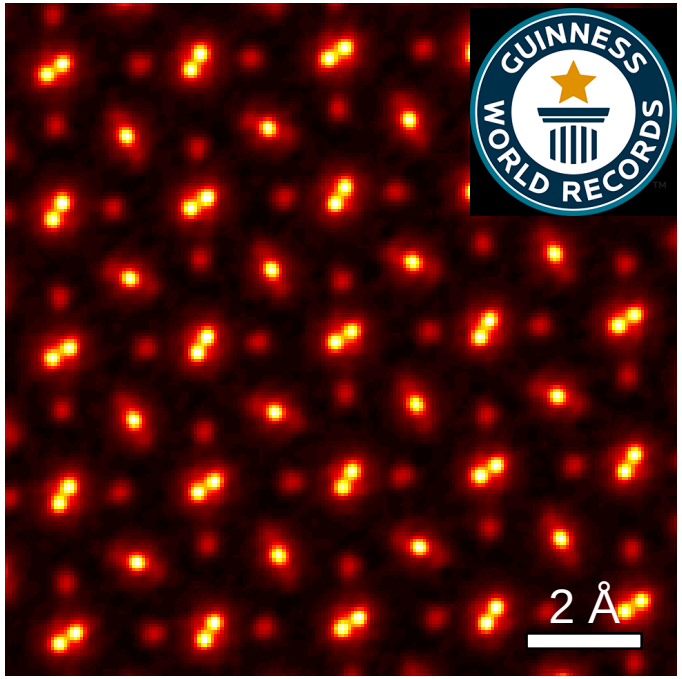
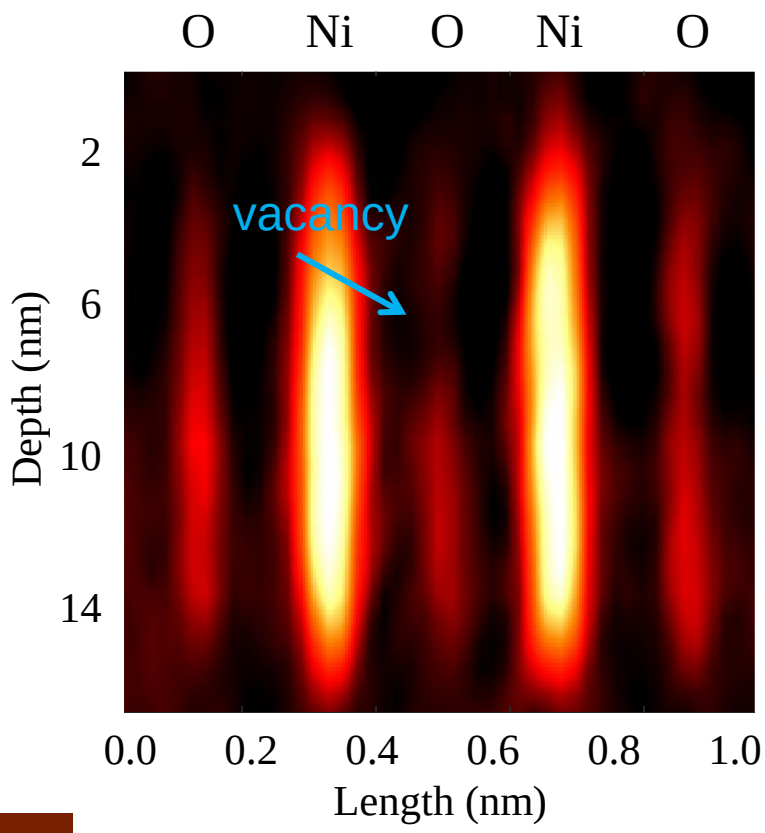
极限空间分辨率下的原子世界

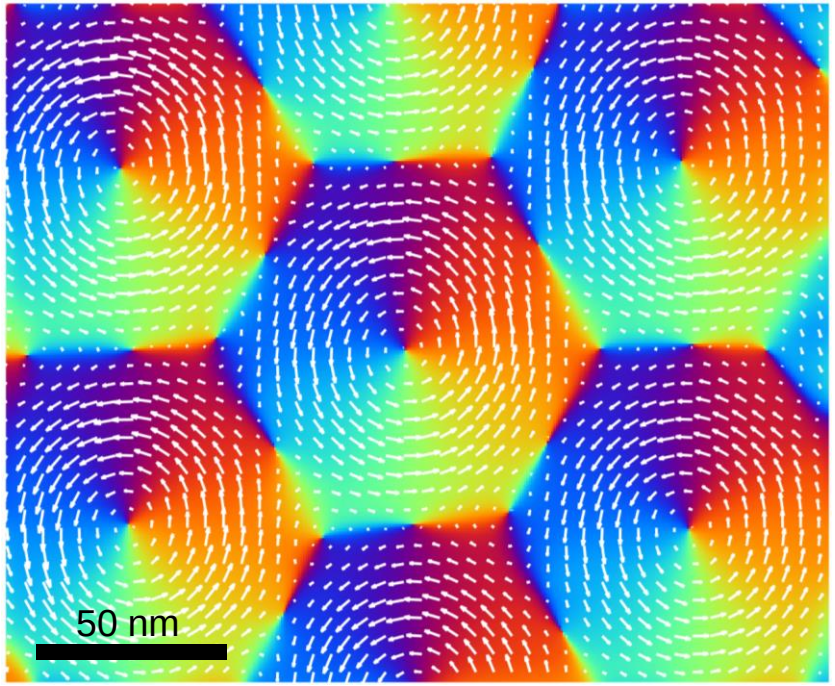
陈震 中国科学院物理研究所

Resolution < 0.2 Å





Electromagnetic fields



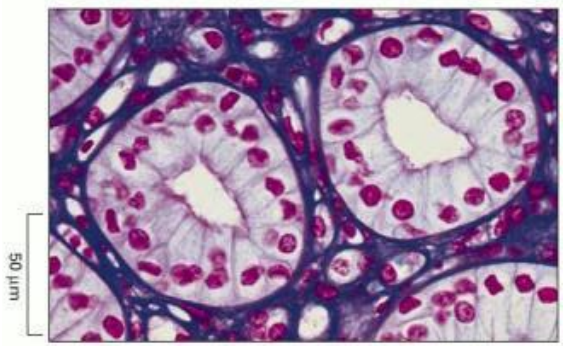
中國科學院物理研究所
Institute of Physics, Chinese Academy of Sciences

先进材料与结构分析实验室
Advanced Materials & Electron Microscopy

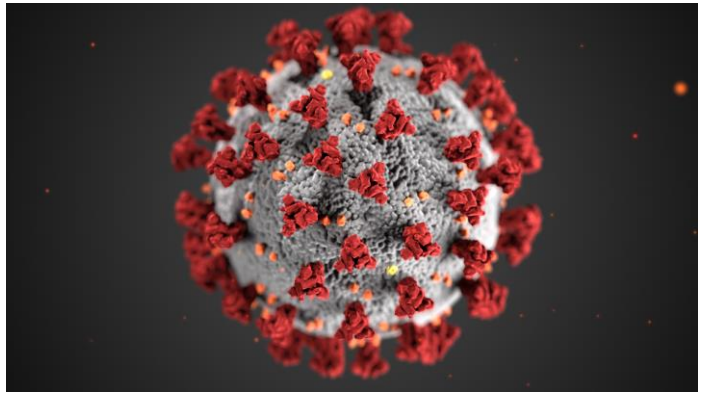
2024/12

眼见为实!

cells



SARS-CoV-2



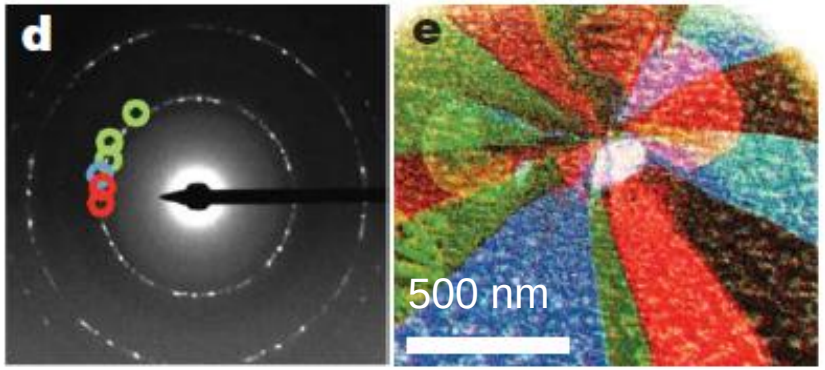
10^{3}m

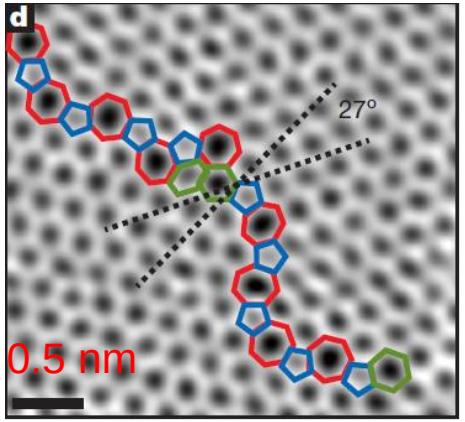
10^{-4}m

10^{-6}m

10^{-9}m

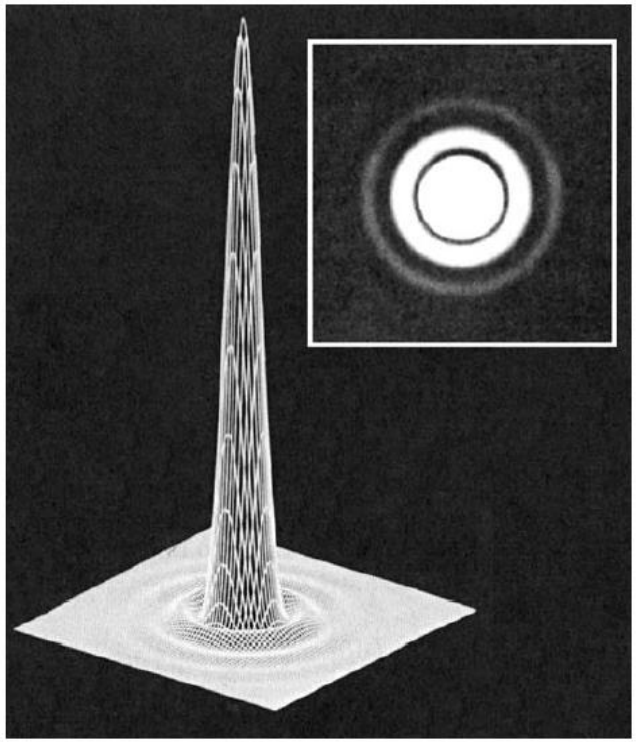
polycrystalline graphene





Alberts, *et al. Molecular Biology of the Cell*. 4th 2002
CDC/ Alissa Eckert, MS; Dan Higgins, MAMS
Huang, *et al. Nature* 469, 389 (2011)

显微镜空间分辨率的极限



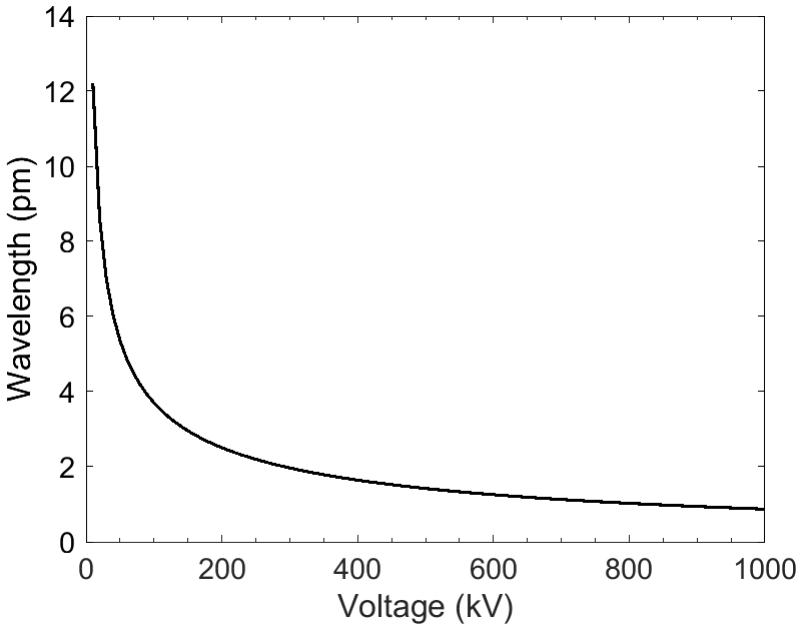
Visible light

$\lambda = 400\ \mathrm{nm}, d_0 = 200\ \mathrm{nm}$

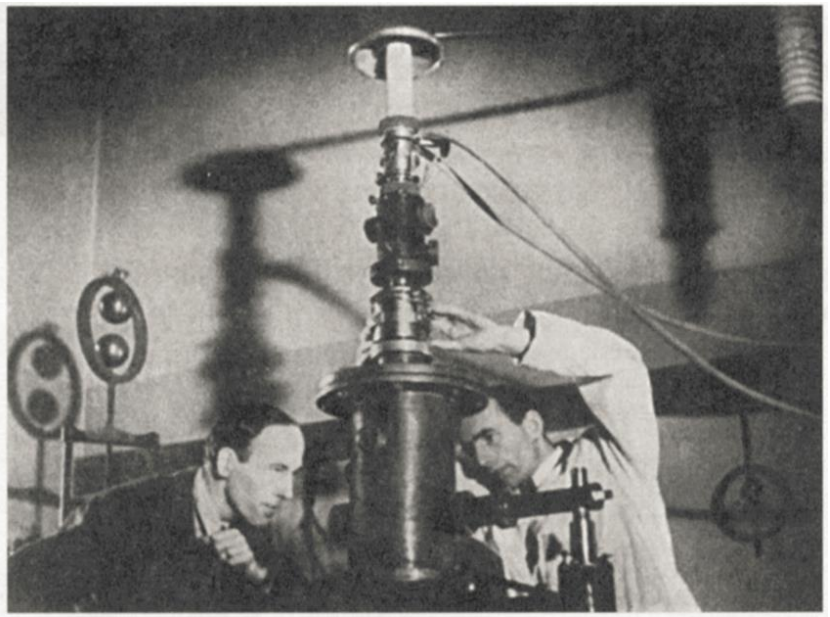
Rayleigh resolution limit $d_0 = \dfrac{0.61\lambda}{\alpha_0}$

