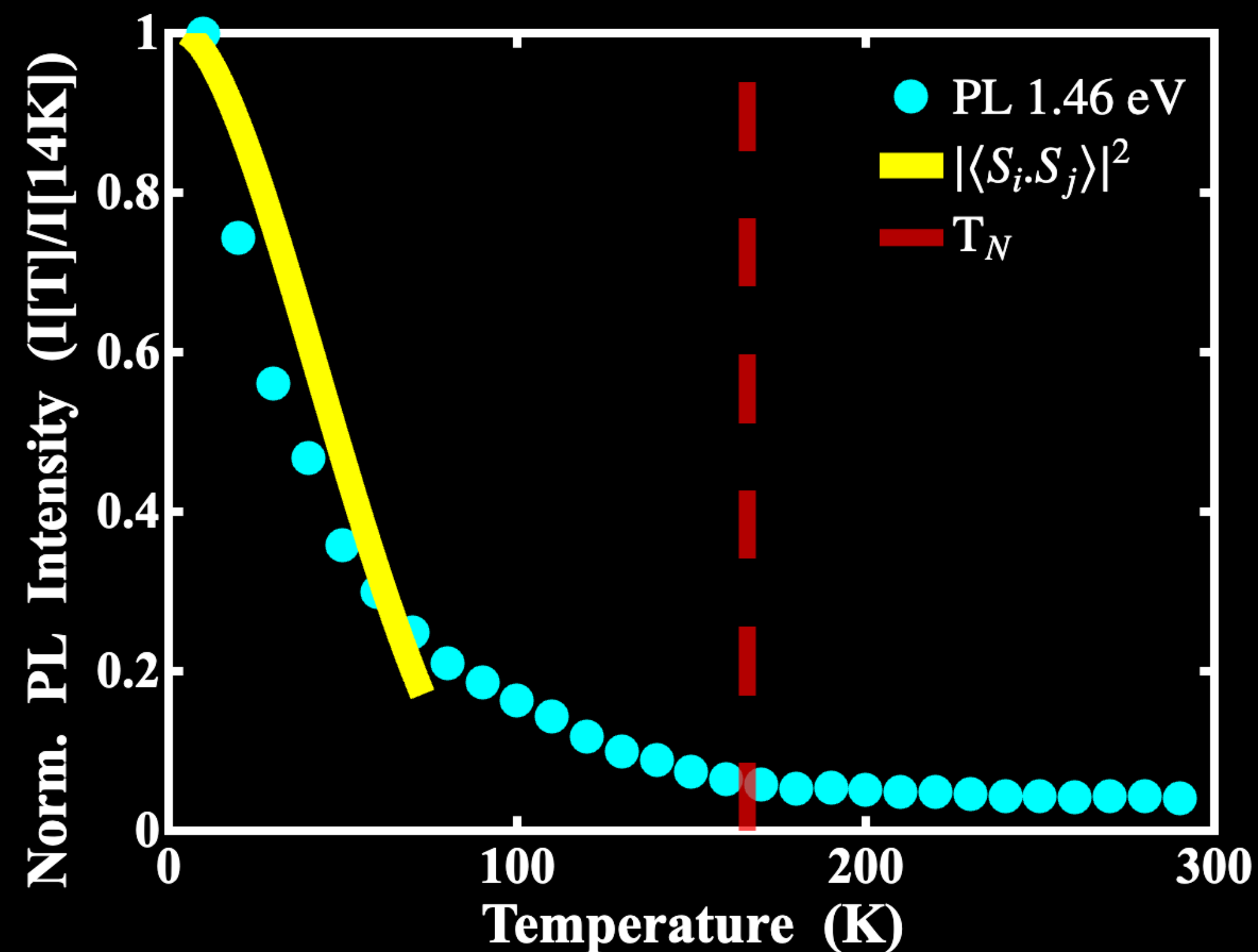
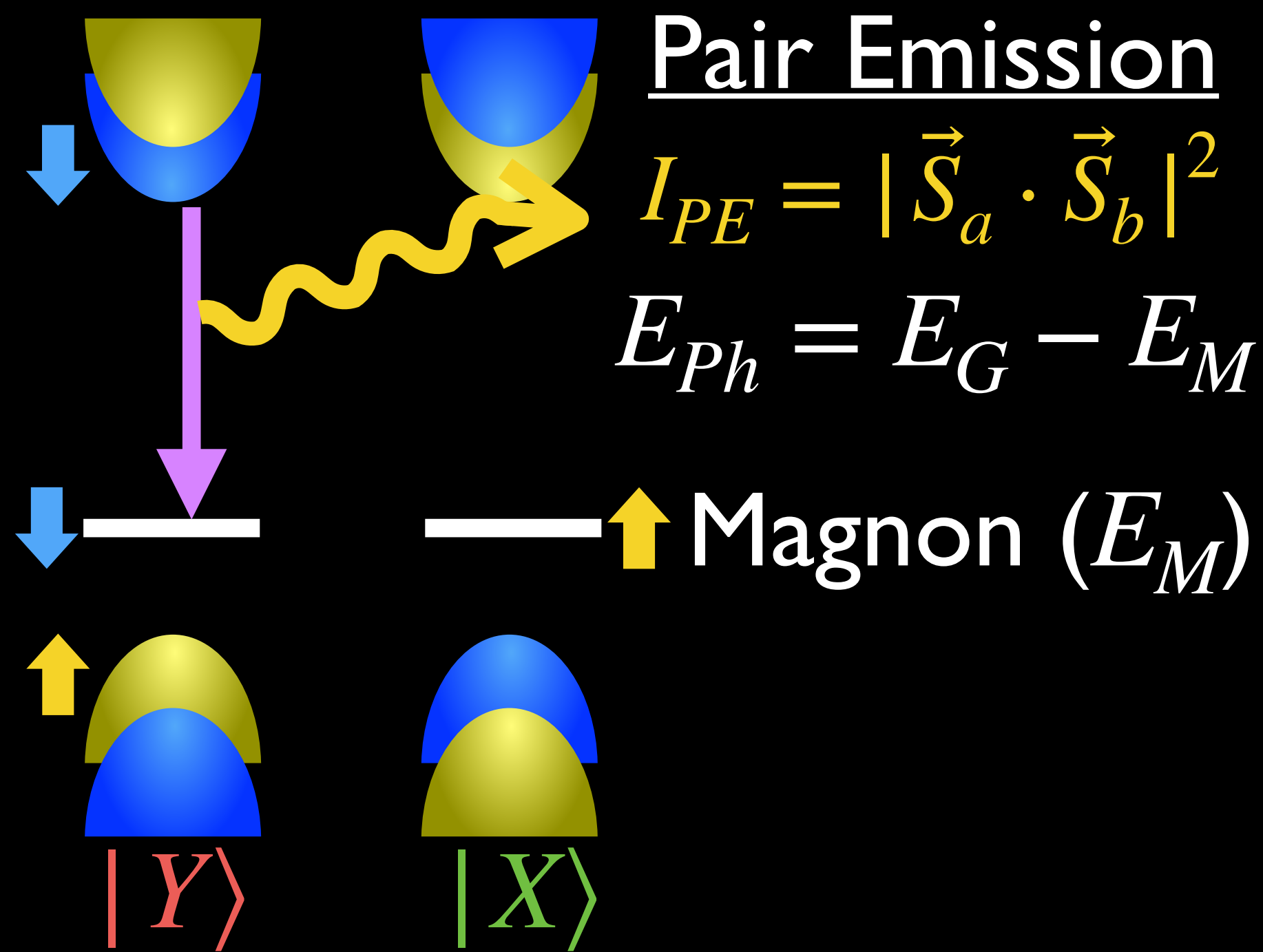
