ÖAW AUSTRIAN ACADEMY OF SCIENCES

SMI - STEFAN MEYER INSTITUTE

CPT & Lorentz invariance tests by H & D hyperfine spectroscopy

…and implications for ASACUSA's antihydrogen programme

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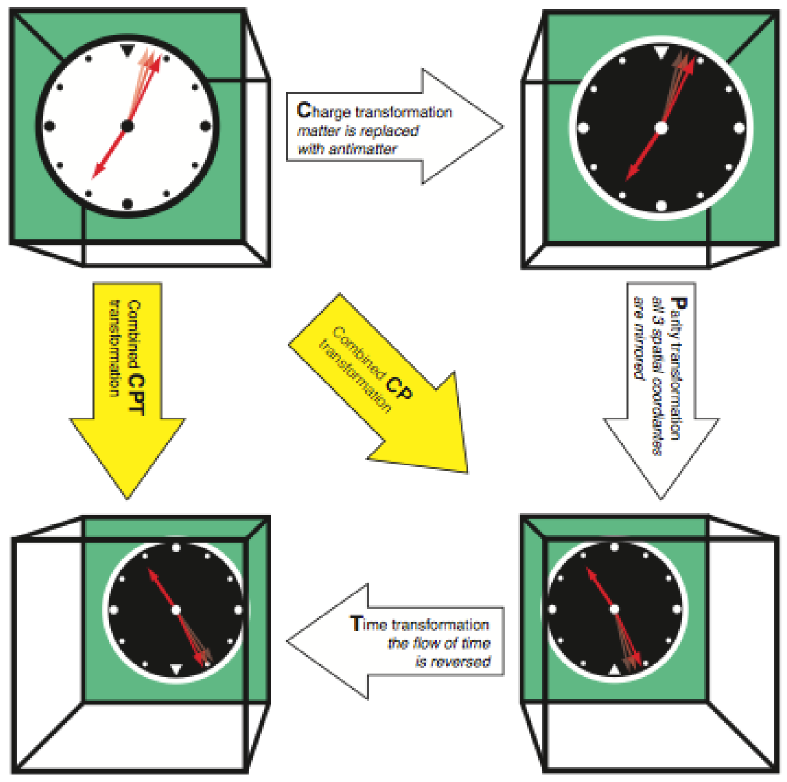
Stefan Meyer Institute

FAKT Workshop 2024: Particle Physics Retreat

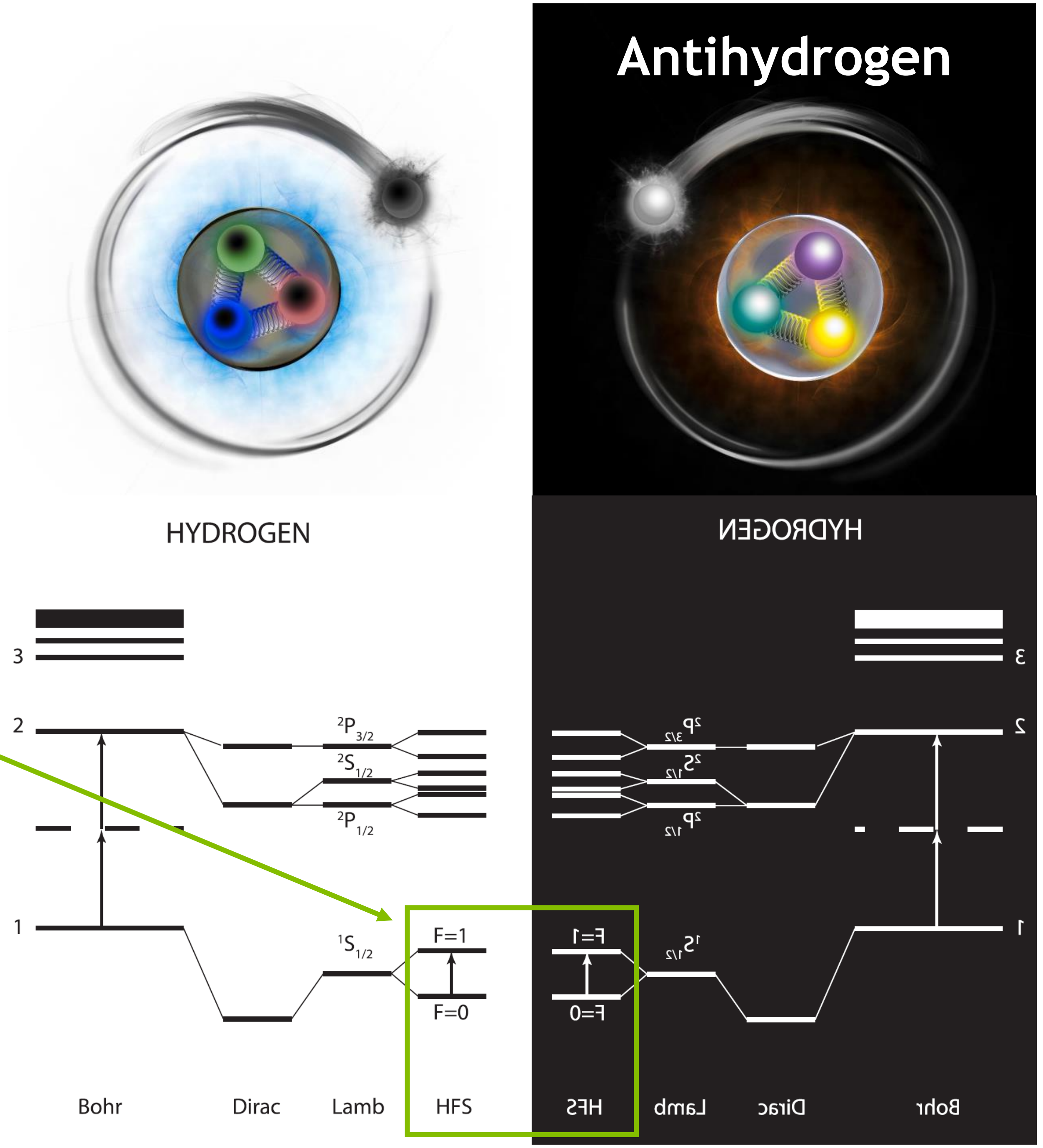
22^{nd} - 23^{rd} Feb. 2024

Motivation

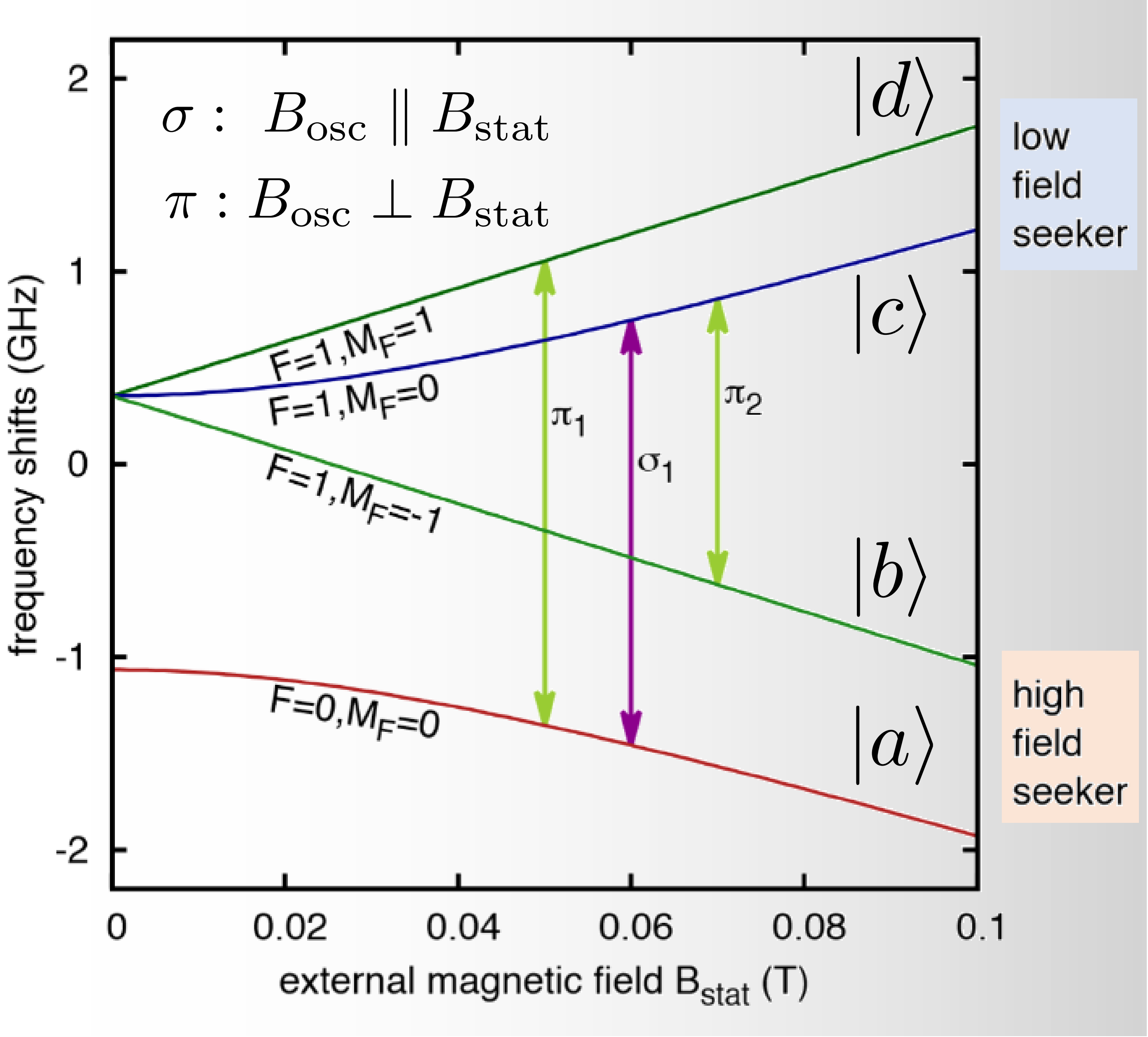
CPT symmetry ⇔ matter-antimatter asymmetry



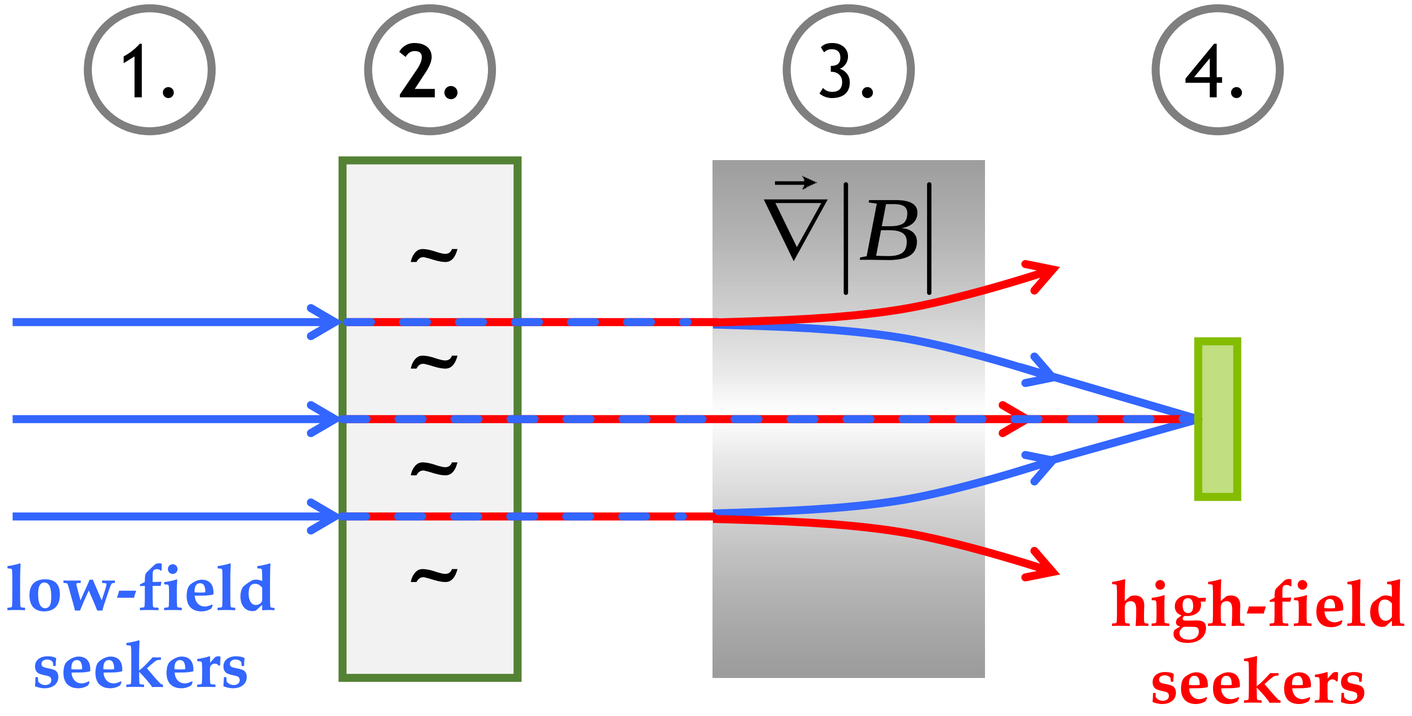
- **Antihydrogen**
  ideal test bench
- **Hyperfine splitting**
  1 420 405 751.768+-0.001 Hz
  highest absolute precision
- **Standard Model Extension**
  sensitivity governed by absolute precision