Electrons $\lambda = \dfrac{h}{\sqrt{2m_0 eV}} = \dfrac{1.23}{\sqrt{V}}\ \mathrm{nm}\ (\mathrm{V\ in\ volts})$

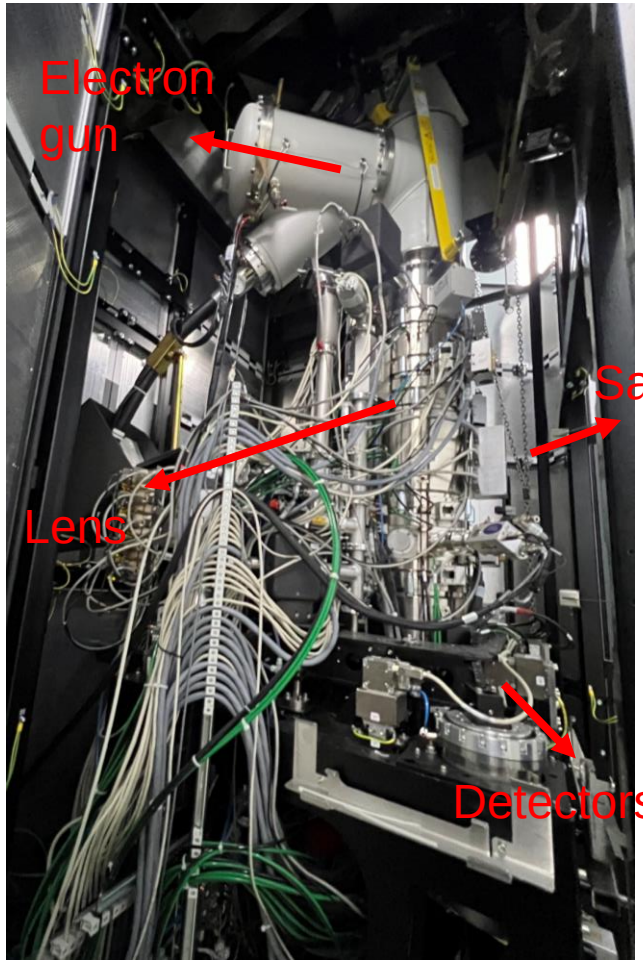
Resolution < 0.1 nm



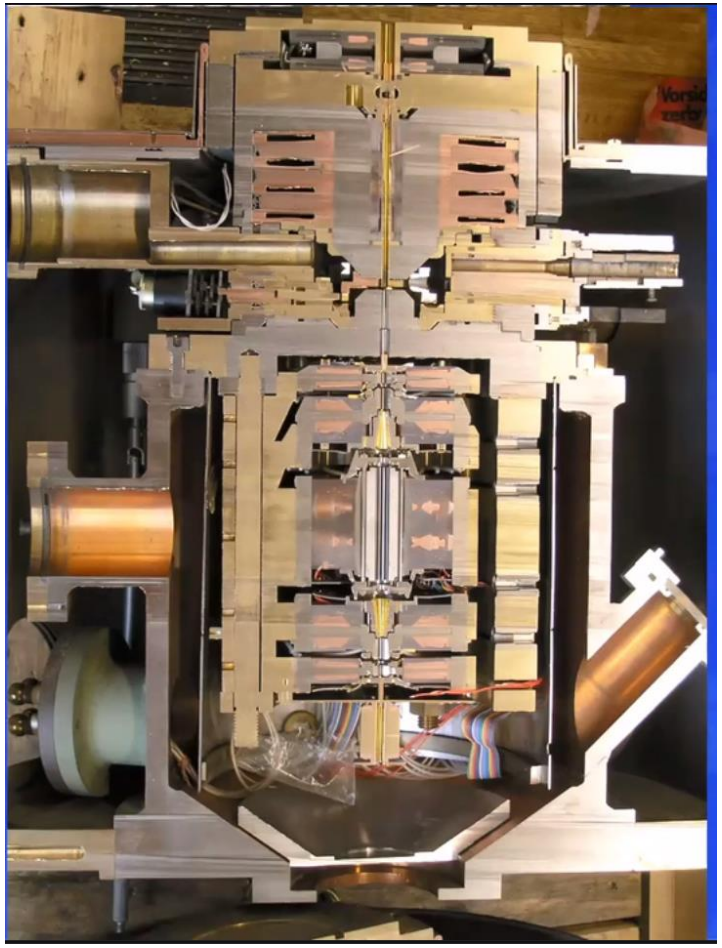
透射电子显微镜的原理



Ernst Ruska and Max Knoll,
1st electron microscope in 1931
(Nobel Prize to Ruska in 1986)



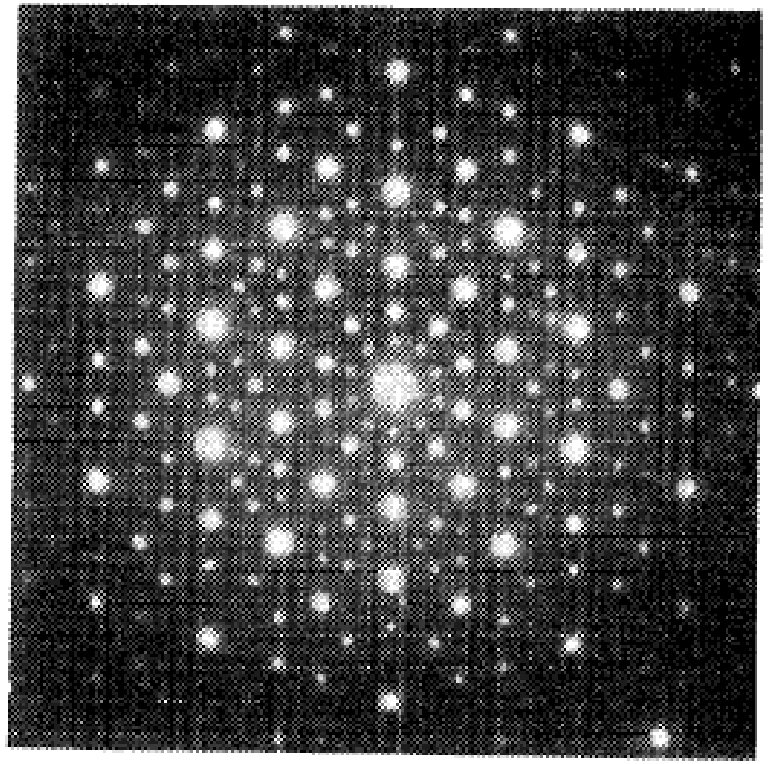
现代电镜



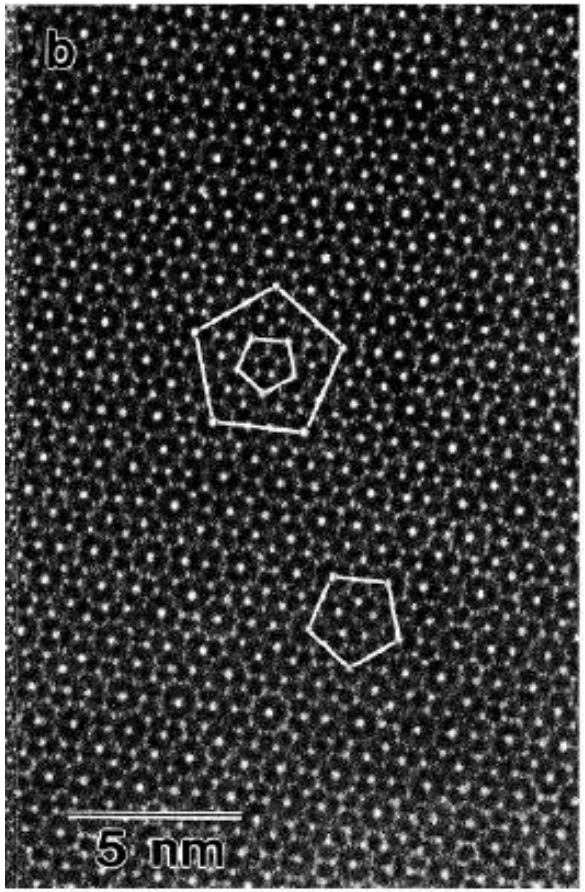
镜筒截面

纳米-原子尺度的物质世界

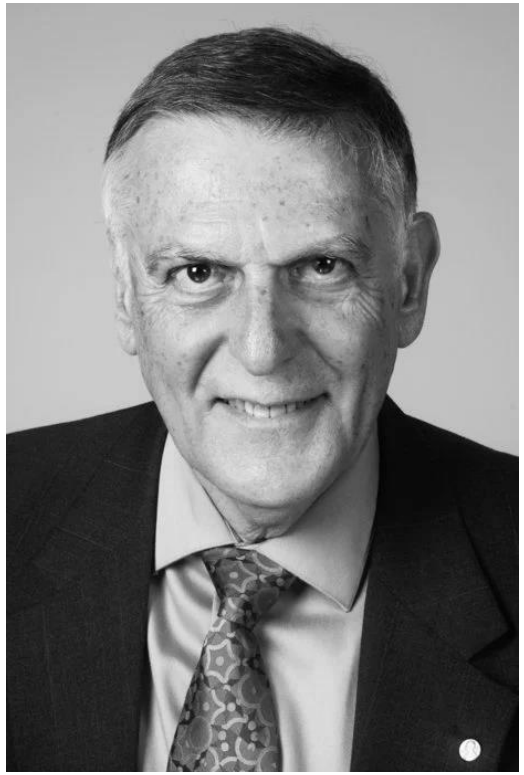
固体的新形态：准晶



五重对称



Dan Shechtman



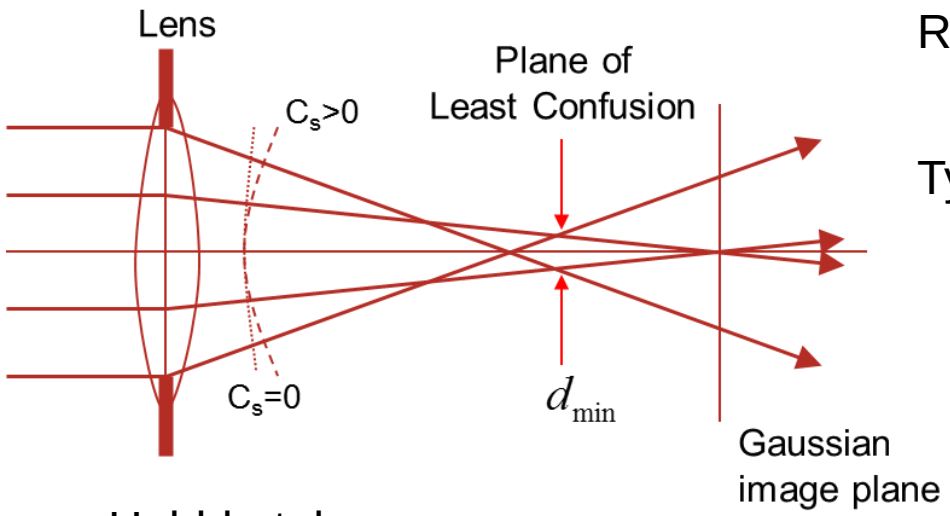
The Nobel Prize in Chemistry 2011

"for the discovery of quasicrystals"

D. Shechtman, *et al*., PRL 53, 1951 (1984)
K. Hiraga, *et al*., Jpn. J. Appl. Phys., 27, L951 (1988)

分辨率极限: 成像系统的像差校正

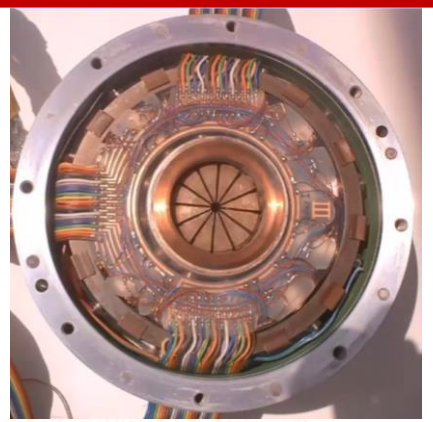
球差矫正器



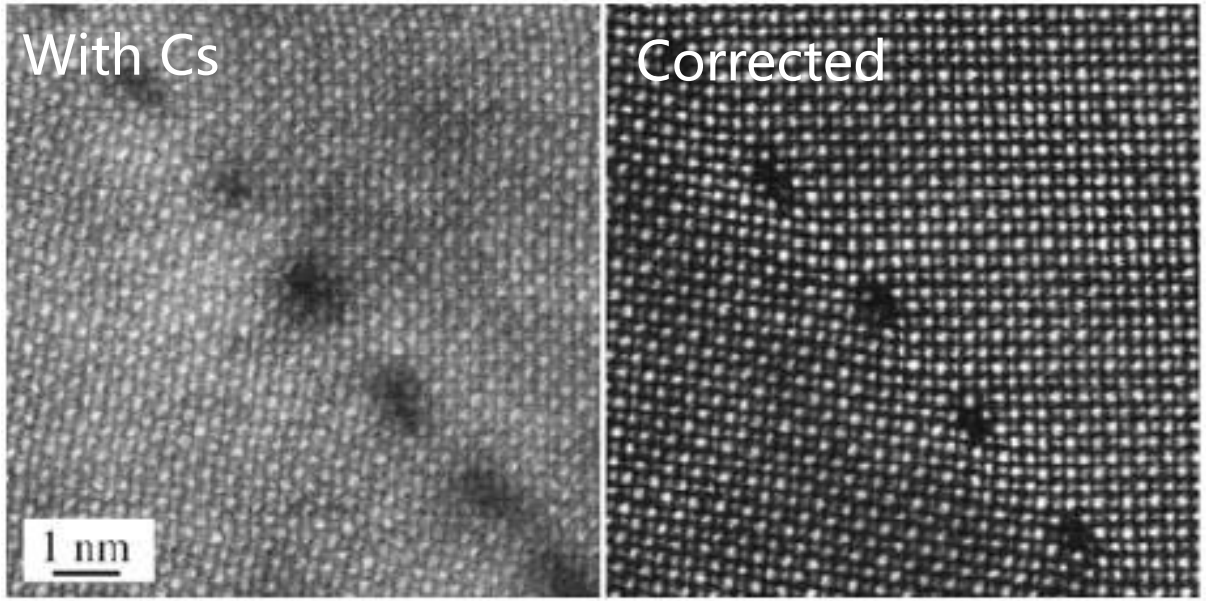
Resolution $$d_{min} = \frac{1}{2} C_s \alpha^3$$

