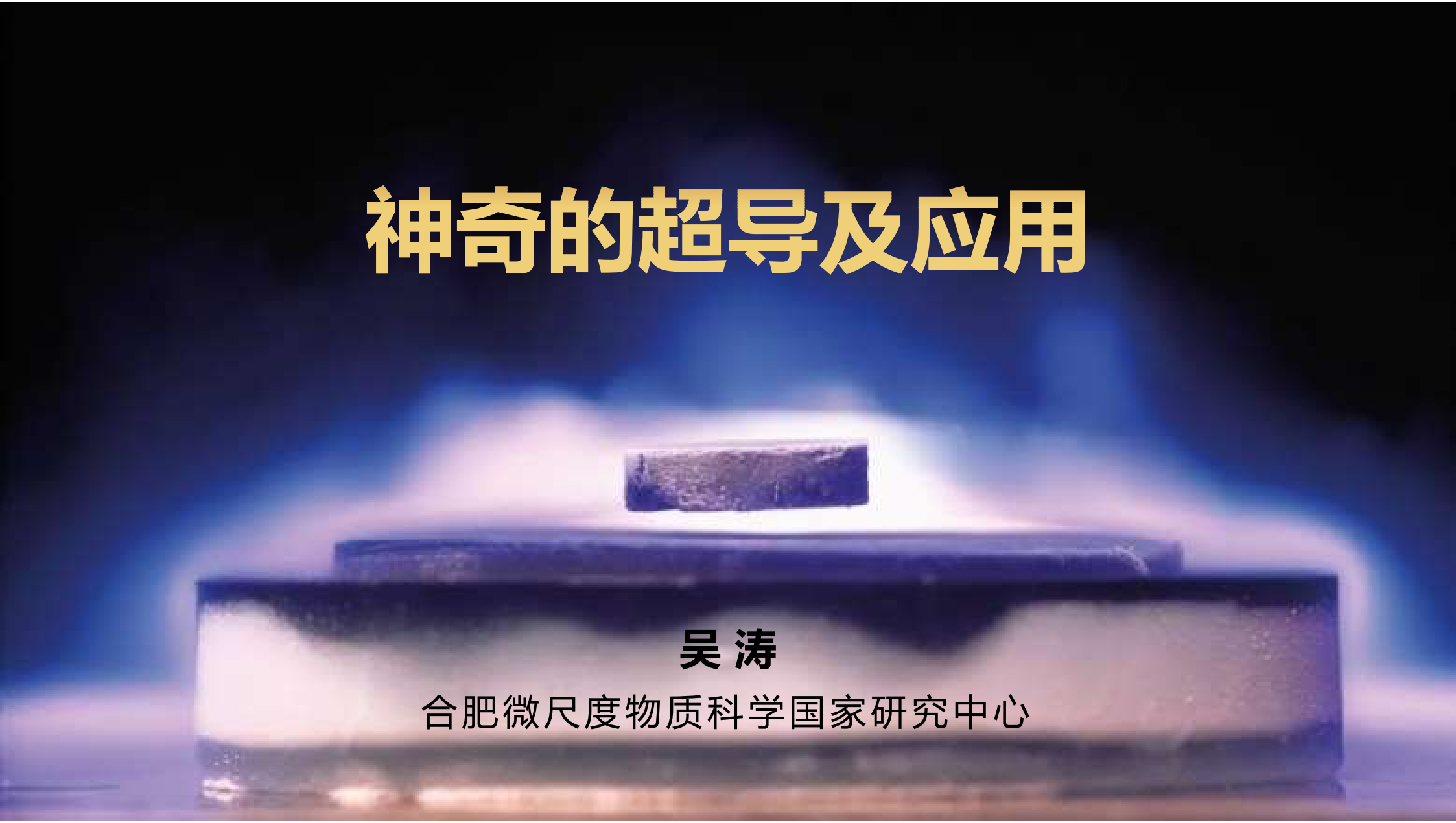
神奇的超导及应用

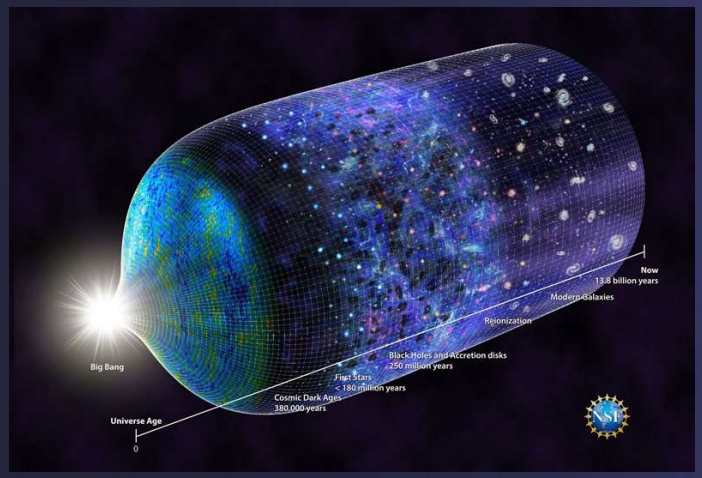


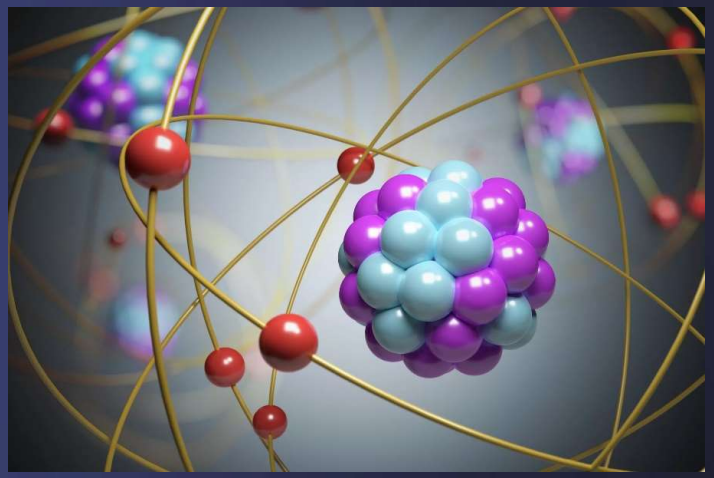
吴 涛

合肥微尺度物质科学国家研究中心

• 物质科学研究

“宇观” → “宏观” → “介观” → “微观”



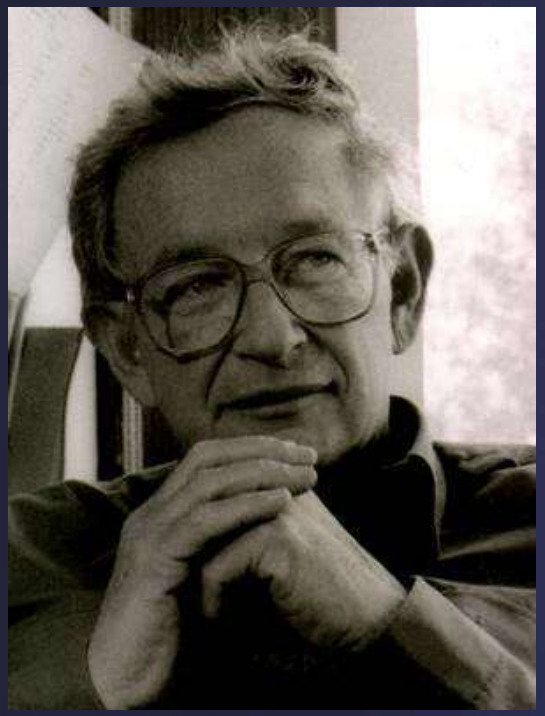


• 宇宙的起源

• 宏观物质中的物态和量子现象

• 物质的结构

- **演生物理**



Philip W. Anderson:

More is different (1972)

"…, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other."

"Emergent phenomena"

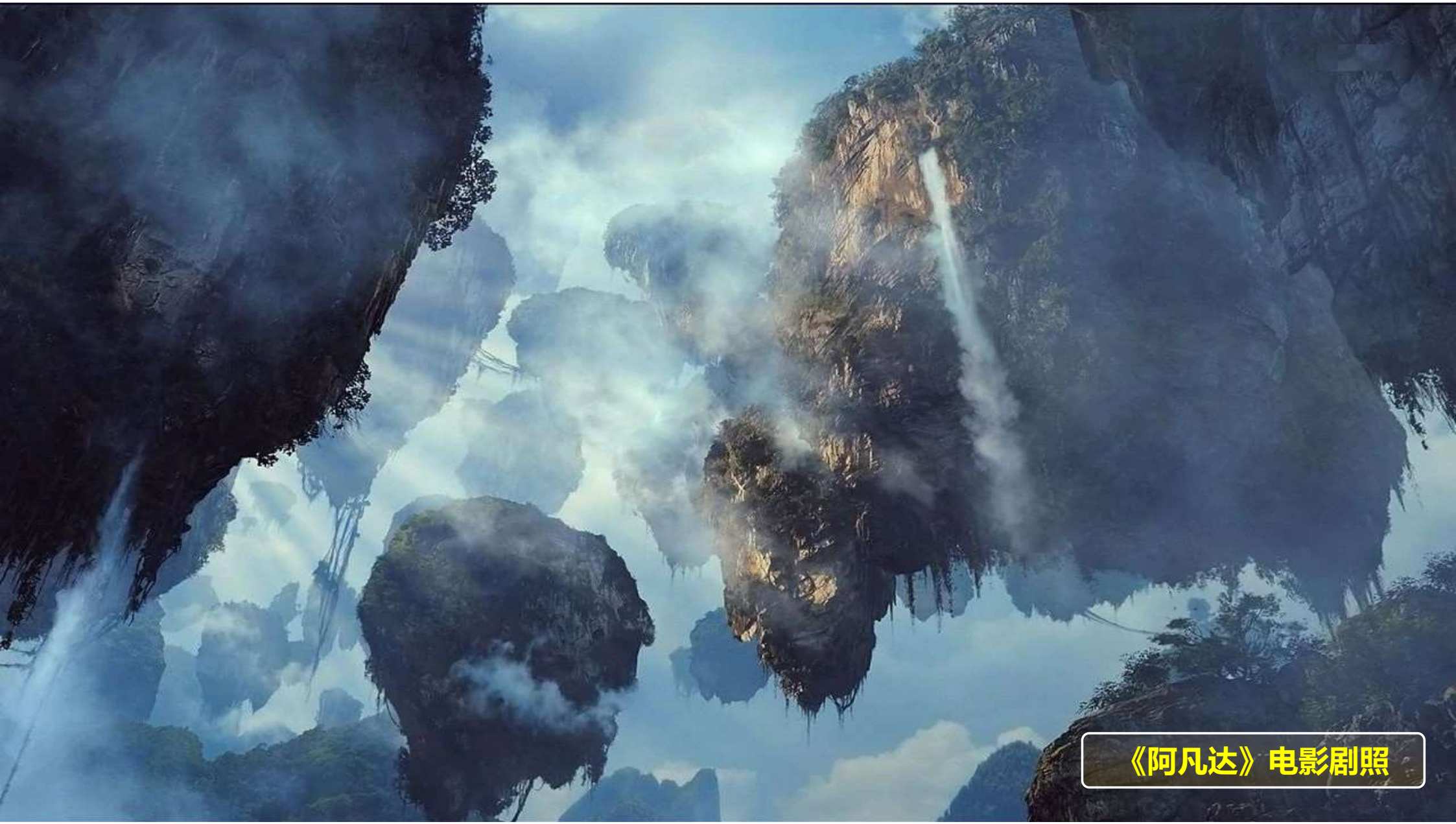
P. W. Anderson, Science **177,** 393(1972)

"演生"

认为整体大于各组分的总和，当各组分被有机地组合在一起时，整体表现出新的性质

演生物态是演生物理研究中一个重要的研究内容

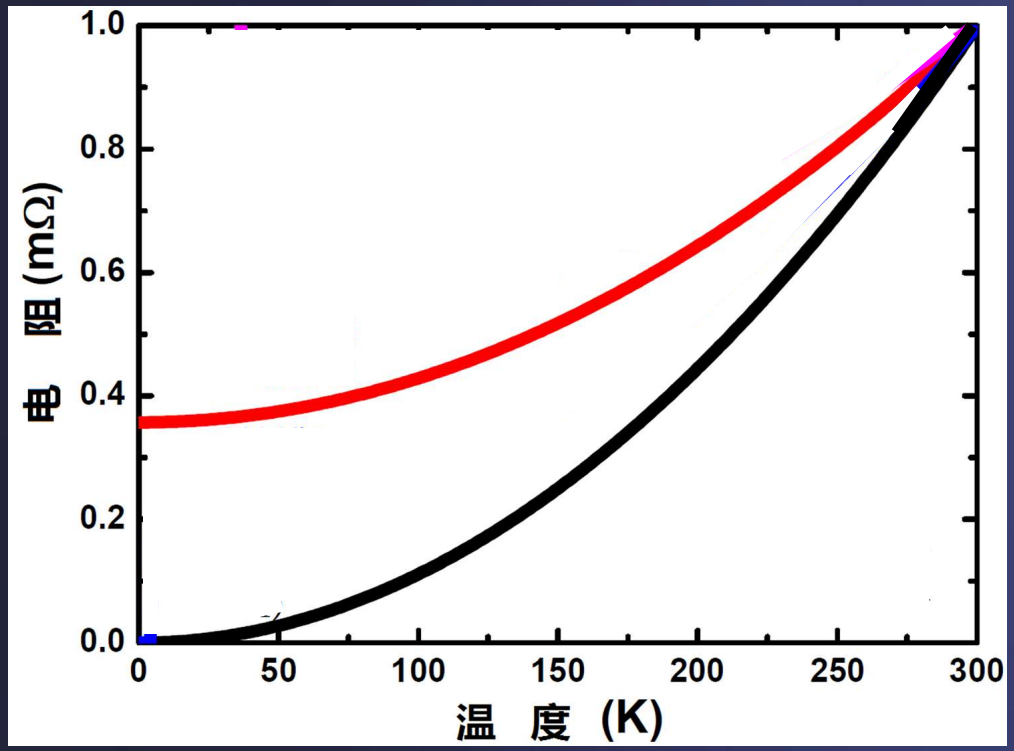
在宏观尺度上，有没有我们能看得见、觉察得到的演生量子现象？



《阿凡达》电影剧照

• 低温的获得

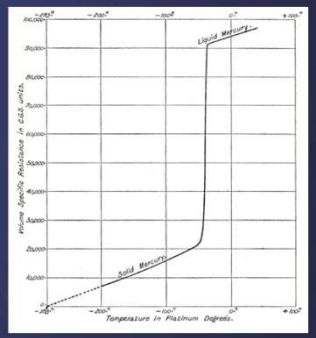
在接近绝对零度时，纯金属的电阻如何变化?



0 K= -273.15 ℃

- 1823年，法拉第成功液化氯气（~239K）。很快，除了O_2, N_2, H_2, He等“永恒气体”之外的已知气体都被液化。
- 1896年，杜瓦液化了空气（~77K）。**对水银电阻的线性外推，认为0K时电阻为零。**
- 杜瓦与昂尼斯在液化氢气上展开了竞争。1898年，杜瓦成功液化了氢气（~21K）。**对大量金属的测量结果显示电阻的减小在低温下会变缓，零温下将出现有限值。**

詹姆斯·杜瓦

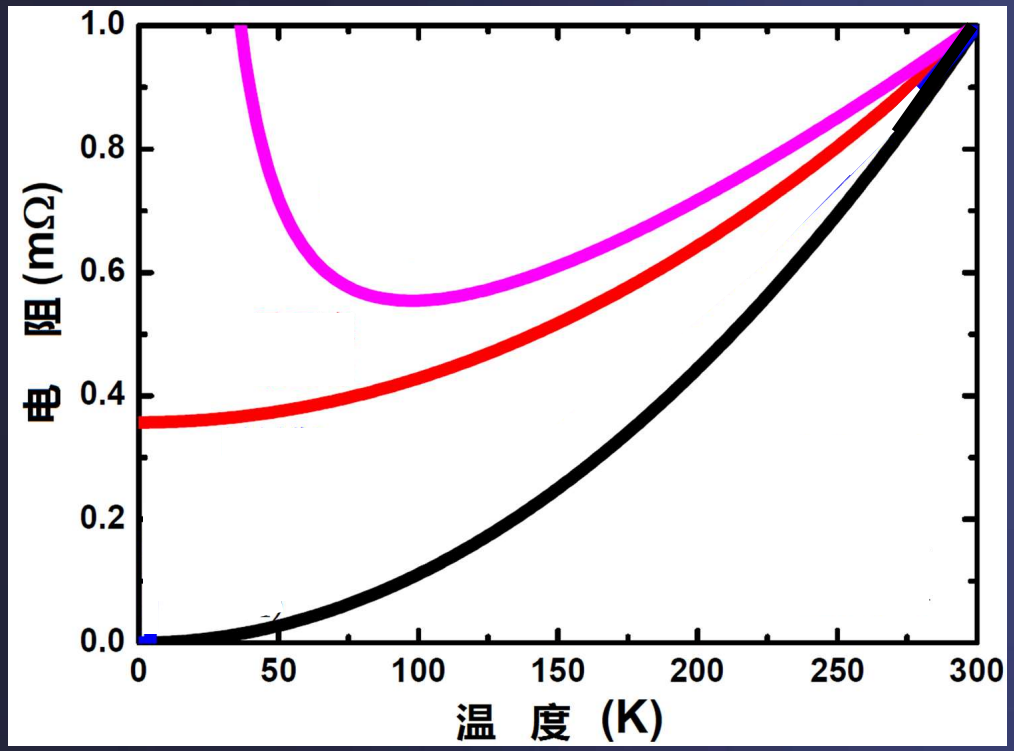


液态空气温度
水银的电阻测量

杜瓦瓶

• 氦的液化

在接近绝对零度时，纯金属的电阻如何变化?



0 K= -273.15 ℃

- 1902年，开尔文提出接近绝对零度时，由于电子的运动性消失，电阻将上升，在有限温度出现一个极小值。
- 1908年，在获得氦气资源的13年后，昂尼斯成功液化了氦气（~4.2K）。在接下来的15年时间内，昂尼斯的实验室是世界上唯一可以获得液氦的实验室。
- 1908-1910年，昂尼斯进行了大量液氦温区实验，并没看到电阻的极小值。为了测量最纯净的金属中的电阻行为，昂尼斯选择了水银。

卡默林·昂尼斯

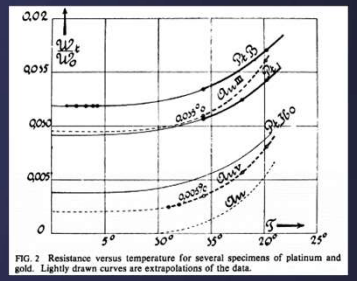
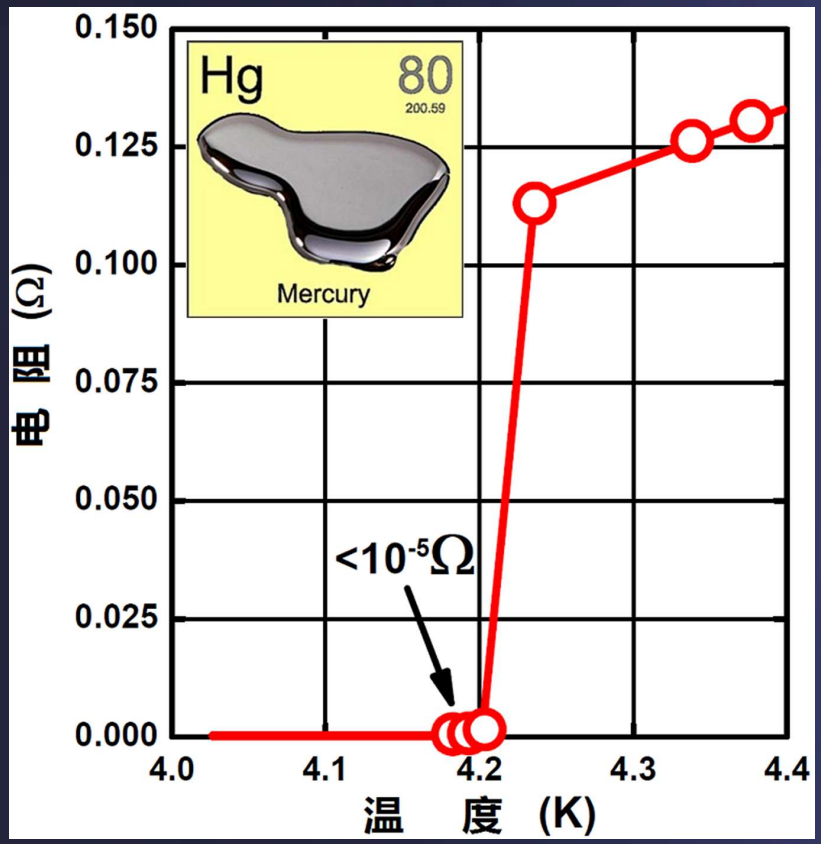


FIG. 2 Resistance versus temperature for several specimens of platinum and gold. Lightly drawn curves are extrapolations of the data.

液氦温区
金和铂的电阻

• 超导体的发现



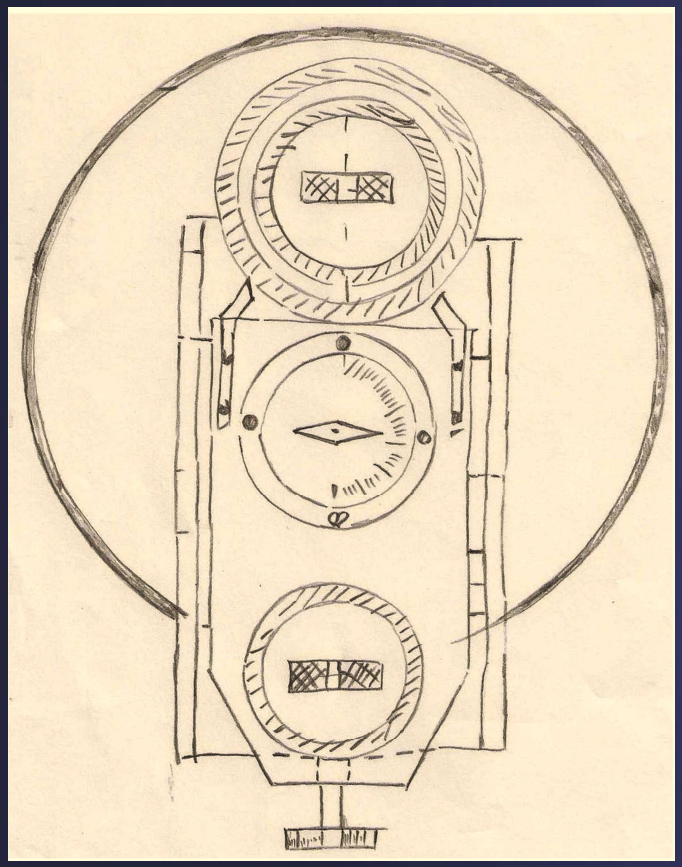
0 K= -273.15 ℃

卡默林·昂尼斯

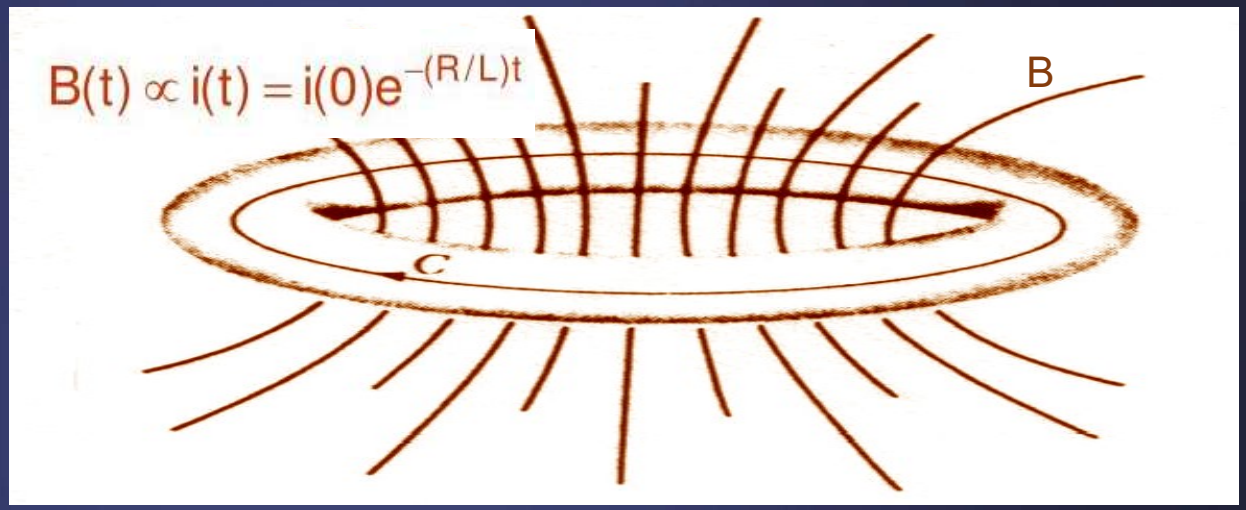
1913年
诺贝尔奖

1911年，昂尼斯发现超导现象，正值首届索尔维会议召开，当时物理学正处于从经典物理学向现代物理学、特别是向量子力学的过渡时期。超导电性作为首个发现的宏观量子现象，对物理的发展起到极大促进作用。

• 超导体的神奇性质——零电阻



超导环的零电阻实验验证
Gerrit Flim 手稿绘图

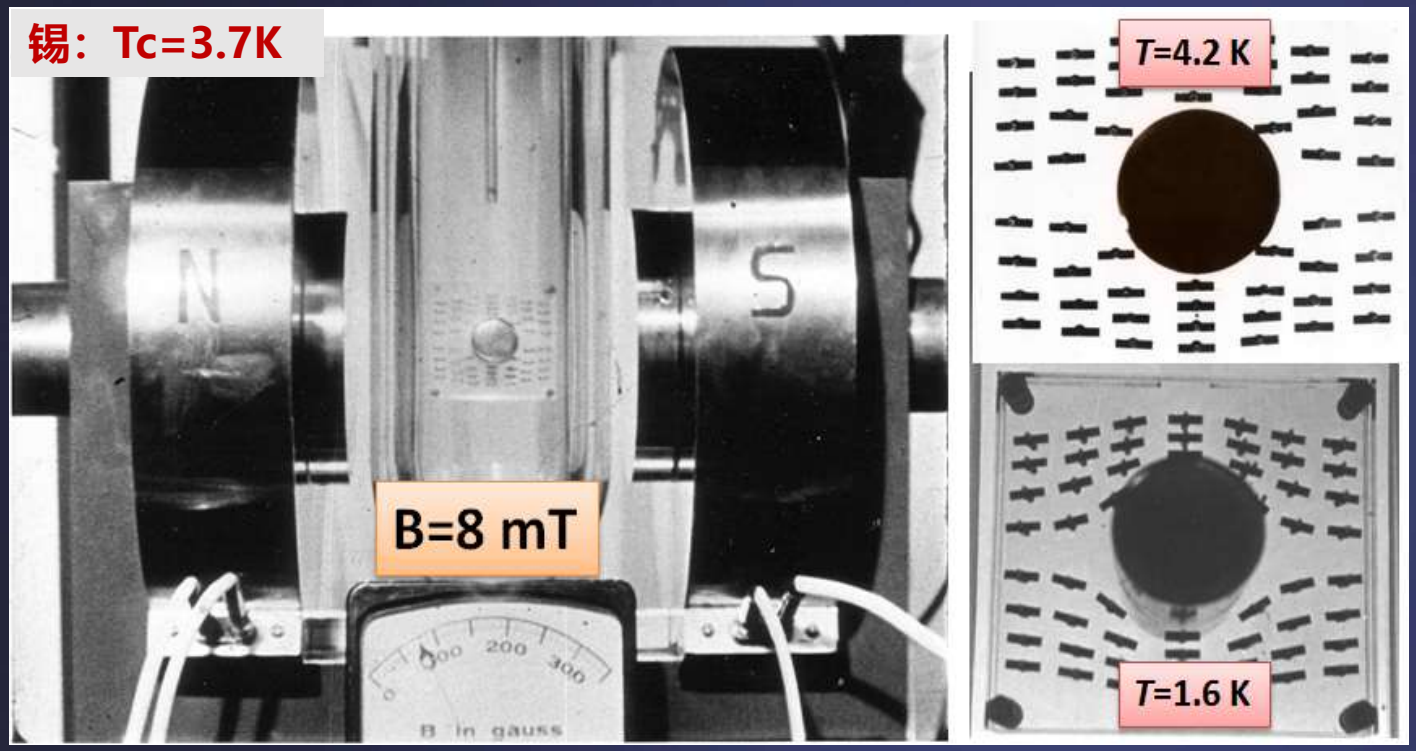


超导的电阻是绝对的零。

1962年，人们用超导环进行实验，连续监测环外磁场的变化，以仪器灵敏度推测超导体电阻率小于 10^{-25} 欧姆·米，后来更精密实验证明小于 10^{-28} 欧姆·米。

这意味着超导体中电流数十万年甚至数亿年不衰减！

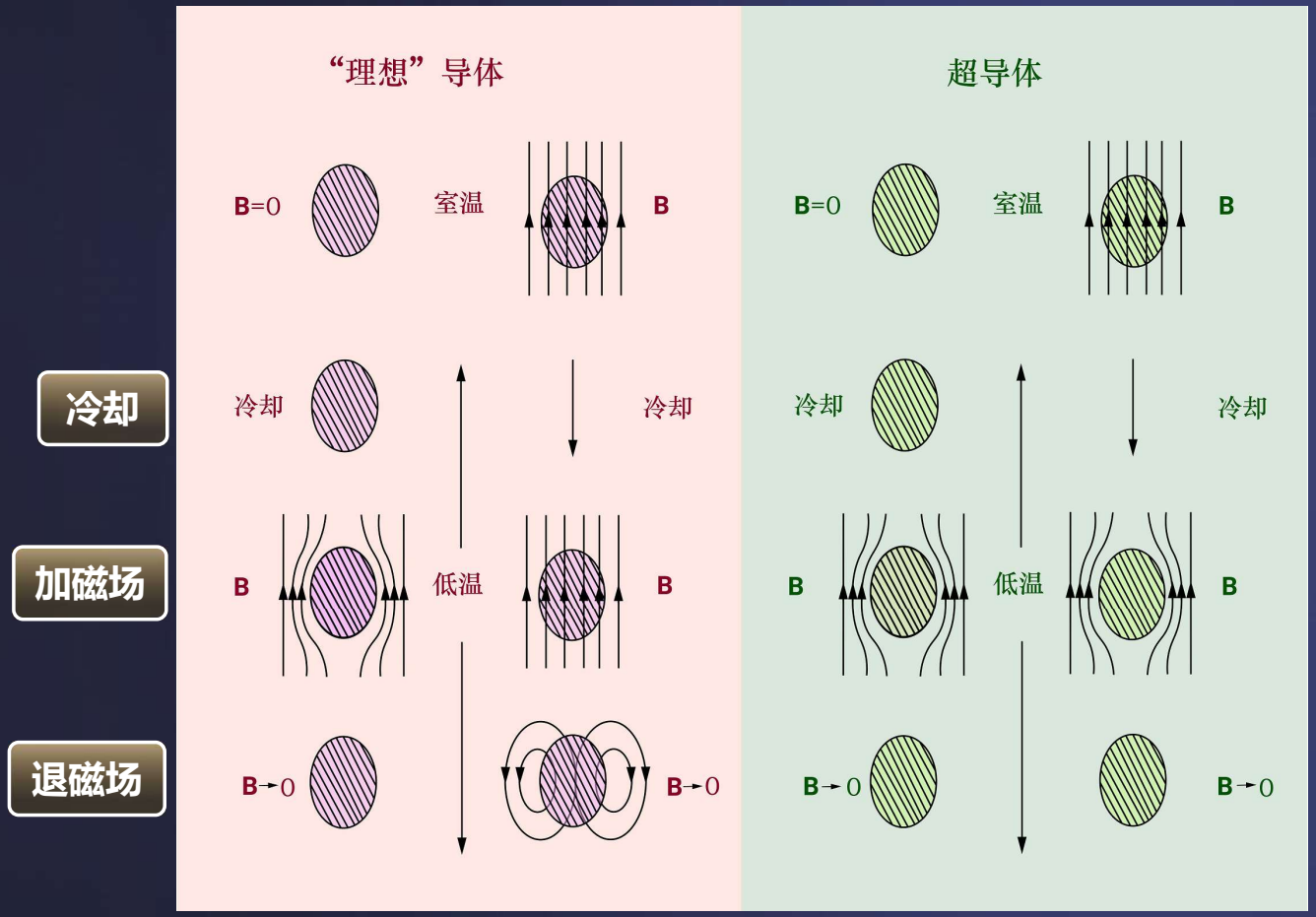
• 超导体的神奇性质——完全抗磁性



1933 年
迈斯纳和奥切森菲尔德
发现超导的完全抗磁性

超导体的完全抗磁性又称“迈斯纳效应”，它不依赖于降温和加磁场的先后顺序。其本质原因是超导态属于“宏观量子现象”，与所谓“理想导体”有天壤之别。

• 超导体的神奇性质——完全抗磁性



“理想”导体（零电阻）：

动态抗磁性！

1. 先降温从正常导体变为完美导体，再加磁场：**体内无磁场**
2. 先加磁场，再降温：**体内有磁场**

超导体（零电阻）：

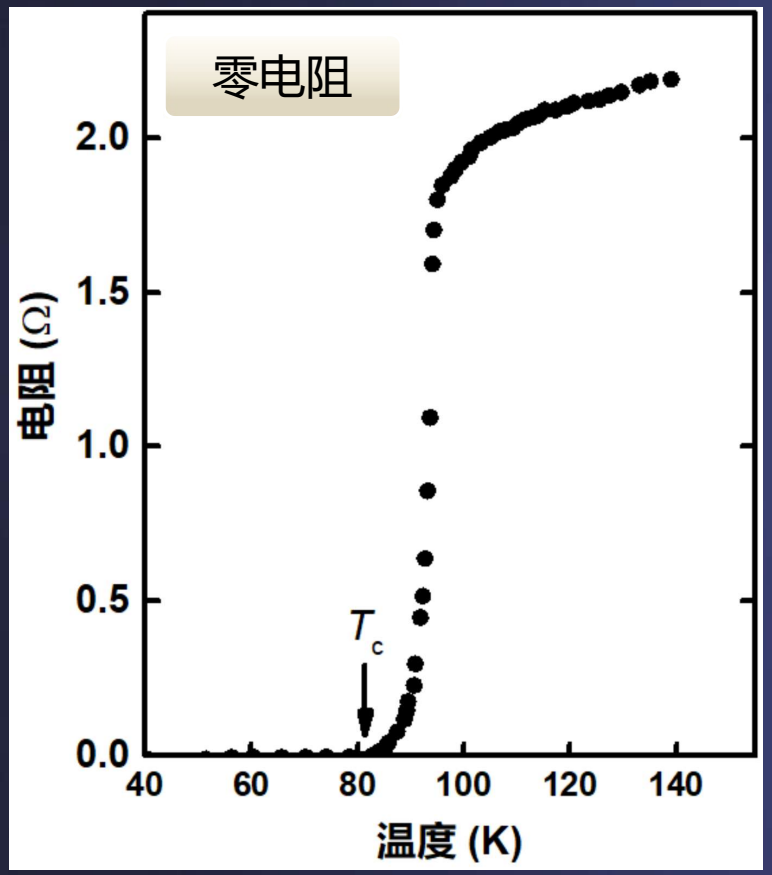
完全抗磁性！

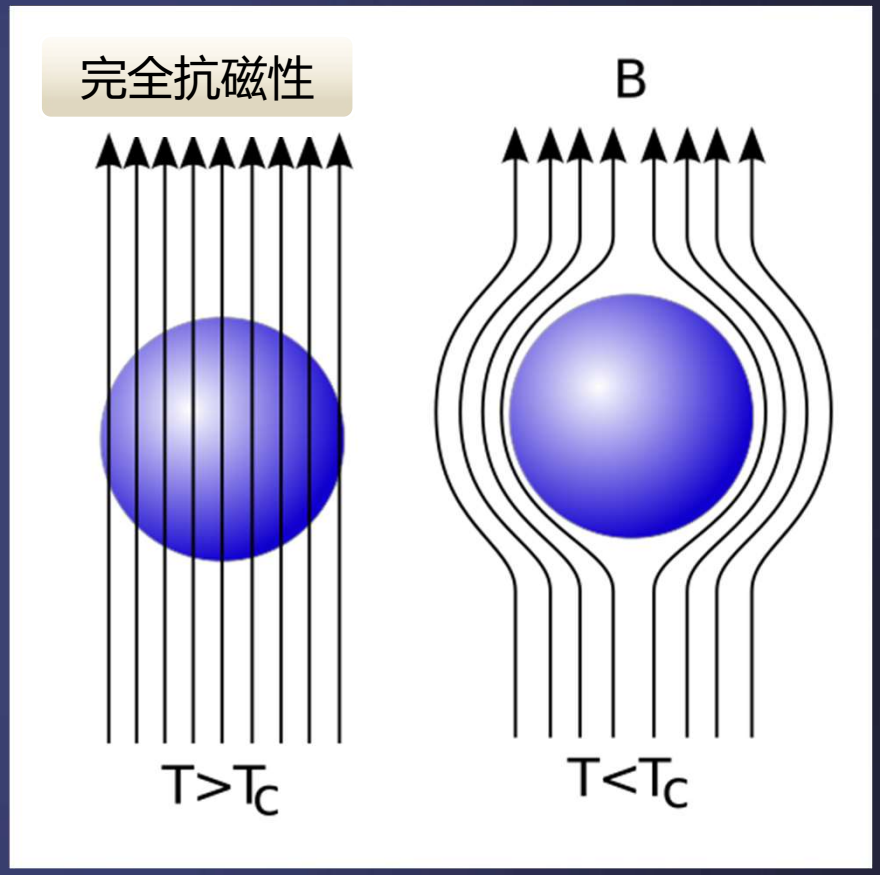
先降温后加磁场；先加磁场后降温

体内始终没有磁场

完全抗磁性是比零电阻更为基本的超导特性！

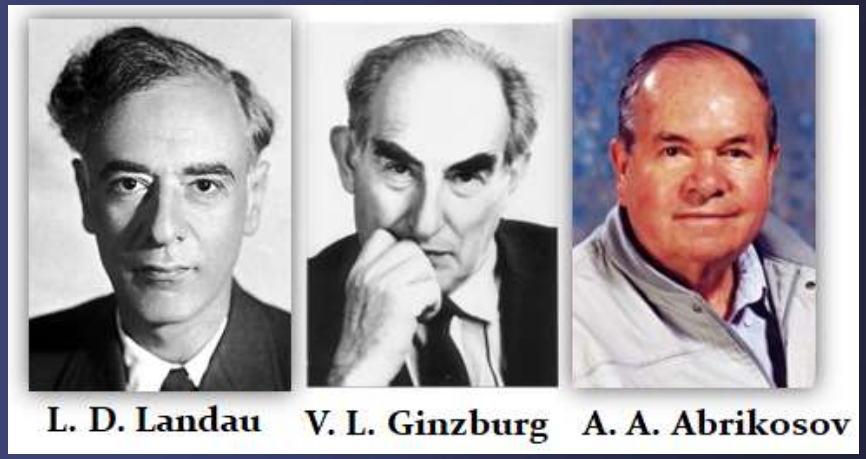
• 超导体的两个基本特征





超导体必须具备两个“零”特征：零电阻（ρ=0）和 完全抗磁性 (B=0)

