# Vector-Chiral Multiferroic $\beta$-$TeVO_4$:

# Control of a Polar Order via Magnetic Field

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Helmuth Berger – sample synthesis

HRZZ IP-2018-01-2730
HRZZ IP-2013-11-1011

HrZZ Croatian Science Foundation

KaCIF
KRIOGENI °CENTAR INSTITUTA ZA FIZIKU

User facilities:

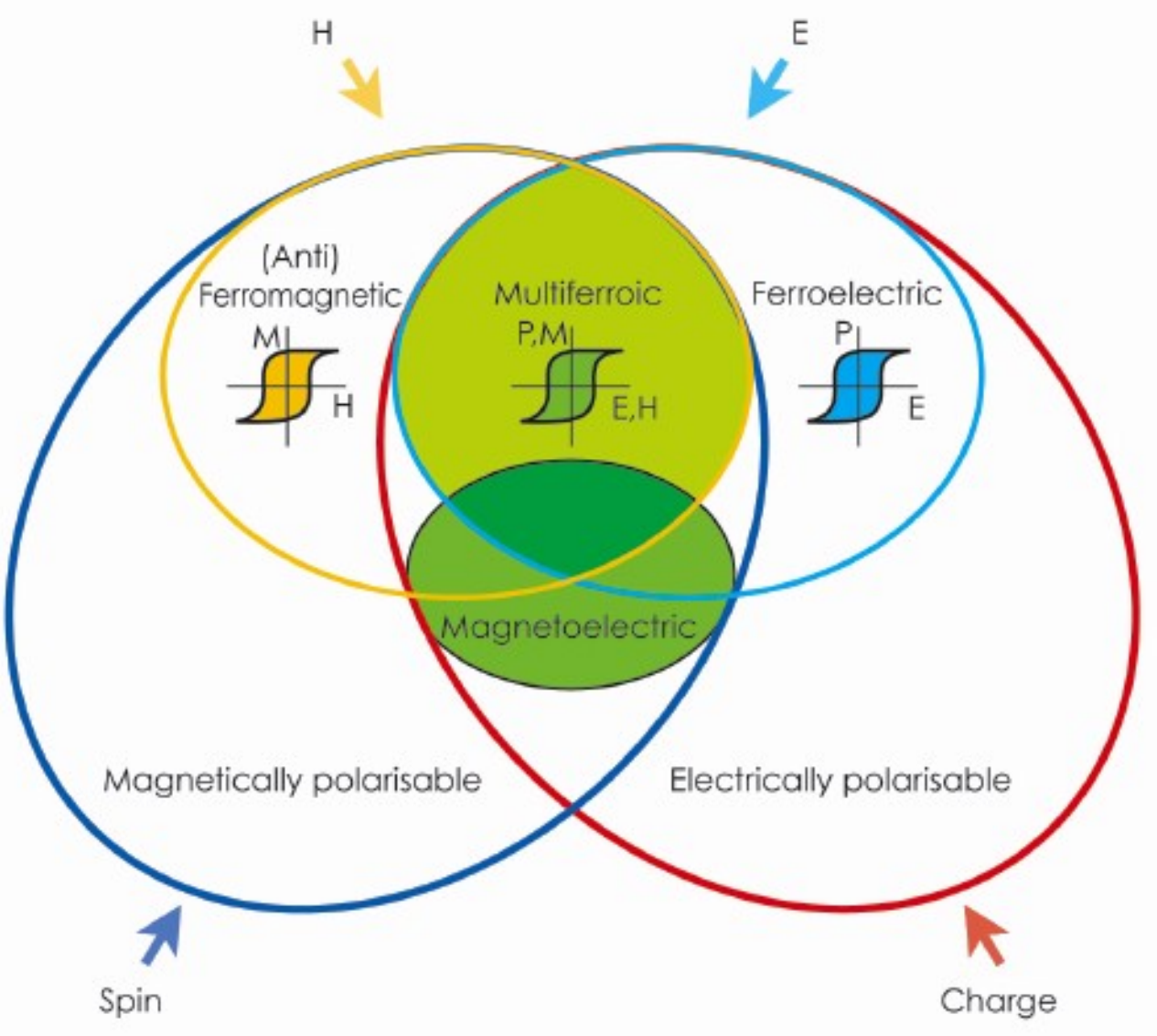
- magnetotransport
- dc & ac magnetization, SQUID
- specific heat
- ...
- temperatures down to **~ 10 mK**
- magnetic fields up to **20 T**
- hydrostatic pressure

Expanded cryogenic/LHe infrastructure

Prototype workshop

PI-3: Damir Dominko et al., Bulk-like thin films of blue bronze

PI-6: Virna Kisiček et al., Linear magnetoelectric effect in multidomain antiferromagnet $Cu_3TeO_6$




**Multiferroic:**
More than one ferroic order

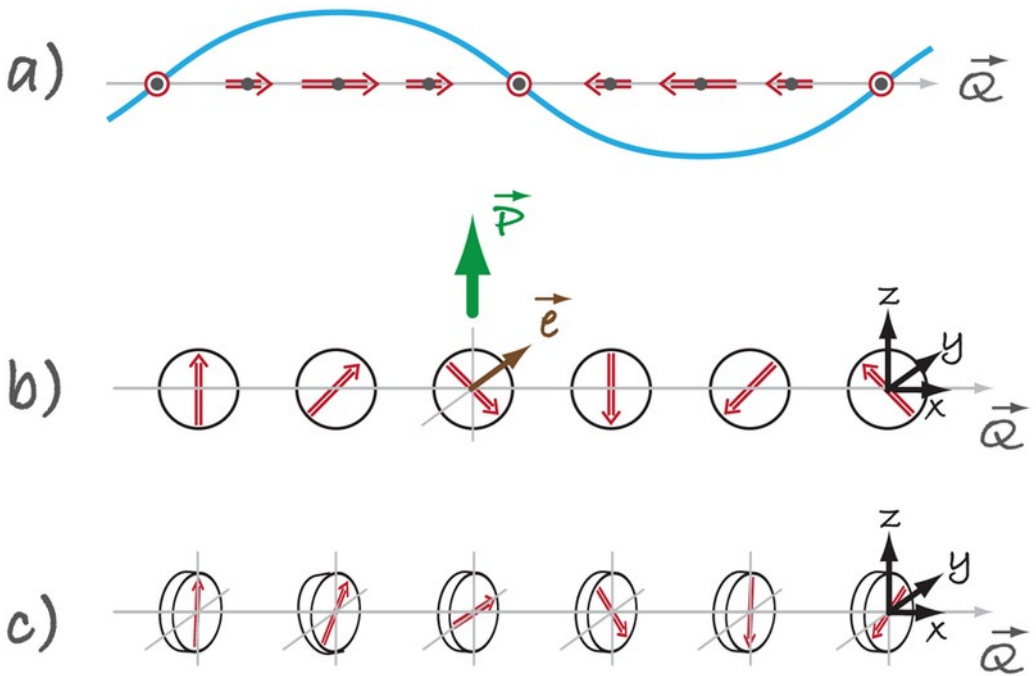
**Magnetoelectric:**
**H** induces **P**,
**E** induces **M**

Khomskii, Physics 2, 20 (2009)

Mochizuki et al., J. Phys.: Condens. Matter 27, 503001 (2015)

Spiral or toroidal AFM
+
Frustrated interactions

→ Static electric polarization



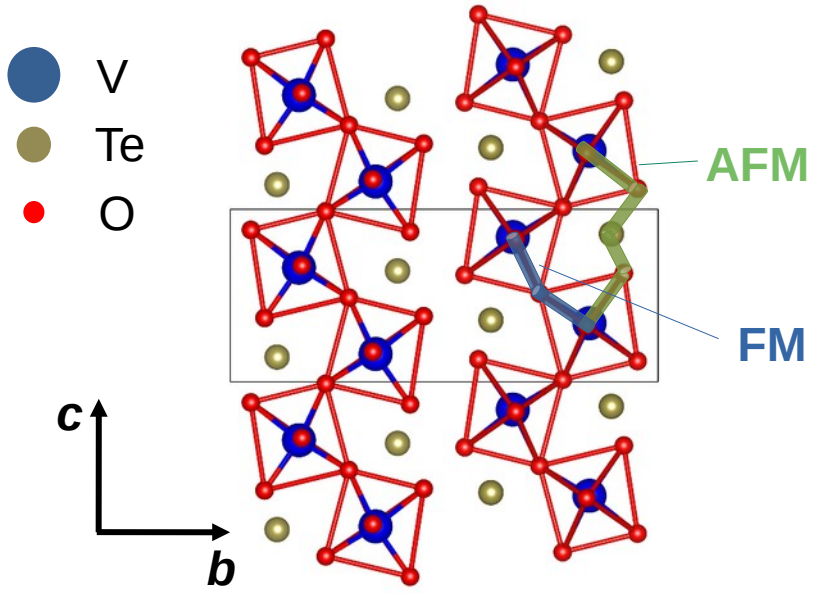

SDW: centrosymmetric

Cycloidal spiral: nonzero P

Proper screw spiral: not centrosymmetric, but often P=0

Khomskii, Physics 2, 20 (2009)

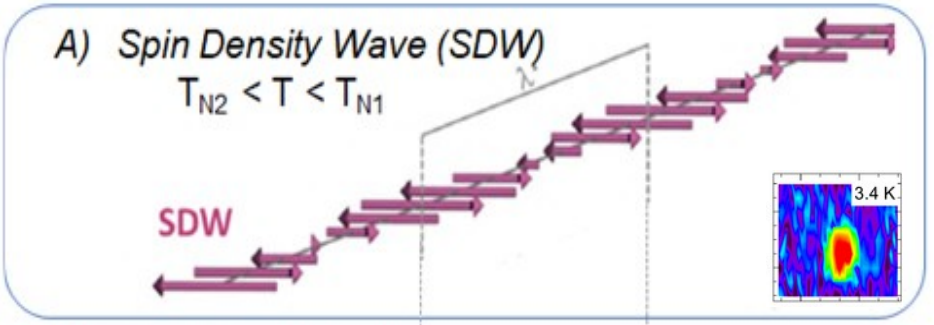
# $\beta$-$TeVO_4$ – zig-zag spin chains




**Frustrated**, **anisotropic** interactions between V spins

Saul et al, Phys. Rev. B 89, 104414 (2014).
Savina et al, Phys. Rev. B 84, 104447 (2011).

