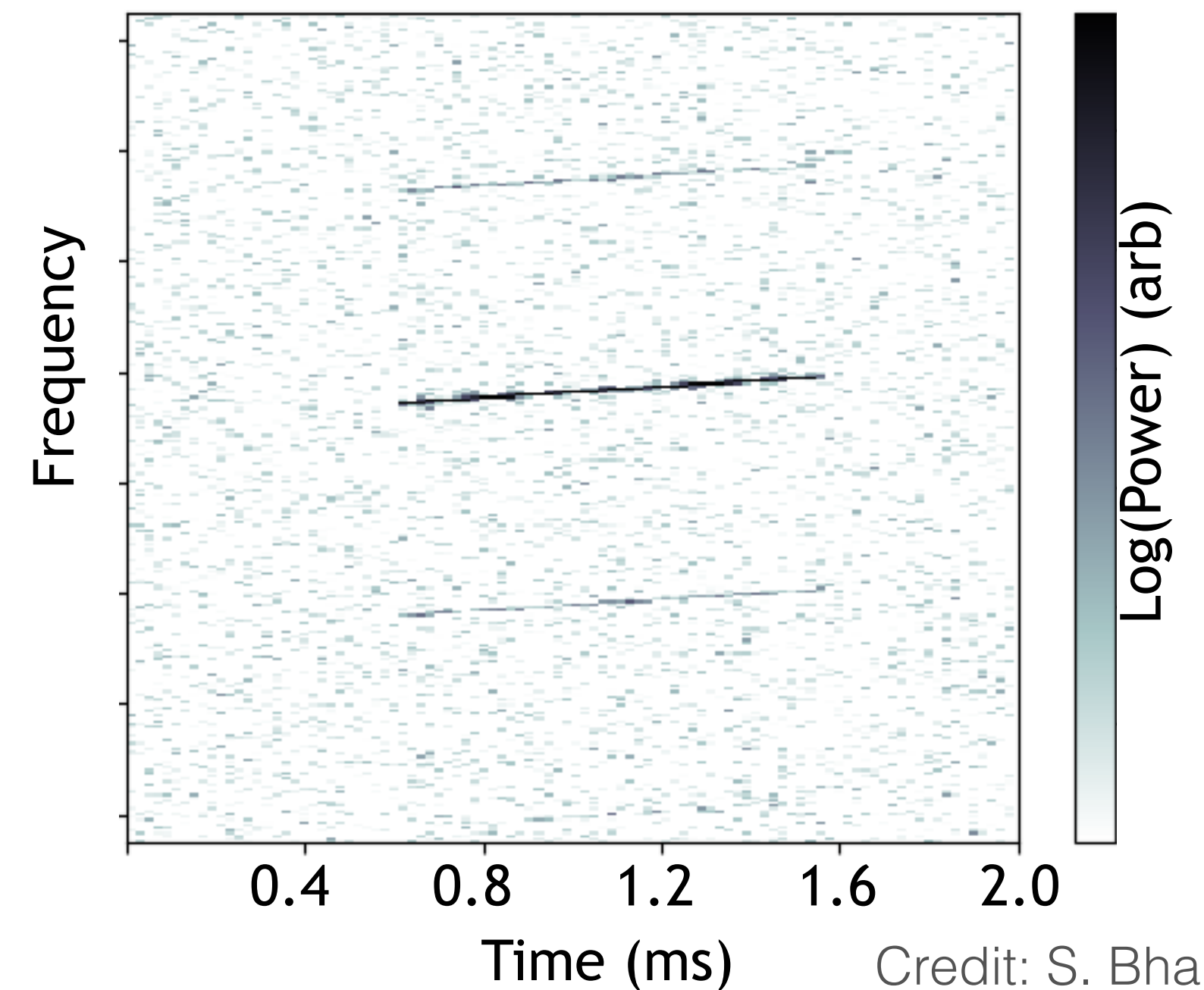


- $\langle B \rangle$ experienced by electrons depends on pitch angle

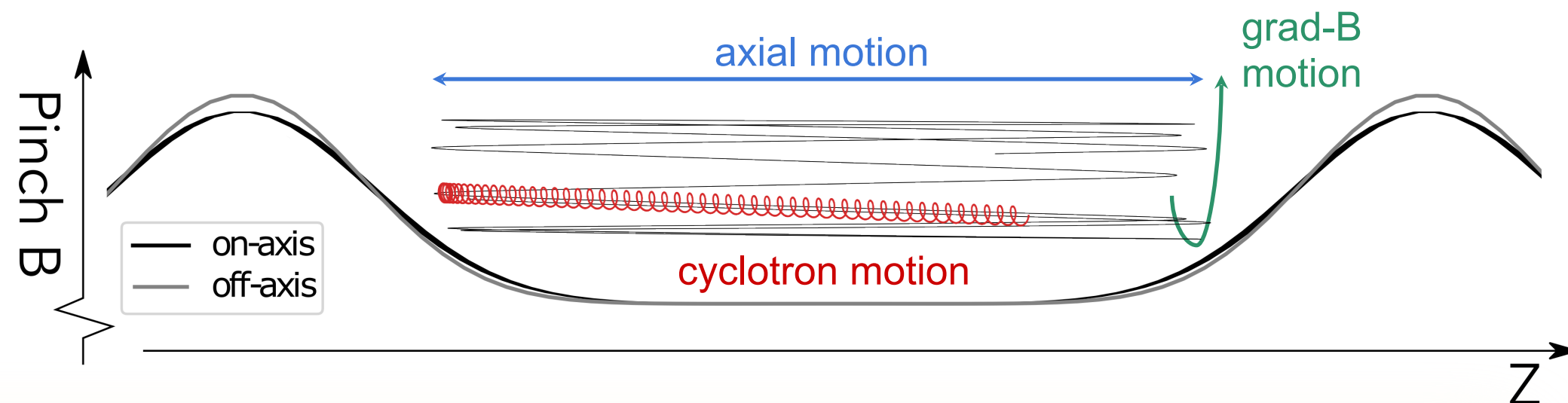
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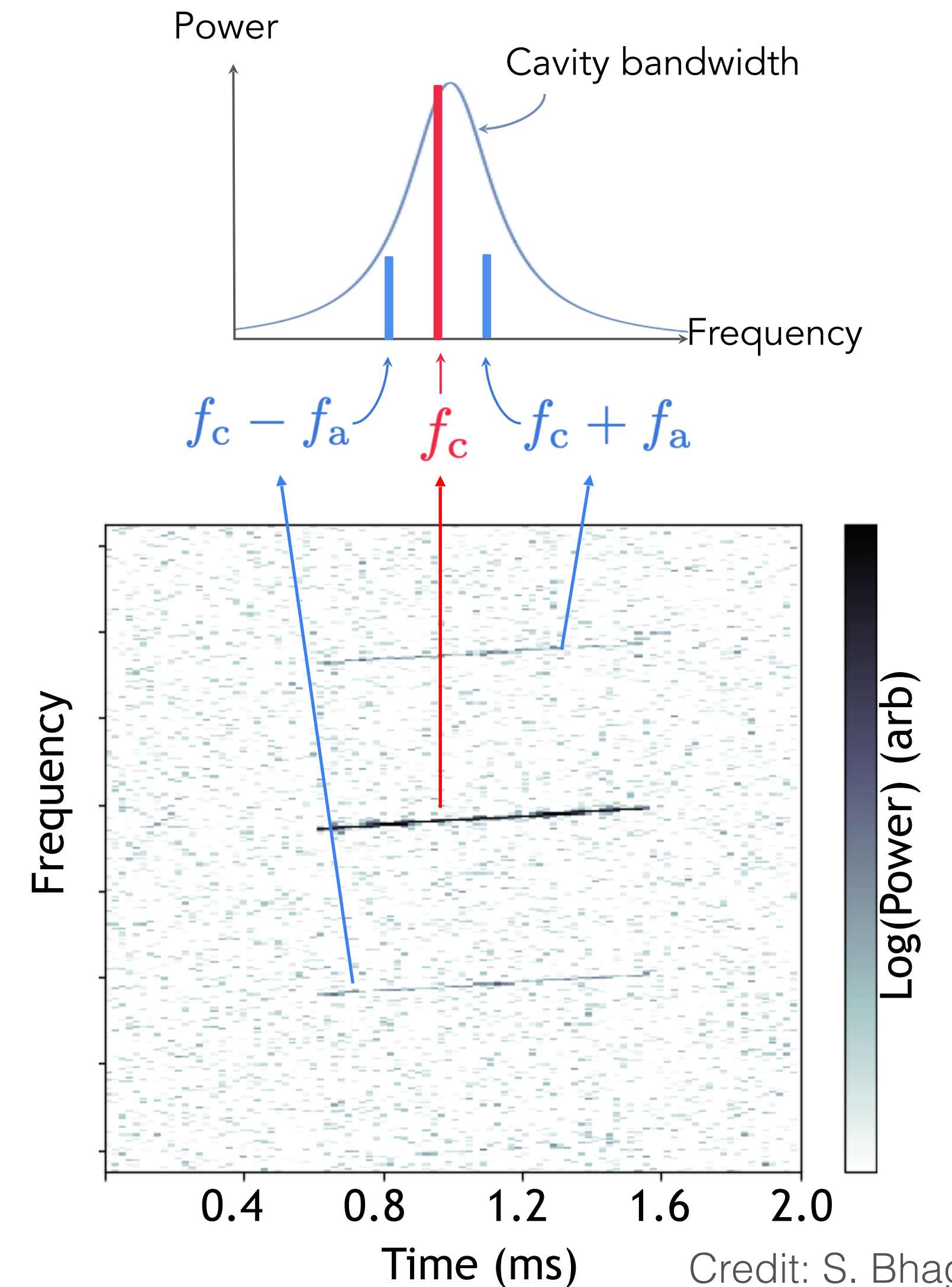
- $\langle B \rangle$ experienced by electrons depends on pitch angle
- Necessitates the detection of the carrier frequency and a sideband
 - links $\langle B \rangle$ to individual electron
 - allows accurate energy reconstruction



CRES in Cavities



- $\langle B \rangle$ experienced by electrons depends on pitch angle
- Necessitates the detection of the carrier frequency and a sideband
 - links $\langle B \rangle$ to individual electron
 - allows accurate energy reconstruction
- Range of axial motions sets bandwidth requirements for the cavity design



Credit: S. Bhagvati

- Scale up in volume:
 - $f = 560 \text{ MHz}$, $B = 0.02 \text{ T}$, $V \sim 1.5 \text{ m}^3 \rightarrow \mathcal{O}(10^5)$ larger than current demonstrator
- Scale down in collected power:
 - $P \propto B^2 \rightarrow 0.05\%$ of radiated power compared to previous demonstrator

ONE DOES NOT SIMPLY

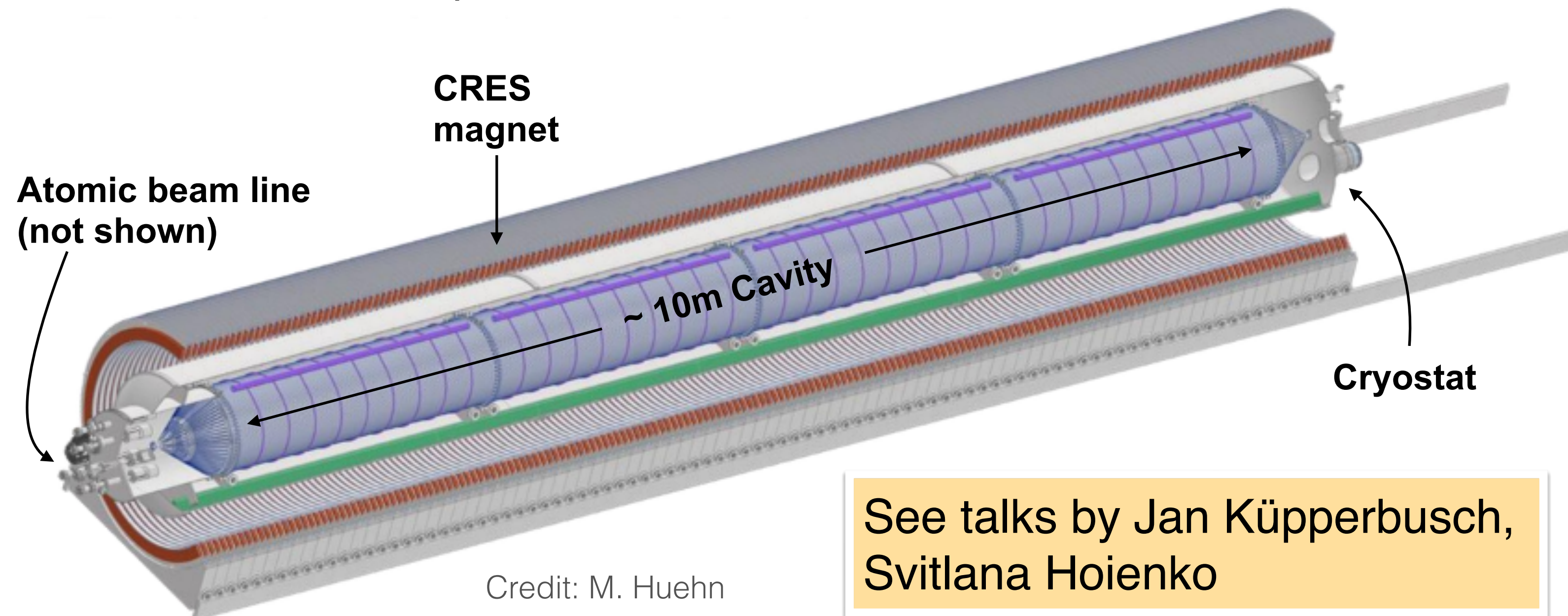


SCALE A DETECTOR BY ORDERS OF MAGNITUDE

- Scale up in volume:
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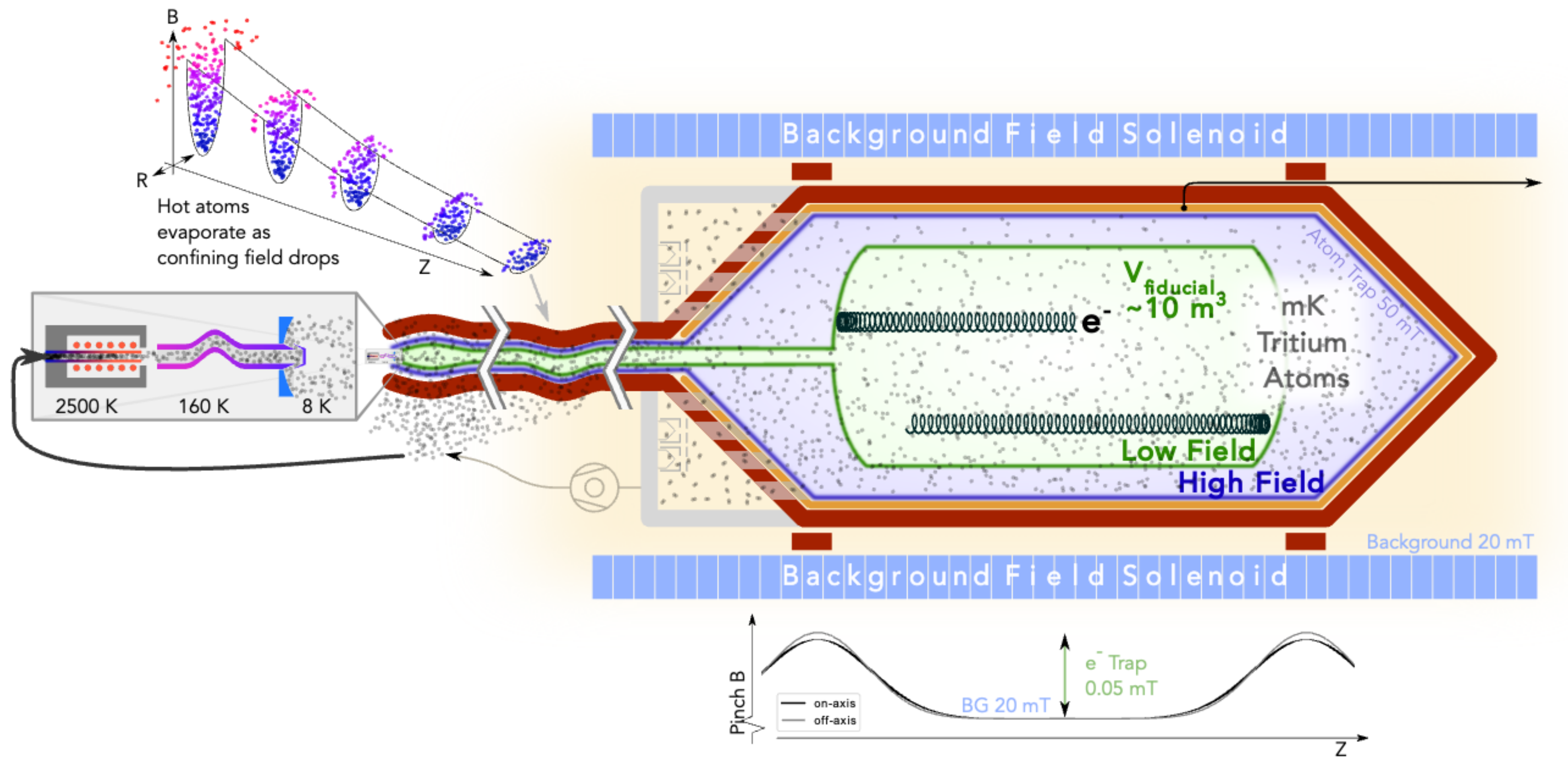


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See talks by Jan Küpperbusch,
Svitlana Hoienko

