

Some propaganda

**Strings**  
Vienna 2022  
July 18-22

**Main Organizers:**  
Stefan Fredenhagen + Daniel Grumiller  
+ local organizing committee + international  
advisory committee + scientific program committee

Outreach: Joint effort, FAKT, HEPHY,

**Wiener String Quintett**  
Eine öffentliche Vortragsreihe zu Raum,  
Zeit, Quanten und Teilchen

<b>String&amp;Mathe</b> Volker Schomerus 17.03.2022 19:00h TUforMath Boltzmannngasse 5, 1090 Wien	<b>Dark Matter</b> Karoline Schäffner 14.04.2022 19:00h Hephy@ÖAW Nikolsdorfer Gasse 18, 1050 Wien	<b>Unified Theory</b> Mr. Pint 12.05.2022 19:00h Pint of Science Teilnehmende Bars in der ganzen Stadt	<b>Black holes</b> Daniel Grumiller 26.05.2022 19:00 U Münze Österreich Am Heumarkt 1, 1030 Wien	<b>Strings&amp;Scientific Methods</b> Richard Dawid 12.06.2022 19:00h Wiener Vorlesungen Friedrich-Schmidl- Platz 5, 1052 Wien
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Koch; TU-Vienna

Corrections for direct observation  
of electron  $g$  factor

Benjamin Koch

TU Vienna

In collaboration with F. Asenjo and S. Hojman

Joint Annual Meeting of the  
**AUSTRIAN PHYSICAL SOCIETY**  
**SWISS PHYSICAL SOCIETY**

**30 August - 3 September 2021,**  
**Universität Innsbruck**

## 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:

- Introduction  $g-2$  a successful story of two:



theory

and

experiment



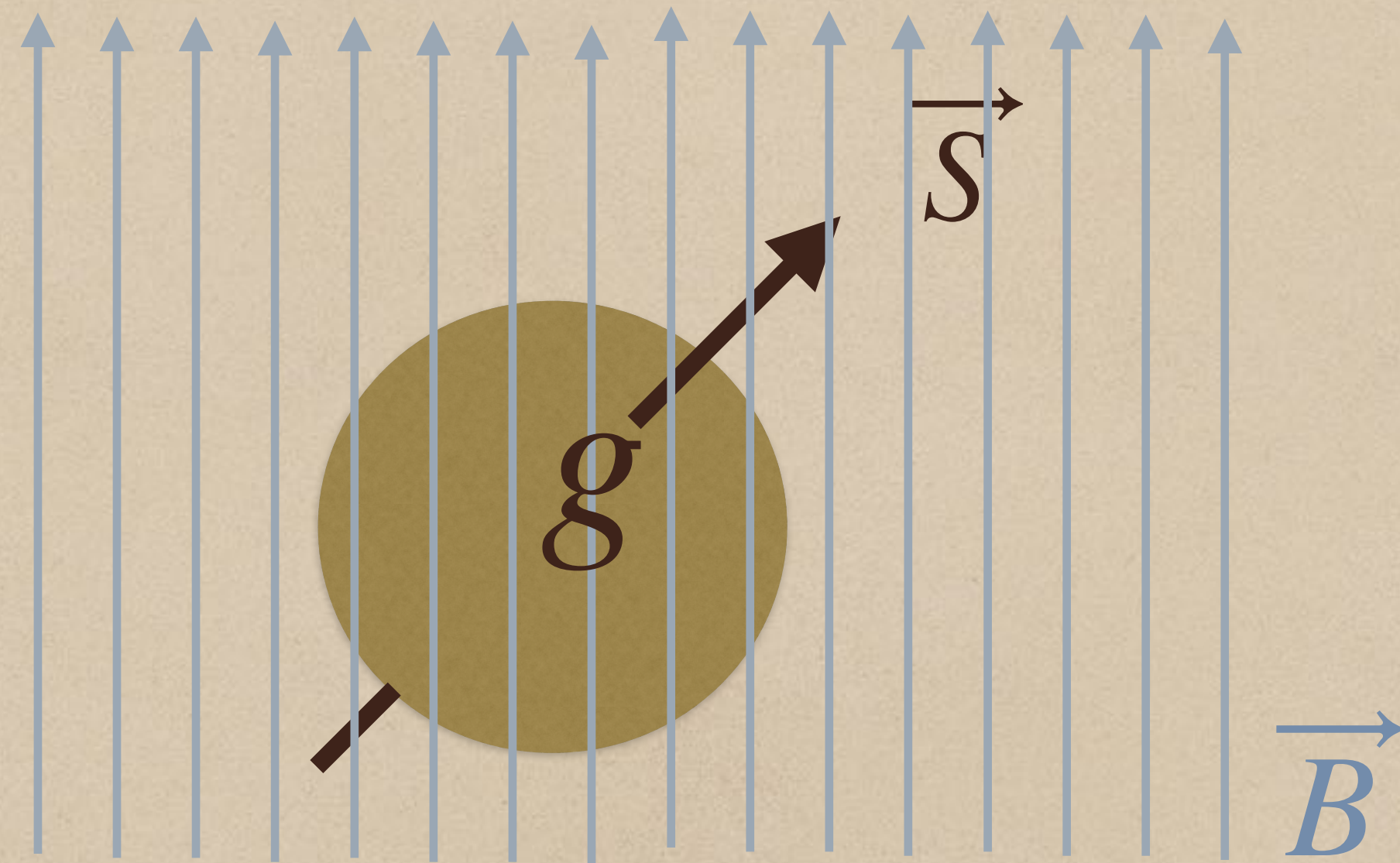
- Introduction  $g-2$  a successful story of two:



theory

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

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theory

$g$

experiment



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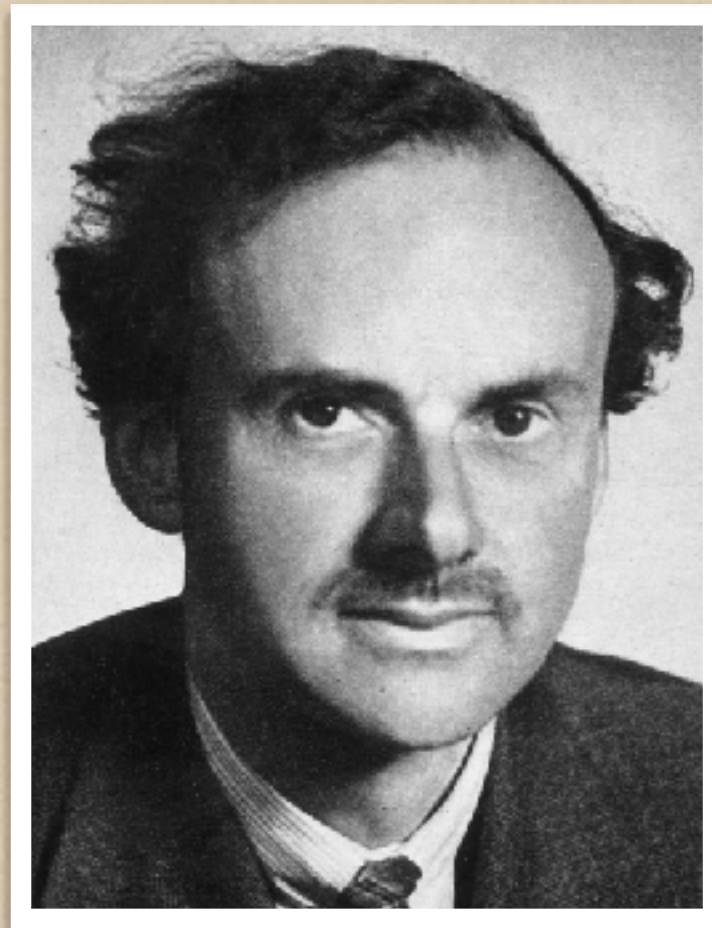
theory

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experiment



Paul Dirac



1928

$$(i\hbar\gamma^\mu D_\mu - m)\psi = 0$$



- Introduction  $g=2$  a successful story of two:



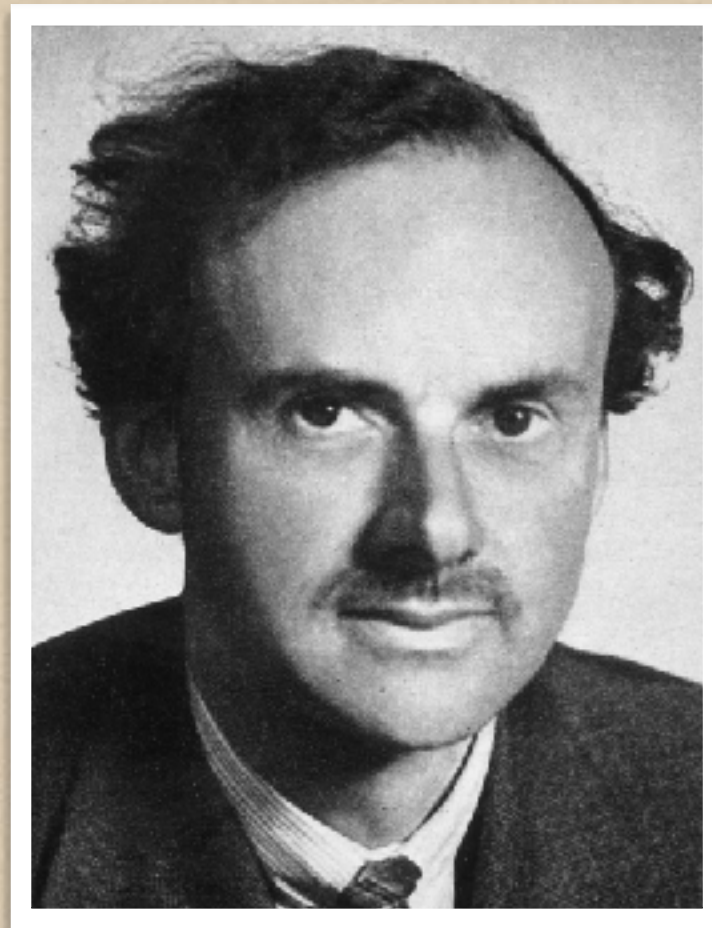
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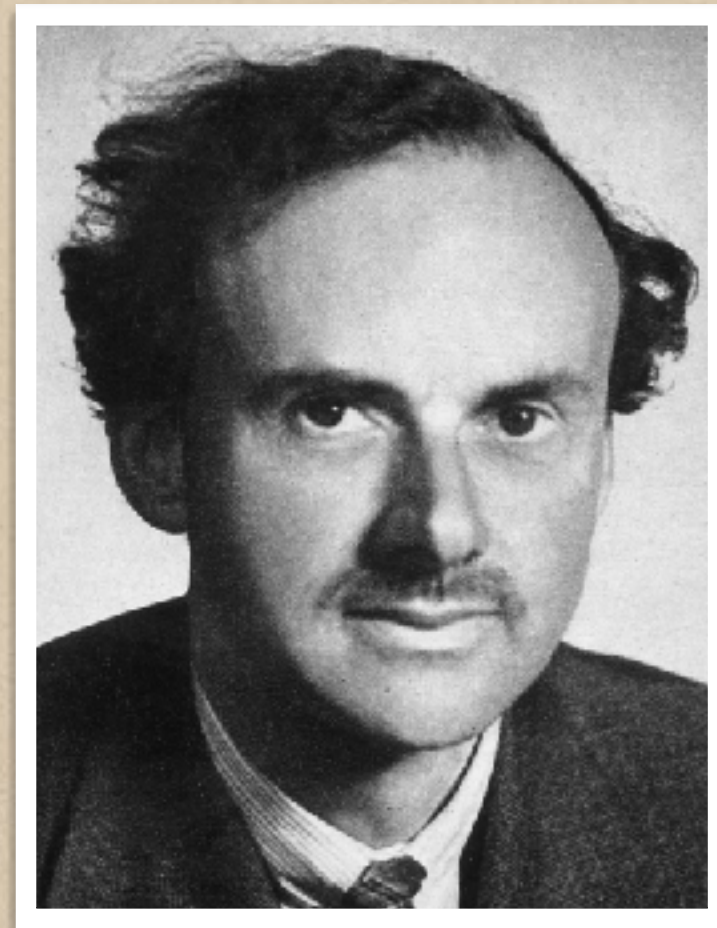
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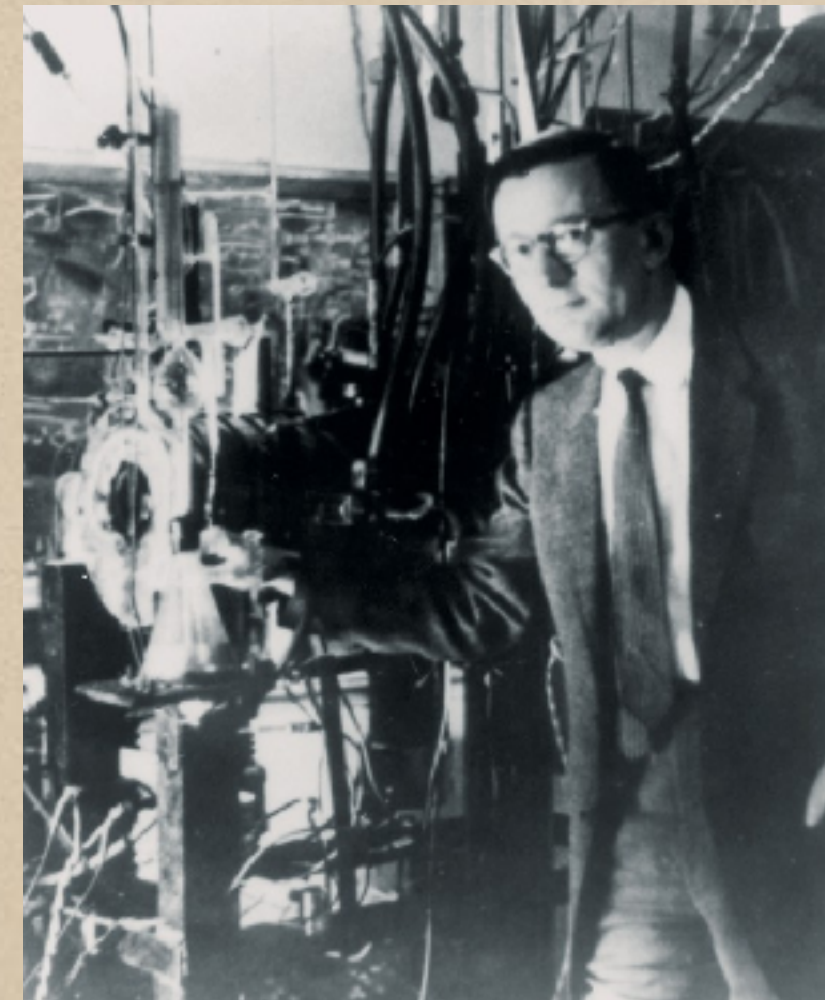
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Polykarp  
Kusch

1947

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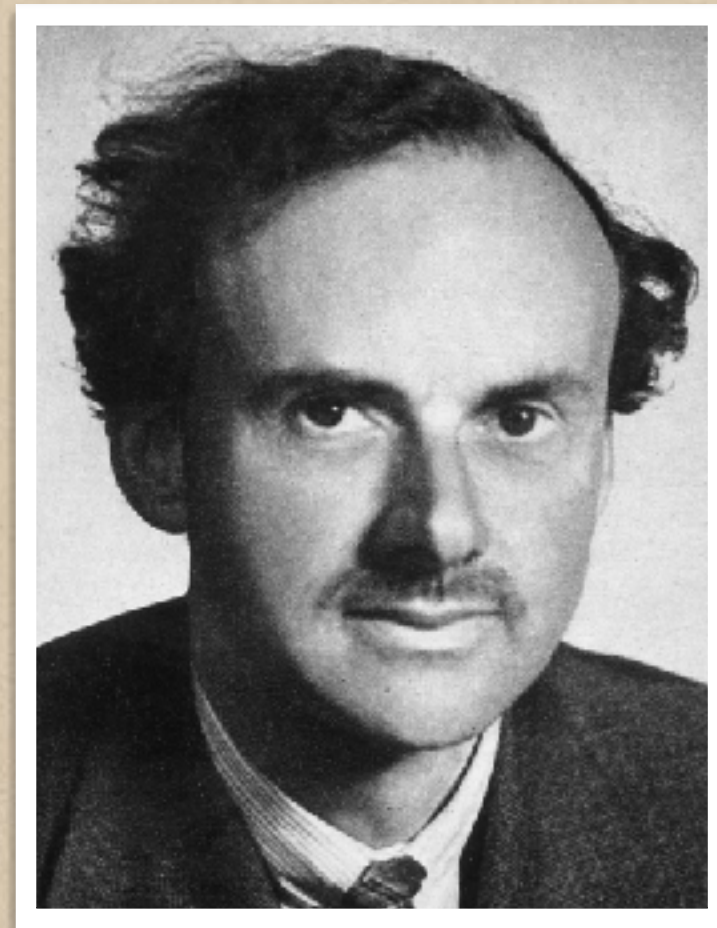
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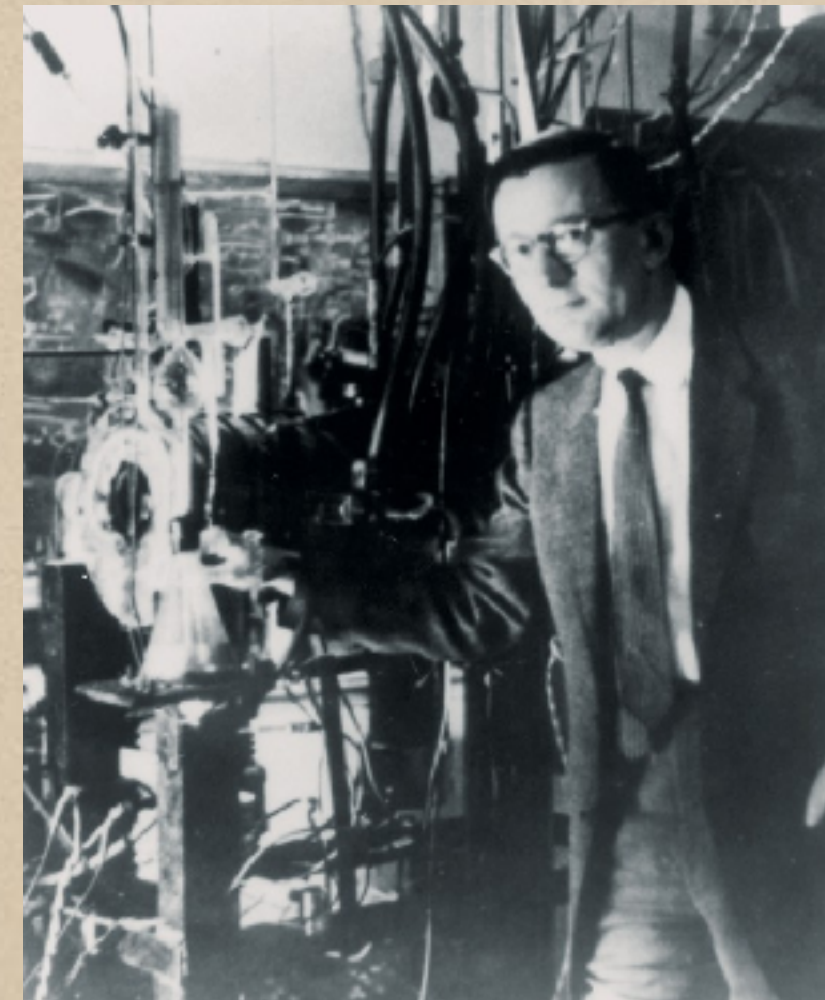


