Atomic Tritium in Project 8

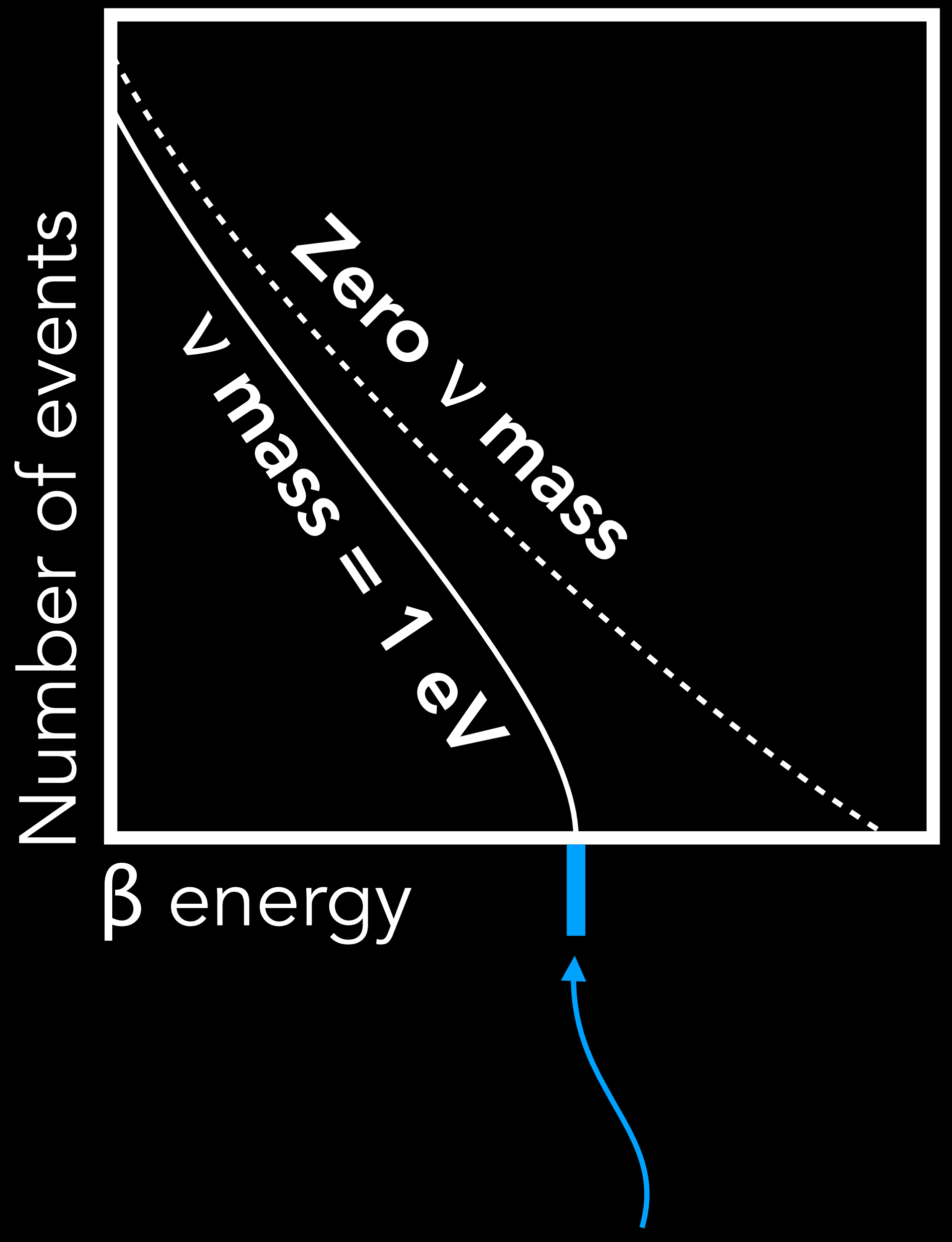
Alec Lindman | Feb. 28th 2024
NuMass Workshop | University of Genoa

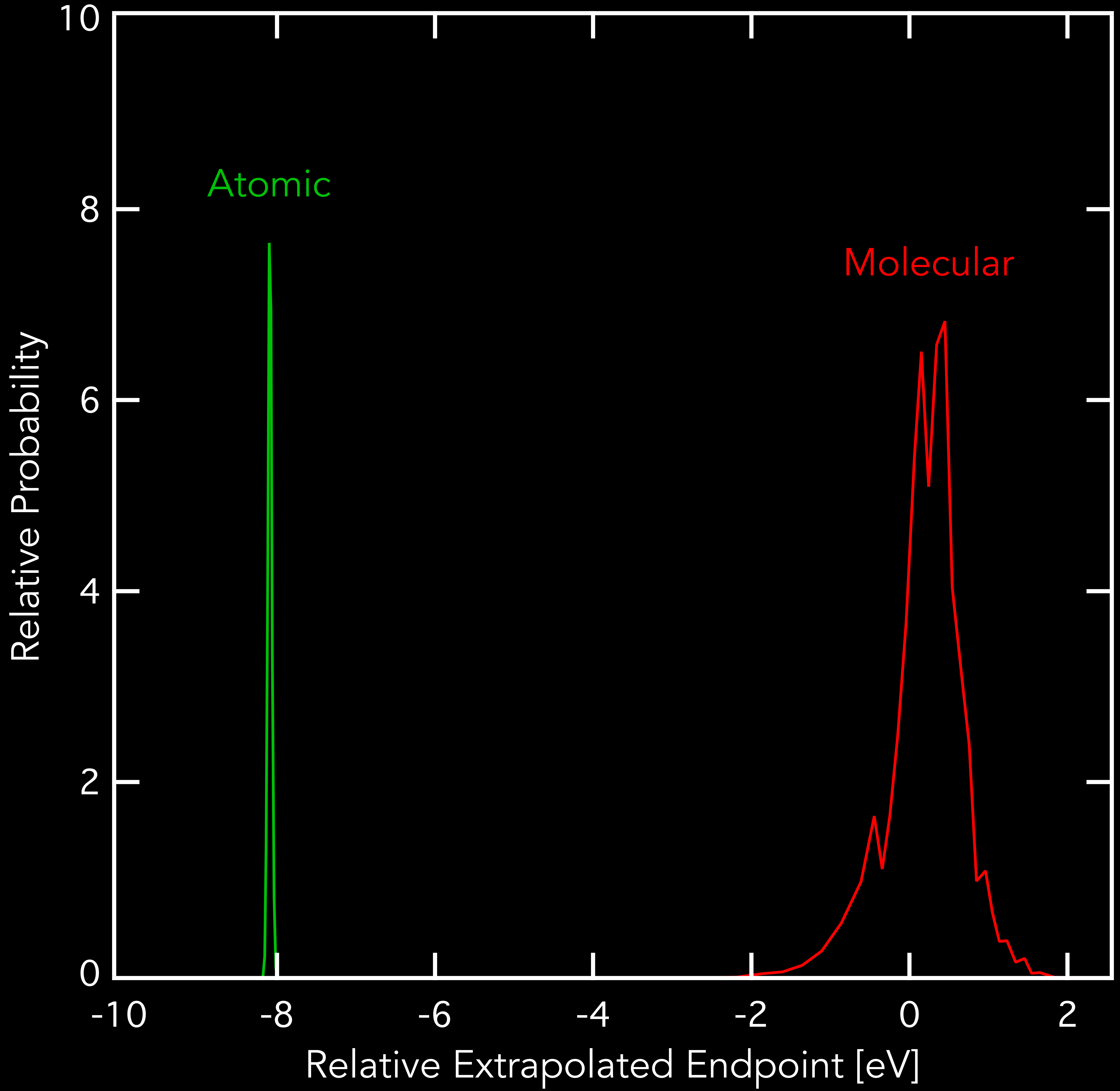
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

Atoms: Why Bother?

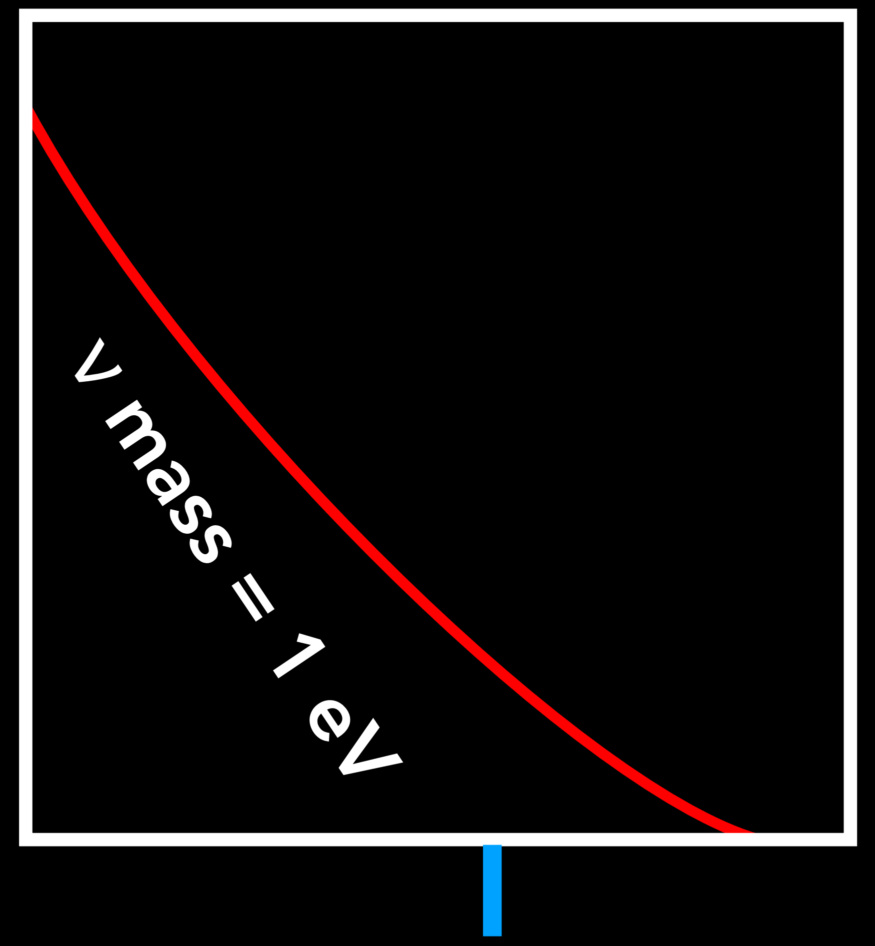
Tritium Final State Spectra

Tritium β Spectrum



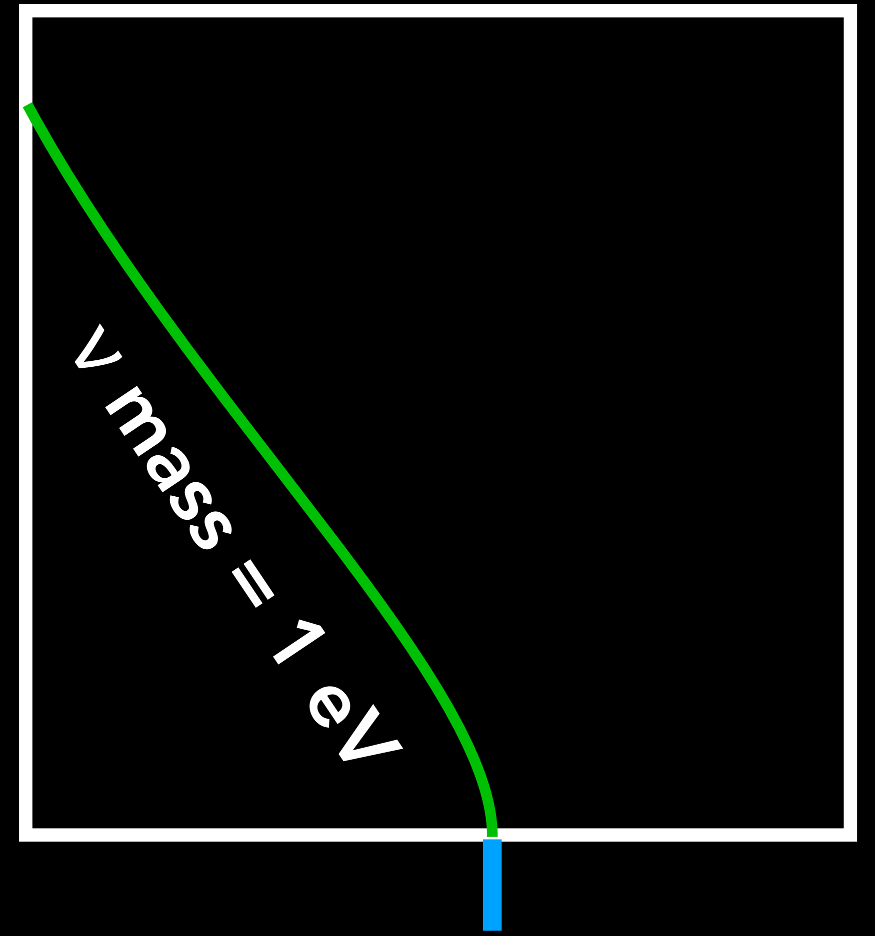


Measured with Molecular FSS



Which one would you rather measure?

Measured with Atomic FSS



The Ideal Experiment

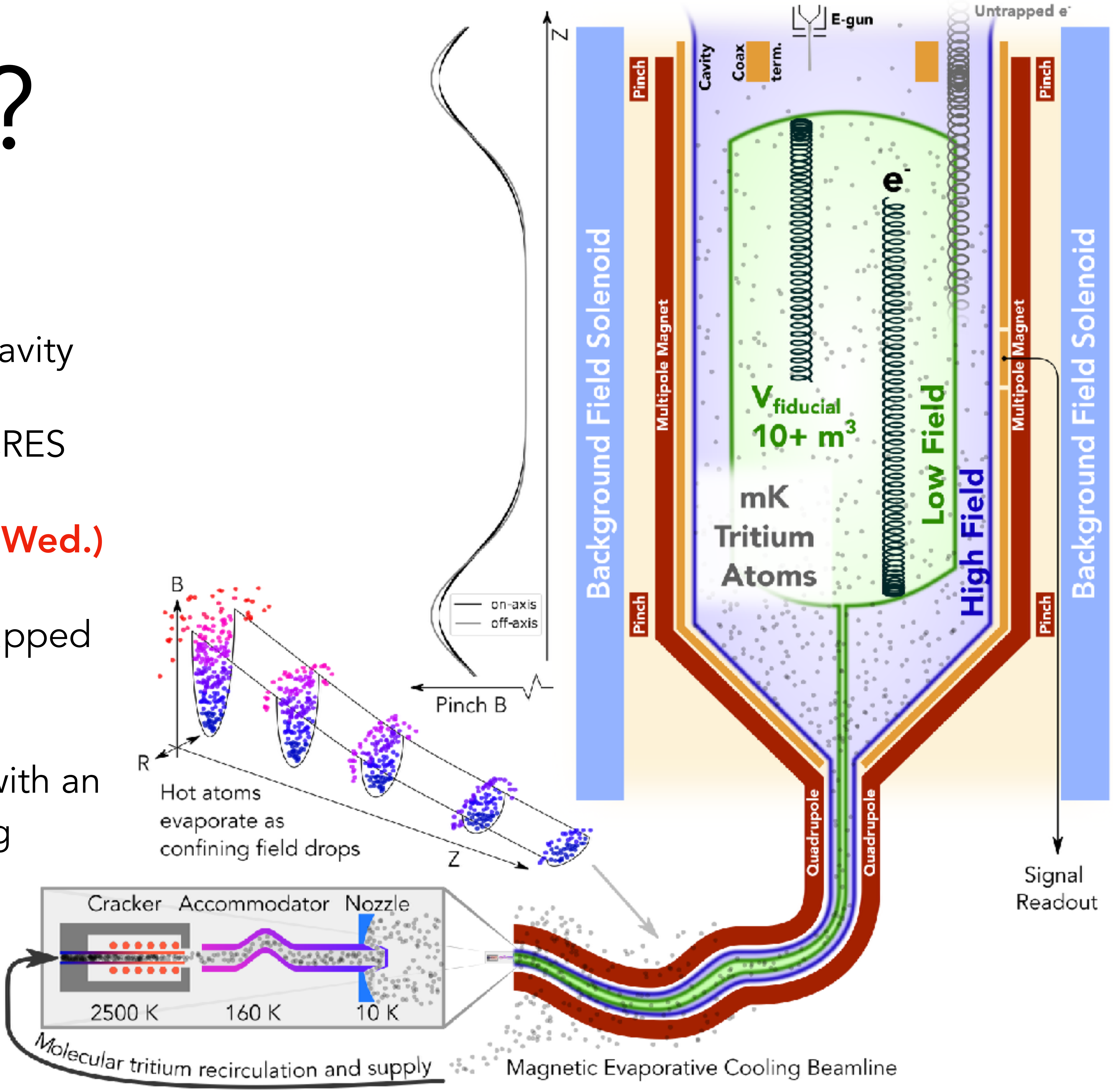
- High precision (sub-eV effect at 18.6 keV)
- High statistics (n^{-4} scaling)
- Control of systematics (enables requisite energy resolution; reduces background effects)

PROJECT 8

- High precision
  - eV resolution to 32 keV
- High statistics
  - Scales with volume
- Control of systematics:
  - Compatible with atomic tritium (10-30x more sensitive than T_2 experiment)
  - Inherently low background

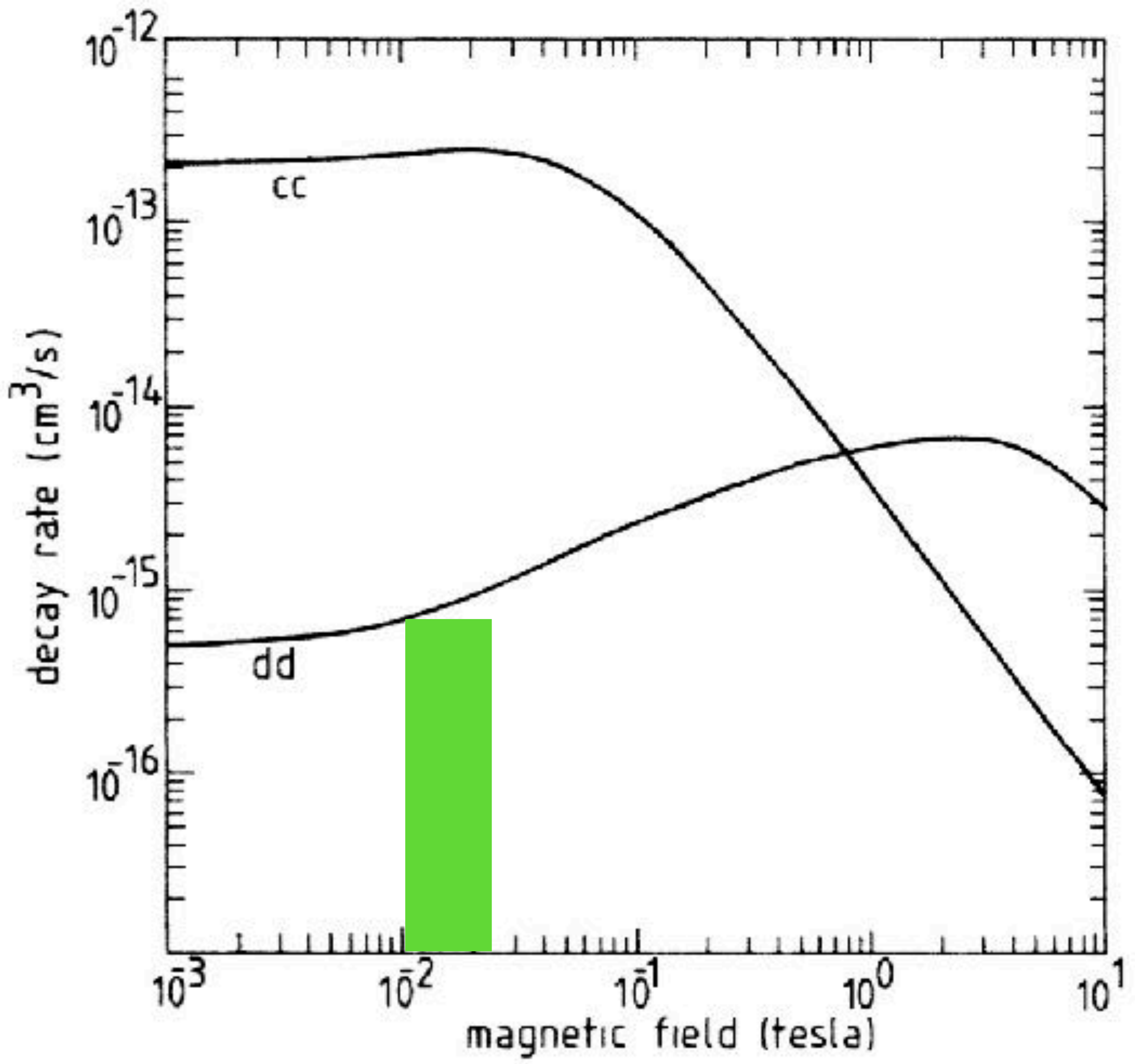
How?

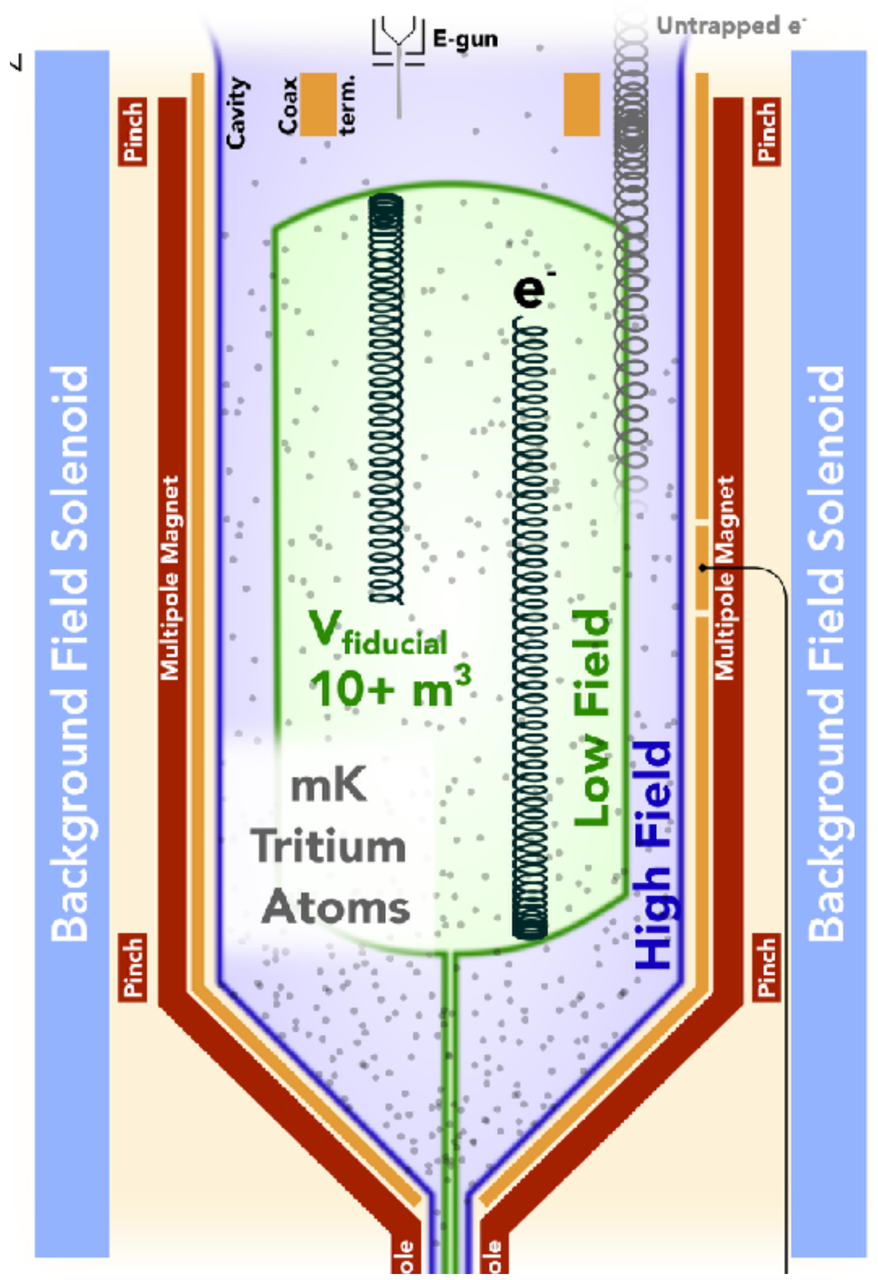
- Trap T atoms in a magnetic minimum, augmented with gravity
  - Must be compatible with CRES
  - **See Juliana S.'s talk (9:00 Wed.)**
- Continuously replenish the trapped population
  - Provide these cold atoms with an external source and cooling beam line



Atom Loss Rate

- Atoms can escape in many ways
- Fastest loss is conversion to anti-trapped states by spin exchange collisions
  - Mitigated by lower absolute field
- This and other losses under study with calculations and simulations
  - Future target of measurements, including with Li
  - **See Ben J.'s talk (11:50 Thu.)**





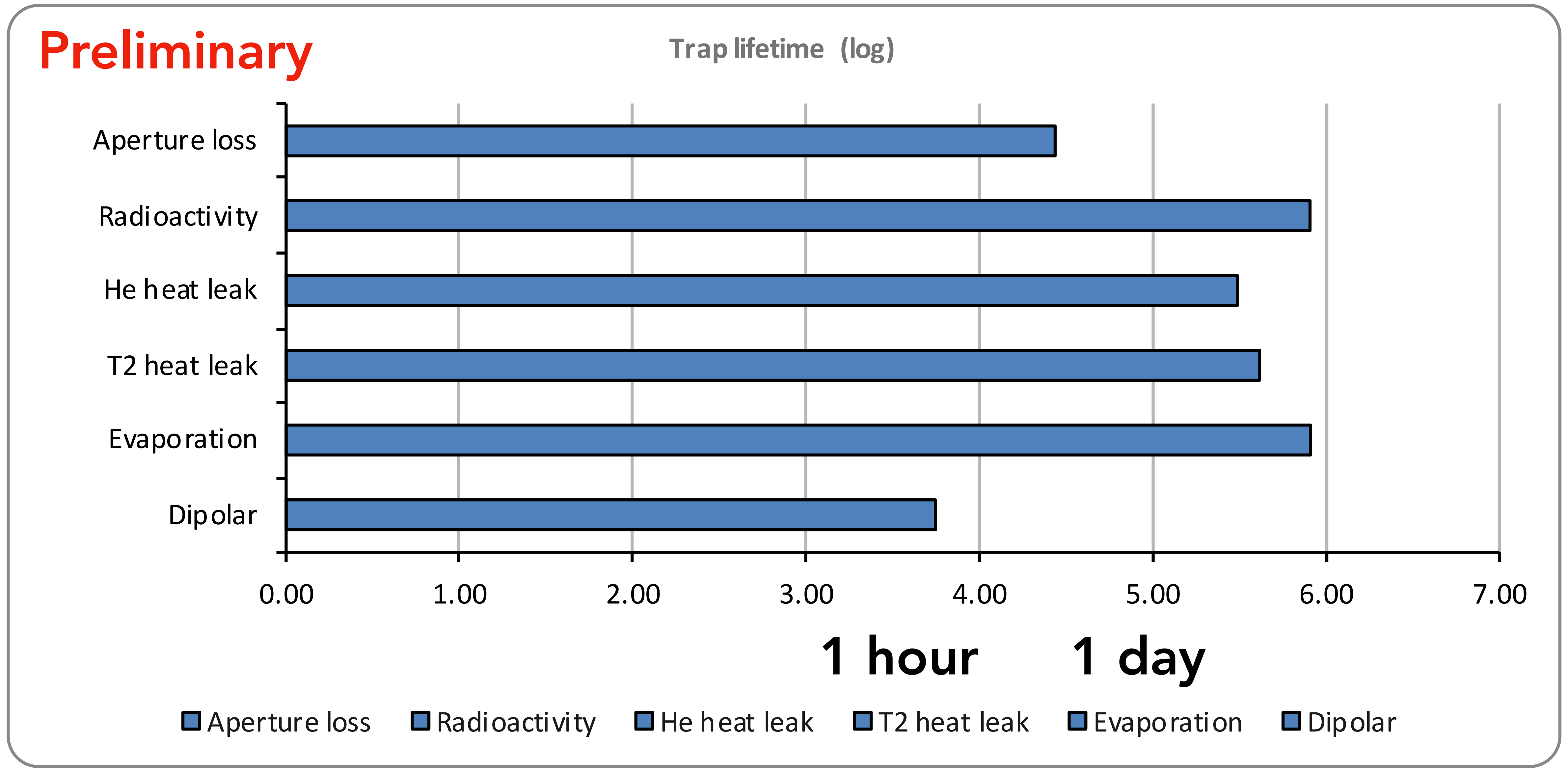
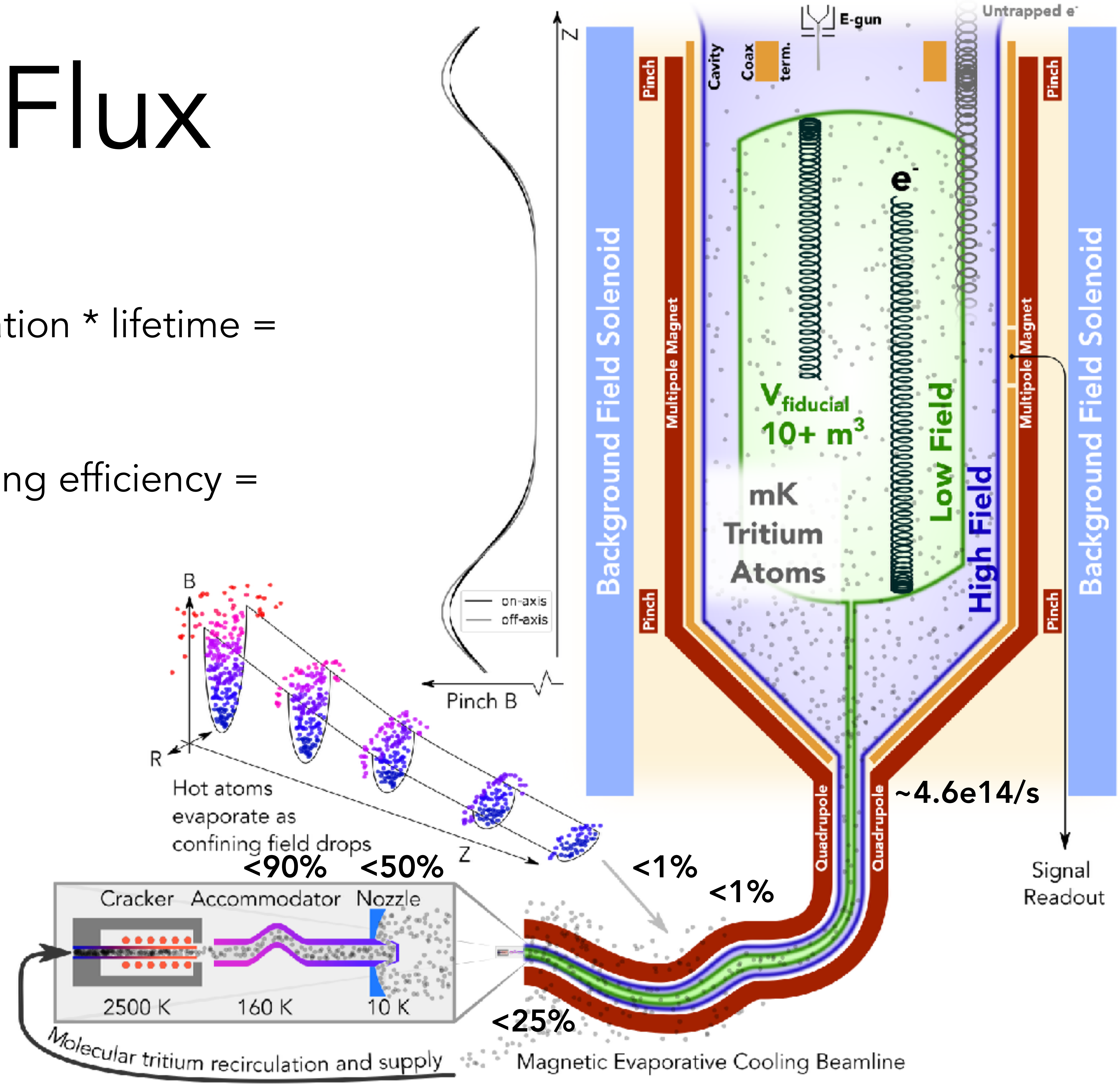