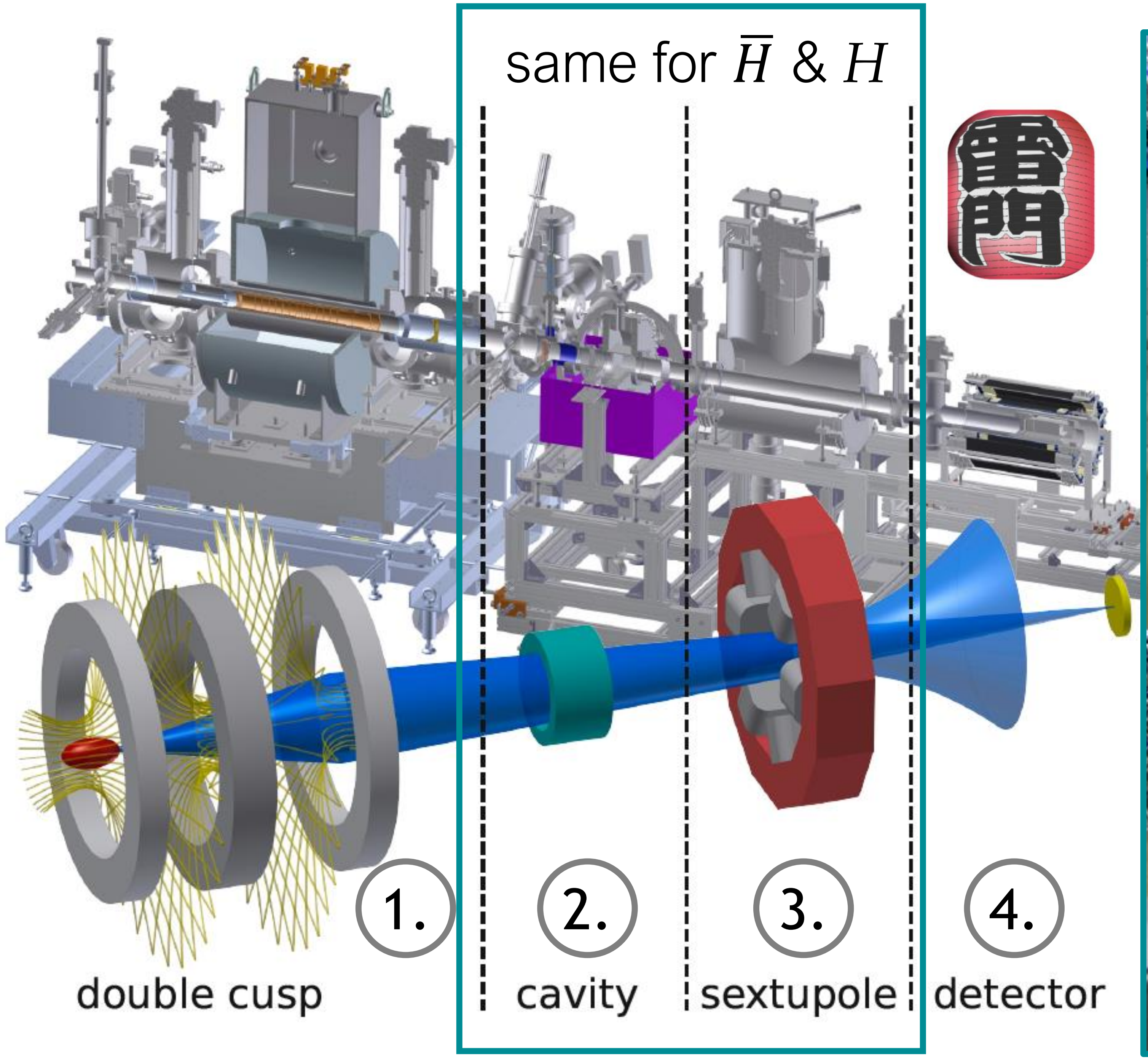
Breit-Rabi Diagram & Rabi Spectroscopy

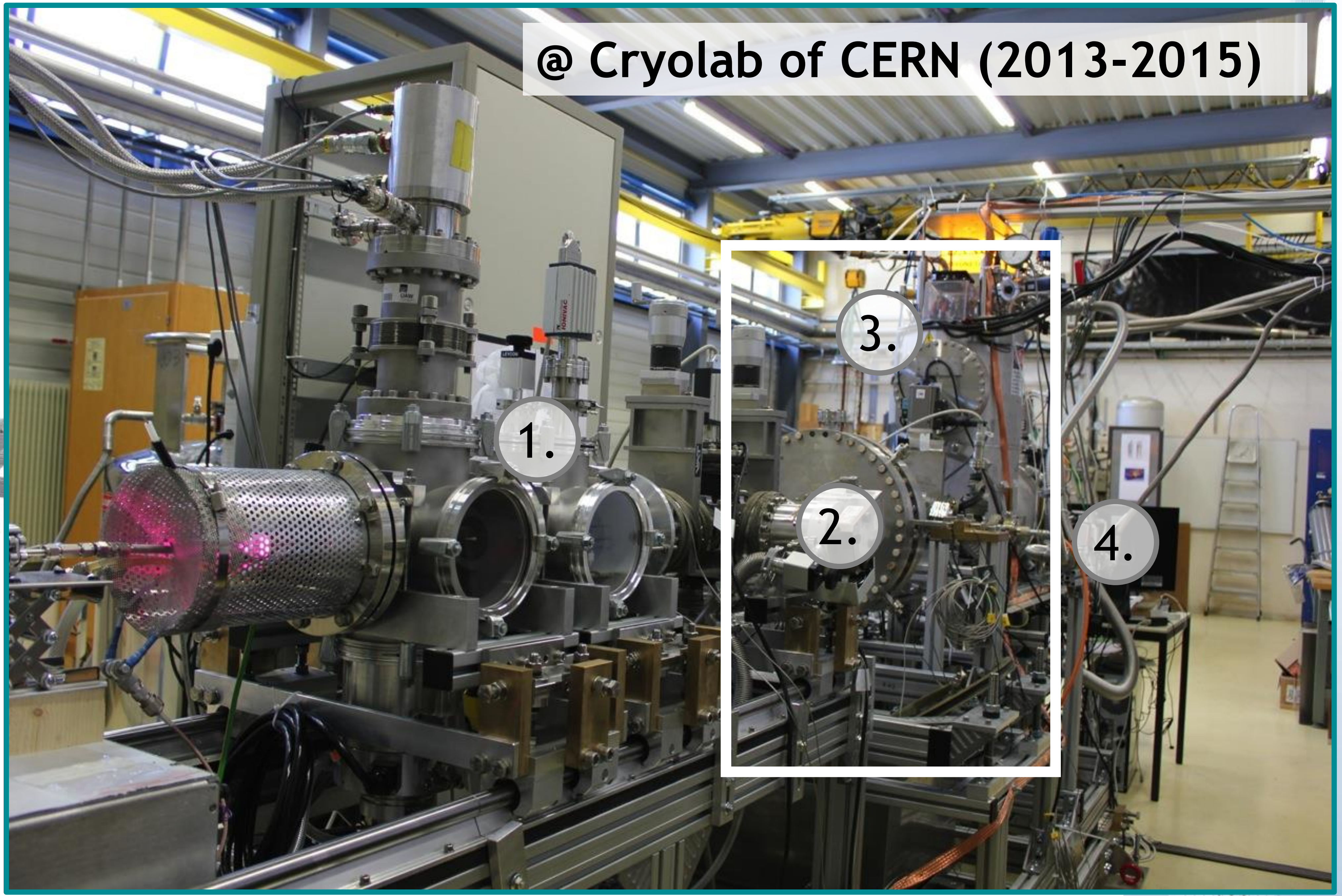


1. polarized beam (low-field seekers)
2. **spin flip drive:**
   osc. B-field ~1.42 GHz & stat. B-field!
3. spin state analysis (Stern-Gerlach effect)
4. detection (count rate drop → spin flip)

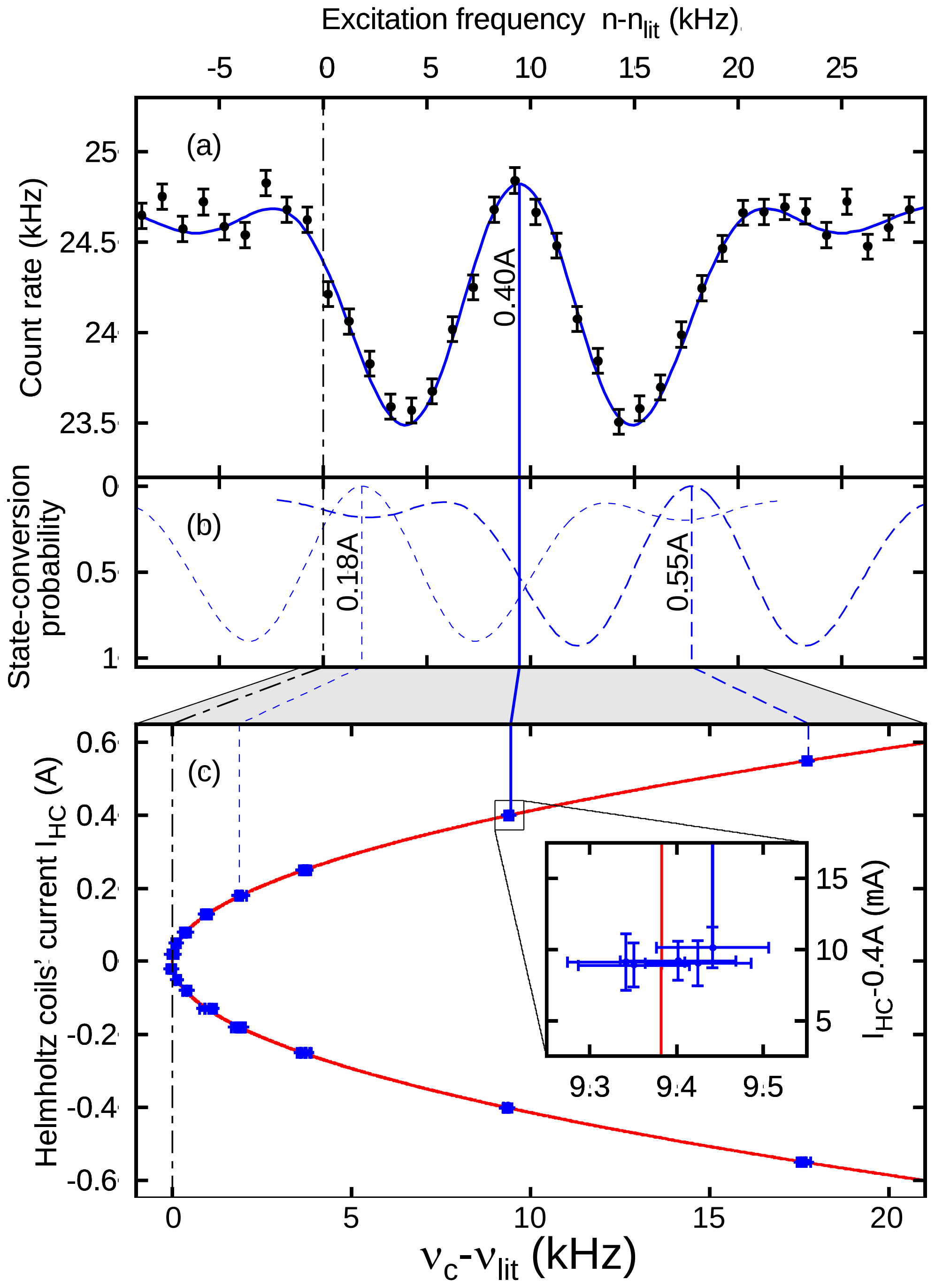


ASACUSA‘s HFS spectrometer





First results: σ transition



ASACUSA *Nat. Commun.* **8**, 15749 (2017).

final result

1 420 405 748.4 (3.4) (1.6) Hz

agrees with literature (maser)

1 420 405 751.768 (0.001) Hz

H. Hellwig *et al.*, *IEEE Trans. Instrum. Meas.* **19**, 200 (1977).
S. G. Karschenboim, *Can. J. Phys.* **78**, 639 (2000).

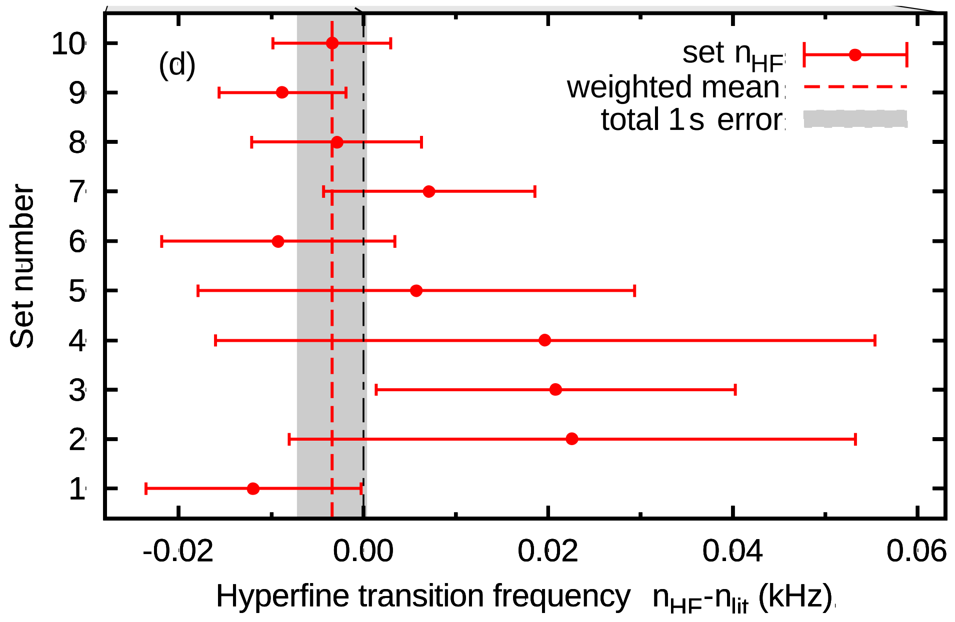
$$\nu_\sigma(B_{stat}) = \sqrt{\nu_{HF}^2 + \left(\frac{\mu_+}{h}\right)^2 B_{stat}^2}$$

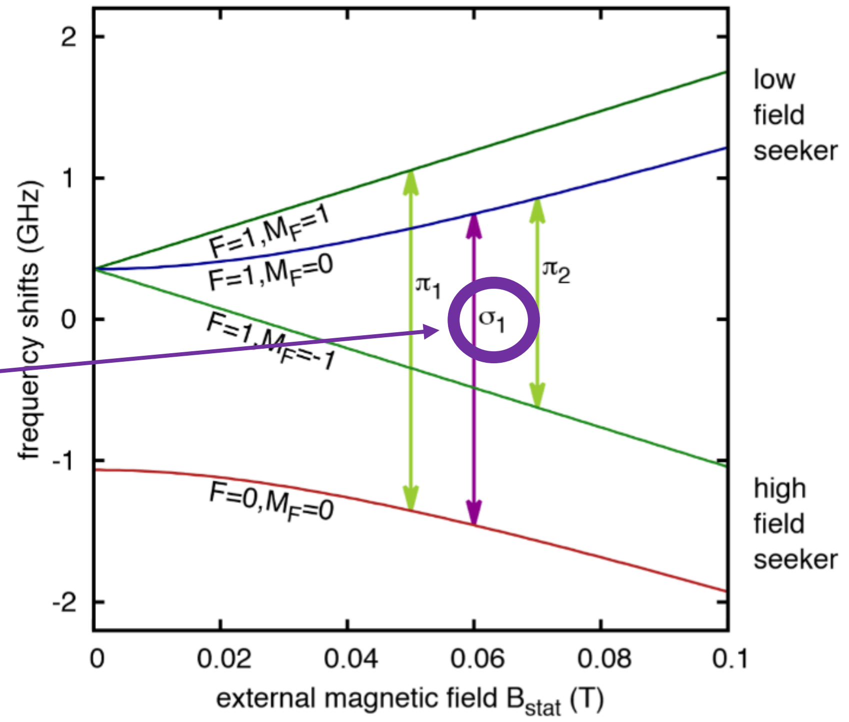
$$\mu_+ = |g_e|\mu_B + g_p\mu_N$$

σ

no syst. uncertainty on ~ppb level

⇔ anti-H 1st stage goal: ppm





SME: Standard Model Extension

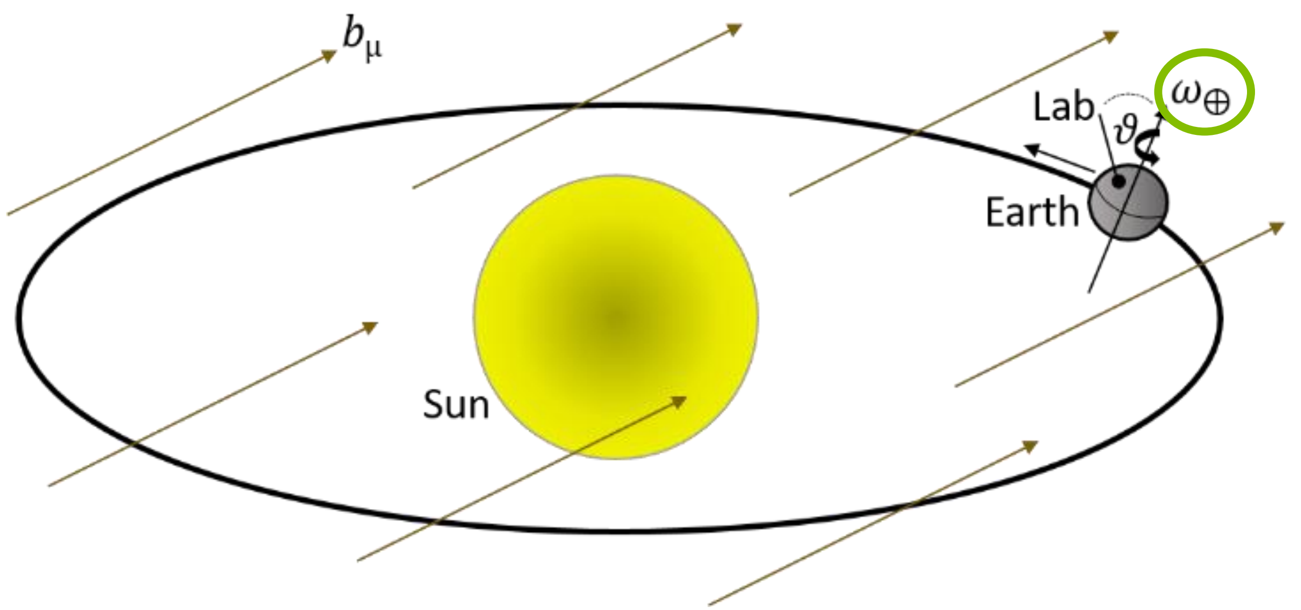
- Systematic framework for violation searches
- Coefficients for violating operators

D Colladay and V A Kostelecky, *PRD* **55** 6760 (1997).
V A Kostelecky and M Mewes, *PRD* **80** 015020 (2009).

