THE ALPHA COLLABORATION

Aarhus University, Denmark

University of Brescia, Italy

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

University of Groningen, Holland

Pisa and Pavia Italy

University of Manchester, UK

NRCN - Nuclear Res. Center Negev, Israel

Purdue University, USA

Federal University of Rio de Janeiro, Brazil

Stockholm University, Sweden

Simon Fraser University, Canada `

TRIUMF, Canada

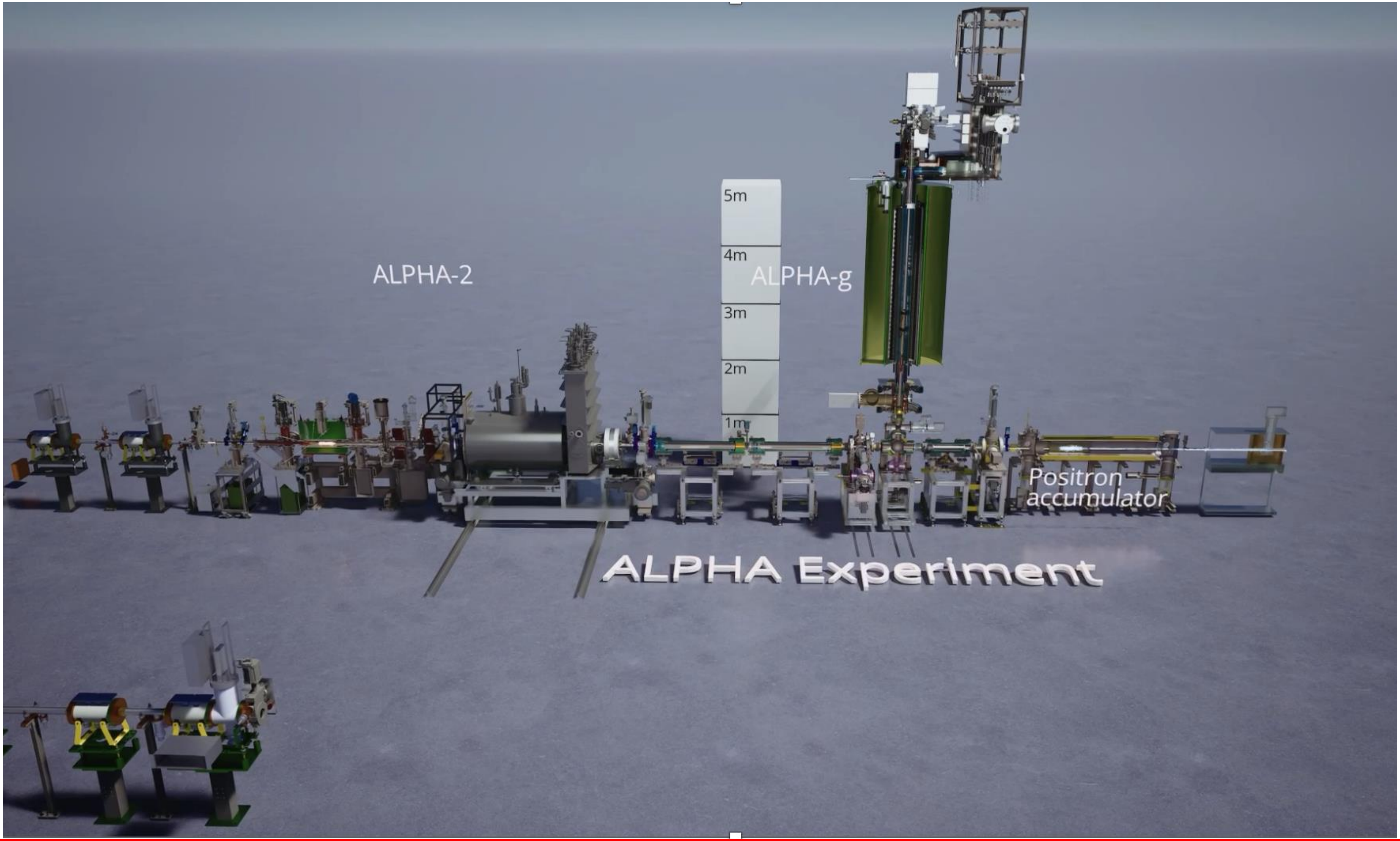
University of Wales Swansea, UK

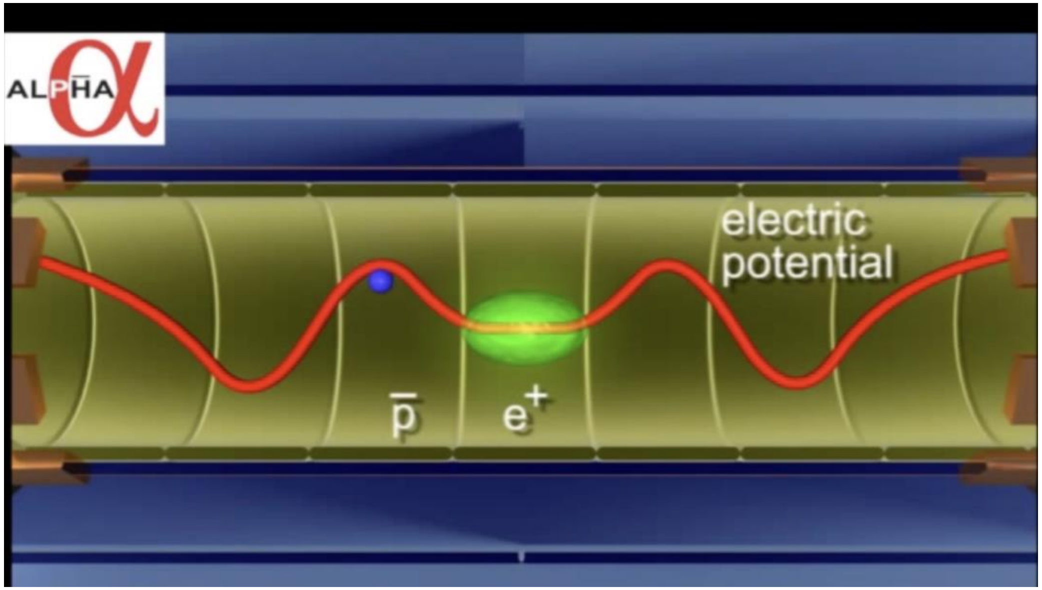
Cockcroft Institute, UK

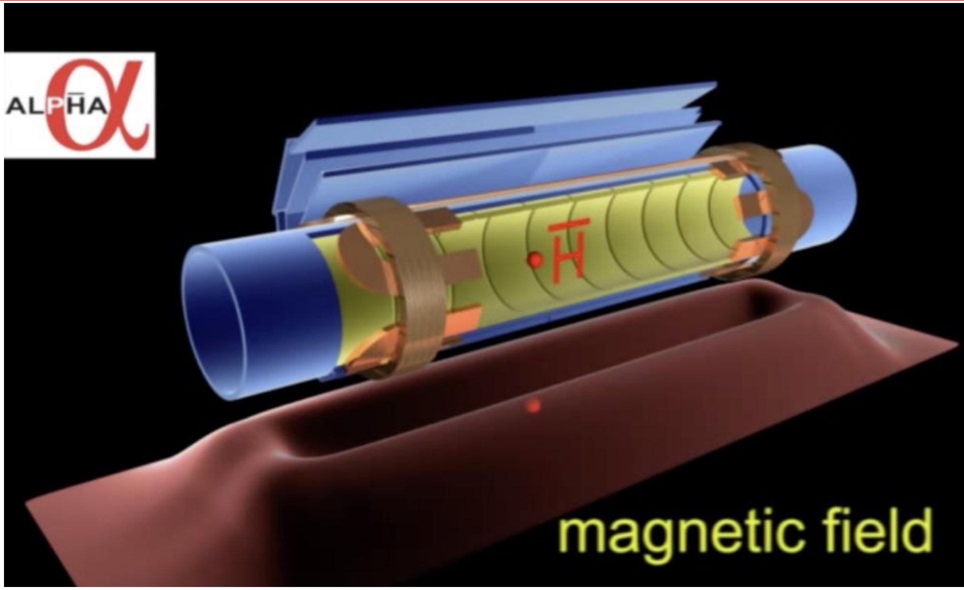
York University, Canada

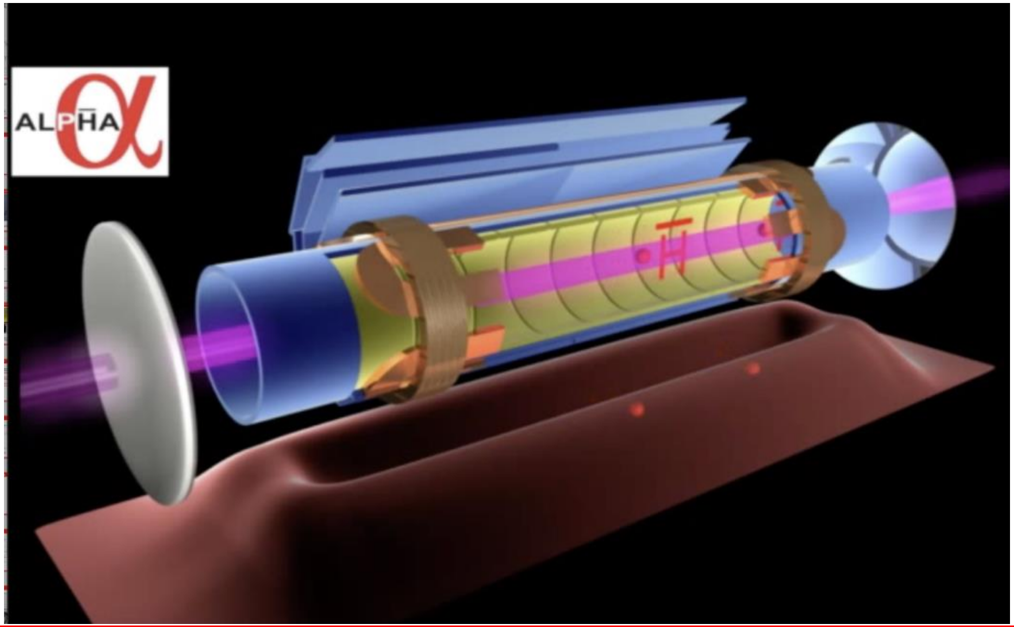
Joel Fajans 1958-2024

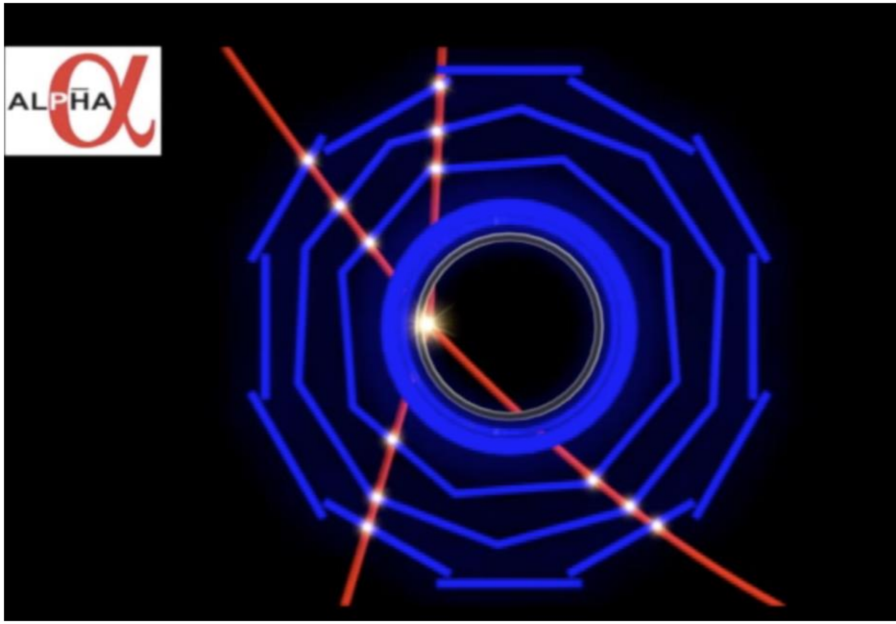
ALPHA spectroscopy and gravitation



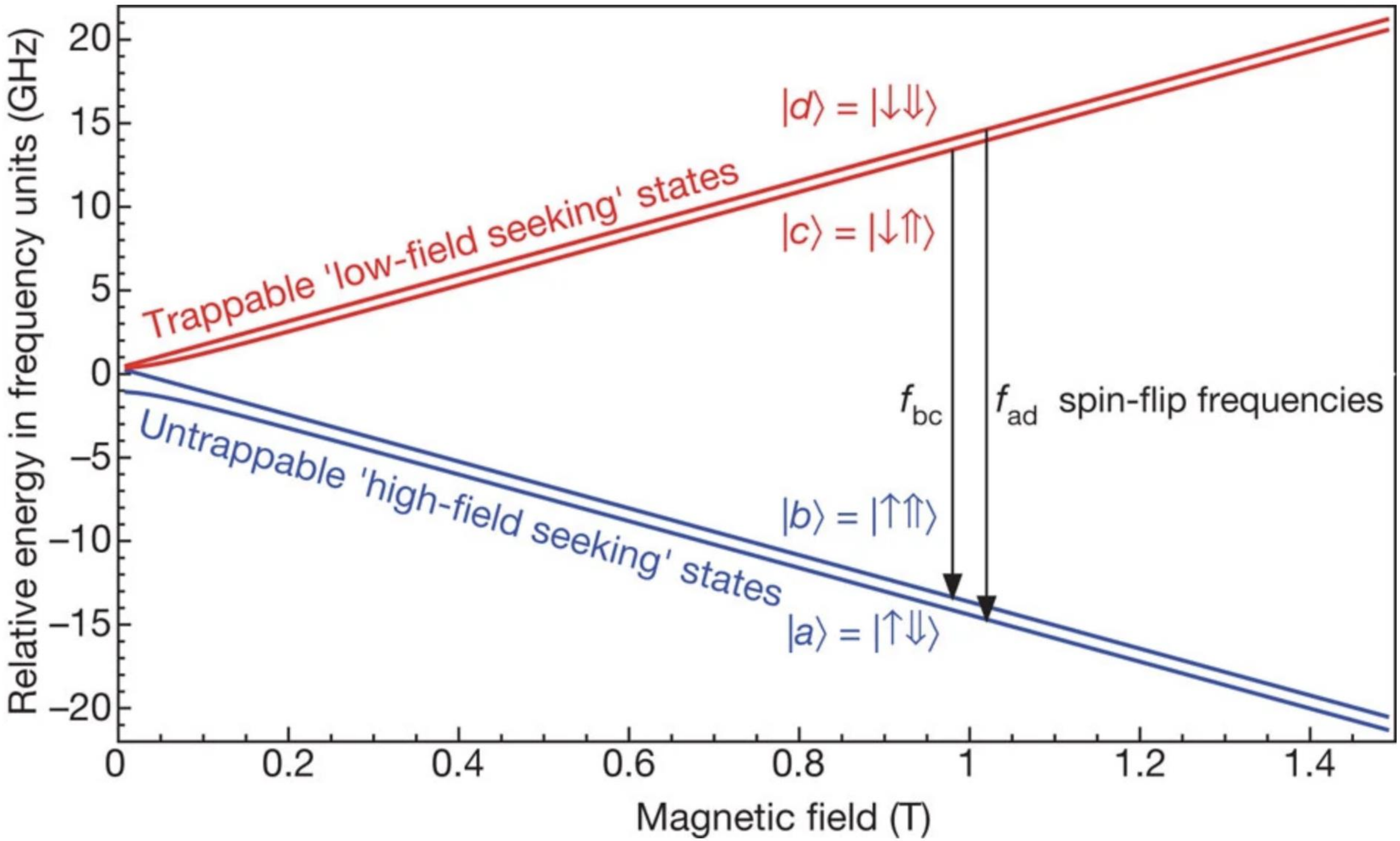

ALPHA
electric
potential
p̄
e^+


ALPHA
H̄
magnetic field


ALPHA
H̄


ALPHA

Breit-Rabi diagram



ALPHA in 2024

- We started physics with ALPHA-2 and ran it from April until early September

- ALPHA-g had been disassembled in 2023 for external solenoid magnet upgrade; it was recommissioned and new gravity measurements conducted

