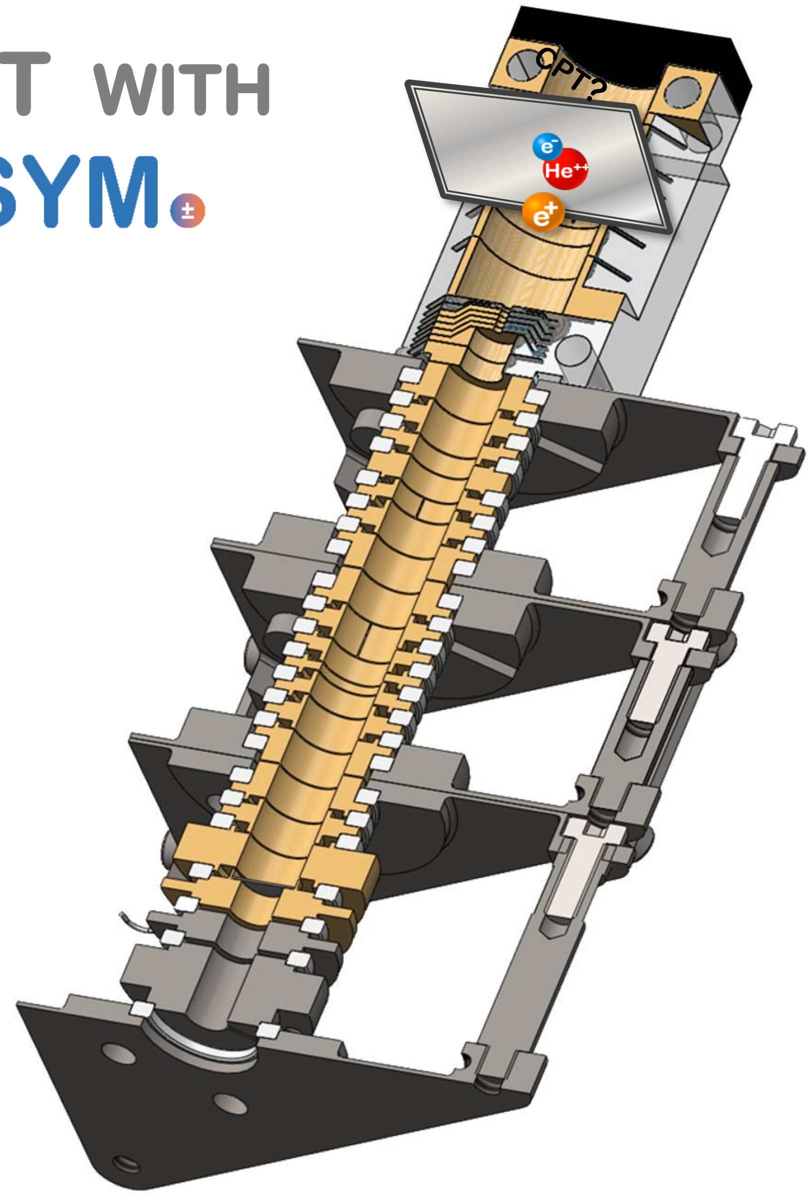
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Testing QED and CPT with Alphatrap and LSym



Sven Sturm

MPIK Heidelberg

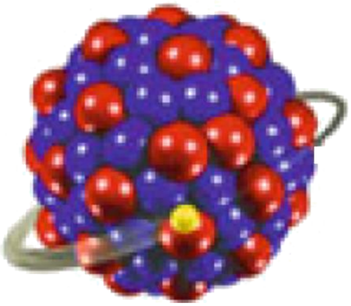
isoQuant SFB1225

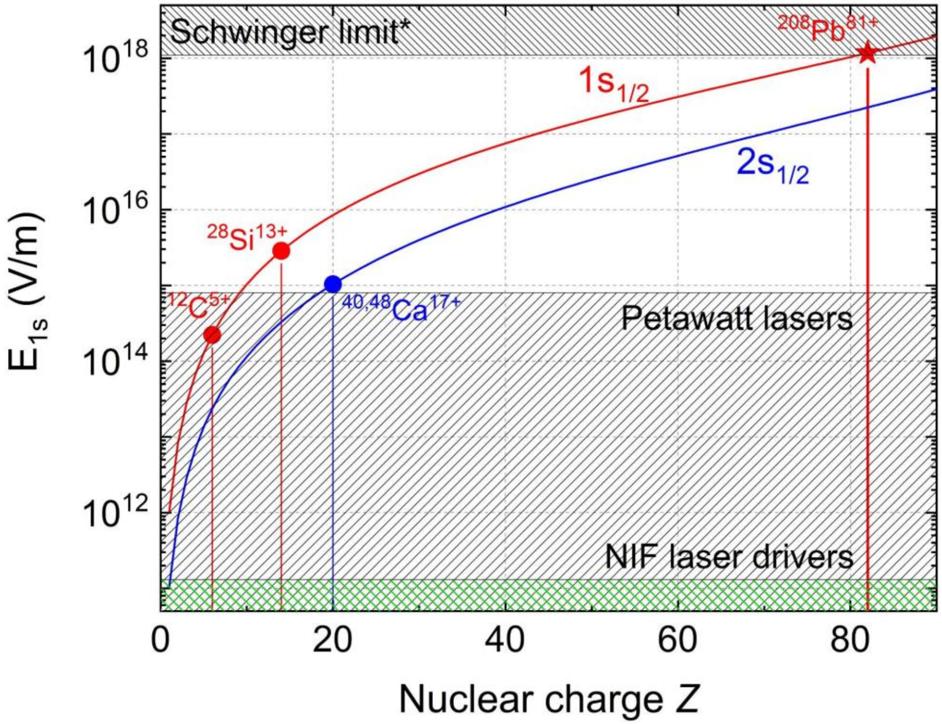
α TRAP

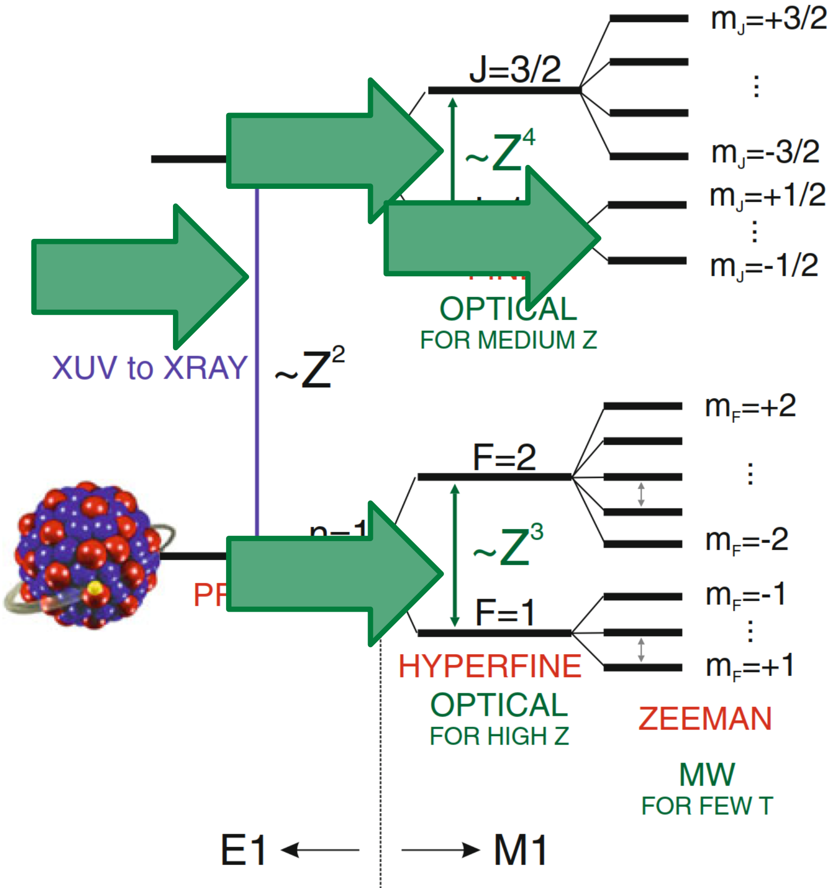
erc

LSym

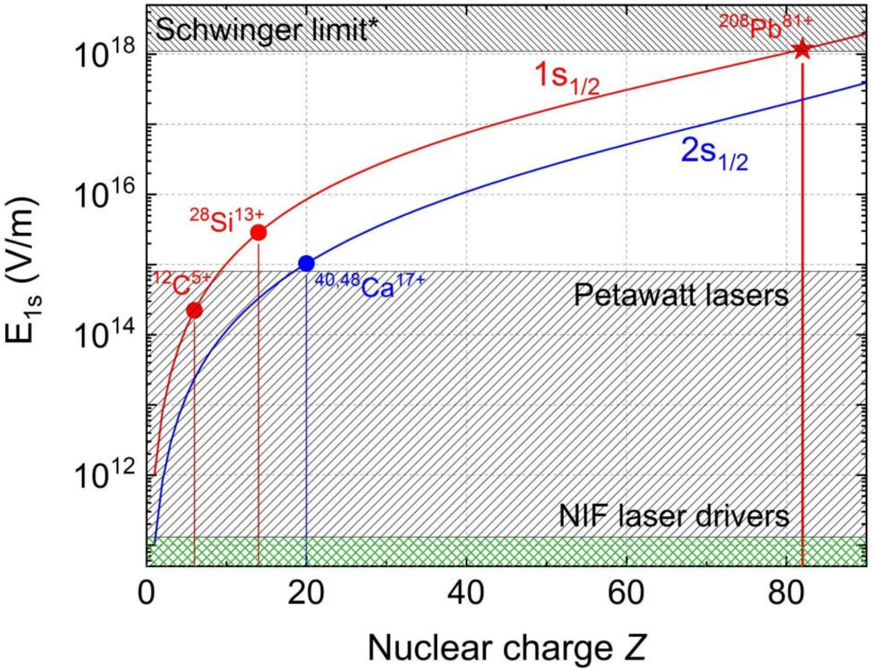
Highly charged ions

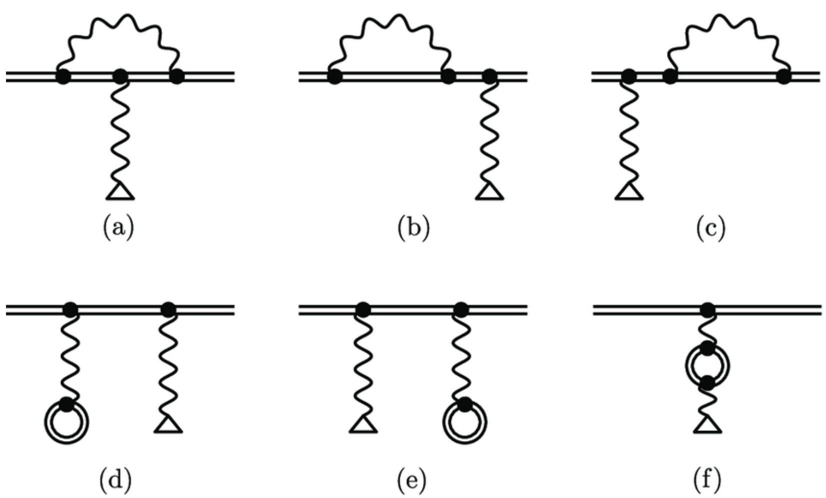


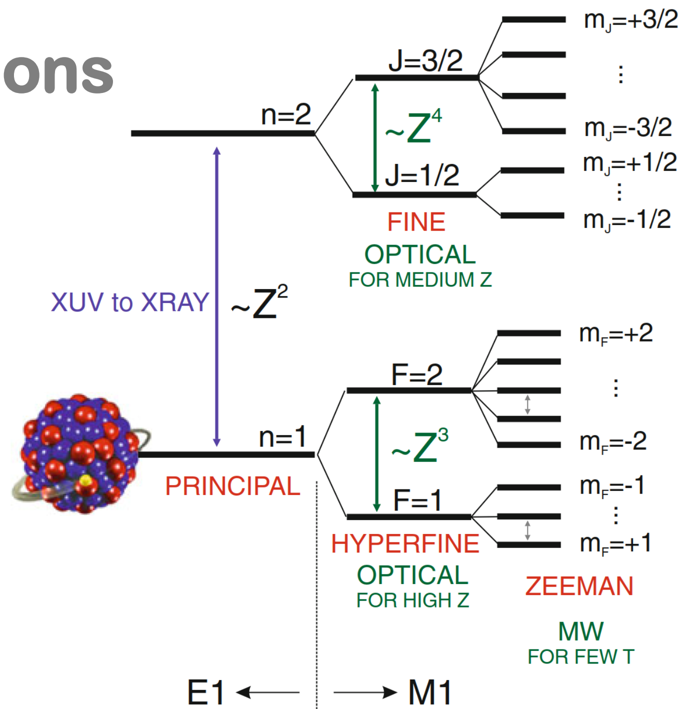


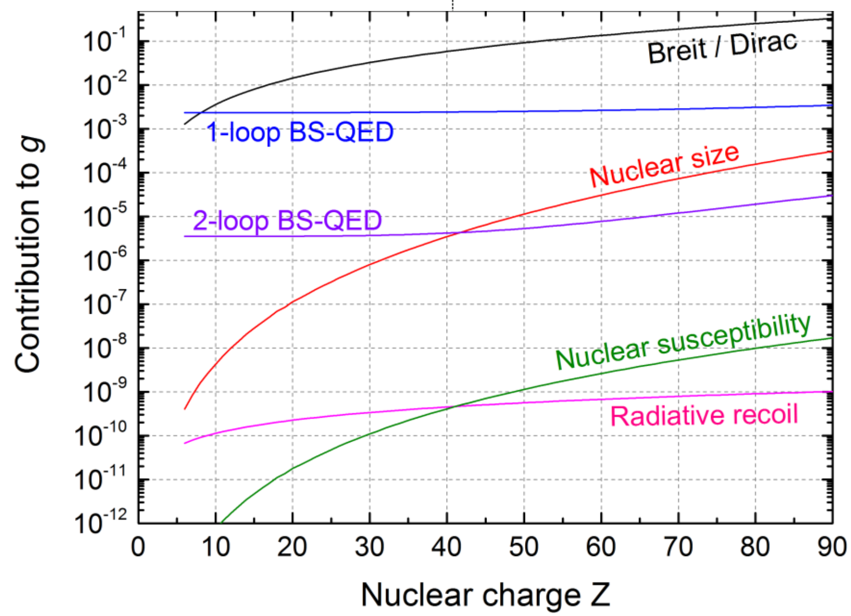


Highly charged ions

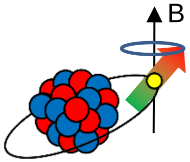






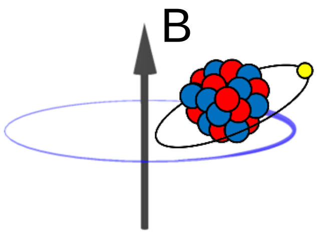


G-FACTOR MEASUREMENT IN A PENNING TRAP



$$\omega_L = \frac{g}{2}\frac{e}{m_e}B$$

Larmor frequency
in a magnetic field B



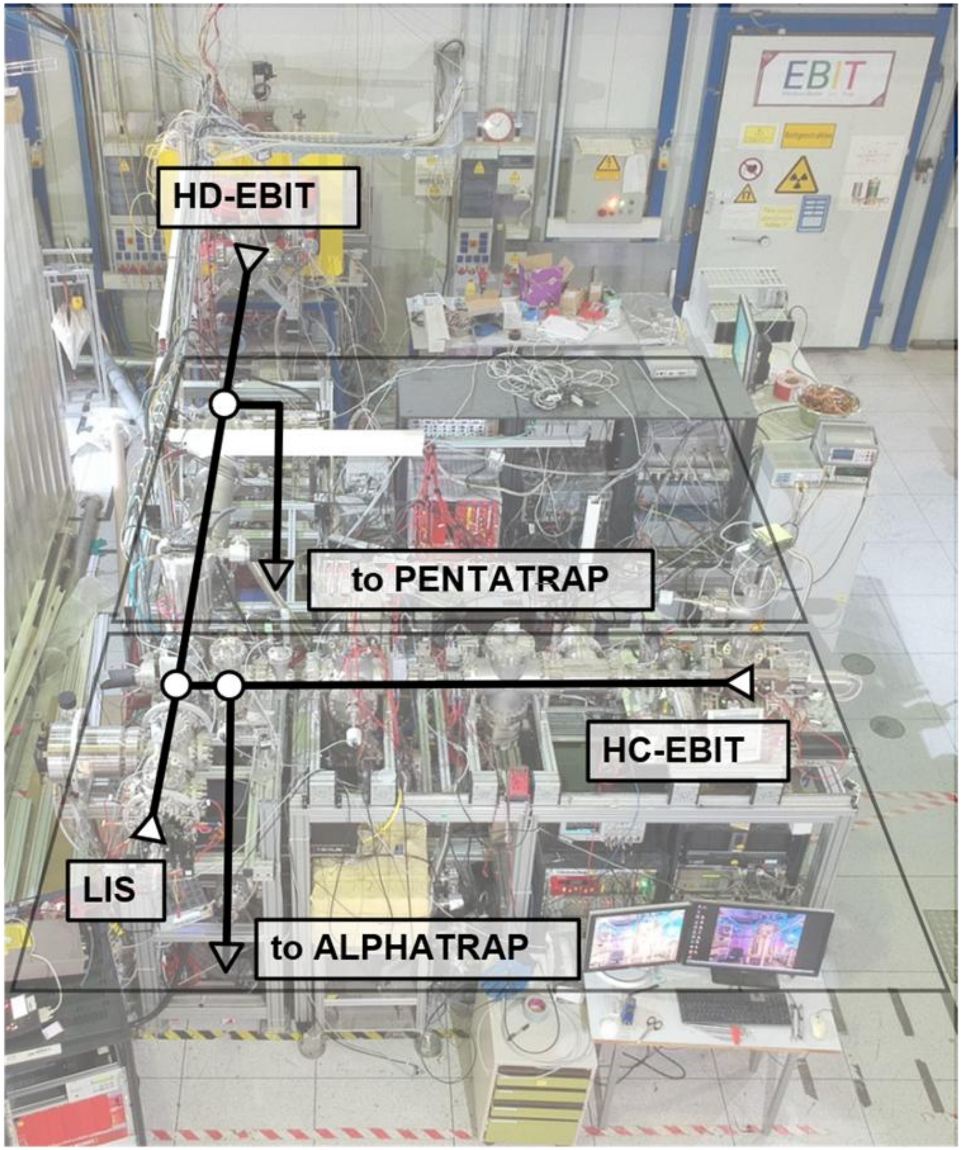
$$\omega_c = \frac{q}{M}B$$

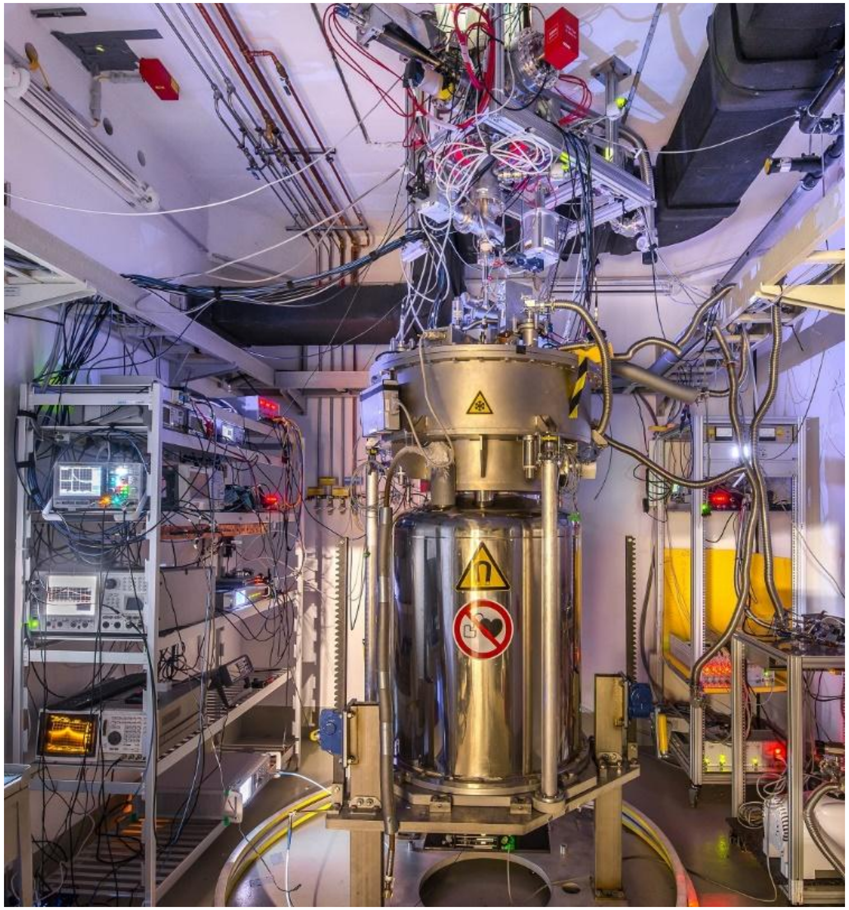
Cyclotron frequency
in the same magnetic field B

