^{3}He-^{129}Xe Comagnetometer with ^{87}Rb Pulse-train Detection & Decoupling

DAMOP 2017

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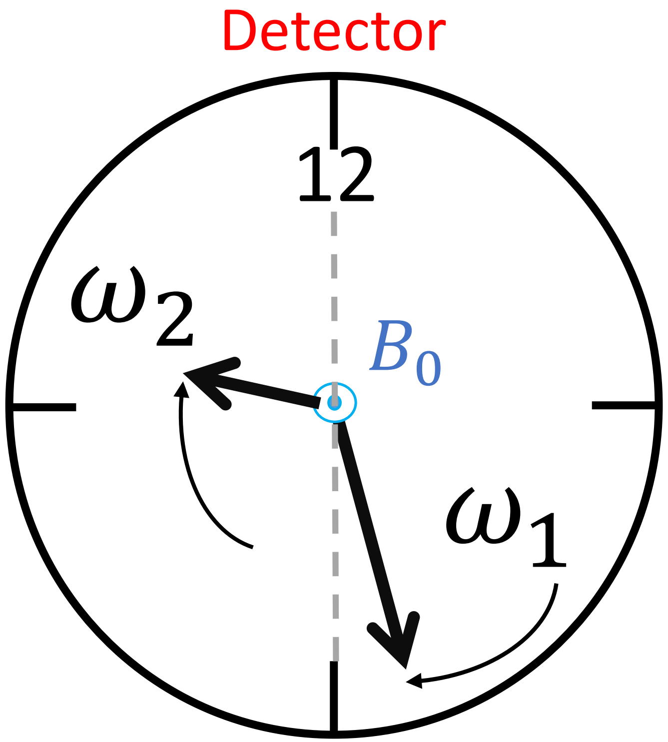
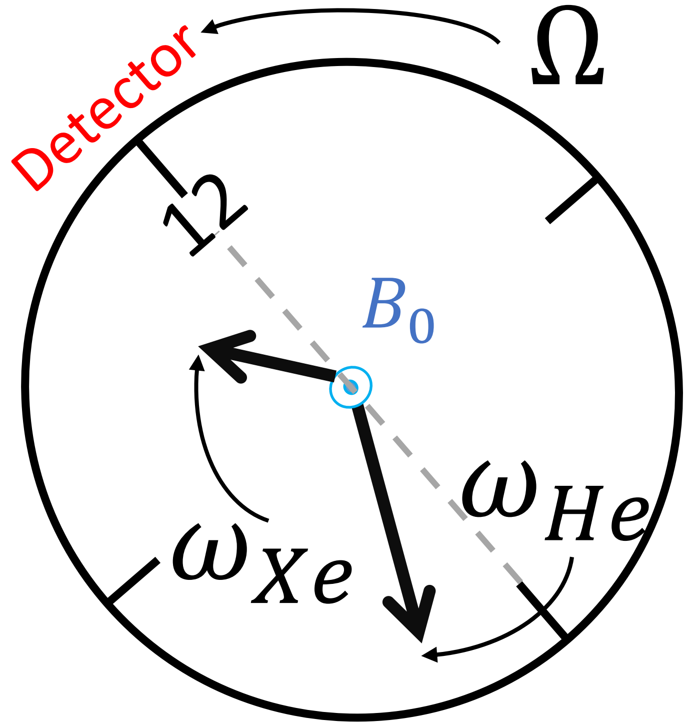
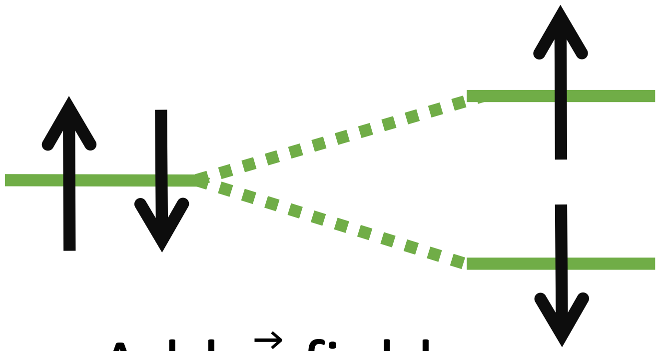


Motivations

- (1) Chip-sized NMR Gyroscope

$$f_r = \frac{\gamma_{He} B_0 \pm \Omega}{\gamma_{Xe} B_0 \pm \Omega}$$





$$\Delta E = h\nu_g$$

Add $\vec{g}$ field

- (2) Spin-gravity interaction $\gamma_G \vec{S} \cdot \vec{g} = \frac{M_{\text{Pl}}^2}{M_S M_{Pj}} (10.4\ \text{nHz}) S$

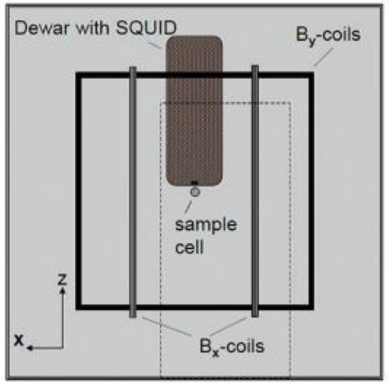
I. Yu. Kobzarev and L. B. Okun, Zh. Eksp. Teor. Fiz. **43**, 1904 (1962) [Sov. Phys. JETP **16**, 1343 (1963)]
B. J. Venema, P. K. Majumder, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson Phys. Rev. Lett. 68, 135 (1992)
V. Flambaum, S. Lambert, M. Pospelov, Phys. Rev. D. **80**, 105021 (2009)

Detection Methods for Dual Nuclear-spin Comag.

- SQUIDs: Good sensitivity

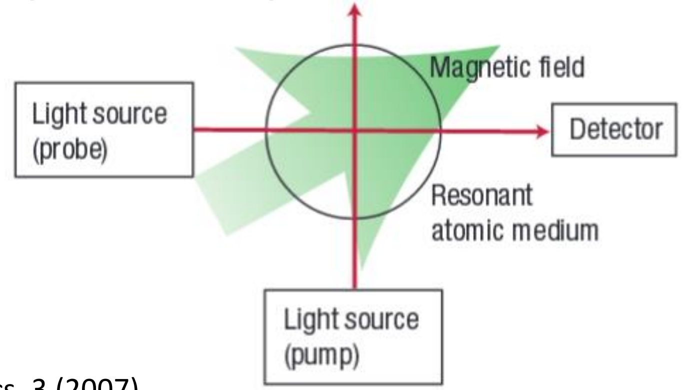
Detects long-range dipolar field

Heil, et al., Ann. Phys. (Berlin) 525 (2013), etc.!

