ALPHA AND LASER COOLING ANTIHYDROGEN

ALPHA Collaboration
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OUTLINE

- The ALPHA collaboration
- Why study antimatter and antihydrogen
- The AD and ALPHA machines
- Making trapped antihydrogen
- Laser cooling
- Spectroscopy experimental procedure
- Results (Laser cooling and 1S-2S)
- Future work at ALPHA

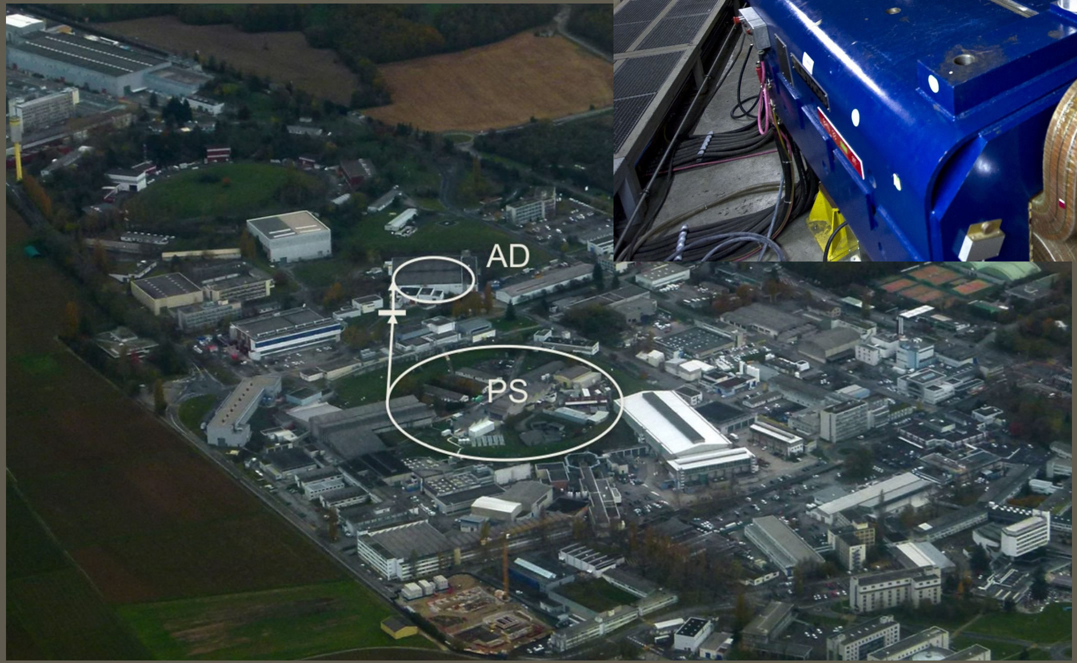
WHY STUDY ANTIMATTER AND ANTIHYDROGEN?

- Study Matter-antimatter asymmetry
  - Why is the universe filled only with matter?
  - Observed symmetry breaking not not sufficiently large to explain cosmic observations
- Use antihydrogen to search for CPT violations
  - Testing fundamental physics
  - Hydrogen is well understood
  - A separate check on high energy studies
- Study the atomic transitions
  - **Measured already to high precision in hydrogen**
- Direct test of the WEP (gravitational measurement)

- Antihydrogen Laser PHysics Apparatus
- 50 people, 8 countries
- At CERN (to be close to the antiprotons)
- Formed in 2006
- Trapped antihydrogen in 2010
- I joined in 2015 when I started my PHD

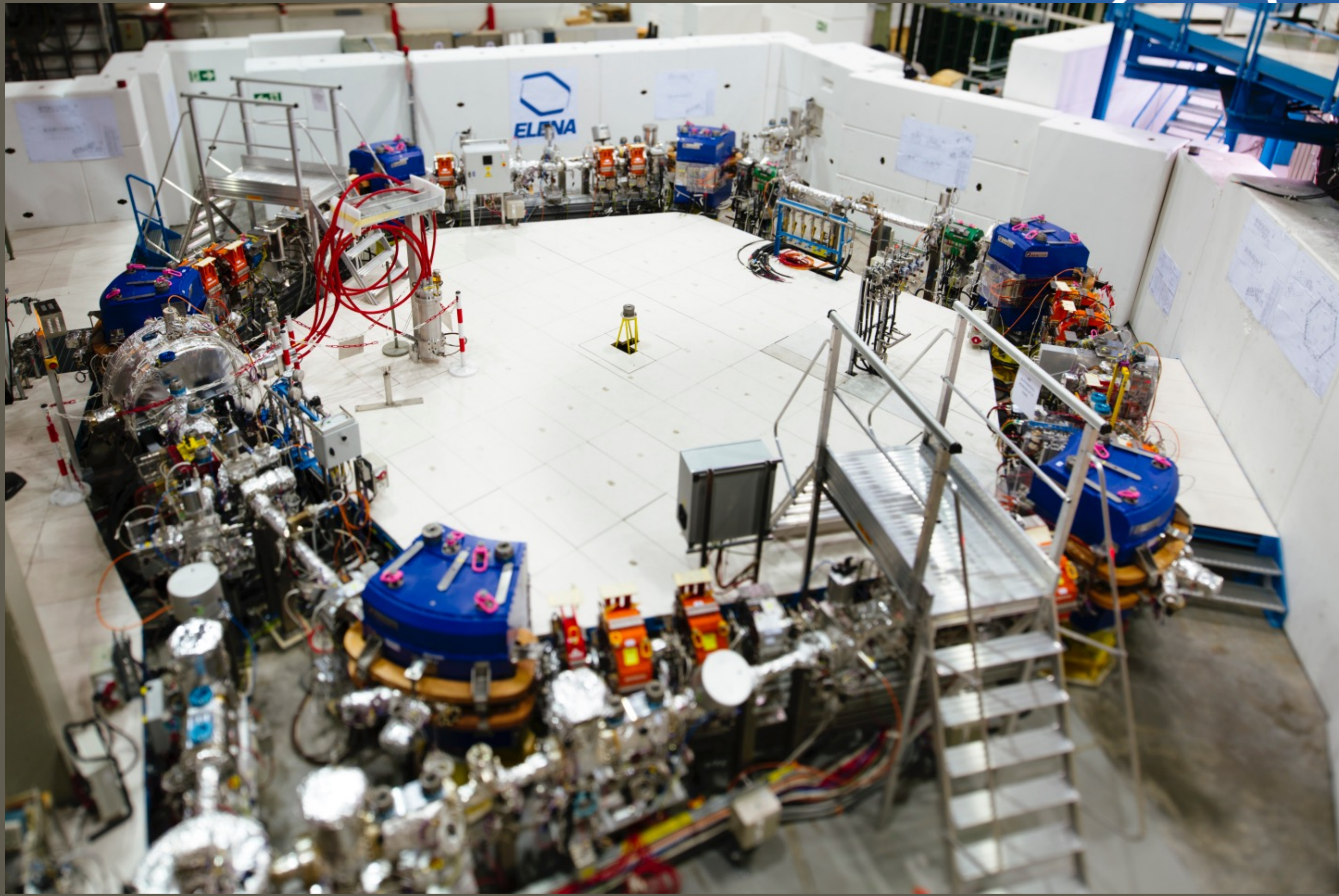
THE ANTIPROTON DECELERATOR & ELENA

- Built in 2000
- Provides bunches of low-energy antiprotons to experiments
  - Uses electron and stochastic cooling to produce bunches of low energy antiprotons. 100 MeV
- Used by many experiments
  - You will hear from more today after me!