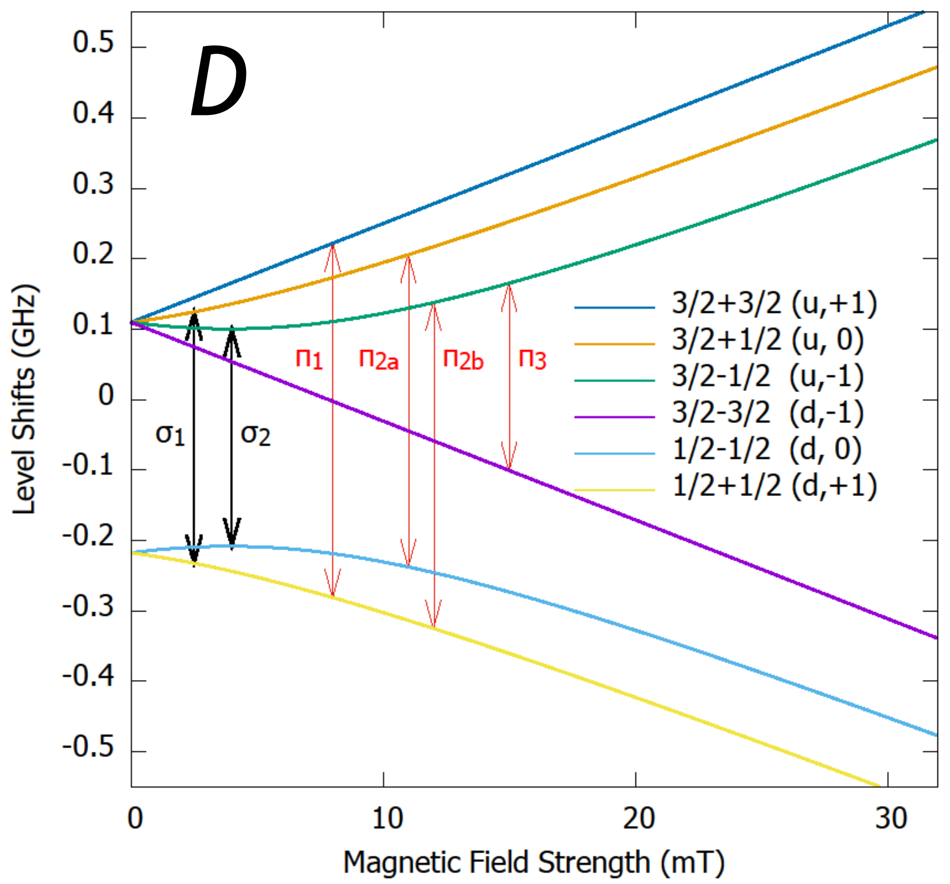
$$\mathcal{K}^{Lab}_{w_{k10}} = \mathcal{K}^{Sun}_{w_{k10}} \cos(\theta) - \sqrt{2}\Re\mathfrak{e}\left(\mathcal{K}^{Sun}_{w_{k11}}\right) \sin(\theta)\cos(\omega_\oplus T_\oplus) + \sqrt{2}\Im\mathfrak{m}\left(\mathcal{K}^{Sun}_{w_{k11}}\right)\sin(\theta)\sin(\omega_\oplus T_\oplus)$$

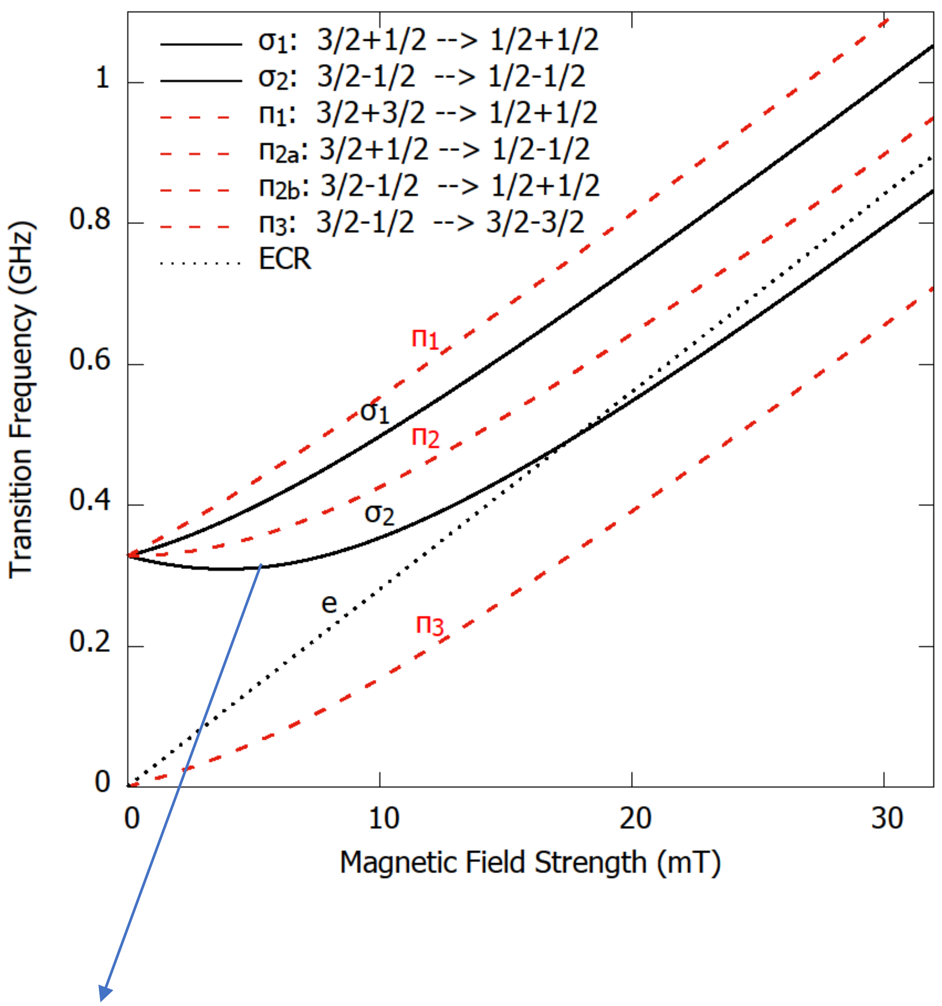
- Generic coefficient $\mathcal{K}$ splits into
  - Spin-independent: $\mathcal{V}$
  - Spin-dependent: $\mathcal{T}$
- $\mathcal{T}$ [$\mathcal{V}$] splits further into
  - CPT even: H [c]
  - CPT odd: g [a]
- splits further by flavour w, mass order k …
  - w = e, p, n (electron, proton, neutron)

V A Kostelecky and A J Vargas, *PRD* **92** 056002 (2015).



Deuterium HFS





minima at 3.89 mT,
at 308.7 MHz

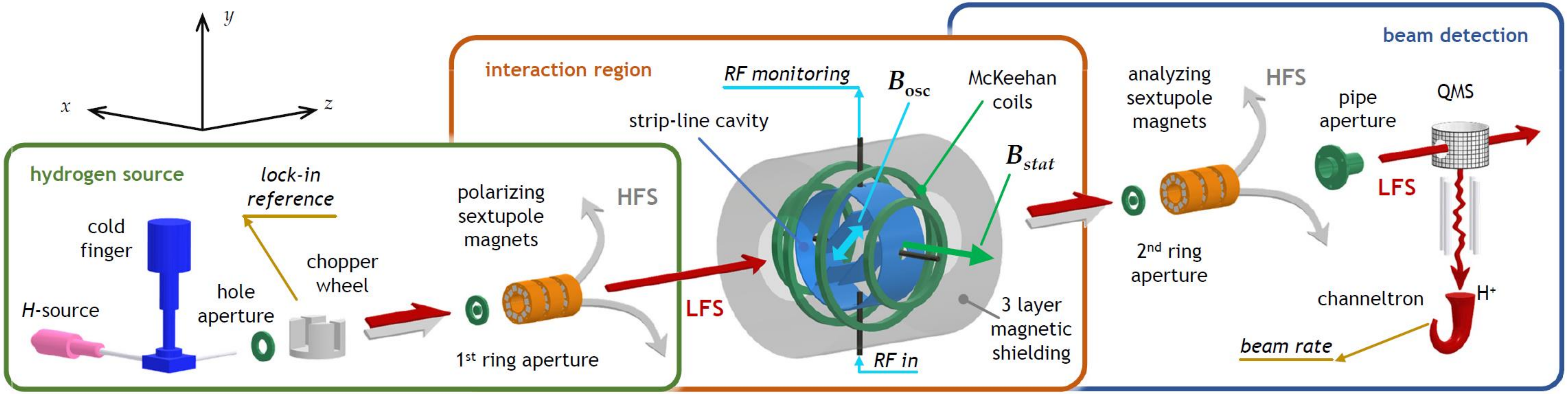
$$\delta\epsilon(F,M_F) = \frac{1}{\sqrt{5\pi}}\frac{2F-1}{(8m_F^2-10)}\sum_{q=0}^{2}\langle \boldsymbol{p}_{pd}^{2q}\rangle' \sum_{\mathcal{W}} \mathcal{V}^{NR}_{\mathcal{W}(2q)20} - \frac{1}{3\sqrt{6\pi}}\frac{m_F}{2^{F-2}}\sum_{q=0}^{2}\langle \boldsymbol{p}_{pd}^{2q}\rangle \times \sum_{\mathcal{W}}(\mathcal{T}^{NR(0B)}_{\mathcal{W}(2q)10}+\mathcal{T}^{NR(1B)}_{\mathcal{W}(2q)10}) - \frac{m_F}{3\sqrt{3\pi}}\sum_{q=0}^{2}\frac{(\alpha m_r)^{2q}}{(2F-1)}(1+4\delta_q^2)\times(\mathcal{T}^{NR(0B)}_{e(2q)10}+\mathcal{T}^{NR(1B)}_{e(2q)10})$$

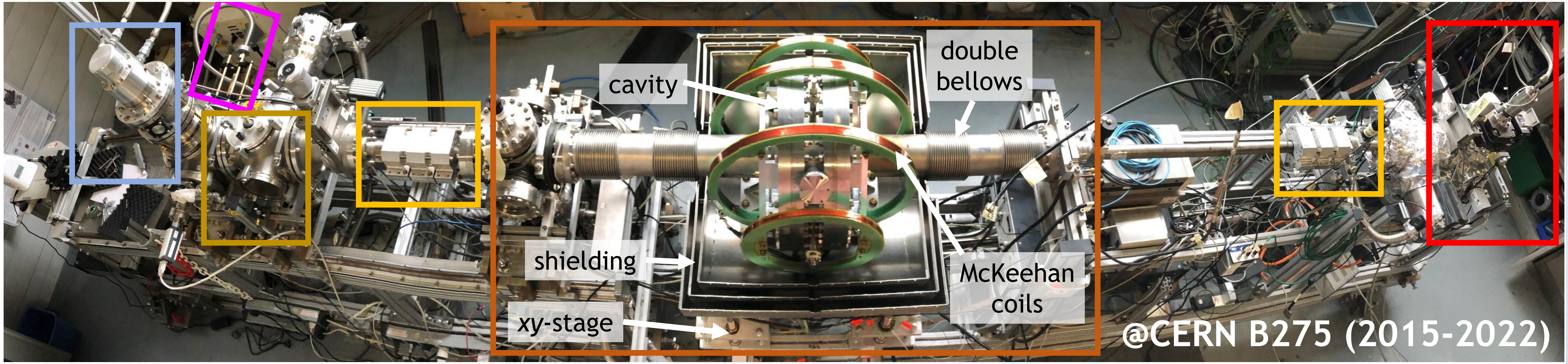
momentum of *p* in *H* ~ a few keV
momentum of *p* in *D* ~ 100 MeV

V A Kostelecky and A J Vargas
PRD **92** 056002 (2015).

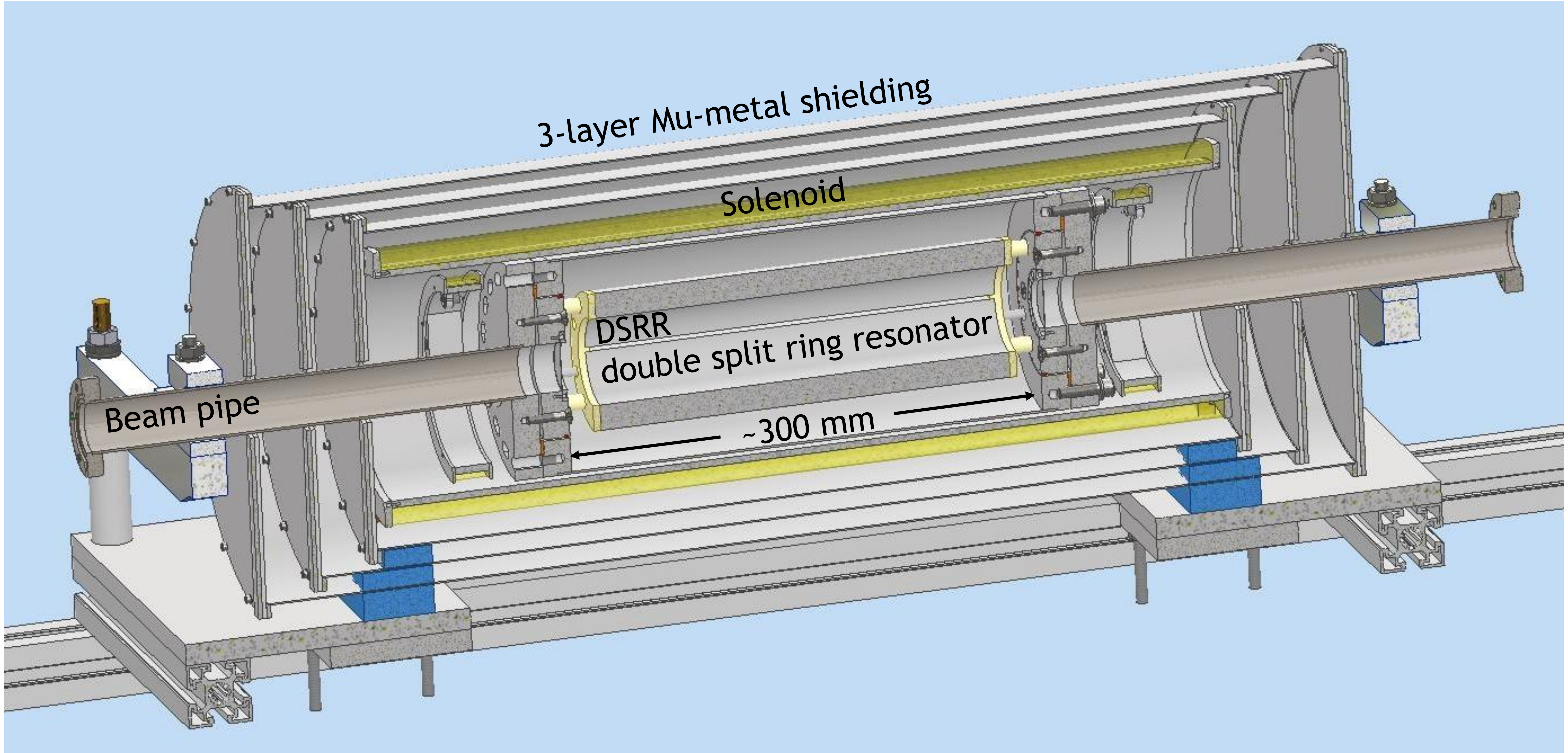
$\Delta F \neq 0$. Moreover, the dependence on the expectation values $\langle \boldsymbol{p}_{pd}^{2q}\rangle$ acts to enhance the sensitivity to the coefficients for Lorentz and *CPT* violation by factors of a billionfold for coefficients with $k=2$ and by 10^{18}-fold for