$$g = 2\frac{\omega_L}{\omega_c}\frac{q}{e}\frac{m_e}{M}$$

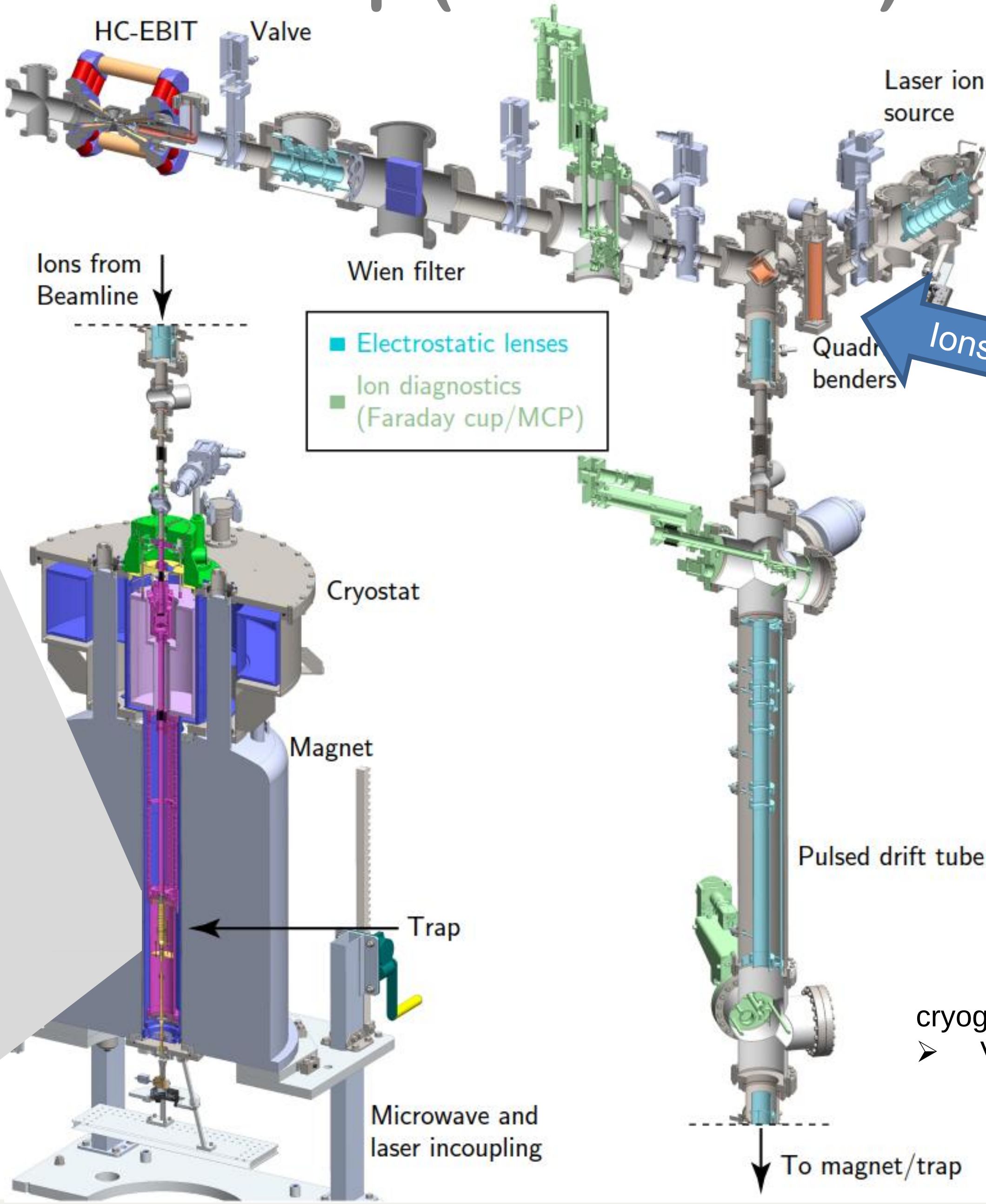
Larmor-to-cyclotron frequency ratio (Γ)

Experimental Setup





Experimental Setup (ALPHATRAP)

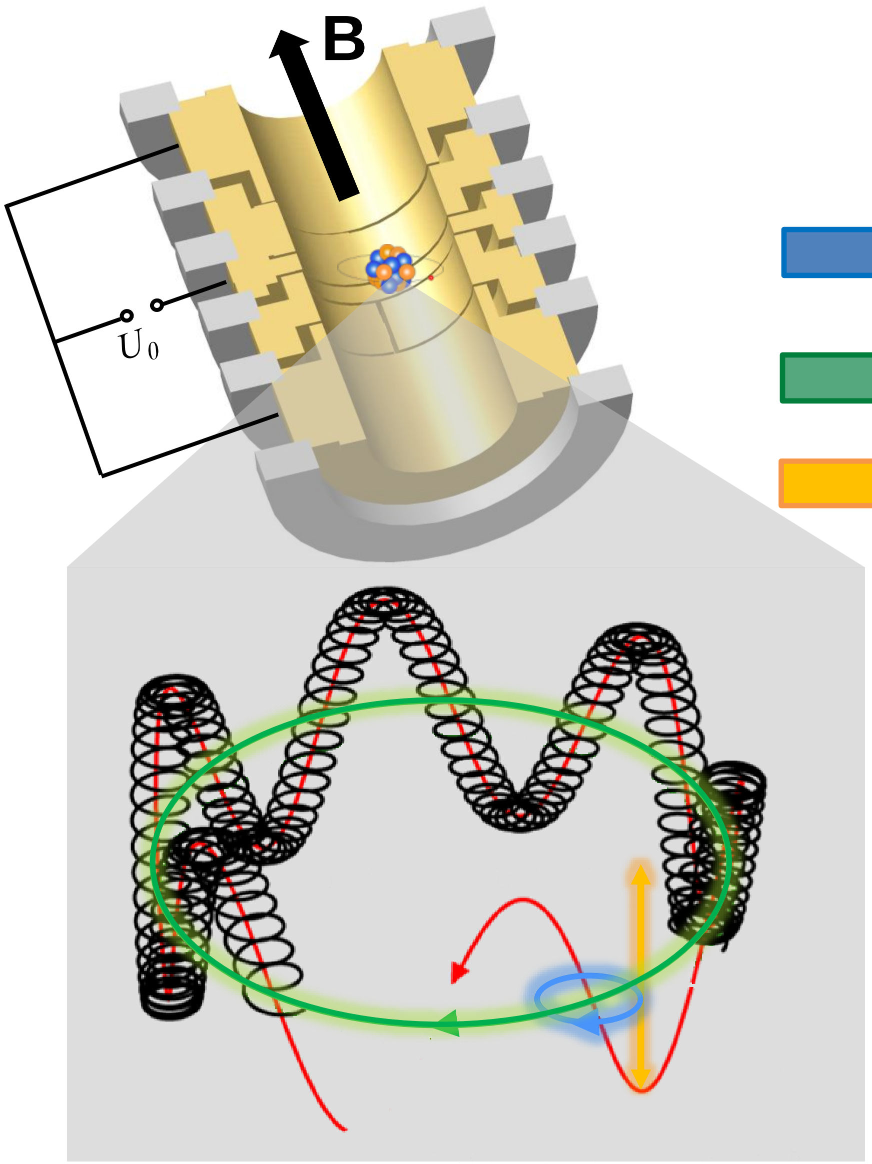


cryogenic temperatures (**4.2K**)

- ➢ Vacuum better than **10^{-17} mbar**
  - ➢ basically no rest gas

A look into our toolbox - the Penning trap

The Penning trap



Ion | Electron

Trap eigenfrequencies

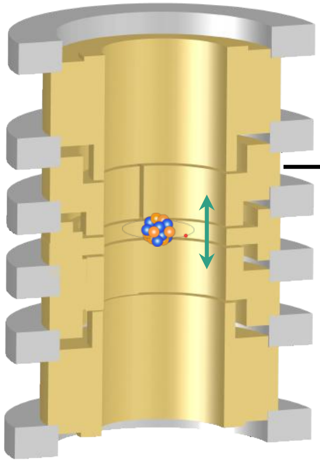
- Reduced cyclotron frequency: ~$2\pi\cdot$ 20 MHz (140Ghz)
- Magnetron drift frequency: ~ $2\pi\cdot$ 9 kHz (9kHz)
- Axial frequency: ~ $2\pi\cdot$ 600 kHz (50MHz)
- Larmor frequency: ~ $2\pi\cdot$ 140 GHz

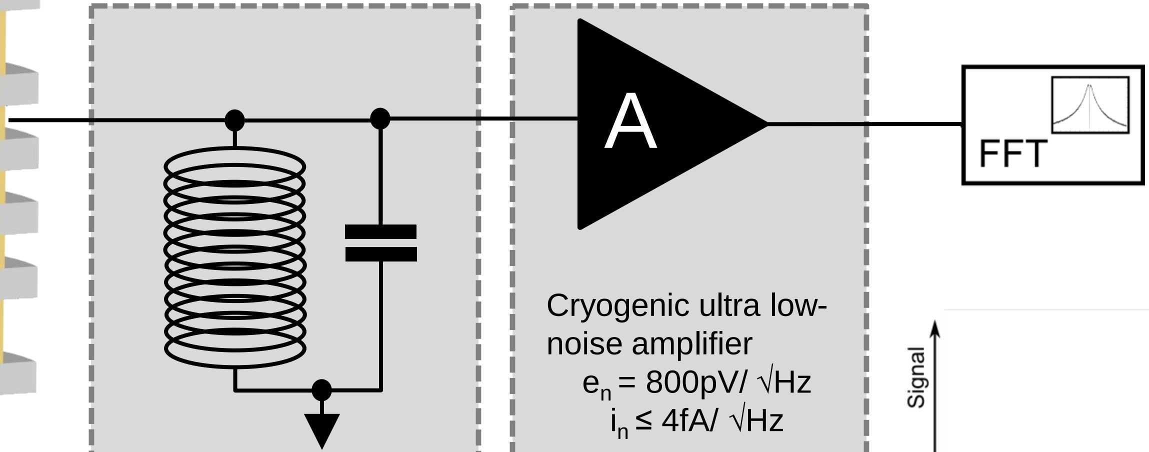
➢ Free cyclotron frequency $\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$

(Brown-Gabrielse invariance theorem)

$$\omega_c = \frac{q}{m} B$$

IMAGE CURRENT DETECTION





Cryogenic ultra low-noise amplifier
$e_n = 800 \mathrm{pV}/\sqrt{\mathrm{Hz}}$
$i_n \leq 4 \mathrm{fA}/\sqrt{\mathrm{Hz}}$

$Q = 43000$
$R_p = 350\ \mathrm{M\Omega}$

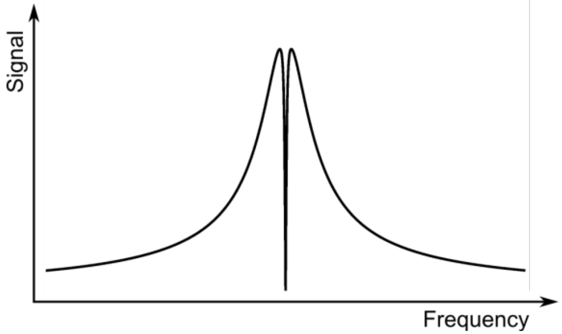


IMAGE CURRENT DETECTION

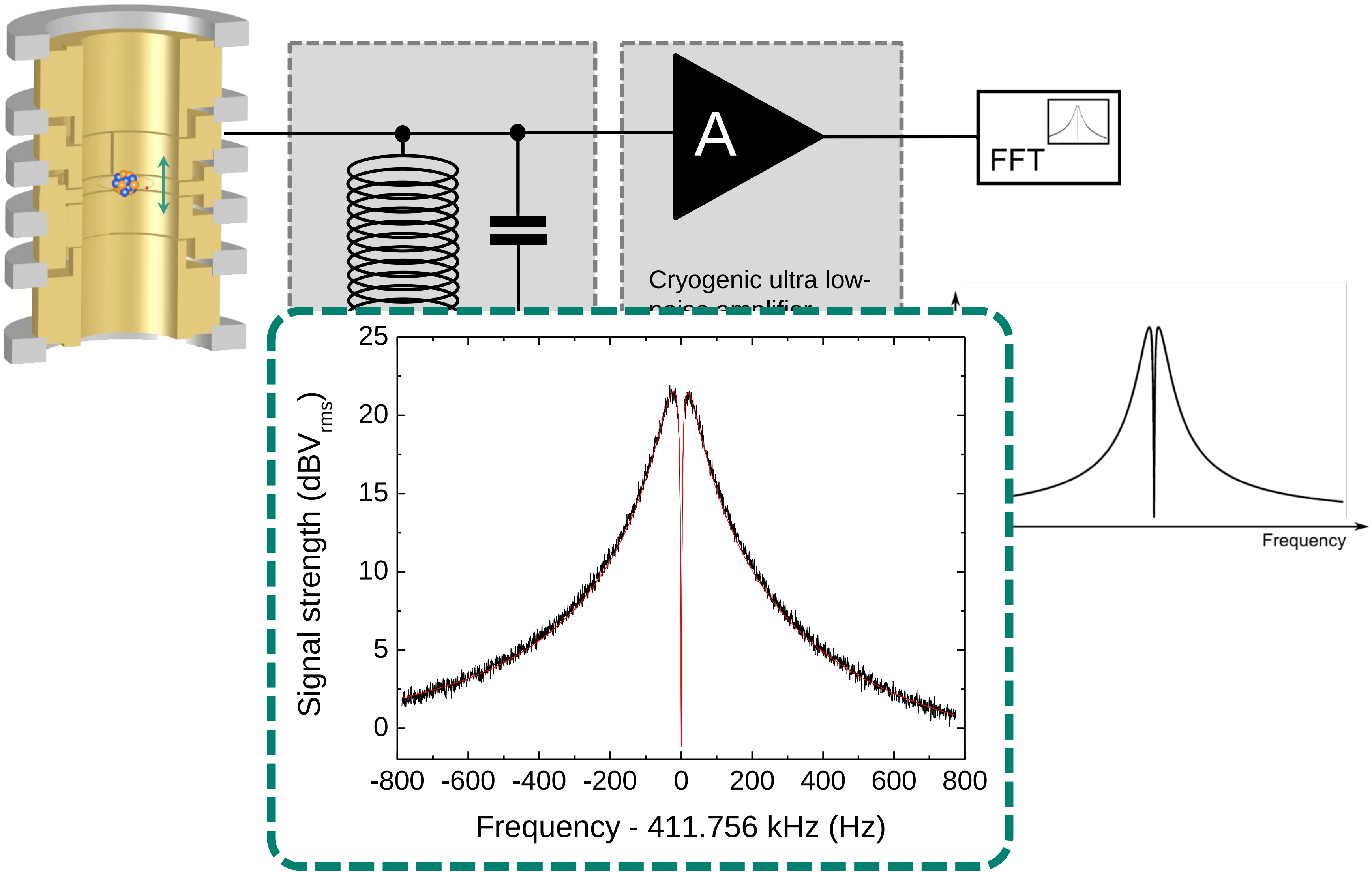


IMAGE CURRENT DETECTION

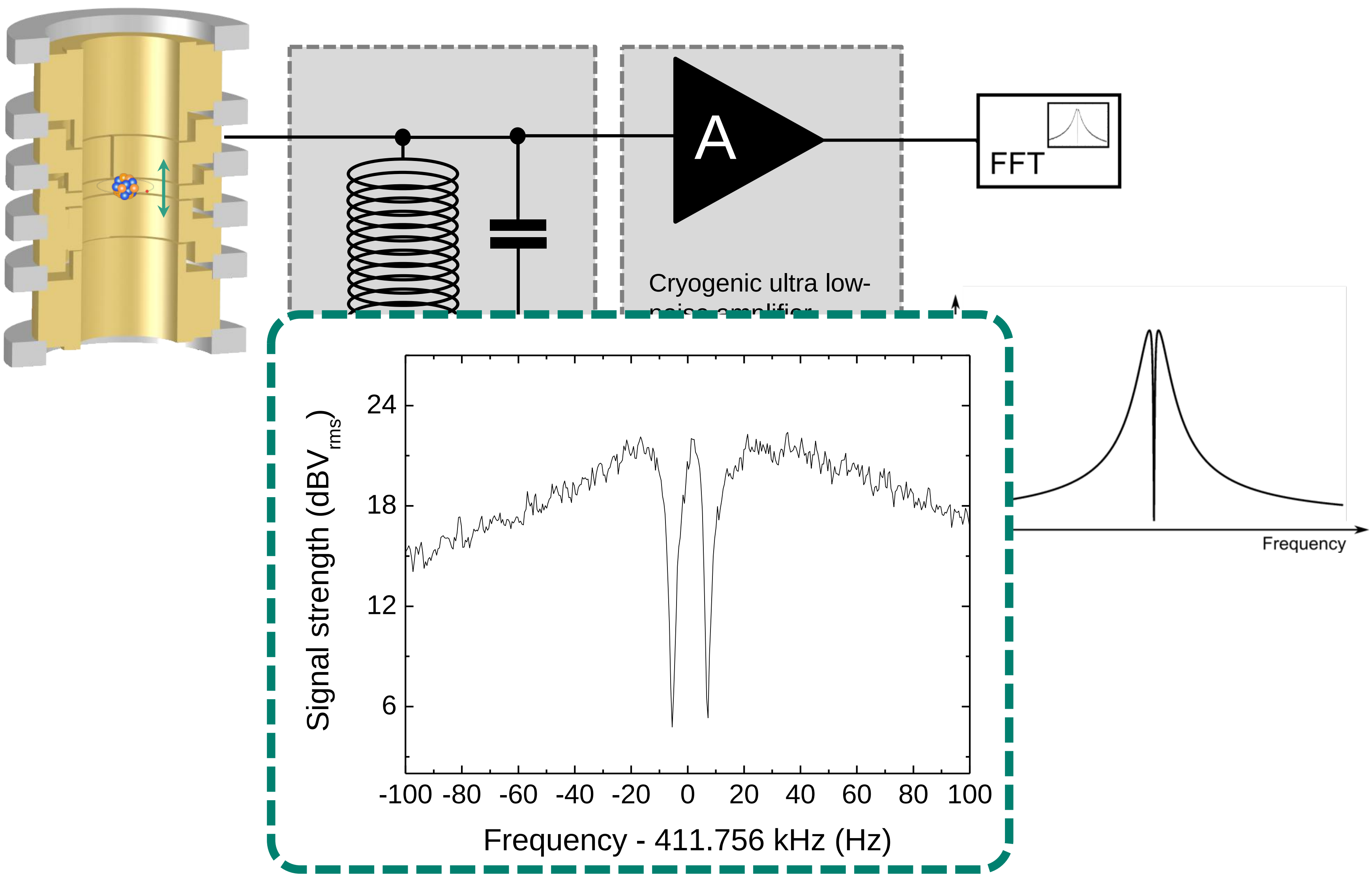
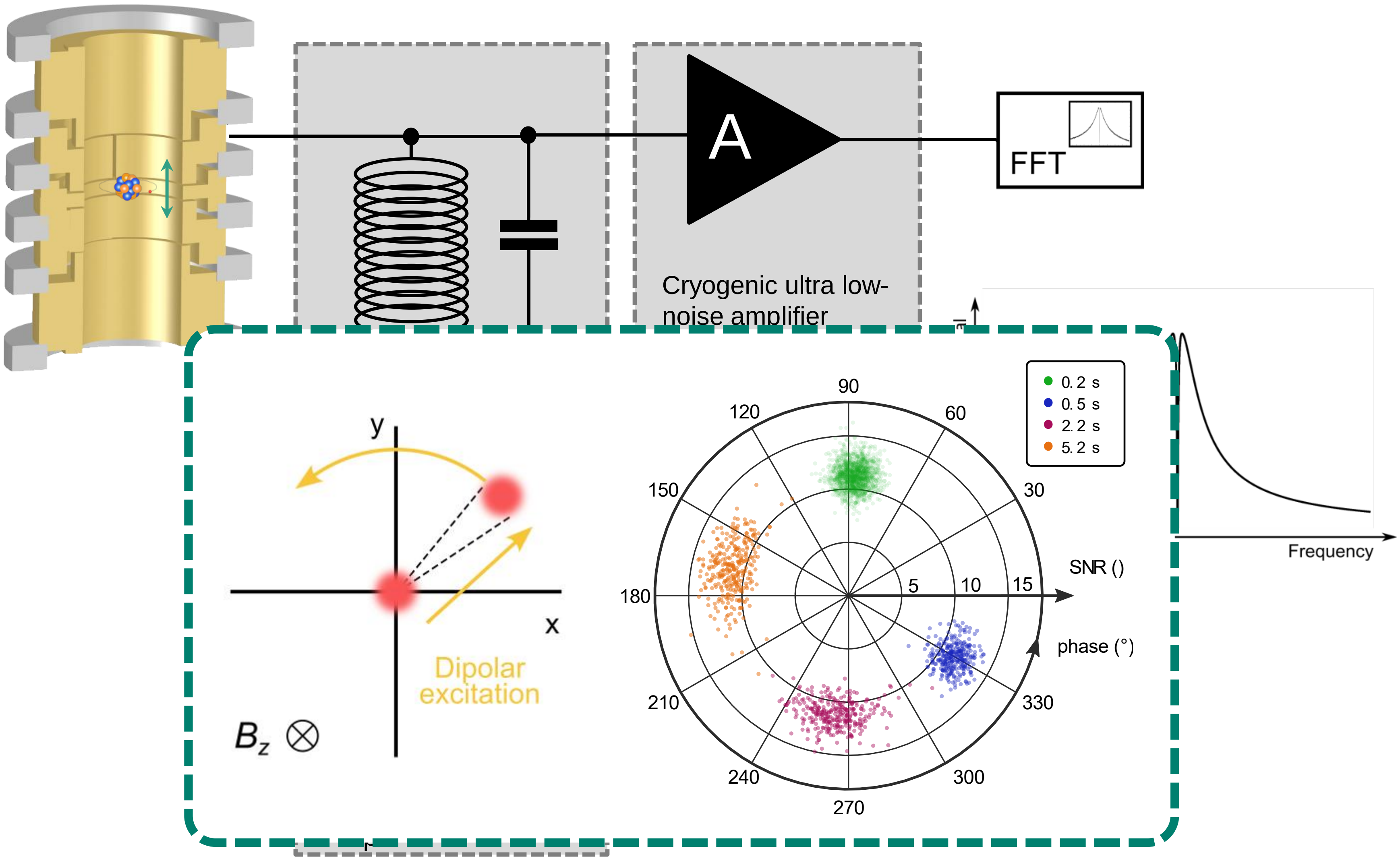
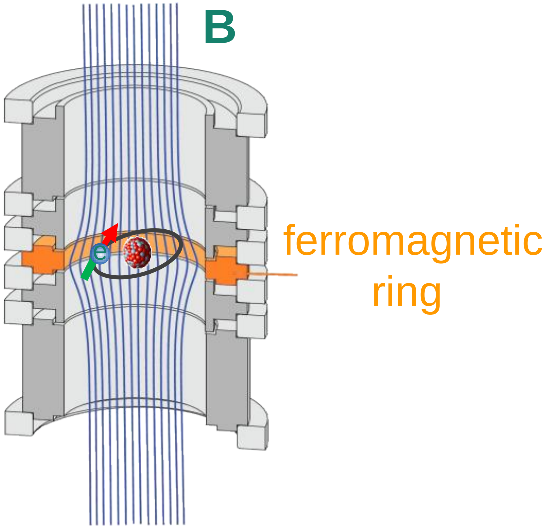


