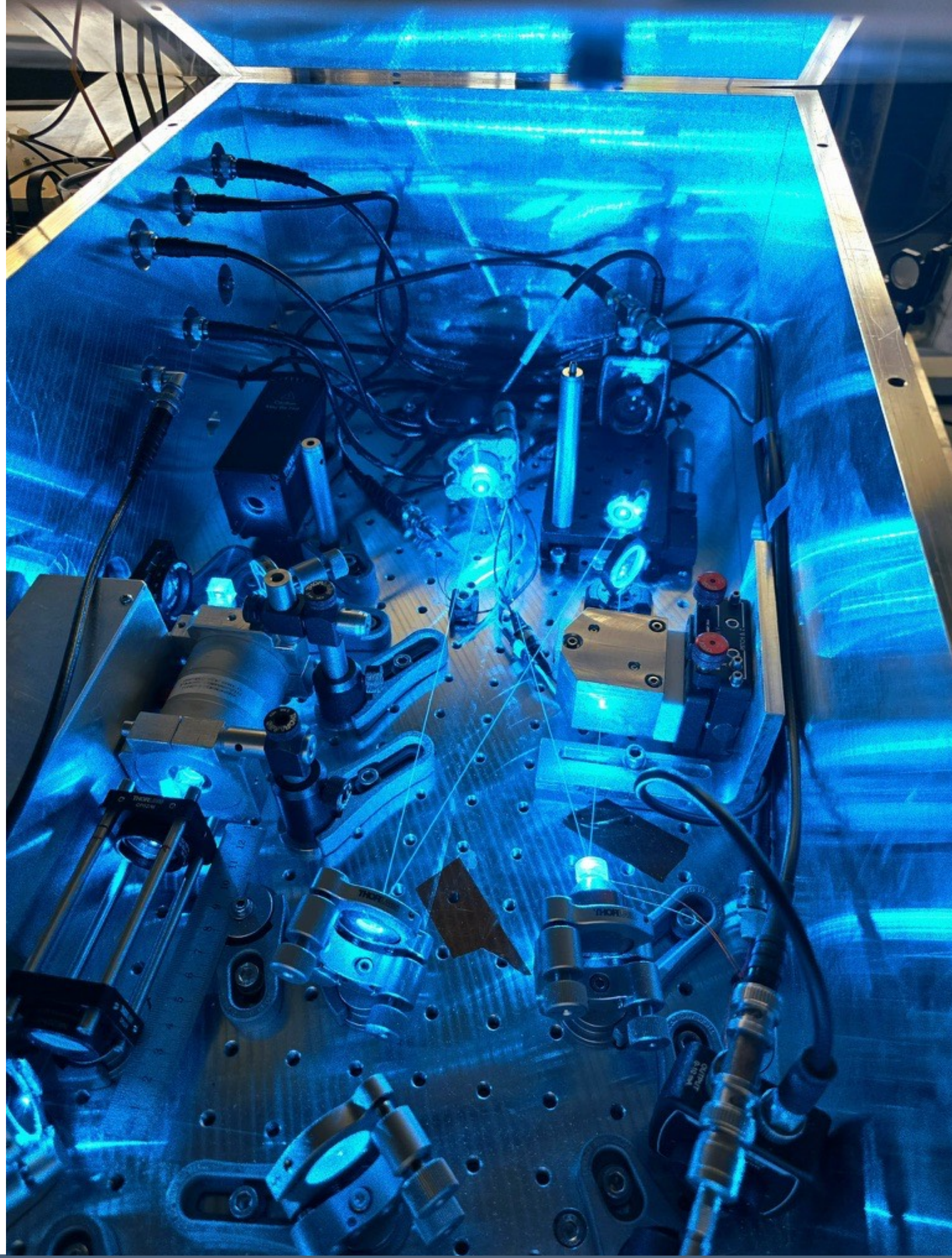
MU-MASS

Latest results and current status of the Mu-MASS experiment

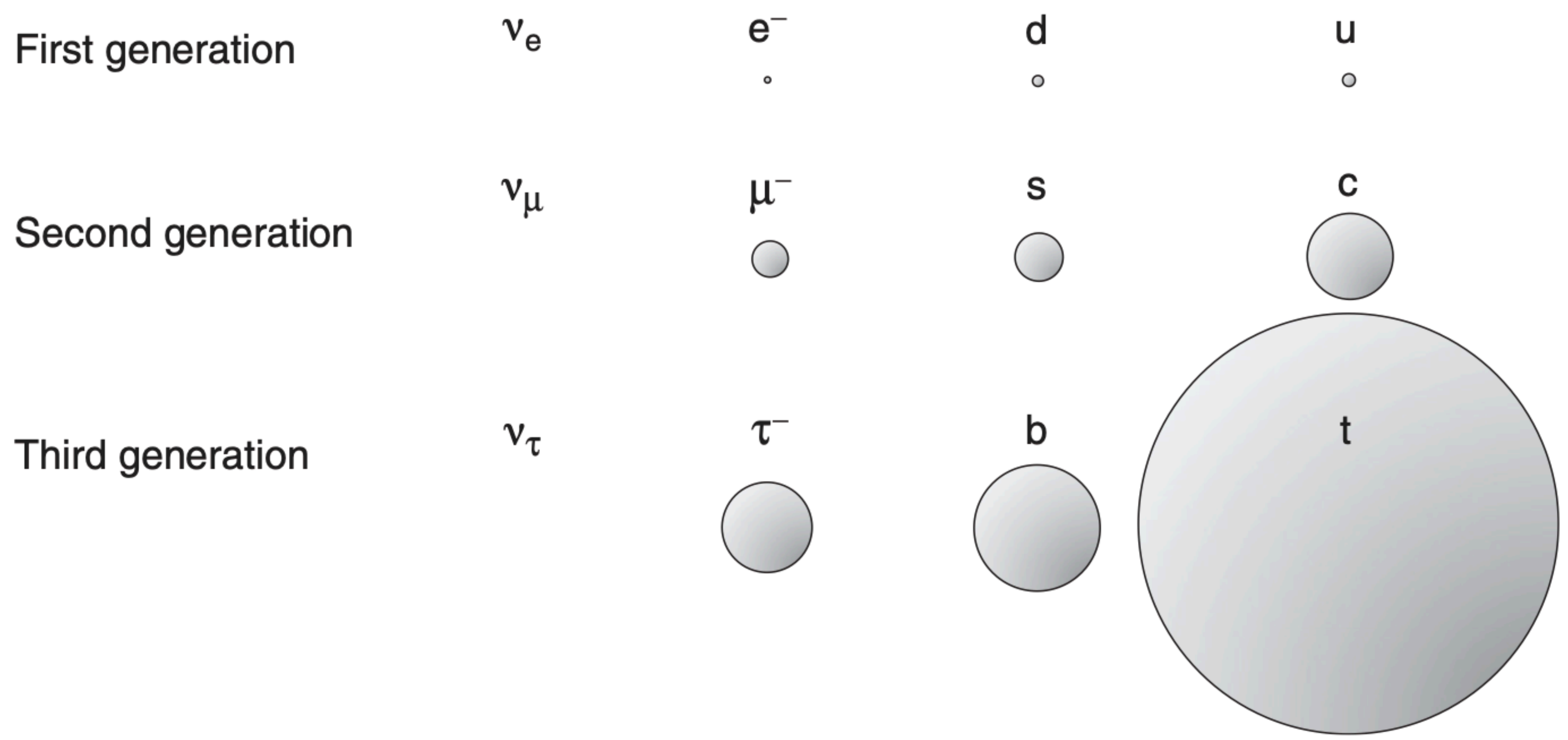


Marcus Mähring 24.06.2025, on the behalf of the Mu-MASS collaboration

Overview

- A brief introduction to leptonic atoms and spectroscopy
- The Mu-MASS Experiment (experimental setup, laser system)
- Future work and improvements

Leptonic Atoms and Muonium



Particle content of the standard model
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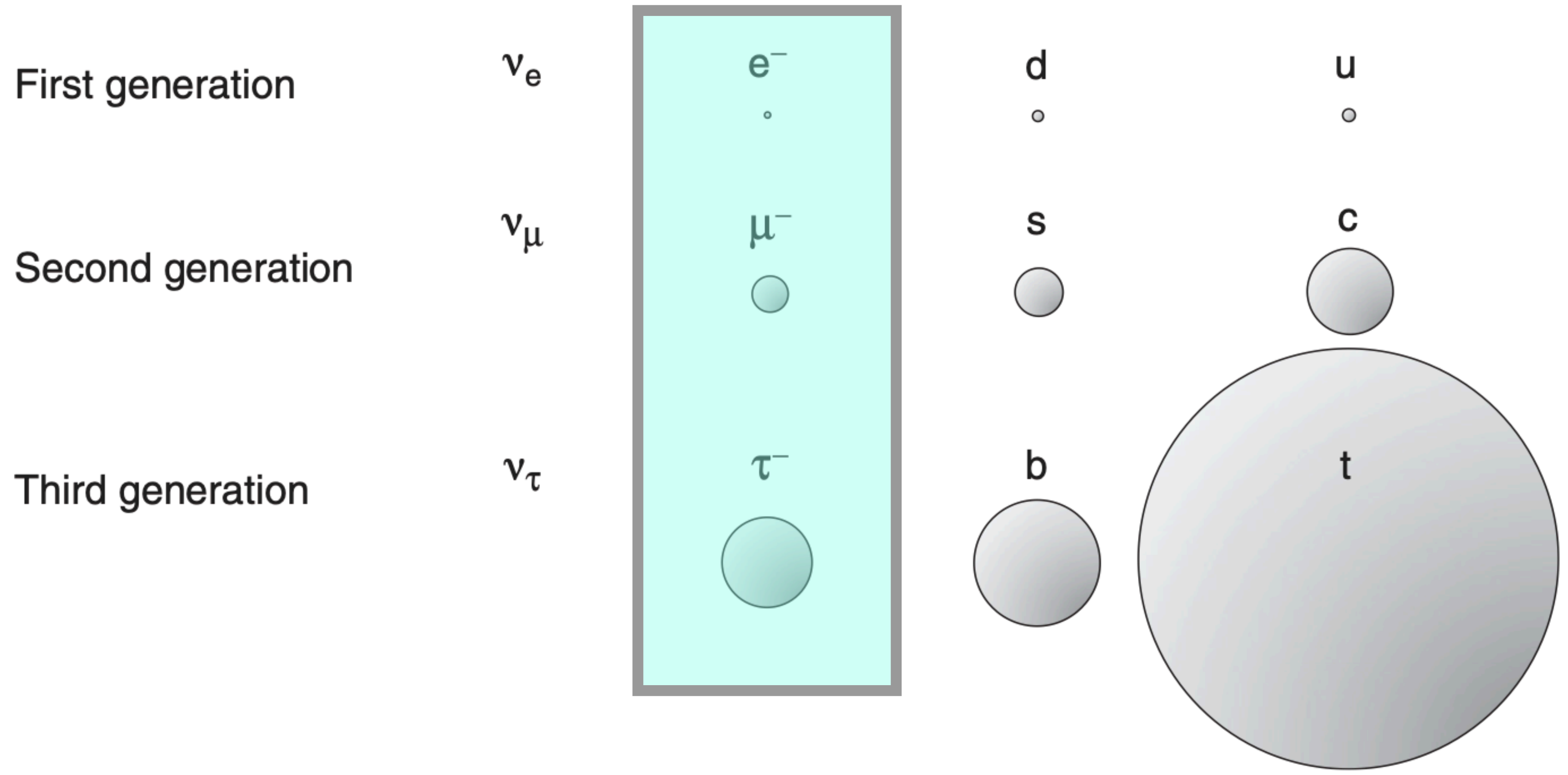
Leptonic Atoms and Muonium

- Leptonic atoms: QED bound systems containing only charged (anti-)leptons



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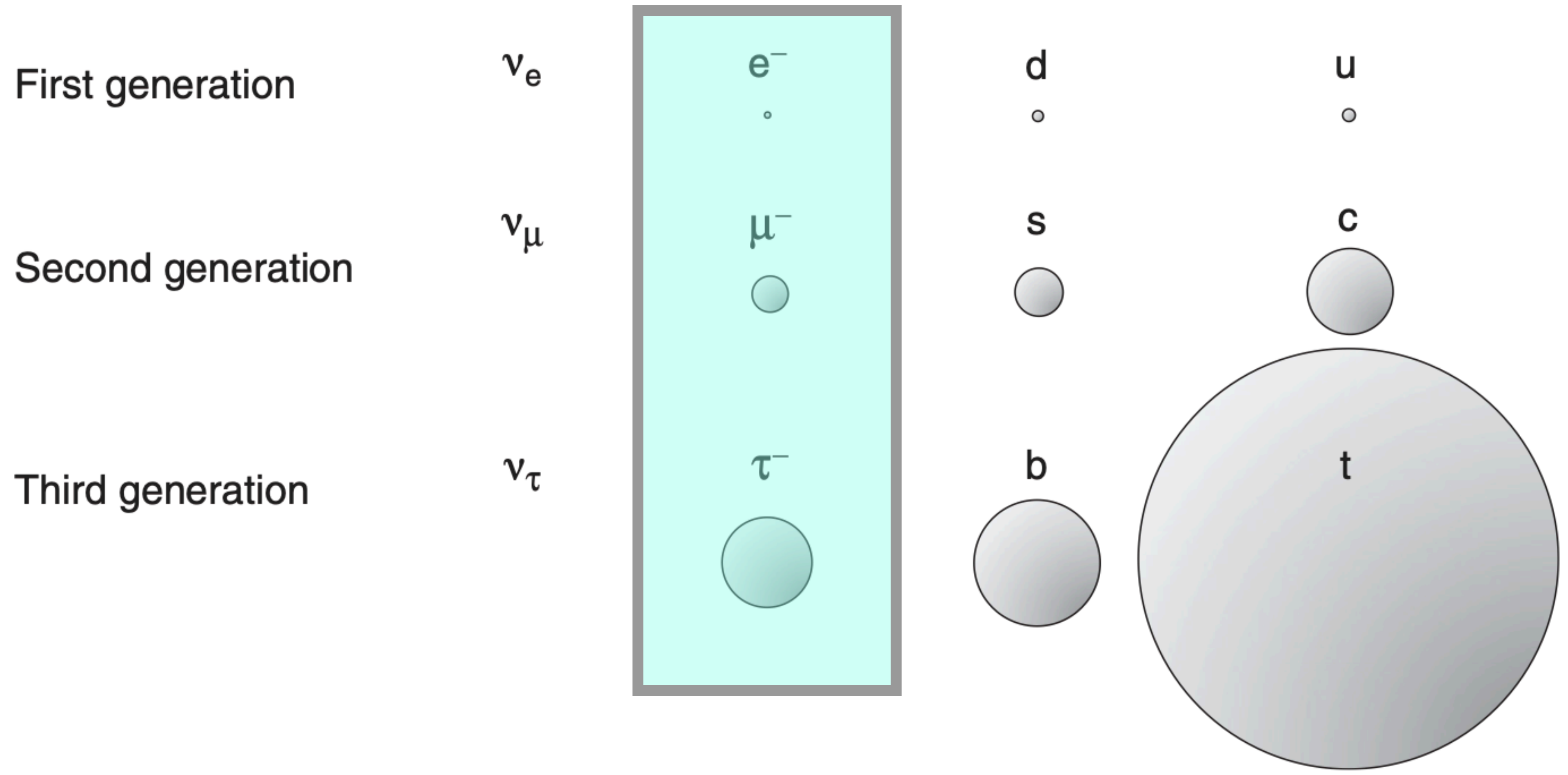

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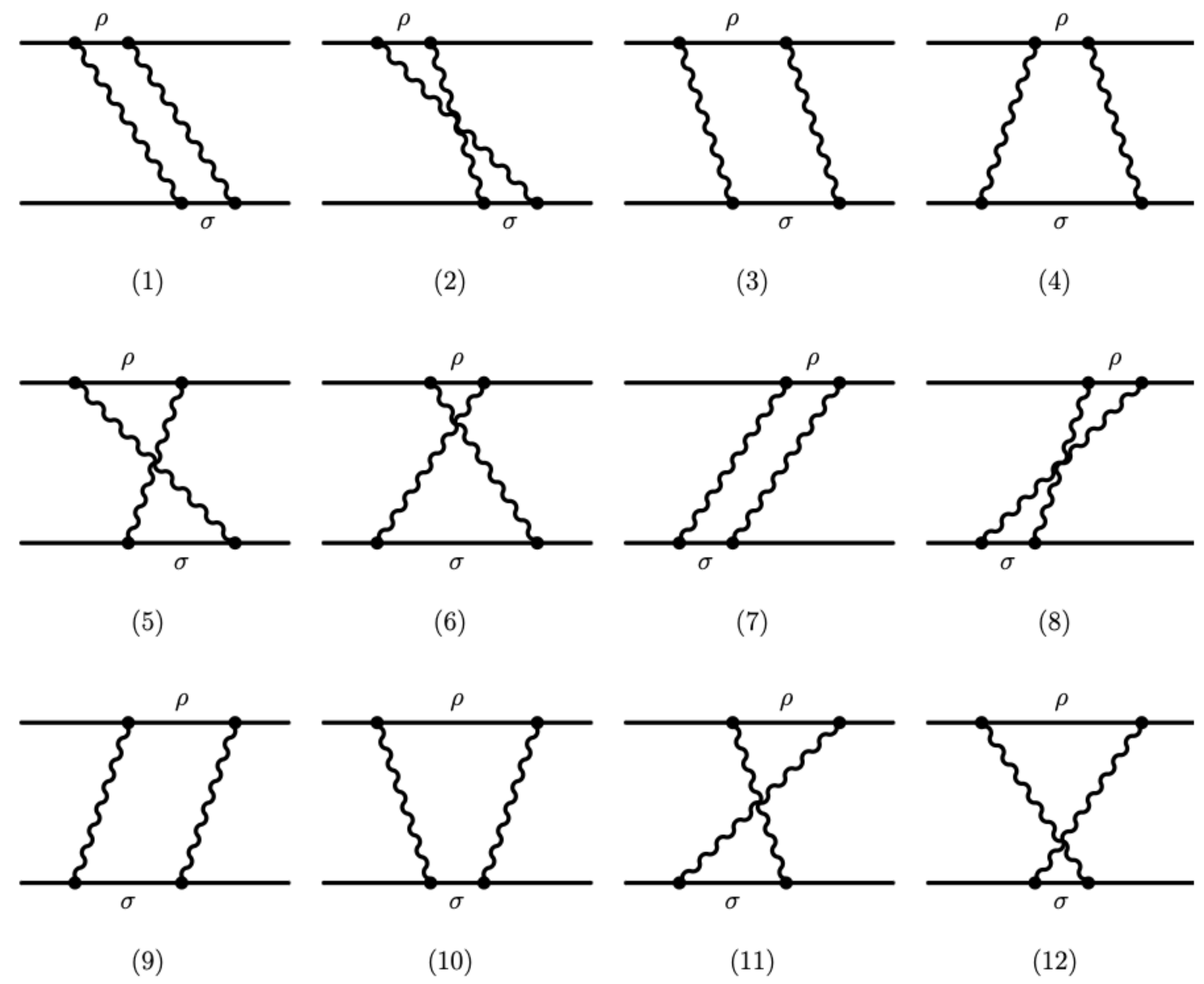

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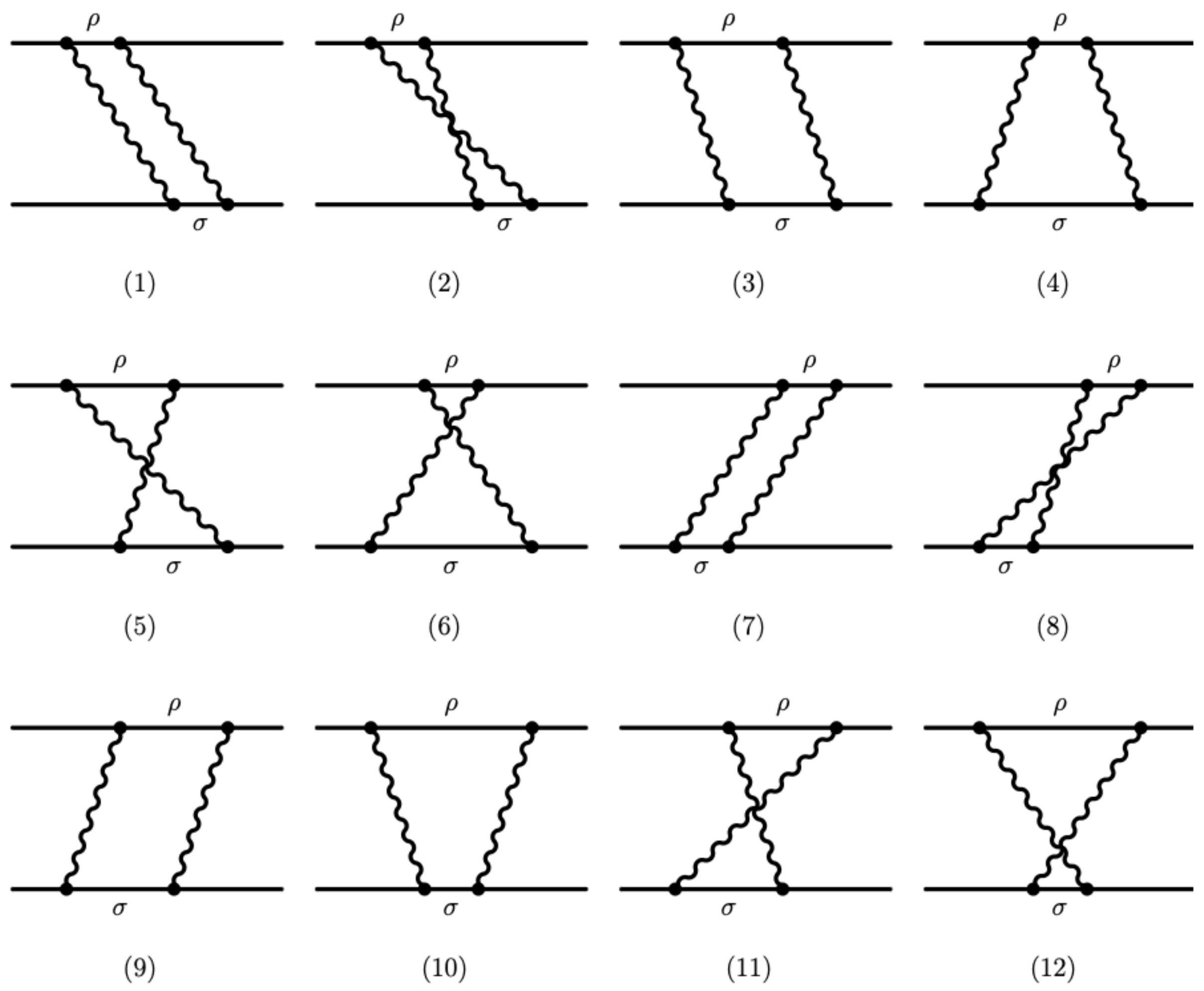

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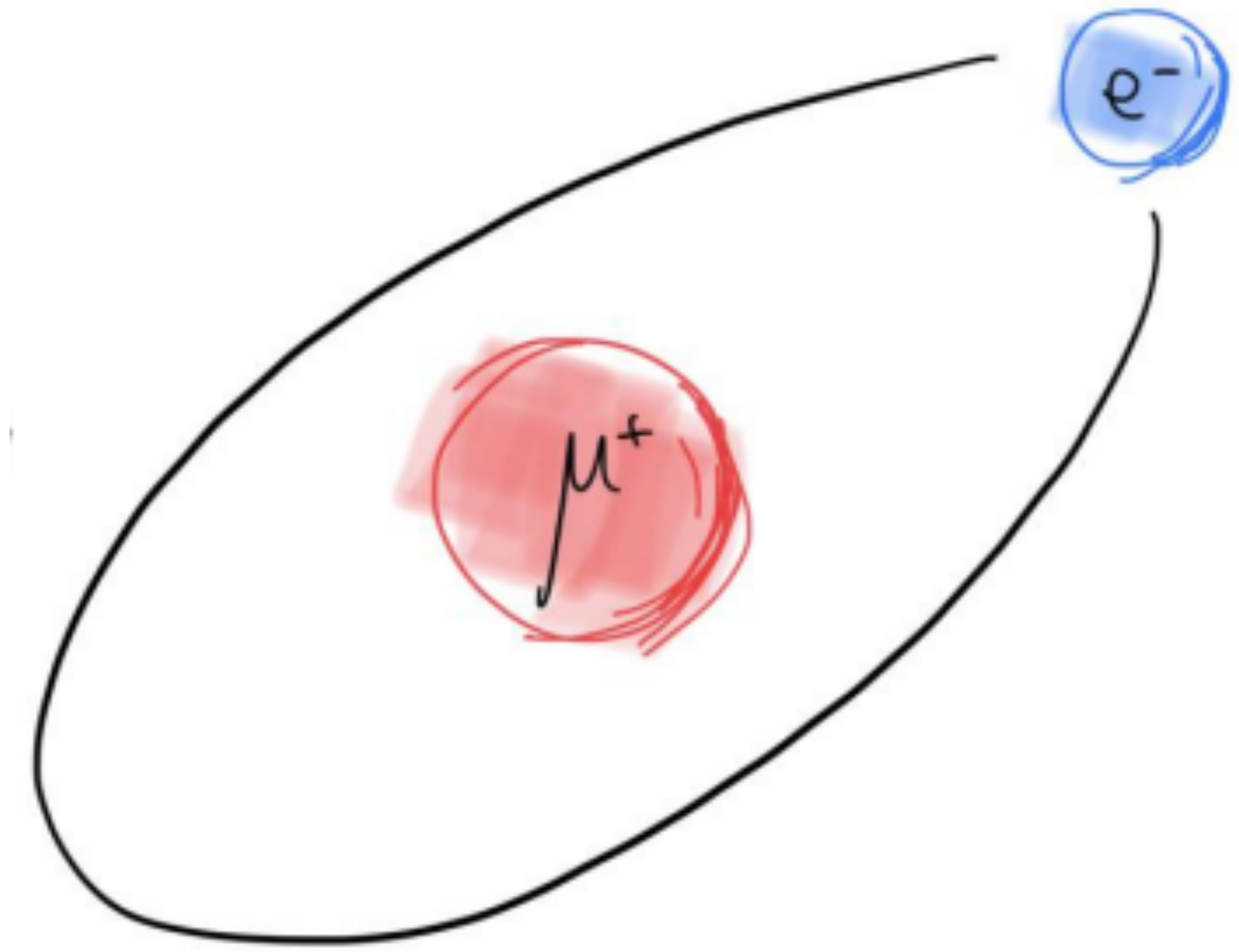

