THz Lasers and Rydberg atoms

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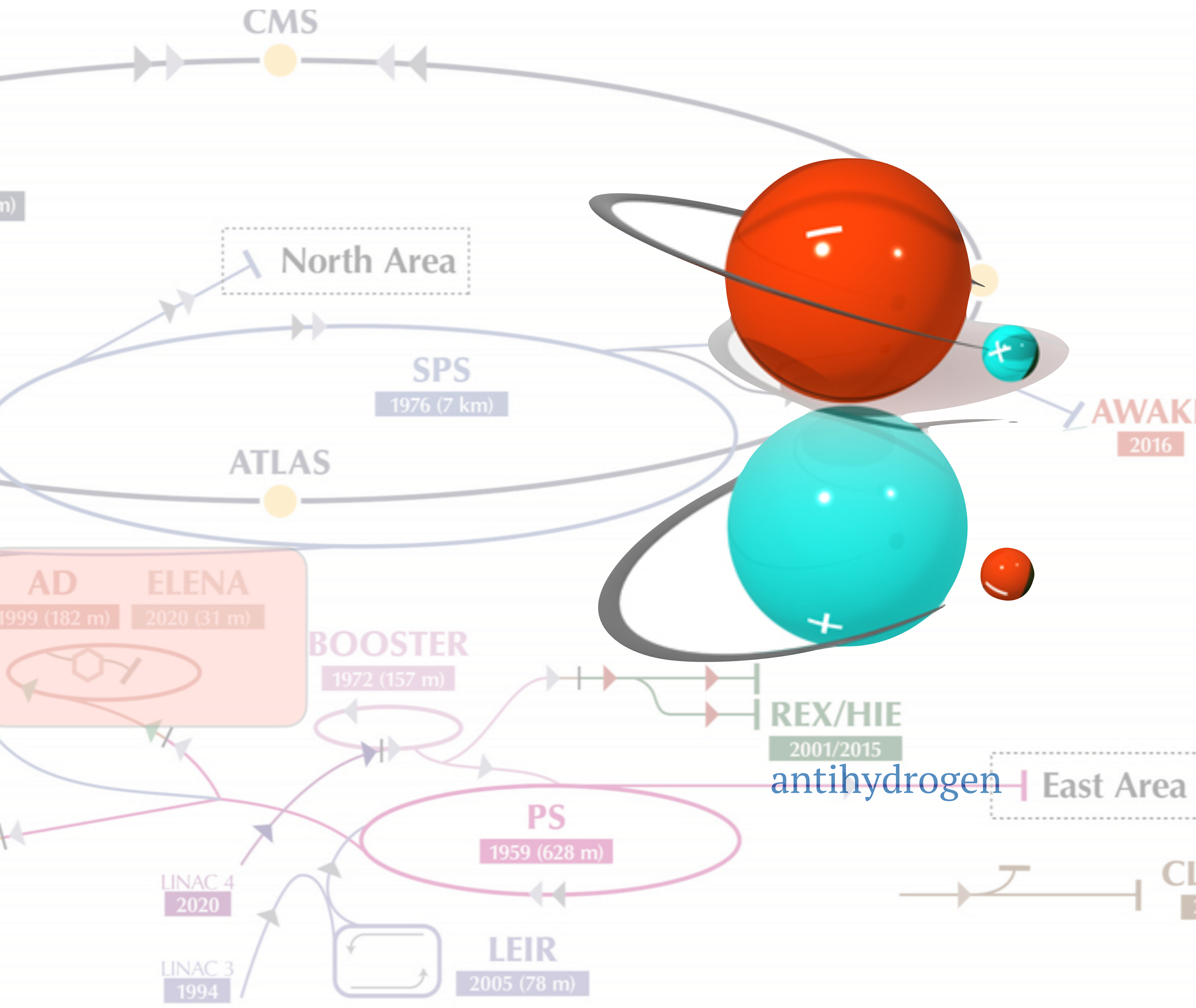
$\bar{H}$ experiments at CERN AD/ELENA

ALPHA
Spectroscopy of 1S-2S in antihydrogen

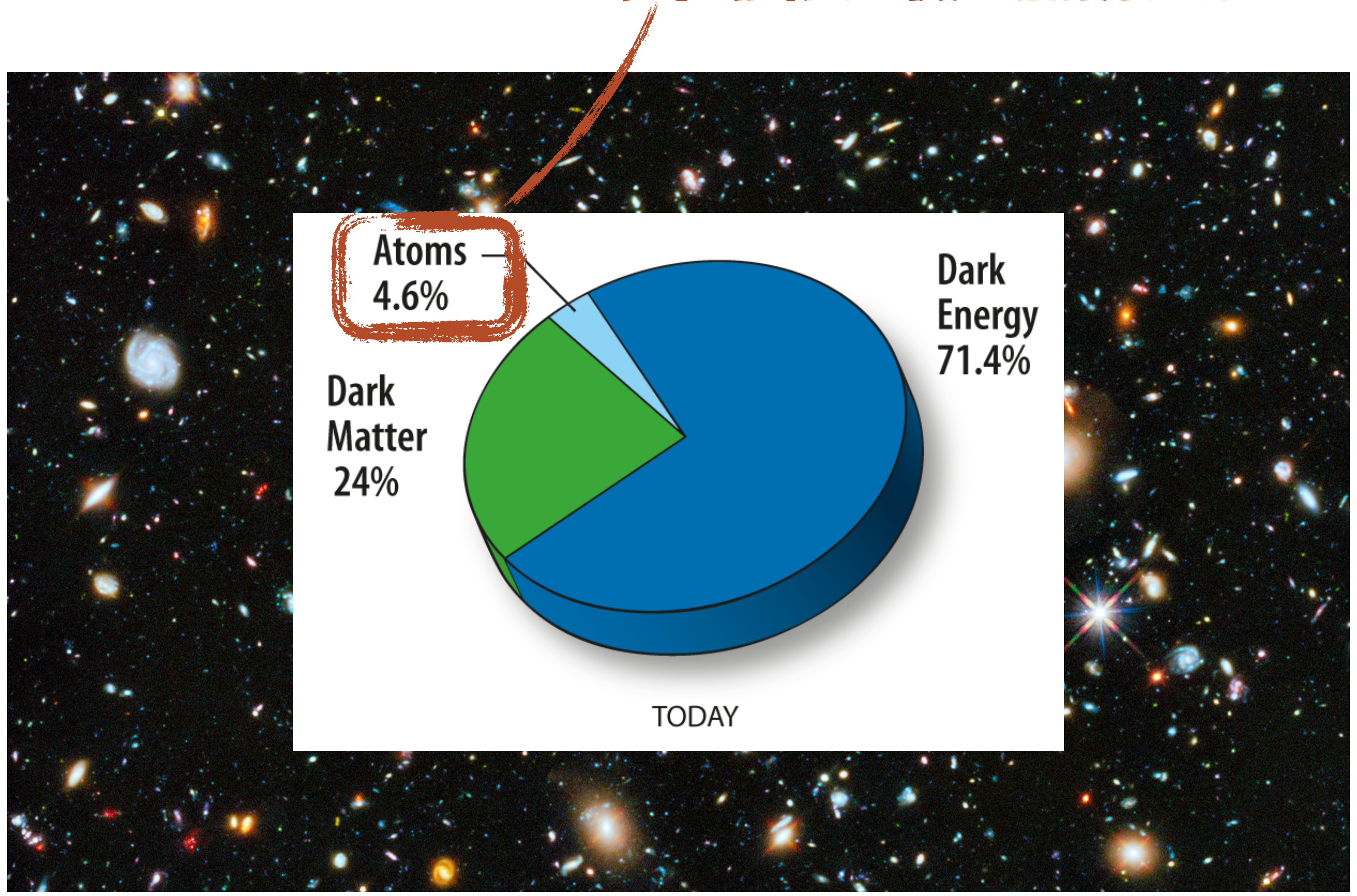
ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ALPHA, AEgIS, GBAR
Test free fall/equivalence principle with antihydrogen



Matter/antimatter asymmetry and CPT tests

Where are the anti-atoms??



Strong baryon asymmetry in the universe

originating from a ~10^{-10} imbalance

CP violation in the SM is by far not enough to explain this imbalance

Could a difference between matter and antimatter fundamental properties explain baryon asymmetry?

Maybe.....

For sure that would be a sign of new physics

CPT theorem: "cornerstone" of QFT (with Lorentz invariance, locality and unitarity) implies properties of matter&antimatter have to be exactly equal or opposite

Dirac equation in the minimal Standard Model Extension

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu$$
$$-\frac{1}{2} H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

e.g. Lorentz and CPT Tests in Hydrogen, Antihydrogen, and Related Systems, A. Kostelecky and A. Vargas, Phys. Rev. D 92, 056002 (2015)

Different measurements (even of the same quantity) are sensitive (or not) to different SME coefficients

Motivations for testing gravity with antimatter

- General relativity is a classical (non quantum) theory
- EEP violations may appear in some quantum theory
- New forces : scalar or vector mediators would not necessarily invalidate GR
  (if similar magnitude cancellation for matter-matter but not for matter-antimatter)

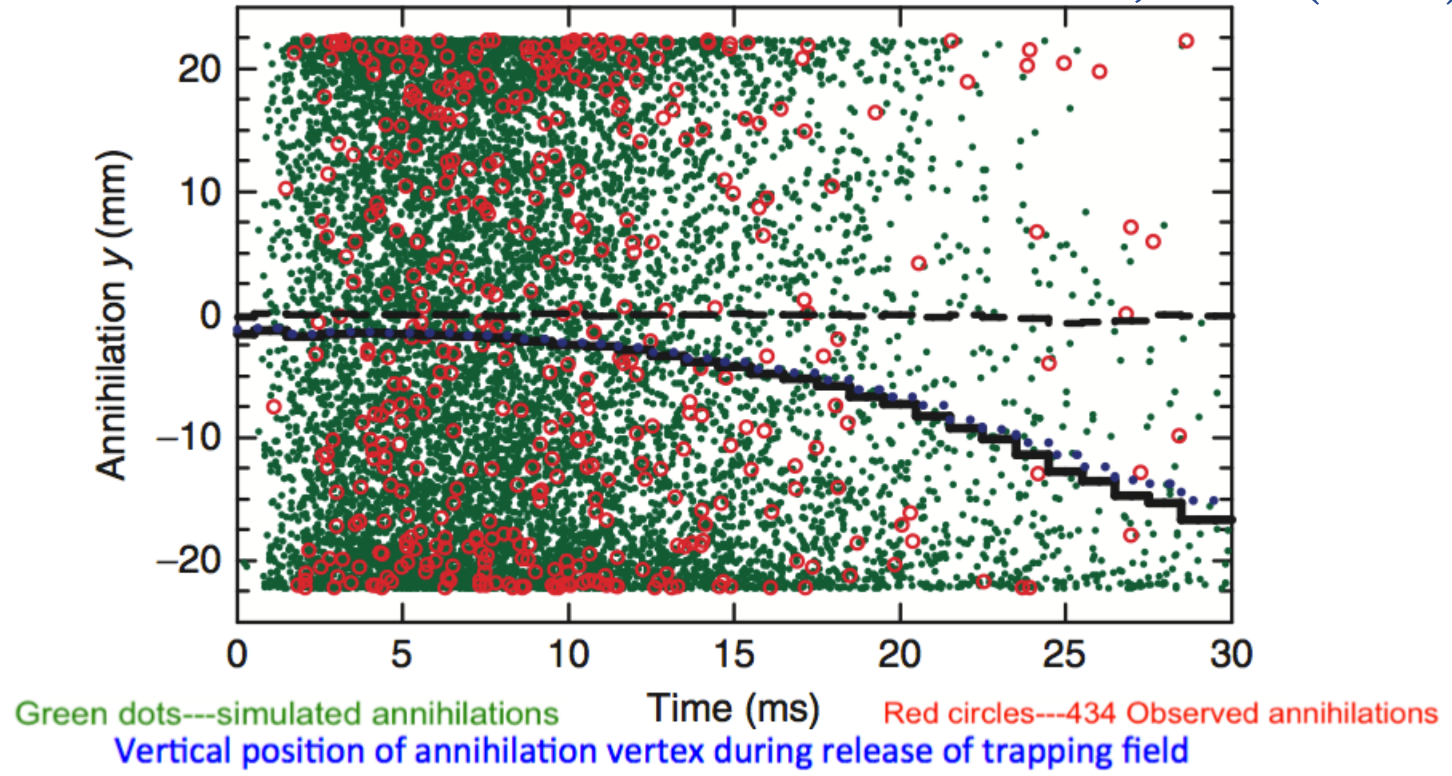
Example: $V = -\frac{G m_1 m_2}{r}(1 \mp a\, e^{-r/v} + b\, e^{-r/s})$

a: Gravivector, b: Graviscalar
− attractive (matter-matter)
+: repulsive: matter-antimatter
matter experiments: |a−b|
antimatter: a+b