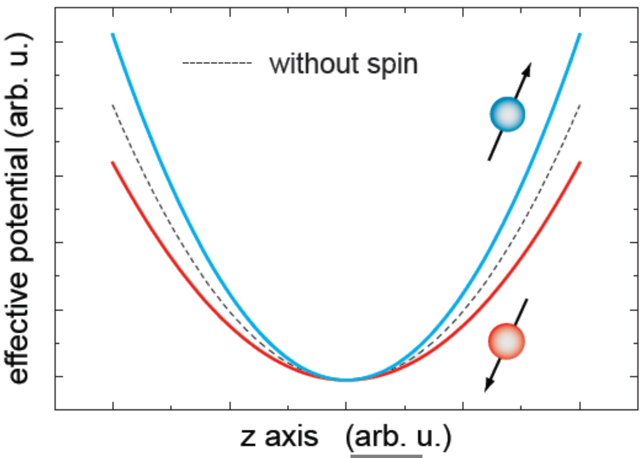
IMAGE CURRENT DETECTION



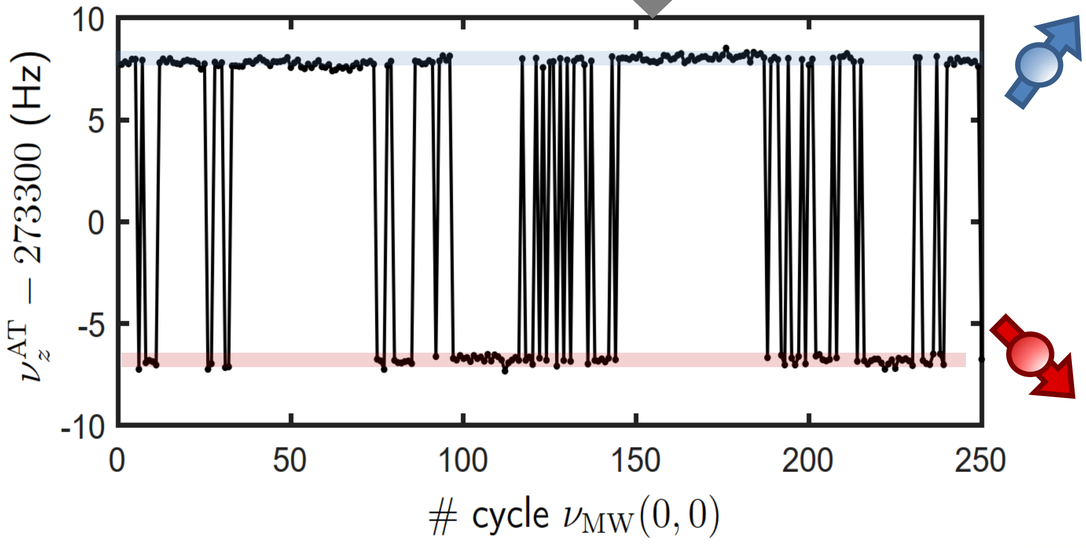
Continuous Stern Gerlach effect

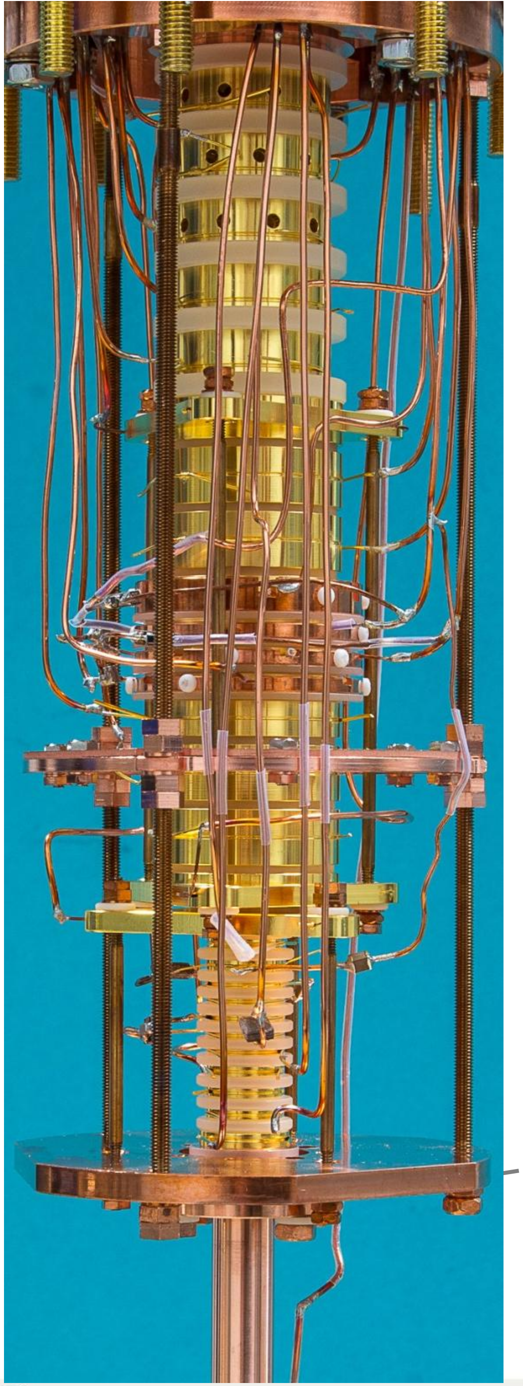
Magnetic bottle





Axial frequency indicates spinflips:





Double Penning trap

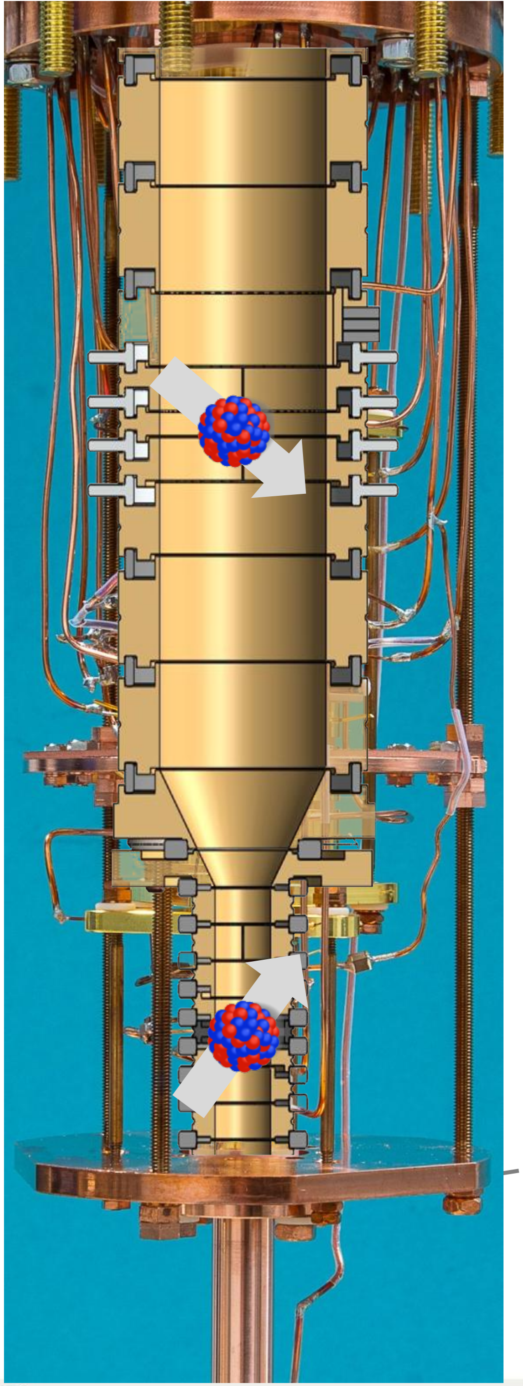
Capture electrodes
- Potential switching
- Dynamic ion capture/storage

Precision trap
- 18mm diameter
- Homogeneous *B*-field: measure $\boldsymbol{\Gamma} = \boldsymbol{\omega_L}/\boldsymbol{\omega_c}$
- Compensation ring for PT: improved *B*-field homogeneity

Analysis trap
- 6mm diameter
- Ferromagnetic ring electrode: spin detection

Beryllium trap
- Be ions storage & detection

Microwave horn
- mm – wave coupling
- Laser access



Double Penning trap

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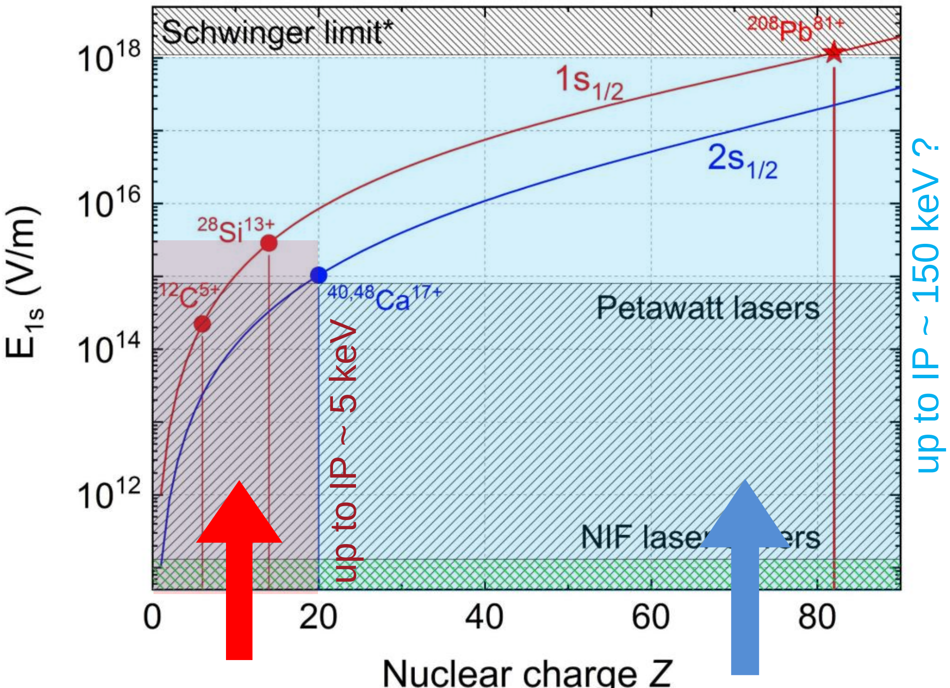
QED of Bound States



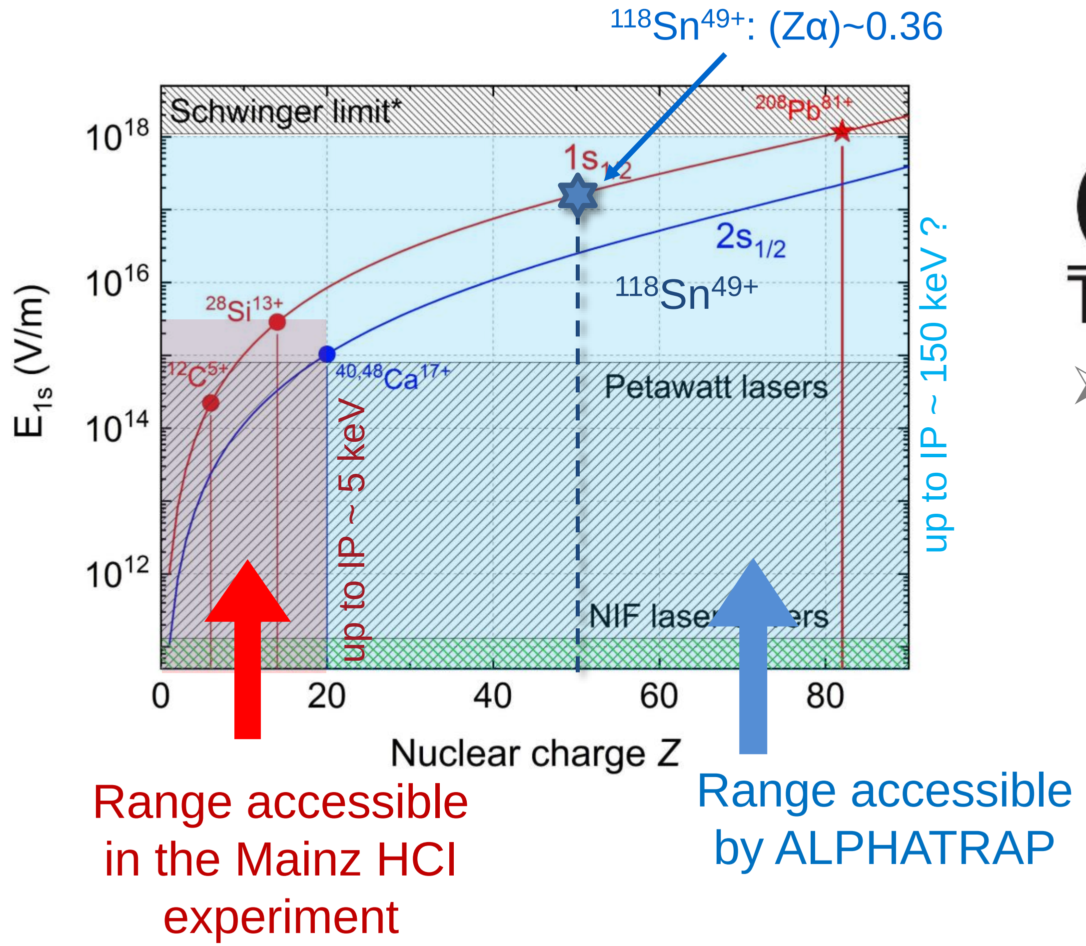
Range accessible in the Mainz HCI experiment

Range accessible by ALPHATRAP

αTRAP

- Probe validity of QED in the **strongest fields**
  - Precision experiment with heavy, highly charged ions
  - **Strongly coupled (Zα≈1)** electron, *beyond the Furry picture*
  - Extract nuclear structure information

QED of Bound States



Jonathan Morgner

- Probe validity of QED in the **strongest fields**
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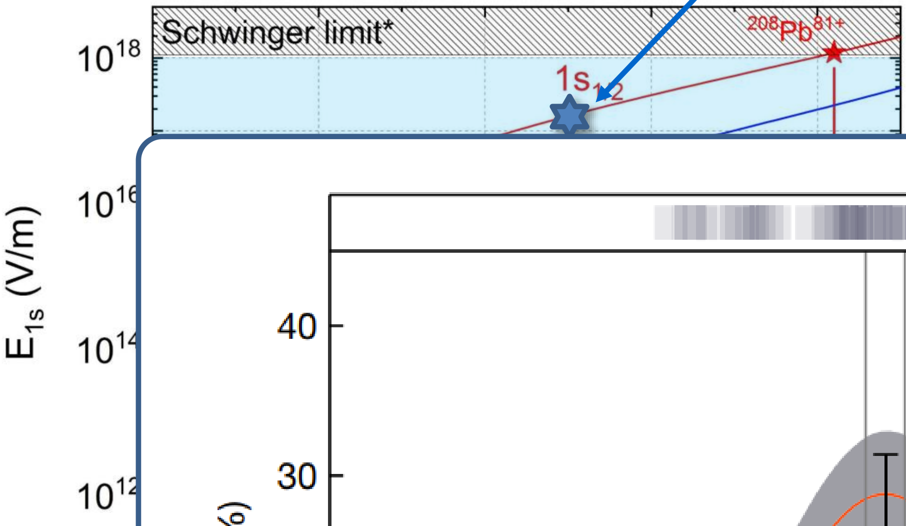
QED of Bound States


Jonathan Morgner

$^{118}Sn^{49+}$: $(Z\alpha)\sim0.36$



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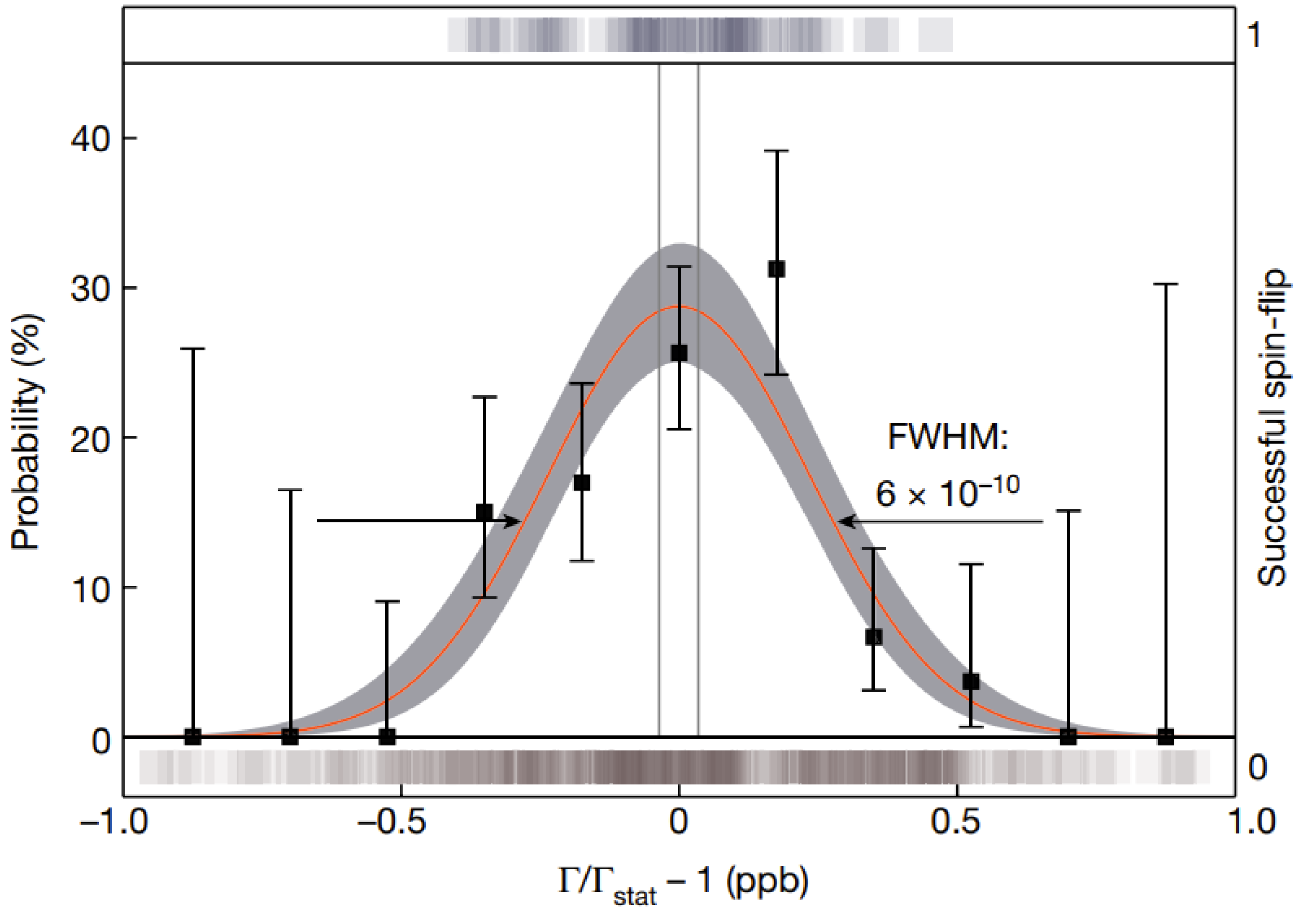
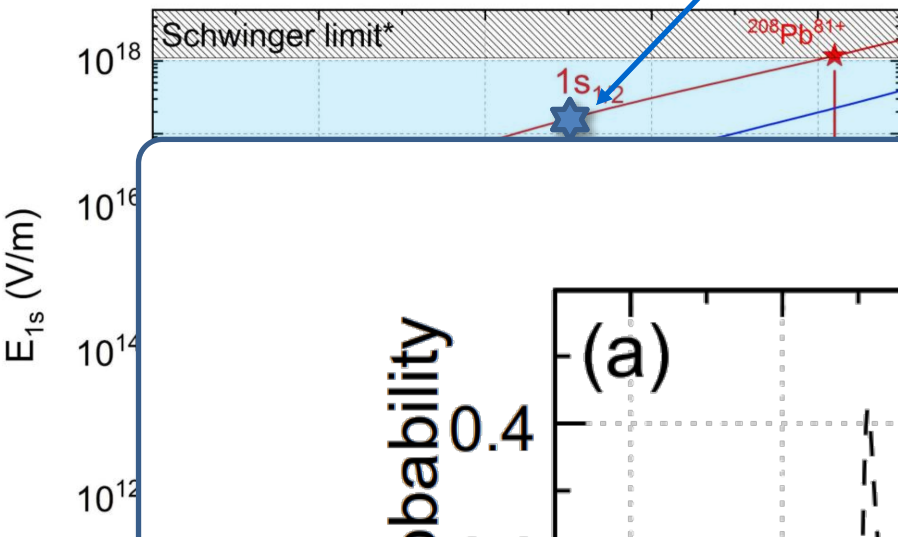