Amit

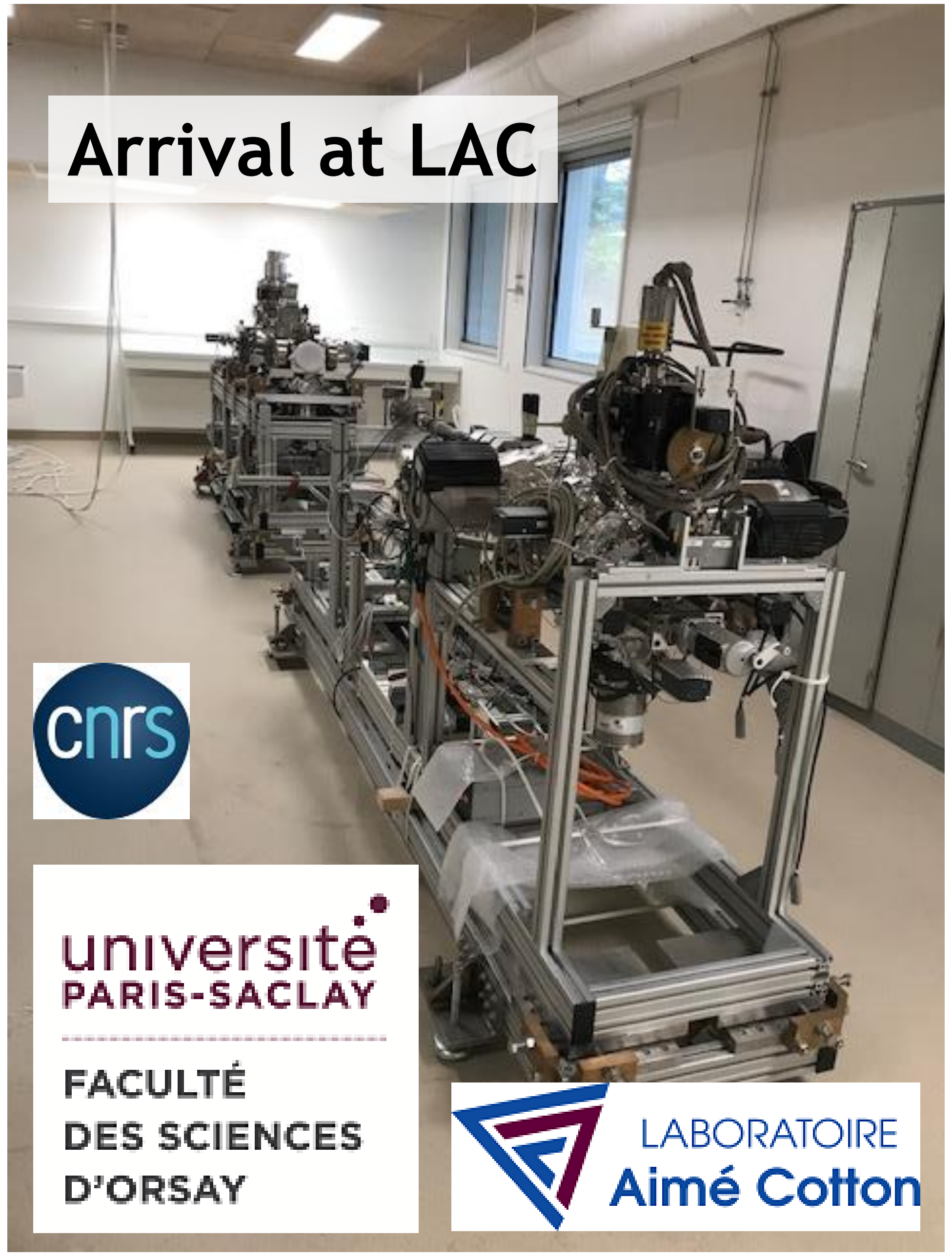

y
x
z
hydrogen source
lock-in reference
cold finger
H-source
hole aperture
chopper wheel
polarizing sextupole magnets
HFS
1st ring aperture
LFS
interaction region
RF monitoring
strip-line cavity
B_{osc}
McKeehan coils
B_{stat}
3 layer magnetic shielding
RF in
beam detection
analyzing sextupole magnets
HFS
pipe aperture
QMS
LFS
2nd ring aperture
channeltron
H+
beam rate


cavity
double bellows
shielding
xy-stage
McKeehan coils
@CERN B275 (2015-2022)

Interaction region for deuterium

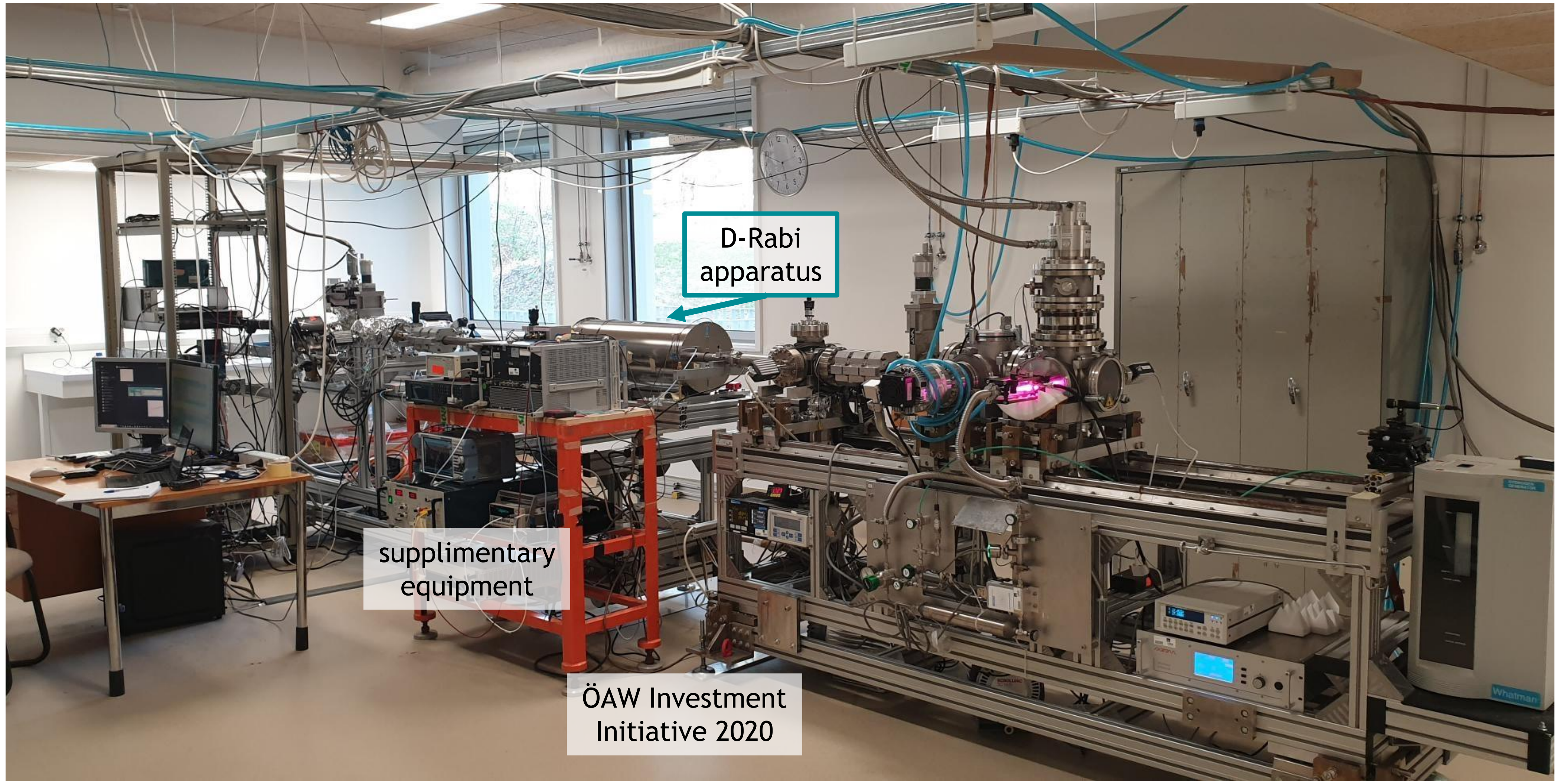


D-Beam in Paris



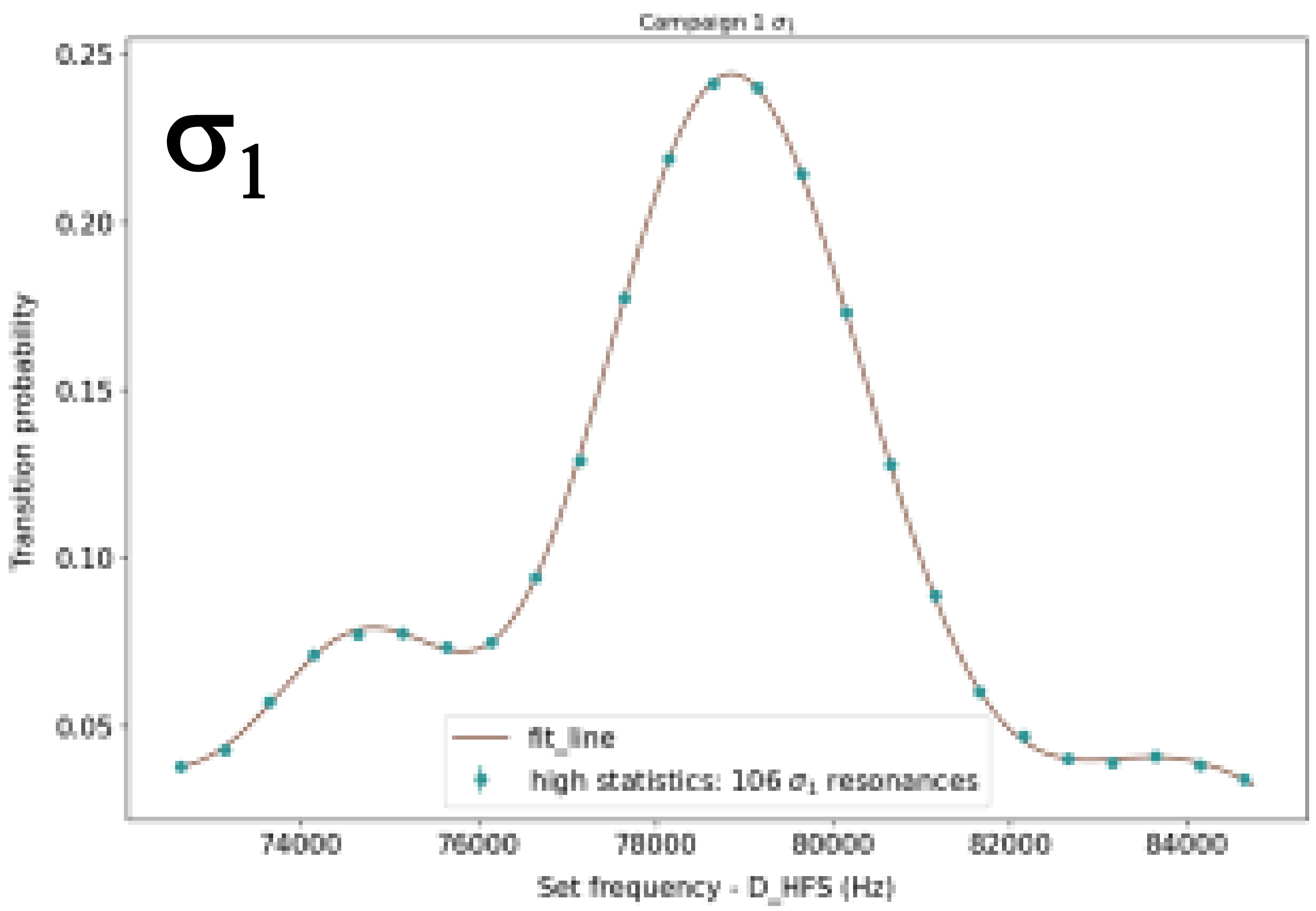
moved in October 2022 → new lab with stable conditions

