



# 声学高阶节点线半金属

报告人：何海龙

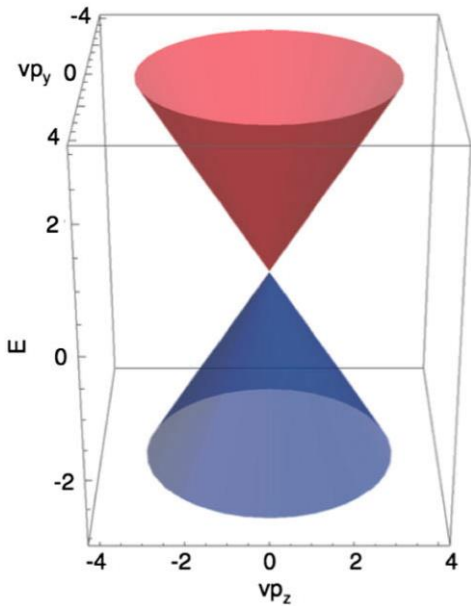
武汉大学 物理科学与技术学院

2023年11月25日

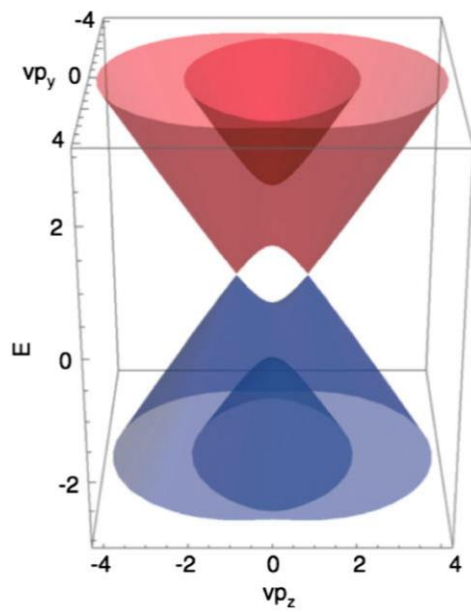
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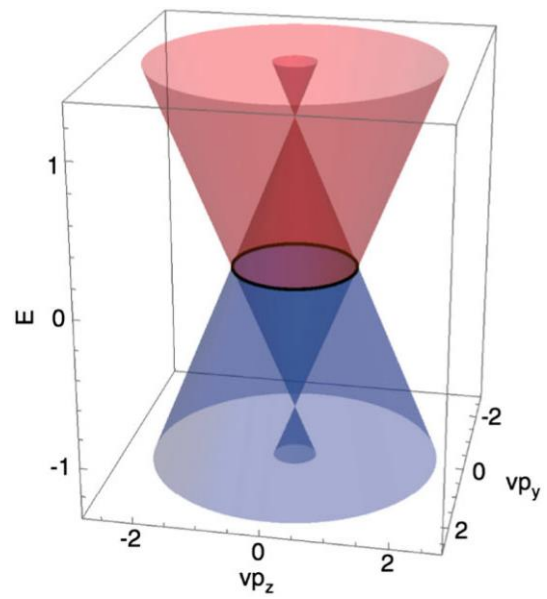
拓扑半金属主要包括：



Dirac半金属

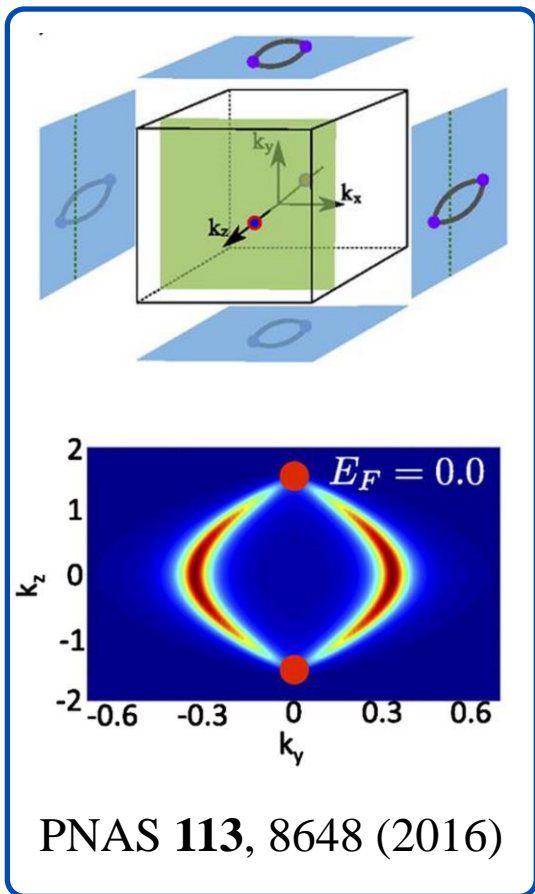


Weyl半金属

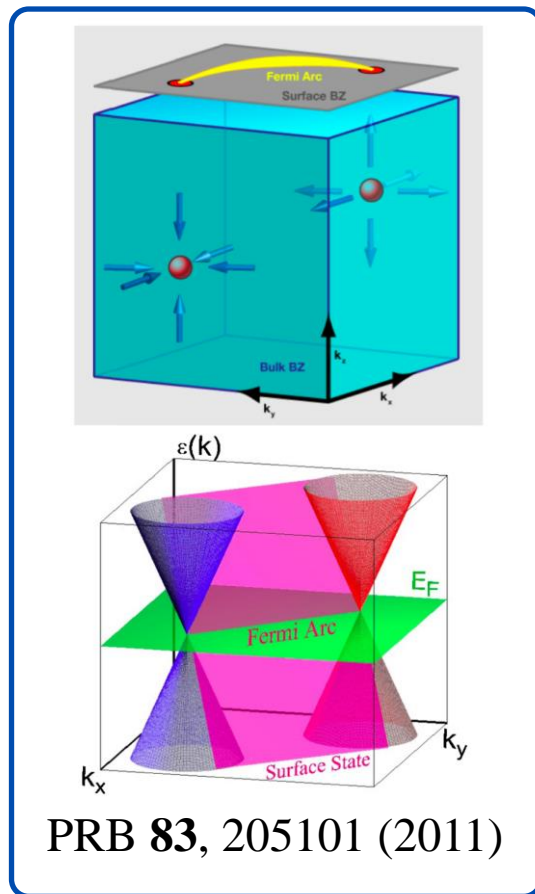


节点线半金属

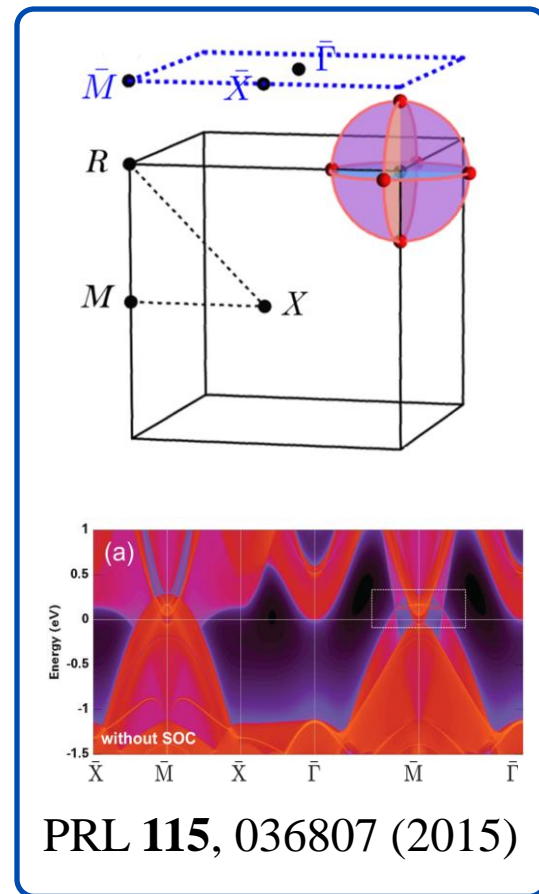
Rev. Mod. Phys. **90**, 015001 (2018)



