

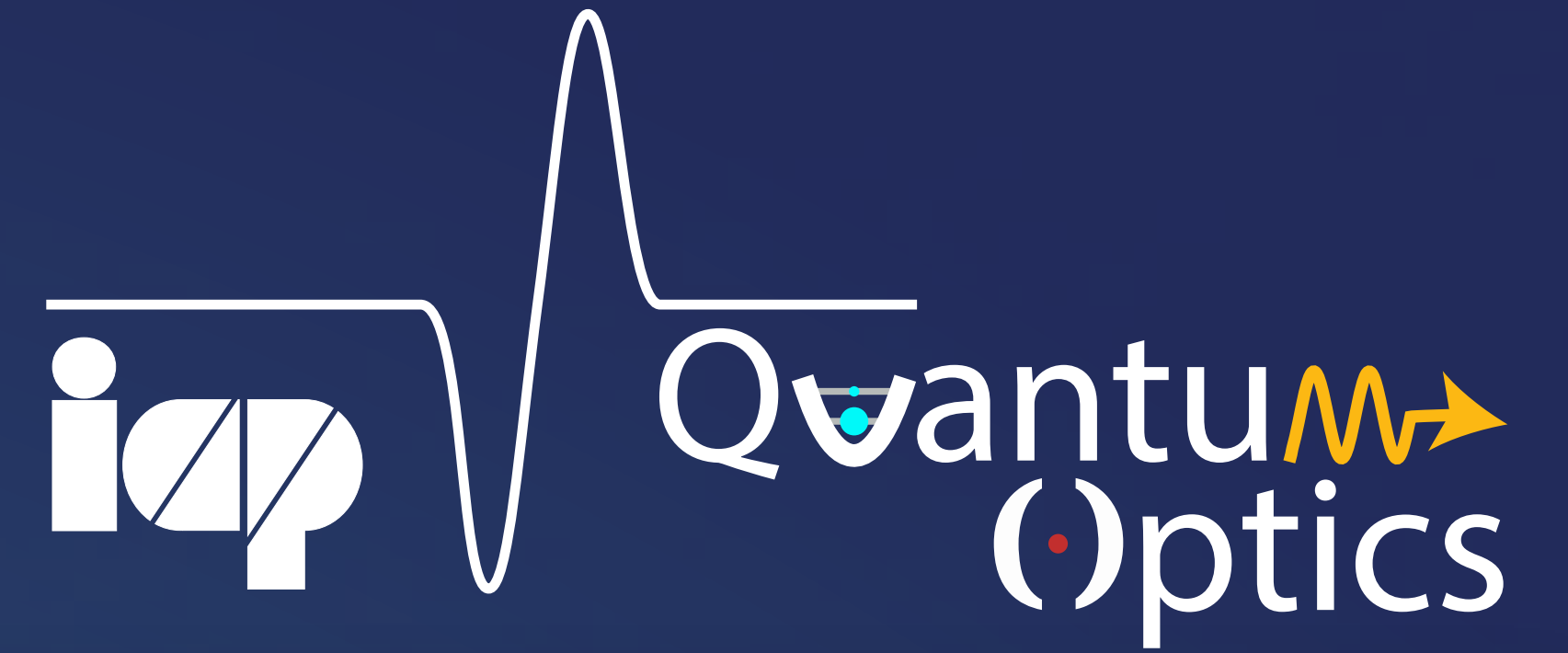
Spectroscopy of Heteronuclear Xenon-Noble Gas Dimers – Toward Bose-Einstein Condensation of Vacuum-UV Photons

