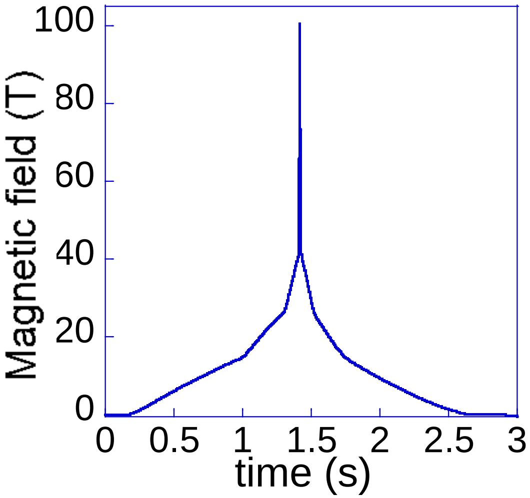
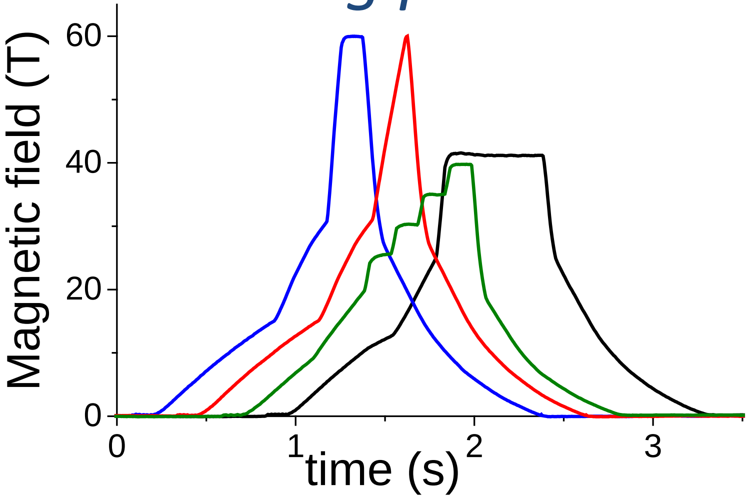
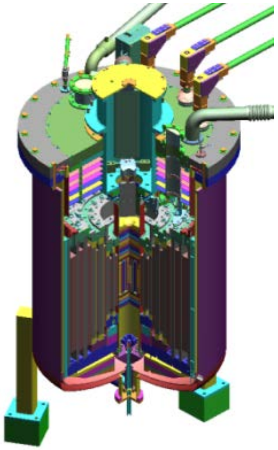
Los Alamos branch of the Magnet Lab Pulsed magnetic fields

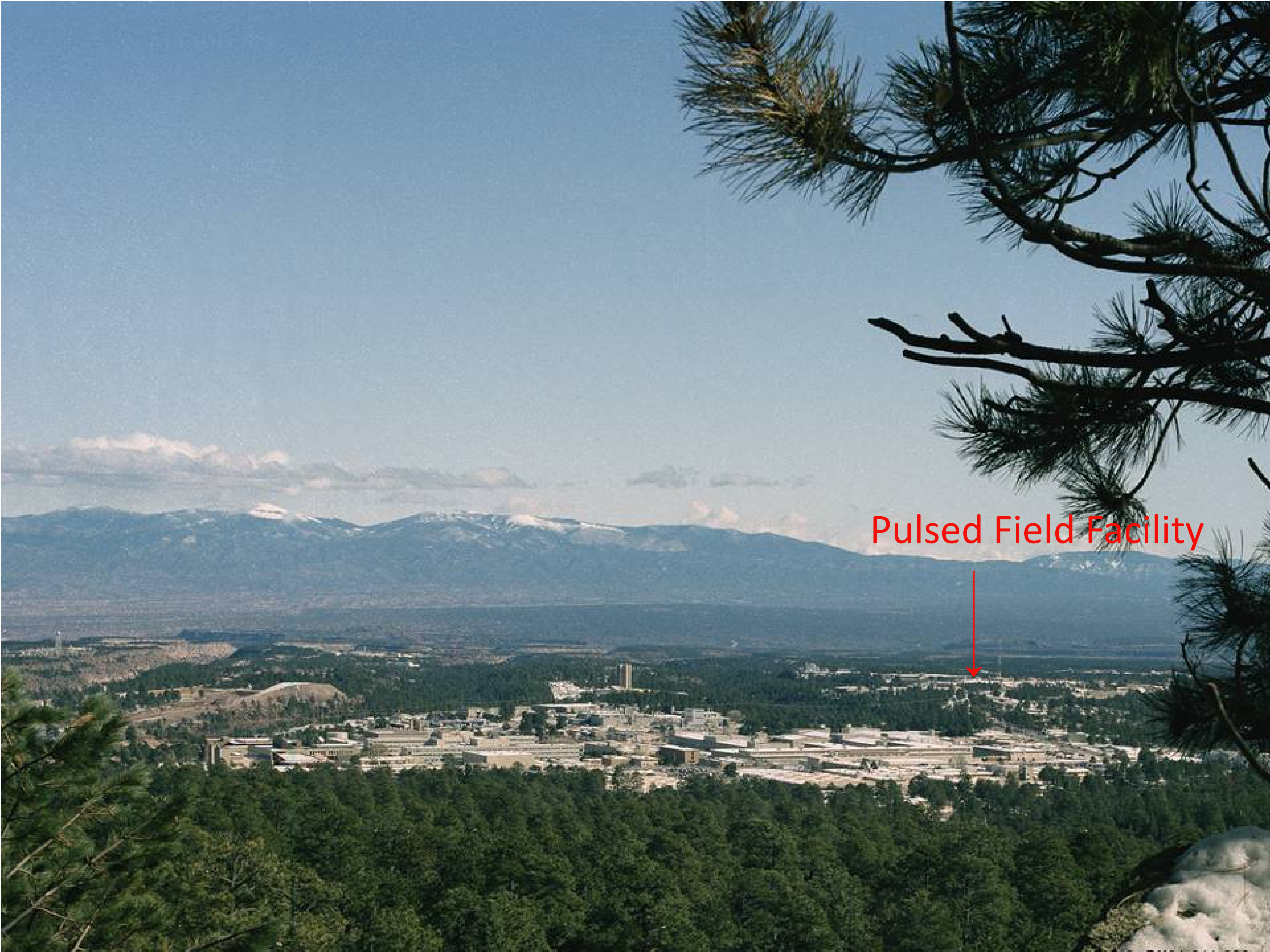
100 Tesla multishot



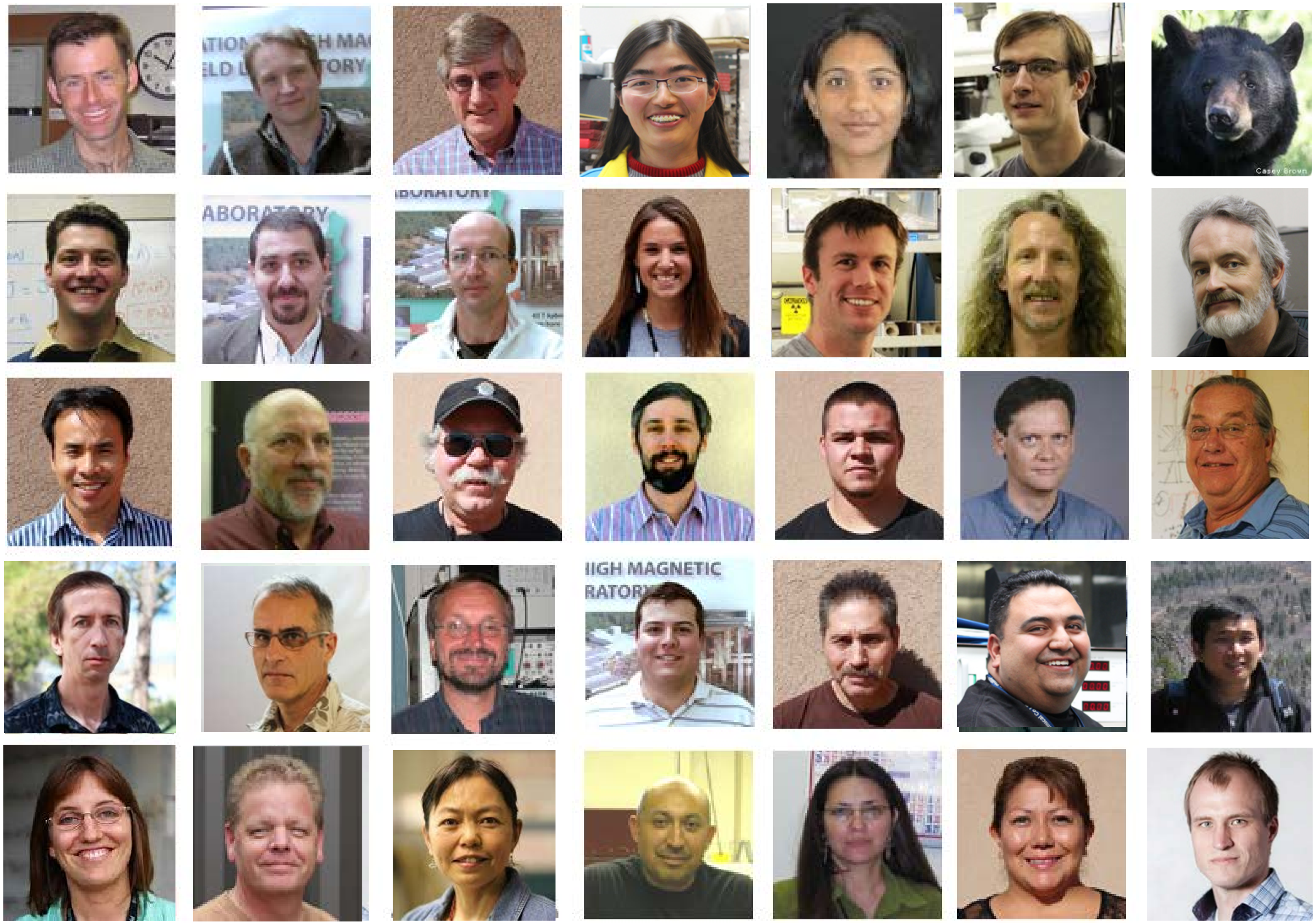
60 Tesla long pulse






Pulsed Field Facility

Magnet Lab Pulsed-Field facility: ~35 people
1/3 scientists, 1/3 engineers & technicians, 1/3 students & post-docs



Frustration and Functionality

Vivien Zapf

Magnet Lab, Pulsed Field Facility

Los Alamos National Lab

Spin liquid
~~*static order*~~

Order by disorder (Fluctuations)
Static order

Spin glass *Static quasi-order*

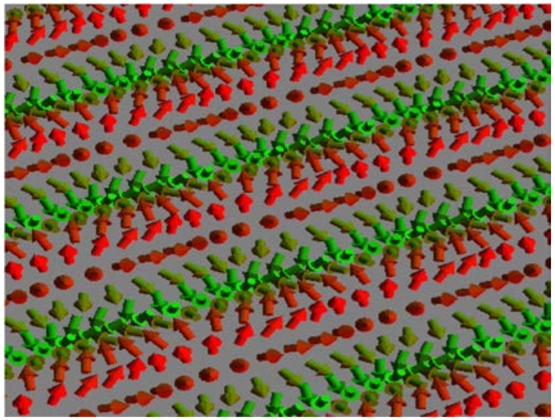
Lattice distortions lifting the frustration
Static order

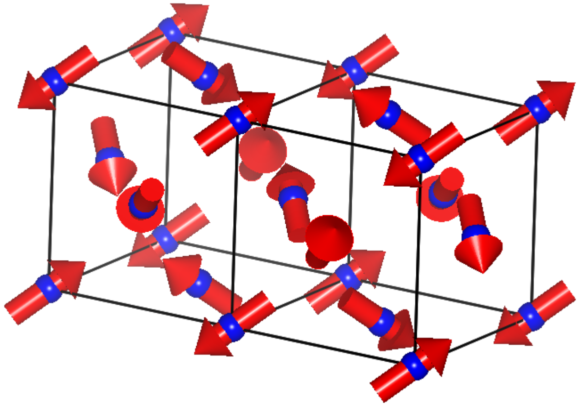
Partial frustration/ Competing interactions
Static order

Order by impurity
Static order

…

Static order near frustration: tends to complex spin textures





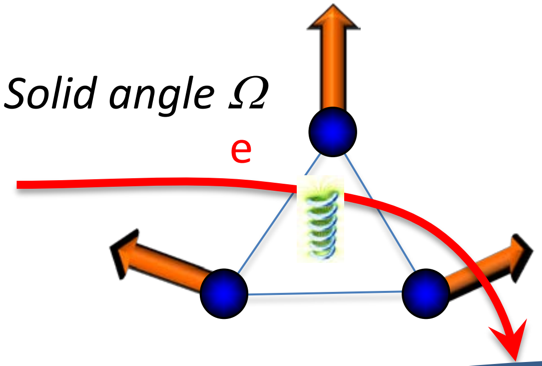
Noncolinear
Non-coplanar
Long-wavelength modulations
Spirals
Spatially segregated phases

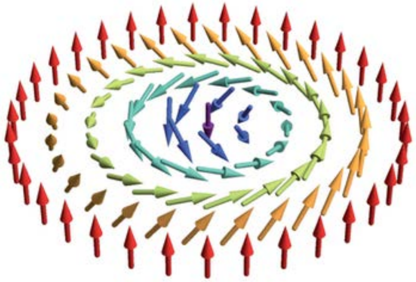
Frustrated spin systems :

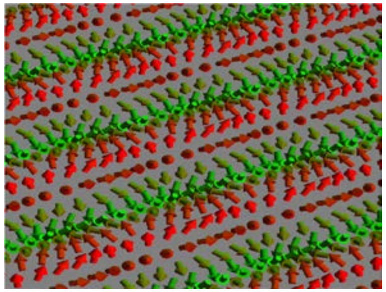
Complex spin textures -> broken symmetries

1. Chirality. Couple to electron transport *(*Hall effects)
e.g. Skyrmions or other spin textures with berry phases

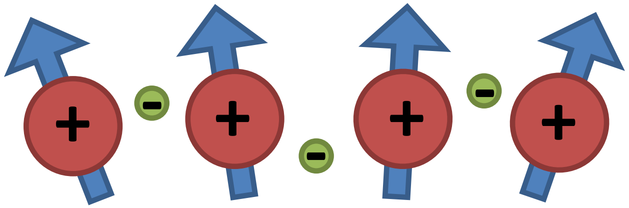
CONDUCTORS,
SEMICONDUCTORS







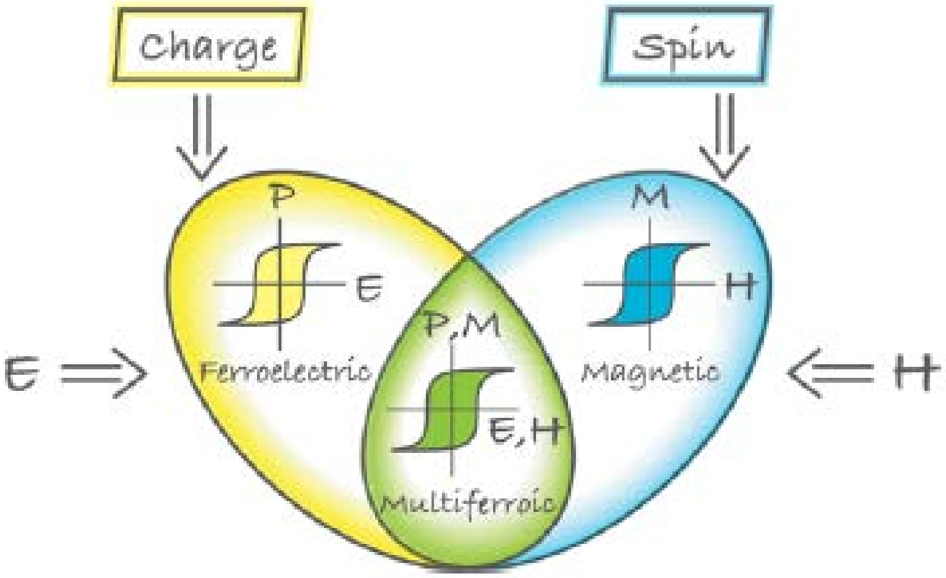
2. Broken mirror symmetry: (chirality is a subset)
Couple to Ferroelectricity



INSULATORS

3. ....

Multiferroics



D. Khomskii, Physics 2, 20 (2009)

Low power consumption
Voltages instead of currents

Record-sensitive magnetic sensors at low powers

Tunable filters, antennas, gyrators, etc.

Tunable microwave devices

Energy harvesting

Memory/smart devices

Electric manipulation of magnetic domain walls, topological objects, etc.

This talk

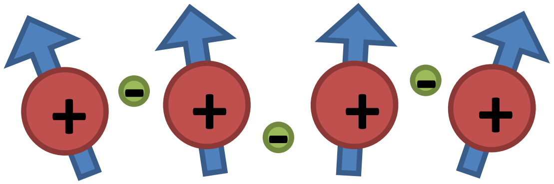
Nearly frustrated static order

Complexity, Broken symmetries

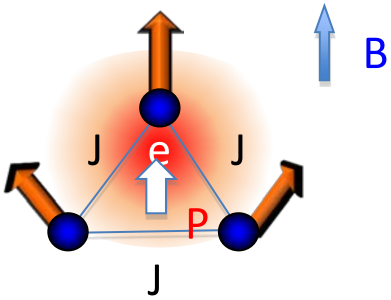
Coupling to ferroelectricity:

4 examples *Microscopic mechanisms*

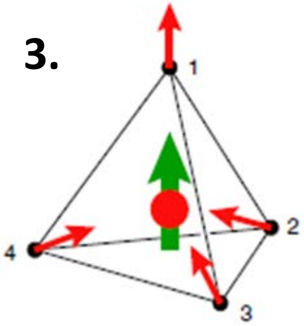
1.



2.



3.



4.