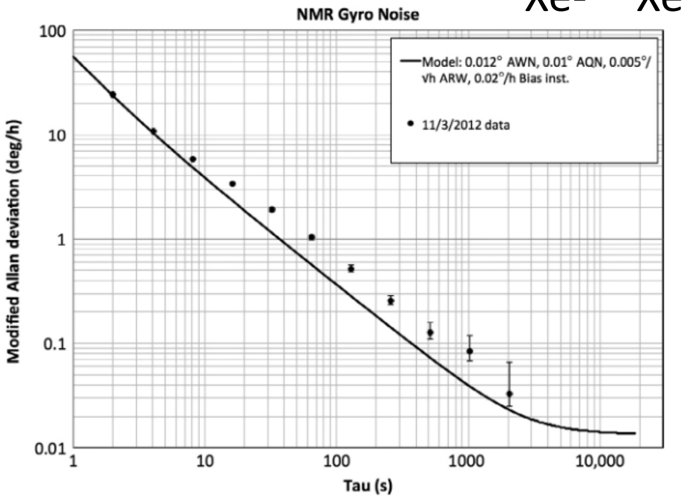


- Alkali Magnetometer

No Cryogens, High SNR: wavefn. overlap



^{129}Xe-^{131}Xe gyro



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T. W. Kornack, R. K. Ghosh and M. V. Romalis. *Phys. Rev. Lett.* **95**, 230801 (2005)

T. Walker, M. Larsen, *Advances In Atomic, Molecular, and Optical Physics*, *65* (2016)
A. Korver, D. Thrasher, M. Bulatowicz, and T. G. Walker, Phys. Rev. Lett. 115, 253001 (2015)
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Rb-noble gas Spin-Exchange: $H_{SK} = \alpha \vec{S} \cdot \vec{K}$

T. Walker, W. Happer, Reviews of Modern Physics, 69, **2** (1997)
M. V. Romalis and G. D. Cates, *Phys. Rev. A* **58**, 3004 (1998)
Z. L. Ma, E. G. Sorte, and B. Saam, Phys. Rev. Lett. **106**, 193005 (2011)

- Alkali $\vec{S}$ Fermi-contact w/ noble-gas nucleus $\vec{K}$
- Enhanced fields ↔ frequency shifts

On Noble Gas

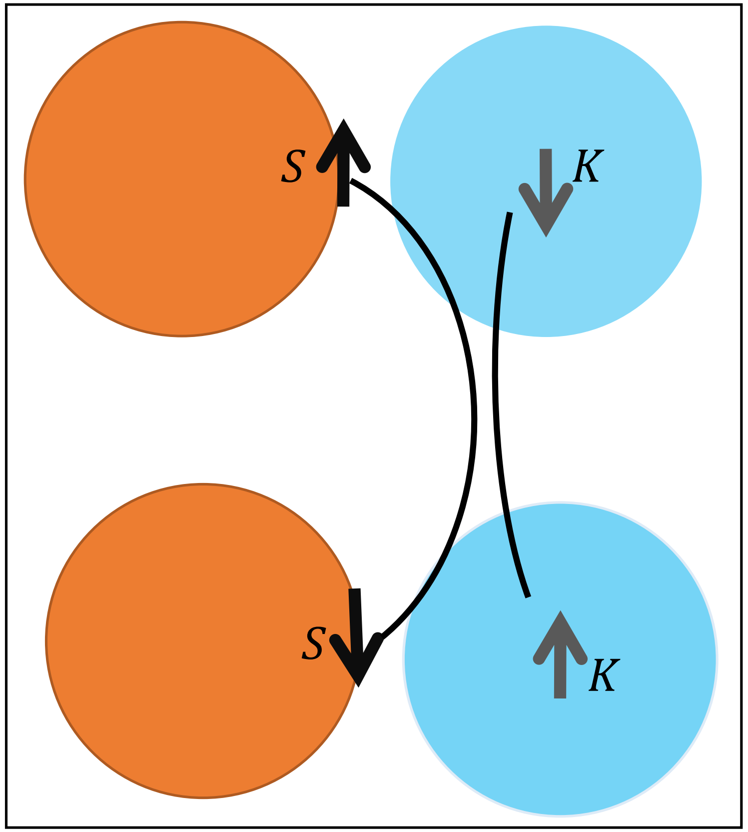
$$\Delta\omega_{\rm NG} \propto -\kappa_0[\mathrm{Rb}]\langle S_z\rangle$$

On Alkali

$$\Delta\omega_{\rm Rb} \propto \kappa_0[\mathrm{NG}]\langle K_z\rangle$$

$$(\kappa_0)_{\rm RbHe} = 5$$
$$(\kappa_0)_{\rm RbXe} = 500$$

Spin-exchange optical pumping (SEOP)