- total of 32 weeks of running; 24/7

Publications since last year:

The ALPHA-2 apparatus - facilitating experimentation with trapped antihydrogen;
Nucl. Inst. & Meth. Phys. A 1072 (2025) 170194

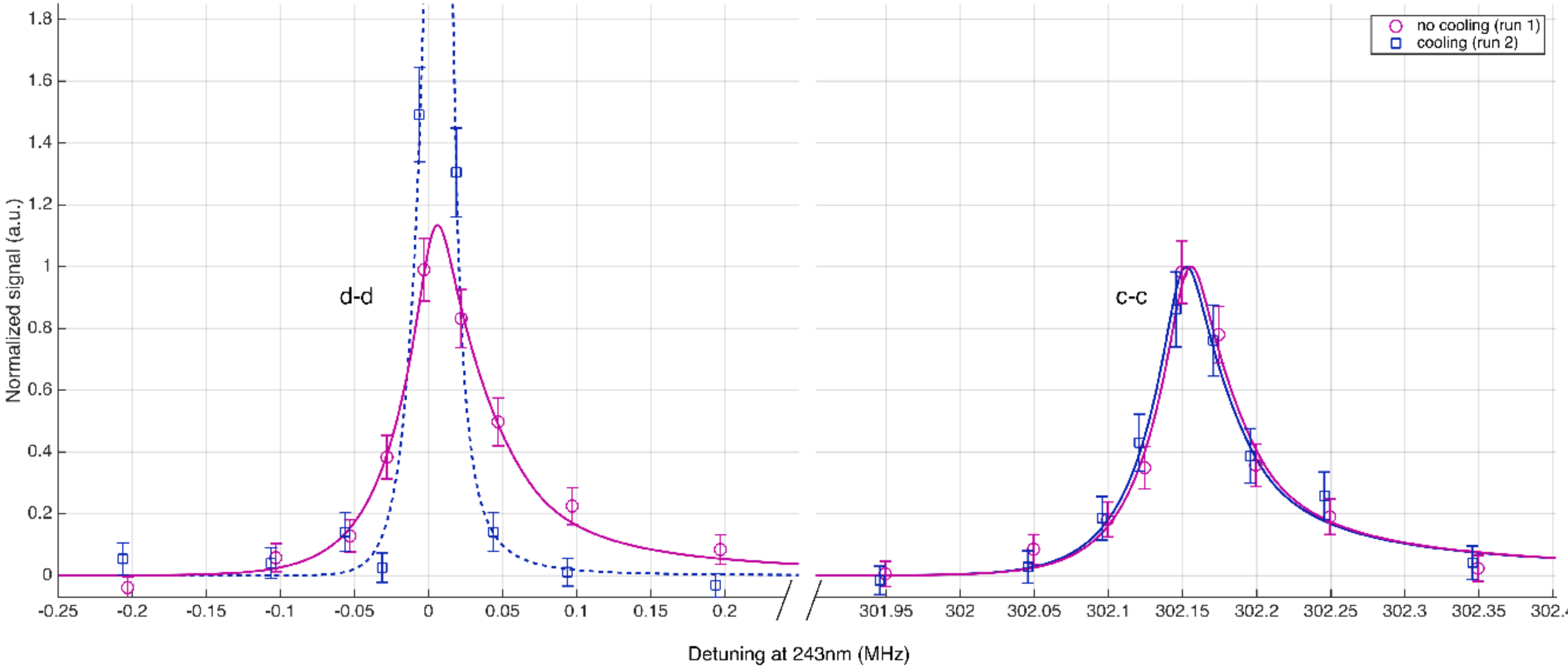
Precision spectroscopy of the hyperfine components of the 1S--2S transition in antihydrogen;
Nature Physics (2025). https://doi.org/10.1038/s41567-024-02712-9

Adiabatic expansion cooling of antihydrogen; Physical Review Research 6 (2024) L032065

Measurements of Penning-Malmberg trap patch potentials and associated performance degradation;
Physsical Review Research Vol. 6, Iss. 1

Recently published in *Nature Physics*

"Precision spectroscopy of the hyperfine components of the 1S-2S transition in antihydrogen"

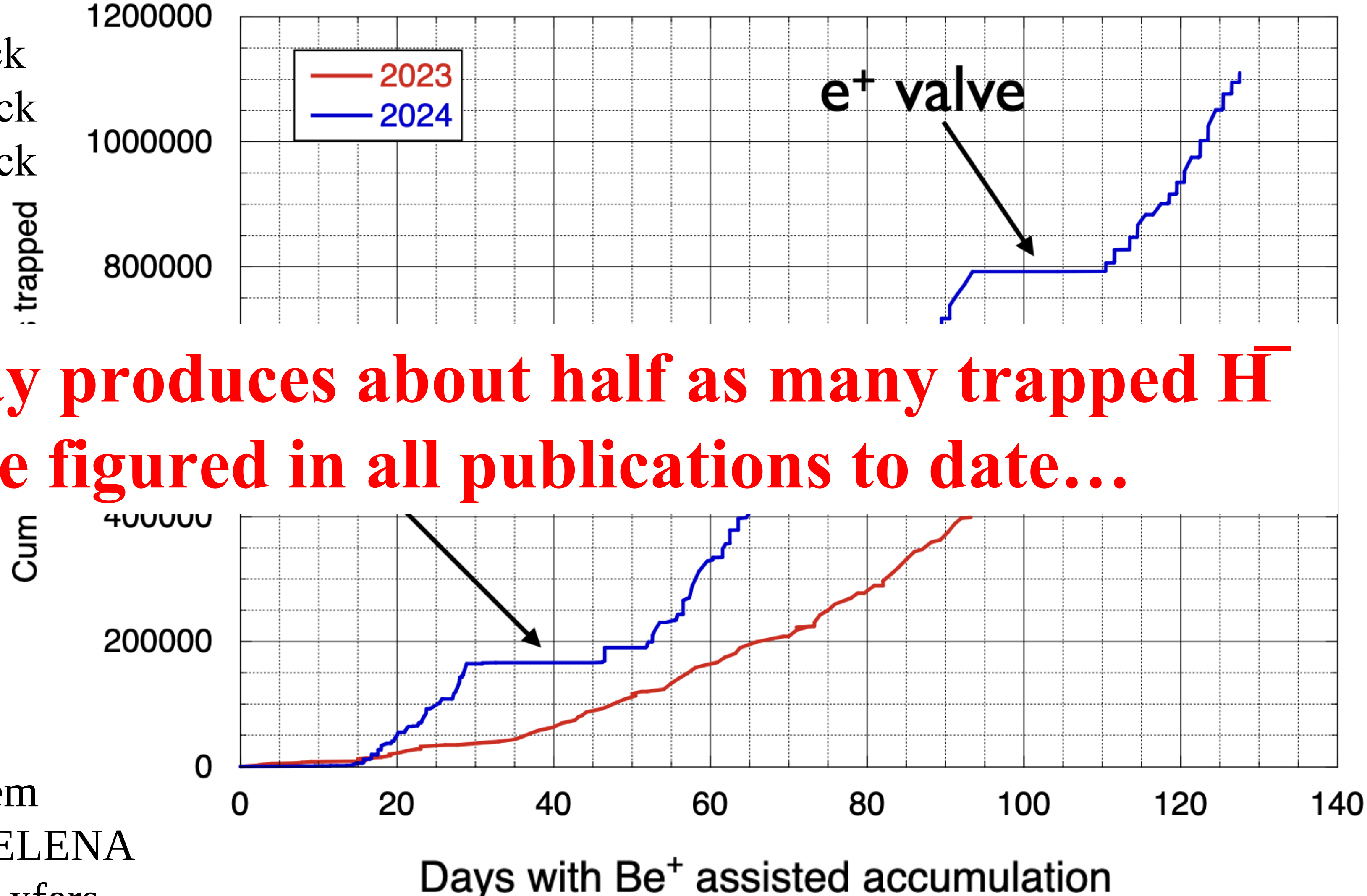


each curve obtained in 1 day
took 10 weeks in 2017...

Accumulation using laser-cooled Be^+ ions to cool the positrons

2023: ~65 $\bar{H}$/stack
2024: ~160 $\bar{H}$/stack
2010: ~0.1 $\bar{H}$/stack

15 stacks/hr

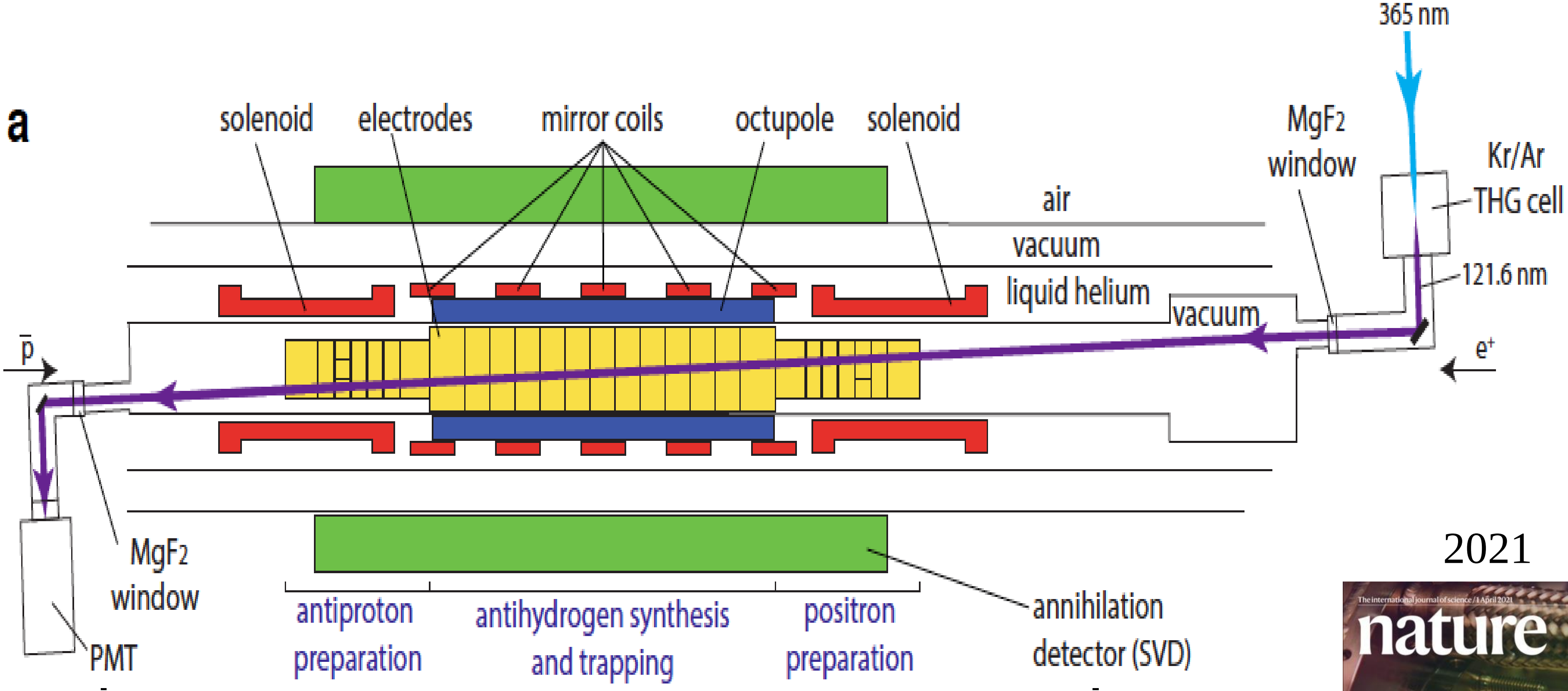


one day produces about half as many trapped $\bar{H}$ as have figured in all publications to date…

Reflects:
tuning of Be system
more pbars from ELENA
improved internal xfers

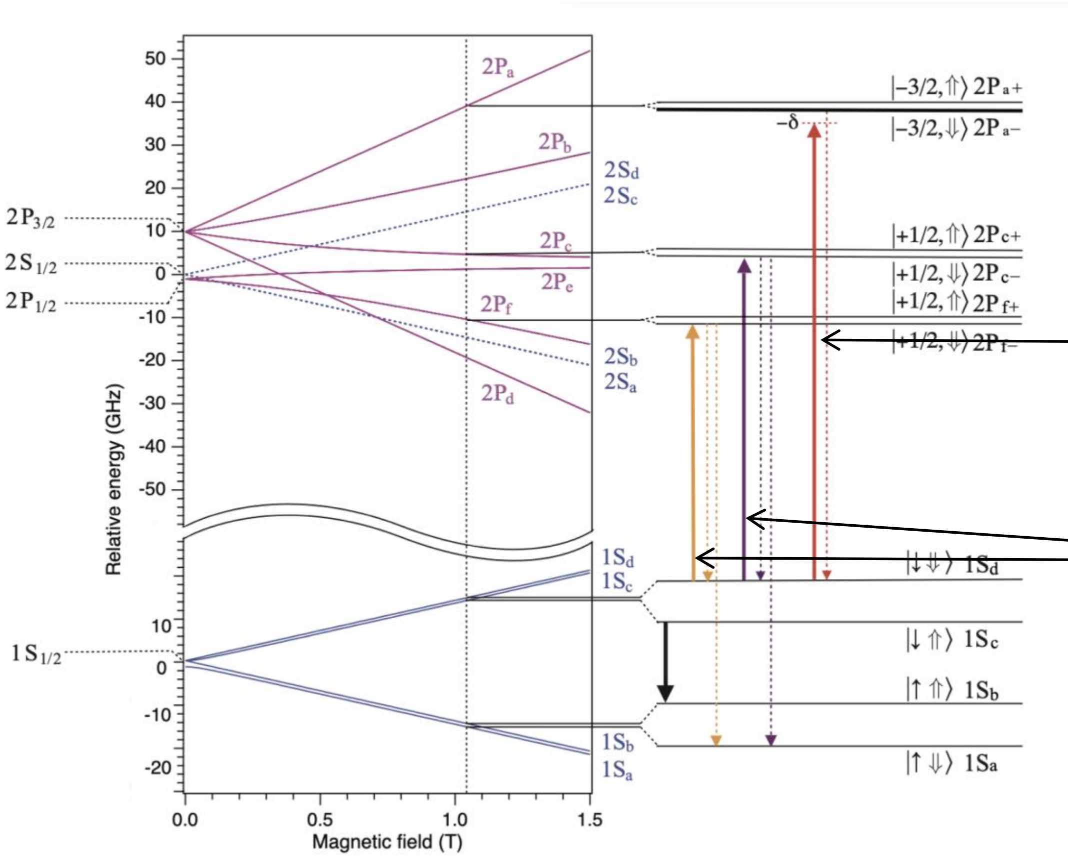
N. Madsen

Laser Cooling of Antihydrogen



2021

Laser Cooling of Antihydrogen



1S – 2P transitions in (anti)hydrogen

cooling

probing

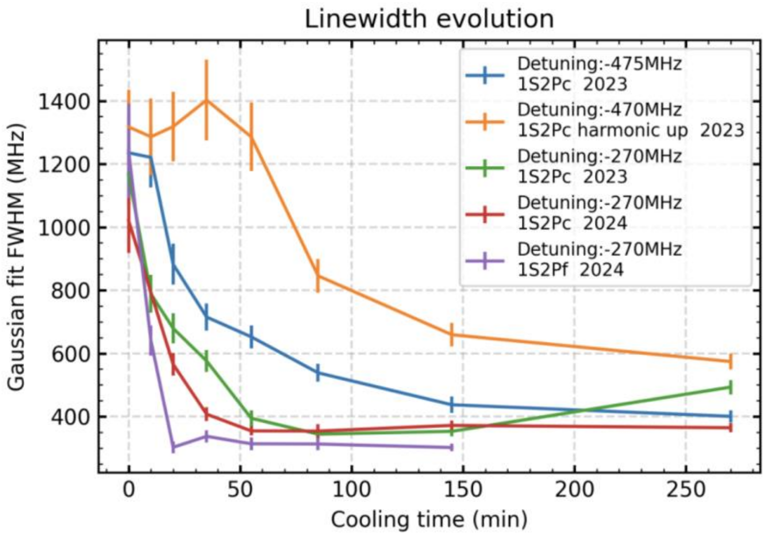
probe the sample after cooling

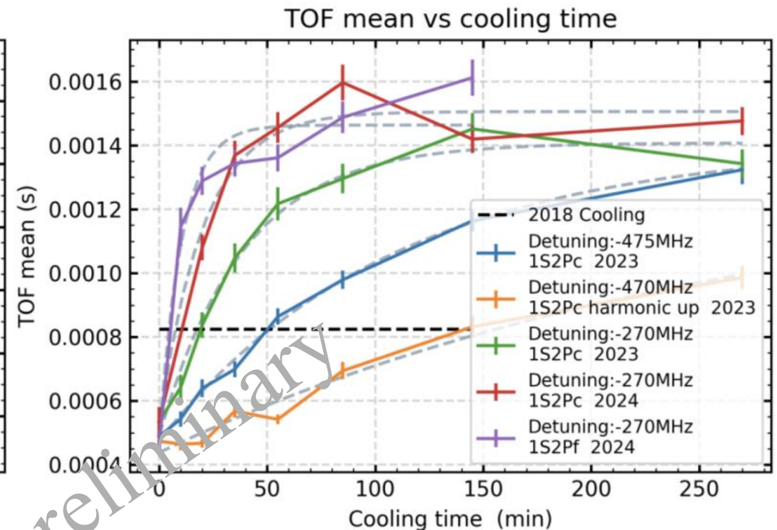
atom will sometimes spin-flip and then annihilate