QED of Bound States

Jonathan Morgner

$^{118}Sn^{49+}$: $(Z\alpha)\sim0.36$



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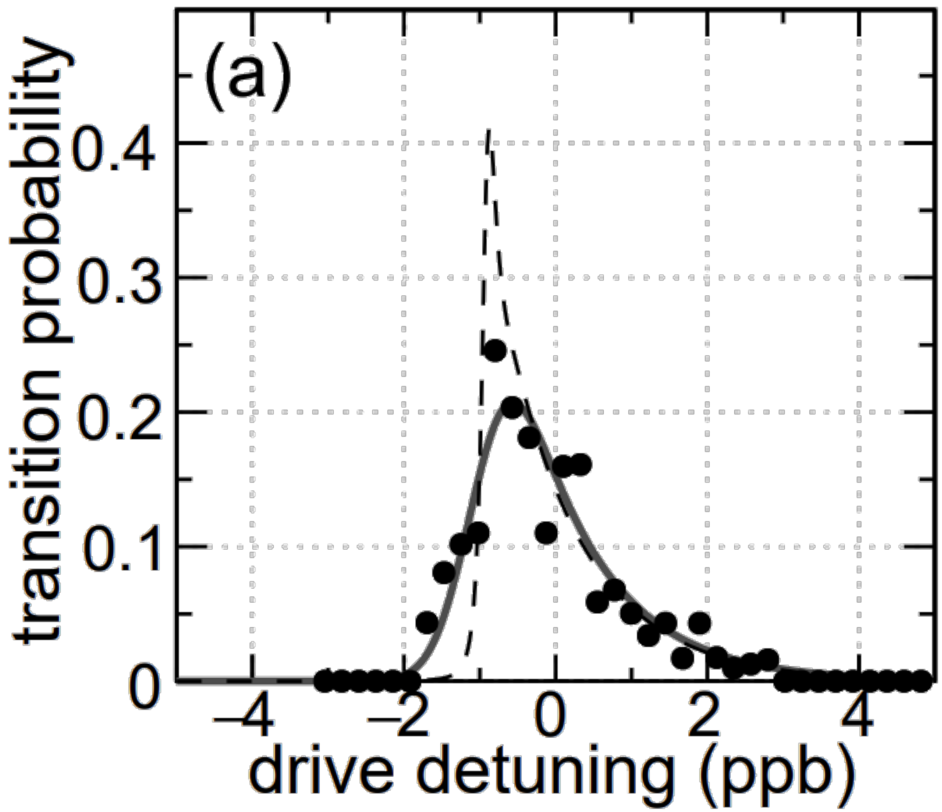
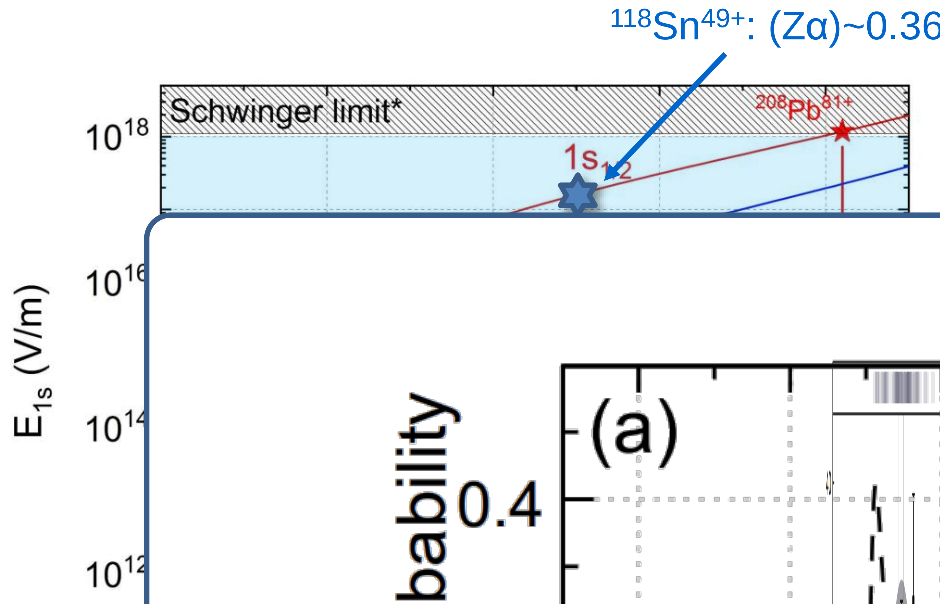


QED of Bound States


Jonathan Morgner



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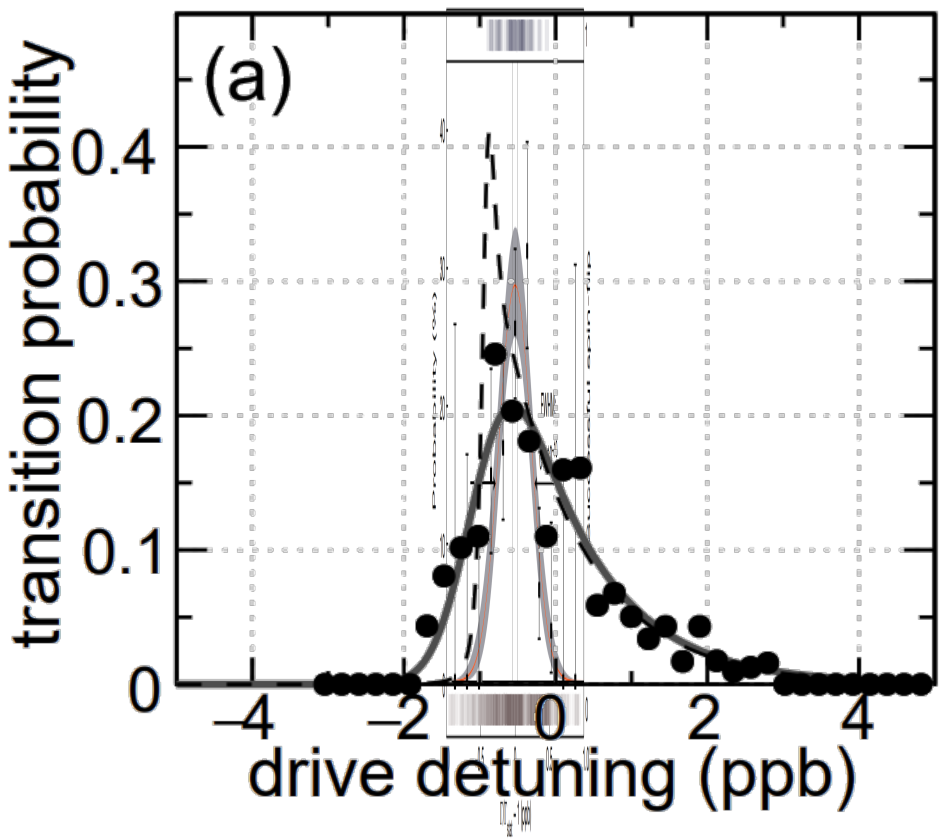

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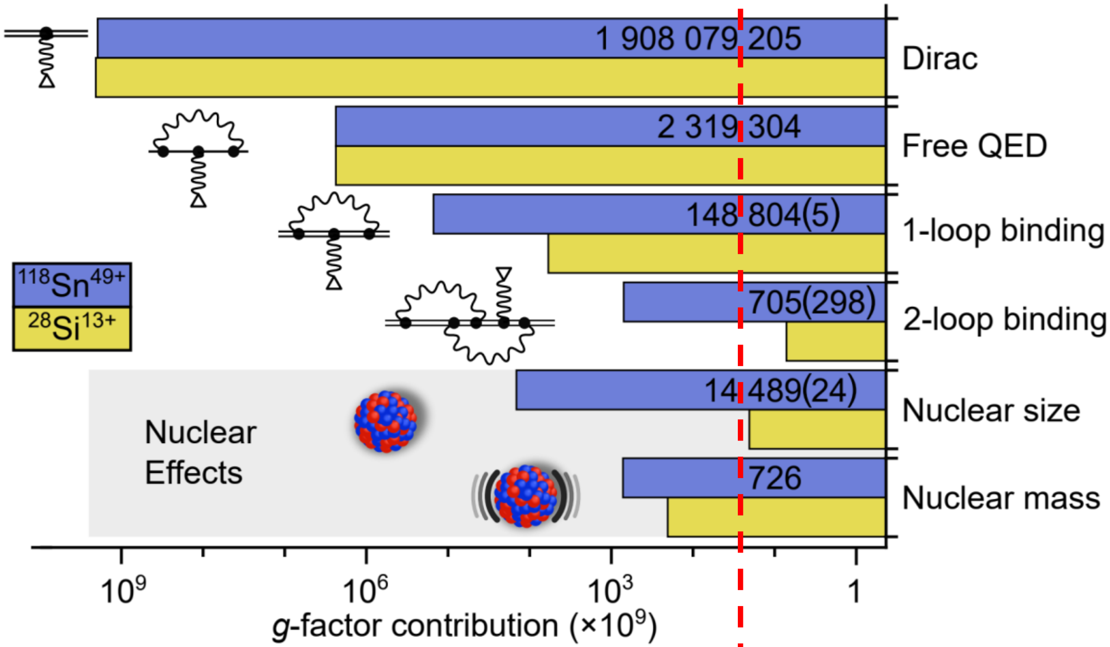
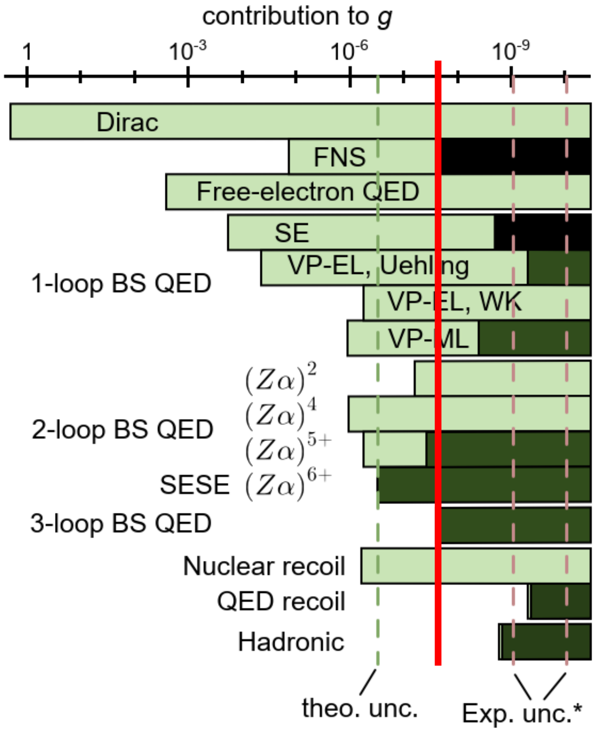
Hydrogen-like tin $^{118}Sn^{49+}$


Jonathan Morgner





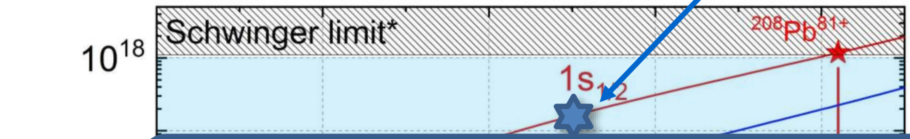
$$g_{exp} = 1.910\,562\,058\,962\,(73)_{\text{stat}}(42)_{\text{stat}}(910)_{\text{ext}}$$

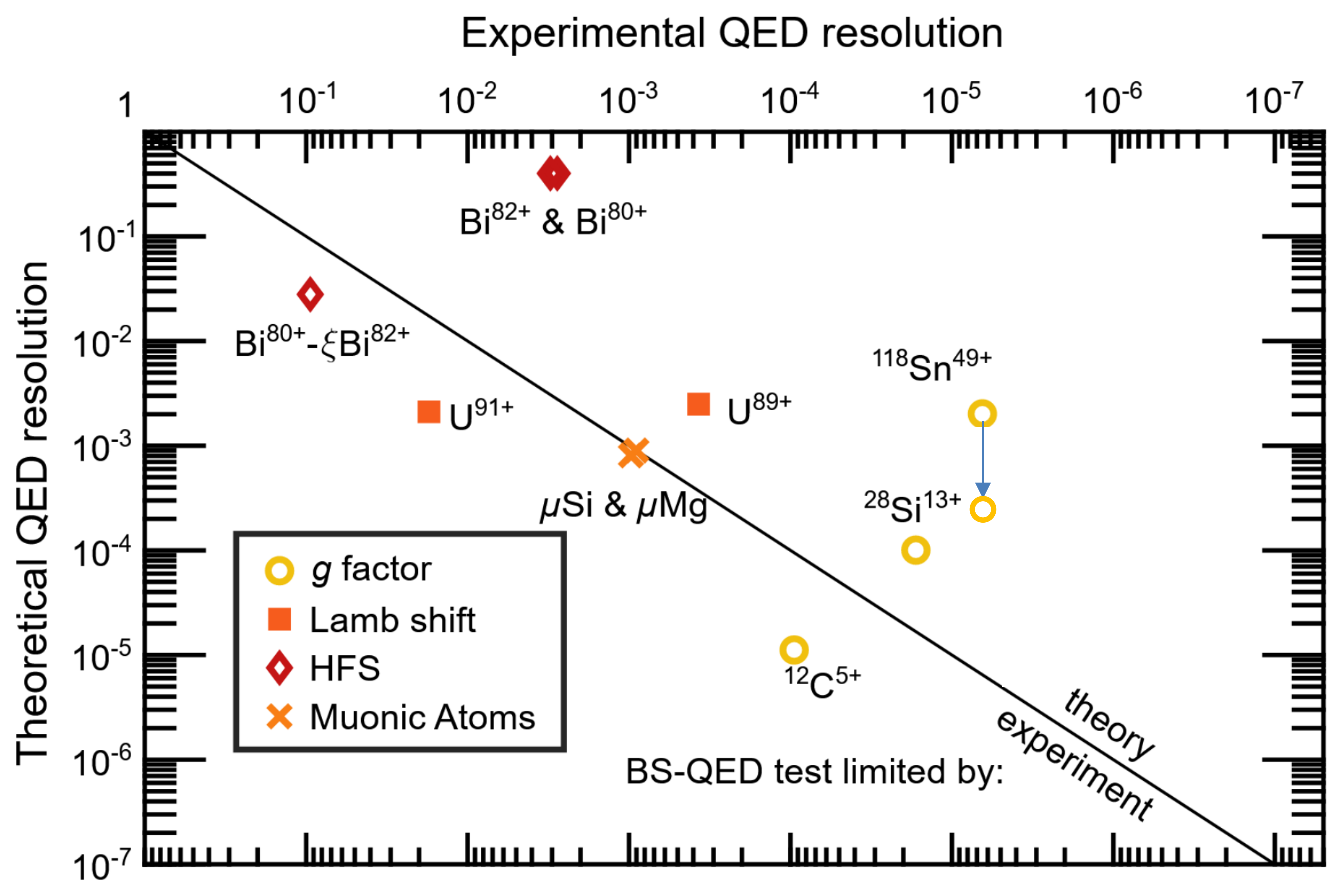
$$g_{\text{theo}}^{Z\alpha} = 1.910\,561\,821\,(299)$$

$$g_{\text{theo}}^{\infty} = 1.910\,561\,975\,(39)$$

QED of Bound States

Jonathan Morgner





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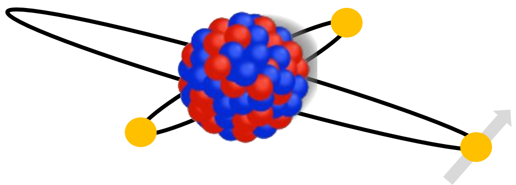
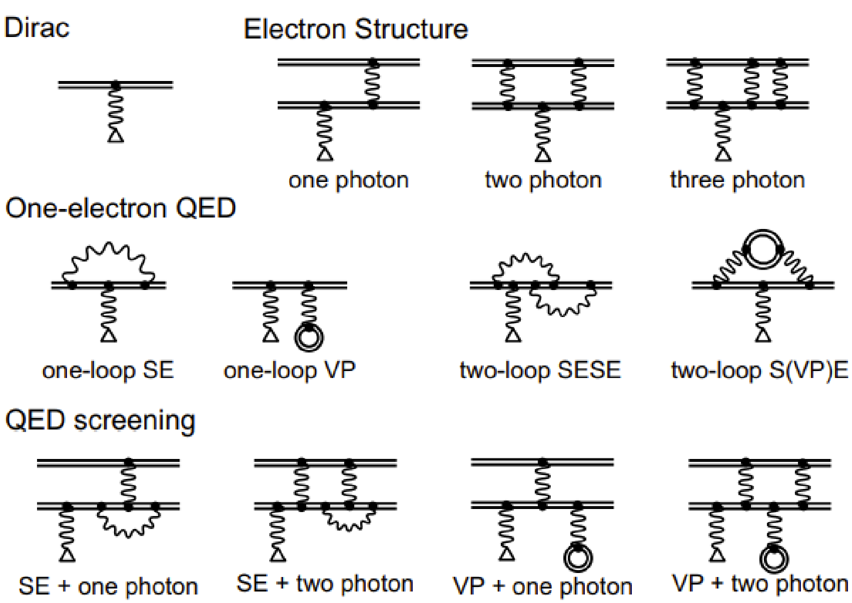
Lithium-like tin $^{118}Sn^{47+}$