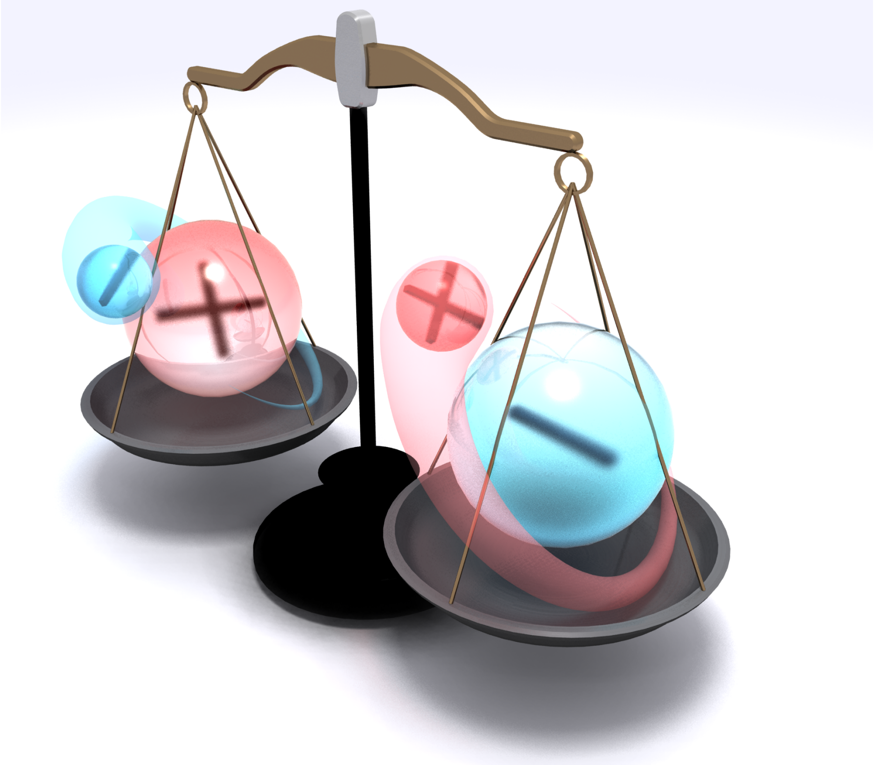
Attempted tests with antimatter

- Attempts with charged positrons ~ 1967
- Attempts with charged antiprotons ~1985
- Indirect limits exist
- measurement with $\bar{H}$ by ALPHA collaboration, 2014
  (rough, sensitivity ~100 times *g*)

C. Amole et al. Nature Communications 4, 1785 (2013)



courtesy: http://newscenter.lbl.gov/2013/04/30/antimatter-up-down/



Any deviation from *g* would be an indication of new physics

plethora of recent ground-breaking measurements with $\bar{H}$

spectroscopy from the ground-state

Letter | Open Access | Published: 04 April 2018

Characterization of the 1S–2S transition in antihydrogen

M. Ahmadi, B. X. R. Alves, ... J. S. Wurtele + Show authors

Nature **557**, 71–75 (2018) | Cite this article

Article | Open Access | Published: 31 March 2021

Laser cooling of antihydrogen atoms

C. J. Baker, W. Bertsche, ... J. S. Wurtele + Show authors

Nature **592**, 35–42 (2021) | Cite this article

Article | Published: 19 February 2020

Investigation of the fine structure of antihydrogen

The ALPHA Collaboration

Nature **578**, 375–380 (2020) | Cite this article

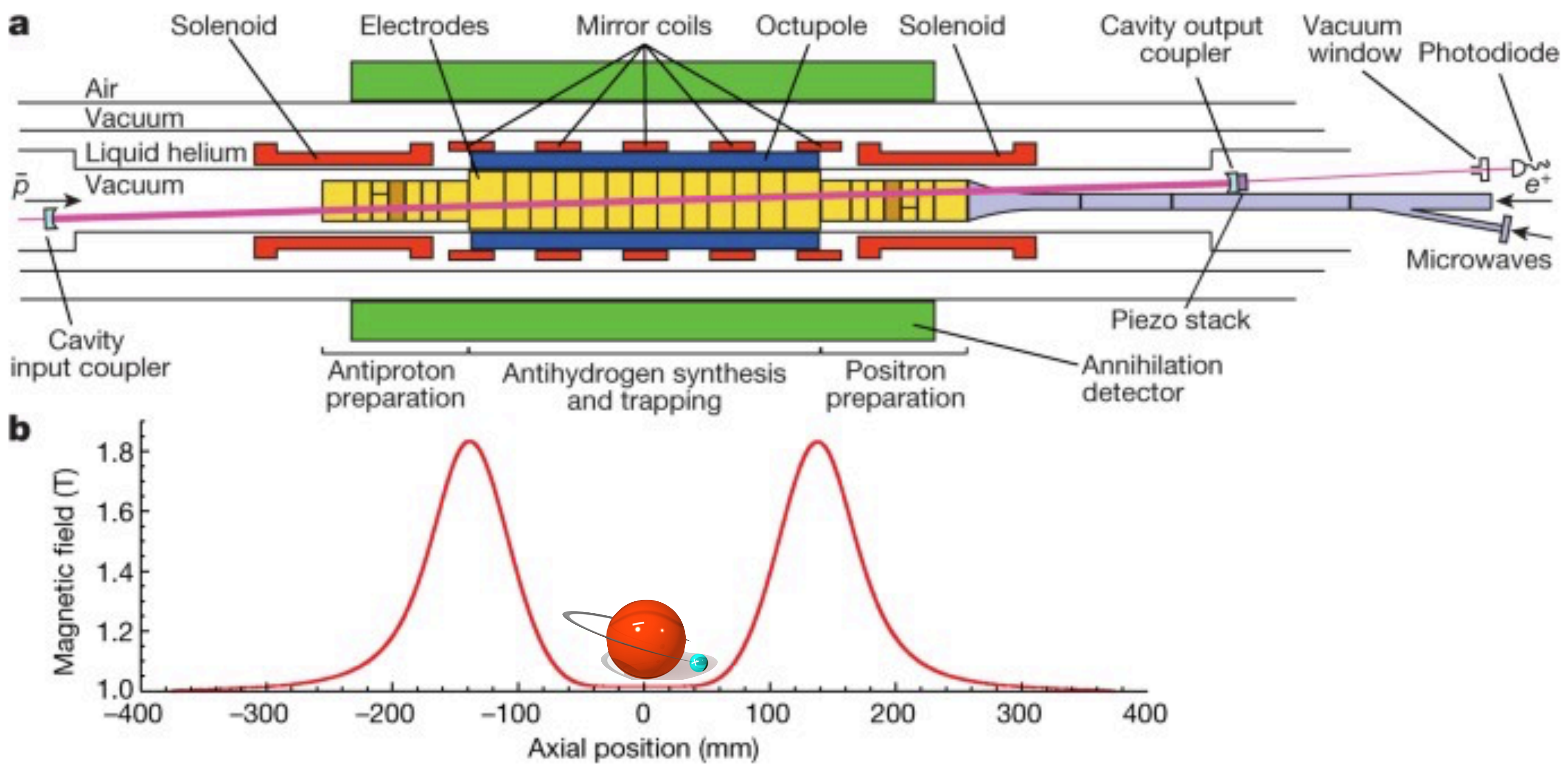
Open Access | Published: 03 August 2017

Observation of the hyperfine spectrum of antihydrogen

M. Ahmadi, B. X. R. Alves, ... J. S. Wurtele + Show authors

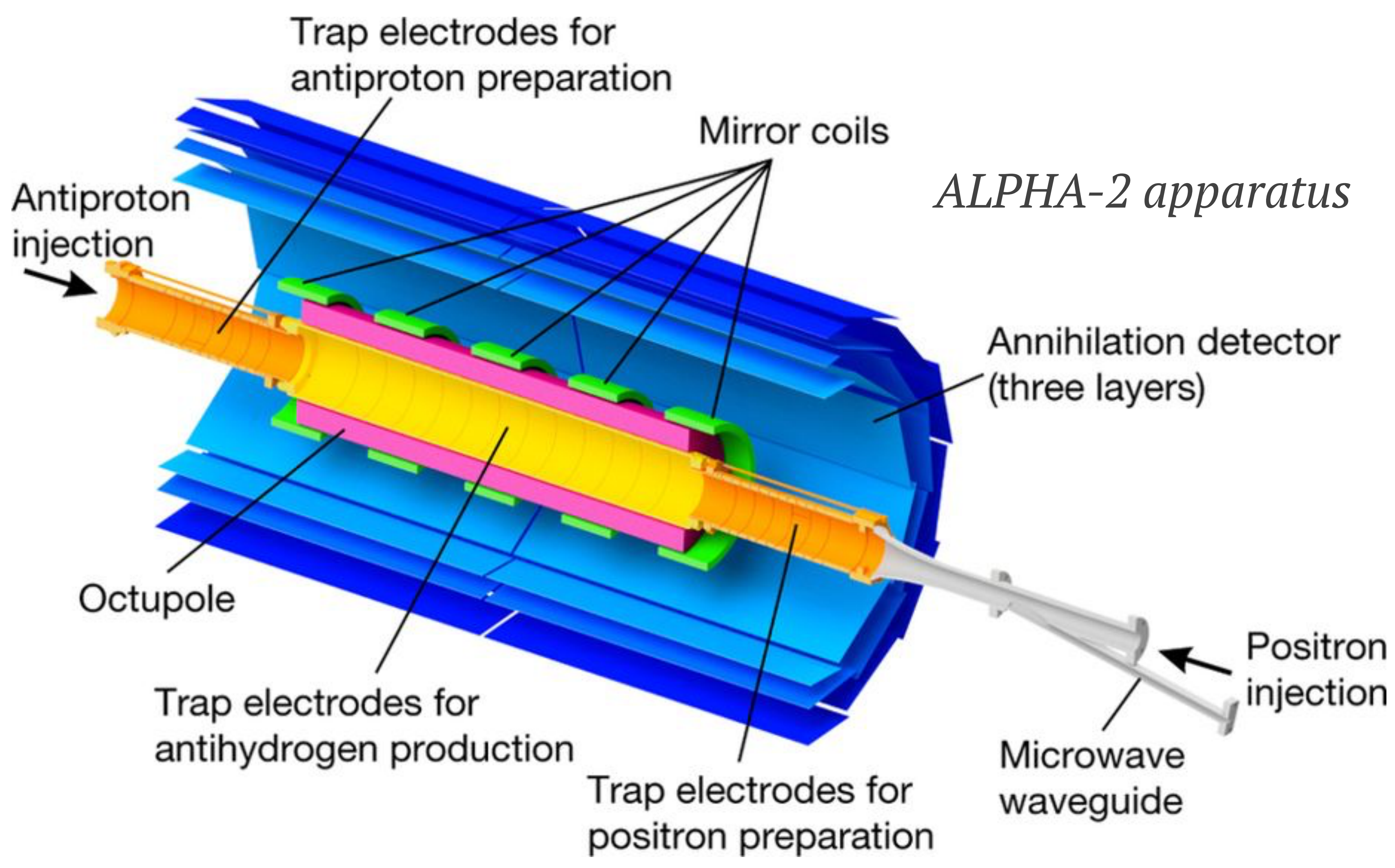
Nature **548**, 66–69 (2017) | Cite this article

Fig. 1: The ALPHA-2 central apparatus and magnetic field profile.