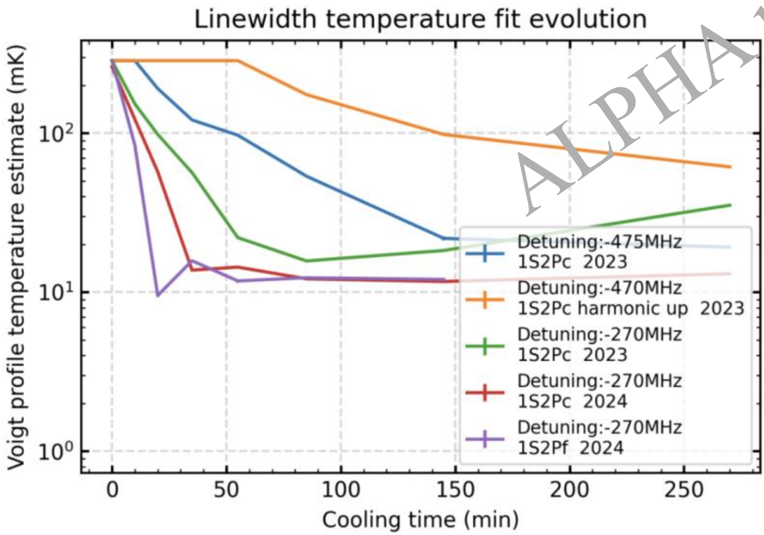
longitudinal velocity information from Doppler broadening

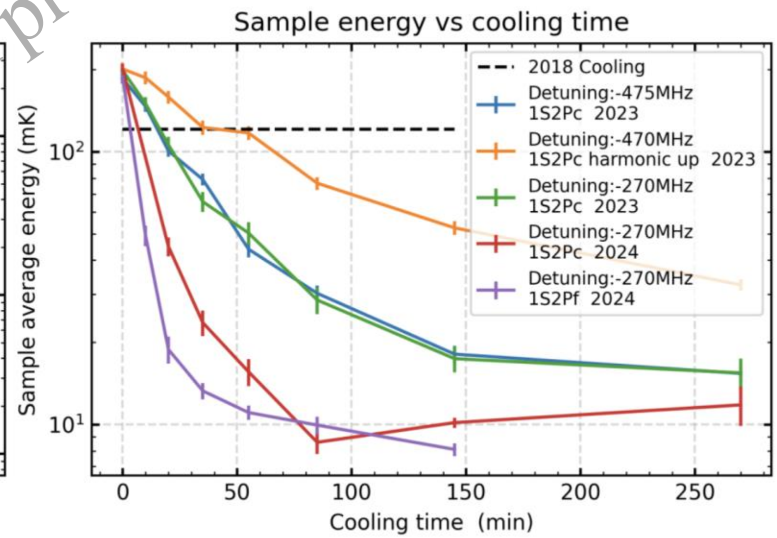
measure TOF between laser pulse and annihilation – gives information about transverse speeds

Laser Cooling of Antihydrogen 2024









~ 8 mK long.
~11 mK transverse

new strategy: reduced cooling power after about 80 minutes of cooling time

A. Evans

Adiabatic Expansion Cooling of antihydrogen 2024

Experimental Protocol

1. Stack and laser cool in 2024 ‘flat’ field

2. Simultaneous ramp of:

    - Octupole from 900A to lower (non-zero) current
    - Mirror A and E from ~500A to lower (non-zero) current

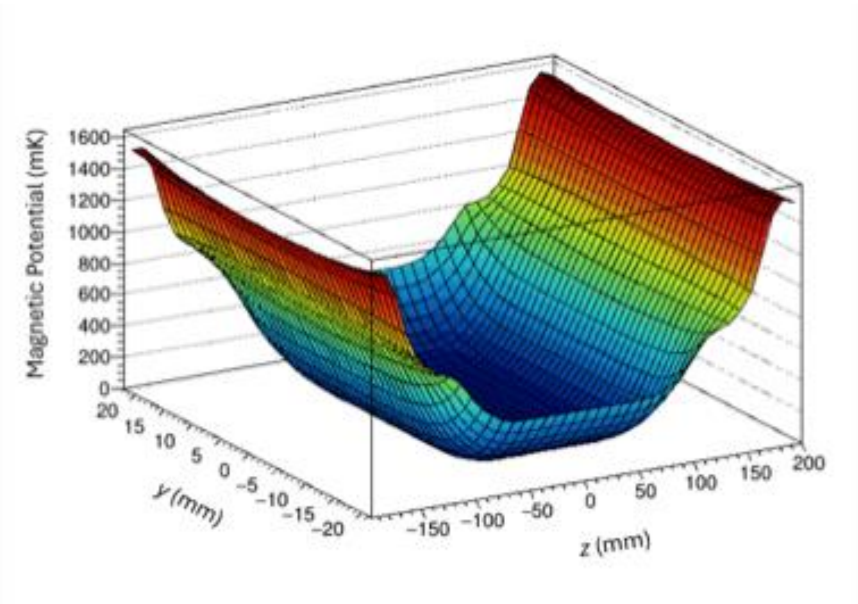
Benefits:

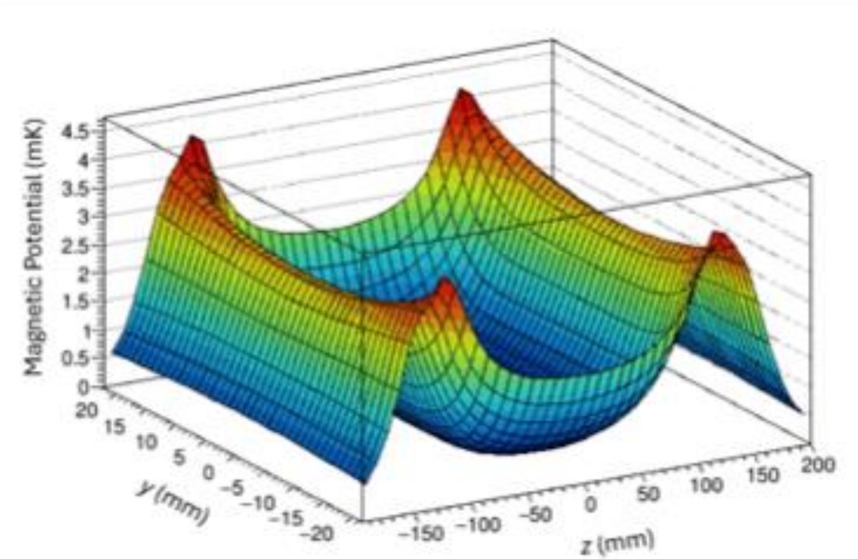
- Radial adiabatic expansion from octupole
- Axial adiabatic expansion from mirrors
- Decreasing trap depth causes loss of high energy antihydrogen
- No large on-axis field in expanded well