Typical numbers: $C_s = 1$ mm, $\alpha = 10$ mrad

$$d_{min} = 0.5 \text{ nm}$$



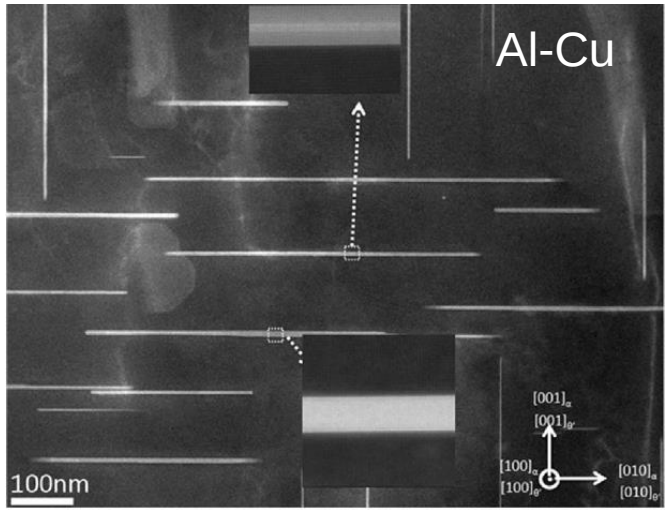
Hubble telescope



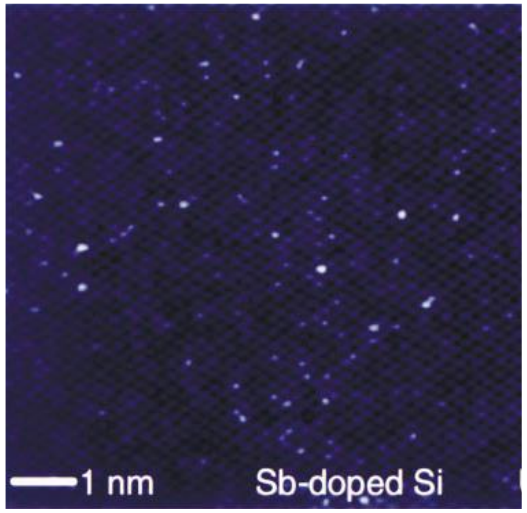
$SrTiO_3$ grain boundary

透射电镜在固体材料中应用广泛

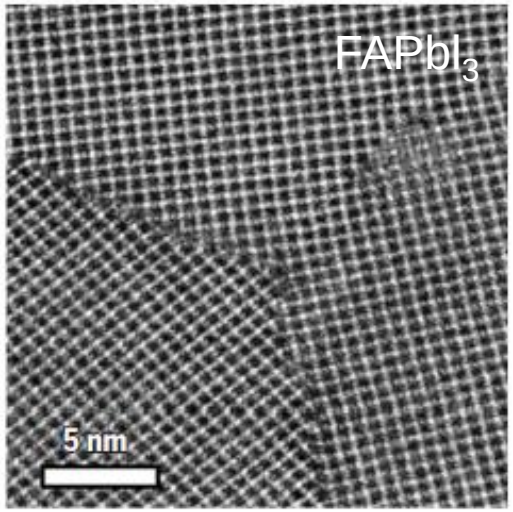
Metal



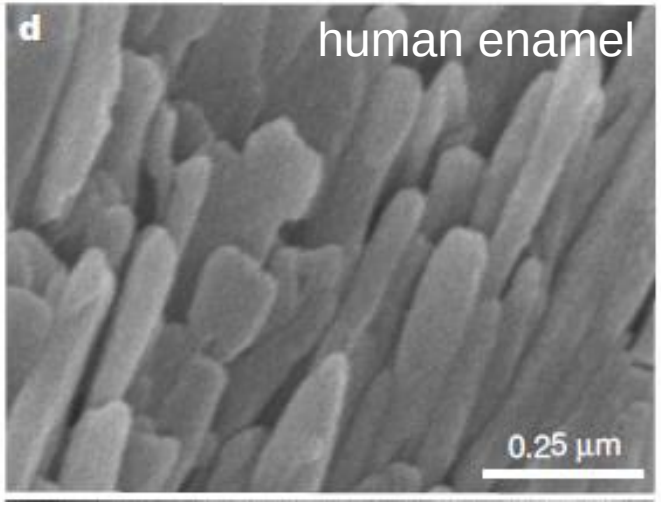
Semiconductor



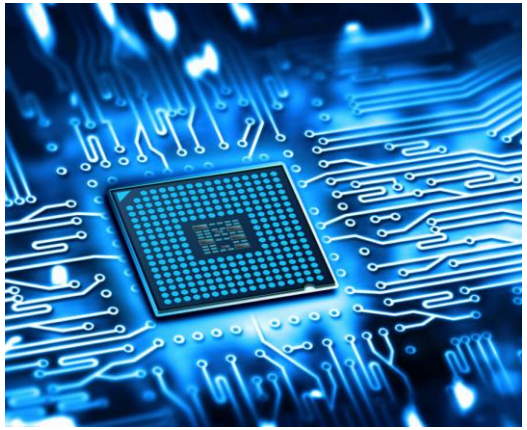
Solar cell



Biomaterial

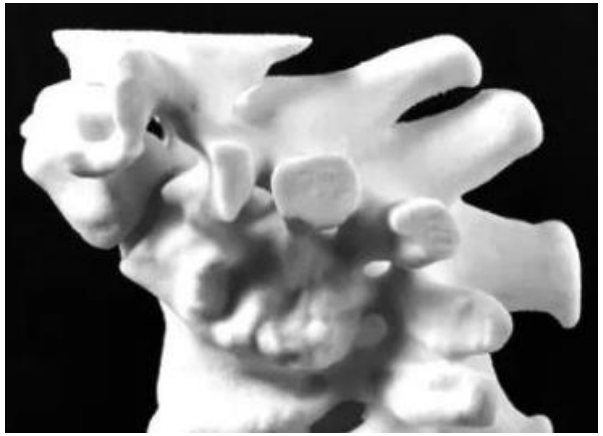


Chen, *et al*., Acta Mater. 125, 340 (2017)



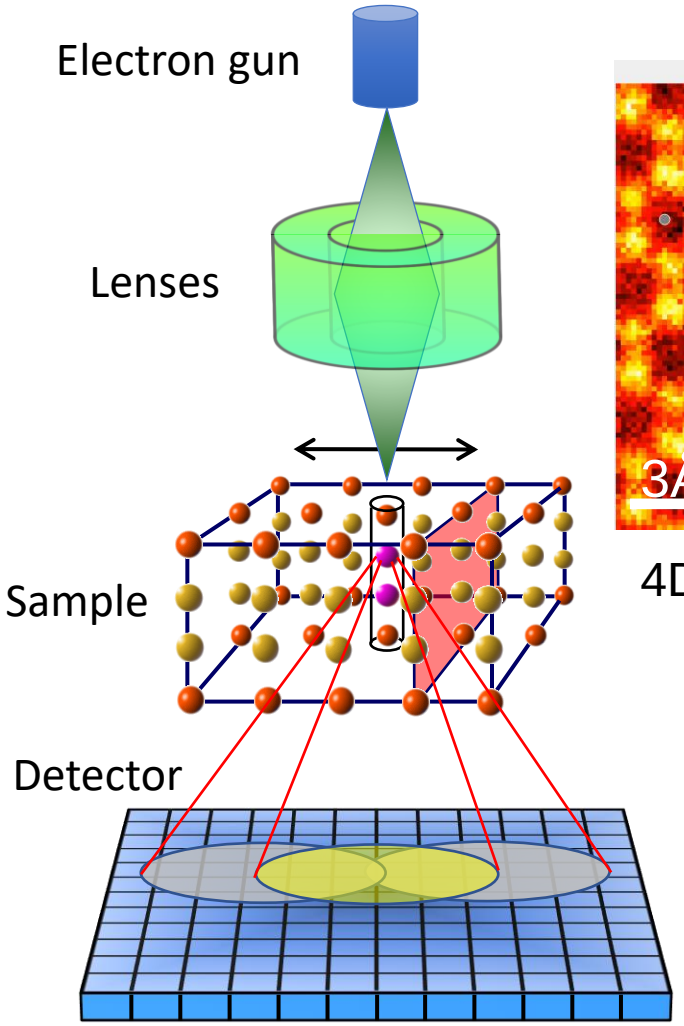
Voyles, Nature 416, 826 (2002)

Rothmann, Science 370, eabb5940 (2020)

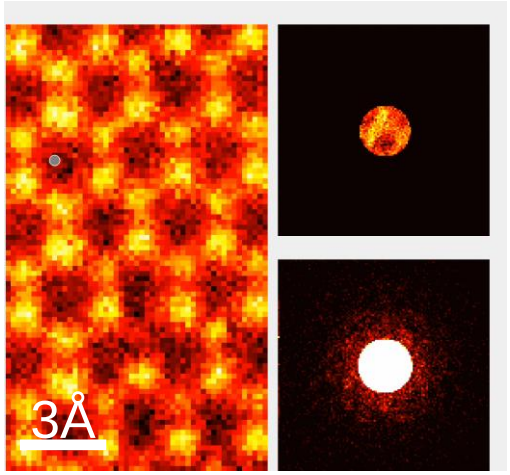


DeRocher, Nature 583, 66 (2020)

求解逆问题:动量分辨电子散射



Monolayer MoS_2



4D-STEM

$$|\psi_{\text{exit}}(\mathbf{r}_i, \mathbf{k})|^2$$

position momentum

Schrodinger equation

$$\left[\frac{-\hbar^2}{2m}\nabla^2 + V(r)\right]\psi = E\psi$$

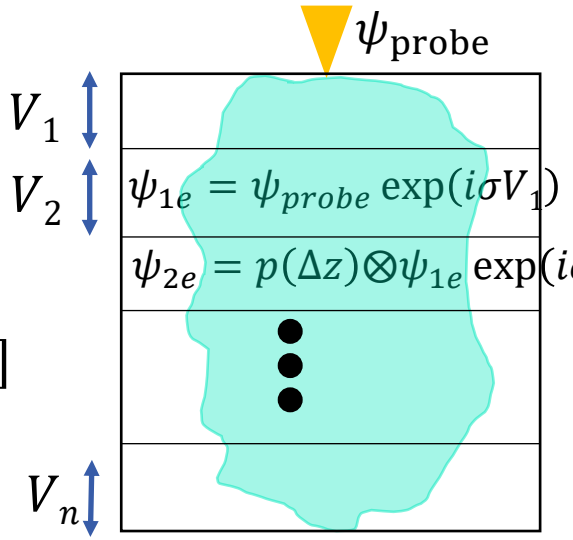
Potential

Structure of sample

$$O_i(\mathbf{r}) = A_i(\mathbf{r})\exp[i\varphi(\mathbf{r}, \mathbf{z}_i)]$$

$$\varphi(\mathbf{r}, \mathbf{z}_i) = C_E \int_{\Delta z} V(\mathbf{r}, z')dz'$$

Multiple scattering



$$\psi_{exit} = p(\Delta z)\otimes\psi_{(n-1)e}\exp(i\sigma V_n)$$

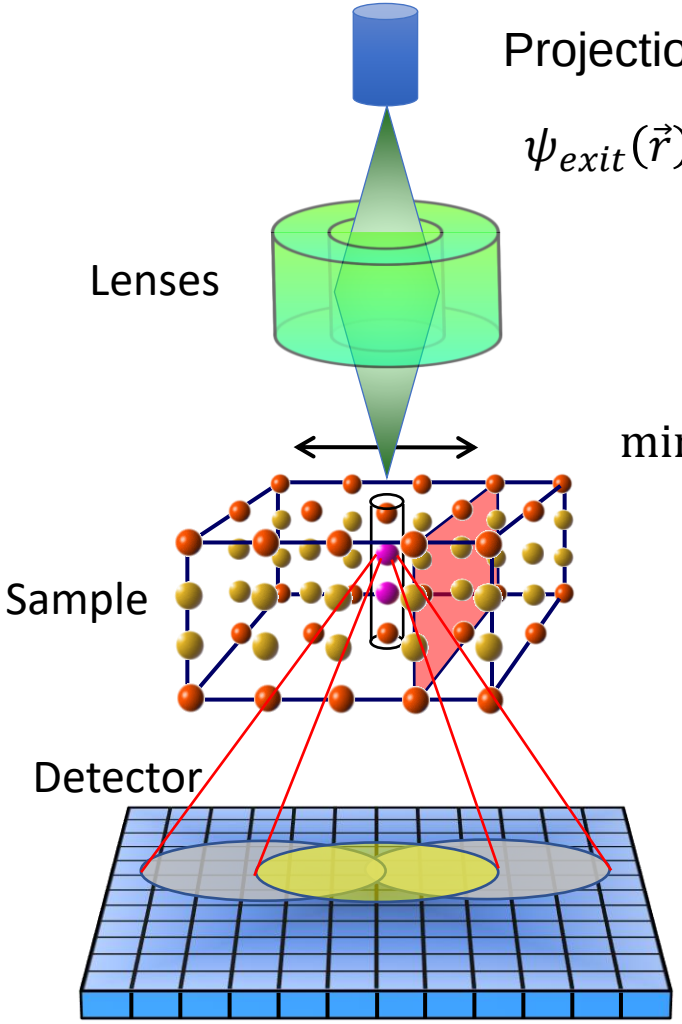
Decouple $O_i(\mathbf{r})$ and ψ_{probe}

