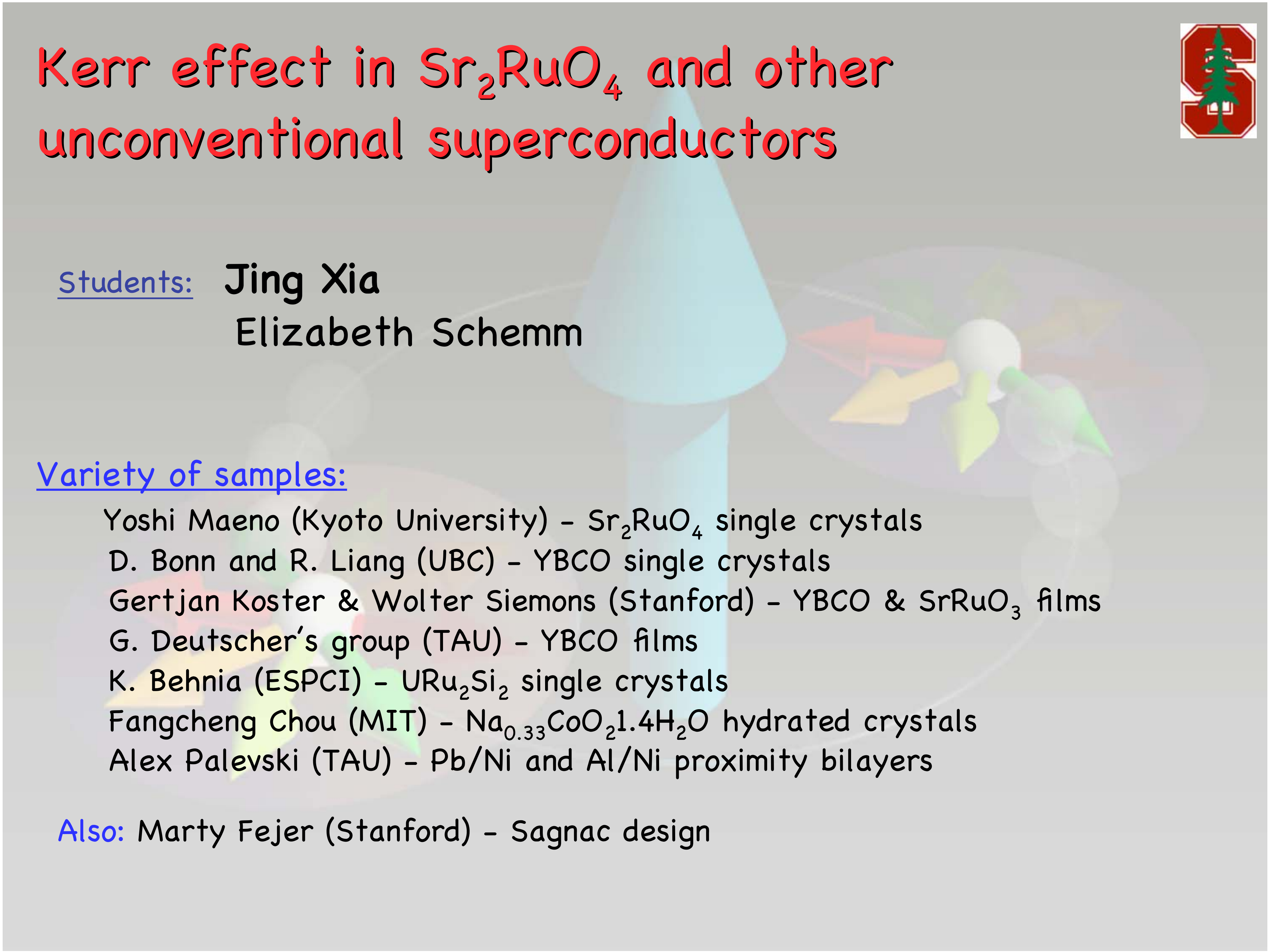
Kerr effect in Sr_2RuO_4 and other unconventional superconductors



Students: **Jing Xia**

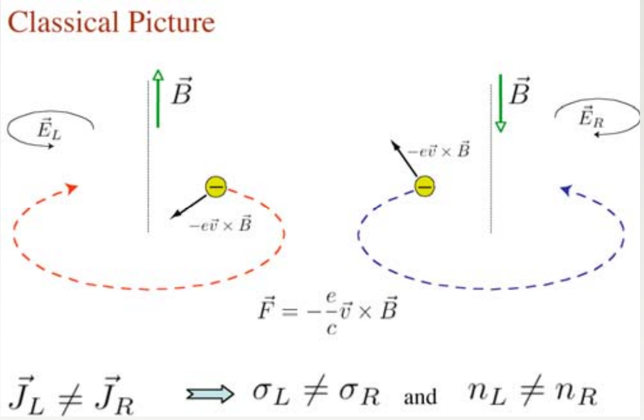
Elizabeth Schemm

Variety of samples:

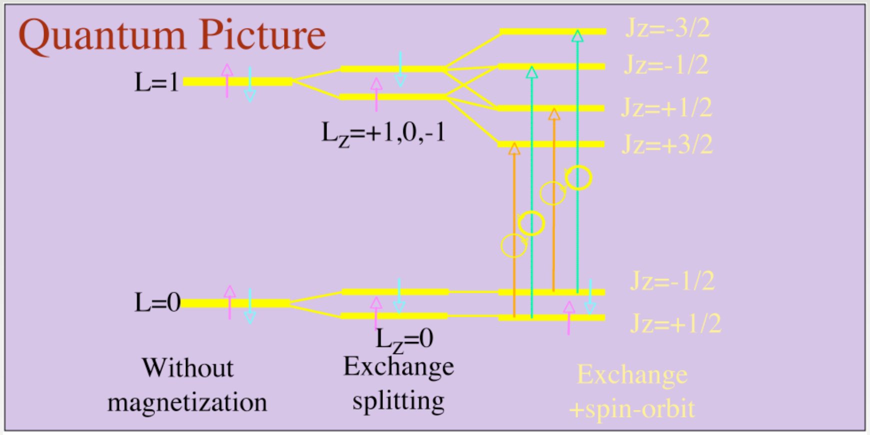
Yoshi Maeno (Kyoto University) - Sr_2RuO_4 single crystals
D. Bonn and R. Liang (UBC) - YBCO single crystals
Gertjan Koster & Wolter Siemons (Stanford) - YBCO & $SrRuO_3$ films
G. Deutscher's group (TAU) - YBCO films
K. Behnia (ESPCI) - URu_2Si_2 single crystals
Fangcheng Chou (MIT) - $Na_{0.33}CoO_2 1.4H_2O$ hydrated crystals
Alex Palevski (TAU) - Pb/Ni and Al/Ni proximity bilayers

Also: Marty Fejer (Stanford) - Sagnac design

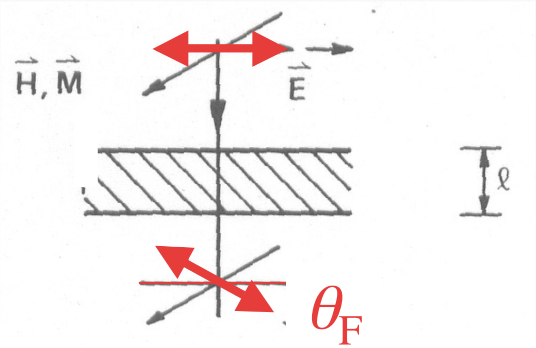
Magneto-Optical-like Measurements!



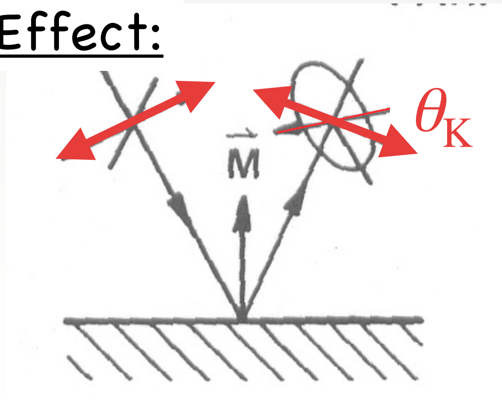
$$n_R \neq n_L$$



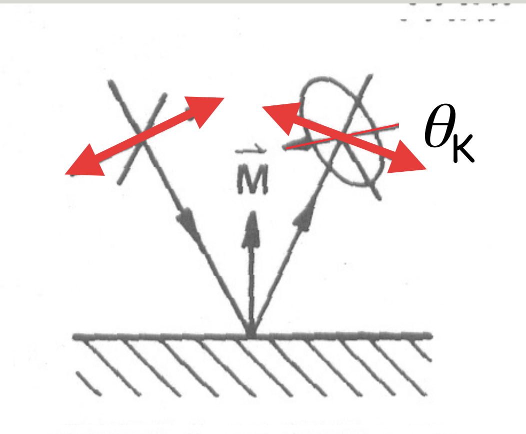
Faraday Effect:



(Polar) Kerr Effect:



Consider a Polar Kerr Effect at normal incidence



$$\frac{E_r}{E_0} \equiv r = |r|e^{i\phi} = -\frac{(n+i\kappa)-1}{(n+i\kappa)+1}$$

$$\frac{r_R}{r_L} = \left|\frac{r_R}{r_L}\right| e^{i(\phi_R-\phi_L)}$$

After reflection the complex amplitudes are different.
The polarization is now elliptical with the major axis rotated by:

$$\theta_K = -\frac{1}{2}(\phi_R-\phi_L) \approx -\mathrm{Im}\frac{(n_R+i\kappa_R)-(n_L+i\kappa_L)}{(n_R+i\kappa_R)(n_L+i\kappa_L)-1}$$

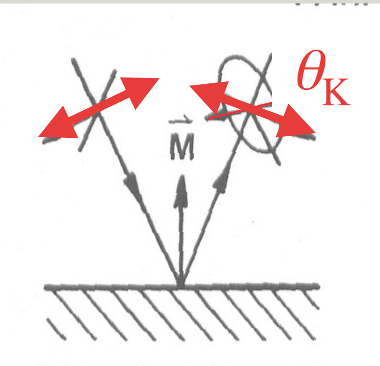
In the last equality we used a small phase difference and small difference of the *n*-s.

