Towards a hydrogen optical clock

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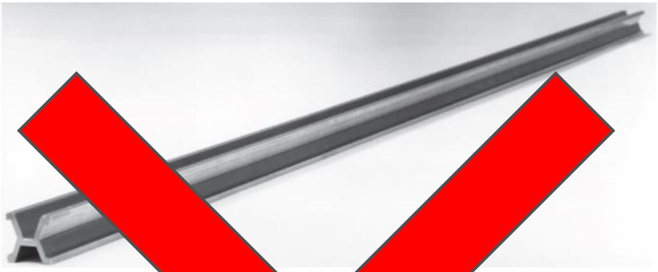
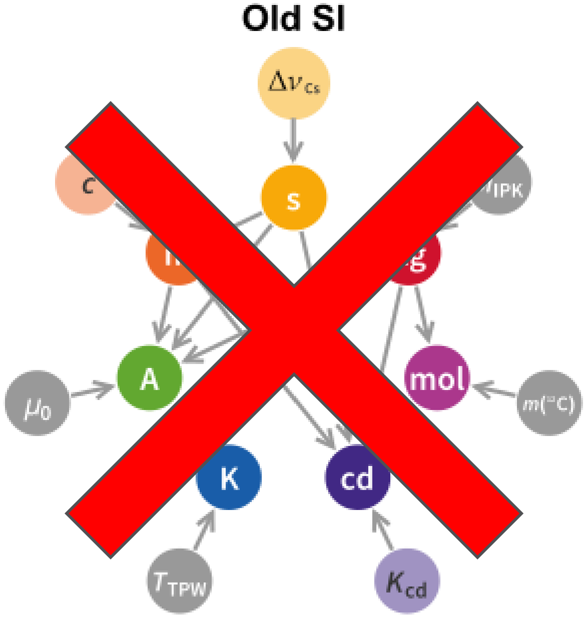
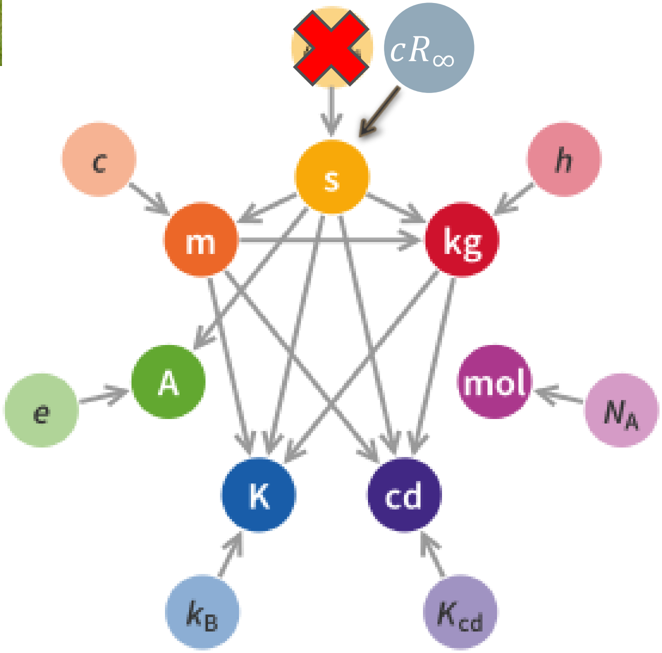


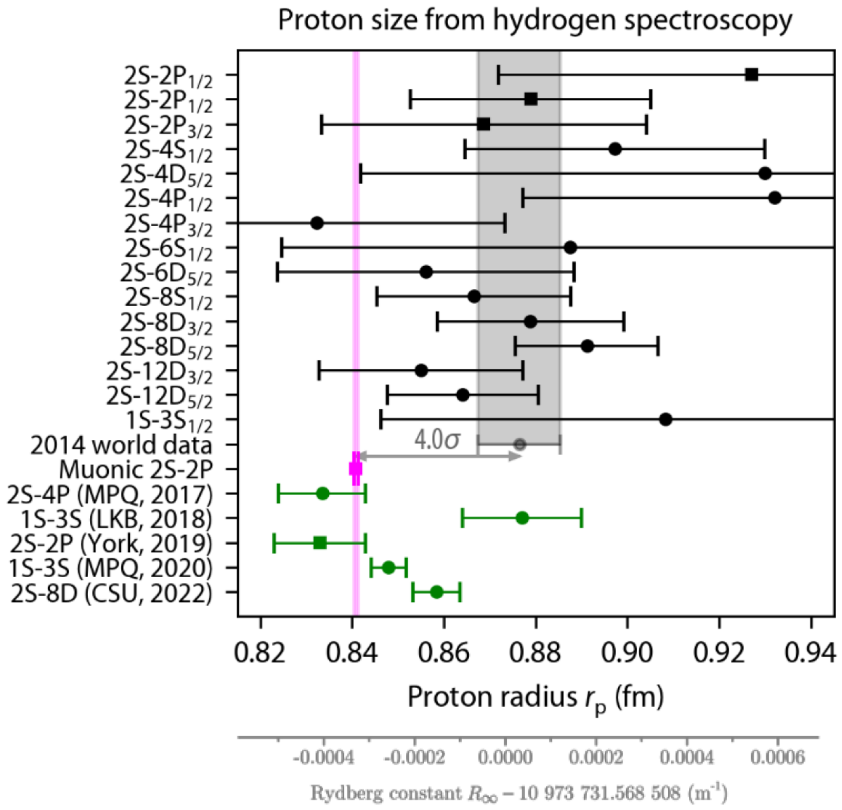




Goals

- The 1S – 2S transition in hydrogen can be calculated exactly.
- Define the “computable second” based on fundamental constants.

Goals



- The 1S – 2S transition in hydrogen can be calculated exactly.
- Define the "computable second" based on fundamental constants.
- Reduce uncertainties in the 1S – 2S measurement.

$$E_{nlj} = hcR_\infty \left[-\frac{1}{n^2} + f_{nlj}\left(\alpha, \frac{m_e}{m_p}, \ldots\right) + \delta_{l,0}\frac{C_{NS}}{n^3} r_p^2 \right]$$

Outline

- Why trap hydrogen? Why hydrogen optical clock?
- Why trapping hydrogen is hard?
- How to trap hydrogen?
- What is being done right now?