CPT tests with H̄: what measurements?

TRAP experiments



ALPHA-2 apparatus

Trapping using magnetic moment
Challenge : shallow trap (~0.5K)

$$kT = \mu(B - B_0)$$
$$\frac{\mu_B}{k} = 0.6\,\mathrm{K.T}^{-1}$$

2018 : 10-20 atoms /trials trapped
Accumulation over 8 hours shift

Suited for 1S-2S measurement

Lifetime of Rydberg states

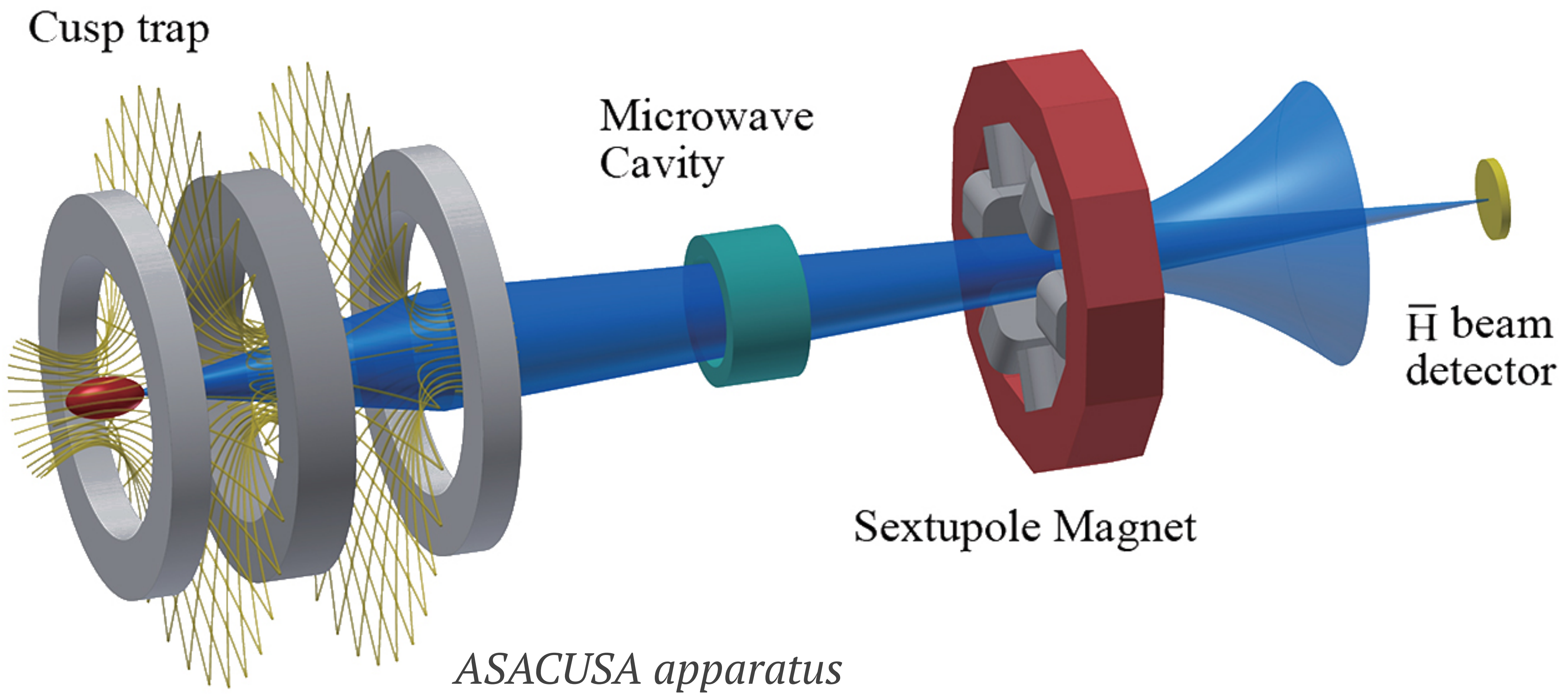
$$\tau_{n,l} \approx \left(\frac{n}{30}\right)^3 \left(\frac{l+1/2}{30}\right)^2 2.4\,\mathrm{ms}$$

Vs.

BEAM experiments

Beam formation through magnetic focussing
Challenge: control of the quantum state

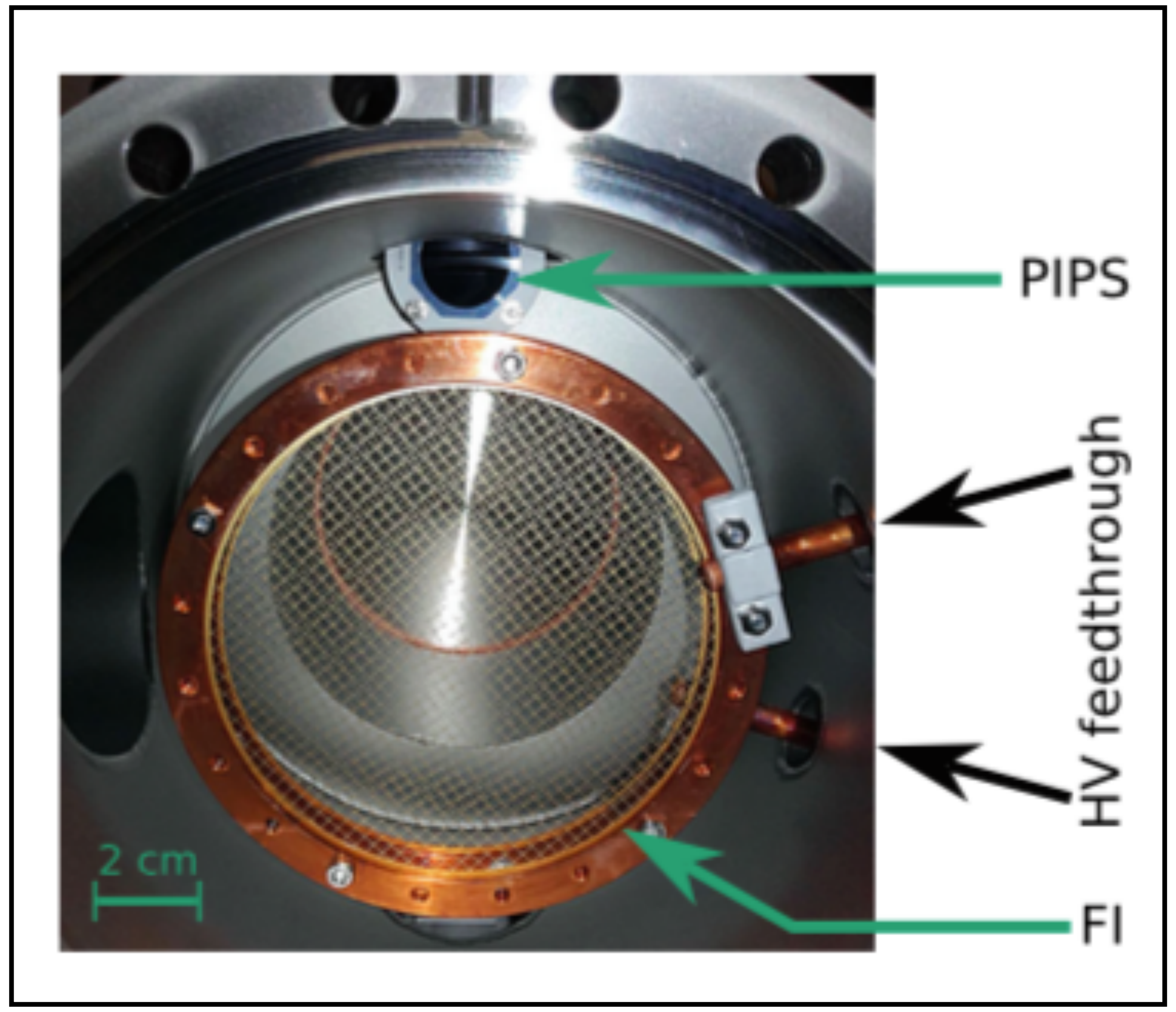
Measurement in a “field-free” region
Suited for hyperfine splitting measurement

