Atomic Source Developing for Project 8's Neutrino Mass Measurements

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MPA Summer School

Chiemsee, Germany

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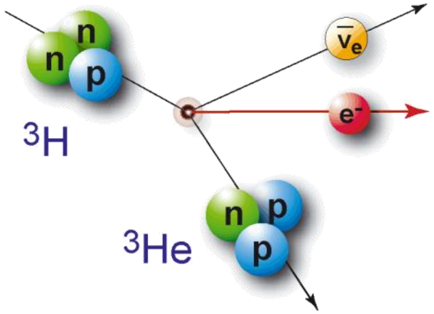
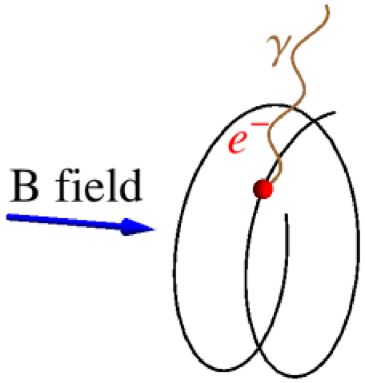
Outline

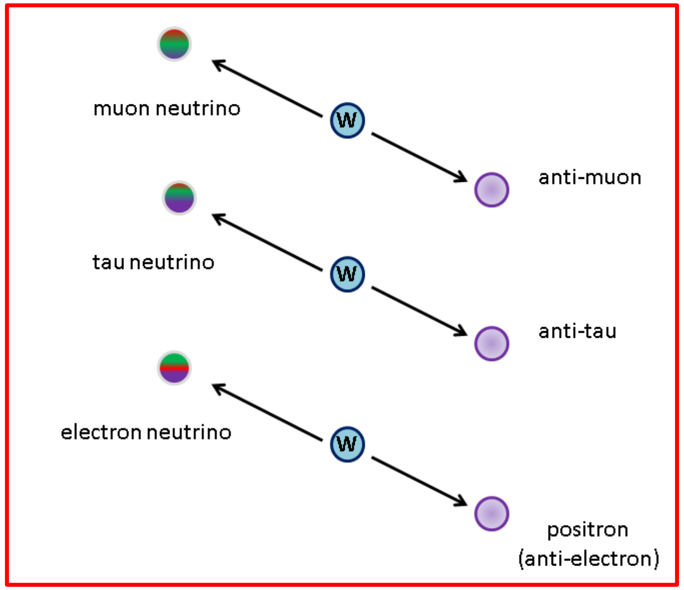




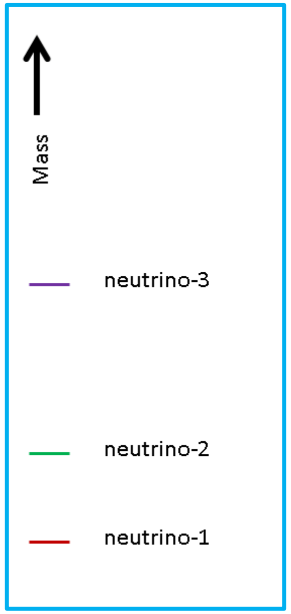
- Introduction
- Methodology: Cyclotron Radiation Emission Spectroscopy
- Methodology: Atomic Tritium
- Source Development at Mainz
- Summary

Introduction: The Neutrino Particle

Flavor type dependent on charged lepton accompanying the reaction



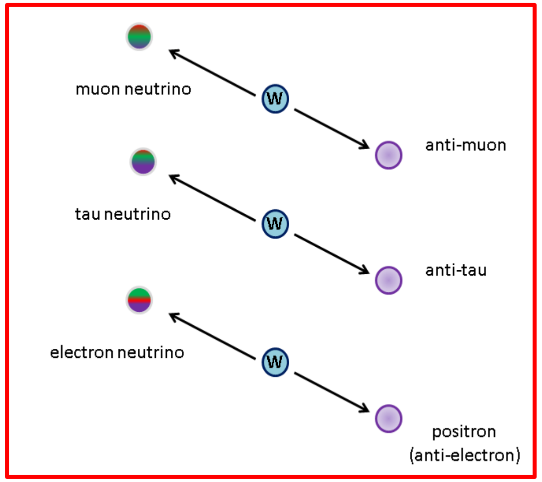
Flavor eigenstates



Mass eigenstates

Different mass eigenstates propagate with different frequencies

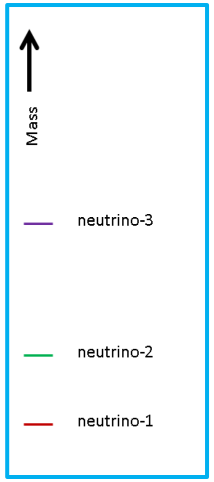
Introduction: The Neutrino Particle



Flavor eigenstates

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

Pontecorvo-Maki-Nakagawa-Sakata Matrix



Mass eigenstates

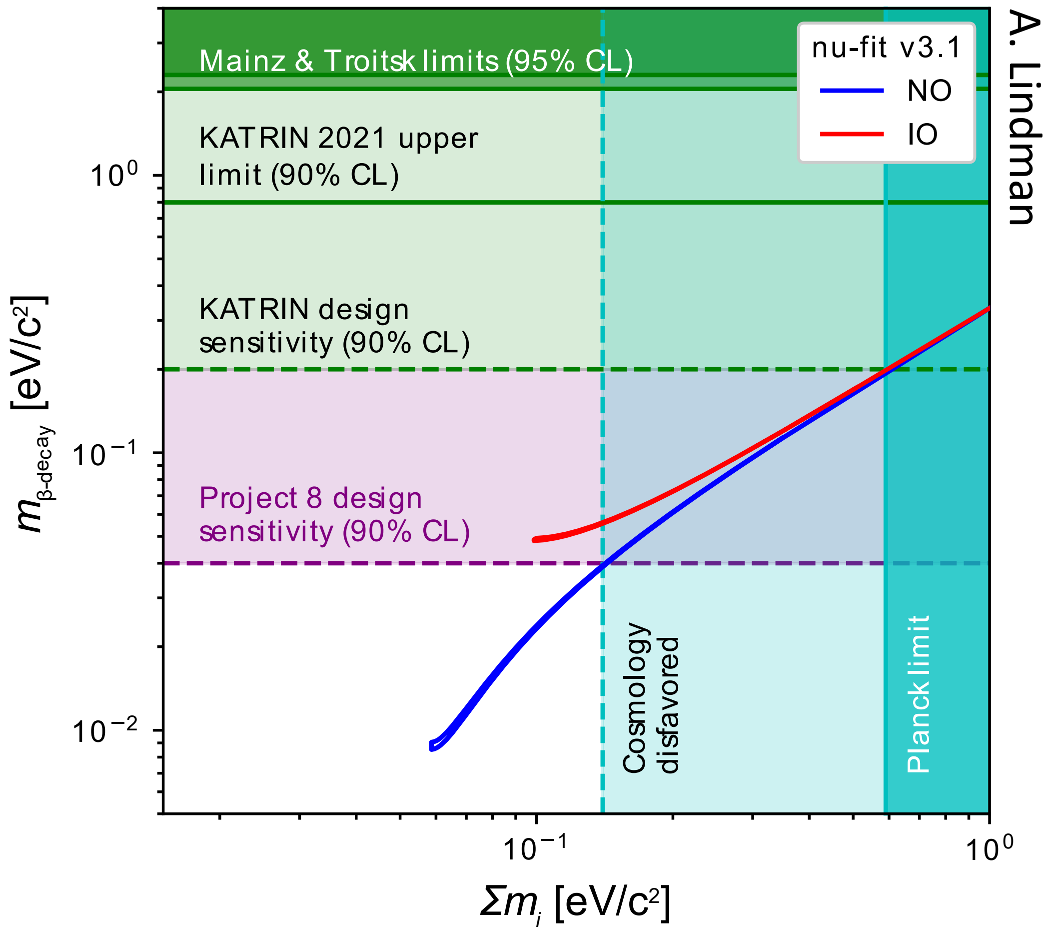
Electron weighted mass

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

Neutrino masses (m_1, m_2, m_3)

Introduction: Neutrino Mass Motivation

- It's nice to know
- The most abundant matter particle in the universe
- Inform Cosmological models
- Mass-generation mechanisms
- Physics beyond the standard model



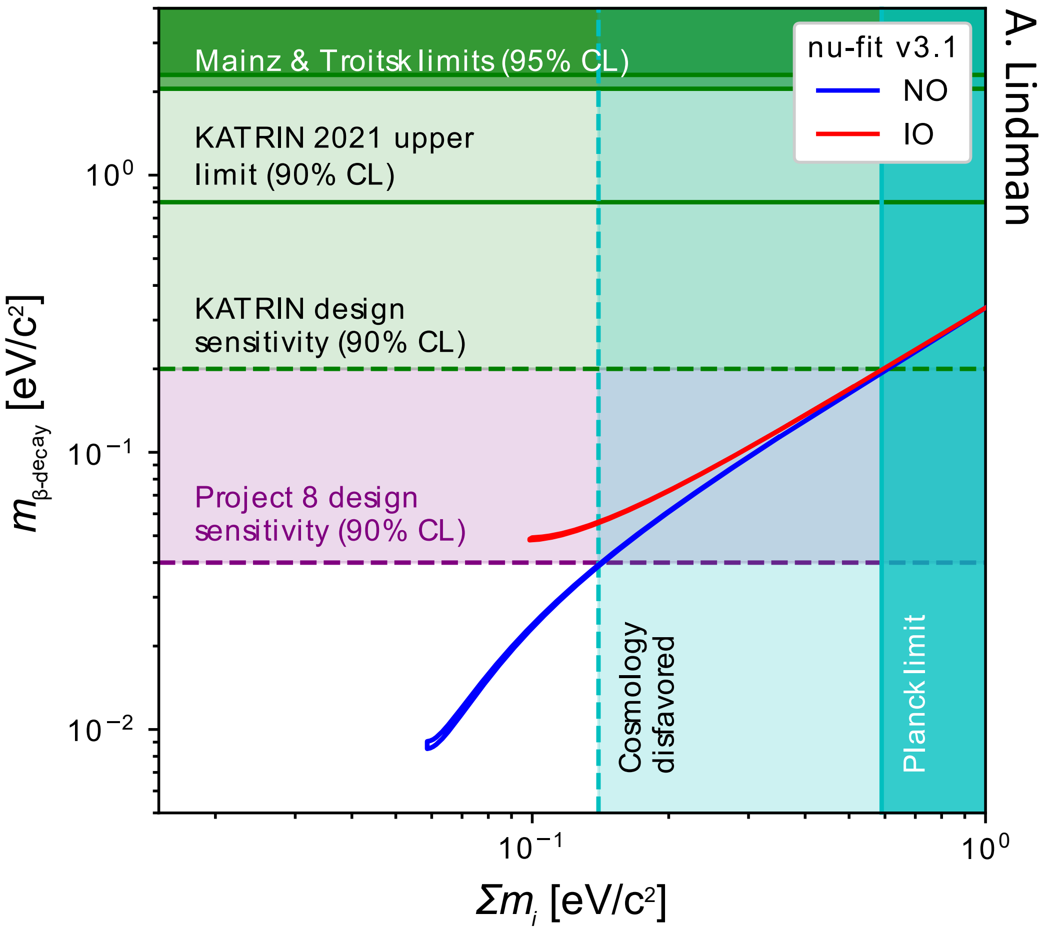
PROJECT 8

Introduction: Neutrino Mass Approach

NOT IMPORTANT!

- Cosmic Microwave Background
- Supernova time-of-flight
- Neutrinoless double beta decay
- Kinematics methods
    - Electromagnetic collimation
    - Electron capture
- Frequency-based measurement

BEST!