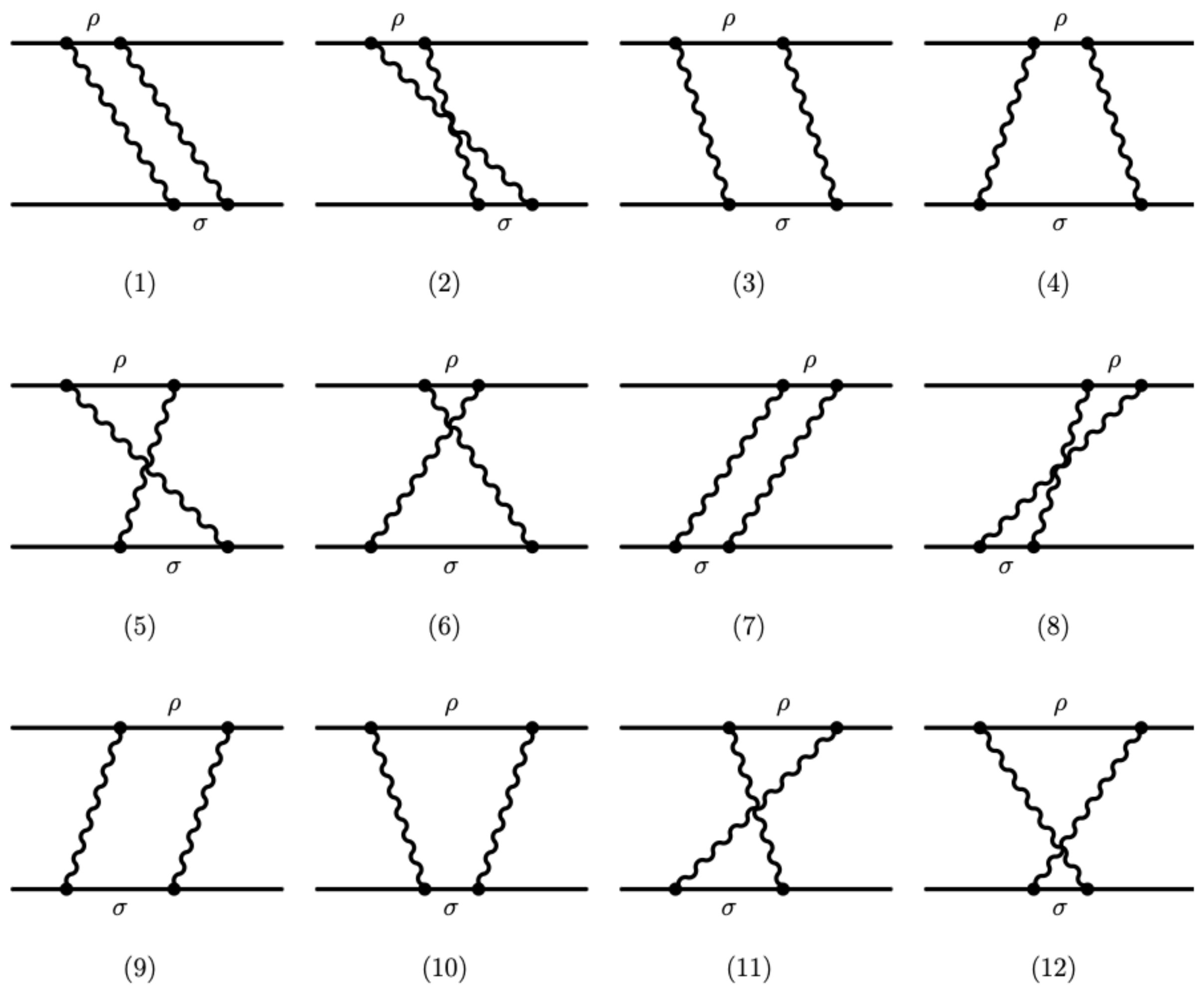

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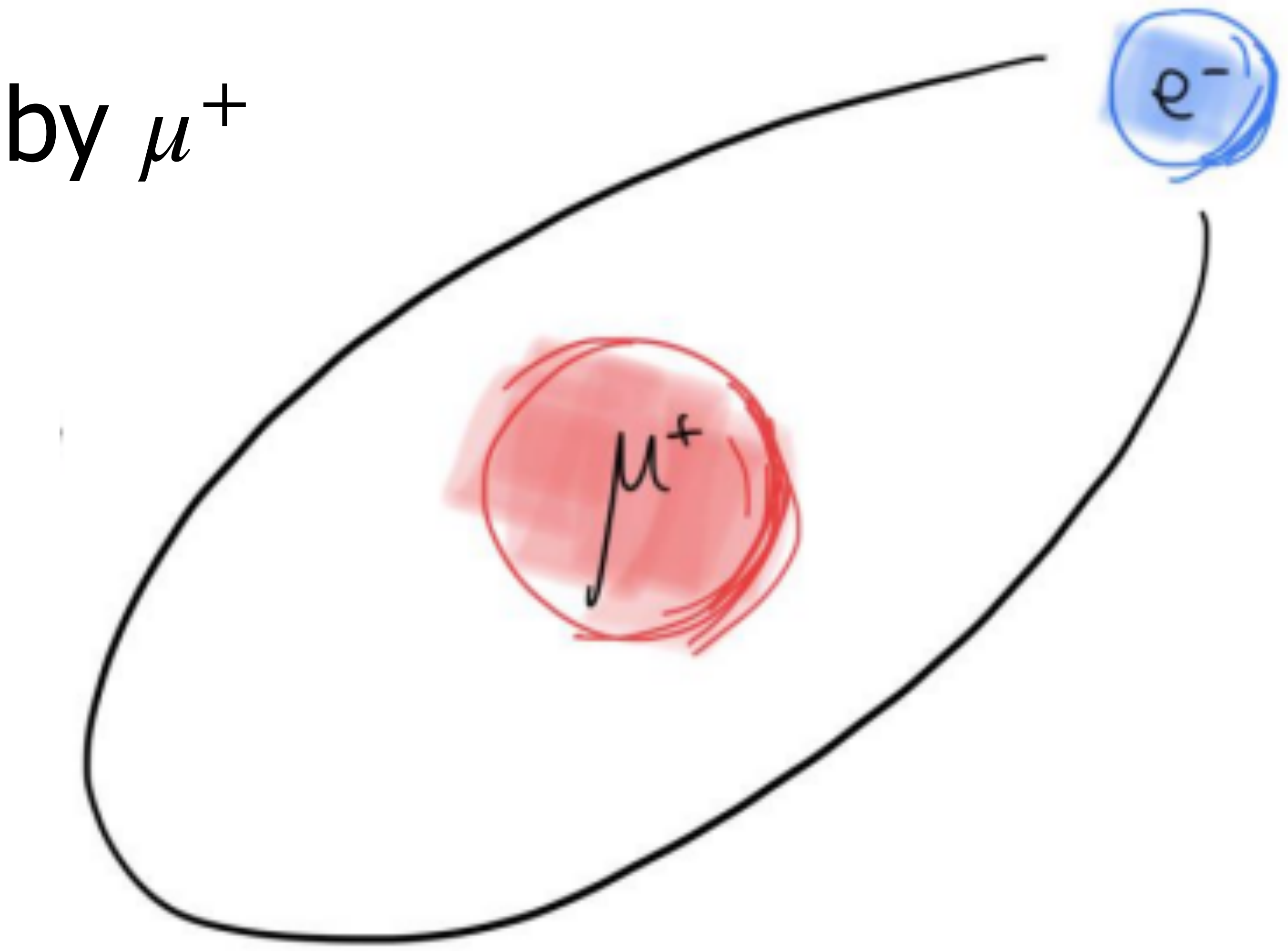
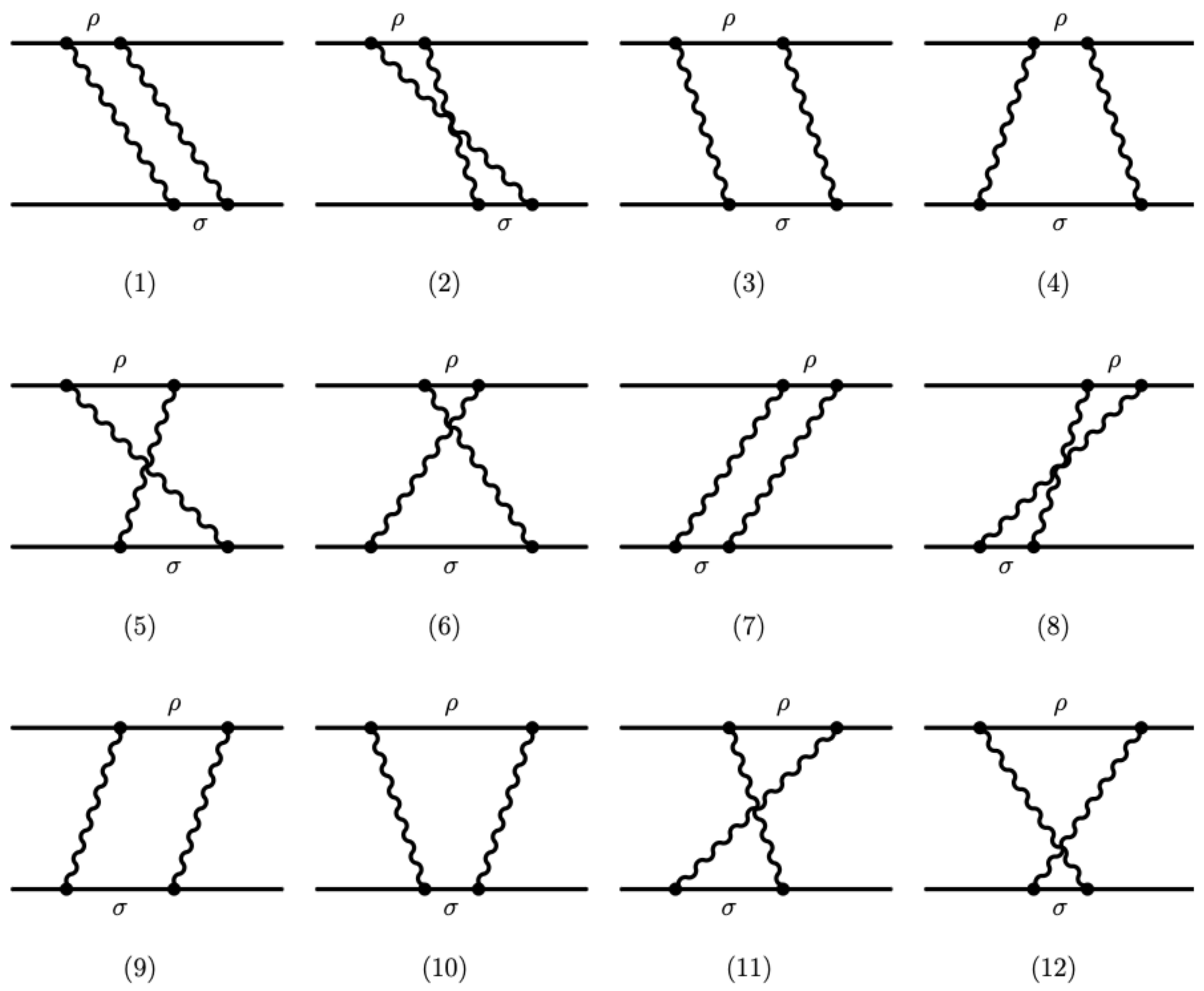
- Why do we target them? Simple atomic systems without finite-size effects
- Muonium (M), a bound system $(\mu^+ e^-)$
- Lifetime of 2.2 μs, limited by μ^+





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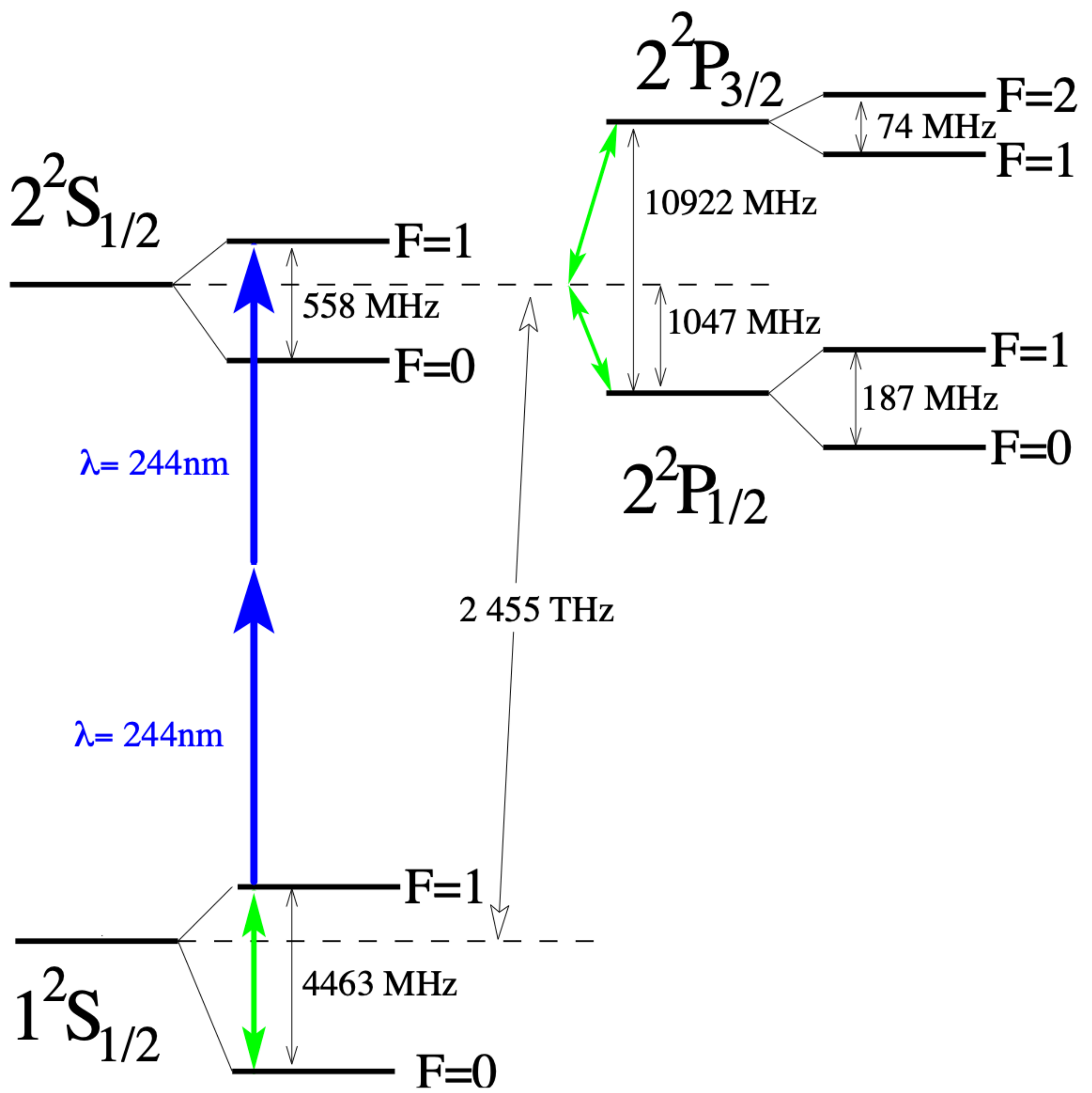
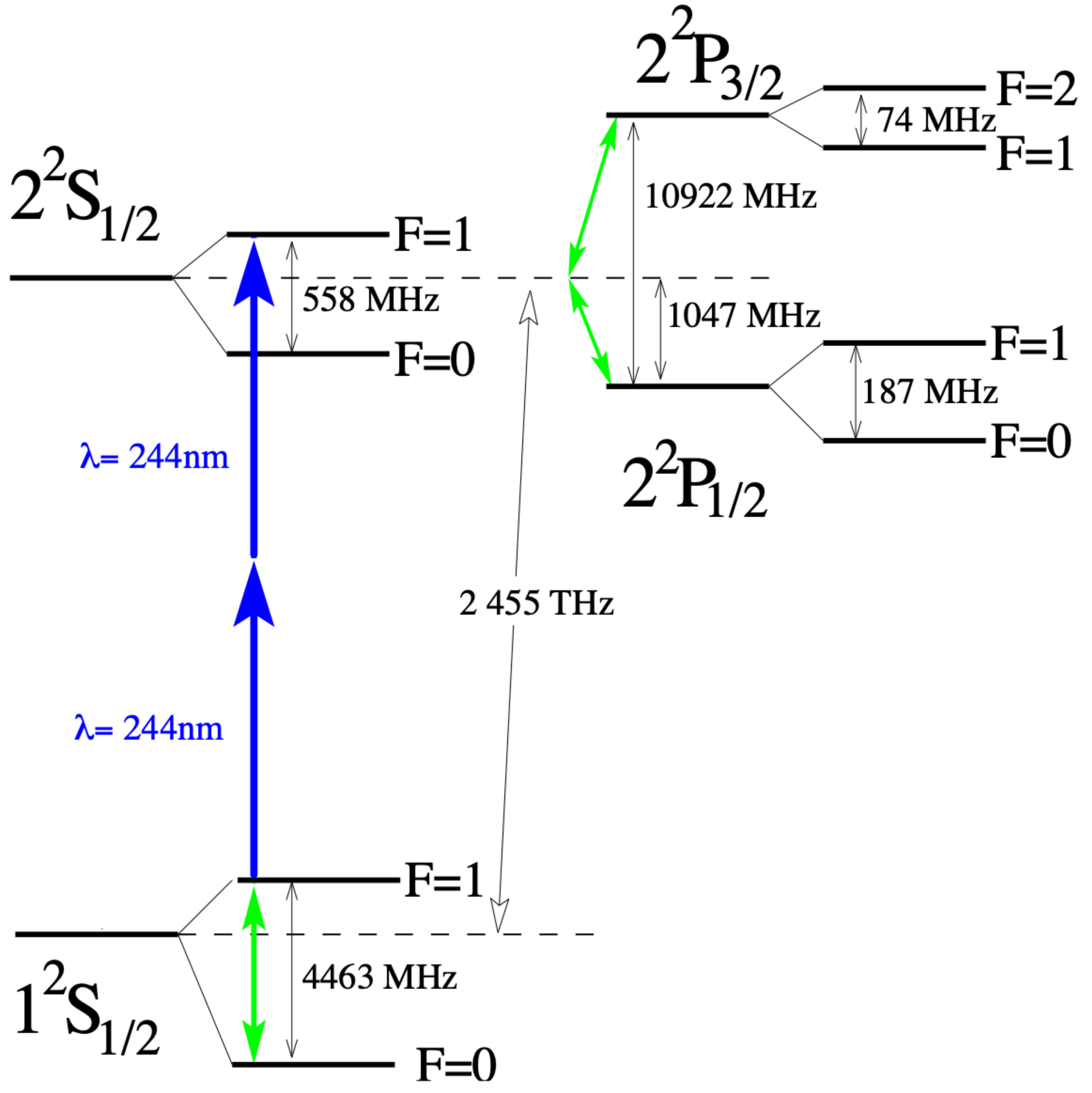
Spectroscopy — the 1S-2S Transition



[From: Jungmann, Klaus P. "Precision muonium spectroscopy.", JPSJ (2016)]

Spectroscopy — the 1S-2S Transition

- To gain knowledge of atom energy structure: probe it with electromagnetic radiation



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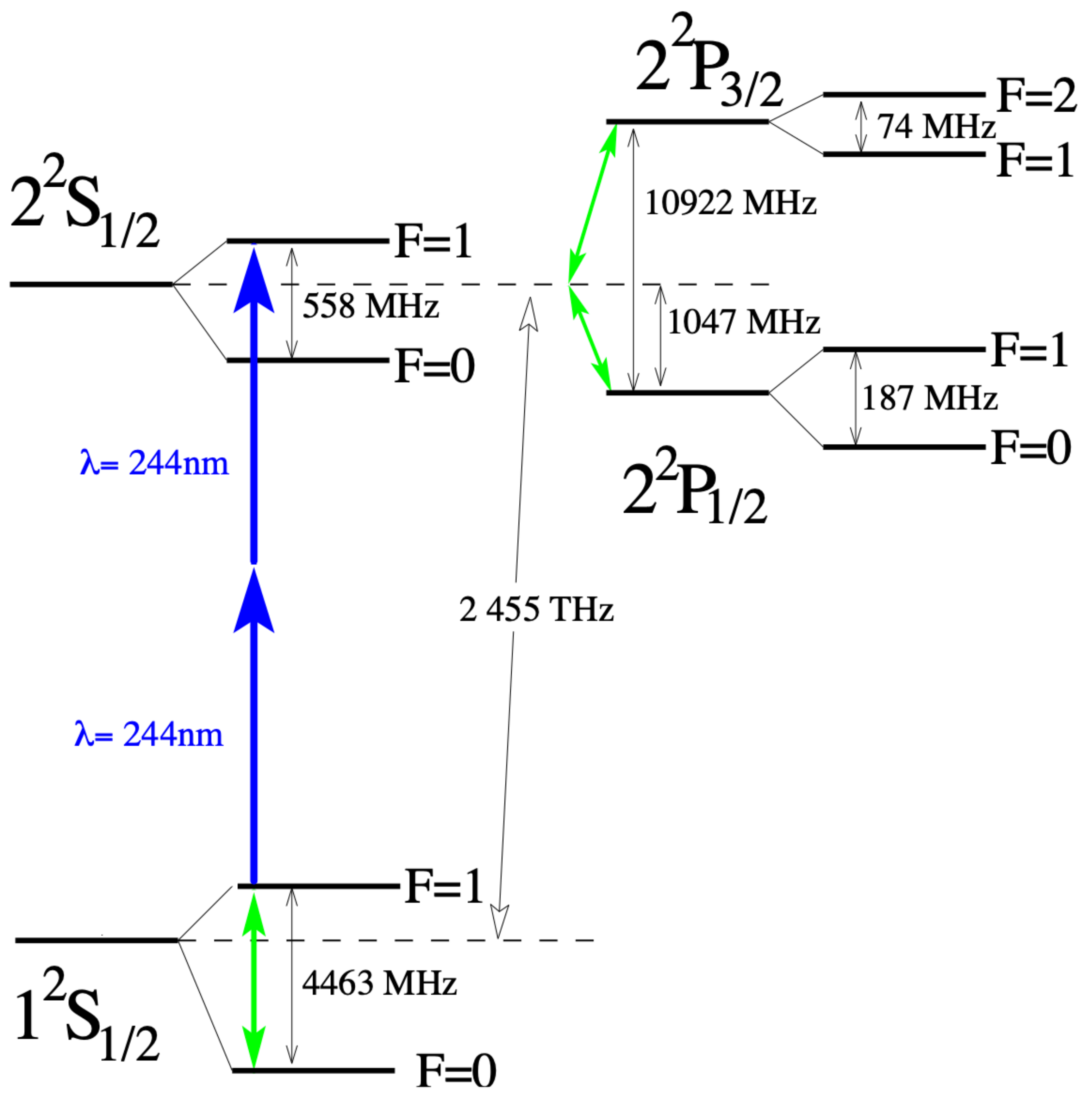

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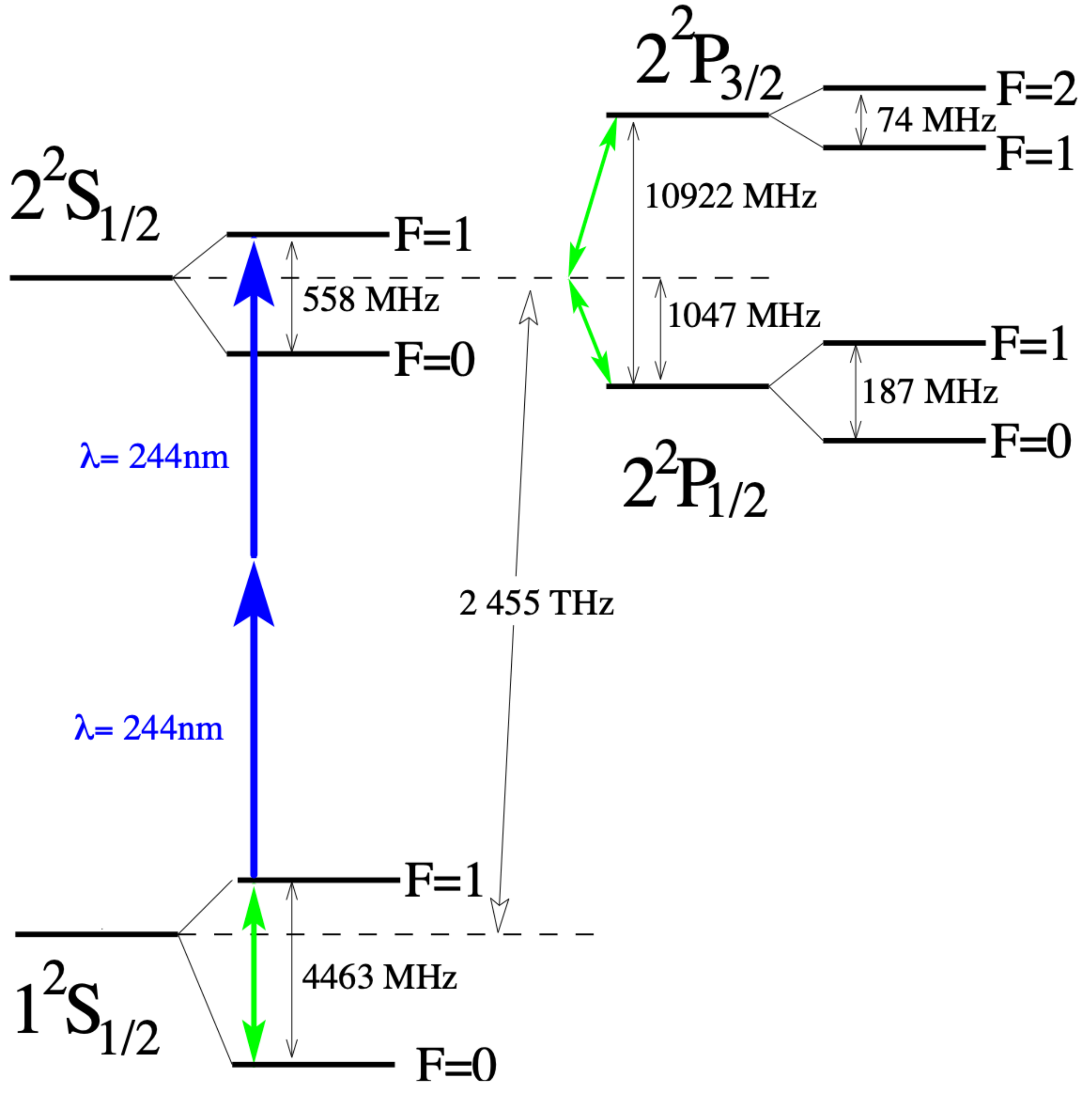