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$$g \neq 2$$



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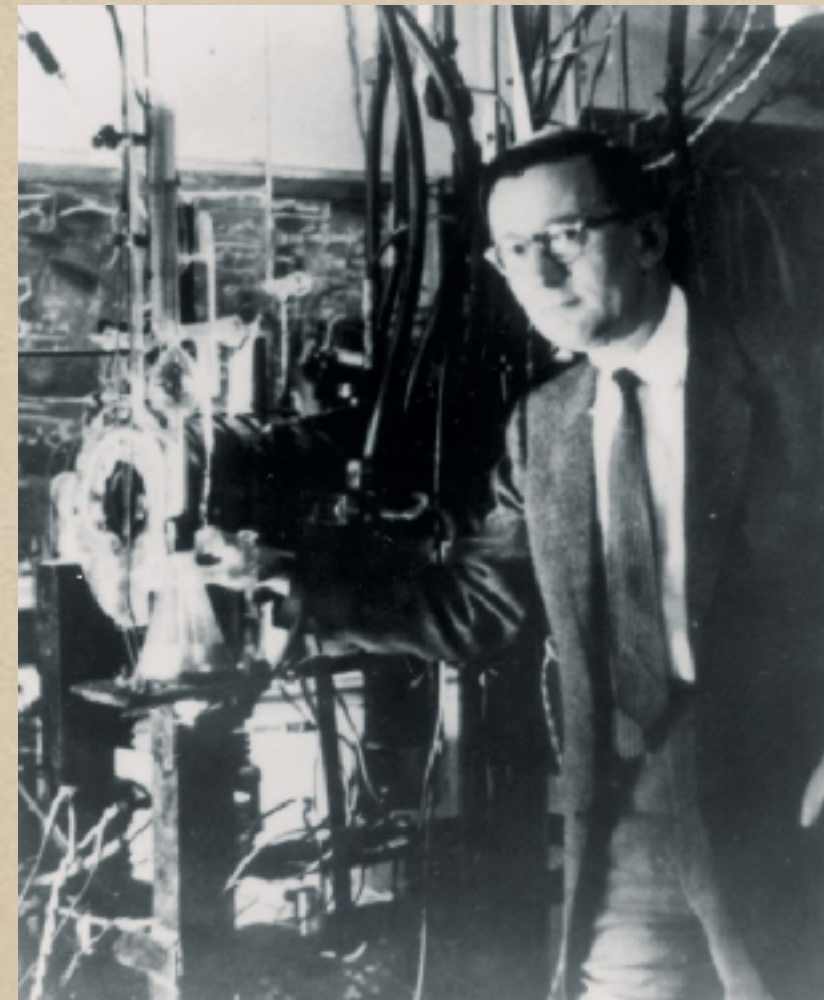
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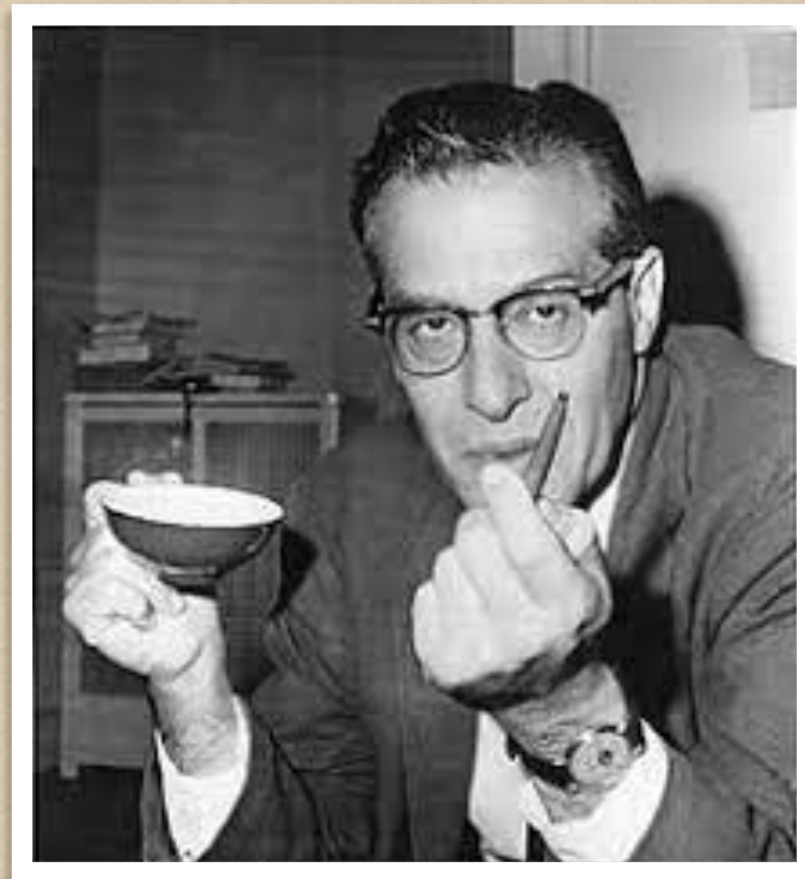
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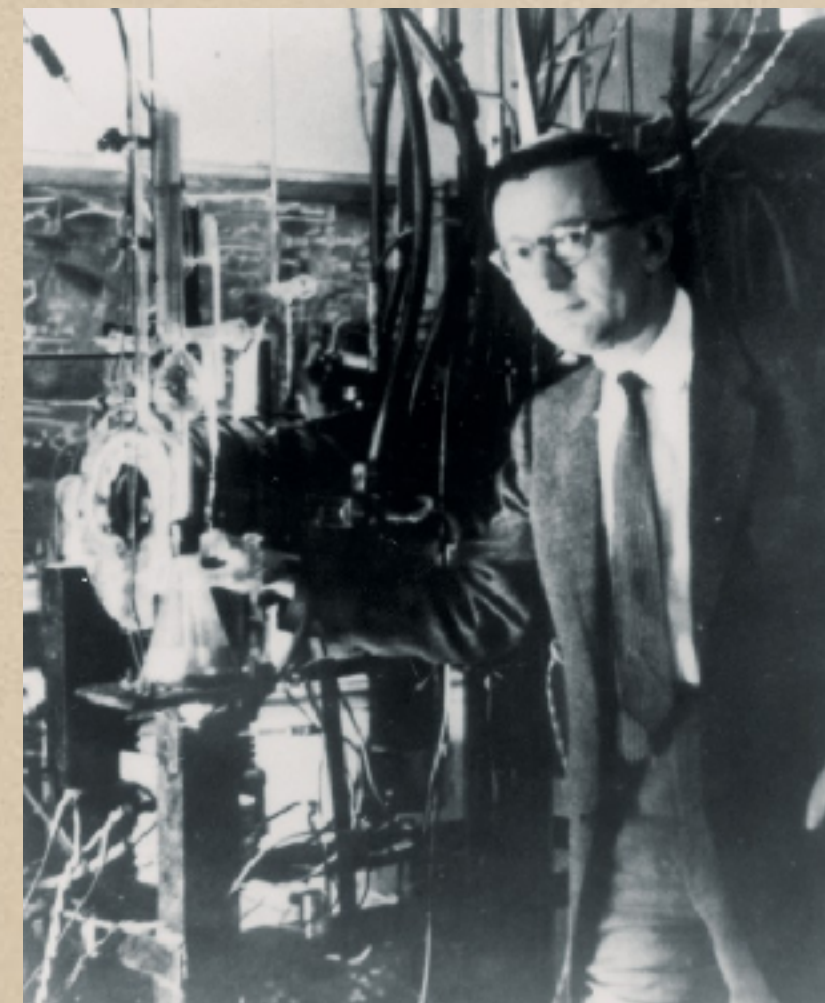
Julian  
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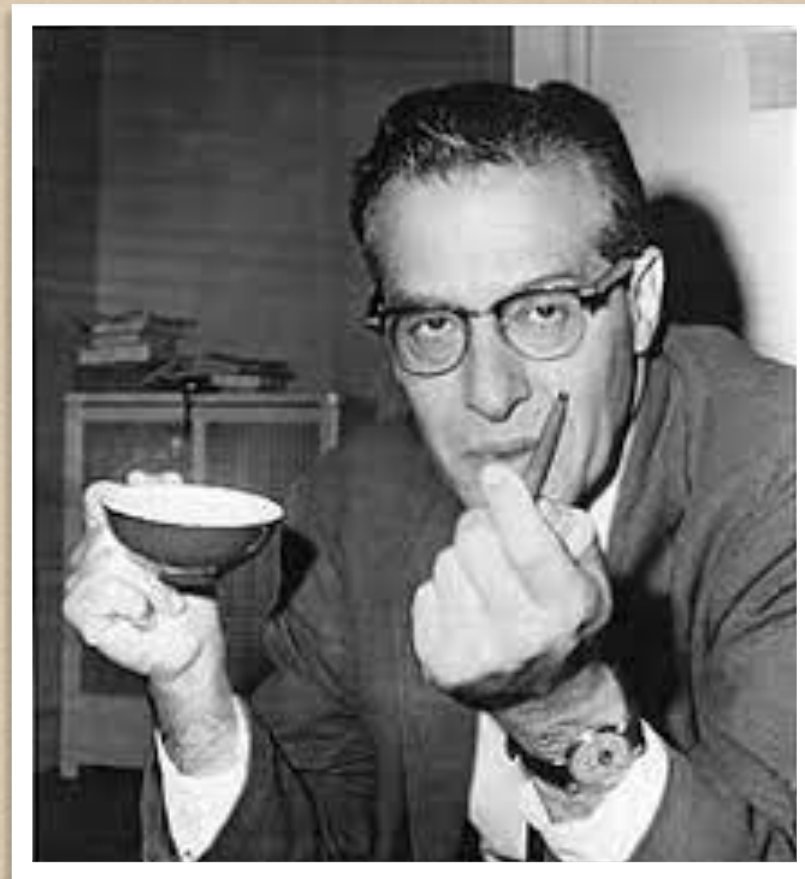
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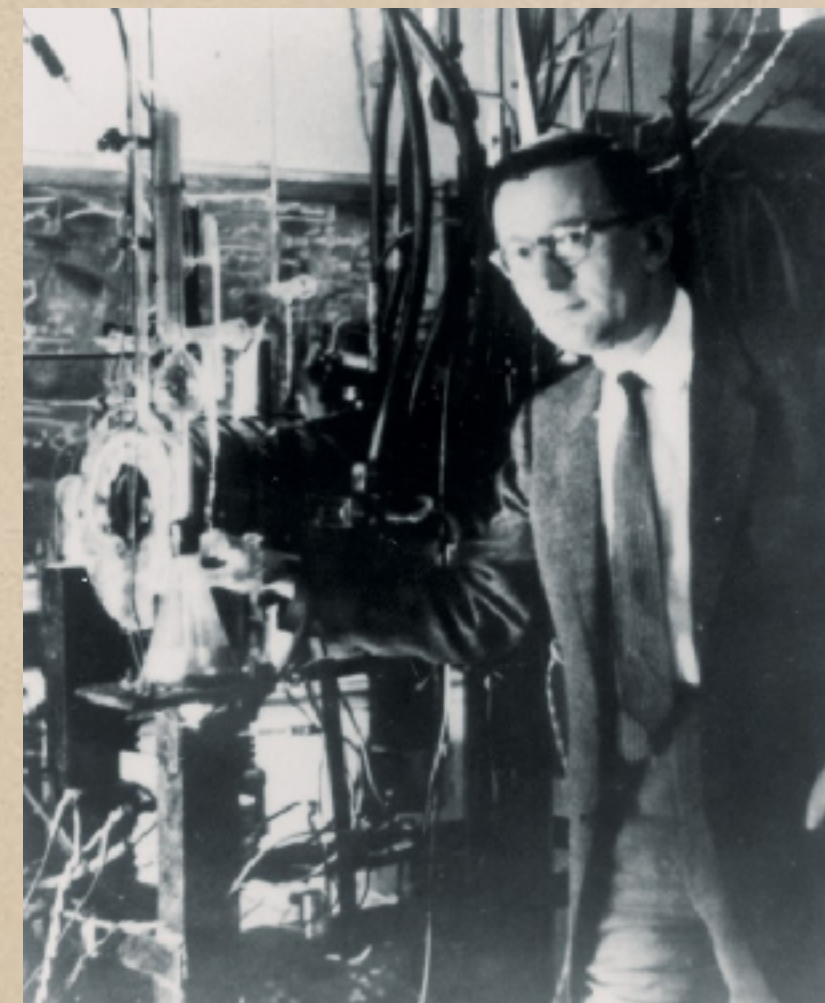