New technique:
Multislice electron ptychography (MEP)

Y. Jiang#, Z. Chen#, *et al.*, Nature 559, 343 (2018)

A. M. Maiden, *et al.*, J. Opt. Soc. Am. A 29, 1606 (2012)
M. Odstrcil, *et al.*, Opt. Express 26, 3108 (2018)
Z. Chen, *et al.*, Science 372, 826 (2021)

开发新的成像技术：分辨率吉尼斯世界纪录



Ptychography

Projection approximation

$$\psi_{exit}(\vec{r}) = \psi_{probe}(\vec{r}) \cdot A(\vec{r})\exp[i\sigma V(\vec{r})]$$

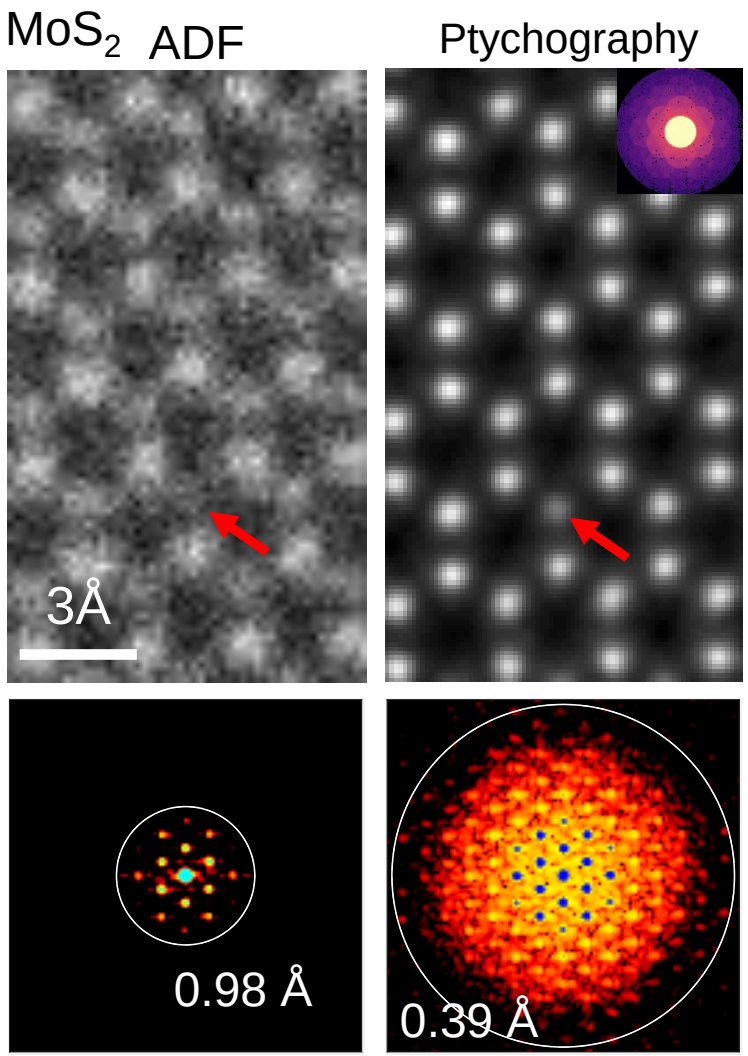
Electrostatic potential

Inverse problem

$$\min \sum_i \left\| \sqrt{I_i\left(\vec{k}\right)} - |\mathcal{F}[\psi_{exit}(\vec{r} - \vec{r}_i)]| \right\|^2$$

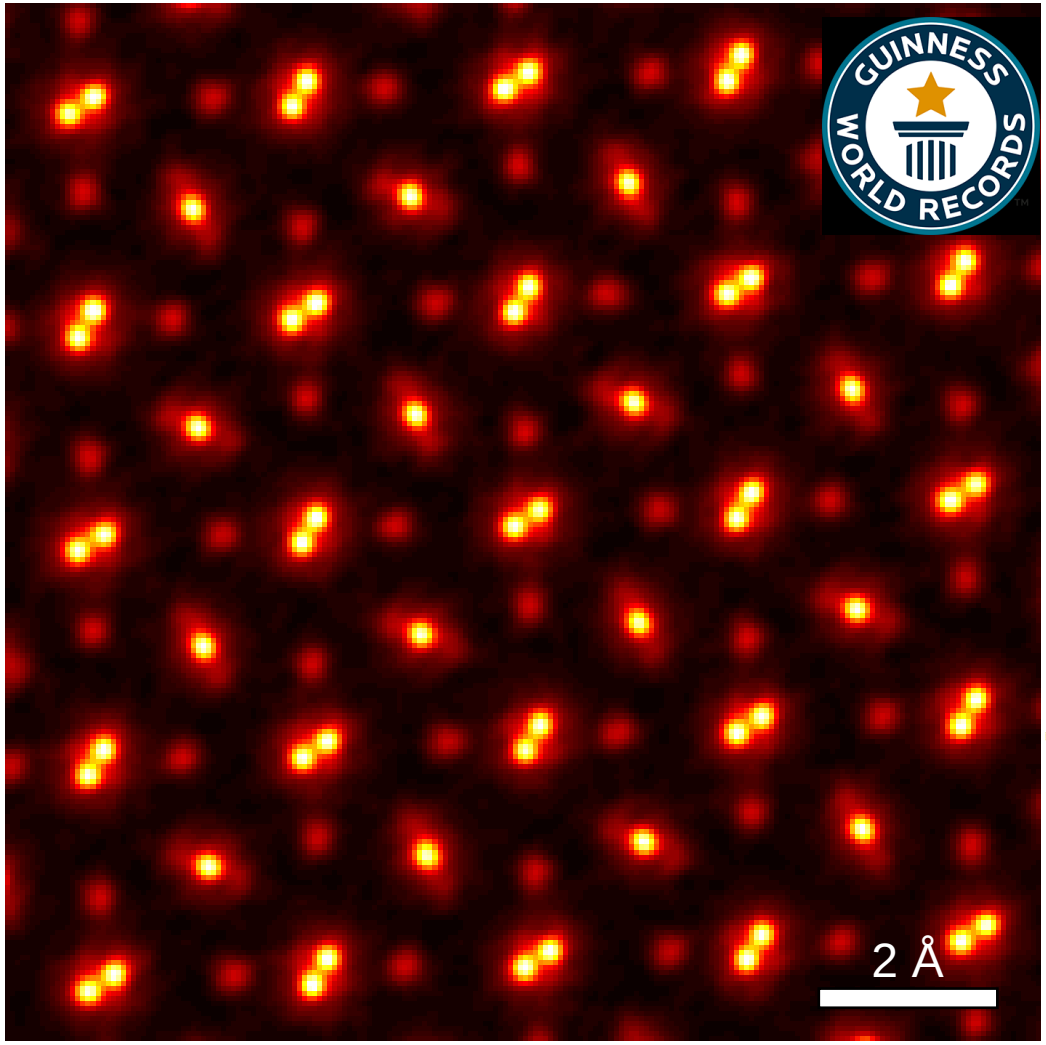
Diffraction

- Resolution ~0.4 Å
- High signal-to-noise
- Low-dose

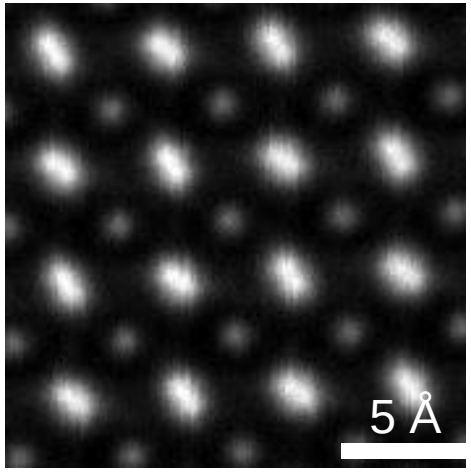


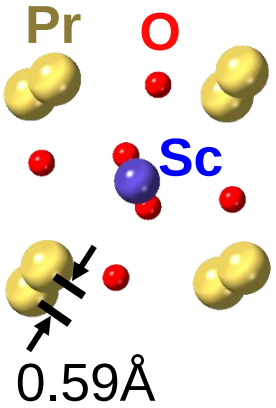
Y. Jiang#, Z. Chen#, *et al.*, Nature 559, 343 (2018)

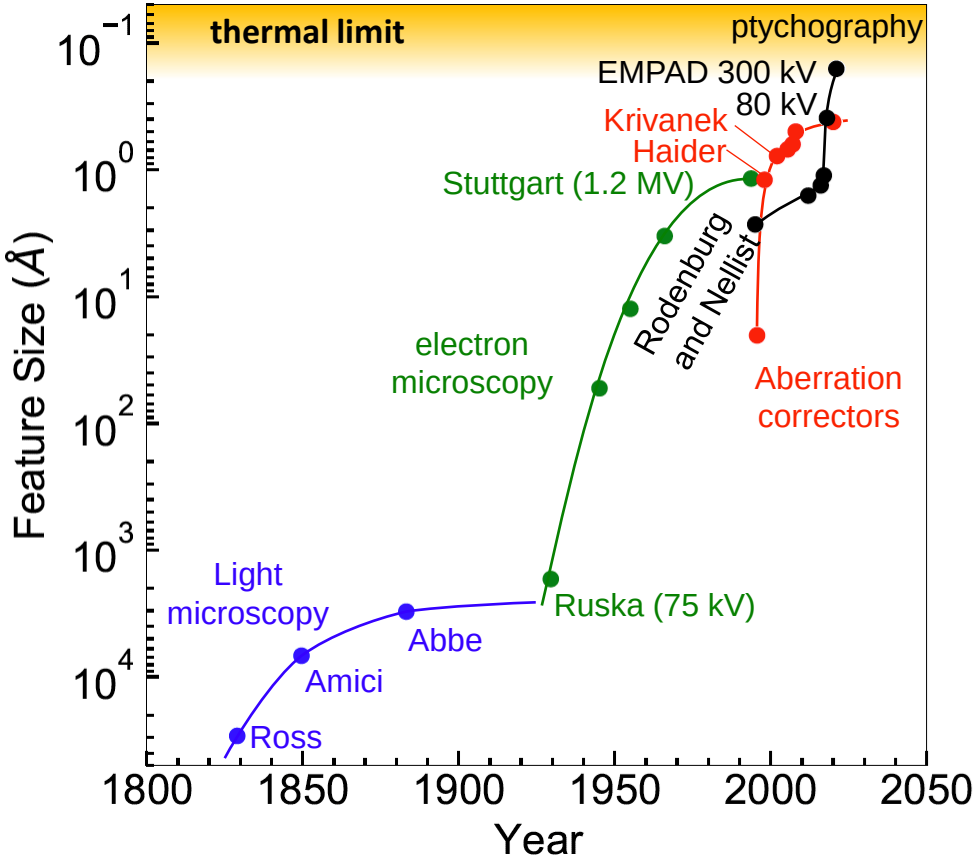
原子晶格振动的极限分辨率：优于20 皮米



HAADF





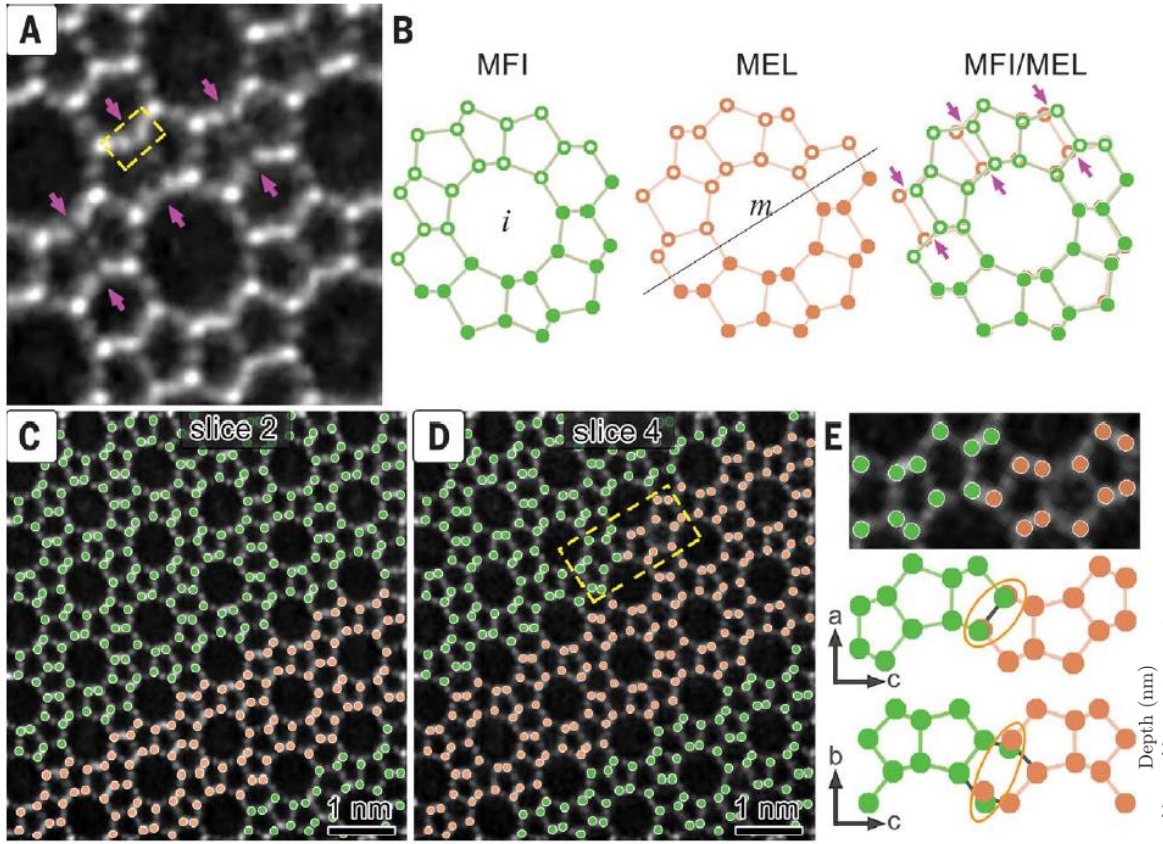


Courtesy of David Muller (2021)