表面具有连接Dirac点的表面态

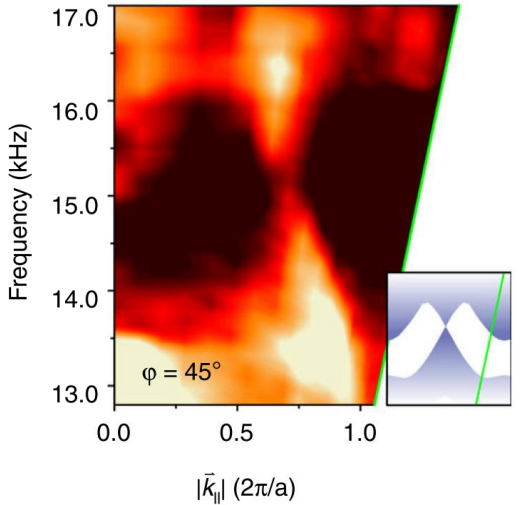
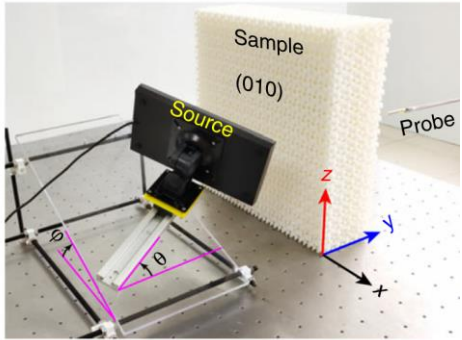


表面具有连接Weyl点的非闭合费米弧



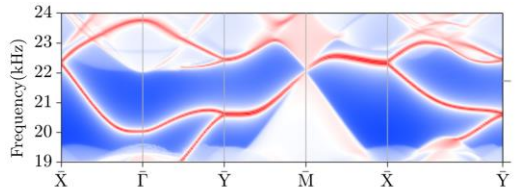
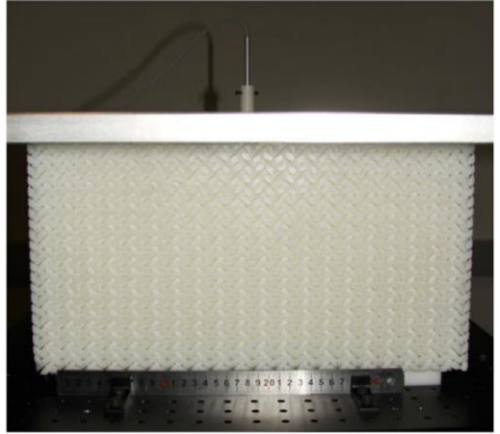
表面具有鼓膜状的拓扑表面态

## 人工结构中的Dirac半金属

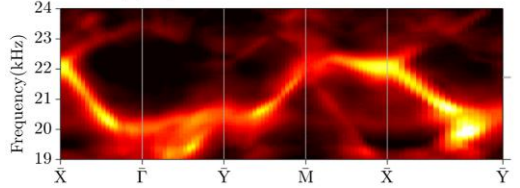


Dirac点的观测

Light-Sci. Appl. **9**, 38 (2020)



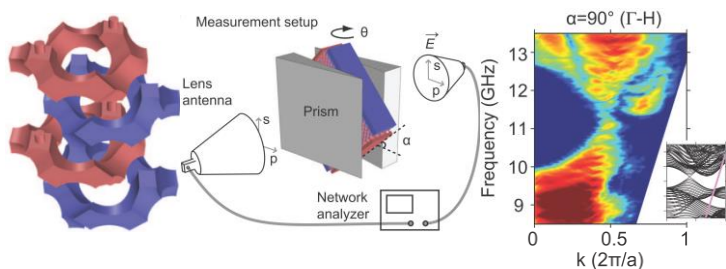
(d) Experimental result of surface states



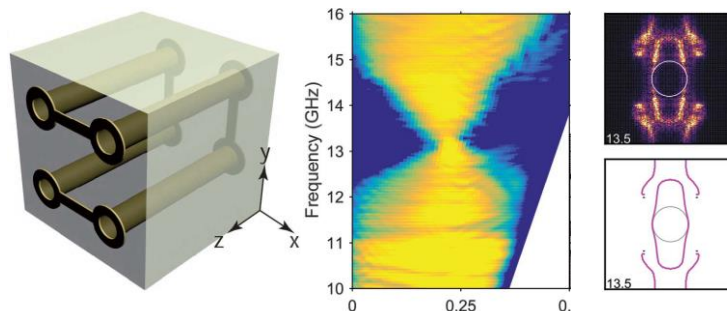
表面态的观测

PRL **124**, 104301 (2020)

## 人工结构中的Weyl半金属

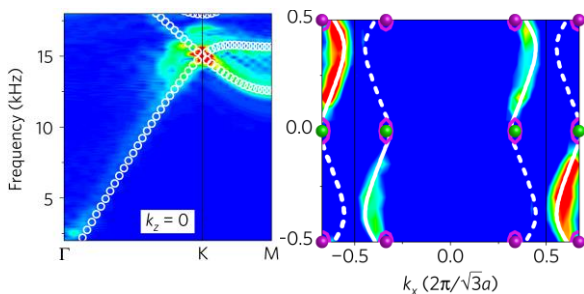
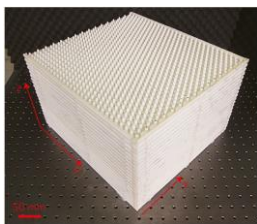


Science **349**, 622 (2015)

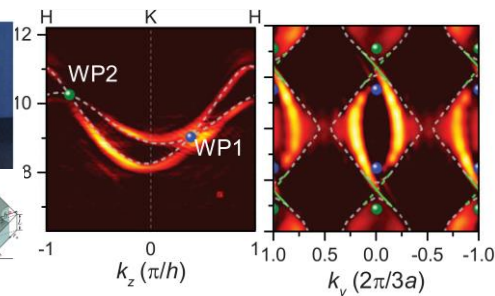
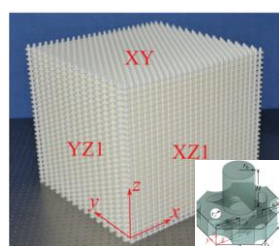


Science **359**, 1013 (2018)

光子晶体中的Weyl点和费米弧



Nat. Phys. **14**, 304 (2018)

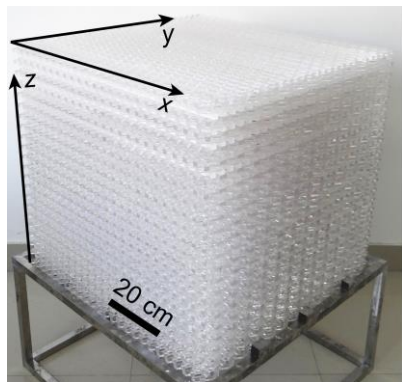


PRL **122**, 104302 (2019)

