Some propaganda

Outreach: Joint effort, FAKT, HEPHY,

Koch; TU-Vienna

Corrections for direct observation of electron g factor

Benjamin Koch
TU Vienna

In collaboration with F. Asenjo and S. Hojman

Outline

- Introduction
- Direct $g-2$ measurement
- Description in effective field theory
- Corrections for strong background field
- Conclusion

- Introduction g-2 a successful story of two:

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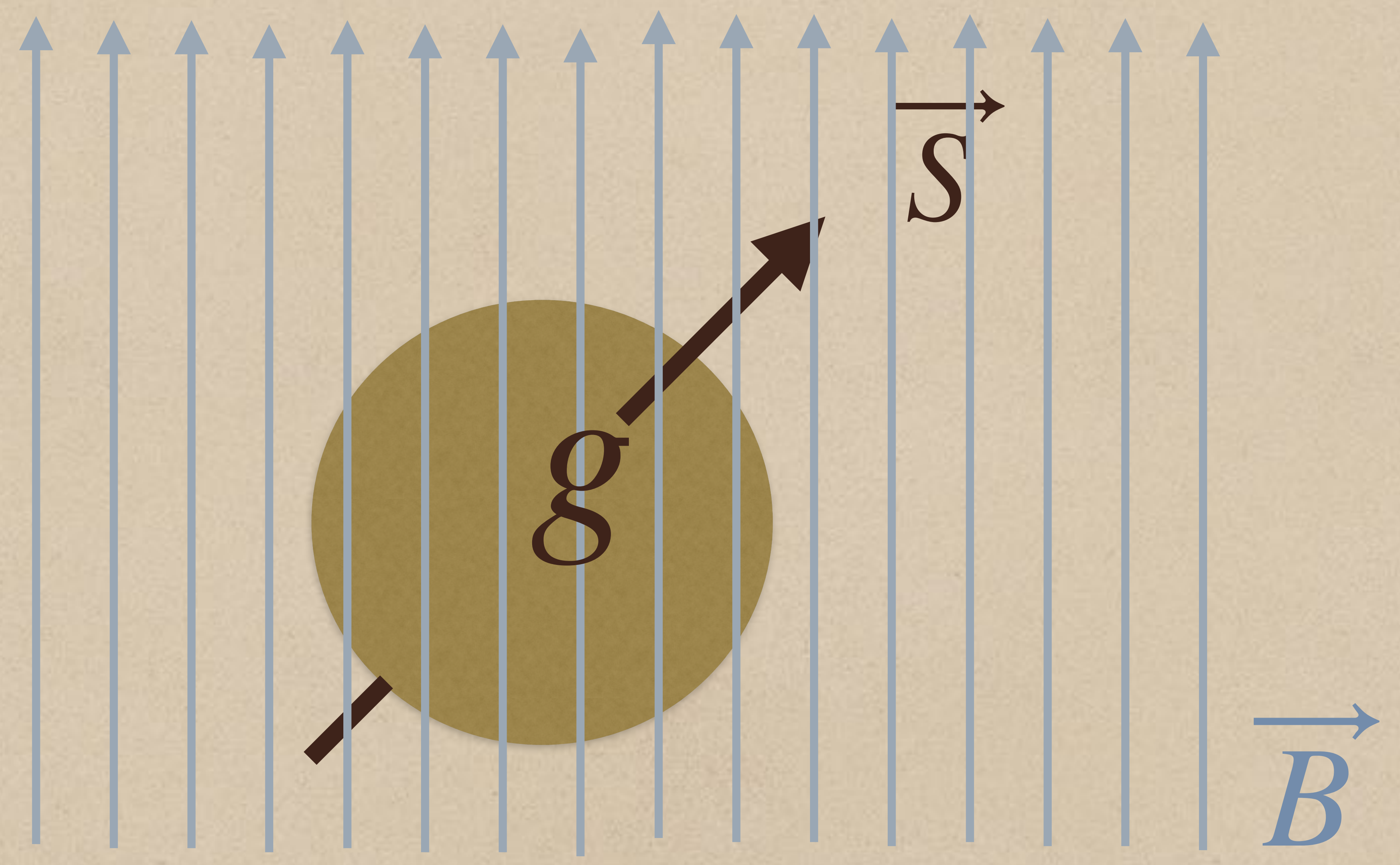
theory and experiment

- Introduction   g-2 a successful story of two:

theory   and   experiment



parametrizes coupling between spin $\vec{S}$ and EM-fields $\vec{E}, \vec{B}$

- Introduction g-2 a successful story of two:

theory g experiment

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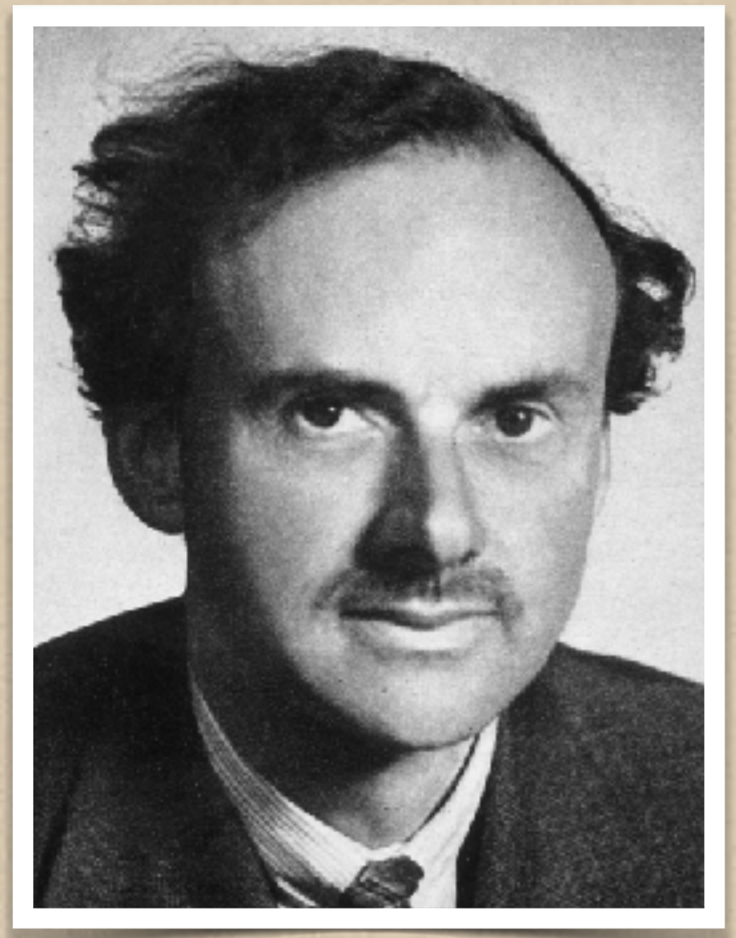
Paul Dirac

1928



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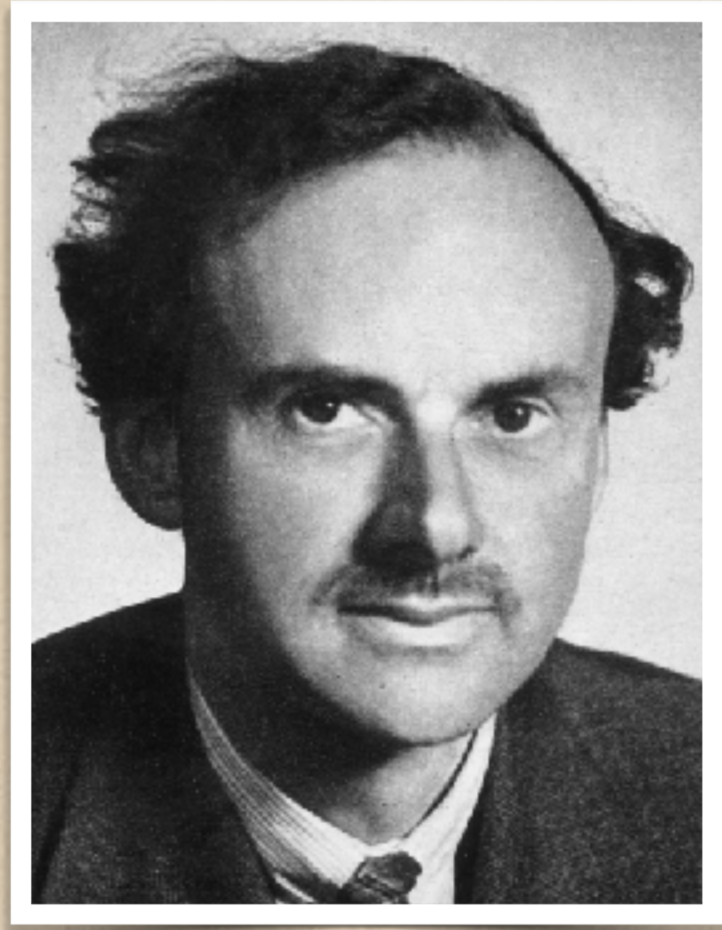
- Introduction

g-2 a successful story of two:

theory g experiment

$$g = 2$$

Paul Dirac



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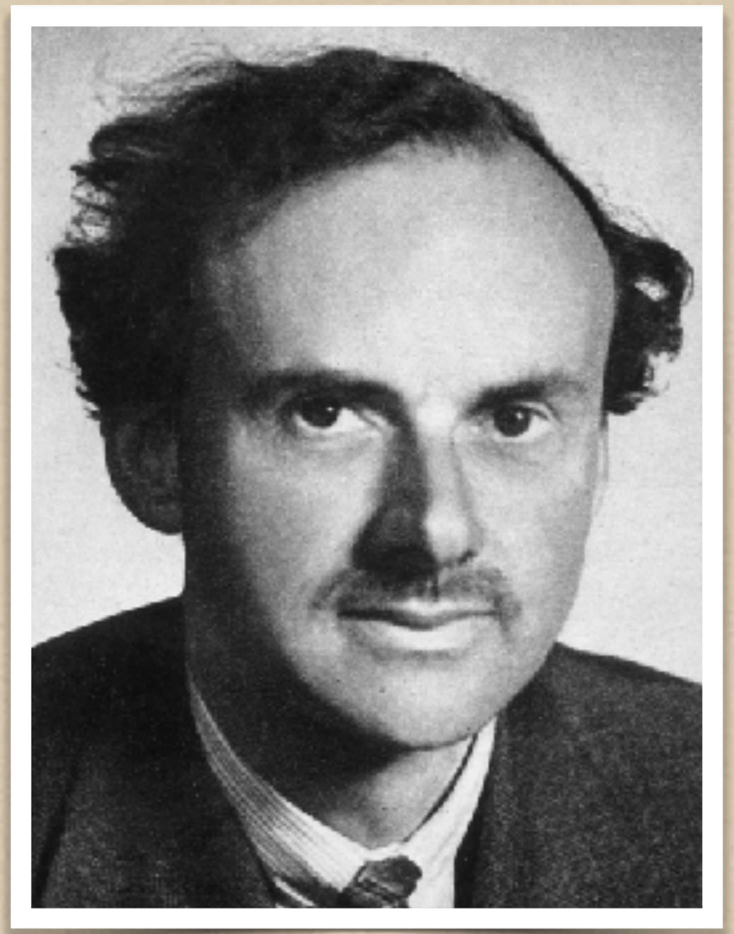

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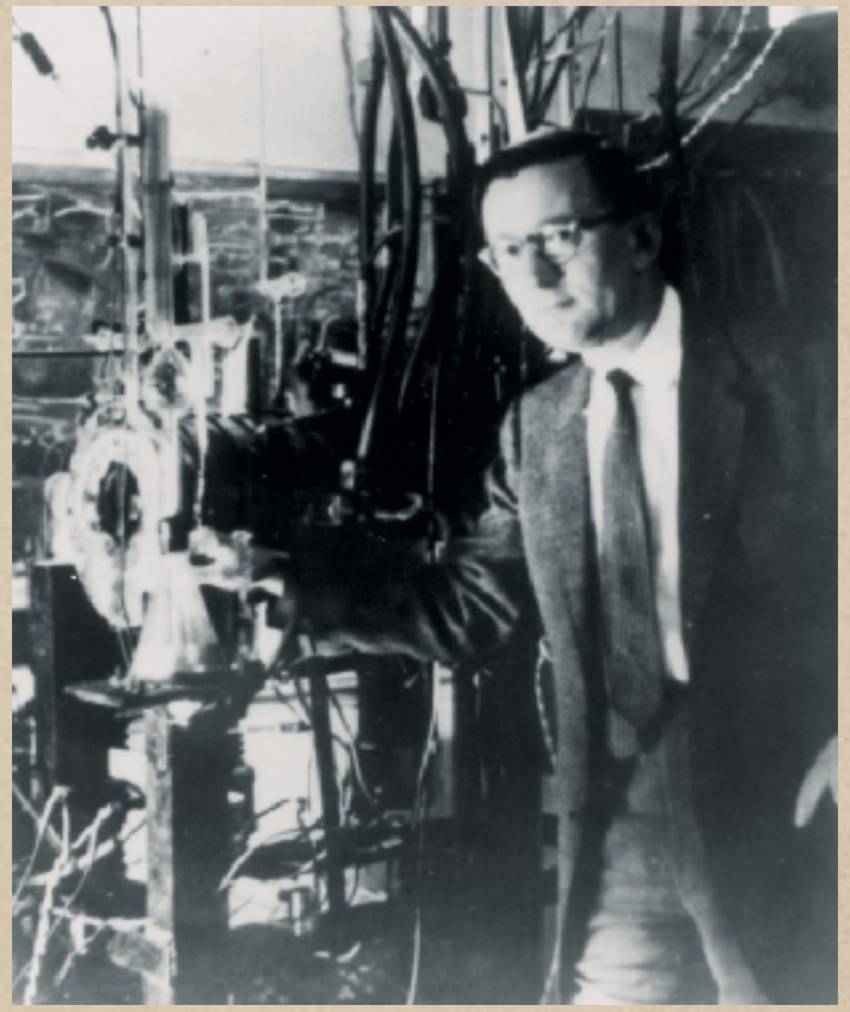

Polykarp Kusch

1947

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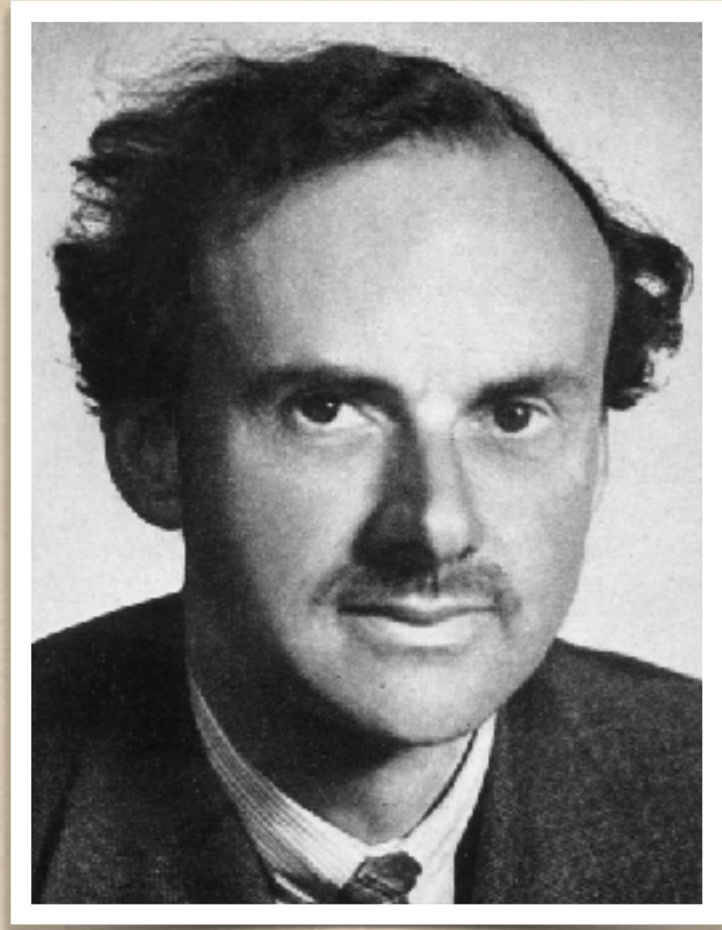

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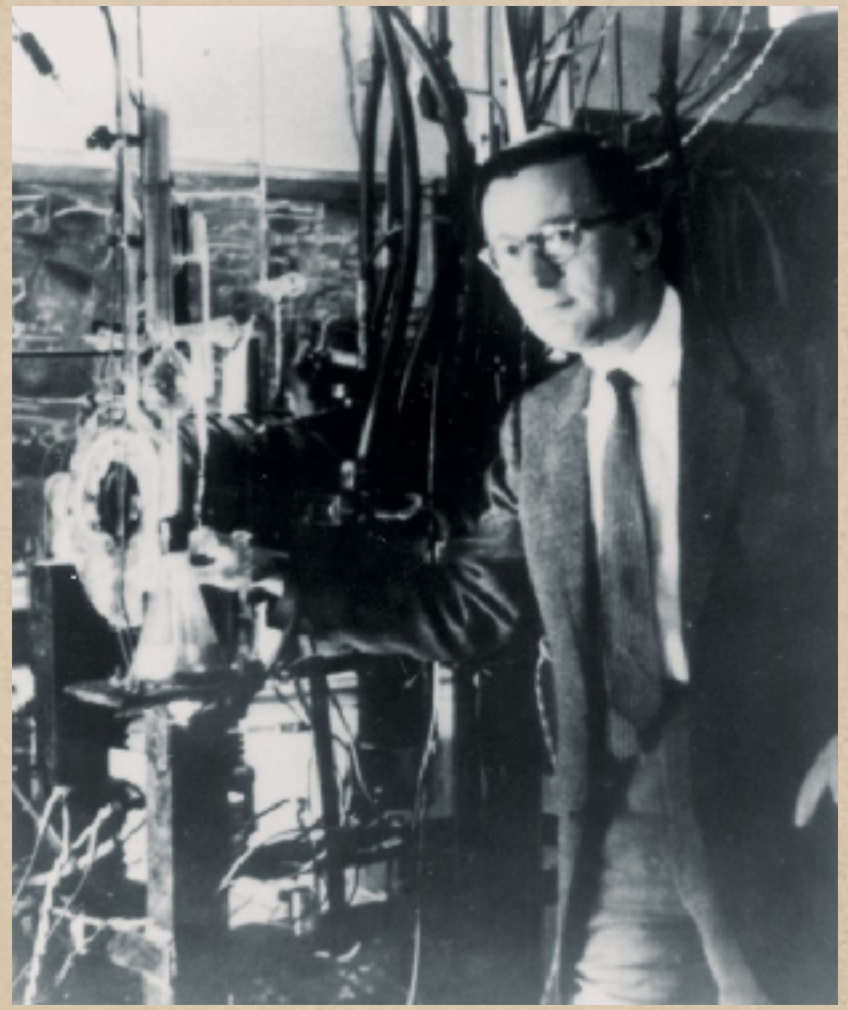

