Gyromagnetic Faraday Rotation Studies on Polarized ^{3}He

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Low-energy Probes of New Physics
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MITP, Mainz

UNIVERSITY OF KENTUCKY

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Outline

- Motivation:

  New idea to search for Asymmetric Dark Matter?

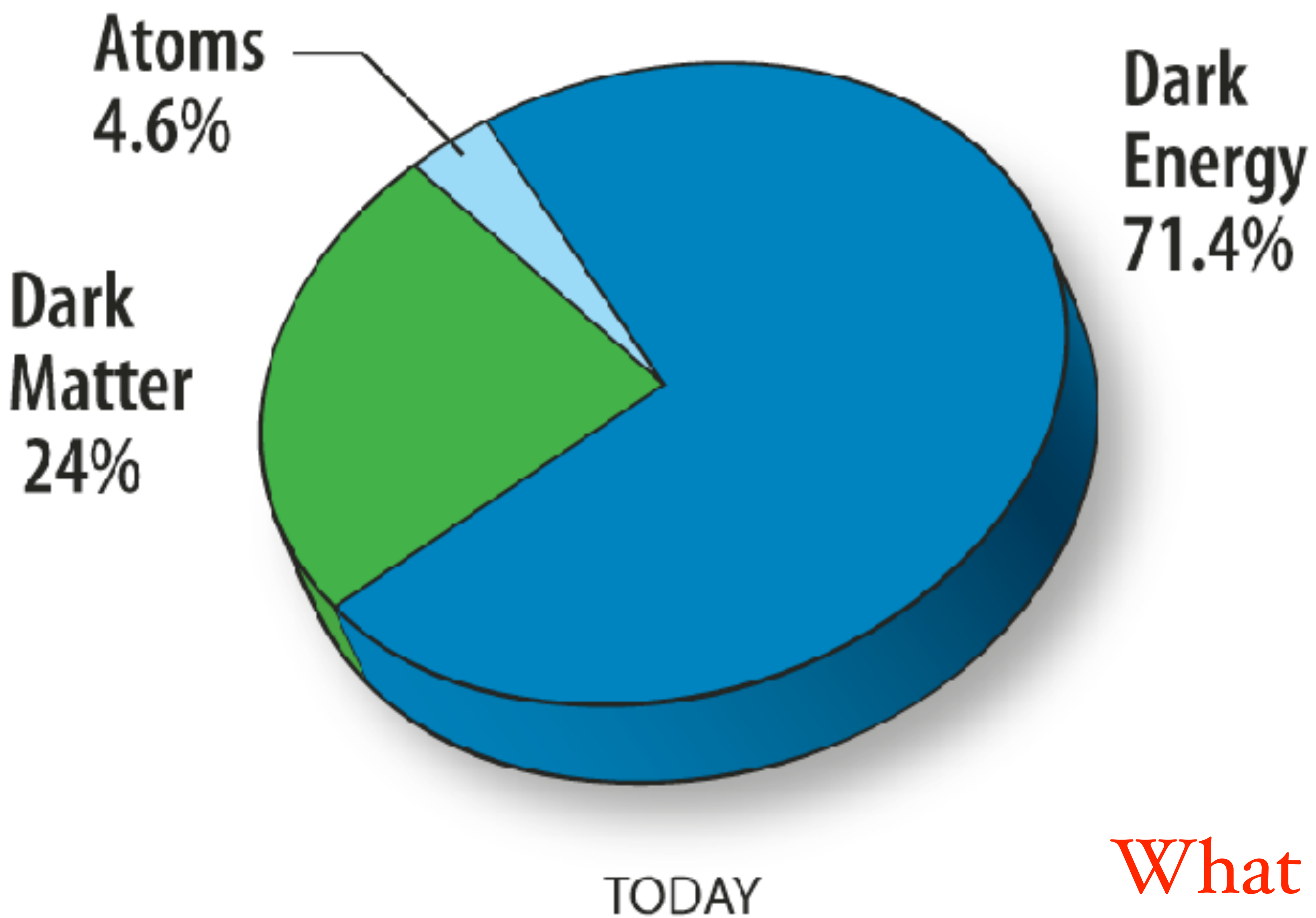
- Test case:

  Gyromagnetic Faraday rotation on polarized ^3He

- Summary

A Dark-Dominated Universe

Most of the cosmic energy budget is in unknown forms!

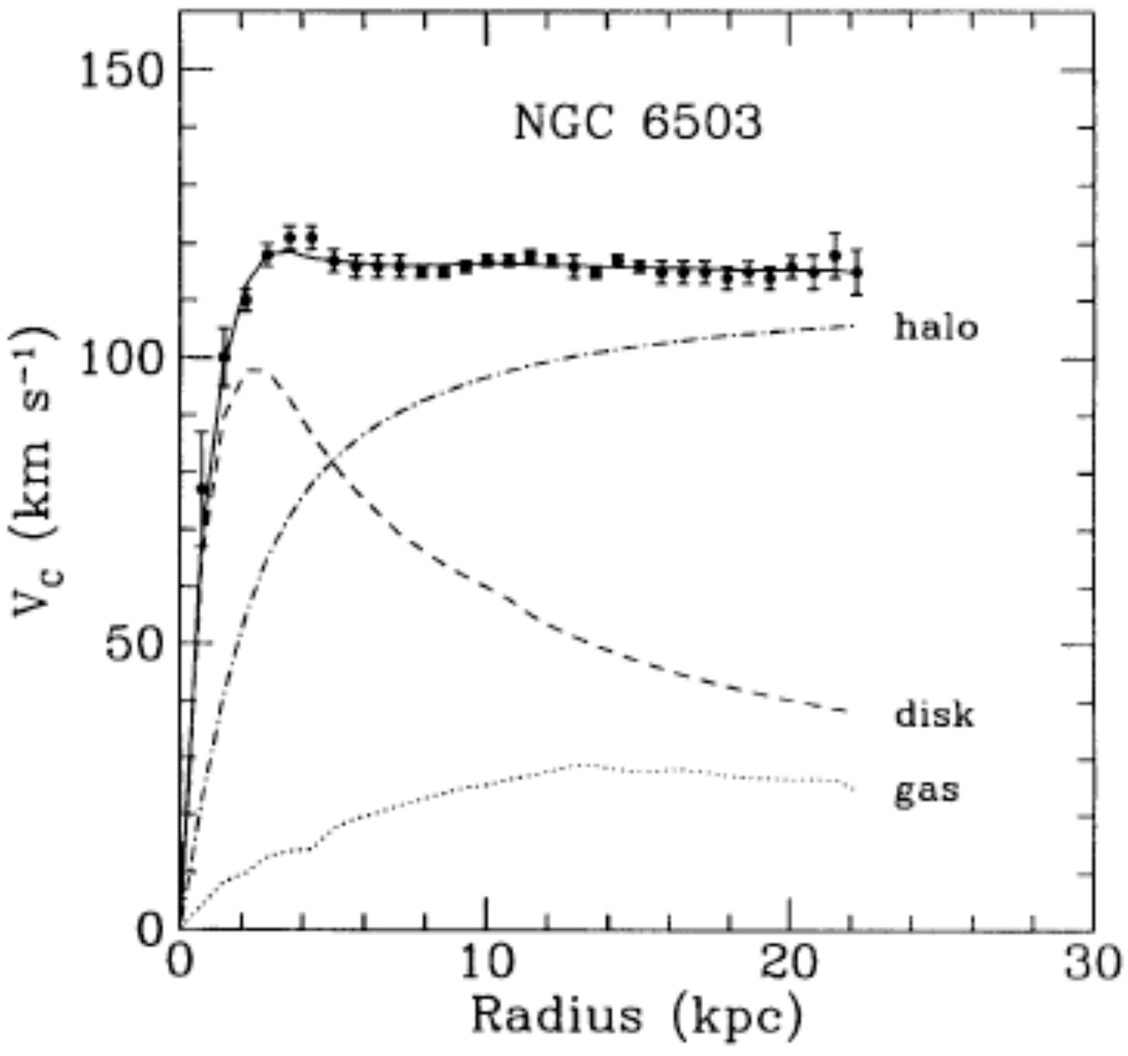


What are they?!

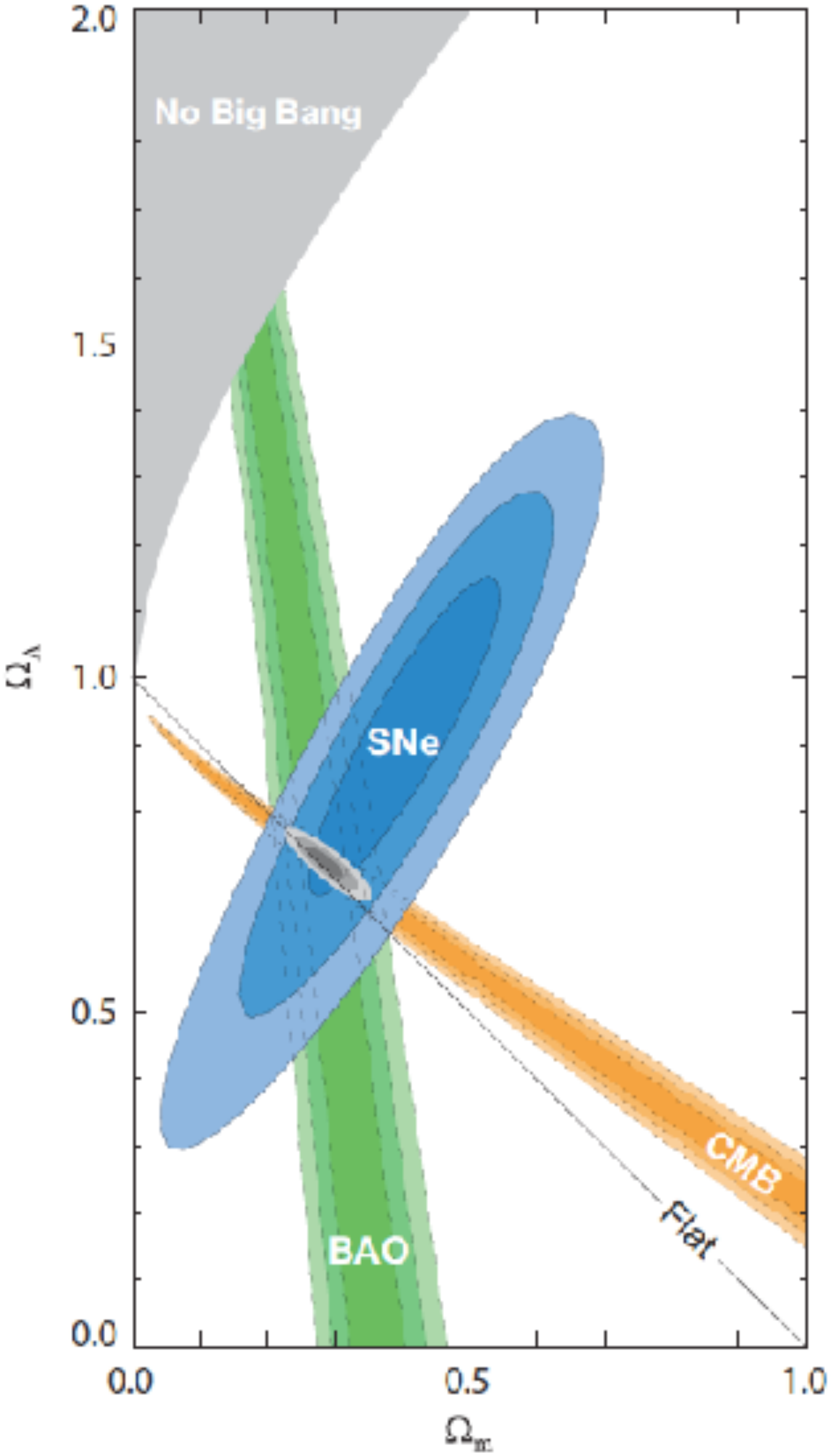
[map.gsfc.nasa.gov/universe/uni_matter.html]

Observational Evidence for Dark Matter

Galactic Rotation Curves:
[e.g., from Begeman, Broeils, and Sanders, 1991]



The observed circular speed does not track the luminous mass.



Most of the cosmic energy budget is of an unknown form!

Dark Matter (DM) Knowns

We do know DM must be...

- stable or effectively on Gyr time scales
- not "hot" - i.e., not relativistic at the time it decoupled from matter in the cooling early Universe
- have no substantial strong or electromagnetic charge

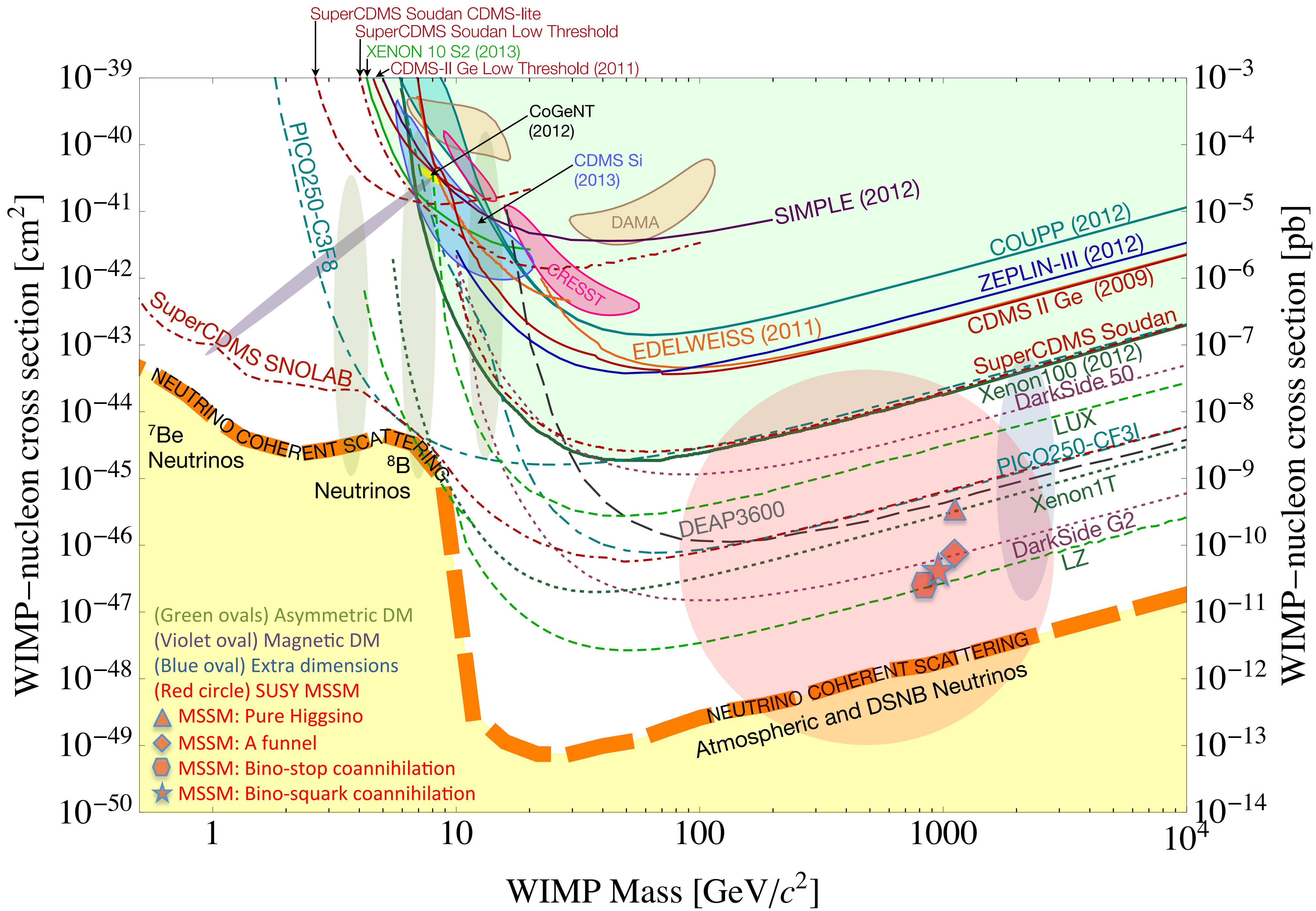
It has long been thought that if DM were produced as a "thermal relic" that it would be a Weakly Interacting Massive Particle or "WIMP"

Such candidates appear in models with weak-scale supersymmetry (MSSM)

