# Stripes developed at the strong limit of nematicity in FeSe film

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# Acknowledgements

## Tsinghua University

Prof. Qi-Kun Xue, Prof. Xi Chen, Dr. Peng Deng, Zhilin Xu, Dr. Hao Ding

**Xue Group members**

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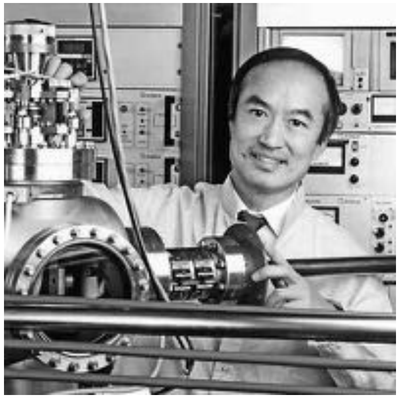
1. Techniques and Examples
2. Introduction
3. Stripes in FeSe
4. Nematicity and Stripes
5. Summary and Perspective

# Techniques and examples

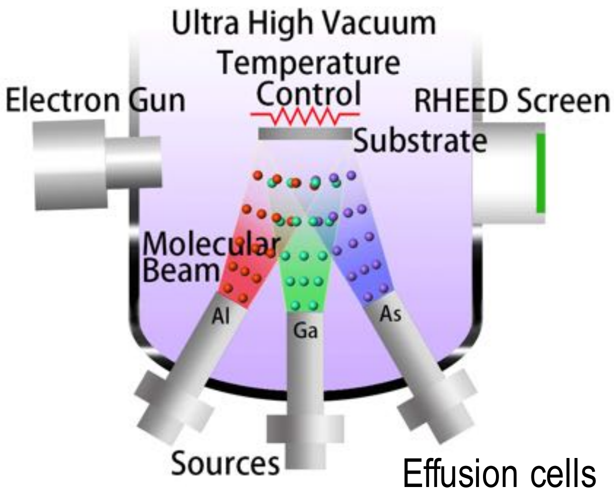
# 1

# Molecular beam epitaxy



Arthur & Cho

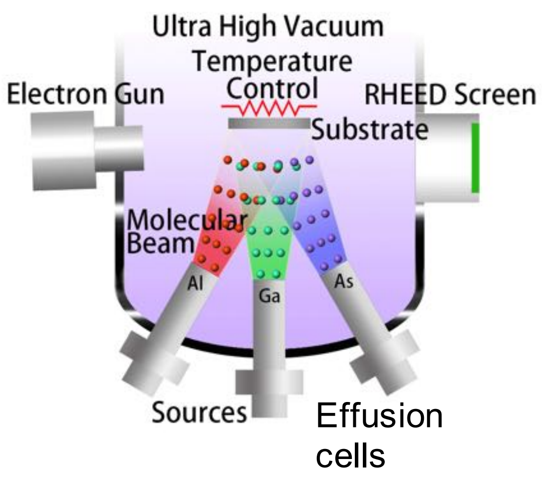
1960s, Bell Lab

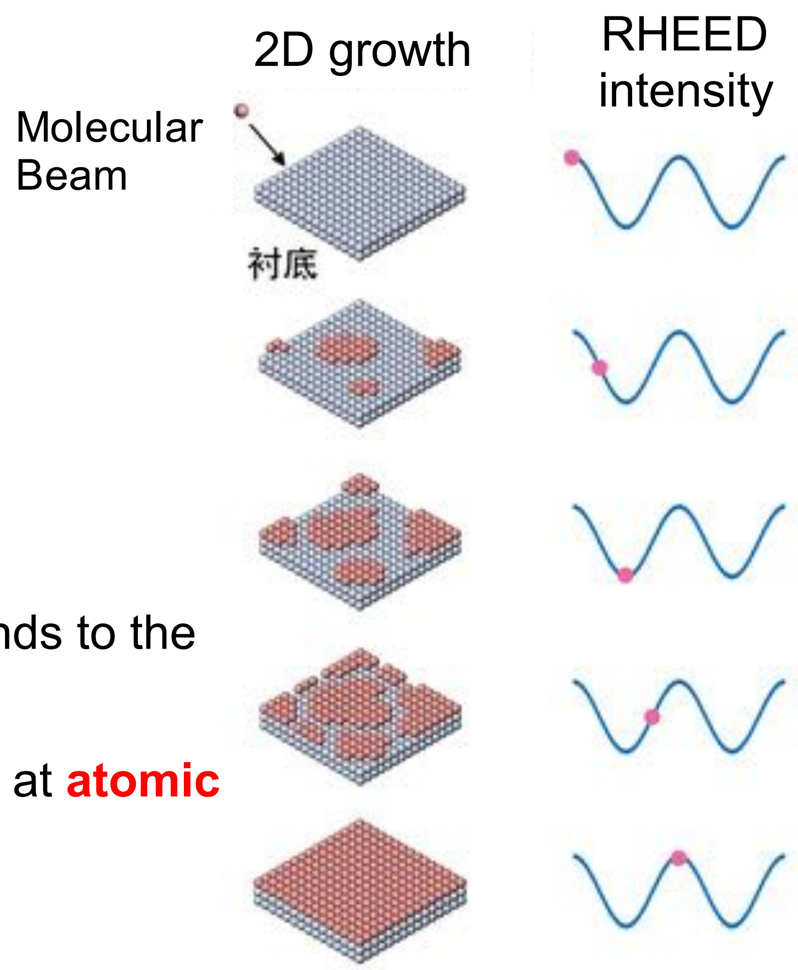



- In UHV ($10^{-11}$ Torr): to form molecular beam; ultra clean environment
- High purity sources and substrates: Si(99.9999%), Fe(99.996%)
- Precise control of the temperatures: sub & cells
- Reflection high-energy electron diffraction: Monitor the growth rate

# Molecular beam epitaxy

Reflection high-energy electron diffraction

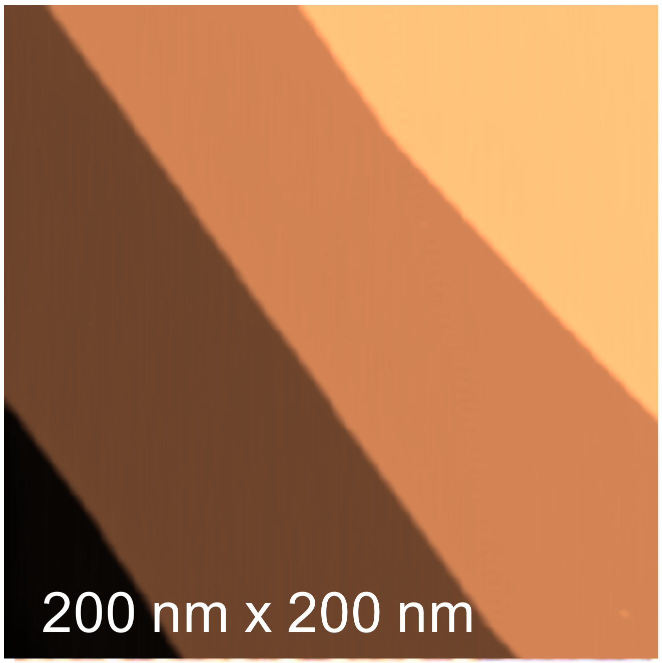


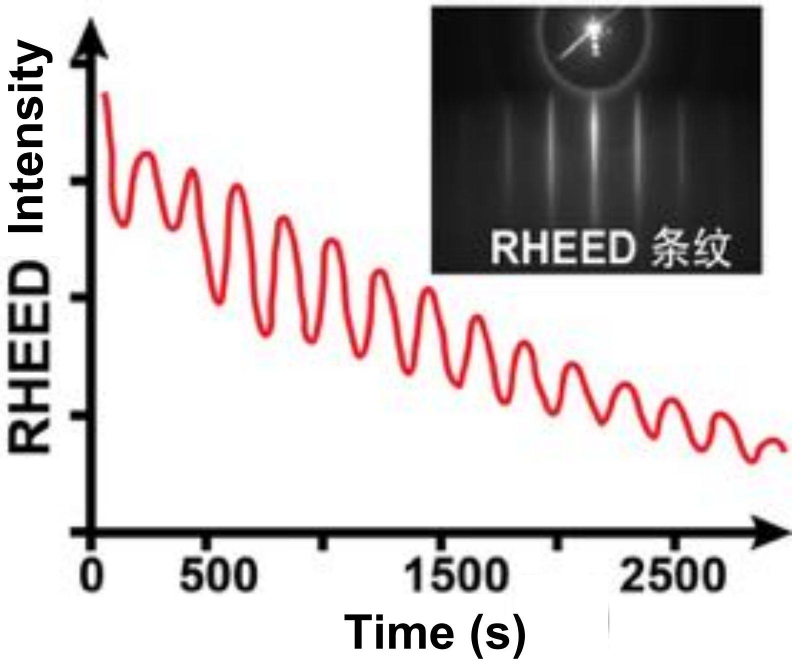

- Oscillation frequency corresponds to the growth rate
- Design and construct materials at **atomic** scale

# Molecular beam epitaxy

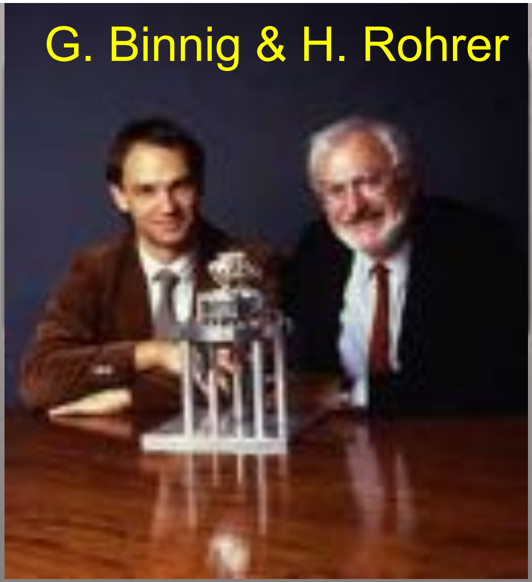
A high quality $Bi_2Se_3$ film and its RHEED oscillation

