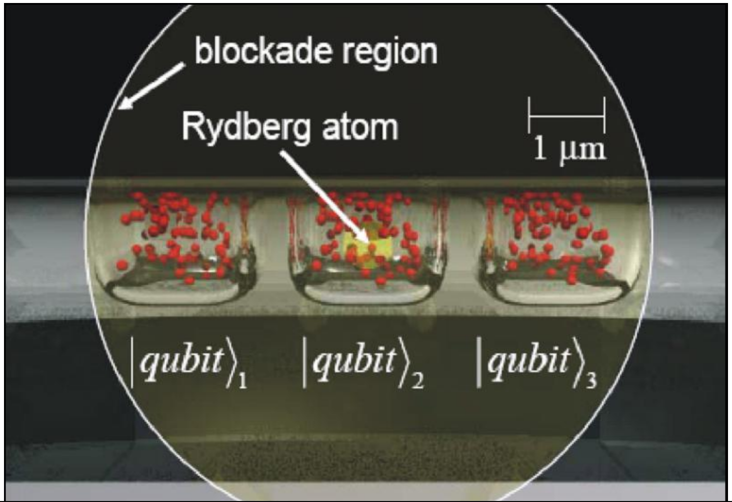
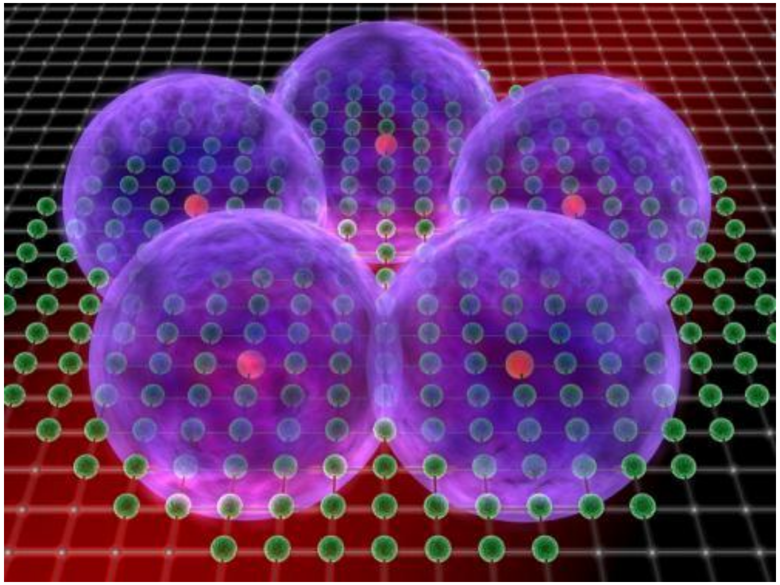
Rydberg atoms
part 2

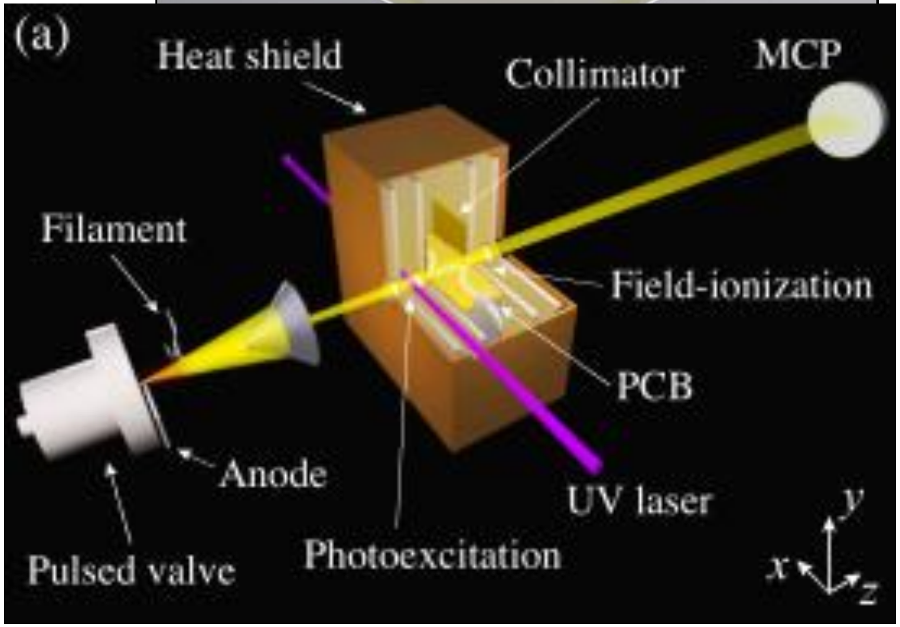
Tobias Thiele

Part 2- Rydberg atoms

- Typical Experiments:
  - Beam experiments
  - (ultra) cold atoms
  - Vapor cells







Goal

- Couple atoms to cavities
  - Realize Jaynes-Cummings Hamiltonian

- Single atom(dipole) - coupling to cavity:

$$g = \frac{d\,F_0}{\hbar} = \sqrt{\frac{\omega_0\, d^2}{2\,\epsilon_0 \hbar\, V}}$$

Reduce mode volume

Increase resonance frequency

Increase dipole moment

Coupling Rydberg atoms

- Couple atoms to cavities
  - Realize Jaynes-Cummings Hamiltonian

- Single atom(dipole) - coupling to cavity:

$$g = \frac{d\, F_0}{\hbar} = \sqrt{\frac{\omega_0\, d^2}{2\, \epsilon_0 \hbar\, V}} \approx 110\, n^2 = 2\, \pi\, 43.768\, kHz$$

Increase dipole moment for fixed frequency (~50 GHz, n=50)

- Can we go arbitrarily high with Rydbergs?

$$g = \frac{d\, F_0}{\hbar} = \sqrt{\frac{\omega_0\, d^2}{2\, \epsilon_0 \hbar\, V}}$$

$\omega_0 \propto n^{-3}$, $d^2 \propto n^2$, $V \propto n^9$

Coupling Rydberg atoms

- Couple atoms to cavities
  - Realize Jaynes-Cummings Hamiltonian

- Single atom(dipole) - coupling to cavity:

$$g = \frac{d\,F_0}{\hbar} = \sqrt{\frac{\omega_0\,d^2}{2\,\epsilon_0 \hbar\,V}} \approx 110\,n^2 = 2\,\pi\,43.768\,kHz$$

Increase dipole moment for fixed frequency (~50 GHz, n=50)

- Can we go arbitrarily high with Rydbergs?

$$g = \frac{d\,F_0}{\hbar} = \sqrt{\frac{\omega_0\,d^2}{2\,\epsilon_0 \hbar\,V}} \approx 2\,\pi\,6 * 10^{11}\,n^{-4}$$

$\propto n^2$ (d^2)

$\propto n^{-3}$ (ω_0)

$\propto n^9$ (V)

Advantages microwave regime for strong coupling g>> κ, γ

- Coupling to ground state of cavity
  - λ~0.01 m (microwave, possible) for n=50
  - λ ~10^{-7} m (optical, n. possible),
    - Typical mode volume: 1mm *(50 μm)^2 -> $g \propto \sqrt{n}$

- Linewidth:
  - κ ~ 10 Hz (microwave)
  - κ ~ MHz (optical)

Summary coupling strength

n^{-4}

- Microwave: $g \sim 2\pi\ 40\ kHz, \kappa \sim 2\pi\ 10\ Hz$ frequency limited
- Optical: $g \sim 2\pi\ 5\ MHz, \kappa \sim 2\pi\ 1\ MHz$ Mode volume limited

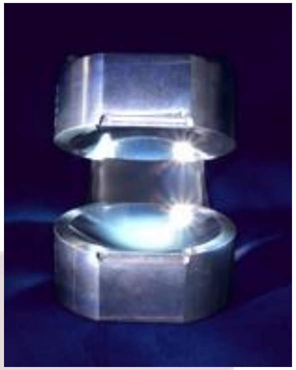
- What about γ?
  - Optical γ_{6p}~ 2.5 MHz
  - Rydberg γ_{50p}~300 kHz, $\gamma_{50,50}$~100 Hz

    n^{-3} n^{-5}

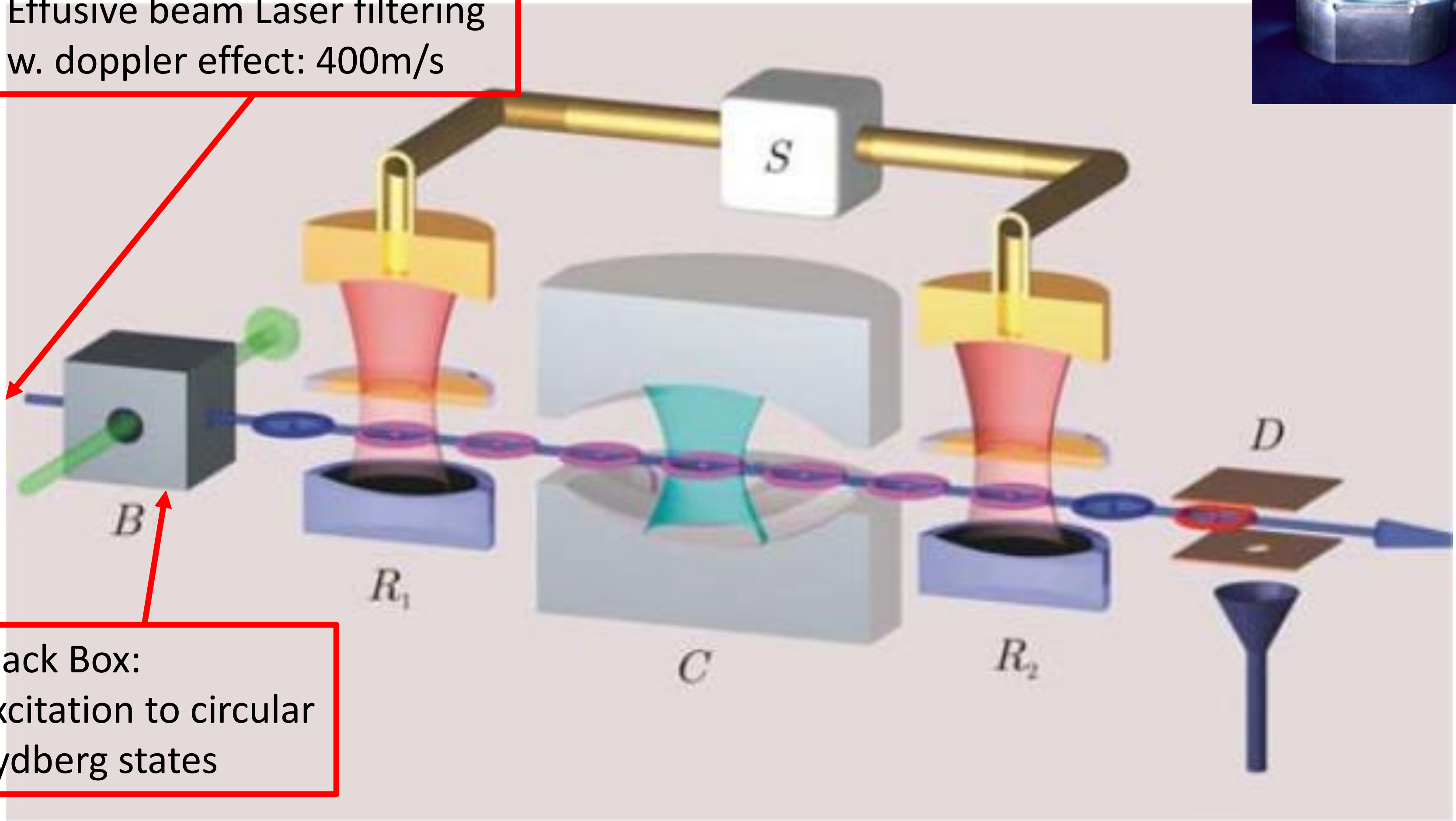
  - > $g/\gamma_{np} \propto 1/n$, $g/\gamma_{n,n-1} \propto n$