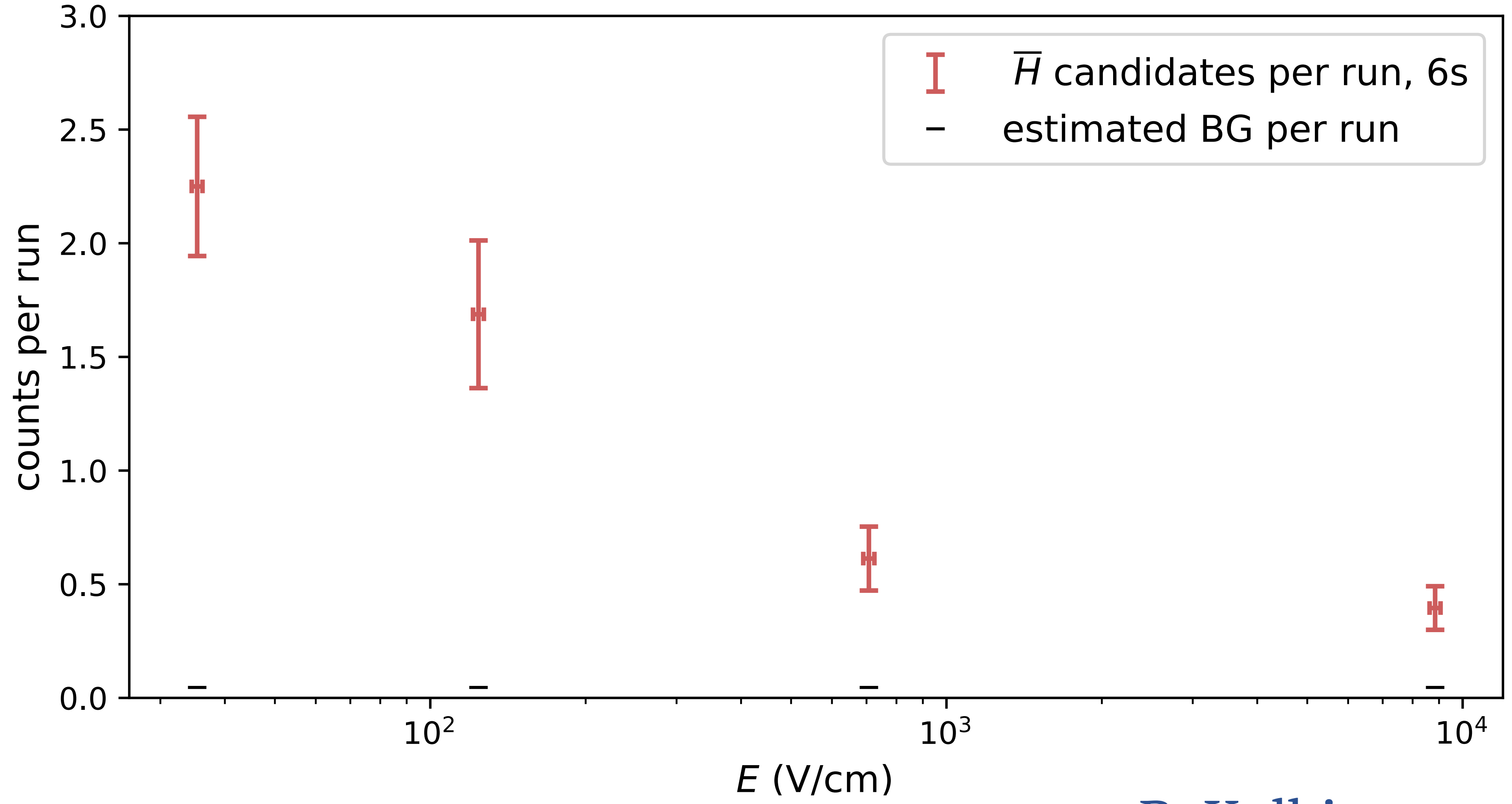


ASACUSA apparatus

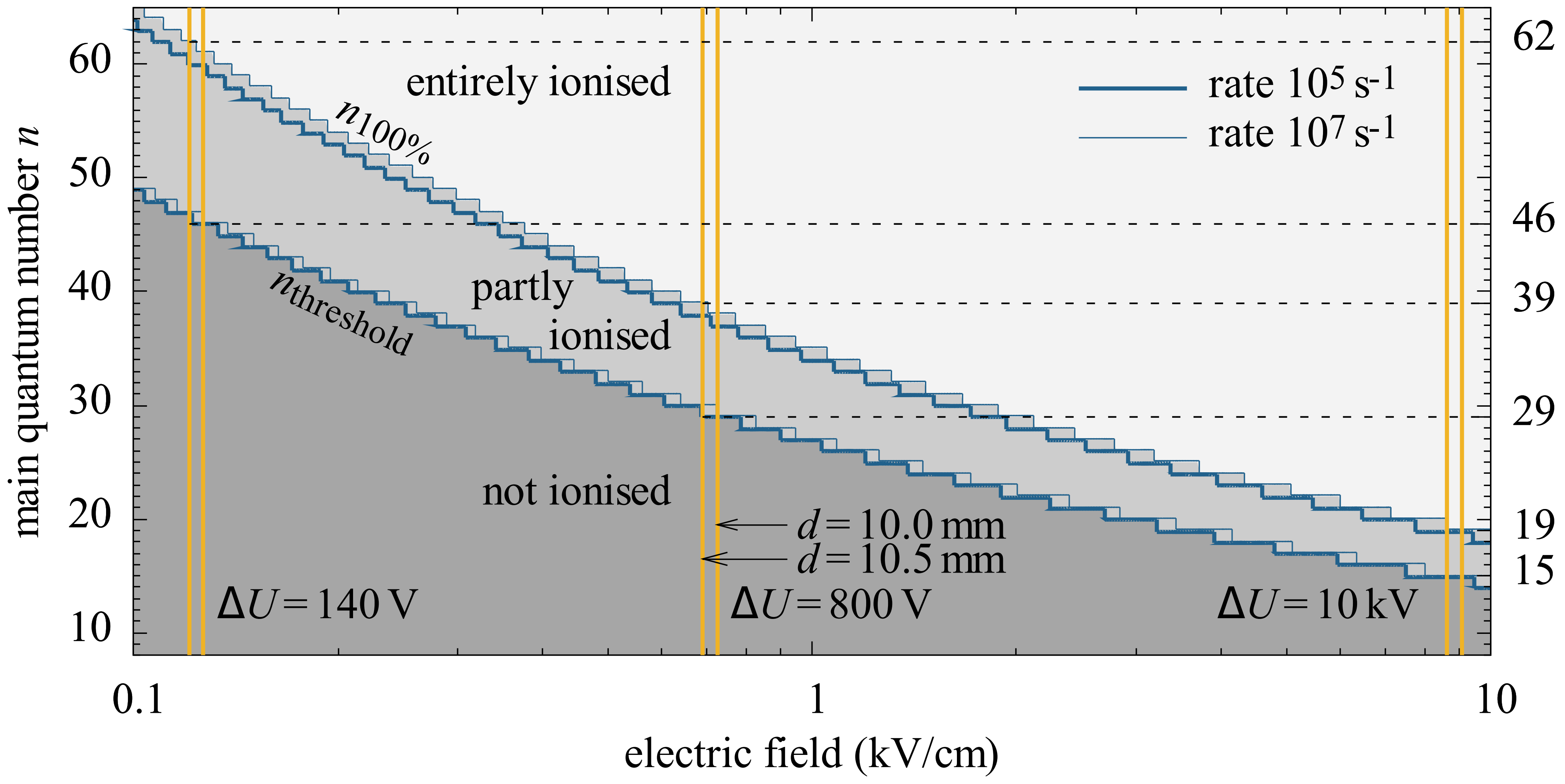
Measurements with H̄

H̄ formed in many high n-states (all sub-states)





B. Kolbinger et al. Eur. Phys. J. D (2021) 75: 91

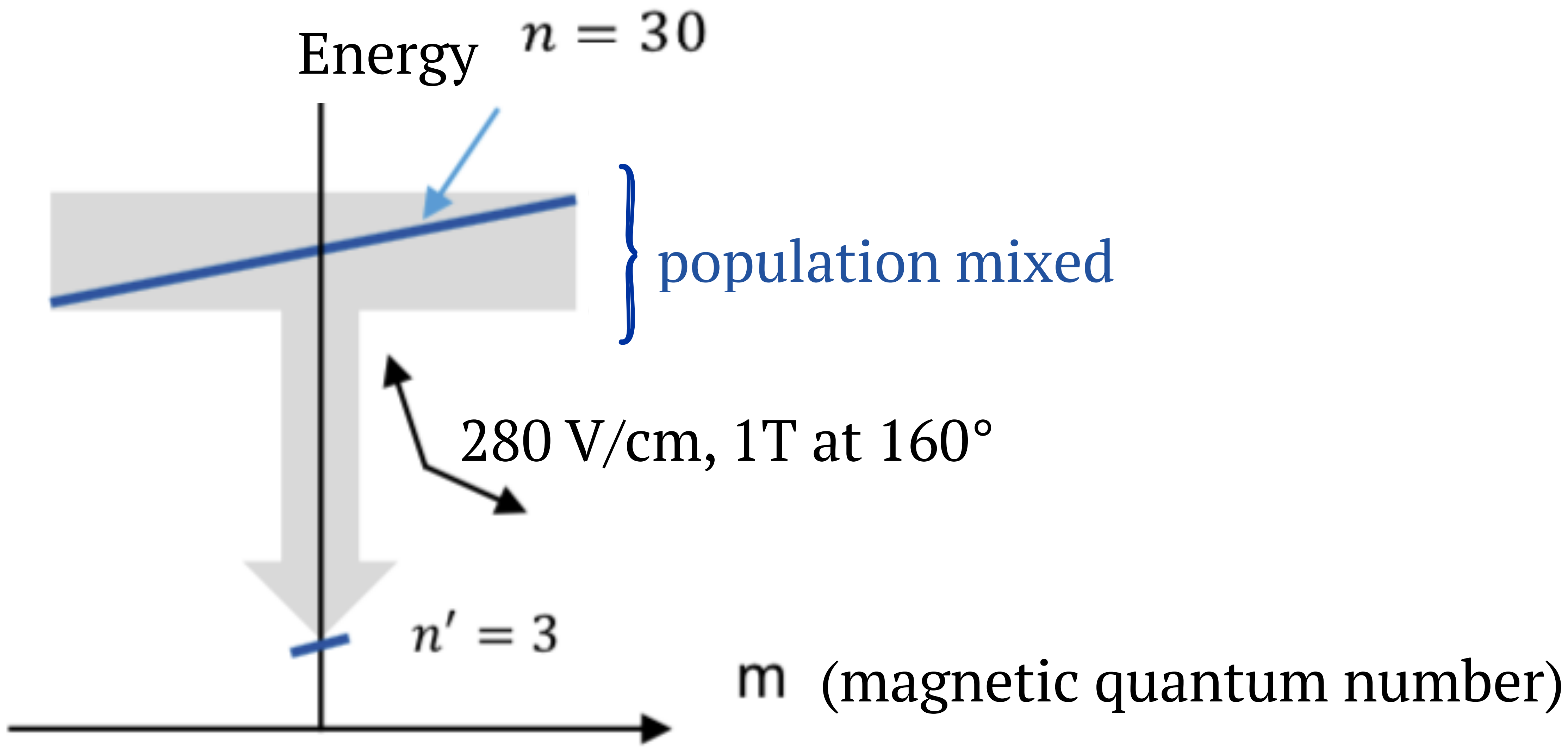


A path to ground-state antihydrogen formation

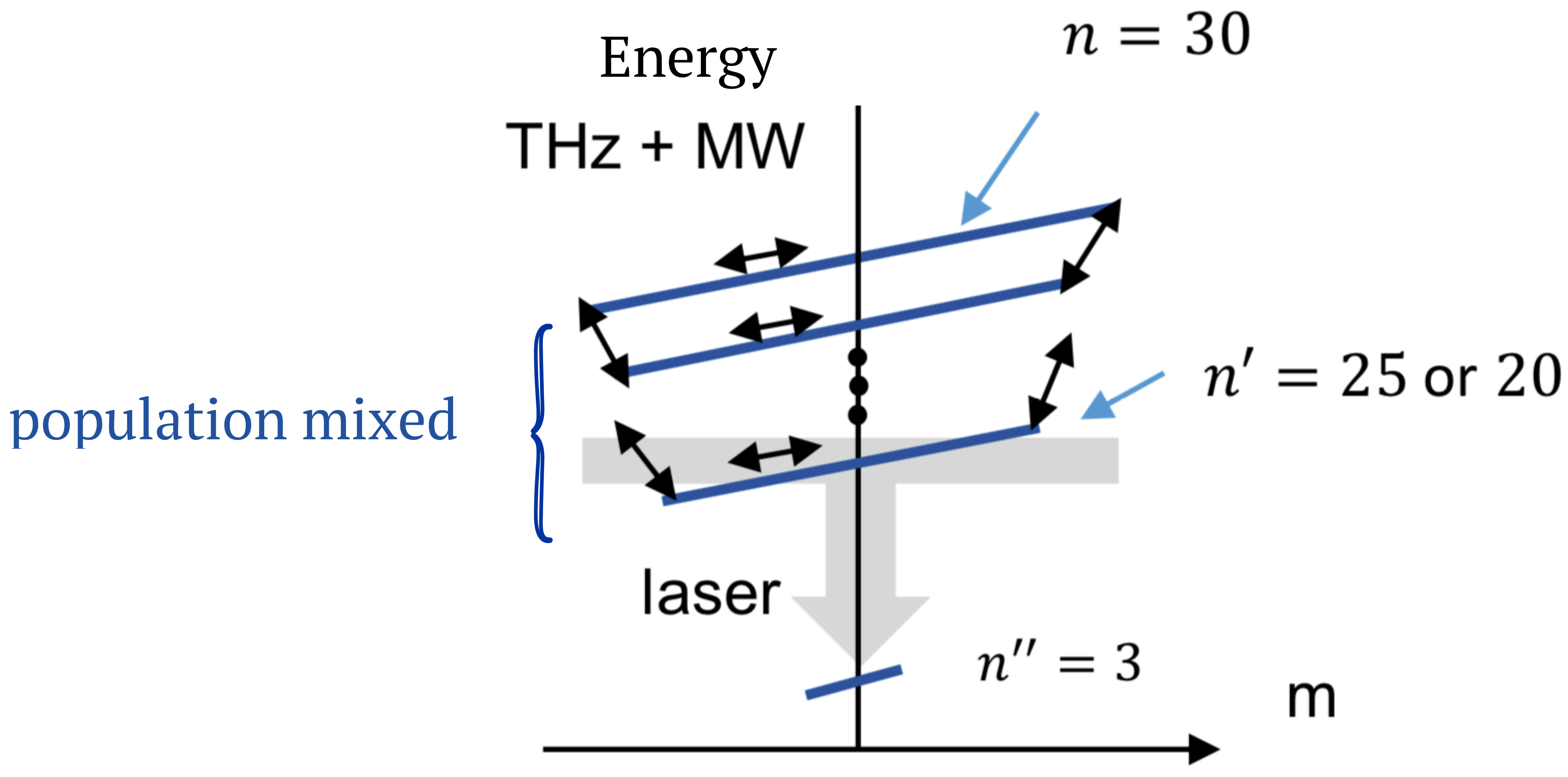
Novel developments addressing large quantum state distribution