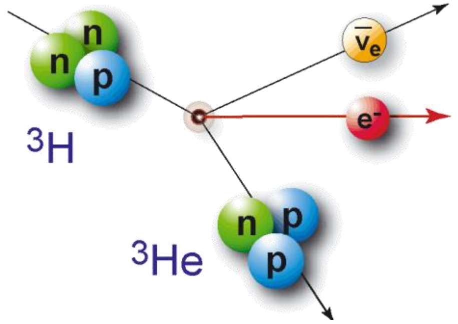


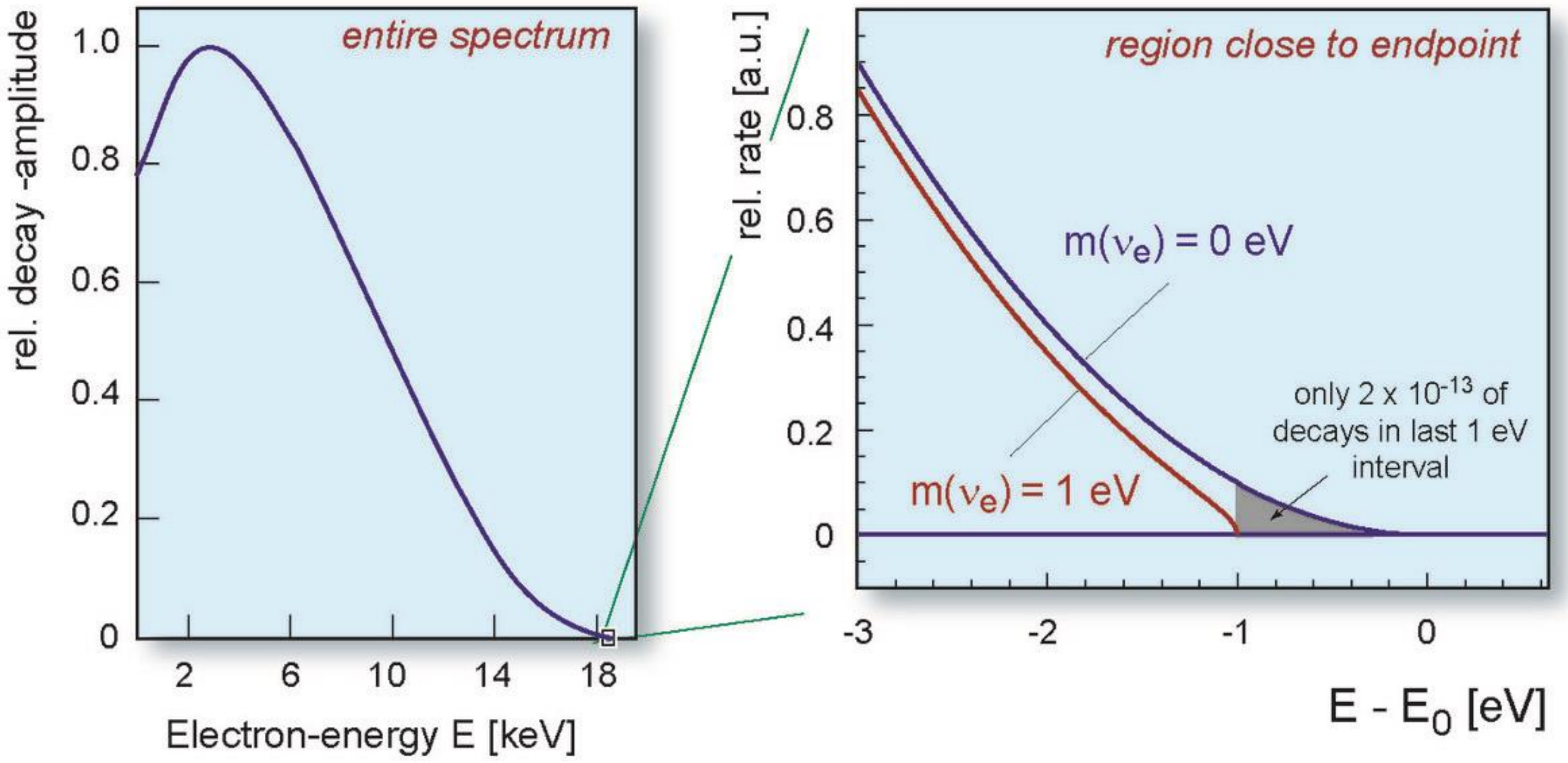
Project 8:

?

A frequency-based approach towards the measurements of the neutrino mass using ultra cold atomic tritium with 40 meV/c^2 sensitivity to m_β

Methodology: Tritium Beta Decay

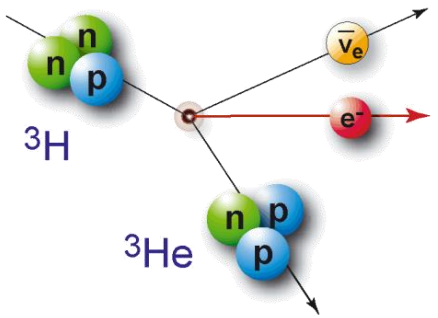




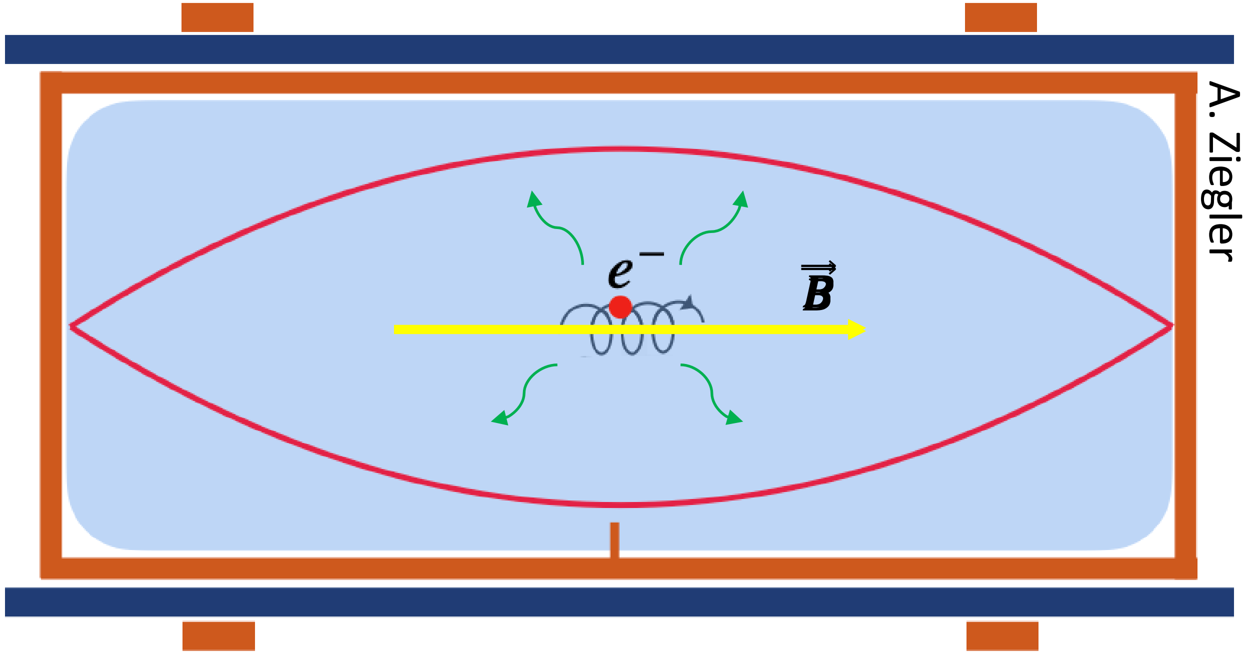
Source: KATRIN

E_0 : endpoint energy (maximum KE of e^- in absence of neutrino mass)

Methodology: Frequency Based Approach

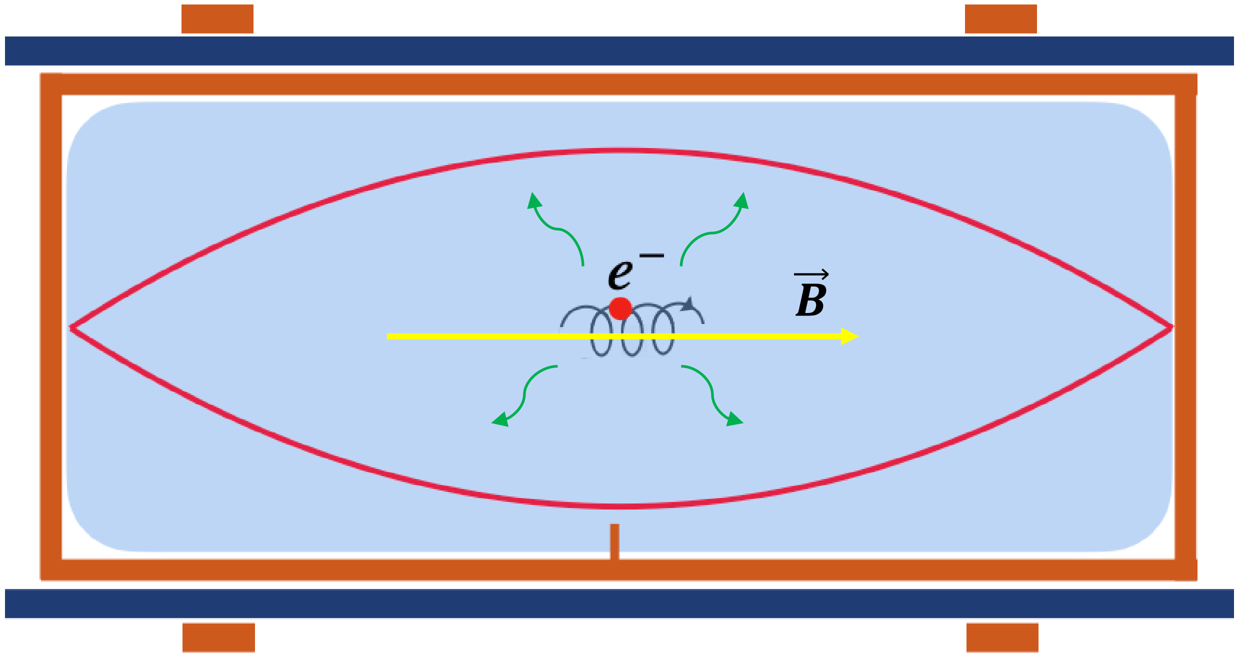


Magnetic Trap



Radiation detected
with resonant cavities

Methodology: Frequency Based Approach



- Radiation from one e^-
- Source is transparent to microwave frequency
- No e^- transportation from source to detector
- Precise frequency measurements