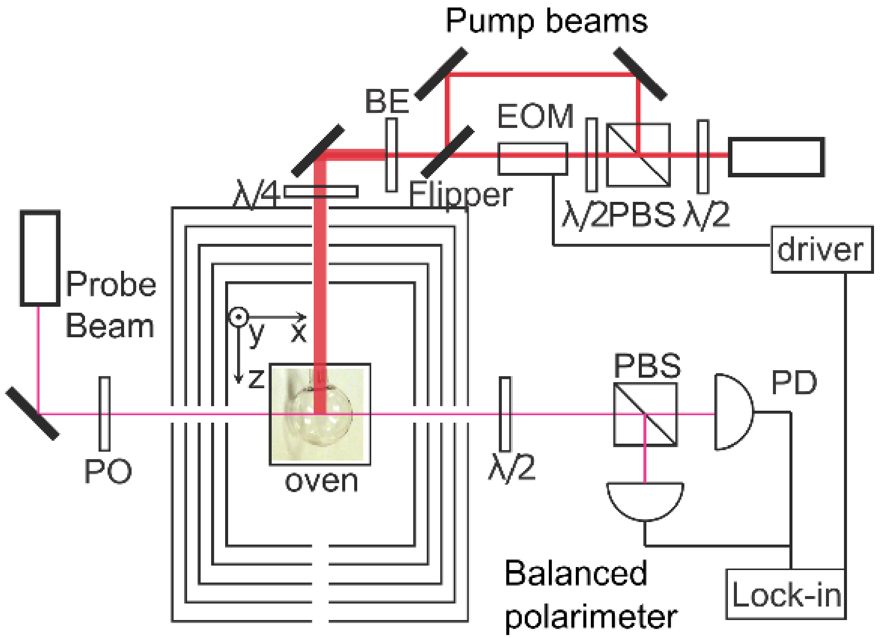


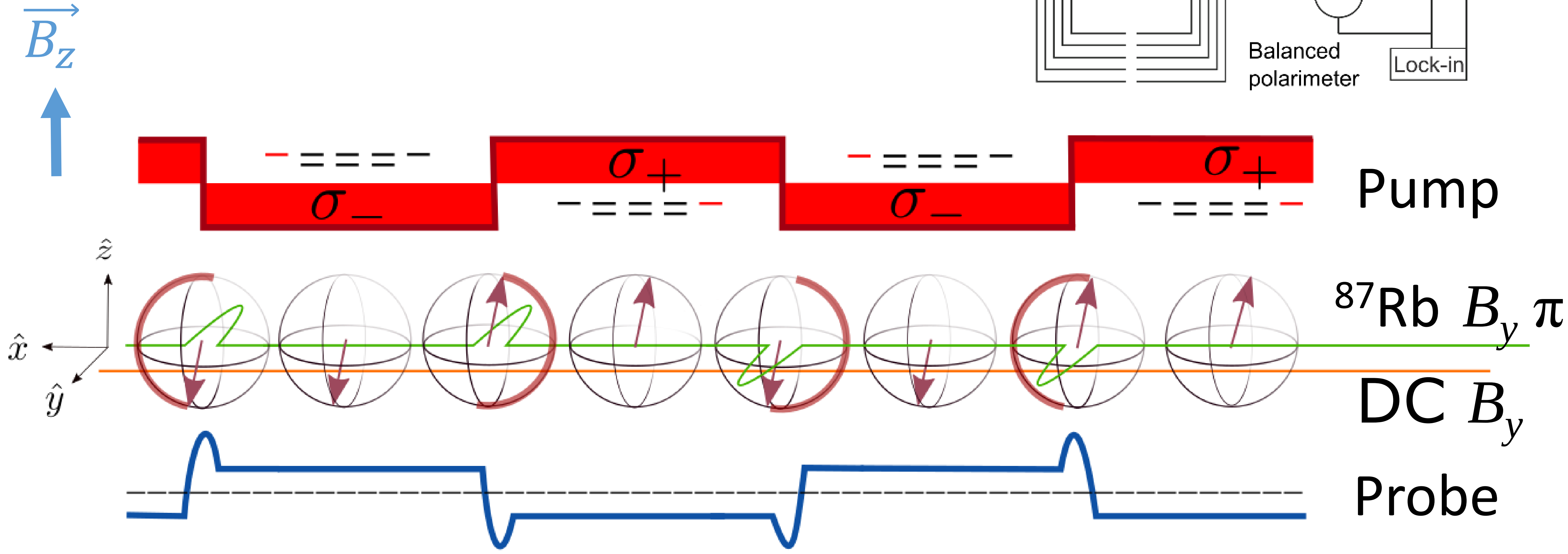
Gist

- 1) Pulse-train ^{87}Rb magnetometer -> High SNR Noble-gas **Detection**
- 2) Ramsey scheme with ^{87}Rb pulse train -> **Precise** measurement
- 3) Rotating ^{87}Rb pulse train -> **Accurate** measurement

^{87}Rb Magnetometer

- ^{87}Rb π pulse train





^{87}Rb Mag.: Spin-Exchange Relaxation Suppression

W. Happer, A. C. Tam, *Phys. Rev. A* **16**, 1877–1991 (1977)

I. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis. *Nature* **422**, 596 (2003)

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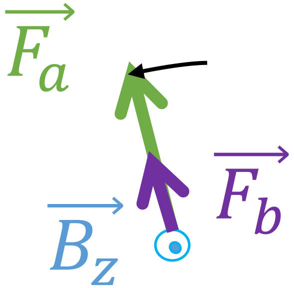
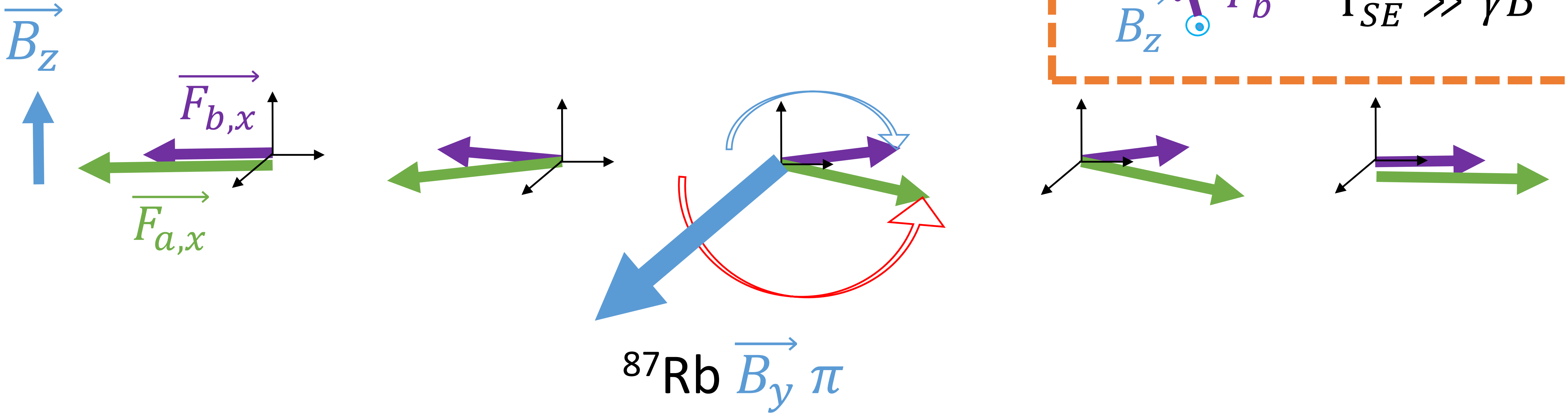
- Hyperfine manifold refocusing $\gamma B_z(\overrightarrow{F_a} - \overrightarrow{F_b})$