They can be detected directly in low-background experiments

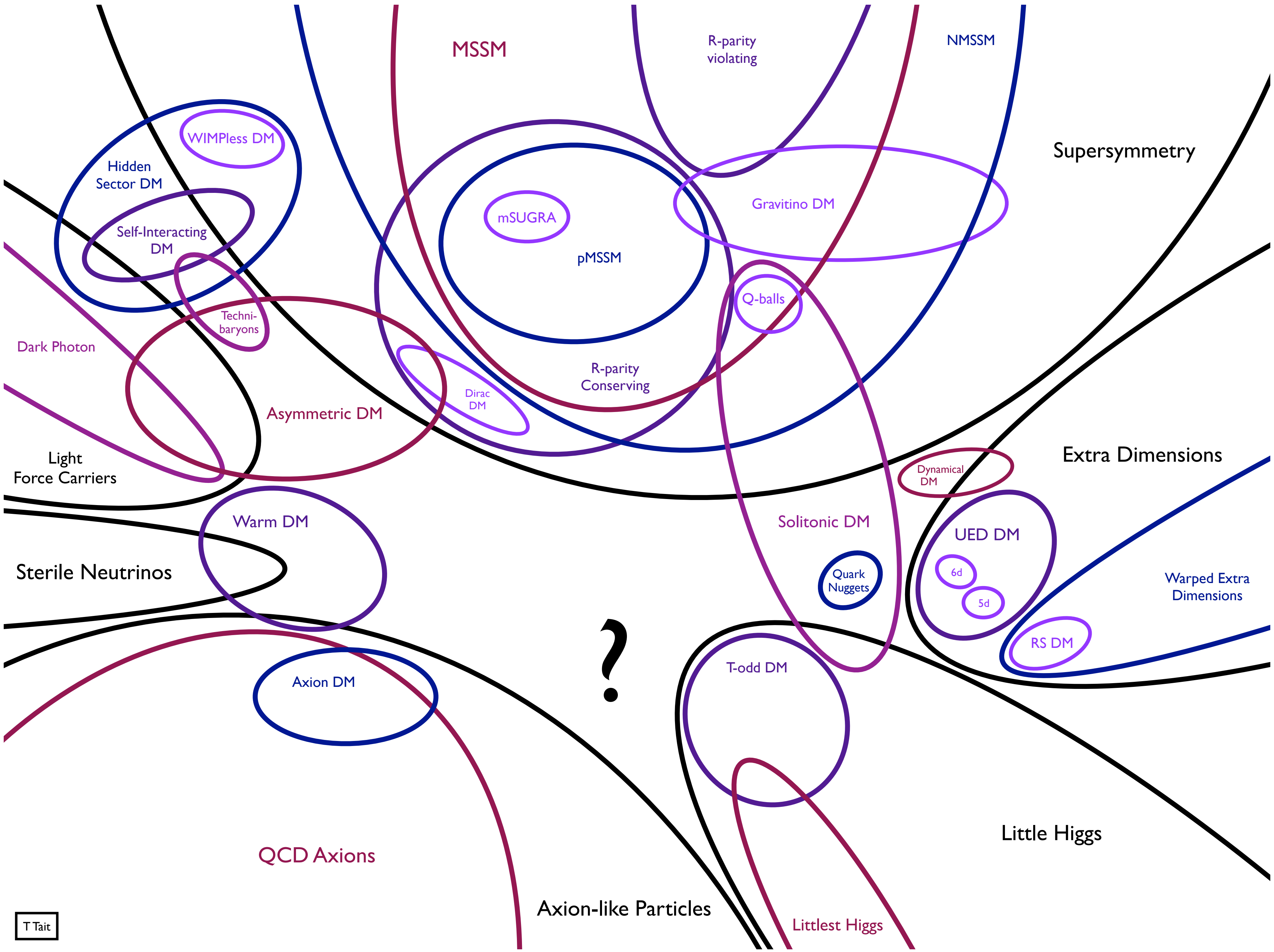
Direct Detection: Dark Matter "WIMPs"

Limits rely on local DM density and velocity distribution



[arXiv:1401.6085]

Theory: Possible DM Candidates



[arXiv:1401.6085]

What if DM is not a WIMP?

Its relic density need not be fixed by thermal freeze-out, and its stability need not be fixed by a discrete symmetry.

What mechanisms then are operative and how do we discover them?

- Its stability may be guaranteed by a hidden conserved charge, much as the electron in the SM is stable.

A complex hidden sector?

- Its relic density may be related to the cosmic baryon asymmetry.
- [axions]....

The hidden sector could be asymmetric, as baryons are?

[Nussinov, PLB 1985; Barr, Chivukula, Farhi, PLB 1990; Harvey and Turner, PRD 1990; Ellis et al., NPB 1992. Ryttov and Sannino, arXiv:0809.0713 [hep-ph]; Kaplan, Luty, Zurek, arXiv:0901.4117 [hep-ph].]

Asymmetric Dark Matter (ADM)

Experimental Signatures

- ADM models can give distinctive collider signatures

  E.g. long-lived metastable states, new charged states at the weak scale, and/or colored states at a TeV. (All not seen as yet.)

- Direct detections signals can arise from interactions that could

  ✳ eliminate the symmetric DM component

  ✳ transfer the fermion asymmetry

These could be realized through magnetic moment or charge radius couplings.

Both interactions can give rise to anomalous nuclear recoils....

[Bagnasco, Dine, and Thomas, PLB 1994; Barger, Keung, Marfatia, arXiv:1007.4345; Banks, Fortin, and Thomas, arXiv:1007.5515]

A magnetic Faraday effect can also discover dark matter if it possesses a magnetic moment... and establish asymmetric dark matter.

S. Gardner, PRL 100, 041303 (2008)
S. Gardner, PRD 79, 055007 (2009)

some reviews: K.M Zurek, Phys. Rep. 537, 91 (2014), D.E. Kaplan et al., PRD 79, 115016 (2009), ...

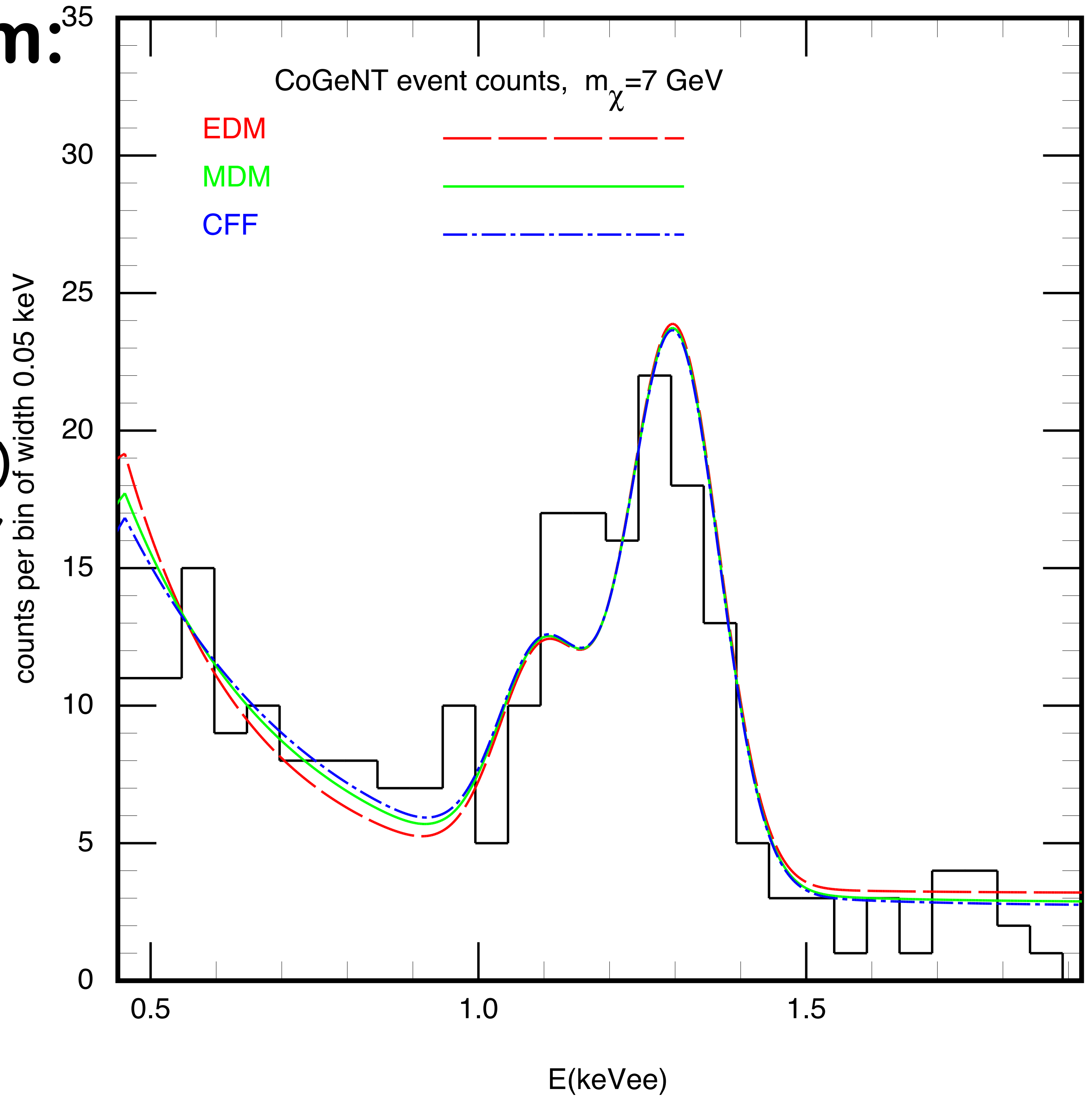
Experimental Signatures of ADM

Impact on recoil spectrum: here CoGent

m_{DM} = 7 GeV

EDM: $d_\chi = 10^{-20}$ e·cm (Λ_{EDM} = 1.97 PeV)

MDM: $g_\chi S$ = 0.00454 (Λ_{MDM} = 3.09 TeV



V. Barger et al., arXiv: 1007.4345v2

Constraints on Magnetic Moments of DM

Properties of DM: Possibility of (anomalous) magnetic moments

Constraints for $M_{DM} \leq 1$ MeV:

- precision electroweak measurements $\rightarrow$ e.w. radiative corrections

  anomalous mag. moment ($\varkappa$): $|\varkappa| < 4 \times 10^{-6}$ for $M_{DM} = m_e$

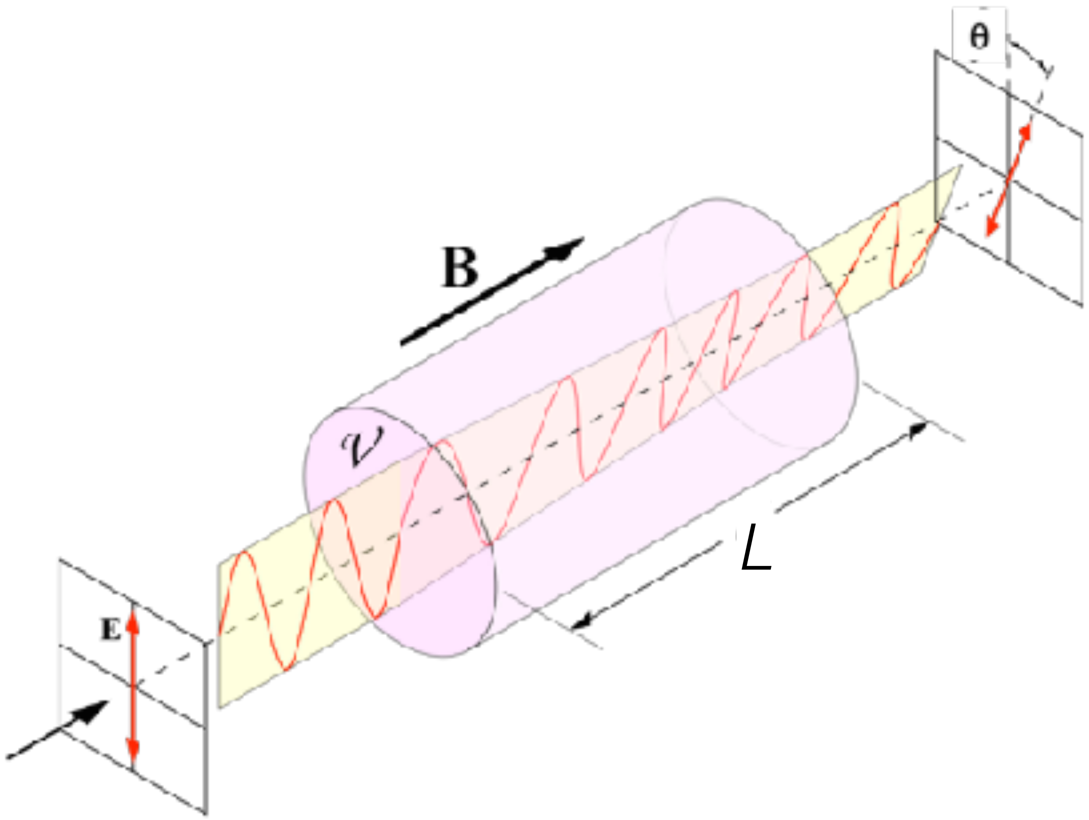
- $e^+e^- \rightarrow \nu\bar{\nu}\gamma \rightarrow \mu_{\nu\tau} \sim$ few $\times 10^{-6}\ \mu_B$

J. Erler and P. Langacker, review in W.M. Yao et al. (Particle Data Group), J. Phys. G 33, 1 (2006)

H. Grotch and R.W. Robinett, Z. Phys. C 39, 553 (1988)

Can Faraday rotation be used to probe μ_{DM}?

Introduction to Faraday Rotation



Faraday Effect: 1846 !!
Optical activity is induced in matter by magnetic field

Faraday, M., Phil. Mall., 28, 294 (1846) ;
Phil. Trans. Roy. Soc. London, 1 (1846)

Angle of rotation:

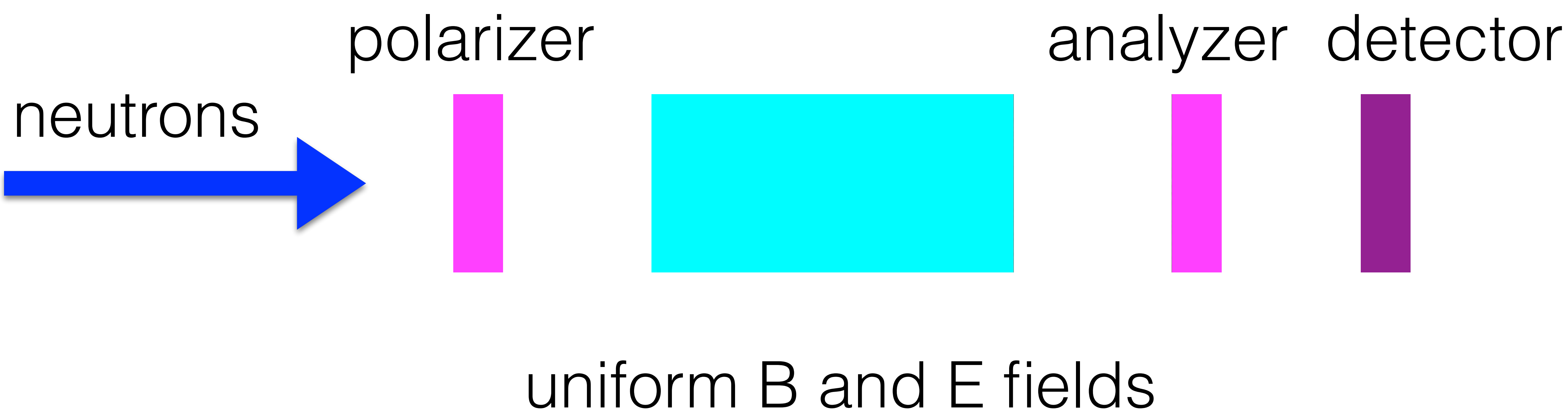
$$\theta = V \cdot B \cdot L = V \int_0^L B dl$$

V: Verdet Constant → Contains physics

https://en.wikipedia.org/wiki/Faraday_effect#/media/File:Faraday-effect.svg

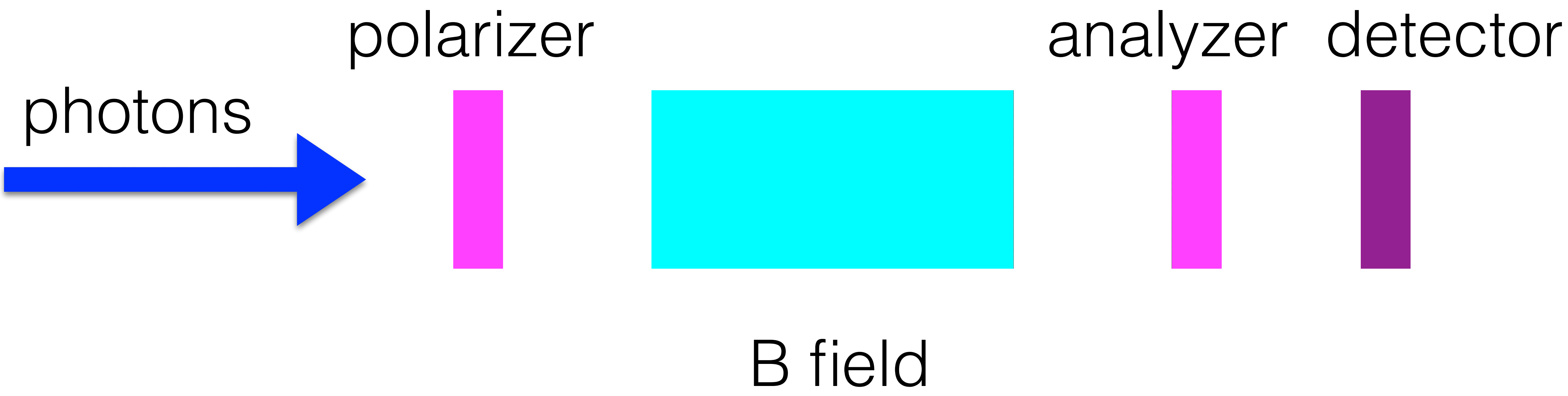
Measurement Principle

D. Beck's talk: Principle of measuring neutron EDMs



Measurement Principle

Principle of measuring Faraday rotation



Similar to PVLAS Experiment

PVLAS: "Testing the polarization of the vacuum with lasers"

Department of Physics and National Institute of Nuclear Physics in Ferrara, Italy