Optimal n when g >> γ ~ κ

Experiment Haroche



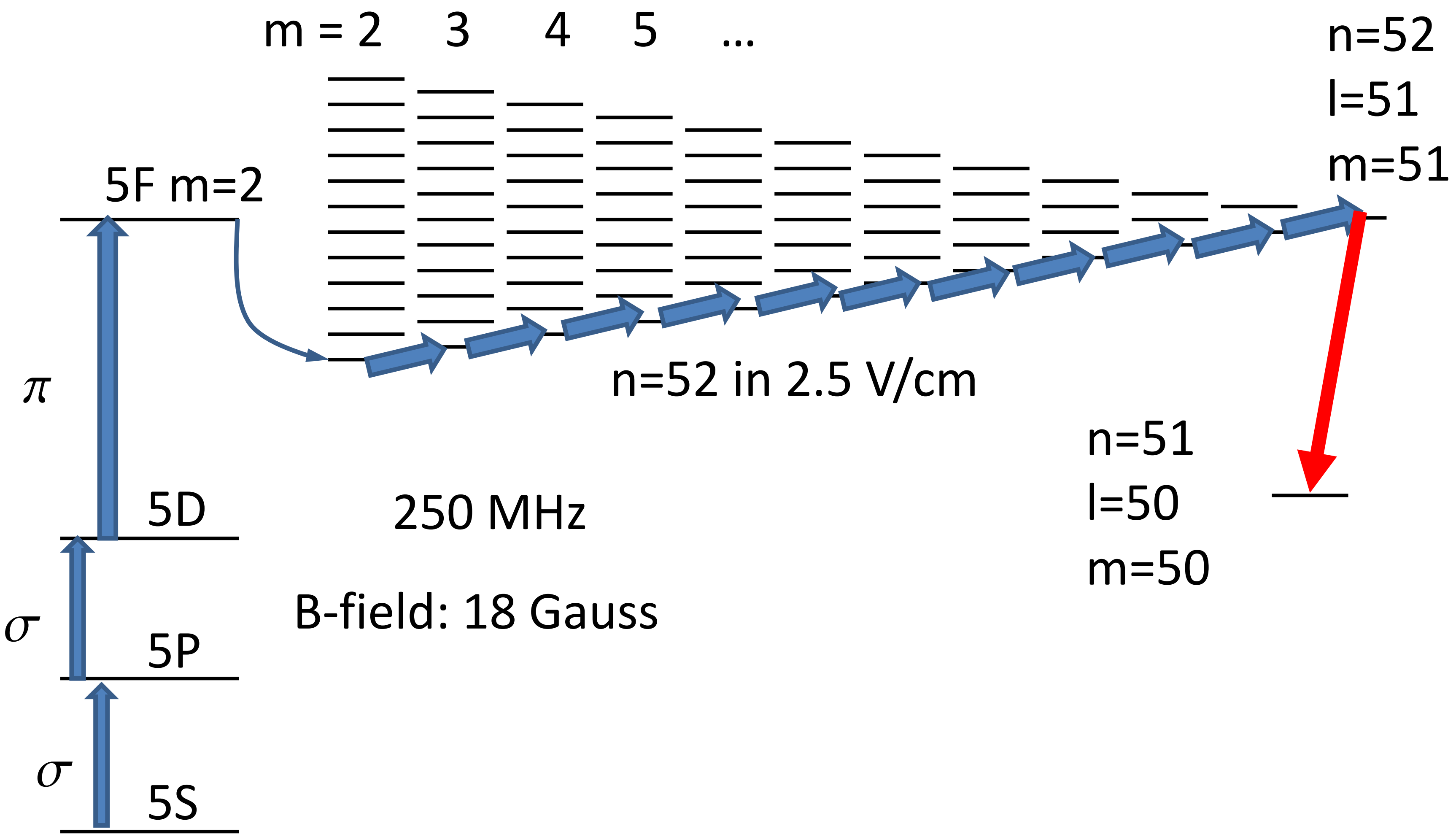
Effusive beam Laser filtering
w. doppler effect: 400m/s



Black Box:
Excitation to circular
Rydberg states

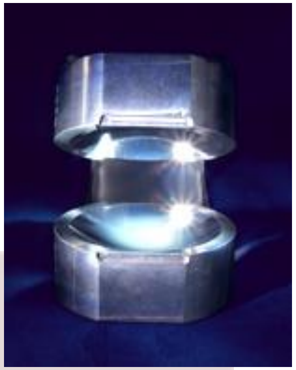
Advanced information: Nobelprize 2012, S. Haroche

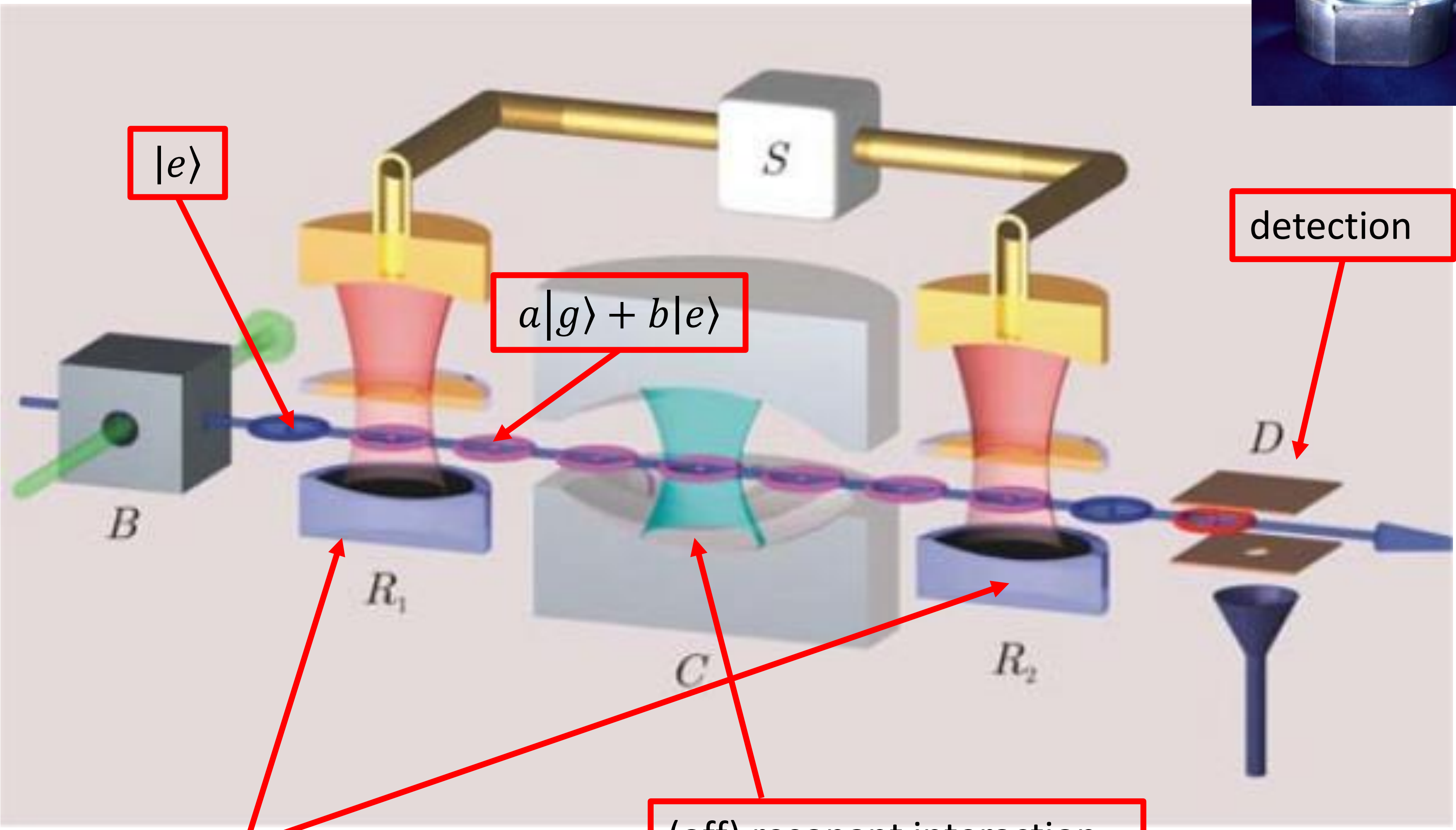
Circular States: 53 photons



Modified from lecture note: S. Haroche: quantumlah.org

Experiment Haroche





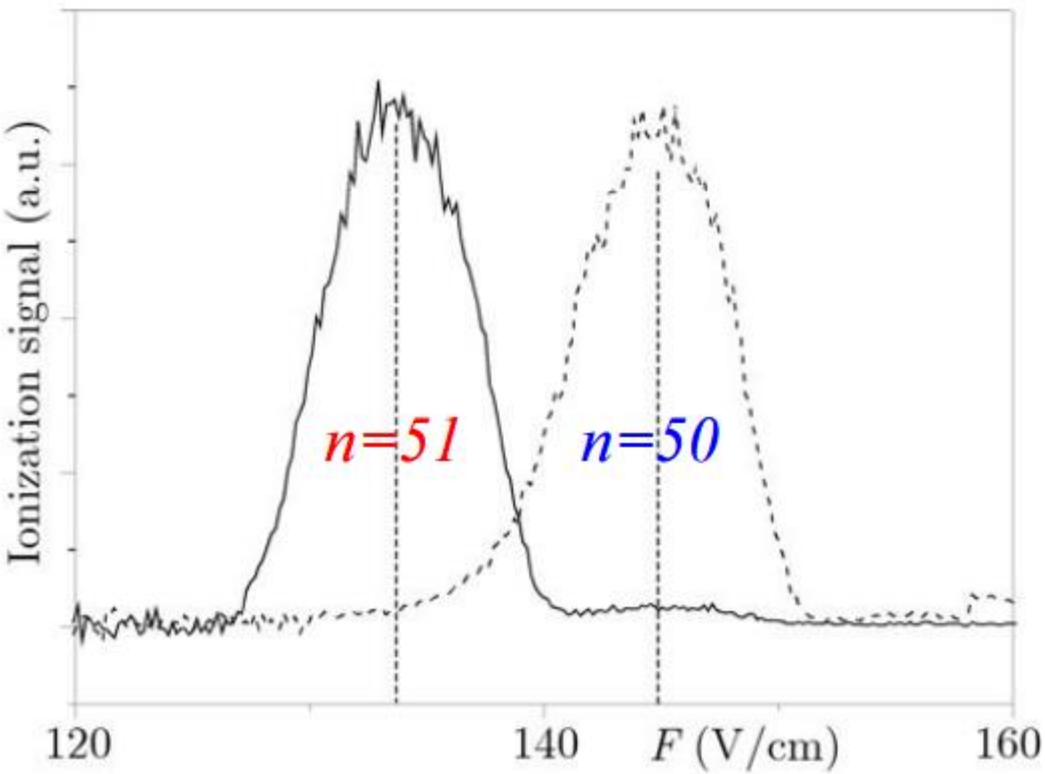
Ramsey interferometer:
apply single atom pulses