Sub-pm precision
Low dose imaging
Single dopant detection

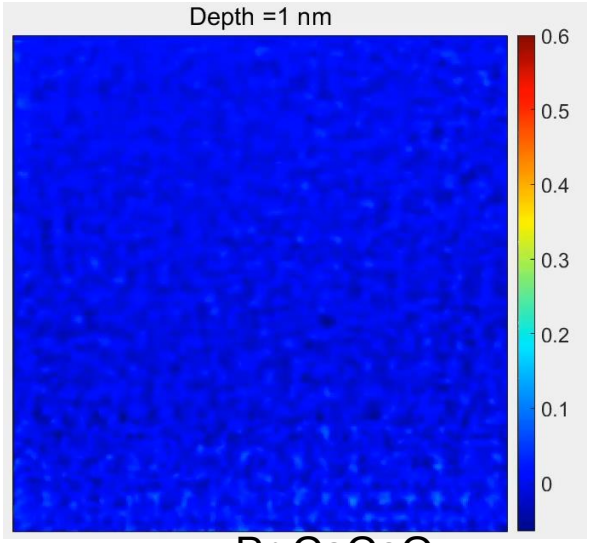
Z. Chen, *et al.*, Science 372, 826 (2021)

多片层电子叠层衍射技术的优势

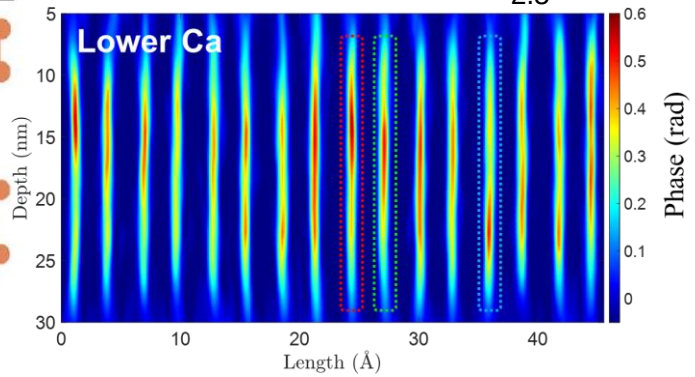


Low-dose for energy materials

H. Zhang, *et al*., *Science* 380, 633 (2023)



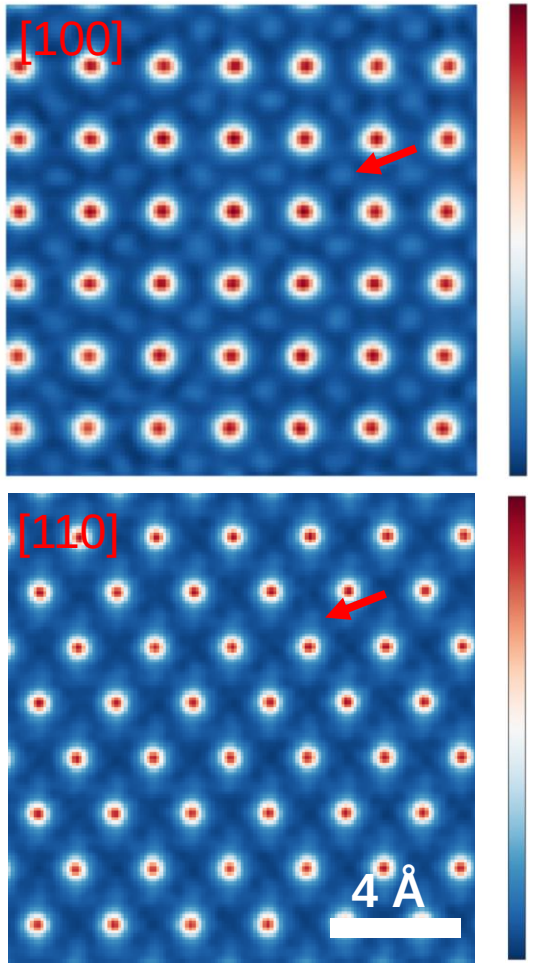
Pr-$CaCoO_{2.5}$



Single dopant detection

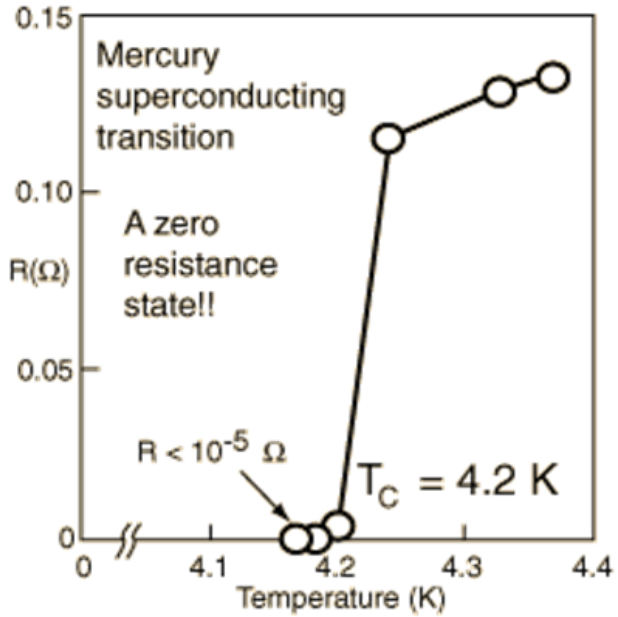
Z. Dong, Z. Chen*, *et al*., arXiv: 2406.04252 (2024)

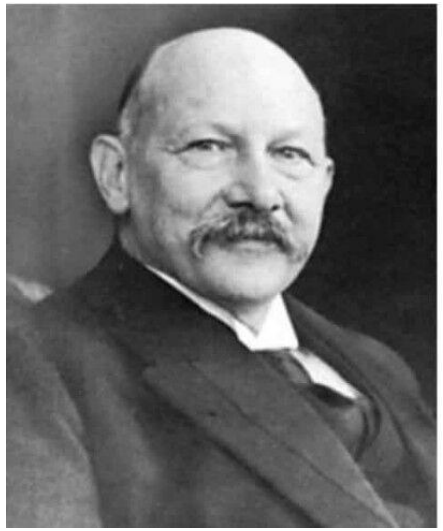
Lightest atom (H)



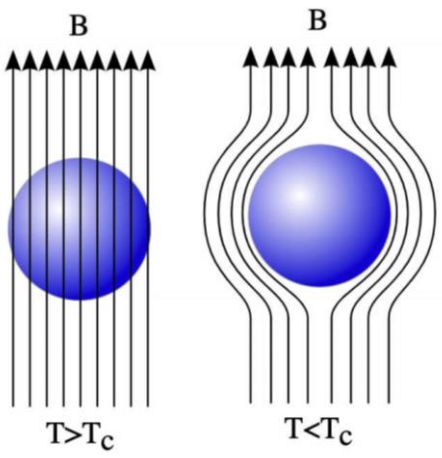
P. Li, Z. Chen, *et al*., *M&M* 30, 1850 (2024)

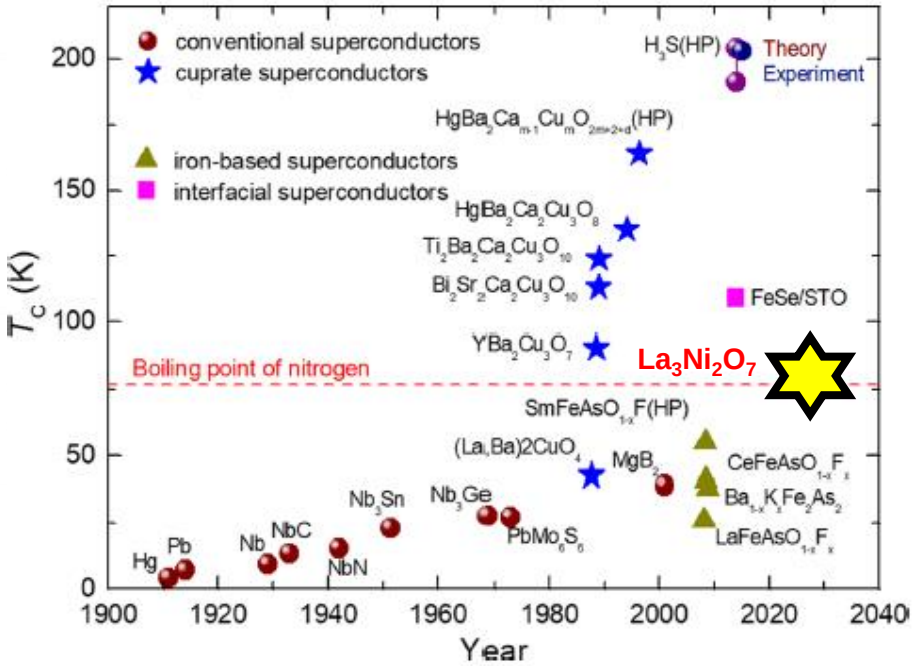
高温超导材料

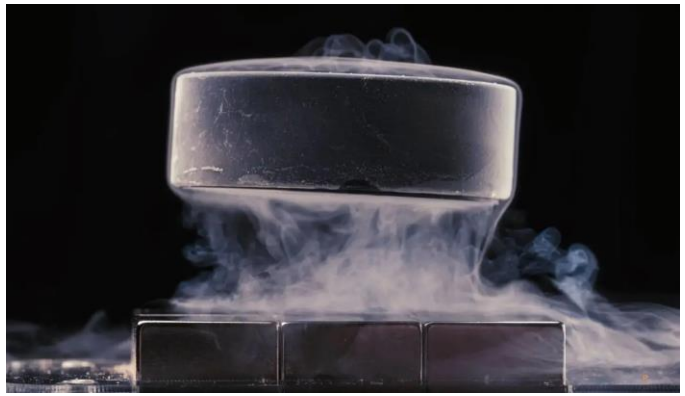




Messiner effect







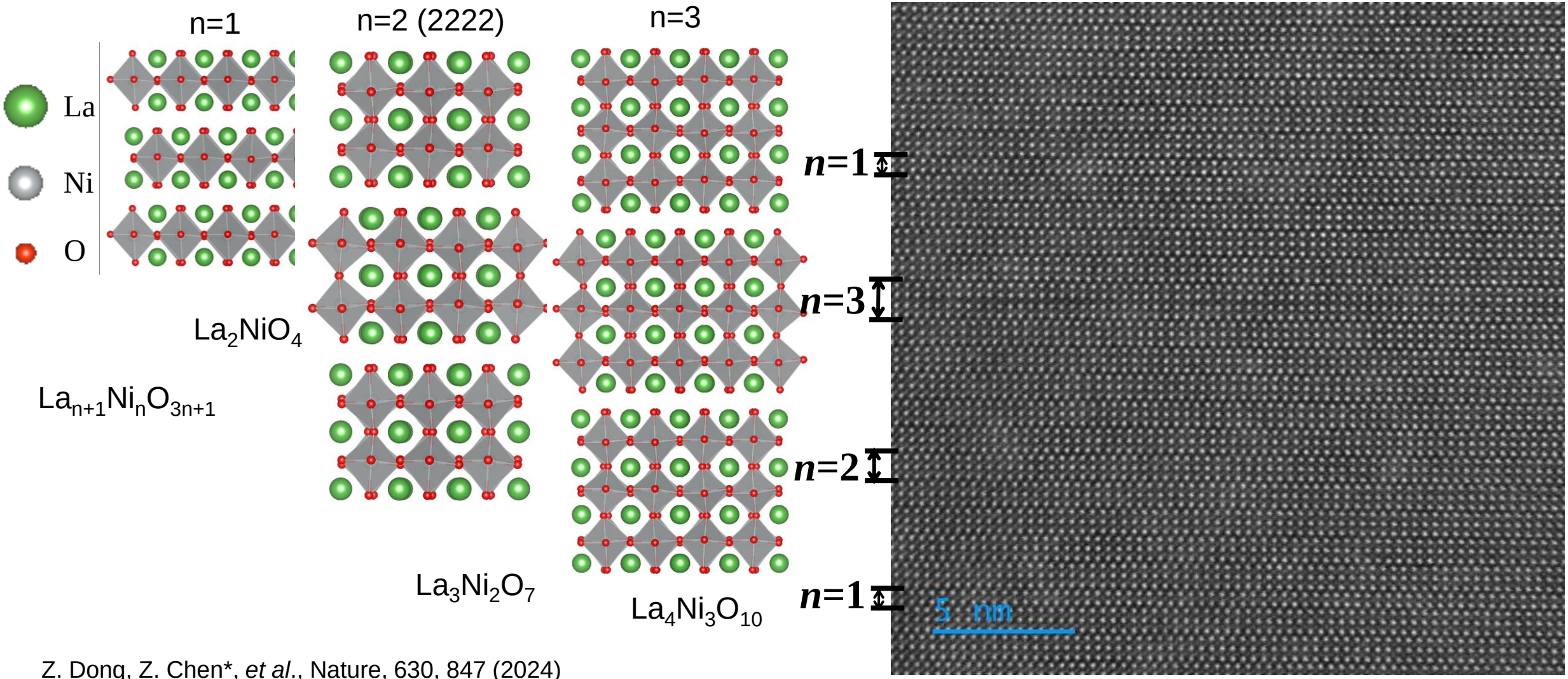
- **Zero resistivity**
- **Perfect diamagnetism**

