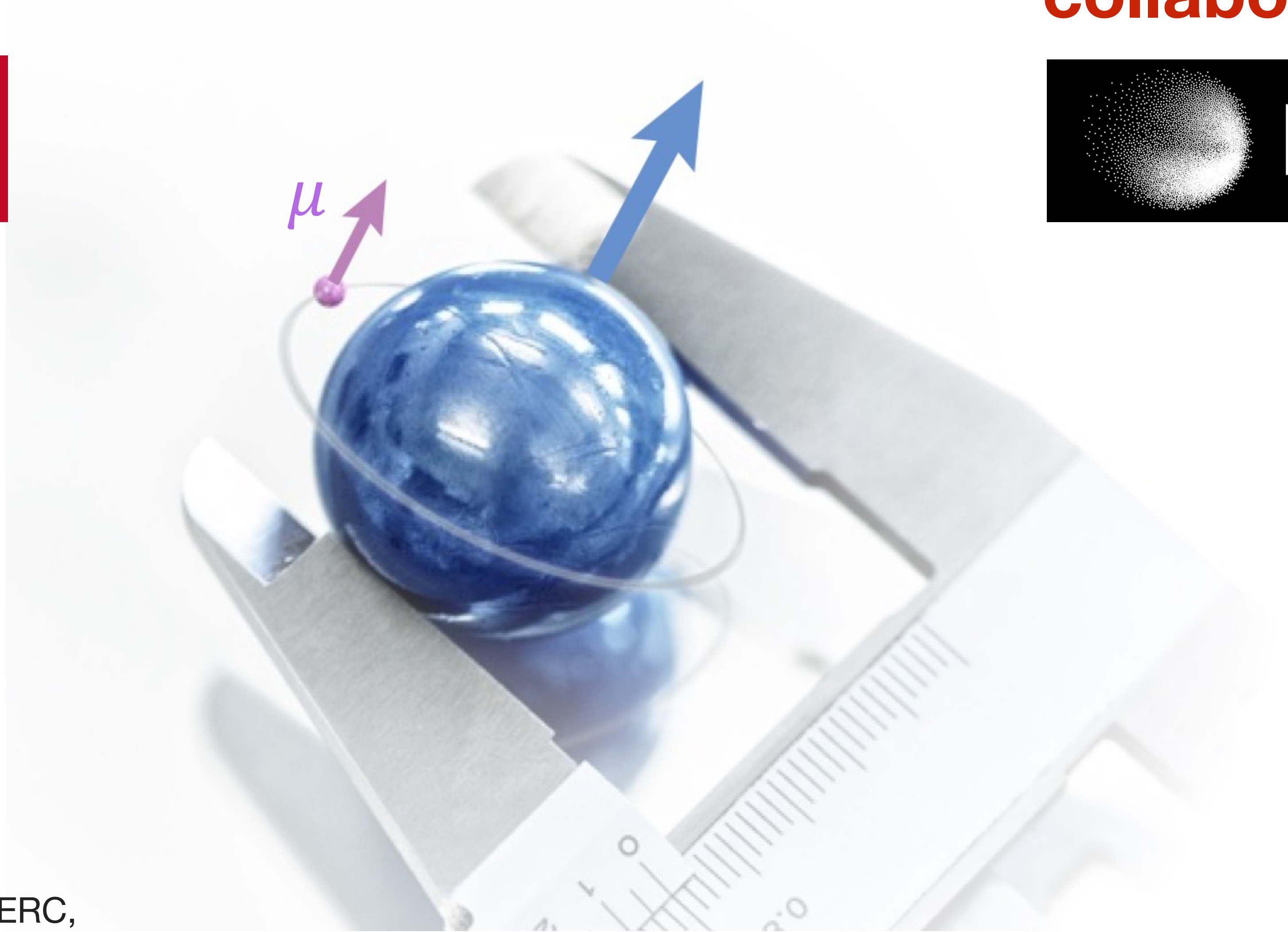
Hyperfine splitting in muonic hydrogen

AG Pohl

JG|U

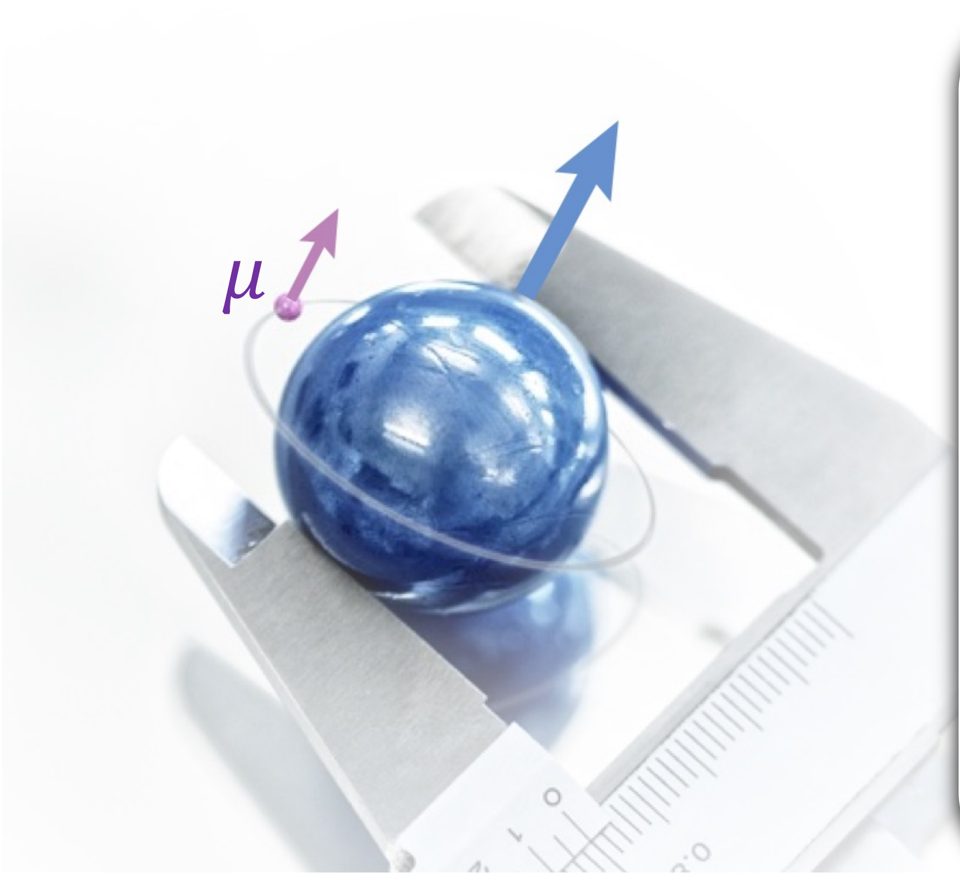
CREMA collaboration

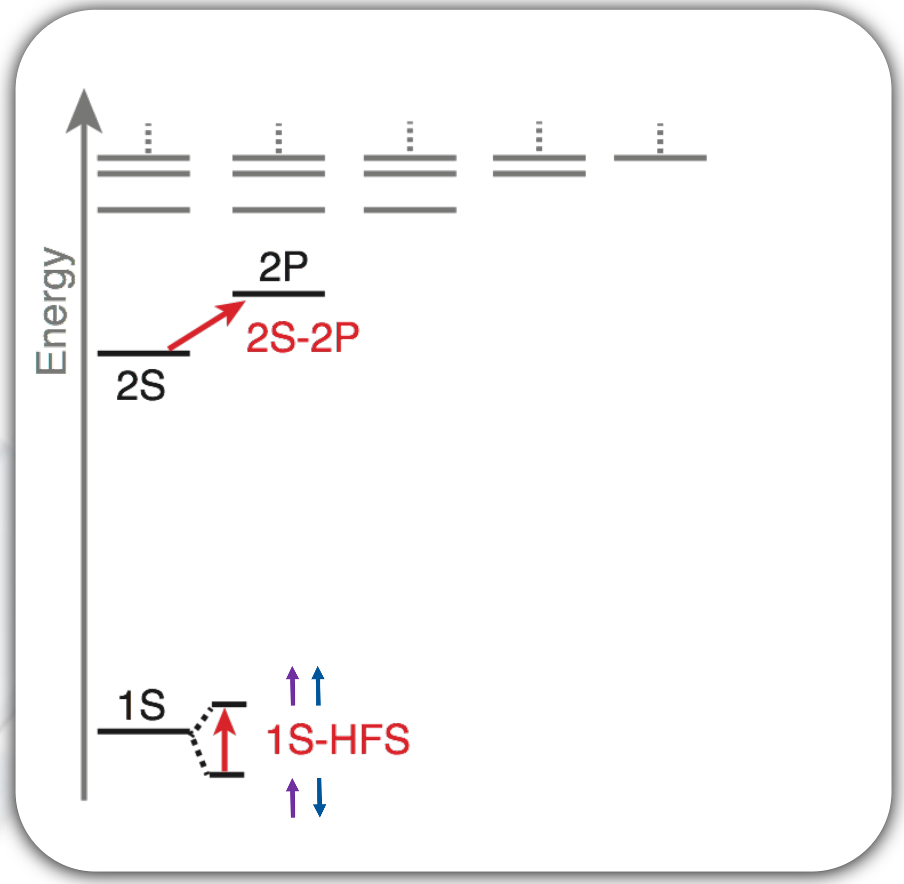
PSI



Supported by ERC, SNF, DFG

Goal



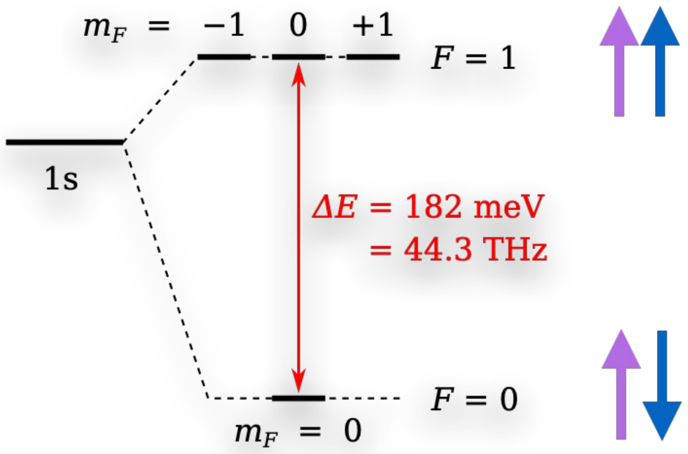


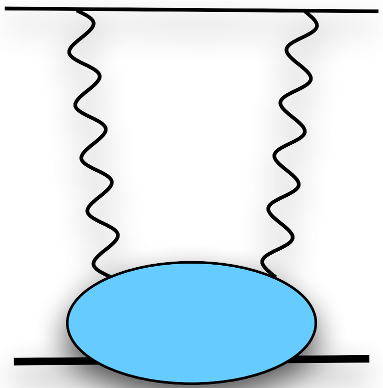
Measure the 1s-HFS in μp with a relative accuracy $\delta \approx 1 \times 10^{-6}$