Recall: SERF



$$\frac{1}{T_{2SE}} \propto \frac{(\gamma B)^2}{\Gamma_{SE}}$$

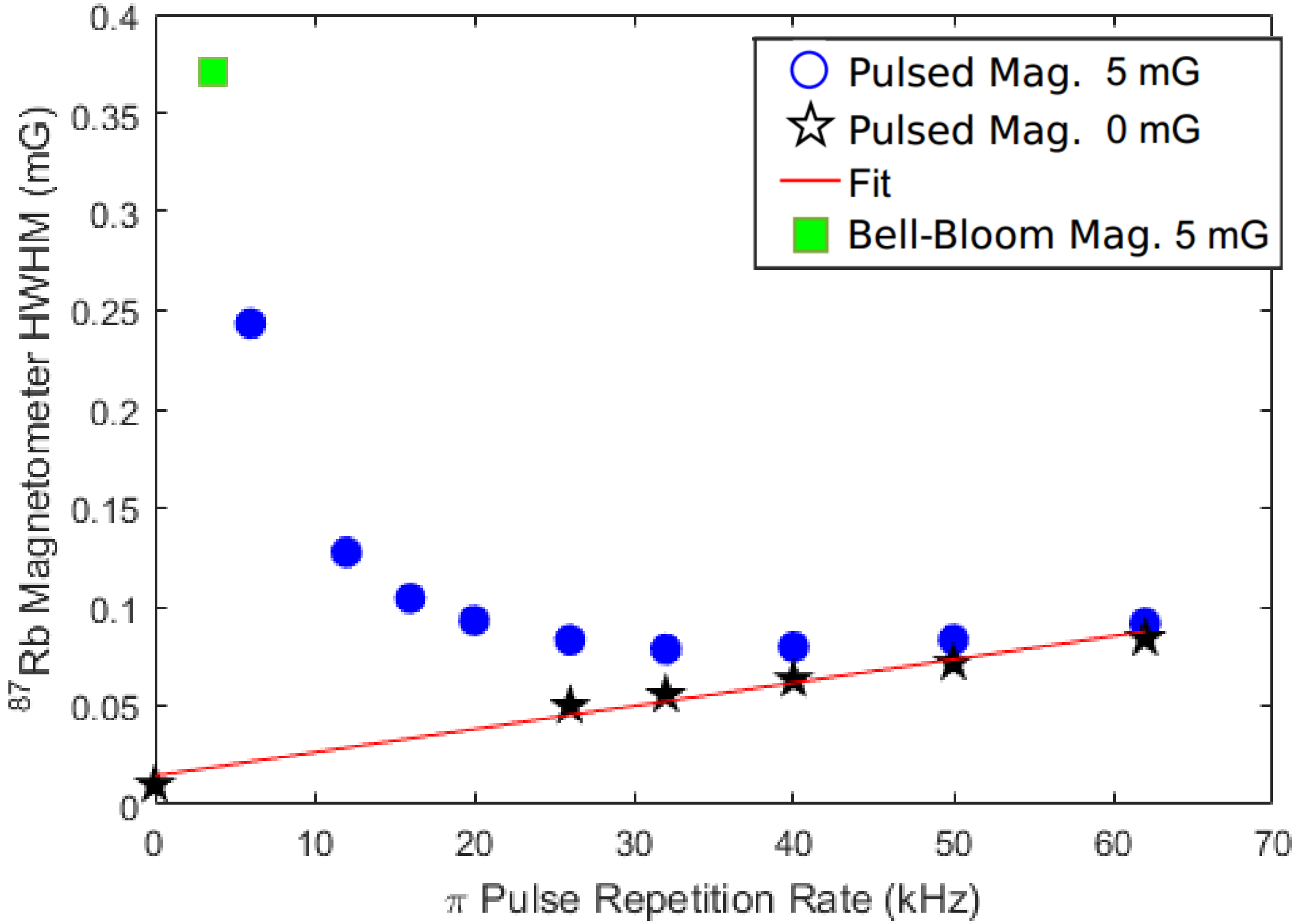
$$\Gamma_{SE} \gg \gamma B$$



If $\Gamma_{pulses} \gg \gamma B_z$, then $\frac{1}{T_{2SE}} \propto t_{pulse}/t_{cycle}$

^{87}Rb Magnetometer Comparison

1.2 us pulse length, Rb-N_2 cell (No H_{SK} broadening)



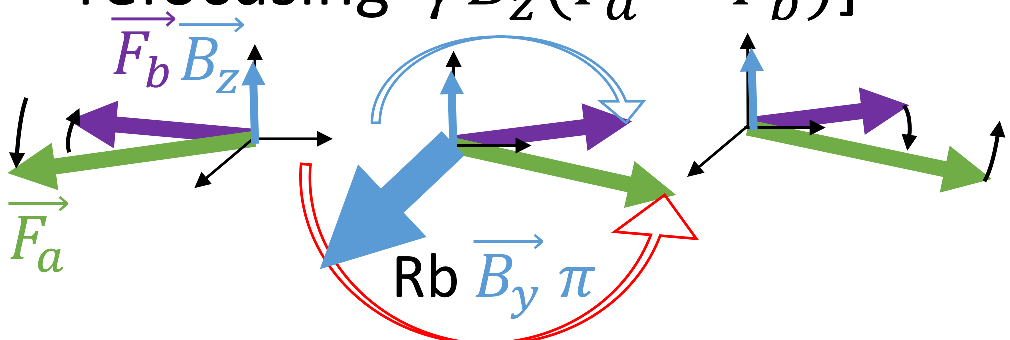
Duty-cycle limited

As $\Gamma_{pulses} \gg \gamma B_z$

$$\frac{1}{T_{2d}} = \Gamma_{SD} + d\Gamma_{SEmax}$$

Spin-Exchange Relaxation Suppression!

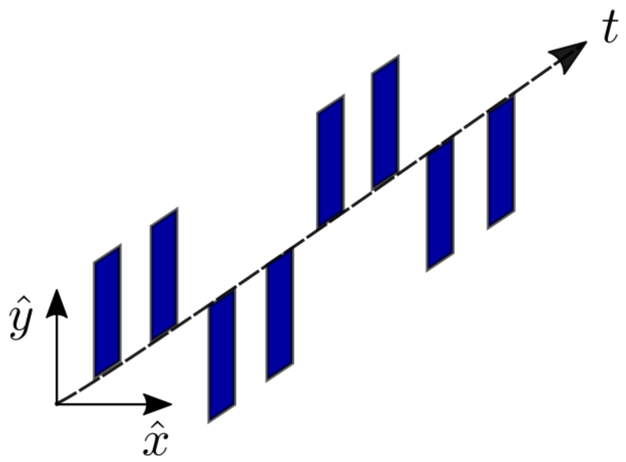
[Hyperfine manifold refocusing $\gamma B_z(\overrightarrow{F_a} - \overrightarrow{F_b})$]



Rb-Xe Decoupling: How good is it?