Searching for new SC with a higher Tc

D. Duan, *et al.*, *Supercond Nov Magn* 32, 53 (2019)
H. Sun, *et al.*, *Nature* 621, 493 (2023)

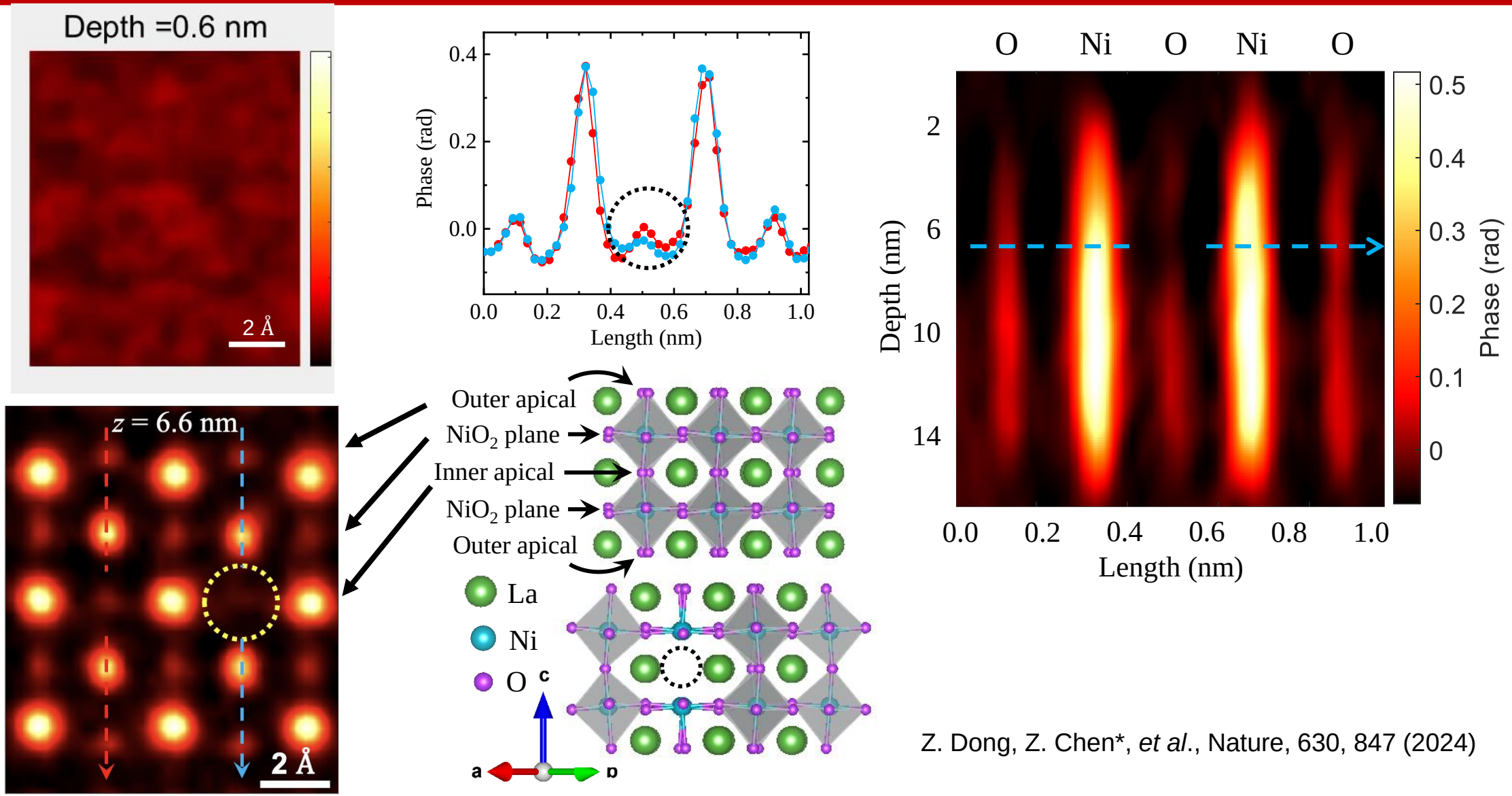
H. K. Onnes, *Commun. Phys. Lab*.12,120 (1911)

镍基氧化物高温超导体的复杂结构



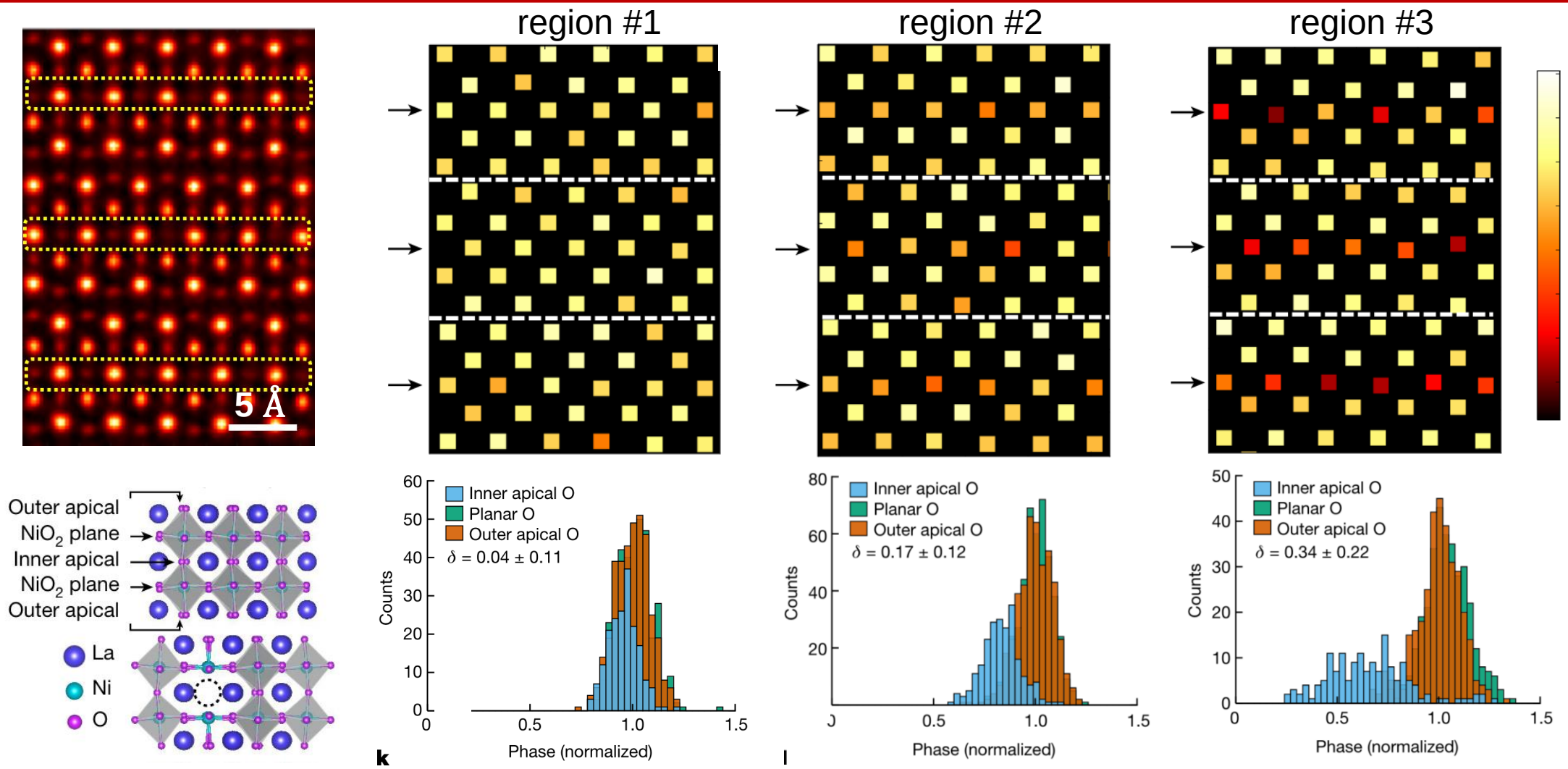
Z. Dong, Z. Chen*, *et al*., Nature, 630, 847 (2024)

氧空位的原子尺度三维直接成像



Z. Dong, Z. Chen*, *et al.*, Nature, 630, 847 (2024)

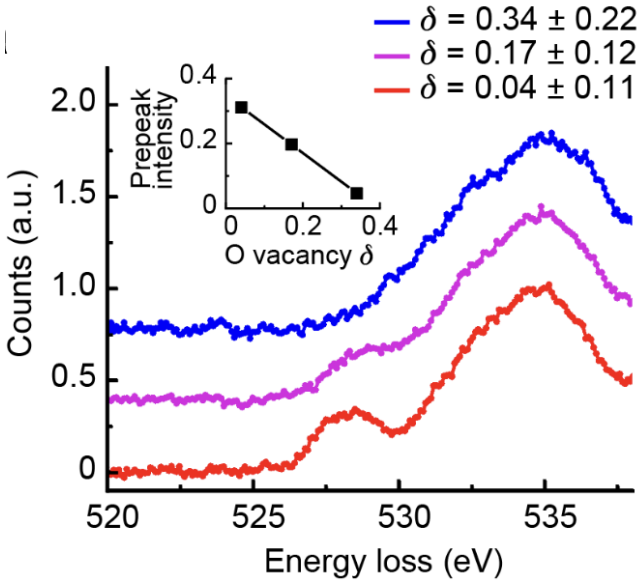
氧空位的原子尺度定量测量

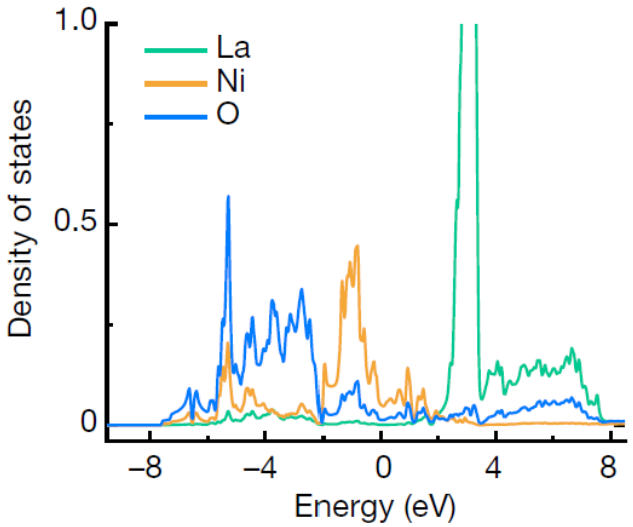


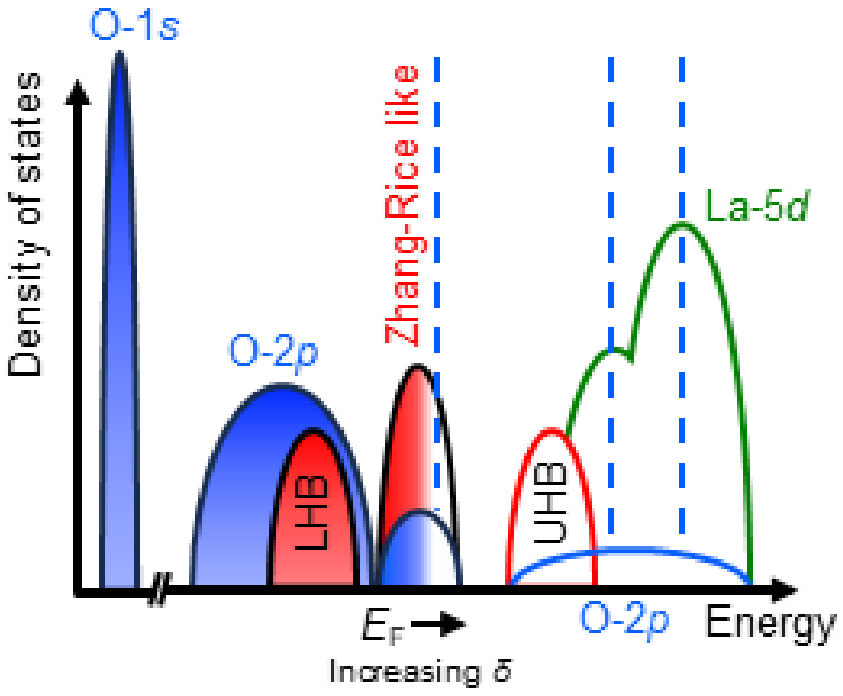
Z. Dong, Z. Chen*, *et al*., Nature, 630, 847 (2024)

