The Role of Atomic Tritium in Future Neutrino Mass Experiments

Larisa Thorne
Johannes Gutenberg University Mainz
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PROJECT 8
JG|U
PRISMA+ Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

Credit: L. Thorne

OUTLINE

- Neutrino mass: why and how?
- Tritium-based experiments
- The molecular problem
- The atomic solution (& challenges)
  - Special focus: Project 8
- Summary

PRIMER ON NEUTRINOS

- Neutrino oscillation:

PMNS mixing matrix

Flavor eigenstates $|\nu_l>$

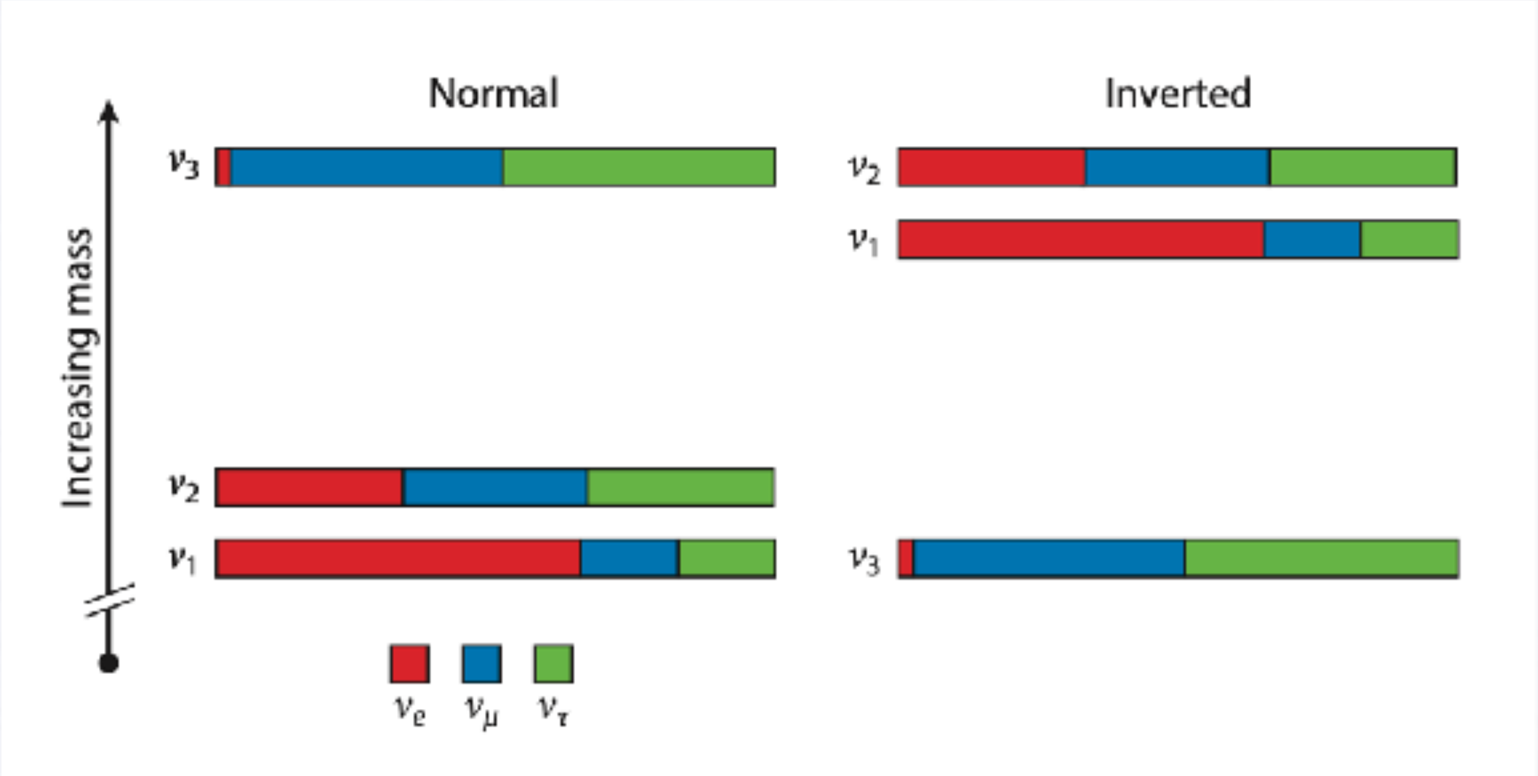
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Mass eigenstates $|\nu_i>$

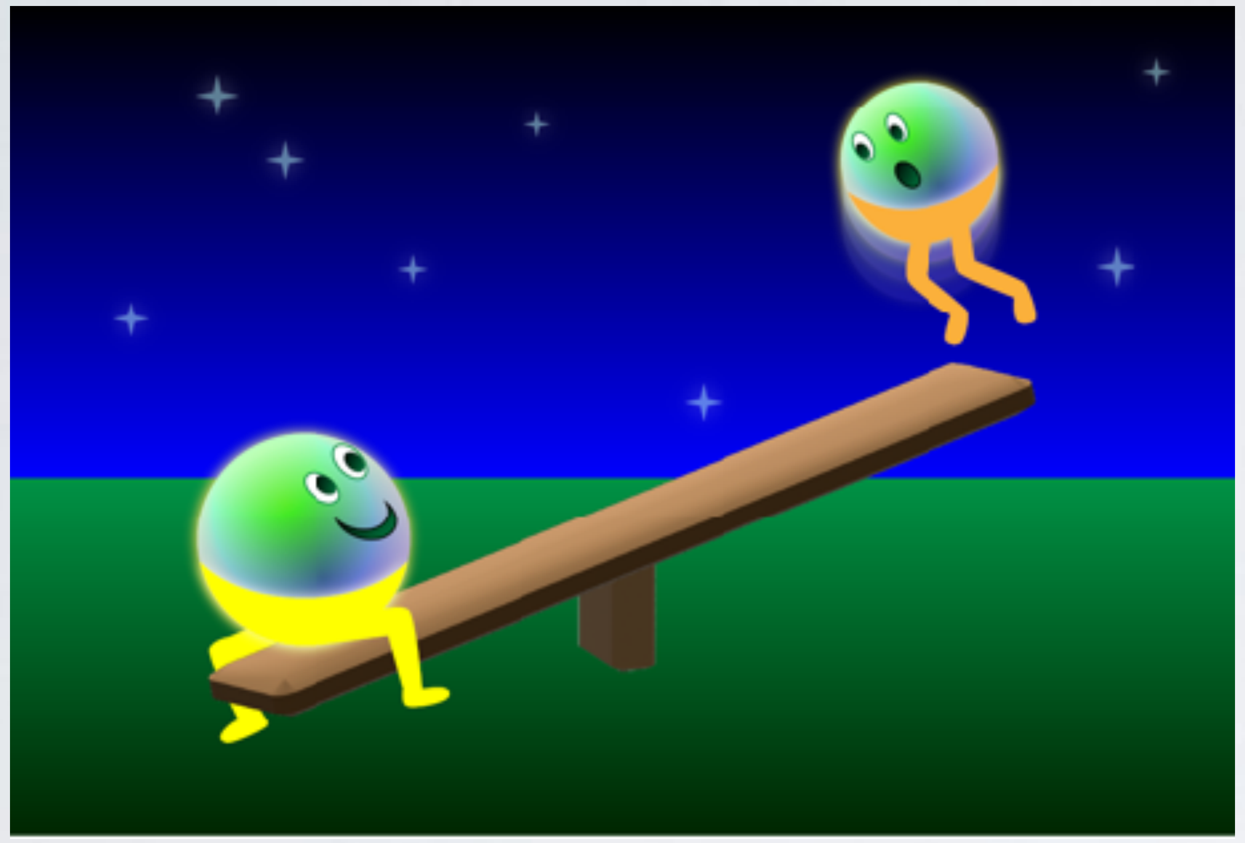
Probability upon detection:

$$P_{ii'} \propto \frac{(m_i^2 - m_{i'}^2)L}{E}$$

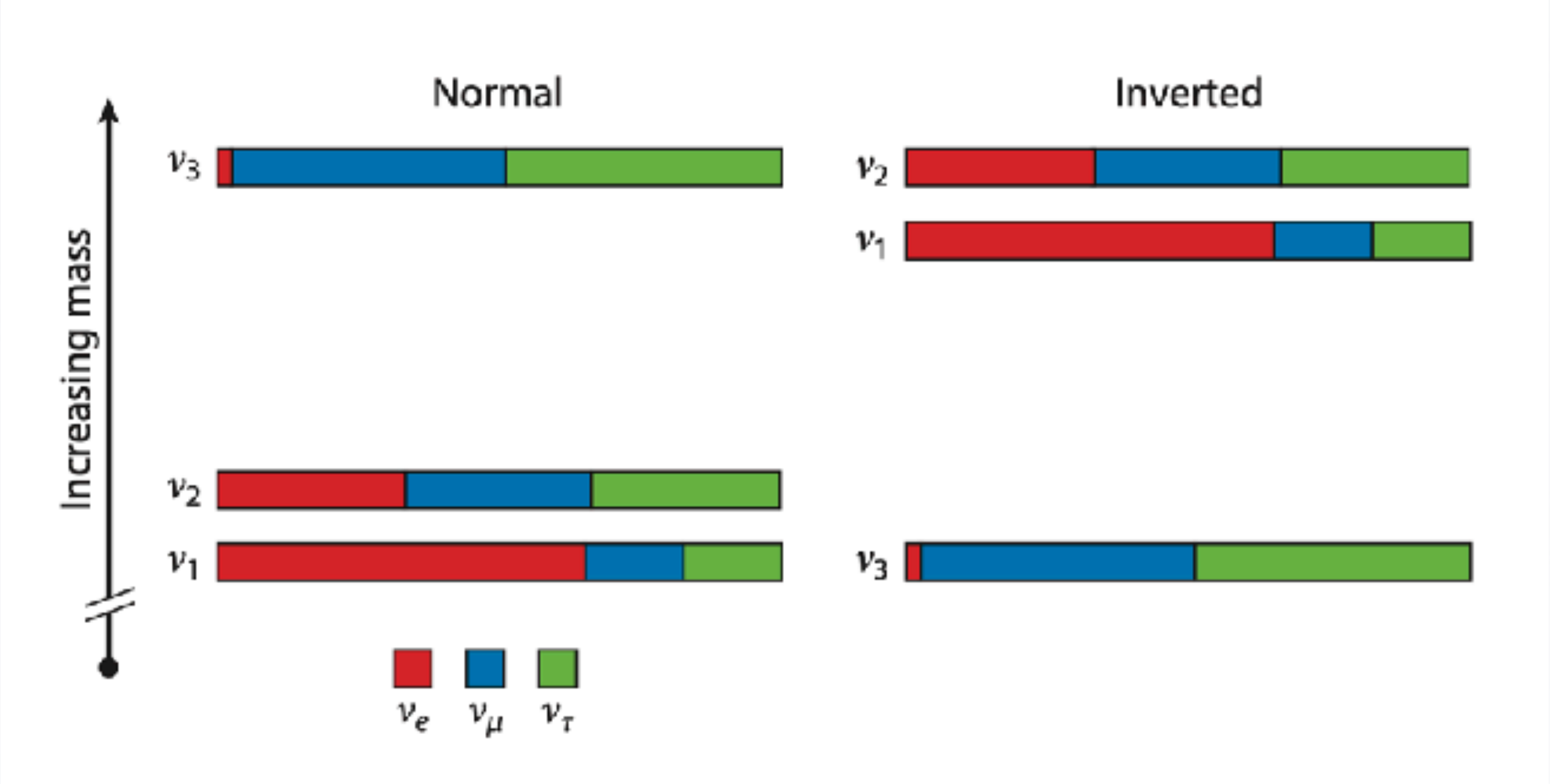
- Neutrino sector has many other interesting features:
  - Mass ordering: normal vs. inverted
  - Type: Majorana vs. Dirac
  - Absolute mass scale ← !



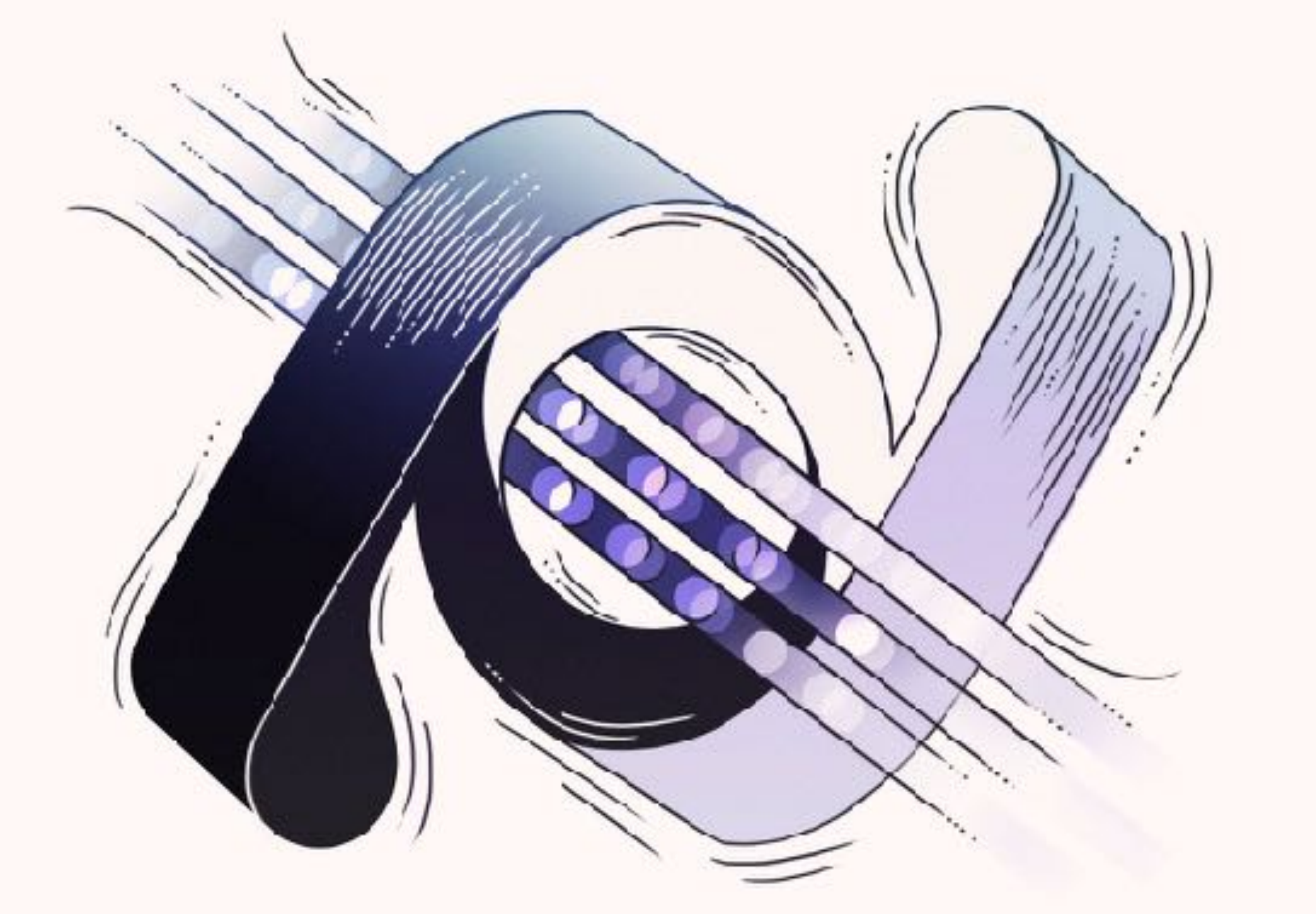
NEUTRINO MASS: WHY?



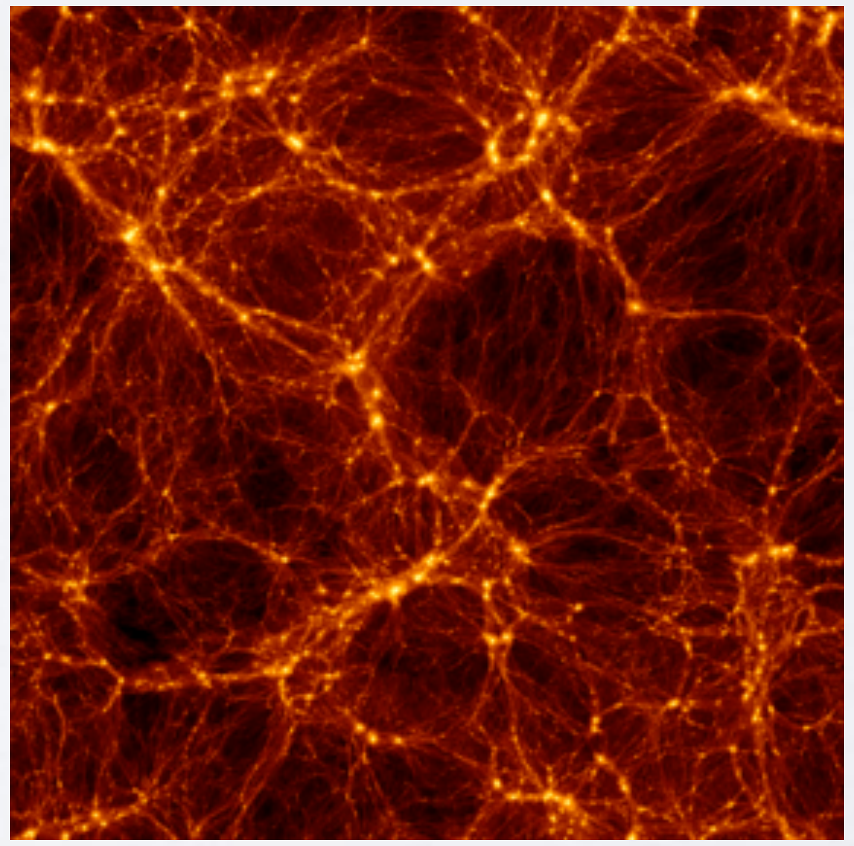
Source: https://physics.aps.org/articles/v16/20



Source: Formaggio et al, 2021



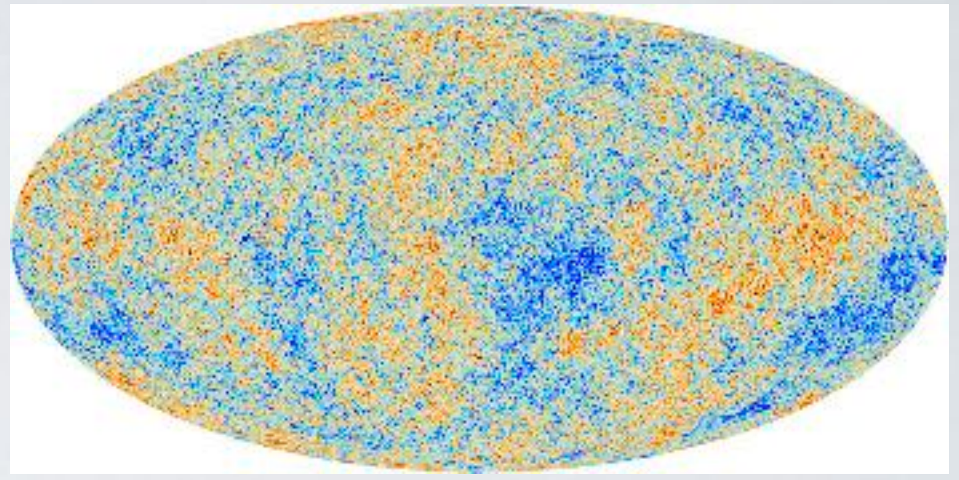
Source: Symmetry Magazine , 2016

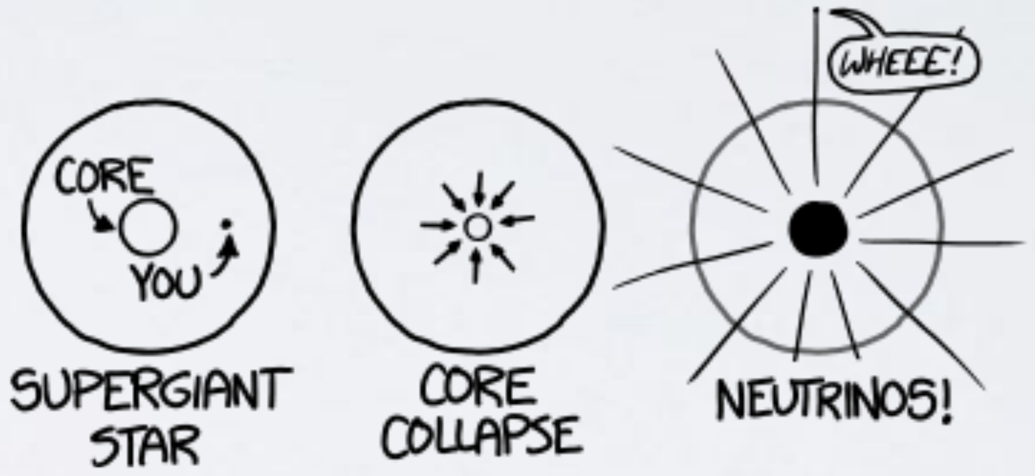


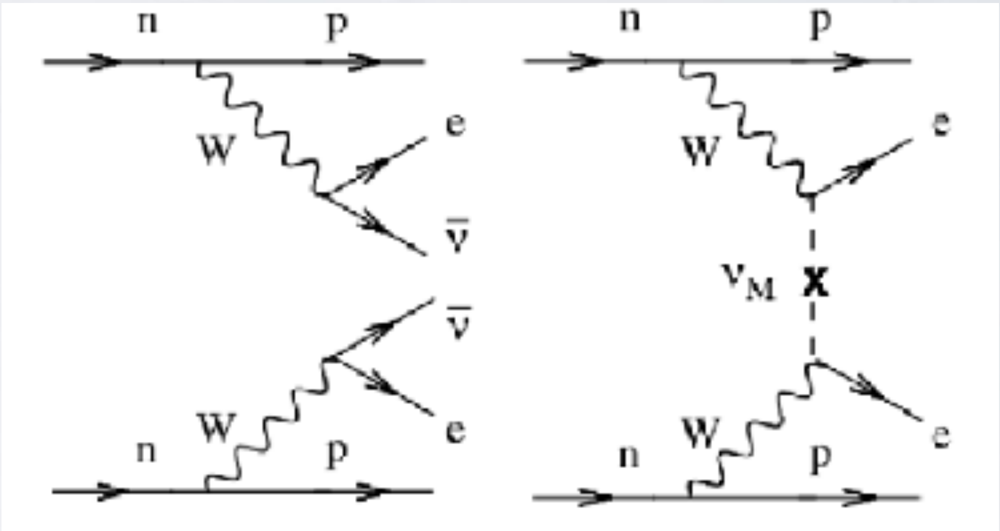
Source:https://arxiv.org/abs/1806.08395

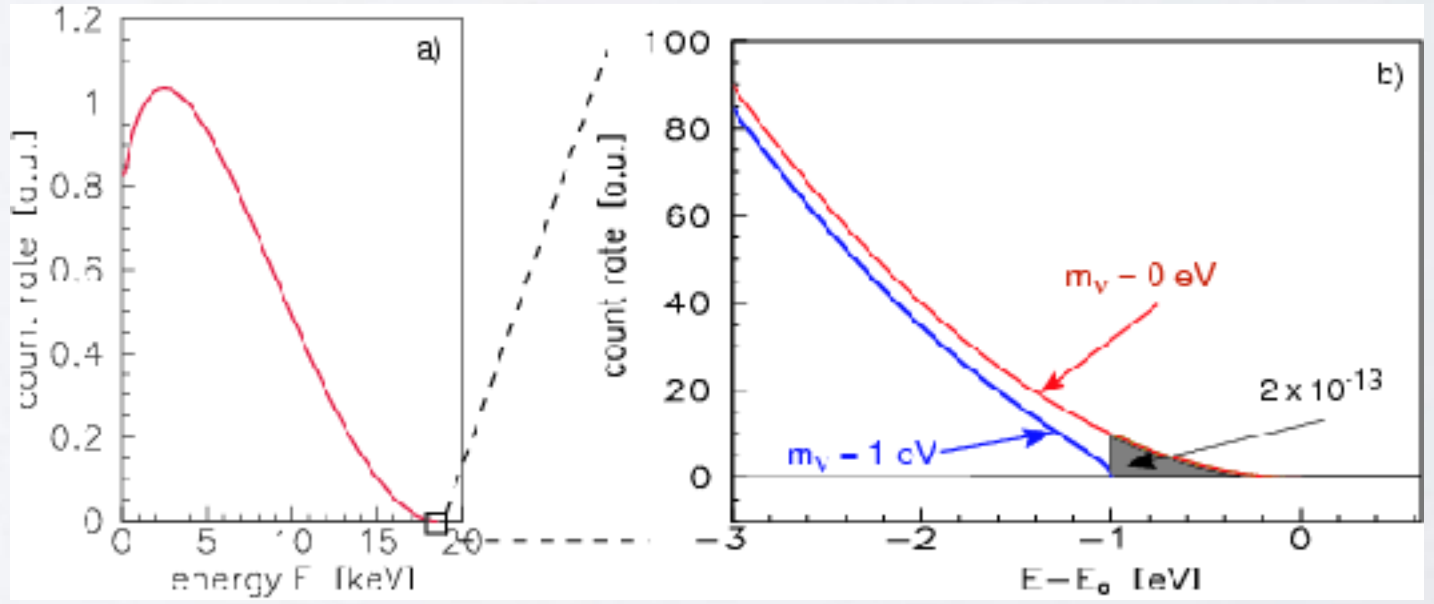
NEUTRINO MASS: HOW?