1S hyperfine splitting in muonic hydrogen

$$E_{1S\text{-HFS}}(\mu\text{H}) = [\underbrace{182.443}_{E_F} \underbrace{+1.350(7)}_{\text{QED+weak}} \underbrace{+0.004}_{\text{hVP}} \underbrace{-1.30653(17)\left(\frac{r_{Zp}}{\text{fm}}\right) + E_F\left(1.01656(4)\Delta_{\text{recoil}} + 1.00402\Delta_{\text{pol}}\right)}_{2\gamma \text{ incl. radiative corr.}}]\text{meV}$$

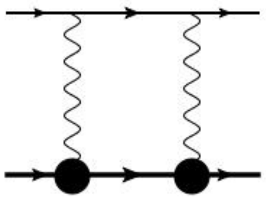
Antognini, Hagelstein, Pascalutsa, Annual reviews 389, 418 (2022)



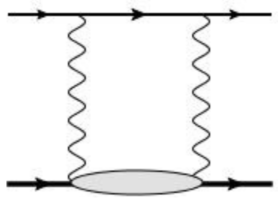


Extract the nuclear structure contribution with $\approx 1 \times 10^{-4}$ relative accuracy

Proton structure dependent contributions



$$E^{\langle 2\gamma \rangle}_{nS\text{-HFS}} = \frac{E_F}{n^3}\left(\Delta_Z + \Delta_{\text{recoil}} + \Delta_{\text{pol}}\right).$$



Zemach

$$\Delta_Z = -2Z\alpha m_r r_Z \qquad r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[\frac{G_E(Q^2)G_M(Q^2)}{1+\kappa_N} - 1\right].$$

$$\Delta_Z(\mu H) = -7403^{+21}_{-16}\ \text{ppm}$$

Lin, Yong-Hui, Hammer, Meißner (2022)

Recoil

$$\Delta_{\text{recoil}} = \frac{Z\alpha}{\pi(1+\kappa)}\int_0^\infty \frac{dQ}{Q}\left\{\frac{8mM}{v_l+v}\frac{G_M(Q^2)}{Q^2}\left(2F_1(Q^2) + \frac{F_1(Q^2)+3F_2(Q^2)}{(v_l+1)(v+1)}\right) - \frac{8m_r G_M(Q^2)G_E(Q^2)}{Q} - \frac{m}{M}\frac{5+4v_l}{(1+v_l)^2}F_2^2(Q^2)\right\}.$$

$$\Delta_{\text{recoil}} = 837.6^{+2.8}_{-1.0}\ \text{ppm}$$

Antognini, Yong-Hui, Hammer, Meißner(2022)

Polarizability

$$\Delta_{\text{pol}} = \Delta_1 + \Delta_2 \equiv \frac{Z\alpha m}{2\pi(1+\kappa_N)M}\left[\delta_1 + \delta_2\right],$$

$$\delta_1 = 18\int_0^\infty \frac{dQ}{Q}\,\kappa_0(Q^2)\,I_1^{(\text{pol})}(Q^2) + 16M^4\int_0^\infty \frac{dQ}{Q^3}\int_0^{x_0} dx\,\kappa_1(x,Q^2)\,g_1(x,Q^2),$$

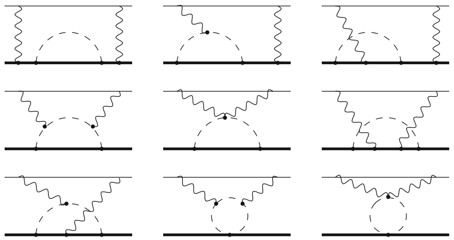
$$\delta_2 = 96M^2\int_0^\infty \frac{dQ}{Q^3}\int_0^{x_0} dx\,\kappa_2(x,Q^2)\,g_2(x,Q^2),$$

$$\Delta_{pol} = 200.6(54)\ \text{ppm}$$

Carlson et al. 2024

Proton polarizability

Chiral Perturbation theory



$\Delta_{pol} = \ 38(62)$ ppm

Hagelstein, Pascalutsa (2023)