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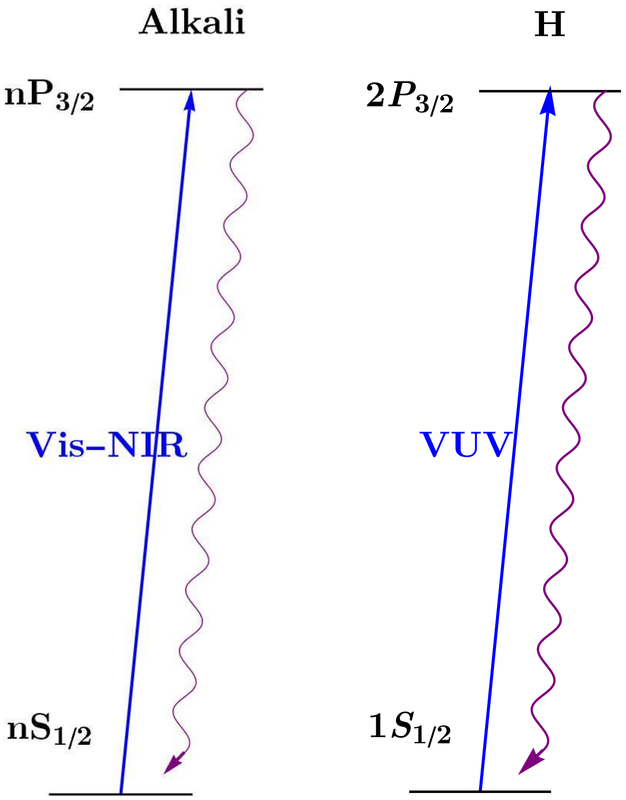
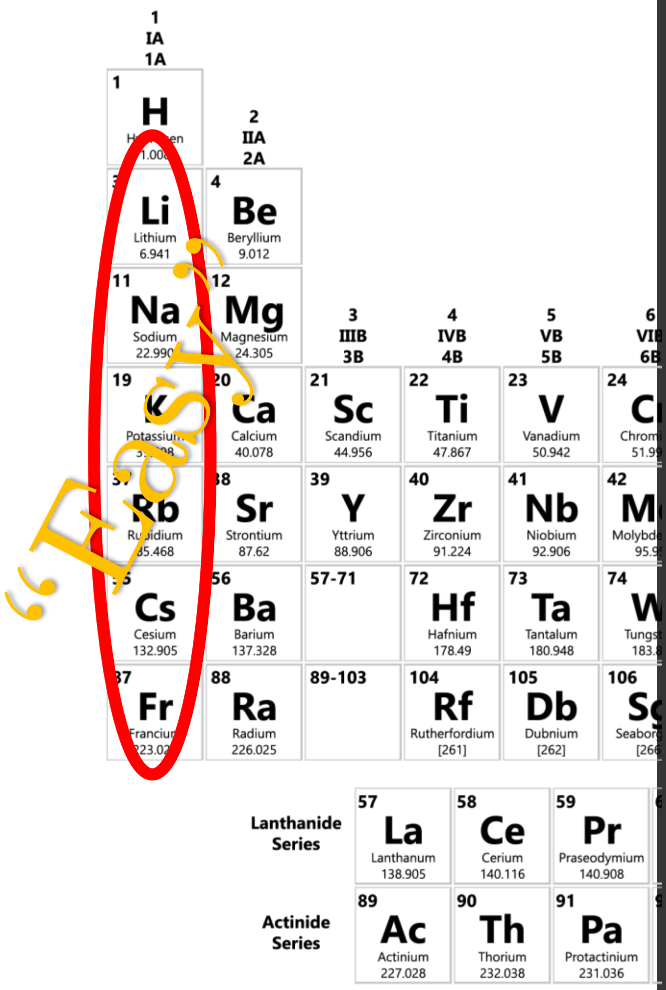
Why trapping hydrogen is hard?

- First excited level is very energetic.
- Small mass.

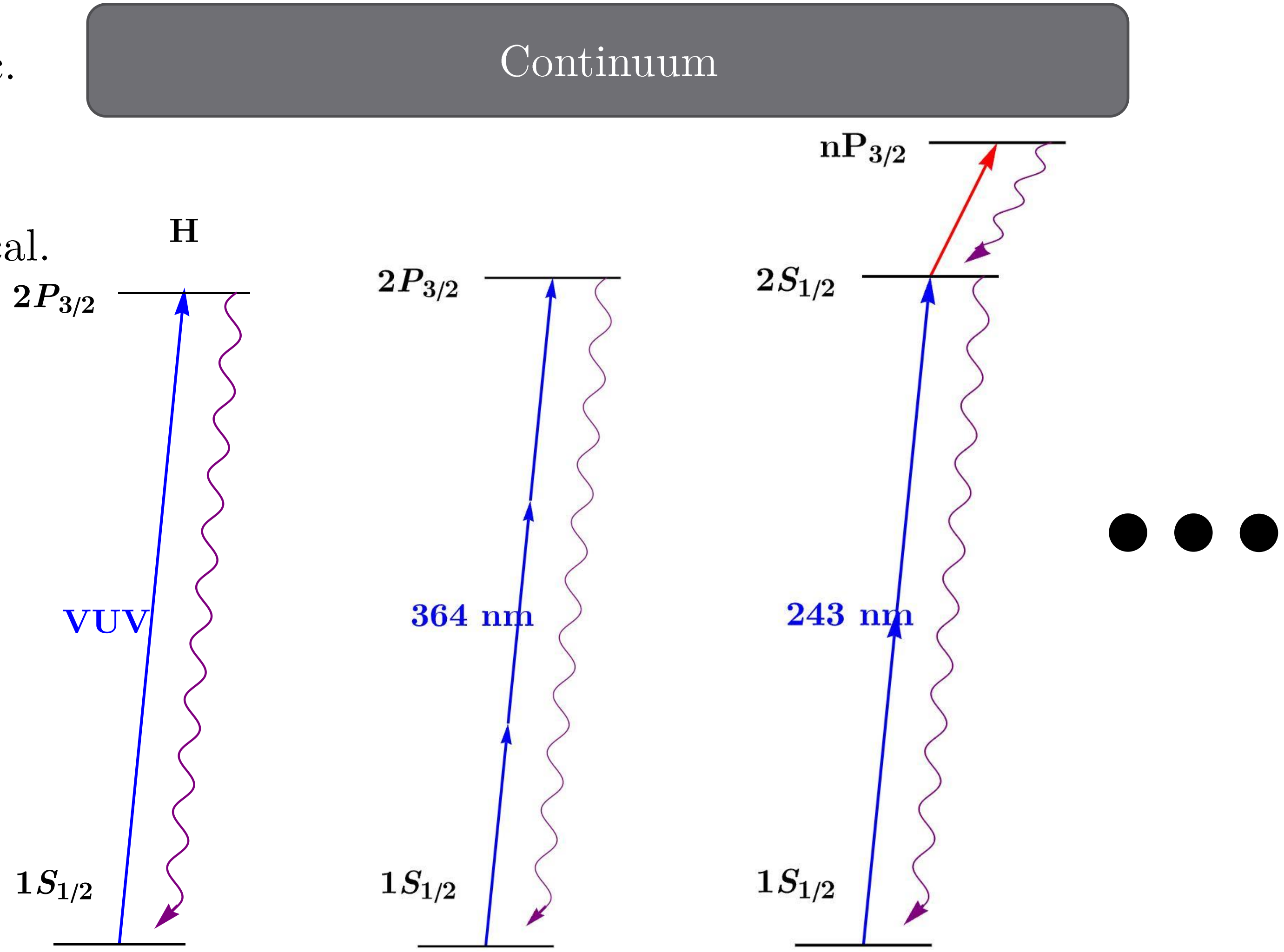


	H	Rb
Mass	1 u	87 u
Wavelength	121 nm	780 nm
Linewidth	100 MHz	6 MHz
Doppler Temp.	2.3 mK	145 μK
Recoil Temp.	1.2 mK	360 nK
Recoil velocity	3.2 m/s	5.6 mm/s
Doppler shift	27 MHz	7.5 kHz



Why trapping hydrogen is hard?

- First excited level is very energetic.
- The 2S level can be easily ionized.
- Standard laser cooling is impractical.