Figure 6.13: Partial lifetimes (as logarithms for the 325-MHz cavity in atomic mode)

Atomic Flux

- In the trap: trapped population * lifetime = replacement rate
    - Replacement rate / cooling efficiency = required source output
- Present goal at source ~ 10^{19} hot atoms/s



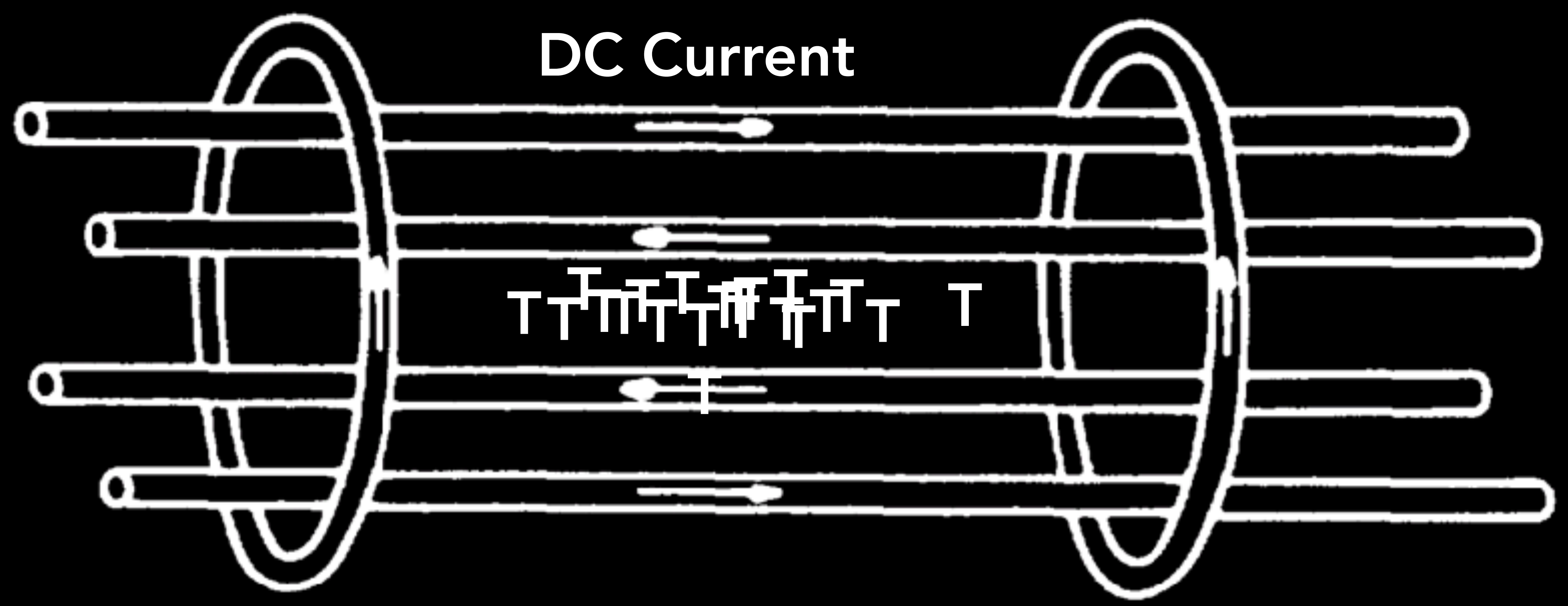
Atom Trapping

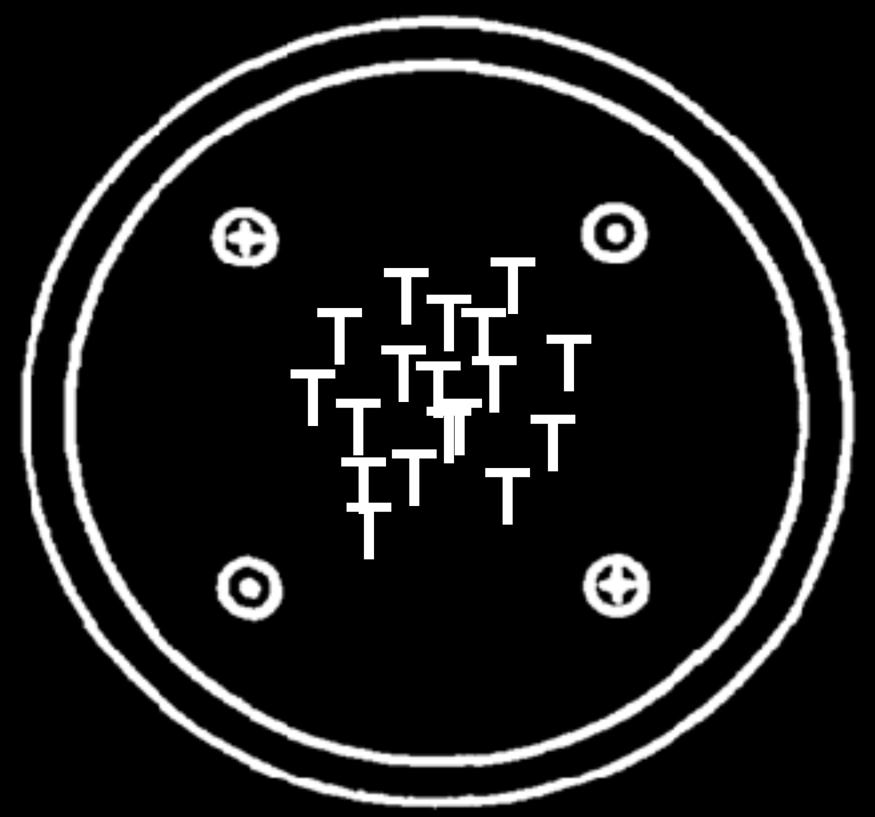
Storing Tritium Atoms

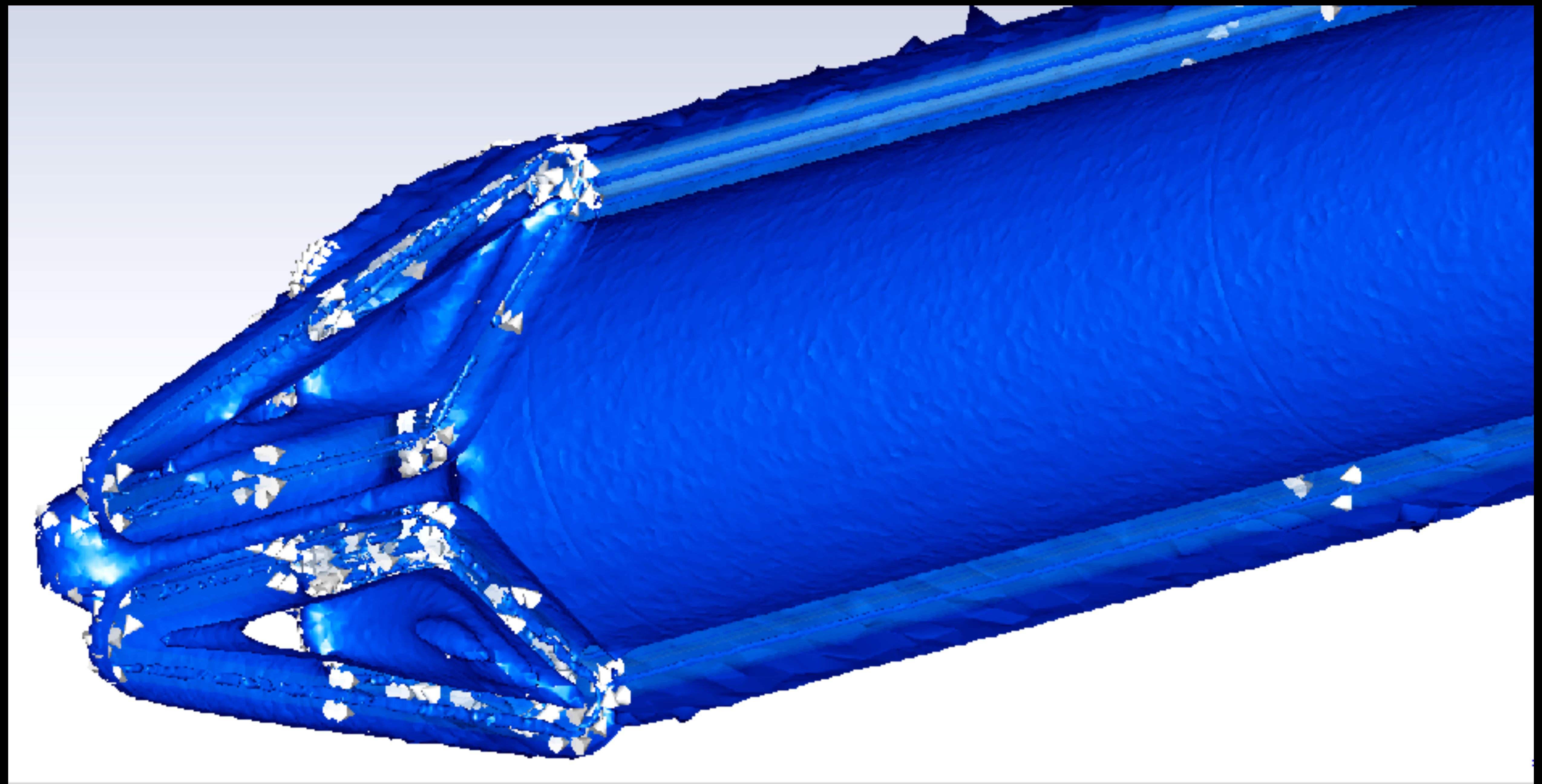
Tritium atoms have a nonzero magnetic moment, and can be trapped in a magnetic minimum

A quadrupole with closed ends forms a simple trap; we will use a higher-order multipole

This provides a large volume, plus a uniform central region for precise CRES measurements



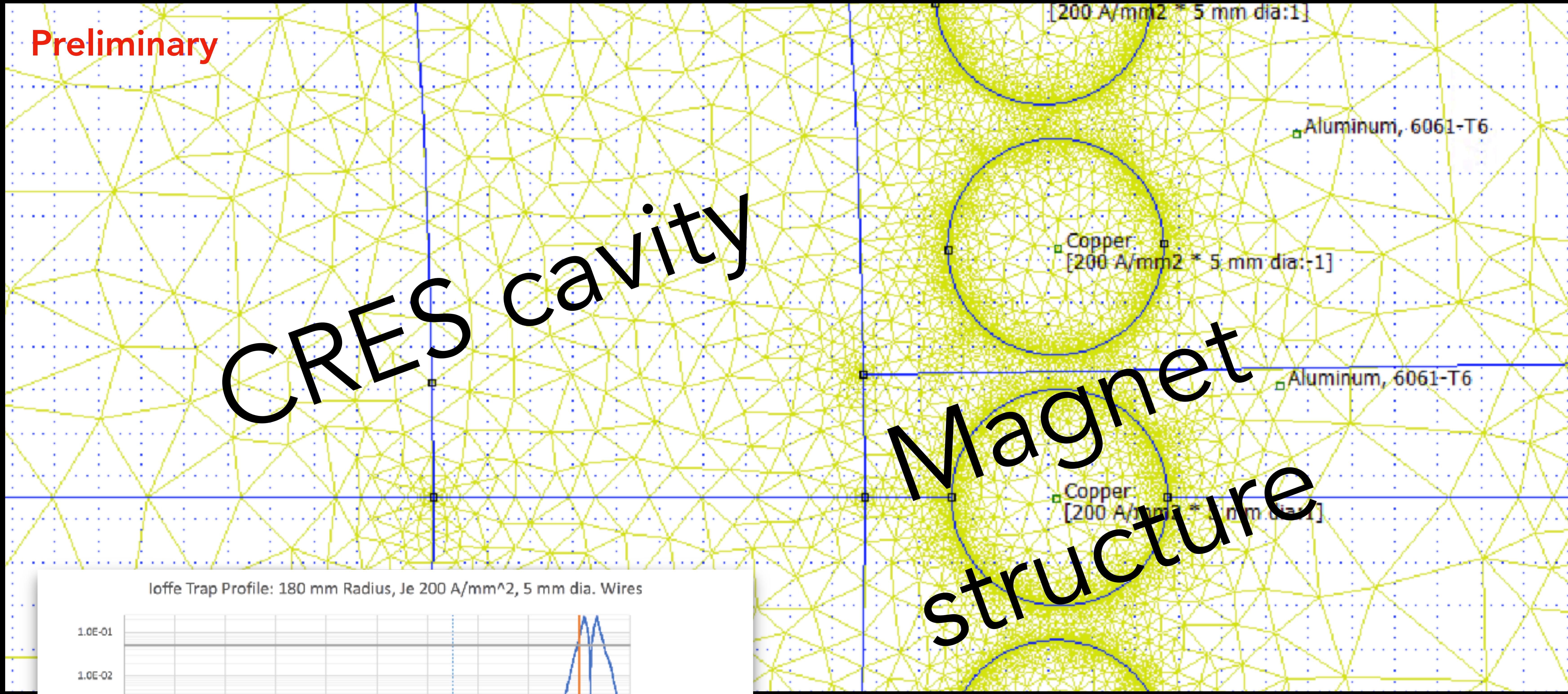


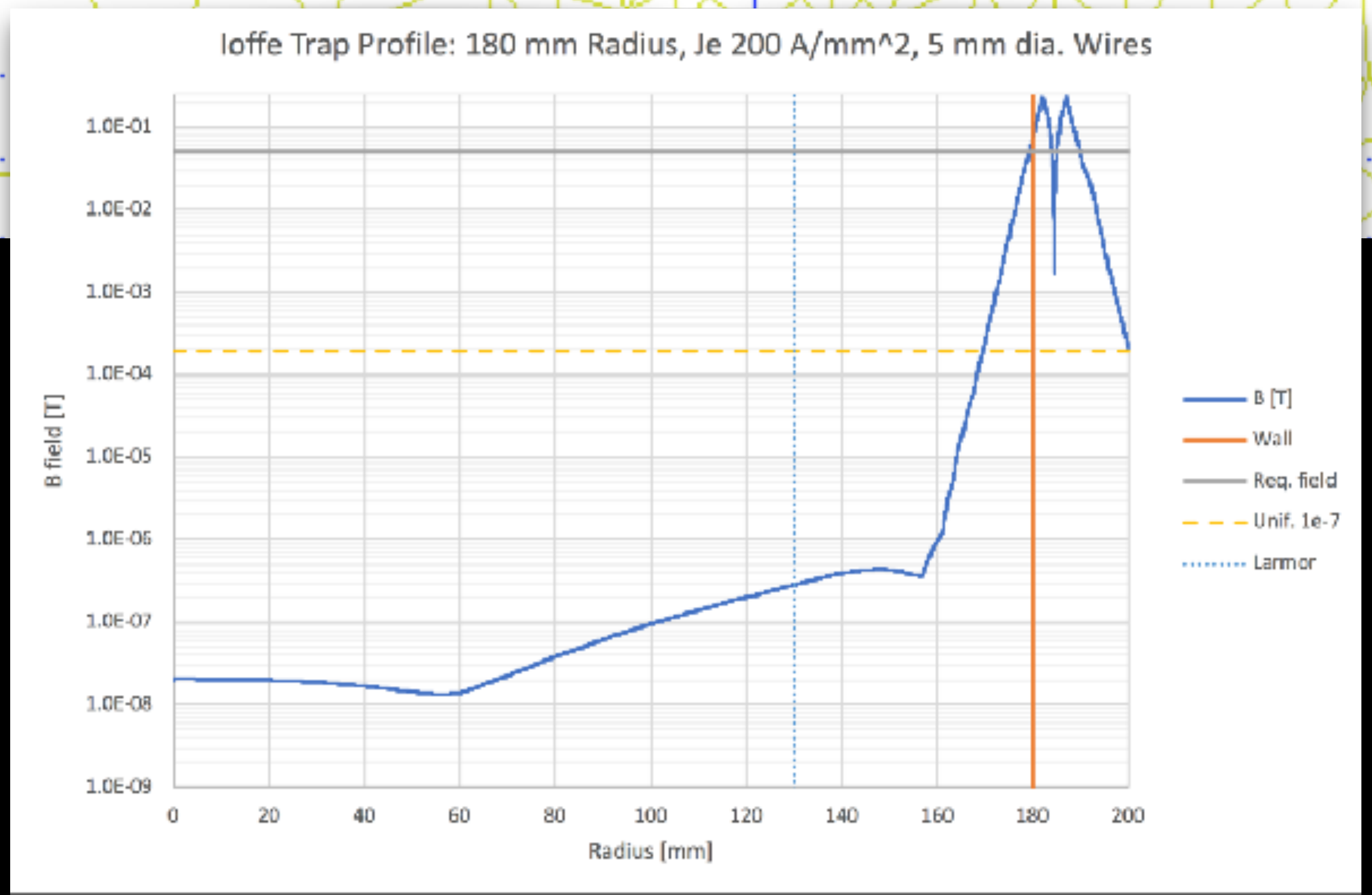


See 10.1109/TASC.2020.2974173 and 10.1109/TASC.2020.2985675

Atom Trap Geometry Optimization

- Choose a realistic conductor
  - Baseline: NbTi (4 K, 200 A/mm^2)
- Simulate 2D magnetic field
- Evaluate for compatibility with CRES

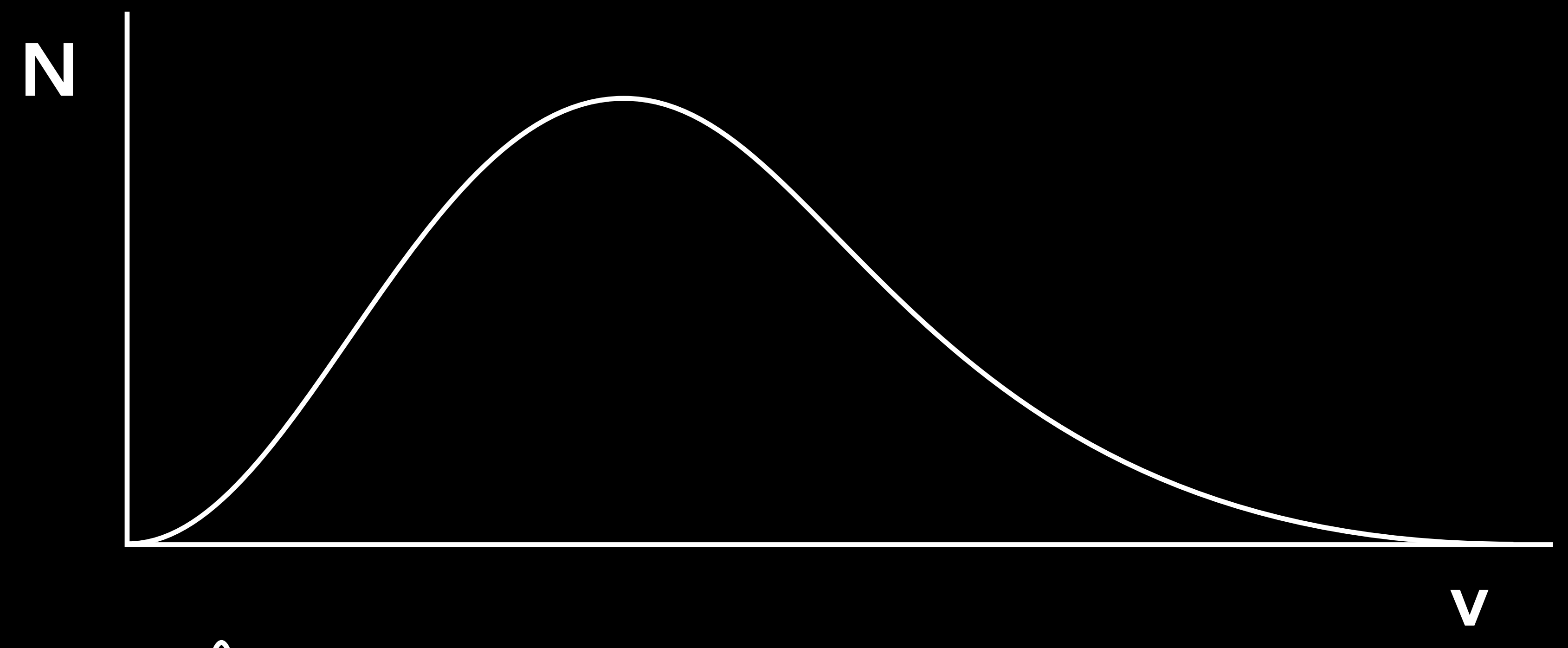




Atom Cooling

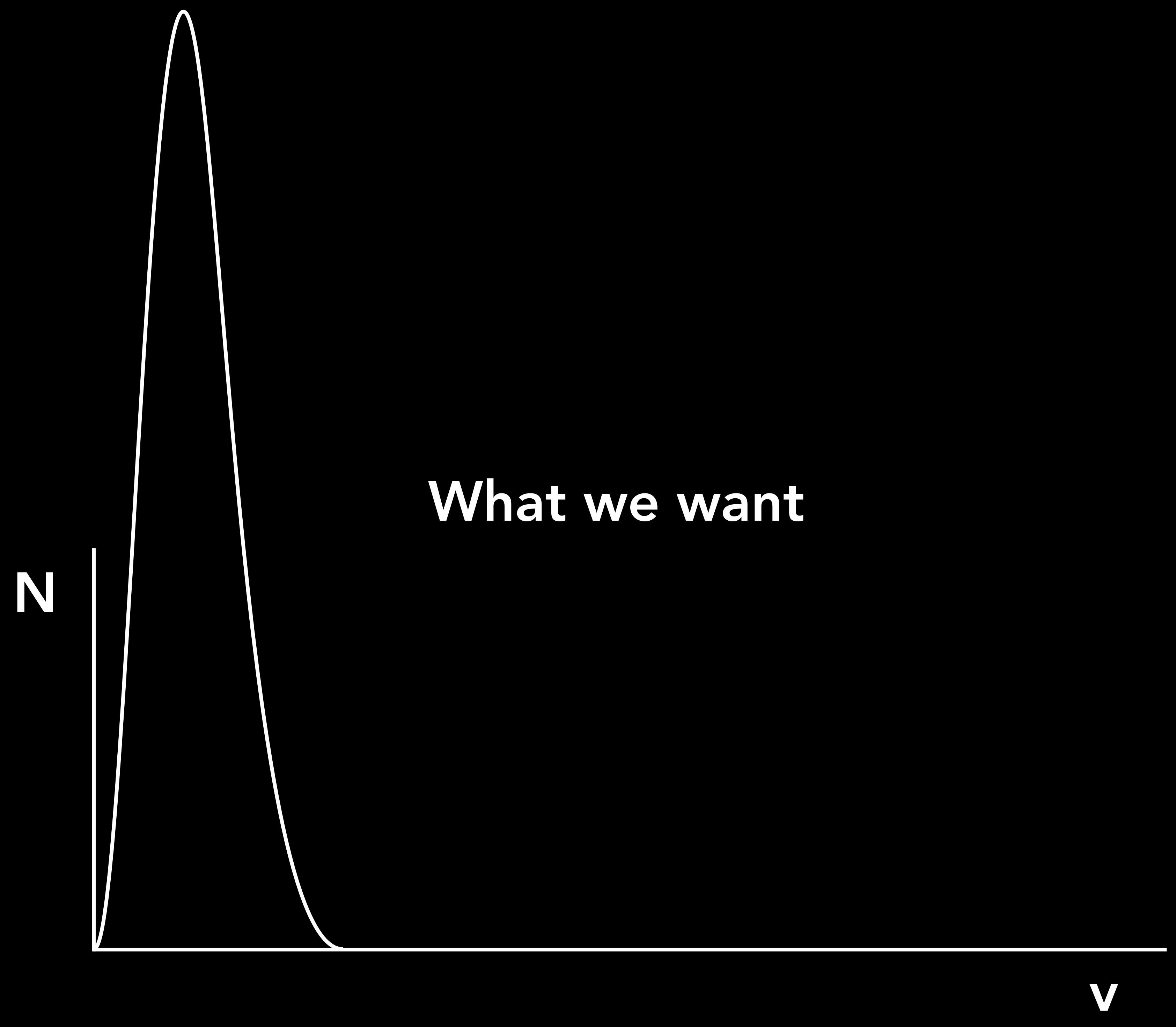
Cooling Goal

What we have

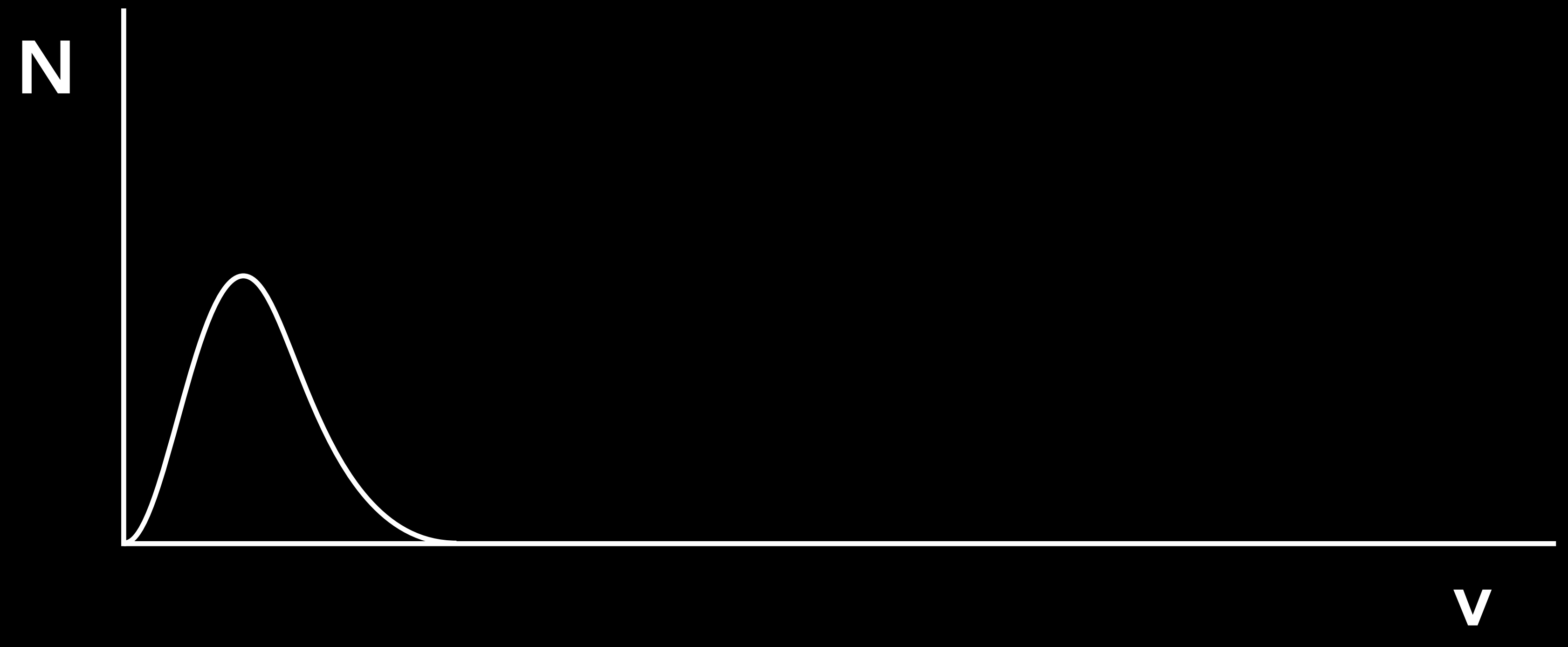


- Remove energy (required)
- Preserve particle number (nice to have)

