Perspectives for gravity measurement and spectroscopy of cold antiH

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Outline

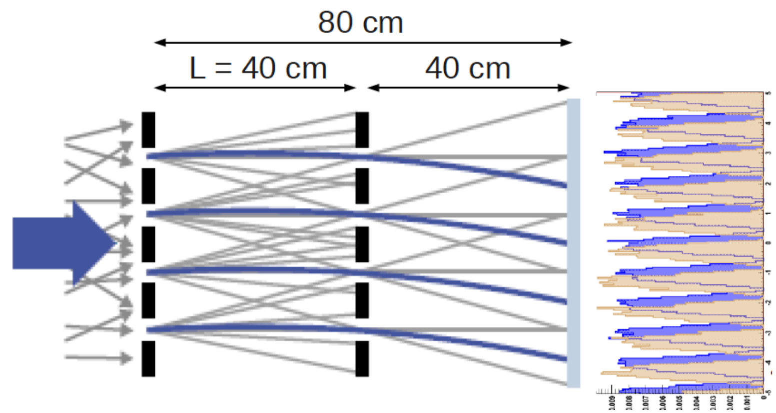
- Challenges for high precision measurements on antiatoms
  - temperature
  - flux
  - laser sources
- Possible experimental schemes for advanced measurements
  - positronium & antiproton cooling
  - antihydrogen cooling
  - light-pulse atom interferometry on antihydrogen
  - 1S-2S spectroscopy

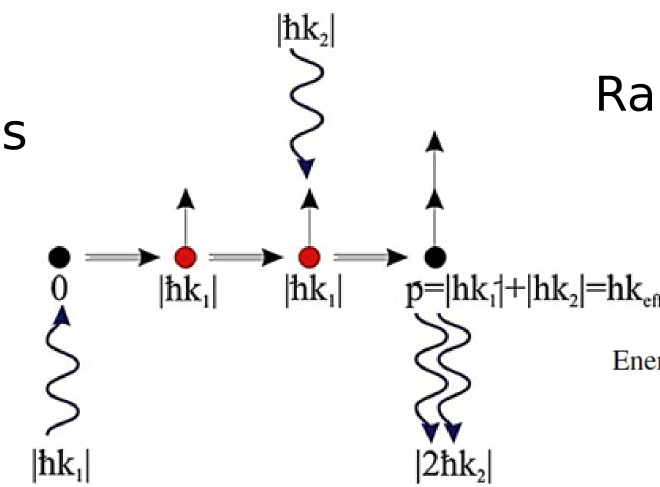
Challenges

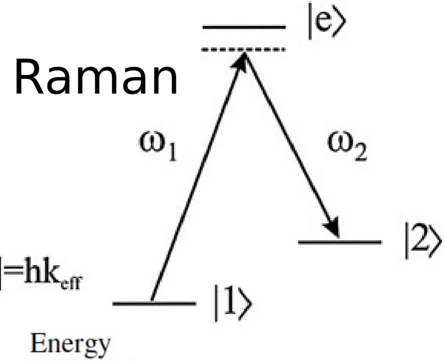
- High precision measurements on atomic systems
  - acceleration -> atom interferometry
  - frequencies -> high resolution laser spectroscopy
- Measurement precision is limited by
  - number of detected atoms (SNR)
  - RMS velocity (i.e. temperature)
  - both are much worse when working with $\overline{H}$ as compared to H, since antimatter is produced from its charged constituents
  - requires state of the art technologies from accelerator physics, ion trapping and atom optics
- Light-pulse atom interferometry with hydrogen is demanding
  - large transition frequencies –> requirements on laser sources
  - small mass –> large recoil temperature
- One advantage over ordinary matter is the possibility to detect atoms via annihilation products

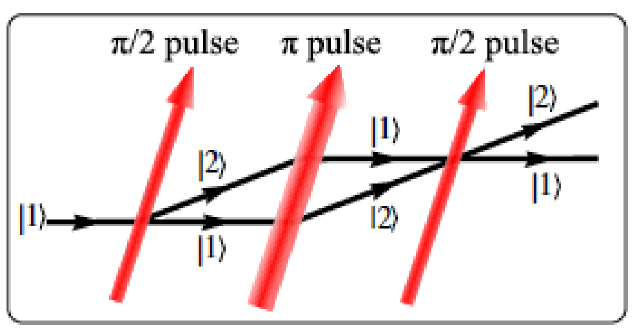
High precision *g* measurement

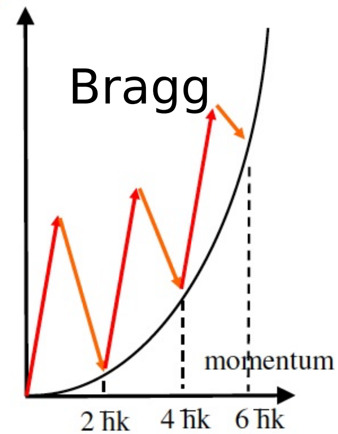
- Current effort (see AEgIS) is to measure *g* on antiH with low precision (1% at most) using deflectometry on material gratings
  - T~0.1 K
  - flux ~ 1 atom /min
- Higher precision (10-4÷10-6) is possible by light-pulse atom interferometry
  - need a suitable AI scheme
  - larger antihydrogen flux
  - X 100 with ELENA
  - lower temperatures
  - is 1 mK cold enough?
  - how to achieve it?





