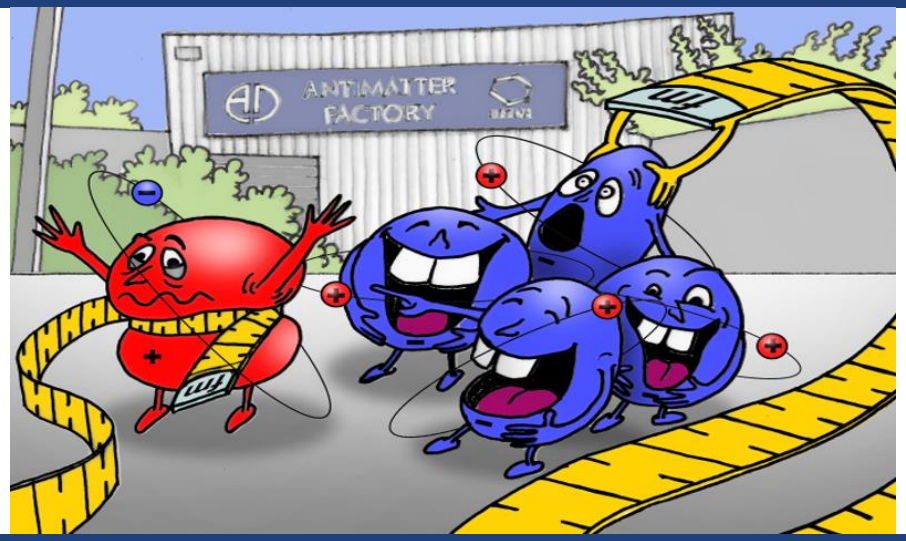

Progress towards the first measurement of the antihydrogen Lamb shift

Gianluca Janka

Group of Prof. A. Rubbia, PI: Dr. Paolo Crivelli

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Introduction: Matter-antimatter asymmetry

- Standard Model (SM) predicts equal amount of matter and antimatter produced right after Big Bang
- Observations disagree with SM → new theories arose, e.g. Standard Model Extension (SME) [*]
- SME is built from SM and General Relativity and includes Lorentz- and CPT violating operators
- SME coefficients need to be determined experimentally

[*] Colladay, D., & Kostelecký, V. A.
CPT violation and the standard model. Phys. Rev. D, 55(11), 6760-6774 (1997)

Introduction: Tests of CPT

ALPHA (2016)

Observation of the 1S-2S transition
in trapped antihydrogen.
Nature, 541:506510, 2016.

ALPHA (2017)

Observation of the hyperfine spectrum of antihydrogen.
Nature,548(7665):6669, 2017.

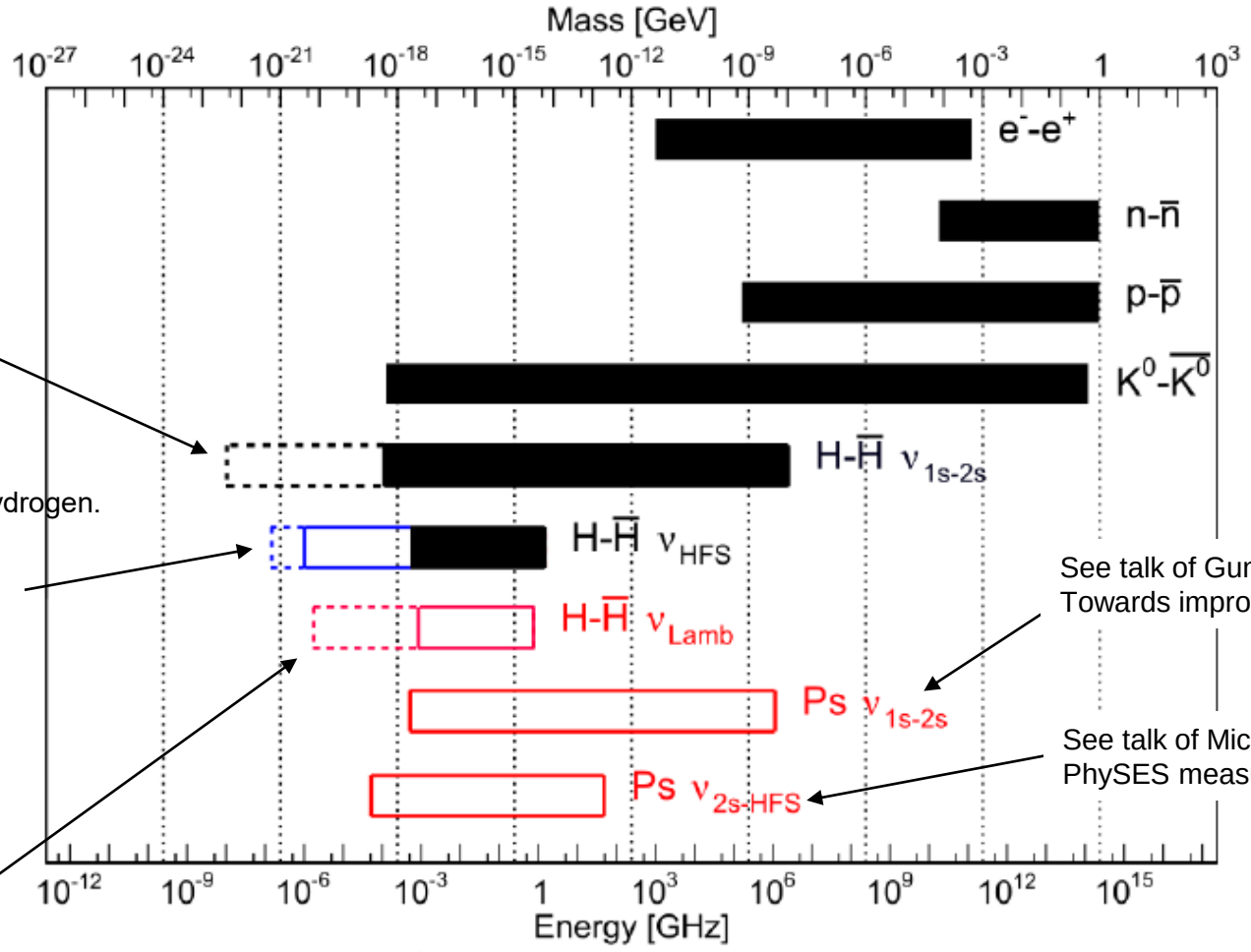
ASACUSA (ongoing)

Measurement of the hyperfine structure of
antihydrogen in a beam
Hyperfine Interact., 215(1-3):18, 2013.