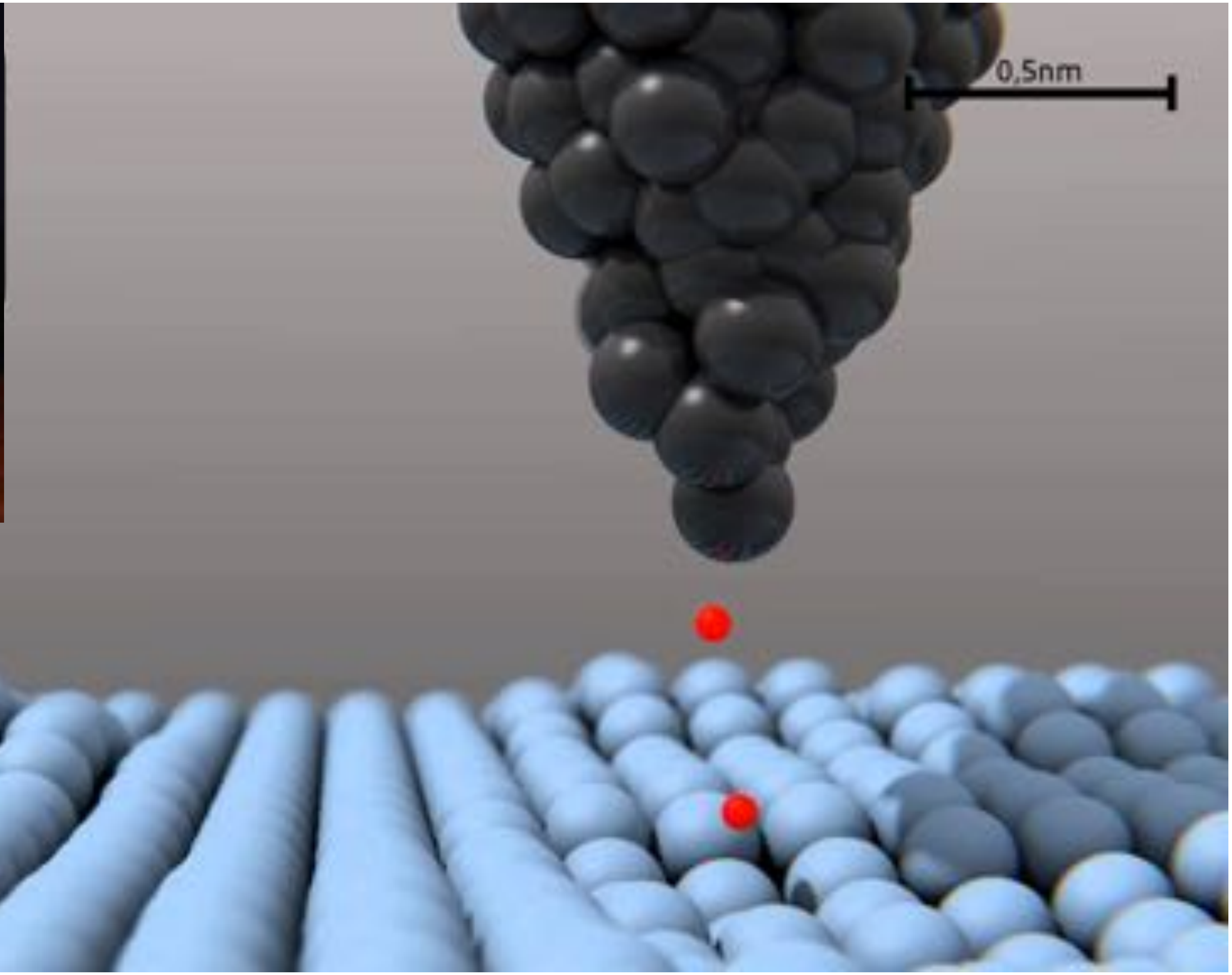



A STM topographic image



# Scanning Tunneling Microscopy

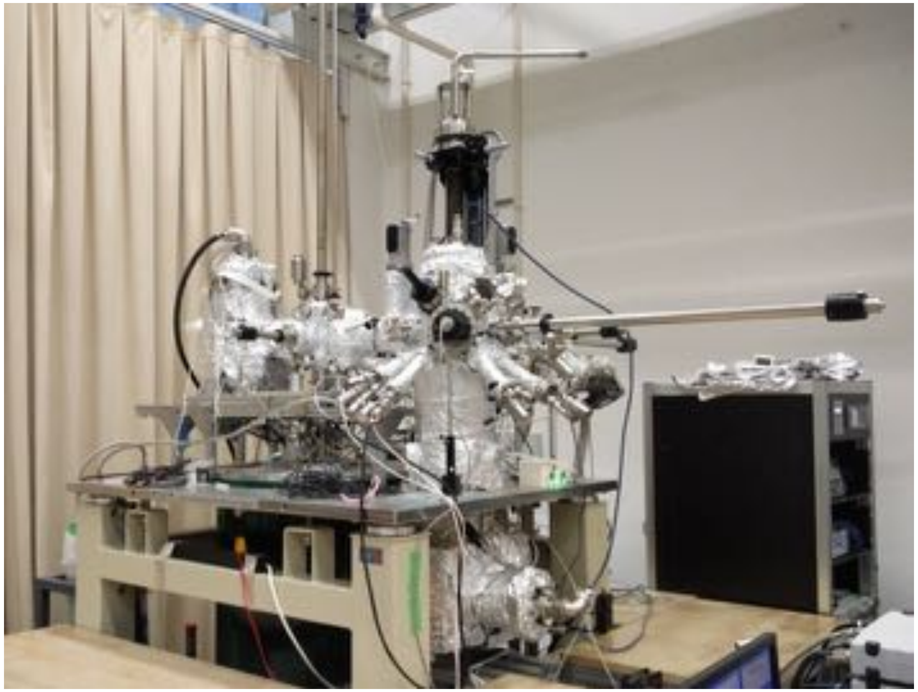


# MBE + STM + ARPES

## Design and construct materials at atomic scale

- Control the orientation of MBE-grown films
- Construct novel interfaces (doping, proximity…)
- Tune the chemical pressure of the lattice

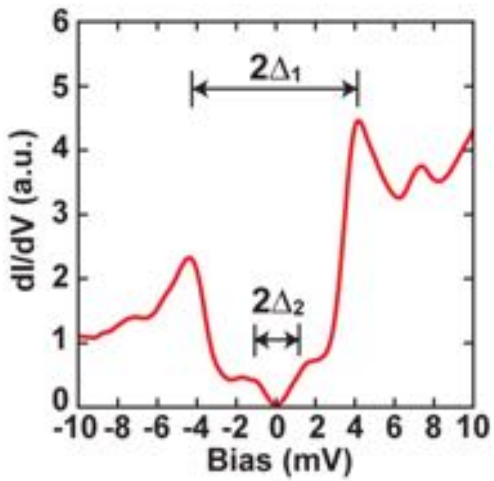


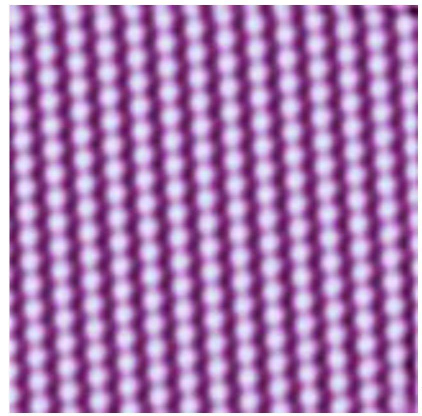
# Control the orientation of MBE-grown films

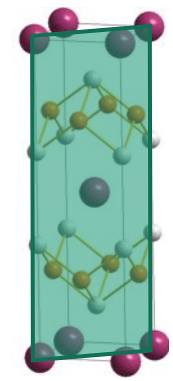
# Control the orientation of MBE-grown films

## SC and AFM **Phase separation** in $K_xFe_{2-y}Se_2$

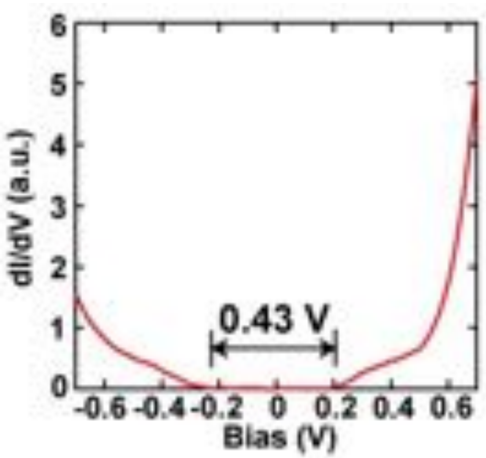
SC phase

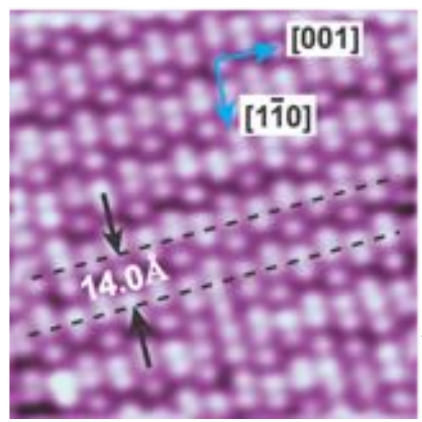


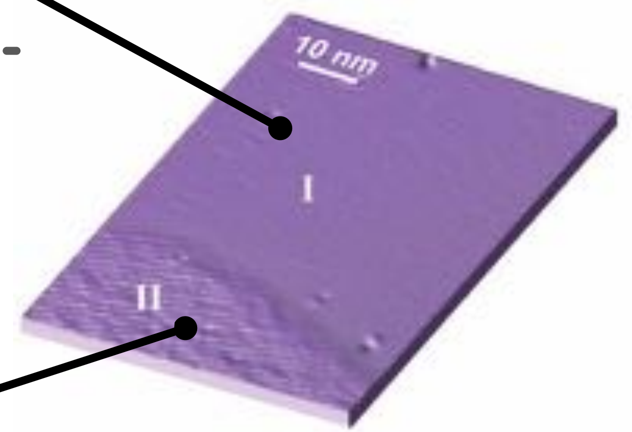





AFM phase



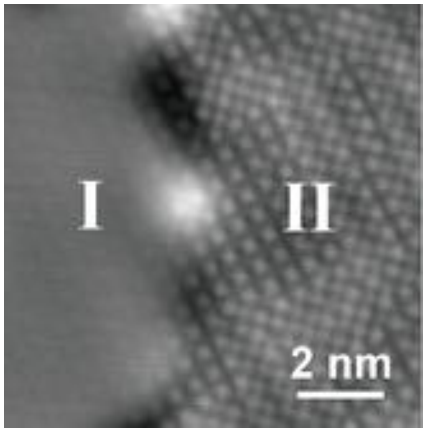



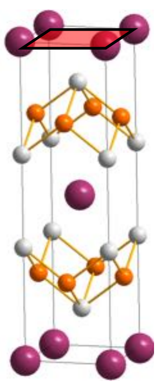

$K_xFe_{2-y}Se_2(110)$

Li, Wei *et al., Nat. Phys*. 8, 126 (2012)