- 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
     - Via electromagnetic collimation
     - Via frequency-based measurement
     - Via calorimetric measurement









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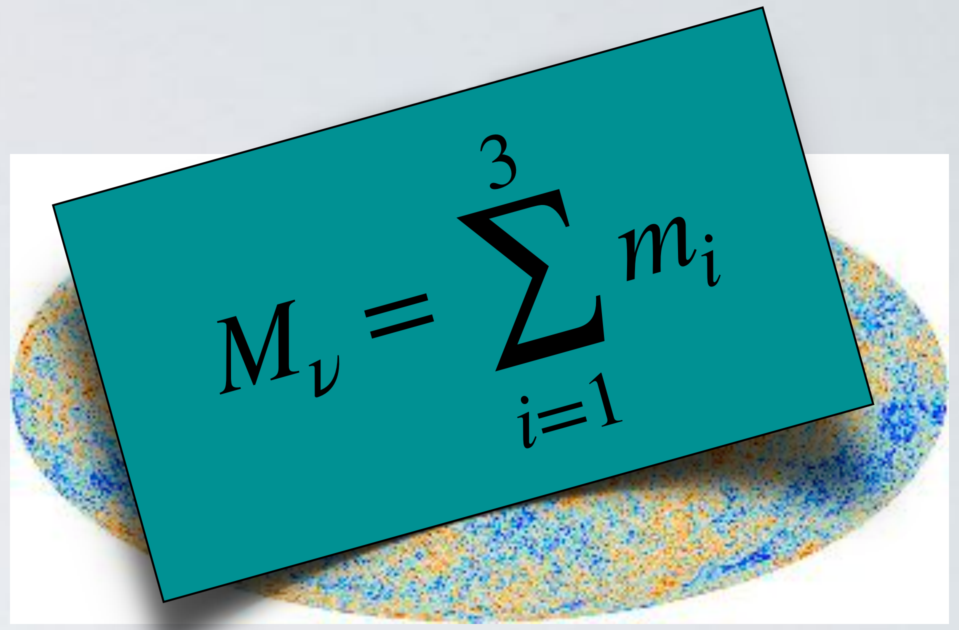
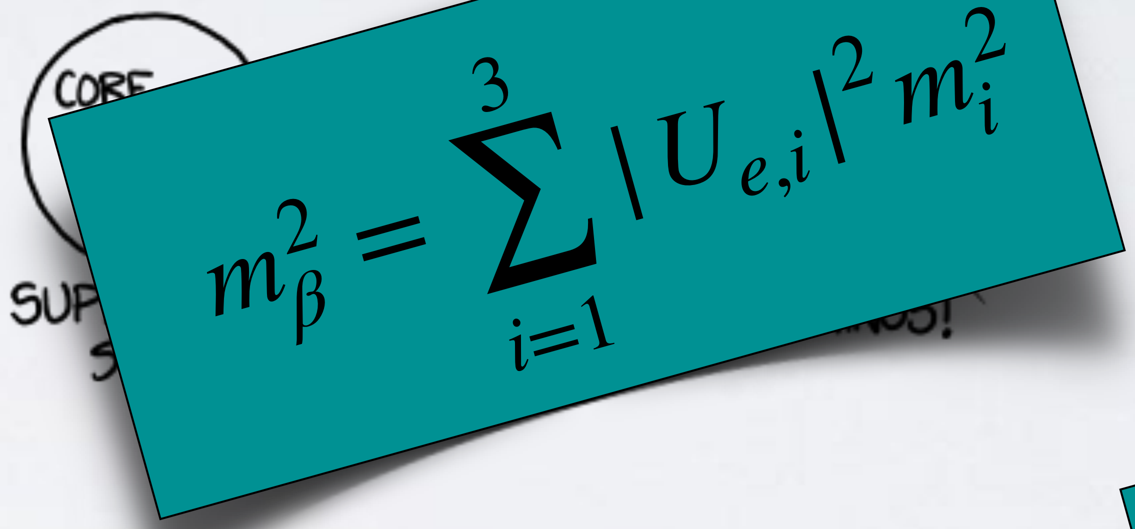
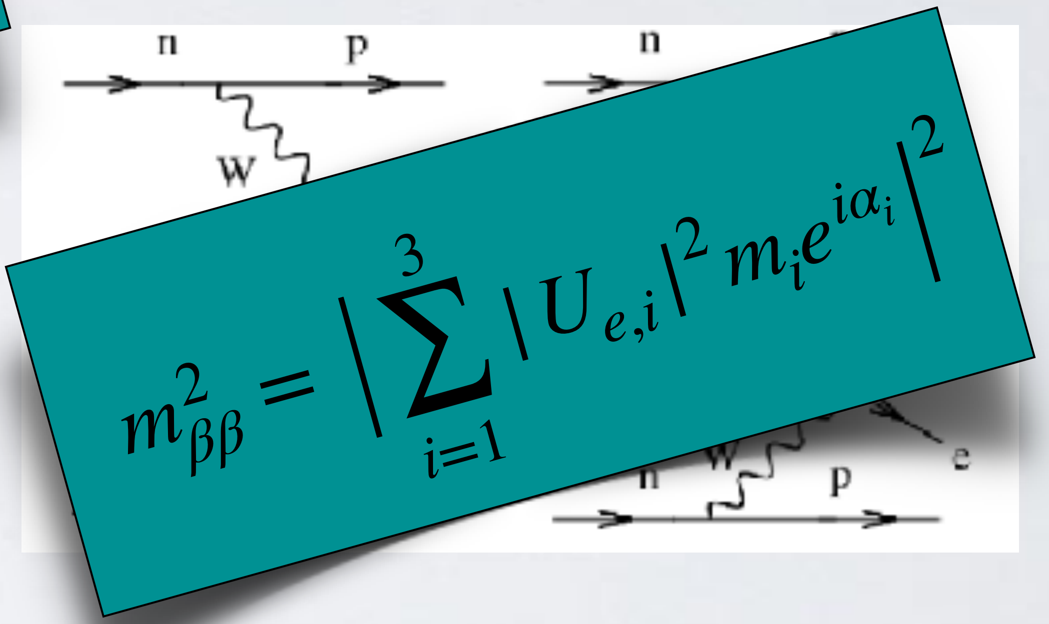


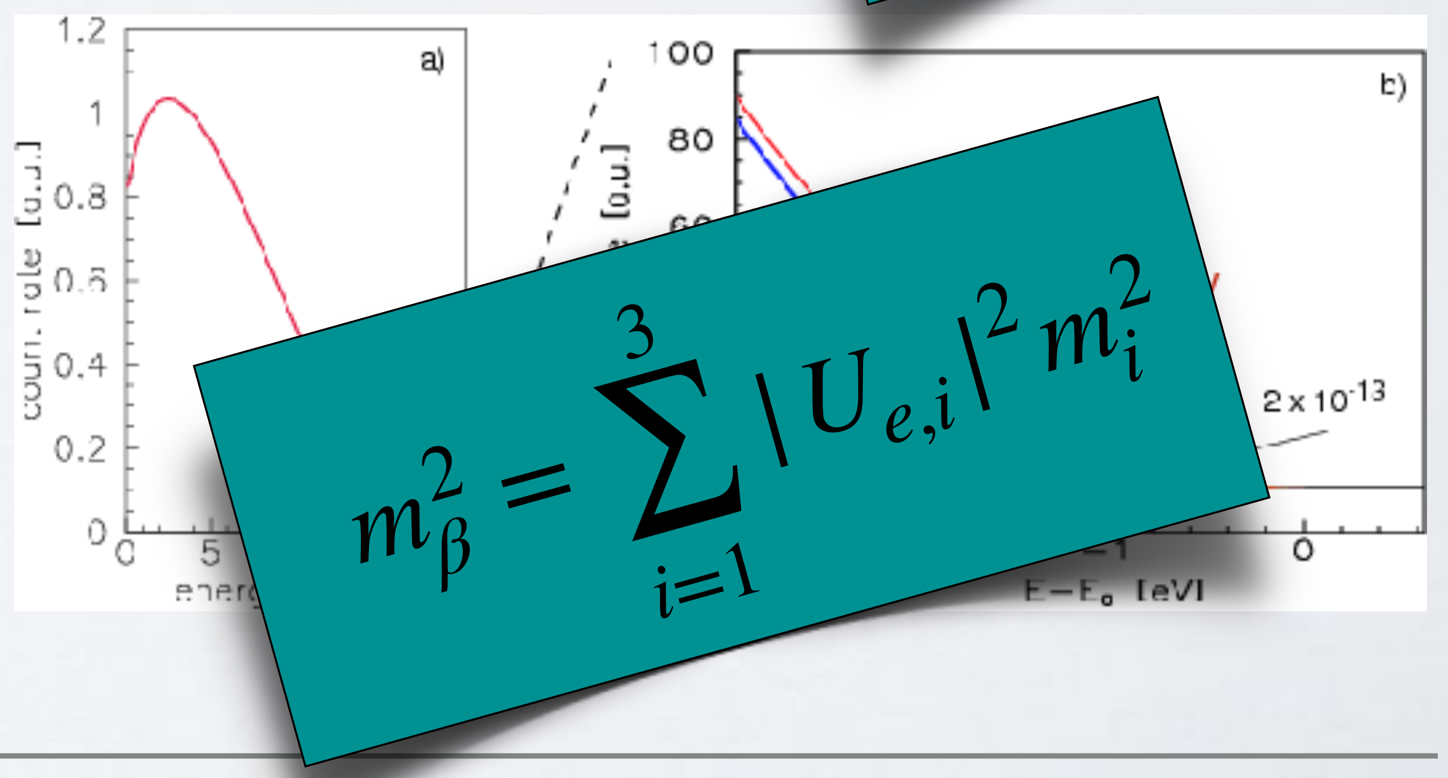
$$M_\nu = \sum_{i=1}^{3} m_i$$



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



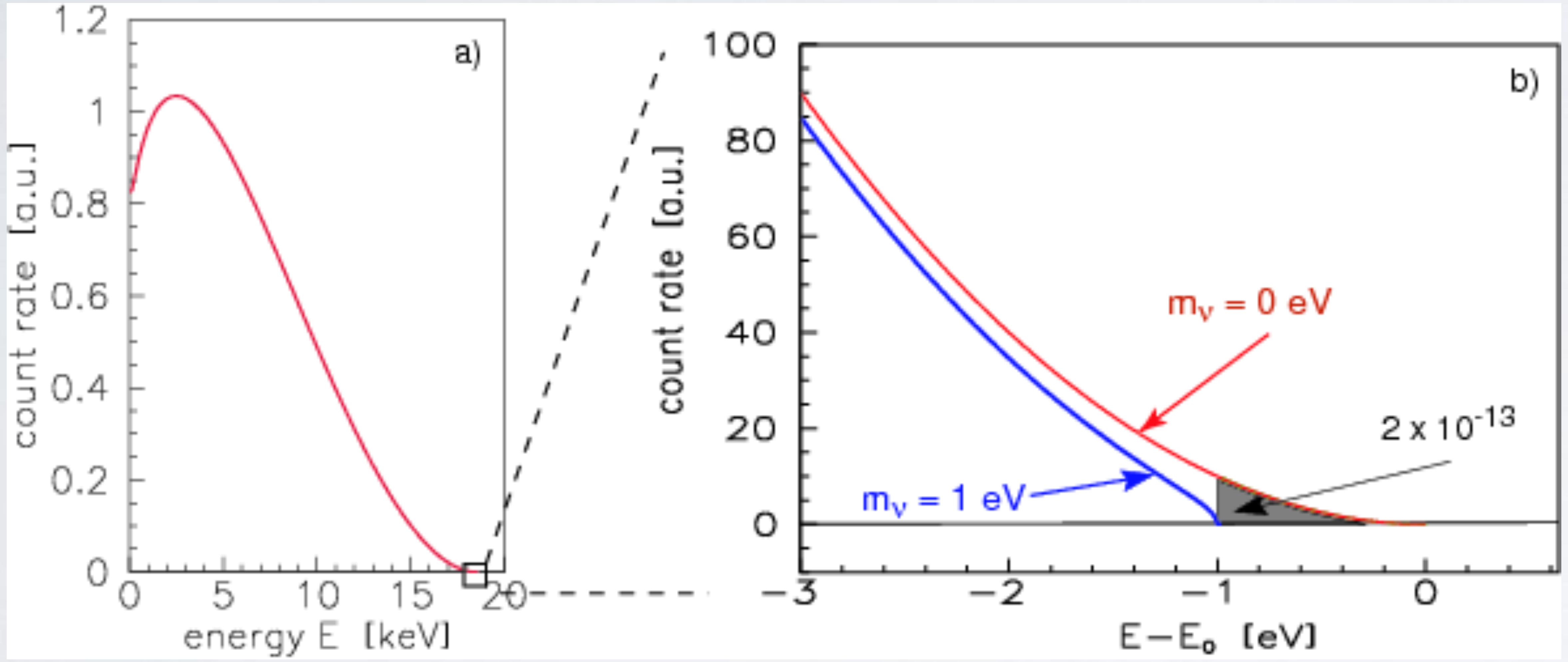
$$m_{\beta\beta}^2 = \left|\sum_{i=1}^{3} |U_{e,i}|^2 m_i e^{i\alpha_i}\right|^2$$



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

TRITIUM-BASED EXPERIMENTS

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



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:

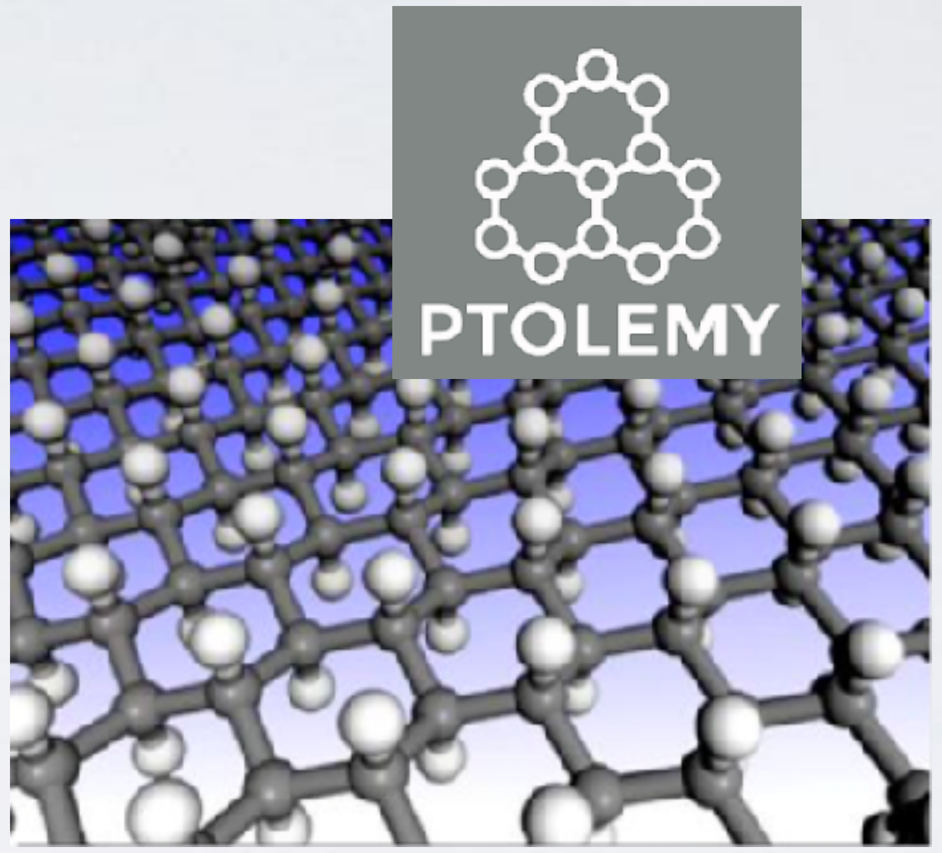
$$\frac{d^2N}{dEdt} = \frac{G_F |V_{ud}|^2}{2\pi^3} |M_{nucl}|^2 F(Z,E) p_e (E + m_e) \cdot \sum_f G_f P_f \epsilon_f \sqrt{\epsilon_f^2 - m_\beta^2}\, \Theta(\epsilon_f - m_\beta)$$

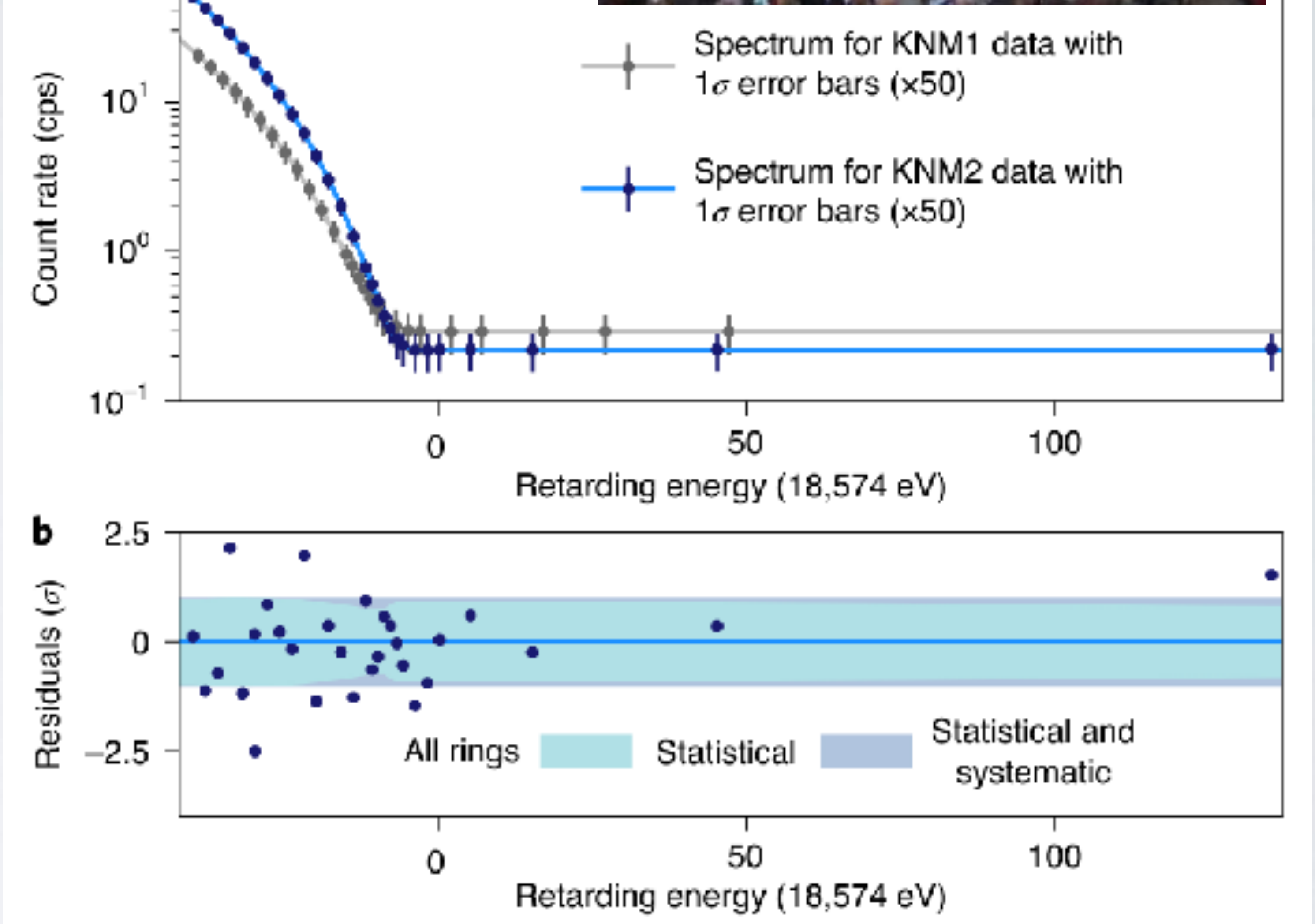
$$m_{\beta,eff}^2 = \sum_{i=1}^{3} |U_{e,i}|^2 m_i^2 \approx m_\beta^2$$

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

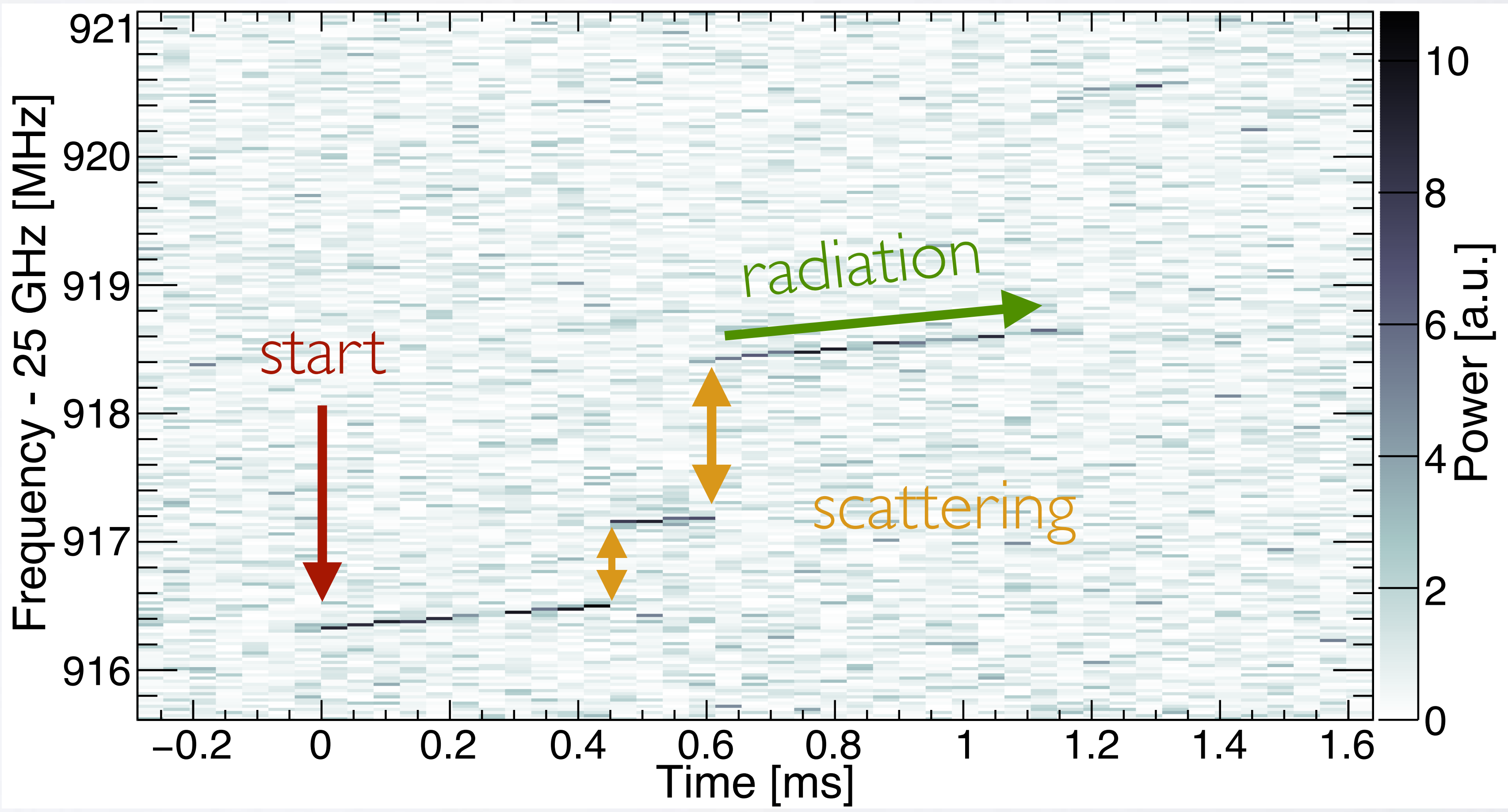
TRITIUM-BASED EXPERIMENTS

- *Technique*: measurement of beta particle energy
- *Neutrino mass:* $m_\beta \leq 0.45$ eV @ $90\,\%$ C.L. (KATRIN 2024)
- *Advantages*:
  - Cross checks to other experiments (Q values, isotopes)
- *Challenges*:
  - Statistics
  - Systematics (molecular final states, backgrounds)





Source: KATRIN sub-eV result, Nature 2022

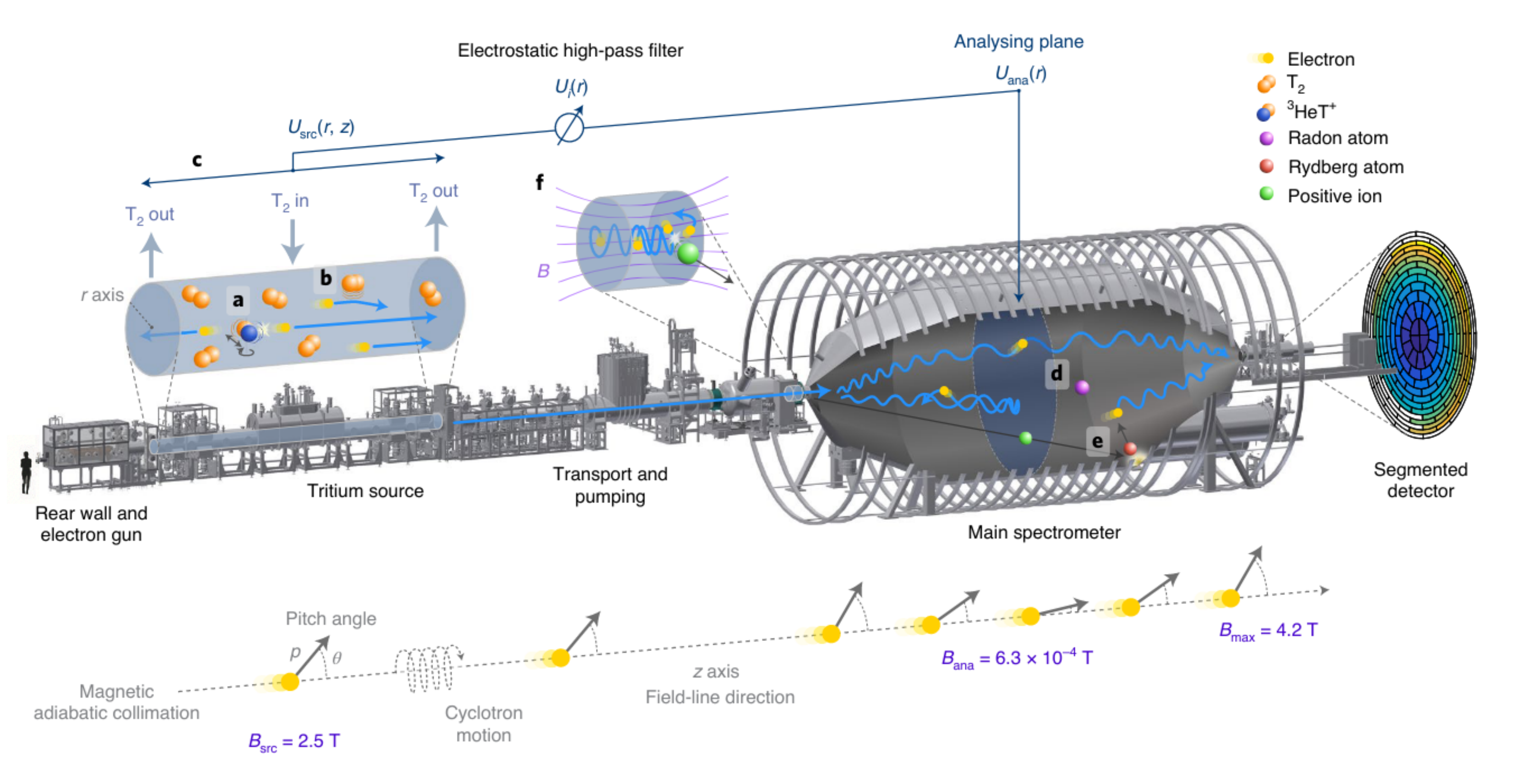


KATRIN, IN A NUTSHELL

(**KA**rlsruhe **TRI**tium **N**eutrino experiment)

