Time-reversal asymmetry without magnetic moments via Directional Scalar Spin Chiral Order

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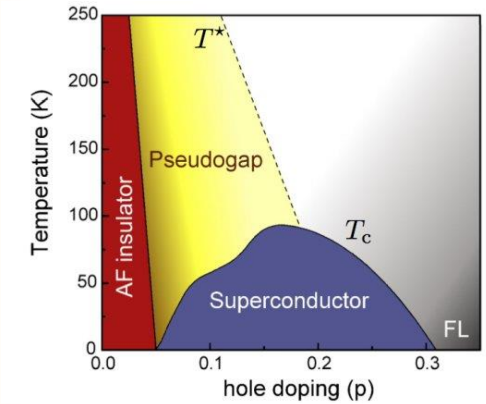
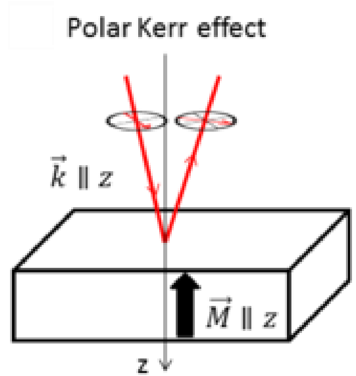
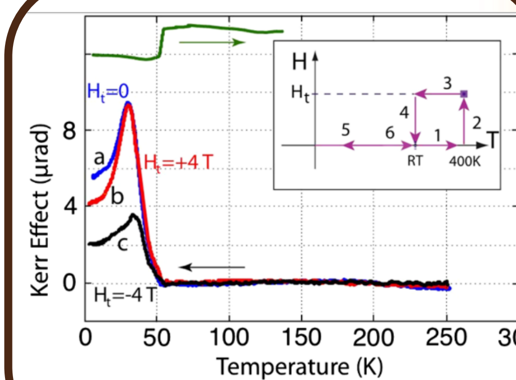
Acknowledgements:
Steve Kivelson
Srinivas Raghu
…others

Inspiration: Kerr effect and NMR in cuprate pseudogap





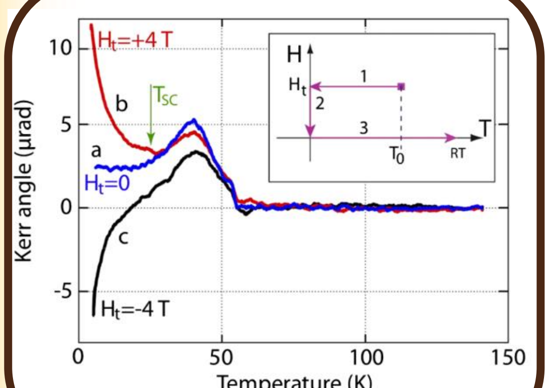
Hysteresis above T_K



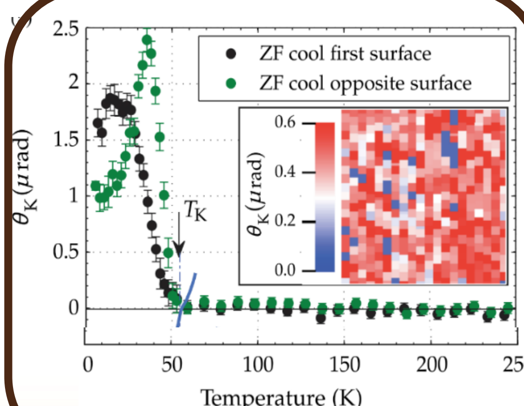
Karpetyan *et. al.*, PRL '12

Untrainable by ***B***

Same sign on flipping



Karpetyan *et. al.*, PRL '12



Karpetyan *et. al.*, PRL '14

No magnetism seen in NMR!