• 超导体的神奇性质——磁通量子化

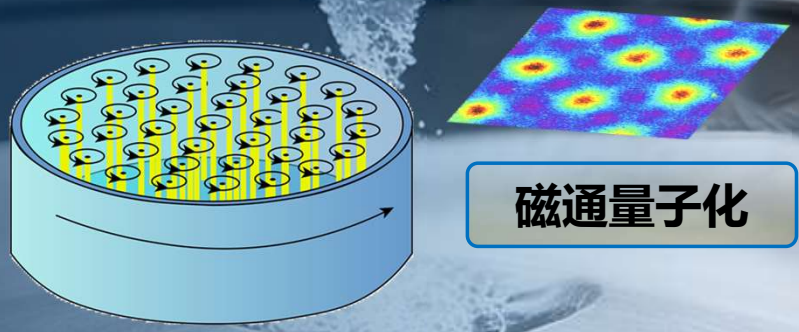


1962年
诺贝尔奖

2003年
诺贝尔奖

1950-1957年，朗道和金兹堡建立超导唯象理论，从热力学相变出发理解了超导现象；此后阿布里科索夫解此方程，提出磁通量子化的概念，奠定了超导强电应用基础。

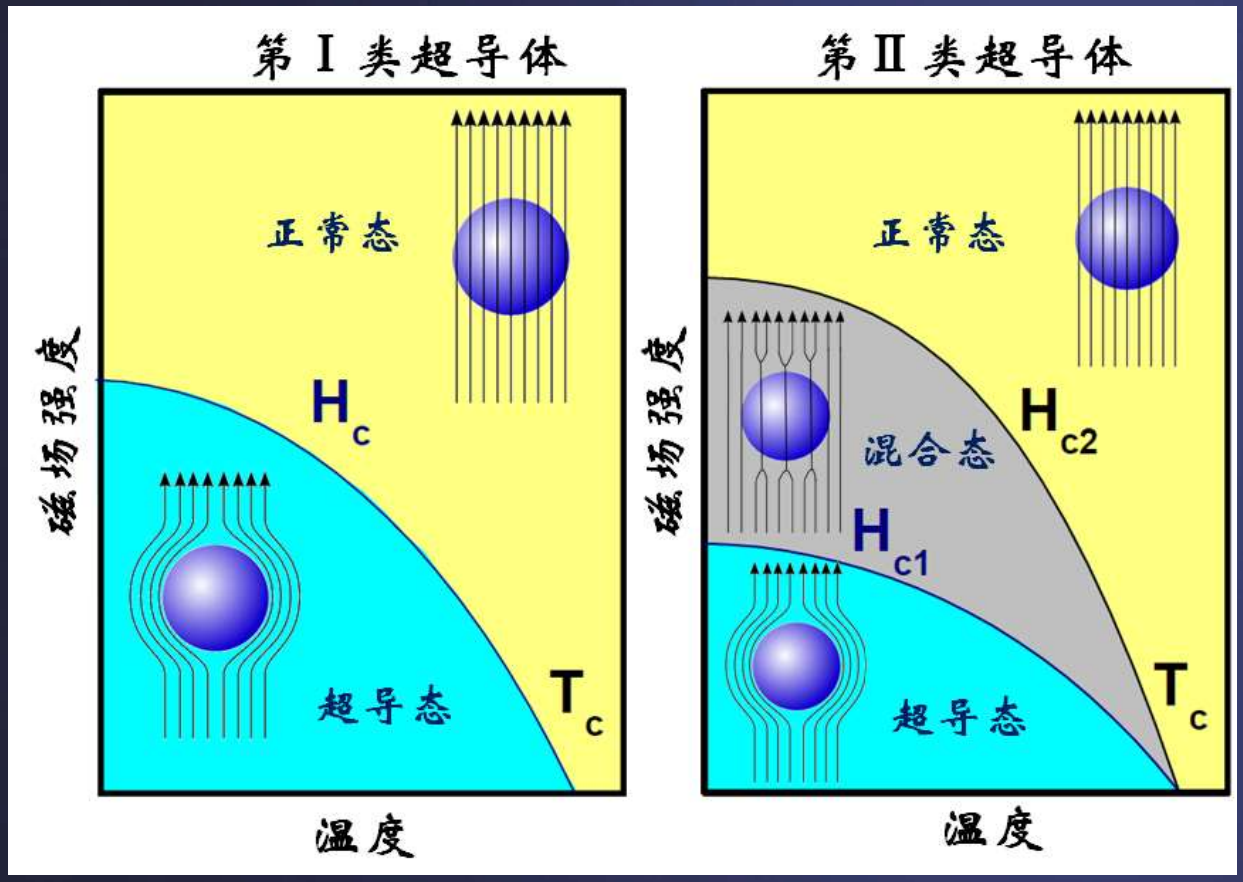
• 超导体的神奇性质——磁通量子化



在特定温度/磁场下，磁力线进入超导体内部形成“磁通量子化”现象，以磁通的量子单元（Φ= h/2e）形式存在，会出现磁通钉扎行为，磁通钉扎是超导磁悬浮的物理本质。

• 超导体的神奇性质——磁通量子化

超导体可分为：



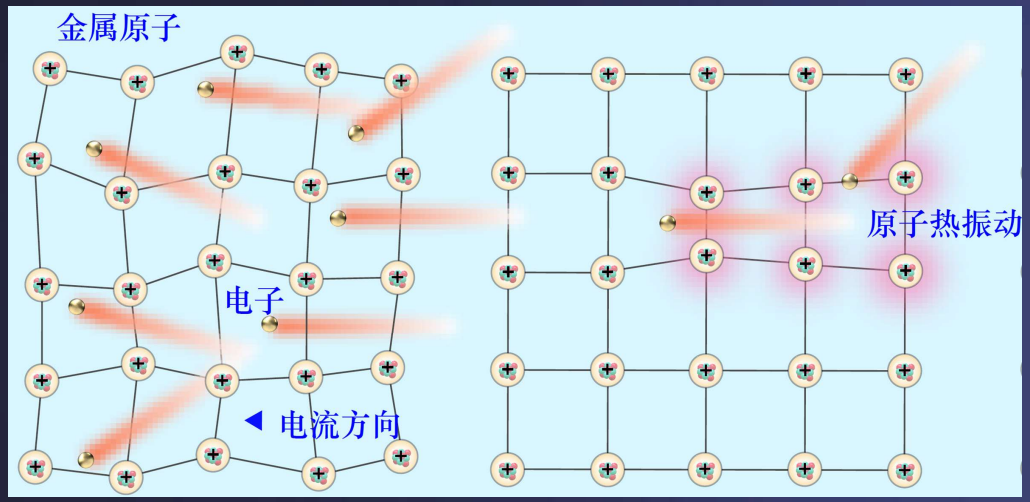
第二类超导体

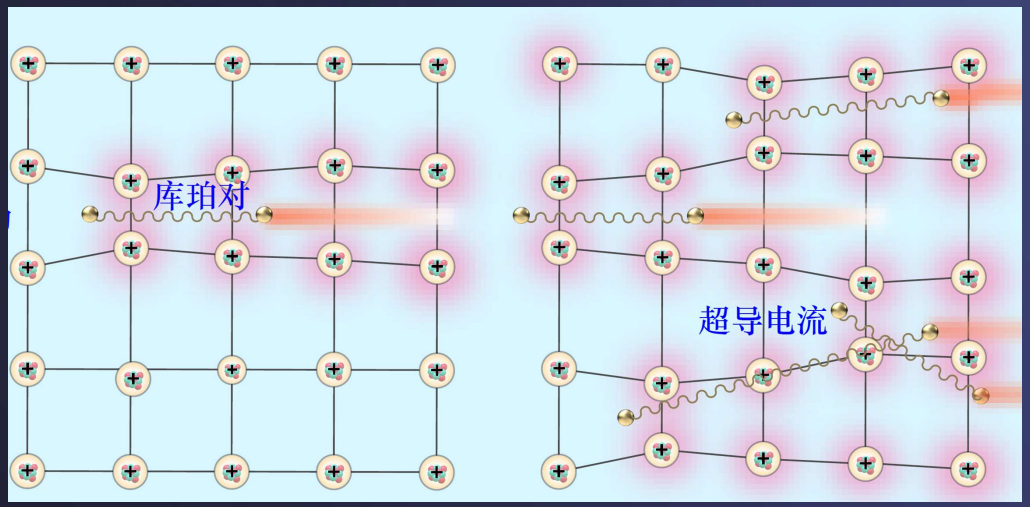
有电流通过时，自由空间中的磁力线被推动，磁力线移动会消耗能量，产生热；

有缺陷的时候，磁力线会被固定在缺陷附近不能移动，保持零电阻 ⟶ 高临界电流、临界磁场和稳定的磁悬浮

磁通钉扎是超导强电应用的基础，超导体是能源材料！

• 超导电性的微观理论



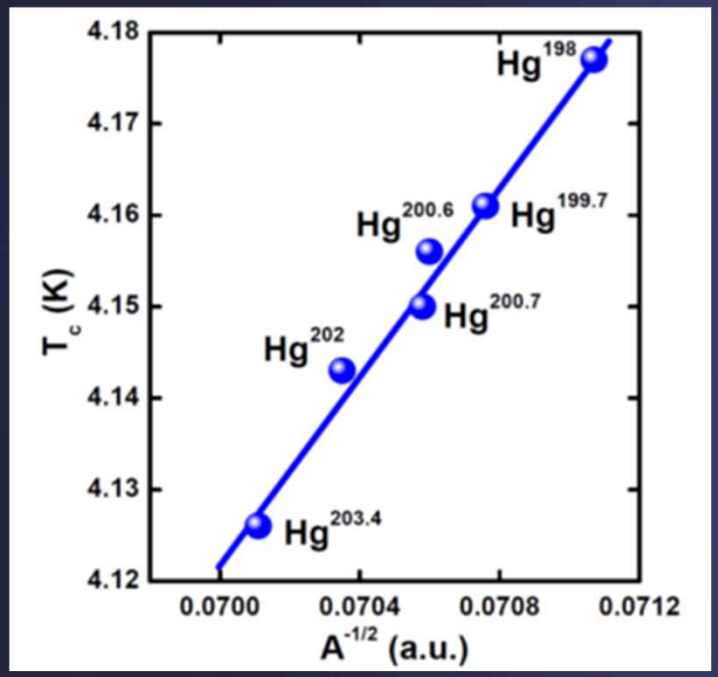


John Bardeen 1908-1991 | Leon Cooper 1930- | John Schrieffer 1931-2019

1957年，巴丁、库伯和施里弗建立超导微观理论——BCS理论，利用电子配对的思想给出了超导形成的微观图像。
相关概念被粒子物理和宇宙学理论借用，催生了希格斯机制等。

1972年
诺贝尔奖

昂尼斯的物理直觉

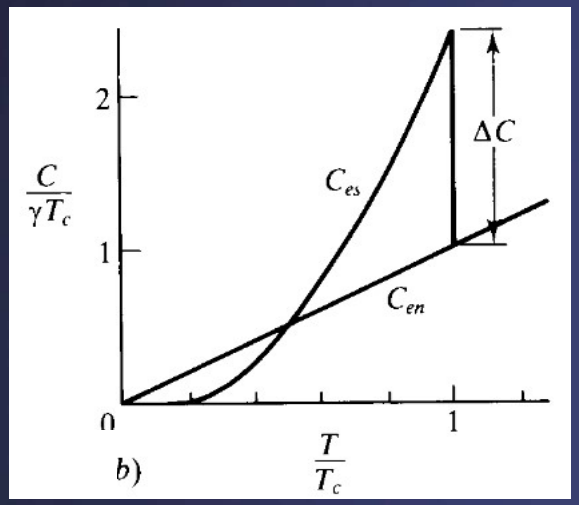


"to trace a possible difference in the vanishing point (of resistivity) of Pb and Uranium Pb (Pb-206 isotope). Regarding a difference of vanishing point temperature for isotopes, it seemed not impossible that the occurrence of the superconductivity might be influenced the mass of the nucleus"

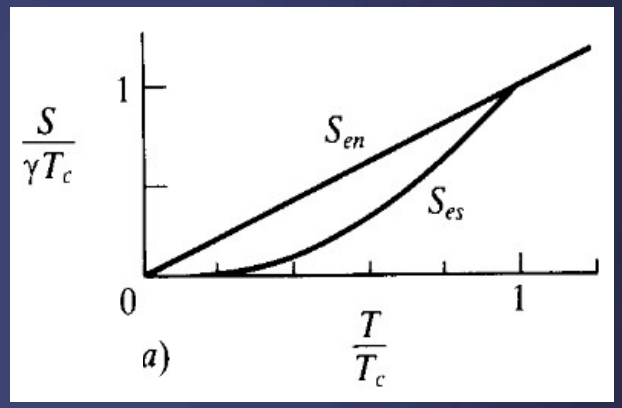
H. Kamerlingh Onnes and W. Tuyn, Comm. Leiden 160a (1922)

同位素效应

超导能隙



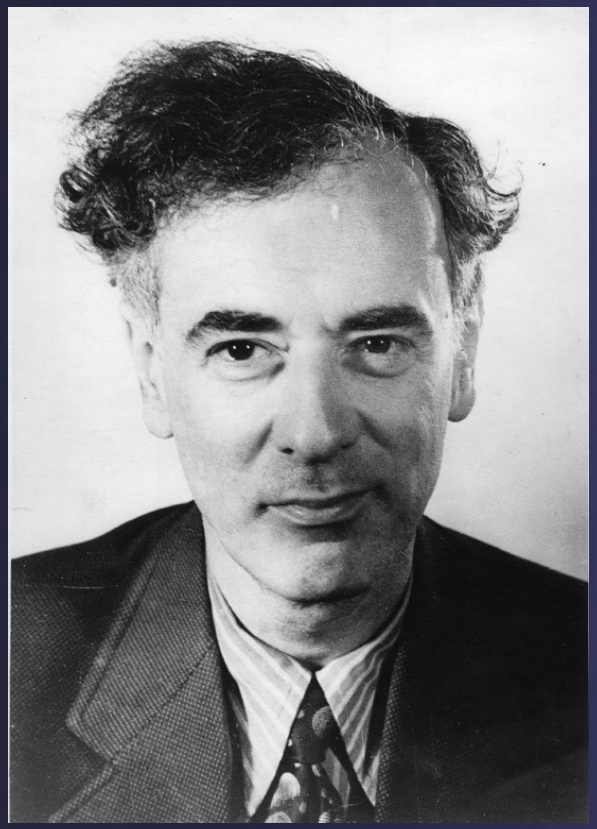
Schematic of the electronic specific heat of a superconductor



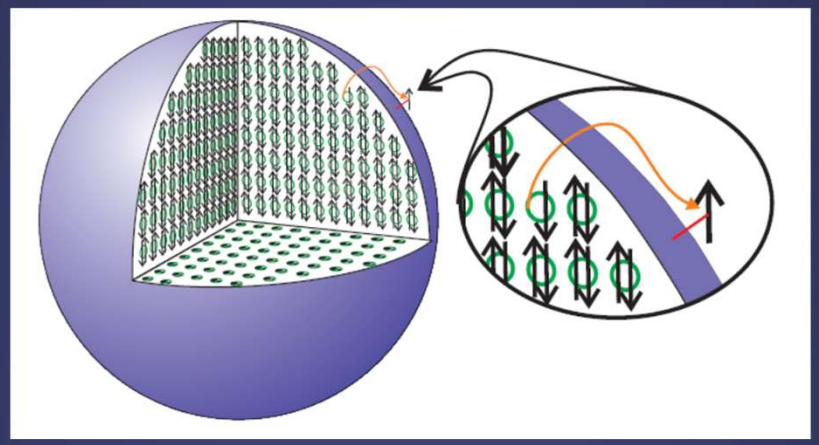
Schematic of the electronic entropy of a superconductor

- A sharp jump at T_C from the linear behavior of normal quasi-particle C_{en}
- Below T_C it has an exponential behavior $C_{es} \sim e^{-1.5Tc/T}$, so the system condenses into an ordered state with an energy gap per particle ~ 1.5 $k_B T_C$

Landau's Fermi Liquid theory (1957)

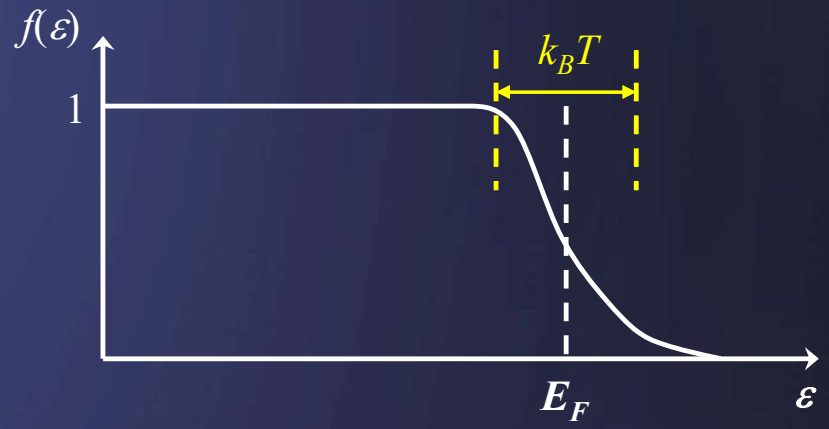


Lev D. Landau (1908-1968)



A particle-hole excitation: an electron jumps from a state below E_F to an empty one above it

$$f(\epsilon) = \frac{1}{e^{(\epsilon-\mu)/kT} + 1}$$

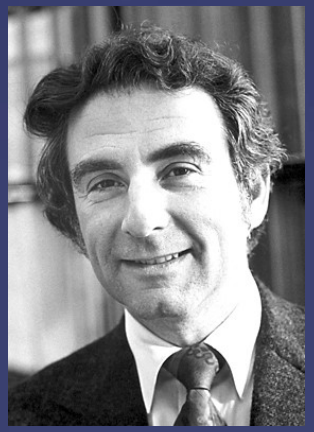


electronic states spill over E_F

合作与坚持：超导微观机理的诞生

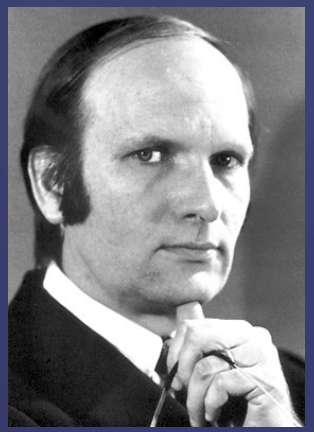
John Bardeen

1940年巴丁就开始研究超导，但因1941年巴丁参加了战时军事研究工作而中断。1950年超导体同位素效应的发现让巴丁再次注意到超导问题，他**意识到电-声子相互作用的重要性**。



Leon N. Cooper

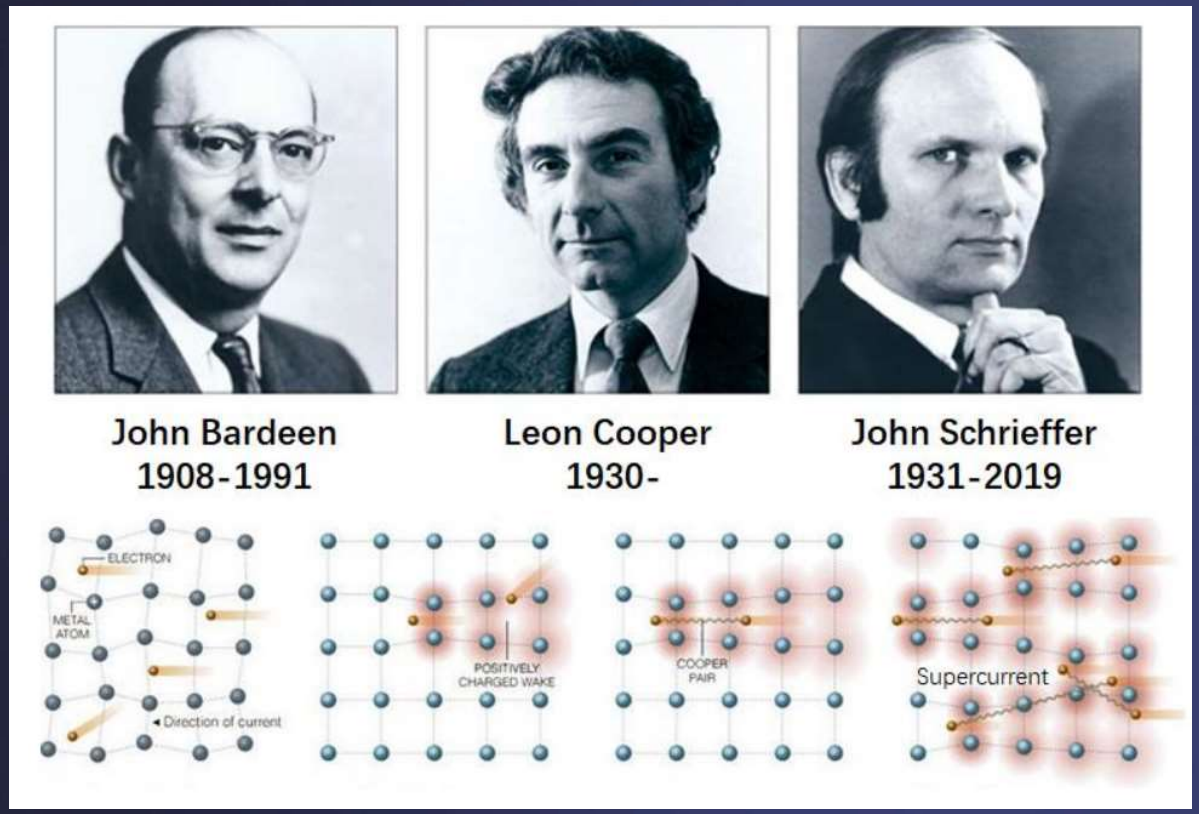
巴丁急需一名理论家处理复杂的多体问题，便打电话给当时在普林斯顿的杨振宁，推荐了正在那里作博士后的库珀，1955 年 9 月库珀来到UIUC，并最终**提出“库珀对”的概念**。

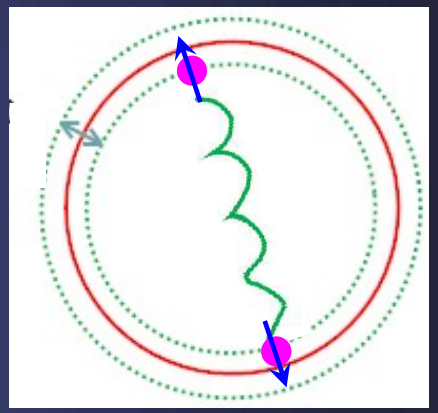


John R. Schrieffer

巴丁的研究生施里弗负责研究超导体的基态波函数，但进展并不顺利，希望换一个博士论文题目。巴丁力劝施里弗再坚持工作一个月，并终于在1957年1月底，凭借直觉和灵感，**顿悟出库珀对的超导基态波函数的可能形式**。

合作与坚持：超导微观机理的诞生

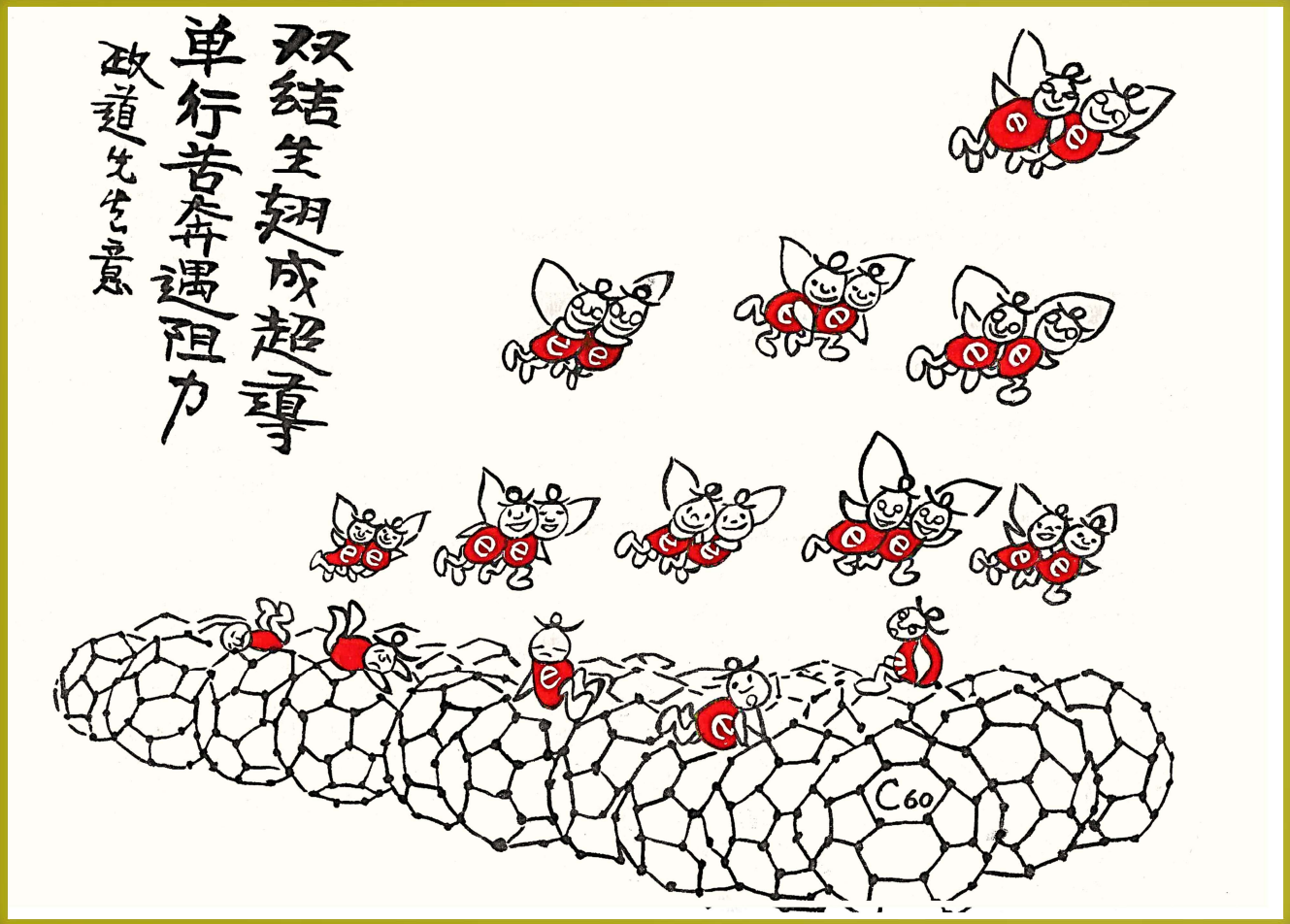




1957年12 月，第一篇完整概述他们理论的文章发表在了《物理评论》上，这一理论即为

Bardeen-Cooper-Schrieffer（BCS）理论。

- **超导的微观机制**

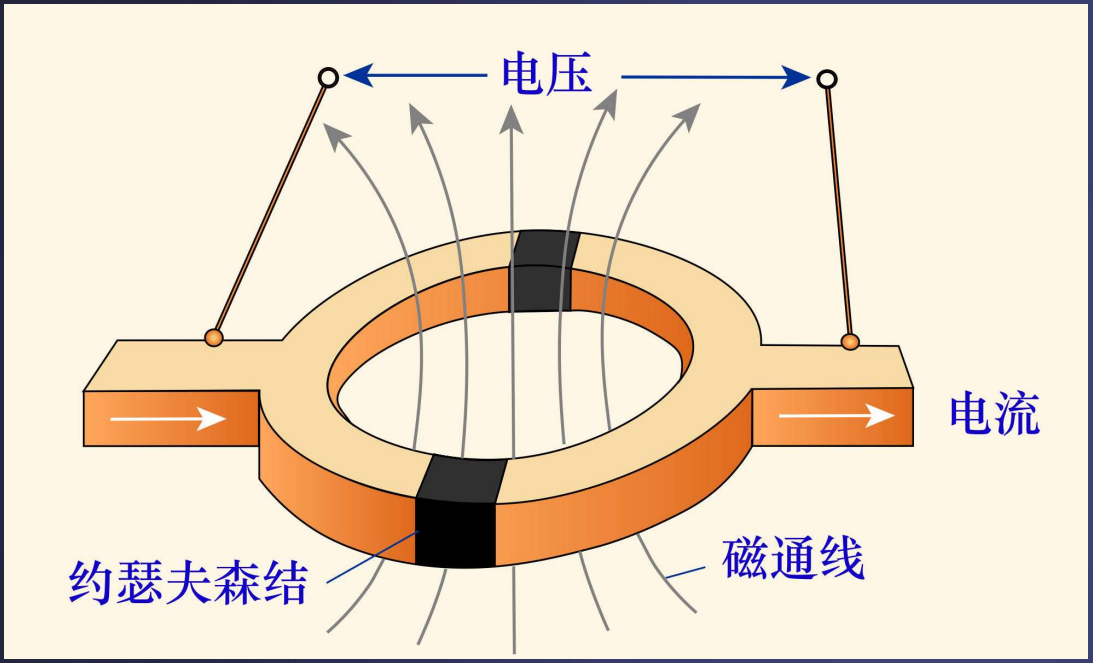


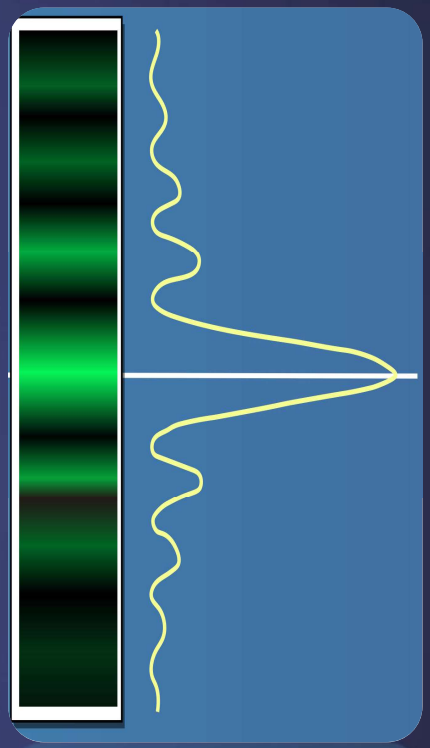
超导形成的两个关键因素

1. 电子配对——超导能隙

2. 相位相干——超流密度

- **超导的约瑟夫森效应**

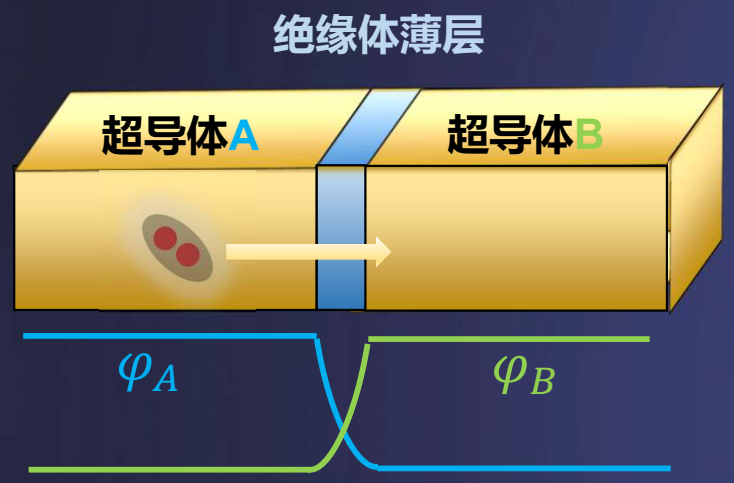




超导是一种“宏观量子现象”：超导内部电子具有一个整体的相位，当两个不同超导体库珀对隧穿时，会发生量子干涉现象，是超导量子应用的基础。

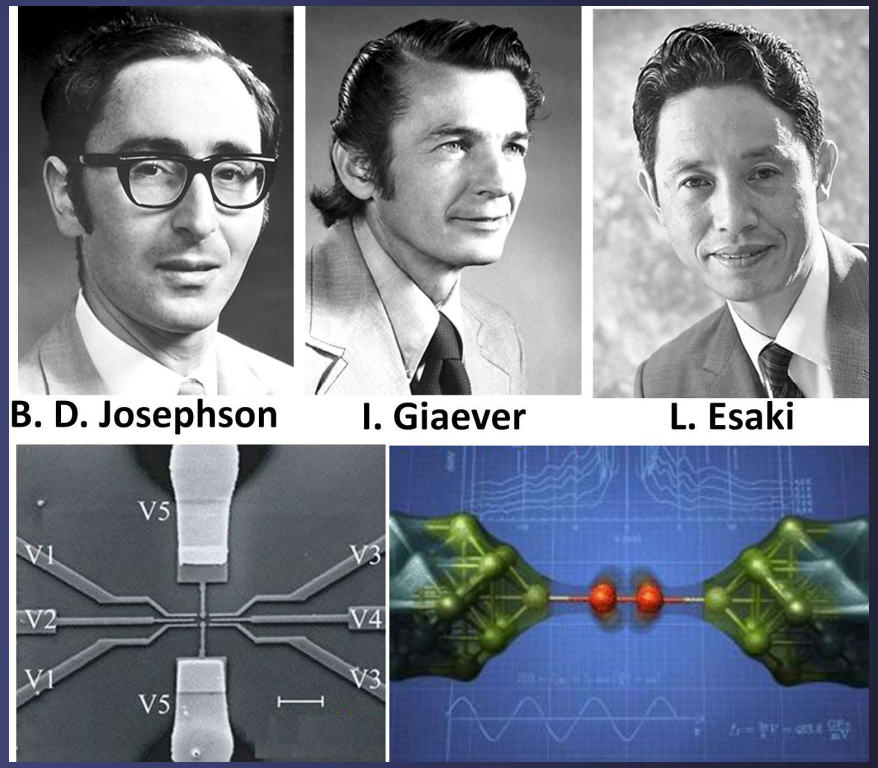
（超导电子学，信息材料）

超导的约瑟夫森效应



1962年，约瑟夫森预言，当两个超导体之间设置一个绝缘薄层时，电子对可以穿过绝缘体从一个超导体到达另一个超导体：当结两端电压为零时，存在一股很小的直流超导电流；当电压不为零时，存在一个交变的超导电流。

1963年，安德森和罗厄尔在实验中观察到了零电压超电流，即直流约瑟夫森效应。

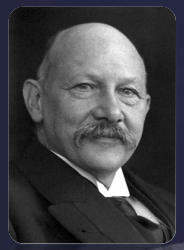


1960-1962 年
超导隧道效应的理论与实验

1973年
诺贝尔奖

- **百年经久不衰的超导研究，乃充满活力！**

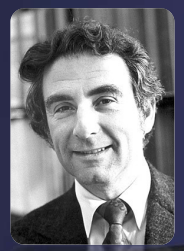
1913



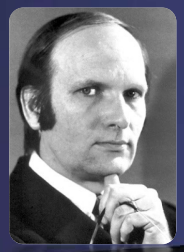
H. K. Onnes

1972

J. Bardeen

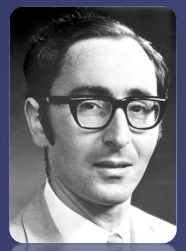


L. N. Cooper

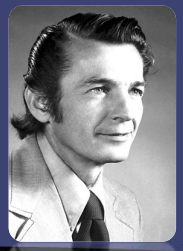


J. R. Schrieffer

1973

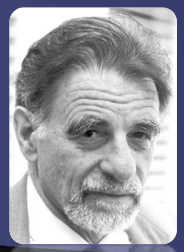


B.D. Josephson

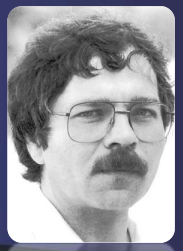


I. Giaever

1987

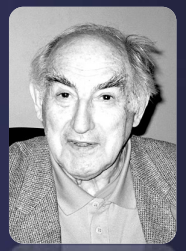


K.A. Müller

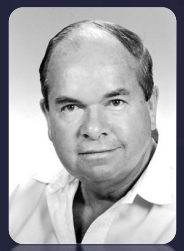


J. G. Bednorz

2003



V. L. Ginzburg



A. A. Abrikosov

从1913-2003年，超导研究一共有

10 人　　5 次

获诺贝尔物理学奖

Nobel Prize in Physics 2025

Ill. Niklas Elmehed © Nobel Prize Outreach

John Clarke

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

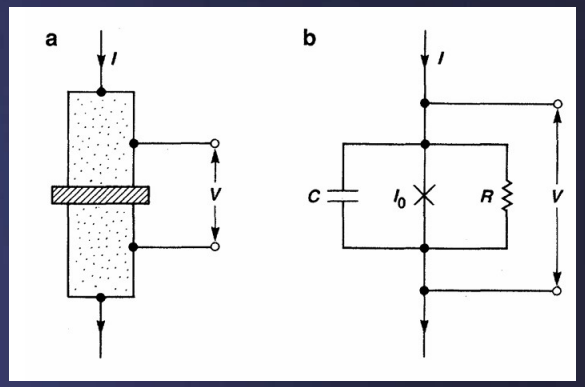
Michel H. Devoret

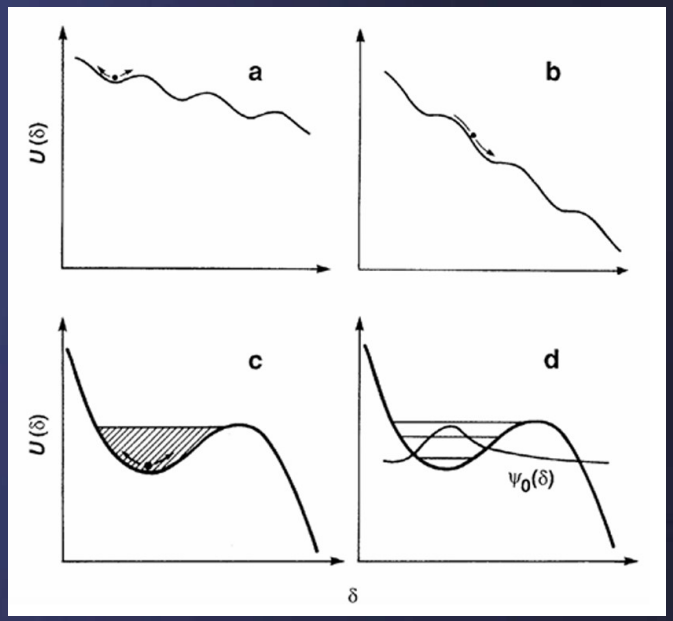
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John M. Martinis