# $\beta$-$TeVO_4$ magnetic phases




$T_{N1}$ ~ 4.6 K


Savina et al., Phys. Rev. B 84, 104447 (2011).

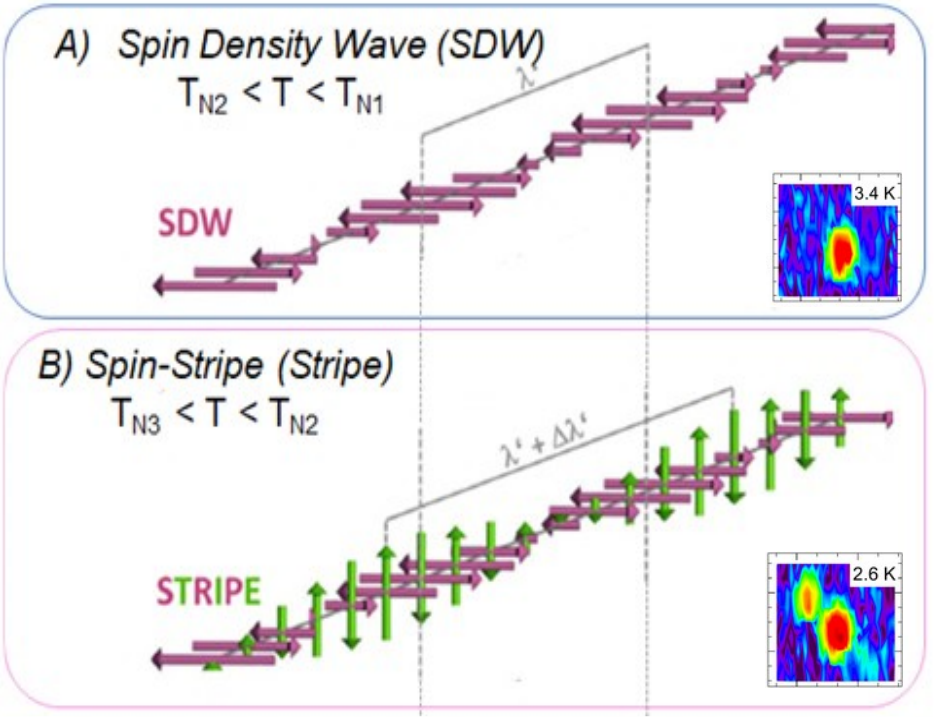
Pregelj et al., Nat. Comm. 6 (2015), 10.1038/ncomms8255.

Savina et al. Low Temp. Phys 41, 283, (2015)

Pregelj et al., Phys. Rev. B 94, 081114 (2016)

Herak et al., Physical Review B 102, 024422 (2020).

# $\beta$-$TeVO_4$ magnetic phases




$T_{N1}$ ~ 4.6 K

$T_{N2}$ ~ 3.3 K


Savina et al., Phys. Rev. B 84, 104447 (2011).

Pregelj et al., Nat. Comm. 6 (2015), 10.1038/ncomms8255.

Savina et al. Low Temp. Phys 41, 283, (2015)

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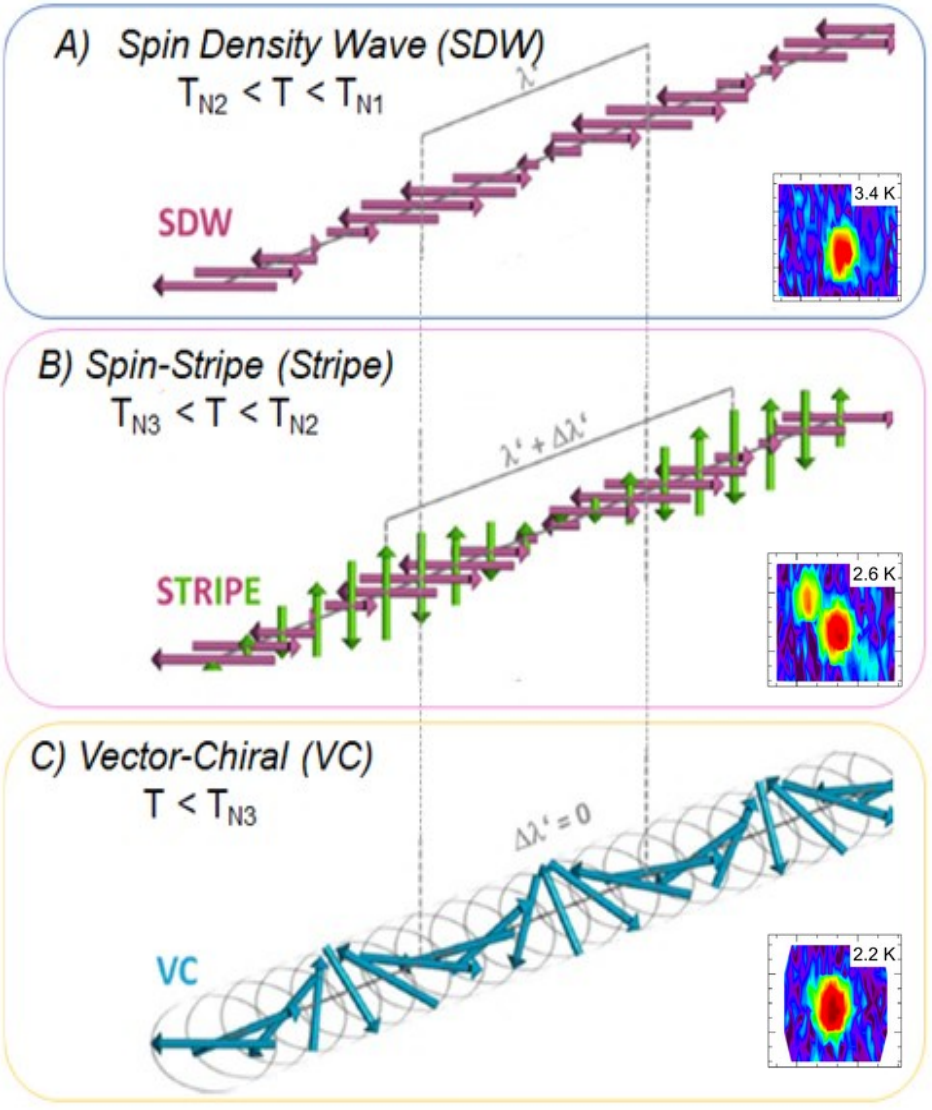
# $\beta$-$TeVO_4$ magnetic phases




$T_{N1}$ ~ 4.6 K

$T_{N2}$ ~ 3.3 K

$T_{N3}$ ~ 2.3 K


Savina et al., Phys. Rev. B 84, 104447 (2011).