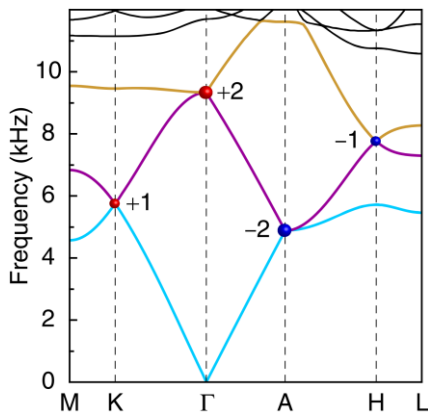
声子晶体中的Weyl点和费米弧

## 人工结构中的Weyl半金属

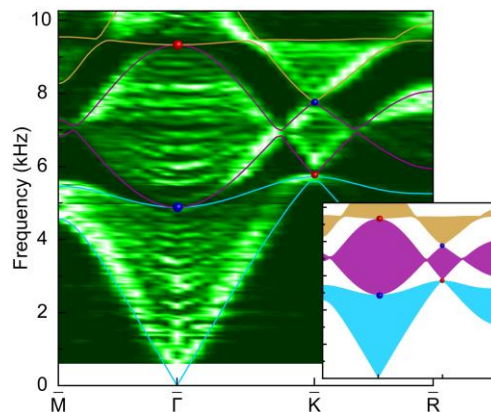
### 声子晶体中的二次线Weyl点



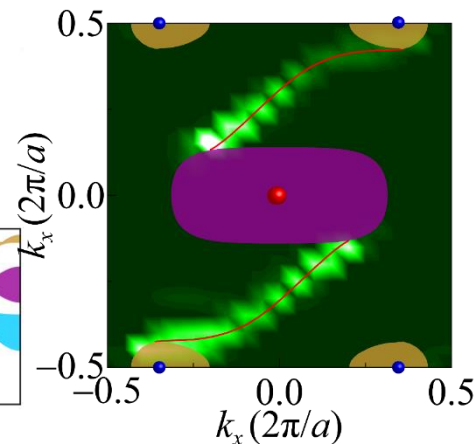
Weyl声子晶体



体带结构



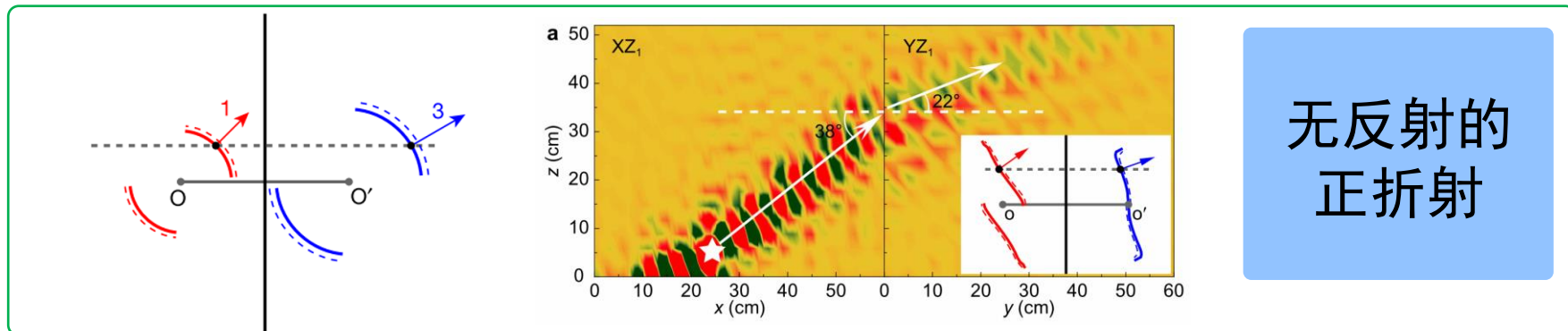
二次型Weyl点观测



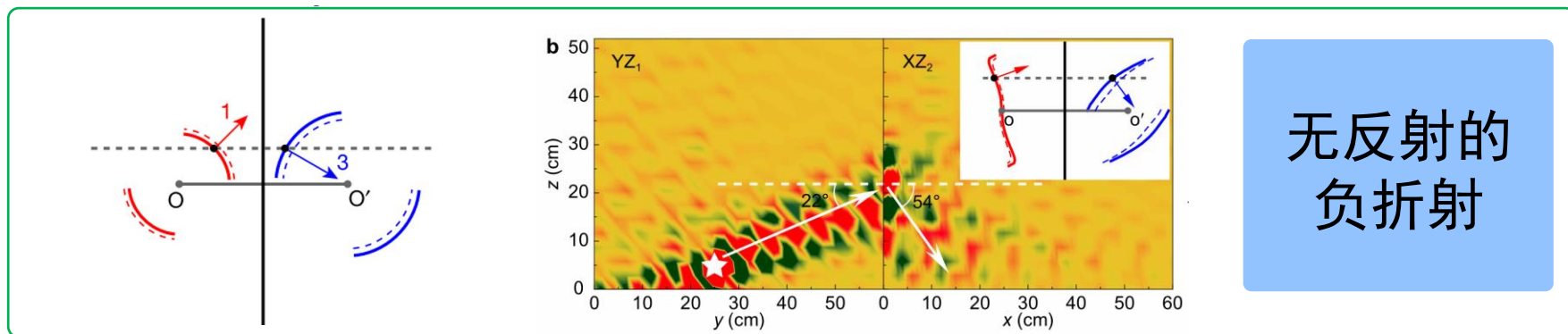
开放费米弧观测

不仅有拓扑荷为1的线性Weyl点，也有拓扑荷为2的二次型Weyl点；  
Weyl半金属的标志是开放费米弧，怎么使用费米弧的开放特性？

## 人工结构中的Weyl半金属



无反射的  
正折射

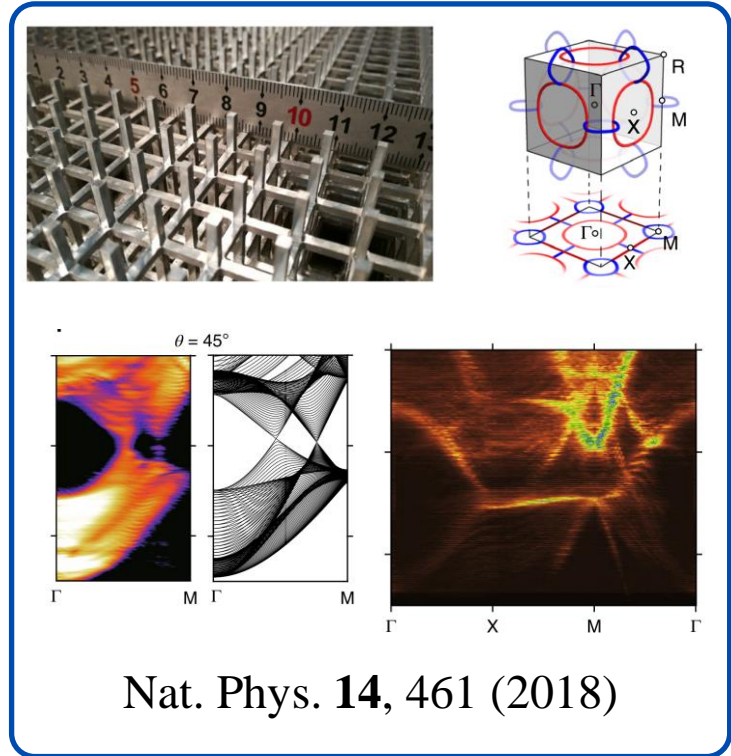