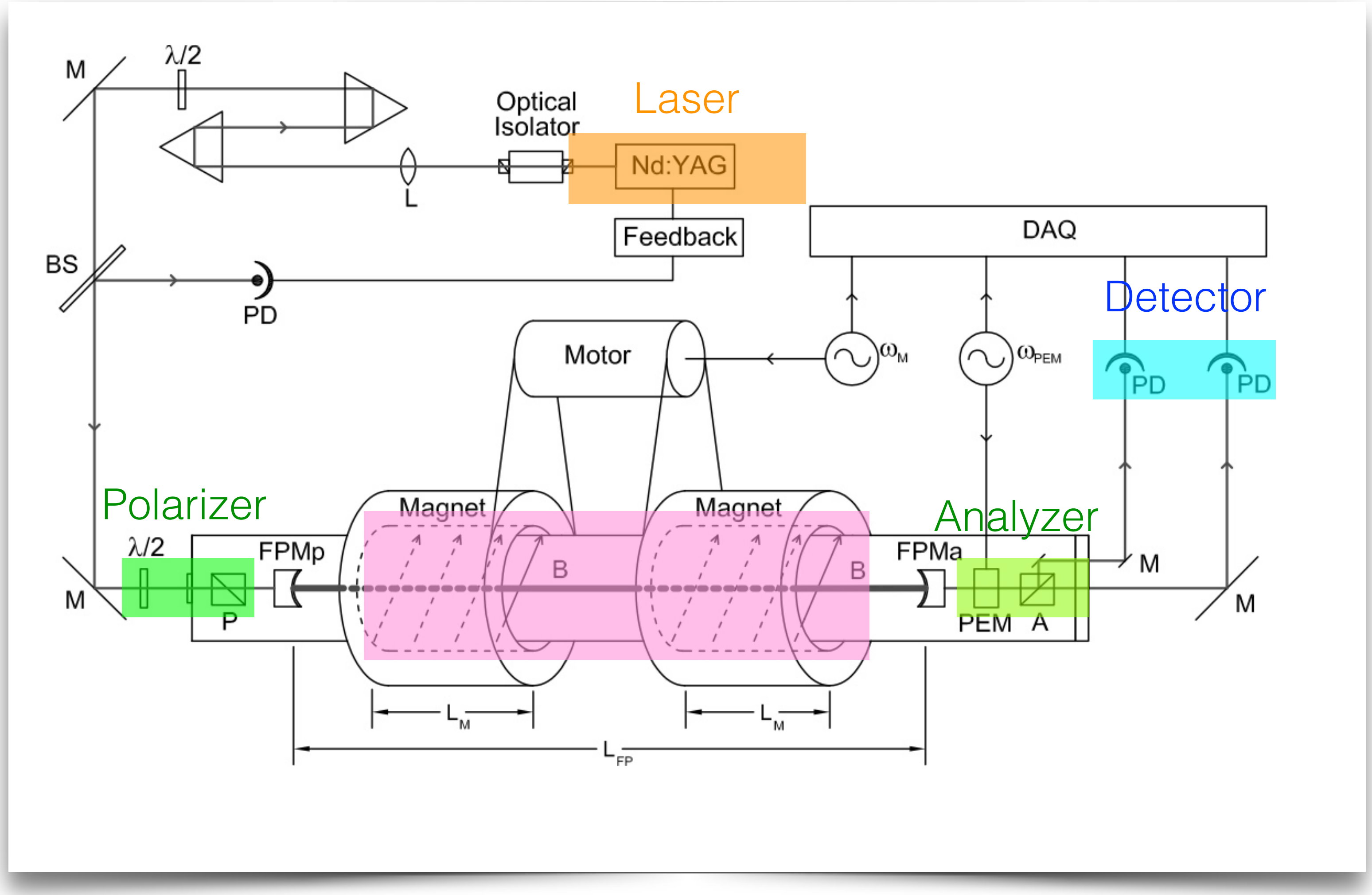
Nonlinear effects due to magnetic birefringence (of vacuum)
→sensitivity to axions

$$\Delta n = 3 A_e B_{ext}^2$$

"nonlinearity" const.

no effect observed:

$$A_e < 2.9 \cdot 10^{-21}\ T^{-2}$$



Total sensitivity: Δθ ~ 10 nrad

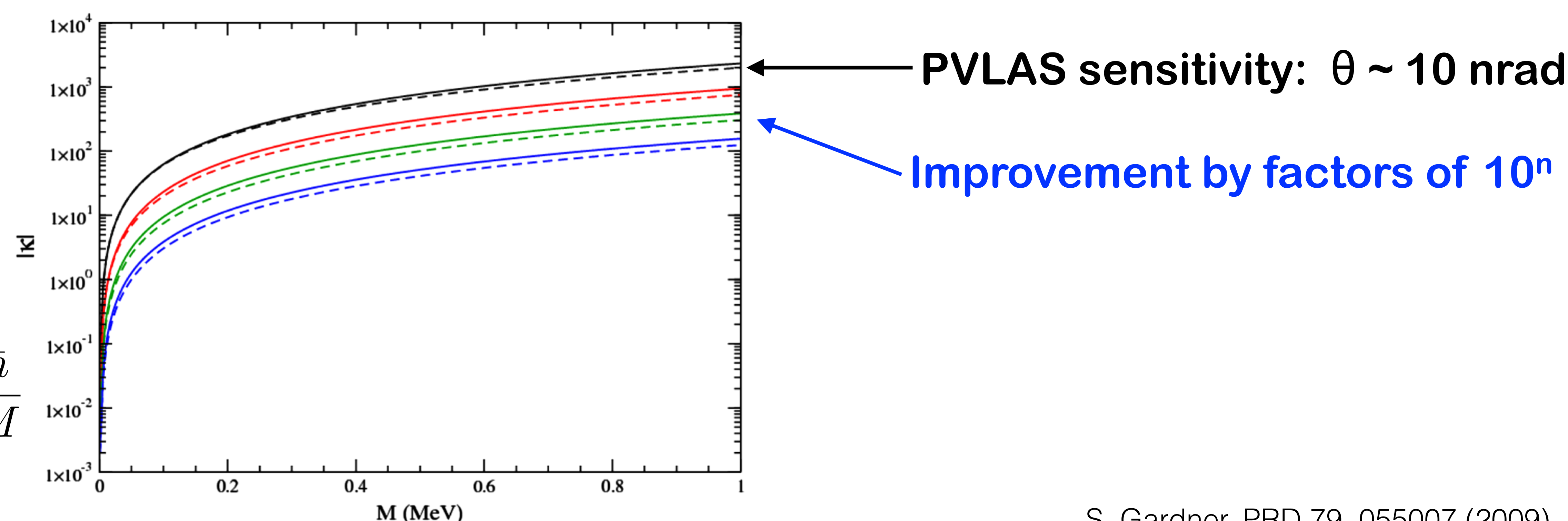
G. Zavattini et al, Int. J. Mod. Phys. A 27, 1260017 (2012)

Sensitivity to Magn. Moments of Light DM

Possible anomalous magnetic moment vs. m_{DM}

$\kappa = \mu/\mu_M$

$$\mu_M = \frac{e\hbar}{2M}$$



S. Gardner, PRD 79, 055007 (2009)

Matter in E. & M. Fields

Matter in e.m fields: dielectric displacement and magnetic induction

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

$\epsilon = 1 + 4\pi N \alpha$ → dielectric constant

$\mu = 1 + 4\pi N \chi$ → permeability

Magnetic Moments in E&M Fields

Matter in e.m fields: dielectric displacement and magnetic induction

$$\mathbf{D} = \epsilon\mathbf{E} + ig\mathbf{H} + if_1\mathbf{E}\times\mathbf{H}' + k\mathbf{H}\times\mathbf{H}'$$

$$\mathbf{B} = \mu\mathbf{H} - ig\mathbf{E} + if_2\mathbf{H}\times\mathbf{H}' - k\mathbf{E}\times\mathbf{H}'$$

$\mathbf{E}, \mathbf{H}$ → e.m. wave

$\mathbf{H}'$ → static field

$\epsilon = 1 + 4\pi N\alpha$ → dielectric constant

$\mu = 1 + 4\pi N\chi$ → permeability

$g = \omega 4\pi N\beta$ → natural gyration constant

$$\left.\begin{array}{l} f_1 = \omega 4\pi N\eta \\ f_2 = \omega 4\pi N\xi \end{array}\right\}$$ → magneto-optical gyration constants

$k = 4\pi N\delta$ → contribution to polarizability and birefringence in optically active molecules

Magnetic Moments in E&M Fields

Precession of $\mathbf{M}$ in $\mathbf{B}_0$: $$\frac{d\mathbf{M}}{dt} = \frac{g\mu_M}{\hbar}\mathbf{M} \times \mathbf{B}_0$$

Relativistic eq. (BMT eq. for neutral particles)

$$\gamma \frac{d\mathbf{M}}{dt} = \frac{g\mu_M}{\hbar}(\mathbf{M} \times \mathbf{B}_0 + \mathbf{M}_0 \times (\mathbf{B} - \boldsymbol{\beta} \times \frac{\mathbf{E}}{c}))$$

For LH and RH circularly polarized light:

$$M_\pm = \pm \frac{\omega_M(1+\beta)}{\gamma\omega \pm \omega_B} B_\pm \equiv \chi_\pm B_\pm$$

$$n_\pm = \sqrt{1+\chi_\pm}$$

$$\omega_M = g\mu_M M_o/\hbar$$

$$\omega \gg \omega_B$$

$$n_- - n_+ = \frac{\omega_M(1+\beta)}{\gamma c}$$

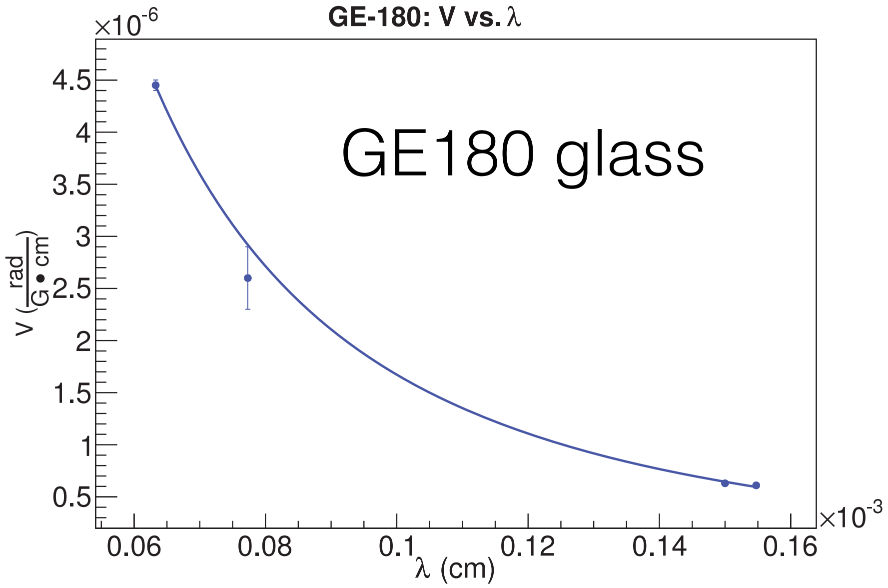
$$\theta = \frac{g\mu_M M_0 L}{2\hbar c}$$

$\rightarrow$ gyromagnetic optical rotation independent of frequency

D. Polder, Philos. Mag. 40, 99 (1949)
C.L. Hogan, Rev. Mod. Phys. 25, 253 (1953)
S. Gardner, PRL 100, 041303 (2008)

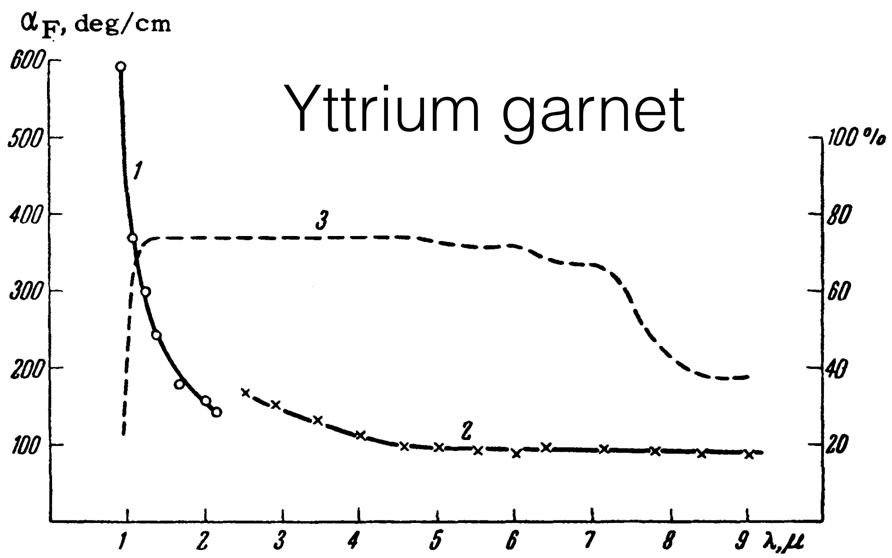
FR on Different Systems

Here: Far off-resonance FR →different frequency dependence



electric effect: $\sim \lambda^{-2}$

G. Phelps et al., RSI 86, 073107 (2015)



magnetic effect: λ^{0}

G.S. Krinchik and M.V. Chetkin, JETP 38, 1643 (1960)

Plasma (free electrons) → electric effect: $\sim \lambda^{2}$

Faraday rotation: 2nd order time-dependent theory

A. D. Buckingham and P.J. Stephens, Ann. Rev. Phys. Chem. 17, 399 (1966)

Gyromagnetic Faraday Effect

Gyromagnetic FR:

- off-diagonal elements of magnetic susceptibility tensor: $\chi_M^{\pm}$
- precession of the $\vec{M}$ under the influence of the B-field of e.m. wave

$$\theta = \frac{g\mu}{2\hbar c} M L = \frac{g\mu^2}{2\hbar c} N P L$$

magnetic moment

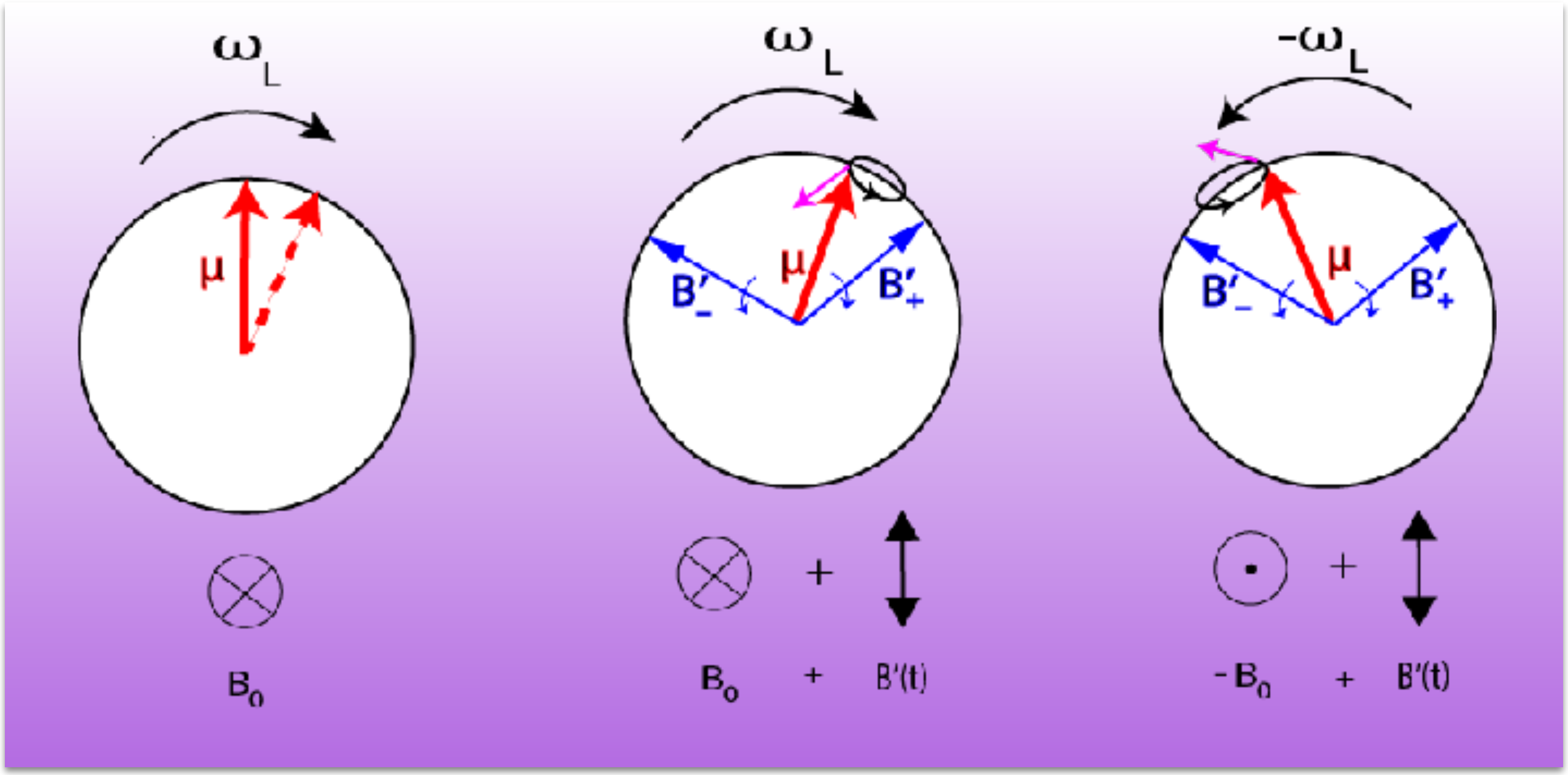
density

polarization

length

G.S. Krinchik & M.V. Chetkin, Sov. Phys. JETP 14, 485 (1961)
S. Gardner, PRD 79, 055007 (2009)
…..