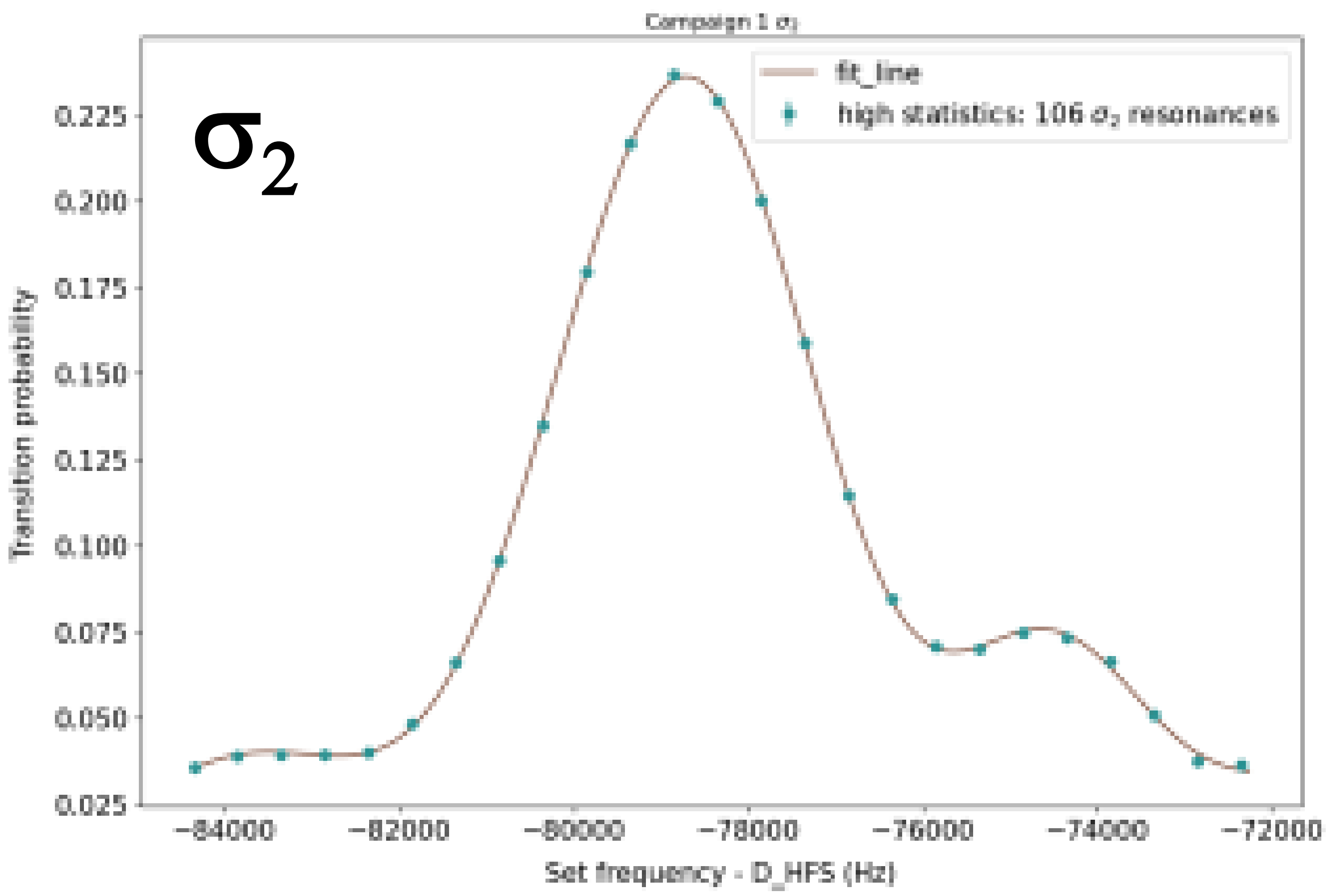
2 campaigns in May and August 2023



Resonance lineshape

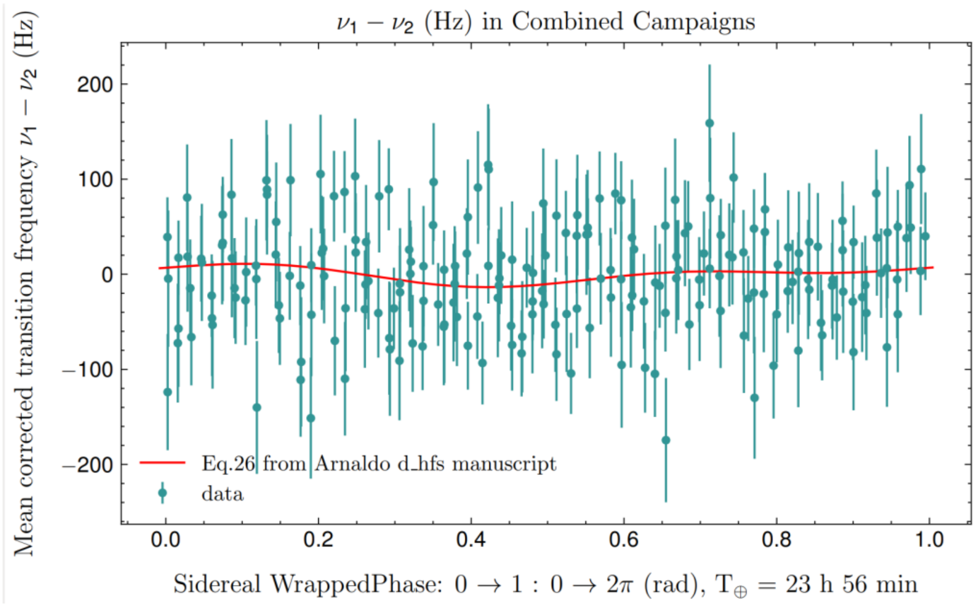
- Sidereal variation → fit template from summed data
- Point-by-point interleaved measurements with reference rates → plot probabilities

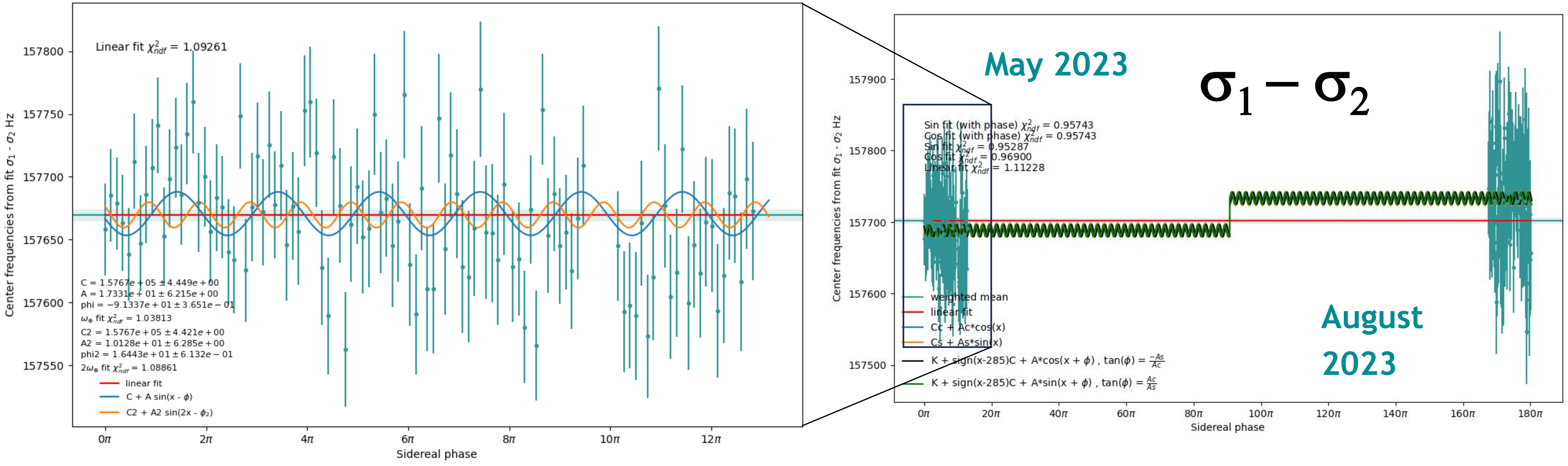




two completed campaigns

- May and August 2023:
  >100 σ_1 and σ_2 transition at B~8µT (I=2mA on solenoid)
- Fits based on template
- Use sum and difference of σ_1 and σ_2
- Use single campaign and combined data → ~ 5 Hz limits
- Extract amplitudes for sin/cos of 1st/2nd harmonic for sidereal/solar day
- Systematic checks, Fourier transform / Lomb-Scargle periodogram





Theory status

- Dedicated calculations on deuterium by A. Vargas available on arXiv: https://arxiv.org/abs/2401.03272
- "Paris nucleon-nucleon potential" used to evaluate momentum matrix elements
- Assumes 10 Hz experimental limit
- Improved constraints by D-HFS experiment for 16 SME-coefficients

TABLE VI. Potential sensitivity of the SMI/LAC experiment on the nonrelativistic coefficients.

	Coefficient $\mathcal{K}$	Constraint on $\lvert\mathrm{Re}\,\mathcal{K}\rvert, \lvert\mathrm{Im}\,\mathcal{K}\rvert$
	$H_{w011}^{\mathrm{NR}(0B),\mathrm{Sun}}, g_{w011}^{\mathrm{NR}(0B),\mathrm{Sun}}$	$< 4 \times 10^{-22}$ GeV
	$H_{w011}^{\mathrm{NR}(1B),\mathrm{Sun}}, g_{w011}^{\mathrm{NR}(1B),\mathrm{Sun}}$	$< 2 \times 10^{-22}$ GeV
w=p	$H_{w211}^{\mathrm{NR}(0B),\mathrm{Sun}}, g_{w211}^{\mathrm{NR}(0B),\mathrm{Sun}}$	$< 3 \times 10^{-20}$ GeV^{-1}
	$H_{w211}^{\mathrm{NR}(1B),\mathrm{Sun}}, g_{w211}^{\mathrm{NR}(1B),\mathrm{Sun}}$	$< 6 \times 10^{-20}$ GeV^{-1}
	$H_{w411}^{\mathrm{NR}(0B),\mathrm{Sun}}, g_{w411}^{\mathrm{NR}(0B),\mathrm{Sun}}$	$< 7 \times 10^{-20}$ GeV^{-3}
	$H_{w411}^{\mathrm{NR}(1B),\mathrm{Sun}}, g_{w411}^{\mathrm{NR}(1B),\mathrm{Sun}}$	$< 2 \times 10^{-19}$ GeV^{-3}
	$c_{w221}^{\mathrm{NR},\mathrm{Sun}}, a_{w221}^{\mathrm{NR},\mathrm{Sun}}$	$< 4 \times 10^{-20}$ GeV^{-1}
	$c_{w222}^{\mathrm{NR},\mathrm{Sun}}, a_{w222}^{\mathrm{NR},\mathrm{Sun}}$	$< 6 \times 10^{-20}$ GeV^{-1}
	$c_{w421}^{\mathrm{NR},\mathrm{Sun}}, a_{w421}^{\mathrm{NR},\mathrm{Sun}}$	$< 2 \times 10^{-19}$ GeV^{-3}
	$c_{w422}^{\mathrm{NR},\mathrm{Sun}}, a_{w422}^{\mathrm{NR},\mathrm{Sun}}$	$< 4 \times 10^{-19}$ GeV^{-3}

Reversing B-Field to Constrain SME-Coefficients

$$\mathcal{K}^{Lab}_{W_{k10}} = \mathcal{K}^{Sun}_{W_{k10}}\cos(\theta) - \sqrt{2}\,\Re\mathfrak{e}\left(\mathcal{K}^{Sun}_{W_{k11}}\right)\sin(\theta)\cos(\omega_\oplus T_\oplus) + \sqrt{2}\,\Im\mathfrak{m}\left(\mathcal{K}^{Sun}_{W_{k11}}\right)\sin(\theta)\sin(\omega_\oplus T_\oplus)$$

V A Kostelecky and A J Vargas, *PRD* **92** 056002 (2015).

ASACUSA, *Phil. Trans. R. Soc.* **A** 376:20170273, (2018).

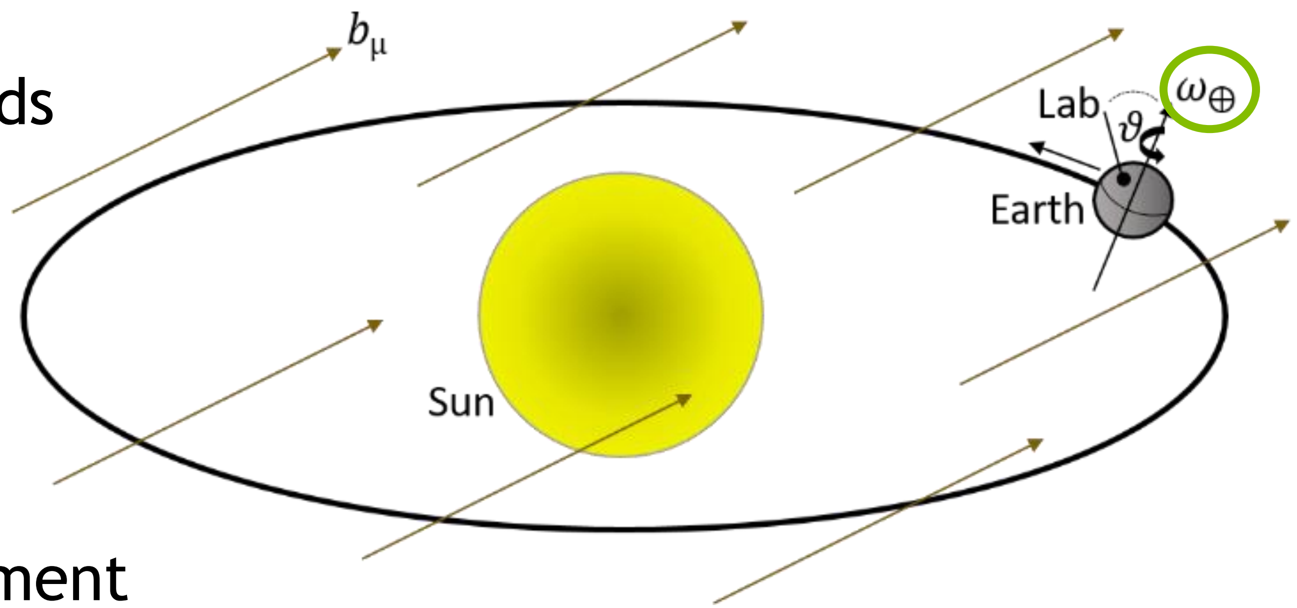
sidereal variation constraints by maser (~mHz, 10^{-27} GeV):

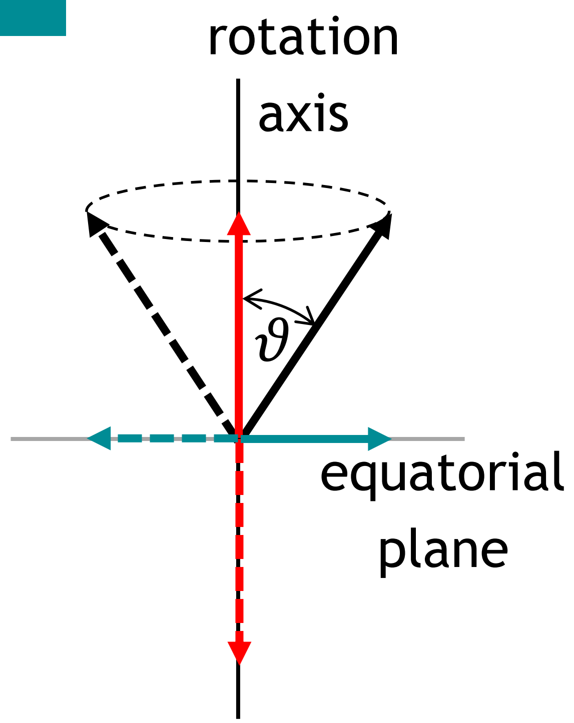
M A Humphrey et al., *PRA* **68** 063807 (2003).