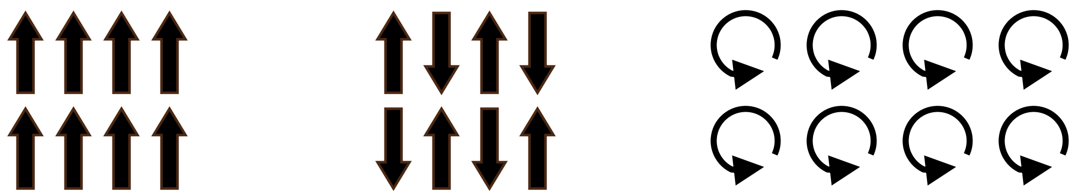
Wu *et. al.*, Nat. Comm. '15

Usually, Kerr effect = ferromag.
Strictly, Kerr effect = T-breaking

Goal: T-breaking phase without moments

- Invariably, T-breaking ground states contain a set of total angular momentum operators J_i such that $\sum_i \langle J_i \rangle$ is extensive

  E.g. ferromagnets, antiferromagnets, chiral phases…



- Melting these moments restores T-symmetry
- Thus, T-breaking usually = magnetism

Q: Can we find exceptions?

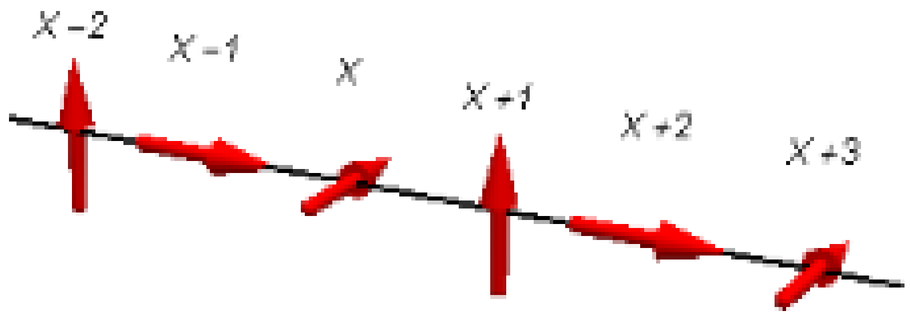
A: Directional scalar spin chiral order (*this talk*)

Directional scalar spin chiral order (DSSCO) in 1D

$$\Phi = \sum_{\boldsymbol{r}} \langle \boldsymbol{S}(\boldsymbol{r} - \hat{\mathbf{x}}) \cdot \boldsymbol{S}(\boldsymbol{r}) \times \boldsymbol{S}(\boldsymbol{r} + \hat{\mathbf{x}}) \rangle$$

$$\Phi \xrightarrow{\text{Time-reversal}} -\Phi$$

$$\Phi \xrightarrow{\text{Spin-rotation}} \Phi$$

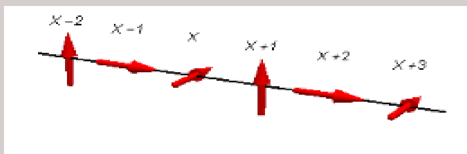
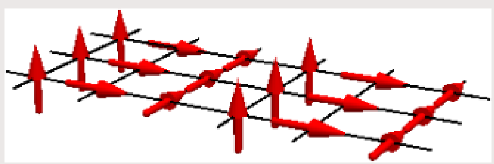
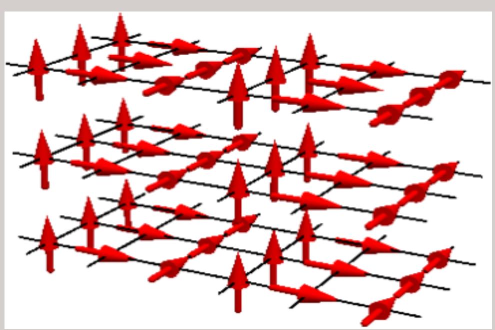


Key idea: Melt continuous symmetries with fluctuations, preserve discrete symmetry breaking. Φ breaks discrete symmetries, so…

Time-reversal violation without moments, but with spin chirality!