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- To gain knowledge of atom energy structure: probe it with electromagnetic radiation
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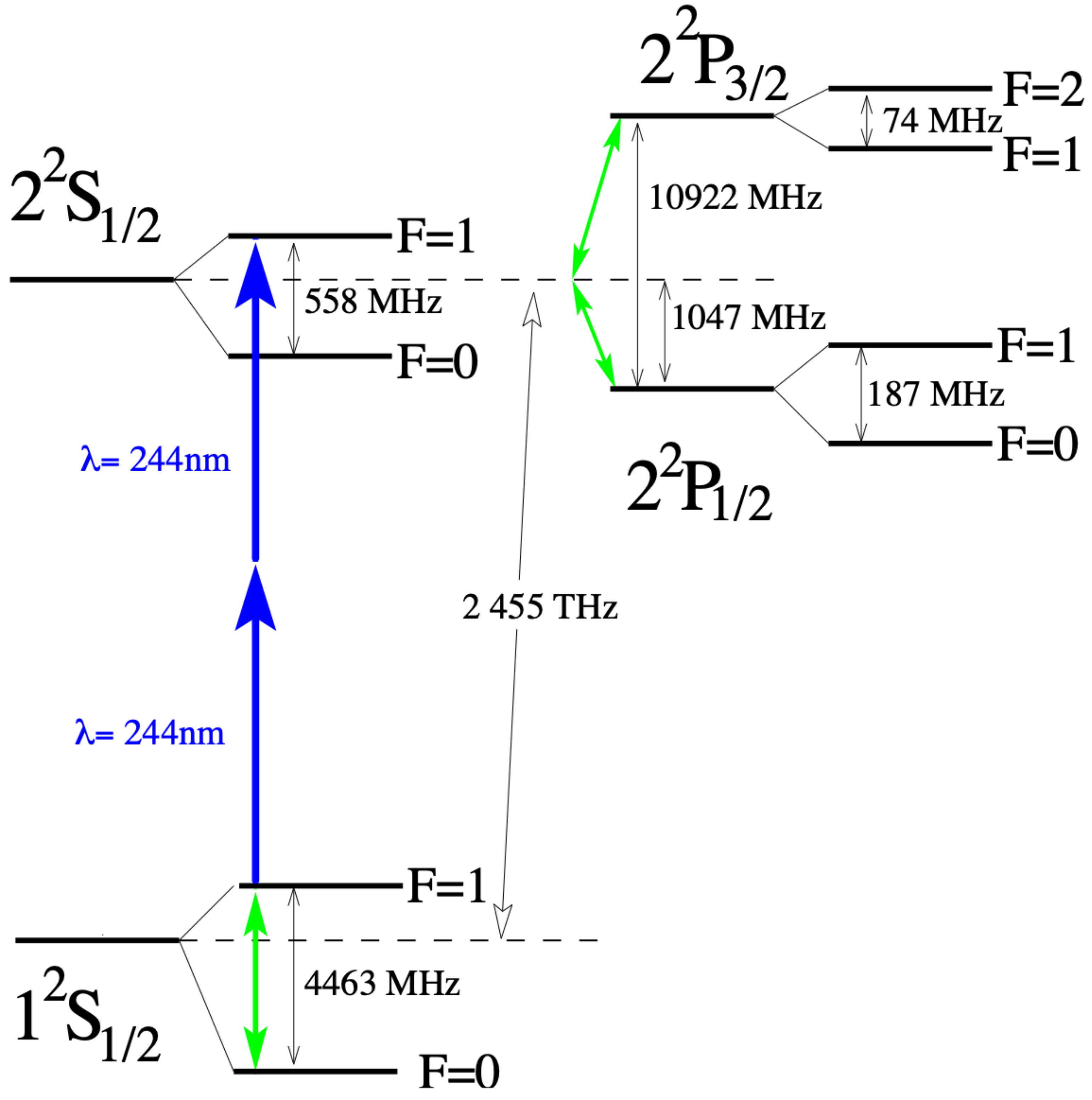
  - Meta-stable (long lifetime)



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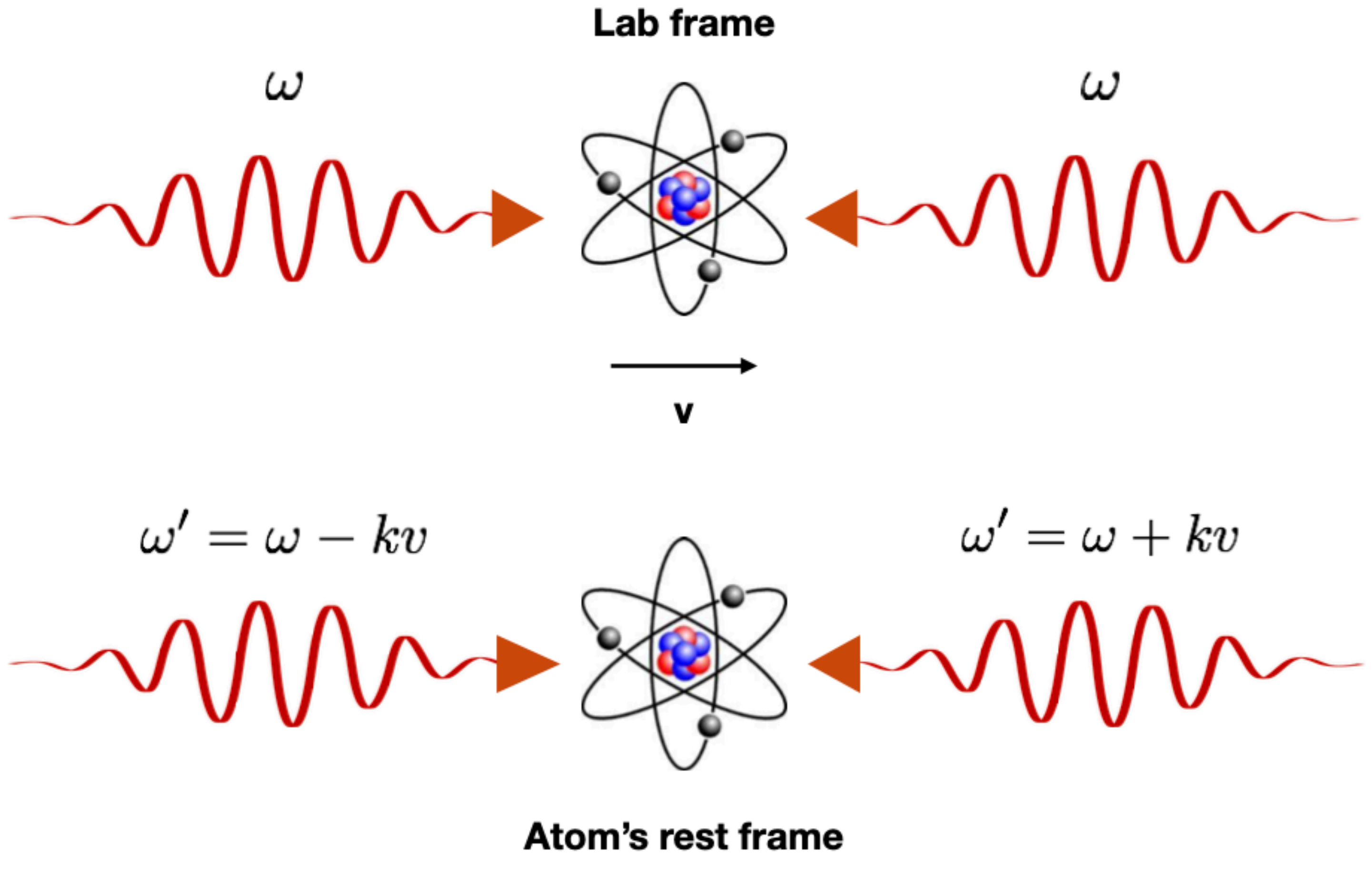
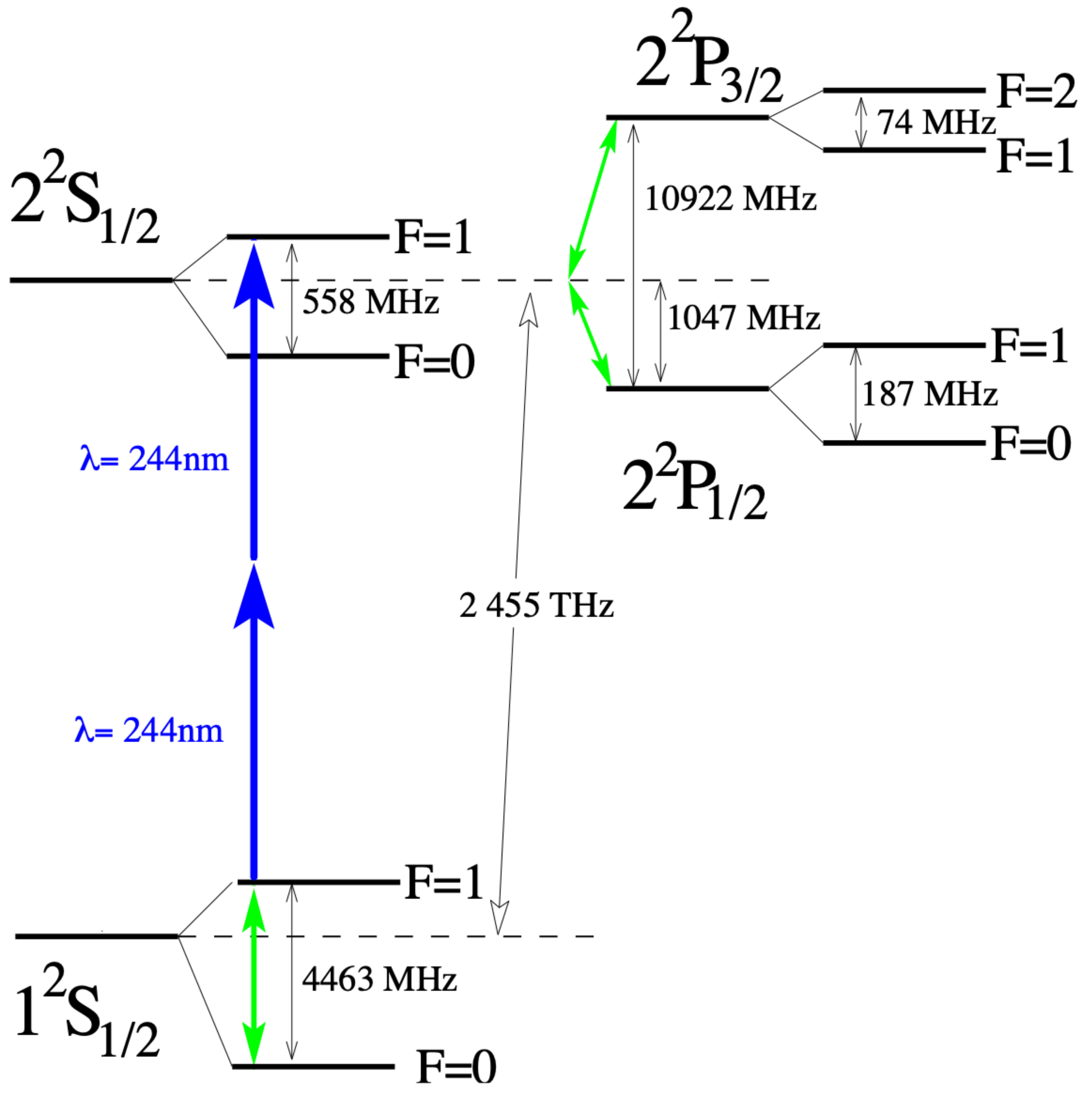
Spectroscopy — the 1S-2S Transition

- To gain knowledge of atom energy structure: probe it with electromagnetic radiation
- Most of this talk focuses on the 1S-2S transition
- Attractive as it is a two-photon transition:
  - Meta-stable (long lifetime)
  - Doppler free to first order in cavity



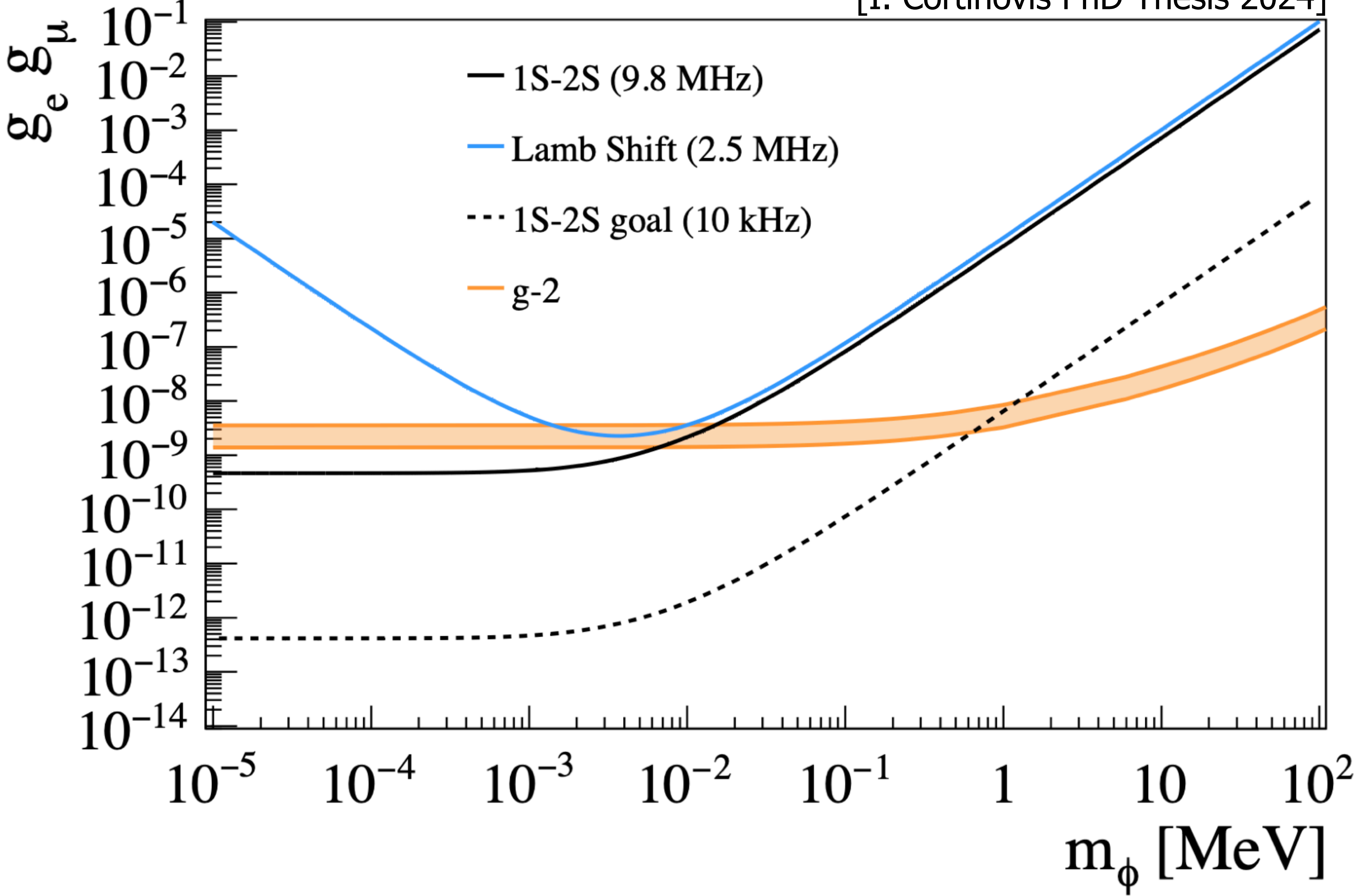


[From: Jungmann, Klaus P. "Precision muonium spectroscopy.", JPSJ (2016)]

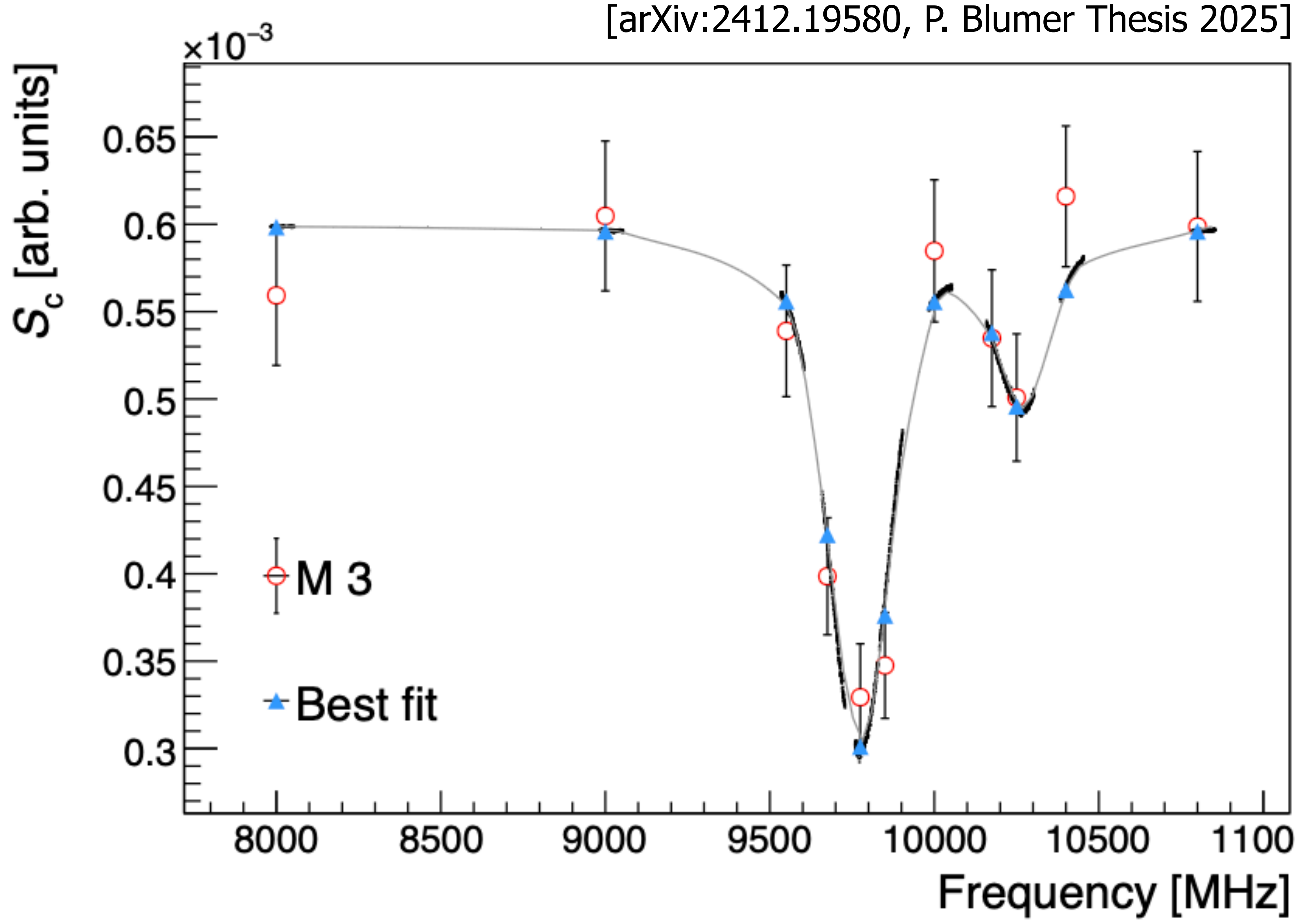
The Mu-MASS Collaboration

- Goal: a 1000-fold improvement of the 1S-2S transition in M
- Measurements of MW transitions (Lamb shift, fine structure)

[I. Cortinovis PhD Thesis 2024]



[arXiv:2412.19580, P. Blumer Thesis 2025]

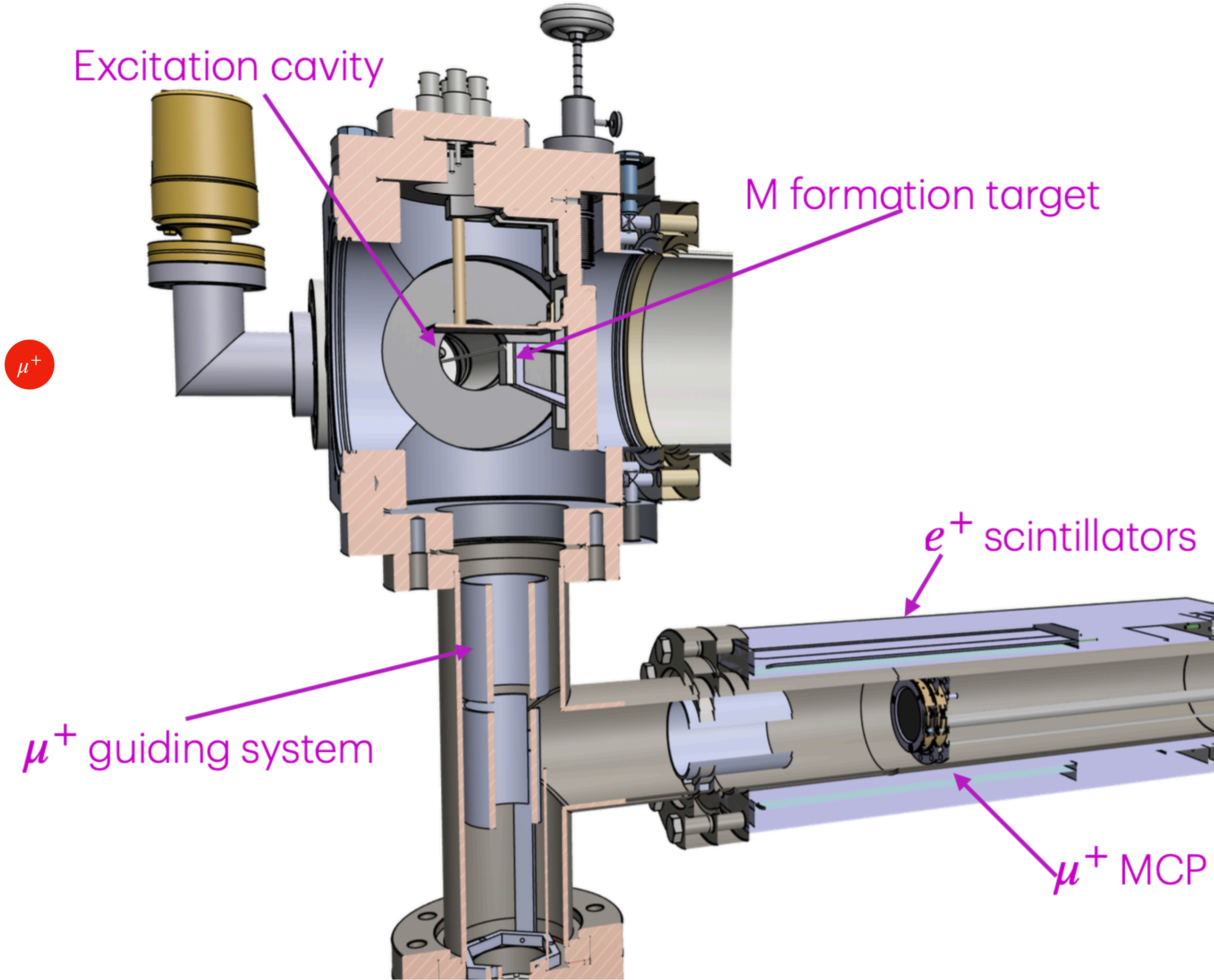


Motivations for M Spectroscopy

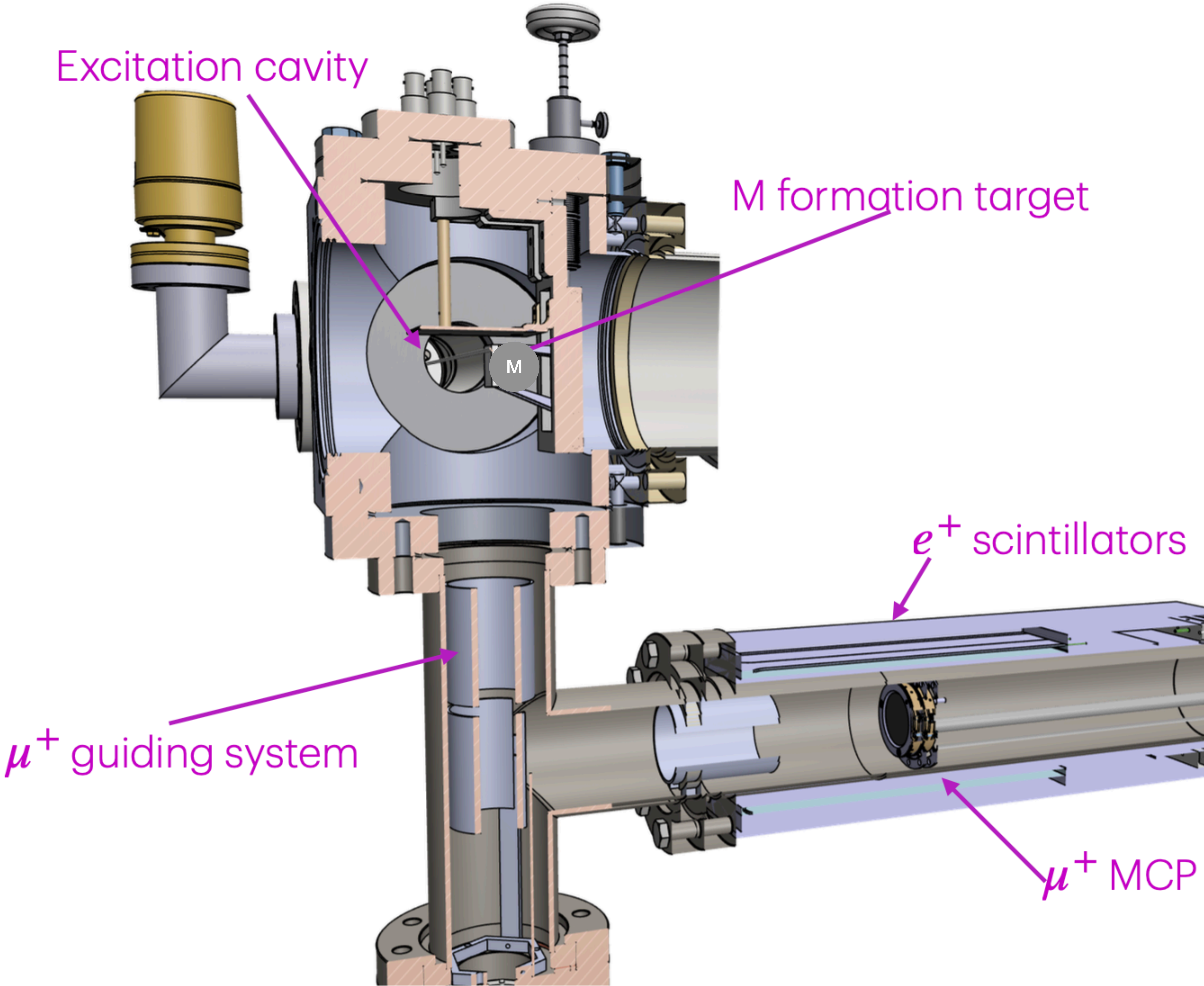
- Allows access to muon mass determination

$$\frac{\sigma_{m_e/m_\mu}}{m_e/m_\mu} \approx \frac{\sigma_{\nu_{1S-2S}}}{\nu_{1S-2S}} \cdot \frac{m_\mu}{m_e}$$