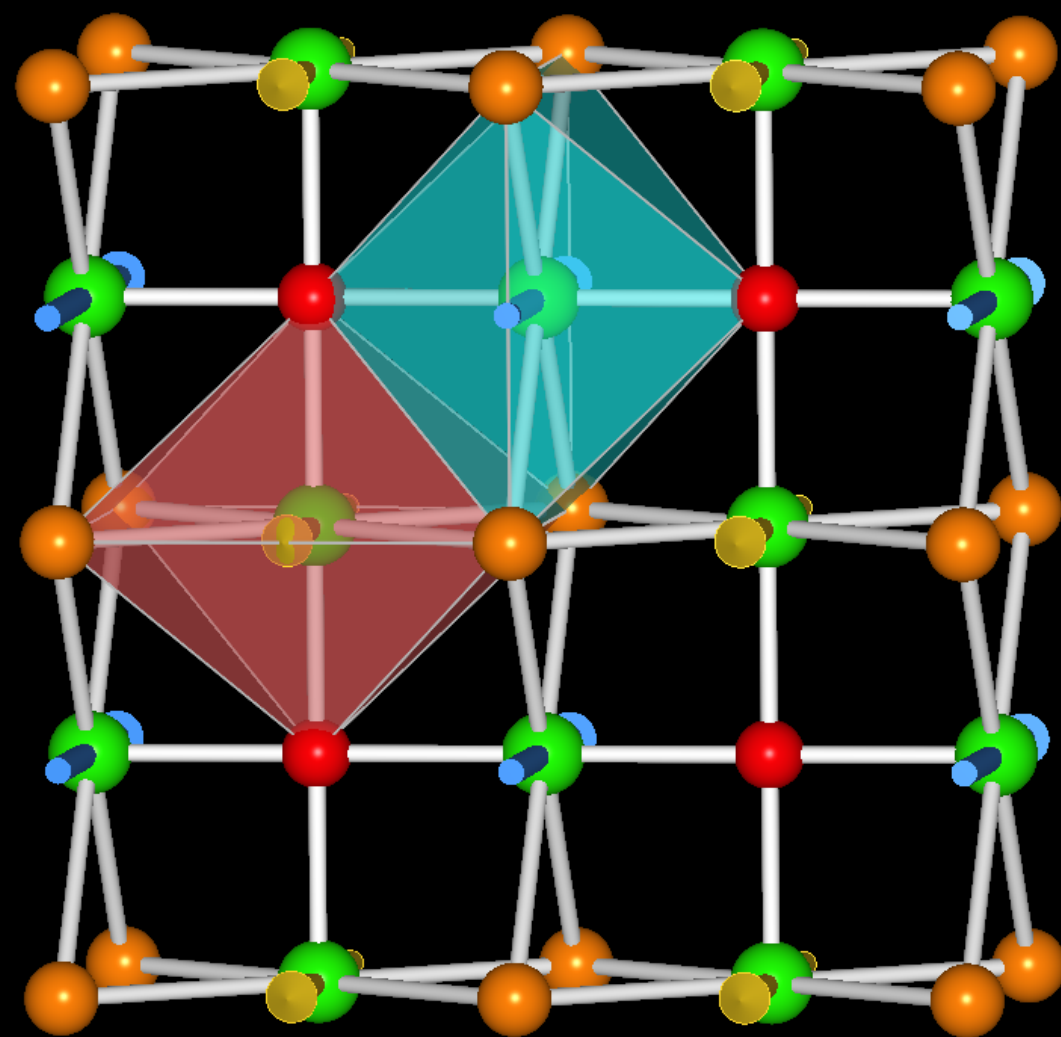