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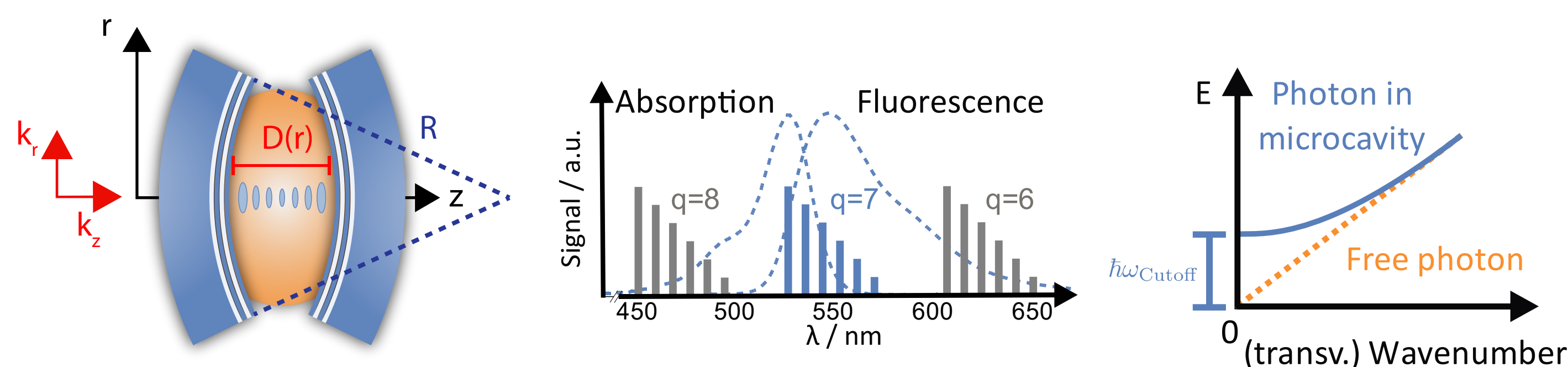
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Bose-Einstein Condensation of Photons

Bose-Einstein condensation emerges in gases of massive bosons at thermal equilibrium. By confining photons in a dye-filled optical microcavity, both an effective mass and a number-conserving thermalization can be realized [1]:



- **Thermalization** by absorption and emission of photons on dye molecules
- Locally elevated surface of mirror realizes **arbitrarily shaped repulsive potential**

Dispersion relation:

$$E(k_r, r) \simeq m_{ph} \frac{c^2}{n^2} + \frac{\hbar^2 k_r^2}{2m_{ph}} + \frac{1}{2} m_{ph} \Omega^2 r^2 + m_{ph} \frac{c^2}{n^3} \Delta n(r)$$

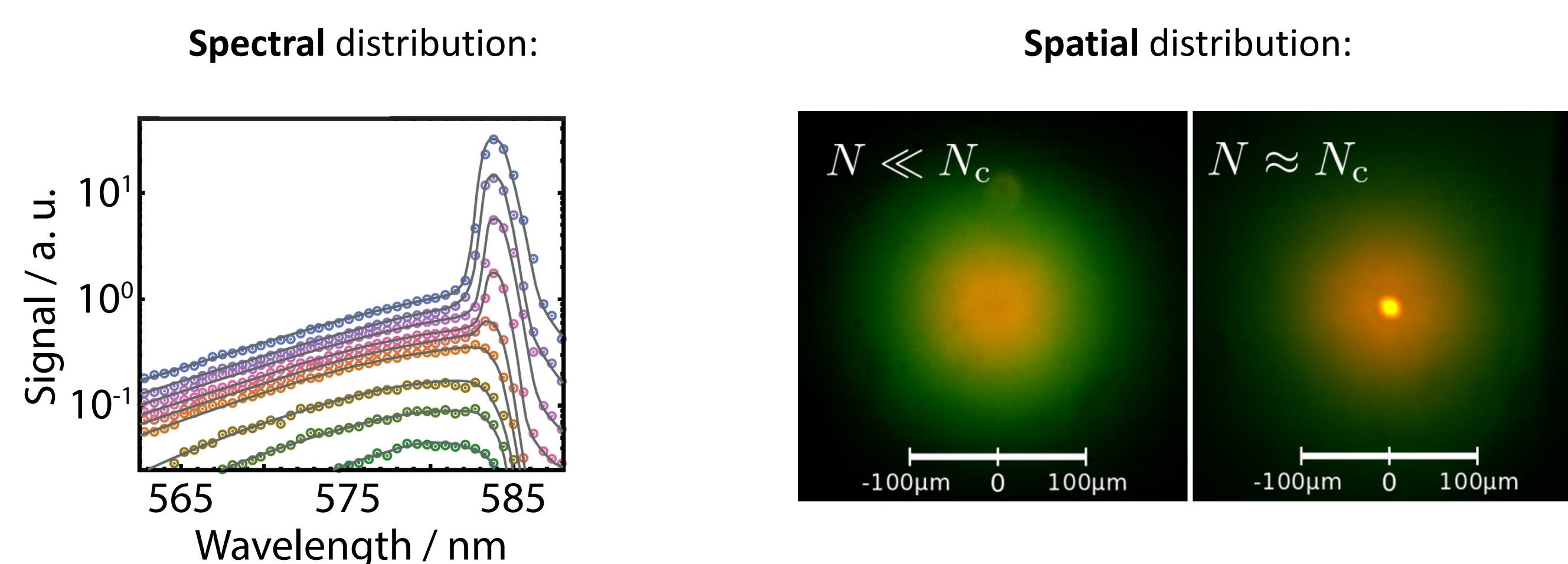
$$m_{ph} := \frac{\hbar q \pi n}{c D_0} \simeq 10^{-35} \text{ kg} \quad \Omega := \frac{c}{n \sqrt{D_0 R/2}} \simeq 10^{11} \text{ Hz}$$