D. Hodgkinson

Flat field
900 A octupole;
500 A mirrors

50A in octupole, 3A in Mirrors A and E





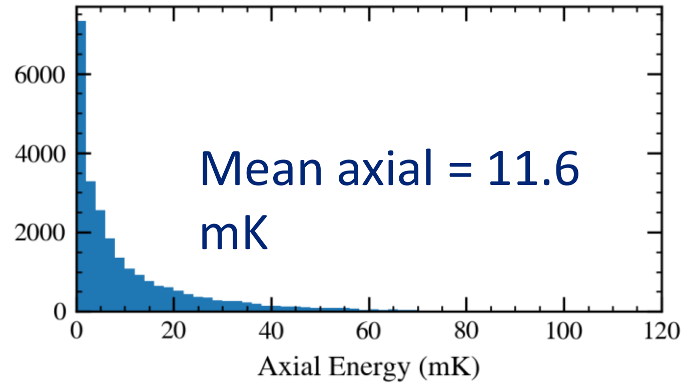
Trap depth
decreases by
about 200x

D. Hodgkinson

Adiabatic Expansion Cooling of antihydrogen 2024

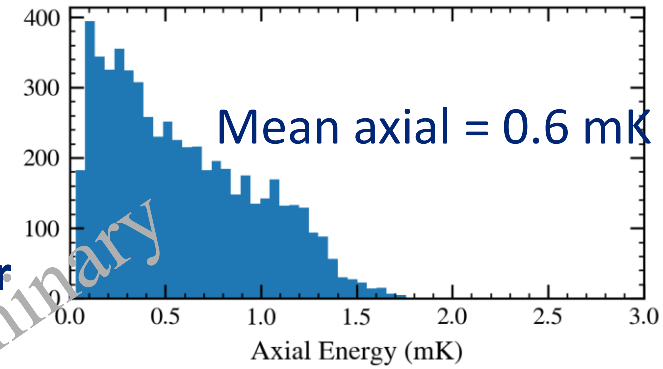
Simulation Predictions

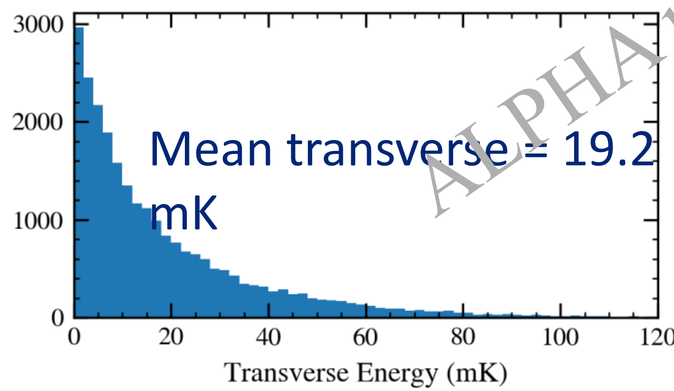
Flat field



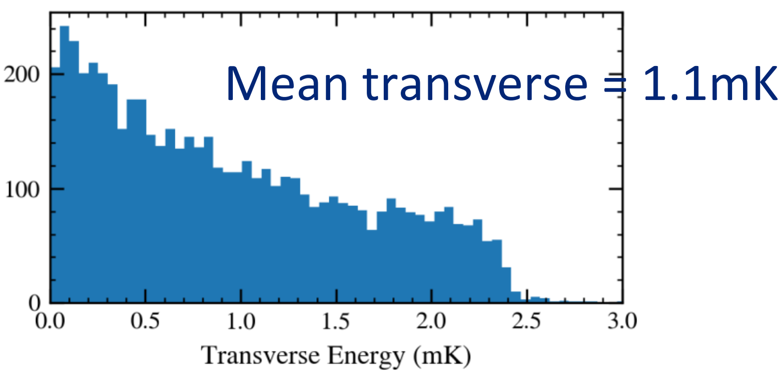
~20x colder

50A in octupole, 3A in mirror coils





~20x colder



- 76% simulated particle losses

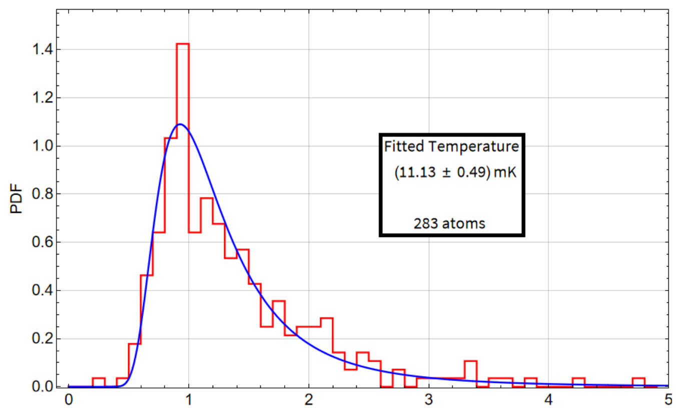
D. Hodgkinson

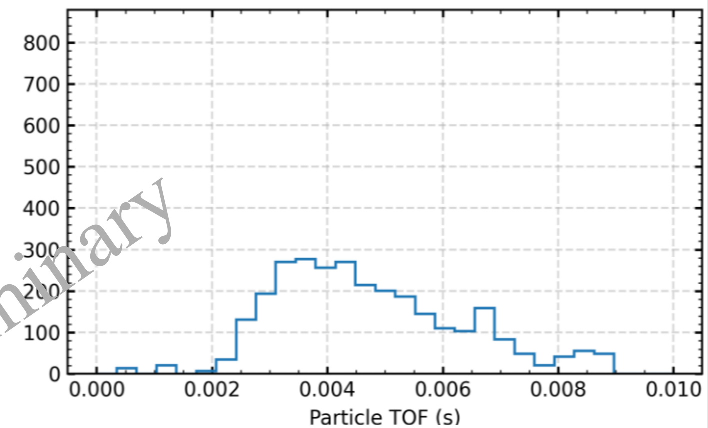
Experimental Results

Flat field

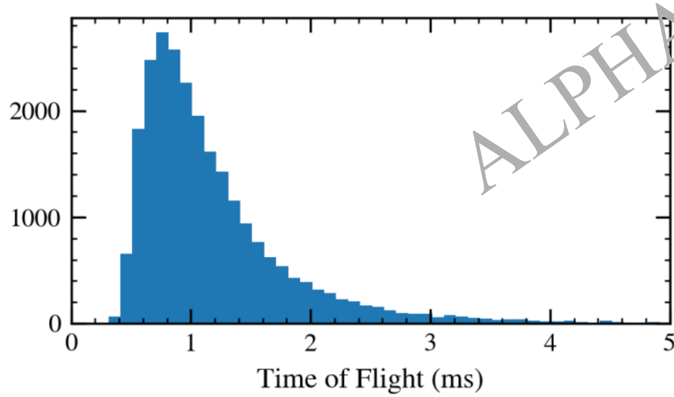
50A in octupole, 3A in MA and ME

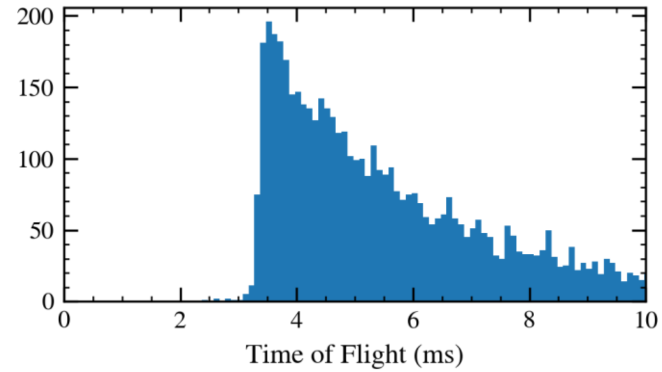
Experiment





Simulation

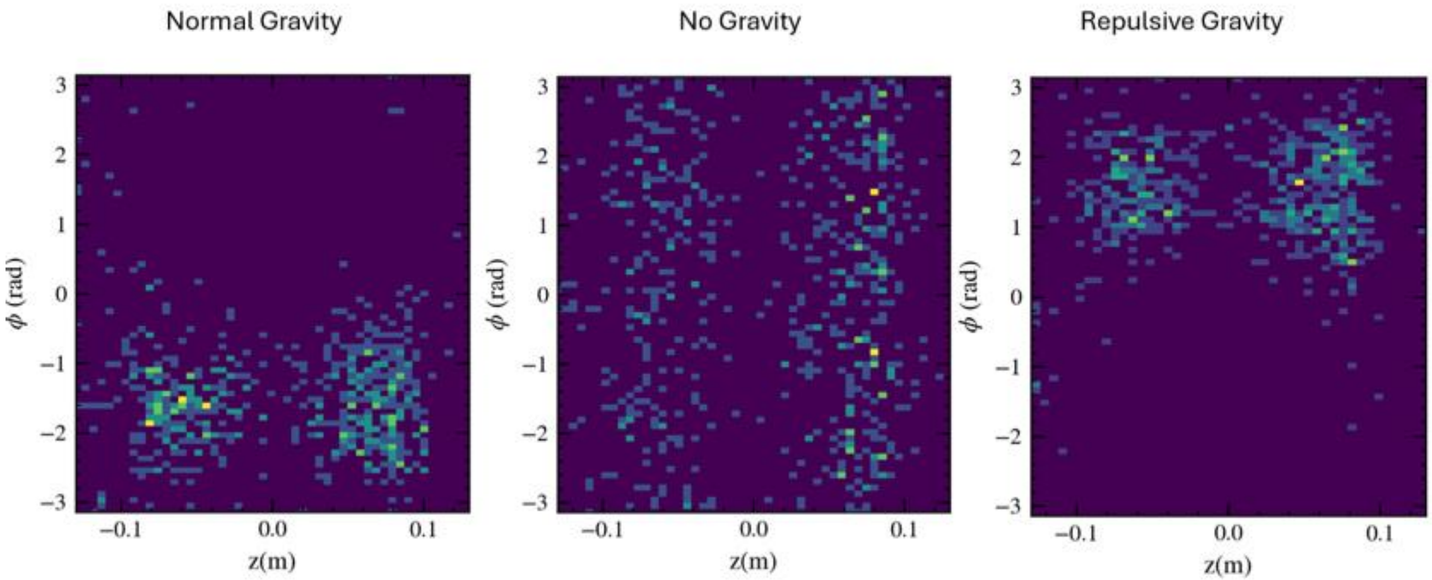




- ~ 70% simulated particle losses

D. Hodgkinson

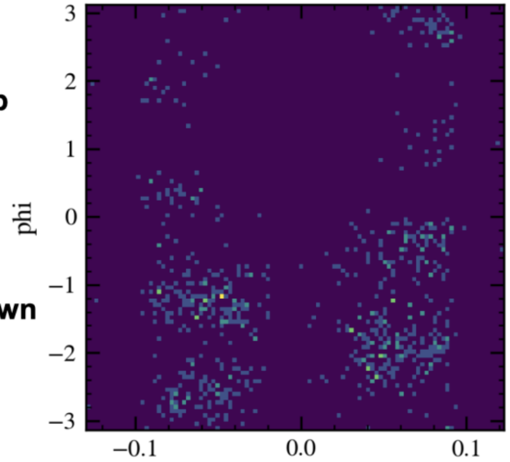
Gravity in ALPHA-2???



simulation: octupole release of
mK hbars

Phi > 0 is up

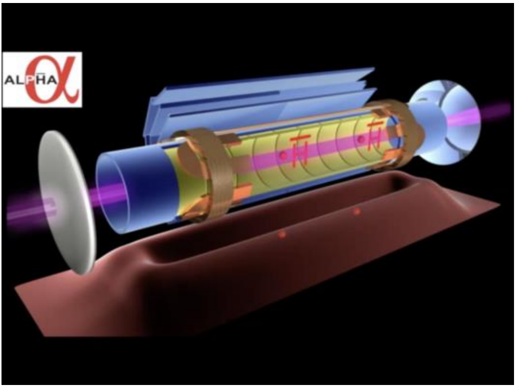
Phi < 0 is down

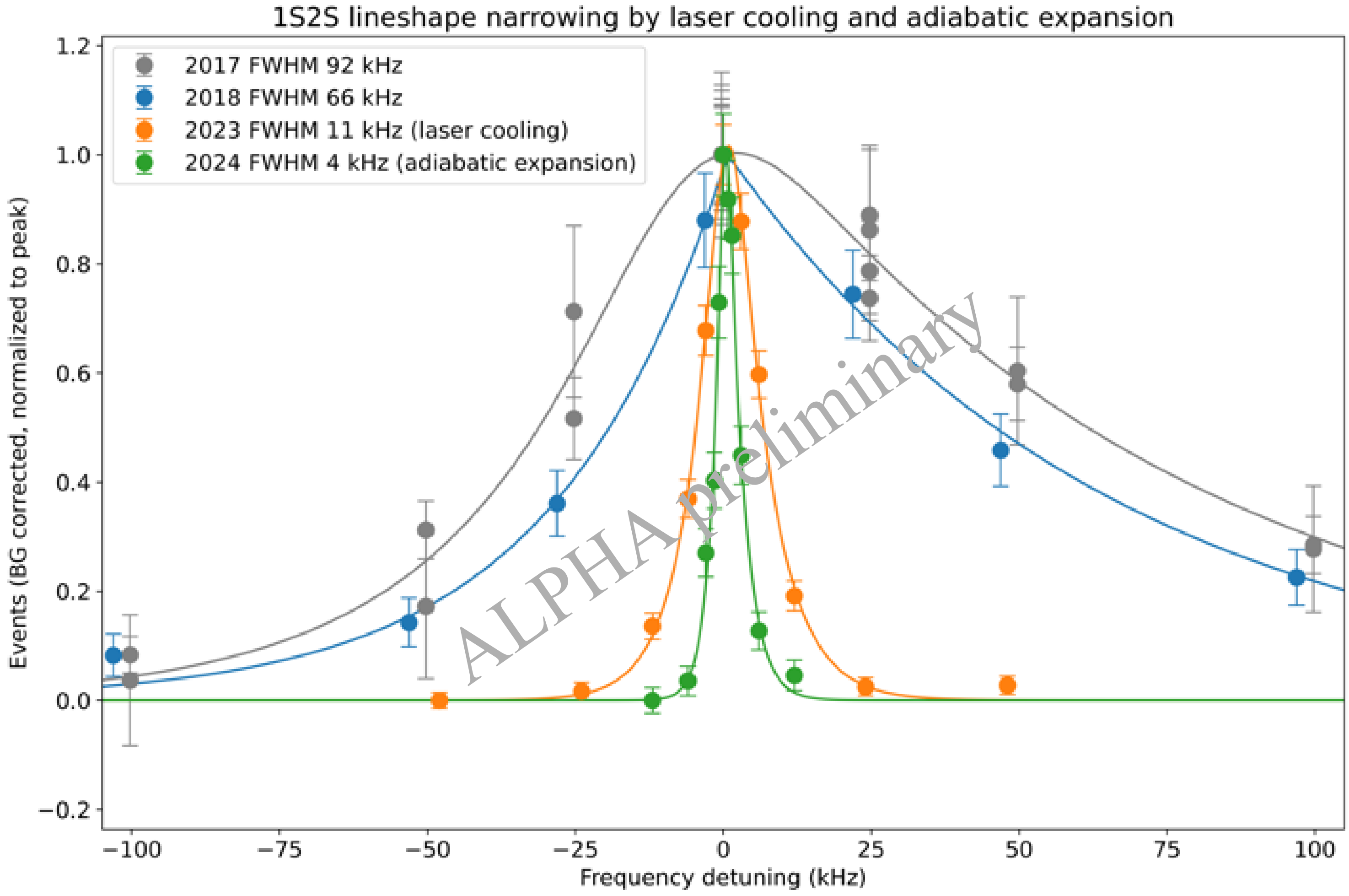


experiment: octupole release of laser
and adiabatically cooled hbars

D. Hodgkinson

The 1S-2S transition with laser and adibatic cooling





@243 nm

J. Nauta

CF: for hydrogen (Parthey *et al.*, 2011), the FWHM is about 2 KHz @ 121 nm

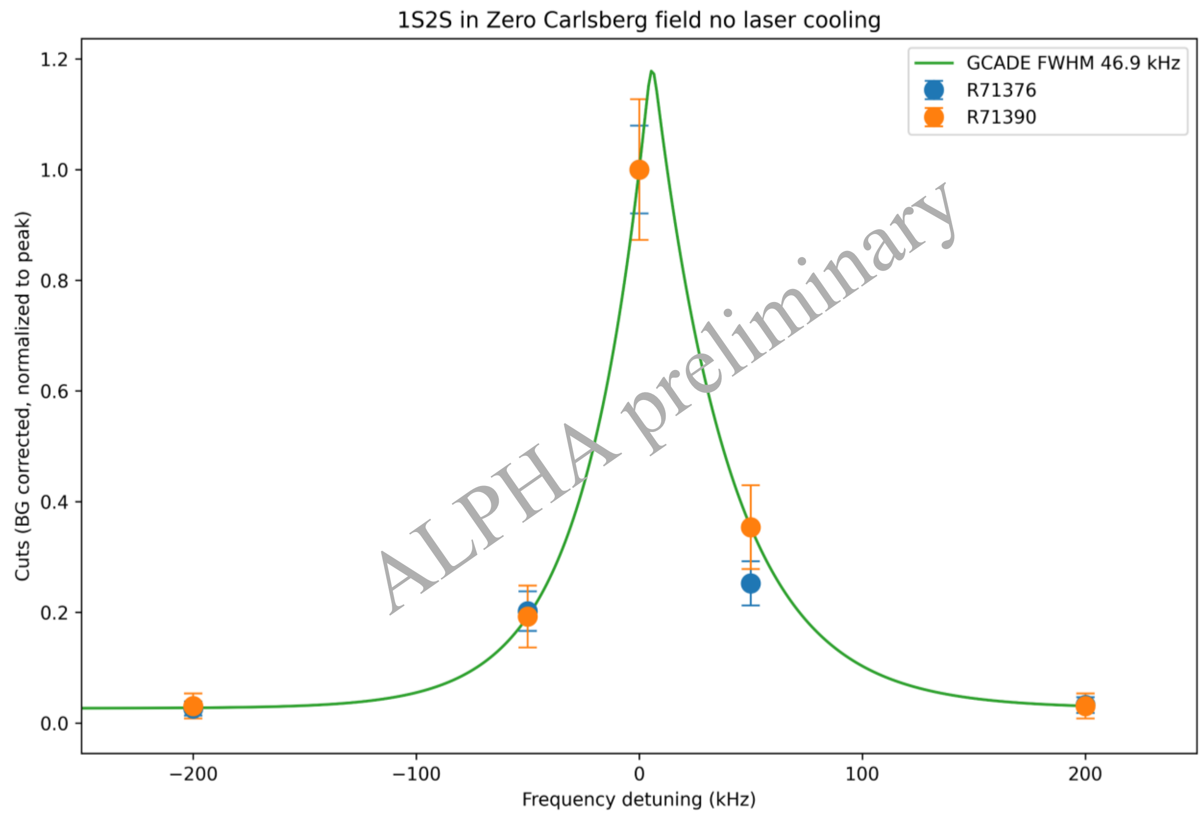
1S-2S at zero external solenoid field

R71376: Stack,
ramp down Carlsberg,
spectroscopy on d-d
laser power 275 mW, 245 atoms

R71390: Stack,
ramp down Carlsberg,
spectroscopy on d-d
laser power 250 mW, 101 atoms