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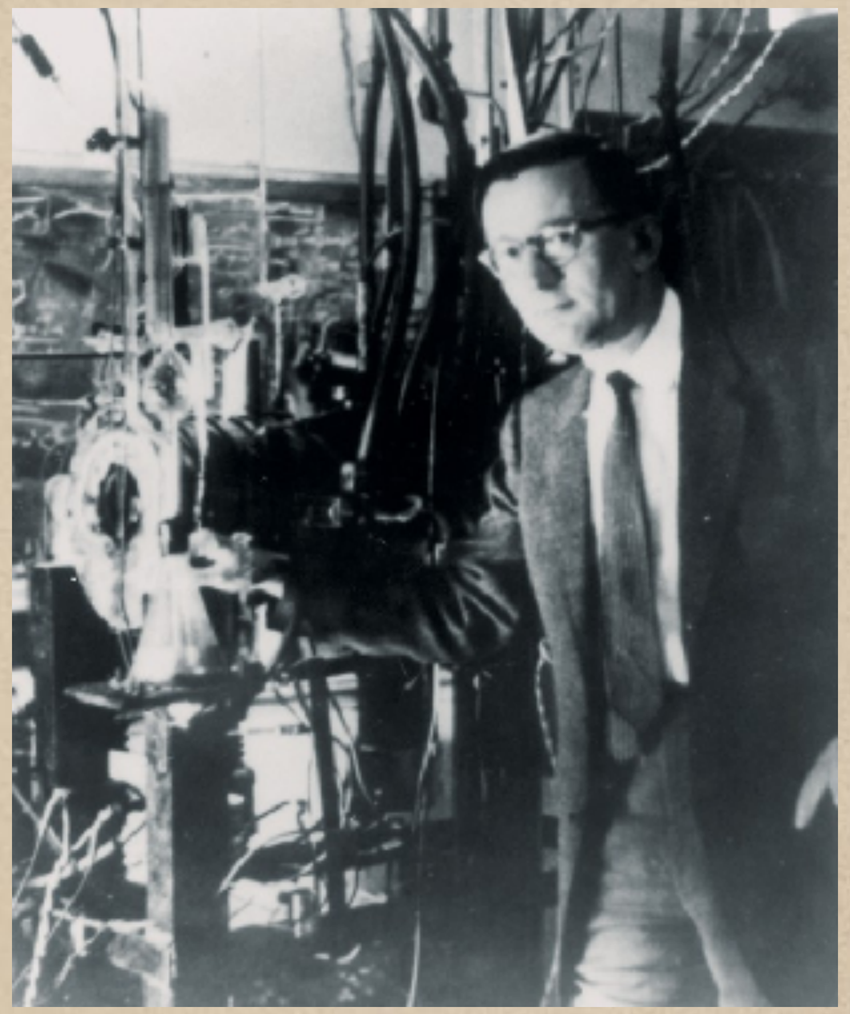

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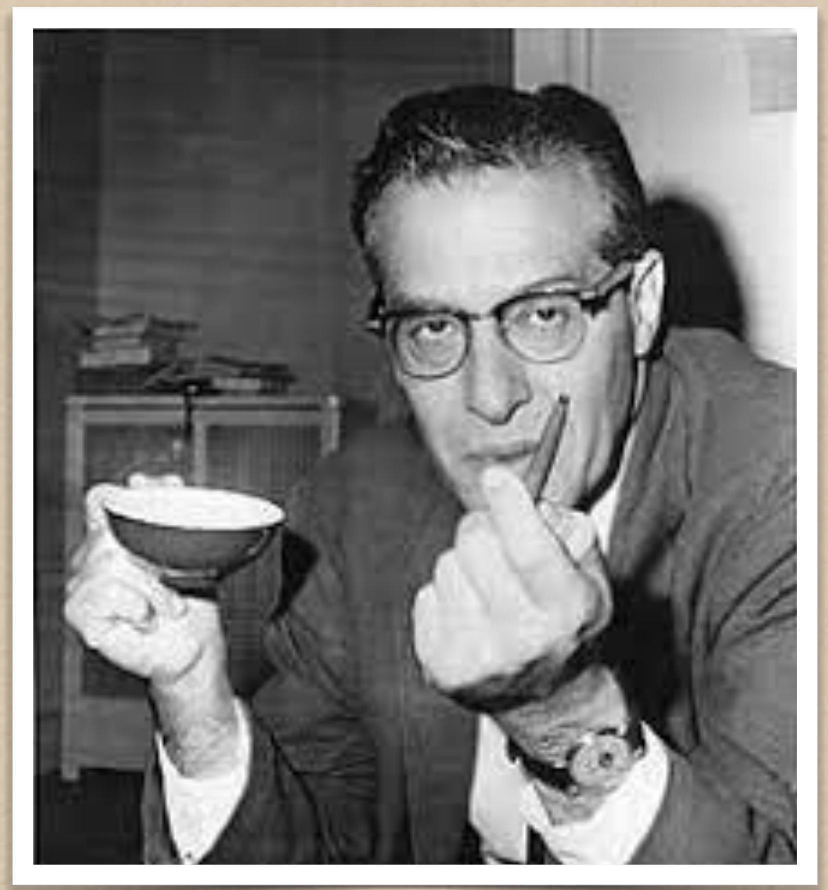

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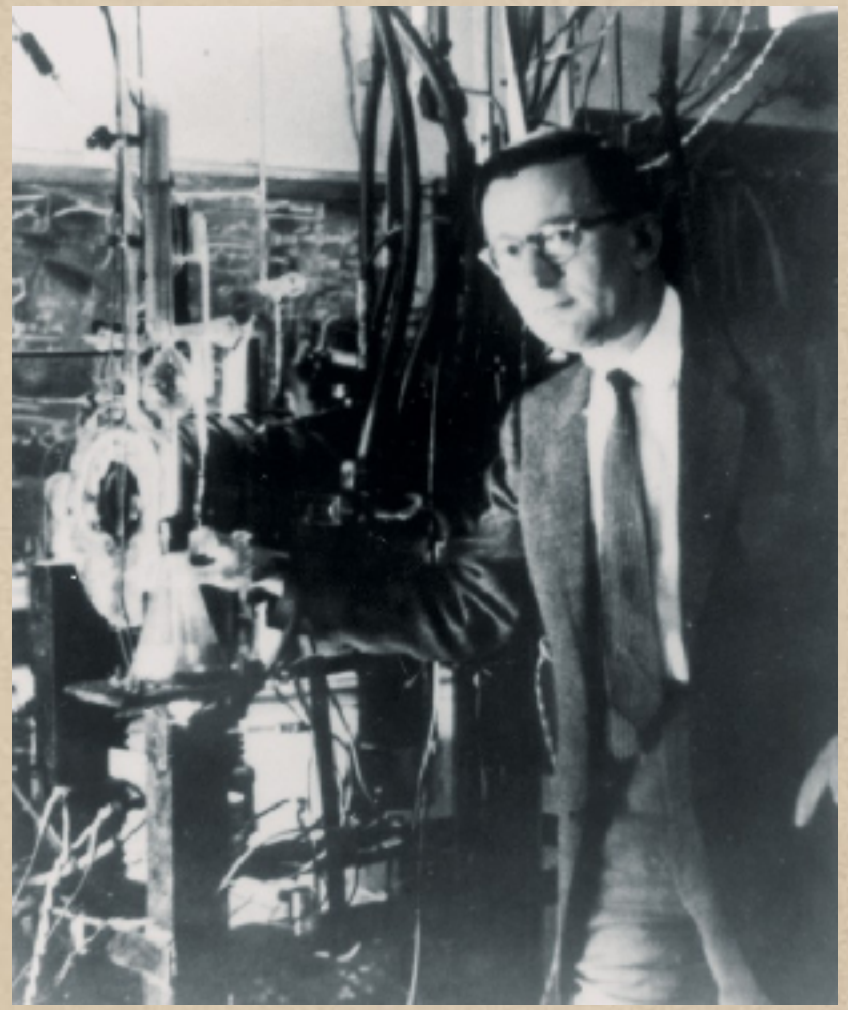