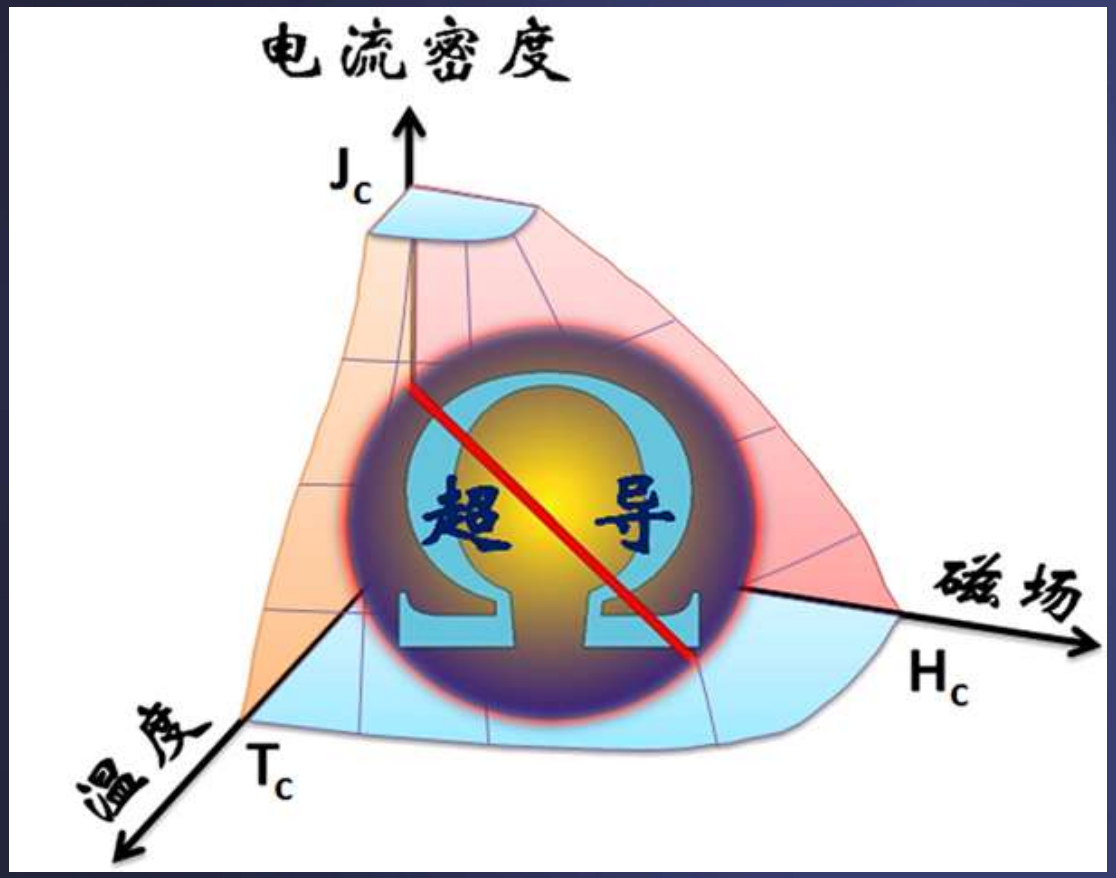
Prize share: 1/3





"for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

• 超导材料应用的关键要素



“好用的”超导材料必须“三高”(T_c，H_{c2}， J_c)

超导材料的应用受限于它的“临界曲面”，由三个临界参数决定：

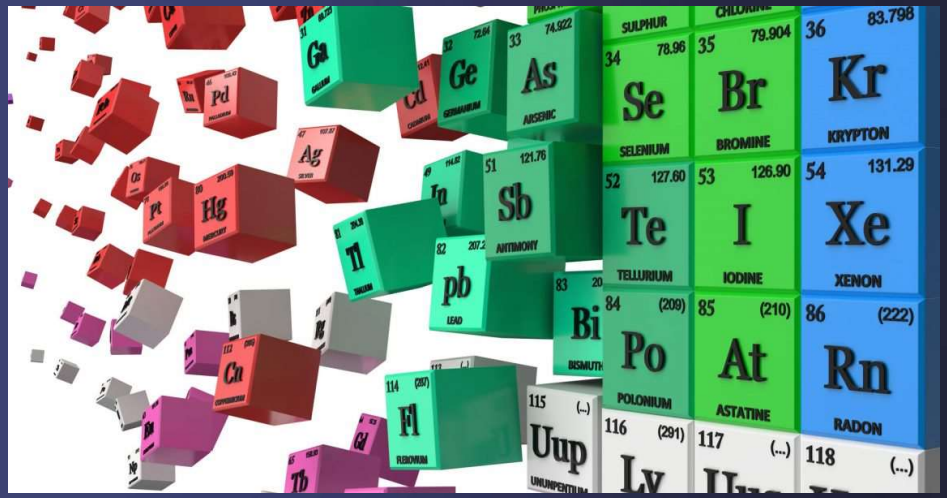
临界温度 T_c

临界磁场 H_c

临界电流密度 J_c

即使电阻为零，电流和磁场也不能无穷大，而是存在上限！

• 超导材料的探索

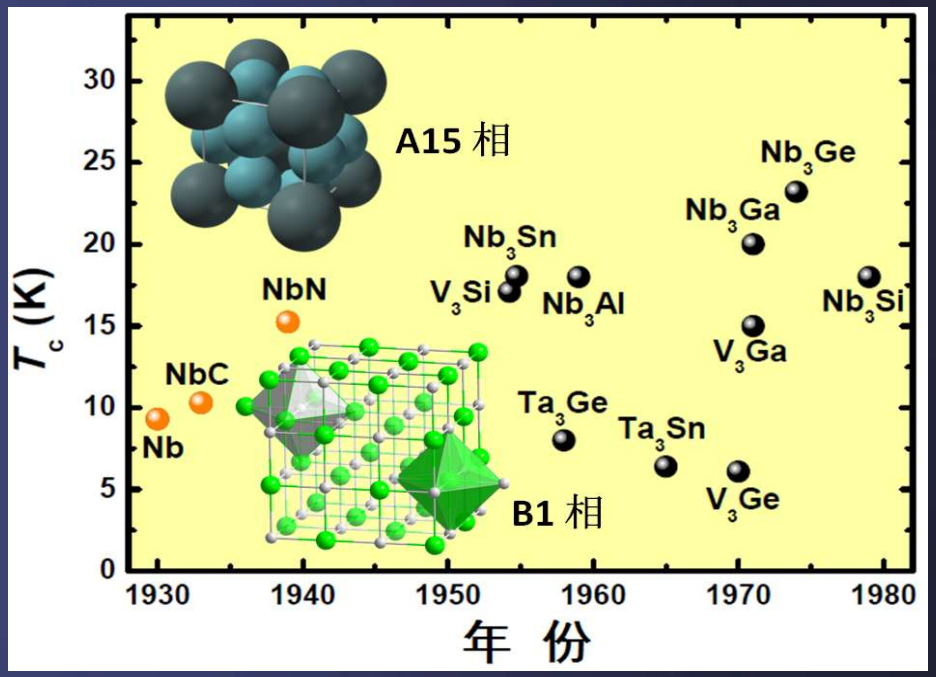


超导材料广泛存在于各类单质、合金和化合物中，目前至少有万种以上超导体。

- **超导材料探索的经验规律**

探索新超导体黄金六则：

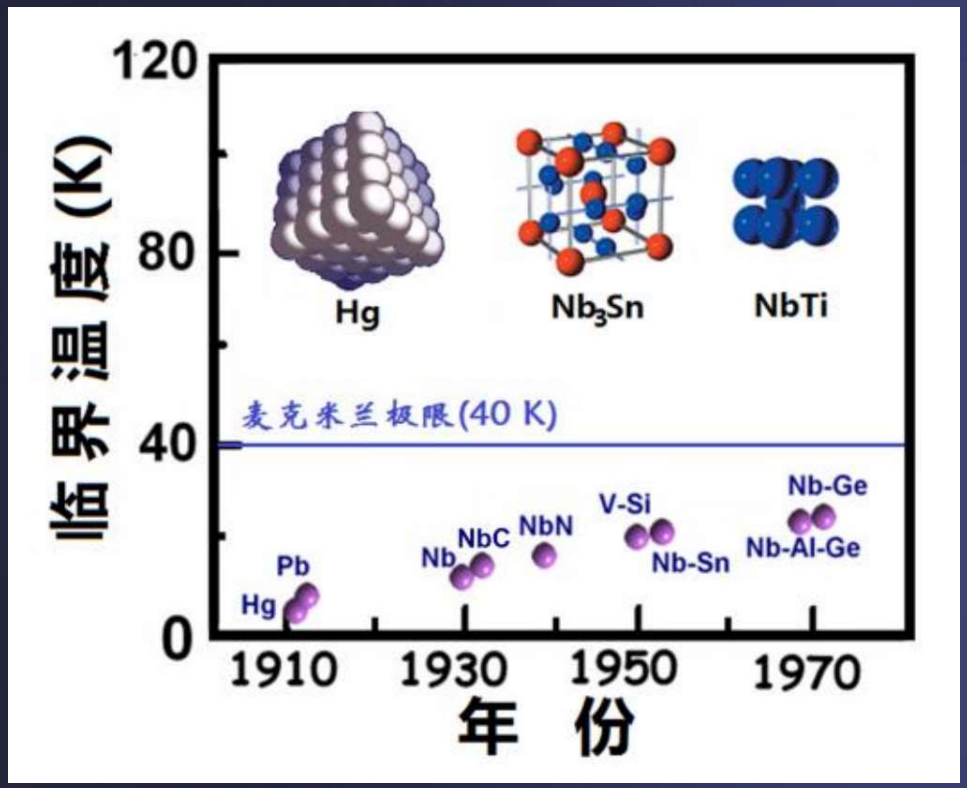
1. 高对称性、最好立方结构；
2. 高电子态密度（浓度）；
3. 不含氧元素；
4. 没有磁性；
5. 非绝缘体；
6. 不要信理论学家；



马蒂亚斯定律

超导强电应用的关键材料

- **超导温度的“天花板”**

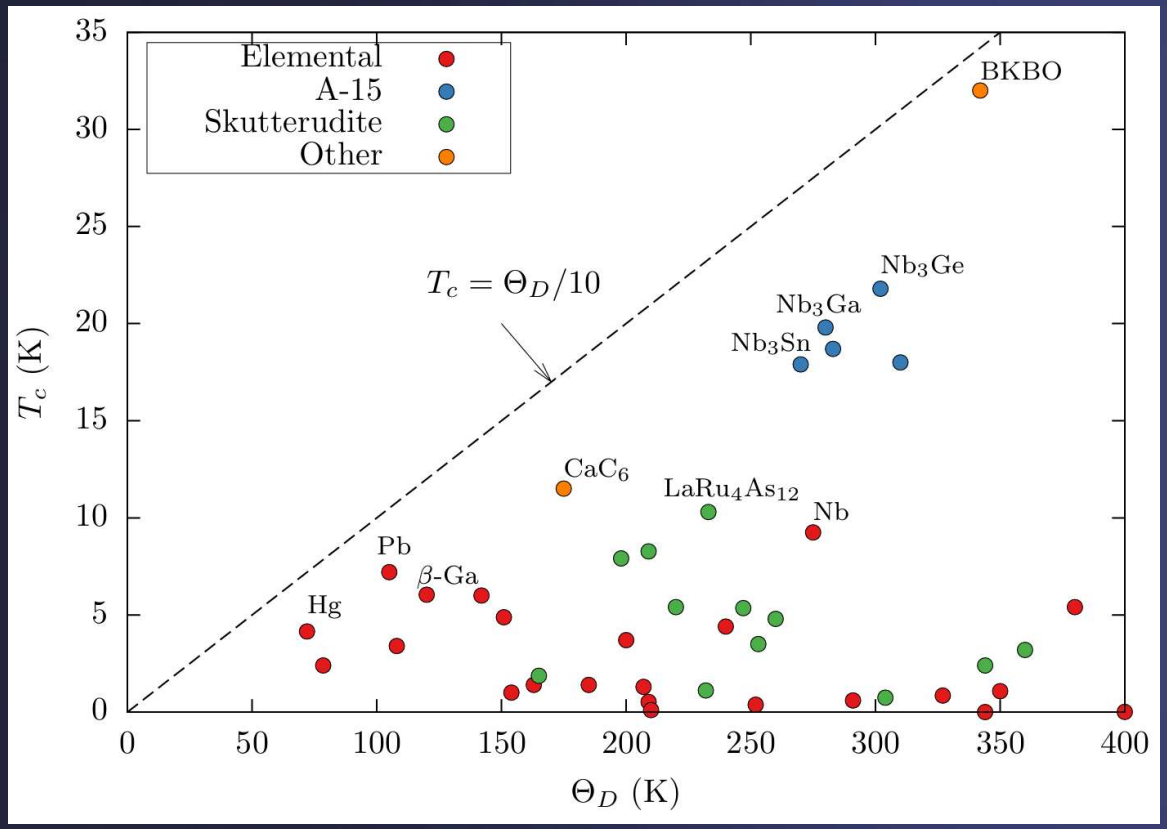


麦克-米兰极限 （40 K）

$$T_c \sim (\theta_D/1.2)\exp\left[-\frac{1.04(1+\lambda)}{\lambda-\mu^*(1+0.62\lambda)}\right]$$

θ_D: 德拜温度 – 晶格振动最高频率
λ: 耦合强度 – 电子和晶格相互作用
μ^*: 库仑赝势 - 屏蔽作用库仑势

- **探索室温超导材料**



$$T_c \sim (\theta_D/1.45)\exp[-\frac{1.04(1+\lambda)}{\lambda-\mu^*(1+0.62\lambda)}]$$

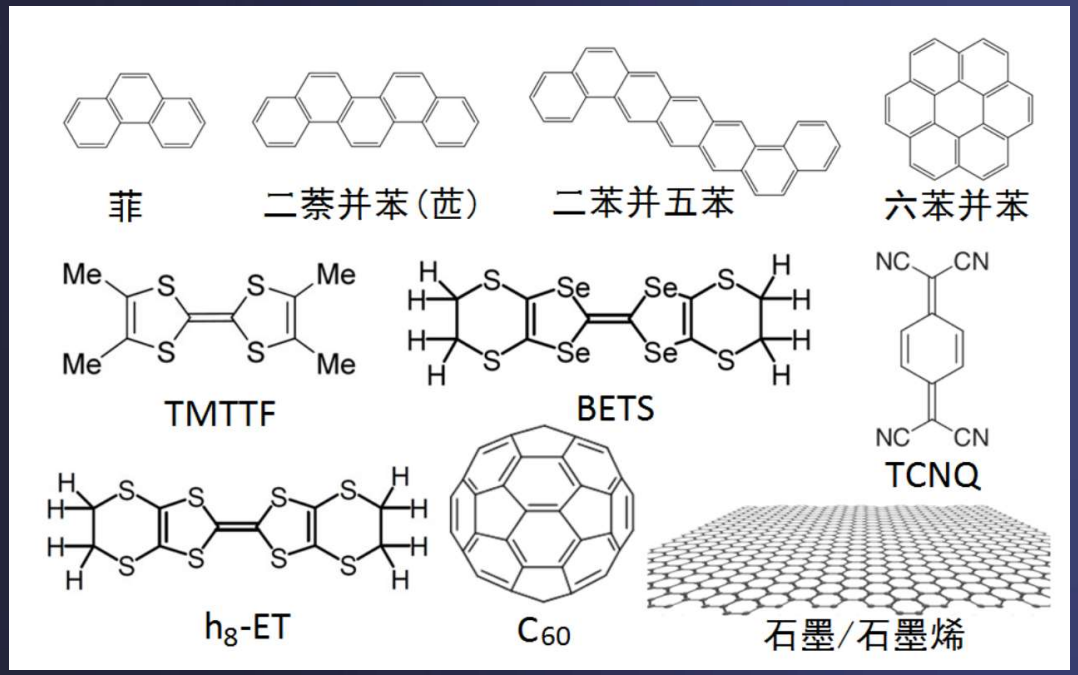
$$T_c \sim \theta_D/10$$

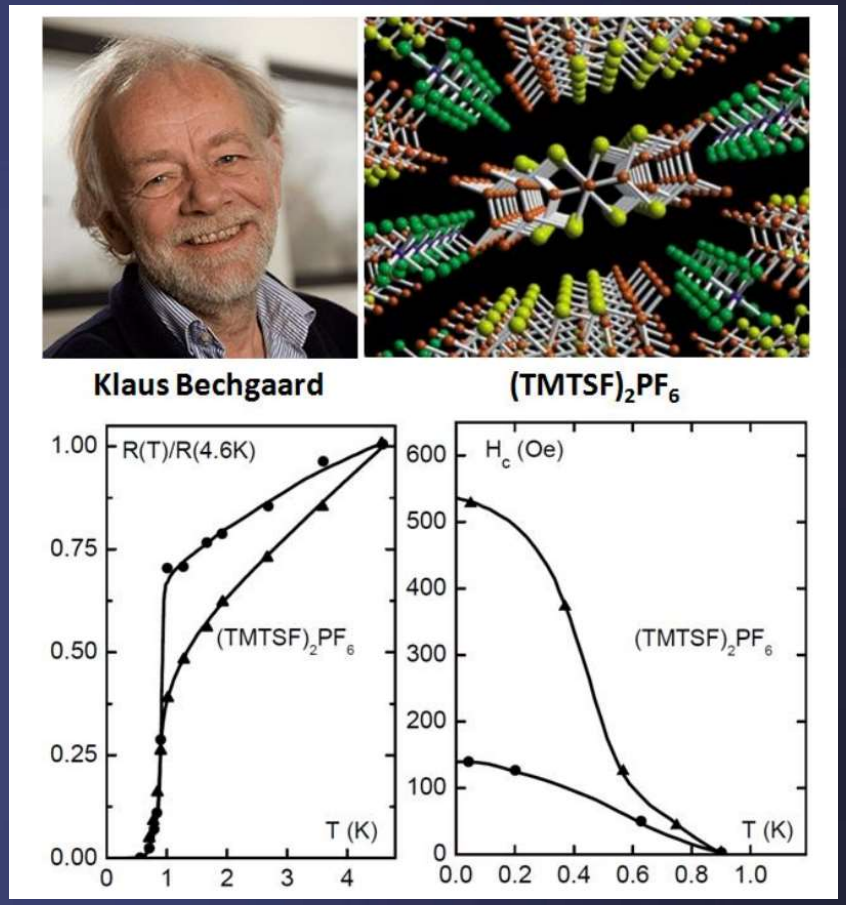
实现室温超导需要德拜温度

达到 ~ 3000K

• 有机超导体探索

1964 年，物理学家 Little 基于 BCS 理论预言，在某些具有高度极化悬挂链的导电聚合物中可能存在 1000 K 以上的超导电性。

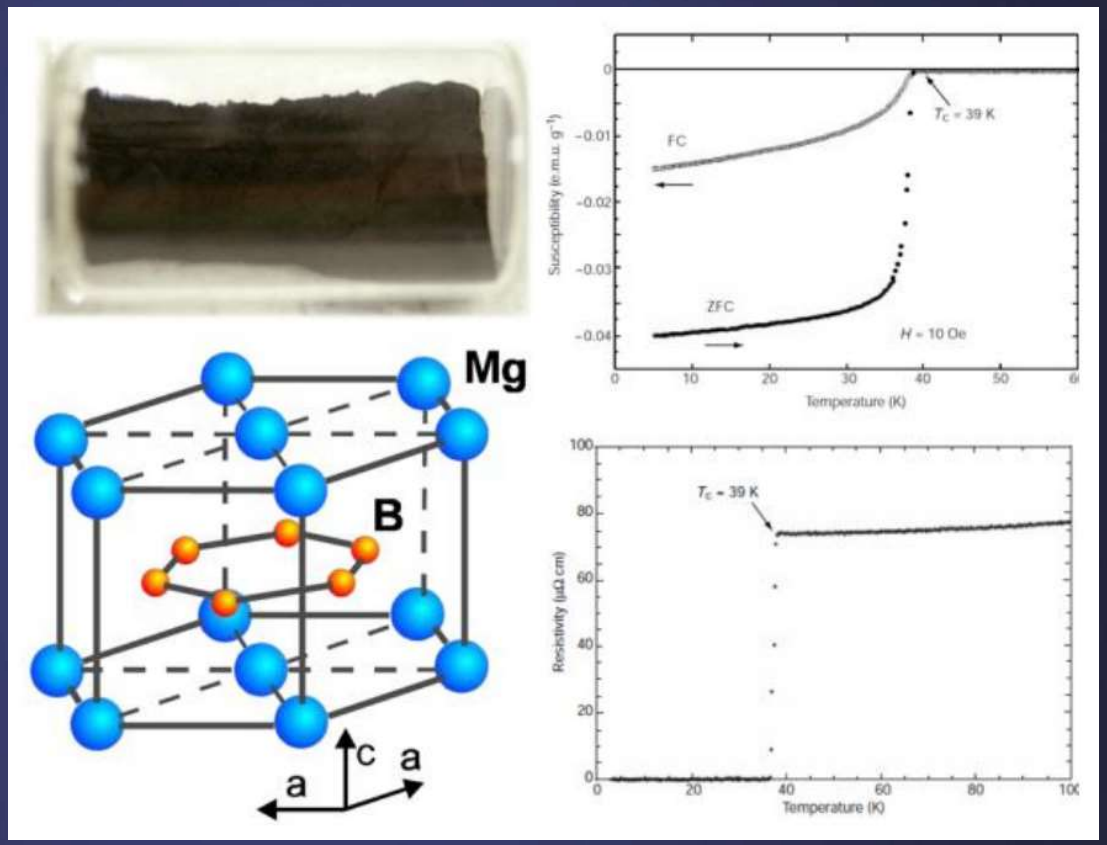




1979 年丹麦科学家 Klaus Bechgaard 与法国合作者们在有机盐$(TMTSF)_2PF_6$中发现了 0.9 K 的超导电性。

- 轻元素超导体探索

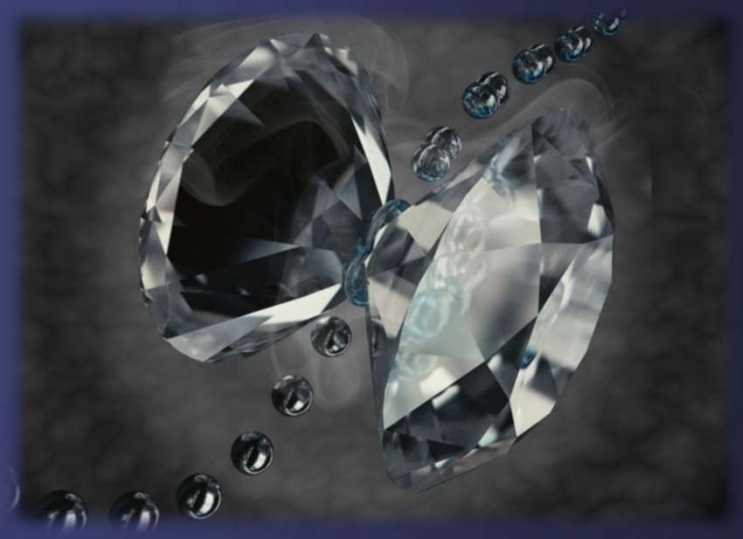
二硼化镁发现者：
秋光纯



MgB_2 T_c=39 K

• 高压下的高温超导体

高压是实现室温超导的重要手段，理论预言金属氢是室温超导体。



• 高压下的高温超导体

Neil William Ashcroft

VOLUME 21, NUMBER 26 PHYSICAL REVIEW LETTERS 23 DECEMBER 1968

METALLIC HYDROGEN: A HIGH-TEMPERATURE SUPERCONDUCTOR?

N. W. Ashcroft
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850
(Received 3 May 1968)

VOLUME 92, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 7 MAY 2004

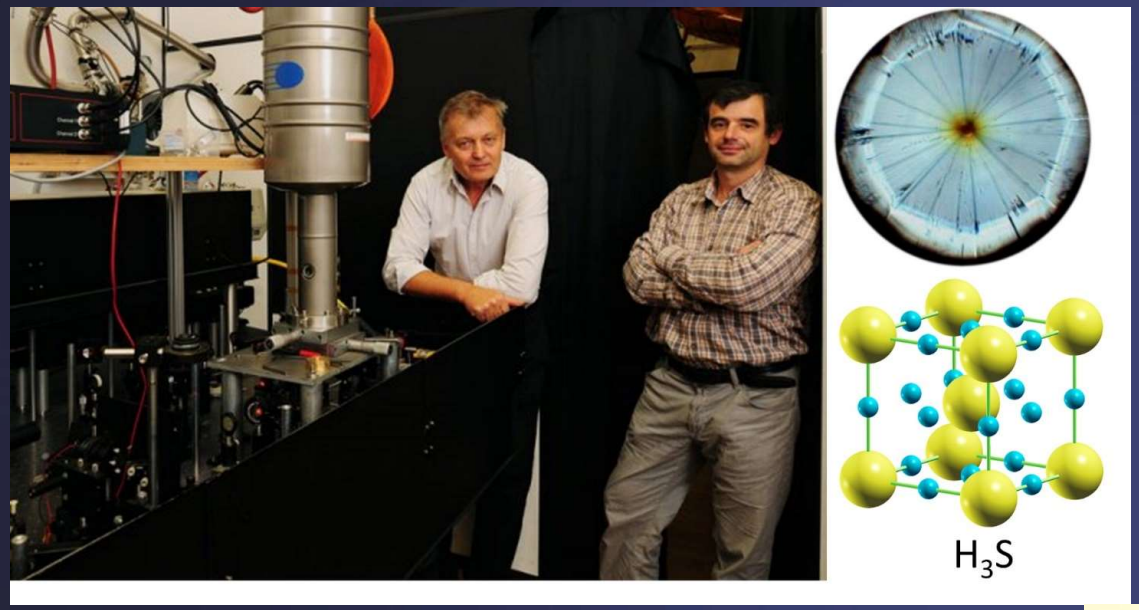
Hydrogen Dominant Metallic Alloys: High Temperature Superconductors?

N.W. Ashcroft
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853-2501, USA
Donostia International Physics Center, San Sebastian, Spain
(Received 29 December 2003; published 6 May 2004)

$$T_c = 0.85\Theta_D \exp(-1/N_0 V)$$

德拜温度　费米能级处的电子态密度　交换声子产生的电子对吸引势

• 高压下的高温超导体



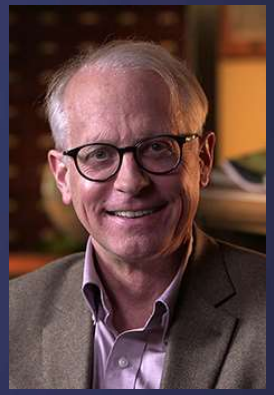
2015年, 德国马普研究所的
M. I. Eremets 发现H_3S超导

百万大气压环境下
T_c = 203 K (-70 ℃)

- **2015 H_3S, T_c≈203K@150-170GPa**
  Drozdov et al., Nature **525**, 73 (2015)

- **2019 LaH_{10}, T_c≈250K@170GPa**
  Drozdov et al., Nature **569**, 528 (2019);
  Somayazulu et al., PRL **122**, 027001 (2019)

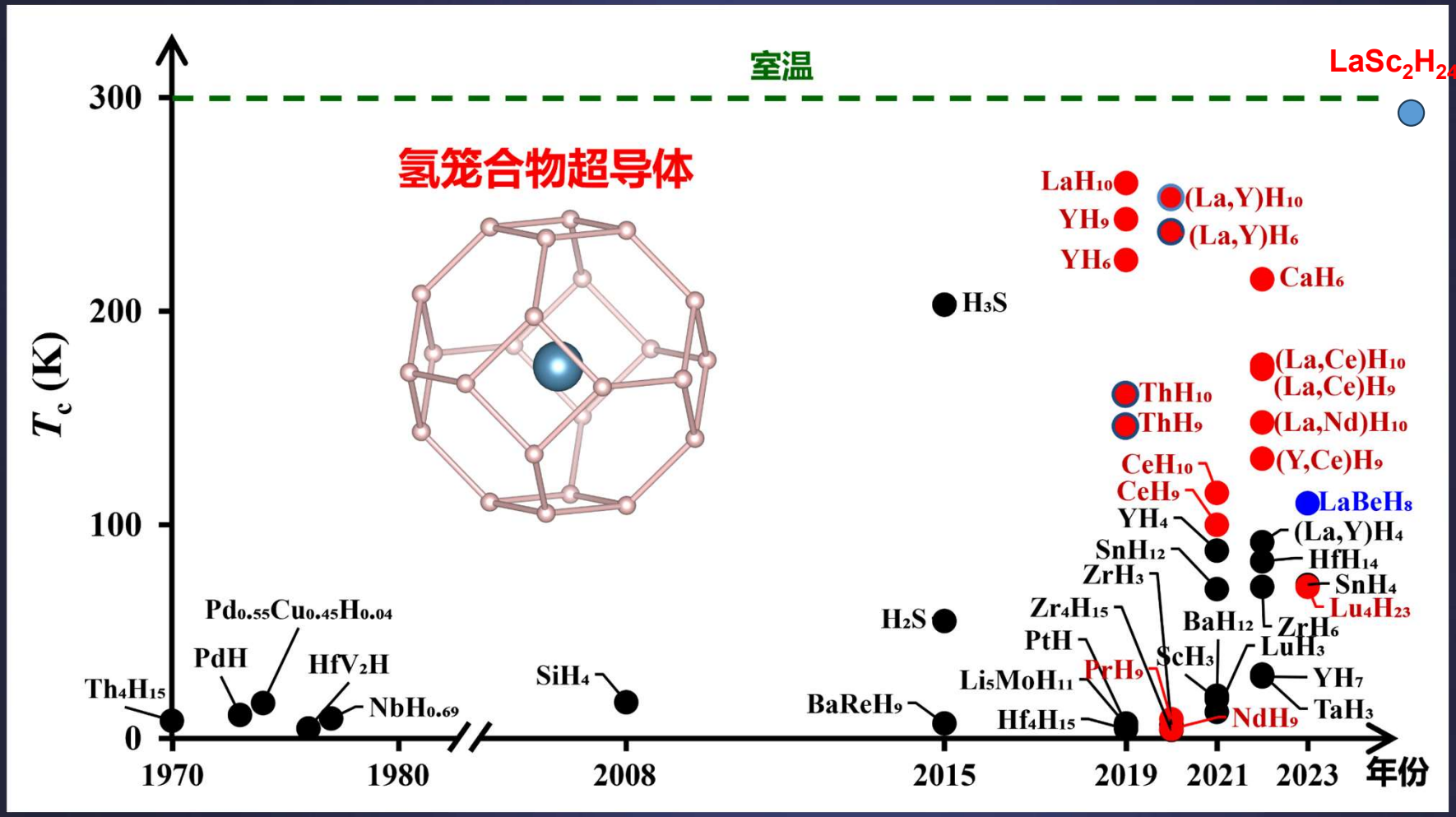
M. Somayazulu



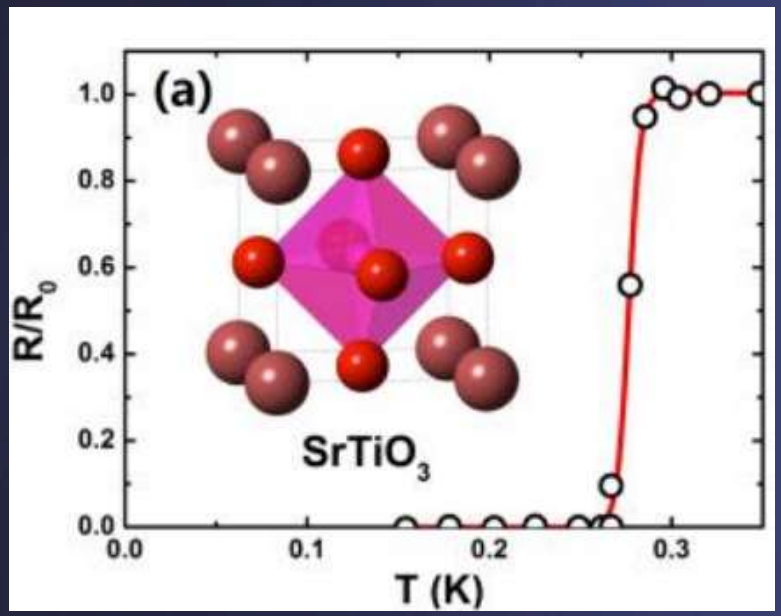
R. J. Hemley

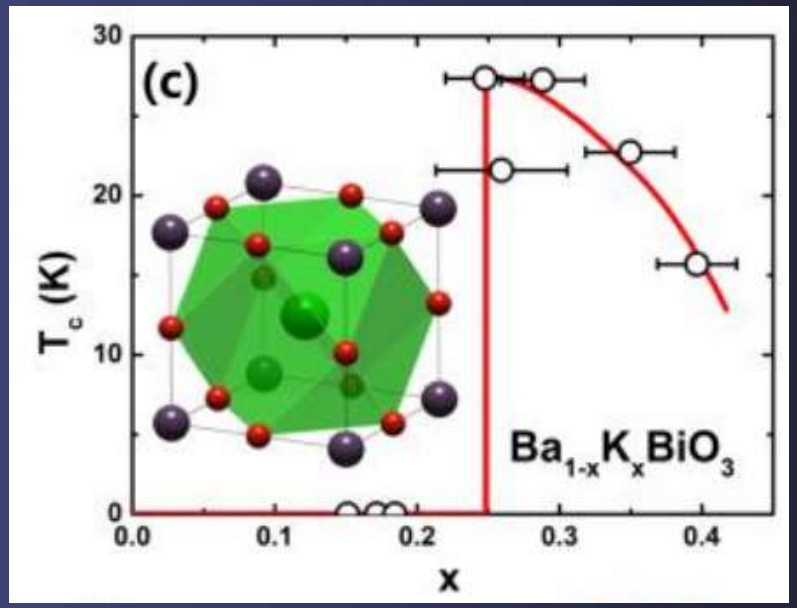
M. Eremets

• 高压下的高温超导体


室温
LaSc2H24
氢笼合物超导体
300
200
100
0
Tc (K)
LaH10
YH9
YH6
(La,Y)H10
(La,Y)H6
CaH6
H3S
(La,Ce)H10
(La,Ce)H9
ThH10
ThH9
(La,Nd)H10
(Y,Ce)H9
CeH10
CeH9
LaBeH8
YH4
(La,Y)H4
SnH12
HfH14
ZrH3
SnH4
Lu4H23
Zr4H15
BaH12
ZrH6
H2S
PtH
LuH3
ScH3
PrH9
YH7
Li5MoH11
TaH3
NdH9
Hf4H15
BaReH9
Pd0.55Cu0.45H0.04
PdH
HfV2H
Th4H15
NbH0.69
SiH4
1970
1980
2008
2015
2019
2021
2023
年份