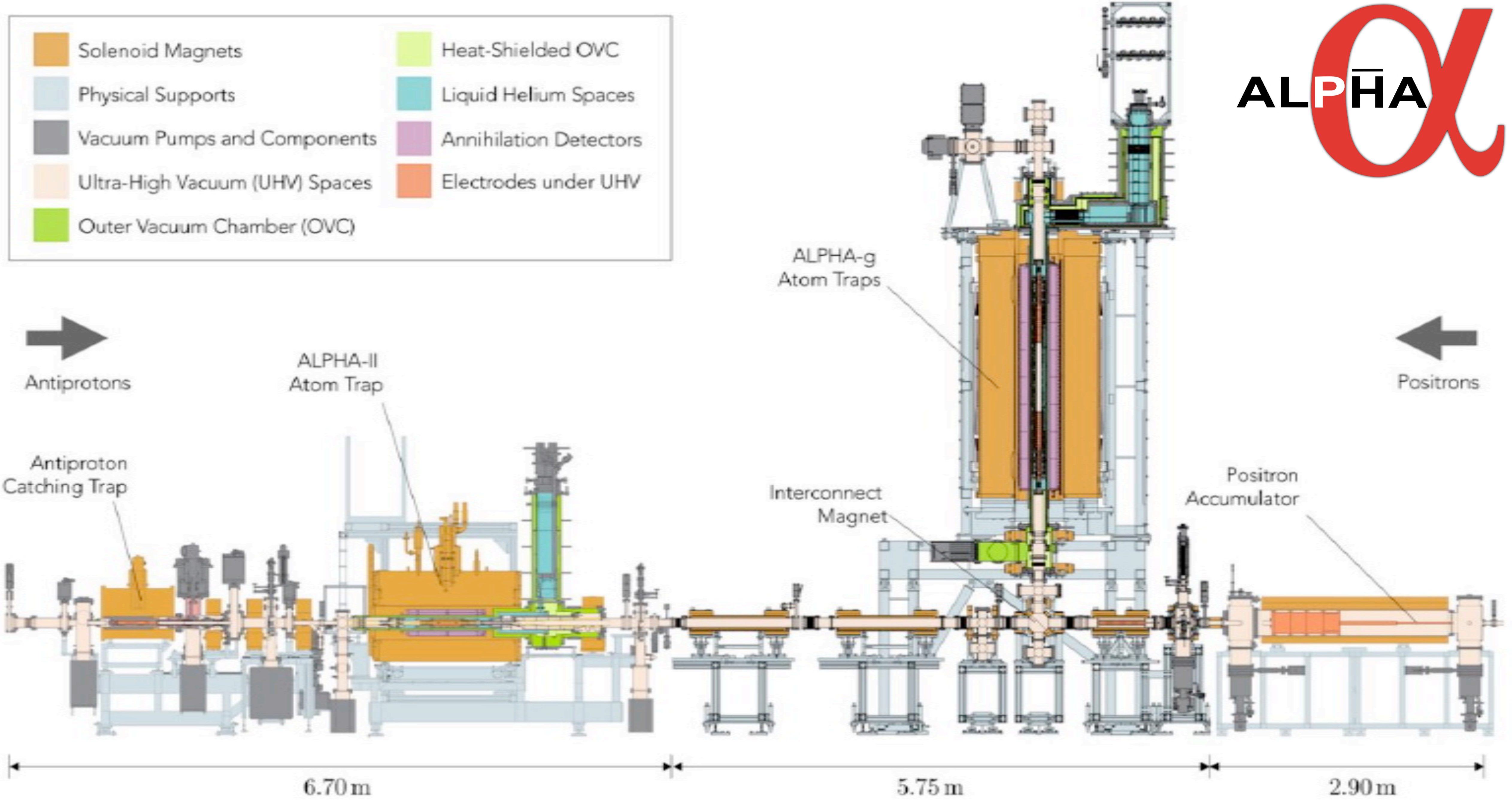


THE ANTIPROTON DECELERATOR & ELENA

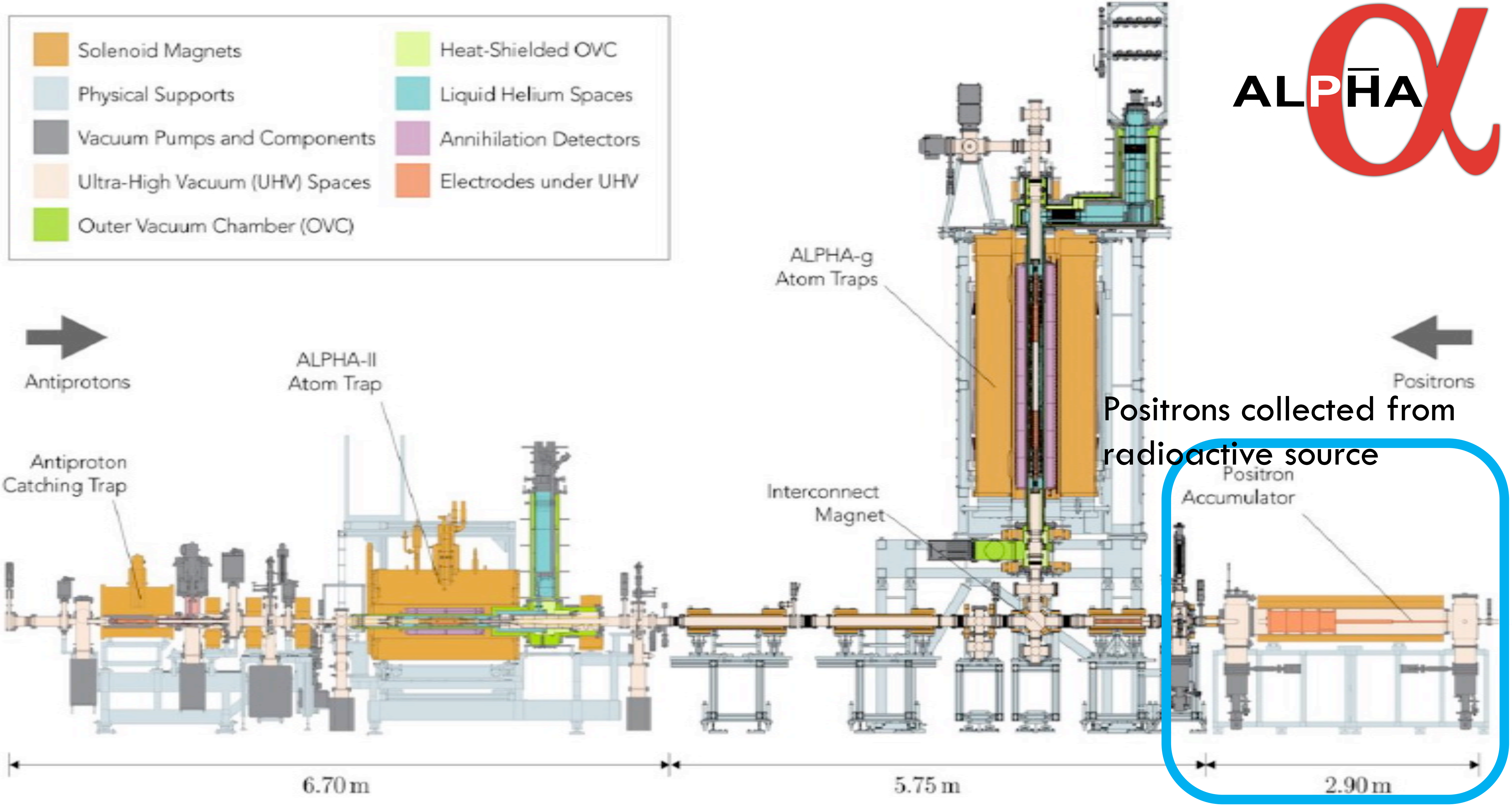
- ELENA first used for antiproton physics in 2021
- Provides antiproton bunches with an energy of 0.1MeV
- Beam all the time!