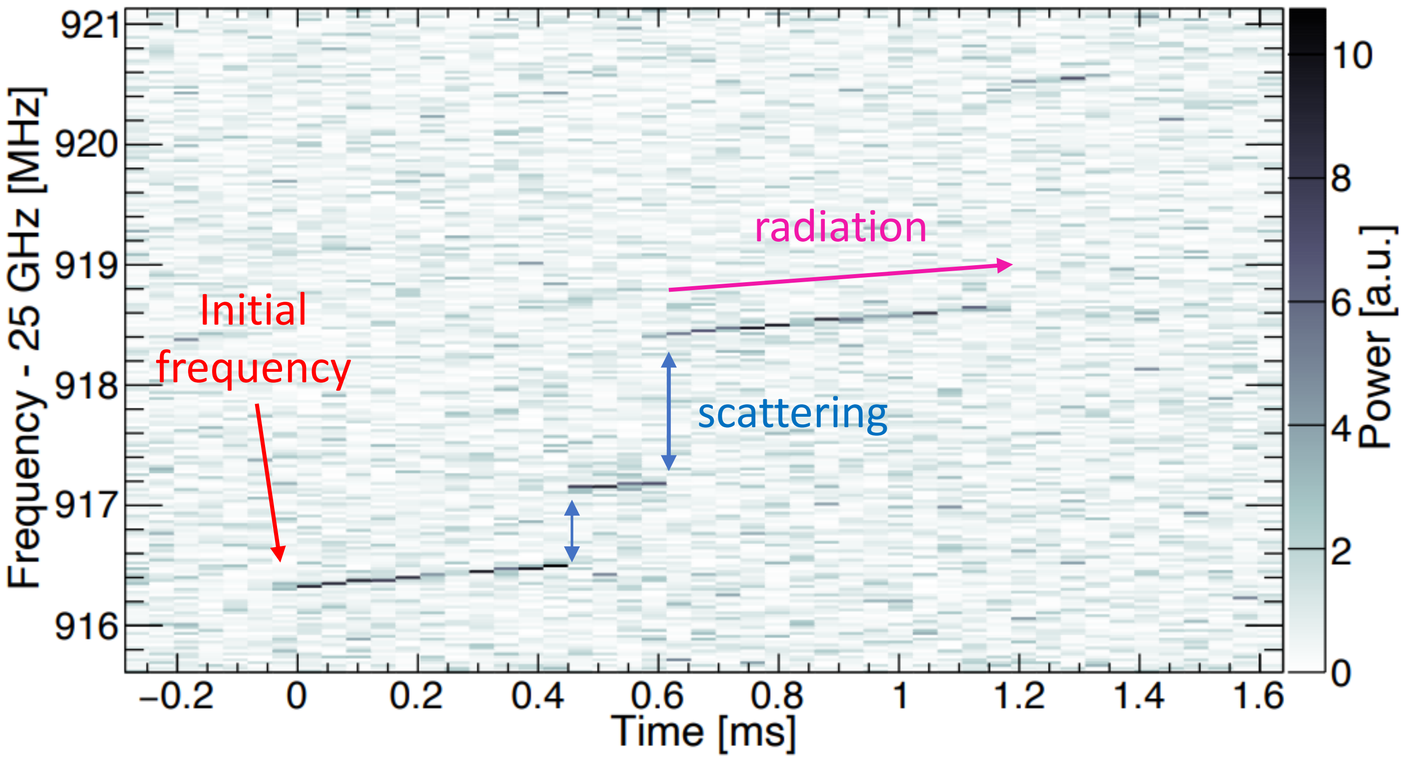
$$\omega_c = \frac{eB}{\gamma m_e} = \frac{e\,B}{m_e + E_{kin}/c^2}$$

Cyclotron Radiation Emission Spectroscopy (CRES)

J. Formaggio and B. Monreal, Phys. Rev D 80:051301 (2009)

Methodology: CRES

First tritium beta decay electron CRES spectrogram



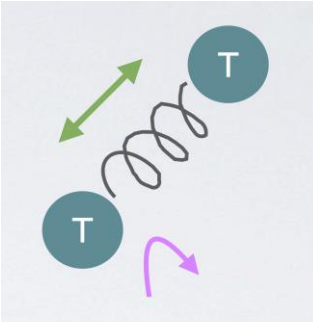
$$\omega_c = \frac{eB}{\gamma m_e} = \frac{e\,B}{m_e + E_{kin}/c^2}$$

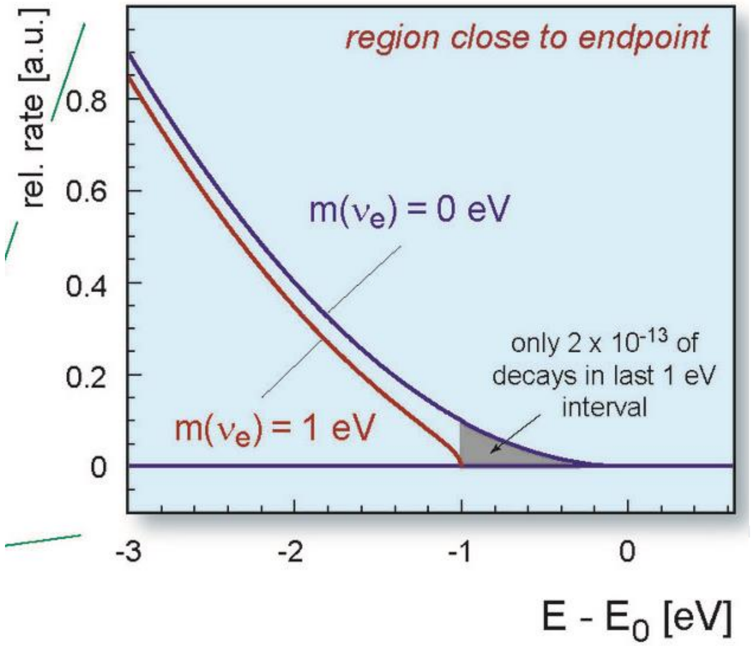
Esfahani, A. Ashtari, et al. "Tritium Beta Spectrum Measurement and Neutrino Mass Limit from Cyclotron Radiation Emission Spectroscopy." (2023).

Project 8:

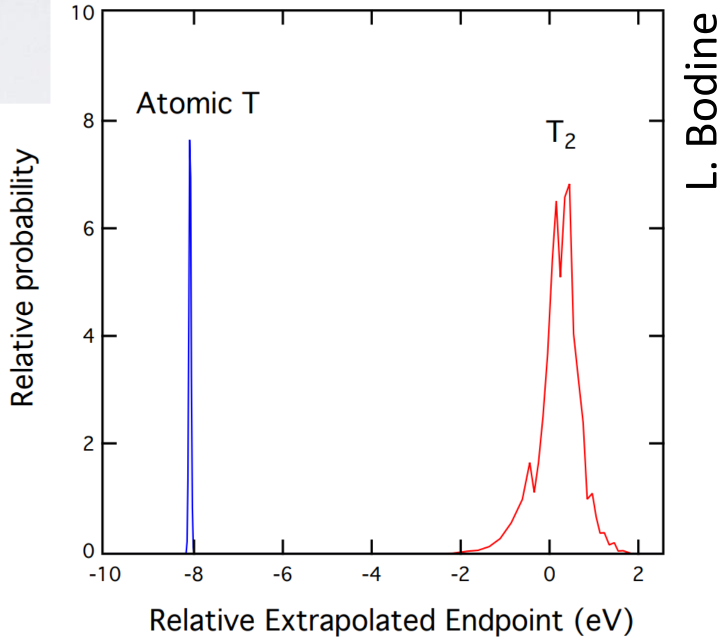
A frequency-based approach towards the measurements of the neutrino mass using ultra cold atomic tritium with 40 meV/c^2 sensitivity to m_β ?

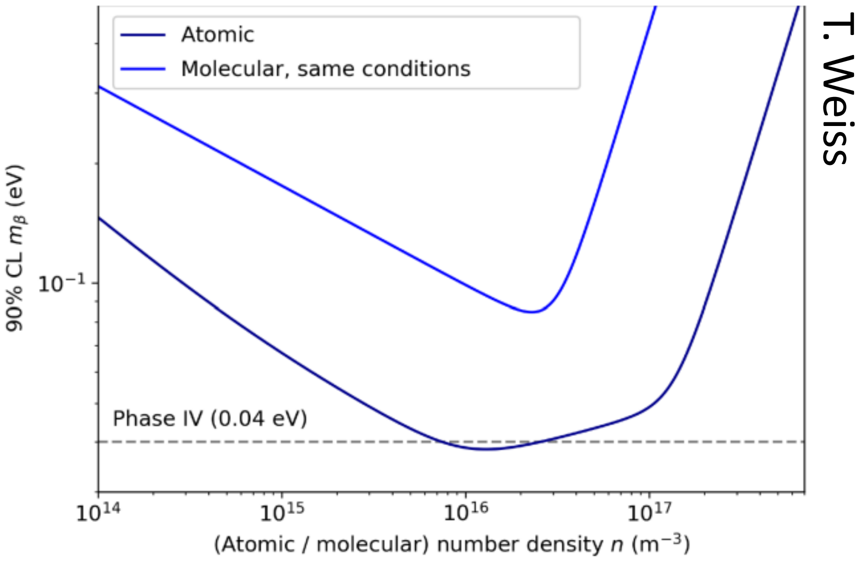
Methodology: Atomic Tritium





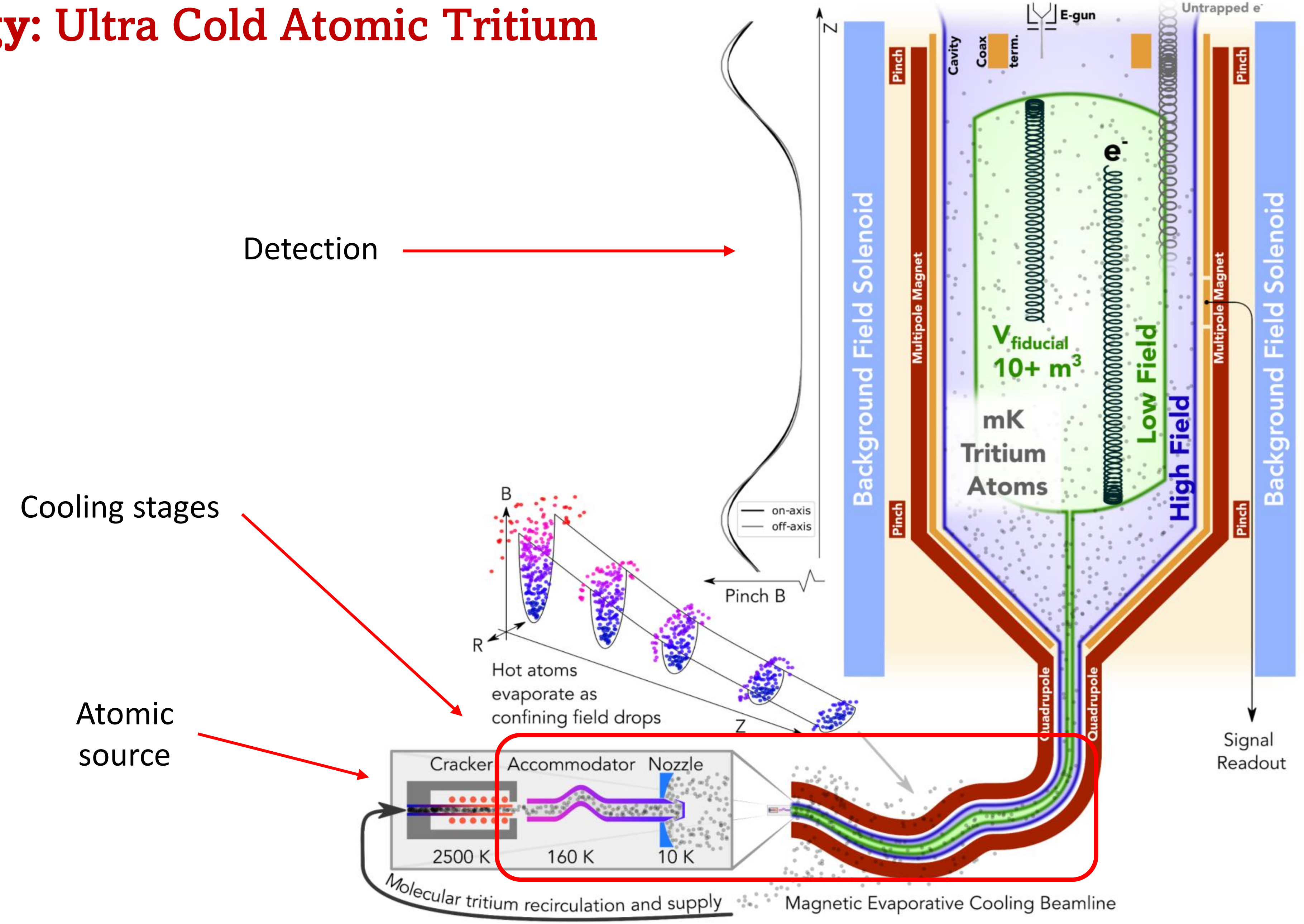
- event rarity
- molecular state limits sensitivity to 0.1 eV
- background noise