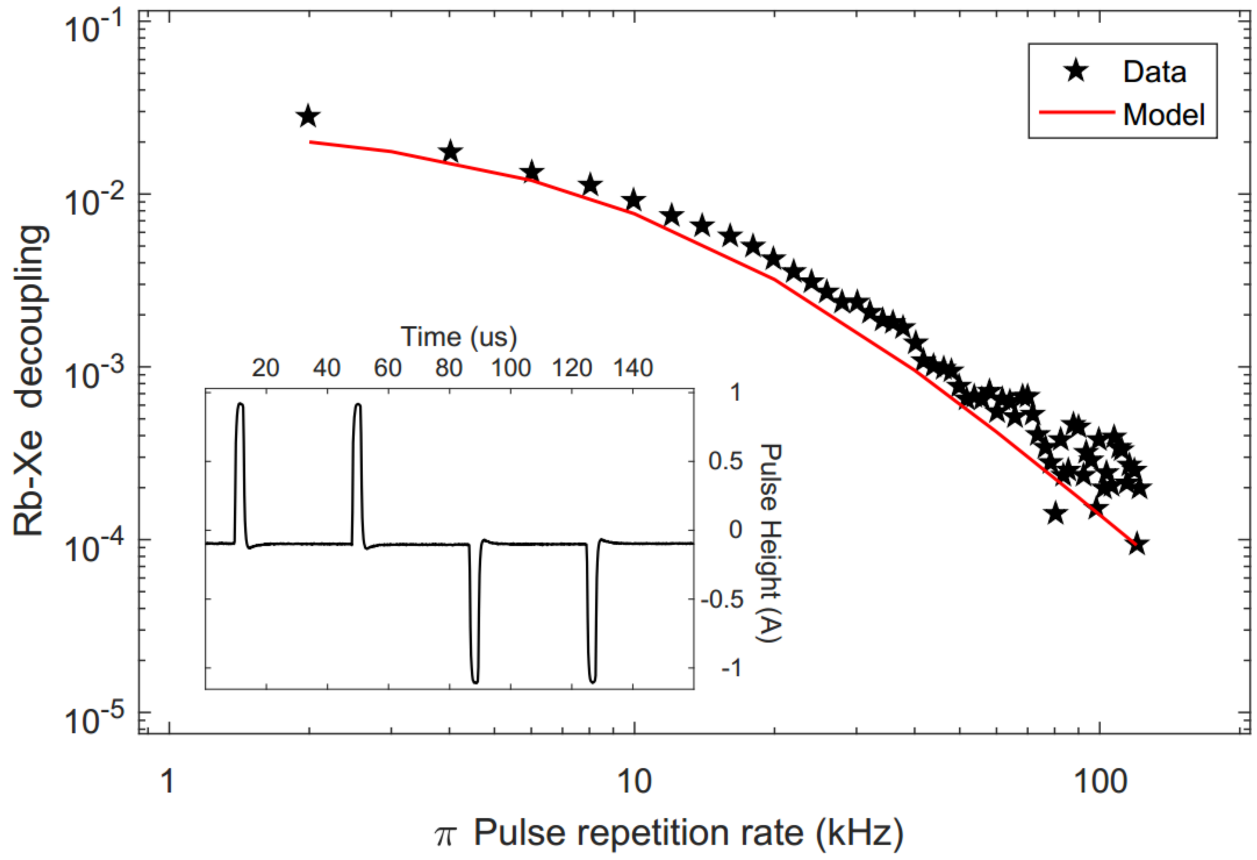
$\overline{H_{SK}} \approx 0$?

- 10^4 decoupling factor of $\vec{K} \cdot \vec{S}$ (along z and x)



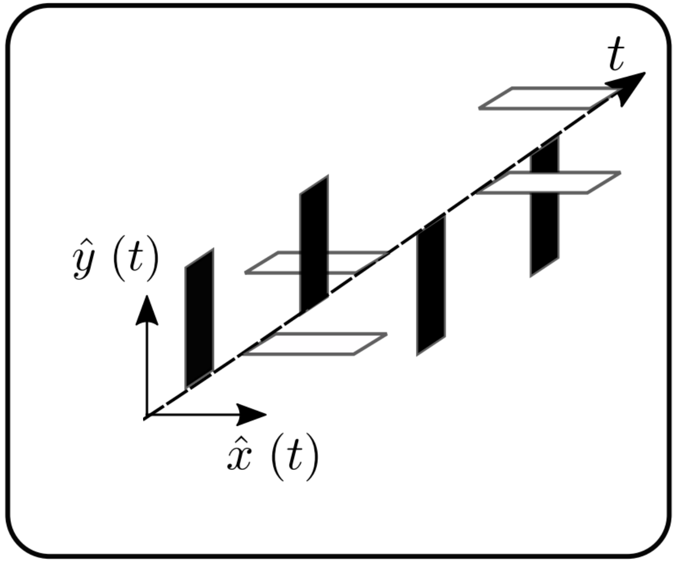
Freq. shift from pulses
on noble gas precession, AHT

$$\omega = \gamma B_0 (1 - \left(\frac{\gamma B_1 t_p}{2}\right)^2)$$

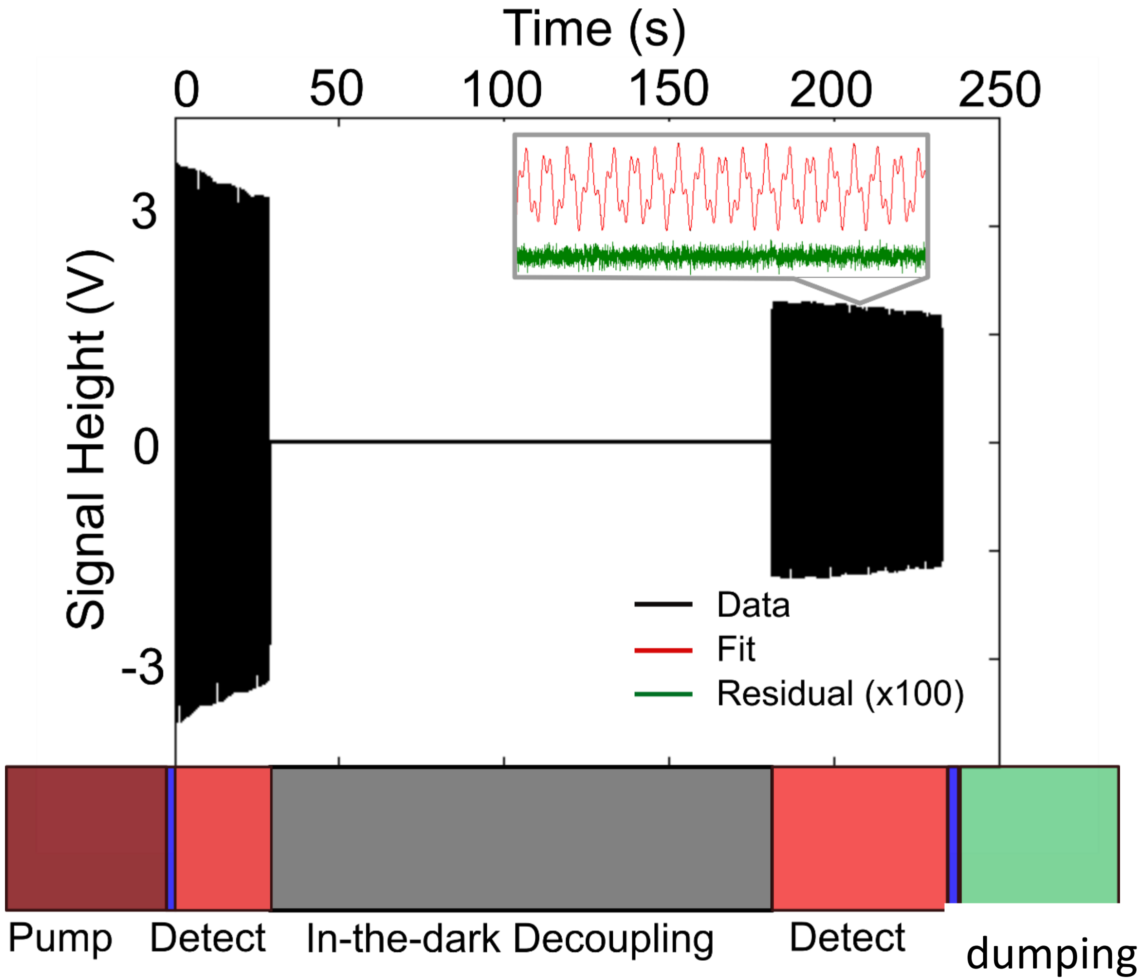


`In-the-dark' Pulse train -> **Precision**

- Ramsey scheme, get $f_r = \frac{\omega_{\mathrm{He}}}{\omega_{\mathrm{Xe}}}$
- 2-axis pulses => 3 axis H_{SK} decoupling