- “离经叛道”的超导材料

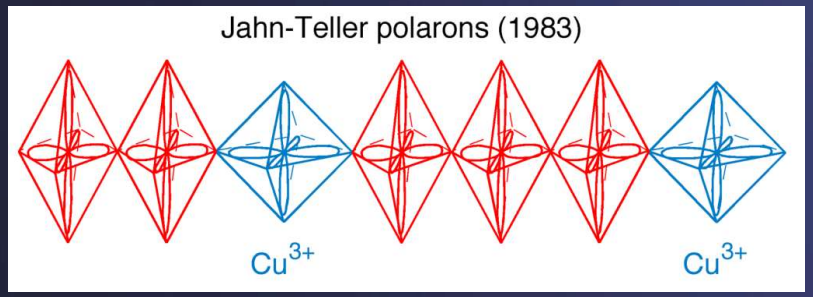




从绝缘体和氧化物中寻找超导电性打开了一个探索超导体的新大门

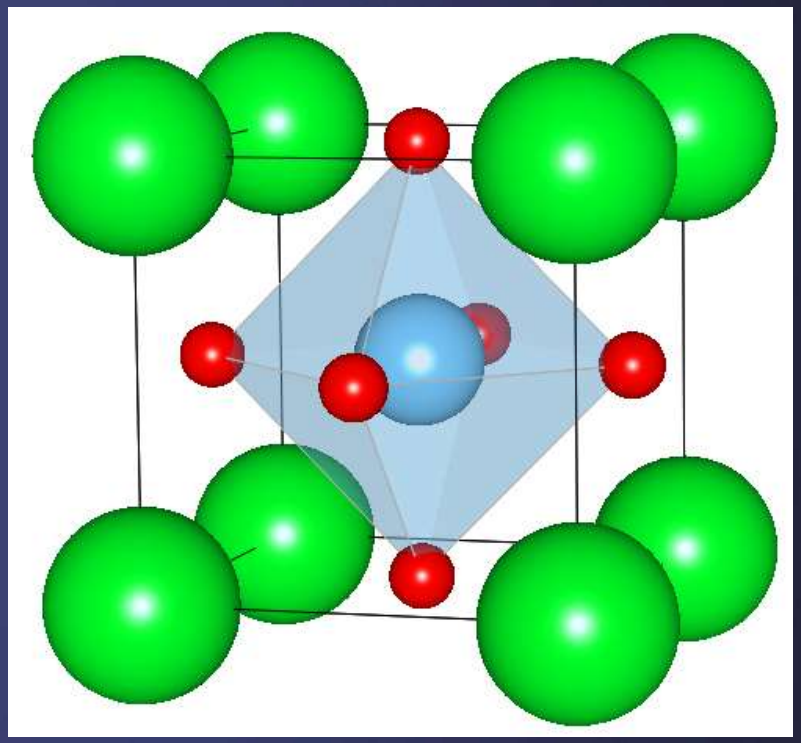
突破传统，解放思想

K. Alex Müller

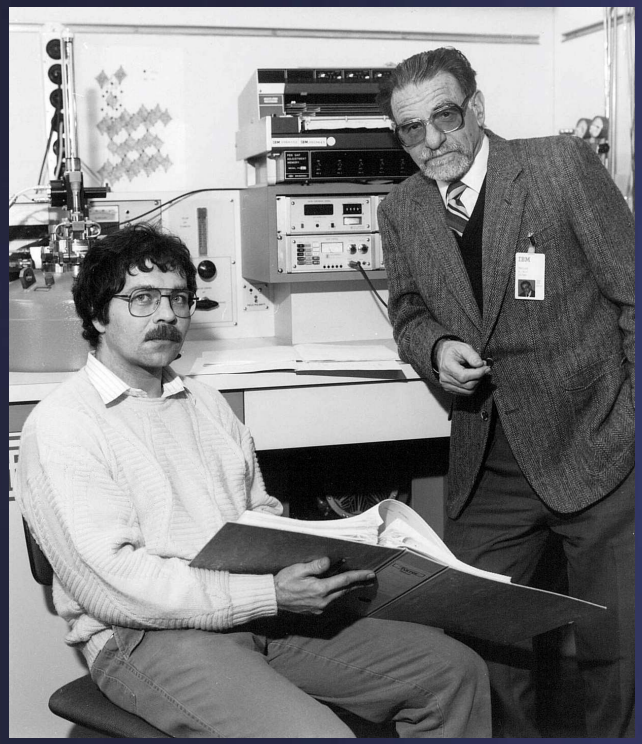


极化子

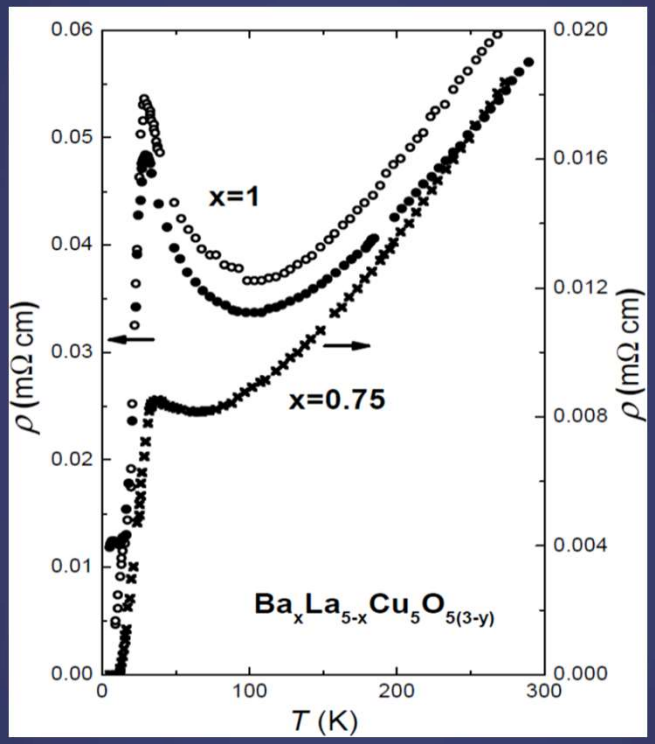
钙钛矿结构



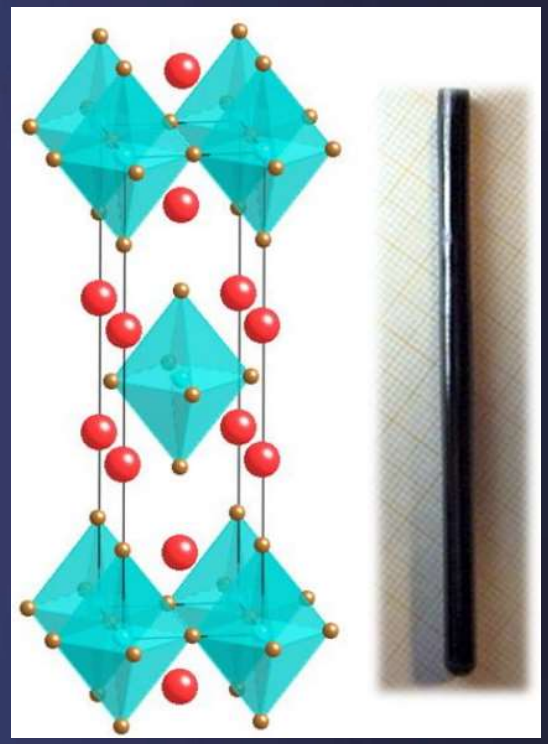
• 高温超导材料的发现



1986 年
柏诺兹和缪勒
发现Ba-La-Cu-O高温超导
T_c= 35 K

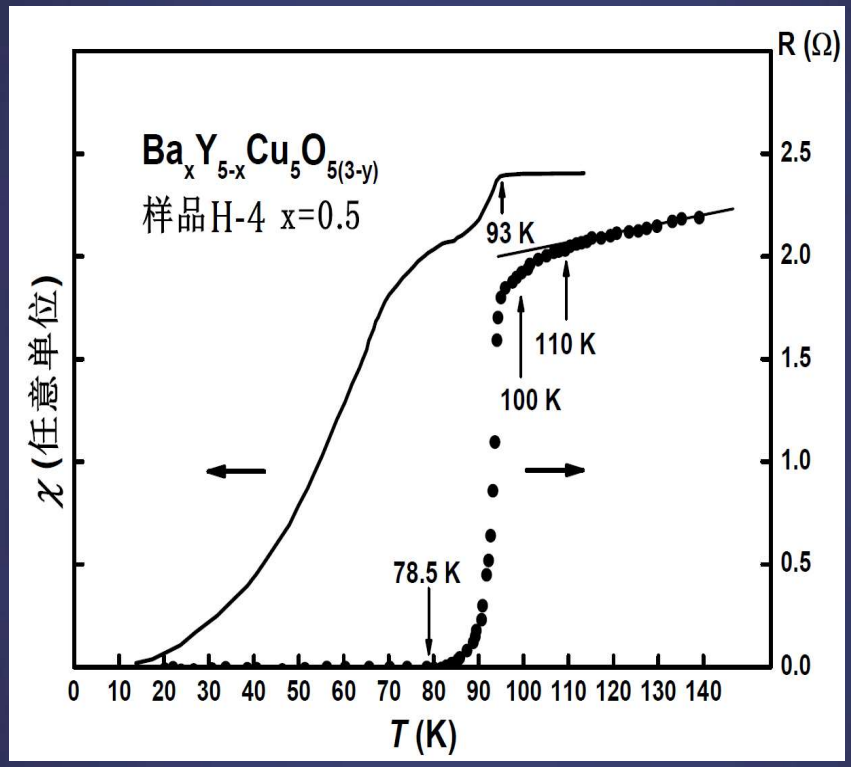


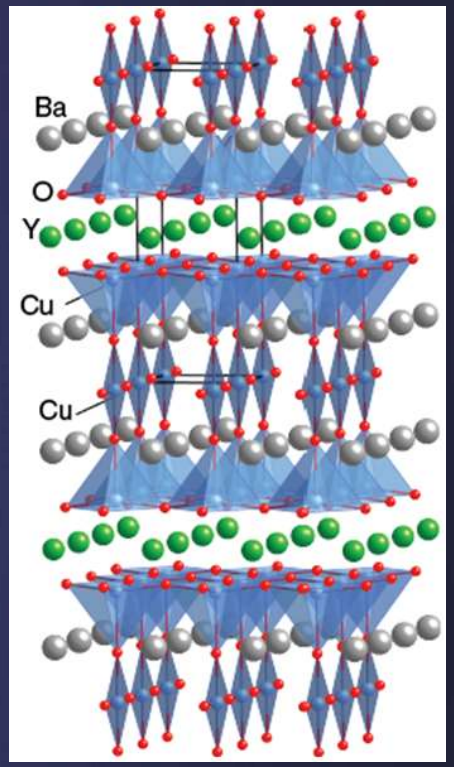
1987年
诺贝尔奖



铜氧化物高温超
导体晶体结构

• 突破液氮温区的超导材料



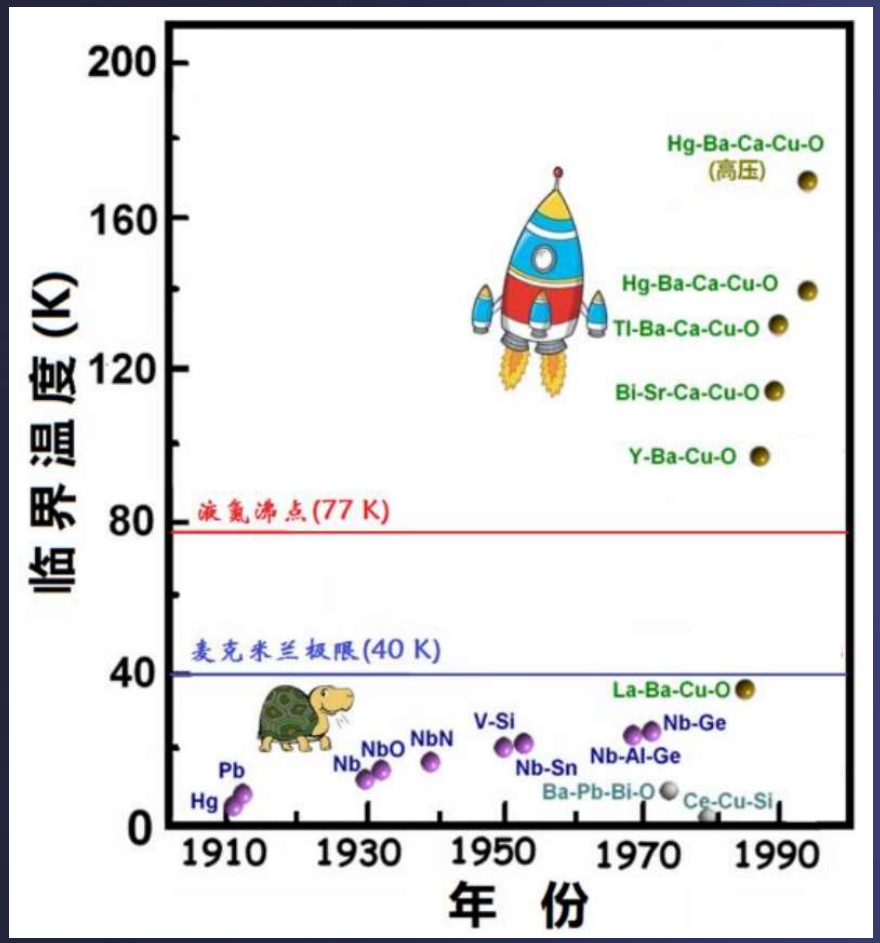


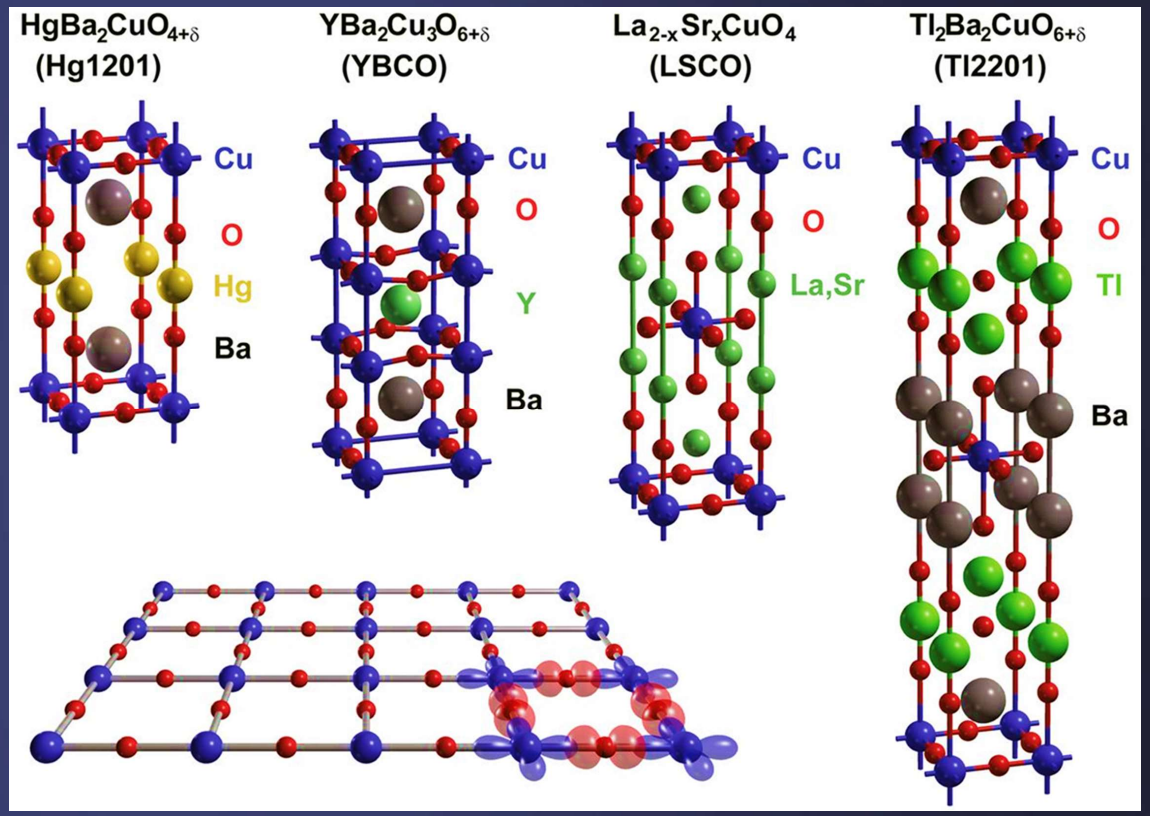
1987 年
朱经武和吴茂昆，赵忠贤等分别独立发现Y-Ba-Cu-O高温超导。
T_c= 93 K

超导临界温度突破液氮温度

液氮温区超导体晶体结构

• 铜氧化物高温超导家族





铜氧化物高温超导：都具有铜氧二维平面结构

最高超导转变温度 (常压)：135K（-138 °C)

“Woodstock of Physics”

“Woodstock of Physics”

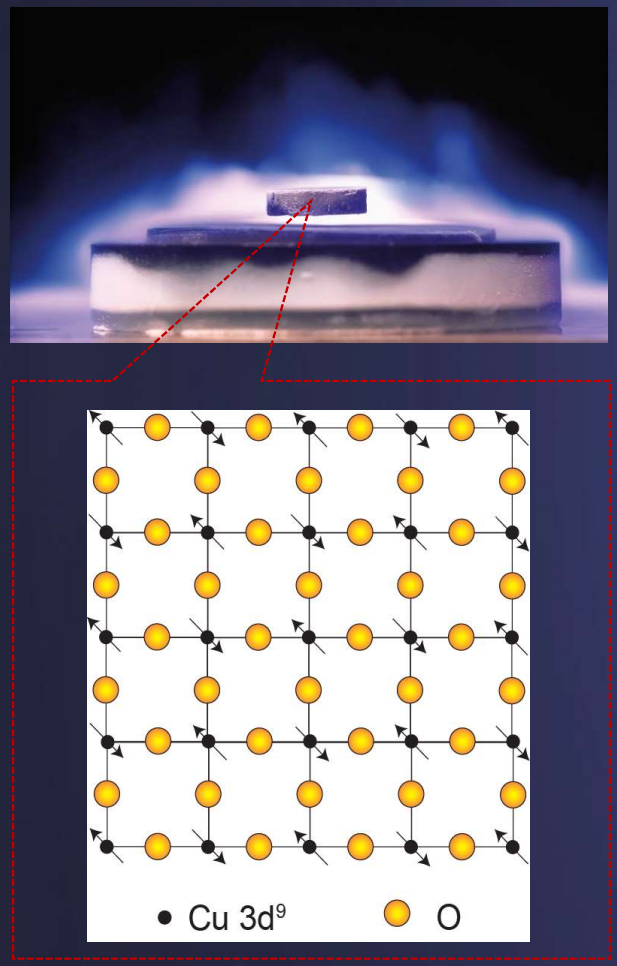
1987, APS March Meeting in NYC

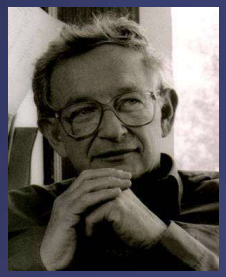
“Woodstock Festival of Rock&Roll”

1969, Woodstock, New York

The Society added a last-minute session to their annual meeting to discuss the new research in superconductors. The session was scheduled to start at 7:30 PM in the Sutton ballroom of the NewYork Hilton hotel, but excited scientists started lining up at 5:30. Nearly 2,000 scientists tried to squeeze into the ballroom. Those who could not find a seat filled the aisles or watched outside the room on television monitors. The session ended at 3:15 AM, but many lingered until dawn to discuss the presentations.

• 高温超导的机理研究





- P. W. Anderson:

  It is pretty much a solved problem by his RVB theory.

- R. B. Laughlin:

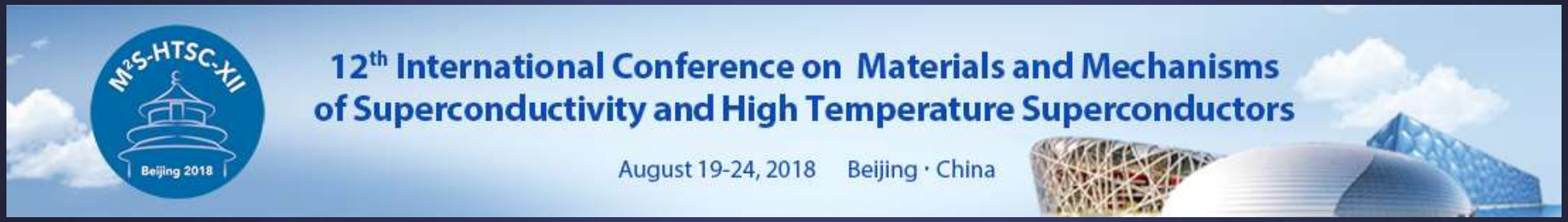
  It is such a complicated problem that we will never be able to solve it.

- Shou-Cheng Zhang:

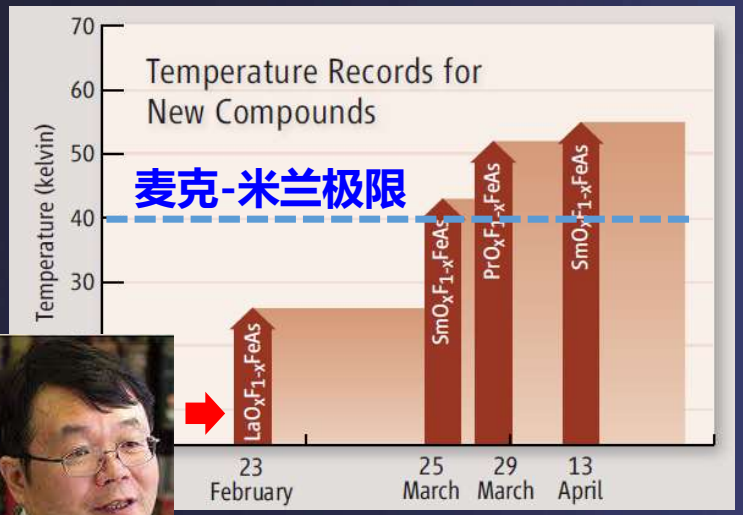
  Is there really any big problem to be solved?

- Others:

Yes, there are big questions (such as the super high T_C values). They remain to be the most mysterious phenomena in modern physics. We believe that they will be eventually solved beautifully, just like what we have done for conventional BCS superconductivity.

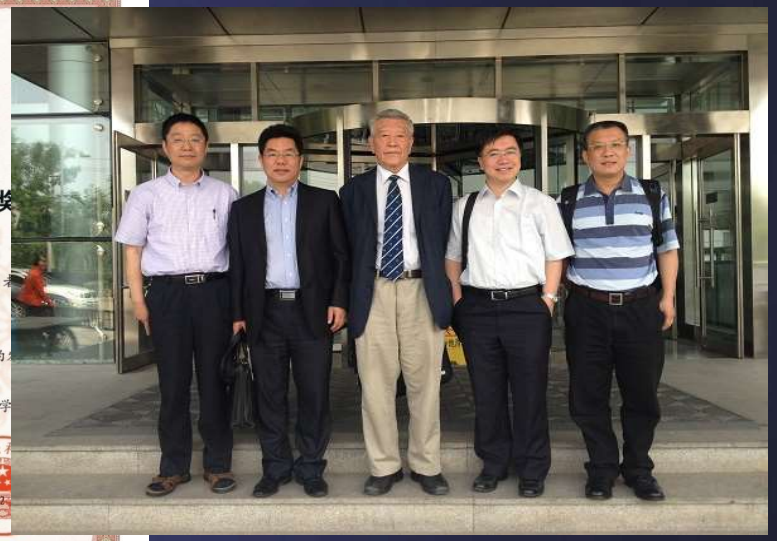


• 高温超导体的新大陆：铁基超导体



H. Hosono 教授
（日本，东京工业大学）

超导转变温度突破麦克-米兰极限

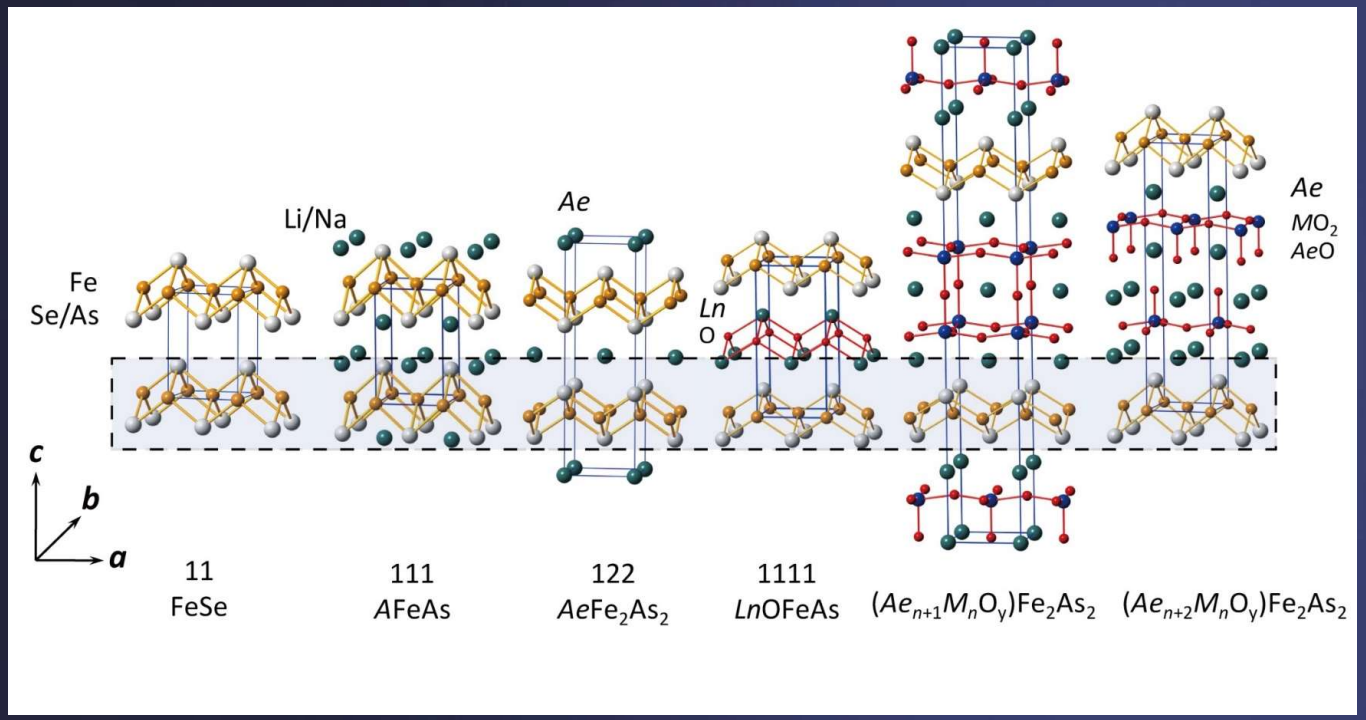


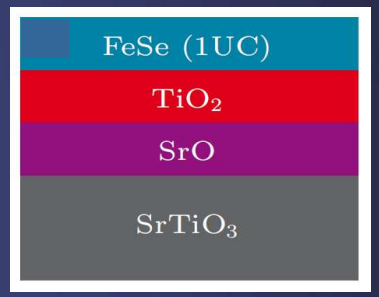
CONDENSED MATTER PHYSICS

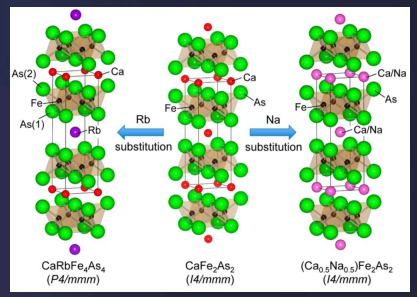
New Superconductors Propel Chinese Physicists to Forefront

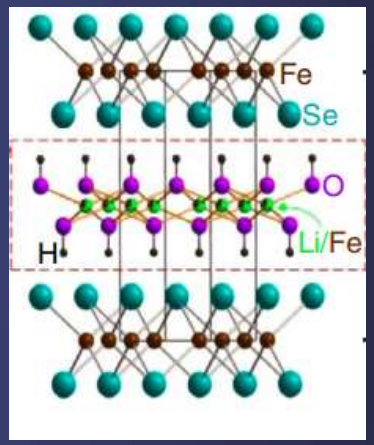
中科院物理所和中科大团队在铁基高温超导体的工作获2013年国家自然科学一等奖

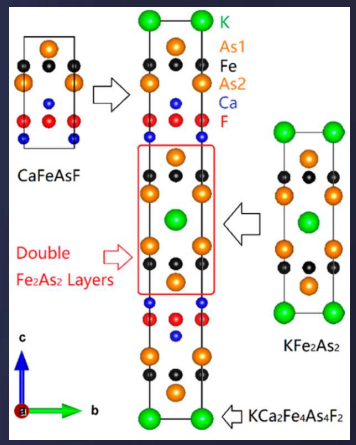
• 铁基高温超导体家族









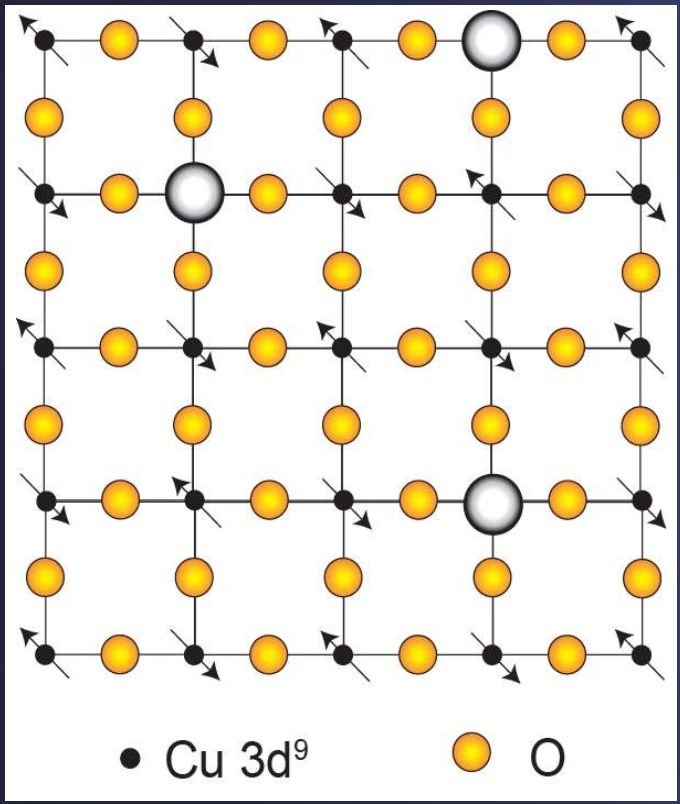


铁基高温超导材料家族：都具有铁砷/硒二维结构单元

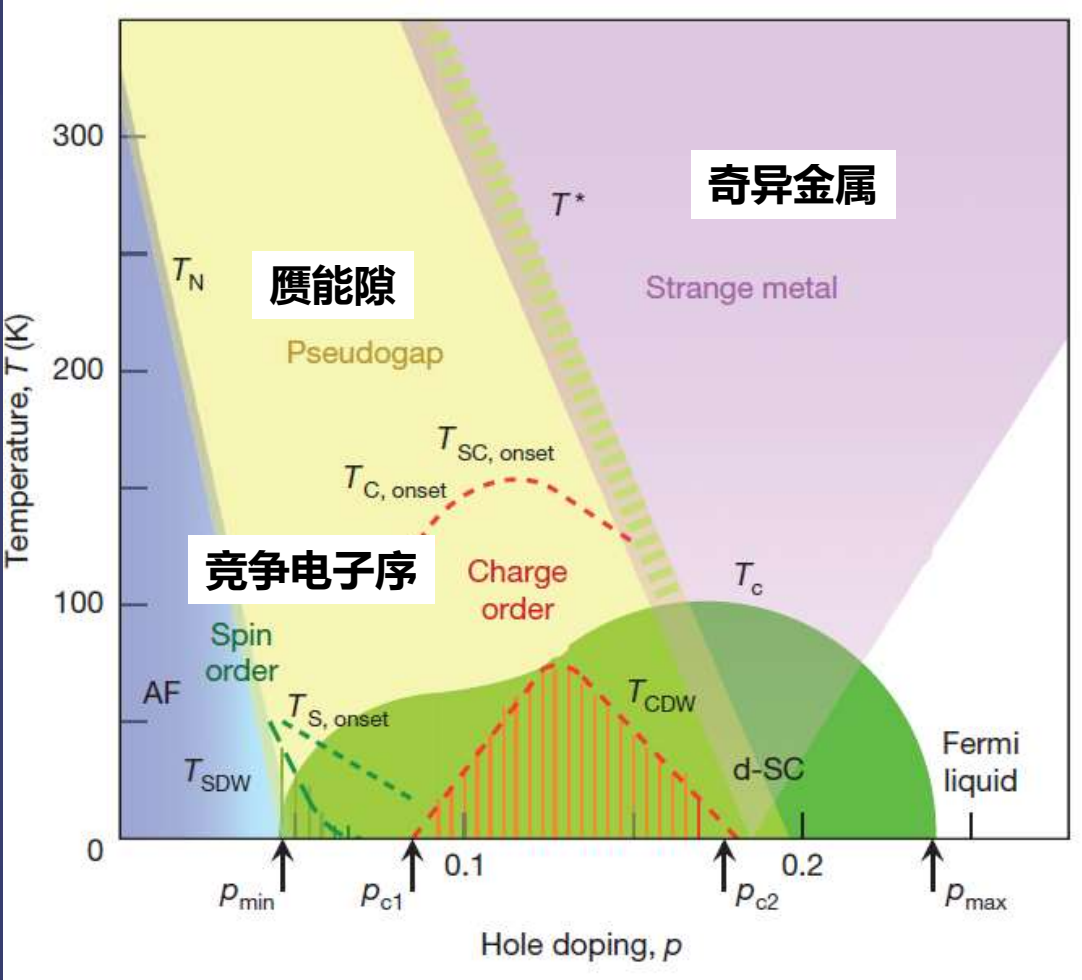
最高超导转变温度（常压）：~ 56 K（-217°C）

• 高温超导的机理研究

“Doping a Mott Insulator: Physics of High Temperature Superconductivity”



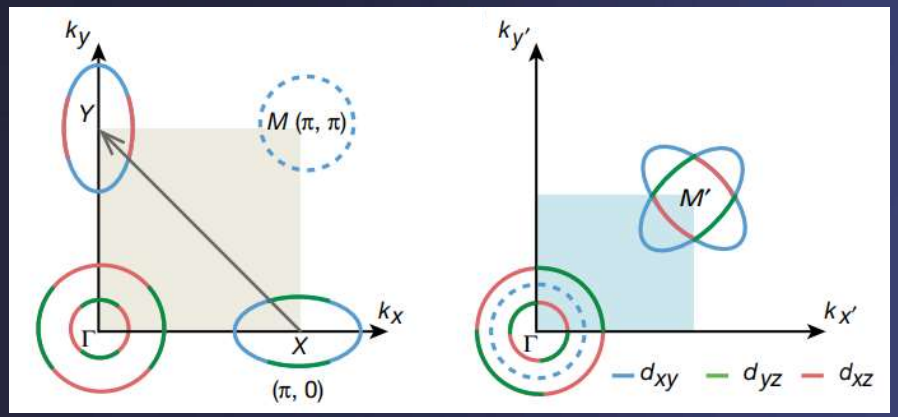
P. A. Lee *et al.*, Rev. Mod. Phys. **78**, 17 (2006)



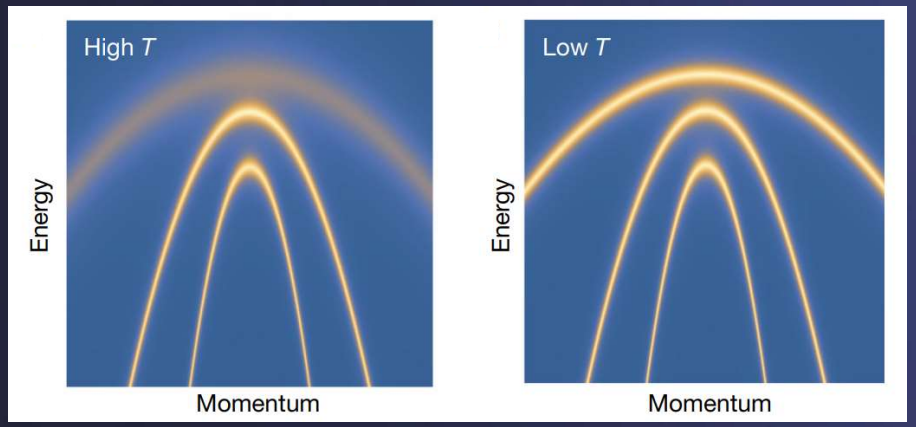
B. Keimer *et al.*, Nature **518**, 179 (2015)

• 高温超导的机理研究

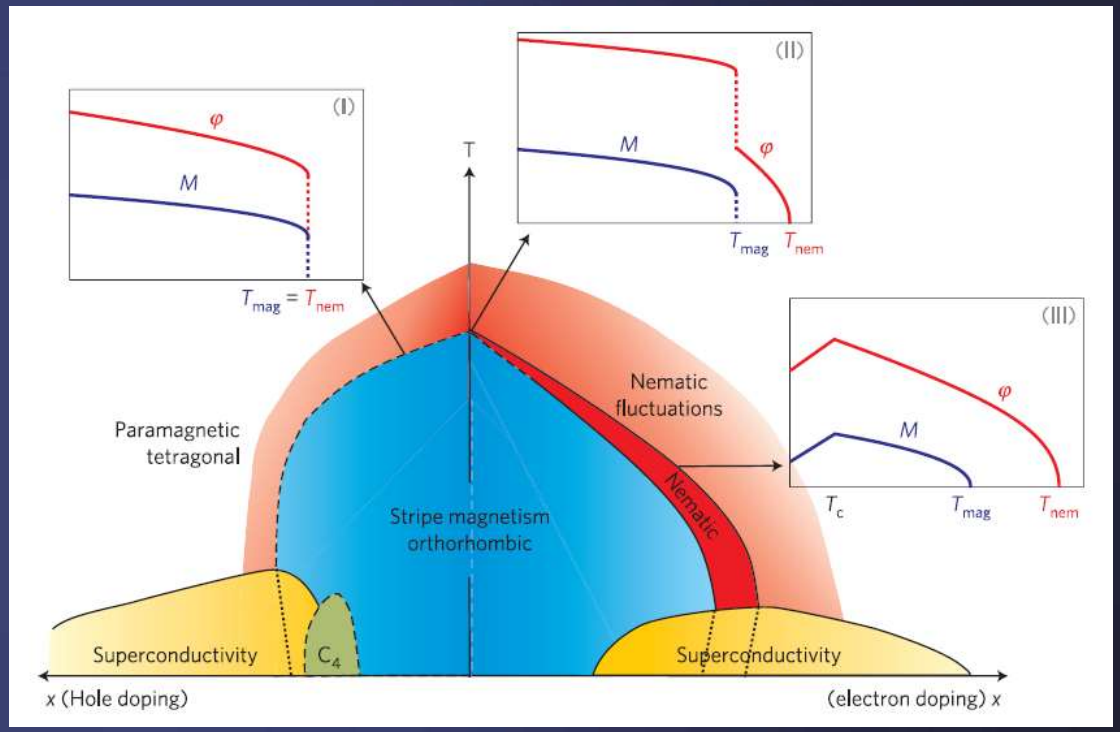
多能带体系



“洪特金属”



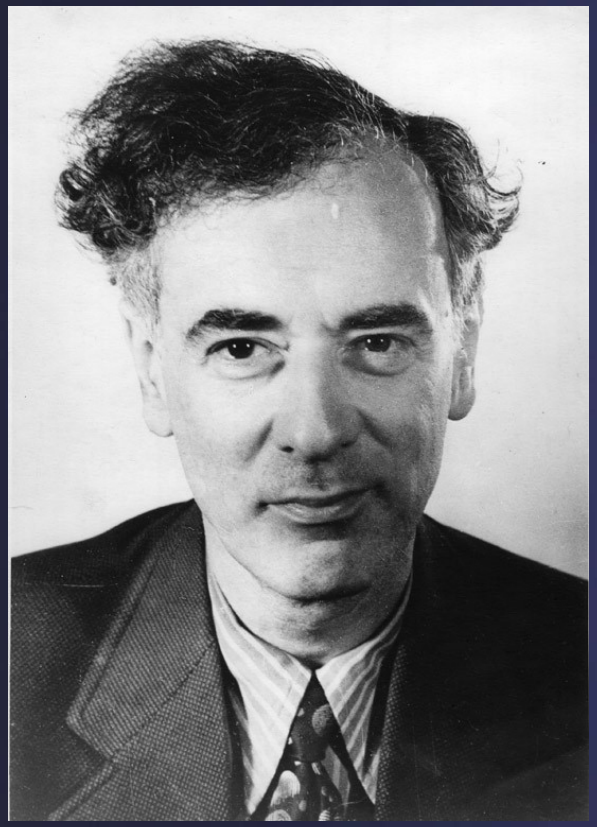
Rafael M. Fernandes *et al.*, Nature **601**, 35-44 (2022)



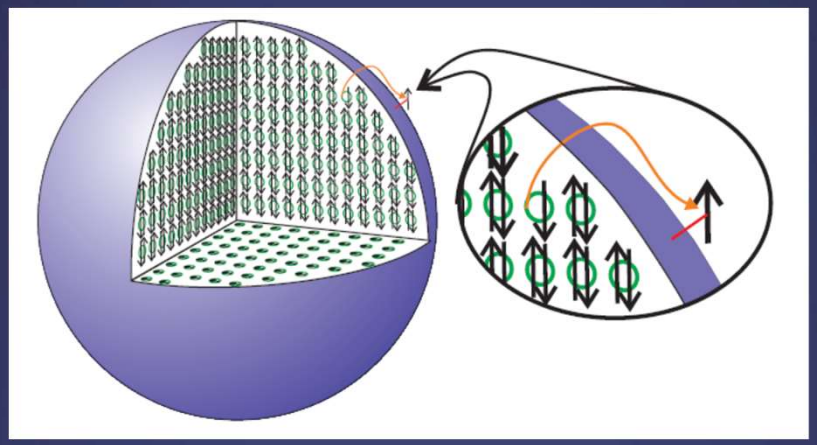
R. M. Fernandes *et al.*, Nat. Phys. **10**, 97 (2014)

铁基高温超导体家族的发现为高温理论的建立提供了重要依据。

• 高温超导机理的挑战



Lev D. Landau (1908-1968)



Landau Fermi Liquid Theory

A particle-hole excitation: an electron jumps from a state below E_F to an empty one above it

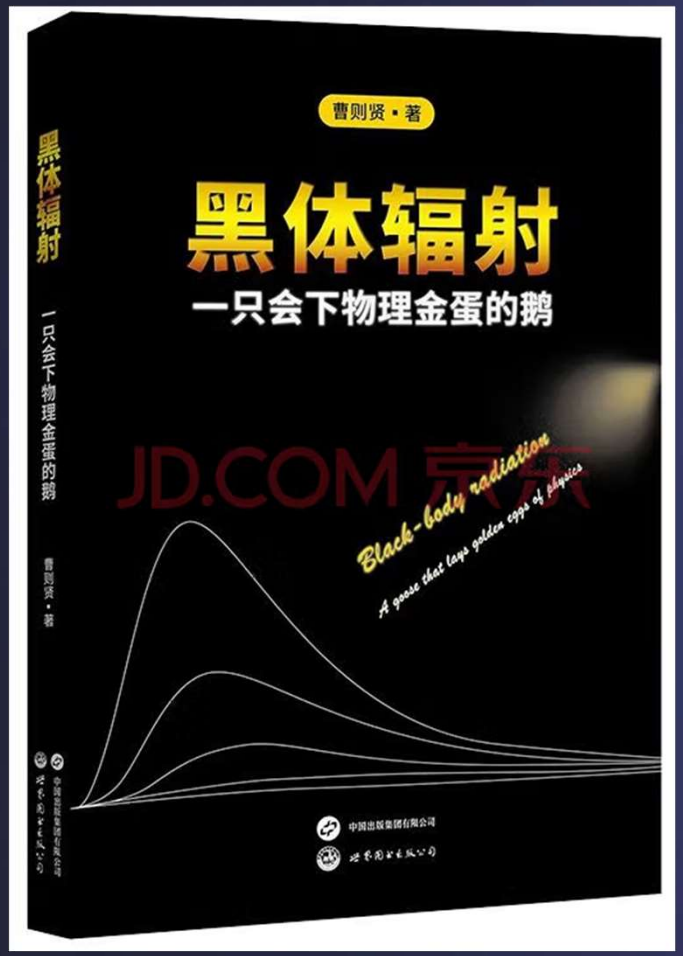
$$H = -t \sum_{\langle ij \rangle \sigma} c_{i\sigma}^{+} c_{j\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

Single-particle excitation = Landau qp + incoherent

emergent

"dark matter"

- 高温超导机理的挑战



High-T_c Superconductivity:

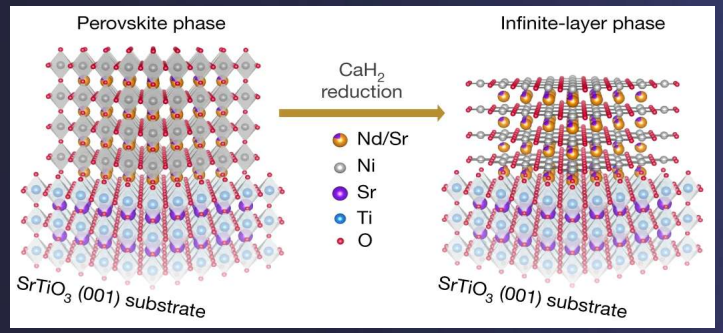
A goose that lays golden eggs of quantum field theory

--- 向涛 院士

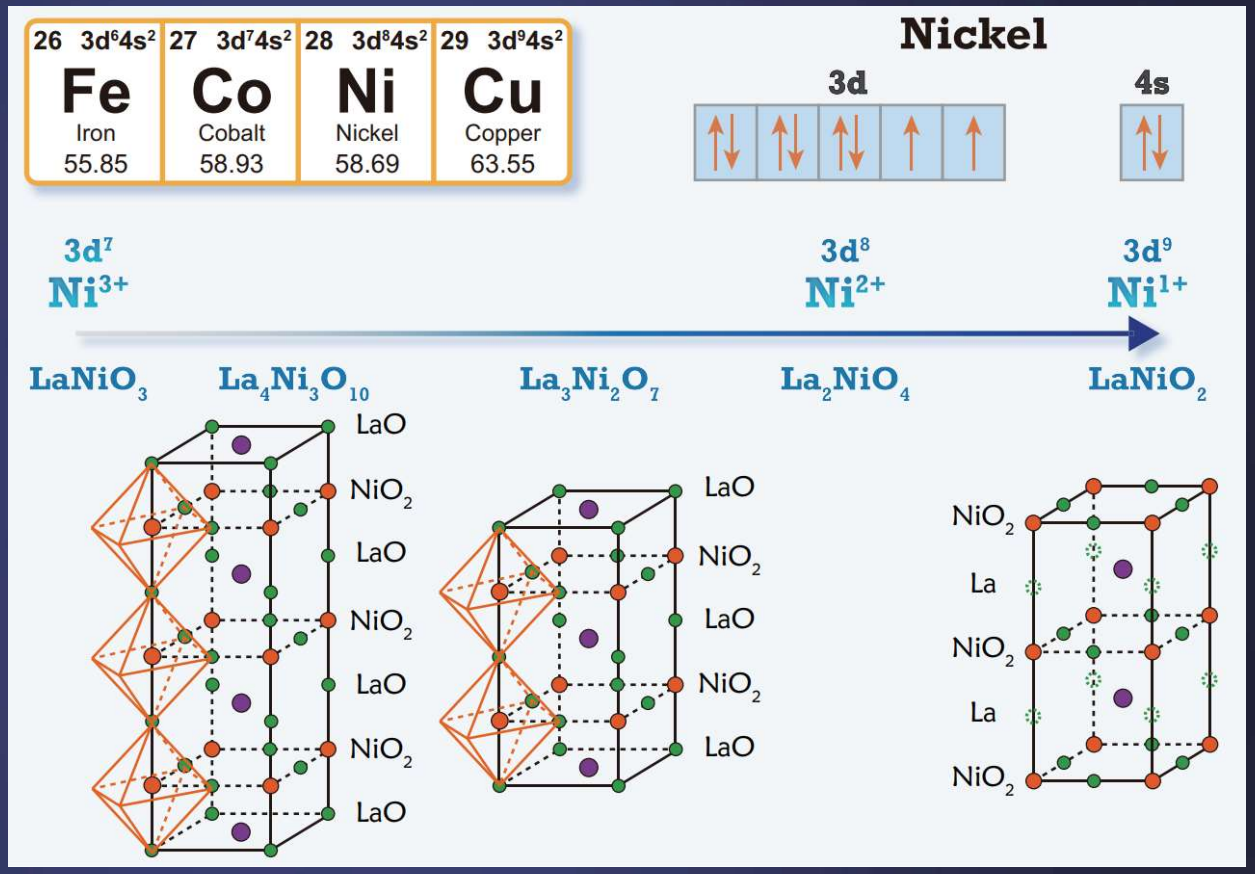
• 镍基高温超导体家族

Danfeng Li

Harold Y. Hwang



Danfeng Li *et al.*, Nature **572**, 624 (2019).