GBAR

(presented in this talk)

P. Crivelli, D. Cooke, M. Heiss,
Antiproton charge radius
Phys. Rev. D 94, 052008 (2016)

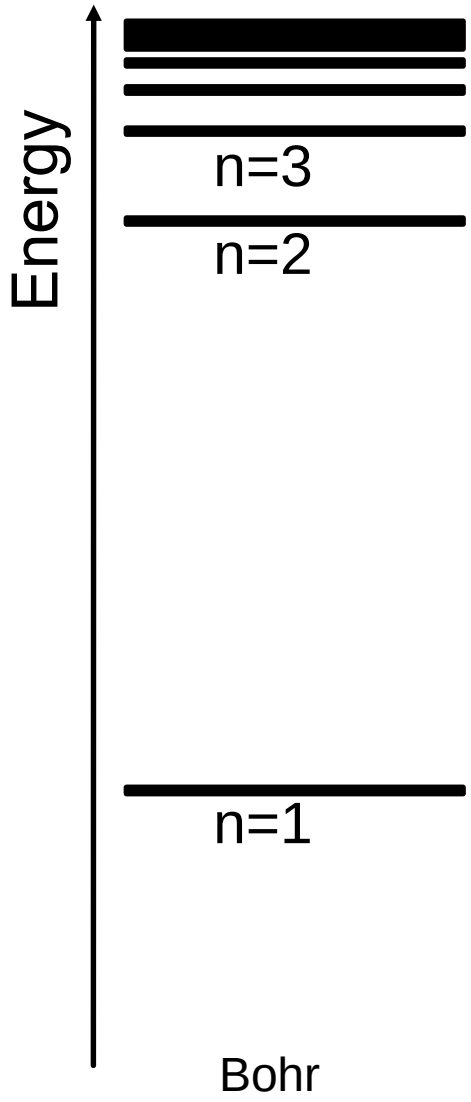


Adapted from: E. Widmann et al., Hyperfine Interact. 215, 1 (2013).

See talk of Gunther Wichmann, PhD Seminar Nov. 2016:
Towards improved 1S-2S spectroscopy of positronium

See talk of Michael Heiss, PhD Seminar Nov. 2016:
PhySES measurement of the Positronium Hyperfine Structure

Introduction: Gross energy spectrum of 2-body atom



- The atomic gross structure of the atomic energy levels is given by the Bohr and the Schrödinger equation (SEQ) with the Coulomb potential:

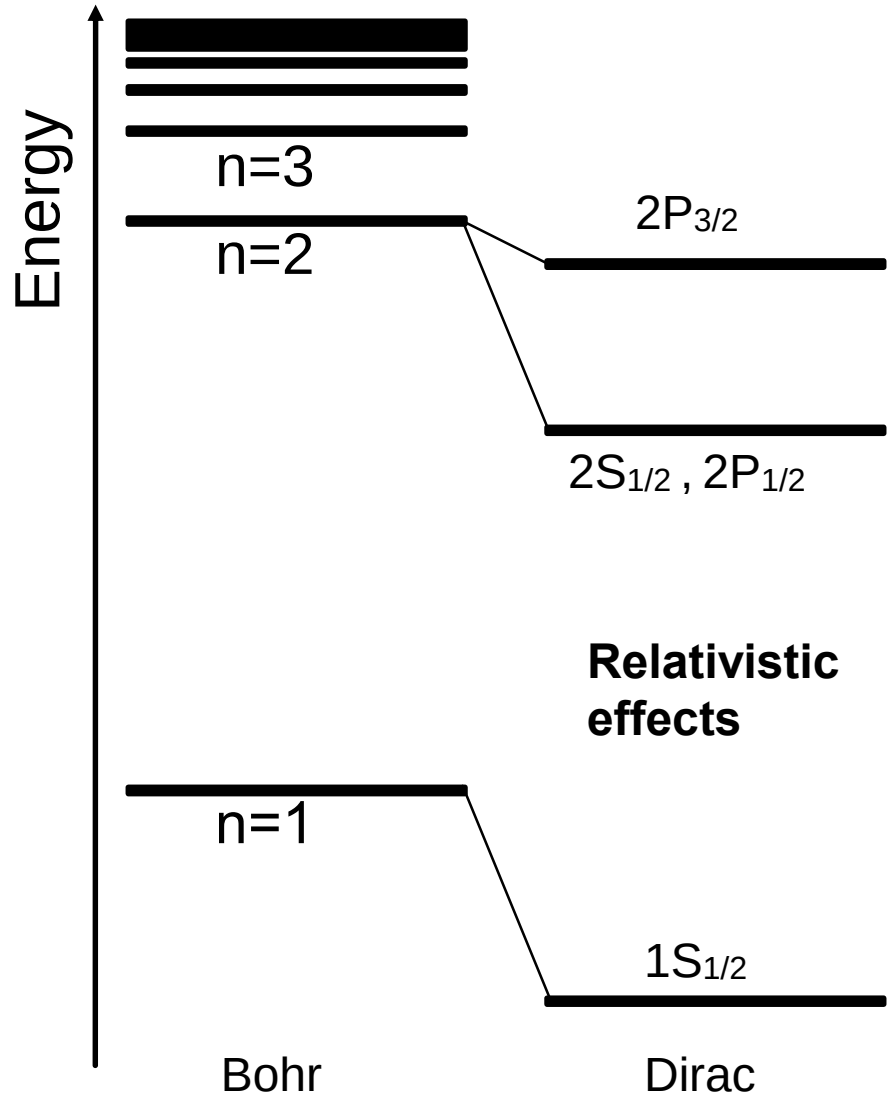
$$E_n = -\frac{(Z\alpha)^2 m_R c^2}{2n^2}$$