- **Goal**: precision absolute effective neutrino mass measurement
- **Design sensitivity:** 0.2eV, at 90% C.L.
- 10x more sensitive than predecessors (Mainz, Troitsk)

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



Source KATRIN Nature 2022

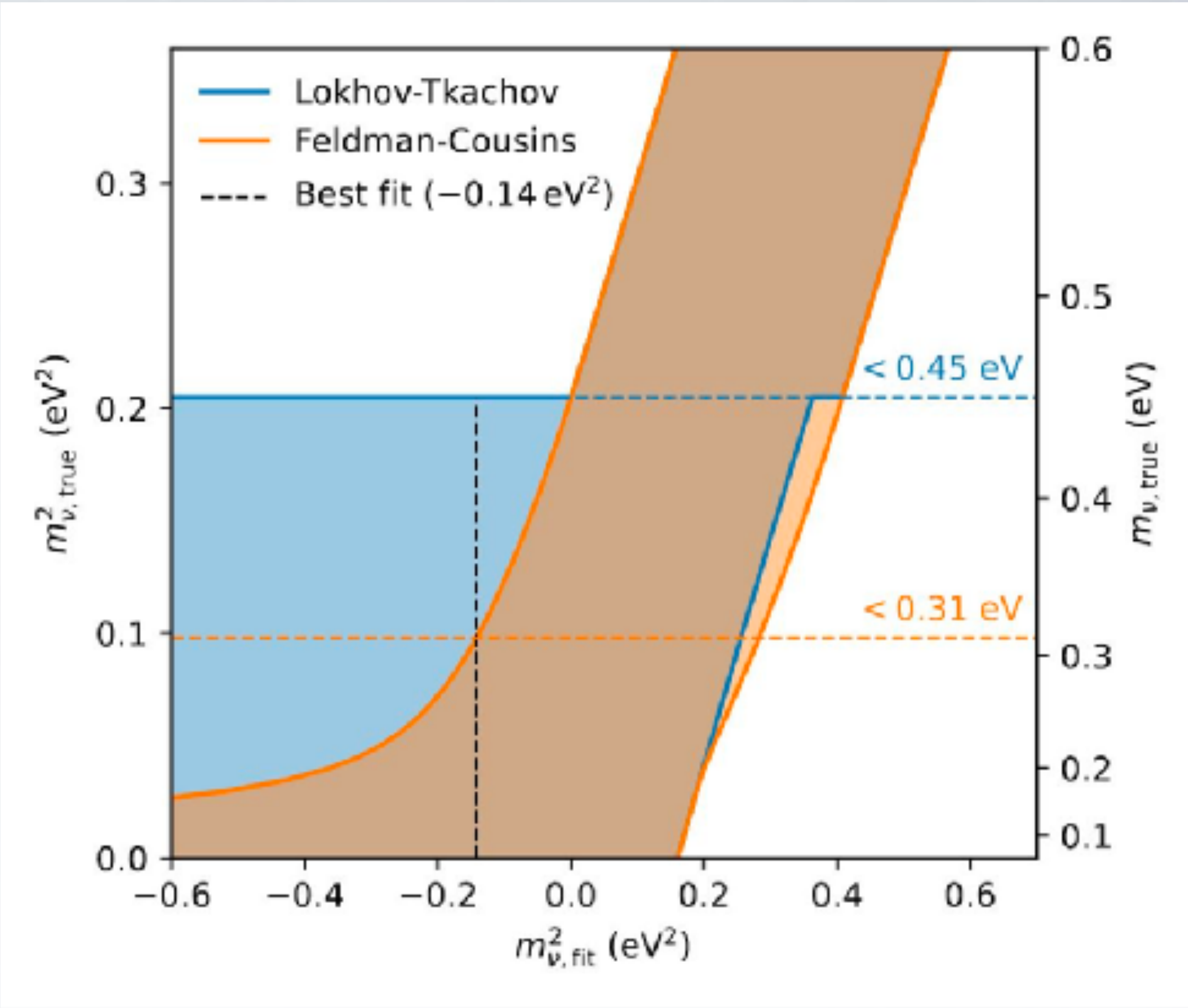
RECENT KATRIN RESULTS

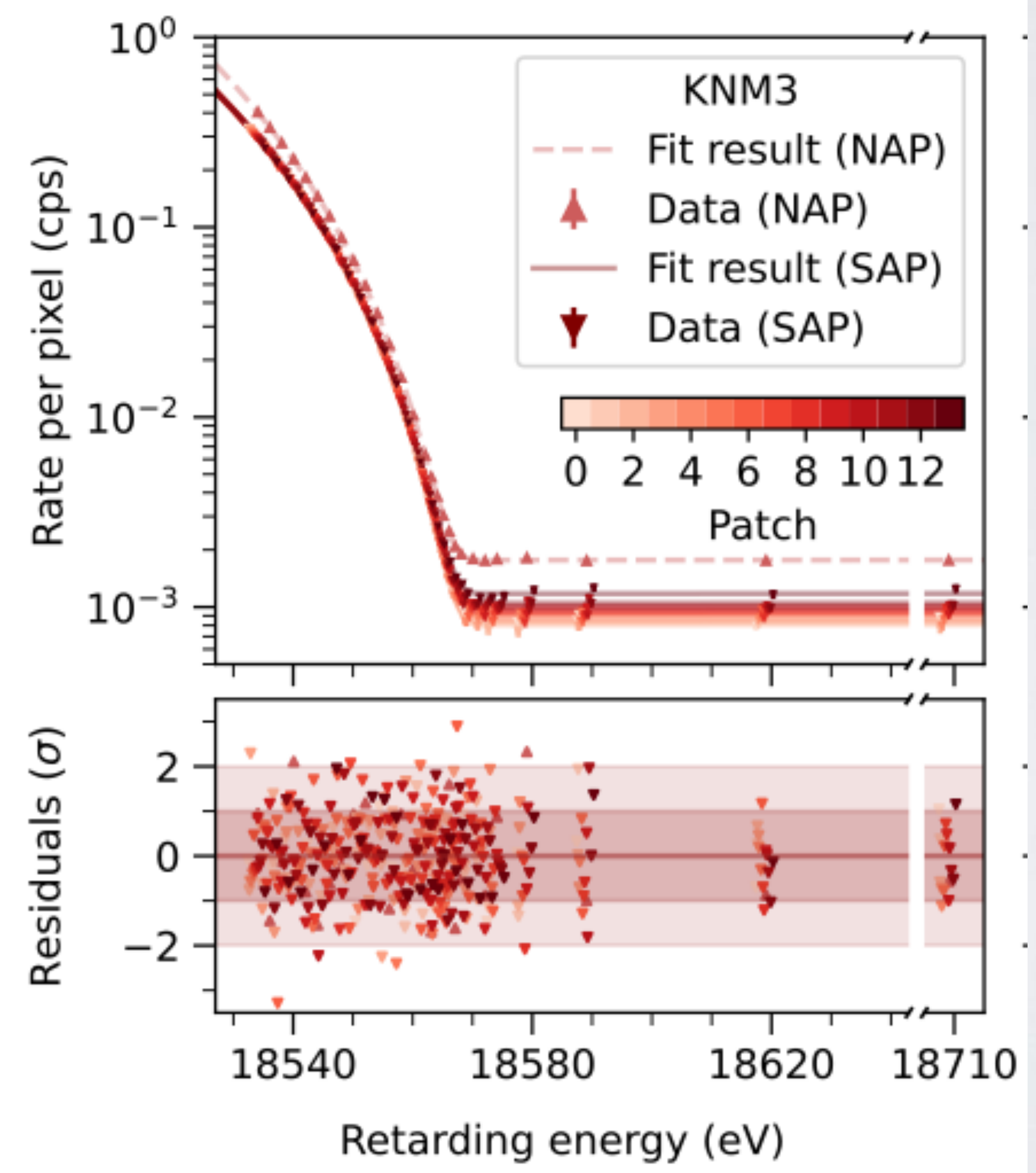
Paper on arXiv (https://arxiv.org/abs/2406.13516):

- KNM1-5: 259 days' measurement (36 million electrons)

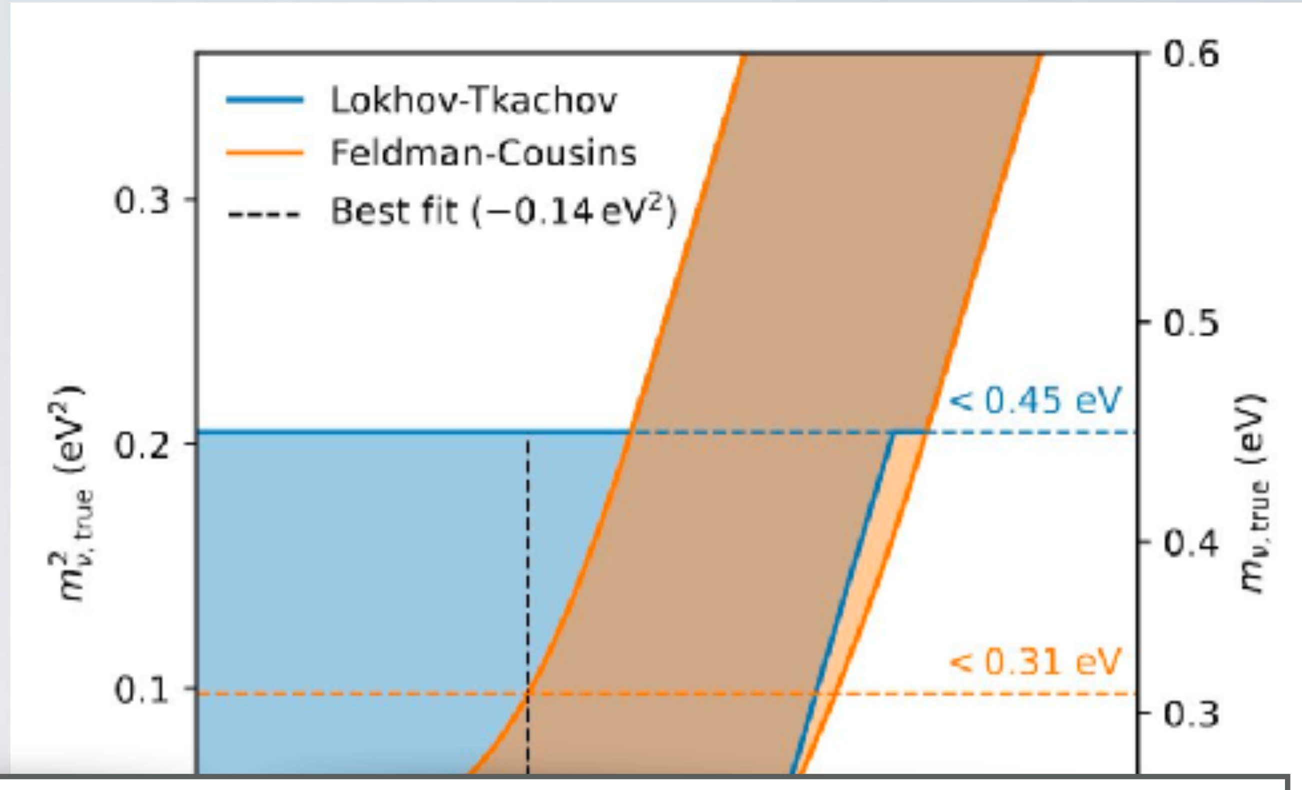
- Results:
  - Best fit: $m_\nu^2 = (-0.14^{+0.13}_{-0.15})$ eV²/c⁴ (90% C.L.)

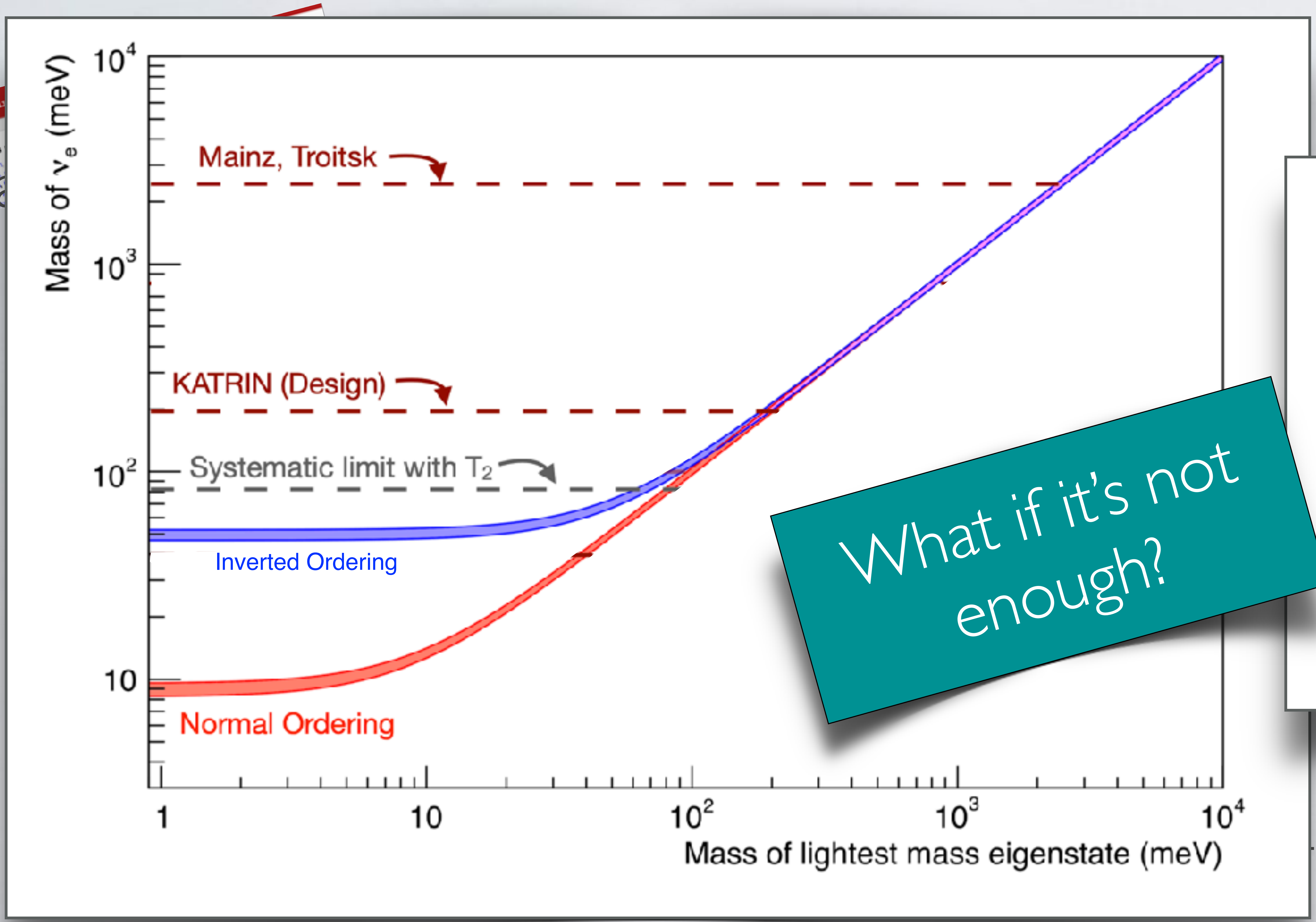
  - New upper limit: $m_\nu < 0.45$ eV/c² (90% C.L.)



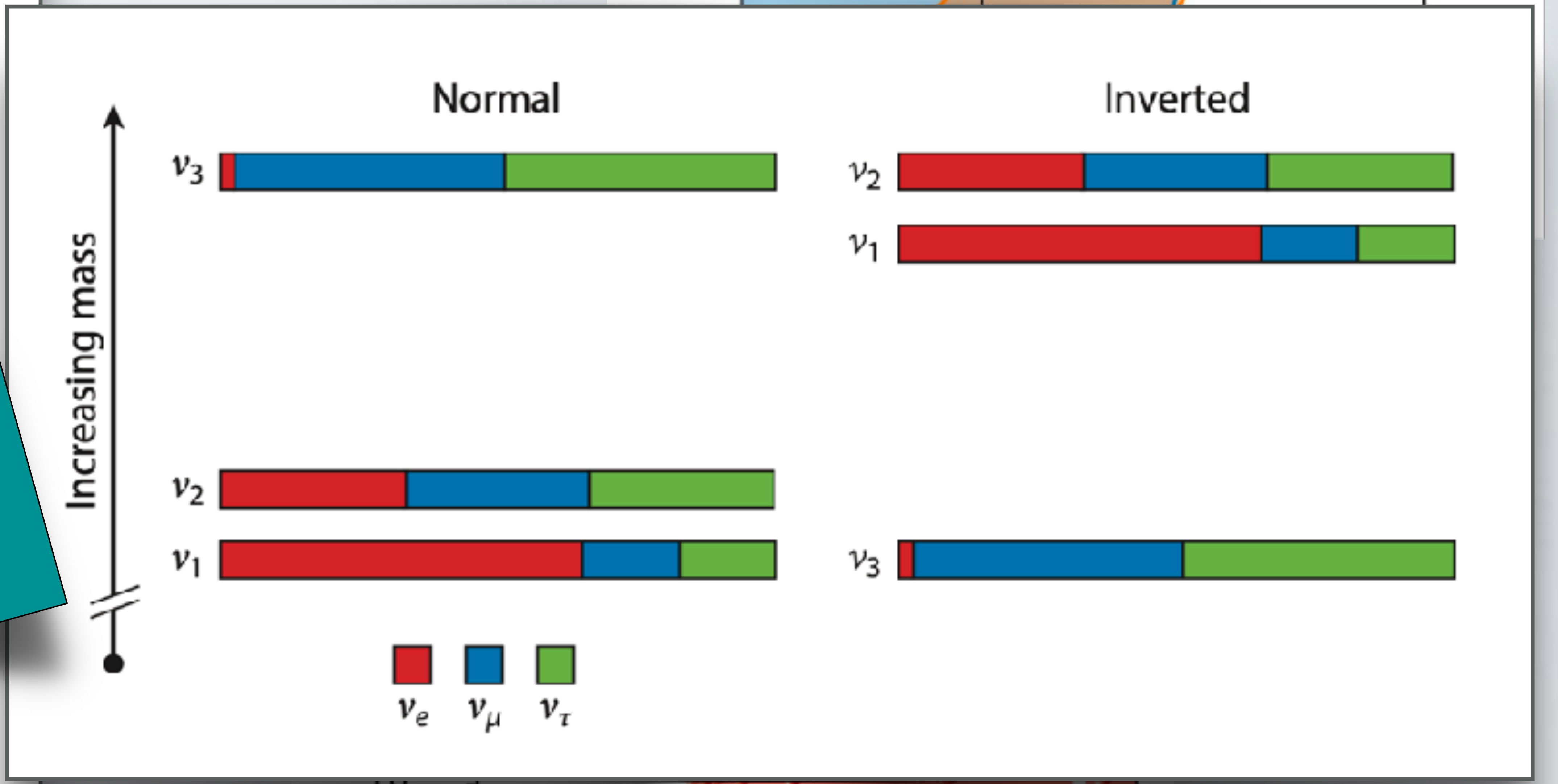


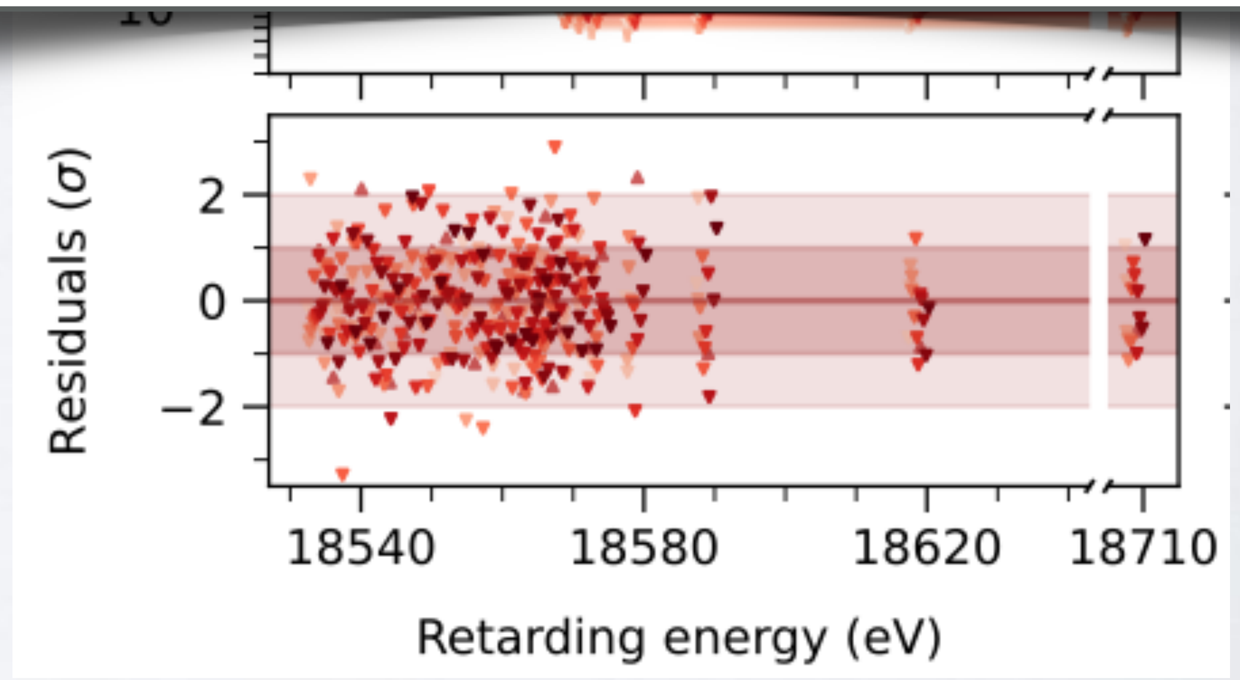
RECENT KATRIN RESULTS



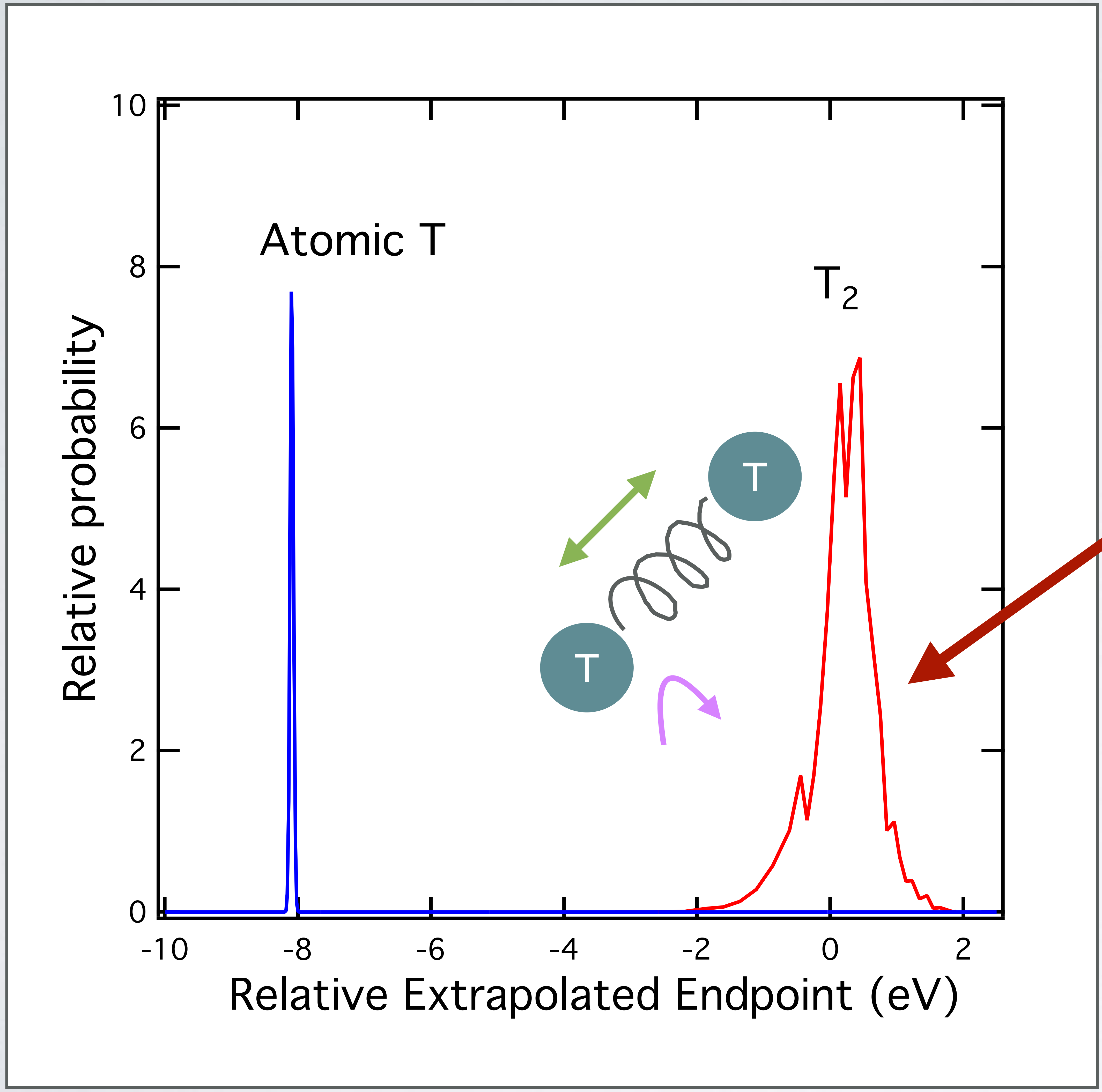


What if it's not enough?