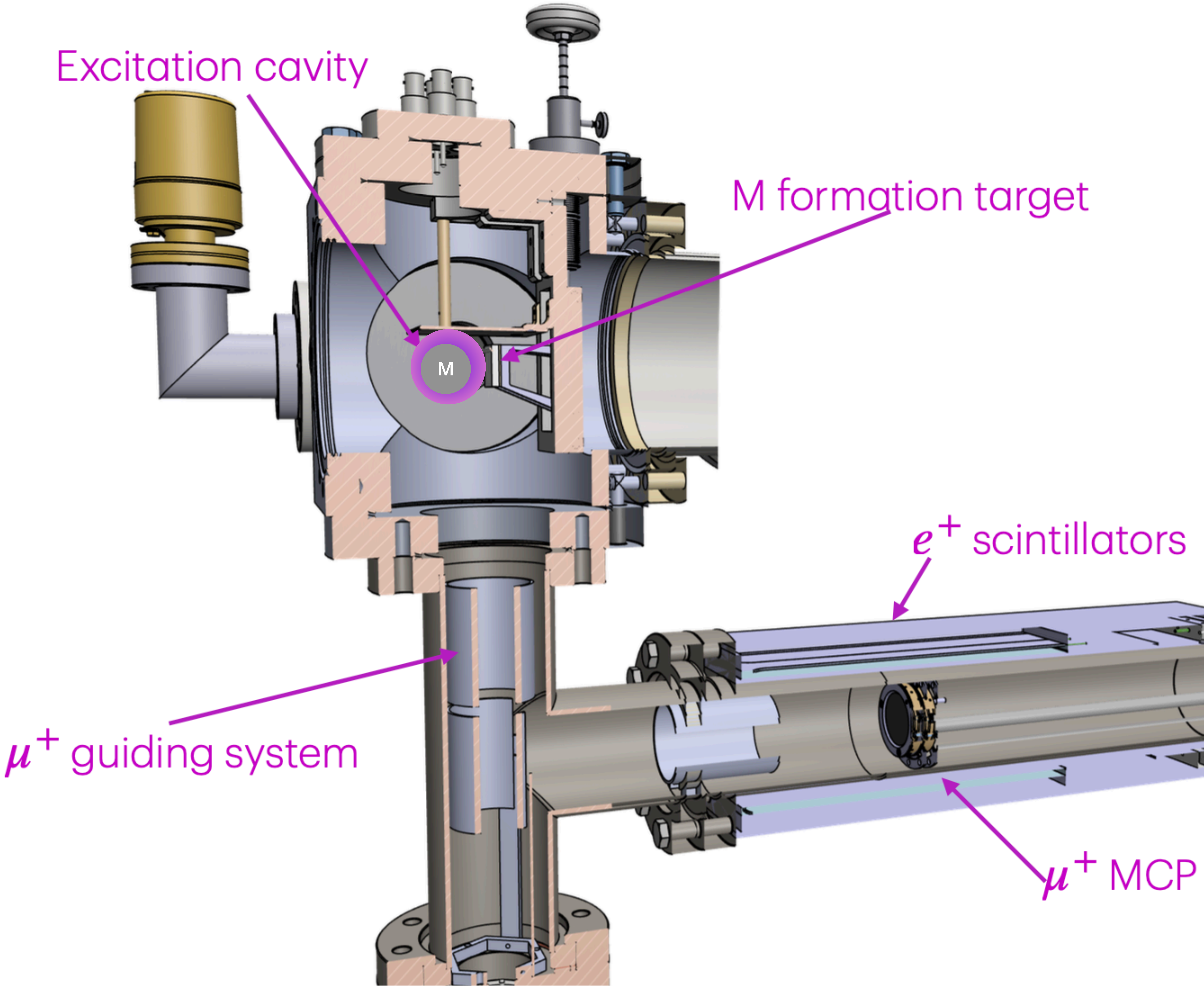
- Combine with ground state hyperfine splitting to get BSQED test
- Search for new physics (muonic forces, probe SME coefficients)
- Determinations of physical constants involving the second generation of particles and spectroscopy based determination of $(g-2)_\mu$


μ^+
Excitation cavity
M formation target
e^+ scintillators
μ^+ guiding system
μ^+ MCP

1. A μ^+ is tagged and strikes a SiO_2 target, becoming muonium



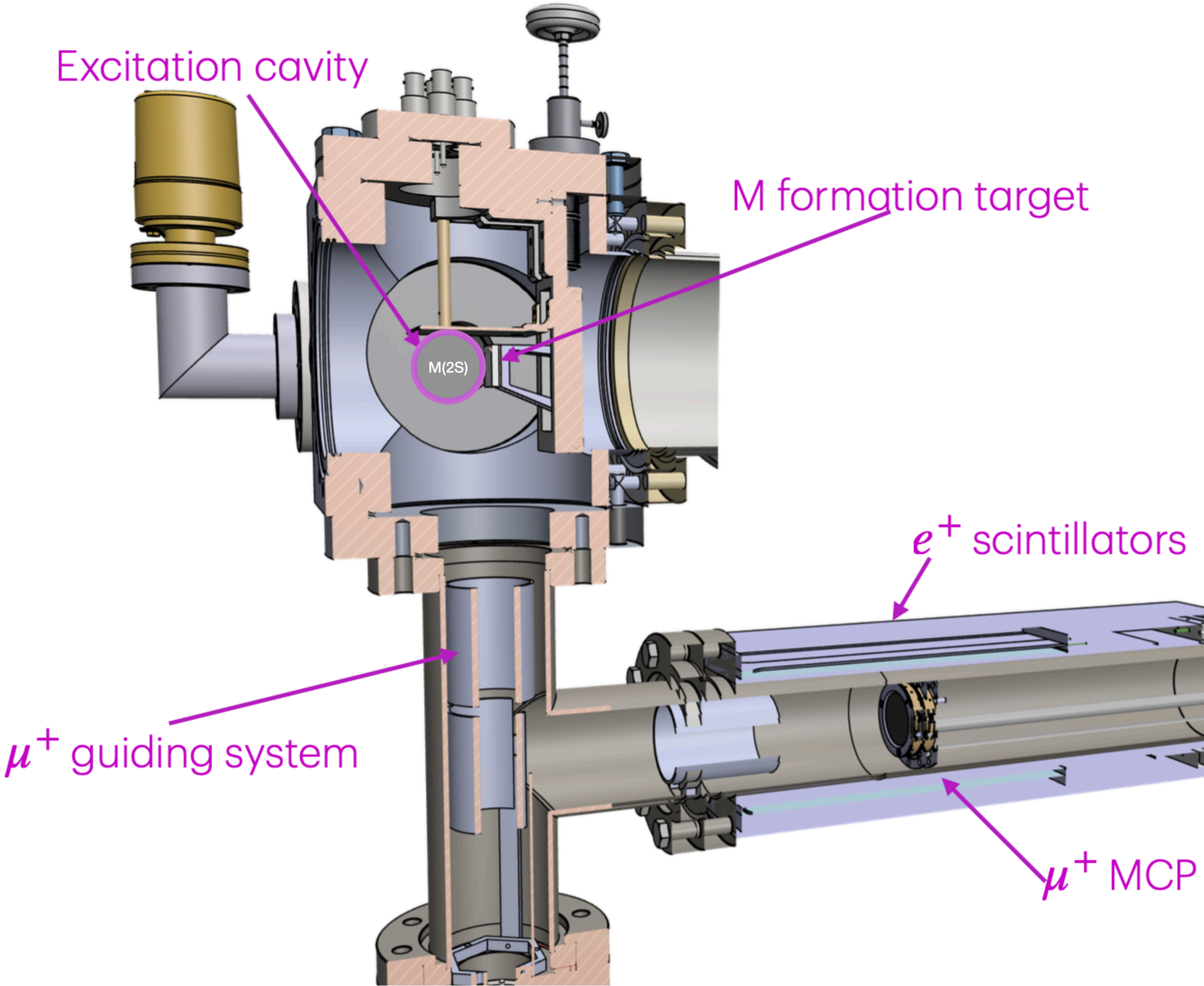
1. A μ^+ is tagged and strikes a SiO_2 target, becoming muonium
2. The M diffuses out into vacuum



1. A μ^+ is tagged and strikes a SiO_2 target, becoming muonium

2. The M diffuses out into vacuum

3. M is excited to the 2S state in an enhancement cavity of 244 nm light



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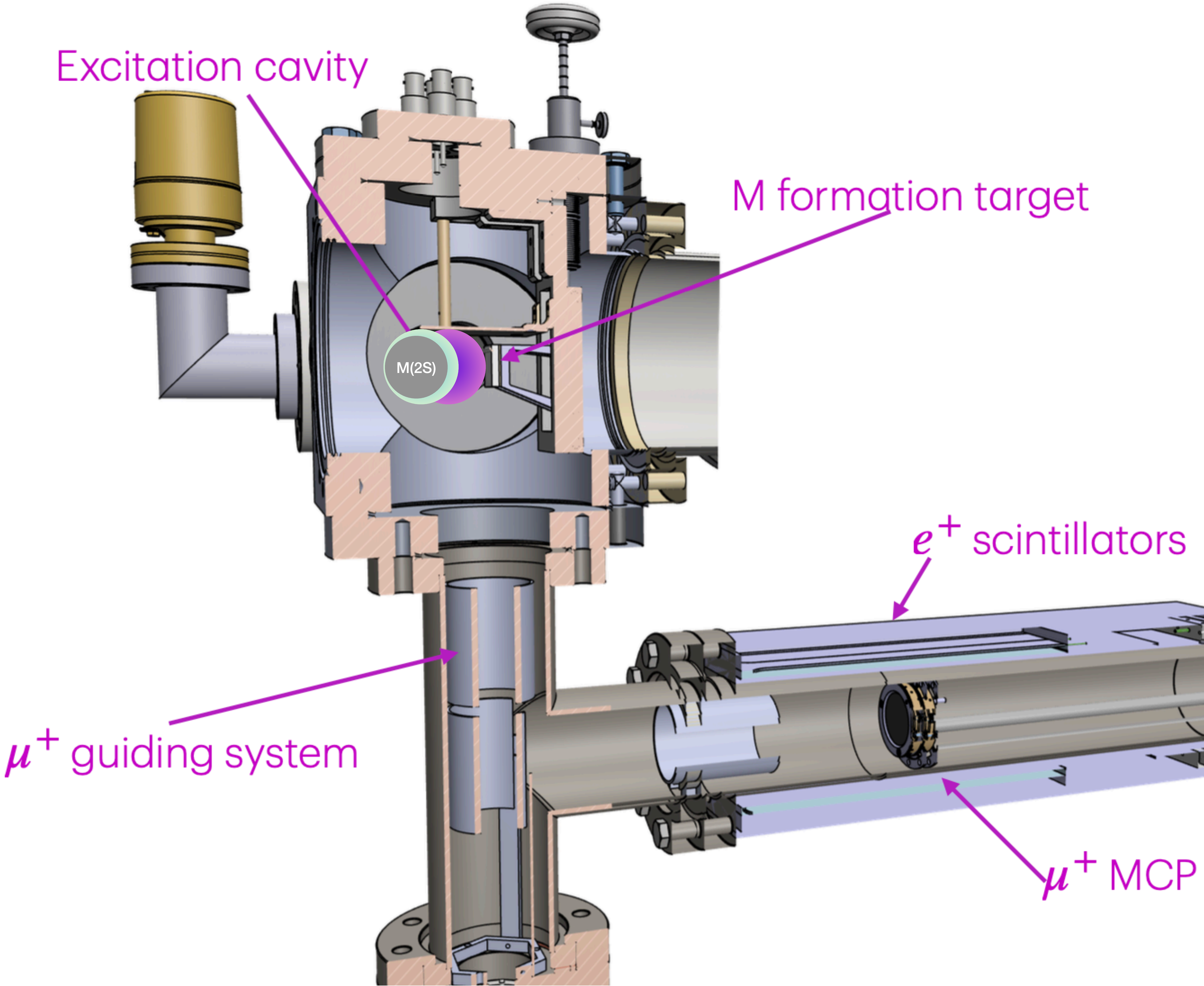

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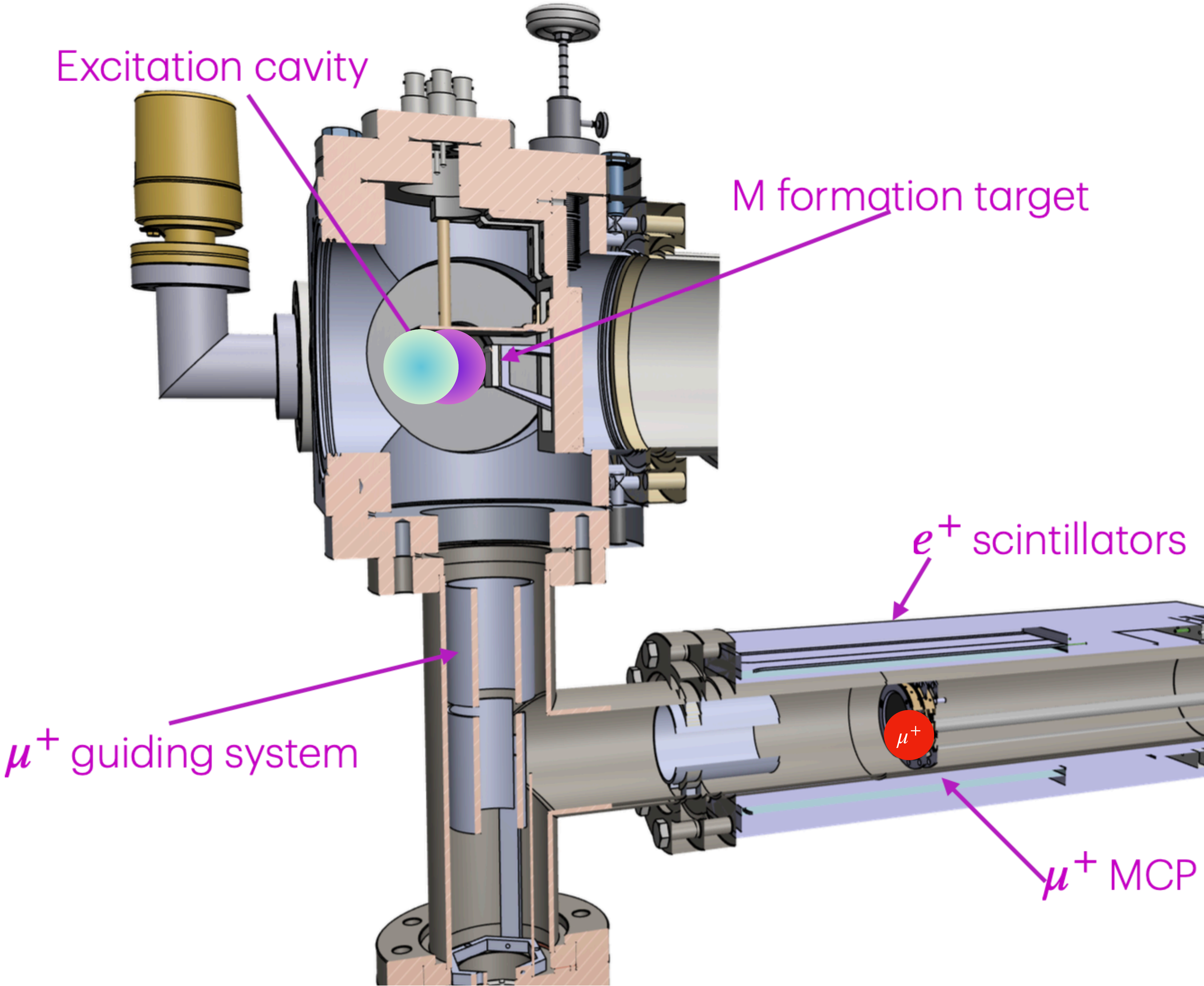

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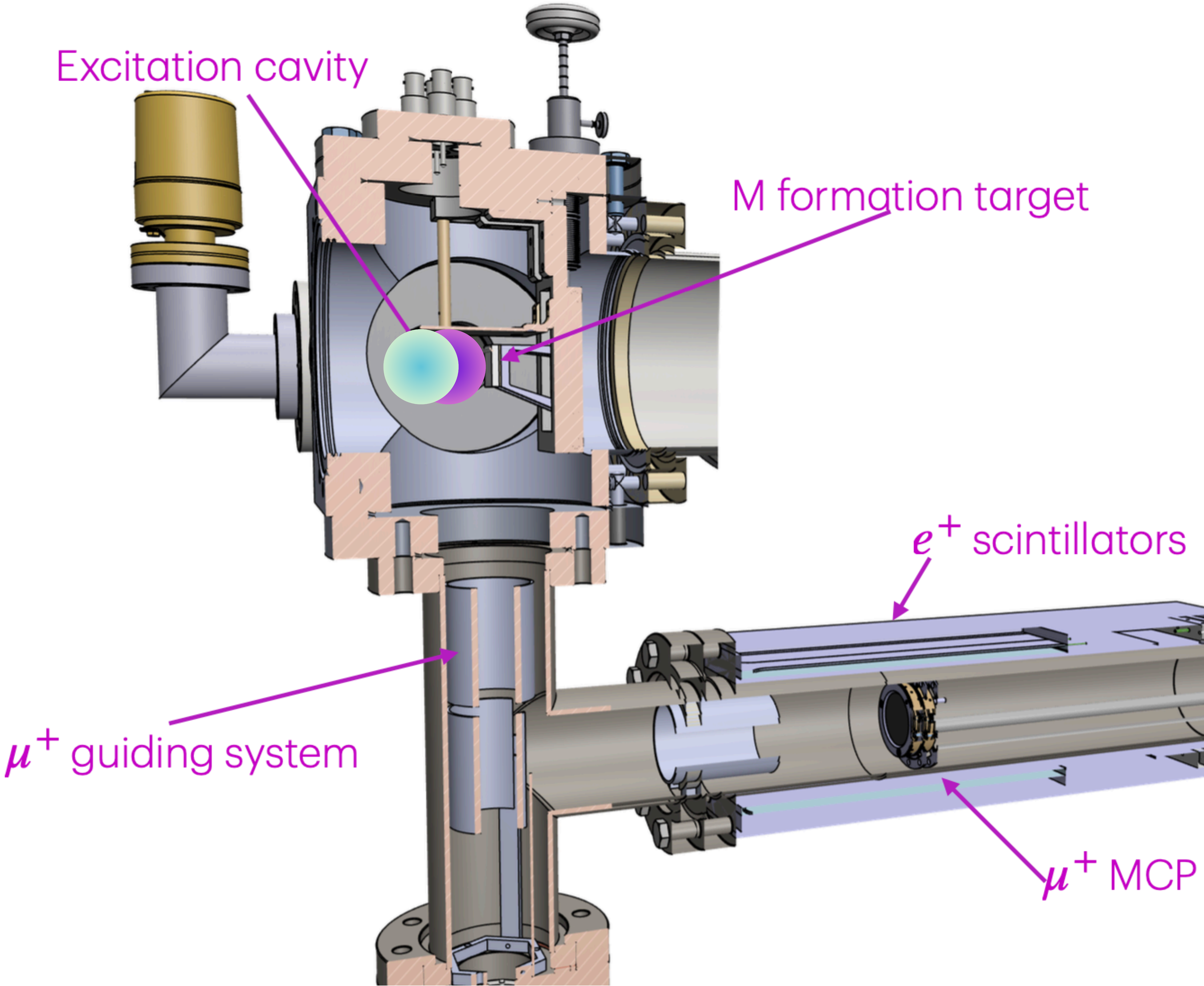
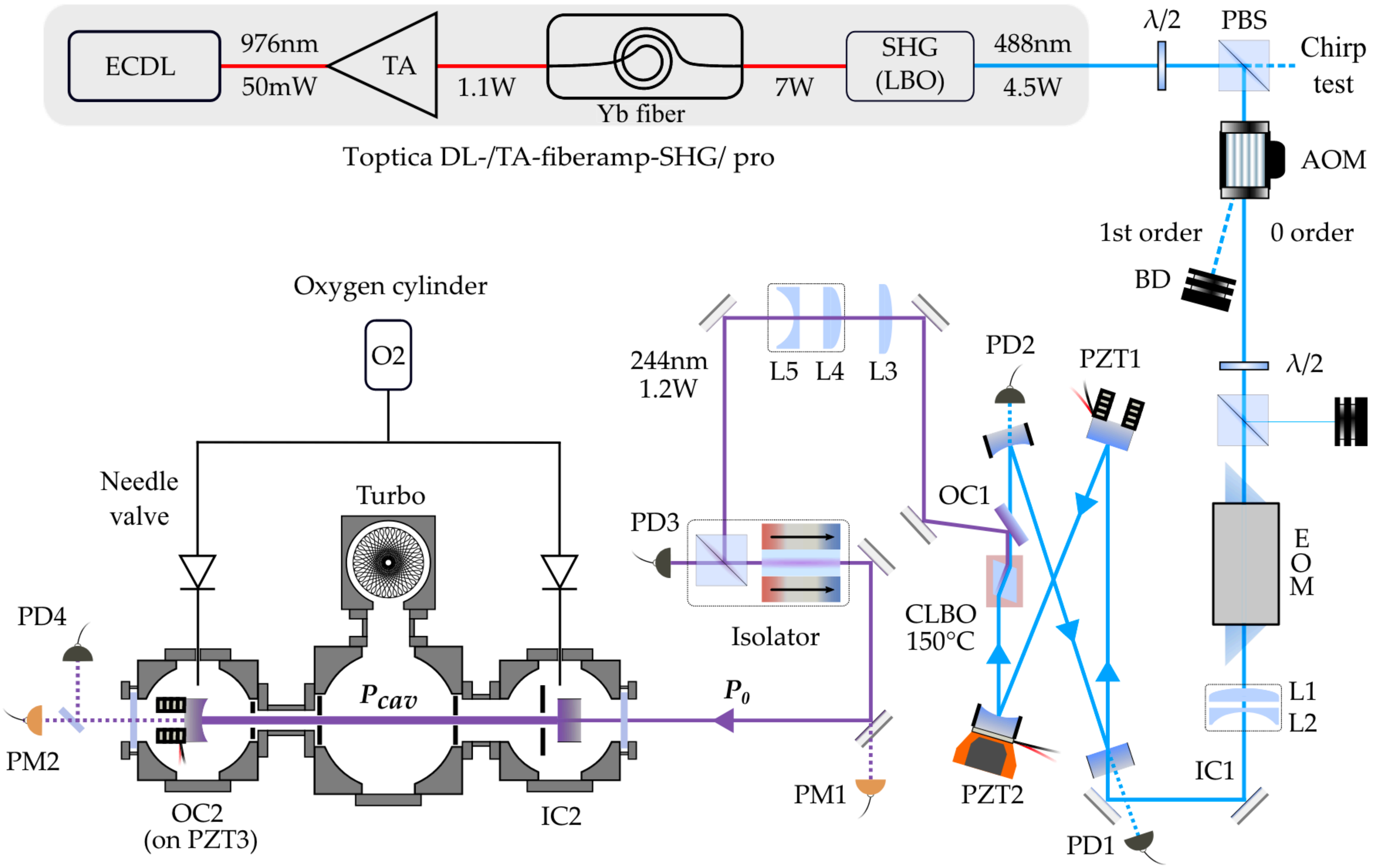
6. Event signature: coincidence of tagging μ^+ with detecting a signal in the μMCP and e^+ scintillators



The Mu-MASS Laser System

- Custom-built Toptica system



Zhadnov, Nikita, et al. "Pulsed CW laser for long-term spectroscopic measurements at high power in deep-UV." Optics Express 31.17 (2023): 28470-28479.