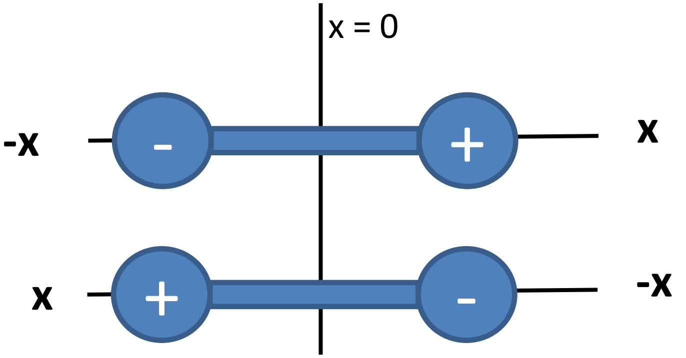
High magnetic fields and explosions

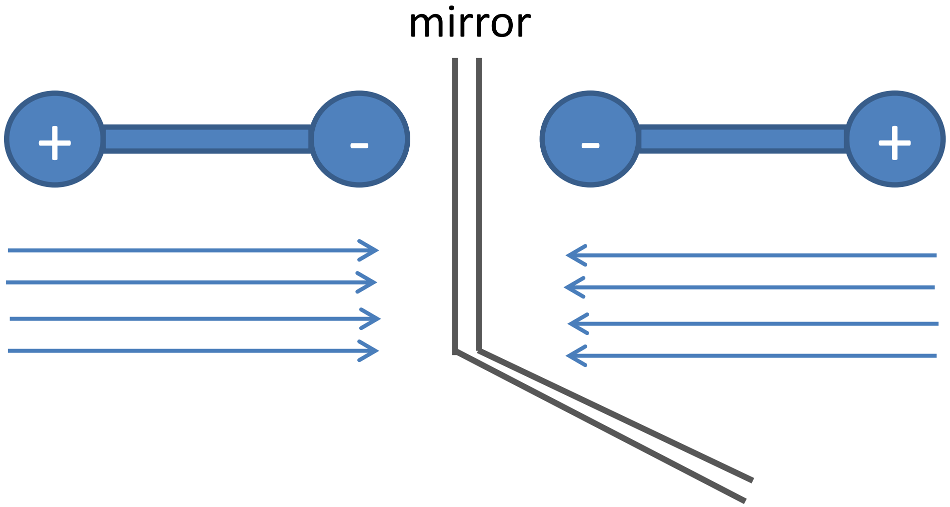
Electric fields break *mirror* symmetry (SIS)

A unique polar axis

Is there ***any*** choice of origin for which x -> -x conserves symmetry?

No: breaks spatial inversion symmetry

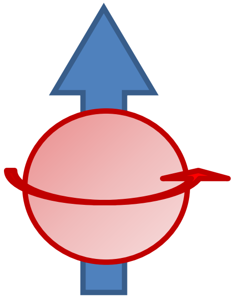




Frustrated spin systems :

Can I create a magnetic pattern that matches that of an electric field?

If so, I have a chance to create ferroelectricity



Cut the arrows

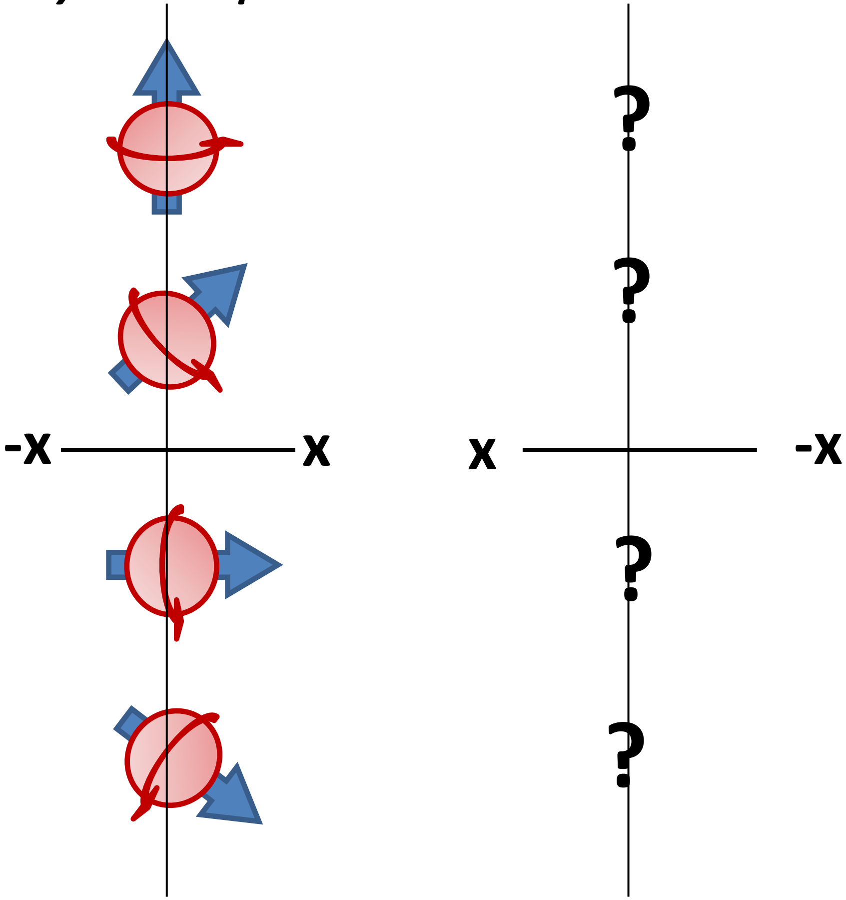
Sorted the arrows

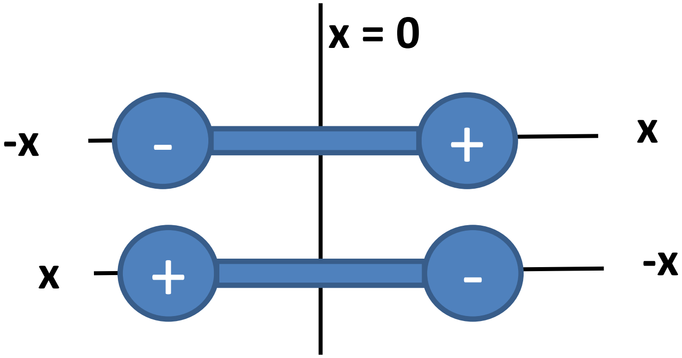
Frustrated spin systems :

Exercise:
Perform mirror inversion about x on this spiral

SIS = spatial inversion symmetry

Cycloidal spiral



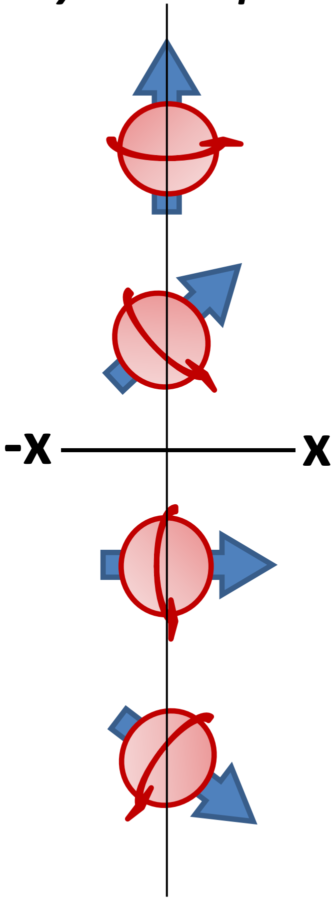


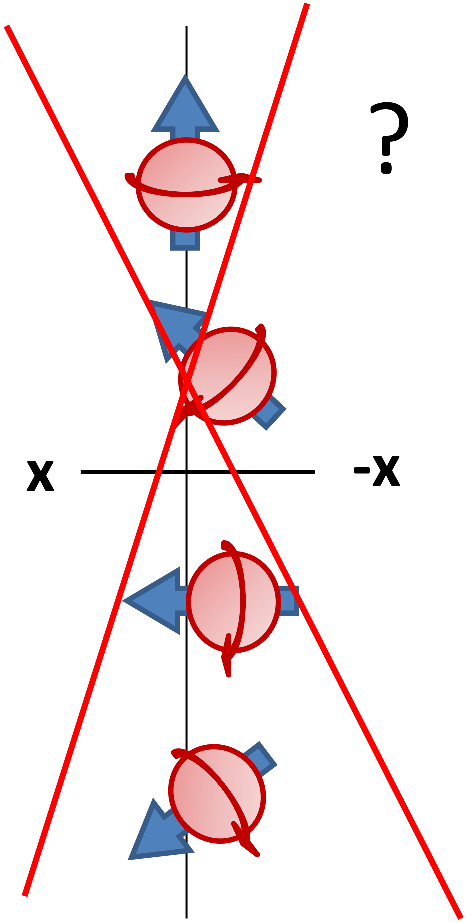
Frustrated spin systems :

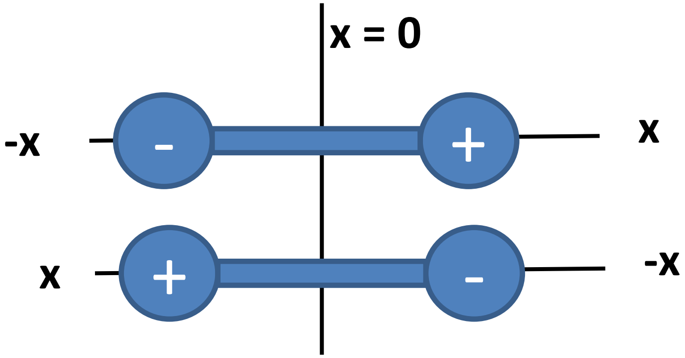
Exercise:
Perform mirror about x on this spiral

SIS = spatial inversion symmetry

Cycloidal spiral



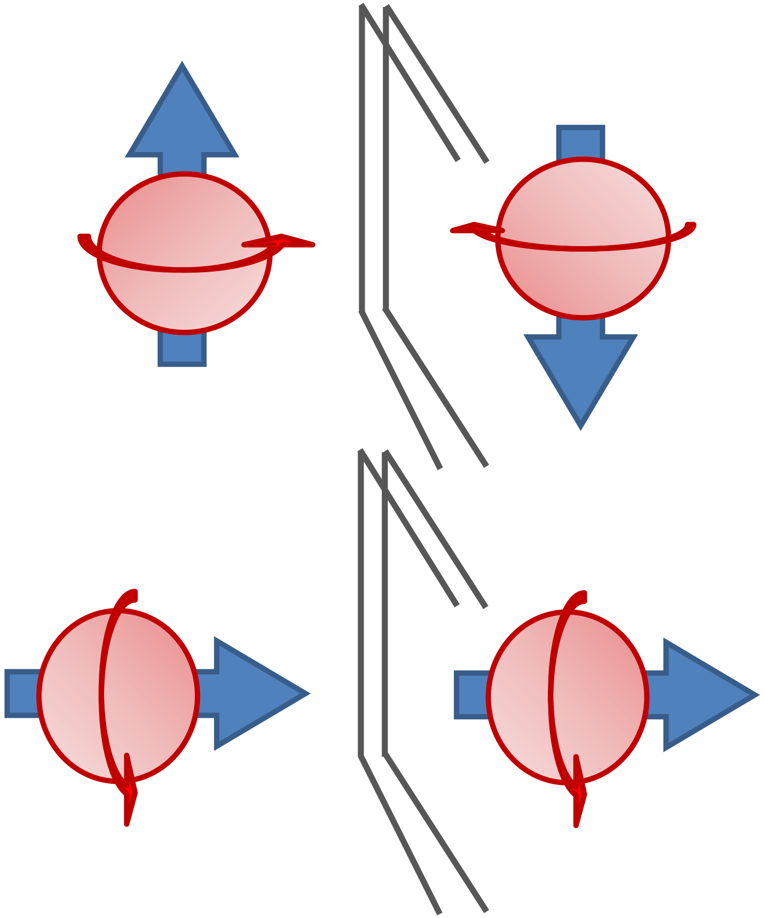


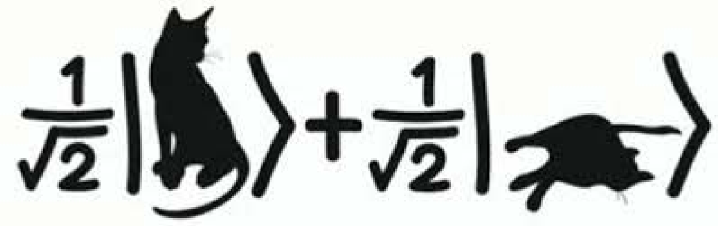


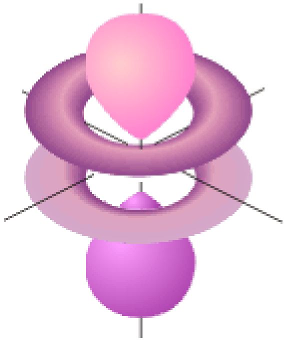
Frustrated spin systems :

“Spins are not arrows”

Spin transforms as a rotation

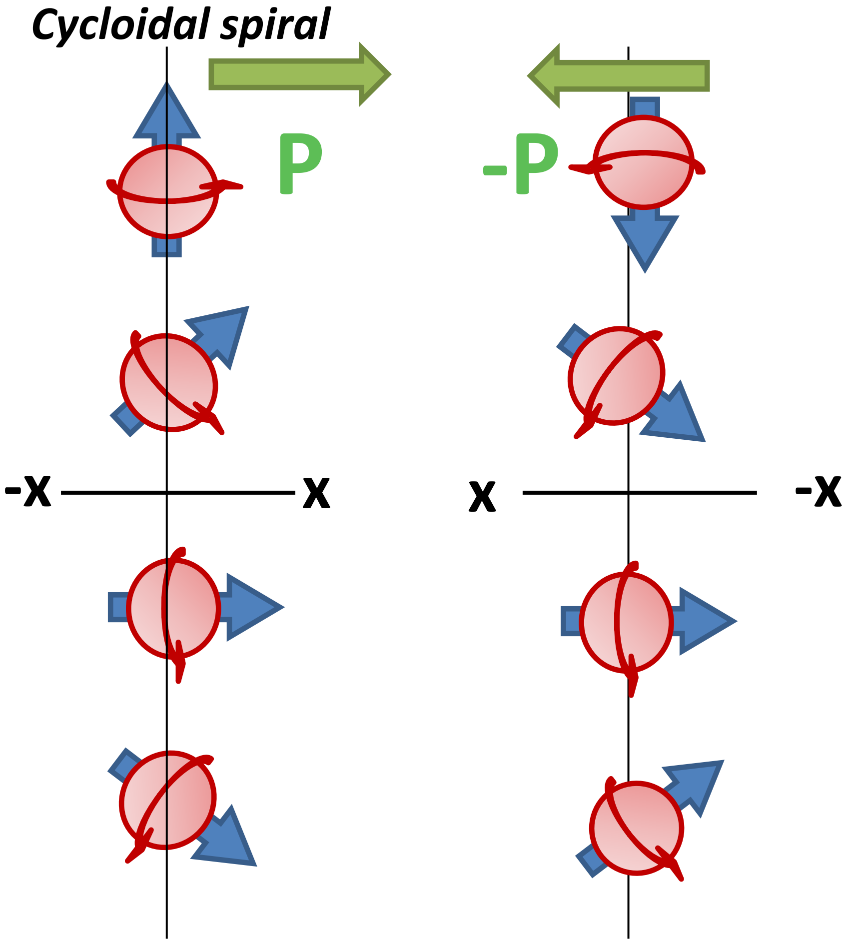






Frustrated spin systems :

Exercise (complete):
Perform mirror inversion about x on this spiral



Breaks spatial inversion about x

In the attempt to regain my original pattern, I'm allowed to translate the spiral because an electric FIELD (as opposed to a dipole) conserves translational symmetry.