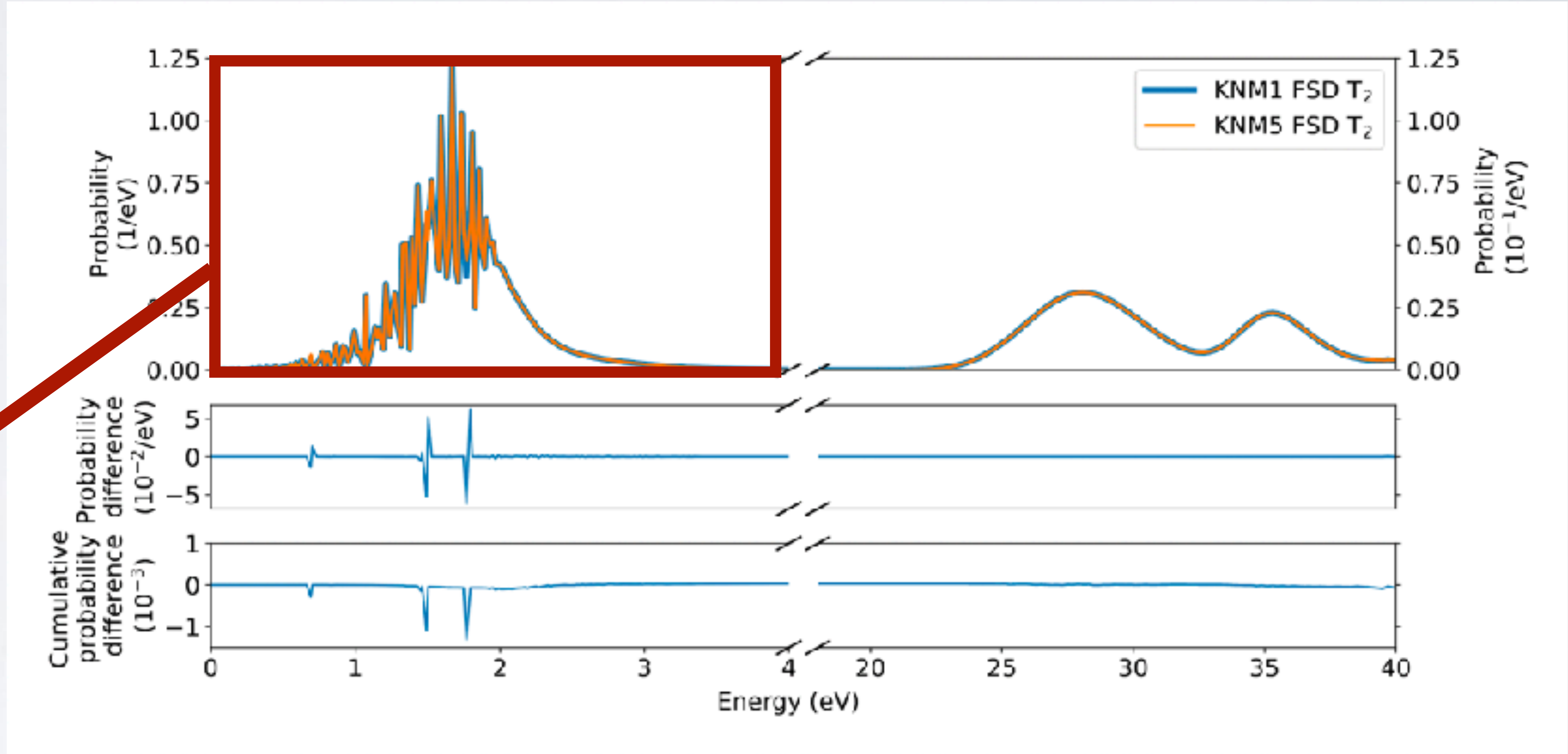




THE MOLECULAR PROBLEM



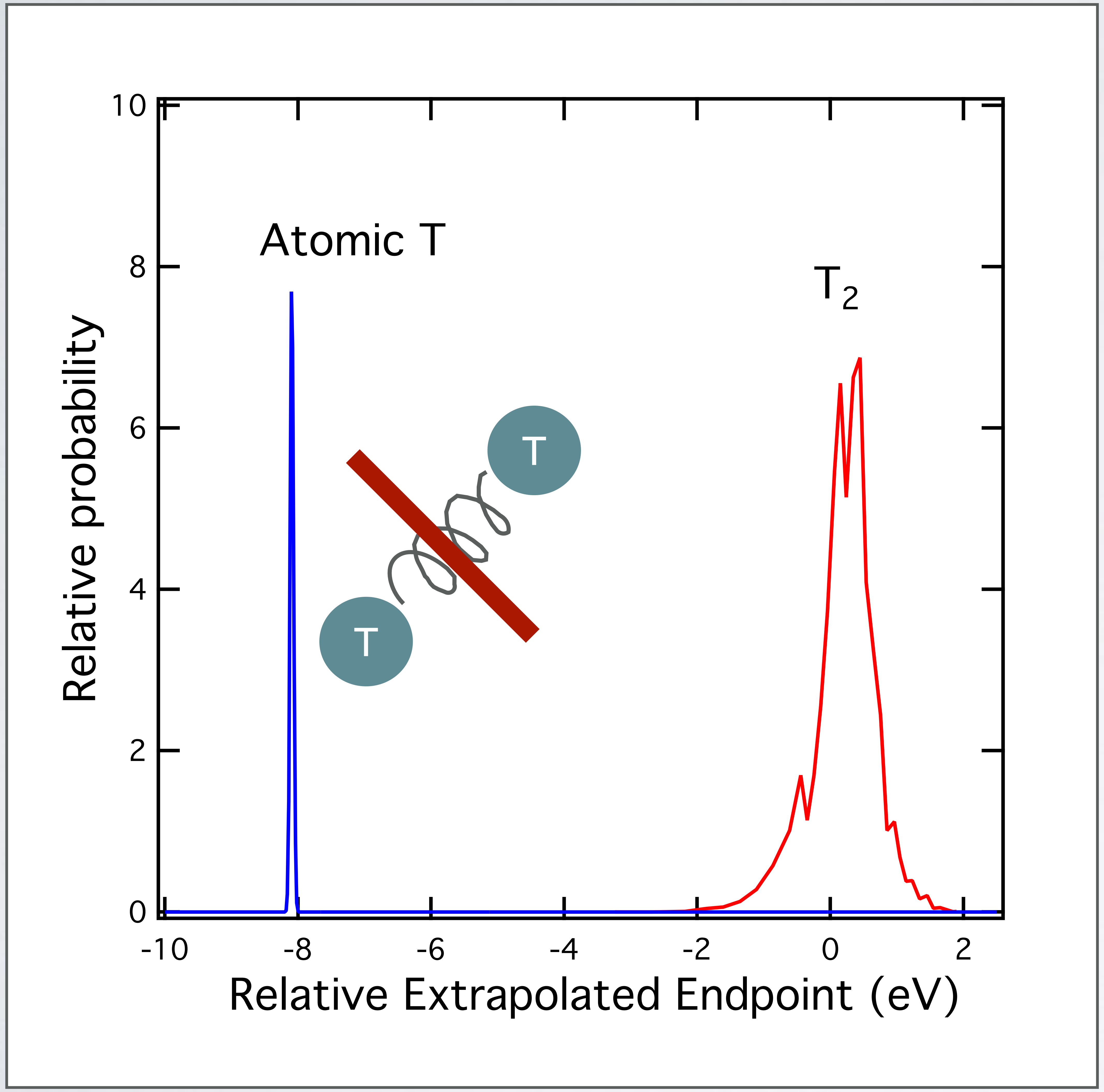
Adapted from L. Bodine



Source: KATRIN 2024

Molecular final state distribution, at 30K.

THE ATOMIC SOLUTION



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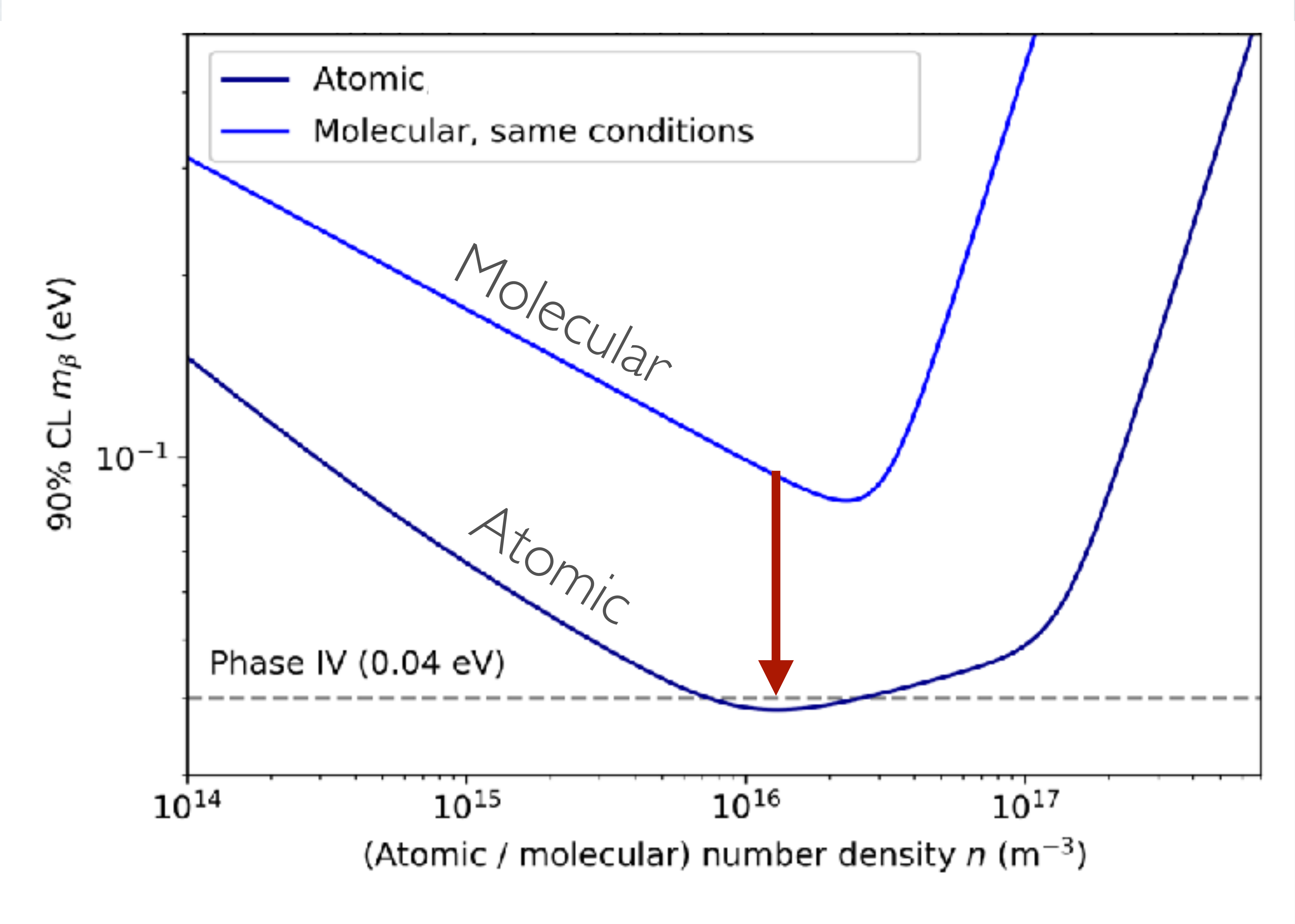

Adapted from T. Weiss

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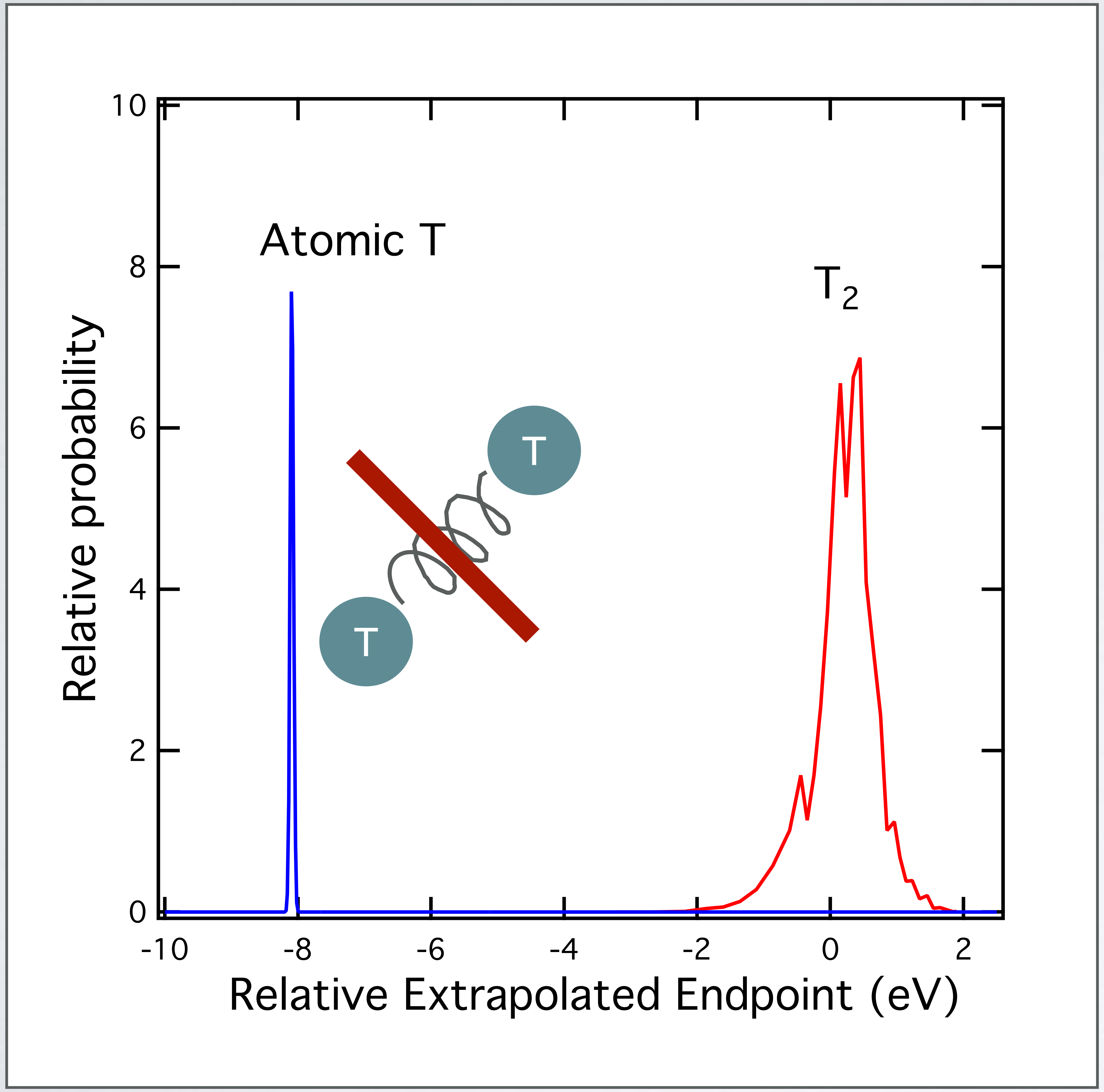
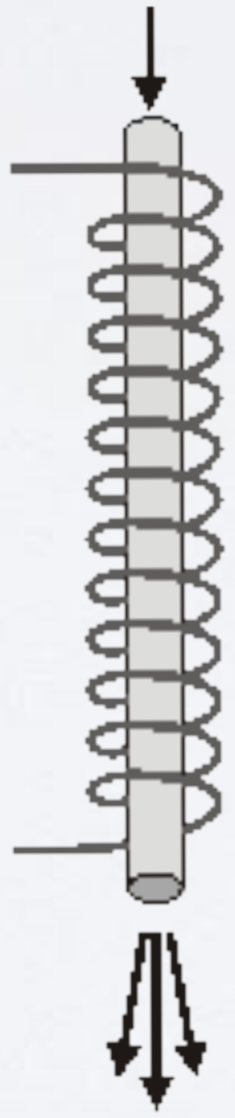


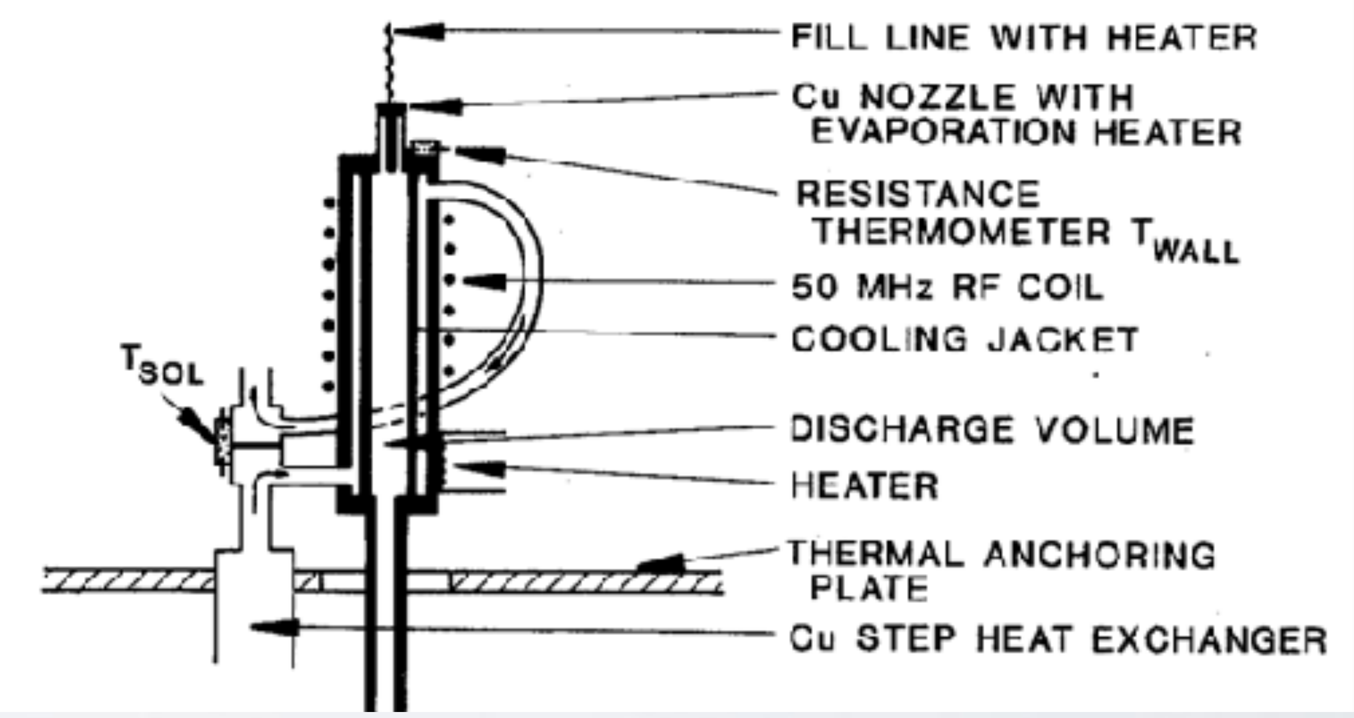
Adapted from L. Bodine

Many options to synthesize atomic T ("dissociation"):