Test Case: Polarized ^3He



- Can produce dense highly polarized targets
- No unpaired electrons ☞ diamagnetic atoms

Gyromagnetic Faraday Effect on Polarized ^3He

Pol. 3He as a test case for DM:

Conditions:

- Independent of frequency
- Small rotations:
- L = 40 cm, p = < 8 atm, P < 1

Expectation: 490 nrad for p = 8 atm, P = 1

Some order of magnitude numbers:

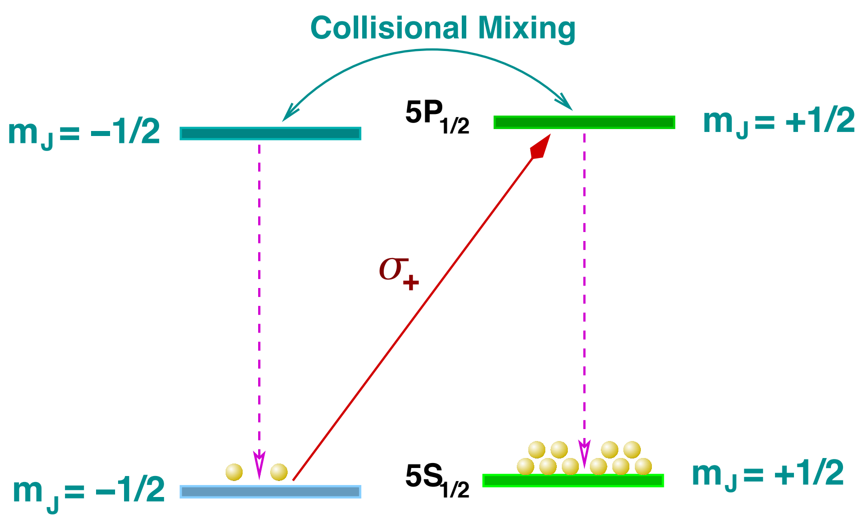
off-resonance

Material	Length	Θ at B = 4G
Flint Glass	1.27 cm	80 µrad
Aluminosilicate glass	0.4 cm	6.5 µrad
Air	3 m	1.5 µrad

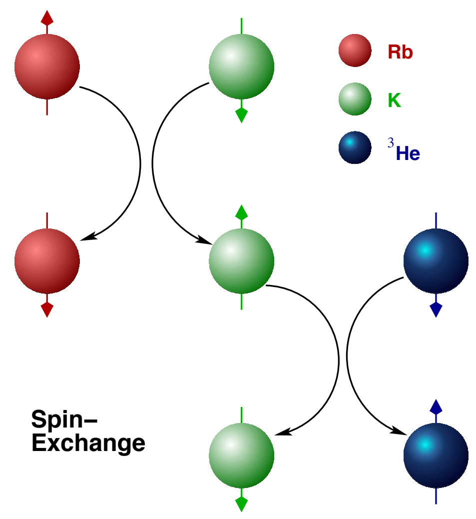
λ = 633 nm

Producing Densely Polarized ^{3}He Gas

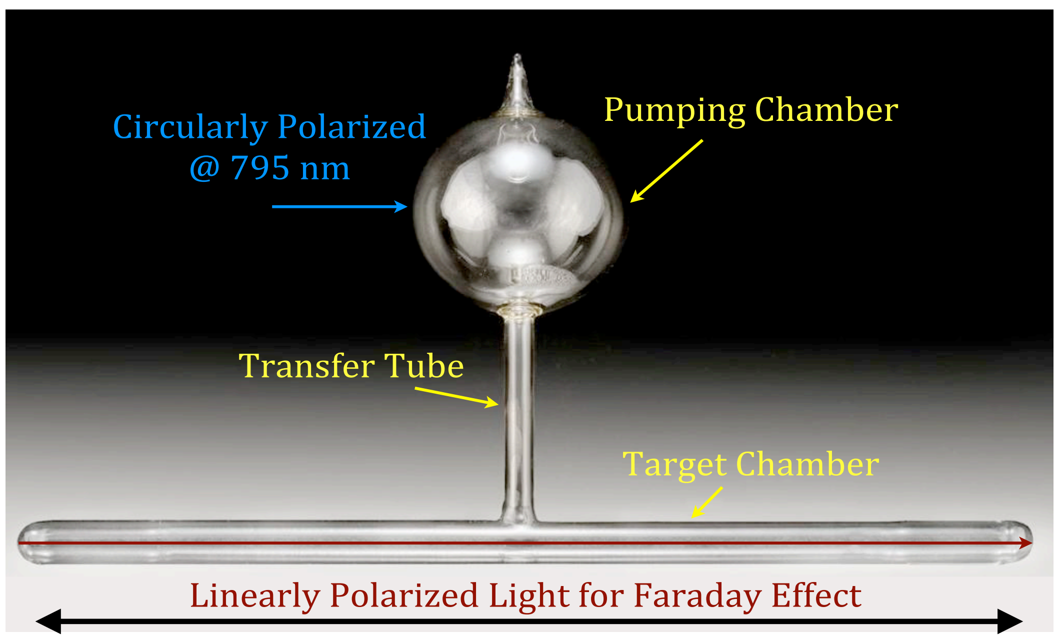
Polarizing ^{3}He:
spin exchange
optical pumping
(SEOP)



(a) Optical pumping

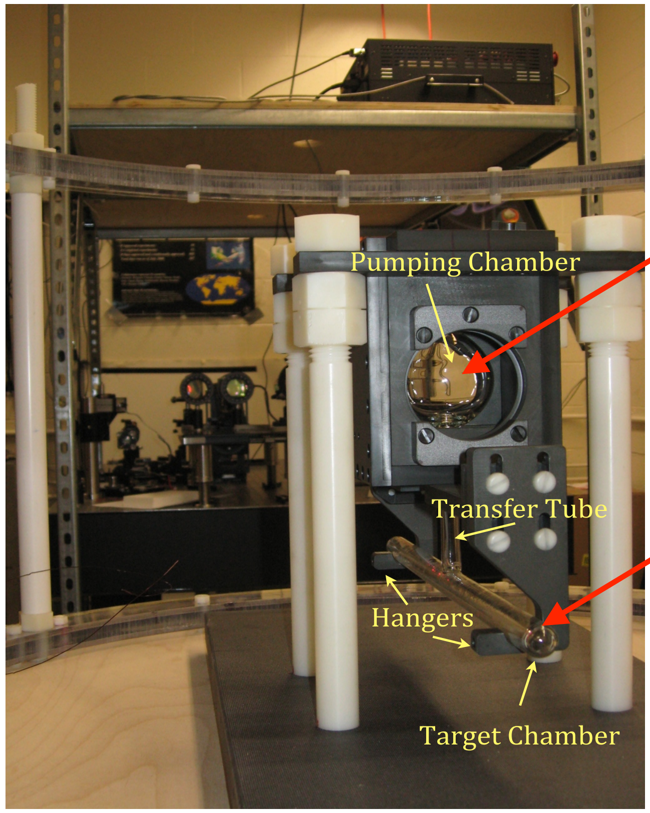


(b) Two-step spin-exchange



40 cm

Jefferson Lab geometry

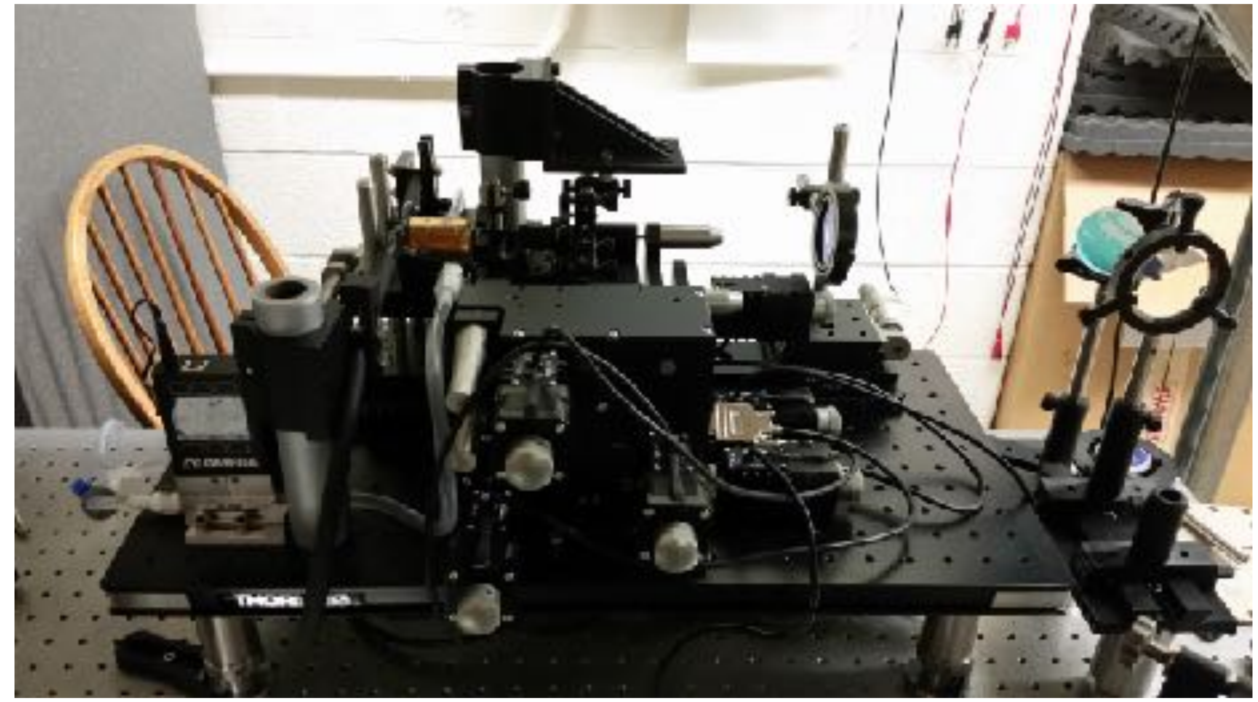


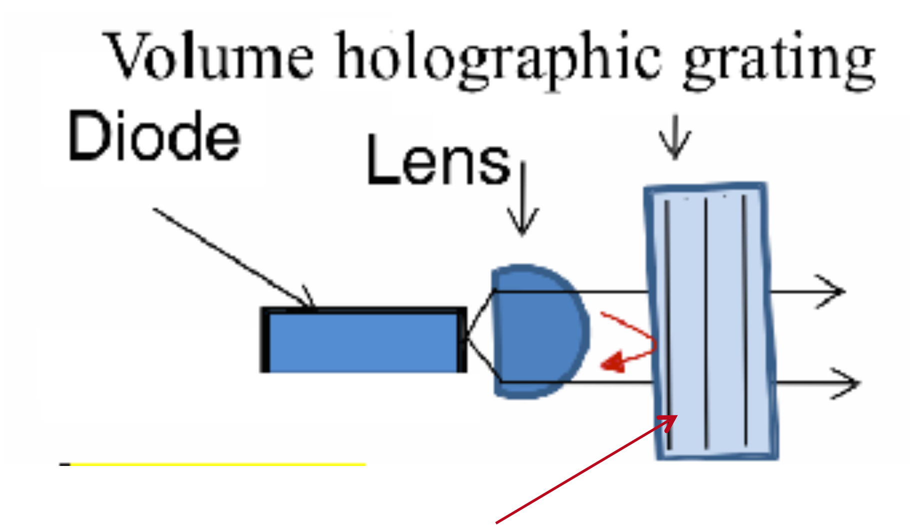
~220°C

~30°C

Polarizing ^3He: SEOP

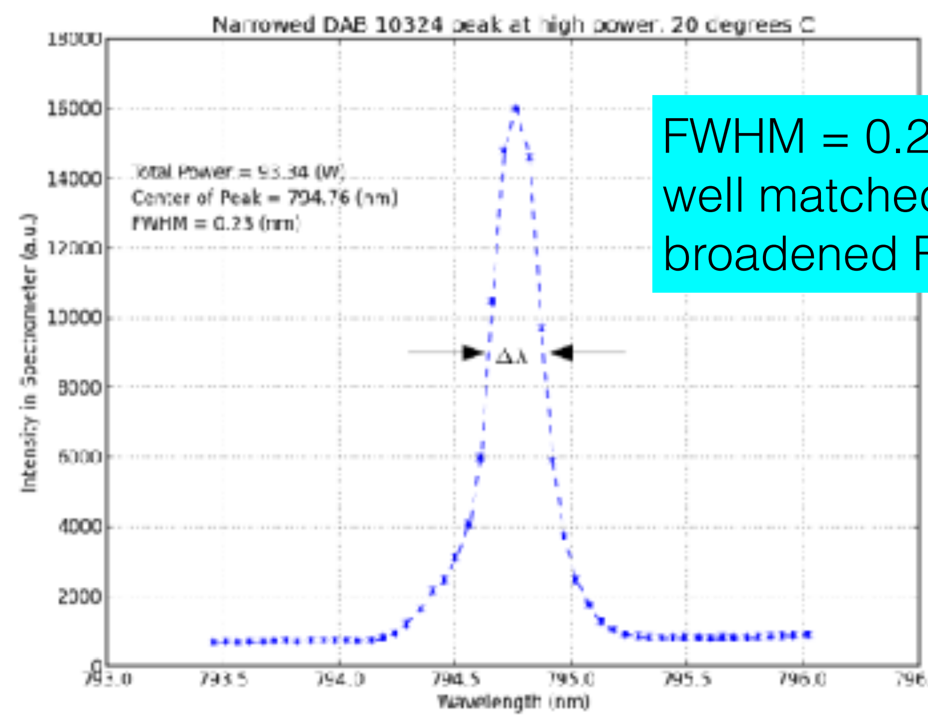
Pumping on D1 line:
~100 W CW @ 795 nm





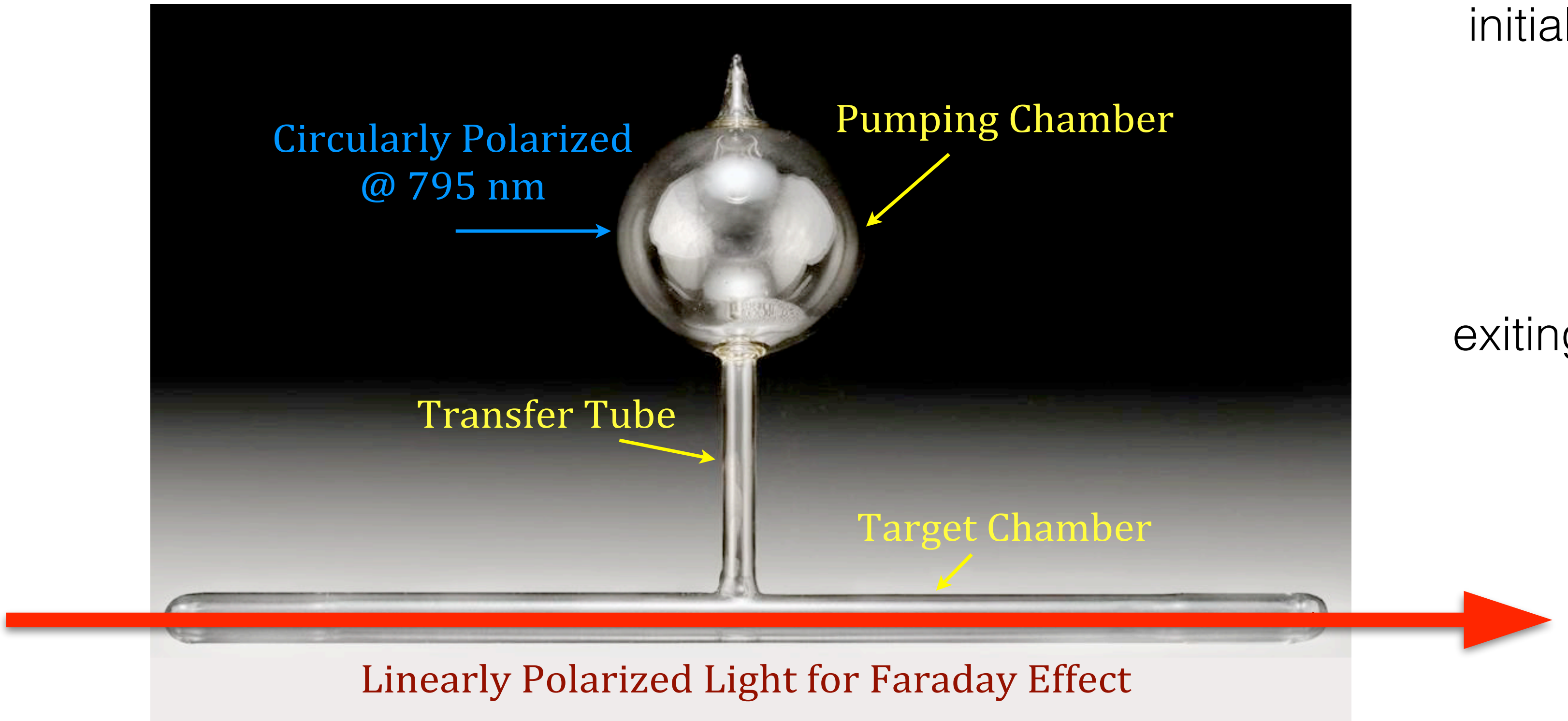
93% power transmitted

Light at 795nm reflected back into diode



FWHM = 0.23 nm
well matched to pressure broadened Rb atoms

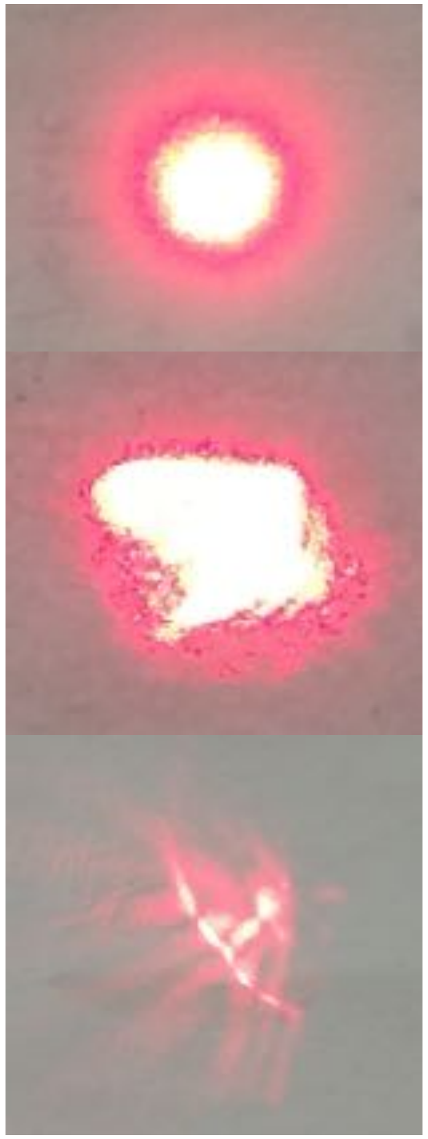
High Pressure Cells



initial probe beam

exiting probe beam
(1 pass)

