



Observation of Coherent Ferrons

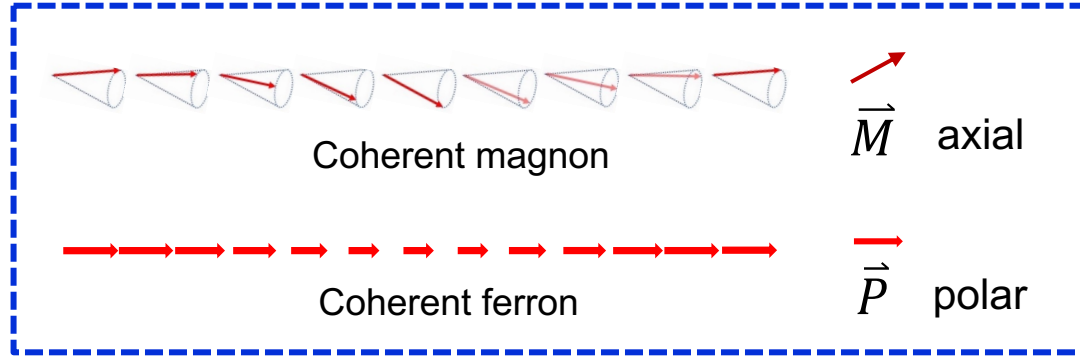
Nature Mater. **2026**, [10.1038/s41563-026-02597-4](https://doi.org/10.1038/s41563-026-02597-4)

Nature Mater. **2025**, 24, 1203

Nature Comm. **2025**, 16, 1896.

arXiv:2512.06139

Magnons vs. Ferrons



Solid State Communications **1963**, 1, 132-137.

COLLECTIVE MOTIONS OF HYDROGEN BONDS

P.G. de Gennes

PHYSICAL REVIEW B **106**, L081105 (2022)

Excitations of the ferroelectric order

Ping Tang¹, Ryo Iguchi², Ken-ichi Uchida^{2,3,4} and Gerrit E. W. Bauer^{1,3,4,5,6}

Journal of Magnetism and Magnetic Materials 541 (2022) 166466



Magnonics vs. Ferronics

Gerrit E.W. Bauer^{a,b,c,d,*}, Ping Tang^a, Ryo Iguchi^e, Ken-ichi Uchida^{a,b,c}

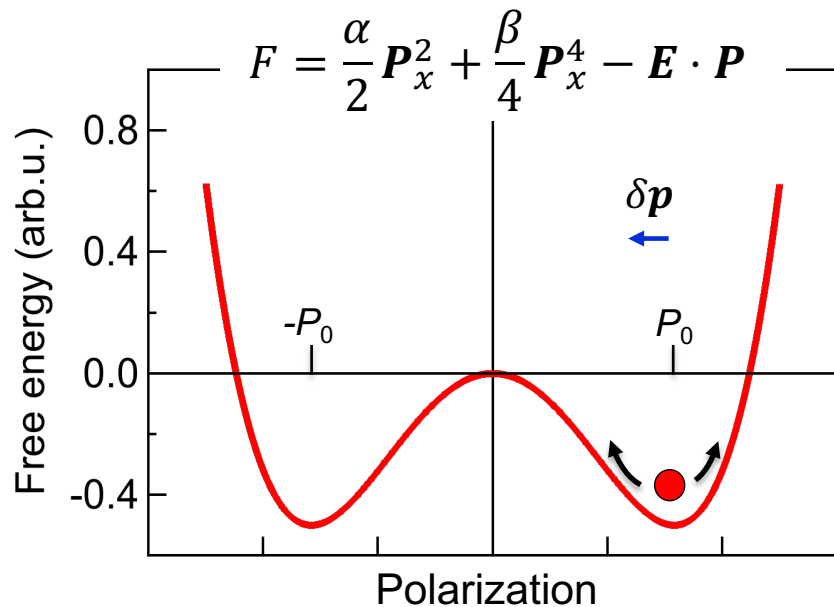
PHYSICAL REVIEW APPLIED **20**, 050501 (2023)

Perspective

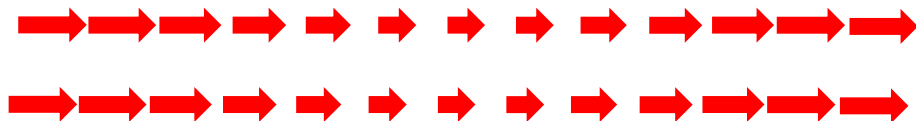
Polarization transport in ferroelectrics

G.E.W. Bauer^{1,2,3,*}, P. Tang,¹ R. Iguchi⁴, J. Xiao,⁵ K. Shen⁶, Z. Zhong^{7,8}, T. Yu⁹, S.M. Rezende,¹⁰ J.P. Heremans^{11,12,13} and K. Uchida^{4,2}

What do we expect from a coherent ferron?

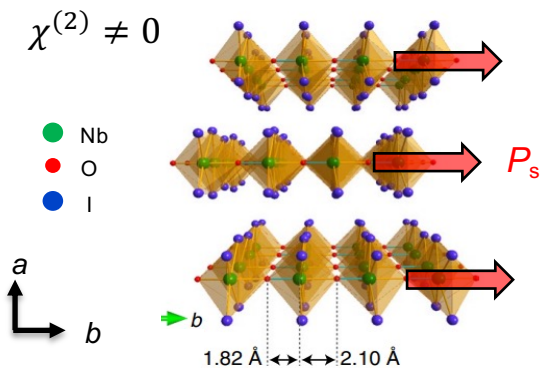


$$\delta \mathbf{p}_q = \frac{\hbar}{m_p \omega_q} \frac{3\beta}{2\alpha} \cdot \mathbf{P}_0$$



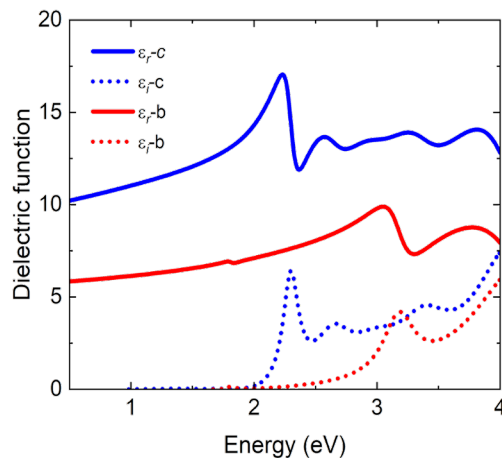
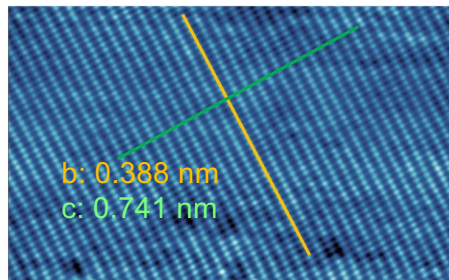
- Maxwell's equations!
- Oscillating polarization should emit EM radiation into far field.
- Oscillating polarization should propagate at high velocities in the material.

NbOI₂: a 2D vdW ferroelectric semiconductor

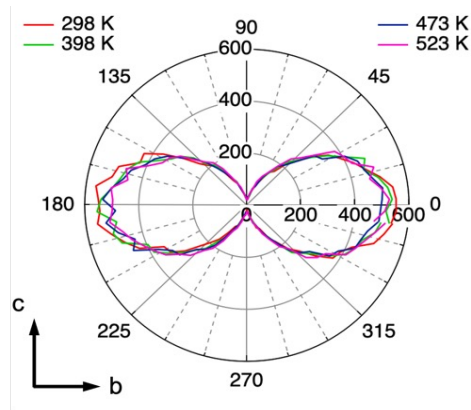
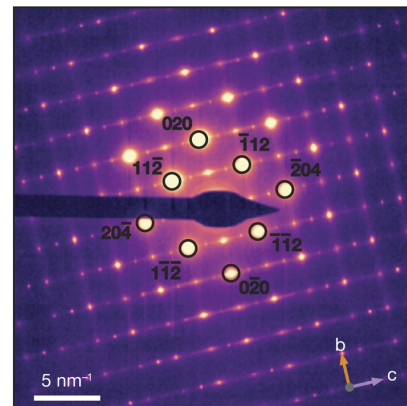


**vdW semiconductor
In-plane ferroelectric
Giant SHG from $\chi^{(2)}$**

Nat. Photon. **2022**, 16, 644;
Adv. Mat. **2021**, 33, 2101505.
Nat Commun **2022**, 13, 1884.