Frustrated spin systems :

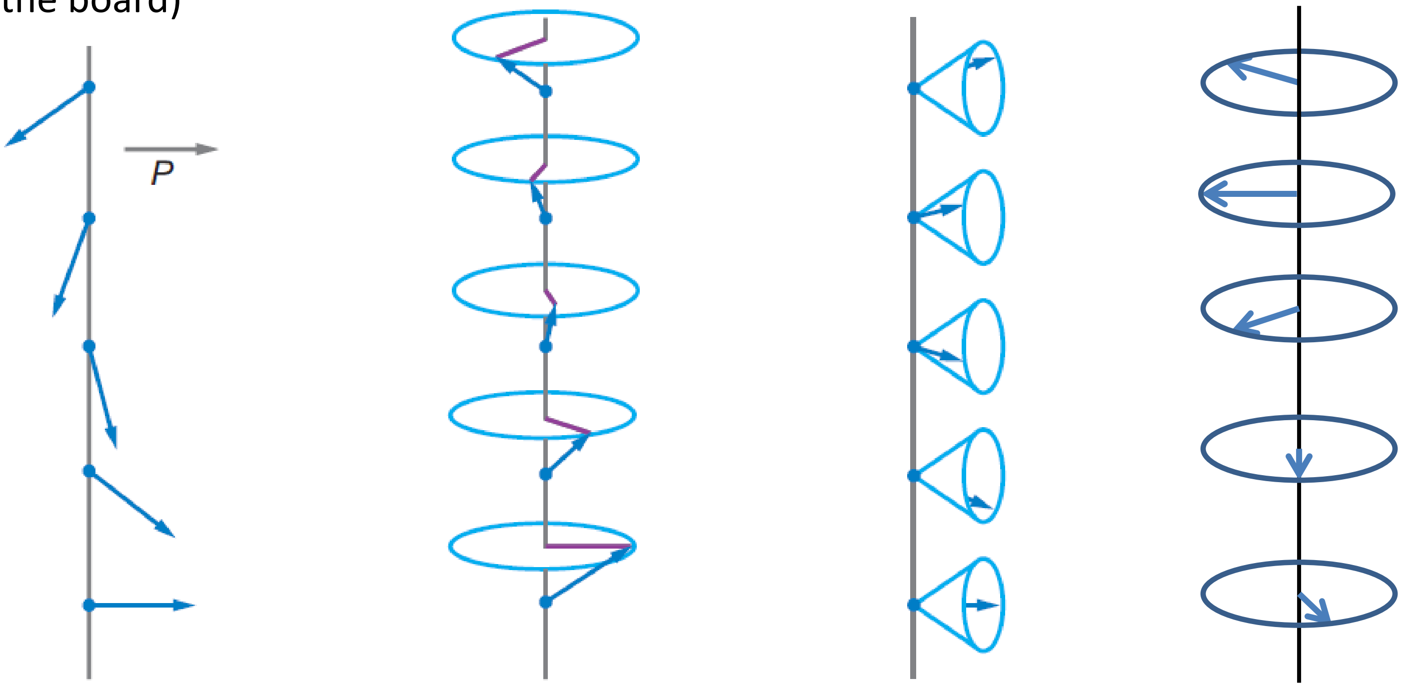
Some spirals that break mirror symmetry
CAN BE SPONTANEOUSLY GENERATED BY FRUSTRATION

Cycloidal
(spins are in the plane of the board)

Conical (I)

Conical (II)

Helical (with caveats)



T. Kimura, Annu. Rev. Mater. Res. 37, 387 (2007)

Frustrated spin systems :

Magnetoelectric materials with spirals

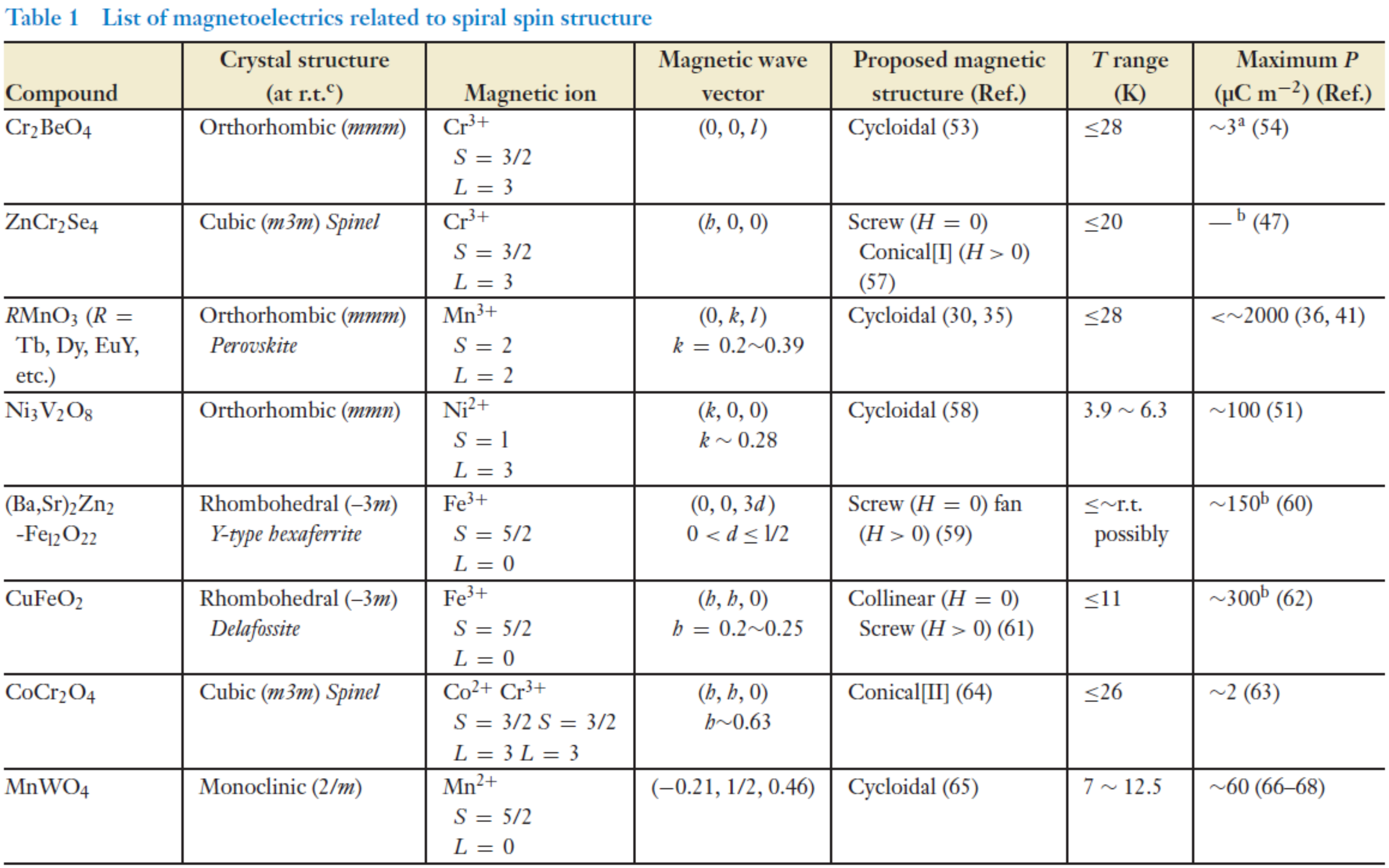


Table 1 List of magnetoelectrics related to spiral spin structure

Compound	Crystal structure (at r.t.[c])	Magnetic ion	Magnetic wave vector	Proposed magnetic structure (Ref.)	T range (K)	Maximum P (μC m^{-2}) (Ref.)
Cr_2BeO_4	Orthorhombic (*mmm*)	Cr^{3+} $S = 3/2$ $L = 3$	$(0, 0, l)$	Cycloidal (53)	≤ 28	$\sim 3^a$ (54)
$ZnCr_2Se_4$	Cubic (*m3m*) *Spinel*	Cr^{3+} $S = 3/2$ $L = 3$	$(h, 0, 0)$	Screw ($H = 0$) Conical[I] ($H > 0$) (57)	≤ 20	$—^b$ (47)
$RMnO_3$ (R = Tb, Dy, EuY, etc.)	Orthorhombic (*mmm*) *Perovskite*	Mn^{3+} $S = 2$ $L = 2$	$(0, k, l)$ $k = 0.2 \sim 0.39$	Cycloidal (30, 35)	≤ 28	$<\sim 2000$ (36, 41)
$Ni_3V_2O_8$	Orthorhombic (*mmn*)	Ni^{2+} $S = 1$ $L = 3$	$(k, 0, 0)$ $k \sim 0.28$	Cycloidal (58)	$3.9 \sim 6.3$	~ 100 (51)
$(Ba,Sr)_2Zn_2$-$Fe_{12}O_{22}$	Rhombohedral ($-3m$) *Y-type hexaferrite*	Fe^{3+} $S = 5/2$ $L = 0$	$(0, 0, 3d)$ $0 < d \leq 1/2$	Screw ($H = 0$) fan ($H > 0$) (59)	$\leq \sim$r.t. possibly	$\sim 150^b$ (60)
$CuFeO_2$	Rhombohedral ($-3m$) *Delafossite*	Fe^{3+} $S = 5/2$ $L = 0$	$(h, h, 0)$ $h = 0.2 \sim 0.25$	Collinear ($H = 0$) Screw ($H > 0$) (61)	≤ 11	$\sim 300^b$ (62)
$CoCr_2O_4$	Cubic (*m3m*) *Spinel*	Co^{2+} Cr^{3+} $S = 3/2$ $S = 3/2$ $L = 3$ $L = 3$	$(h, h, 0)$ $h \sim 0.63$	Conical[II] (64)	≤ 26	~ 2 (63)
$MnWO_4$	Monoclinic ($2/m$)	Mn^{2+} $S = 5/2$ $L = 0$	$(-0.21, 1/2, 0.46)$	Cycloidal (65)	$7 \sim 12.5$	~ 60 (66–68)

T. Kimura, Annu. Rev. Mater. Res. 37, 387 (2007)

Frustrated spin systems :

GOAL: Couple magnetism to ferroelectricity

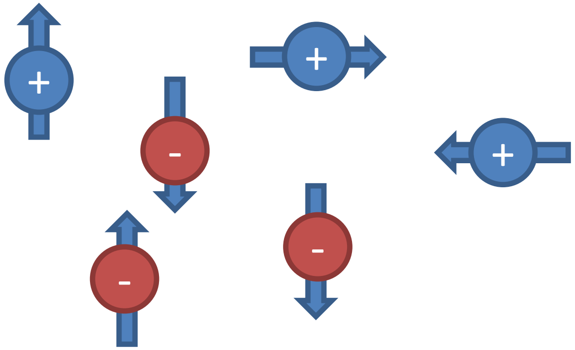
We can give magnetism a symmetry
that matches an electric field

But to create ferroelectricity we need to add charges to the spins
Spins <-> orbits <-> lattice.

Microscopic mechanisms

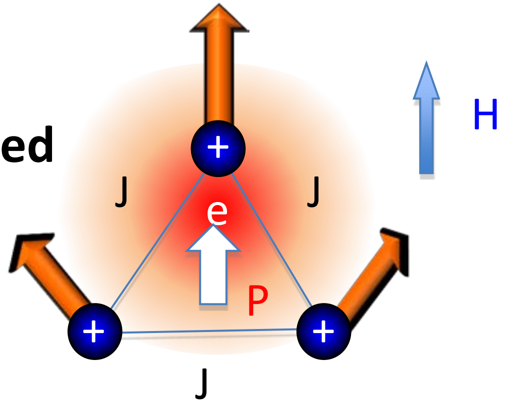
(usually both happen in a given material)

1. Magnetostriction [Always happens]. Let magnetic forces move charged ions around to create electric dipoles.



2. Polar bonds. Magnetic exchange bonds can have polar distribution of electron density.

Frustration required

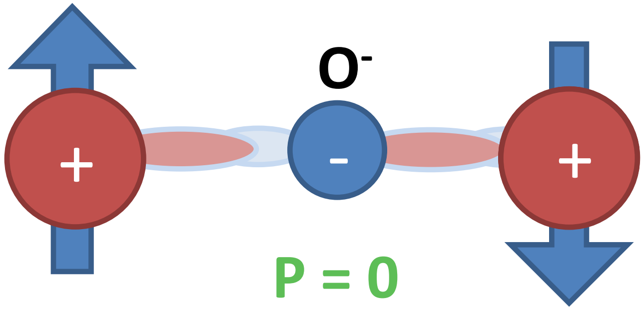


Frustrated spin systems :

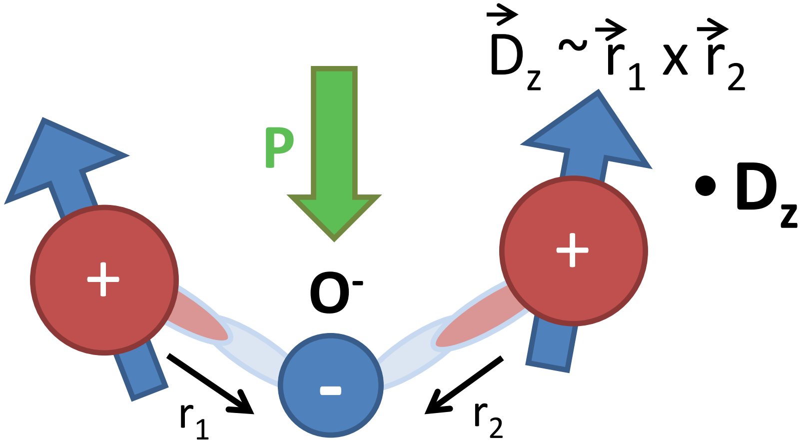
Example 1: Dzyaloshinskii-Moryia interaction

$$H = \vec{D}_z \circ (\vec{S}_1 \times \vec{S}_2)$$

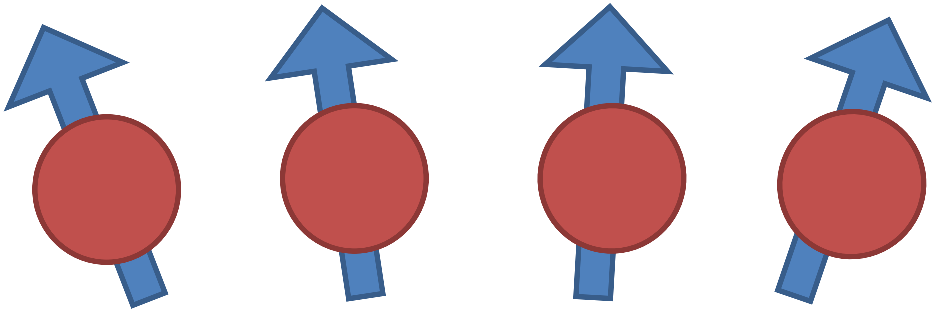
Exchange tensor $H = \vec{S}_1 \overleftrightarrow{T} \vec{S}_2$



SIS is conserved

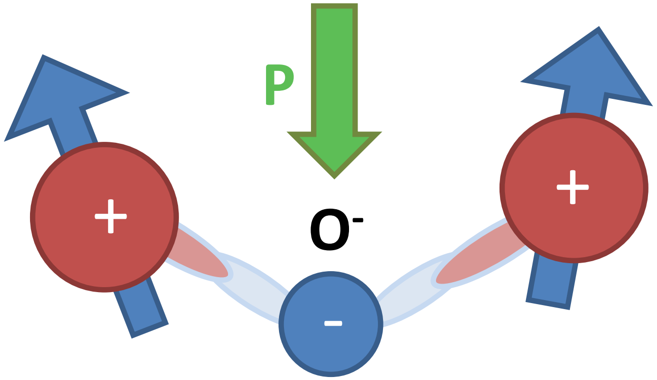


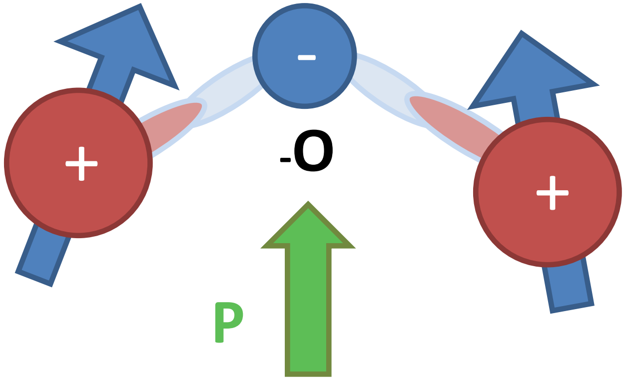
Consequence: Cycloidal spiral



Broken SIS, vertically
In both the spins and the bond.

Frustrated spin systems :





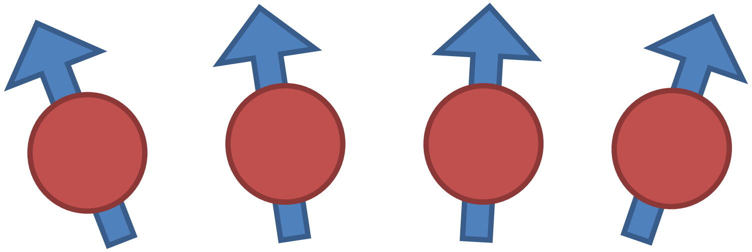
Mirror symmetry is broken

Spins, charges separately

Frustrated spin systems :

Reverse cause and effect.

1. Frustration creates a spiral

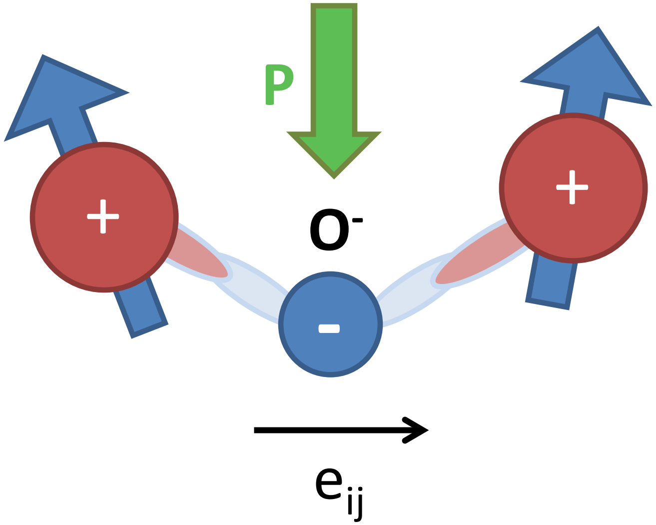


3. Generate a DM interaction
Lowers magnetic energy

$$H = D_z \circ (S_1 \times S_2)$$

2. Bonds distort to match magnetic symmetry

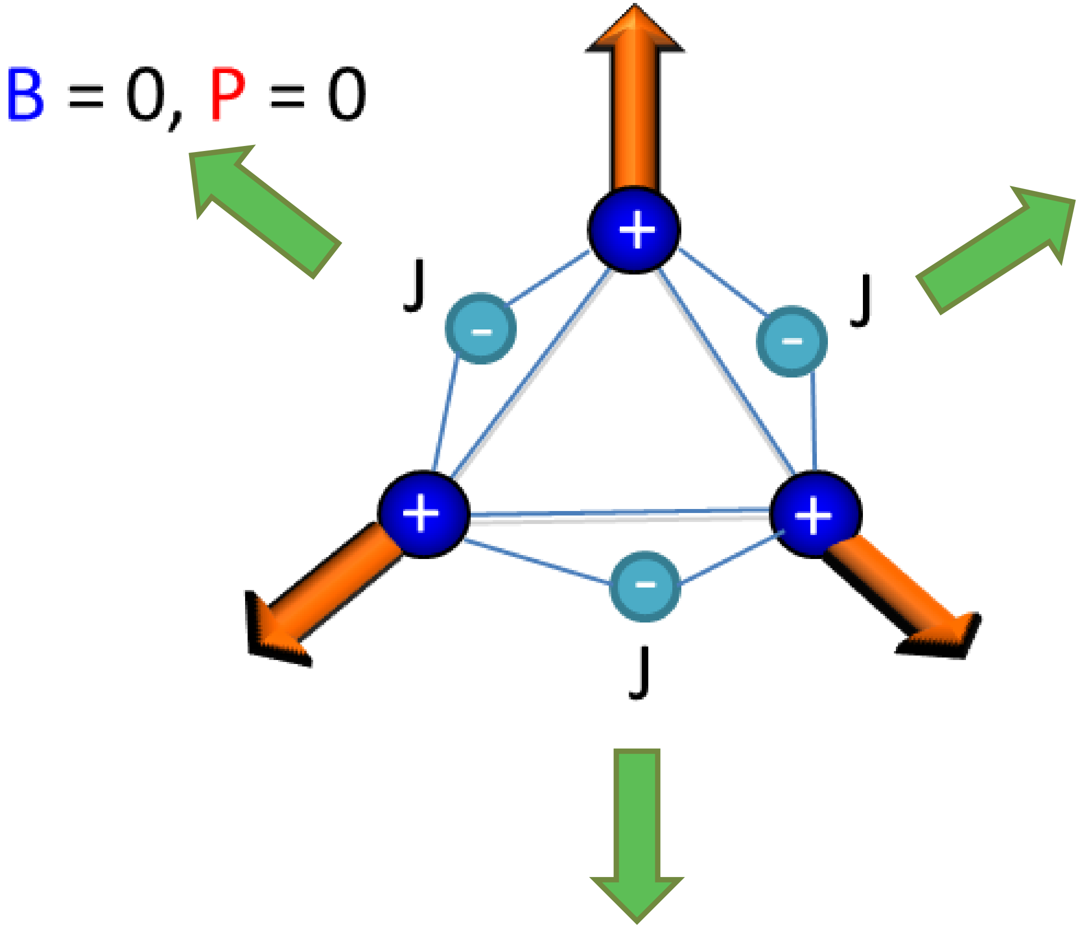
(Electric polarization created as a byproduct.)