spectroscopy on c-c
no peak observed yet

1T : 1.9 kHz / Gauss
0.05T: 406 kHz / Gauss



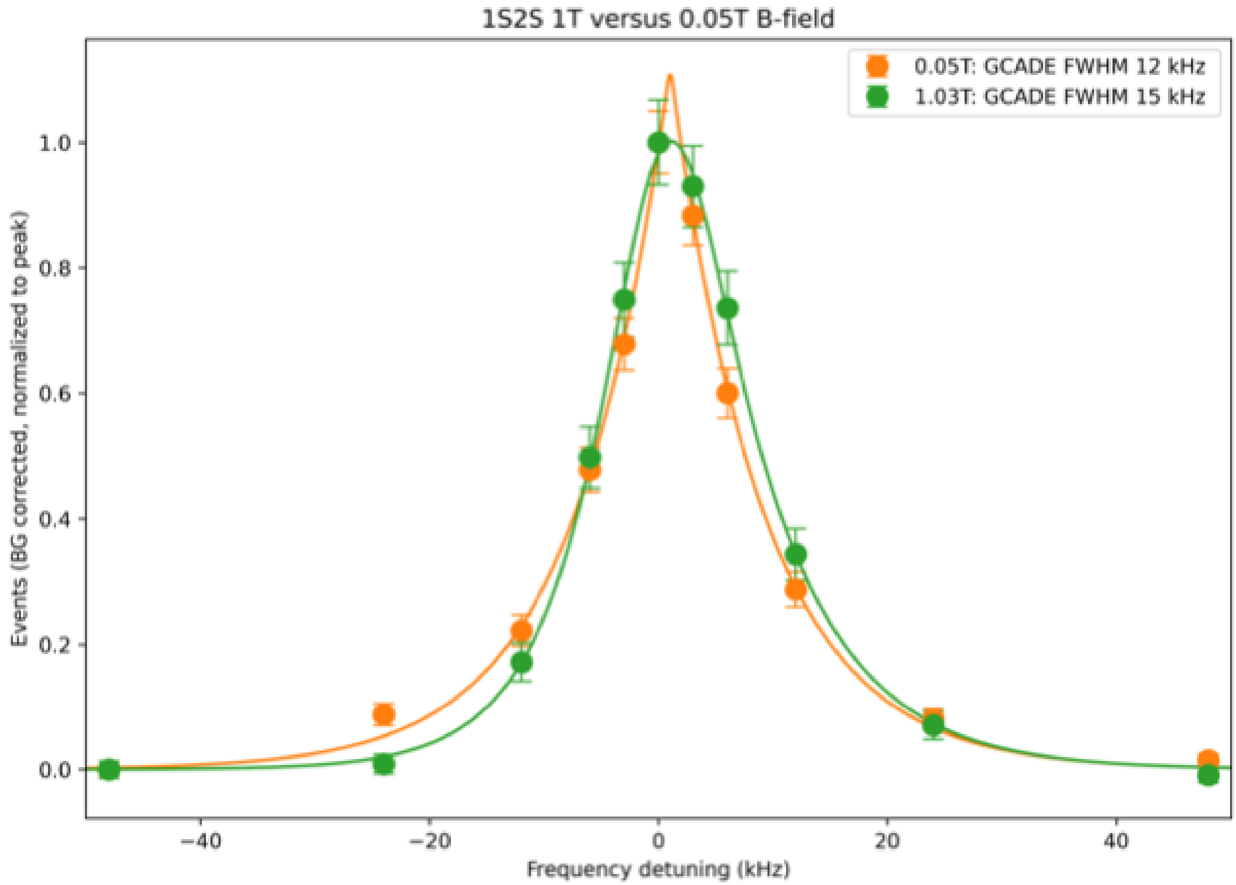
proof of principle only so far

J. Nauta

1S-2S Laser cooling and no external solenoid field

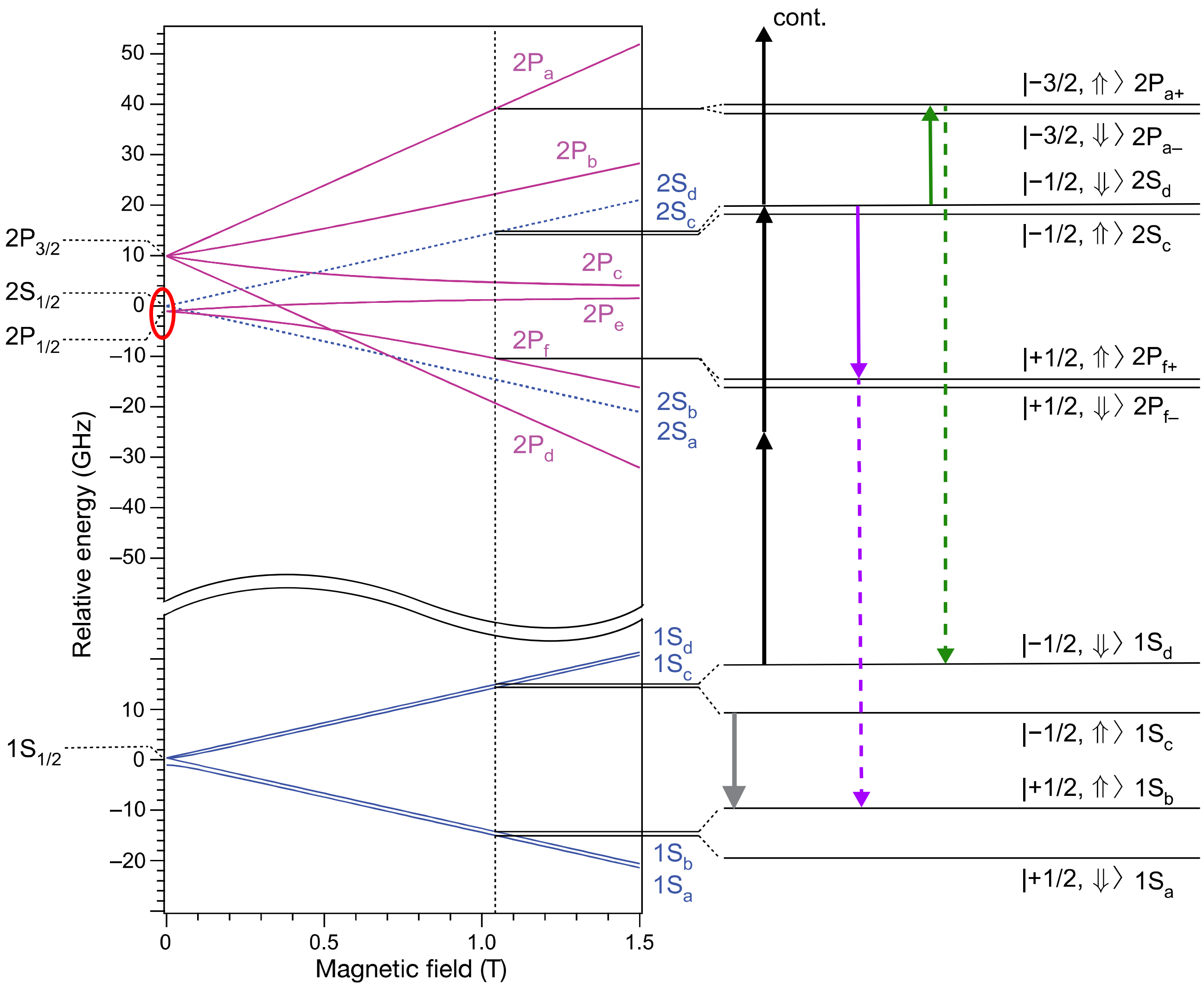
1921 atoms

1.032T: 99 Hz/Gauss
0.054T: 23 Hz/Gauss



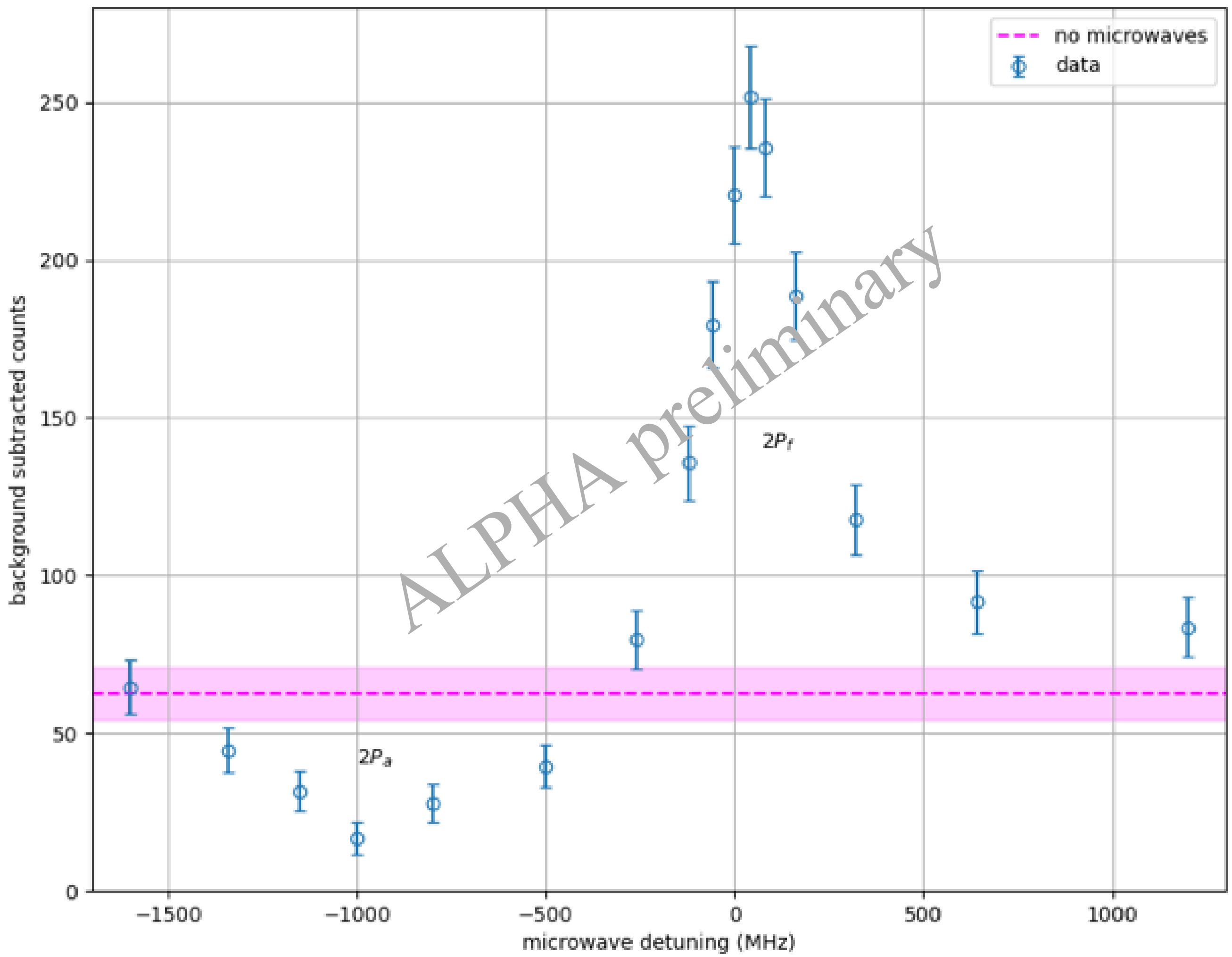
J. Nauta

Recall: 2023 excited state spectroscopy: the 2S-2P transition



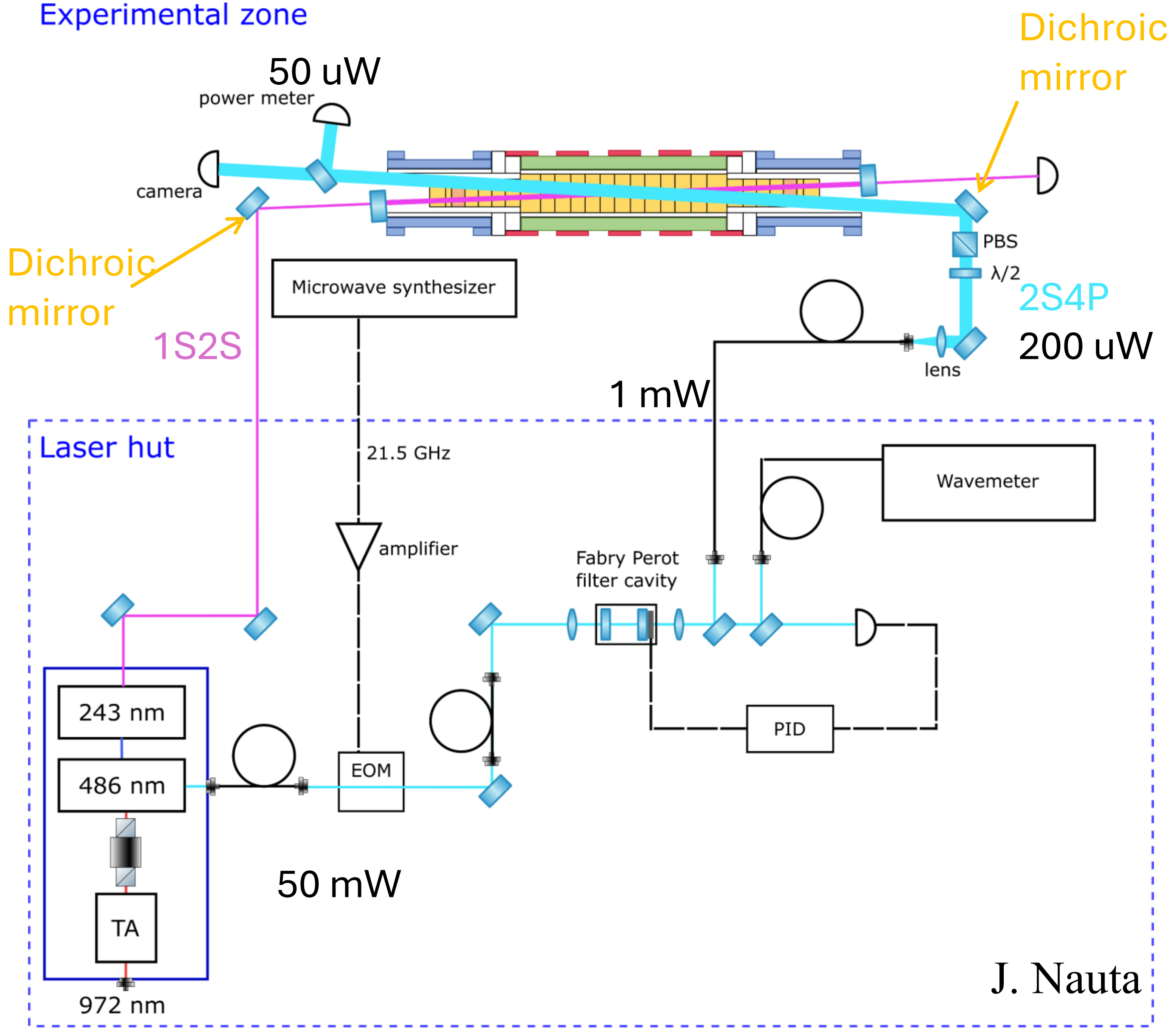
Double resonant:
two-photon excitation to 2S
microwave excitation to 2P

2023 excited state spectroscopy: the 2S-2P transition



2S-4P spectroscopy setup 2024

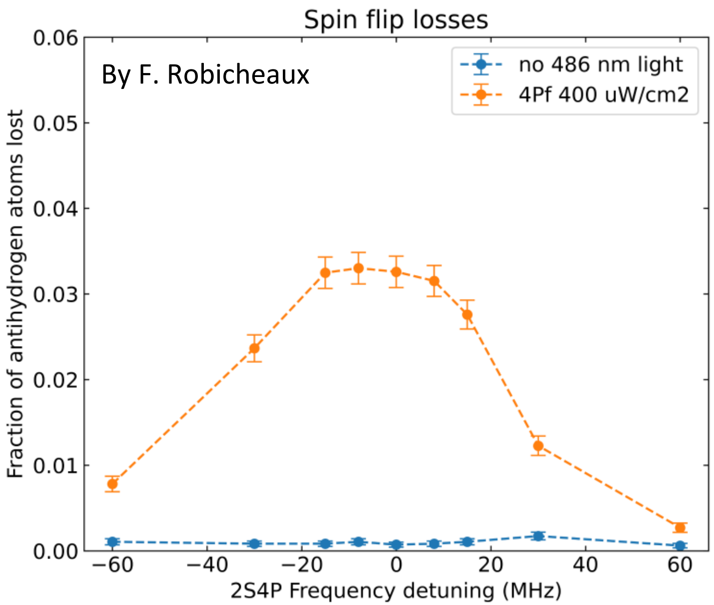
- A2 Off-axis laser path shared with Be+ laser
- Electro-Optical Modulator to shift laser frequency ~` 3% efficient
- EOM driven by the Microwave synthesizer around 21 GHz
- Fabry-Perot filter cavity to remove main frequency
- Large beam to ensure overlap with 243 laser

