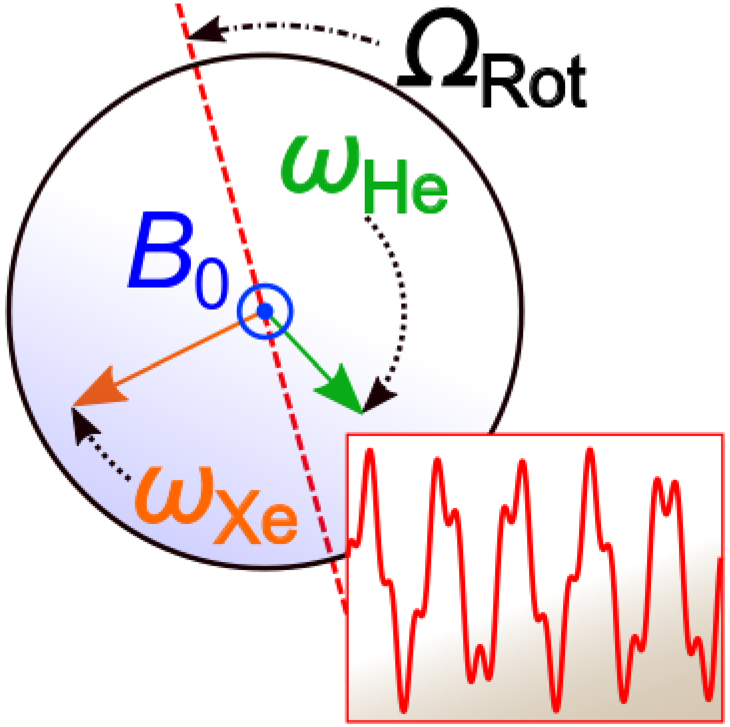
Dipolar and scalar ^{3}He-^{129}Xe frequency shifts in mm-sized stemless cells



arxiv.org/abs/1805.11578

DAMOP 2018, Ft. Lauderdale (Thurs. May 31, 2:48, Grand F)

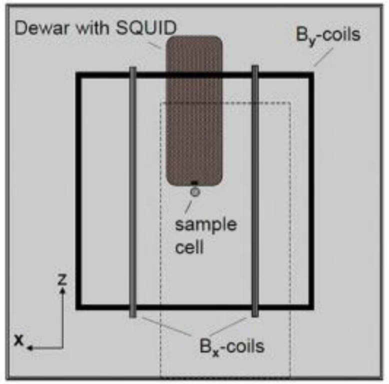
Mark Limes, Nezih Dural, Mike Romalis, Princeton University

Elizabeth Foley, Tom Kornack, Allan Nelson &

Larry Grisham, Twinleaf LLC

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

Dual Nuclear-spin Comag. detection



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

- SQUIDs: Good sensitivity H06 : 9 Terrano, Meinel, Sachdeva, Chupp

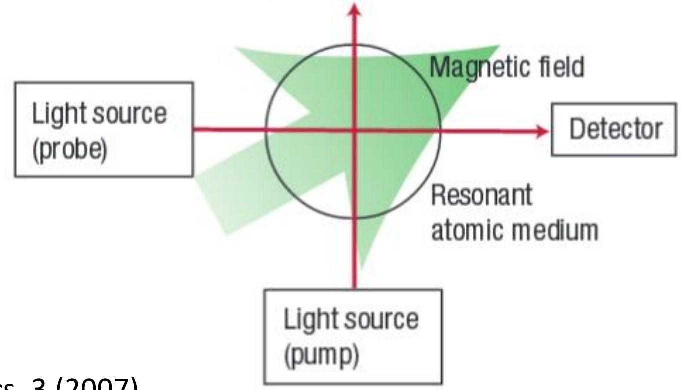
  Detects dipolar field of ^{3}He-^{129}Xe outside sphere

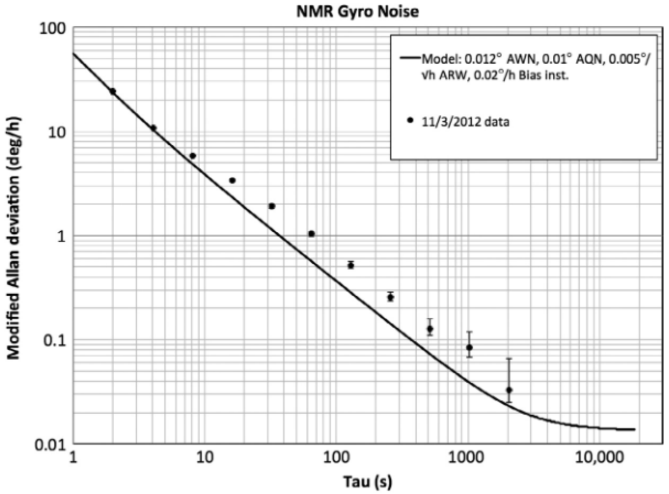
S08 : 2 Thrasher, Sorensen, Weber, Korver, Walker

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

- Alkali Magnetometer

No Cryogens, High SNR: wavefn. overlap





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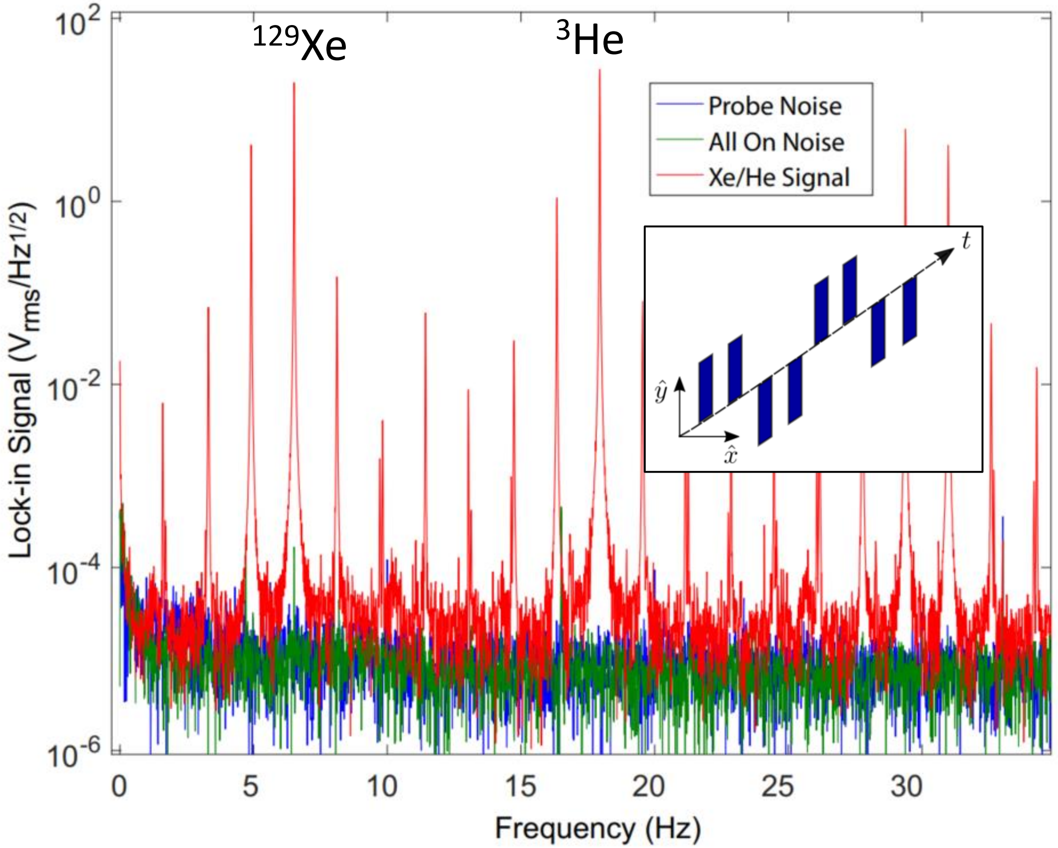
M. Bulatowicz, R. Griffith, M. Larsen, J. Mirijanian, C. B. Fu, E. Smith, W. M. Snow, H. Yan, and T. G. Walker, Phys. Rev. Lett. 111, 102001 (2013)