Principle: compare π transition in B-fields of same strength, but opposite polarity

Challenge: B-field determination

Approach: use σ transition (ΔM_F = 0) for independent B-field measurement





$$2\pi\delta\nu(\Delta M_F) = \frac{\Delta M_F}{2\sqrt{3\pi}}\sum_{q=0}^{2}\alpha m_r^{2q}(1+4\delta_{q2}) \times \sum_{W}\left[-g^{0B}_{W(2q)10} + H^{0B}_{W(2q)10} - 2g^{1B}_{W(2q)10} + H^{1B}_{W(2q)10}\right]$$

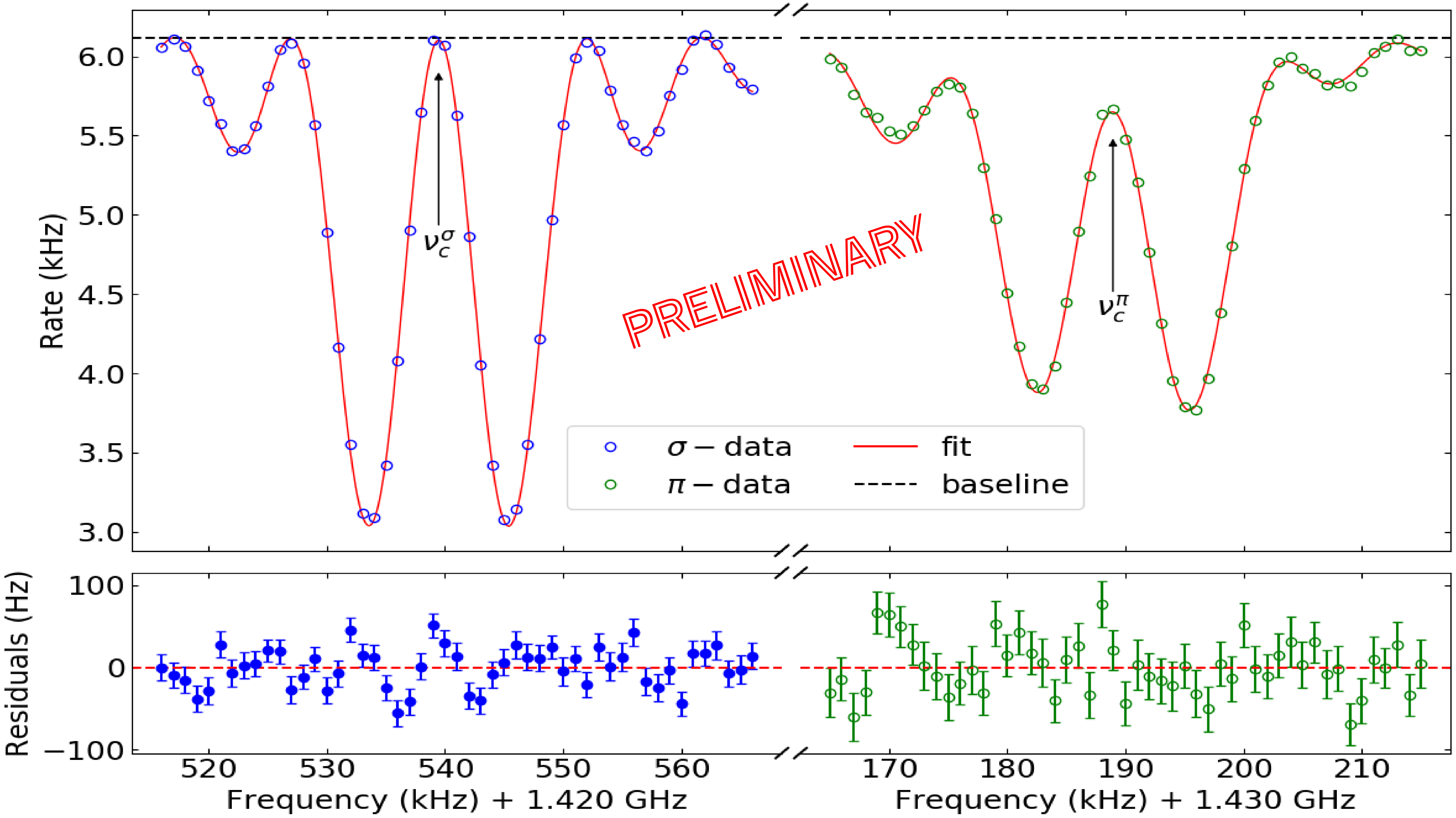
Lilian

σ – π resonance comparison

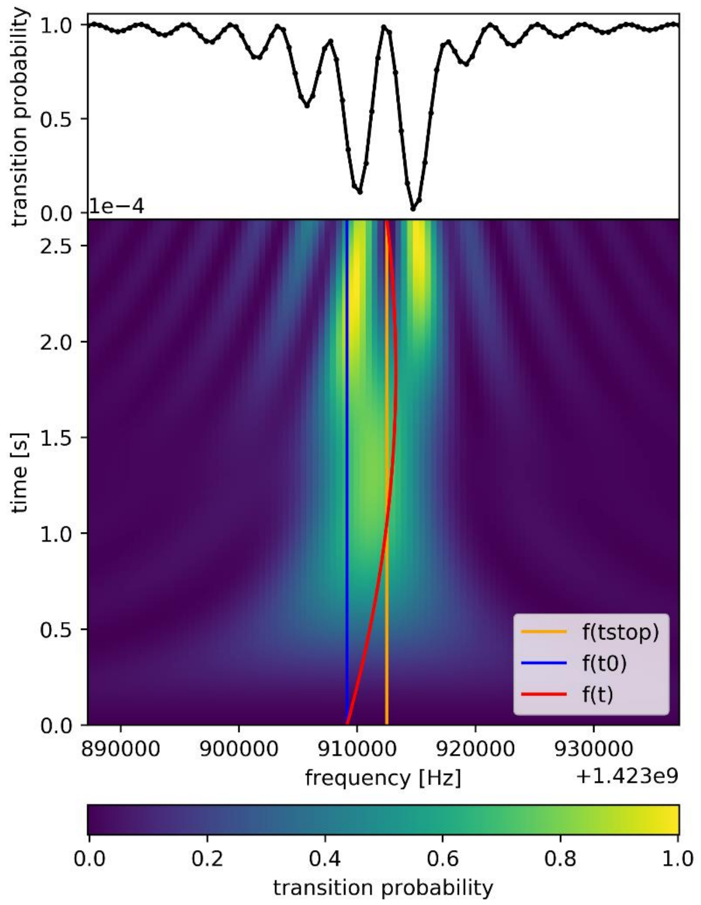
Example:
-0.68 mT (-3 A)

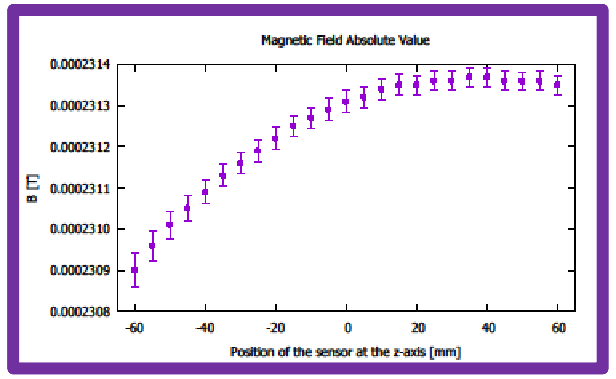
σ–π pair data:

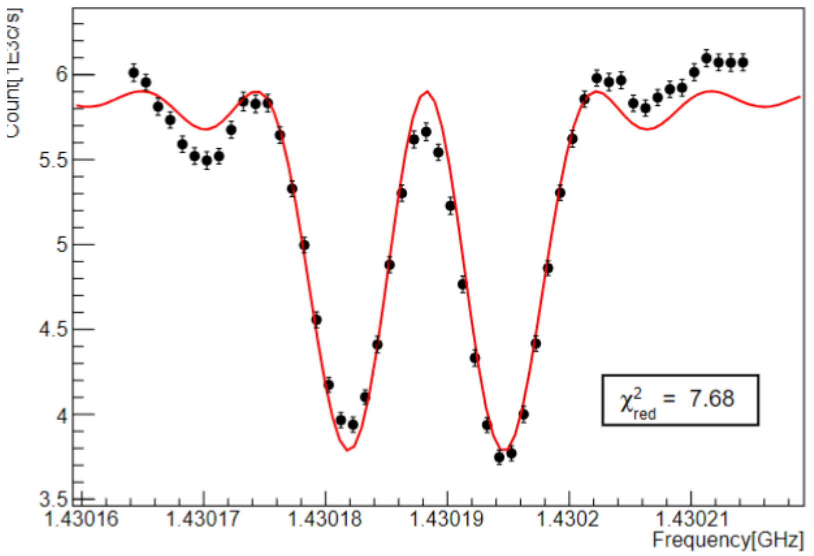
- Successively recorded
- σ: 45min
- π: 15min
- Polarisation close to 50:50 !



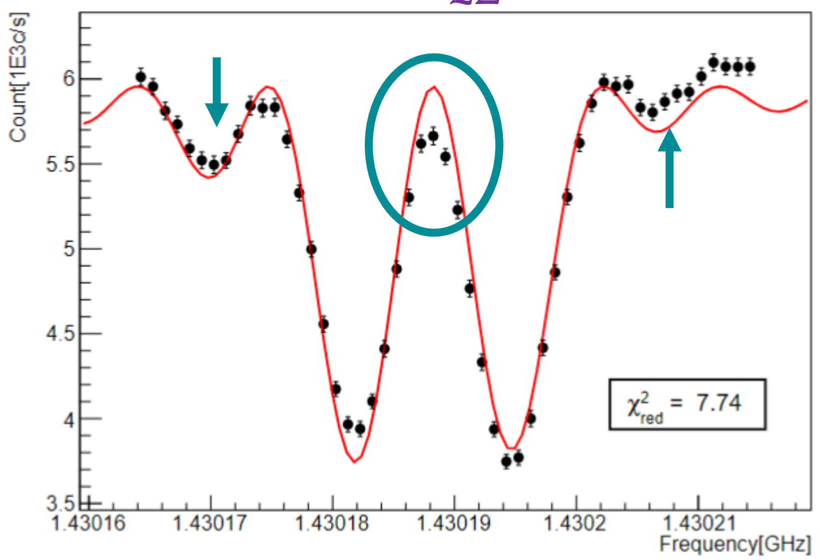
Combination of B-field parameters needed!

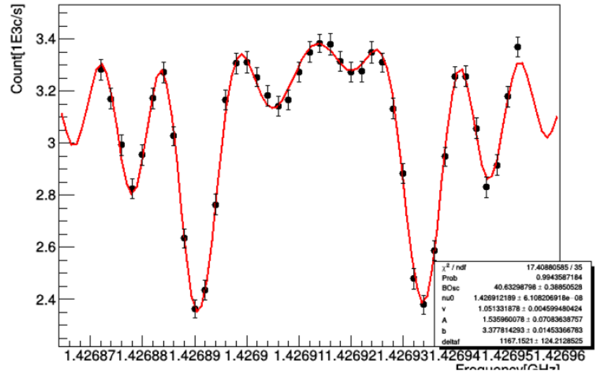


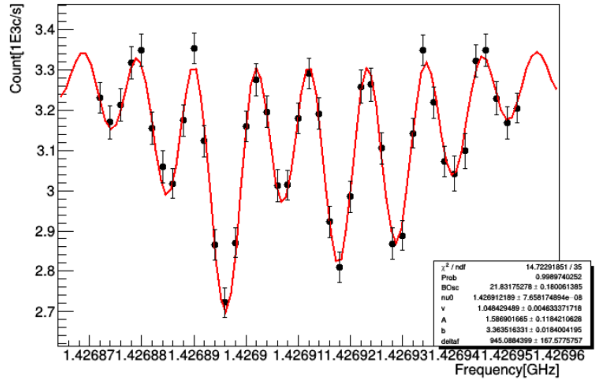




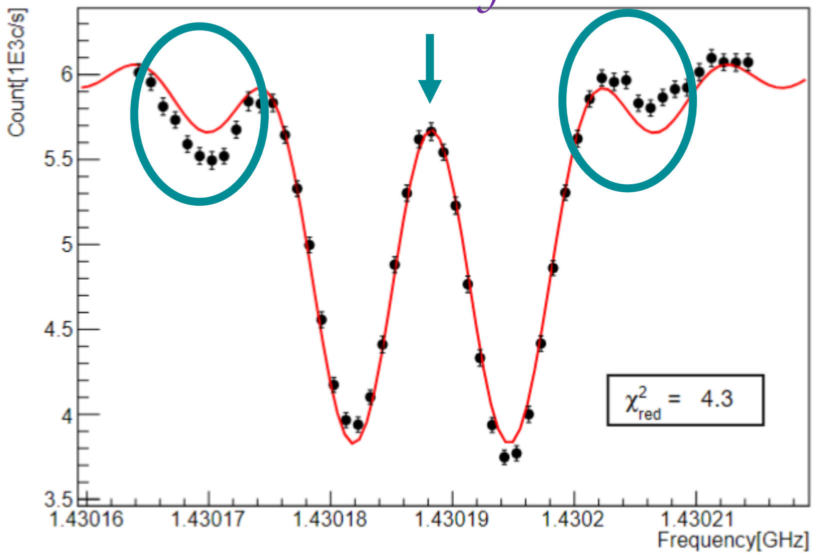
ΔB_{z2}



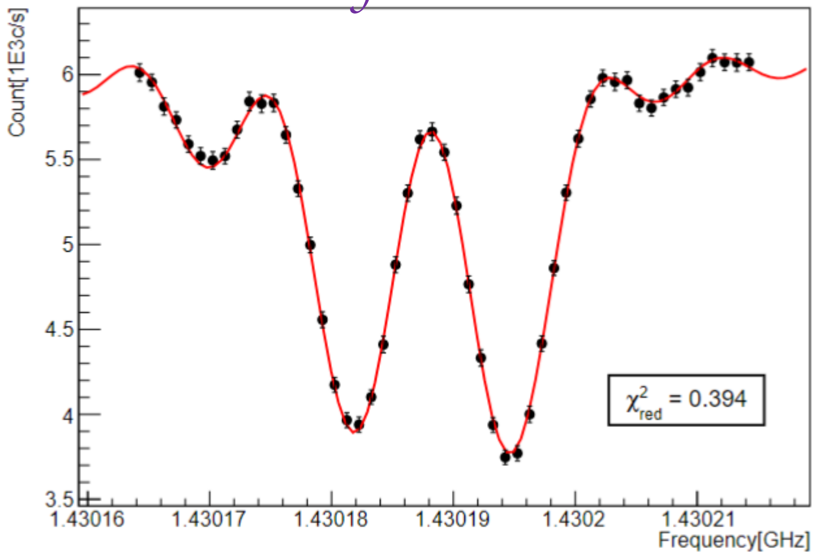


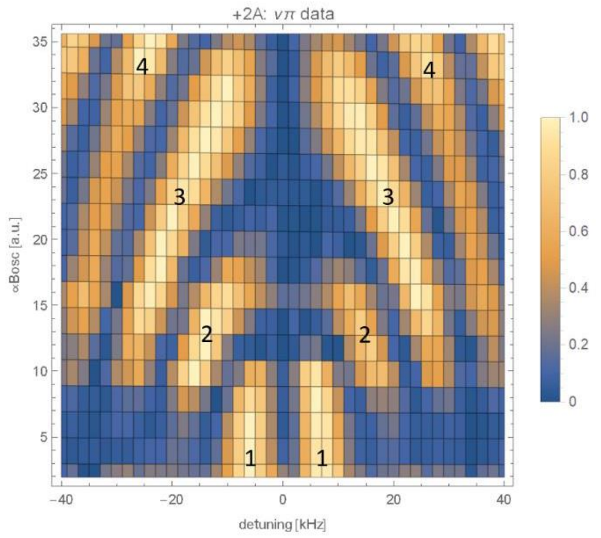


$\Delta \nu_{xy}$



$\Delta \nu_{xy}$ & ΔB_{z2}





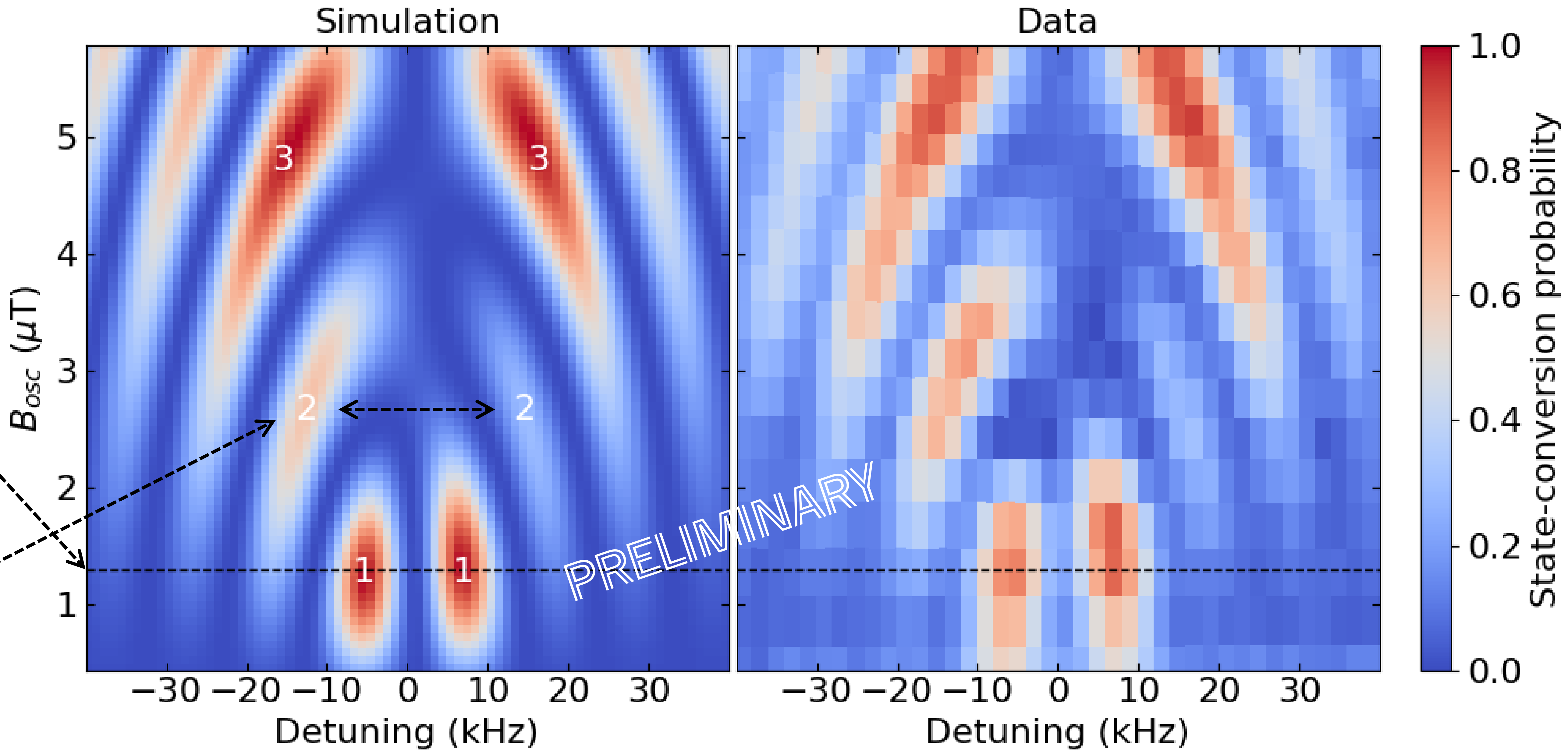
π - probability maps

Independent data sets: extract field parameters (ΔB_{z1} & ΔB_{z2}), fix probability map used in fitting routine