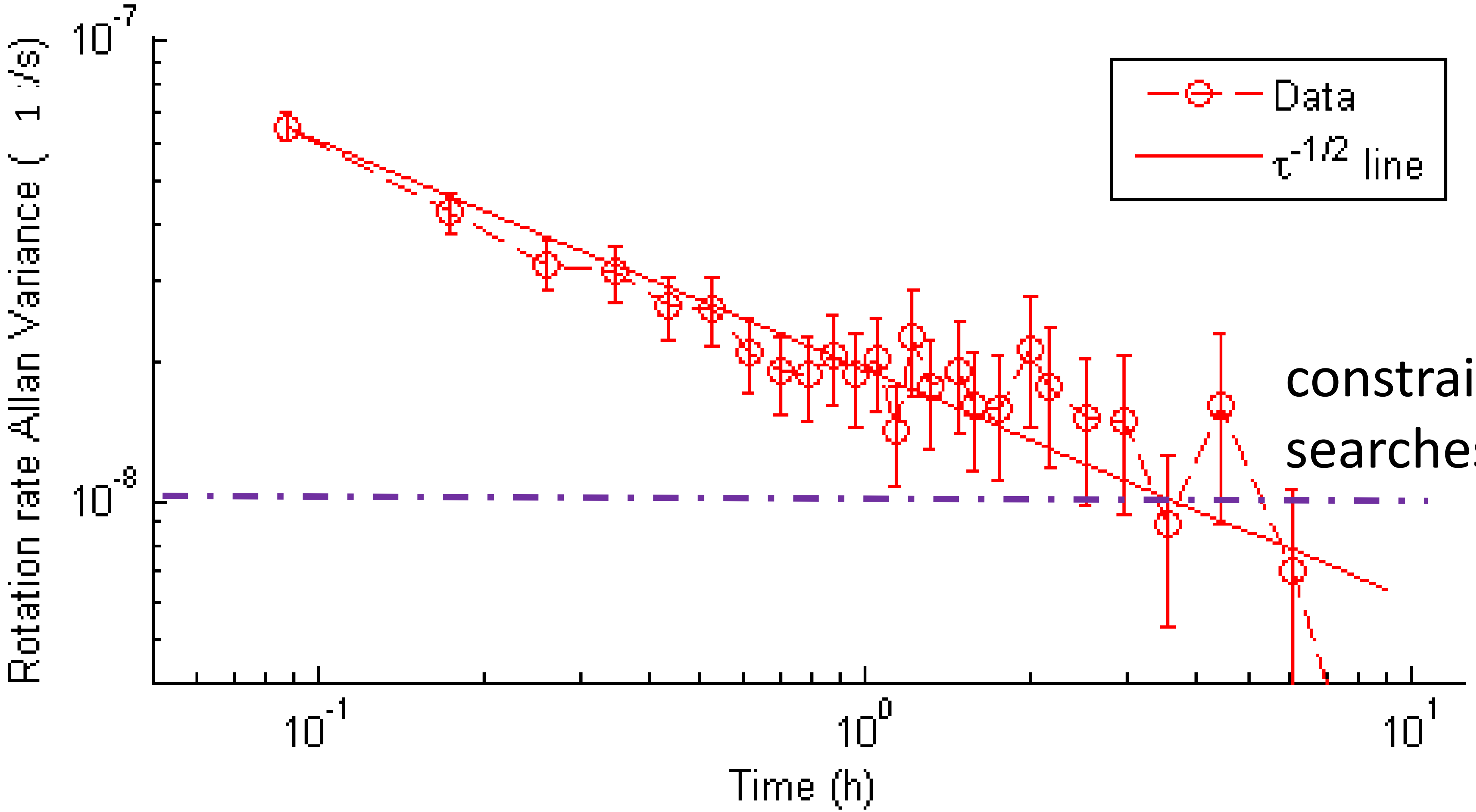


- "Helicity free" π pulse train



^{129}Xe wall T_2 = 1000 s

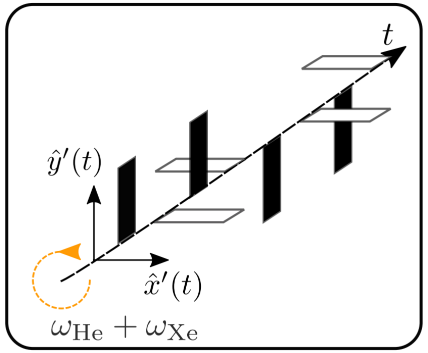
`In-the-dark' Pulse train -> **Precision**