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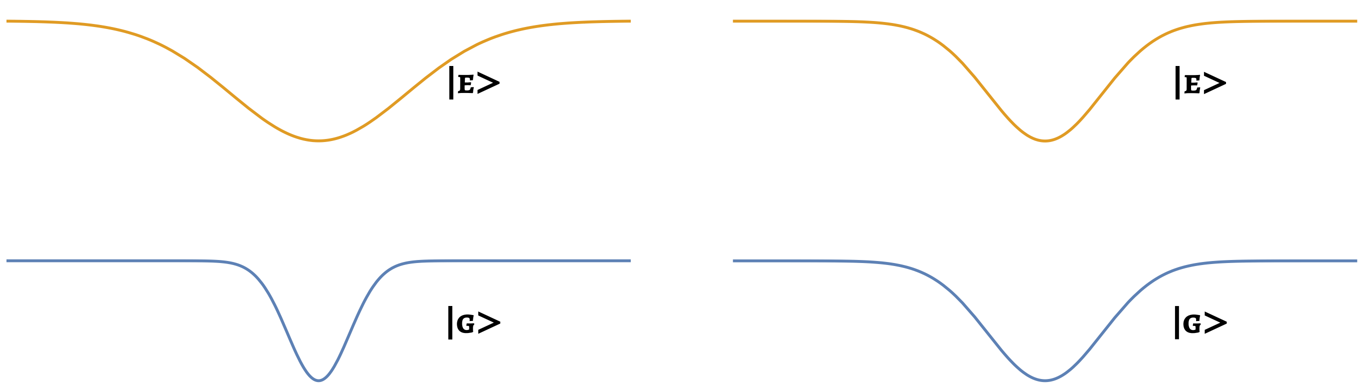
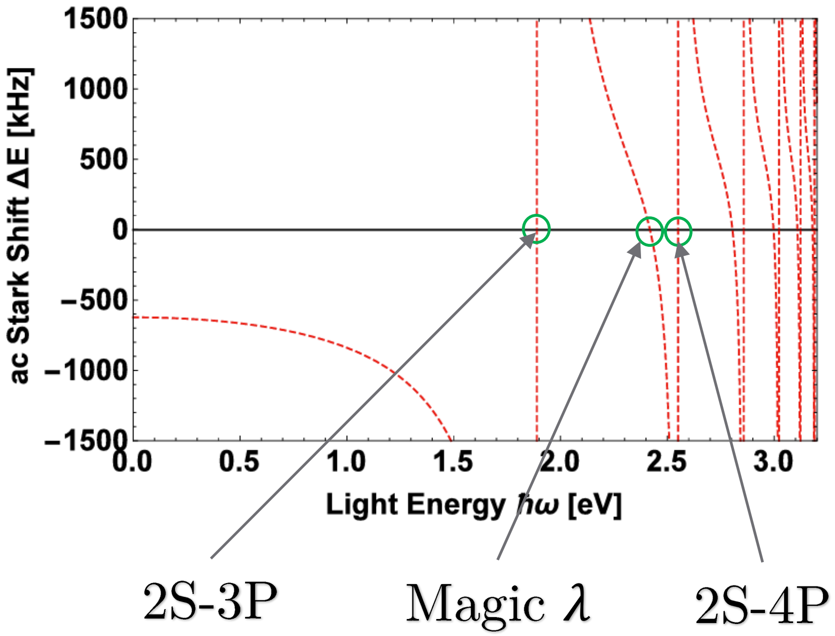
Magic wavelength dipole trap

- Magic wavelength $1S \rightarrow 2S$, $\lambda = 514.6\, nm$

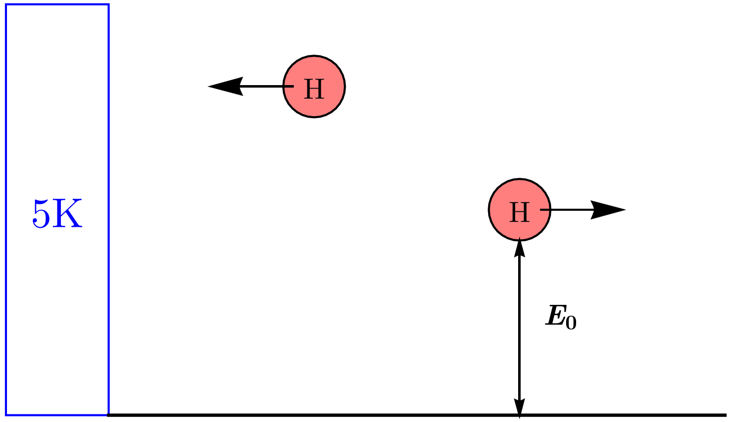
Non-magic | Magic



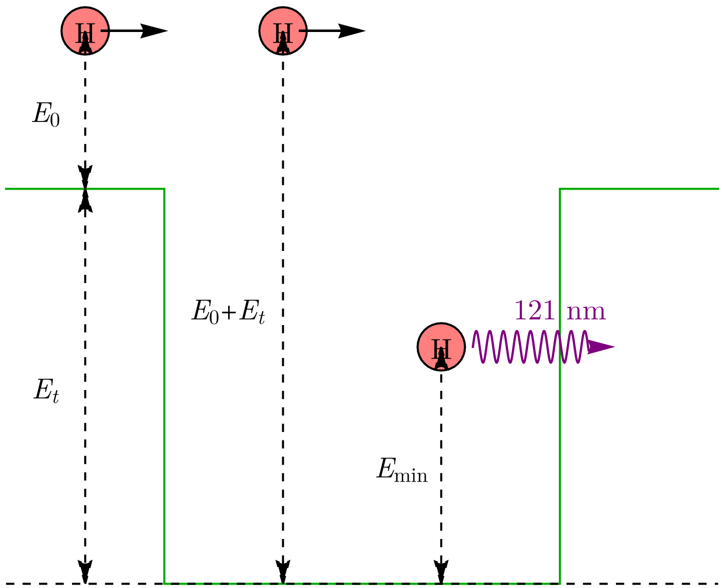


C. M. Adhikari et al. PRA **94**, 032510 (2016)

How to trap hydrogen?