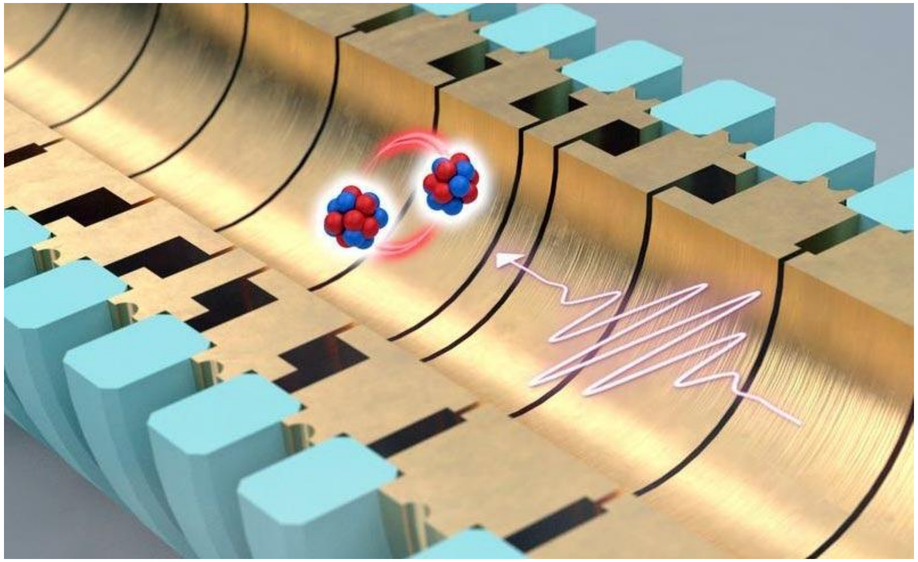
Jonathan Morgner





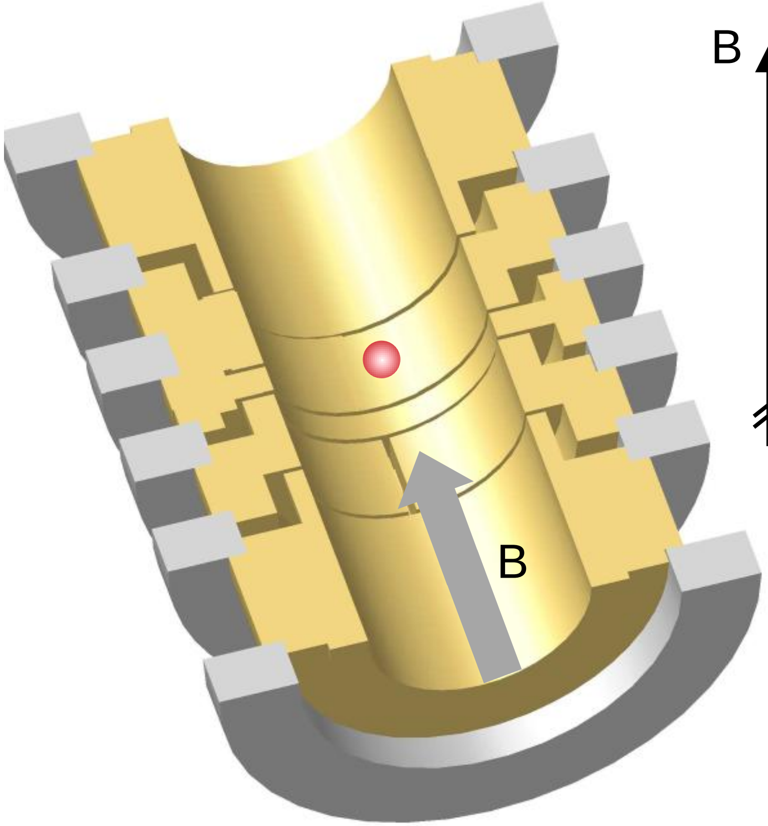
Effect	Value (× 10^{-6})
Dirac, point nucleus	−23,181.721
Dirac, FNS	2.040(3)
Electron structure	1,192.179 (7)
One-loop QED	23.977(1)
Two-loop QED	−0.107(33)
Two-loop QED , enhanced	−0.080(6)
QED screening	−1.076(8)
Nuclear recoil	0.172(1)
$g_e(5, 21)$	2,002,319.304361
g_{theo}	1,980,354.769(35)
g_{theo} (enh)	1,980,354.797(12)

$$g_{\text{exp}} = 1.980\,354\,799\,750(84)_{\text{stat}}(47)_{\text{sys}}(944)_{\text{ext}}$$



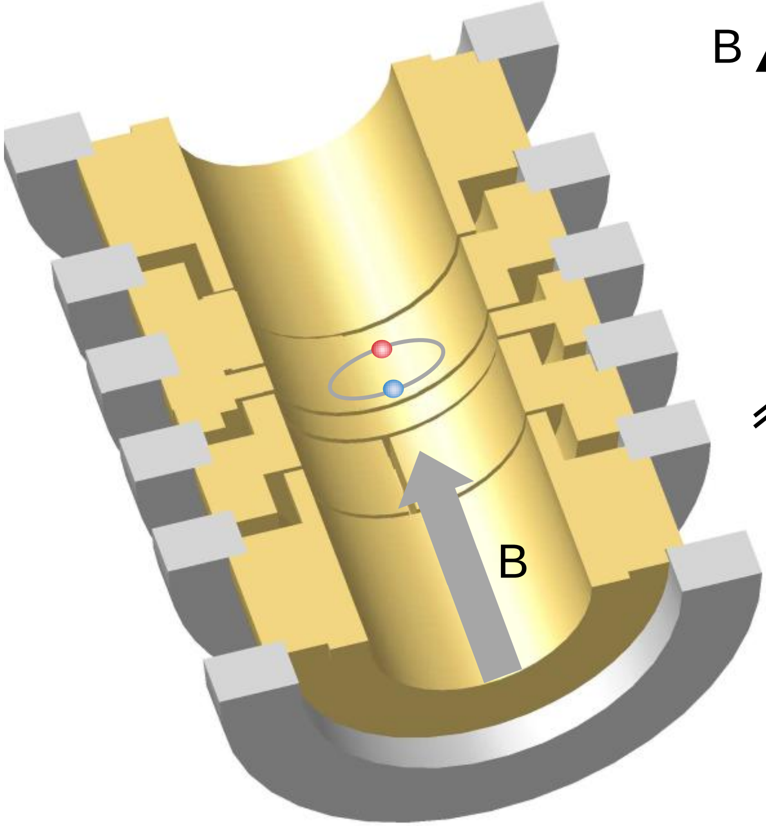
A leap in precision:
FULLY COHERENT SIMULTANEOUS MEASUREMENTS

Coherent g_1-g_2 difference measurement



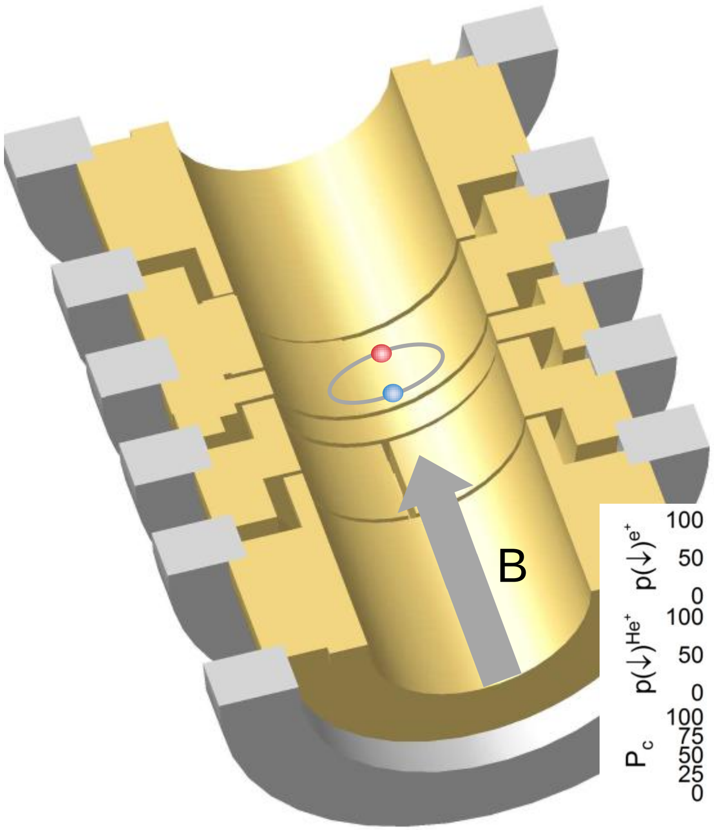
- Magnetic field fluctuations quickly (~ms) render Larmor precession **incoherent**

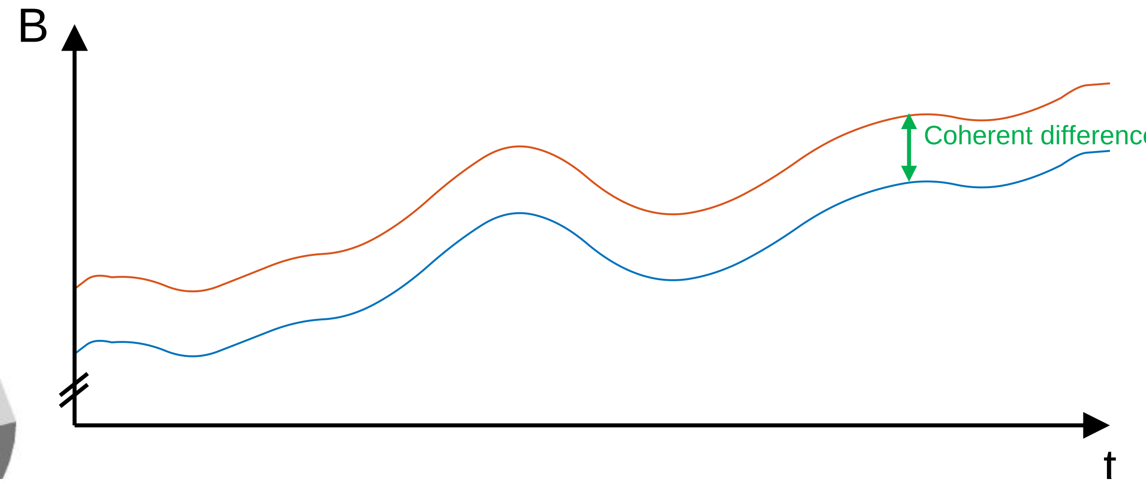
Coherent g_1-g_2 difference measurement

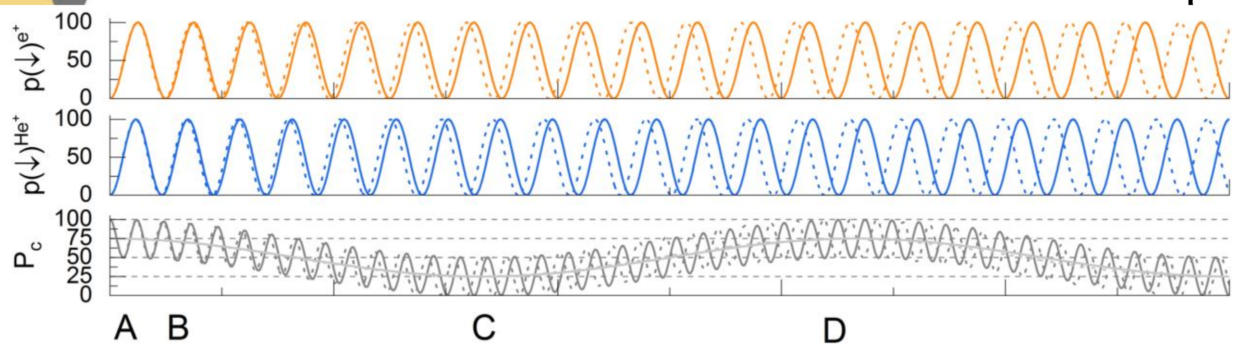


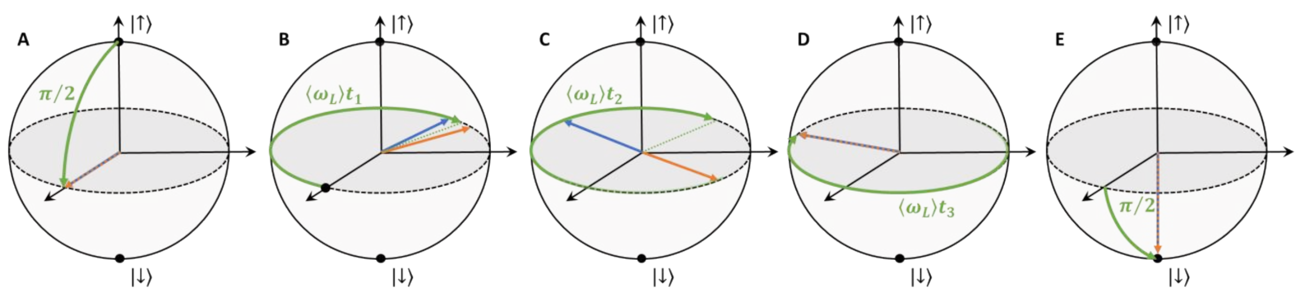
- Magnetic field fluctuations quickly (~ms) render Larmor precession **incoherent**
- Crystallized ions see the identical field
  - The **phase difference (correlation)** stays coherent (>seconds!)

Coherent g_1-g_2 difference measurement

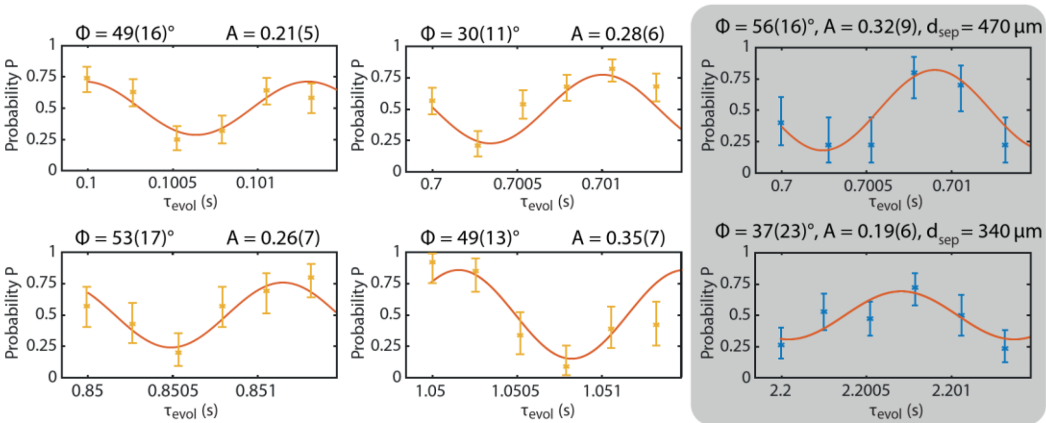






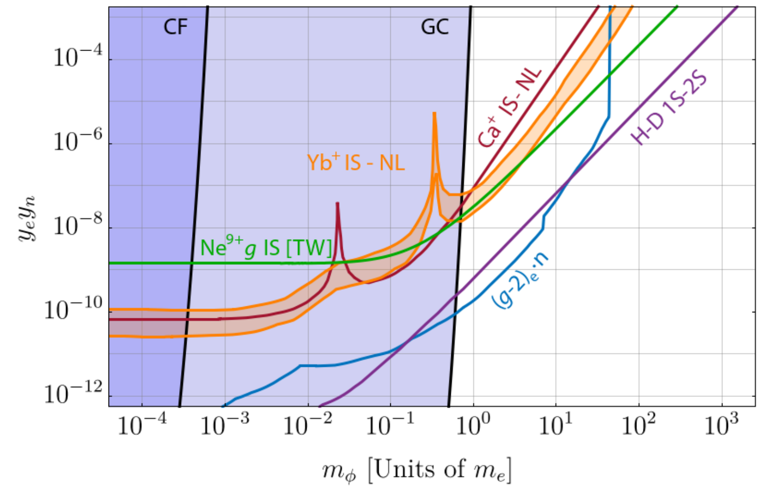


Coherent g_1-g_2 difference measurement



Dr. Tim Sailer

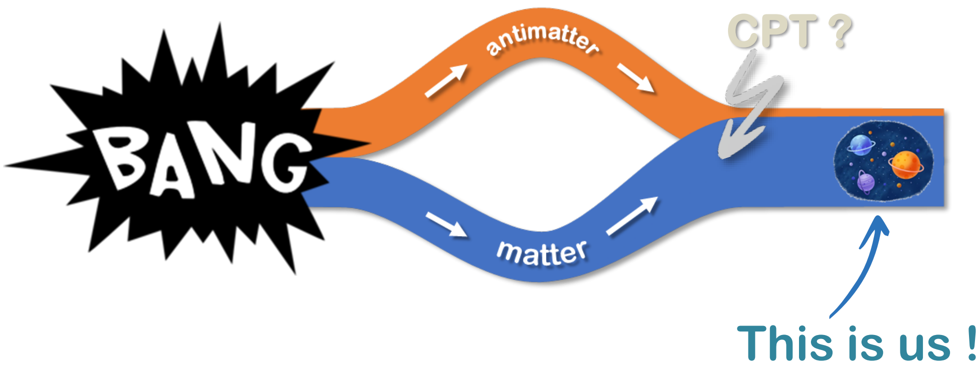
	$^{20}Ne^{9+}$	$^{22}Ne^{9+}$
Dirac value (point nucleus)	1.996 445 170 898(2)	1.996 445 170 898(2)
Finite nuclear size, FNS	0.000 000 004 762(7)	0.000 000 004 596(12)
QED, one loop (α)	0.002 325 473 294(1)	0.002 325 473 294(1)
QED, two loop $(\alpha)^2$	− 0.000 003 547 780(117)	− 0.000 003 547 780(117)
QED, ≥ three loop $(\alpha)^{3+}$	0.000 000 029 524(1)	0.000 000 029 524(1)
Recoil		
Non-QED	0.000 000 146 093 420	0.000 000 132 810 693
QED	0.000 000 000 477 954(1)	0.000 000 000 434 499(1)
$(\alpha/\pi)(m_e/M)$	− 0.000 000 000 113 2(6)	− 0.000 000 000 102 9(5)
$(m_e/M)^2$	− 0.000 000 000 044 1(2)	− 0.000 000 000 036 5(2)
Hadronic vacuum pol.	0.000 000 000 003 36(3)	0.000 000 000 003 36(3)
Nuclear polarization	− 0.000 000 000 001 9(9)	− 0.000 000 000 002 0(10)
g factor total theory	1.998 767 277 112(117)	1.998 767 263 638(117)
Difference (in 10^{-9})		
FNS	0.166(11)	
Recoil, non-QED	13.2827	
Recoil, QED	0.0435	
Recoil, $(\alpha/\pi)(m_e/M)$	− 0.0103	
Recoil, $(m_e/M)^2$	− 0.0077	
Deformation	< 0.0001	
Polarization	0.0001(3)	
Δg Total theory	$13.474(11)_{FNS}$	
Δg Experiment	$13.47524(53)_{stat}(99)_{sys}$	



Sets limits on scalar bosons coupling neutrons and electron

$\delta\Delta g/g = 5.6\ 10^{-13}$

THE ANTI/MATTER ASYMMETRY IN OUR UNIVERSE



The anti/matter asymmetry:

<u>Far more</u> matter than antimatter in our universe:

$$n_B \gg n_{\bar{B}}$$
$$n_L \gg n_{\bar{L}}$$

Standard Model predicts $n_B \cong n_{\bar{B}}$!

Sakharov criteria:

[Andrei Sakharov, A. D., *JETP Letters*, **5** 1 (1967)]

I. Baryon number non-conservation
II. Thermal non-equilibrium
III. CP violation

SM CP violation <u>insufficient</u> !