The strategy: couple many states together to deexcite them to low n states

Fast (~50 μs) and efficient (>50% of atoms in ground-state) methods



Mixing via E,B fields



Mixing via THz and microwave light

D. Comparat and C. Malbrunot Phys. Rev. A 99 (2019) 013418

T. Wolz, C. Malbrunot et al. Phys. Rev. A 101 (2020) 043412

Requirements: many sharp transitions between 200GHz and ~40 THz (n'=5)

Total power several mW/cm^2 (THz only scheme)

A path to ground-state antihydrogen formation

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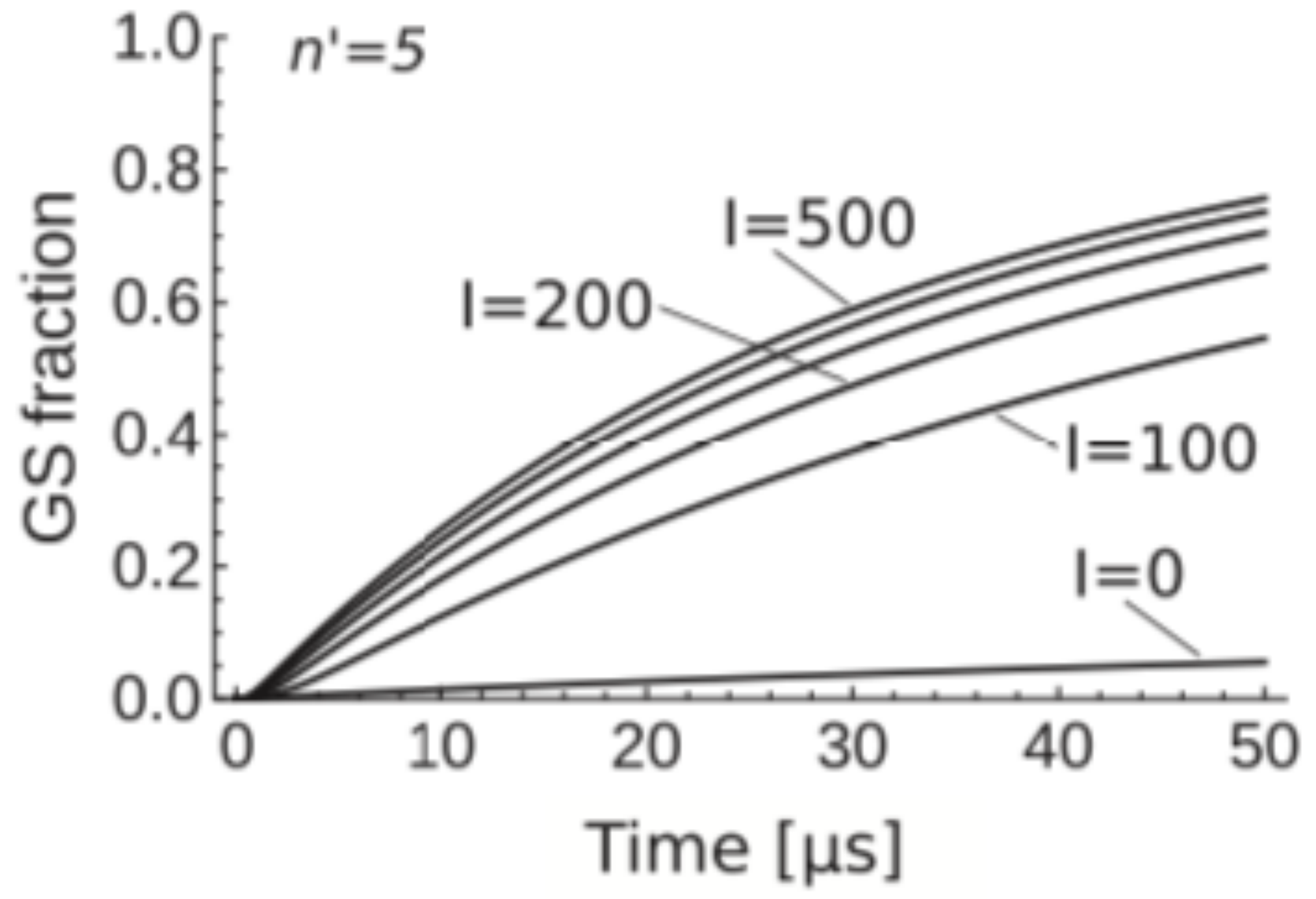
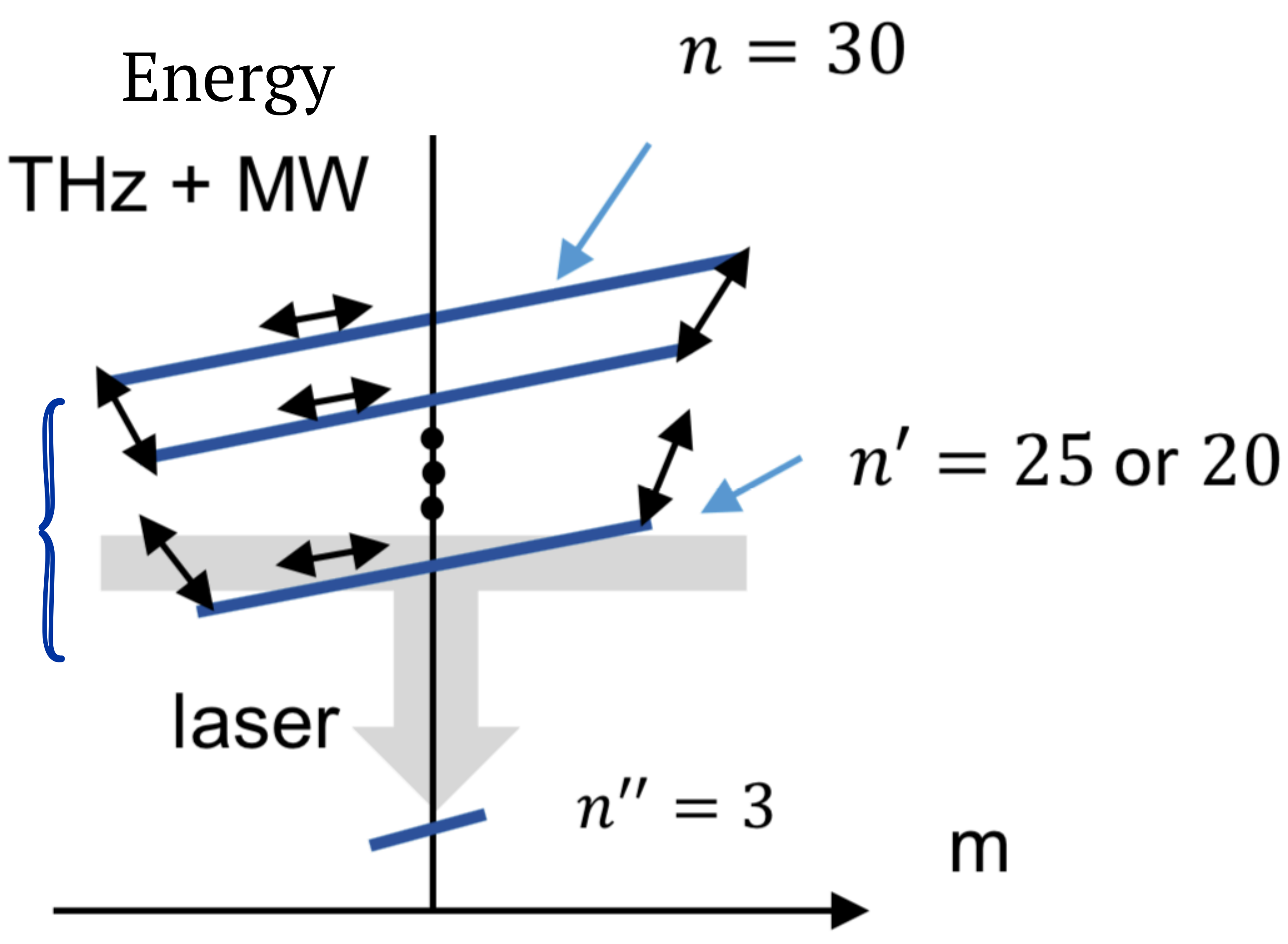




Mixing via THz and microwave light

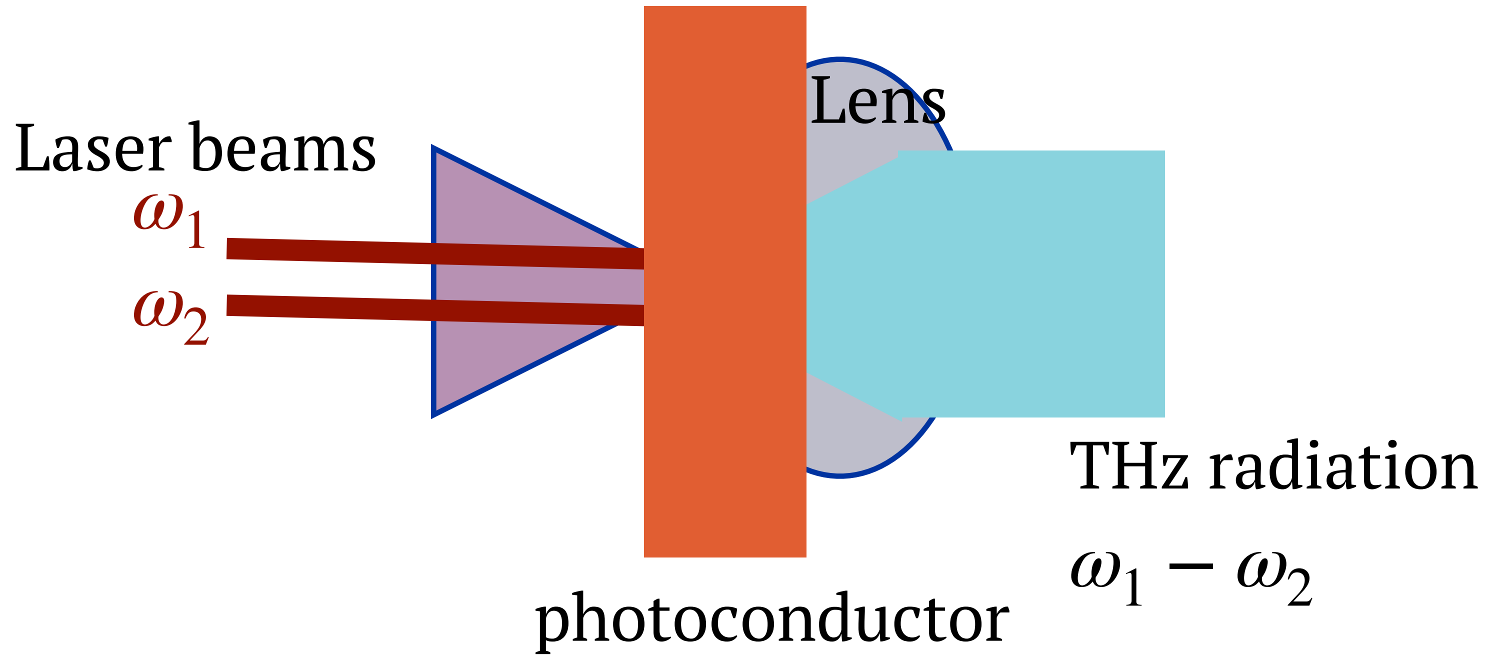
T. Wolz, C. Malbrunot et al. Phys. Rev. A 101 (2020) 043412