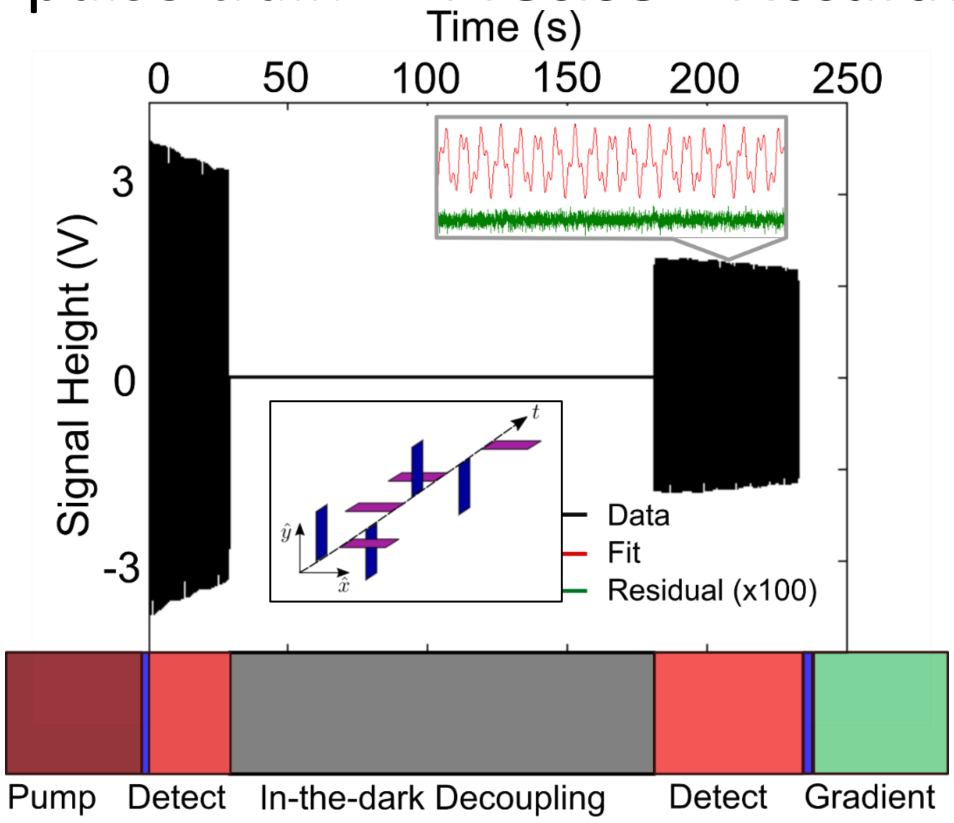
M. V. Romalis and G. D. Cates, *Phys. Rev. A* **58**, 3004 (1998)
Z. L. Ma, E. G. Sorte, and B. Saam, Phys. Rev. Lett. **106**, 193005 (2011)

Gist

$$\Delta\omega_{NG} \propto -\kappa_0[\mathrm{Rb}]\langle S_z\rangle \quad (\kappa_0)_{\mathrm{RbHe}} = 5 \quad (\kappa_0)_{\mathrm{RbXe}} = 500$$

- We need to mitigate differential frequency shifts due to polarized Rb!
- 1) Pulse-train ^{87}Rb magnetometer -> **High SNR Detection of ^{3}He-^{129}Xe**
- 2) Ramsey scheme with rotating ^{87}Rb pulse train -> **Precise + Accurate**





M.E.Limes, D. Sheng, M. V. Romalis, PRL, **120** 033401 (2018)

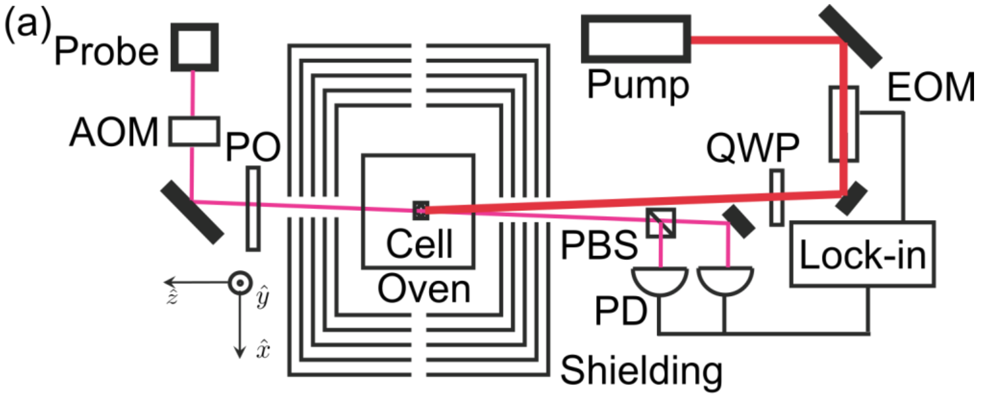
Anodically bonded cells

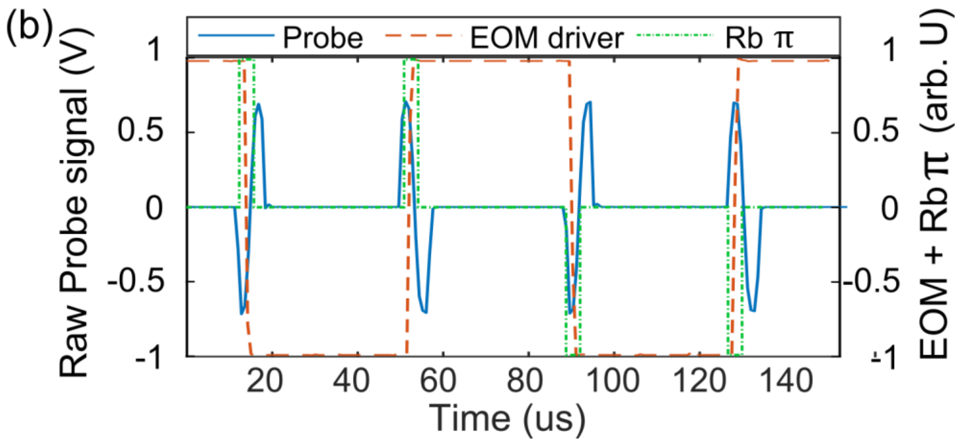
Liew, Knappe, Moreland, Robinson, Hollberg, Kitching, Appl. Phys. Lett. 84, 2694 (2004)

