Lecture - II

Apparatus and Results

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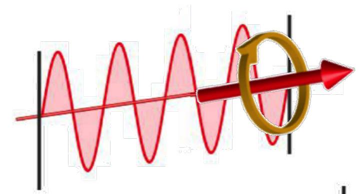
A reminder from Lecture - I

Conditions for a finite polar Kerr effect

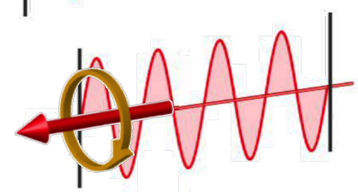
To measure the Kerr effect we send circularly polarized light onto a material and examine the amplitude and polarization of the reflected light.

Compare the reflected light of the two possible circularly-polarized states relevant for Polar Kerr Effect (PKE):

Forward going, right-circularly polarized: $|\mathbf{k},+\rangle$

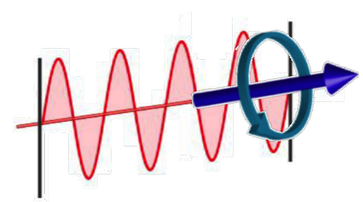


which is **backscattered** into right-circularly polarized $|-\mathbf{k},+\rangle$

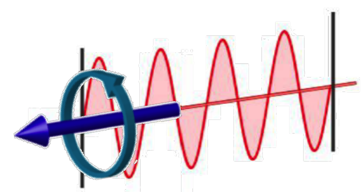


Vs.

Forward going, left-circularly polarized: $|\mathbf{k},-\rangle$



which is **backscattered** into left-circularly polarized: $|-\mathbf{k},-\rangle$



Conditions for a finite polar Kerr effect

To measure the Kerr effect we send circularly polarized light onto a material and examine the amplitude and polarization of the reflected light.

We then calculate the **transition amplitudes** which are basically the relevant reflection coefficients:

Reflection coefficient of **RCP**: $\langle \mathbf{k}, +|\hat{T}(\omega)| - \mathbf{k}, +\rangle \equiv R_{++}$

Reflection coefficient of **LCP**: $\langle \mathbf{k}, -|\hat{T}(\omega)| - \mathbf{k}, -\rangle \equiv R_{--}$

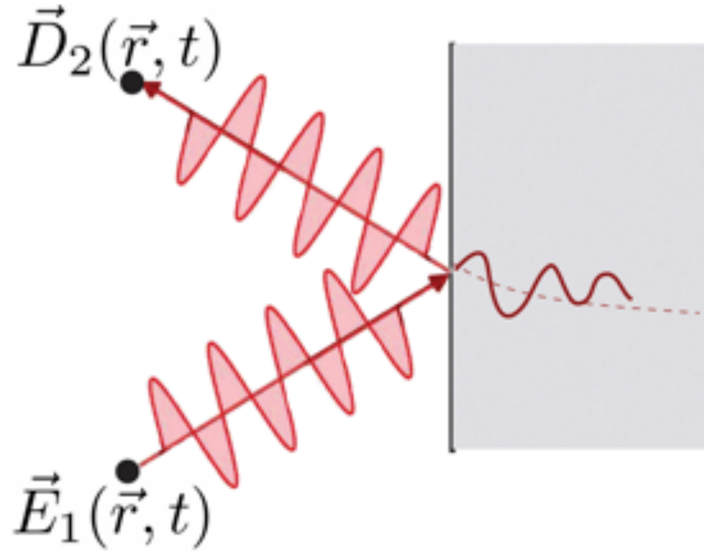
And the **Kerr effect** is:

$$\theta_K = \frac{1}{2} \{\arg[R_{++}] - \arg[R_{--}]\}$$

Reciprocity

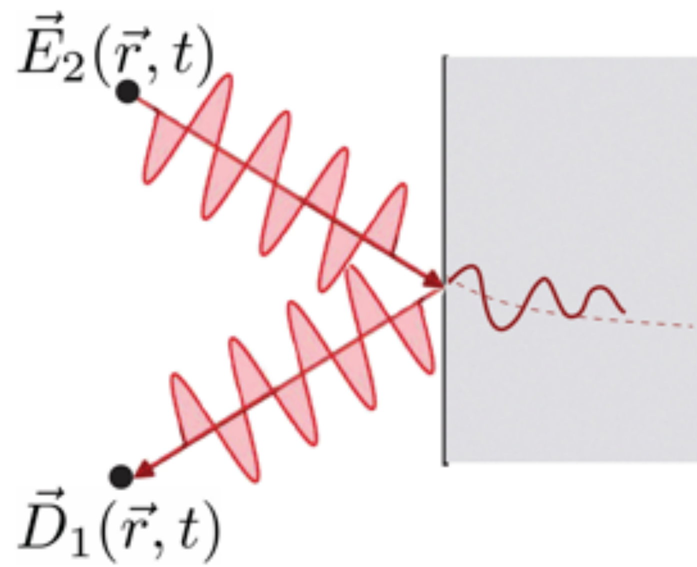
Apply: $\mathbf{E}(\mathbf{r}, t)$

The response after interaction with the sample: $\mathbf{D}(\mathbf{r}, t)$



and the condition for **RECIPROCITY**

$$\int d^3r \mathbf{D}_1 \cdot \mathbf{E}_2 = \int d^3r \mathbf{D}_2 \cdot \mathbf{E}_1$$



Reciprocity

Start from the response of the medium to an applied electric field:

$$D_i(\mathbf{r};\omega) = \int d^3r' \epsilon_{ij}(\mathbf{r},\mathbf{r}';\omega) E_j(\mathbf{r}';\omega)$$

The requirement of **RECIPROCITY** means that if we denote the position of the source and detector with "**1**" and "**2**" respectively, the following should hold:

$$\int d^3r \mathbf{D}_1 \cdot \mathbf{E}_2 = \int d^3r \mathbf{D}_2 \cdot \mathbf{E}_1$$

Which is equivalent to:

$$\epsilon_{ij}(\mathbf{r},\mathbf{r}';\omega) = \epsilon_{ji}(\mathbf{r}',\mathbf{r};\omega)$$

Where we did not make any assumption about absorption in the material.

This implies for the transition amplitudes tensor:

$$T_{ij}(\mathbf{r},\mathbf{r}';\omega) = T_{ji}(\mathbf{r}',\mathbf{r};\omega)$$

Conditions for a finite polar Kerr effect

If reciprocity is preserved:

$$\langle \mathbf{k},+|\hat{T}(\mathbf{r},\mathbf{r}';\omega)|-\mathbf{k},+\rangle = \langle \mathbf{k},-|\hat{T}(\mathbf{r}',\mathbf{r};\omega)|-\mathbf{k},-\rangle$$

$$\Rightarrow \quad R_{++} = R_{--}$$

The Kerr effect is therefore:

$$\boxed{\theta_K = \frac{1}{2}\{\arg[R_{++}] - \arg[R_{--}]\} = 0}$$

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$\rightarrow$ $R_{++} = R_{--}$

The Kerr effect is therefore: $\boxed{\theta_K = \frac{1}{2}\{\arg[R_{++}] - \arg[R_{--}]\} = 0}$

If reciprocity is violated (e.g. by an external magnetic field $\mathbf{H}$):

$$\hat{\mathcal{T}}\hat{T}(\mathbf{r},\mathbf{r}';\omega,\mathbf{H})\hat{\mathcal{T}}^{-1} = \hat{T}^*(\mathbf{r}',\mathbf{r};\omega,-\mathbf{H})$$

$$\langle \mathbf{k},+|\hat{T}(\mathbf{r},\mathbf{r}';\omega,\mathbf{H})|-\mathbf{k},+\rangle \neq \langle \mathbf{k},-|\hat{T}(\mathbf{r},\mathbf{r}';\omega,-\mathbf{H})|-\mathbf{k},-\rangle$$

$\rightarrow$ $R_{++} \neq R_{--}$

The Kerr effect is finite: $\boxed{\theta_K = \frac{1}{2}\{\arg[R_{++}] - \arg[R_{--}]\} \neq 0}$

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➔ $R_{++} \neq R_{--}$

The Kerr effect is finite: $\boxed{\theta_K = \frac{1}{2}\{\arg[R_{++}] - \arg[R_{--}]\} \neq 0}$

For the following considerations reciprocity is violated via **broken time reversal symmetry** because of either spontaneous symmetry breaking such as magnetism, or the application of an external magnetic field.

Continue….

Summary for the polar Kerr effect

A finite Kerr effect requires time reversal symmetry breaking!

then $$\theta_K = \frac{1}{2}\{\arg[R_{++}] - \arg[R_{--}]\} \neq 0$$

And, using the expressions for the dielectric function, we can again obtain the relation

$$\theta_K = \Im\left\{\frac{n_+ - n_-}{1 - n_+ n_-}\right\}$$

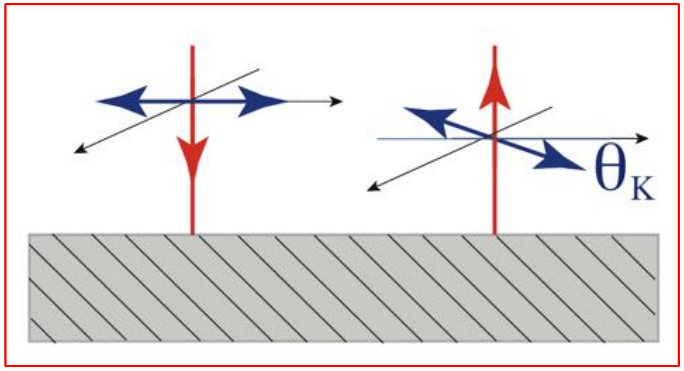
Recall: $n_\pm^2 = \epsilon \pm g$, and $n_\pm^2 = 1 - \frac{4\pi i}{\omega}(\sigma_{xx} \pm \sigma_{xy})$

and for $g \ll \epsilon$

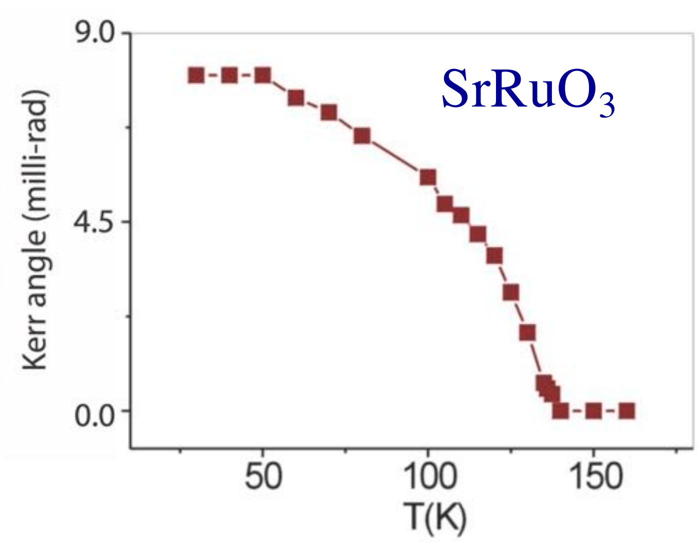
we find: $$\theta_K \approx -\frac{4\pi}{\omega}\Im\left\{\frac{\sigma_{xy}}{n(n^2-1)}\right\}$$

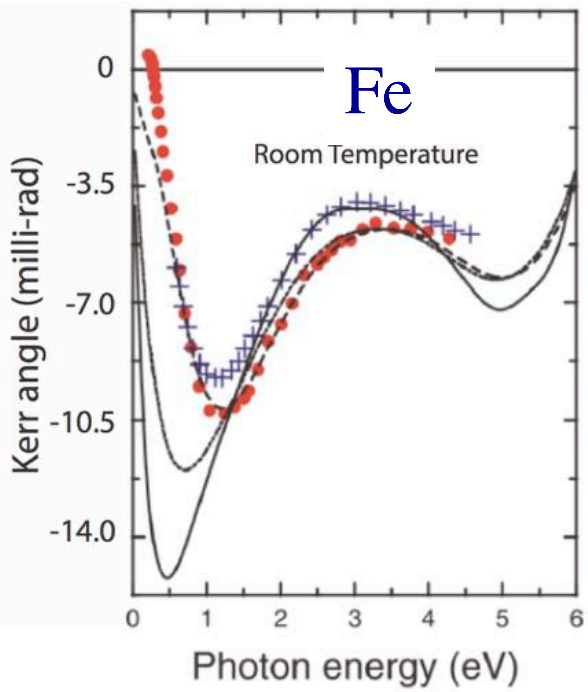
Scale of MO in ferromagnets

Typical Kerr effect in Ferromagnets is of order 10 milli-rad, but can be as large as **1** *rad* in strong ferromagnets!



Examples:





Searches for Broken Time Reversal Symmetry (TRSB)

➢ **Searches for TRSB in superconductors started with the proposal that High-Tc superconductors exhibit Anyon** superconductivity* (1987-92)

(Note: this case it is not a simple *L*>0 pairing mechanism)

Positive results appeared soon after theory:

VOLUME 64, NUMBER 24 PHYSICAL REVIEW LETTERS 11 JUNE 1990

Search for Circular Dichroism in High-T_c Superconductors

K. B. Lyons, J. Kwo, J. F. Dillon, Jr., G. P. Espinosa, M. McGlashan-Powell, A. P. Ramirez, and L. F. Schneemeyer
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 13 March 1990)

We report observation of circular dichroism in reflection from various cuprate supe... terials, including $YBa_2Cu_3O_{7-x}$ films, an etched $YBa_2Cu_3O_7$ crystal, and a Bi_2Sr_2CaCu... signal develops as T is lowered below 200 K and exhibits little change near T_c. The exa... tures differ for the various materials.

Evidence for broken time reversal symmetry in cuprate superconductors

H.J. Weber[(a)], D. Weitbrecht[(a)], D. Brach[(a)], A.L. Shelankov[(a), (b)], H. Keiter[(a)], W. Weber[(a)], Th. Wolf[(c)], J. Geerk[(d)], G. Linker[(d)], G. Roth[(d)], P.C. Splittgerber-Hünnekes[(e)] and G. Güntherodt[(e)]

Received 23 July 1990; revised 16 August 1990. by M. Cardona. Available online 23 September 2002.

Abstract

Reflection measurements on a one-dimensional single crystal of $YBa_2Cu_3O_{7-\delta}$ and transmission measurements on single crystals of $Bi_2Sr_2CaCu_2O_8$ are reported which indicate optical circular effects below temperatures Ts somewhat above the respective superconducting temperatures Tc. The signs of rotation can be controlled by an external magnetic field. We interpret these results as strong evidence for a state with broken time reversal symmetry below Ts, as predicted by the theories of anyon or flux phase superconductivity.

Observed effect ~ 200 *mrad*!

*V. Kalmayer & R.B. Laughlin, Phys. Rev. Le

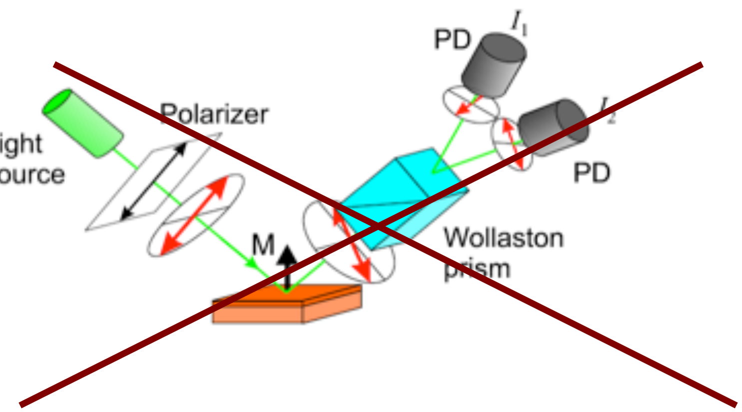
Searches for Broken Time Reversal Symmetry (TRSB)

However, a **good** experiment should:

1. Reject **all** reciprocal effects such as linear birefringence and optical activity.

1. Measure an absolute value of the Kerr effect, rather than a result of a modulated signal*.

A simple cross polarization method will not be enough!



* When searching for magnetism, it is common to measure the Faraday/Kerr effects while modulating an external magnetic field, and “locking-in” to the frequency of the modulation. This increases the SNR substantially

Searches for Broken Time Reversal Symmetry (TRSB)

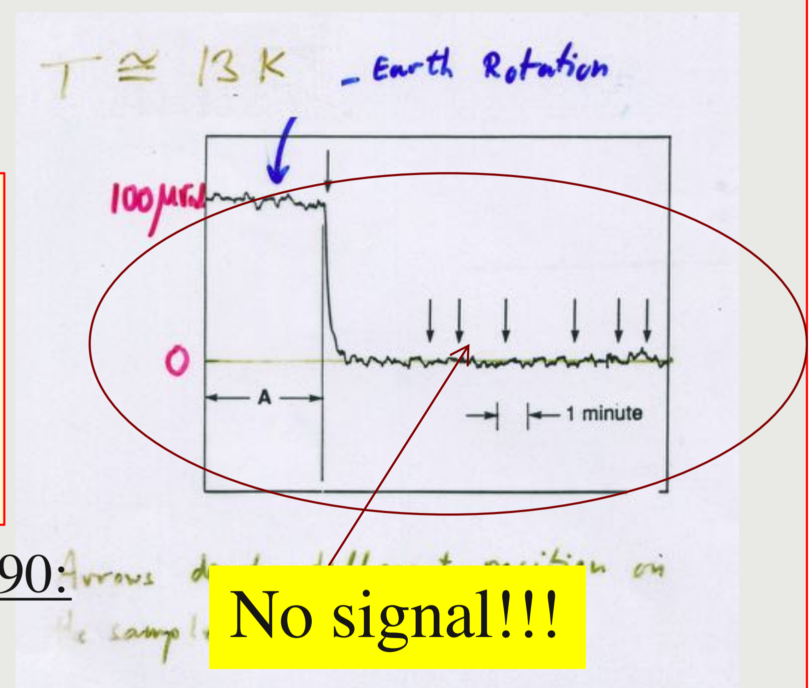
However, a **good** experiment should:

1. Reject **<u>all</u>** reciprocal effects such as linear birefringence and optical activity.

1. Measure an absolute value of the Kerr effect, rather than a result of a modulated signal*.

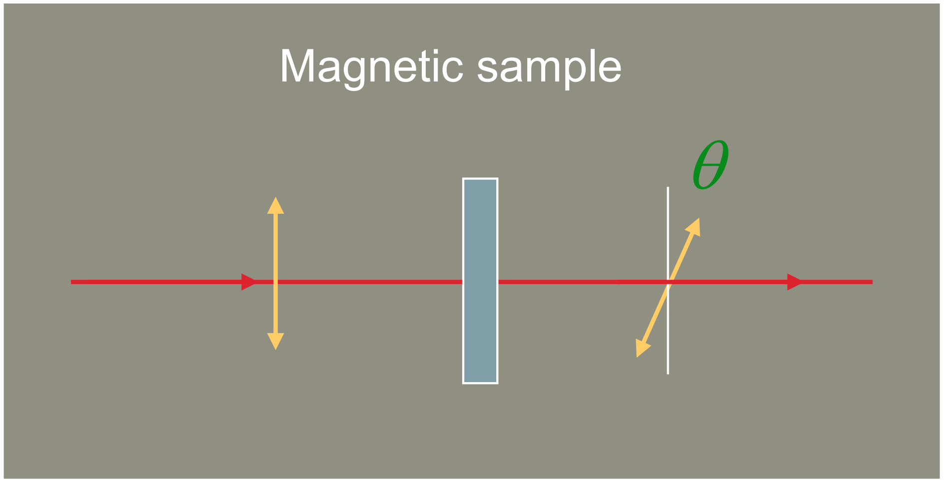
The positive experiments were shown to be wrong because they did not pay attention to reciprocal effects!

<u>Kapitulnik's lab-notebook, March, 15 1990:</u>



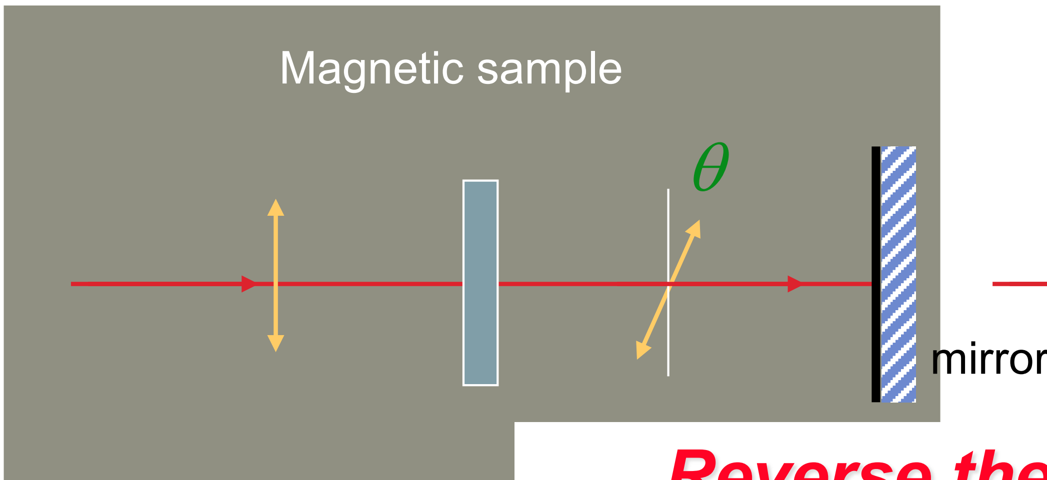
A Simple (Warm up) Experiment

A simple experiment



Sample with reciprocal polarization rotation
(i.e. linear birefringence)

A simple experiment



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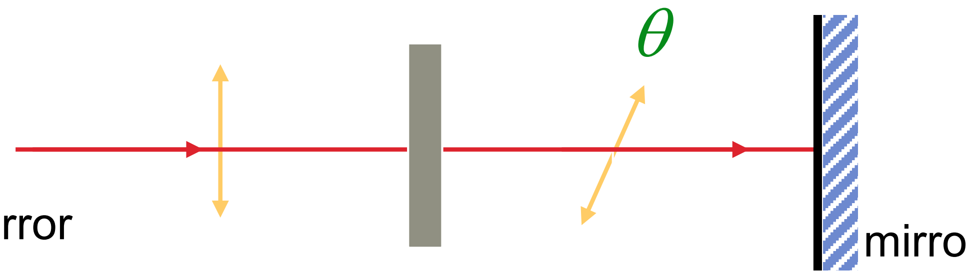
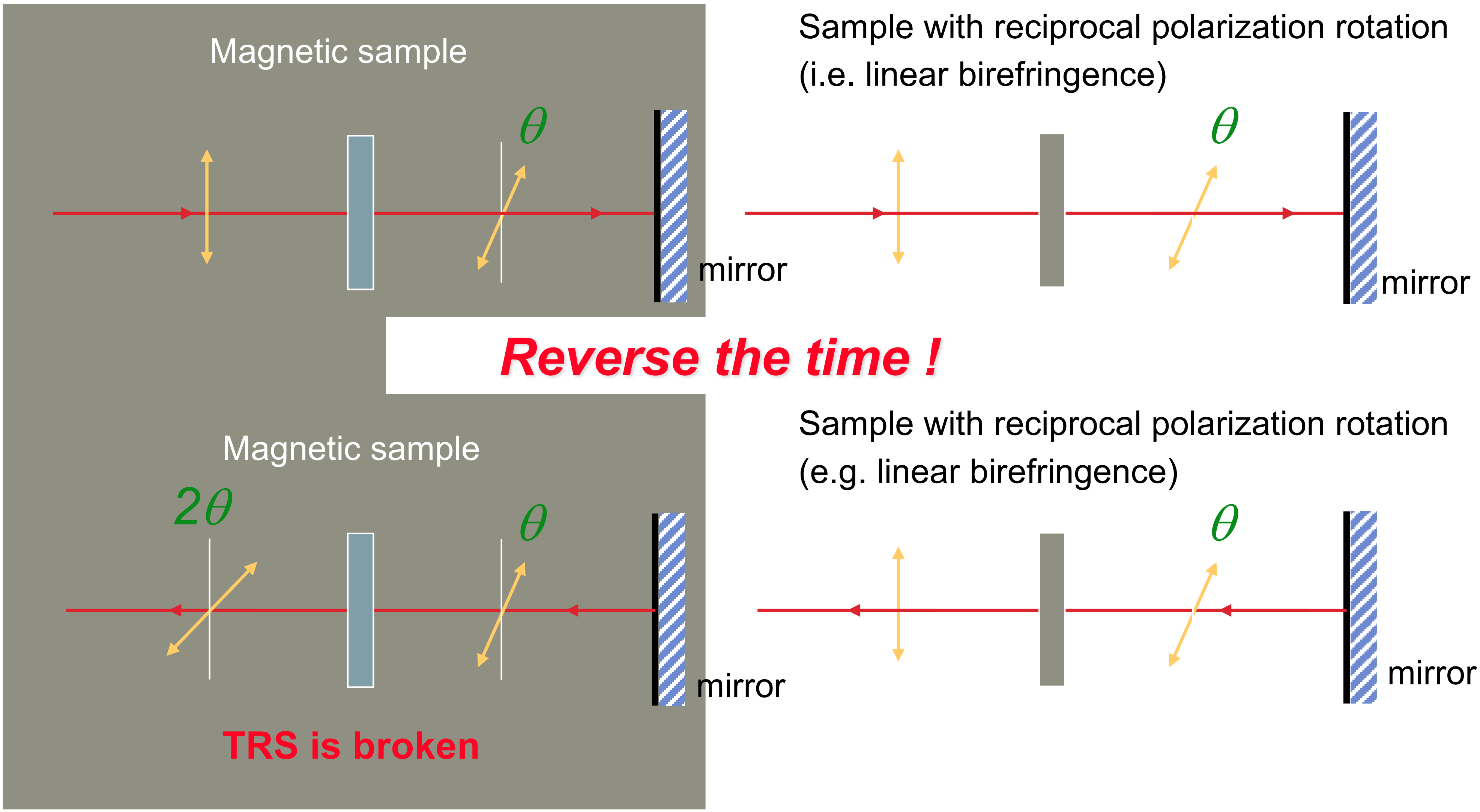


Reverse the time !