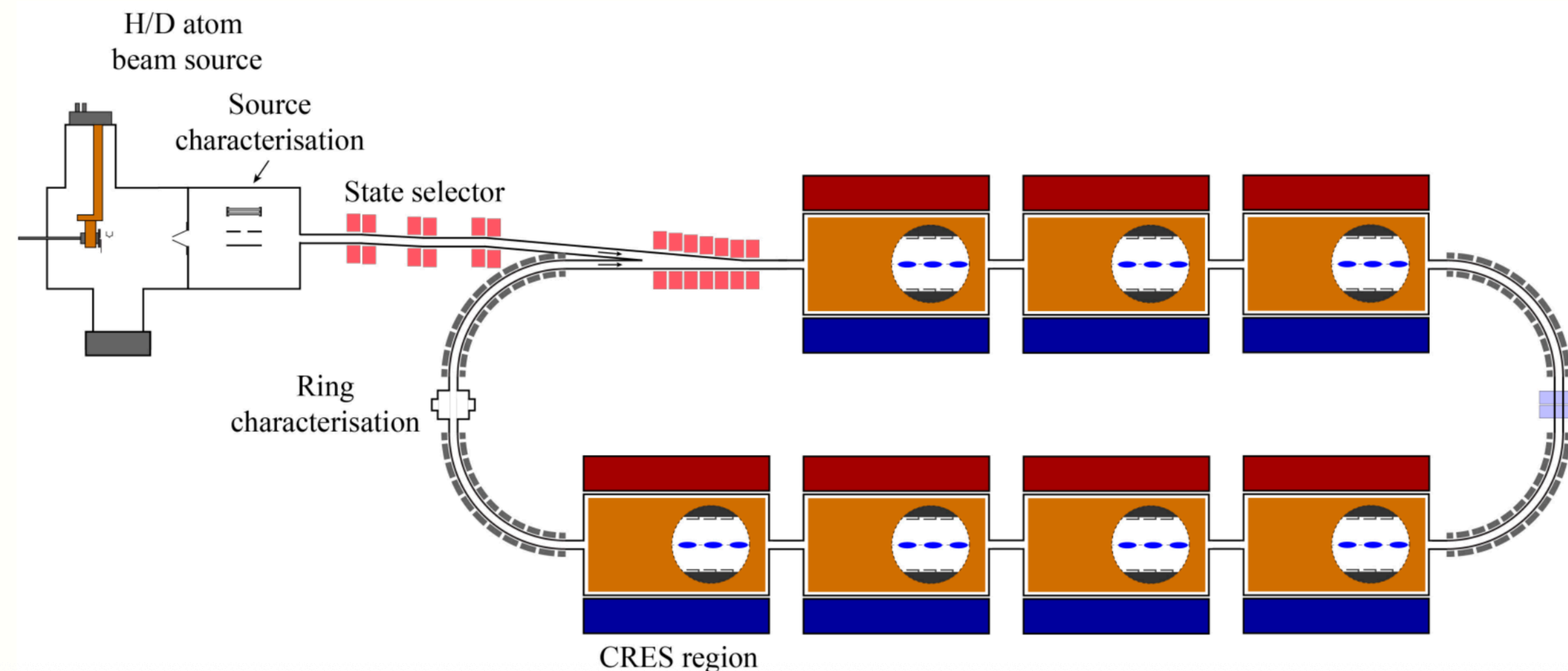
Final 40meV Experiment



x 10

CRES in QTNM

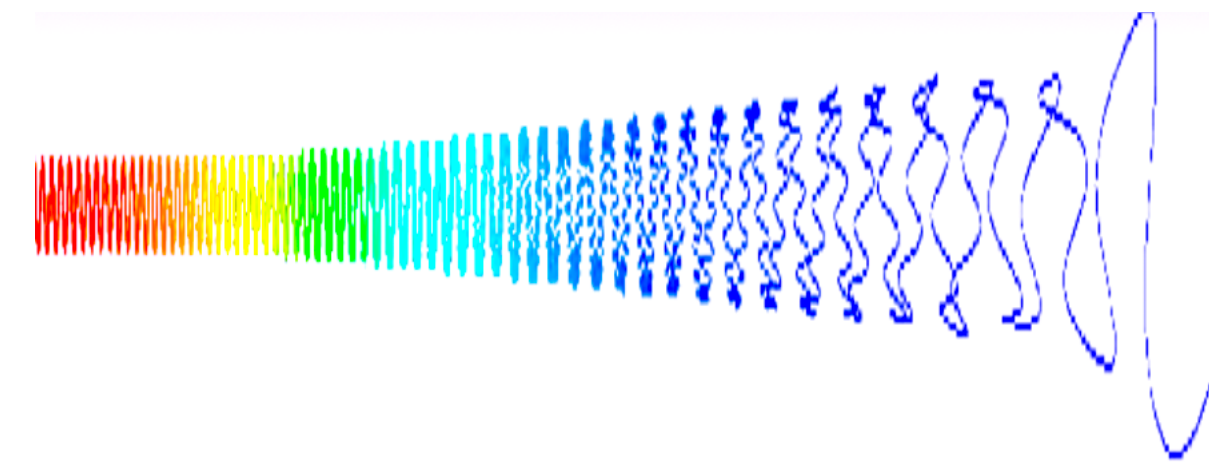
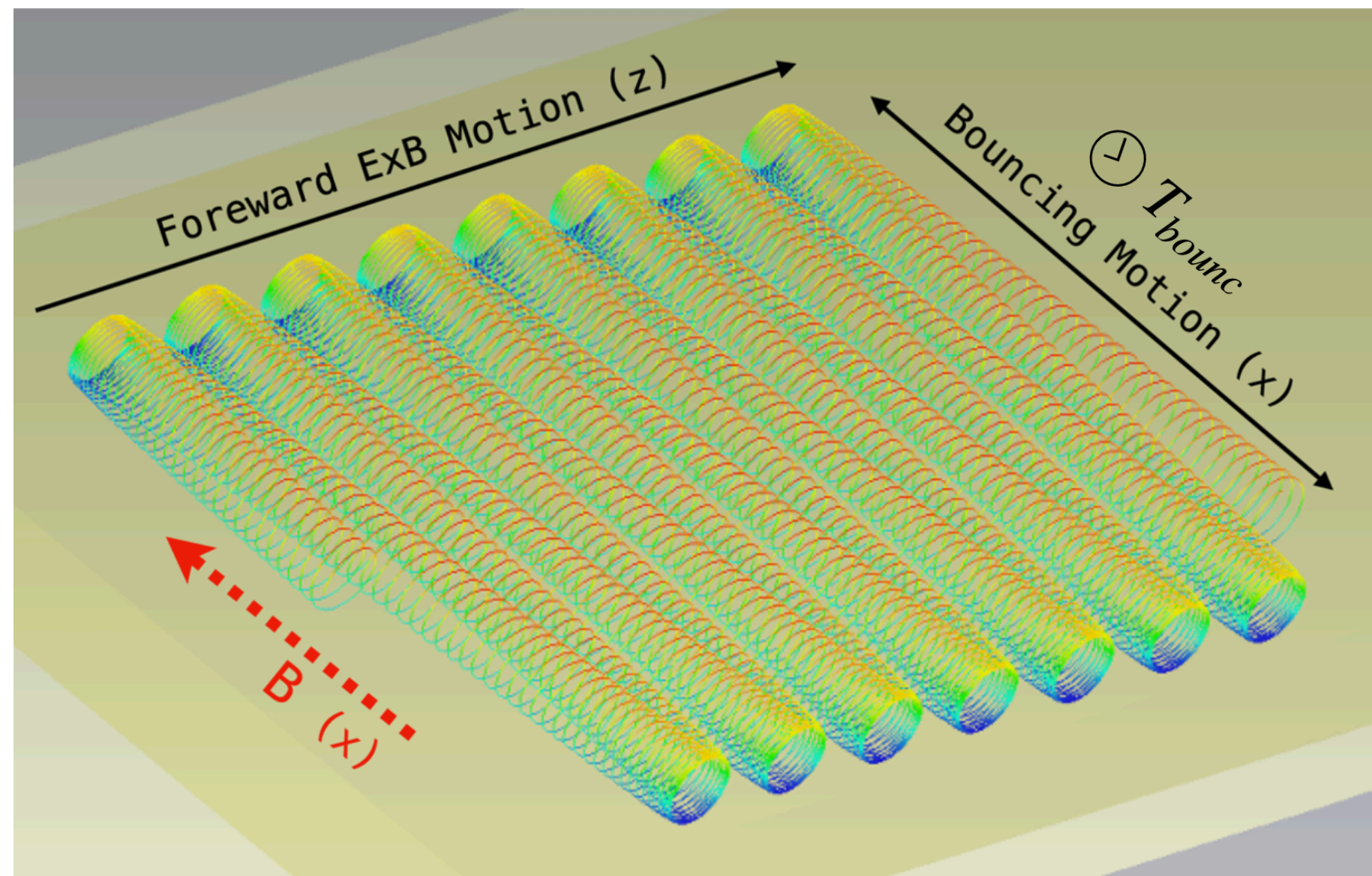
- Also plan to use CRES
- Exploring antenna arrays, waveguides and cavities
- Modular CRES regions



Can We Make It More Complicated?

See M. Pofi's talk

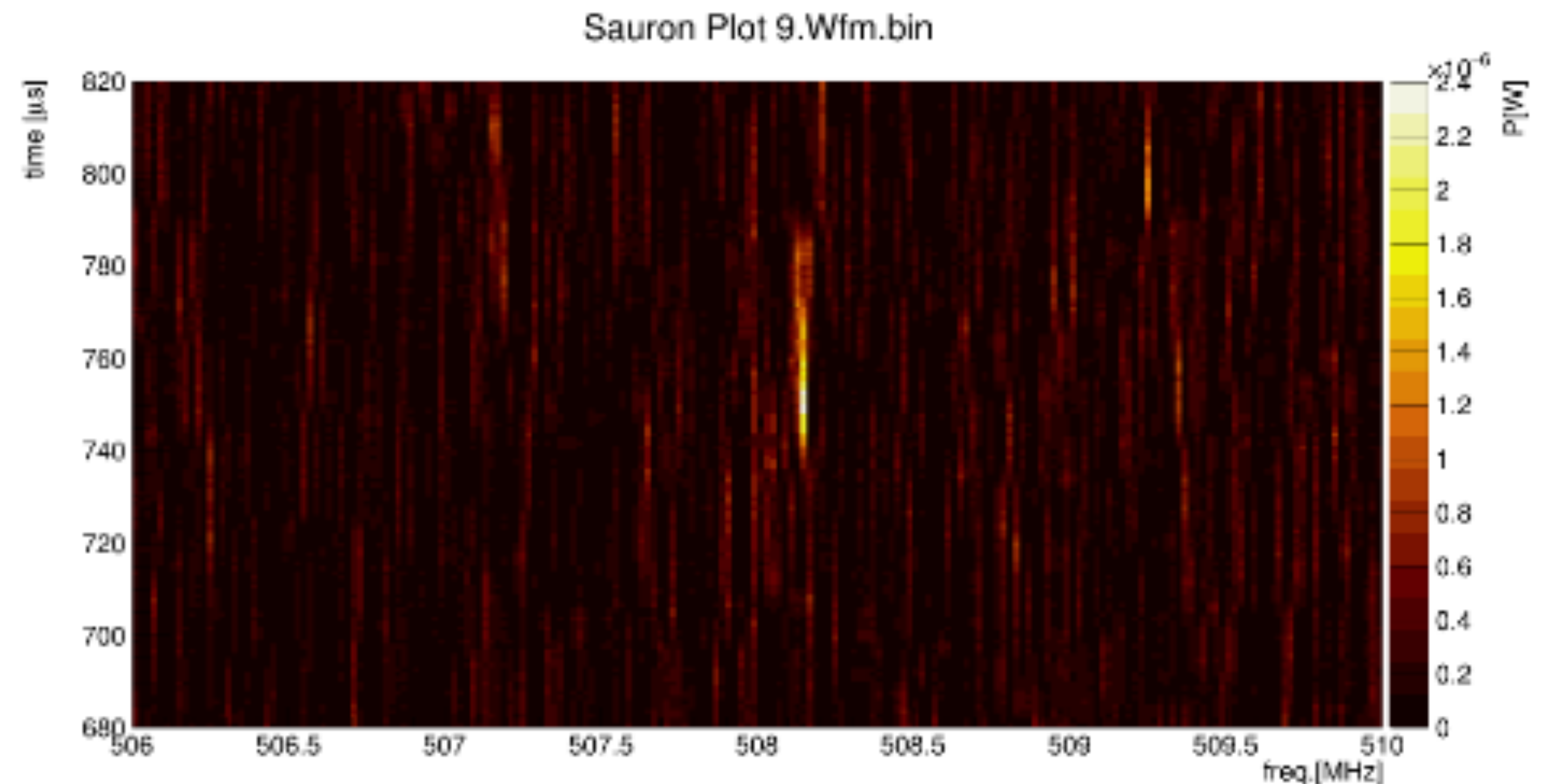
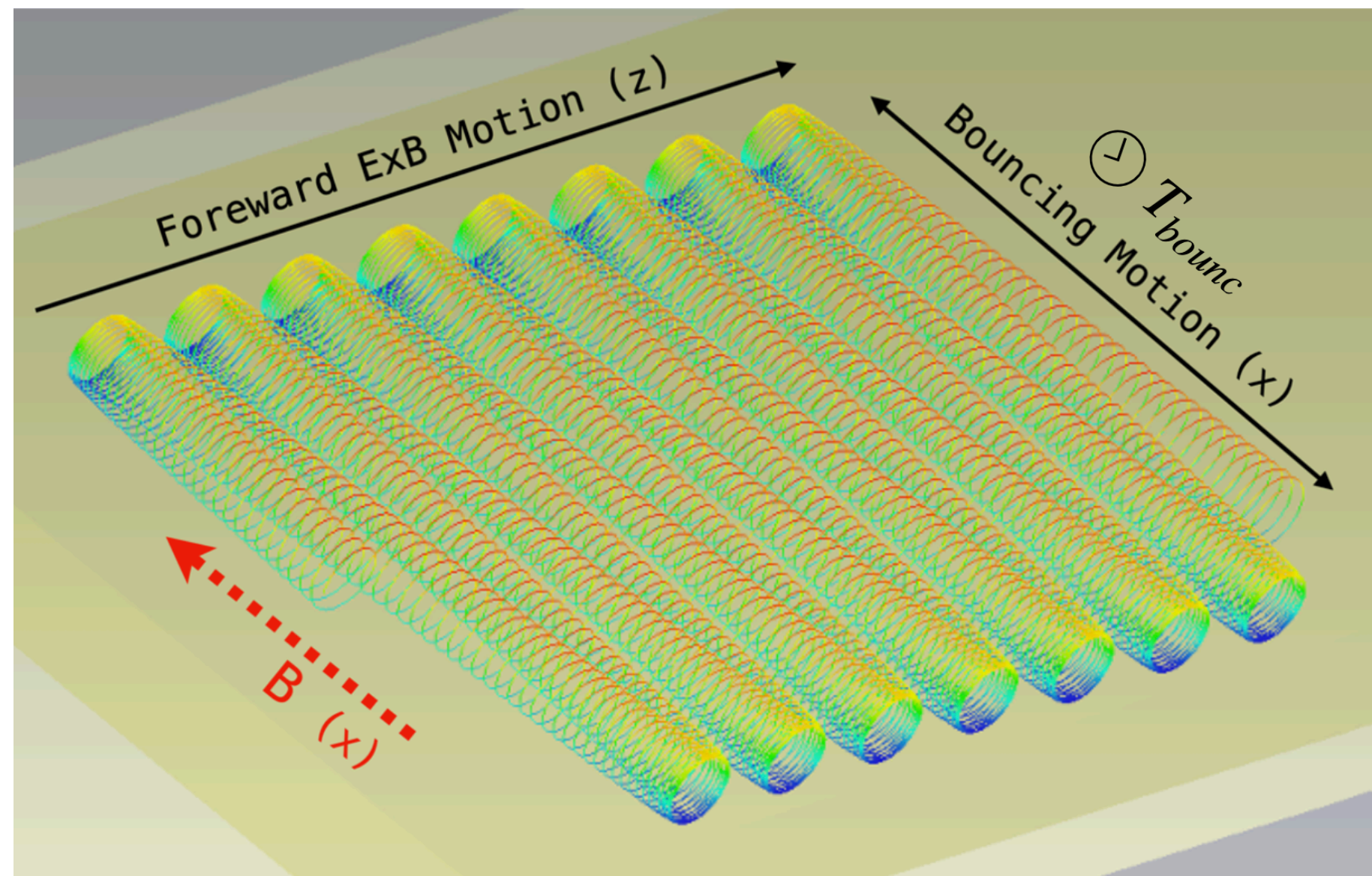
- PTOLEMY: combination of E & B fields for $\sim$ CRES
 + electron drift for electron tracking, filter adjustment
 + dynamic drift filter / slower
 + destructive electron detection



Can We Make It More Complicated?

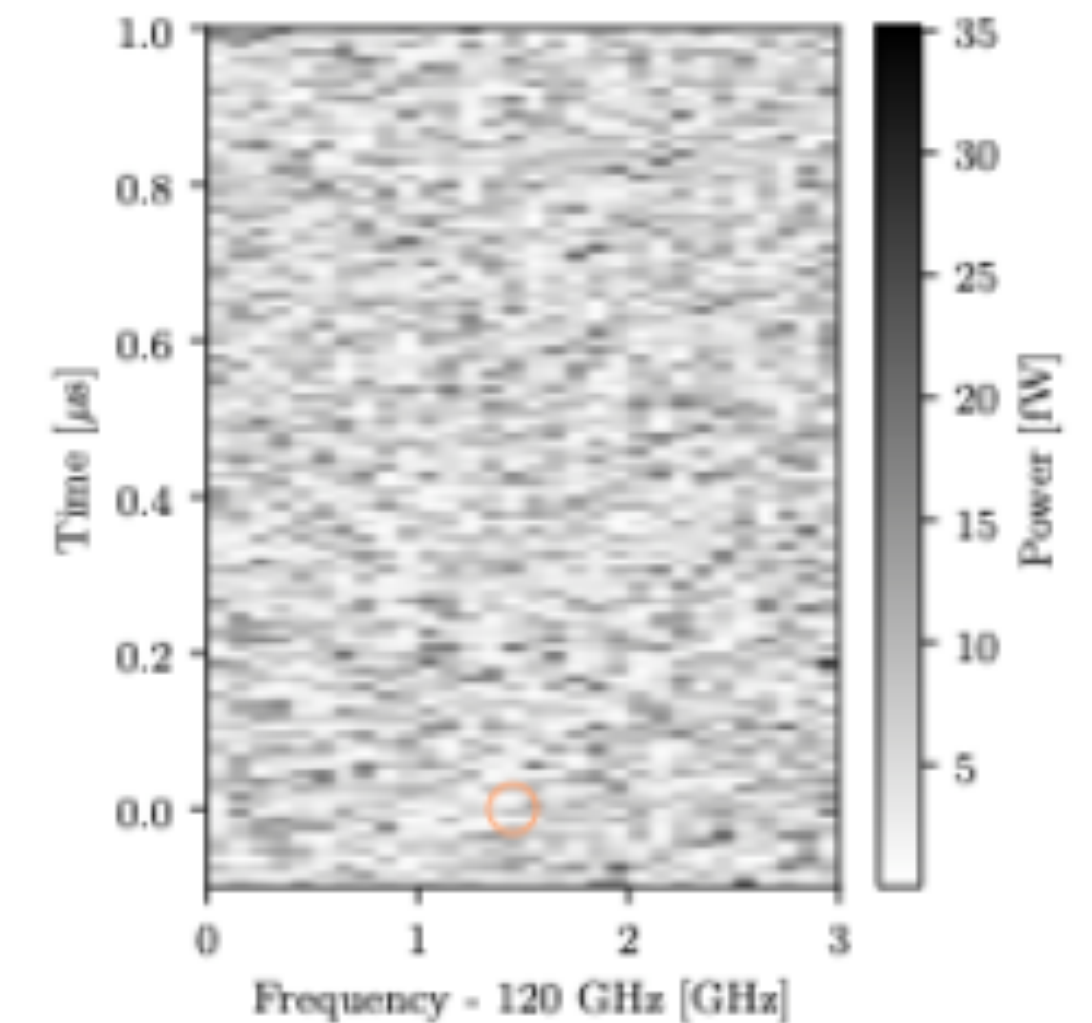
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- PTOLEMY: combination of E & B fields for $\sim$ CRES
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KATRIN (++)

- Electron Tagger for time-of-flight
- Can we use CRE for tagging (no spectroscopy)?
 - Tag electron before electron enters spectrometer
 - Count at detector after spectrometer
 - Time-of-flight gives energy resolution, background cancellation
 - Issue: SNR
- Other idea: Transverse Energy Compensator



See C. Weinheimer's talk

Recap: Tritium-based Experiments

- Common challenges: current technology cannot be easily scaled
- Consensus: We need
 - Atomic tritium
 - Differential energy measurement
 - Larger exposure
 - Quantum devices