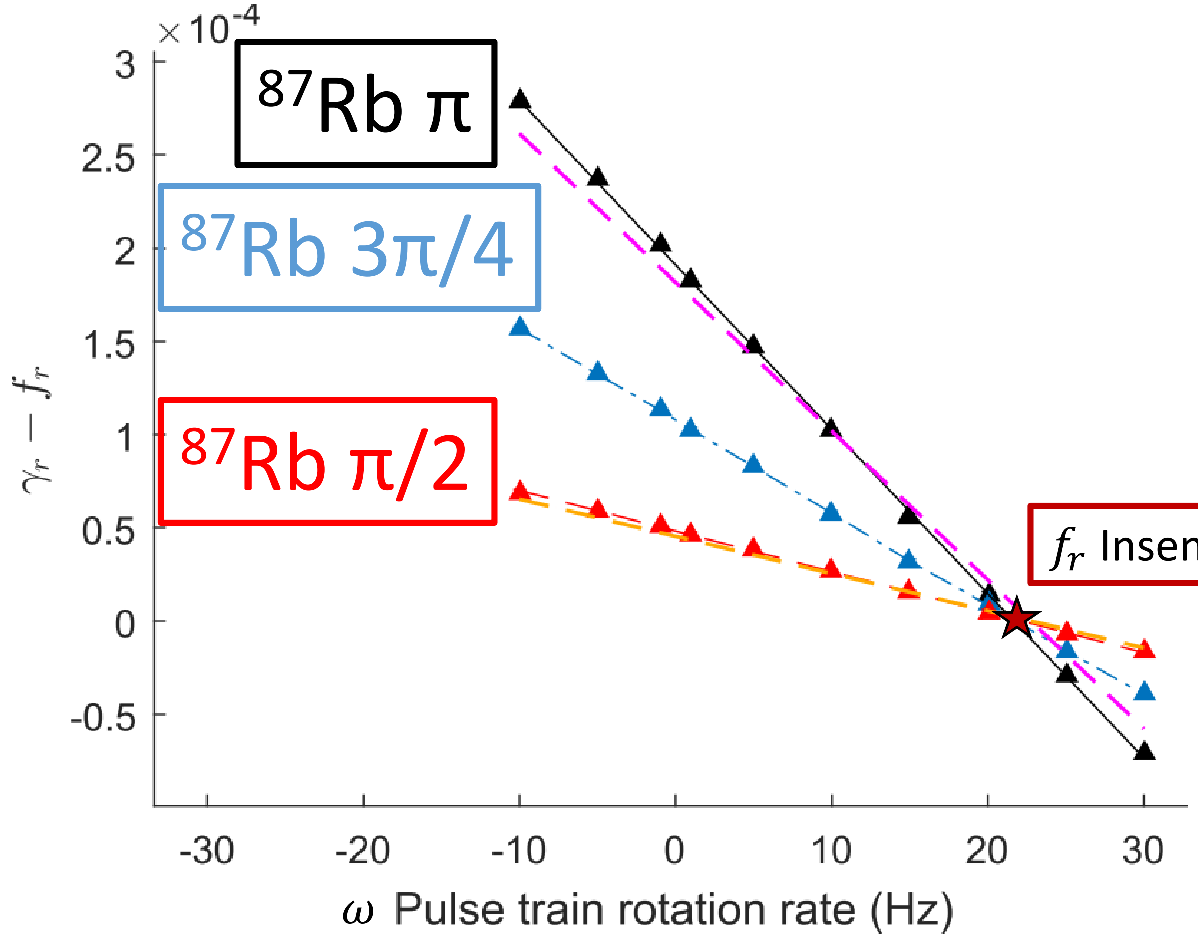
$$f_r = \frac{\omega_{He} \pm \Omega}{\omega_{Xe} \pm \Omega}$$

constrain spin-gravity searches at the Planck scale

Rotating Pulses-> **Accuracy**



- Null effect of pulses on ^{3}He-^{129}Xe freq. ratio by rotating pulse train



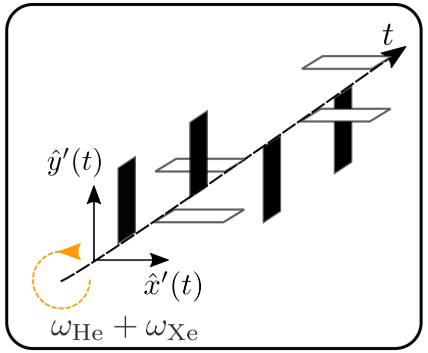
Avg. Ham. Theory

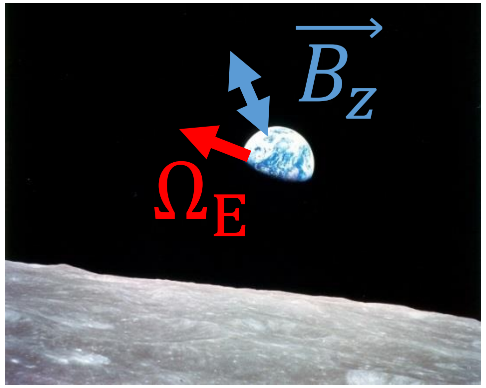
$$f_r = \frac{\omega_{\mathrm{He}}}{\omega_{\mathrm{Xe}}} = \frac{\omega + (\gamma_{\mathrm{He}}\ B_0 - \omega)\left(1 - \frac{3}{8}(\gamma_{\mathrm{He}} B_1 t_p)^2\right)}{\omega + (\gamma_{\mathrm{Xe}}\ B_0 - \omega)\left(1 - \frac{3}{8}(\gamma_{\mathrm{Xe}} B_1 t_p)^2\right)}$$

$$\omega_{\mathrm{He}} + \omega_{\mathrm{Xe}}$$

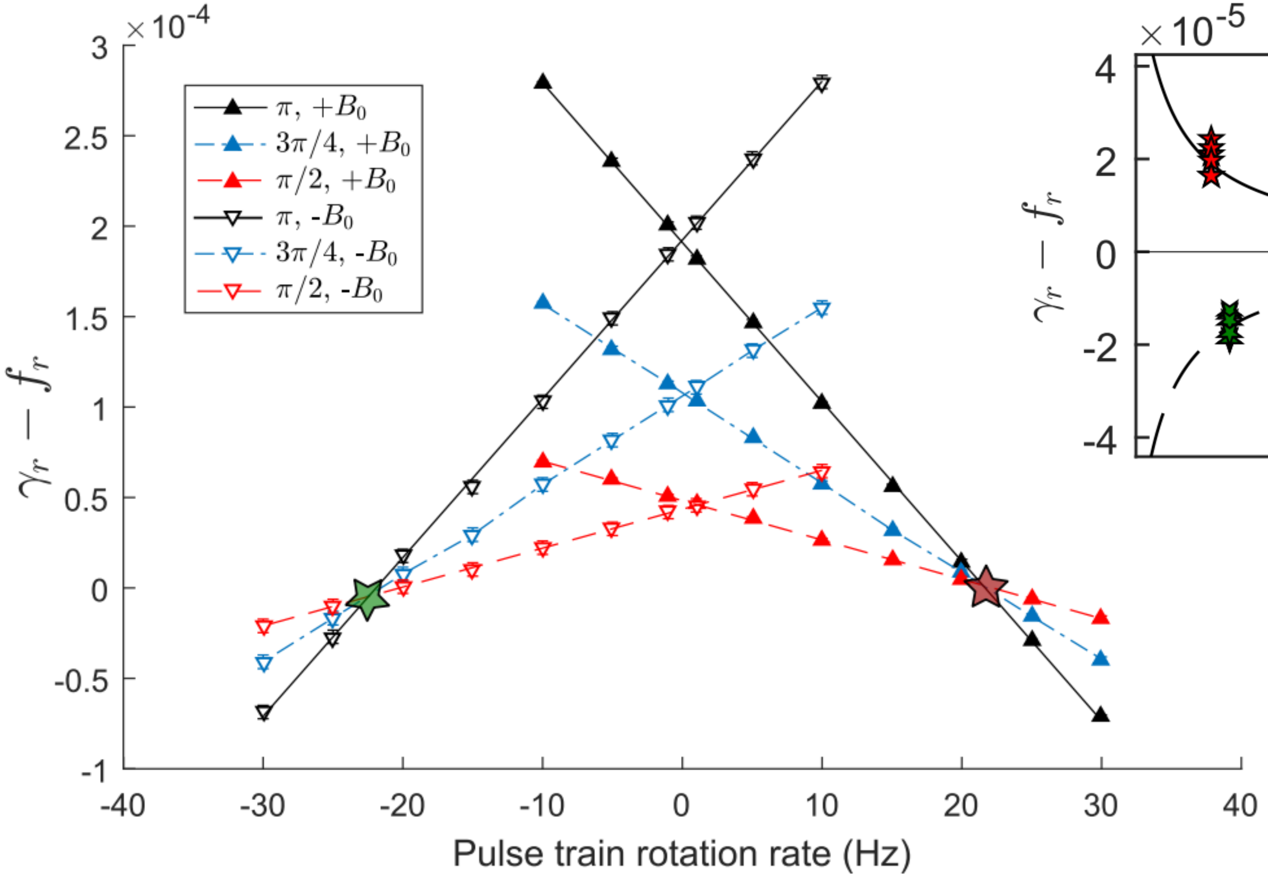
$$\frac{\omega_{\mathrm{He}}}{\omega_{\mathrm{Xe}}} = \frac{\gamma_{\mathrm{He}}}{\gamma_{\mathrm{Xe}}}$$