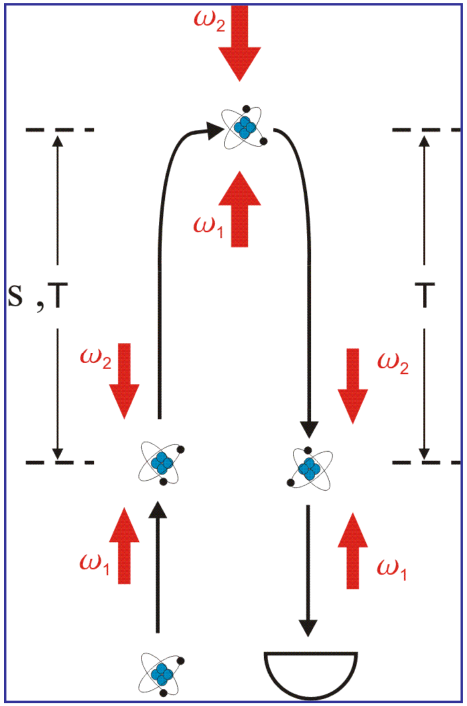


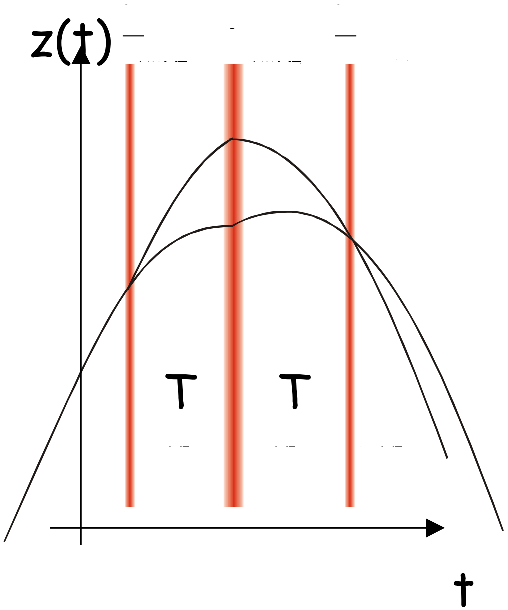




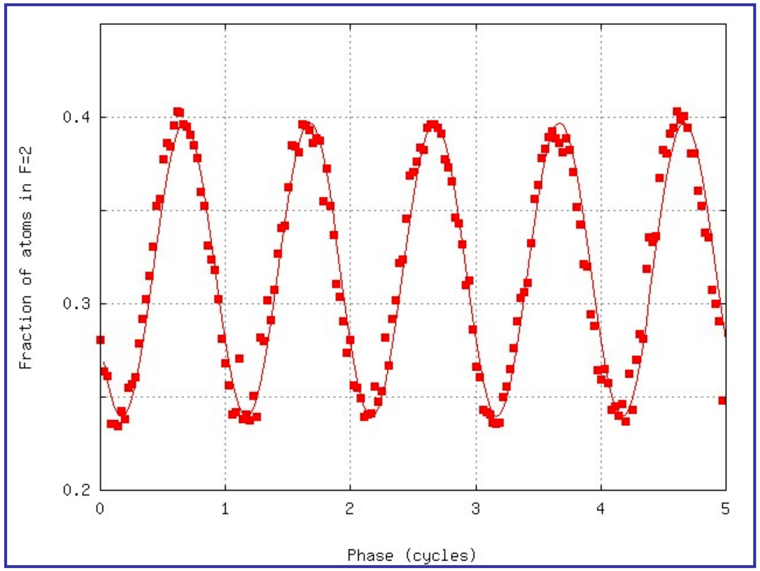
Raman interferometry gravimeter

Phase difference between the paths:
$\Delta\Phi = k_e[z(0) - 2z(T) + z(1T)] + \Phi_e$
$k_e = k_1 - k_2$
with $z(t) = -gt^2/2 + v_0 t + z_0$ & $\Phi_e = 0$
$\rightarrow \Delta\Phi = k_e g T^2$





Final population:
$N_a = N/2(1 + cos[\Delta\Phi])$



$T = 1\,\mathrm{ms}$, $k_e \sim 2 \times 10^7\,\mathrm{m}^{-1} \rightarrow k_e T^2 \sim 20$
$N = 25 \rightarrow S/N \simeq 5 \rightarrow$Sensitivity $\sim 10^{-3}\, g/$shot

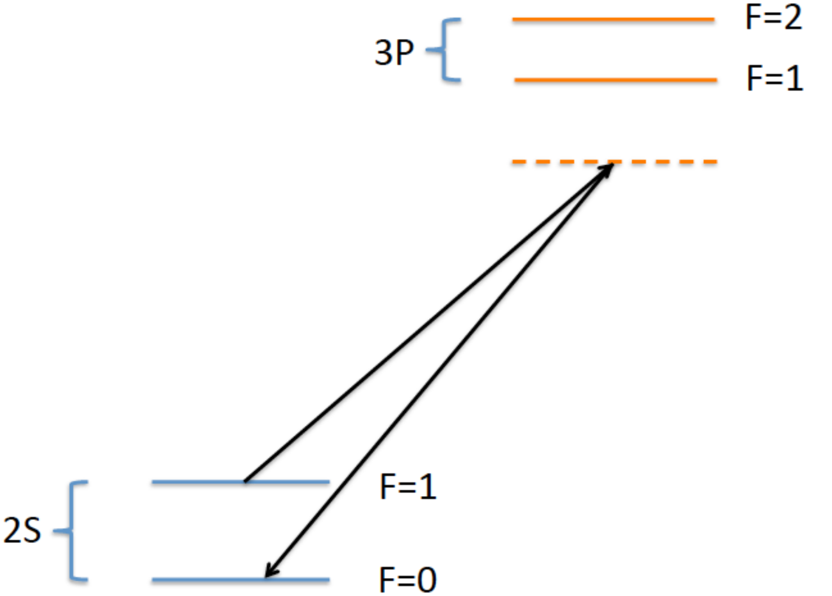
A. Peters et al., Nature **400**, 849 (1999