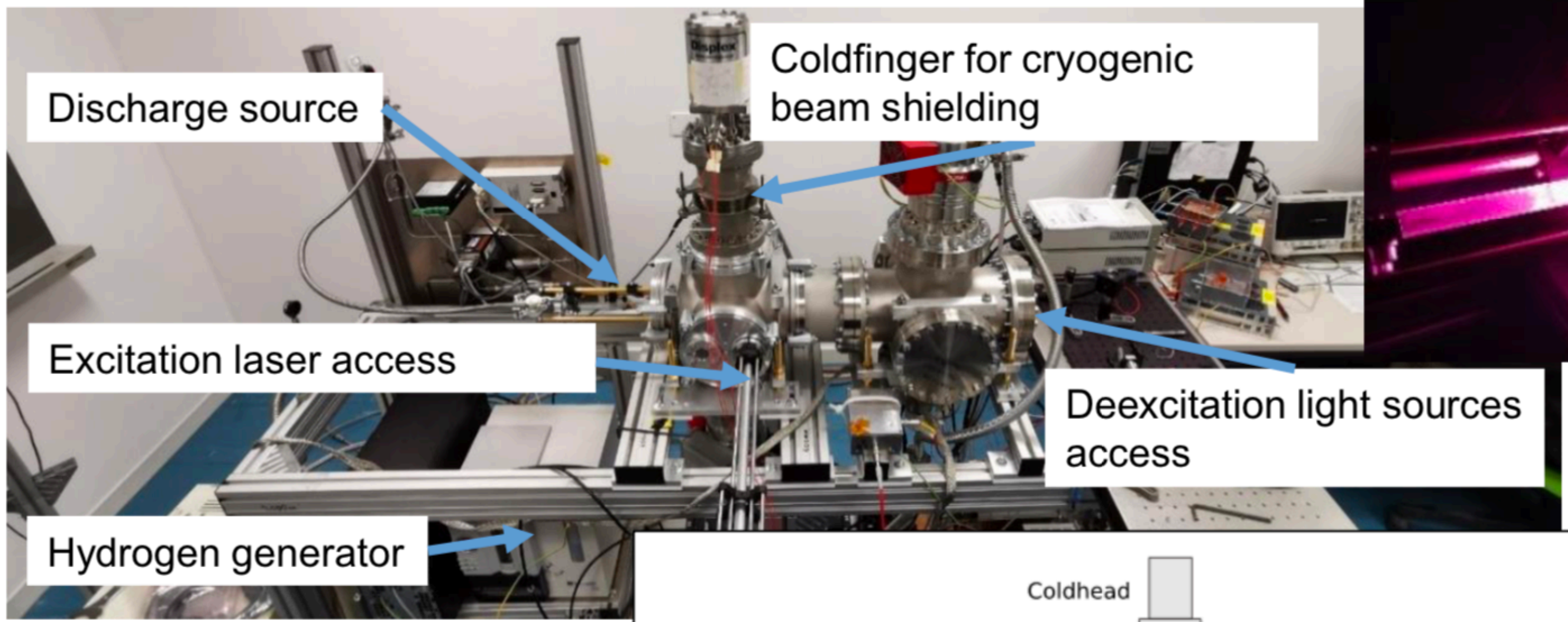
Requirements: many sharp transitions between 200GHz and ~7GHz
Total power several mW/cm^2 (THz only scheme)

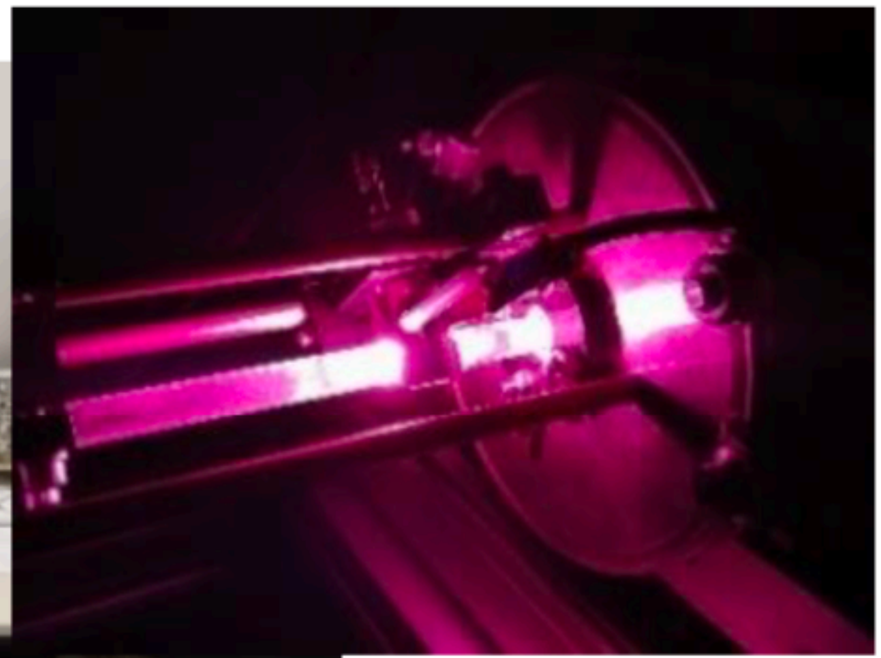
Experimental demonstration

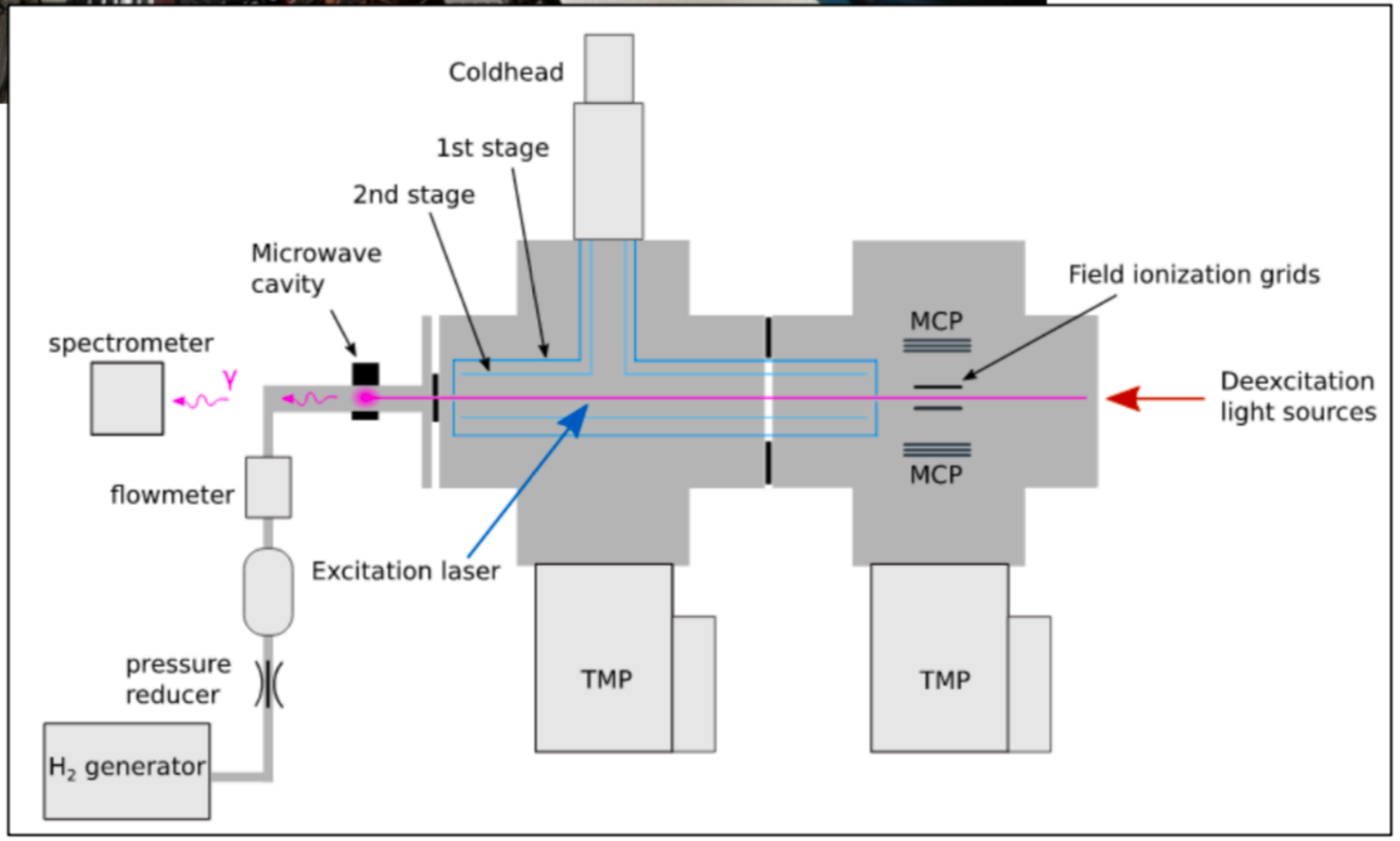
Experimental demonstration on-going with H