(off) resonant interaction
with cavity

Advanced information: Nobelprize 2012, S. Haroche

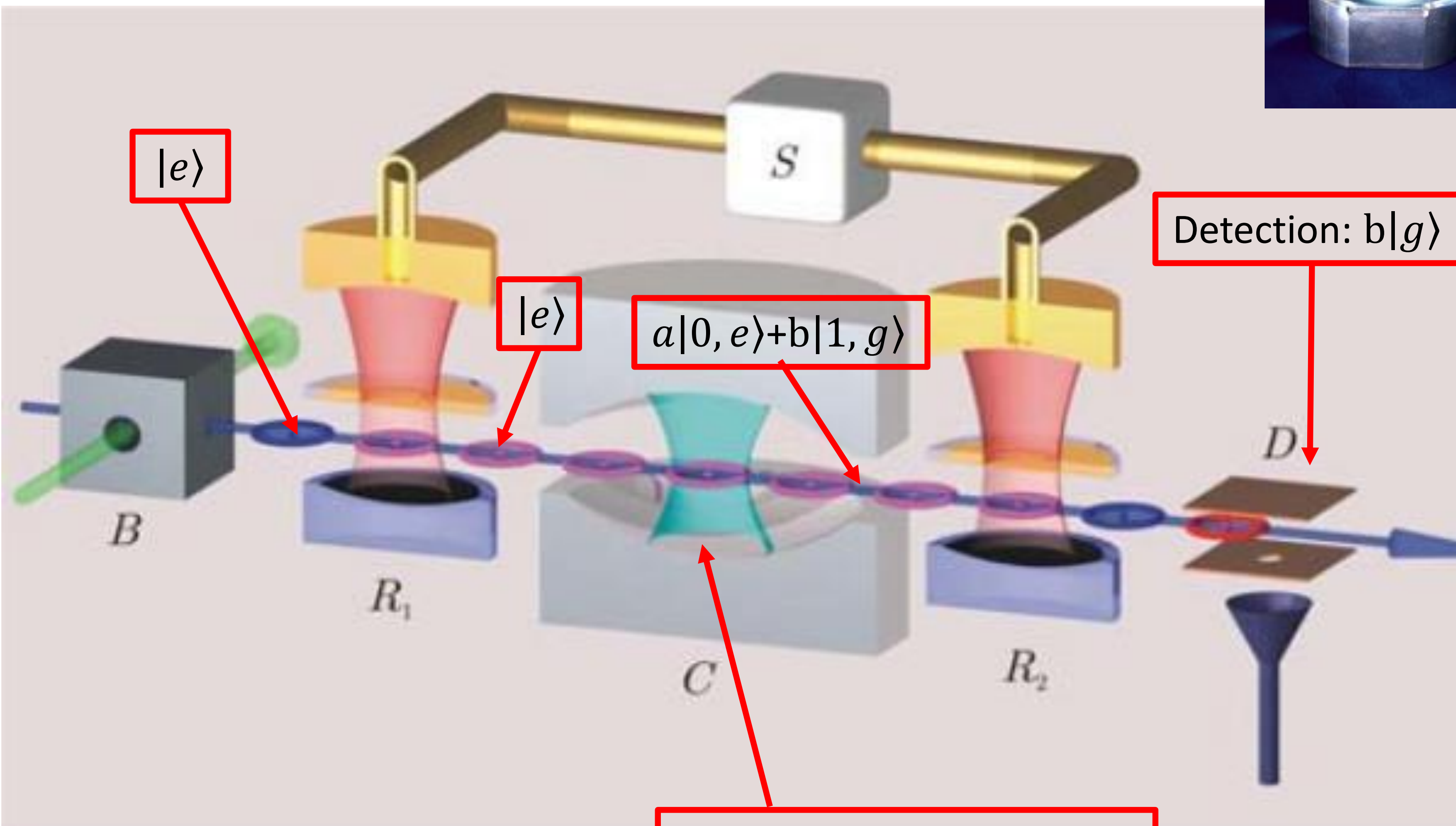
Detection

- Ramped field ionization: n^{-4}
- Detecetion efficiency > 50%



From lecture note: S. Haroche: quantumlah.org

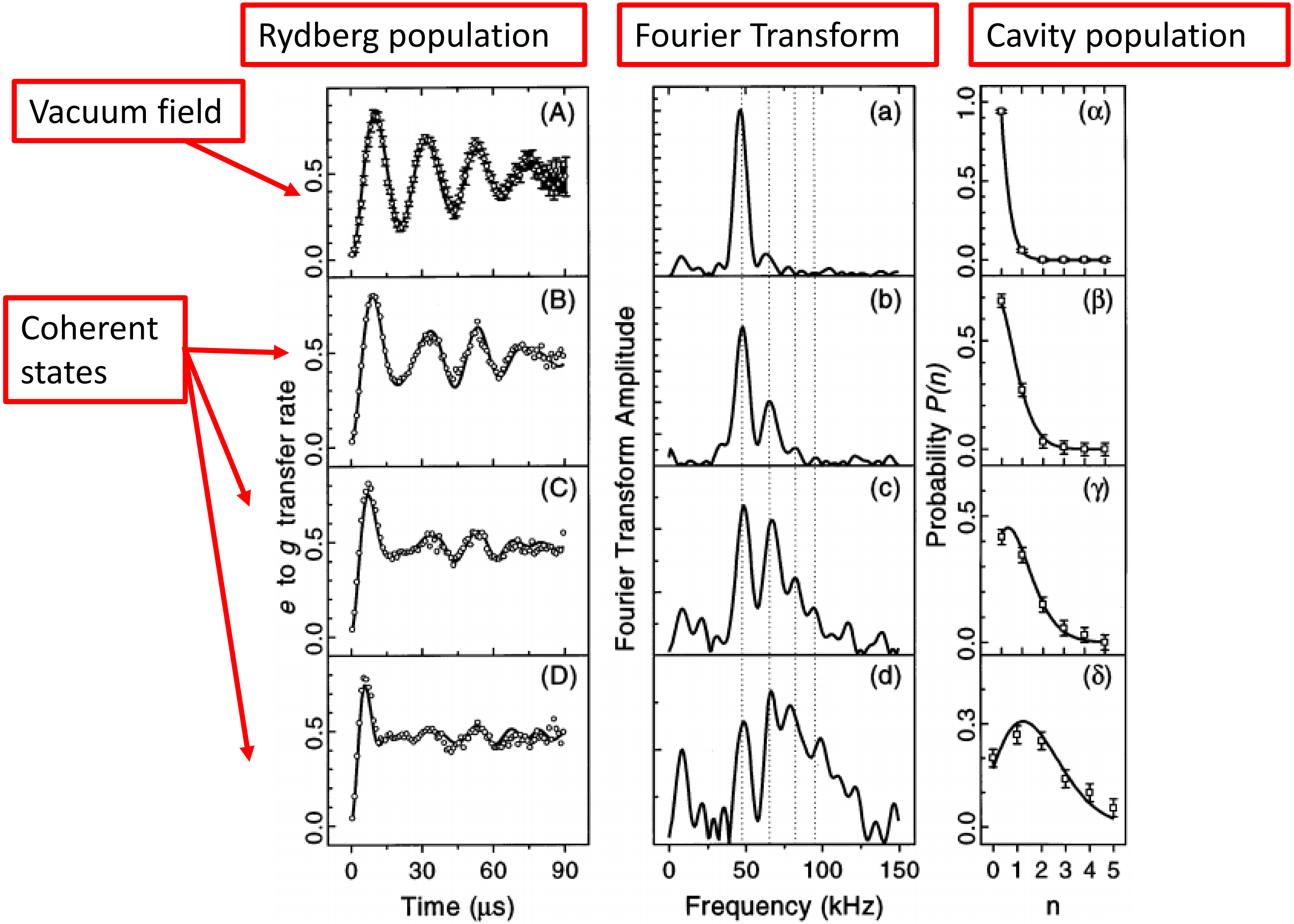
Rabi oscillations



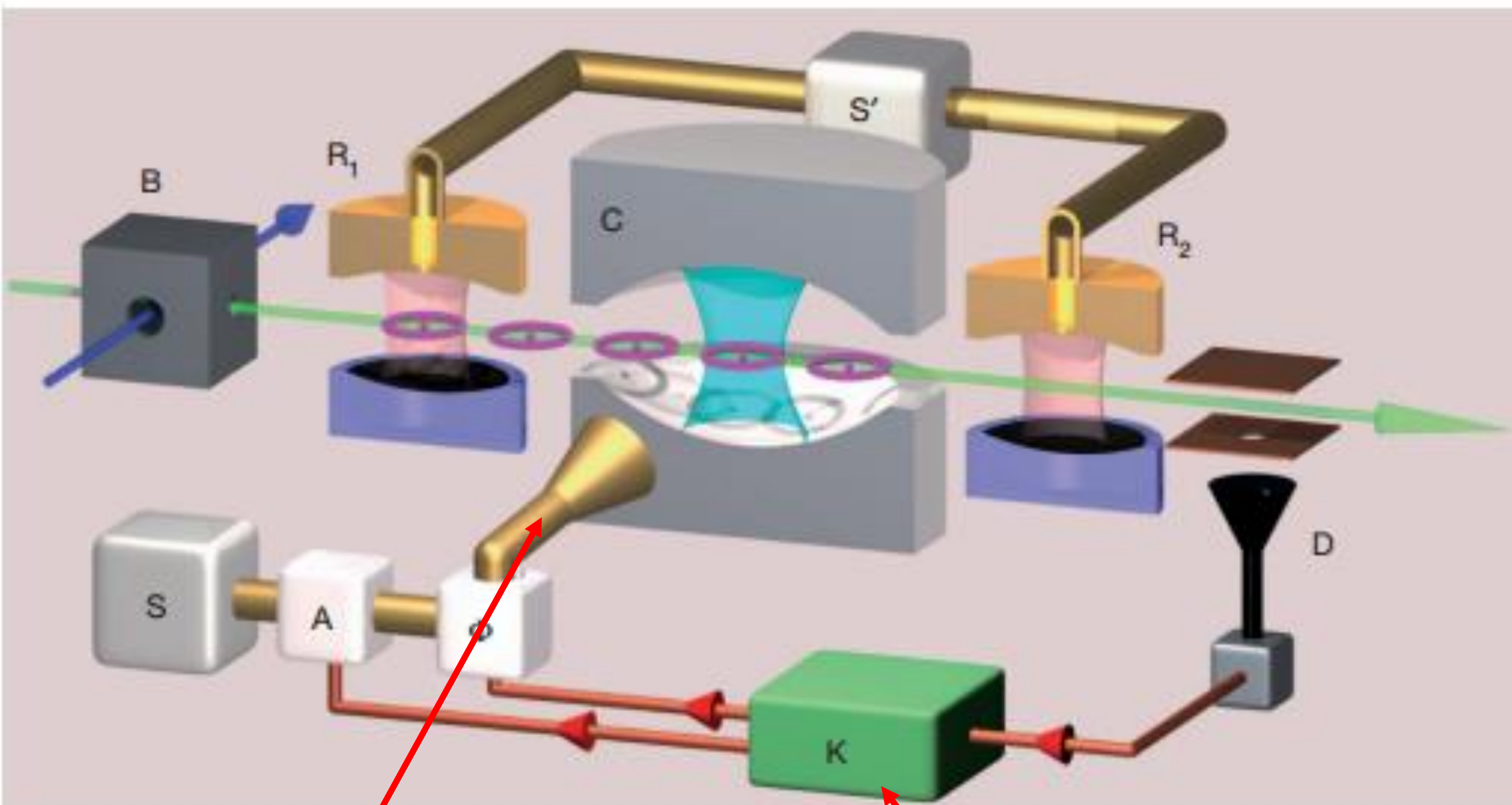
Advanced information: Nobelprize 2012, S. Haroche

PRL **76**, 1800 (1996)