What we want

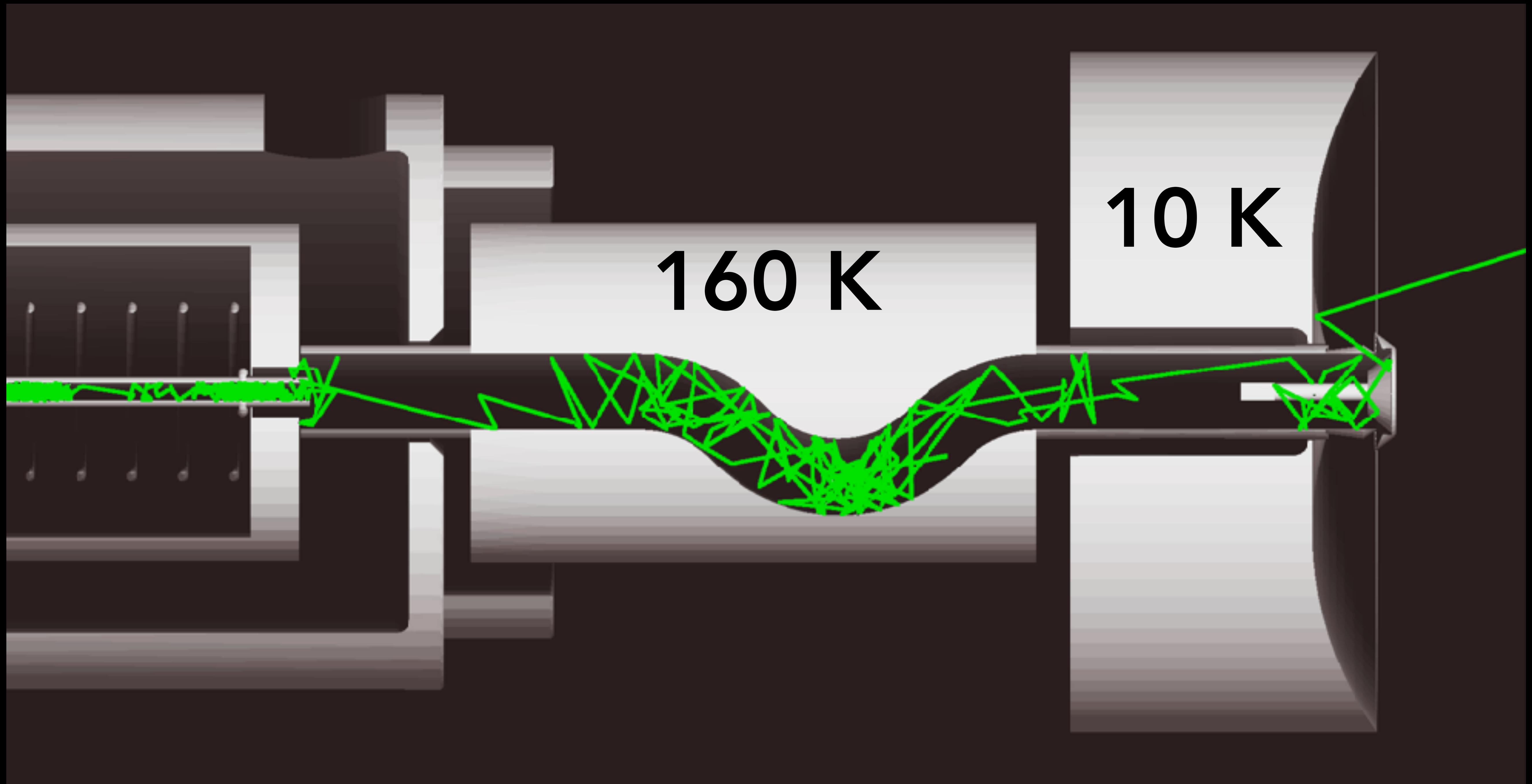


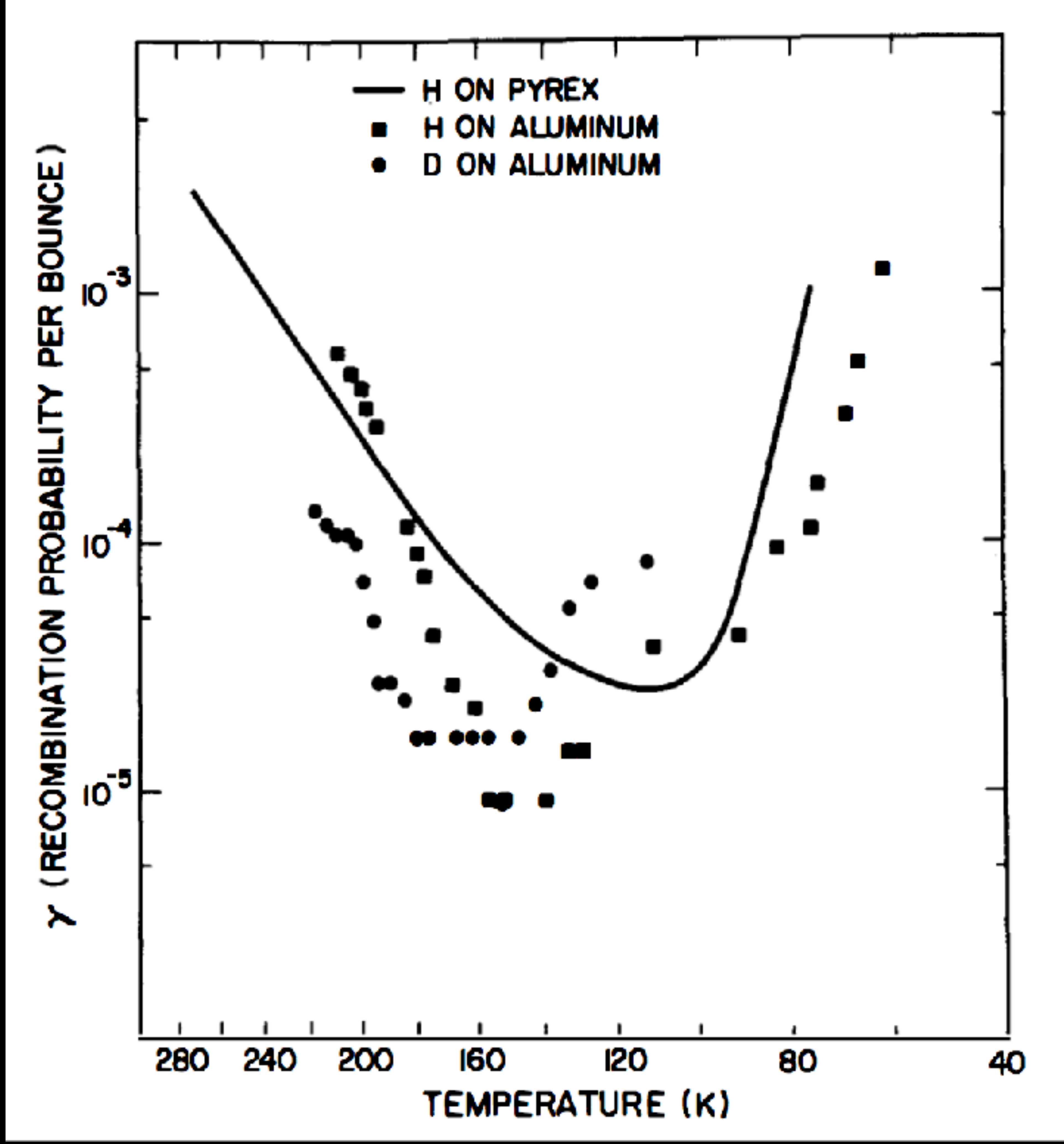
What's possible



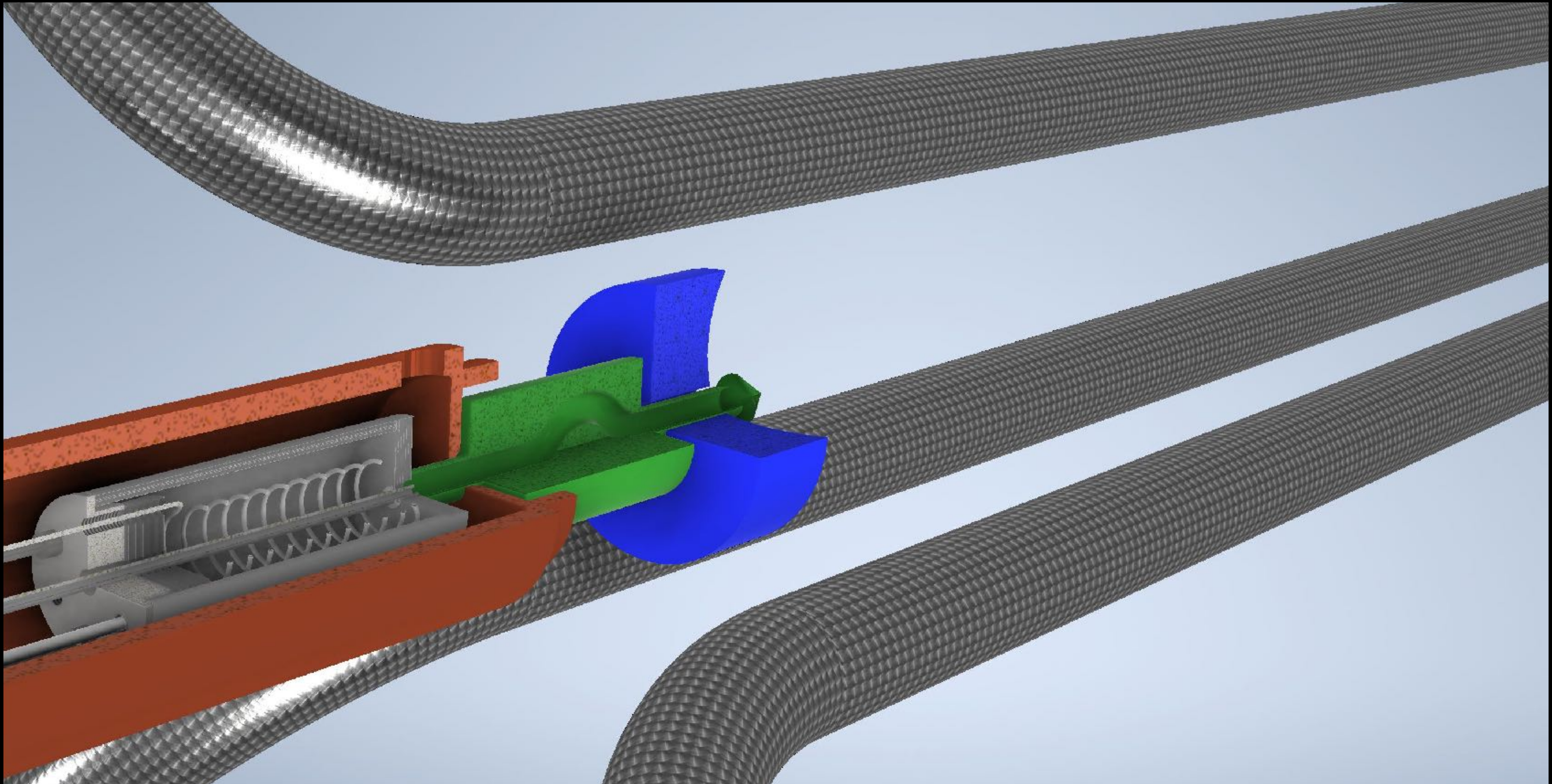
Cooling on Surfaces

- Surface accommodation is good at cooling, but can cause atoms to recombine
- Plan: many bounces on a low-recombination surface, one on a colder high-recombination surface



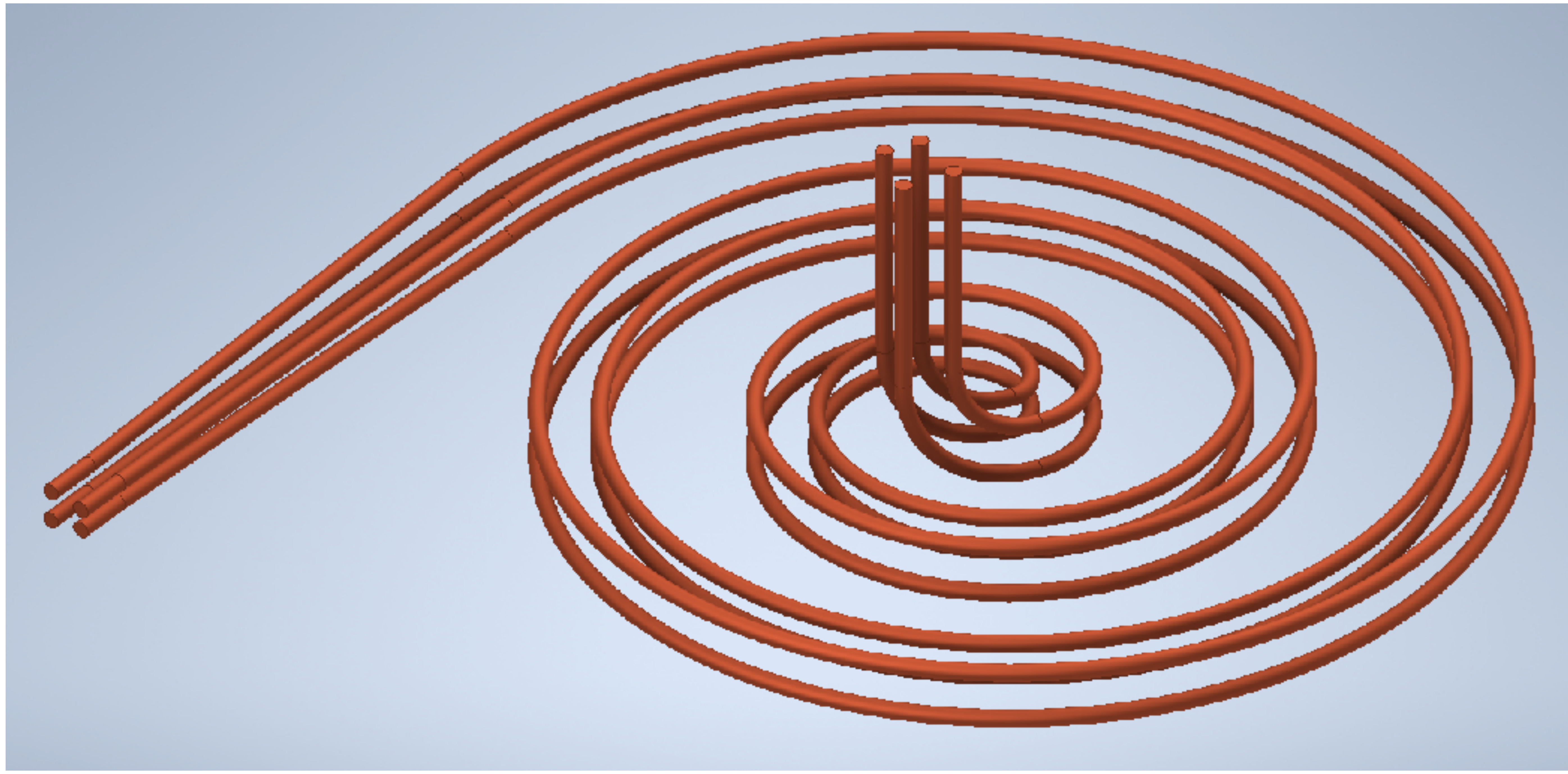


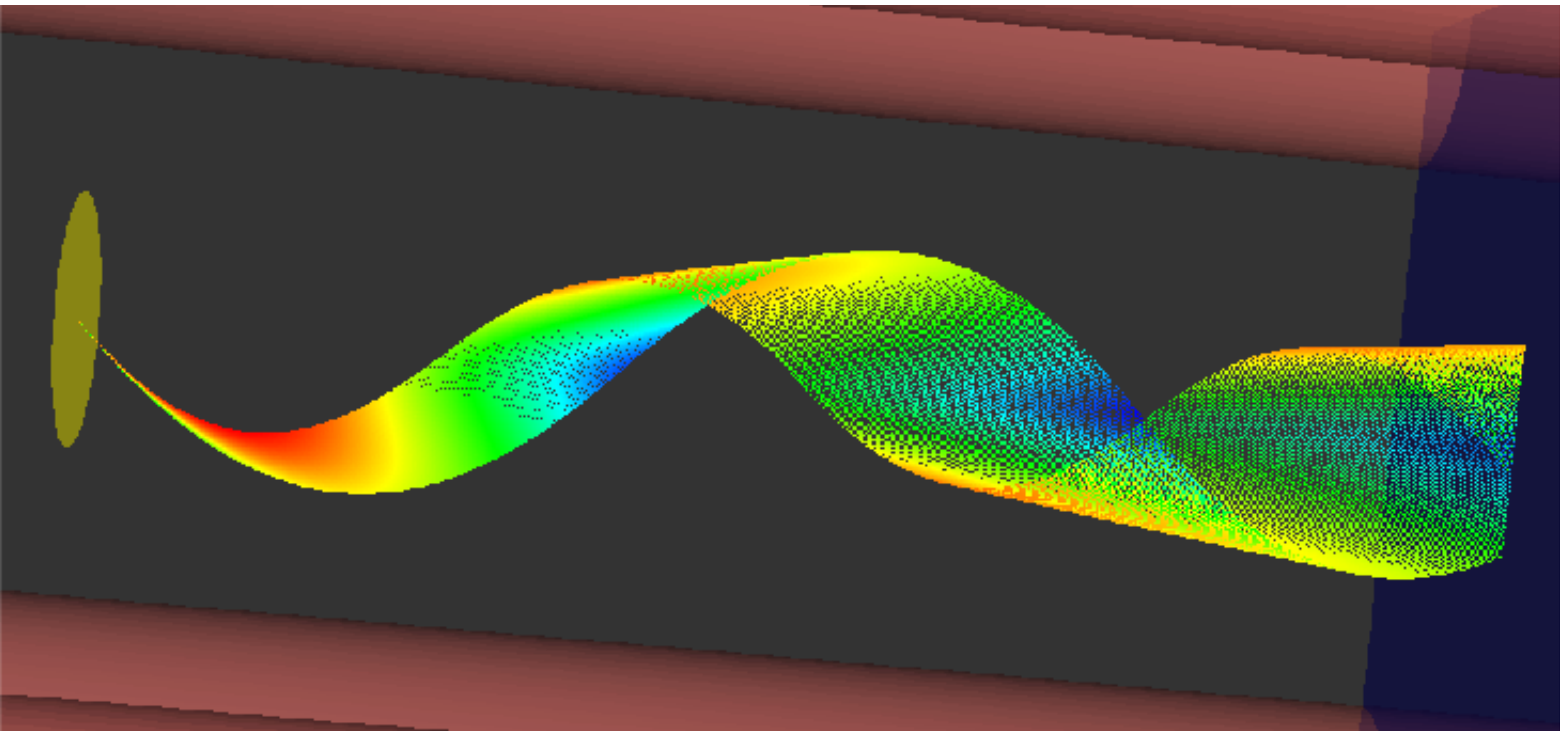
Cooling on Surfaces

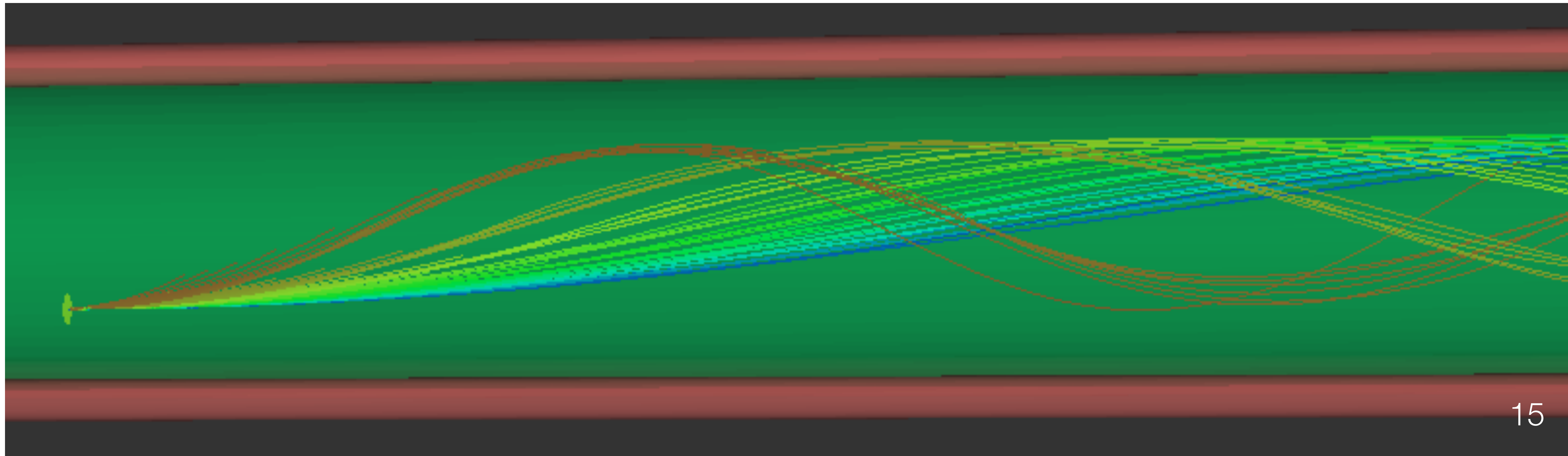


Cooling vs. Slowing

- Evaporation-in-motion cools the transverse temperature
- Bending the guide converts forward momentum to transverse, which can be evaporated; this slows the beam
- Many options: spiral, sinusoidal, or pulsed guide shape with angled or off-center injection
- **See Ben J.'s talk (11:50 Thu.)**







Making Atoms

Who?

- Project 8 has many members and external collaborators working on atomic development
  - Univ. of Washington: accommodator and time-of-flight tests
  - Indiana Univ. - Bloomington: ECR atom source
  - Univ. of Texas - Arlington: test beam production and laser thermometry with lithium **Ben J.'s talk (11:50 Thu.)**
  - Tritium Laboratory Karlsruhe: building a parallel test stand for tritium validation
  - Johannes Gutenberg Univ. Mainz: high-flow atom source measurements **This talk**
- Only possible thanks to many others working on the rest of Project 8 **Juliana S.'s talk (9:00 Wed.)**

PROJECT 8

UNIVERSITY of WASHINGTON

INDIANA UNIVERSITY

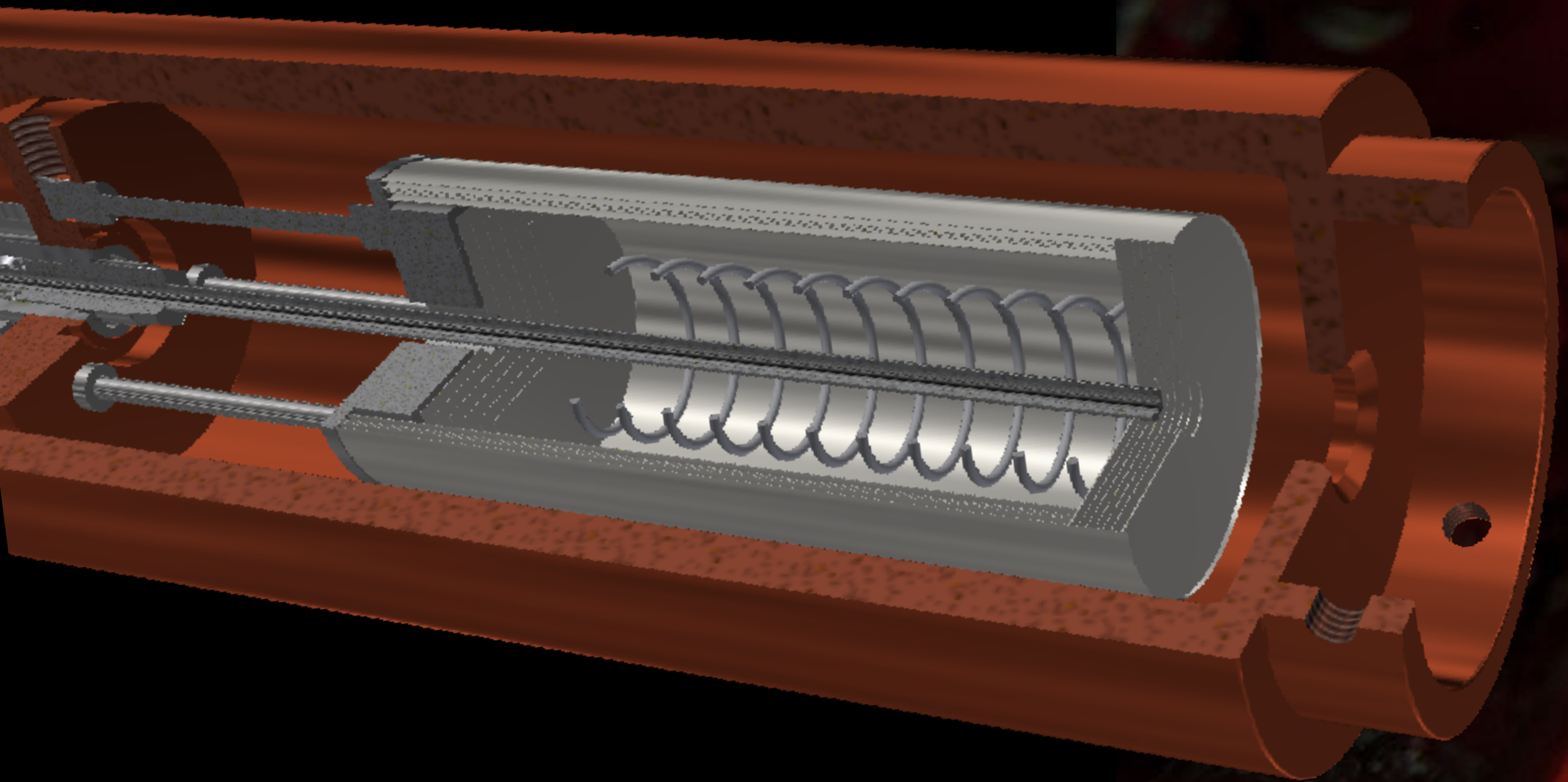
UNIVERSITY OF TEXAS ARLINGTON

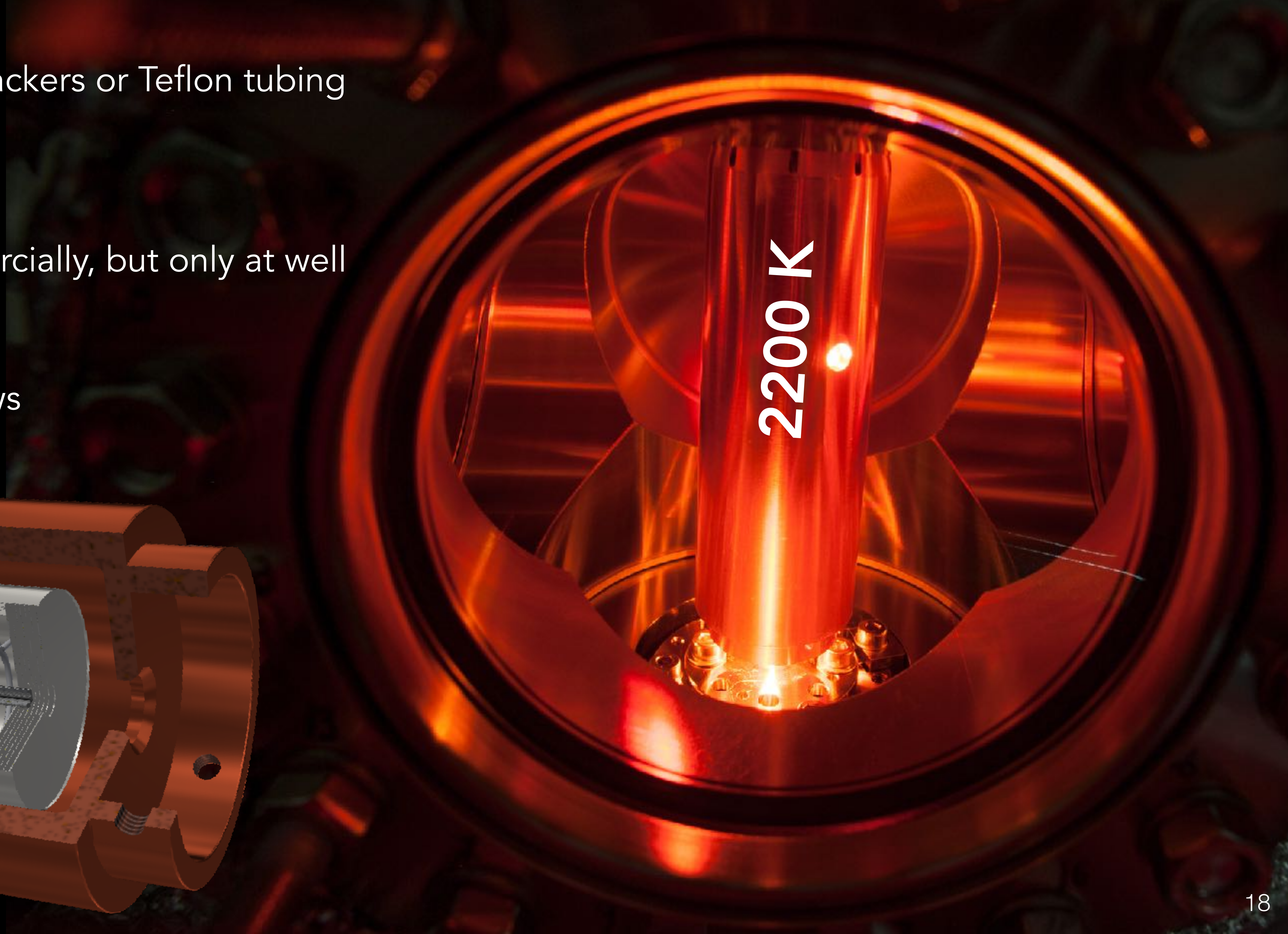
TLK Tritium Laboratory Karlsruhe

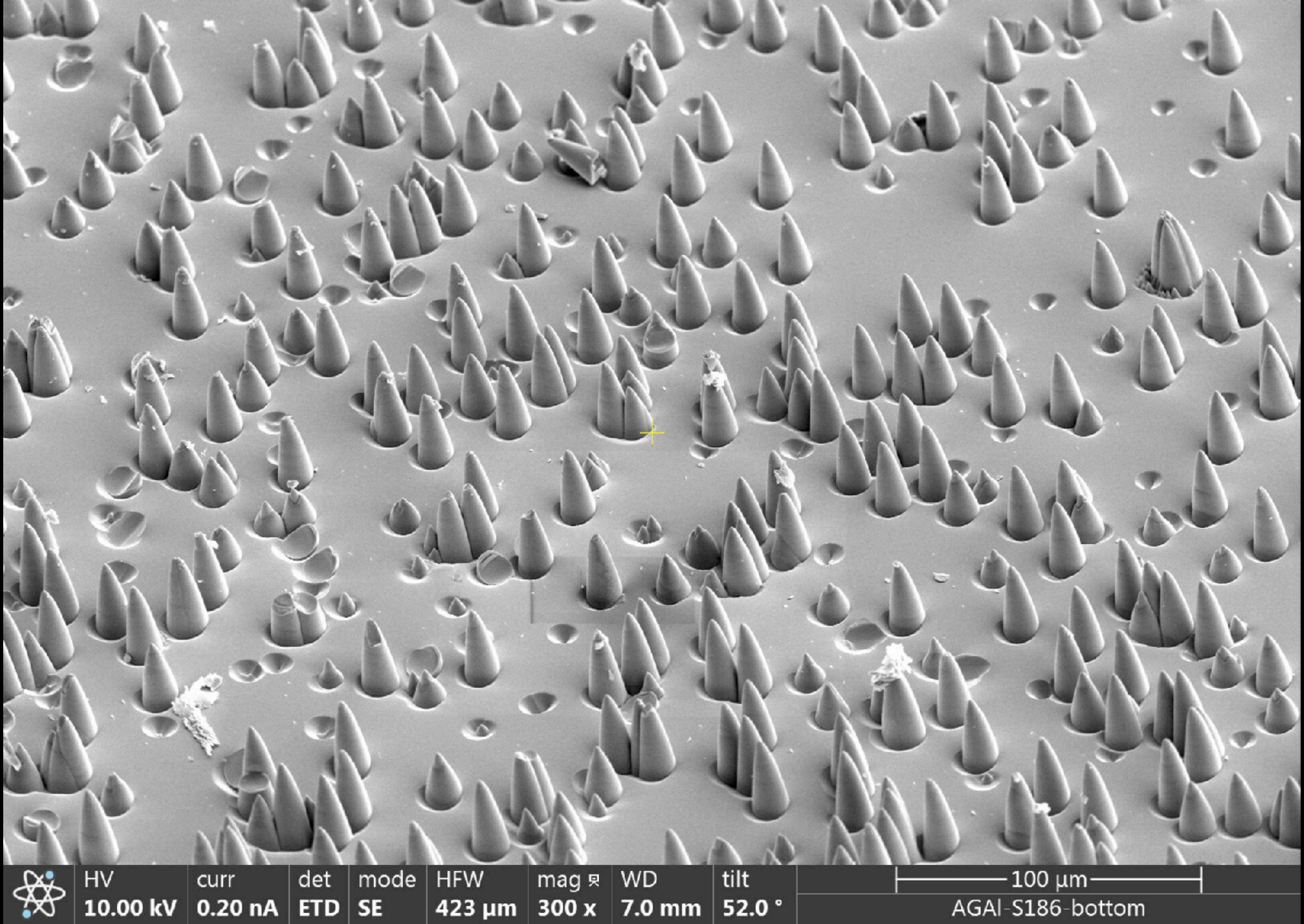
JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U

High-Flow Atomic Tritium

- Can't use glass RF/microwave crackers or Teflon tubing
- Need all-metal atom source
- Exist in the literature and commercially, but only at well below the flow we need
- Literature models fail at high flows





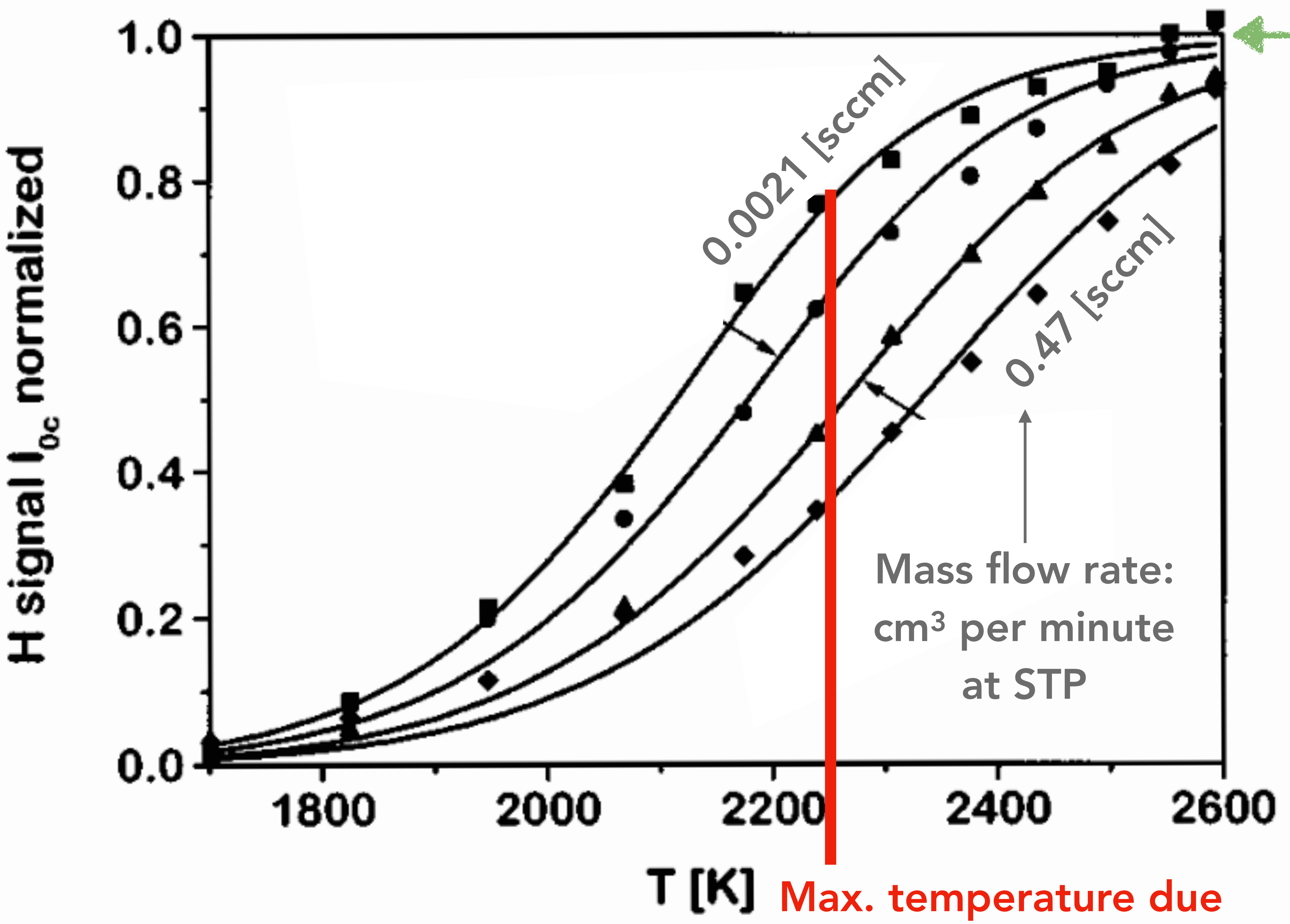


https://www.esa.int/ESA_Multimedia/Images/2024/01/Micro-world_within_atomic_clock