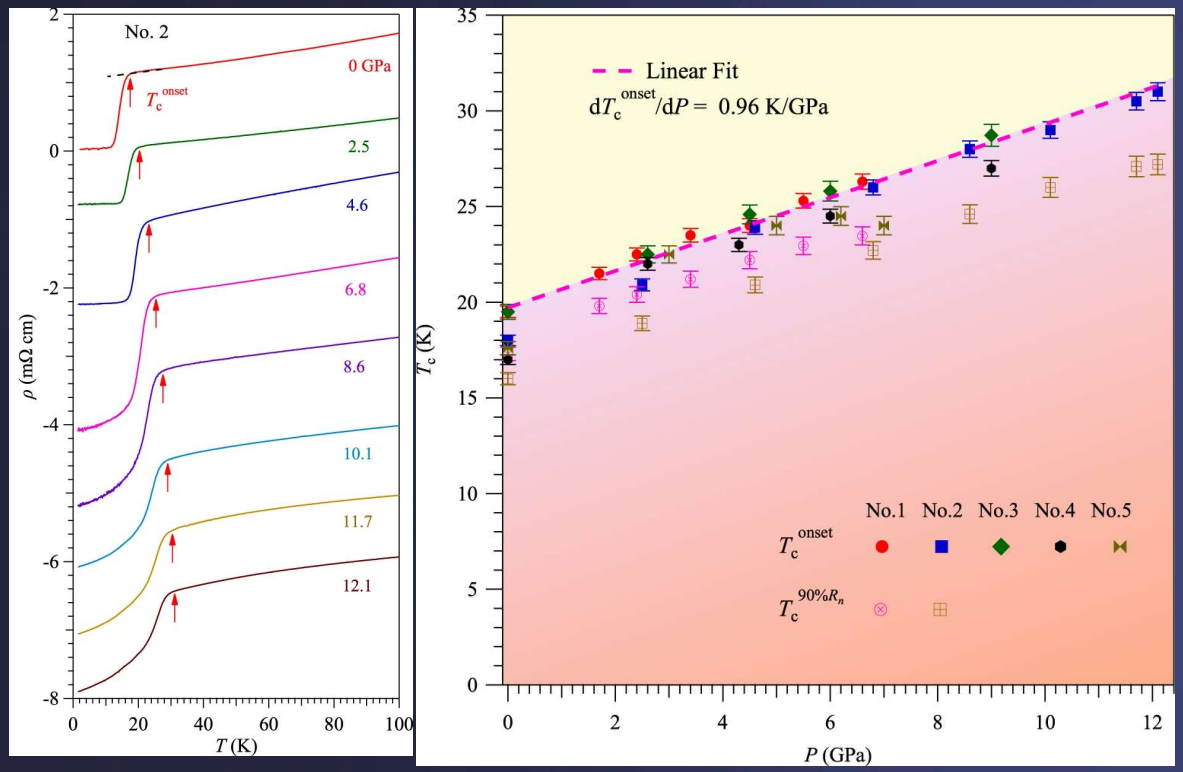


镍基高温超导材料家族：都具有镍氧二维结构单元

最高超导转变温度（高压）：~ 80 K（-193°C）

无限层镍氧化物超导薄膜

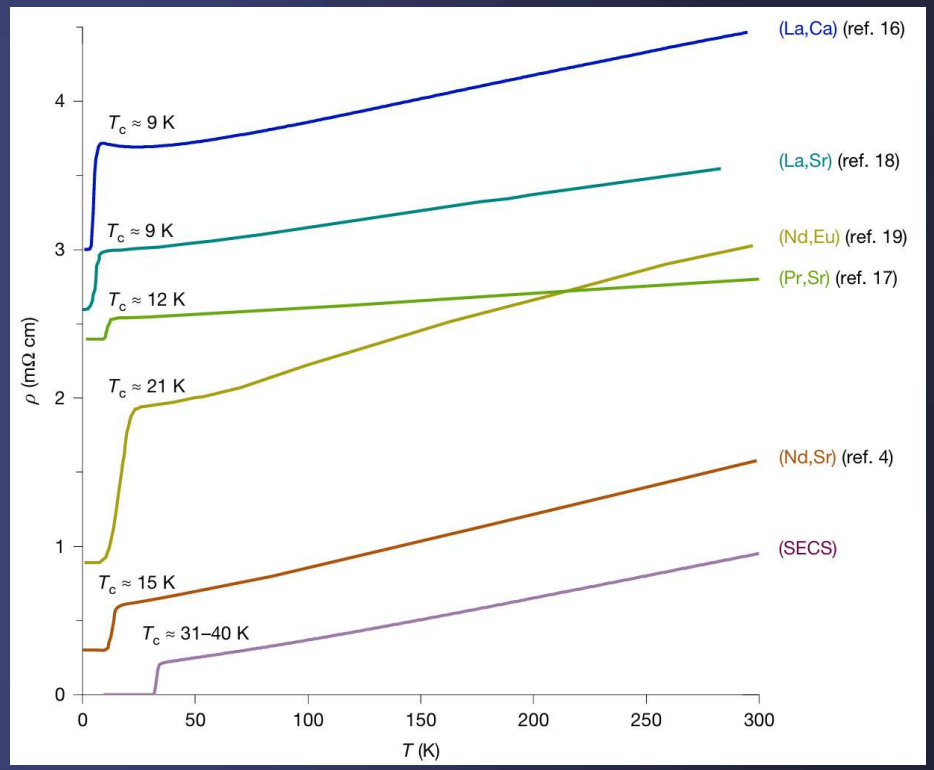
$Pr_{0.82}Sr_{0.18}NiO_2$



$T_c^{onset} \sim 30$ K

N. N. Wang *et al.*, Nat. Commun. **13**, 4367 (2022)

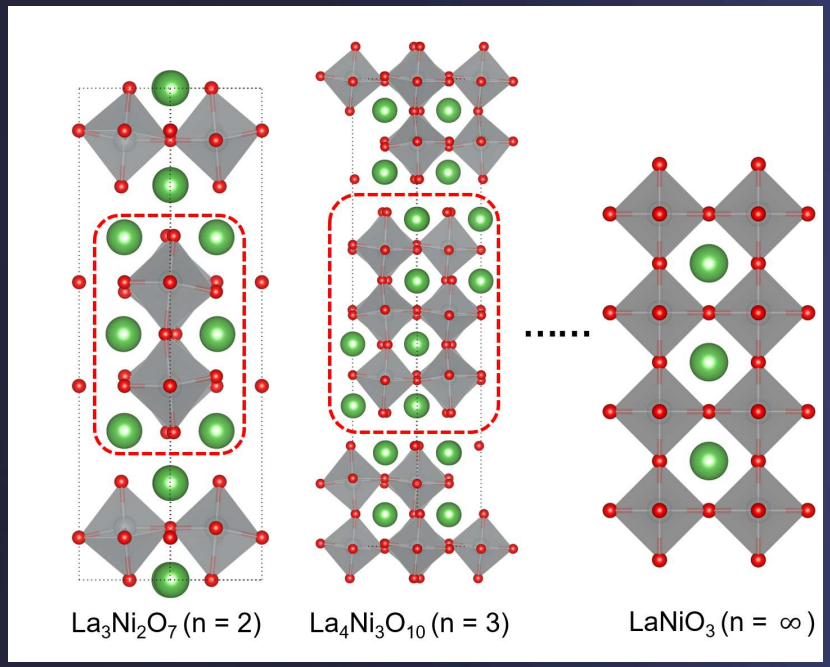
(Sm-Eu-Ca-Sr)NiO_2



$T_c^{onset} \sim 40$ K

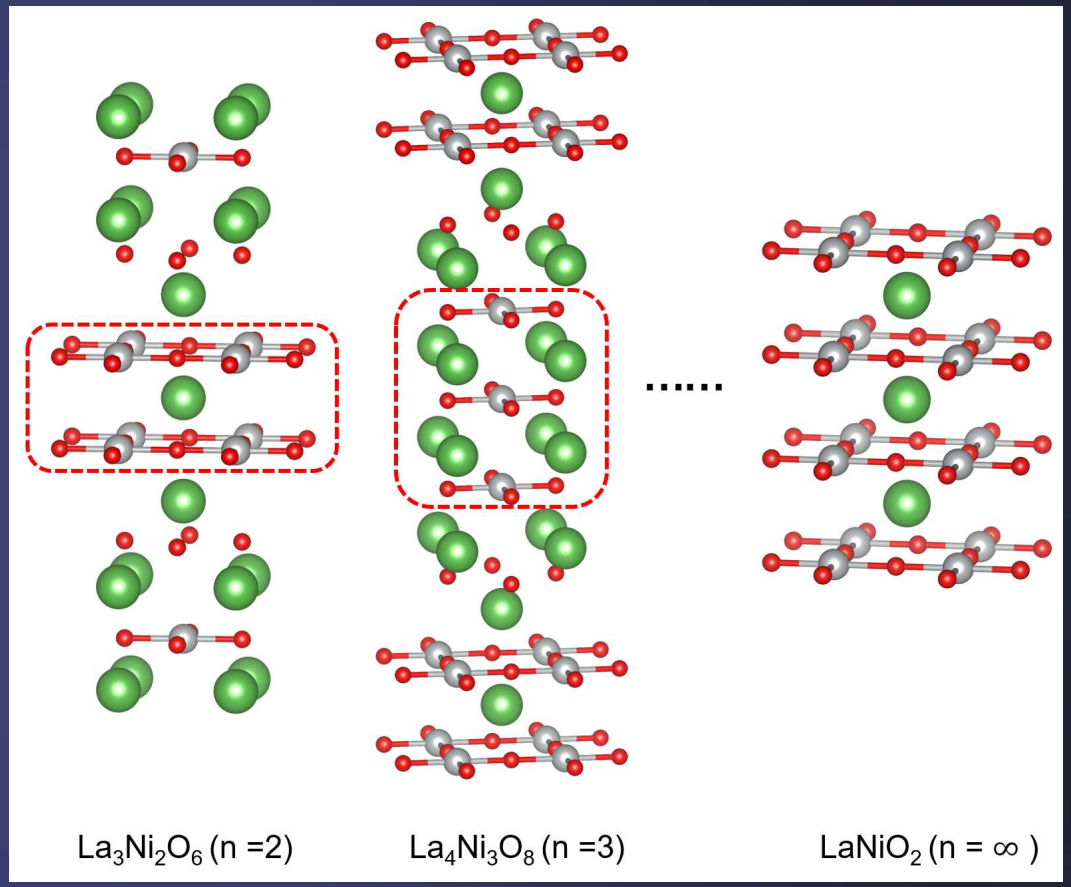
S. Lin Er Chow *et al.*, Nature **642**, 58–63 (2025)

Ruddlesden-Popper结构的镍基材料



Reduction

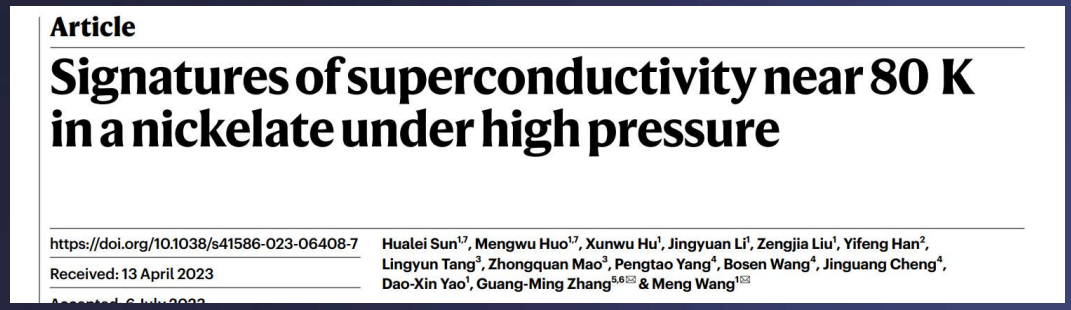
CaH_2 / H_2



RP Phase: $R_{n+1}Ni_nO_{3n+1}$

Reduced RP phase: $R_{n+1}Ni_nO_{2n+2}$

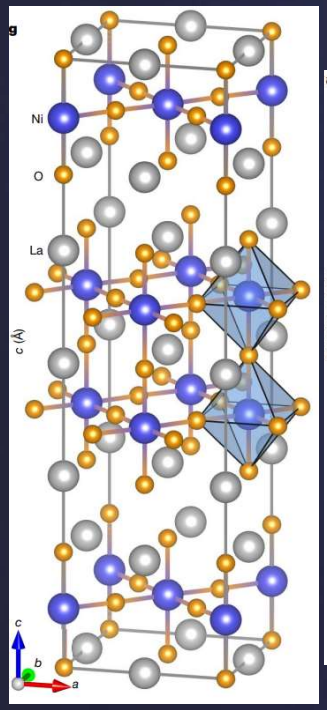
高压下RP相镍基超导 - 327

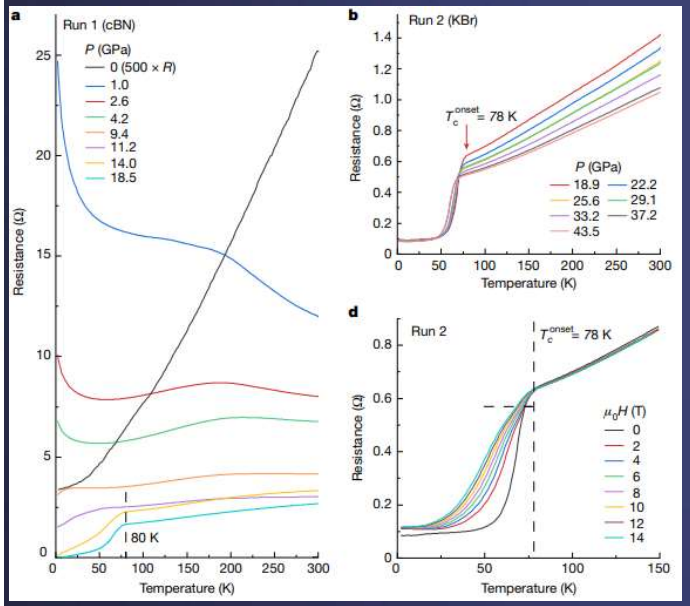

Article

Signatures of superconductivity near 80 K in a nickelate under high pressure

https://doi.org/10.1038/s41586-023-06408-7
Received: 13 April 2023

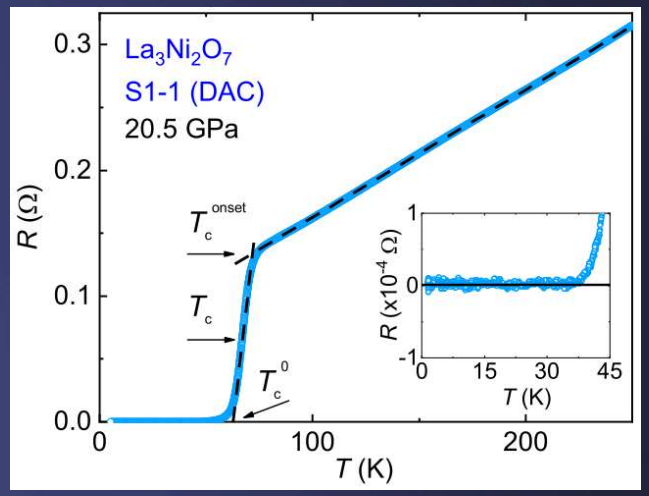
Hualei Sun[1,7], Mengwu Huo[1,7], Xunwu Hu[1], Jingyuan Li[1], Zengjia Liu[1], Yifeng Han[2], Lingyun Tang[3], Zhongquan Mao[3], Pengtao Yang[4], Bosen Wang[4], Jinguang Cheng[4], Dao-Xin Yao[1], Guang-Ming Zhang[5,6] & Meng Wang[1]





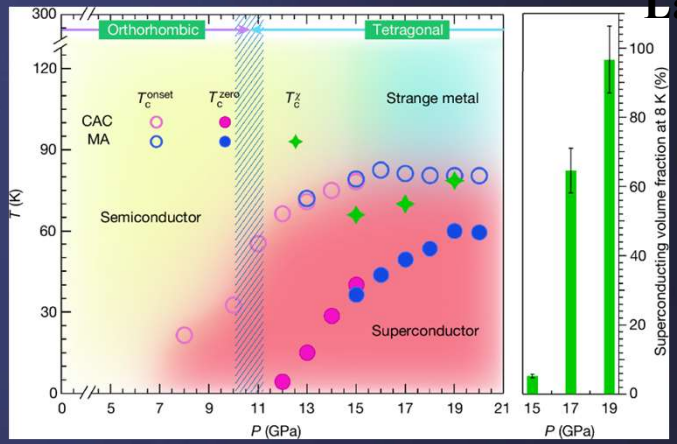
$La_3Ni_2O_7$

Hualei Sun *et al.*, Nature **261**, 493 (2023).



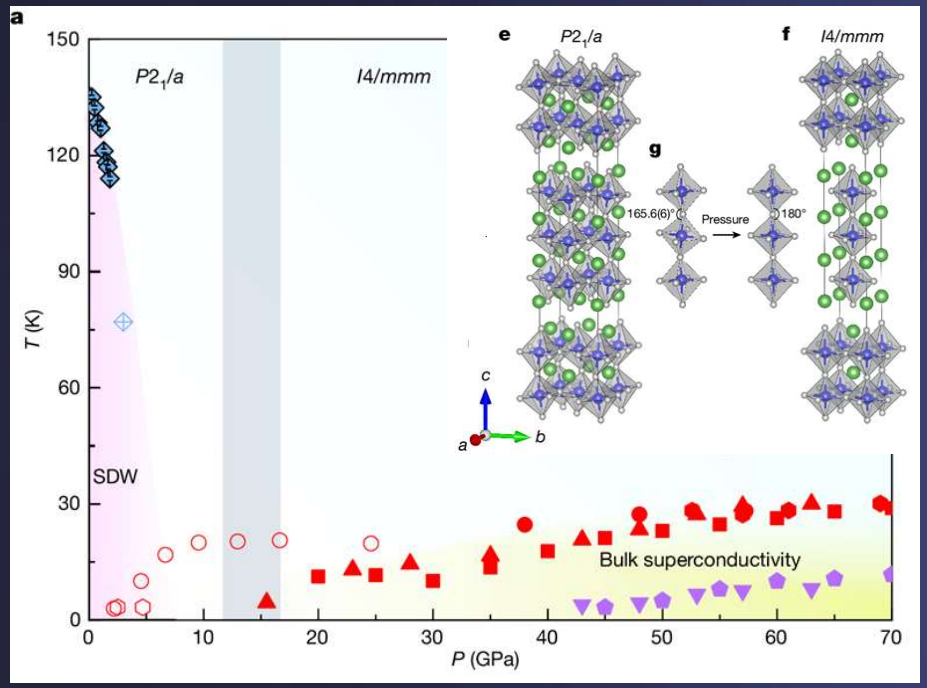
Yanan Zhang *et al.*, Nat. Phys. **20**, 1269 -1273 (2024)

$La_2PrNi_2O_7$



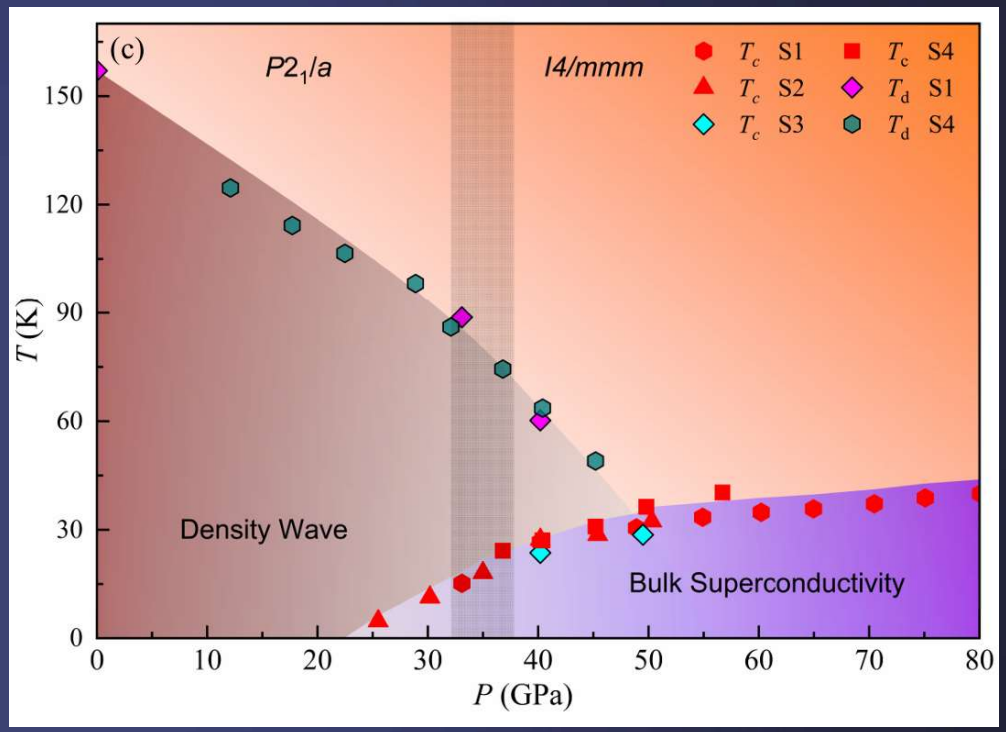
Ningning Wang et al., Nature **634**, 579–584 (2024)

高压下RP相镍基超导 - 4310



$La_4Ni_3O_{10}$

Yinghao Zhu, *et al*., Nature **631**, 531-536 (2024)

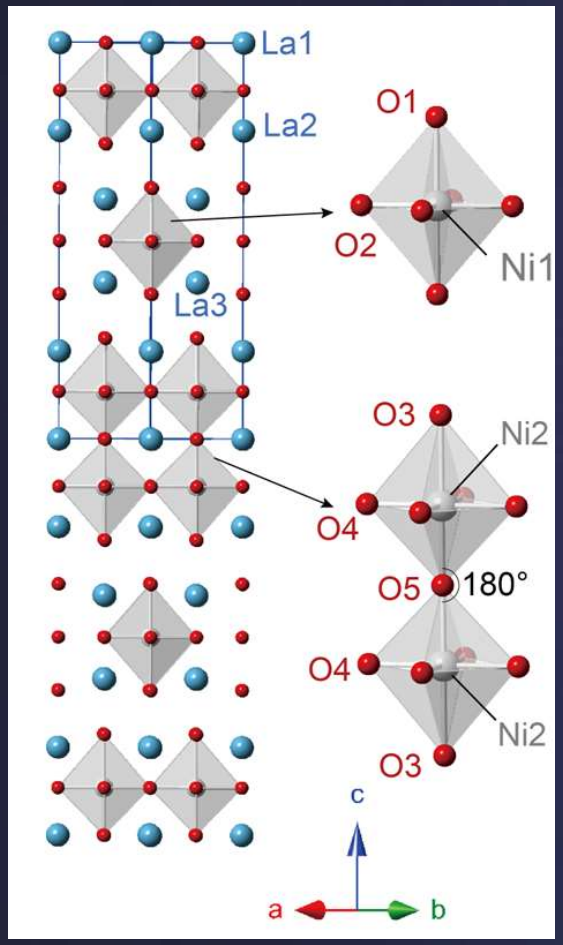


$Pr_4Ni_3O_{10}$

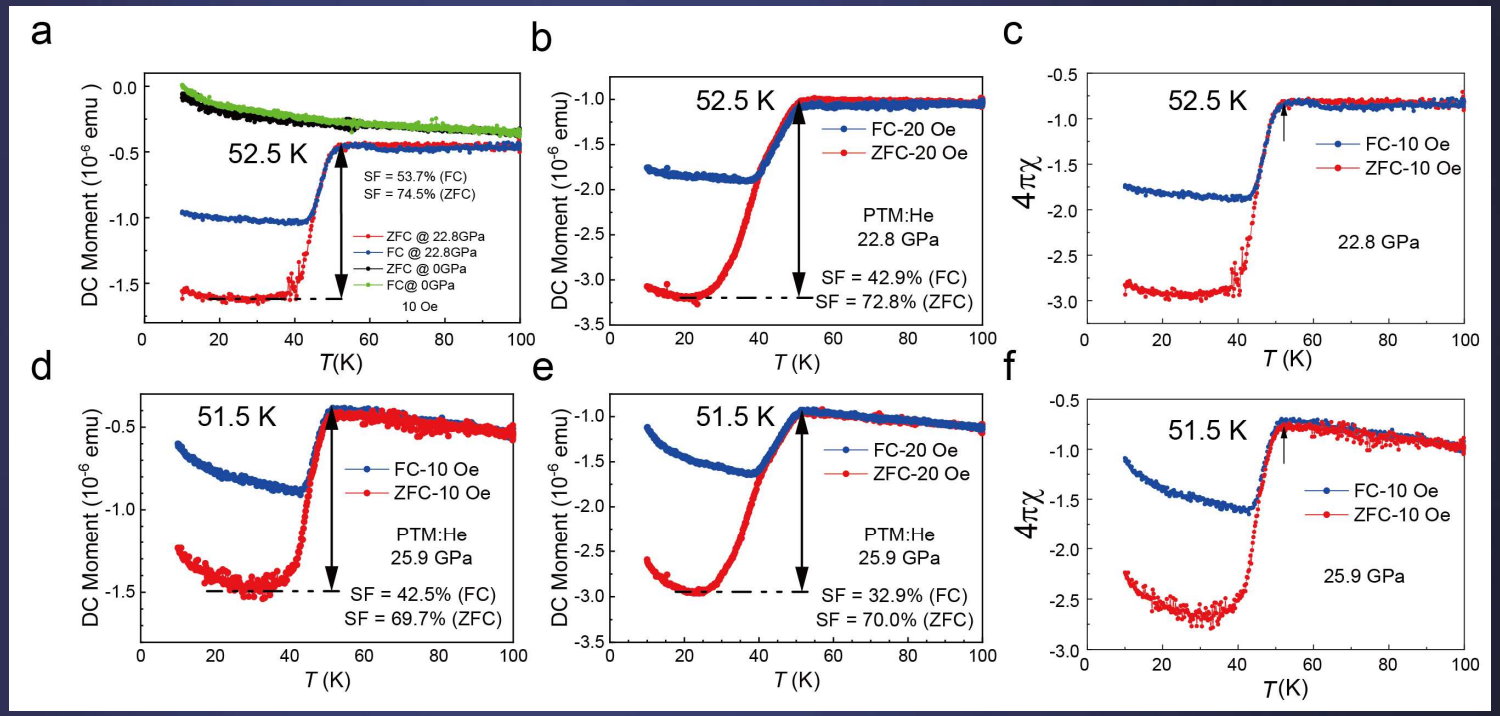
Enkang Zhang *et al*., Phys. Rev. X **15**, 021008 (2025)

Also see:
Hirofumi Sakakibara *et al*., PRB **109**, 144511 (2024)
Qing Li, *et al*., Chin. Phys. Lett. **41** 017401 (2024)
Mingxin Zhang, *et al*., Phys. Rev. X **15**, 021005 (2025)

高压下混合RP相镍基超导 - 5311



$La_5Ni_3O_{11}$



中科大陈仙辉团队

Mengzhu Shi *et al.*, Nat. Phys. 21, 1780–1786 (2025)

常压下RP相镍基超导薄膜

Article

Signatures of ambient pressure superconductivity in thin film $La_3Ni_2O_7$

https://doi.org/10.1038/s41586-024-08525-3
Received: 30 July 2024

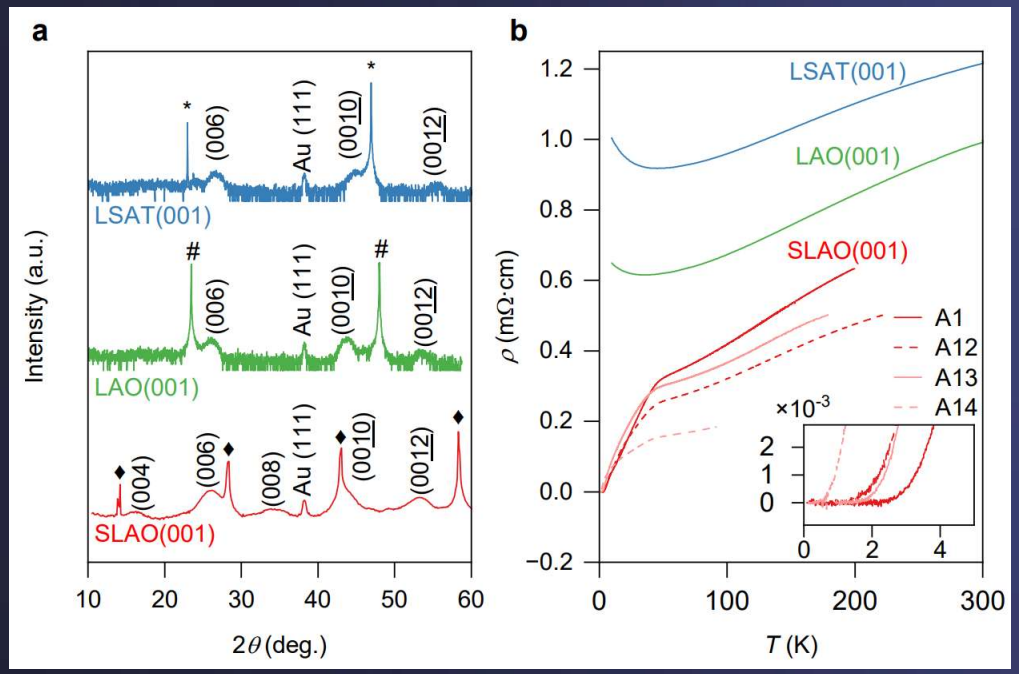
Eun Kyo Ko[1,2,8]✉, Yijun Yu[1,2,8]✉, Yidi Liu[1,3], Lopa Bhatt[4], Jiarui Li[1,2], Vivek Thampy[5], Cheng-Tai Kuo[5], Bai Yang Wang[1,3], Yonghun Lee[1,2], Kyuho Lee[1,3], Jun-Sik Lee[5], Berit H. Goodge[6], David A. Muller[4,7] & Harold Y. Hwang[1,2]✉

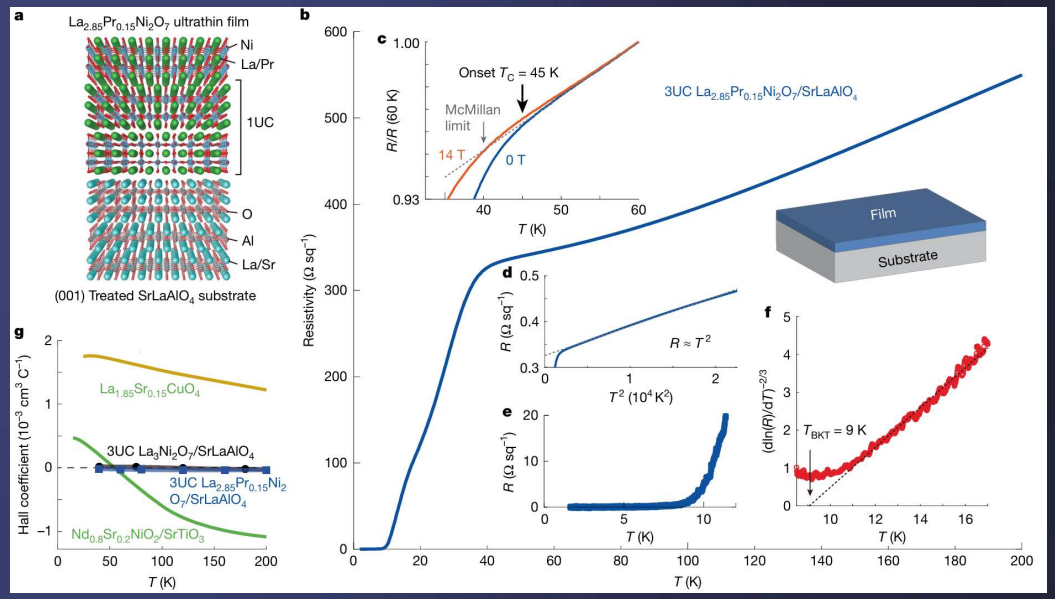
Article

Ambient-pressure superconductivity onset above 40 K in $(La,Pr)_3Ni_2O_7$ films

https://doi.org/10.1038/s41586-025-08755-z
Received: 16 November 2024

Guangdi Zhou[1,4], Wei Lv[1,4], Heng Wang[1,4], Zihao Nie[1,4], Yaqi Chen[1], Yueying Li[1], Haoliang Huang[1,2], Wei-Qiang Chen[1,2], Yu-Jie Sun[1,2], Qi-Kun Xue[1,2,3]✉ & Zhuoyu Chen[1,2]✉





常压下RP相镍基超导薄膜

nature materials

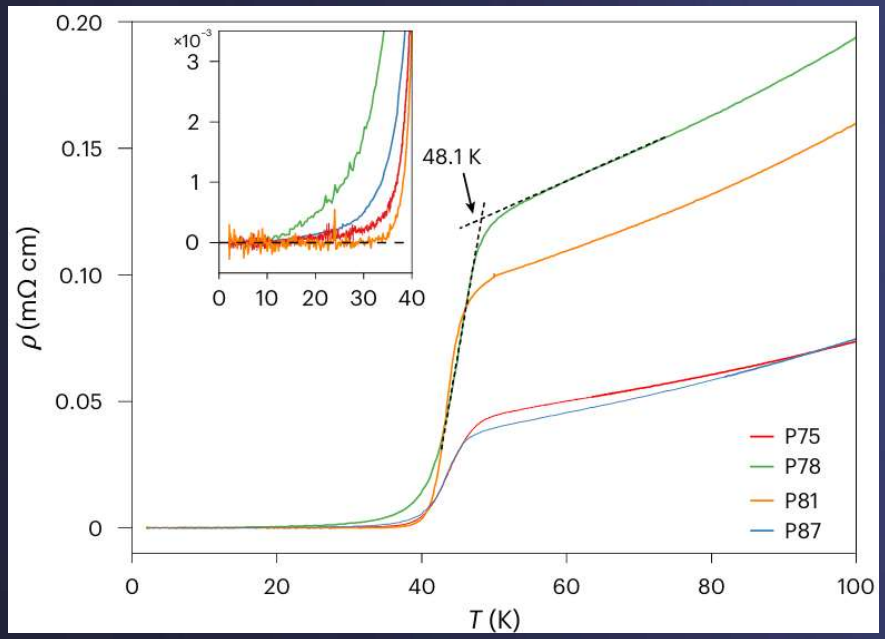
Article https://doi.org/10.1038/s41563-025-02258-y

Superconductivity and normal-state transport in compressively strained $La_2PrNi_2O_7$ thin films

Received: 14 January 2025

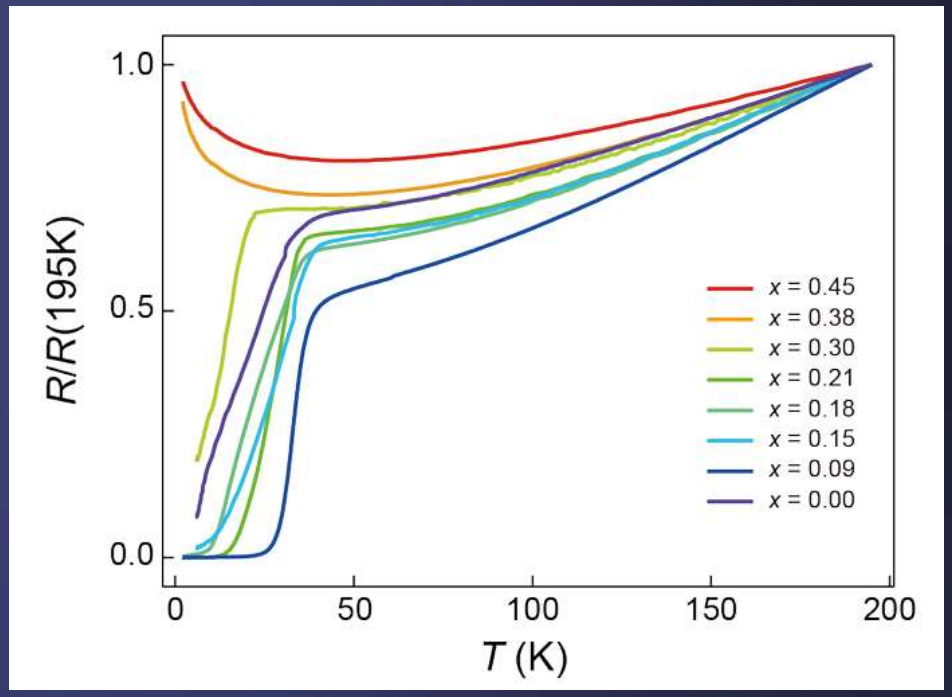
Accepted: 5 May 2025

Yidi Liu[1,2], Eun Kyo Ko[1,3], Yaoju Tarn[1,3], Lopa Bhatt[4], Jiarui Li[1,3], Vivek Thampy[5], Berit H. Goodge[6], David A. Muller[4,7], Srinivas Raghu[1,2], Yijun Yu[1,3] & Harold Y. Hwang[1,3]



Superconductivity and phase diagram in Sr-doped $La_3Ni_2O_7$ thin films

*Bo Hao[1, 2, ‡], Maosen Wang[1, 2, ‡], Wenjie Sun[1, 2, ‡], Yang Yang[3, ‡], Zhangwen Mao[1, 2], Shengjun Yan[1, 2], Haoying Sun[1, 2], Hongyi Zhang[1, 2], Lu Han[1, 2], Zhengbin Gu[1, 2], Jian Zhou[1, 2], Dianxiang Ji[3, *], Yuefeng Nie[1, 2, 4, *]*



- 高温超导机理

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125 QUESTIONS: EXPLORATION AND DISCOVERY

Physics

物理学

有衍射极限吗?
Is there a diffraction limit?