^{129}Xe ~ 5 torr, ^{3}He ~ 1000 torr, N_2-^{87}Rb

^{129}Xe T_w ~300 s, ^{3}He T_2 4 h

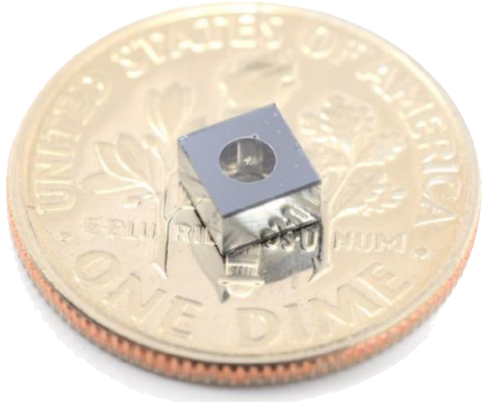
- 1) Single-axis pump/probe scheme
- 2) Record ^{129}Xe lifetimes for mm-sized cells

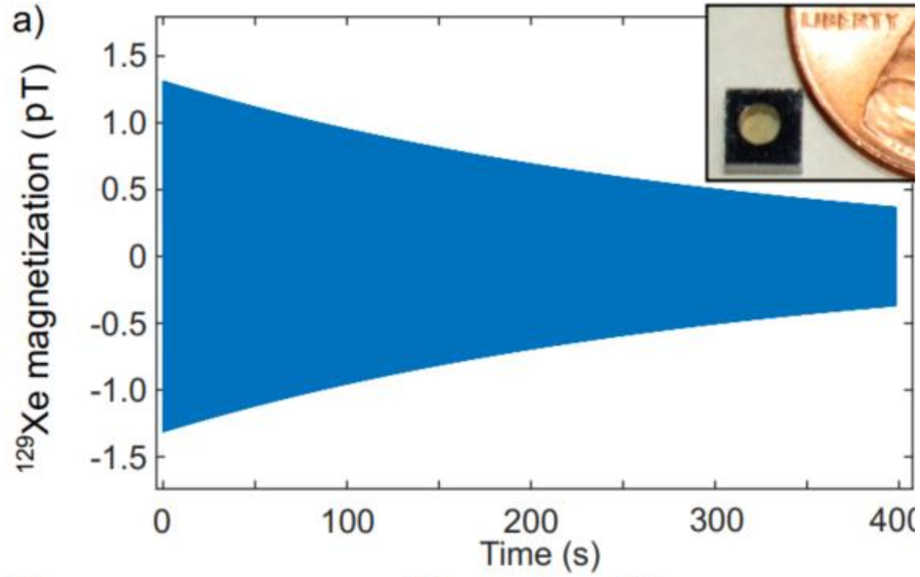


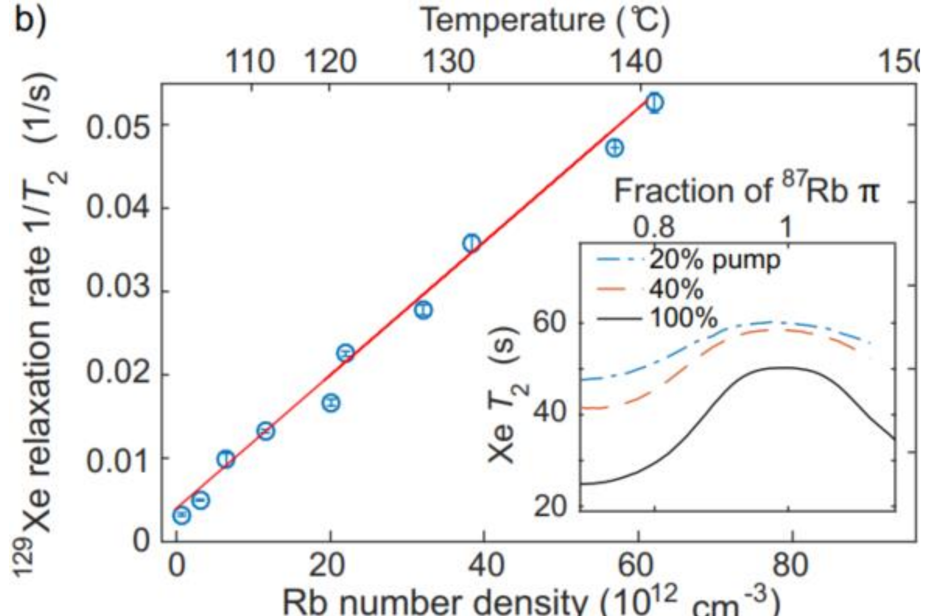


arxiv.org/abs/1805.11578

6 mm^3 active volume







Dipolar fields (NMR shape effect)

arxiv.org/abs/1805.11578

- Spherical cells null classical dipolar fields

  -Glass blown spheres imperfect, stems need plugged

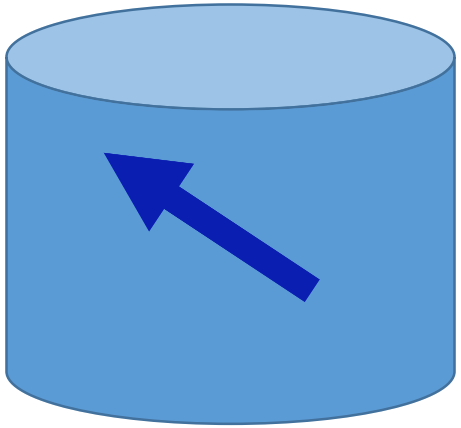
- There also exists a ***cylinder size*** h/d = 0.9065**,** dipolar effect vanishes!