Nature Comm. **2025**, 16, 1896
Nature Mat. **2025**, 24, 1203-1208



Raman 3.13 THz mode

X-Y Zhu Columbia University



Xavier Roy

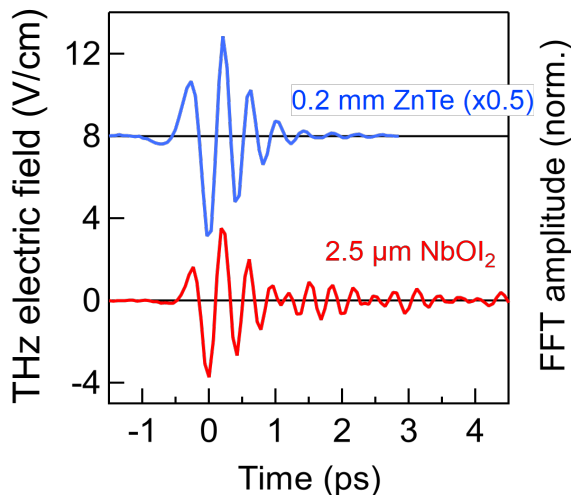
THz emission from giant optical rectification



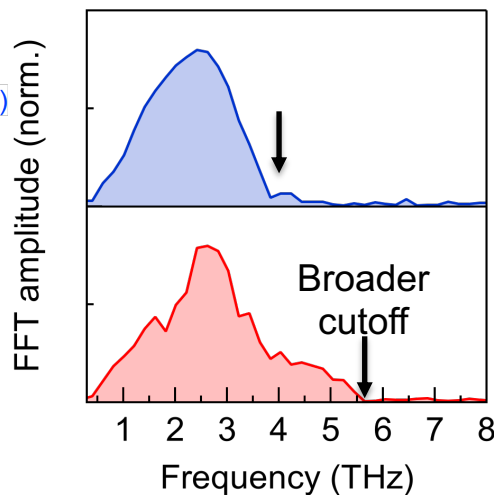
Taketo Handa

Optical rectification: $P^{(2)} = \epsilon_0 \chi^{(2)} E^2 \cos^2 \omega_0 t = \epsilon_0 \chi^{(2)} E^2 (\cos 2\omega_0 t + 1)/2$

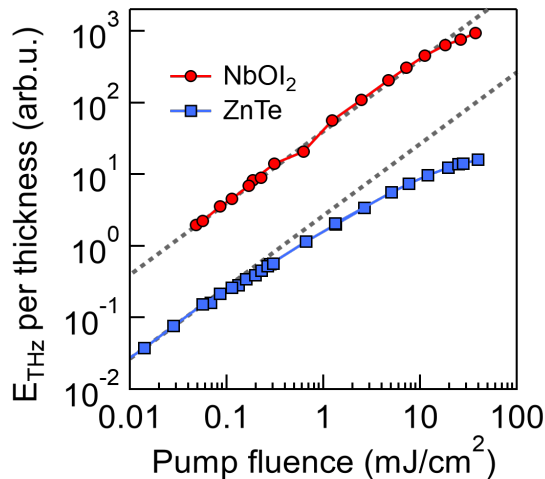
Observation of THz emission



Frequency domain



THz field per thickness

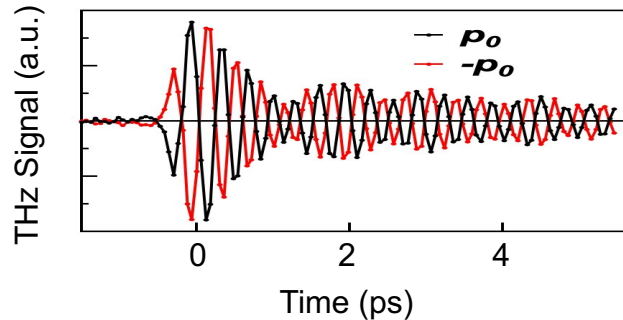
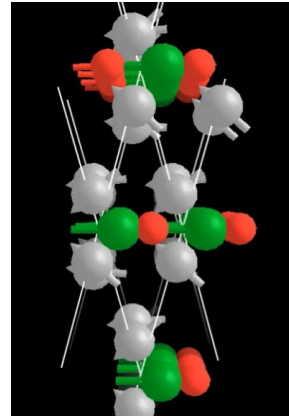
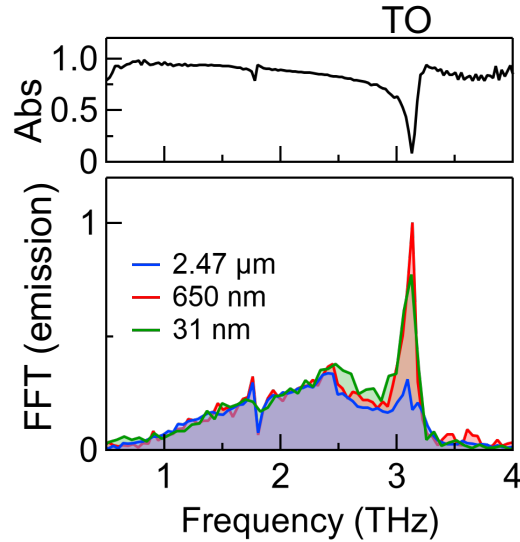
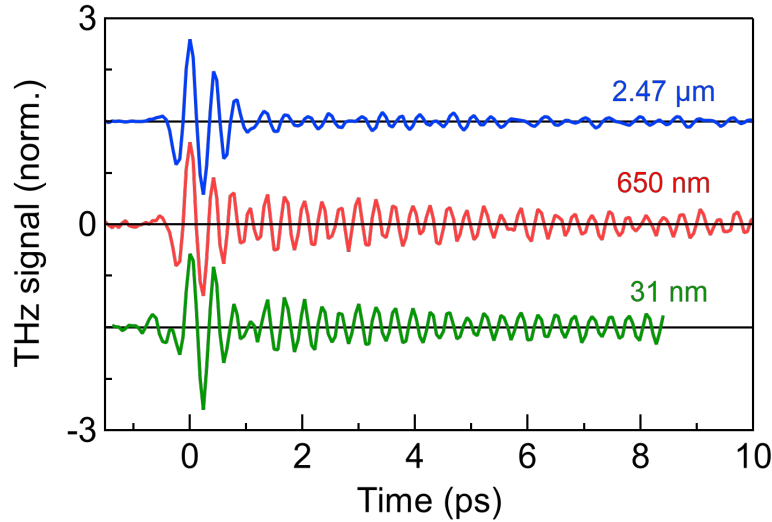


- $I_{\text{THz}, \text{NbOI}_2} \gg I_{\text{THz}, \text{ZnTe}}$ by 20x – 100x
- Broadband up to 5.5 THz
- High saturation threshold

THz emitter to nm thickness: *long-lived ringing*



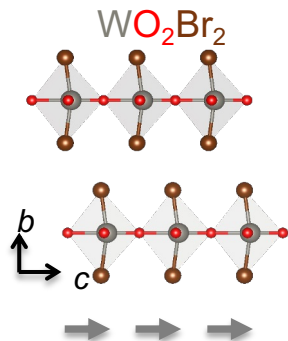
Taketo Handa



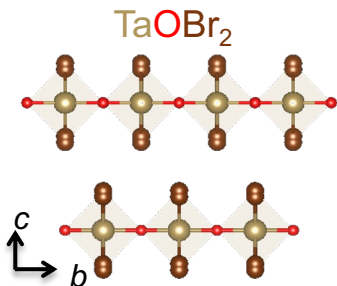
- Emission at 3.13 THz, the ferroelectric TO mode
- Collective excitation of ferroelectric order – the Higgs mode