$$P \sim (S_i \times S_{i+1}) \times e_{ij}$$

Frustrated spin systems :

Breaks mirror symmetry -- but not along a unique axis



Frustrated spin systems :

Unique polar axis selected by magnetic field

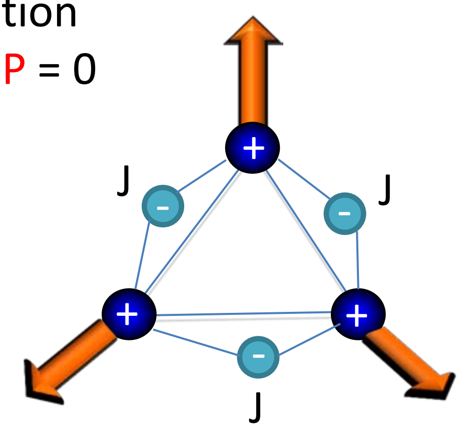
Frustrated spin systems :

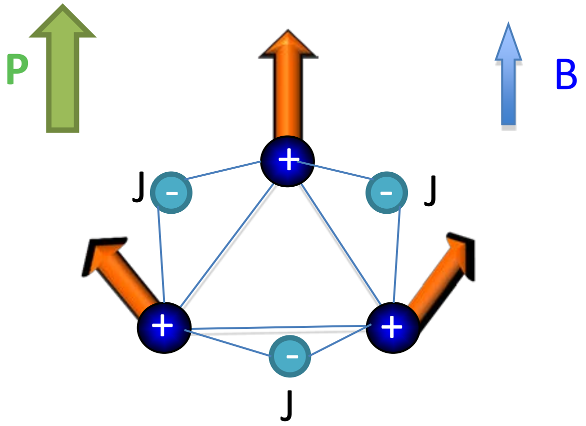
Example 2: Trimers.

L. N. Bulaevskii, C. D. Batista, M. V. Mostovoy, and D. I. Khomskii, PRB 78, 024402(2008).

Magnetostriction

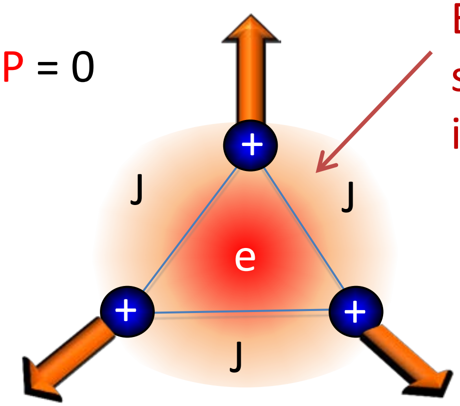
B = 0, P = 0



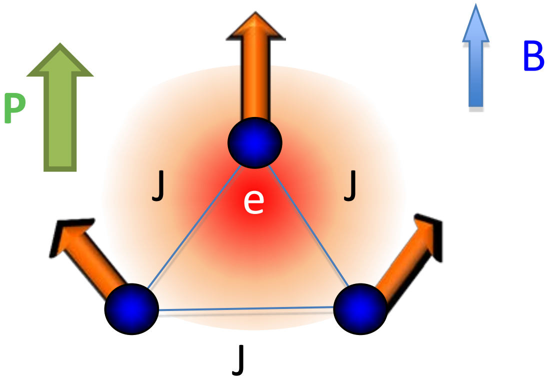


Orbital magnetoelectric coupling.

B = 0, P = 0



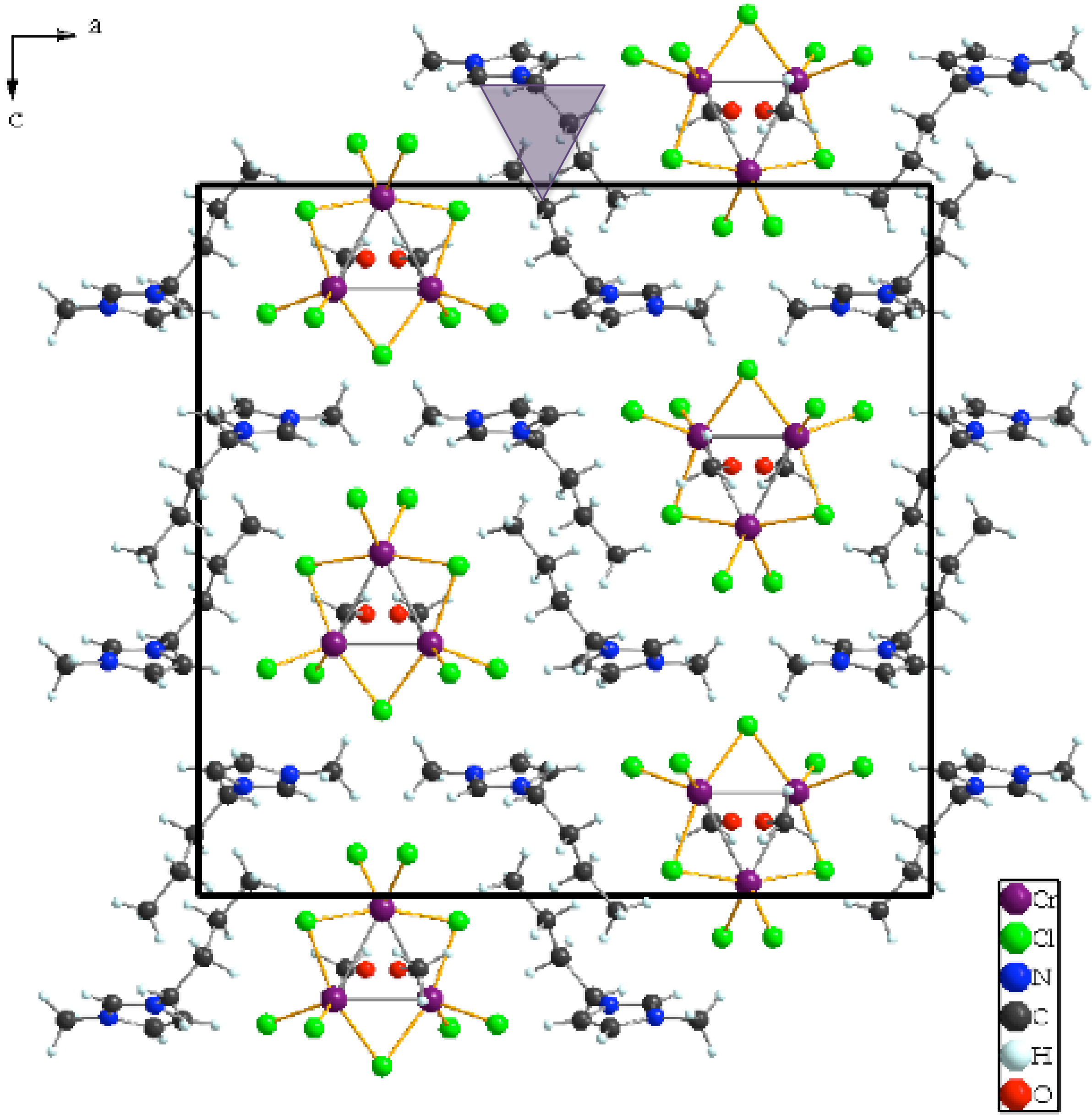
Electron of the superexchange interaction



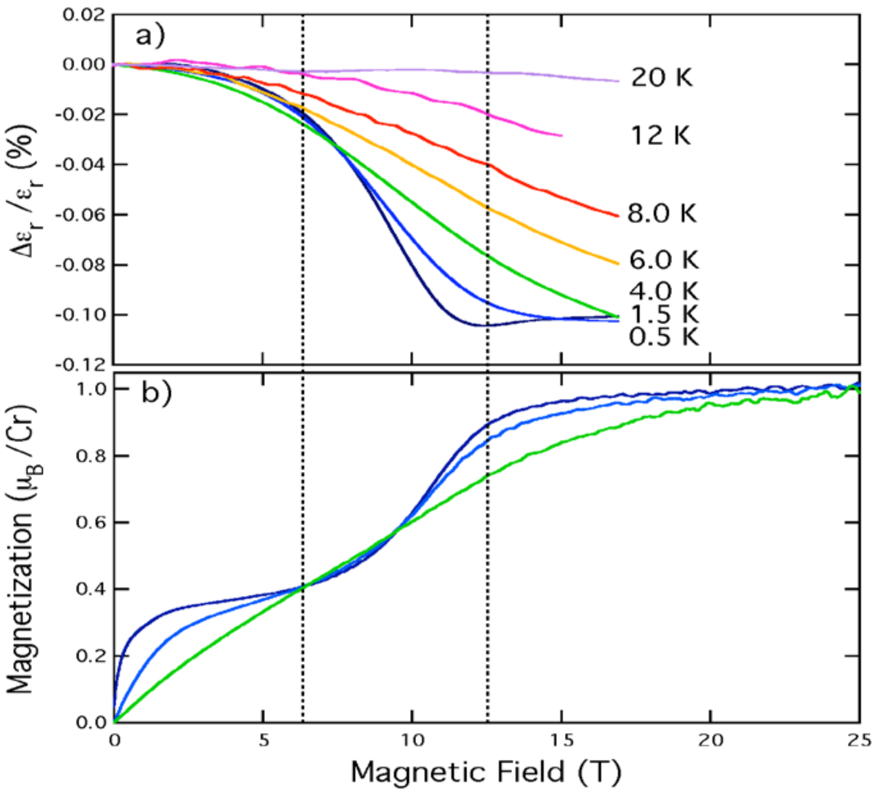
Conserves SIS

Breaks SIS

A metal-organic material with Cr trimers

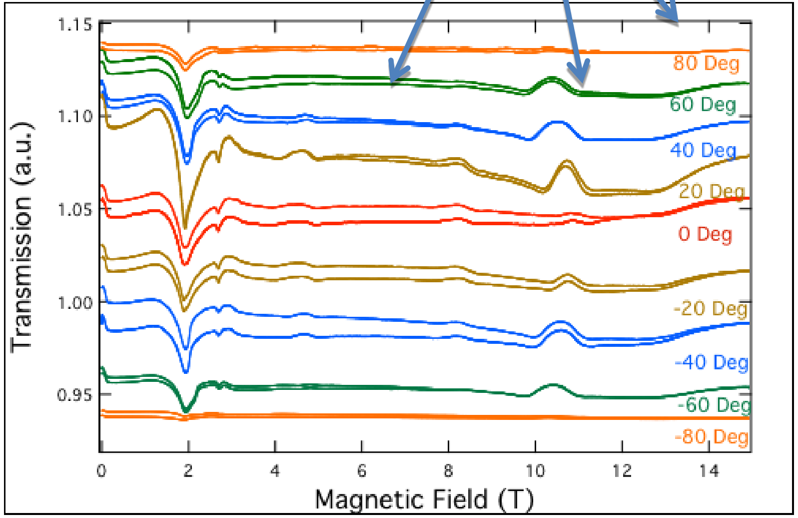


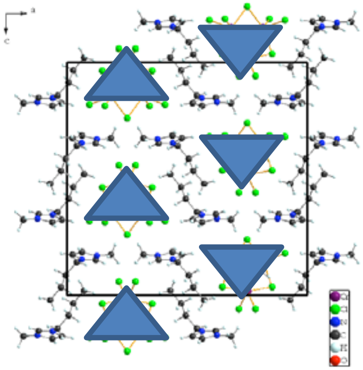
Electron spin resonance experiments

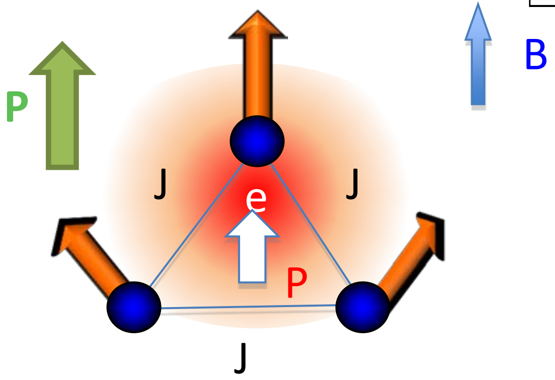


Electric dipole active features associated with magnetic level crossings

T = 4.0K







ESR

The only problem with this material
Is that triangles point in both direction

Frustrated spin systems :

nature
COMMUNICATIONS

D. Khomskii

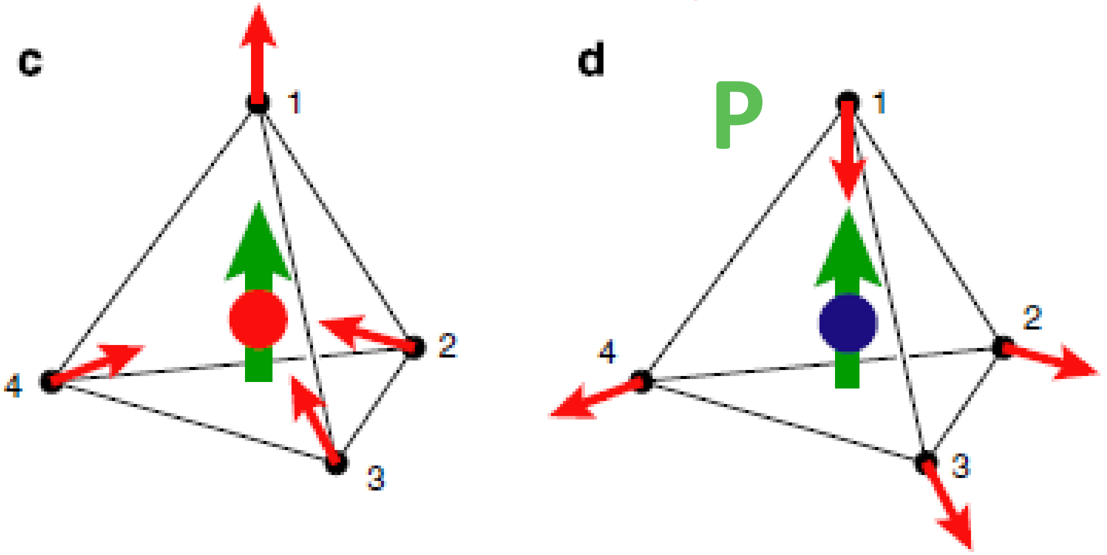
ARTICLE

Received 23 Feb 2012 | Accepted 14 May 2012 | Published 19 Jun 2012

DOI: 10.1038/ncomms1904

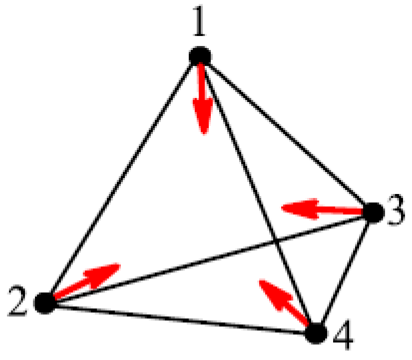
Electric dipoles on magnetic monopoles in spin ice

3-in-1-out (monopole)

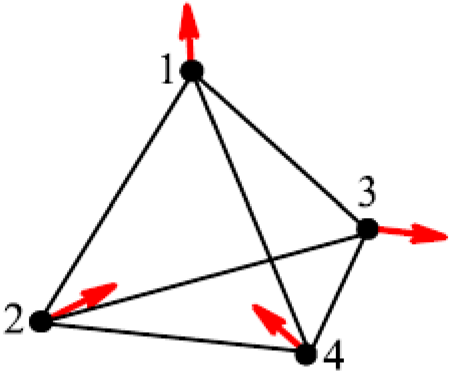


$$P \sim \delta n = 8t^3/U^3 (S_1 \bullet S_2 + S_1 \bullet S_3 - 2\, S_2 \bullet S_3)$$

P=0



(a) 4-in cell



(b) 2-in-2-out cell

JOURNAL OF APPLIED PHYSICS **113**, 17D901 (2013)