- The use of the reduced mass

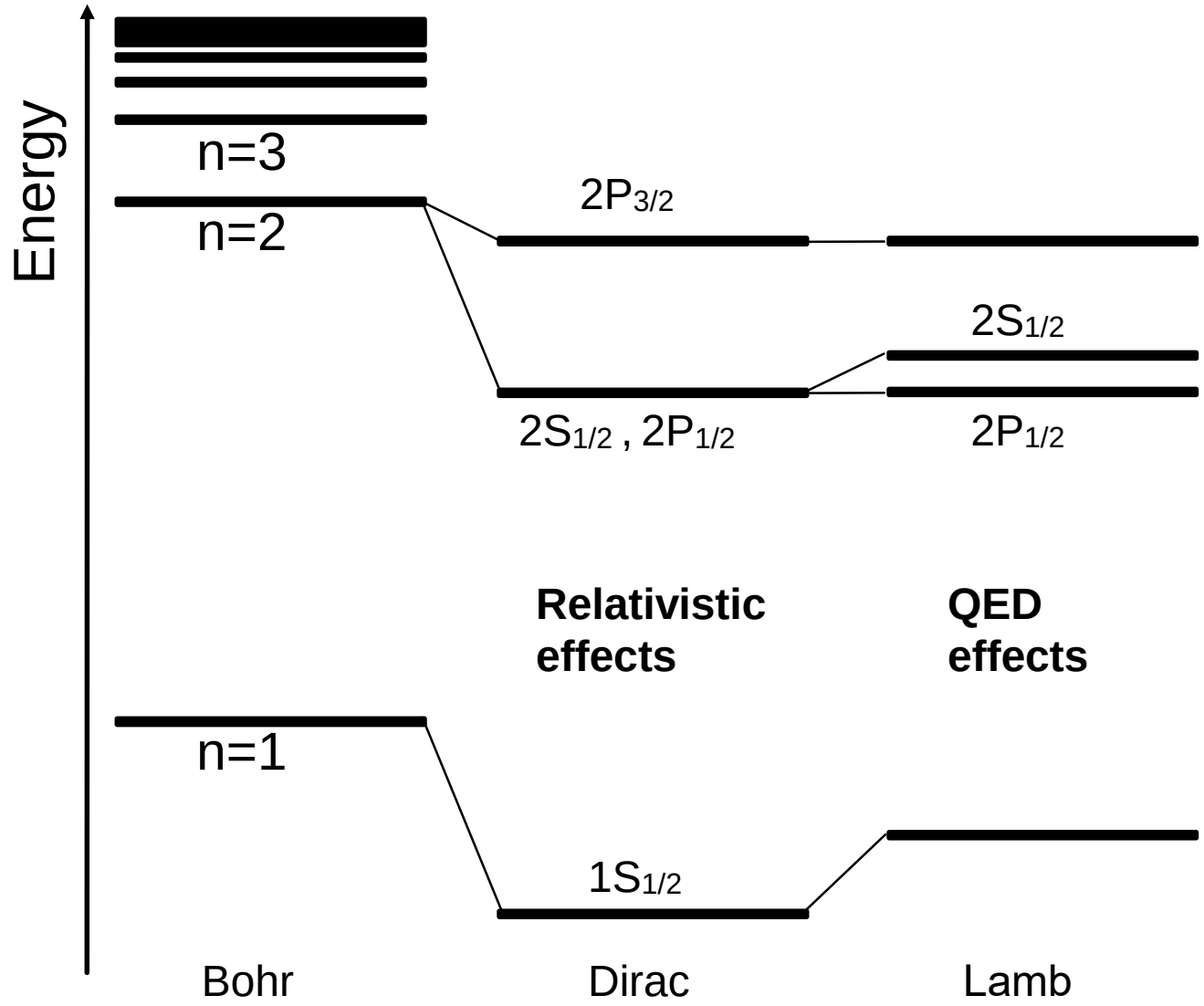
$$m_R = \frac{M\,m}{M+m}$$

- takes into account the finite mass of the nucleus providing a first (non-relativisitic) corrections