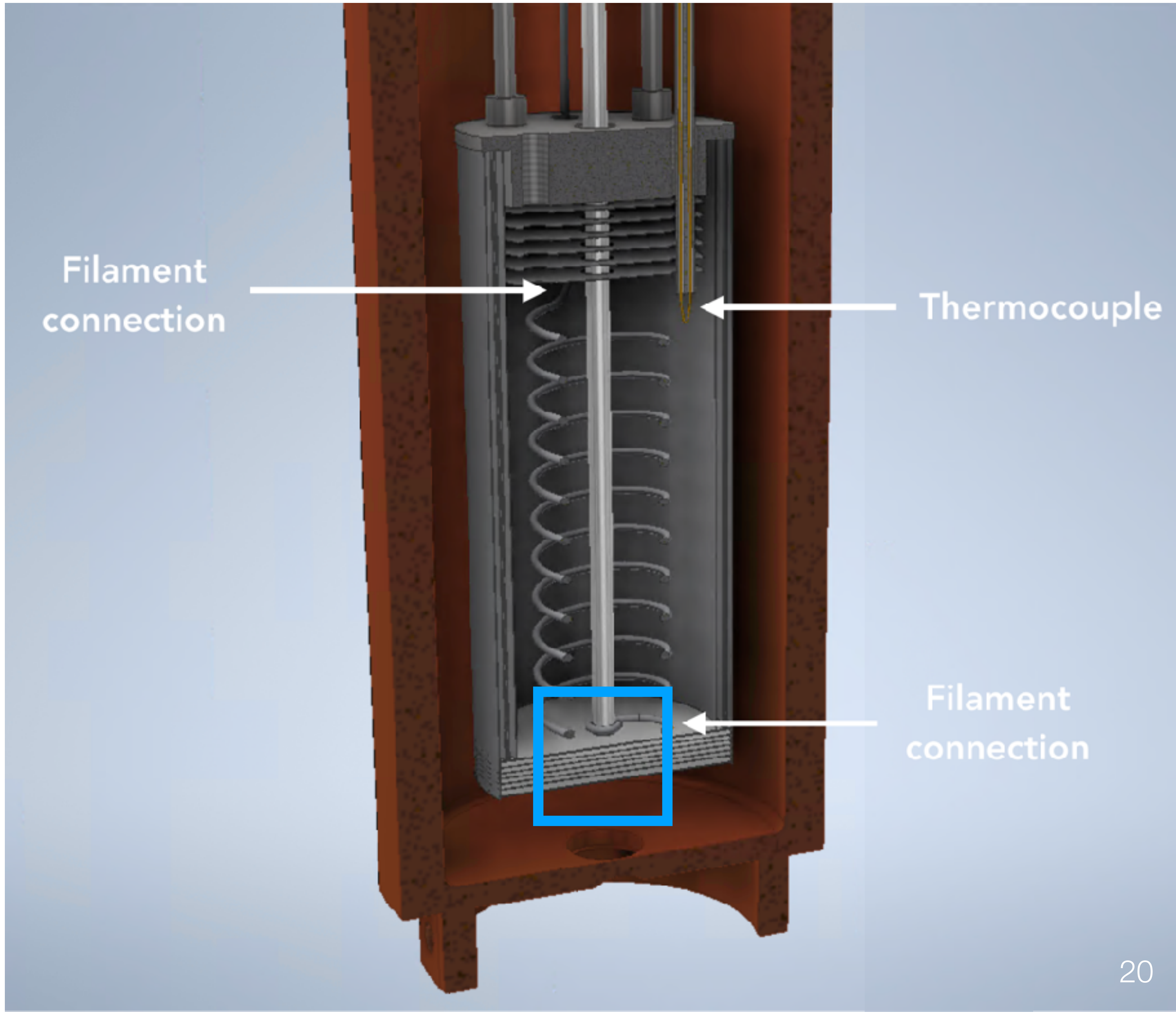
Thermal Cracker

$$\alpha \equiv \frac{n_{\mathrm{atom}}}{n_{\mathrm{atom}} + n_{\mathrm{mol.}}}$$

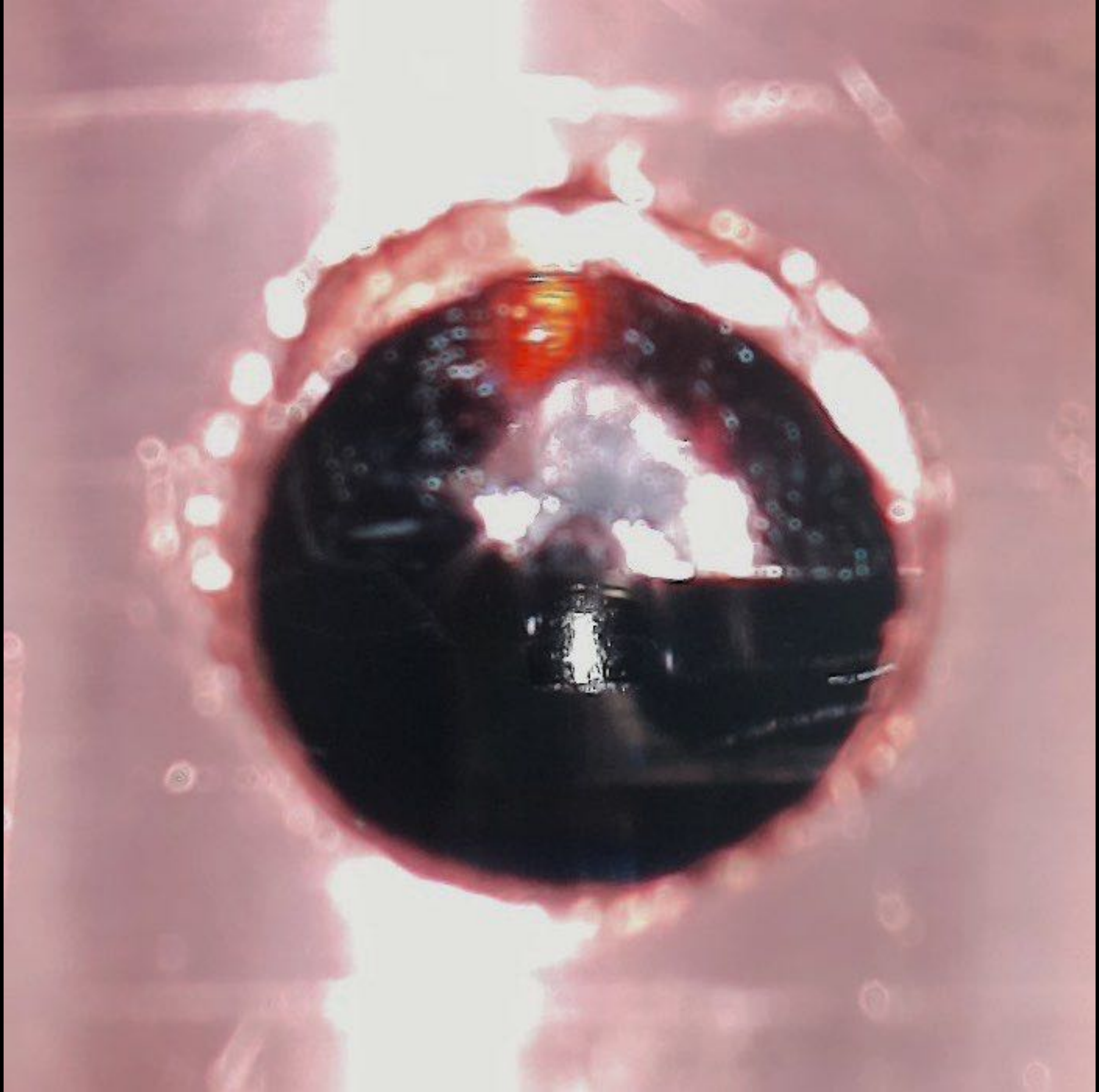
Plateau at 100% dissociation: α = 1

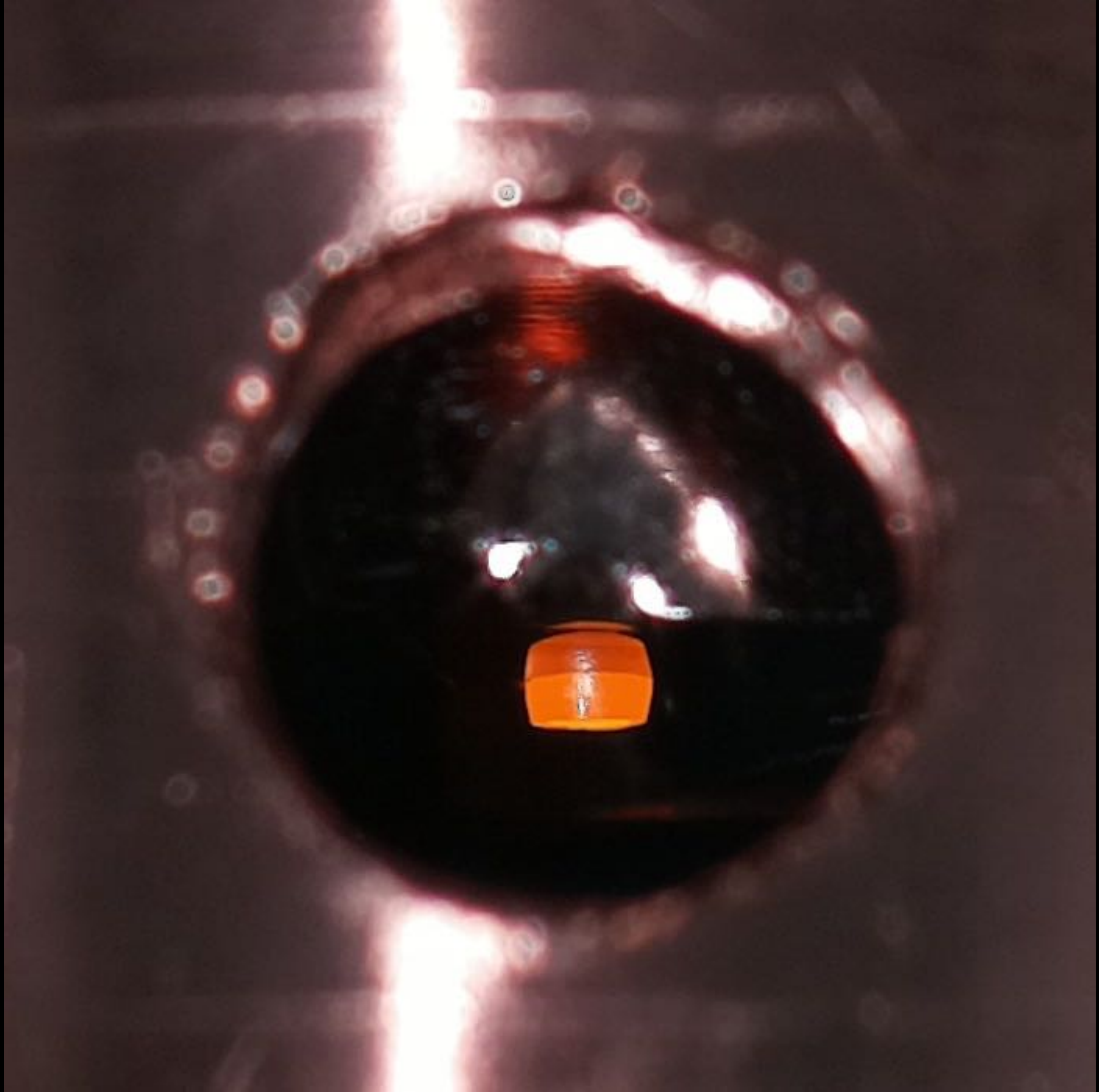


Max. temperature due to thermocouple insulation

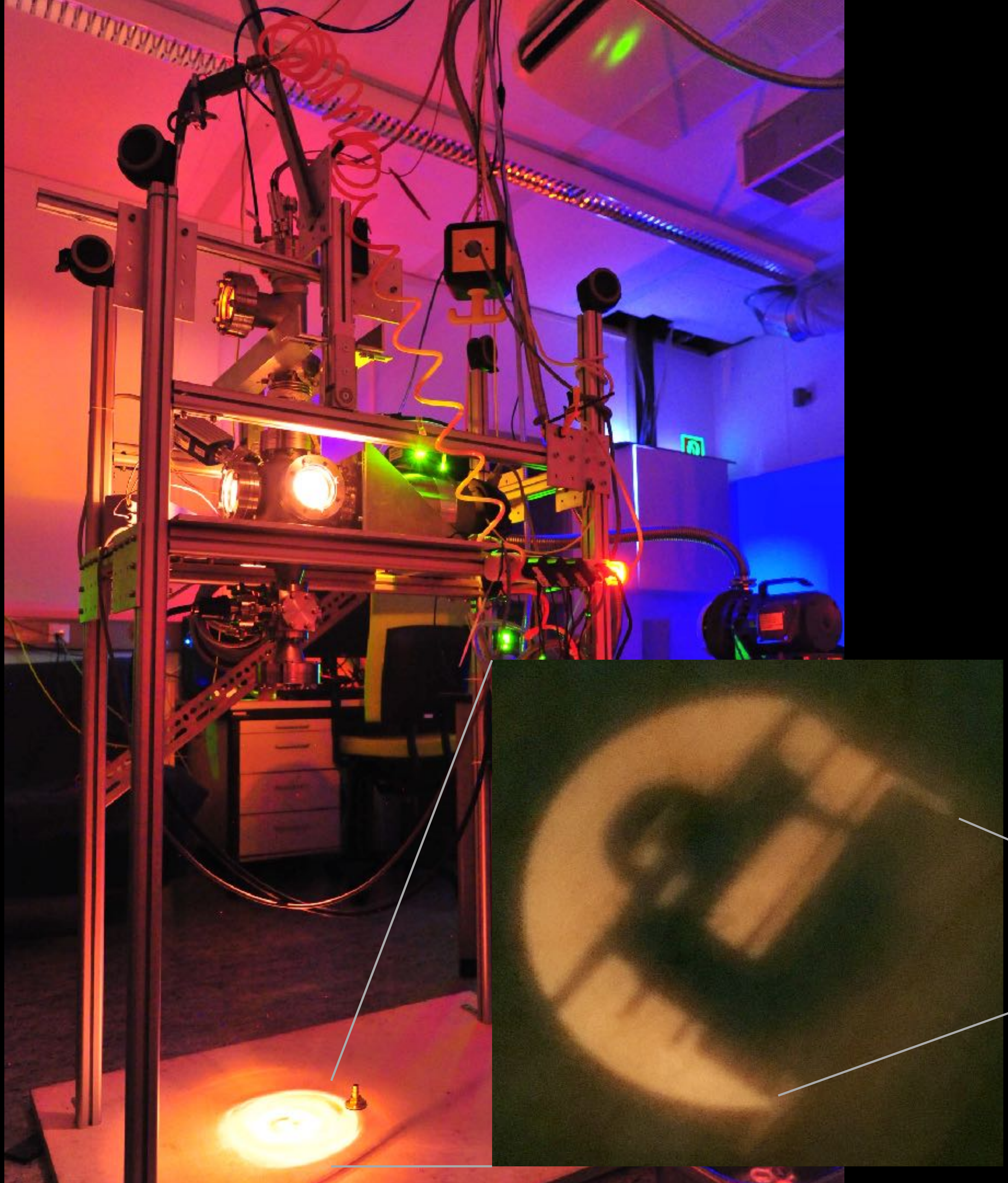


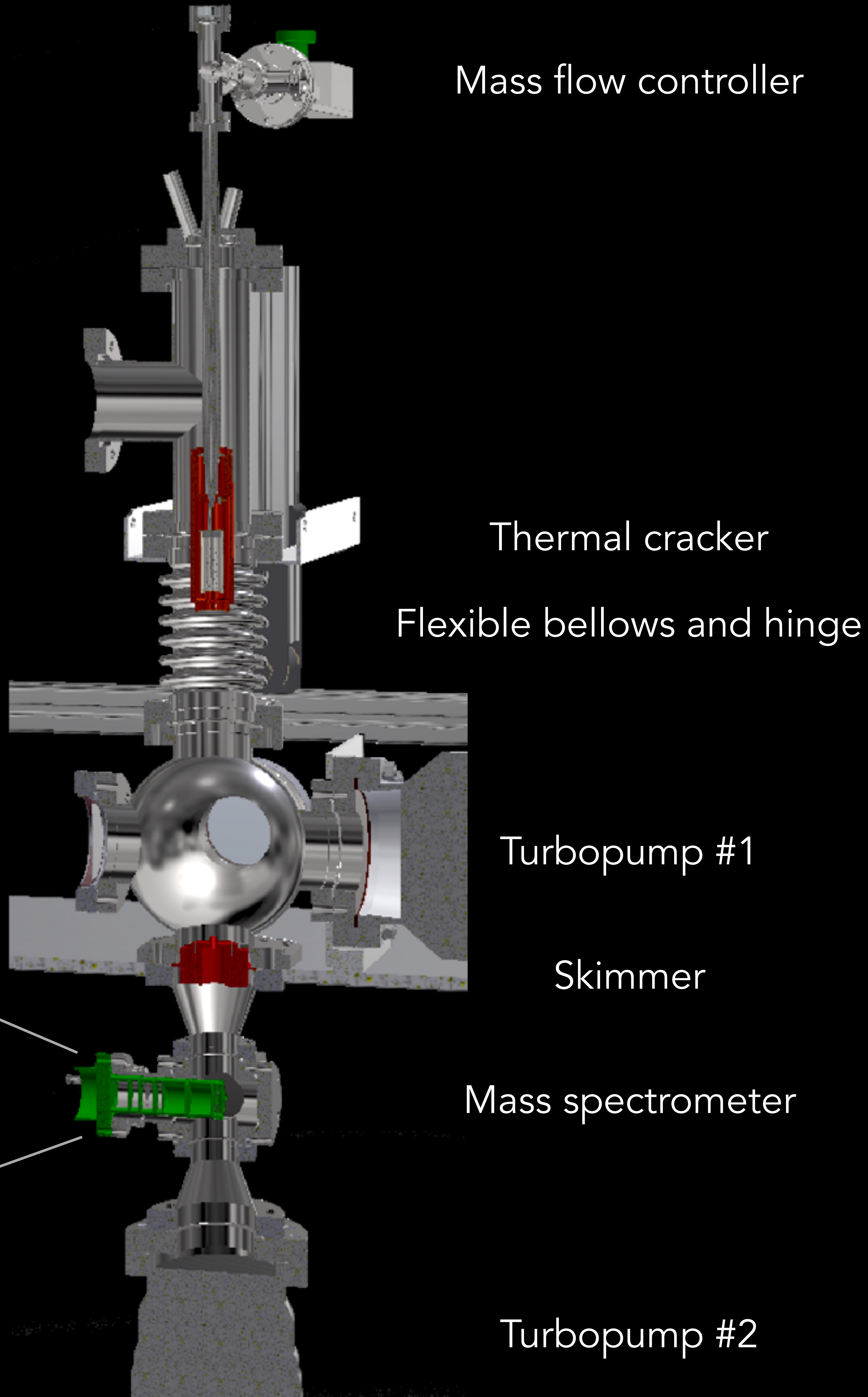
K. G. Tschersich, Journal of Applied Physics 87, 2565 (2000); doi: 10.1063/1.372220





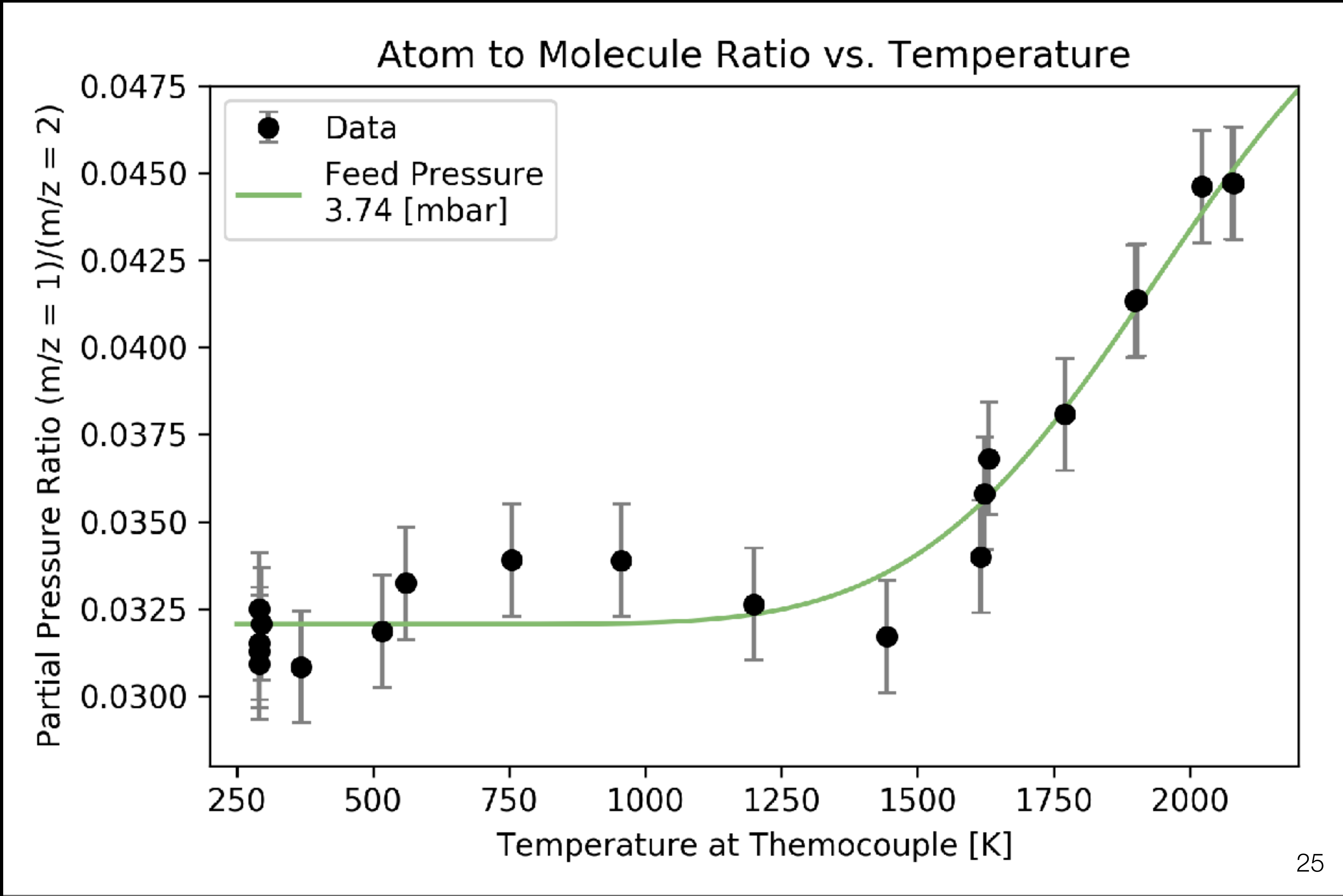
Mainz Atomic Test Stand: 2018-02





Intermediate Results

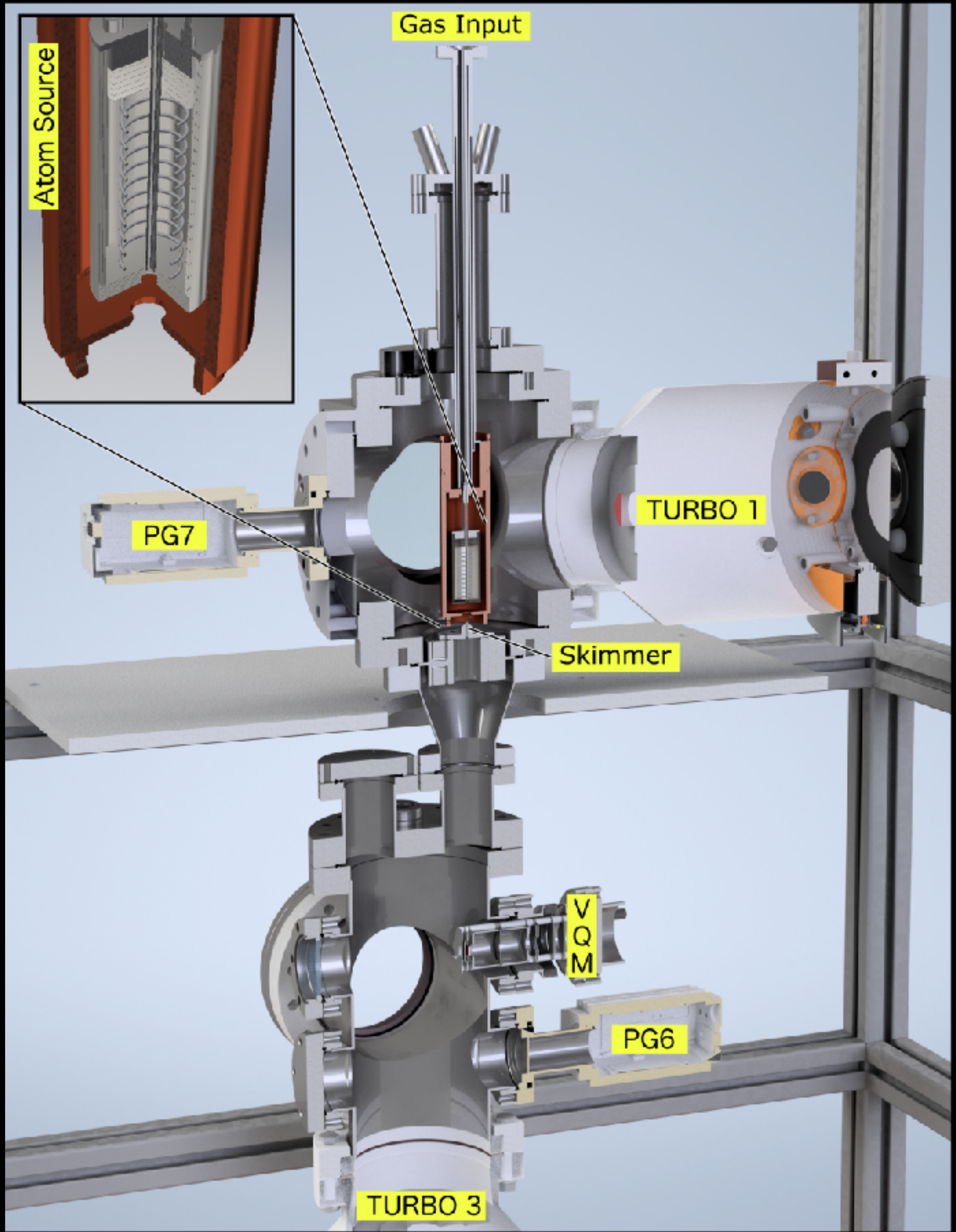
- We see an atom signal
  - But with low SNR
- What can we change?