Rabi oscillations – change velocity



The next step: Quantum feedback

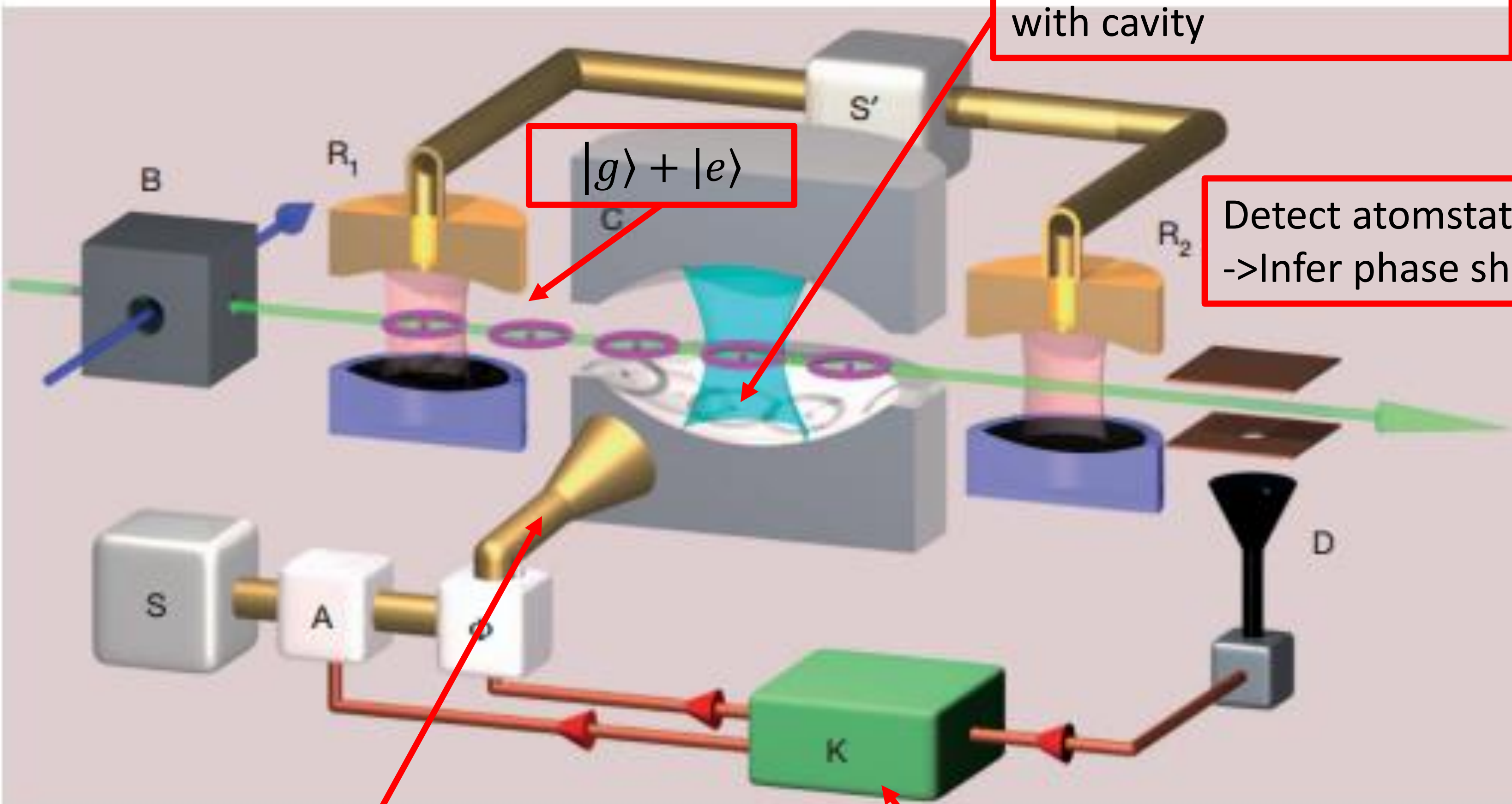


Injects single photons into cavity

Feedback calculation

Nature **477**, 73-77 (2011)

The next step: Quantum feedback

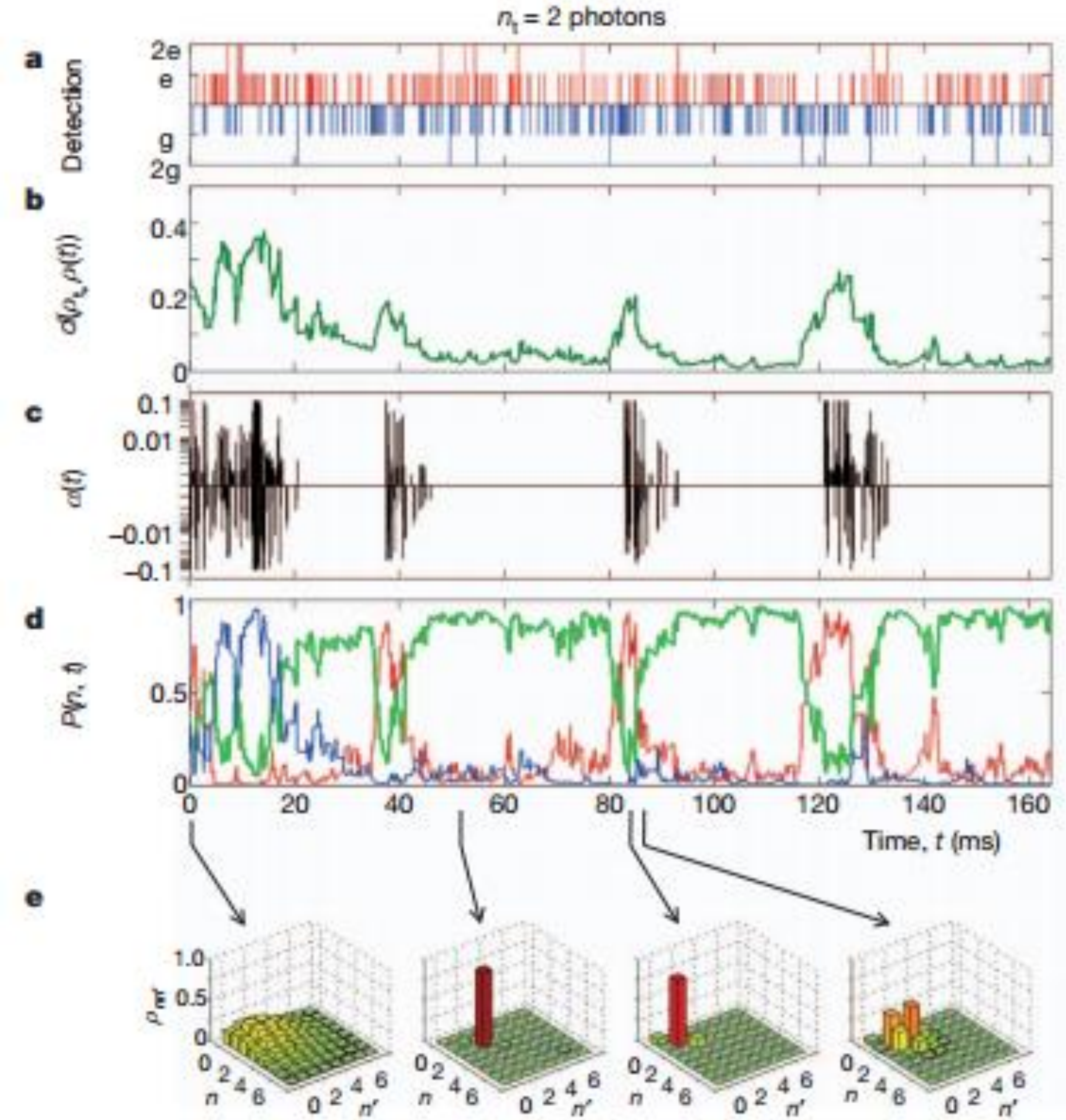


Injects single photons into cavity

Feedback calculation

Nature **477**, 73-77 (2011)

The next step: Quantum feedback



Atom state detection

Mathematic distance to target state

Applied power to feedback antenna

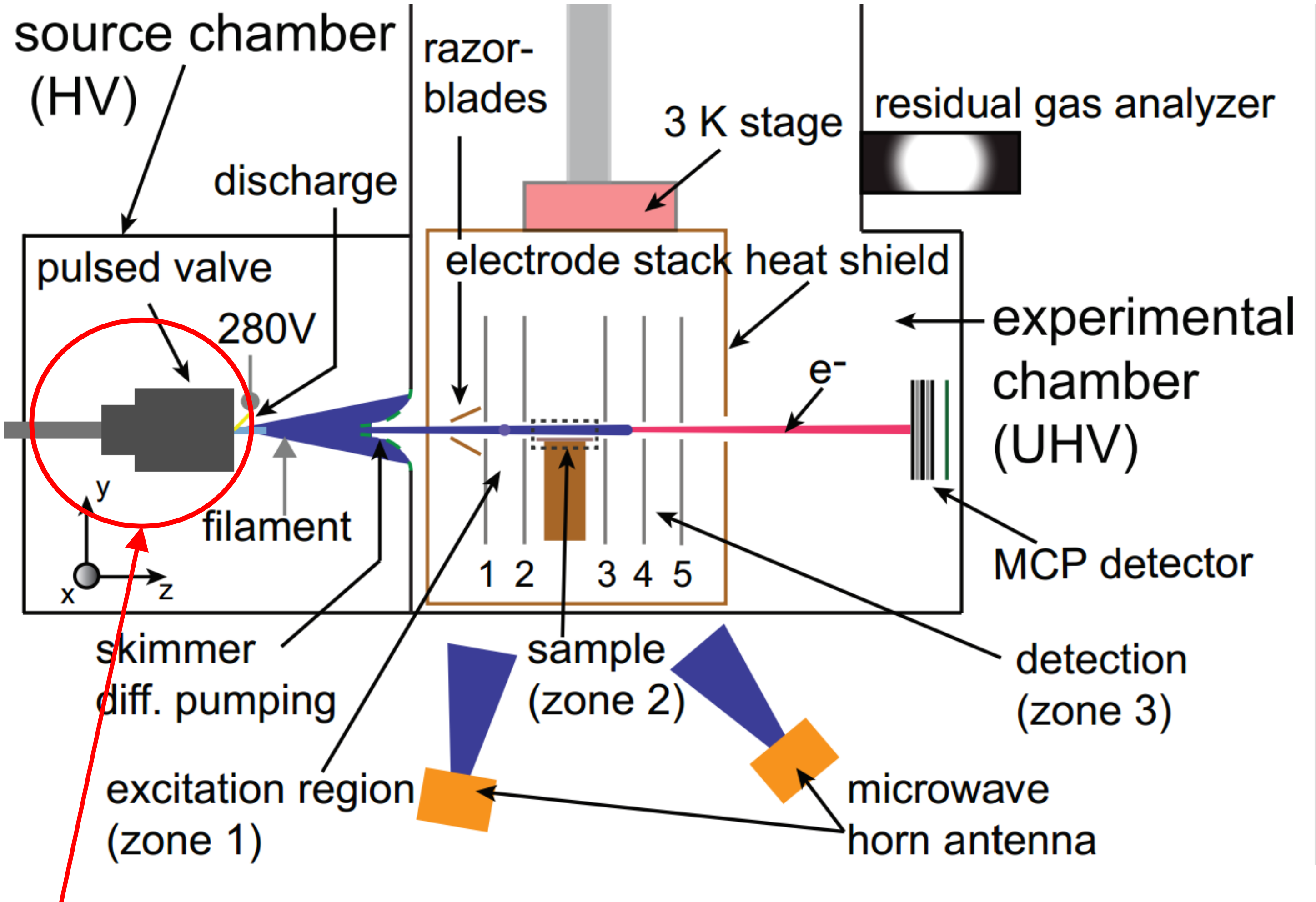
Probability photon state:
g =target
r= too few
b=too many

Calculated density matrix

Nature **477**, 73-77 (2011)