Demonstrate the use of photomixer for fast deexcitation

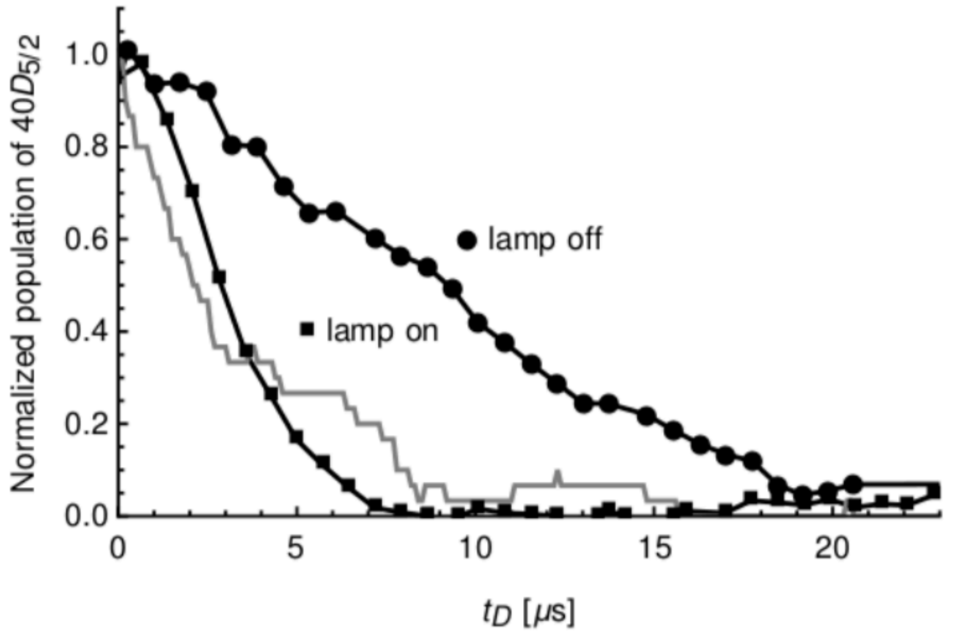




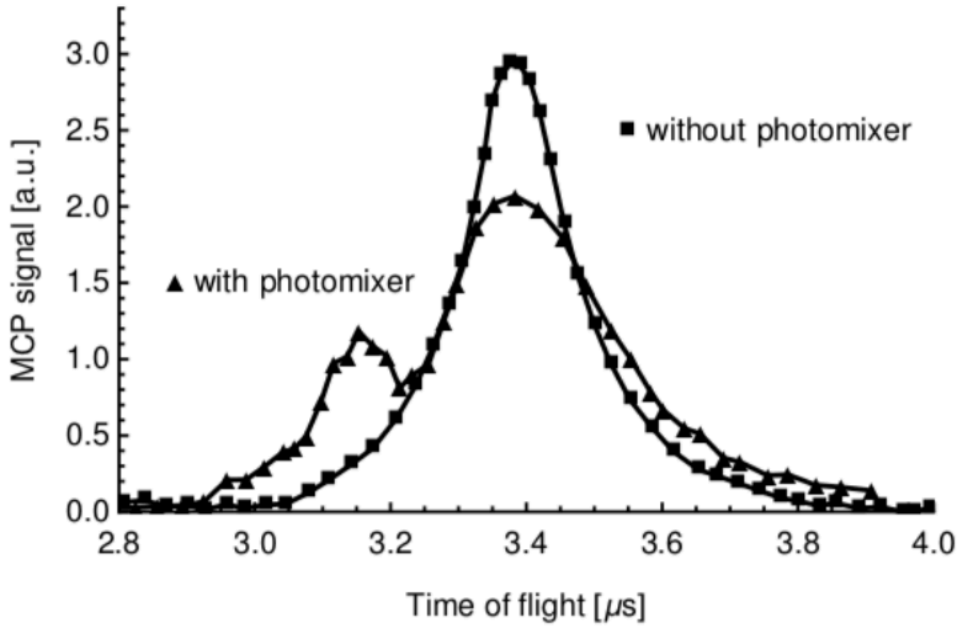




proof-of-principle demonstration on targeted transitions in Cs
Eur. Phys. J D 75:27 (2021)



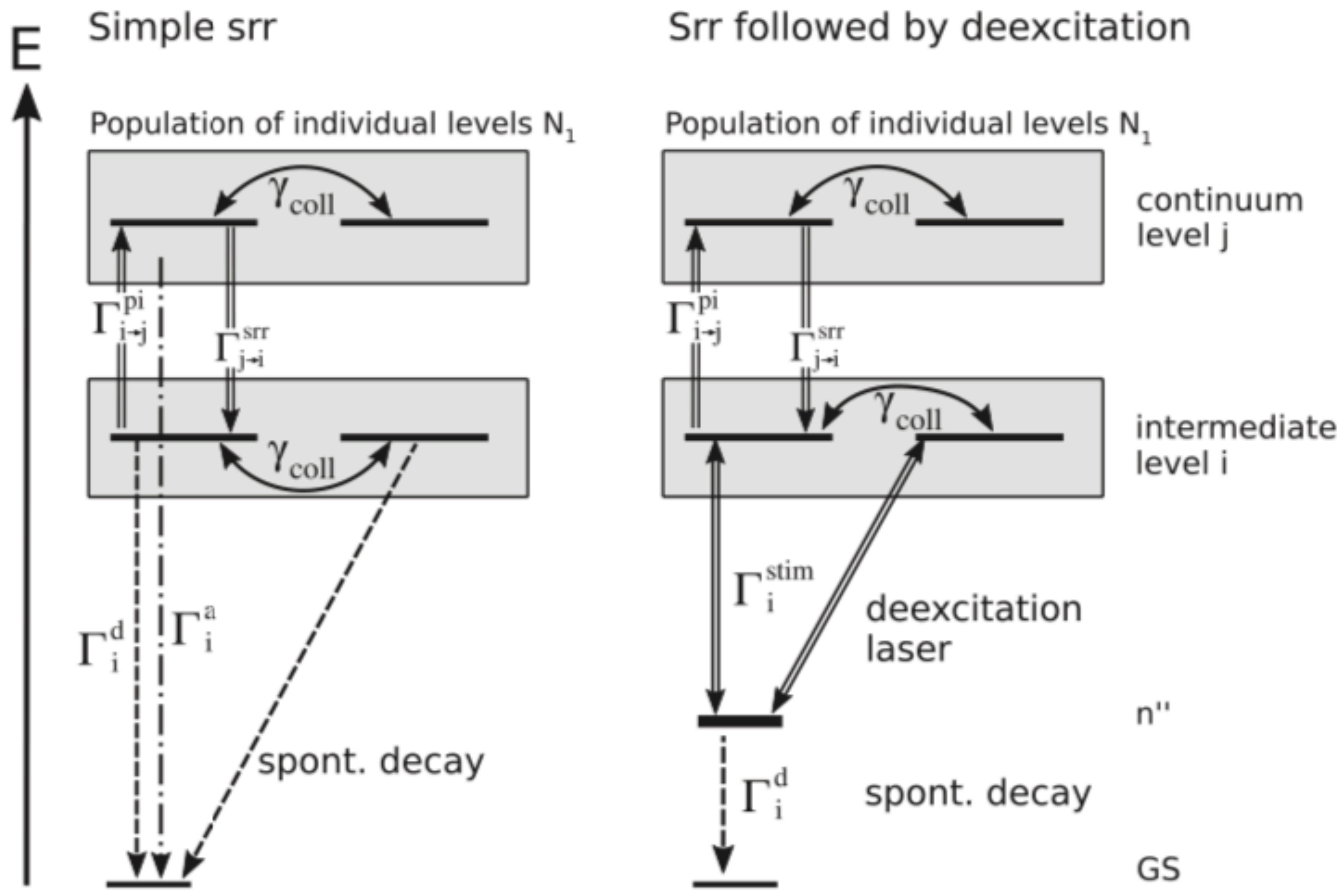
Population of $40D_{5/2}$ level as a function of the FI delay with respect to the excitation laser as stimulated by a BB lamp. Simulation data for a BB spectrum of 1200K is indicated in grey.

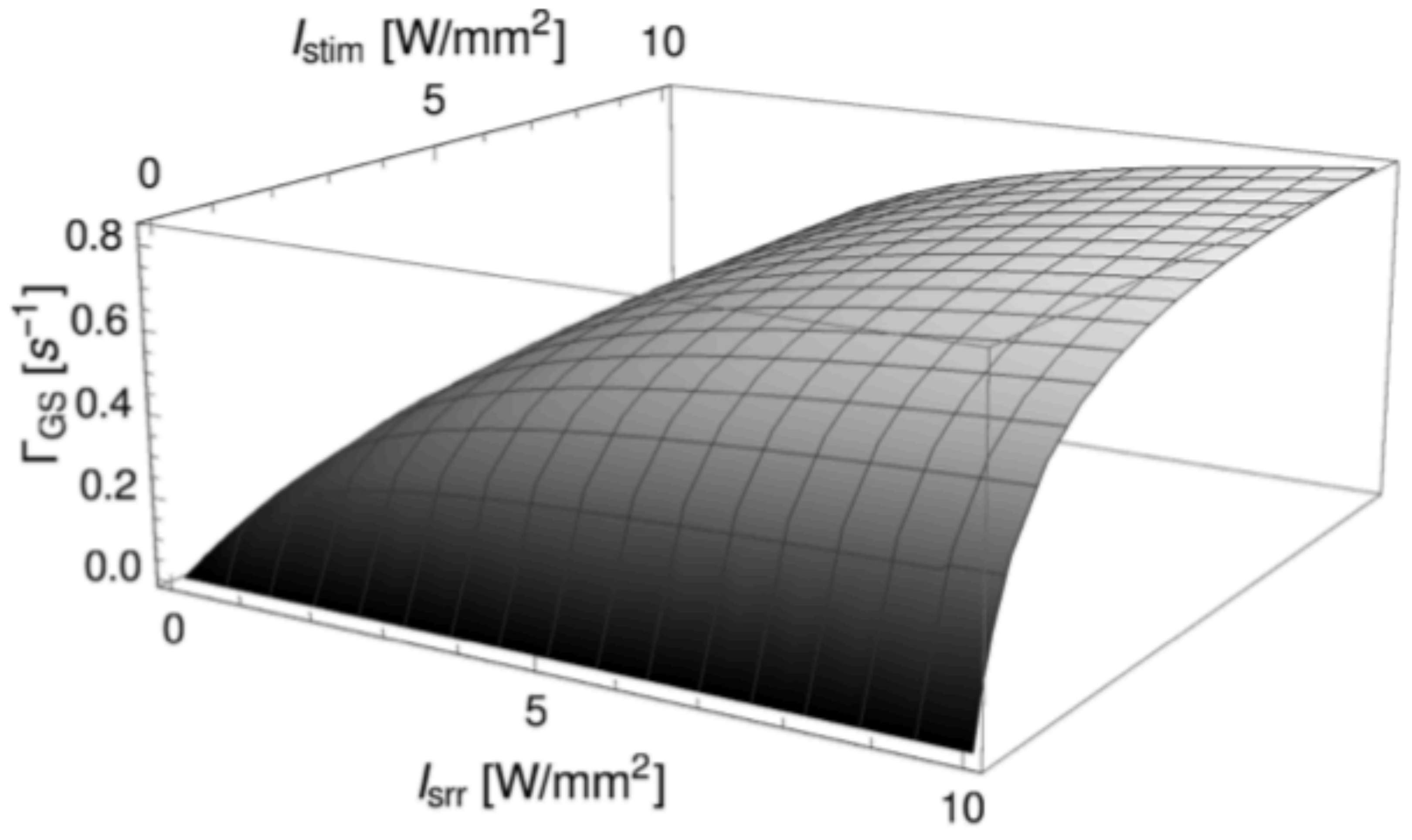


Stimulated $36S_{1/2} \rightarrow 36P_{3/2}$ transfer stimulated by a photomixer (97 GHz, spectral width 5 MHz).