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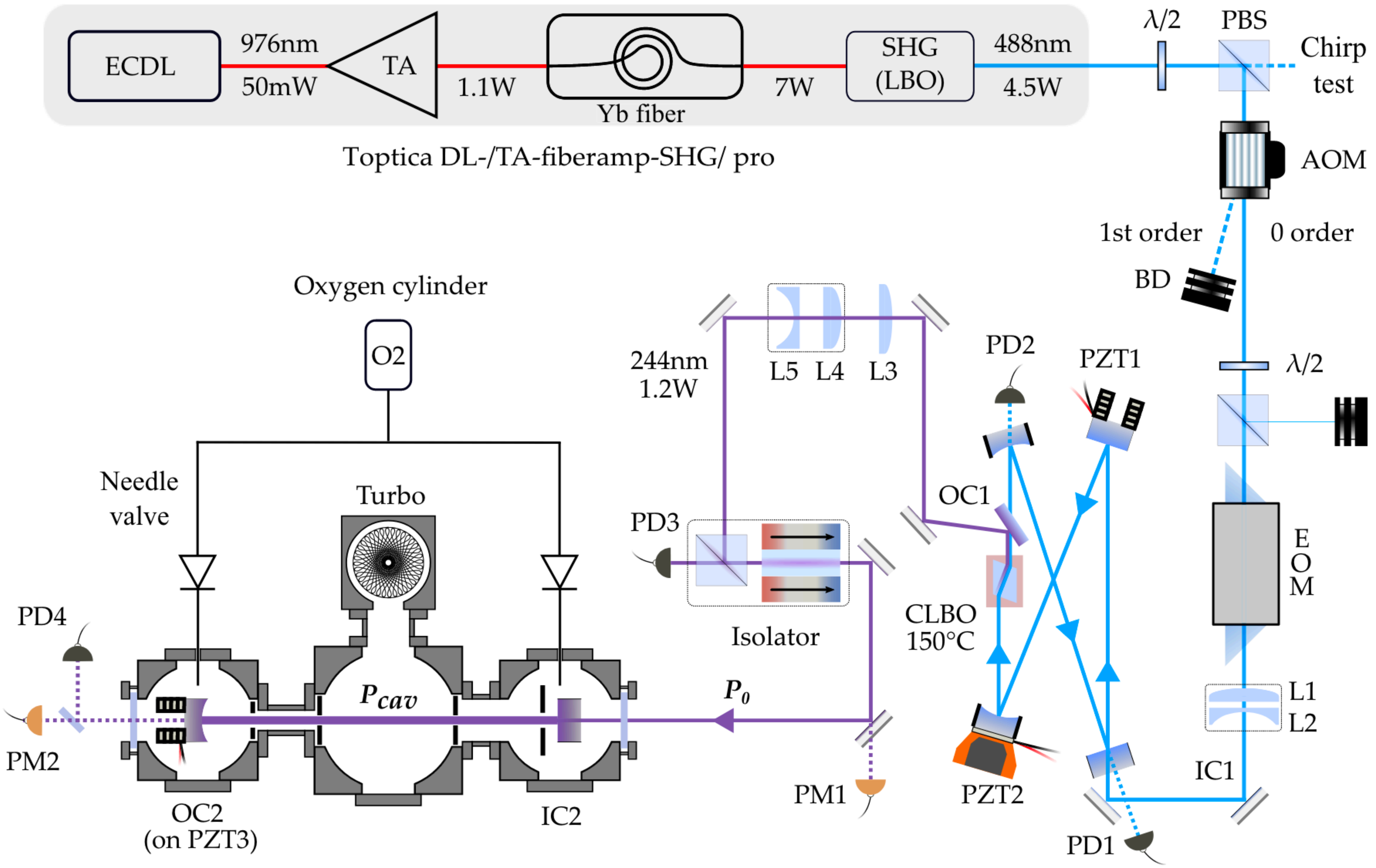
- Recently upgraded with new fiber amplifier (Azurlight)



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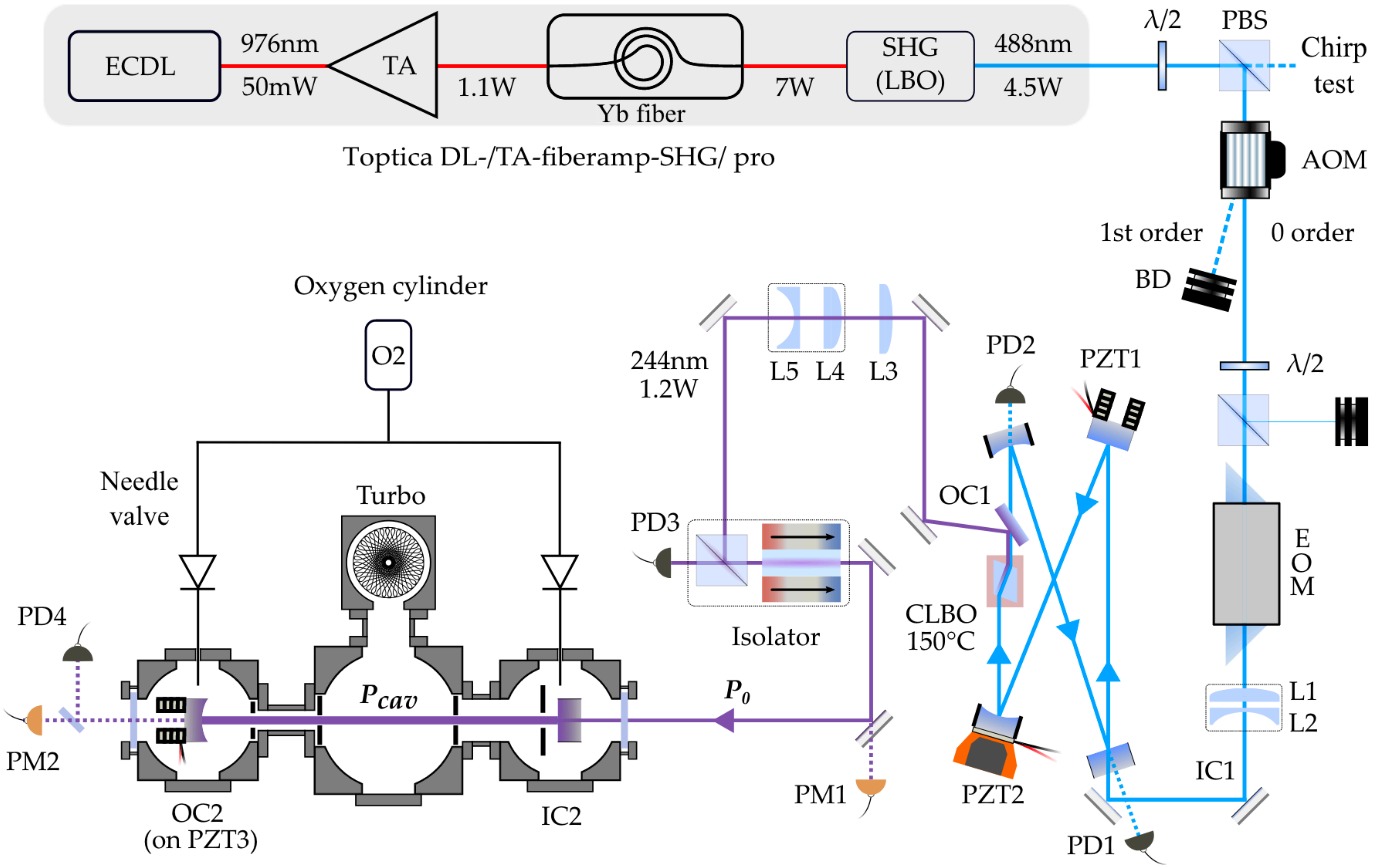

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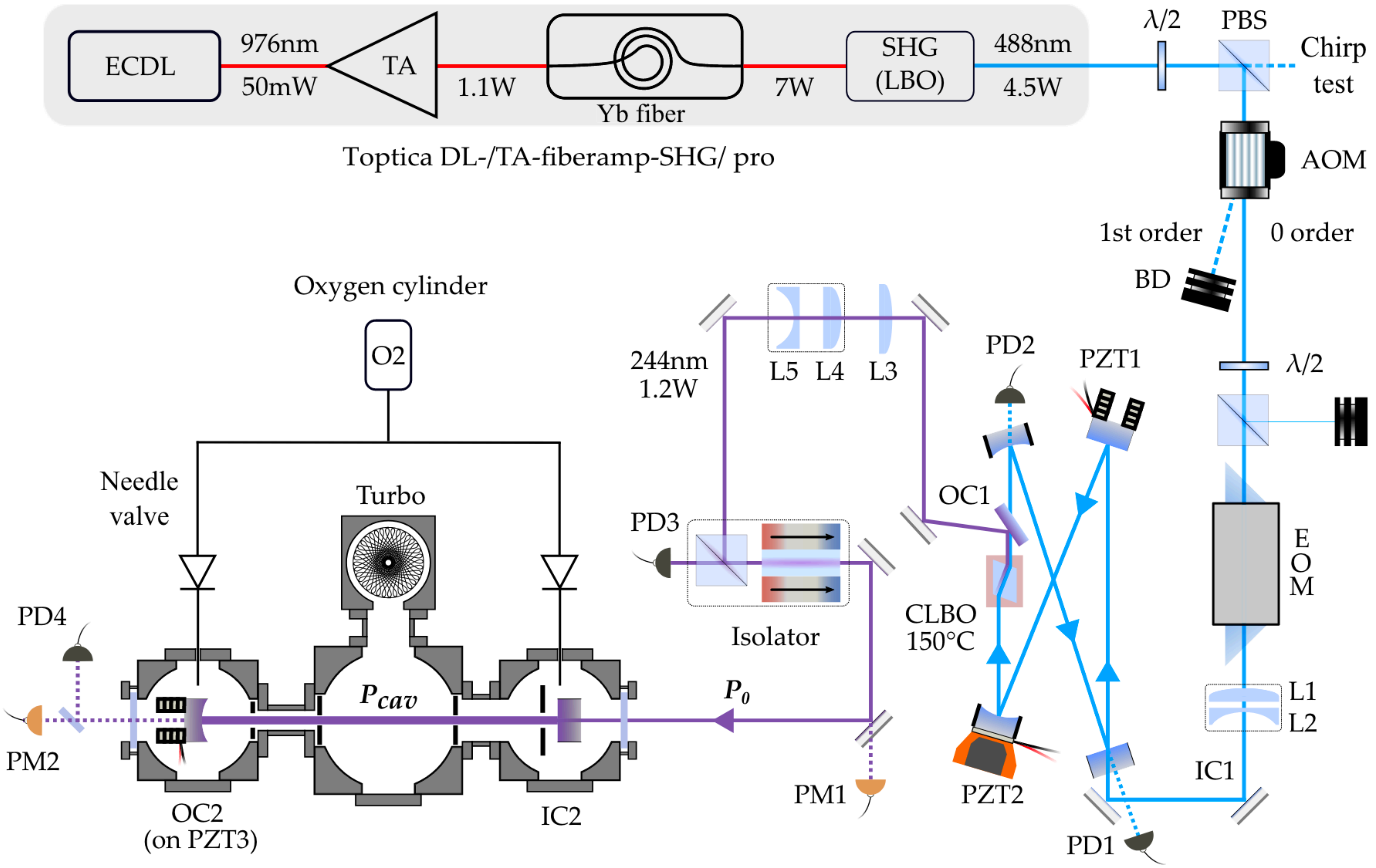

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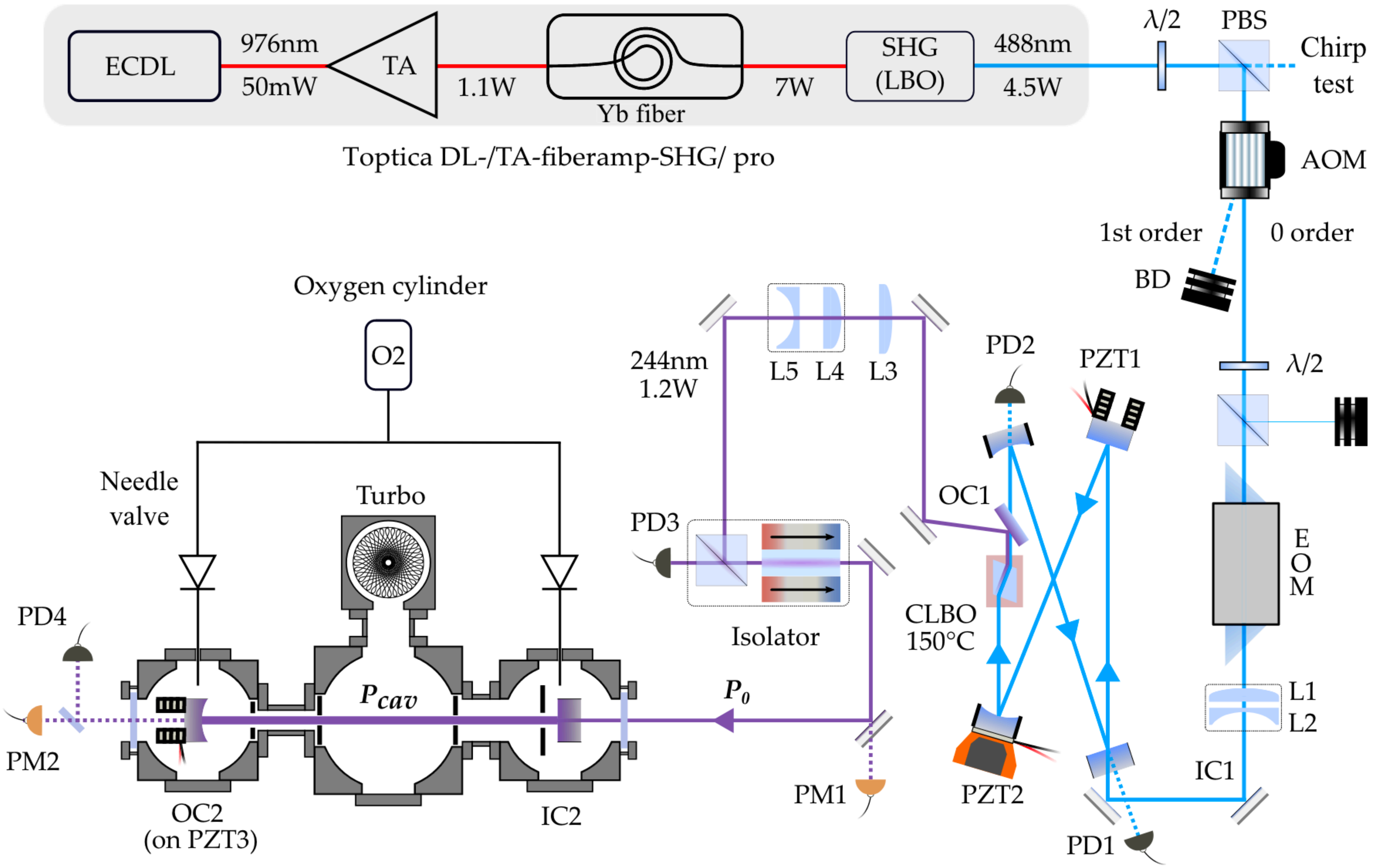
- Bowtie cavities to improve SHG efficiency
- But high-power UV degrades our optics…



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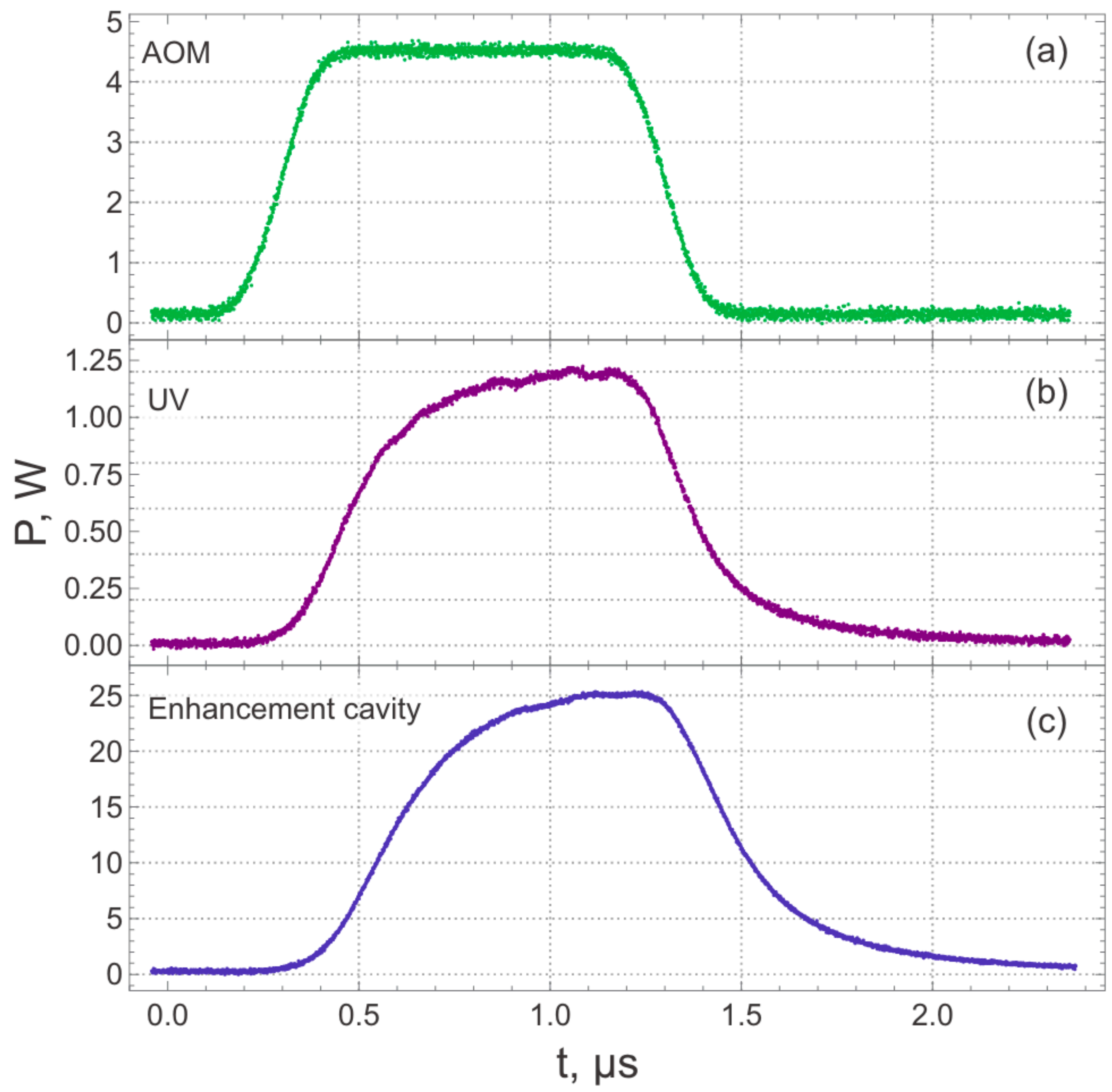
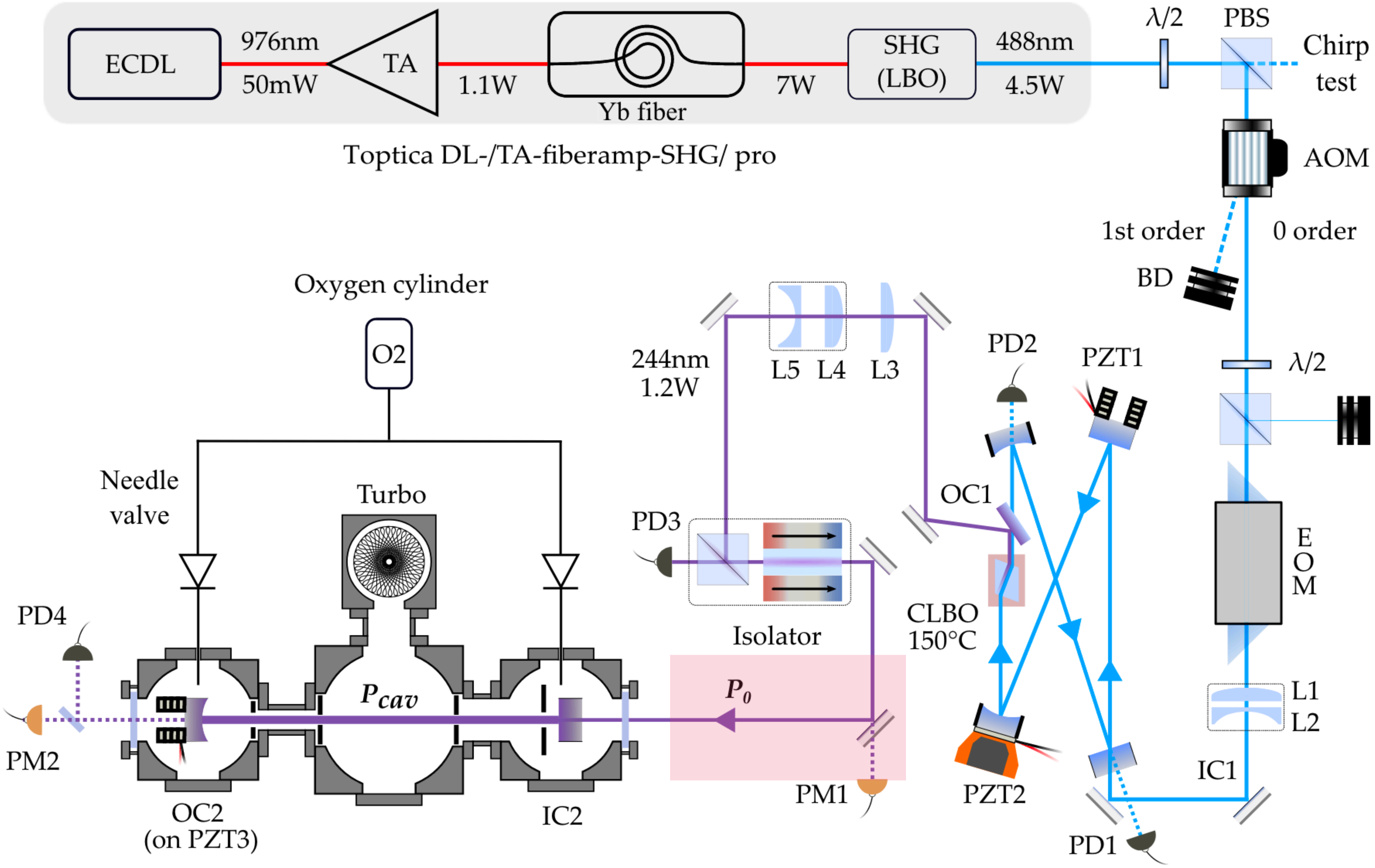
Dealing with UV — the “Pulsed-CW” Scheme

- To prevent degradation: lock cavities at low power, increase when μ^+ incoming
- Time to pulse up power limited by cavity fill times (more UV, better fill times)



Recent Upgrades

- Active beam stabilization



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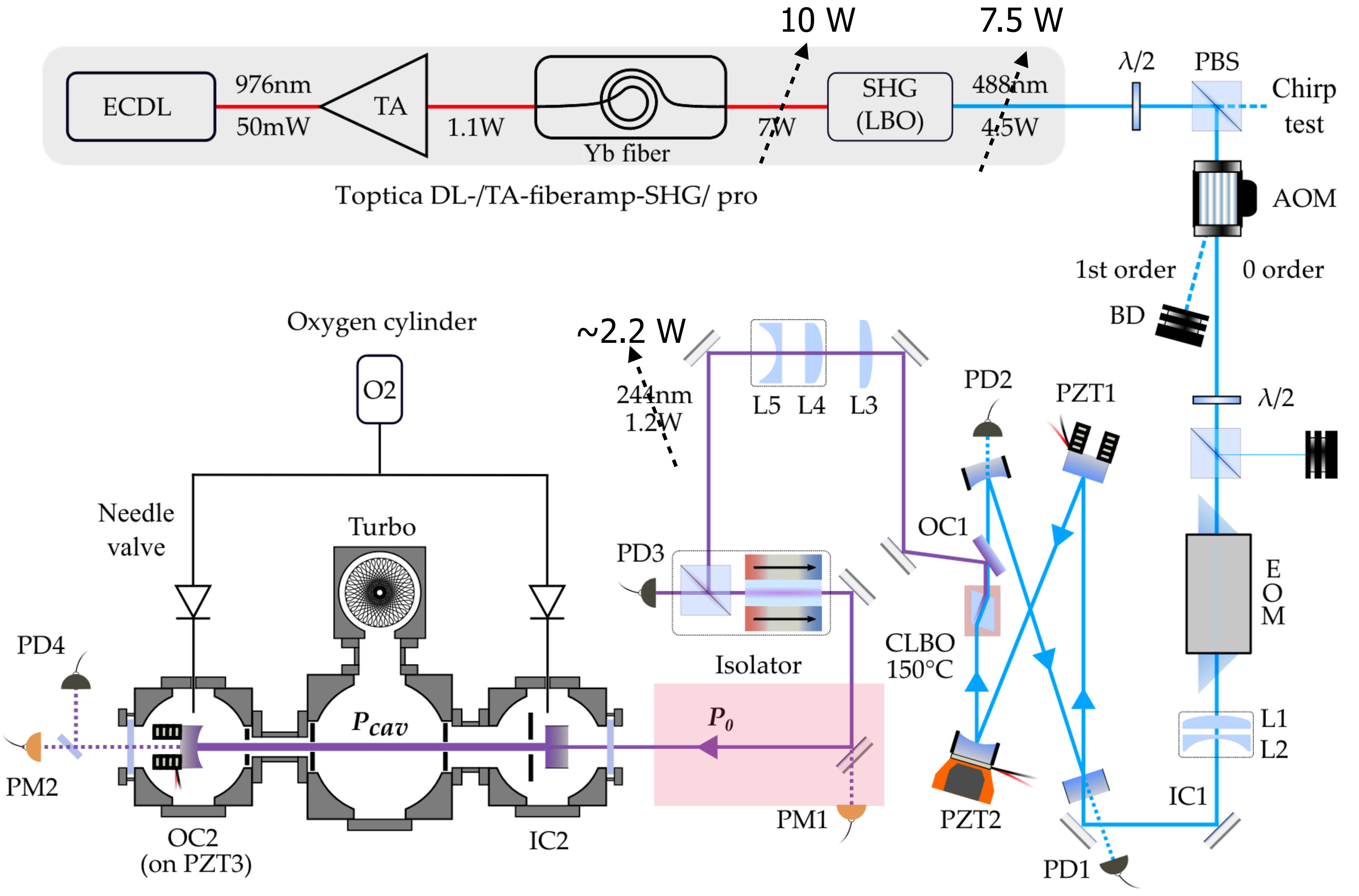

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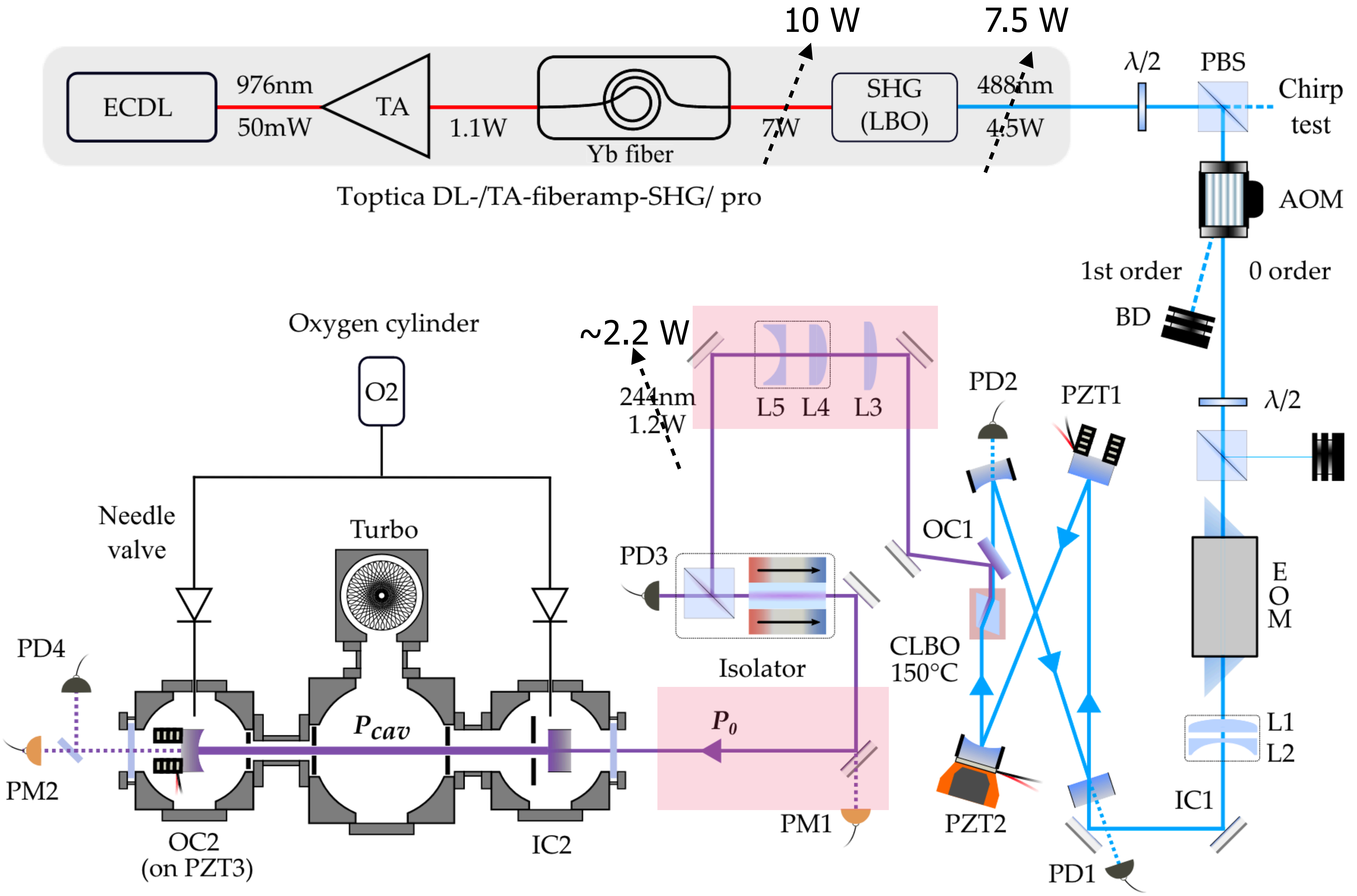