THz coherent ferron emission from vdW ferroelectrics

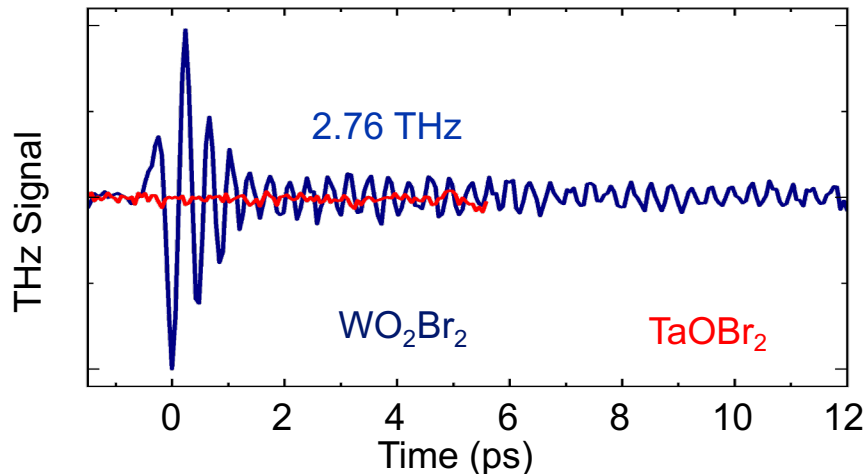
Ferroelectric



Non-ferroelectric



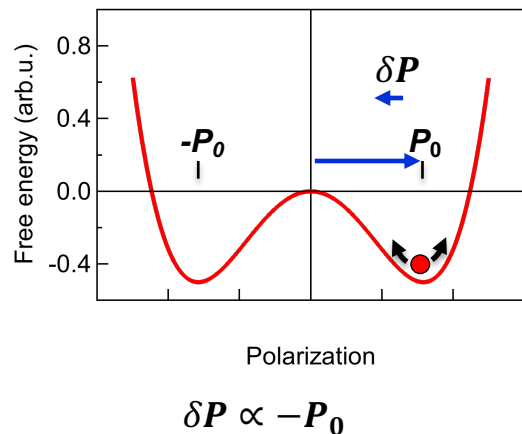
$$P = 0$$



Taketo Handa
Jeongheon Choe
Chun-Ying Huang
Willa Mihalyi-Koch

co-PI: **Xavier Roy**

Nonlinear mechanisms for THz emission from the coherent ferron



Impulsive Raman Excitation

$$V = \frac{1}{2} \omega_{IR}^2 Q_{IR}^2 + (Z^* Q_{IR} + \alpha Q_{IR}^3) E + \frac{1}{2} (\chi_{ee}^{(1)} + \beta Q_{IR}^2) E^2$$

$$= \frac{1}{2} \omega_{IR}^2 \frac{P^2}{Z^{*2}} + \left(P + \alpha \frac{P^3}{Z^{*3}} \right) E + \frac{1}{2} (\chi_{ee}^{(1)} + \beta \frac{P^2}{Z^{*2}}) E^2 \quad \leftarrow P = Z^* Q_{IR}$$

$$P = \frac{\partial V}{\partial E} = \left(P + \alpha \frac{P^3}{Z^{*3}} \right) + \left(\chi_{ee}^{(1)} + \beta \frac{P^2}{Z^{*2}} \right) E$$

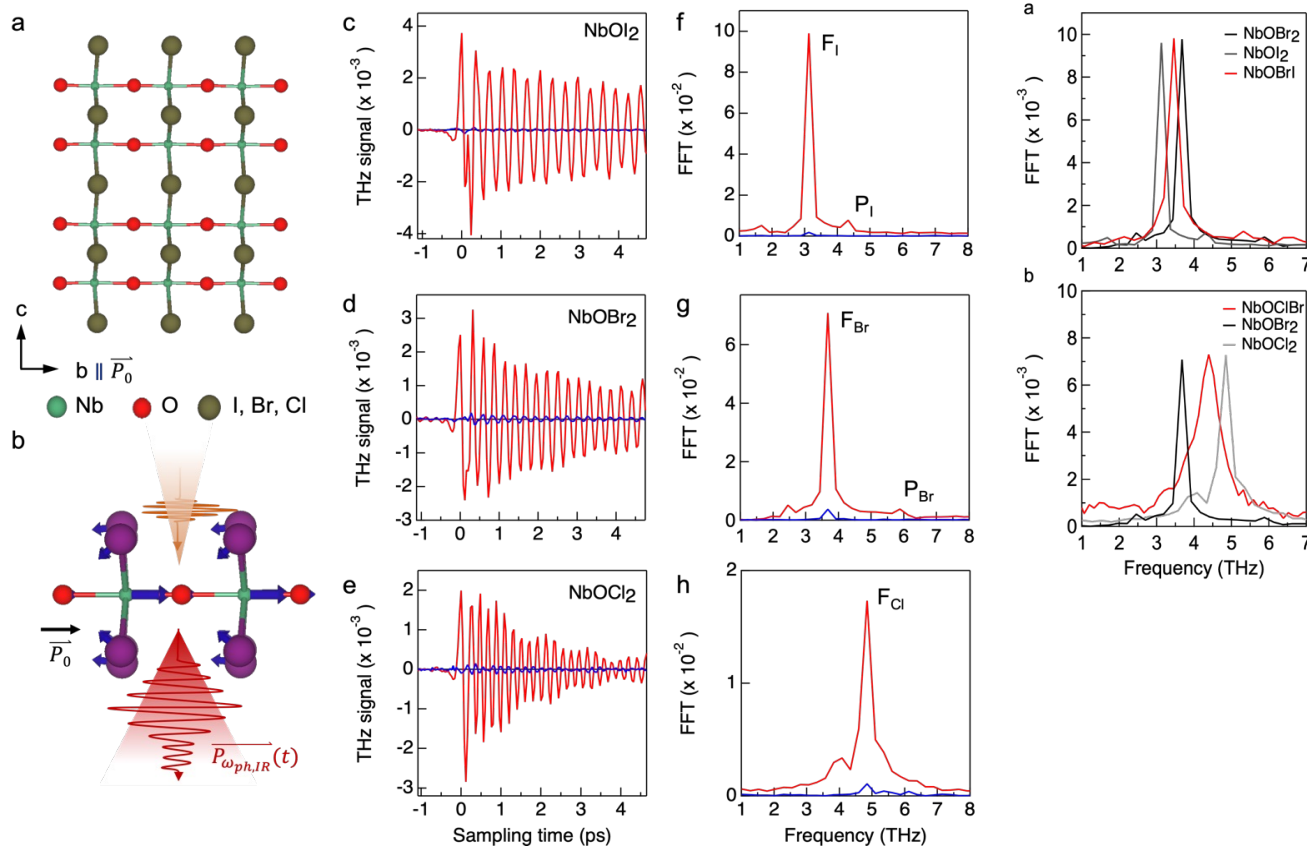
$$= P_0 + \frac{\alpha P_0^3}{(Z^*)^3} + \left(1 + \frac{3\alpha P_0^2}{(Z^*)^3} \right) \delta P + \dots \quad \leftarrow \begin{aligned} P_0 &= Z^* Q_{IR,0} \\ \delta P &= Z^* \delta Q_0 \end{aligned}$$

$$\frac{\partial^2 P}{\partial t^2} = \left(1 + \frac{3\alpha P_0^2}{(Z^*)^3} \right) (\delta P)'' \quad \text{THz emission}$$