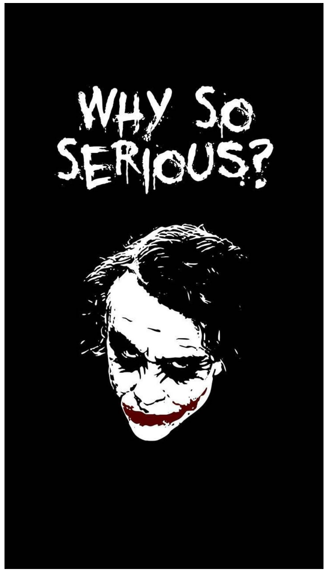
Dispersive analysis Data driven

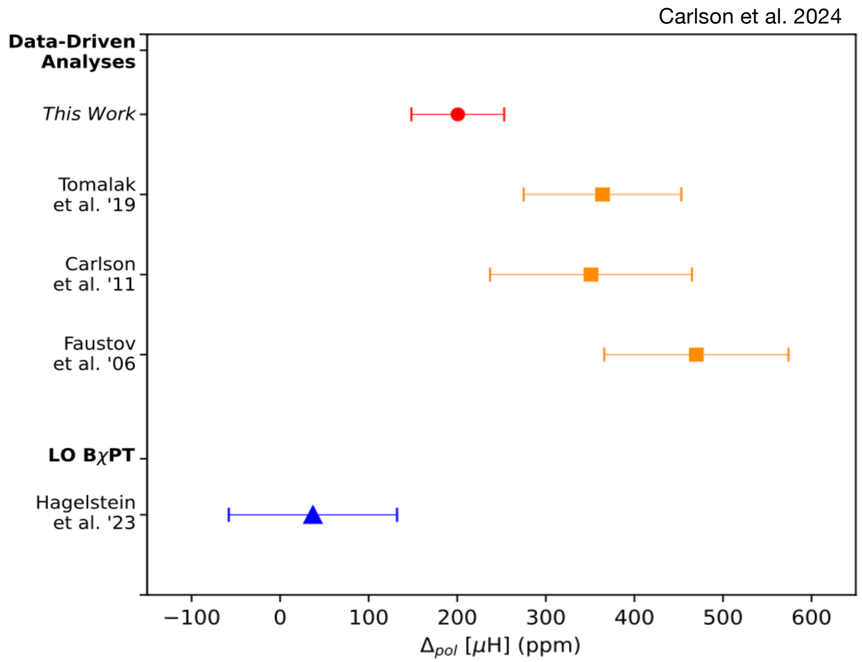
Structure functions,
Form factors

$g_1(x,Q^2)$, $g_2(x,Q^2)$, F_2 …

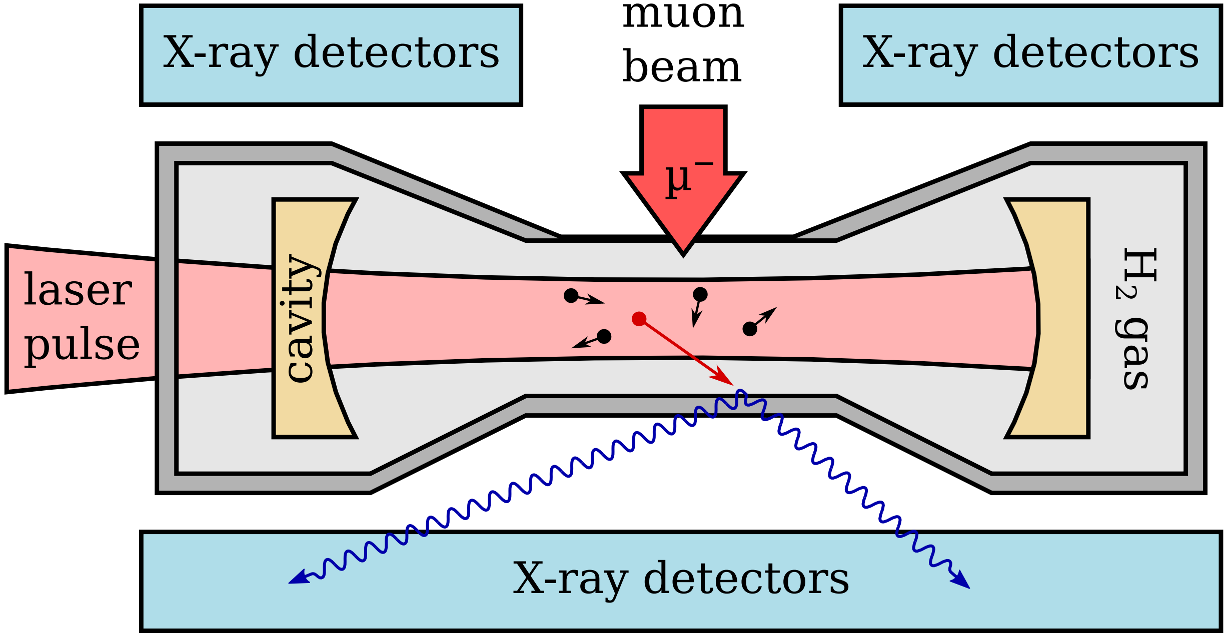
$\Delta_{pol} = \ 200.6(54)$ ppm

Carlson et al. 2024

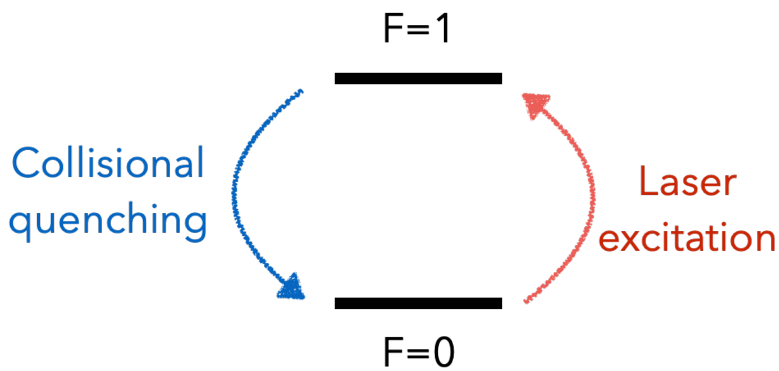




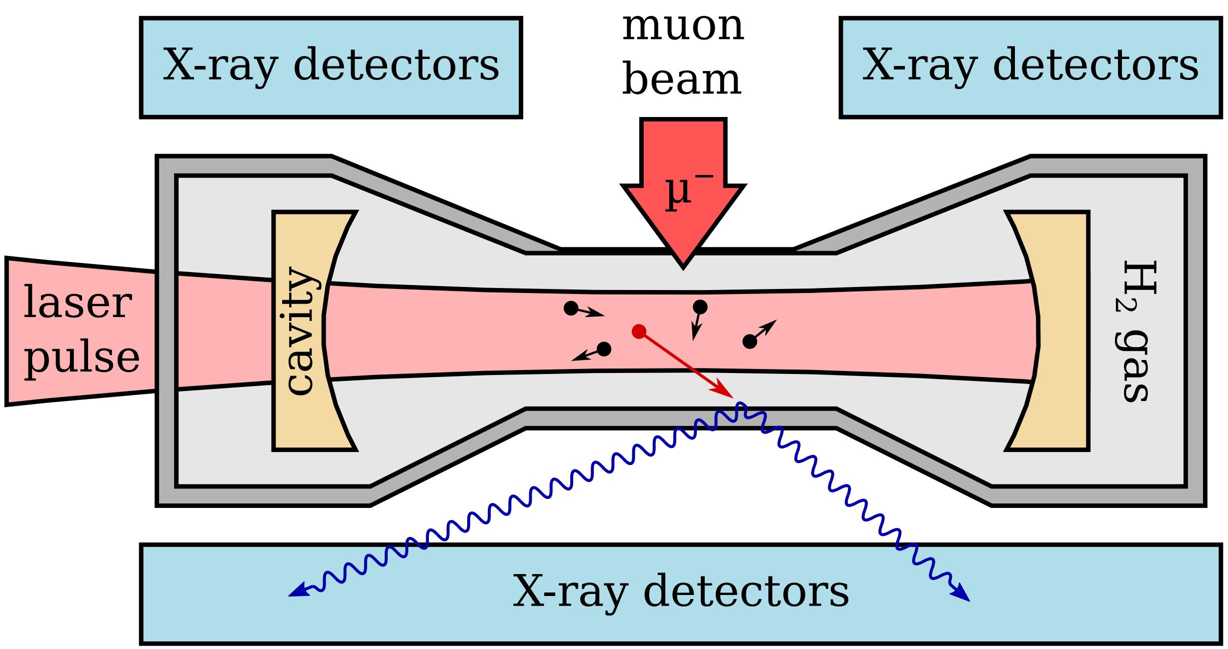
The principle of the experiment



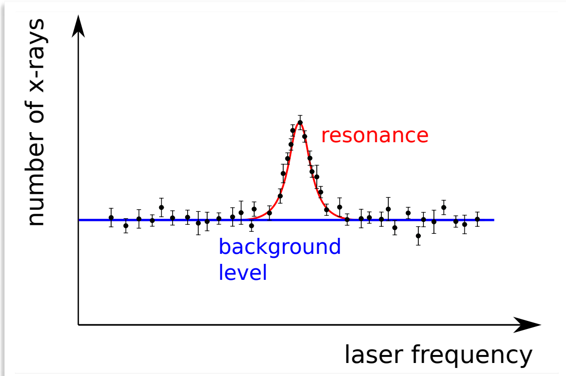
- Stop muon beam in 1 mm H_2 gas target at 22 K, 0.5 bar
- Wait until μp atoms de-excite and thermalize
- Laser pulse: μp(F=0) + γ → μp(F=1)
- De-excitation: μp(F=1) + H_2→μp(F=0) + H_2 + E_{kin}



The principle of the experiment



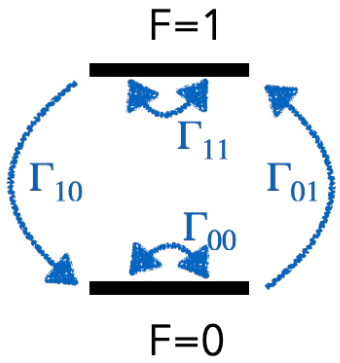
- Diffusion: μp diffuses to Au-coated target walls
- Detection: formed μAu* de-excites producing X-rays
- Resonance: Plot number of X-ray events vs laser frequency

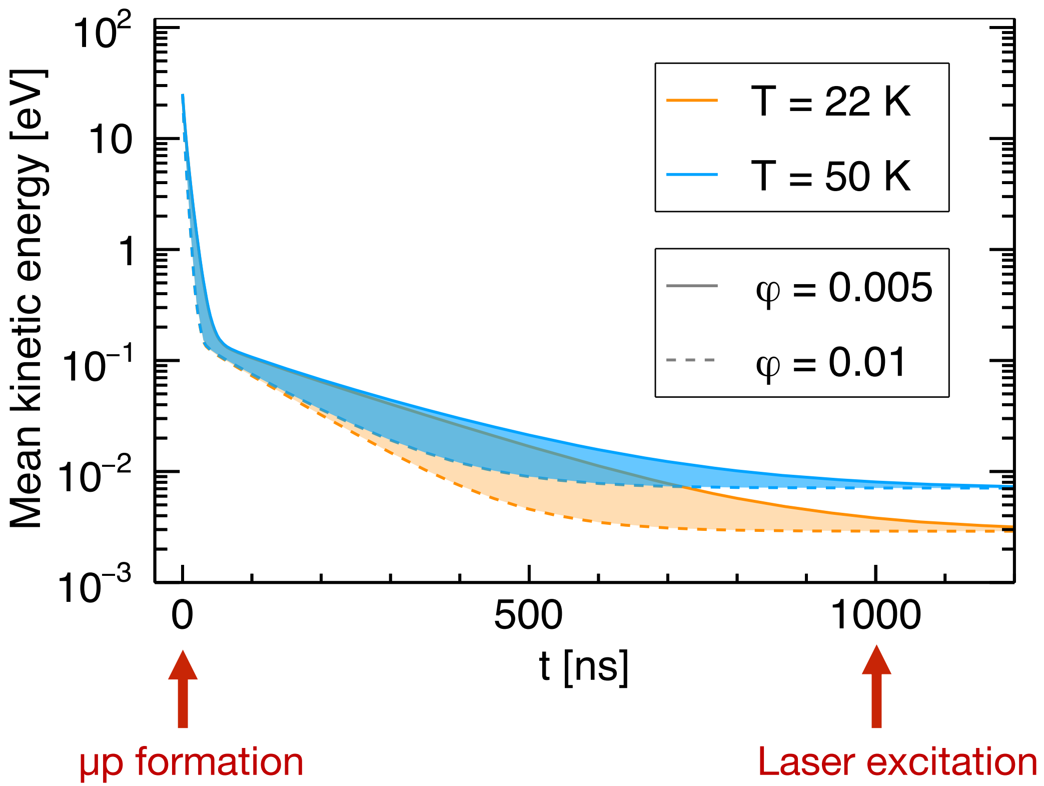


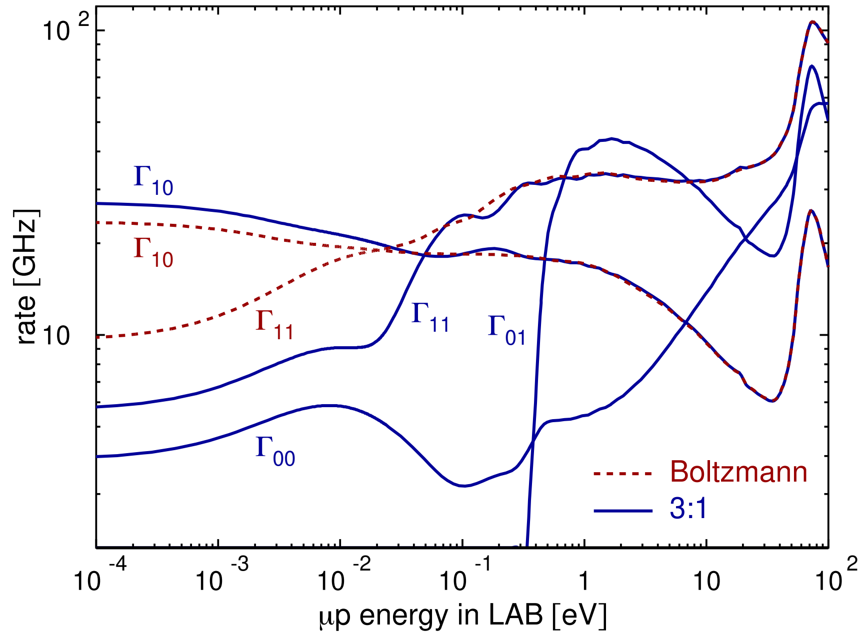
Related Proposals: FAMU at RIKEN/RAL, muonic H at J-PARC

μp thermalization

$$\mu p^{F=0} + H_2 \rightarrow \mu p^{F=0} + H_2^*$$
$$\mu p^{F=0} + H_2 \rightarrow \mu p^{F=1} + H_2^*$$
$$\mu p^{F=1} + H_2 \rightarrow \mu p^{F=0} + H_2^*$$
$$\mu p^{F=1} + H_2 \rightarrow \mu p^{F=1} + H_2^*$$