A simple experiment



We can distinguish between magneto optic signal (Kerr and Faraday) from reciprocal effects if we measure the difference between a light beam with its time reversal counter part beam.

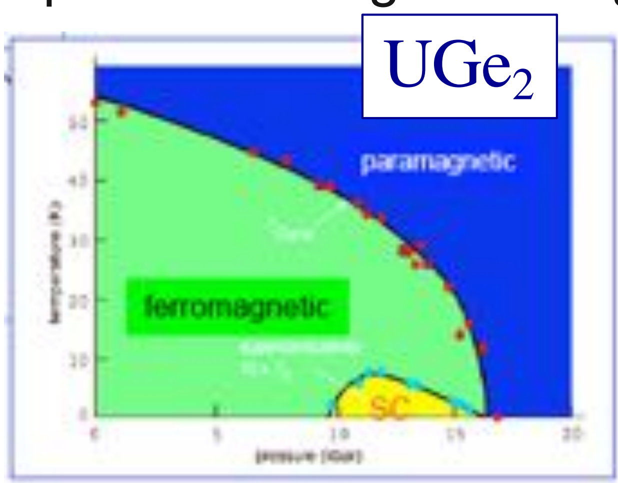
Unconventional Superconductors … again

Searches for Broken Time Reversal Symmetry (TRSB)

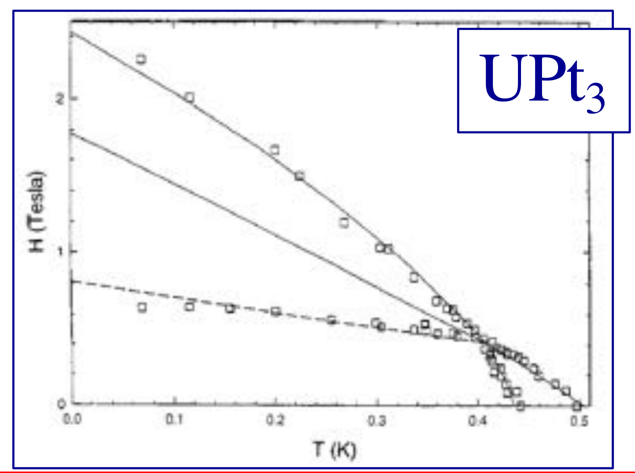
- ~~Searches for TRSB in superconductors started with the proposal that High-Tc superconductors exhibit **Anyon** superconductivity (1987-92)~~
  ~~(Note: this case it is not a simple *L*>0 pairing mechanism)~~

- **More recent searches concentrated on cases for which** *L>0*

Superconducting ferromagnets



Heavy Fermion Superconductors



Where if time-reversal symmetry is broken, the gap function is complex: $\Delta_{\pm}(T) = \Delta_R(T) \pm i\Delta_I(T)$

The superconducting gap function

$$\Delta_{\vec{k}} = -\sum_{\vec{k}'} V_{\vec{k}\vec{k}'} \Delta_{\vec{k}'} \frac{1 - 2f(E_{\vec{k}'})}{2E_{\vec{k}'}} \qquad E_{\vec{k}} = \sqrt{\xi_{\vec{k}^2} + |\Delta_{\vec{k}}|^2}$$

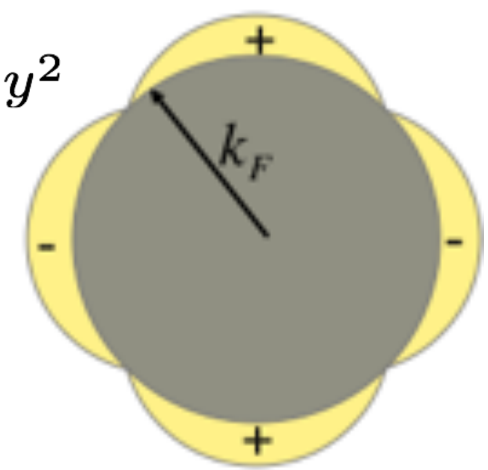
In general: $\Delta_{\vec{k}} = \Delta_0 \cdot \Phi(\vec{k})$ where $\Phi(\vec{k}) = f_R(\vec{k}) + i f_I(\vec{k})$

TRSB is broken if $f_R(\vec{k}), f_I(\vec{k}) \neq 0$

For example, “d-wave” symmetry
(TRSB NOT broken):

$$\Delta_{\vec{k}} = \Delta_0[\cos(k_x) - \cos(k_y)]$$

$d_{x^2-y^2}$



TRSB in unconventional superconductors

Assume a gap function that has the form:

$$\Delta_\pm(T) = \Delta_R(T) \pm i\Delta_I(T)$$

For example, "p-wave" ($L = 1$) symmetry = $\Delta = \Delta_0[k_x \pm ik_y]$

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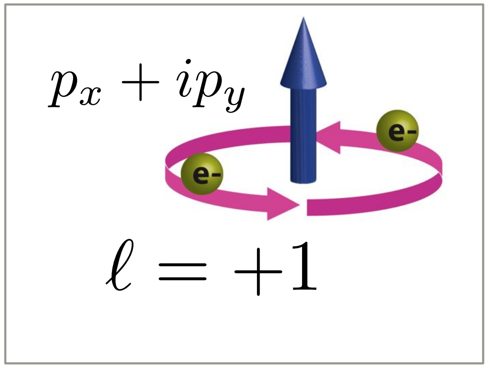
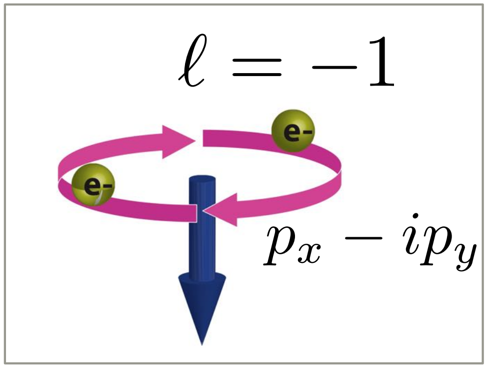
For example, "p-wave" ($L = 1$) symmetry = $\Delta = \Delta_0[k_x \pm ik_y]$

The broken time reversal symmetry of the two solutions, $\Delta_{\pm}(T)$, is manifested by the two possible orientations of the internal orbital angular momentum of the Cooper-pairs:

$$\vec{\mu} = \frac{-e^*}{2m^*c}\vec{L}$$





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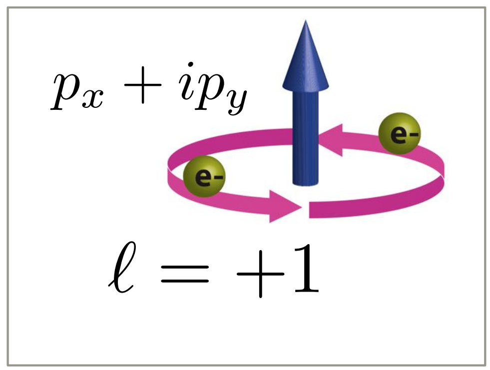
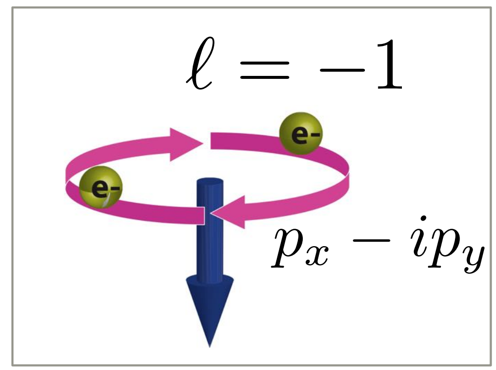




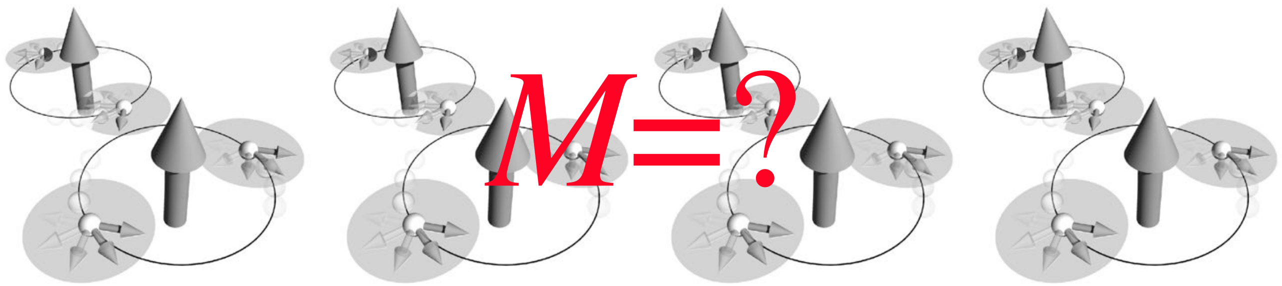
Effective Pairs magnetization:

$$\boxed{\vec{M} = n_s \frac{-e^*}{2m^*c}\vec{L}}$$

$$n_s = n/2; \;\; e^* = 2e; \;\; m^* = 2m_e$$

TRSB in unconventional superconductors

Can we measure a spontaneous magnetization?



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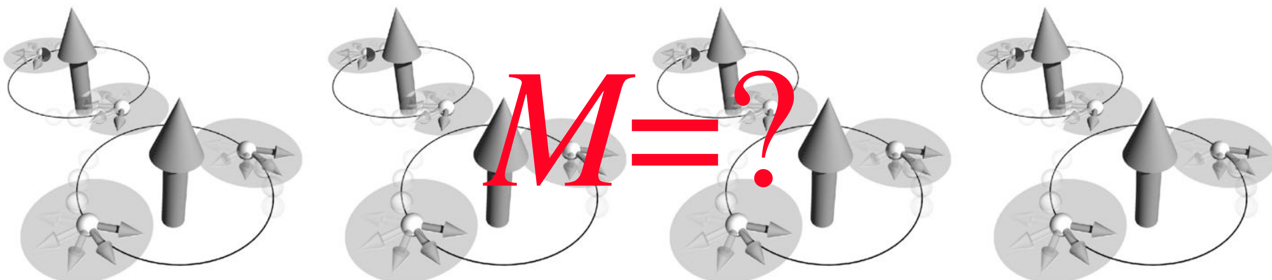
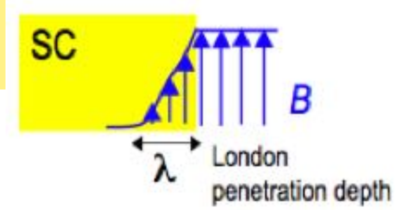


NO! Because of Meissner Effect!

➔ *Total* M=0

No spontaneous magnetic moment can be detected because of compensating Meissner currents*.



Note: sample will always contain **surfaces and defects** at which the Meissner screening of the TRS-breaking moment is not perfect, and a small magnetic signal is expected.

TRSB in unconventional superconductors

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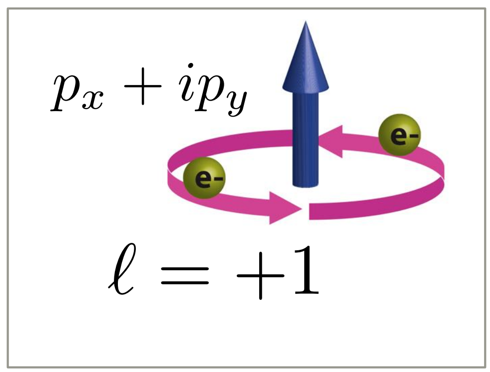

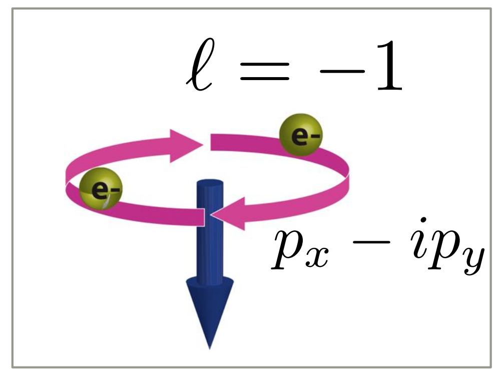

Effective Pairs magnetization: $\boxed{\vec{M} = n_s \frac{-e^*}{2m^*c}\vec{L}}$ $\quad n_s = n/2;\ e^* = 2e;\ m^* = 2m_e$

Theory of Kerr Effect in TRSB Superconductors

Start from the effective pairs-magnetization: $\boxed{\vec{M}^{(a)} = n_s \frac{-e^*}{2m^* c}\vec{L}} = n\frac{-\hbar e}{4m_e c}\hat{z}$

The associated "anomalous" current [N.D. Mermin and P. Muzikar, Phys. Rev. B 21, 980 (1980).]

$$\vec{j}^{(a)} = c\nabla \times \vec{M}^{(a)} = \frac{\hbar e}{4m_e}\hat{z} \times \vec{\nabla} n = \frac{\hbar e}{4m_e}\frac{dn}{d\mu}\hat{z} \times \vec{\nabla}\mu$$

For a superconductor:

$$\mu = 2eV + \hbar\frac{\partial}{\partial t}\left(\varphi - \frac{2e}{\hbar c}\int \vec{A}\cdot d\vec{\ell}\right)$$

Yielding ($\sigma_{xy} = \frac{e^2}{h}\frac{1}{2d}$):

$$\vec{j}^{(a)} = \sigma_{xy}\hat{z} \times \left[-\vec{E} + \frac{\partial}{\partial t}\left(\frac{\hbar}{2e}\vec{\nabla}\varphi - \frac{1}{c}\vec{A}\right)\right] =$$

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Remember London Equation: $\frac{\partial \vec{J}_s}{\partial t} = \frac{c^2}{4\pi\lambda_L^2}\vec{E}$ where $\lambda_L^2 = \frac{mc^2}{4\pi n_s e^2}$

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(parentheses vanish because it is exactly London equation for the super-current)

and therefore: $\theta_K \equiv 0$

Theory of Kerr Effect in TRSB Superconductors

However,

a finite Kerr effect can still be obtained for:

i. **Impurity scattering** (broken translational symmetry).
(extrinsic effect)

- Jun Goryo, Phys. Rev. B 78, 060501(R) (2008)
- R. M. Lutchyn, et al., Phys. Rev. B 77, 144516 (2008).

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- R. M. Lutchyn, et al., Phys. Rev. B 77, 144516 (2008).

ii. **Multiband superconductor** with interband coupling.
(intrinsic effect)

- E. Taylor & C. Kallin, Phys. Rev. Lett. 108, 157001 (2012).
- M. Gradhand, K.I. Wysokinski, J. F. Annett, and B. L. Györffy, Phys. Rev. B 88, 094504 (2013).

Since the materials that we will study are very clean, with RRR ~ 1000, the first scenario is less likely.

We concentrate on the second scenario of
superconductivity in multiband superconductors.

Kerr effect in a multiband superconductor

Start with a BCS Hamiltonian with two coupled orbitals:

$$\hat{\mathcal{H}} = \sum_{\mathbf{k}} \left(c^\dagger_{\mathbf{k}_1} c^\dagger_{\mathbf{k}_1} \right) \begin{pmatrix} \xi_1(\mathbf{k}) & \epsilon_{12}(\mathbf{k}) \\ \epsilon_{12}(\mathbf{k}) & \xi_2(\mathbf{k}) \end{pmatrix} \begin{pmatrix} c_{\mathbf{k}_1} \\ c_{\mathbf{k}_2} \end{pmatrix} + \sum_{\alpha,\beta} \sum_{\mathbf{k},\mathbf{k}'} V_{\alpha,\beta}(\mathbf{k},\mathbf{k}') c^\dagger_{-\mathbf{k}\alpha} c^\dagger_{\mathbf{k}\beta} c_{\mathbf{k}'\beta} c_{-\mathbf{k}'\alpha}$$

Inter-orbital coupling

Quasiparticle energies

Orbital labels

Yielding a multi-component complex gap function: $\Delta_{ij} = \begin{pmatrix} \Delta_{11} & \Delta_{12} \\ \Delta_{12} & \Delta_{22} \end{pmatrix}$

It can be shown that if ϵ_{12} is finite, and there is a finite phase shift between the phases of the two order parameters:

$$\boxed{\theta_K \approx \alpha \frac{\epsilon_{12}}{\pi n (n^2 - 1)} \mathcal{A} \frac{\lambda}{d} \frac{|\Delta_{11}||\Delta_{22}|}{(\hbar\omega)^2}}$$

$\alpha = e^2/\hbar c$ = fine structure constant

A numerical constant

E. Taylor & C. Kallin, Phys. Rev. Lett. 108, 157001 (2012).
M. Gradhand, K.I. Wysokinski, J. F. Annett, and B. L. Györffy, Phys. Rev. B 88, 094504 (2013).

Kerr effect in a multiband superconductor

Using: $$\theta_K \approx \alpha \frac{\epsilon_{12}}{\pi n(n^2-1)} \mathcal{A} \frac{\lambda}{d} \frac{|\Delta_{11}||\Delta_{22}|}{(\hbar\omega)^2}$$

and, assume for simplicity that $|\Delta_{11}(0)| = |\Delta_{22}(0)| = |\Delta_0|$

and using the expression of the fine structure constant $\alpha = e^2/\hbar c$ we obtain:

$$\theta_K \approx \alpha \underbrace{\frac{\epsilon_{12}}{n(n^2-1)} \frac{\lambda}{d}}_{\text{Materials parameters Of order (1)}} \frac{|\Delta_0|^2}{(\hbar\omega)^2}$$

Fine-structure constant $\alpha = e^2/\hbar c$

Gap-energy

Light-energy

Kerr effect in a multiband superconductor

Using: $$\theta_K \approx \alpha \frac{\epsilon_{12}}{\pi n(n^2-1)} \mathcal{A} \frac{\lambda}{d} \frac{|\Delta_{11}||\Delta_{22}|}{(\hbar\omega)^2}$$

and, assume for simplicity that $|\Delta_{11}(0)| = |\Delta_{22}(0)| = |\Delta_0|$

and using the expression of the fine structure constant $\alpha = e^2/\hbar c$ we obtain:

Very small!

$$\theta_K \approx \alpha \frac{\epsilon_{12}}{n(n^2-1)} \frac{\lambda}{d} \frac{|\Delta_0|^2}{(\hbar\omega)^2}$$

Very small!

Gap-energy

Fine-structure

const

nergy

$n \sim 3$, frequency $\hbar\omega \sim 10^{15}$ Hz (λ=1.55μm), $T_c \sim 1$ K

We estimate: $\theta_K \sim 50 \div 100$ nanorad

High-Resolution Magneto-optics with a Sagnac Loop

Searches for Broken Time Reversal Symmetry (TRSB)

A **good** experiment should:

1. Reject **all** reciprocal effects such as linear birefringence and optical activity.

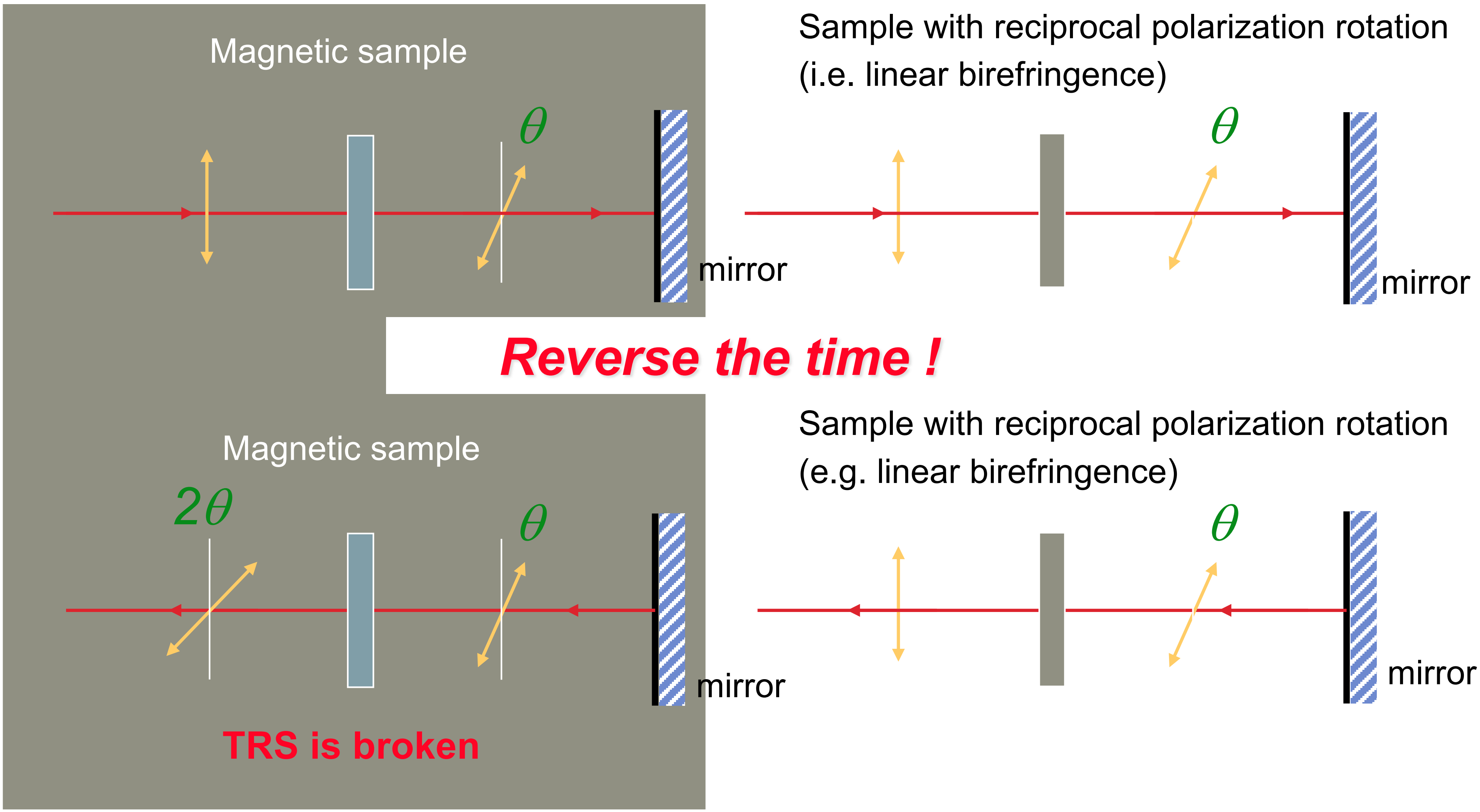
1. Measure an absolute value of the Kerr effect, rather than a result of a modulated signal*.

2. High sensitivity - since the effect is expected to be very small

$$\theta_K \lesssim 100 \text{ nanorad}$$

* When searching for magnetism, it is common to measure the Faraday/Kerr effects while modulating an external magnetic field, and "locking-in" to the frequency of the modulation. This increases the SNR substantially

Recall: a simple experiment

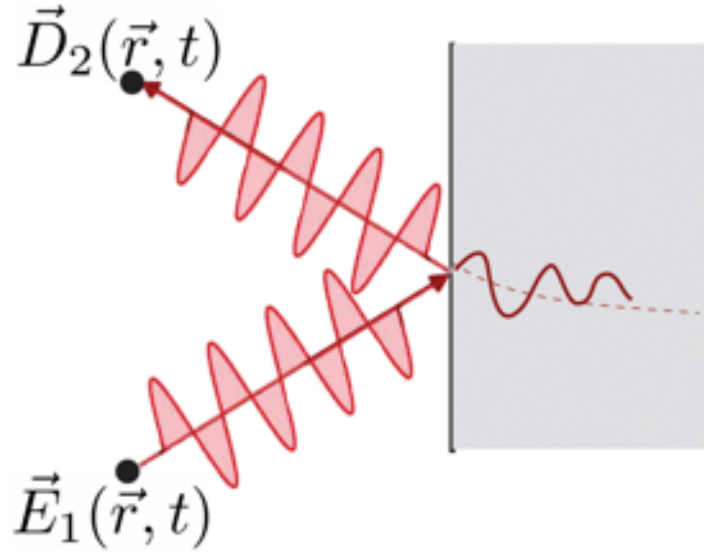


We can distinguish between magneto optic signal (Kerr and Faraday) from reciprocal effects if we measure the difference between a light beam with its time reversal counter part beam.