高温超导的微观机理是什么?
What is the microscopic mechanism for high-temperature superconductivity?

物质传热的极限是什么?
What are the limits of heat transfer in matter?

我们可以制作出真人大小的隐形斗篷吗?
Can we make a real, human-size invisibility cloak?

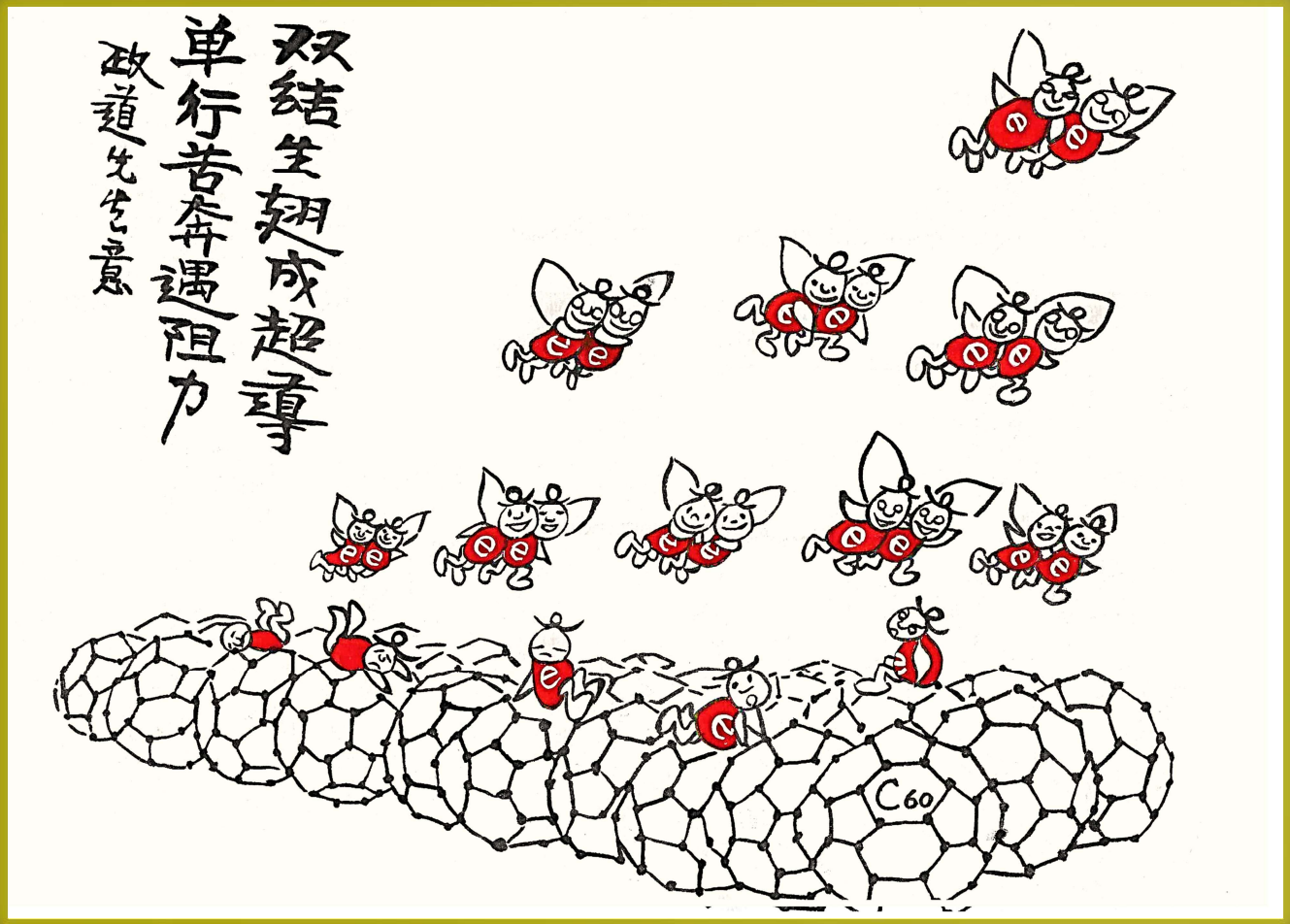
是否存在与光子性质或状态相反的粒子?
Are there any particles that behave oppositely to the properties or states of photons?

高温超导材料研究的机遇与挑战

- Cuprate superconductors (铜基)
- Iron-based superconductors (铁基)
- Nickelate superconductors (镍基)

1. Better understanding of the origin of high-Tc pairing
2. Predicting power of finding new high-Tc superconductors
3. Promoting large-scale applications

超导电性的微观理论

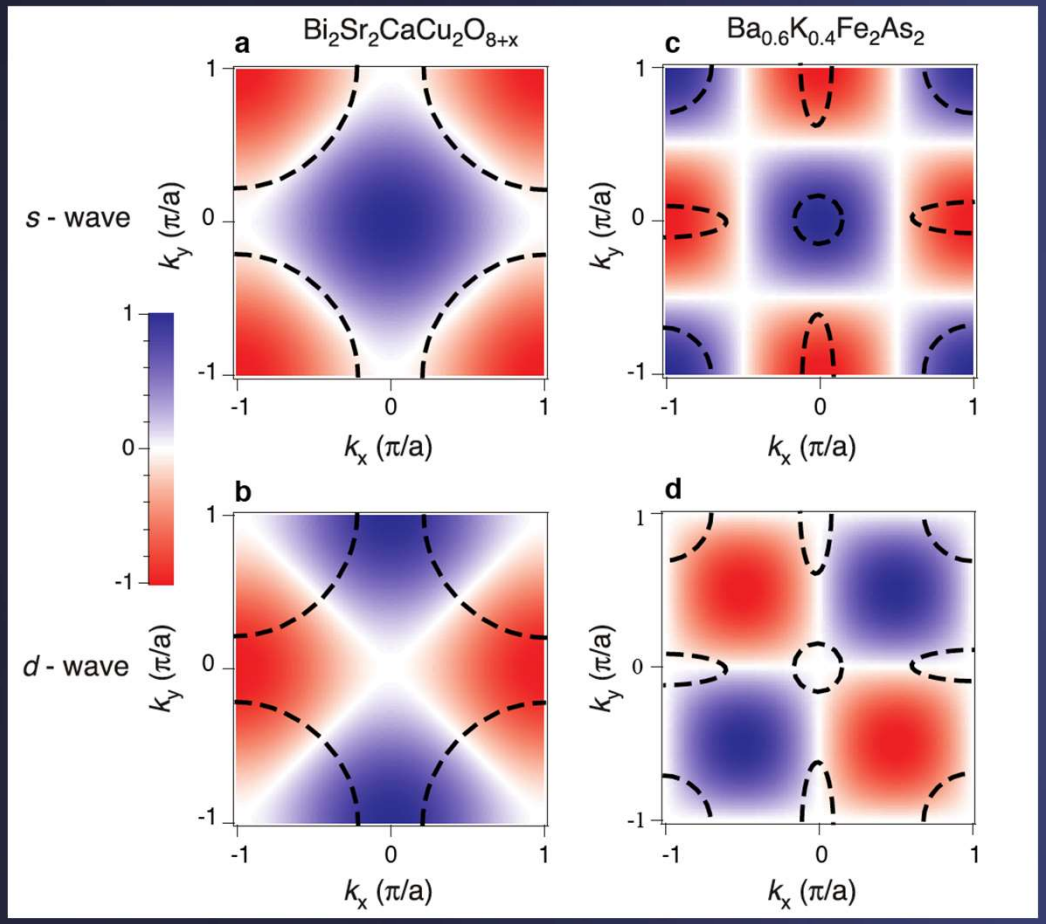


超导形成的两个关键因素

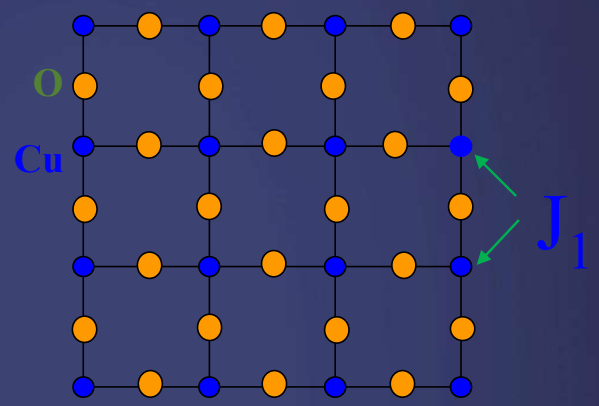
1. 电子配对——超导能隙

2. 相位相干——超流密度

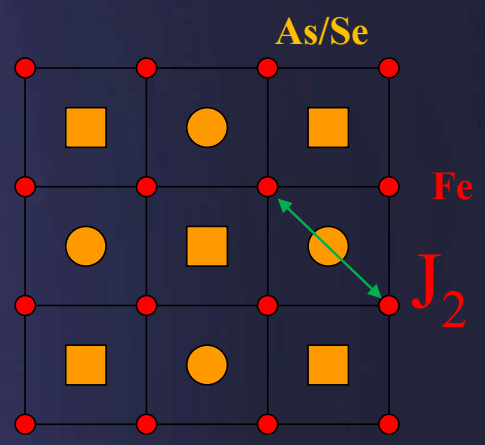
高温超导体中的配对相互作用



J. P. Hu and H. Ding, Scientific Reports **2**, 381 (2012)



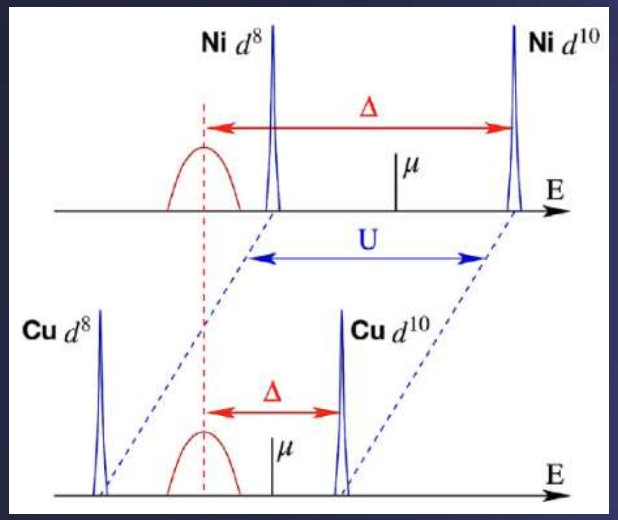
铜基: Cu-O 面

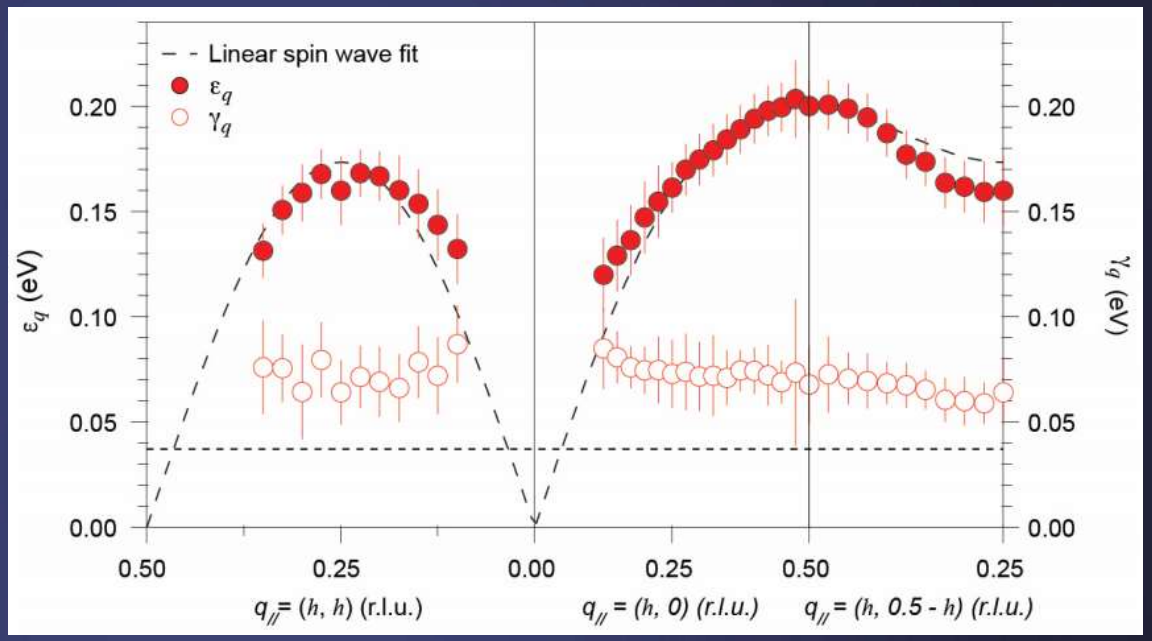


铁基: Fe-As/Se 面

	铜基	铁基
反铁磁温度:	~ 400K	~ 150K
反铁磁耦合强度:	J_1 ~ 120meV	J_2 ~ 45meV
超导转变温度	~ 130K	~ 50K

无限层镍氧化物中的反铁磁相互作用





$$J = \frac{4t_{dp}^4}{(\Delta + V)^2}\left(\frac{1}{U_d} + \frac{2}{2\Delta + U_p}\right)$$

~ 10%

$$H = J_1 \sum_{\langle i,j \rangle} S_i \cdot S_j + J_2 \sum_{\langle i,i' \rangle} S_i \cdot S_{i'}$$

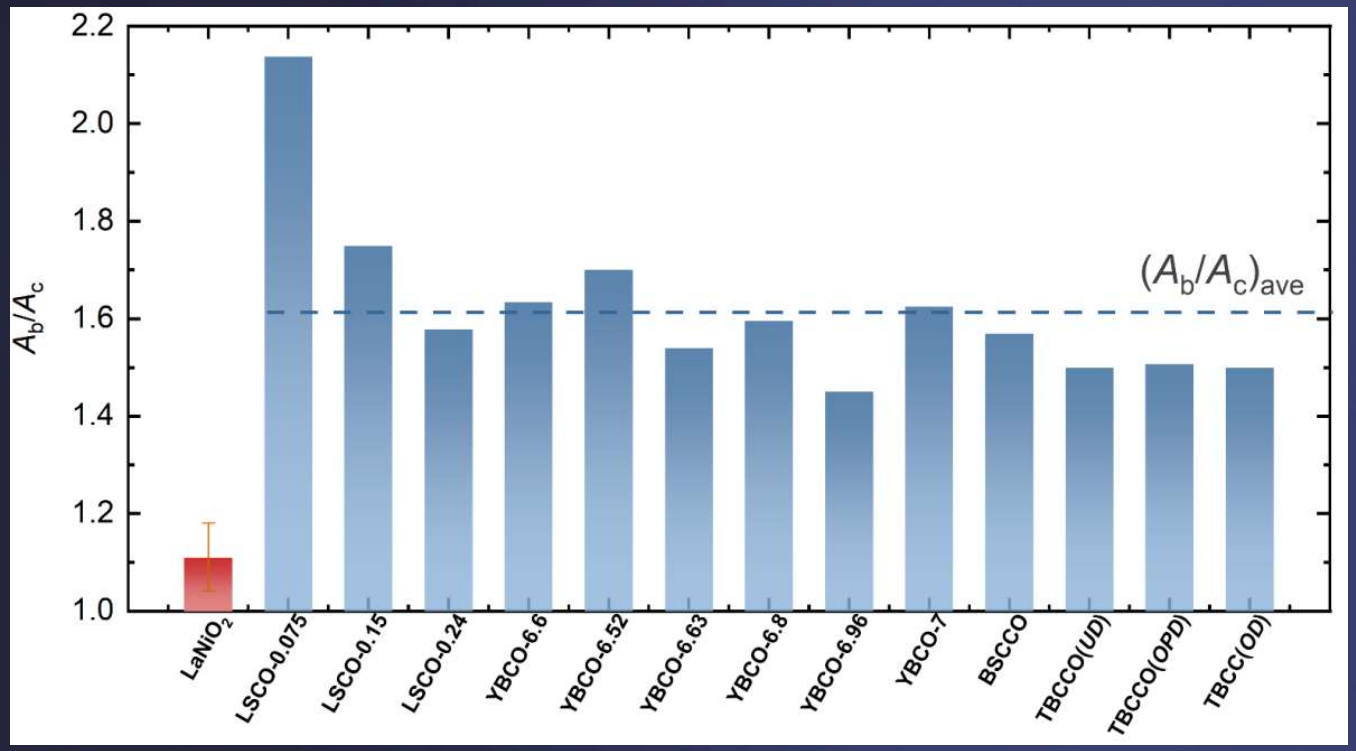
J_1 = 63.6 ± 3.3 meV

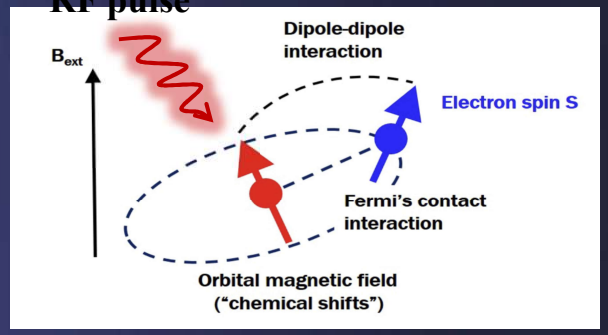
J_2 = −10.3 ± 2.3 meV

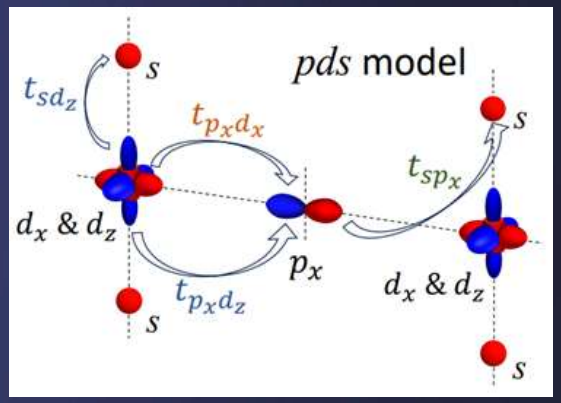
Mi Jiang *et al.*, Phys. Rev. Lett. **124**, 207004 (2020)

H. Lu *et al.*, Science **373**, 213 (2021)

镍基超导体磁性相互作用的探测







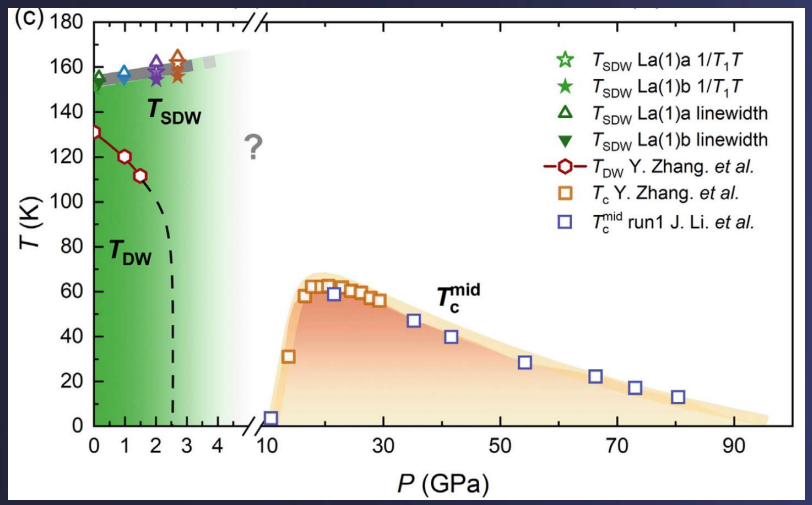
Yanbing Zhou *et al.*, Phys. Rev. X (under review)

Dan Zhao *et al.*, Phys. Rev. Lett. **126**, 197001 (2021)

中科大陈仙辉团队

镍基超导相图研究

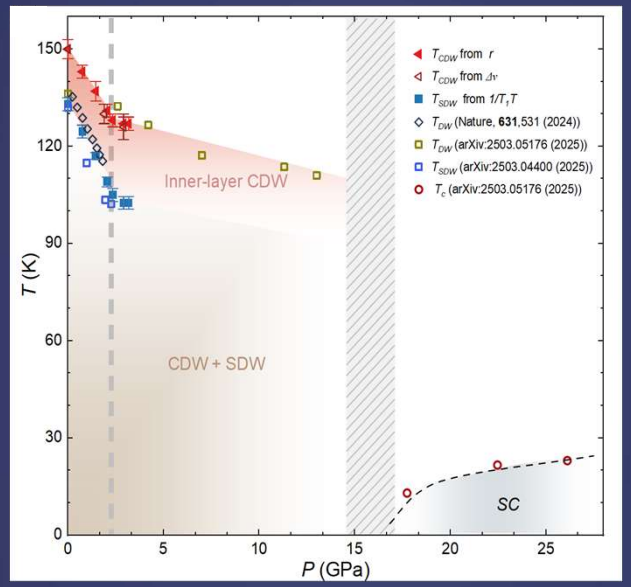
La-327



Dan Zhao *et al.*, Sci. Bull. **70** 1239 (2025)

Mengzhu Shi *et al.*, Nat. Commun. **16**, 9141 (2025)

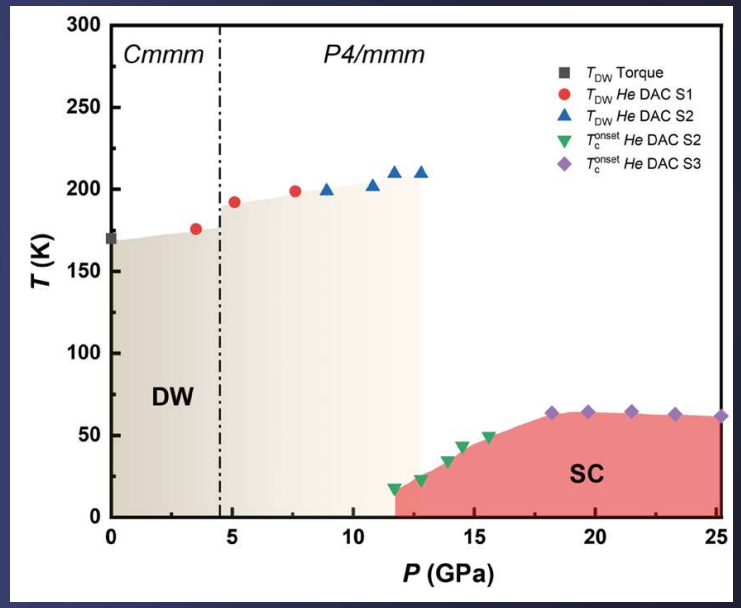
La-4310



Y. Wang *et al.*, Nat. Commun. (Under review)

Mengzhu Shi *et al.*, Nat. Commun. **16**, 2887 (2025)

La-5311



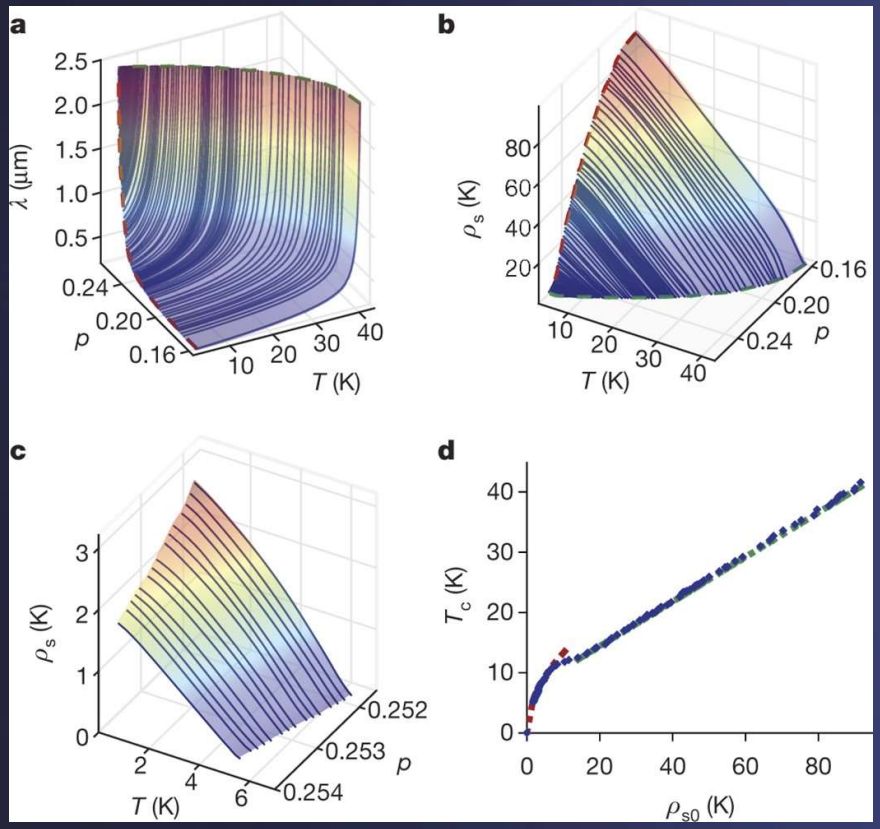
Mengzhu Shi *et al.*, Nat. Phys. 21, 1780–1786 (2025)

相图研究表明：磁性相互作用与压力诱导的超导电性有关联性

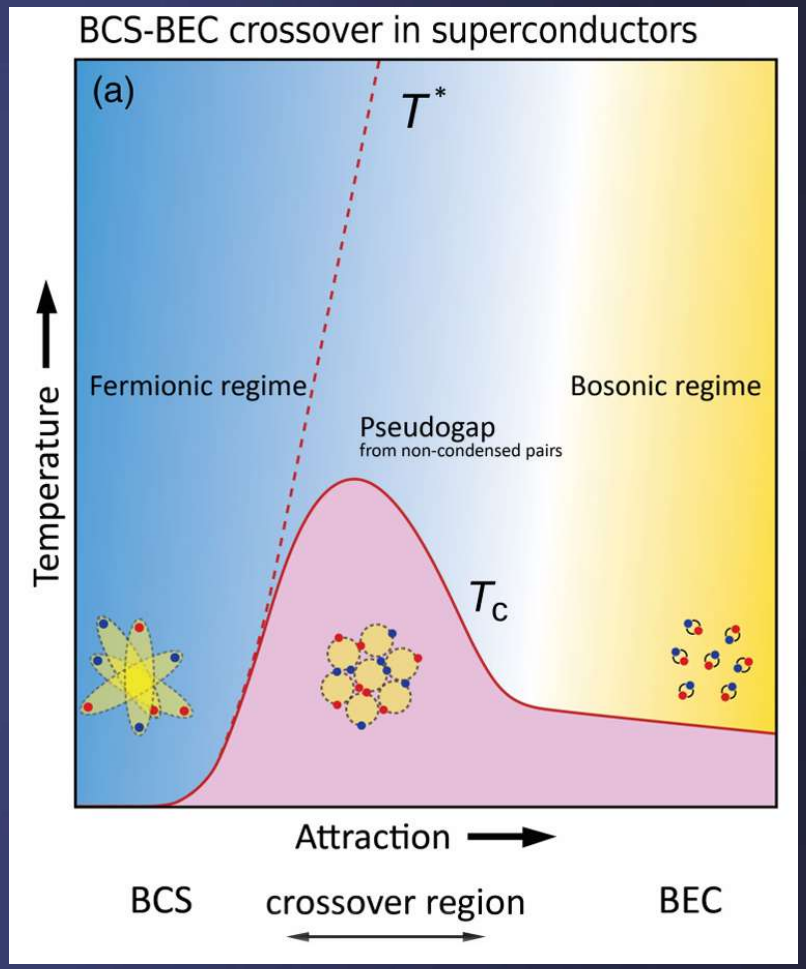
中科大陈仙辉团队

高温超导体中的超导凝聚

超流密度决定超导转变温度

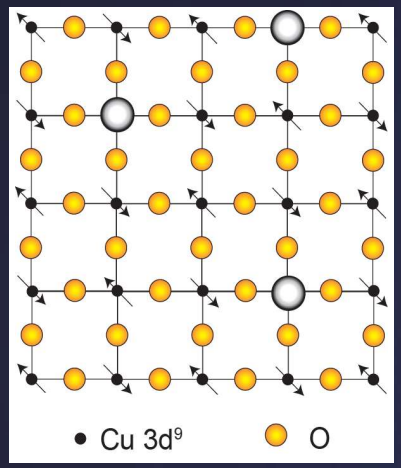


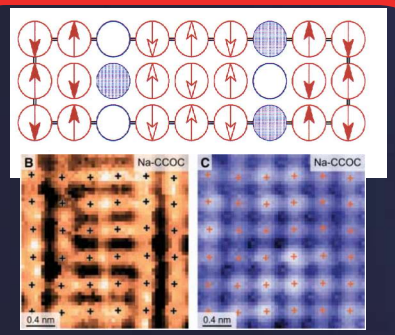
I. Bozovic et al., Nature **536**, 309–311 (2016)



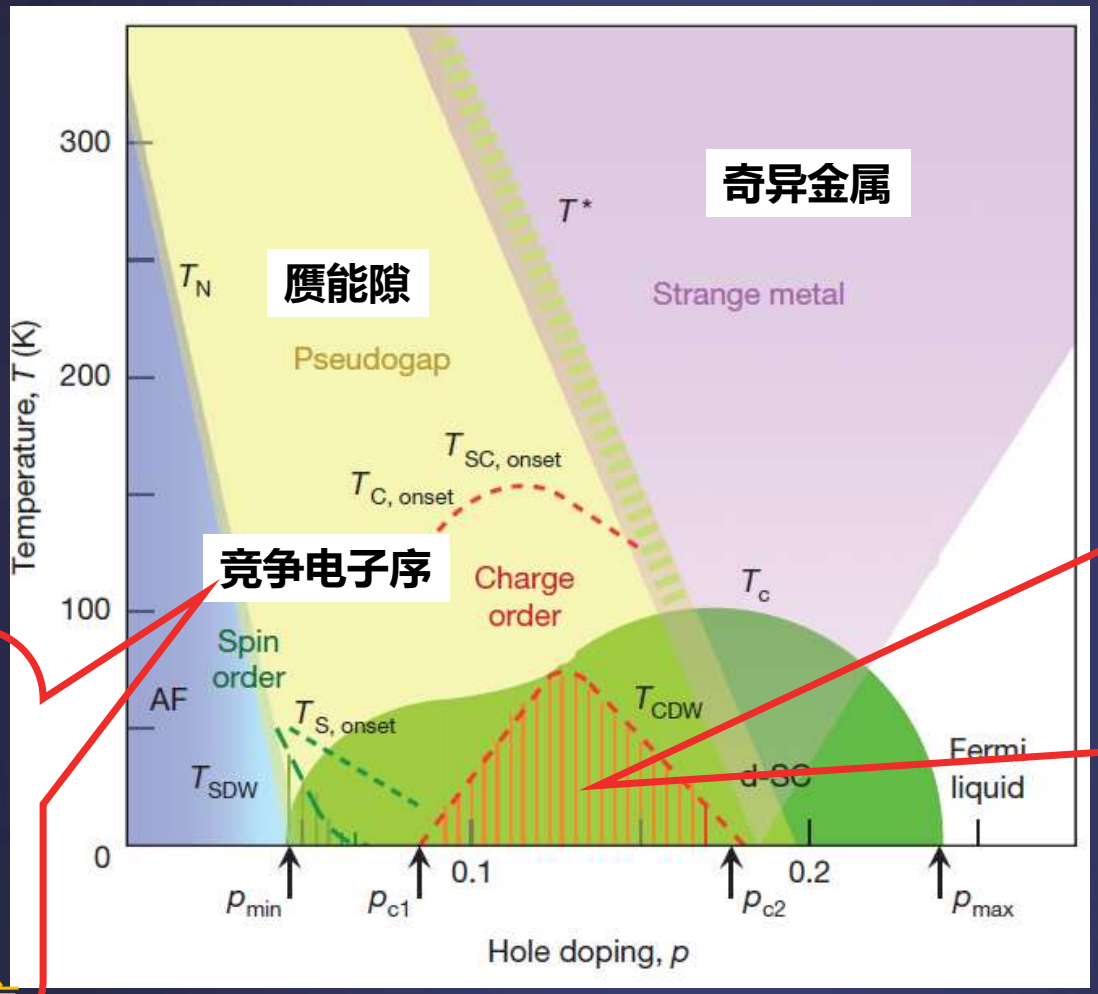
Q. Chen et al., Rev. Mod. Phys. **96**, 025002 (2024)

高温超导体中的演生物态

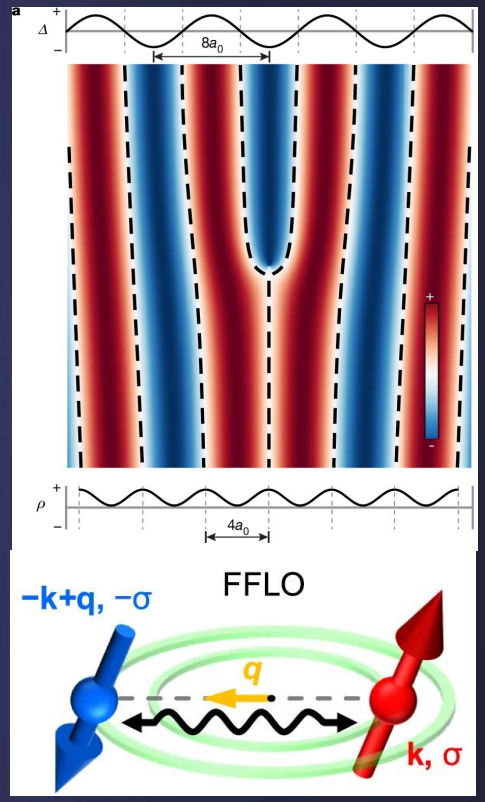




条纹序：自旋序+电荷序



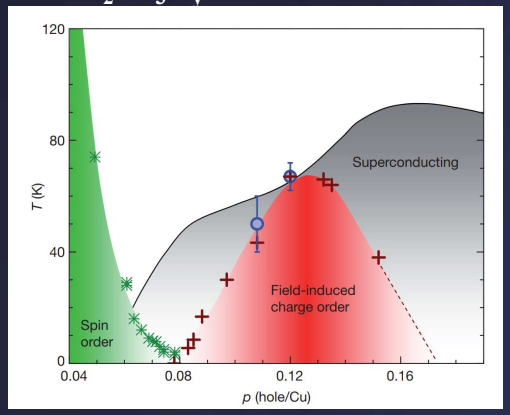
B. Keimer *et al.*, Nature **518**, 179 (2015)