Directional scalar spin chiral order (DSSCO) in 1D, 2D, 3D

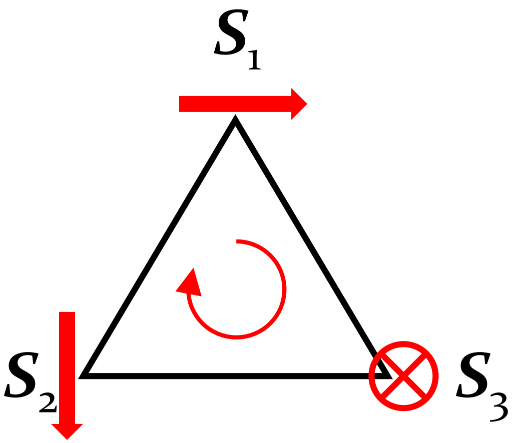
$$\Phi = \sum_{\boldsymbol{r}} \langle \boldsymbol{S}(\boldsymbol{r}-\hat{\mathbf{x}}) \cdot \boldsymbol{S}(\boldsymbol{r}) \times \boldsymbol{S}(\boldsymbol{r}+\hat{\mathbf{x}}) \rangle$$

	Classical magnetic order	**Conditions for DSSCO**	$\langle S \rangle = 0$ **due to**
1D		$T = 0$, clean	Mermin-Wagner (quantum fluctuations)
2D		$T \neq 0$, clean	Mermin-Wagner (thermal flcutuations)
3D		Any T, field disorder	Imry-Ma (disorder-driven fluctuations)

Contrast with other scalar spin chiral phases

Other phases

Chiral ordered spins on triangle;
⇦ moment allowed by symmetry

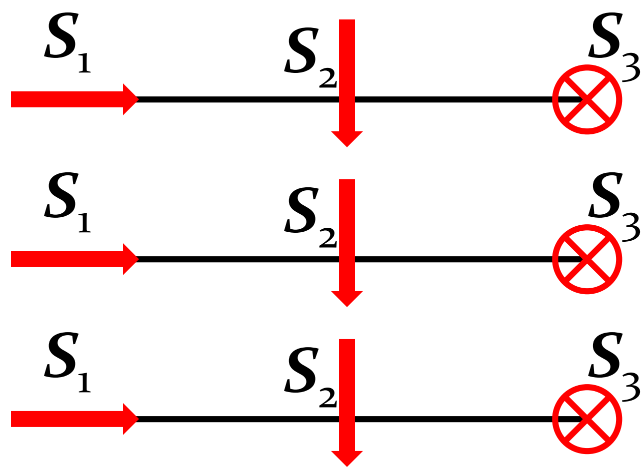


Flux thru ⇆ ◂ 🡐S_1↙S_2 ← S_3

Eg. Grohol, Nat. Mat. '05, Lee, PRB '13 etc.

DSSCO

Chiral ordered spins in a line;
moment forbidden by symmetry



Hamiltonian guesses

- S > ½

$$H_{1D} = \sum_x K_1 \left(\boldsymbol{S}_x \cdot \boldsymbol{S}_{x+1}\right)^2 + K_2 \left(\boldsymbol{S}_x \cdot \boldsymbol{S}_{x+2}\right)^2 - J \left(\boldsymbol{S}_x \cdot \boldsymbol{S}_{x+3}\right)$$

- S = ½

$$H_{1D} = \sum_x J \left(\boldsymbol{S}_x \cdot \boldsymbol{S}_{x+1}\right) - g \left(\boldsymbol{S}_{x-1} \cdot \boldsymbol{S}_x \times \boldsymbol{S}_{x+1}\right)^2$$

$$\rightarrow \int_x K(\partial_x \phi)^2 + (\partial_x \theta)^2/K - g\Phi(\partial_x\phi)(\partial_x\theta)$$