Recall Reciprocity

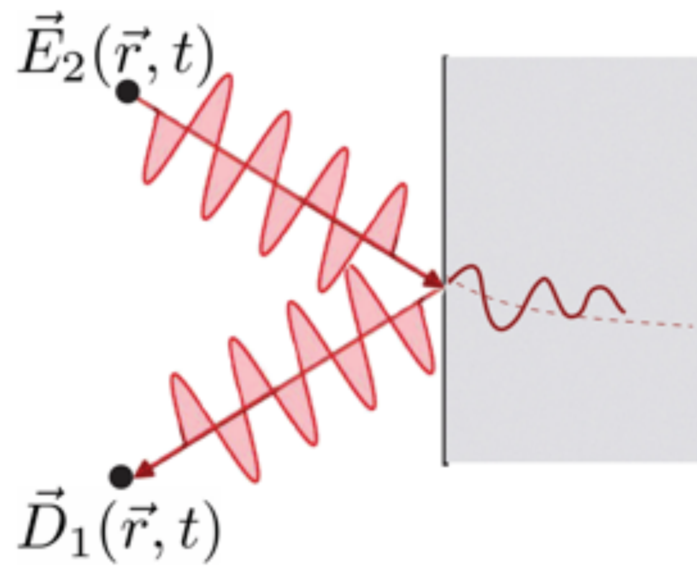
Apply: $\mathbf{E}(\mathbf{r}, t)$

The response after interaction with the sample: $\mathbf{D}(\mathbf{r}, t)$



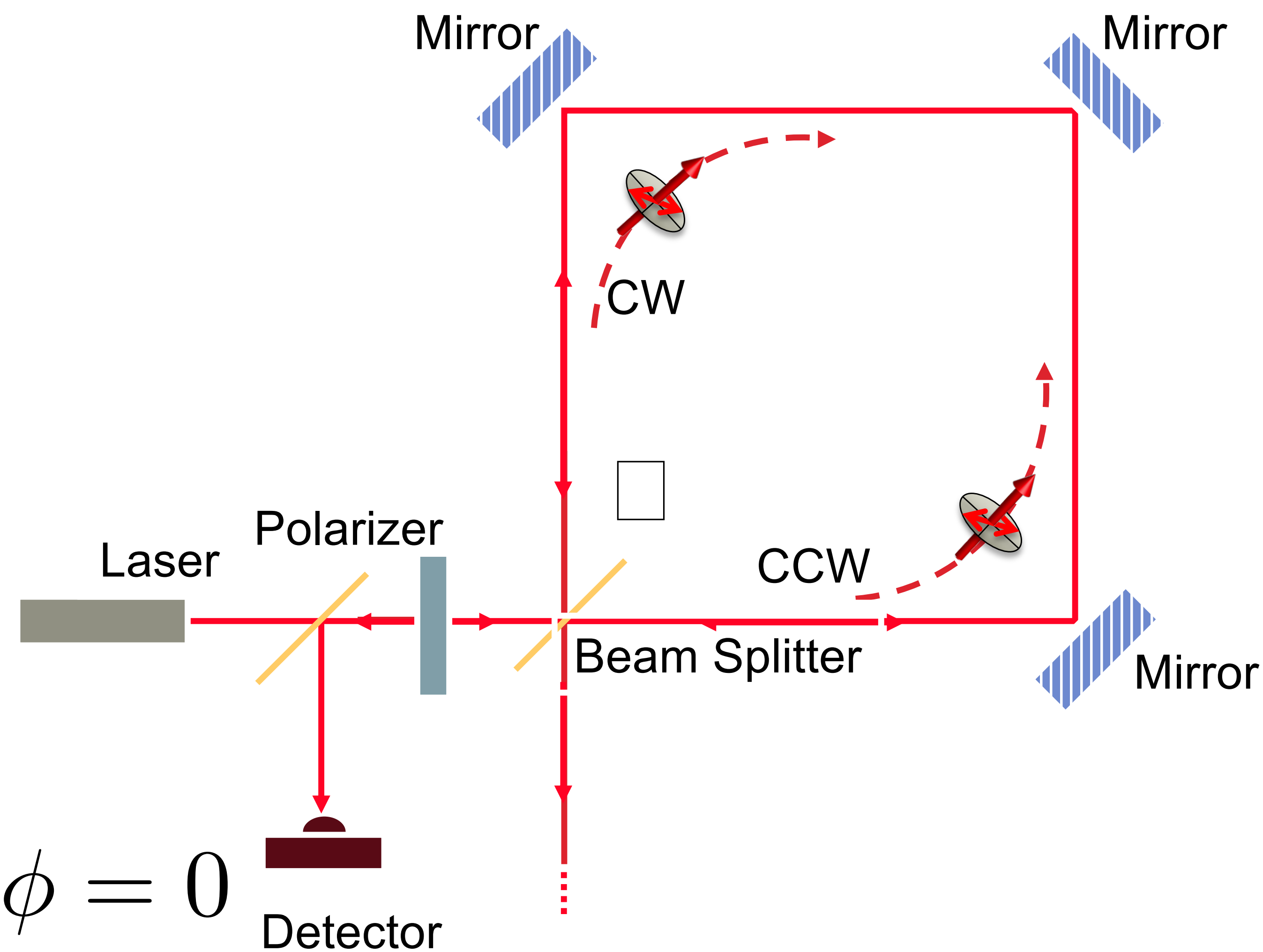
and the condition for reciprocity

$$\int d^3r\,\mathbf{D}_1 \cdot \mathbf{E}_2 = \int d^3r\,\mathbf{D}_2 \cdot \mathbf{E}_1$$



Solution: use the Sagnac effect

A sagnac loop at rest is **reciprocal**:
no phase shift at the detector



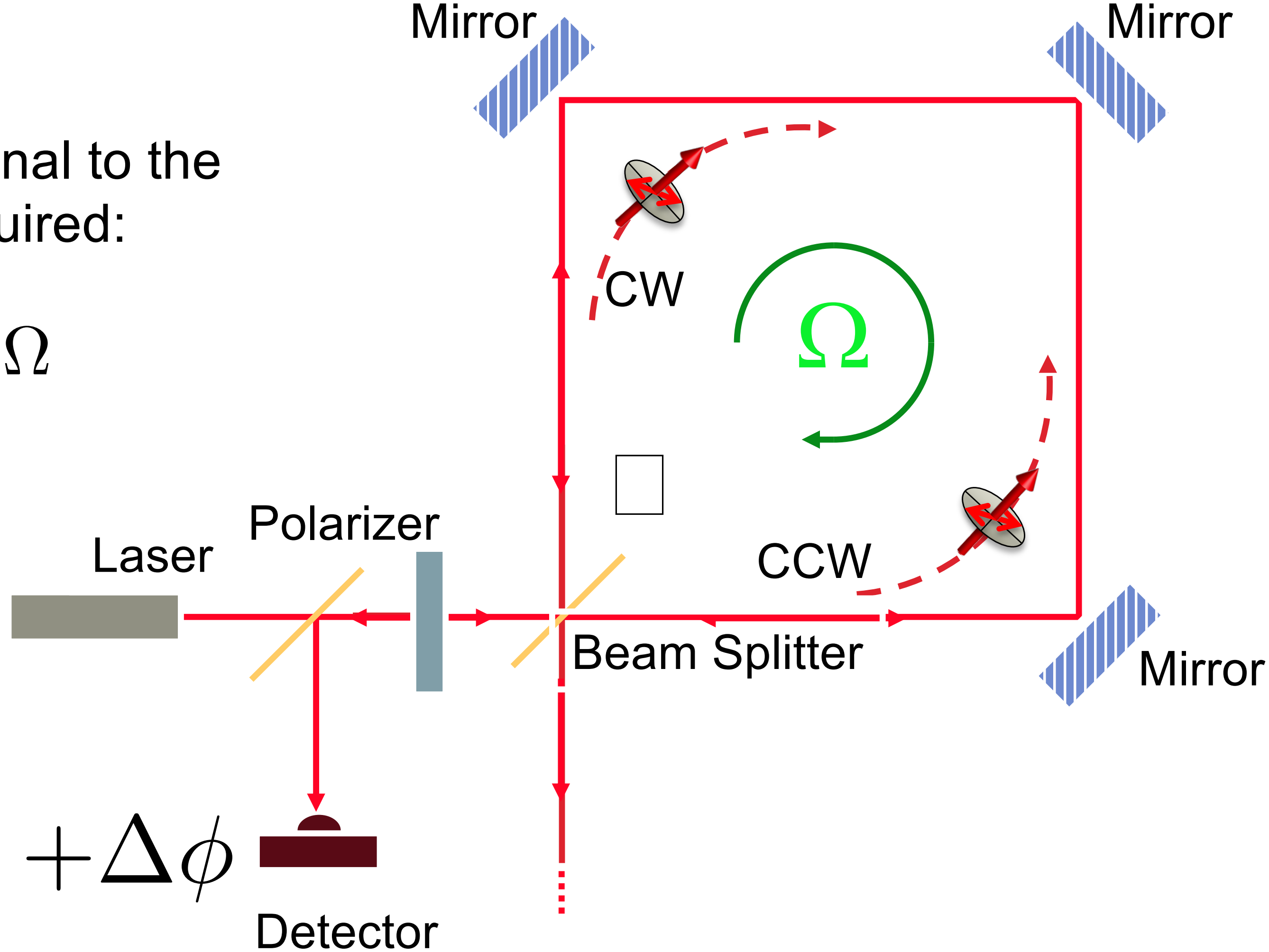
$$\Delta\phi = 0$$

Solution: use the Sagnac effect

When rotated:
time-reversal symmetry is broken

A phase-shift proportional to the angular velocity is acquired:

$$\Delta\phi = \frac{2\pi}{\lambda}\frac{4A}{c}\Omega$$



Michelson-Gale Sagnac experiment

The Effect of the Earth's Rotation on the Velocity of Light

This experiment utilized a large rectangular array of pipes and mirrors, with the legs lying in the direction of the earth's rotation having a **length of 2010 feet**, and the legs lying along longitudinal lines having a **length of 1113 feet**. A calibration loop had the same longitudinal length, but only a very short length in the direction of the earth's rotation, so that the effect of the earth's motion in the direction of the light traveling the 2010 foot legs could be compared to the effect in the calibration loop in which light traveled only a negligible distance in this direction. By comparing the fringe displacement of the large loop to that of the calibration loop, the effect of the earth's motion (through the aether) was to be discovered.

Letters to the Editor.

[The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.]*

The Effect of the Earth's Rotation on the Velocity of Light.

In the *Philosophical Magazine* (6), 8, 716, 1904, an experiment was described, designed to test the effect of the earth's rotation on the velocity of light. In consequence of atmospheric disturbances, it was quite impossible to measure the interference fringes in the open air. Accordingly a twelve-inch water-pipe was laid on the surface of the ground in the form of a rectangle, 2010 ft. by 1113 ft. The residual pressure was reduced to about one-half an inch by means of a fifty horse-power pump. One of the ends was double, as shown in Fig. 1. At *A*, light from a carbon arc

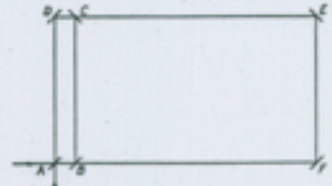


Fig. 1.

was divided by a plane parallel plate, thinly covered with gold, into two beams, one traversing the circuit in a clockwise, the other in a counter-clockwise direction.

Observations showed that the beam going in the counter-clockwise direction was retarded with respect to the other by 0·230 of a fringe.

TABLE I.

	Displacement in Fringes.	Number of Observations.	Deviation from Mean.
1	0·252	20	0·022
2	·255	20	·025
3	·193	20	·037
4	·246	20	·016
5	·235	20	·005
6	·207	20	·023
7	·232	20	·002
8	·230	20	·000
9	·217	20	·013
10	·198	20	·032
11	·252	20	·022
12	·237	20	·007
13	0·230	29	0·000
	Mean 0·230	Total 269	Av. dev. from mean 0·016

Observations 1-6 inclusive, without collimator; 7-13 inclusive, with collimator.

	Obs.	Calc.
Displacement . .	0·230 ± 0·005	0·236 ± 0·002

The theoretical value,[1] on the assumption of a stagnant ether, is given by the formula $\Delta = \frac{4lh\omega\sin\phi}{\lambda c}$. With the actual dimensions of the apparatus, the calculated displacement is 0·236 of a fringe. In this formula the latitude, ϕ, is 41° 46′, and the wave-length, λ, as measured by comparison with sodium light, is 5700 Å.U.; ω is the angular velocity of the earth's rotation, and c the velocity of light.

Two hundred and sixty-nine observations were made, and averaged, usually in groups of twenty, in the order taken. Thirteen such means are given in Table I.

The results are interpreted to mean that the calculated and observed displacements agree to within the limits of observational error.

A. A. MICHELSON.
HENRY G. GALE.

University of Chicago,
March 21.

[1] This is twice the value given in the original article. Attention was directed to this correction by L. Silberstein in the Journal of the Optical Society of America, 5, 291, 1921.

Atmospheric Electric Transmission.

It appears to be of interest and value, in relation to current investigations on the circumstances of wireless transmission at short ranges, to note the intensity of reflection of electric waves that might be expected at the sharp boundary of an ionised layer, high in the atmosphere. The term sharp here implies practically that the transition is completed in, say, not less than one-tenth or, for nearly direct incidence, one-fifth of a wave-length. The relative amplitudes in the reflected waves are then, for the two polarised components, given sufficiently by the Fresnel expressions

$$-\frac{\sin(i-r)}{\sin(i+r)} \text{ and } \frac{\tan(i-r)}{\tan(i+r)}.$$

When the index of refraction μ is $1-\epsilon$ where ϵ is small, they become

$$-\frac{\epsilon}{2\cos^2 i} \text{ and } \frac{\epsilon\cos 2i}{2\cos^2 i};$$

e.g. for rays inclined at 30° to the horizontal they are -2ϵ and $-\epsilon$.

For the most favourable case (NATURE, November 1, 1924, p. 650,[1] or *Phil. Mag.*, December, p. 1031), that of free ions, N per cubic cm., unhampered by collisions, therefore high up, the value of ϵ is

$$\frac{1}{2}N\lambda^2\frac{e^2}{\pi m},$$

which is $\frac{1}{4}\times 10^{-8}N$ for free electrons and for wave-length of one kilometre. To ensure a reflection of 10 per cent. in amplitude (or 1 per cent. in energy) of rays inclined at 30° as above, N would have to be about 300 electrons or else 5×10^5 hydrogen ions per cubic cm. If the wave-length is 10 times smaller, namely, 100 metres, these numbers have to be multiplied by 10^2.

At the other extreme, if a gradual transition is to bend round the complete ray through the same angle of 60° in traversing a curve of whatever length, the difference of the values of N at the top and bottom of this curved path figures out (*cf. loc. cit.*) of the order of 300 electrons per cubic cm. when λ is one kilometre, much the same density of ions being thus necessary in the two cases.

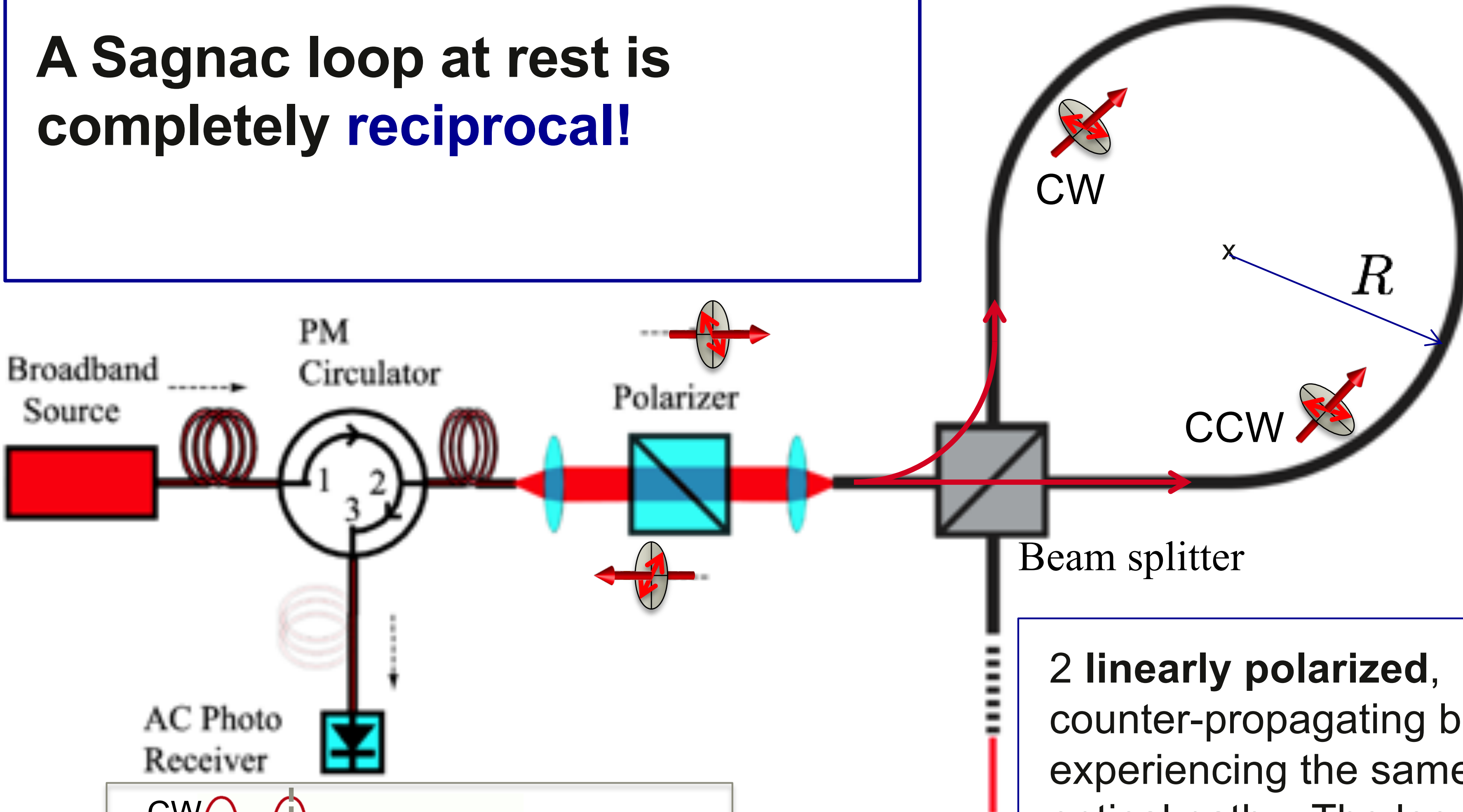
For the first case, however, that of transition practically sharp, a layer a few wave-lengths in thickness would play the part of Newton's thin plate in optics, by reflecting from both its faces: thus as the wave-length is gradually changed, there would be regular fluctuations at the receiver. Ionic clouds drifting across the sky might cause irregularity of

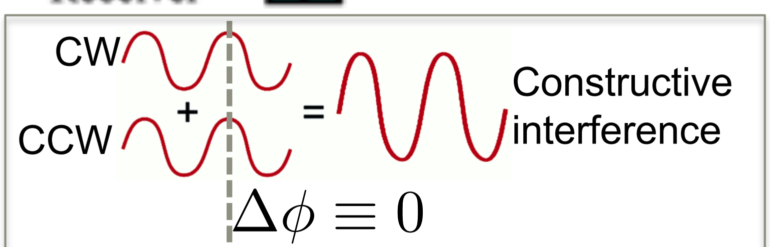
[1] At top of column 2 read $\frac{1}{2}\times 10^{-4}$ watts per square cm.

A Sagnac Loop

(with an optical fiber realization)

A Sagnac loop at rest is completely reciprocal!





2 **linearly polarized**, counter-propagating beams experiencing the same optical path – The loop is completely reciprocal and:

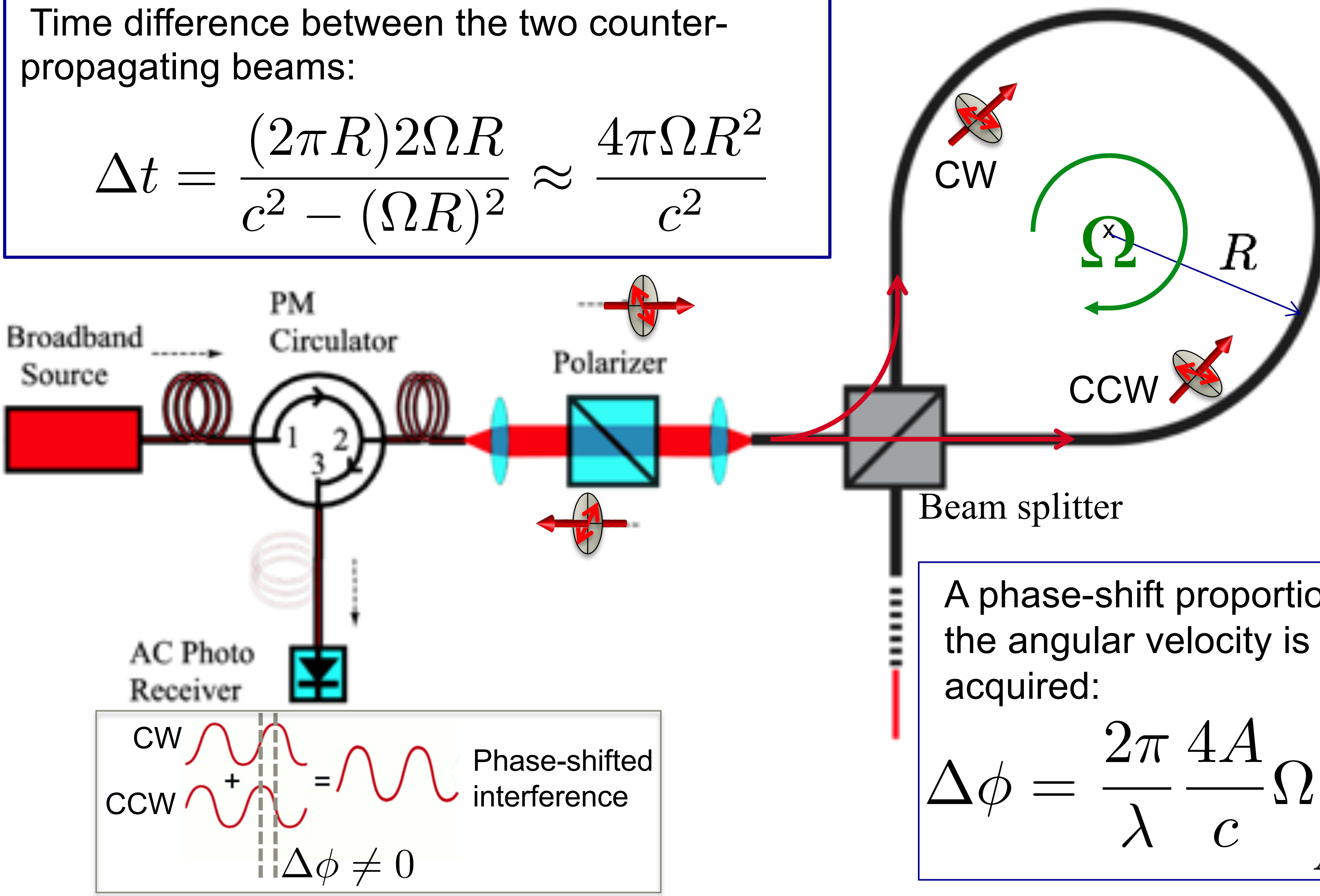
$$\Delta\phi = 0$$

A Sagnac Loop for mechanical rotation

(with an optical fiber realization)

Time difference between the two counter-propagating beams:

$$\Delta t = \frac{(2\pi R)2\Omega R}{c^2 - (\Omega R)^2} \approx \frac{4\pi\Omega R^2}{c^2}$$



A phase-shift proportional to the angular velocity is acquired:

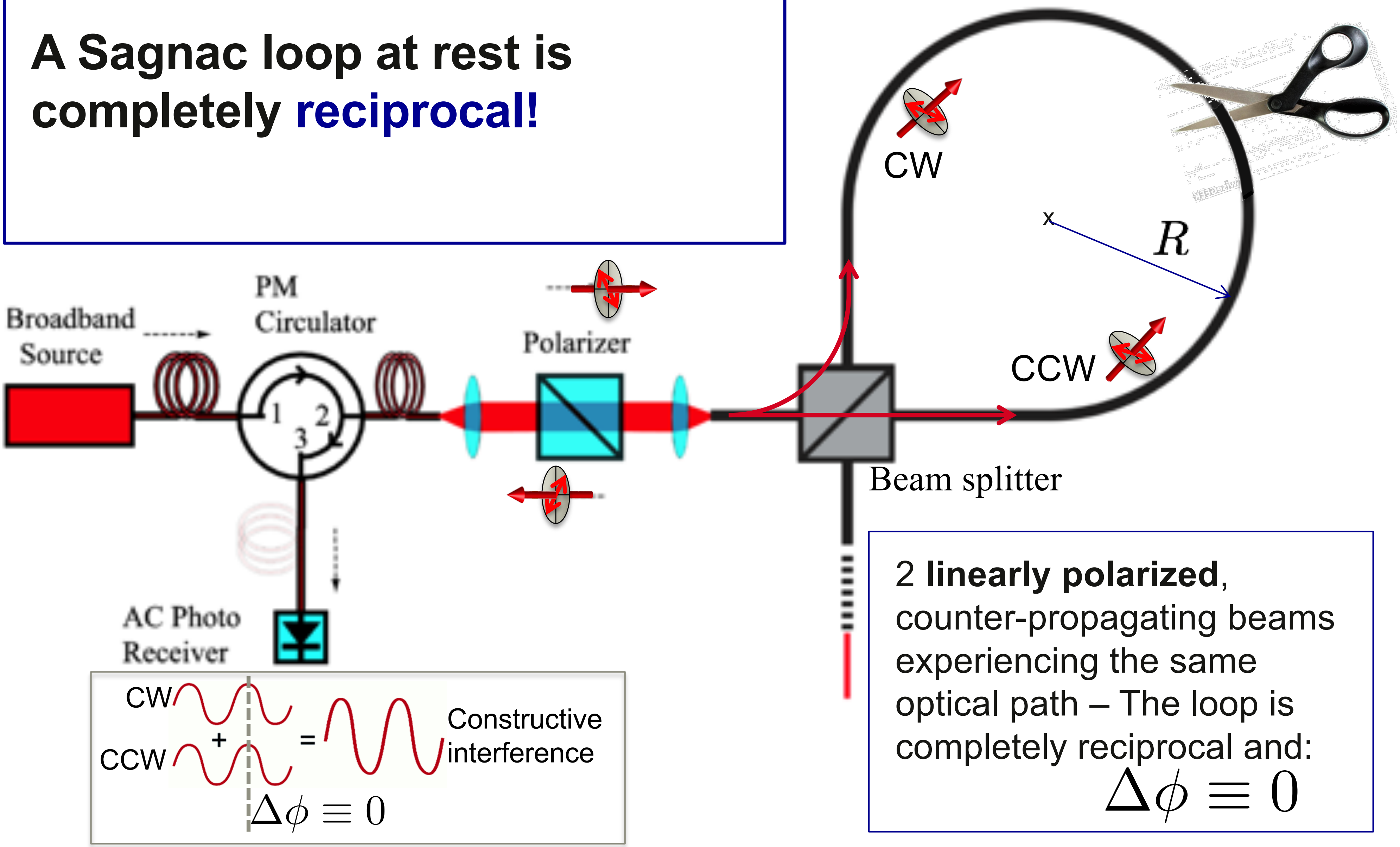
$$\Delta\phi = \frac{2\pi}{\lambda}\frac{4A}{c}\Omega$$

$A = \pi R^2$

A Sagnac Loop magnetometer

(with an optical fiber realization)

A Sagnac loop at rest is completely reciprocal!



2 **linearly polarized**, counter-propagating beams experiencing the same optical path – The loop is completely reciprocal and:

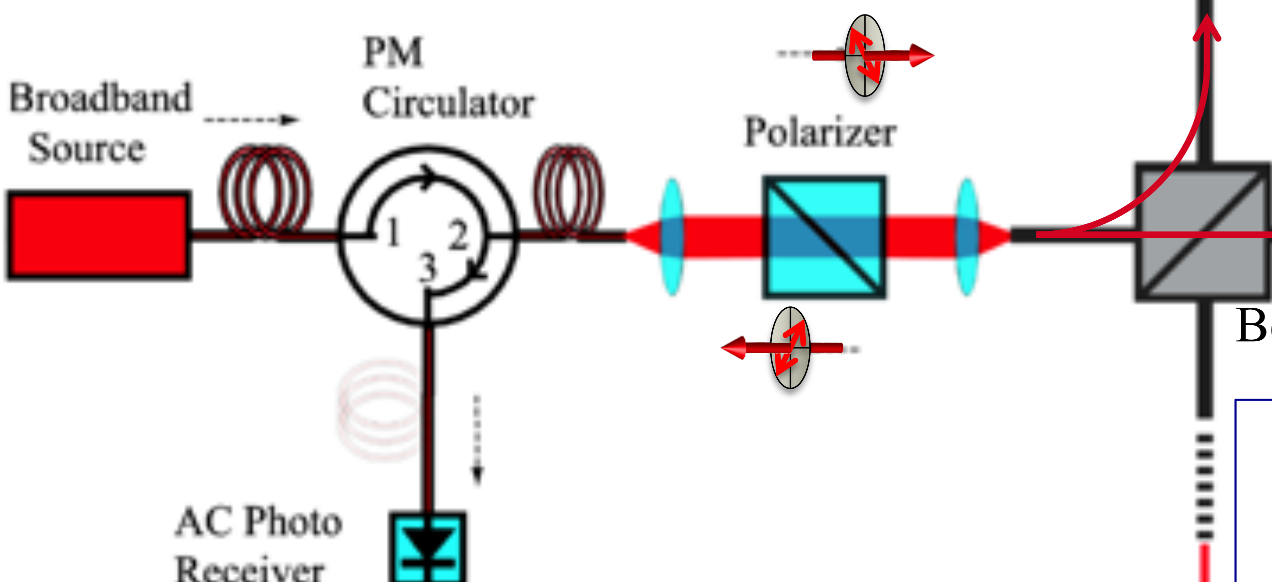
$$\Delta\phi = 0$$

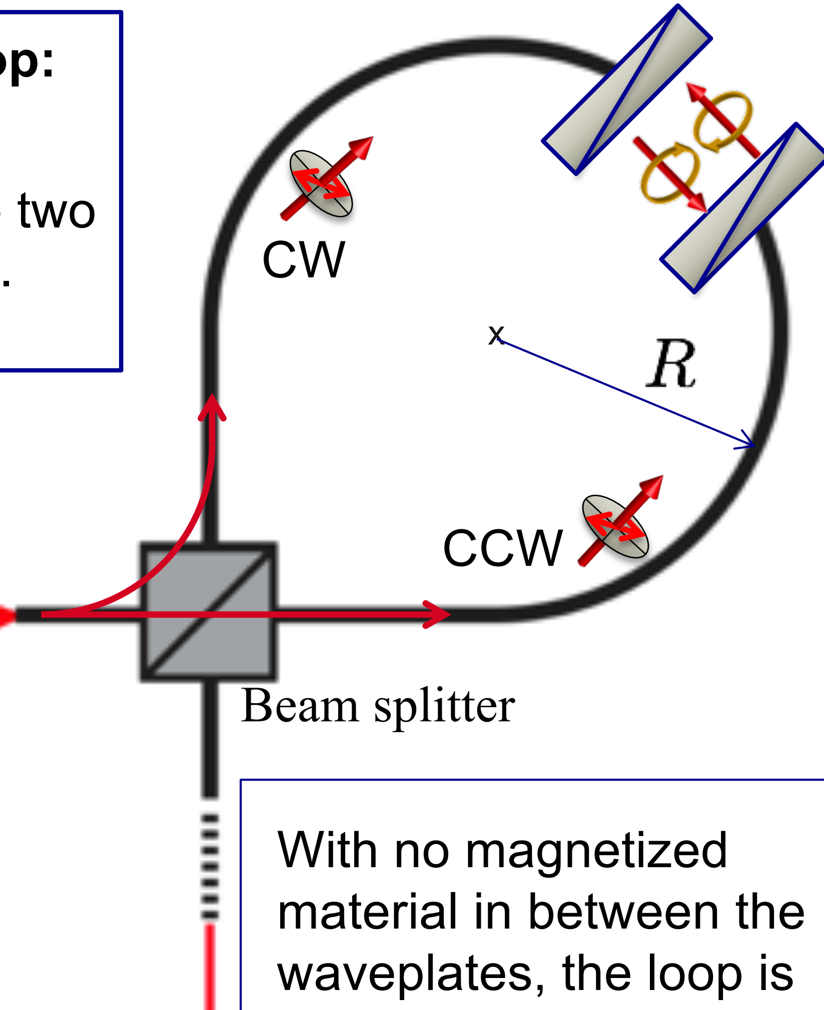
A Sagnac Loop magnetometer

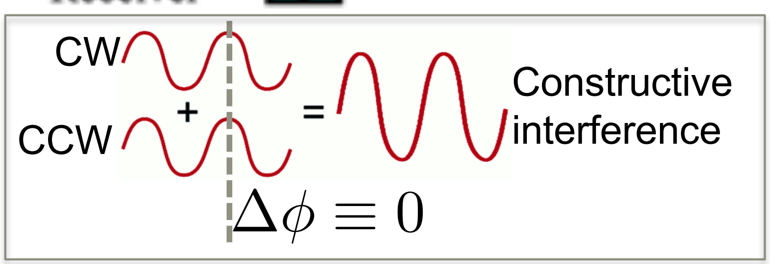
(with an optical fiber realization)

Insert 2 quarter waveplates in the loop:

To use the Sagnac loop <u>at rest</u> as a "magnetometer", we create a region where two counter-circularly polarized light propagate.







With no magnetized material in between the waveplates, the loop is completely reciprocal and:

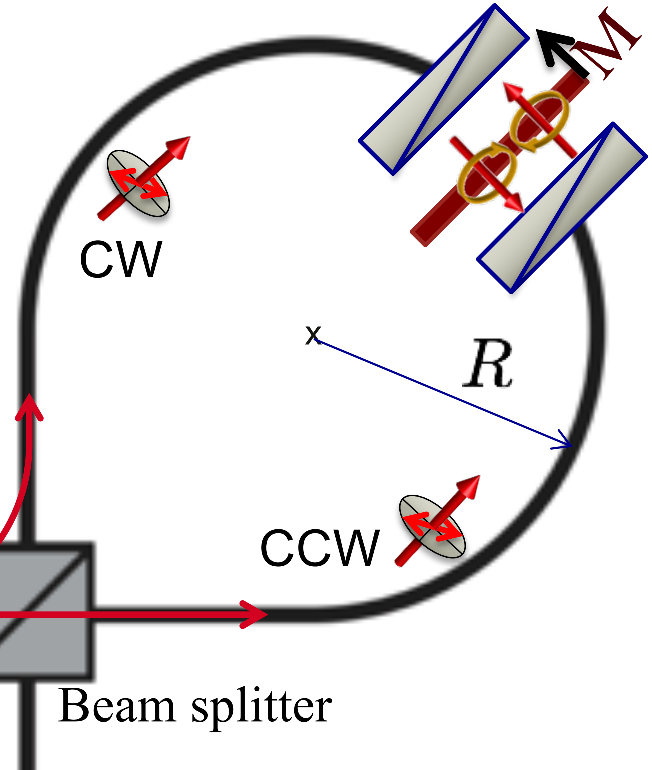
$$\Delta\phi = 0$$

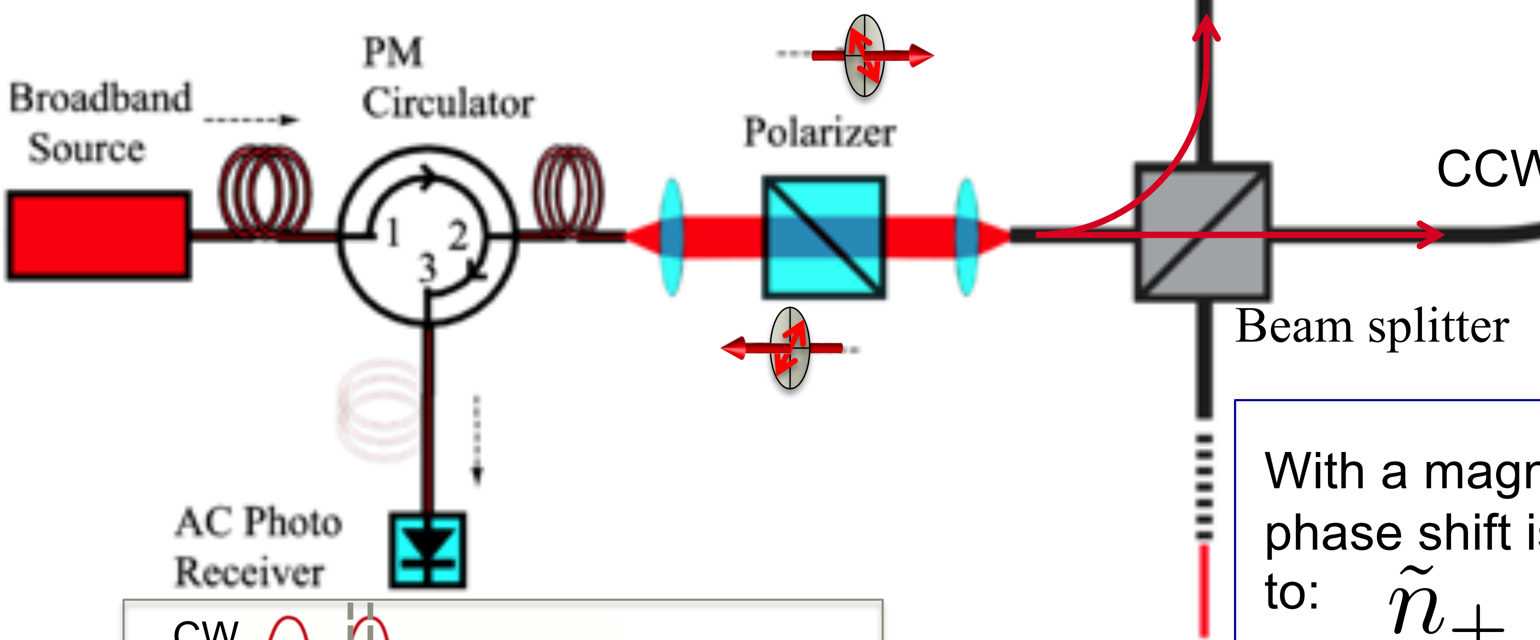
A Sagnac Loop magnetometer

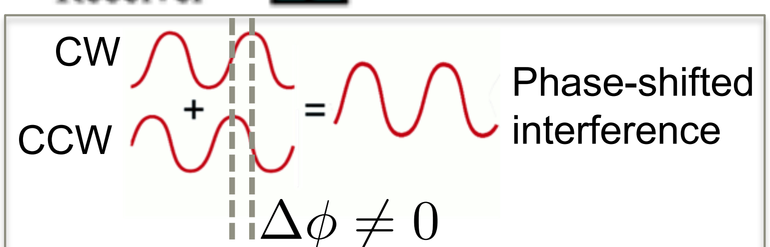
(with an optical fiber realization)

To use the Sagnac loop <u>at rest</u> as a "magnetometer", we create a region where two counter-circularly polarized light propagate.

These are the light eigenmodes in the magnetized material



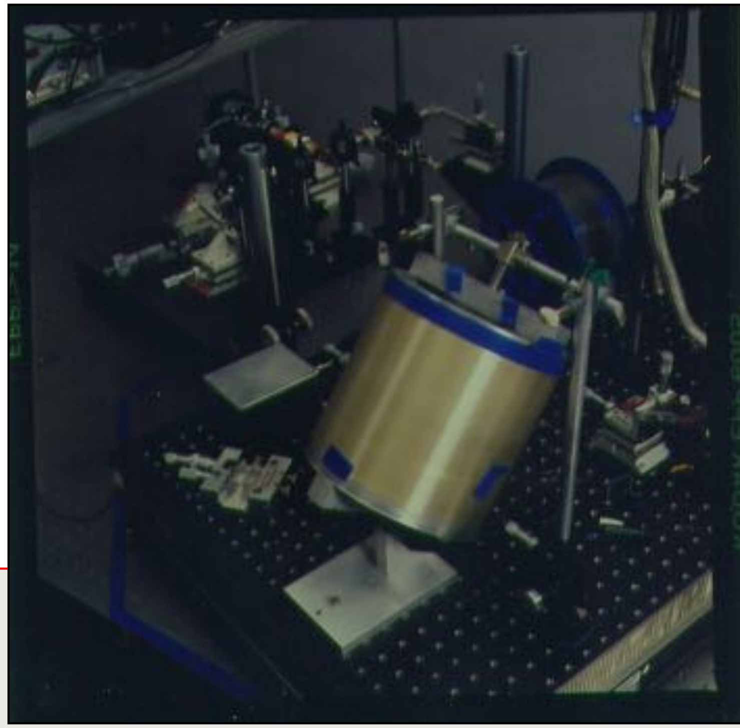


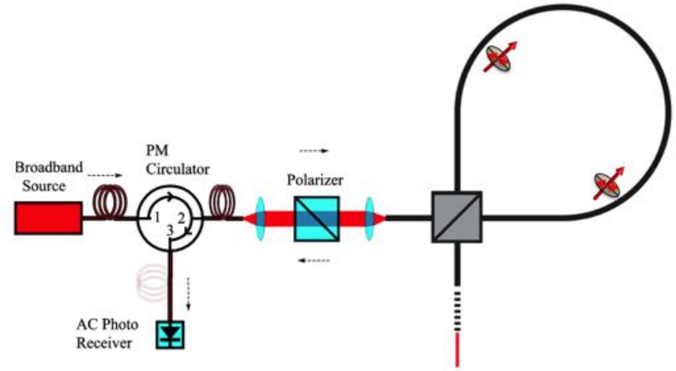


With a magnetic material a phase shift is acquired due to: $\tilde{n}_+ \neq \tilde{n}_-$

and $\Delta\phi \propto 2\theta_F$

First experiment to search for anyons

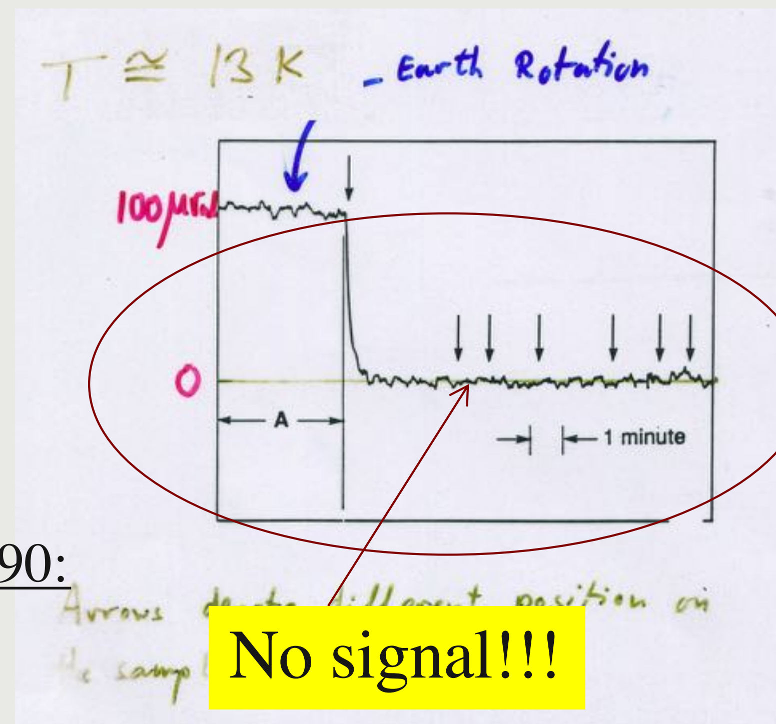




The positive experiments were shown to be wrong because they did not pay attention to reciprocal effects!

Sensitivity ~2 μrad

<u>Kapitulnik’s lab-notebook, March, 15 1990:</u>

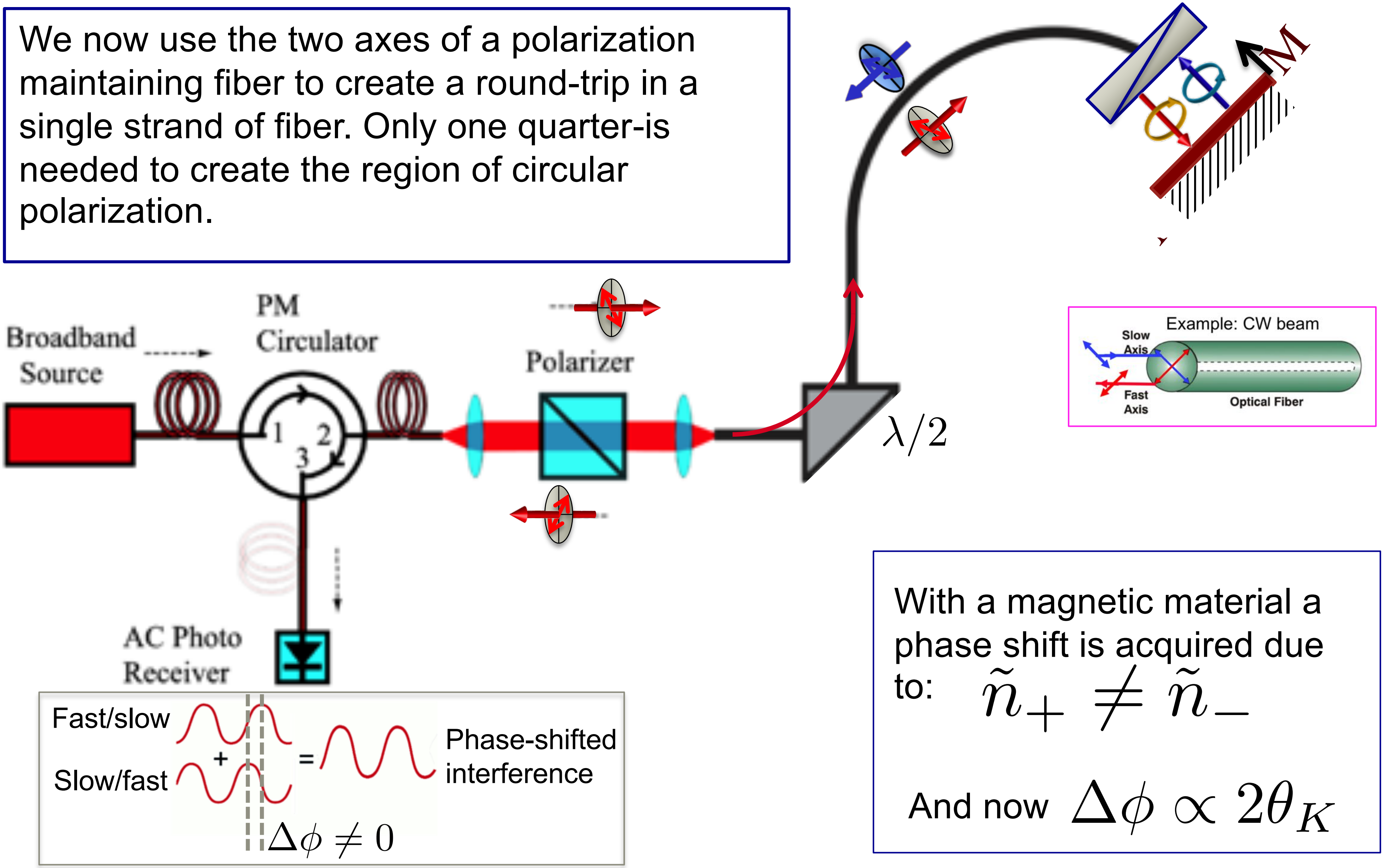


No signal!!!

A "Zero-Area" Sagnac Loop magnetometer

(with an optical fiber realization)

We now use the two axes of a polarization maintaining fiber to create a round-trip in a single strand of fiber. Only one quarter-is needed to create the region of circular polarization.