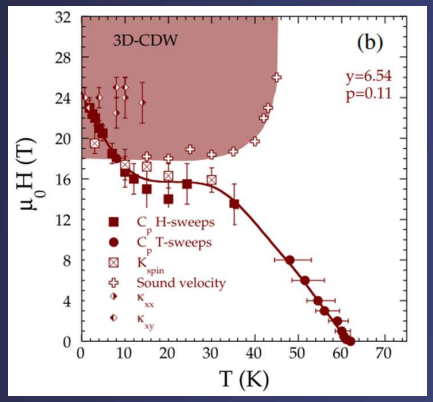
配对密度波：超导序+电荷序

高温超导体中的演生物态

$YBa_2Cu_3O_y$

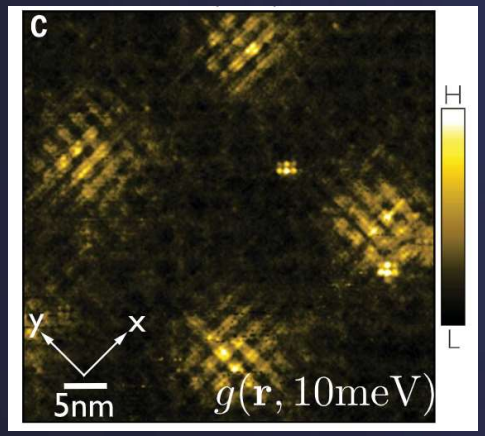


T. Wu *et al.*, Nature **477**, 191–194 (2011).

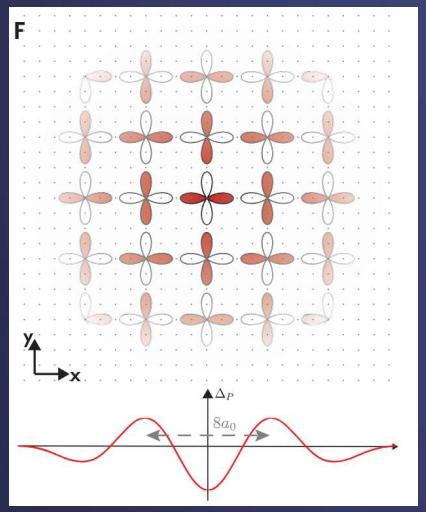


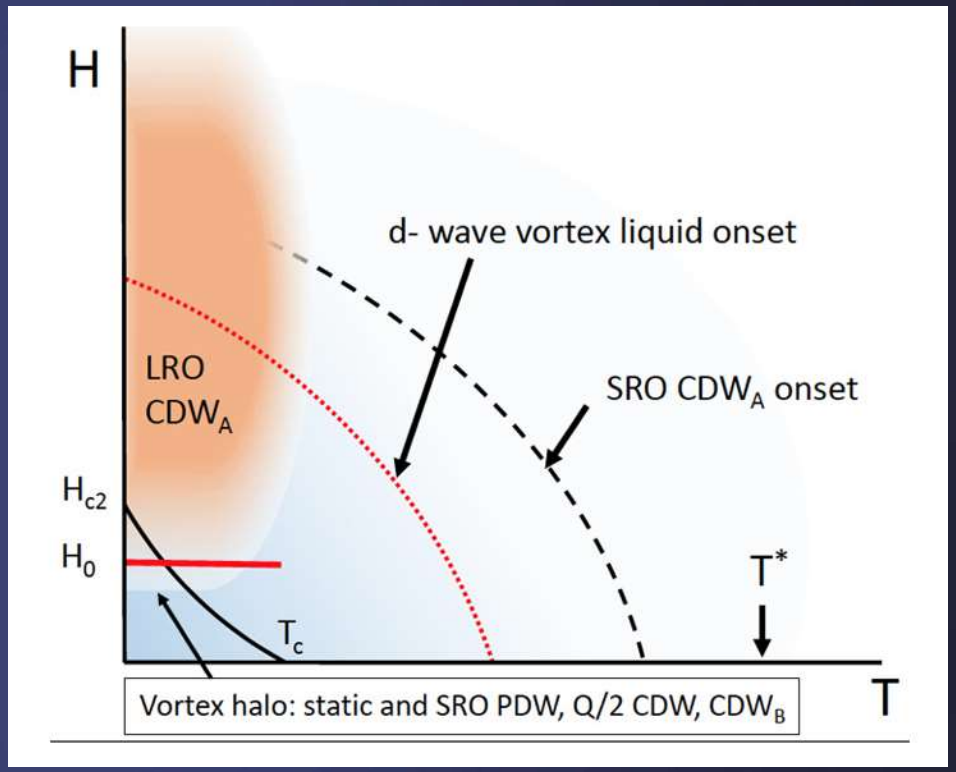
J. Kačmarčík *et al.*, Phys. Rev. Lett. **121**, 167002 (2018)

Bi2212



E. D. Edkins *et al.*, Science **364**, 976-980 (2019)



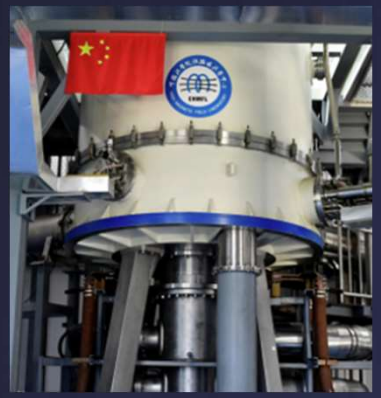


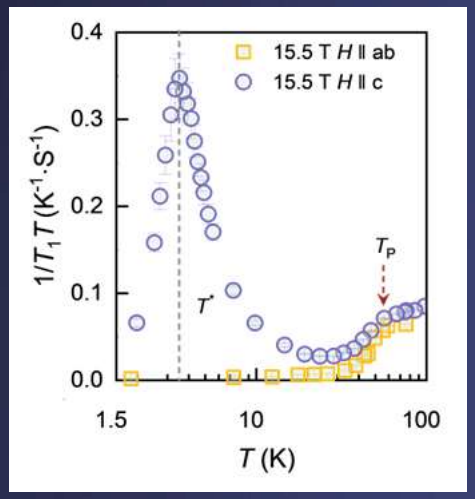
P. A. Lee, Phys. Rev. X **4**, 031017 (2014)

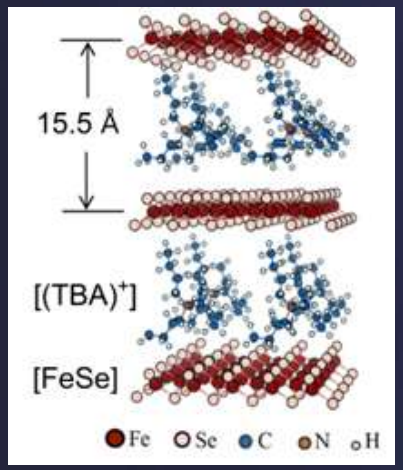
Z. Dai *et al.*, Phys. Rev. B **97**, 174511 (2018)

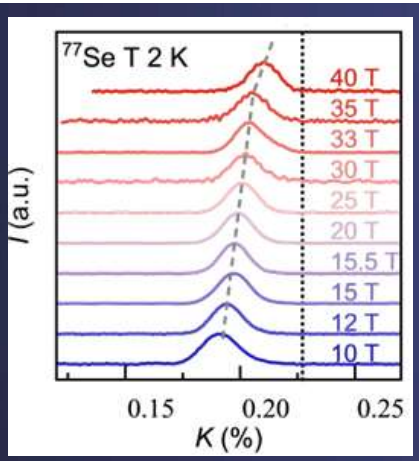
- **配对密度波态为理解赝能隙提供了一个新的可能**

高温超导体中的演生物态



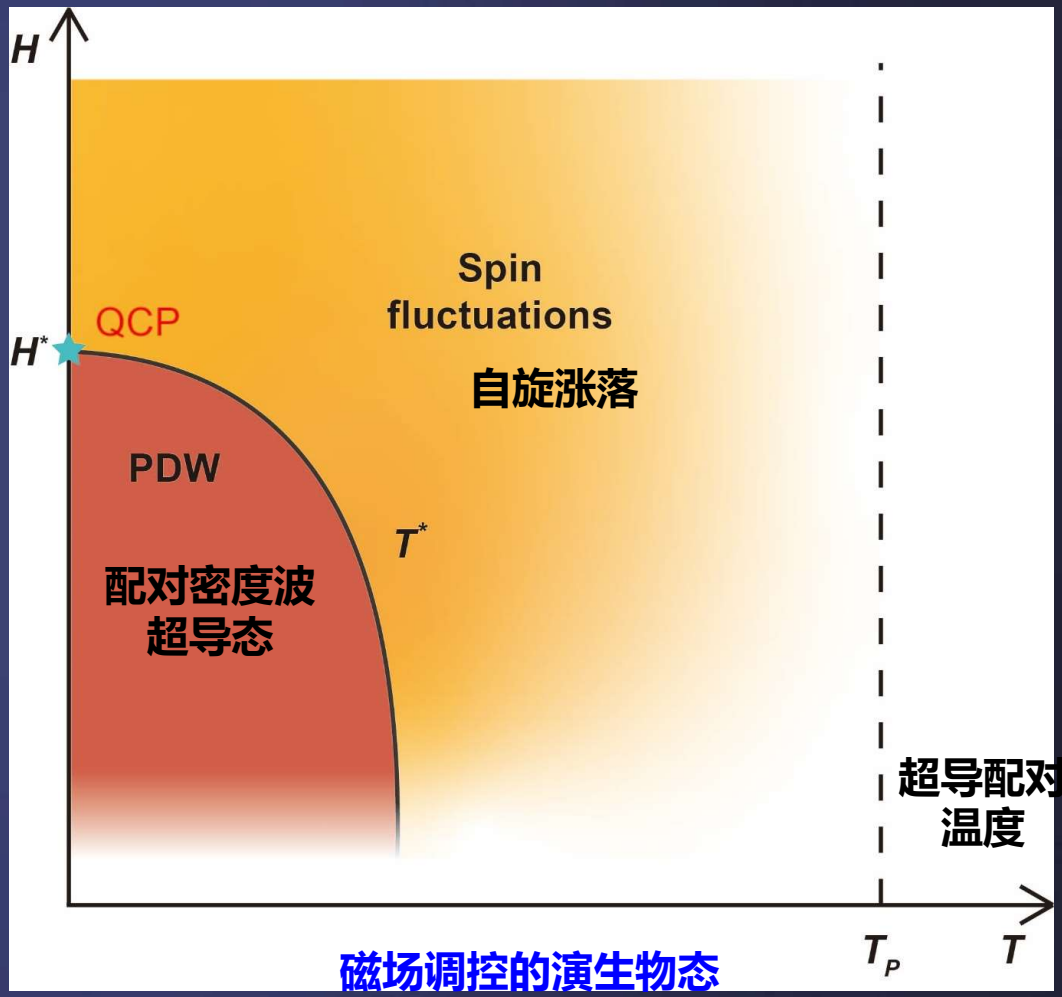






合肥强磁场中心 + 怀柔极端条件平台

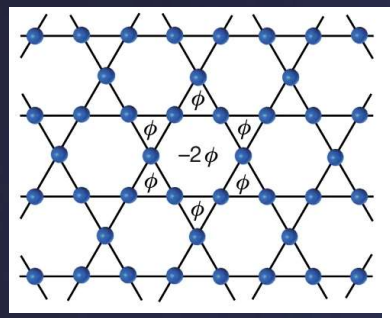
铁基高温超导体

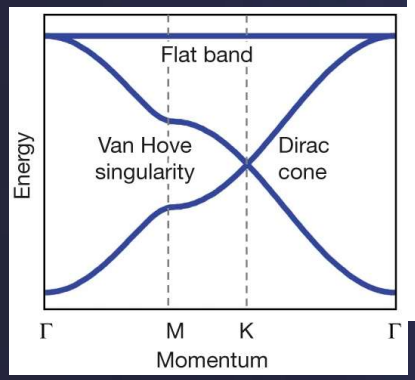


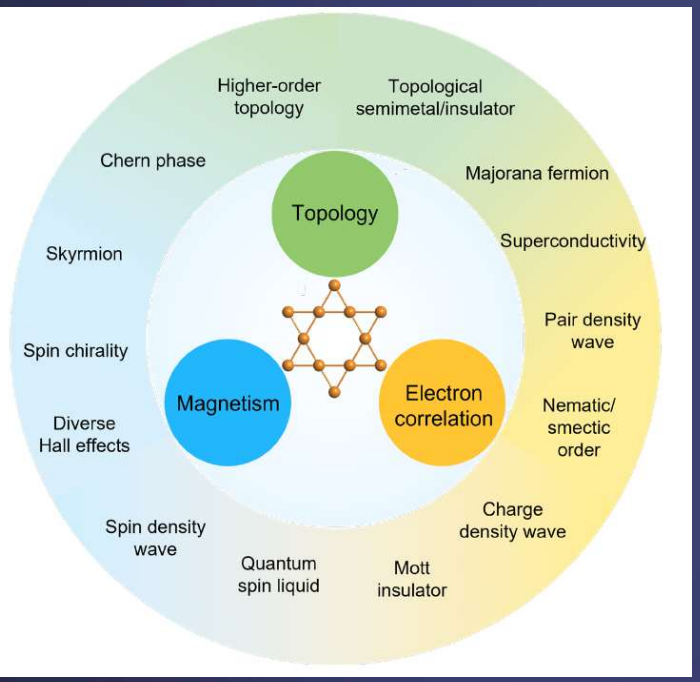
磁场调控的演生物态

笼目超导体中的演生物态

二维笼目晶格

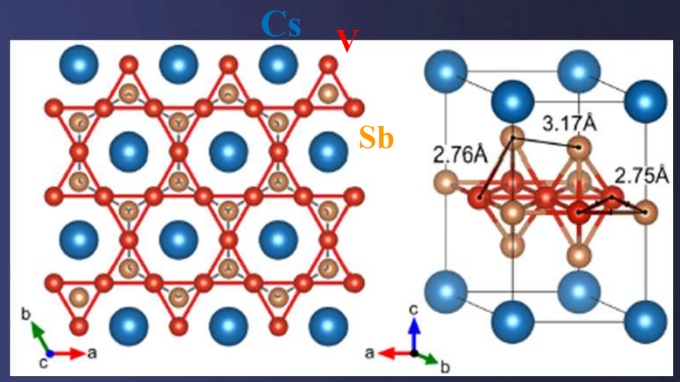






Mazhar N. Ali et al., Nat. Rev. Phys. **5**, 635–658 (2023)

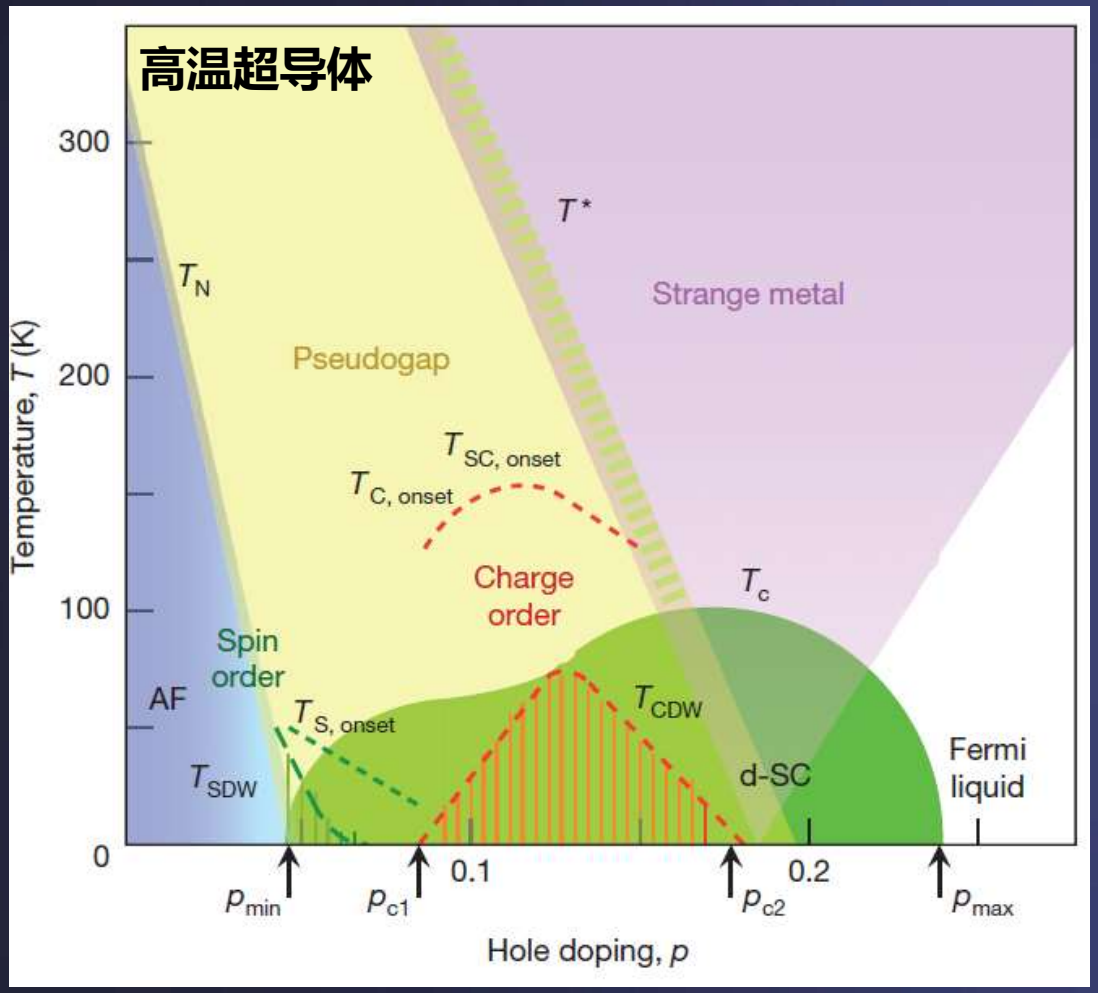
a 2D Kagome lattice of V atoms



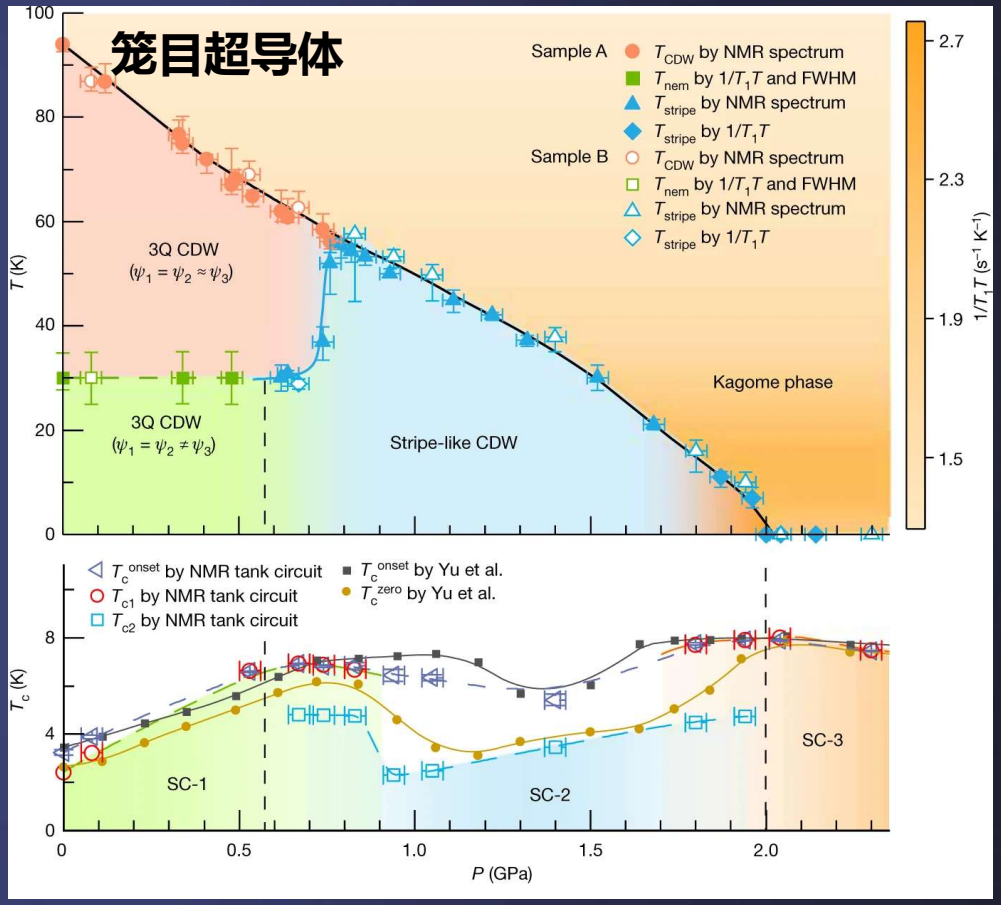
	c	T_c	T_{CDW}
CsV_3Sb_5	9.31 Å	2.5 K	94 K
RbV_3Sb_5	9.07 Å	0.75 K	103 K
KV_3Sb_5	8.95 Å	0.93 K	78 K

B. R. Ortiz et al., Phys. Rev. Mater. **3**, 094407 (2019)
B. R. Ortiz et al., Phys. Rev. Lett. **125**, 247002 (2020)
B. R. Ortiz et al., Phys. Rev. Mater. 5, 034801 (2021)
Q. Yin et al., Chin. Phys. Lett. **38**, 037403 (2021)

笼目超导体中的演生物态



B. Keimer *et al.*, Nature **518**, 179 (2015)



L. X. Zheng *et al.*, Nature **611**, 682–687 (2022)

L. P. Nie *et al.*, Nature **604**, 59-64 (2022)

中国科学院学部“室温超导”科学与技术前沿论坛
2023.6 中国黄山黟县

高温超导材料研究的机遇与挑战

Bernd Matthias rules

1. high symmetry is good, cubic symmetry is the best
2. high density of electronic states is good
3. stay away from oxygen
4. stay away from magnetism
5. stay away from insulators
6. stay away from theorists.

Wish Garden rules

1. black is good (要够黑)
2. metalizing sigma-bonding is good
3. proximity to a critical instability is good
4. light element and 3d are good
5. high pressure is good
6. stay harmony with theorists

高温超导材料研究的机遇与挑战

面向国家战略：探索“好用的”超导材料

常压室温超导材料

Room-temperature Superconductors

It is a big potato

Experiment + Theory

“坚持十年，会有重大的成就”

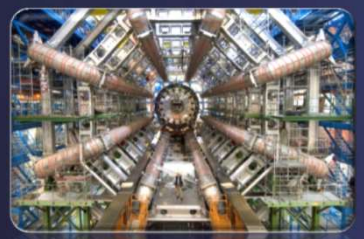
--- 赵忠贤 院士

• 超导体用武之地

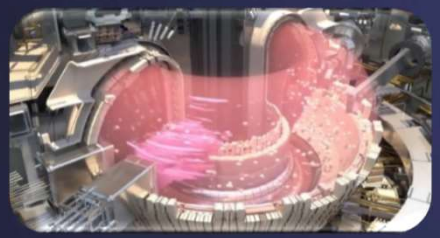
强电应用

核磁共振成像仪

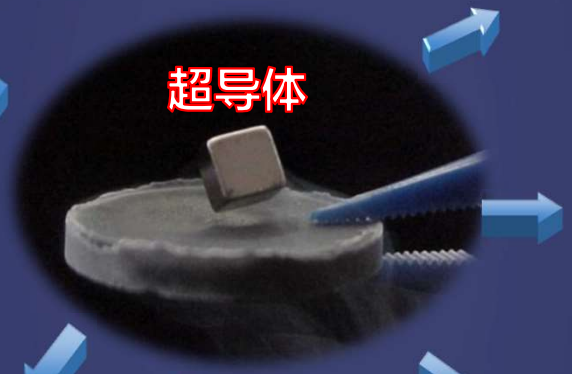
大型强子对撞机上的超导磁体



可控核聚变



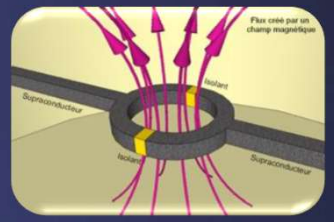
在能源、信息等领域带来深刻变革的战略级科技



超导电缆

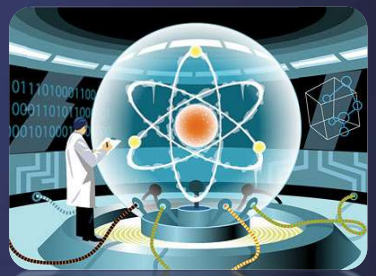
超导磁悬浮列车

SQUID



超导量子比特

超导量子计算机



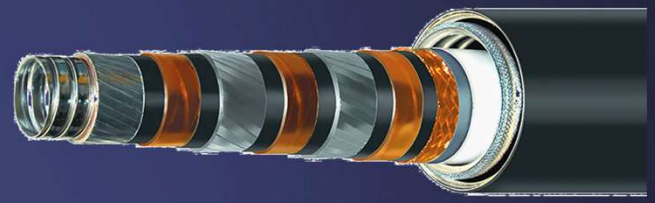
弱电应用

超导强电应用

与能源有关方面

- 电力工业的一个革命性的技术储备
- 粒子加速器
- 磁约束受控核聚变

……



交通

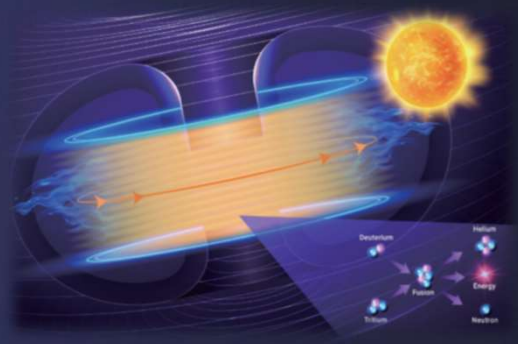
- 新一代的舰船推动系统的基础
- 超导磁悬浮列车

……

生物医学

- 医用核磁共振成像系统
- 高分辨率核磁共振超导磁体

……



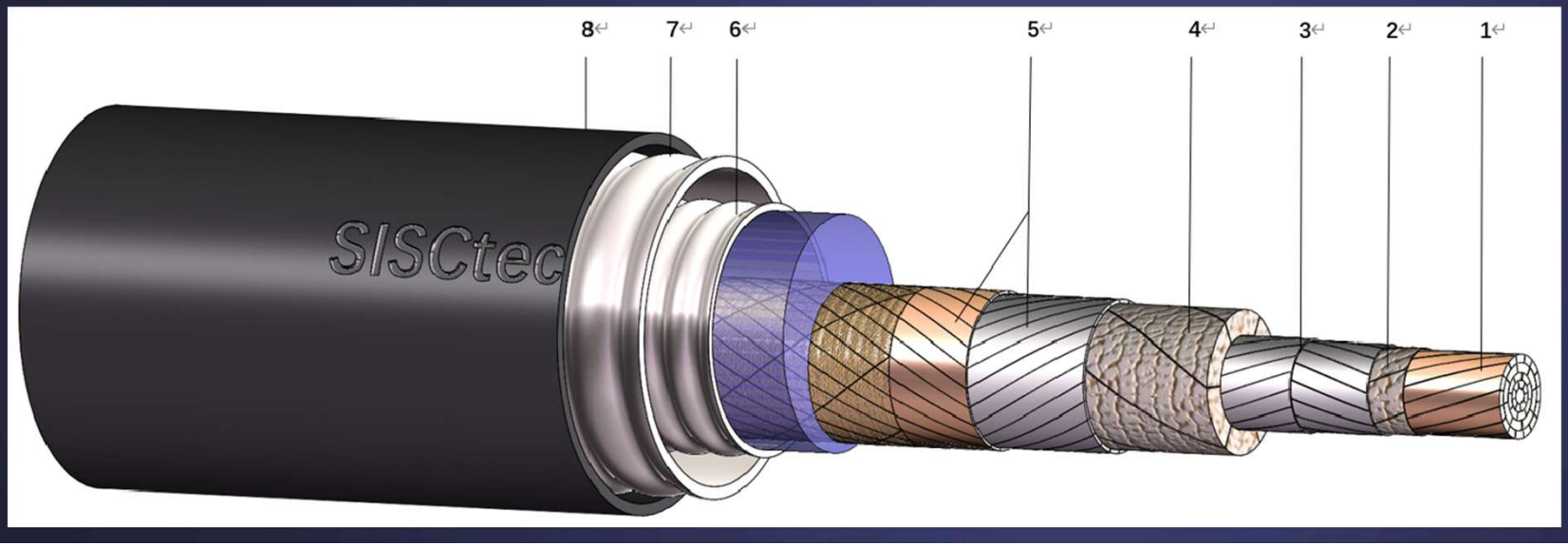
• 超导输电技术：高温超导电缆

上海国际超导科技公司

上海超导电缆：
- 三芯一体结构，35kV/2.2kA
- 连接上海徐家汇漕溪站和长春站；
- 用于替换220 kV线路；
- 国内首条公里级超导电缆，长度为1.2 km；

超导通电导体生产线

低温管道连续成型生产线

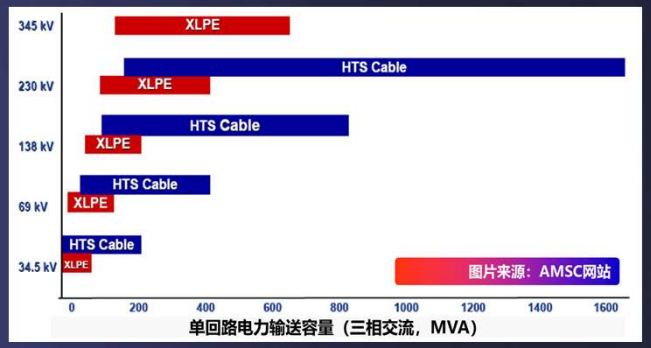


1.衬心；
2.隔层；
3.超导导体；
4.绝缘；
5.屏蔽层；
6.内波纹管；
7.外波纹管；
8.外护套

• 高温超导电缆战略布局

低损耗电力传输

- 中国的新能源主要分布在西部、北部和西北部，远距离输电损耗巨大
- 2022年我国用电量86369亿度电，输电损耗4145亿度电 (线损率4.82%)，经济损失高达~2000亿元 (数据来源：中国电力企业联合会数据)
- **超导电缆的输送容量与高2-3个电压等级常规电力电缆输送容量相当**

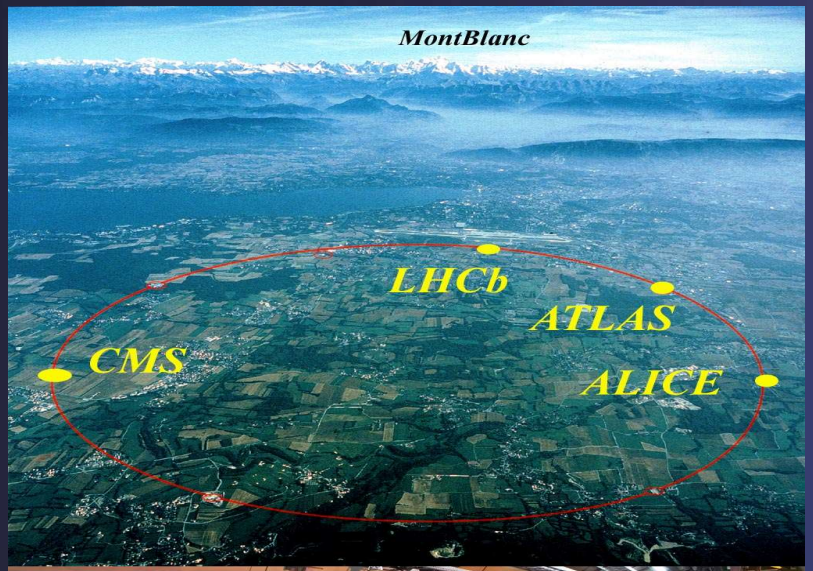


高温超导电缆是低损耗、大容量、长距离电力输送的变革性技术

- ✓ 2021年9月，我国首条自主研制的三相同轴超导电缆在深圳投入使用，是全球首个应用于超大型城市中心区的超导电缆 (**400m-10kV/2.8kA**)
- ✓ 2021年12月，国际首条**35千伏公里级高温超导电缆**示范工程在上海投入运行，是目前世界上输送容量最大、线路最长、全商业化运行的35千伏高温超导电缆。(**1.2km-35kV**)

短距离、大容量、特殊应用场景

• 超导磁体是高能量粒子加速器的关键

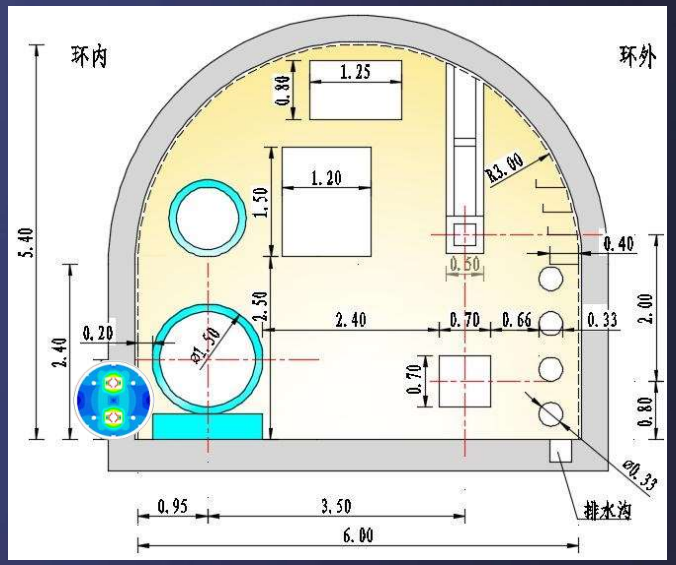


- 欧洲核子研究中心（CERN）建造的大型强子对撞机(LHC)采用了1734个大型超导磁体；超导谐振腔（电子加速）
- LHC使用了1200吨超导线；130吨液氦提供磁体低温环境。
- 2012年上帝粒子发现后，
  - 中国提出环形正负电子对撞机-高能质子对撞机（CEPC-SPPC）
  - 欧洲提出未来环形对撞机（FCC）

急需解决高场技术问题

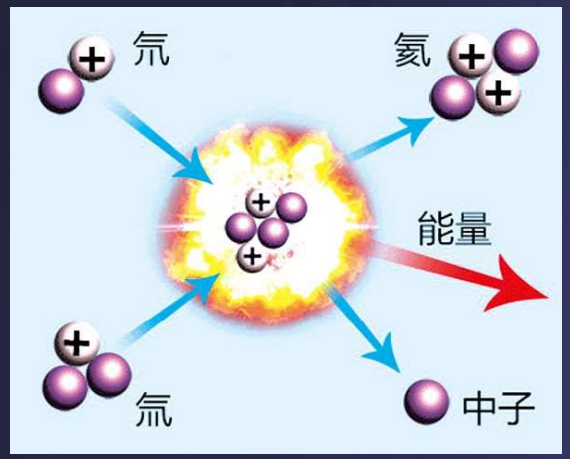
• 超导粒子加速器

SPPC或FCC需数千个高场超导磁体



SPPC隧道截面布局

• 全超导可控核聚变

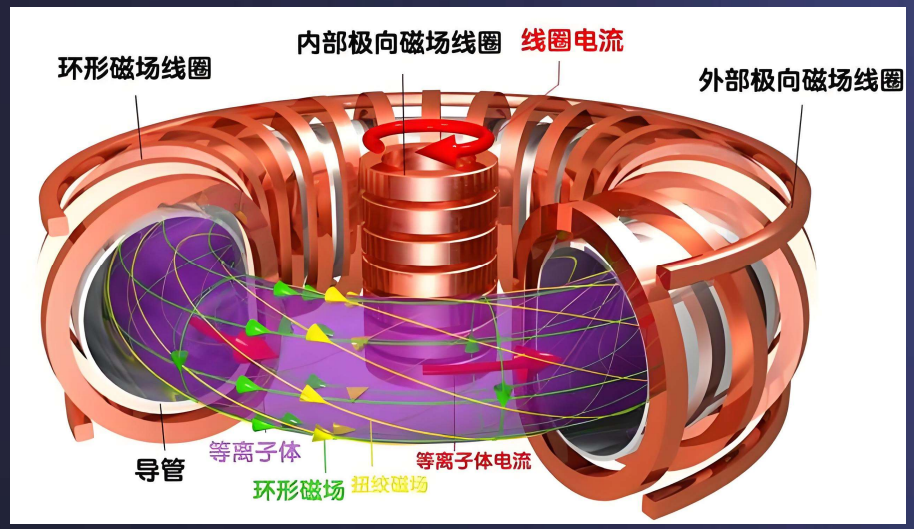


受控热核聚变是解决能源的最有效手段之一

- 温度>1亿度；磁约束是最有效的手段之一
- 需要强磁场 (11 T)；超导磁体不可缺少

•未来聚变堆运行环境：

高磁场：15 T ：大电流：100 kA；大尺寸：10 m



高场优势：

- ☐ 提高聚变功率($\propto B^4$)
- ☐ 增强等离子体约束能力
- ☐ 减小规模，提高经济性

磁场升高 ↑ 发电成本 ↓

装置名称	ITER	EU-DEMO	CFETR
国家	国际	欧盟	中国
最高场 （T）	10.8	~13.5	~15

磁体系统是聚变堆的核心，超导占成本37%

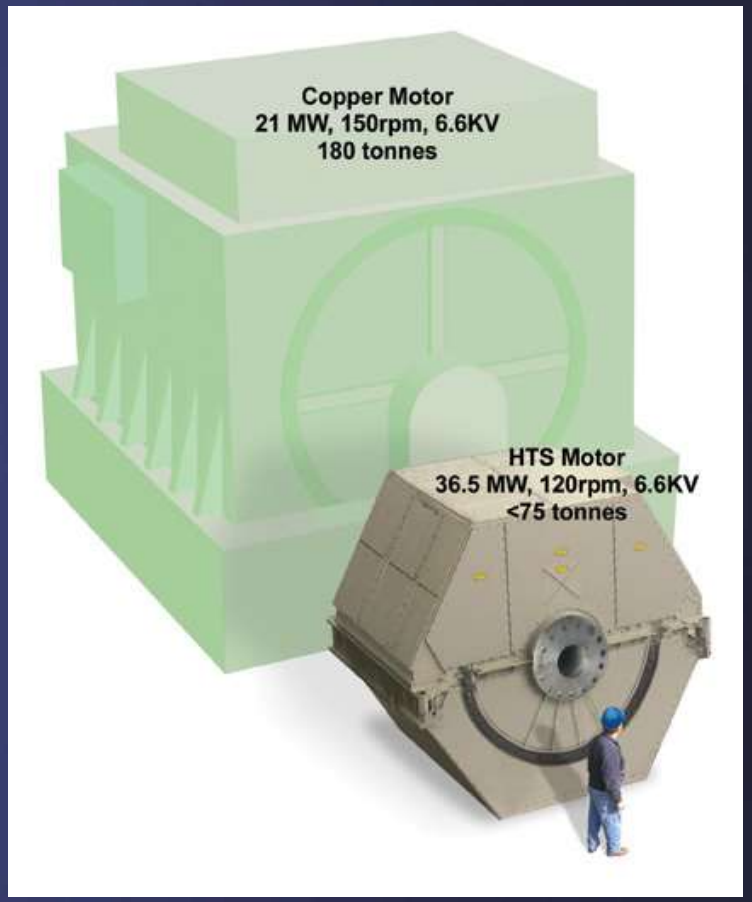
• 超导船舶推进电机

电推进是目前舰船推进的主要方式

超导电机的优点：

- 更高效率
- 体积小
- 重量轻
- 噪声小

36.5MW舰船推进实验电机



铜线圈和超导线圈电机的尺寸的比较

• 超导磁体应用于高速磁悬浮列车

高温超导是实现高速磁悬浮交通的主要途径之一

- 2023年中国高铁运营里程~4.5万公里，最高时速达~350公里，世界领先
- 2019年国务院印发《交通强国建设纲要》，明确提到合理统筹安排**时速600公里级高速磁悬浮系统…等技术储备研发。**
- **超导磁悬浮列车时速可达600公里**，欧美日加速研发，正向技术实用化、低成本方向发展