# Discovering and Understanding Emergence with Light

K.S. Burch, Boston College

Mott Insulating  
Altermagnet



BURCH GROUP

burchlab.org

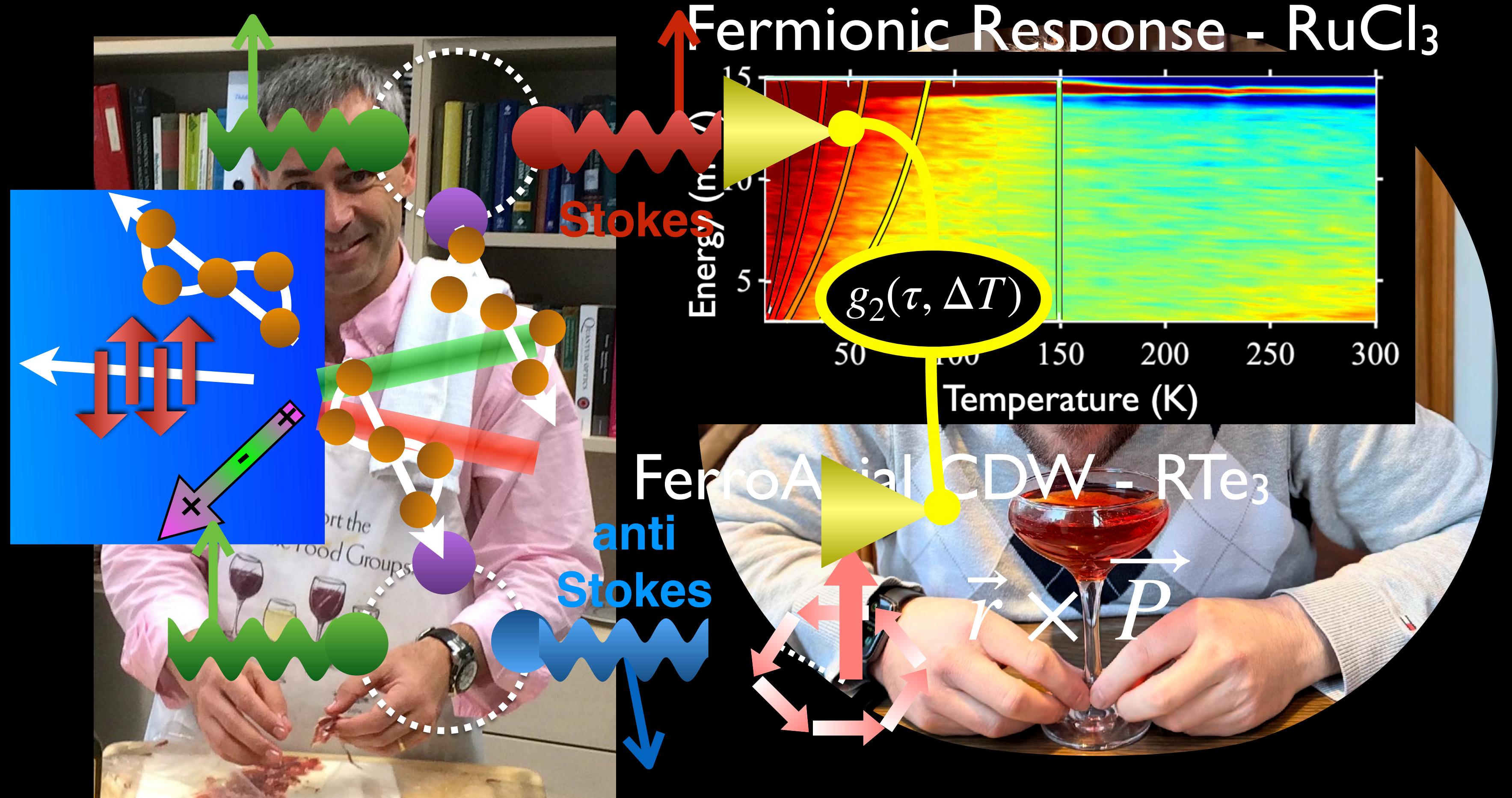
# Discovering and Understanding Emergence with Light