Example:
-3A

σ−π pair data:
at first conversion

high field sensitivity:
at second conversion



Error Budget (systematic)

B_{osc} → open fit parameter (like ν_c, b, a)

PRELIMINARY

$\Delta\nu_{xy}$

v

	$\pi+$: $\overline{\Delta\nu_c} \pm \sigma^s_{\nu_c}$ [Hz]	$\pi-$: $\overline{\Delta\nu_c} \pm \sigma^s_{\nu_c}$ [Hz]	$\sigma+$: $\overline{\Delta\nu_c} \pm \sigma^s_{\nu_c}$ [Hz]	$\sigma-$: $\overline{\Delta\nu_c} \pm \sigma^s_{\nu_c}$ [Hz]
$\pm 3A$ shifts				
$\Delta\nu^{x,y} + \sigma_{\Delta\nu^{x,y}_{\pi/\sigma}}$	-0.24 ± **0.46**	-0.41 ± 0.42	0.00 ± 0.00	0.00 ± 0.00
$\Delta\nu^{x,y} - \sigma_{\Delta\nu^{x,y}_{\pi/\sigma}}$	0.21 ± 0.43	0.38 ± 0.41	0.00 ± 0.00	0.00 ± 0.00
$vel + \sigma_{vel_{\pi/\sigma}}$	0.01 ± 0.71	**1.20** ± 1.01	-0.19 ± 0.20	-0.15 ± 0.21
$vel - \sigma_{vel_{\pi/\sigma}}$	0.01 ± 0.70	-1.11 ± 1.00	**0.22** ± 0.20	0.18 ± 0.20
$\pm 2.5A$ shifts				
$\Delta\nu^{x,y} + \sigma_{\Delta\nu^{x,y}_{\pi/\sigma}}$	-0.09 ± 0.27	-0.49 ± **0.60**	0.00 ± 0.00	0.00 ± 0.00
$\Delta\nu^{x,y} - \sigma_{\Delta\nu^{x,y}_{\pi/\sigma}}$	0.06 ± 0.25	0.43 ± 0.57	0.00 ± 0.00	0.00 ± 0.00
$vel + \sigma_{vel_{\pi/\sigma}}$	0.02 ± **0.76**	0.80 ± 1.00	-0.16 ± 0.20	-0.19 ± **0.23**
$vel - \sigma_{vel_{\pi/\sigma}}$	-0.01 ± 0.75	-0.74 ± 0.99	0.17 ± 0.19	0.20 ± 0.22
$\pm 2A$ shifts				
$\Delta\nu^{x,y} + \sigma_{\Delta\nu^{x,y}_{\pi/\sigma}}$	-0.15 ± 0.31	-0.11 ± 0.20	0.00 ± 0.00	0.00 ± 0.00
$\Delta\nu^{x,y} - \sigma_{\Delta\nu^{x,y}_{\pi/\sigma}}$	0.12 ± 0.27	0.10 ± 0.19	0.00 ± 0.00	0.00 ± 0.00
$vel + \sigma_{vel_{\pi/\sigma}}$	-0.24 ± 0.41	0.30 ± 0.52	-0.12 ± 0.13	-0.18 ± 0.14
$vel - \sigma_{vel_{\pi/\sigma}}$	0.25 ± 0.41	-0.25 ± 0.51	0.13 ± 0.13	0.19 ± 0.13

ΔB_{z2}

+3 A transition	shift type	$\Delta\nu_c^i$ [Hz]	$\Delta\nu_c^{OBF}$ [Hz]	$\lvert\Delta\nu_c^{OBF} - \Delta\nu_c^i\rvert$ [Hz]
π	$\Delta B_2^z + \sigma_{\Delta B_2^z}$	26.67	29.75 ± 0.33	2.99
π	ΔB_2^z - $\sigma_{\Delta B_2^z}$	-26.56	-29.71 ± 0.35	**3.15**
σ	$\Delta B_2^z + \sigma_{\Delta B_2^z}$	0.71	0.73 ± 0.01	0.02
σ	ΔB_2^z - $\sigma_{\Delta B_2^z}$	-0.69	-0.73 ± 0.01	**0.04**
−3 A transition	**shift type**	**$\Delta\nu_c^i$ [Hz]**	**$\Delta\nu_c^{OBF}$ [Hz]**	**$\lvert\Delta\nu_c^{OBF} - \Delta\nu_c^i\rvert$ [Hz]**
π	$\Delta B_2^z + \sigma_{\Delta B_2^z}$	27.03	30.09 ± 0.29	3.06
π	ΔB_2^z - $\sigma_{\Delta B_2^z}$	-26.92	-30.05 ± 0.30	**3.13**
σ	$\Delta B_2^z + \sigma_{\Delta B_2^z}$	0.70	0.73 ± 0.01	0.03
σ	ΔB_2^z - $\sigma_{\Delta B_2^z}$	-0.69	-0.73 ± 0.01	**0.04**

ΔB_{z1}

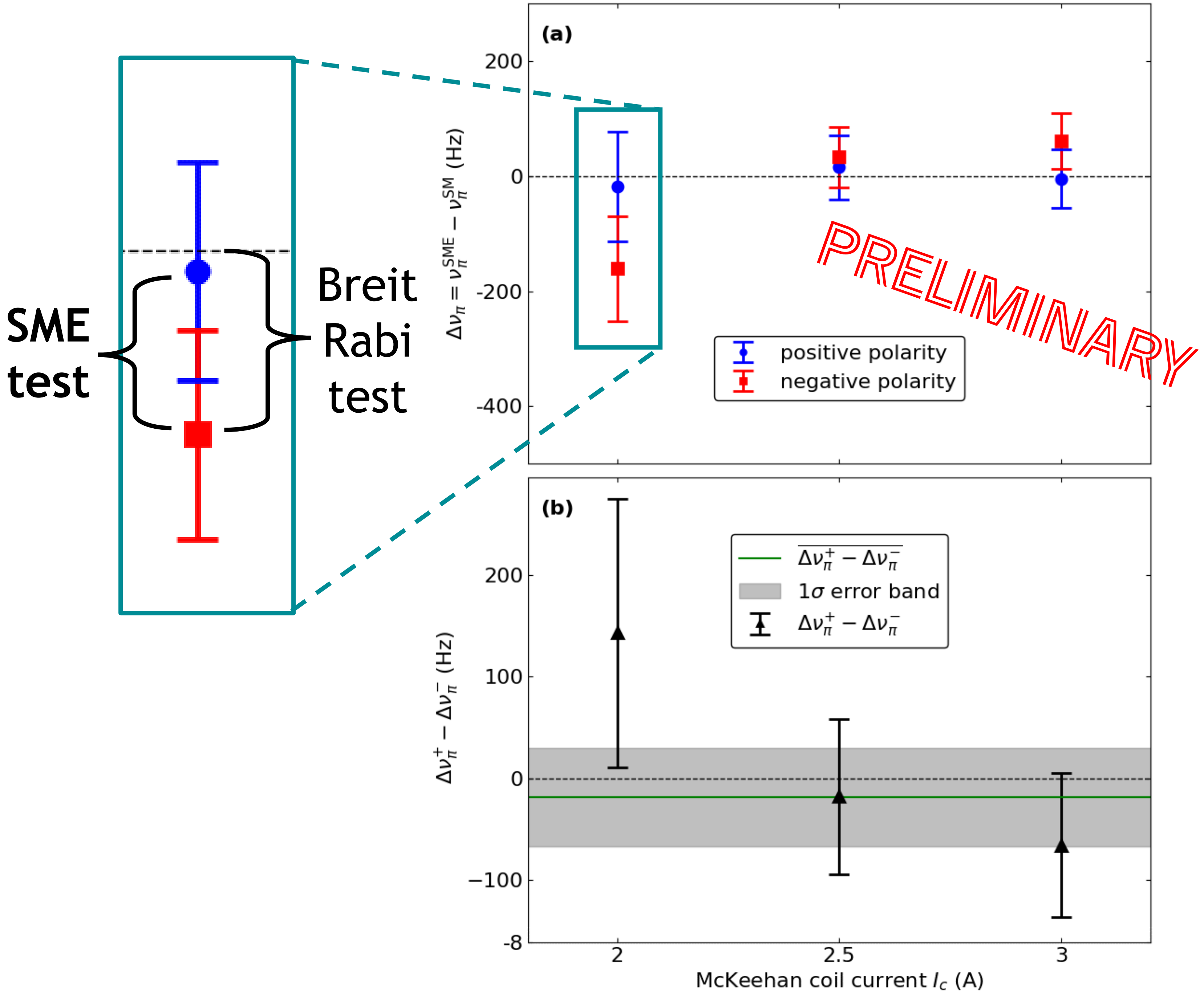
Current [A]	Transition	shift type	$\Delta\nu_c^i$ [Hz]	$\Delta\nu_c^{OBF}$ [Hz]	$\lvert\Delta\nu_c^{OBF} - \Delta\nu_c^i\rvert$ [Hz]
+3 A	π	$\Delta B_1^z + 3\sigma_{\Delta B_1^z}$	2.81	**2.81** ± 1.01	0.
−3 A	π	$\Delta B_1^z + 3\sigma_{\Delta B_1^z}$	**1.82**	1.77 ± 0.63	0.05

shift type	π (+ current) [Hz]	π (− current) [Hz]	σ (+ current) [Hz]	σ (− current) [Hz]
$\Delta\nu^{x,y}$	0.46	0.60	0.00	0.00
v	0.76	1.20	0.22	0.23
ΔB_2^z	3.15	3.13	0.04	0.04
total (in quadr.)	**3.27**	**3.41**	**0.22**	**0.23**
ΔB_1^z	2.81	1.82		
low errorbar	**4.38**	**3.86**		

Polarity	σ_σ^{fin} [Hz]	${}_{\mathrm{lo}}\sigma_\pi^{fin}$ [Hz]	${}_{\mathrm{hi}}\sigma_\pi^{fin}$ [Hz]
+	0.22	4.31	3.27
-	0.23	3.86	3.41

Source \ Transition	σ^+	π^+	σ^-	π^-
$\Delta\nu^{x,y}$	<10 mHz	0.46	<10 mHz	0.60
v_H	0.22	0.76	0.23	1.20
ΔB_2^z	0.04	3.15	0.04	3.13
total (in quadr.)	**0.22**	**3.27**	**0.23**	**3.41**
ΔB_1^z (only positive shift)	<10 mHz	2.81	<10 mHz	1.82
Total lower error [Hz]	**0.22**	**4.38**	**0.23**	**3.86**
Total upper error [Hz]	**0.22**	**3.27**	**0.23**	**3.41**

Unblind: July 19th - CPT/LIV Test



Statistical uncertainties only:

Current (A)	Err νπ (Hz)	Err νσ (Hz)	Err νπ(σ) (Hz)	Δνπ⁺ – Δνπ⁻ (Hz)
+ 2.0	±1.93	±0.82	±45.8	**- 18.7 ± 48.3** $\mathcal{K}_{W_{k10}}^{Sun}$ ~<10^-21 GeV
+ 2.5	±1.34	± 0.60	±26.9	
+ 3.0	±1.32	± 0.51	±19.1	
- 2.0	±2.28	±0.84	±46.9	
- 2.5	±1.61	± 0.60	±26.9	
- 3.0	±1.70	± 0.51	±19.1	

Figure of merit: double differential:

$$(\nu_\pi - \nu_{\pi(\sigma)})_{pos} - (\nu_\pi - \nu_{\pi(\sigma)})_{neg}$$

Uncertainty blows up due to:

$$\nu_\pi(B(\nu_\sigma)) \rightarrow \frac{\partial \nu_\sigma}{\partial B} / \frac{\partial \nu_\pi}{\partial B}$$