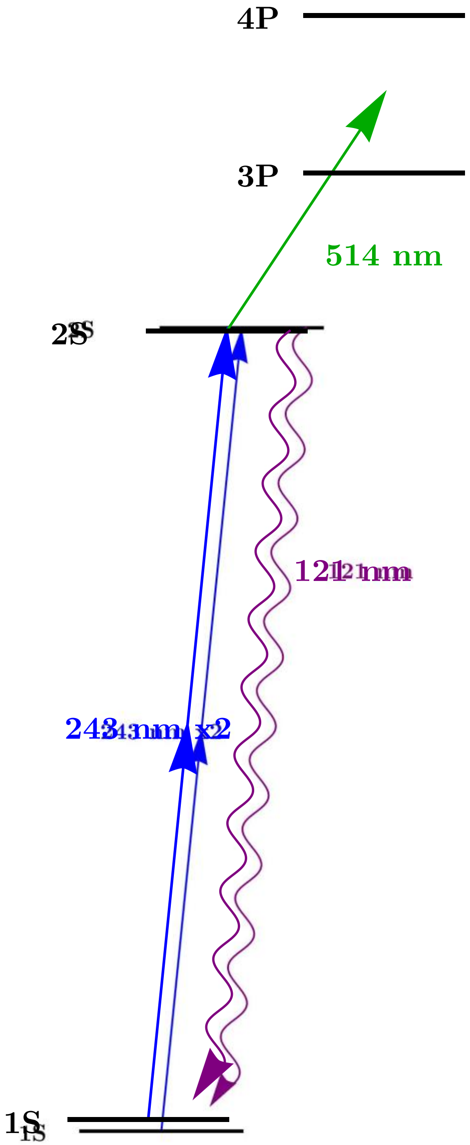
Thermalization to 5 K



Quenching and momentum kick

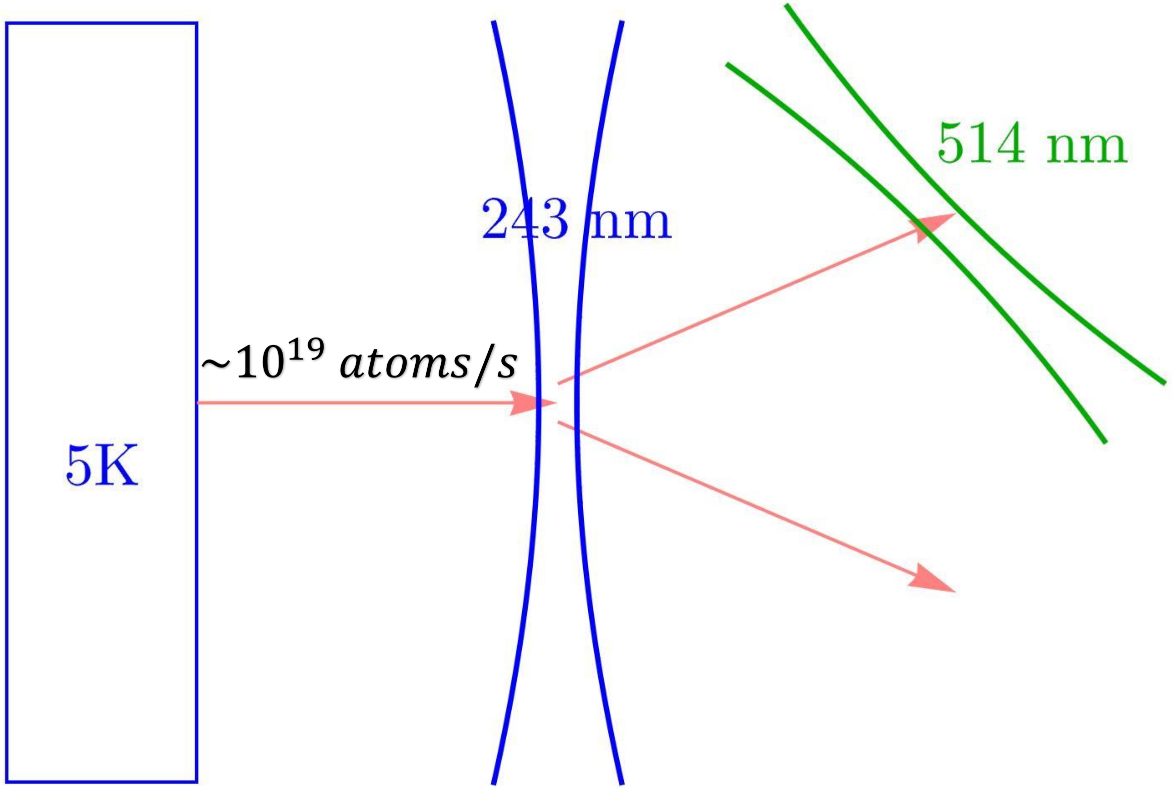
$\sim 10^{19}$ *atoms/s*

2-photon excitation
1S - 2S



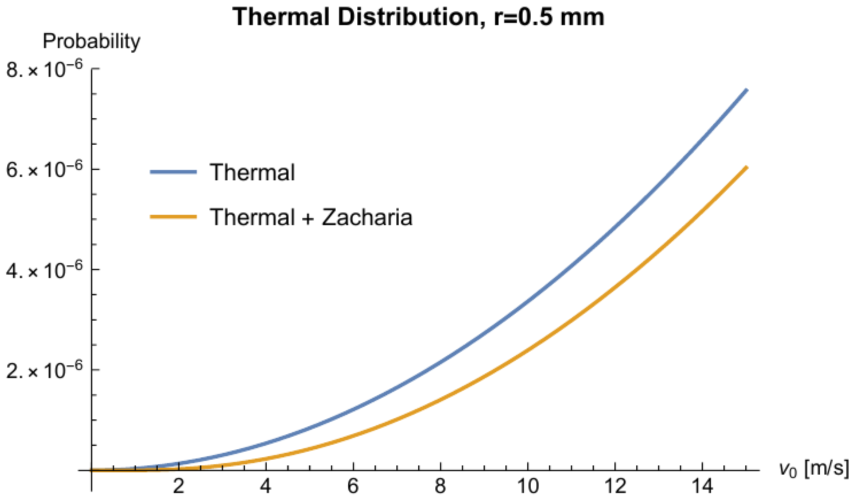
How to trap hydrogen?

- Using the doppler-sensitive 2-photon transition.
- In a FP cavity, two beams are produced.
- Deflection angle is velocity-dependent.
- Produce cold, low-velocity atomic beam.
- Interesting for 2S-nP spectroscopy.



Zacharias effect and the tale of the missing slow atoms

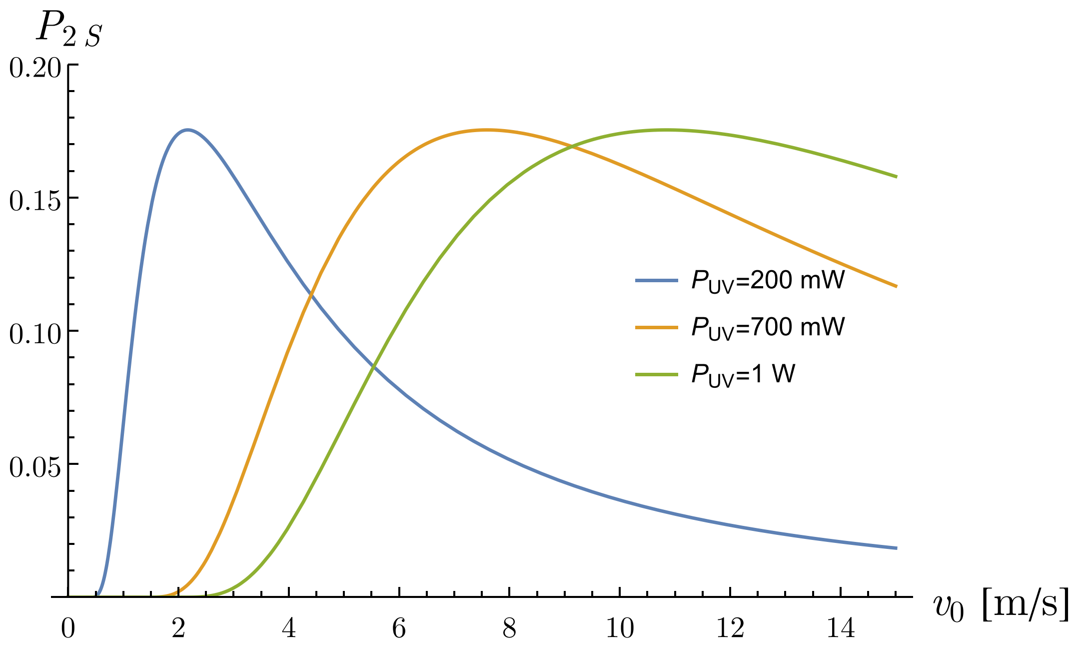
- Slow atoms are being pushed out of the atomic beam by fast moving atoms.

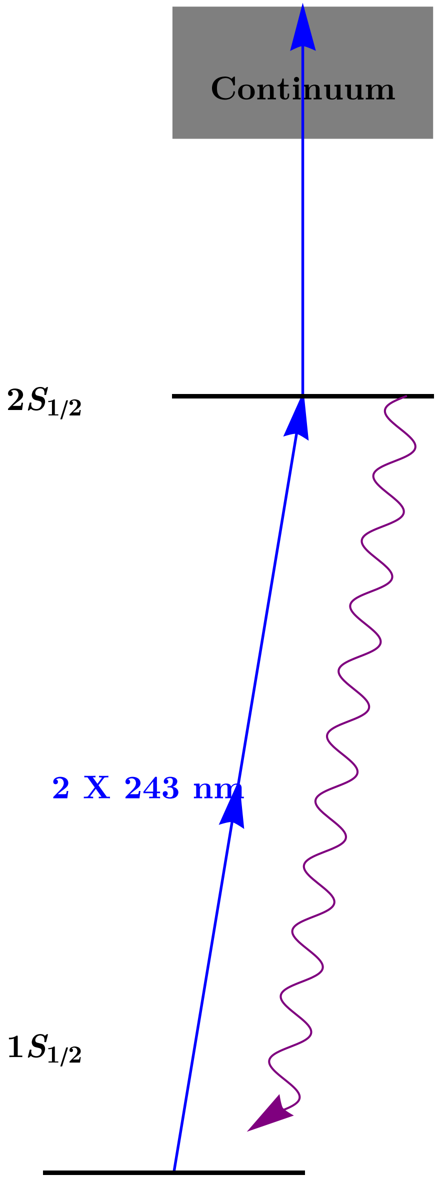


I. Estermann et al. Physical Review **71**, 4 (1947)

Excitation probability

- Excitation using 2-photon transition 1S – 2S.
- 3-photon ionization limits the efficiency of the process.
- Max efficiency around 17%.
- Starting from 10^{19} atoms/s, still leaves 10^{18} atoms/s.