# I Control the orientation of MBE-grown films

## Relationship between SC and AFM in $K_xFe_{2-y}Se_2(001)$



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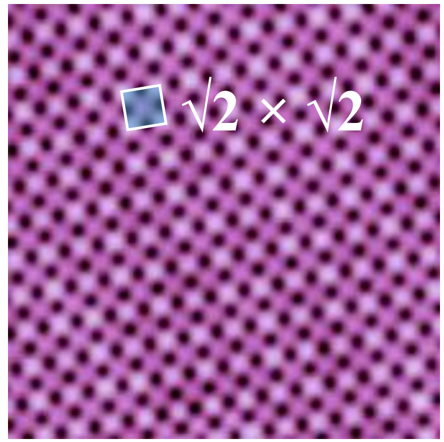
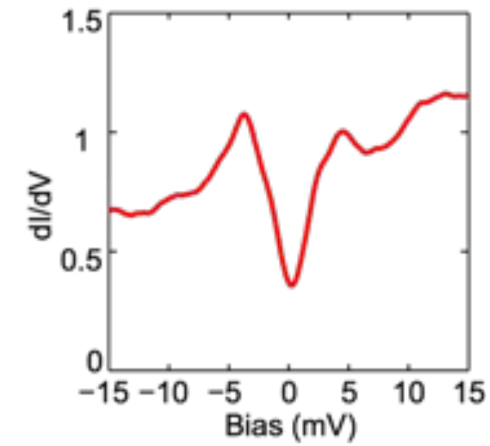
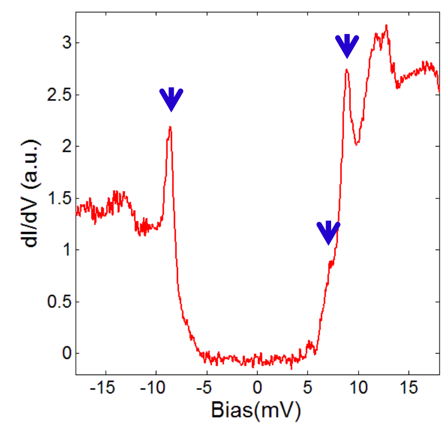


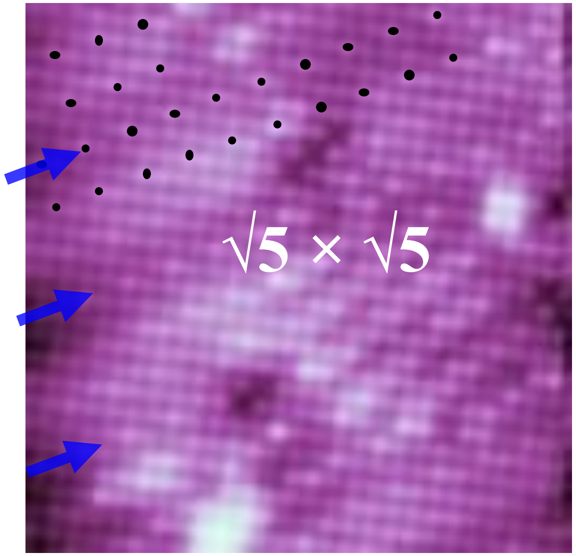

II

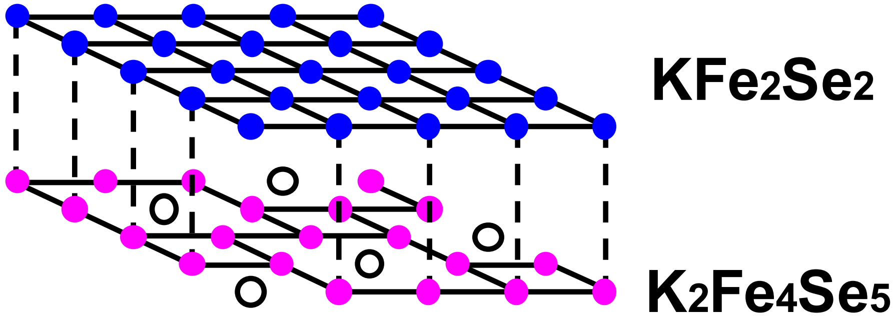




Li, Wei *et al., Phys. Rev. Lett.* 109, 057003 (2012). Li, Wei *et al., Phys. Rev. B* 88, 140506(R) (2013).

# Control the orientation of MBE-grown films

**Symbiotic relationship between SC and AFM in $K_xFe_{2-y}Se_2$**



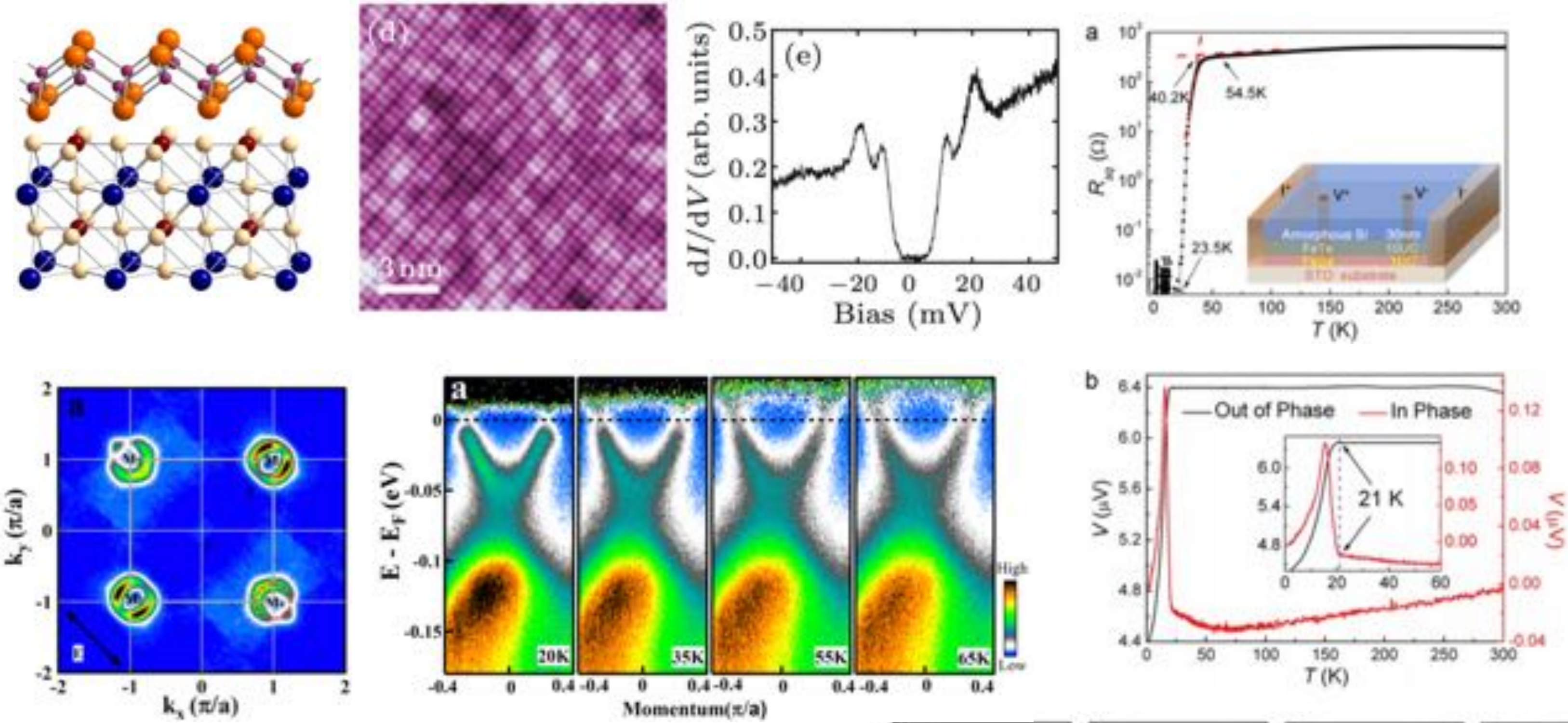




Li, Wei *et al., Phys. Rev. Lett.* 109, 057003 (2012). Li, Wei *et al., Phys. Rev. B* 88, 140506(R) (2013).

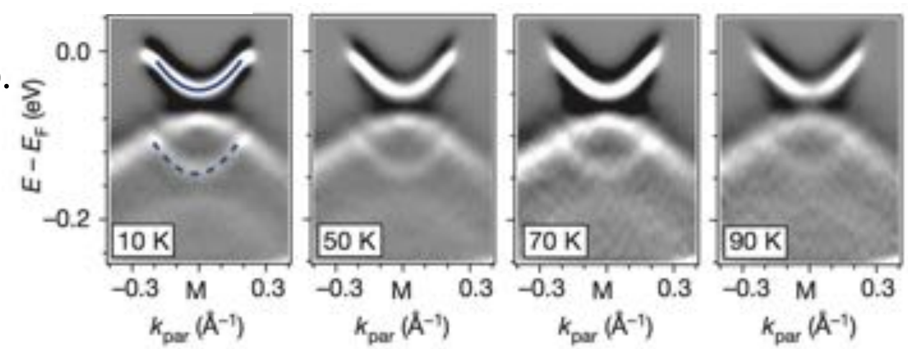
# Construct novel interfaces

# I Construct novel interfaces

## Interfacial enhancement of superconductivity

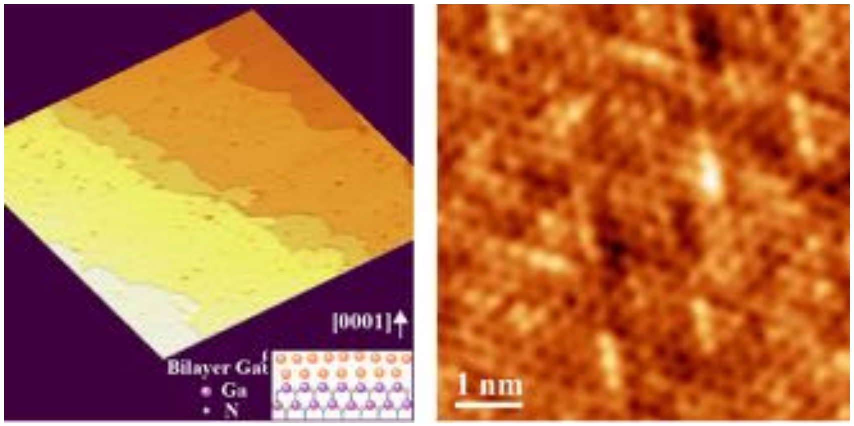


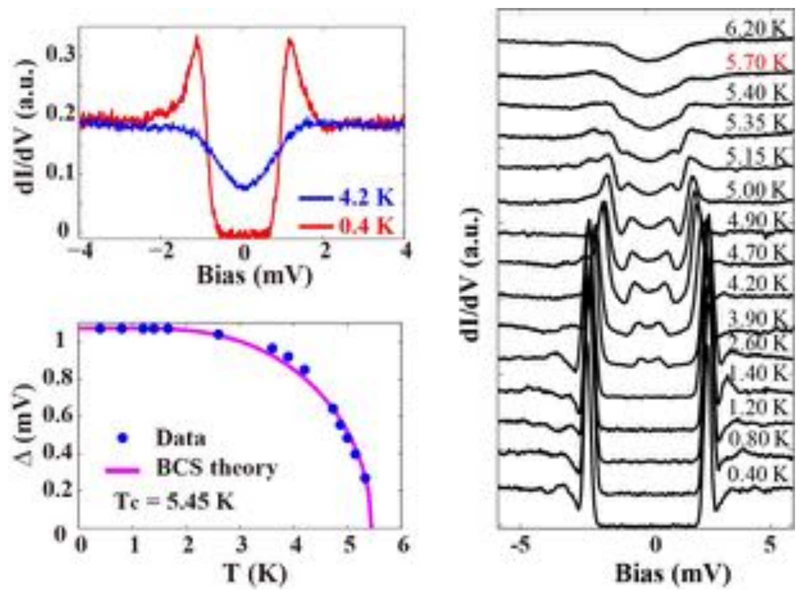

Wang, Q. Y. *et al*. *Chin. Phys. Lett*. **29**, 037402 (2012).
Liu, D. F. *et al*. *Nat. Commun*. **3**, 931 (2012).
Tan, S. Y. *et al*. *Nat. Mater*. **12**, 634 (2013).
He, S. L. *et al*. *Nat. Mater*. **12**, 605 (2013).
Lee, J. J. *et al*. *Nature* ***515***, 245 (2014).
...