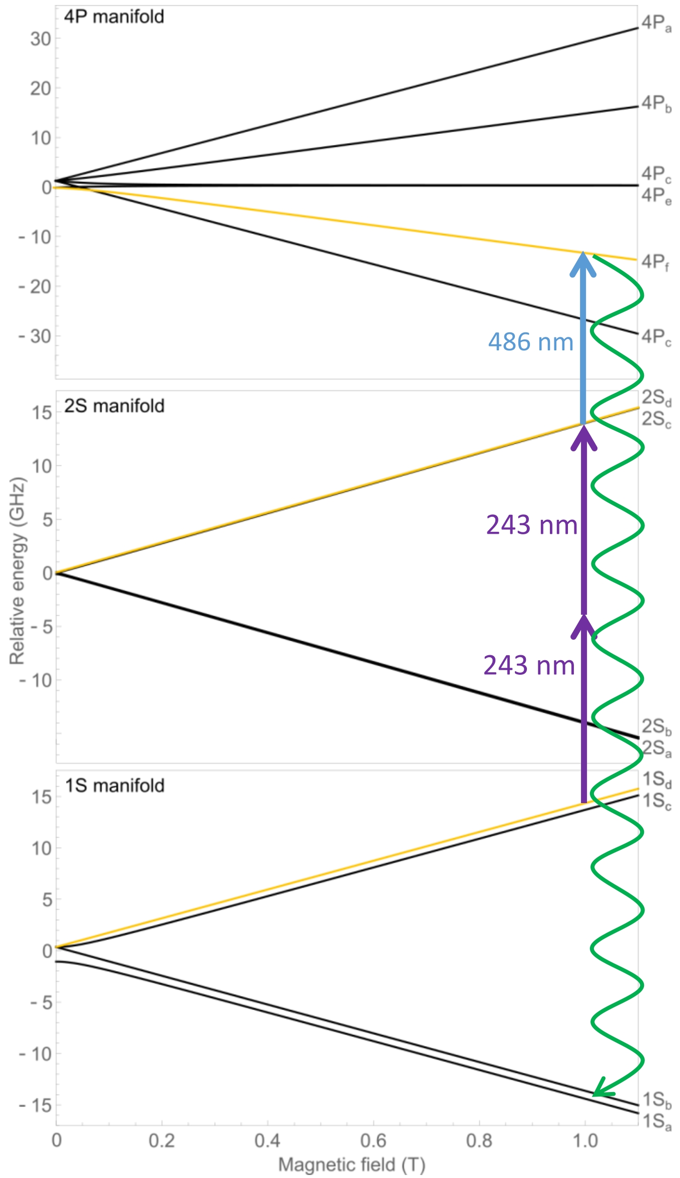


2024: Observation of the 2S-4P transition

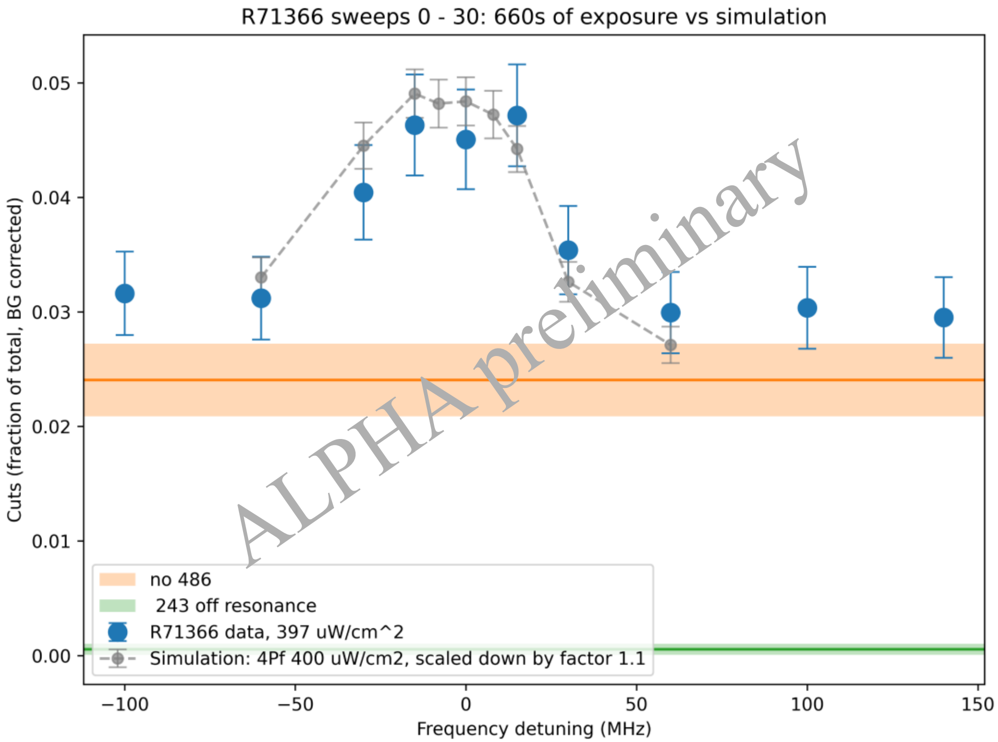
Ionisation loss from 2S contaminates the signal

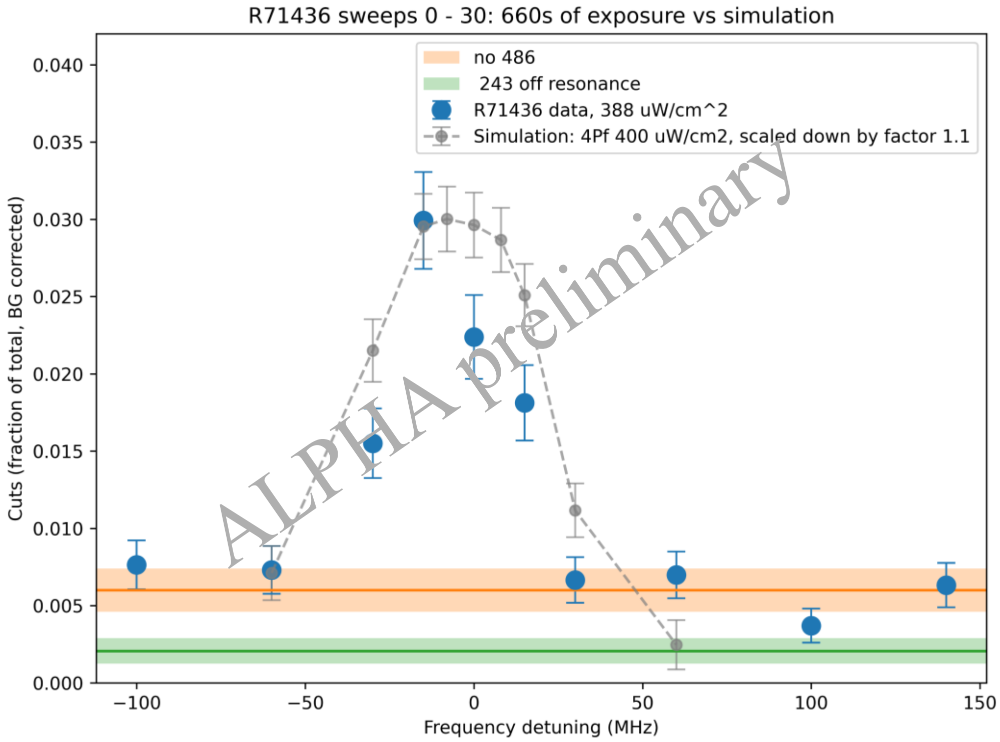
Decrease FWHM further with Adiabatic Cooling





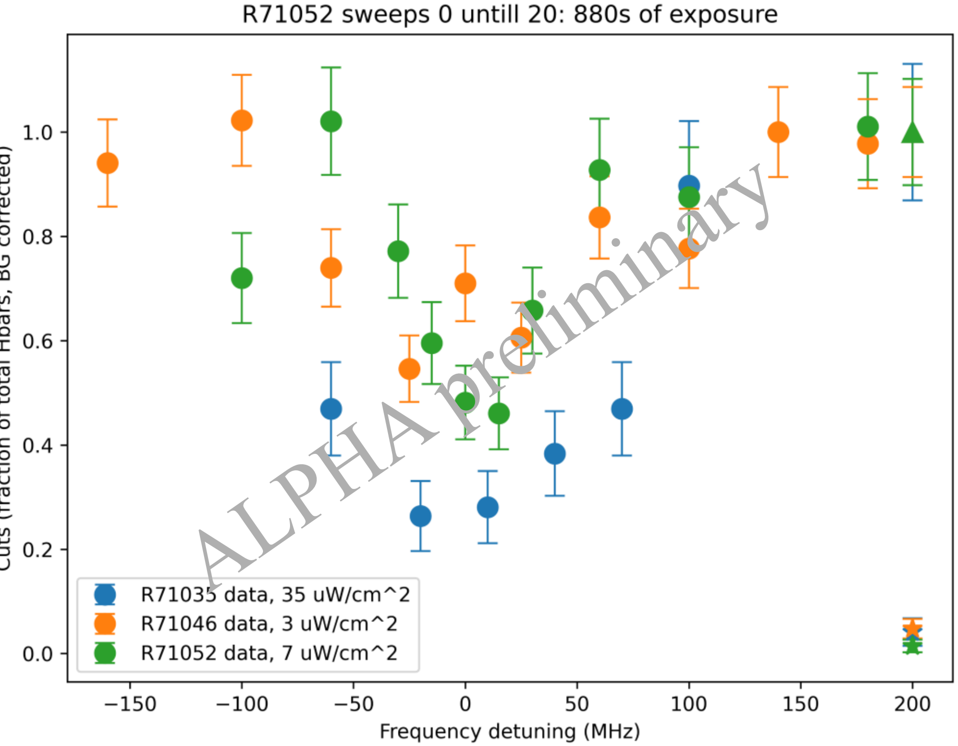
Observation of the 2S-4P transition

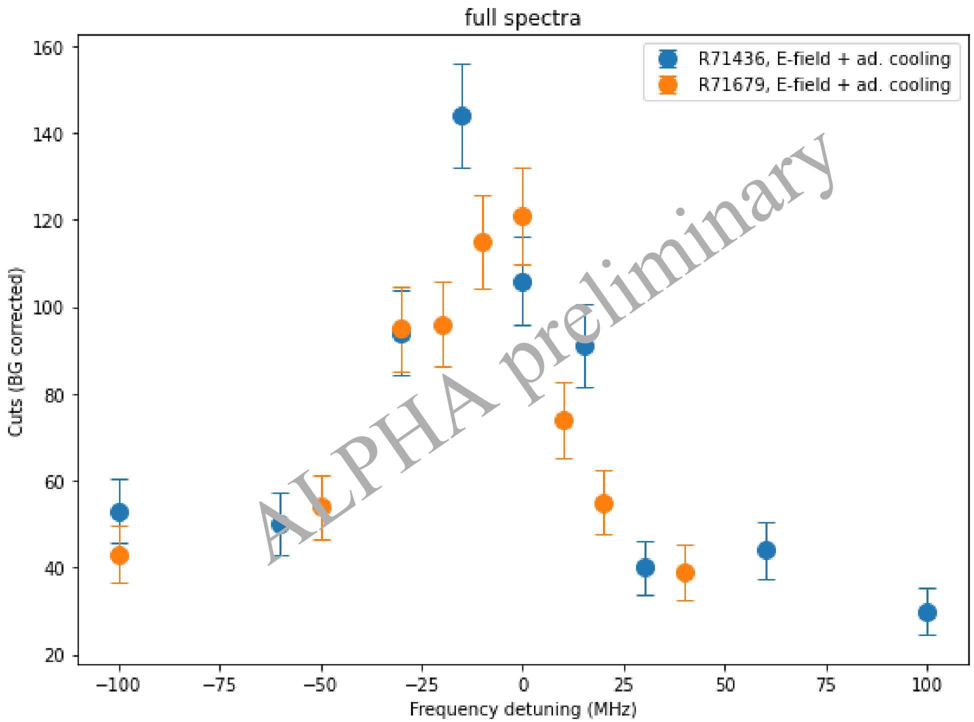




J. Nauta

2S - 4P summary plots



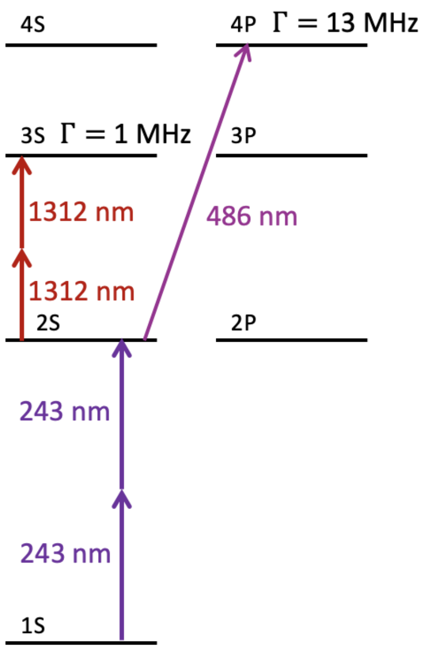


$4P_a$
3 runs

$4P_f$
with adiabatic cooling and E-field
2 runs

J. Nauta

Towards the antiproton charge radius



$$E_{nlj} = \underbrace{R_\infty}_{\text{Rydberg constant}} \left(-\frac{1}{n^2} + \underbrace{f_{nlj}\left(\alpha, \frac{m_e}{m_p}, \ldots\right)}_{\text{QED term}} + \delta_{\ell 0}\frac{C_{NS}}{n^3}\underbrace{r_p^{\,2}}_{\text{Proton radius}}\right)$$

We have measured 1S2S with 2×10^{-12}

Need (at least) two transitions to measure R_∞ and r_p:

Antiproton radius effect on 1S-2S transition: $\frac{\Delta f\ \bar{p}\ radius}{f_{1S-2S}} = \frac{968\ kHz}{2.47\ PHz} = 4.0\times10^{-10}$

→ **Second transition needs to constrain R_∞ better than 4×10^{-10}**

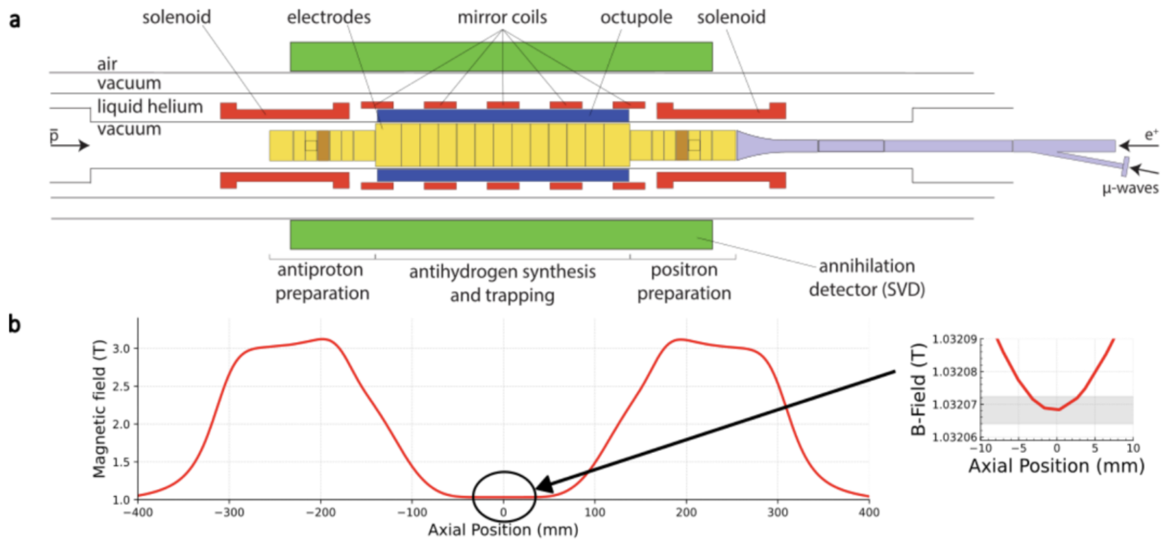
For 1S-4P: $\Delta f_{1S-4P} < 4.0\times10^{-10}\times f_{1S-4P} = 4\times10^{-10}\times 3.08\times10^{15} = 1.2\ MHz$

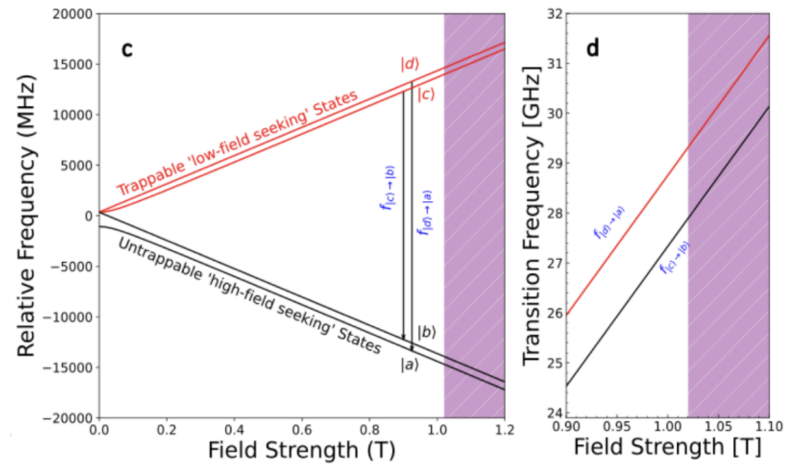
For 1S-3S: $\Delta f_{1S-3S} < 4.0\times10^{-10}\times f_{1S-3S} = 4.0\times10^{-10}\times 2.92\times10^{15} = 1.2\ MHz$