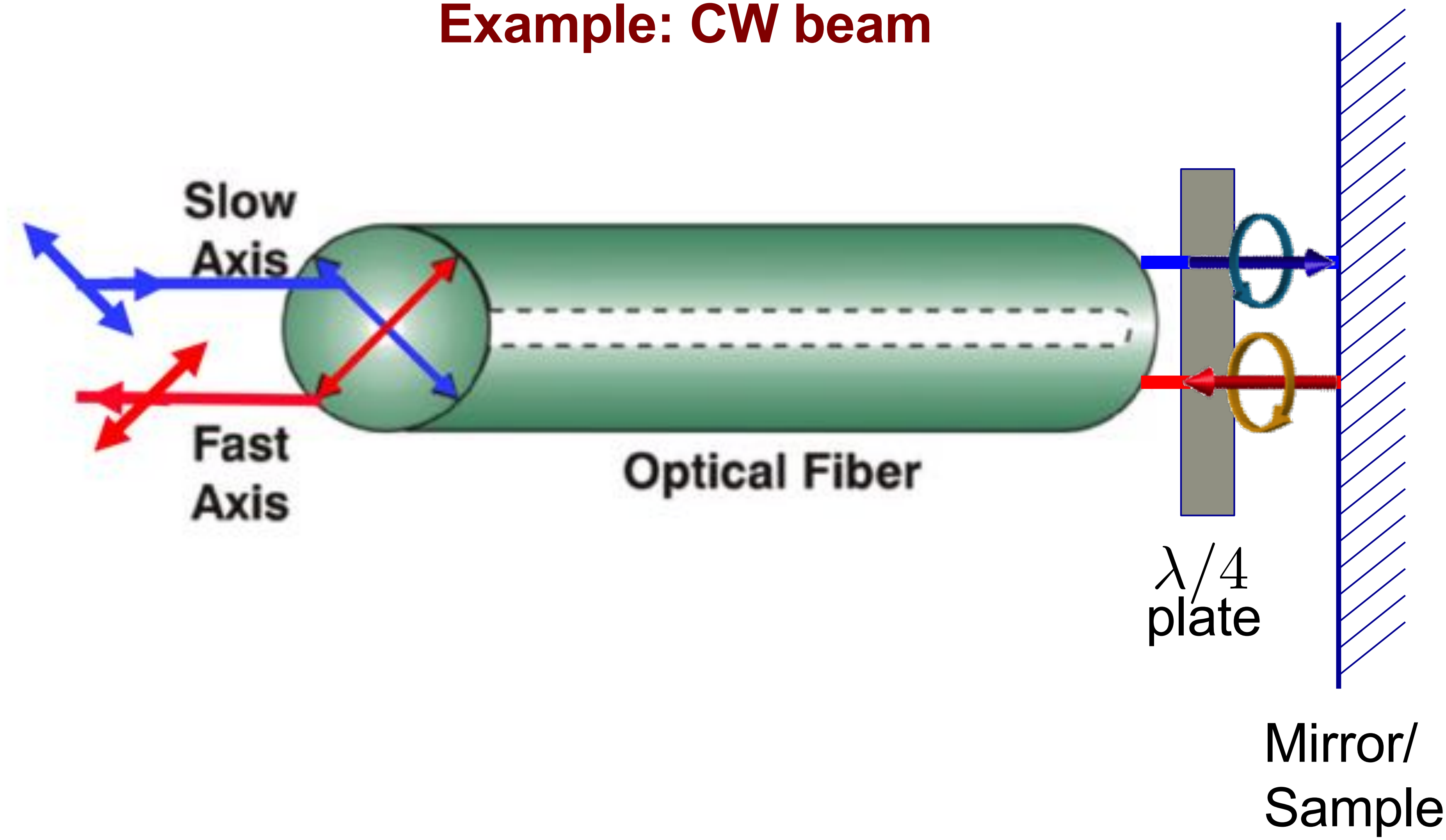
With a magnetic material a phase shift is acquired due to: $\tilde{n}_+ \neq \tilde{n}_-$

And now $\Delta\phi \propto 2\theta_K$

A "Zero-Area" Sagnac Loop magnetometer

(with an optical fiber realization)

Example: CW beam



A “Zero-Area” Sagnac Loop magnetometer

(with an optical fiber realization)

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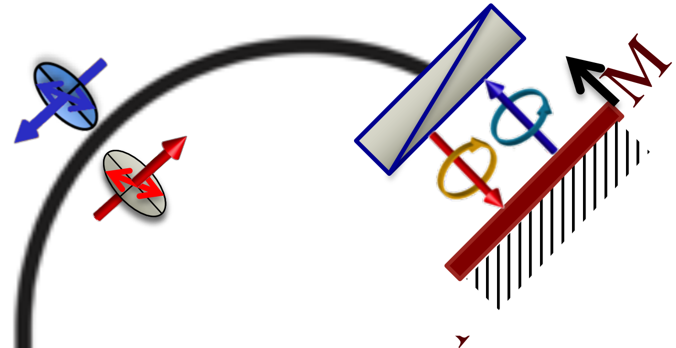
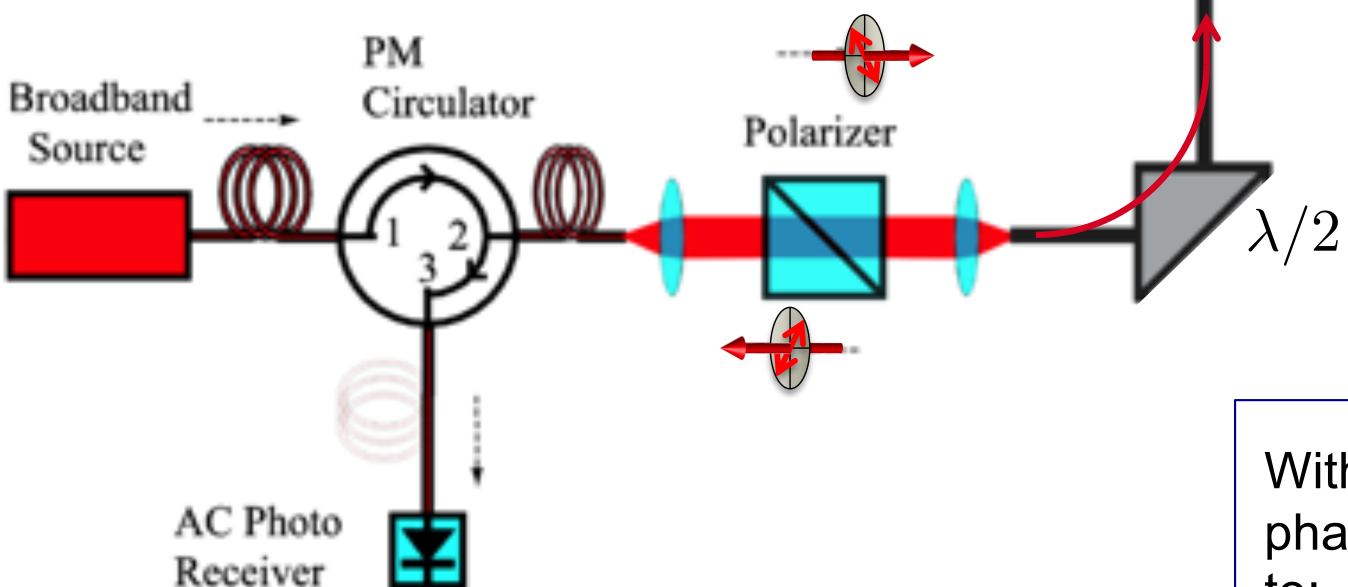
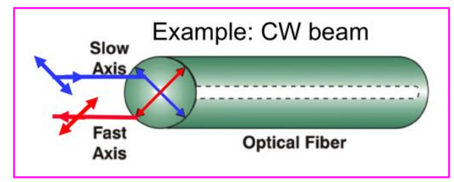
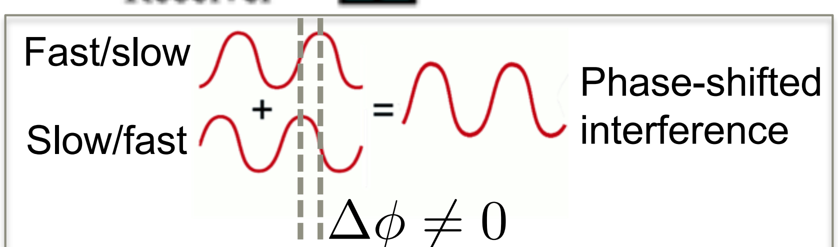






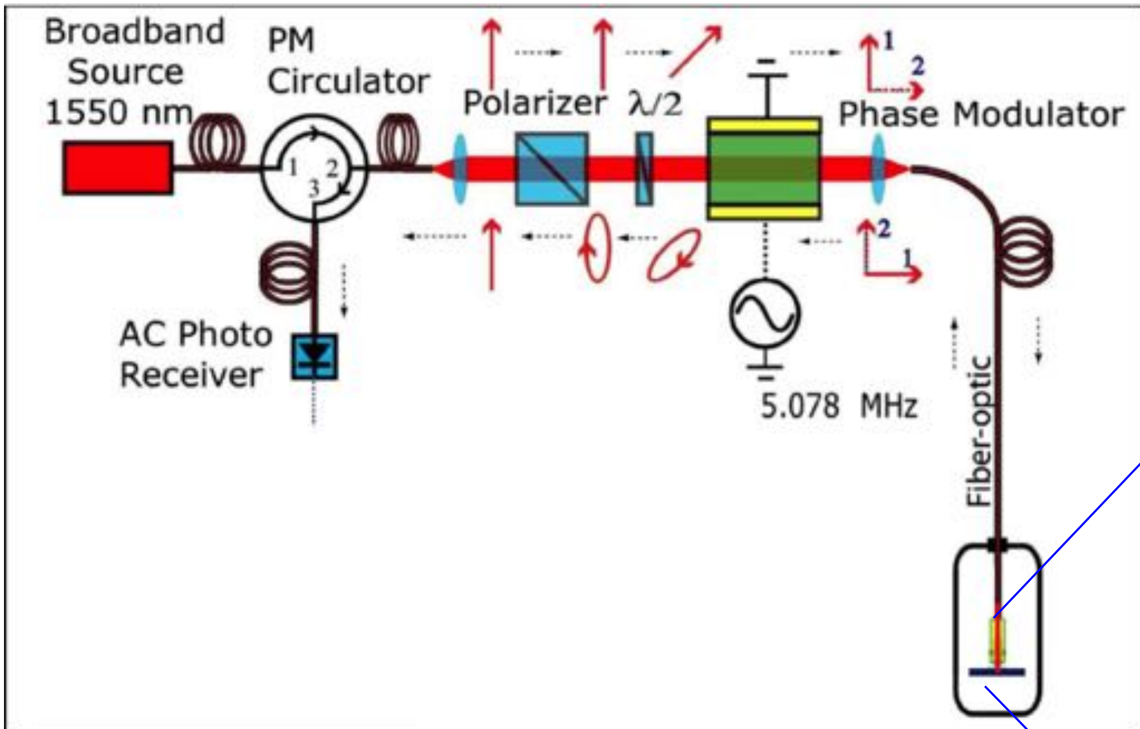


With a magnetic material a phase shift is acquired due to: $\tilde{n}_+ \neq \tilde{n}_-$

And now $\Delta\phi \propto 2\theta_K$

Measurements with "Zero-Area" Sagnac Magnetometer

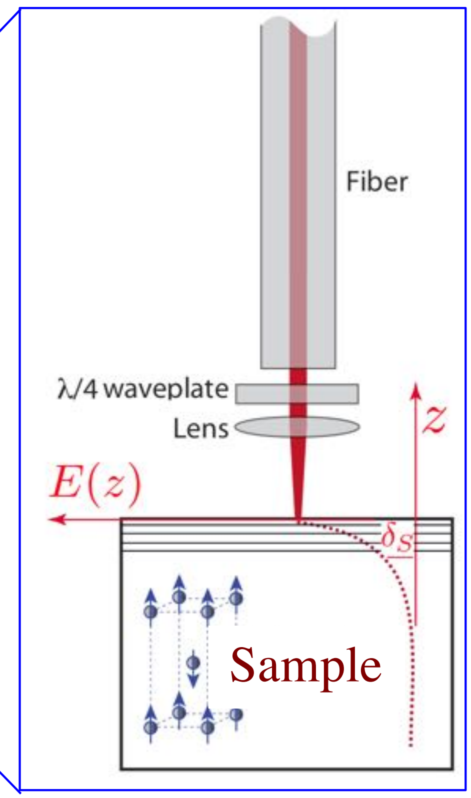
Experimental Configuration:



$$0.3K < T < \ 50K \ (300K)$$

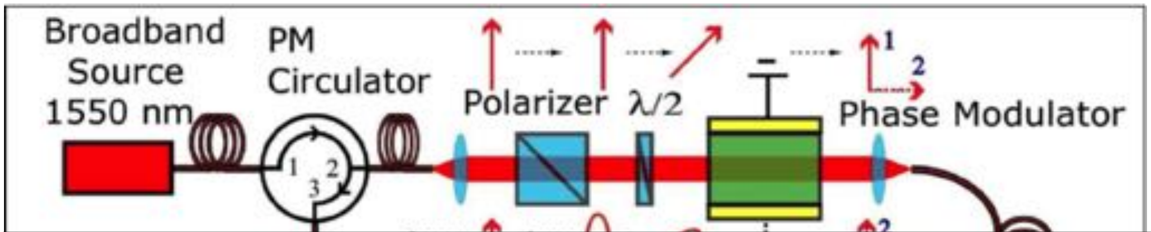
All Kerr data taken perpendicular to surface, mostly in zero applied field.
Wavelength: λ=1.55 μm

For all materials studied, estimated optical penetration depth at λ=1.55 μm: $\delta_S \gtrsim 100$ nm



Measurements with “Zero-Area” Sagnac Magnetometer

Experimental Configuration:



For all materials studied, estimated optical penetration depth at λ=1.55 μm: $\delta_S \gtrsim 100$ nm

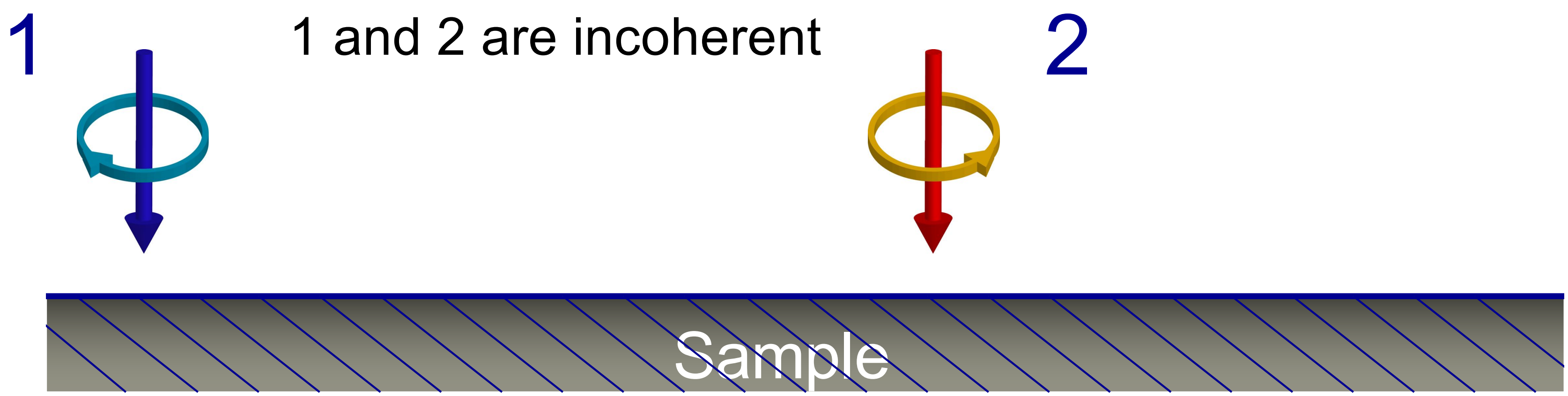
By symmetry –
The Sagnac Interferometer Measures
ONLY
Non-reciprocal effects!

Samples that break time reversal symmetry* also violate reciprocity and will exhibit a phase-shift that we measure as q_K.

*spontaneous TRSB, or with an applied magnetic field; not with absorption

J.S. Dodge, L. Klein, M.M. Fejer, A. Kapitulnik, “Symmetry of the Magneto-optic Response of the Sagnac Interferometer,” J. Appl. Phys. 79, 6186 (1996).

How does this eliminate reciprocal effects?



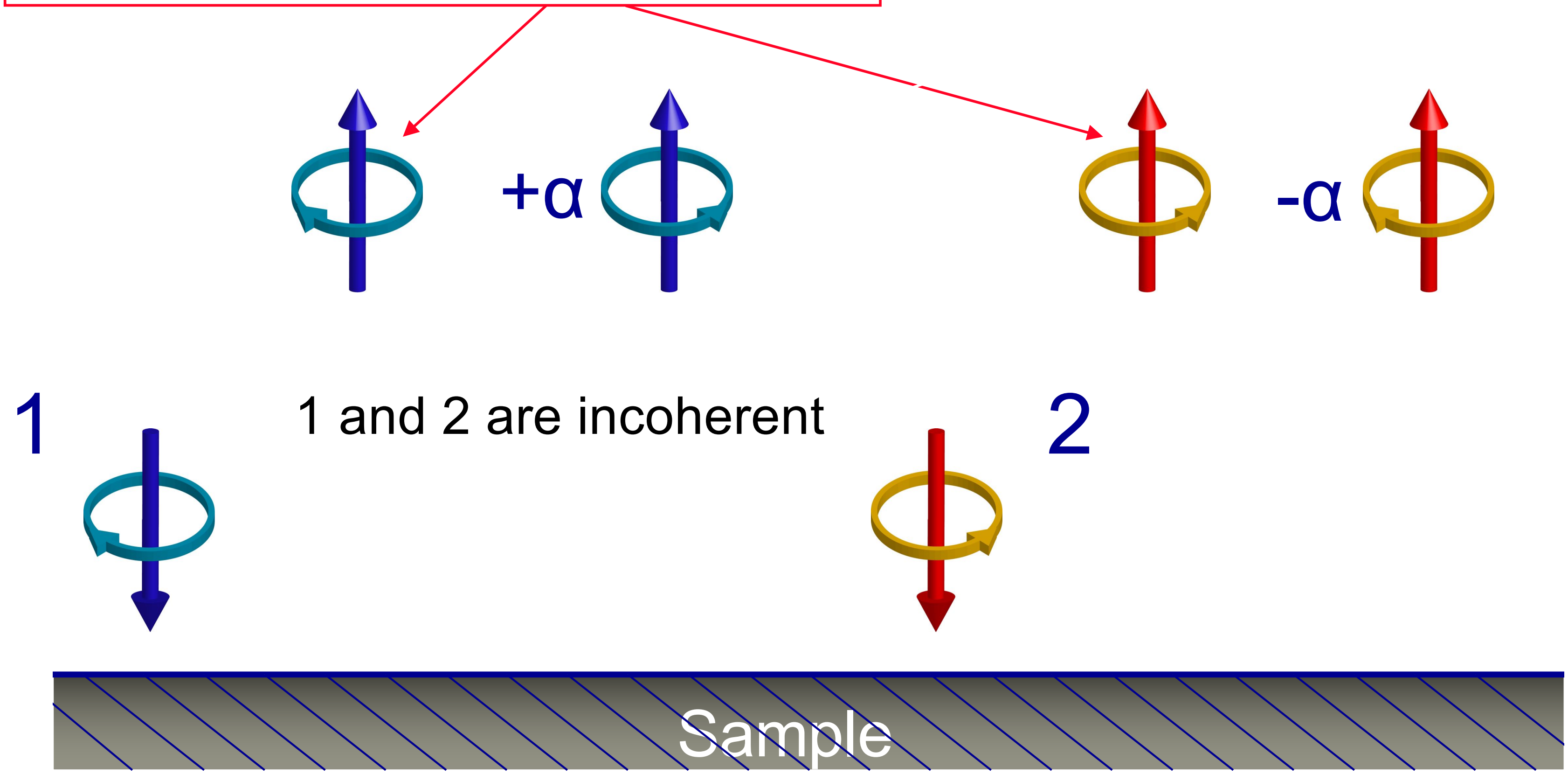
Coherence length of light: 30 µm

Birefringence of fiber and EOM: 2 mm

How does this eliminate reciprocal effects?

Follow the correct return path, and become coherent at the detector.

Return along the wrong paths. And become more incoherent.



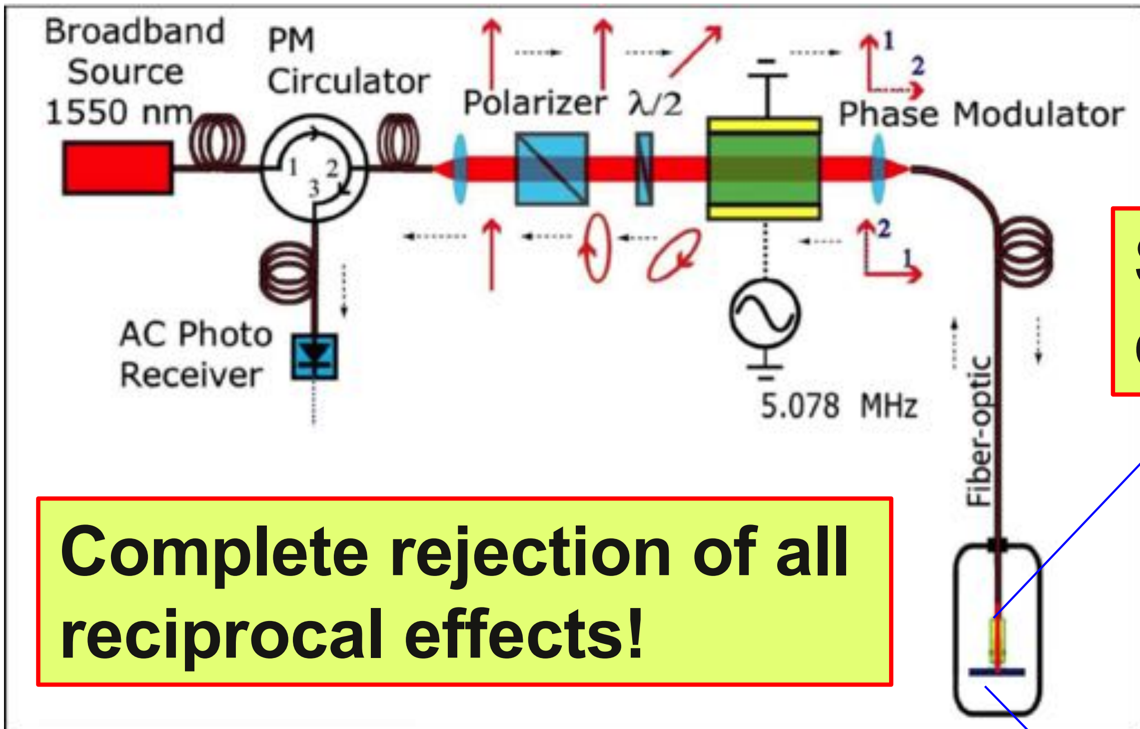
Coherence length of light: 30 µm

Birefringence of fiber and EOM: 2 mm

* Lights that follow “correct” paths will generate interference pattern at 5Mhz or 10Mhz. Other lights only contribute to DC backgrounds.