From www.cern.ch

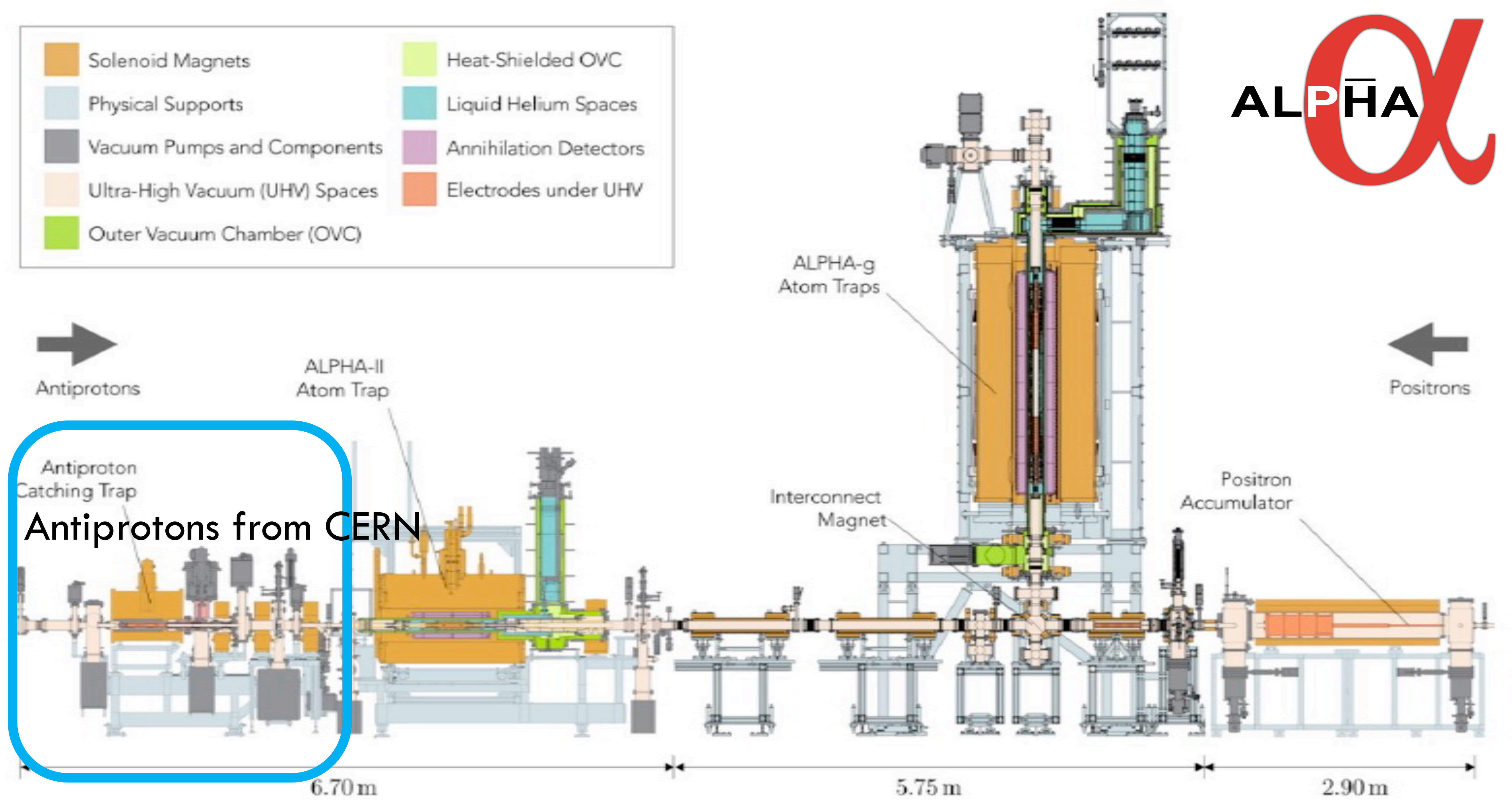


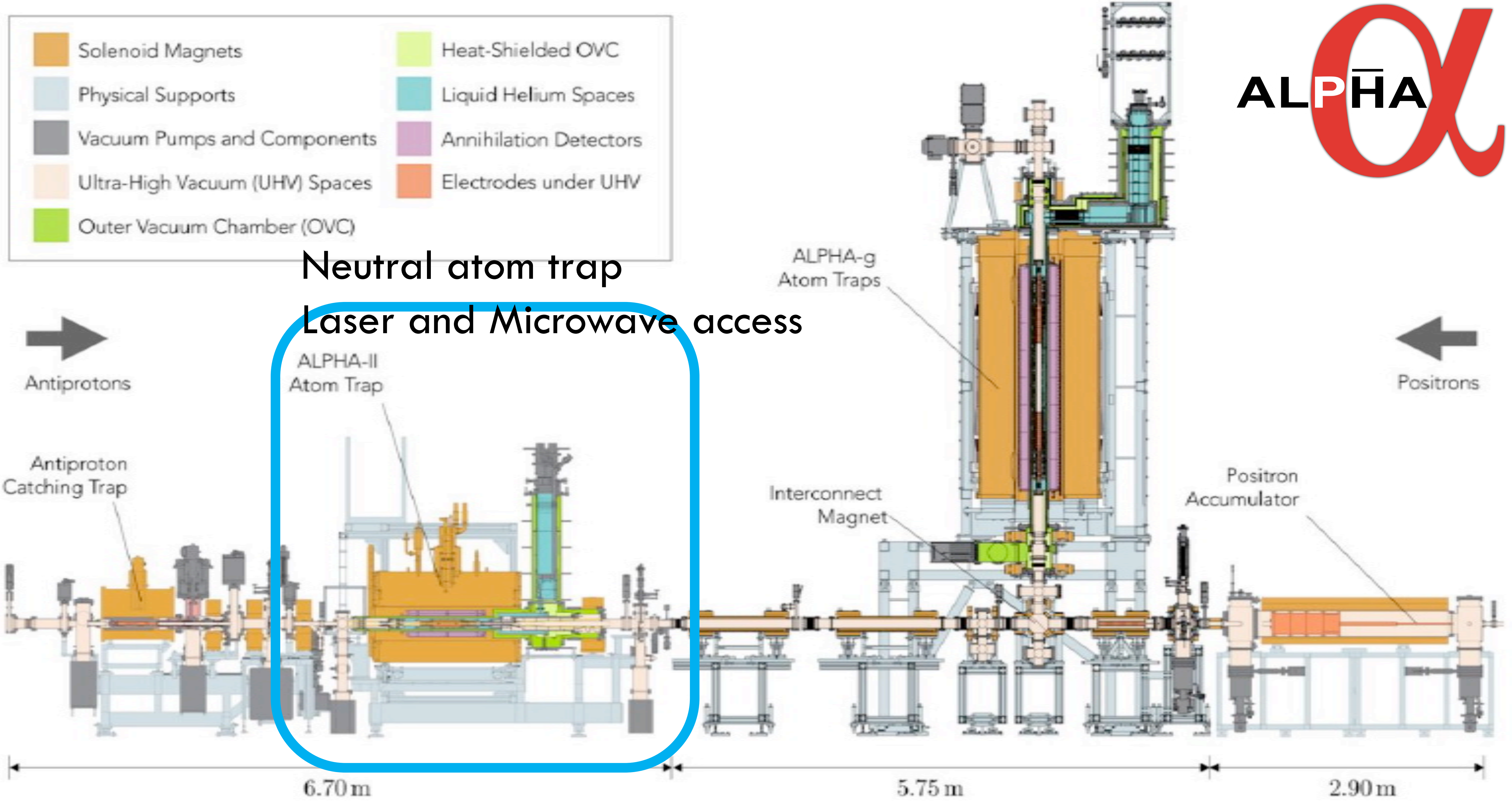
Credit Mark Johnson



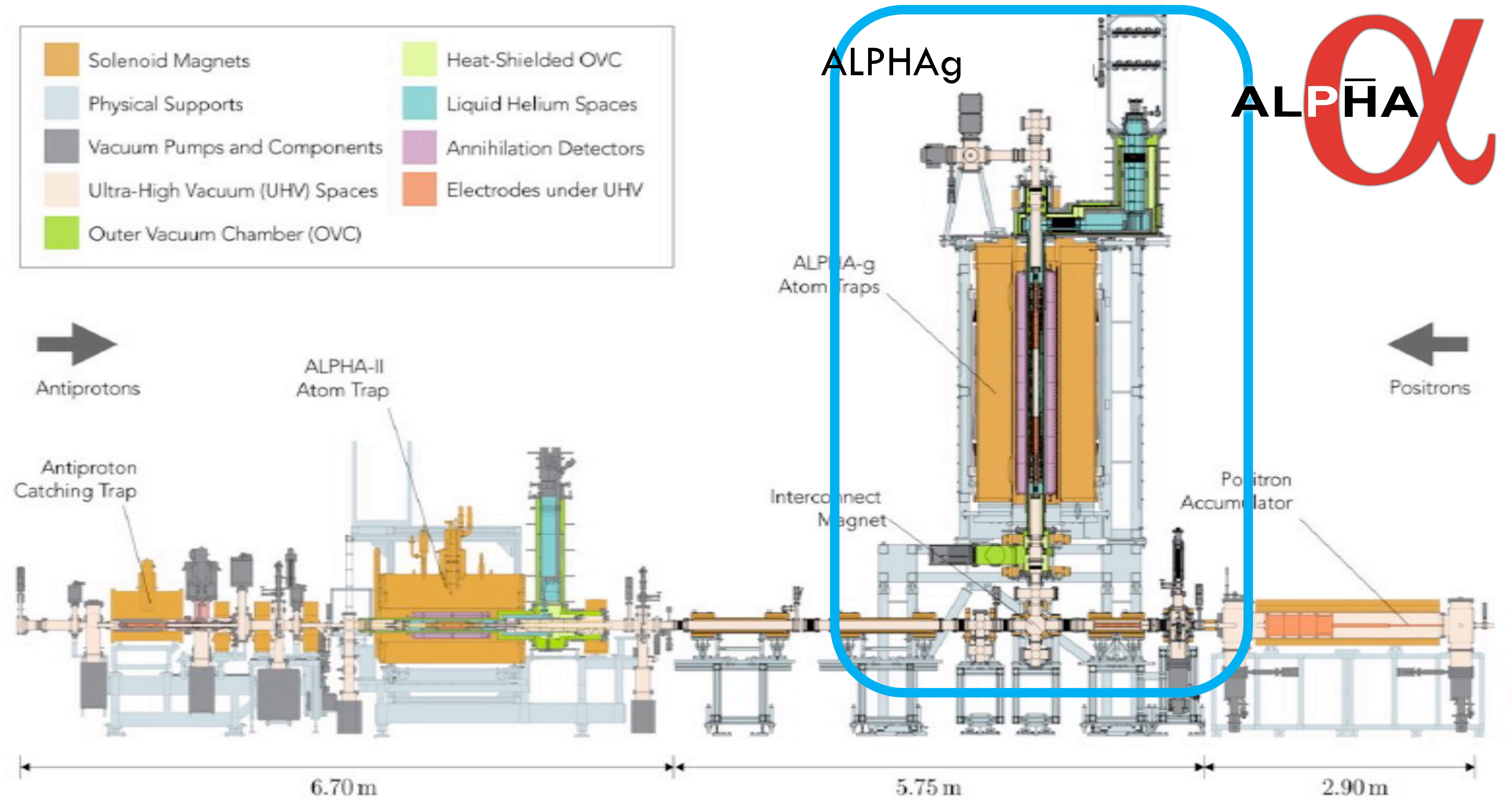
Positrons collected from radioactive source

Credit Mark Johnson


Solenoid Magnets
Physical Supports
Vacuum Pumps and Components
Ultra-High Vacuum (UHV) Spaces
Outer Vacuum Chamber (OVC)
Heat-Shielded OVC
Liquid Helium Spaces
Annihilation Detectors
Electrodes under UHV
ALPHA
ALPHA-g
Atom Traps
Antiprotons
ALPHA-II
Atom Trap
Positrons
Antiproton
Catching Trap
Antiprotons from CERN
Interconnect
Magnet
Positron
Accumulator
6.70 m
5.75 m
2.90 m