2014

时速500公里的超导磁悬浮开建，27年开通东京至名古屋区间（286公里），2045年延至大阪。

2015

低温超导磁悬浮试验线-山梨线(42.8km），创造载人时速603公里世界纪录。

2021

自研设计、制造的世界首台高温超导高速磁浮工程化样车及试验线启用@成都。

2023

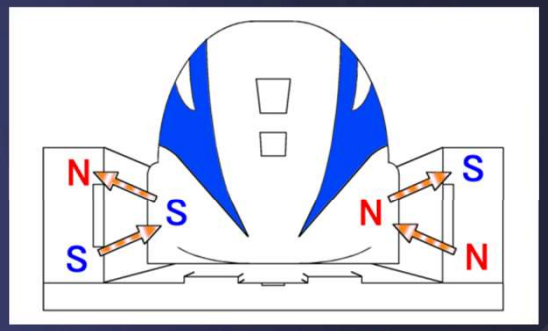
航天科工三院完成了商业航天电磁发射高温超导电动悬浮航行试验，在380米线路实现234公里/小时国内最高速度纪录。

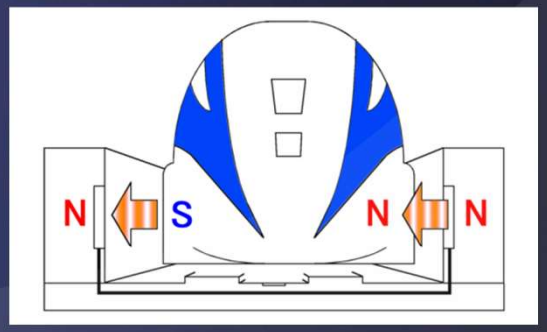
日本正研制高温超导磁浮列车

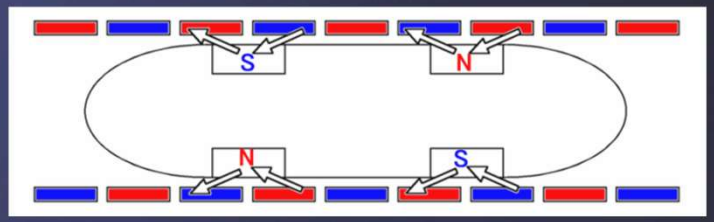
• 超导磁体应用于高速磁悬浮列车

西南交通大学：高温超导磁悬浮样车

超导磁悬浮列车的磁悬浮原理





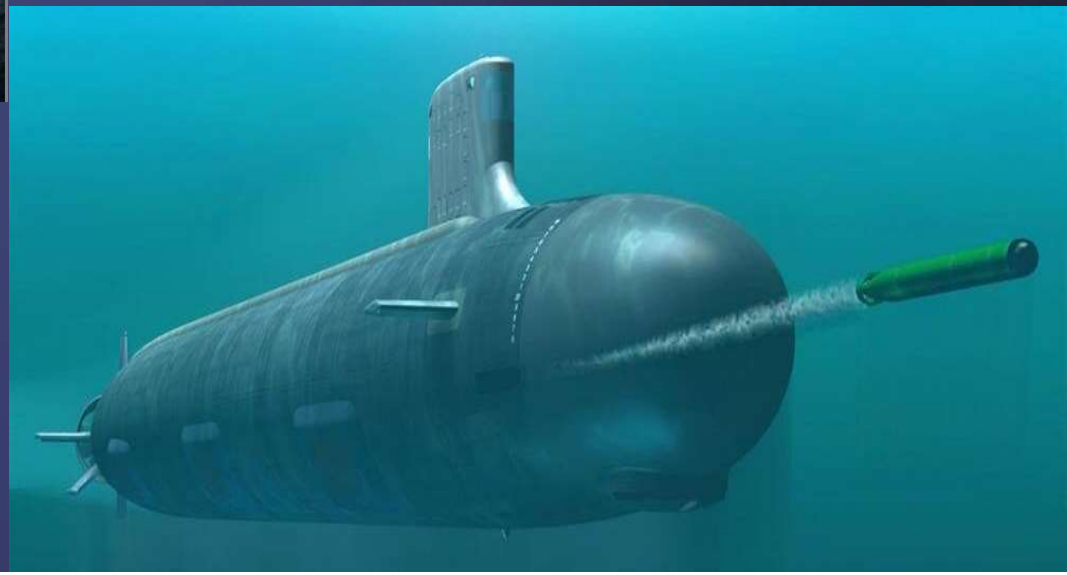


- **军事应用**

超导核潜艇

利用超导推进电机

低噪音、高效、 体积小、 重量轻

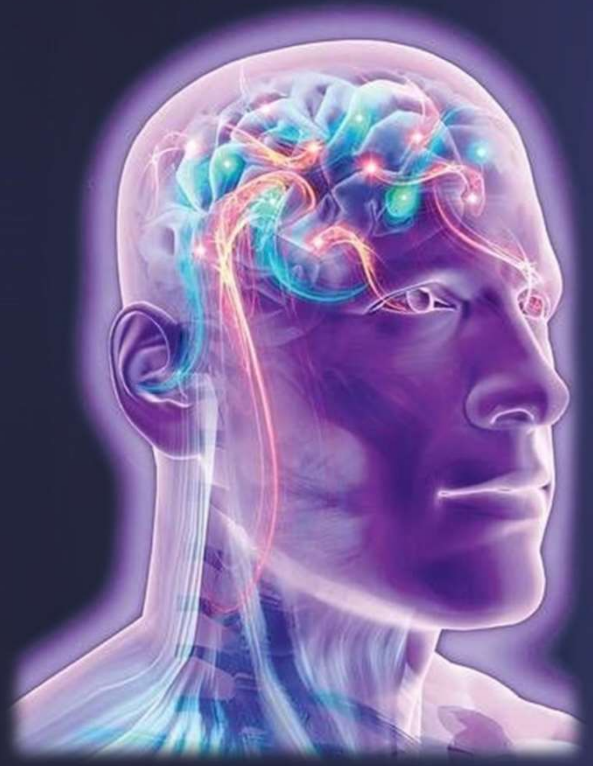


超导电磁弹射

大幅提升载荷能力和任务执行效率

• 高场磁共振成像磁体

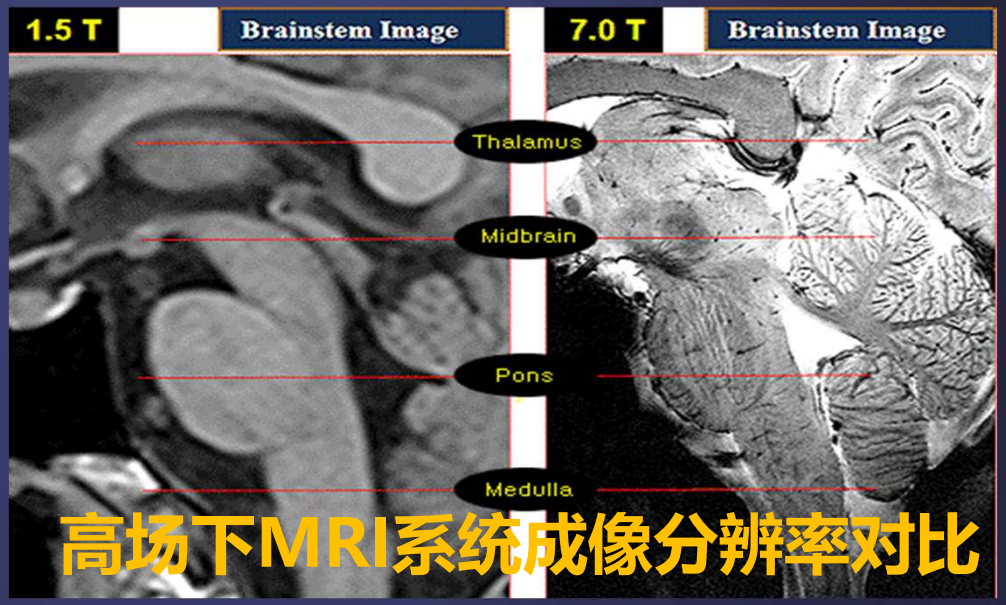
脑科学研究及疾病诊断



超导核磁共振功能成像

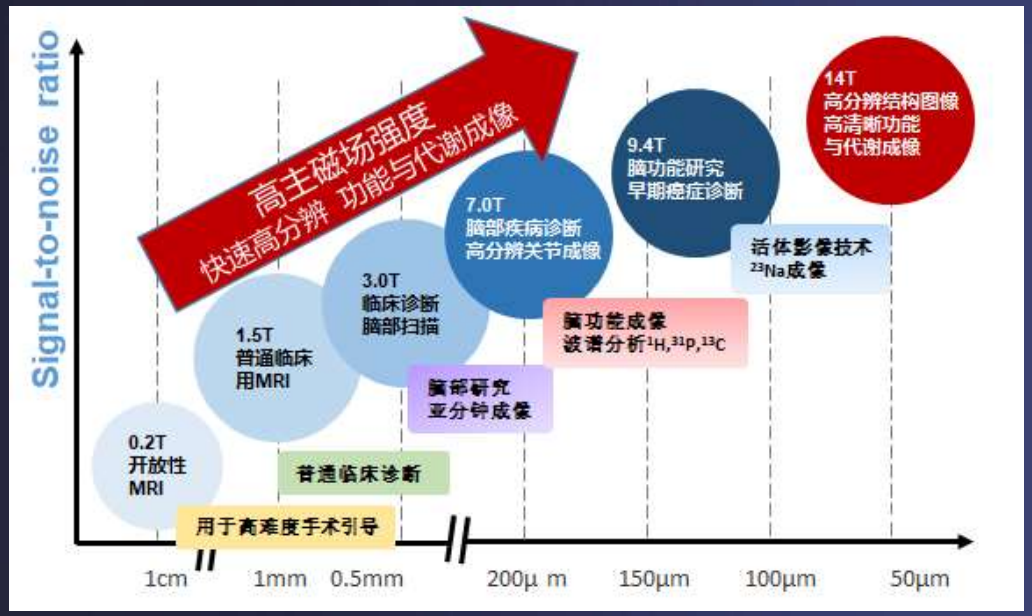
- 超高场MRI系统分辨率高，在脑科学研究、早期脑部疾病、早期心脏疾病、早期癌症诊断方面，有着十分重要的应用。
- 国内在高场MRI研究领域处于起步阶段。

高场强 → 高信噪（SNR） → 高分辨率



高场下MRI系统成像分辨率对比

• 高场磁共振成像磁体



设计目标

- □中心场：14 Tesla
- □室温孔径：65 cm
- □中心球形成像区域磁场不均匀度：$<10^{-6}$
- □高场磁体关键技术突破

美国、法国、韩国等国家计划装备10.5 T，11.7 T和14 T的更高的场系统，处于规划阶段。我国相关计划正在开展中。

• 超导弱电应用

精密仪器

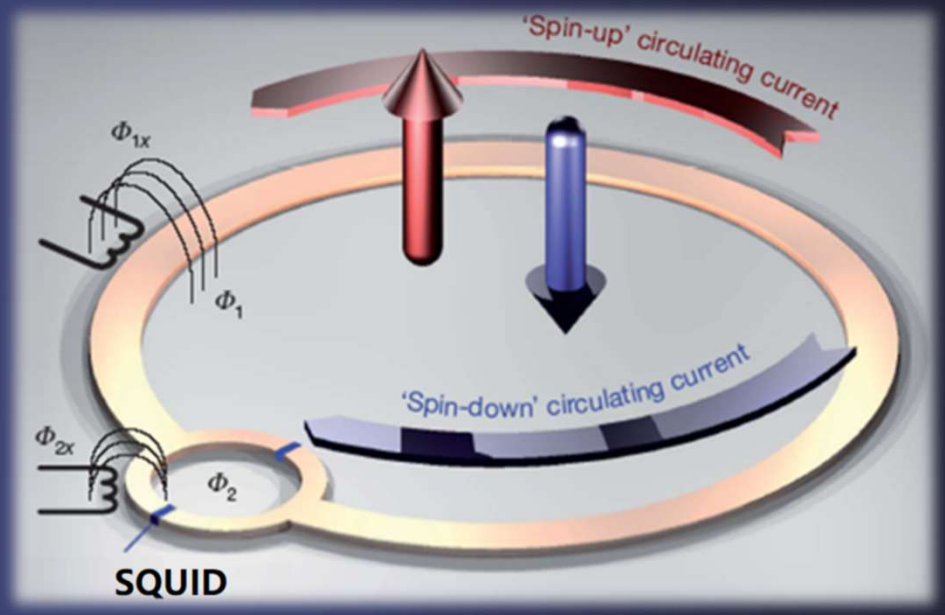
- 超导量子干涉仪（SQUID）
- 超导隧道结电压基准
- 超导单光子探测器
- 超导太赫兹探测

……

信息科学

- 超导滤波器
- 超导量子计算

……



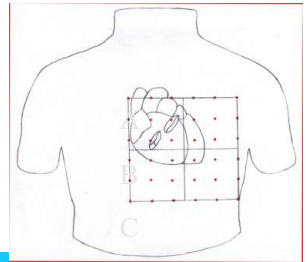
能够检测出相当于地球磁场的几十亿分之一的变化，其灵敏度理论上只受量子力学测不准原理的限制。

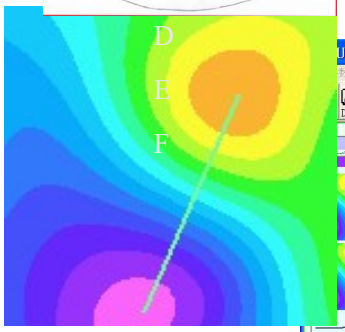
• 超导量子干涉仪（SQUID）

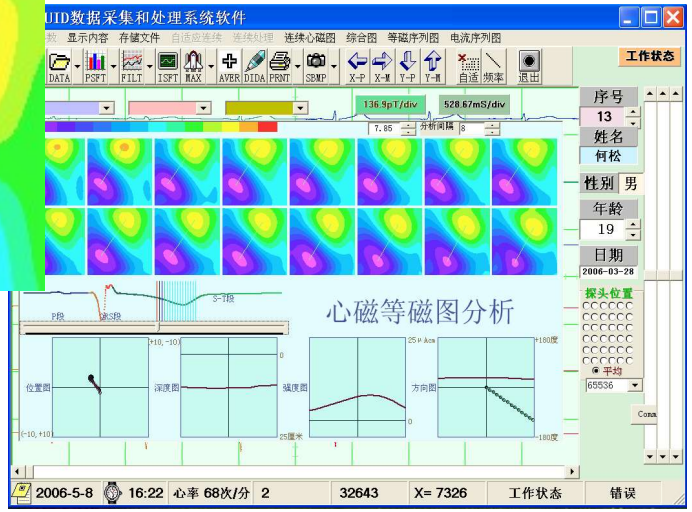
SQUID测量心磁图、脑磁图

无创、无接触、快速
比电测量信息多

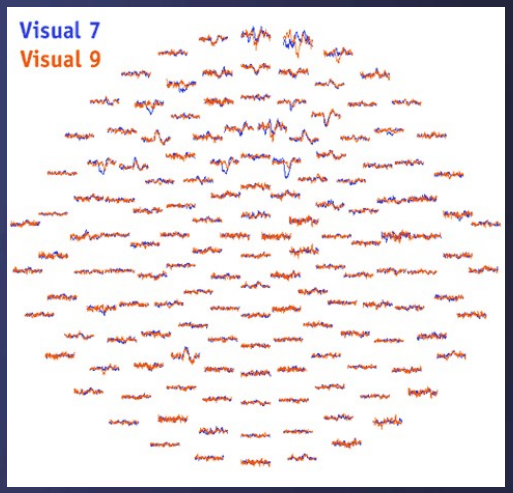
心磁、脑磁信号非常微弱，SQUID必不可少！







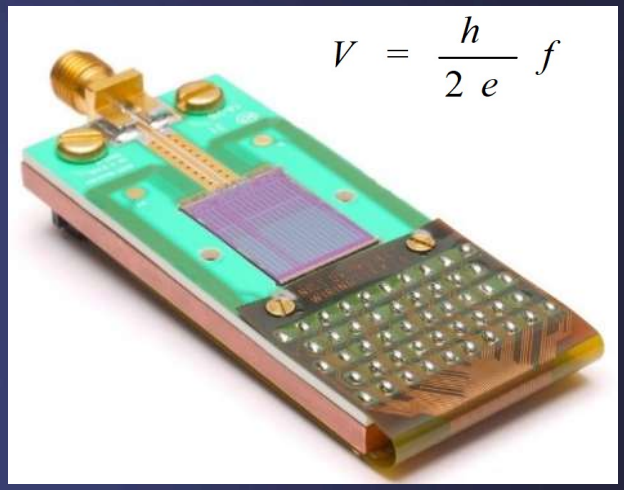
中科院物理所与中日友好医院心磁图实验结果



• 约瑟夫森超导隧道结电压基准

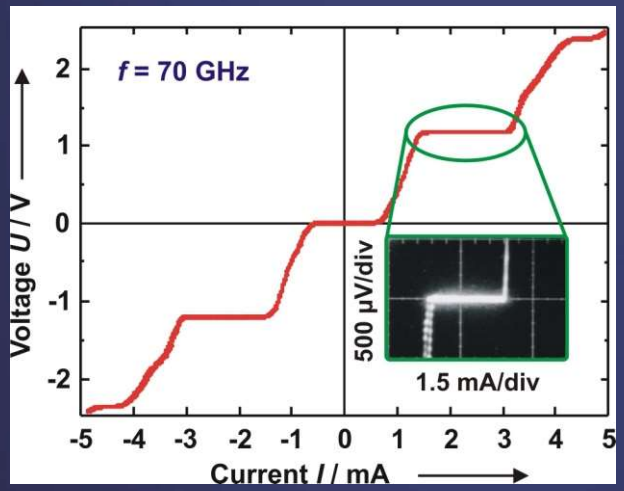
约瑟夫森超导隧道结电压基准
已经代替了化学电池电压基准

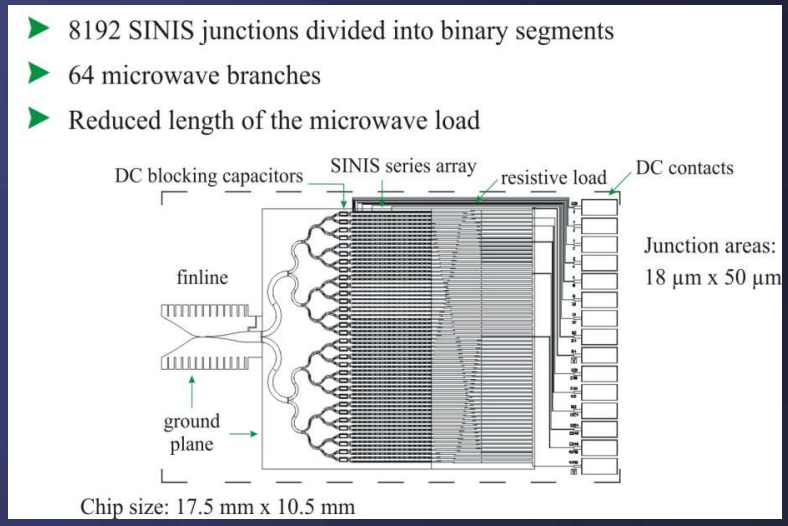
电压标准 $V=\frac{h}{2e}f$



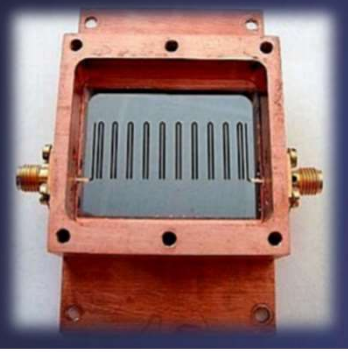
交流电压标准

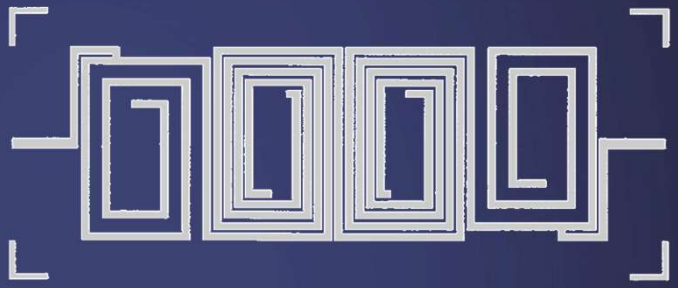
- 与材料性质无关
- 环境条件(如温度，磁场)无关
- 与结的类型无关
- 高精度 $<10^{-9}$ (3×10^{-19})

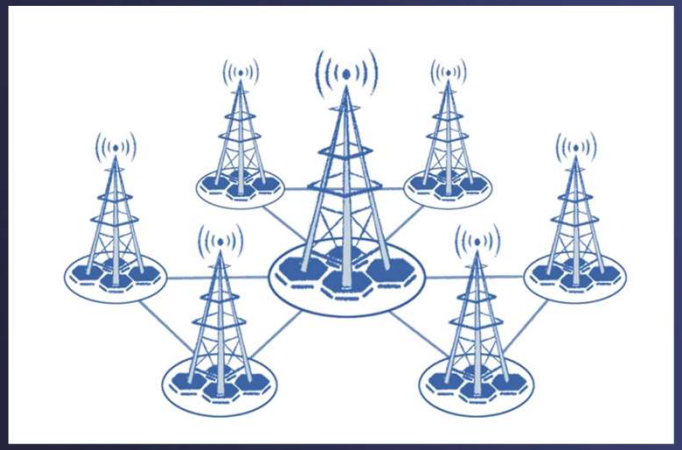


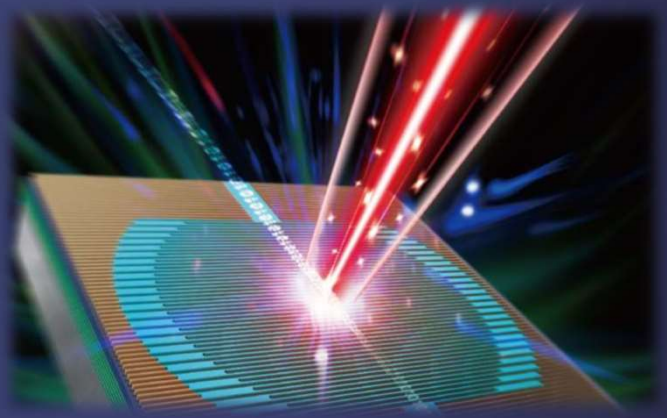


- **超导滤波器**





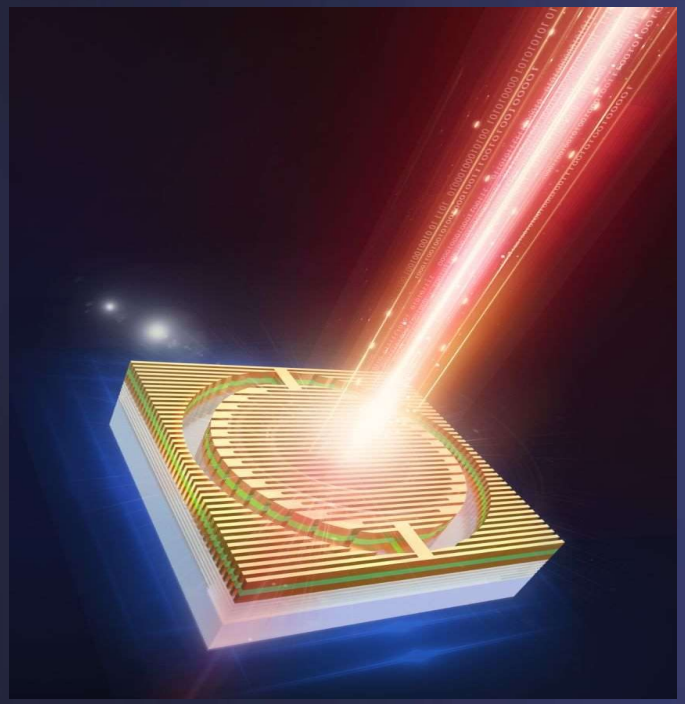




超导滤波器在移动信号基站的使用，大大提高了移动信号的品质。

• 超导单光子探测器

超导纳米线单光子探测器



实现量子极限灵敏度探测

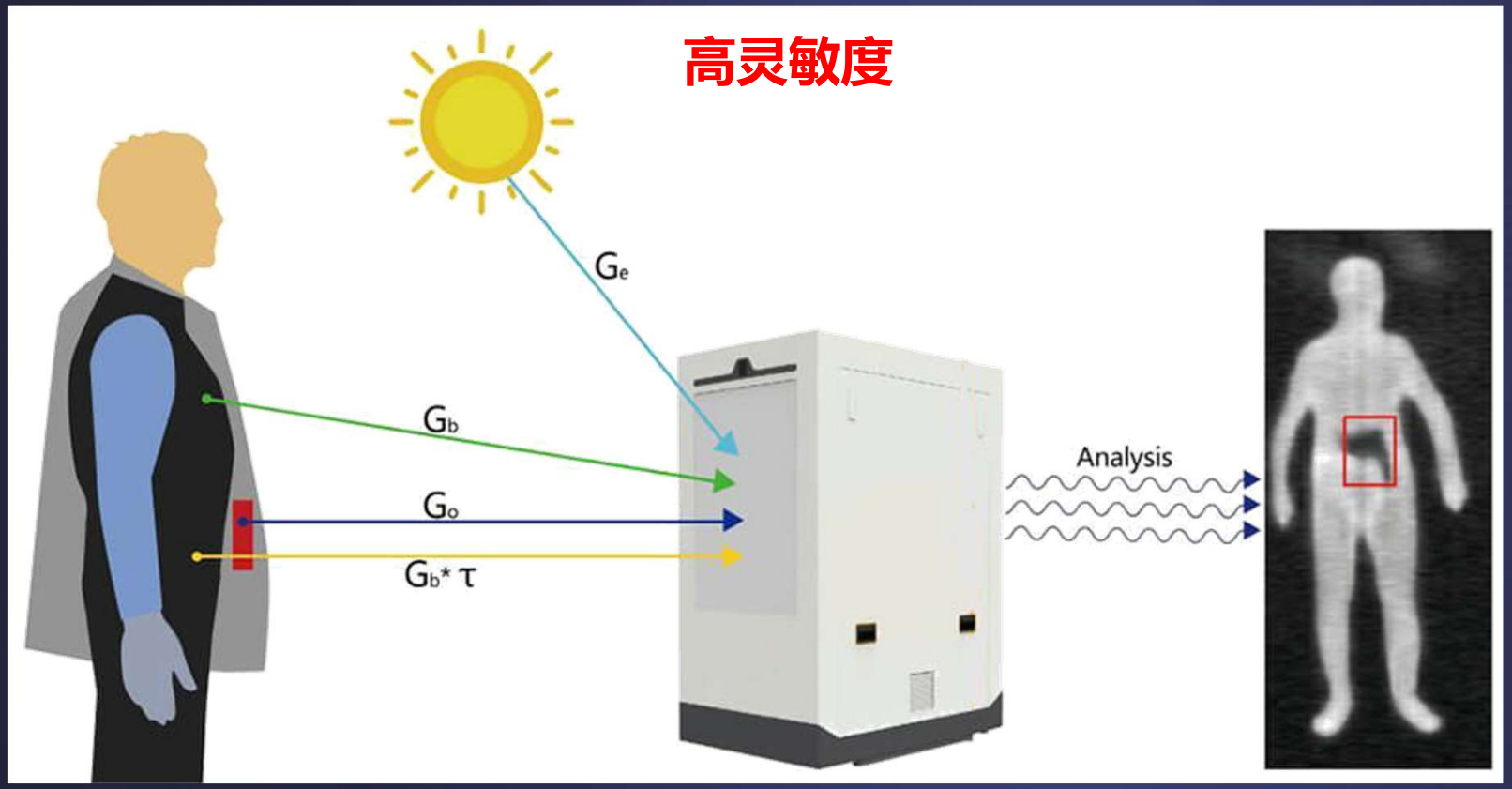
高探测效率、低暗计数等优异性能

超导单光子探测与量子通讯

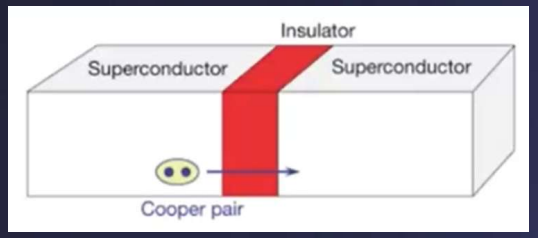
实现远距离量子通讯的“秘密武器”

• 超导太赫兹探测

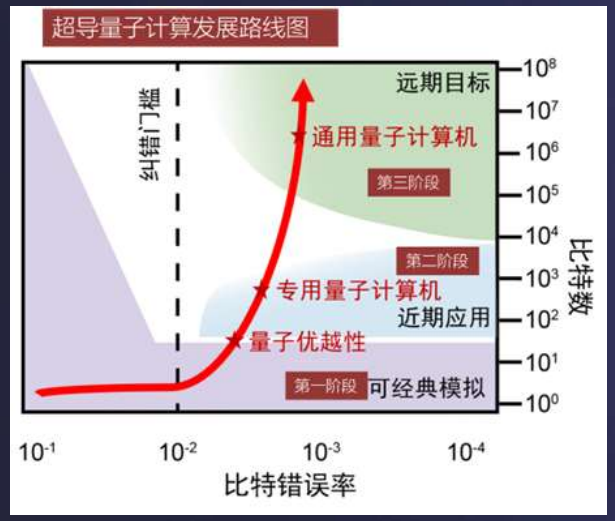
太赫兹探测技术的核心是“超导探测器”



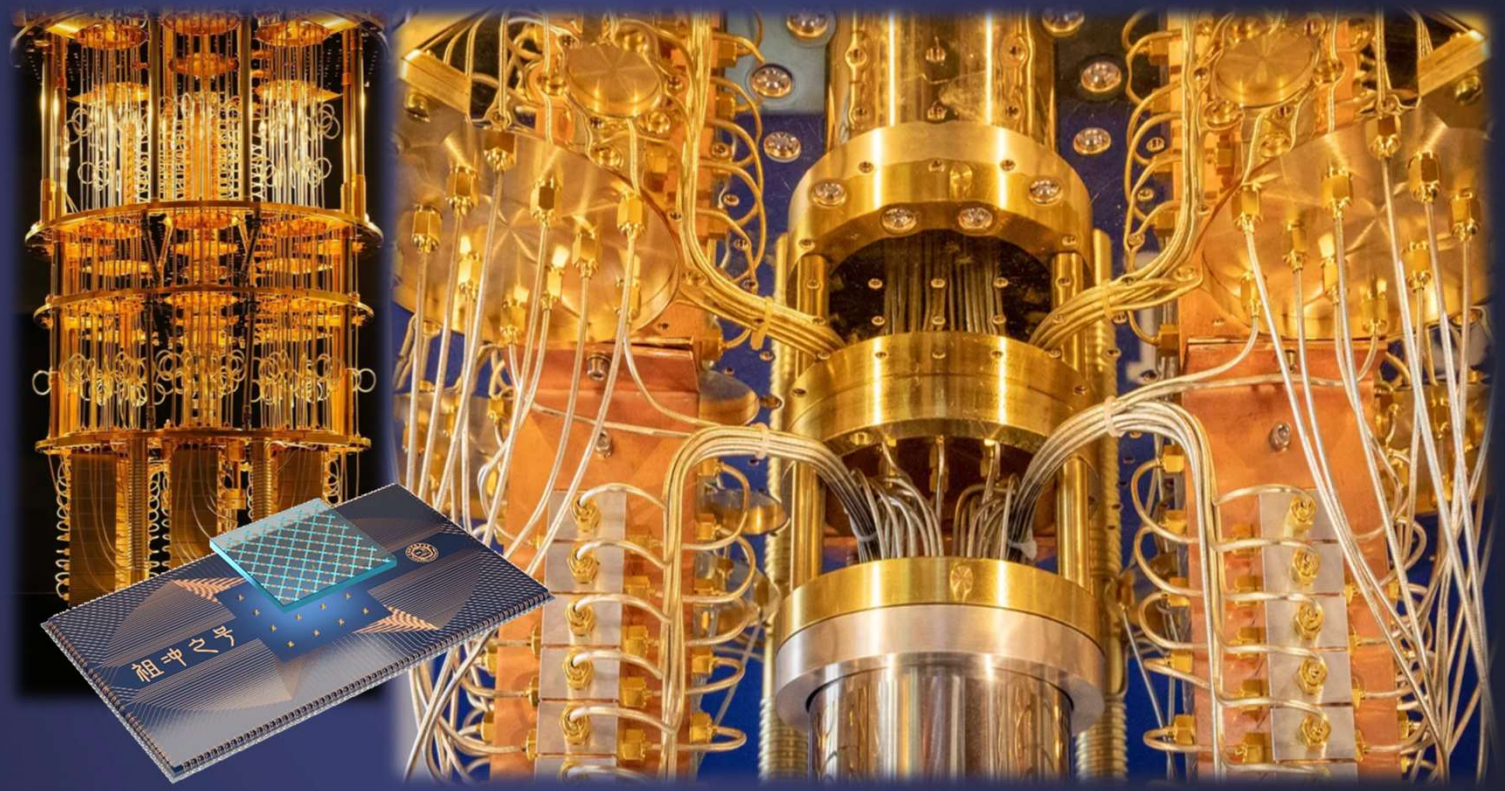
• 超导量子计算



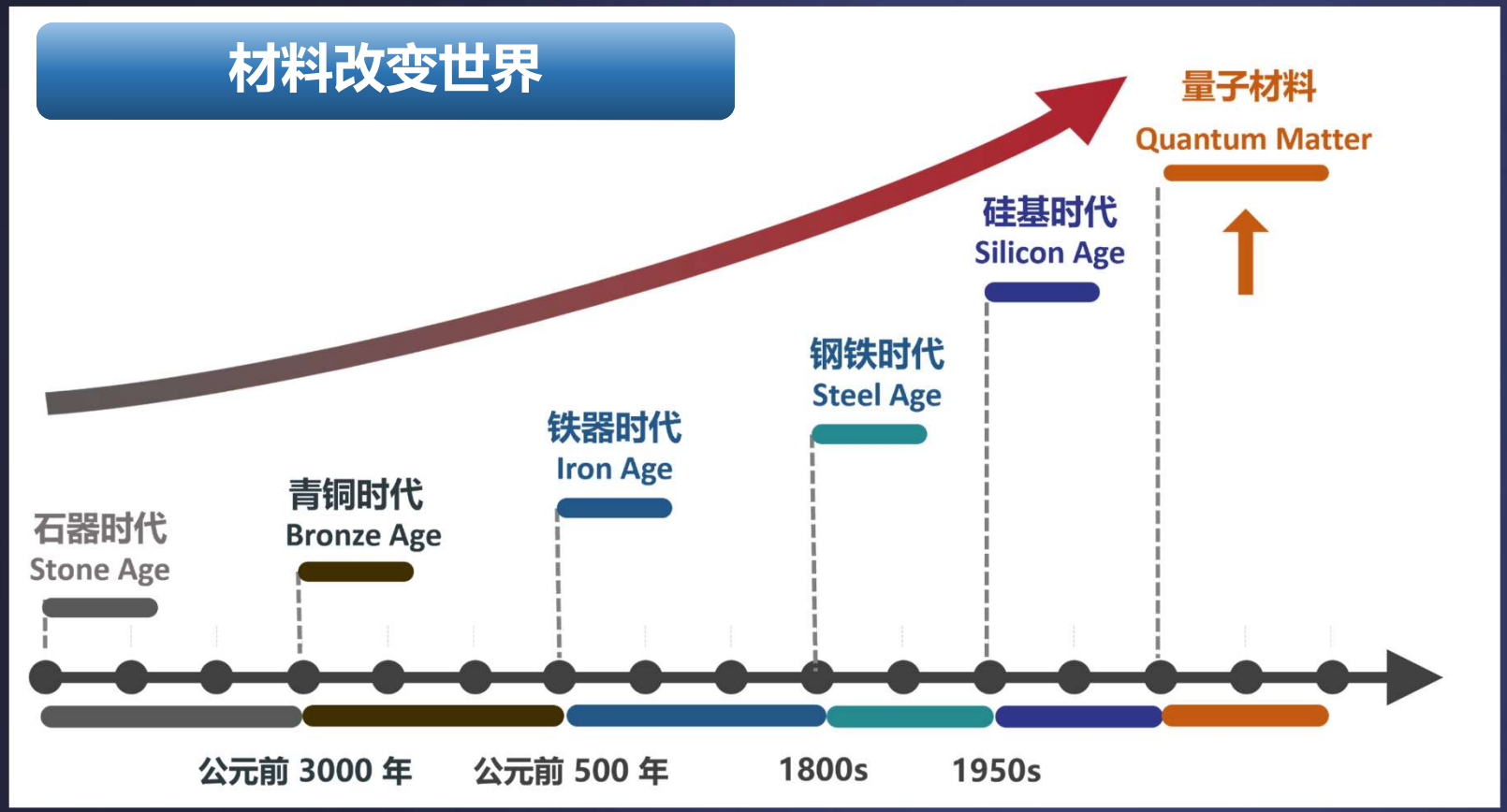
超导约瑟夫森结



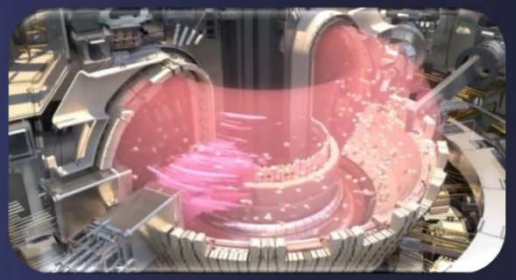
超导量子计算处理器“祖冲之号”



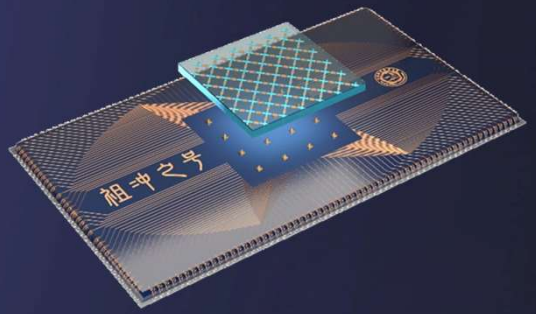
• 室温超导将推动下一次技术革命



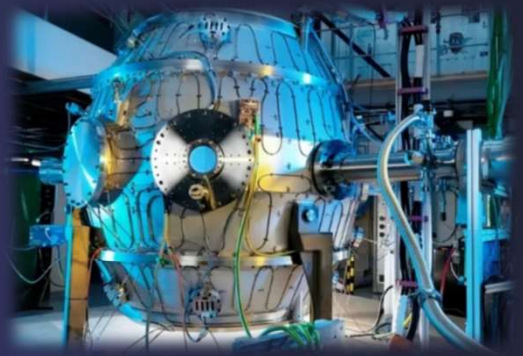
可控核聚变



量子计算



- **超导筑梦未来**



未来能源工业、电力传输、交通、医疗都会因超导技术的应用发生翻天覆地变化！

谢谢大家聆听！