→ **We need to measure a second transition better than 1.2 MHz**

J. Nauta

positron spin resonance: GSHFS





A. Jimenez

Protocol data point

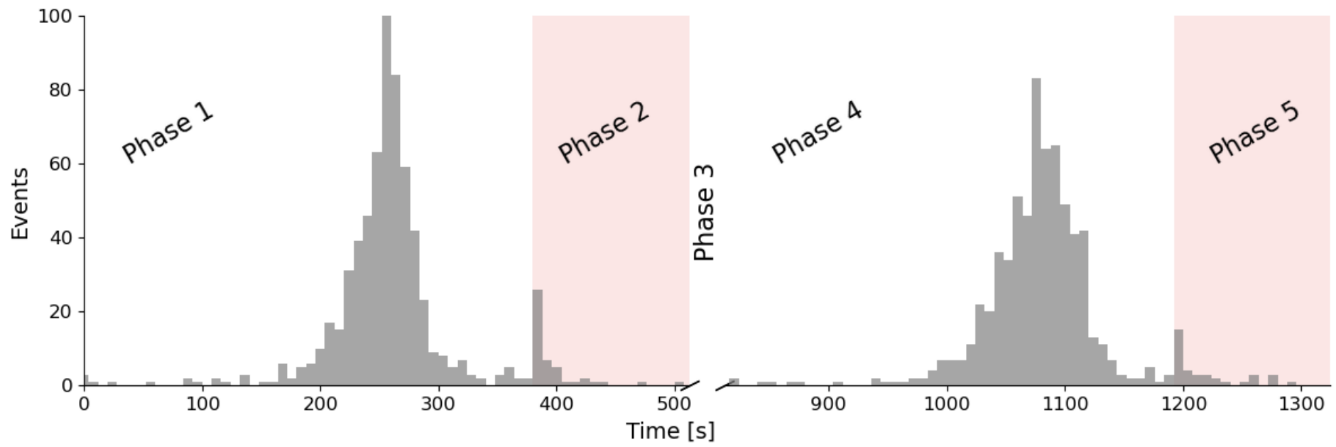
Phase 1. Induction |c> to |b> transition:
- 48 frequency steps
- Power 12 dBm (series 6 and 8) and 18 dBm (series 7)

Phase 2. Clearing |c> atoms:
- 16 frequency steps
- Power 18 dBm (series 6, 7, and 8)

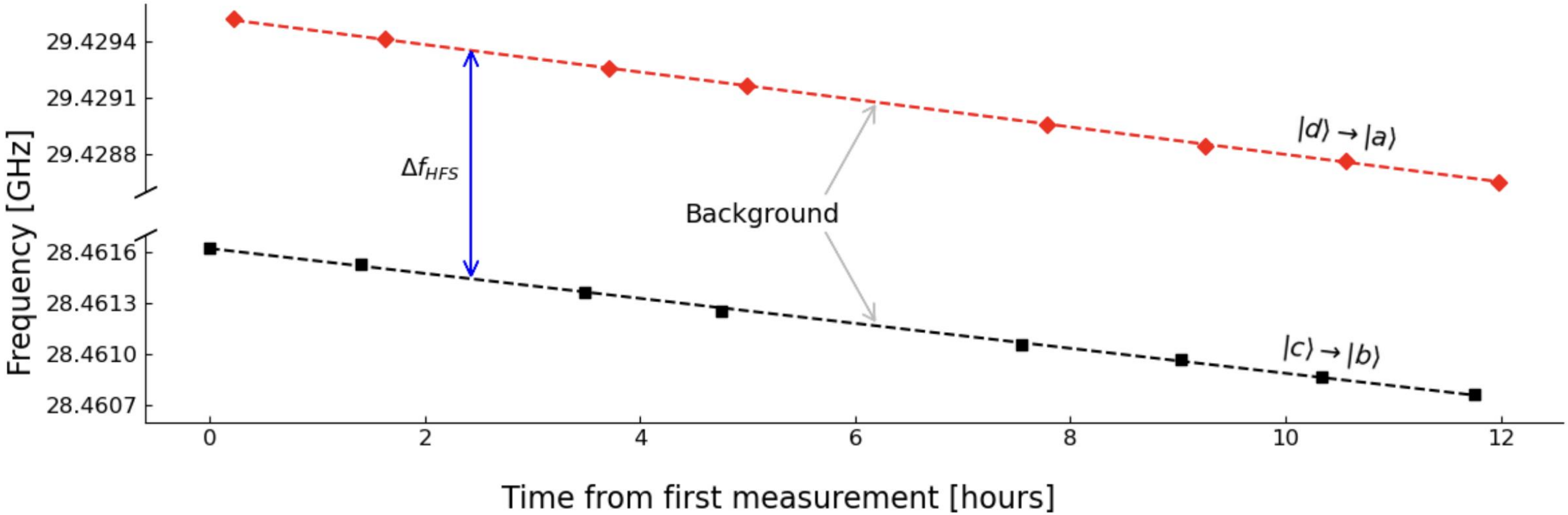
Phase 3. 300 seconds MW off

Phase 4. Induction |d> to |a> transition:
- 48 frequency steps
- Power 12 dBm (series 6 and 8) and 15 dBm (series 7)

Phase 5. Clearing |d> atoms:
- 16 frequency steps
- Power 18 dBm (series 6, 7, and 8)

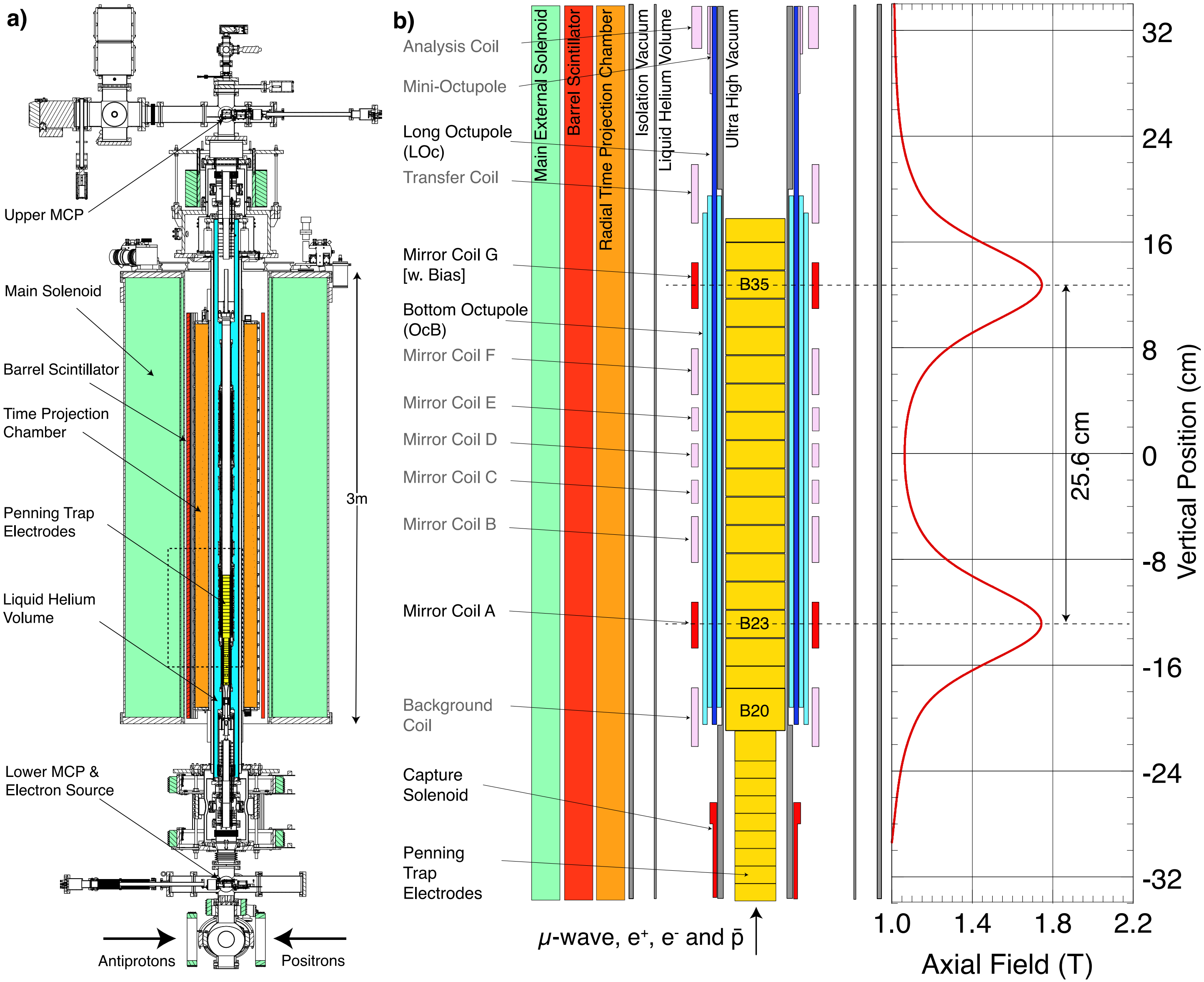


GSHFS - evolution



A. Jimenez

ALPHA-g Schematic

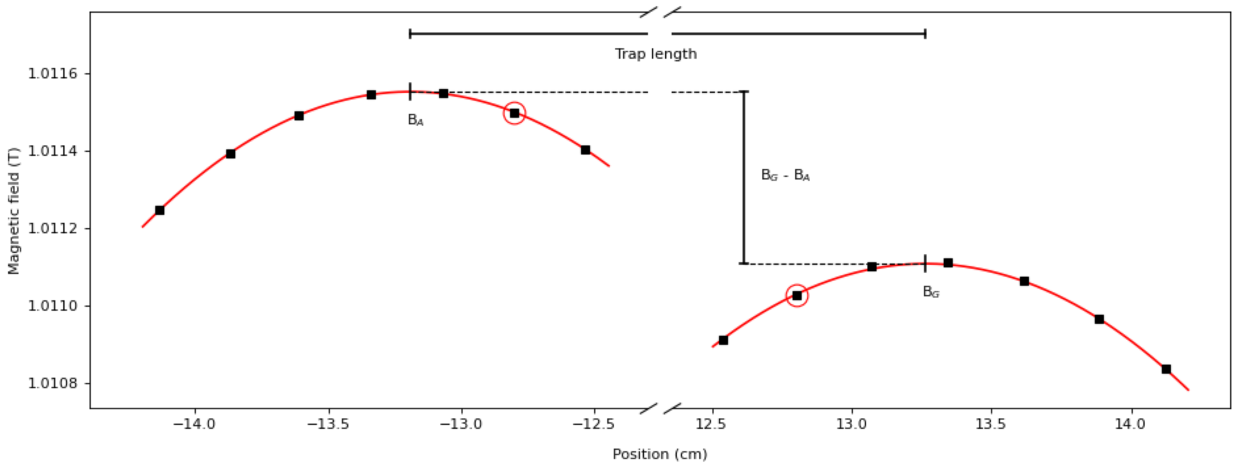


J.S. Hangst, Aarhus University

Magnetic bias concept (J. Fajans)

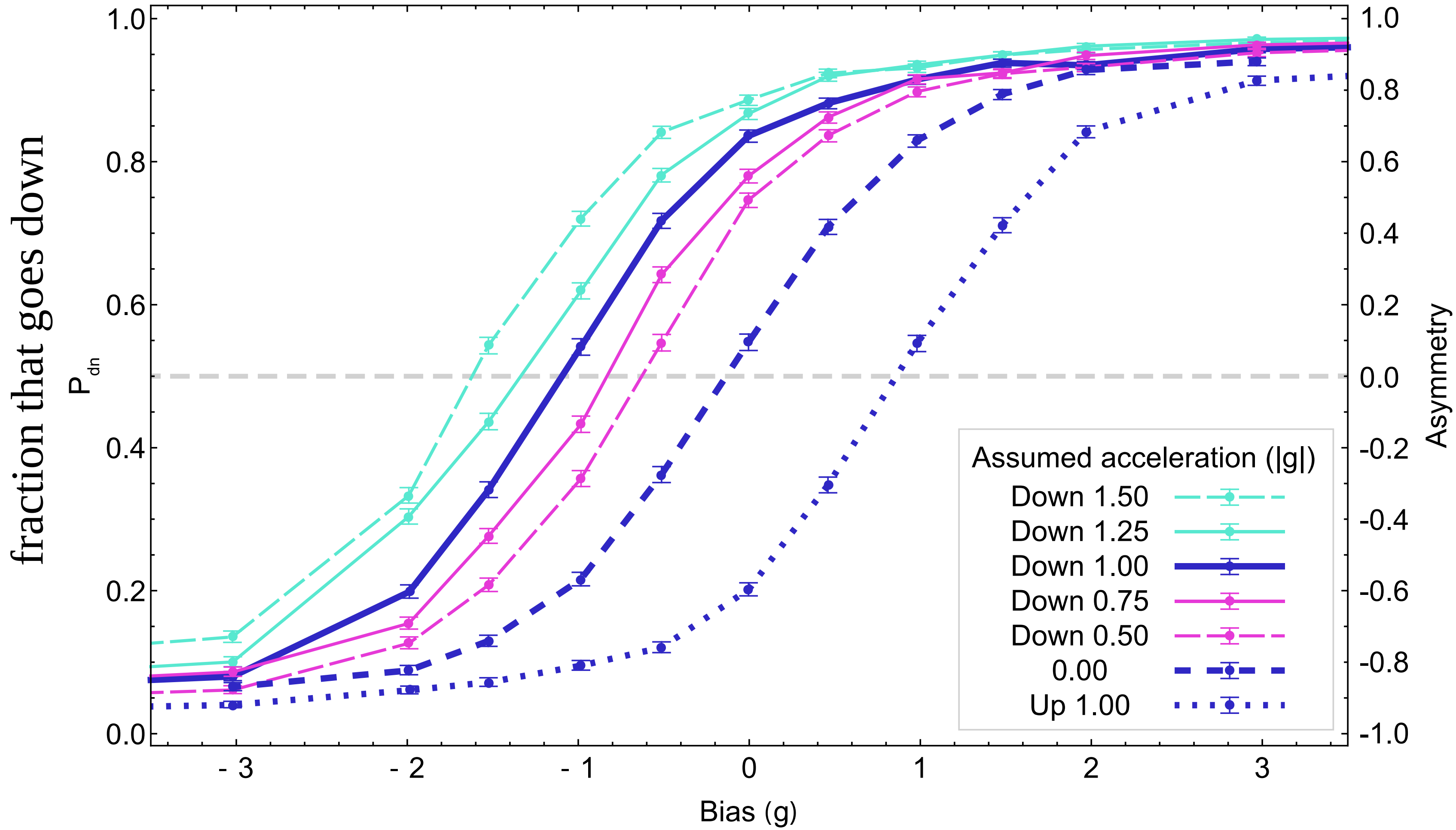
Add a differential current to one of the mirror coils

$$\frac{\mu_B(B_G - B_A)}{m_H(z_G - z_A)}$$ we call this the bias – units of acceleration

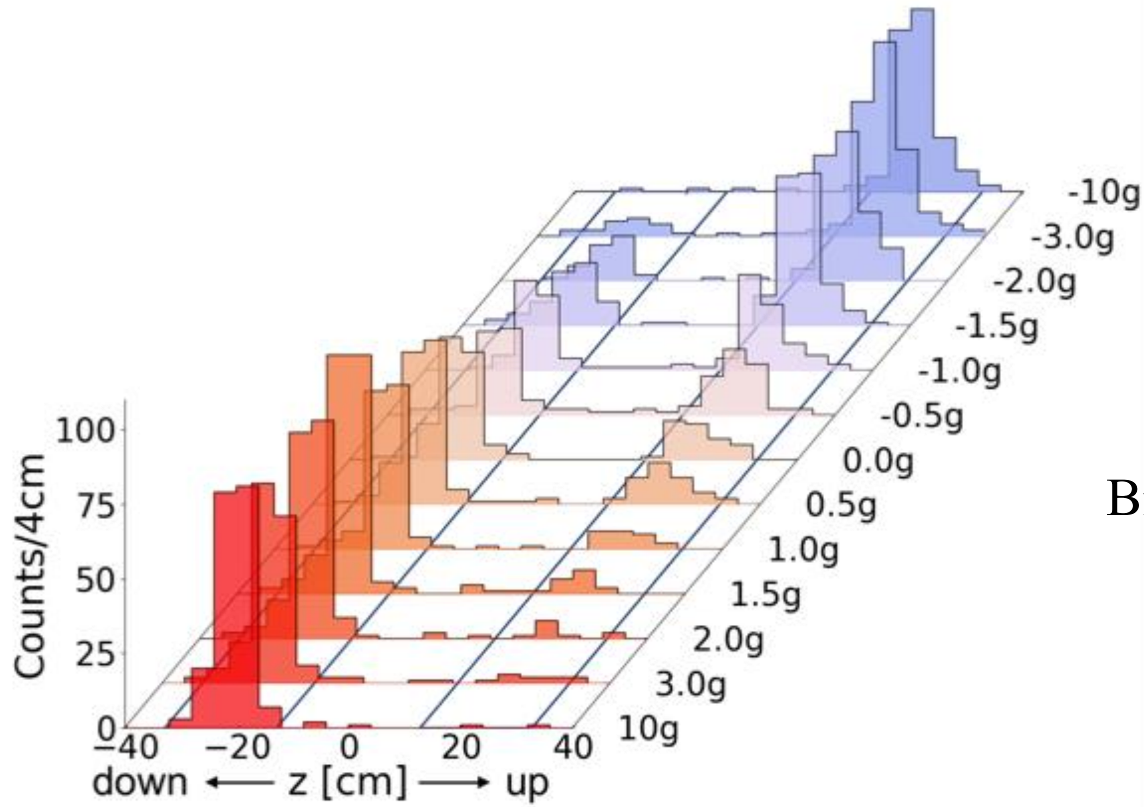


in a real experiment – ramp both mirror currents down while maintaining this difference