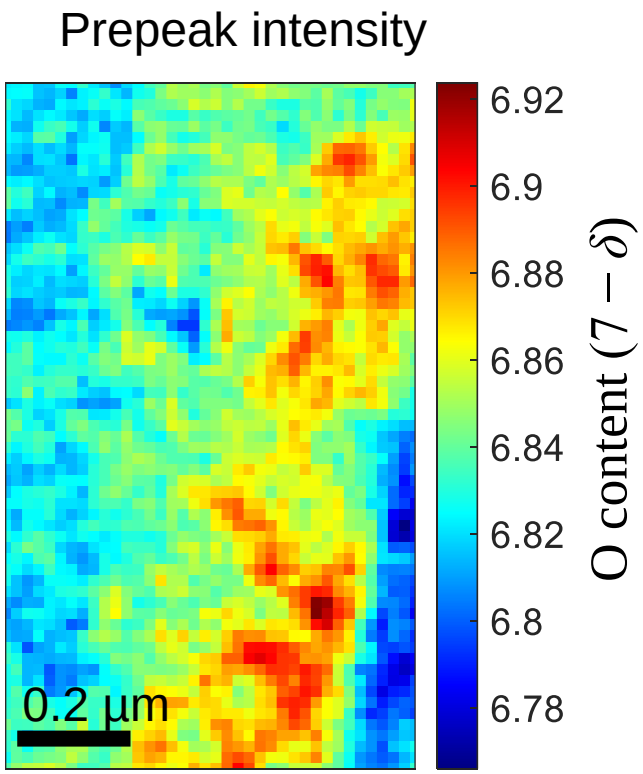
国际上首次实现氧的原子尺度三维定位和定量测量

氧空位含量与空穴态电子结构关联O-K EELS





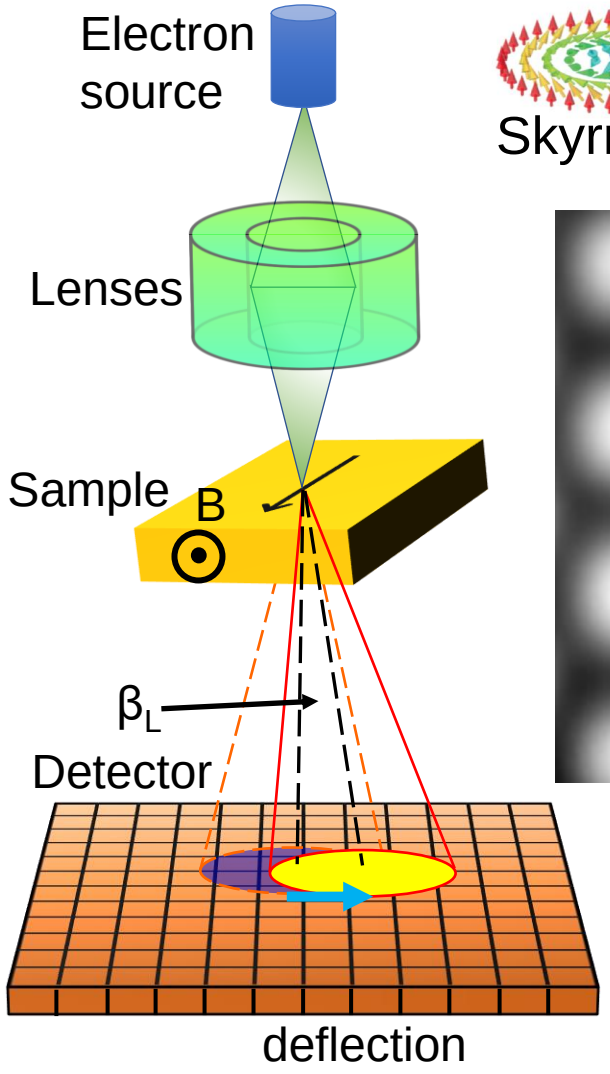


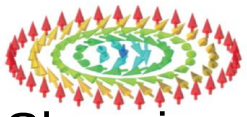


- Charge-transfer dominant
- Oxygen inhomogeneity at sub-100 nm scale

Z. Dong, Z. Chen*, *et al.*, Nature, 630, 847 (2024)

拓扑磁结构和量子物态成像

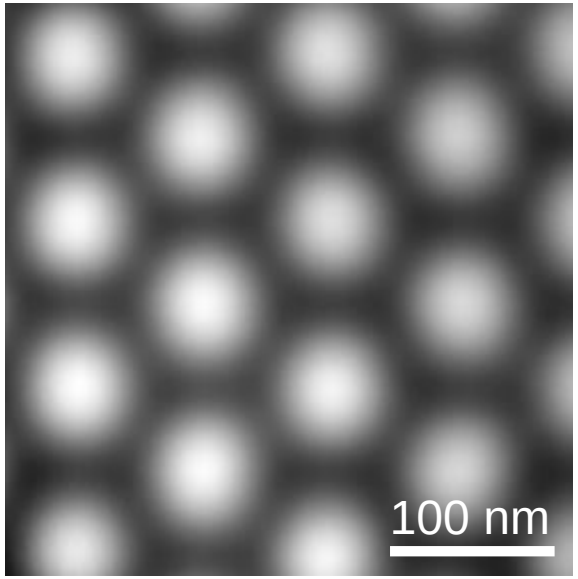




Skyrmions

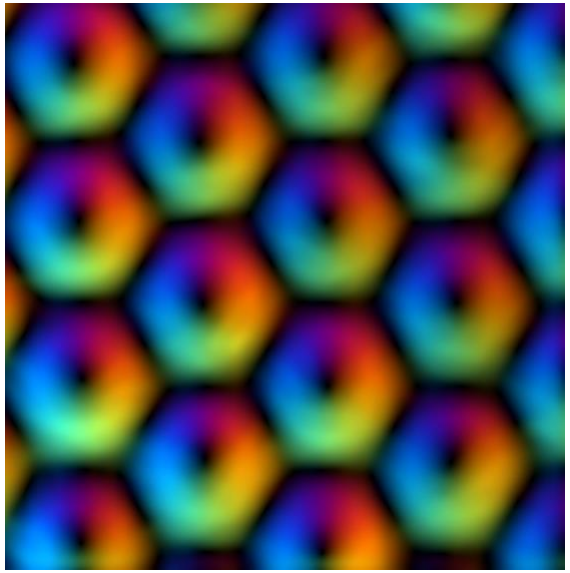
Three Melodies of theoretical physics in 20th century:
Quantization, Symmetry and Phase Factor ---- **Chen Ning Yang**

Phase



FeGe at 94 K

Magnetic field



Phase Electrostatic

$$\varphi(\mathbf{r}, z_0) = C_E \int_{-\infty}^{z_0} V(\mathbf{r}, z')\,\mathrm{d}z' - \frac{e}{\hbar}\int_{-\infty}^{z_0} A_z(\mathbf{r}, z')\,\mathrm{d}z'$$

Magnetic

First magnetic ptychography realized in TEM

Resolution ~2 nm

Z. Chen*, *et al.*, Nat. Nanotech., 17, 1165 (2022)

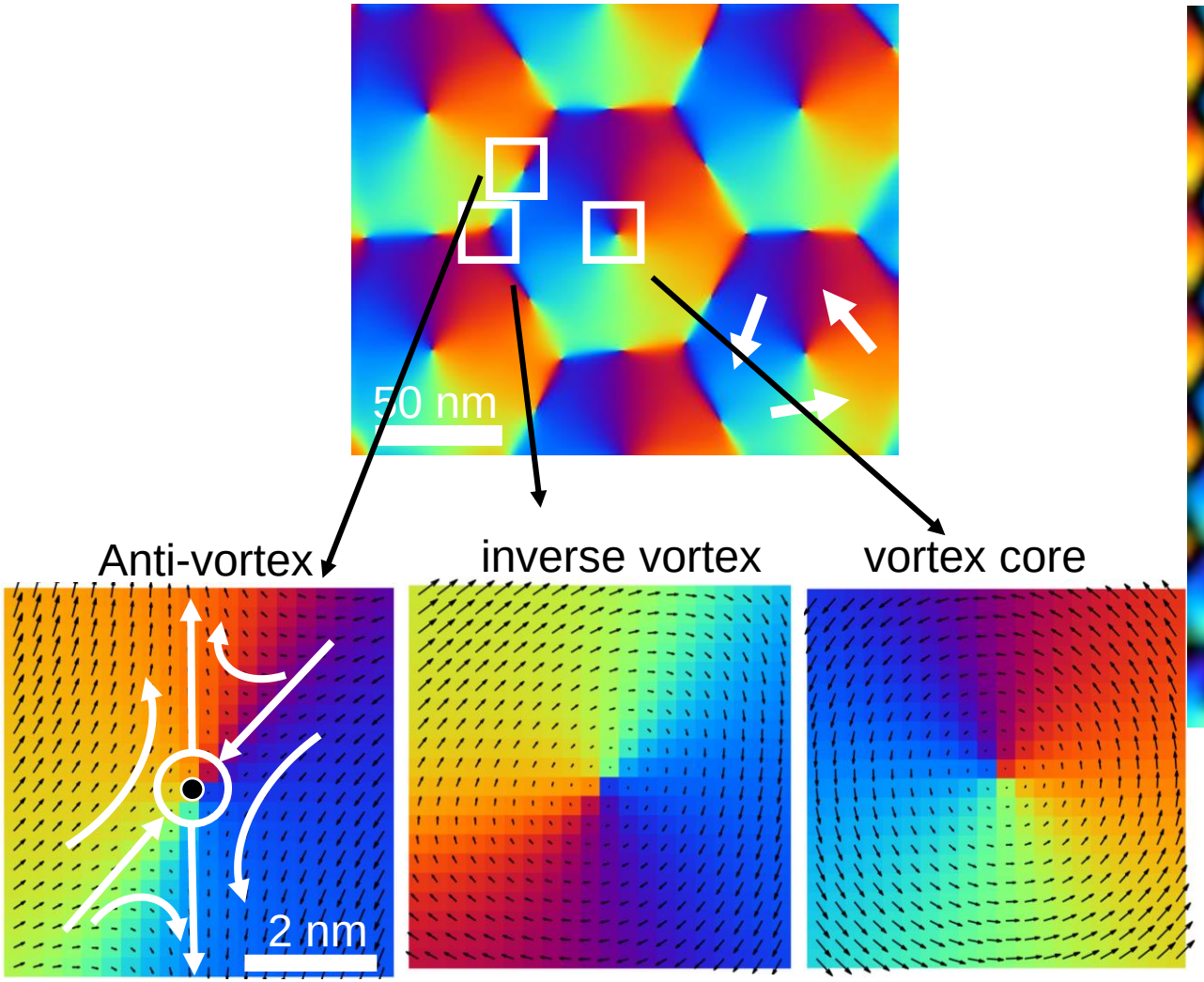
News & views

Magnetic imaging

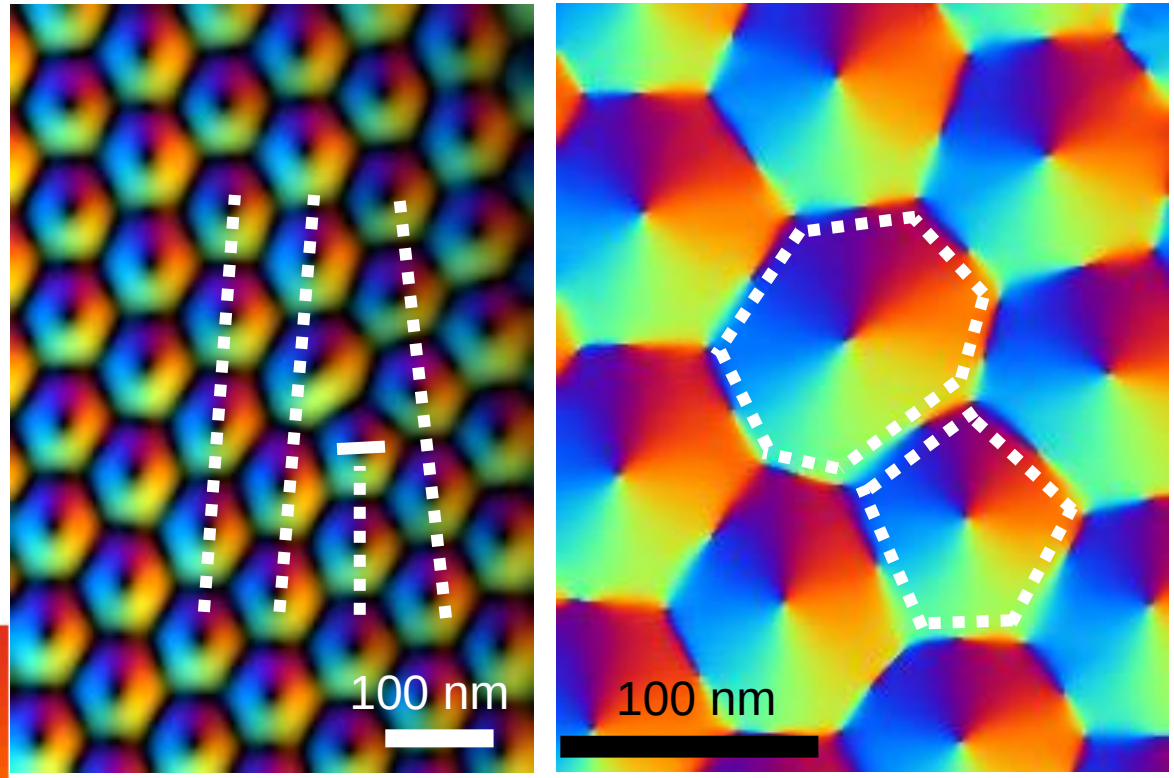
A closer look at spin textures

Jianwei Miao & Margaret M. Murnane

磁斯格明子内禀磁结构



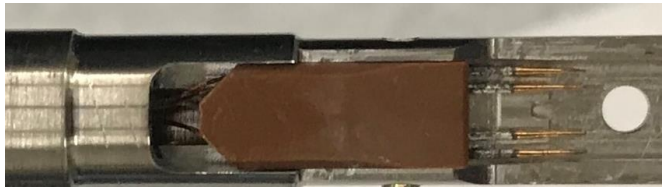
FeGe, T=94 K, μ_0H=130 mT

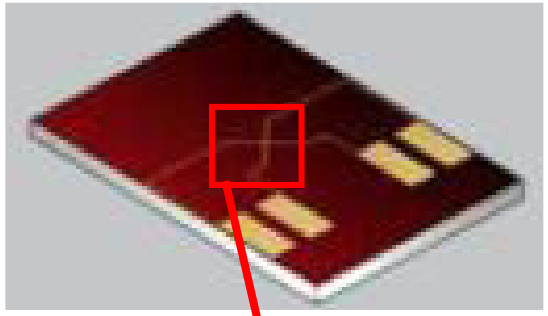


Clear spin orders imaged at ~ 2 nm resolution

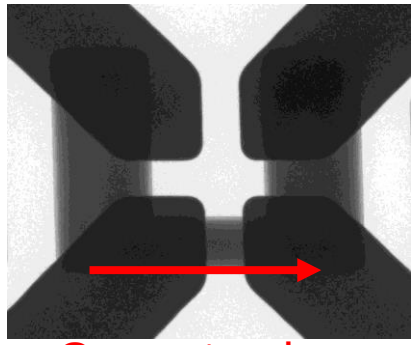
Z. Chen*, *et al*., Nat. Nano., 17, 1165 (2022)