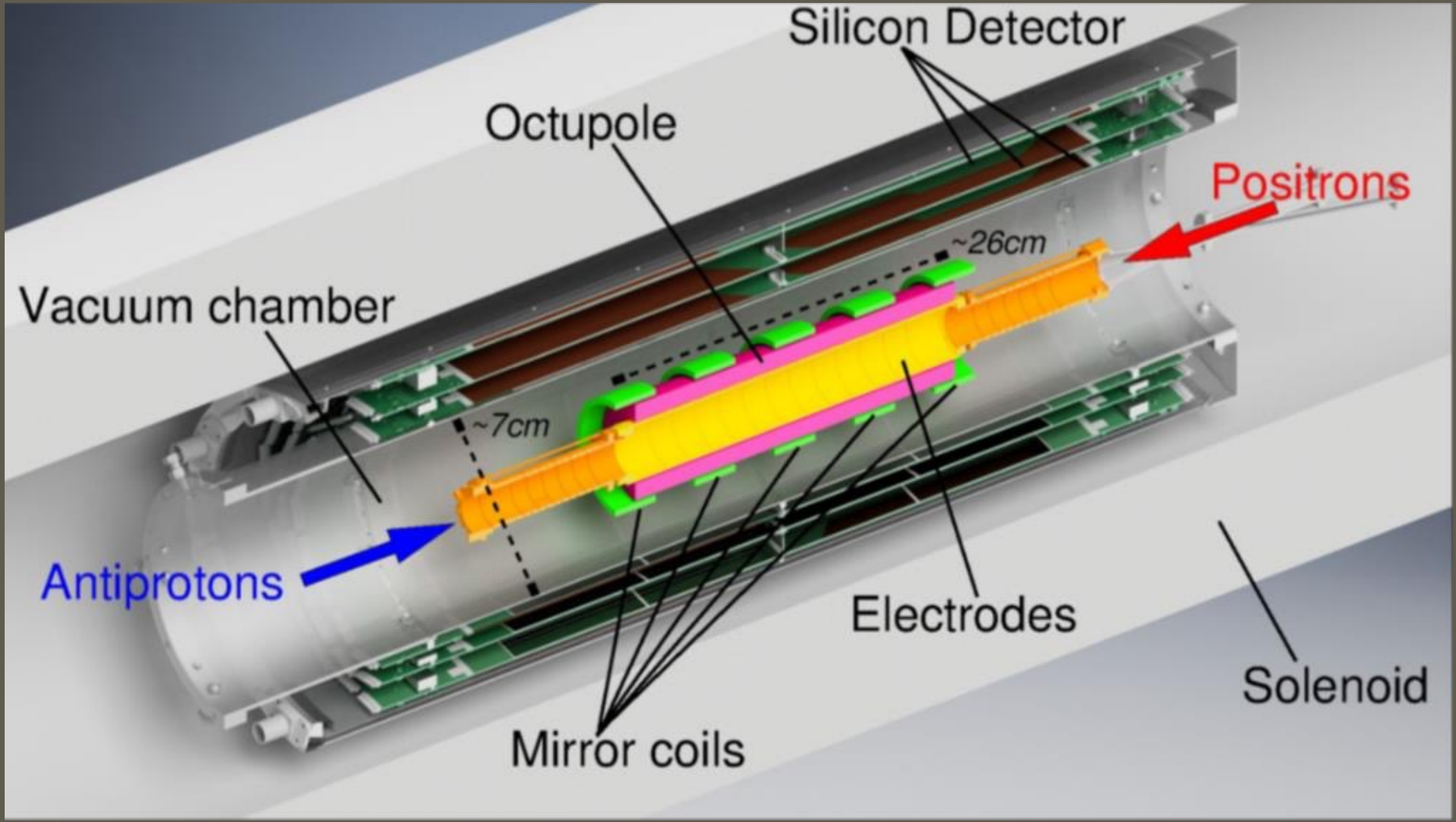
Credit Mark Johnson



Credit Mark Johnson

MAKING ANTIHYDROGEN

Figure credit to Joseph McKenna



Here is a better picture of the inside of ALPHA2

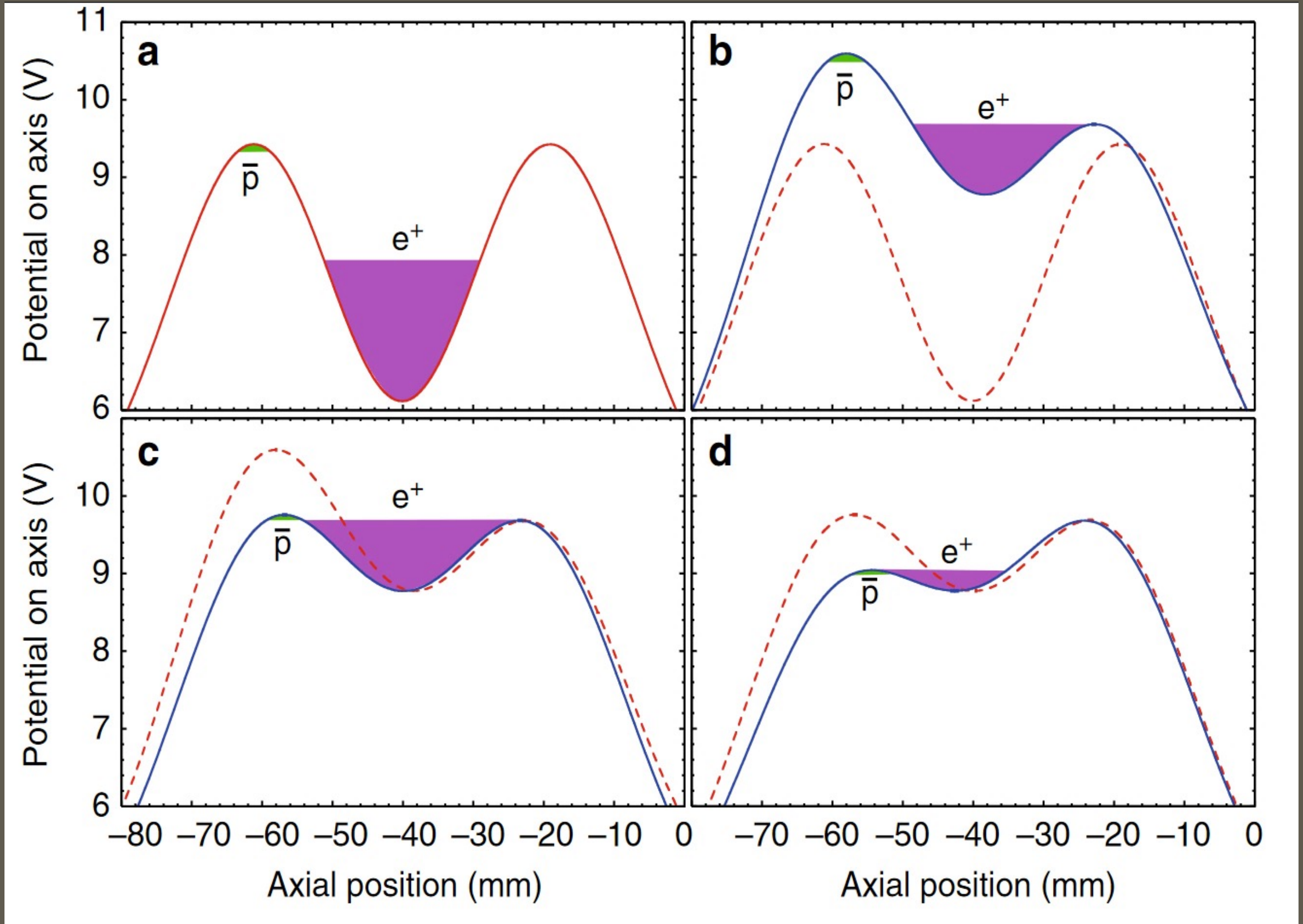
Penning traps for plasma manipulations

Minimum B trap for confining cold antihydrogen

Silicon vertex detector to distinguish matter- antimatter annihilations

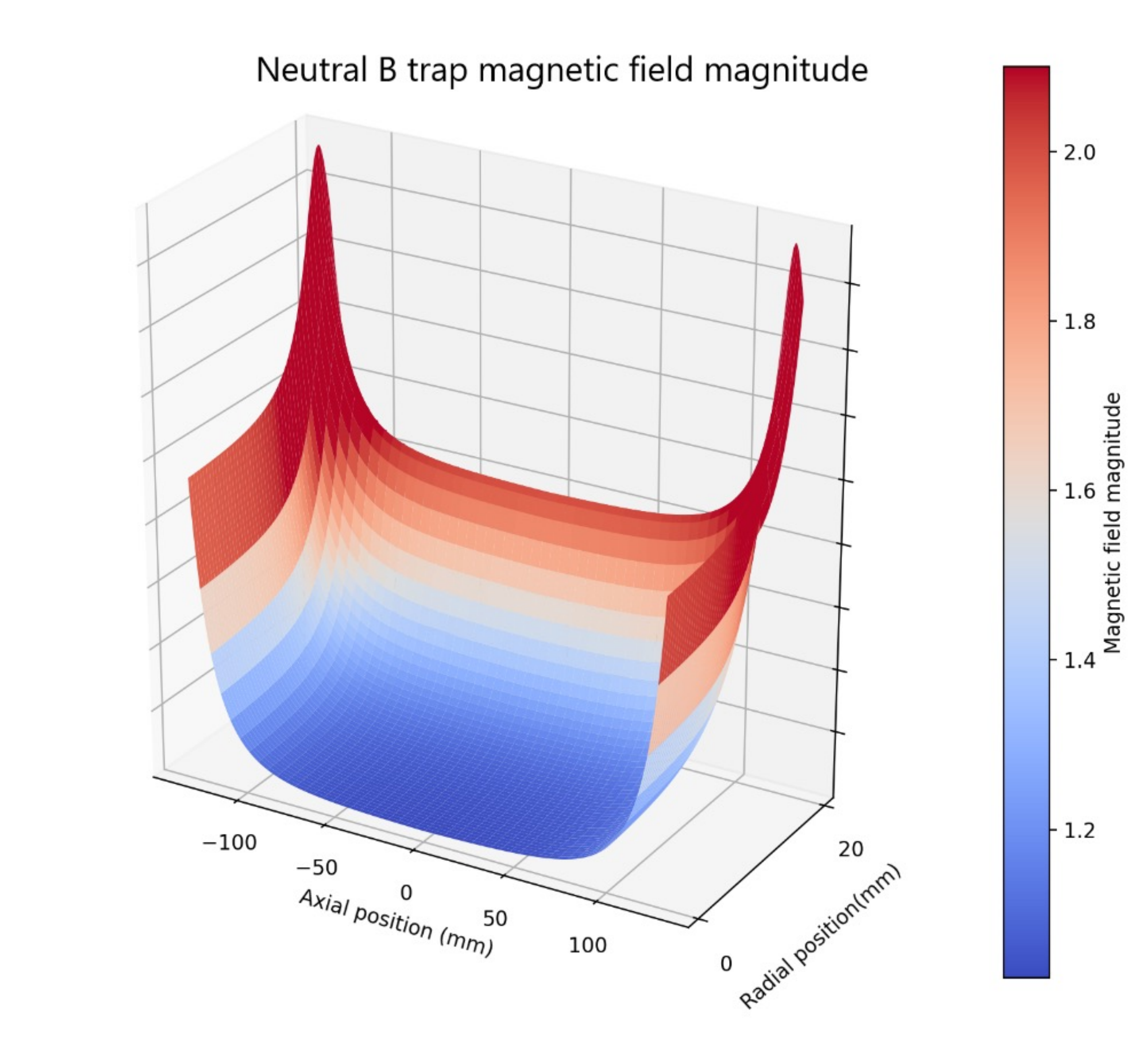
Laser paths and microwave waveguide

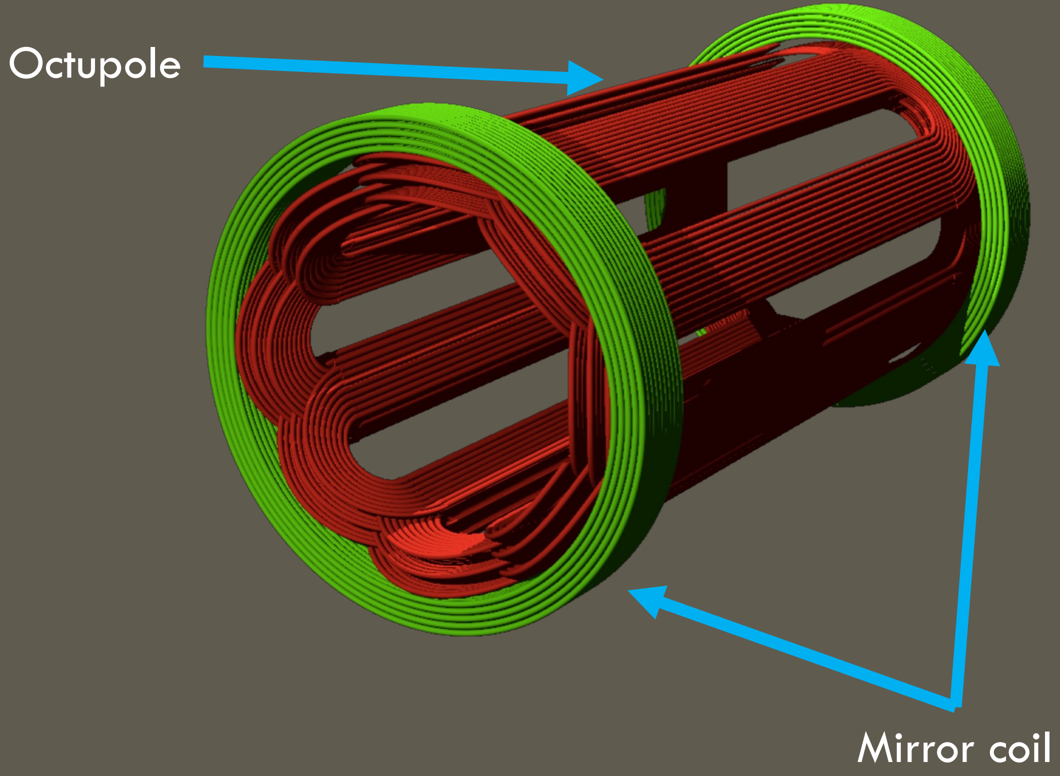
MAKING ANTIHYDROGEN



- Penning trap for non-neutral plasma manipulations
- Antiprotons and positrons simultaneously held
- The positrons are evaporatively cooled, then brough into contact with antiprotons
- Can “reliably” produce samples >1000 antiatoms
- Multiple production steps repeated
- Lifetime for antihydrogen in the trap very long (>60 hours)

MAKING ANTIHYDROGEN





We use a minimum B trap to confine cold antihydrogen (under 0.5K)

$$U_B = \vec{\mu}_H \cdot \vec{B}(r)$$

Atoms with spin aligned with the magnetic field are confined

Other mirror coils used to make magnetic field as flat as possible near the middle of the trap

LASER COOLING

Ubiquitous in atomic physics

Necessary for high precision spectroscopy

Being able to laser cool antihydrogen is a game-changing breakthrough in the study of antimatter

High precision anti-atom spectroscopy will soon become possible

Laser cooling hydrogen is UGLY!