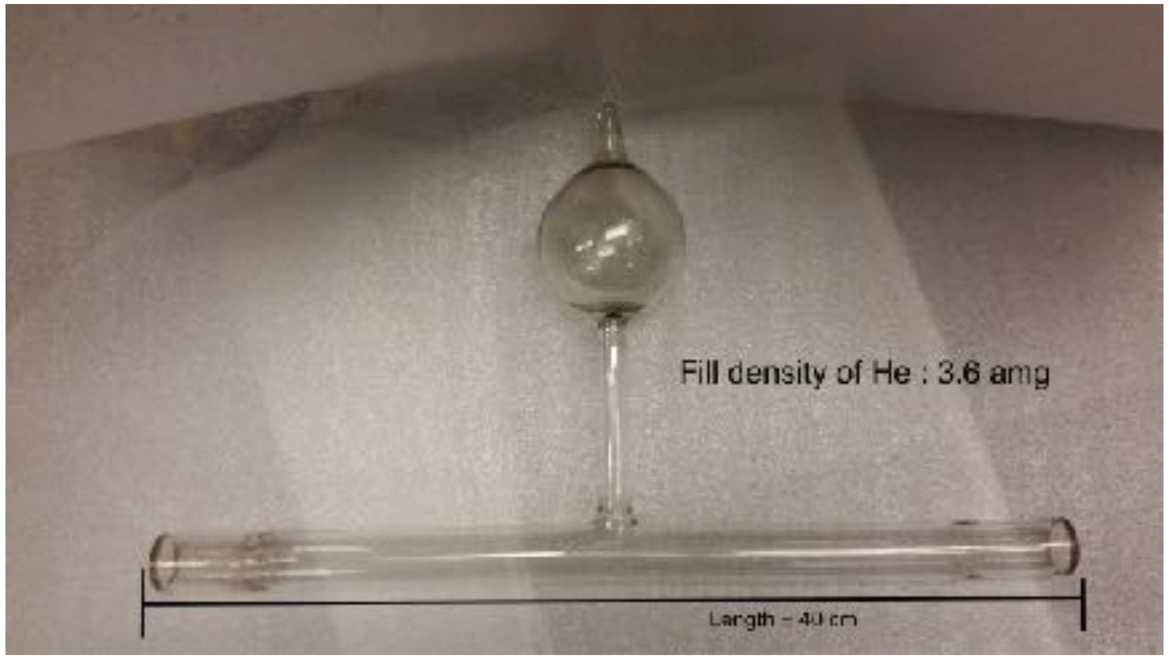
exiting probe beam
(3 passes)



High Pressure Cell for FR Studies

- New SEOP cell: flat, anti-reflective coated end windows designed for multiple passes with laser.
- Target chamber length: 40 cm
- Fill density is 3.6 amg (atm).

(Lower density due to flat end windows)



rotation angle drops by factor of 2:

→ θ~250 nrad

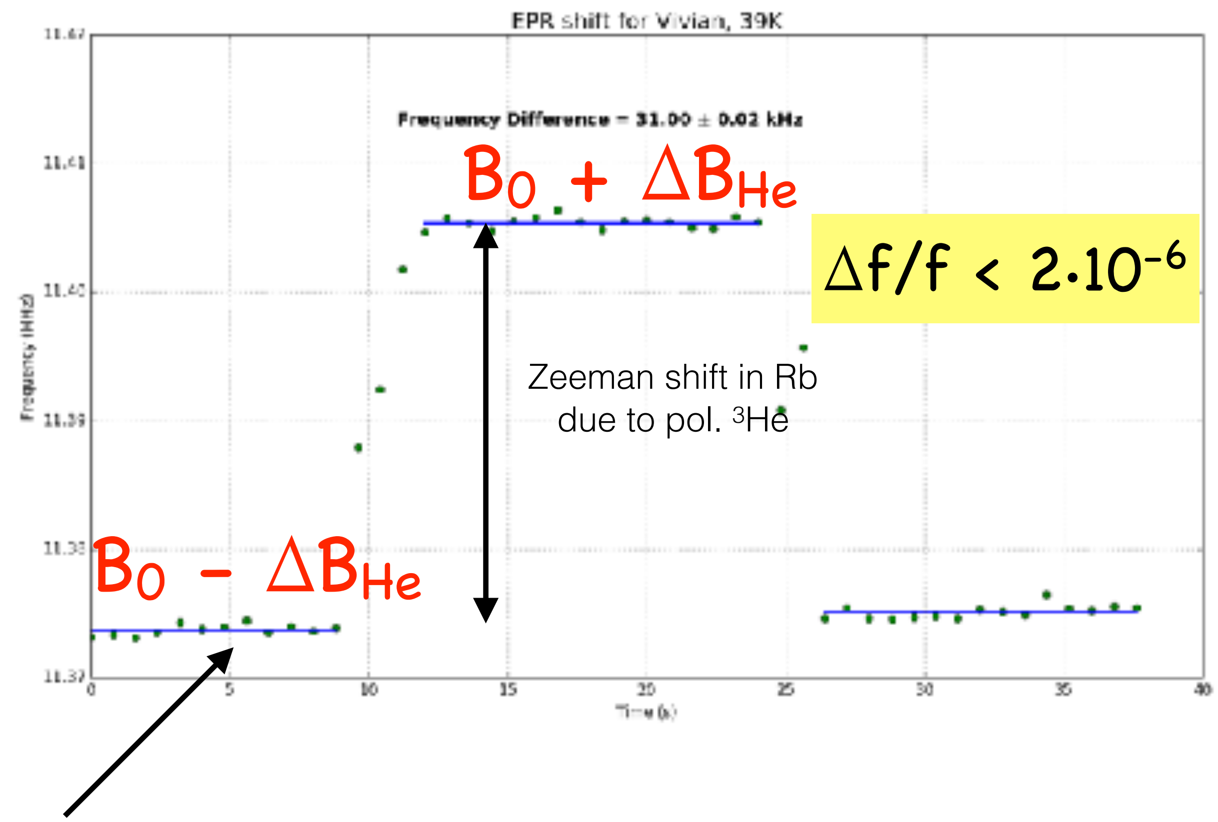
Corning 1720/1723

Determining the Polarization

Polarization measurement and monitoring

<u>Absolute pol. measurement</u>:

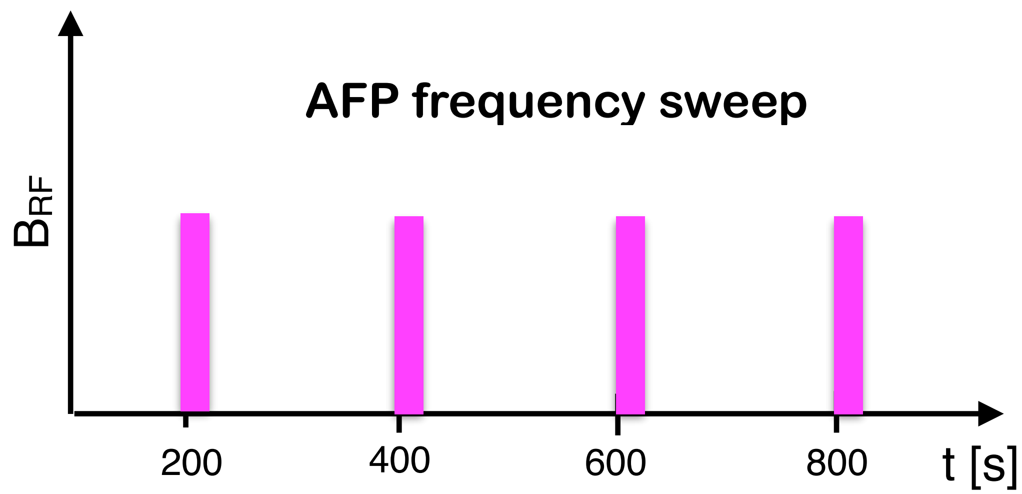
- *Electron Parametric Resonance (EPR) (pumping chamber)*
  - *Zeeman level shift in Rb due to ^{3}He "magnetization"*
- *NMR (target chamber)*

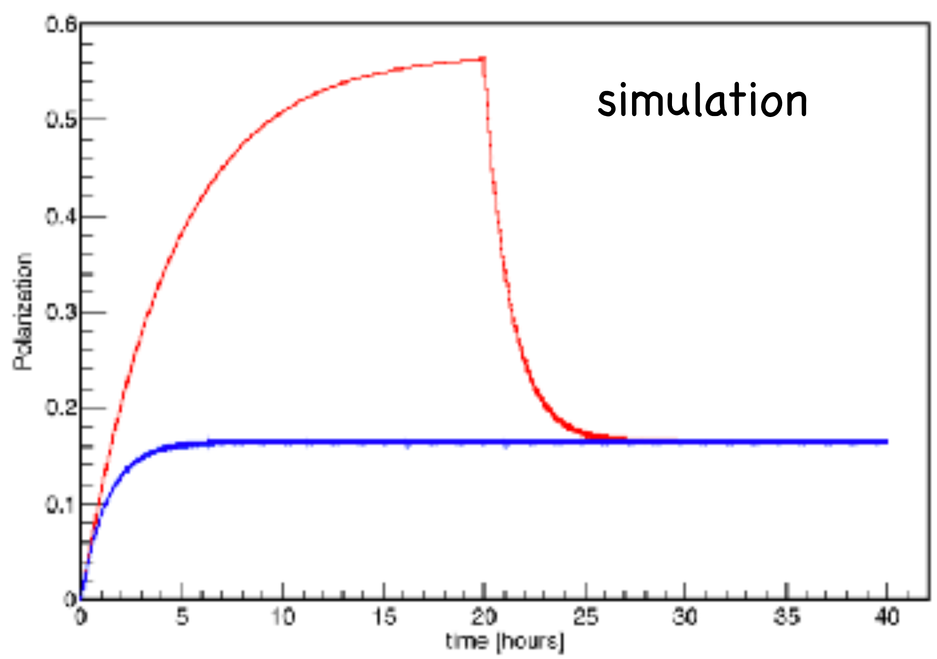


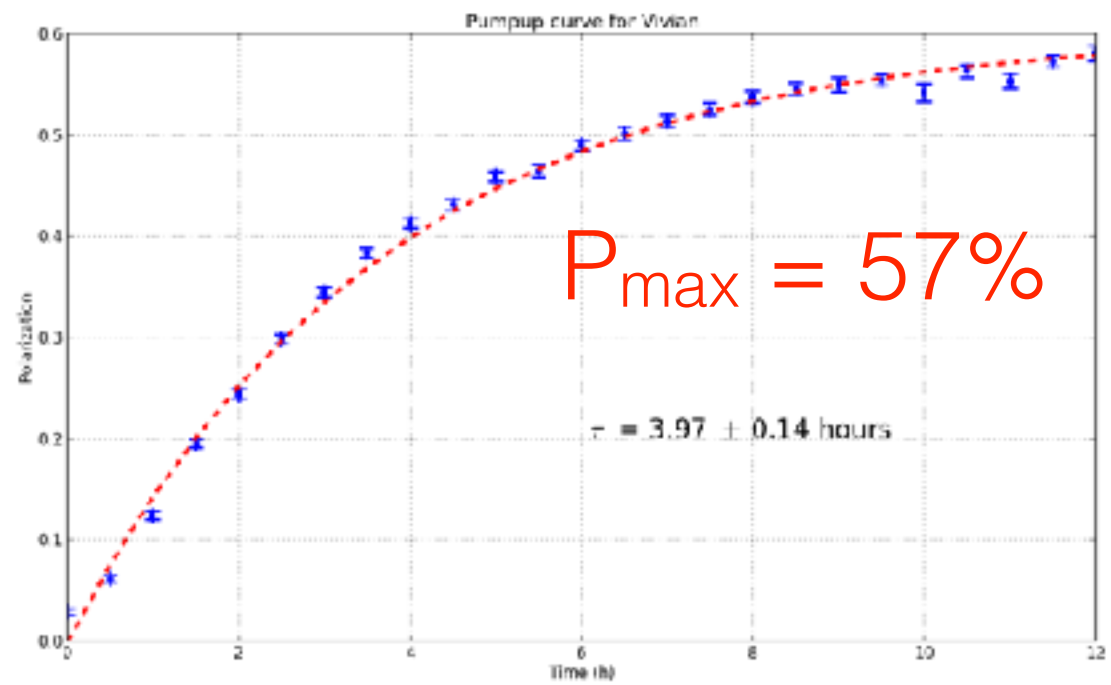
active B-field stabilization (ΔB ~ nT level)