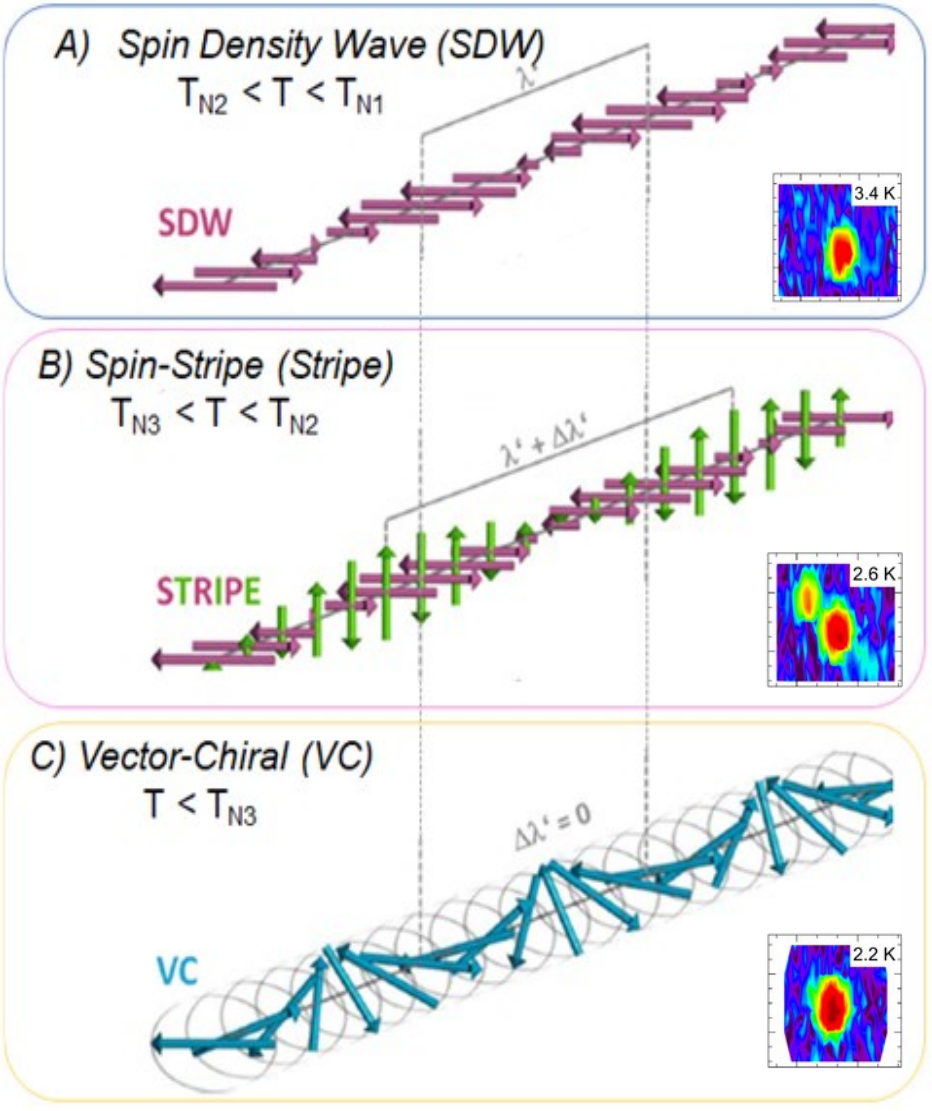
Pregelj et al., Nat. Comm. 6 (2015), 10.1038/ncomms8255.

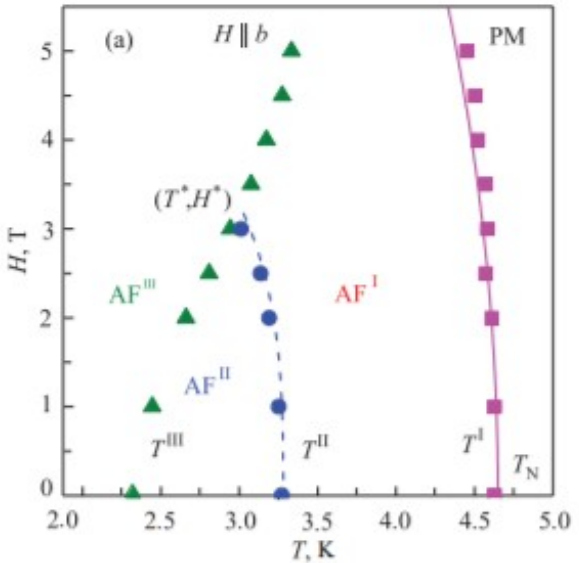
Savina et al. Low Temp. Phys 41, 283, (2015)

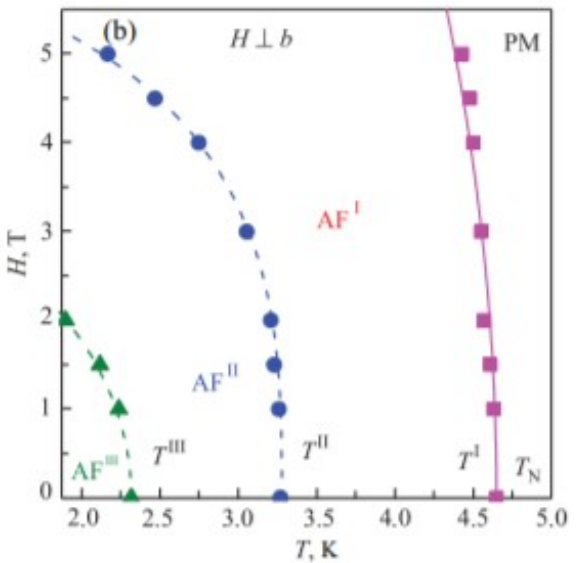
Pregelj et al., Phys. Rev. B 94, 081114 (2016)

Herak et al., Physical Review B 102, 024422 (2020).

# $\beta$-$TeVO_4$ magnetic phases





Savina et al., Phys. Rev. B 84, 104447 (2011).

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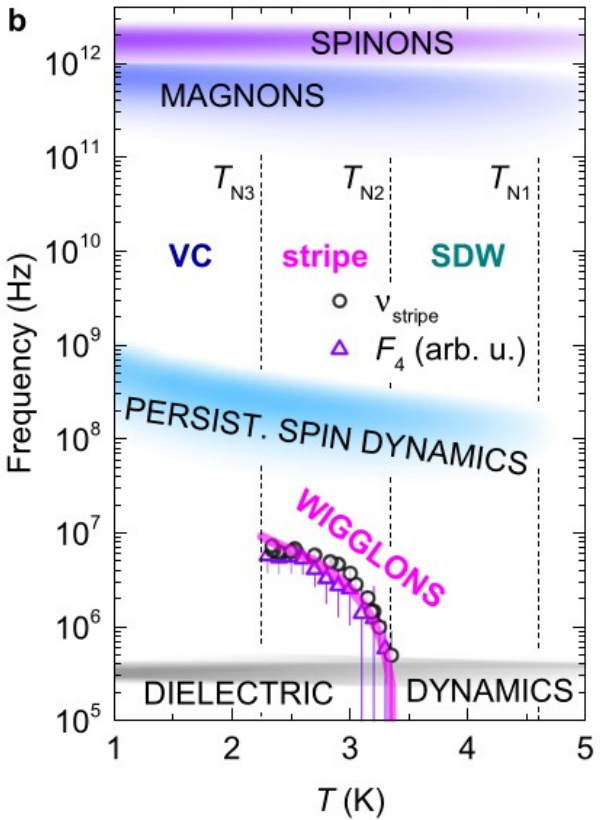
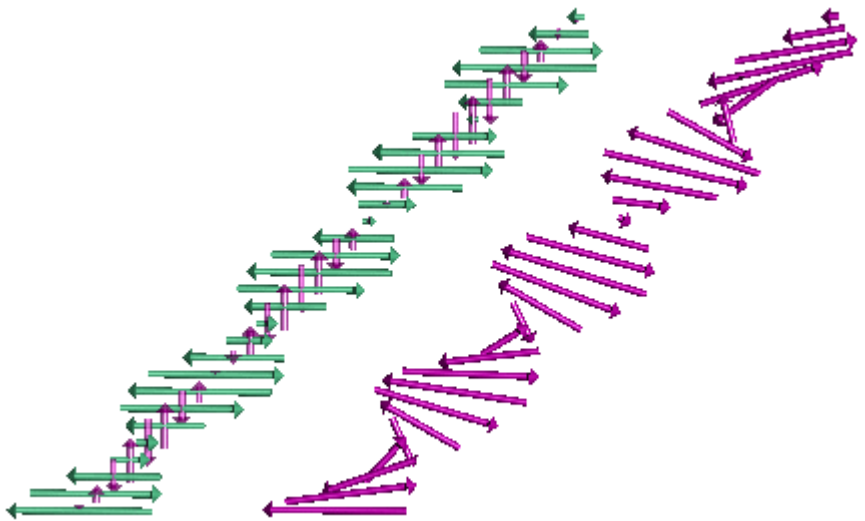
Savina et al. Low Temp. Phys 41, 283, (2015)

Pregelj et al., Phys. Rev. B 94, 081114 (2016)

Herak et al., Physical Review B 102, 024422 (2020).