Measurements with "Zero-Area" Sagnac Magnetometer

Experimental Configuration:



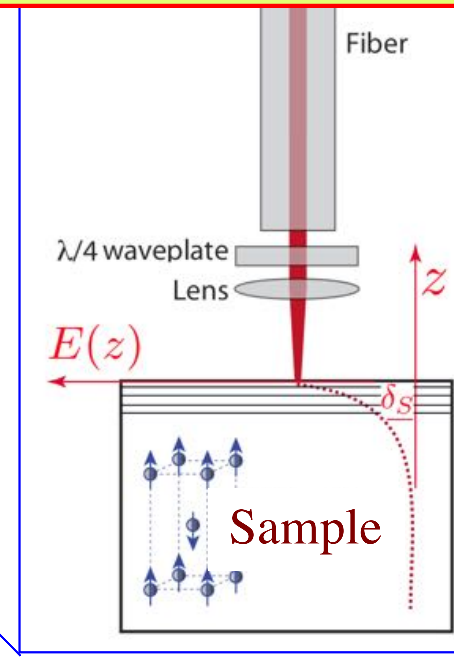
Complete rejection of all reciprocal effects!

$$0.3K < T < \ 50K \ (300K)$$

All Kerr data taken perpendicular to surface, mostly in zero applied field.
Wavelength: λ=1.55 μm

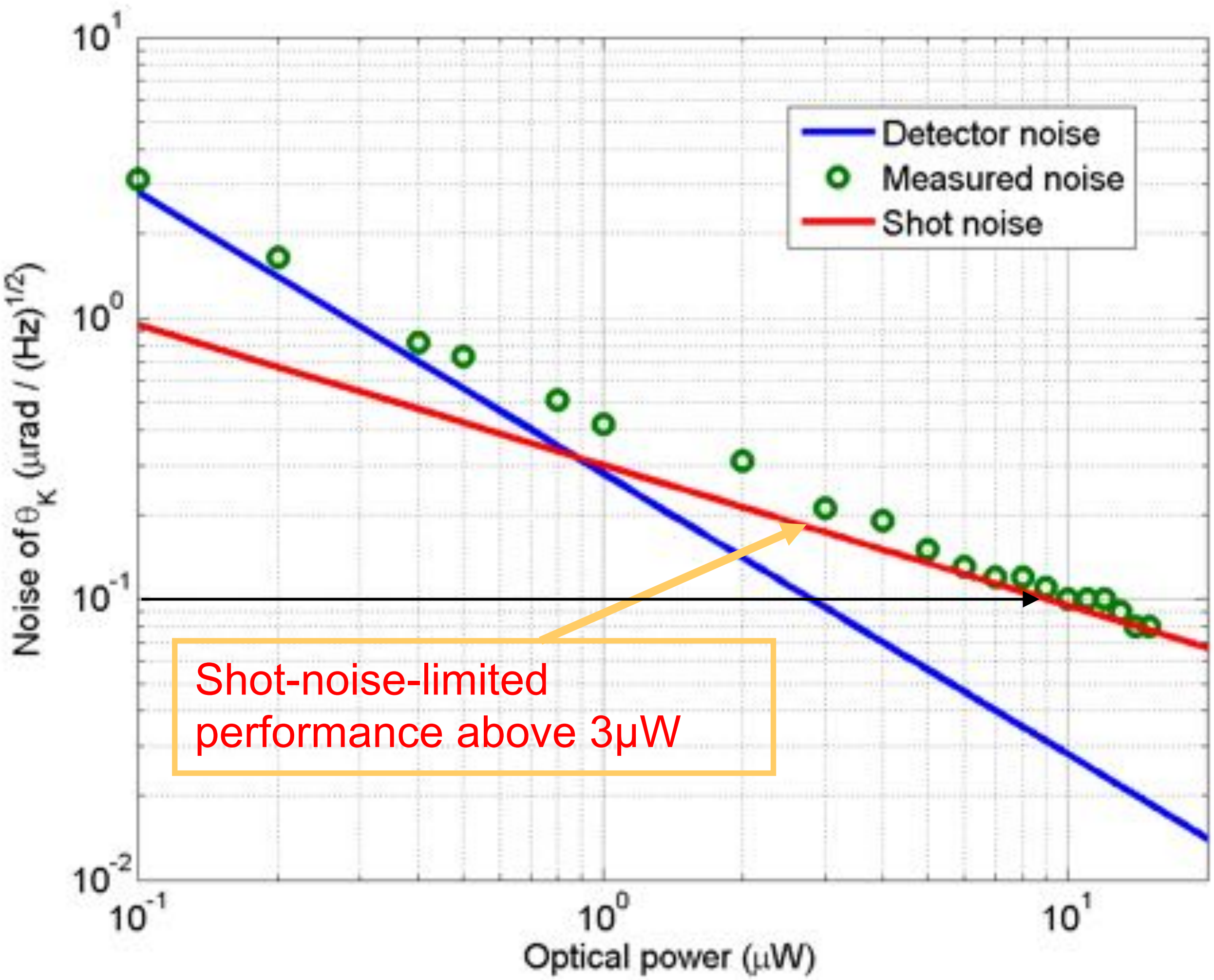
For all materials studied, estimated optical penetration depth at λ=1.55 μm: $\delta_S \gtrsim 100$ nm

Shot-noise limited optical detection above ~3μW



*

Performance: Noise



Photon shot noise for 1.55 um wavelength and 80% detector efficiency, P_{ave} in μW:

$$\sigma_{shot-noise} \cong 0.6\sqrt{\frac{2\hbar\omega\Delta f}{P_{ave}}}$$

$$\cong 0.3/\sqrt{P_{ave}}\,(\mu rad/\sqrt{Hz})$$

Detector noise: Detector noise found to be 0.5 pW/sqrt(Hz), this gives:

$$\sigma_{det.} \cong 0.56\frac{\text{detector-}NEP}{P_{ave}}$$

$$\cong 0.28/P_{ave}(\mu rad/\sqrt{Hz})$$

To achieve 10 nano-radian resolution, minimum averaging time will be:

100 seconds, with 10 μW optical power

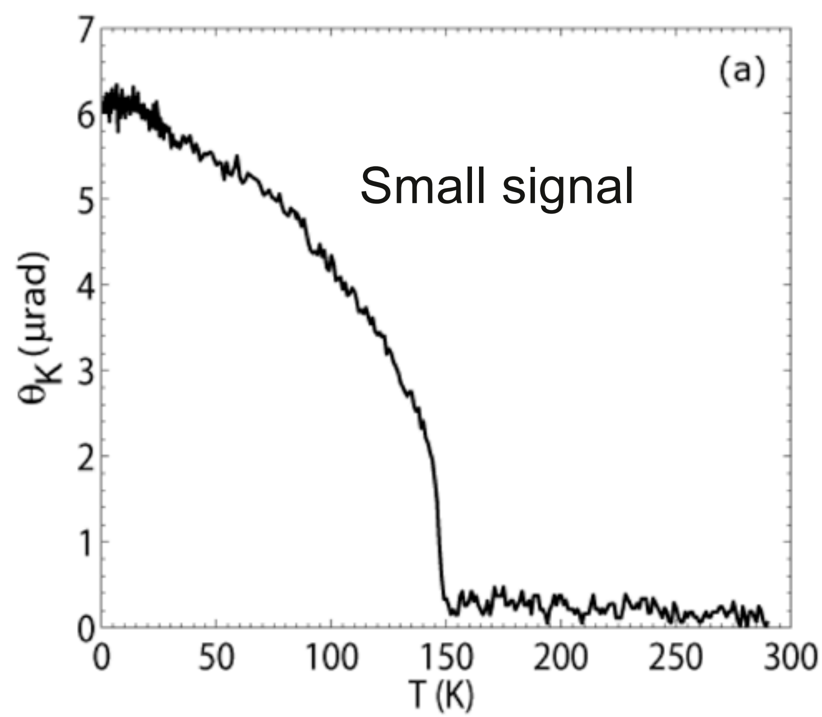
50 seconds, with 20 μW optical power

Simple Measurement: The itinerant ferromagnet $SrRuO_3$

$$\lambda = 1550 \text{ nm}$$

$SrRuO_3$, T_c~150 K

Zero-field cooled (Multi-domain)



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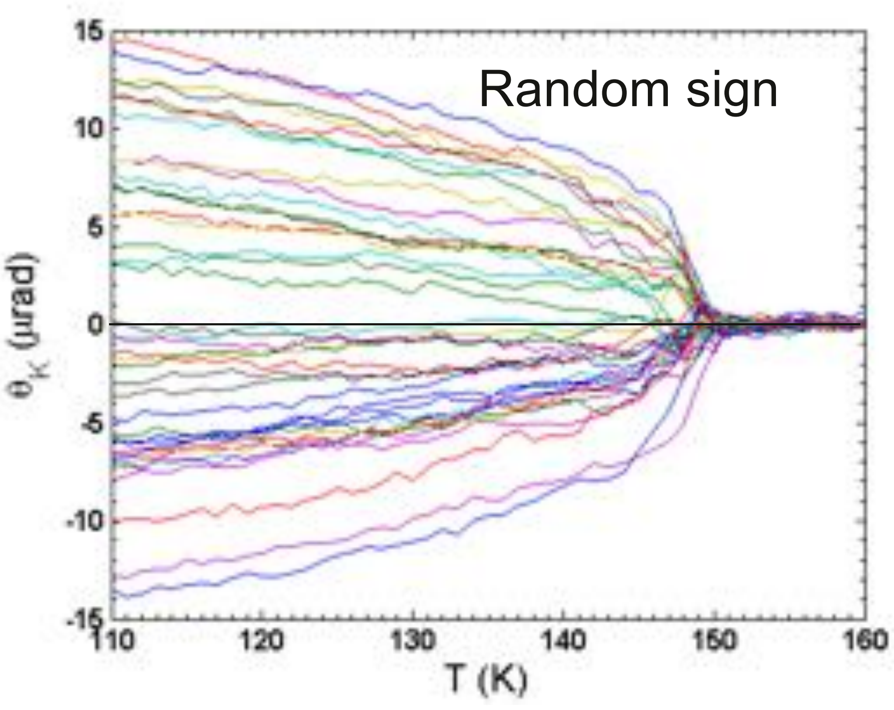
$SrRuO_3$, T_c~150 K

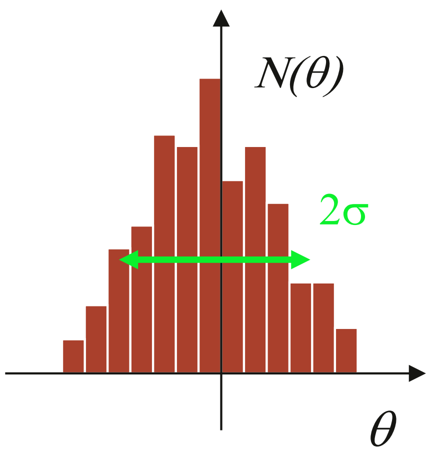
Zero-field cooled (Multi-domain)

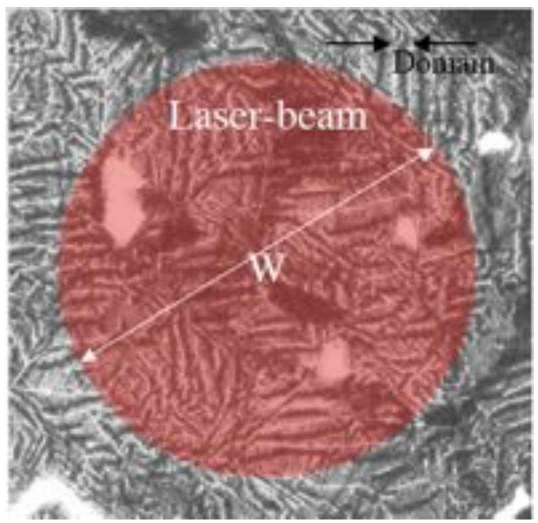


Simple Measurement: The itinerant ferromagnet $SrRuO_3$

$$\lambda = 1550 \text{ nm}$$

$SrRuO_3$, T_c~150 K





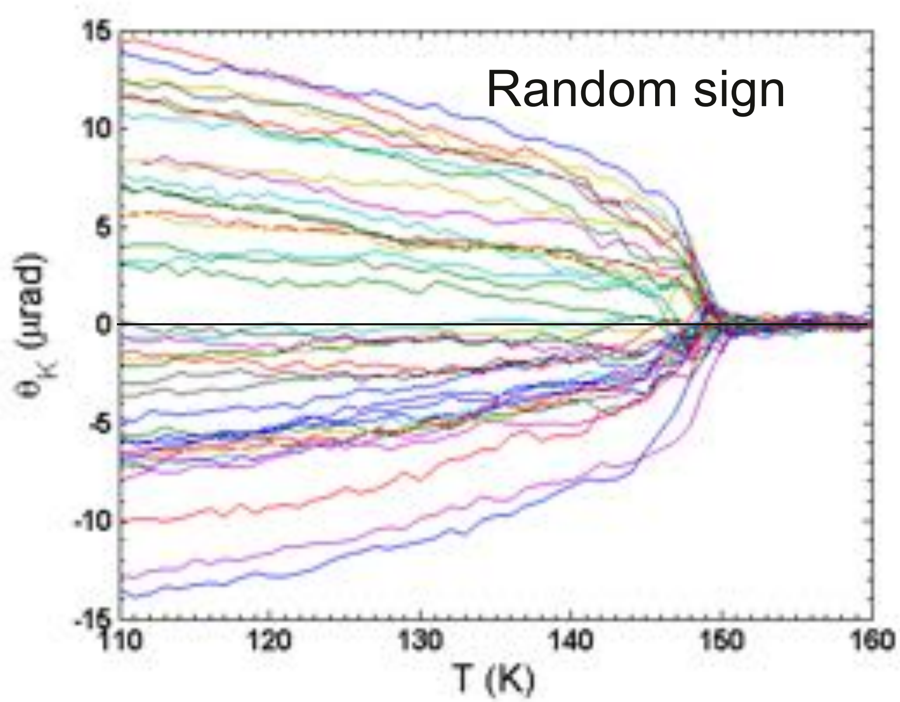
Beam-size diameter w= 3μm

σ = 3μrad

θ_{sat}(110K)=1441 μrad

Domain size ≈ (σ/θ_{sat})w ≈ 18nm

Zero-field cooled (Multi-domain)



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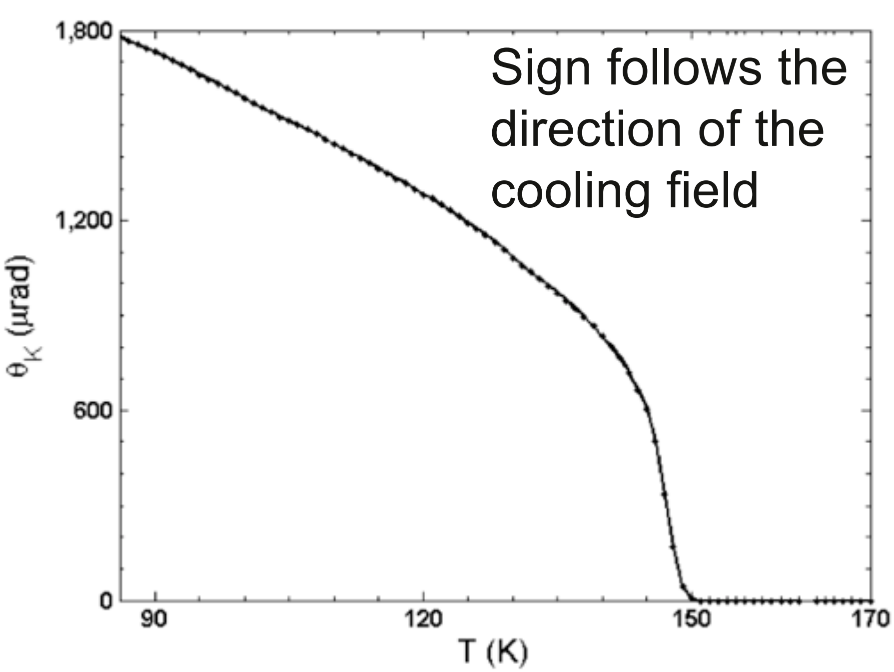
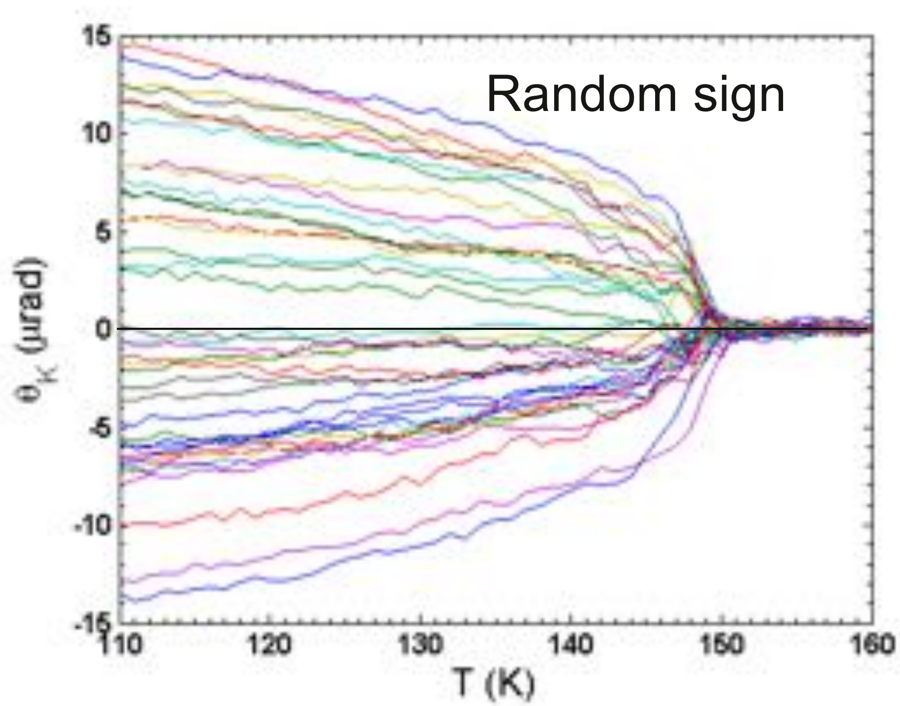
$SrRuO_3$, T_c~150 K

Field-cooled (oriented-single domain)

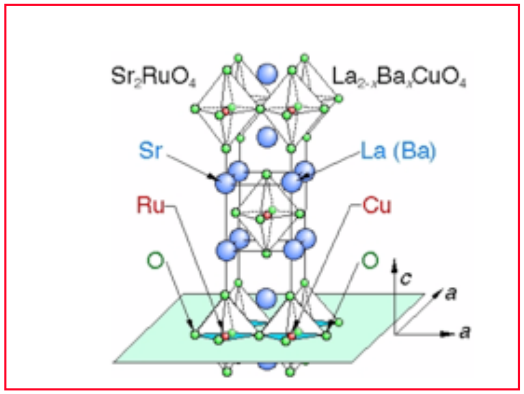


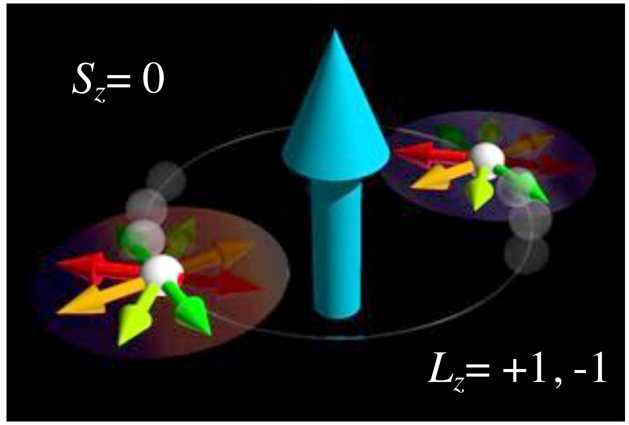
Zero-field cooled (Multi-domain)

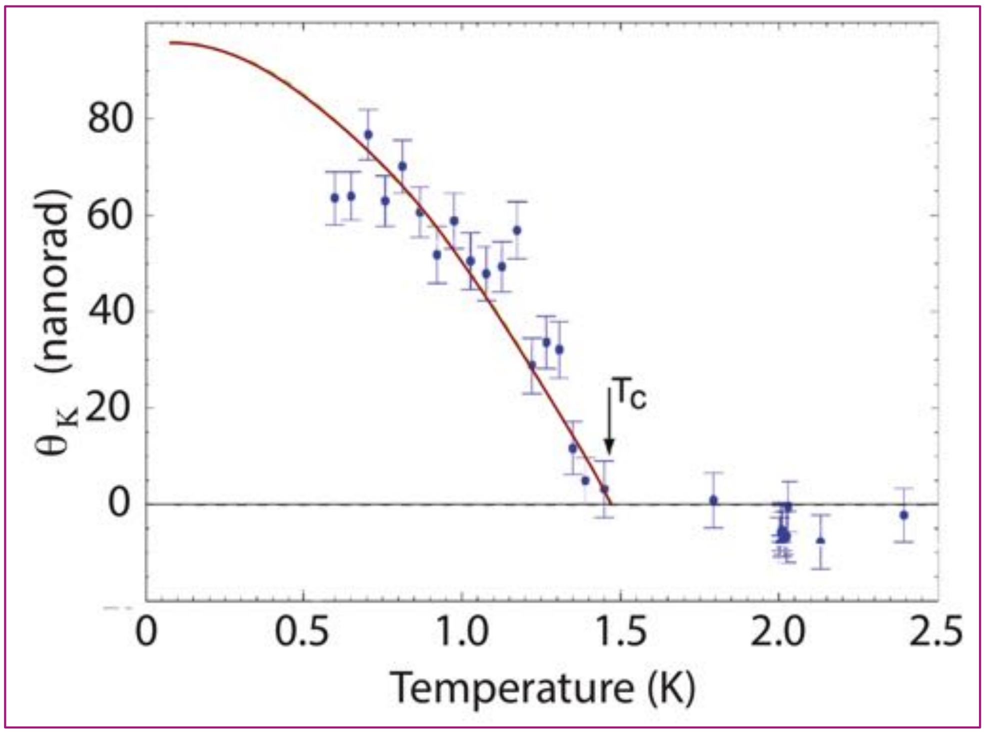


Measurements

Kerr effect measurements on Sr_2RuO_4







Time reversal symmetry is broken below T_C

A key measurement that helps identifying the nature of superconductivity in this system.

Jing Xia, Yoshiteru Maeno, Peter Beyersdorf, M. M. Fejer, and A. Kapitulnik, Phys. Rev. Lett. 97, 167002 (2006).

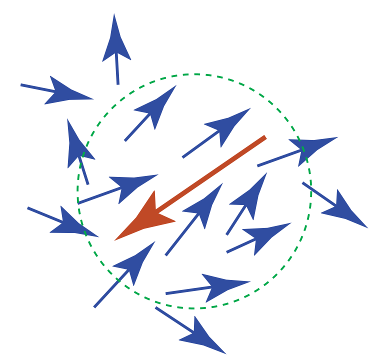
Heavy Fermion Superconductors

Heavy Fermions in one slide

- At high temperatures ($T > \sim T^*$), It is a metal, with local moments from f-electrons exhibiting a Curie –Weiss-type magnetic susceptibility.

- At low temperatures ($T < \sim T^*$), compensation of the *f*-moments occurs through an antiferromagnetic exchange interaction which produces a virtual bound state between the *f*-moments and the conduction electrons. This strong exchange coupling leads among other effects to a large effective mass for the conduction electrons $\boldsymbol{m^* >> m_e}$. Nevertheless, this strongly correlated state is a Fermi liquid.

(The hybridization is reminiscent of the Kondo effect observed for a single localized magnetic impurity in a non magnetic normal host.)



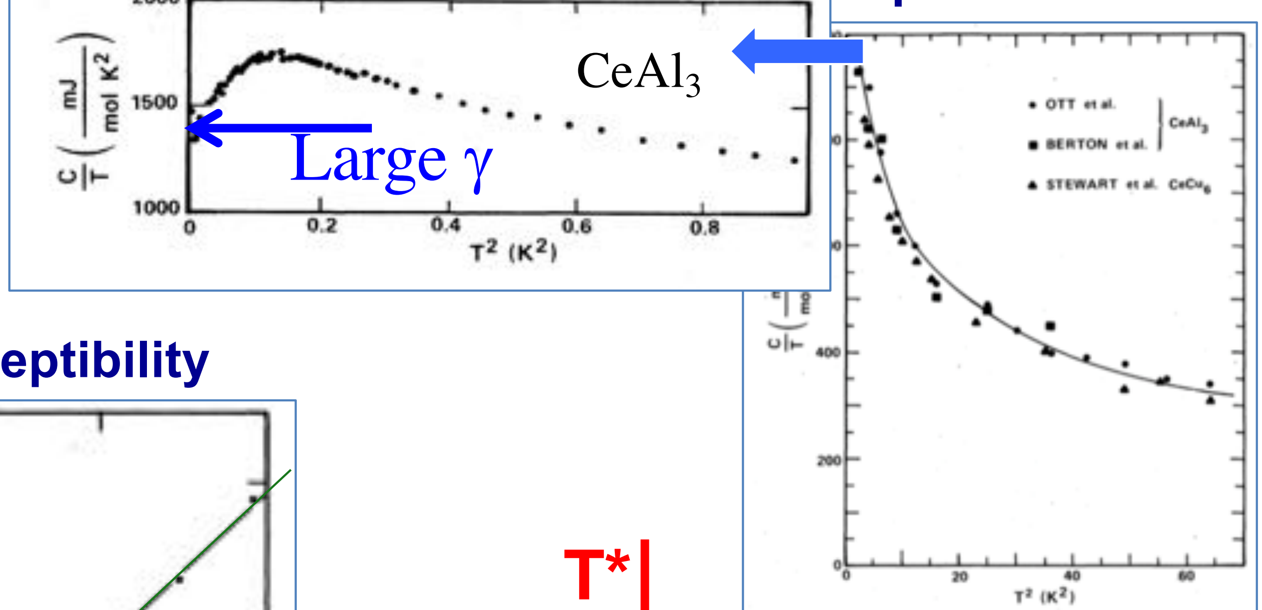
- HF compounds may exhibit novel electronic phases as they are cooled towards T=0

- **Some HF compounds can become superconductors.**

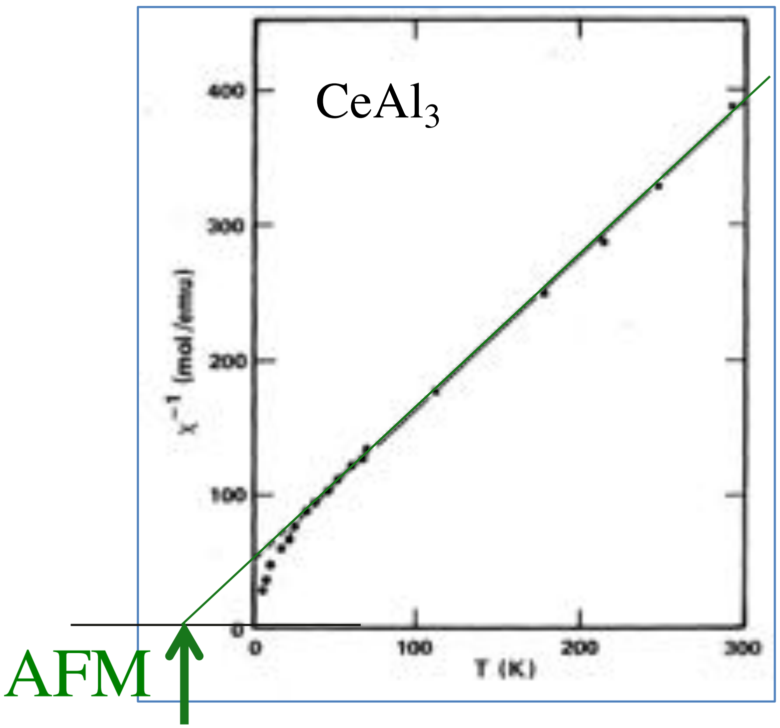
  ★ Usually superconductivity in such systems is found to be unconventional as a result of spin fluctuations.