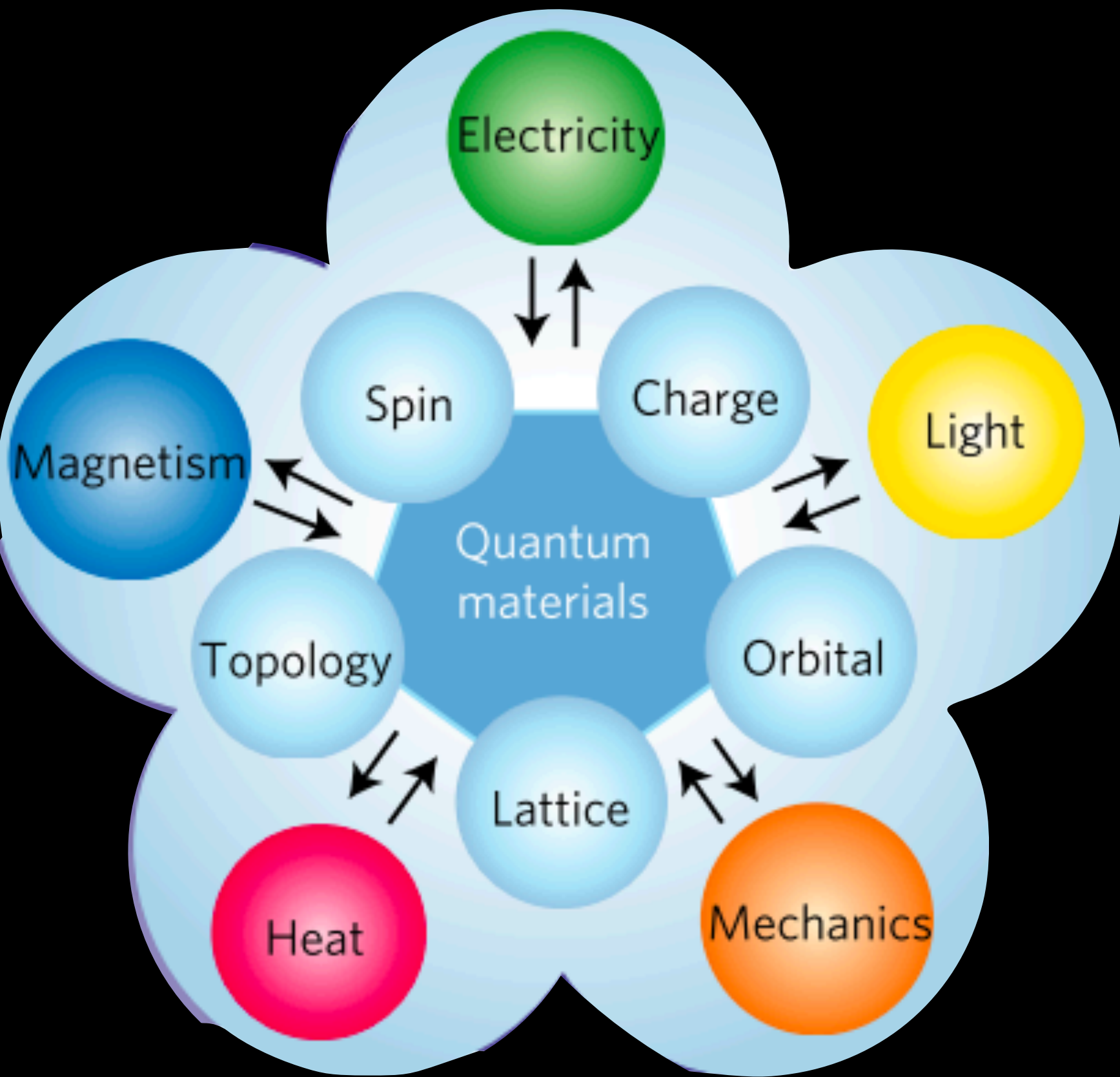
K.S. Burch, Boston College