# Spin-stripe phase: „Wigglon” dynamics



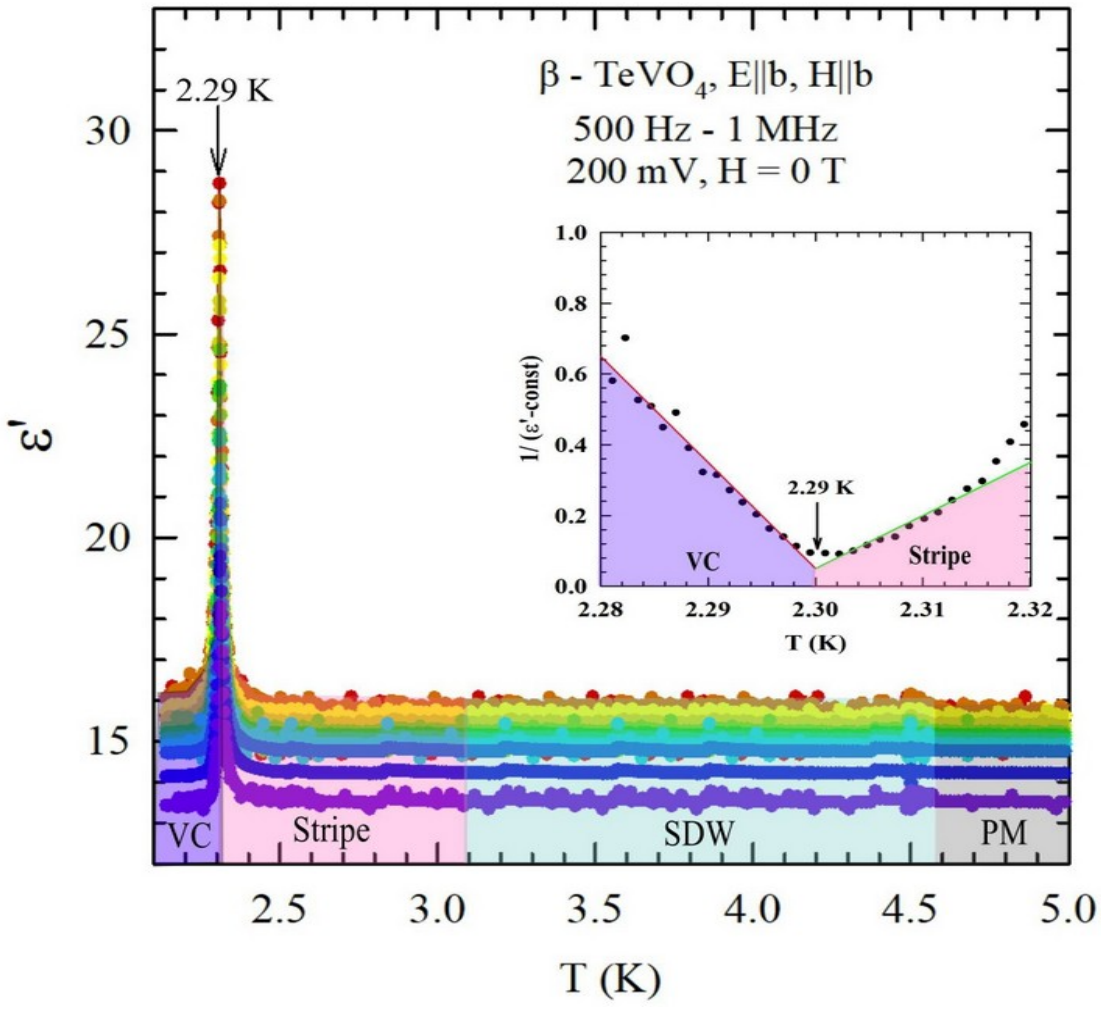



A gapped, two-phason excitation

Pregelj et al., npj Quantum Materials 4, 22 (2019).

# AC dielectric response

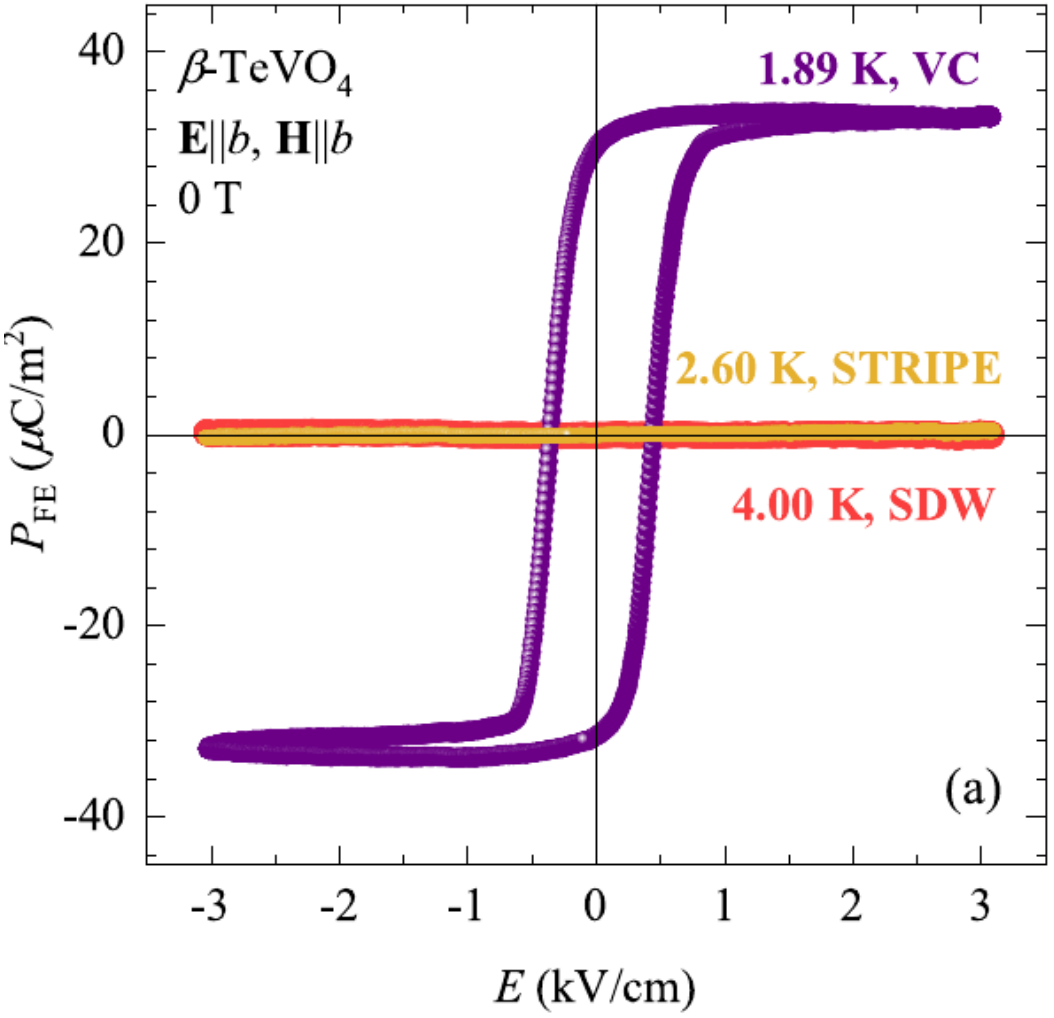
- Curie-Weiss-like peak at the **vector-chiral** phase transition
- **Para-to-ferroelectric?**