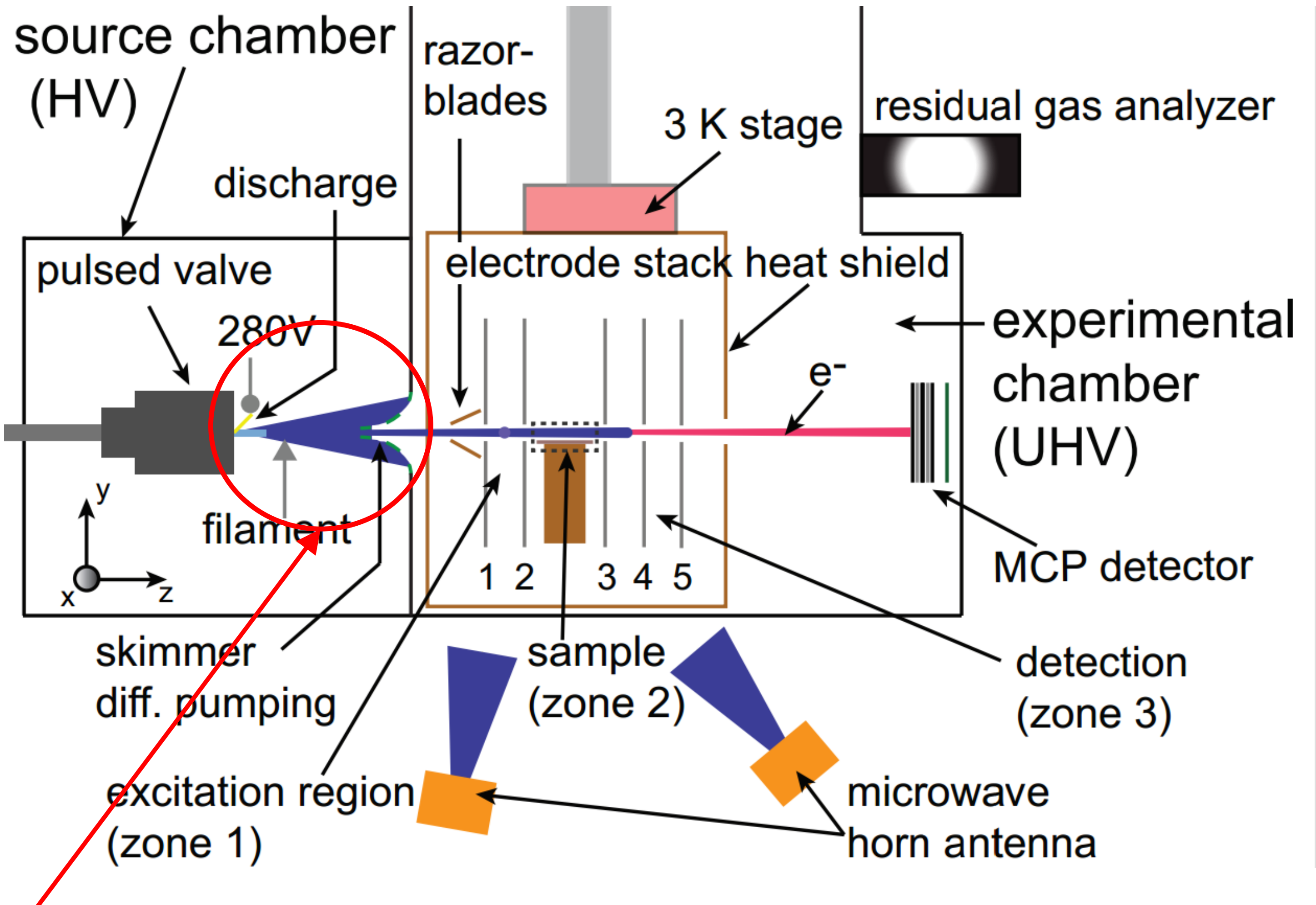
END

ETH physics Rydberg experiment



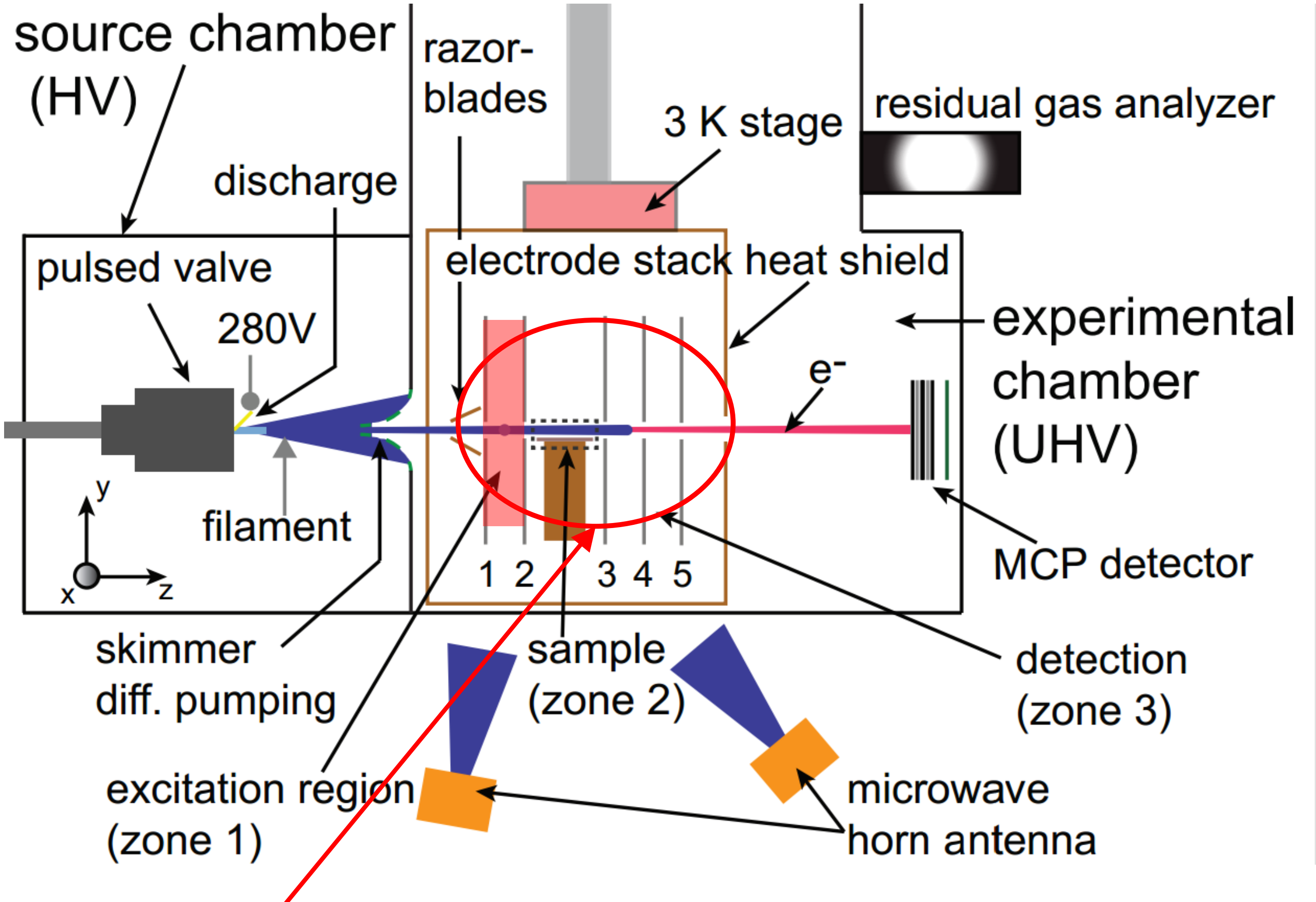
Creation of a cold supersonic beam of Helium.
Speed: 1700m/s, pulsed: 25Hz, temperature atoms=100mK

ETH physics Rydberg experiment



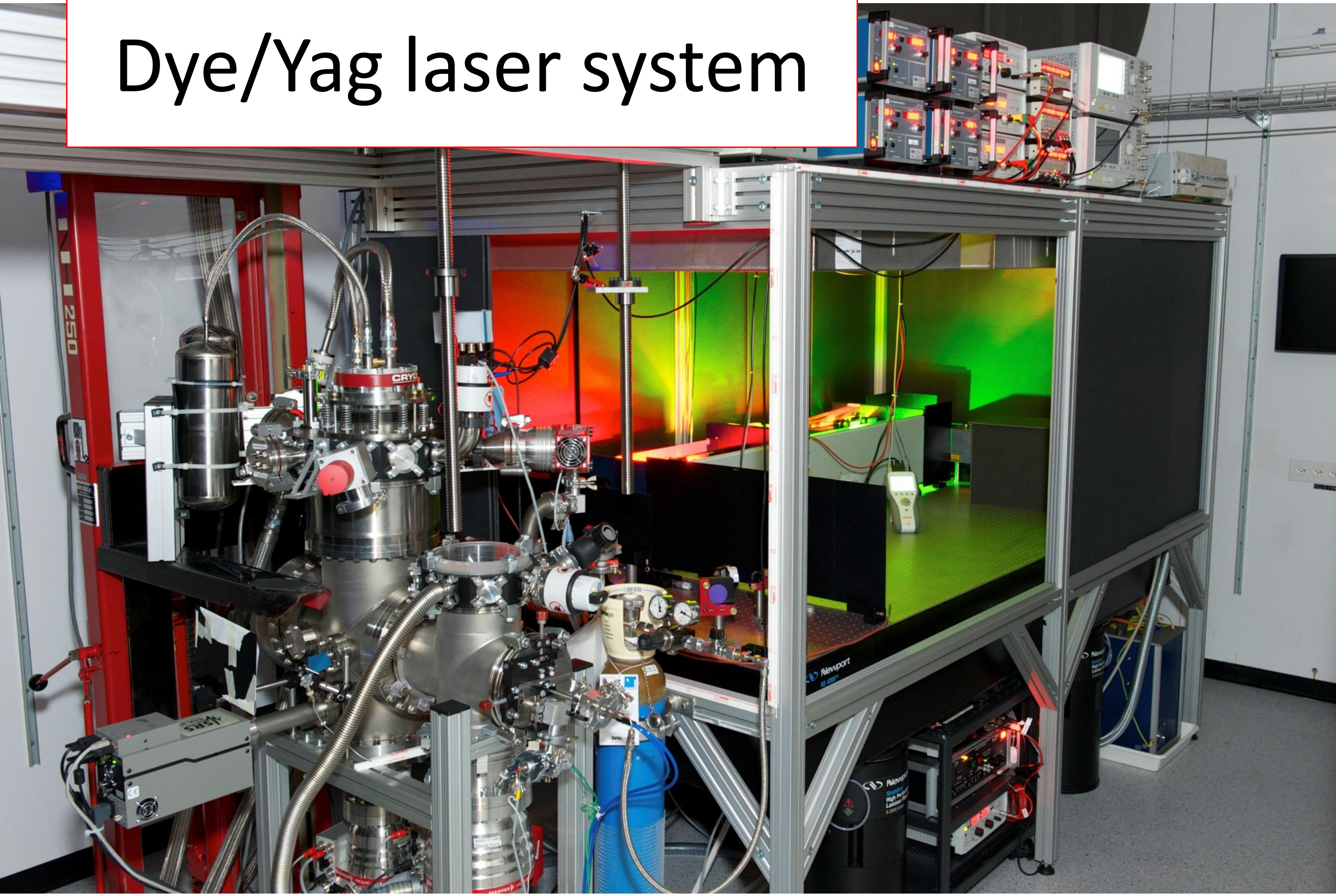
Excite electrons to the 2s-state, (to overcome very strong binding energy in the xuv range) by means of a discharge – like a lightning.

ETH physics Rydberg experiment

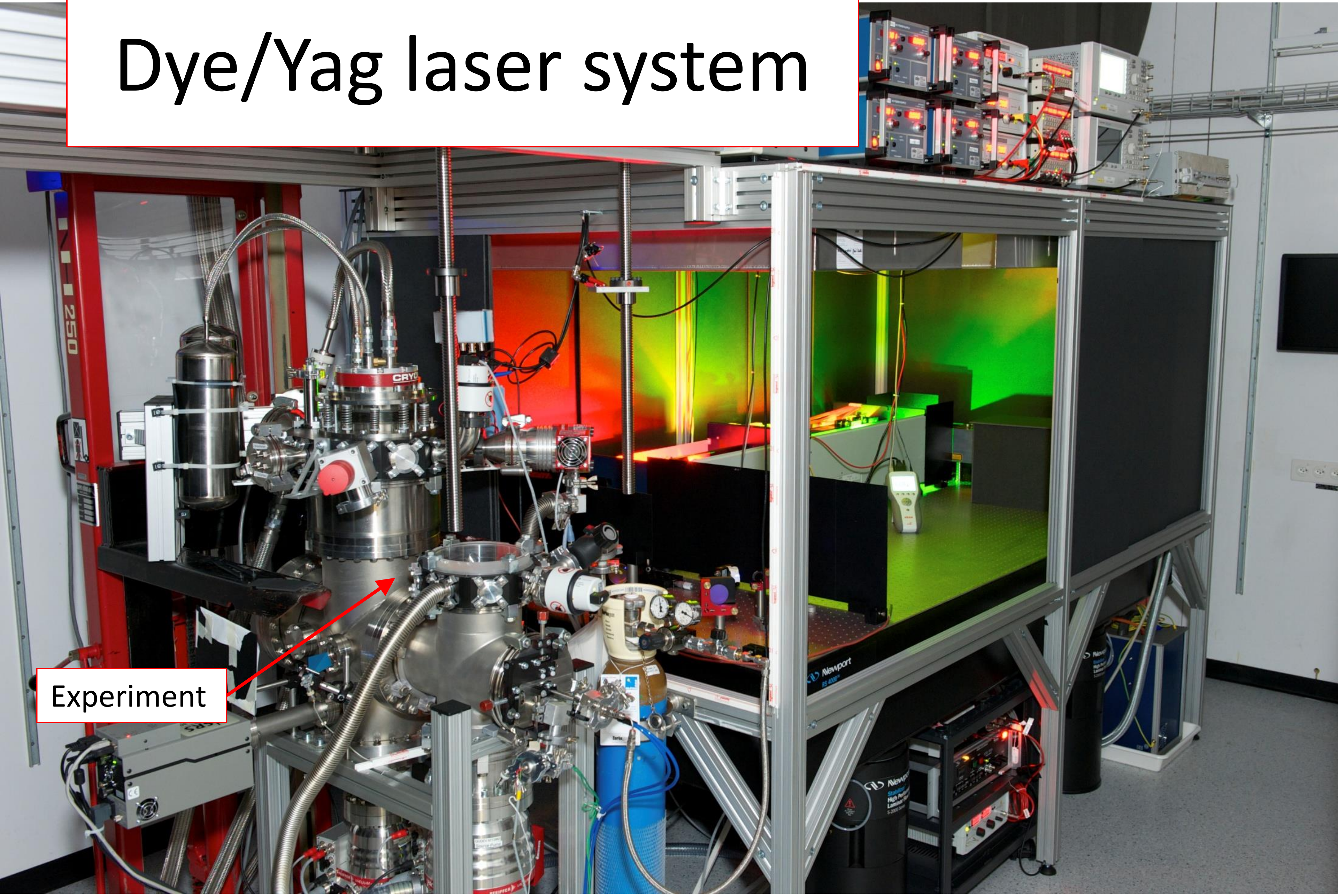


Actual experiment consists of 5 electrodes. Between the first 2 the atoms get excited to Rydberg states up to n=inf with a dye laser.