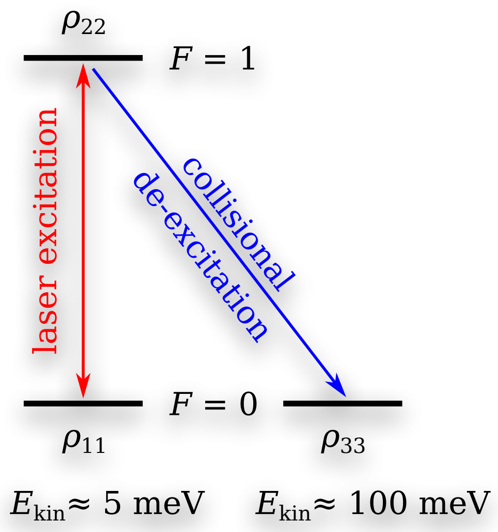






J. Nuber, Scipost (August. 2023)

Laser excitation modeled including collision

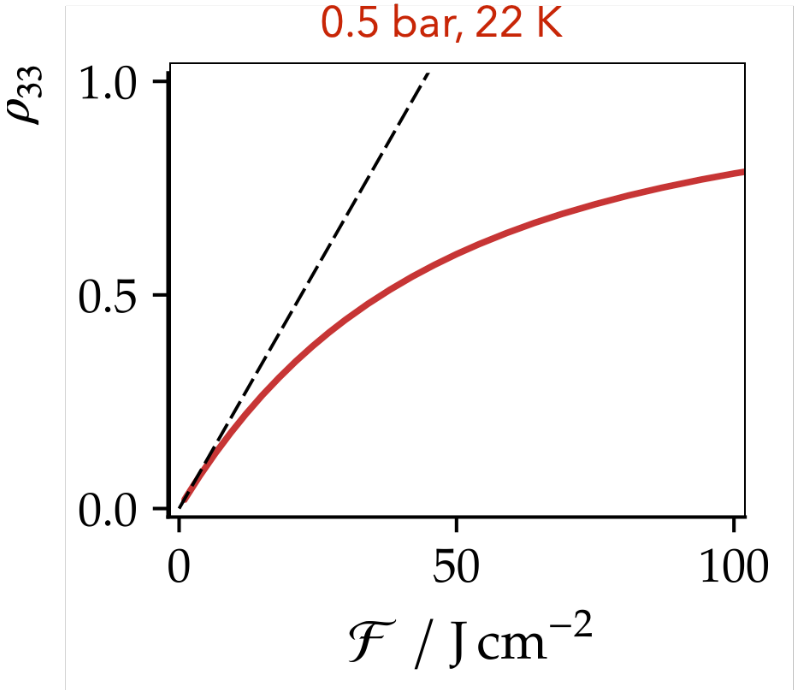


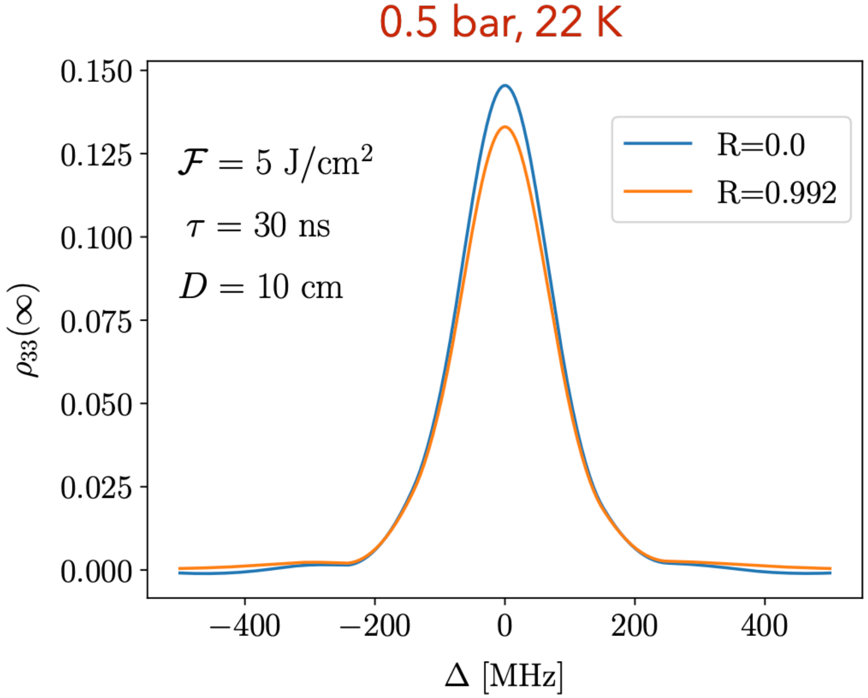
$$
\begin{aligned}
\frac{d\rho_{11}}{dt}(t) &= -\mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right) + \Gamma_{\mathrm{sp}}\rho_{22} \,, \\
\frac{d\rho_{22}}{dt}(t) &= \mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right) - (\Gamma_i + \Gamma_{\mathrm{sp}})\rho_{22} \,, \\
\frac{d\rho_{12}}{dt}(t) &= \frac{i\Omega^*}{2}(\rho_{11} - \rho_{22})e^{-i\Delta t} - \frac{\Gamma_c}{2}\rho_{12} \,, \\
\frac{d\rho_{33}}{dt}(t) &= \Gamma_i\rho_{22} \,,
\end{aligned}
$$

- ✓ Inelastic collisions
- ✓ Elastic collisions
- ✓ Laser bandwidth
- ✓ Doppler broadening

P.Amaro et al. (scipost 2022)

Saturation fluence and lienwidth



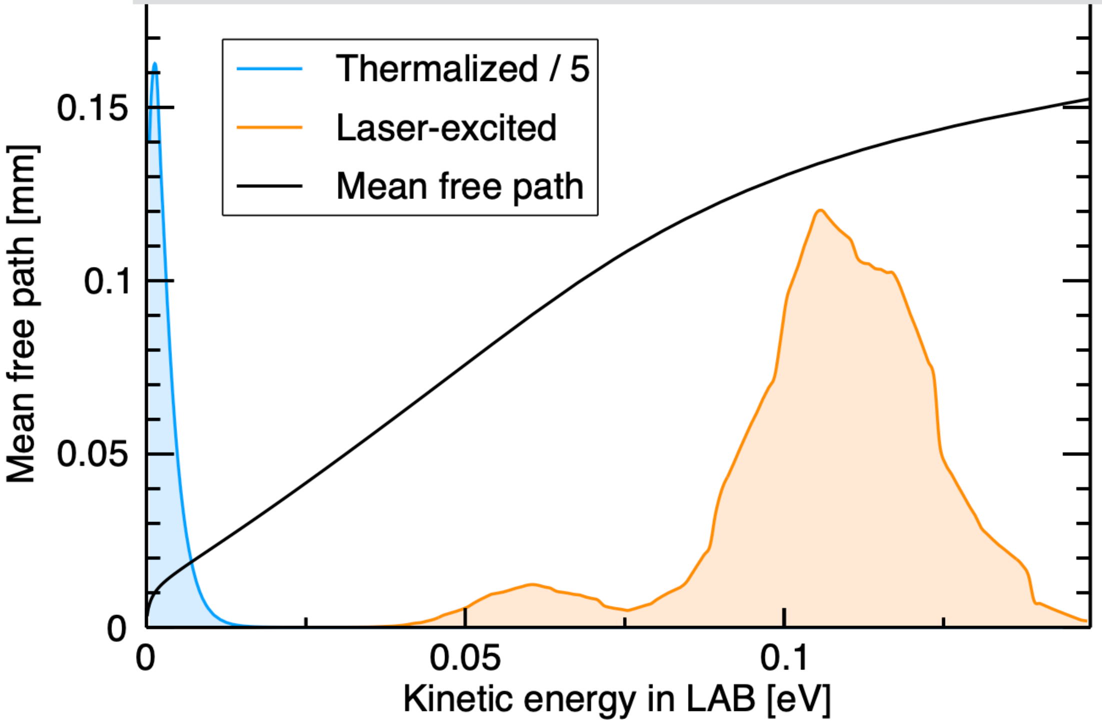


Transition	Linewith	Saturation fluence
2S-2P	20 GHz	0.016 J/cm^2
HFS	200 MHz	44 J/cm^2

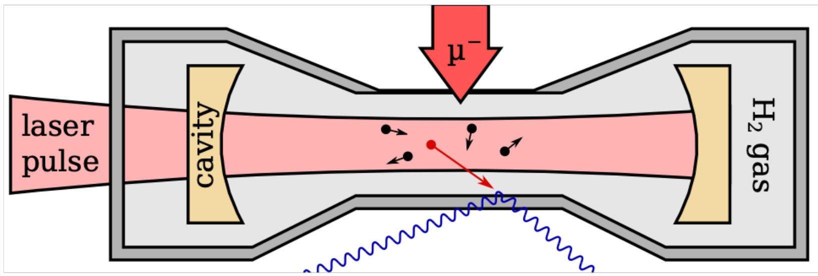
Thermalized vs laser excited atoms

- De-excitation: $\mu p(F=1) + H_2 \rightarrow \mu p(F=0) + H_2 + E_{kin}$
- μp diffuses to Au-coated target walls

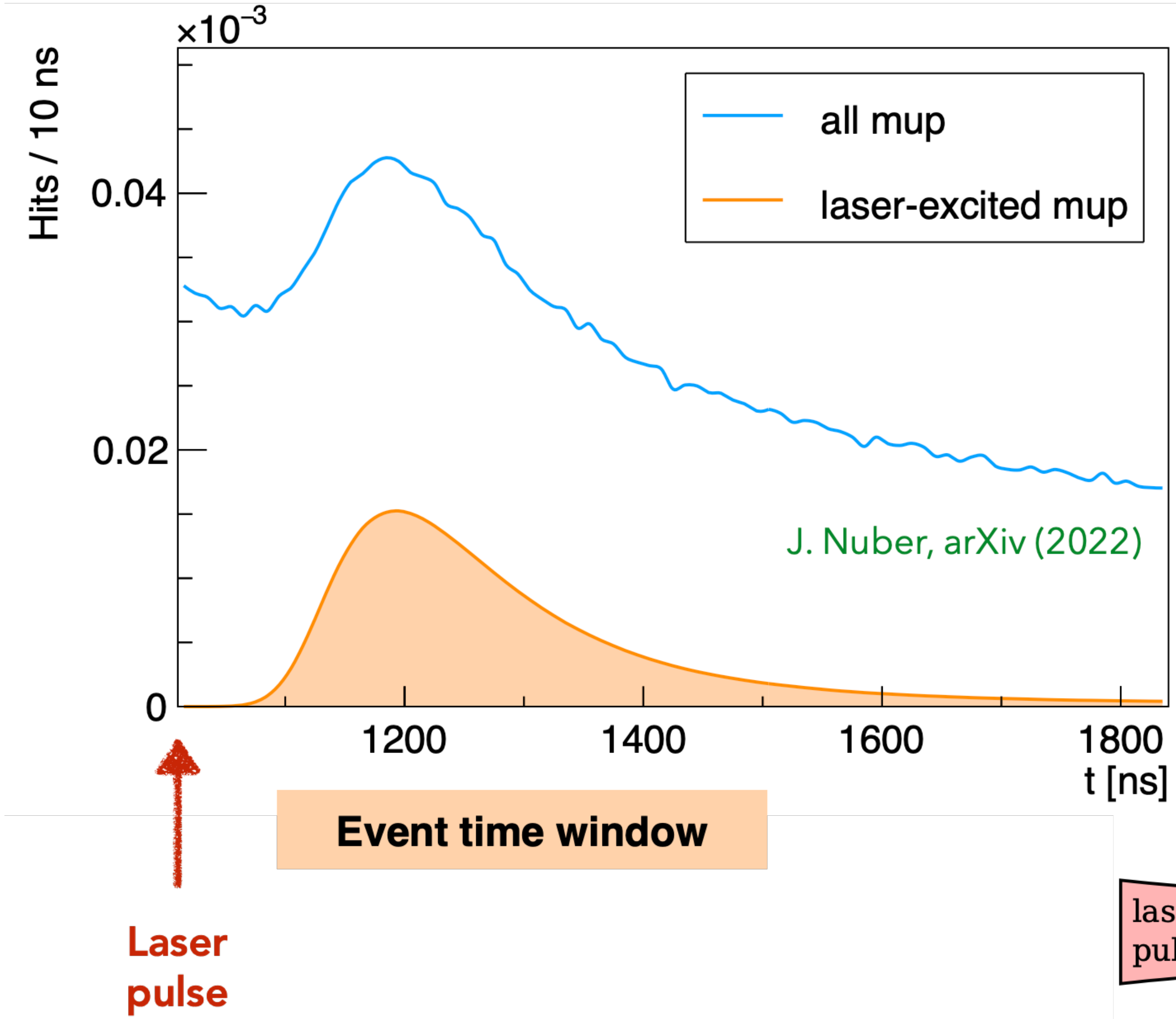
Kinetic energy distribution with/without laser excitation



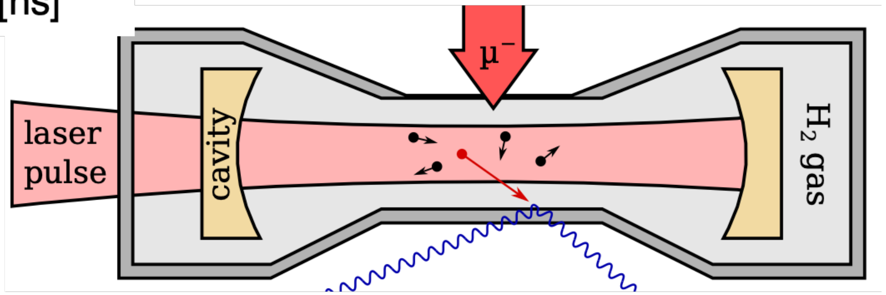
On average μp atoms wins 0.1 eV kinetic energy after a successful laser excitation