Multiferroicity in spin ice $Ho_2Ti_2O_7$: An investigation on single crystals

D. Liu,[1] L. Lin,[1] M. F. Liu,[1] Z. B. Yan,[1] S. Dong,[2] and J.-M. Liu[1,3,a)]
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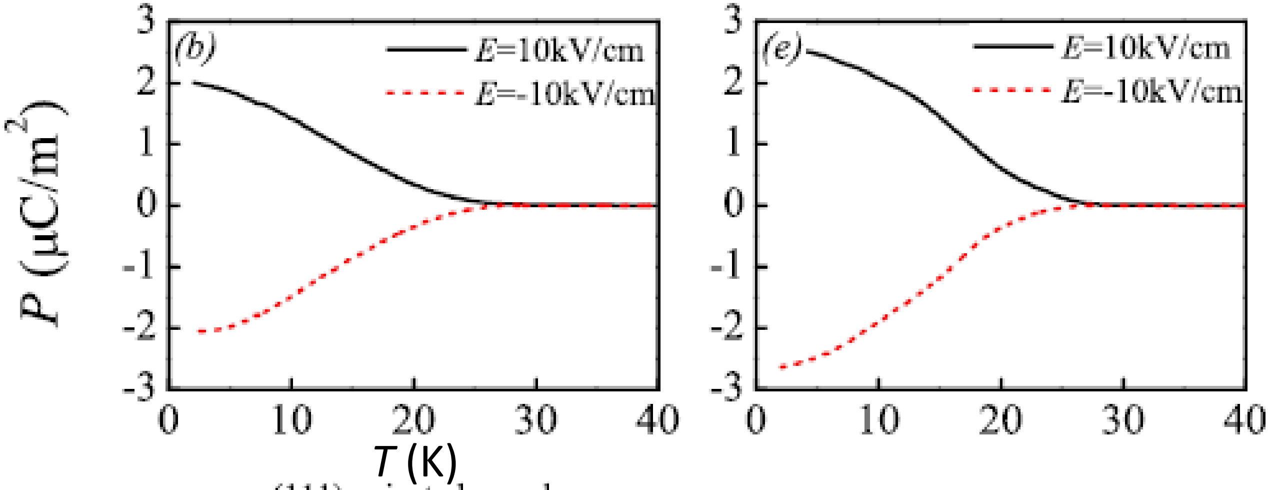
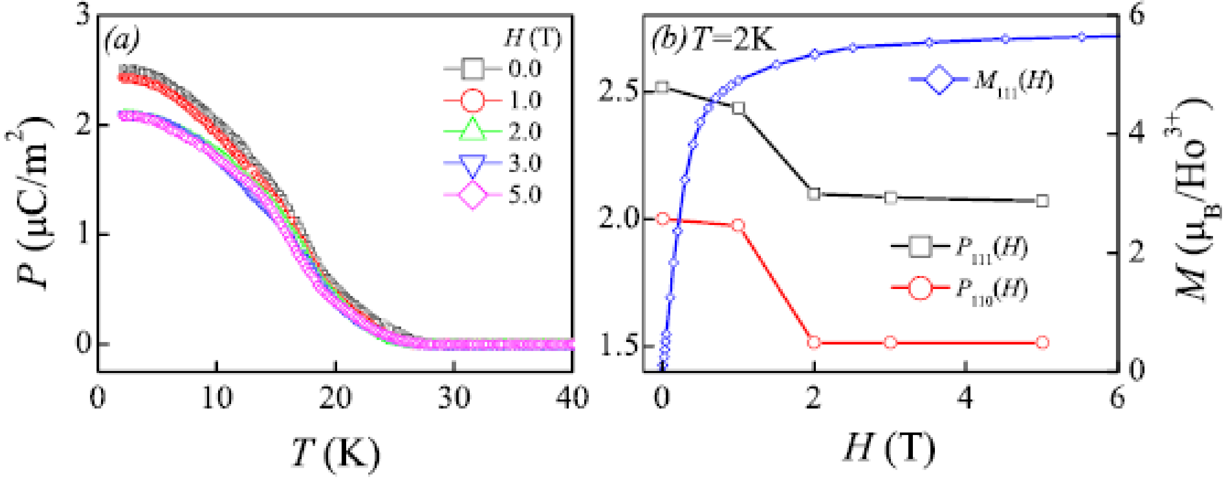
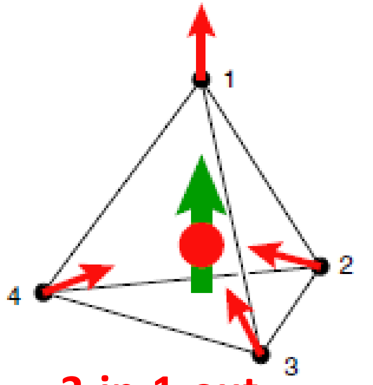
[3]*Institute for Advanced Materials, South China Normal University, Guangzhou 510006, China*



(111)-oriented sample

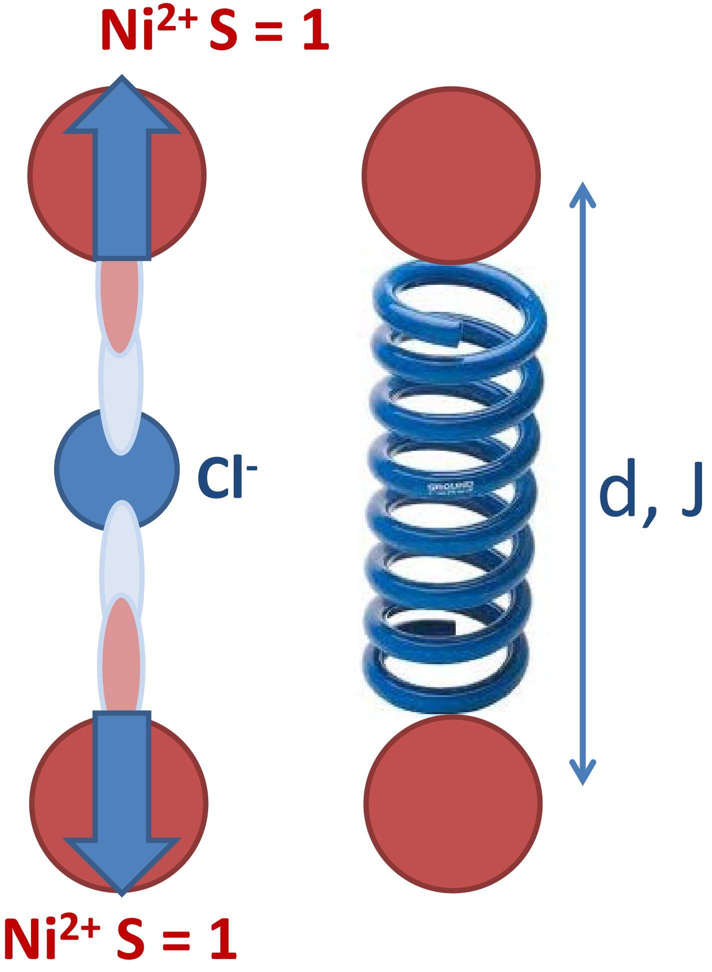


Electric field stabilizes monopoles



3-in-1-out (monopole)

Example 2: Linear exchange striction



Superexchange

$$H = J\vec{S}_1\circ\vec{S}_2 \qquad \text{AFM J}$$

$\Delta J \sim (\Delta d)^4$ to $(\Delta d)^{10}$ for small Δd

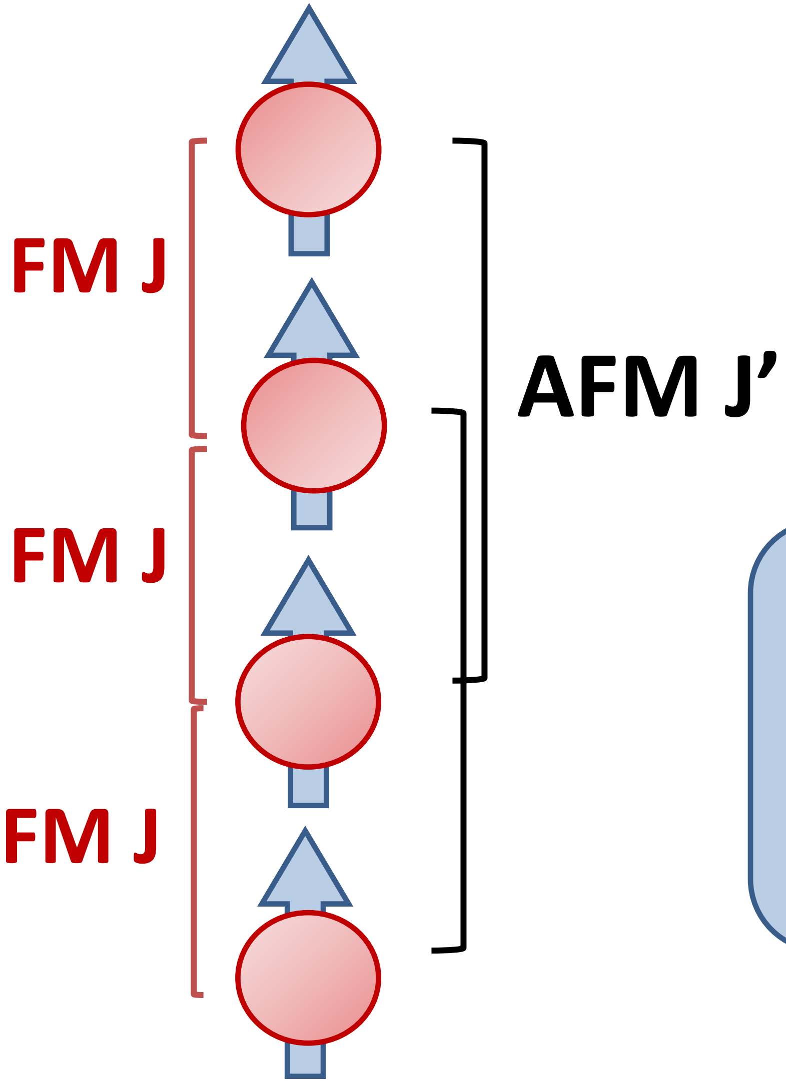
Maybe be linear, or due to changing the angle.

If the spins are not satisfying J
distort the lattice, make J smaller.

Or if the spins are satisfying J,
distort the lattice to make J bigger.

Balance magnetic energy gain
against at energy cost of lattice distortion

Frustrated spin systems :



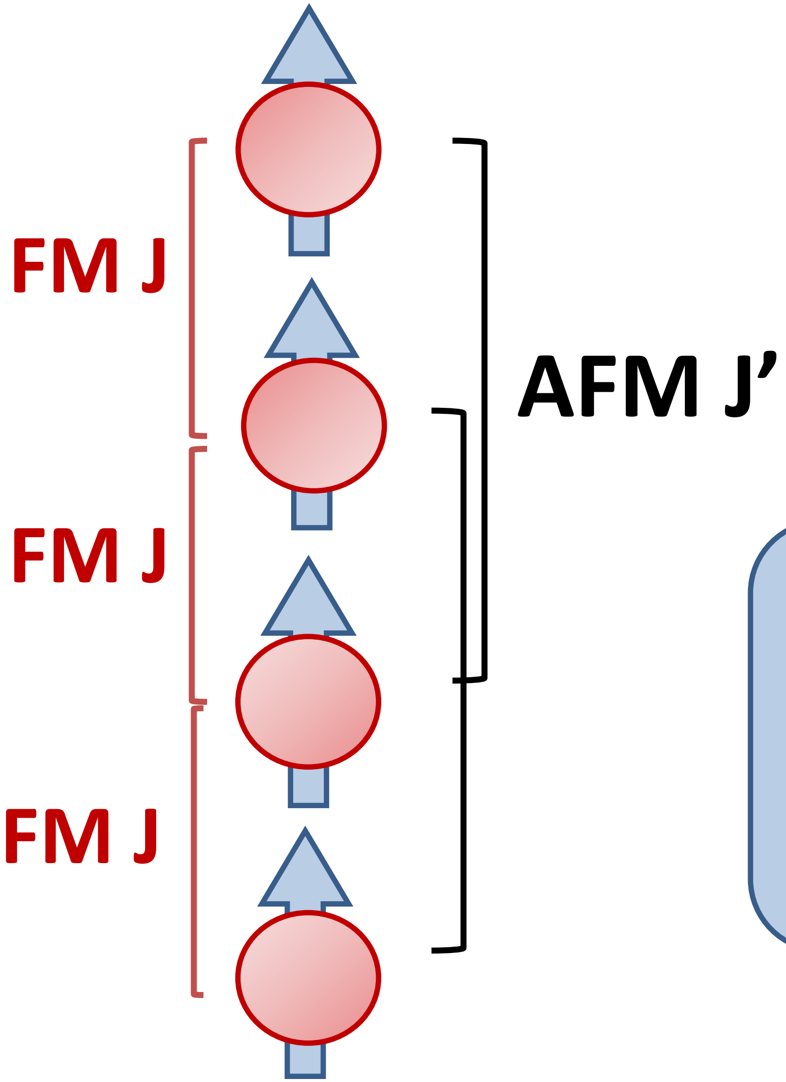
FM = ferromagnetic
AFM = antiferromagnetic

Exercise:

Place the spins so as to satisfy the bonds
Assume Ising spins.

Frustrated spin systems :

FM = ferromagnetic
AFM = antiferromagnetic



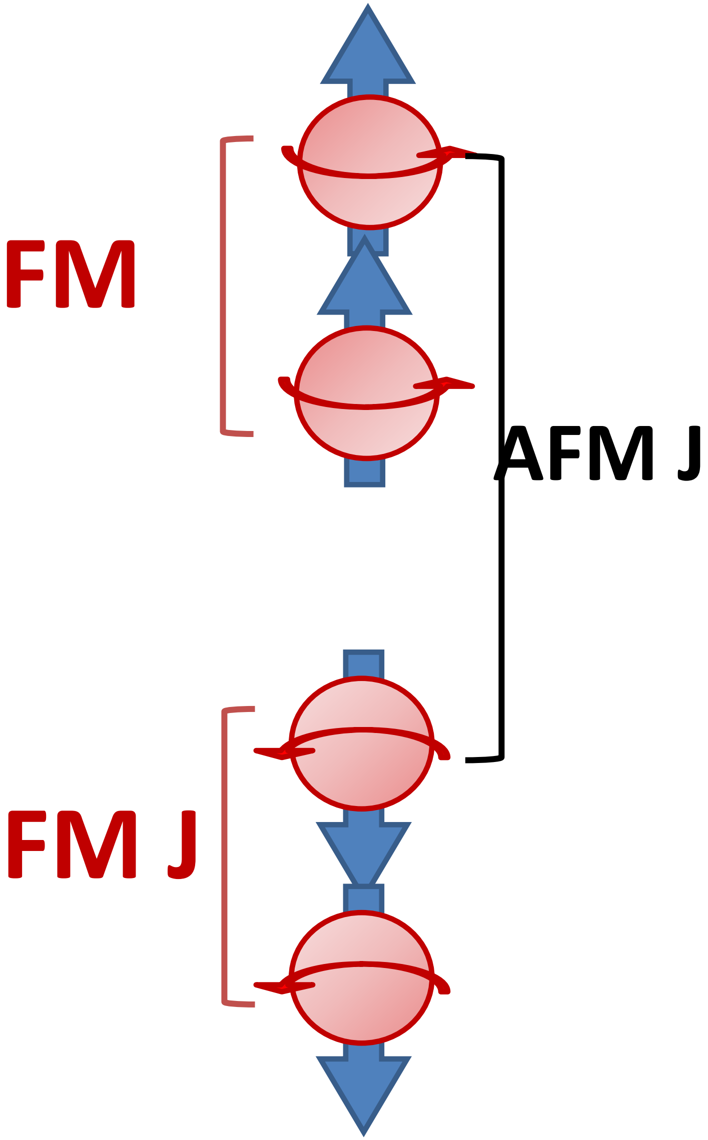
Answer:

It’s frustrated

Frustrated spin systems :

The lattice comes to the rescue: Frustration-lifting distortion

(Similar to Spin Peierls)



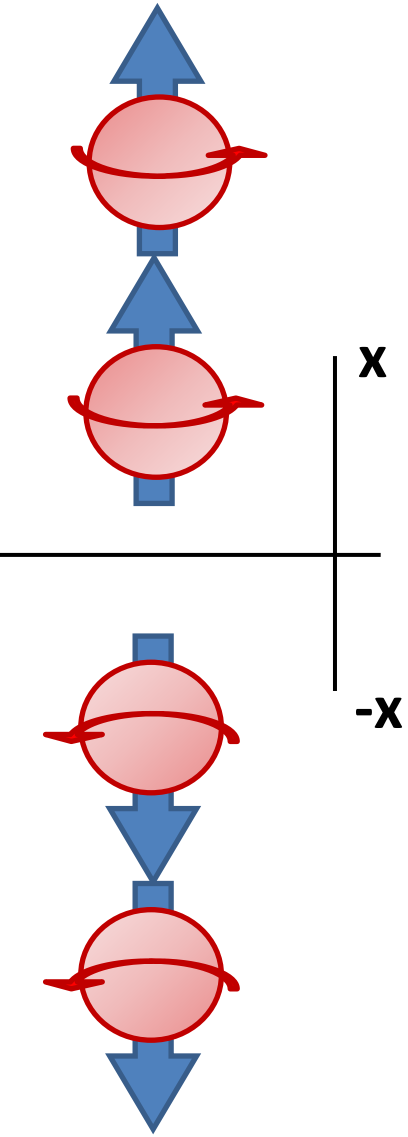
$$H = JS_1 \circ S_2$$

$J \sim d^4$ to d^{10}

Minimize energy of spins + lattice.

Disclaimer:
Actual distortions
1 part in 10^3-10^4

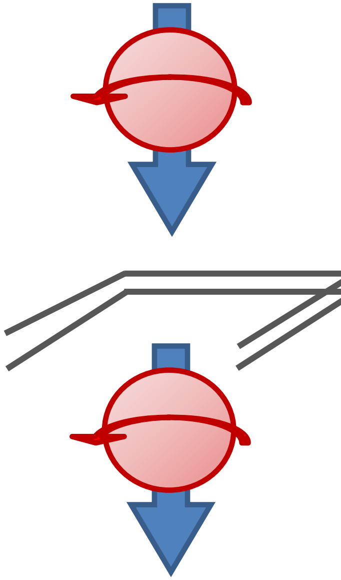
Frustrated spin systems :

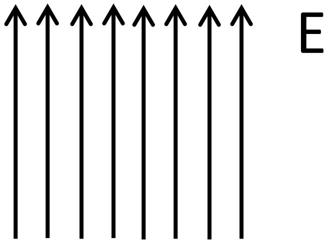


Exercise:
Does it break mirror symmetry?