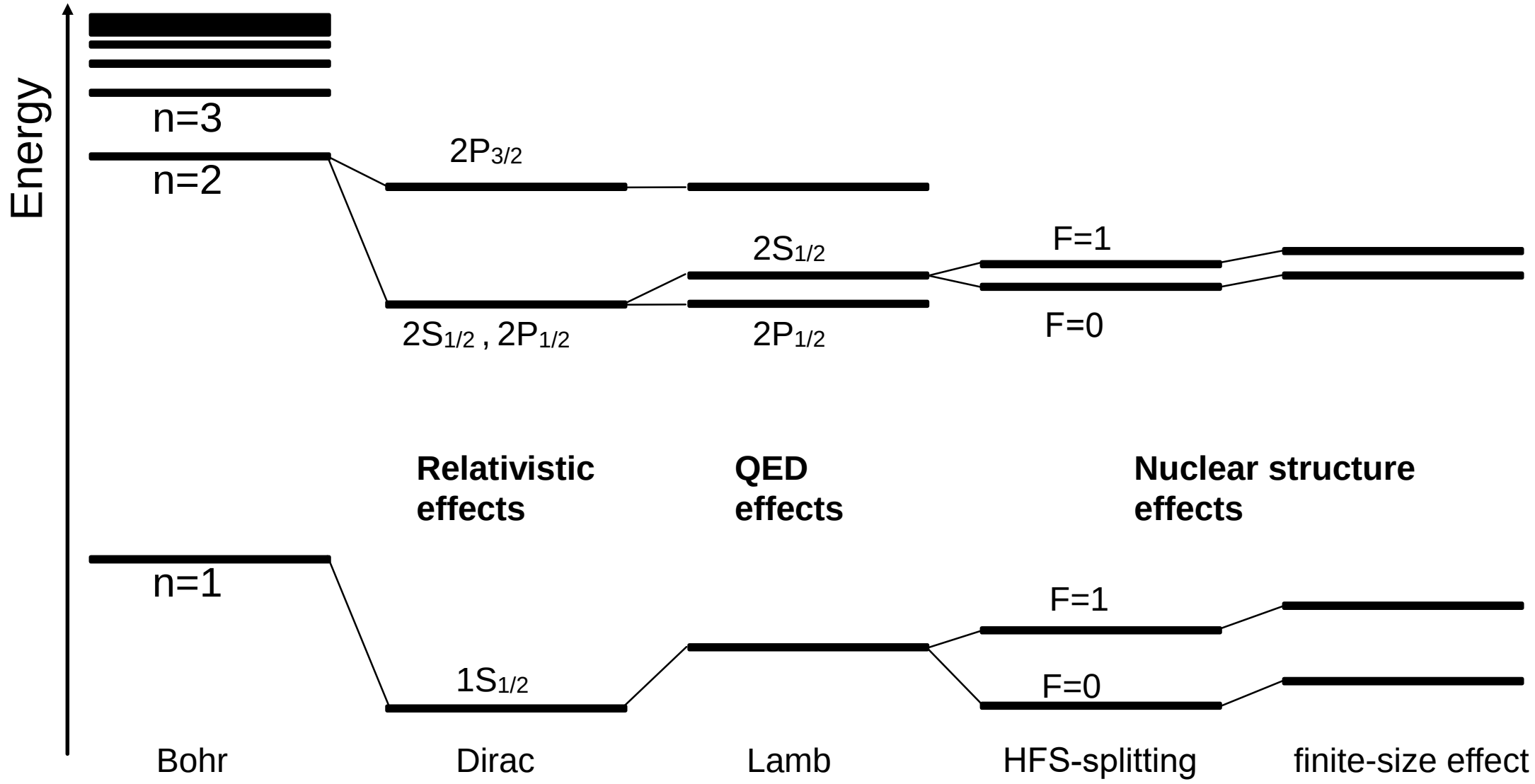
Introduction: Relativistic effects



Introduction: QED effects

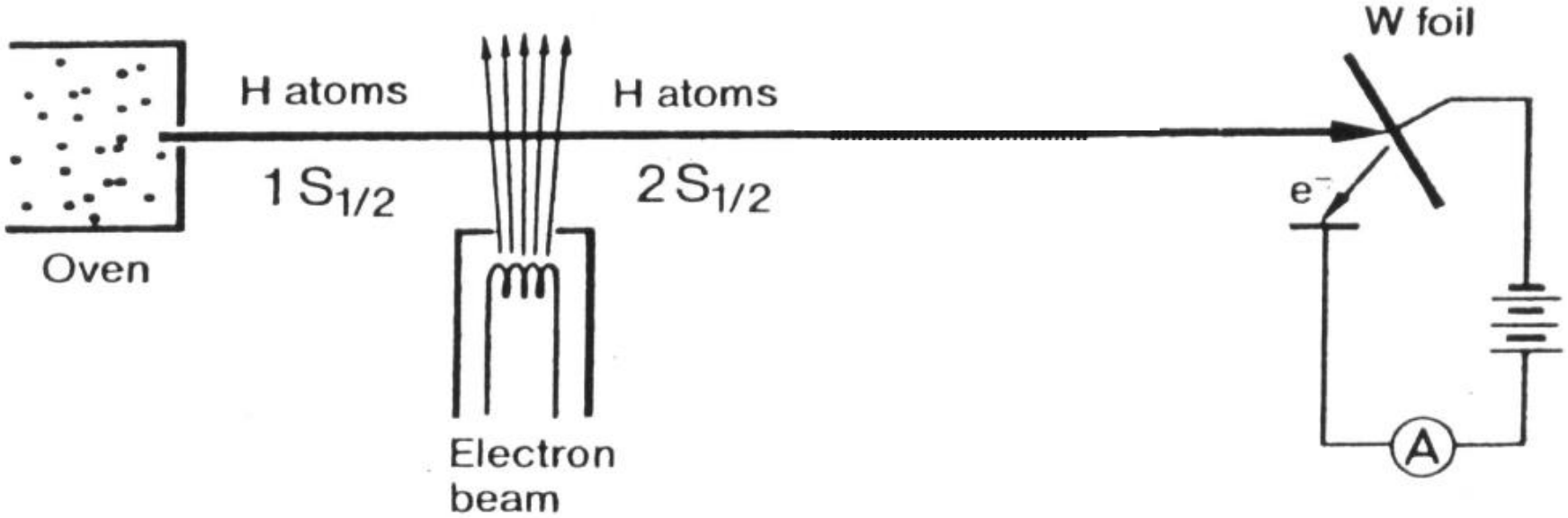


Introduction: Corrected energy spectrum of Hydrogen



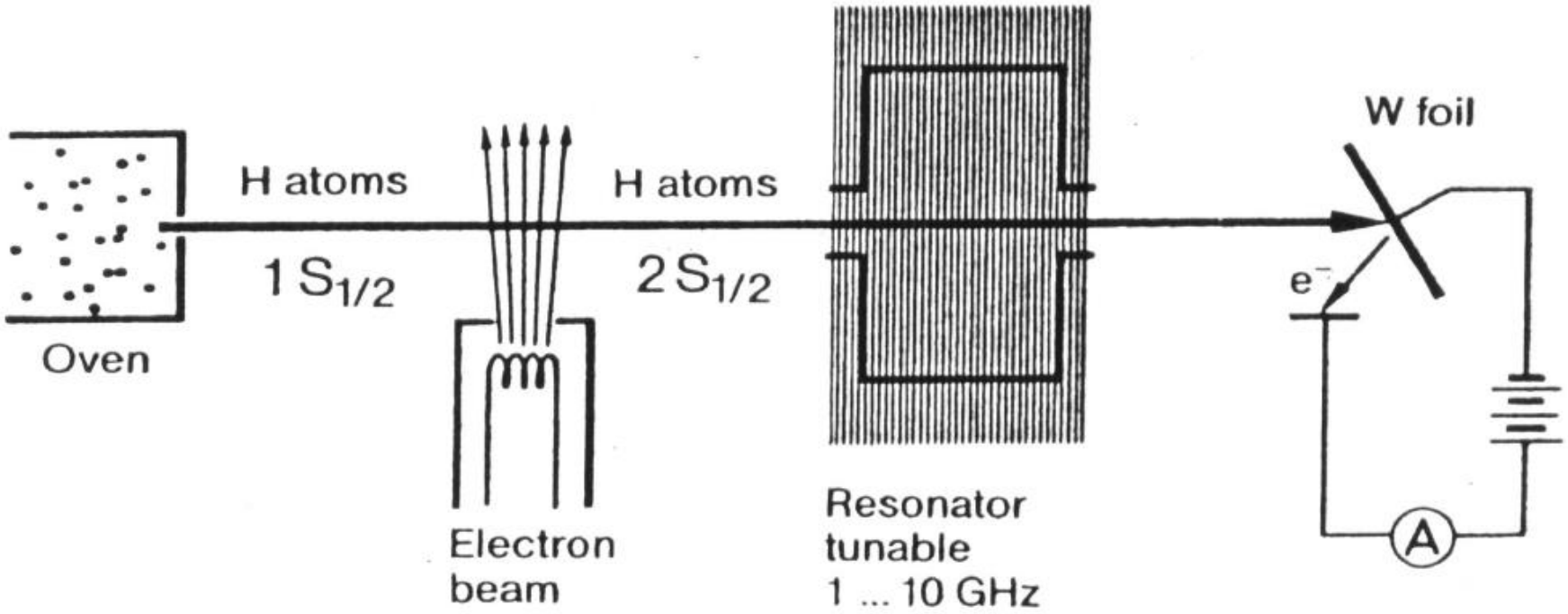
Introduction: Lamb's experiment

- Basic idea: produce a beam of hydrogen atoms in the metastable 2S state, $\tau_{2S} \simeq 10^8\,\mathrm{ns} = 100\,\mathrm{ms}$, by bombarding ground state atoms with electrons
  - The atoms in the 2S impinging on a metal surface release their electrons that can be detected with an electrometer while this process does not occur for the atoms in the ground state (1S)



Introduction: Lamb's experiment

- Applying an RF field at the resonance frequency one can induce transition from the 2S to the 2P state
  - The 2P state, $\tau_{2P} \simeq 1\ \mathrm{ns}$, decays quickly to the ground state and therefore the signal in the electrometer will decrease



Introduction: Lamb shift measurement

- An additional contribution to the Lamb shift is given by the finite size of the (anti-)proton:

$$\Delta E_{nucl} = \frac{2}{3}\frac{(Z\alpha)^4 m_R}{n^3} m_R^2 R_p^2$$

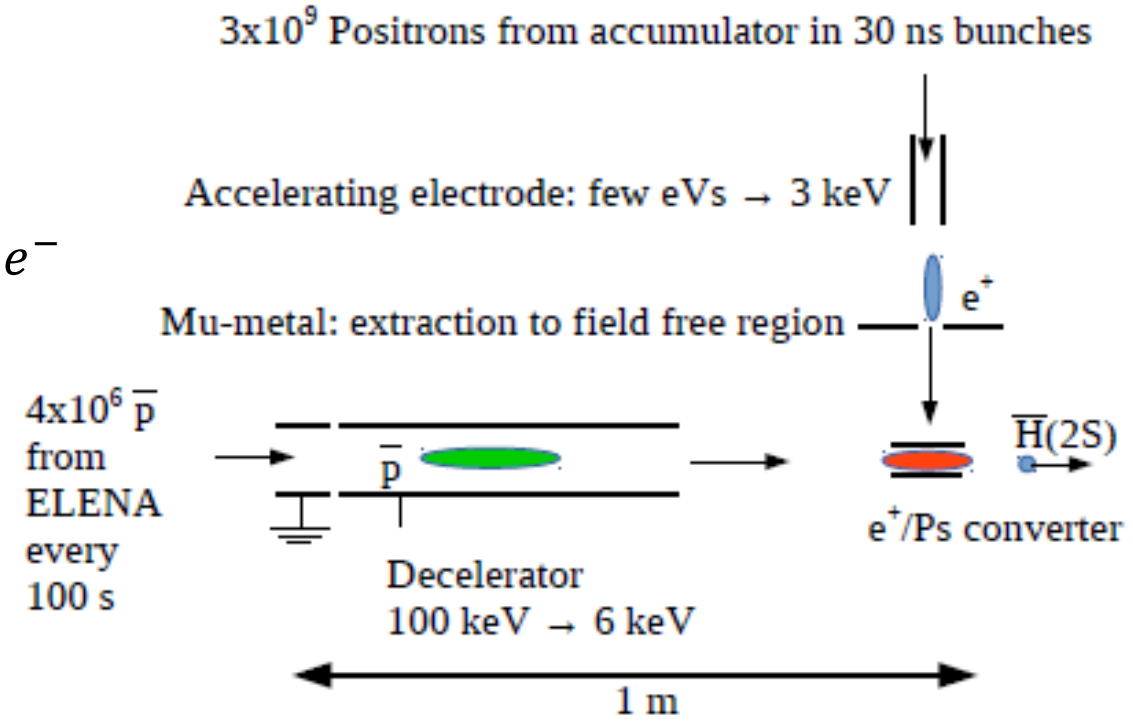
- by measuring the Lamb shift of antihydrogen, one can determine the antiproton charge radius

- **Goal: Measuring the antihydrogen Lamb shift at a precision of 100ppm, which allows to extract the antiproton charge radius at a level of 10%.**

Experiment: $\bar{H}(2S)$ beam formation

- $\bar{p}$ from ELENA in AD hall at CERN
- Positrons from the intense slow positron beam from GBAR

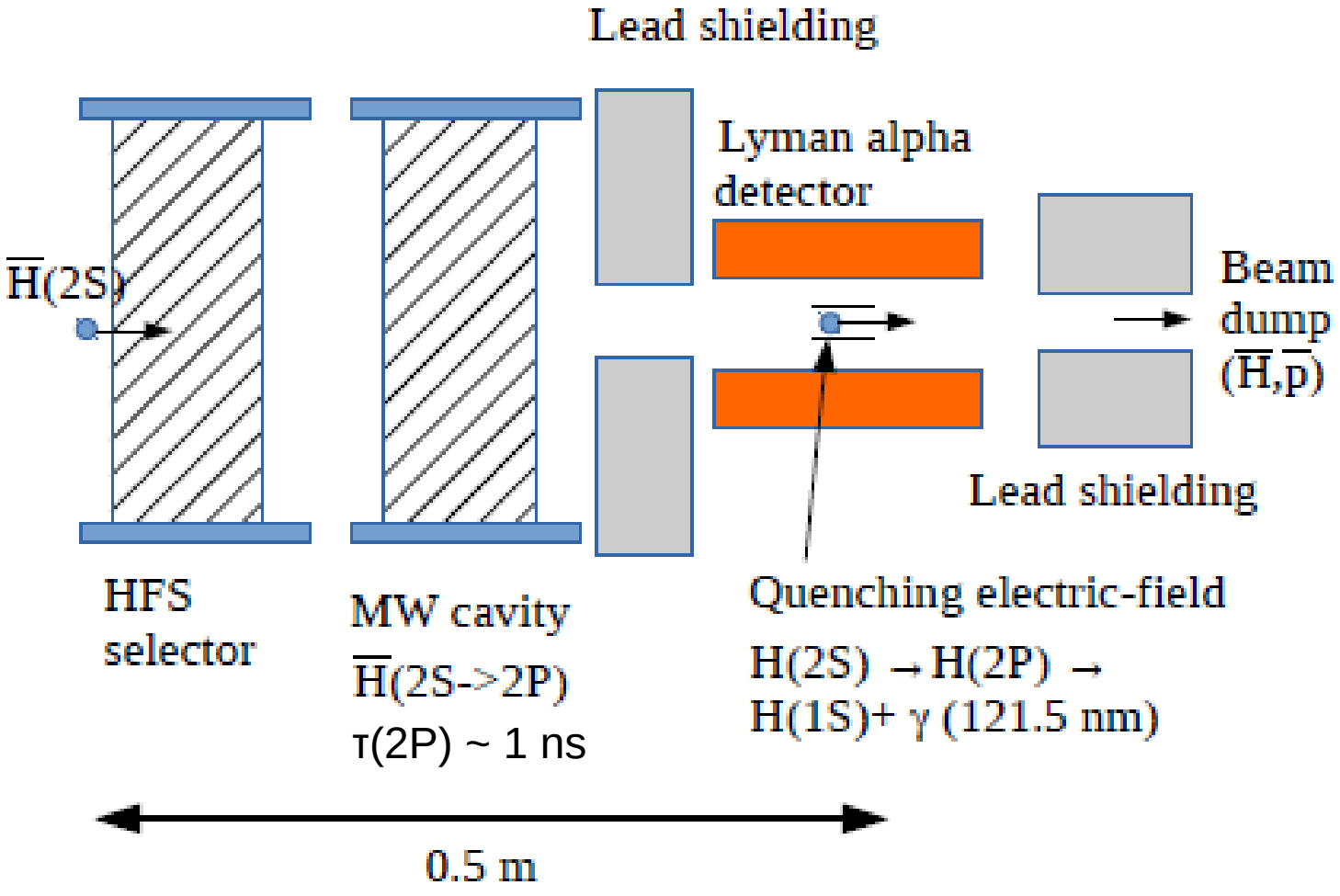
- Charge exchange reaction: $\bar{p} + Ps \rightarrow \bar{H} + e^-$
- H formation with protons already been measured in good accordance with calculations [*]
- Cross section for $\bar{H}(2S)$ formation similar to $\bar{H}(1S)$ at an antiproton energy of 6 keV



[*] C. M. Rawlins, A. S. Kadyrov, A. T. Stelbovics, I. Bray, and M. Charlton, Phys. Rev. A 93, 012709 (2016).