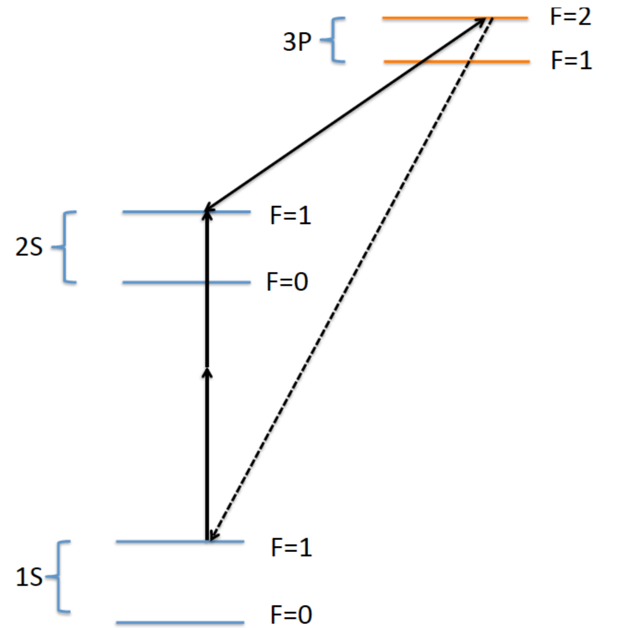
Numerical examples

- Bragg scattering on 1S with far-off detuned laser [P. Hamilton et al., Phys. Rev. Lett. 112 , 121102 (2014)]
  - $$\Omega_e = \frac{9\pi a_0^3 I}{\hbar c}$$
  - e.g. with a 1064 nm laser
  - 1 mK requires 30 MW/cm2 on ~100 ns pulses
- Raman or Bragg on Lyman-alpha
  - $$\Omega_e = \frac{\Gamma^2}{2 I_s \Delta} I$$
  - *IS*=43 W/cm2
  - 1 mK and 10 GHz detuning would require ~400 W/cm2
  - CW laser sources @ 121 nm achieve 6 µW [D. Kolbe et al., Phys. Rev. Lett. 109 , 063901 (2012)].

AI on metastable 2S state

- Raman interferometry with a laser intensity of ~10 W/cm2 @ 657 nm and 40 ns pulses (to interrogate atoms @1 mK)
- State-sensitive detection by sequentially pushing F=1 and F=0 atoms towards the detector
- Reasonable requirements on laser intensity
  - 6W/cm2 with 10 GHz detuning





Requirements on atomic source

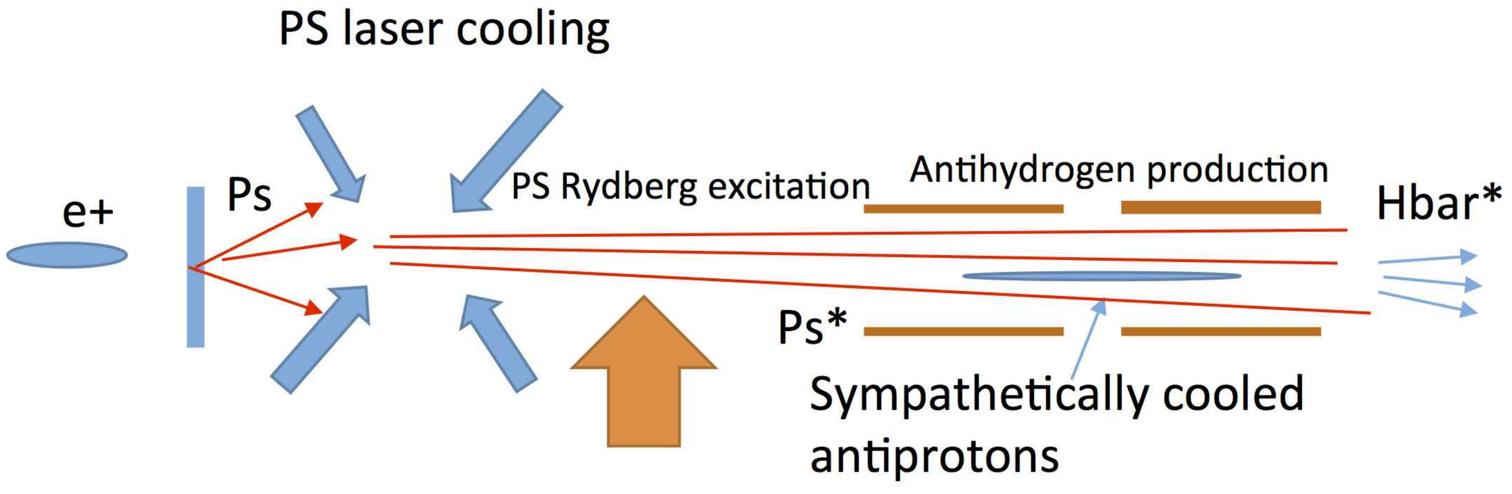
- Temperature:
  - atom optics splitters are velocity selective: higher temperatures require higher Rabi frequency -> larger laser intensity
  - expansion of atomic cloud: RMS velocity is 3 m/s @1mK
- Atomic flux:
  - SNR is determined by the number of detected atoms
  - in the QPN limit, sensitivity scales as √ (number of detected atoms per shot)
- Numerical example
  - Raman interferometry @657 nm
  - T=1 ms (compatible with 1 mK temperature)
  - 50% contrast
  - 60 atoms/cycle
  - repetition rate ~ 1 cycle/min
  - **-> sensitivity ~ 1.3×10-3 g /shot**
  - Down to 3×10-6 g after 5 months integration time