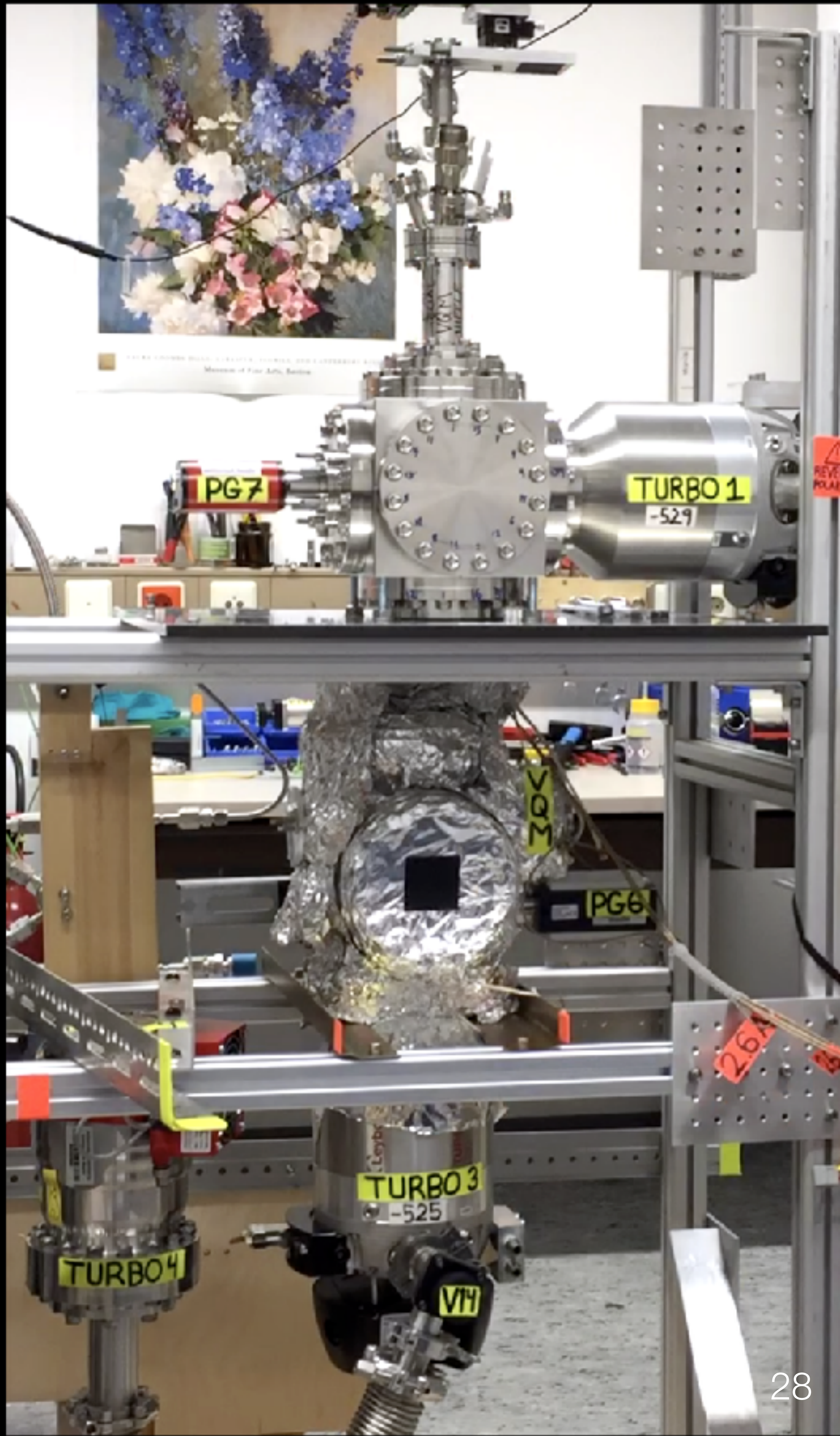



TURBO 1


PG7
TURBO 1
SOUTH

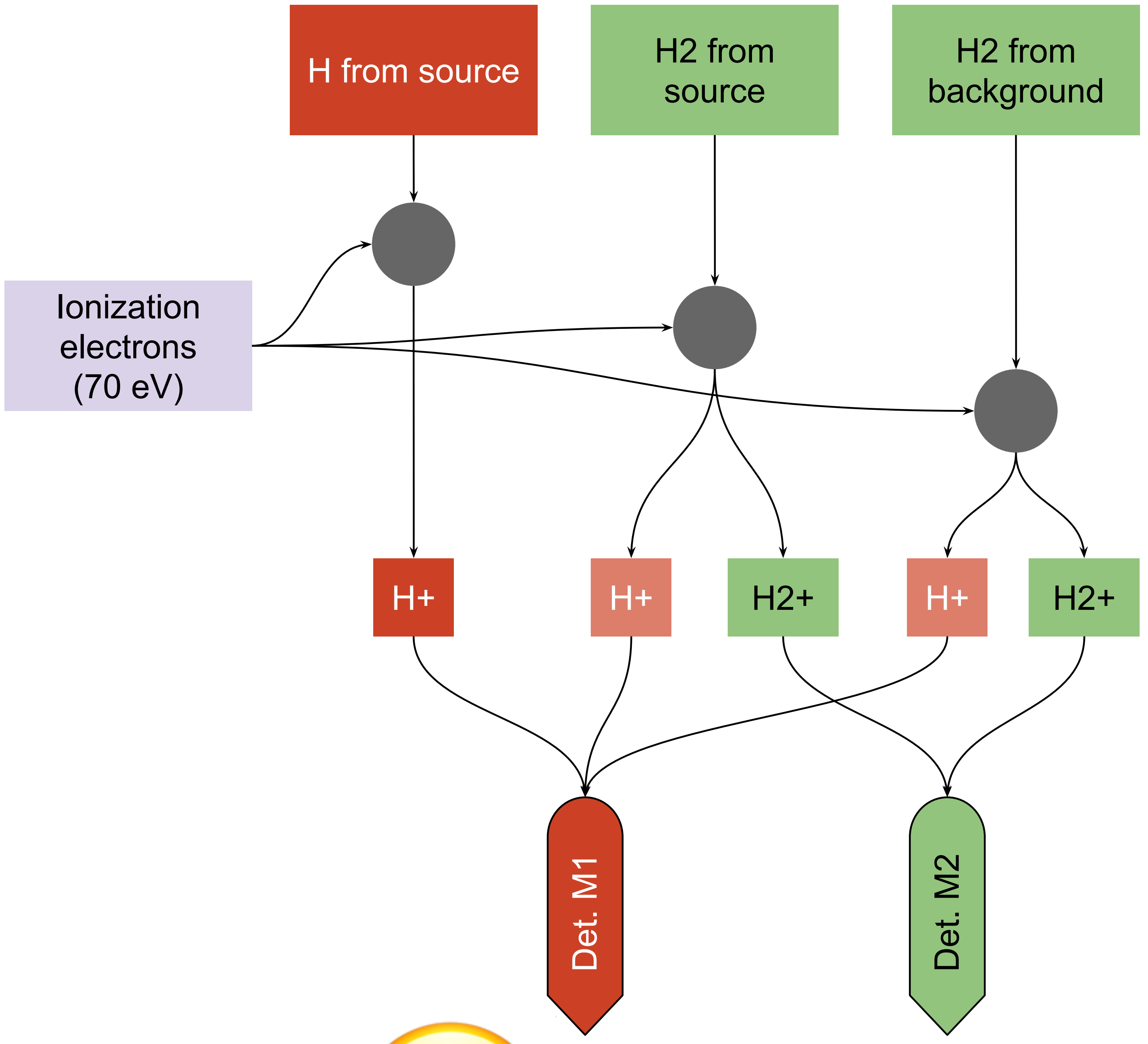
Mainz Atomic Test Stand: 2020



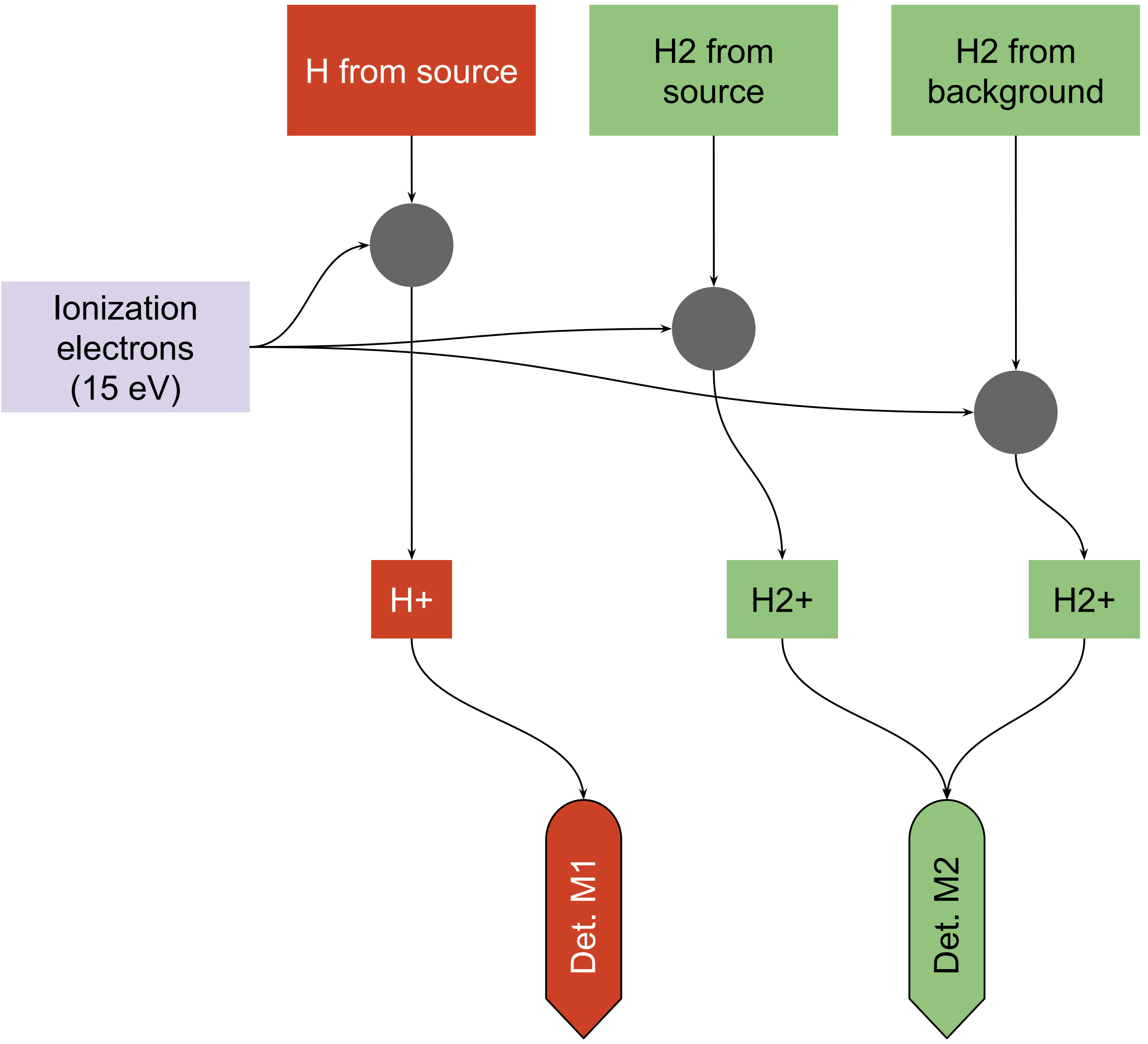


Selectively Detecting Atoms

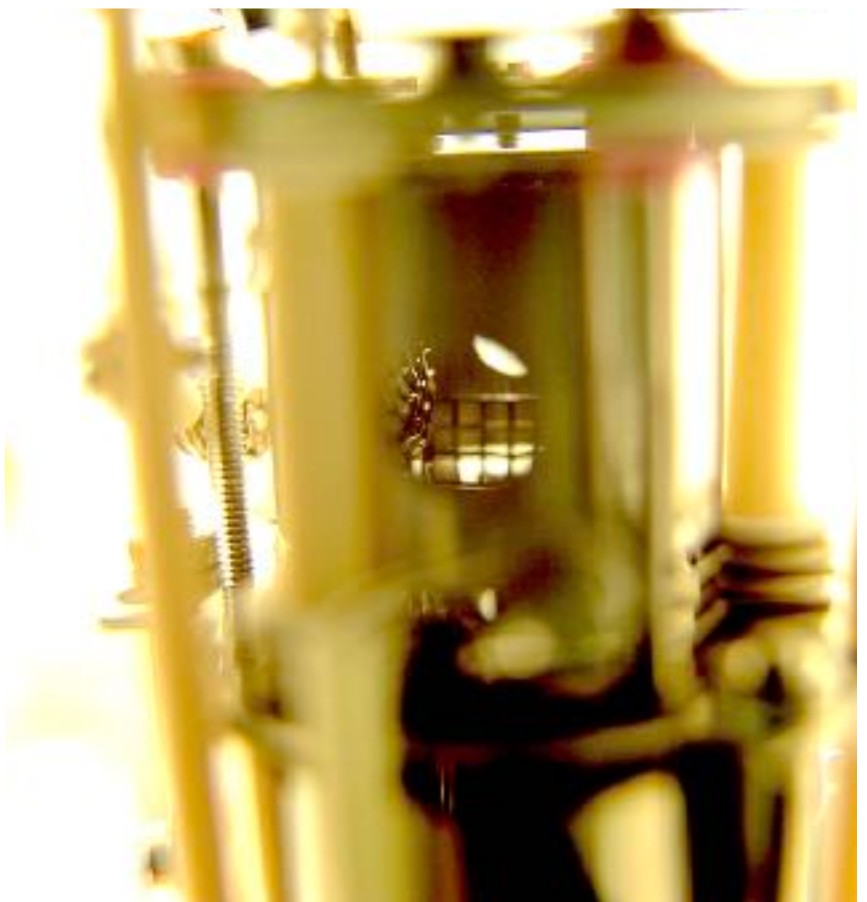
Typical Electron Energy



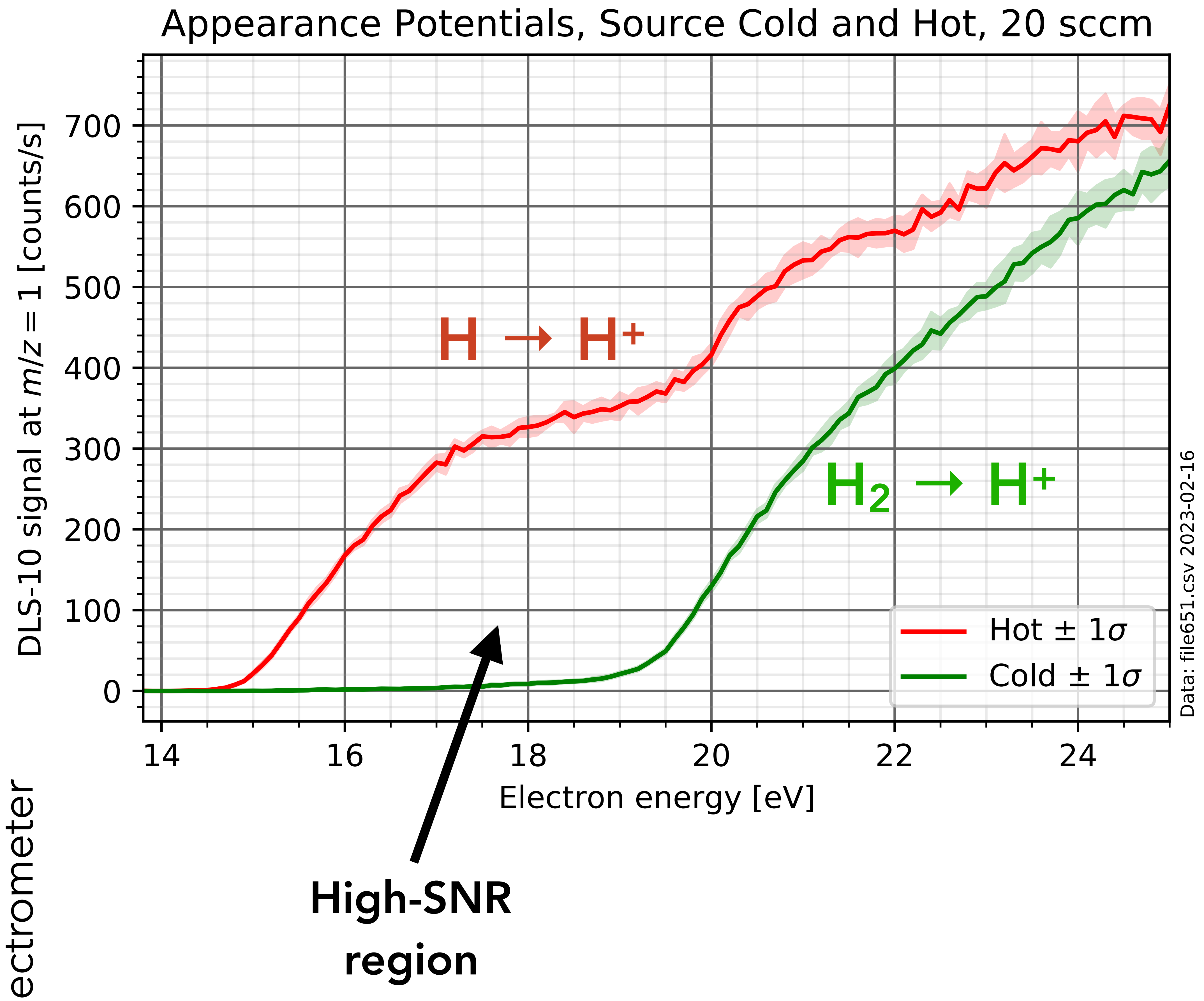
Low Electron Energy

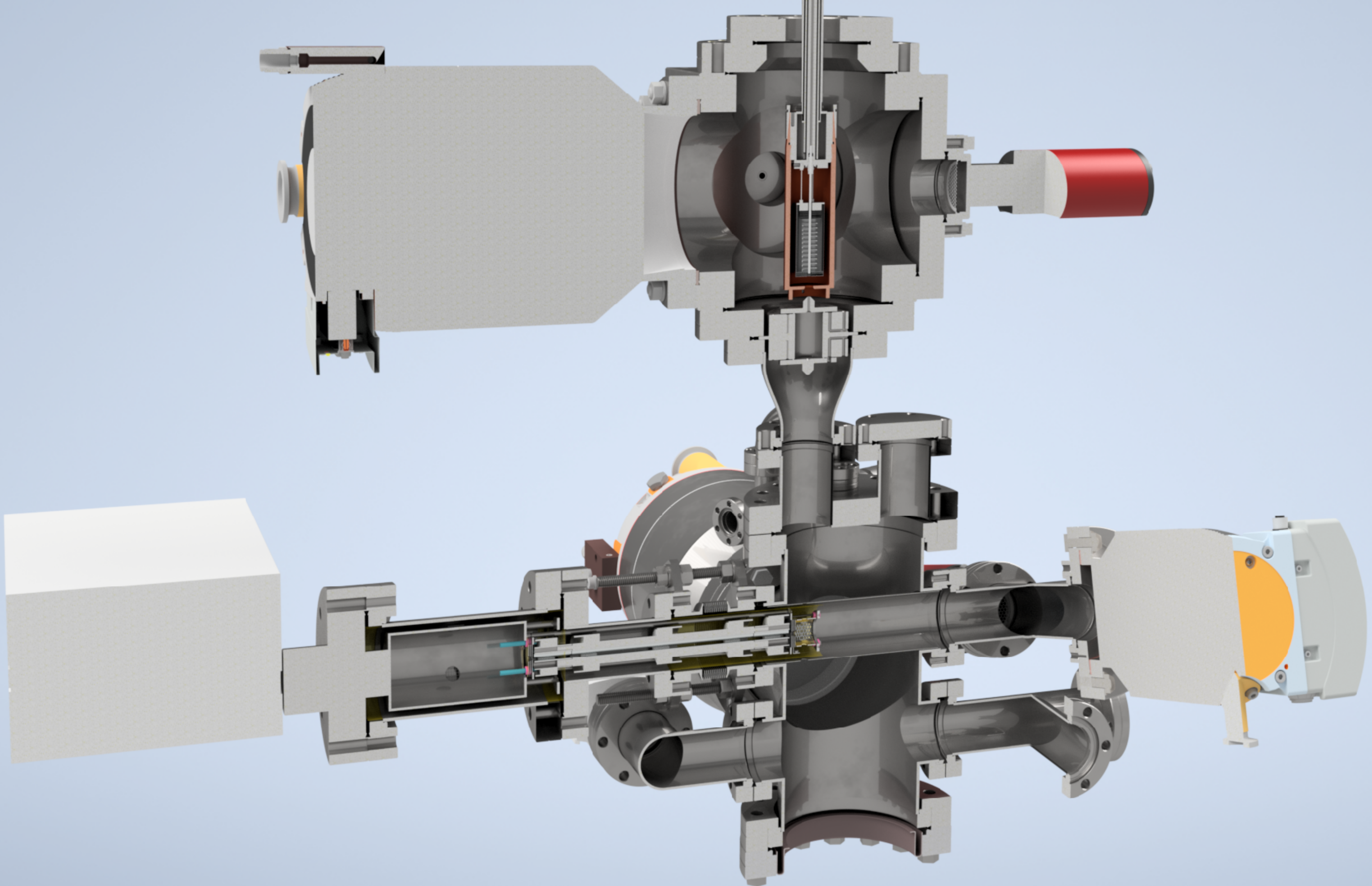


Solution: employ a detector that can unambiguously count H atoms from the beam →



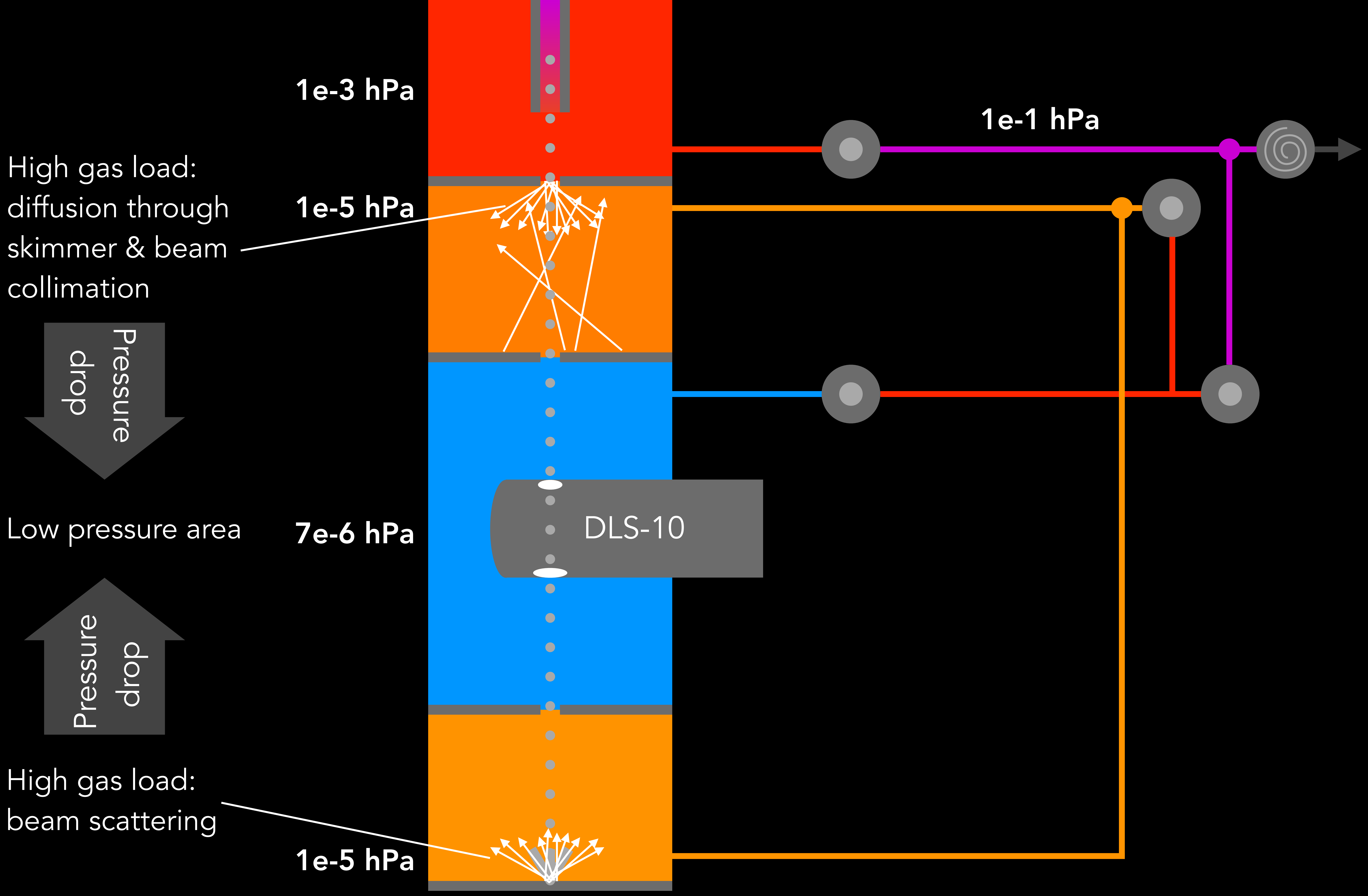
The Hiden DLS-10 mass spectrometer



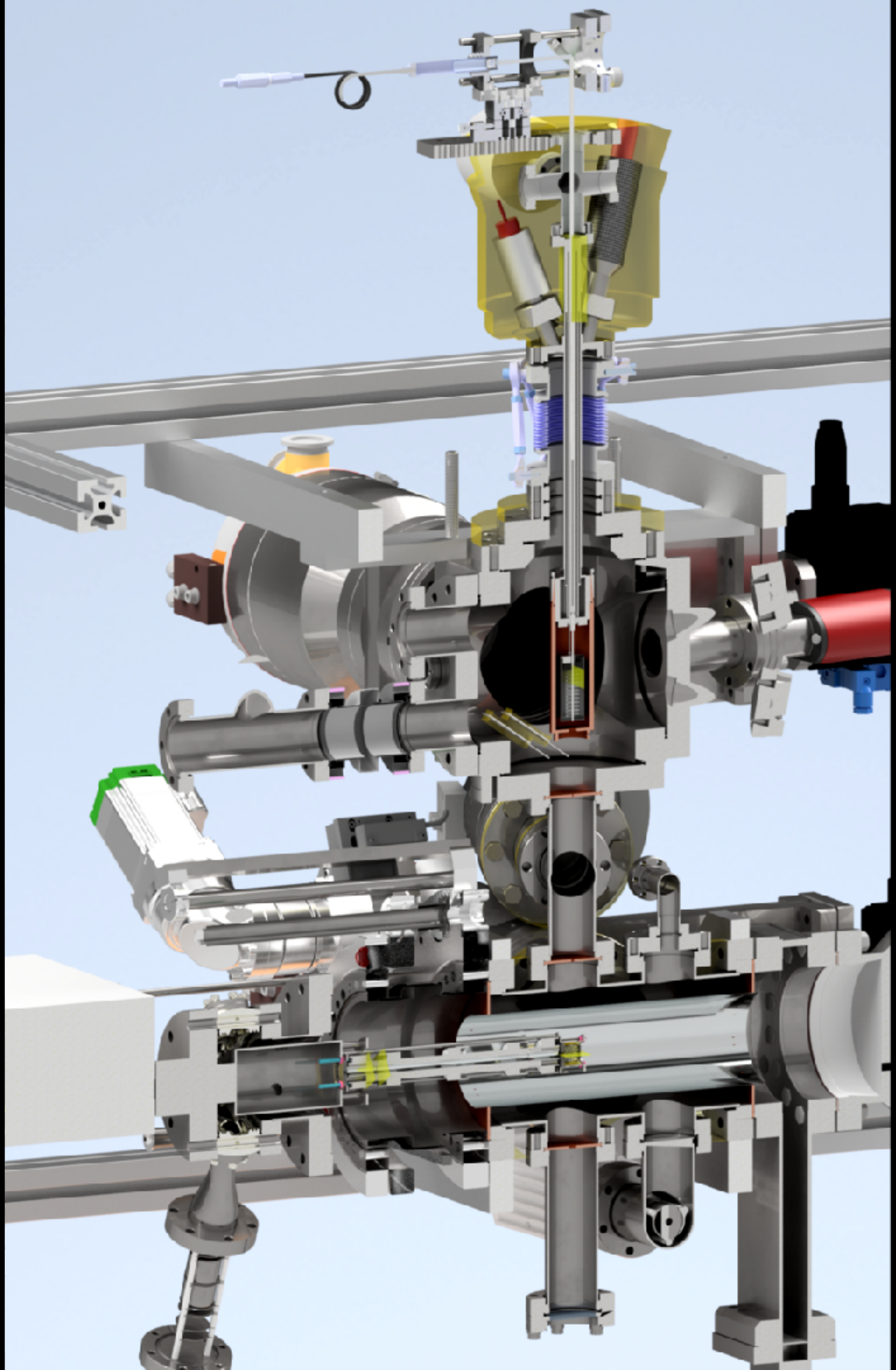


Symmetry

- Gas loads raise local pressures
- Skimmers create pressure drops
- Doesn't matter where gas comes from
- Pumping problem is symmetric top and bottom



Molflow+ 2.8.5 (Dec 17 2020) [interior volume of 2022-03-13 new chamber layout - medium res run 5.zip]
Paper in preparation
Texture Scaling
Profile plotter
Source chamber
Skimmer 1-2
Beam dump
Lower chamber
Interior of shroud
Atom source
Skimmer 1
Skimmer 2
Shroud
DLS-10 mass spectrometer
Sk. 3
Beam dump
Detection region
Intense beam
Low background density