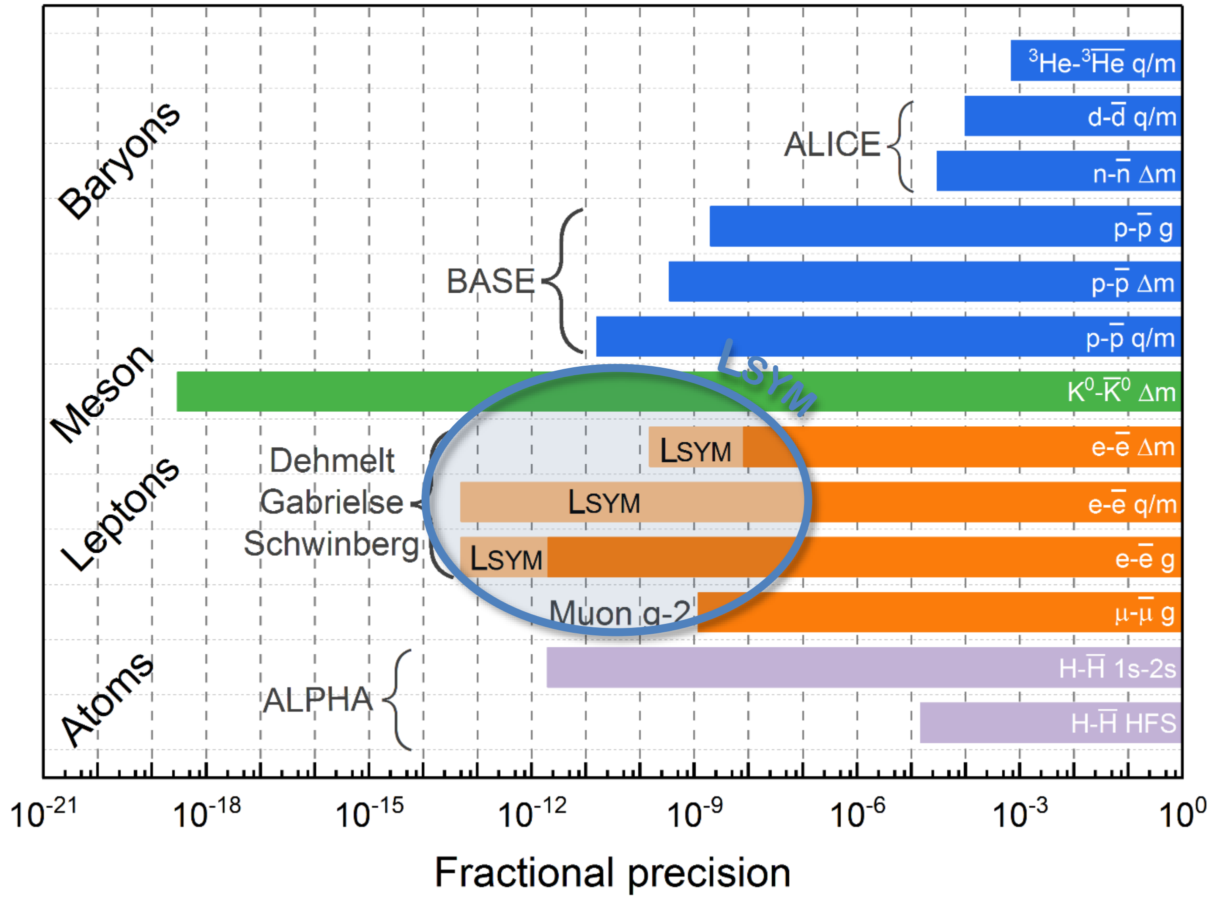
Even tiny **CPT violation** explains asymmetry

OR

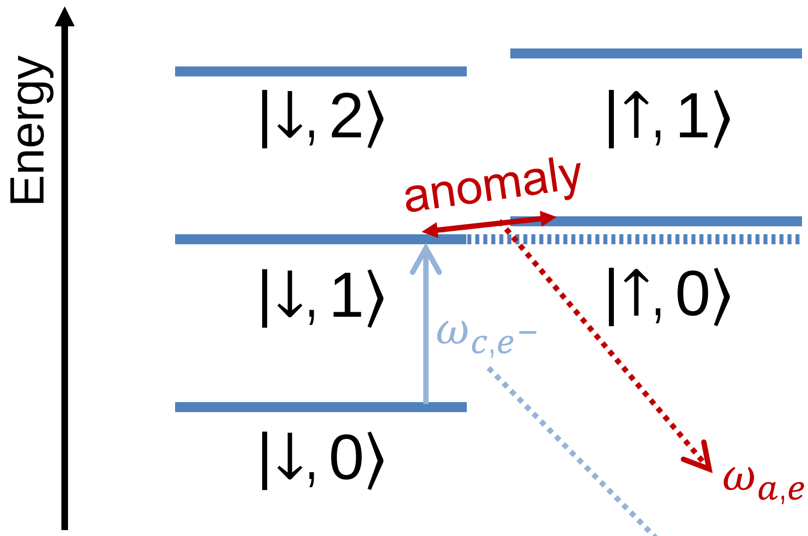
LABORATORY SEARCHES FOR CPT VIOLATION

A uniquely stringent CPT test: LSYM compares

- q/m (direct) 1,000,000x
- *g*-factor: >50x



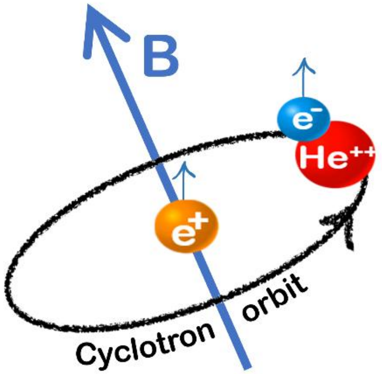
Electron in magnetic field



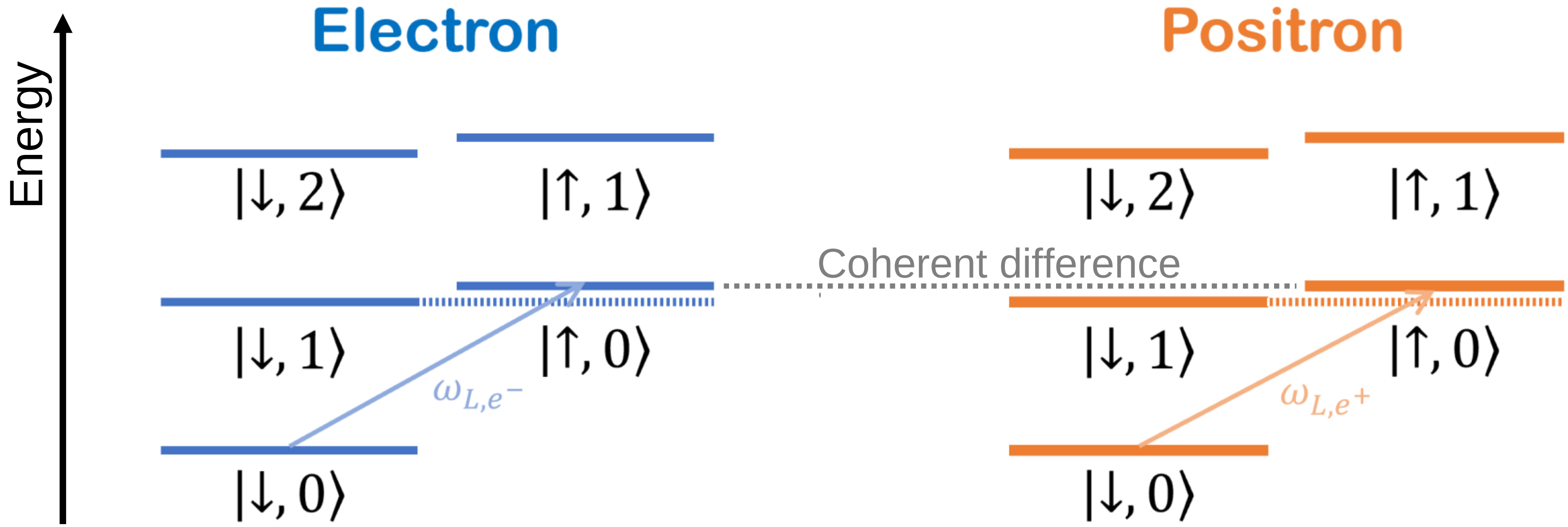
$$\omega_{a,e^-} = \frac{g-2}{2}\frac{q_{e^-}}{m_{e^-}}B$$

$$\omega_{c,e^-} = 1 \; \frac{q_{e^-}}{m_{e^-}}B$$

LSYM Lepton Symmetry experiment

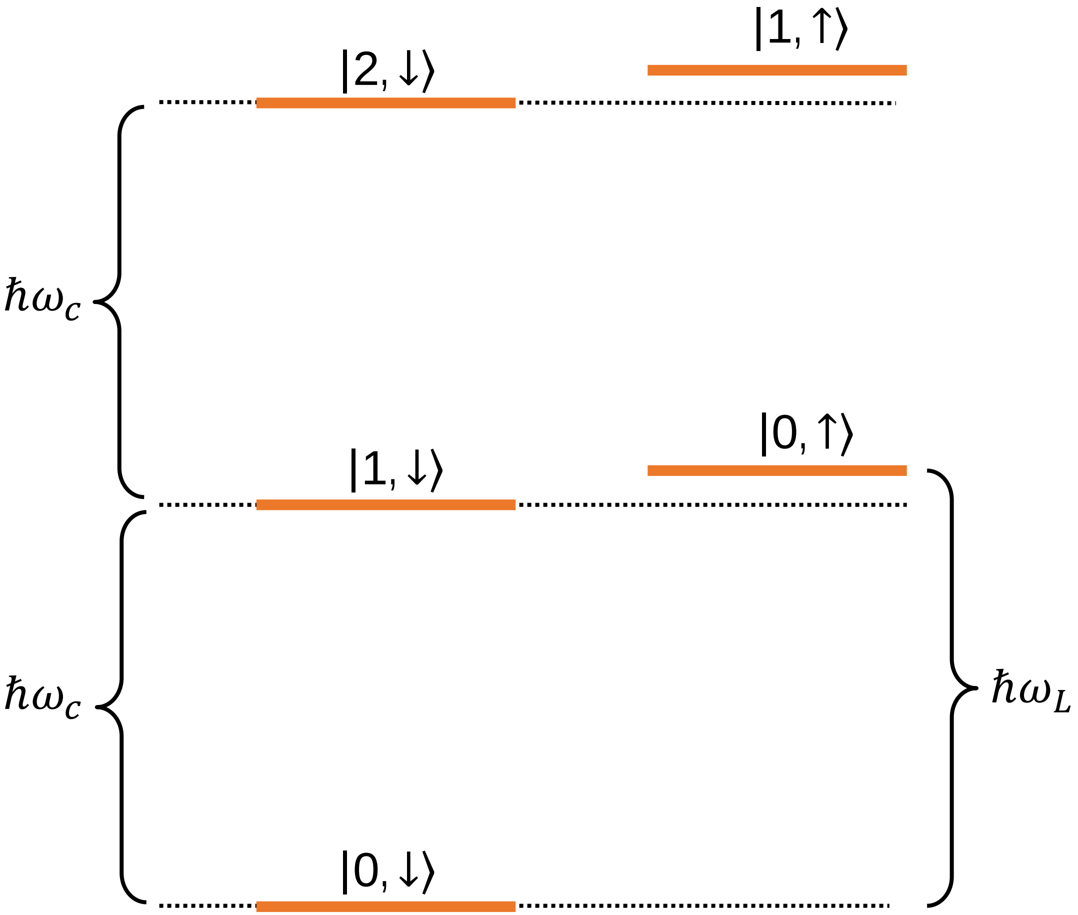


Compare electron and positron spin precession **simultaneously** in the same trap

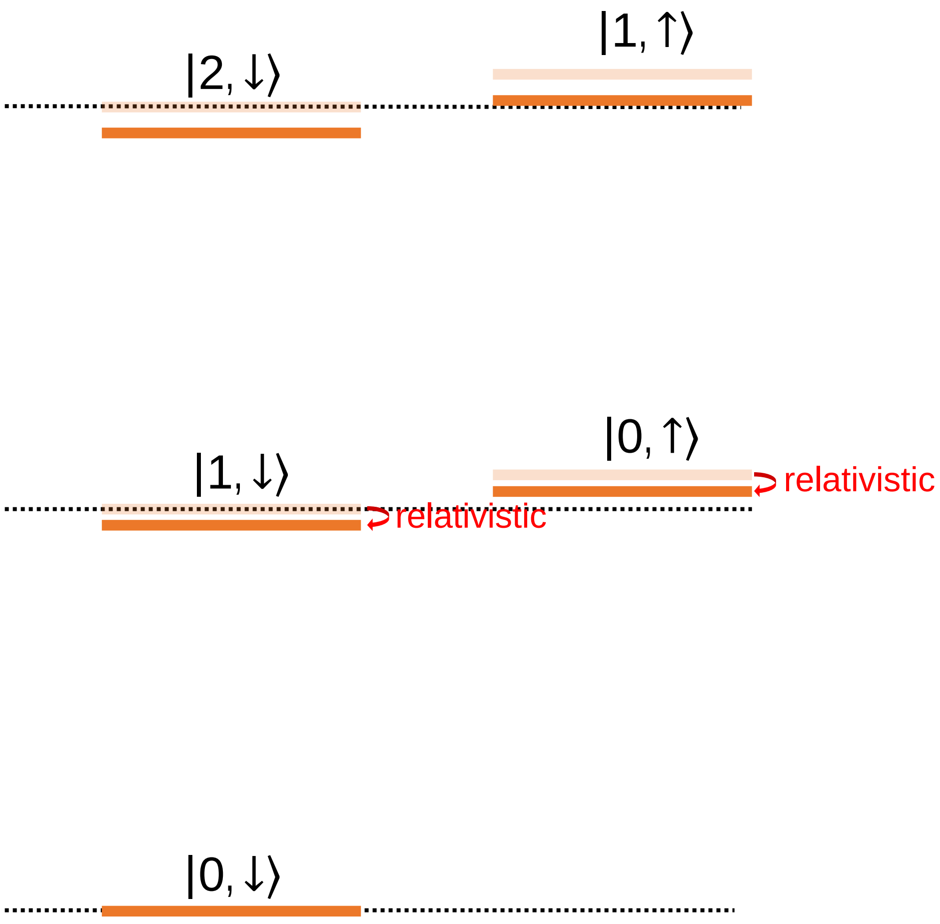


$$\omega_{L,e^-} - \omega_{L,e^+} \sim \frac{q}{m} g_{e^-} - \frac{q}{m} g_{e^+}$$