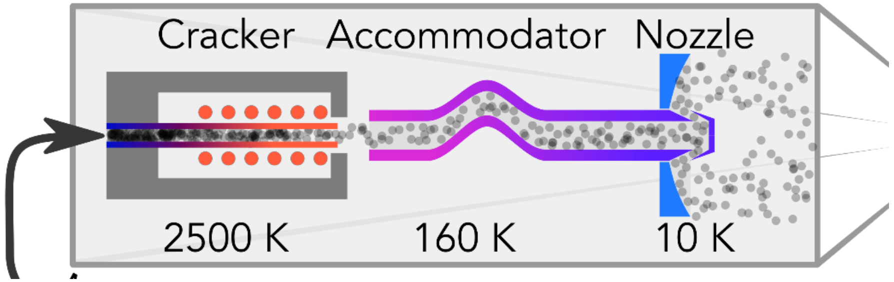
$m_\beta \geq 40$ meV/c^2

Methodology: Ultra Cold Atomic Tritium

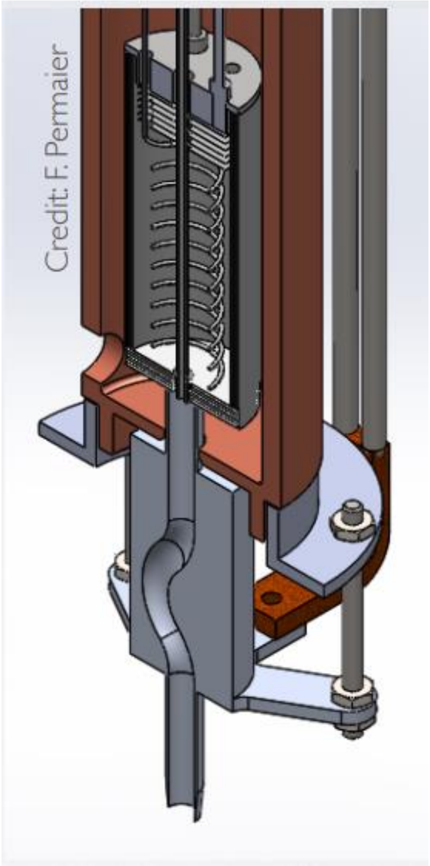


A. Lindman

Project 8 in Mainz:



- Developing the source for Project 8 using an atomic hydrogen beam
- Determining dissociation efficiency of the setup
- Designing and constructing accommodator and nozzle (currently on initial stages)
- Test with tritium at the TLK facilities (future steps)

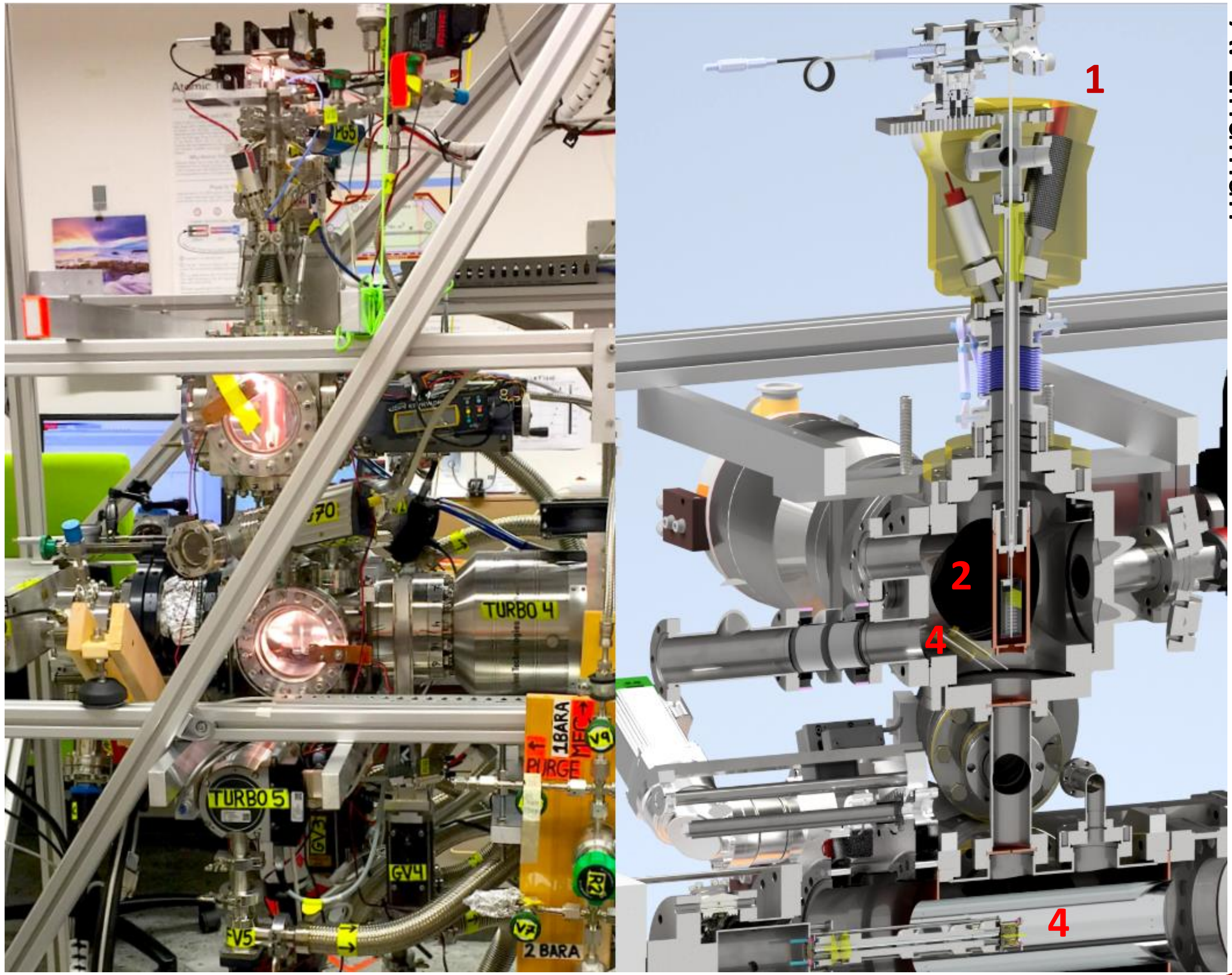


Atomic Hydrogen Setup:

Current R&D efforts are focused on an Atomic Hydrogen Setup.

Atomic Hydrogen Setup components:

1. Flow Controller to set hydrogen flow rate
2. Hydrogen cracker to produce hydrogen atoms
3. High vacuum system for good signal to noise ratio
4. Mass Spectrometer + Wire detector for beam characterization

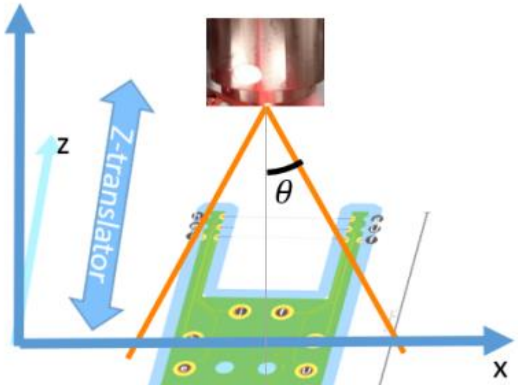


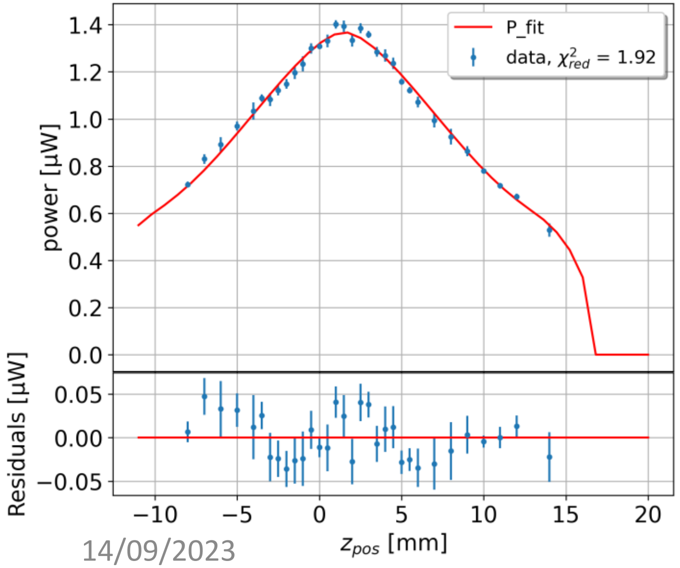
A. Lindman

Atomic Hydrogen Setup:

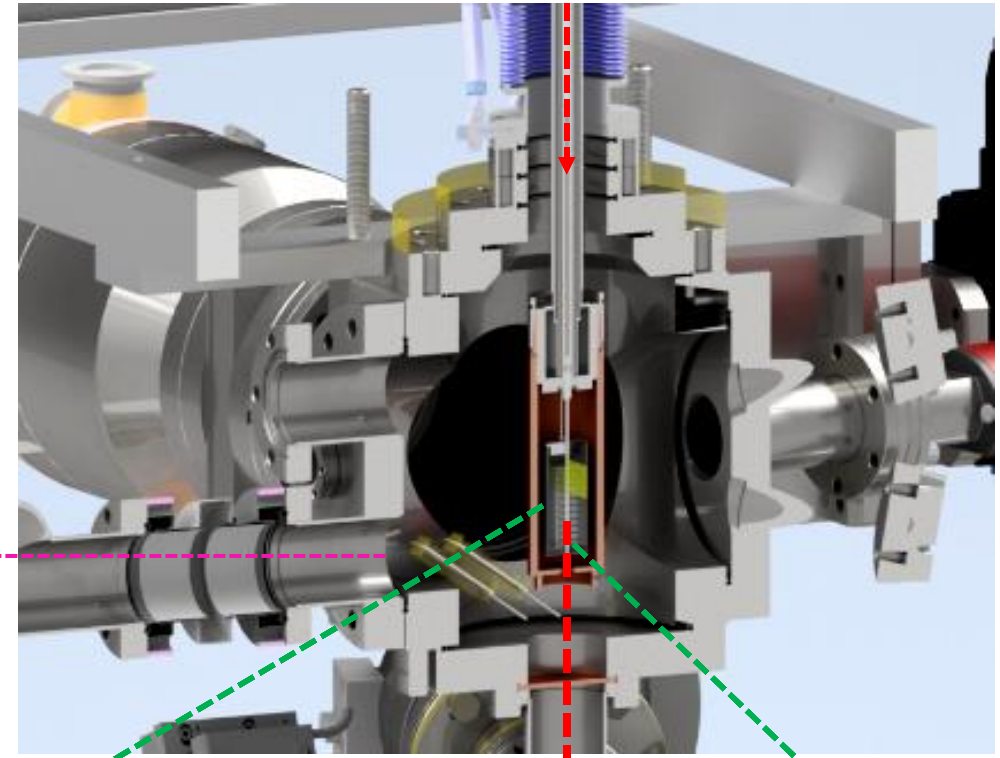
Goal: 10^{19} atoms/s

C. Matthé





Hydrogen gas



Wire detector

Filament heating up to ~2300 K

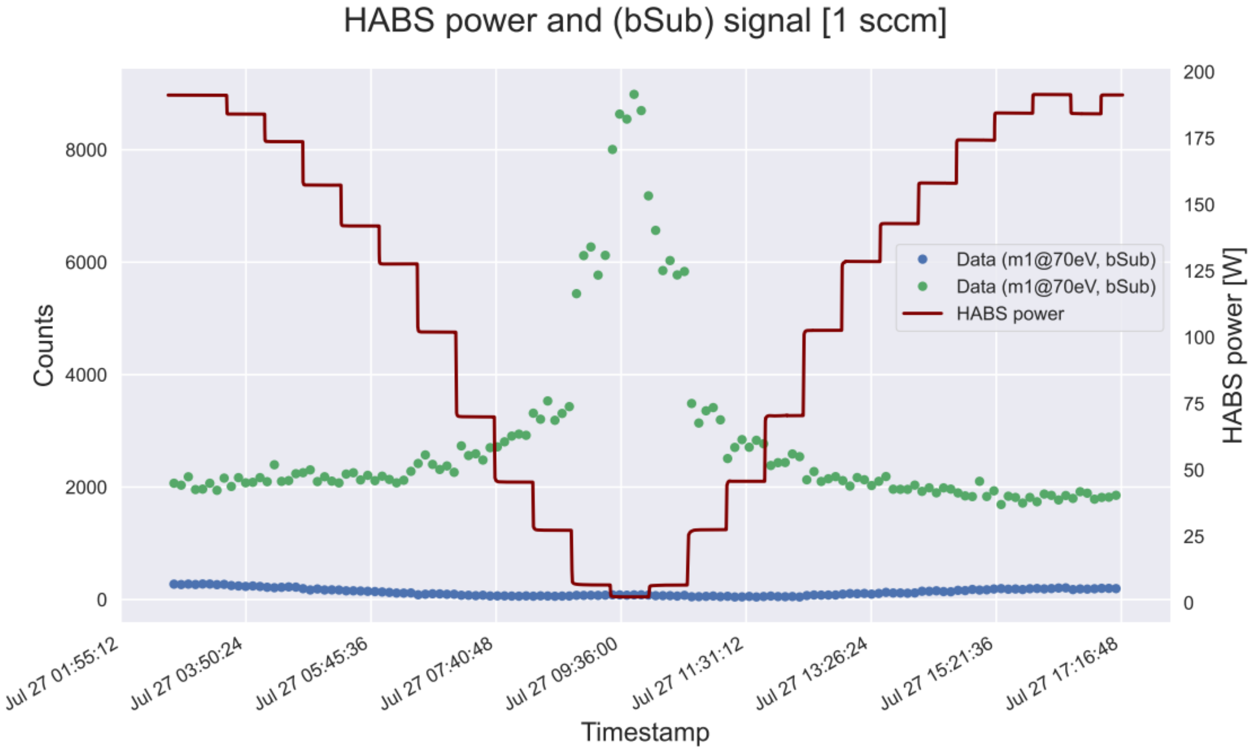
Hydrogen atoms (hopefully)

1 mm tungsten capillary

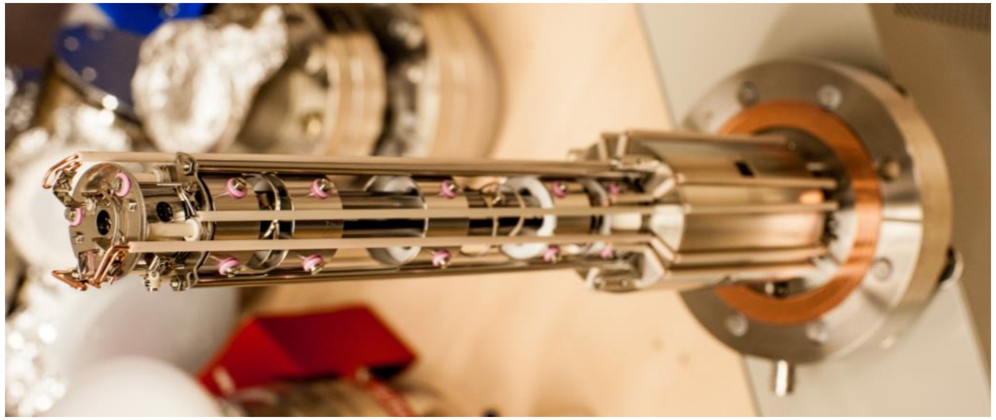
PROJECT 8

Atomic Hydrogen Setup:

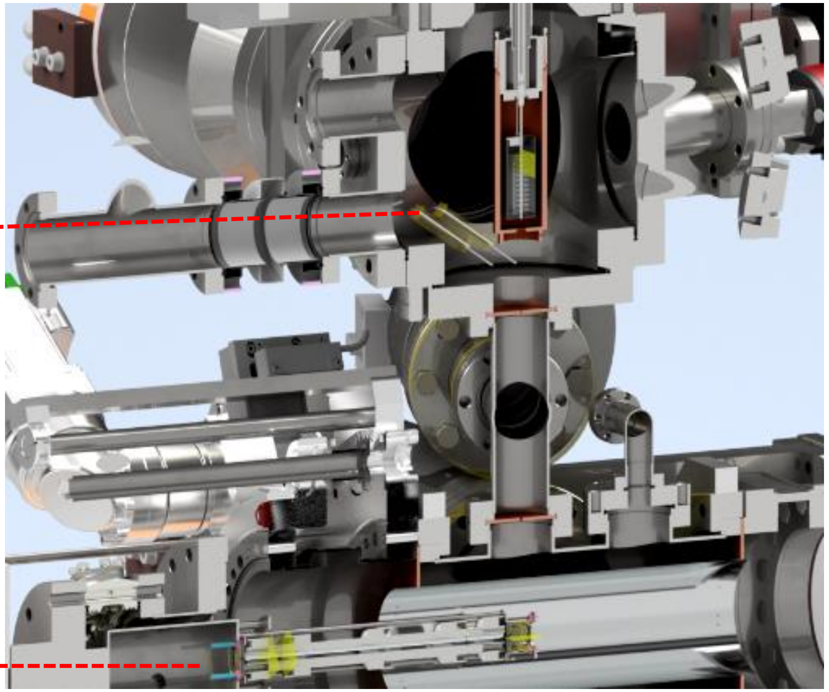
Goal: 10^{19} atoms/s



L. Thorne



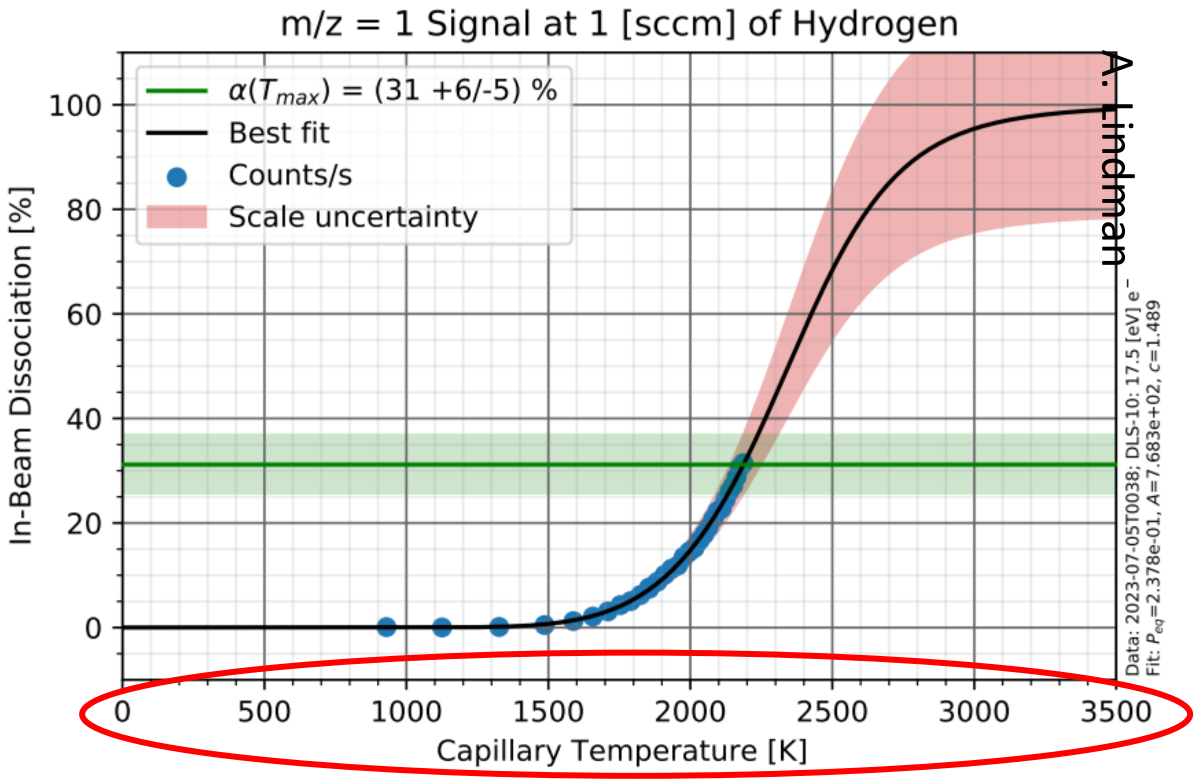
Wire detector



Mass Spectrometer

Atomic Hydrogen Setup: Source Uncertainties

H2 dissociation efficiency dependent on the source temperature.



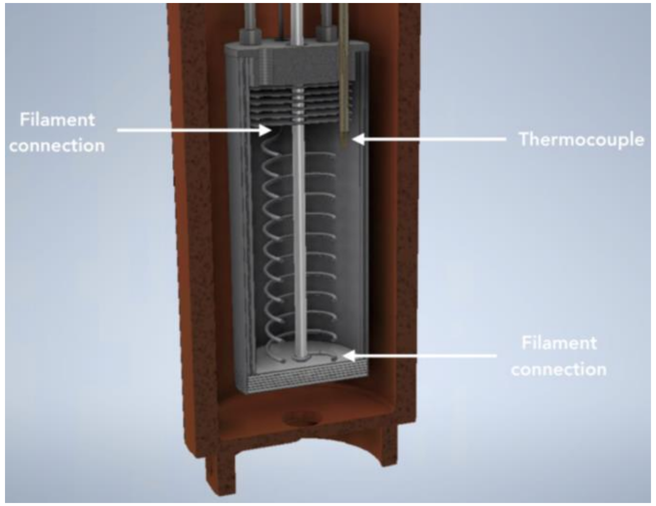
Challenges:

- No direct contact temperature measurements possible (T ~2300 K).
- Ultra high vacuum (1 x 10^{-10} hPa).
- Opening the setup to insert new devices takes a lot of time.
- Current method using a thermocouple is not reliable.

Temperature of HABS is not well calibrated!