M. Pregelj et al., npj Quantum Materials 4, 22 (2019).

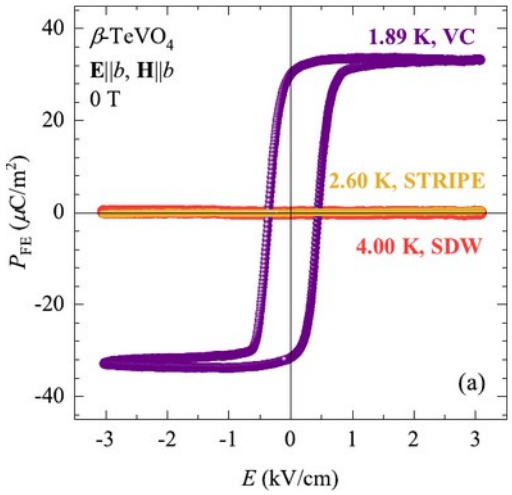
# Static electric polarization

- **P**||*b*
- **Ferroelectric hysteresis** in the vector-chiral phase



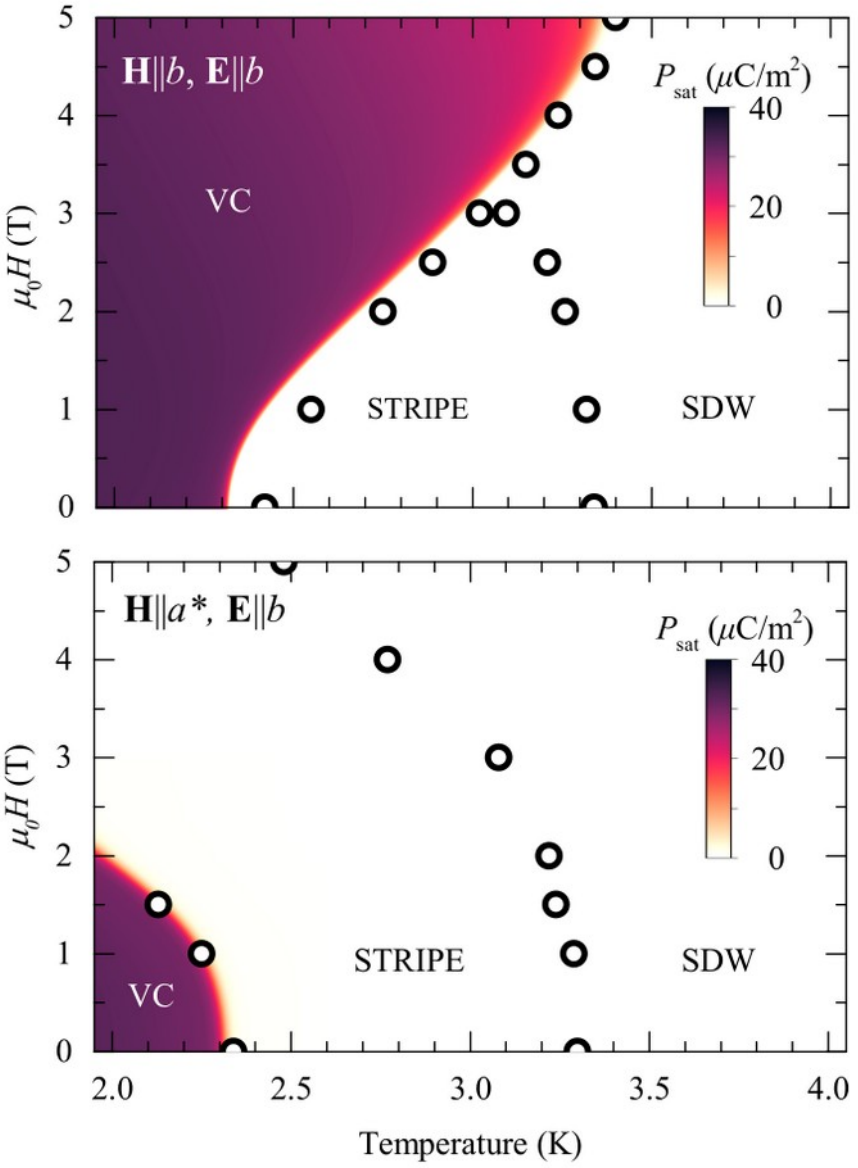

M. Dragičević, et al., Phys. Rev. B 104, L121107 (2021)

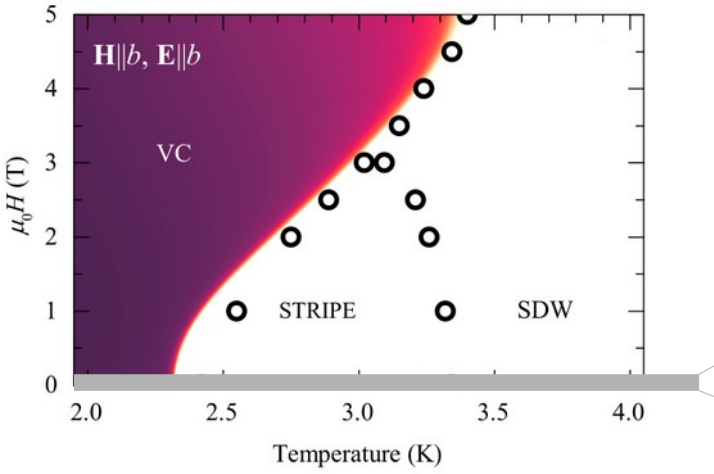
# Ferroelectric phase diagram

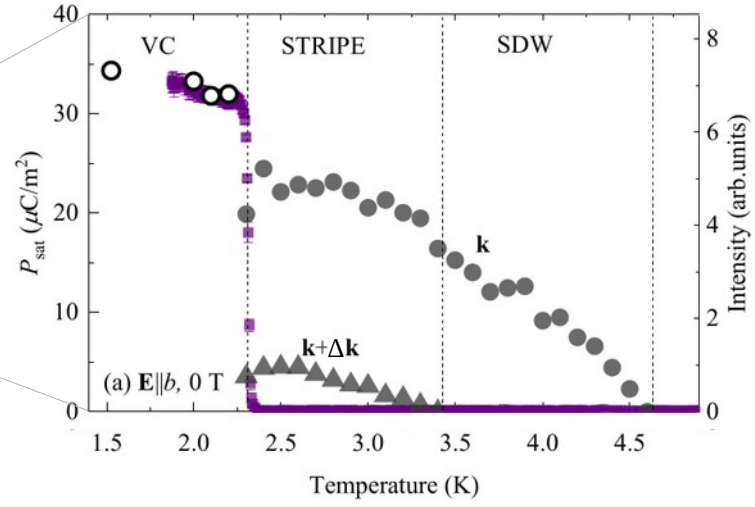


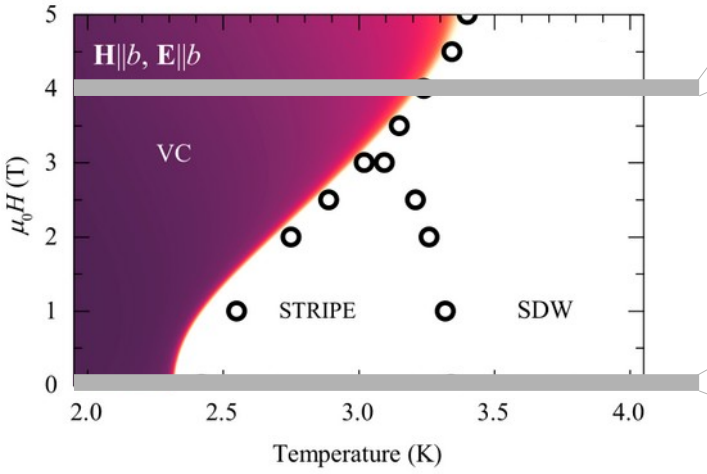

$P_{sat}$

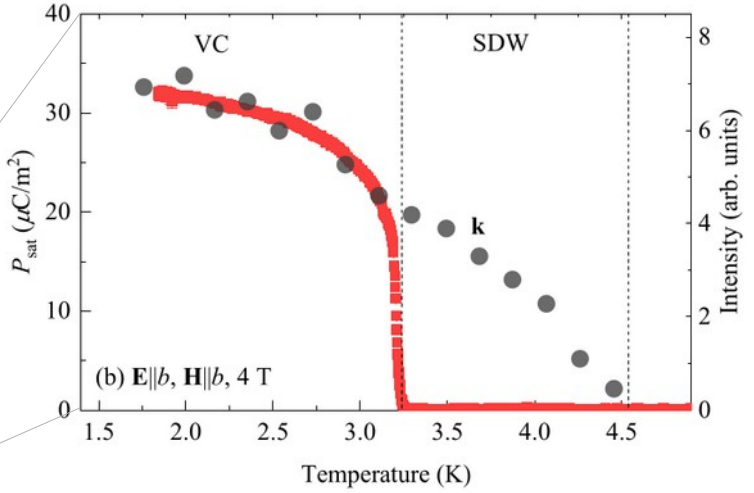
- Highly anisotropic response
- Matches the magnetic phase diagram
- Relation of FE to vector-chiral ordering?

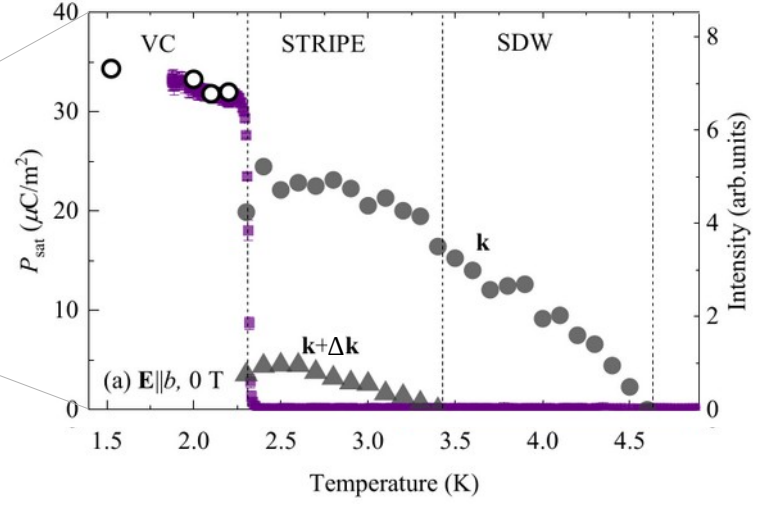



H||b, E||b
VC
STRIPE
SDW
$\mu_0 H$ (T)
Temperature (K)

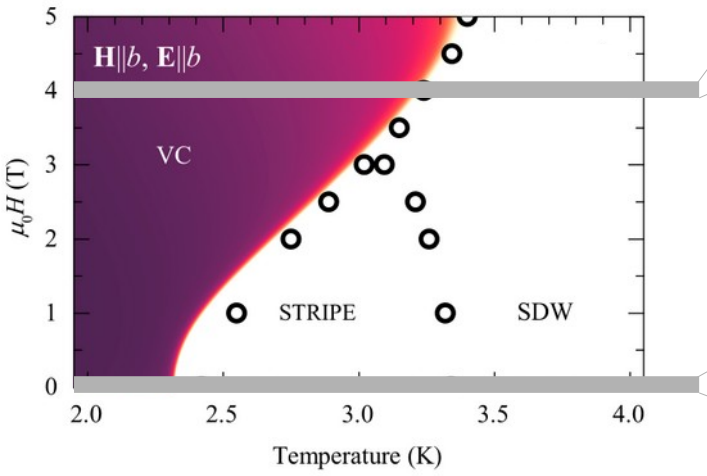

VC
STRIPE
SDW
k
k+Δk
(a) E||b, 0 T
$P_{sat}$ ($\mu$C/m$^2$)
Intensity (arb.units)
Temperature (K)

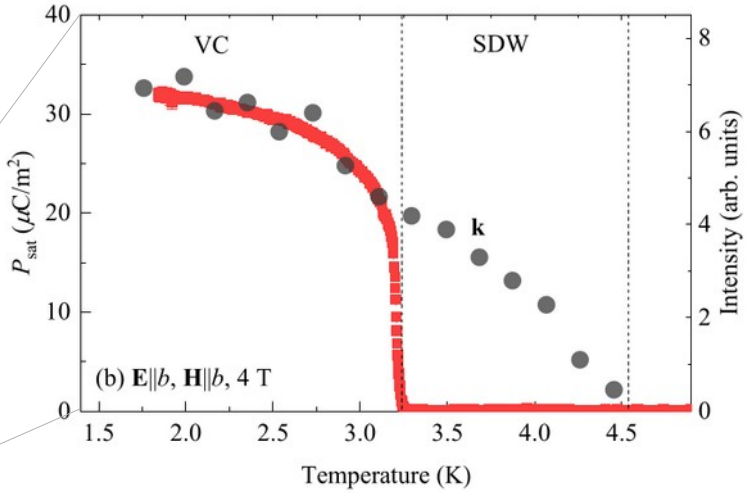

H||b, E||b
VC
STRIPE
SDW
$\mu_0 H$ (T)
Temperature (K)