Tuning coherent ferrons

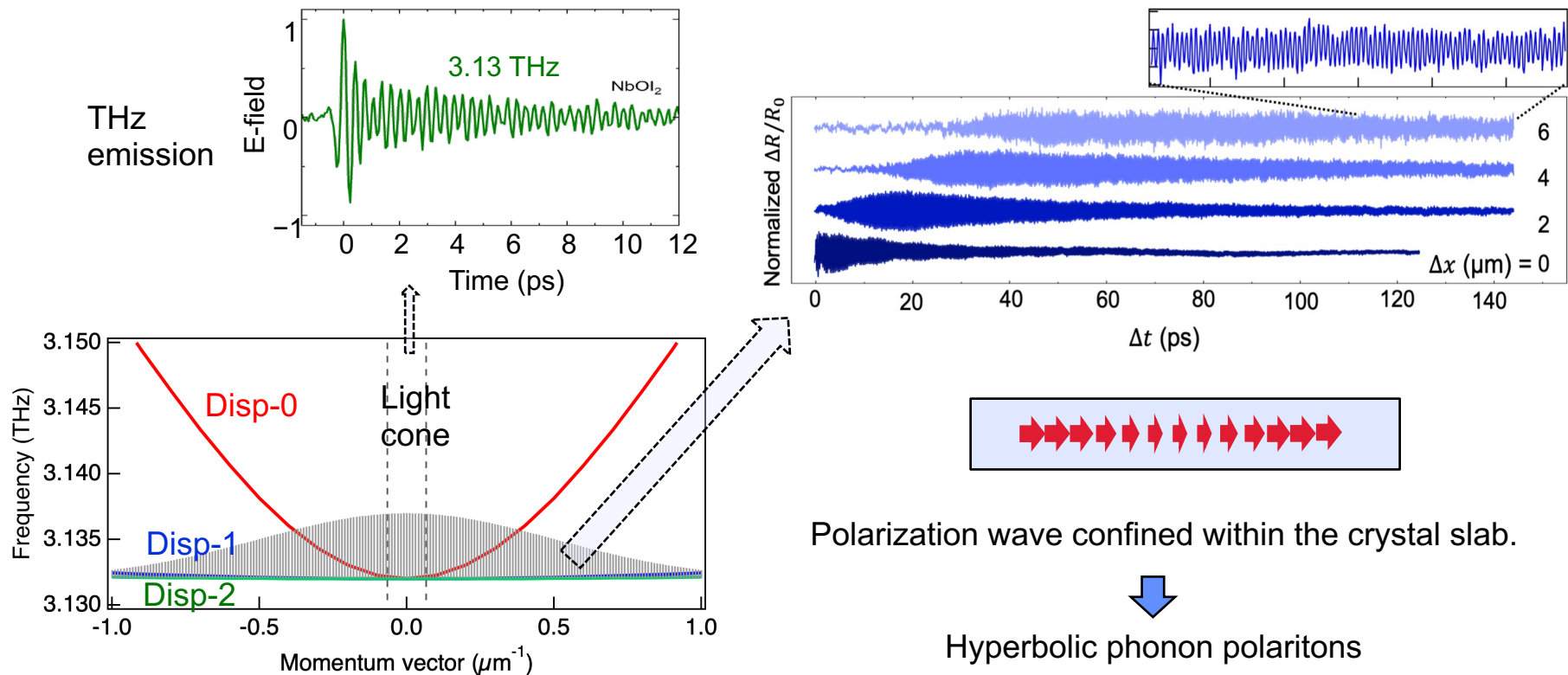


Chun-Ying Huang



arXiv:2512.06139

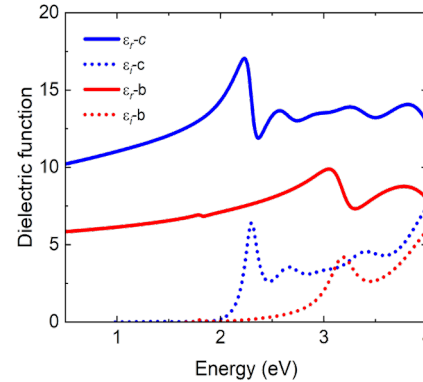
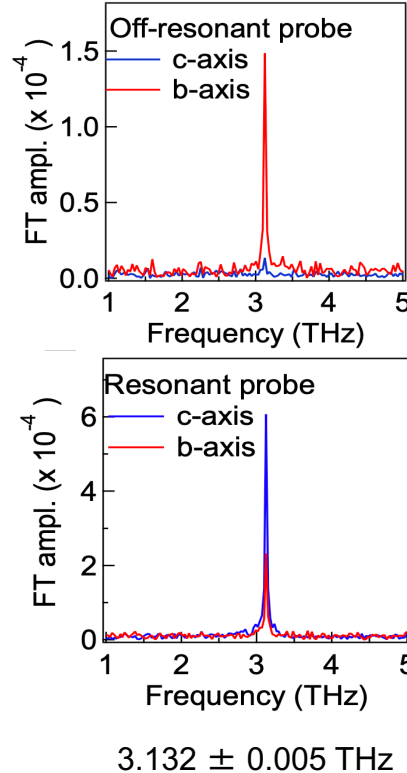
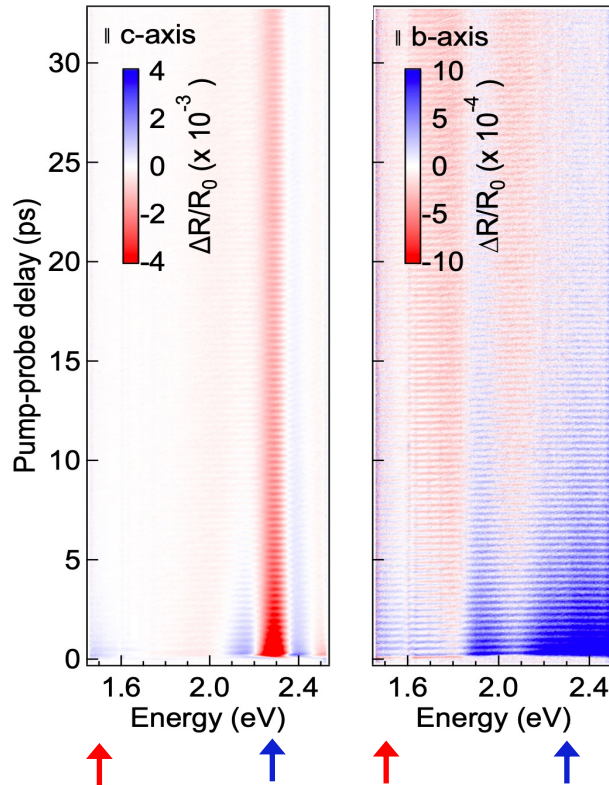
Two aspects of coherent ferrons



Exciton sensing of the coherent ferron in NbOI₂



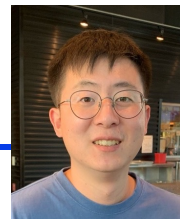
Chun-Ying Huang



- In conventional semiconductors, e- or ex-ph coupling dominated by LO phonons
- In ferroelectric semiconductor, NbOI₂, ex-ph coupling dominated by TO phonon.