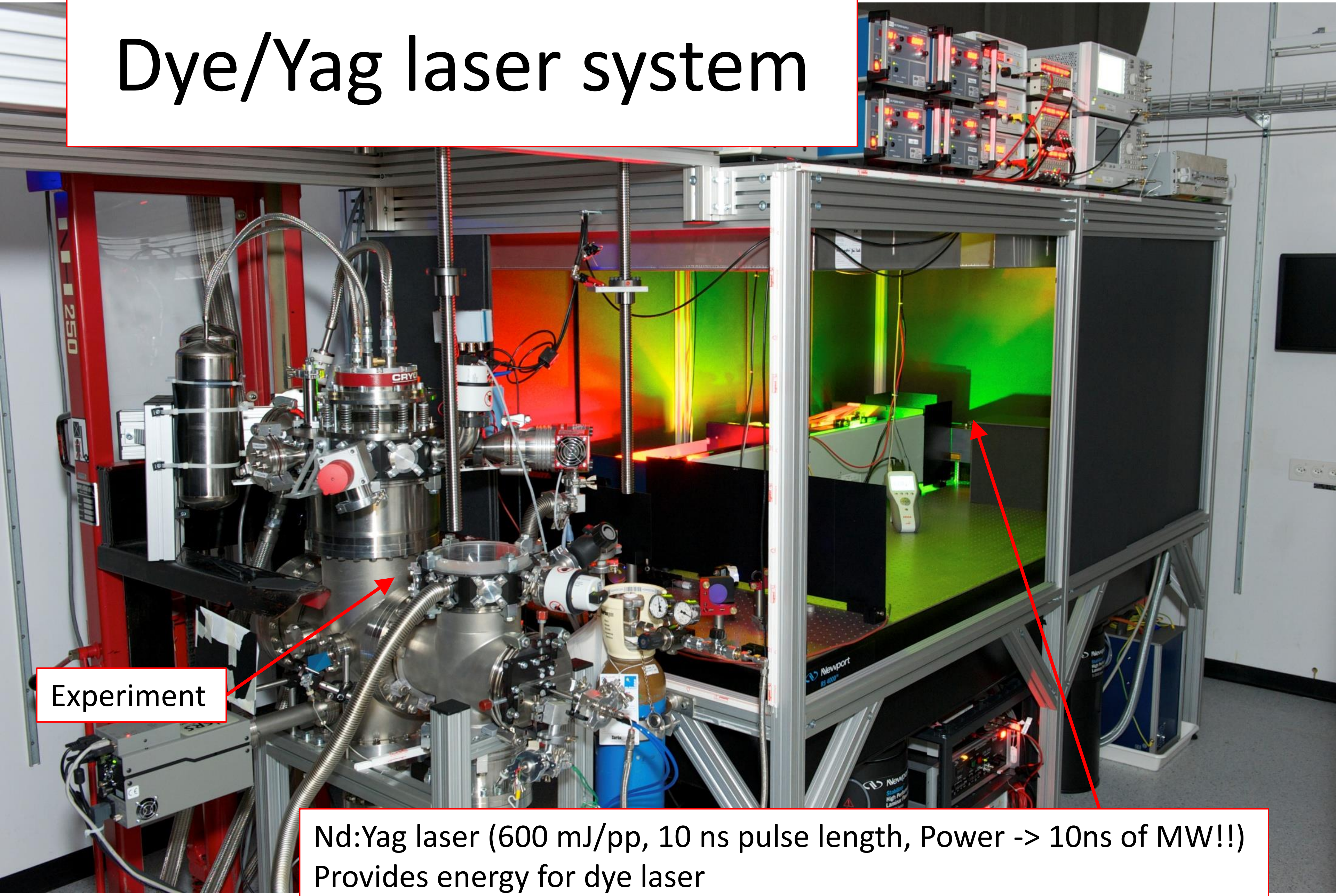
Dye/Yag laser system



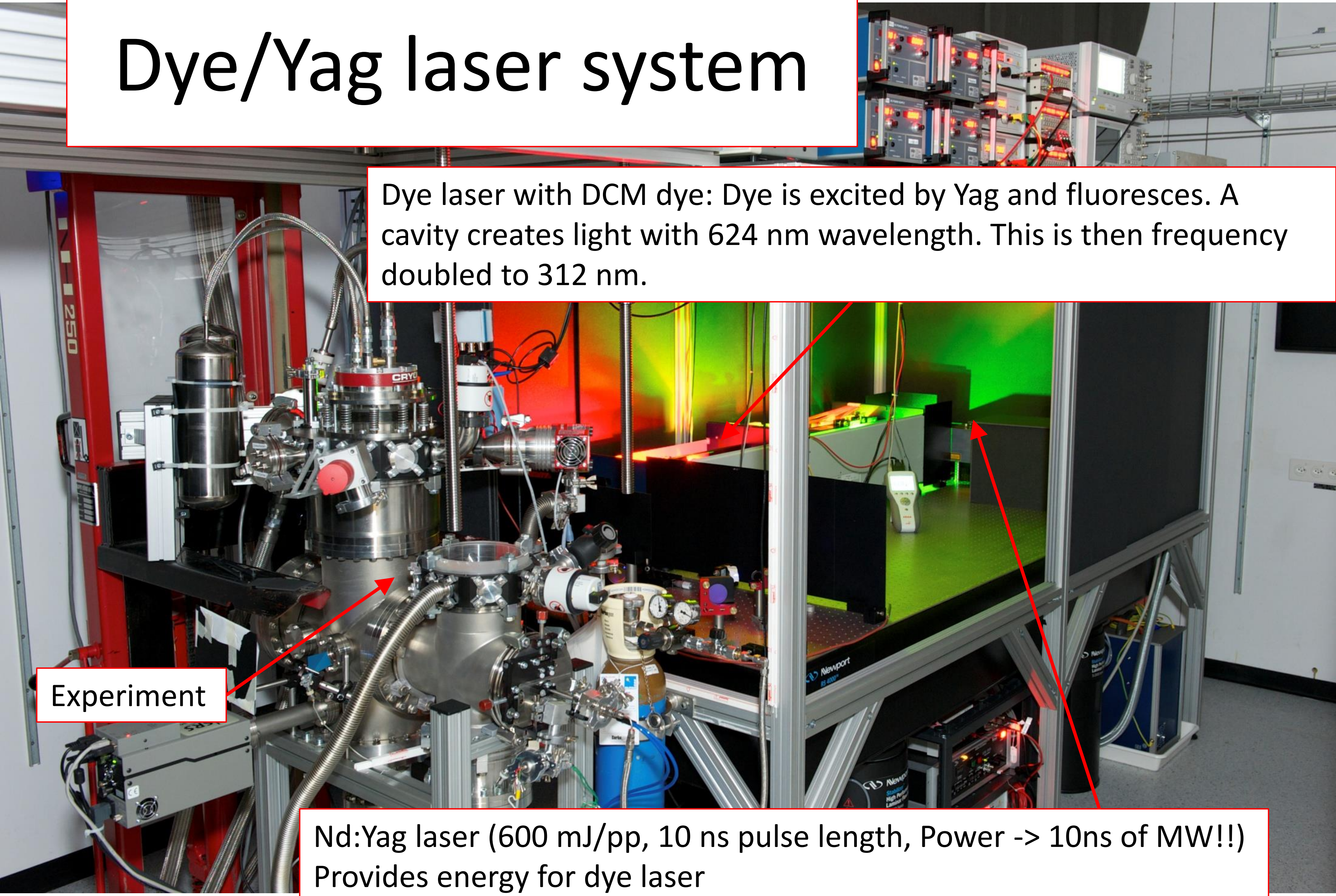
Dye/Yag laser system



Dye/Yag laser system



Dye/Yag laser system

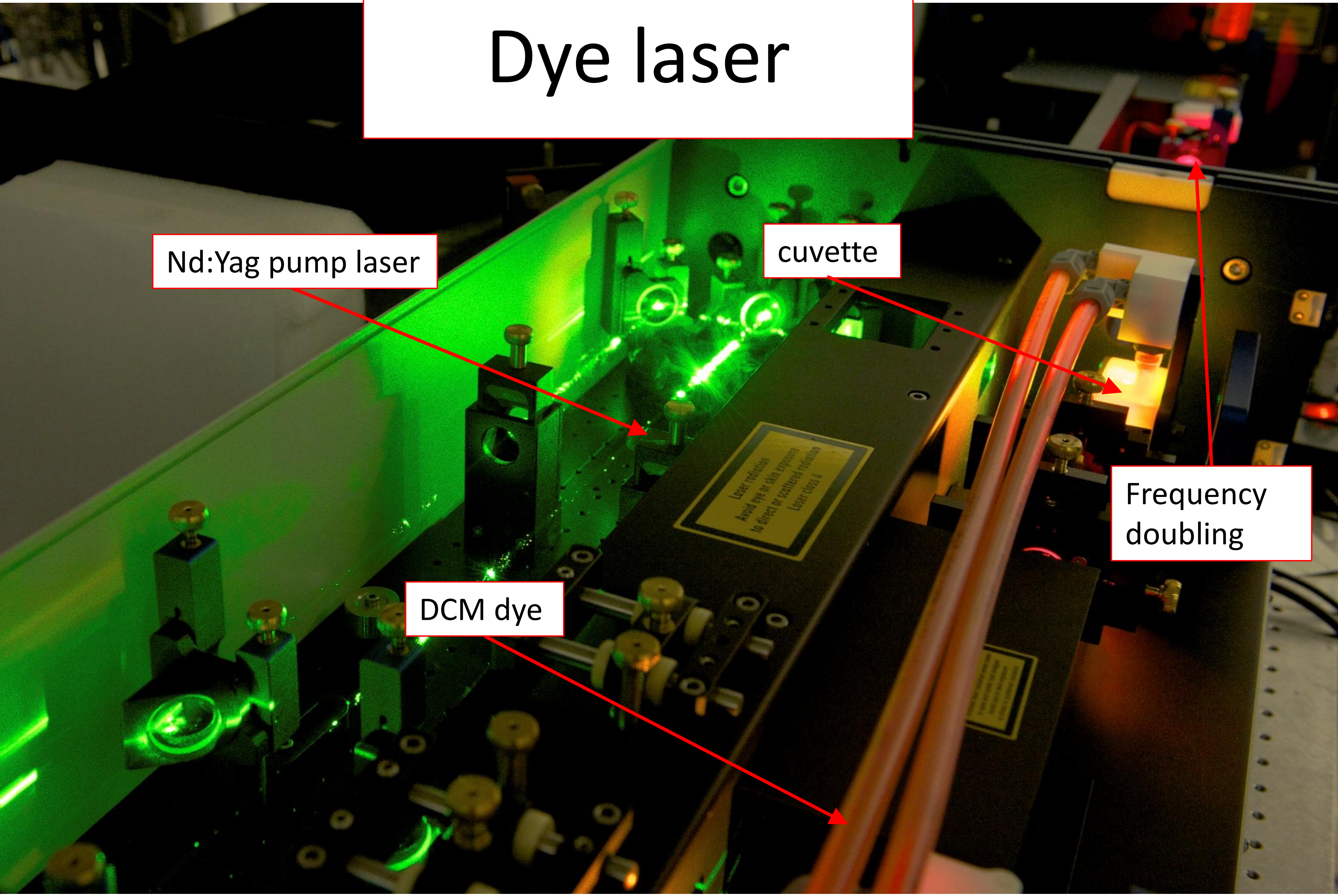


Dye laser with DCM dye: Dye is excited by Yag and fluoresces. A cavity creates light with 624 nm wavelength. This is then frequency doubled to 312 nm.