For small k:

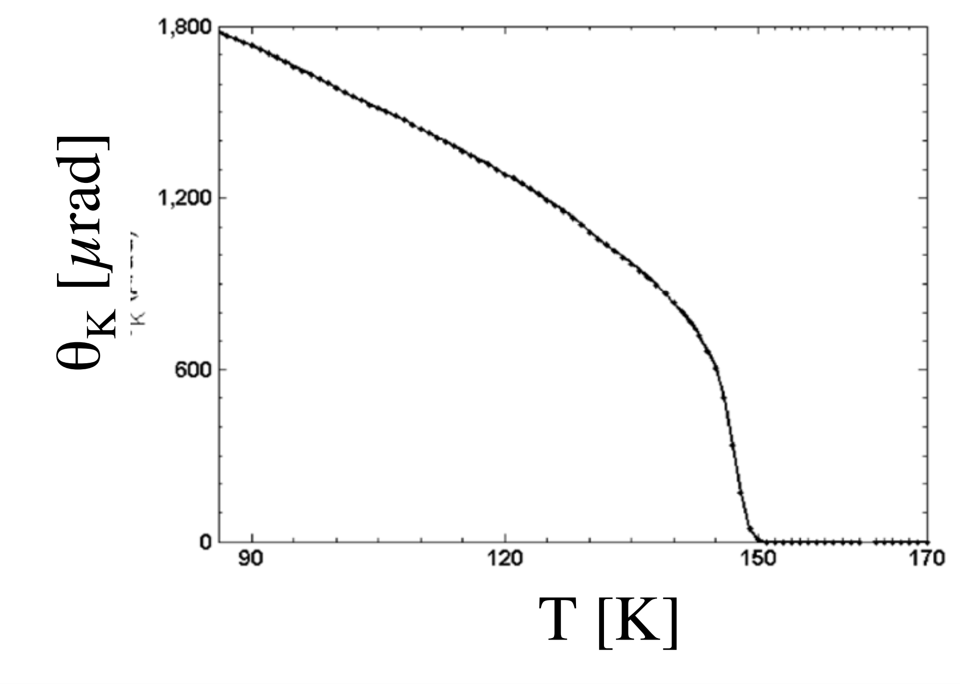
$$\boxed{\theta_K = \frac{2\lambda}{cn(n^2-1)}\sigma''_{xy}}$$

Example:

Kerr effect of thick film Ferromagnetic **$SrRuO_3$**:



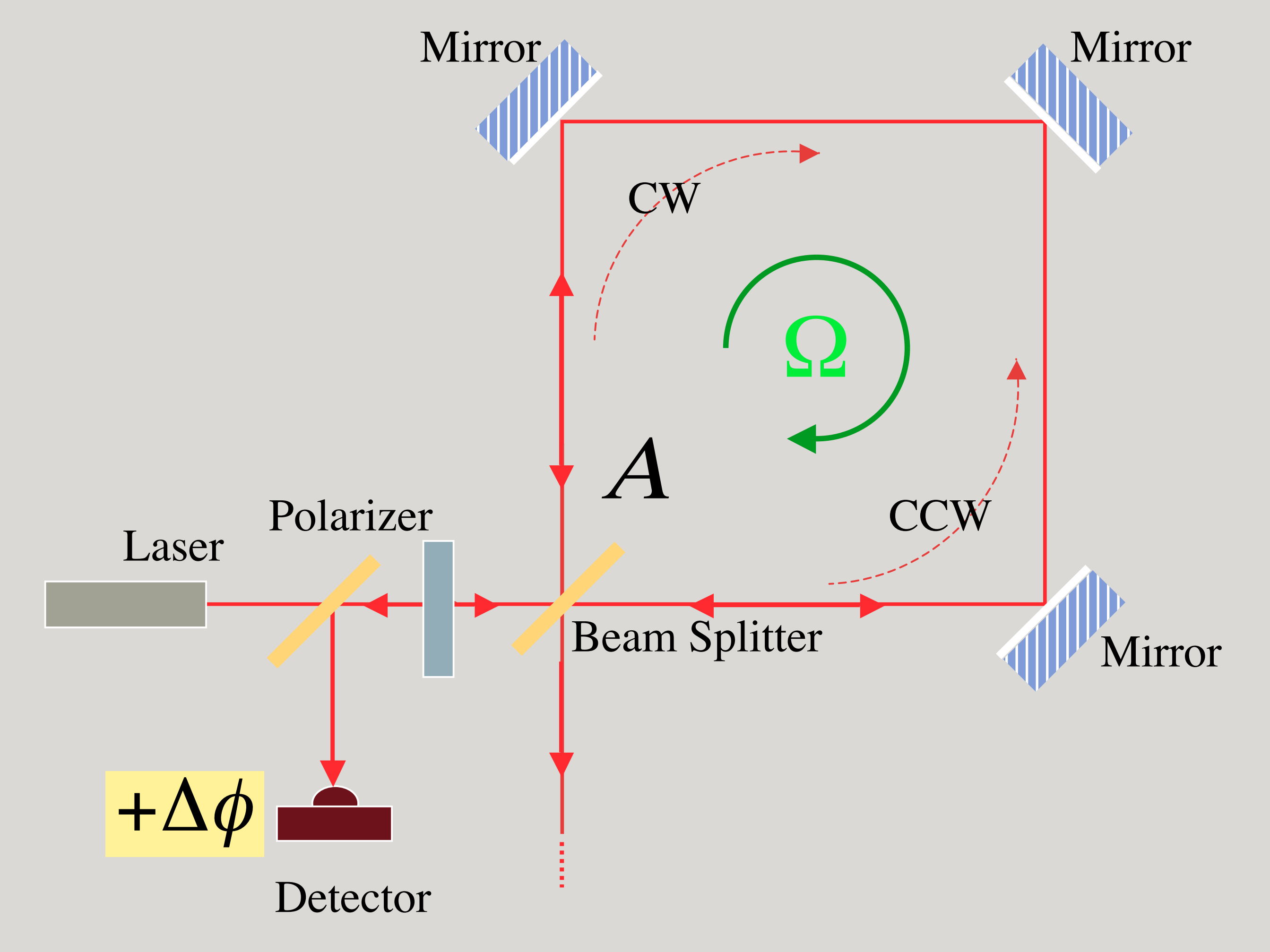
Note size of effect:
Saturation value is
<u>~ 10 millirad !!!</u>



For some ferromagnets θ_K can be of order ~rad!

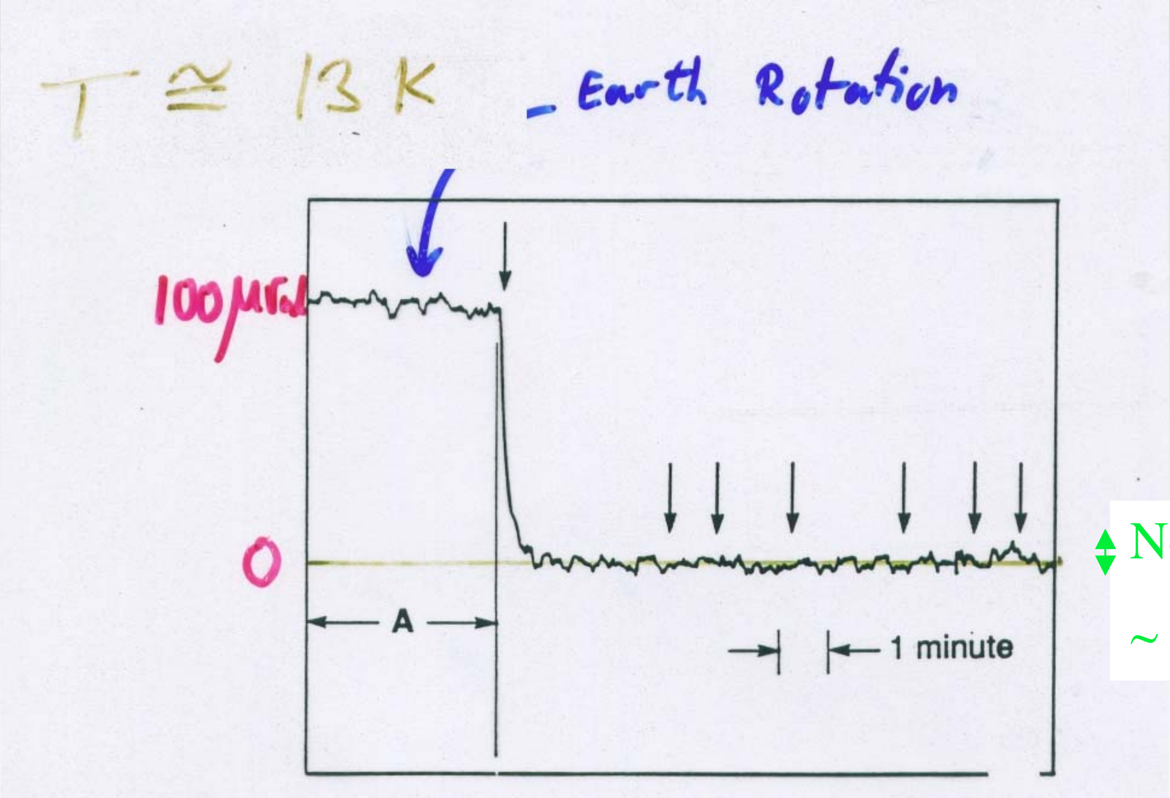
Solution: The Sagnac Effect

A Sagnac Loop at rest
is reciprocal!