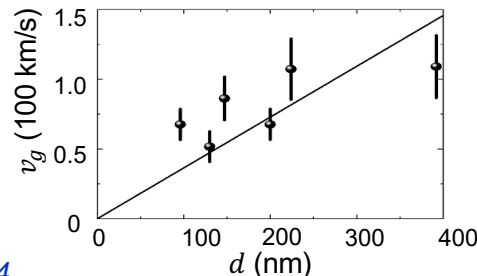
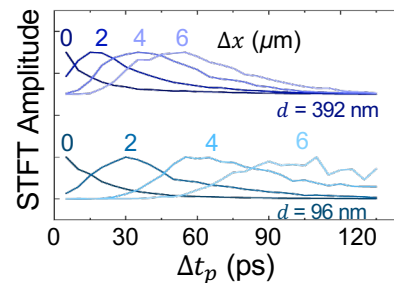
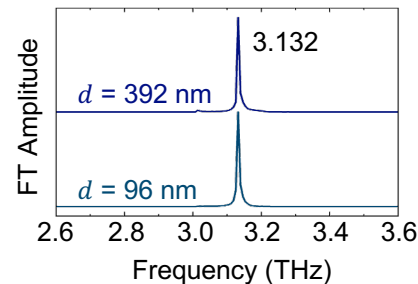
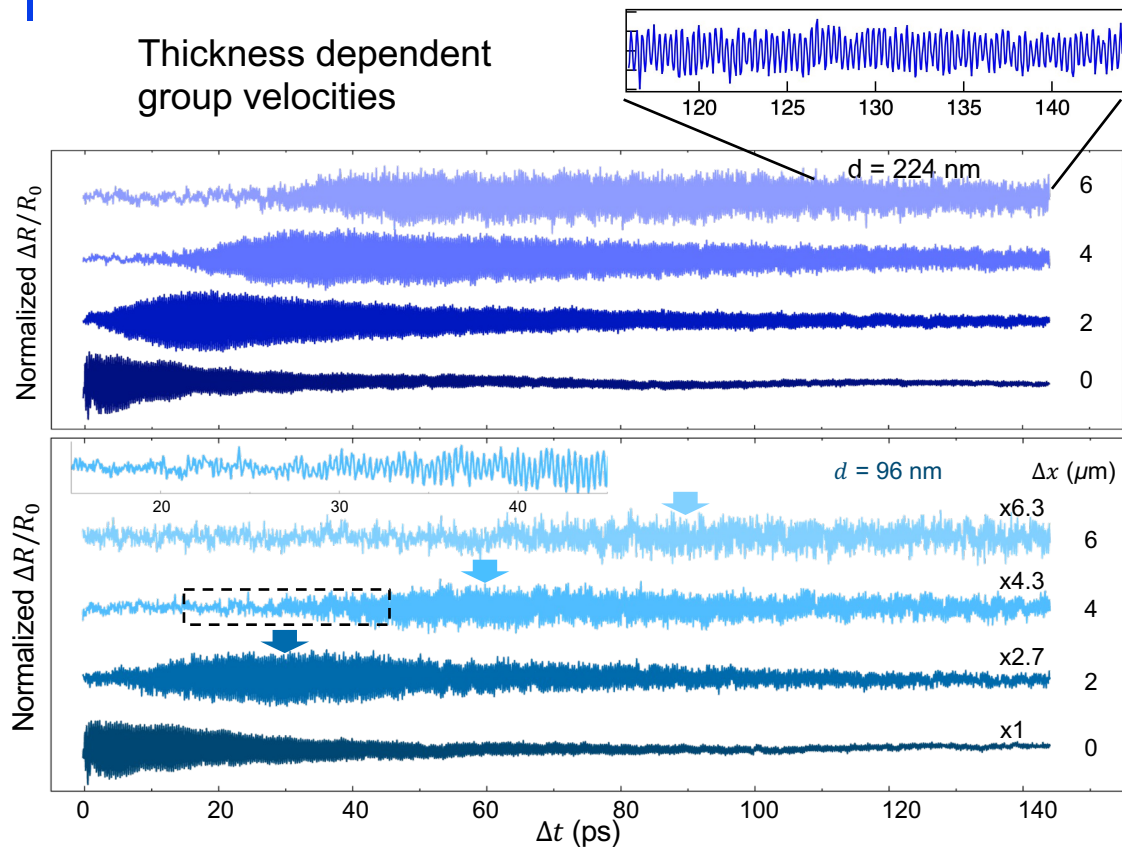
Nature Comm. **2025**, 16, 1896.

Spatially resolved exciton sensing reveals extreme group velocity, $v_g \sim 10^5$ m/s, and coherence time, $\tau_{\text{coh}} \geq 200$ ps



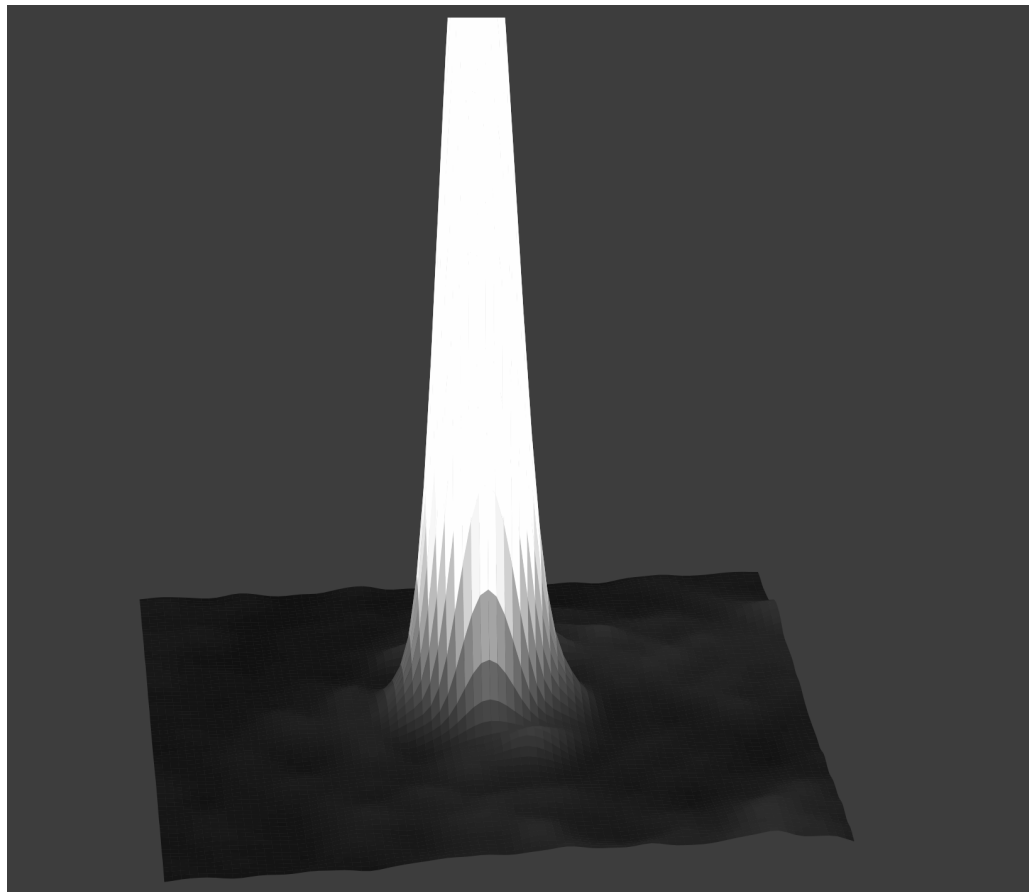
Joengheon Choe

Q = 500-1000

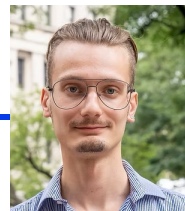


$\sim 10^{-3}$ of C,
 $\sim 10^3$ of v_{TO}

Ferron propagation: the movie



StroboSCAT imaging



Andre Liston

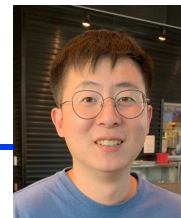


Milan Delor

$$v_g \sim 10^5 \text{ m/s}$$

Nature Mater. **2026**,
[10.1038/s41563-026-02597-4](https://doi.org/10.1038/s41563-026-02597-4)

Another defining character: extreme propagation velocity from long-range dipolar interactions



Joengheon Choe



Landau-Khalatnikov-Tani (LKT)