Large recoil velocity (1.2mK)

Large doppler limit (2.4mK)

High energy photons (121nm)

Small sample size (antihydrogen)

- ~500 -1000

LASER COOLING

Use photon collisions to slow trapped atoms

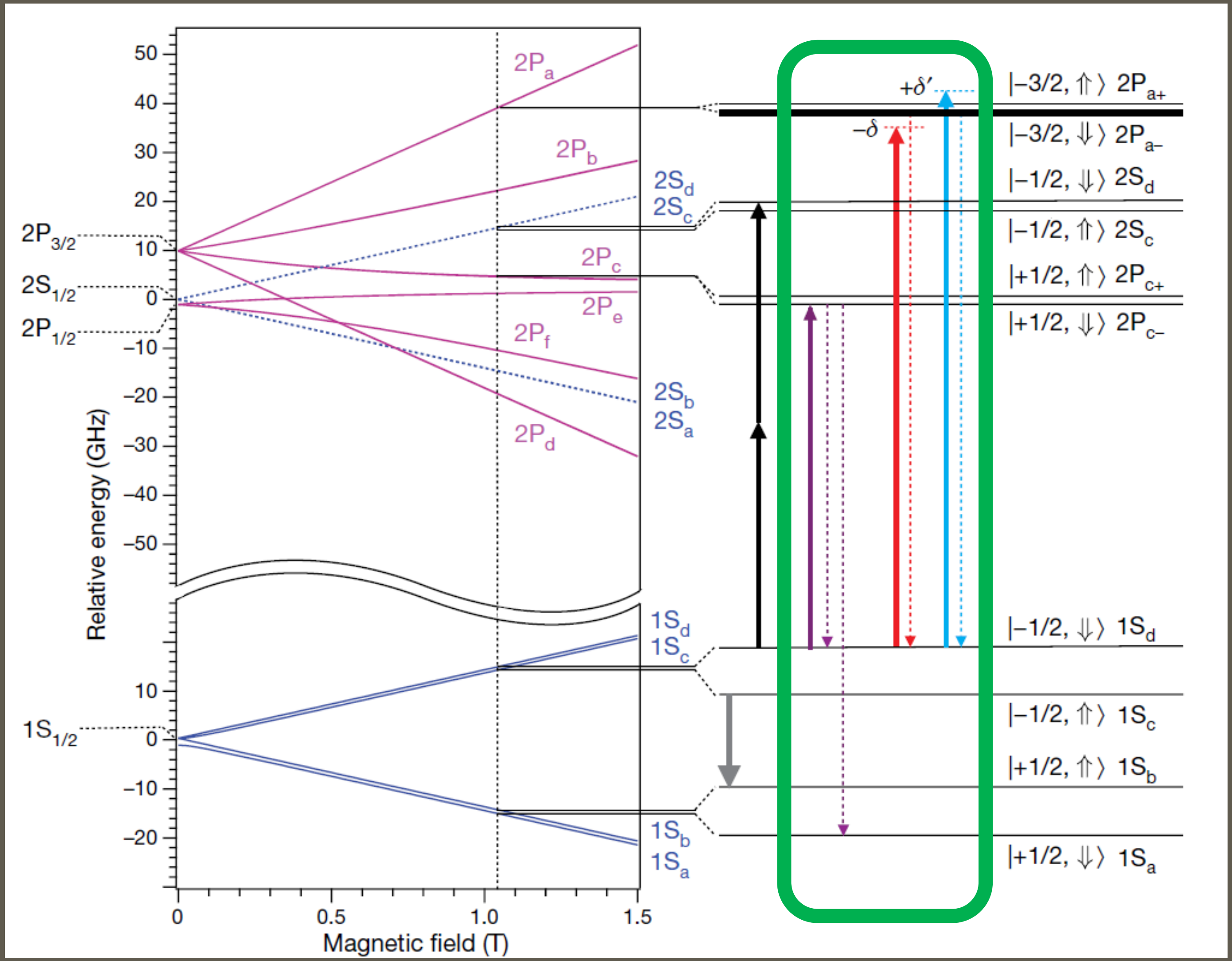
Drive a detuned optical transition

- Doppler cooling

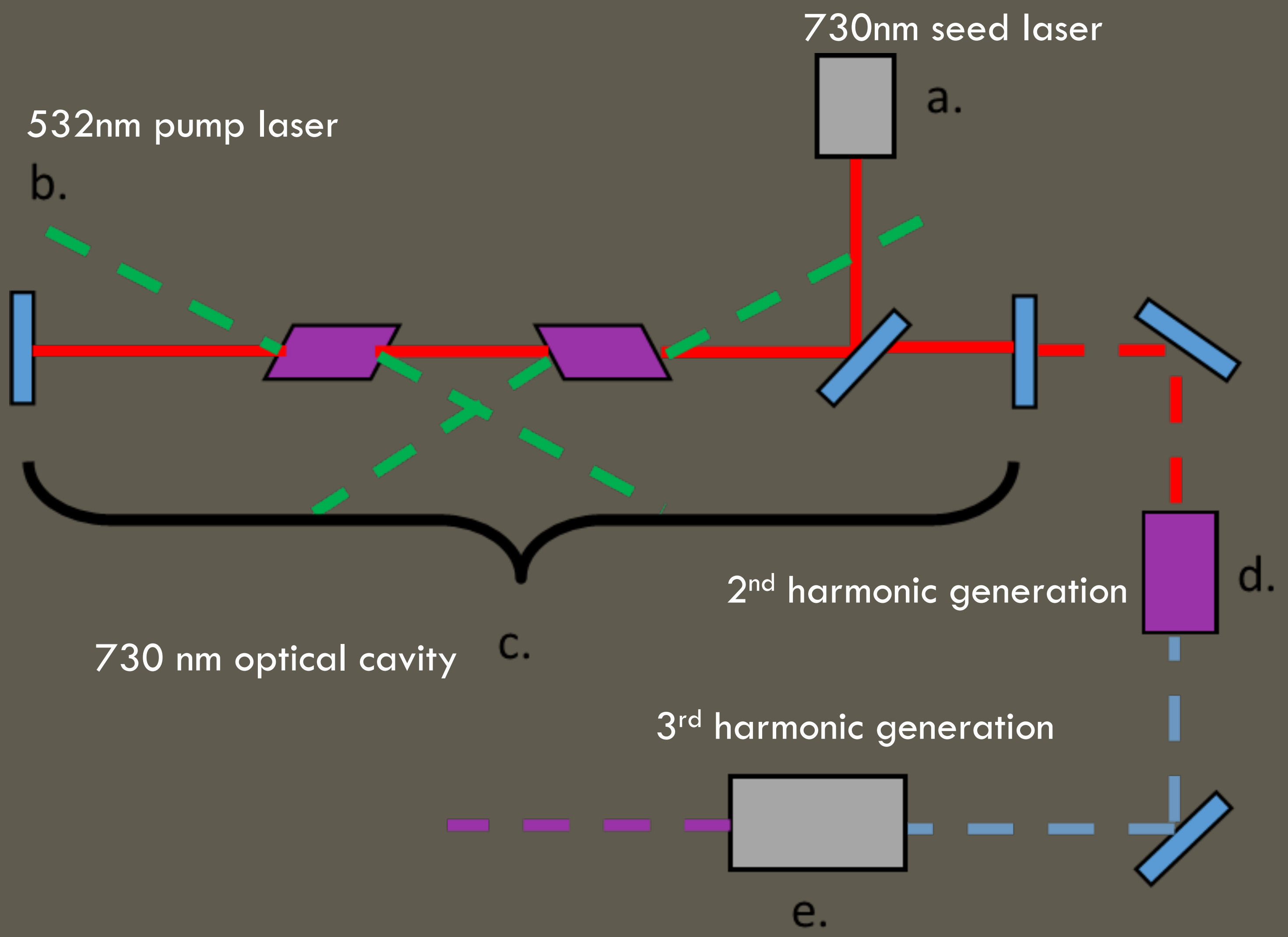
Not many choices in hydrogen

- Energy level difference between ground and first excited state is large

Breit Rabi diagram for hydrogen



121NM LASER



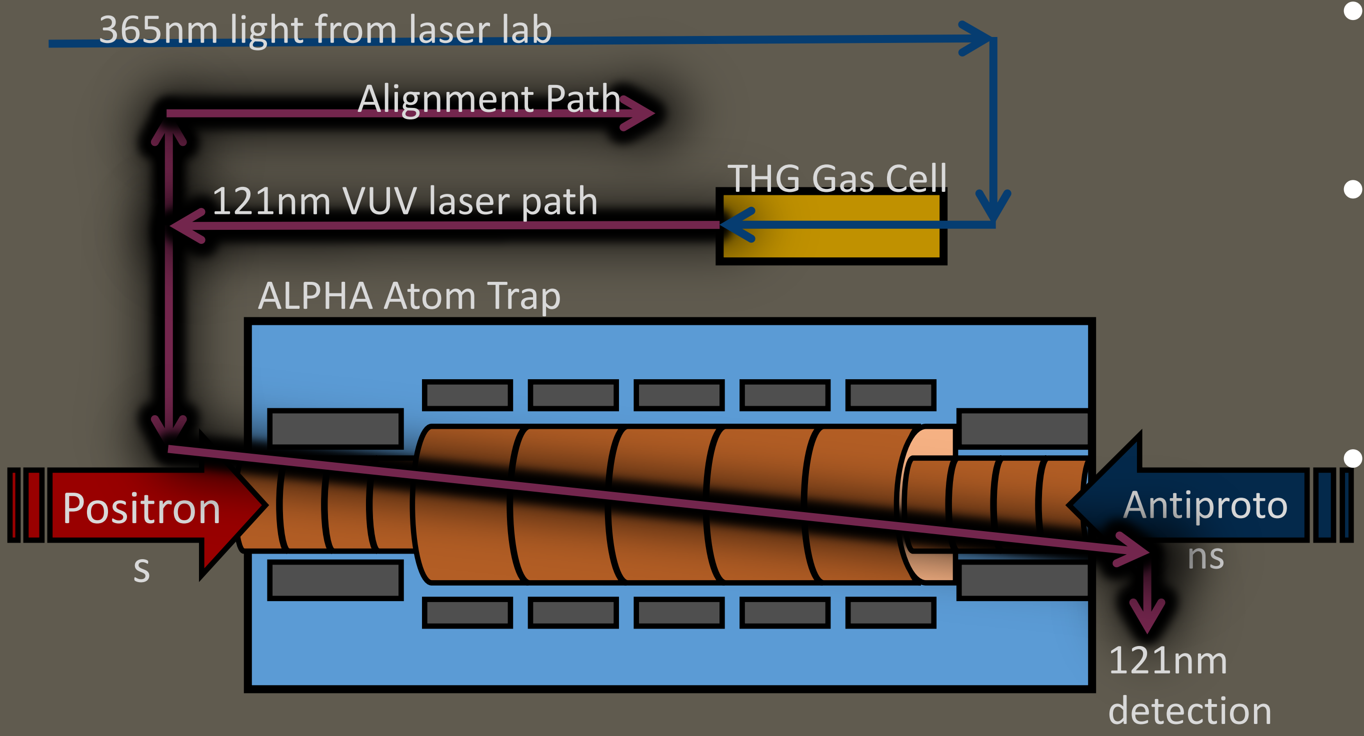
Short wavelength light is hard to produce at high powers!