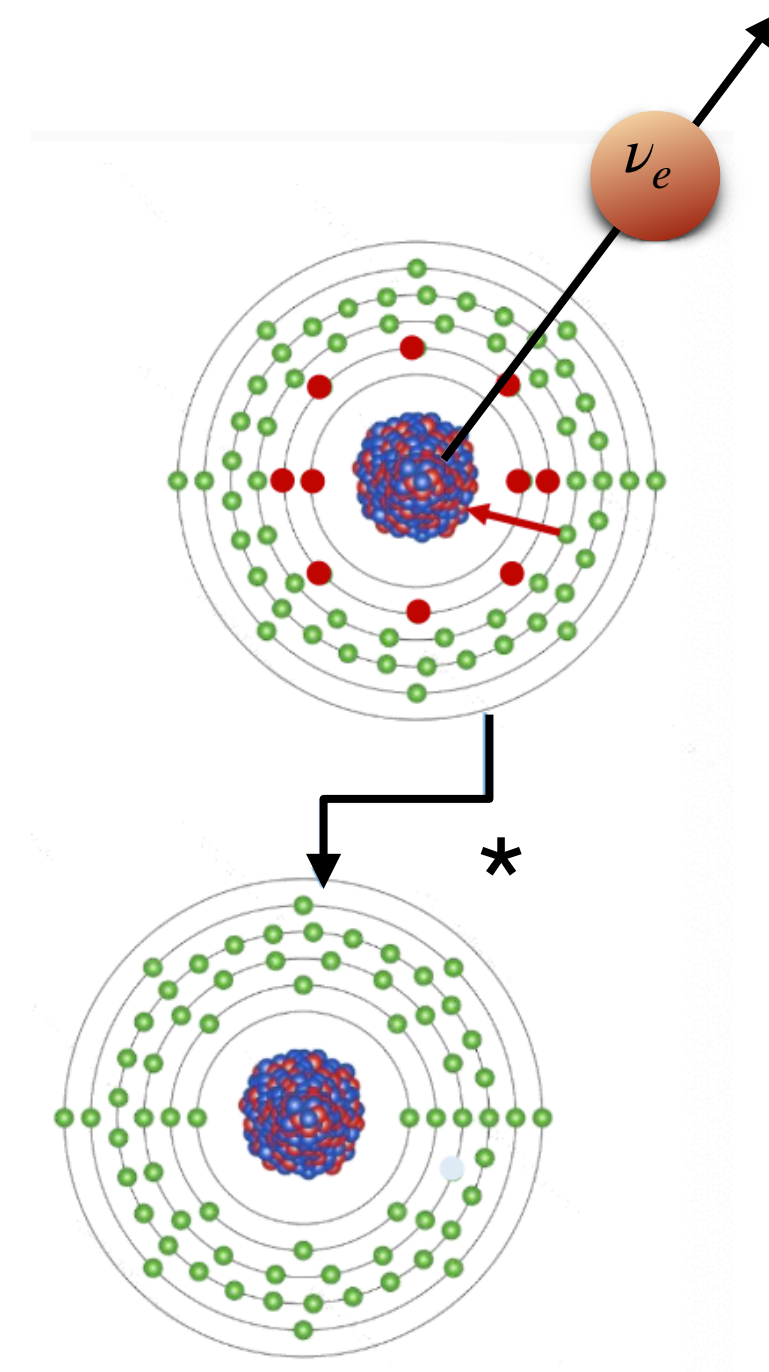
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Name	KATRIN	KATRIN++	Project 8	QTNM	PTOLEMY
Tritium source	Molecular	Atomic	Atomic	Atomic	Graphene-adsorbed
Detection method	Destructive counter	MMCs?	CRES	CRES	CRE + dynamic filter + TES
Electron transport	yes	yes	no	no	yes
Spectrum	Integrated	Differential	Differential	Differential	Differential
Sensitivity	~200 meV		40 meV		~5 meV
Limit (90% C.L.)	0.45 eV		155 eV		
When?	Soon	2030s	2030s	2030s	2030s

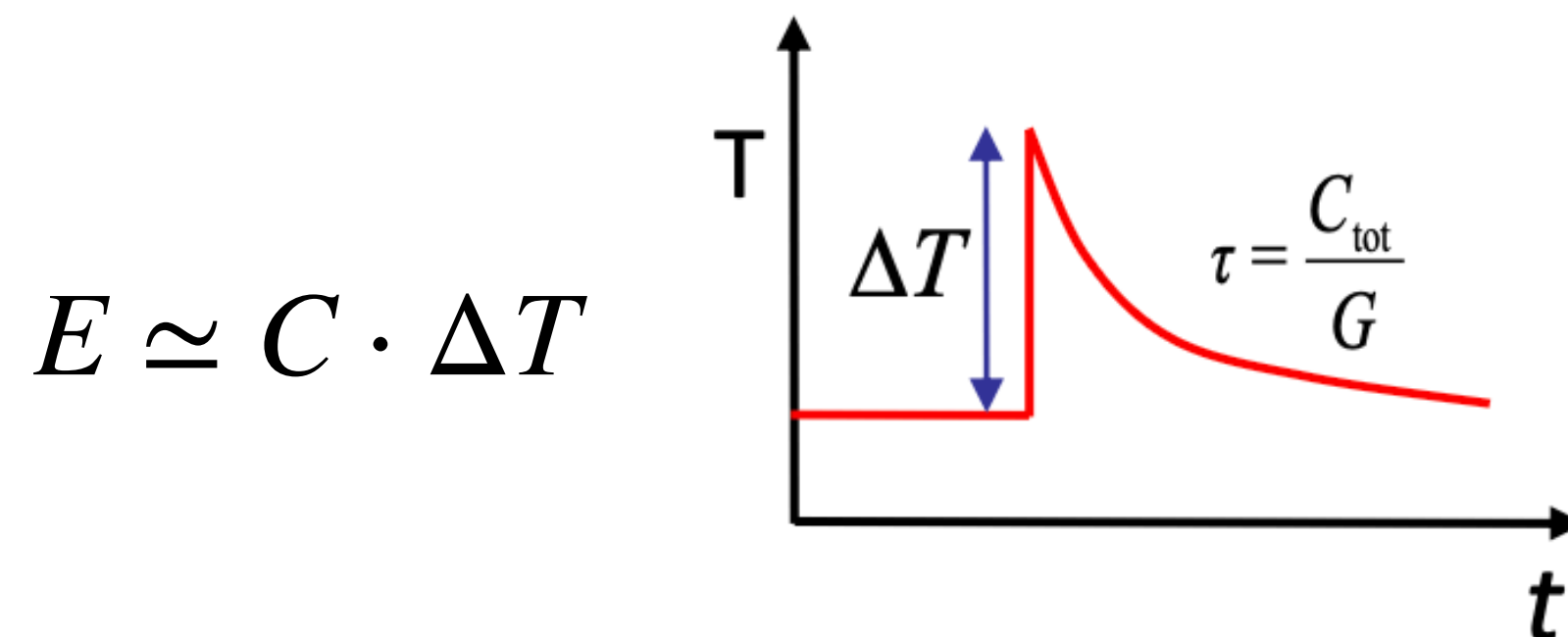
The Electron Capture Future

The Electron Capture Future



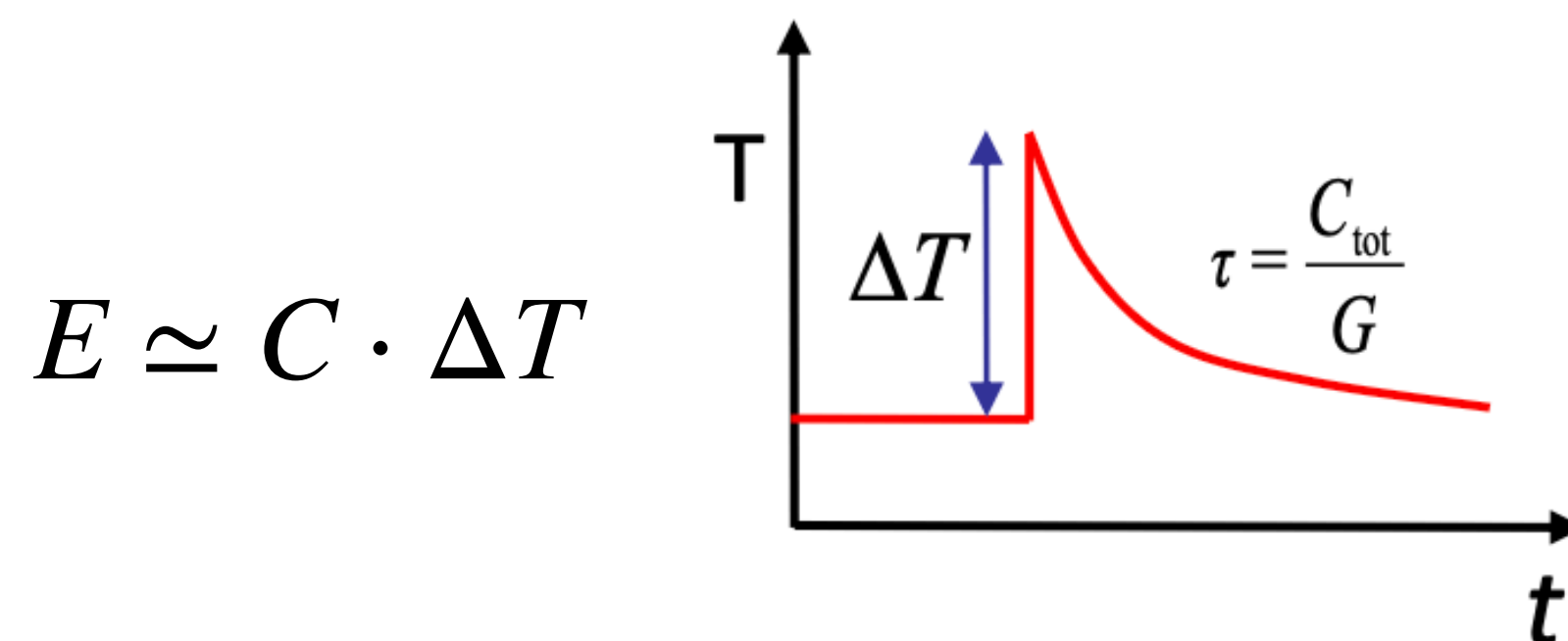
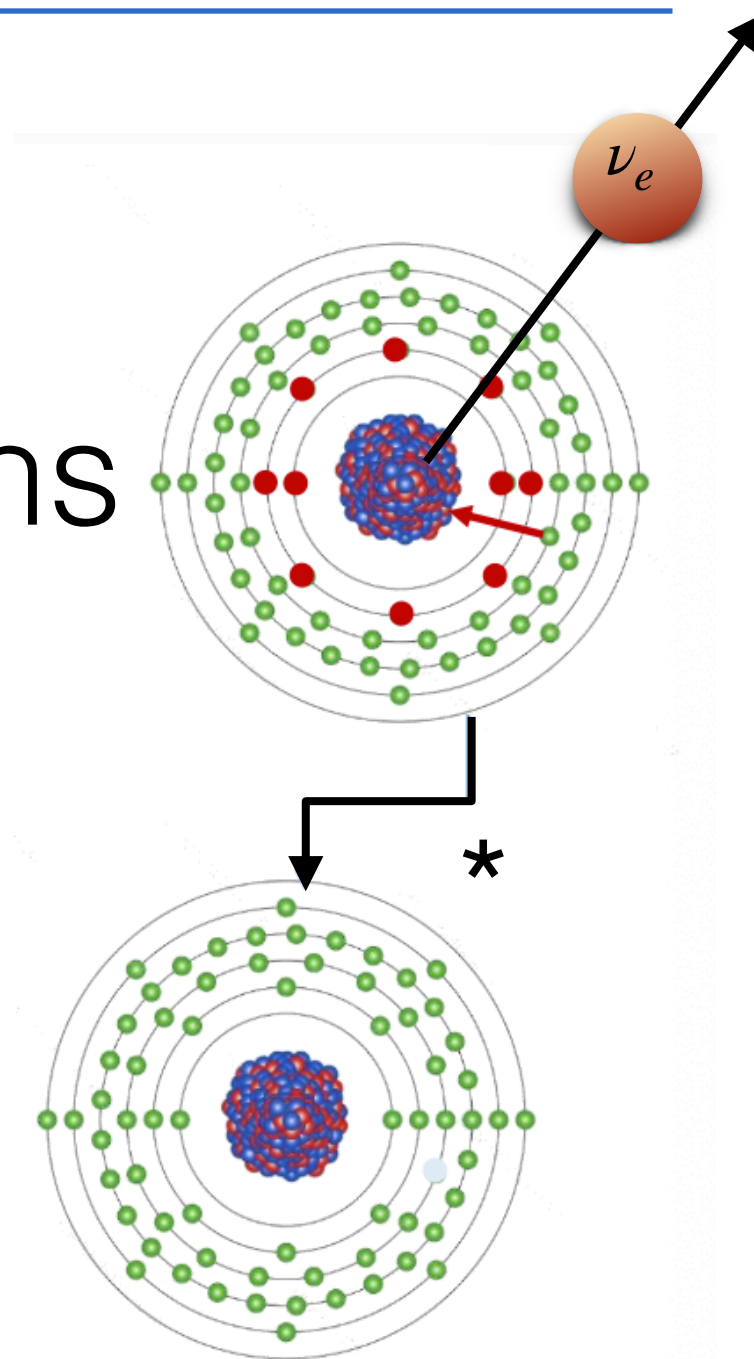
Holmium Experiments

- $^{163}\text{Ho} \rightarrow ^{163}\text{Dy}^* + \nu_e$, $^{163}\text{Dy}^* \rightarrow ^{163}\text{Dy} + E_0$
- De-excitation energy mainly emitted via Auger electrons
- Holmium implanted into detectors
 - Calorimetric measurement via absorbed heat
 - Requires very sensitive low-T detectors
- High activity can be achieved with compact, pixelated sources
- Complicated source needs to be carefully modeled

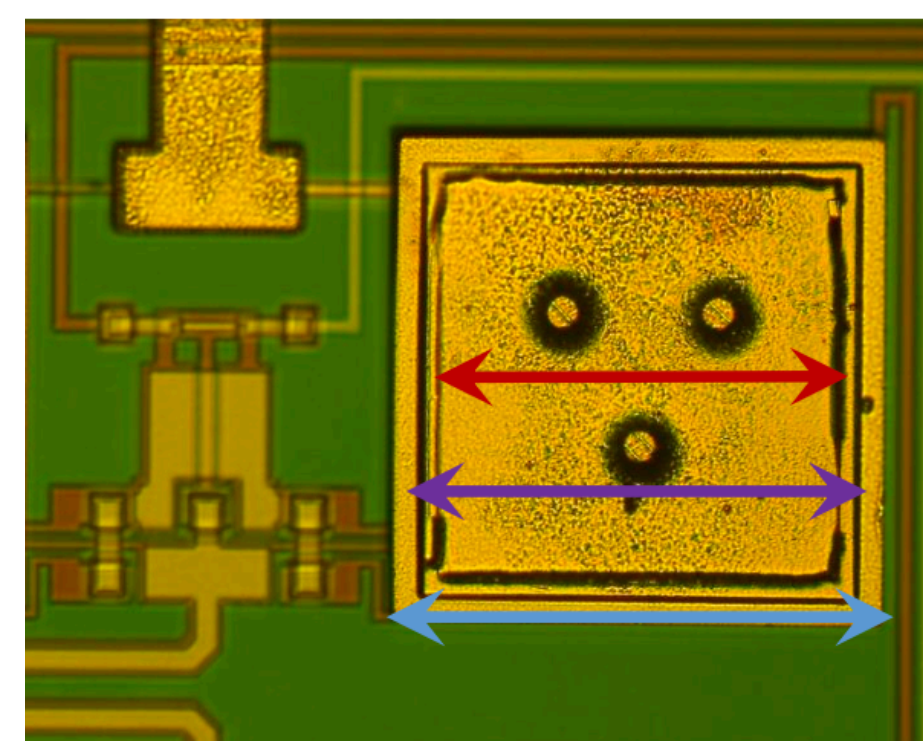
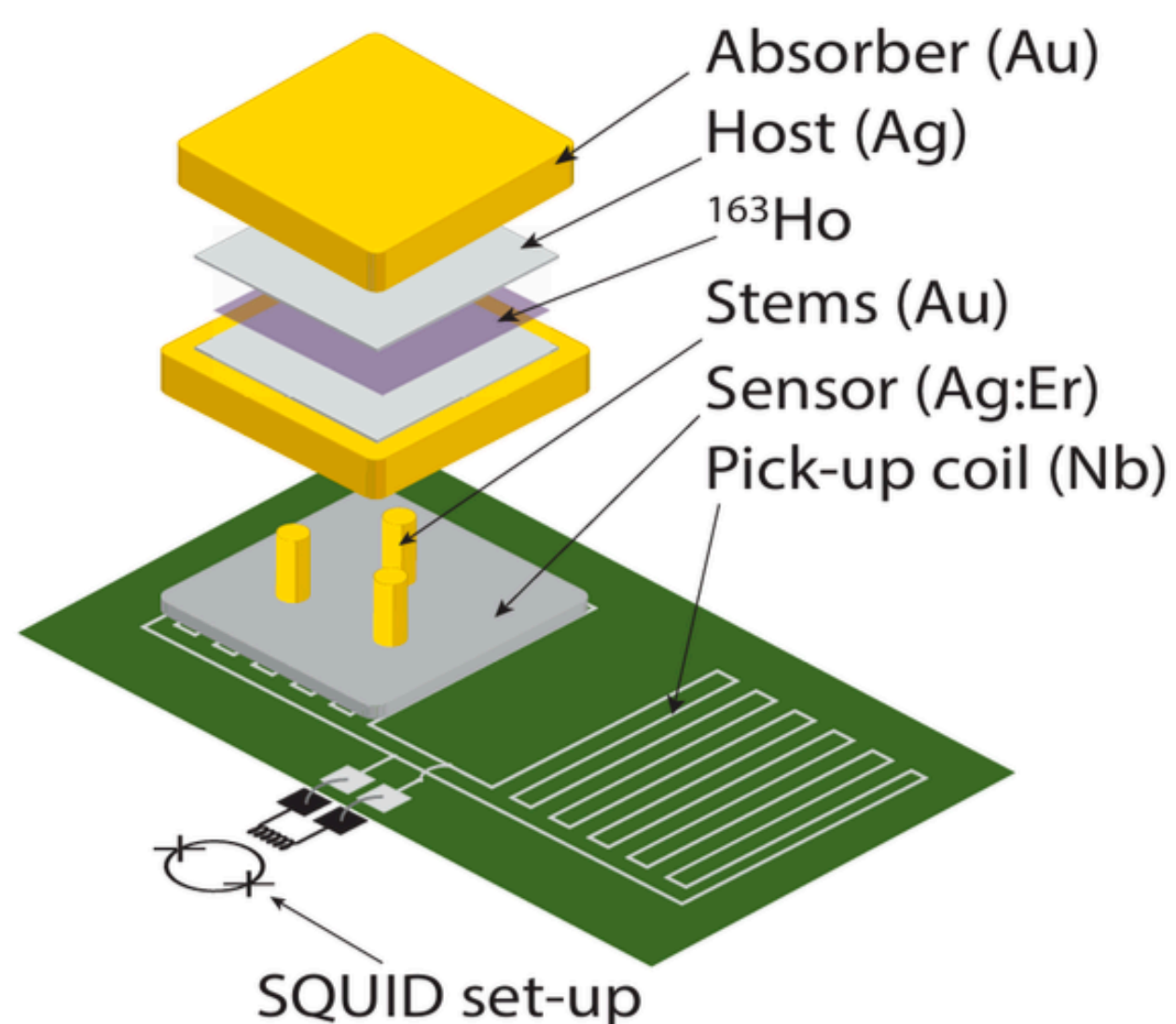


Holmium Experiments

- $^{163}\text{Ho} \rightarrow ^{163}\text{Dy}^* + \nu_e$, $^{163}\text{Dy}^* \rightarrow ^{163}\text{Dy} + E_0$
- De-excitation energy mainly emitted via Auger electrons
- Holmium implanted into detectors
 - Calorimetric measurement via absorbed heat
 - Requires very sensitive low-T detectors
- High activity can be achieved with compact, pixelated sources
- Complicated source needs to be carefully modeled



- Uses Holmium implanted in microcalorimeters
- Operates in dilution refrigerator
- Current limit: 15 eV