Experiment: Proposed scheme

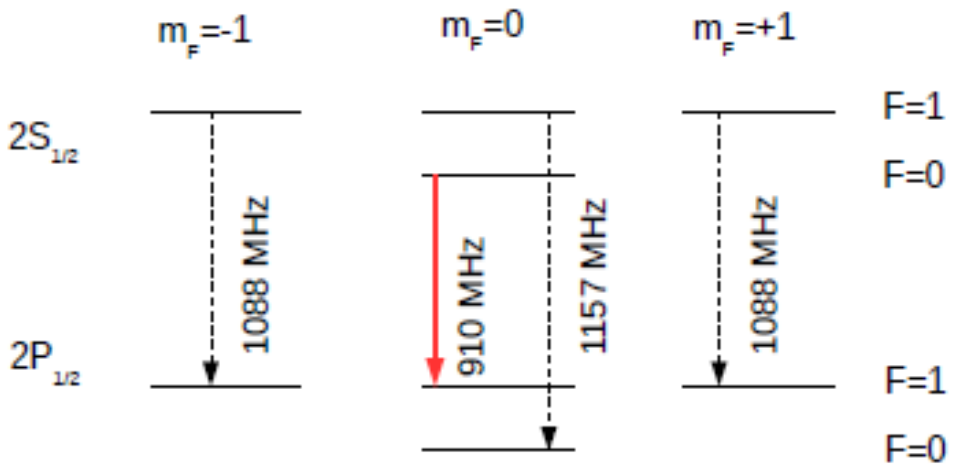
v ~ 1 mm/ns
τ(2S) ~ 100 ms

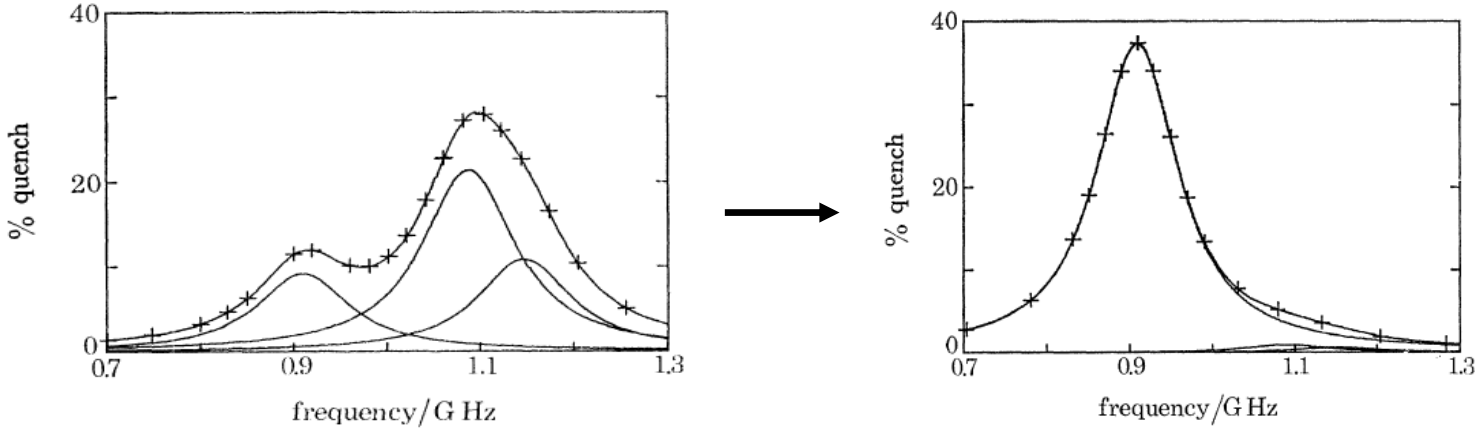


Experiment: HFS selector

- Several 2S and 2P hyperfine levels
- In order to reduce distortion of the resonance line shape, $2S_{1/2}$ F=0 state is isolated
- Method: single frequency to drive down all the $2S_{1/2}$ F=1 to short lived $2P_{1/2}$, shown by Newton et al. [*]

  -> 1% of F=1, but 60% of F=0 retained





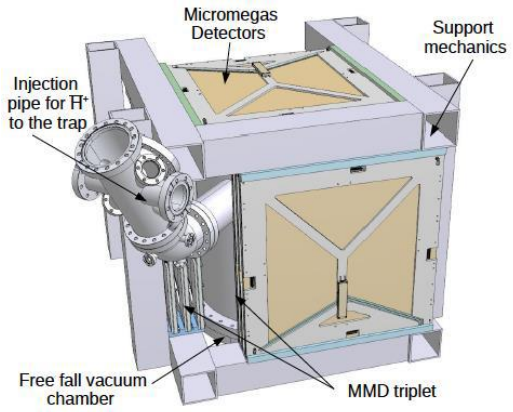
[*] G. Newton, D.A. Andrews, P.J. Unsworth
Philosophical Transactions of the Royal Society of London,
Vol. 290, No. 1373. (Jan. 29, 1979), pp. 373-404.

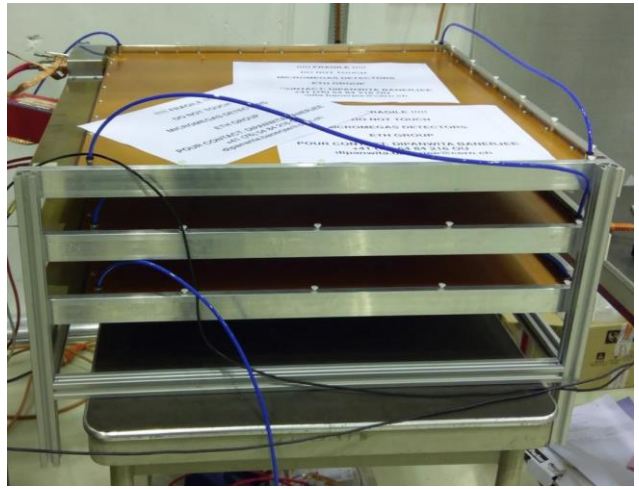
Experiment: Single Ly-α detector

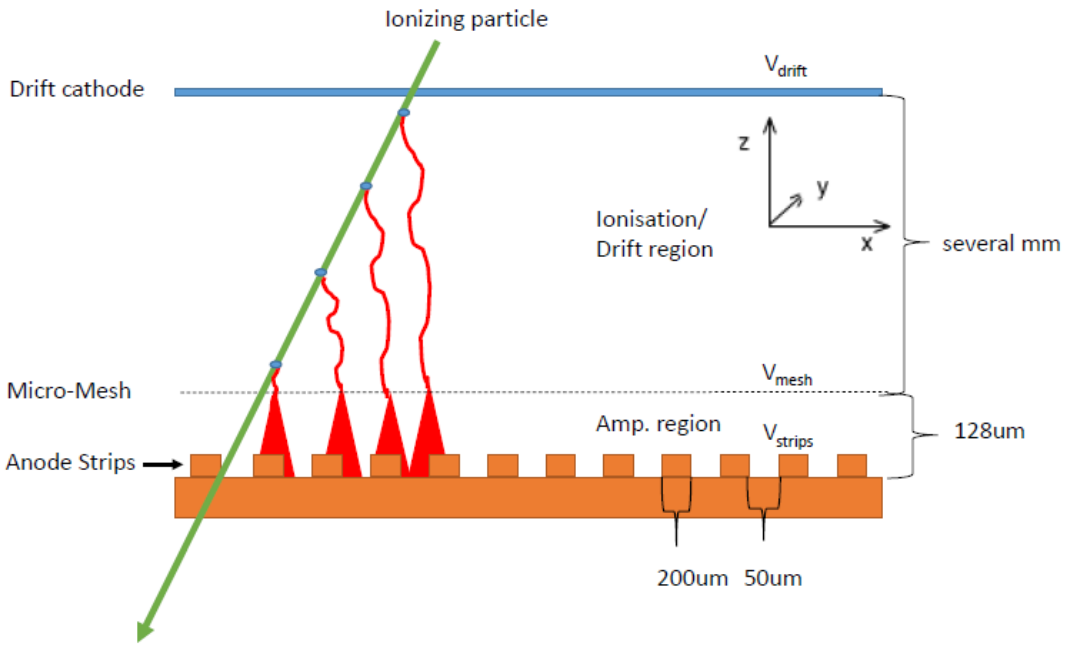
Micromegas:

- Prototype with MgF_2 window and Ar/DME filling gas (90/10) built and tested
- Differentiation between cosmics / antiprotons and Ly-α possible
- Low efficiency due to
  - small photoionization yield at 121nm (~15%)
  - loss through window (~50%)
  - difficulty to distinguish signal from noise

  → improvable with other gas mixtures



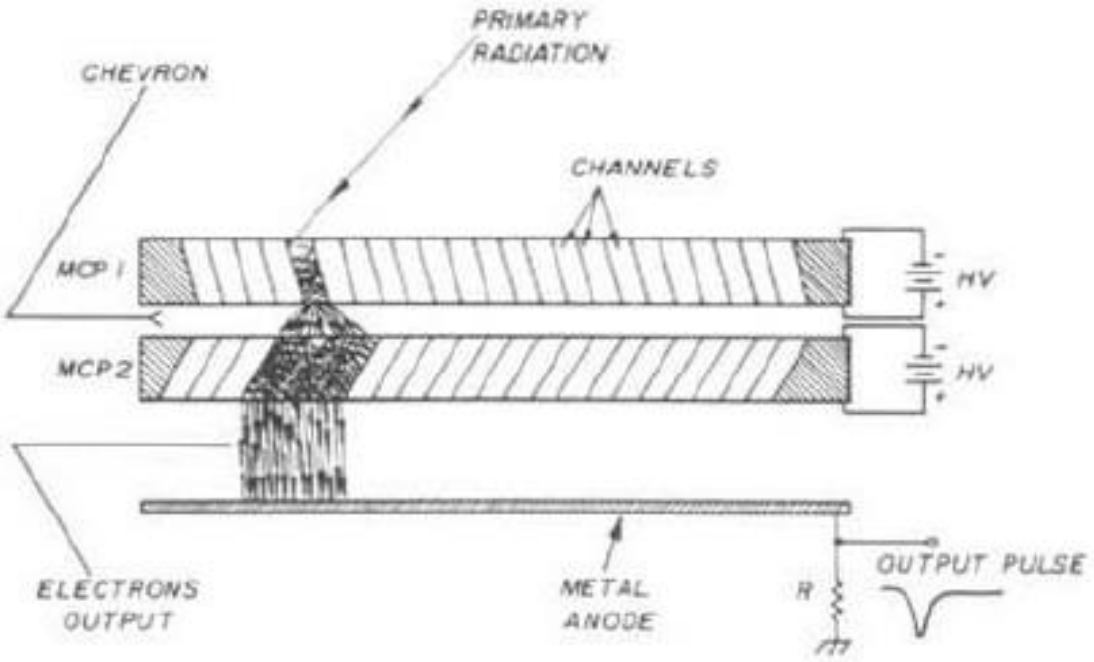




Experiment: Single Ly-α detector

Microchannel Plate (MCP):

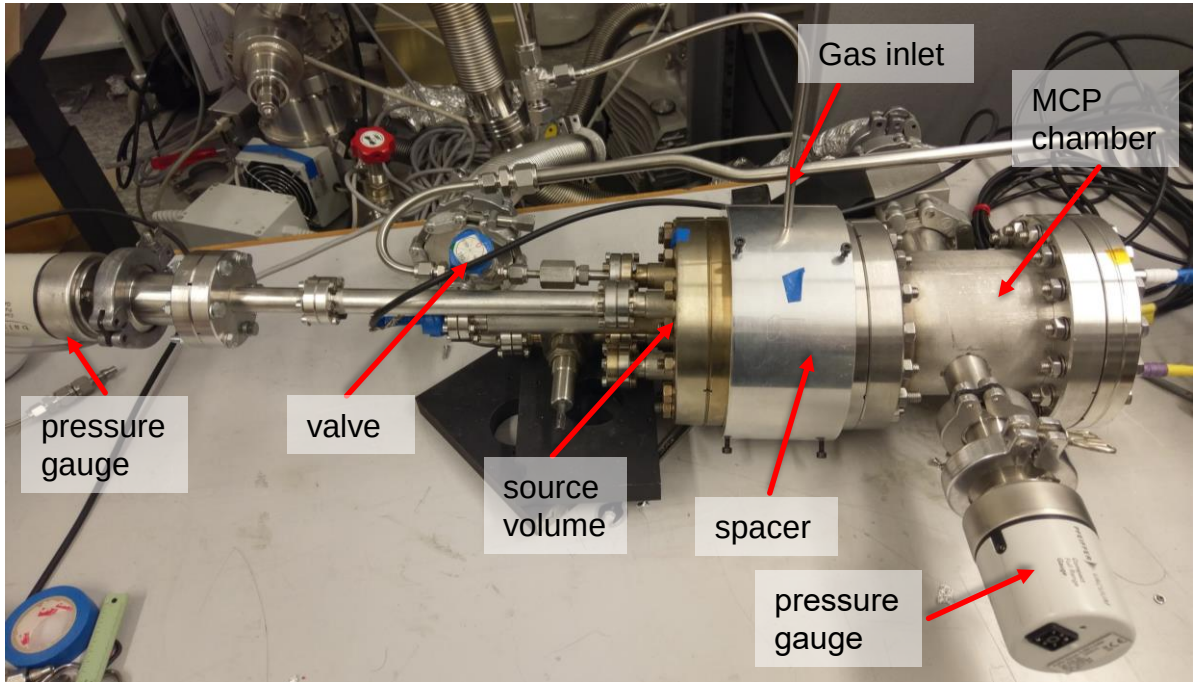
- Two plates for higher gain (~10^7)
- Deposition of CsI on top plate as converter (~50% quantum efficiency) [*]
- Estimated detection efficiency for single Ly-α ~40%
- Tests with a 1 inch MCP confirmed this estimated detection efficiency
- Difficult to handle: CsI highly hygroscopic, assembly needs to be done in nitrogen atmosphere