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

Optimally doped $YBa_2Cu_3O_{7-\delta}$ Thin Films in Transmission:



Noise

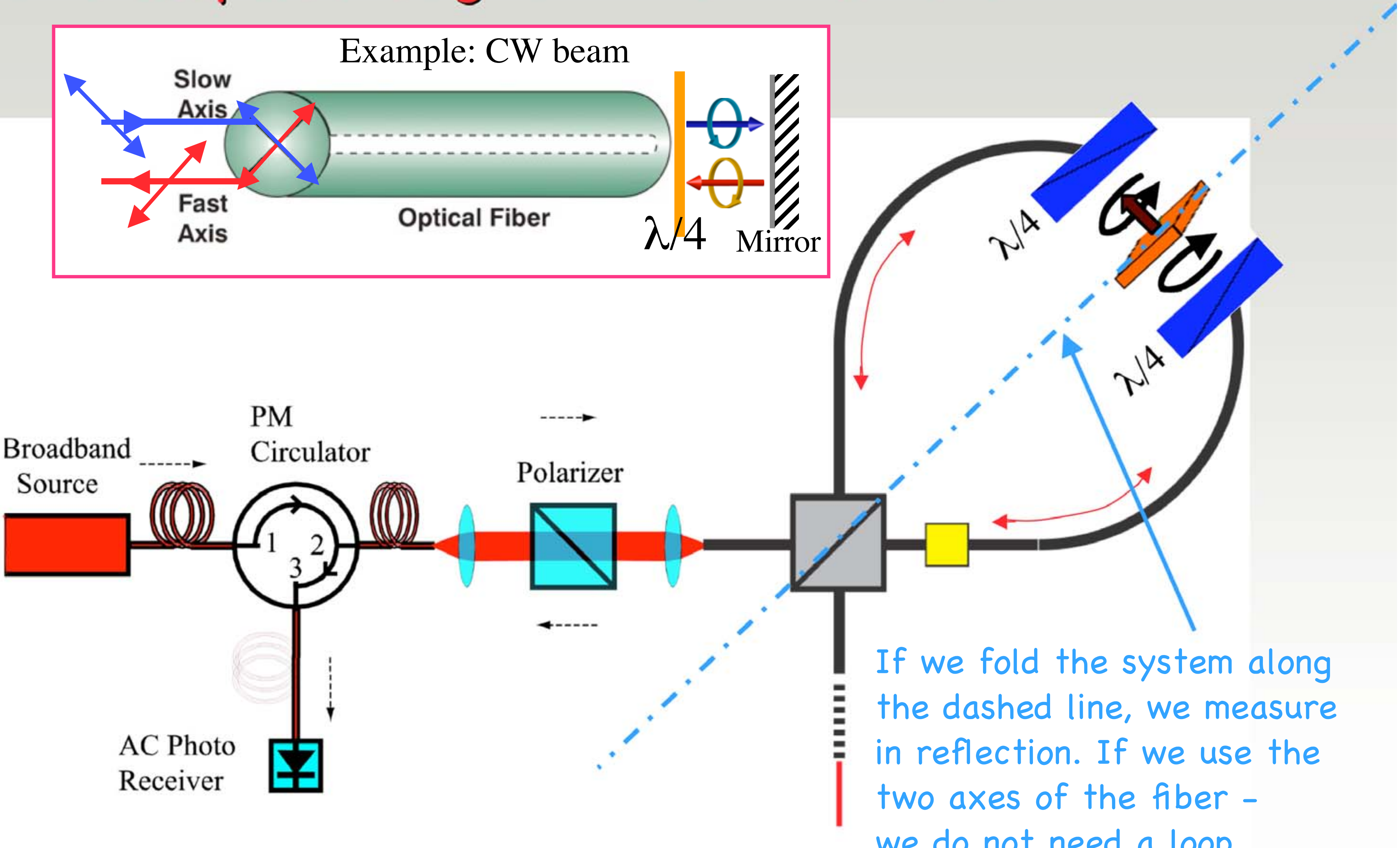
~ 2 μrad/$Hz^{1/2}$

Results: No effect to within 1 μrad

No shot noise limit. Main problems: Drift, need for higher power (~1 mW)

S. Spielman et al.Phys. Rev. Lett. 1990; Phys. Rev. Lett. 1992

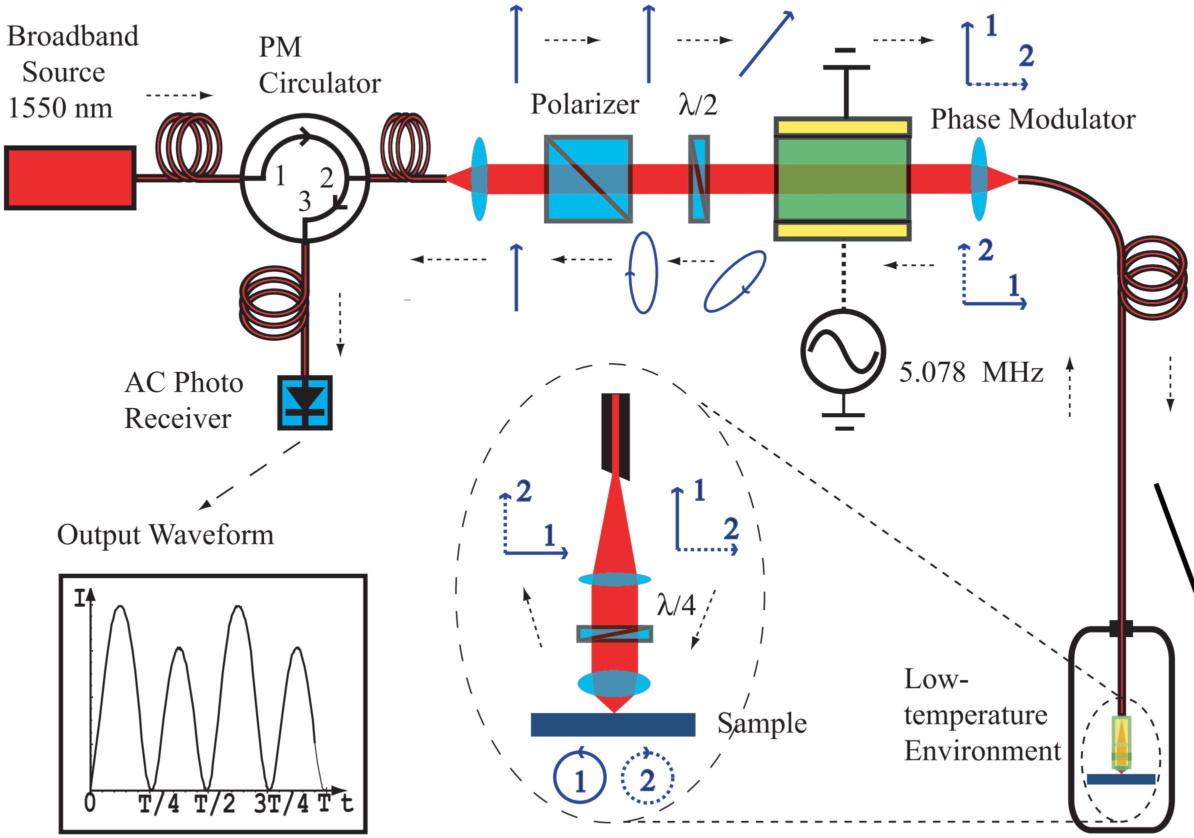
The loopless Sagnac interferometer



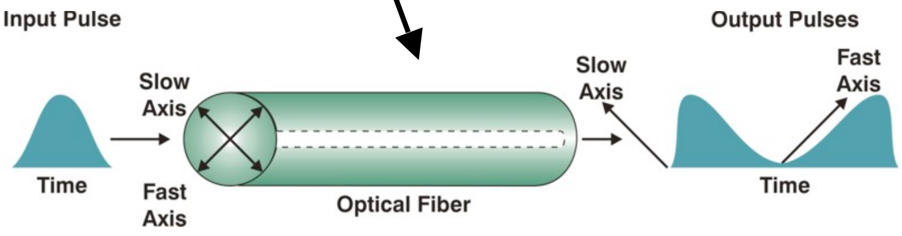
If we fold the system along the dashed line, we measure in reflection. If we use the two axes of the fiber – we do not need a loop.