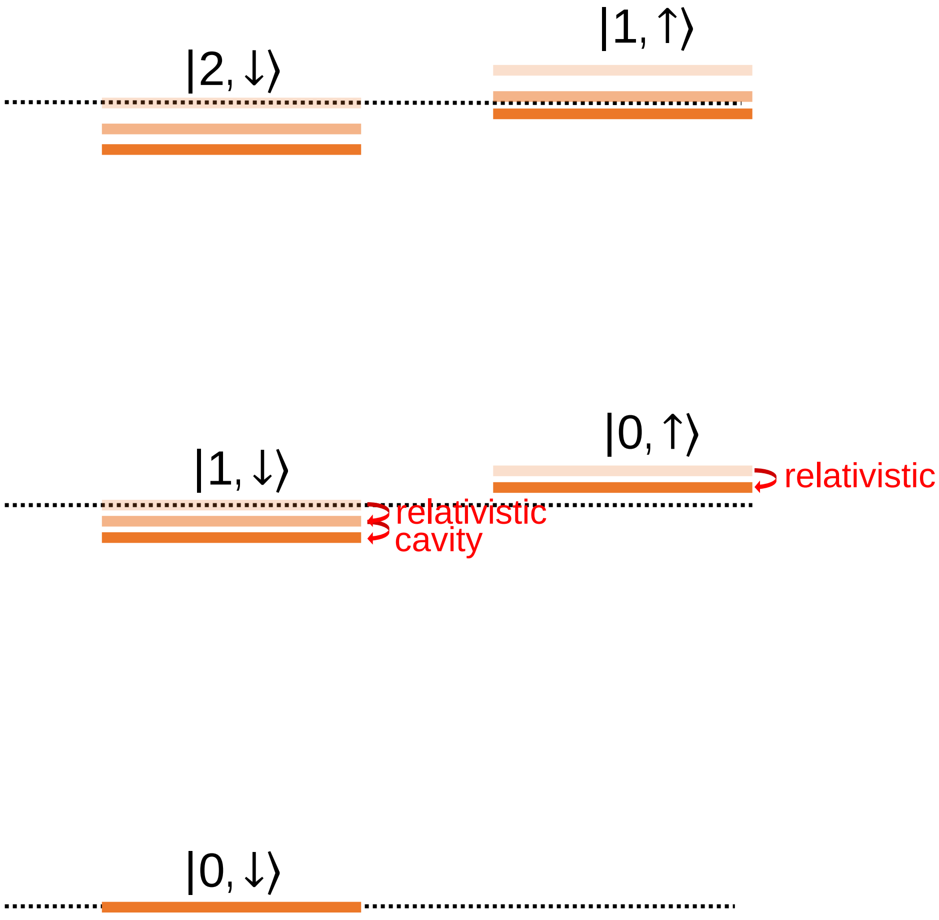
Trapped positron Energy levels



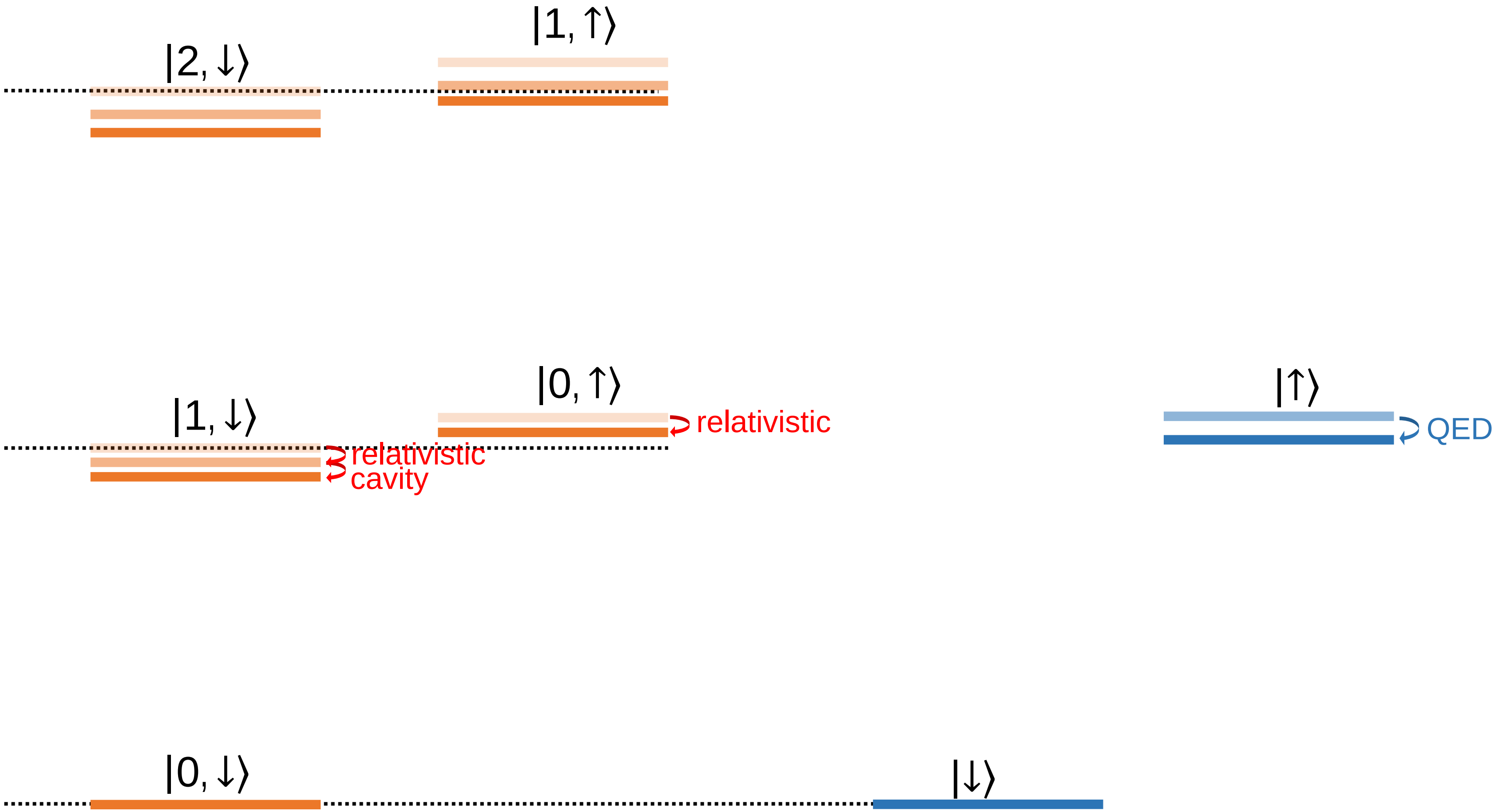
Trapped positron Energy levels



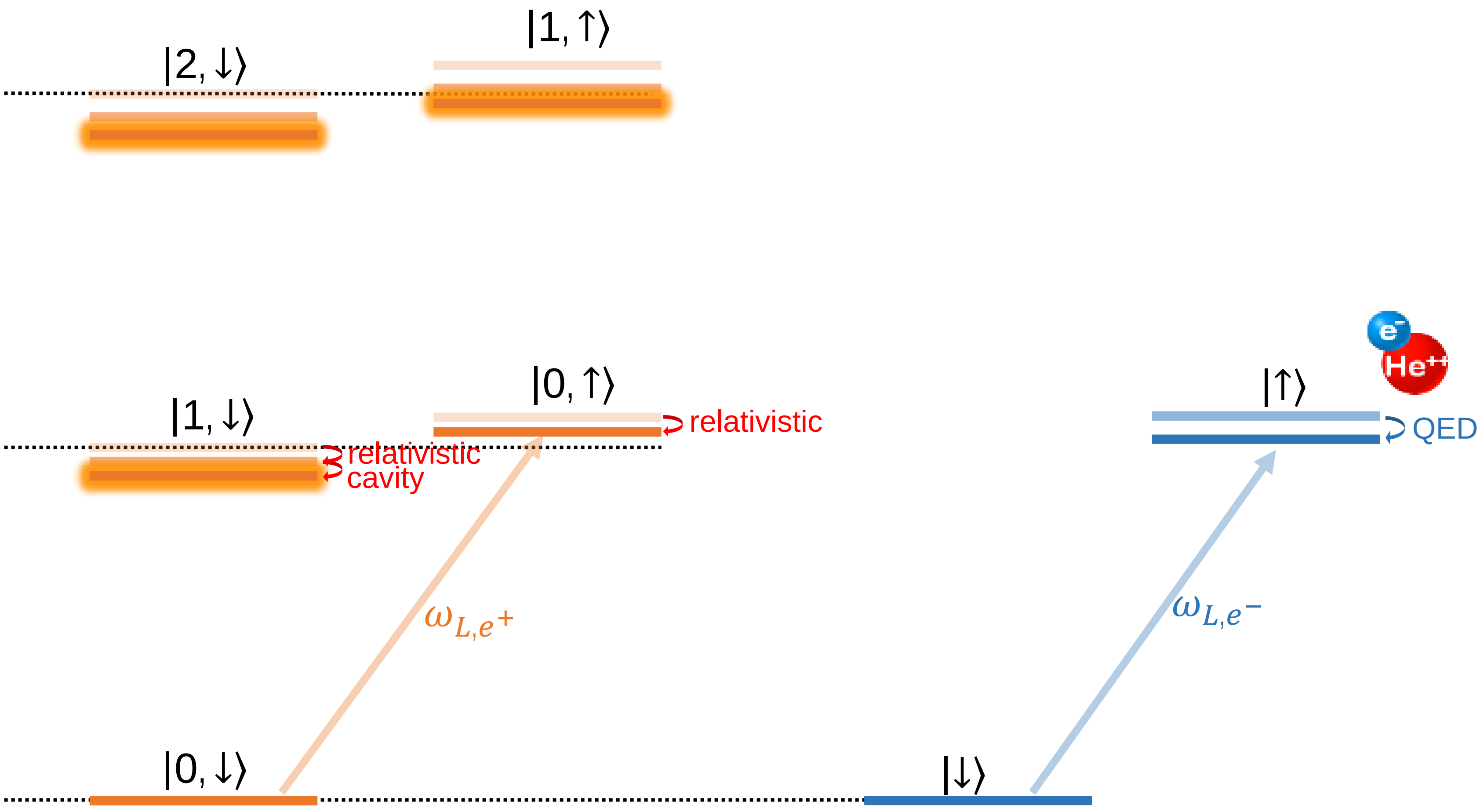
Trapped positron Energy levels



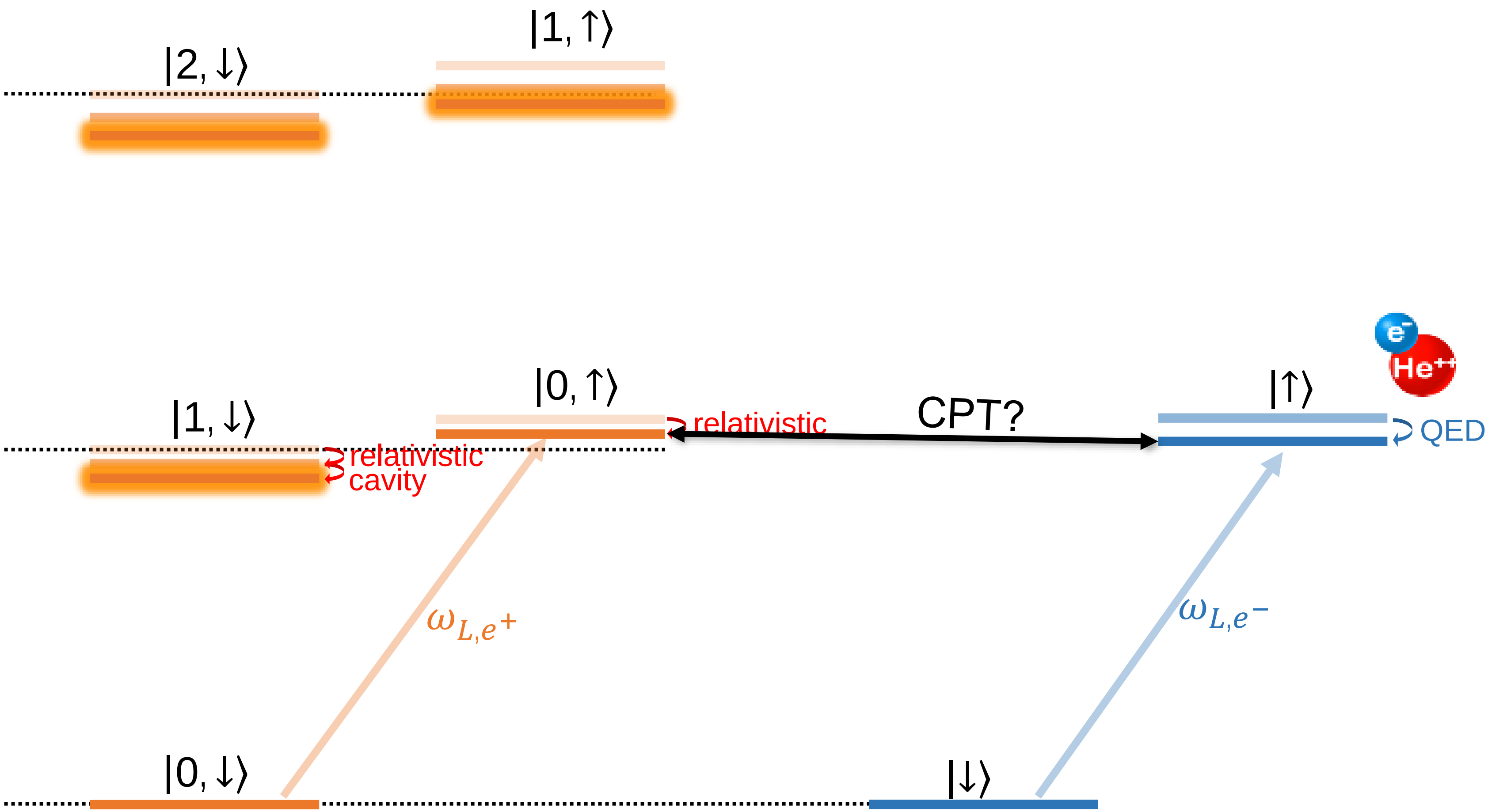
Trapped positron Energy levels



TRAPPED POSITRON ENERGY LEVELS

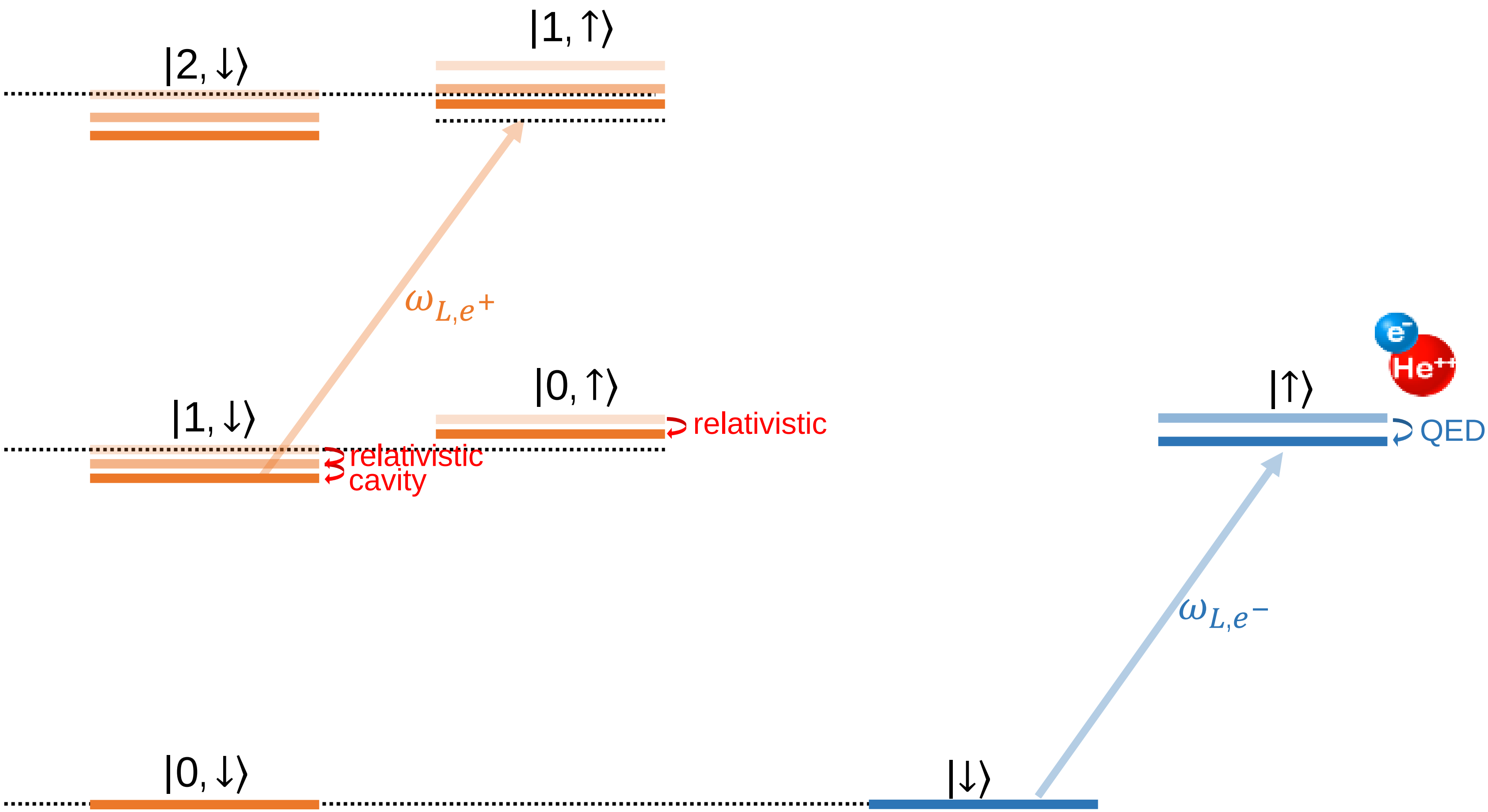


Trapped positron Energy levels



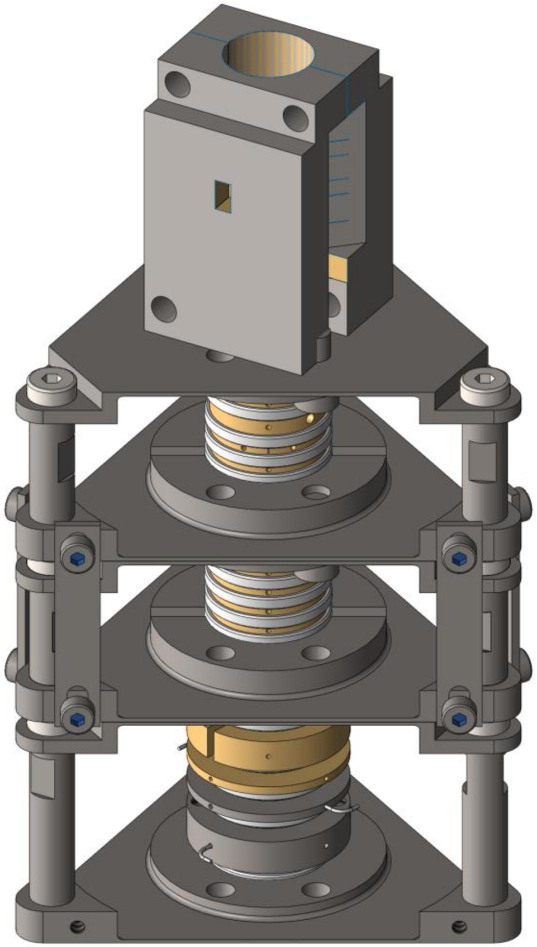
$$g_{e^-} - g_{e^+} \sim \omega_{L,e^-} - \omega_{L,e^+} \sim \frac{q}{m} g_{e^-} - \frac{q}{m} g_{e^+}$$

Trapped positron Energy levels

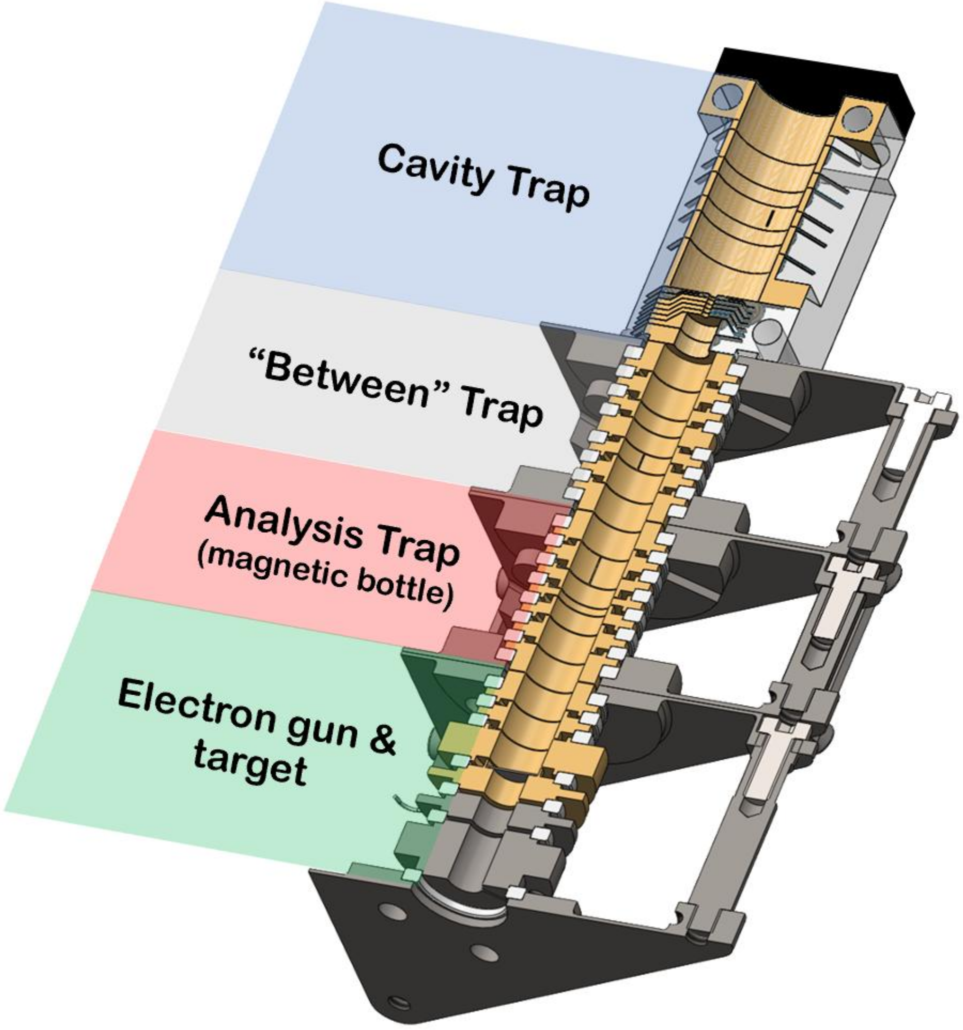


$$g_{e^-} - g_{e^+} \sim \omega_{L,e^-} - \omega_{L,e^+} \sim \frac{q}{m} g_{e^-} - \frac{q}{m} g_{e^+}$$