Kennard-Stepanov relation:

$$\frac{f(\omega)}{\alpha(\omega)} \propto \omega^3 \exp\left(-\frac{\hbar\omega}{k_B T}\right)$$

- Most important **prerequisite** for a medium to act as a **thermalization mediator**

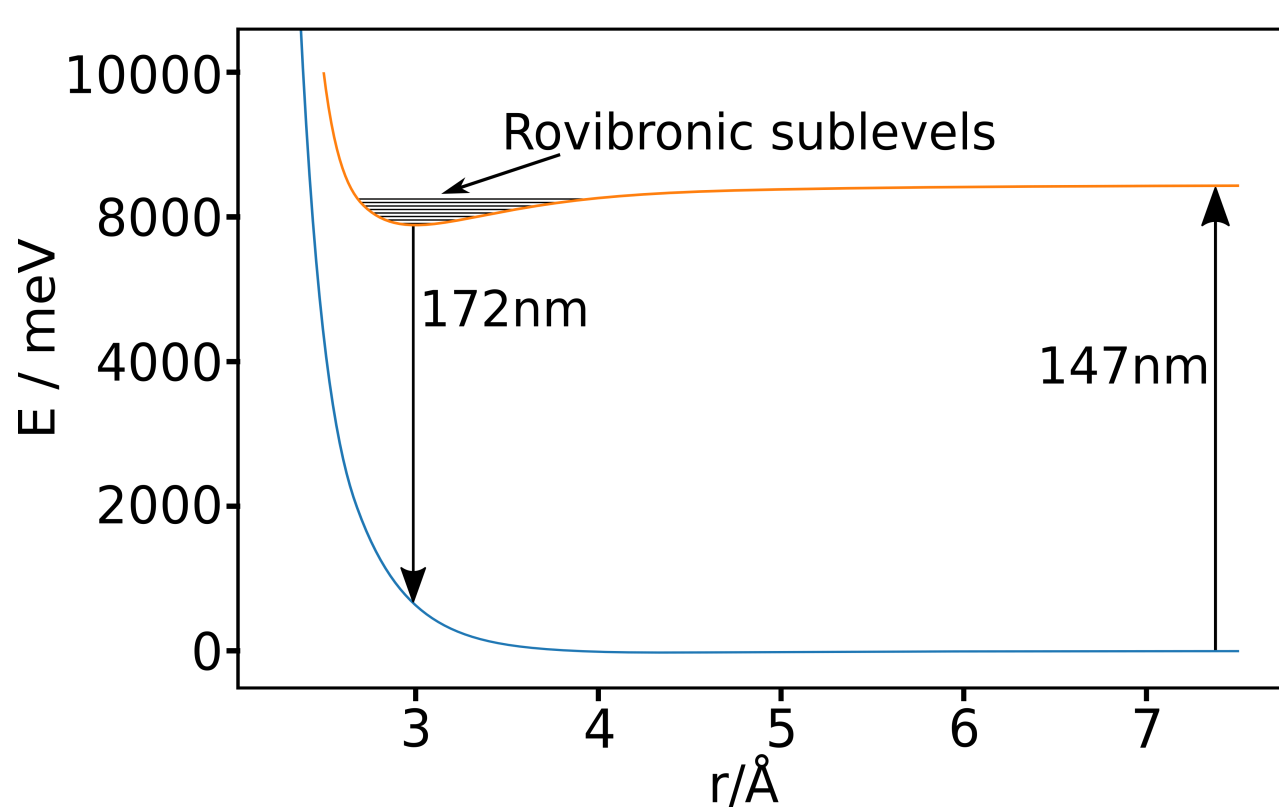
Observation of photon Bose-Einstein condensation:



Adaption to VUV Spectral Regime

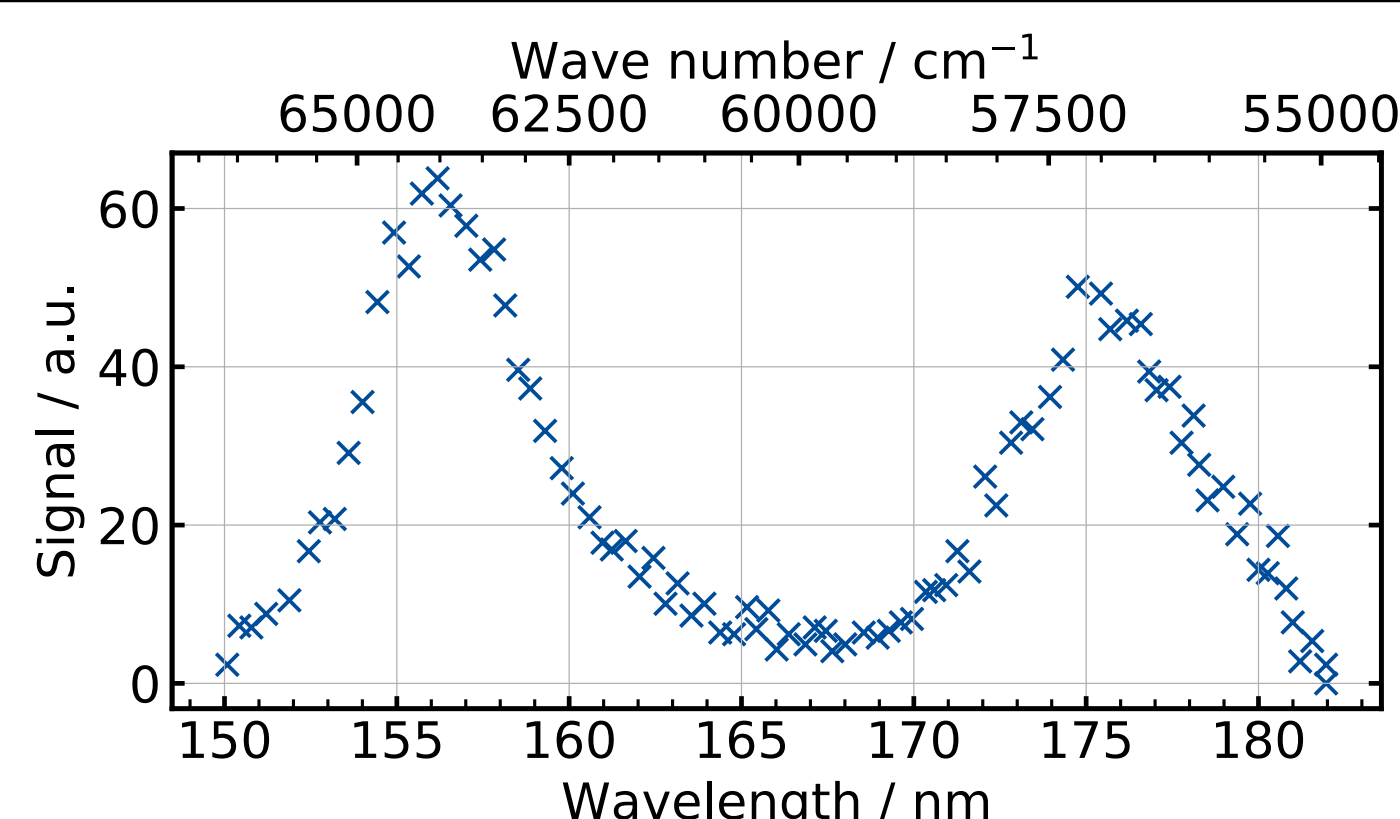
VUV spectral regime: **100nm - 200nm**

→ Need a new thermalization mediator for **Bose-Einstein condensation of VUV photons**