1948

$$g = 2$$

$$g \neq 2$$

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



Polykarp  
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Remiddi



$$g = 2$$

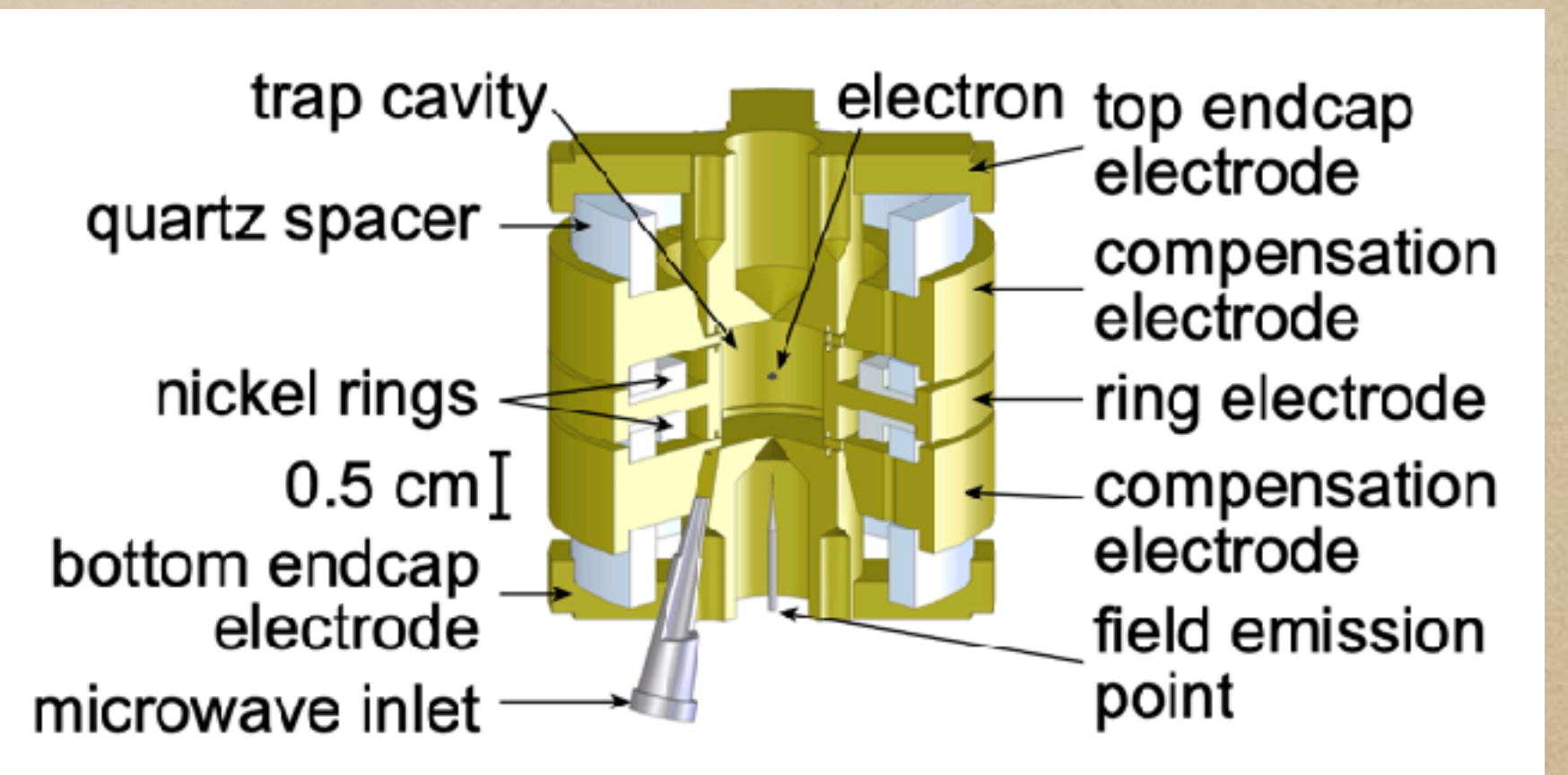
$$g \neq 2$$

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

Gabrielse

...

...