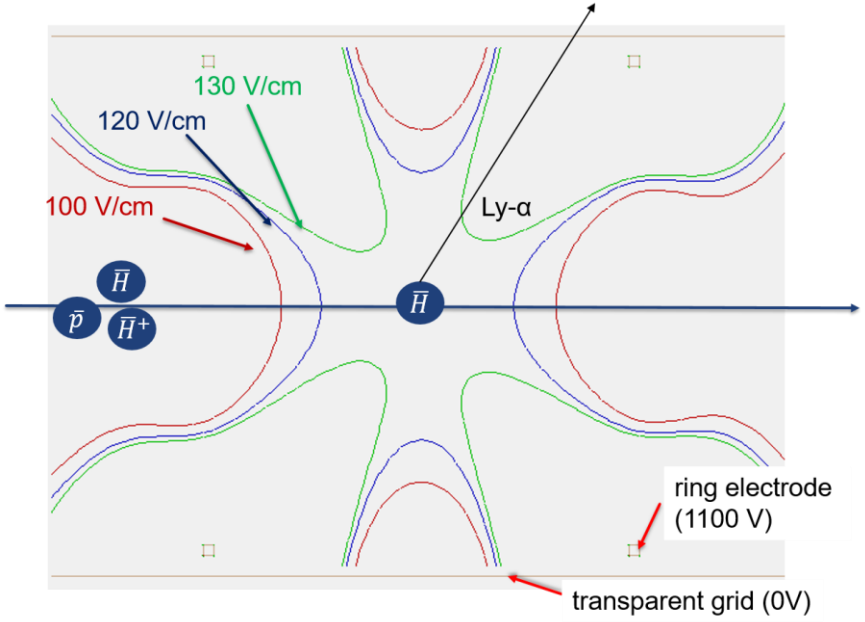
[*] Anton S. Tremsin, Oswald H. W. Siegmund,
"The quantum efficiency and stability of UV and soft x-ray photocathodes",
Ultrafast X-Ray Detectors, High-Speed Imaging, and Applications, 2005

Single Ly-α detector

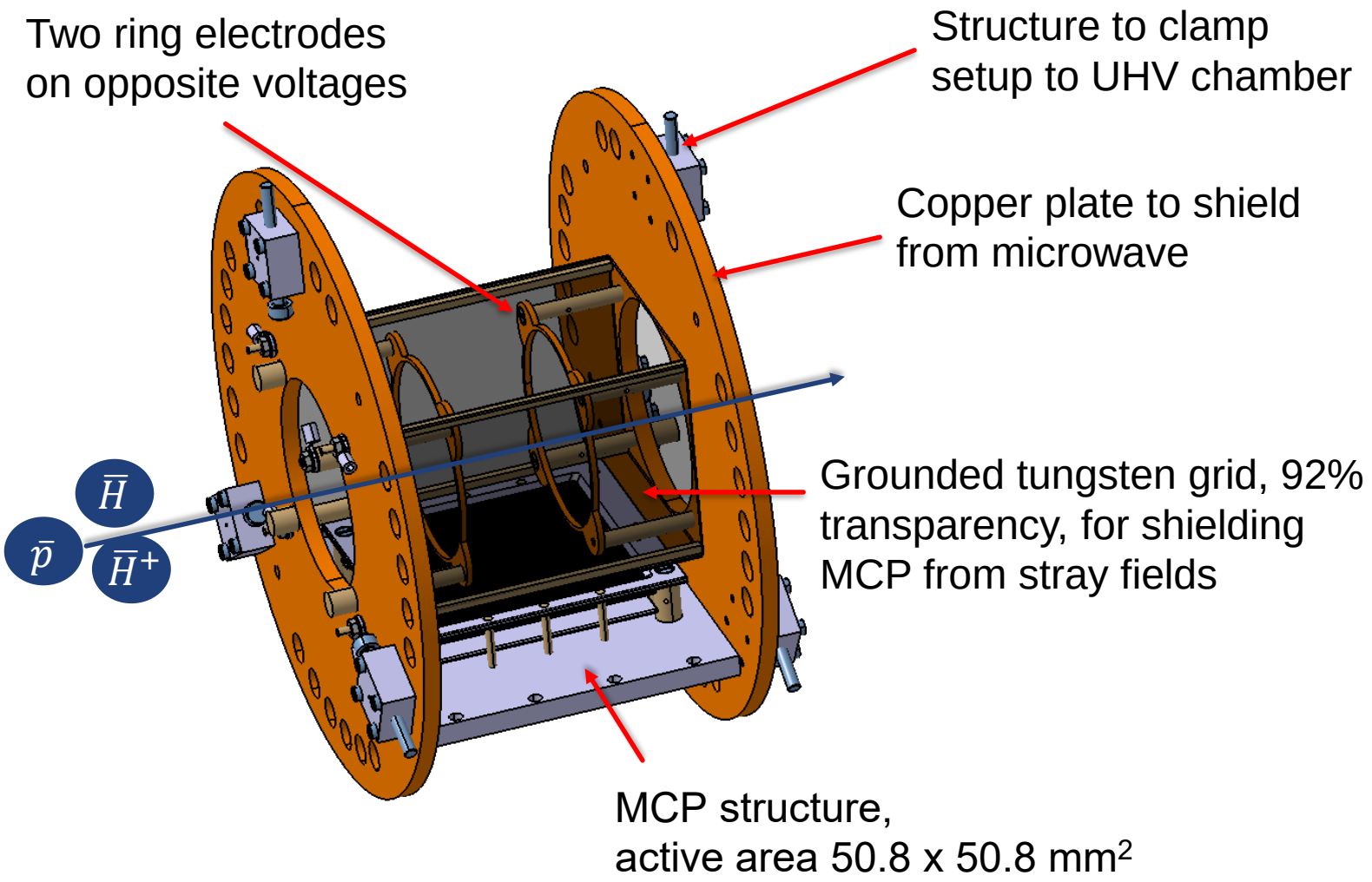
- Tests done with a self-made Ly-α source based on the principle of a low pressure discharge lamp
- Source with Ly-α filter and possibility to tune flux
- Calibrated with a solar blind PMT with known efficiency
- Measured rates up to 400 MHz



Single Ly-α detector



SIMION simulation:
41.5% solid angle covered



Current Status & Outlook

- Lamb shift measurement of $\bar{H}$ at a level of 100ppm seems possible with roughly one month of data taking, thanks to ELENA and GBAR LINAC. The accuracy is limited by statistics (~ 1000 detected events per day, possible improvements).
- 1 inch circular MCP prototype successfully tested
- Most of Ly-α detector parts either ordered or in production, assembly is foreseen in April 2018
- First goal: detection of production of H(2S) via charge exchange (May-July 2018)
- First attempts with $\bar{H}$ can already be done before LS2 assuming ELENA and Ps production working like scheduled (Sept. – Nov. 2018)


QUESTIONS?
COMMENTS?
CONCERNS?