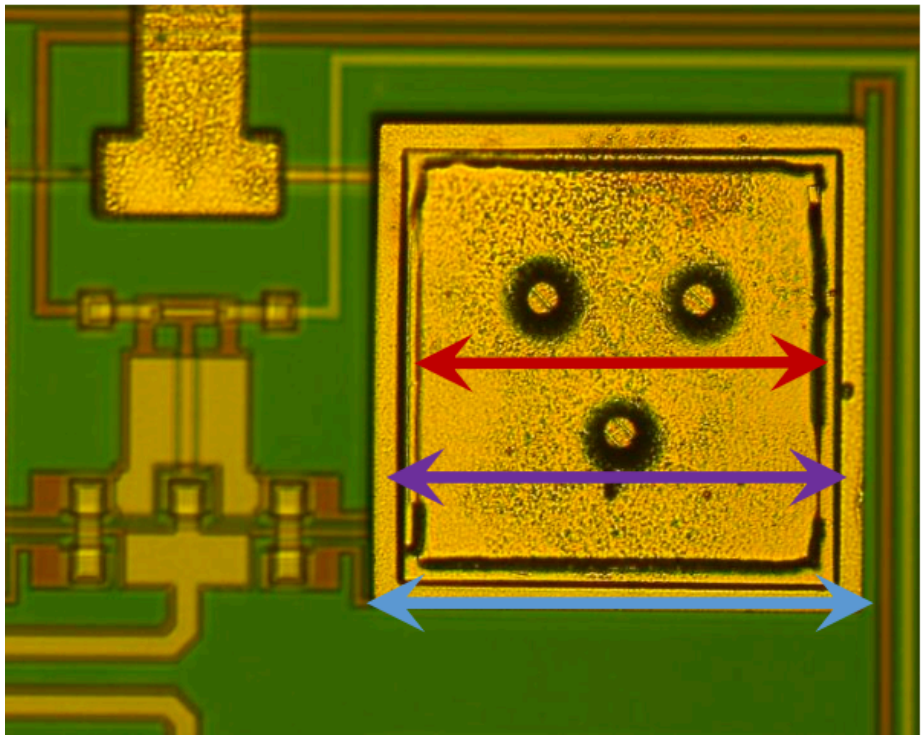
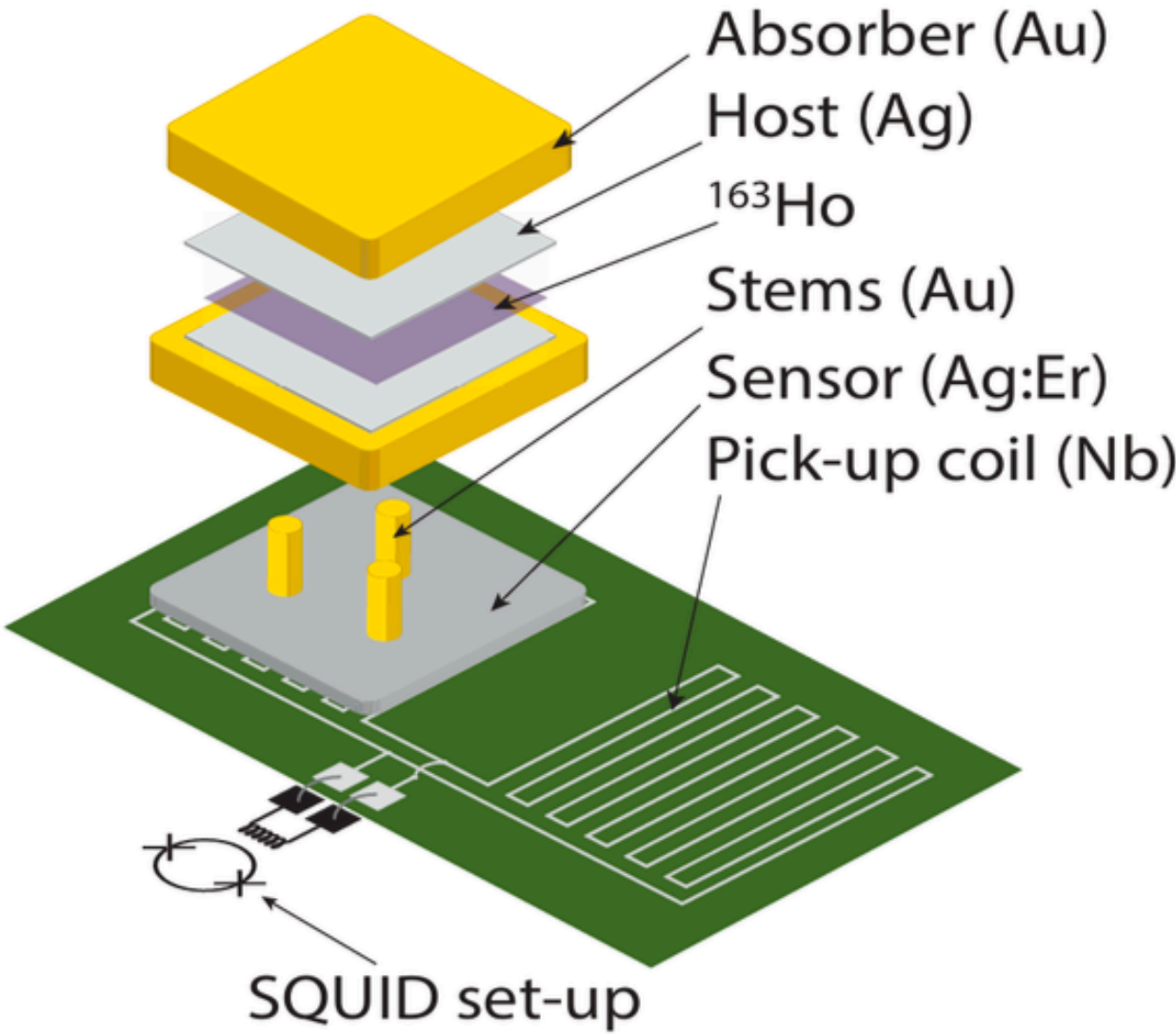


Implantation square:
150 μm x 150 μm

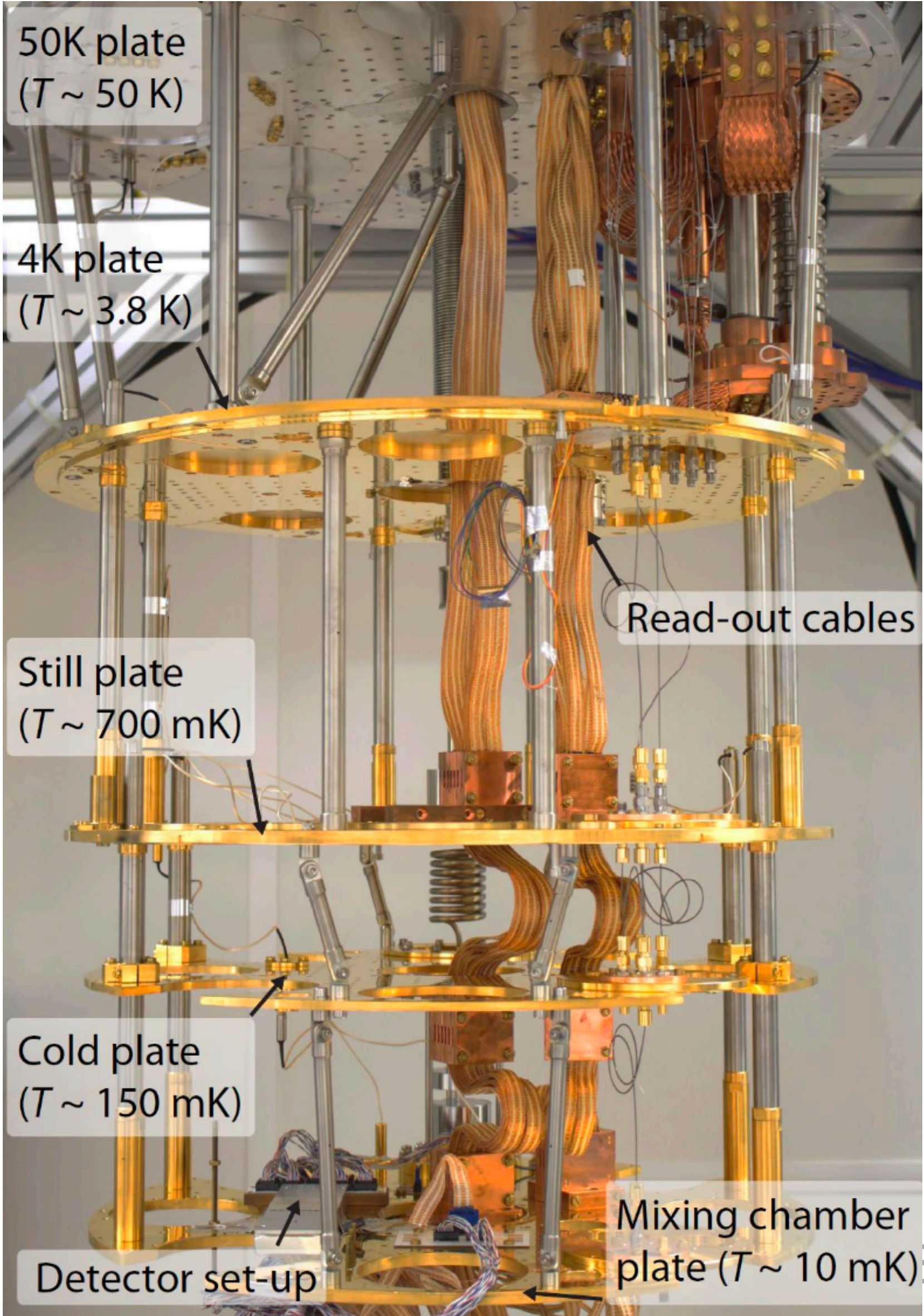
Second absorber:
165 μm x 165 μm

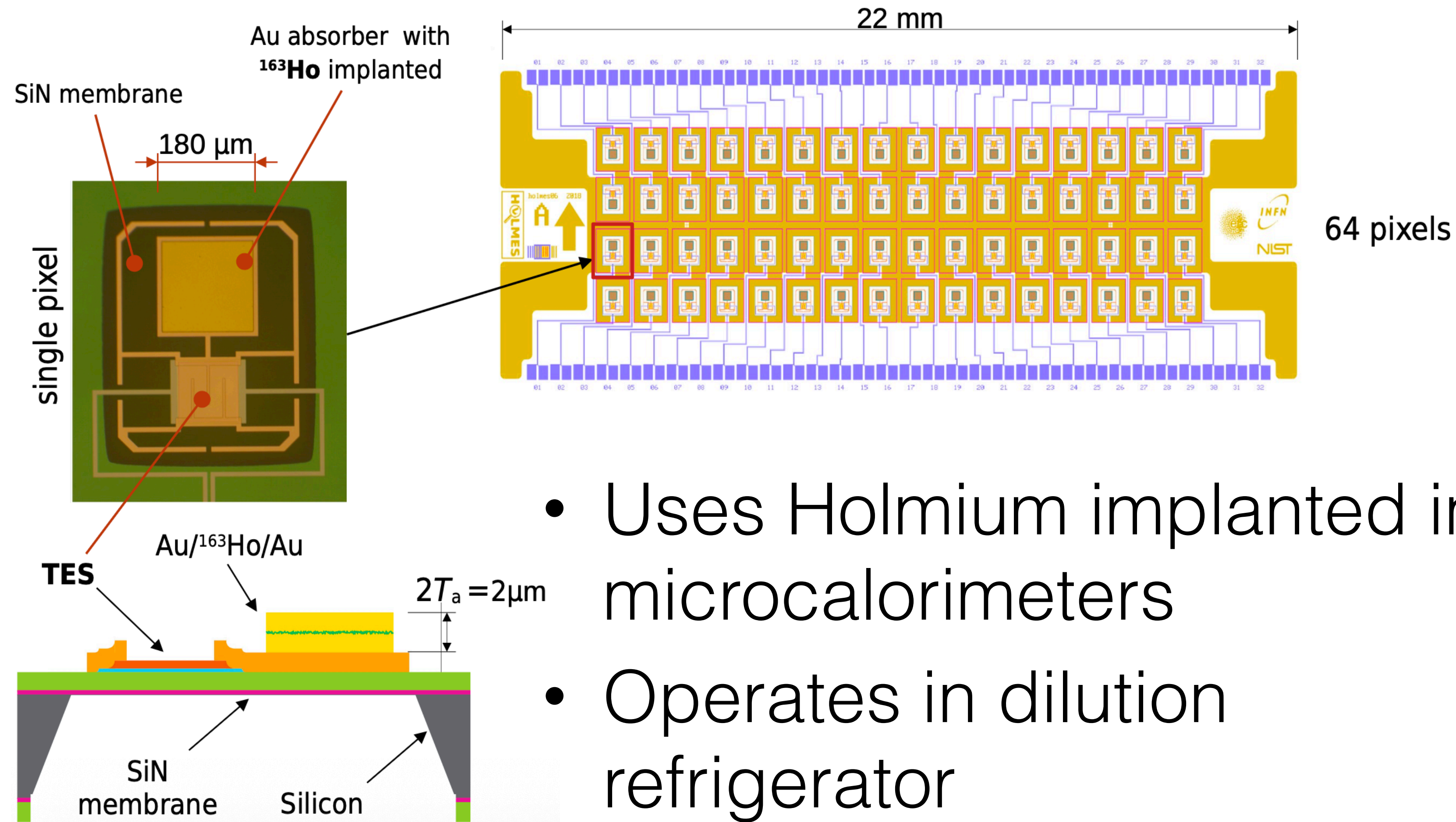
First absorber:
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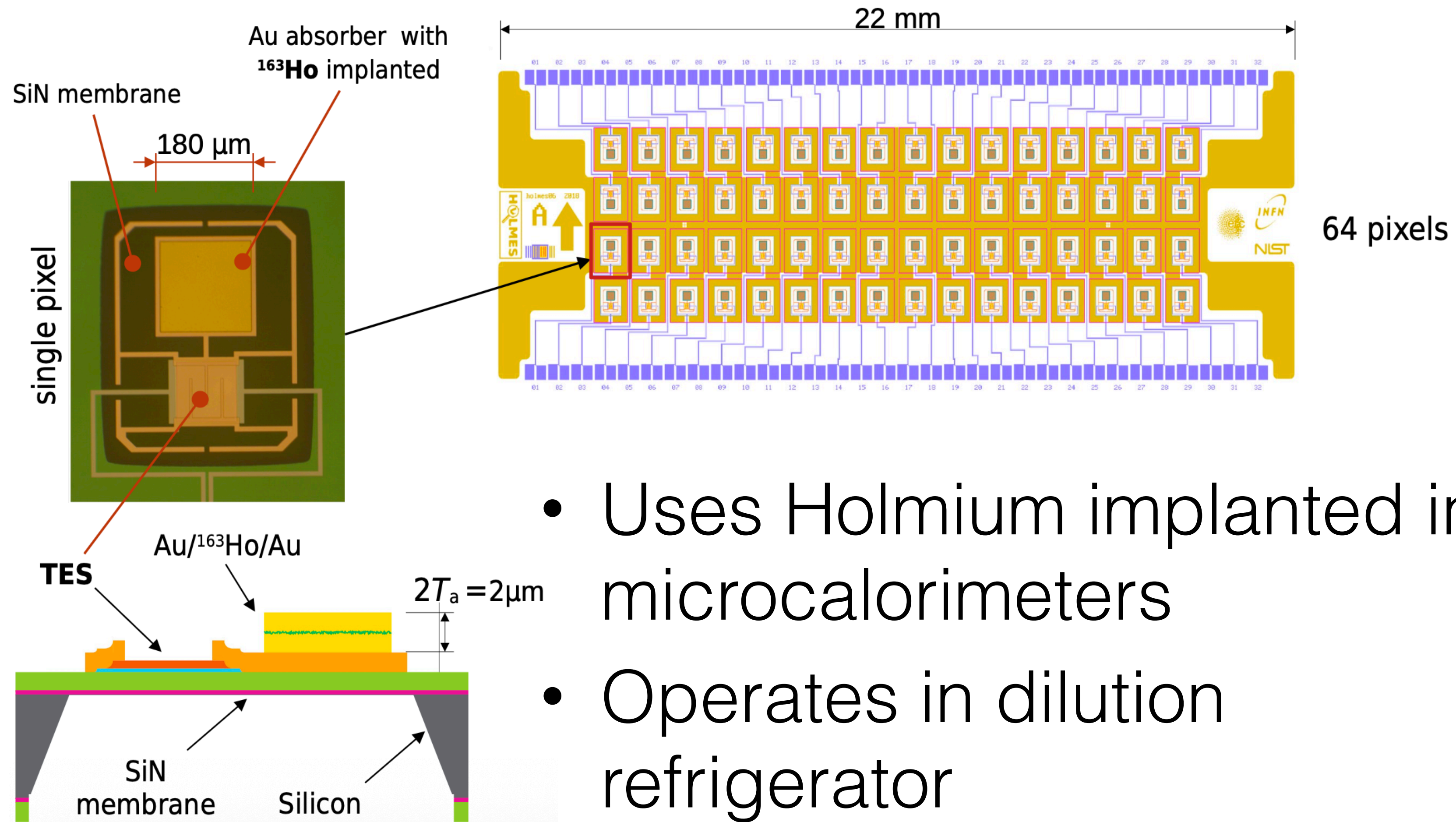


Implantation square:
 $150\ \mu\text{m} \times 150\ \mu\text{m}$
 Second absorber:
 $165\ \mu\text{m} \times 165\ \mu\text{m}$
 First absorber:
 $180\ \mu\text{m} \times 180\ \mu\text{m}$