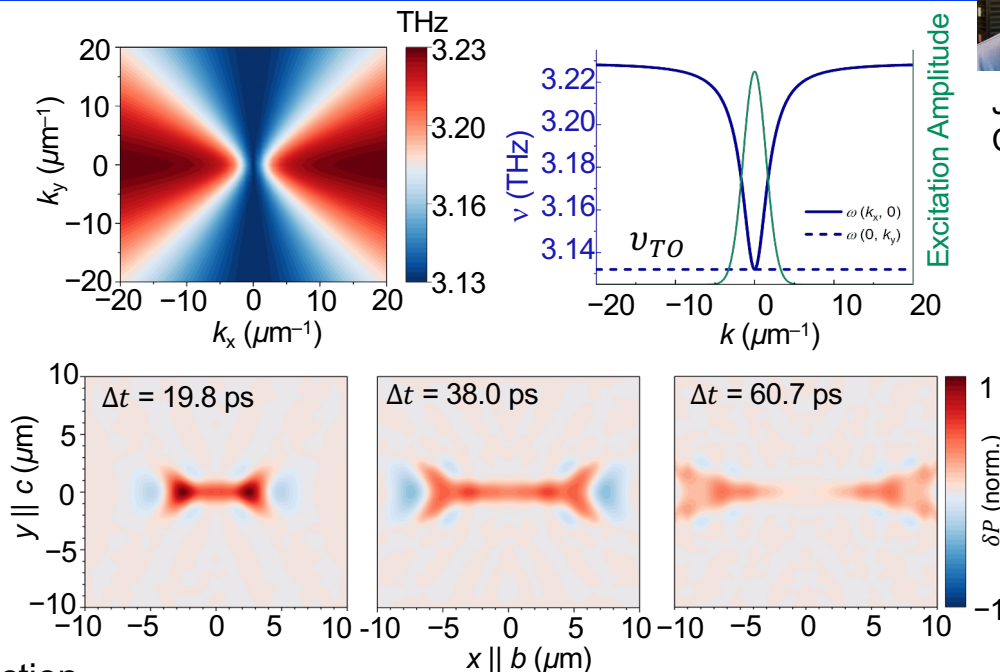
$$\frac{1}{\varepsilon_0 \omega_p^2} \frac{\partial^2 \mathbf{P}}{\partial t^2} + \rho \frac{\partial \mathbf{P}}{\partial t} = \mathbf{E}_{eff}$$

$$\mathbf{E}_{eff} = -\frac{\partial F}{\partial \mathbf{P}}$$

$$F = \frac{\alpha}{2} P_x^2 + \frac{\beta}{4} P_x^4 - \mathbf{E} \cdot \mathbf{P}$$

$$\mathbf{P}(\mathbf{r}, t) = P_x \hat{x} + \mathbf{p} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)}$$

$$\delta \mathbf{p}_q = \frac{\hbar}{m_p \omega_q} \frac{3\beta}{2\alpha} \cdot \mathbf{P}_0 \quad \text{Ferron}$$



Electrostatics = long range dipolar interaction

$$\begin{aligned} \nabla \times \mathbf{E} &= 0; \quad \nabla \cdot \mathbf{D} = 0 \\ \mathbf{D} &= \varepsilon_0 \mathbf{E} + \mathbf{P} \end{aligned} \quad \Rightarrow \quad \psi(\mathbf{r}, t) = \frac{-1}{4\pi\varepsilon_0} \int d\mathbf{r}' \frac{\nabla' \cdot \mathbf{P}(\mathbf{r}', t)}{|\mathbf{r} - \mathbf{r}'|}$$

$$v_g \sim 10^5 \text{ m/s}$$

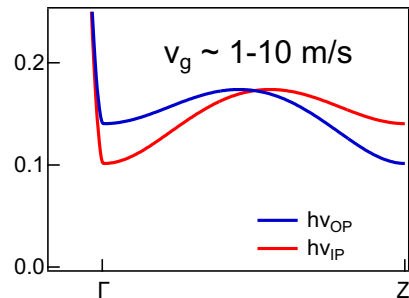
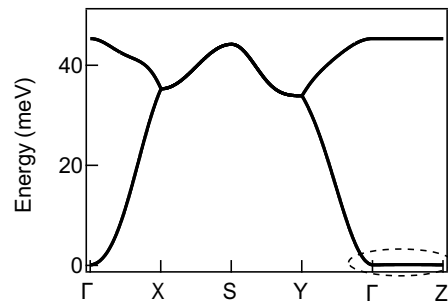
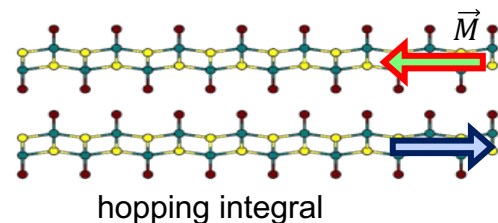
Nature Mater. **2026**, [10.1038/s41563-026-02597-4](https://doi.org/10.1038/s41563-026-02597-4)

PRB **106**, L081105 (2022); *Ferroelectrics* **300**, 43–55 (2004); *Chinese Phys. Lett.* **40**, 087103 (2023)

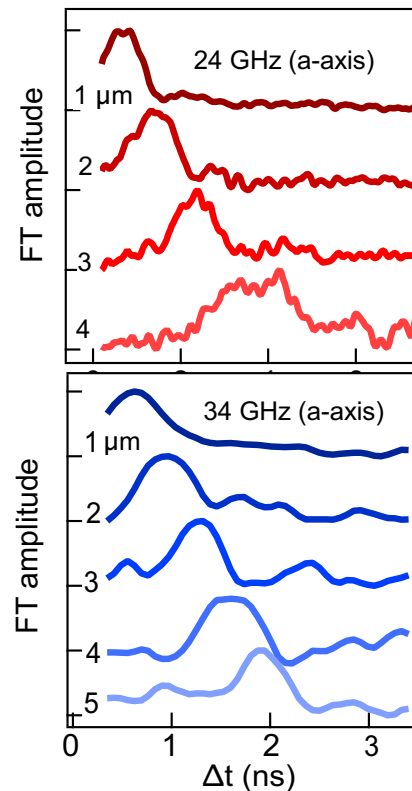
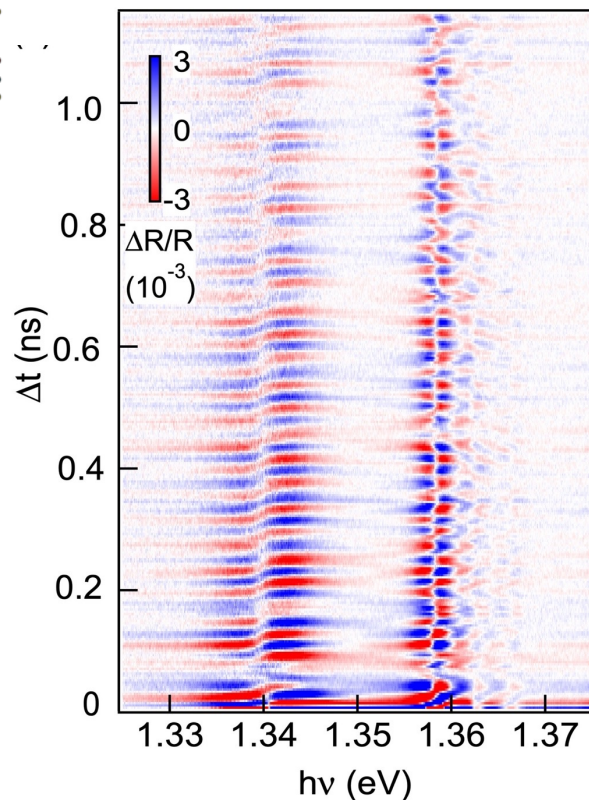
A comparison to coherent magnons in CrSBr: why do they move so fast?



Eunice Bae
(Cornell)



$$t \propto \langle S_1 | S_2 \rangle = \cos(\theta/2)$$



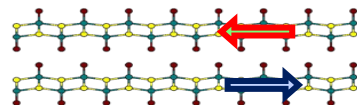
$$v_g = 3 \text{ km/s}$$

$$1 \text{ km/s}$$

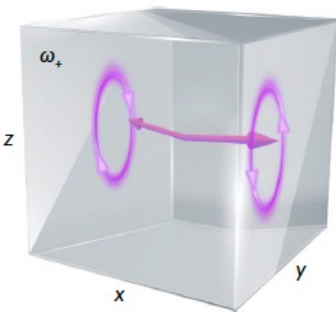
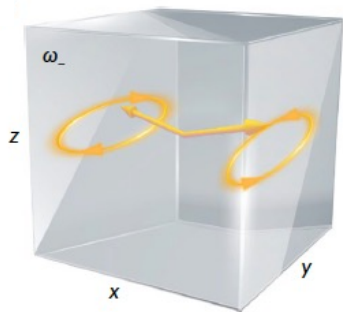
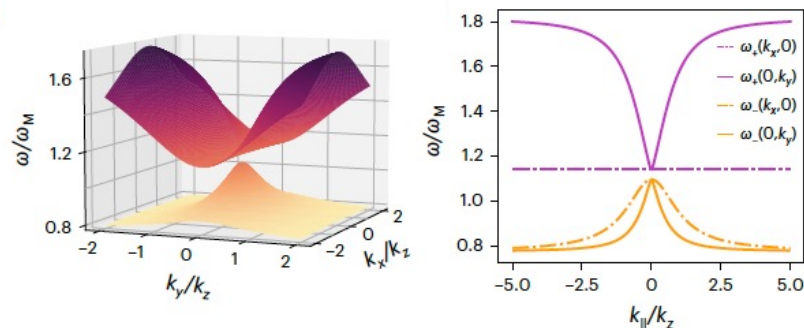
Dipolar spin wave packet transport in a van der Waals antiferromagnet