# I Construct novel interfaces

## Superconductivity enhancement in bi-layer Ga fluid




**$T_c$ ~ 5.4 K**

Bulk Ga $T_c$ ~ 1.09K

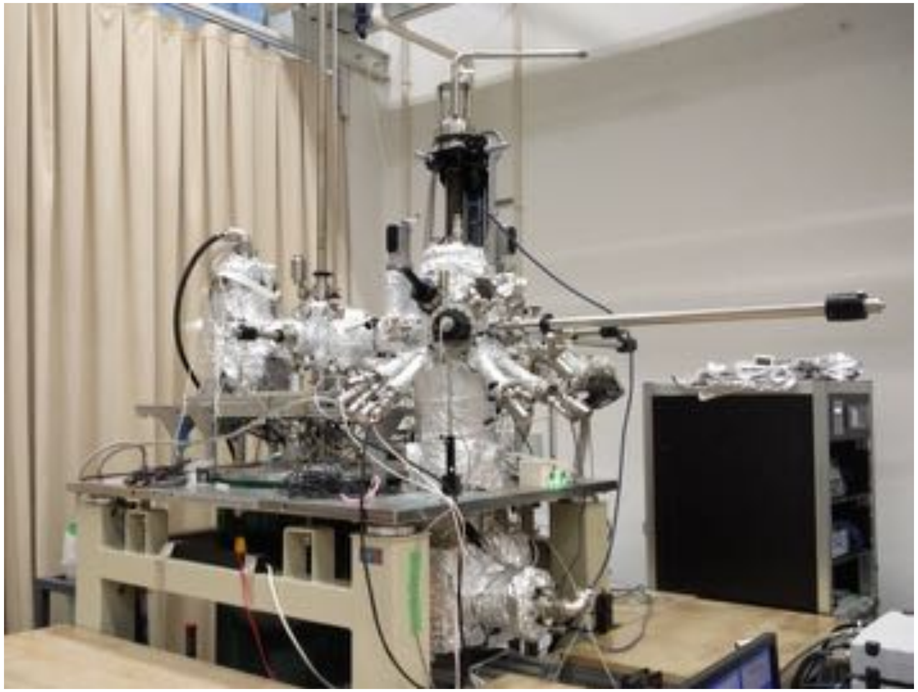
Zhang, H. *et al., Phys. Rev. Lett.* 114, 107003 (2015).

*Science 350, 542 (2015).*

# MBE + STM + ARPES

**Design and construct materials at atomic scale**

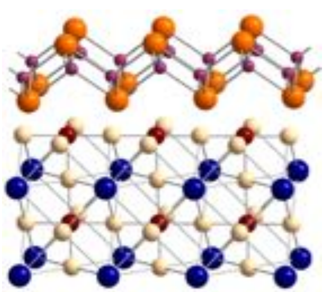
- Control the orientation of MBE-grown films
- Construct novel interfaces (doping, proximity…)
- **Tune the chemical pressure of the lattice**

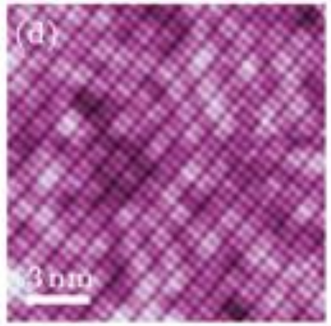


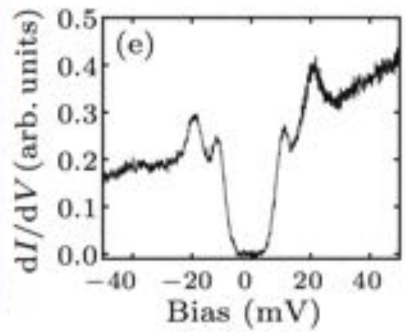
# Introduction

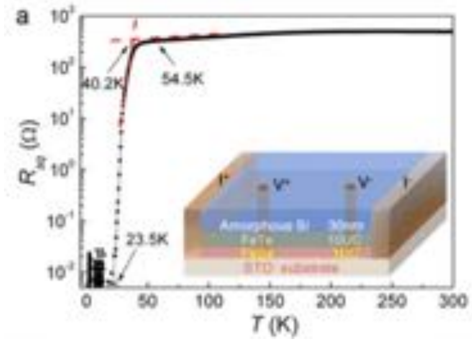
# 2

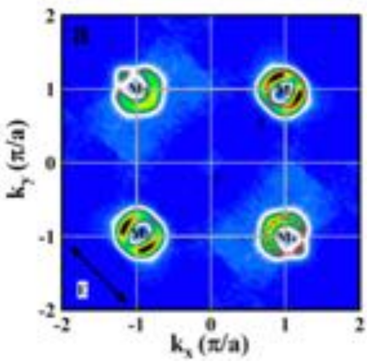
# II Superconductivity enhancement in 1 UC FeSe/STO

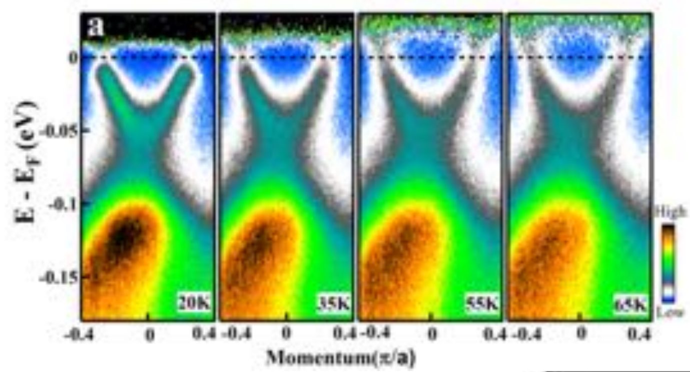


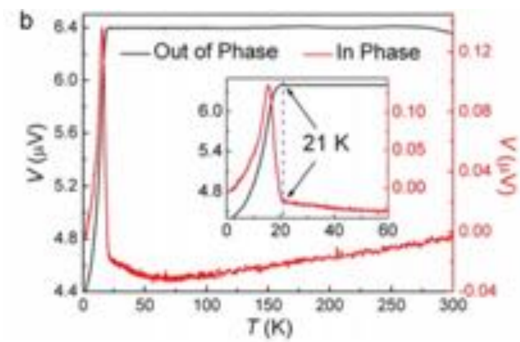


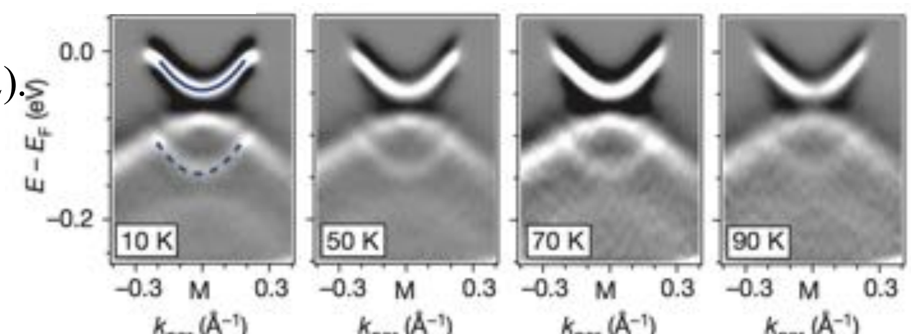



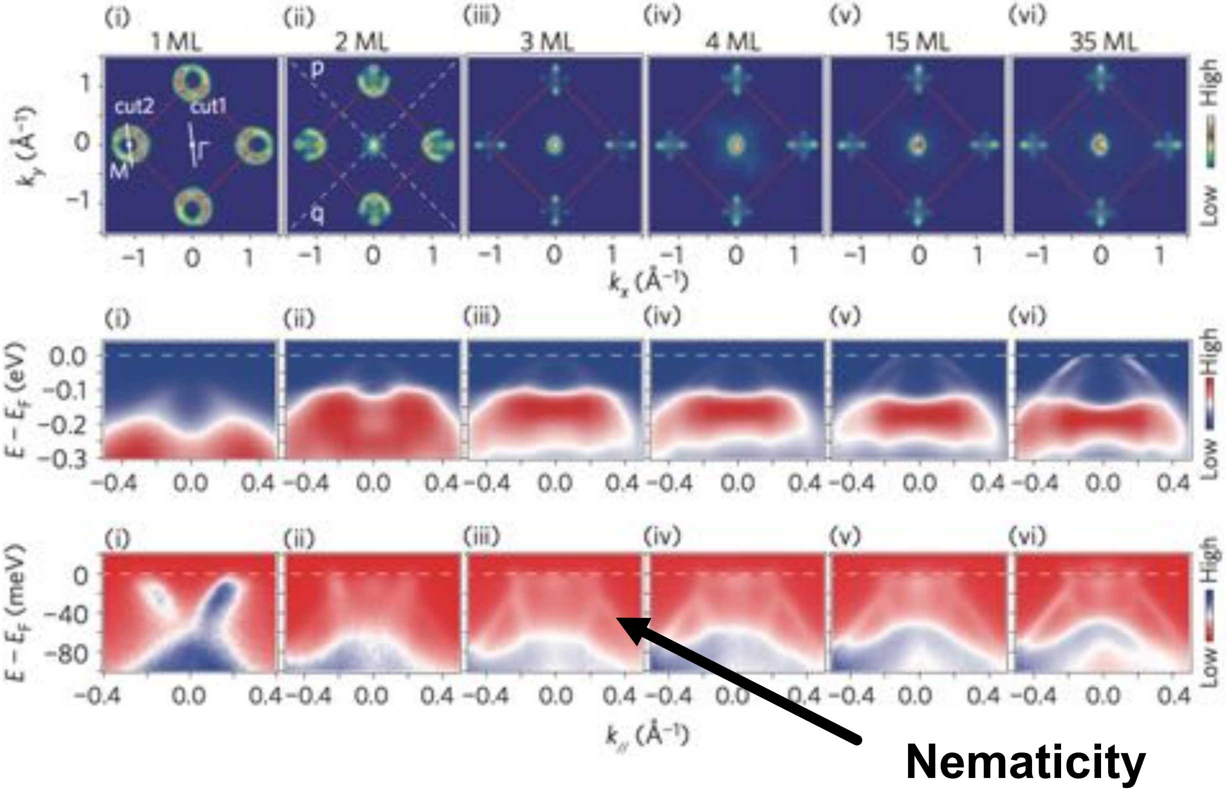




Wang, Q. Y. *et al. Chin. Phys. Lett.* **29**, 037402 (2012).
Liu, D. F. *et al. Nat. Commun.* **3**, 931 (2012).
Tan, S. Y. *et al. Nat. Mater.* **12**, 634 (2013).
He, S. L. *et al. Nat. Mater.* **12**, 605 (2013).
Lee, J. J. *et al. Nature* ***515***, 245 (2014).
...