We use a pulsed Lyman alpha laser (10hz) for maximum peak power

- SHG ∝ E^2
- THG ∝ E^3

14-25 mj 356nm pulses
500-900 pJ 121nm pulses

121NM LASER



Short wavelength light is hard to work with

- Absorbed by everything
- Must be kept in vacuum (1E-6mbar)
- You cant see it! Aligning it through anything is awful
- Alignment path used to help recover after interventions on the apparatus
- Laser is 2.3° off axis

SPECTROSCOPY PROCEDURE

- Repeat the antihydrogen production sequences back-to-back while keeping the neutral trap on (~2-4h) produced samples of about 500- 1000 antiatoms
  - Called "stacking"
- (Optional) Laser cool while the antihydrogen sample is being prepared
- Wait for antihydrogen atoms with high energy leave the trapping field and for sample to decay to the ground state
- Microwave ejection of 1Sc hyperfine state
  - Can't cool both at the same time!
- Laser cool trapped antihydrogen sample (~2-4h)

SPECTROSCOPY PROCEDURE

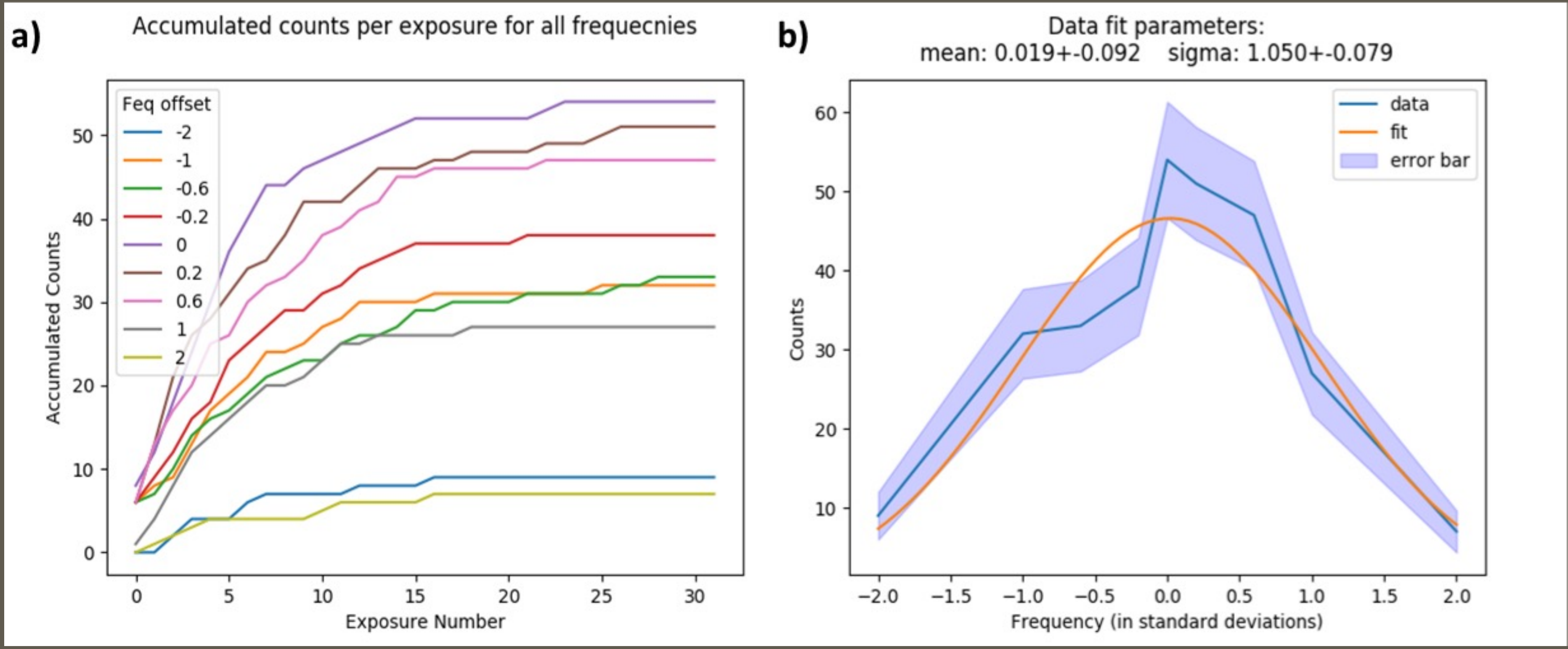
Study multiple frequencies with a single sample

Set of frequencies is cycled through (forward then in reverse)
- This is repeated

20 – 50s per frequency point

Can only remove a small fraction of the sample each time to avoid systematic error

Simulation

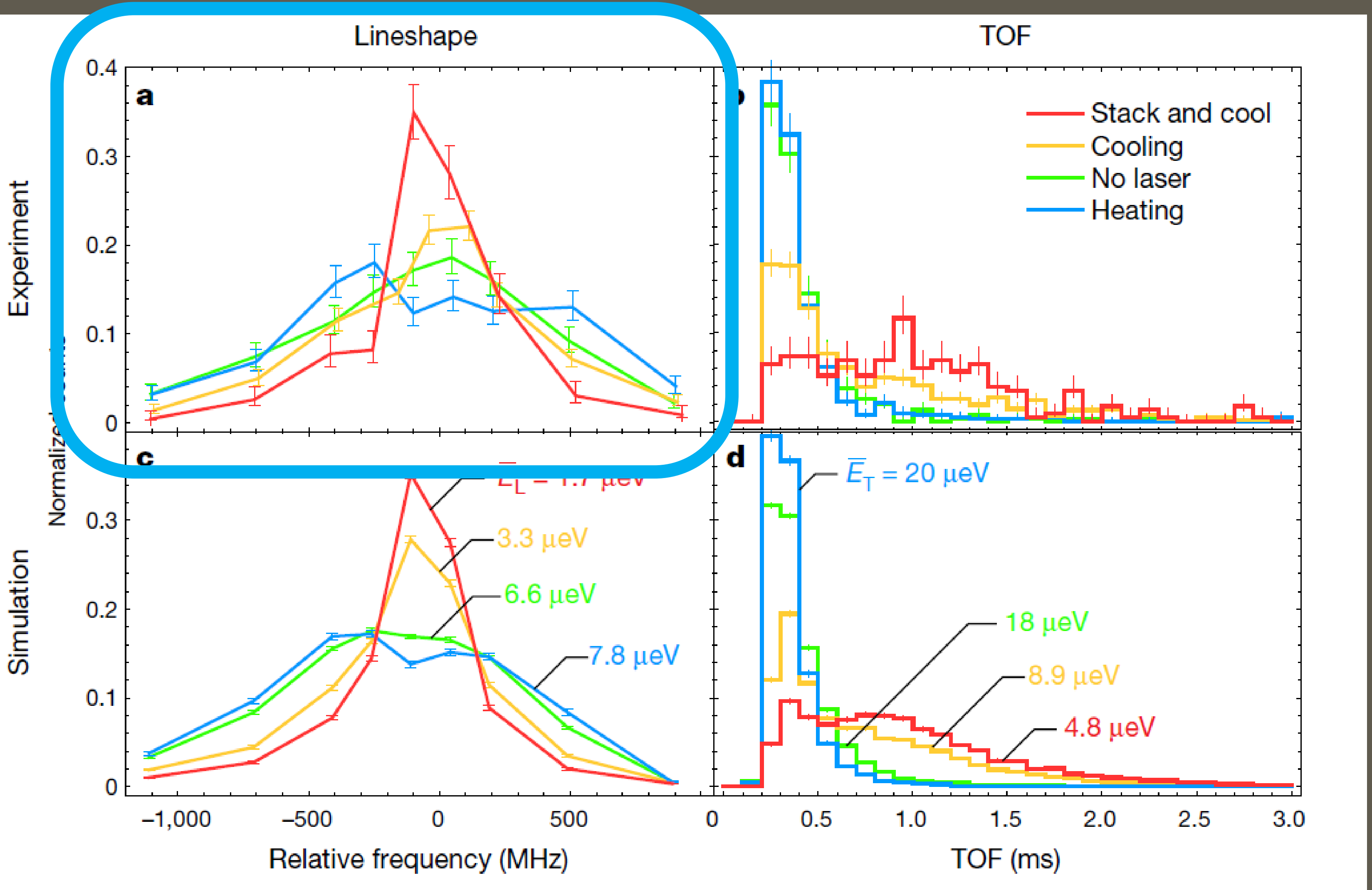


RESULTS

This represents the culmination of years of work by many people

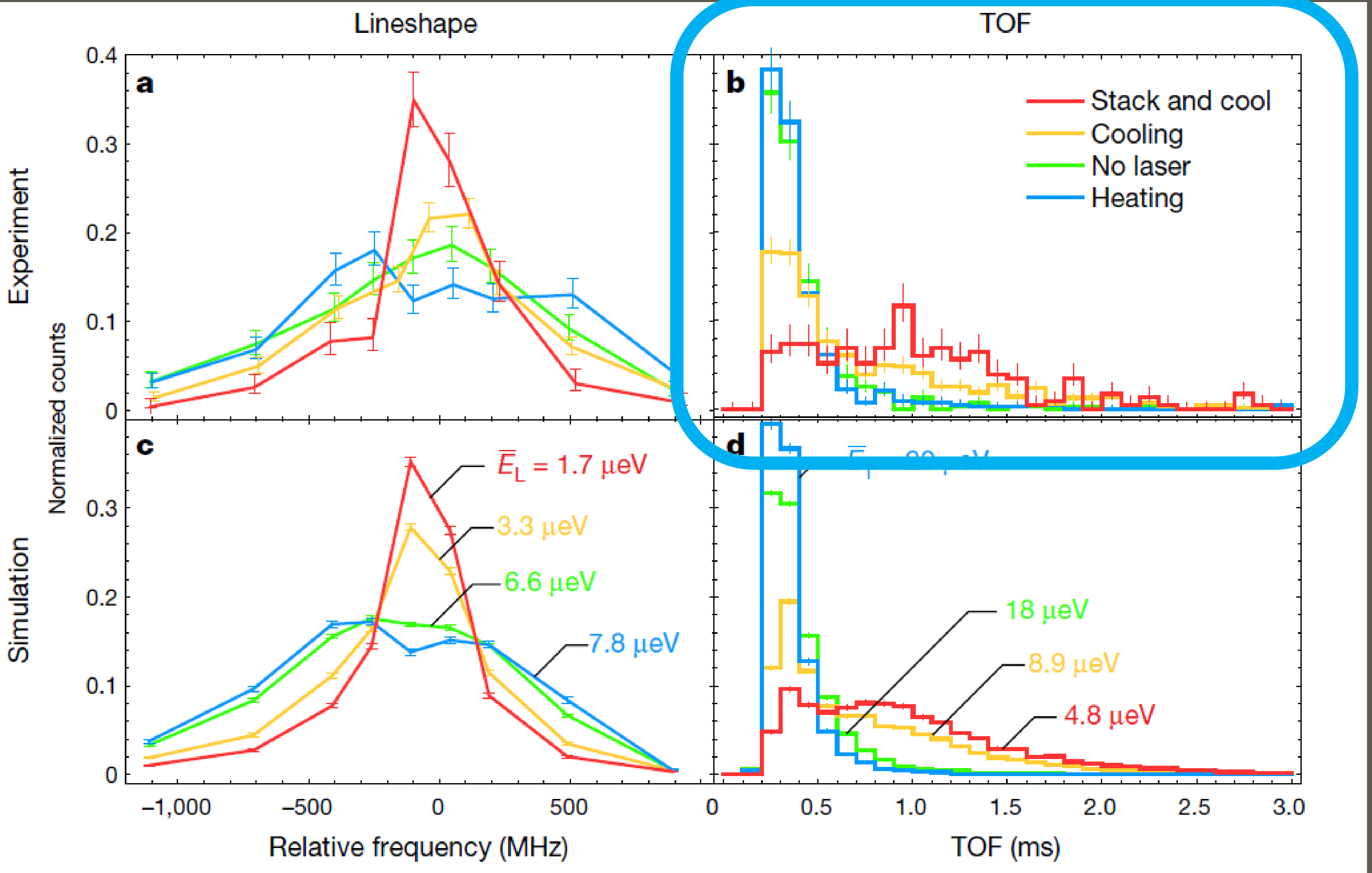
LASER COOLING

- We see a change in the spectrum line-width
  - Doppler broadening
  - Cooling frequency detuned by -230 MHz
  - Heating frequency detuned by +160 MHz



1Sd-2Pc-

LASER COOLING



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  - Pulsed laser allows gating measurement