- Challenge

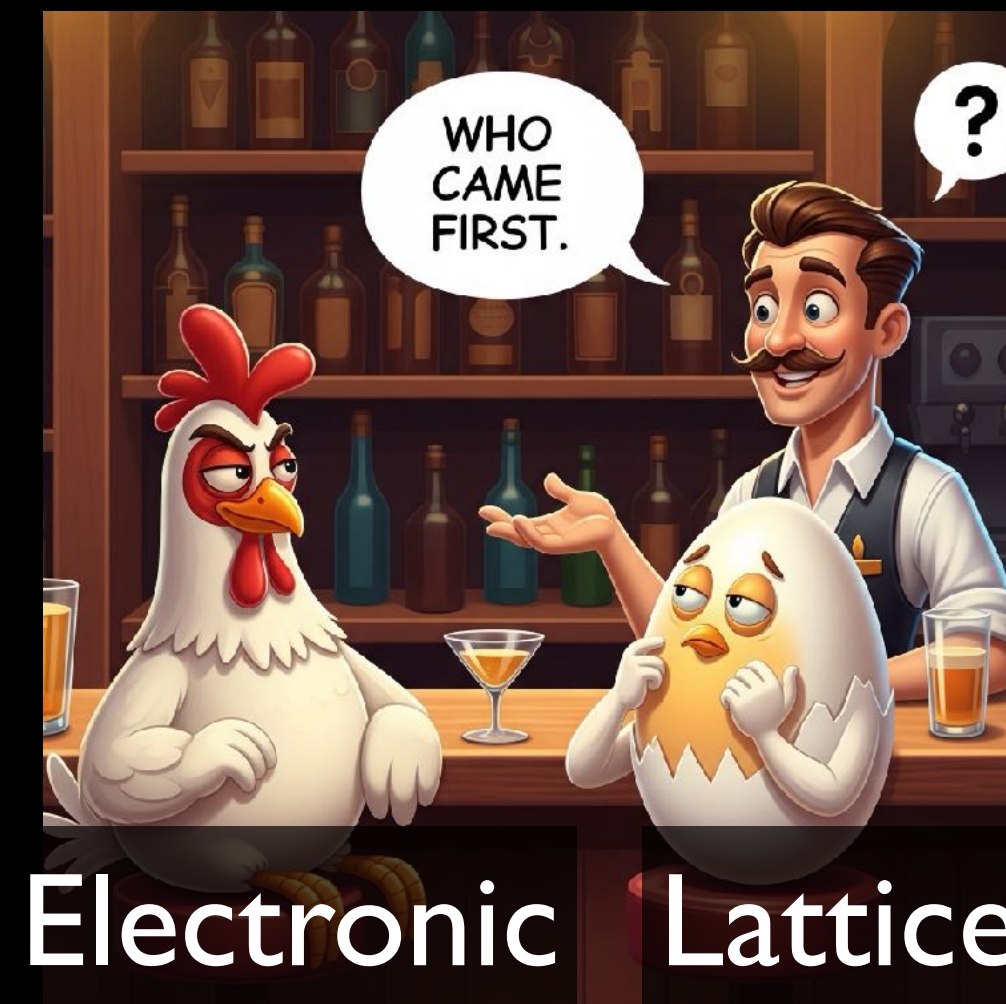