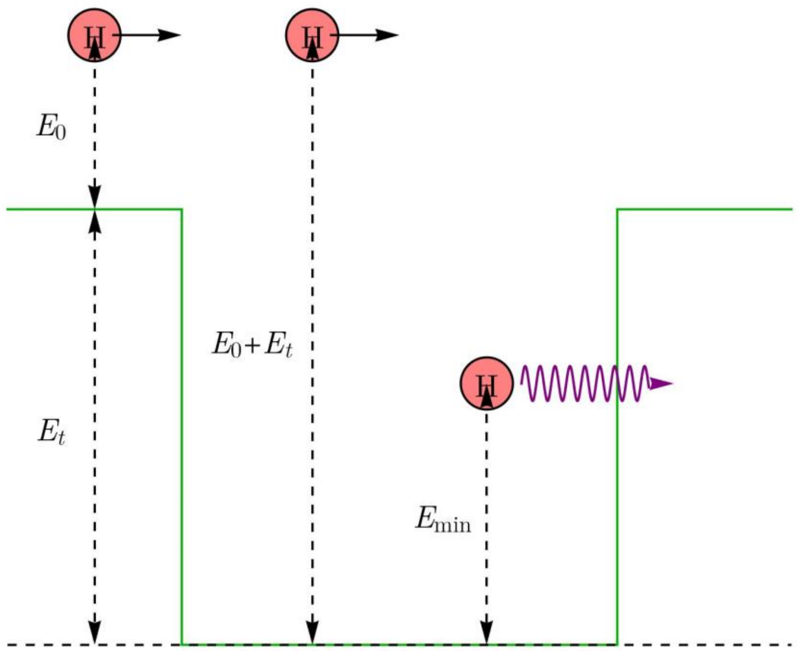


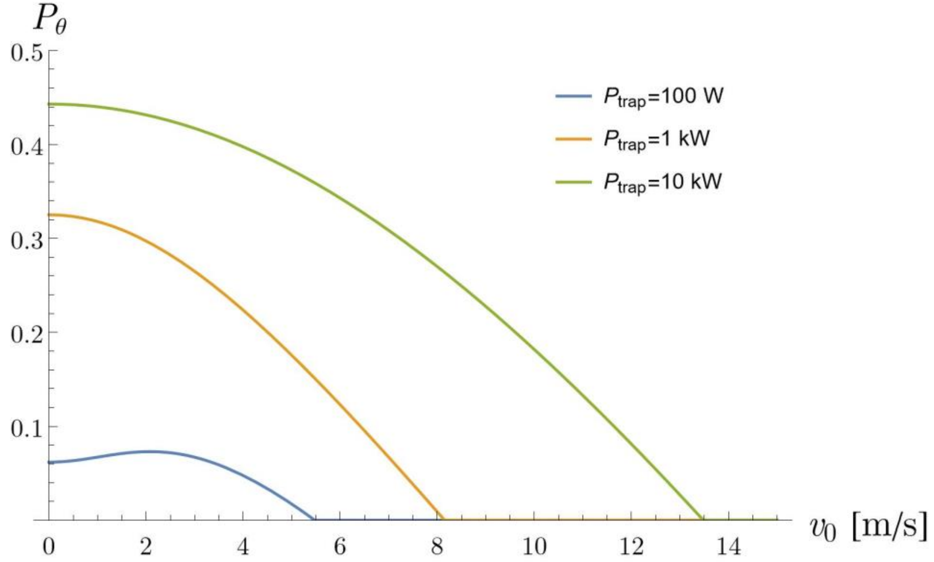


Trapping probability

- Initial kinetic energy $E_0 = \frac{m}{2} v_0^2$
- Maximal velocity $v_{max} = \sqrt{\frac{2(E_0+E_t)}{m}}$
- Velocity after recoil $\overrightarrow{v_f} = (v_{max} - v_{rec} \cdot \cos\theta\,, v_{rec} \cdot \sin\theta)$
- Energy after recoil $E_{min} = \frac{m}{2}\left|v_f\right|^2 < E_t$
- Trapping condition $\theta_{max} = \cos^{-1}\left(\frac{E_0+E_{rec1}+E_{rec2}}{2\sqrt{E_{rec2}(E_0+E_t+E_{rec1})}}\right)$
- Probability $P_\theta = (1 - \cos\theta_{max})/2$