- Heating
- RF discharge



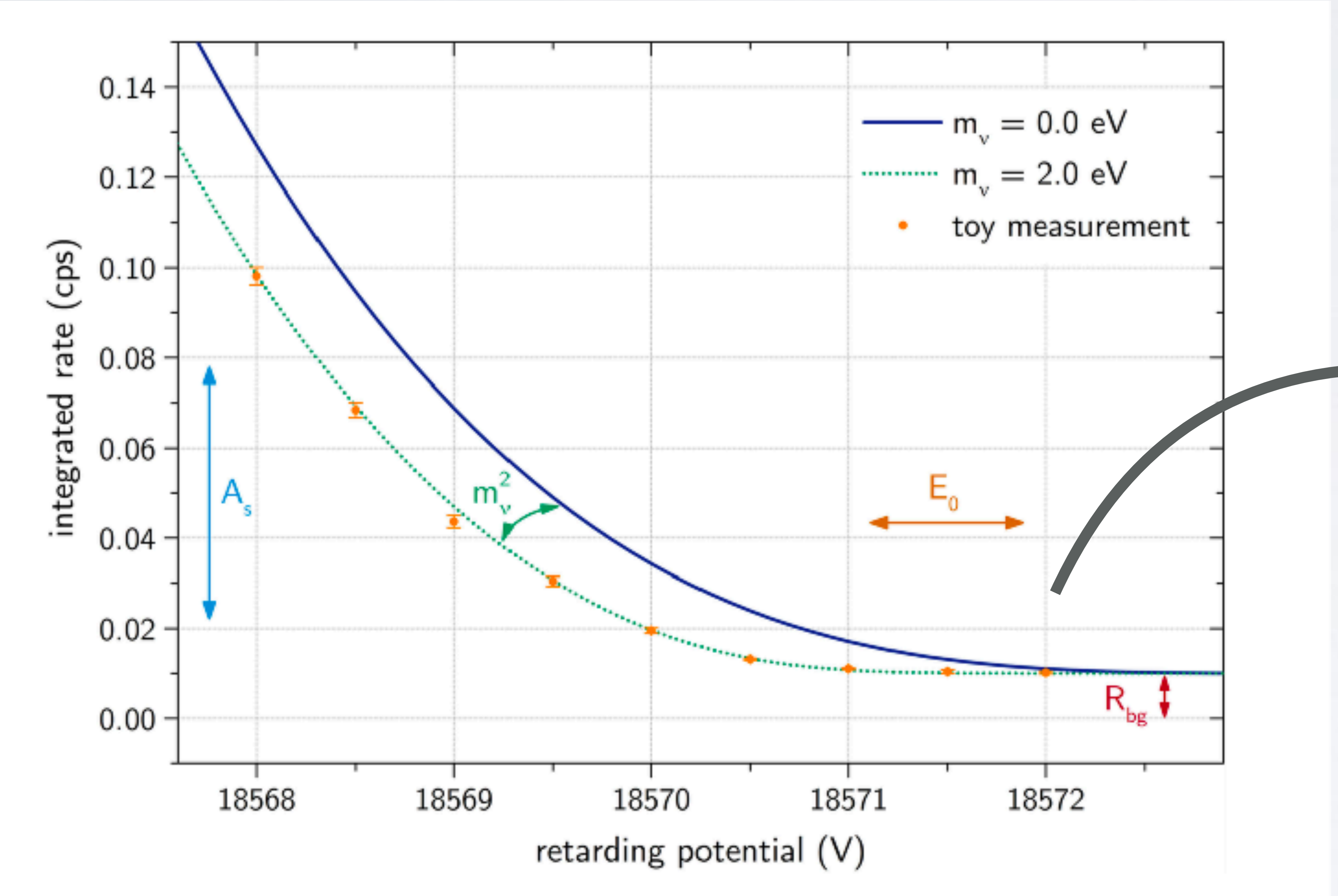
Source: MBE Komponenten

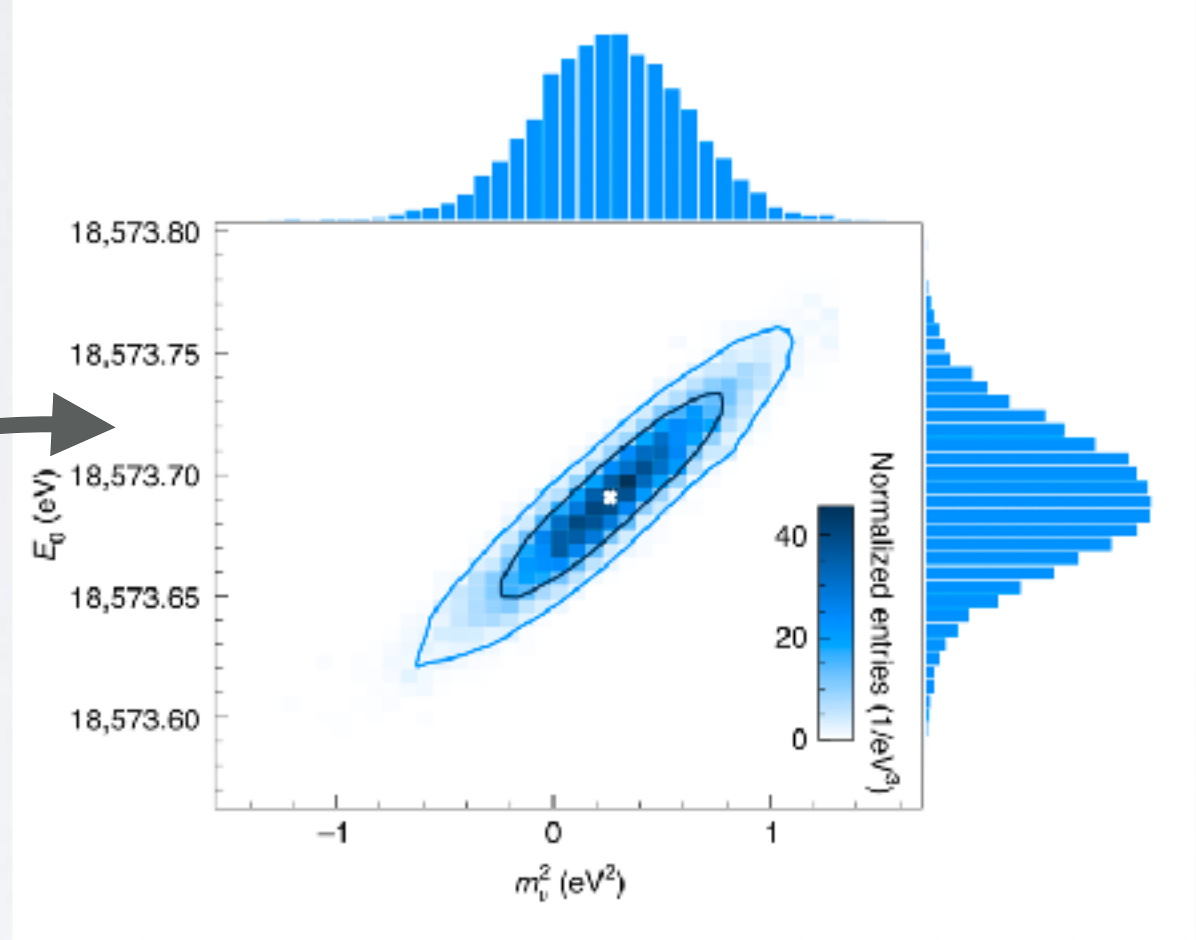


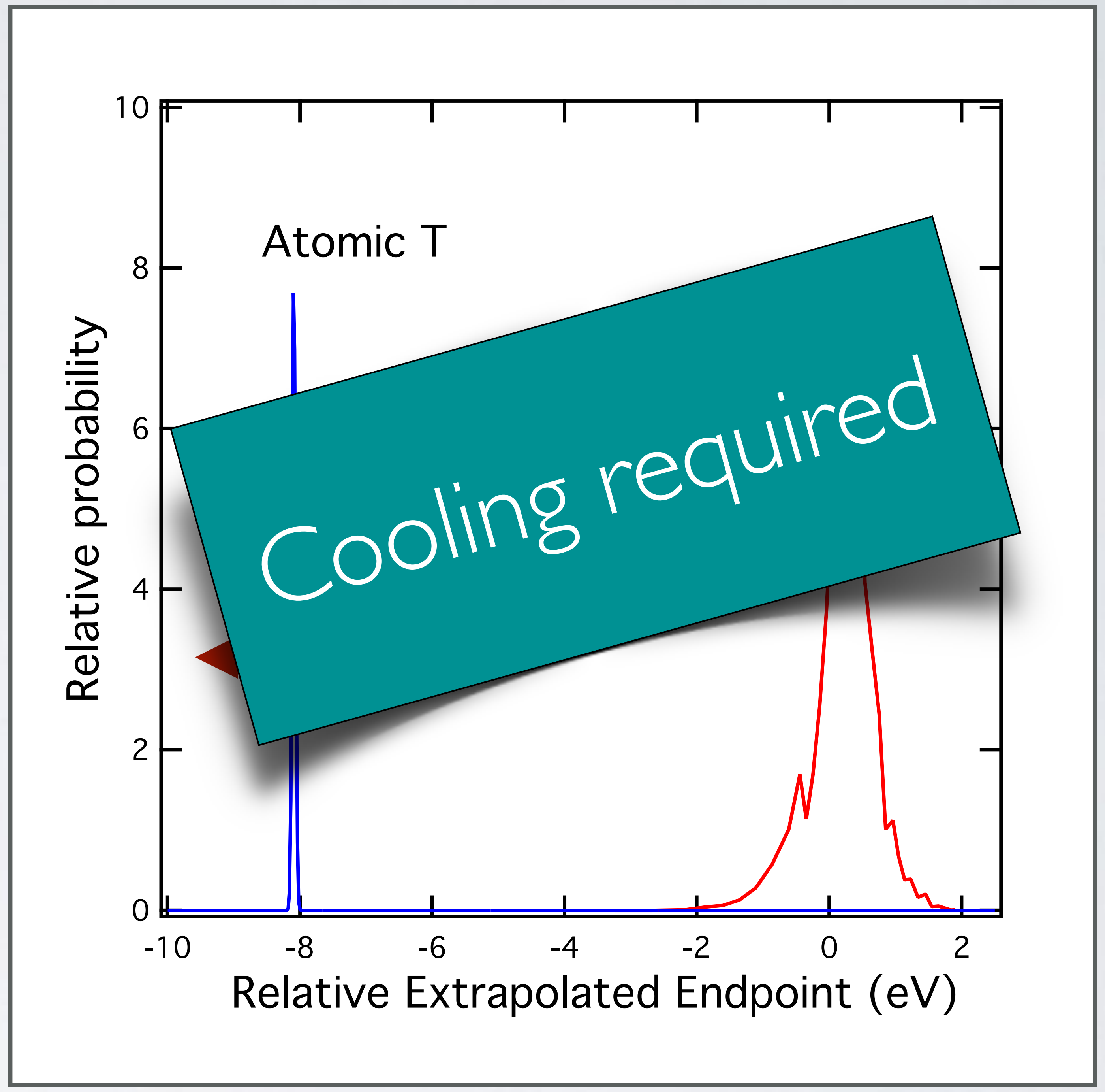
Source: Helfrich 1987

ATOMIC CHALLENGES

1. Endpoint broadening effects







4 fit parameters:

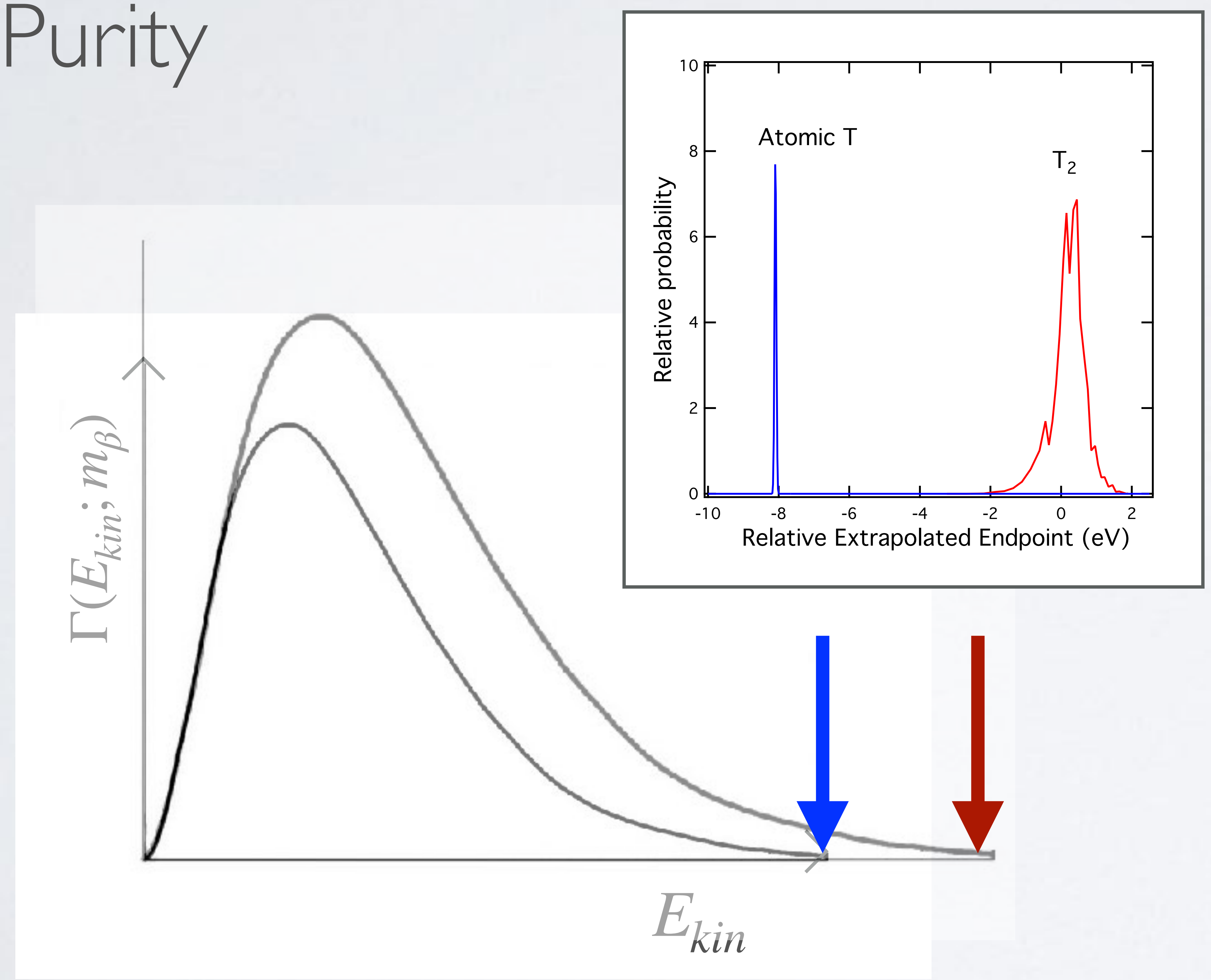
$$\{A, B, E_0, m_\nu^2\}$$

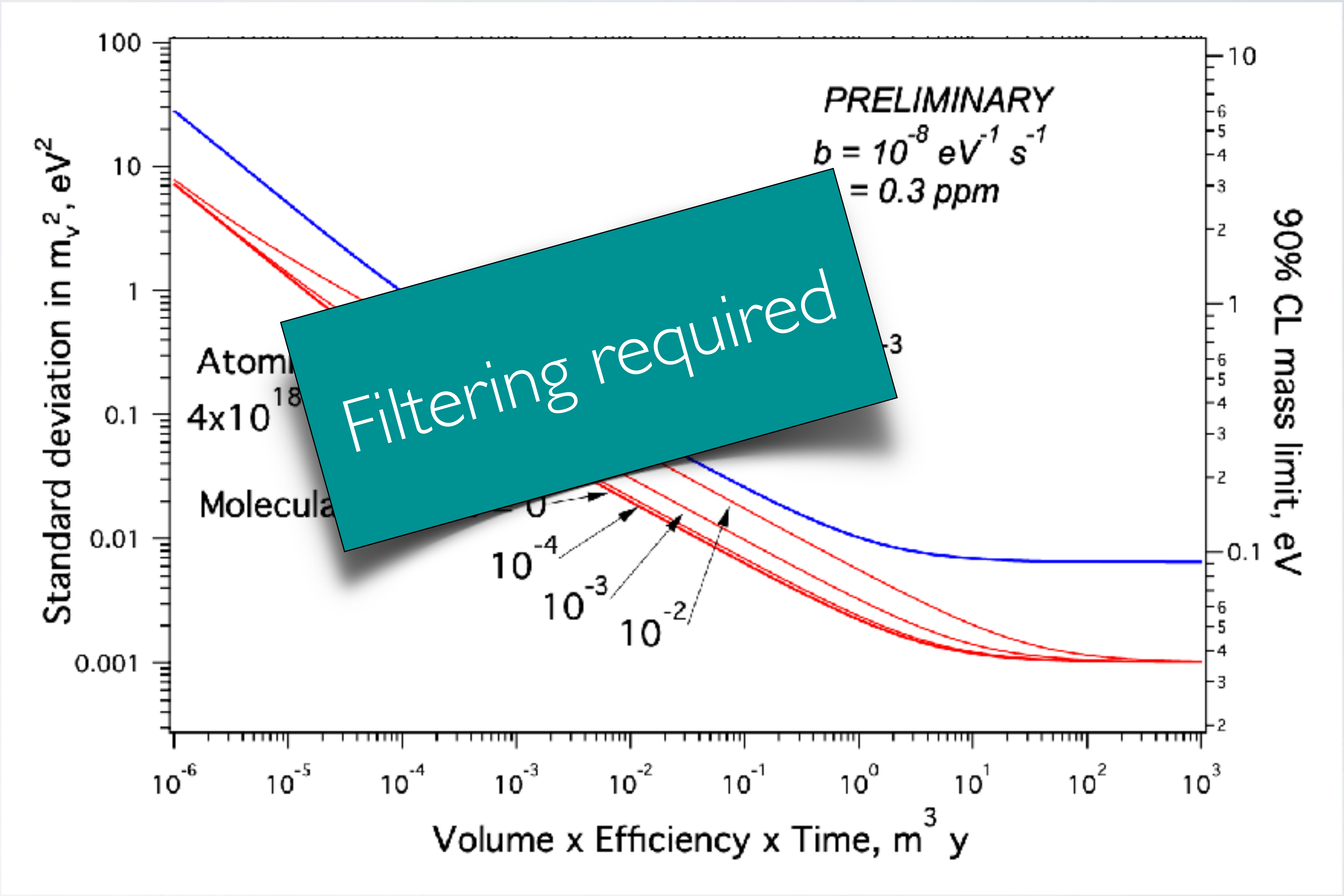
Hyperfine: $\sim 1\text{meV}$

Doppler: $\propto \sqrt{T}$

ATOMIC CHALLENGES

1. Endpoint broadening effects
2. Purity

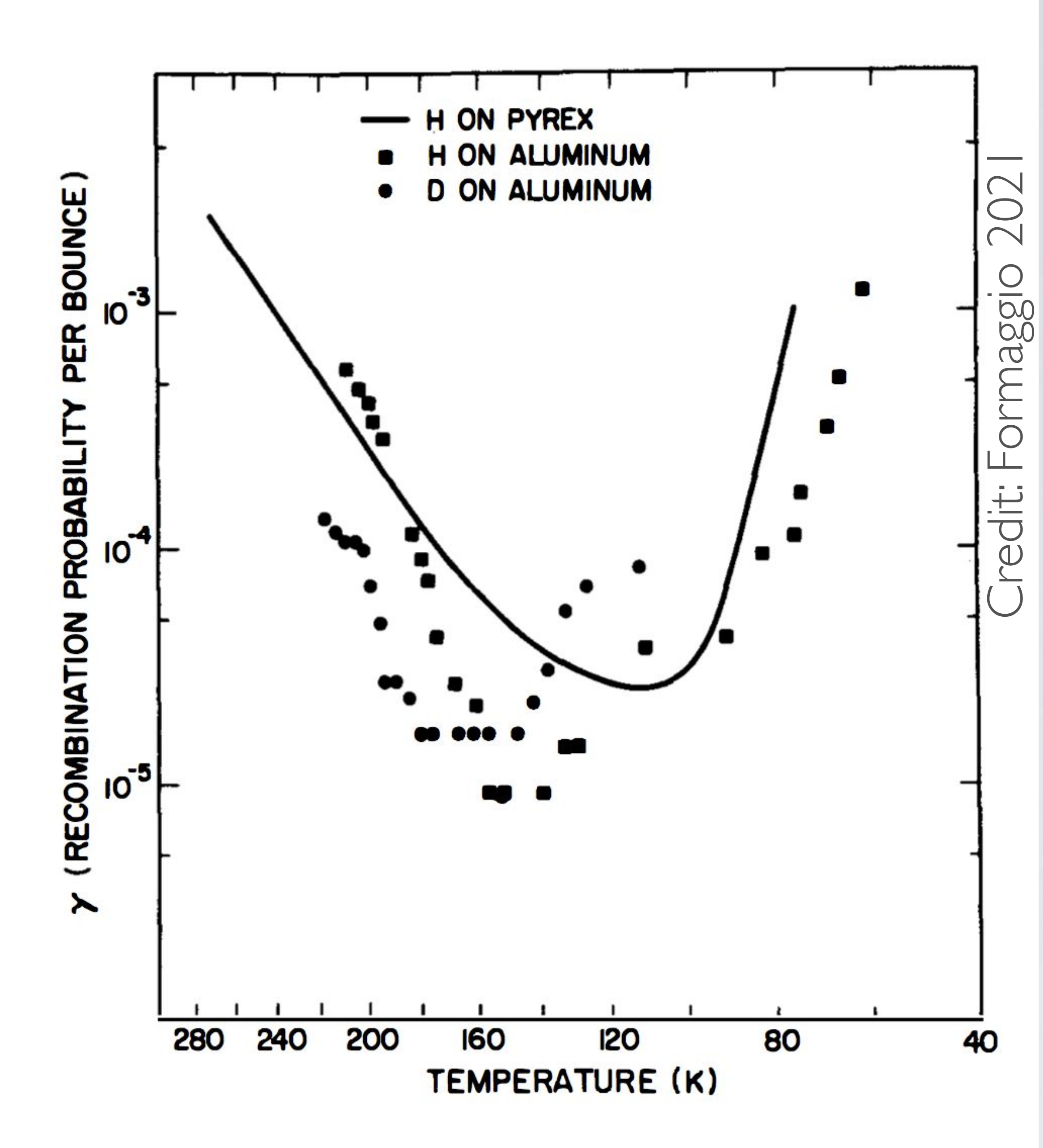




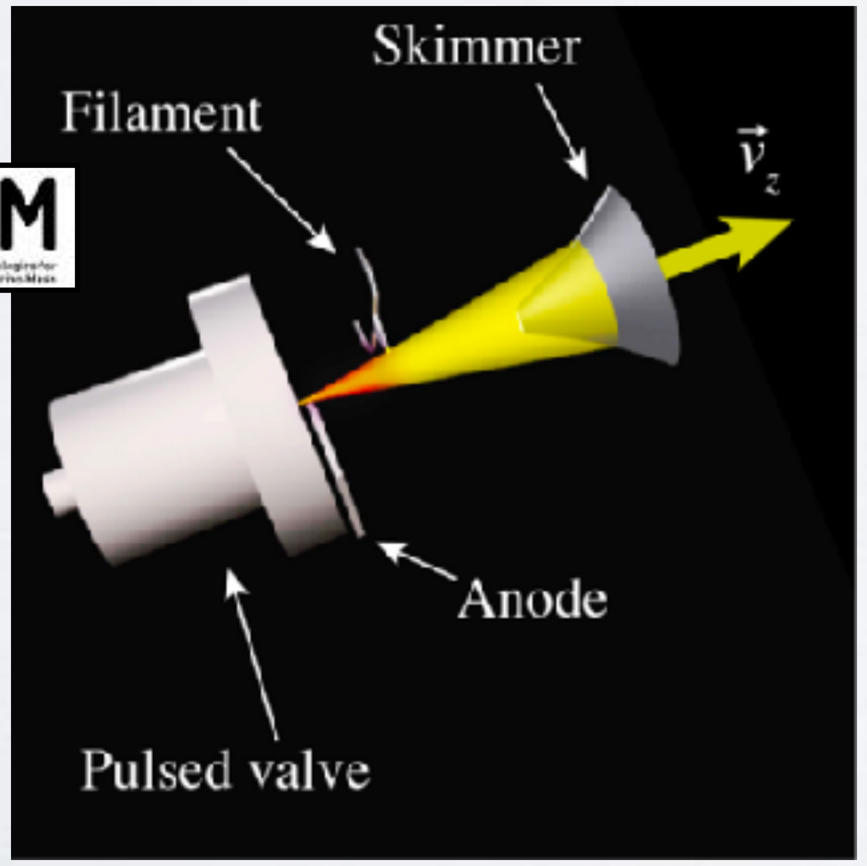
ATOM CHALLENGES: COOLING

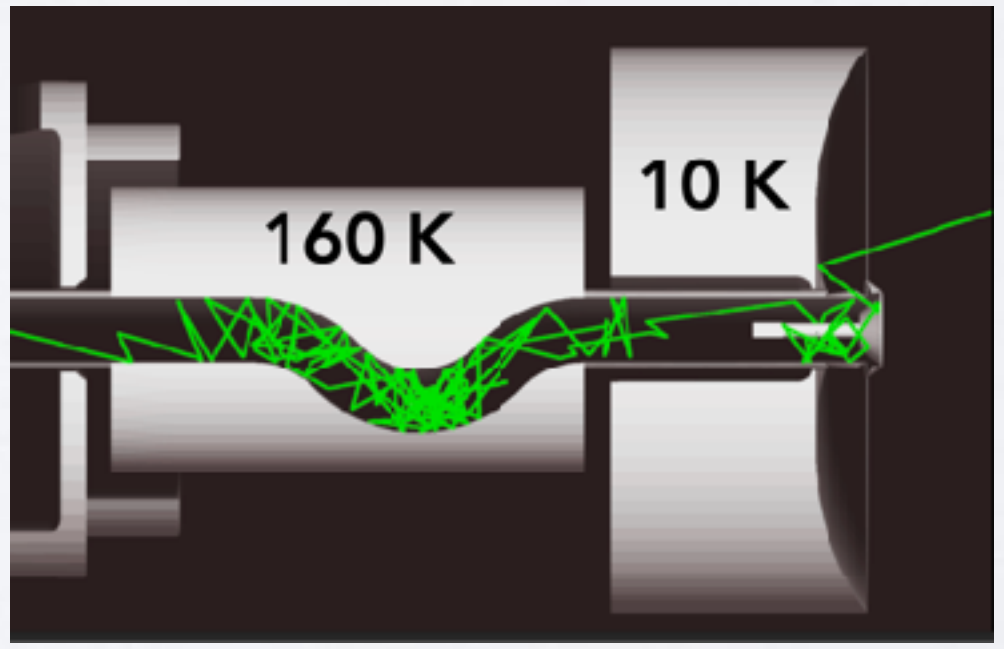
Options:

- Laser-cooling → large laser energies
- Superfluid He walls → high absorption energy for T
- Surface scattering → high T recombination



Credit: Formaggio 2021



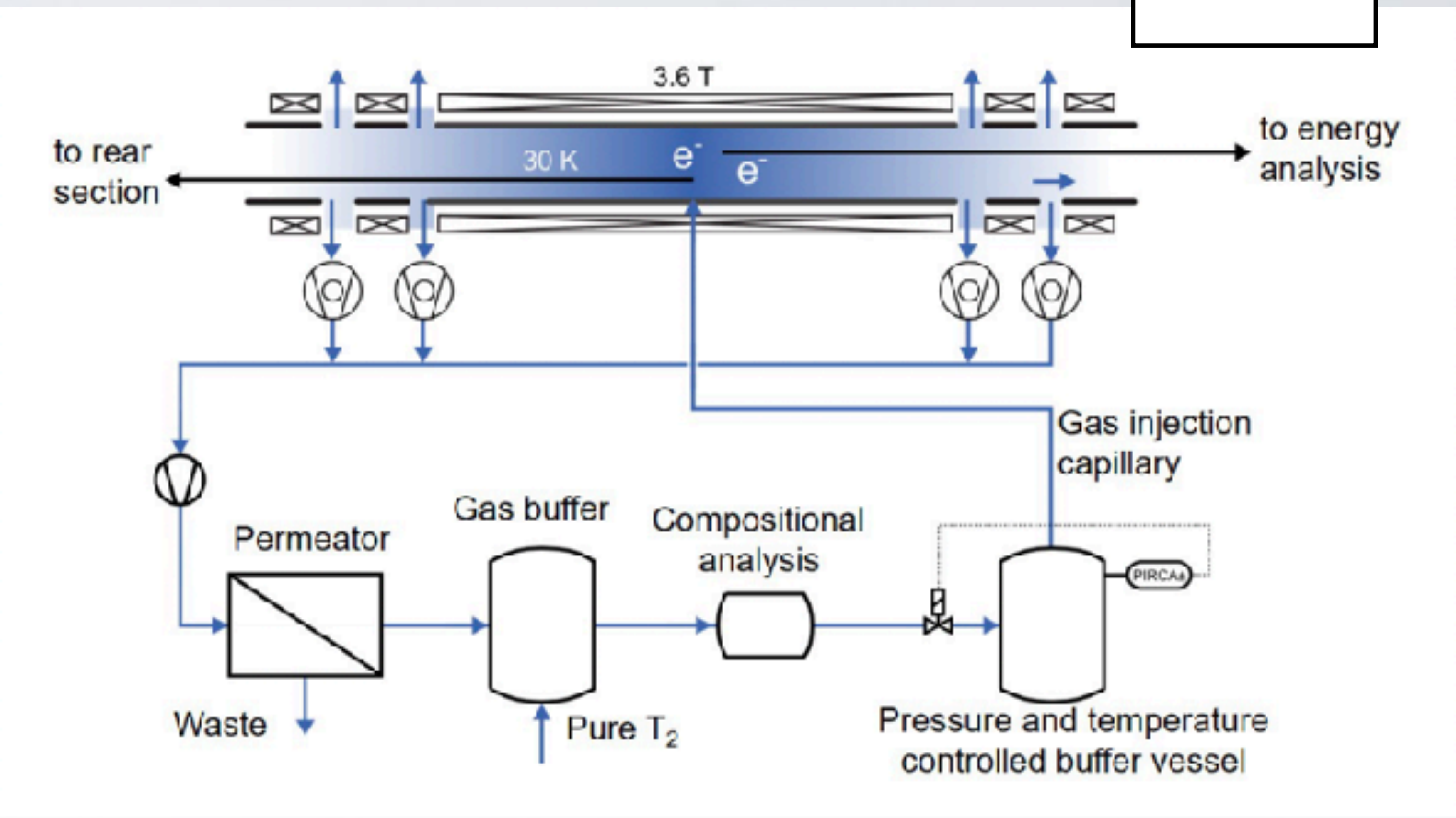


ATOM CHALLENGES: PURITY

Options:

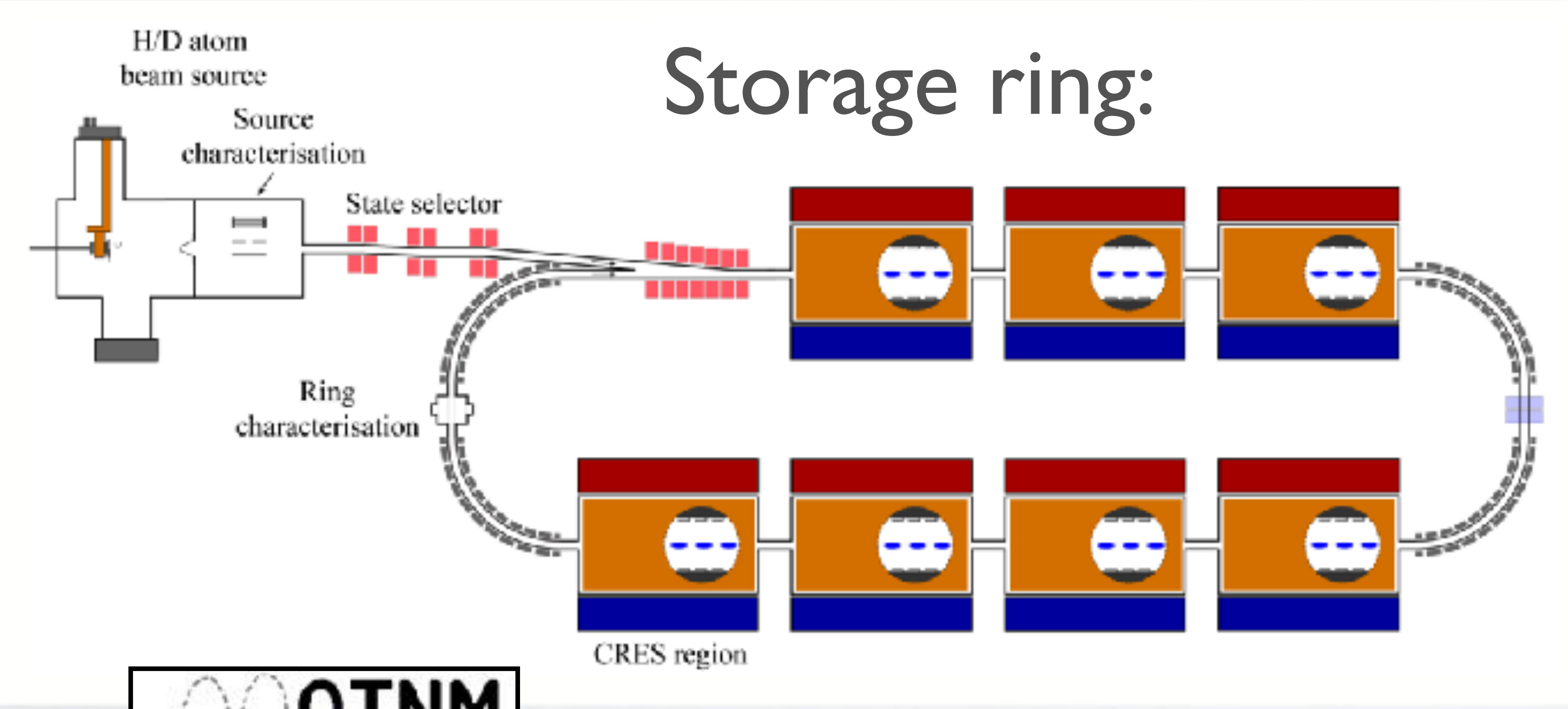
- Tritium recycling loops
- Cold walls will absorb impurities