  -Anodically bonded cells have very well-defined geometries

$$B_{dip}(\hat{r}) = \frac{3\hat{r}(\hat{r} \cdot m) - m}{r^3}$$

$$B_{con} = \frac{8\pi\kappa}{3} M_{He}$$

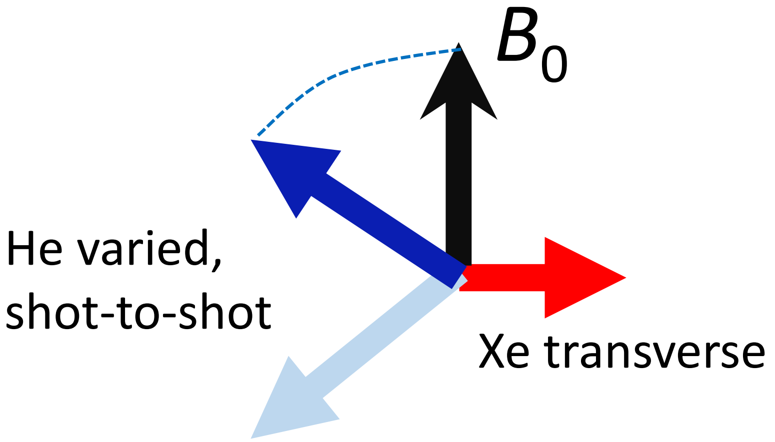
uniform density of dipoles, n=M/m

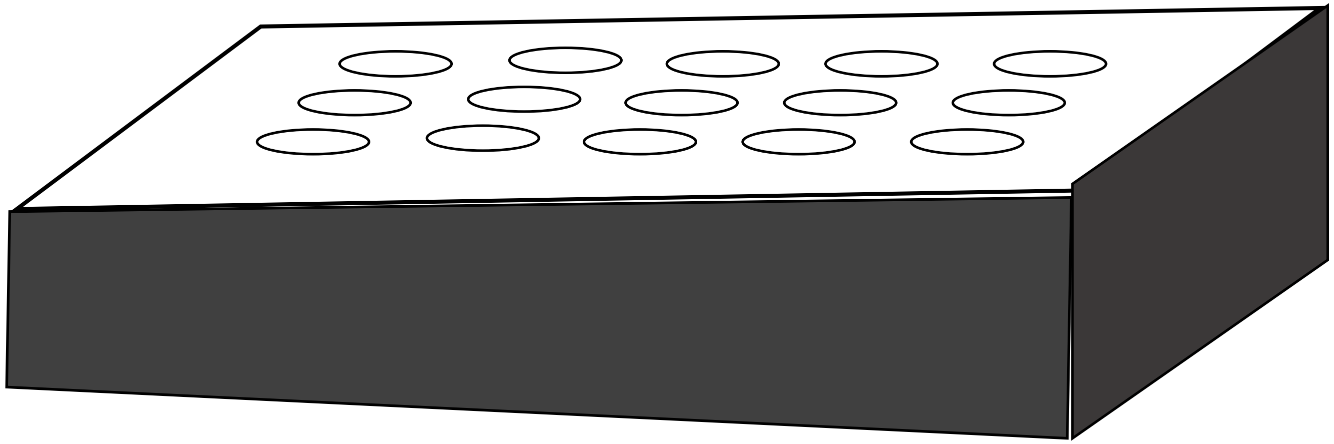


Dipolar fields (NMR shape effect)

arxiv.org/abs/1805.11578

- Experiment: Vary projection of ^{3}He M on B_0, and vary cell size





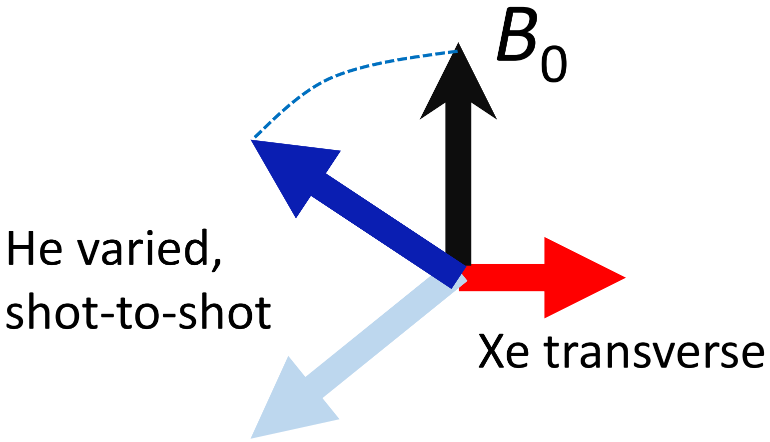
For different cell sizes, anodically bond with graded silicon wafers,
Get cells with sizes about h/d = 0.9065

$$f_r - \gamma_r = \frac{\omega_{He}}{\omega_{Xe}} - \frac{\gamma_{He}}{\gamma_{Xe}}$$

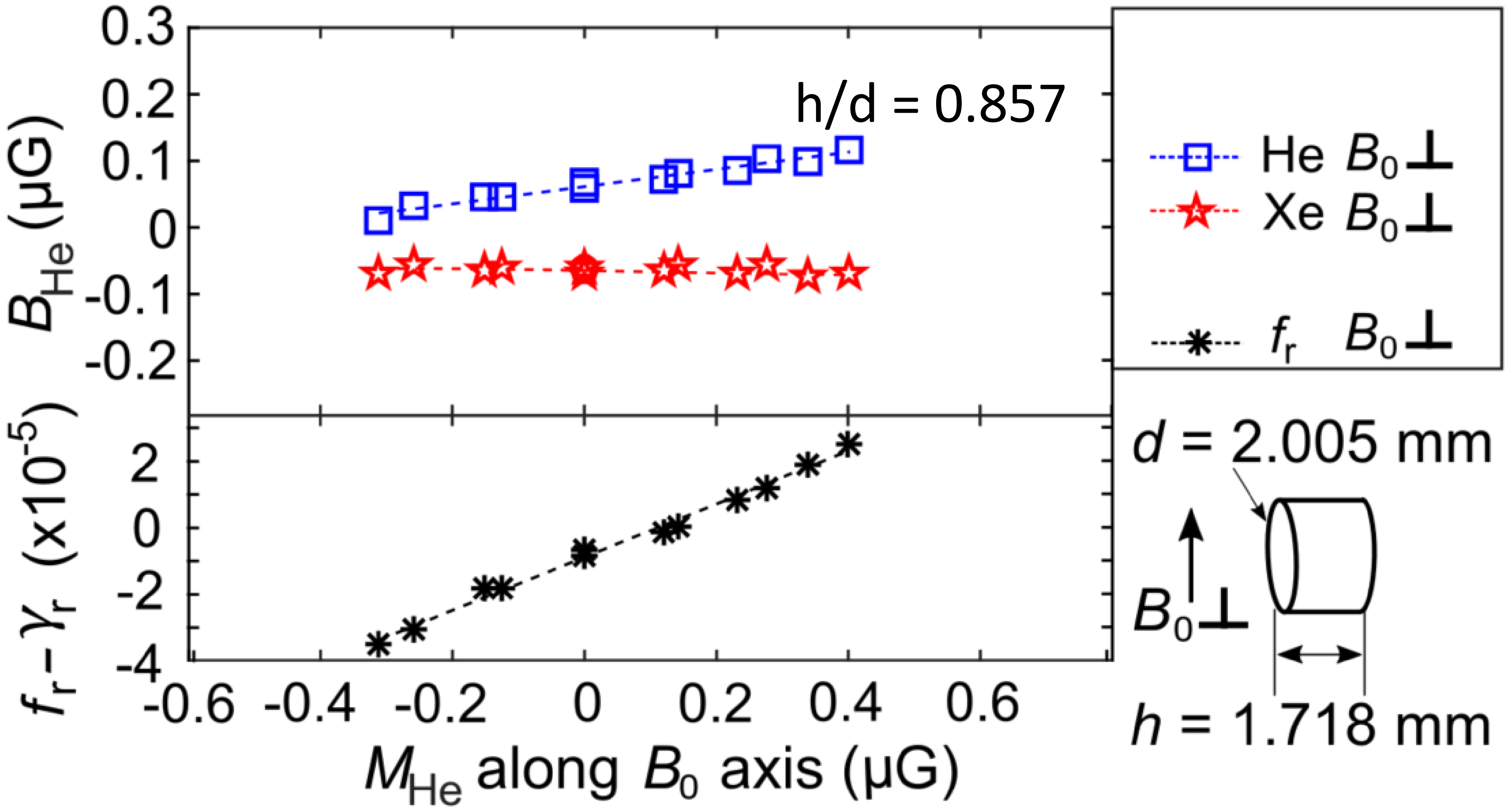
Experiment

arxiv.org/abs/1805.11578

- Vary projection of ^{3}He M on bias field B0 axis



$$f_r - \gamma_r = \frac{\omega_{He}}{\omega_{Xe}} - \frac{\gamma_{He}}{\gamma_{Xe}}$$