Penning trap

Kinoshita

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

Benjamin Koch; TU-Vienna

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

- Indirect v.s. direct  $g-2$  measurement



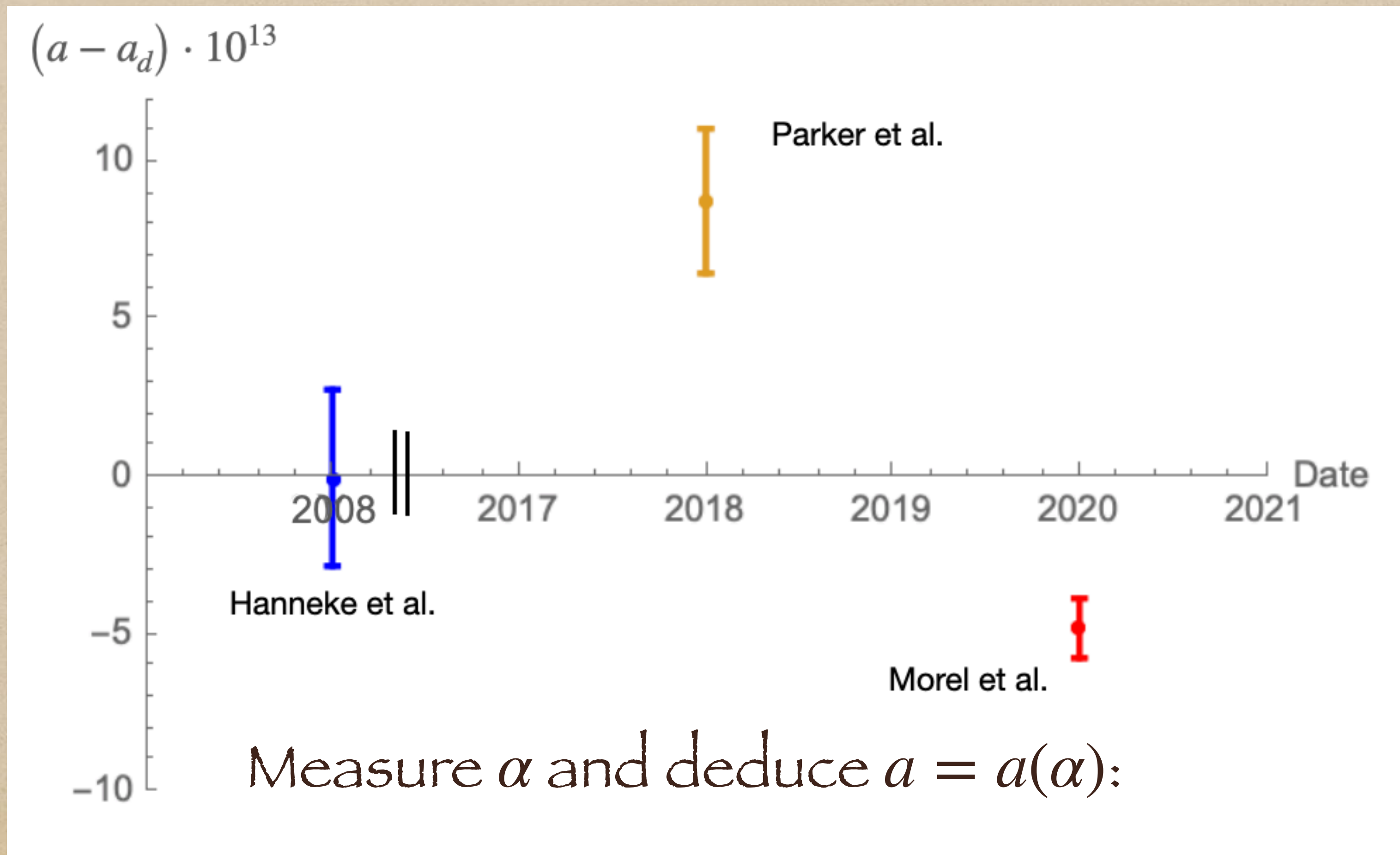
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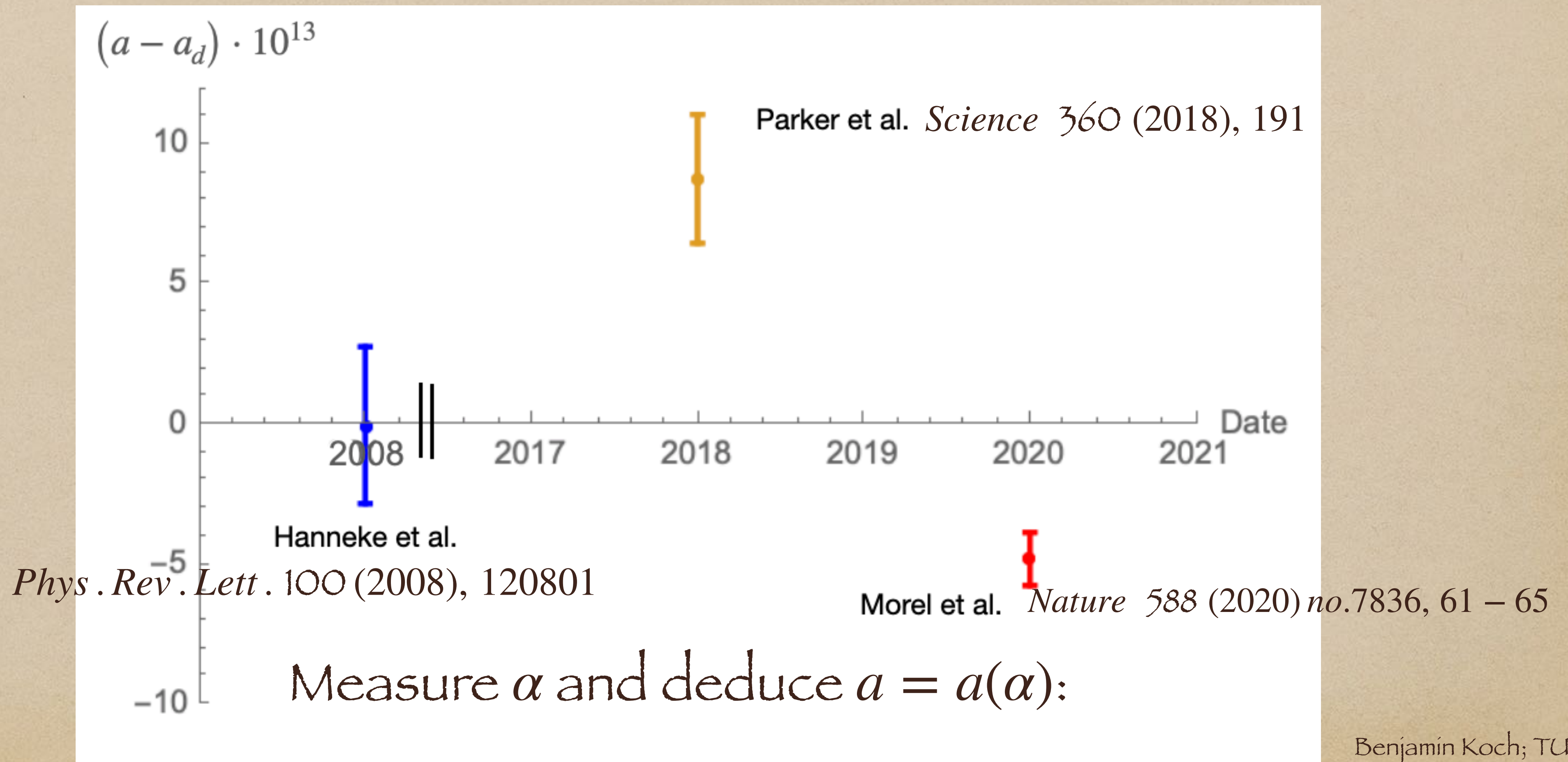
relates two measurable quantities