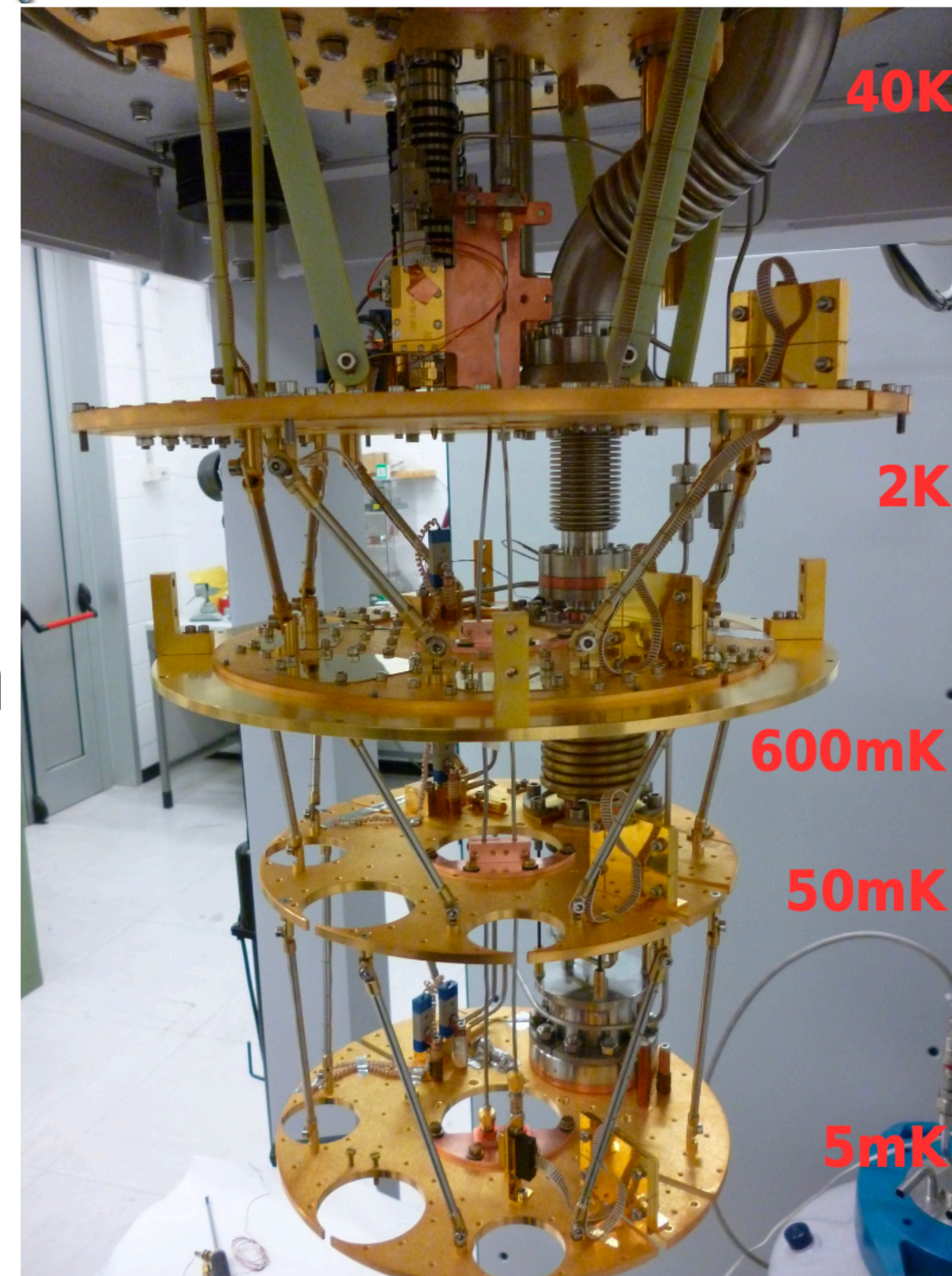




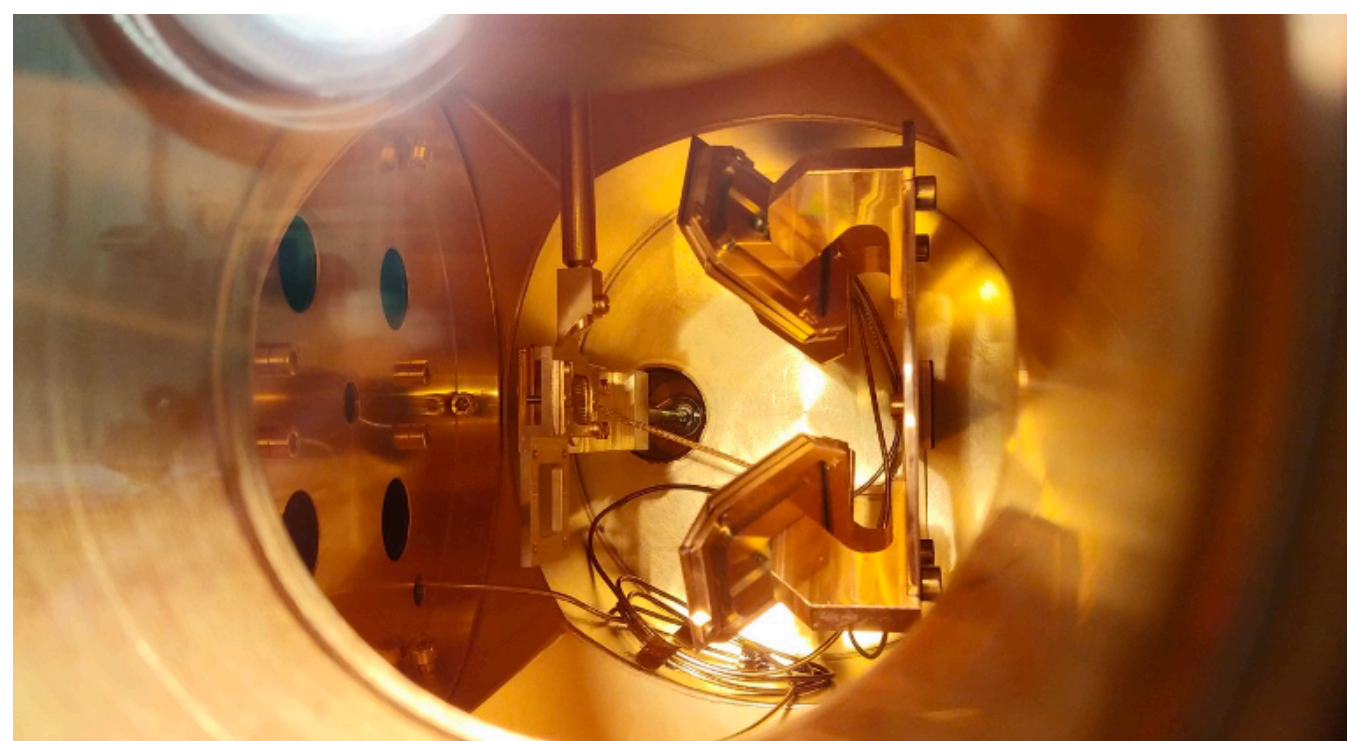
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Holmium Source Development



Source Production

1. Holmium produced through irradiation of Erbium:



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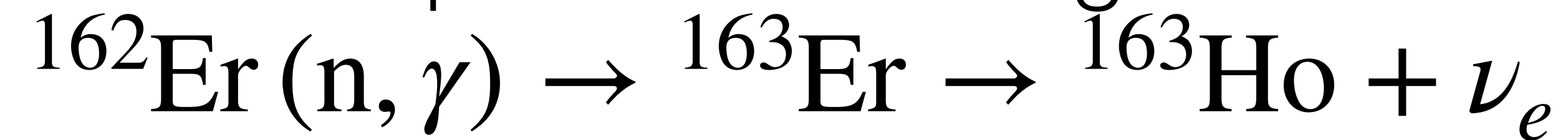
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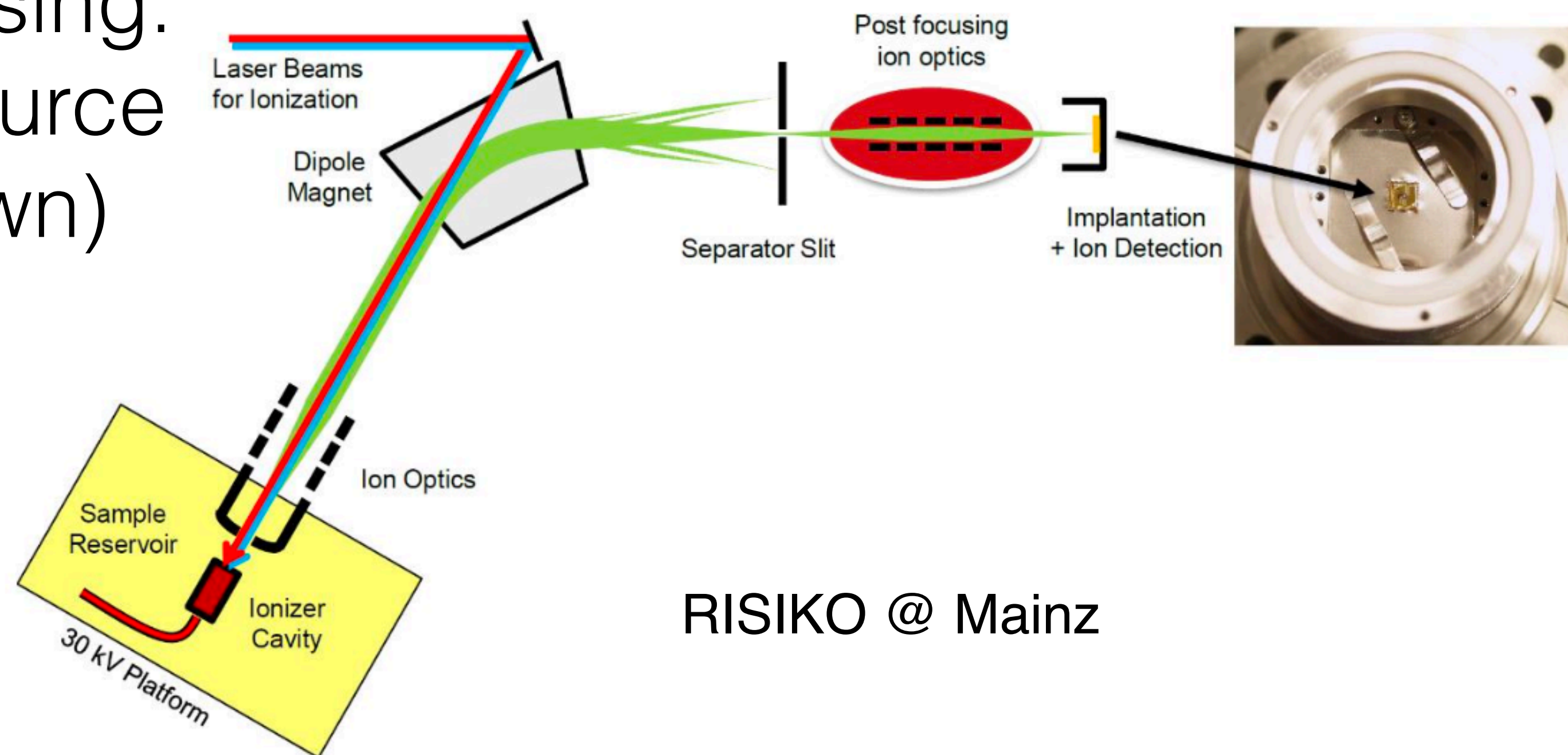


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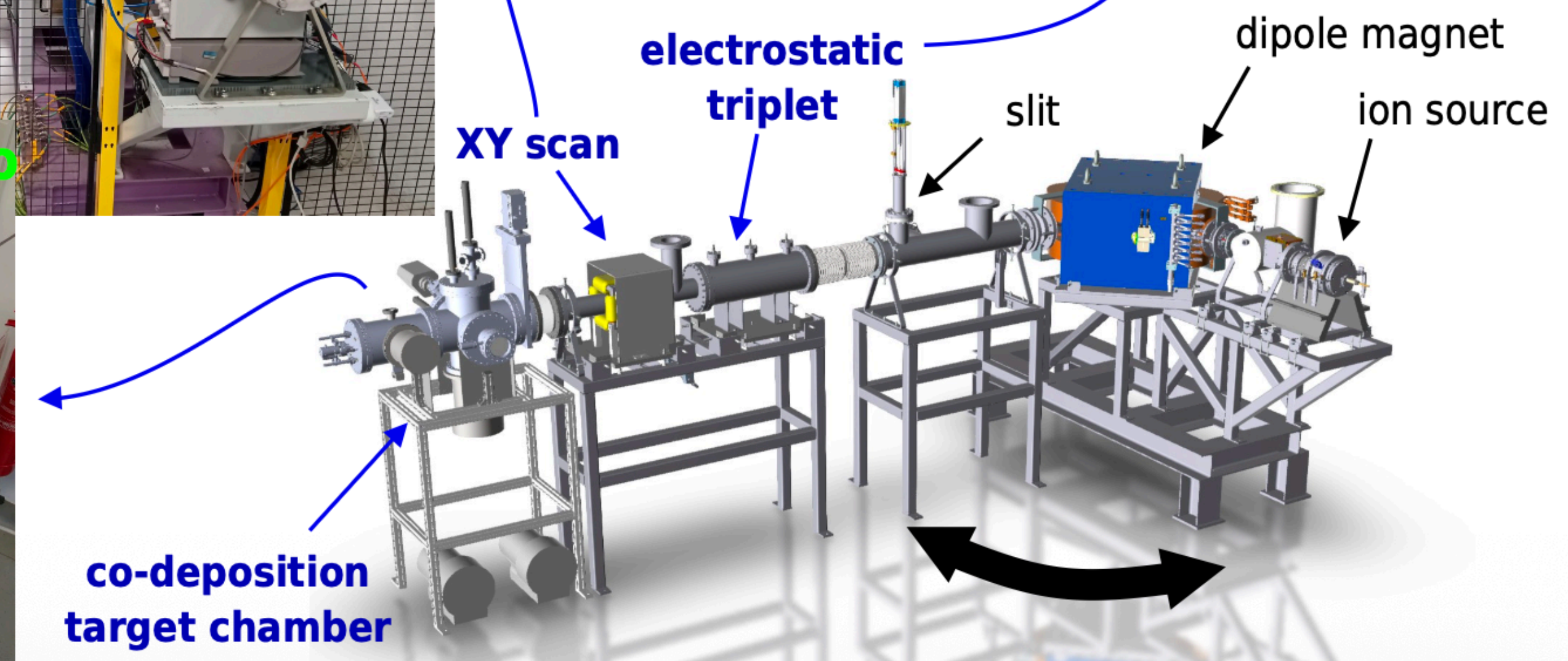
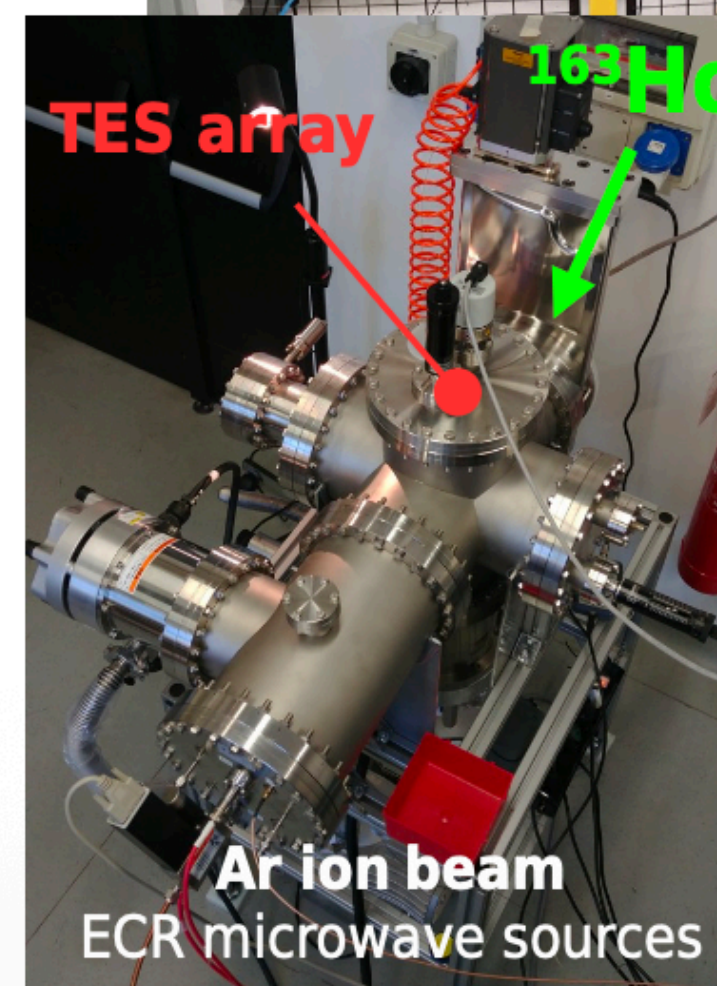
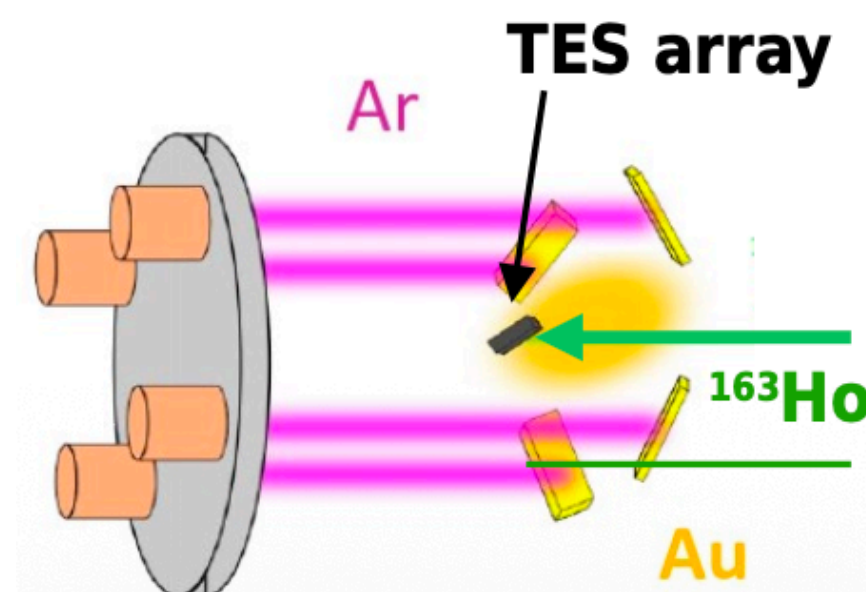
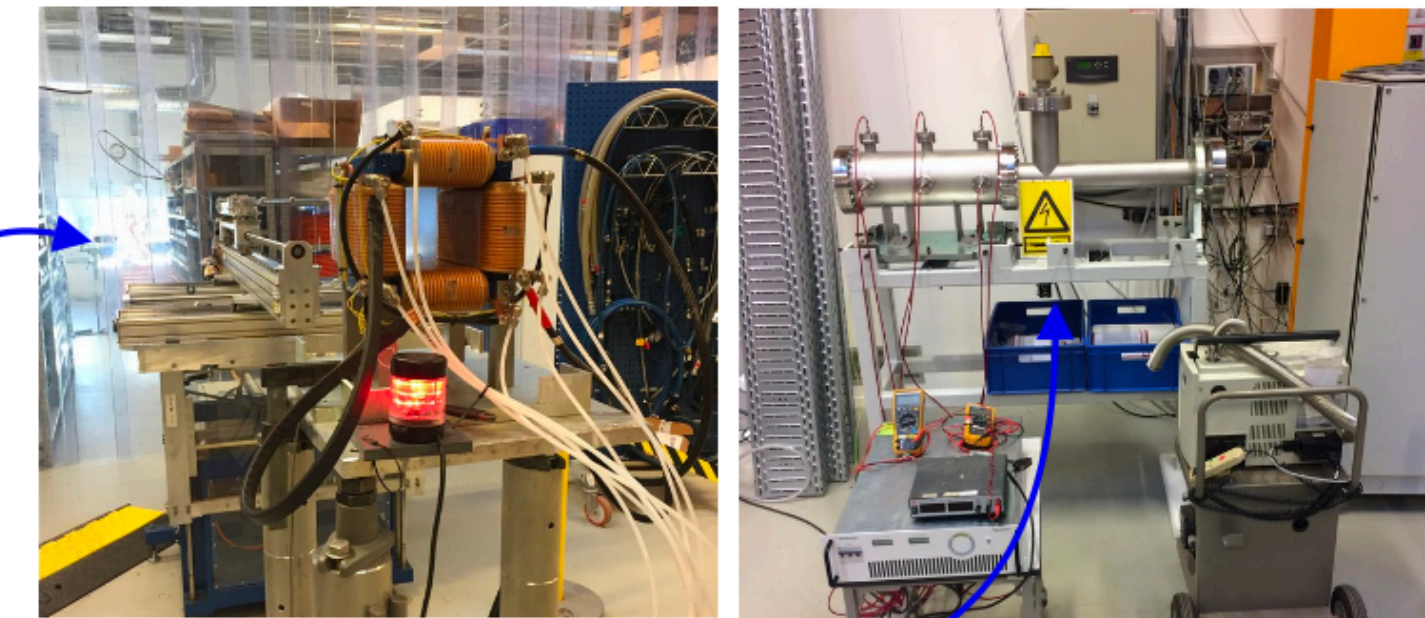
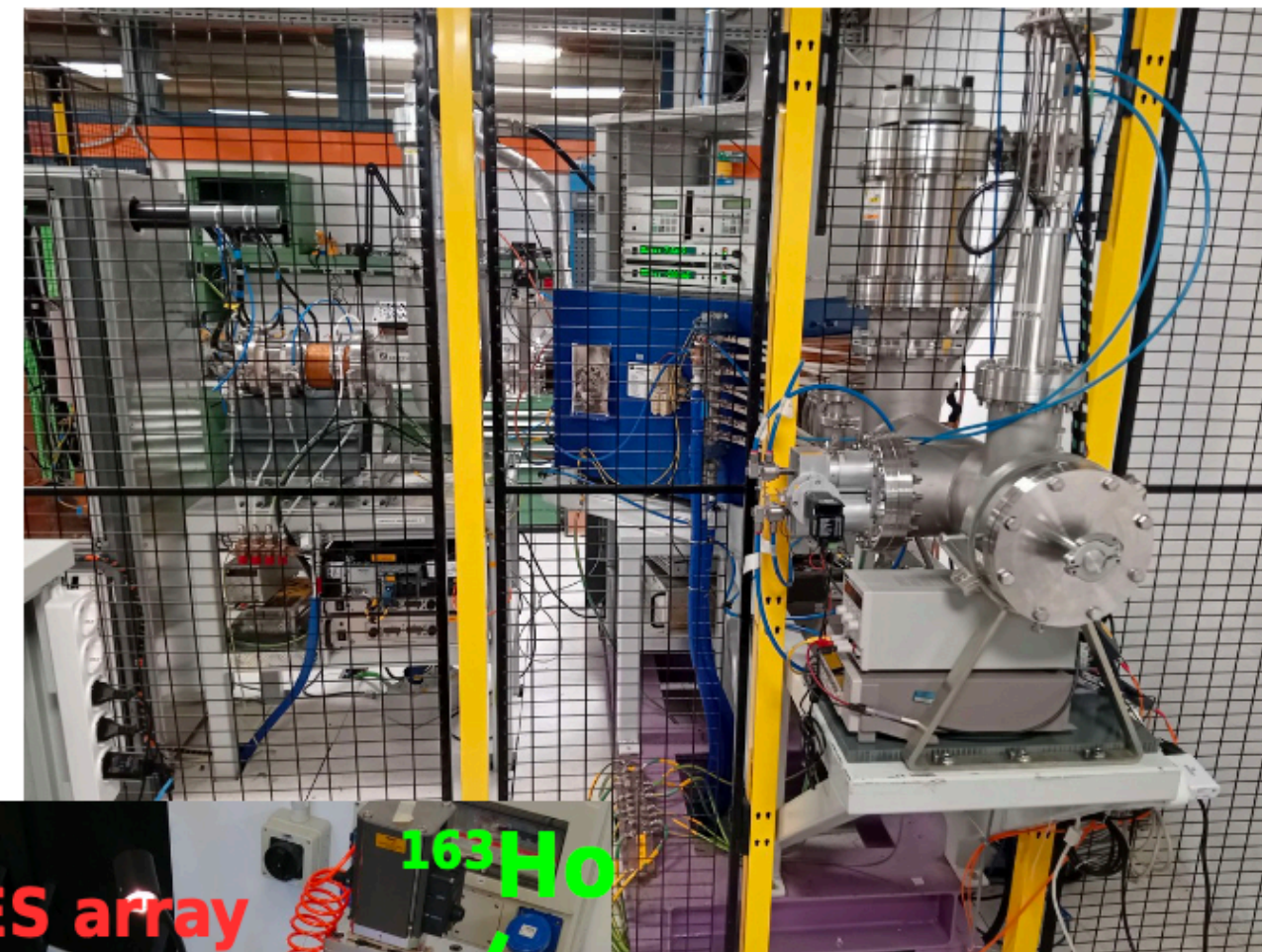