Fast deexcitation: application to $\bar{H}$ formation

A. Wolf, Hyperfine Interact. 76, 189 (1993)





Two lasers with 10W power leads to $\Gamma \sim 1\ s^{-1}/\bar{p}$

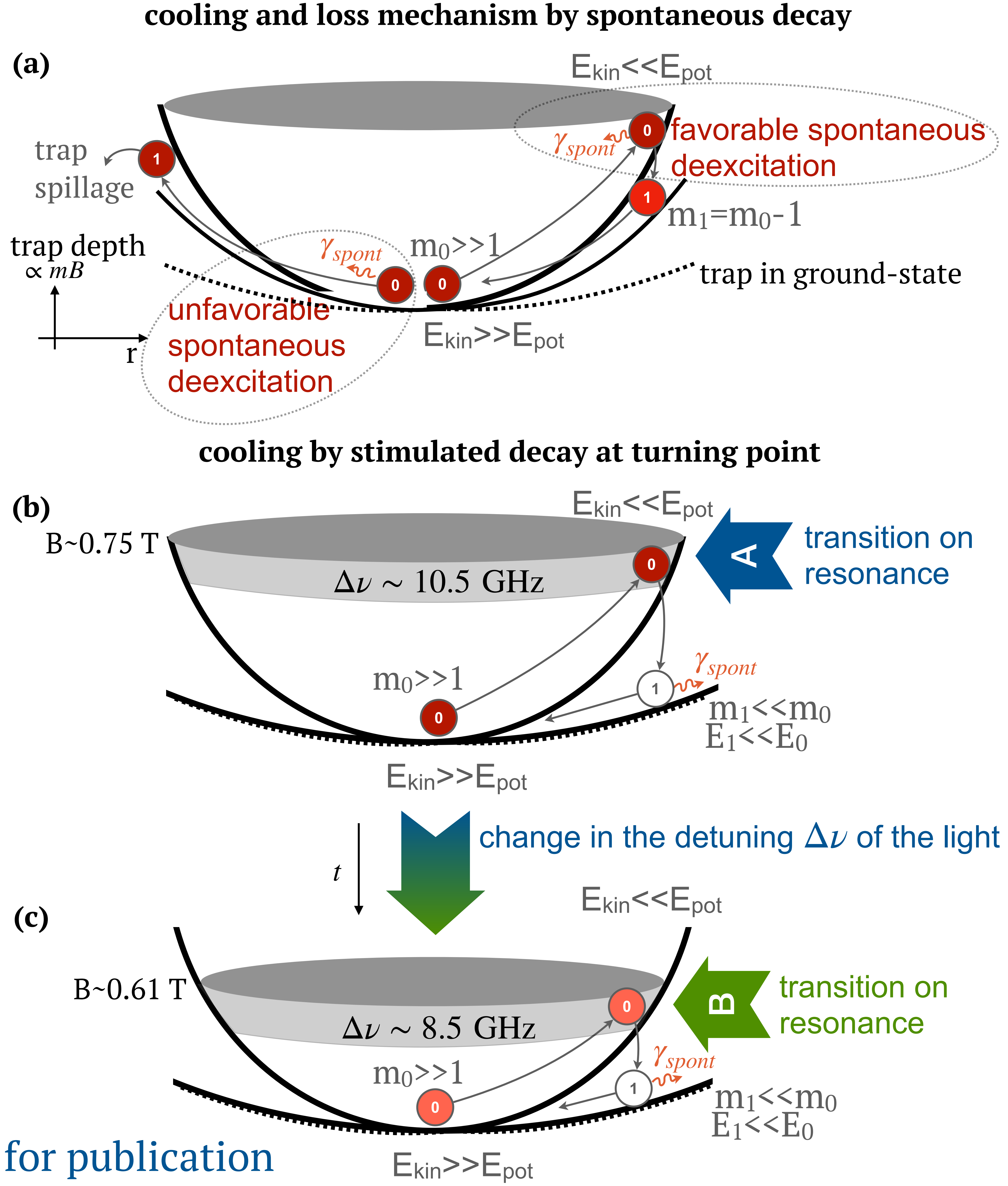
T. Wolz, C. Malbrunot et al. Phys. Rev. A 101 (2020) 043412

Fast deexcitation: application to trapped atoms

Cooling by deexcitation in a trap
Spontaneous decay case

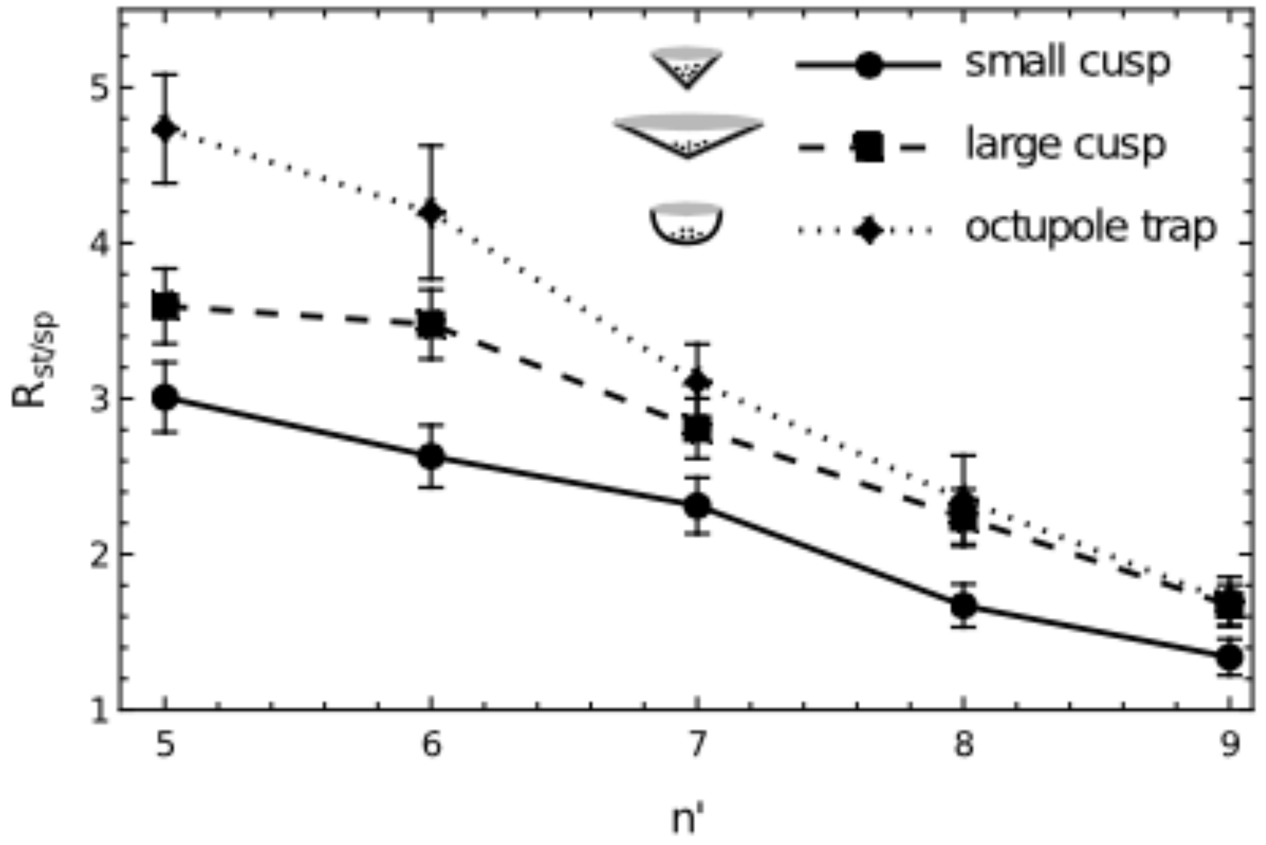
$$kT = \mu(B - B_0)$$
$$\mu = m \times \mu_B$$

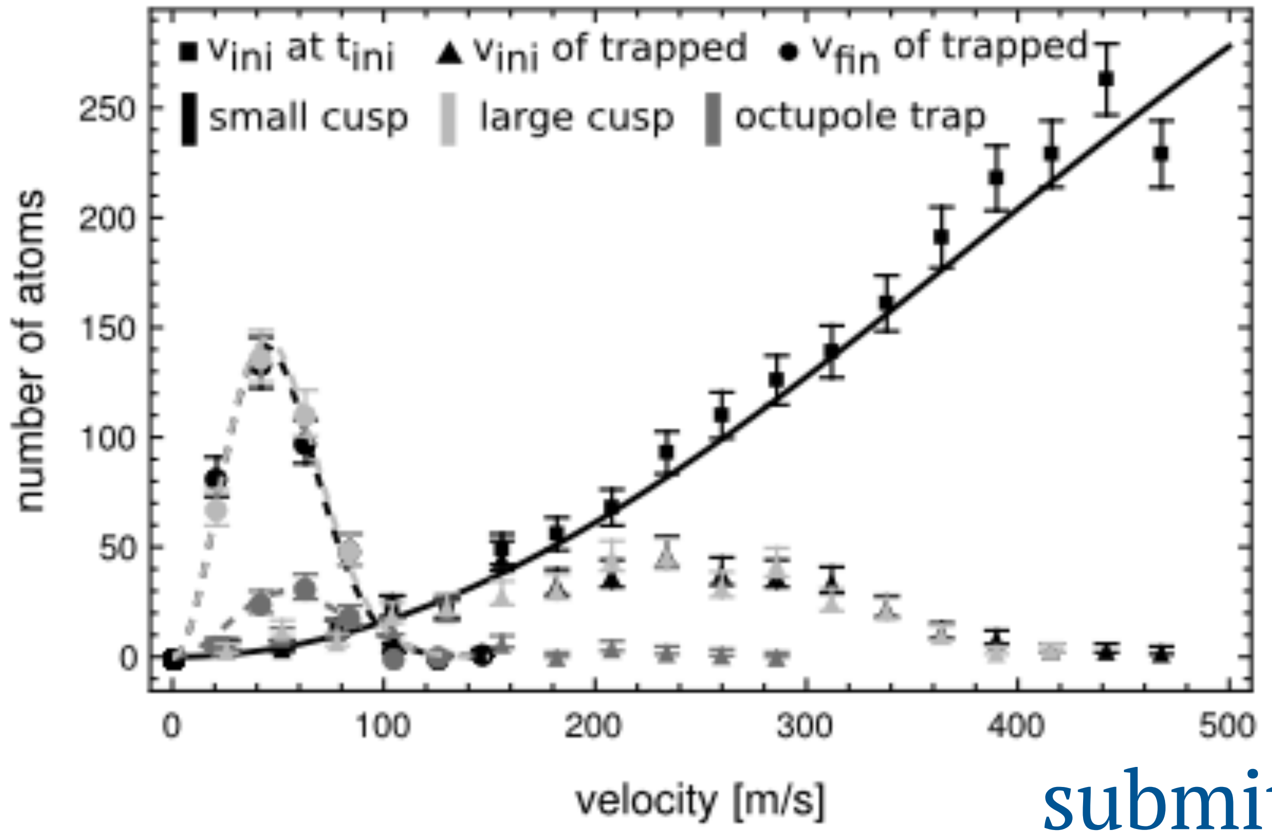
Pohl et al. PRL **97,** 213001 (2006)
Taylor et al. J. Phys. B: At. Mol. Opt. Phys. **39** (2006) 4945–4959



Enhance this effect by stimulating the deexcitation at the edges
(see also PRA **80**, 041404R (2009))

Challenge: address rapidly and at the appropriate time all transitions and all velocities. Limited by the spontaneous lifetime of the lowest targeted state





submitted for publication

Conclusions

- THz technology: fast evolving field
- Rydberg atoms manipulation: hot topic. Quantum computing etc
- $\bar{H}$ atoms formed in Rydberg states
- Stimulation of their decay needed for beam experiments
- Stimulation based on light mixing is promising. Performance of THz-only solution limited by available powers at high frequencies
- Experimental demonstration on hydrogen ongoing
- Several other application of fast stimulated decay: $\bar{H}$ production directly in ground state, cooling in magnetic trap