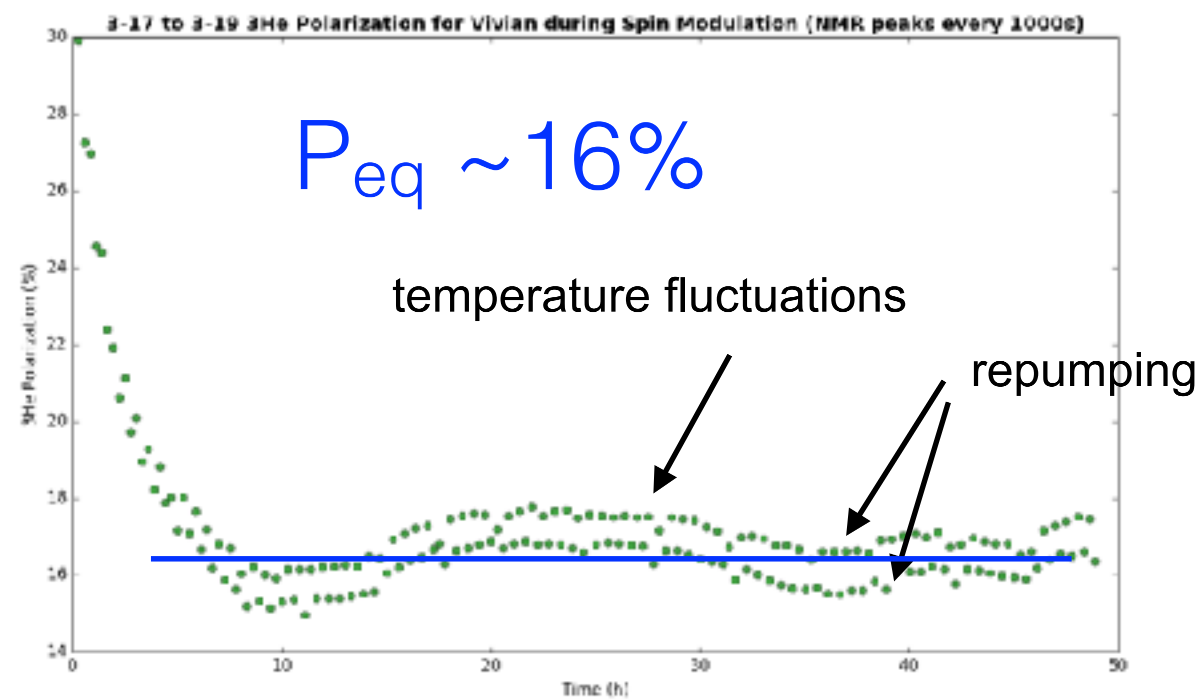
Polarized ^3He

Target cell polarization studies





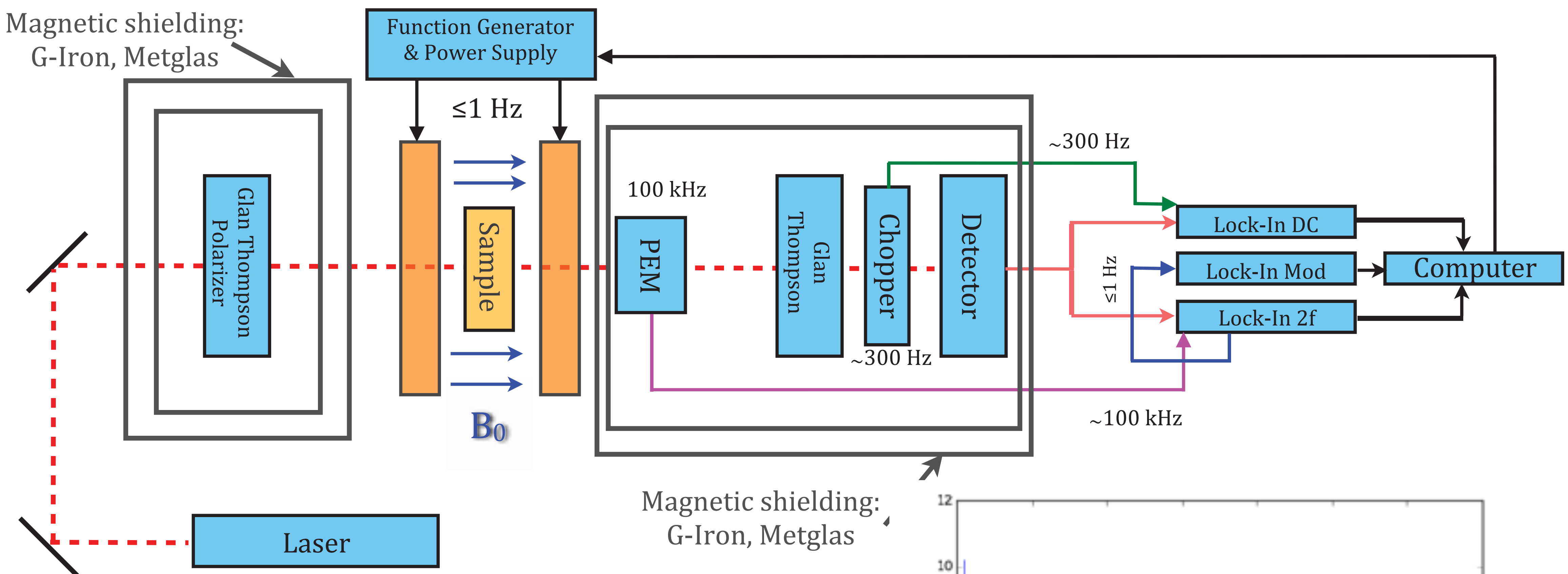




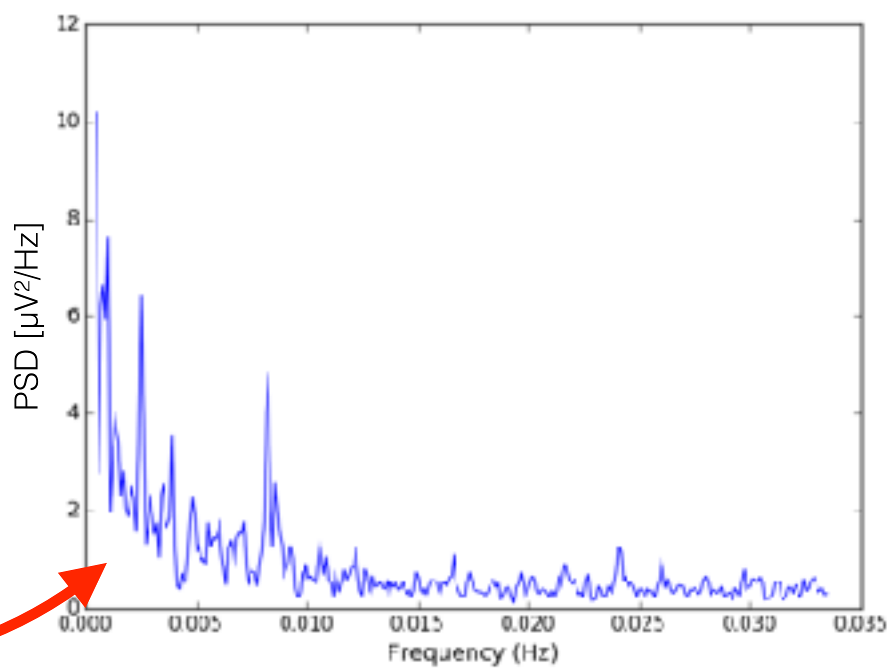
$P \sim 0.16 \rightarrow \theta \sim 50$ nrad !!!

Faraday Detection

Triple modulation technique

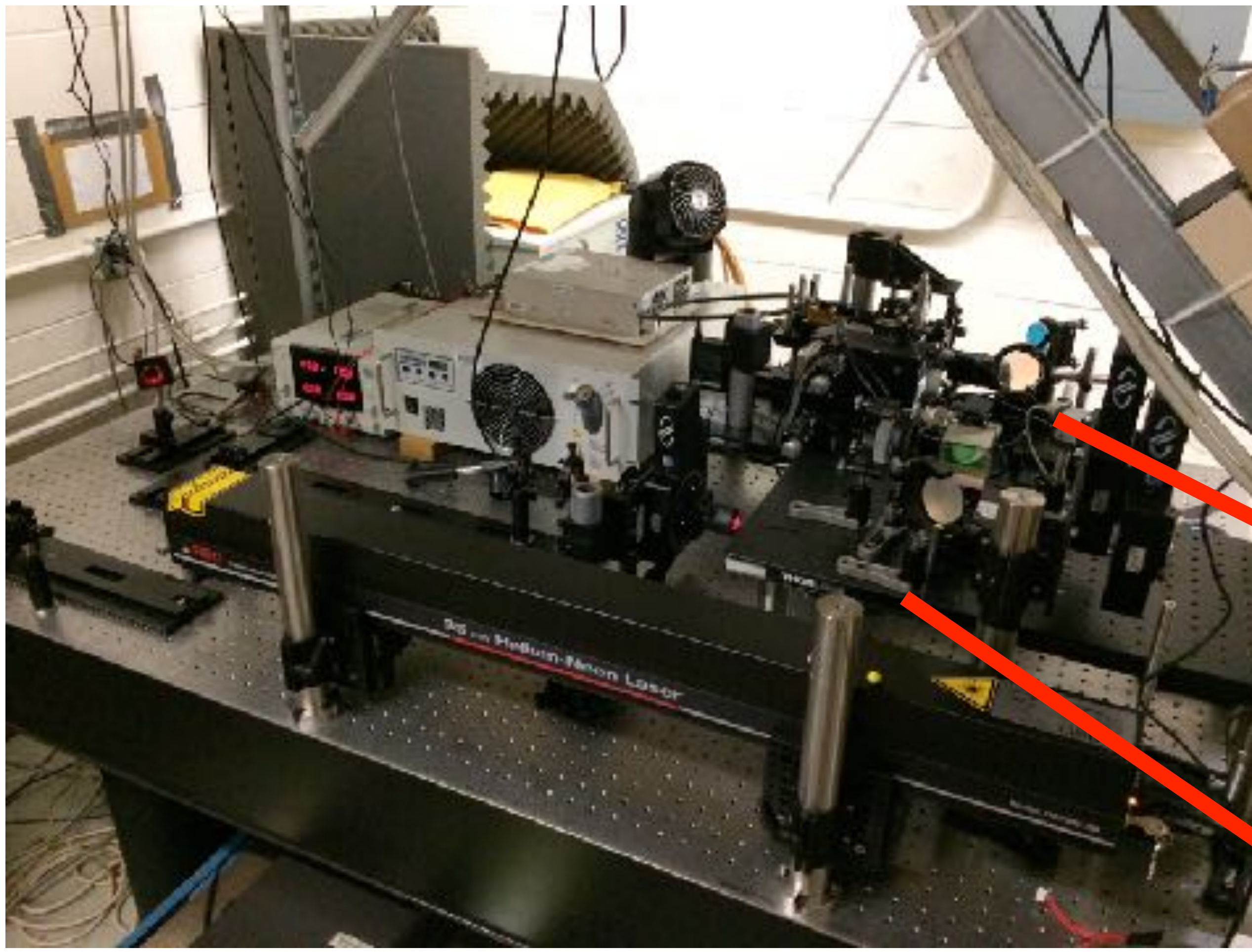


Three different mod. frequencies:
- polarization mod. of light (100 kHz)
- intensity mod. of light (~100 Hz)
- field mod. (~ < 1 Hz (→ few mHz))



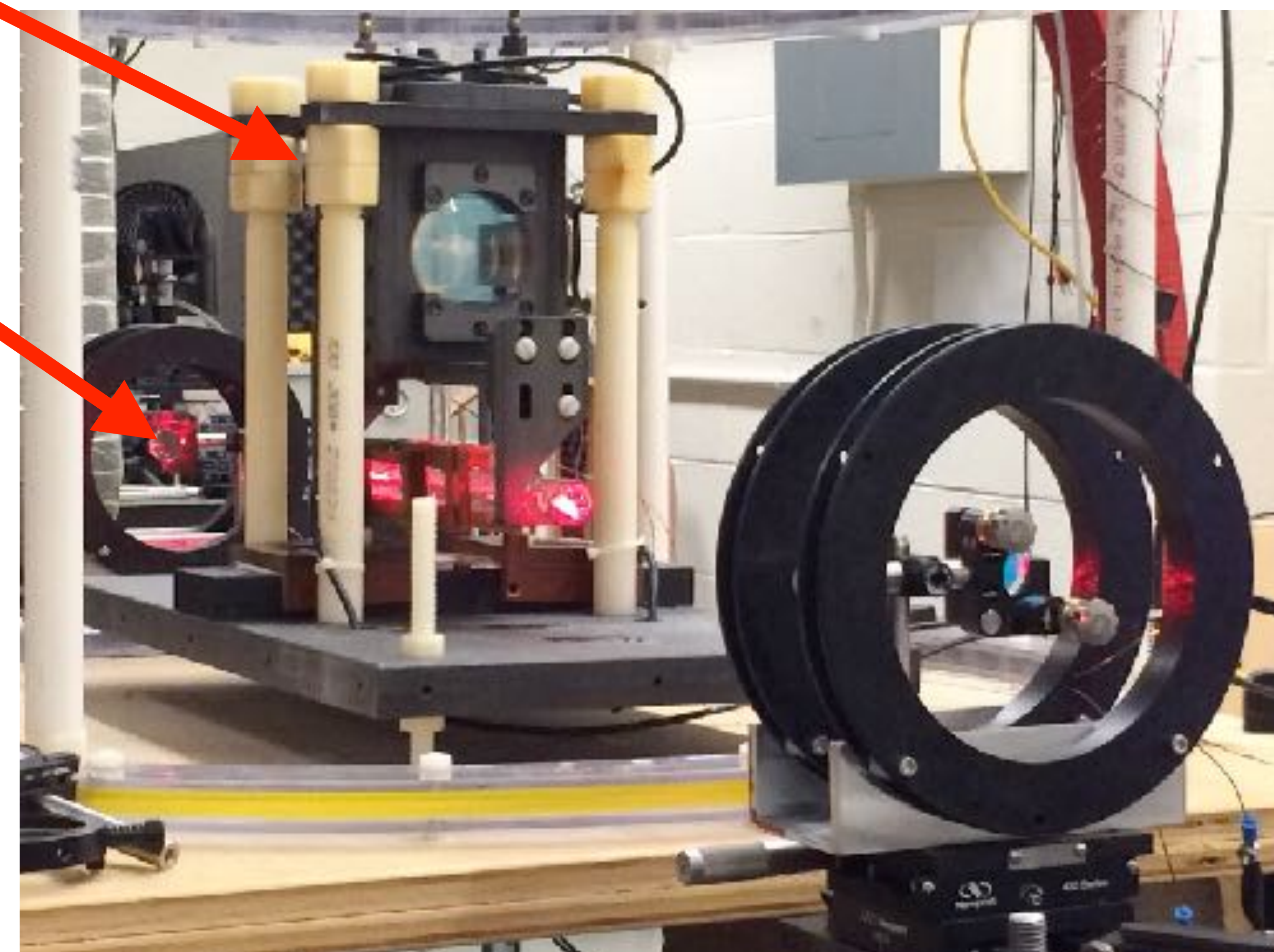
1/f noise!!

Complete Setup



Pump and probe laser systems

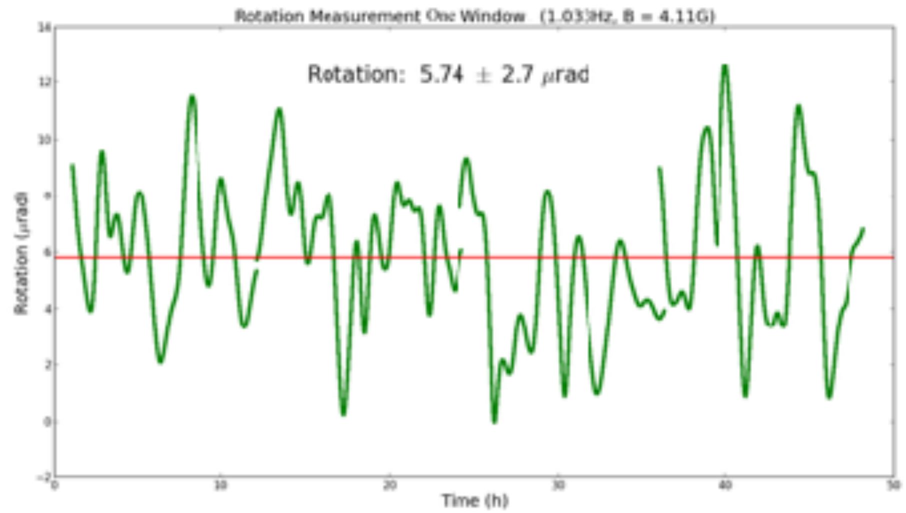
Target region



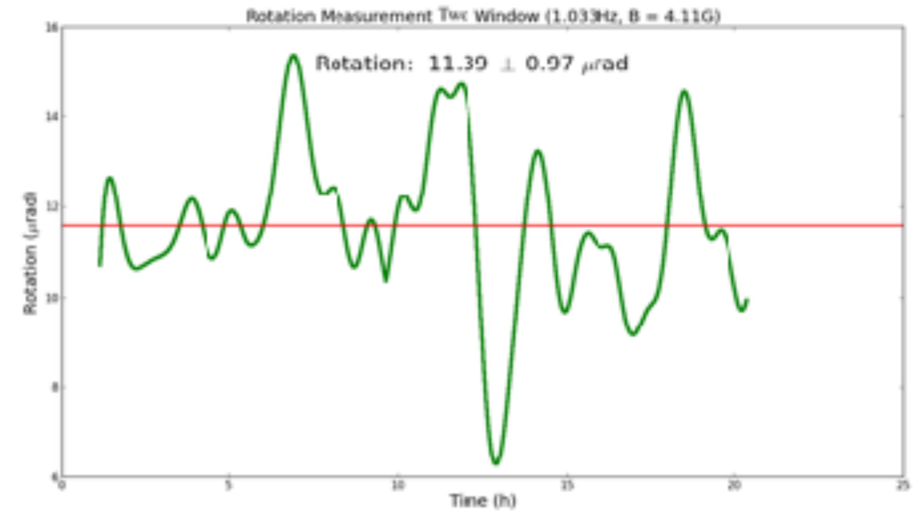
Some Systematic Checks

- Does the FR from multiple objects in the beam path add up with our measurement method?
- Are there errors associated with windows in the beam path?