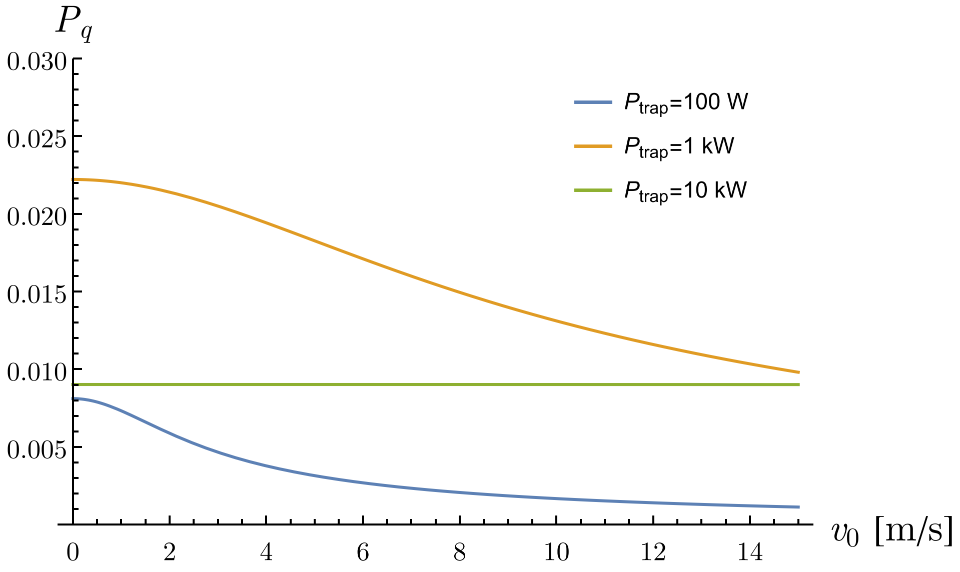
Only the slow atoms are trappable

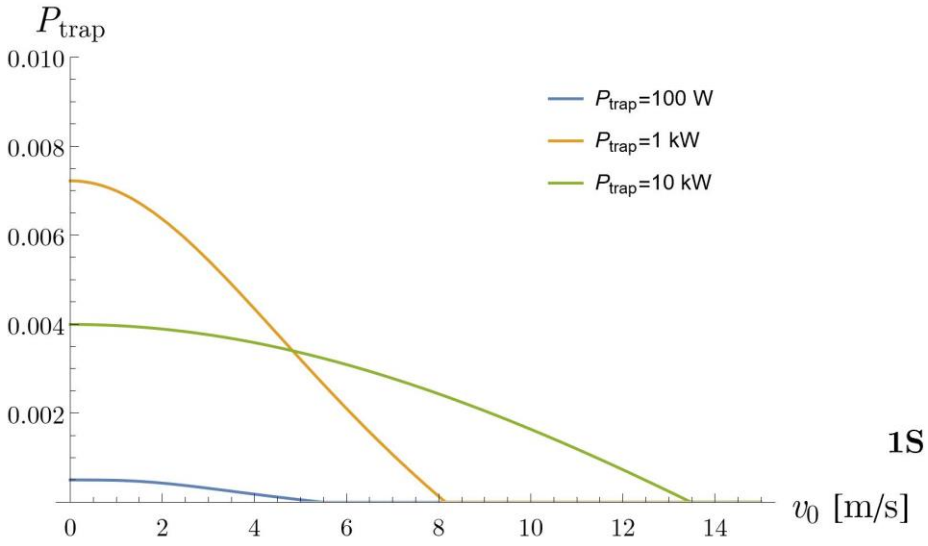


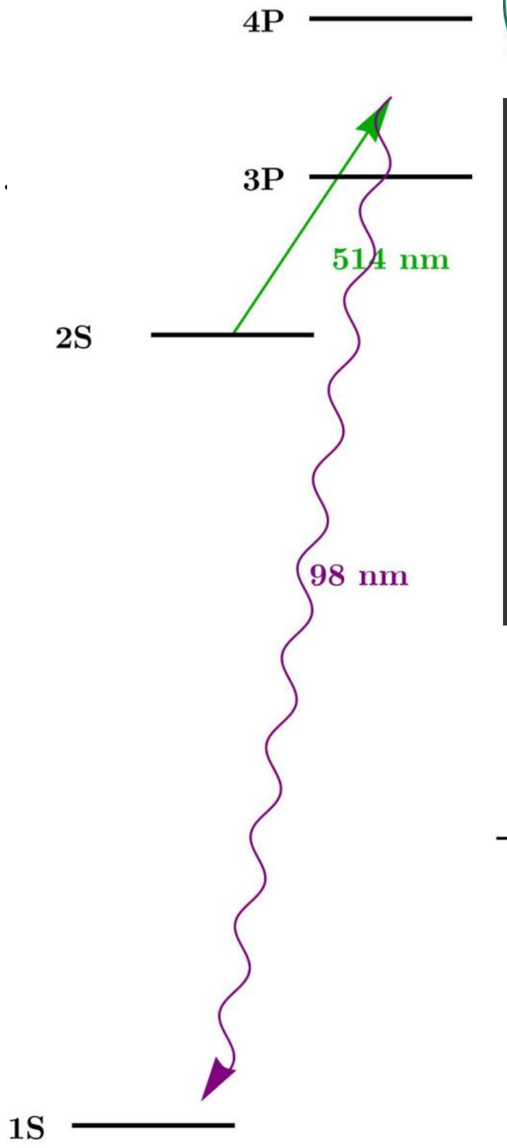


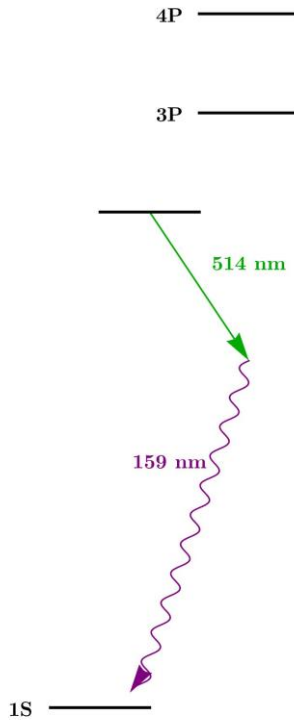
Trapping probability

- Quenching of the 2S state is done by mixing 3P and 4P using the trapping laser.
- 2-photon ionization limits the maximum efficiency of this process.
- $P_{trap} = P_{\theta} \cdot P_q$
- $\mathbf{10^{18}}$ atoms/s, still leaves $\mathbf{10^{15}}$ atoms/s.