- Indirect v.s. direct  $g-2$  measurement

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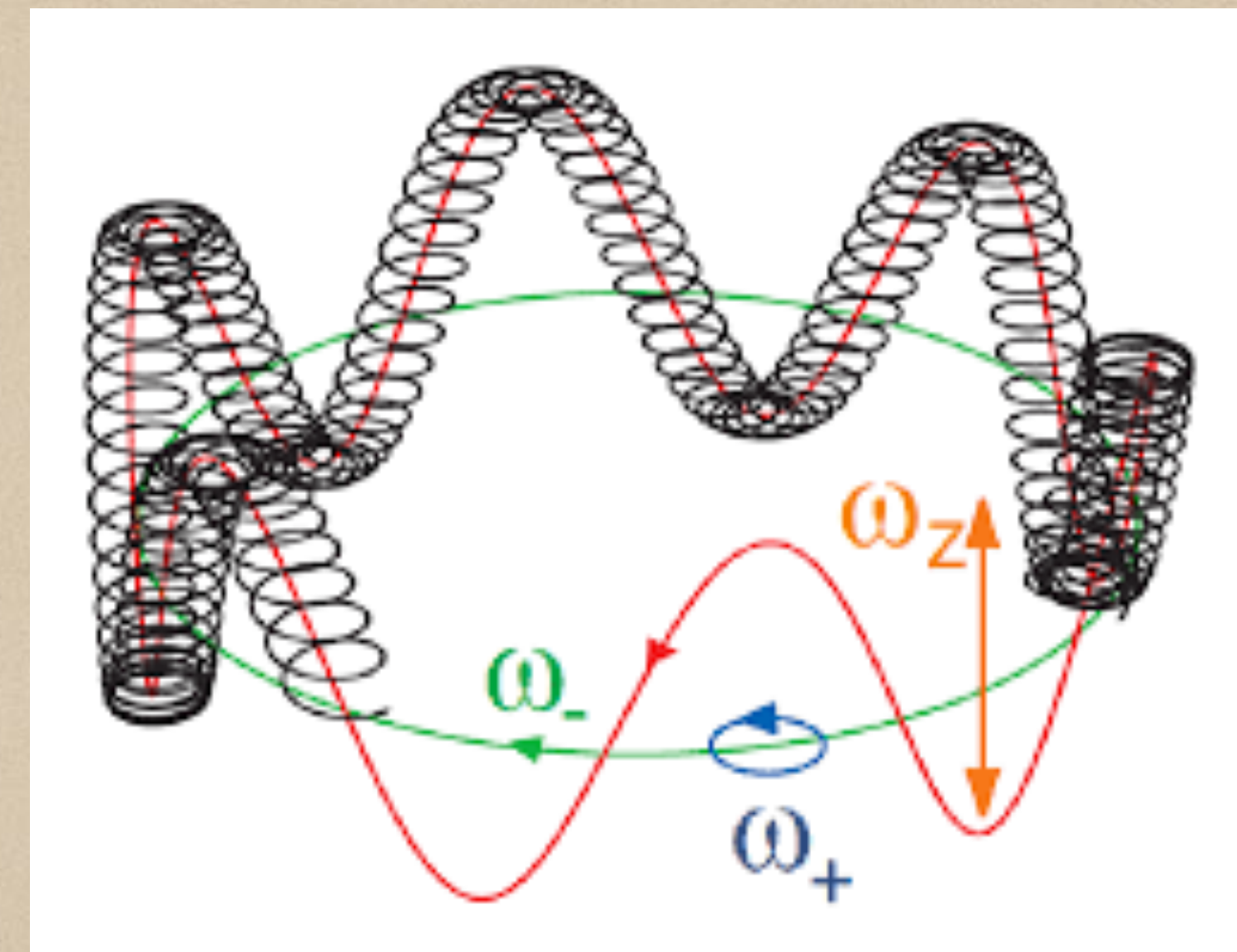
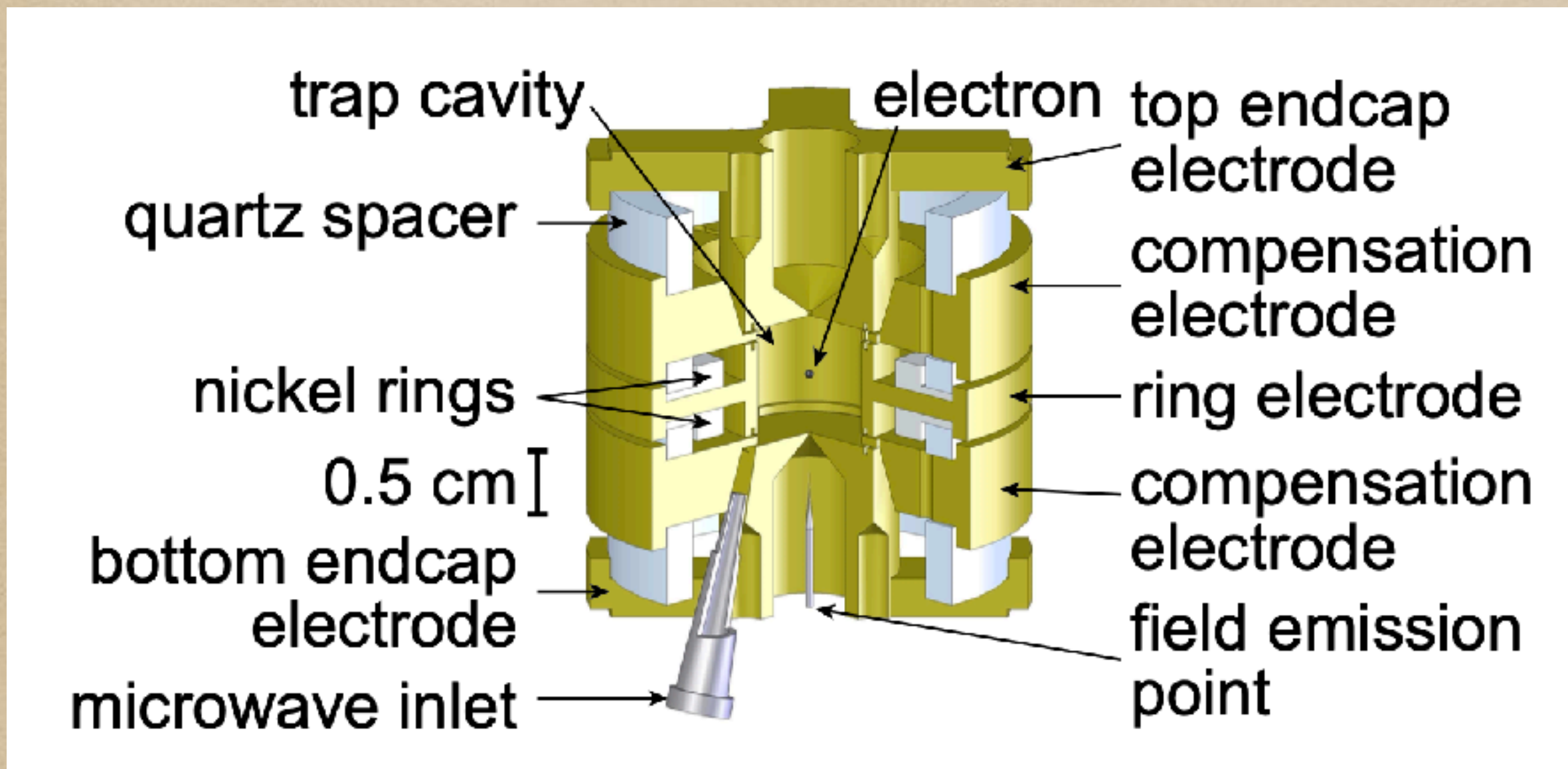


- Indirect v.s. direct  $g-2$  measurement



- Direct  $g-2$  measurement

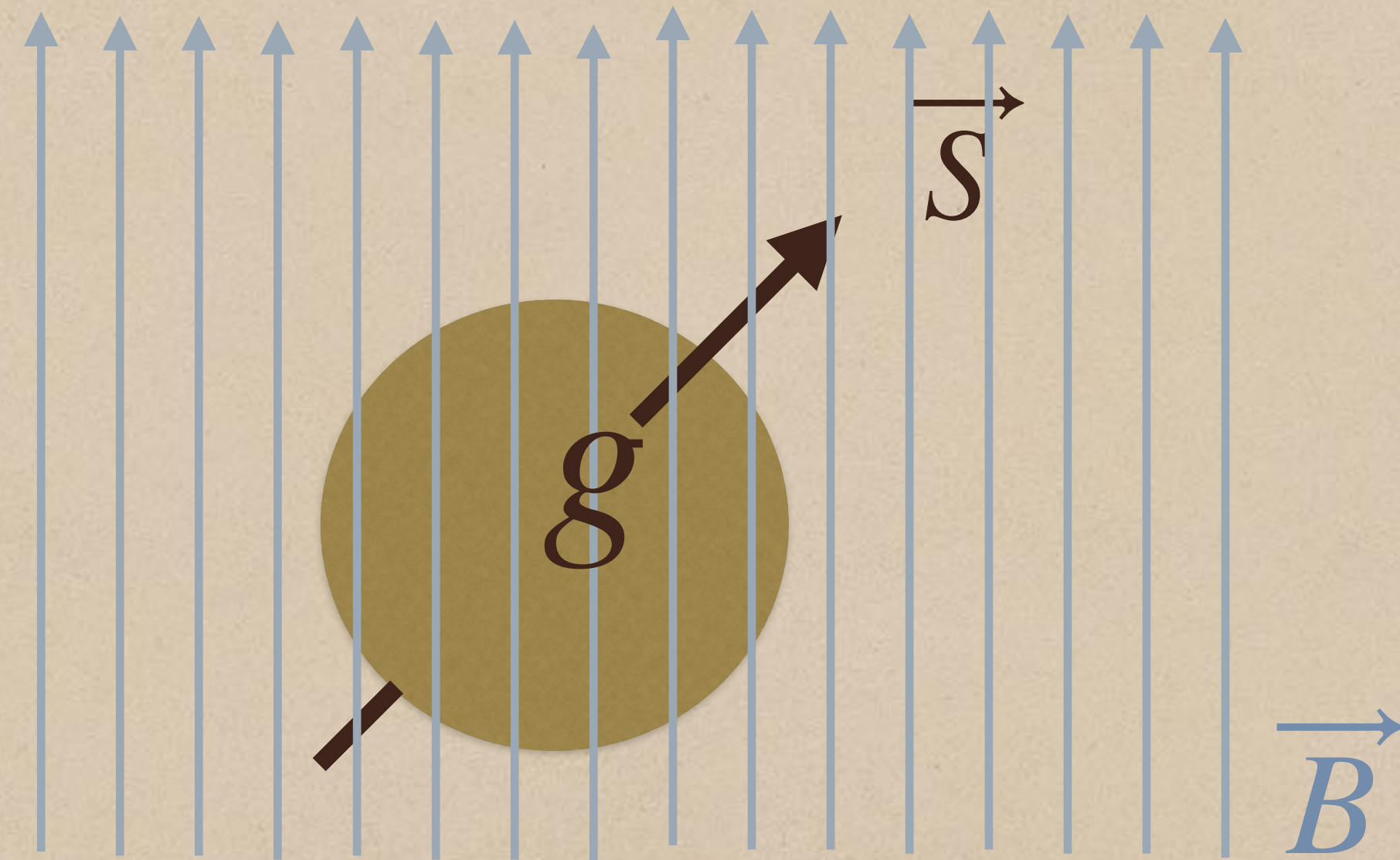
Penning trap



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"

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

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

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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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## Two combined expansions!