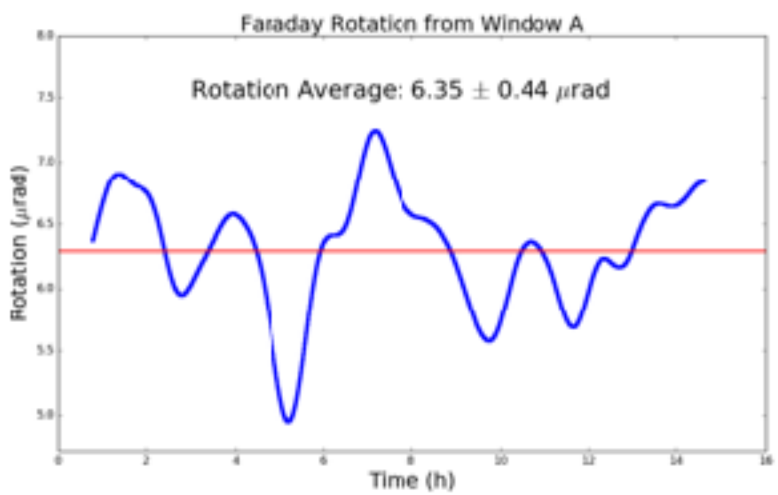
1 window



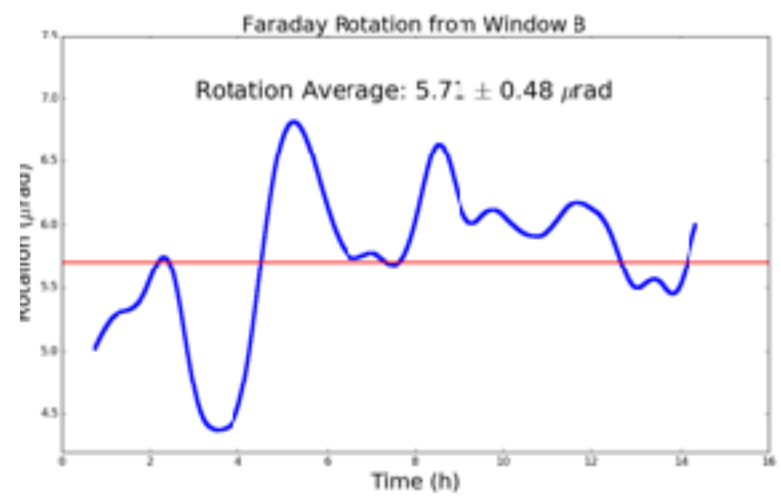
2 windows



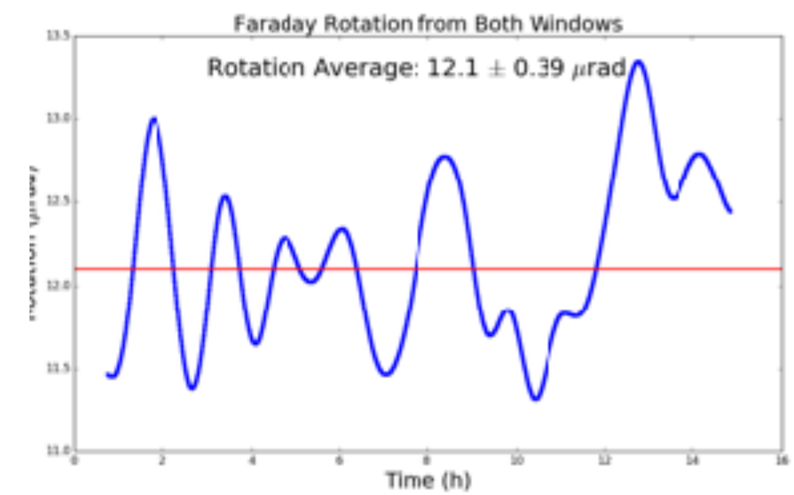
test window A



test window B

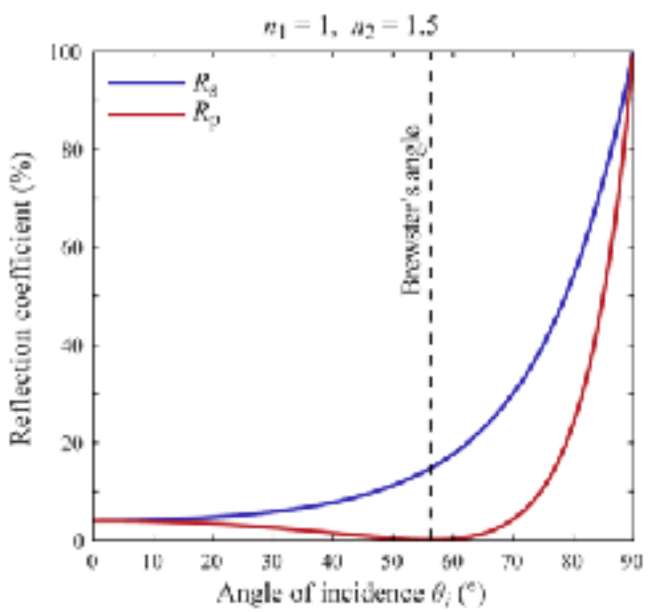


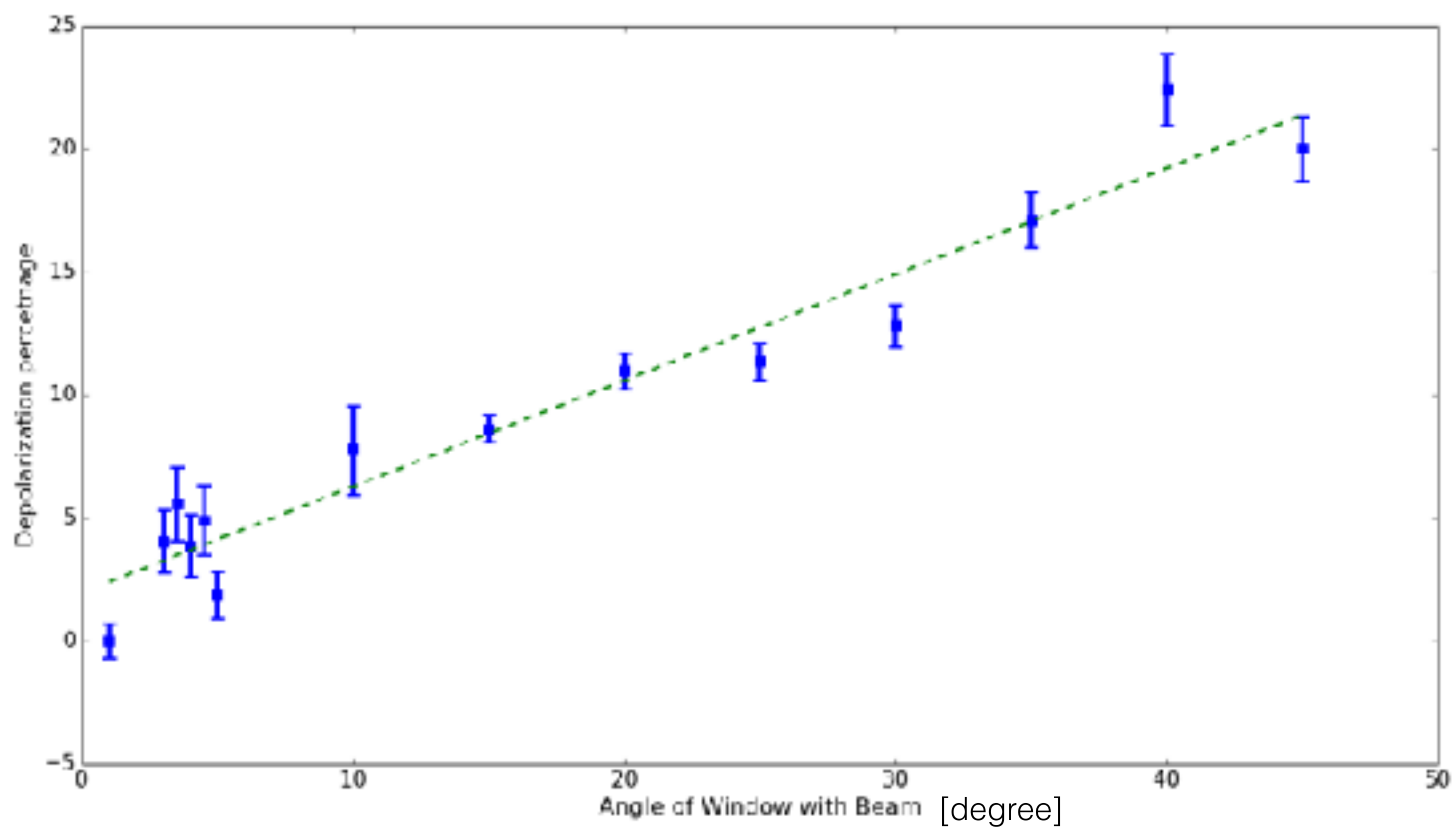
windows A + B



Light Depolarization

s- and p-polarizations:
- depolarization due to reflections
- effect of magnetic field





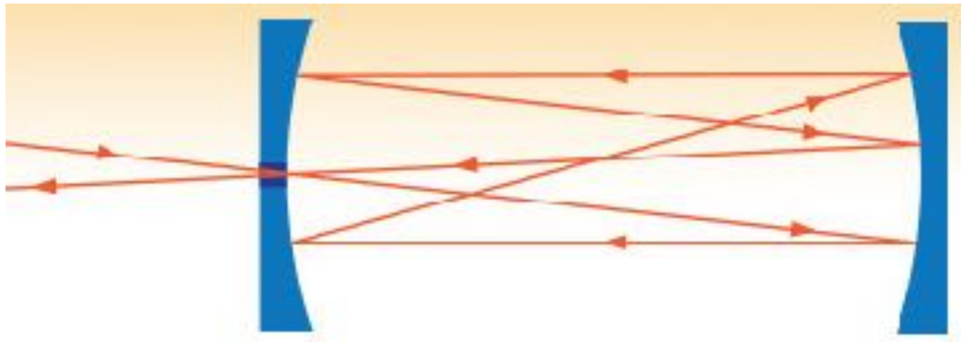
$$Depol\ \% = \frac{Measured\ Value\ at\ AOI}{Measured\ Value\ at\ 0^o\ AOI}$$

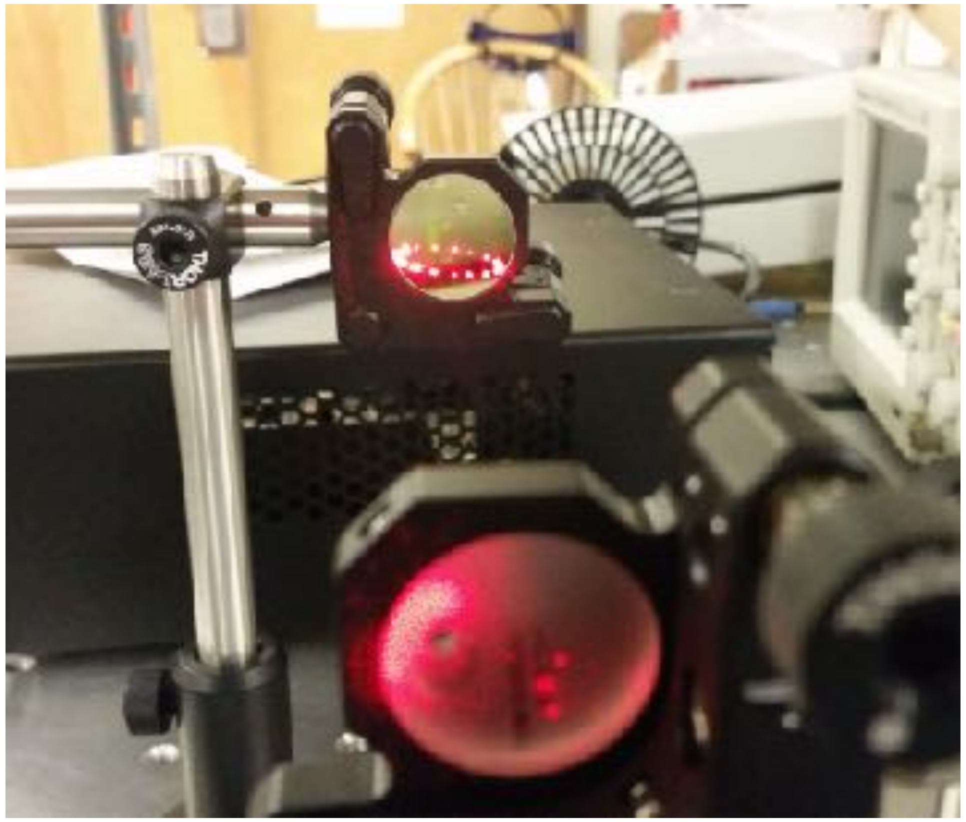
Polarization loss: < 3%

Increased Sensitivity (Multi-pass Cavity)

Improving SNR: θ_{FR} is additive under reflection → θ_{FR} increases

Herriott Cavity

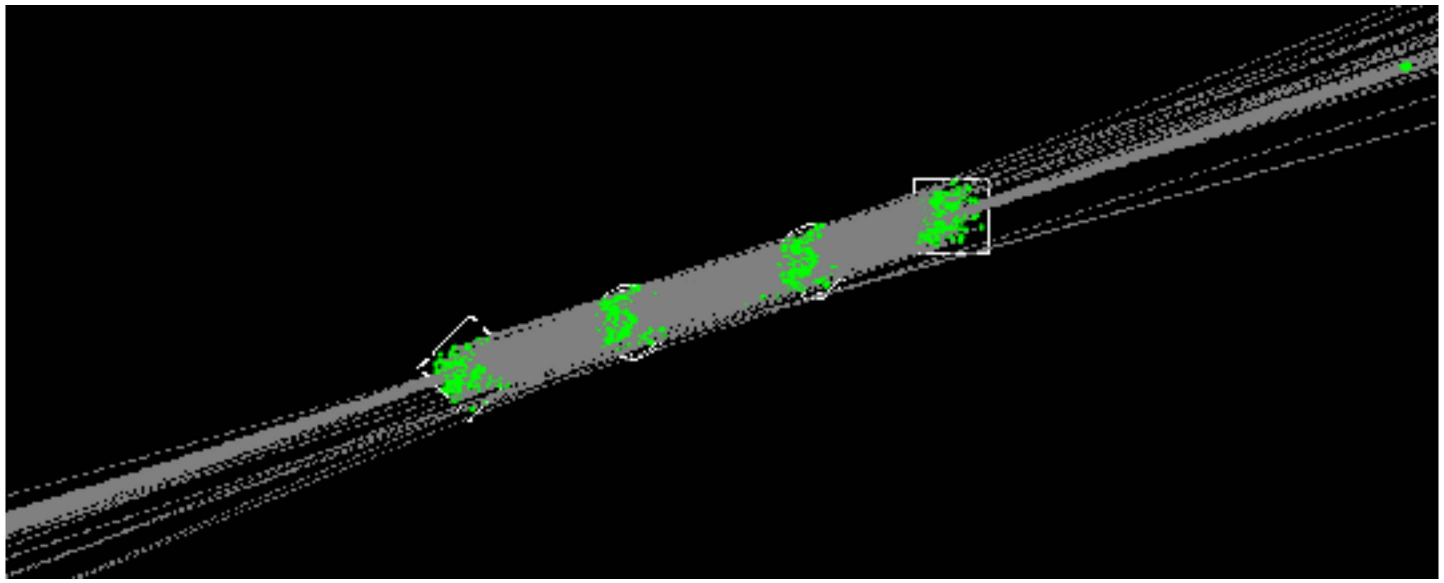


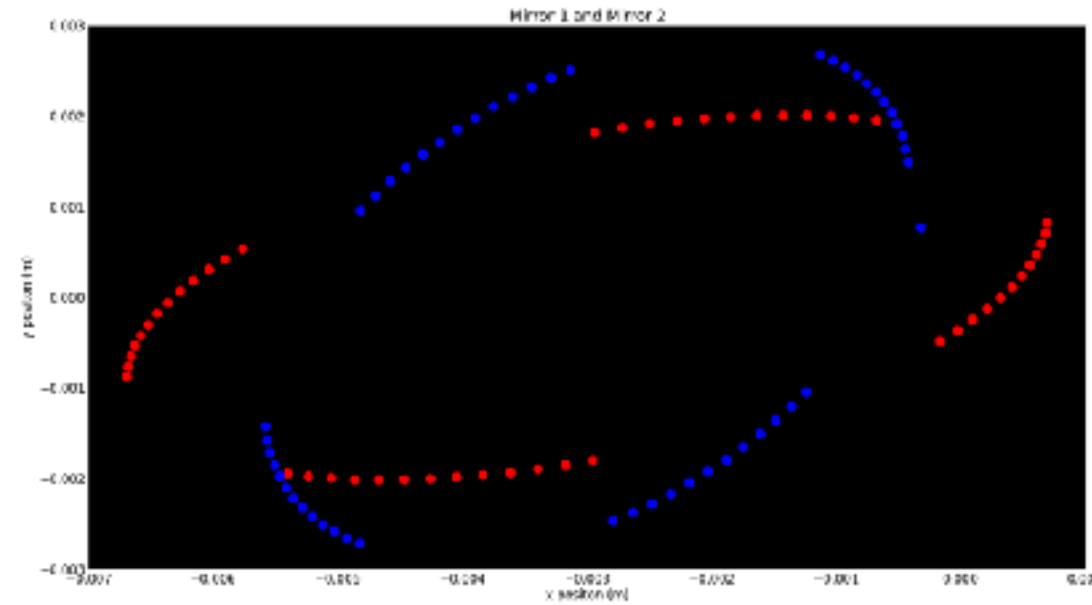


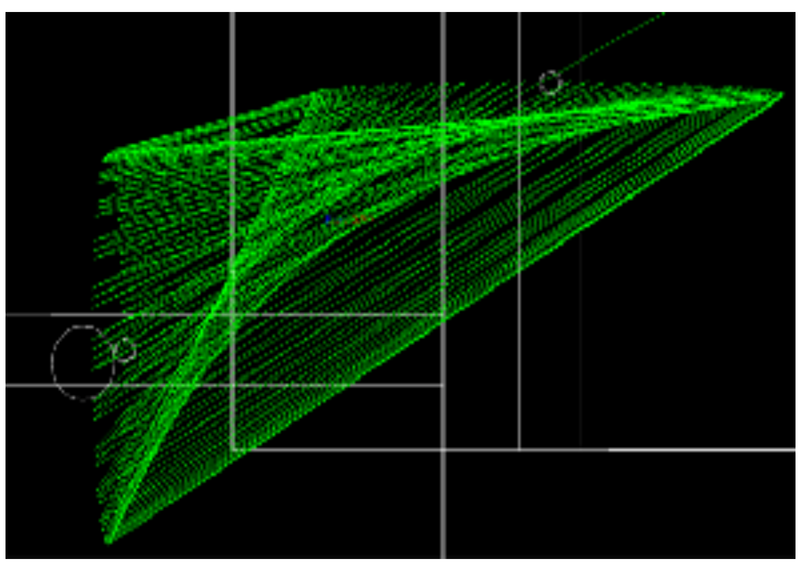
- Flat mirrors: not optimal
  need better beam focusing
- Cylindrical mirrors: concave ✓
- Spherical mirrors: concave ✓