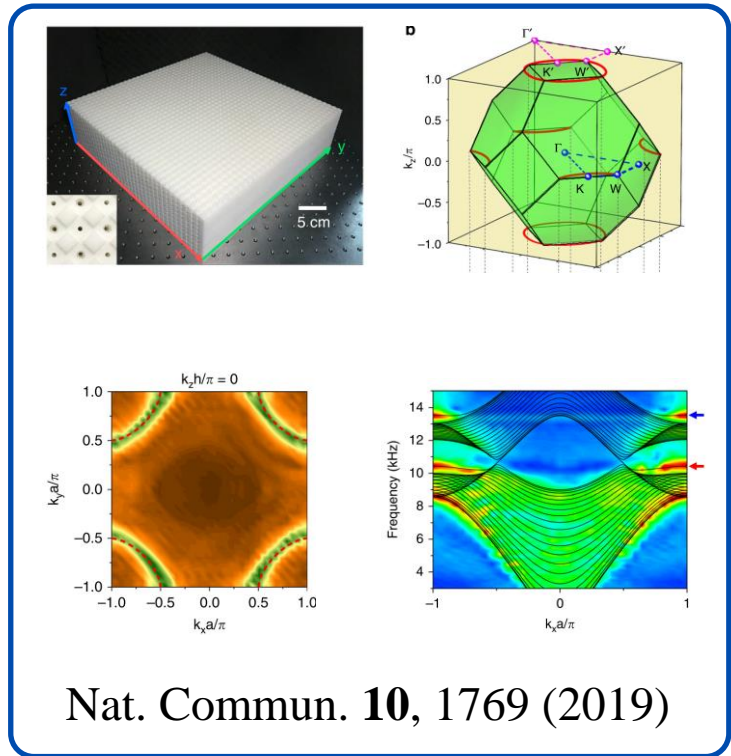


无反射的  
负折射

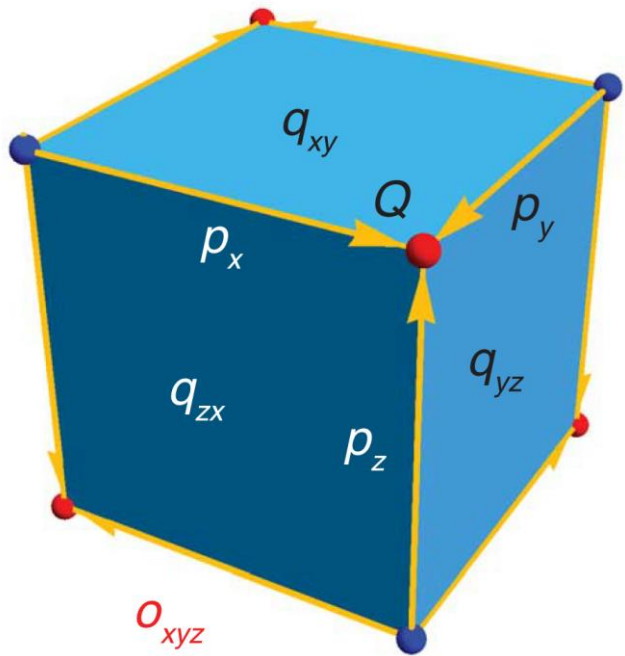
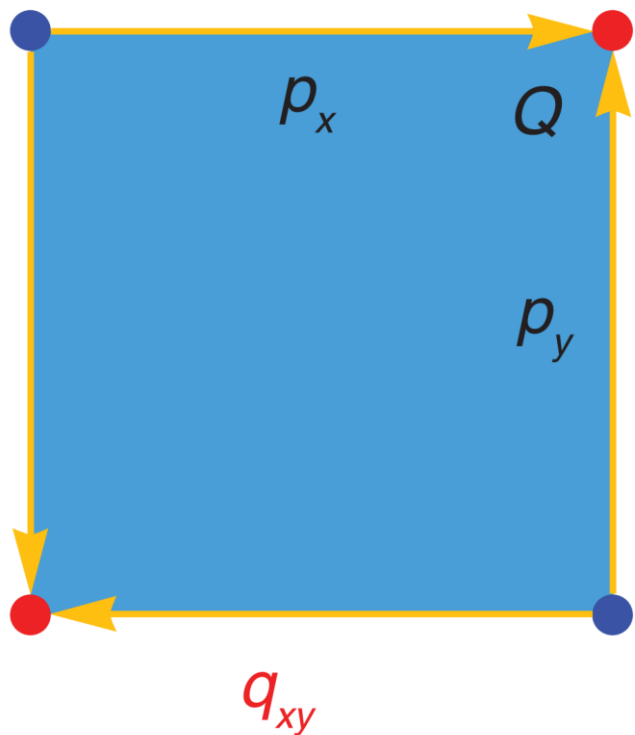
利用Weyl半金属表面弧的开放特性，提出并实现了声表面波的——拓扑正/负折射。



## 人工结构中的节点线半金属



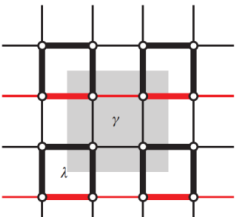
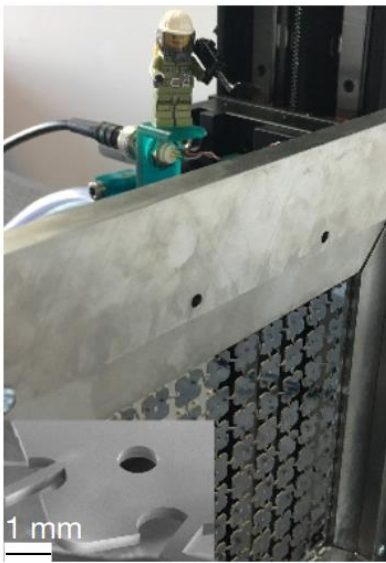
这些拓扑边界态存在于d维系统的(d-1)维边界



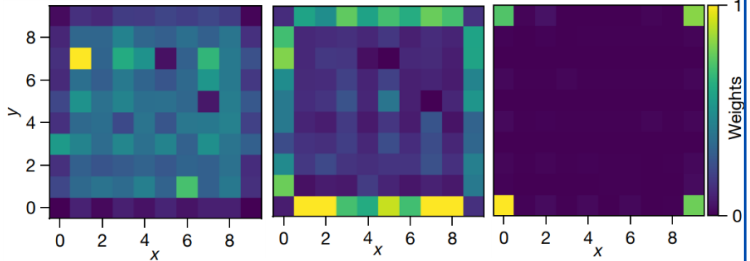
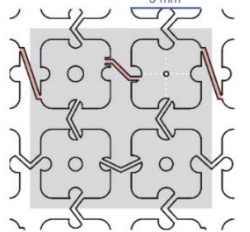
Science 357, 66 (2017)