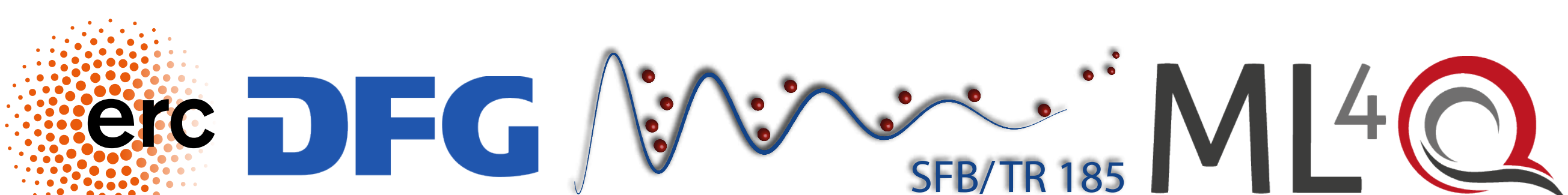
- Xenon has transition energies in the VUV [2]
- Transition from the $5p^6$ to the $5p^5 6s$ ($J = 1$) state at **147nm**
- **High pressure:** excimer emitting at **172nm**
- BUT: **Spectral gap is too large** [3]

- **Heteronuclear emission of Xenon-Krypton** [4]
- **Emission emerges around 156nm**
- Shallower excited state potential
- **IDEA:** Use **xenon-noble gas mixtures** as a thermalization mediator for VUV photons