# II Superconductivity enhancement in 1 UC FeSe/STO

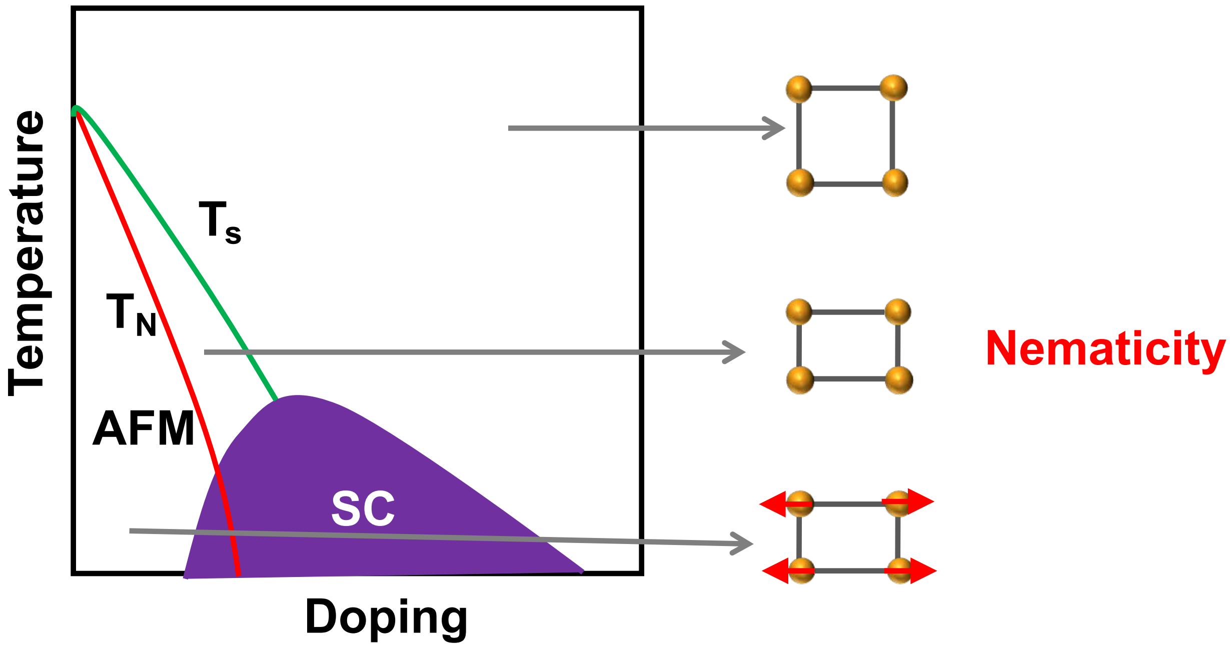
## Suppression of superconductivity in multilayer FeSe film?




Tan, S. Y. *et al. Nat. Mater.* **12**, 634 (2013).

# II Nematicity in Fe-based superconductors

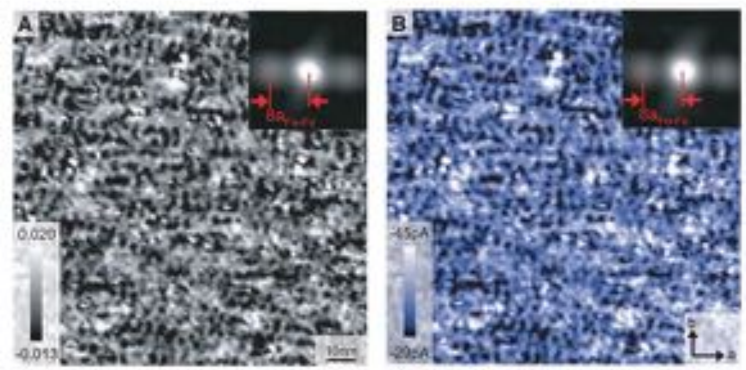
## Phase diagram and lattice symmetry



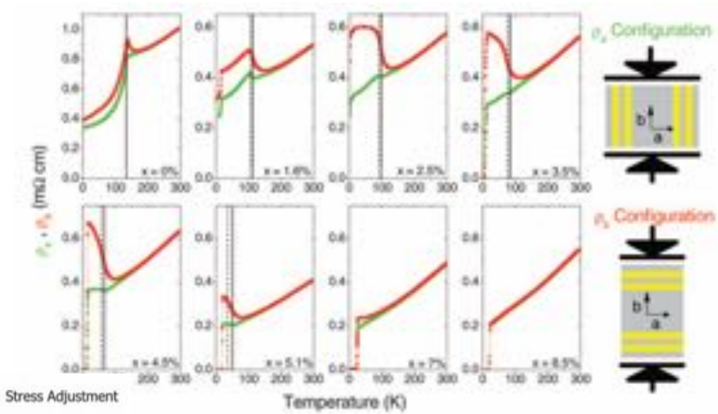

*Nature Physics 5, 555 (2009); Science 327, 181 (2010) ;Science 329, 824 (2010)…*

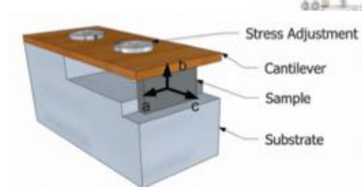
# II Nematicity in Fe-based superconductors

**Static unidirectional electronic nanostructures in $Ca(Fe_{1-x}Co_x)_2As_2$**




**Resistivity anisotropy in $Ba(Fe_{1-x}Co_x)_2As_2$**



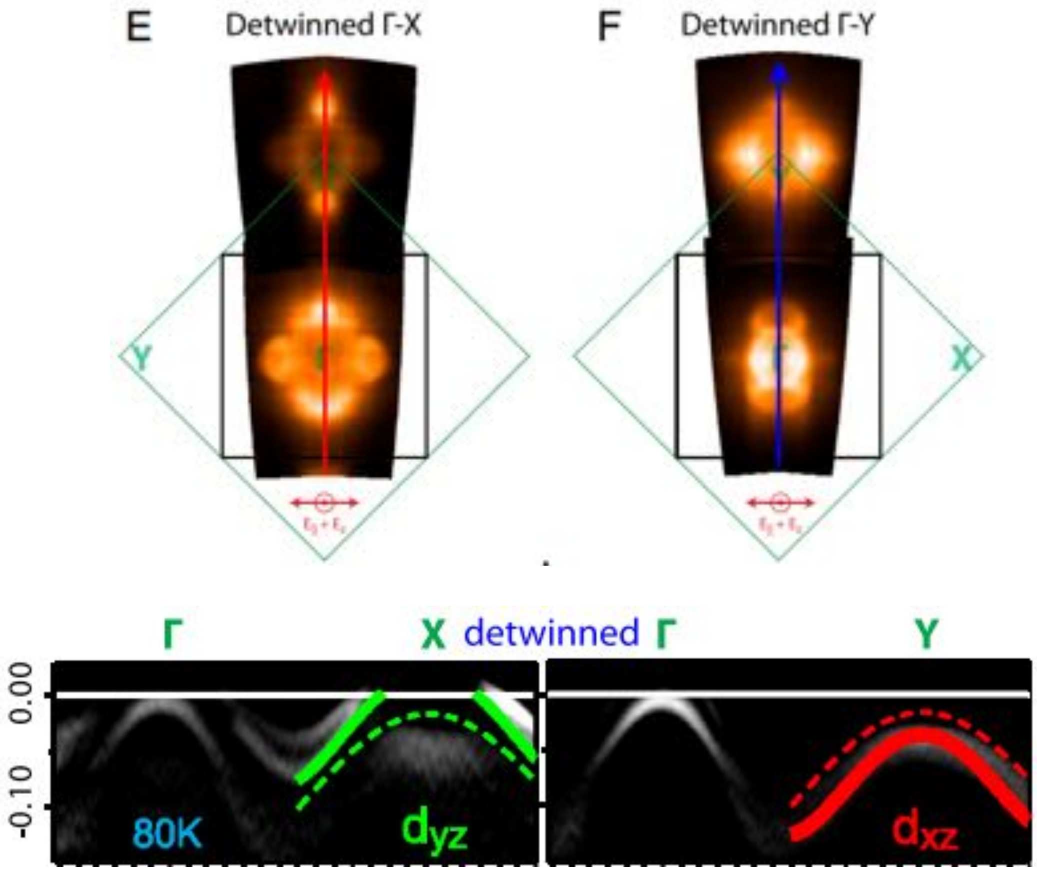




*Davis, S. et al. Science 327, 181 (2010).*

*Zhao, J. et al. Nat. Phys. 5, 555-560 (2009).*

*Fisher, I. et al. Science 329, 824 (2010).*

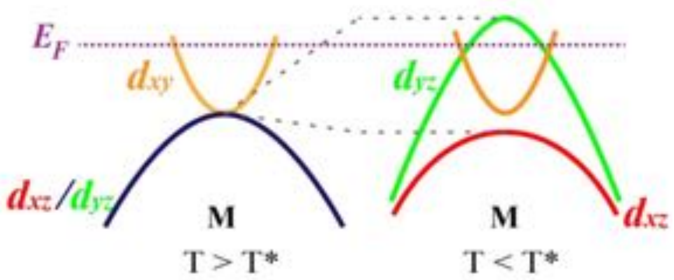
## Orbital anisotropy in $Ba(Fe_{1-x}Co_x)_2As_2$