拓扑边界态也可以出现在d维系统的(d-n)维 (n>1) 边界

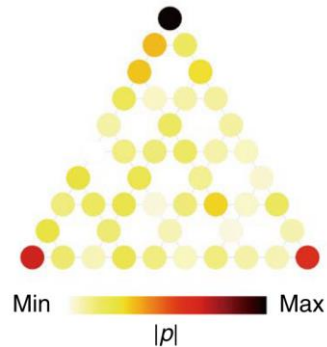
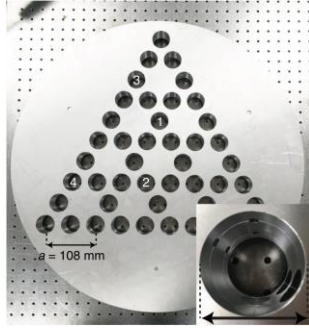
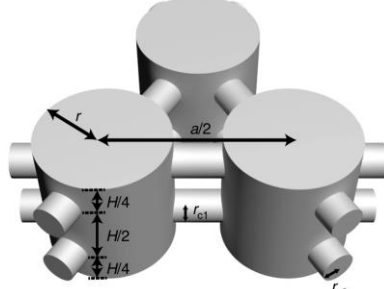
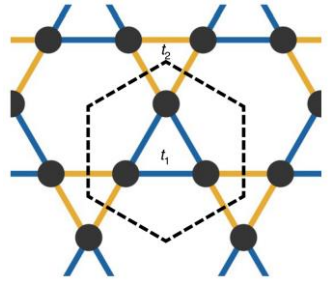
## 高阶拓扑绝缘体



- Weak positive coupling
- Weak negative coupling
- Strong positive coupling
- Strong negative coupling



四极子拓扑绝缘体  
Nature 555, 342 (2018)



Kagome格子  
Nat. Mater. 18, 108 (2019)

## 高阶拓扑半金属

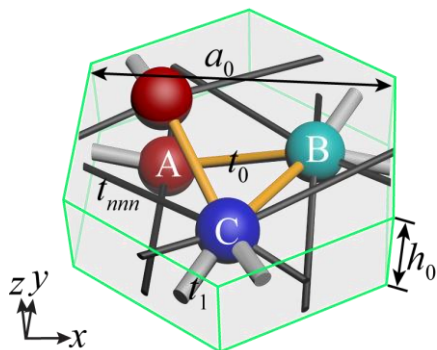
Nat. Mater. **20**, 794 (2021)  
 Nat. Mater. **20**, 812 (2021)

高阶Weyl半金属

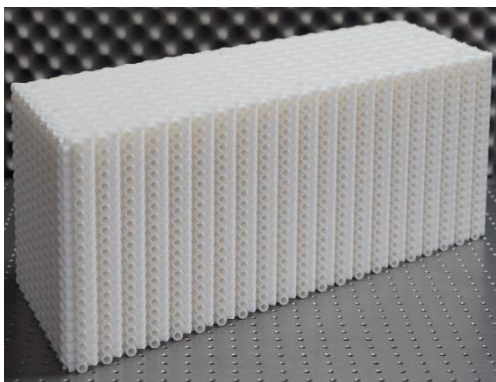
PRL **127**, 146601 (2021)

高阶Dirac半金属

## 高阶拓扑半金属



紧束缚模型



Weyl声子晶体样品

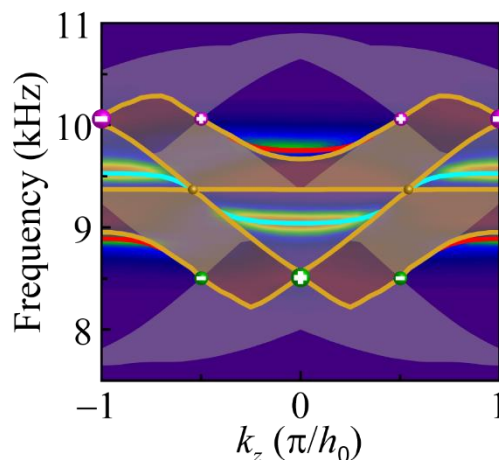
哈密顿量:

$$H(\mathbf{k}) = \begin{pmatrix} 0 & h_{12} & h_{13} \\ h_{12}^* & 0 & h_{23} \\ h_{13}^* & h_{23}^* & 0 \end{pmatrix}$$

$$h_{12} = t_0 + t_1 e^{-ia_0 k_x} + t_{nnn} \left[ e^{-ia_0 \left( \frac{1}{2} k_x - \frac{\sqrt{3}}{2} k_y \right)} + e^{-ia_0 \left( \frac{1}{2} k_x + \frac{\sqrt{3}}{2} k_y \right)} \right]$$

$$h_{13} = \left\{ t_0 + t_1 e^{-ia_0 \left( \frac{1}{2} k_x - \frac{\sqrt{3}}{2} k_y \right)} + t_{nnn} \left[ e^{ia_0 \left( \frac{1}{2} k_x + \frac{\sqrt{3}}{2} k_y \right)} + e^{-ia_0 k_x} \right] \right\} e^{-ih_0 k_z}$$

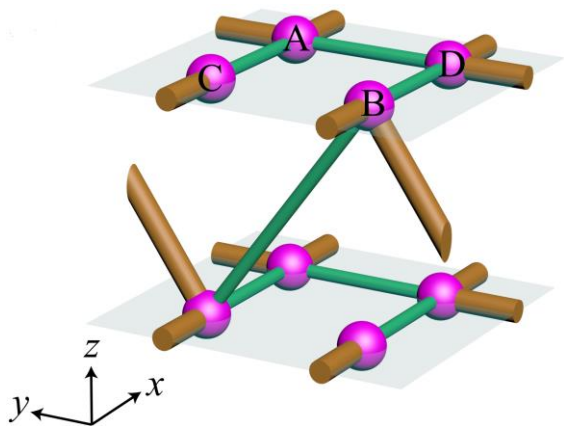
$$h_{23} = t_0 + t_1 e^{ia_0 \left( \frac{1}{2} k_x + \frac{\sqrt{3}}{2} k_y \right)} + t_{nnn} \left[ e^{-ia_0 \left( \frac{1}{2} k_x - \frac{\sqrt{3}}{2} k_y \right)} + e^{ia_0 k_x} \right]$$



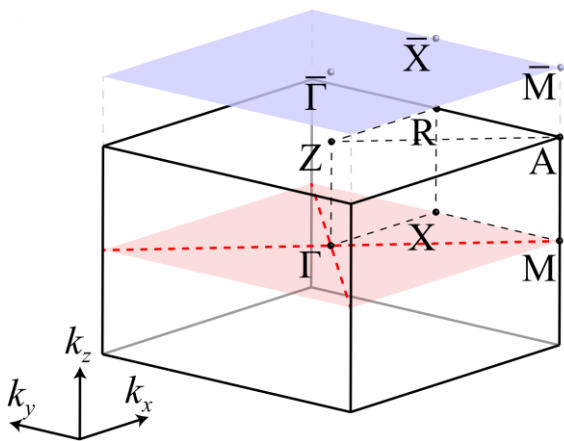
不仅存在带隙中的棱态，也发现了存在于体带中的棱态BIC

Z. Pu, H. He\*, et al., PRL **130**, 116103 (2023)

## 紧束缚模型



模型示意图



布里渊区

哈密顿量:

$$H = \begin{pmatrix} 0 & 0 & h_{13} & h_{14} \\ 0 & 0 & h_{23} & h_{24} \\ h_{13}^* & h_{23}^* & 0 & 0 \\ h_{14}^* & h_{24}^* & 0 & 0 \end{pmatrix}$$