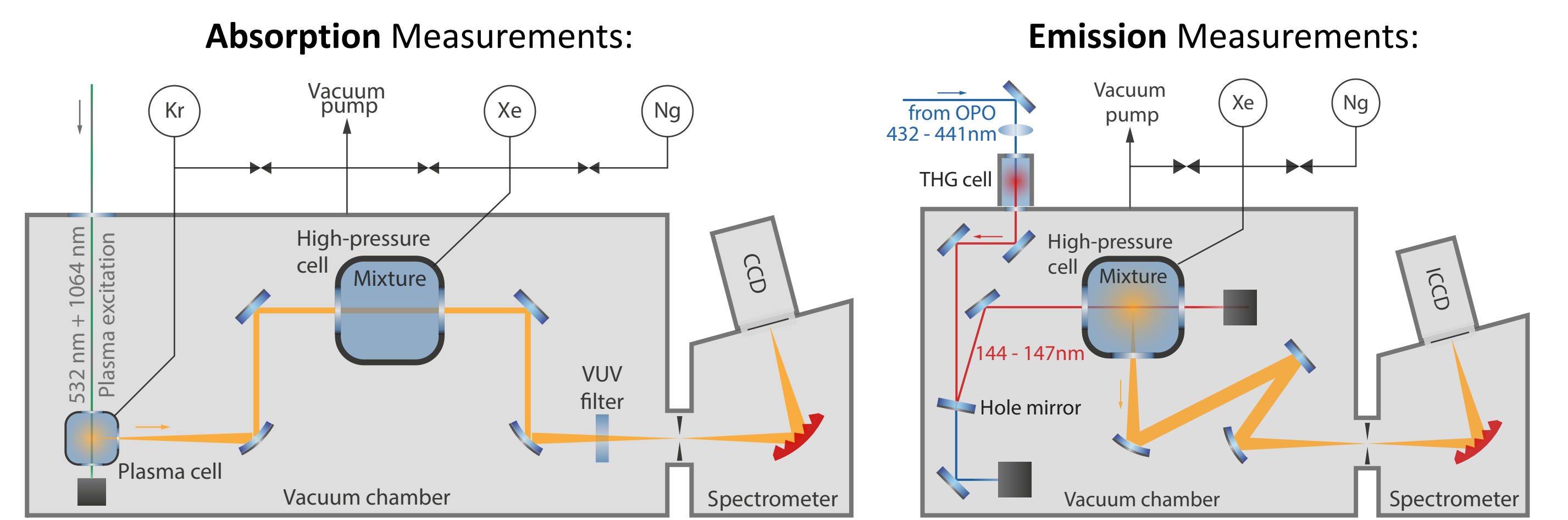


References + Funding

- [1] J. Klärs et al., *Nature* **468**, 545-548 (2010)
- [2] M. Selg, *Journal of Molecular Spectroscopy* **220** 187-200 (2003)
- [3] C. Wahl et al., *Physical Review A* **103**, 022831 (2021)
- [4] G. Nowak and J. Fricke, *J. Phys. B: Atom. Mol. Phys.* **18** 1355 (1985)
- [5] P. Laporte et al., *Optics Letters* **12**, 12 (1987)
- [6] J. M. Gray et al., *J. Chem. Phys.* **154**, 024201 (2021)
- [7] T. vom Hövel et al., *Physical Review A* **108**, 012821 (2023)