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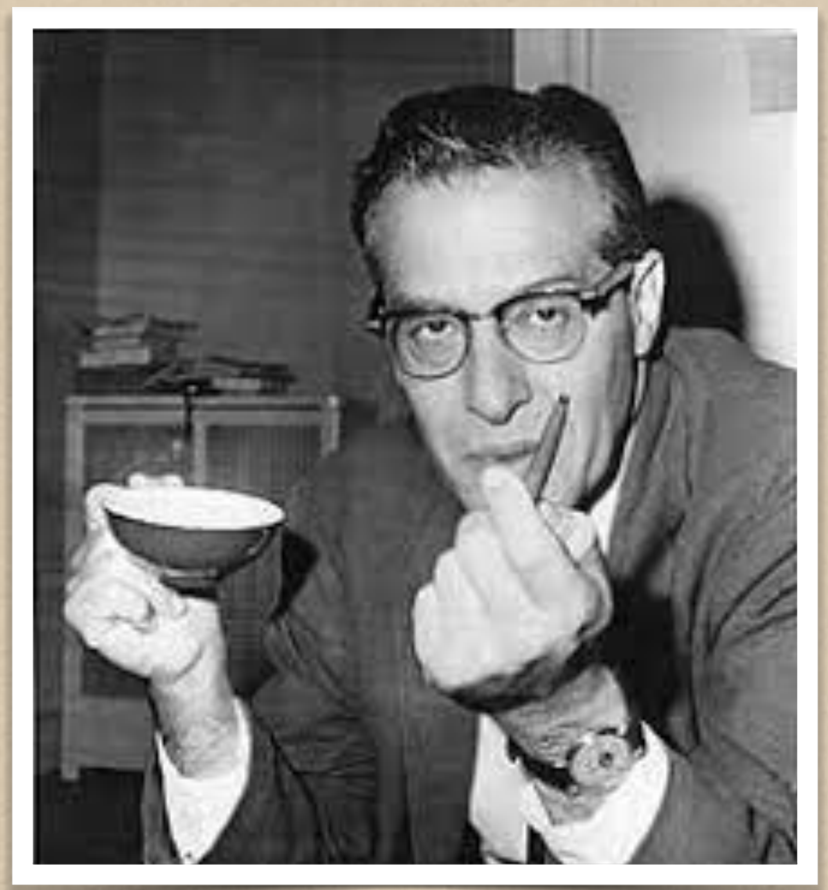
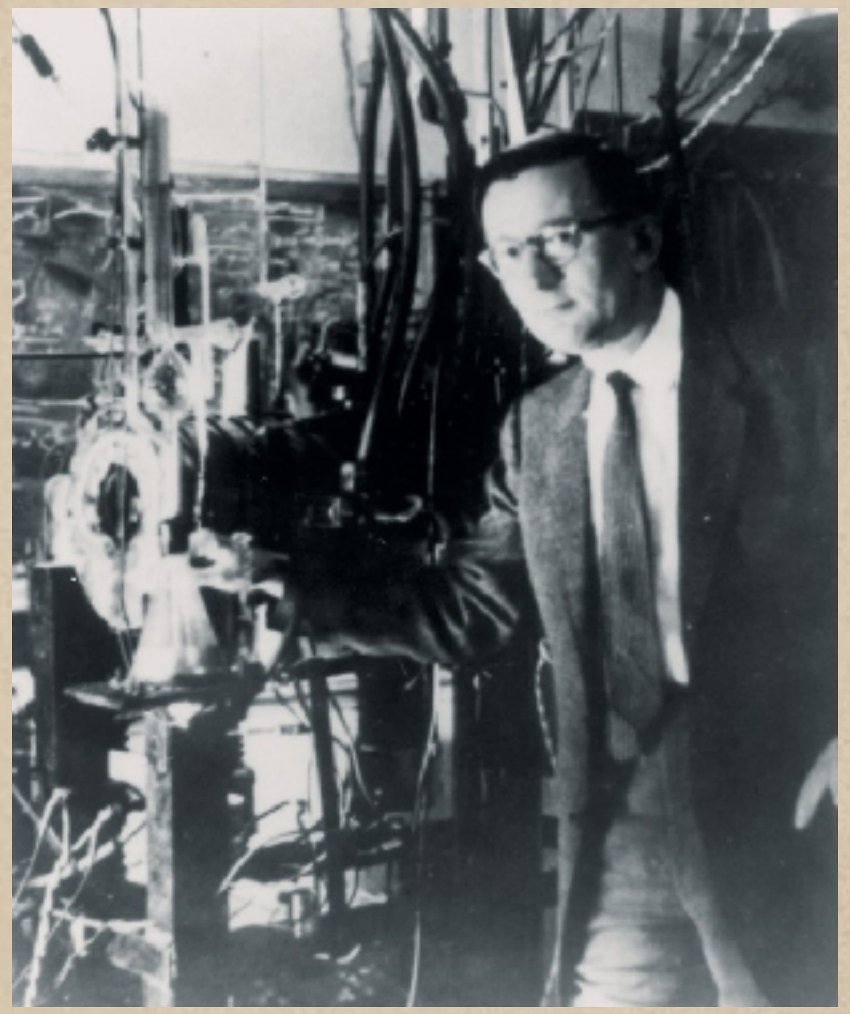


$$g = 2$$

$$g \neq 2$$

$$g = 2 + \frac{\alpha}{\pi}$$



Polykarp Kusch

1948

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Remiddi

Gabrielse

Kinoshita

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$g \neq 2$

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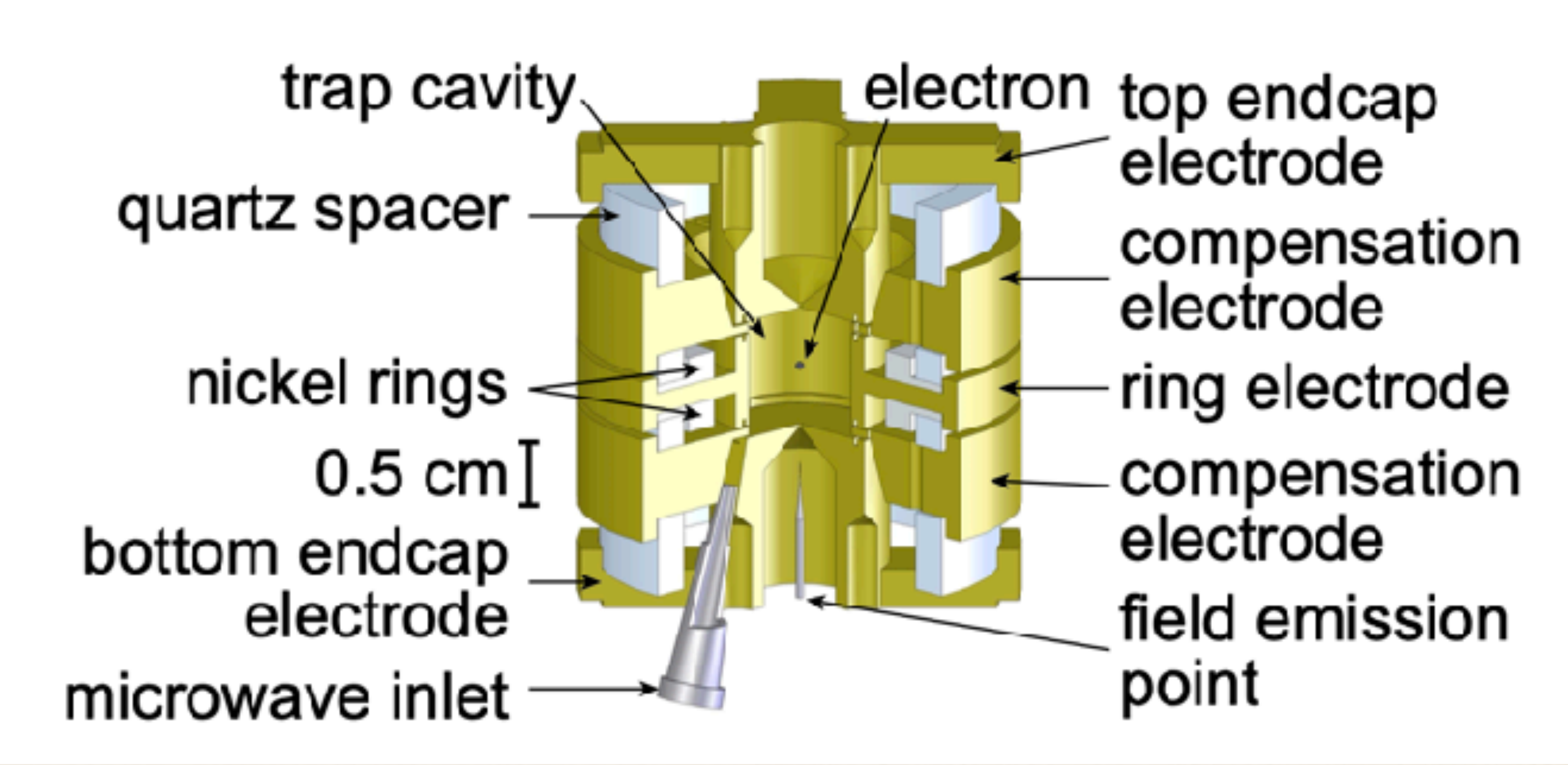
…