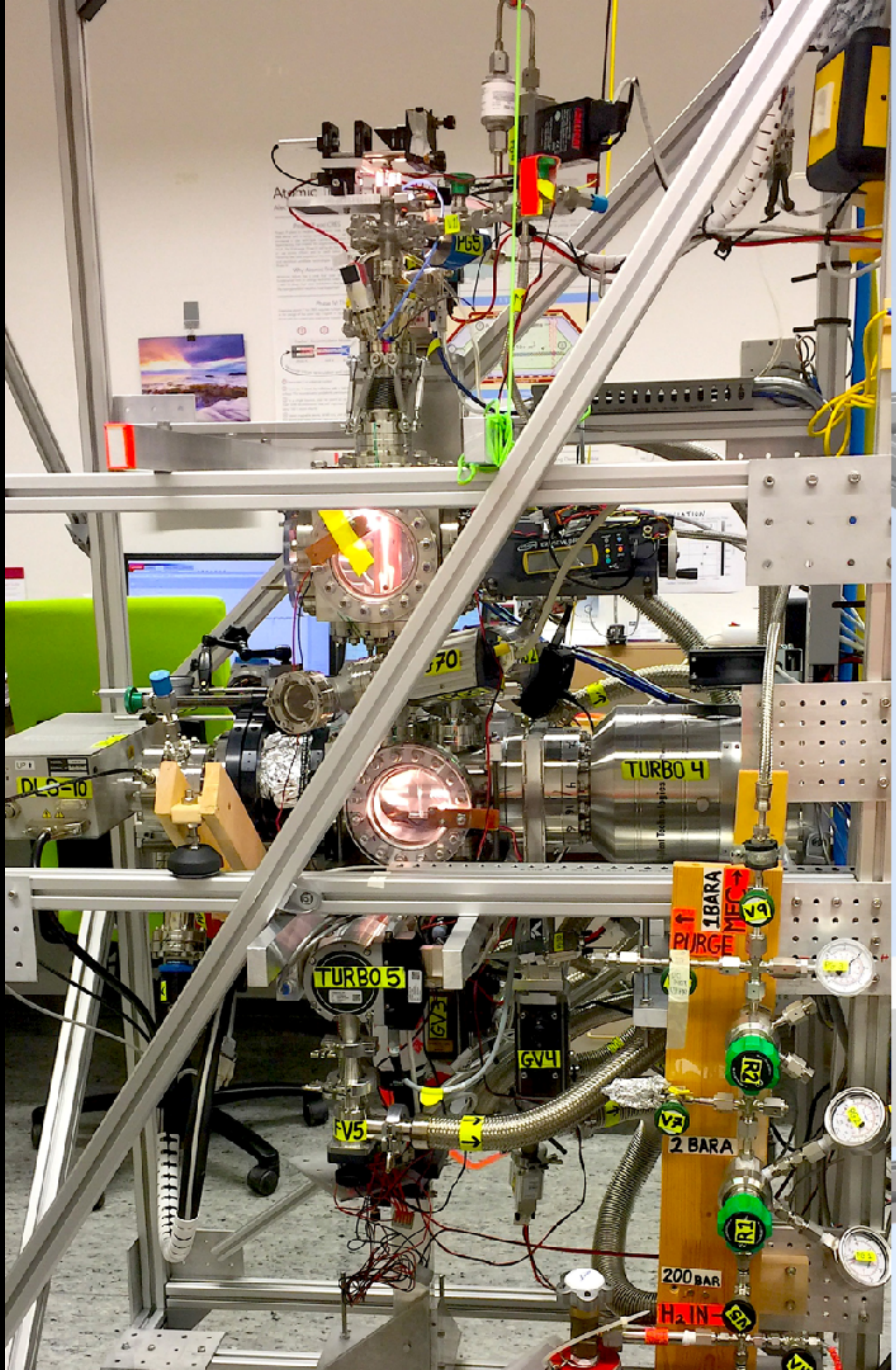

PNEUMATICS
DLS-10
VCR

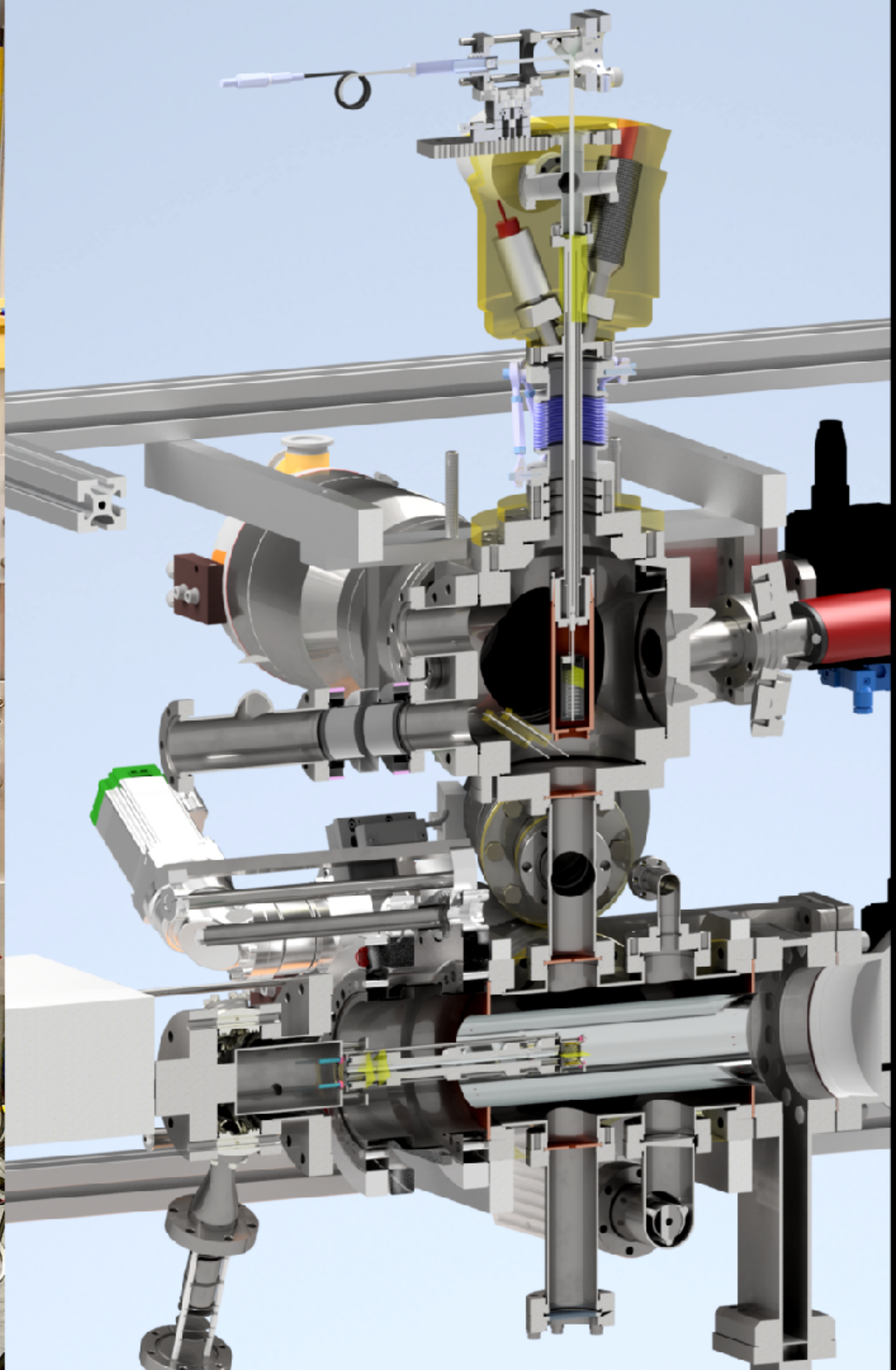

Atomic Tritium: Phase IV of Project 8
PNEUMATICS
DLS-10
VCR


PNEUMATICS
DLS-10
VCR

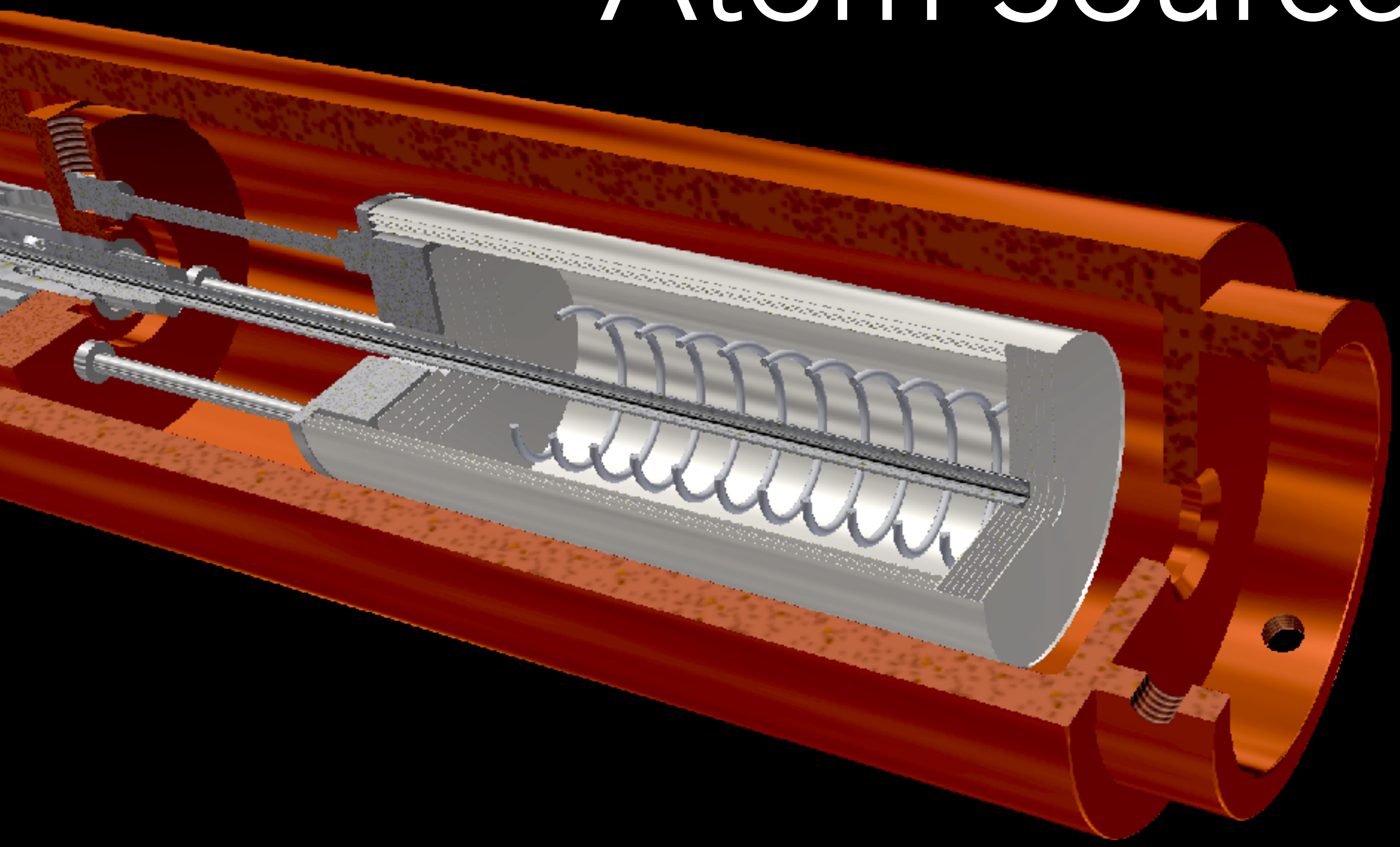

PLEASE REMOVE
SHIPPING HOUSING
ALUFOLIE
2 BARA

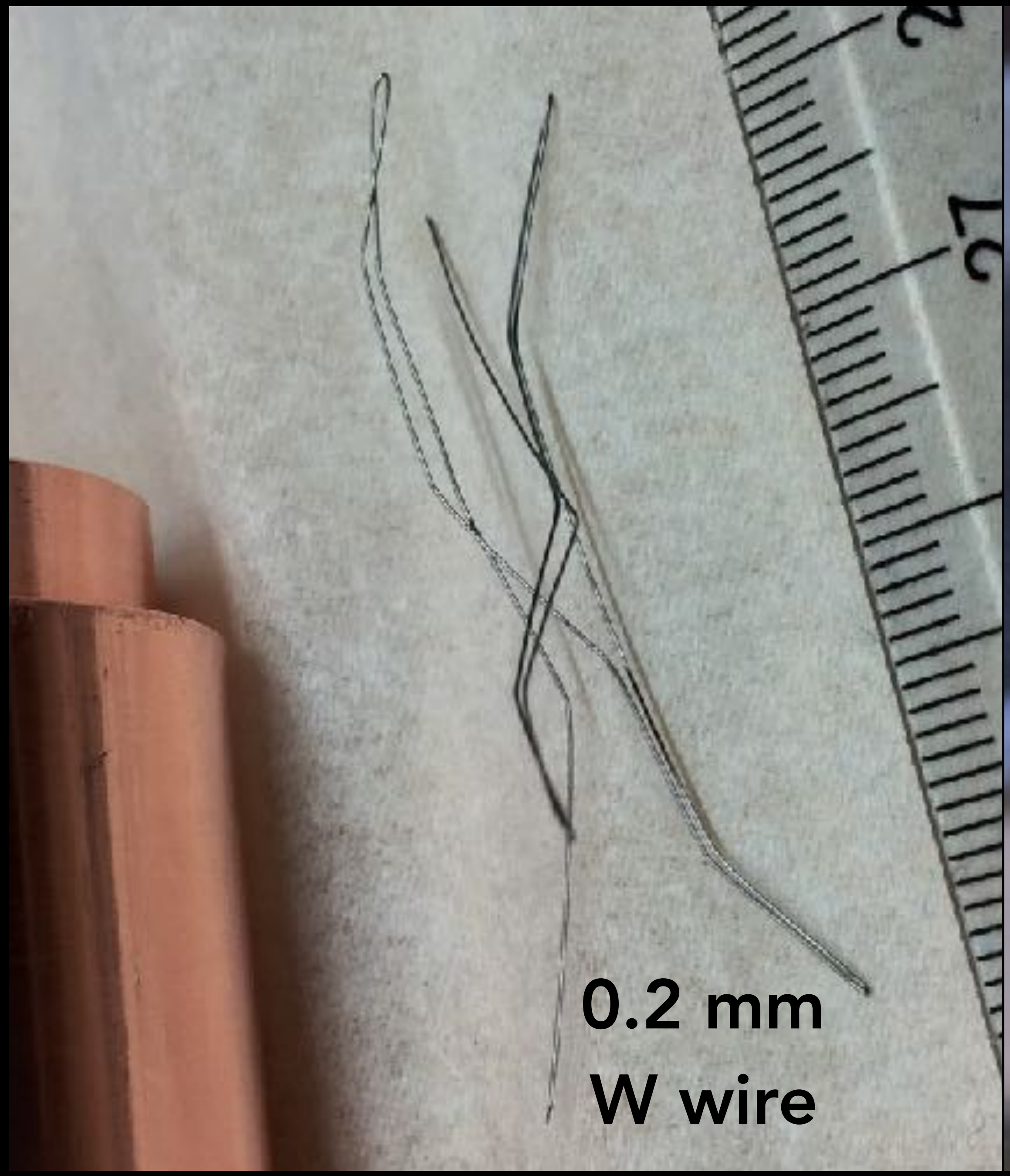
Mainz Atomic Test Stand: 2022

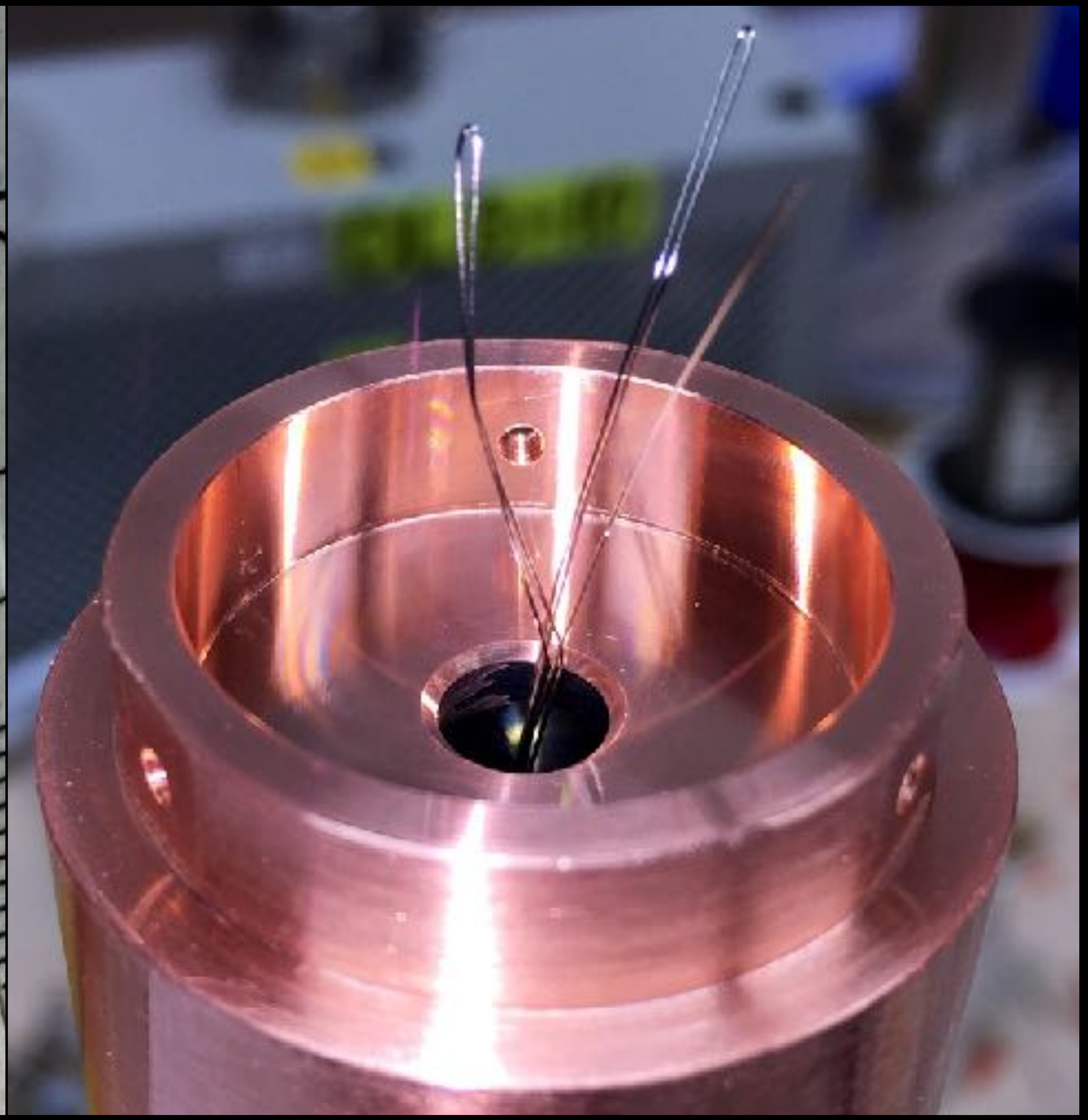




Atom Source Modification

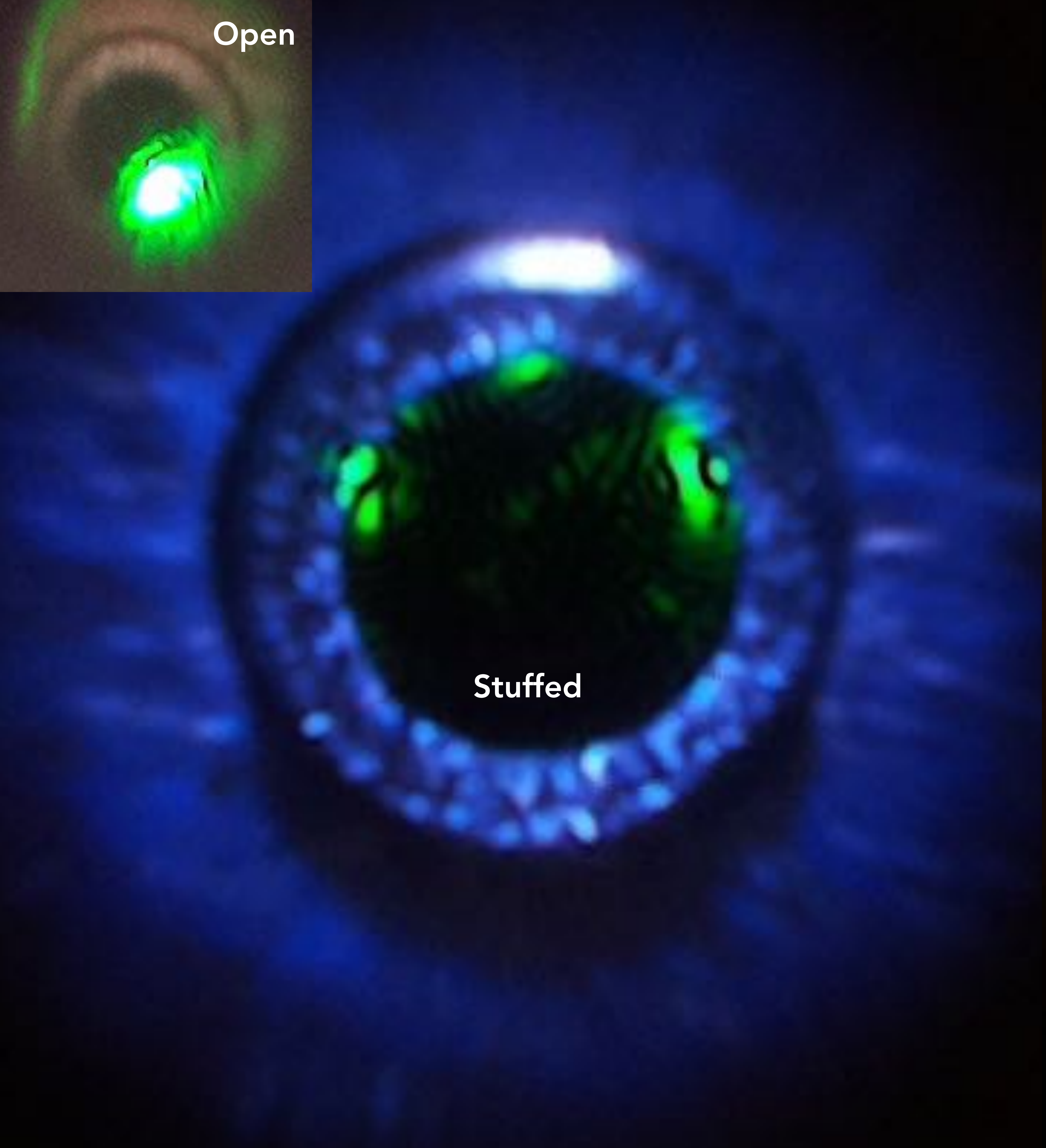
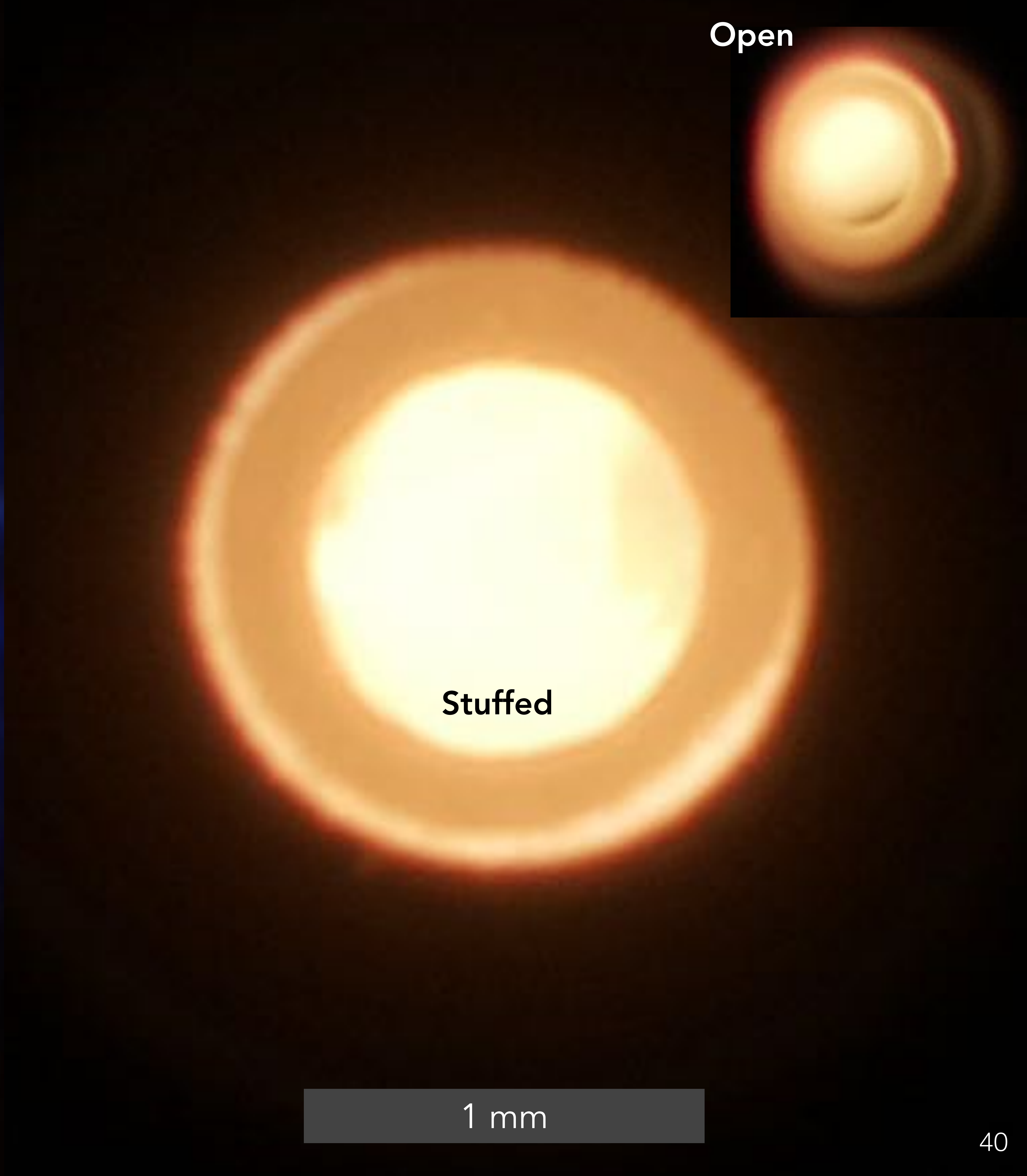






Low efficiency at high flow: gas-gas collisions prevent some molecules from touching the hot capillary wall

A bundle of tungsten wires forces more gas-surface collisions (higher Knudsen number); should boost efficiency at high flow


Open
Stuffed

Open
Stuffed
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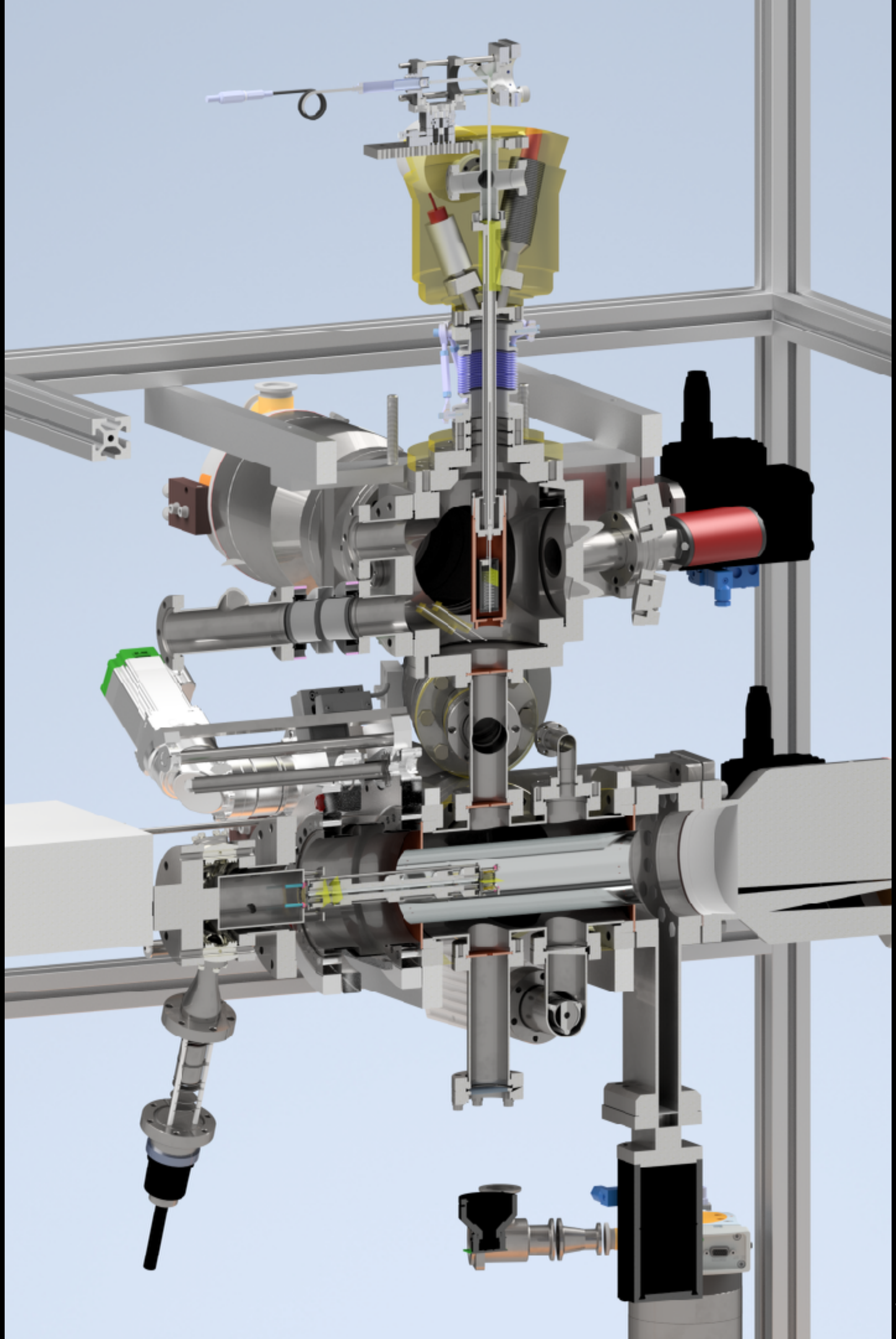
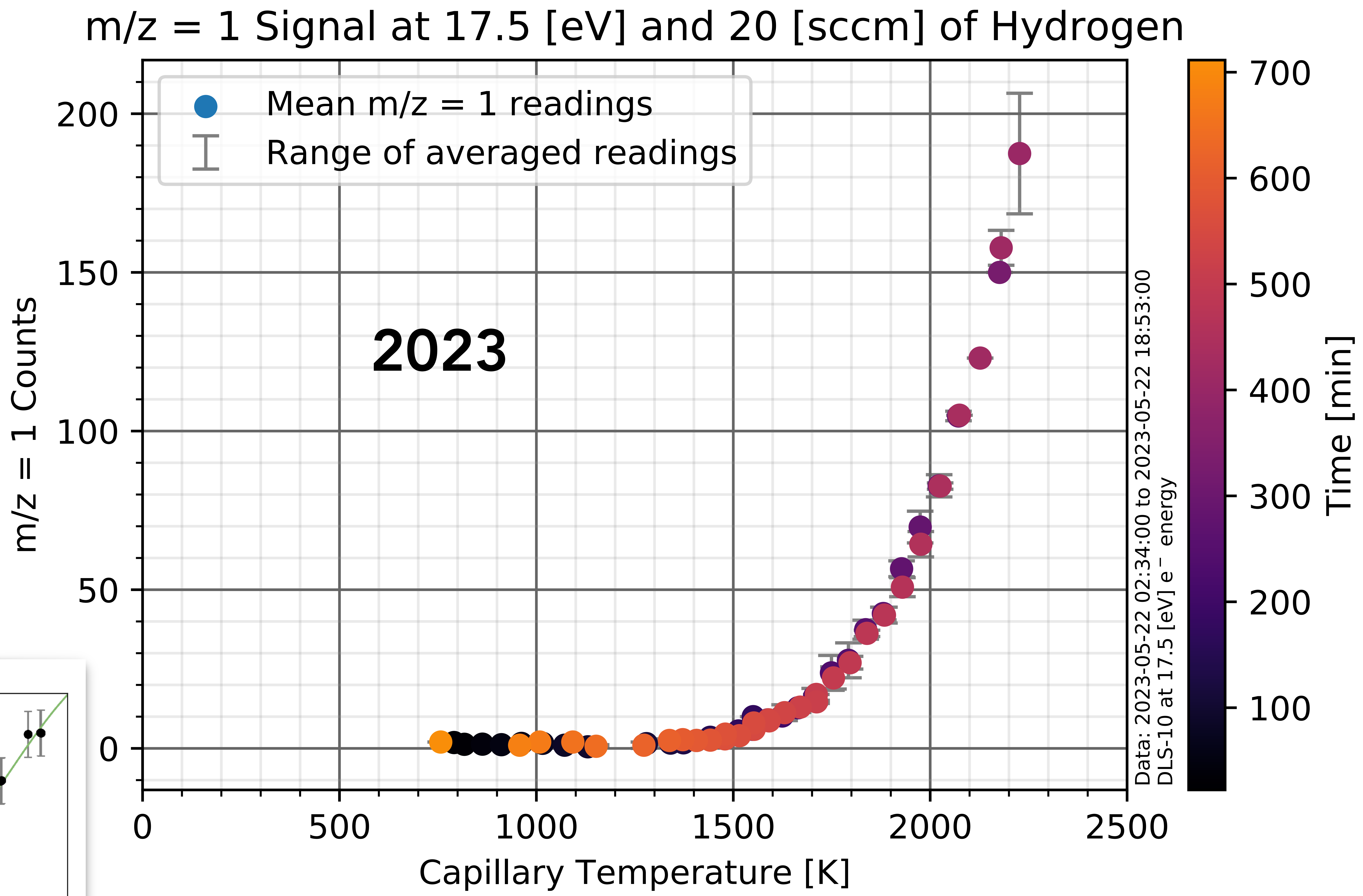
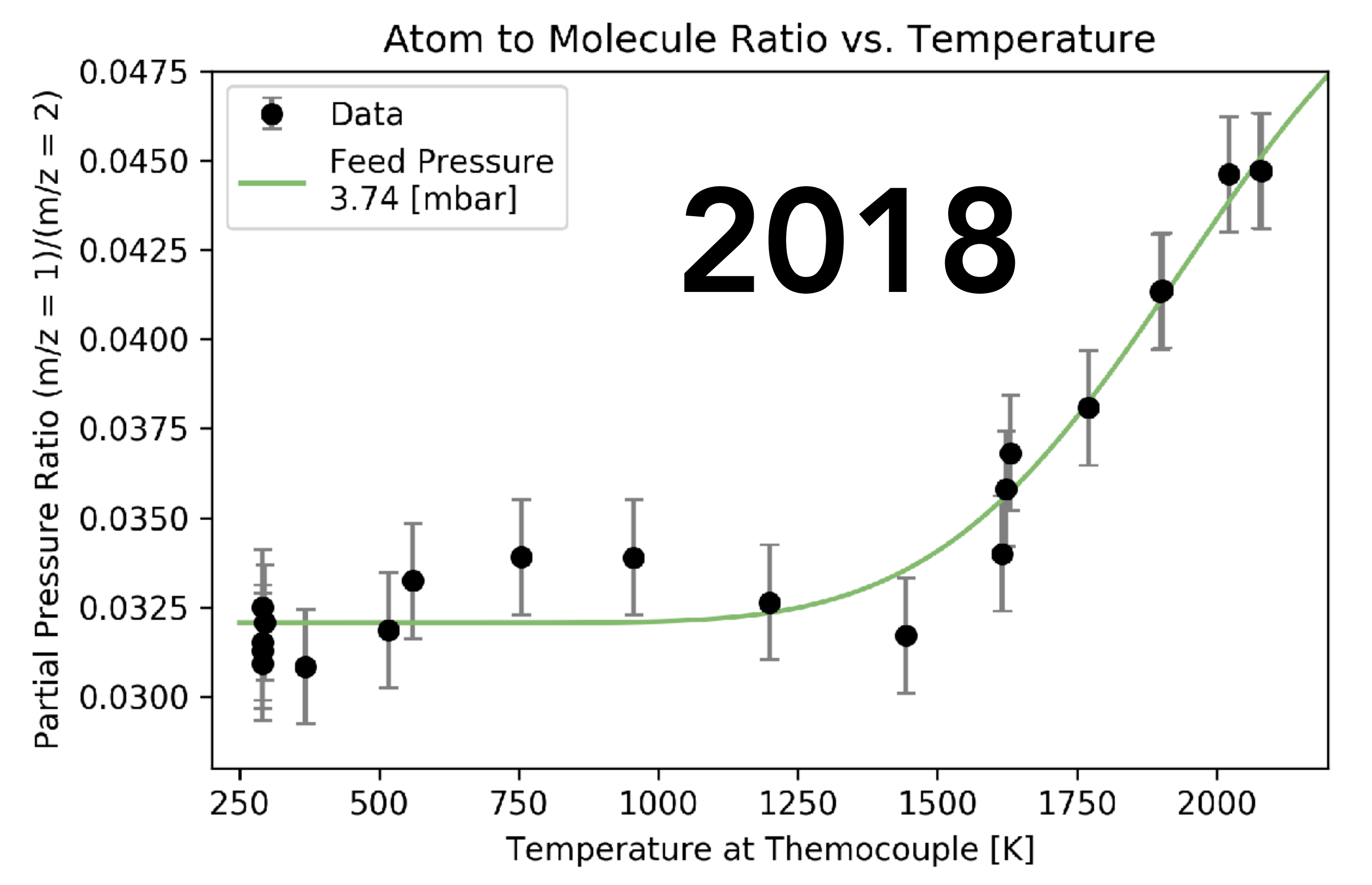
Measurement Types

- Atoms: increase with temperature, fit plateau and extract alpha
  - Also: use H and H_2 count rates
- Molecules: disappear with temperature, convert missing molecules to resulting atoms
- Wire detector: measure power of atoms recombining on wire

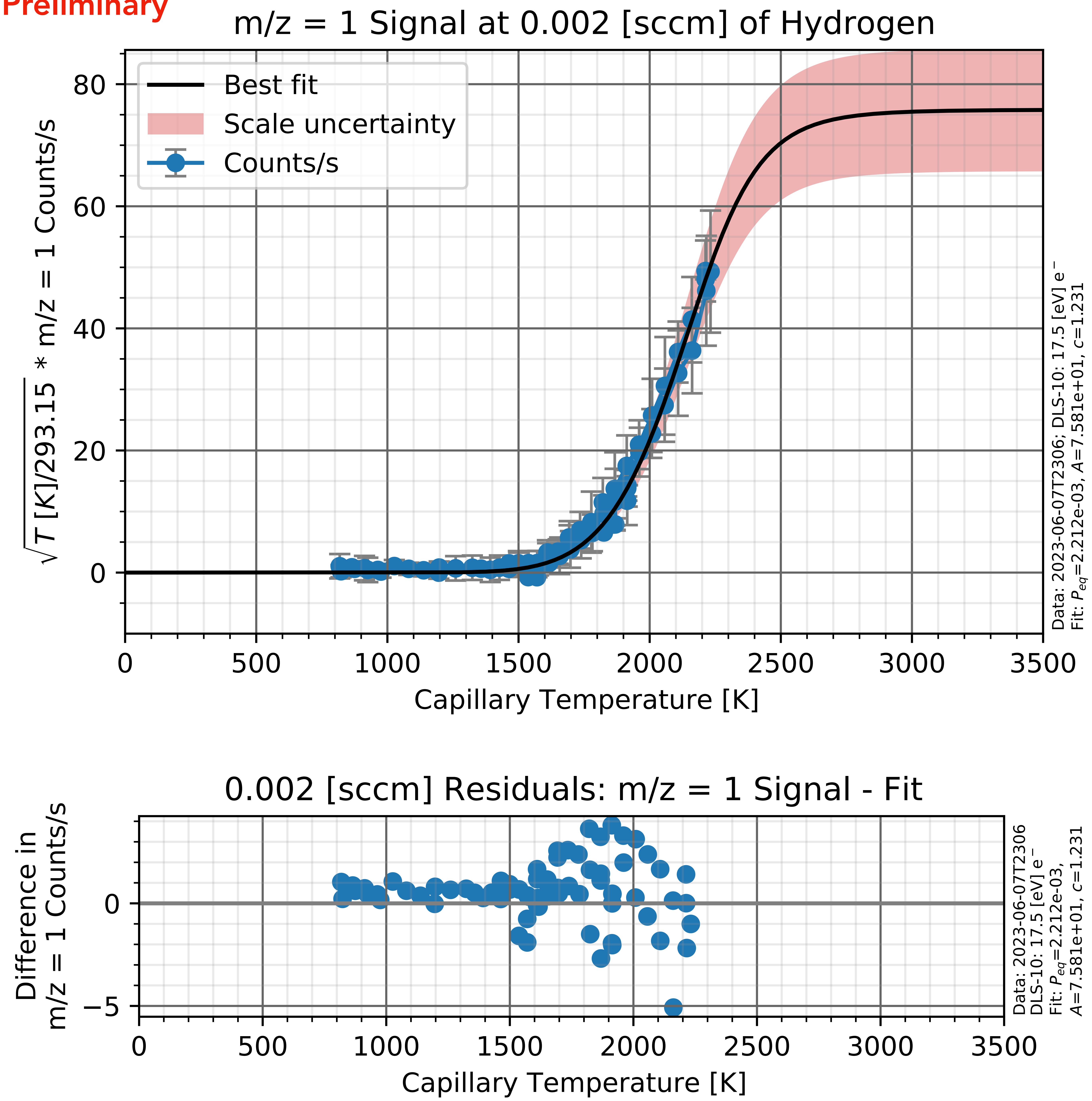


- SNR much higher than previous versions
- Allows clear analysis at the flows that Project 8 needs