Experimental Setup

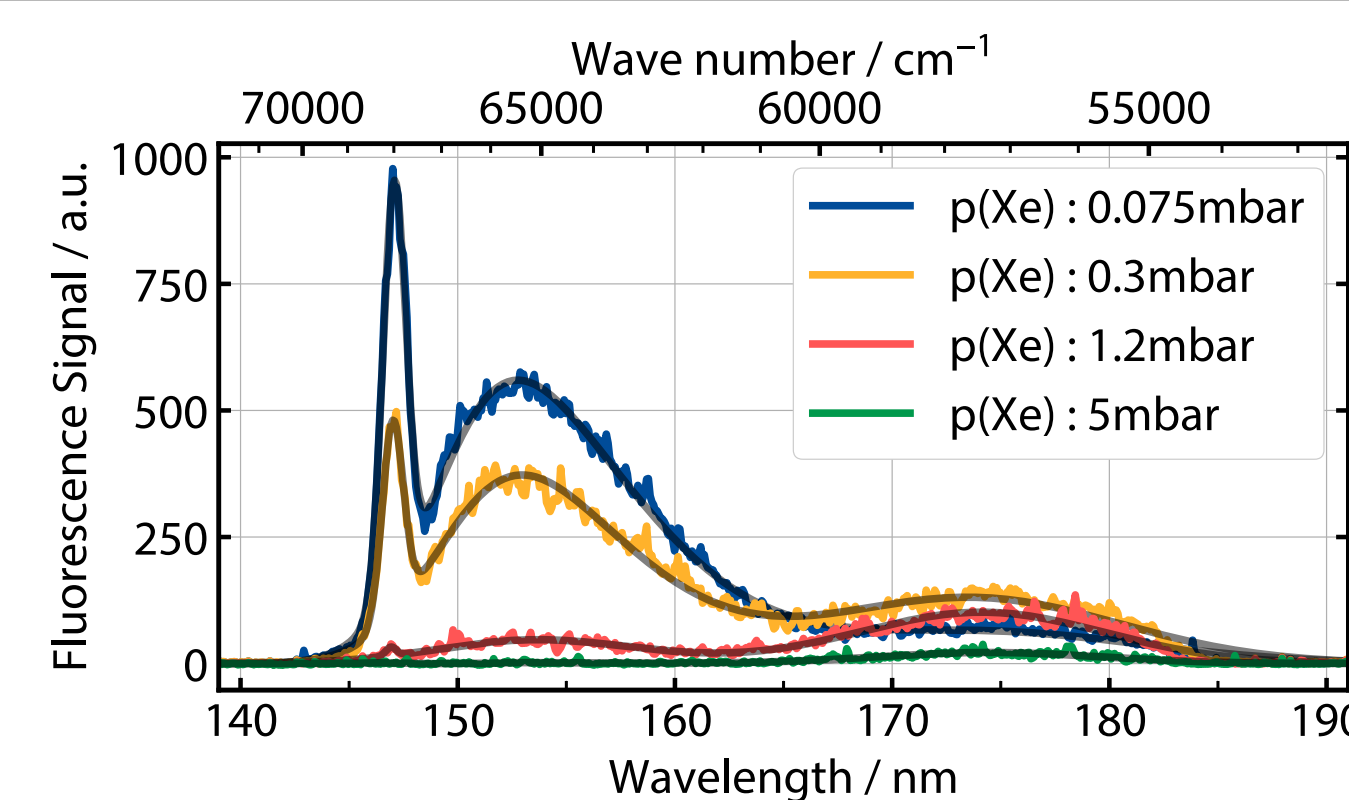
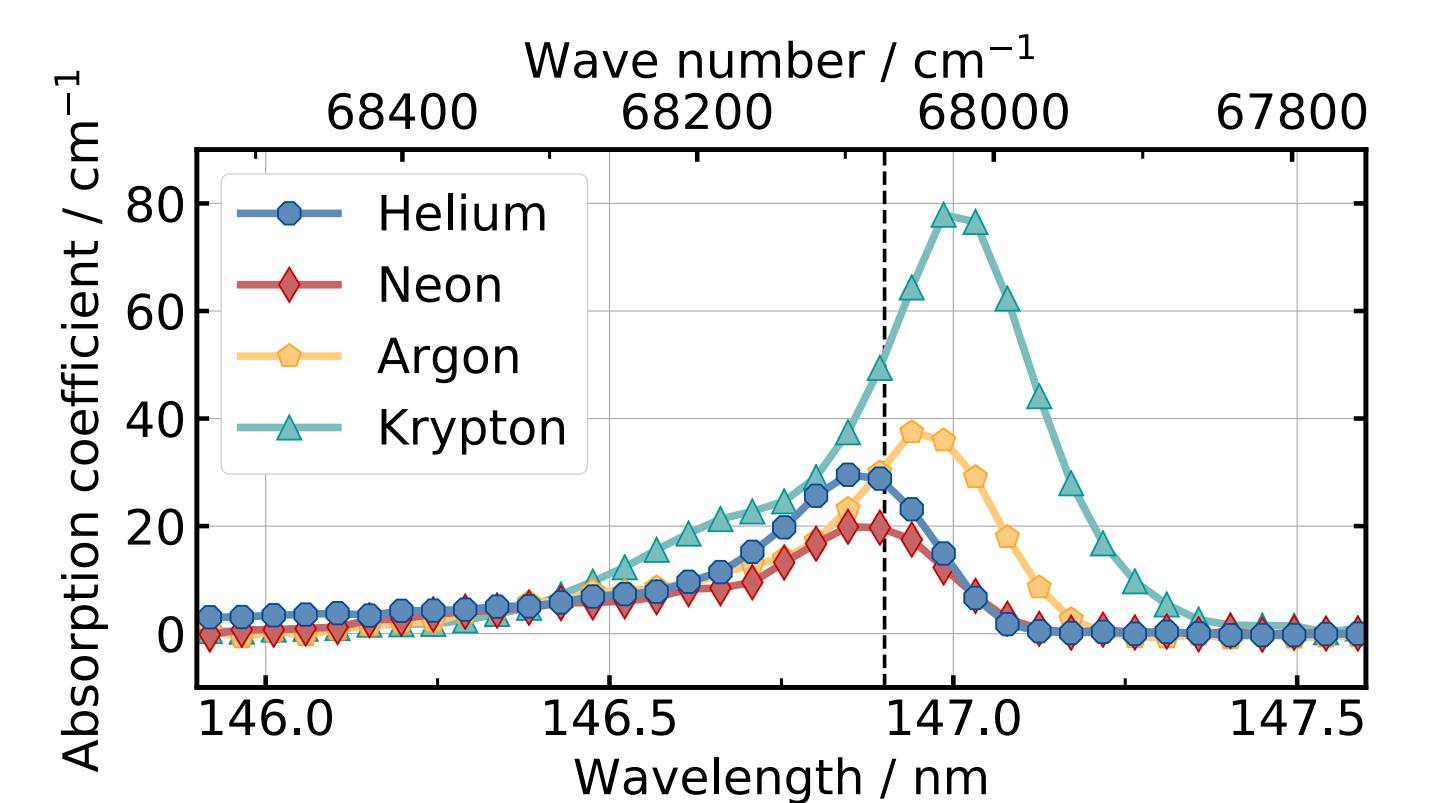