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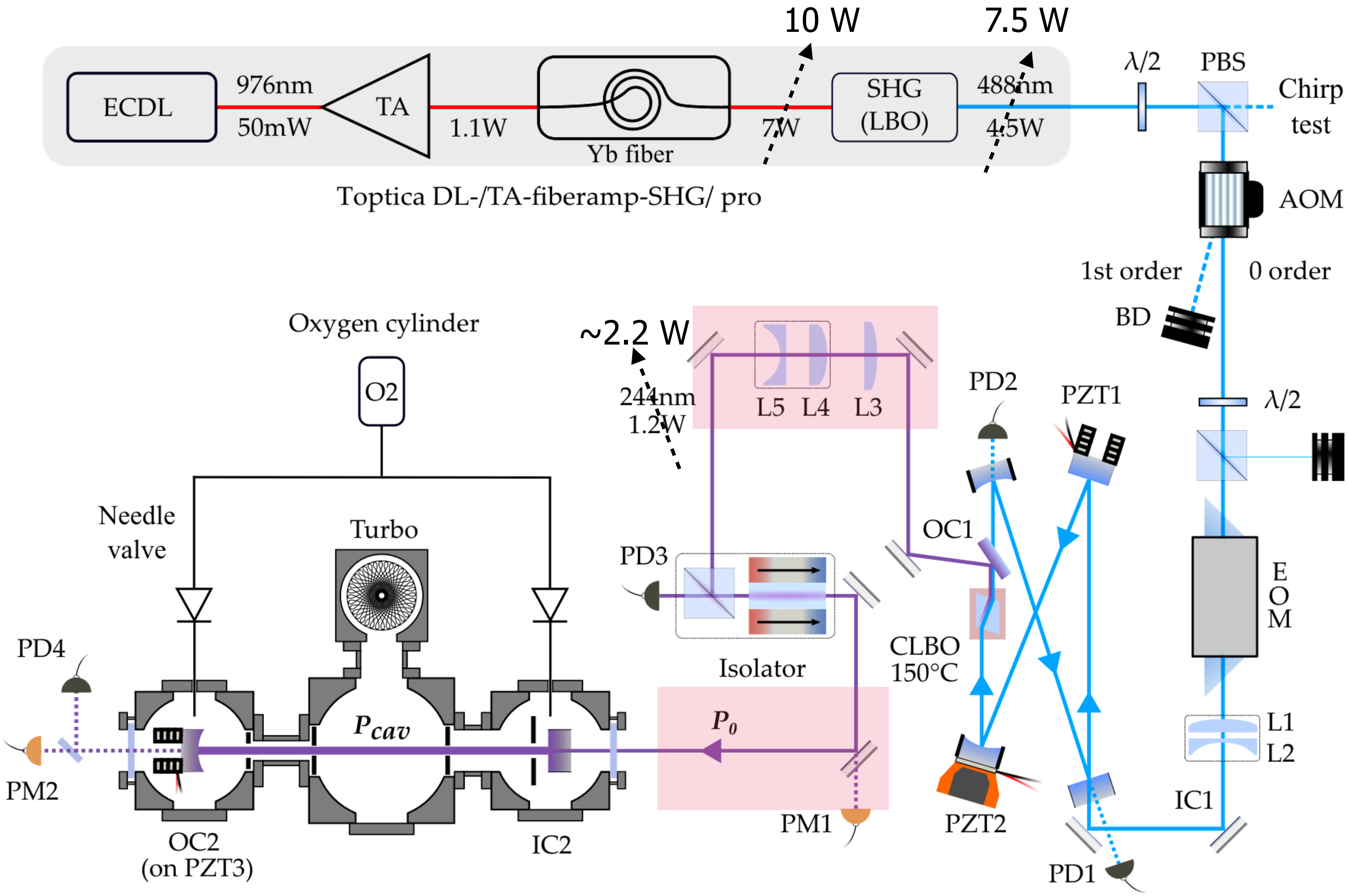

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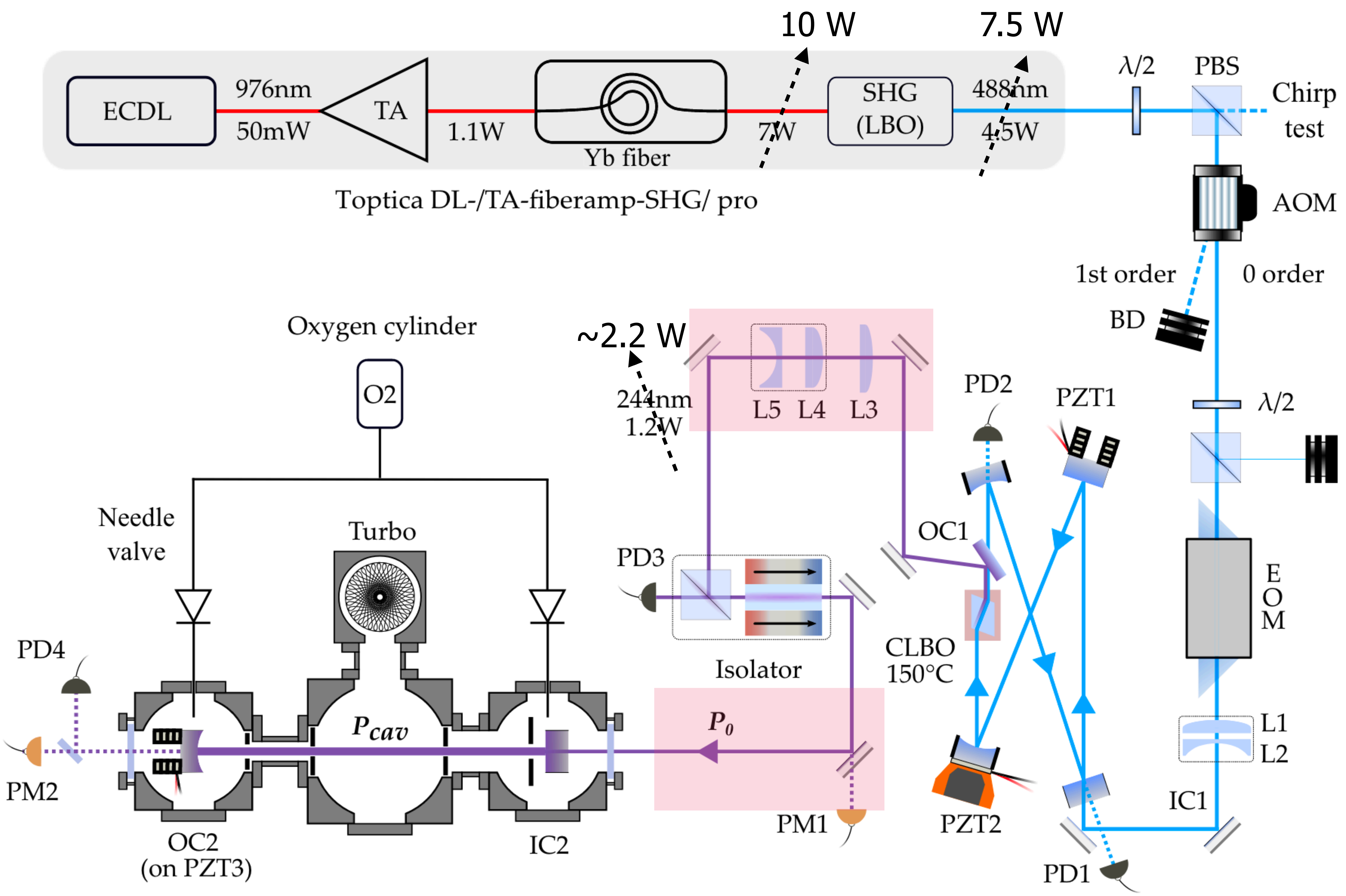
- Work on reducing laser background on tagging



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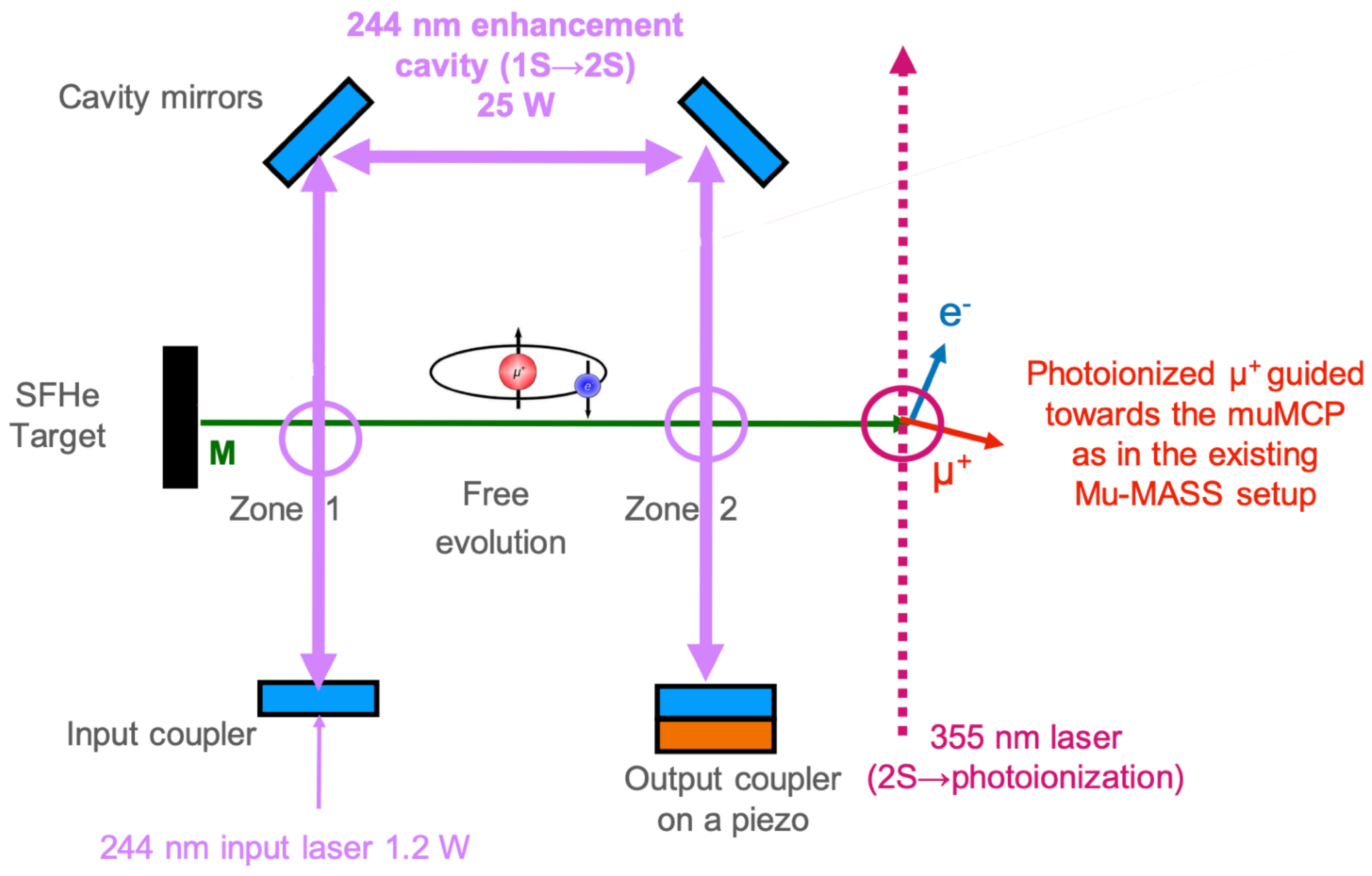
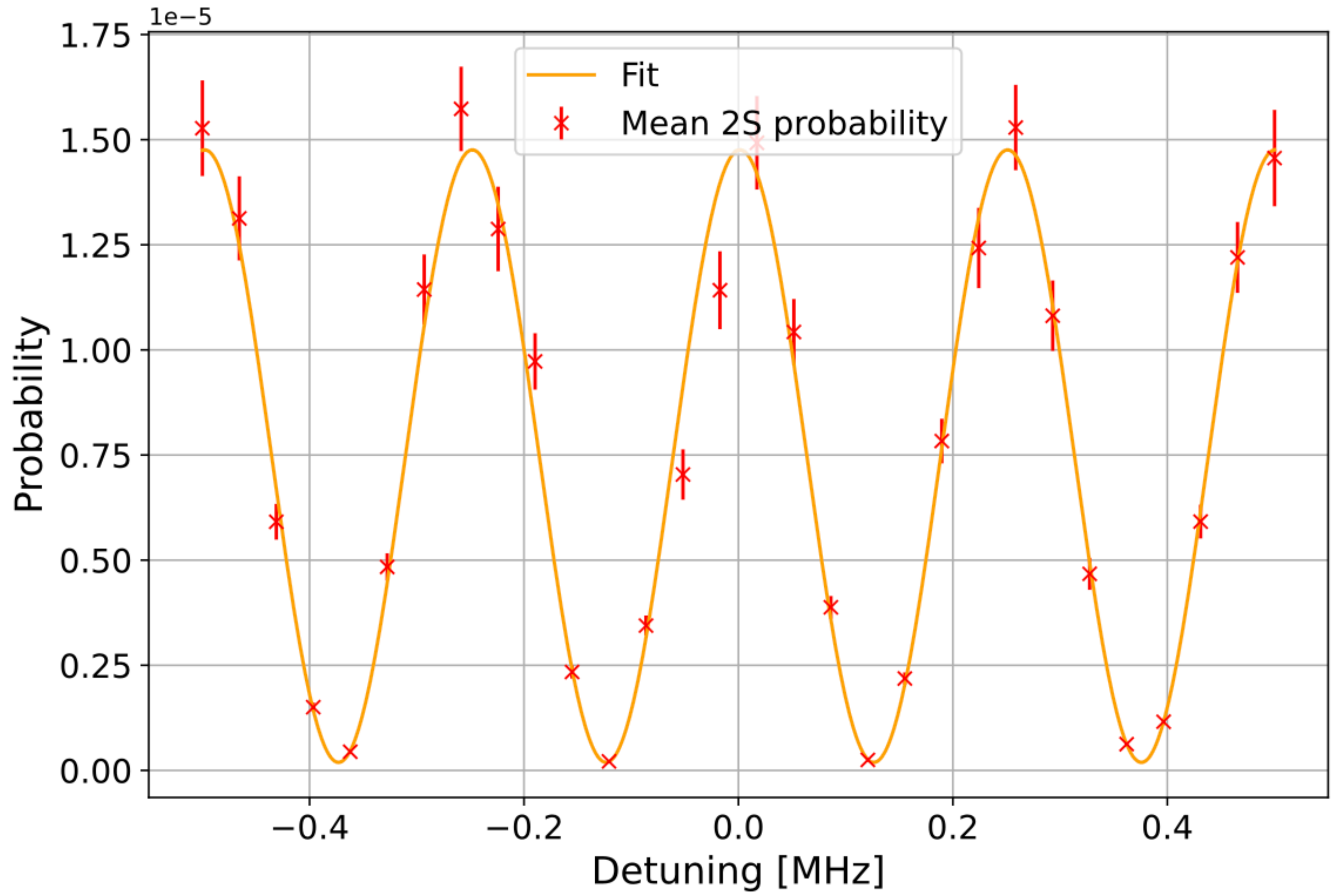
Future Improvements and Prospects

- Beamtime in November this year
- Improved rates: HIMB
- Better phase-space beams:
  - MuCOOL (phase space compression)
  - SFHe sources (colder atoms)
- Alternative spectroscopic technique: Ramsey spectroscopy

Ramsey Spectroscopy

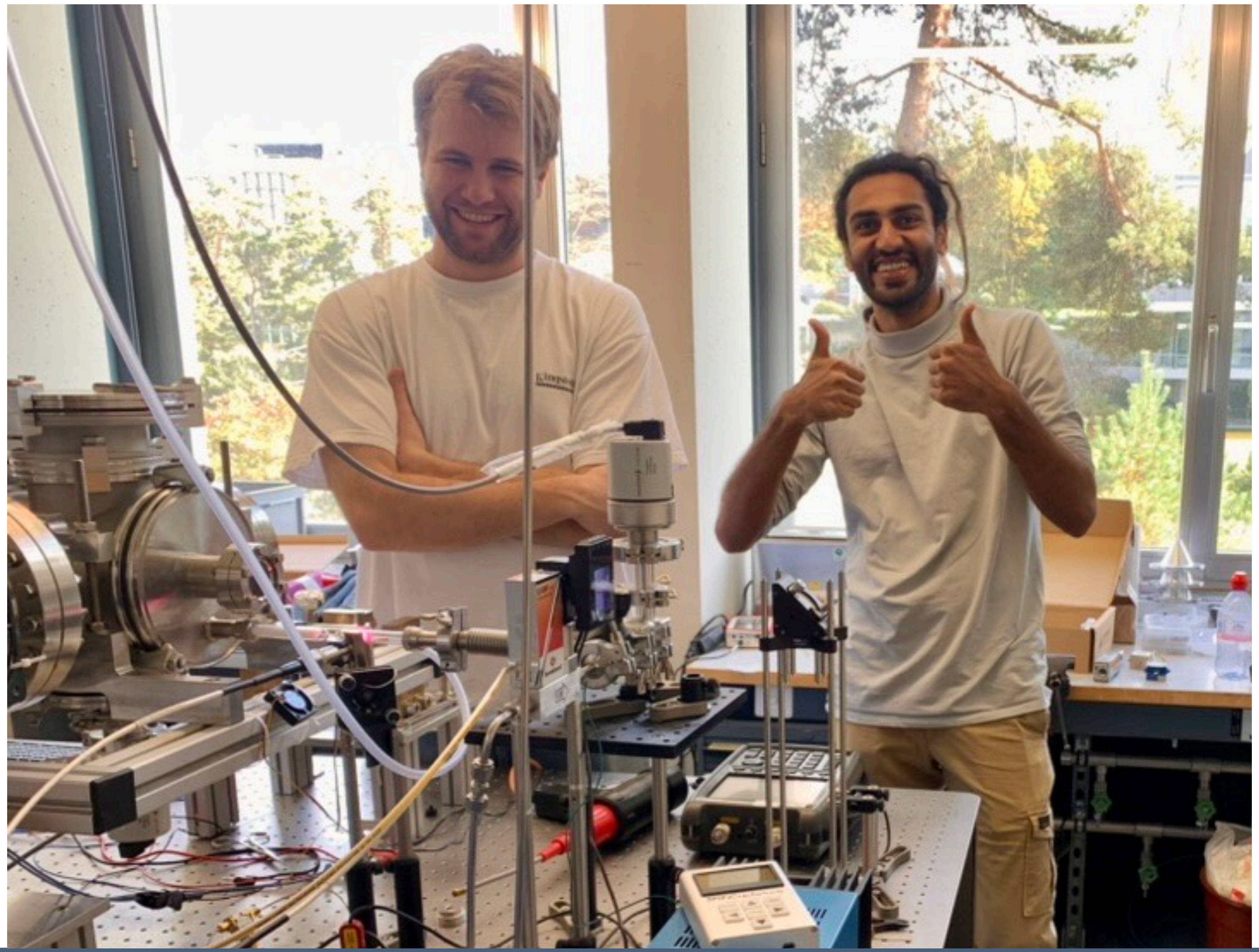
- Two interaction regions, narrower natural linewidth
- For classical Ramsey, mono-energetic atoms (2nd Doppler)

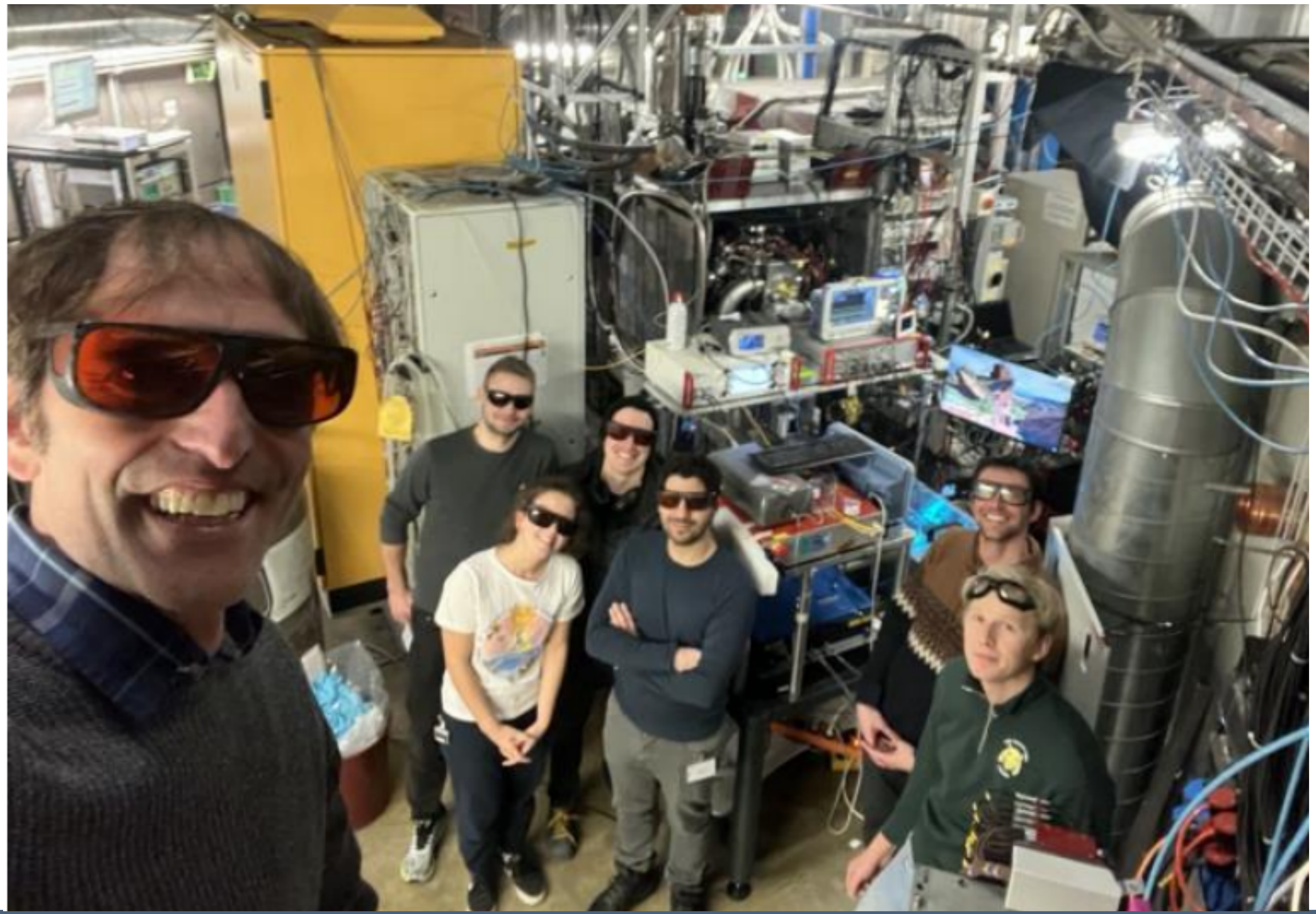


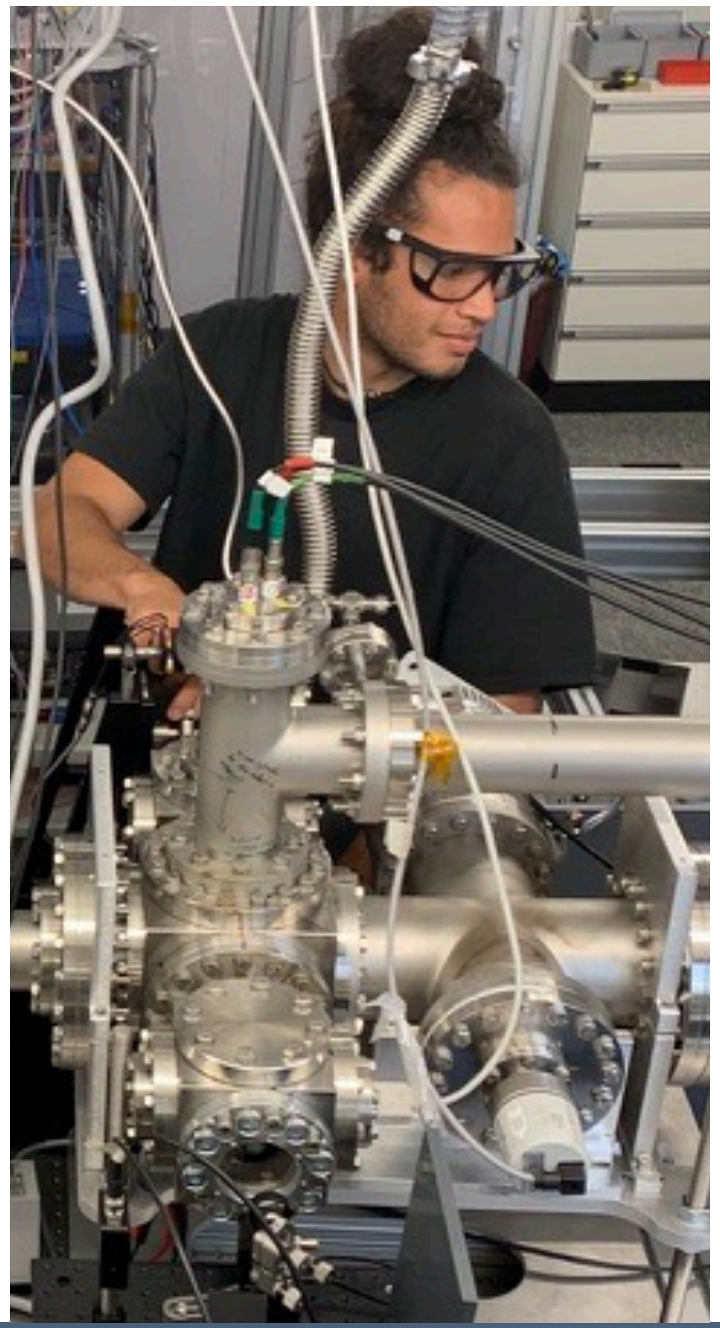


[I. Cortinovis PhD Thesis 2024, Javary, E., Thorpe-Woods, E., Cortinovis, I. et al. Eur. Phys. J. D 79, 15 (2025).]