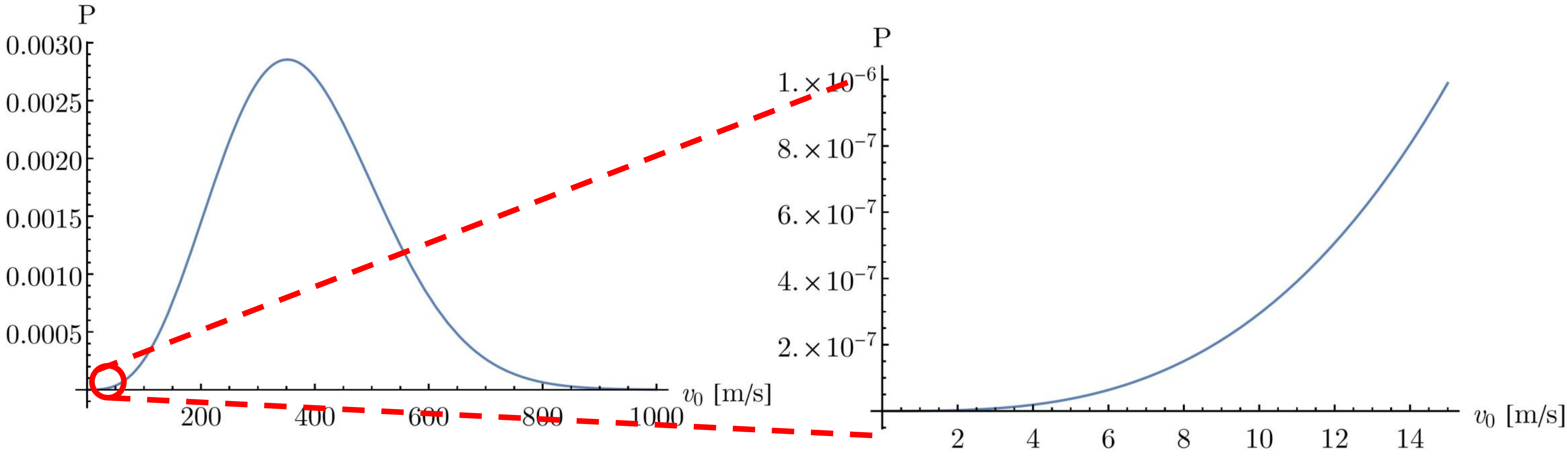






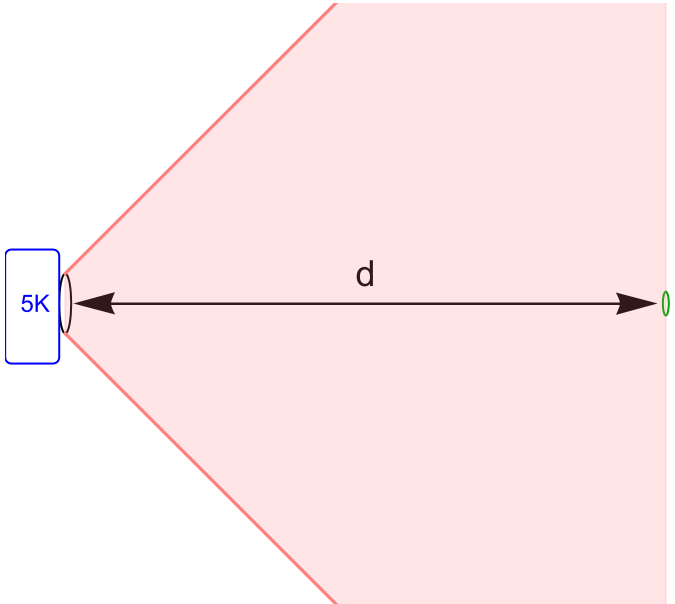
Thermal flux distribution

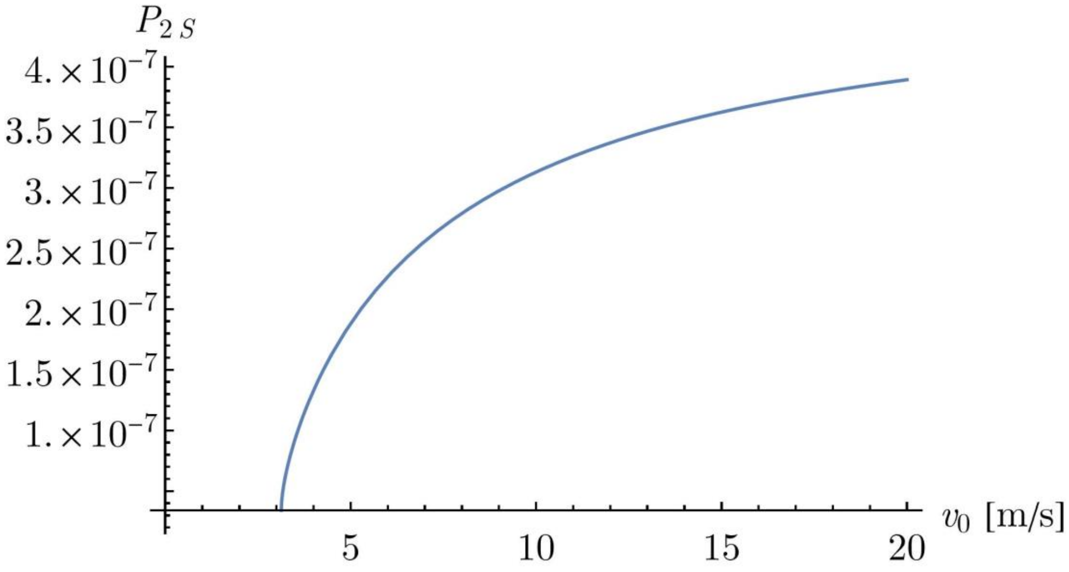
- High energy photon + Small mass = single recoil is enough to trap an atom.
- Trap only the tail of the thermal distribution.
- 10^{15} atoms/s, still leaves 10^{8} trappable atoms/s.



Transport

- Atoms leaving the nozzle need to hit the trapping volume.
- $P_{hit} = A/d^2$
- Very small fraction of atoms reach the trap. $P_{hit} \approx 5 \cdot 10^{-7}$ for $d = 0.5$ m
- Atoms need to survive in the 2S state (0.12 second lifetime).
- 10^8 atoms/s, still leaves 10^1 trappable atoms/s.





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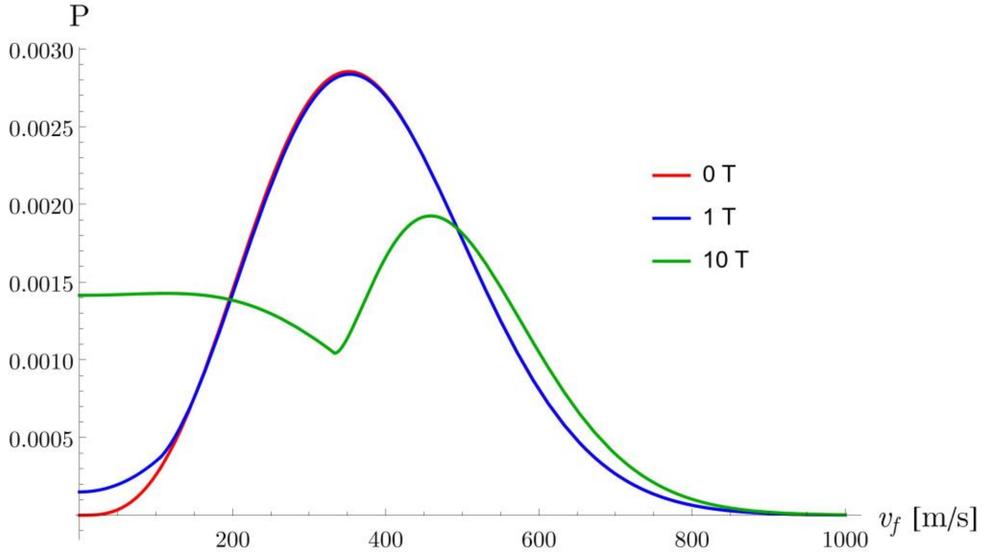
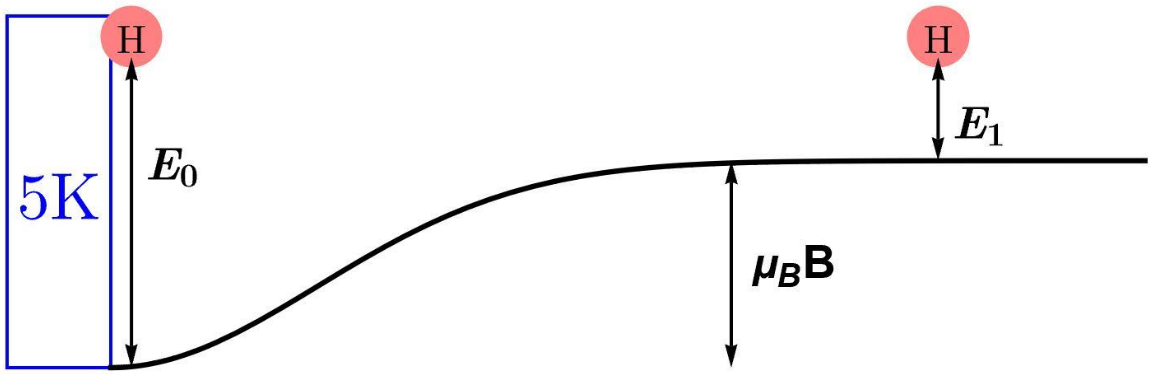
- Why trap hydrogen? Why hydrogen optical clock?
- Why trapping hydrogen is hard?
- How to trap hydrogen?
  - Some extra tricks for trapping hydrogen
- What is being done right now?

Pre-deacceleration using magnetic fields

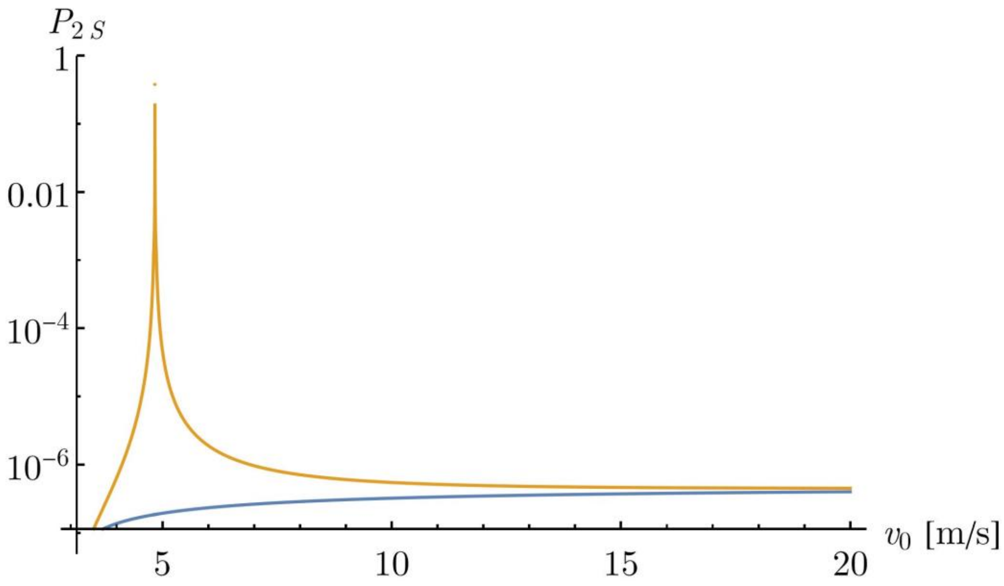
- If an atom is born in a potential well, it will have to trade away its kinetic energy to reach the trap.
- Final velocity $v_1 = \sqrt{v_0^2 \pm 2\mu_B B/m}$
- Low-field seeking atoms are accelerated.
- High-field seeking atoms are deaccelerate.
- 10^1 atoms/s, leaves 10^4 trappable atoms/s.