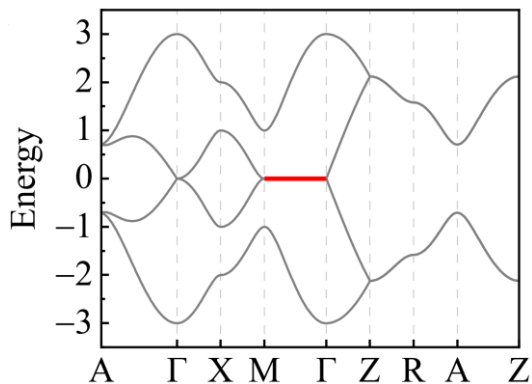
$$h_{13} = t_1 + t_0 e^{ik_x}$$

$$h_{14} = t_1 + t_0 e^{ik_y}$$

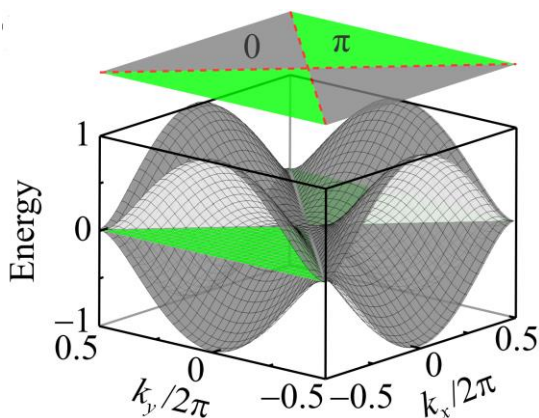
$$h_{23} = (t_1 + t_0 e^{-ik_y}) e^{-ik_z}$$

$$h_{24} = t_1 + t_0 e^{-ik_x}$$

## 紧束缚模型



体带结构中出现零能节点线 (受手征对称保护)



Zak相为 $\pi$ 的区域出现鼓膜状表面态

哈密顿量:

$$H = \begin{pmatrix} 0 & 0 & h_{13} & h_{14} \\ 0 & 0 & h_{23} & h_{24} \\ h_{13}^* & h_{23}^* & 0 & 0 \\ h_{14}^* & h_{24}^* & 0 & 0 \end{pmatrix}$$

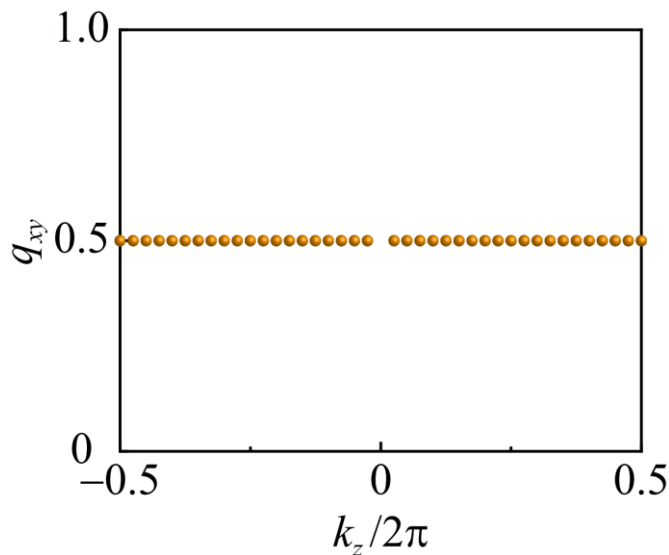
$$h_{13} = t_1 + t_0 e^{ik_x}$$

$$h_{14} = t_1 + t_0 e^{ik_y}$$

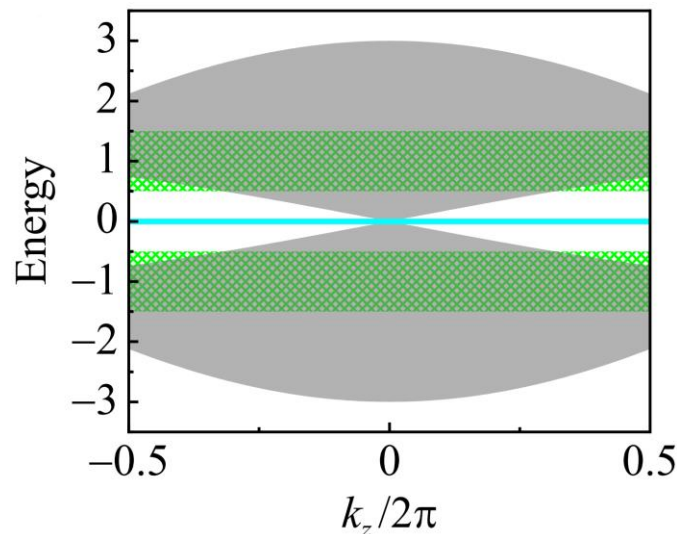
$$h_{23} = (t_1 + t_0 e^{-ik_y}) e^{-ik_z}$$

$$h_{24} = t_1 + t_0 e^{-ik_x}$$

## 紧束缚模型



$k_z$ 相关的四极矩

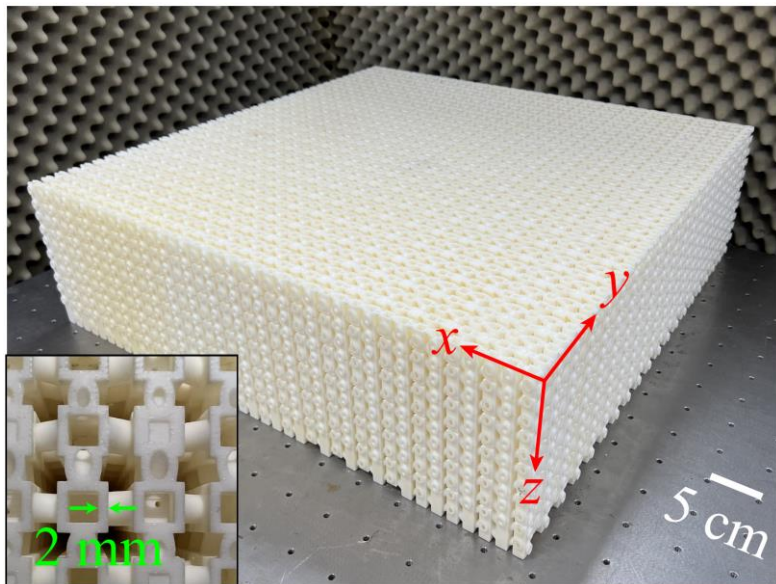


沿着 $k_z$ 方向的投影色散

对不同的 $k_z$ 计算四极矩 $q_{xy}$ ，除了节点线的 $k_z=0$ 平面外， $q_{xy}=0.5$ ，沿着 $k_z$ 方向计算的投影色散，可以出现在1D棱上的局域态——棱态。

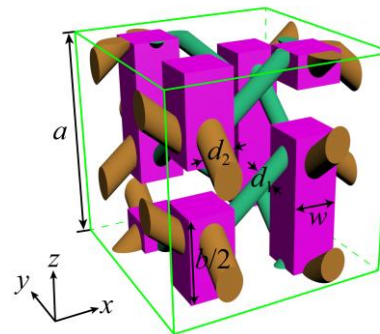


## 声子晶体制备

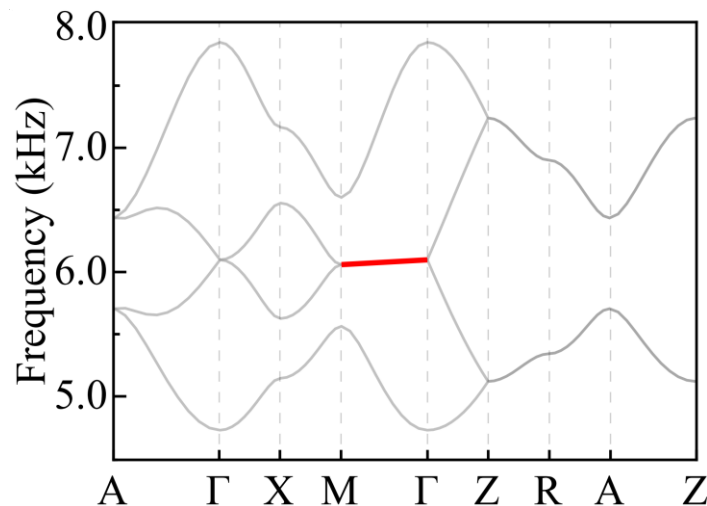


声子晶体样品1 (3D打印)