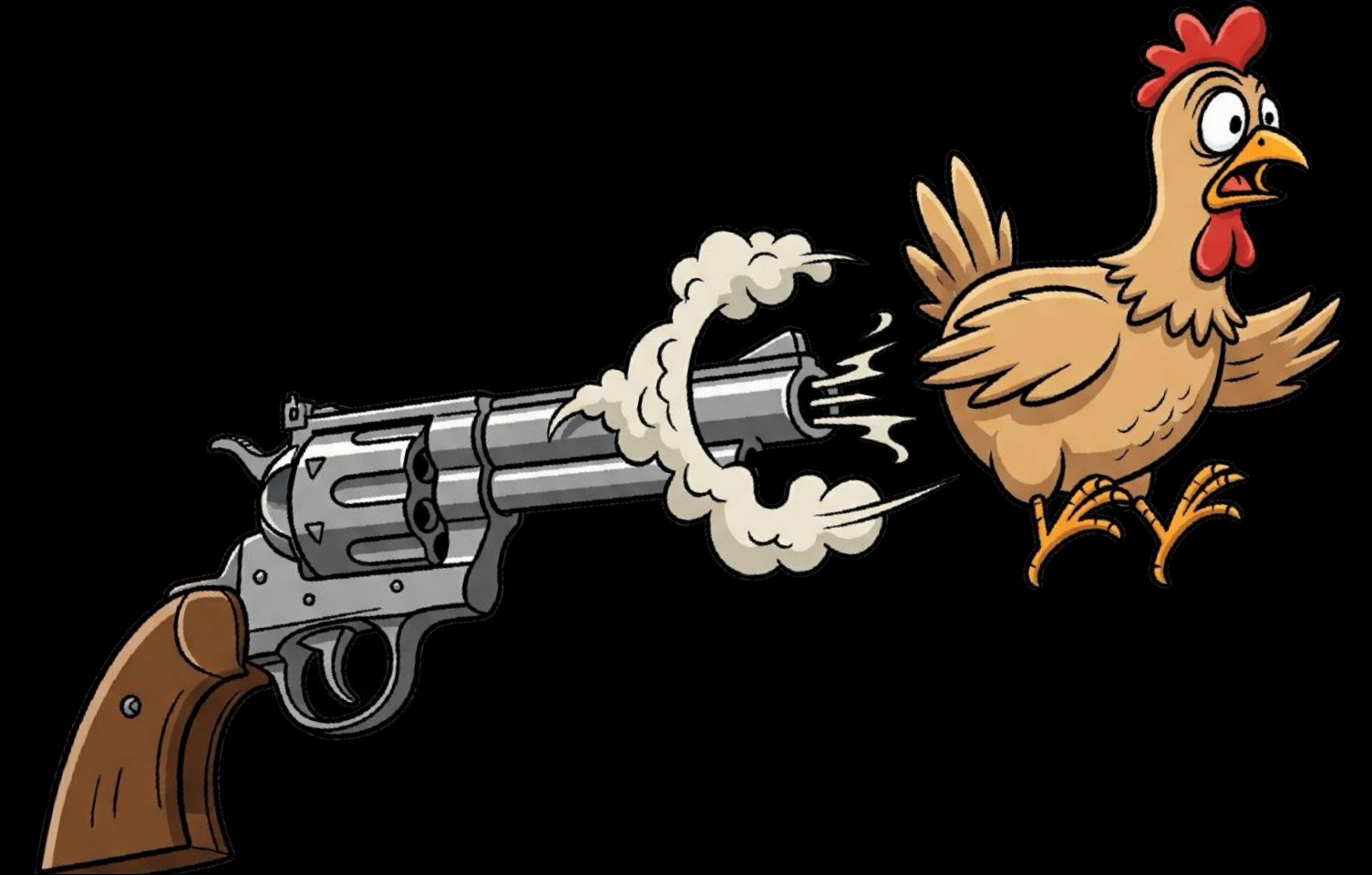
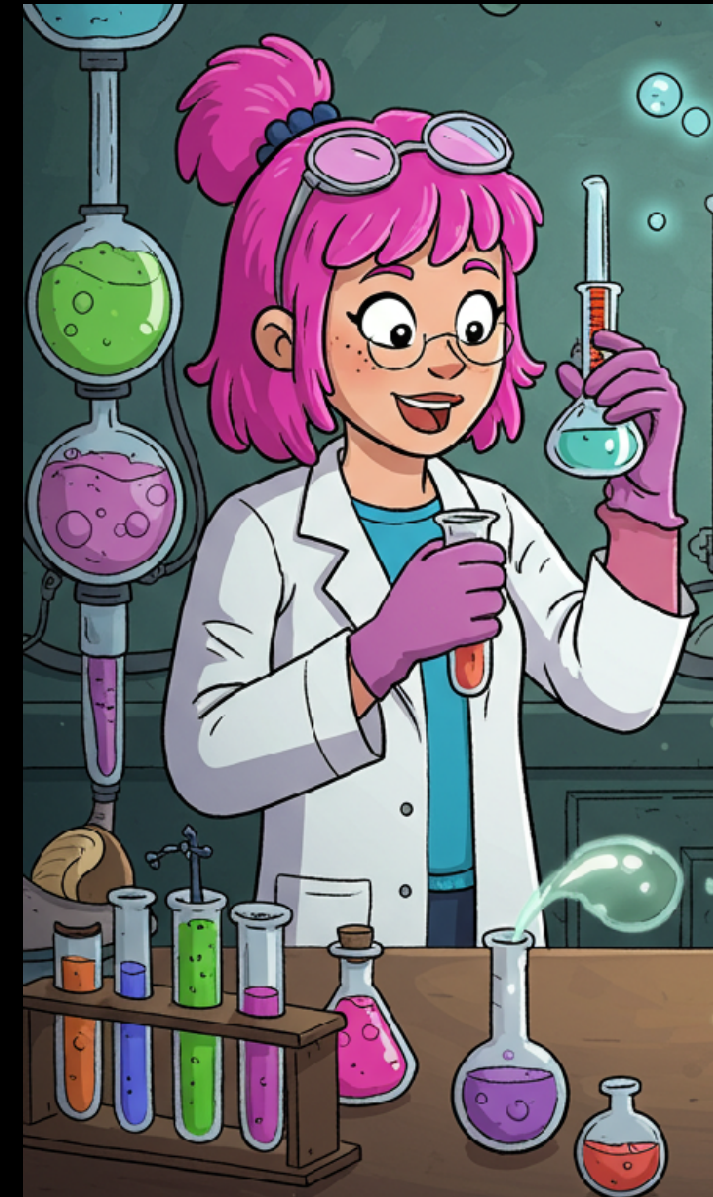
- Raman