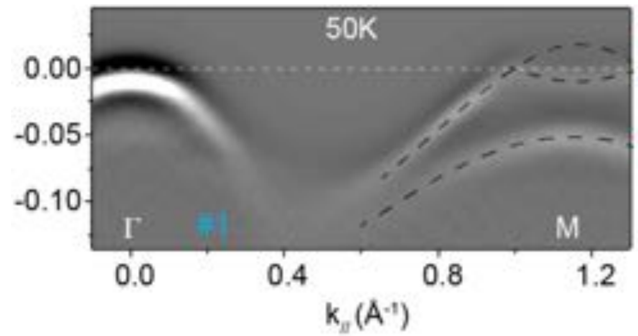

*Yi, Ming et al., PNAS 108, 6878 (2011).*

# II FeSe film *vs.* FeSe single crystal

**FeSe single crystal** **Multilayer FeSe/STO**








**Splitting of $d_{yz}/d_{xz}$ band**

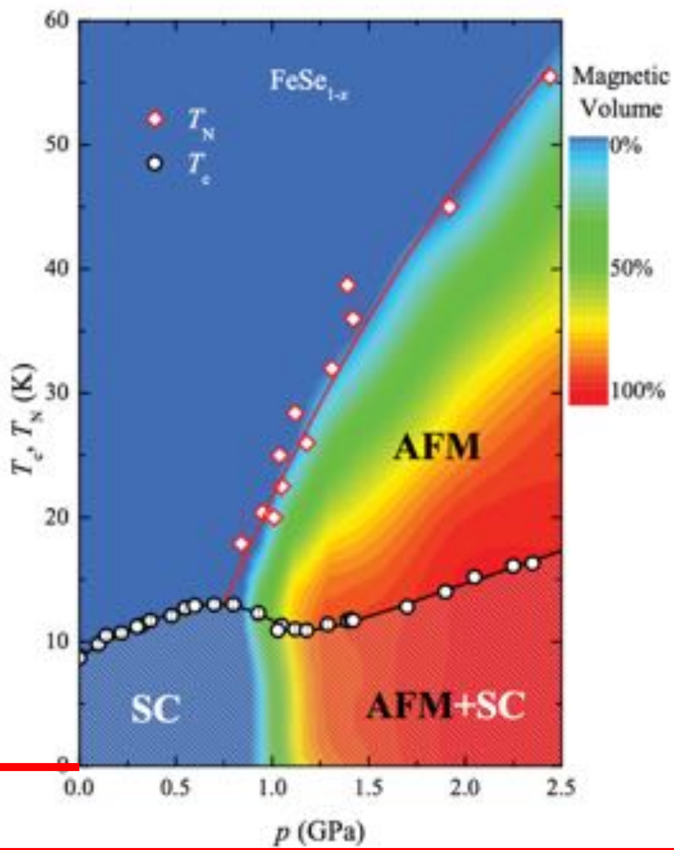
**Larger strength of nematicity**

- **Suppression of superconductivity in multilayer FeSe film?**
- **Other competing phases/orders?**


*Hsu, F. et al. Proc. Natl. Acad. Sci. U.S.A.* **105**, 14262 (2008).
*Watson, M. et al. Phys. Rev. B* **91**, *155106 (2015).*
*Zhang, Y. et al. Phys. Rev. B* **94**, *155153 (2016).*
*Li, W. et al. arxiv: 1509.01892 (2015).*

# Magnetism in FeSe

## Absence of long-range AFM order at ambient pressure




At negative pressure?

A competing order?

- Suppression of superconductivity in multilayer FeSe film?
- Other competing **AFM** phases/orders?

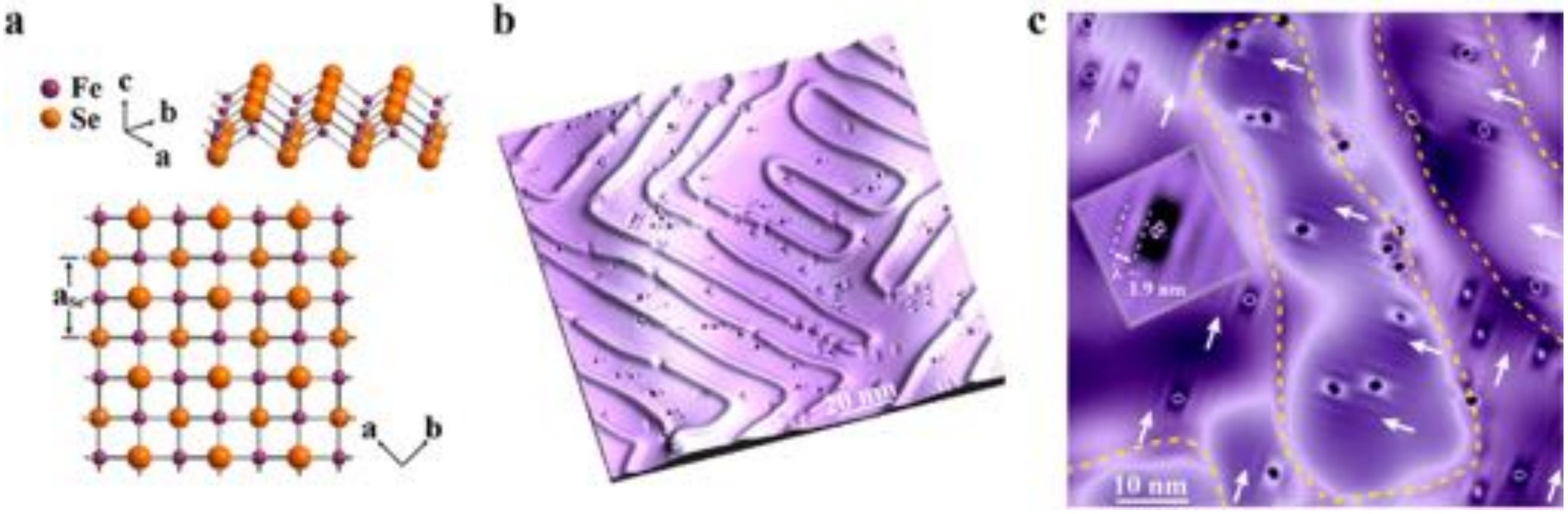
2012).

# Stripes in FeSe

3

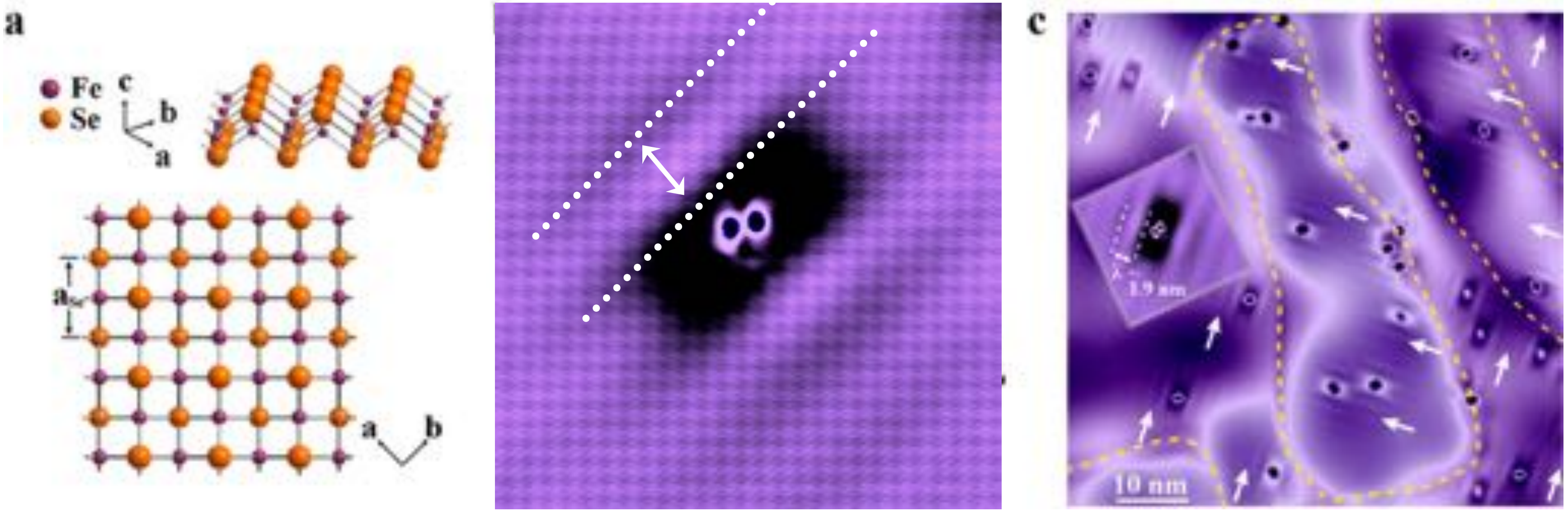
# Stripes in FeSe

- Maze-like $C_2$ domain walls
- Impurity induced stripes



# Stripes in FeSe

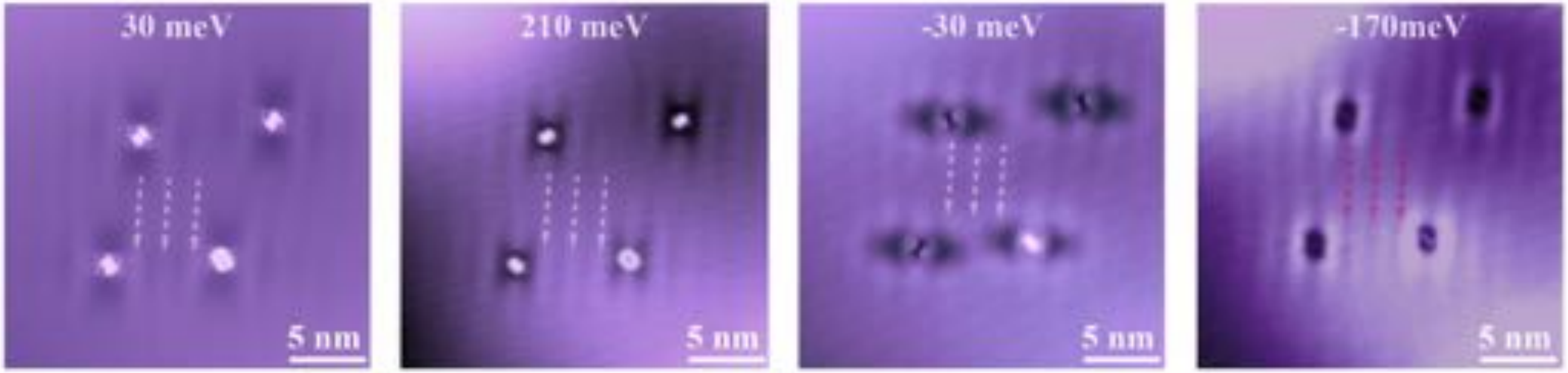
- **Maze-like $C_2$ domain walls**
- **Impurity induced stripes**




- **Along Fe-Fe lattice, ~ 1.9 nm**

# Stripes in FeSe

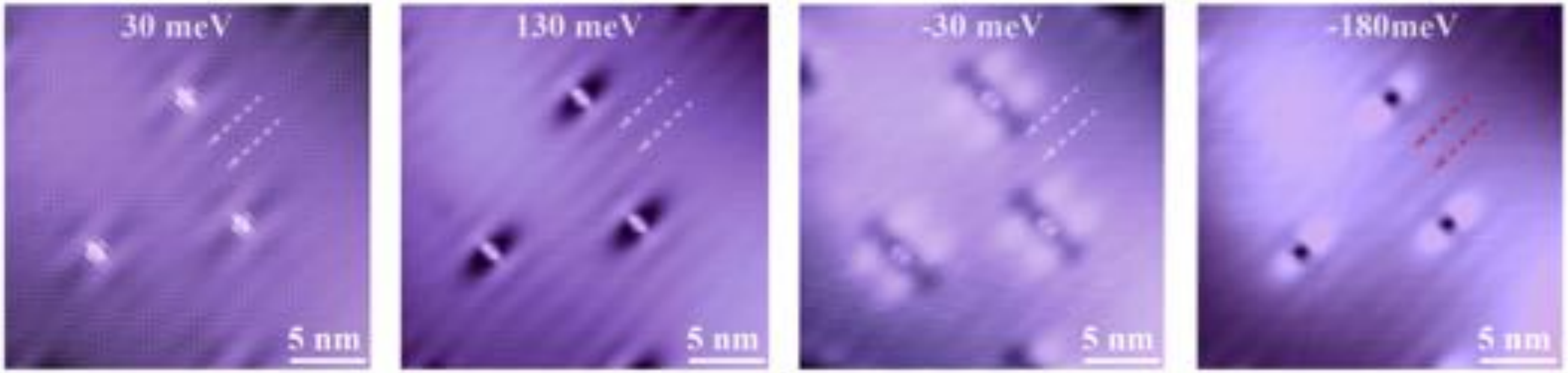
## Bias voltage-dependence of the stripes