样品尺寸: 20x20x6 cells (720x720x216 mm)

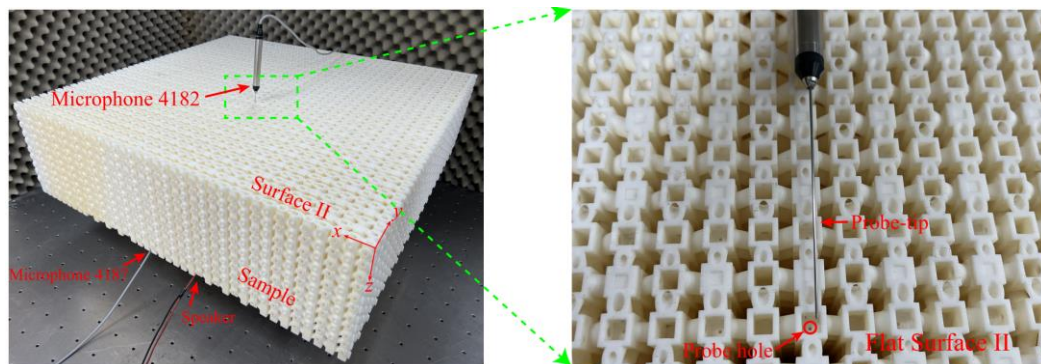


单包示意图

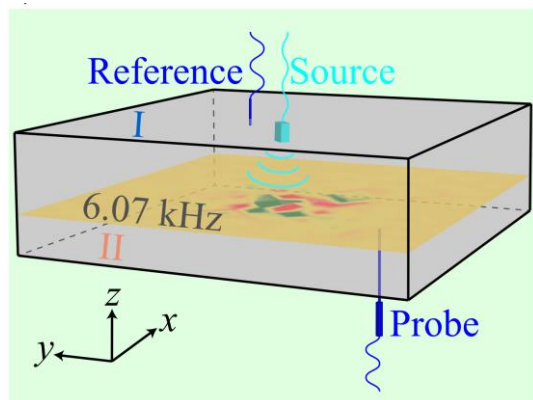


模拟计算体带结构

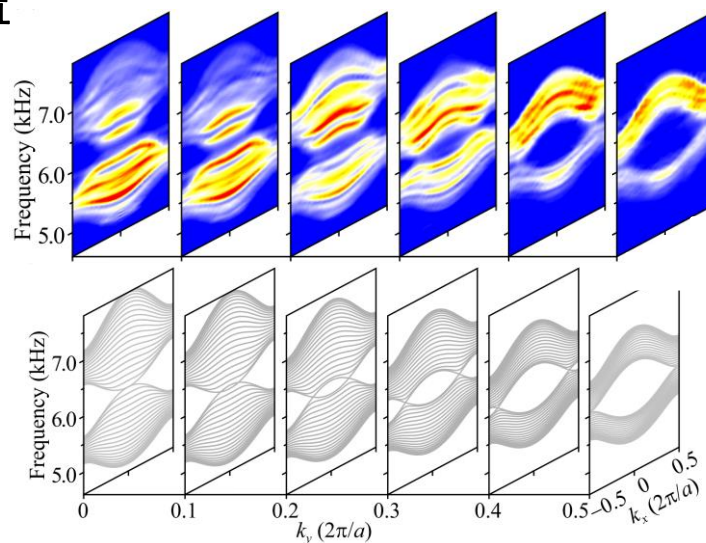
## 观测声子晶体中的节点线



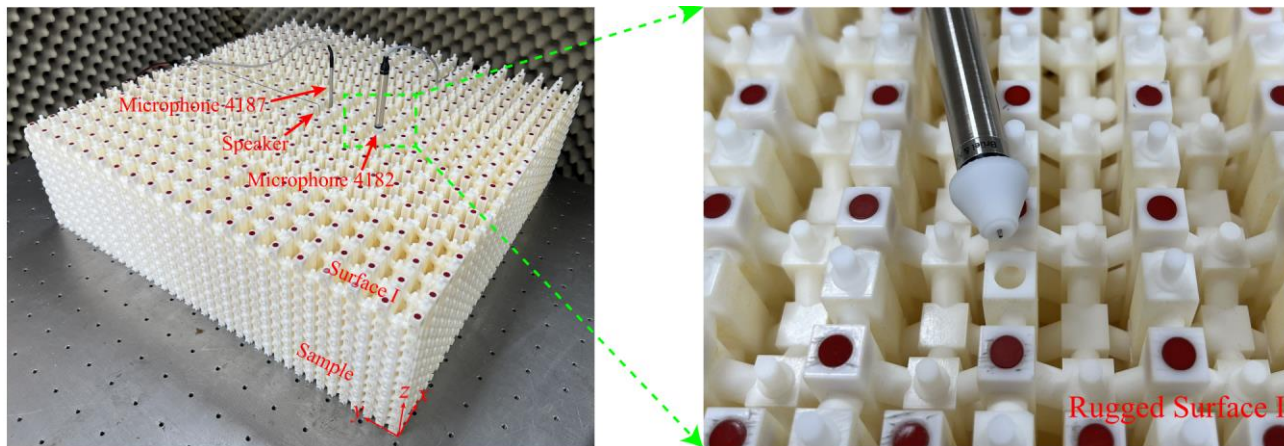
实验装置



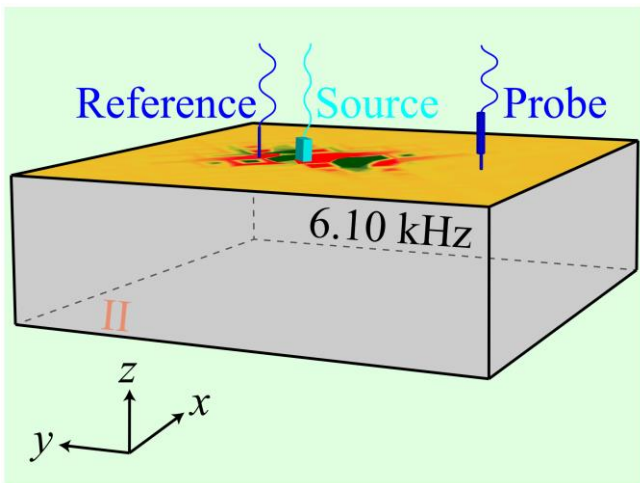
扫描样品内部的一个平面的声场：  
点源距离扫描面有一定的距离，这个平面包含了内面和面外的k信息。