Preliminary



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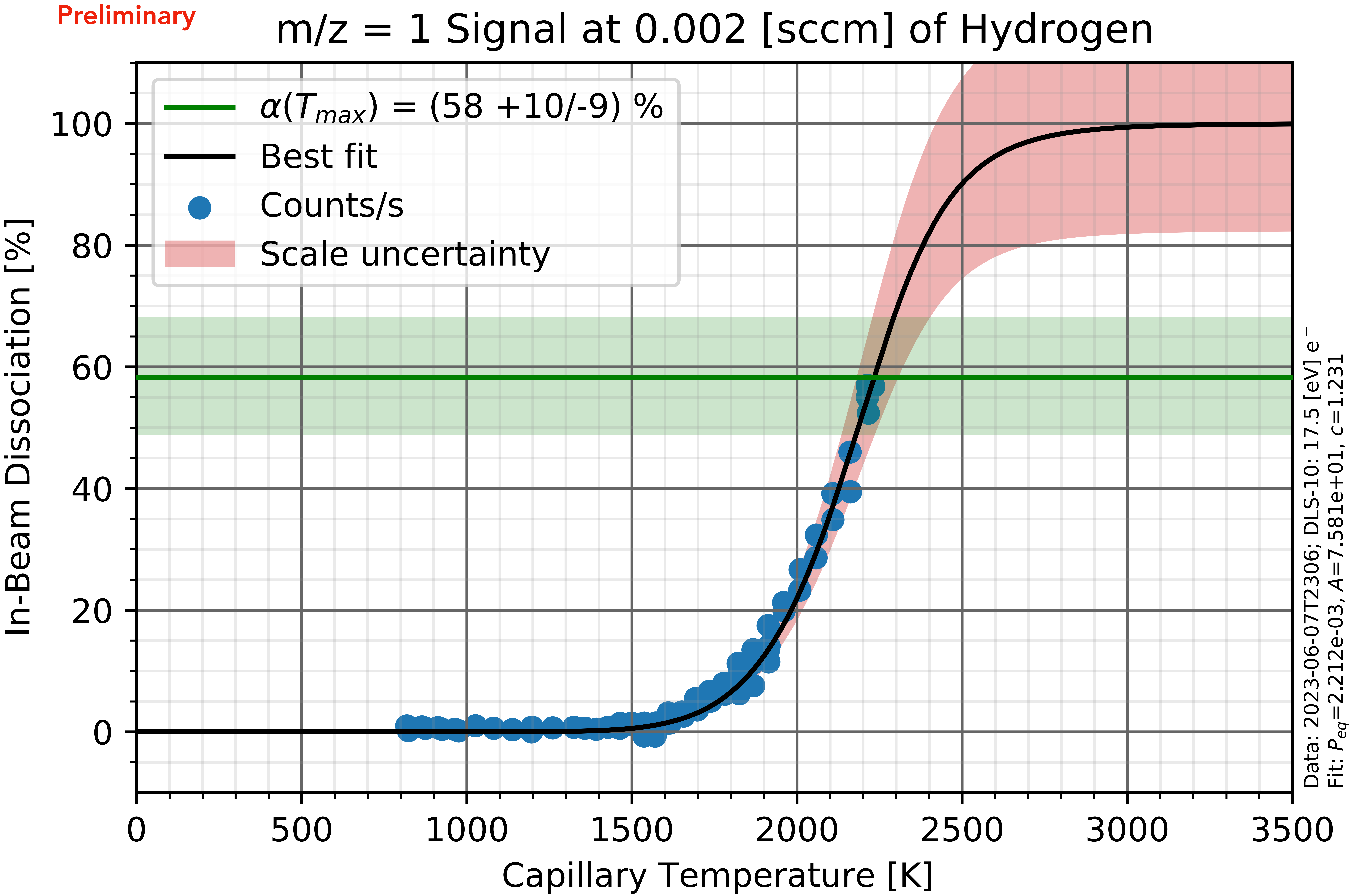

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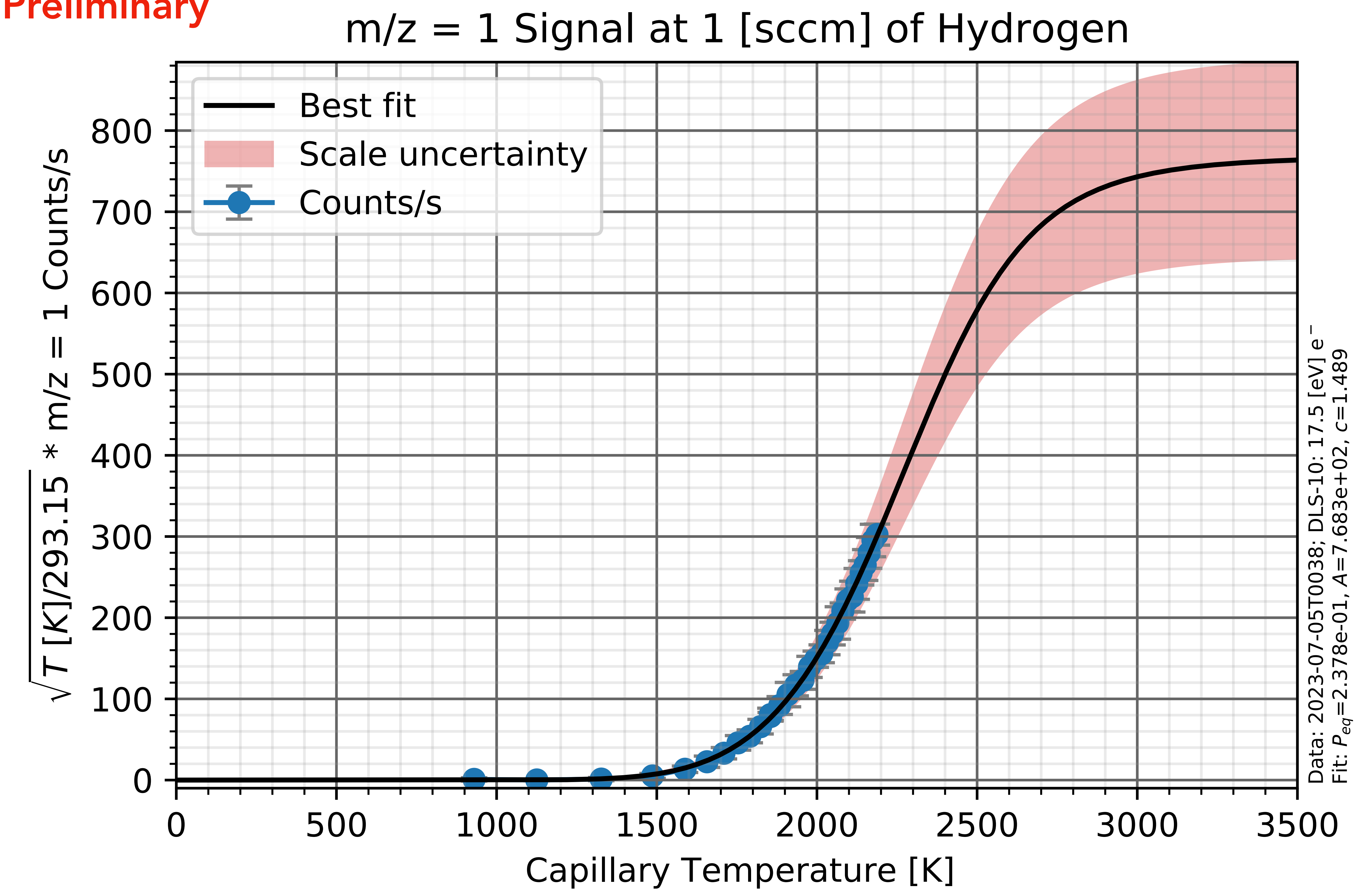

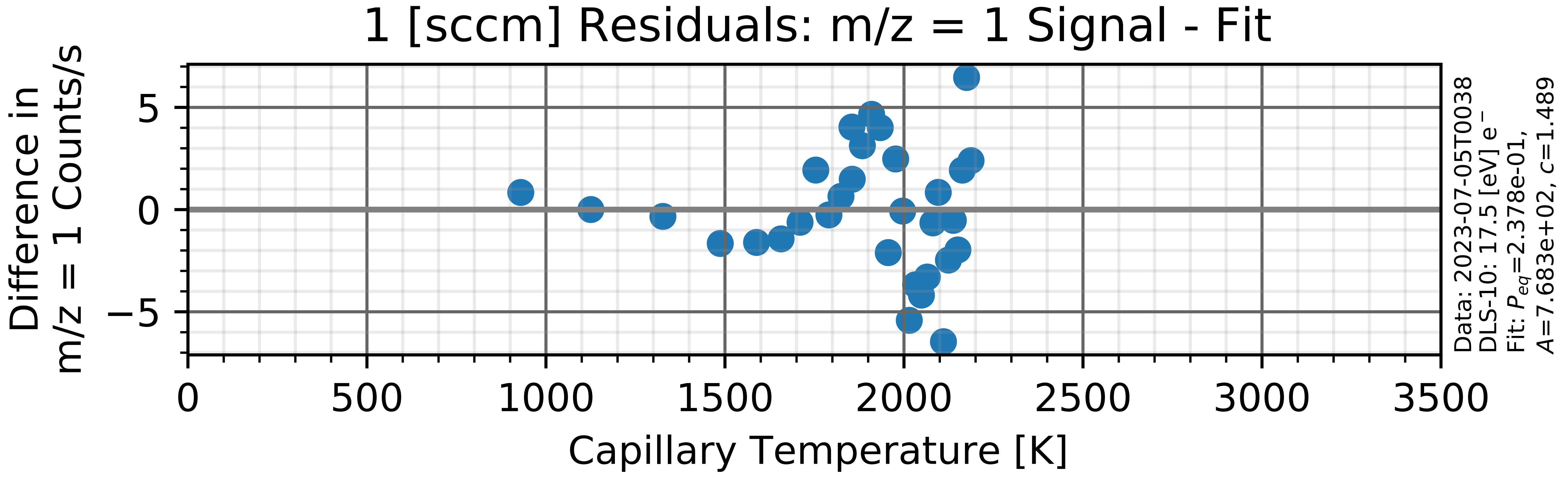

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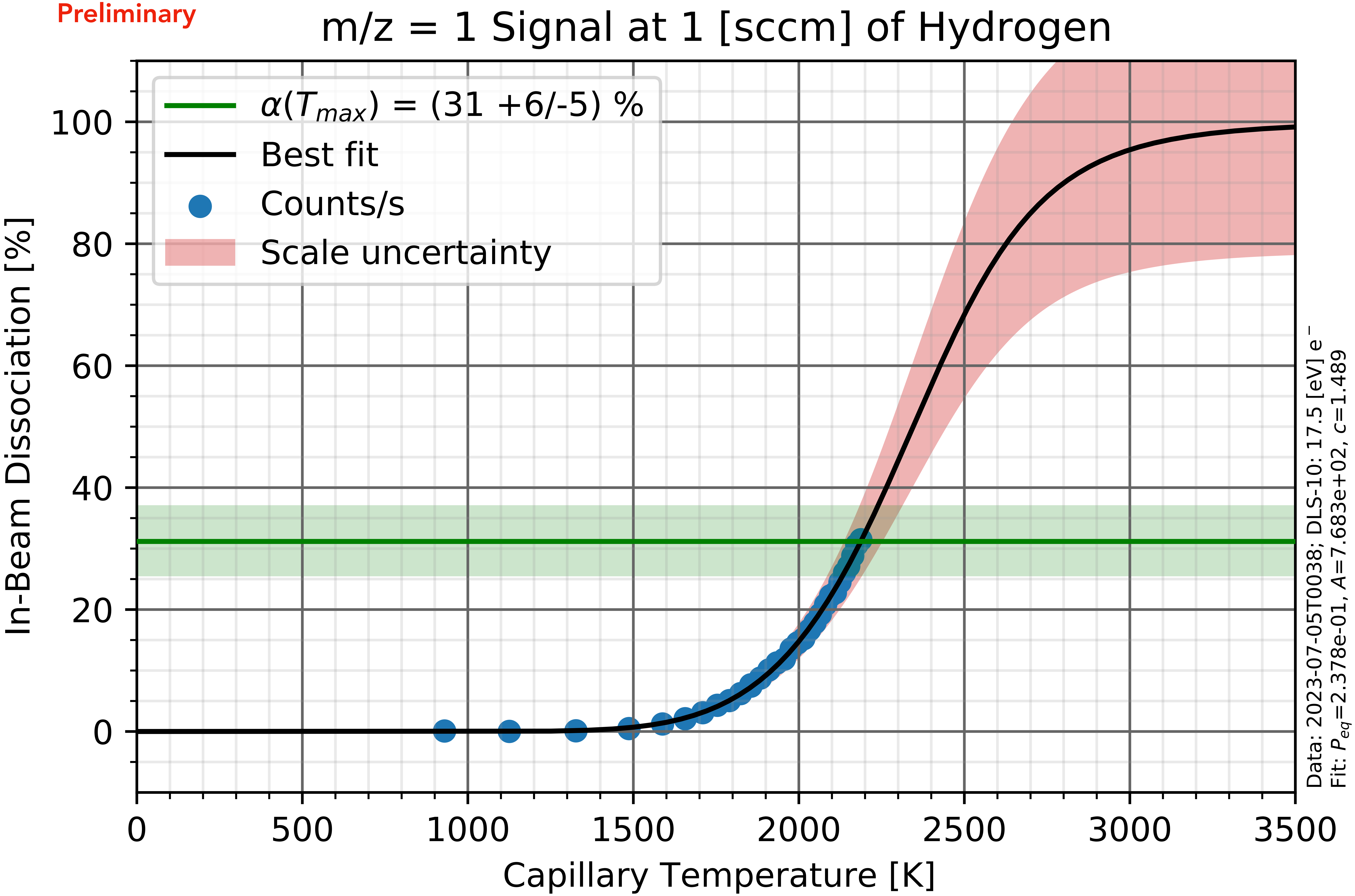

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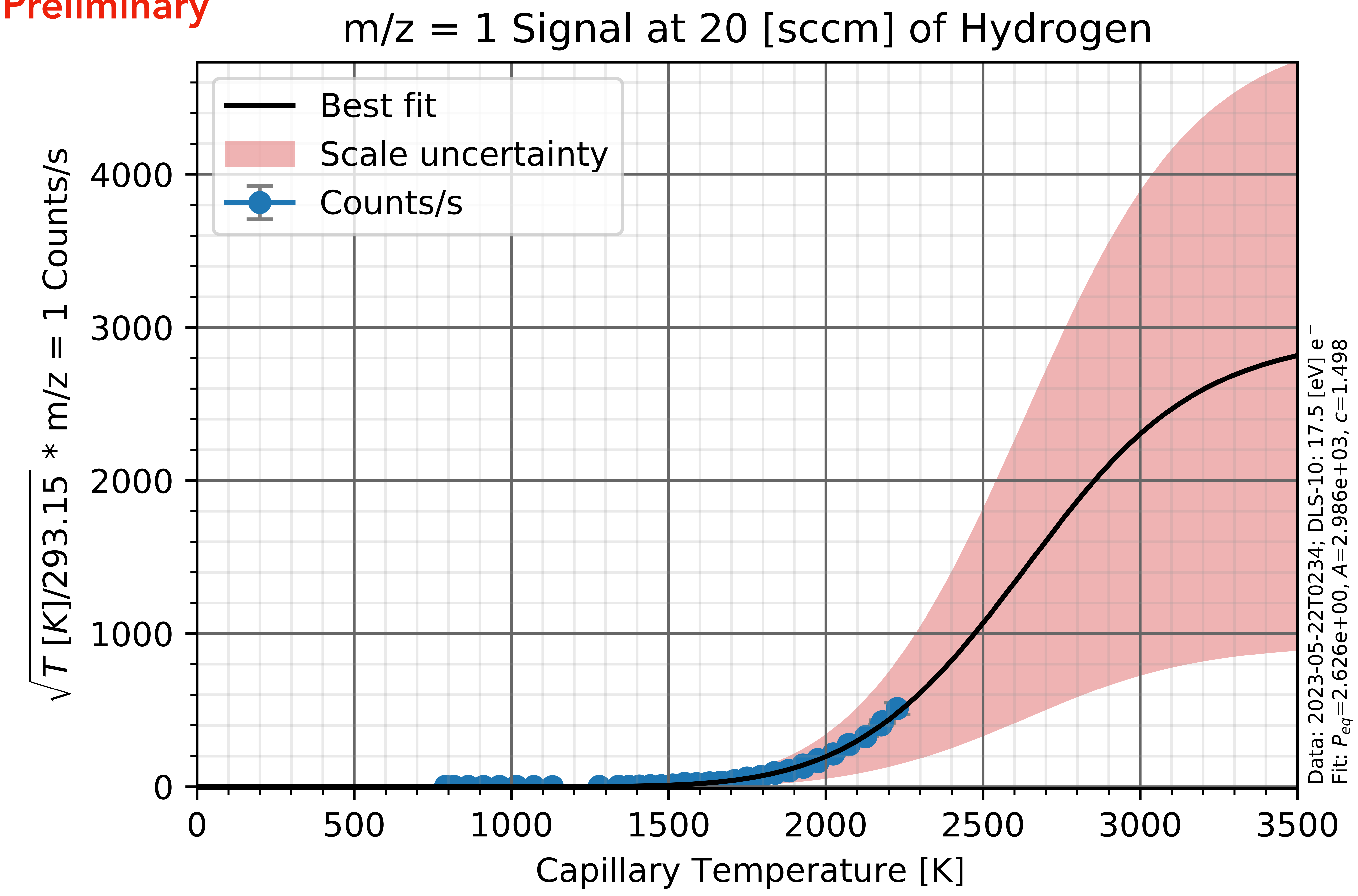

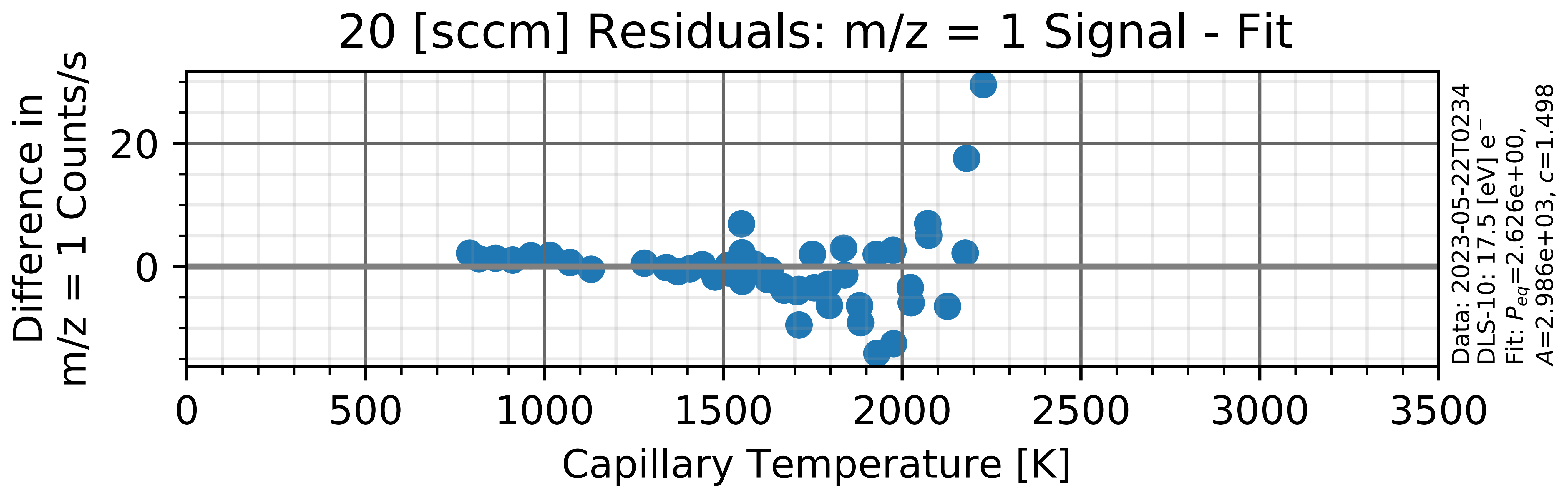

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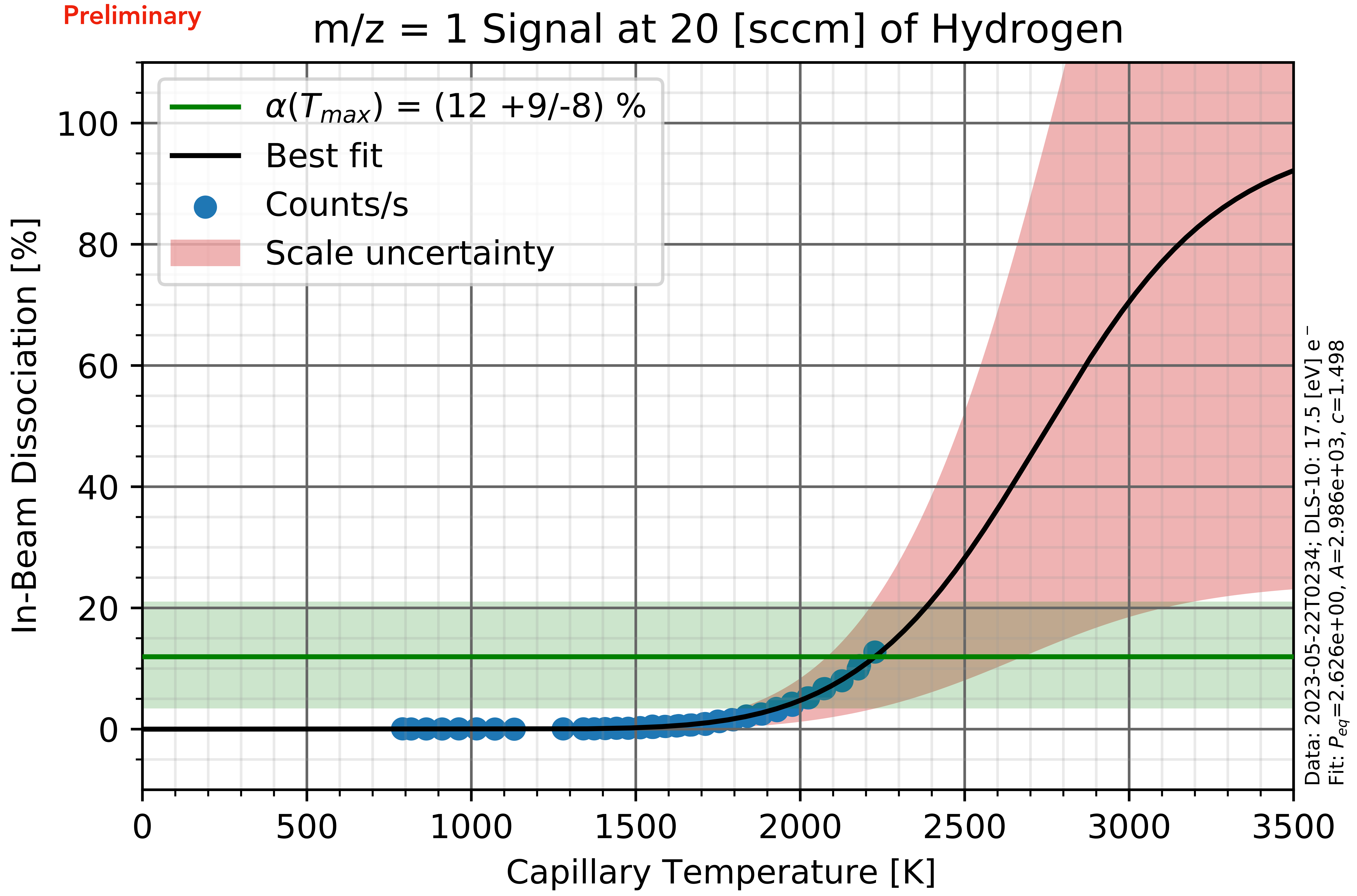
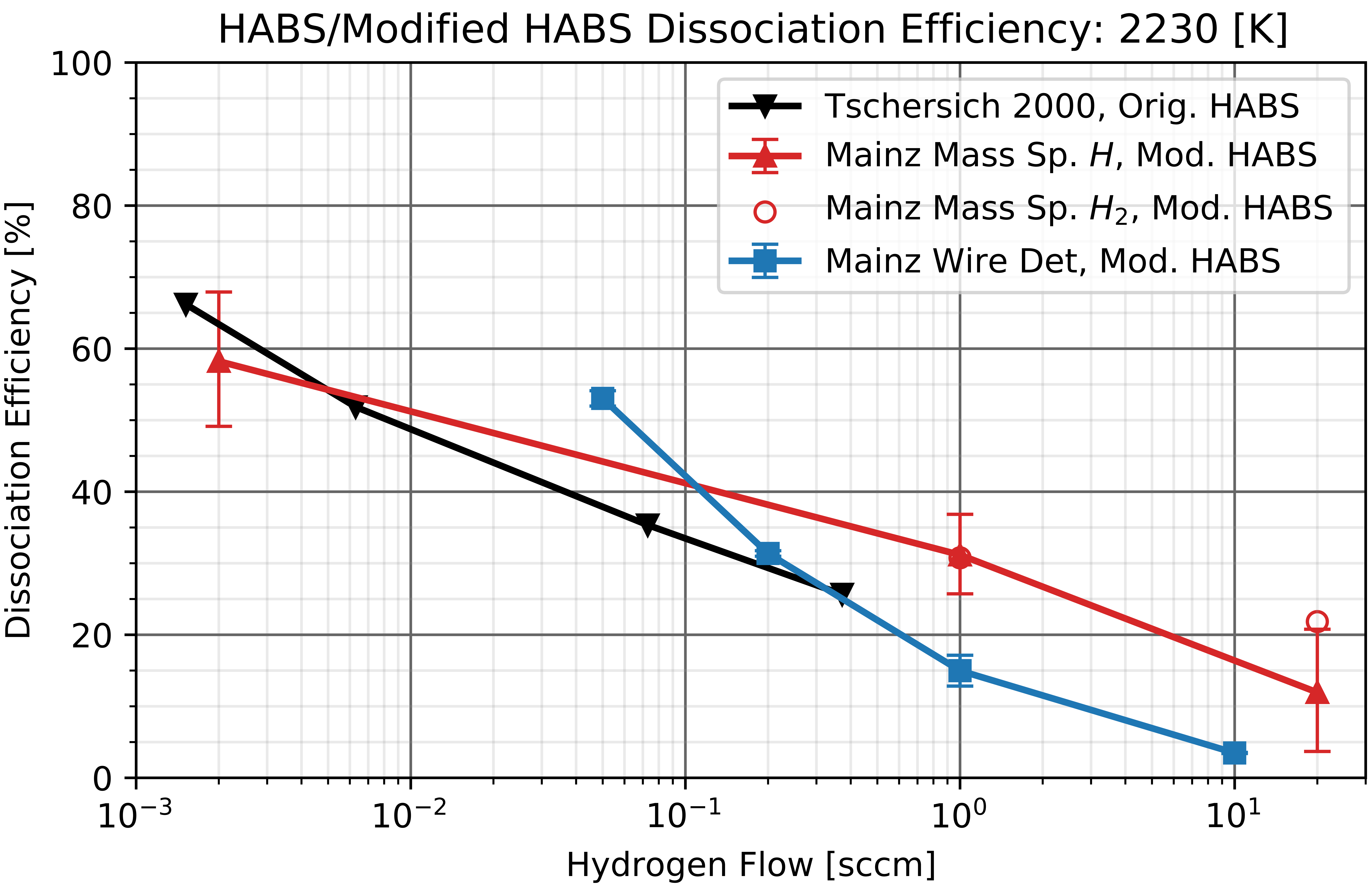
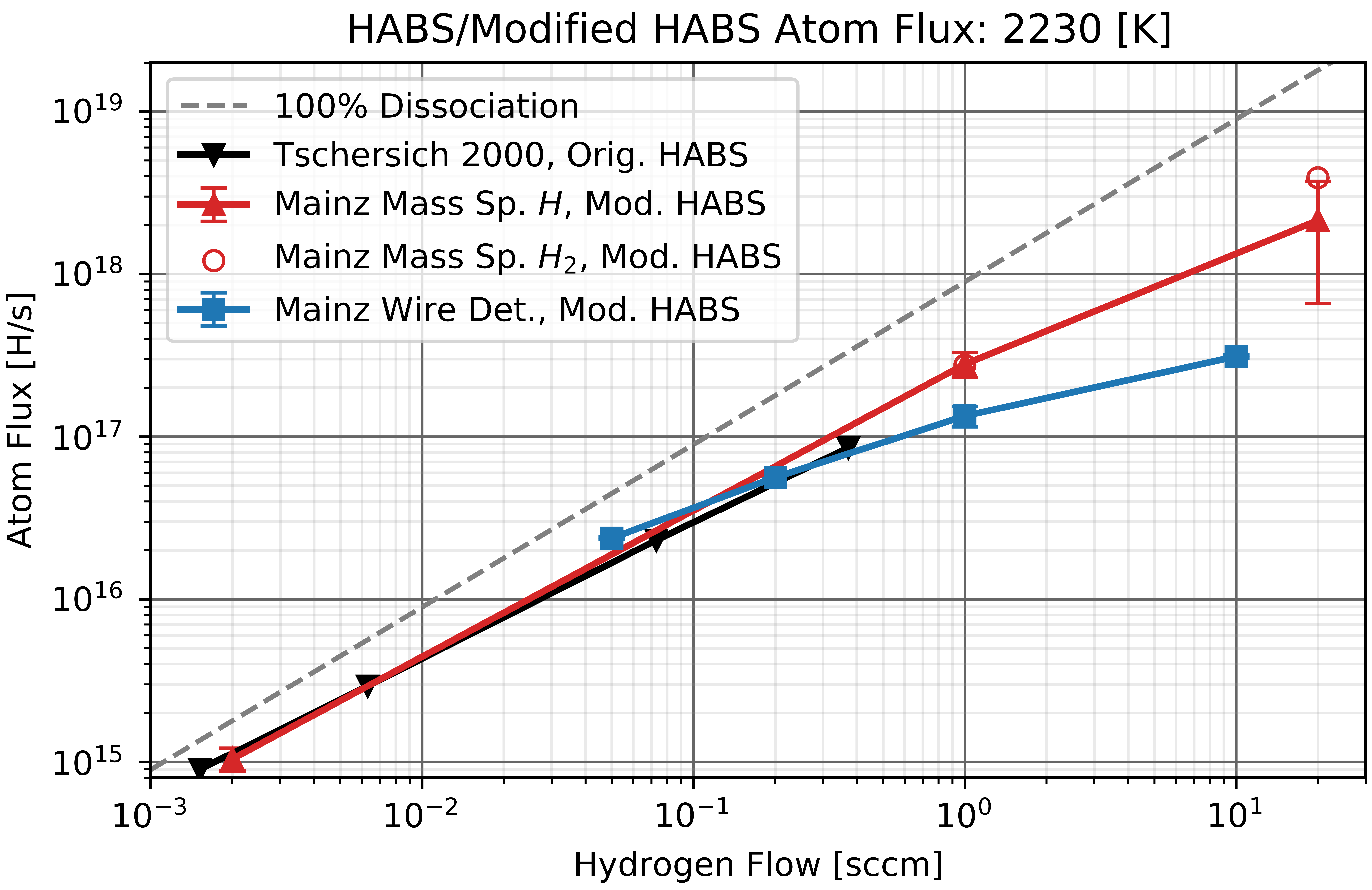