Field experienced due to M_{He} v. orientation

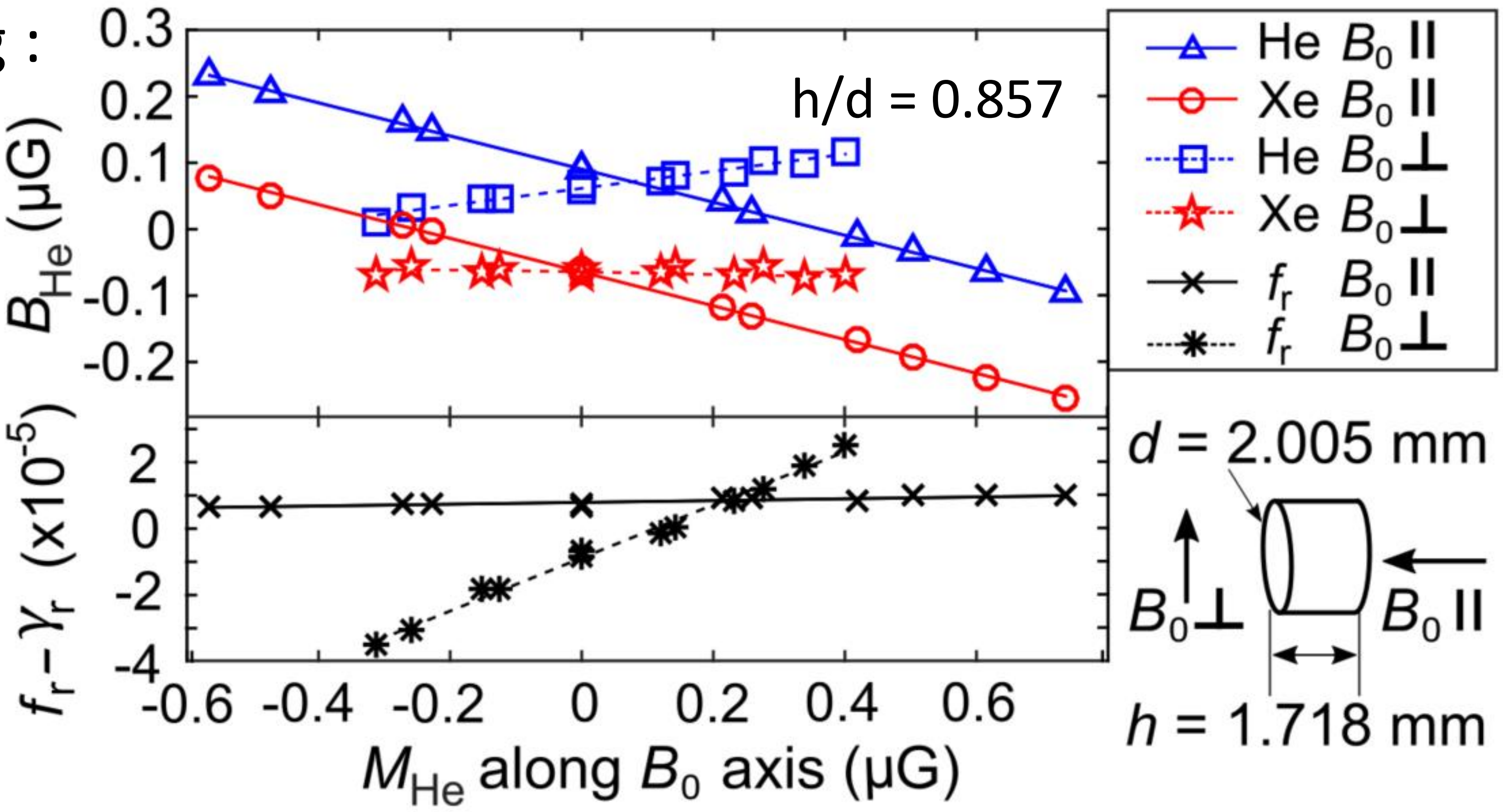
arxiv.org/abs/1805.11578

- Plot slopes v. cylinder dimension with B0 perp and para to cylinder axis

- f_r Sensitivity to He tipping :
- 1) Zeroed out for h/d = 0.857…
- 2) Not at theoretical