Thank You for Your Attention!







Backup Slides

Oxygen Treatment

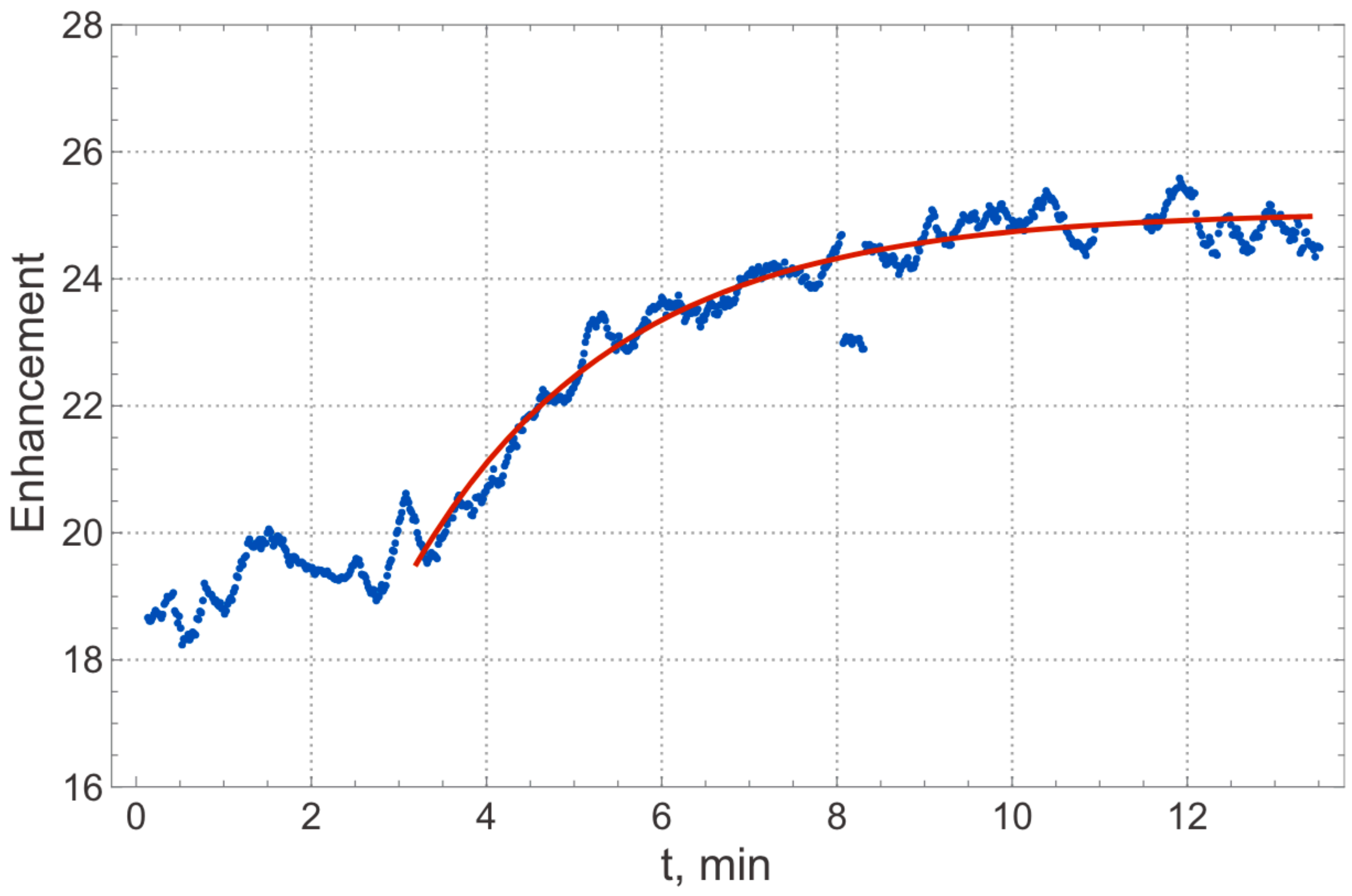
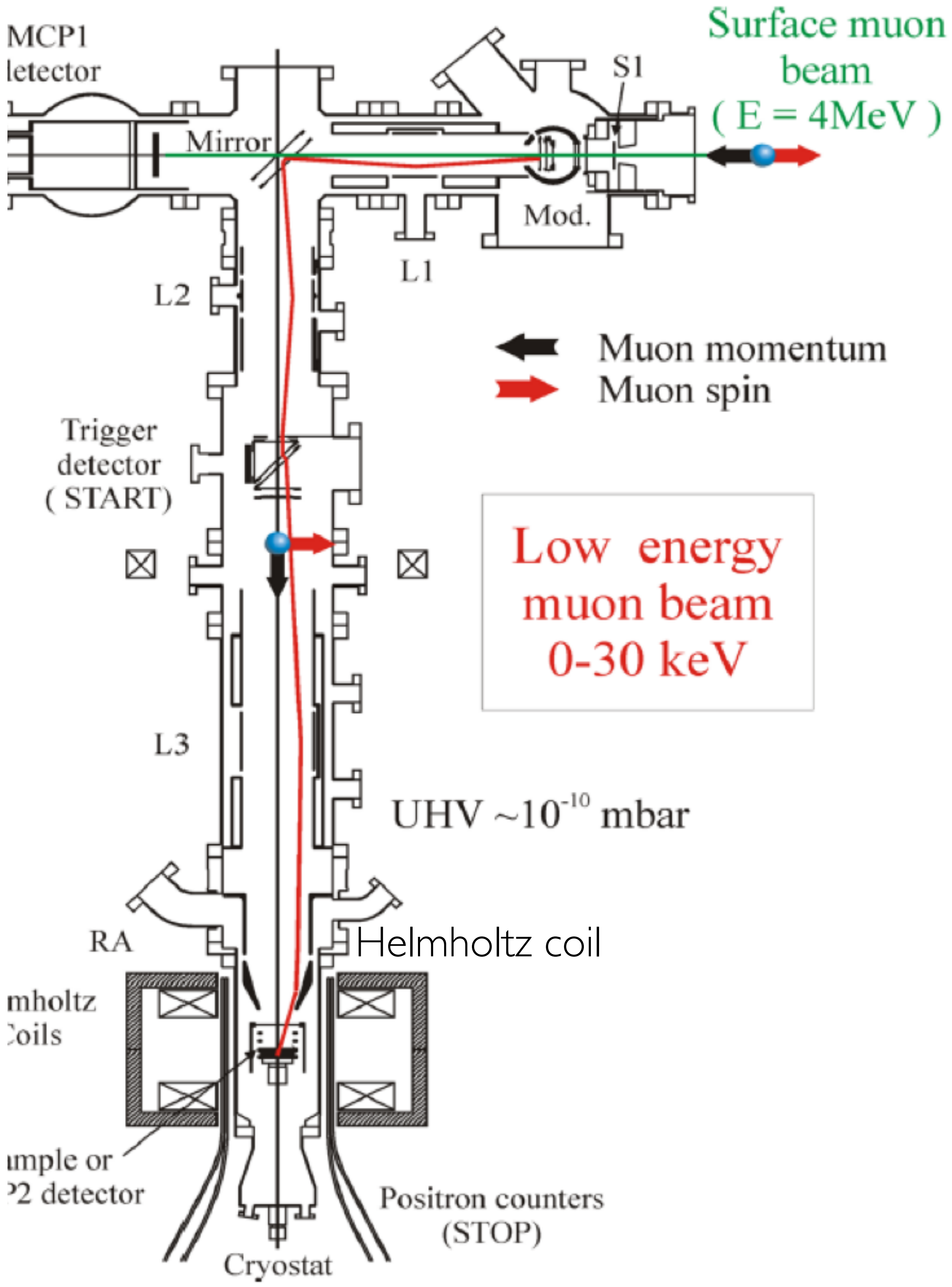
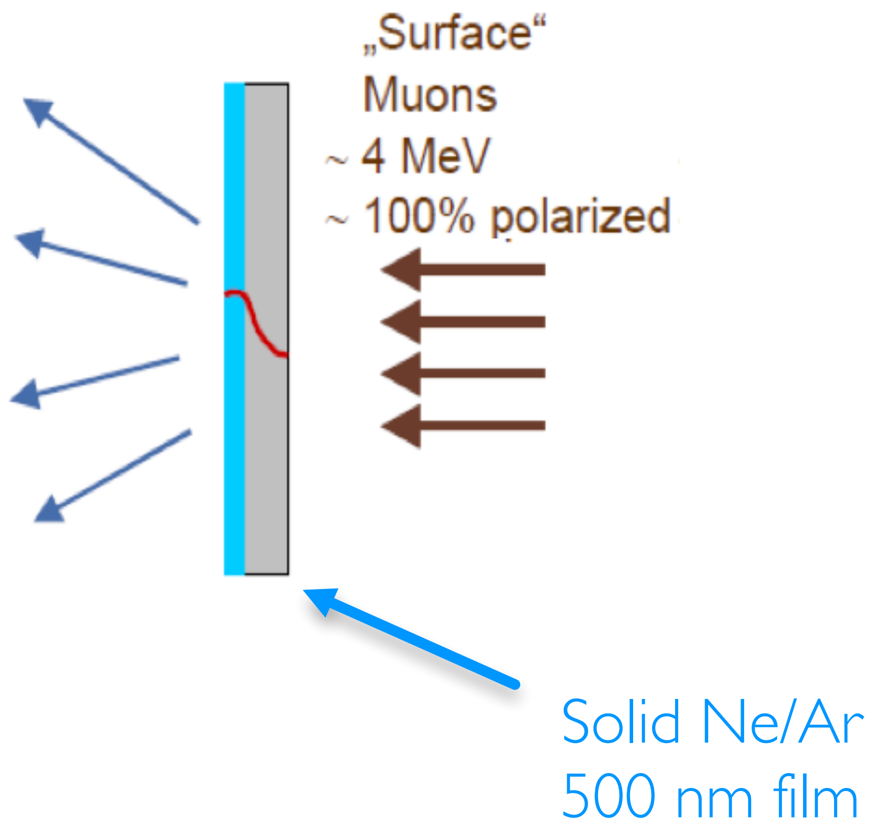
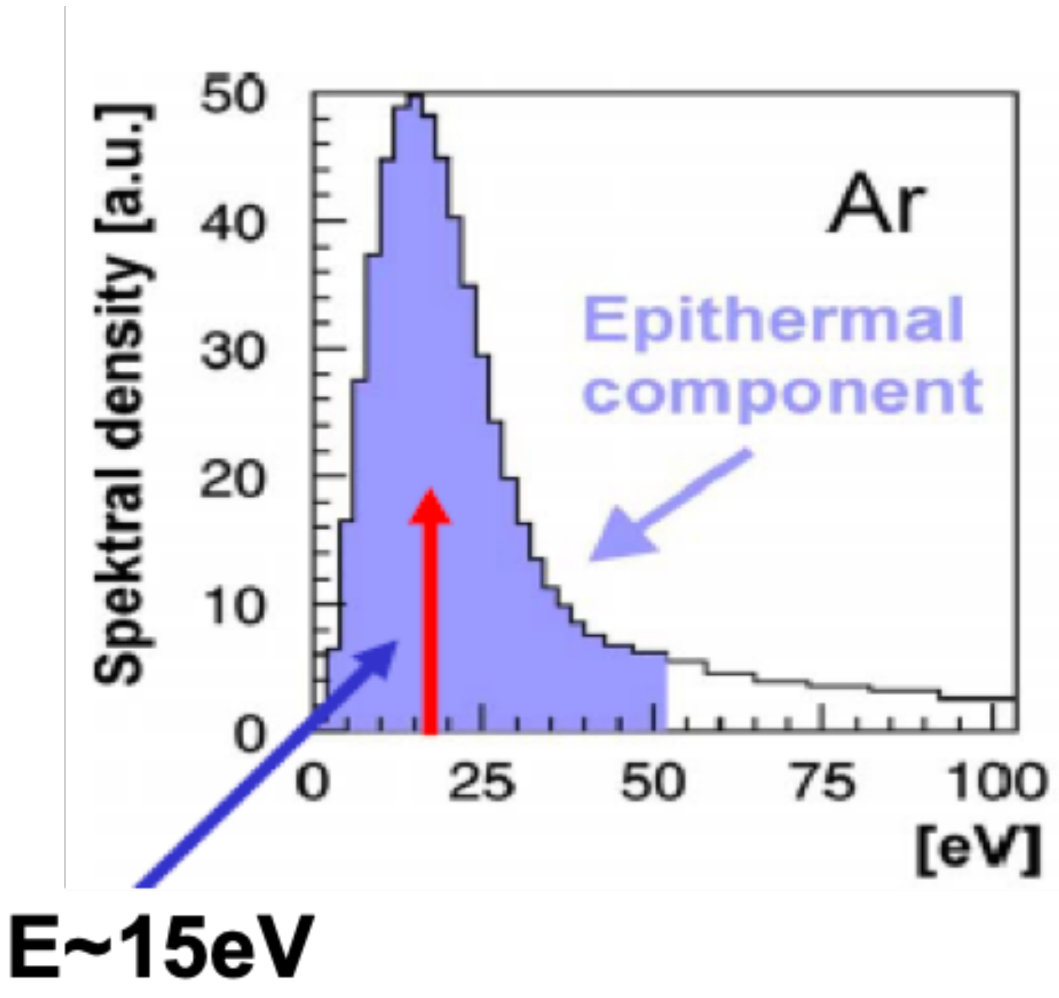


Fig. 3. The cavity's enhancement factor during oxygen conditioning was determined by measuring the cavity input and transmitted powers. The conditioning was performed with 1 W of intracavity UV light and an oxygen pressure of 10^{-2} mbar. The recovery process had a time constant of 2.5 minutes. The fluctuations on the graph are due to the influence of the oxygen flow from the needle valves.

The Low-Energy Muons (LEM) Beamline at PSI





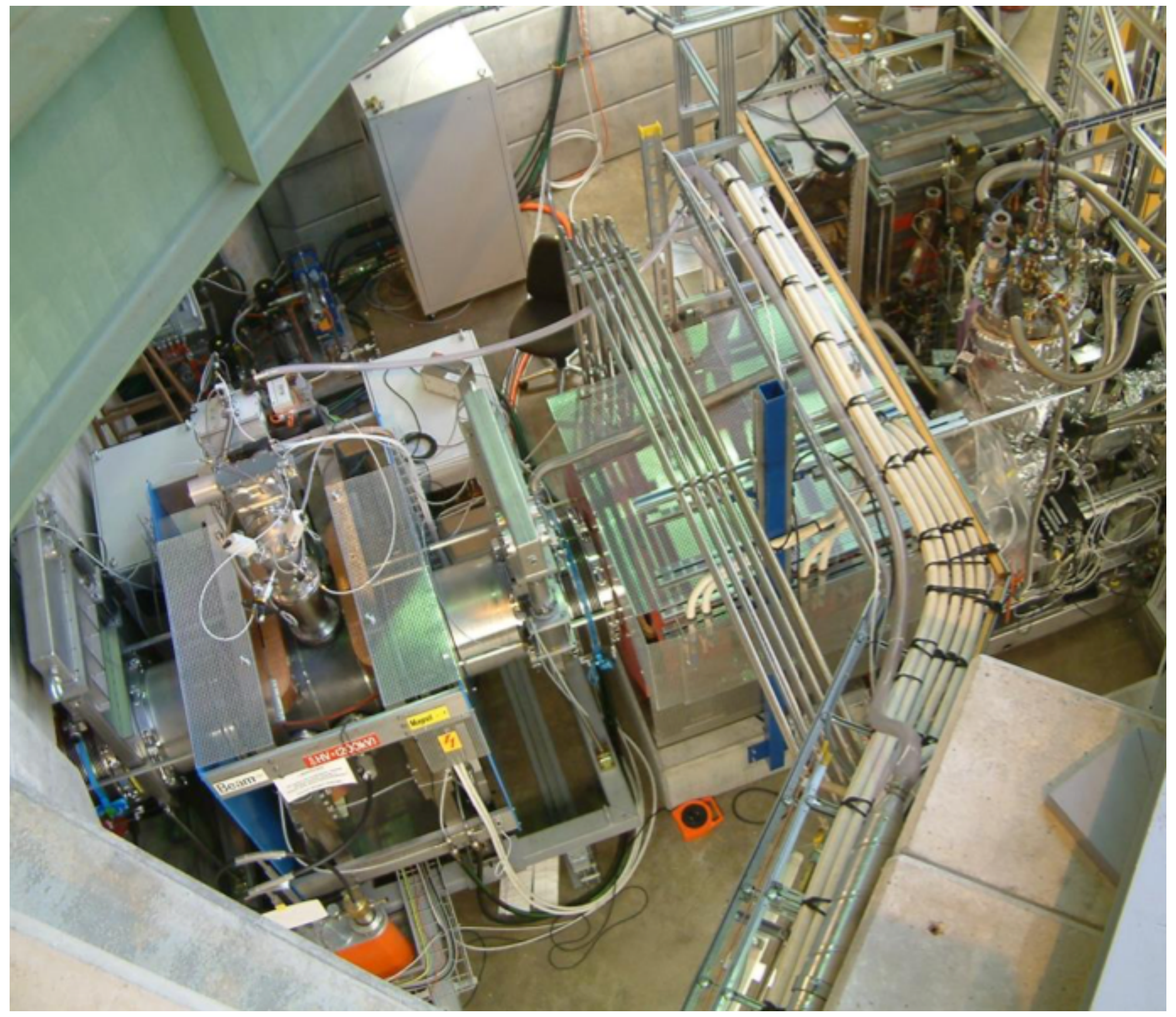


Up to 5x10^3 μ^+/s

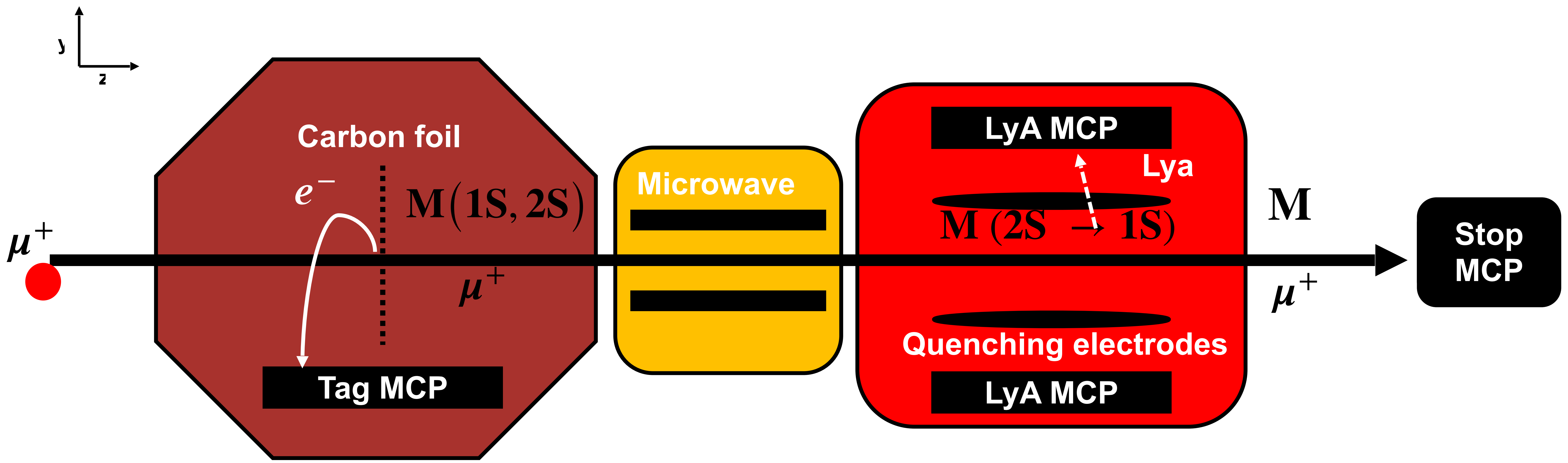
TARGET

https://www.psi.ch/en/low-energy-muons

PAUL SCHERRER INSTITUT PSI



Muonium Microwave Spectroscopy



1. M formed in 2S state as μ^+ beam traverses carbon foil

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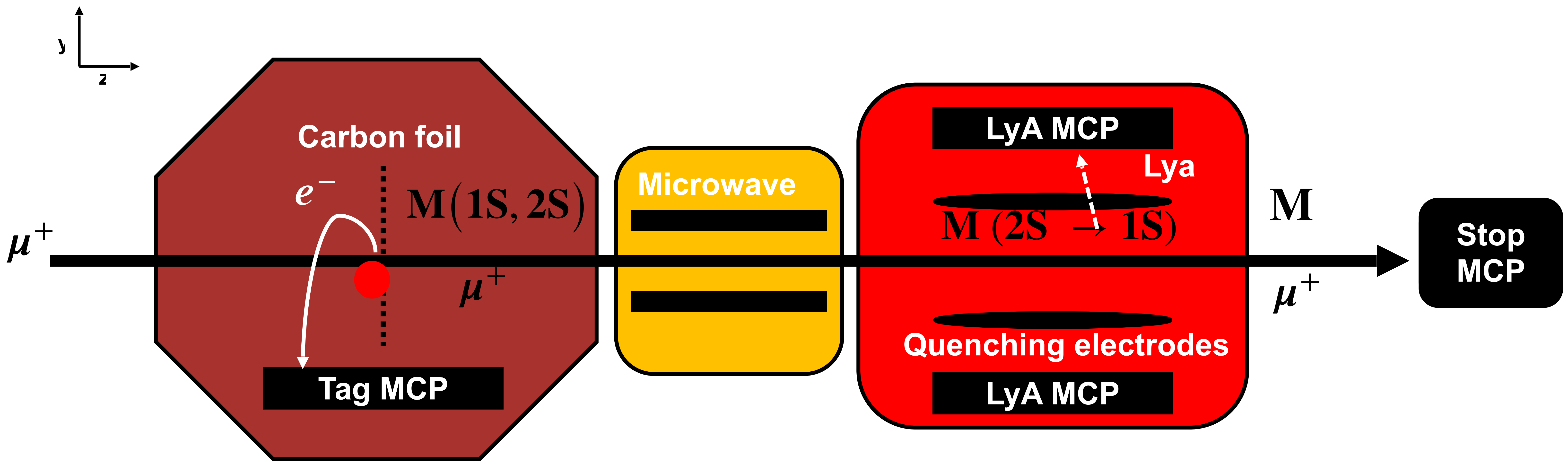

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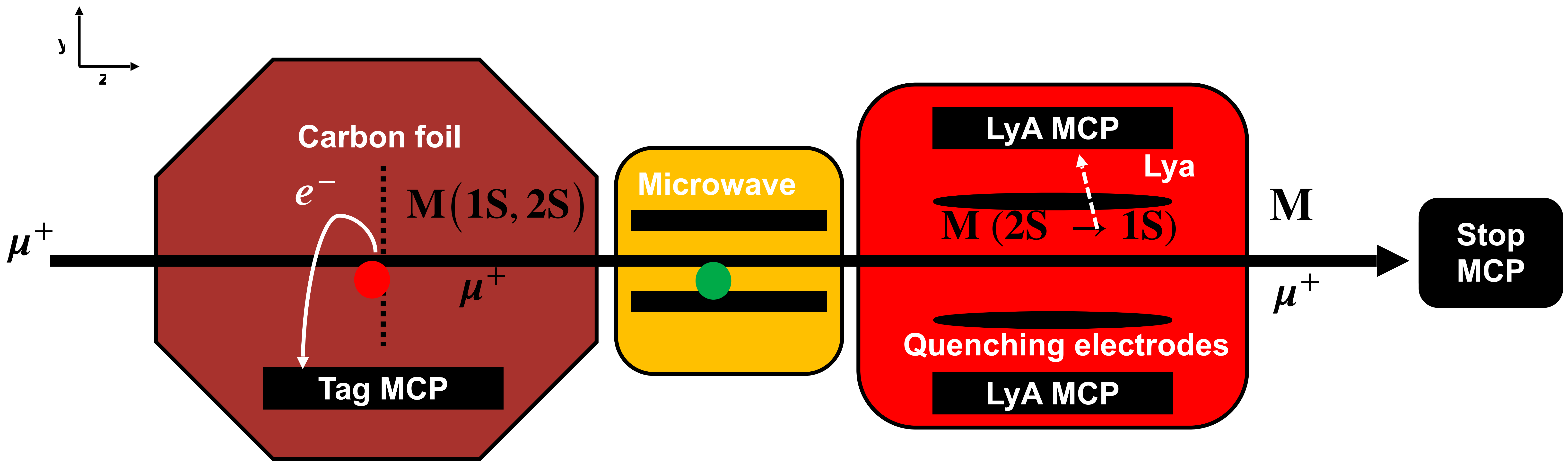
Muonium Microwave Spectroscopy



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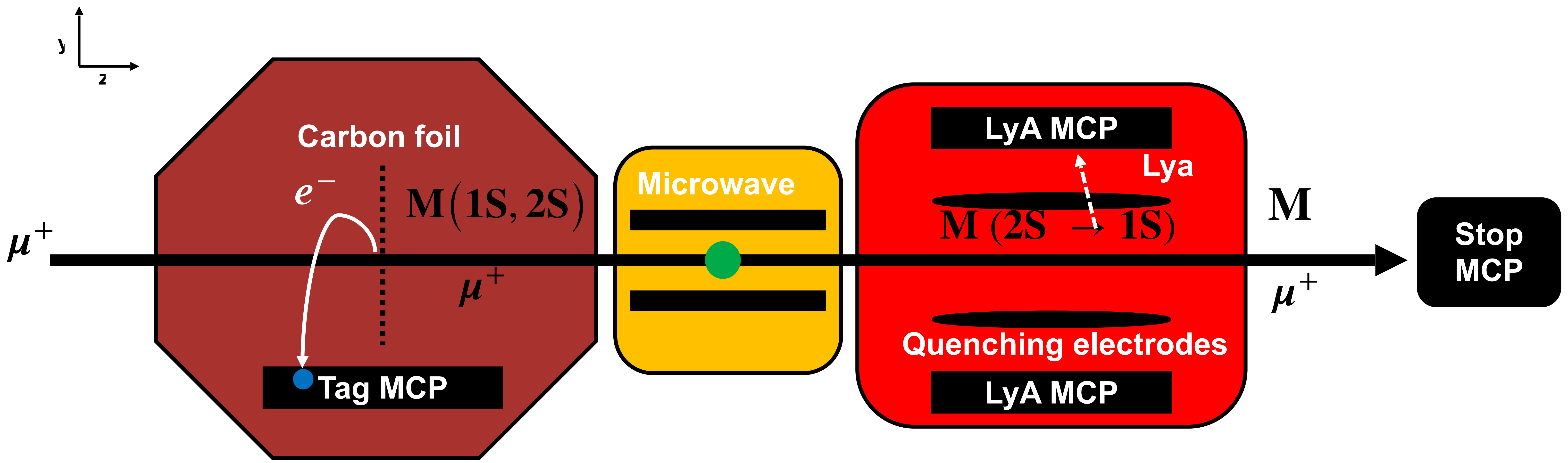