- Description in effective field theory

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Loop expansion



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Background field expansion

- Two combined expansions

Loop expansion

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Background field expansion

$$\delta_c \equiv \frac{h\nu_c}{mc^2} \sim 10^{-9} \sim \epsilon^4$$

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What's next?



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could be  
observable



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$$\delta_c^3 \sim \epsilon^{12}$$

future  
prospect

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- APS/SPS poll:

We answer this question in  
EFT approach

- Corrections in strong field background

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

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

- Corrections in strong field background



- Corrections in strong field background

Lorentz type

1

$\gamma^\mu$

$\sigma^{\mu\nu}$

$\gamma^5 \gamma^\mu$

$\gamma^5$

- Corrections in strong field background

Lorentz type

$\Delta\mathcal{L}$

1

$\gamma^\mu$

$\sigma^{\mu\nu}$

$\gamma^5\gamma^\mu$

$\gamma^5$

- Corrections in strong field background

Lorentz type

$\Delta\mathcal{L}$

1

$$\frac{\xi_{1,FF}}{m^3 c^6} \bar{\psi} F_{\mu\nu} F^{\mu\nu} \psi$$

$$\gamma^\mu \left\{ \frac{\xi_{\gamma,DF}}{m^2 c^4} \bar{\psi} D_\alpha \gamma^\beta F_\beta^\alpha \psi, \frac{\xi_{\gamma,DFF1}}{m^4 c^8} \bar{\psi} D_\alpha \gamma^\alpha F_{\mu\nu} F^{\mu\nu} \psi, \frac{\xi_{\gamma,DFF2}}{m^4 c^8} \bar{\psi} D_\alpha \gamma^\beta F_{\beta\nu} F^{\alpha\nu} \psi \right\}$$

$$\sigma^{\mu\nu} \left\{ \frac{\xi_{\sigma,FFF1}}{m^5 c^{10}} \bar{\psi} \sigma^{\mu\nu} F_{\mu\nu} F_{\alpha\beta} F^{\alpha\beta} \psi, \frac{\xi_{\sigma,FFF2}}{m^5 c^{10}} \bar{\psi} \sigma^{\mu\nu} F_{\mu\alpha} F_{\nu\beta} F^{\alpha\beta} \psi \right\}$$

$$\gamma^5 \gamma^\mu \left\{ mc^2 \xi_{\gamma^5 \gamma^\mu} \bar{\psi} \gamma^5 \gamma^\mu D_\mu \psi, \frac{\xi_{\gamma^5 \gamma^\mu FF}}{m^3 c^6} \bar{\psi} \gamma^5 \gamma^\alpha D_\alpha F^{\mu\nu} F_{\mu\nu} \psi \right\}$$

$$\gamma^5 \left\{ mc^2 \xi_{\gamma^5} \bar{\psi} \gamma^5 \psi, \frac{\xi_{\gamma^5 FF}}{m^3 c^6} \bar{\psi} \gamma^5 F^{\mu\nu} F_{\mu\nu} \psi \right\}$$

- Corrections in strong field background

Lorentz type

$\Delta \mathcal{L}$

$$\Delta E_n^\pm \approx \langle \psi_n^\pm | \gamma^0 \Delta \mathcal{L} | \psi_n^\pm \rangle$$

1

$$\frac{\xi_{1,FF}}{m^3 c^6} \bar{\psi} F_{\mu\nu} F^{\mu\nu} \psi$$

$$\gamma^\mu \left\{ \frac{\xi_{\gamma,DF}}{m^2 c^4} \bar{\psi} D_\alpha \gamma^\beta F_\beta^\alpha \psi, \frac{\xi_{\gamma,DF1}}{m^4 c^8} \bar{\psi} D_\alpha \gamma^\alpha F_{\mu\nu} F^{\mu\nu} \psi, \frac{\xi_{\gamma,DF2}}{m^4 c^8} \bar{\psi} D_\alpha \gamma^\beta F_{\beta\nu} F^{\alpha\nu} \psi \right\}$$

$$\sigma^{\mu\nu} \left\{ \frac{\xi_{\sigma,FFF1}}{m^5 c^{10}} \bar{\psi} \sigma^{\mu\nu} F_{\mu\nu} F_{\alpha\beta} F^{\alpha\beta} \psi, \frac{\xi_{\sigma,FFF2}}{m^5 c^{10}} \bar{\psi} \sigma^{\mu\nu} F_{\mu\alpha} F_{\nu\beta} F^{\alpha\beta} \psi \right\}$$

$$\gamma^5 \gamma^\mu \left\{ mc^2 \xi_{\gamma^5 \gamma^\mu} \bar{\psi} \gamma^5 \gamma^\mu D_\mu \psi, \frac{\xi_{\gamma^5 \gamma^\mu FF}}{m^3 c^6} \bar{\psi} \gamma^5 \gamma^\alpha D_\alpha F^{\mu\nu} F_{\mu\nu} \psi \right\}$$

$$\gamma^5 \left\{ mc^2 \xi_{\gamma^5} \bar{\psi} \gamma^5 \psi, \frac{\xi_{\gamma^5 FF}}{m^3 c^6} \bar{\psi} \gamma^5 F^{\mu\nu} F_{\mu\nu} \psi \right\}$$

- Corrections in strong field background

Lorentz type

$\Delta \mathcal{L}$

$$\Delta E_n^\pm \approx \langle \psi_n^\pm | \gamma^0 \Delta \mathcal{L} | \psi_n^\pm \rangle$$

1

$$\frac{\xi_{1,FF}}{m^3 c^6} \bar{\psi} F_{\mu\nu} F^{\mu\nu} \psi$$

$$\xi_{1,FF} \left( -\frac{h^2 \nu_c^2}{mc^2} + \frac{h^3 \nu_c^3 (2n + 1 \pm 1)}{m^2 c^4} \right)$$

$$\gamma^\mu \left\{ \frac{\xi_{\gamma,DF}}{m^2 c^4} \bar{\psi} D_\alpha \gamma^\beta F_\beta^\alpha \psi, \frac{\xi_{\gamma,DFF1}}{m^4 c^8} \bar{\psi} D_\alpha \gamma^\alpha F_{\mu\nu} F^{\mu\nu} \psi, \frac{\xi_{\gamma,DFF2}}{m^4 c^8} \bar{\psi} D_\alpha \gamma^\beta F_{\beta\nu} F^{\alpha\nu} \psi \right\} \left\{ 0, \xi_{\gamma,DFF1} \left( \frac{2h^2 \nu^2}{mc^2} - \frac{h^3 \nu^3 (1 + 2n \pm 1)}{m^2 c^4} \right), -\xi_{\gamma,DFF2} \frac{h^3 \nu^3 (1 + 2n \pm 1)}{m^2 c^4} \right\}$$

$$\sigma^{\mu\nu} \left\{ \frac{\xi_{\sigma,FFF1}}{m^5 c^{10}} \bar{\psi} \sigma^{\mu\nu} F_{\mu\nu} F_{\alpha\beta} F^{\alpha\beta} \psi, \frac{\xi_{\sigma,FFF2}}{m^5 c^{10}} \bar{\psi} \sigma^{\mu\nu} F_{\mu\alpha} F_{\nu\beta} F^{\alpha\beta} \psi \right\} \left\{ 0, \pm \xi_{\sigma,FFF1} \frac{4h^3 \nu^3}{m^2 c^4}, -\pm \xi_{\sigma,FFF2} \frac{2h^3 \nu^3}{m^2 c^4} \right\}$$

$$\gamma^5 \gamma^\mu \left\{ mc^2 \xi_{\gamma^5 \gamma^\mu} \bar{\psi} \gamma^5 \gamma^\mu D_\mu \psi, \frac{\xi_{\gamma^5 \gamma^\mu FF}}{m^3 c^6} \bar{\psi} \gamma^5 \gamma^\alpha D_\alpha F^{\mu\nu} F_{\mu\nu} \psi \right\} \left\{ \xi_{\gamma^5 \gamma^\mu} mc^2 \left( 1 - (1 + 2n \pm 1) \frac{h\nu_c}{2mc^2} \right), \frac{2\xi_{\gamma^5 \gamma^\mu FF} h^2 \nu_c^2}{mc^2} \left( 1 - (1 + 2n \pm 1) \frac{h\nu_c}{2mc^2} \right) \right\}$$

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

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

Parity even benchmark

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No "n", no "±" ⇒ cancels in  $a_d$

"master equation"