Loopless Sagnac magnetometer

$\lambda = 1.55\ \mu m$

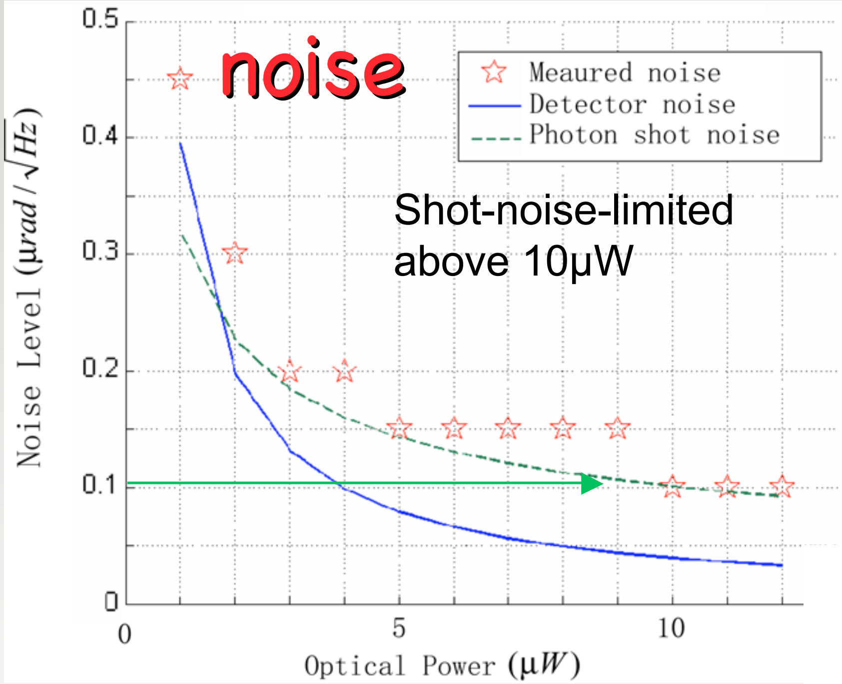


1. **There is no Optic-viewport, allows lower temperatures (0.3 K) operation.**
2. **It rejects depolarization effects such as linear birefringence.**
3. **Both DC and AC performance are shot-noise limited.**

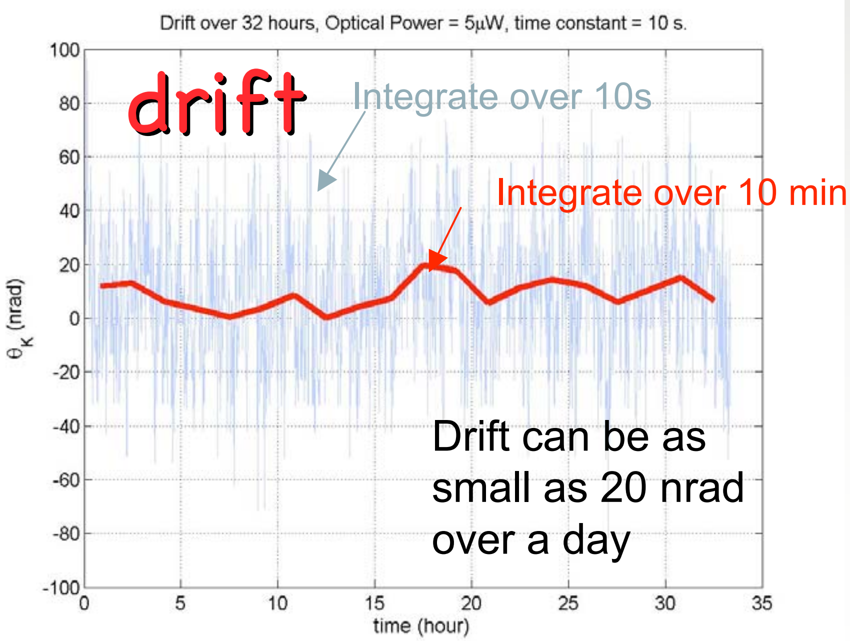


Jing Xia, Peter Beyersdorf, M. M. Fejer, and A. Kapitulnik, Appl. Phys. Lett. 89, 062508

Performance:



Shot-noise-limited above 10μW

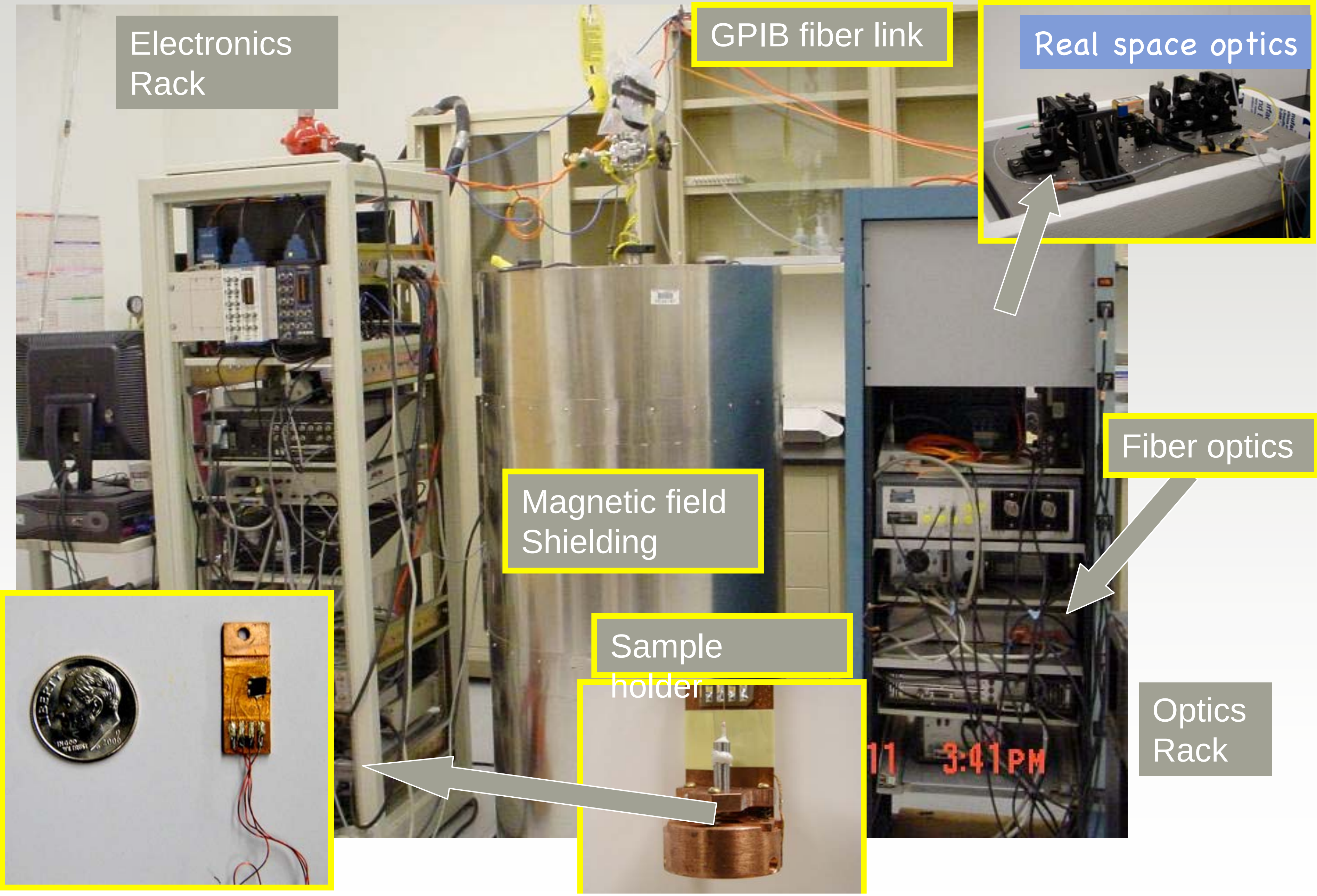


Integrate over 10s

Integrate over 10 min

Drift can be as small as 20 nrad over a day

Pictures of Experimental Setup



Electronics Rack

GPIB fiber link

Real space optics

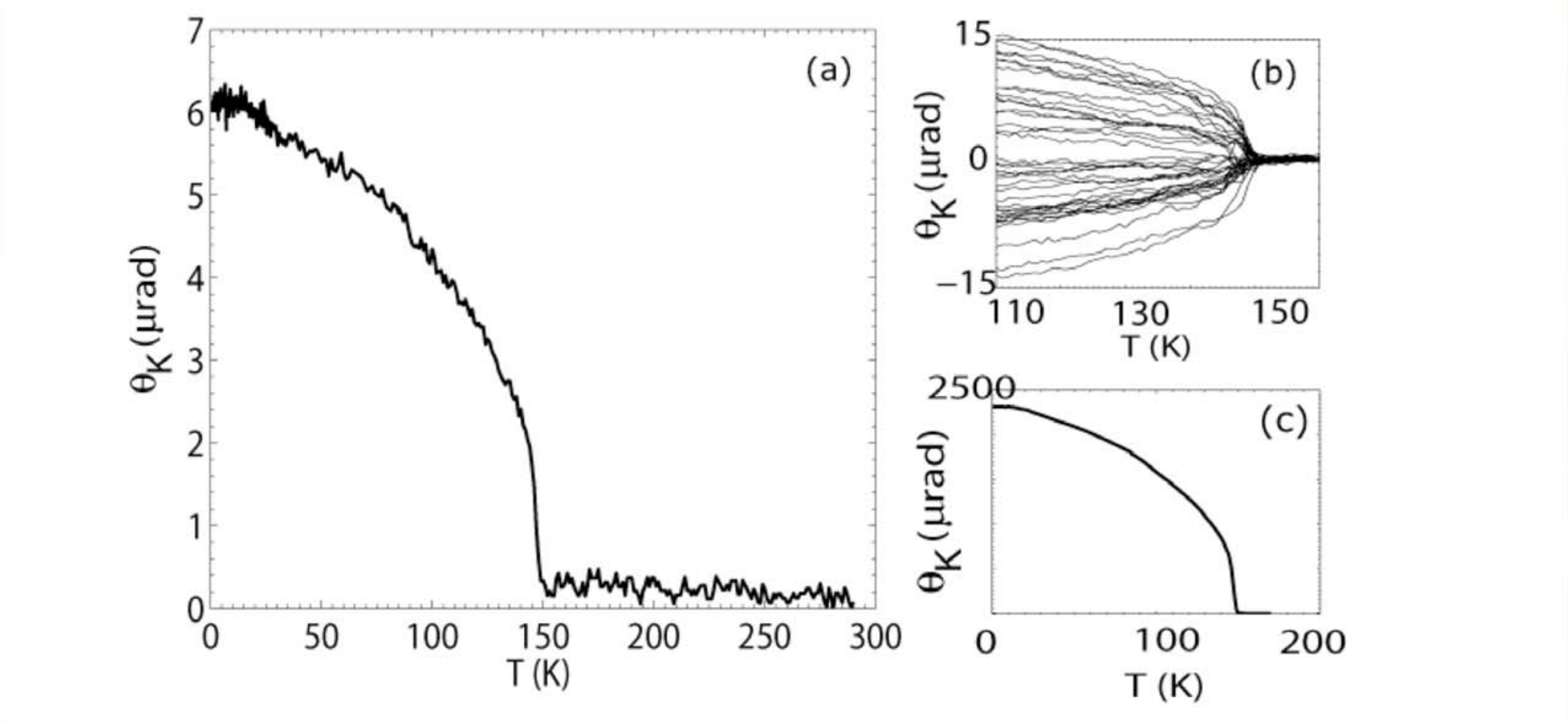
Fiber optics

Magnetic field Shielding

Sample holder

Optics Rack

Kerr effect measurements of ferromagnetic Transition in $SrRuO_3$

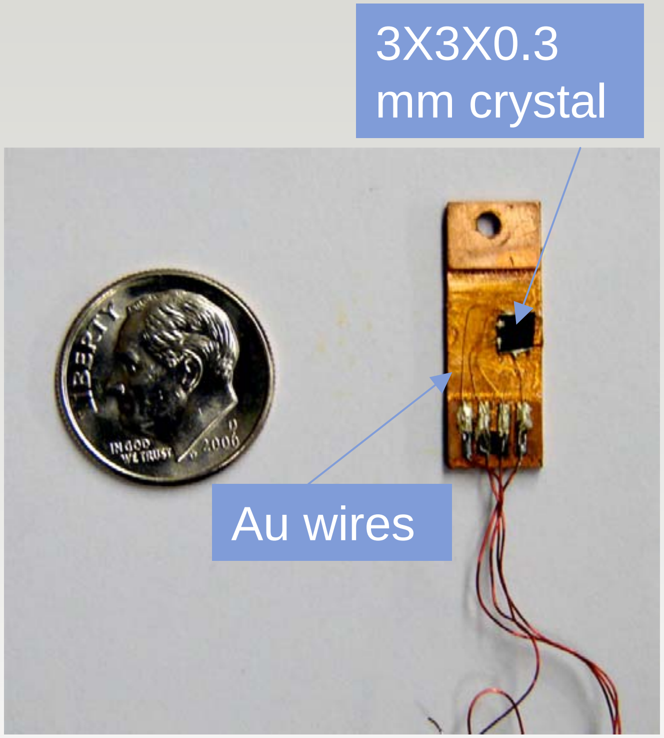


Polar Kerr effect from a 30 nm $SrRuO_3$ thin film. (a) Kerr rotation in zero magnetic field with temperature down to 0.5 K. (b) Kerr rotations of the same sample measured in different cool-downs in zero fields. (c) Kerr rotation in a saturation field of 200 Oe.

Jing Xia, Peter Beyersdorf, M. M. Fejer, and A. Kapitulnik. Appl. Phys. Lett. 89, 062508

Kerr effect measurements of:

Sr_2RuO_4

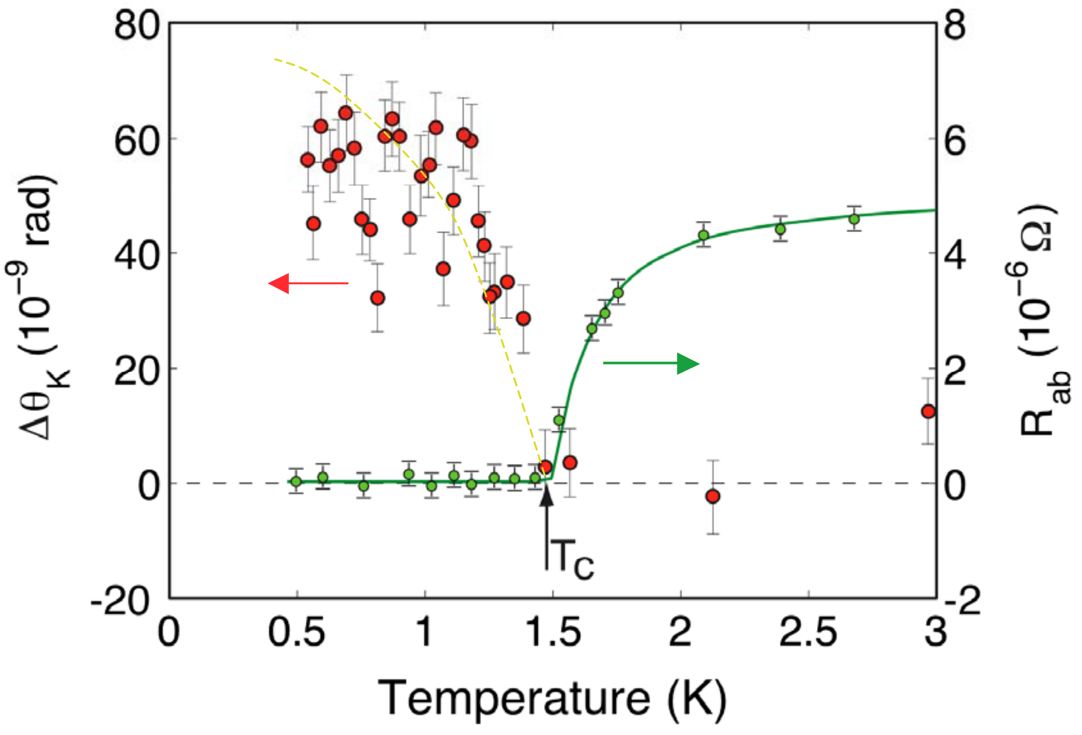


Beam size = 10 – 20 μm

Incident optical power = 0.7÷6 μW

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

Zero field cool



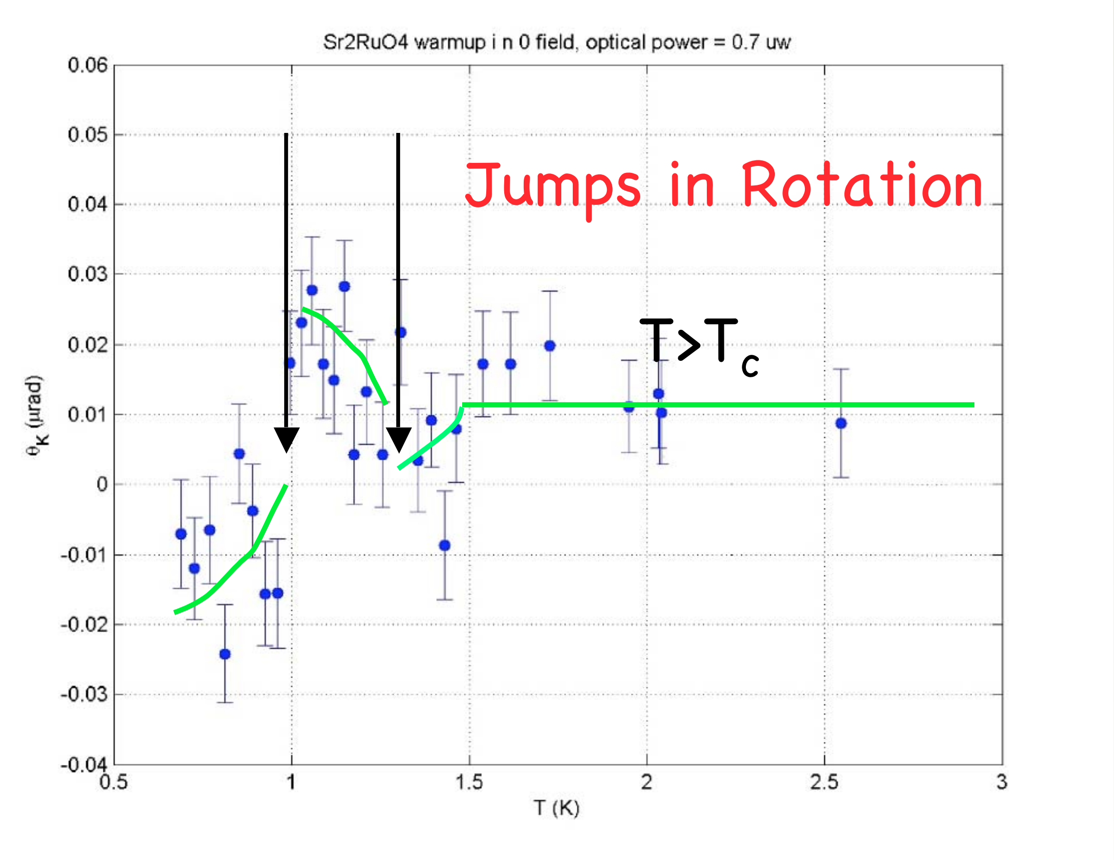
Beam size = 15-20 μm

Incident power =0.7÷ 2 μW

Sign of zero-field-cool data is random

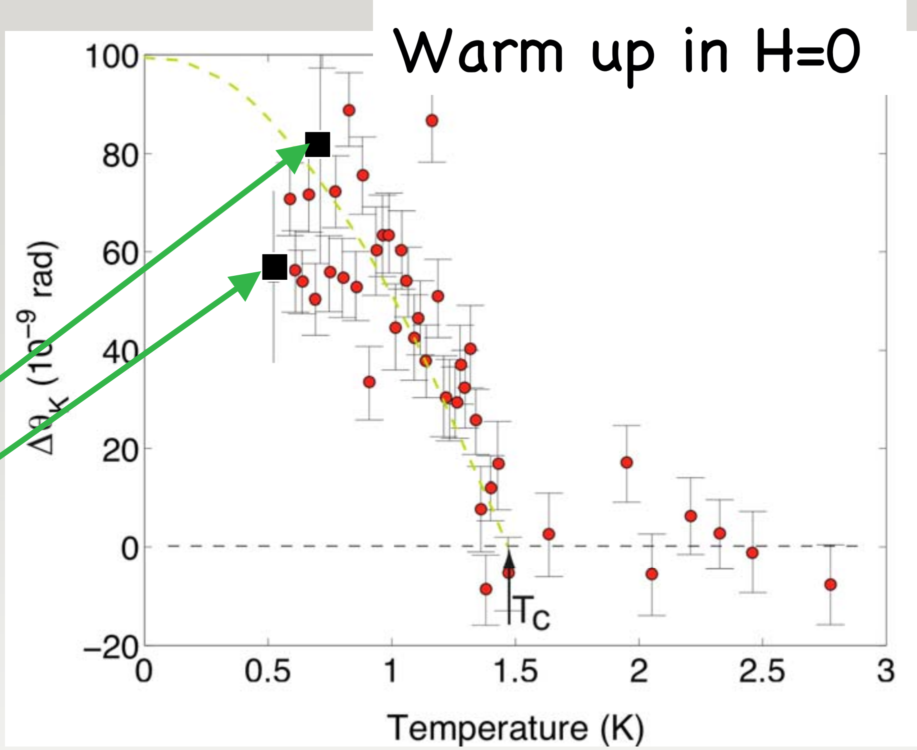
Maximum Kerr rotation of zero-field-cool ~ 65 nanorad

Some zero field cool change sign



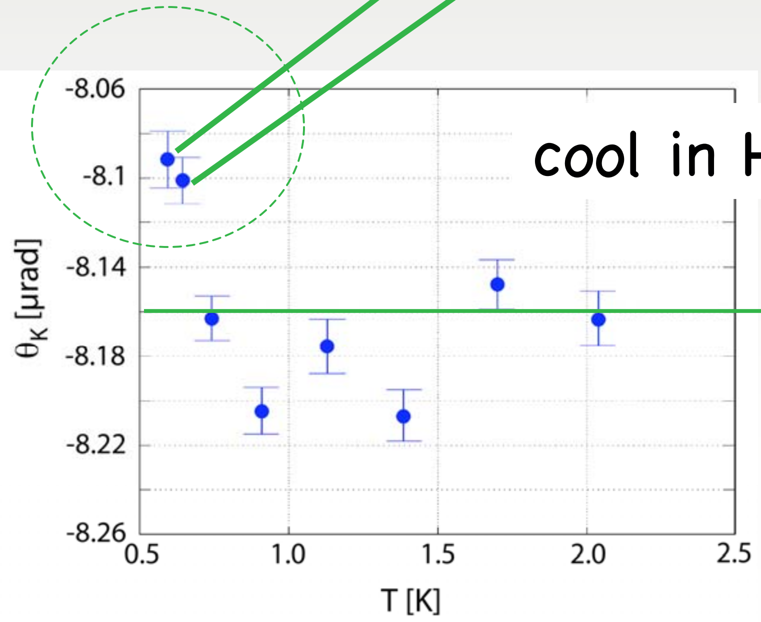
Variation of sign with successive cooldown, and change of sign suggest that domain size is of order of beam size.

Train the chirality with magnetic field:



Warm up in H=0

Last two points before field switched to zero.



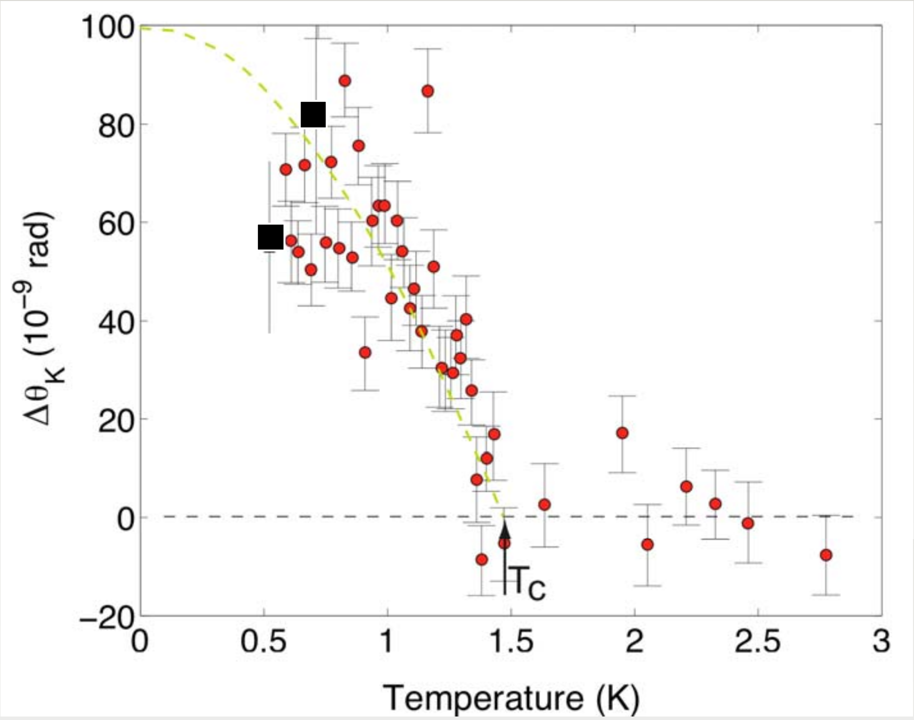
cool in H=+97 Oe

Diamagnetic response of fiber & 1/4 waveplate

Train the chirality with magnetic field:

cool in H=+97 Oe

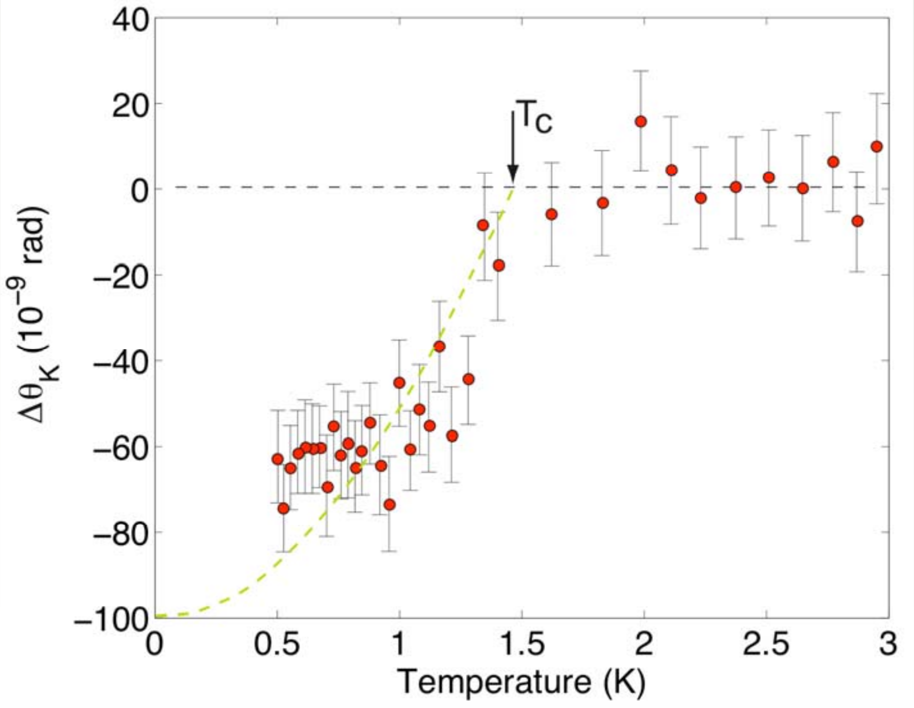
Warm up in H=0



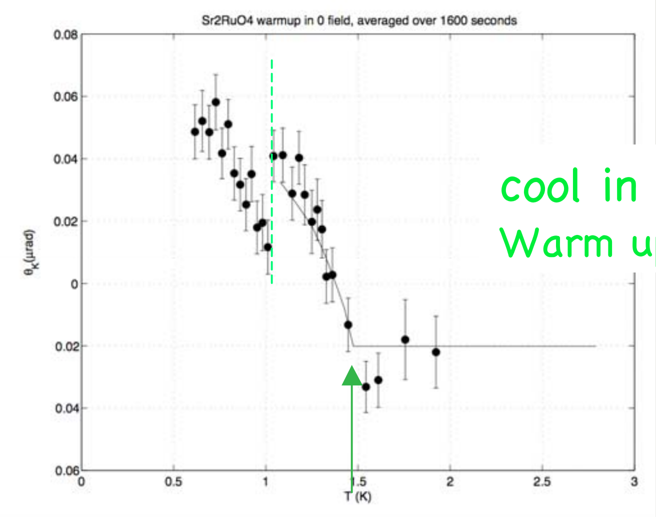
Dashed lines are guide to the eye

cool in H=-47 Oe

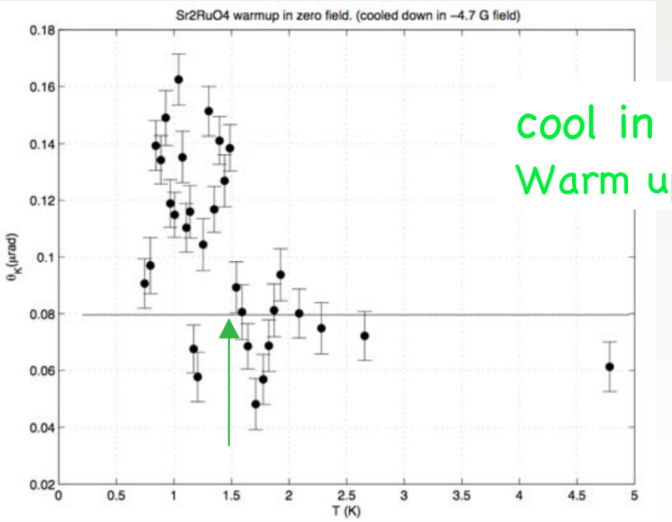
Warm up in H=0



Minimum training field



cool in +4.7 Oe
Warm up in H=0



cool in -4.7 Oe
Warm up in H=0

Fields below ~ 5 Oe do not affect the sign of the chirality.

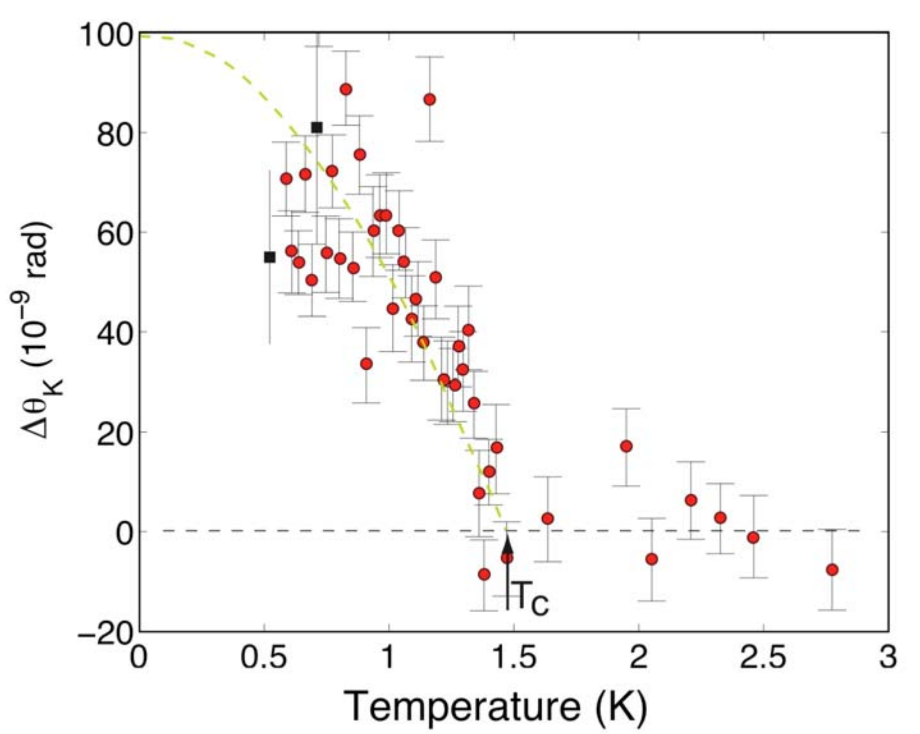
A minimum field between 5 Oe and 10 Oe* is needed to train the sign of the chirality.

* Note that H_{c1} ~ 7÷10 Oe

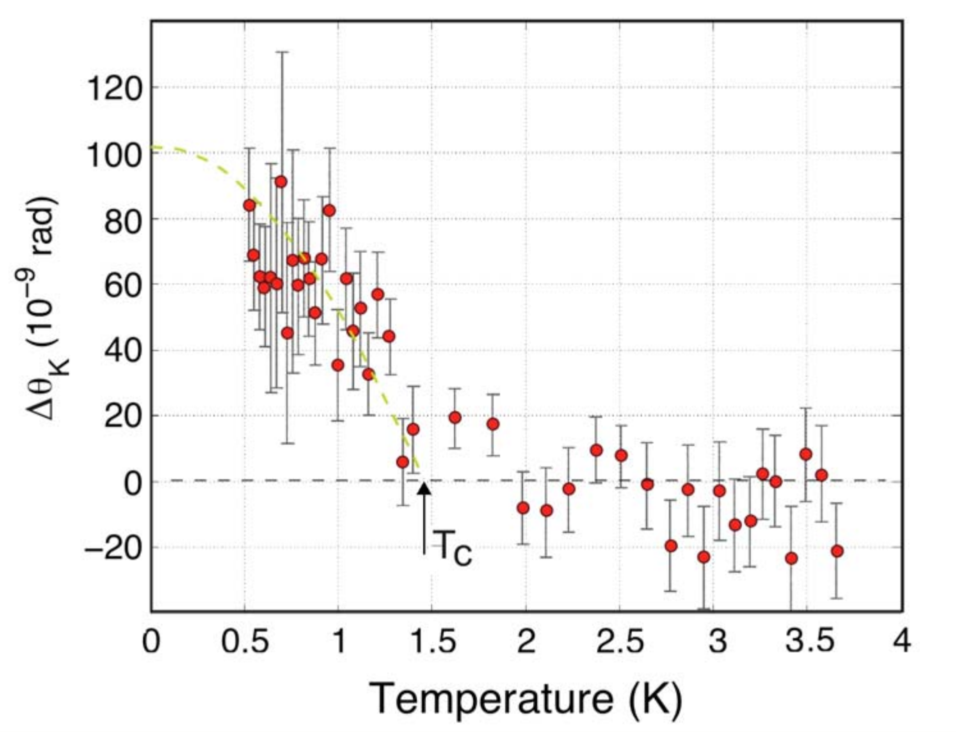
Dependence on incidence power

cool in H=+97 Oe, Warm up in zero field

Incident power = 0.7 μW

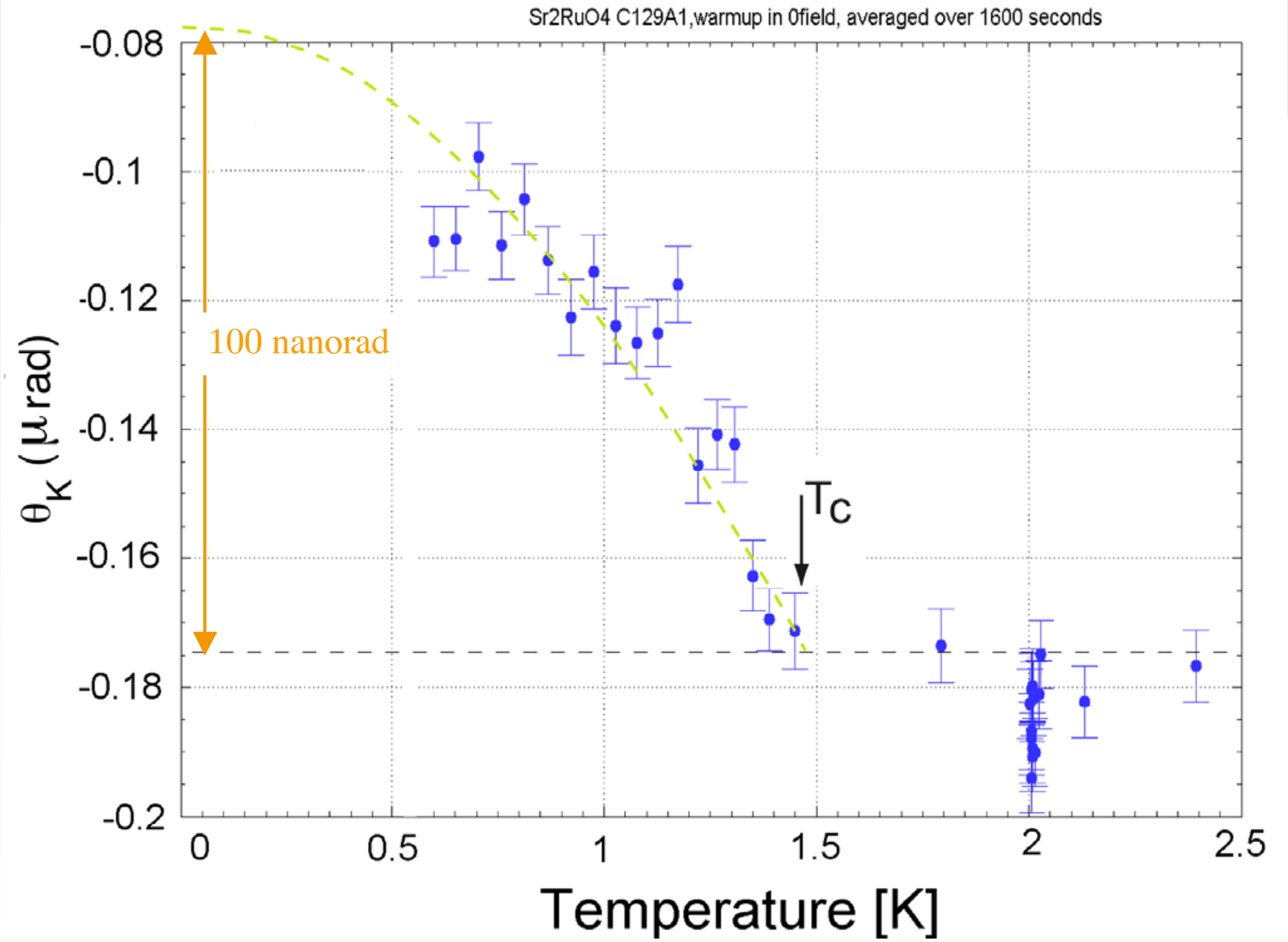


Incident power = 6 μW



No power dependence!