Producing ultracold antihydrogen

- Possible approaches to achieve antiH at ~1 mK or sub-mK temperatures
  - laser cooling (after "standard" generation from thermal charged constituents)
  - **pre-cooling of antihydrogen constituents**
  - antiprotons
  - positronium
  - combination of the two strategies
  - adiabatic cooling on antihydrogen
  - other methods (e.g. sympathetic cooling on Hbar+)
- Measurement geometry
  - magnetic trapping of antihydrogen
  - allows for natural Rydberg de-excitation
  - **free fall**
  - minimal perturbation in view of precision measurements

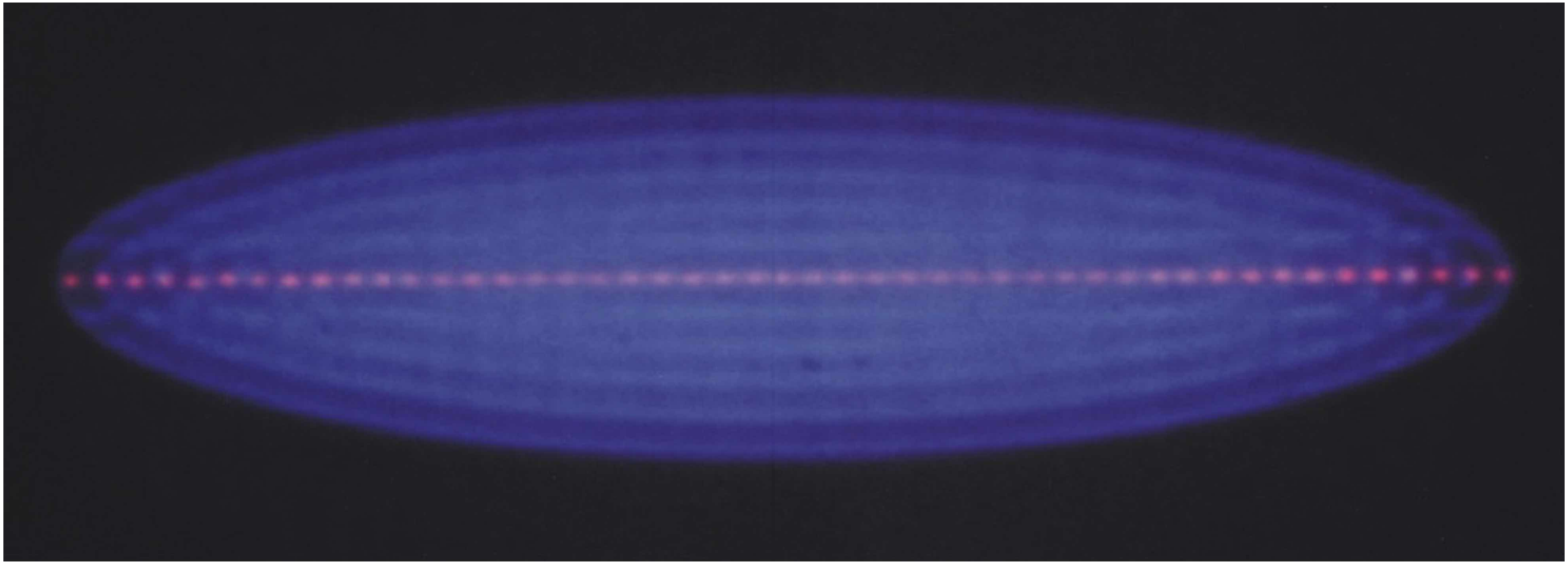
Producing ultracold antihydrogen

- Possible approach to achieve high-flux antiH at ~1mK temperature
  - charge exchange between laser-cooled Ps* and sympathetically cooled positrons
  - Ps produced by collisions of positrons on nanoporous material (transmission target)



Antiproton sympathetic cooling

- two-species Coulomb crystal
- laser cooling on a large ensemble of negative ions will reduce the temperature of antiprotons
- heating due to trap micro-motion will not occur for ions on the axis
  - μK regime in principle achievable for ensembles up to ~50 antiprotons
- however temperature limit on antiH will be limited to a few mK by heating in charge transfer (see a few slides ahead)
  - may be convenient to trade-off temperature for a larger number of antiprotons