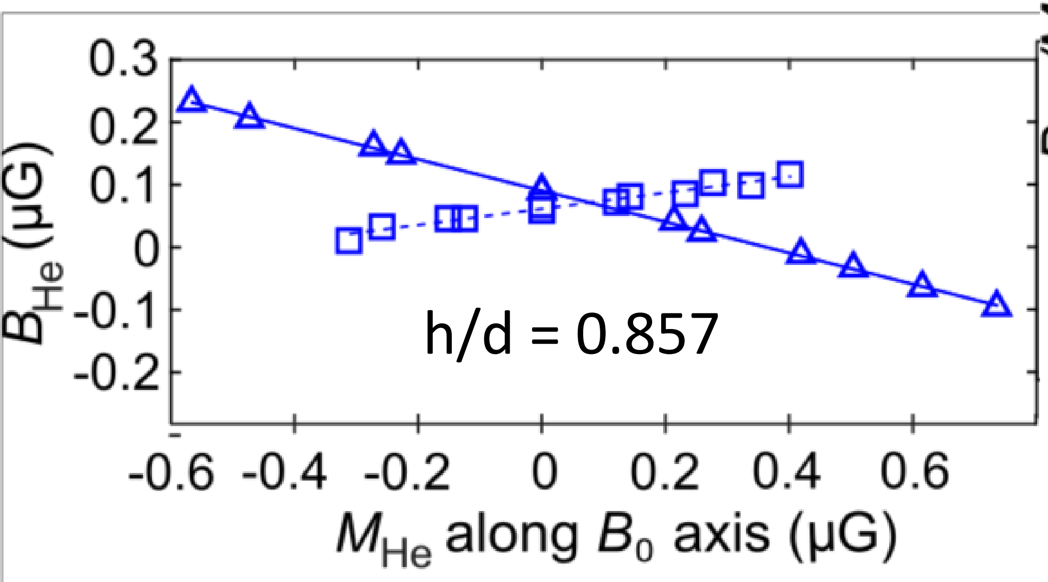
  value of h/d = 0.9065
- 3) Depends on

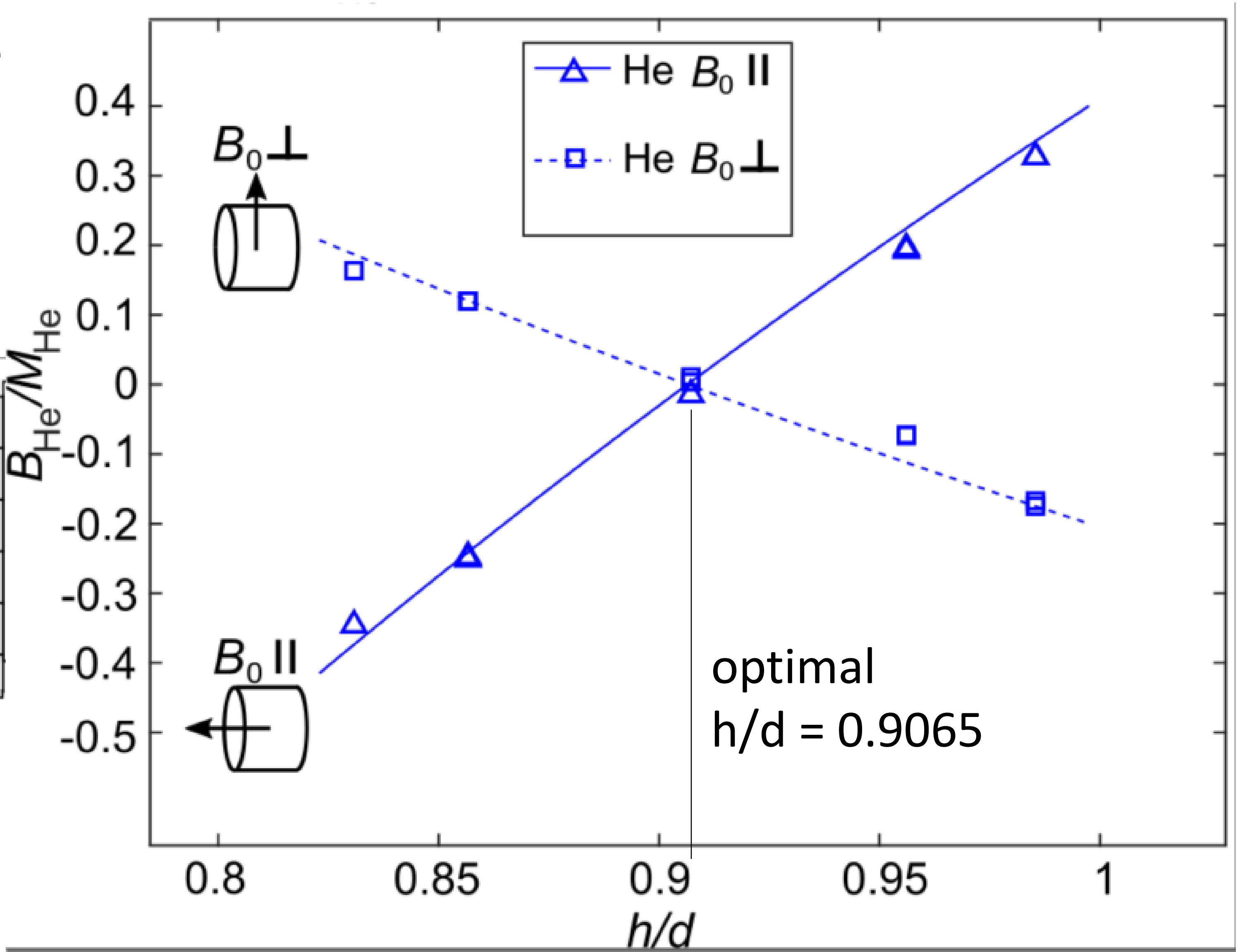
  orientation w.r.t. B_0



Field experienced by ^{3}He due to M_{He} v. cylinder size

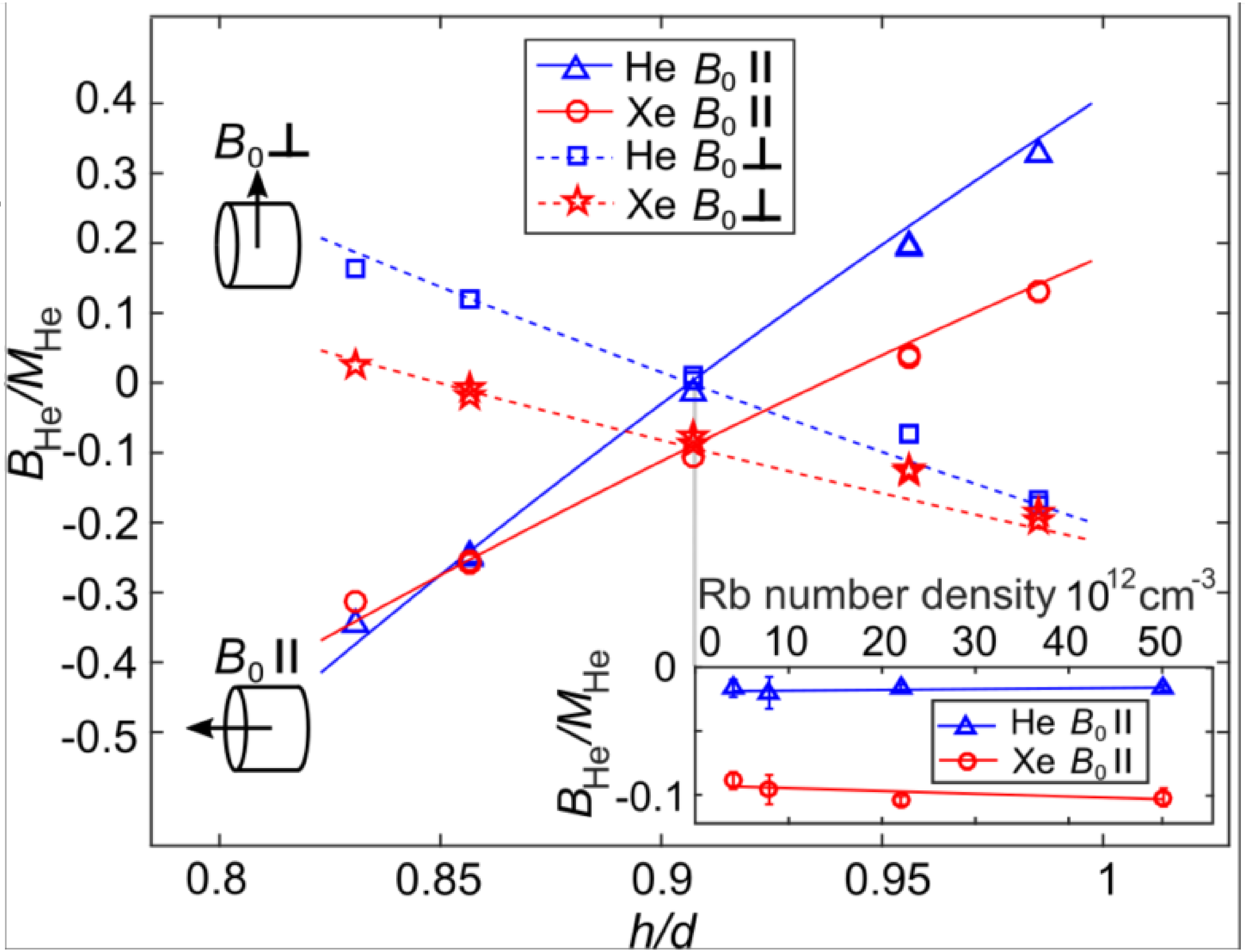
- h/d = 0.9065 is a cylinder where the dipolar field should vanish
- Theory with no free parameters





Field experienced by ^{129}Xe due to M_{He} v. cylinder size

- h/d = 0.9065 is a cylinder where the dipolar field should vanish
- Theory with one free parameter
- ^{129}Xe shifted…
- Independent of Rb density