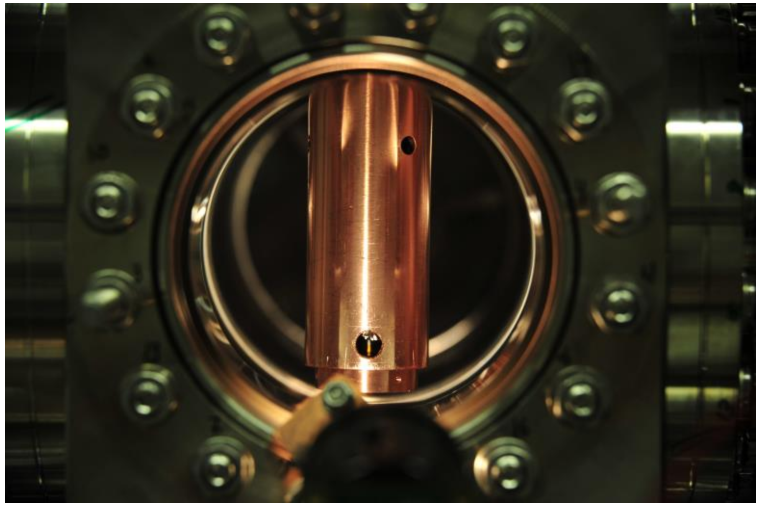
Temperature Measurement Methods:

1. Thermocouple Measurements



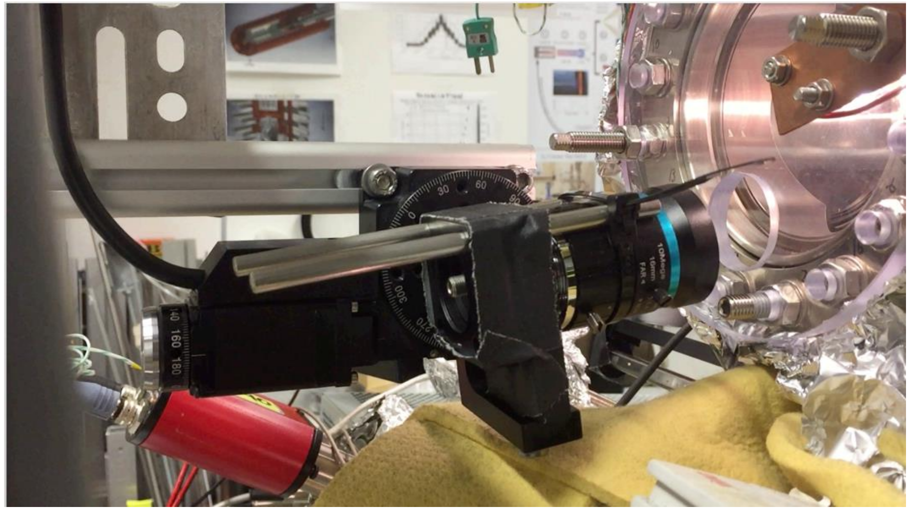
- Aging problems
- Currently $\Delta T \sim 200^o$

2. Optical Spectrometry



3. Camera Imaging

Temperature Measurement: Optical Spectroscopy



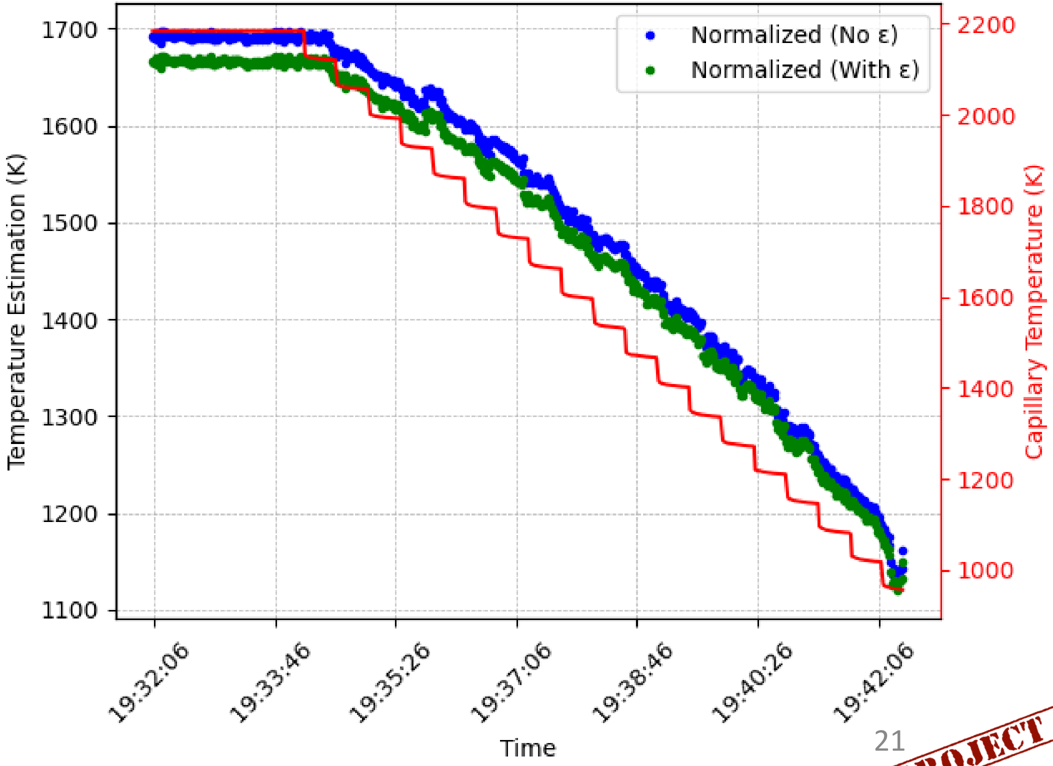
Benefits:

- Capillary observed through a small opening.
- Temperature can be derived from a fit to blackbody spectrum
- Sensitive to small temperature changes.

Issues:

- Lower estimated temperatures
- Dependent on tungsten emissivity
- Small Calibration issues

Currently working with an IR Spectrometer for better peak resolution and temperature estimation!



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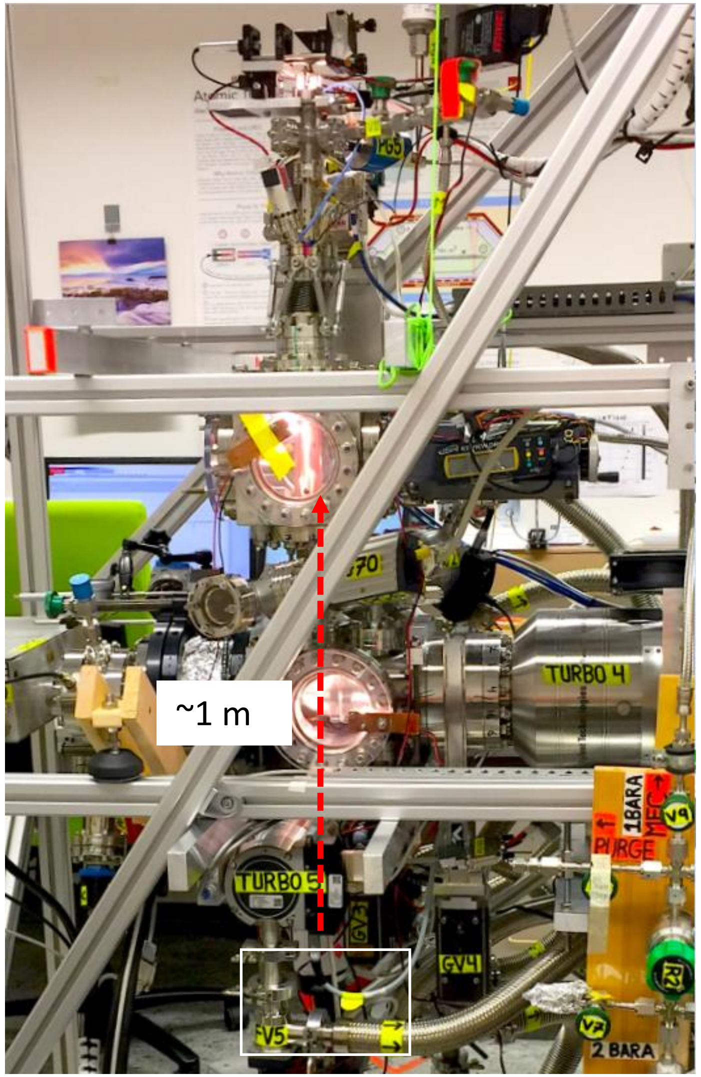
Temperature Measurement: Camera Imaging



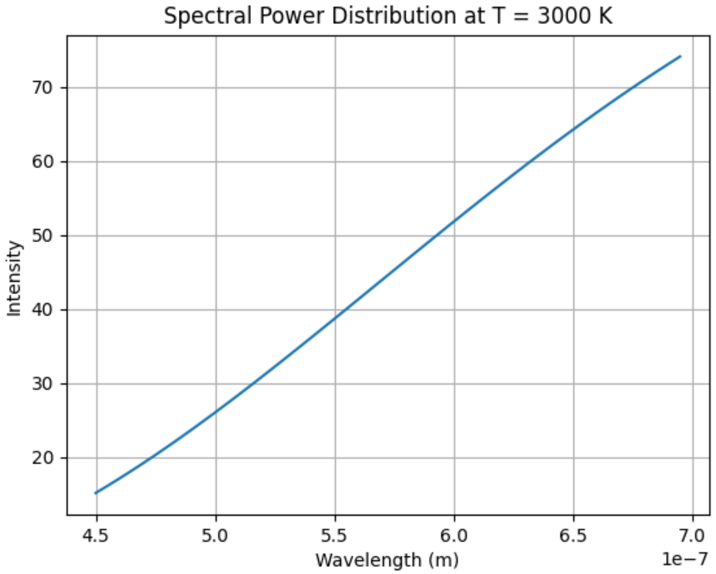
- A Raspberry Pi camera module and a 200 mm camera lens are placed at the bottom of the beamline.
- Light with intensity (I) goes through red/green/blue filters on the CMOS sensor.

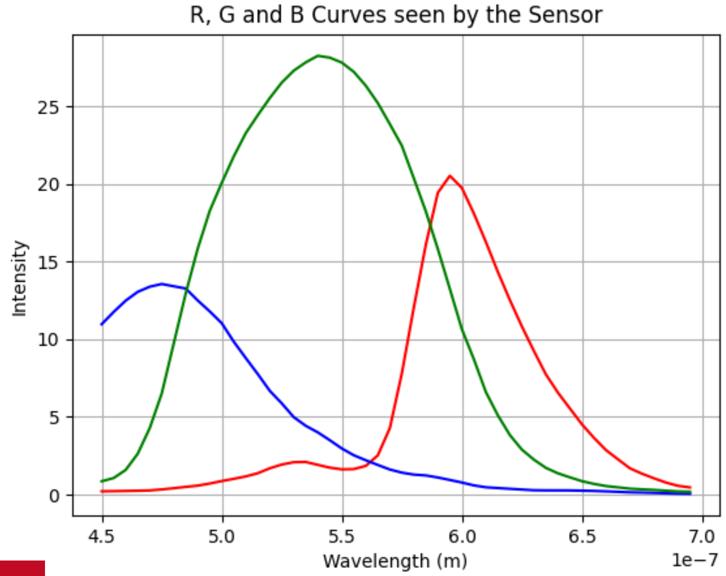
$$I_p = \int_{400\,nm}^{700\,nm} P(\lambda, T)\ T_{IR}(\lambda)\ T_{glass}(\lambda)\ \rho_p(\lambda)\, d\lambda$$

Image of the hot capillary

PROJECT 8

Temperature Measurement: Camera Imaging





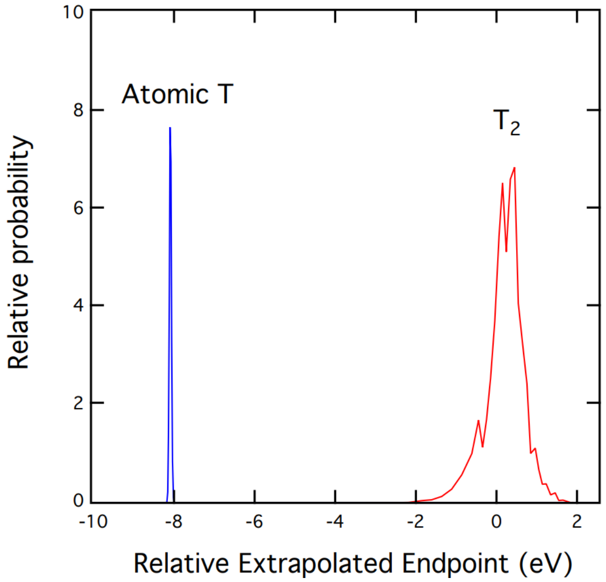
Benefits:

- Spatial resolution of temperature distribution can be determined across the image field
- Sensitive to temperature changes
- No pixel saturation for our application