Towards ultracold antiprotons

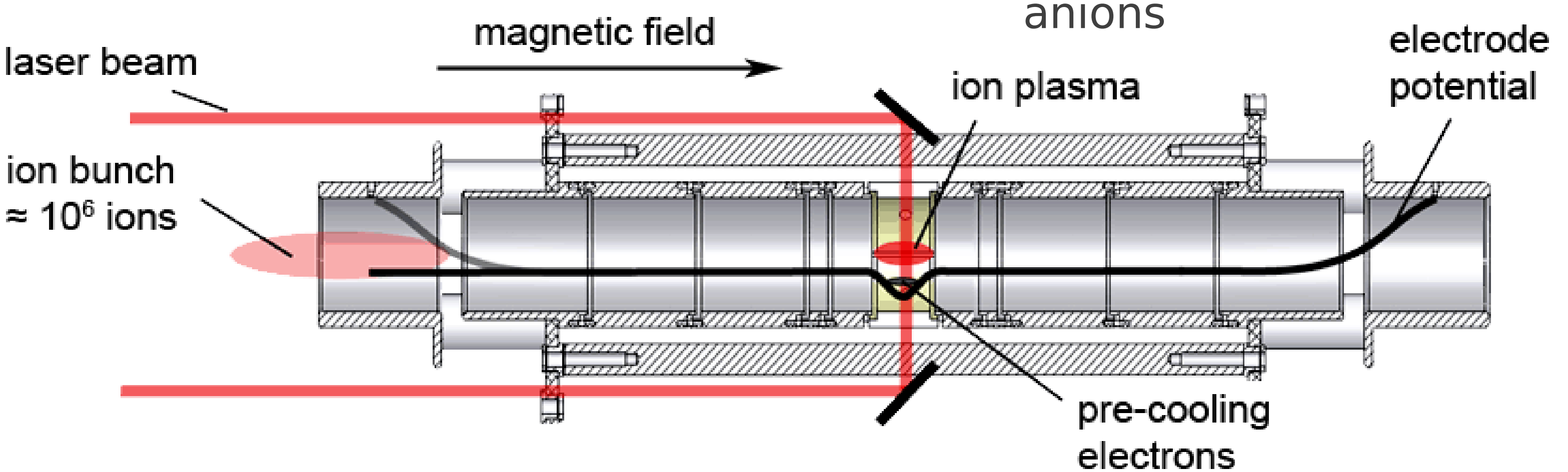
- Collisions of antiprotons with negative ions or molecules laser cooled and trapped with them
- Negative ions: work in progress@Heidelberg (A. Kellerbauer et al.) Os- La-
- Negative molecules: D. Comparat (AEgIS)

2010: DeMille's group demonstrates laser collimation with a radiative force on SrF
2014: Show 3D cooling and trapping: Nature 512, 286–289 (21 August 2014)

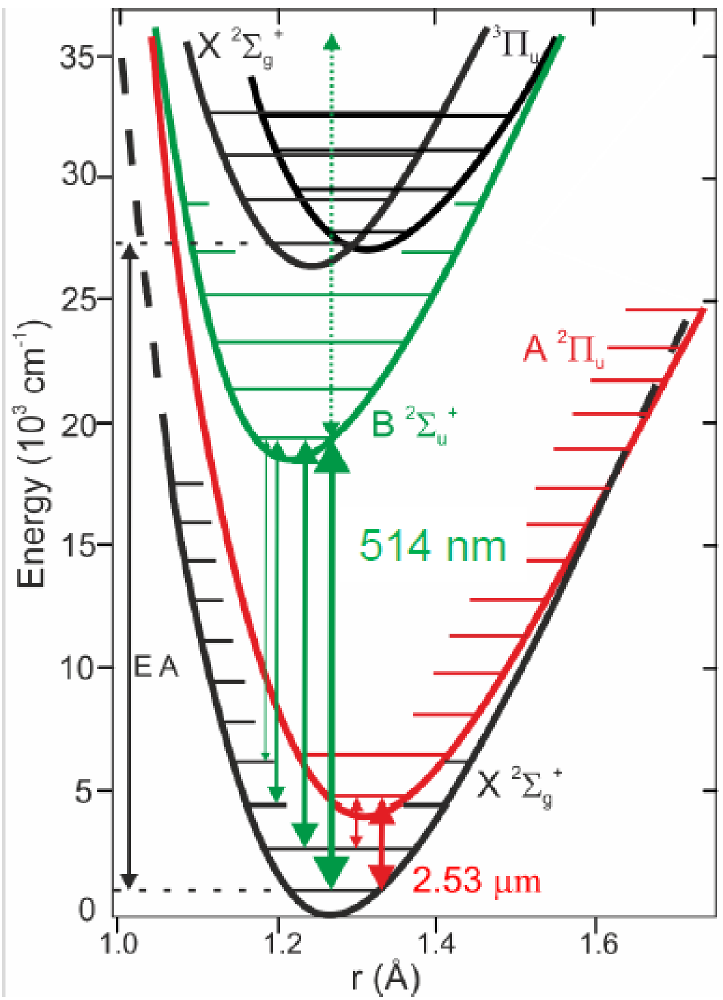
- Experimental procedure:

1. Capture of anions in Penning or Paul trap
2. Pre-cooling of anions with electrons
3. Laser cooling of anions
4. Simultaneous confinement of antiprotons in the trap
5. Sympathetic cooling of antiprotons by anions

[A. K. & J. Walz, New J. Phys. 8 (2006) 45]



Example (best known molecule) C_2^-



2 possible cooling schemes

- $X\ ^2\Sigma_g^+ \rightarrow B\ ^2\Sigma_u^+$

  541, 598, 667, 753 nm
  probability (Franck-Condon) 72, 23, 3, 0.8

  Ultra fast cooling : lifetime 70ns

  high photodetachement $\sigma \sim 10^{-17}$ cm^2
  $\rightarrow$ rate $I\sigma/h\nu = 1/s$ for $I = 30$mW/cm^2