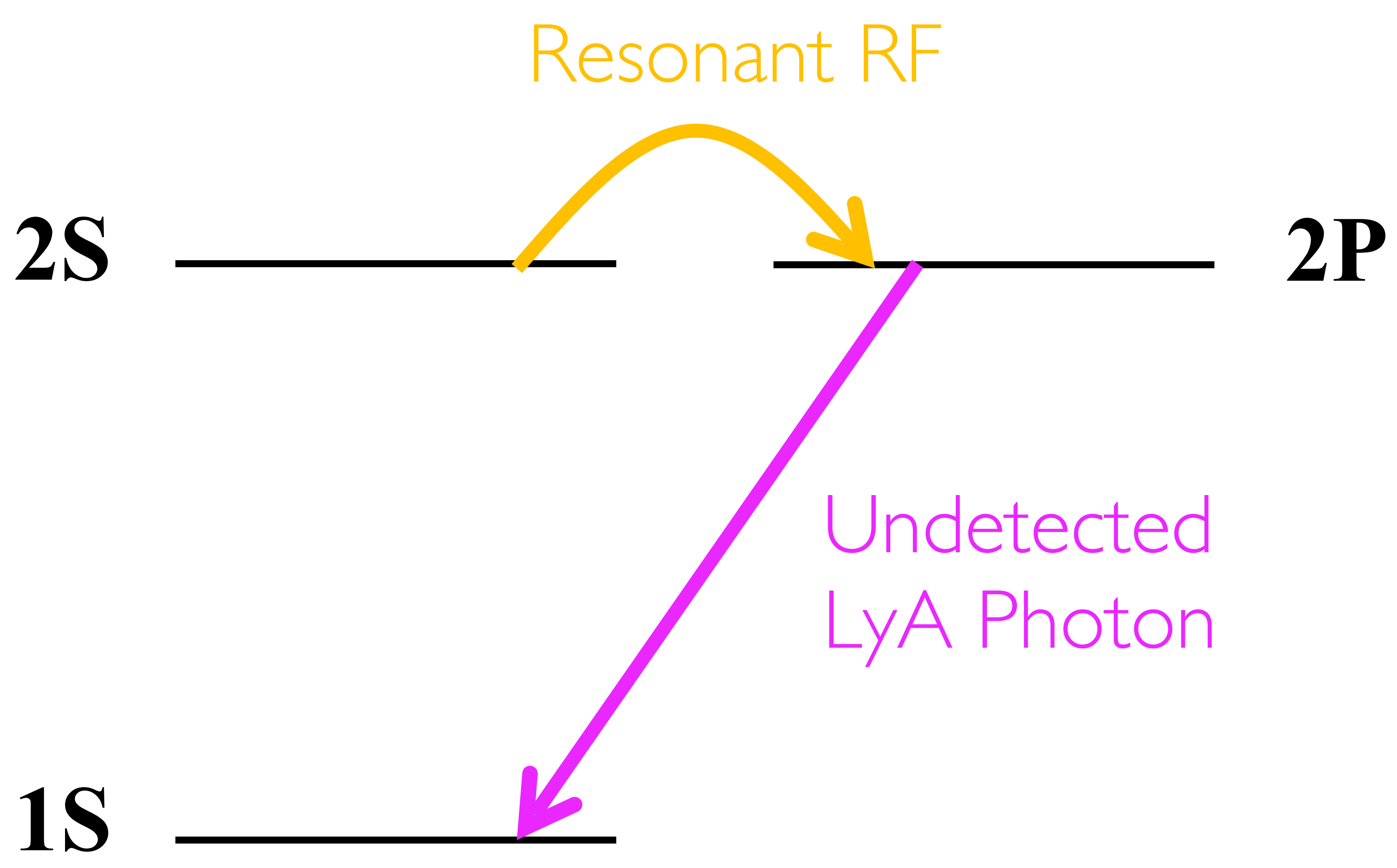

1. M formed in 2S state as μ^+ beam traverses carbon foil
2. Resonant microwaves excite 2S→2P, followed by 2P→1S decay

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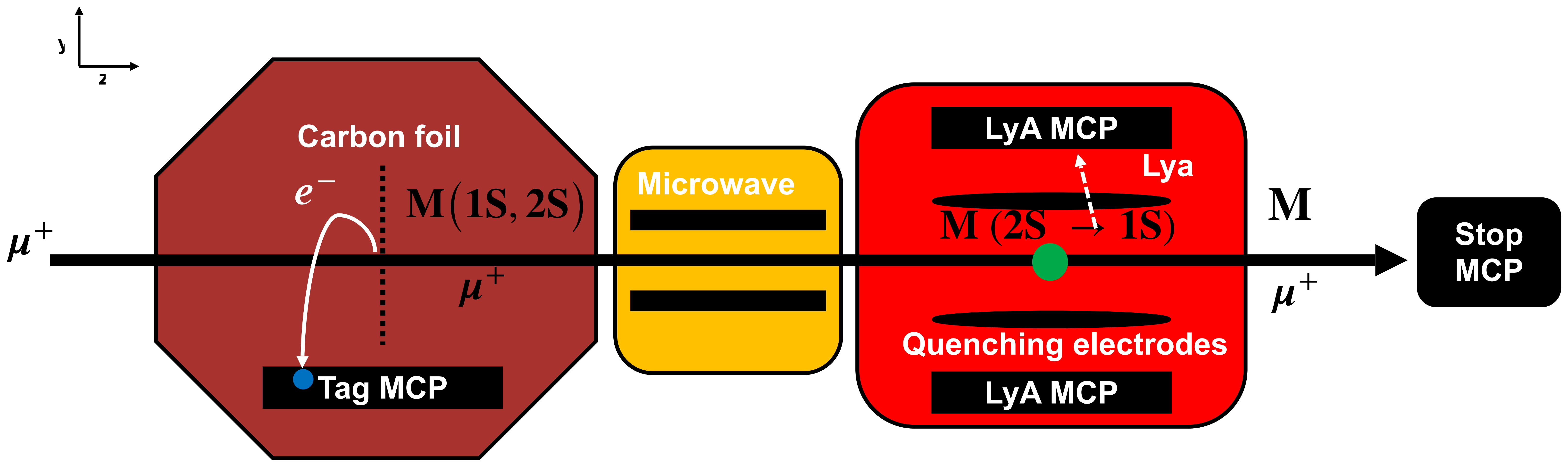

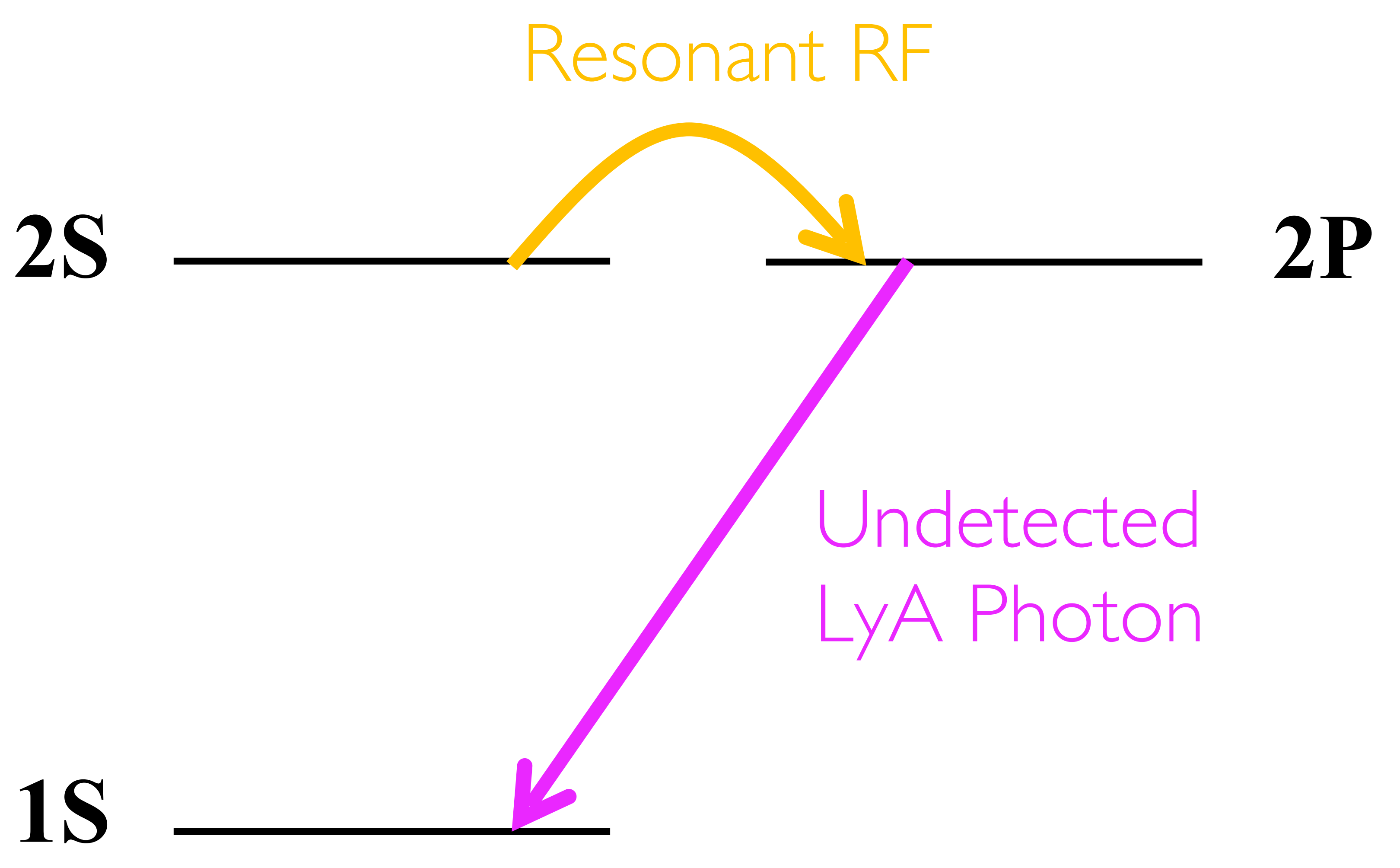

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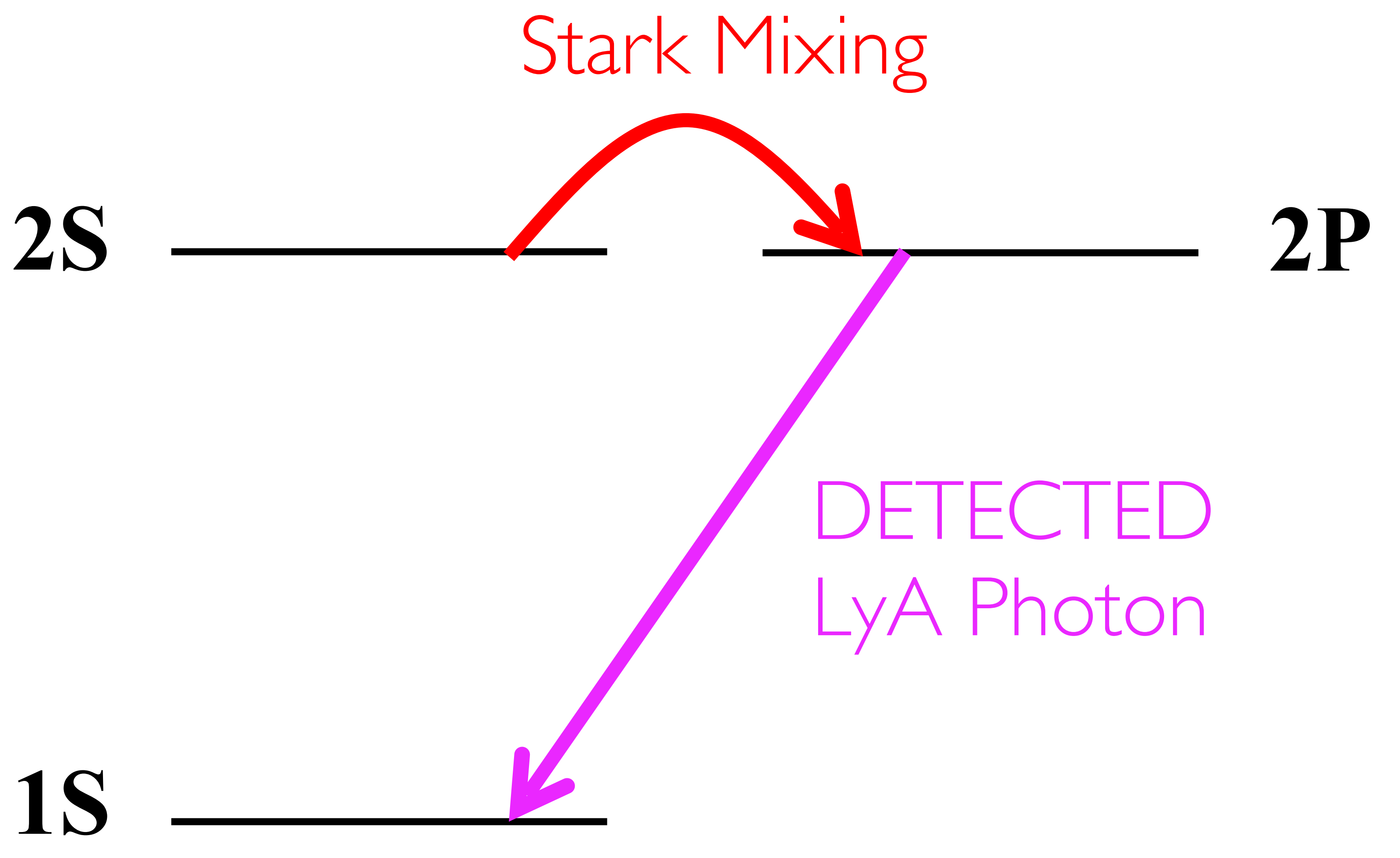

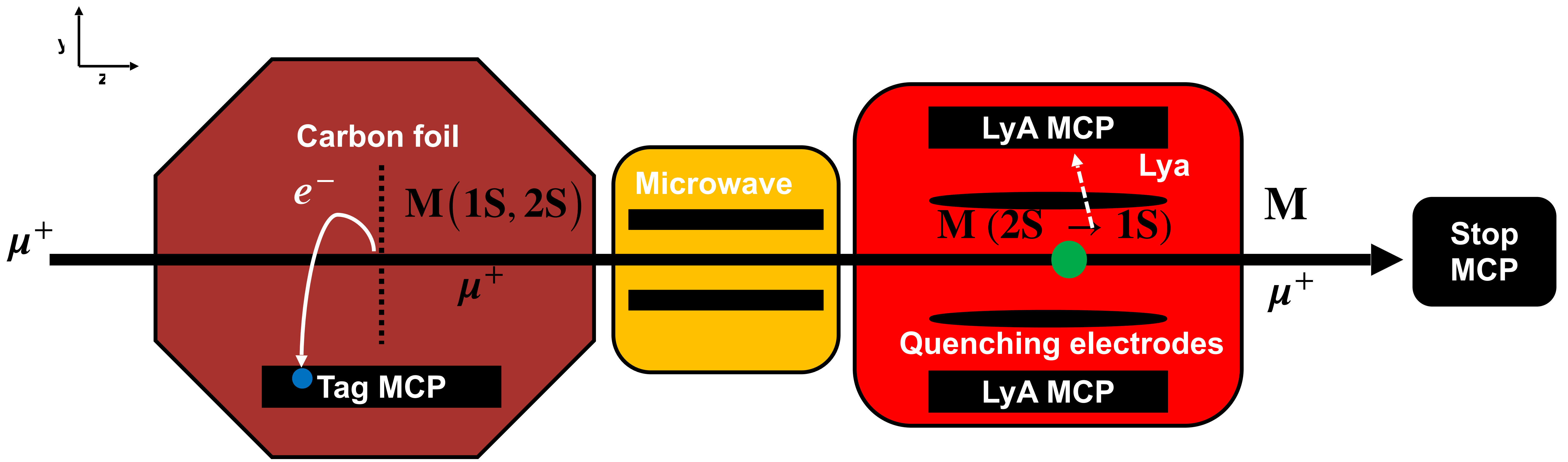

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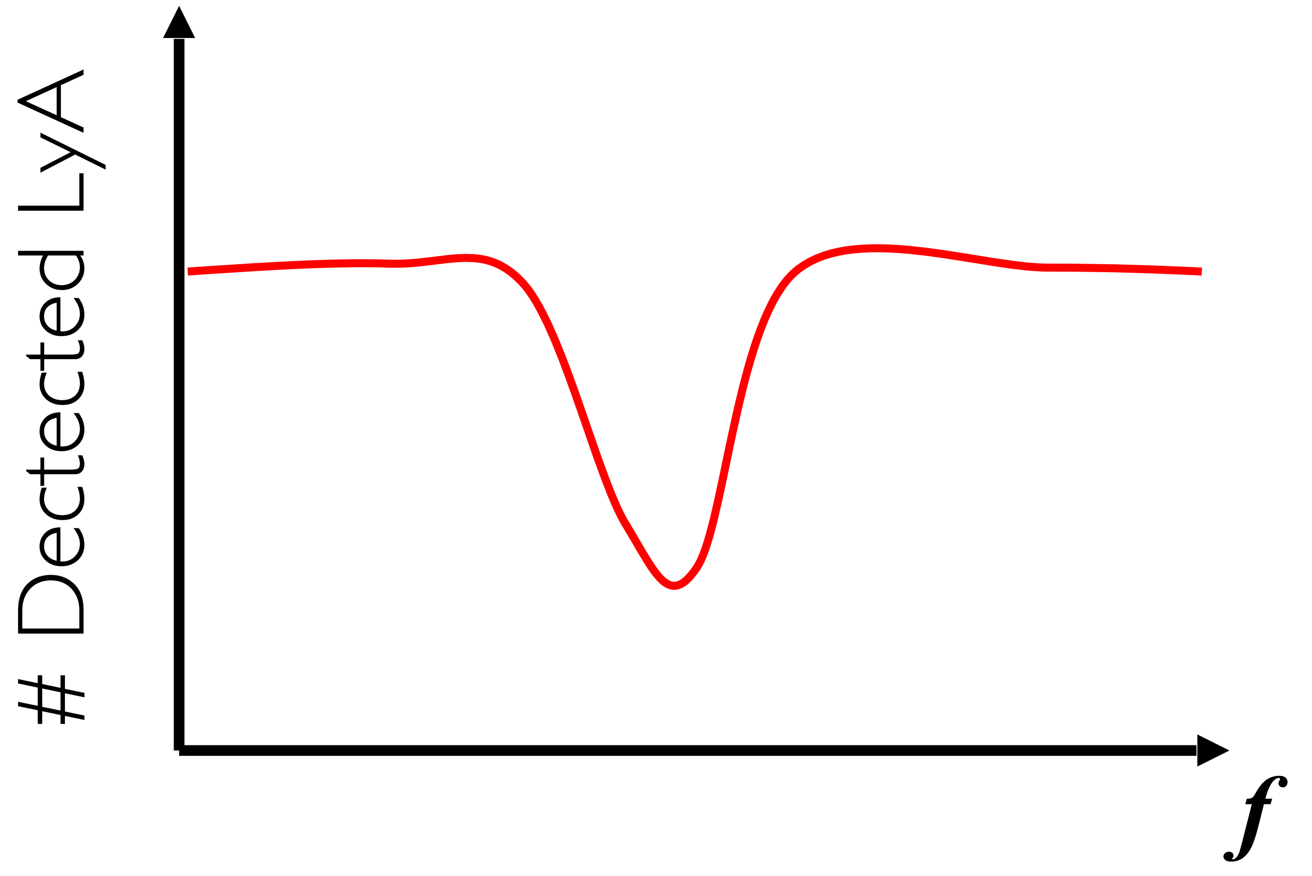
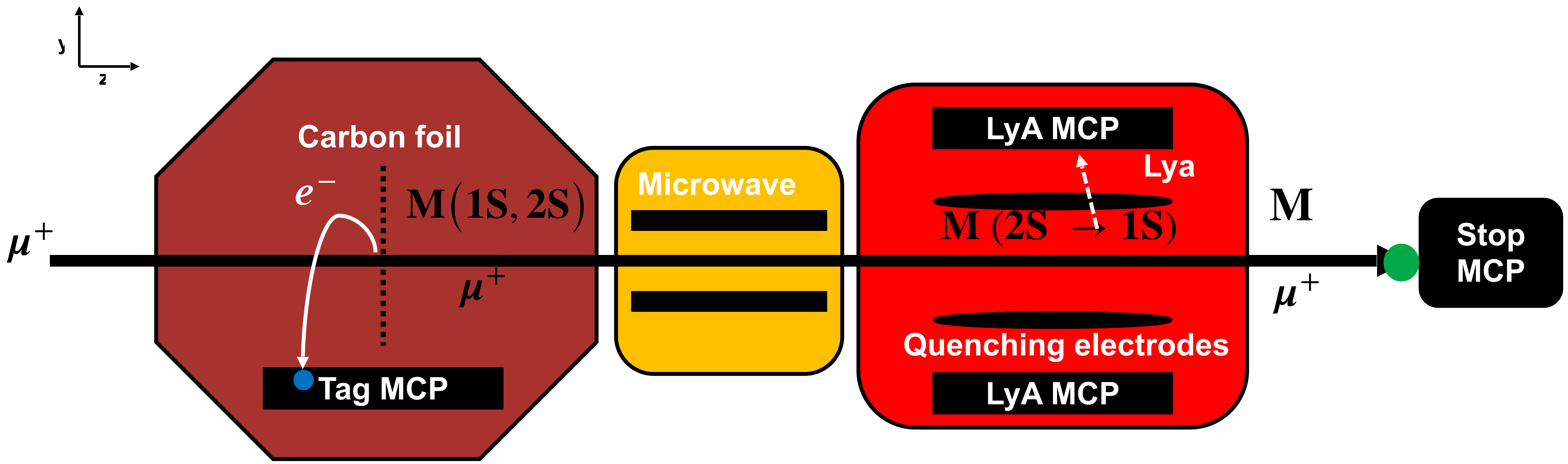
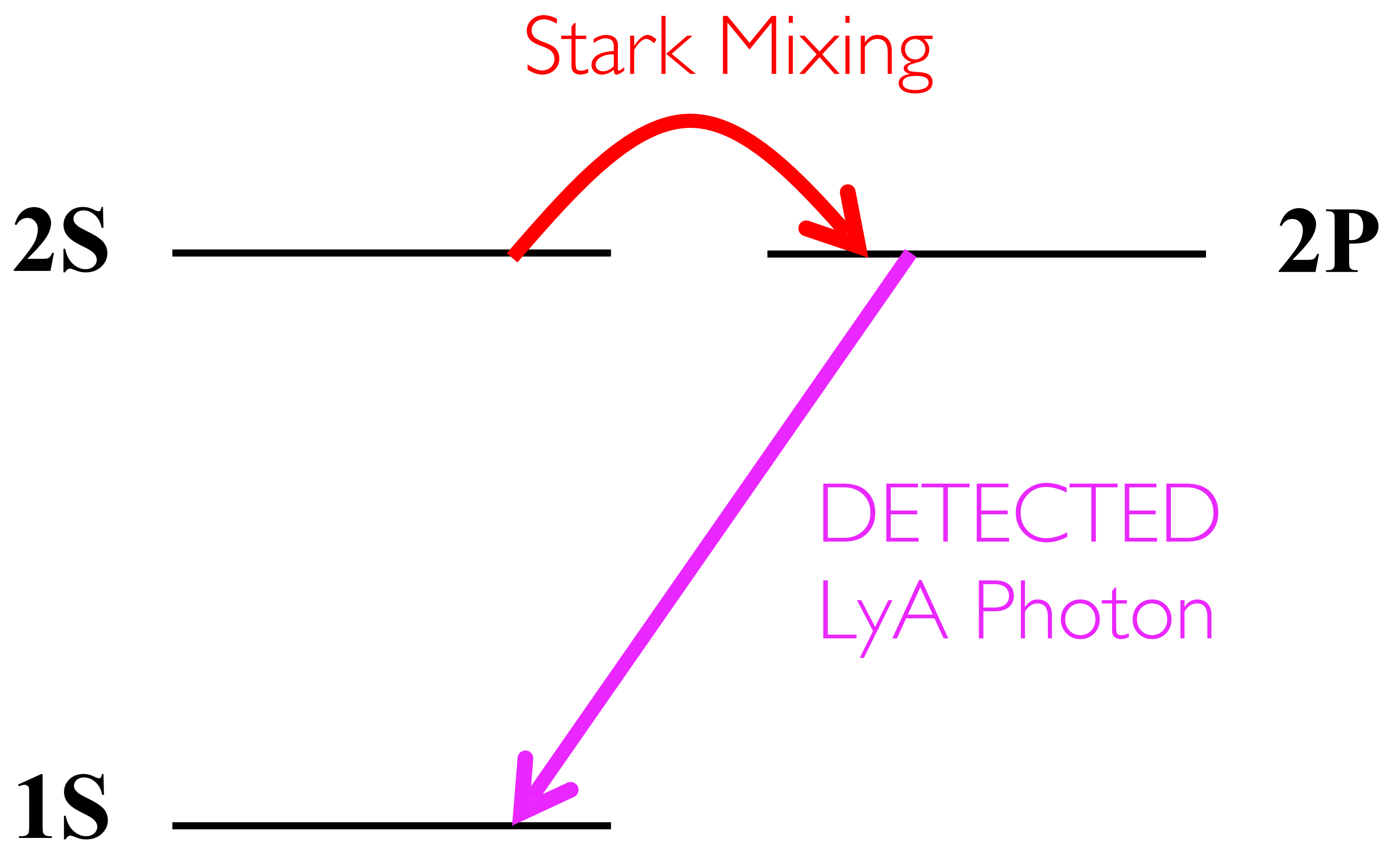
3. Remaining 2S states quenched in detection region, 121nm photon detected



Muonium Microwave Spectroscopy





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