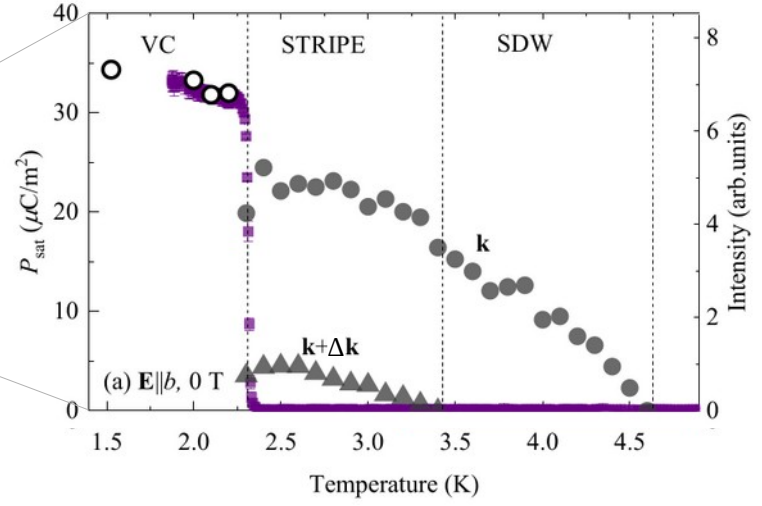

VC
SDW
k
(b) E||b, H||b, 4 T
$P_{sat}$ ($\mu$C/m$^2$)
Intensity (arb. units)
Temperature (K)


VC
STRIPE
SDW
k
k+Δk
(a) E||b, 0 T
$P_{sat}$ ($\mu$C/m$^2$)
Intensity (arb.units)
Temperature (K)

# FE order parameter
# =
# magnetic order parameter

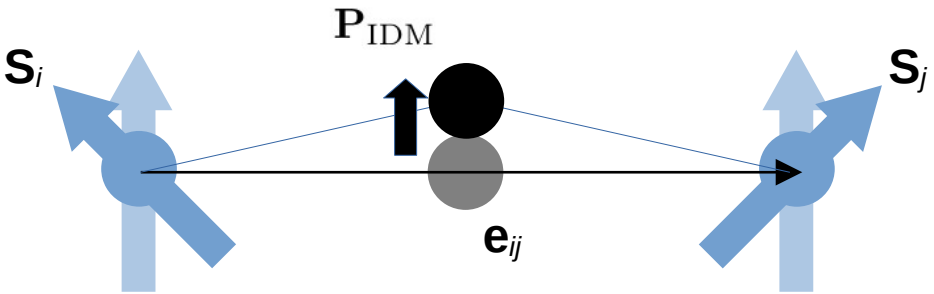


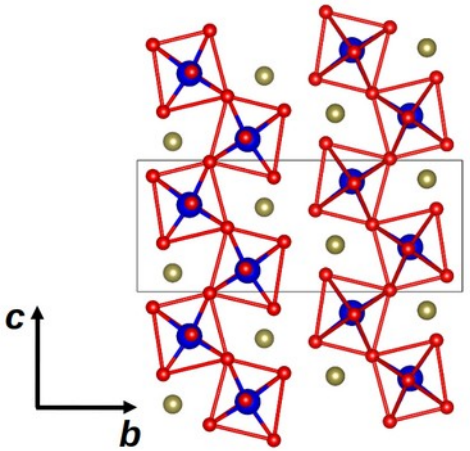
# Inverse Dzyaloshinskii-Moriya interaction

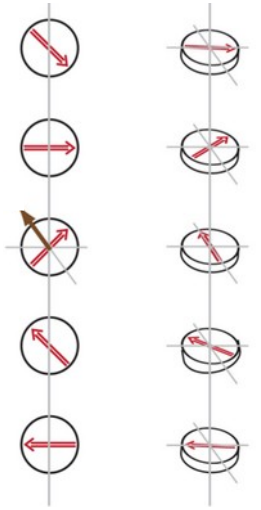
- Also found in: $TbMnO_3$, $MnWO_3$, $MnSb_2S_4$...




$$\mathbf{P}_{\mathrm{IDM}} \propto \sum_{\text{pairs } (i,j)} \gamma \mathbf{e}_{ij} \times (\mathbf{S}_i \times \mathbf{S}_j)$$

$$\propto \hat{\mathbf{b}}$$ in VC phase!



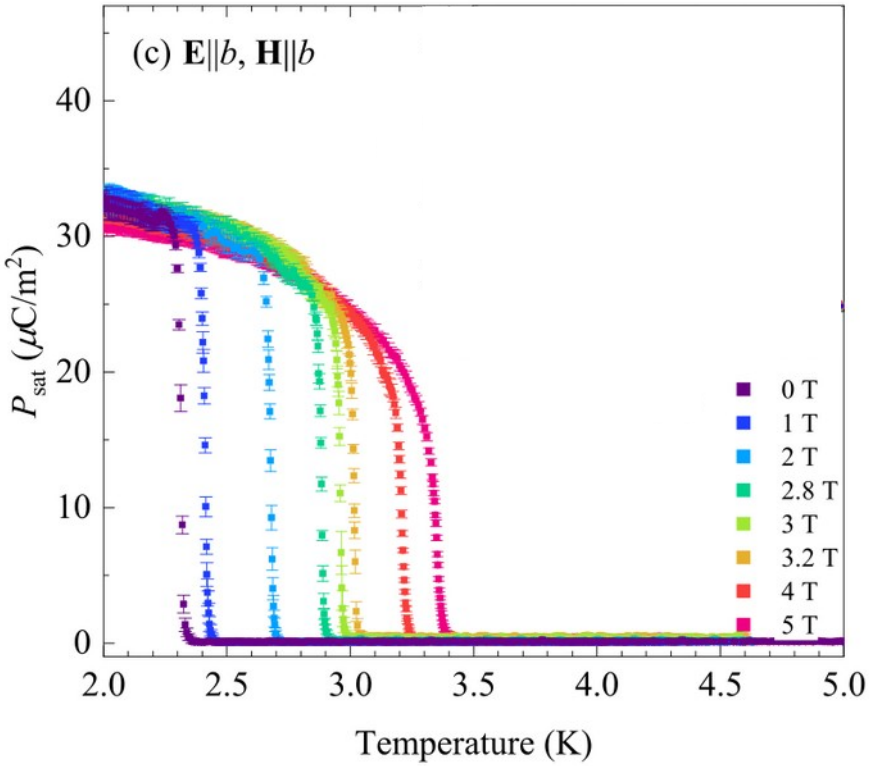



*bc* spiral
**P** ≠ 0

*ab* spiral
**P** = 0

# Not a linear magnetoelectric

- $\mathbf{P}_{sat}$ does not depend significantly on **H**

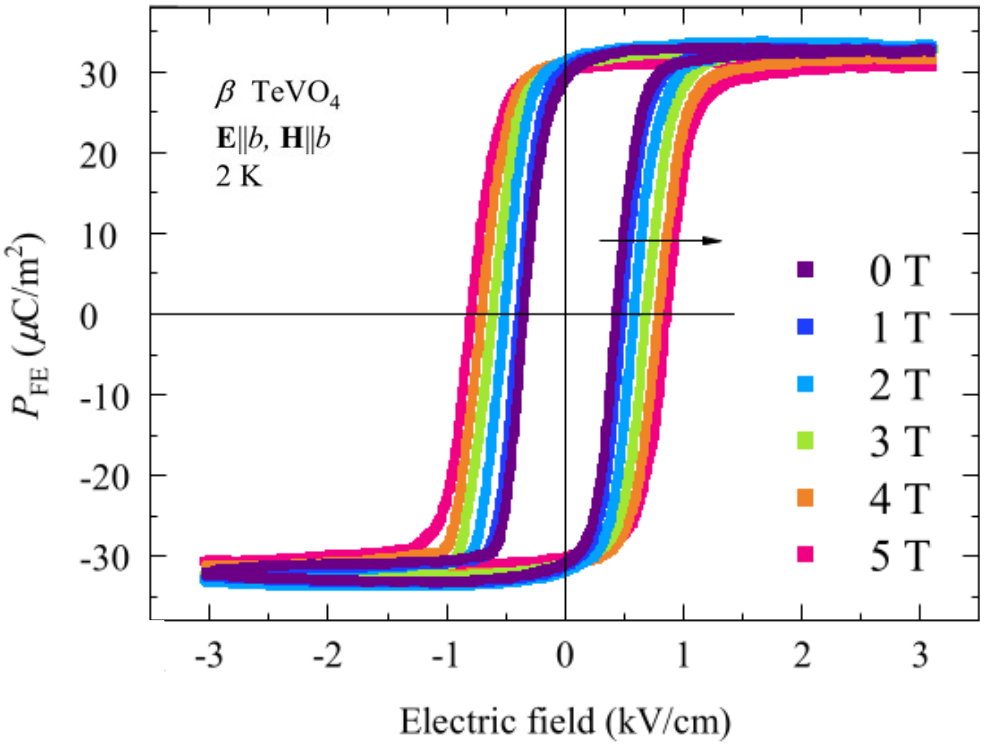


# Electric coercive field

- Coercive field: field required to set the polarization to zero

- Increasing $E_c$:
  - **stronger pinning** of domain walls,
  - **weaker mobility** of domain walls,
  - **less wide** domain walls

- Hysteresis width is not constant
- Promotion of VC phase **hardens** the FE!