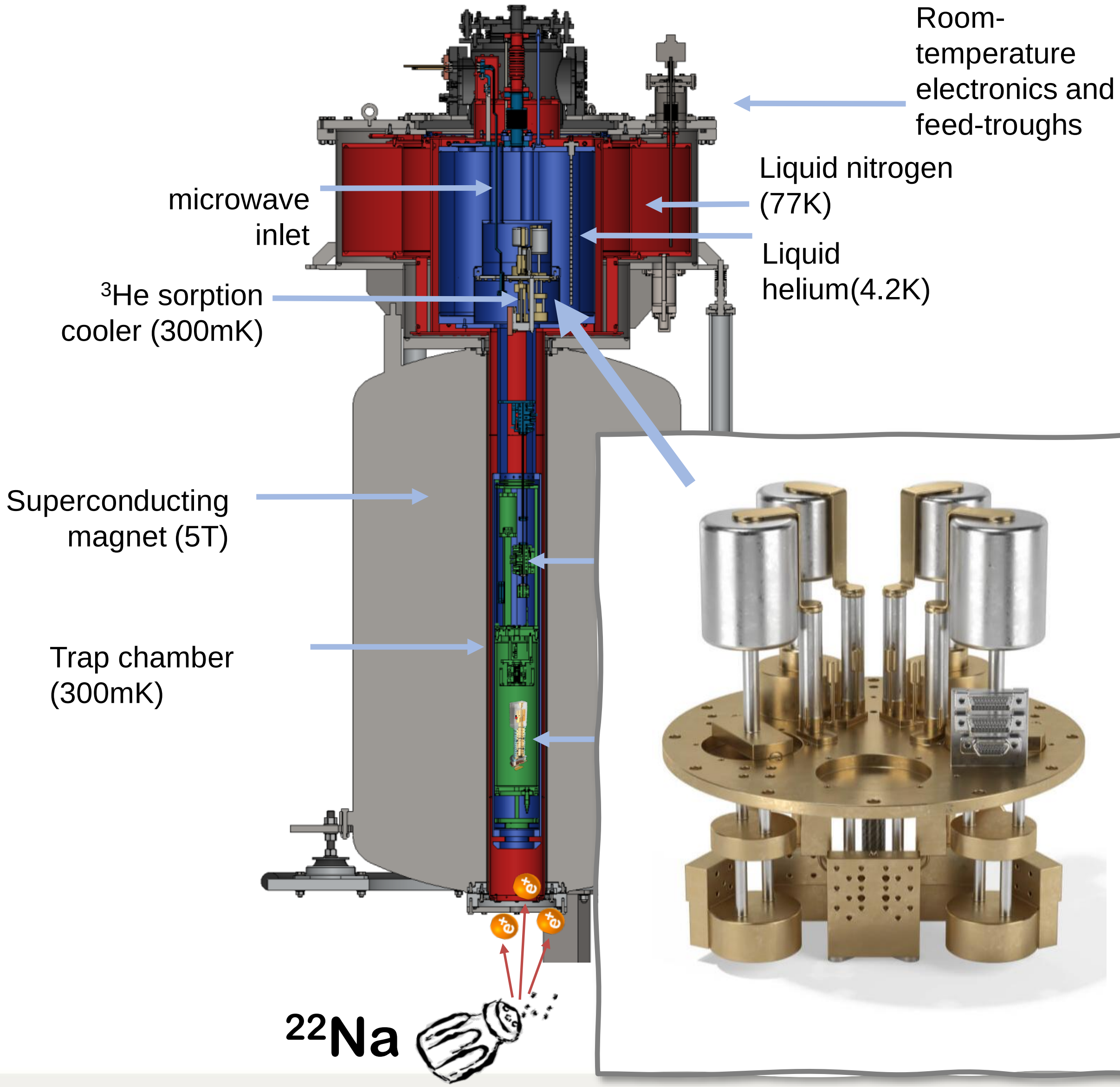
THE LSYM TRAP STACK



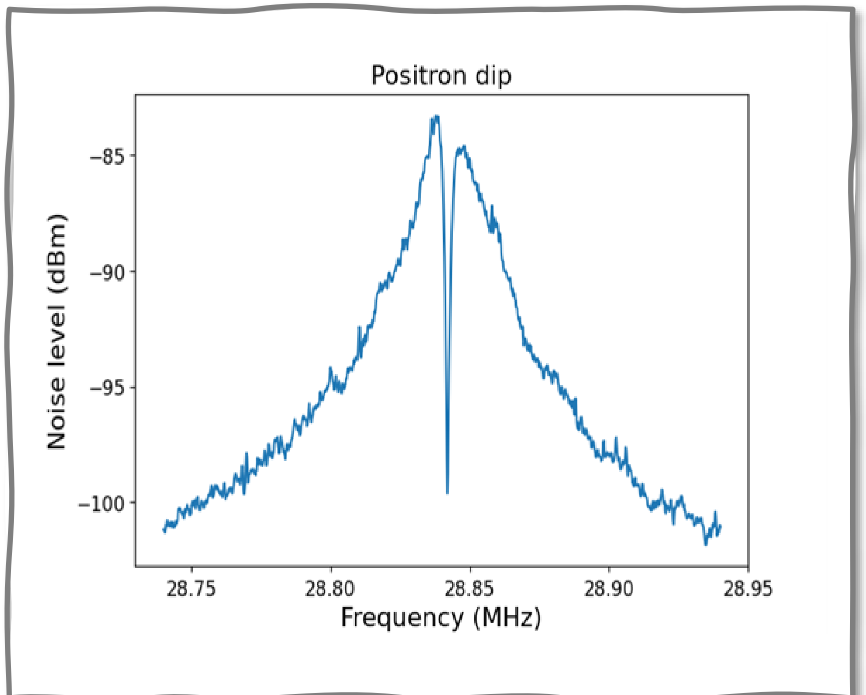
THE LSYM TRAP STACK

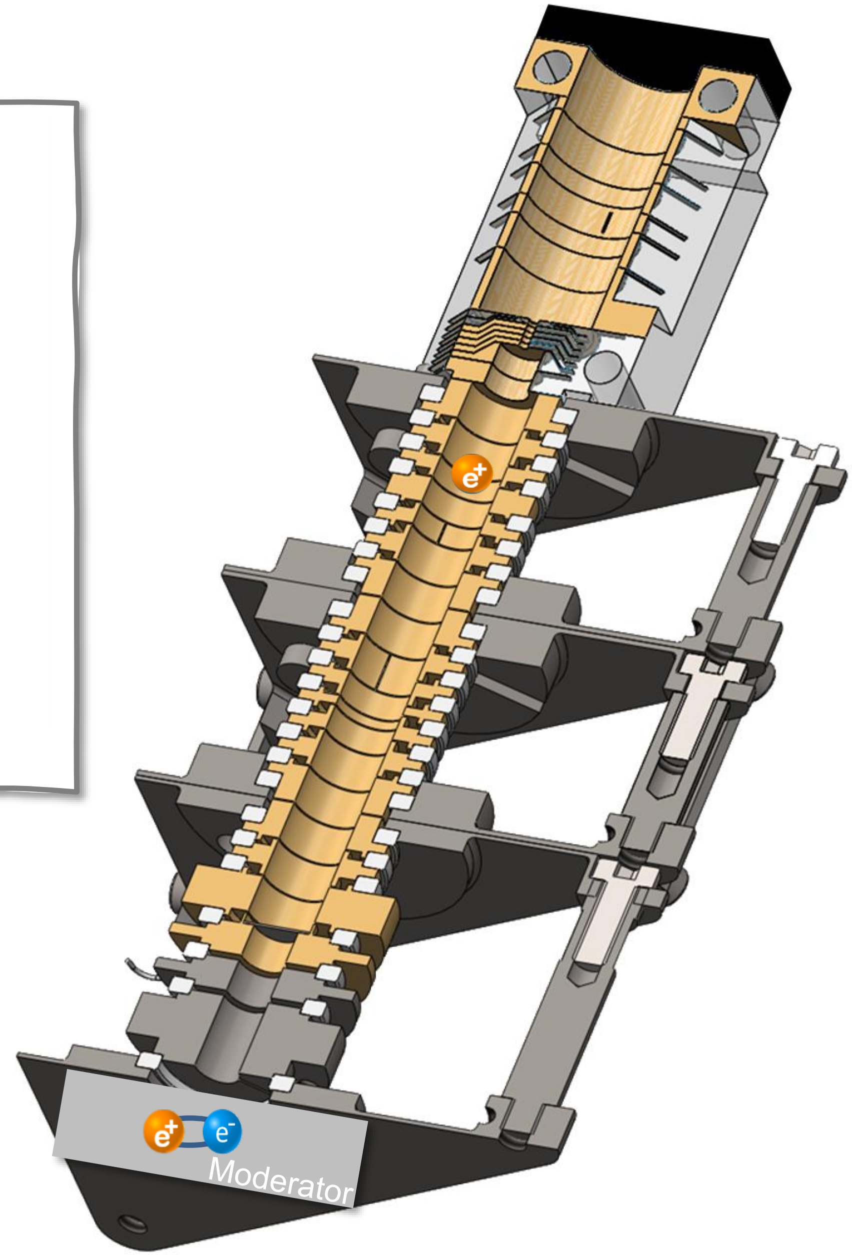


THE LSYM SETUP

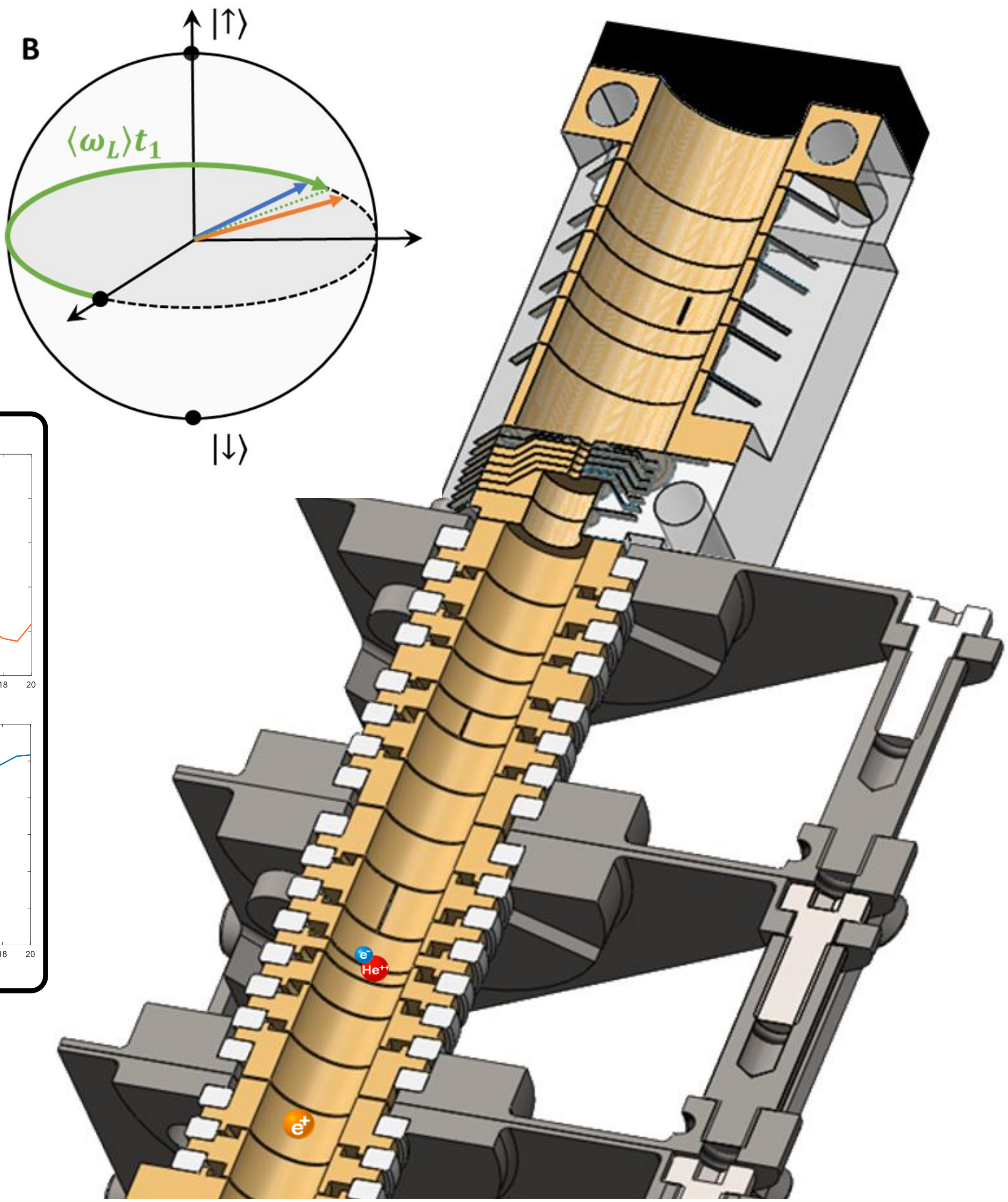


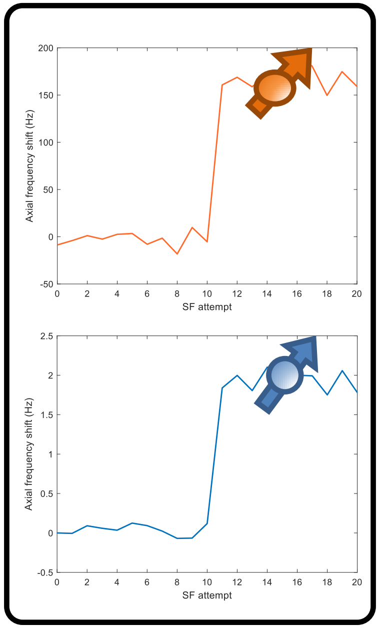
LET'S TRAP POSITRONS



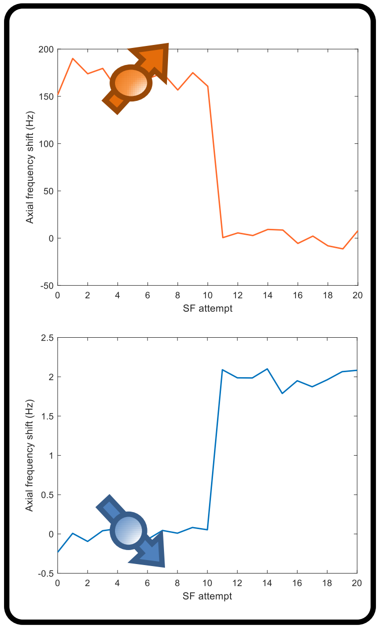


SEQUENCE





Step i



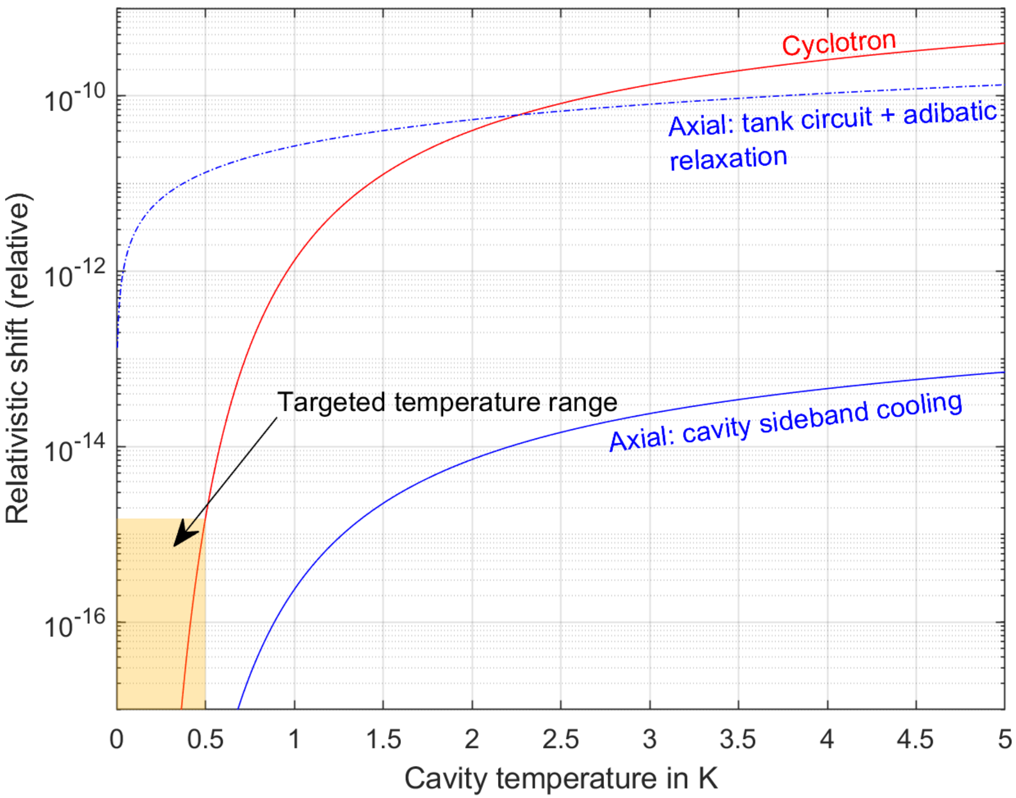
Step i+1

QED CONTRIBUTION

Contribution		$^4He^+$	Electron	Δg
Dirac value		1.999 857 988 825 25 (4)	2.000 000 000 000 00	-0.000 142 011 174 75 (4) (33)
Nuclear size and structure		0.000 000 000 002 28 (4)	0.000 000 000 000 00	0.000 000 000 002 28 (4)
1-loop QED	$(Z\alpha)^0$	0.002 322 819 465 77 (35)	0.002 322 819 465 77 (35)	0.000 000 000 000 00 (0)
	$(Z\alpha)^2$	0.000 000 082 462 19	0.000 000 000 000 00	0.000 000 082 462 19
	$(Z\alpha)^4$	0.000 000 001 976 70	0.000 000 000 000 00	0.000 000 001 976 70
	$(Z\alpha)^{5+}$	0.000 000 000 037 84 (5)	0.000 000 000 000 00	0.000 000 000 037 84 (5)
2-loop QED	$(Z\alpha)^0$	-0.000 003 544 604 50	-0.000 003 544 604 50	0.000 000 000 000 00
	$(Z\alpha)^2$	-0.000 000 000 125 84	0.000 000 000 000 00	-0.000 000 000 125 84
	$(Z\alpha)^4$	0.000 000 000 002 02	0.000 000 000 000 00	0.000 000 000 002 02
	$(Z\alpha)^{5+}$	0.000 000 000 000 03 (10)	0.000 000 000 000 00	0.000 000 000 000 03 ~~(10)~~ (3)
≥3-loop QED	$(Z\alpha)^0$	0.000 000 029 497 83	0.000 000 029 497 83	0.000 000 000 000 00
	$(Z\alpha)^2$	0.000 000 000 001 05	0.000 000 000 000 00	0.000 000 000 001 05
	$(Z\alpha)^{4+}$	0.000 000 000 000 00 (5)	0.000 000 000 000 00	0.000 000 000 000 00 (5)
Recoil		0.000 000 029 167 89 (5)	0.000 000 000 000 00	0.000 000 029 167 89 (5)
Hadronic		0.000 000 000 003 47 (3)	0.000 000 000 003 47 (3)	0.000 000 000 000 00 (0)
Electroweak		0.000 000 000 000 06	0.000 000 000 000 06	0.000 000 000 000 00
Sum		2.002 177 406 712 04 (38)	2.002 319 304 362 63 (35)	-0.000 141 897 650 59 ~~(14)~~ (10)

[B. Sikora priv. comm. (2023)]

POSITRONS IN THE GROUND STATE



Light positron

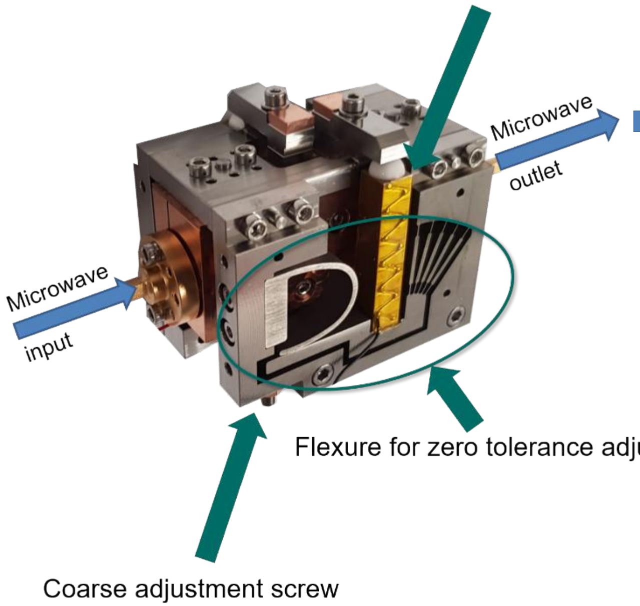
↓

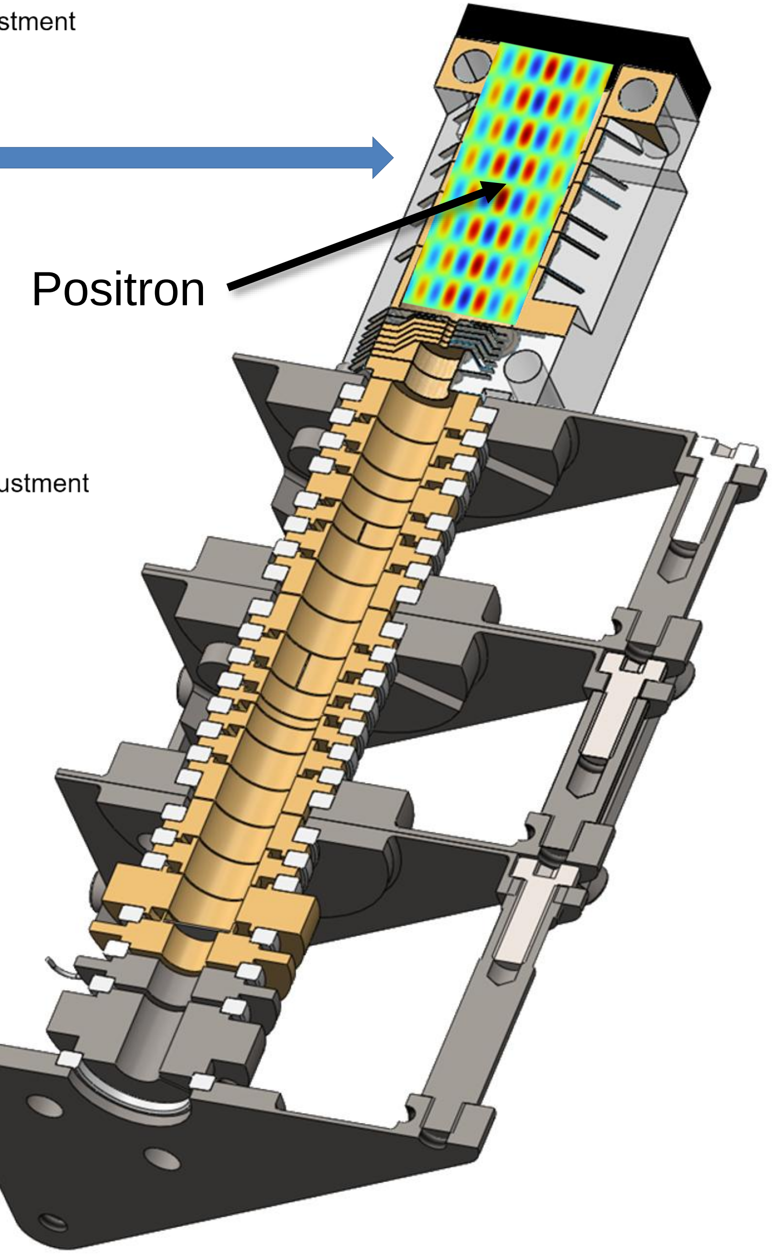
large <u>relativistic shifts</u>

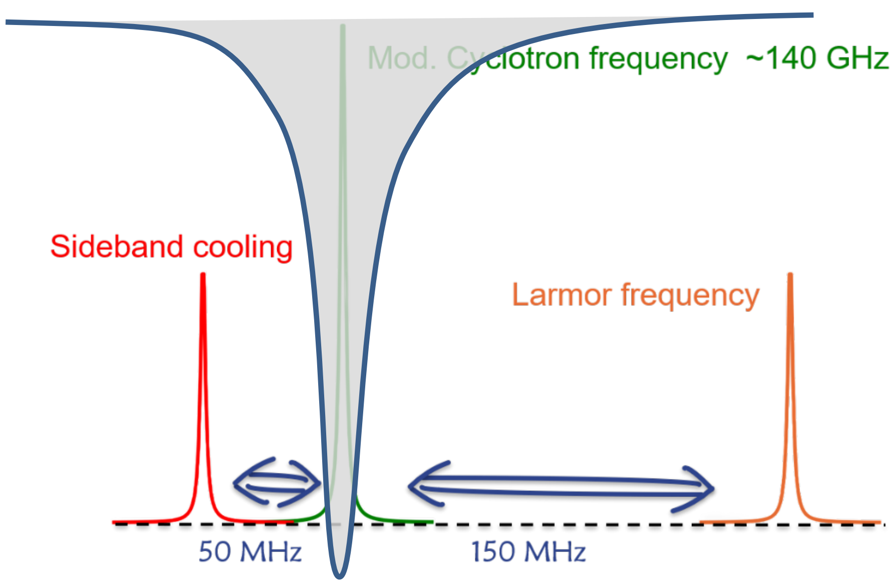
- **$n_+ = 1$ causes a 10^{-9} shift**
- **Even $n_z = 1$ shifts 10^{-13}!**

➢ Cool cyclotron AND axial to ground state !

CavityTrap


Piezo actuator for fine adjustment
Microwave
outlet
Microwave
input
Flexure for zero tolerance adjustment
Coarse adjustment screw


Positron


Mod. Cyclotron frequency ~140 GHz
Sideband cooling
Larmor frequency
50 MHz
150 MHz

The groups

α TRAP

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Dr. Tim Sailer
Dr. Jonathan Morgner
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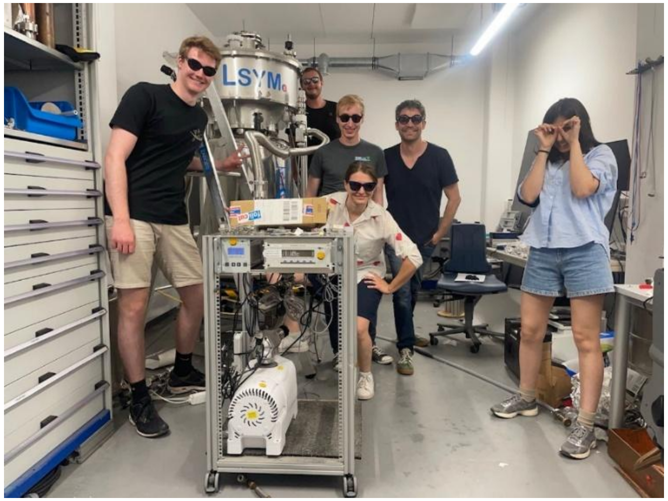
Luca Geissler
Anja Piecuch
Fabian Raab



LSYM

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