Recirculation loops:

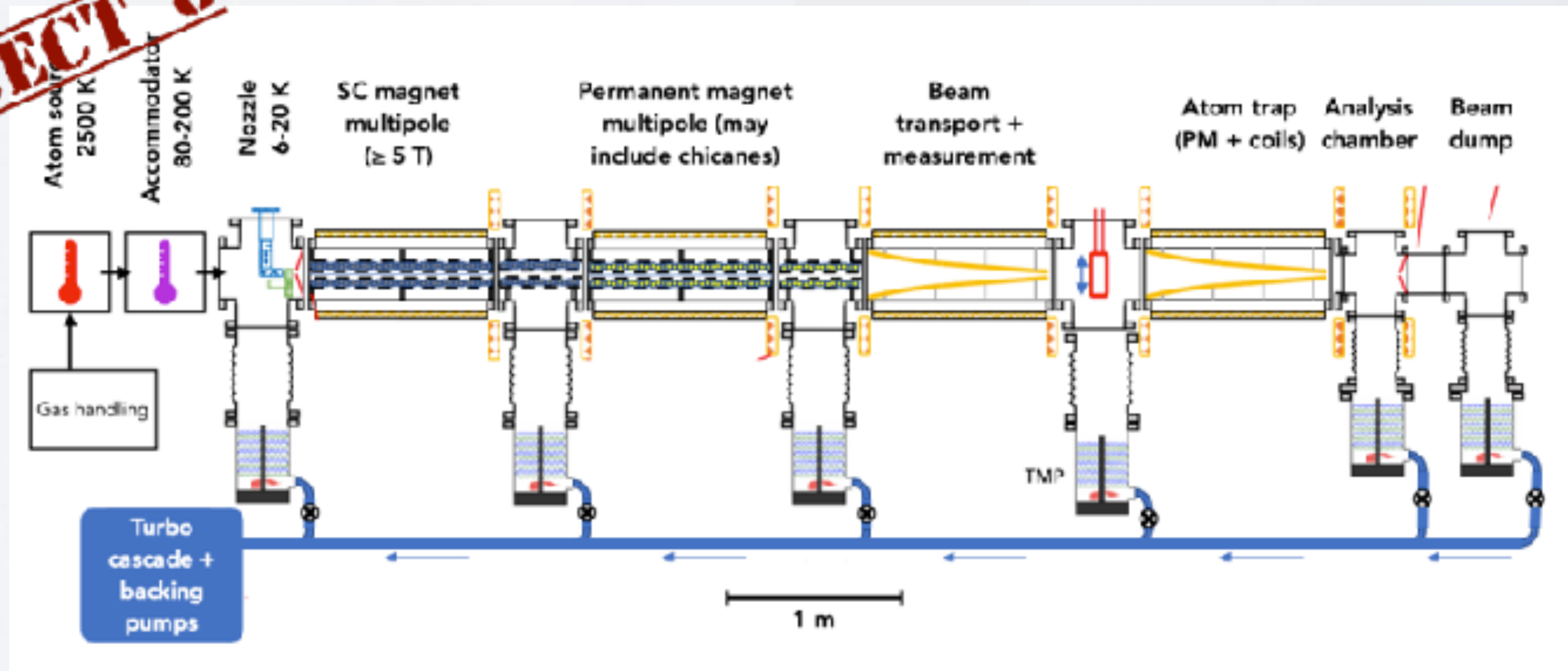


Source: KATRIN hardware paper 2021

Storage ring:



Adapted from: S. Jones



Credit: B. Jones

Who is up to the challenge?

PROJECT 8

PTOLEMY

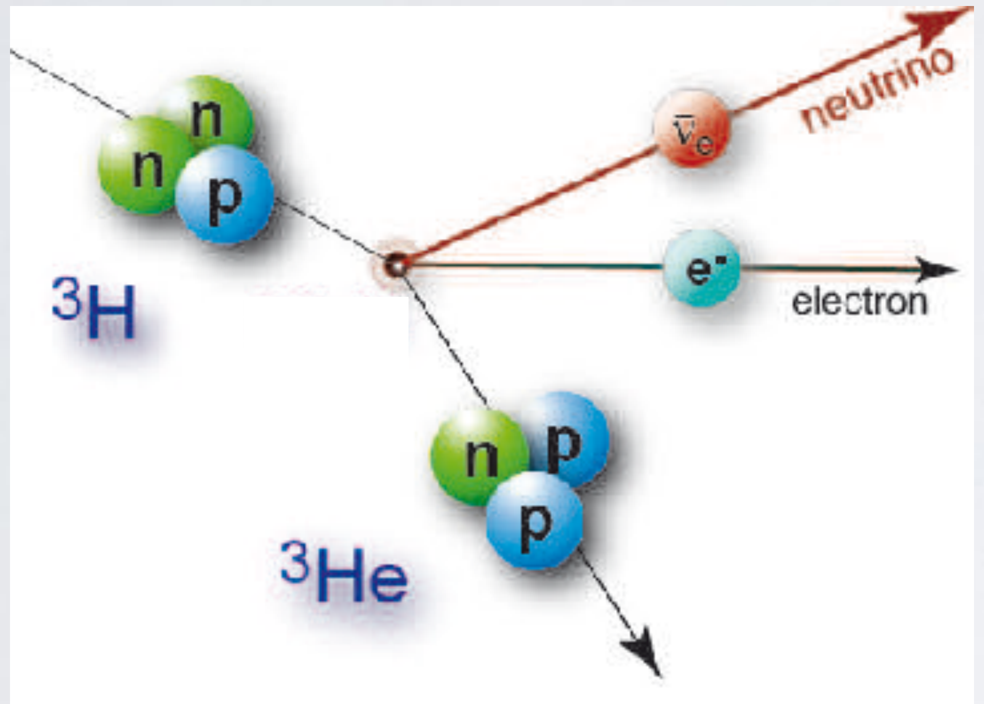
KATRIN++

QTNM
Quantum Technologies for Neutrino Mass

…others?

THE PROJECT 8 EXPERIMENT

- Technique: measure cyclotron radiation from trapped tritium beta decay electrons ("CRES": **c**yclotron **r**adiation **e**mission **s**pectroscopy)
- Design sensitivity: 0.04eV at 90% C.L.

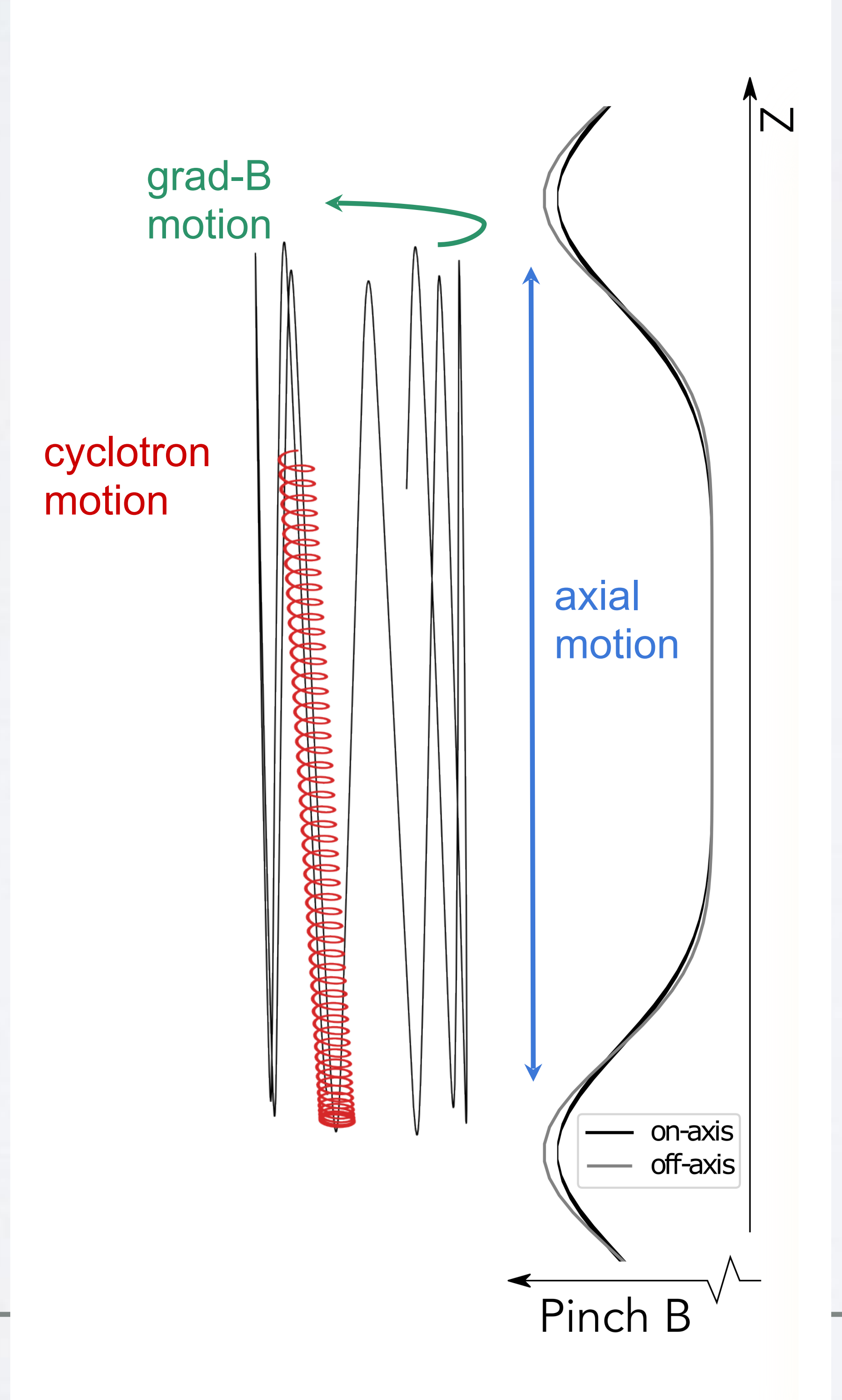


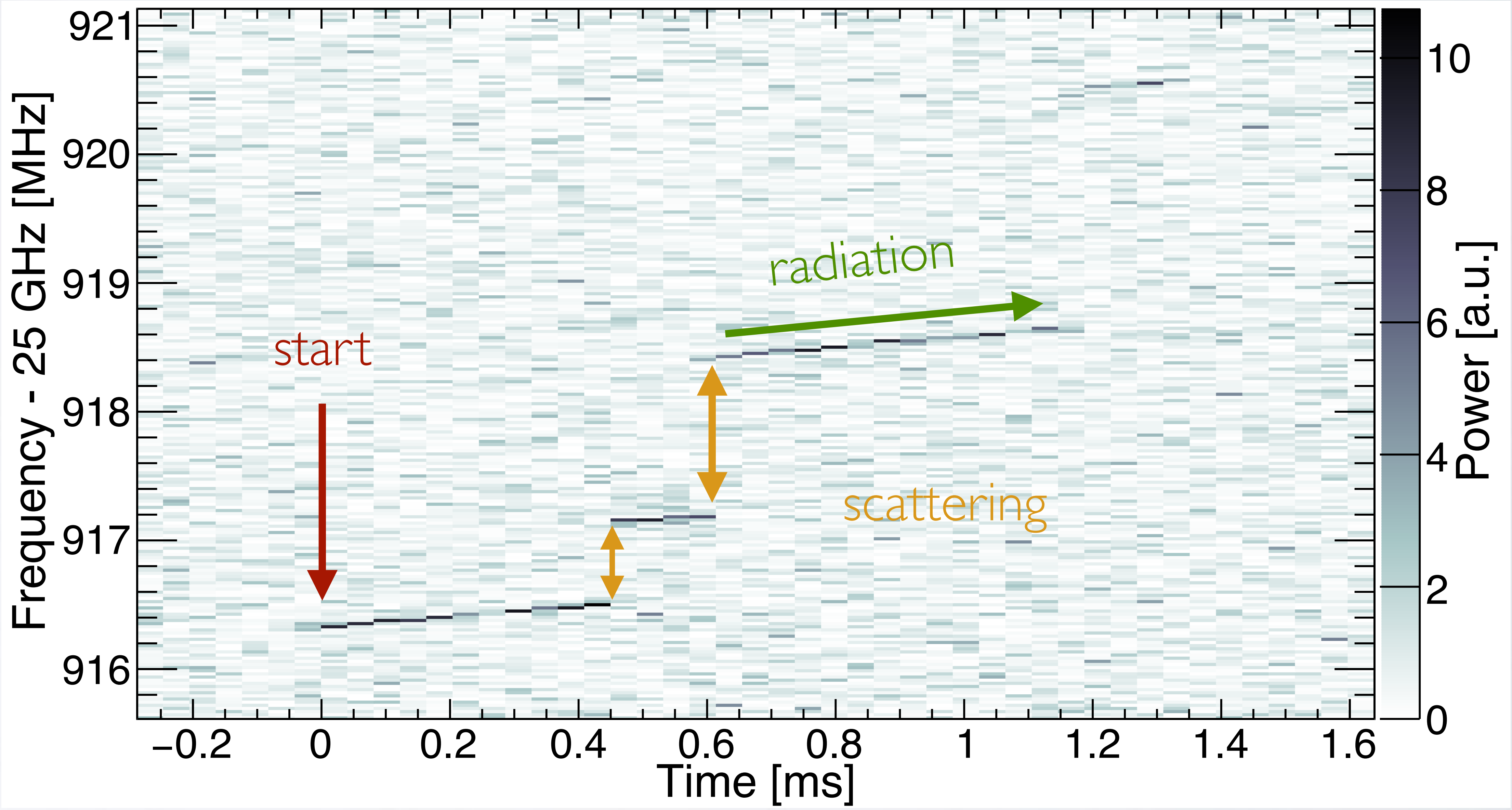
$$f_{cyc} \propto \frac{q\langle B\rangle}{m_e + E_{kin}}$$

~0.1 T

~1 GHz

~18.6 keV





THE PROJECT 8 EXPERIMENT

https://www.project8.org

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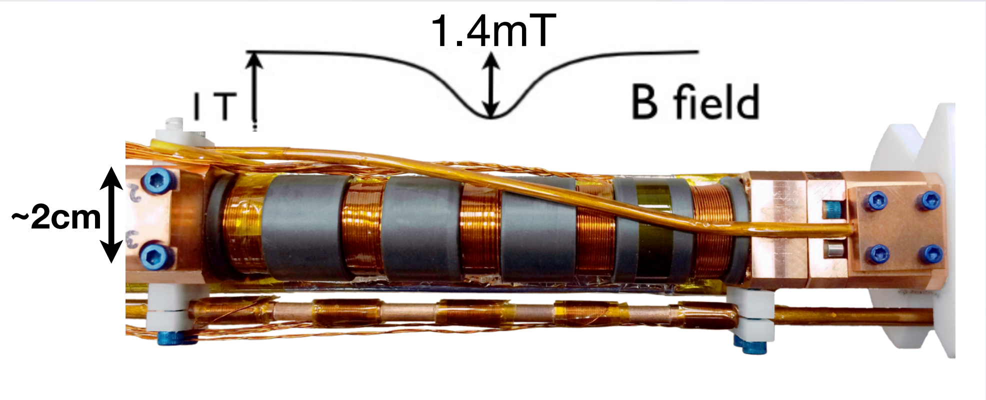

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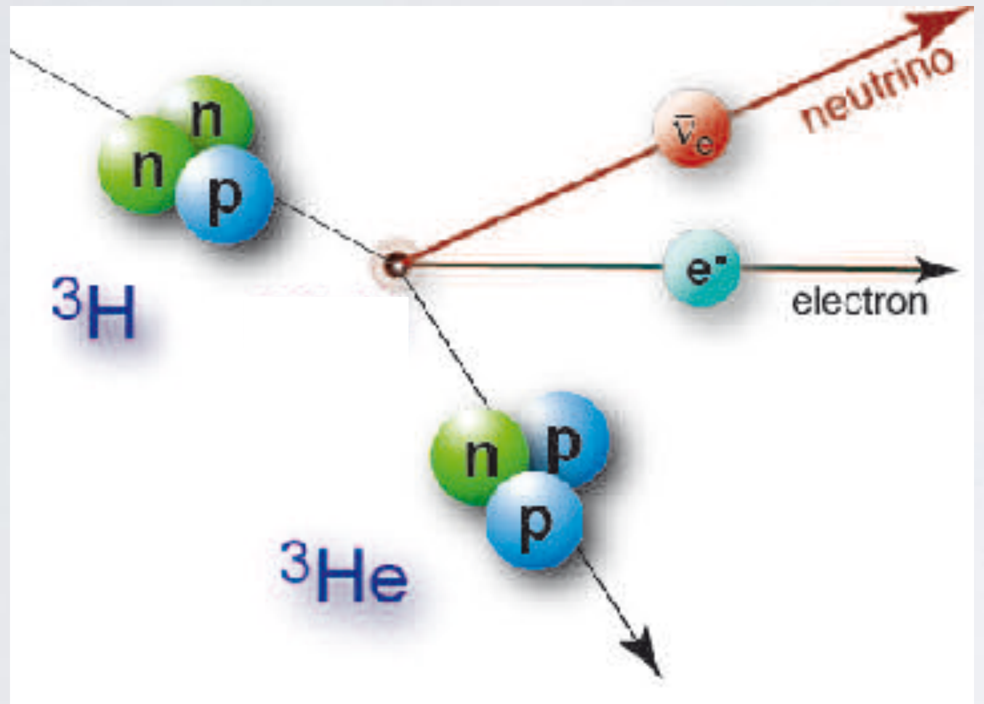

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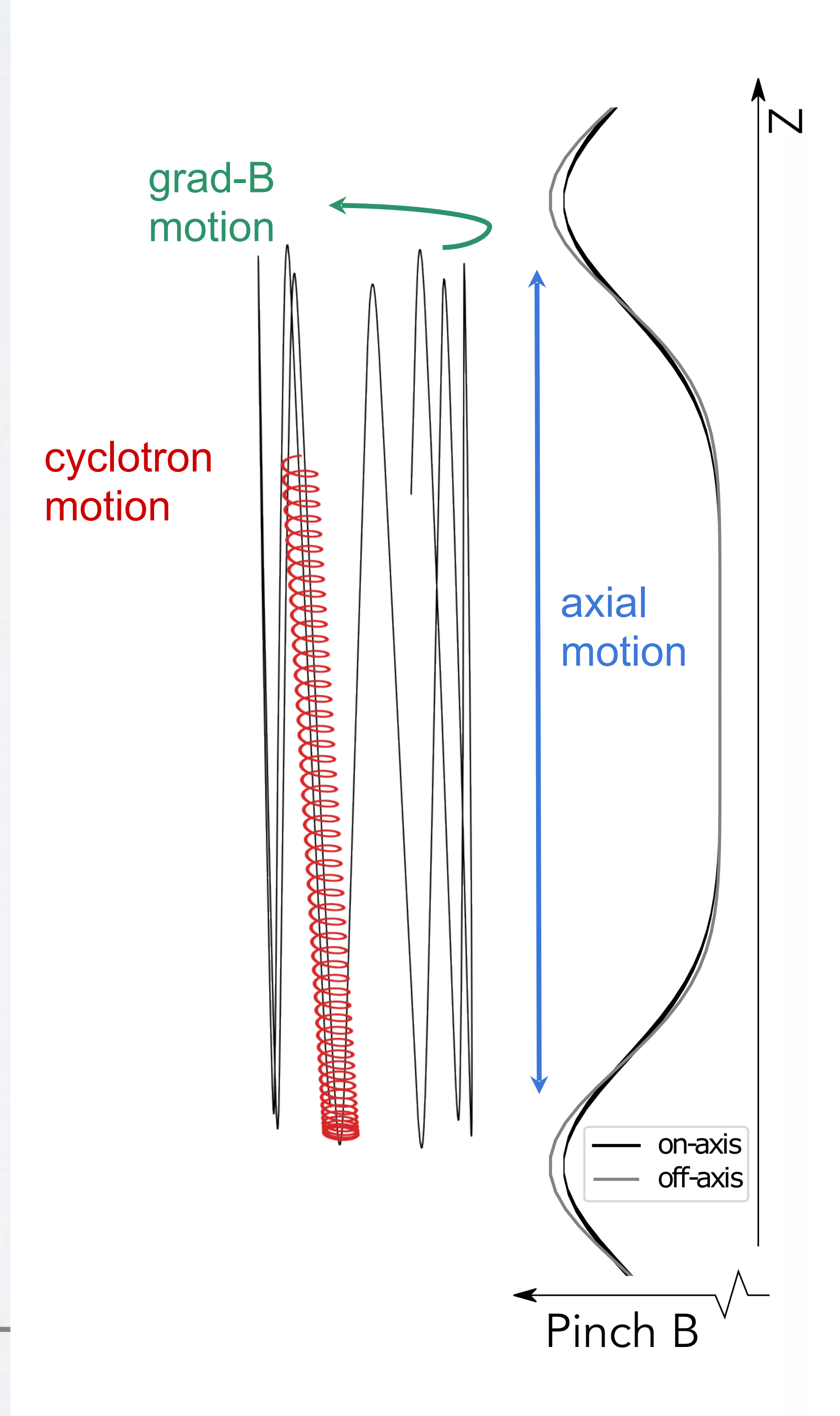
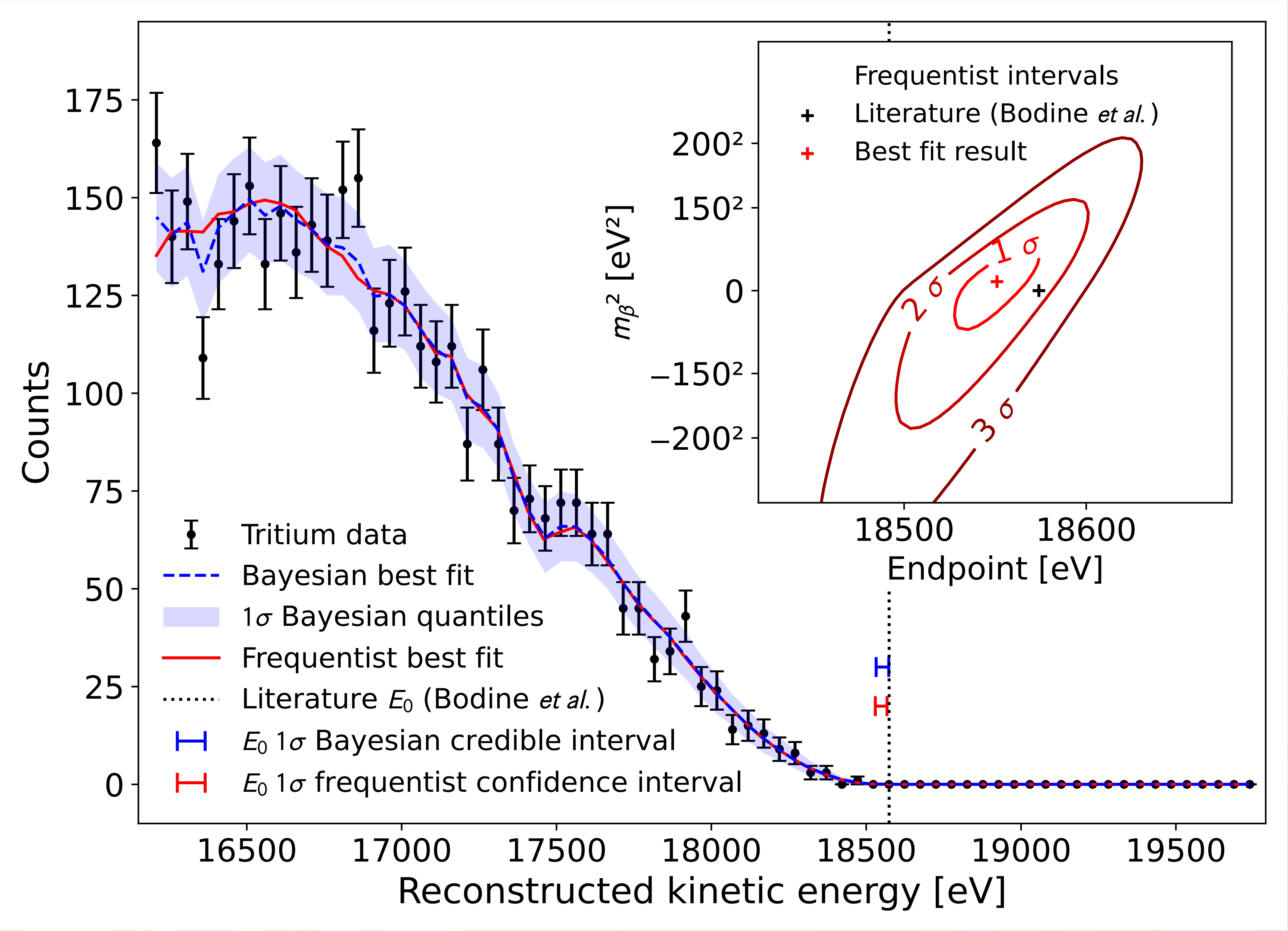
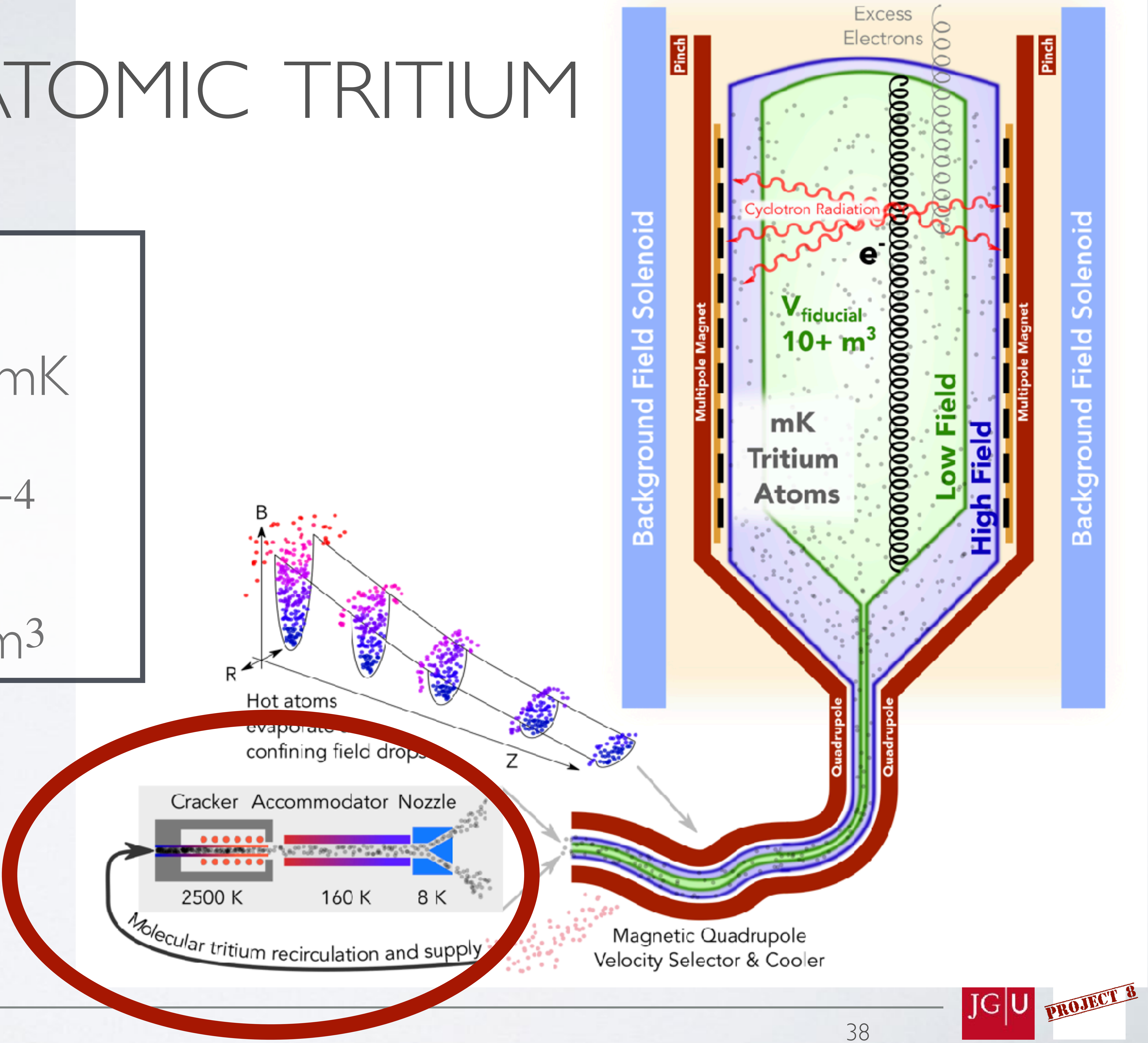