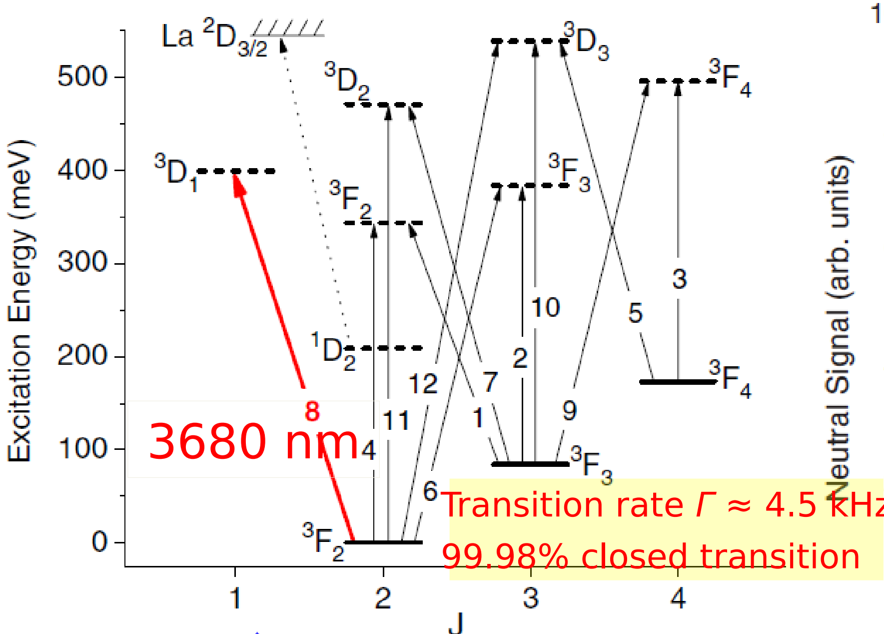
- $X\ ^2\Sigma_g^+ \rightarrow A\ ^2\Pi_u$

  2.53 μm and 4.50 μm

  Less laser needed
  slower cooling (100μs)
  No photodetachement

Adapted from D. Comparat
TCP2014

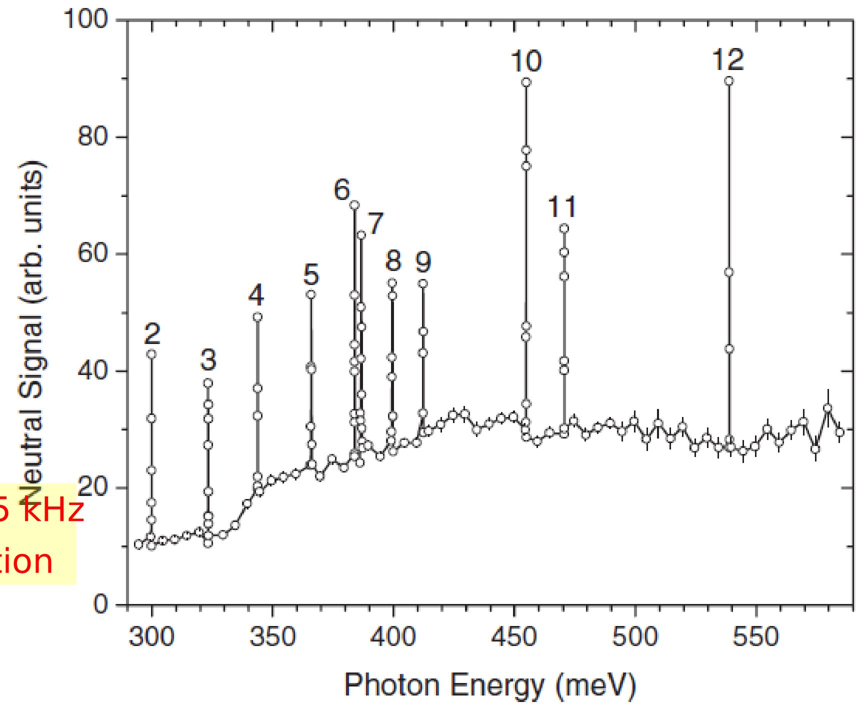
Antiproton cooling with La-



3680 nm

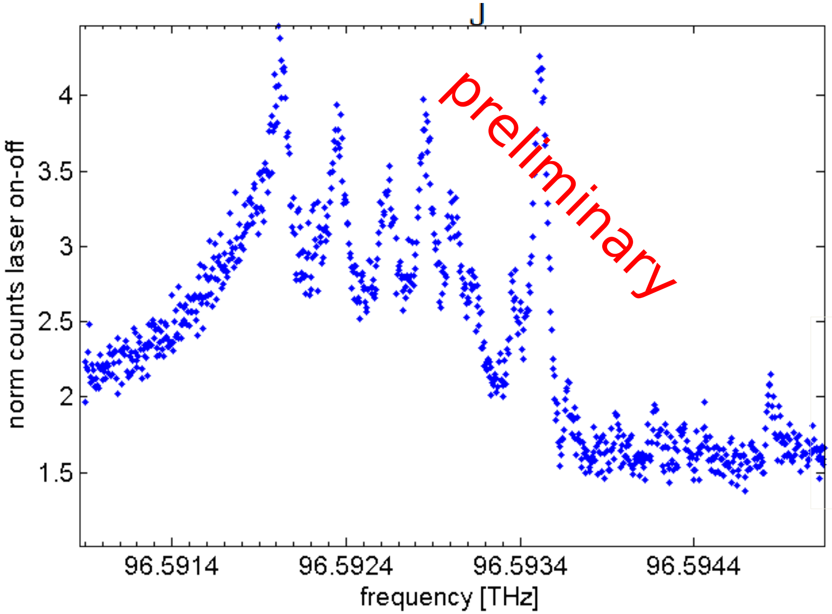
Transition rate $\Gamma \approx 4.5$ kHz