(apply mirror vertically)

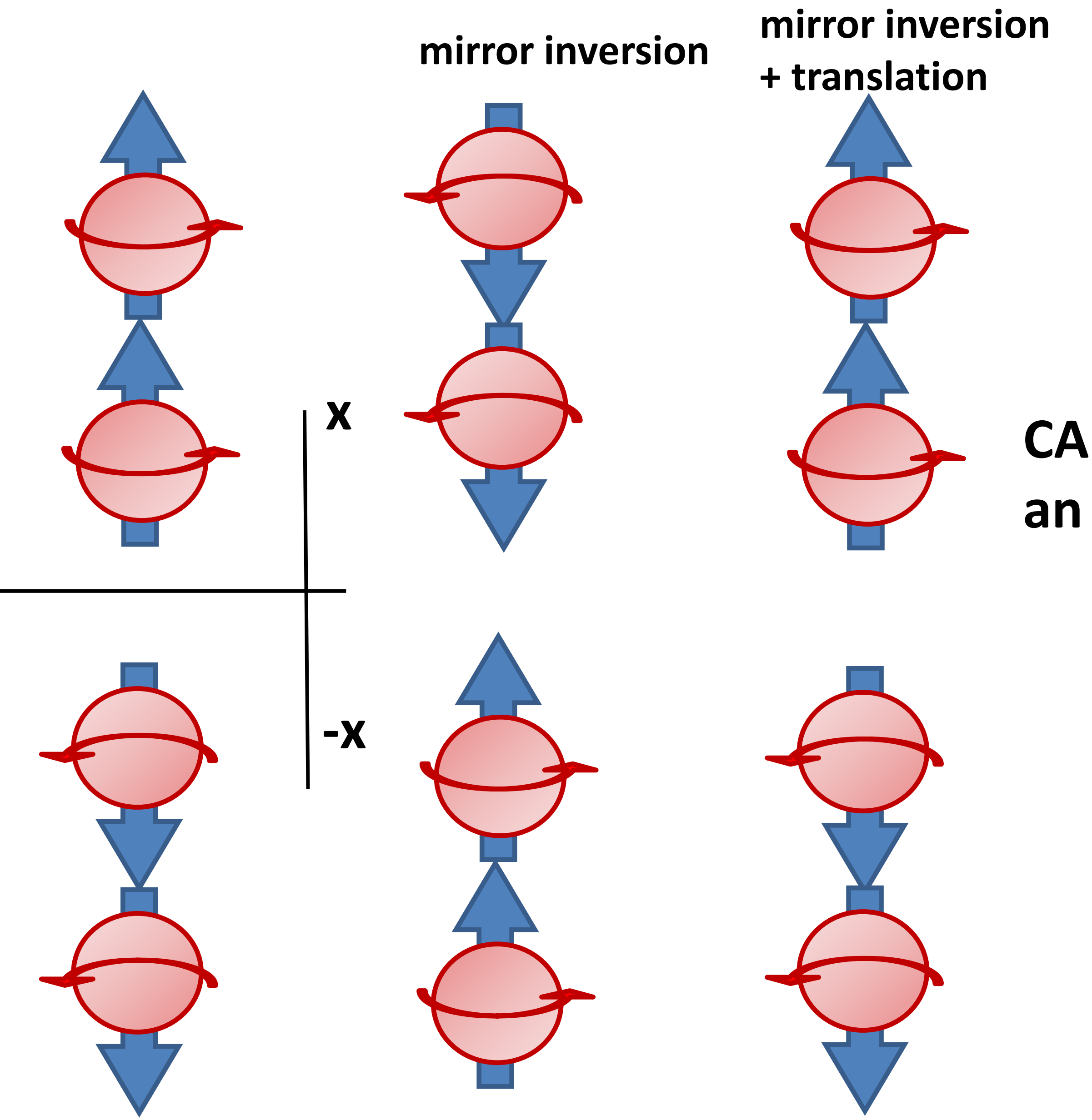
1. Physically interchange the spins along x
2. Apply mirror inversion to the spins
3. You are allowed to vertically translate in an attempt to see if the inverted system match the original





Translational symmetry

Frustrated spin systems :

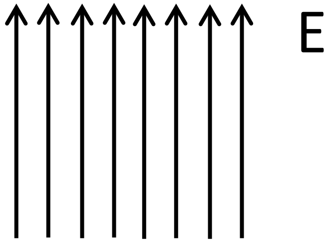


mirror inversion

mirror inversion
+ translation

x

-x



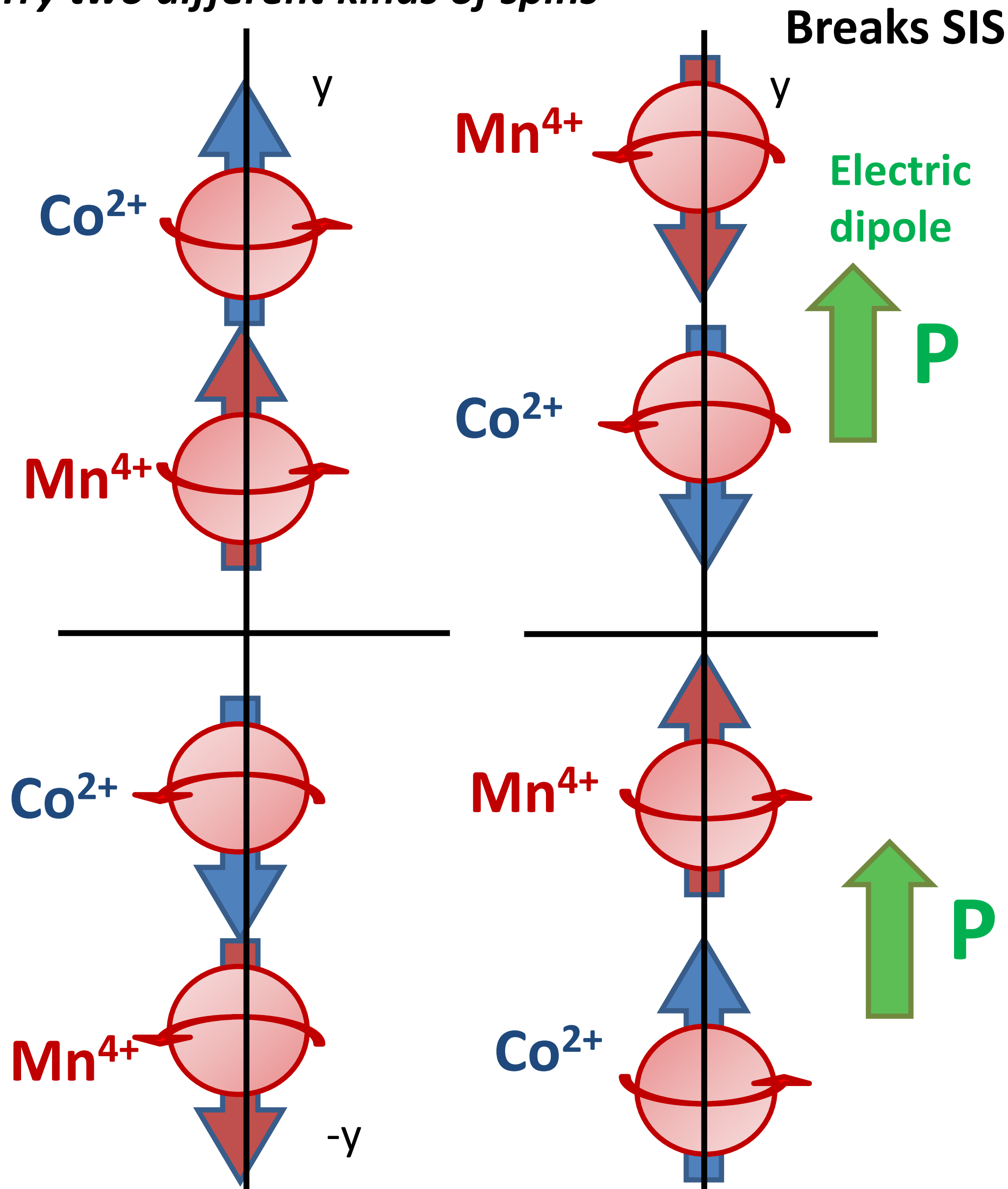
E

Translational symmetry

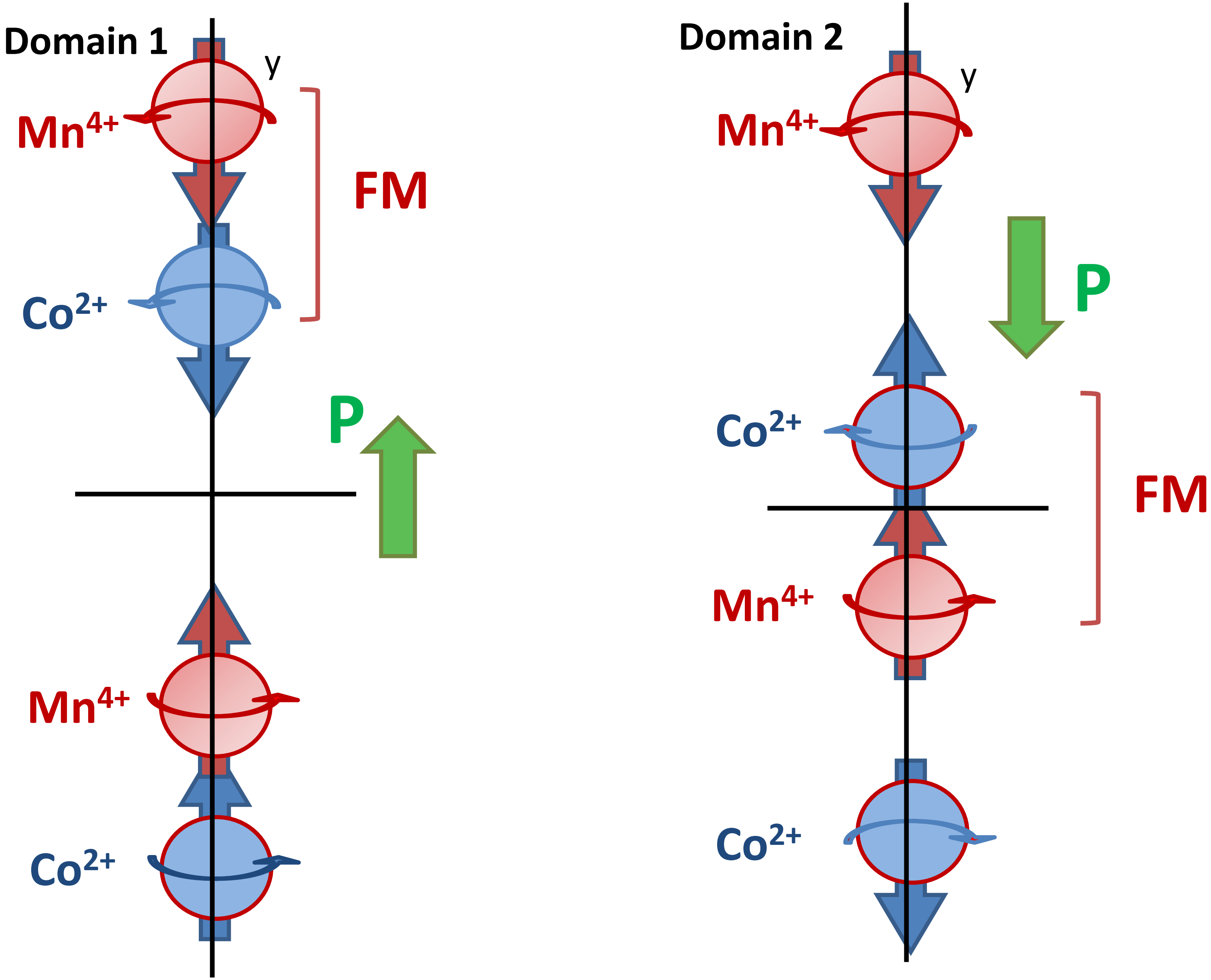
**CANNOT produce
an electric polarization**

Frustrated spin systems :

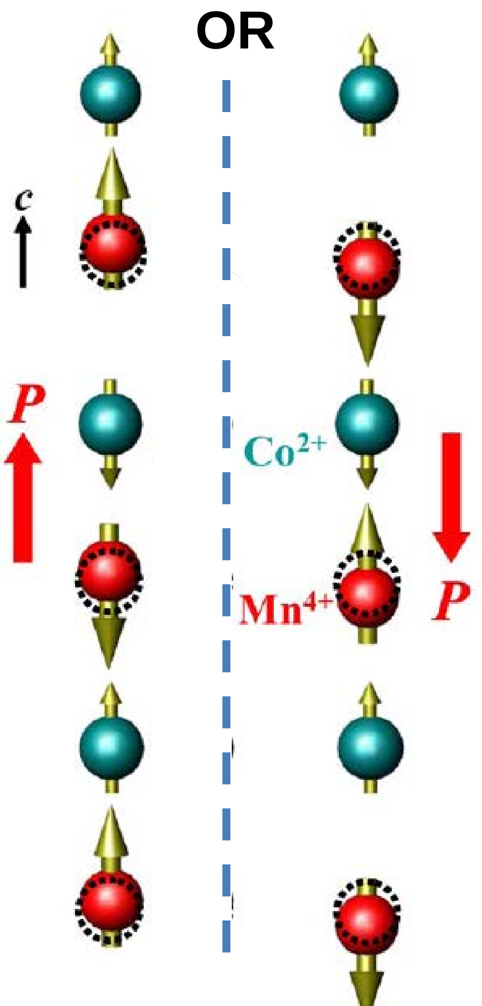
Try two different kinds of spins

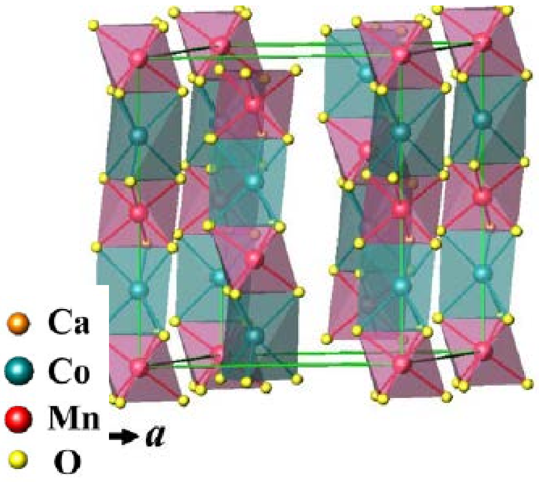


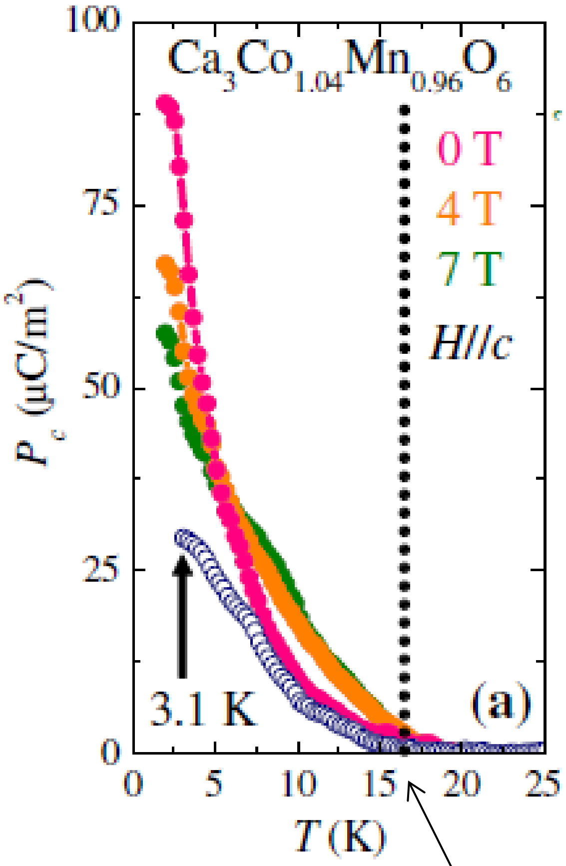
Frustrated spin systems :