- Periodicity is unchanged: Static?
- Phase can change by 180°

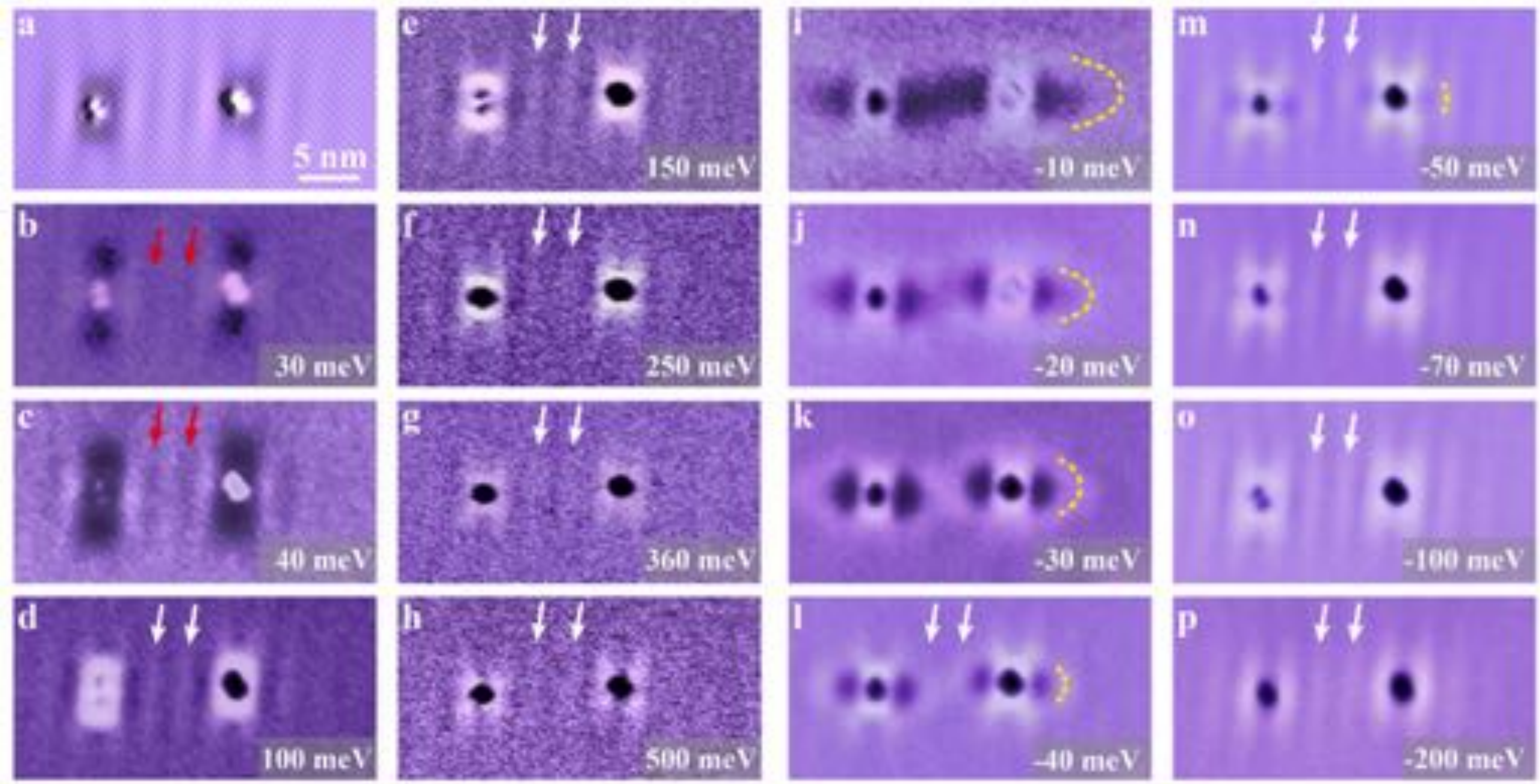
# Stripes in FeSe

## Bias voltage-dependence of the stripes




- Periodicity is unchanged: Static?
- Phase can change by 180°
- Not impurity states, quasiparticle inferences?

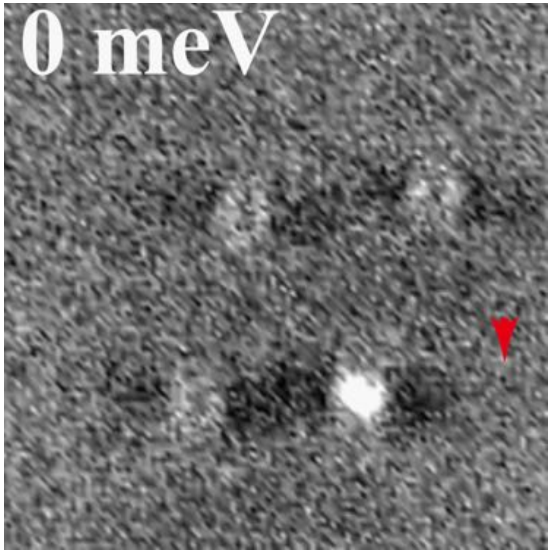
# III Charge ordering origin of the stripes



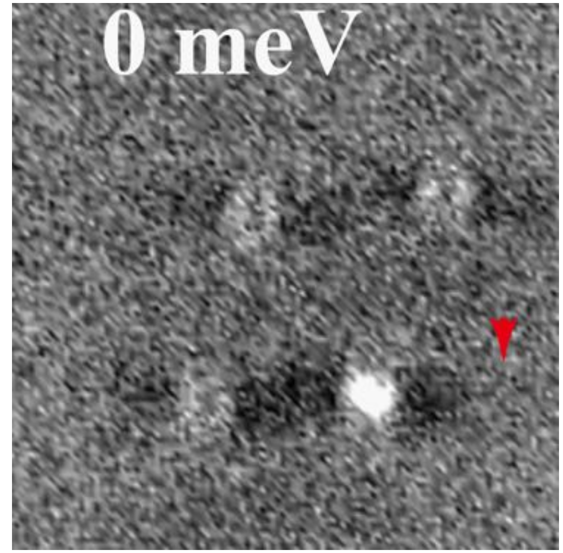

- **Stripes: Static and non-dispersive, the competing order?**
- **QPI: Energy-dependent, $d_{yz}$ hole-like band**

# III Charge ordering origin of the stripes

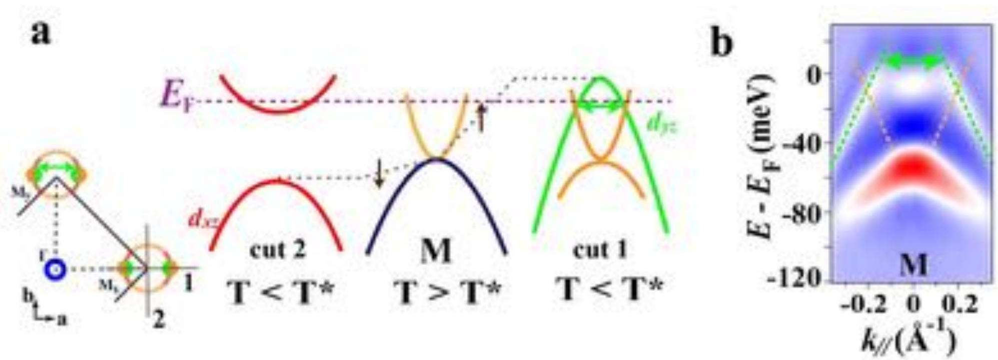
## dI/dV maps in the vicinity of defects