99.98% closed transition



Excited levels detected in

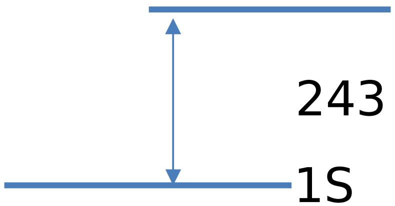
[C. W. Walter *et al.*,
Phys. Rev. Lett. **113** (2014) 063001]



First La- resonances detected
by AEgIS collaborators
(A. Kellerbauer et al.,Heidelberg)

[S. M. O'Malley & D. R. Beck,
Phys. Rev. A **81** (2010) 032503

Positronium cooling

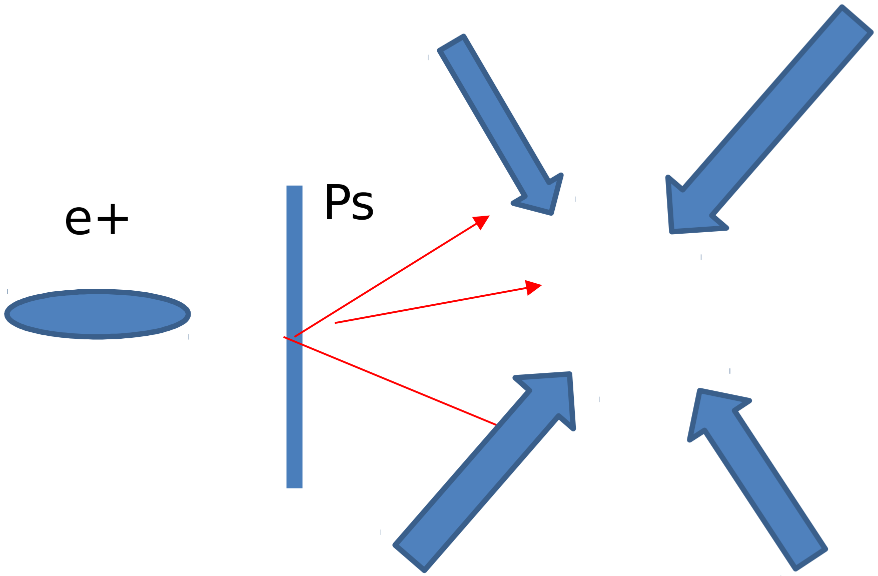


3.2 ns, 100 μsec annihilation

$$v_{recoil} = \frac{hk}{2\pi}\frac{1}{m_{Ps}}$$ =1.5 103 m/s

Recoil limit= 0.1K

It is enough to scatter 30 photons to get a significant collimation



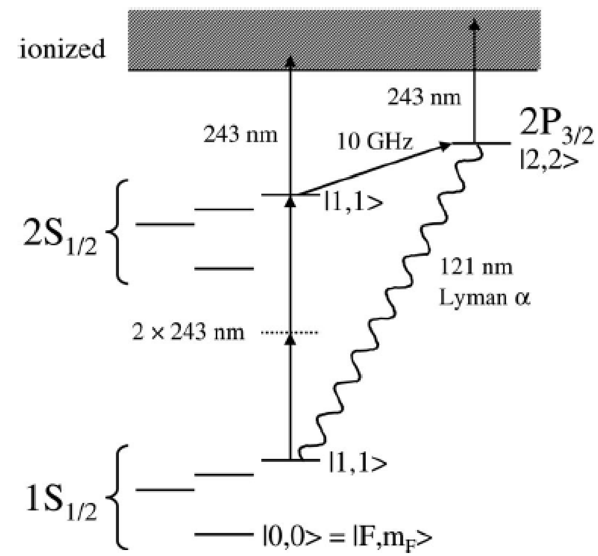
E. Liang Optics Comm. 65 (6) 1988 (419)
H. Iijima et al. Journ. Phys. Soc. Japan 70 11 (2001) 3255
NIMA 455 (2000) 104