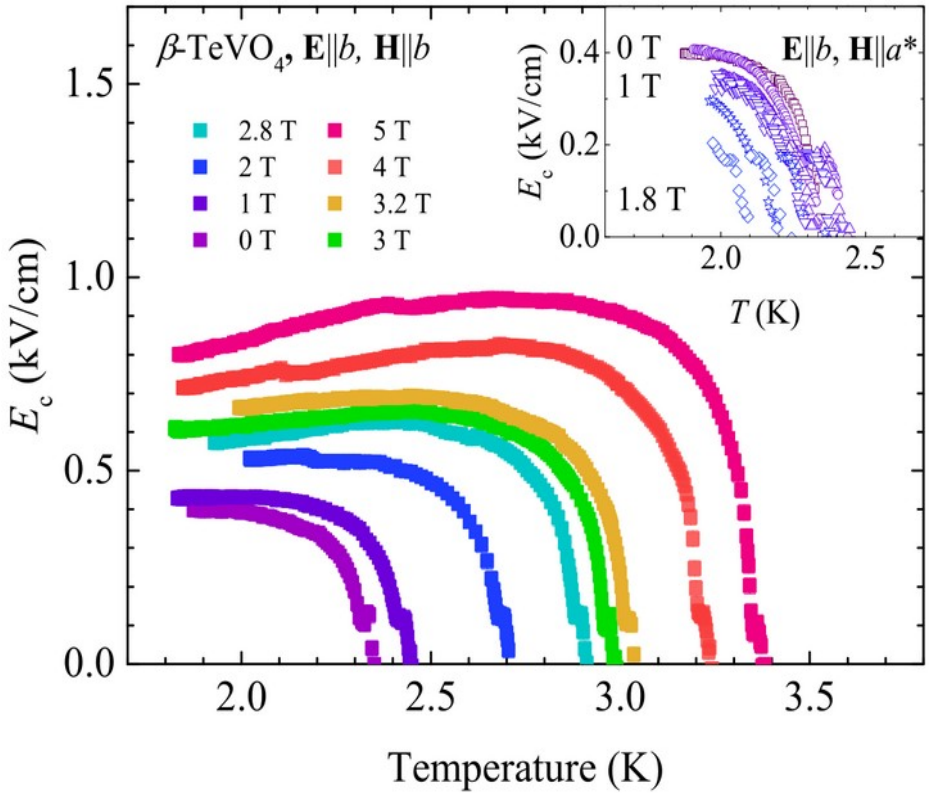


# Nonlinear magnetoelectric effect

- VC phase is **not fully developed** even at lowest temperatures: it is still susceptible to applied *H*!

- **EHH term** in free energy is consistent with IDM

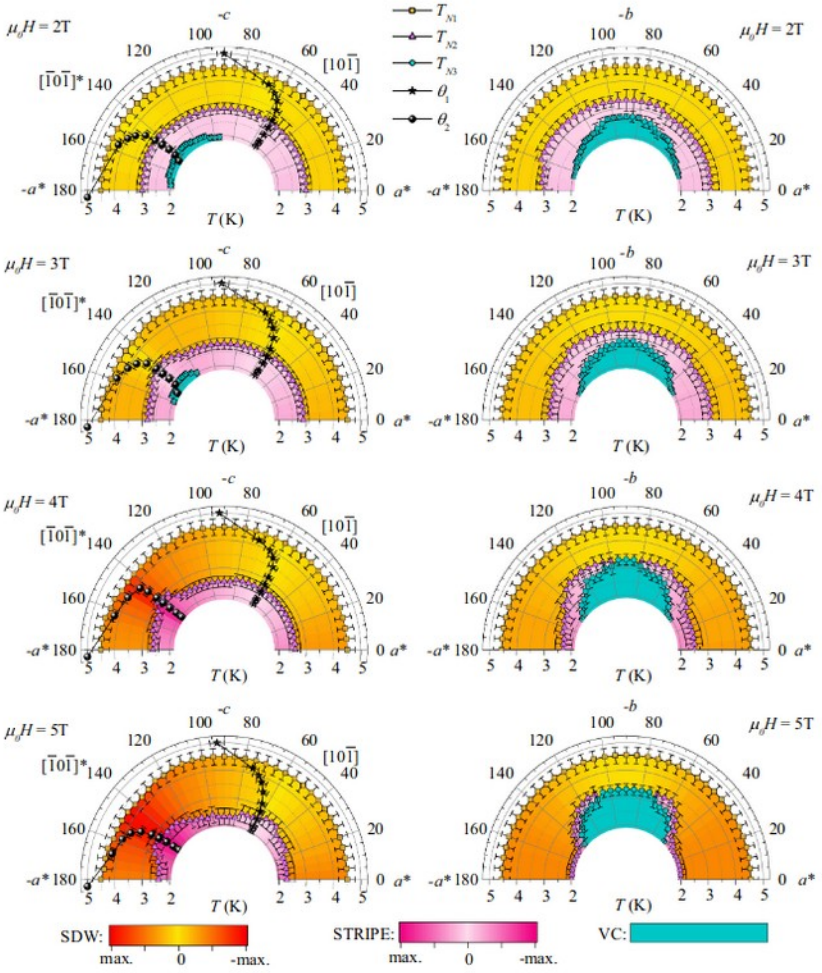
- suppression of VC softens FE
- similar to $TbMnO_3$ or $MnWO_4$, but those compounds undergo polarization flop and field-induced spin reorientation with *H*

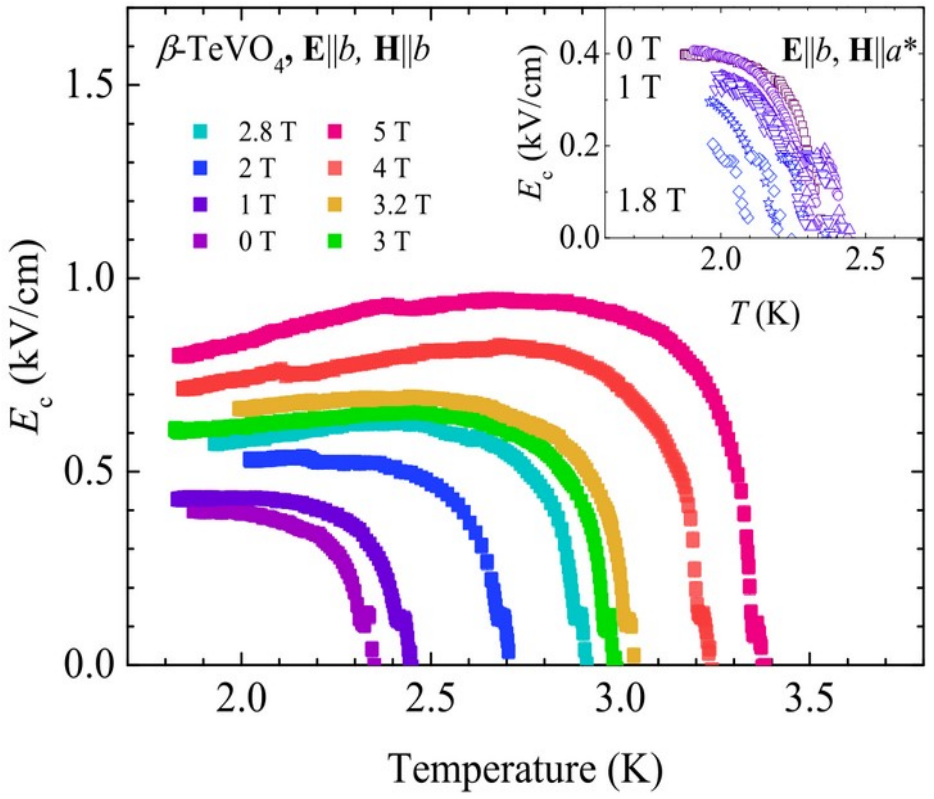




M. Dragičević, et al., Phys. Rev. B 104, L121107 (2021)
M. Herak et al., PRB 102, 024422 (2020).
K. Taniguchi et al., PRL 97, 097203 (2006).