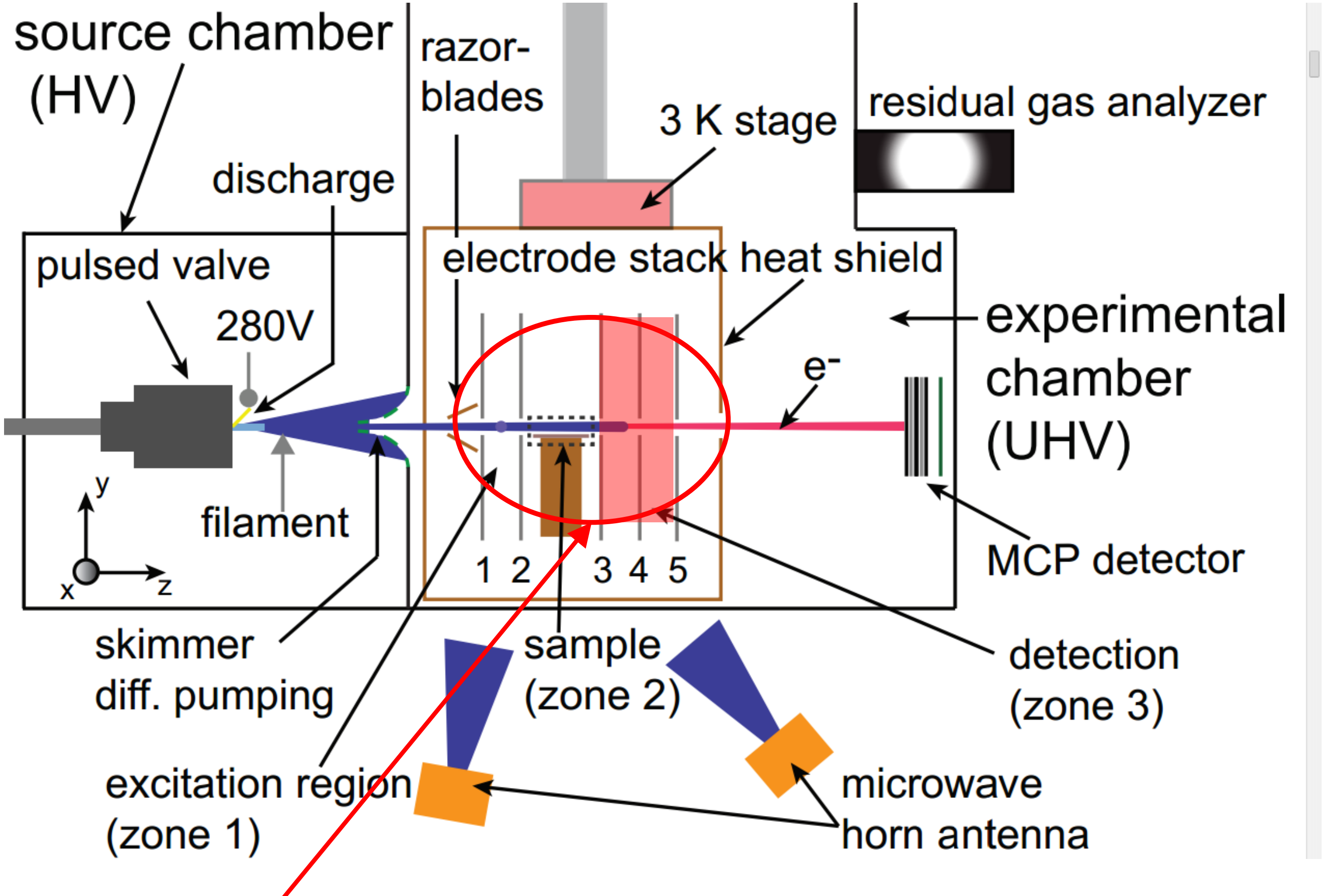
Experiment

Nd:Yag laser (600 mJ/pp, 10 ns pulse length, Power -> 10ns of MW!!)
Provides energy for dye laser

Dye laser

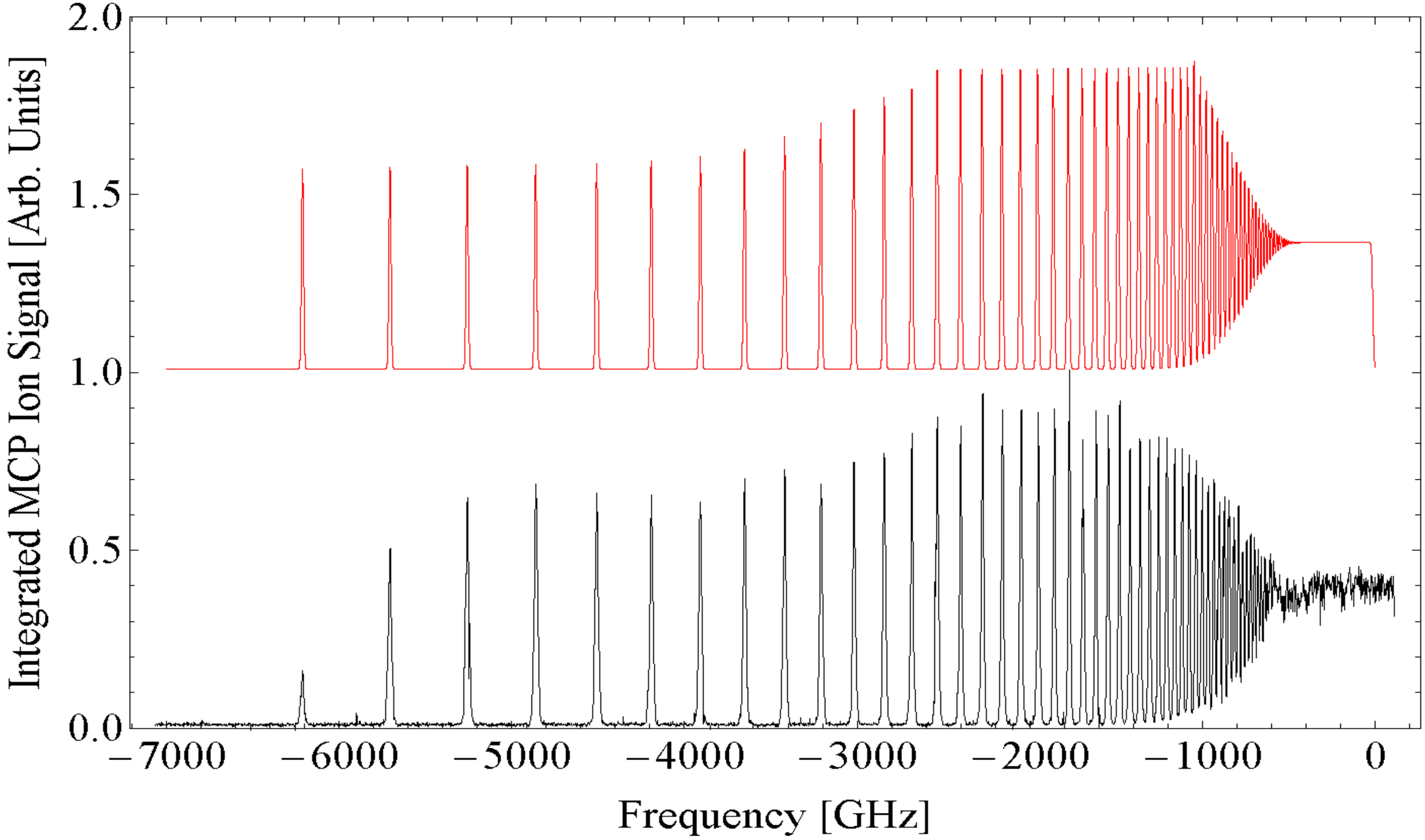


ETH physics Rydberg experiment

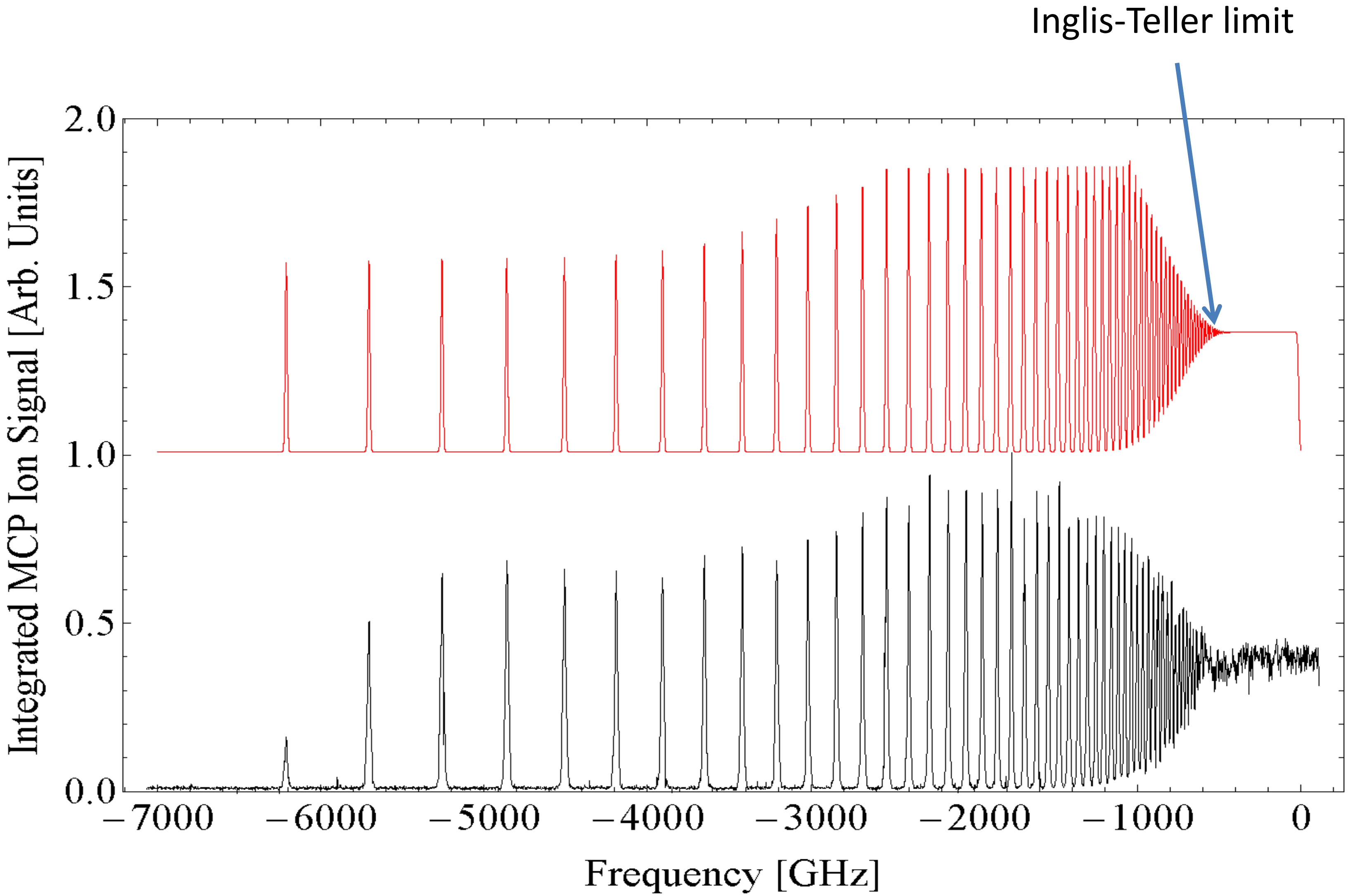


Detection: 1.2 kV/cm electric field applied in 10 ns. Rydberg atoms ionize and electrons are Detected at the MCP detector (single particle multiplier) .