…



Penning trap

$$g = 2 + \left(\frac{\alpha}{\pi}\right) + \tilde{C}_4\left(\frac{\alpha}{\pi}\right)^2 + \tilde{C}_6\left(\frac{\alpha}{\pi}\right)^3 + \tilde{C}_8\left(\frac{\alpha}{\pi}\right)^4 + \tilde{C}_{10}\left(\frac{\alpha}{\pi}\right)^5 + 2a_{\mu\tau} + 2a_{had} + 2a_{weak}$$

* from Kinoshita talk, ** from Hanneke et al. paper

- Indirect v.s. direct g-2 measurement

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relates two measurable quantities

- Indirect v.s. direct g-2 measurement

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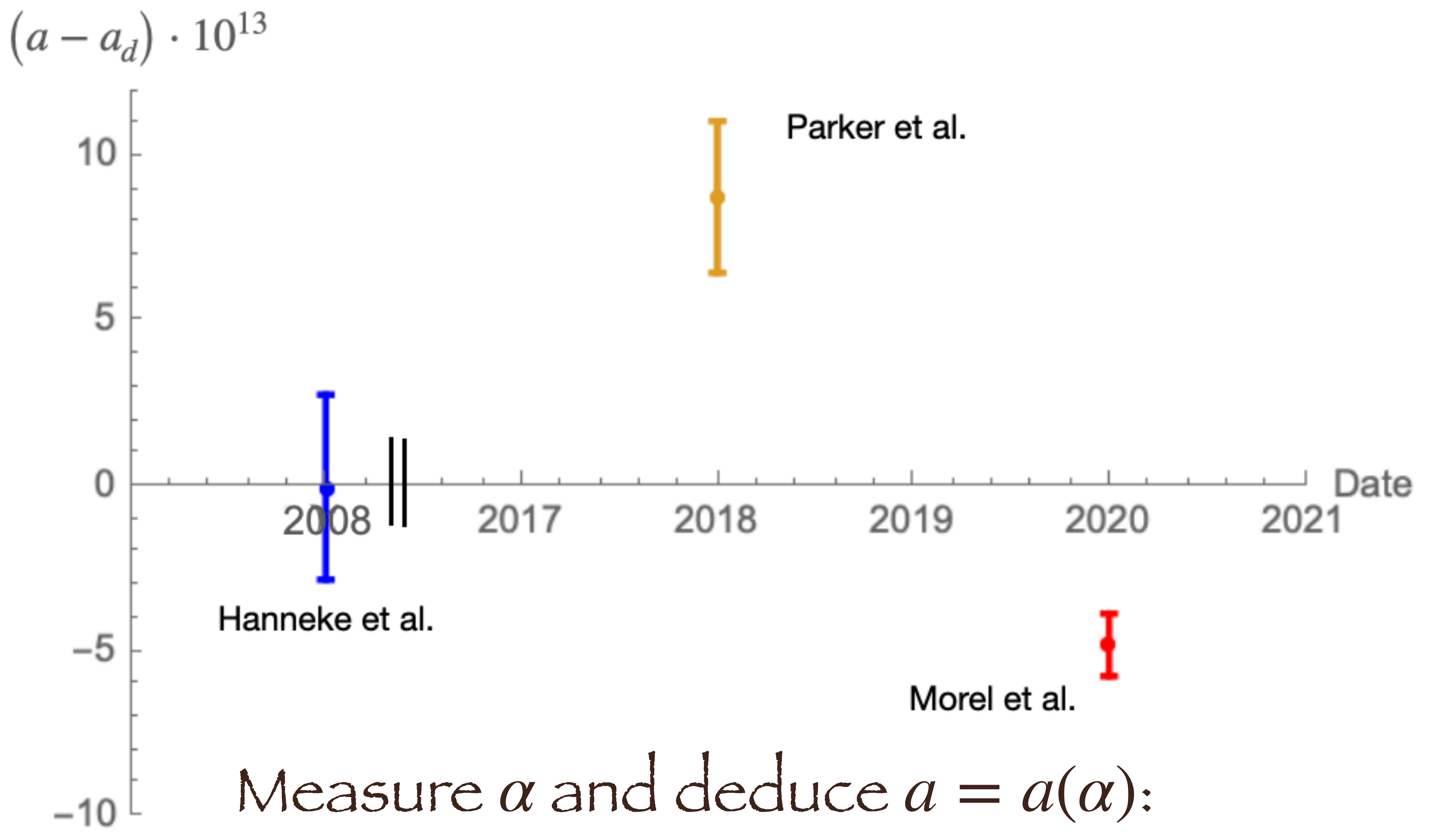
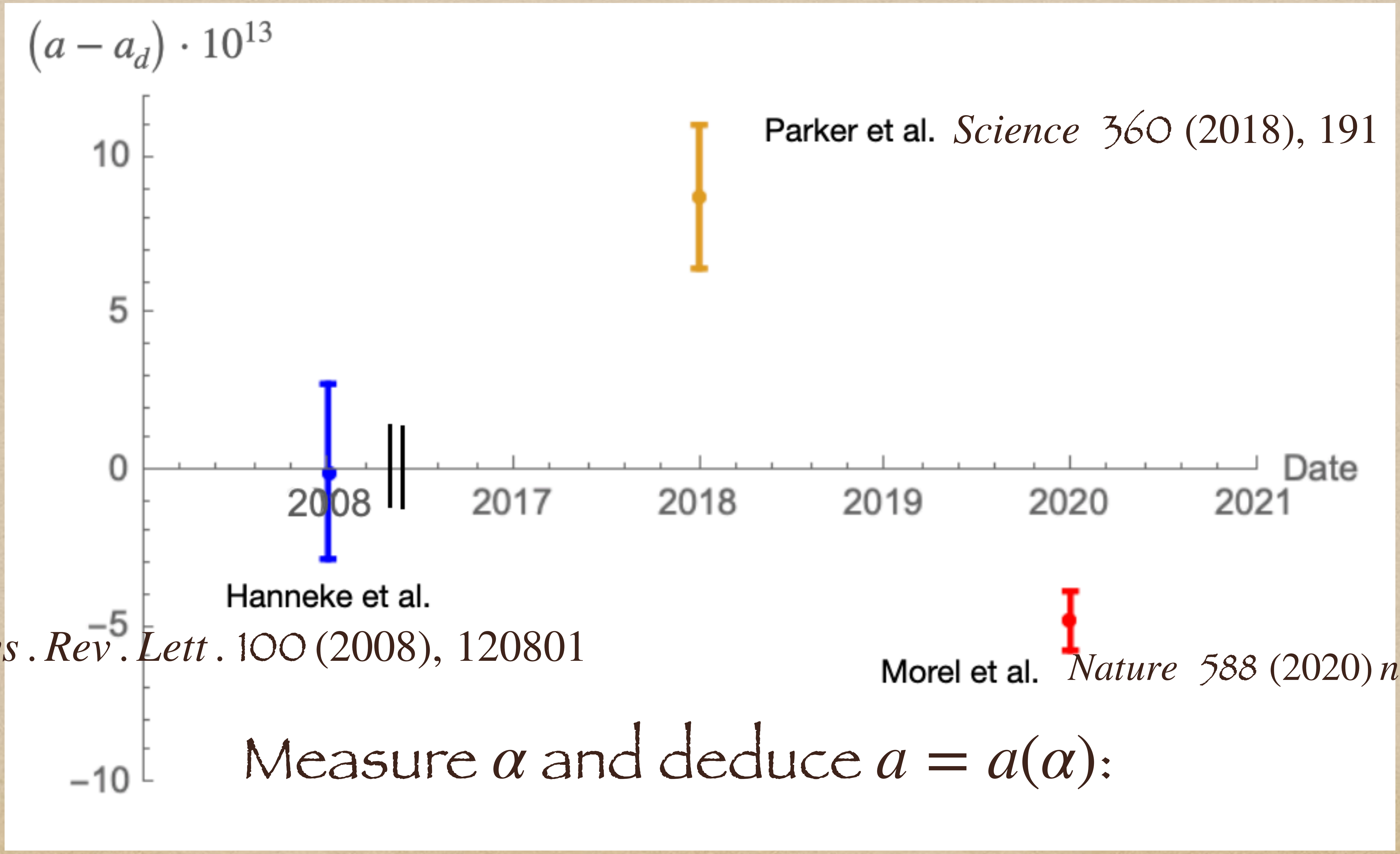


Measure α and deduce $a = a(\alpha)$:

- Indirect v.s. direct g-2 measurement



Science 360 (2018), 191

Phys. Rev. Lett. 100 (2008), 120801

Nature 588 (2020) *no.*7836, 61 – 65

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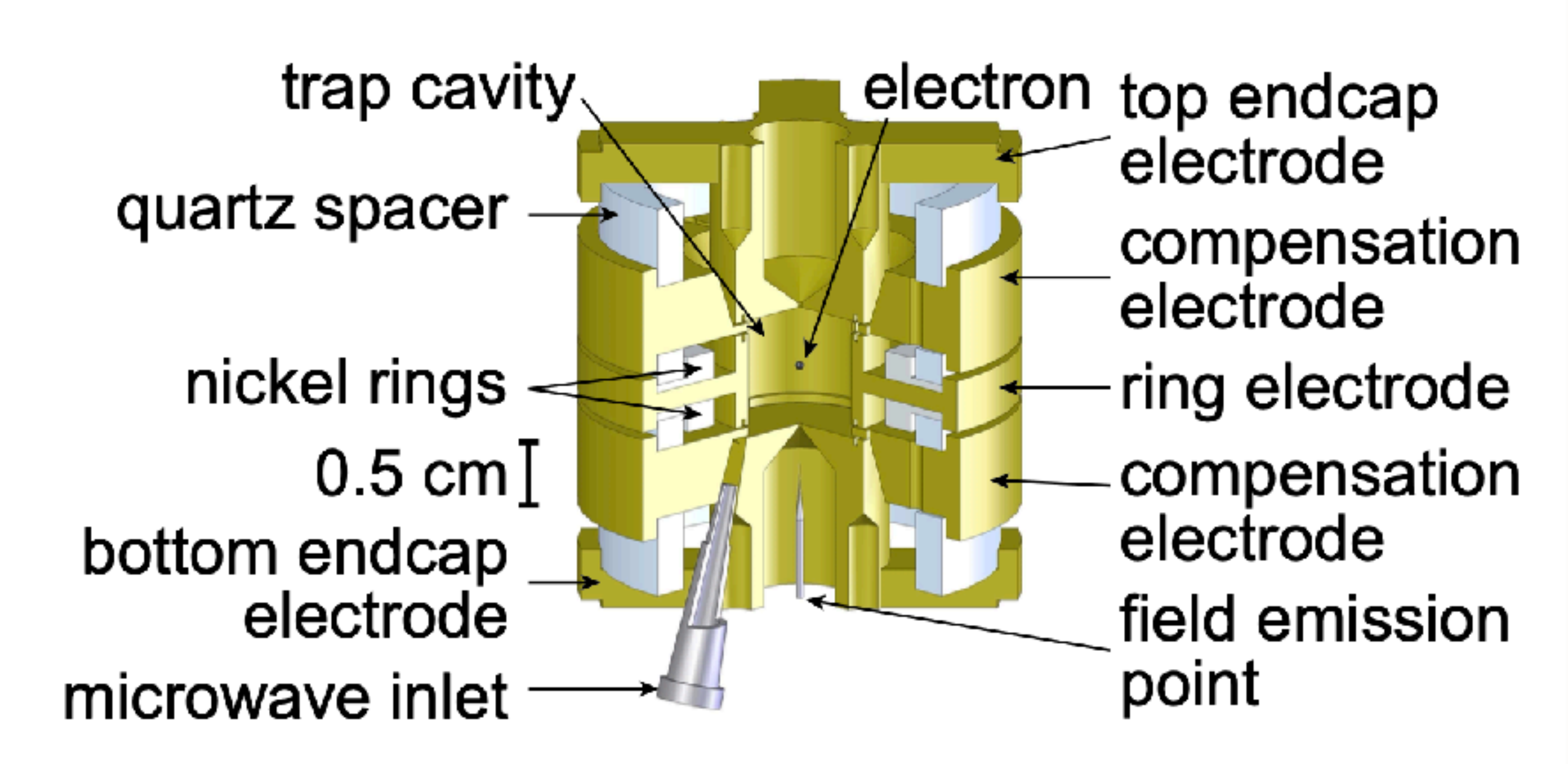
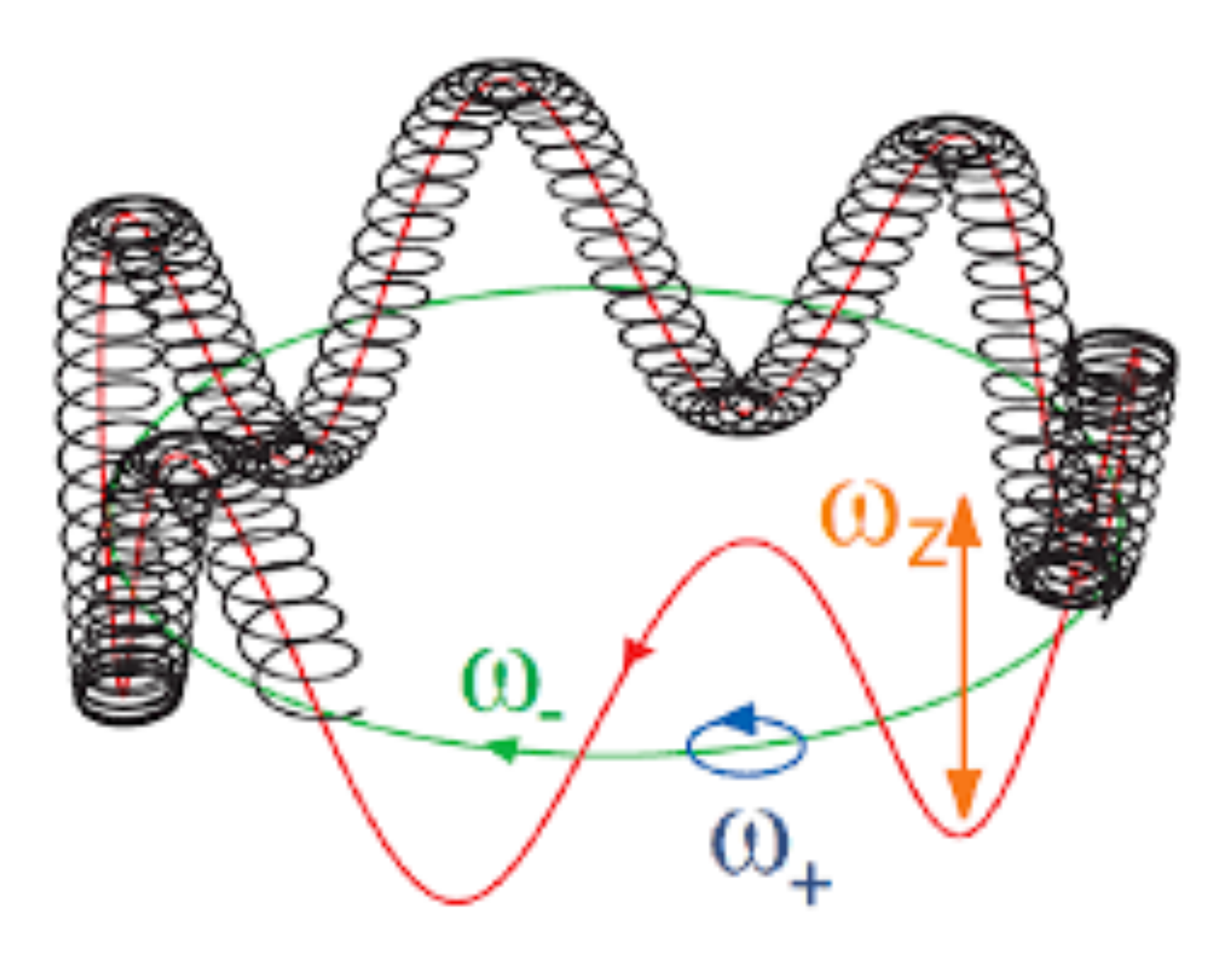
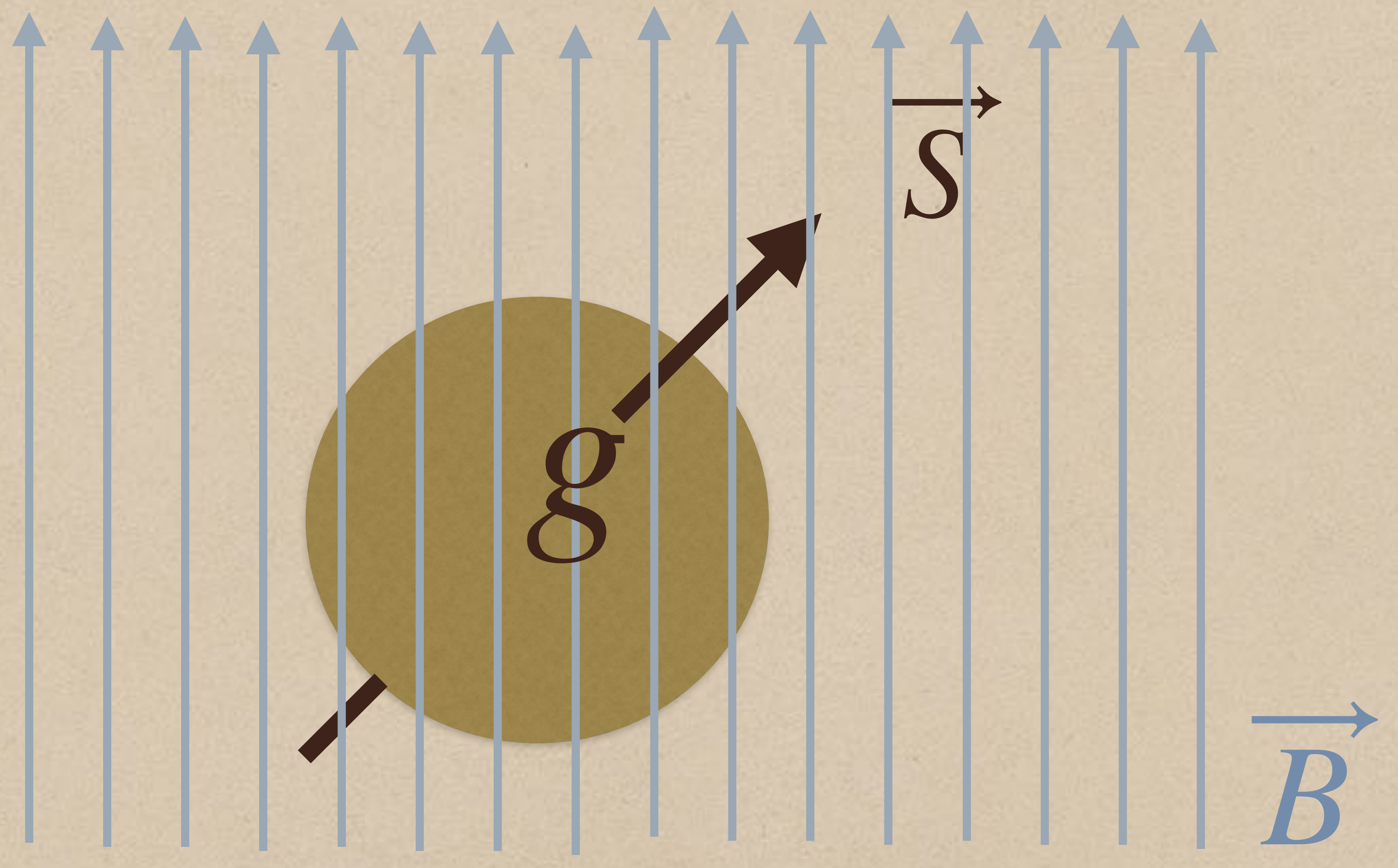