$$S_+ \sim e^{i\theta}$$

$$S_z \sim \partial_x \phi$$

$$K = 2\sqrt{1-(g\Phi)^2}$$

K = 2 for SU(2)-sym without Φ

… and ferromagnetic couplings in transverse directions

arXiv:1510.00975

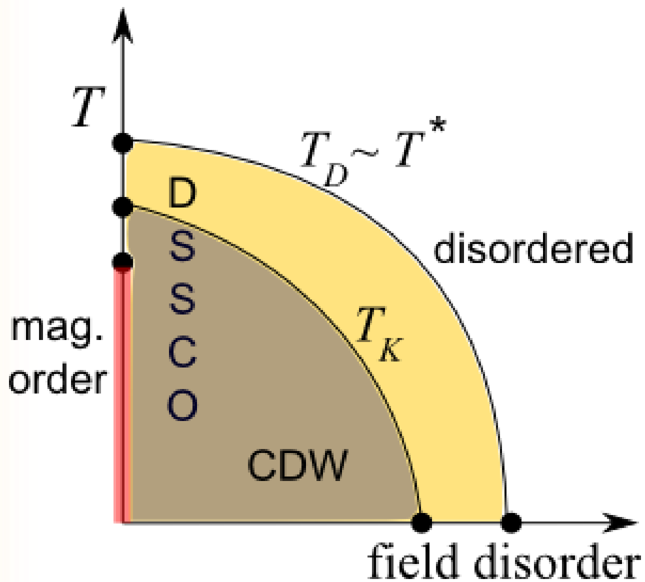
Kerr and other experiments in cuprates

1. Kerr:
    1. Untrainable by magnetic field
    2. Same sign on both surfaces
    3. Memory above T_K
    4. Small magnitude
2. NMR: no magnetism below T_K
3. X-rays: charge ordering tendencies onset at T_K
4. Nernst effect: nematicity above T_K
5. Transmission: vertical reflection breaking below T_K

How to reconcile?

arXiv:1510.00975

Plausible phase diagram including DSSCO



Assume CDW breaks reflections, preserves flipping

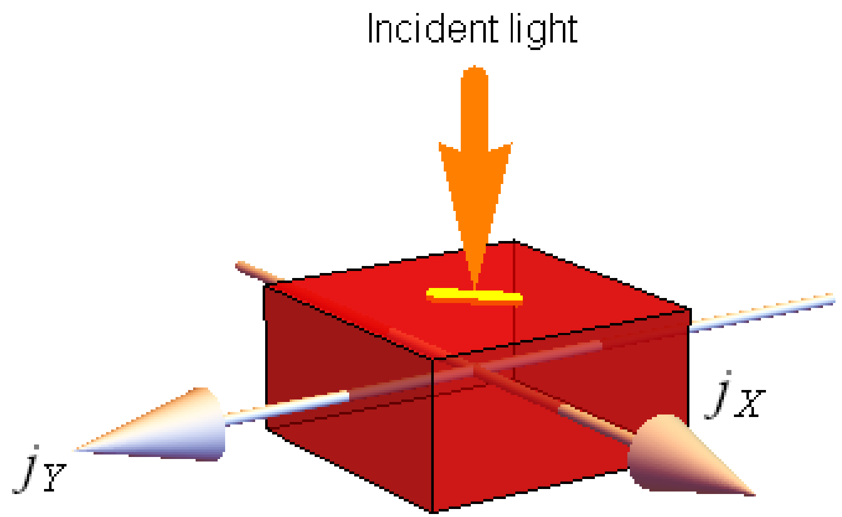
1. Kerr:
   i. Untrainable by magnetic field ✓
   ii. Same sign on both surfaces ✓
   iii. Memory above T_K ✓
   iv. Small magnitude ✓
2. NMR: no magnetism below T_K ↩
3. X-rays: charge ordering tendencies onset at T_K ✓ ✓
4. Nernst effect: nematicity above T_K ✓
5. Transmission: vertical reflection breaking below T_K ✓

	TRS	M_x	M_y	M_z	R_x^2	R_y^2	R_z^2	θ_{Kerr}
DSSCO only	×	×	✓	✓	✓	×	×	$= 0$
DSSCO + CDW	×	×	×	×	✓	×	×	$\neq 0$

arXiv:1510.00975

Probing the 3D DSSCO

For chiral ordering along X, j_Y should produce a polar Kerr effect trainable by it, but j_X should not



	TRS	M_x	M_y	M_z	R_x^2	R_y^2	R_z^2	θ_{Kerr}
DSSCO only	×	×	✓	✓	✓	×	×	$= 0$
DSSCO + j_x	×	×	✓	✓	✓	×	×	$= 0$
DSSCO + j_y	×	×	×	✓	×	×	×	$\neq 0$

arXiv:1510.00975

Summary

- A new phase of matter, DSSCO, breaks time-reversal symmetry but has no (density of) moments
- Plausibly relevant to cuprate pseudogap experiments, especially Kerr and NMR; many experiments fit into a phenomenological phase diagram involving DSSCO

To do

- Iron out microscopics; test candidate Hamiltonians
- Search for other candidate materials
- Look for DSSCO in cuprates expt'ally – drive current and measure Kerr effect above T_K