**Below Fermi level**




**Above Fermi level**




Li, Wei *et al., Nat. Phys.(2017)*

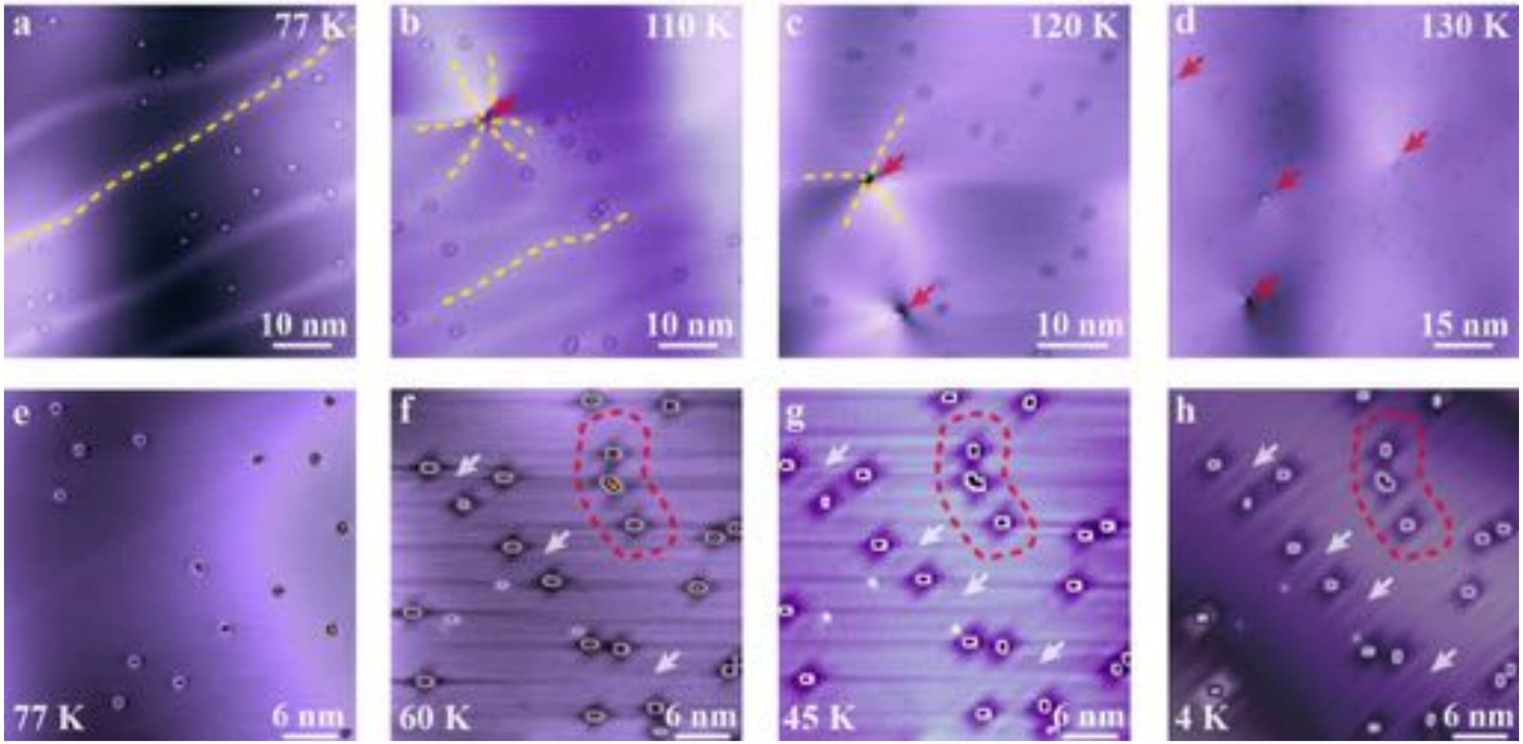
*DOI:10.1038/NPHYS4186*

# Nematicity and charge ordering

# 4

# Nematicity and charge ordering

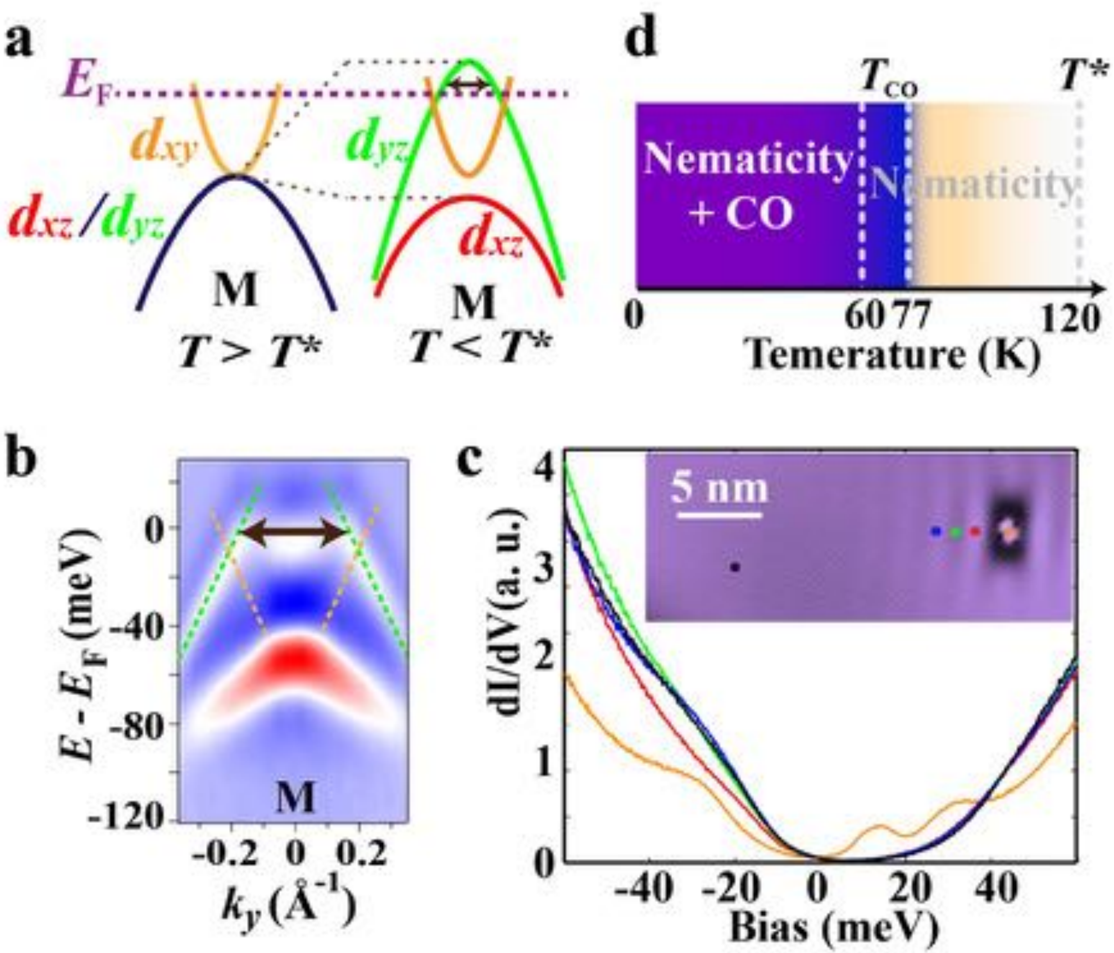
## The effects of temperature on stripes and nematicity




- **Nematic transition at 120 K**
- **Charge ordering develops around 60 K ~ 77 K**
- **Stripes is not sensitive to temperature once formed**

IV

# Nematicity and charge ordering




## Stripes

- Develops beneath nematicity
- Not sensitive to temperature

  ***Not FS nesting driven***

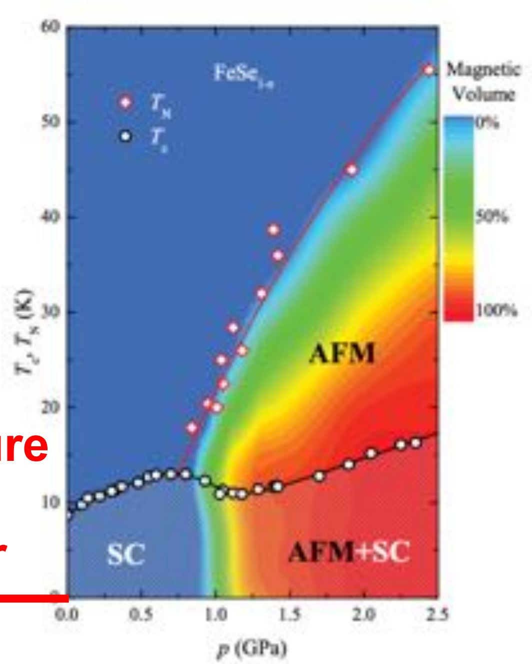
- No fully opened gap in STS

**A SDW with a rather small wave vector *q*.**

Ku, W. *et al. Phys. Rev. Lett.* ***115****, 117001 (2015).*

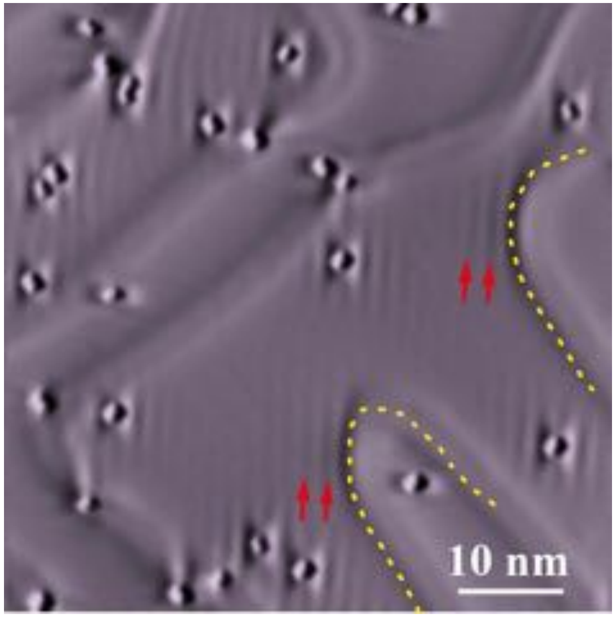
IV

# Nematicity and charge ordering




At negative pressure

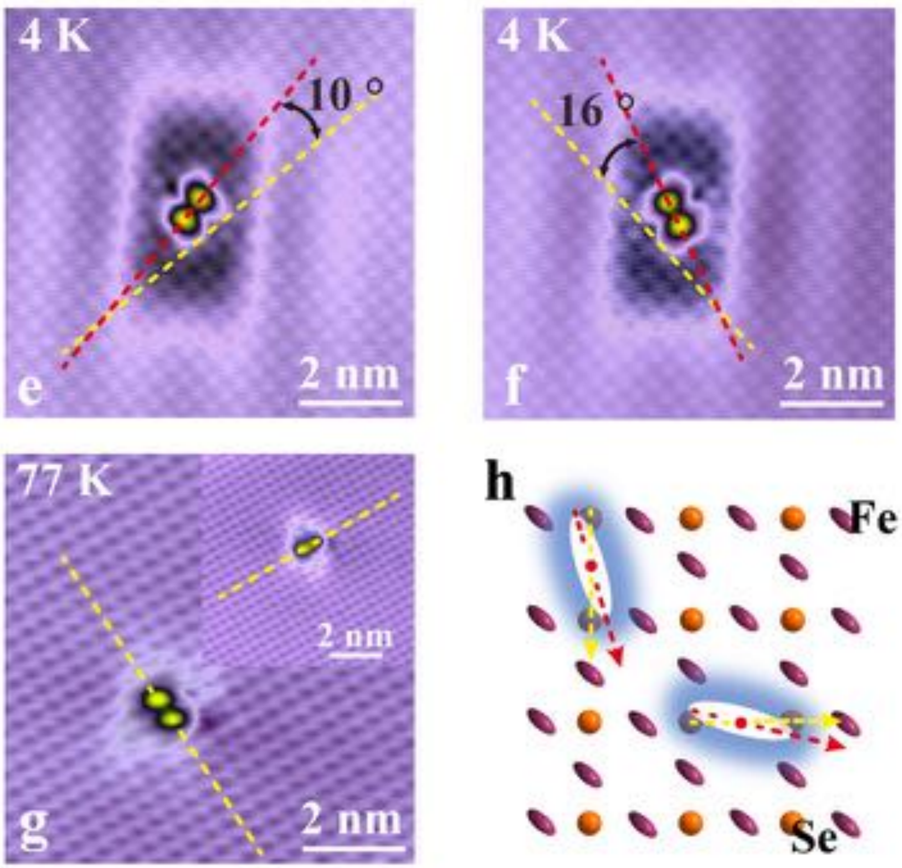
A stripy-AFM order




- Competing AFM order under tensile strain
- No AFM at ambient pressure
- Competing order with SC

# IV Role of the defects

## Stripes develops at the strong limit of nematicity




- Defects further enhance the anisotropy
- Obvious distortion of the impurity state due to interaction with CO
- The distortion is absence in bulk FeSe and FeSe/STO at high temperature

**Iron-vacancy in <u>SC</u> FeSe**

*Song, C. et al. Phy. Rev. Lett.* ***109****, 137004 (2012)*

*Kasahara, S. et al. PNAS* ***111****, 16309 (2014).*

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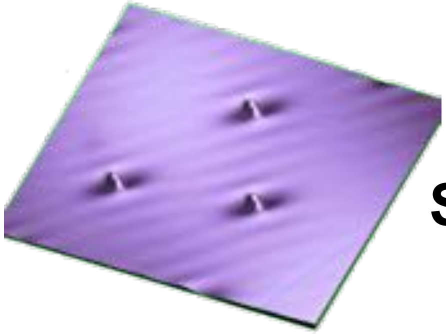
# Summary and perspective



**Stripes in FeSe/STO**

- Developed at the strong limit of nematicity
- Ground state of nematicity
- Originating from a new emergent SDW
- Developed under negative pressure
- Competing with superconductivity

**Tune the strength of nematicity to induce CO?**

**1UC FeSe/STO?**

# Thank you