RISIKO @ Mainz

Upgrading Ho-Implanter

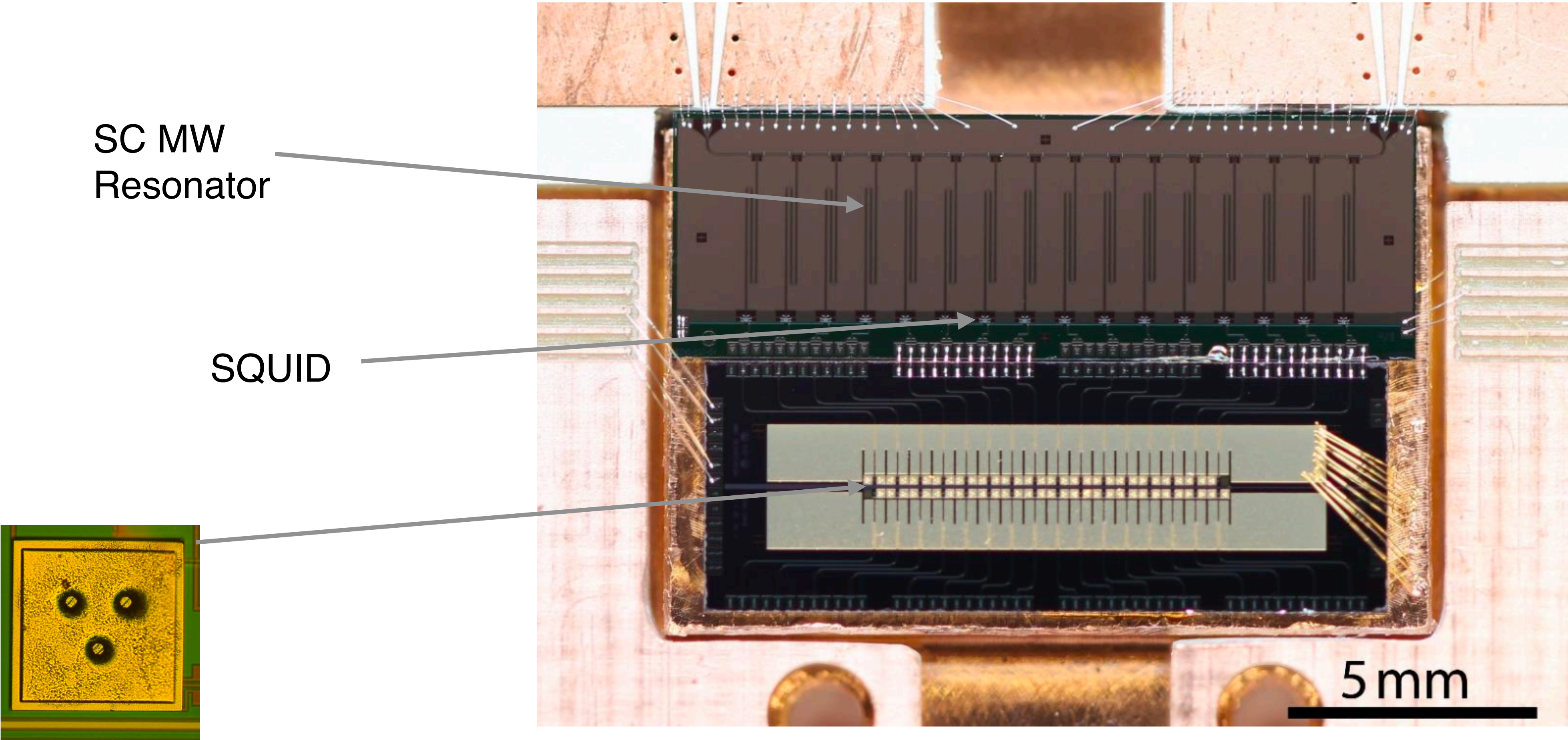
- Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source to increase efficiency
- Au co-deposition in target chamber: activity increase from 3 Bq/pix to 10 Bq/pix

the ion implanter
has been flipped
to allow extension



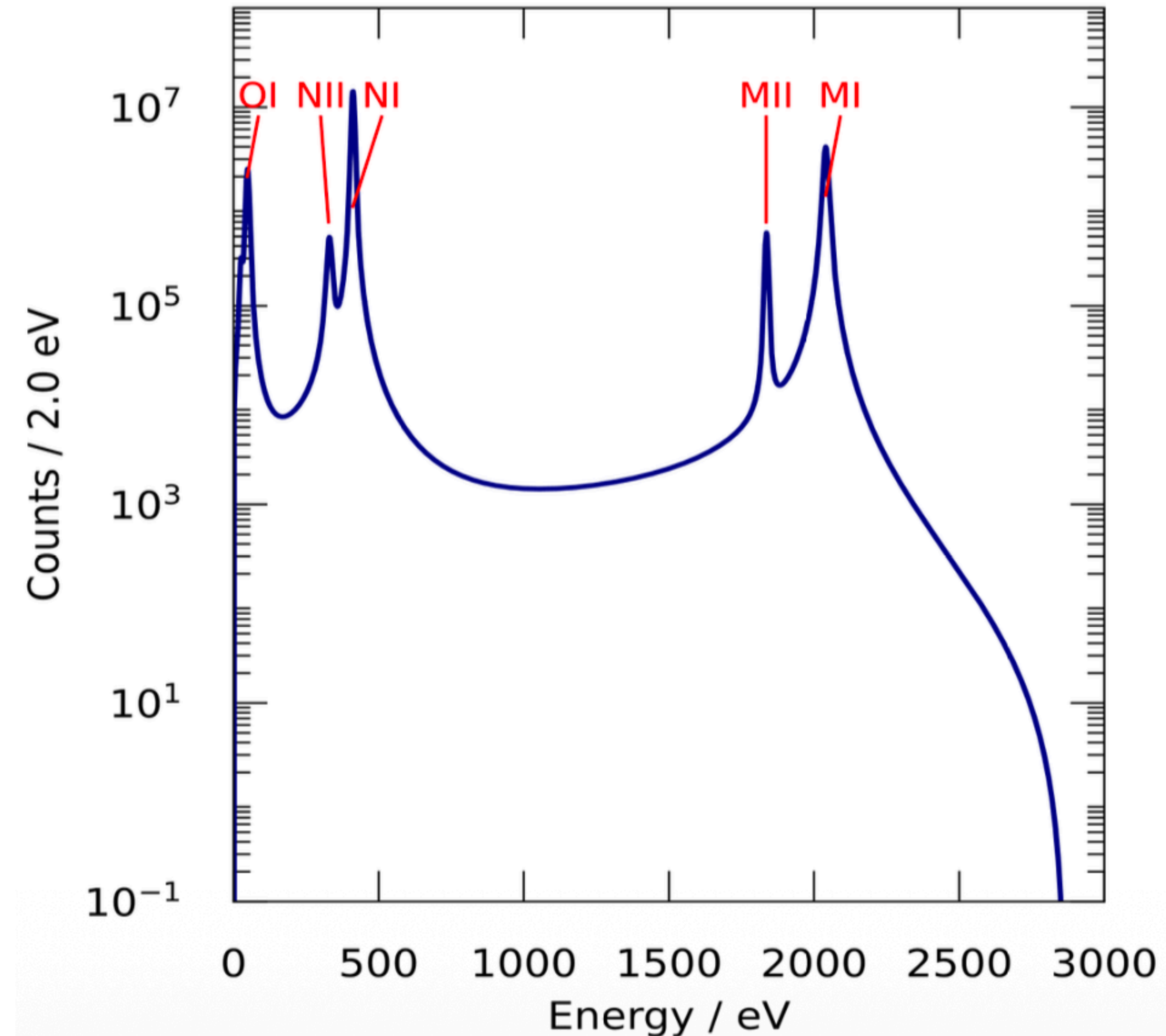
Slide by A. Nucciotti, NuMass 2026

Source Development



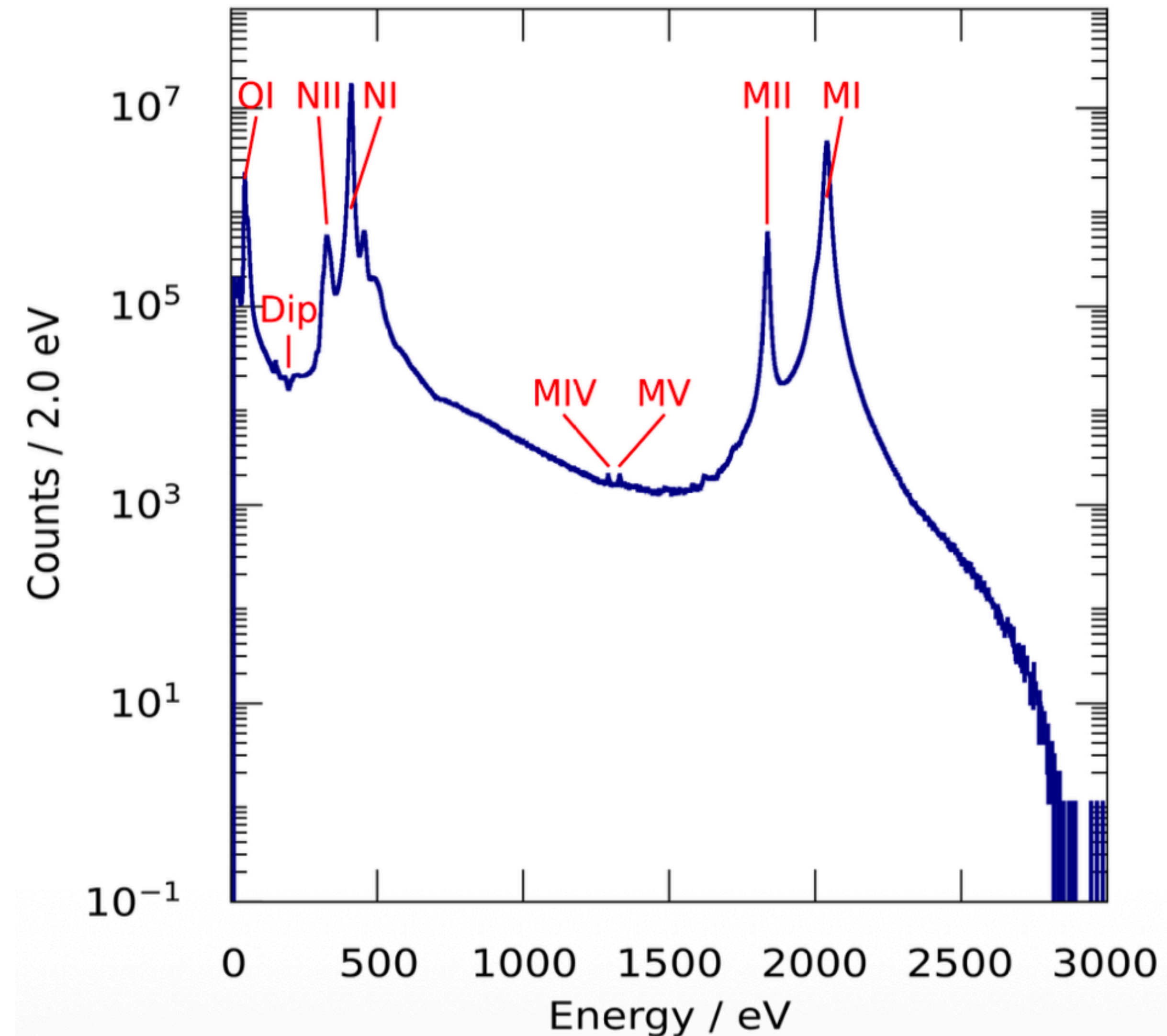
Challenge: Source Modelling

- ^{163}Ho is a complicated nucleus
- Many spectral features



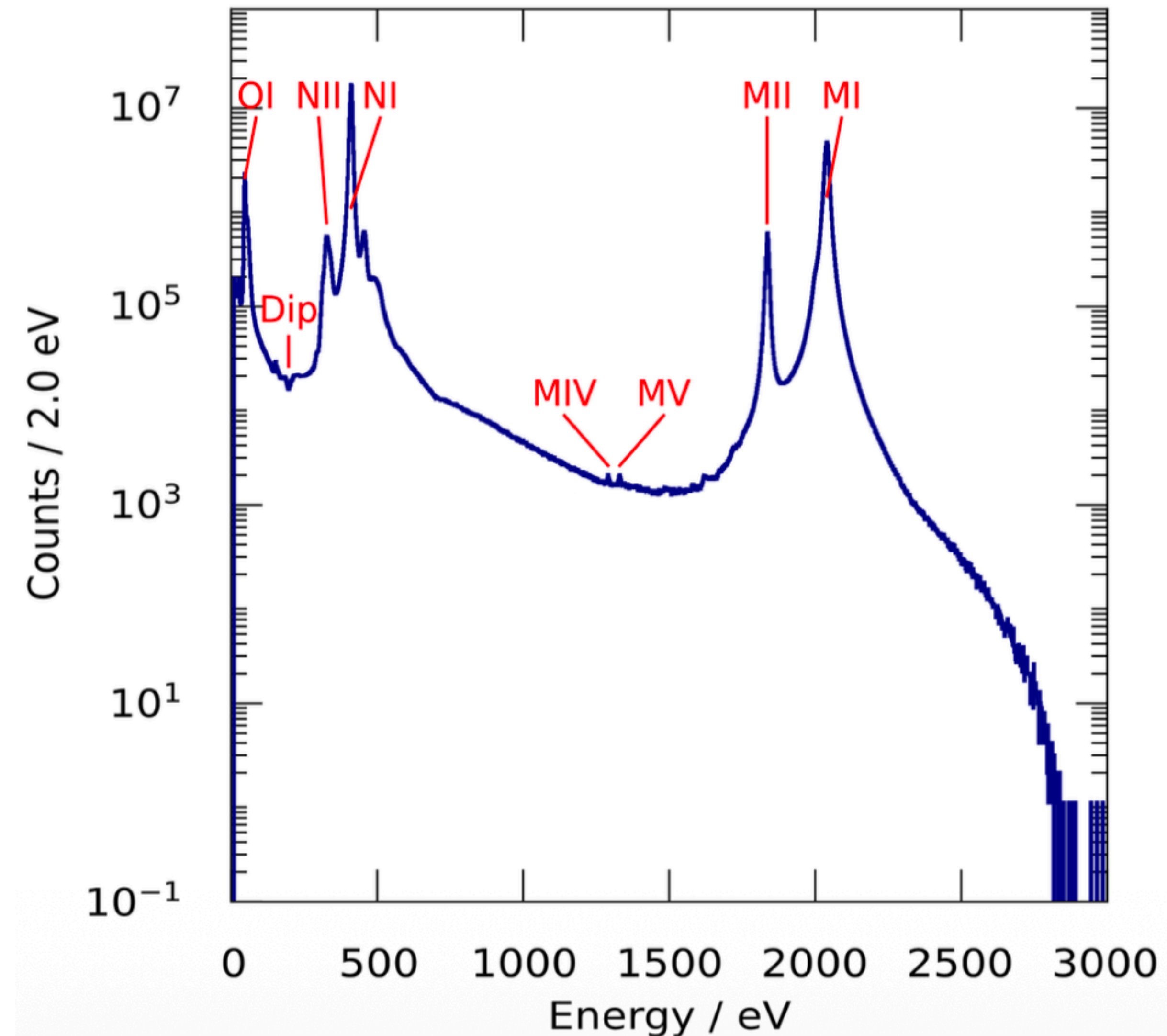
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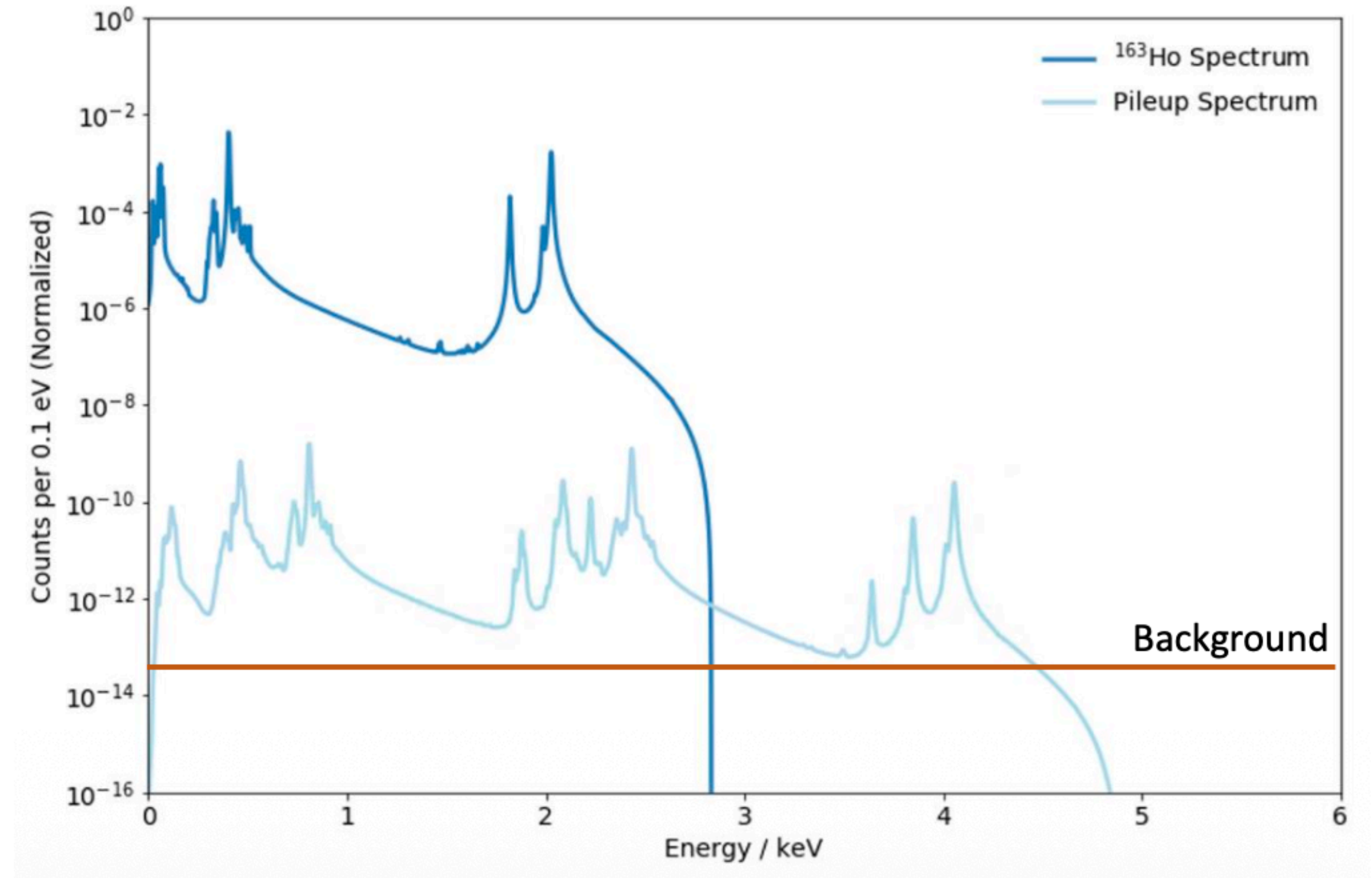
Challenge: Source Modelling