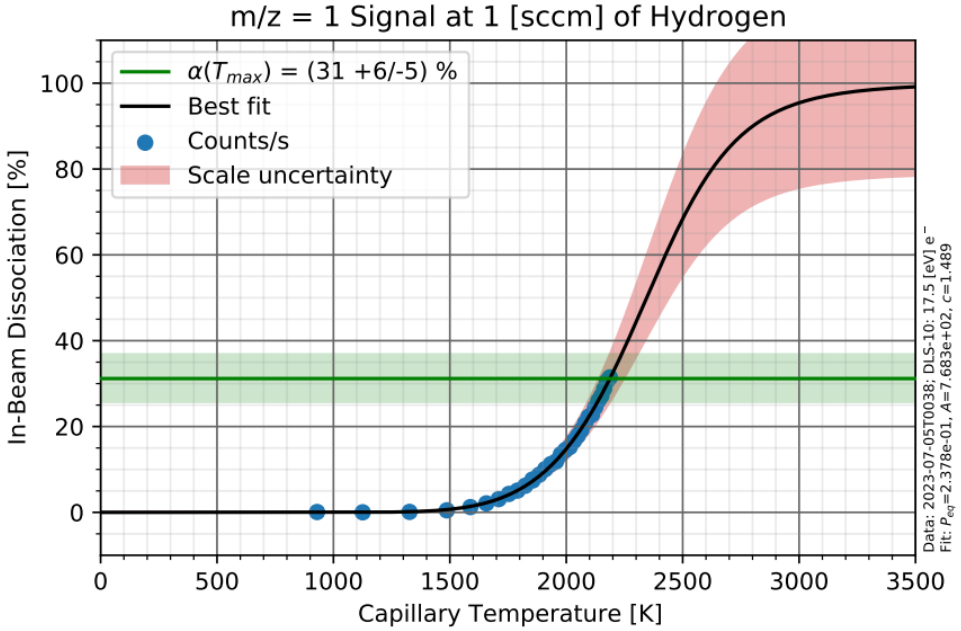
Limitations:

- Image processing steps have to be well known and well implemented
- Known Temperature source for calibration is necessary
- Temperate range limitations:
  - No capillary image until T = 1050 K yet

Summary:



- Project 8 uses CRES for tritium spectroscopy.
- Atomic Tritium is crucial to reaching the $m_\beta \geq 40$ meV/c^2 neutrino mass sensitivity.
- Current R&D efforts on an Atomic Hydrogen Source at Mainz:
  - Reaching the goal atomic flux
  - Finding H2 dissociation efficiency of HABS
  - Absolute temperature measurements



THANK YOU!

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Thomas Thümmler

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PRISMA

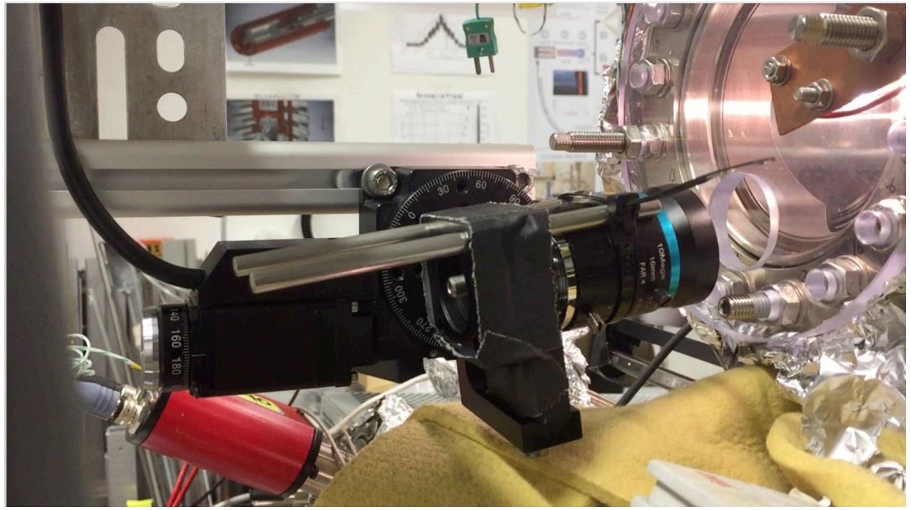
PROJECT 8

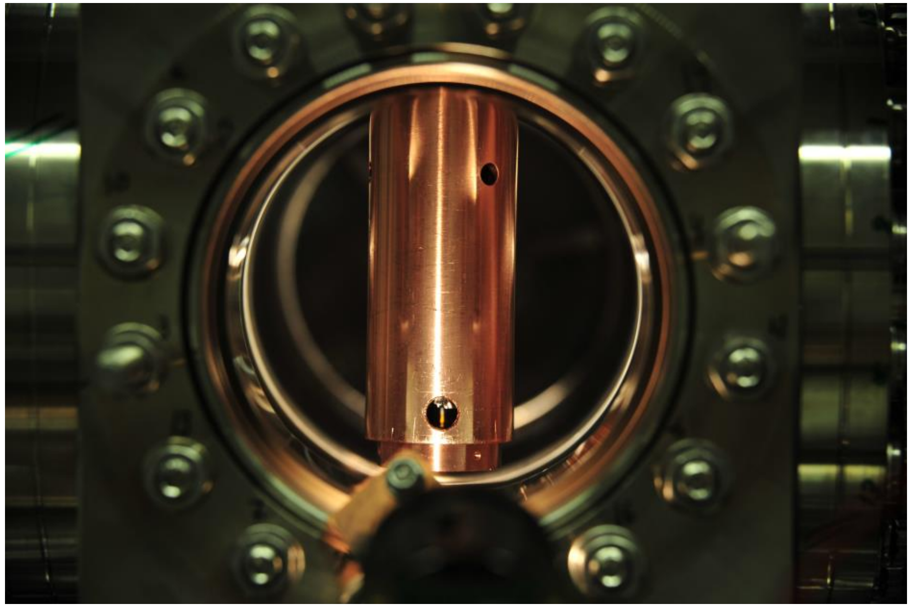
Backup Slides

Optical Spectroscopy

- Situated located at atmospheric pressure.
- Capillary observed through a small opening.
- Spectrometer calibrated for the 350 – 695 nm wavelength range.
- Temperature can be derived from a fit to blackbody spectrum:

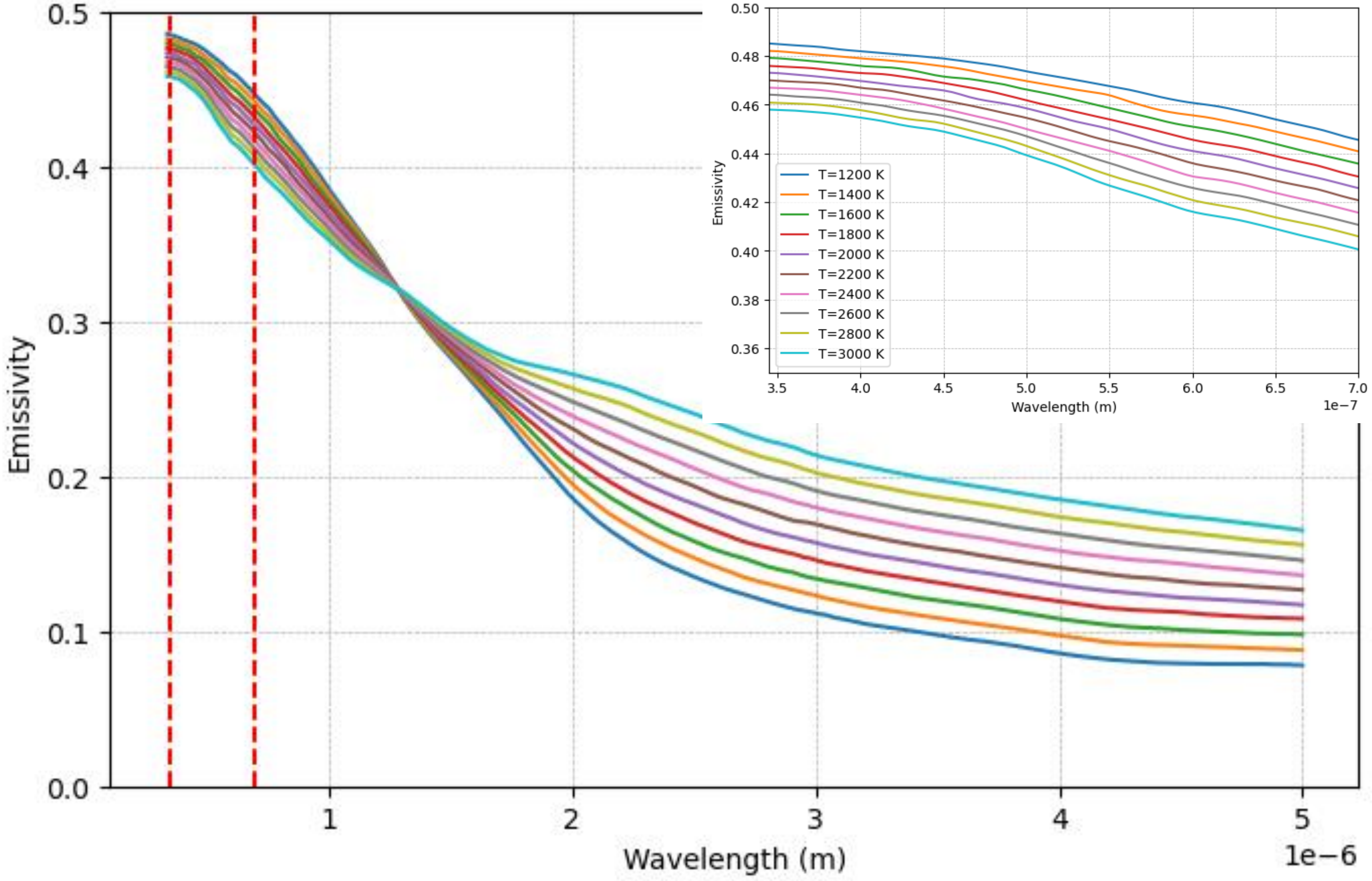
$$I\,(\lambda, T) = \varepsilon\,(\lambda, T)\,\frac{2\,h\,c^2}{\lambda^5}\,\frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1}$$





Method 2: Optical Spectroscopy

Tungsten emissivity is a function of both temperature T and λ. Empirical values for a tungsten wire were adapted [2].