Implications for antihydrogen

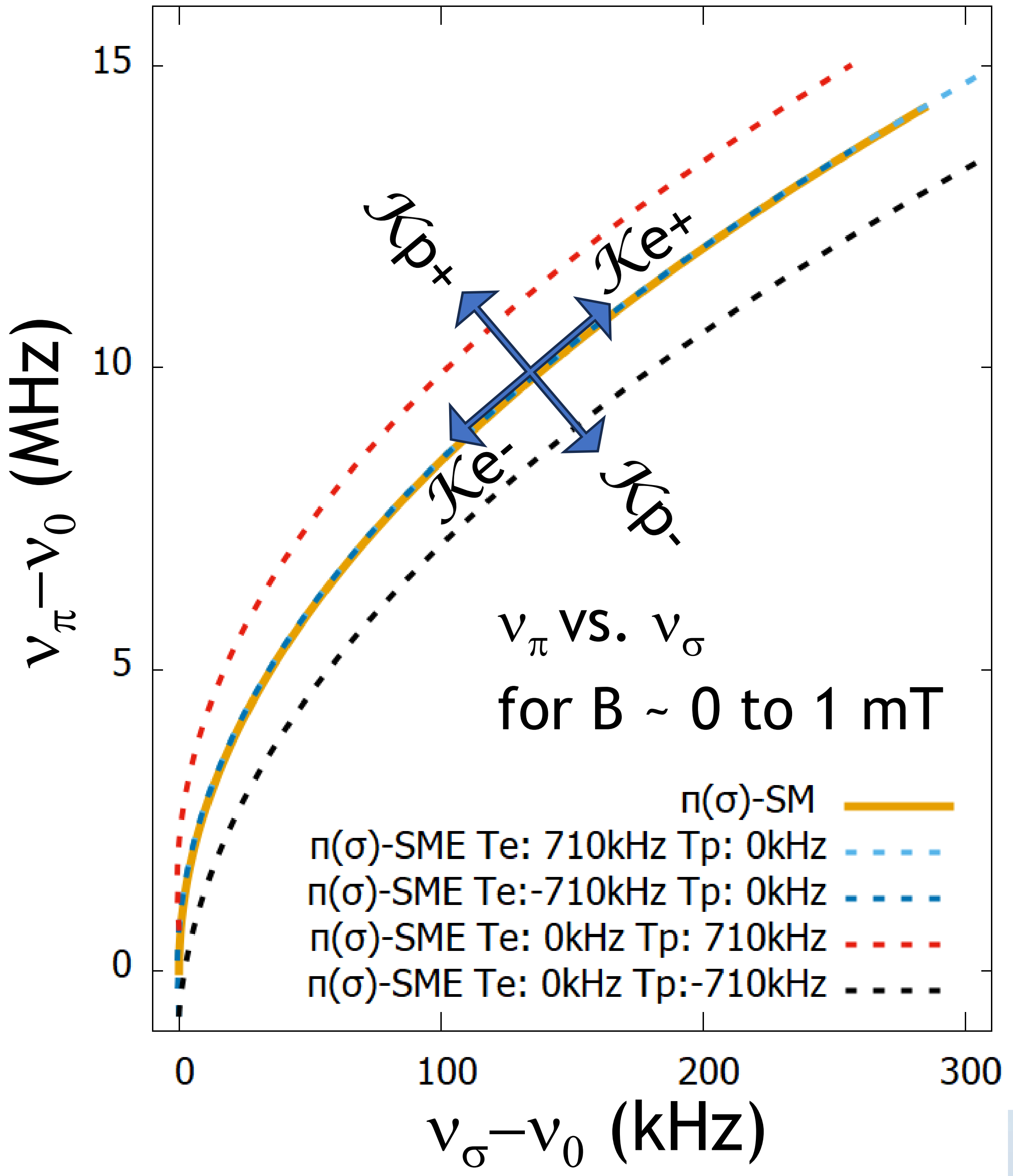
Coefficient $\mathcal{K}$	Constraint on $\lvert\mathcal{K}\rvert$
proton	
$H_{p010}^{NR(0B),Sun}$, $g_{p010}^{NR(0B),Sun}$	$< 1.2 \times 10^{-21}$ GeV
$H_{p010}^{NR(1B),Sun}$, $g_{p010}^{NR(1B),Sun}$	$< 5.8 \times 10^{-22}$ GeV
$H_{p210}^{NR(0B),Sun}$, $g_{p210}^{NR(0B),Sun}$	$< 8.4 \times 10^{-11}$ GeV^{-1}
$H_{p210}^{NR(1B),Sun}$, $g_{p210}^{NR(1B),Sun}$	$< 4.2 \times 10^{-11}$ GeV^{-1}
$H_{p410}^{NR(0B),Sun}$, $g_{p410}^{NR(0B),Sun}$	< 1.2 GeV^{-3}
$H_{p410}^{NR(1B),Sun}$, $g_{p410}^{NR(1B),Sun}$	< 0.6 GeV^{-3}
electron	
$H_{e010}^{NR(0B),Sun}$, $g_{e010}^{NR(0B),Sun}$	$< 7.7 \times 10^{-19}$ GeV
$H_{e010}^{NR(1B),Sun}$, $g_{e010}^{NR(1B),Sun}$	$< 3.8 \times 10^{-19}$ GeV
$H_{e210}^{NR(0B),Sun}$, $g_{e210}^{NR(0B),Sun}$	$< 5.5 \times 10^{-8}$ GeV^{-1}
$H_{e210}^{NR(1B),Sun}$, $g_{e210}^{NR(1B),Sun}$	$< 2.8 \times 10^{-8}$ GeV^{-1}
$H_{e410}^{NR(0B),Sun}$, $g_{e410}^{NR(0B),Sun}$	$< 8.0 \times 10^{2}$ GeV^{-3}
$H_{e410}^{NR(1B),Sun}$, $g_{e410}^{NR(1B),Sun}$	$< 4.0 \times 10^{2}$ GeV^{-3}

← Our new constraints

- Different for e & p !
- Not on the level of maser:
  - Precision
  - Error propagation $\sigma \rightarrow \pi$
  - Sidereal scheme vs. flipping

TABLE III. Constraints on the moduli of the real and imaginary parts of electron and proton nonrelativistic coefficients determined from hyperfine Zeeman transitions in hydrogen using Eq. (52).

Coefficient $\mathcal{K}$	Constraint on $\lvert \mathrm{Re}\mathcal{K}\rvert$, $\lvert \mathrm{Im}\mathcal{K}\rvert$
$H_{011}^{NR(0B)}$, $g_{011}^{NR(0B)}$	$<9 \times 10^{-27}$ GeV
$H_{011}^{NR(1B)}$, $g_{011}^{NR(1B)}$	$<5 \times 10^{-27}$ GeV
$H_{211}^{NR(0B)}$, $g_{211}^{NR(0B)}$	$<7 \times 10^{-16}$ GeV^{-1}
$H_{211}^{NR(1B)}$, $g_{211}^{NR(1B)}$	$<4 \times 10^{-16}$ GeV^{-1}
$H_{411}^{NR(0B)}$, $g_{411}^{NR(0B)}$	$<9 \times 10^{-6}$ GeV^{-3}
$H_{411}^{NR(1B)}$, $g_{411}^{NR(1B)}$	$<5 \times 10^{-6}$ GeV^{-3}



Unblind: July 19th - ν_0 result

Both measurements at the same field:

$$\nu_{Hfs}(\pm) = \frac{g_+^2\ (2\nu_\pi - \nu_\sigma) \pm g_-\ \sqrt{\Delta}}{g_+^2\ +\ g_-^2} = \left(\frac{a}{2\pi}\right)$$

with

$$\Delta \equiv \nu_\sigma^2 g_-^2 - 4g_+^2\nu_\pi^2 + 4g_+^2\nu_\pi\nu_\sigma.$$

$$g_\pm = g_e \pm g_p m_e/m_p$$

PRELIMINARY

Claude Amsler
(SMI Retreat 03.'23)

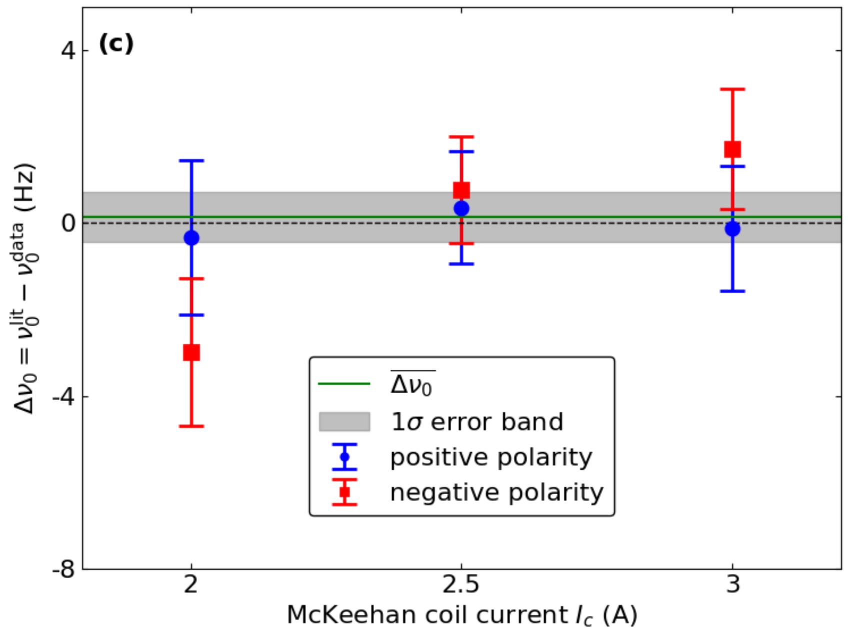
Error propagation:

ν_σ → basically 1:1

ν_π → suppressed by ~10^{-2}

SME sensitivity reduced

but robust method w.r.t. B-field



new best ν_0 determination
for hydrogen HFS in a beam

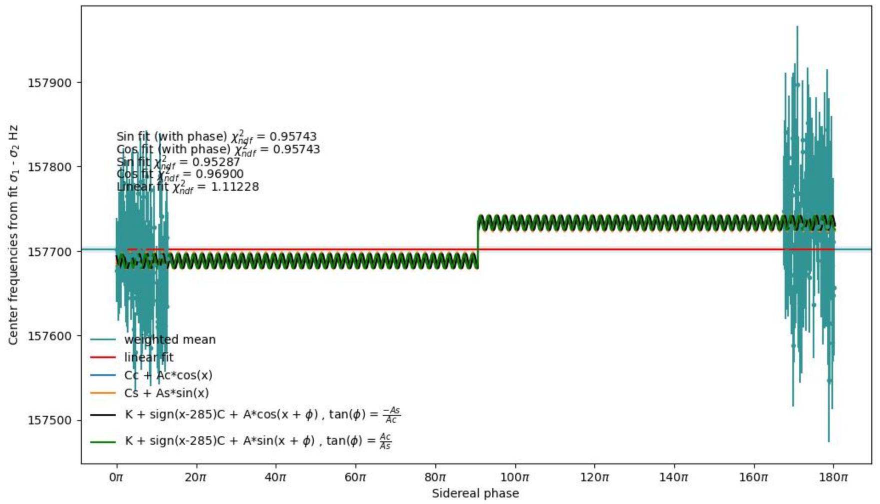
$$\nu_0^{lit} - \nu_0^{data} =$$
$$140 \pm 590(stat) \pm 260(syst)\ \text{mHz}$$

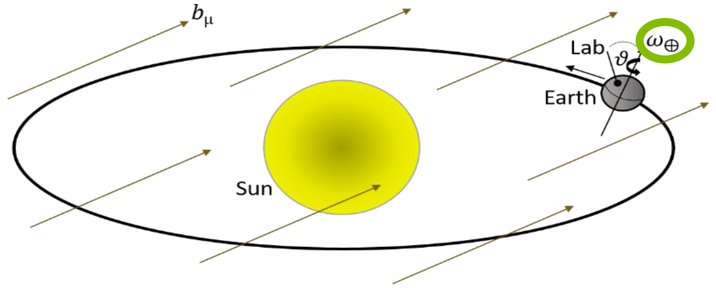
<0.5 p.p.b. result
→ improve systematics propagation
→ check 2nd order QED effects
(for π around 200 mHz - Shabeav)

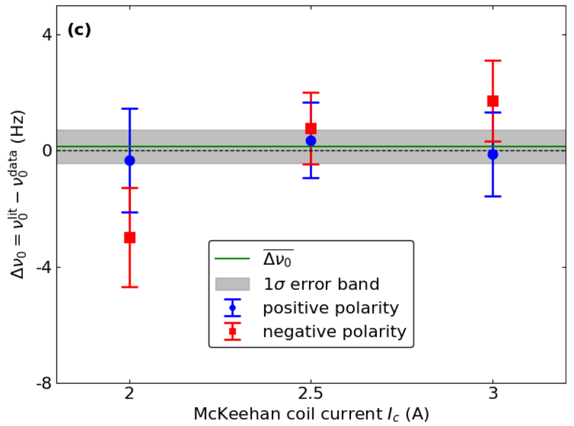
Current (A)	Err $\nu\pi$ (Hz)	Err $\nu\sigma$ (Hz)	ν0 (Hz)
+ 2.0	±1.93	±0.82	**-0.34±1.79**
+ 2.5	±1.34	± 0.60	**0.35±1.29**
+ 3.0	±1.32	± 0.51	**-0.13±1.45**
- 2.0	±2.28	±0.84	**-2.98±1.70**
- 2.5	±1.61	± 0.60	**0.77±1.23**
- 3.0	±1.70	± 0.51	**1.70±1.39**

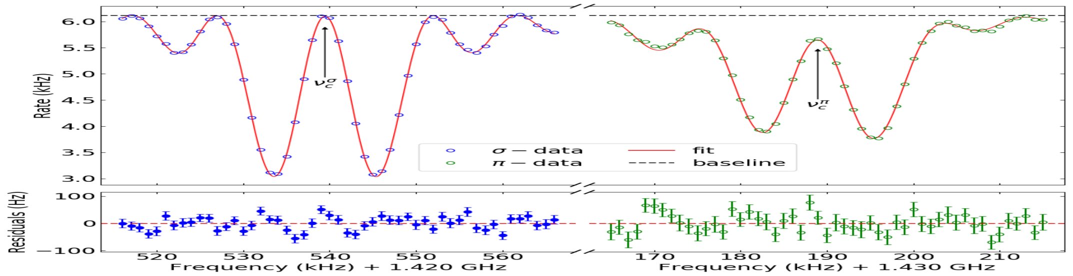
Outlook & Summary

- Deuterium
  - Setup ready for next campaigns
  - Add boost analysis
  - Measure at other/stronger fields
- Hydrogen
  - Presently no activity at CERN
    (return if needed for simultaneous measurements)
  - Testing Ramsey for antihydrogen
- H&D
  - Slower beams in Vienna/Paris
  - Improved Magnetometry









- HFS Rabi-measurements on H & D → new SME constraints
- Sidereal variations (D) vs. field flips (H)
- Effects from B-field inhomogeneities well understood
- Apparatus for antihydrogen well characterized
- Best in-beam HFS values

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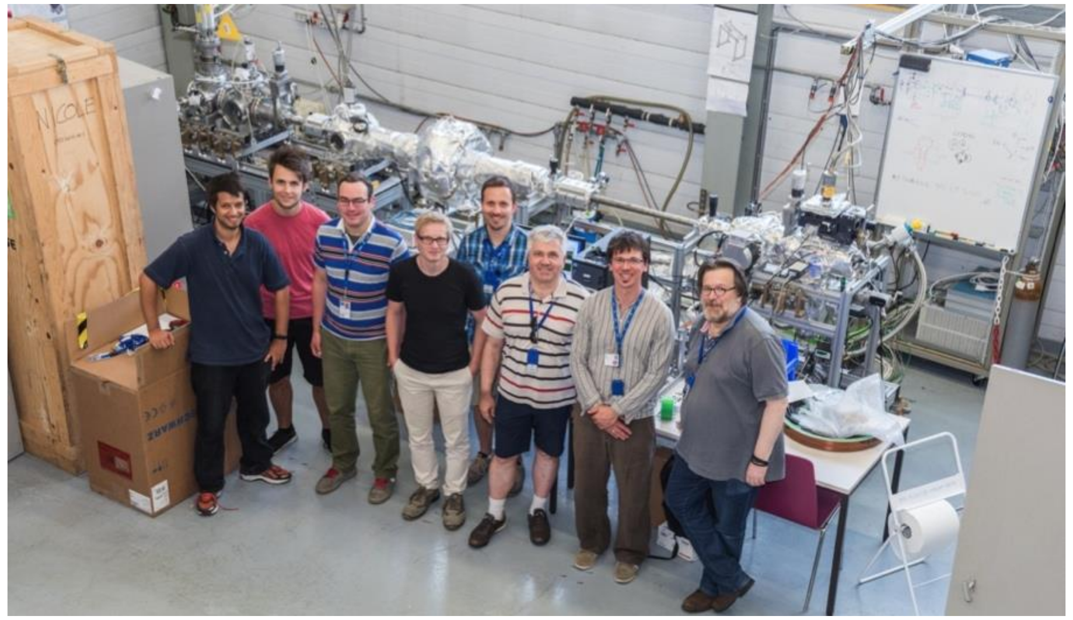

erc 291242-HBAR-HFS

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FWF Der Wissenschaftsfonds.

ÖAW Investment Initiative 2020

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