- ^{163}Ho is a complicated nucleus
- Many spectral features
- A lot of improvement in the past decade!
- But still not a perfect description



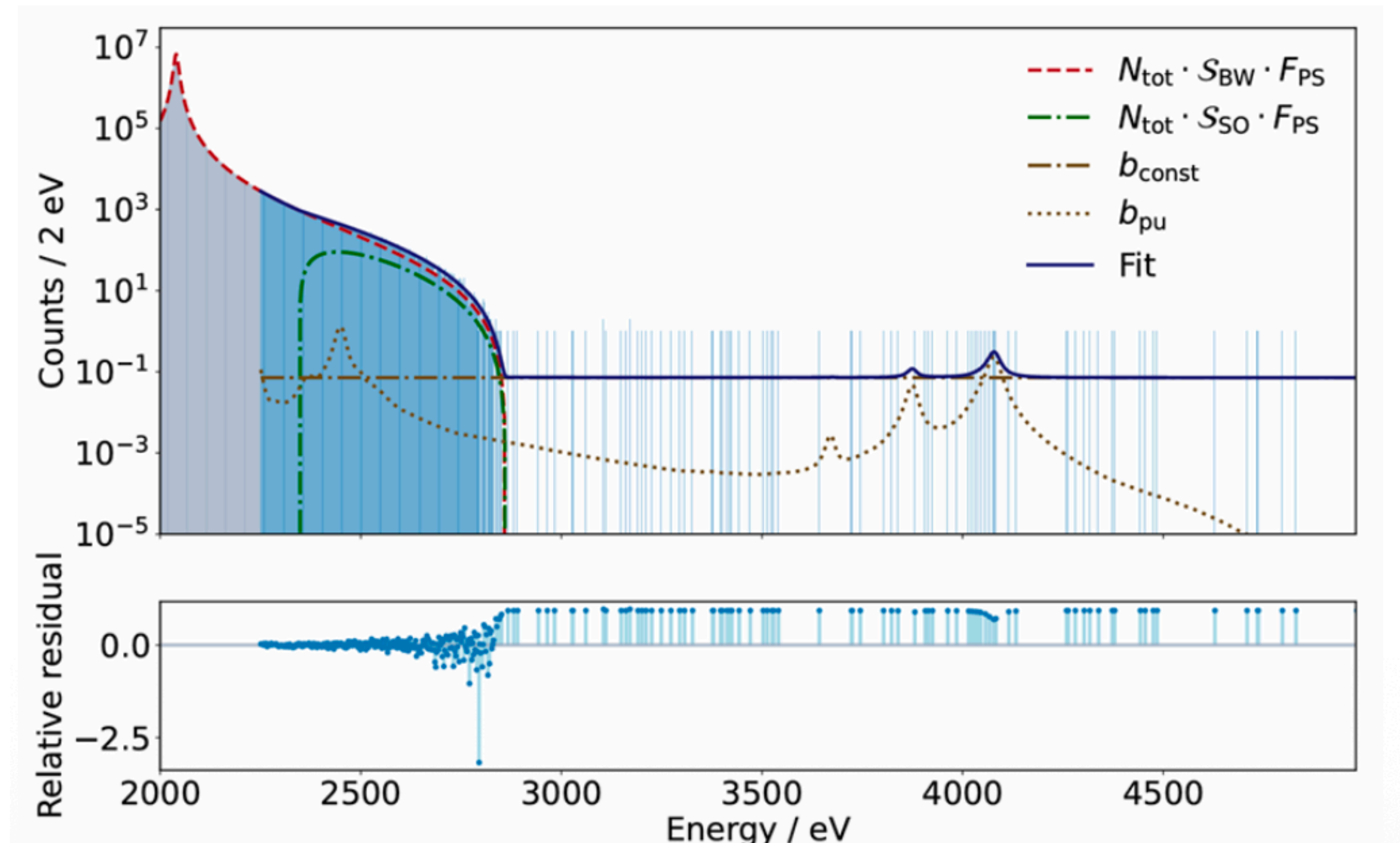
Challenge: Pileup

- Calorimetric detection:
2 events counted as 1
event with high energy
- Irreducible
background
- Limits per pixel
activity
- Need many fast
detectors

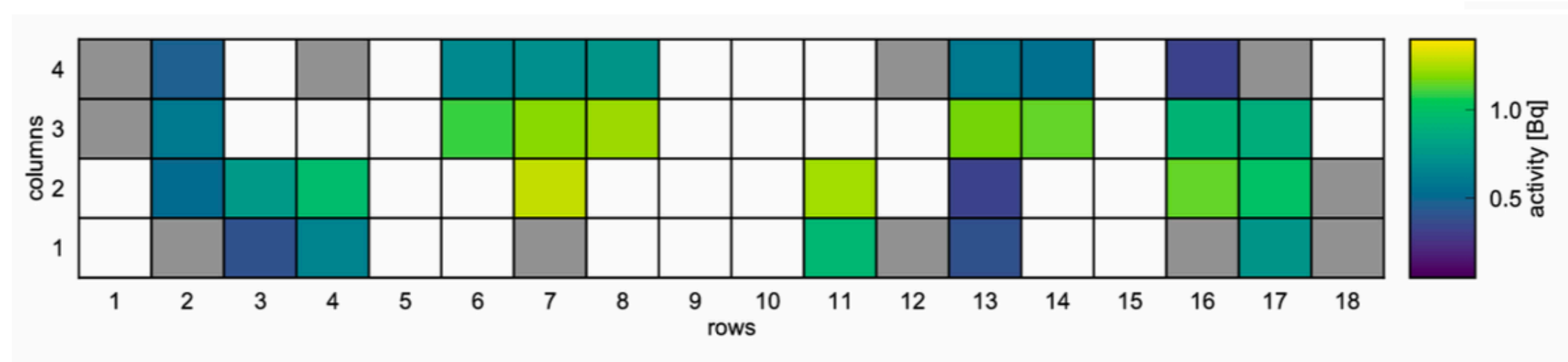


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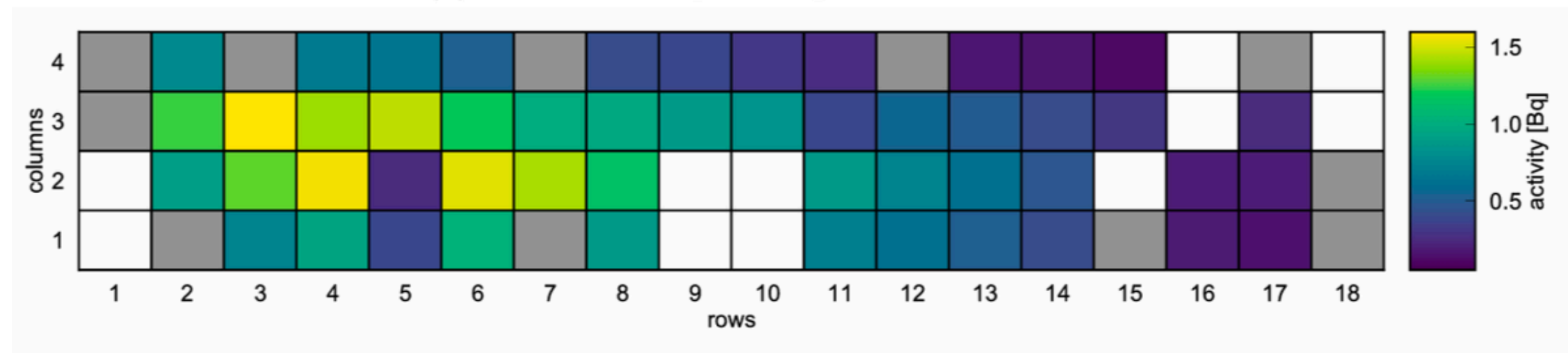
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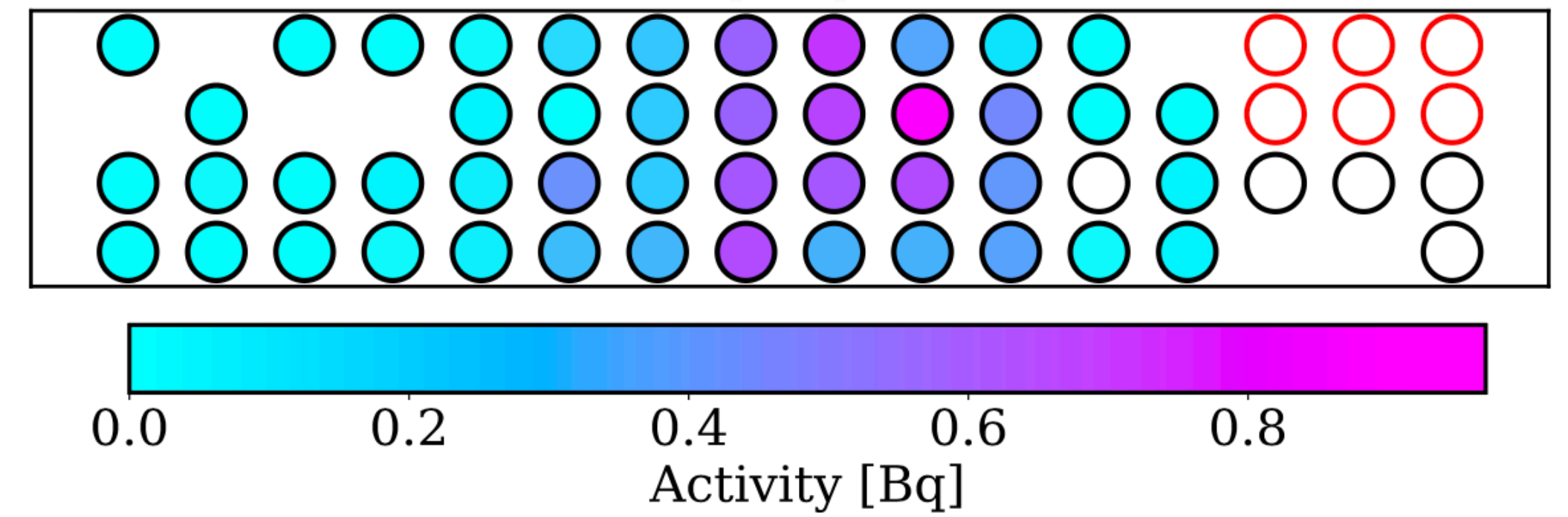
Challenge: Implantation Homogeneity



(a) ECHo-1k chip with gold as host-material



(b) ECHo-1k chip with silver as host-material



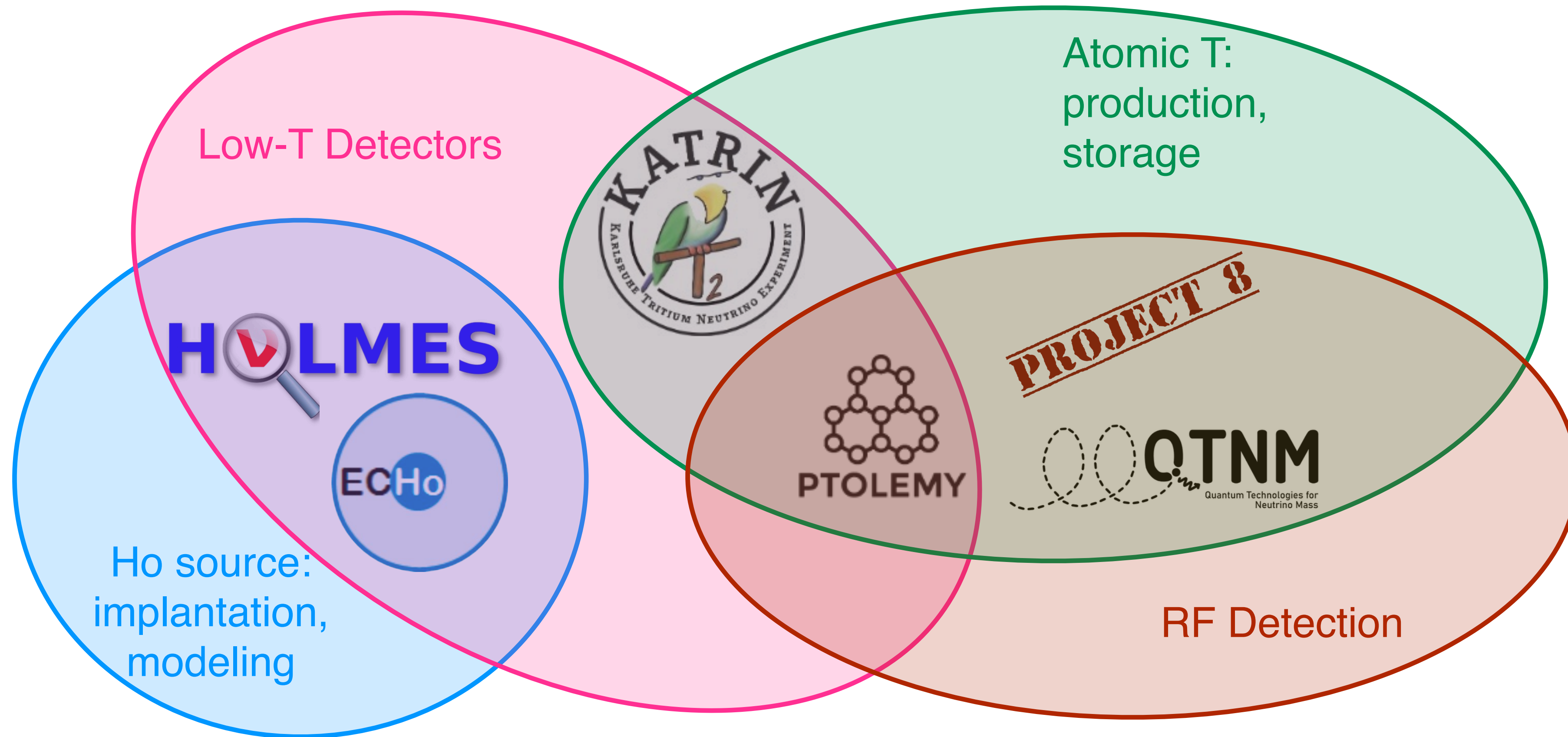
- Different activity levels can be calibrated
- But: there is a “perfect” activity per pixel

Recap: Holmium-based Experiments

- Relatively new experimental effort with amazing progress
- Scaling to $<1\text{eV}$ level remains very difficult

Name	ECHo-1k	ECHo-100k	ECHo-LE	HOLMES	HOMES+	HOLMES++
Detection	MMCs + SQUIDs	MMCs + RF SQUID	MMCs + RF SQUID	TES + RF-SQUID		
Activity / pixel	0.7 Bq / 0.9 Bq	10 Bq	10 Bq	0.3 Bq	3 Bq / 30 Bq	30 Bq
Pixels	57	12k	20k	64	256 / 16	4096
Total activity	46 Bq	120k Bq	200k Bq	15 Bq	758 Bq / 480 Bq	120k Bq
E resolution	7 eV	5 eV	$<5\text{ eV}$	$\sim 10\text{ eV}$ (FWHM)	$\sim 5\text{ eV}$ (FWHM)	
Temperature		20mK		94 mK	50mK	
Limit (90% C.L.)	15 eV	1.5 eV	0.8 eV	27 eV	6 eV / 4 eV	
When?	DONE	Soon	2030	DONE	2028	2032

Neutrino mass is only confirmed effect beyond the standard Model;
but its value remains elusive



Everyone:

- Quantum devices
- Cryogenic setups
- Sensitivity and analysis
- Calibration methods

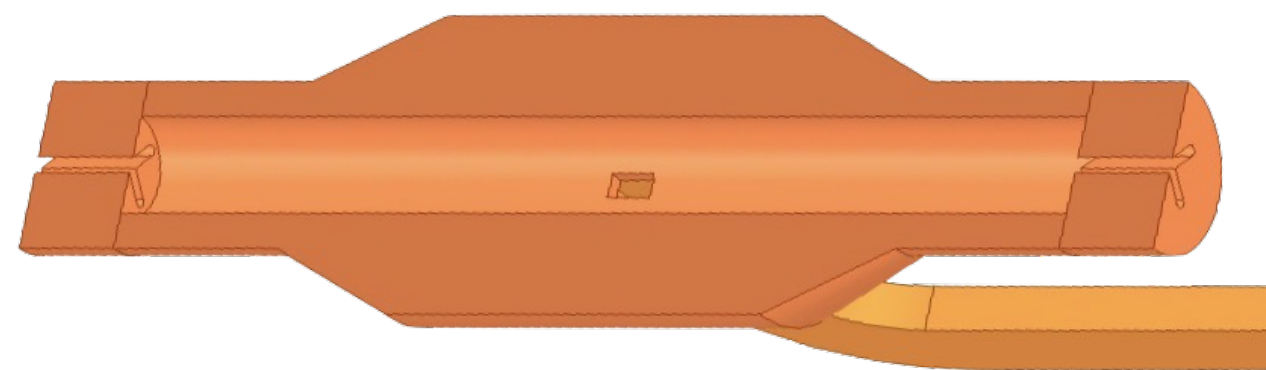
- Many paths to 40 meV being explored
- Currently no clear winner
- Ideal case: 1 Tritium + 1 Holmium experiment: $m_{\bar{\nu}_e, \text{eff}}$ and $m_{\nu_e, \text{eff}}$

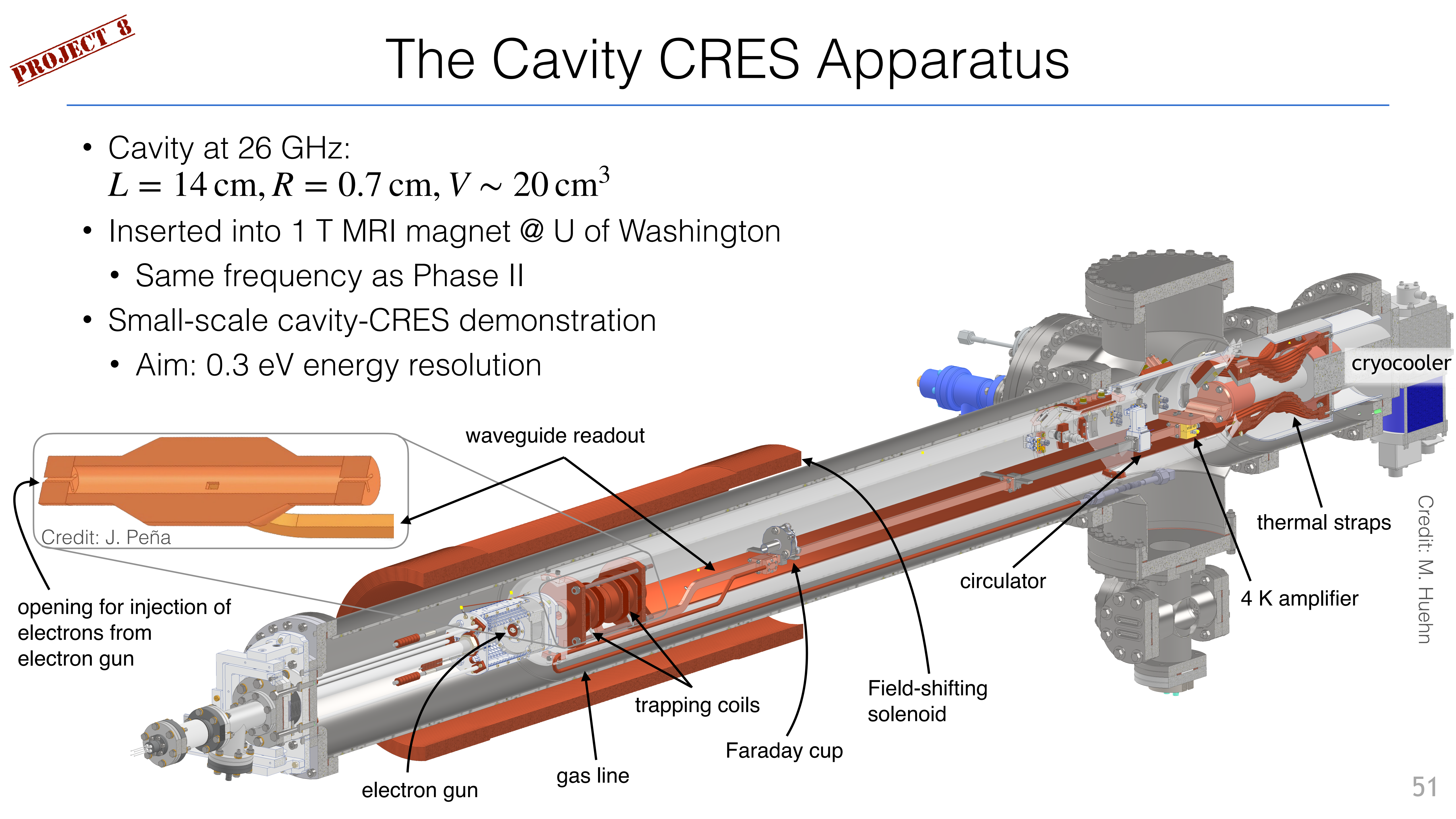
What Will the Next Direct Neutrino Mass Experiment Look Like?