Yue Sun^{1,2}, Fanhao Meng^{2,3}, Changmin Lee^{2,4}, Aljoscha Soll⁵,
Hongrui Zhang^{2,3}, Ramamoorthy Ramesh^{1,2,3}, Jie Yao^{2,3},
Zdeněk Sofer⁵ & Joseph Orenstein^{1,2}✉

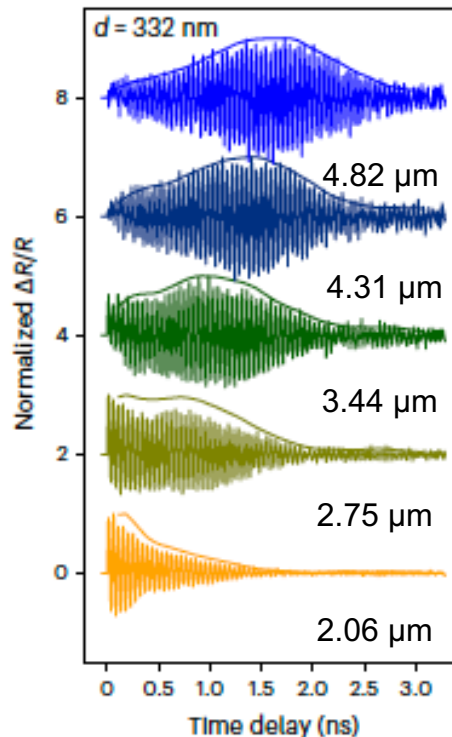
Nature Phys. **2024**, 20, 794-800



CrSBr



Group velocities are increased by $10^3 \times$ to $\sim \text{km/s}$



Landau–Lifshitz equation

$$\frac{\partial \mathbf{M}_i}{\partial t} = -\gamma \mathbf{M}_i \times \mathbf{H}_i^{\text{eff}}$$

$$\mathbf{H}_i^{\text{eff}} = -\frac{\partial F}{\partial \mathbf{M}_i} + \mathbf{h}_i(t)$$

$$F = F_{\text{ex}} + F_{\text{a}}$$

$$F_{\text{ex}} = J \frac{\mathbf{M}_1 \cdot \mathbf{M}_2}{M_s^2}$$

$$F_{\text{a}} = K_z \frac{M_{1z}^2 + M_{2z}^2}{M_s^2} - K_x \frac{M_{1x}^2 + M_{2x}^2}{M_s^2}$$

Magnetostatics

$$\nabla \times \mathbf{B} = 0; \quad \nabla \cdot \mathbf{B} = 0$$



Long-range dipolar

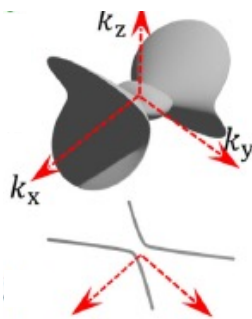
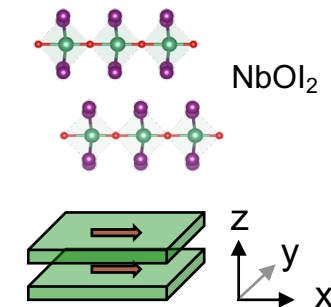
Coherent ferron & hyperbolic phonon polariton

$$\varepsilon \approx \begin{pmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}$$

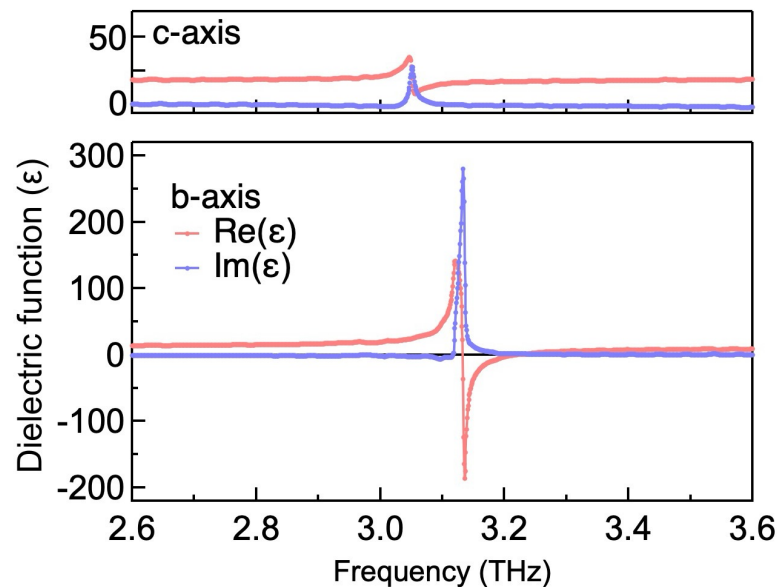
Electrostatic approximation

$$\varepsilon_{xx} \frac{\partial^2 \psi}{\partial x^2} + \varepsilon_{yy} \frac{\partial^2 \psi}{\partial y^2} + \varepsilon_{zz} \frac{\partial^2 \psi}{\partial z^2} = 0$$

$$\frac{k_x^2}{\varepsilon_{xx}} + \frac{k_y^2}{\varepsilon_{yy}} + \frac{k_z^2}{\varepsilon_{zz}} = \left(\frac{2\pi}{\lambda_0}\right)^2$$

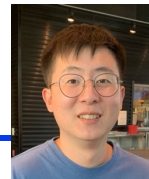


$$\begin{aligned} \text{Re}(\varepsilon_{xx}) &< 0; \\ \text{Re}(\varepsilon_{yy}), \text{Re}(\varepsilon_{zz}) &> 0 \end{aligned}$$



A coherent ferron at $q > k_{hv}$ is an in-plane, canalized, hyperbolic phonon polariton specific to the ferroelectric TO mode

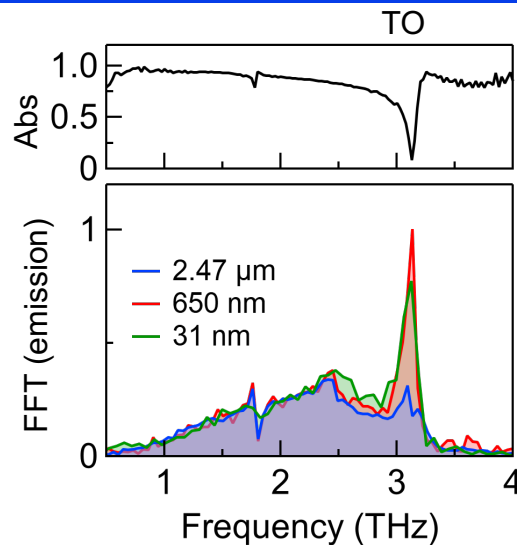
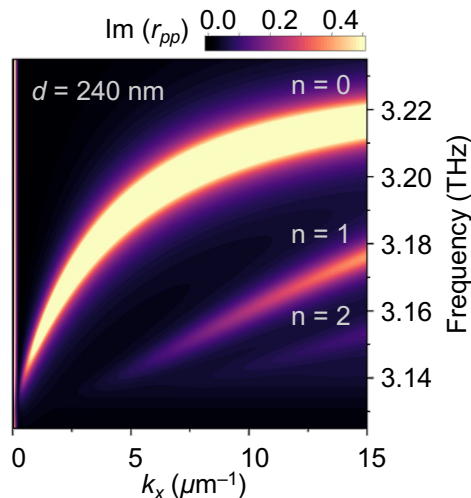
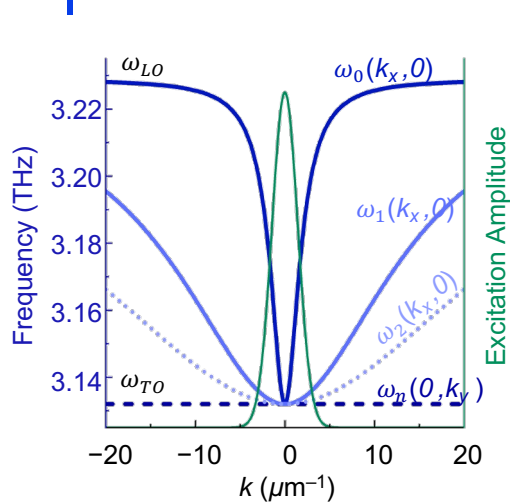
Coherent ferron: ~100% matter wave?