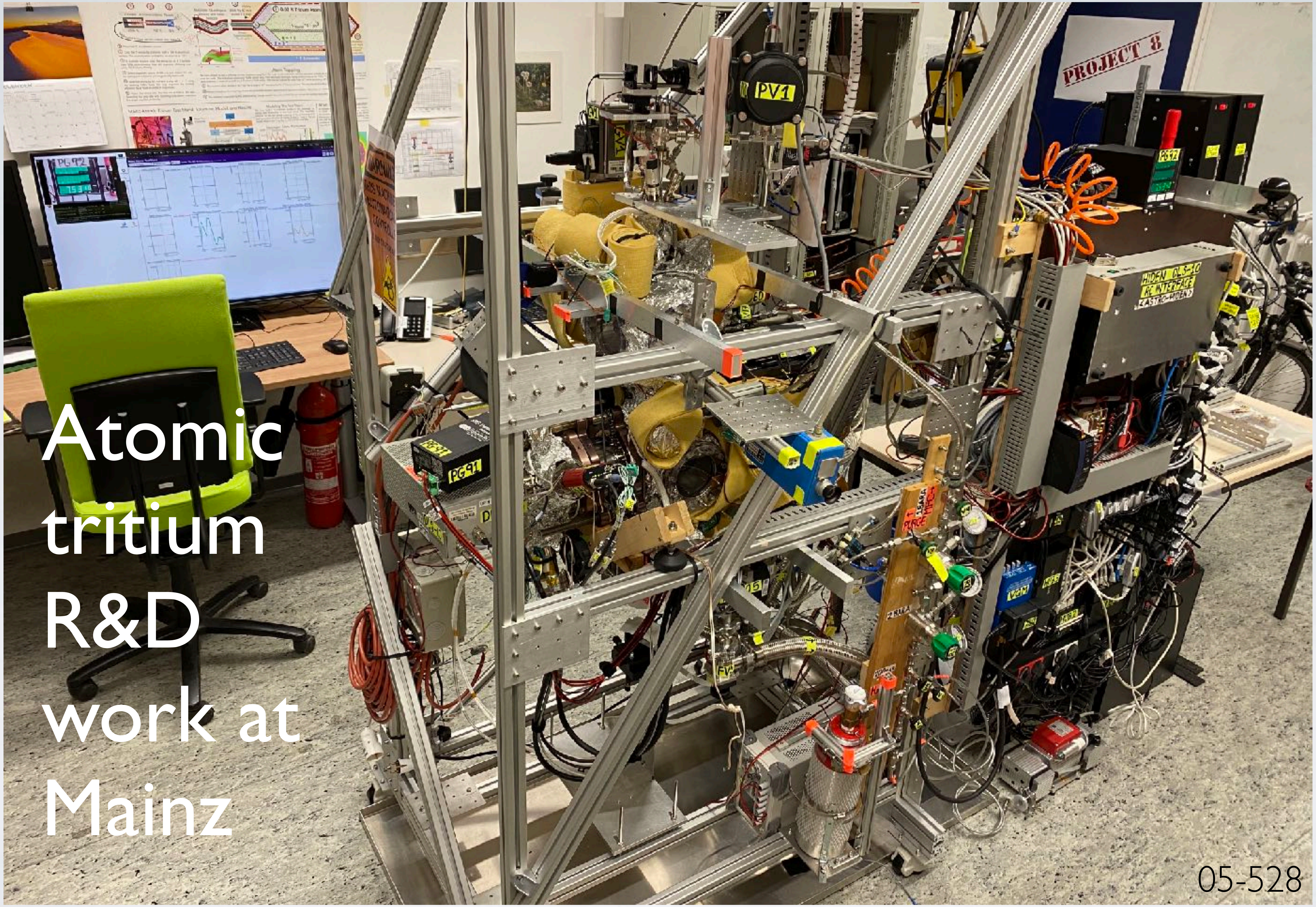
PREPARING ATOMIC TRITIUM

Properties of desired source:

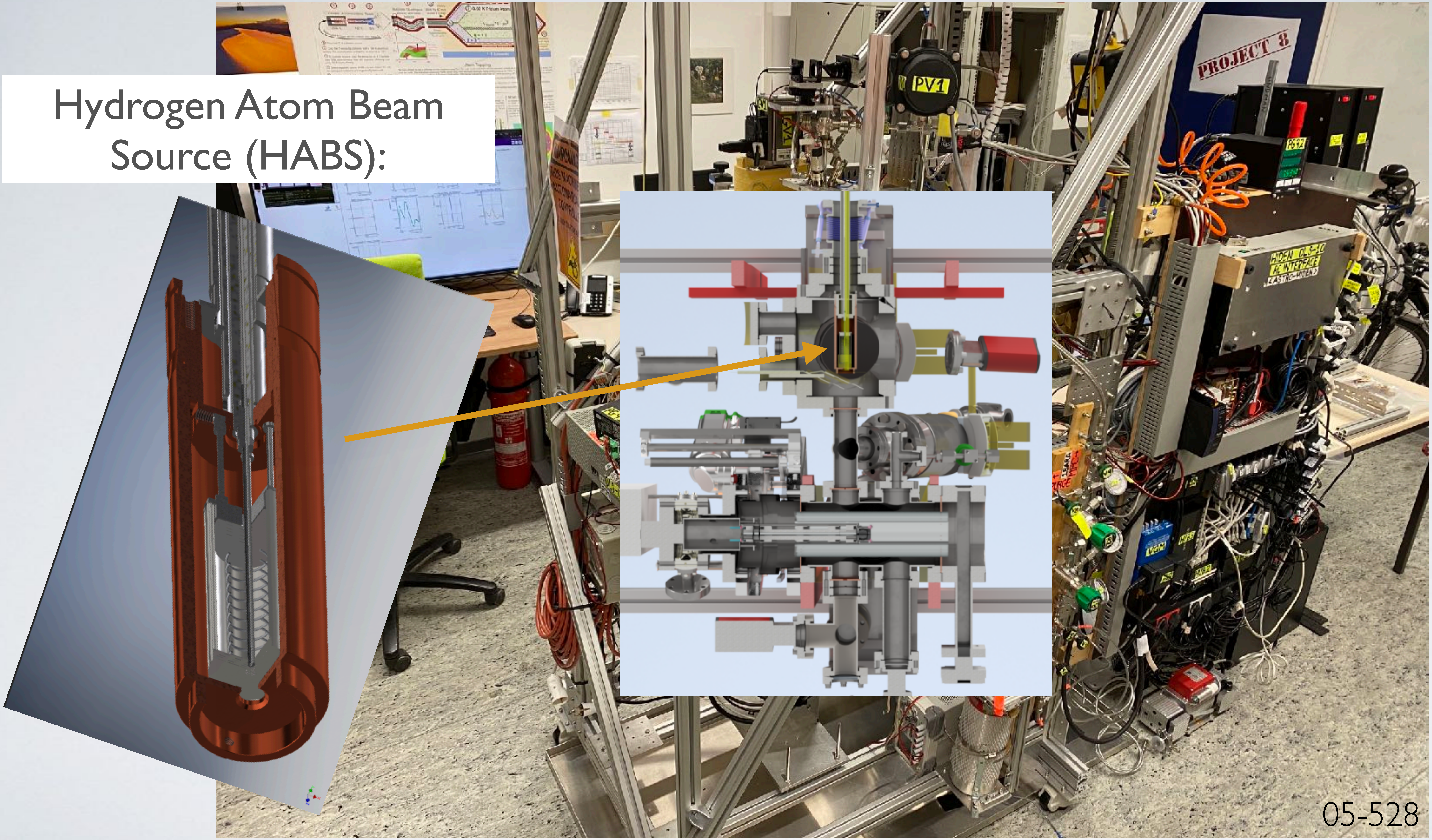
- **Atom temperature:** $\sim 1\text{mK}$
- **Atom purity:** $\frac{n_{T_2}}{n_T} < 10^{-4}$
- **Density:** $n_T \sim 10^{17}$per m^3



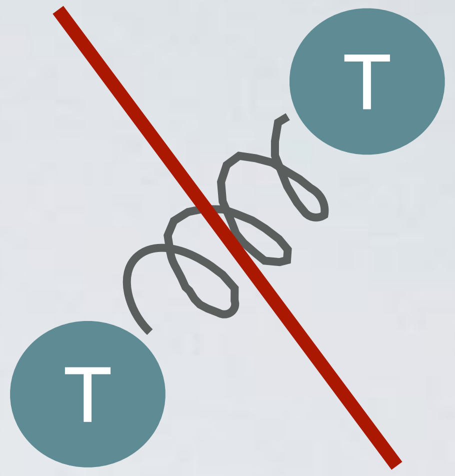
Atomic tritium R&D work at Mainz



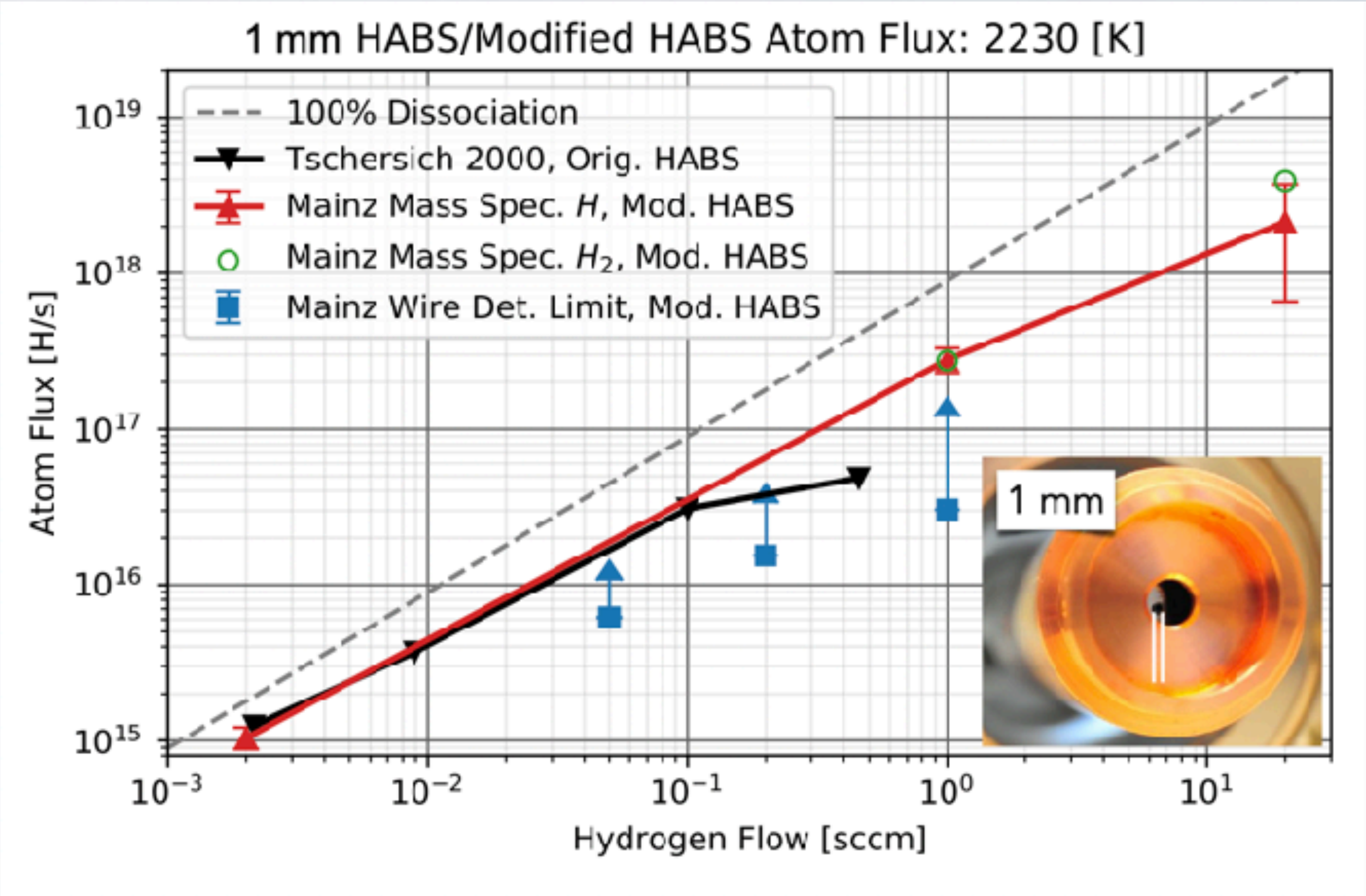
Hydrogen Atom Beam Source (HABS):



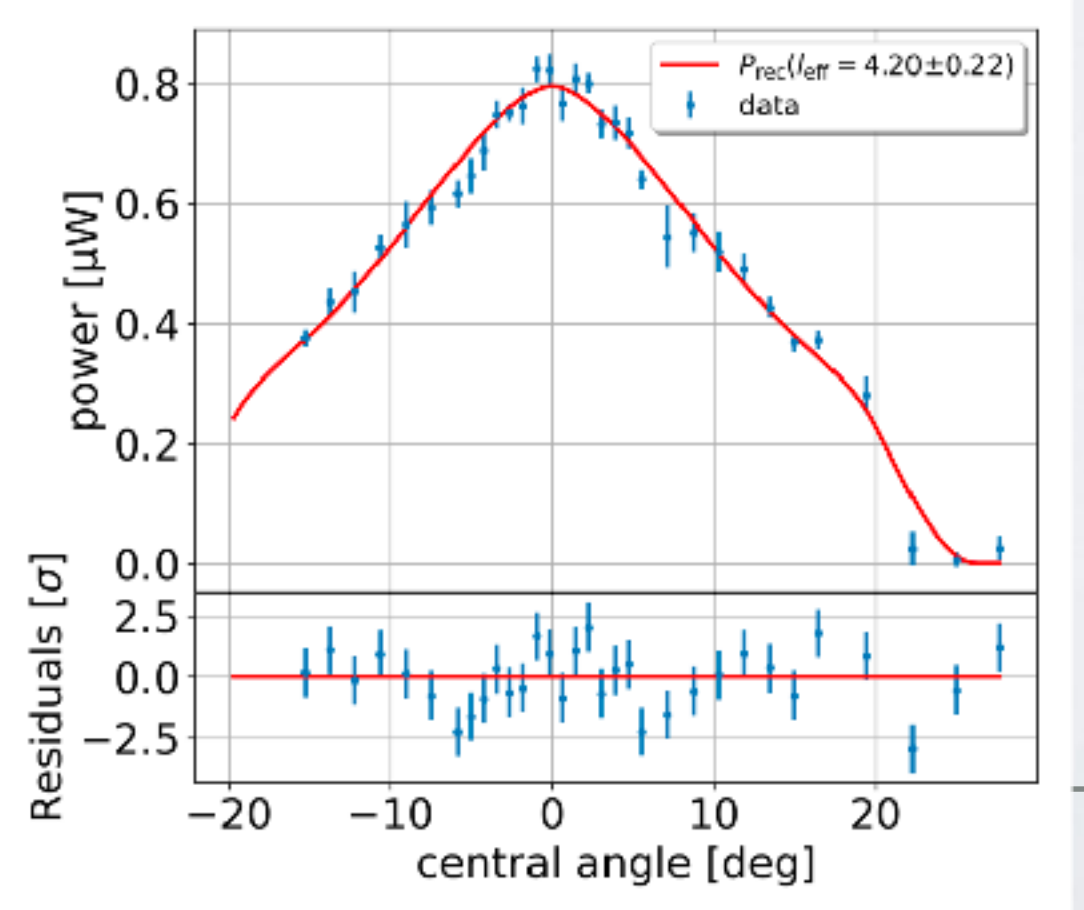
DISSOCIATION



- Required atom flux from dissociator: 10^{19} atoms/s
- Dissociation methods under review: thermal, plasma
- Characterization:
  - Atom flux, via dissociation fraction:
    - ➡ Dissociation is dependent on gas flow, temperature, etc. → optimize
    - ➡ Mass spectrometry and recombination heating
  - Spatial distribution



Credit: A. Lindman

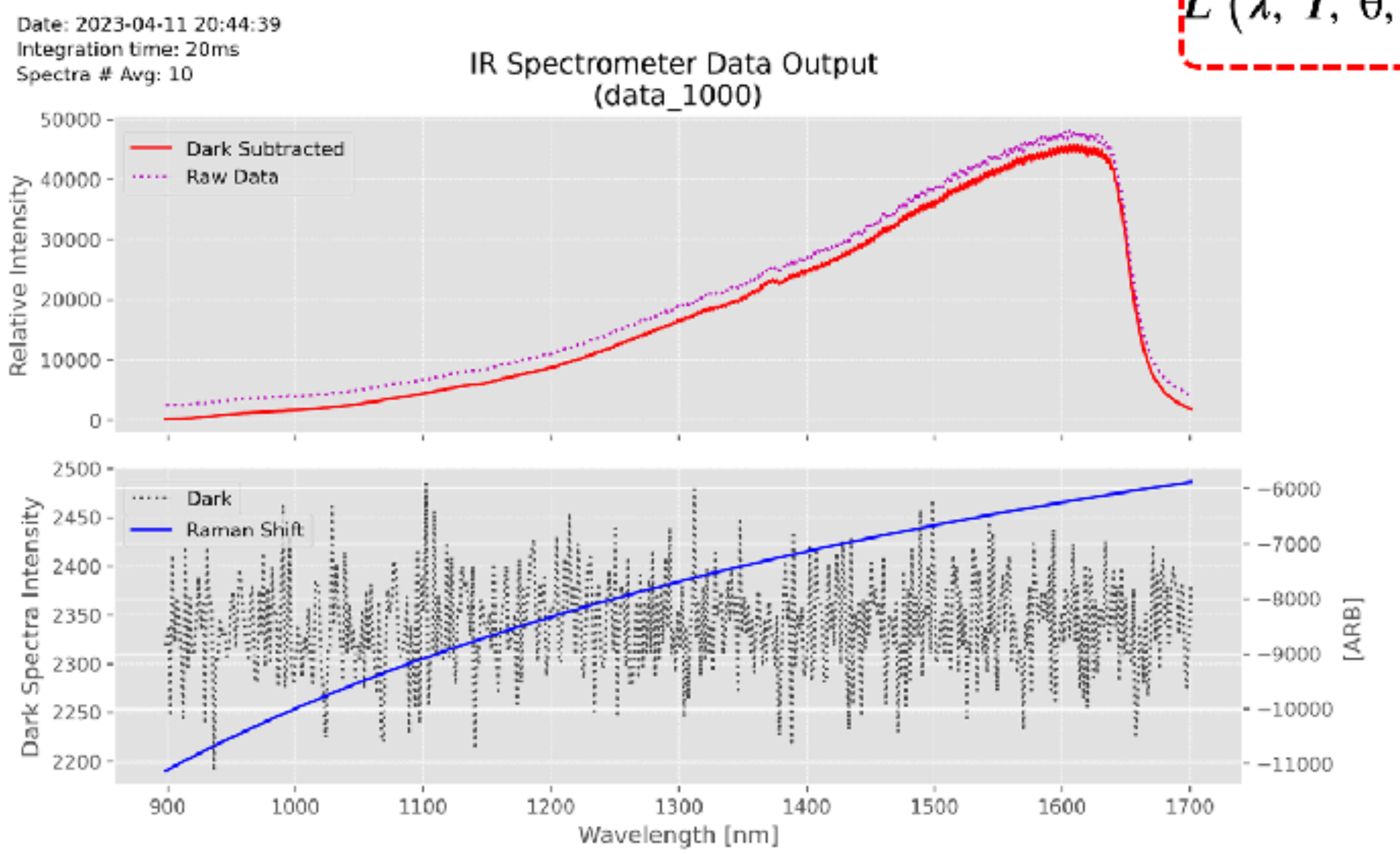


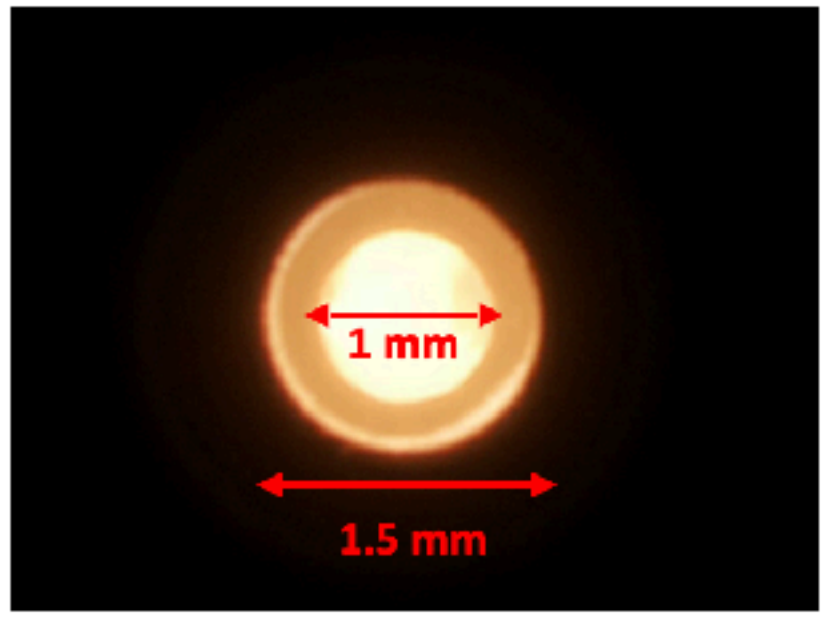
Credit: Ch. Matthé

TEMPERATURE MEASUREMENT

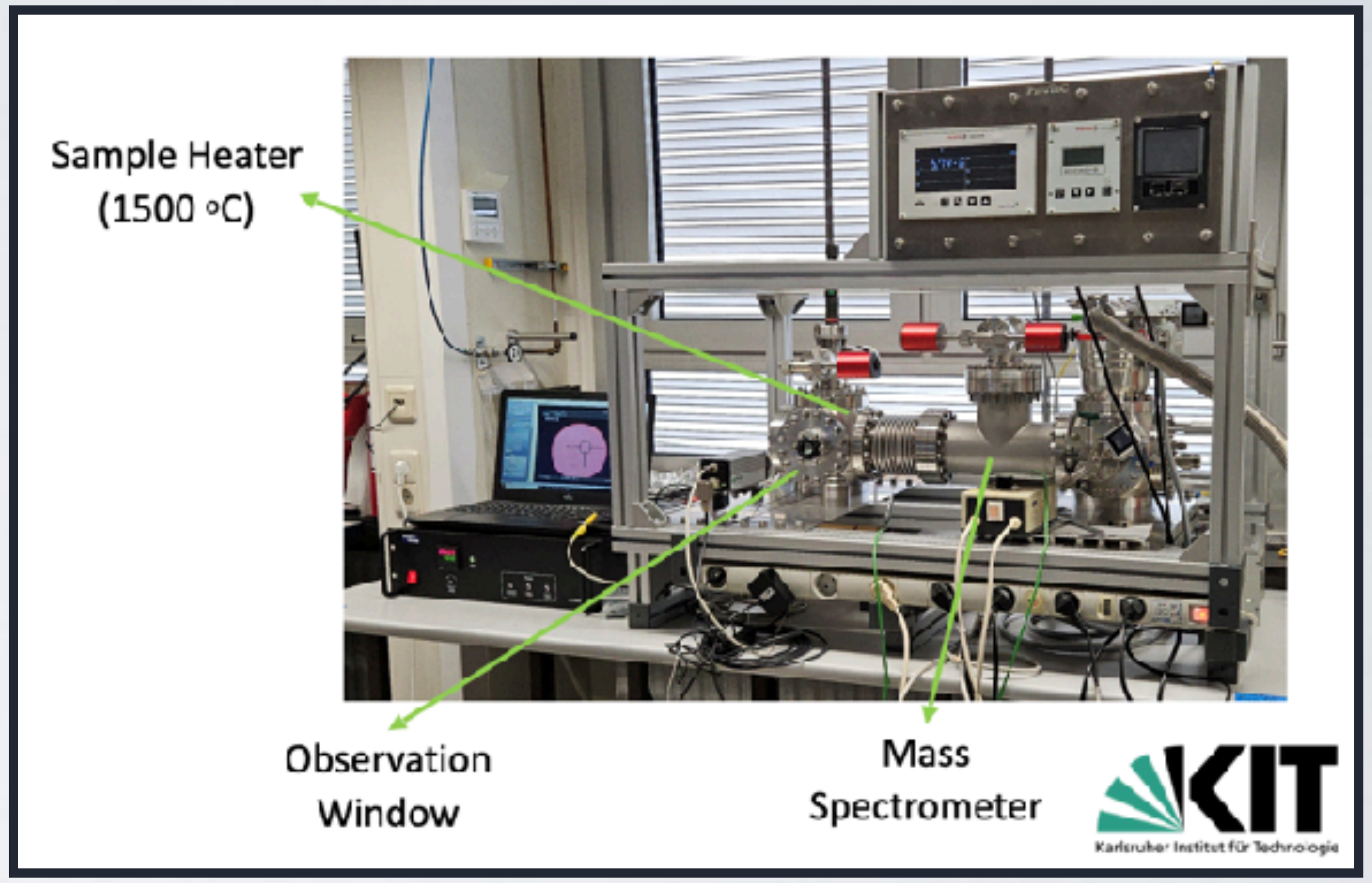
- Measurement of capillary temperature (proxy for atom temperature) to a precision of ~few K
- Collaboration with TLK: "KAMATE"

$$L\,(\lambda,\ T,\ \theta,\ \phi) = \varepsilon\,(\lambda,\ T,\ \theta,\ \varphi)\cdot C(\lambda)\cdot\frac{2\,h\,c^2}{\lambda^5}\,\frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right)-1}$$