- Plasma cell filled with 1bar of krypton [5]
- Broadband light source with **VUV component**
- Spectral analysis with VUV grating
- Spectral resolution $\Delta\lambda \approx 0.3\text{nm}$
- Third-harmonic generation in dilute gases [6]
- Variable excitation from **144nm to 147nm**

Spectroscopic Results

Absorption spectra

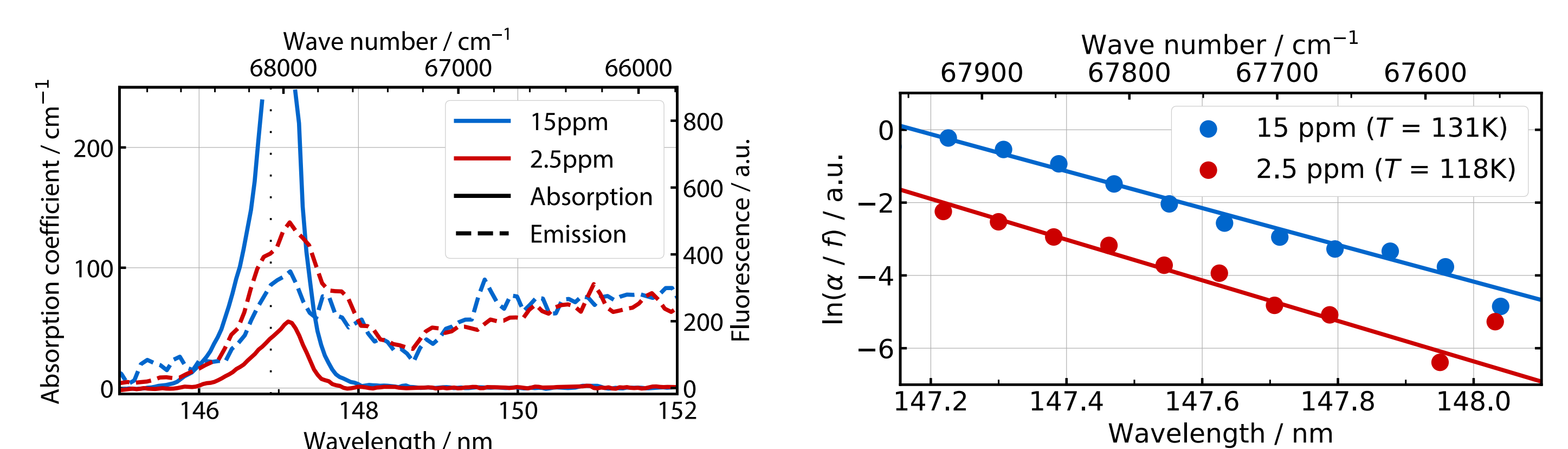
- $p(\text{xenon}) = 0.2\text{mbar}$; $p(\text{noble gas}) = 30\text{bar}$
- Xenon-krypton mixture shows highest absorption strength in the desired region



Emission in 90bar krypton environment

- Emission around **172nm** → Xenon-Xenon excimers
- Emission between **145nm and 160nm** → Xenon-Krypton excimers

- Validate the **Kennard-Stepanov relation**, $p(\text{krypton}) = 90\text{bar}$; $p(\text{xenon}) = 1.2\text{mbar} / 0.2\text{mbar}$



- **Kennard-Stepanov relation fulfilled** in the overlap region
- BUT: Spectral temperature obtained from fit function differs from room temperature

High-Pressure VUV Microcavity

- Microcavity withstanding **pressures up to 100bar**
- Mirror adjustment with a **magnetic feedthrough**
- **Pumping** drives the transition between $5p^6$ ground state and the $5p^5 6s'$ ($J = 1$) state at **129.5nm**
- **Alternatively:** use **2-photon** excitation to the $5p^5 6p$ ($J = 2$) state around **256nm** [7]