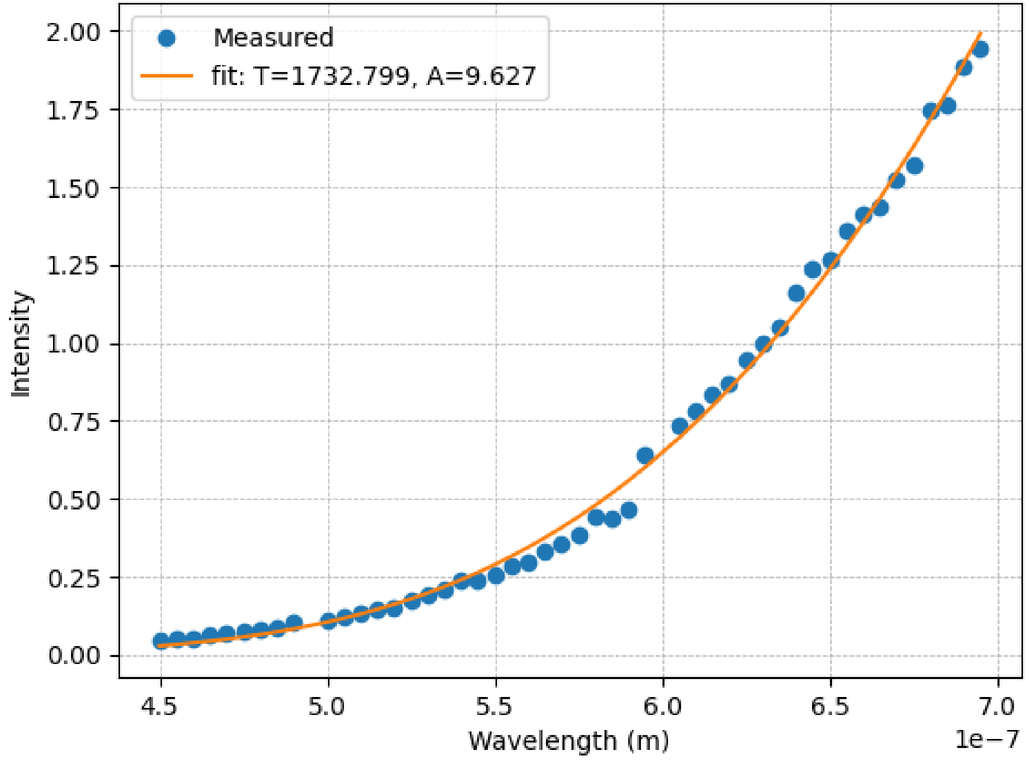
$\varepsilon\ (\lambda, T)$ dependent on:

- Surface roughness/uniformity
- Surface area
- Oxidation
- Aging

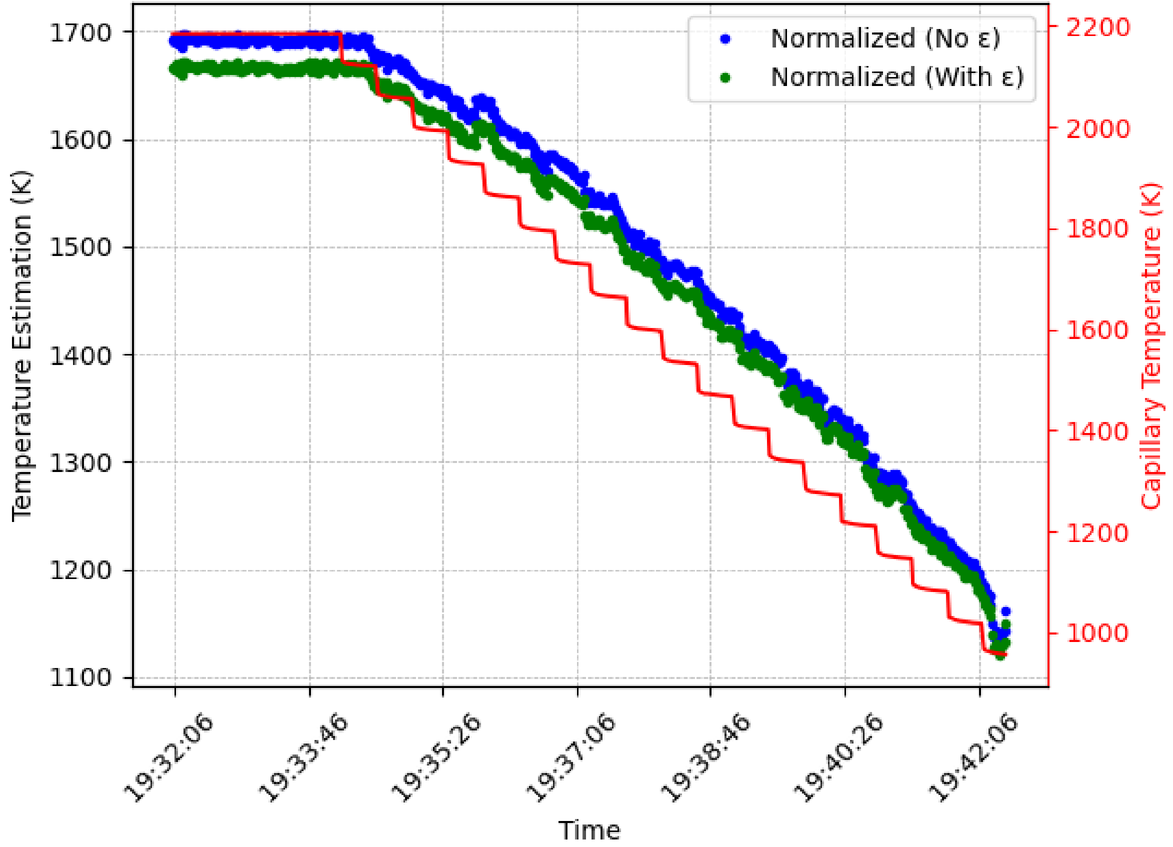
[2] Emissivity of tungsten from Thermophysical Properties of Matter, Vol. 7 – Thermal Radiative Properties, IFI/Plenum, New York, 1970

PROJECT 8

Method 2: Optical Spectroscopy Results

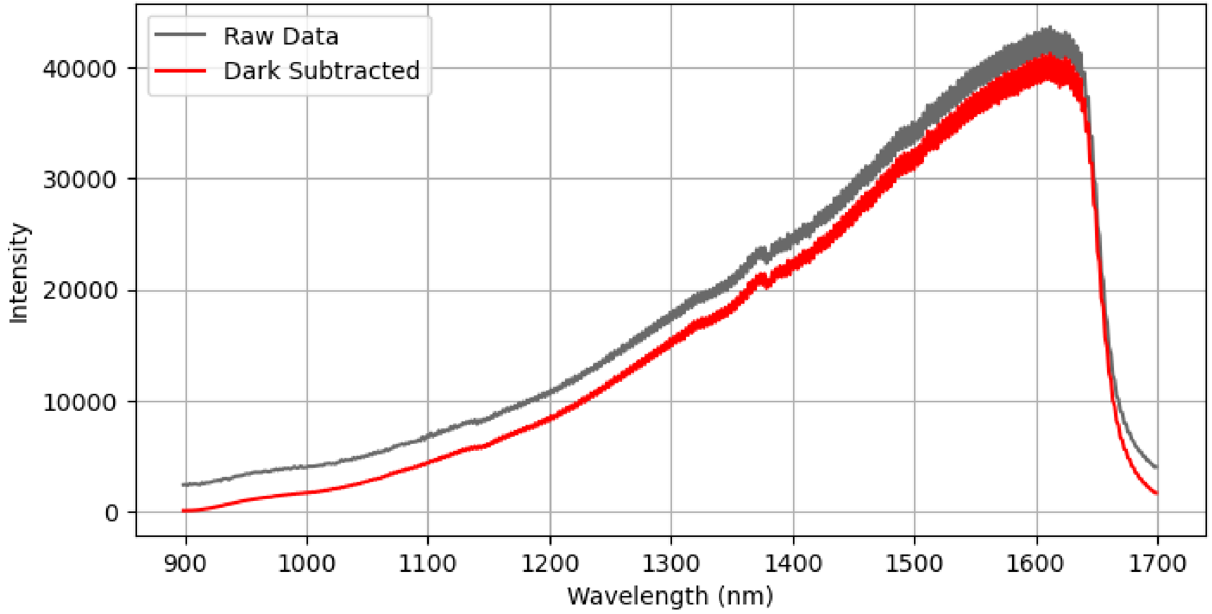


Single intensity spectra with Fit (λ, T, A).

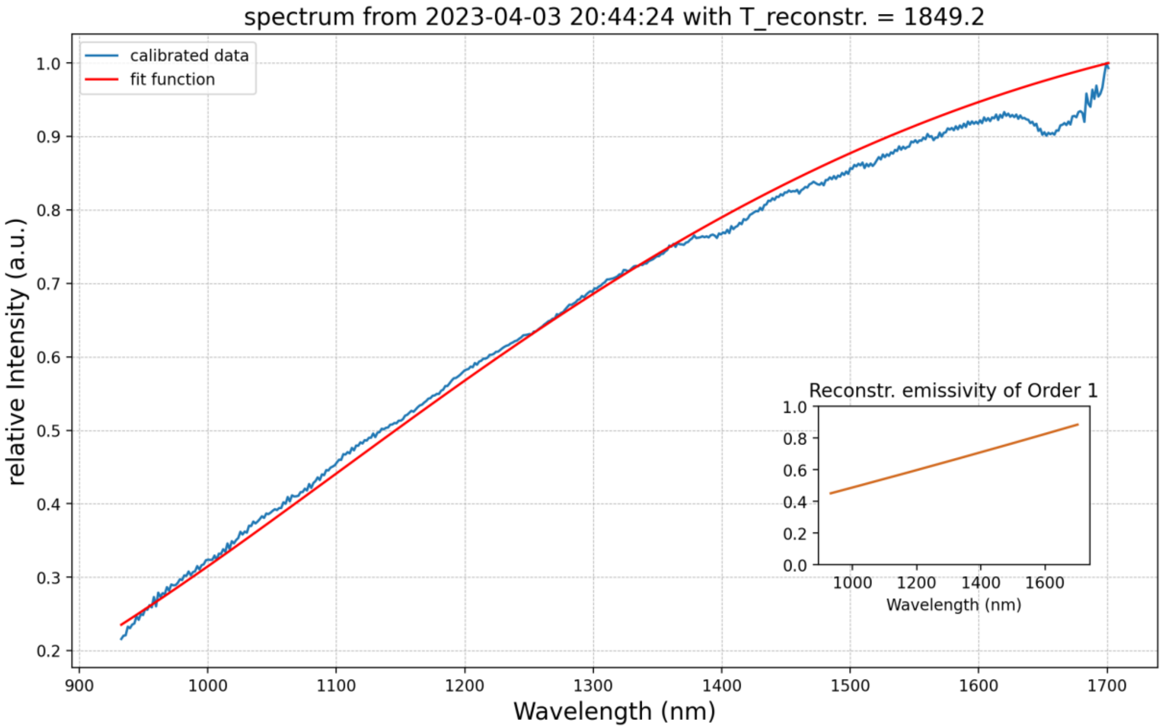


Quick temperature ramp down run results.

Infrared Spectroscopy

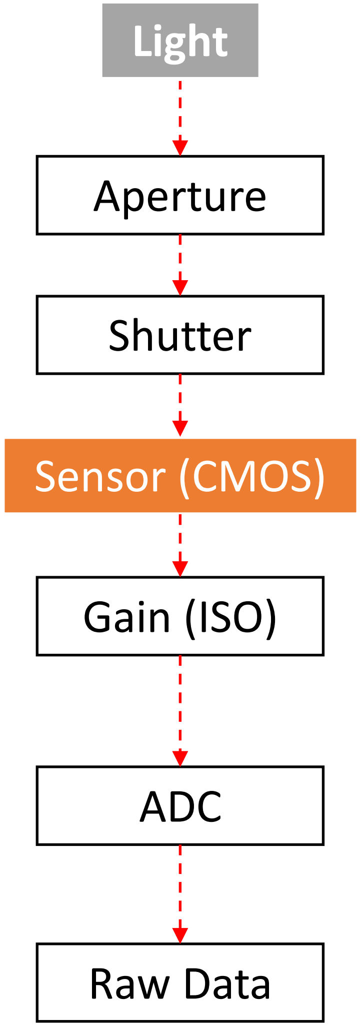


- Current spectrometer only semi-calibrated using a blackbody source
- Proper calibration coming



PROJECT 8

Method 3: Camera Imaging



Light with intensity (I) goes through red/green/blue filters on the CMOS sensor.

$$I_p = \int_{400\,nm}^{700\,nm} P(\lambda, T)\ T_{IR}(\lambda)\ T_{glass}(\lambda)\ \rho_p(\lambda)\ d\lambda$$

Where:

- $T_{IR}(\lambda)$: transmission coefficient of the infrared filter on the sensor,
- $T_{glass}(\lambda)$: transmission coefficient of the Kodial window of the vacuum chamber,
- $\rho_p(\lambda)$ is the R, G and B spectral sensitivity of the sensor from the Bayer filter,
- $P(\lambda, T)$ is the Power Spectrum of the blackbody.

$$P\,(\lambda, T) = \frac{2\,h\,c^2}{\lambda^5}\ \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1}$$

Method 3: Temperature Estimation from Images