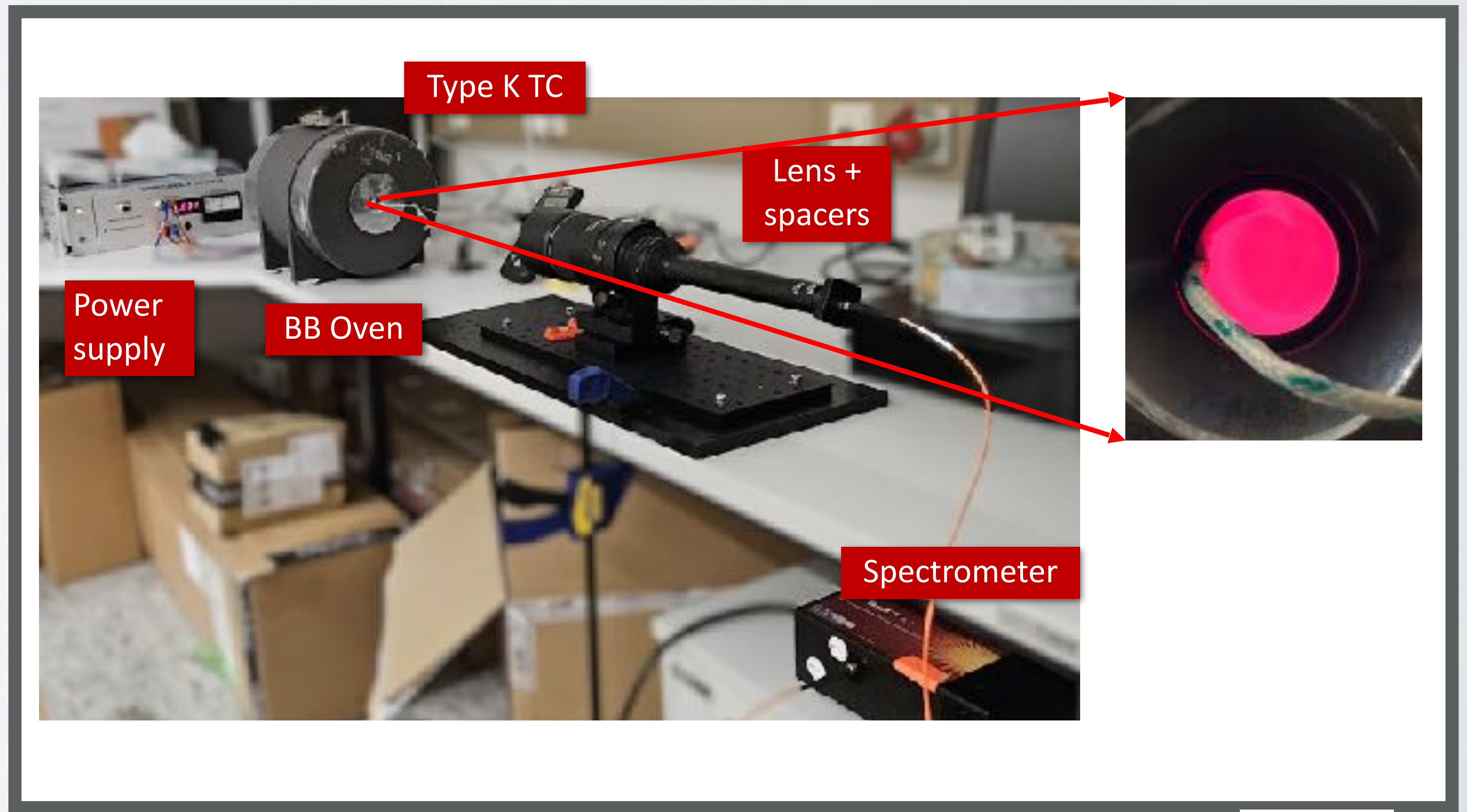




Measurement Method: NIR Spectrometer

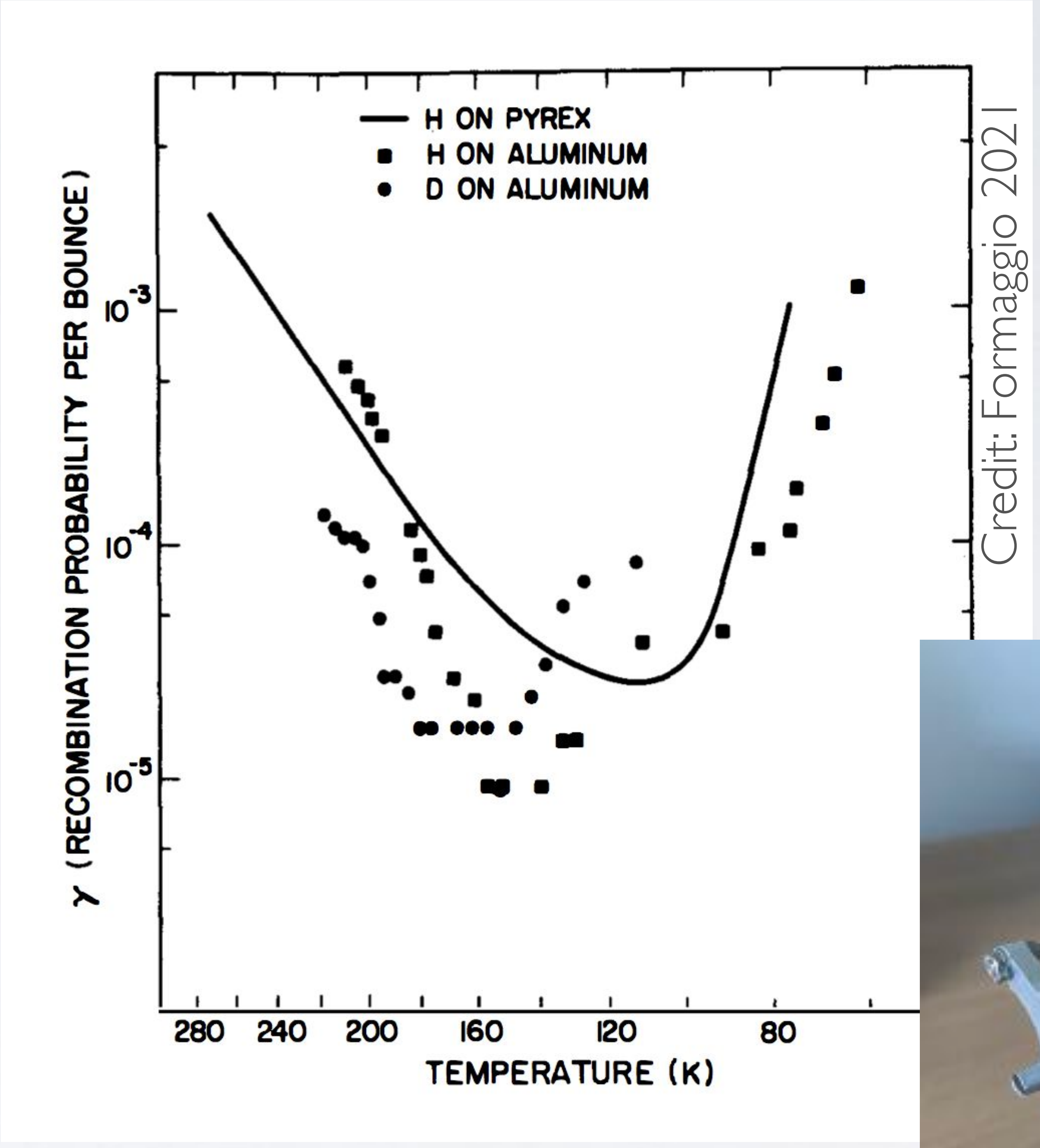


Credit: B. Mucoglava

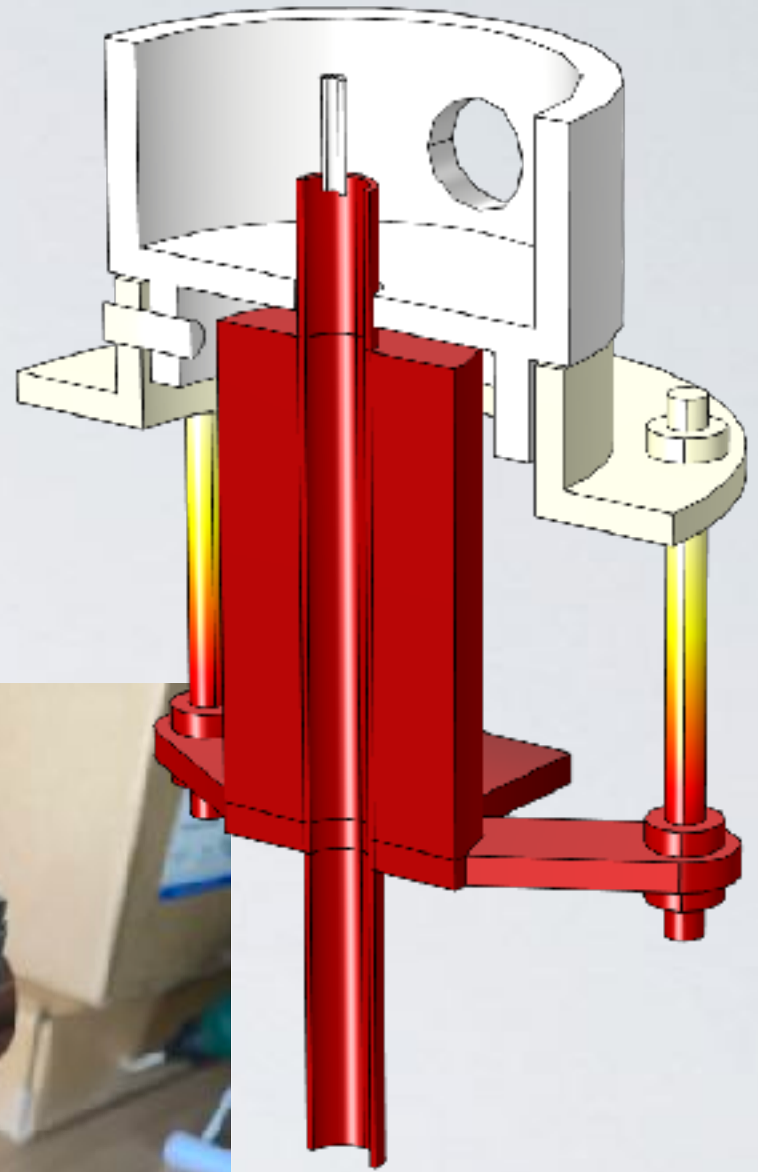


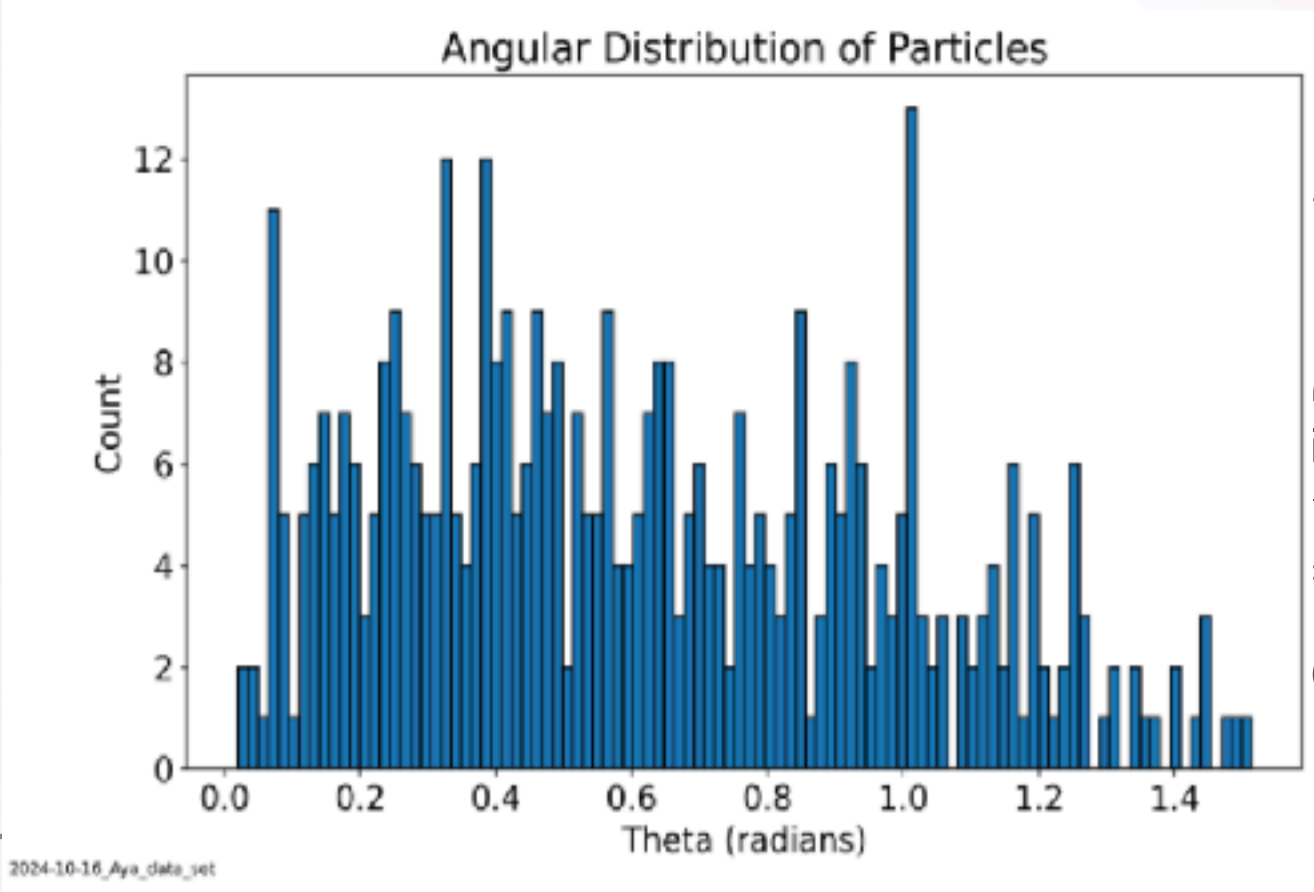
FIRST STAGE COOLING: SURFACE-COOLING

- Challenge: recombination
- Surface cooling at recombination minimum (~150K):
    - COMSOL simulations to calculate required LN2 cooling power
    - First prototype ready to test
    - Modeling gas dynamics with Molflow, Sparta
- For cooling to ~10K: additional "nozzle" on downstream end



Credit: Formaggio 2021


Credit: F. Piermaier

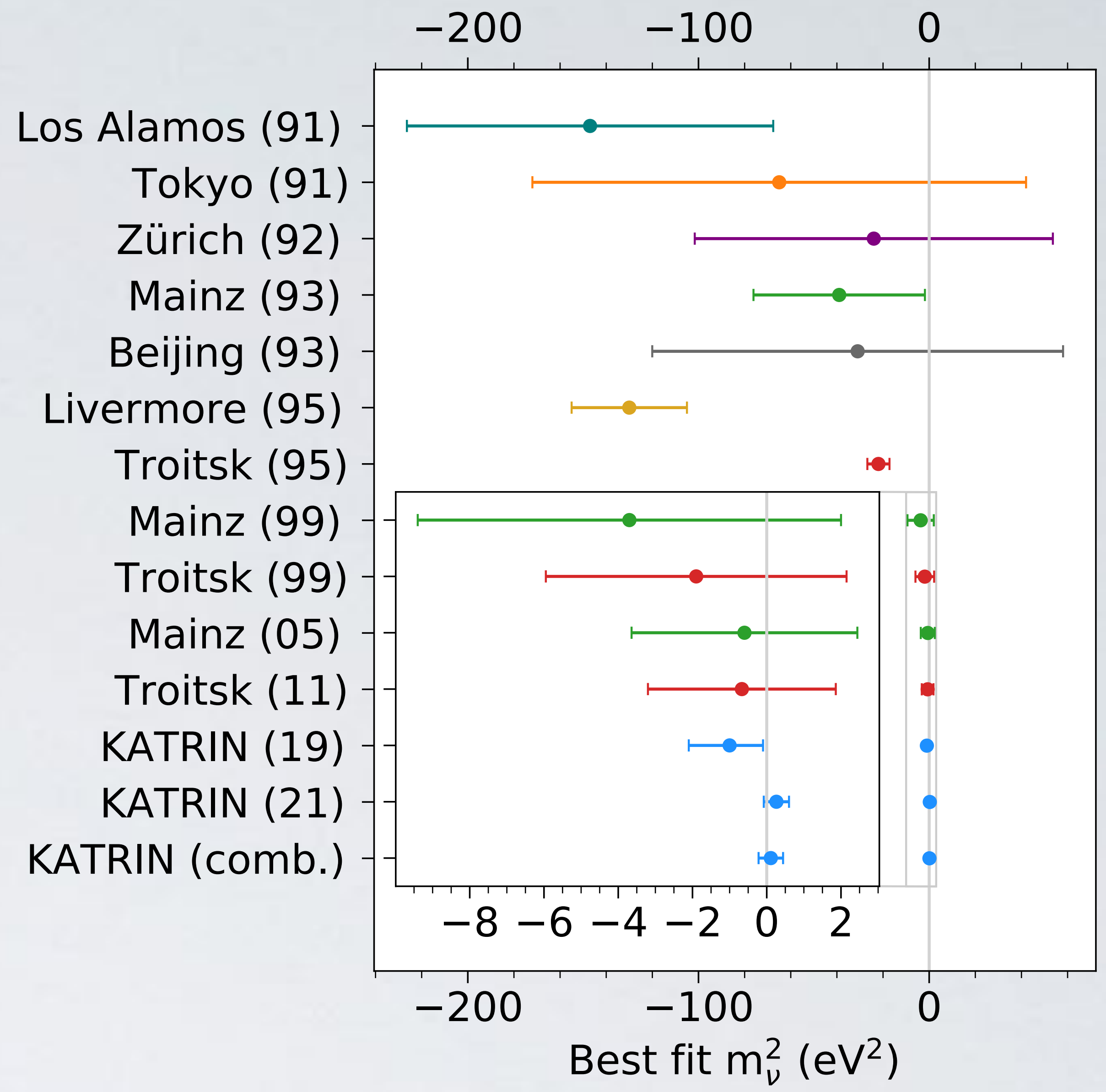


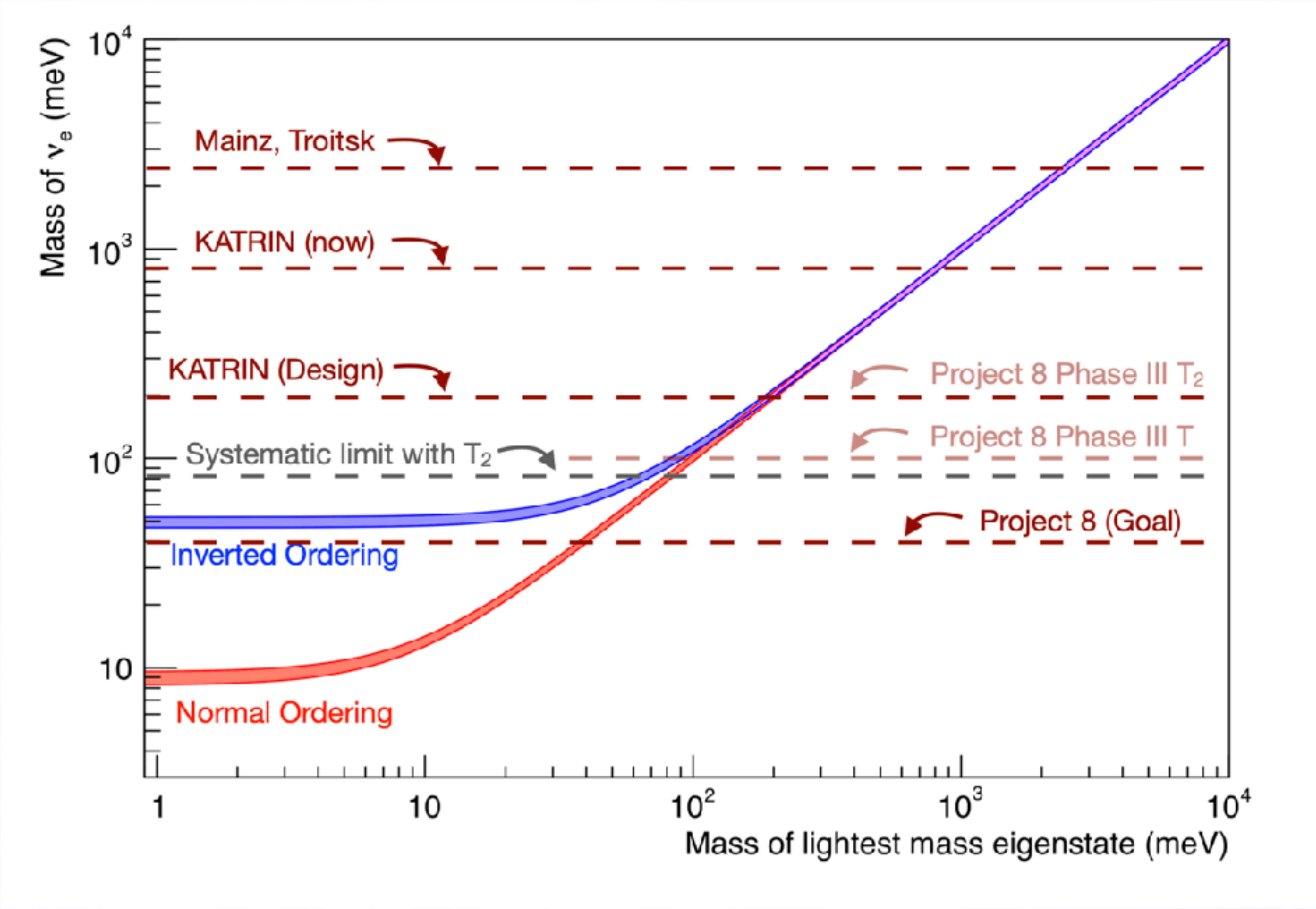
Credit: A.El Boustani

SUMMARY

- Absolute neutrino mass scale continues to be constrained:
  - Current best limits set by the KATRIN experiment ($m_\beta \leq$ 0.45eV/c^2 at 90% C.L.)
- R&D for atomic tritium crucial to gaining sensitivity
  - Many options for addressing challenges
  - Synergies between many working experiments

KAMATE He6 PTOLEMY QTNM KATRIN++ PROJECT 8





Thank you.

Supplemental slides

ABSTRACT

Nearly 70 years since the neutrino was discovered, and 25 years since discovery of neutrino oscillations established its non-zero mass, the absolute neutrino-mass scale remains unknown.

Tritium beta decay endpoint measurements currently offer the best upper limit on the neutrino mass. A next-generation experiment with greater sensitivity must overcome one of the major systematics for this kind of measurement: the molecular nature of the beta source. Past and current tritium beta decay experiments use a molecular tritium source in which one of the tritium atoms undergoes decay. A fraction of the decay energy excites the molecule into rotational, vibrational, or electronic excited states; this causes broadening in the molecule's final state distribution (FSD), and has a smearing effect on the beta decay spectrum. In order to achieve a reduced systematic uncertainty due to this FSD smearing, next-generation experiments must switch to an atomic tritium source.

I will present an overview of the necessary steps to develop such an atomic tritium source, through the lens of the Project 8 experiment. This multi-institution development program includes dissociation and accommodation cooling down to 10K; further cooling to 10mK via magnetic evaporative cooling; and atom trapping using magnet arrays. In addition to this overview, I will focus on the multitude of tritium-compatible diagnostic tools being developed at JGU Mainz to measure atom flux, atom beam shape, and temperature.