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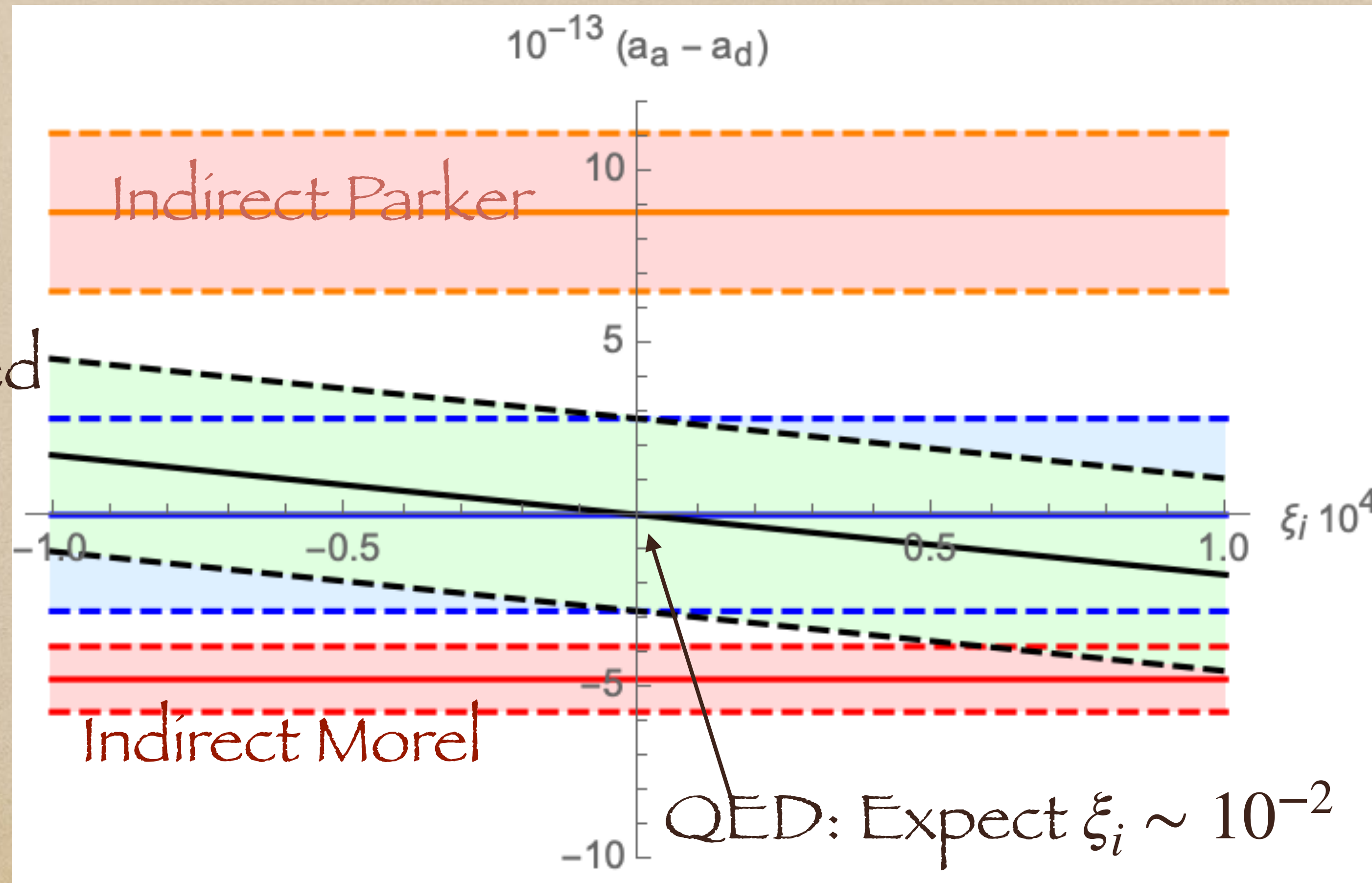
Parity even benchmark

Plot, comparison, direct and indirect:

# Parity even benchmark

Plot, comparison, direct and indirect:

Direct corrected



## Parity odd benchmark

$$\xi_{\gamma^5 \gamma^\mu} \equiv \xi_{\gamma^5 i} \neq 0 \quad \text{rest} = 0$$

SM: Expect  $\xi_{\gamma^5 \dots} \sim G_F$

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Different story, but ...



- Conclusion

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- Interesting energy corrections  $\sim \alpha \cdot \delta_c^2$
- But, cancelations in observable  $a_d$
- Useful relations  $a_d = a_d(a_a, \xi \dots)$  for all sorts of bSM studies

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always wins

Thats life!

Some propaganda ...

Some propaganda

**Strings**  
Vienna 2022  
July 18-22

**Main Organizers:**  
Stefan Fredenhagen + Daniel Grumiller  
+ local organizing committee + international  
advisory committee + scientific program committee

Outreach: Joint effort, FAKT, HEPHY,

**Wiener String Quintett**  
Eine öffentliche Vortragsreihe zu Raum,  
Zeit, Quanten und Teilchen

Topic	Date	Time	Location
String&Mathe	17.03.2022	19:00h	TUforMath Boltzmannngasse 5, 1090 Wien
Dark Matter	14.04.2022	19:00h	Hephy@ÖAW Nikolsdorfer Gasse 18, 1050 Wien
Unified Theory	12.05.2022	19:00h	Mr. Pint Pint of Science Teilnehmende Bars in der ganzen Stadt
Black holes	26.05.2022	19:00 U	Daniel Grumiller Münze Österreich Am Heumarkt 1, 1030 Wien
Strings&Scientific Methods	12.06.2022	19:00h	Richard Dawid Wiener Vorlesungen Friedrich-Schmidl- Platz 5, 1052 Wien

Koch; TU-Vienna

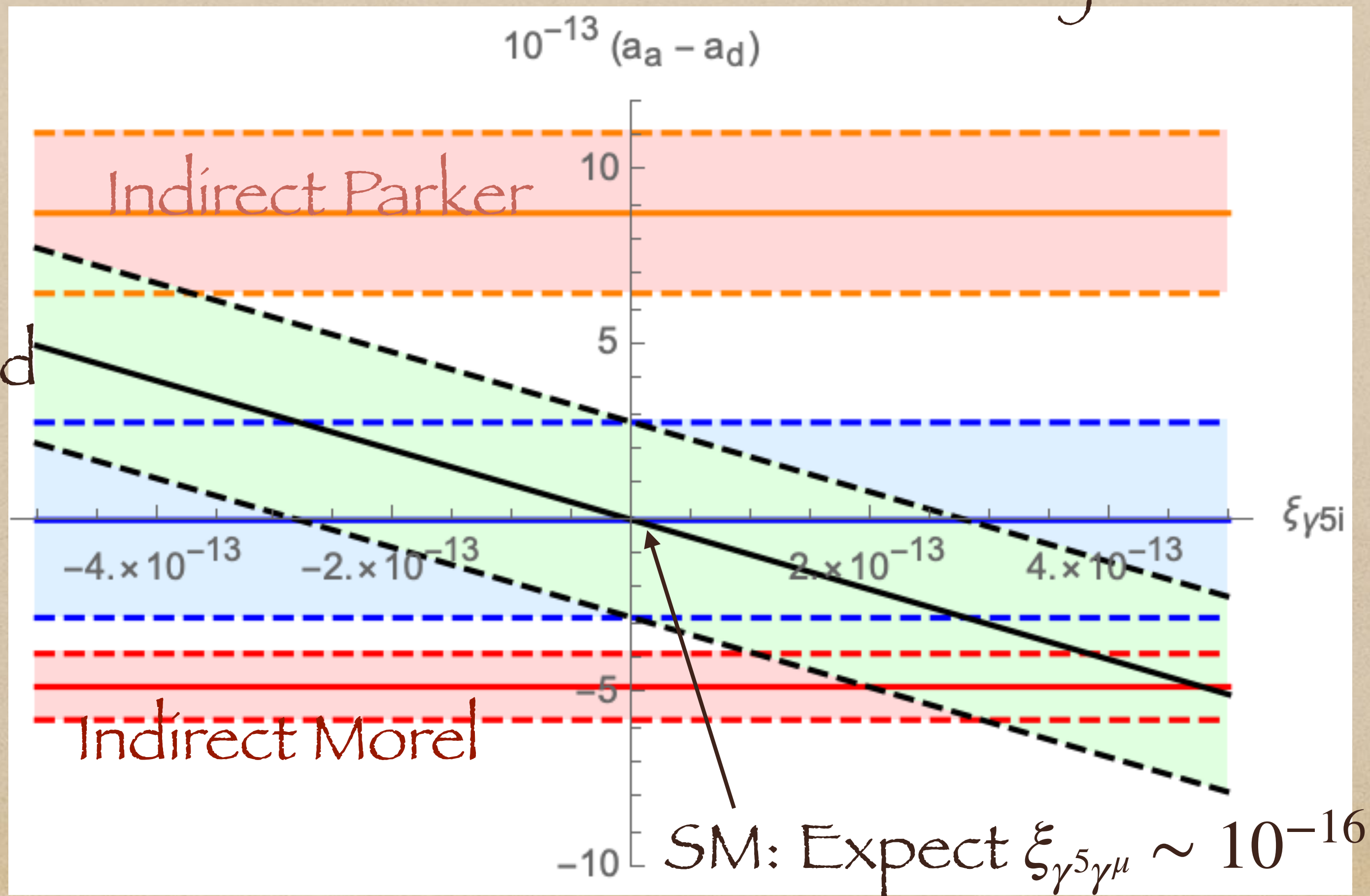
Backup

- Corrections in strong field background

Comparison, direct and indirect:

Parity odd benchmark

Direct corrected



$$\xi_{\gamma^5 \gamma \mu} \equiv \xi_{\gamma^5 i} \neq 0$$

rest = 0