Hallmarks of heavy fermions

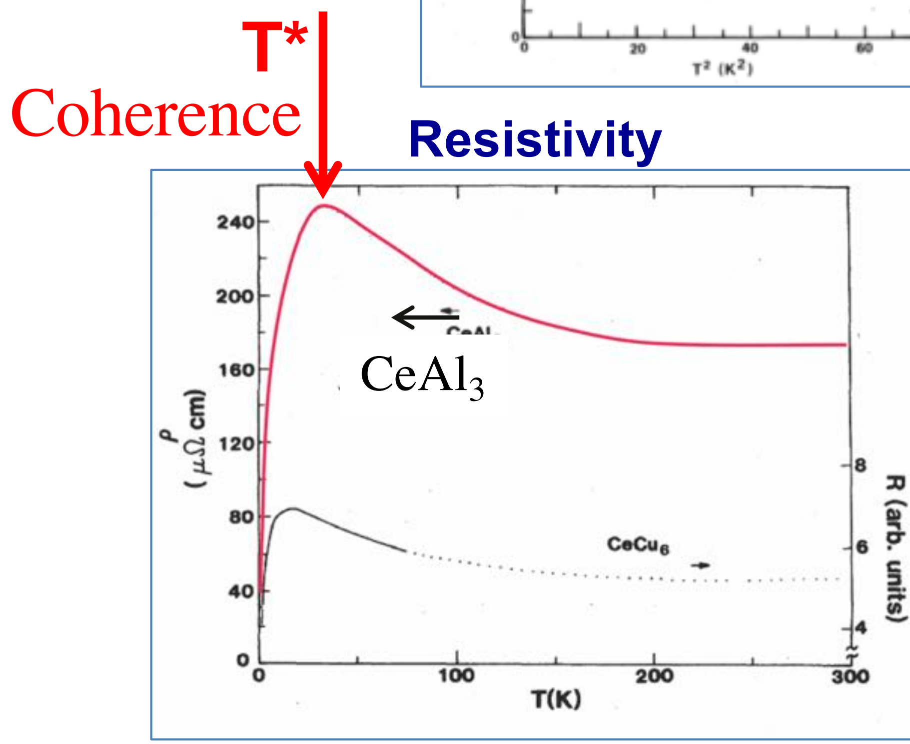
Specific heat



Magnetic Susceptibility



Resistivity



K. Andres, J. E. Graebner and H.R. Ott,
Phys. Rev. Lett. 35, 1779 (1975)

UPt_3

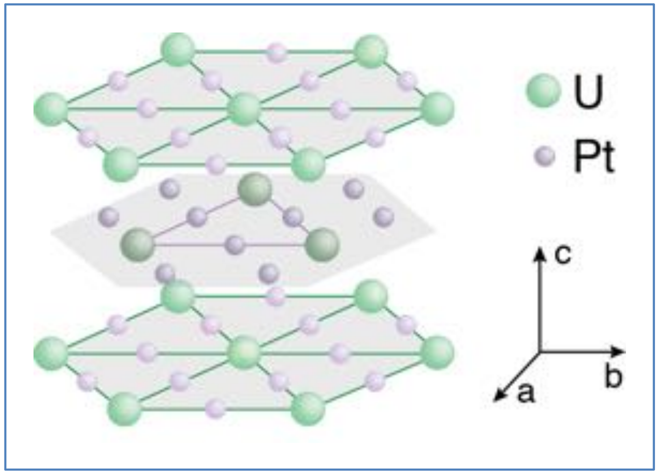
Maybe the first "official" **unconventional superconductor**
Early proposals predicted a "$p+ip$" order parameter -
chiral superconductor

E. R. Schemm, W. J. Gannon, K. Avers, W. P. Halperin, and Aharon Kapitulnik, Science 345, 190 (2014).

UPt_3

UPt_3 is a heavy-fermion compound with $m^* \approx 50 m_e$

Superconductivity was deemed unconventional through multiple superconducting phases



The **uranium** atoms form a closed-packed hexagonal structure. The **platinum** atoms bisecting the planar bonds.

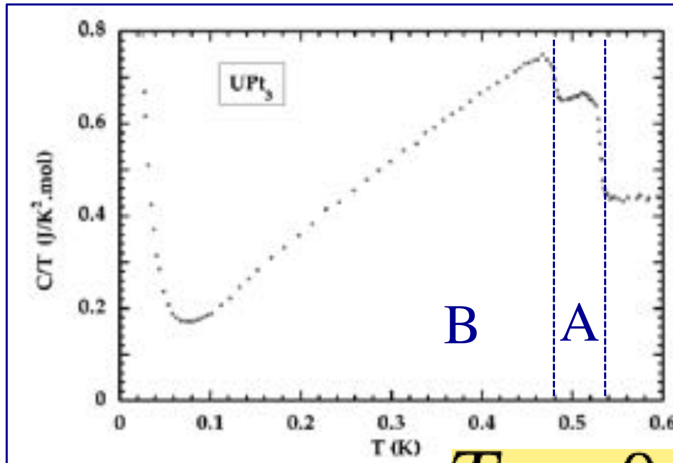
Space group: $P6_3$ /mmc

Point group: D_{6h}

The lattice parameters:

a=5.764 Å, c= 4.899 Å

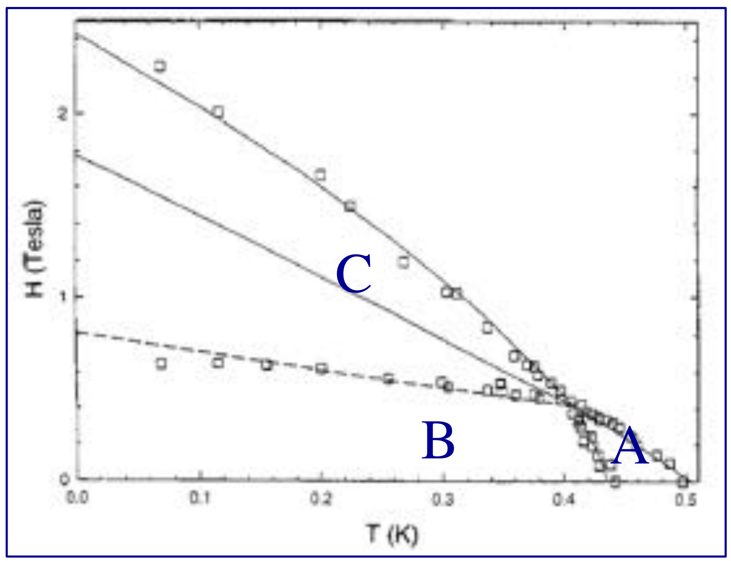
e.g. R. Joynt and L. Taillefer, Rev. Mod. Phys. 74, 235 (2002).



$T_c = 0.56\mathrm{K}$

Double-peak in specific heat

J.P. Brison, *et al.*, J. Low Temp. Phys. 95, 145 (1994).



Three phases in ultrasonic attenuation

S. Adenwalla, *et al.*, Phys. Rev. Lett. 65, 2298 (1990).

Some initial considerations

Note: Before considering any TRSB effect in the superconducting state, we need to understand from which state the condensate originates.

Early measurements on UPt_3 showed Antiferromagnetism

-- but no AFM is observed in recent measurements on much better samples

Some initial considerations

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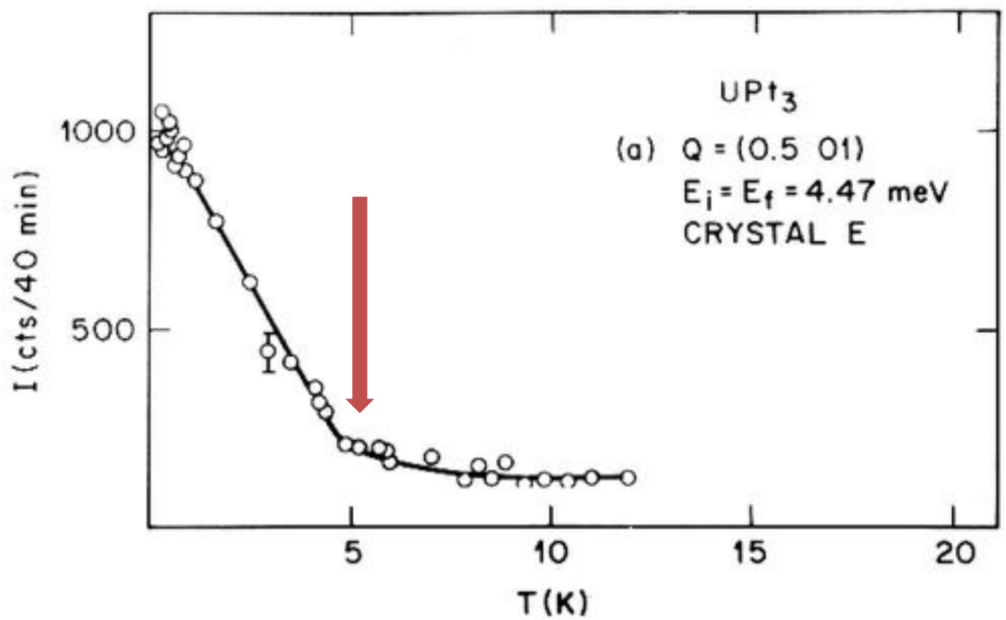
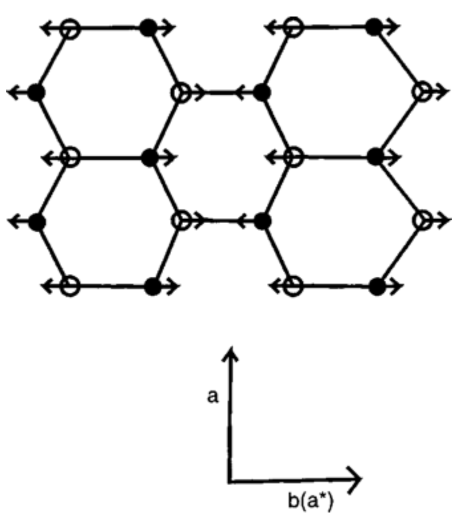
Temperature dependence of neutron scattering intensity below 20 K for (a) the elastic peak at Q=(1/2,0,1)



Antiferromagnetic order below **~5K** with a very small moment.

G. Aeppli, E. Bucher, C. Broholm, J. K. Kjems, J. Baumann, and J. Hufnagl, Phys. Rev. Lett. 60, 615 (1988).



While TRS is broken due to AFM, it should not produce a Kerr signal since moments order in the plane and perfectly cancel, so that there is not component in the c-direction.

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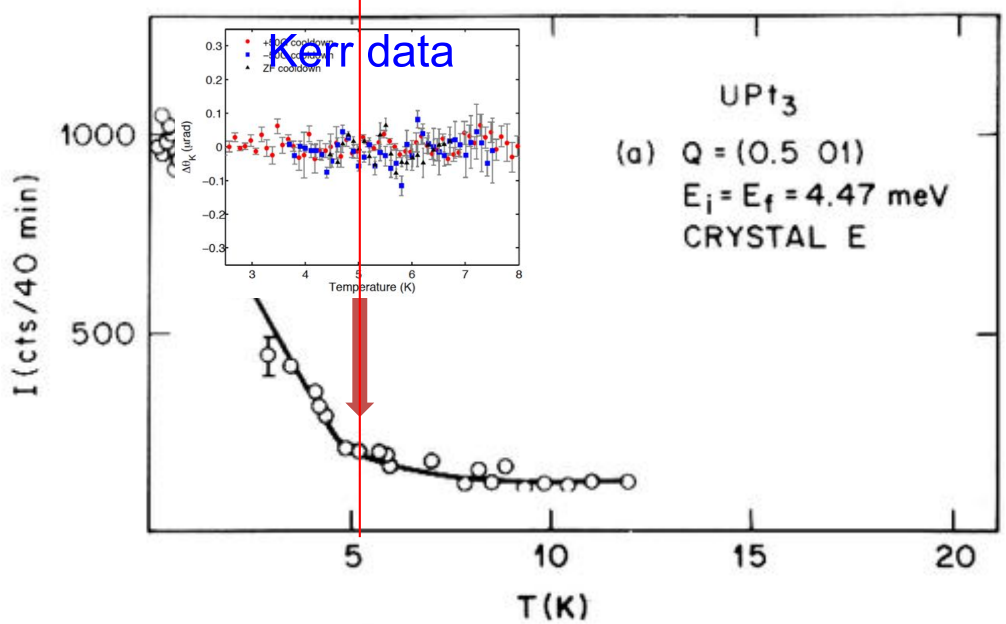

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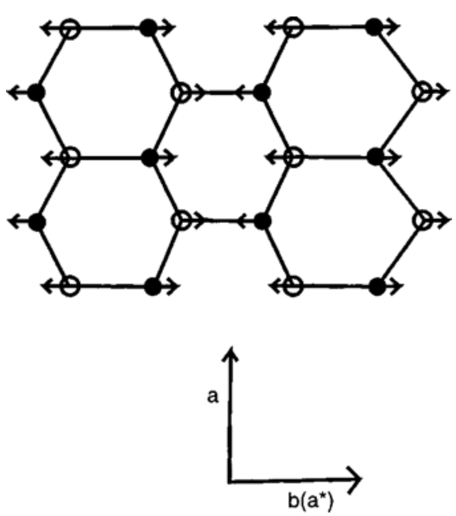

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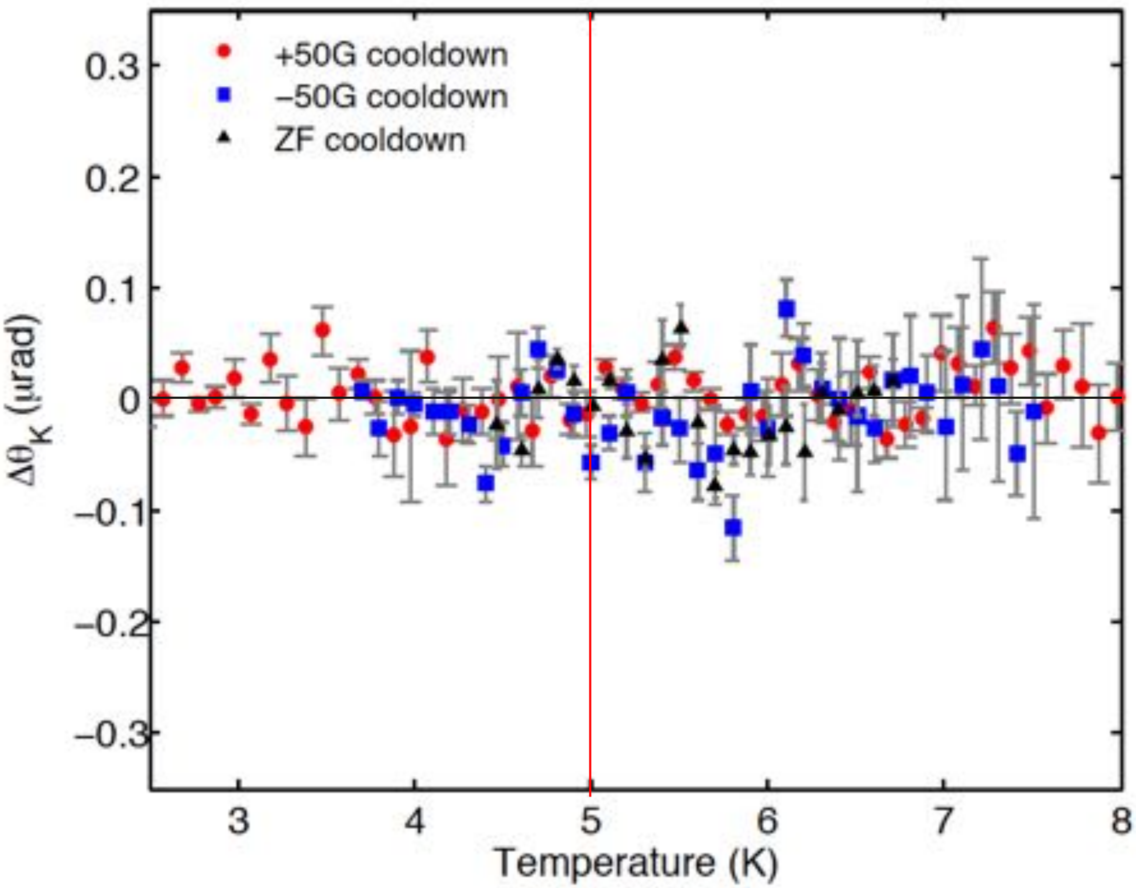
Sagnac data through the AFM transition



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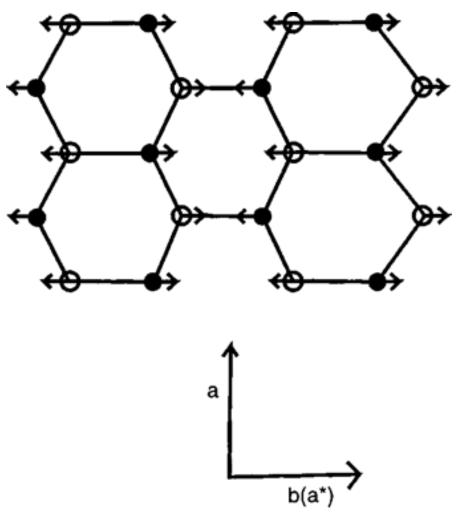


No detectable signal in the Kerr data through 5K!

The superconducting state of UPt_3

The order parameter of UPt_3

Identifying the order parameter of UPt_3 by its symmetries

Even parity		Odd parity	
A_{1g}	1	A_{1u}	$\mathbf{z}\, k_z$
A_{2g}	$Im(k_x + ik_y)^6$	A_{2u}	$\mathbf{z}\, k_z Im(k_x + ik_y)^6$
B_{1g}	$k_z\, Im(k_x + ik_y)^3$	B_{1u}	$\mathbf{z}\, Im(k_x + ik_y)^3$
B_{2g}	$k_z\, Re(k_x + ik_y)^3$	B_{2u}	$\mathbf{z}\, Re(k_x + ik_y)^3$
E_{1g}	$k_z \begin{pmatrix} k_x \\ k_y \end{pmatrix}$	E_{1u}	$\mathbf{z} \begin{pmatrix} k_x \\ k_y \end{pmatrix}$
E_{2g}	$\begin{pmatrix} k_x^2 - k_y^2 \\ 2k_x k_y \end{pmatrix}$	$\boxed{E_{2u}}$	$\boxed{\mathbf{z}\, k_z \begin{pmatrix} k_x^2 - k_y^2 \\ 2k_x k_y \end{pmatrix}}$

- J. A. Sauls, Adv. Phys. 94, 113 (1994)

Parity

- NMR Knight shift: (pseudo) spin triplet

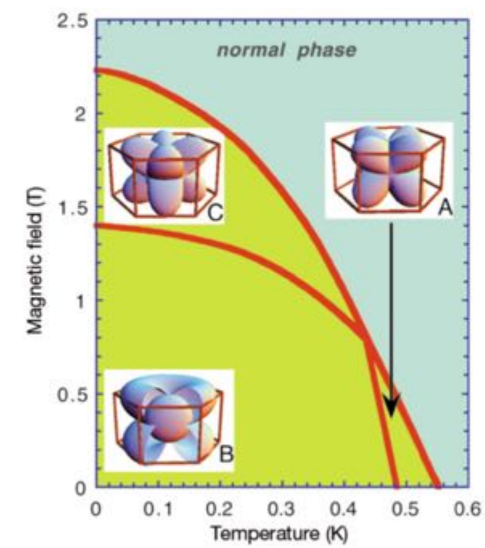
Nodal structure

- Thermal conductivity: anisotropic gap
- Ultrasonic attenuation: basal plane line node
- Point contact spectroscopy: point nodes along c axis
- Josephson interferometry: basal plane 45° line nodes in A phase; isotropic B phase

Time reversal

- May be inferred from other experiments
- Direct' measurement via μSR: inconclusive!