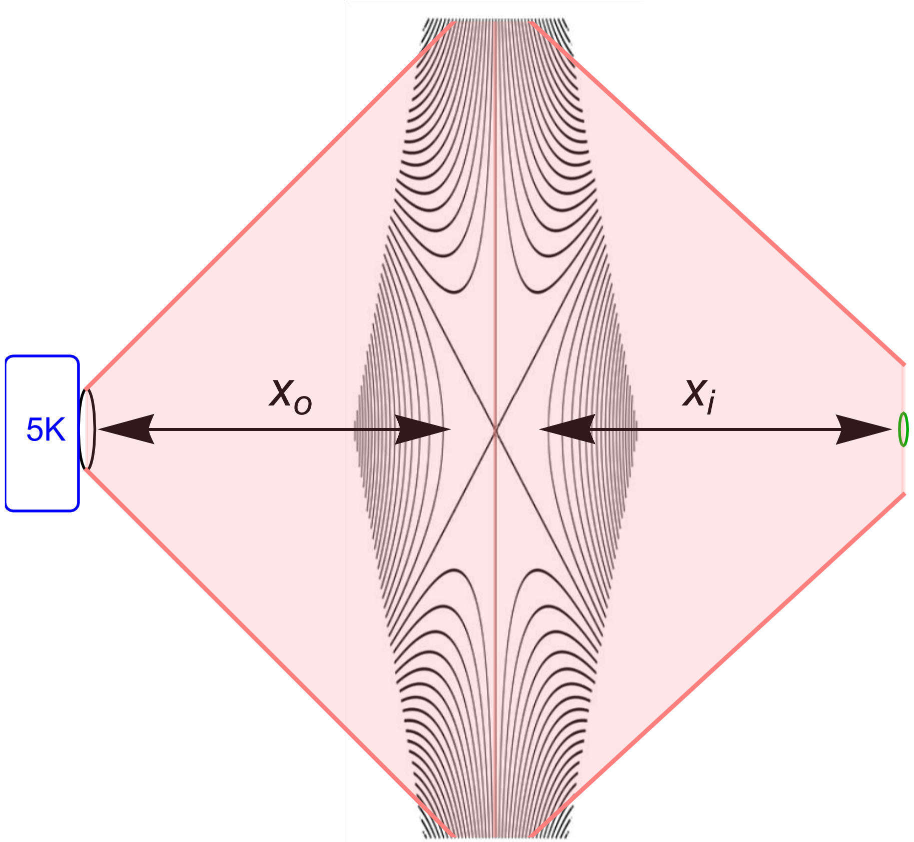




P_{hit} with magnetic focusing

- $P_{hit} = \frac{A}{r_i(v_0)^2}$
- $r_i(v_0) = x_i + (x_o + r)\left(1 - \frac{x_i}{f(v_0)}\right), \quad f(v_0) = \frac{\pi m R^3}{6\mu_0 \mu_B I L} v_0^2$
- Velocity dependent. More slow atoms less fast atoms.
- Only focus low-field-seeking atoms.
- 10^4 atoms/s, leaves 10^8 trappable atoms/s.





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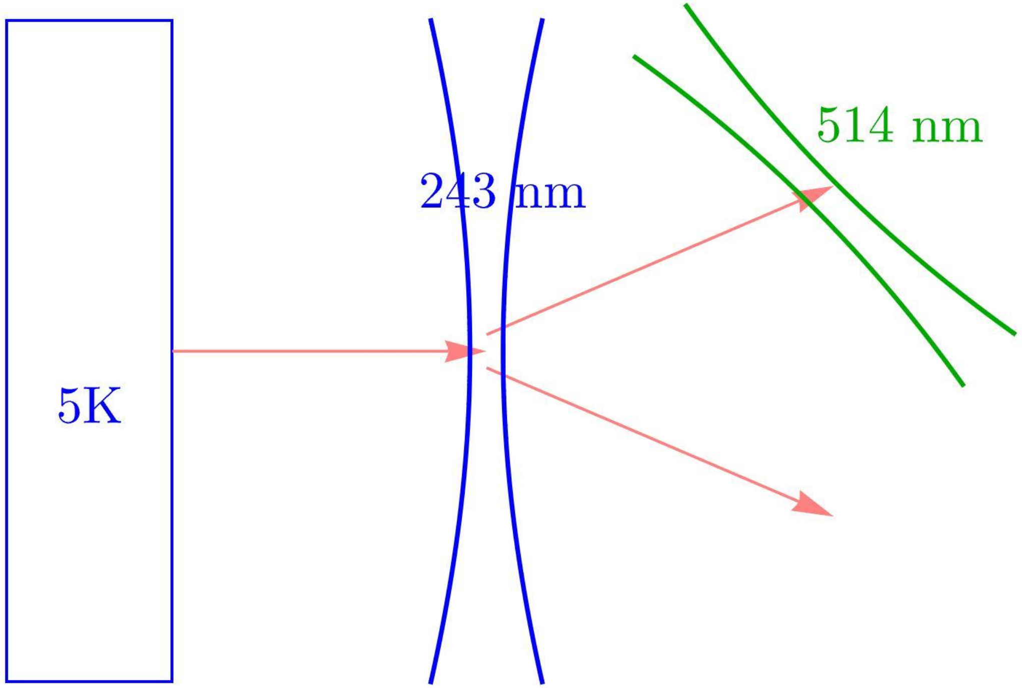
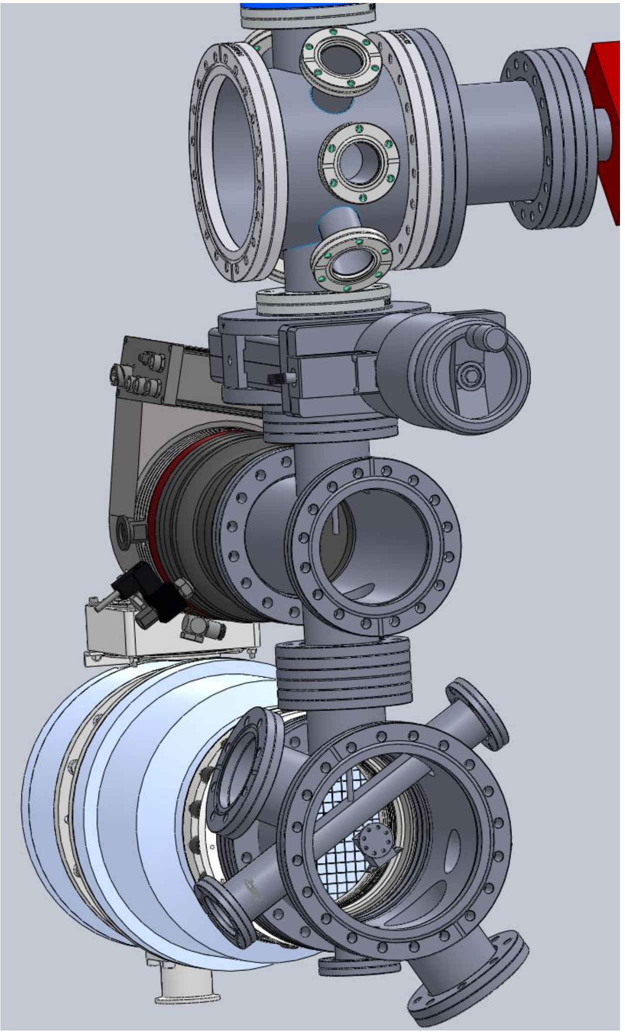
What is being done right now?

- Construction of the system.
- Construction of the lasers.
- More simulations.
- First Goal: Measure a low-velocity atomic beam.





Thank you