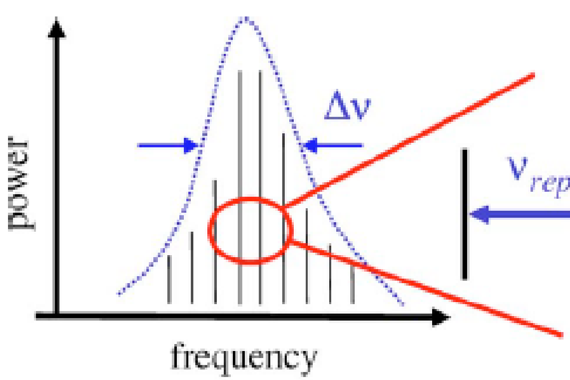
Beam collimation and de-excitation

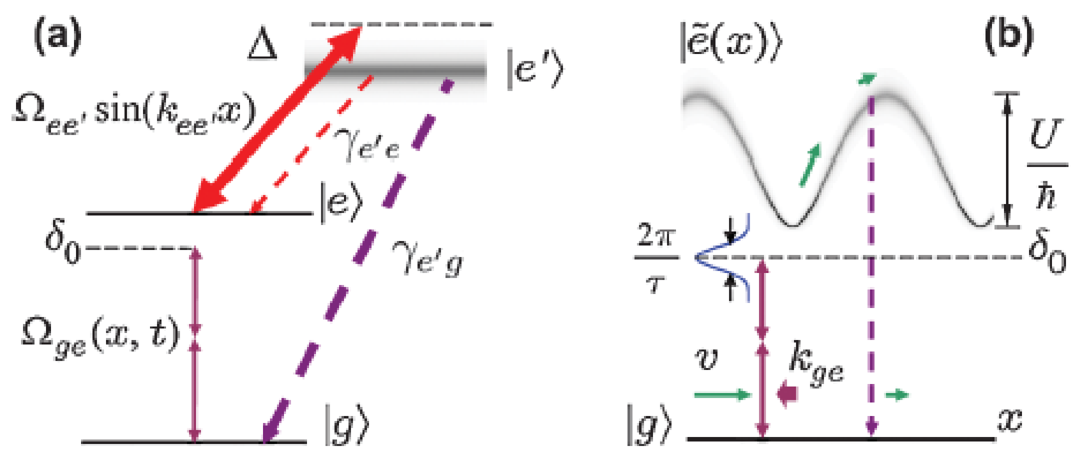
- Distribution on different Rydberg levels detrimental for precision measurements
  - systematics due to large sensitivity to external fields
  - hard to find unique atom optics tools for wavepacket manipulation
- However, Stark force on Rydberg atoms can be employed to reduce the radial velocity prior to de-excitation
- Two-steps de-excitation to 2S
  - laser de-excitation to 3P level requires a laser at 835 nm with bandwidth <100 GHz
  - 3P-2S decay with ~30% BR
  - optionally recycle atoms in 1S with 243 nm laser pulse

Laser cooling of antihydrogen

- Doppler temperature $T_D = \frac{\hbar\Gamma}{2k_B}$
- Recoil temperature $T_r = \frac{\hbar^2 k^2}{k_B m}$
- cooling on the Lyman-alpha line
  - Requires technol. development on laser source
- cooling on the 2-photon 1S-2S line
  - PHYSICAL REVIEW A 73, 063407 2006
- 1S-2S-3P pulsed Sisyphus cooling
  - PRL 106, 213001 (2011)
- theoretical limits in the 1÷2 mK range
  - Useful option as an alternative to the other scheme, or to dissipate trap extra-heating





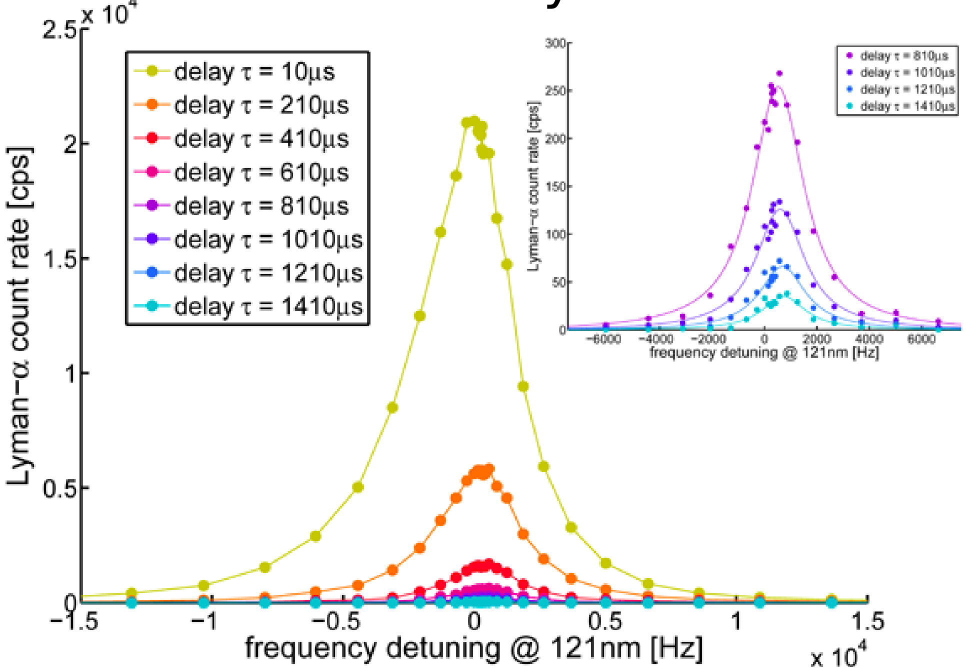


Sub-mK cooling of antihydrogen

- Evaporative cooling
  - Demonstrated on hydrogen [I. D. Setija et al., PRL 70, 2257 (1993)]
- Adiabatic cooling
  - magnetic trapping
  - laser cooling to dissipate extra trapping energy
  - slow decrease of magnetic trap potential
- Raman sideband cooling
  - in magnetic trap or optical lattice trap
- Sympathetic cooling

High resolution spectroscopy

- Similar to H, cold antihydrogen beam interrogated with 243 nm laser
- Single shot sensitivity inversely proportional to SNR and interaction time
- Detection of ~30 atoms/cycle, linewidth <10 kHz -> <10-12/shot statistical uncertainty



Conclusions

- Gravity measurements on antihydrogen are feasible with
  - 10-6 precision with ~1 mK and ~30 atom/min flux
  - ELENA antiproton source
  - laser cooling of Ps to recoil limit (100 mK)
  - sympathetic cooling of antiprotons below 1 mK
  - Raman interferometry on Balmer-alpha line @ 657 nm
  - Sub-μ*g* precision level with temperatures in the μK range
  - Adiabatic cooling, evaporative Raman sideband cooling
- Spectroscopy on 1S-2S transition
  - Possible at 10-12 level in similar conditions