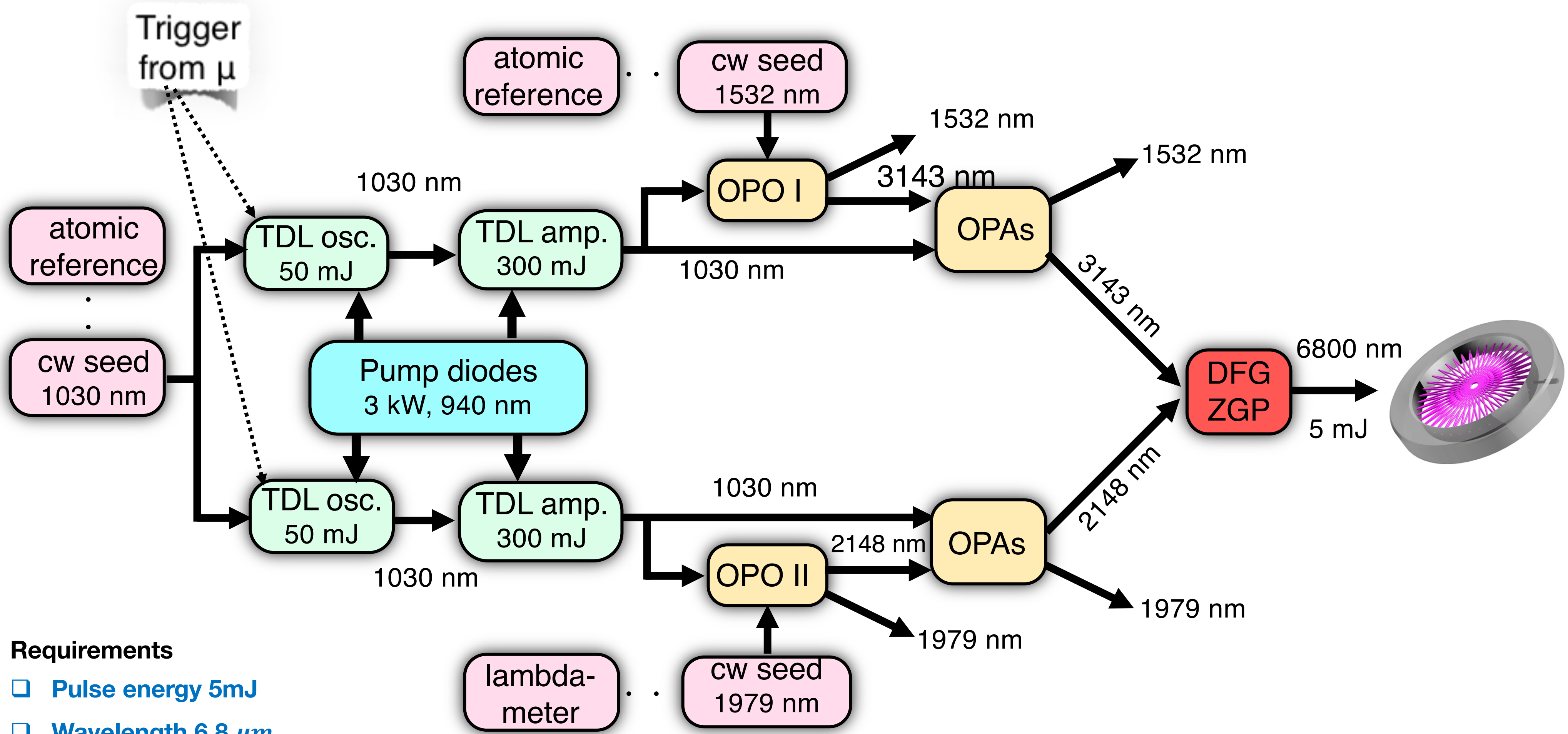
Diffusion to target walls



- 100 ns after laser excitation the first μp atoms reach the target walls
- Signal on top of a large background from μp atoms formed closed to the target walls



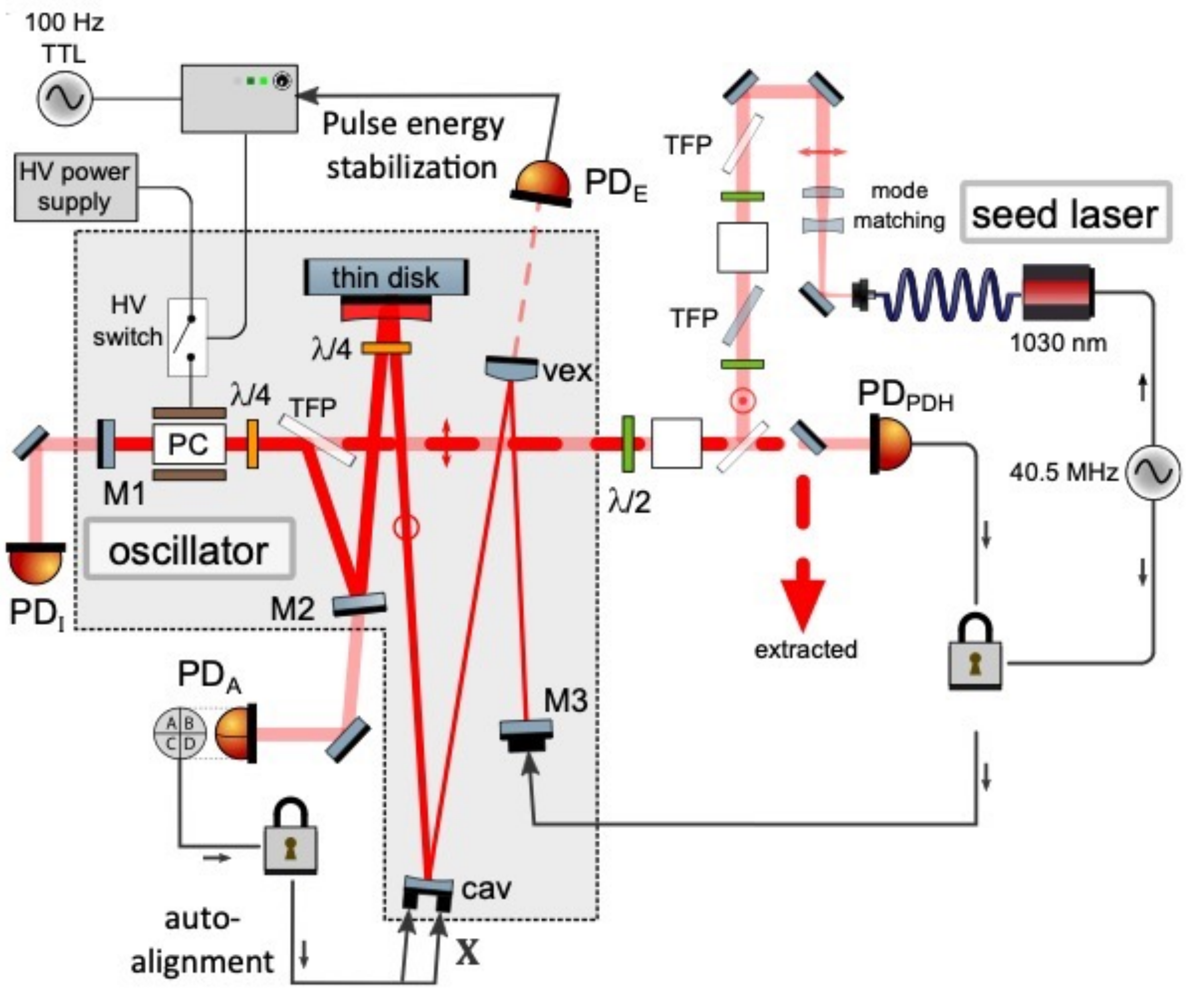
The laser system

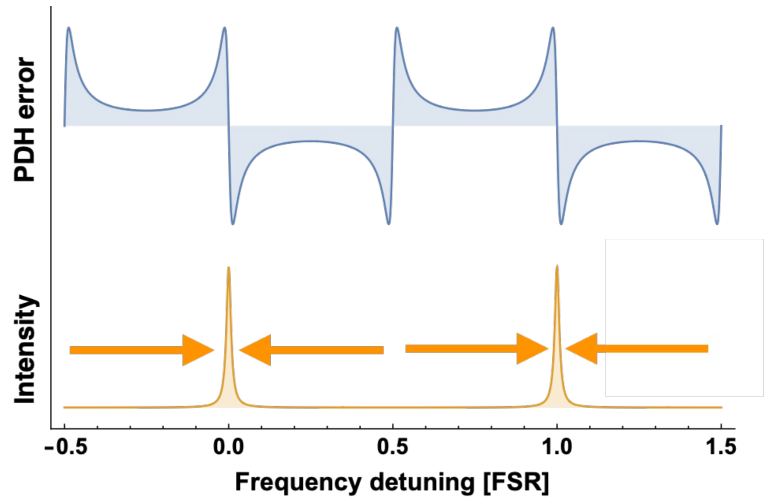


Requirements

- Pulse energy 5mJ
- Wavelength 6.8 μm
- Linewidth < 100 MHz
- Stochatic trigger (detected muon)
- Response time 1 μs
- Tunability 40 GHz

Thin-disk oscillator





Zeyen, Manuel, et al. review of scientific instruments 2023.

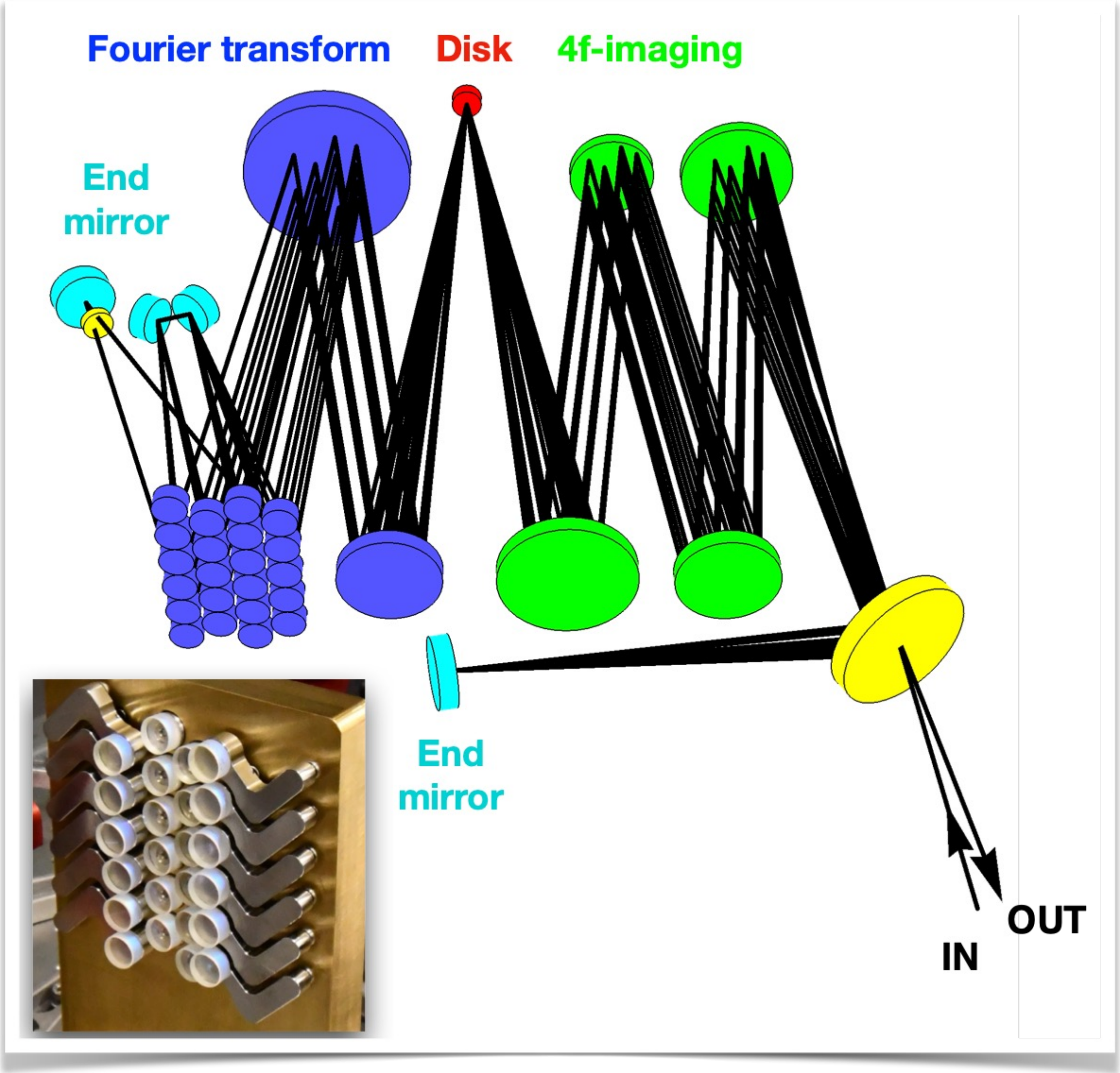
Zeyen, Manuel, et al. Optics express, 2023.