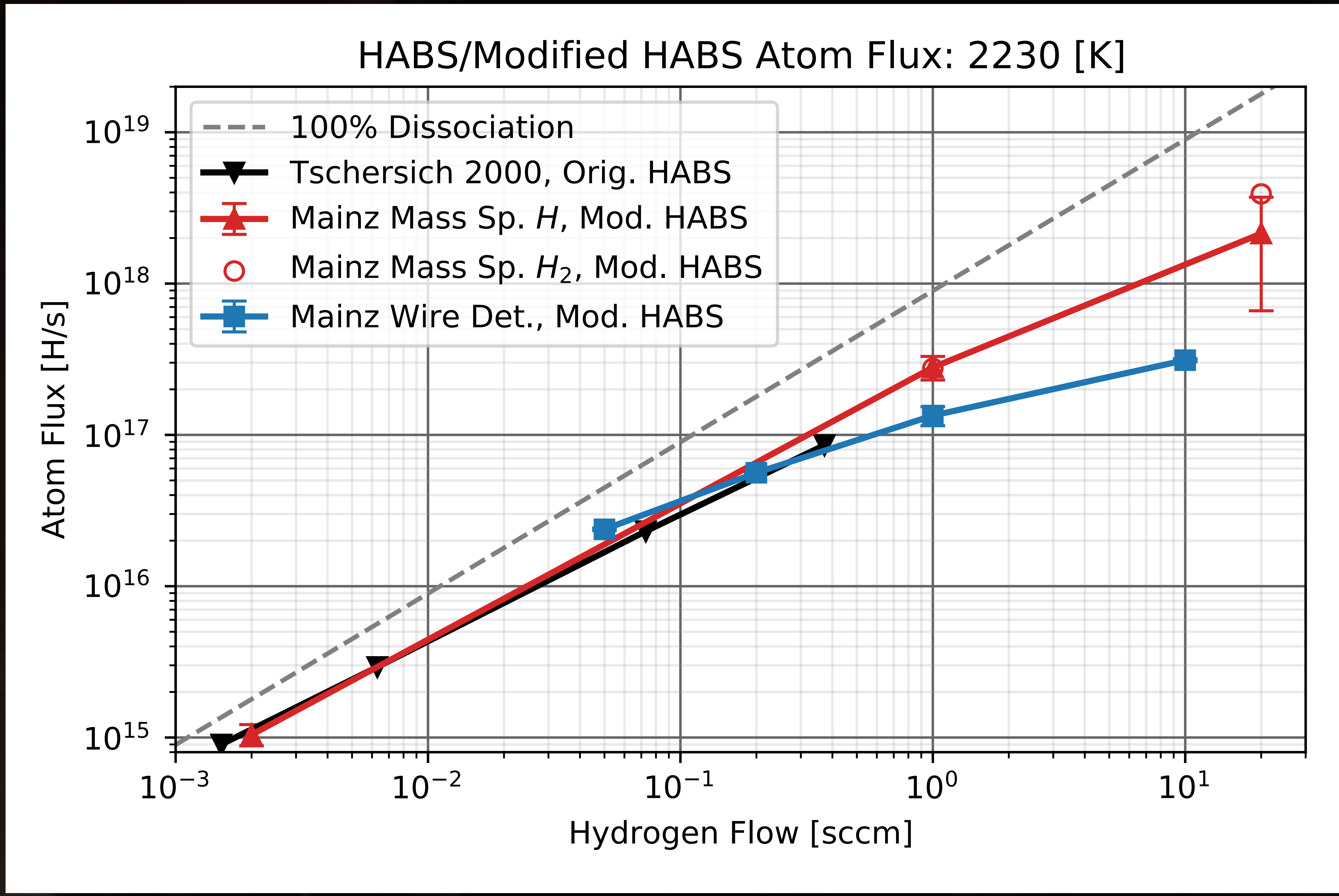


HABS/Modified HABS Dissociation Efficiency: 2230 [K]
Tschersich 2000, Orig. HABS
Mainz Mass Sp. H, Mod. HABS
Mainz Mass Sp. H_2, Mod. HABS
Mainz Wire Det, Mod. HABS
Dissociation Efficiency [%]
0
20
40
60
80
100
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Hydrogen Flow [sccm]


HABS/Modified HABS Atom Flux: 2230 [K]
100% Dissociation
Tschersich 2000, Orig. HABS
Mainz Mass Sp. H, Mod. HABS
Mainz Mass Sp. H_2, Mod. HABS
Mainz Wire Det., Mod. HABS
Atom Flux [H/s]
Hydrogen Flow [sccm]
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

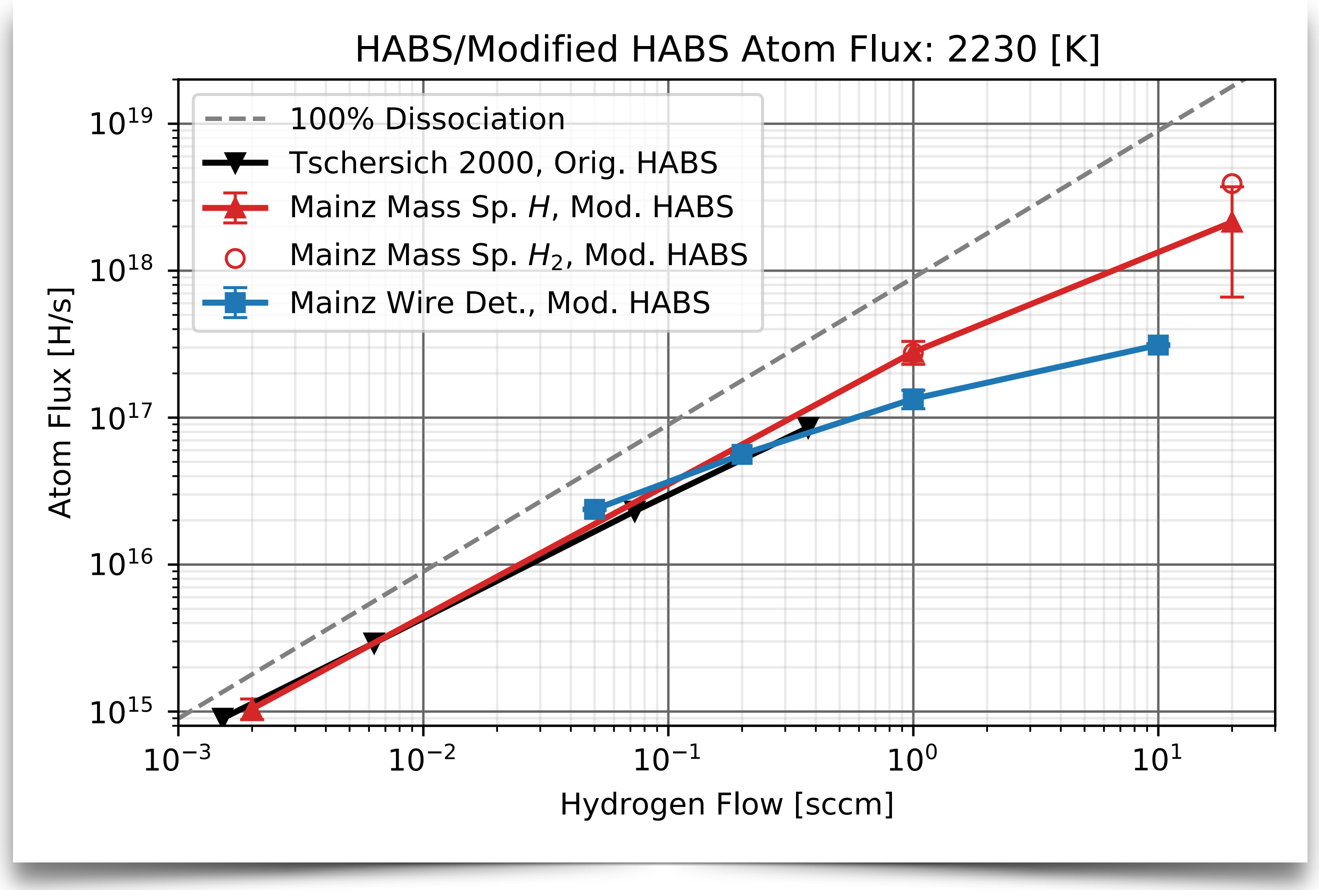
High-Flux Atomic Source

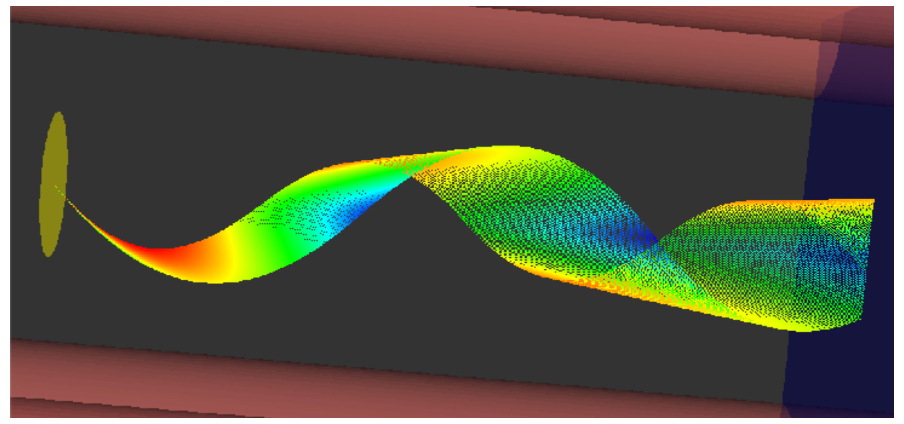
- The source produces 2e18 H/s with a 1 mm dia. capillary
- Wire stuffing makes the output a linear function of capillary area; a 2.5 mm dia. capillary will make 1e19 H/s
- We have a proven design for the first step in Project 8's full-scale atomic apparatus

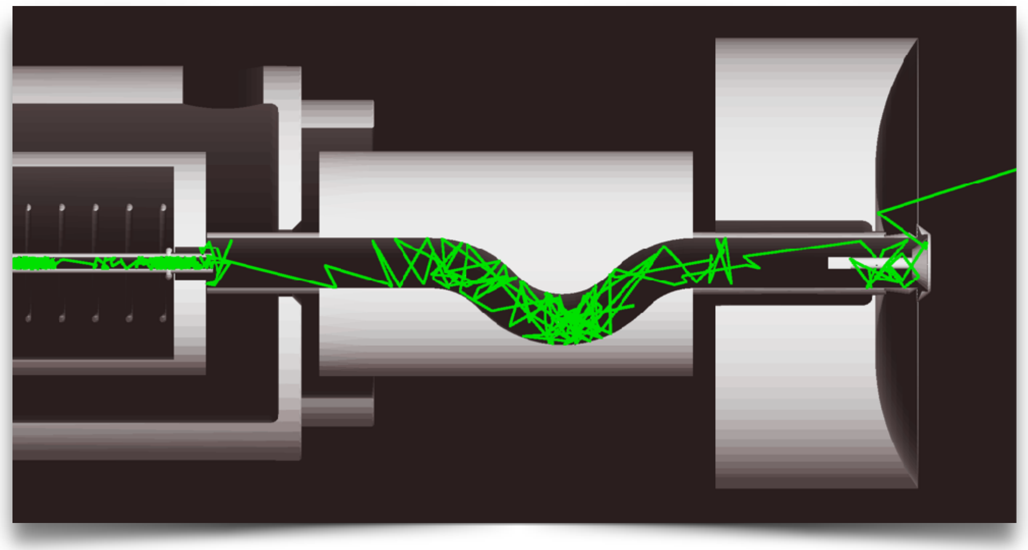


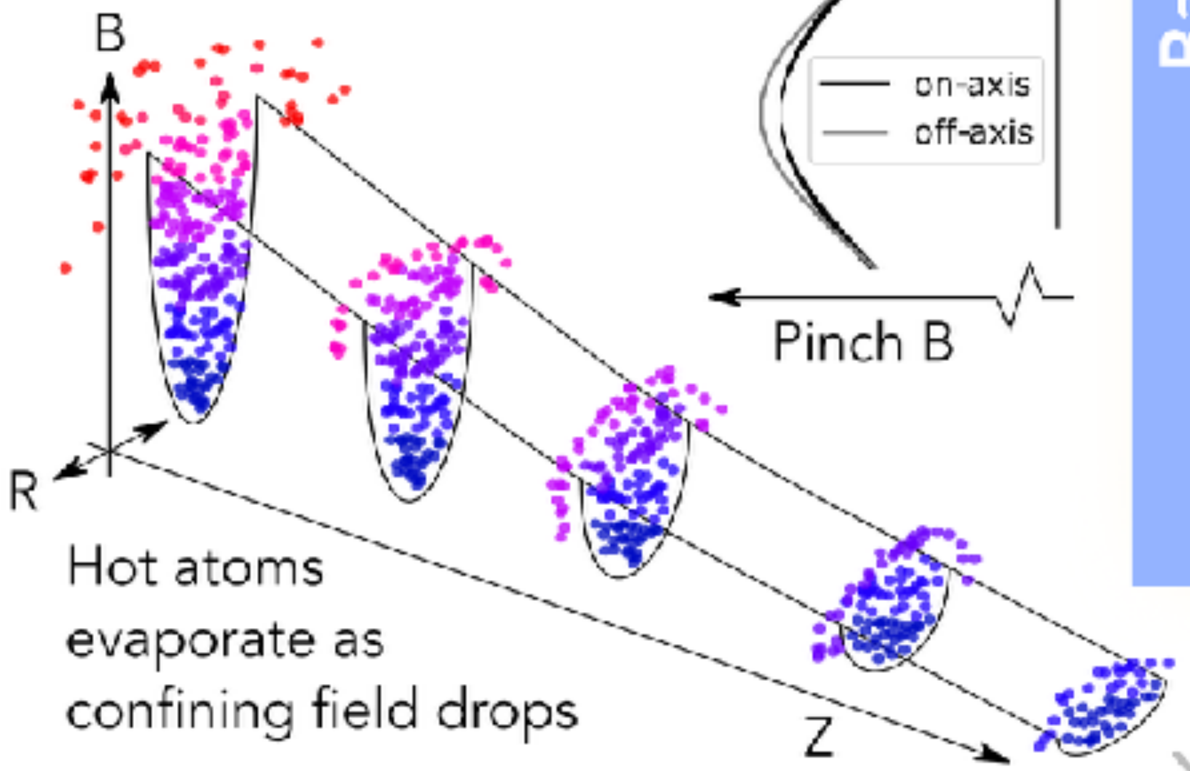
Project 8: Atomic T & CRES

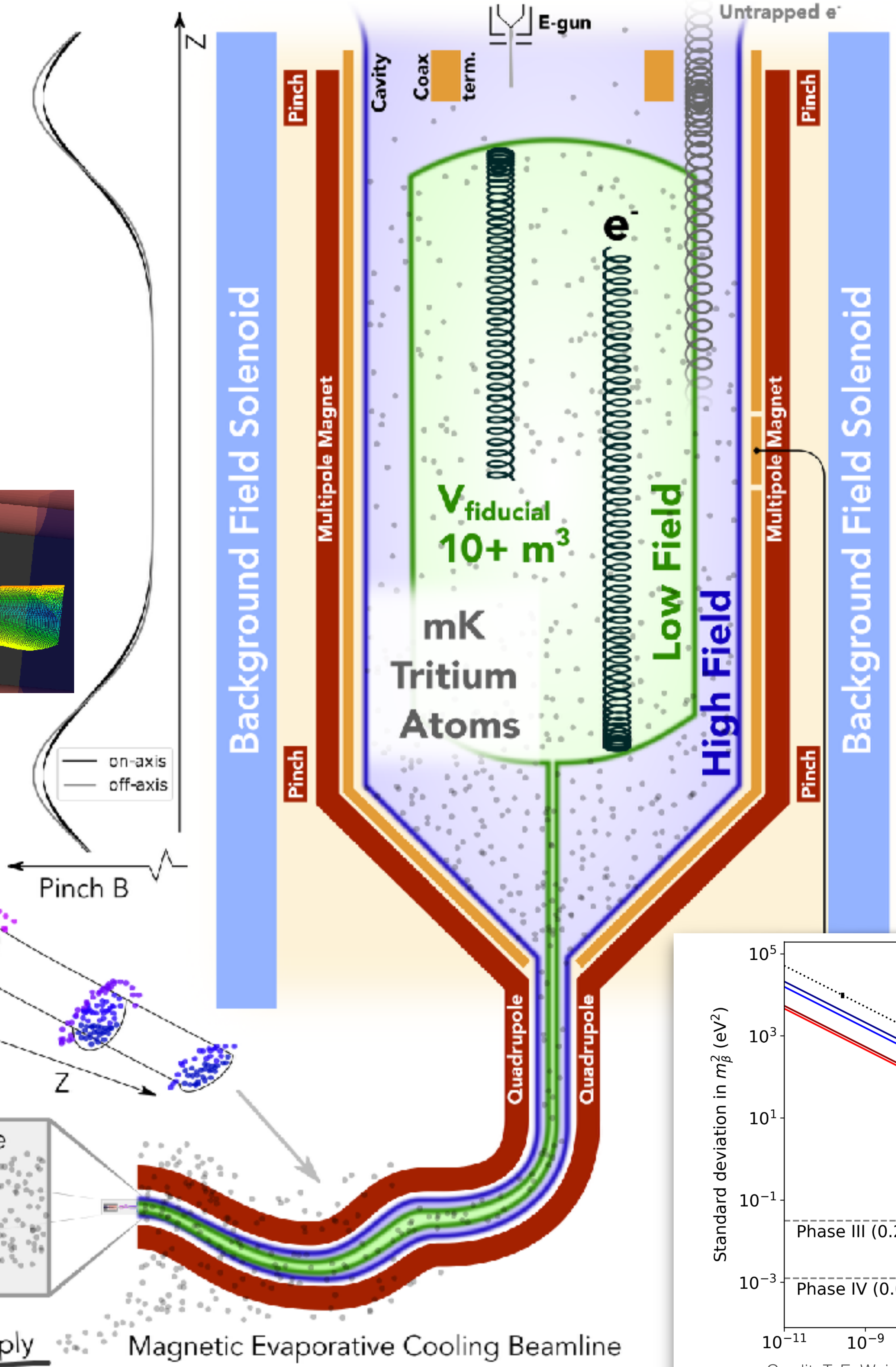
- Juliana S. (9:00 Wed.)
- Ben J. (11:50 Thu.)

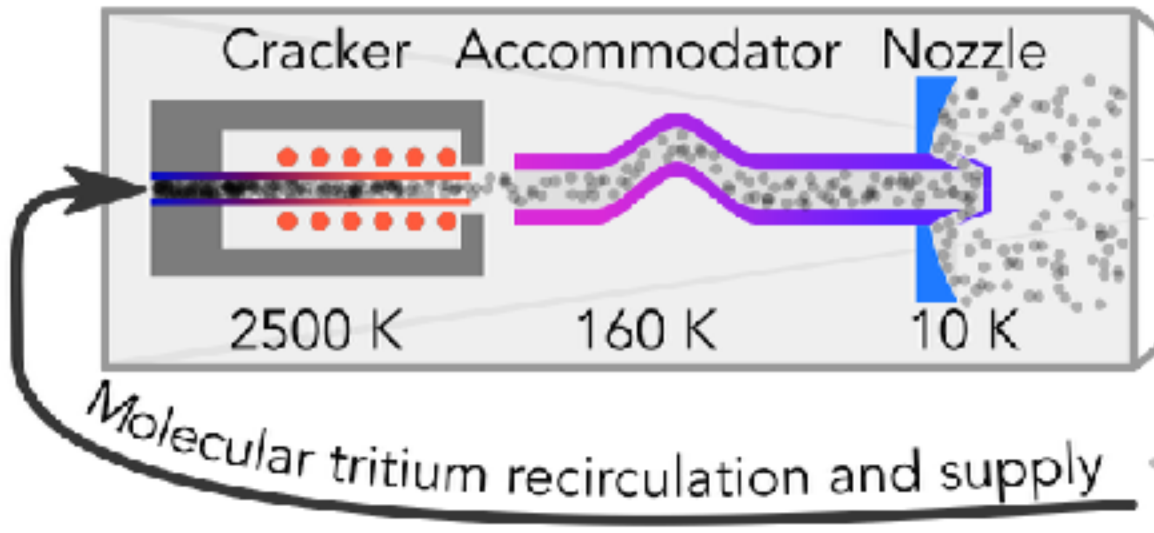


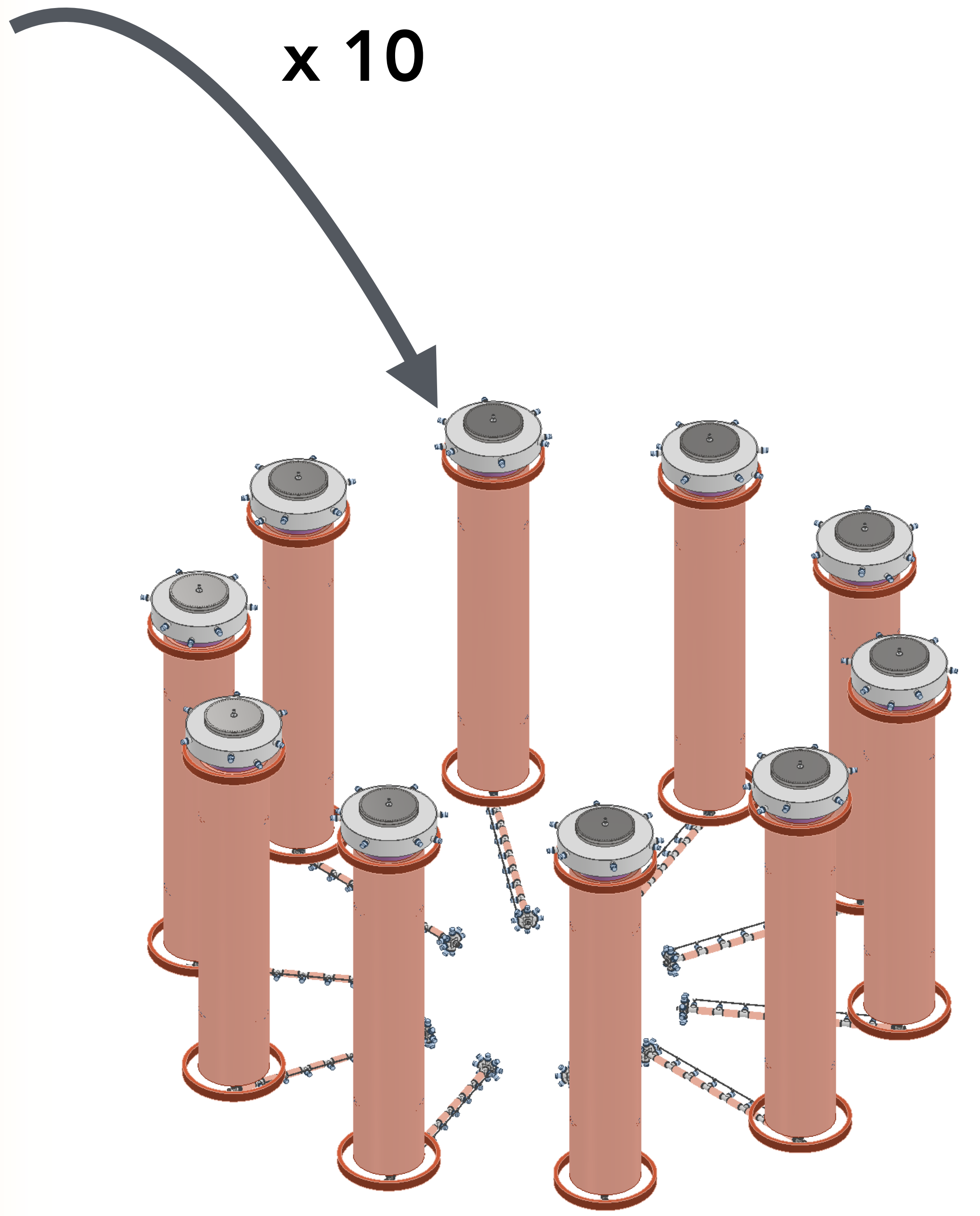


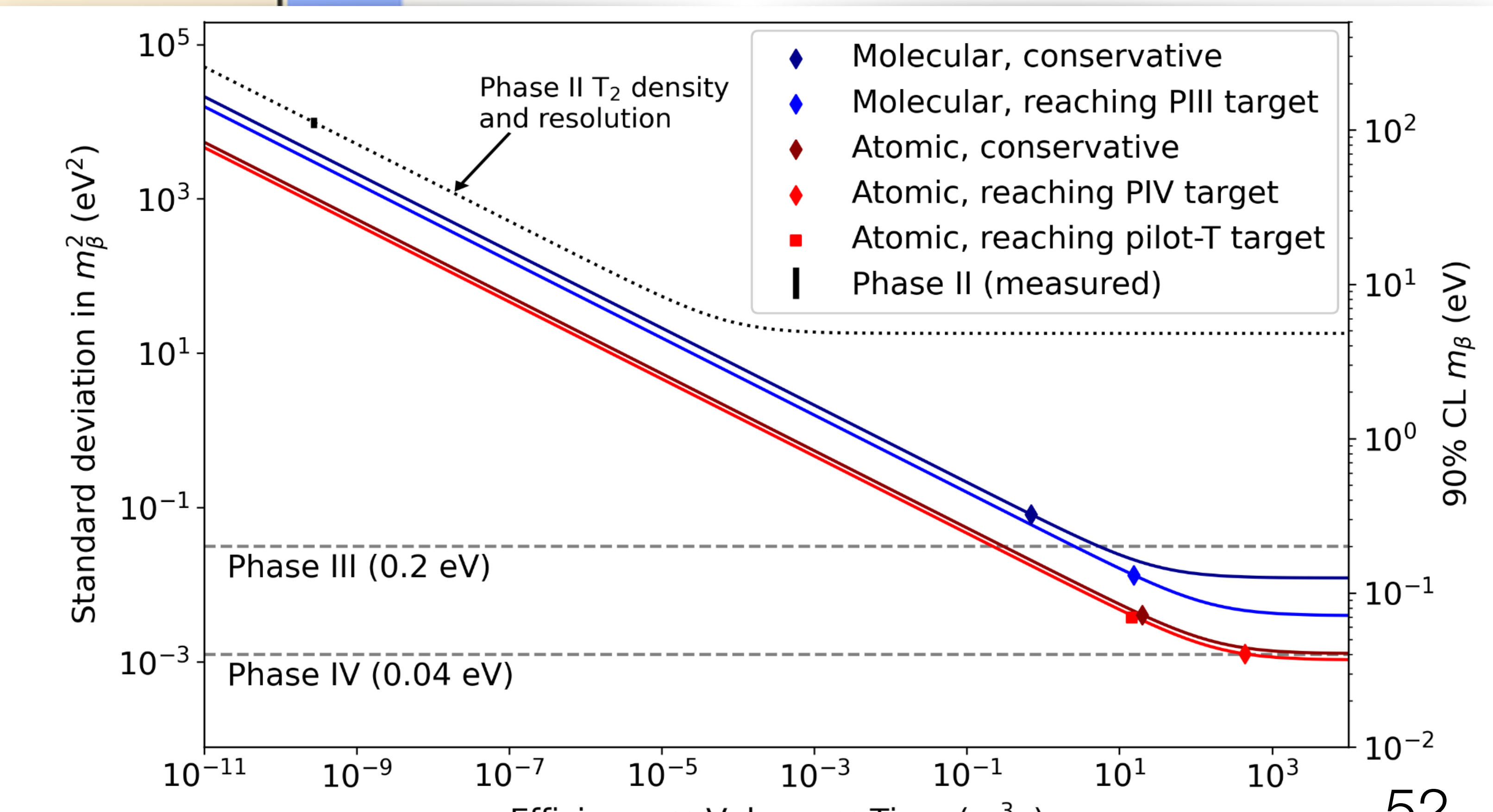






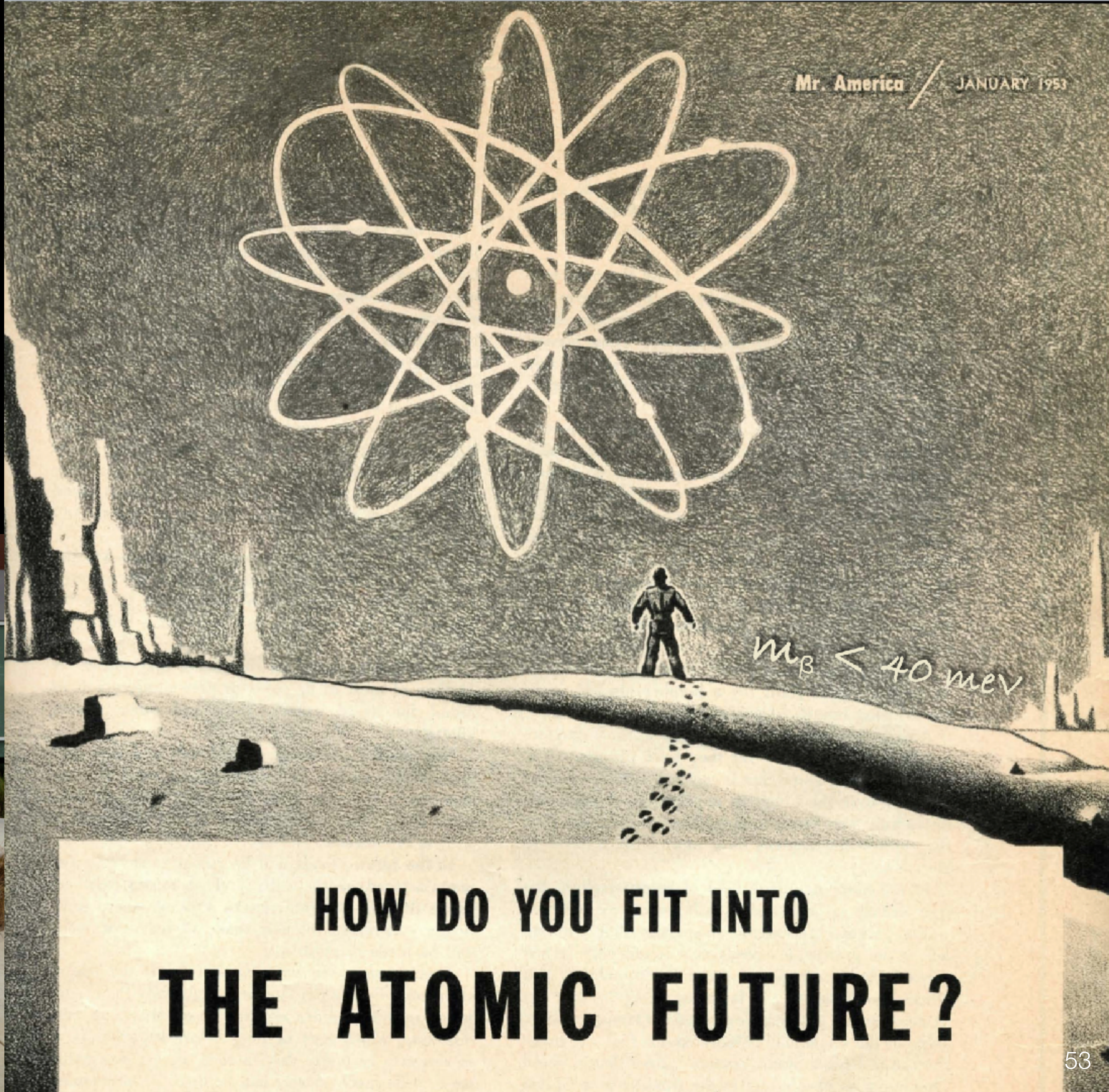






Credit: T. E. Weiss

PROJECT 8


Mr. America / JANUARY 1953
$m_\beta < 40$ meV
HOW DO YOU FIT INTO
THE ATOMIC FUTURE?