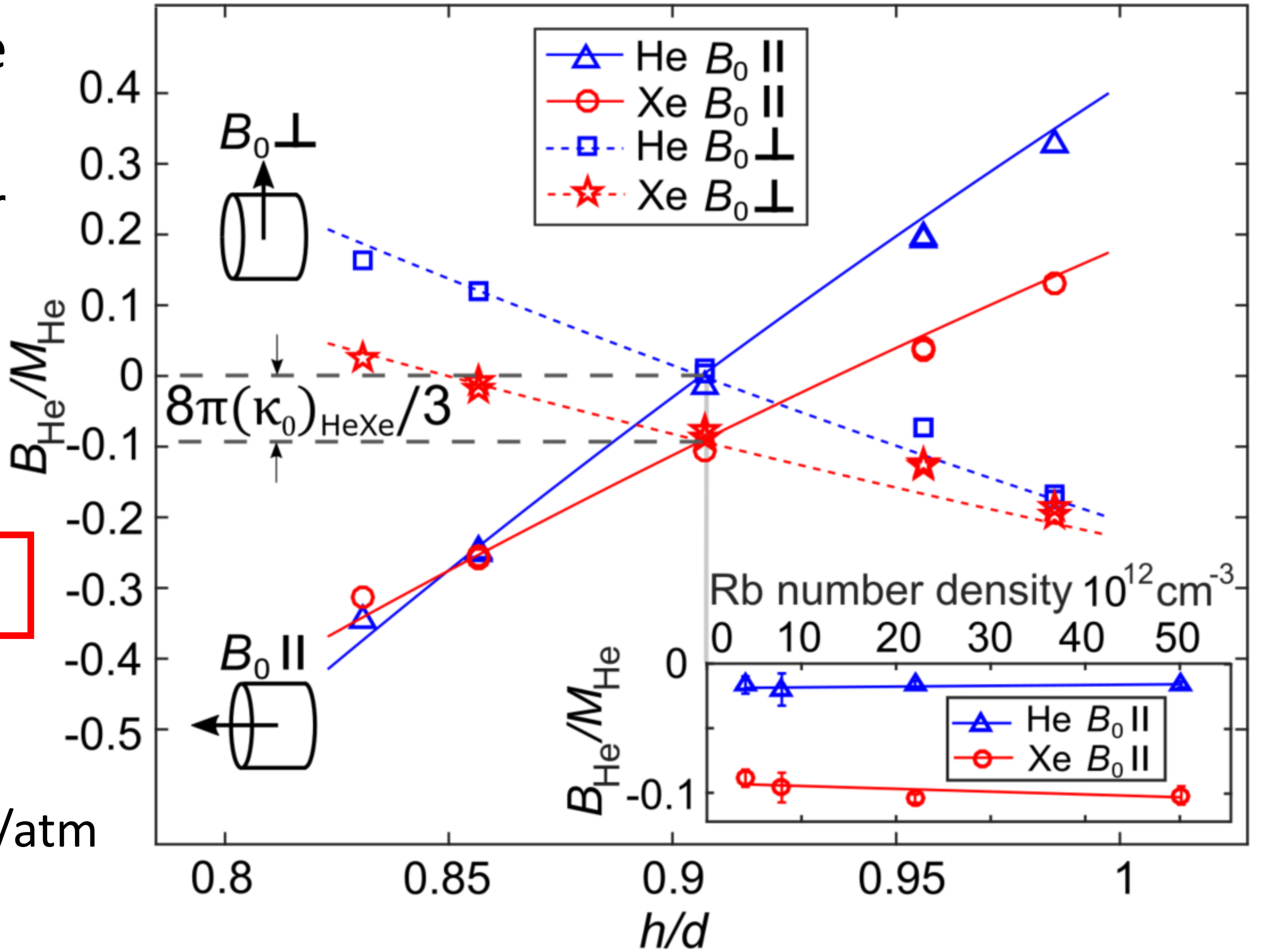
^{129}Xe experiences scalar field from ^{3}He

- h/d = 0.9065 is a cylinder where the dipolar field should vanish
- Theory with one free parameter
- ^{129}Xe shifted…
- Independent of Rb density
- $B_{dipole} + B_{contact}$!

$$\kappa_{\mathrm{HeXe}} = -0.011 \pm 0.001$$

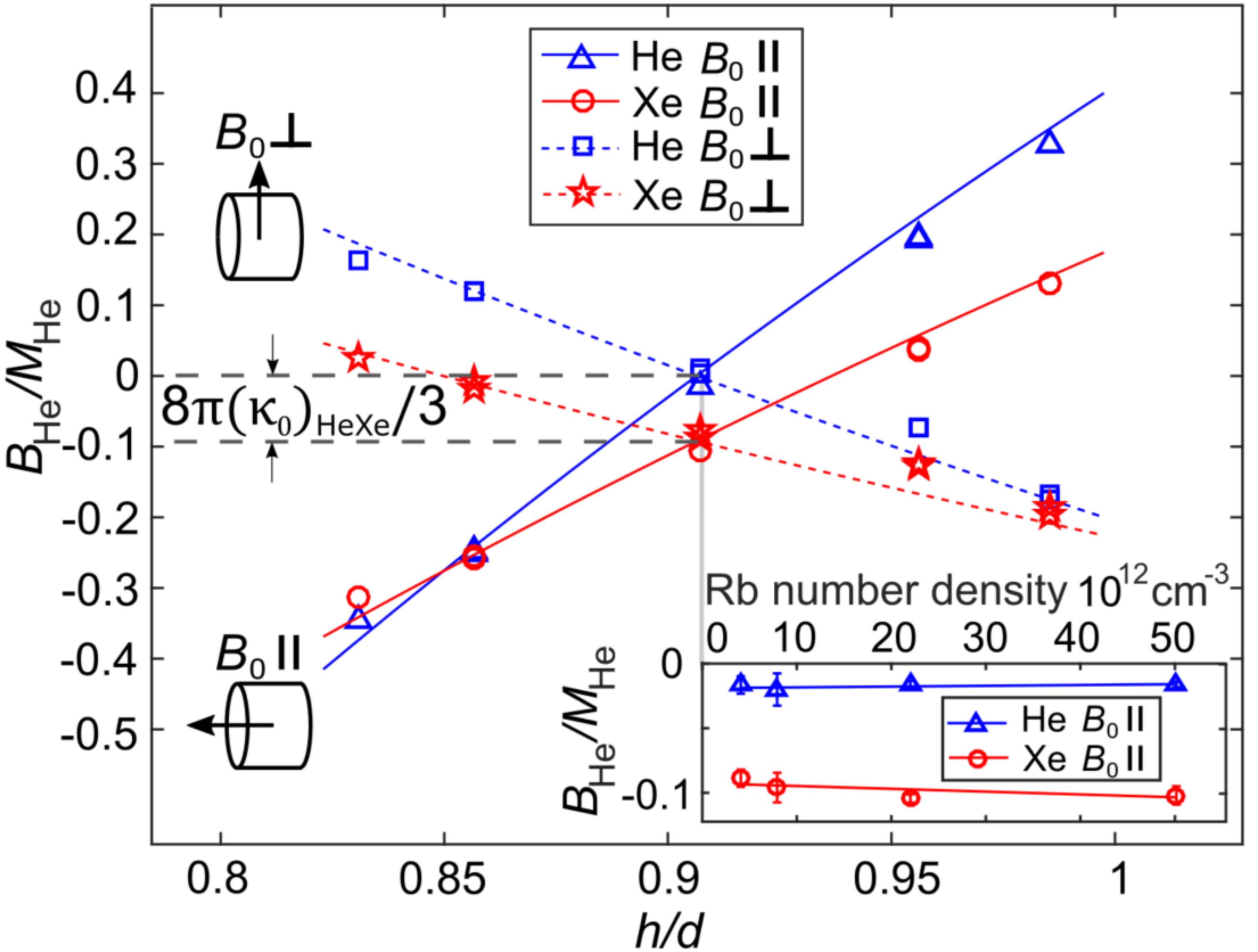
$$H = J\overrightarrow{I_{He}} \cdot \overrightarrow{I_{Xe}}$$

$$\frac{J}{P_{\mathrm{He}}} = \frac{8}{3}\gamma_{\mathrm{Xe}}\mu_{\mathrm{He}}n_0 = -62 \text{ mHz/atm}$$