- ✓ **Delay: 700 ns**
- ✓ **Energy: 50 mJ**
- ✓ **Pulse-to-pulse stability: <0.5% (rms)**
- ✓ **Single-frequency operation**
- ✓ **Laser chirp < 2 MHz**
- ✓ **PDH lock scheme with infinite dynamic range**

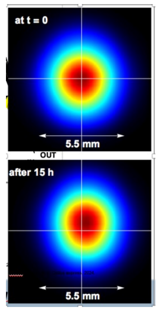
Multipass amplifier

Sequence

4f
amplification
Fourier transform
amplfication
4f
4f
amplification
Fourier transform
amplfication
4f
4f
amplification
Fourier transform
amplfication
4f
4f
.
.
.



- ✓ **Insensitive to thermal lensing**
- ✓ **Energy: 330 mJ**
- ✓ **M2 < 1.17**
- ✓ **Pointing stability**

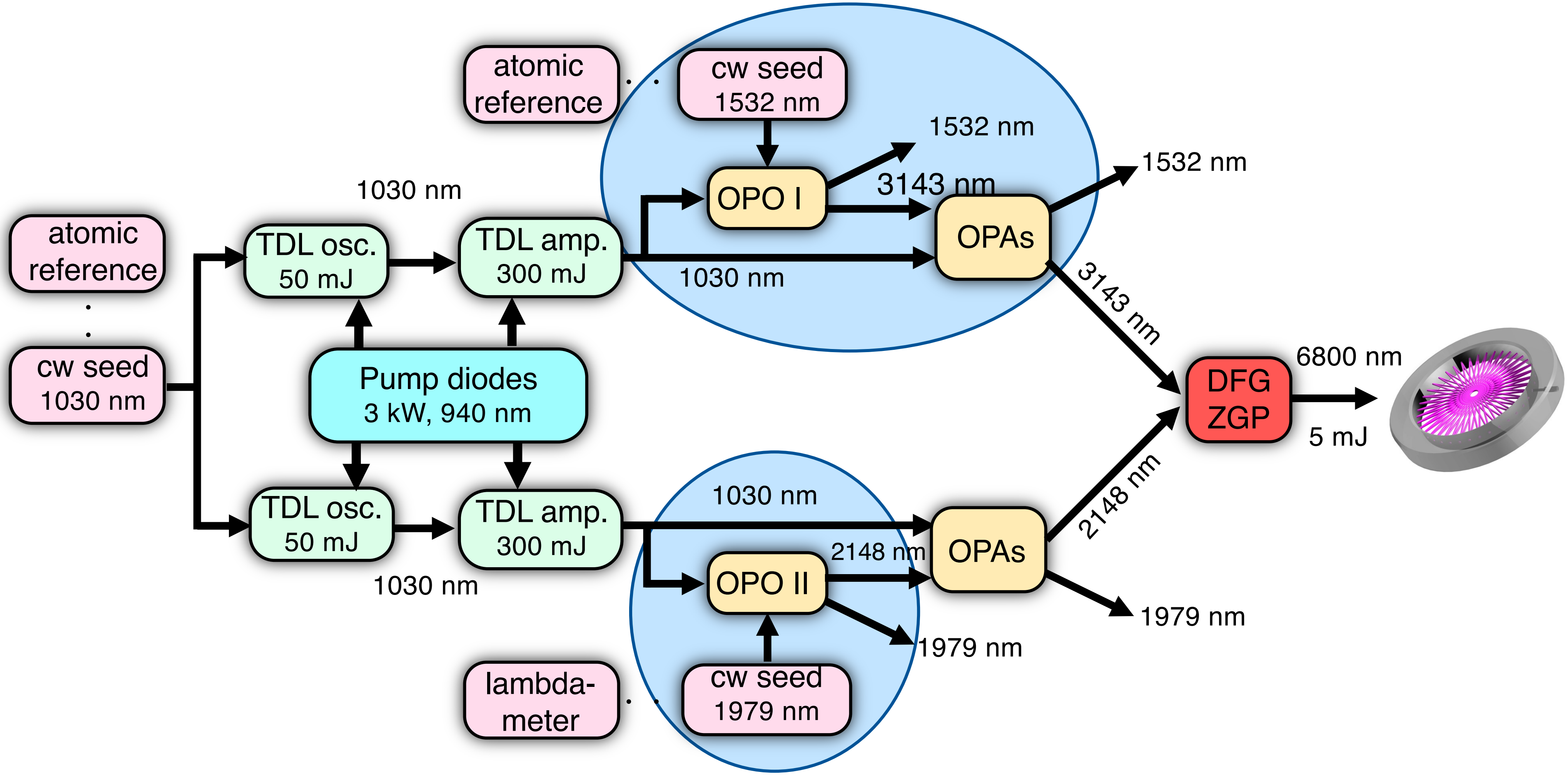


Zeyen, Manuel, et al. 2019

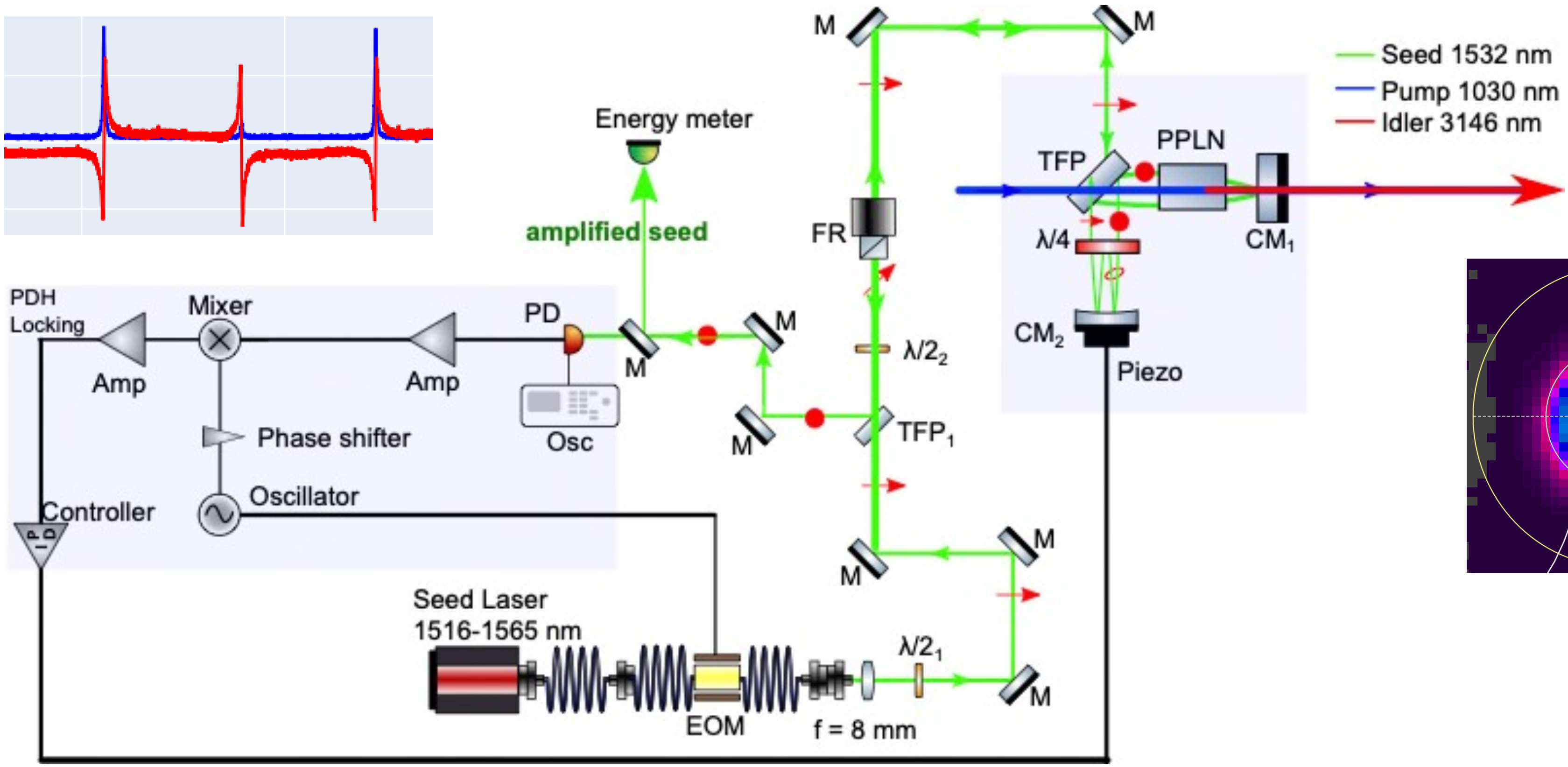
K. Schuhmann et al., Appl. Opt. 57, 10323-10333 (2018)

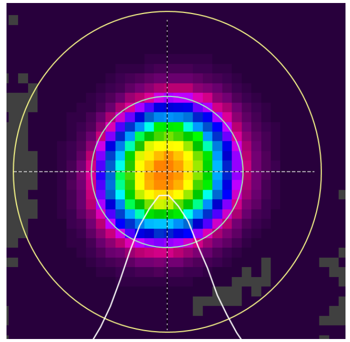
Zeyen, Manuel, et al. Optics express, 2024.