E_{2u}:



$$\Delta(\mathbf{k}) = \Delta_R + i\Delta_I = \eta_1 k_z (k_x^2 - k_y^2) + i\eta_2 k_z 2k_x k_y$$

Preferred symmetry: E_{2u}

A. Huxley, P. Rodiere, D. M. Paul, N. van Dijk, R. Cubitt, and J. Flouquet: Nature 406, 160 (2000).

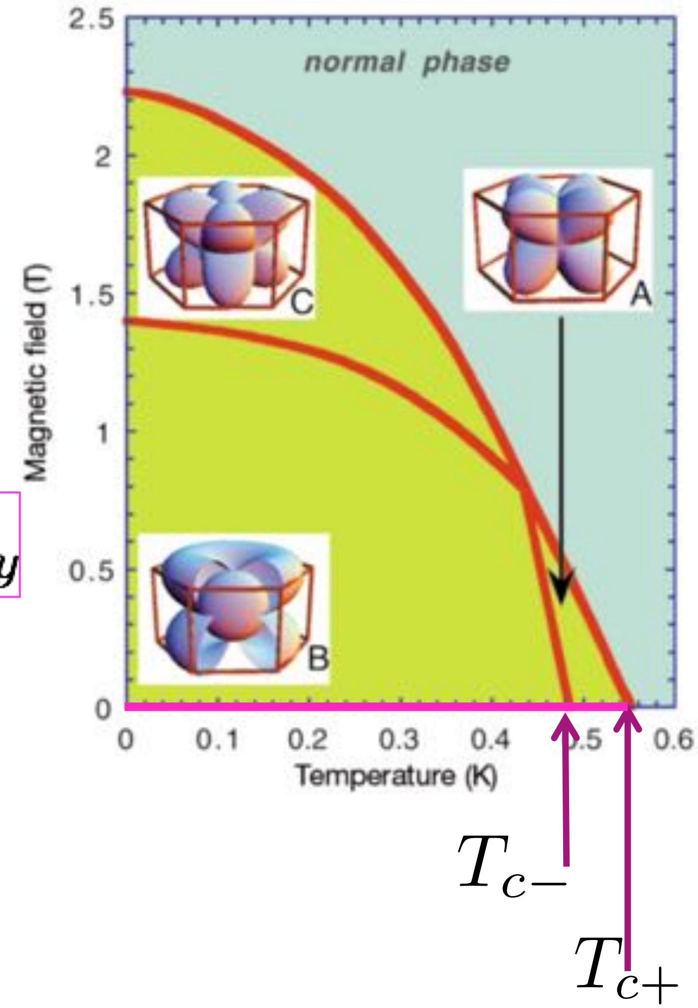
2-D order parameter: $\eta = (\eta_1, \eta_2)$

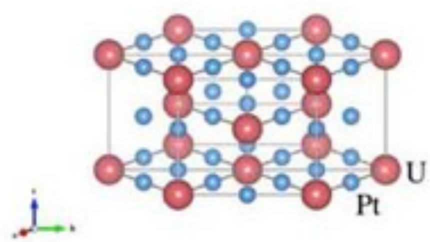
$$\boxed{\Delta(\vec{k}) = \eta_1(T) k_z \left(k_x^2 - k_y^2\right) + 2\eta_2(T) k_z k_x k_y}$$

A – phase: $\eta = (1, 0)$

B – phase: $\eta = (1, \pm i)$

C – phase: $\eta = (0, 1)$





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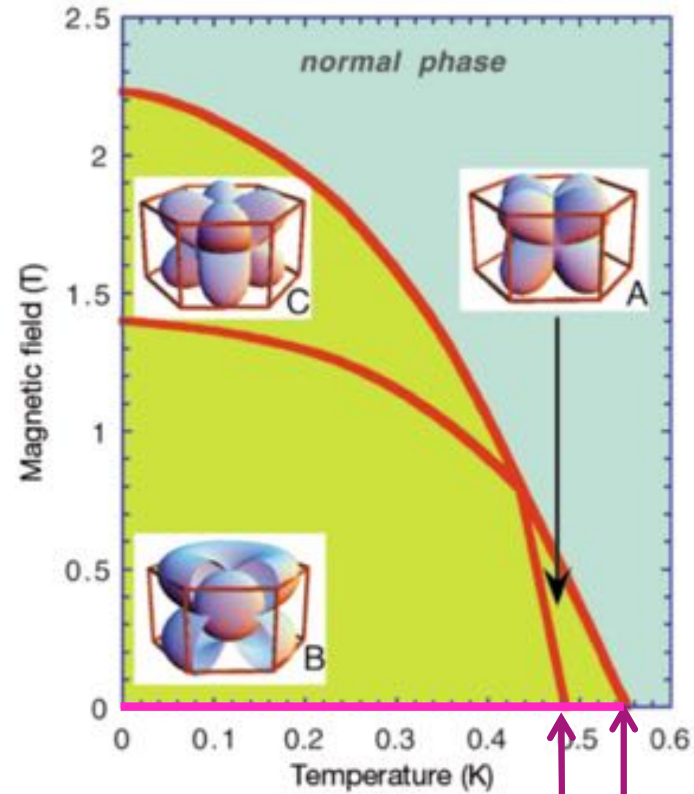


T_{c-}

T_{c+}

In the B-phase:

$$\Delta_\pm = \Delta_R \pm i\Delta_I$$

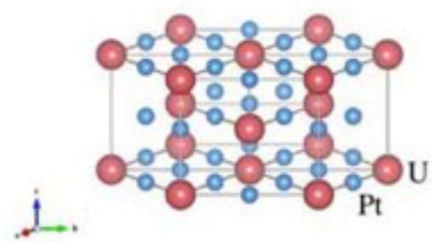
$$\Delta_R = \Delta_A k_z (k_x^2 - k_y^2)$$

$$\Delta_I = \Delta_B k_z k_x k_y$$

Where we expect:

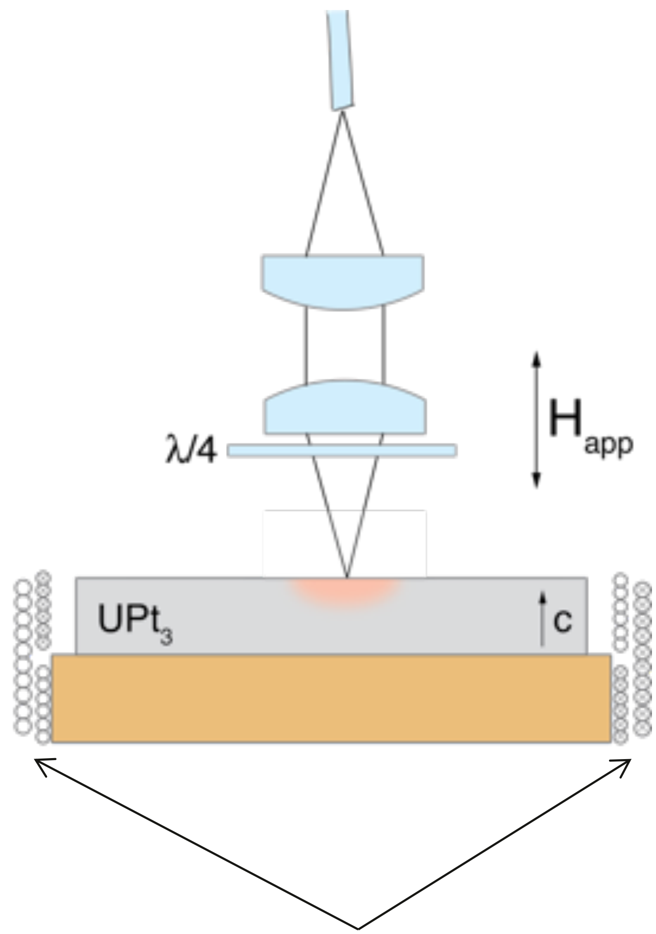
$$\Delta_A \propto \left[1 - \left(\frac{T}{T_{c+}}\right)^2\right]^{1/2}$$

$$\Delta_B \propto \left[1 - \left(\frac{T}{T_{c-}}\right)^2\right]^{1/2}$$



Kerr effect measurements on UPt_3

Zero-field cool/Zero-field warmup, Measure when warming up



Mutual-inductance locates T_{c+}

Kerr effect measurements on UPt_3

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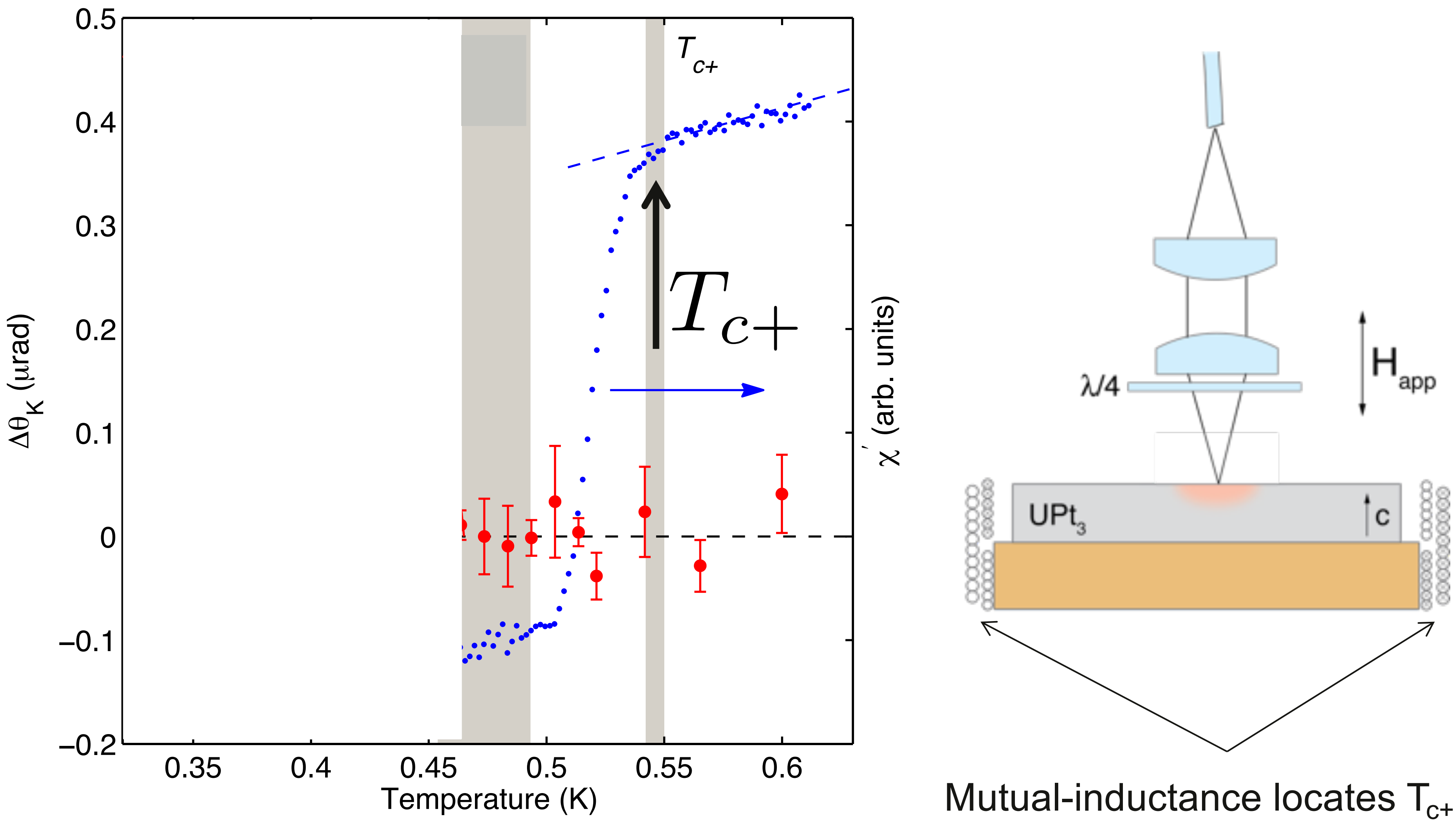

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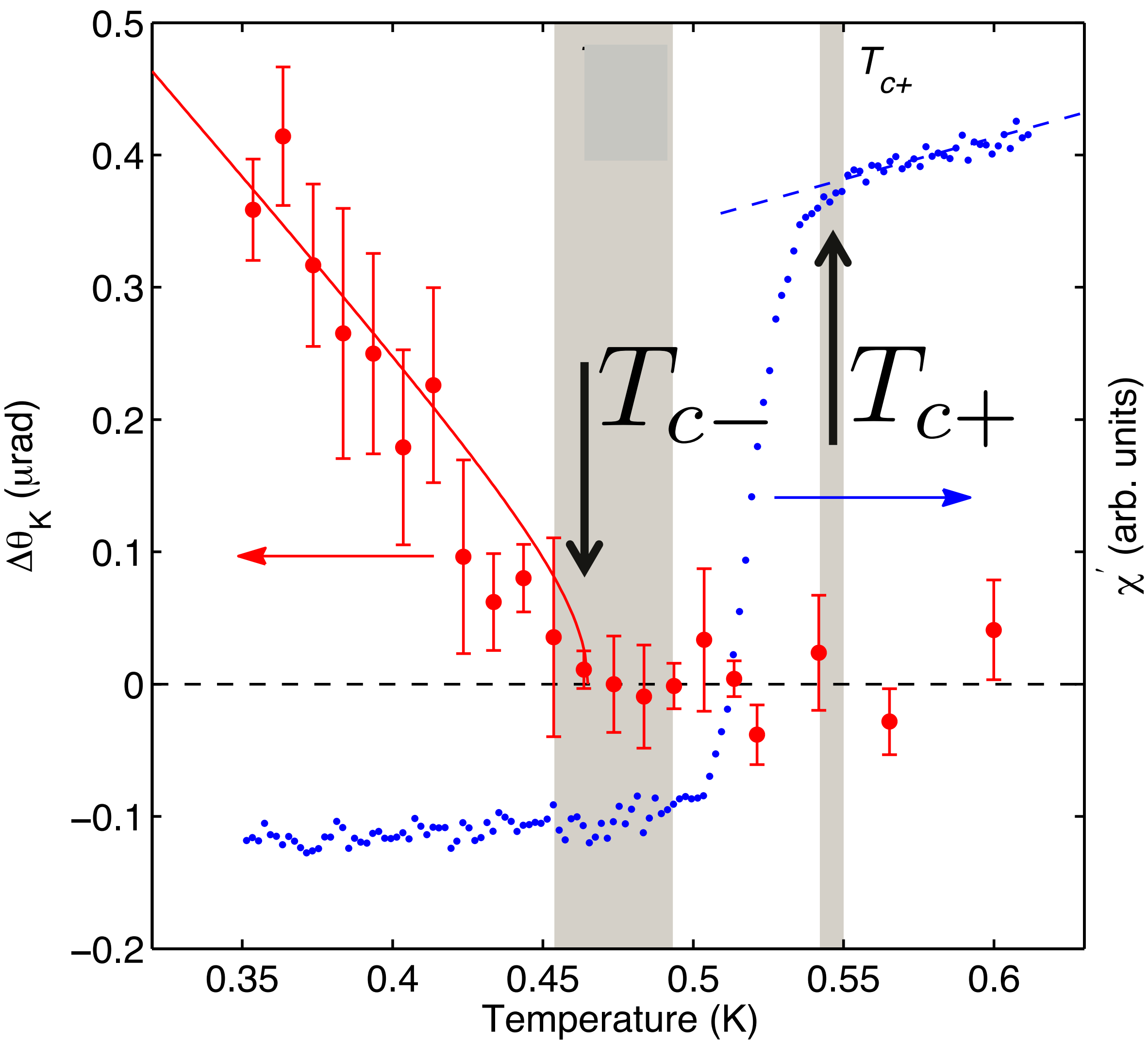

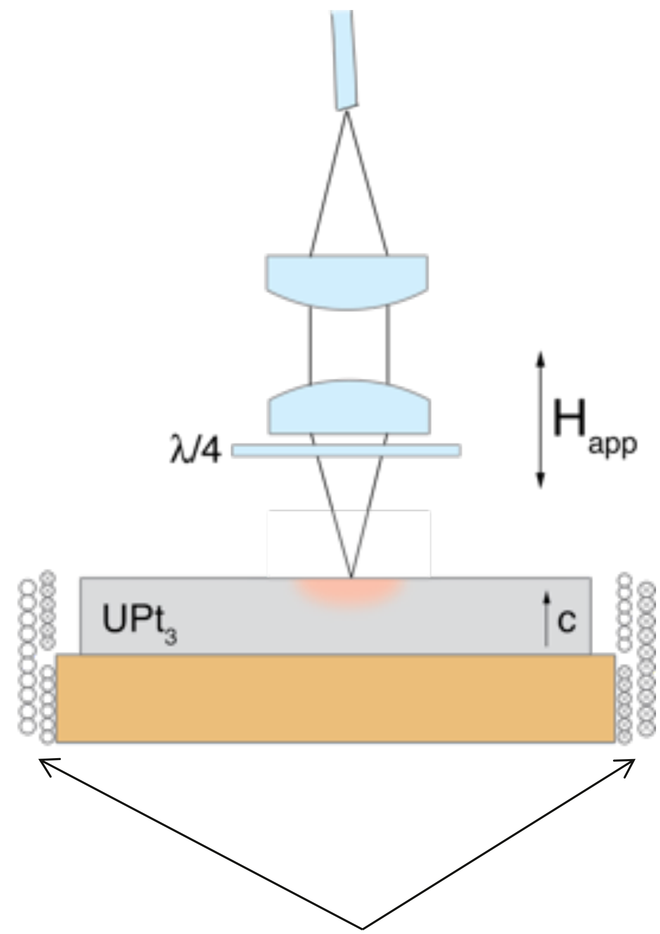

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Kerr effect measurements on UPt_3

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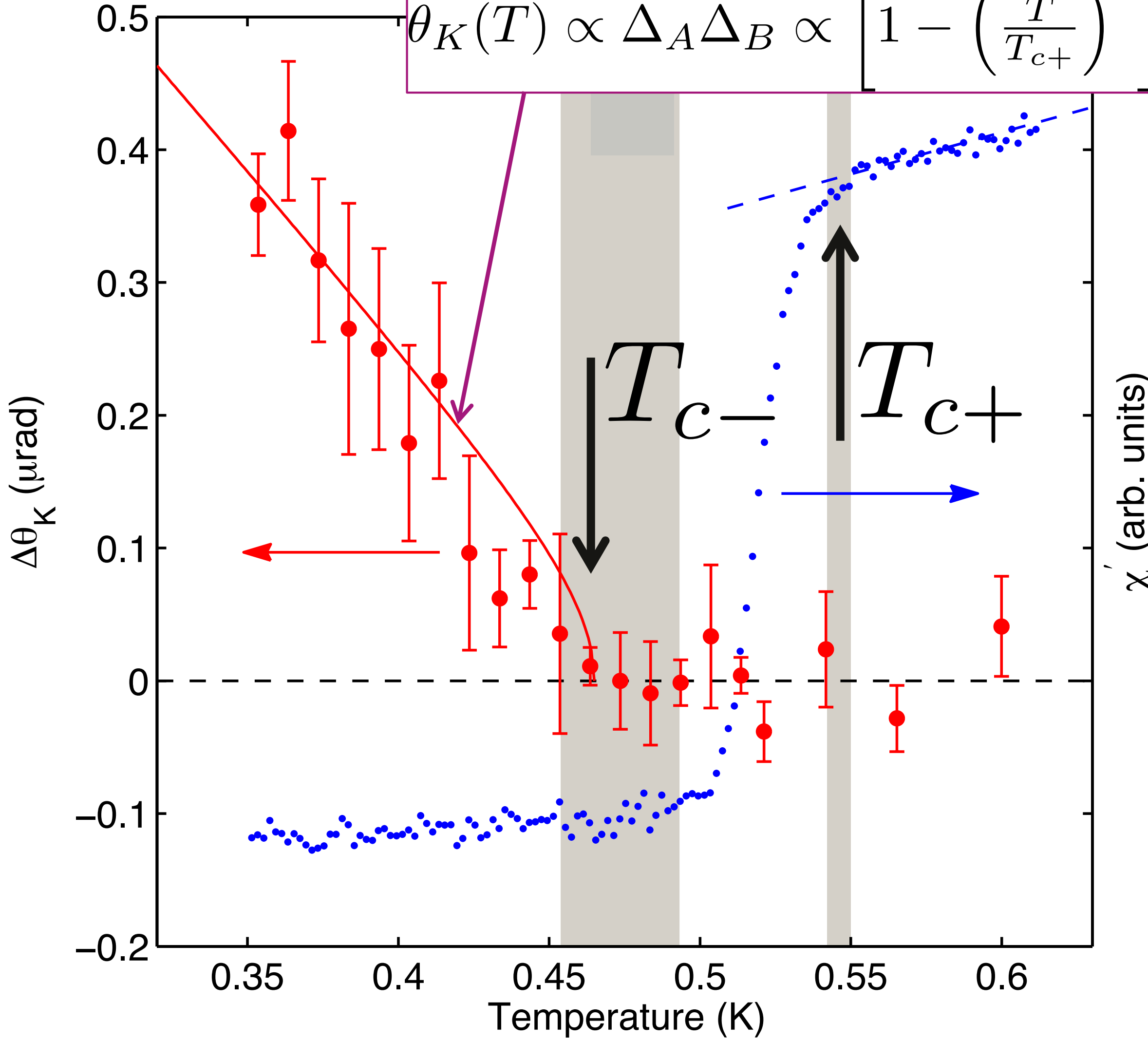
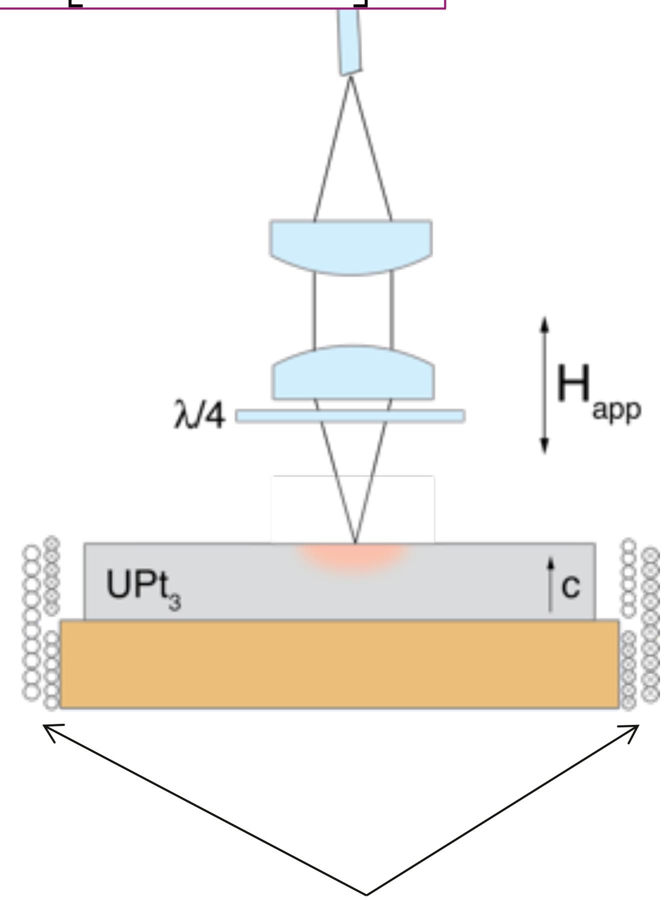
$$\theta_K(T) \propto \Delta_A \Delta_B \propto \left[1-\left(\frac{T}{T_{c+}}\right)^2\right]^{1/2} \cdot \left[1-\left(\frac{T}{T_{c-}}\right)^2\right]^{1/2}$$





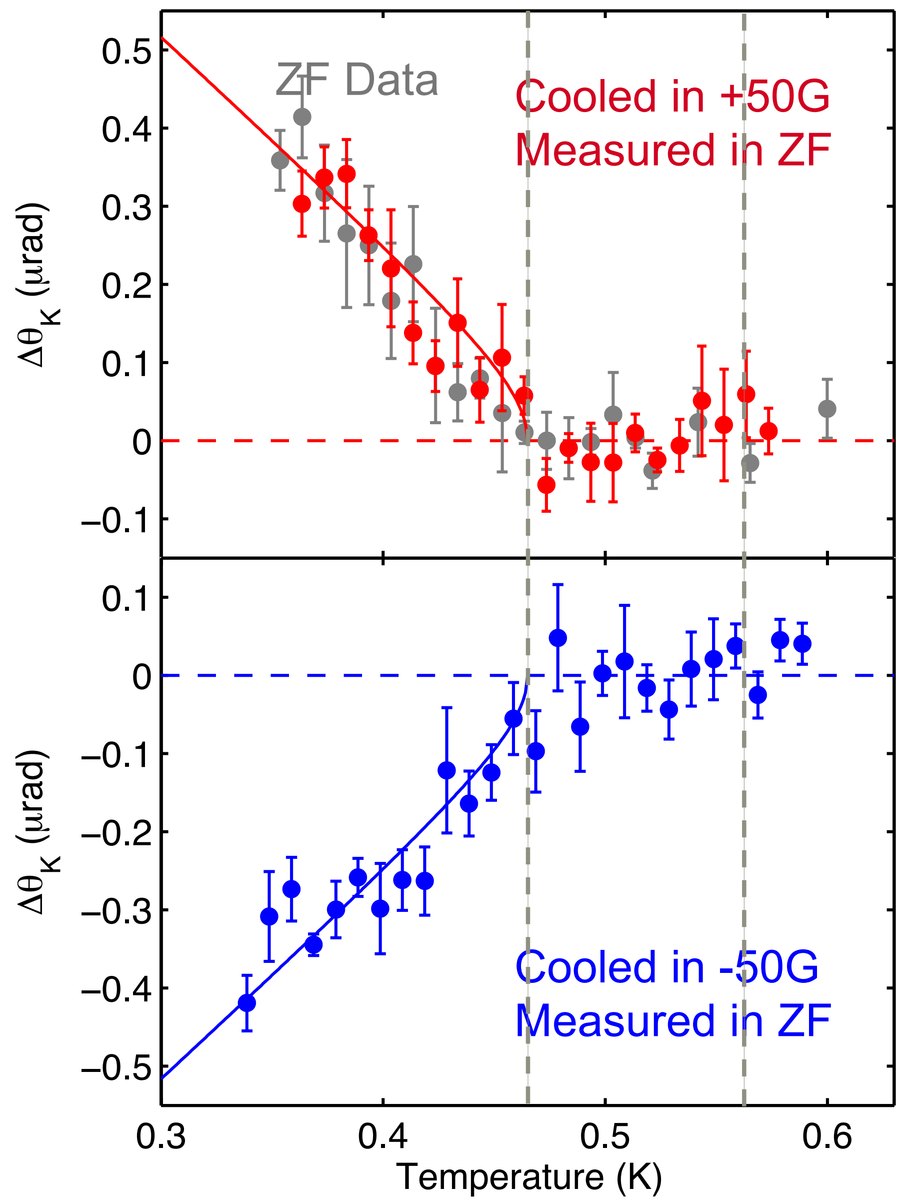
Mutual-inductance locates T_{c+}

Kerr effect measurements on UPt_3

Field-training data:

Observations/implications:

1. θ_K can be trained with a small symmetry-breaking field
2. No additional signal for FC measurements
   - Single domain formation
   - θ_K not a vortex effect



TRS is broken in the B-phase of the superconducting state of UPt_3

Summary of observations on UPt_3

- Maximum signal is ~400 nanorad (extrapolated to ~900 nanorad at T=0)
- Signal onsets at $T_{C-} \approx$ 480 mK (**B-phase)**,
  while superconductivity onsets at $T_{C+} \approx$ 560 mK
- Temperature dependence of signal can be fitted with a product of two gaps function.
- Chirality can be trained with a magnetic field.
- It seems like a single domain for the whole sample! (beam size ~10µm)
- Signal cannot be explained by trapped flux -
  zero-field cool signal equals field cool
- There is no Light-power dependence on the size of the signal (no heating effect, power was changed x20 times!)

B-phase breaks time reversal symmetry