More on temperature dependence



Measurements are consistent with $\theta_K \propto \Delta_0^2$

Some theory:

Victor Yakovenko, Phys. Rev. Lett. 98, 087003 (2007)

Start with the lagrangian:

$$L = \begin{pmatrix} i\partial_t + \nabla^2/2m + \mu & i(\nabla \cdot \Psi + \Psi \cdot \nabla)/2 \\ i(\nabla \cdot \Psi^* + \Psi^* \cdot \nabla)/2 & i\partial_t - \nabla^2/2m - \mu \end{pmatrix}$$

where: $\Psi = \Delta_x \hat{x} + i\Delta_y \hat{y}$

Calculate the off-diagonal part of the conductivity:

$$\theta_K = \frac{2\pi}{\tilde{n}(\tilde{n}^2 - 1)} \frac{e^2}{d} \frac{\Delta^2}{(\hbar\omega)^3}$$

Estimate: $\theta_K \approx 5 \times 10^{-8} \frac{\Delta^2}{(k_B T_c)^2} \approx 200 \ \ \text{nanorad}$

More theory:

Vladimir Mineev, arXiv:cond-mat/0703624

Using phenomenological two-fluid model we derive the Kerr rotation of the polarization direction of reflected light from the surface of a superconductor in a state breaking time-reversal symmetry. We argue that this effect found recently in superconducting state of Sr_2RuO_4 by Xia et al (Phys.Rev.Lett. 97, 167002 (2006)) originates from the spontaneous magnetization in this superconductor.

$$\theta_K \approx \overbrace{\frac{e^2 k_F}{\pi\hbar\omega}\frac{\Delta^2}{(\hbar\omega_p)^2}}^{\text{Chiral state}} - \overbrace{\cancel{\frac{n_n}{n\omega\tau}\frac{eH_s}{mc\omega}}}^{\text{Vortex contribution}} \quad \text{negligible}$$

Estimate: $$\theta_K \approx 2\times 10^{-8}\frac{\Delta^2}{(k_B T_c)^2} \approx 80 \ \ \text{nanorad}$$

A comment:

The equation for the transverse current is:

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

Both Yakovenko and Mineev neglect the second term as being ineffective at high frequencies.

The derivation requires to find the equation of motion to the superconducting phase and φ substitute it in the above equation for the current. This may lead to: $\vec{j} = 0$

However*:

The beam of light IS NOT a plane wave. It is of finite size with a gaussian profile and thus includes electric field gradients. This leads to a finite effect, of the same order as before that now depends on the size of the beam:

$$\theta_K \approx \theta_K^0 \times C \times \left(\frac{\lambda}{d_{beam}}\right)^2$$

* R. Lutchyn and V. Yakovenko, preprint of preprint

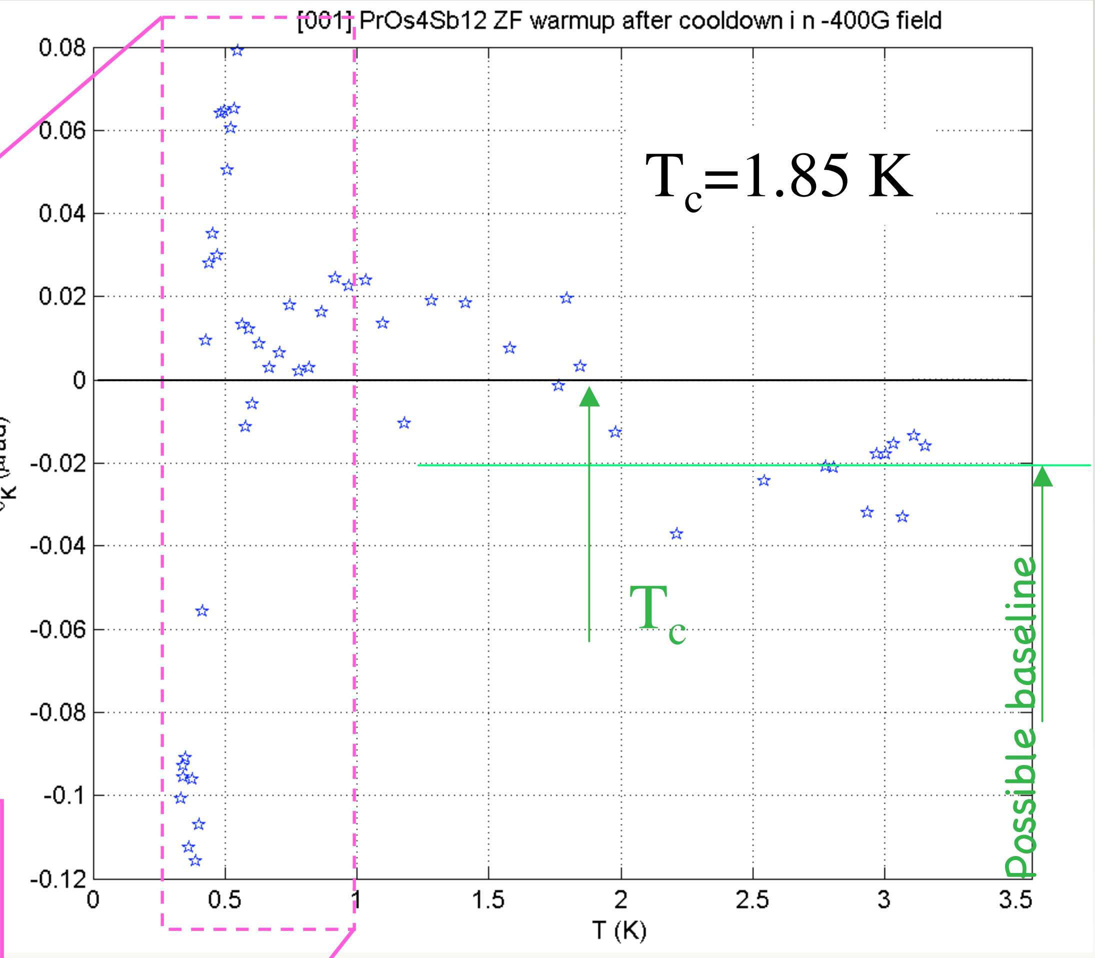
Summary of observations:

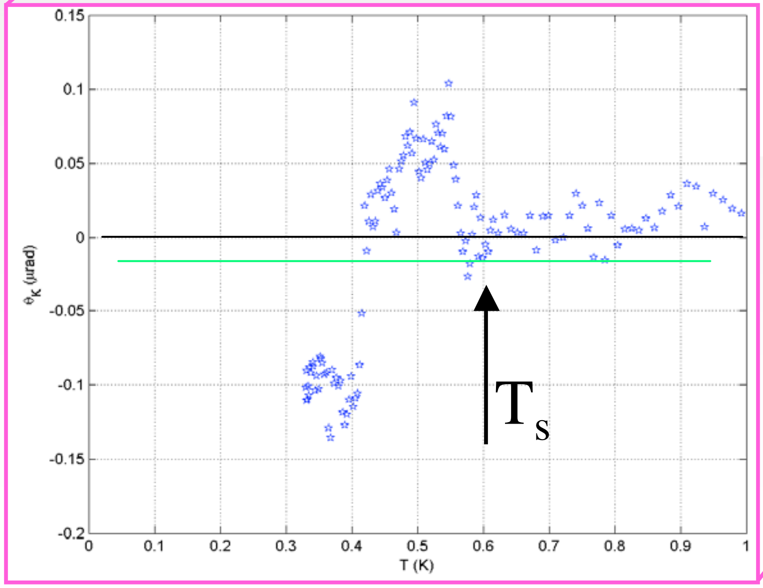
- Maximum signal is ~65 ÷ 100 nanorad
- Signal onsets at T_C
- Temperature dependence of signal can be fitted with a quadratic dependence on the gap.
- Chirality can be trained with a magnetic field.
  - A minimum field is needed.
- Domain size is large, of order beam size $>20\ \mu m$
  - Zero-field cool show some fluctuations
- Signal cannot be explained by trapped flux
  - max. zero-field cool signal equals field cool
- There is no Light-power dependence on the size of the signal (no heating effect).

$PrOs_4Sb_{12}$

Cool down in -400 Oe
Then
Turn field
to zero

Measure on
Warming up
From 0.3 K





While it is not clear if we see a signal below T_c, there is a clear signal below $T_s \approx 0.6$ K

Evidence for a phase transition at 0.6 K.

T. Cichorek, A. C. Mota, F. Steglich, N. A. Frederick,
W. M. Yuhasz, M. B. Maple
PRL 94, 107002 (2005)