1Sd-2Pc-

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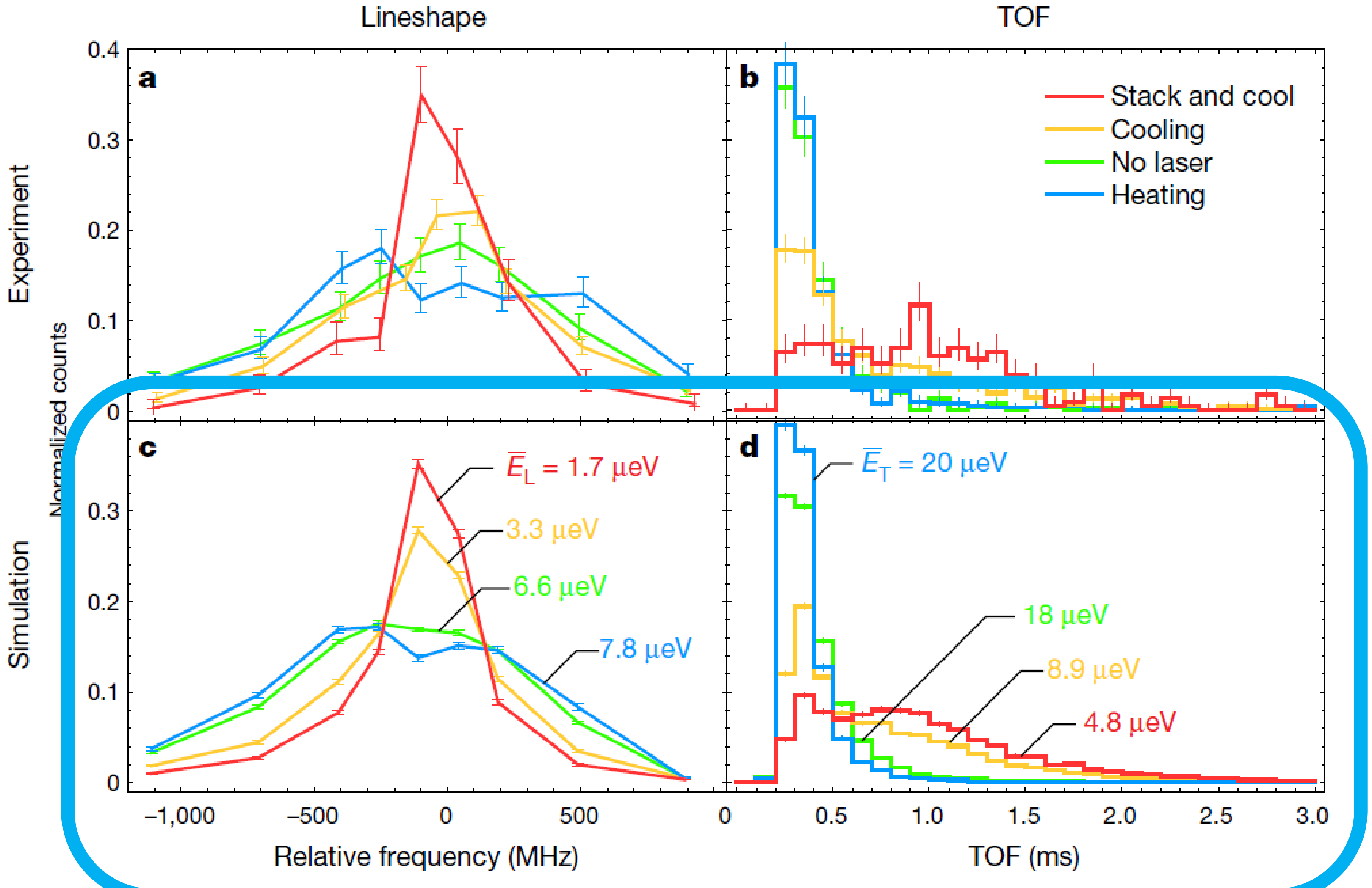

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- Computer simulations of laser cooling process qualitatively match experimental data
  - Samples do not have the same axial and transverse energy…expected

1Sd-2Pc-

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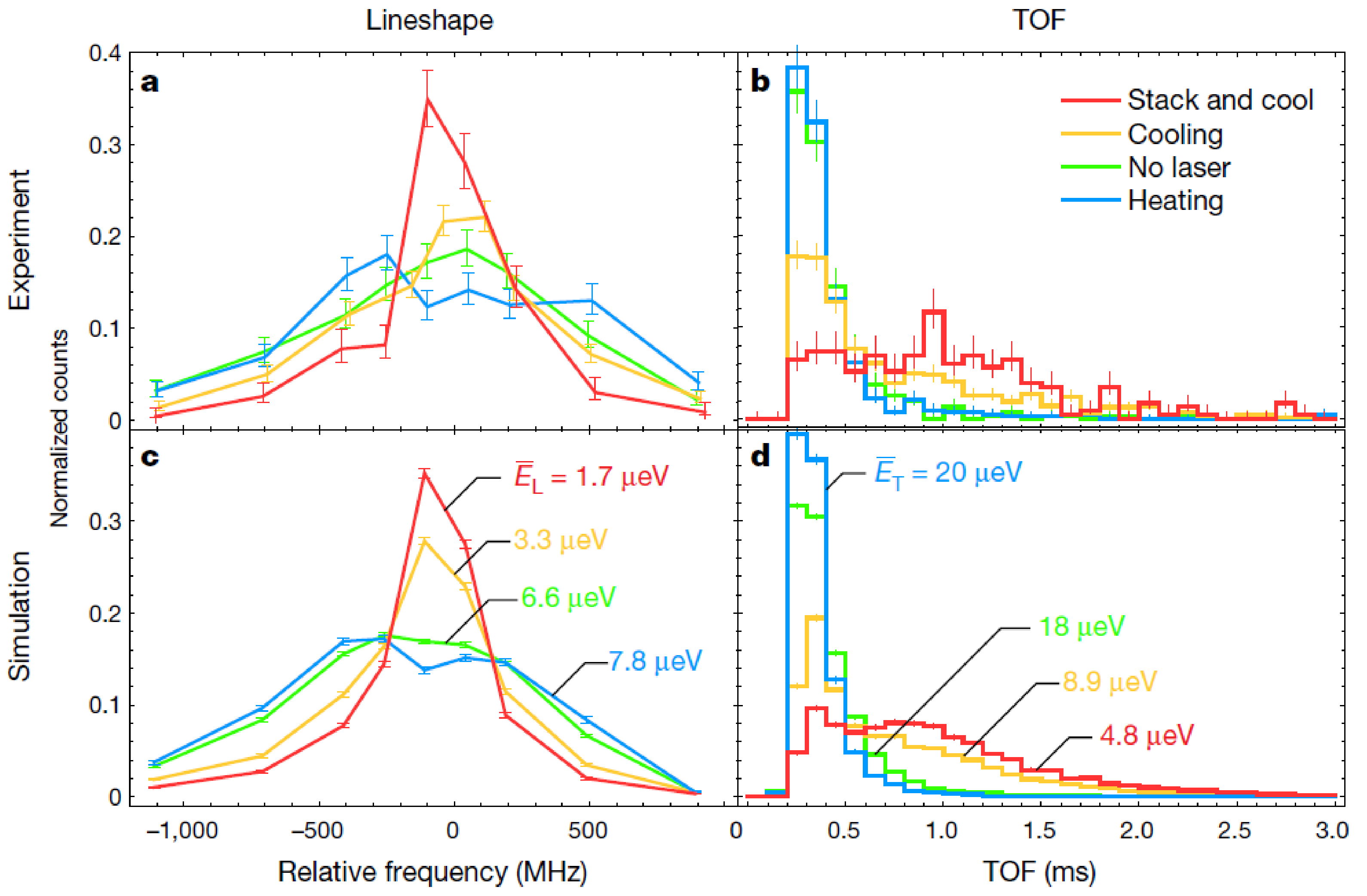