OPOs & OPAs


atomic reference
cw seed 1030 nm
TDL osc. 50 mJ
1030 nm
TDL amp. 300 mJ
Pump diodes 3 kW, 940 nm
TDL osc. 50 mJ
1030 nm
TDL amp. 300 mJ
atomic reference
cw seed 1532 nm
OPO I
1532 nm
3143 nm
1030 nm
OPAs
1532 nm
3143 nm
DFG ZGP
6800 nm
5 mJ
2148 nm
1030 nm
OPAs
2148 nm
OPO II
1979 nm
1979 nm
cw seed 1979 nm
lambda-meter

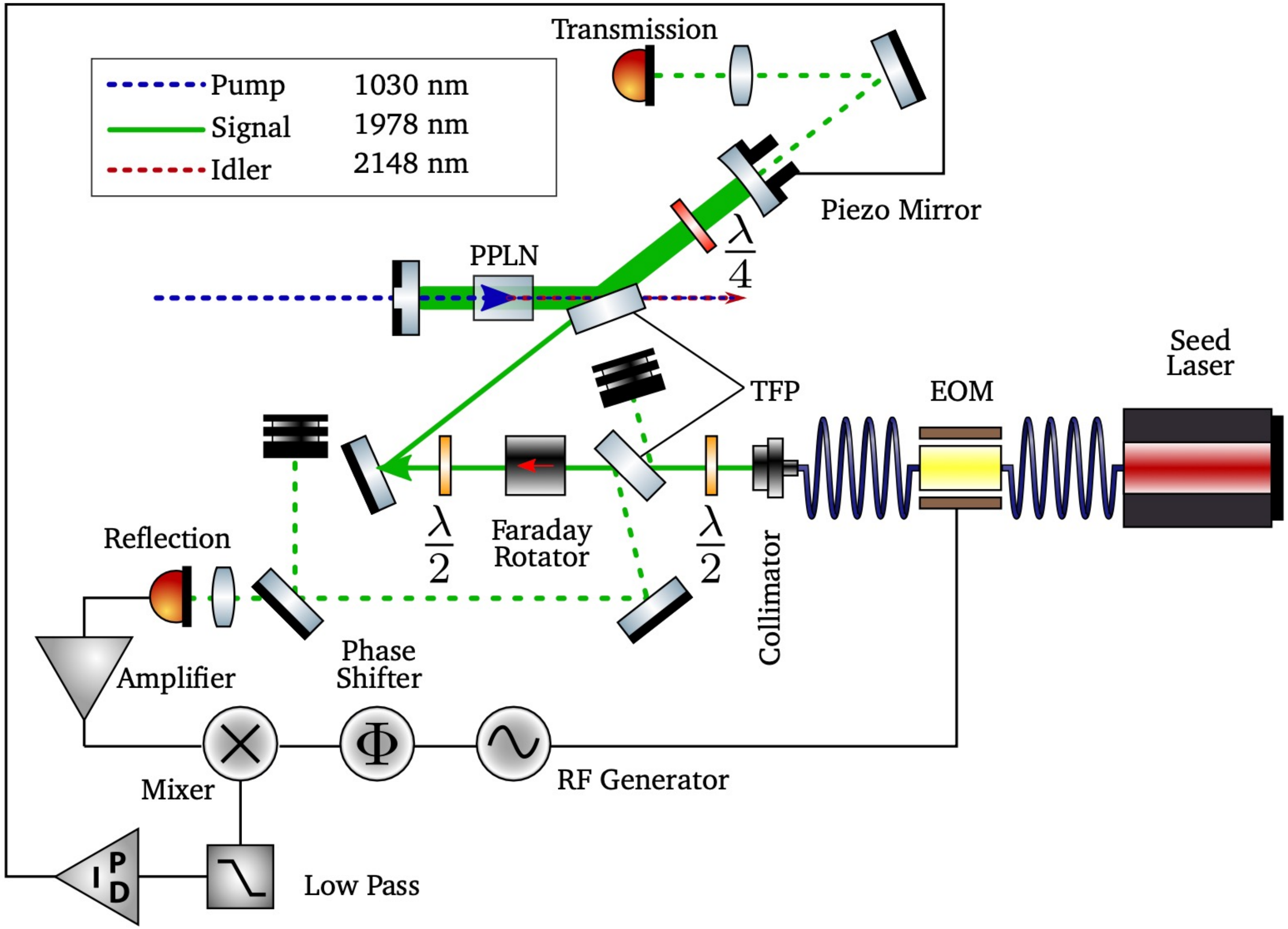
OPO & OPA @3146 nm

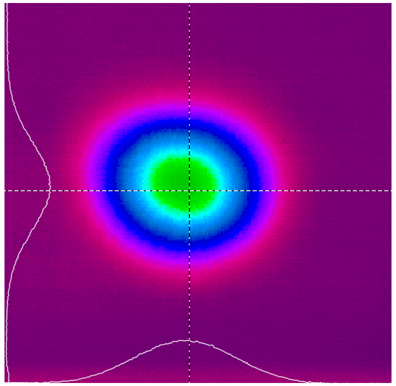




- ✓ **Variable outcoupling cavity**
- ✓ **Infinite locking range (PDH locking)**
- ✓ **3.3 mJ @ 3146 nm**
- ✓ **M2 = 1.01 (excellent beam quality)**
- ✓ **Pulse chirp < 2 MHz**
- ✓ **Rms energy stability < 2%**
- ✓ **Tunability of 2 nm**

OPO & OPA @2148 nm





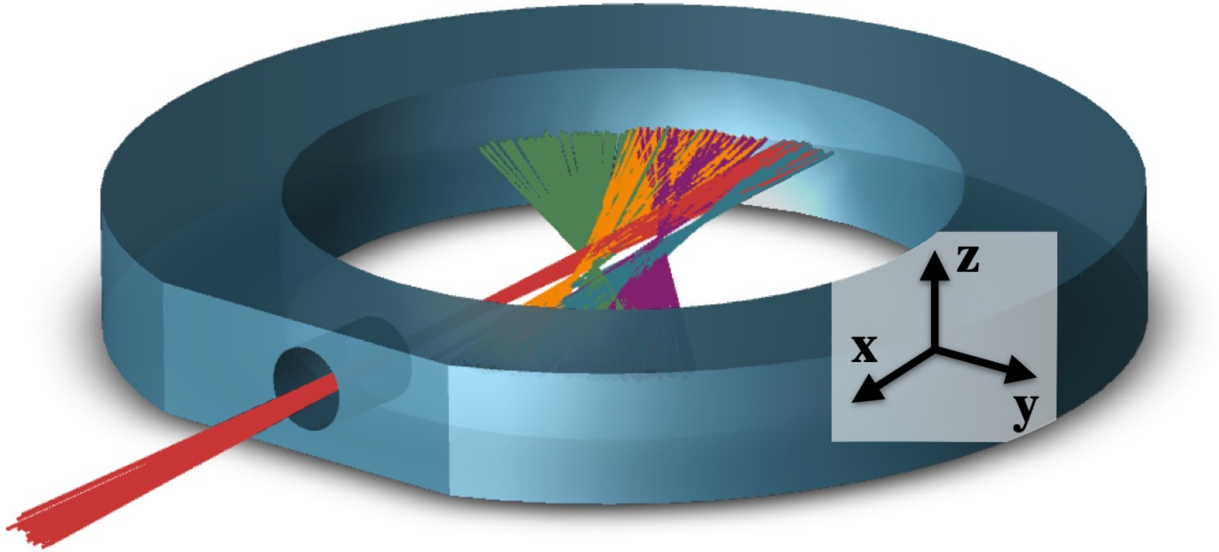
Preliminary

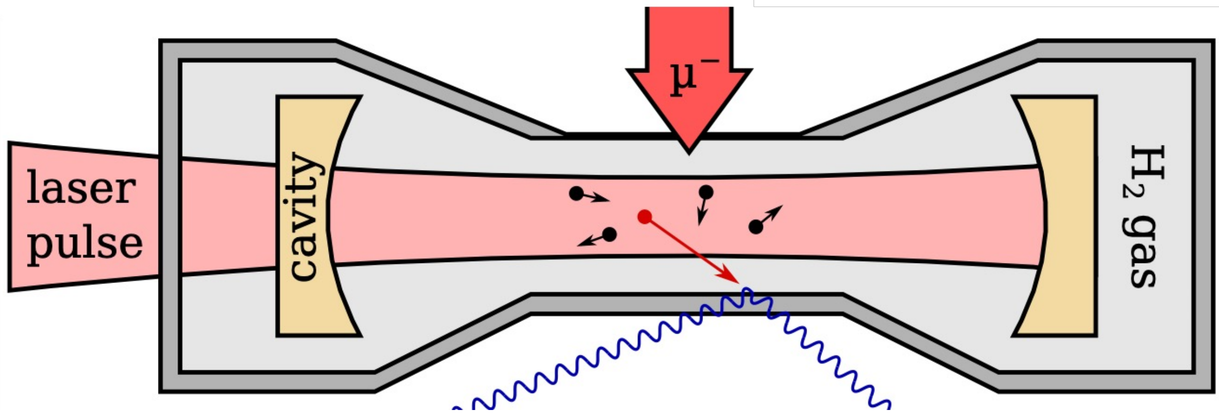
- ✓ 1.5 mJ @ 2148 nm
- ✓ Efficiency 40-50 %
- ✓ excellent beam quality
- ❑ OPA in preparation