拓扑物态的动态测量和调控

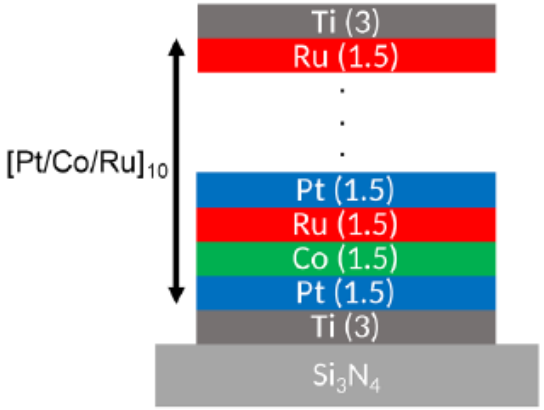


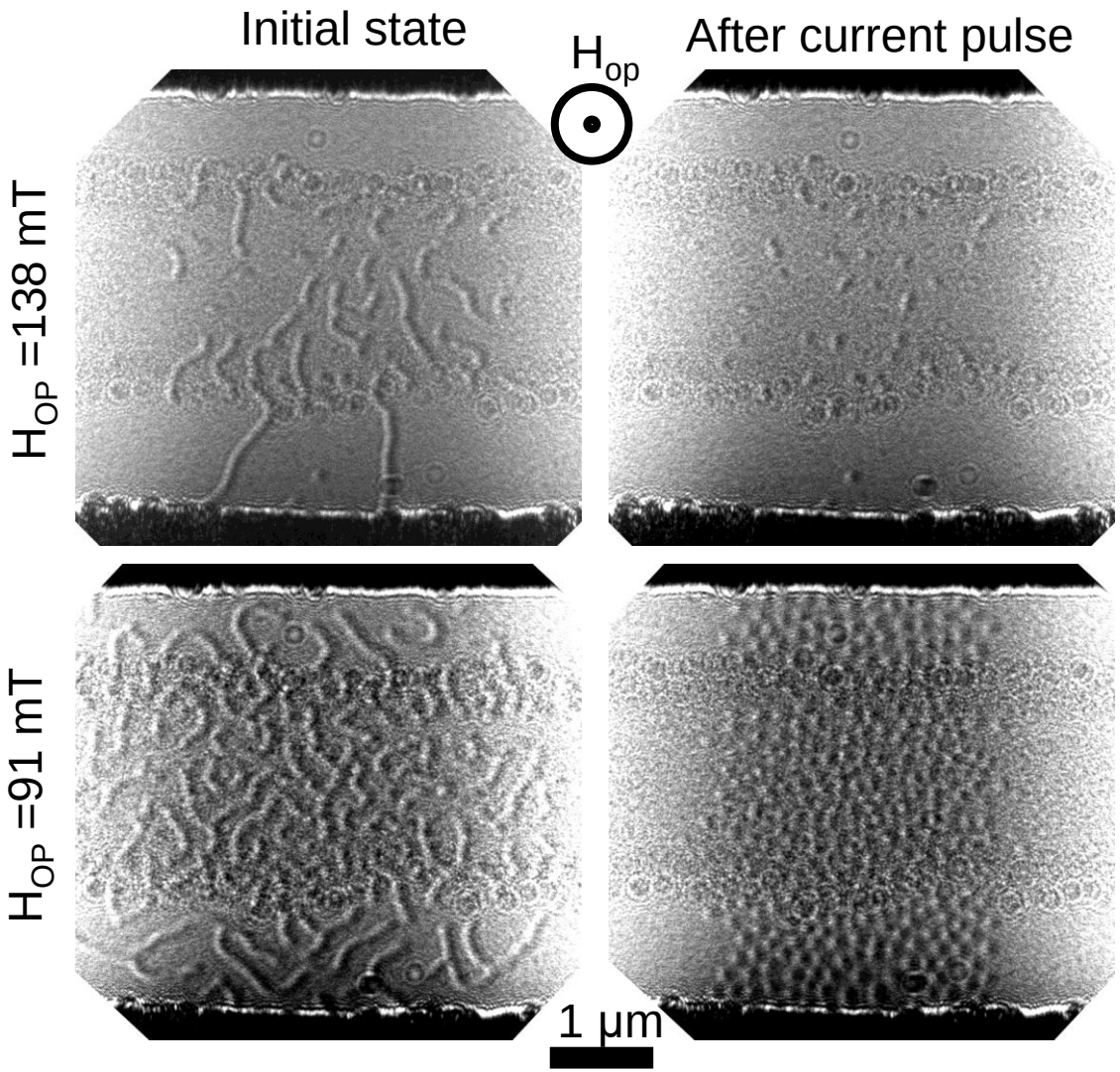


Electrodes



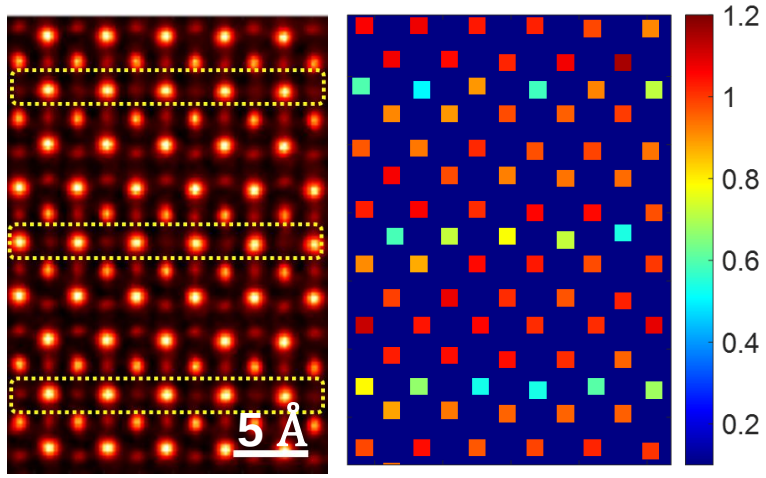
Current pulse



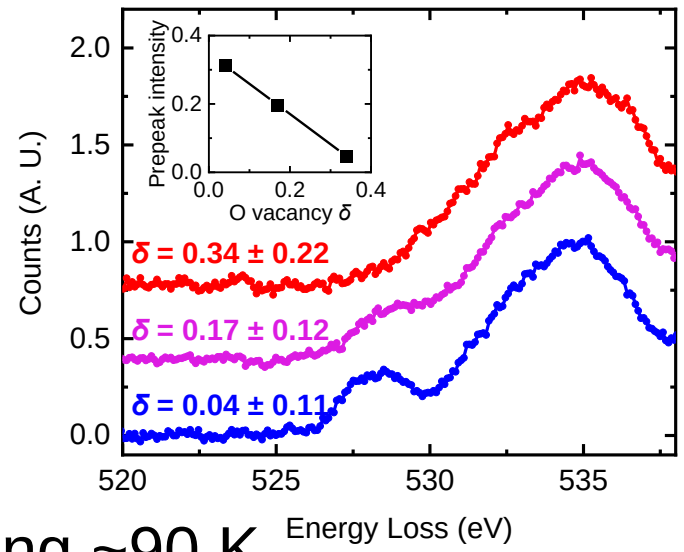


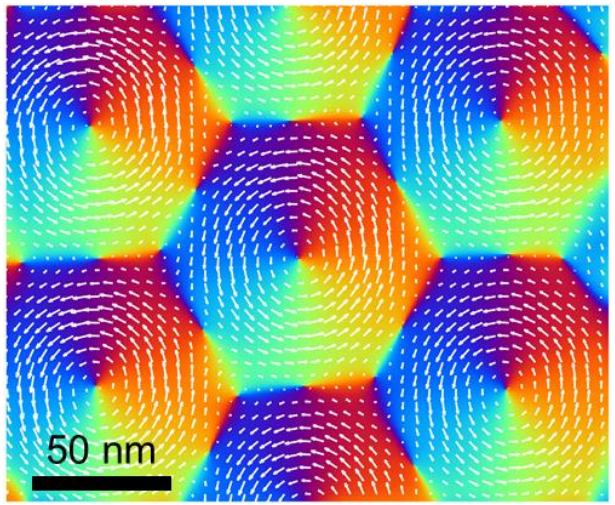
A. M. Park#, Z. Chen#, *et al*. J. Appl. Phys. 128, 233902 (2020)

研究领域：探索量子材料的微观结构和量子态



Nature, 559， 343 (2024)
Science 372,826 (2021)



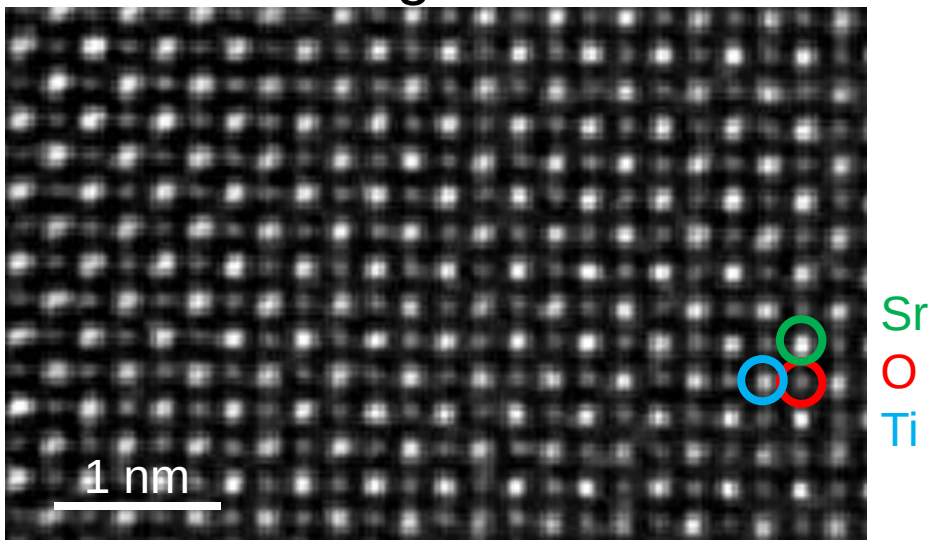


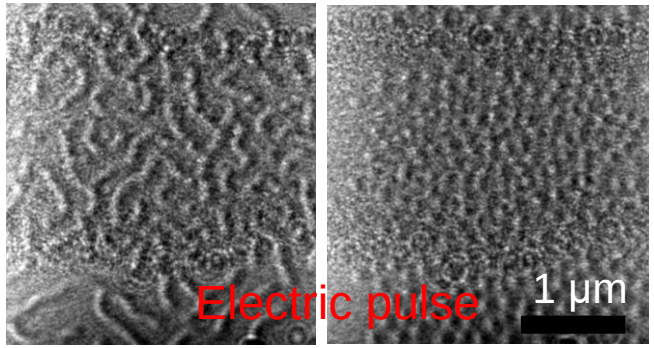
Nat. Nano., 17, 1165 (2022)
Nano Lett., 24, 2727 (2024)

物理和材料：
超导、铁电、二维和半导体材料

Cooling ~90 K

动态演变

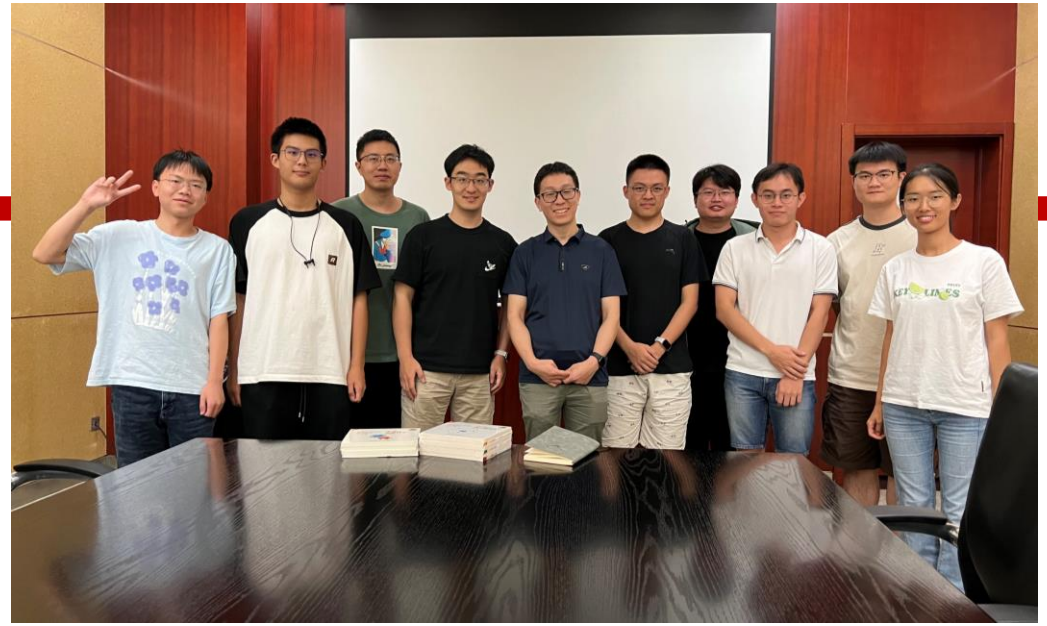




J. Appl. Phys. 128, 233902 (2020)

Acknowledgements

Yayu Wang, Pu Yu, Yang Zhang
Lin Gu, Pengcheng Li, Chenglin Pua
(Tsinghua University)
Meng Wang, Mengwu Huo, Hualei Sun
(Sun Yat-Sen University)
Yi Lu, Jie Li
(Nanjing University)
Jan-Chi Yang, Yu-Chen Liu
(National Cheng Kung University)
Suya Liu (Thermo Fisher)
Daniel Stroppa (Dectris)
Dong Su, Huaicheng Yuan,
Changsheng Chen (IOP)



Contact:
zhen.chen@iphy.ac.cn

依托中国科学院北京电子显微镜重点实验室

（8位院士工作过）

中國科學院物理研究所
Institute of Physics, Chinese Academy of Sciences

先进材料与结构分析实验室
Advanced Materials & Electron Microscopy