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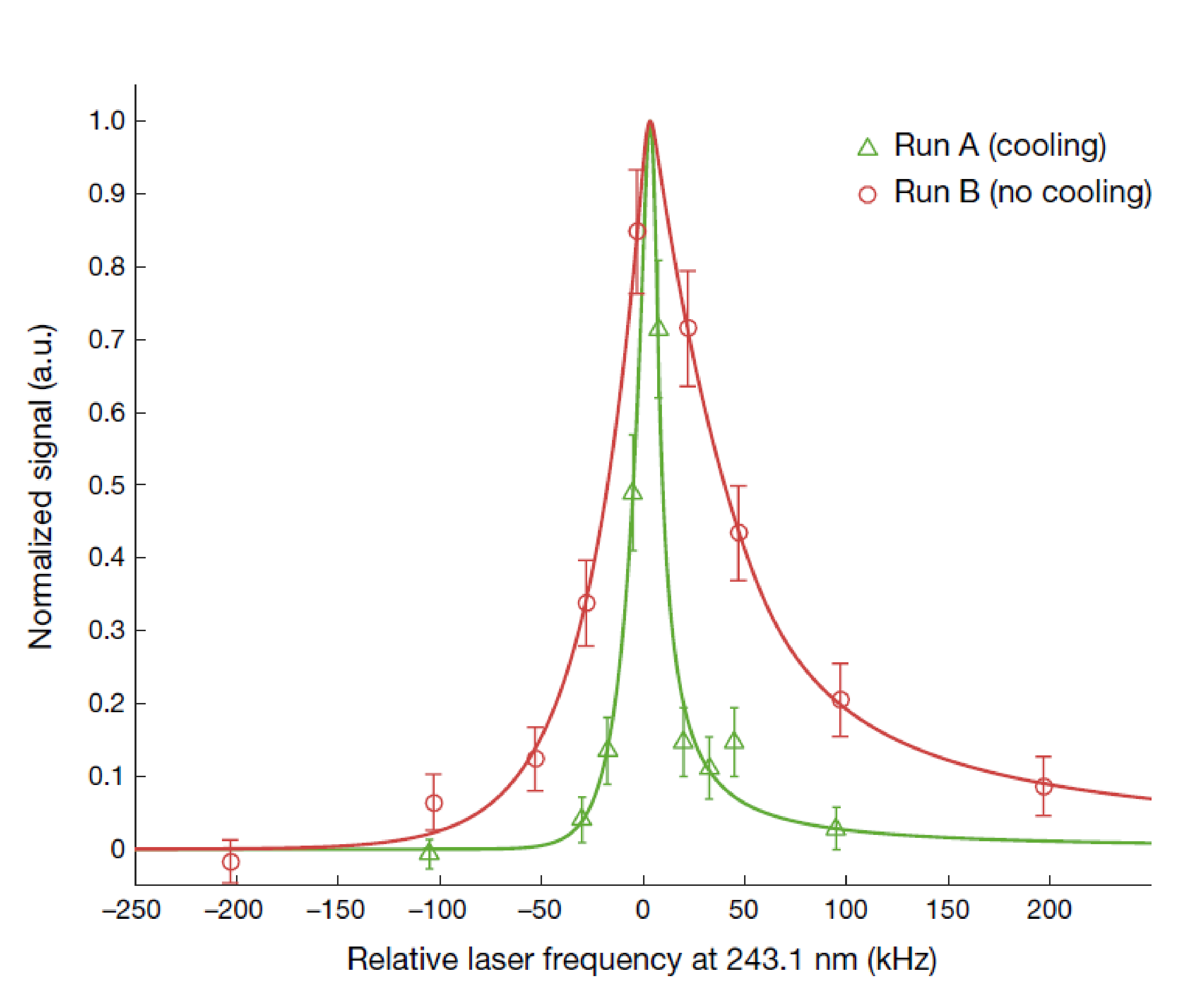
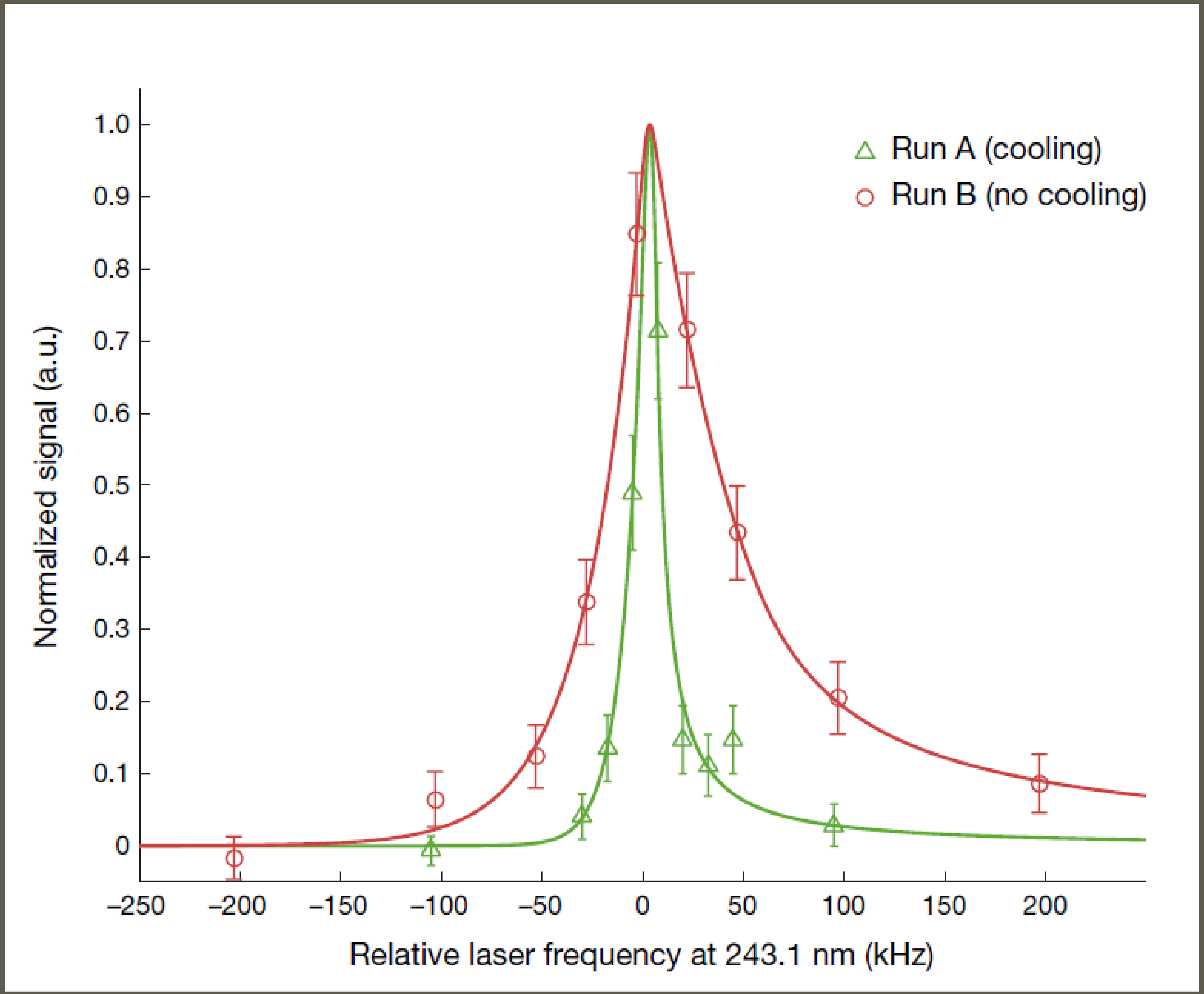


A set of laser cooled 243nm spectroscopy runs were performed using the same experimental procedure as the 121nm runs

The FWHM decreased by about a factor or four

We estimate a change in the kinetic energy by a factor of 16

LASER COOLING



ALPHA will measure this transition many more times. This was only the third time we have measured this line-shape.

New cesium clock (time reference)

New physics campaign (more statistics)

- Each of these runs had a antihydrogen sample of about 500

Old measuring (2018)

- Measured $F_{d\text{-}d}$=2,466,061,103,079±5 kHz
- Expected $F_{d\text{-}d}$=2,466,061,103,080.3±0.6 kHz

Measurement in hydrogen is more accurate by 3 orders of magnitude

UNFORESEEN PROBLEMS

Long Runs

- Magnet systems need to stay on!

Timing of events must be very precise

- Clock stability becomes an issue

Laser stability

- Making gas mixtures is gross

Low laser power

- Bigger pump laser!

FUTURE STUDIES OF ANTIHYDROGEN

ALPHAg

- Gravitational measurement

ALPHA2

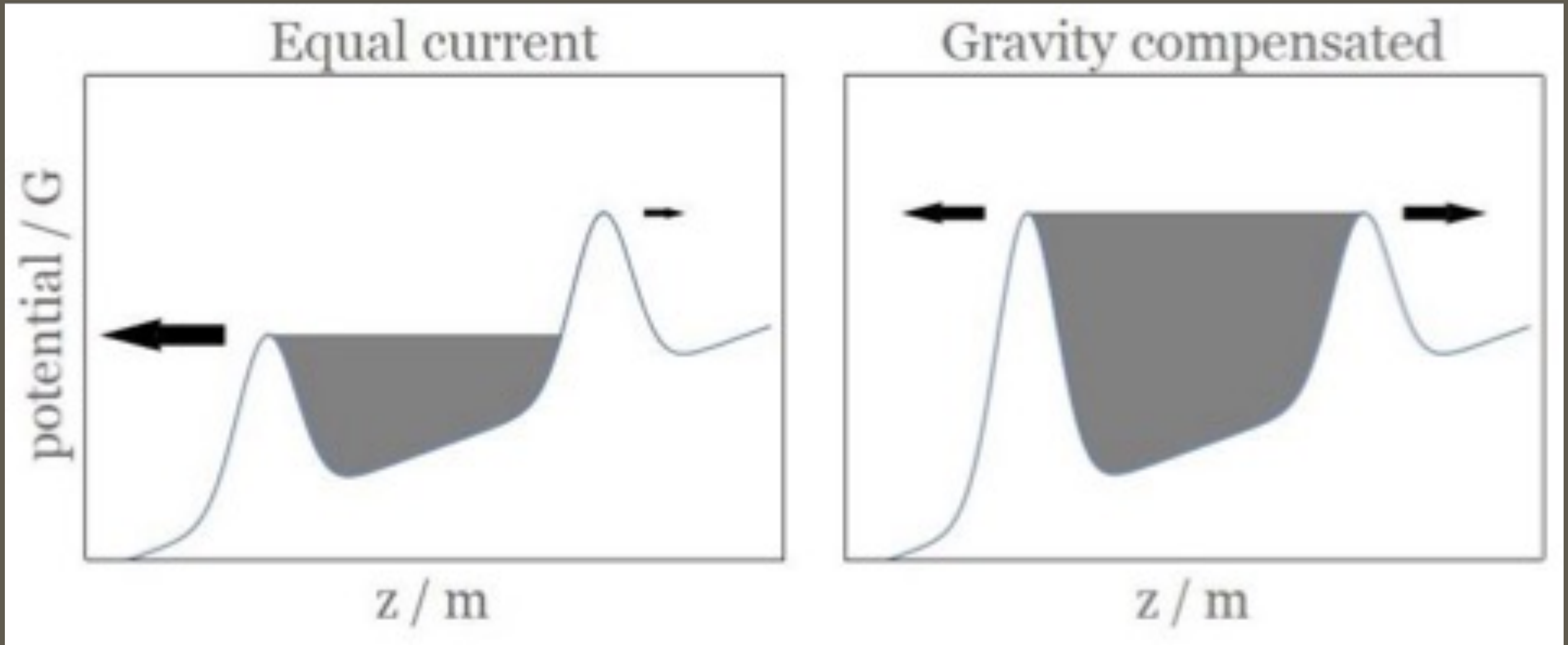
- Direct Lamb shift measurement
- Laser cooled positrons (beryllium)
- Laser and metrology upgrade

Hydrogen source

- Comparing both species in the same environment

Exciting future for study of antihydrogen

FUTURE STUDIES OF ANTIHYDROGEN



ALPHAg

- Gravitational measurement
- New apparatus
  - New magnet system, detector, Penning trap…..
- Create antihydrogen, then slowly release it with different potential well configurations
- Laser cooling important for precision measurement
- Magnetometry is very important
  - 400 μT for “up/down”
  - 7 μT for “high precision”
  - Current magnetometry near 35μT

CONCLUSION

- Demonstrated laser cooling of antihydrogen
- Measured 1S-2S, and 1S-2P transitions of antihydrogen in a laser cooled sample
- No symmetry violations …. Yet …..
- Hard at work on preparing ALPHAg for the "up/down" measurement
- Future plans
  - Improve the precision of the 1S-2S and direct lamb shift measurement
  - Hydrogen spectroscopy in the same magnetic environment

THANK YOU

PUBLICATIONS

Publications:

- Baker, C.J., Bertsche, W., Capra, A. *et al*. Laser cooling of antihydrogen atoms. *Nature* **592**, 35–42 (2021)
- The ALPHA Collaboration., Ahmadi, M., Alves, B.X.R. *et al*. Investigation of the fine structure of antihydrogen. *Nature* **578**, 375–380 (2020)
- Ahmadi, M., Alves, B.X.R., Baker, C.J. *et al*. Observation of the 1S–2P Lyman-α transition in antihydrogen. *Nature* **561**, 211–215 (2018)
- Ahmadi, M., Alves, B.X.R., Baker, C.J. *et al*. Characterization of the 1S–2S transition in antihydrogen. *Nature* **557**, 71–75 (2018)
- M. Ahmadi et al. (ALPHA Collaboration) Enhanced Control and Reproducibility of Non-Neutral Plasmas. Phys. Rev. Lett. 120, 025001 (2018)
- Ahmadi, M., Alves, B.X.R., Baker, C.J. *et al*. Antihydrogen accumulation for fundamental symmetry tests. *Nat Comm* **8**, 681 (2017)
- Ahmadi, M., Alves, B., Baker, C. *et al*. Observation of the hyperfine spectrum of antihydrogen. *Nature* **548**, 66–69 (2017)
- Ahmadi, M., Alves, B., Baker, C. *et al*. Observation of the 1S–2S transition in trapped antihydrogen. *Nature* **541**, 506–510 (2017)