Eigen frequencies: spin-, cyclotron-, axial-, and magnetron-frequency

Tricky ... for our purpose use simpler idealization,

- Direct g-2 measurement Penning trap simplified



Eigen frequencies: spin-, cyclotron

$\Rightarrow$ In Quantum mechanical description: Eigen energies $E_n^{\pm}$

- Direct g-2 measurement Penning trap simplified

- Direct g-2 measurement   Penning trap simplified

Energies:

$$E_n^{\pm} = \pm \frac{1+a}{2} h\nu_c + \left(n + \frac{1}{2}\right) h\nu_c - \frac{1}{2} mc^2 \delta_c^2 \left(n + \frac{1 \pm 1}{2}\right)^2,$$

with $$\delta_c = \frac{h\nu_c}{mc^2},$$

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Useful relation: "Master equation"

$$a_d = \frac{E_0^+ - E_1^-}{E_1^+ - E_0^+ + 3mc^2\delta_c^2/2},$$

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Result: $a_d = 0.001\,159\,652\,180\,73\,(28),$

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Where does this come from?

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$$\mathscr{L}_{eff} = \bar{\psi} \left[\gamma^\mu (i\hbar\partial_\mu - eA_\mu 1 - mc^2 + a\frac{e\hbar}{4m}\sigma \cdot F + \ldots \right] \psi \,.$$

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Two combined expansions!

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Loop expansion

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What's next?

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We answer this question in
EFT approach

- Corrections in strong field background

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- All representation of 4×4 matrices
- Bi-linear Lorentz invariant
- Gauge invariant
- Up to 3rd order in $F^{\mu\nu}$

- Corrections in strong field background

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Lorentz type

1

γ^μ

$\sigma^{\mu\nu}$

$\gamma^5\gamma^\mu$

γ^5

- Corrections in strong field background

Lorentz type	$\Delta\mathscr{L}$
1	
γ^μ	
$\sigma^{\mu\nu}$	
$\gamma^5\gamma^\mu$	
γ^5	

- Corrections in strong field background

Lorentz type	$\Delta\mathscr{L}$
1	$\frac{\xi_{1,FF}}{m^3c^6}\,\bar{\psi}F_{\mu\nu}F^{\mu\nu}\psi$
γ^μ	$\left\{\frac{\xi_{\gamma,DF}}{m^2c^4}\,\bar{\psi}D_\alpha\gamma^\beta F^\alpha_\beta\psi,\quad \frac{\xi_{\gamma,DFF1}}{m^4c^8}\,\bar{\psi}D_\alpha\gamma^\alpha F_{\mu\nu}F^{\mu\nu}\psi,\quad \frac{\xi_{\gamma,DFF2}}{m^4c^8}\,\bar{\psi}D_\alpha\gamma^\beta F_{\beta\nu}F^{\alpha\nu}\psi\right\}$
$\sigma^{\mu\nu}$	$\left\{\frac{\xi_{\sigma,FFF1}}{m^5c^{10}}\,\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}F_{\alpha\beta}F^{\alpha\beta}\psi,\quad \frac{\xi_{\sigma,FFF2}}{m^5c^{10}}\,\bar{\psi}\sigma^{\mu\nu}F_{\mu\alpha}F_{\nu\beta}F^{\alpha\beta}\psi\right\}$
$\gamma^5\gamma^\mu$	$\left\{mc^2\xi_{\gamma^5\gamma^\mu}\bar{\psi}\gamma^5\gamma^\mu D_\mu\psi,\quad \frac{\xi_{\gamma^5\gamma^\mu FF}}{m^3c^6}\bar{\psi}\gamma^5\gamma^\alpha D_\alpha F^{\mu\nu}F_{\mu\nu}\psi\right\}$
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- Corrections in strong field background

Lorentz type	$\Delta\mathscr{L}$	$\Delta E_n^{\pm} \approx \langle \psi_n^{\pm} \vert \gamma^0 \Delta\mathscr{L} \vert \psi_n^{\pm} \rangle$
1	$\frac{\xi_{1,FF}}{m^3c^6}\,\bar{\psi}F_{\mu\nu}F^{\mu\nu}\psi$	
γ^μ	$\left\{\frac{\xi_{\gamma,DF}}{m^2c^4}\,\bar{\psi}D_\alpha\gamma^\beta F^\alpha_\beta\psi,\quad \frac{\xi_{\gamma,DFF1}}{m^4c^8}\,\bar{\psi}D_\alpha\gamma^\alpha F_{\mu\nu}F^{\mu\nu}\psi,\quad \frac{\xi_{\gamma,DFF2}}{m^4c^8}\,\bar{\psi}D_\alpha\gamma^\beta F_{\beta\nu}F^{\alpha\nu}\psi\right\}$	
$\sigma^{\mu\nu}$	$\left\{\frac{\xi_{\sigma,FFF1}}{m^5c^{10}}\,\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}F_{\alpha\beta}F^{\alpha\beta}\psi,\quad \frac{\xi_{\sigma,FFF2}}{m^5c^{10}}\,\bar{\psi}\sigma^{\mu\nu}F_{\mu\alpha}F_{\nu\beta}F^{\alpha\beta}\psi\right\}$	
$\gamma^5\gamma^\mu$	$\left\{mc^2\xi_{\gamma^5\gamma^\mu}\bar{\psi}\gamma^5\gamma^\mu D_\mu\psi,\quad \frac{\xi_{\gamma^5\gamma^\mu FF}}{m^3c^6}\bar{\psi}\gamma^5\gamma^\alpha D_\alpha F^{\mu\nu}F_{\mu\nu}\psi\right\}$	
γ^5	$\left\{mc^2\xi_{\gamma^5}\bar{\psi}\gamma^5\psi,\quad \frac{\xi_{\gamma^5 FF}}{m^3c^6}\bar{\psi}\gamma^5F^{\mu\nu}F_{\mu\nu}\psi\right\}$	