The S-curve - simulation

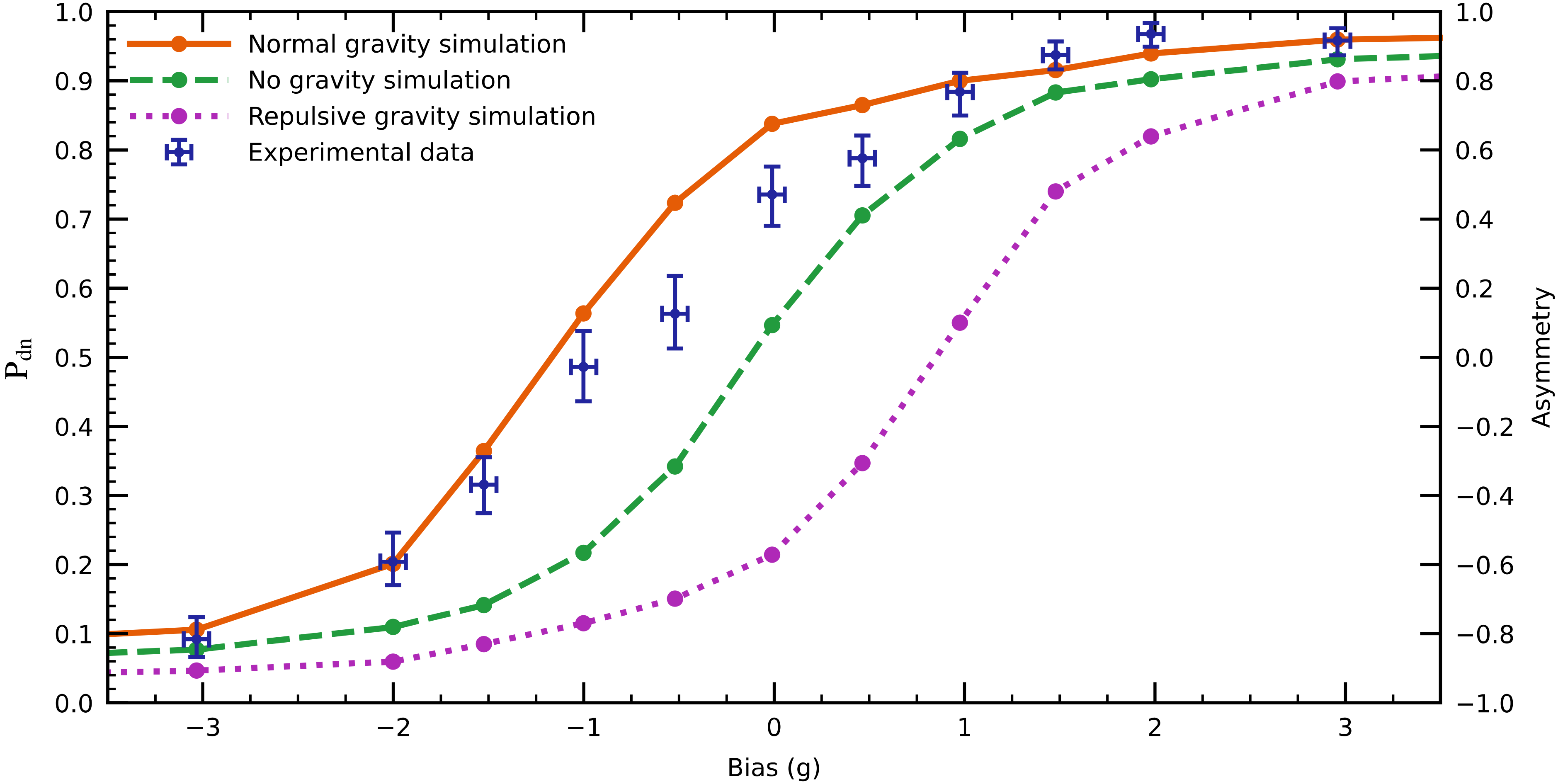


Data from 2022 run



Bias

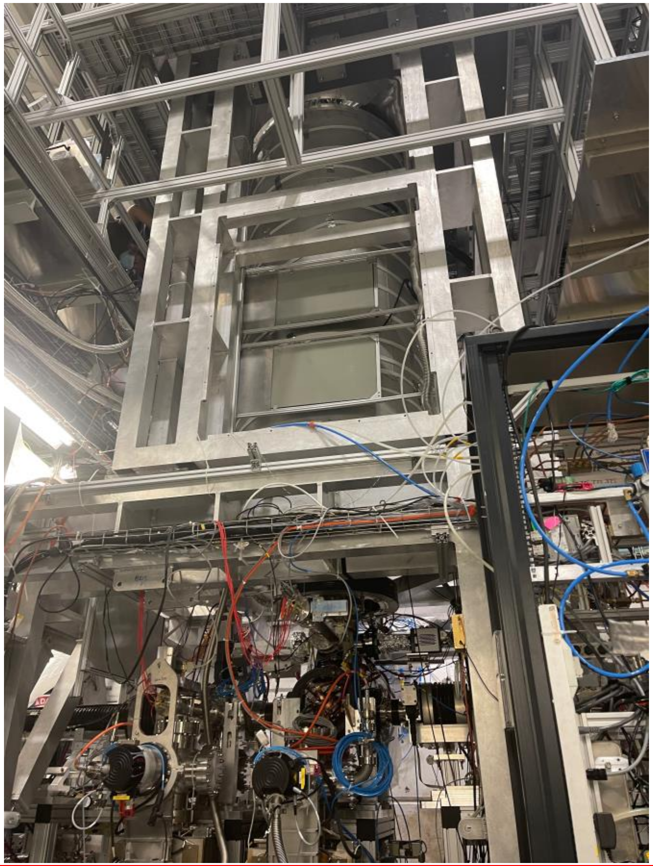
The Result



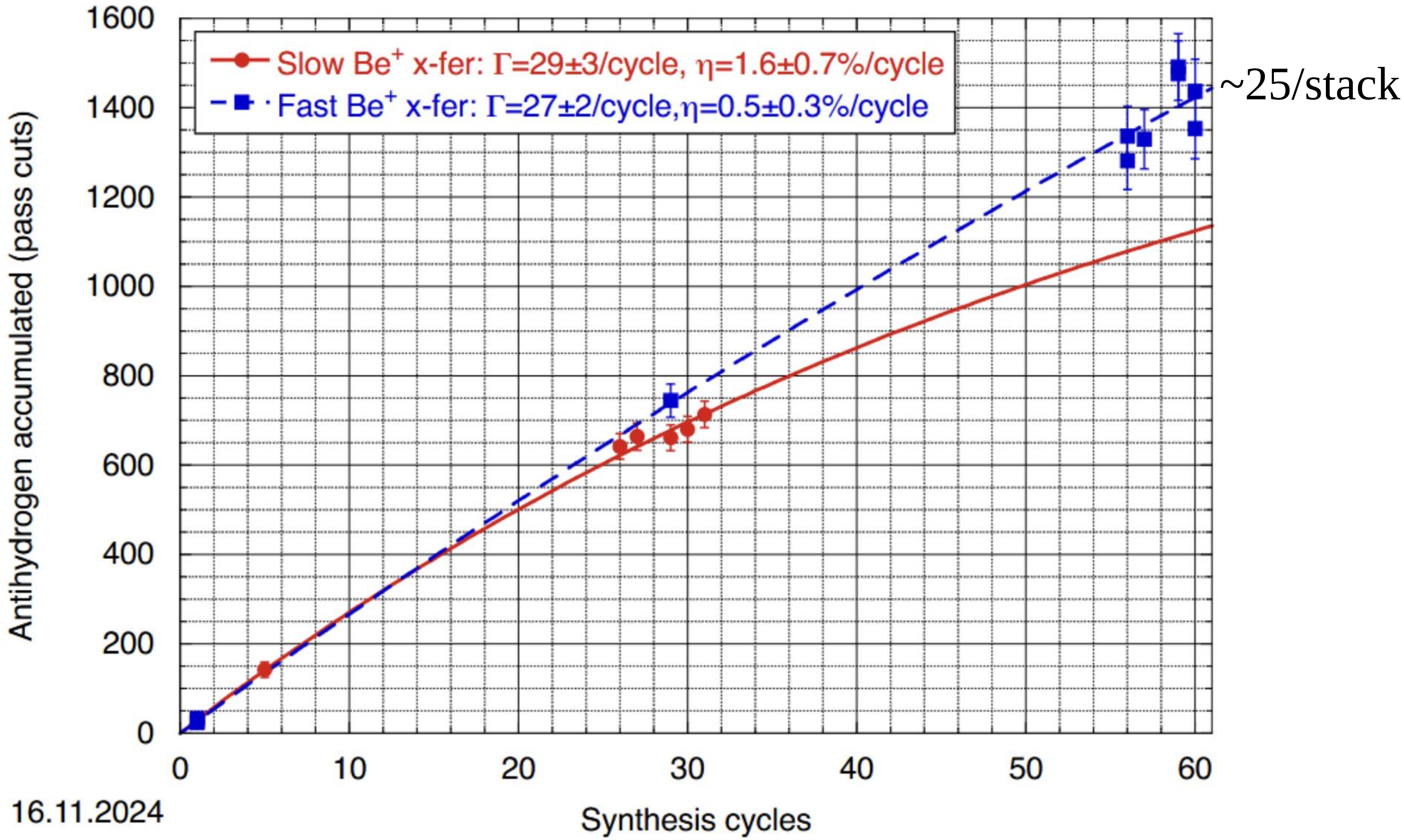
$a_{\bar{g}}$ = (0,75 ± 0,13 (stat. + syst.) ± 0,16 (simulation)) • g where g = 9,81 m/s^2

ALPHA-g in 2024

- first run with the upgraded solenoid magnet cryo-coolers – performed admirably
- new helium transfer line installed – reduced helium consumption ~15 %
- ~15% of helium usage is still dewar-to-dewar transfer loss
- complete system for Be^+ assisted stacking installed and commissioned
- some variations on 2023 (Nature) measurements, but no time for full systematic checks
- ~13 weeks of running in 2024



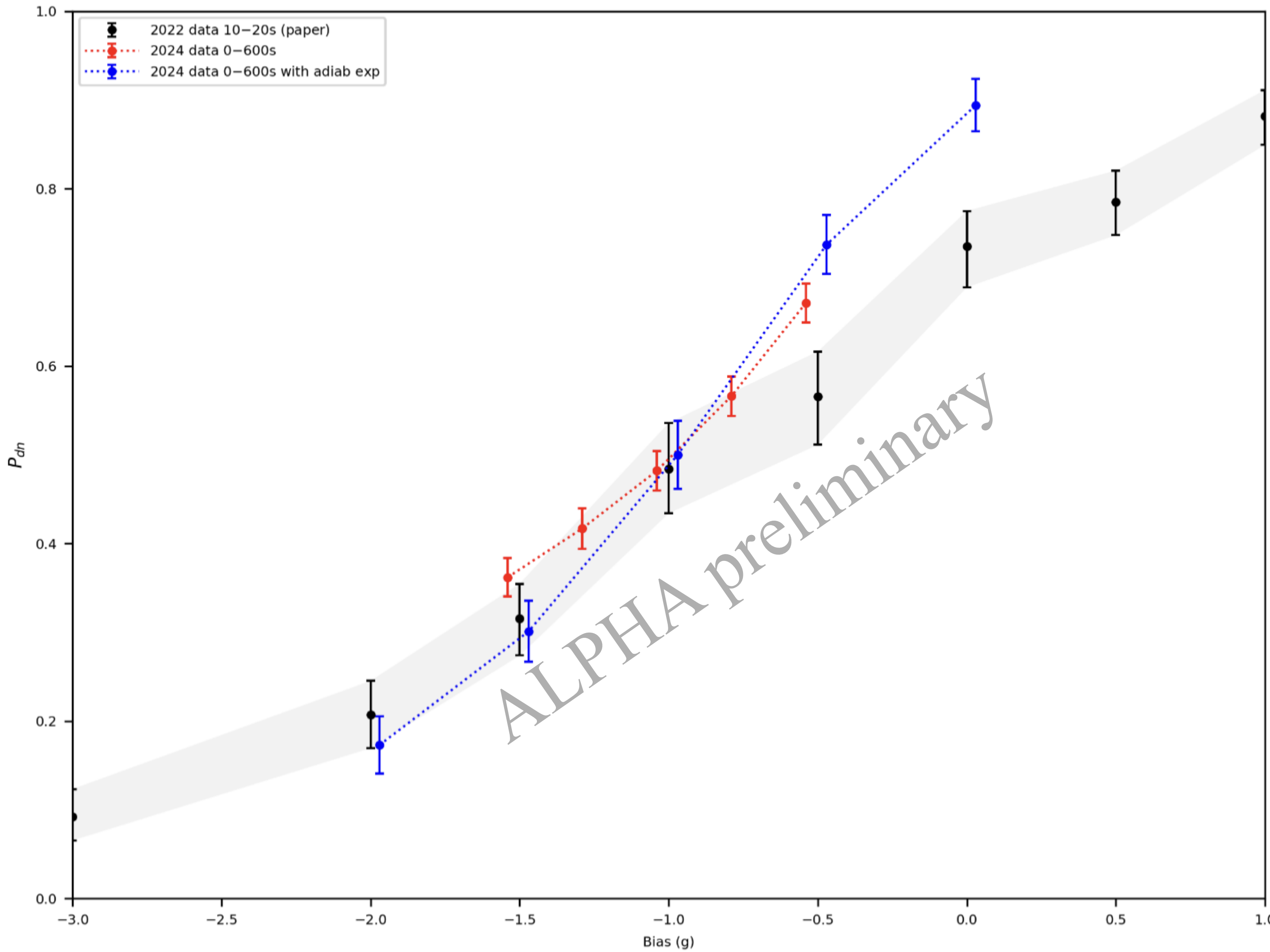
Be-assisted stacking in ALPHA-g



in 2022: 50 stacks gave ~100 atoms and took four hours

2024: maximum of 43 atoms for 1 stack

ALPHA-g 2024 results



Other news

- new CERN Fellow for 2025:
  Adam Powell
  ALPHA Technical Coordinator

- new CERN Fellow for 2025:
  April Mathad

farewell and good luck
to Chris Rasmussen!

ALPHA from 2025 onward

- gravity with antimatter – precision measurements

1. laser cooling in ALPHA-g
2. **Be system for ALPHA-g✔**
3. commissioning of the other neutral traps in ALPHA-g

- antimatter 1S-2S spectroscopy to hydrogen precision
  - ALPHA-3 upgrade: new buildup cavity, internal photon detection

- excited state spectroscopy: other spectral lines – antiproton charge radius (*e.g.* 2S-3S **2S-2P✔** **2S-4P✔**)

- systematic exploitation of adiabatic cooling in both machines

- ***in situ*** measurements on *hydrogen* with ALPHA-developed techniques for MCP diagnostics – after LS3

- antihydrogen extraction for field-free measurements

Thanks as always…

to the AD/ELENA crew – best year ever!

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