Results TOF 100ns

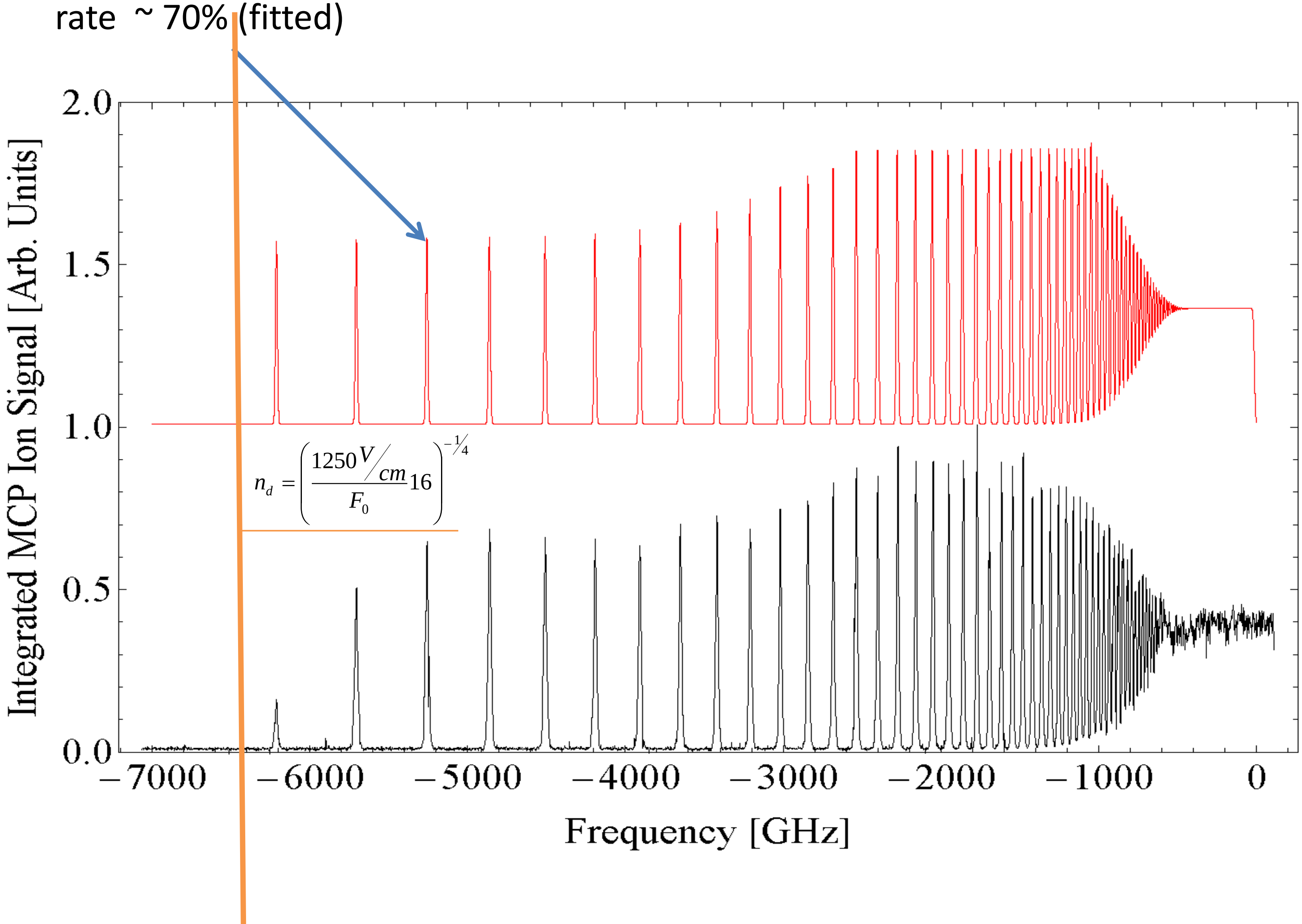


Results TOF 100ns



Results TOF 100ns

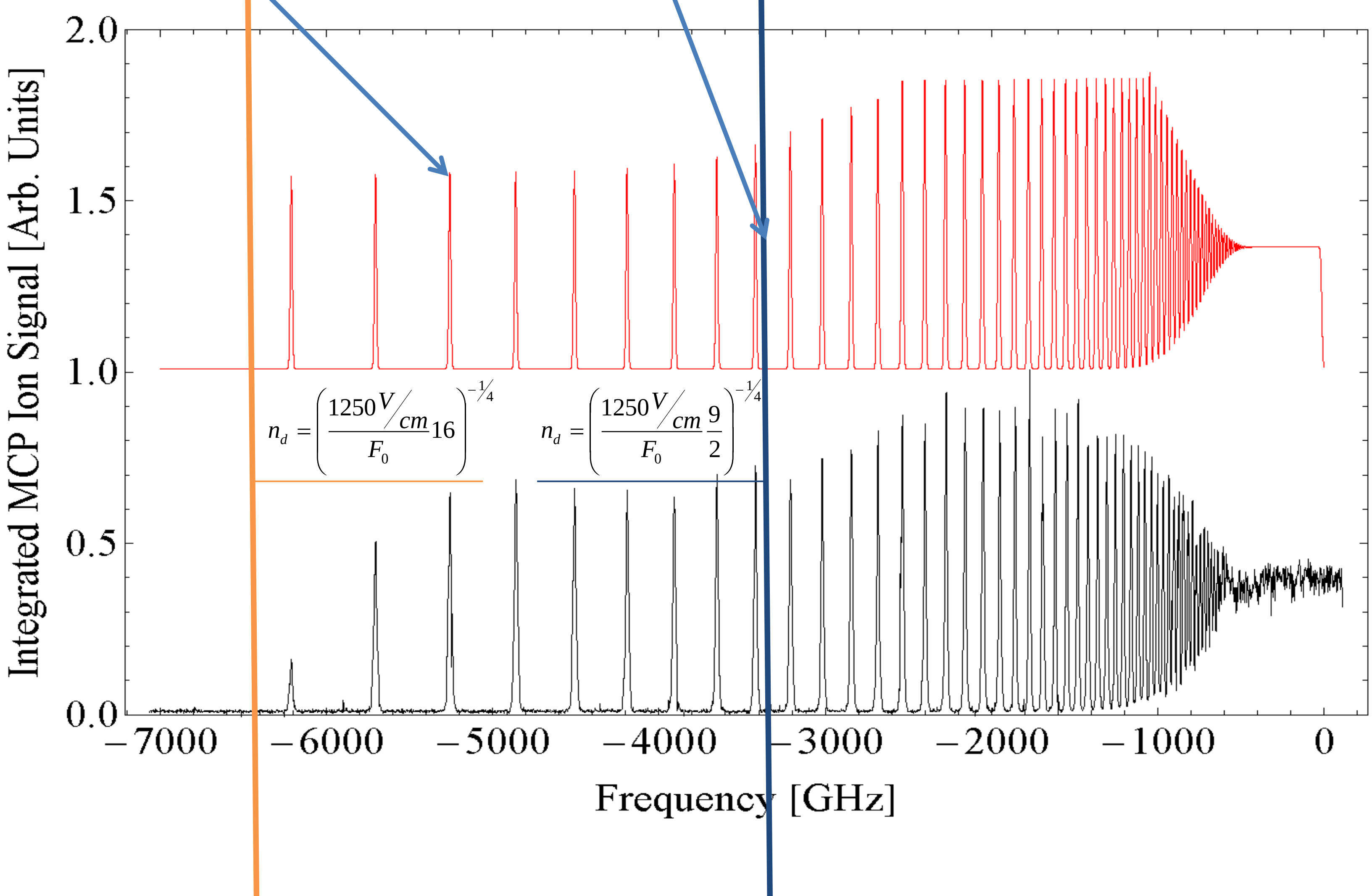
Adiabatic Ionization-
rate ~ 70% (fitted)



Results TOF 100ns

Adiabatic Ionization-rate ~ 70% (fitted)

Pure diabatic Ionization-rate: $\exp(-\Gamma t)$



Results TOF 100ns

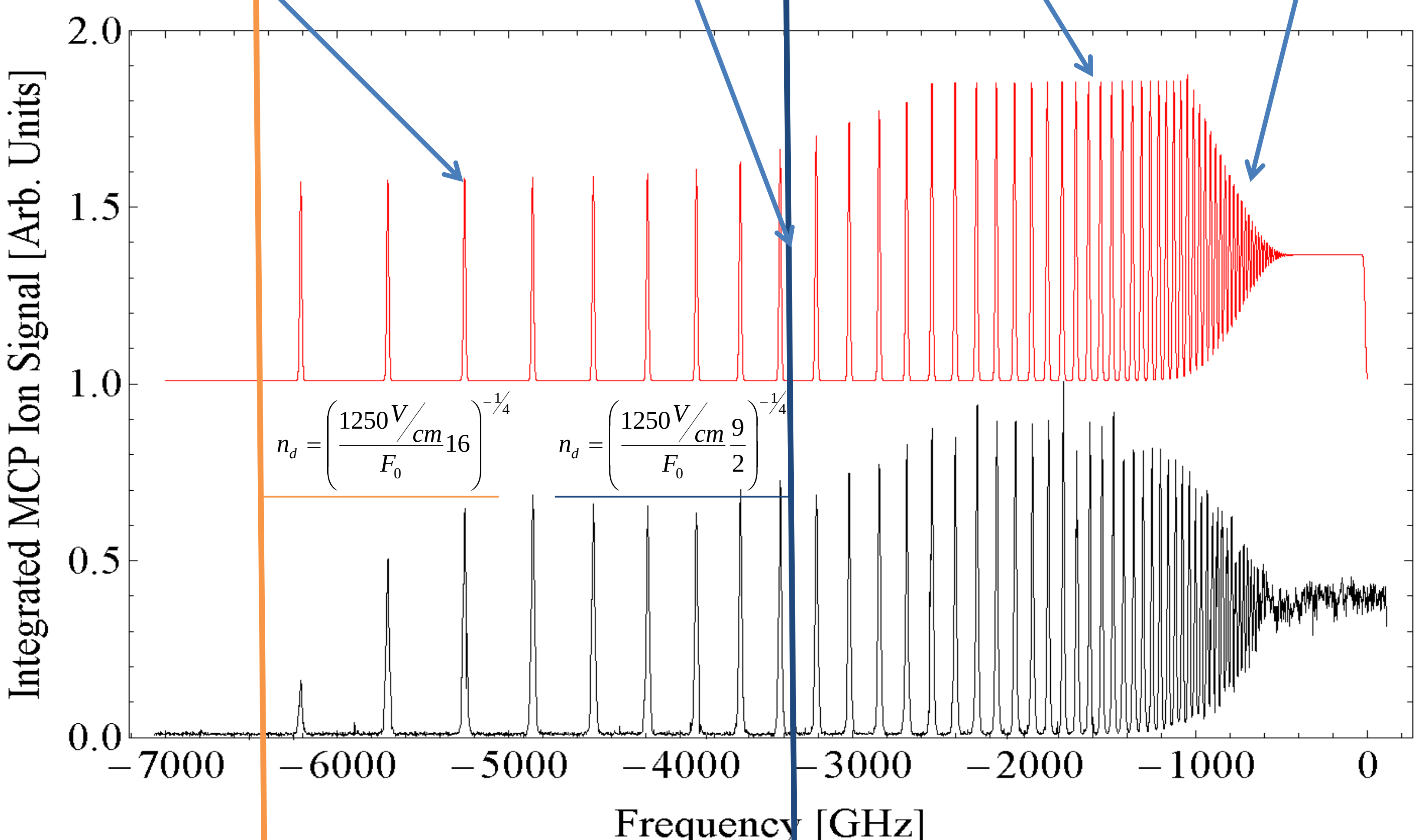
Adiabatic Ionization-rate ~ 70% (fitted)

Pure diabatic Ionization-rate: $\exp(-\Gamma t)$

saturation

$\sigma \propto \langle r \rangle^2 \propto n^{-3}$

From ground state



Results TOF 15 s