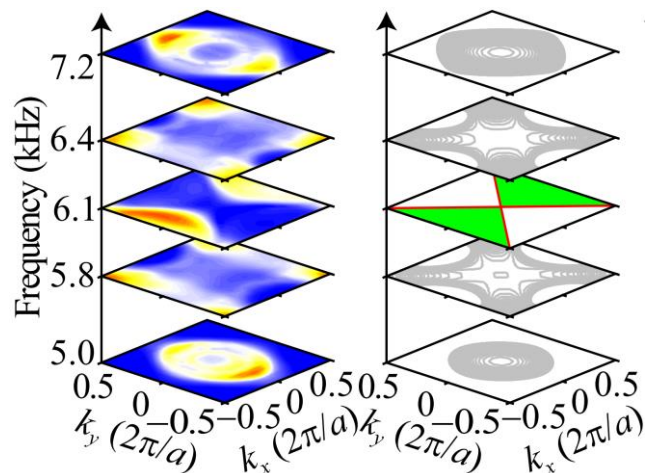
## 观测声子晶体中的鼓膜状表面态



实验装置

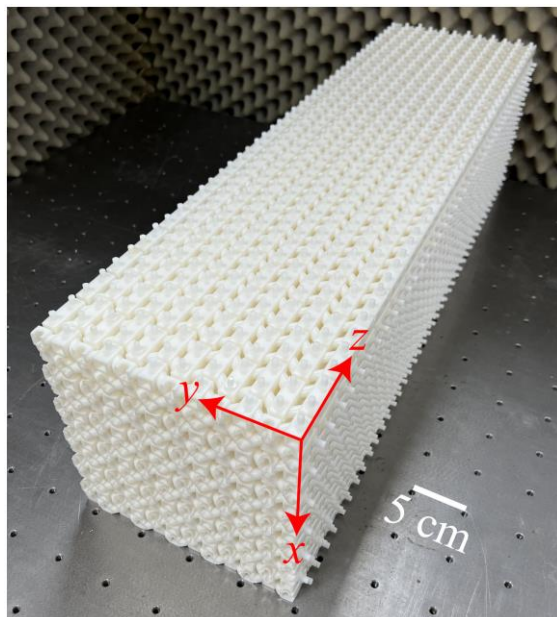


扫描样品顶面的声场



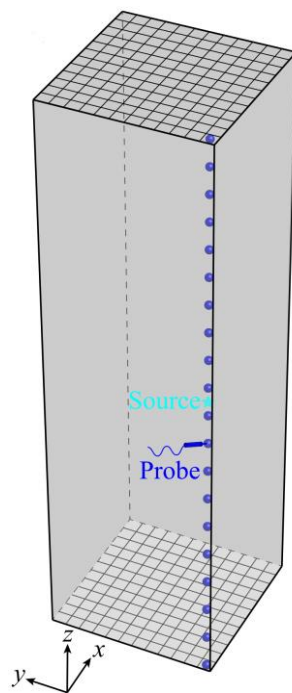
鼓膜状表面态 (对声场FFT)

## 观测声子晶体中的1D棱态

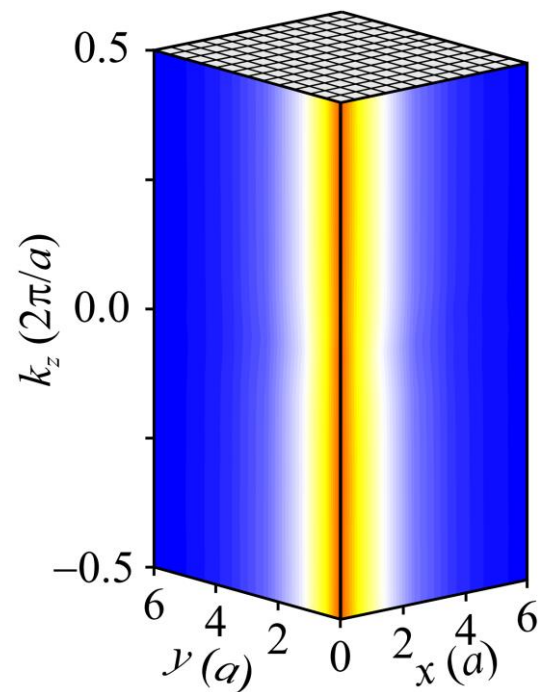


声子晶体样品2 (3D打印)

样品尺寸: 6x6x21 cells (216x216x756 mm)

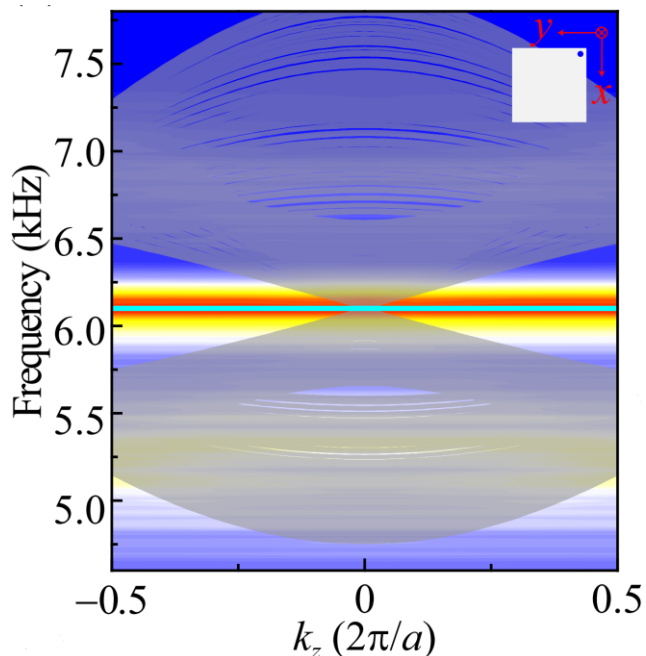


实验装置

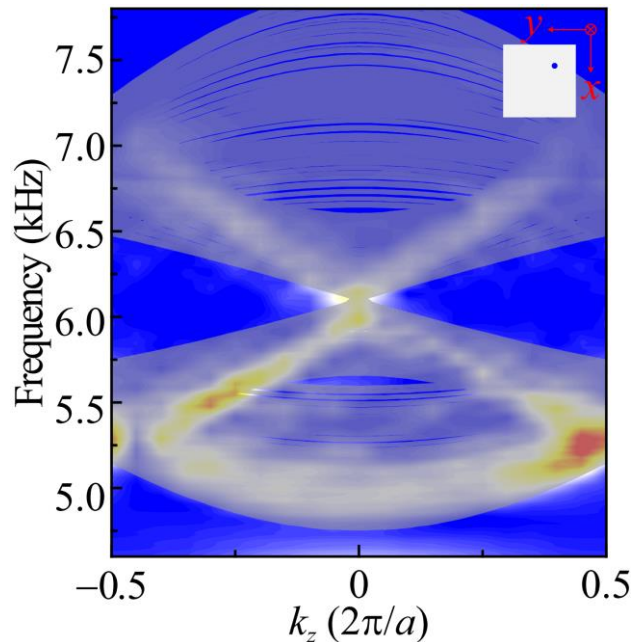


局域棱态

## 观测声子晶体中的1D棱态



沿着 $k_z$ 方向的投影色散



沿着 $k_z$ 方向的投影体带

**不仅观测到了体带结构中的节点线，2D表面上的鼓膜状表面态，以及1D铰链上的棱态。**

Qiyun Ma, et al., Observation of Higher-Order Nodal-Line Semimetal in Phononic Crystals (submitted to **PRL**)

- ✓ 理论提出了高阶节点线拓扑半金属；
- ✓ 成功制备了高阶节点线声子晶体，观测到了体带结构中的节点线以及由Zak相相关的鼓膜状表面态；
- ✓ 也观测了由 $k_z$ 依赖的四极矩保护的1D平面铰链态。

*Thank you!*