- QuILS

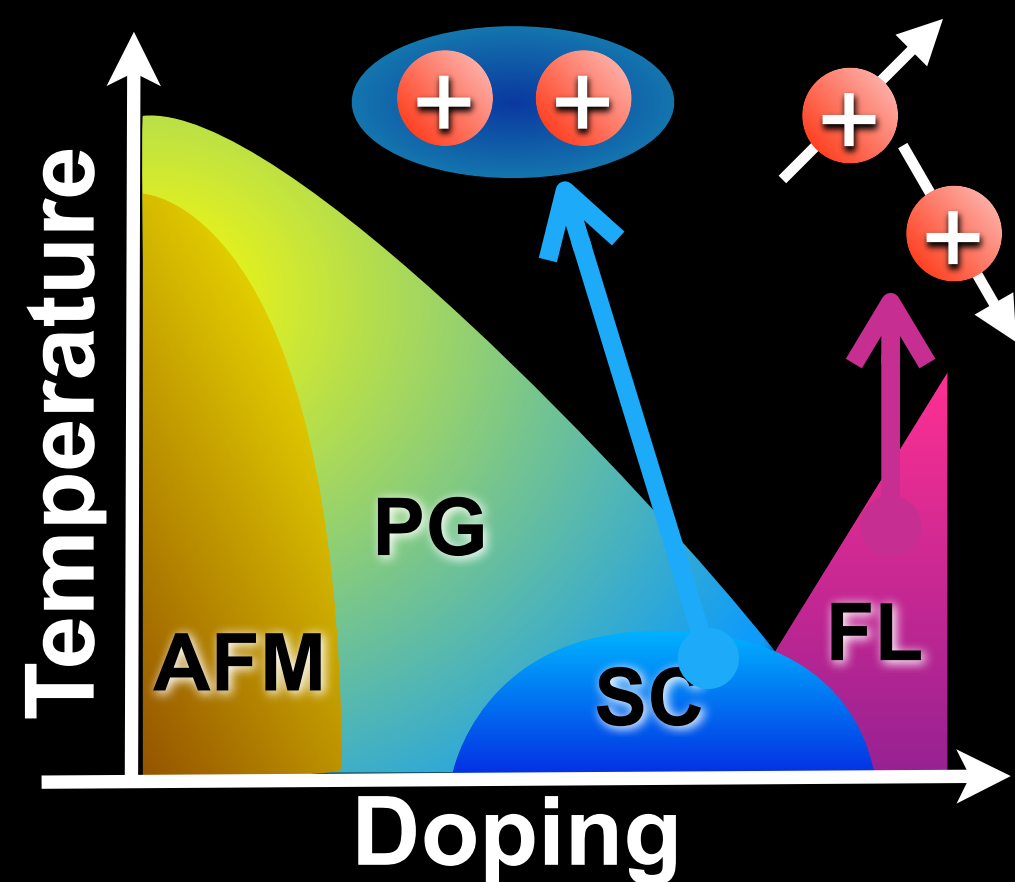




Y. Tokura et al., Nature Physics (2017)



What's  
Quantum  
about  
Quantum  
Materials?



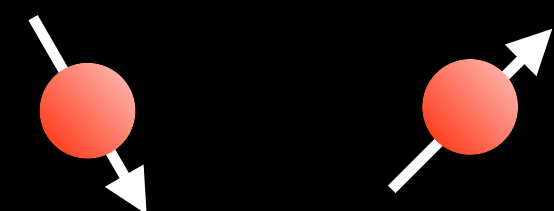
What if no symmetry is broken?  
QSL or FQH - purely by wavefunction!

$$|\psi_1\psi_2\rangle = e^{i\frac{H(r)t}{\hbar}} |\psi_2\psi_1\rangle = e^{i\theta} |\psi_2\psi_1\rangle$$