Ca_3CoMnO_6





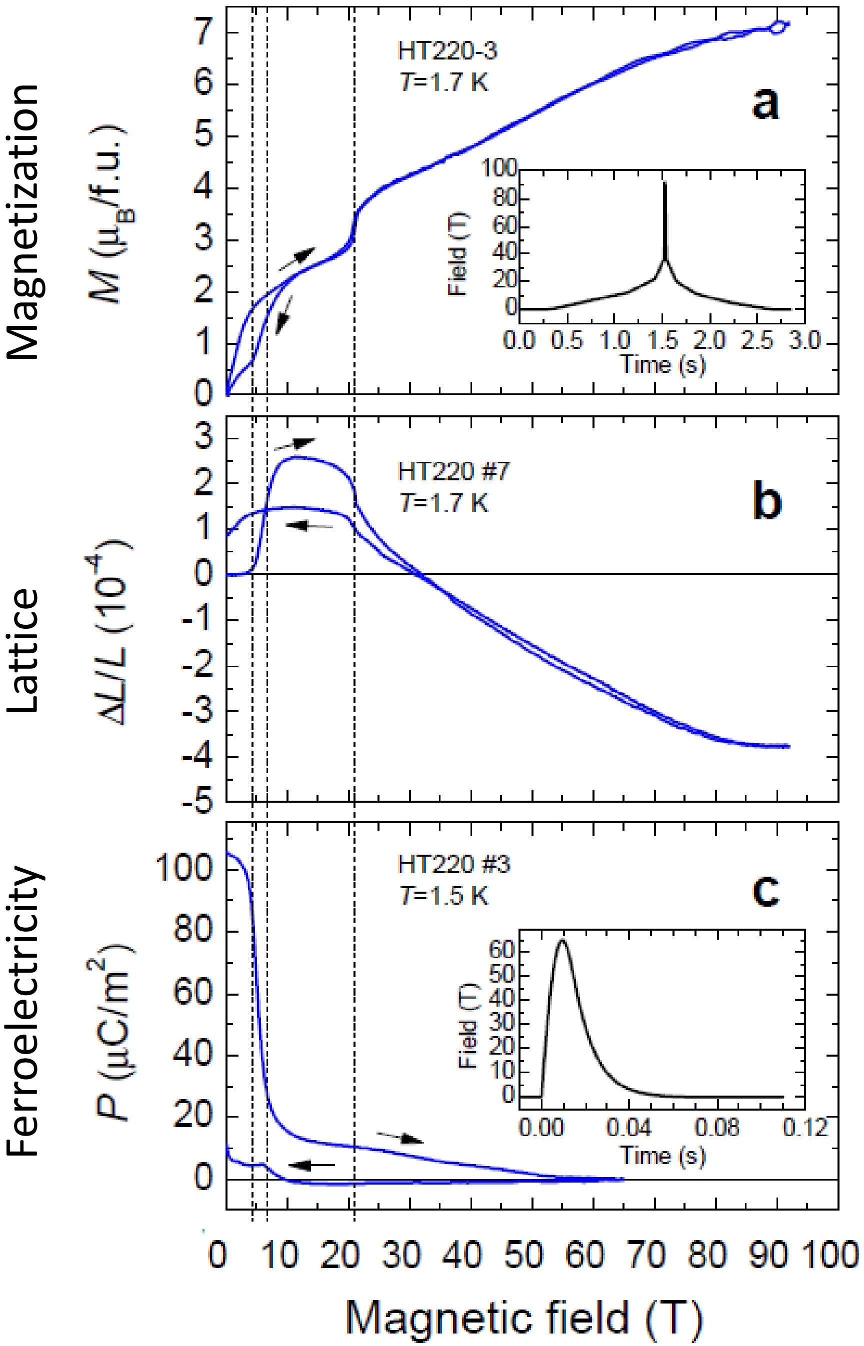


Onset of magnetic order

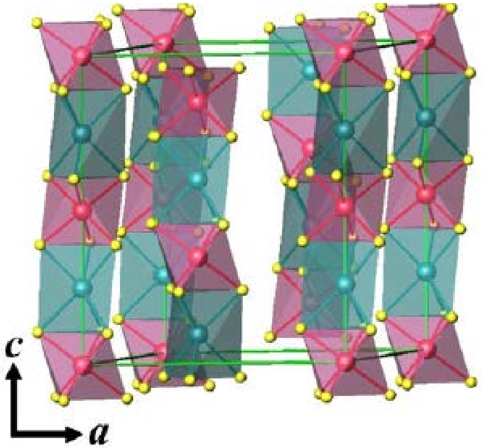
Two ways to distort:
Two ferroelectric domains

Elastic neutron diffraction @ 1.4 K

Y. Choi et al., PRL 100, 047601 (2008)



Ca_3CoMnO_6



Evolve, kill, and ultimately understand the magnetoelectric coupling

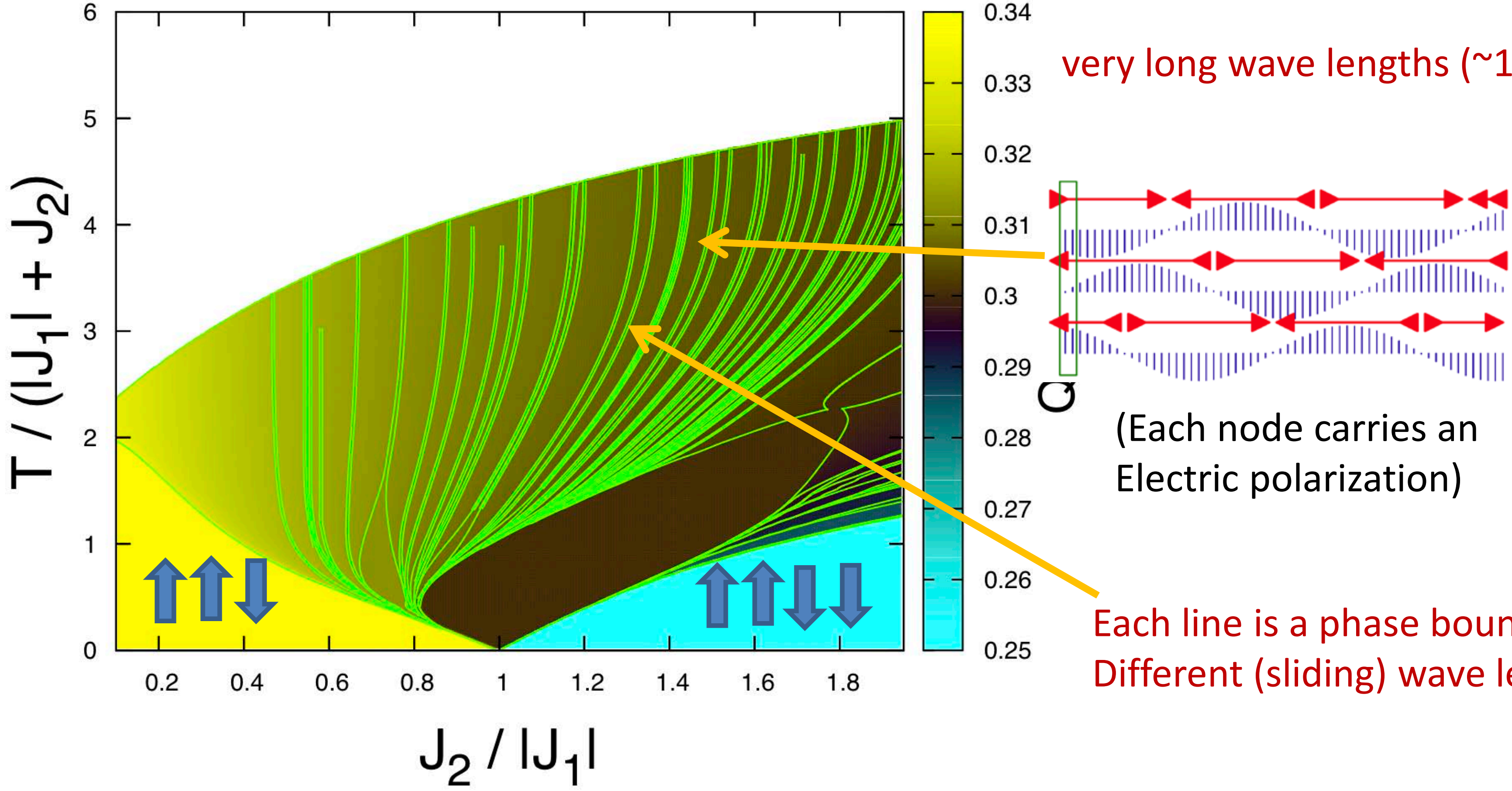
J. W. Kim et al, PRB 89, 060404 R (2014)

Y. Kamiya & C. D. Batista

ANNNI model

(Anisotropic next nearest neighbor interactions)

Ising spins have few options for satisfying competing interactions
-> resort to long wavelengths

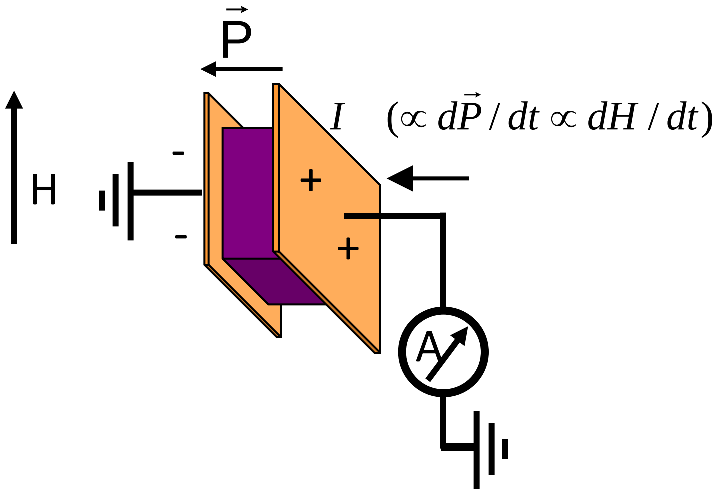


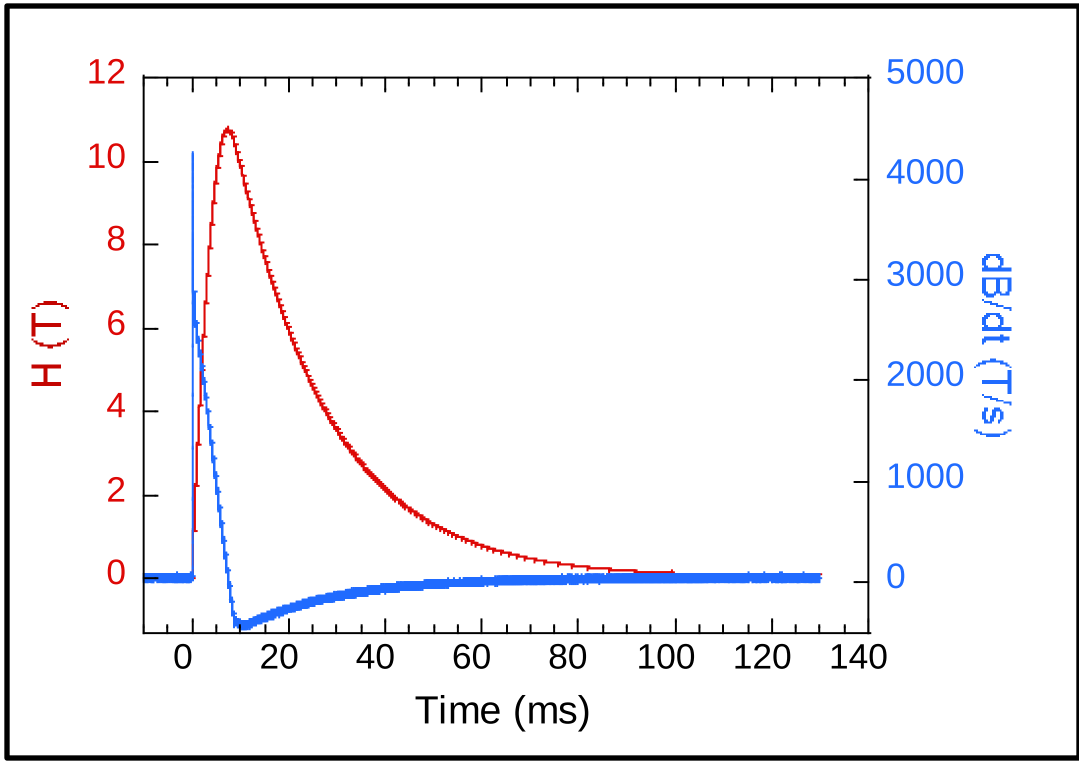
very long wave lengths (~1000 A)

(Each node carries an
Electric polarization)

Each line is a phase boundary
Different (sliding) wave lengths

Pulsed-field measurements of the electric polarization





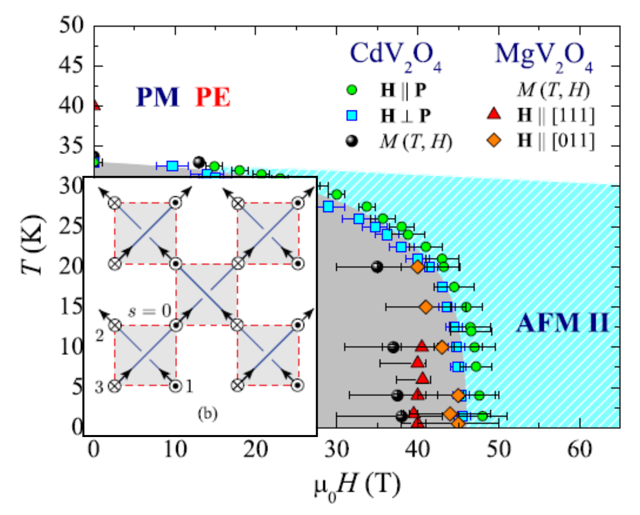
P(H) up to 65 T (95 T…?)

Signal to noise *increases* with speed of pulse

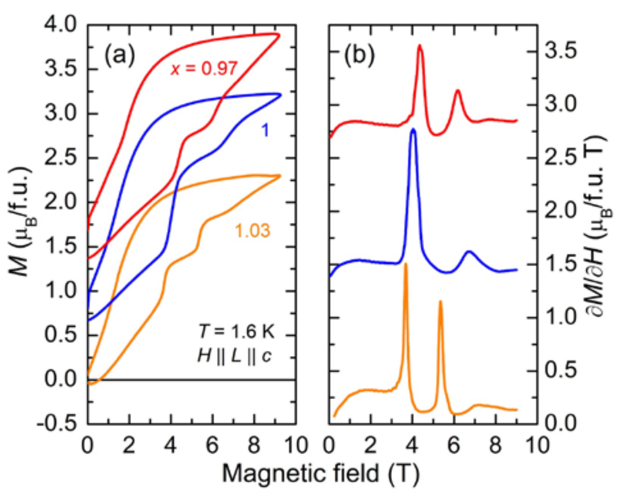
Sub pC/cm^2 resolution

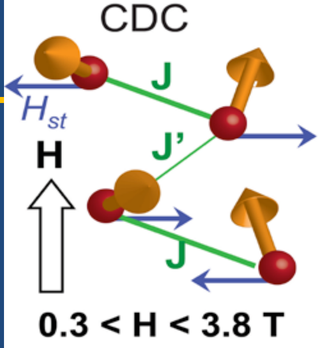
Selection of frustration-induced ferroelectrics at the NHMFL

CdV_2O_4

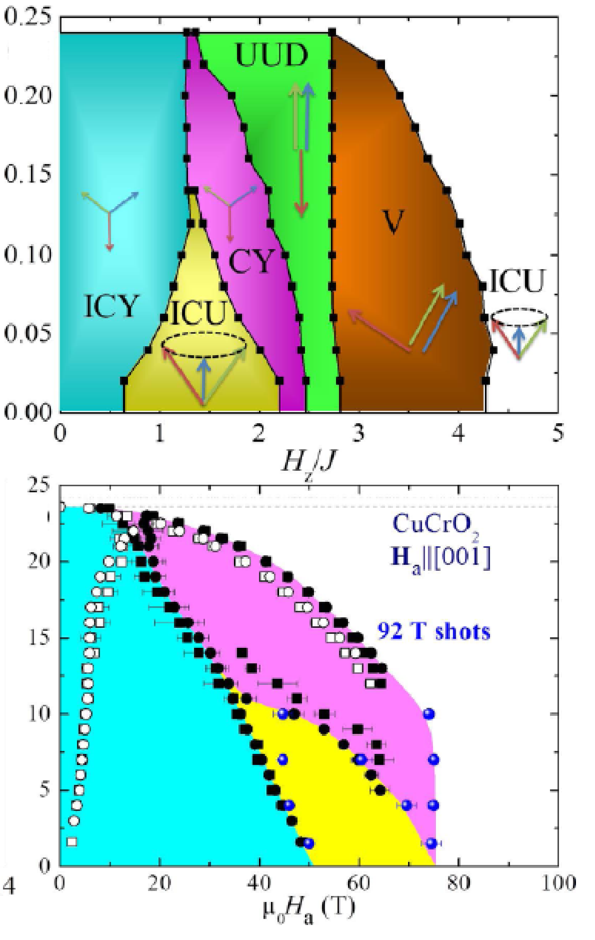


$Ca_3Co_2O_6$ and Ca_3CoMnO_6

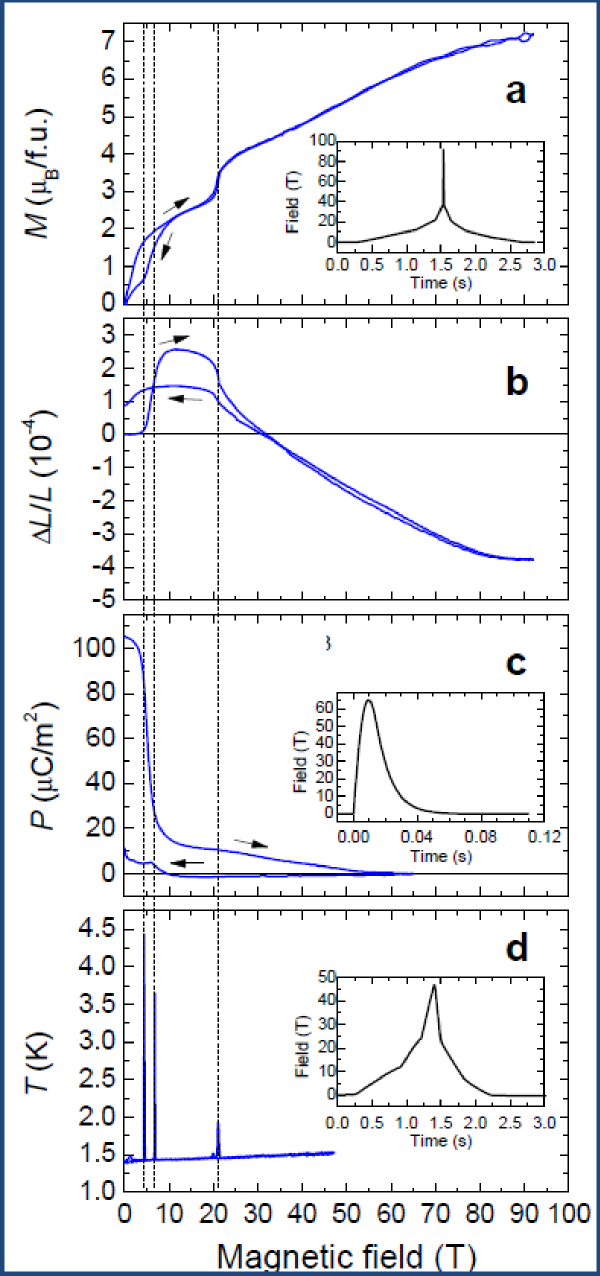




$CuCrO_2$

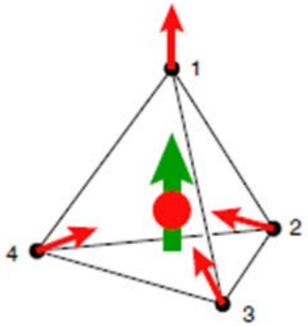


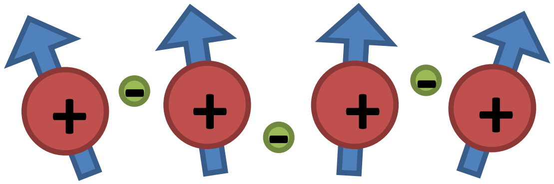
Ca_3CoMnO_6

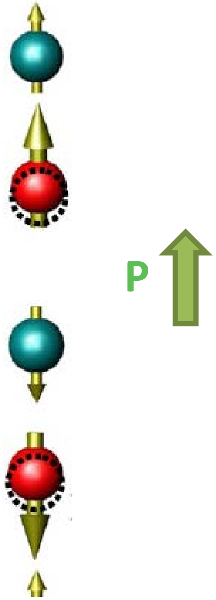


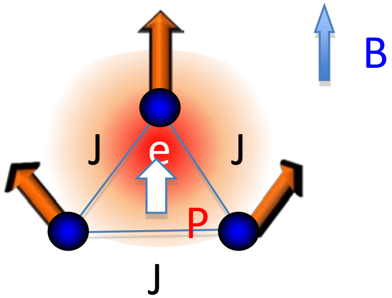
Summary

- Competing interactions are a source of low symmetry spin states
- Match the symmetry of an electric field
- Create multiferroic behavior