# Nonlinear magnetoelectric effect

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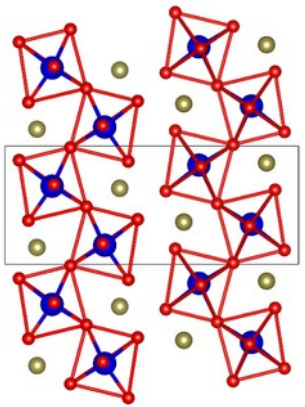
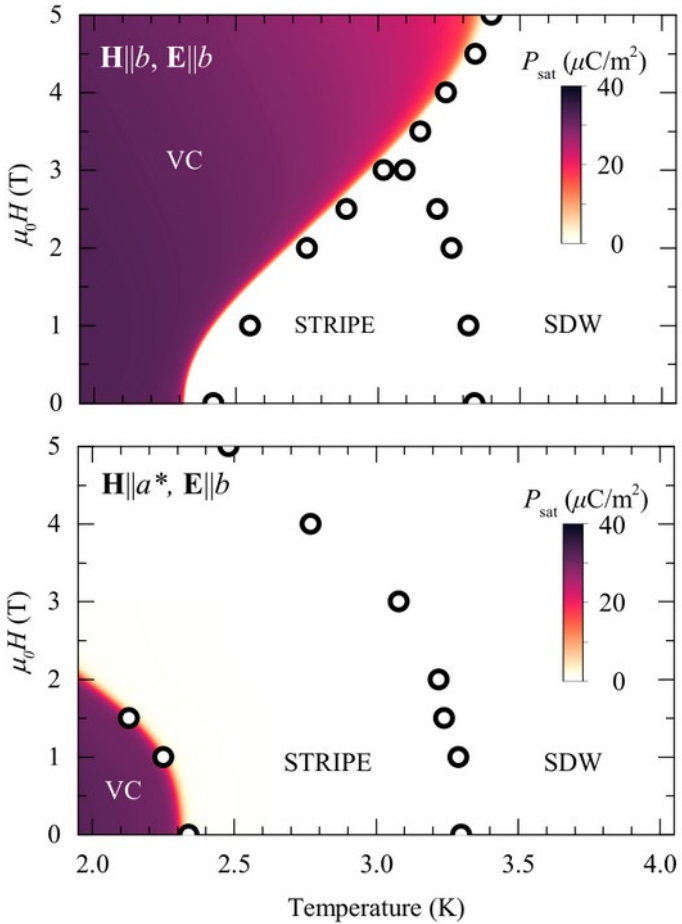
# $\beta$-$TeVO_4$ – frustrated zig-zag spin chain

- **Vector-chiral** ground state is **ferroelectric**
- VC domain = FE domain

- **Chiral-FE domain population** is controlled via **E**

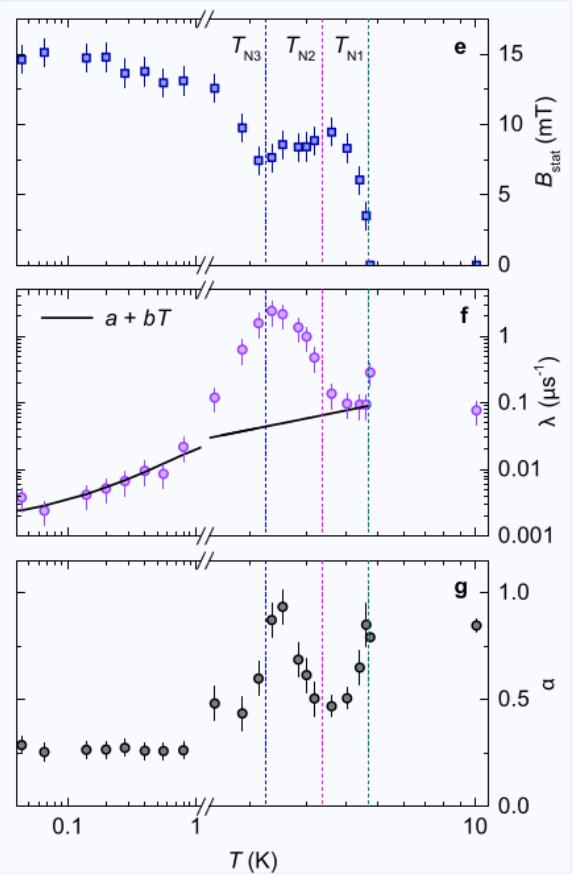
- **Stability of chiral-FE information** is controlled via **H**



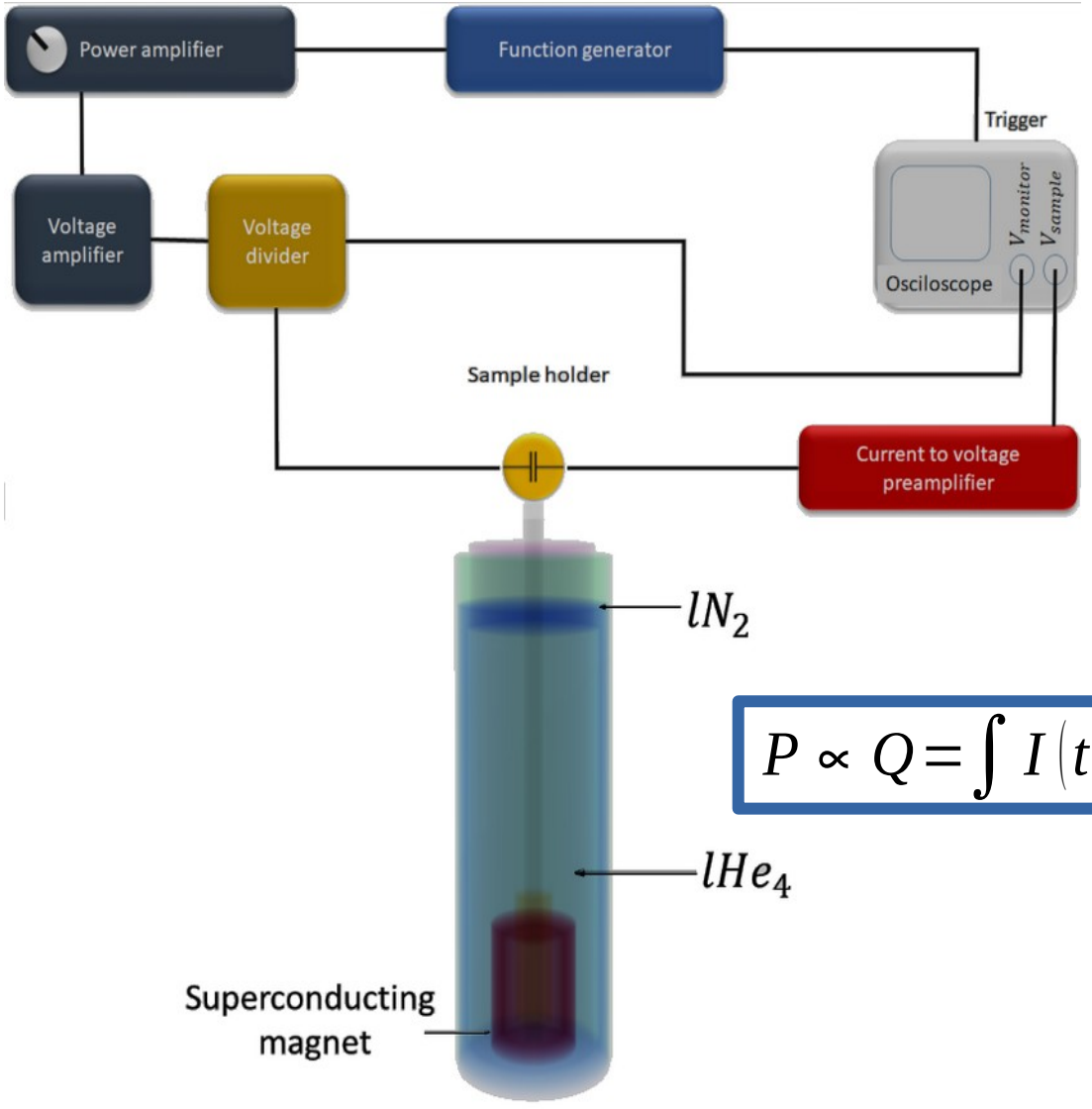



M. Dragičević, et al., Phys. Rev. B 104, L121107 (2021)

# Spin-stripe phase: μSR




Pregelj et al., npj Quantum Materials 4, 22 (2019).




$$P \propto Q = \int I(t)\,dt$$

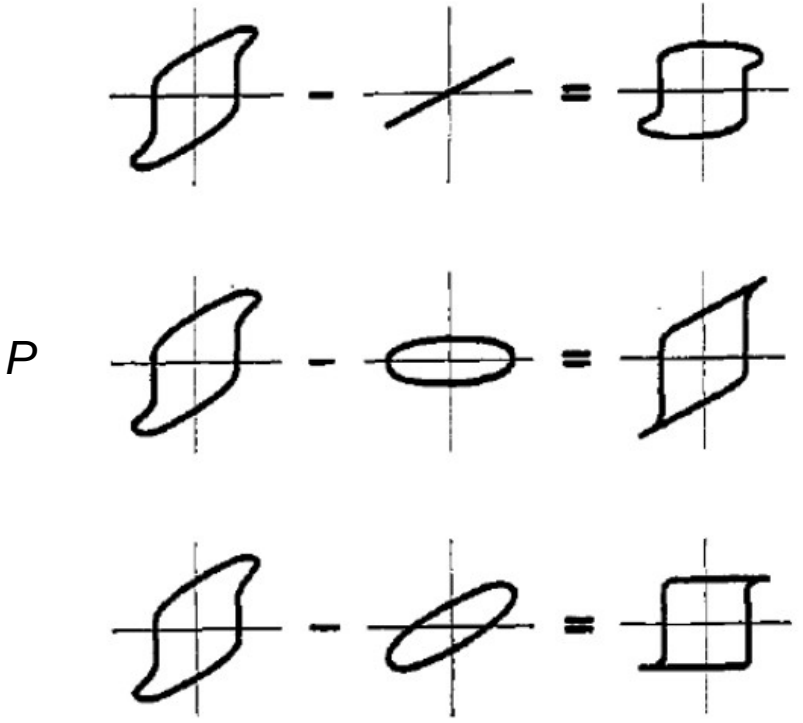
# Static electric polarization setup

- Sine signal generator Tabor 8023
- Amplifier & transformer
- Current preamp SR570
- Oscilloscope

# Static electric polarization

**Static electric polarization**
**Sawyer-Tower circuit (home-made)**
**0-20 kV/cm**

$$P \propto Q = \int I(t)\,dt$$




Ž. Rapljenović, D. Altus