Optimizing Mirror Geometry

Two spherical mirrors with glass windows

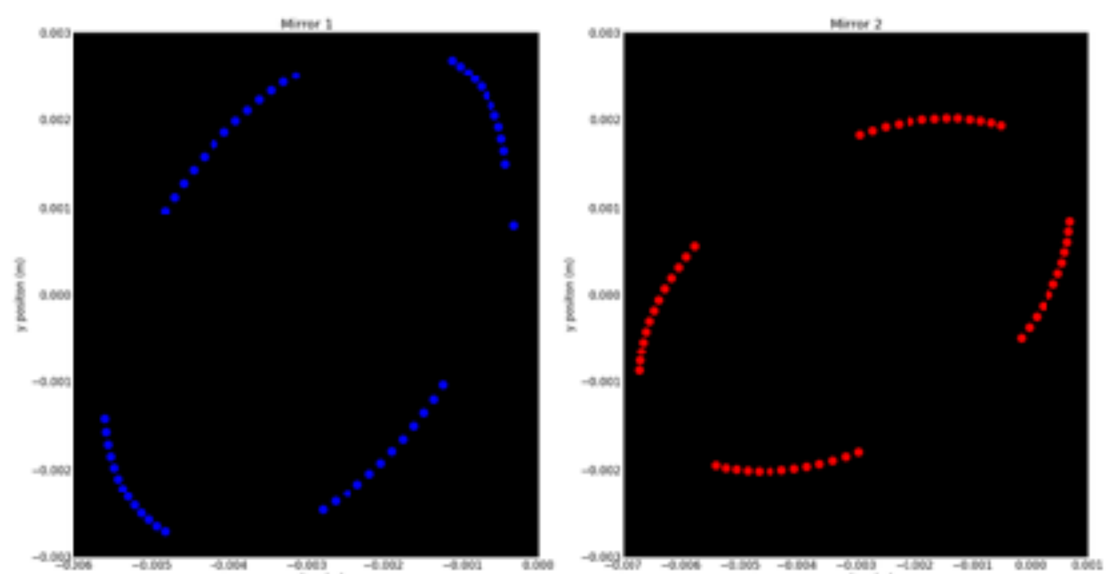






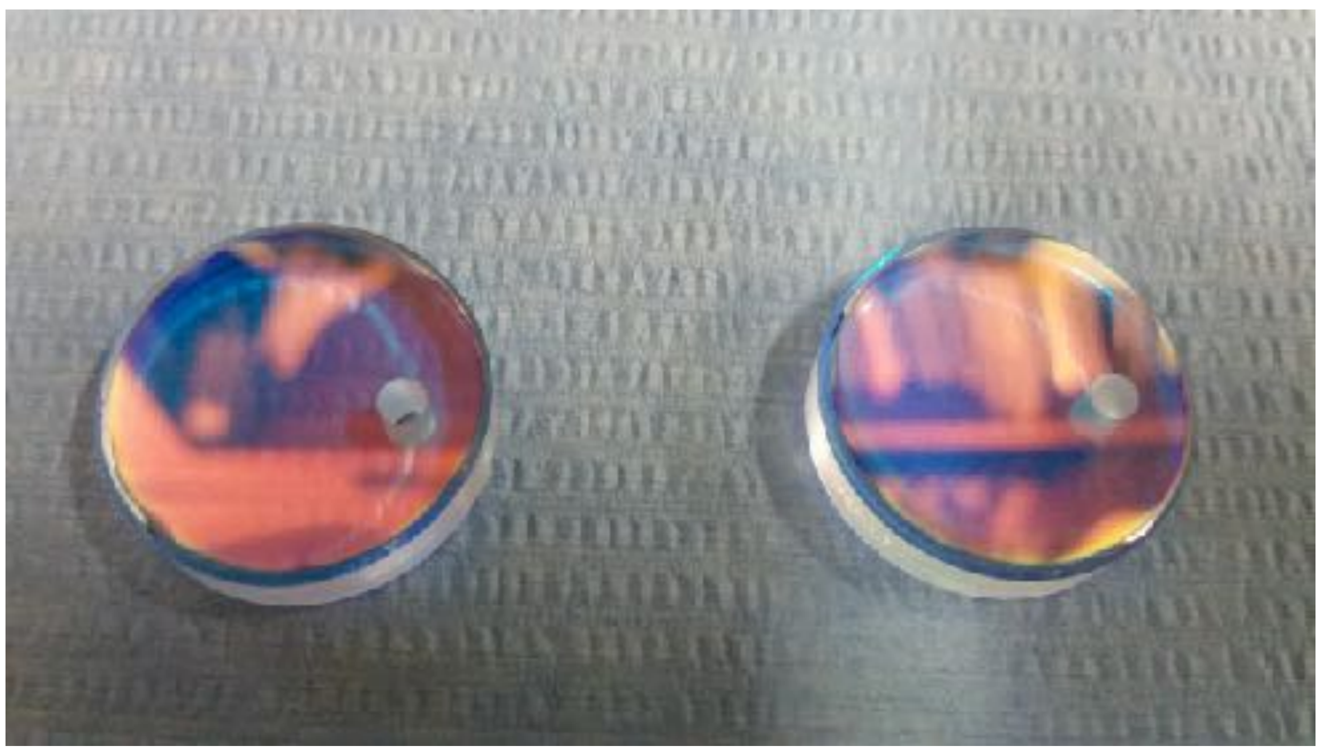
Cylindrical mirrors

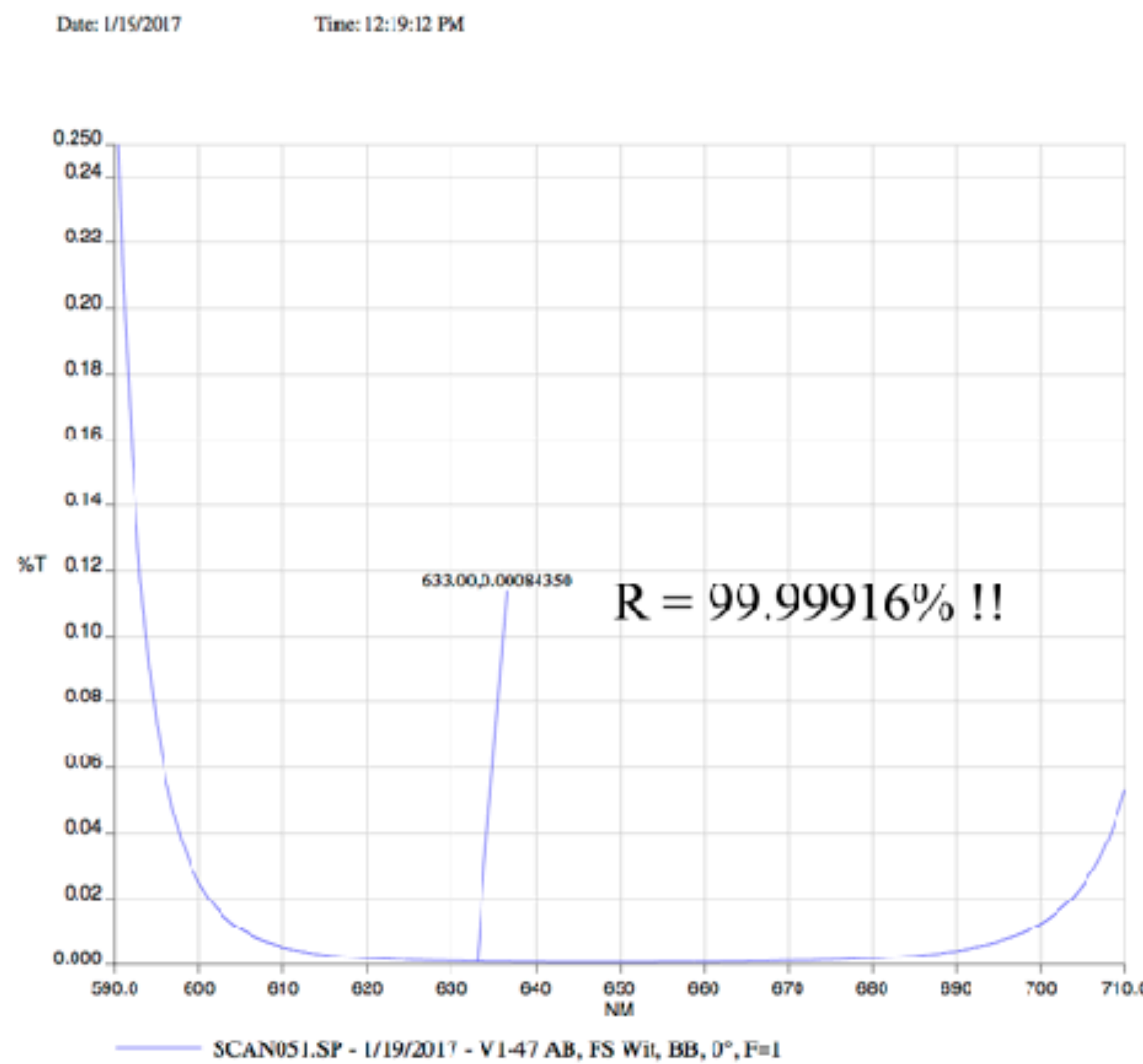
Gold covered spherical mirror



Single photon pattern on mirror surface

Cavity Mirrors





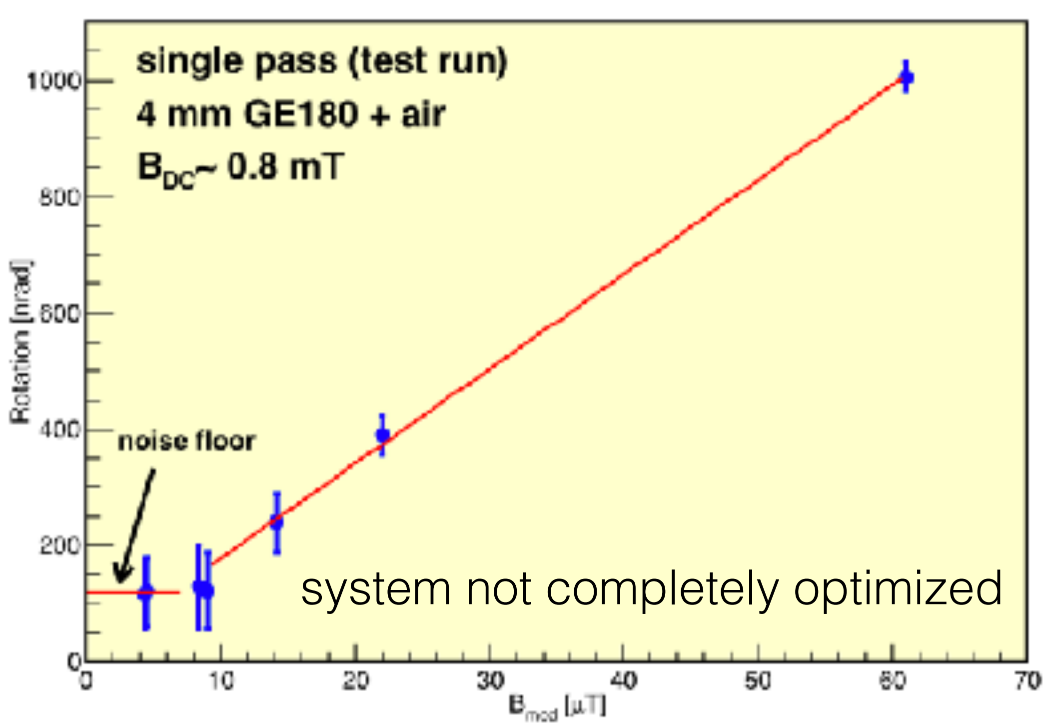
R = 99.99916% !!

Experimental Tests

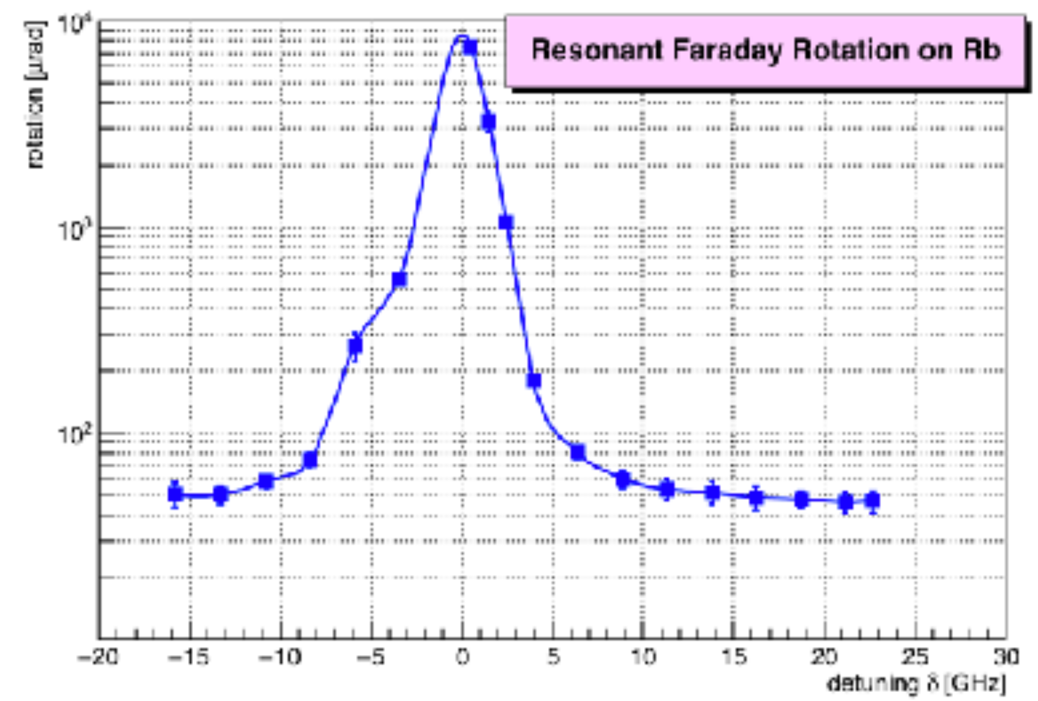
Single pass vs multi pass: 4 mm GE180 + air

# of passes	θ"meas" [μrad]	θ_{air} [μrad]	θ_{glass} [μrad]
1	8.95	2.15	6.80
15 × 1	134.25	-	102.00
15	126.05	1.69	100.24

Single pass: B-field scan 4 mm GE180 + air

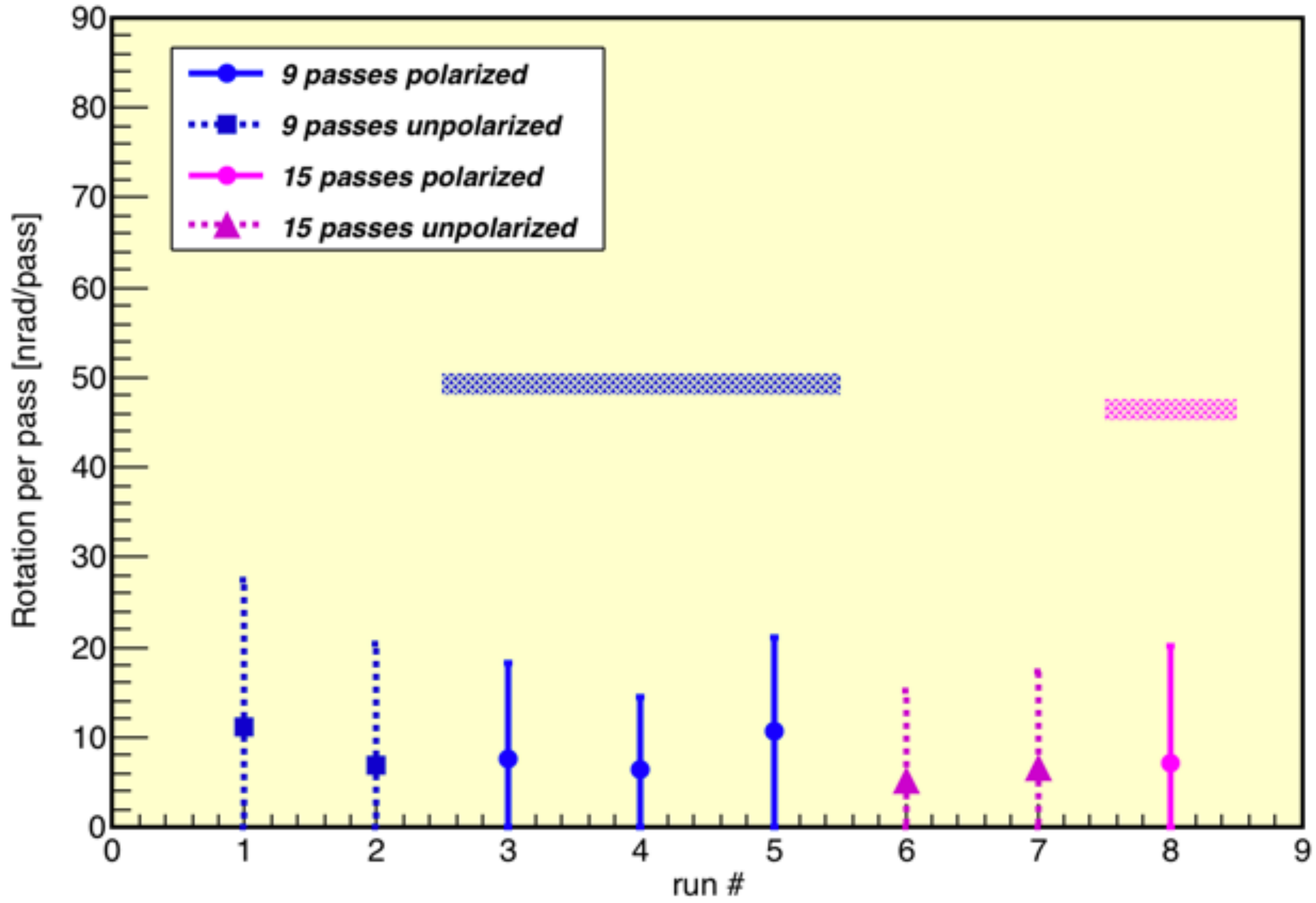


Single pass: On-resonance
10 cm Rb gas at T_{room}



First FR Measurement on Polarized ^{3}He

Preliminary!!



Best measurement so far (w/o ^{3}He cell): θ = (15 +/- 9) nrad (15 passes)
→ (1 +/- 2) nrad/pass

Summary

- Gyromagnetic Faraday rotation as a probe of a possible DMAU
- Developed apparatus with a sensitivity of 2 nrad/pass

  → $\Delta n \sim 4 \times 10^{-14}$/cm @ 633 nm
- Test case → polarized ^{3}He: no effect at level of ~10 nrad/40 cm observed yet
- Further systematic studies in progress
- Do results place limits on SME (e.g. limit on $\vec{\sigma}_{photon} \cdot \vec{\sigma}_{^3He}$ correlations ?)