Time will tell...

TRL	Definition
1	Can't prove laws of physics violated.
2	Reasonable to think laws of physics aren't violated.
3	Proof-of-principle demonstrated.
4	Low-fidelity prototype successfully tested.
5	High-fidelity prototype successfully tested.
6	Standalone final component successfully tested.
7	Integrated subsystem successfully tested.
8	First physics data collected.
9	Results published.

- Cavity at 26 GHz:
 $L = 14\text{ cm}, R = 0.7\text{ cm}, V \sim 20\text{ cm}^3$
- Inserted into 1 T MRI magnet @ U of Washington
 - Same frequency as Phase II
- Small-scale cavity-CRES demonstration
 - Aim: 0.3 eV energy resolution



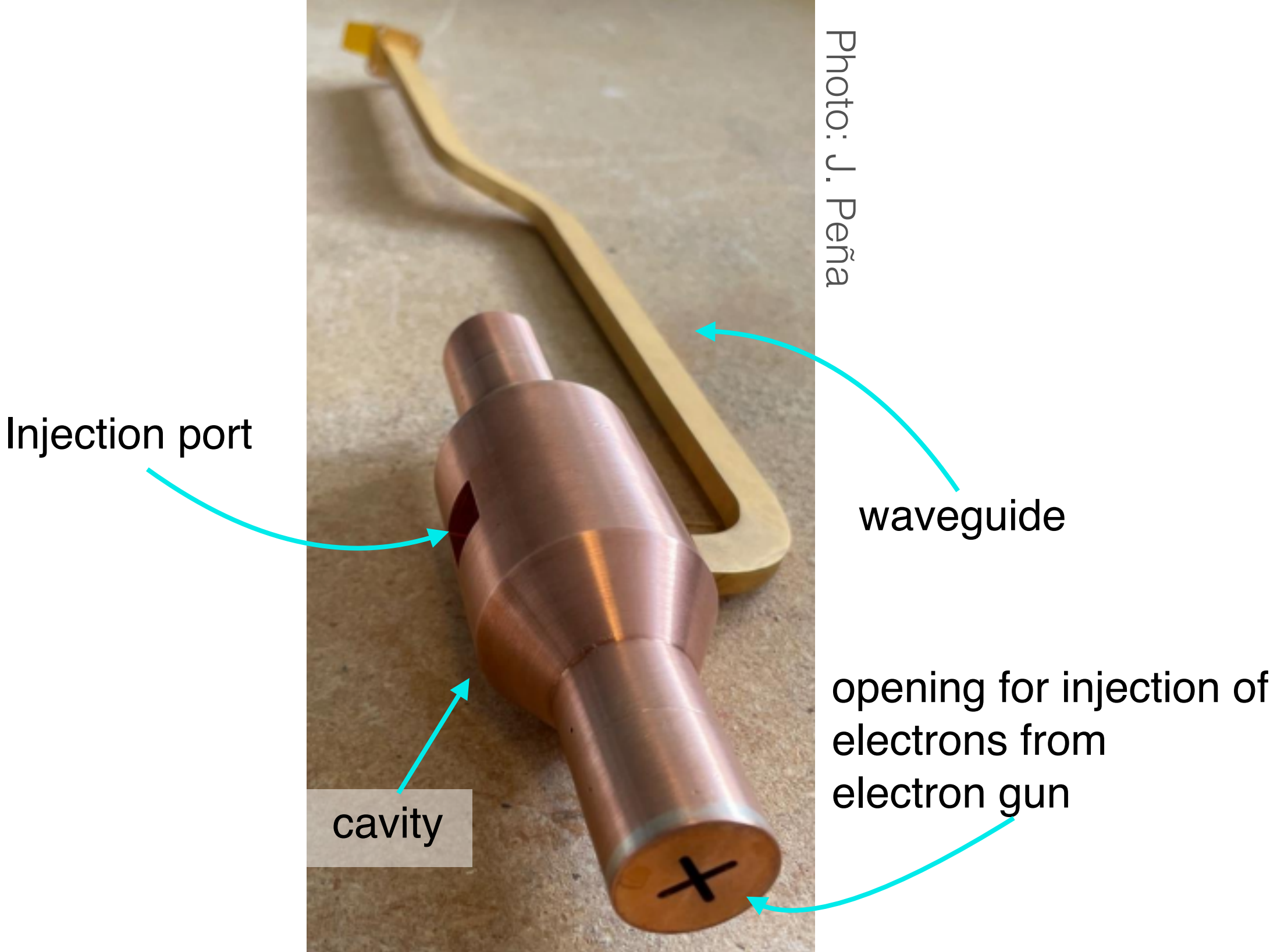


The Cavity CRES Apparatus

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Credit: M. Huehn

CCA - Commissioning



- Status: Commissioning ongoing
- Expect first cavity CRES data soon

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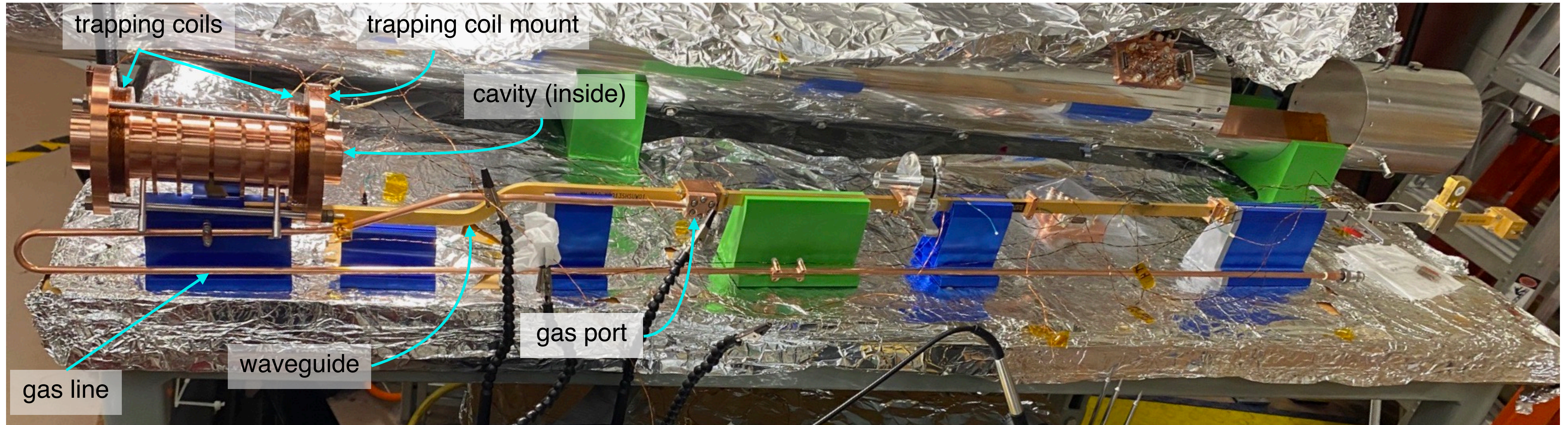
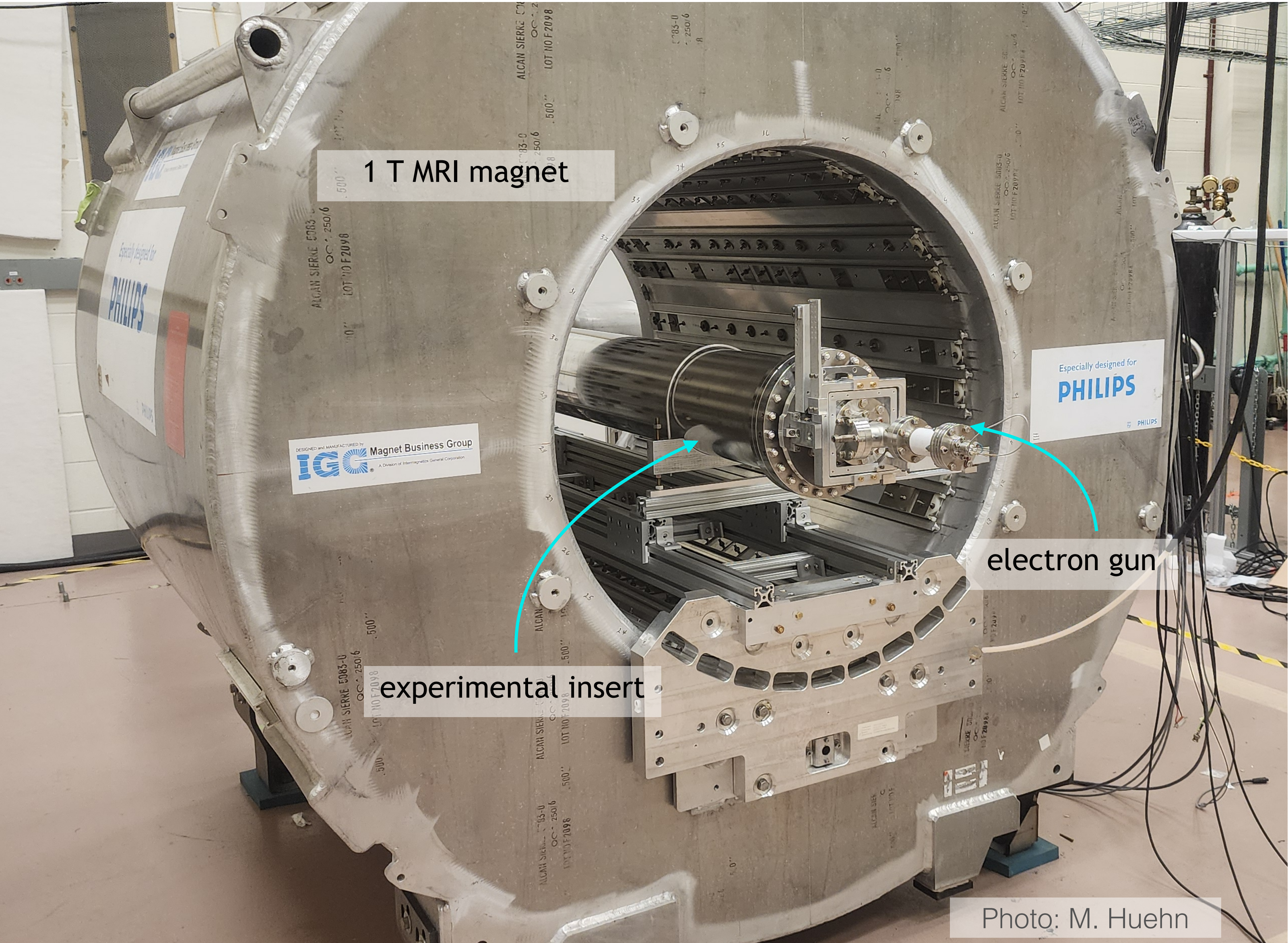


Photo: T. E. Weiss

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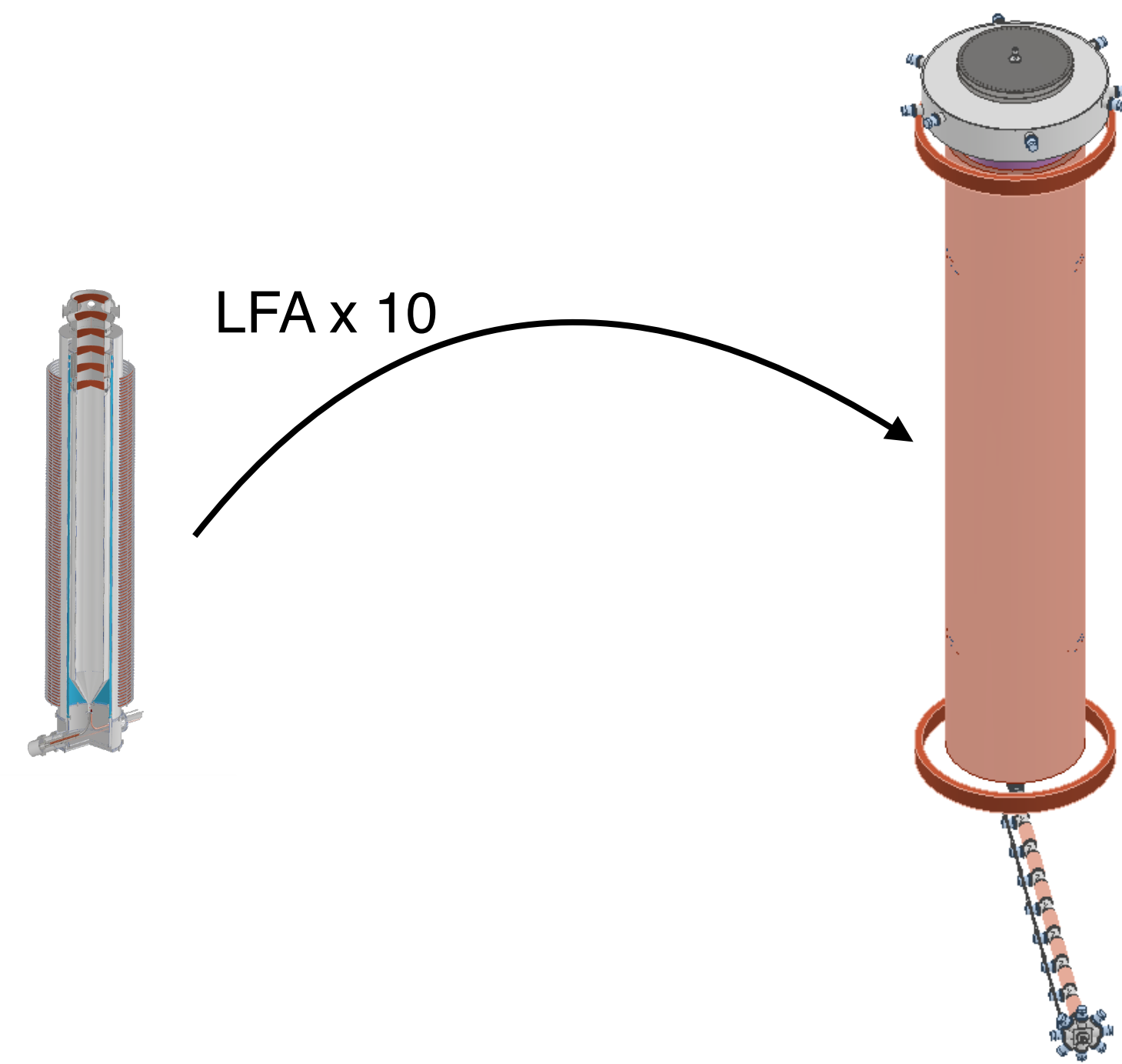
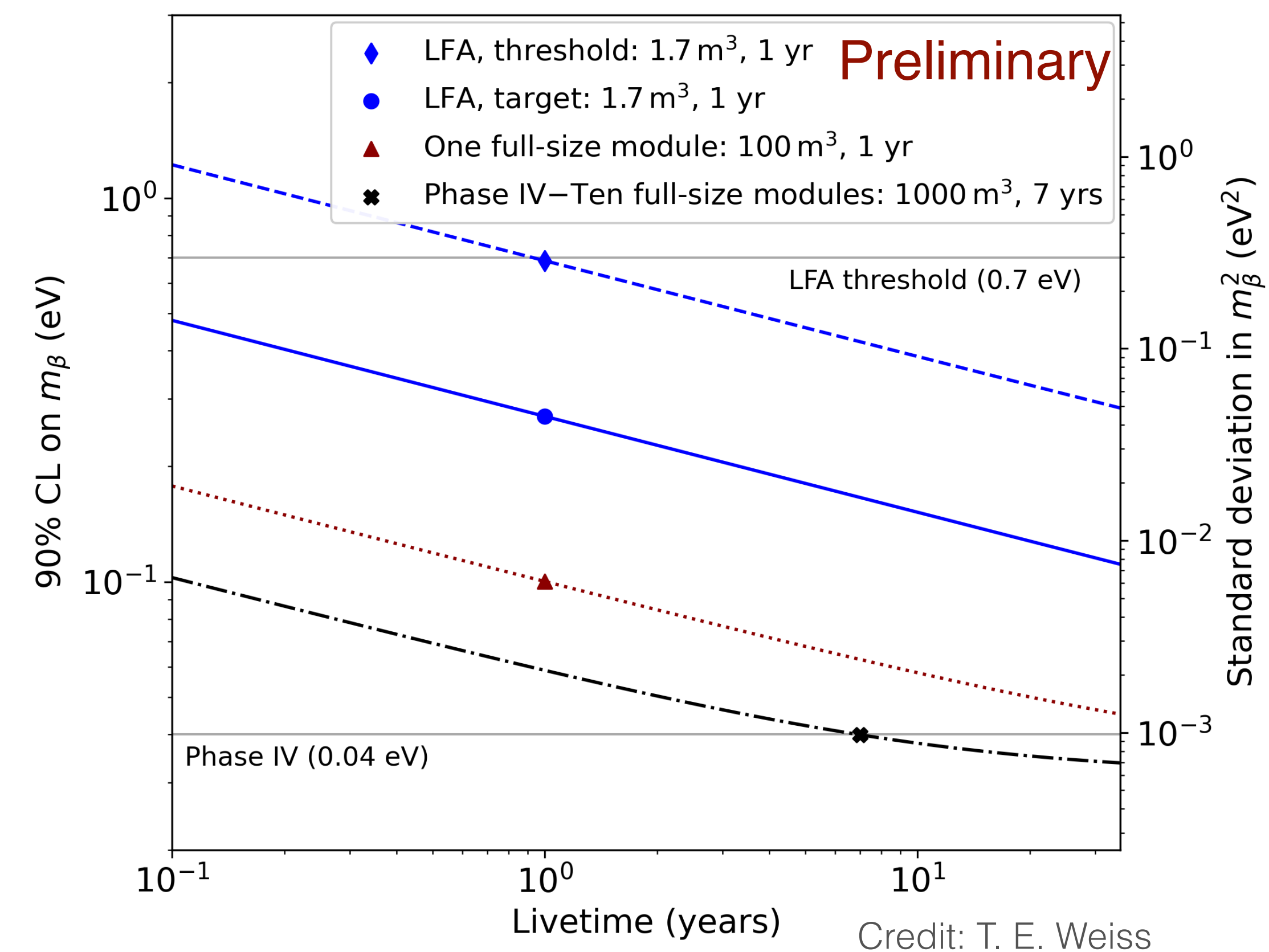
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Phase IV concept

- Even bigger: $f = 150 \text{ MHz}$, $V \sim 100 \text{ m}^3$
- 10 detector modules
- 40 meV sensitivity



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