Joengheon Choe



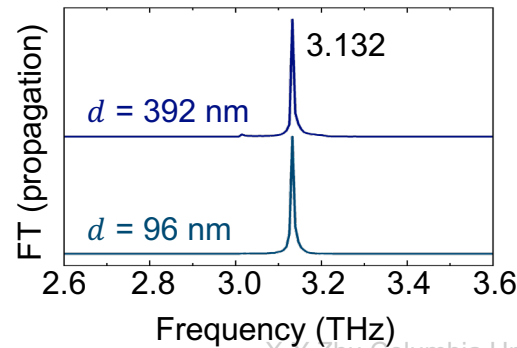
Fuyang Tay
(D. Basov)



$$\omega(\mathbf{k}) = \omega_p \left(1 + \frac{K_x}{2} \frac{k_x^2}{k_x^2 + k_z^2} \right)$$

$$k_z = \frac{K_0 + n\pi}{2} \quad (n = 0, 1, 2, \dots)$$

**A coherent ferron is
~100% matter wave.**



A comparison of coherence times

In-plane anisotropic and **ultra-low-loss** polaritons
in a natural van der Waals crystal

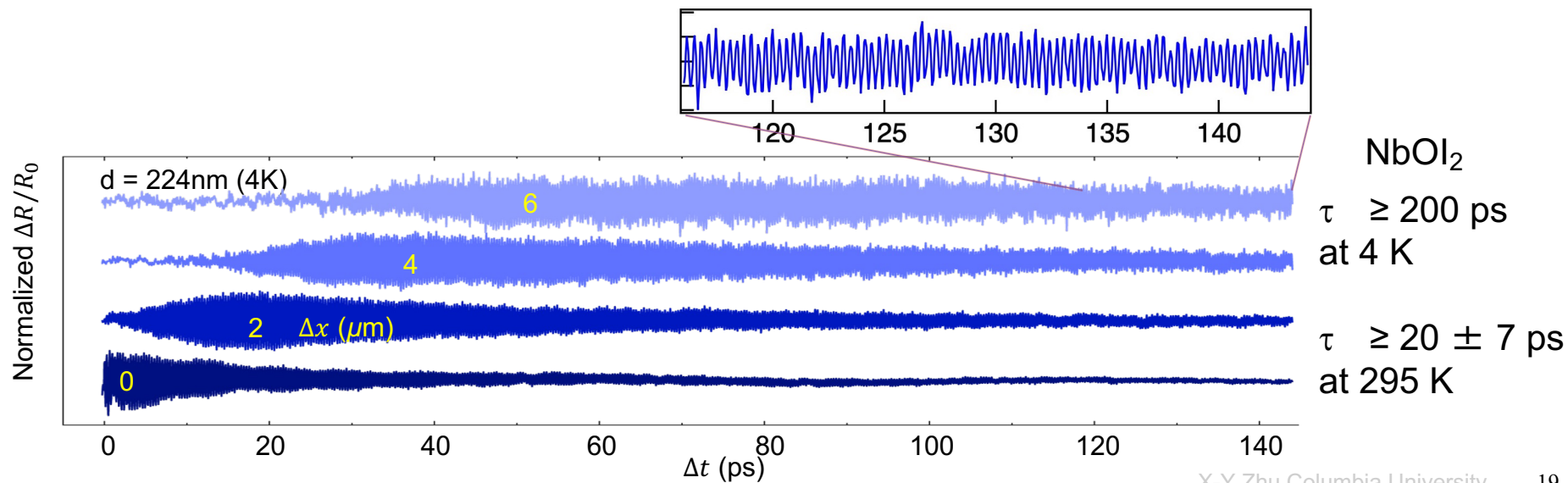
Ma *et al.*, *Nature* **2018**, 562, 577

α -MoO₃, $\tau = 2$ ps
(in-plane hyperbolic)

Ultralow-loss polaritons in isotopically pure
boron nitride

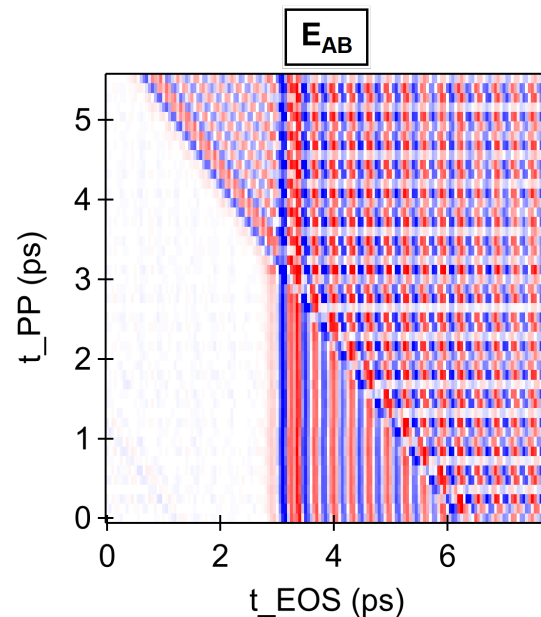
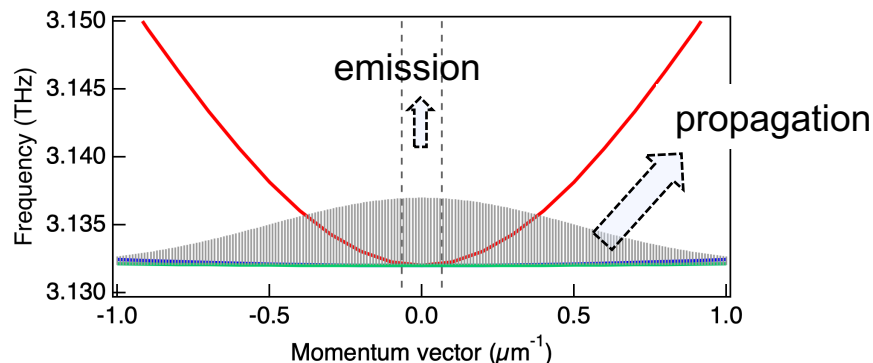
Giles *et al.* *Nature Mat.* **2018**, 17, 134

h-BN, $\tau = 2$ ps



Summary & Acknowledgement

- Experimental observation of coherent ferrons
- Intense emission at the TO phonon frequency
- Extraordinary propagation at $v_g \sim 10^5$ m/s
- Long coherence time exceeding 200 ps
- Ultra-confined THz waves $\rightarrow$ ferronics & 6G?



Jeongheon Choe^{1,3}, Taketo Handa^{1,3}, Chun-Ying Huang¹,
André Koch Liston¹, Jordan Cox¹, Jonathan Stensberg^{1,2},
Yongseok Hong¹, Daniel G. Chica¹, Ding Xu¹, Fuyang Tay^{1,2},
Samra Husremovic¹, Vinicius da Silveira Lanza Avelar¹, Eric A. Arsenault¹,
Zhuquan Zhang¹, James McIver², Dmitri N. Basov², Milan Delor¹,
Xavier Roy¹ & X.-Y. Zhu¹

Funding:
US-ARO, W911NF-23-1-0056.
US-NSF-MRSEC, DMR-2011738.
US-AFOSR, FA9550-22-1-0389.