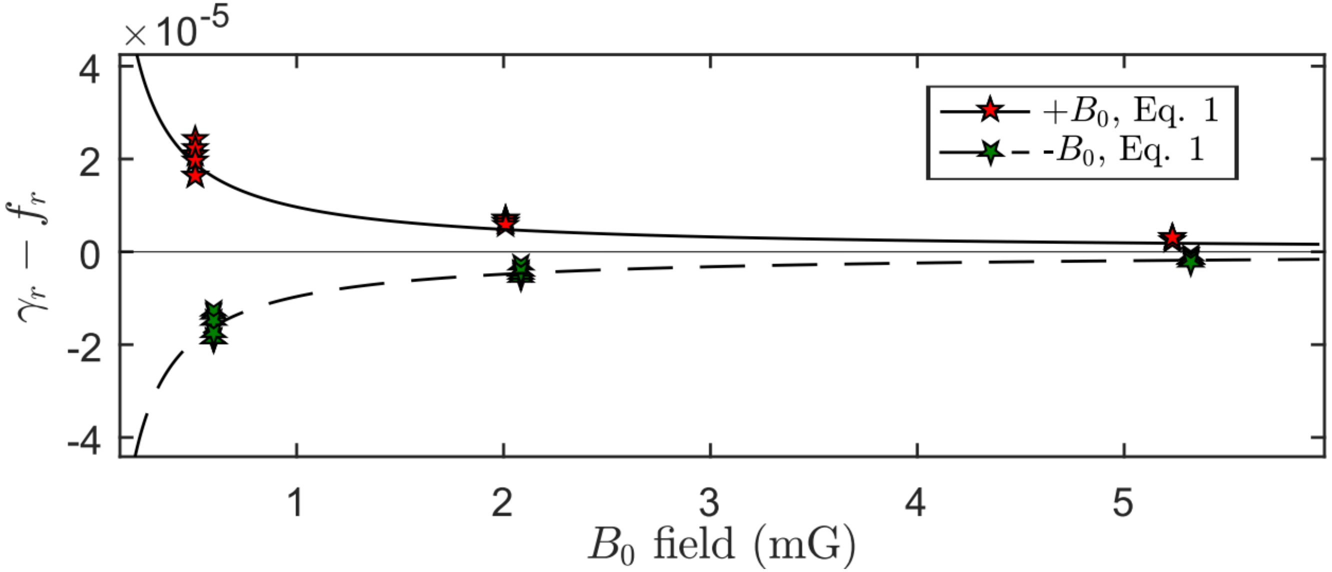
Rotating Pulses-> **Accuracy**





- Considering angle between $\pm B_0$ and Ω_{E}, pick up Ω =6.5 x 10^{-6}



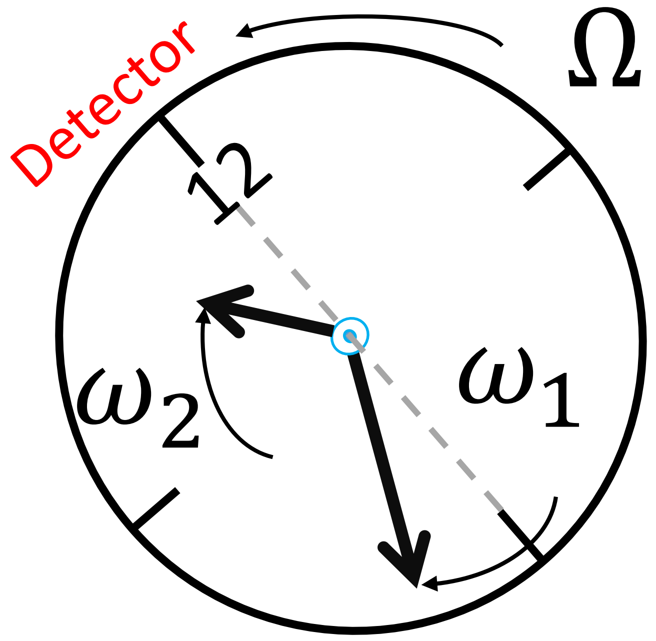


$$f_r = \frac{\omega_{He} \pm \Omega}{\omega_{Xe} \pm \Omega}$$

^{3}He-^{129}Xe Comagnetometer with Pulse-train ^{87}Rb Detection & Decoupling

- **Detection** using ^{87}Rb Pulse-train Magnetometer
- **Precision** at 10 nHz level
- **Accuracy** by rotating pulse train

$$f_r = \frac{\omega_{He} \pm \Omega}{\omega_{Xe} \pm \Omega}$$



Thanks!

- Princeton Group
- PI: Mike Romalis

Bonded cells: Nezih Dural

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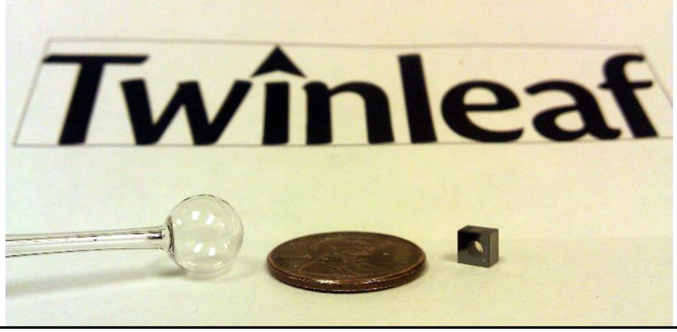
- Twinleaf LLC

Tom Kornack

Jill Foley



^{129}Xe wall T_2 = **100 s!** in anodically bonded cell

Princeton Glassblower

Mike Souza