A few practical take-aways from κ_{HeXe}

- J coupling between gases!
- Null projection of He on bias field (good tipping pulses)
- To null frequency ratio dep., consider cylinder size, orientation w.r.t. bias field
- A **perfectly spherical** comagnetometer cell ***is sensitive*** to imperfect tipping pulses



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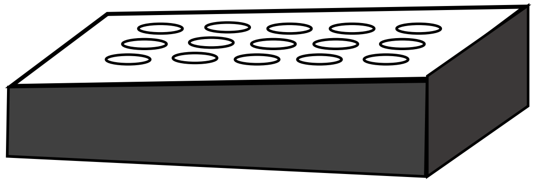
Dipolar and scalar ^{3}He-^{129}Xe frequency shifts in mm-sized stemless cells

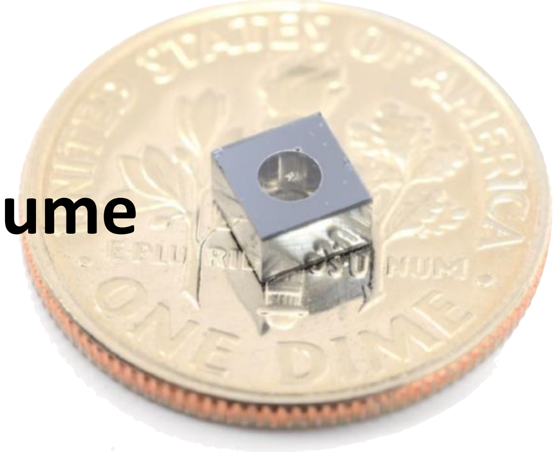
$$f_r = \frac{\omega_{He} \pm \Omega}{\omega_{Xe} \pm \Omega}$$

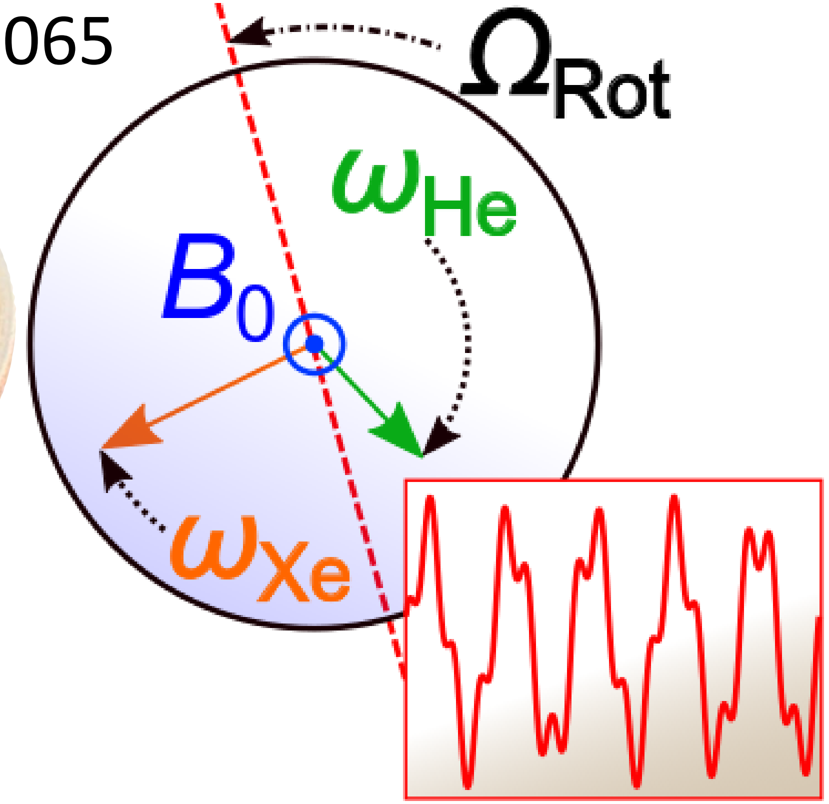
arxiv.org/abs/1805.11578

- **Precise and Accurate Detection** with ^{87}Rb pi Pulse-trains + Ramsey
- Single-axis pump/probe, 300 s Xe wall time in anodically bonded cell
- **Control and null** classical dipolar fields h/d = 0.9065



6 mm^3 active volume





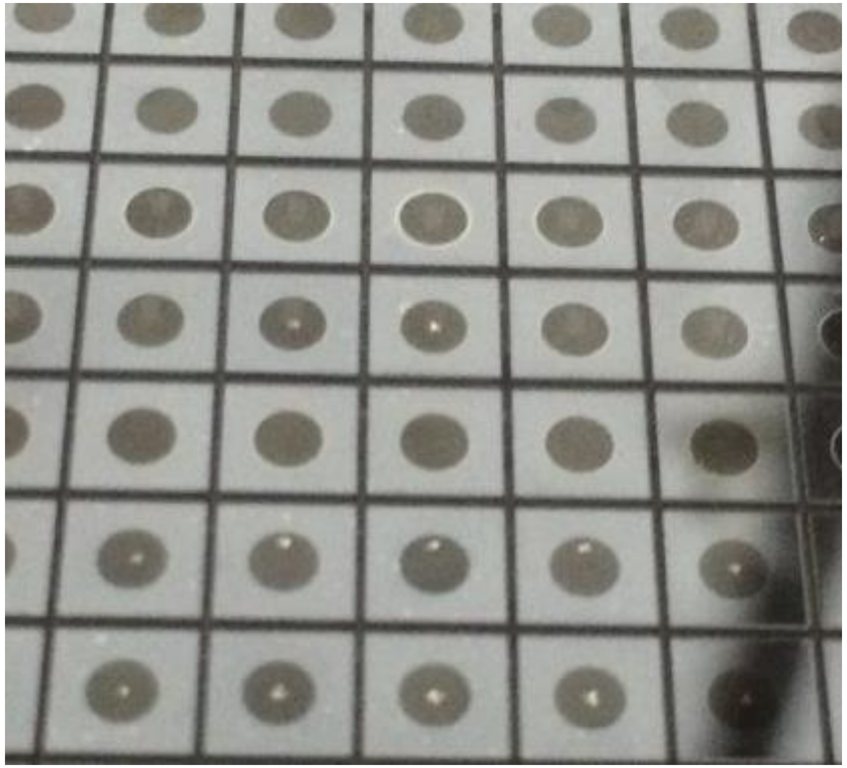
- **Observed ^{3}He-^{129}Xe J-coupling**

$$\kappa_{\mathrm{HeXe}} = -0.011 \pm 0.001$$

PRINCETON UNIVERSITY

Twinleaf

Thanks!



Contact- **info@twinleaf.com** if you have interesting uses for bonded cells

Romalis group

arxiv.org/abs/1805.11578

NSF

DARPA