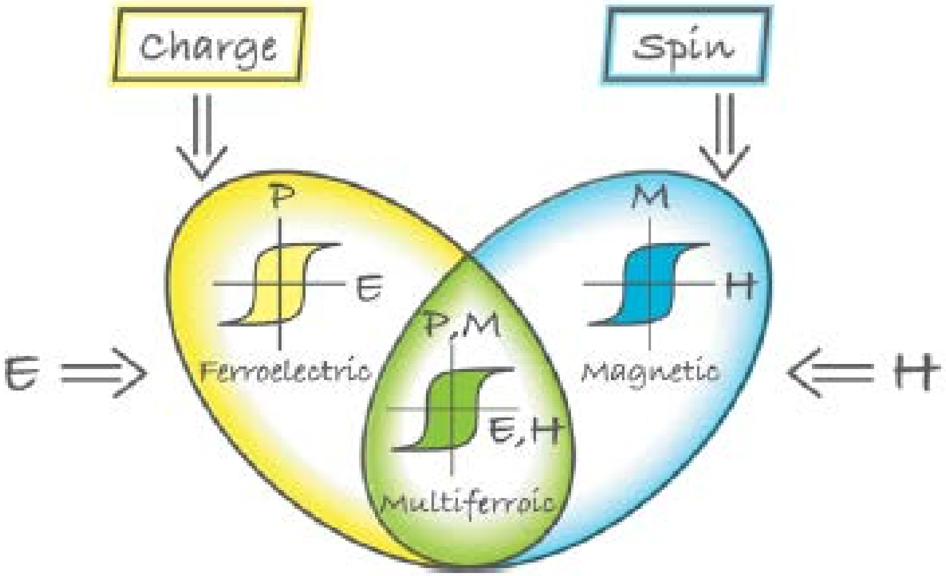








Multiferroics



D. Khomskii, Physics 2, 20 (2009)

Low power consumption
Voltages instead of currents

Record-sensitive magnetic sensors at low powers

Tunable filters, antennas, gyrators, etc.

Tunable microwave devices

Energy harvesting

Memory/smart devices

Electric manipulation of magnetic domain walls, topological objects, etc.

Caveat: frustration reduces ordering temperatures, so applications mostly focus on 'type 1' unfrustrated multiferroics. E.g. magnetism modifies a ferroelectricity that is already present.
Or: heterostructures.

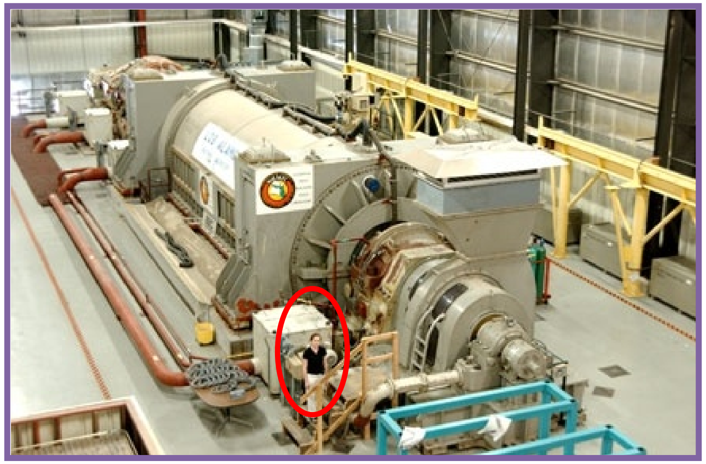
45 Tesla DC

45 Tesla Hybrid magnet (DC), Tallahassee

45 T coke can (SOUND OFF).flv

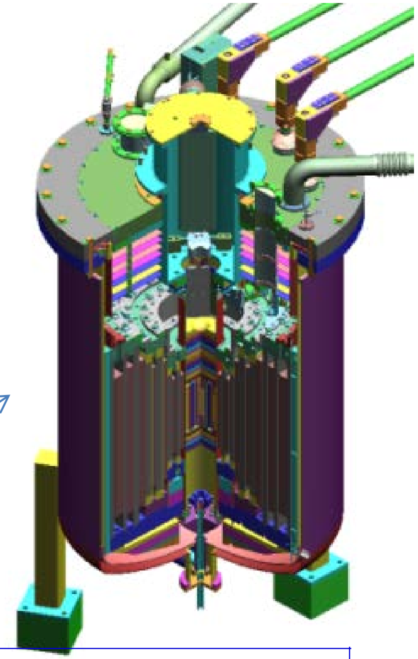
Record Pulsed Field (non-destructive)

1.4 GigaWatts power generator:
this could power Los Angeles



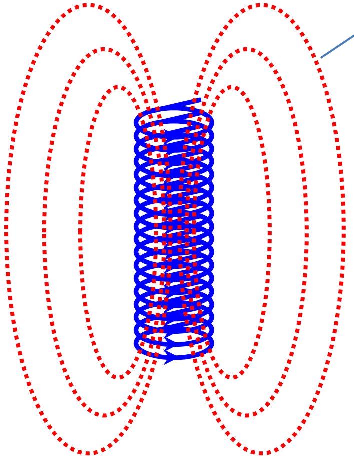
~ 15%

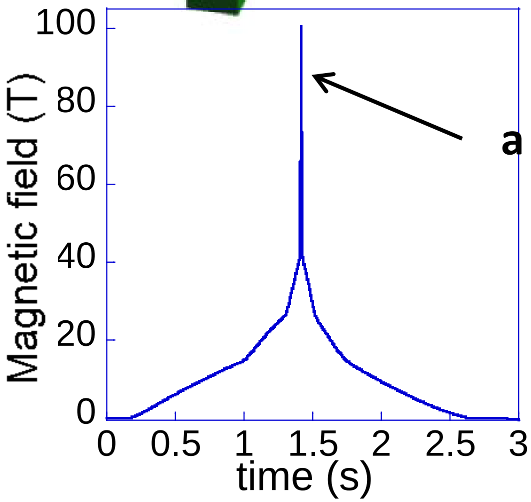
100 Tesla



Power is high
But energy is low

20x





a few milliseconds

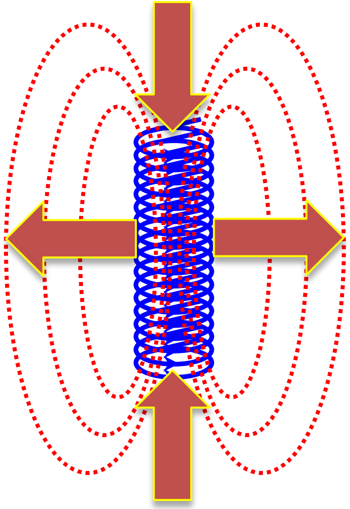
Limitation on high magnetic fields: Strength of materials

1x

Released in 1 millisecond
10s of kAmps, 10s of kVolts

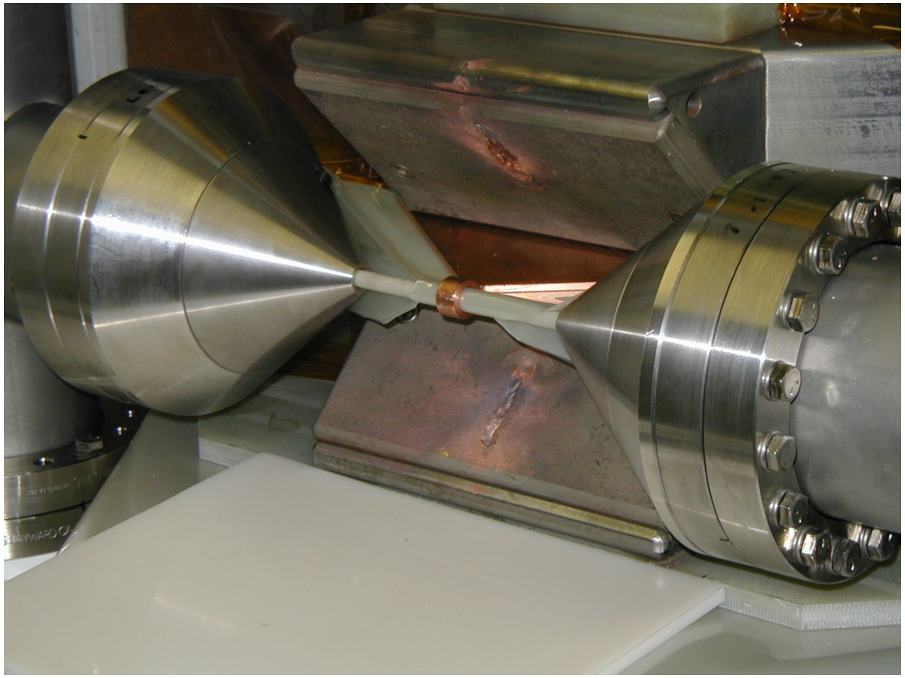
Worlds' strongest steel

Force on a solenoid

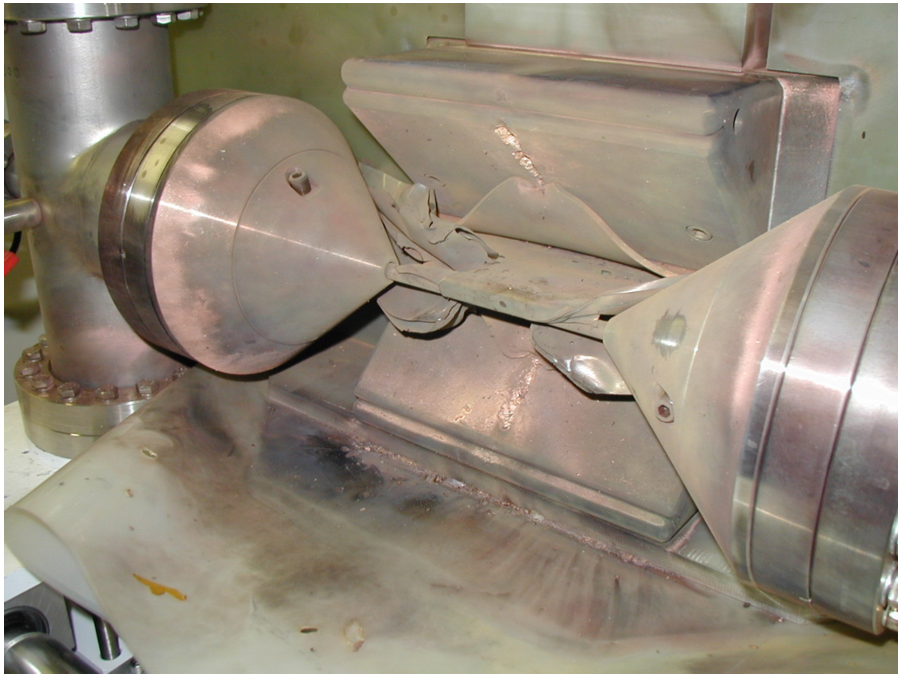


200T (microseconds): forget about saving the magnet
Sample is unharmed (usually)

Microsecond pulse



Before



After

300 T movie.mov

800 Tesla

800 Tesla: H_{c2} of YBCO

800T movie.mov

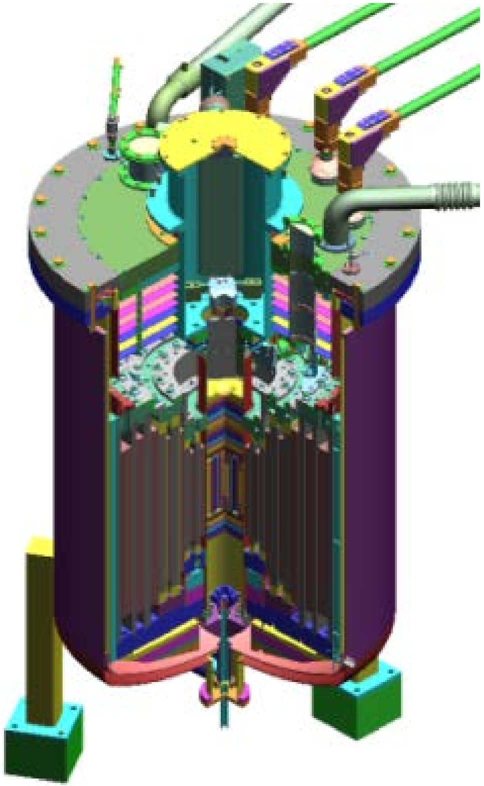
100 Tesla

The greater accomplishment:

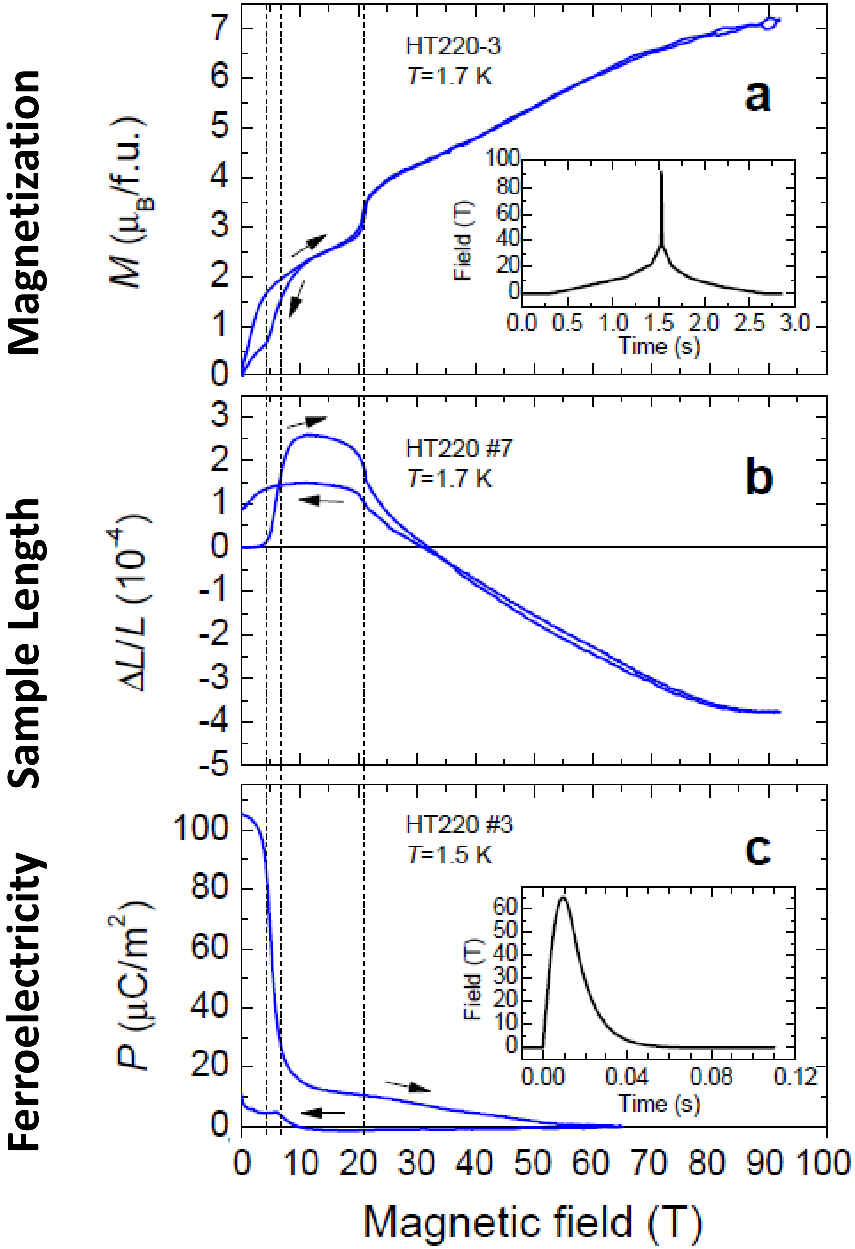
A 100 Tesla magnet that does *not* explode

Maximize useful measurements

Milliseconds



What can you measure in a few milliseconds?



Frustrated Ca_3CoMnO_6

Magnetization

10-100x less sensitive than in DC magnets

Sample Length (magnetostriction)

Comparable to DC measurements

1 part in 10^6 to 10^7 magnetostriction

Ferroelectricity

10-1,000x MORE sensitive than DC magnets

Acknowledgements

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