- Corrections in strong field background

Lorentz type	$\Delta\mathscr{L}$	$\Delta E_n^\pm \approx \langle \psi_n^\pm \,|\, \gamma^0 \Delta\mathscr{L} \,|\, \psi_n^\pm \rangle$
1	$\frac{\xi_{1,FF}}{m^3c^6}\,\bar\psi F_{\mu\nu}F^{\mu\nu}\psi$	$\xi_{1,FF}\left(-\frac{h^2\nu_c^2}{mc^2}+\frac{h^3\nu_c^3(2n+1\pm 1)}{m^2c^4}\right)$
γ^μ	$\left\{\frac{\xi_{\gamma,DF}}{m^2c^4}\,\bar\psi D_\alpha\gamma^\beta F^\alpha_\beta\psi,\quad \frac{\xi_{\gamma,DFF1}}{m^4c^8}\,\bar\psi D_\alpha\gamma^\alpha F_{\mu\nu}F^{\mu\nu}\psi,\quad \frac{\xi_{\gamma,DFF2}}{m^4c^8}\,\bar\psi D_\alpha\gamma^\beta F_{\beta\nu}F^{\alpha\nu}\psi\right\}$	$\left\{0,\quad \xi_{\gamma,DFF1}\left(\frac{2h^2\nu^2}{mc^2}-\frac{h^3\nu^3(1+2n\pm 1)}{m^2c^4}\right),\quad -\xi_{\gamma,DFF2}\frac{h^3\nu^3(1+2n\pm 1)}{m^2c^4}\right\}$
$\sigma^{\mu\nu}$	$\left\{\frac{\xi_{\sigma,FFF1}}{m^5c^{10}}\,\bar\psi\sigma^{\mu\nu}F_{\mu\nu}F_{\alpha\beta}F^{\alpha\beta}\psi,\quad \frac{\xi_{\sigma,FFF2}}{m^5c^{10}}\,\bar\psi\sigma^{\mu\nu}F_{\mu\alpha}F_{\nu\beta}F^{\alpha\beta}\psi\right\}$	$\left\{0,\quad \pm\,\xi_{\sigma,FFF1}\frac{4h^3\nu^3}{m^2c^4},\quad -\pm\xi_{\sigma,FFF2}\frac{2h^3\nu^3}{m^2c^4}\right\}$
$\gamma^5\gamma^\mu$	$\left\{mc^2\xi_{\gamma^5\gamma^\mu}\bar\psi\gamma^5\gamma^\mu D_\mu\psi,\quad \frac{\xi_{\gamma^5\gamma^\mu FF}}{m^3c^6}\bar\psi\gamma^5\gamma^\alpha D_\alpha F^{\mu\nu}F_{\mu\nu}\psi\right\}$	$\left\{\xi_{\gamma^5\gamma^\mu}mc^2\left(1-(1+2n\pm 1)\frac{h\nu_c}{2mc^2}\right),\quad \frac{2\xi_{\gamma^5\gamma^\mu FF}h^2\nu_c^2}{mc^2}\left(1-(1+2n\pm 1)\frac{h\nu_c}{2mc^2}\right)\right\}$
γ^5	$\left\{mc^2\xi_{\gamma^5}\bar\psi\gamma^5\psi,\quad \frac{\xi_{\gamma^5 FF}}{m^3c^6}\bar\psi\gamma^5F^{\mu\nu}F_{\mu\nu}\psi\right\}$	$\left\{\xi_{\gamma^5}mc^2\left(1-(1+2n\pm 1)\frac{h\nu_c}{2mc^2}\right),\quad \frac{2\xi_{\gamma^5 FF}h^2\nu_c^2}{mc^2}\left(1-(1+2n\pm 1)\frac{h\nu_c}{2mc^2}\right)\right\}$

- Corrections in strong field background

Combined in Energy:

$$\frac{\Delta E_n^{\pm}}{mc^2} = \xi_0 \delta_c^0 + \xi_1 \delta_c^1 + \xi_2 \delta_c^2 + \xi_3 \delta_c^3 + \dots$$

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$$\xi_0 = \xi_{\gamma^5} + \xi_{\gamma_5\gamma^\mu}$$

$$\xi_1 = -(1 + 2n \pm 1)(\xi_{\gamma^5} + \xi_{\gamma^5\gamma^\mu})$$

$$\xi_2 = \frac{1}{8}\left(+3(1 + 2n \pm 1)^2\xi_{\gamma^5} + 16\xi_{\gamma^5 FF} + 3(1 + 2n \pm 1)^2\xi_{\gamma^5\gamma^\mu} + 16(\xi_{\gamma^5\gamma^\mu FF} + \xi_{\gamma^\mu FF1} - \xi_{1,FF})\right)$$

$$\xi_3 = (1 + 2n \pm 1)\xi_{1,FF} - \frac{5}{16}(1 + 2n \pm 1)^3(\xi_{\gamma^5} + \xi_{\gamma^5\gamma^\mu}) - (1 + 2n \pm 1)(\xi_{\gamma^5 FF} + \xi_{\gamma^5\gamma^\mu FF} + \xi_{\gamma^\mu FF1} + \xi_{\gamma^\mu FF2}) \pm 4\xi_{\sigma FFF1} \pm 2\xi_{\sigma FFF2}$$

- Corrections in strong field background

Adopted ``Master formula''

$$a_d = \frac{E_0^+ - E_1^-}{E_1^+ - E_0 + \frac{3}{2}mc^2\delta_c - \frac{7}{2}mc^2\delta_c^2}$$

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$$+\Big(4a_a(\xi_{1FF} - \xi_{\gamma^5FF} - \xi_{\gamma^5\gamma^\mu FF} - \xi_{\gamma^\mu FF1} - \xi_{\gamma^\mu FF2}) - 8(2\xi_{\sigma FFF1} + \xi_{\sigma FFF1}) - 35a_a(\xi_{\gamma^5} + \xi_{\gamma^5\gamma^\mu})\Big)\delta_c^2 + \mathcal{O}(\xi_i^2, \delta^3)$$

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$$a_d = a_d(a_a, \xi_i, \ldots)$$

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Parity even benchmark

Plot, comparison, direct and indirect:

Parity even benchmark

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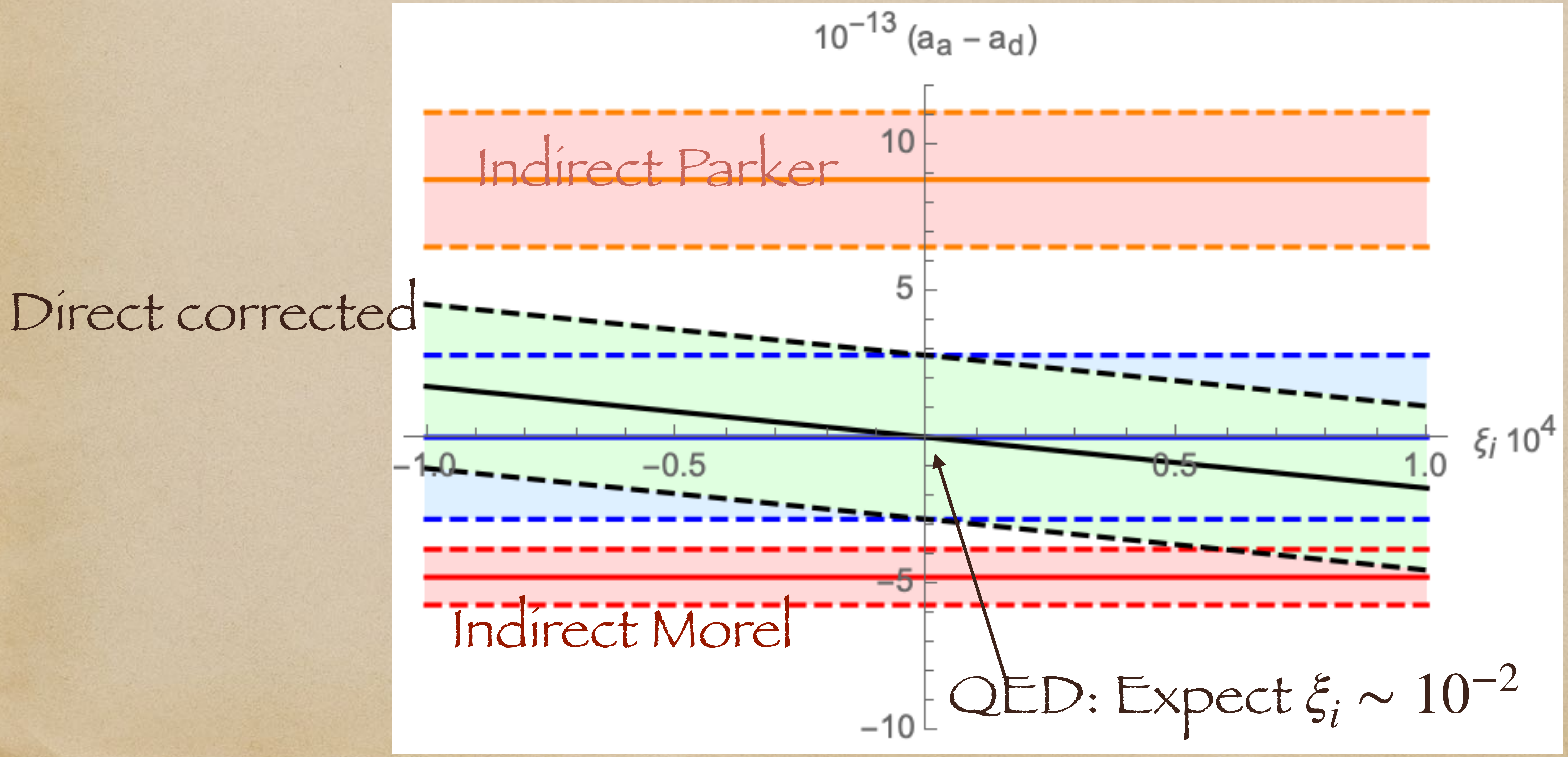

Parity odd benchmark

$\xi_{\gamma^5\gamma^\mu} \equiv \xi_{\gamma^5 i} \neq 0$ rest = 0 SM: Expect $\xi_{\gamma^5 \ldots} \sim G_F$

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Different story, but …

wins!

- Conclusion

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    - Interesting energy corrections $\sim \alpha \cdot \delta_c^2$
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always wins

Thats life!

Some propaganda …

Some propaganda

Outreach: Joint effort, FAKT, HEPHY,

Koch; TU-Vienna

Backup

- Corrections in strong field background

Comparison, direct and indirect:

Parity odd benchmark

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rest = 0