Enhancement cavity

M. Marszalek , PhD Thesis, ETH 2022

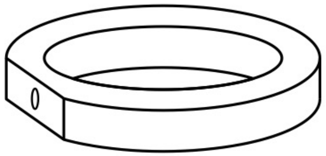
M. Marszalek et.al , arXiv:2402.07223



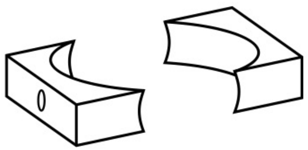


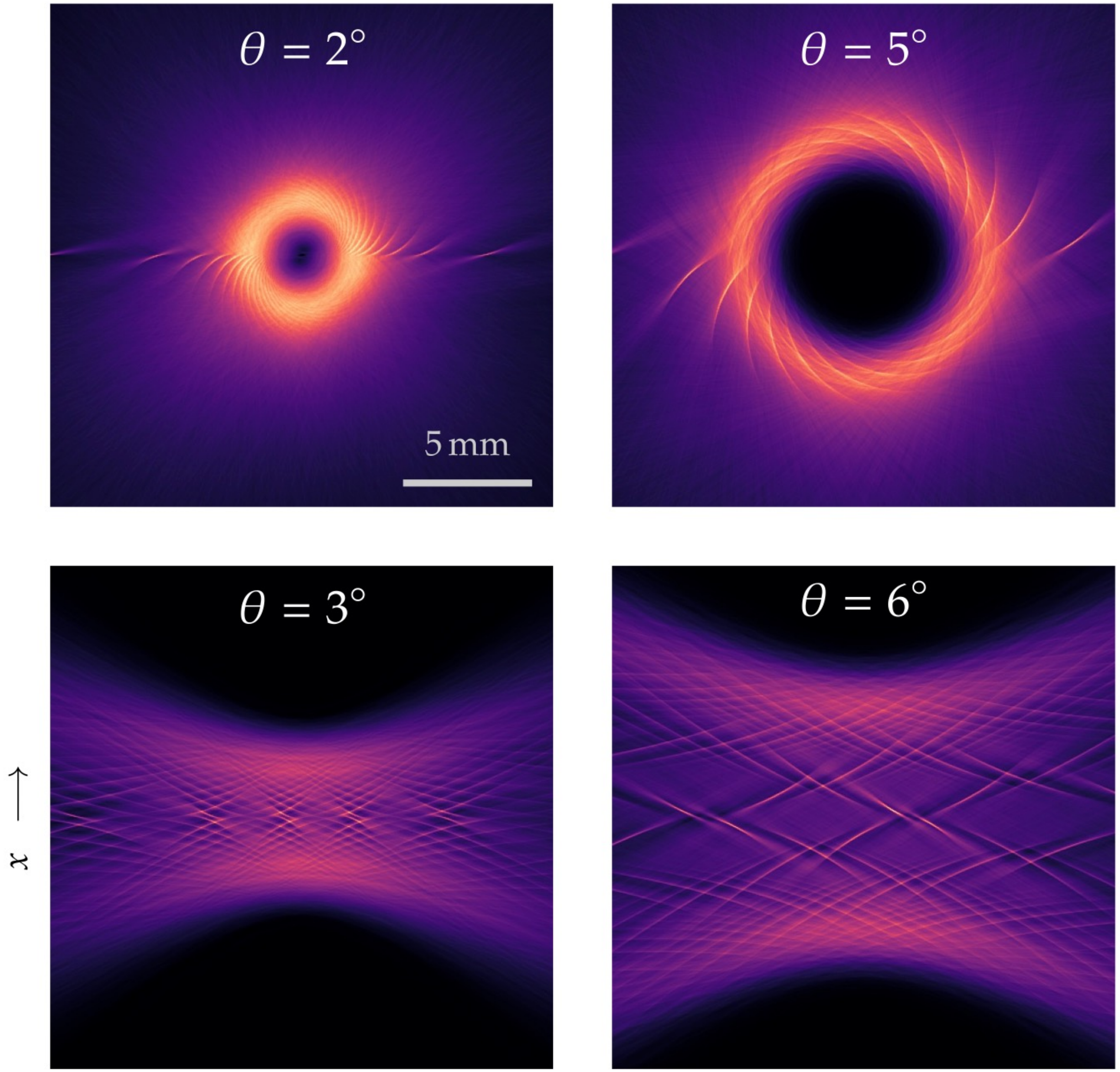
Two different configurations

- Resonant vertically
- Unstable horizontally



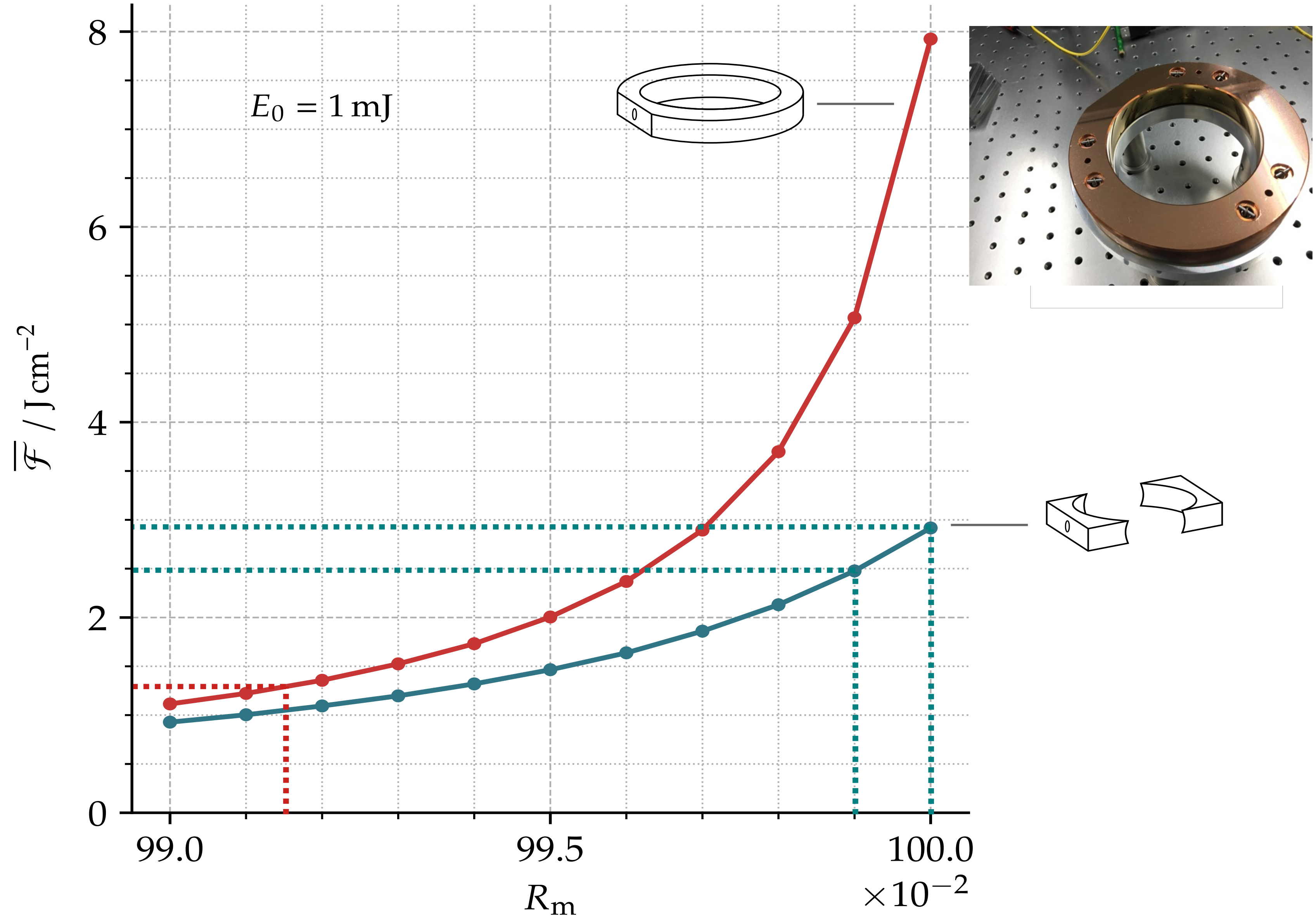
- Resonant vertically
- Stable horizontally





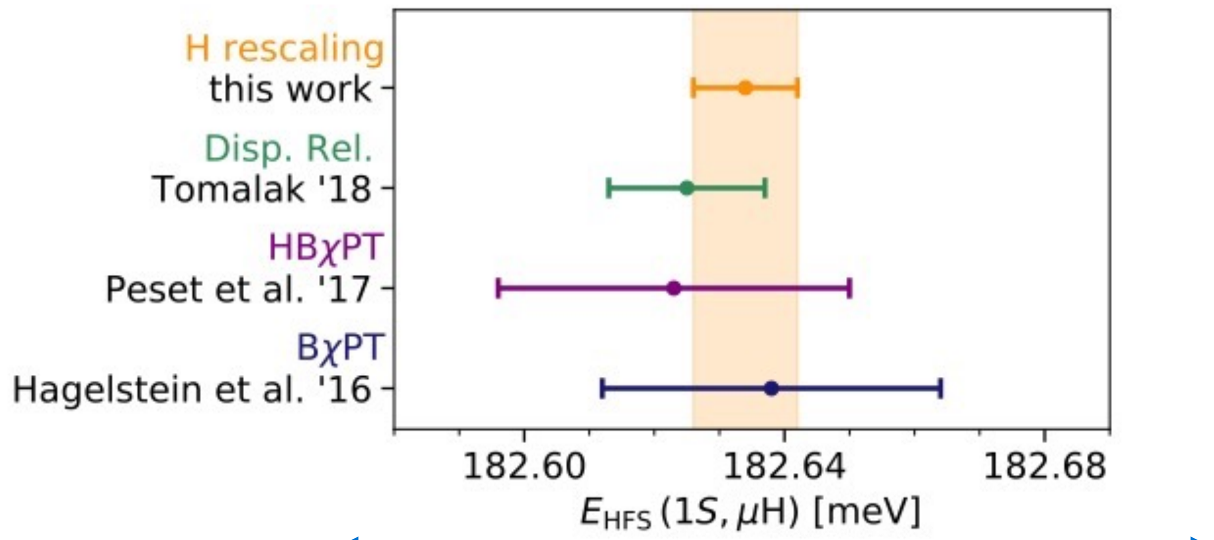
M. Marszalek , PhD Thesis, ETH 2022

Comparison



$E_0 = 1\,\mathrm{mJ}$
8
6
4
2
0
99.0
99.5
100.0
$\times 10^{-2}$
R_m
$\overline{\mathcal{F}}$ / J cm^{-2}

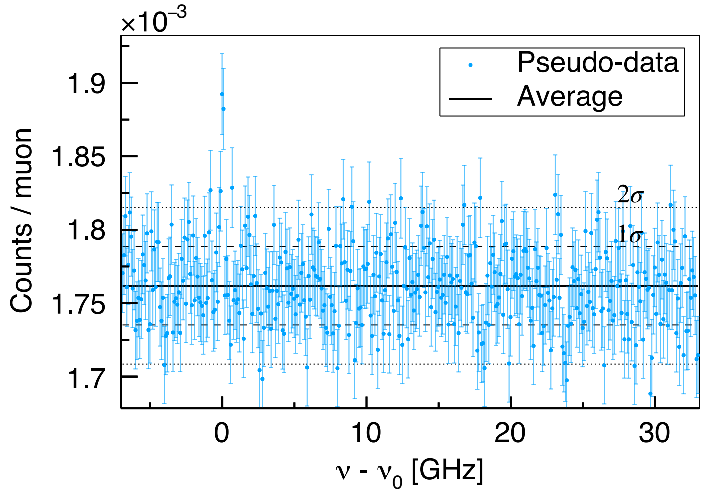
Search for the resonance



0.16 meV (40 GHz) search range

- **Steps to search for resonance**
- Measure 1.4 h at fixed wavelength to expose a 4 σ effect over background
- 1 h to change the laser frequency in steps of 100 MHz

- ***Simulation of the search for resonance***



Simulated resonance

Assuming the resonance has been found and given:

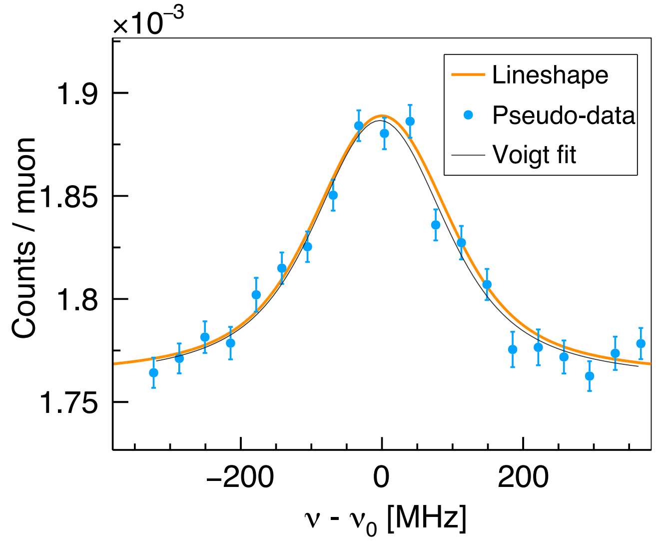
- Laser pulse 1mJ
- Target length 1.2 mm
- Cavity R = 99.2%
- Detection system: $\epsilon_{\mathrm{Au}} = 70\%$, $\epsilon_{\mathrm{Au-false}} = 9\%$

⇩

Determine resonance position with

$$\sigma = 4\ \mathrm{MHz}\ (1.6 \times 10^{-8}\ \mathrm{eV})$$

$$\frac{\sigma}{E_{\mathrm{HFS}}} = \frac{4\ \mathrm{MHz}}{44\ \mathrm{THz}} = 1 \times 10^{-7}$$



- **Theory improvement needed**

Collaboration

Laboratoire Kastler Brossel
Physique quantique et applications

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MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK GARCHING
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C.M.B. Monteiro, J.M.F. dos Santos,
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Our lab at PSI

Questions ?