**Bosons**  
 $\Theta_B = 2\pi$



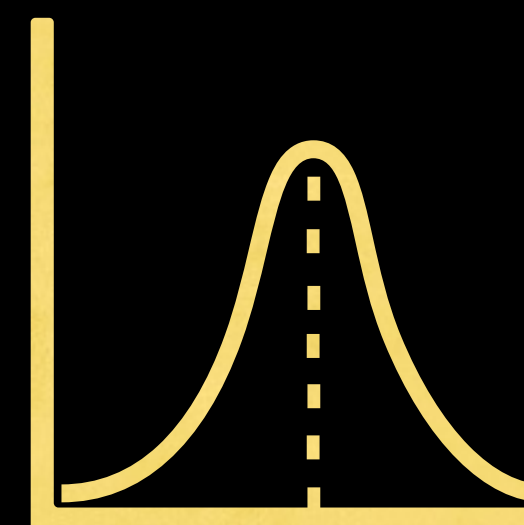
**Fermions**  
 $\Theta_F = \pi$



**Anyons**  
 $\Theta_A = ??$

● **Challenge**

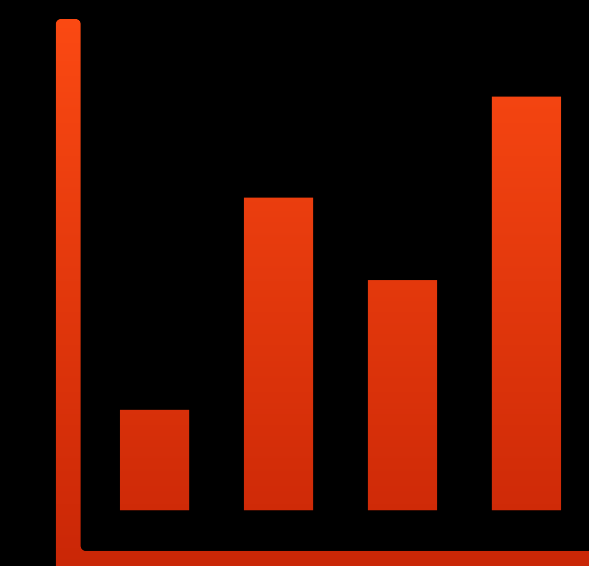
Energy



Cn, Mirrors



Statistics



**Laboratory for  
Assembly &  
Spectroscopy of  
Emergence**

Spin-Orbit



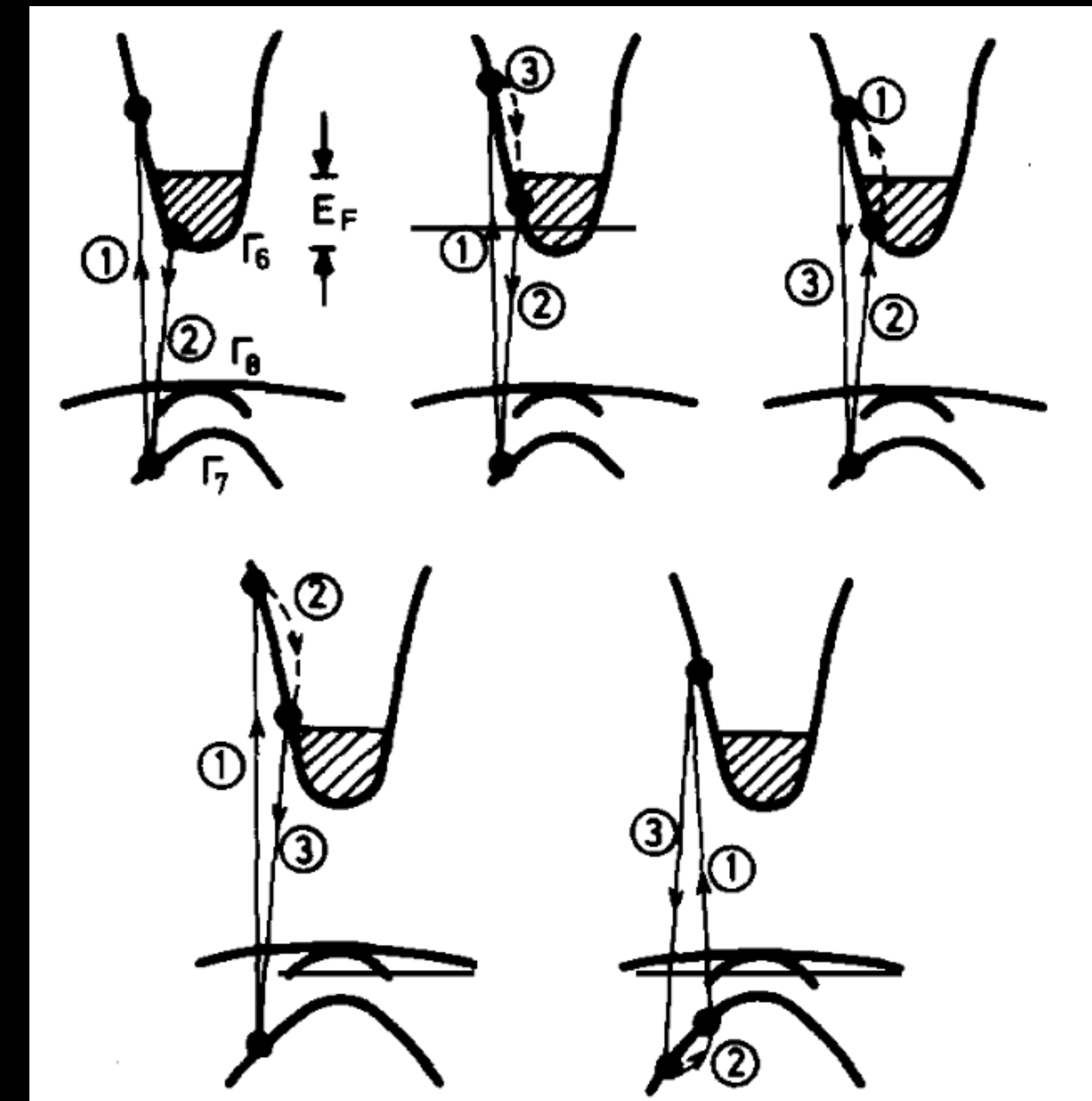
Symmetry  
Breaking

Raman

$$\vec{P} = \alpha \vec{E} = \left( \alpha_0 + \frac{d\alpha}{d\hat{O}} \delta\hat{O} \right) \vec{E}$$

Generate Sidebands

## Quantum



**Solid State Comm. 30, 429 (1979)**

$$I_{ij}(\omega) = |\hat{e}_i \cdot R_{ij} \cdot \hat{e}_j|^2 \rightarrow \text{Symmetry}$$

$$\hat{O} = \hat{a} \rightarrow \text{Phonon}$$

$$\hat{O} = f(\hat{S} \cdot \hat{S}) \rightarrow \text{Magnons/Spinons}$$

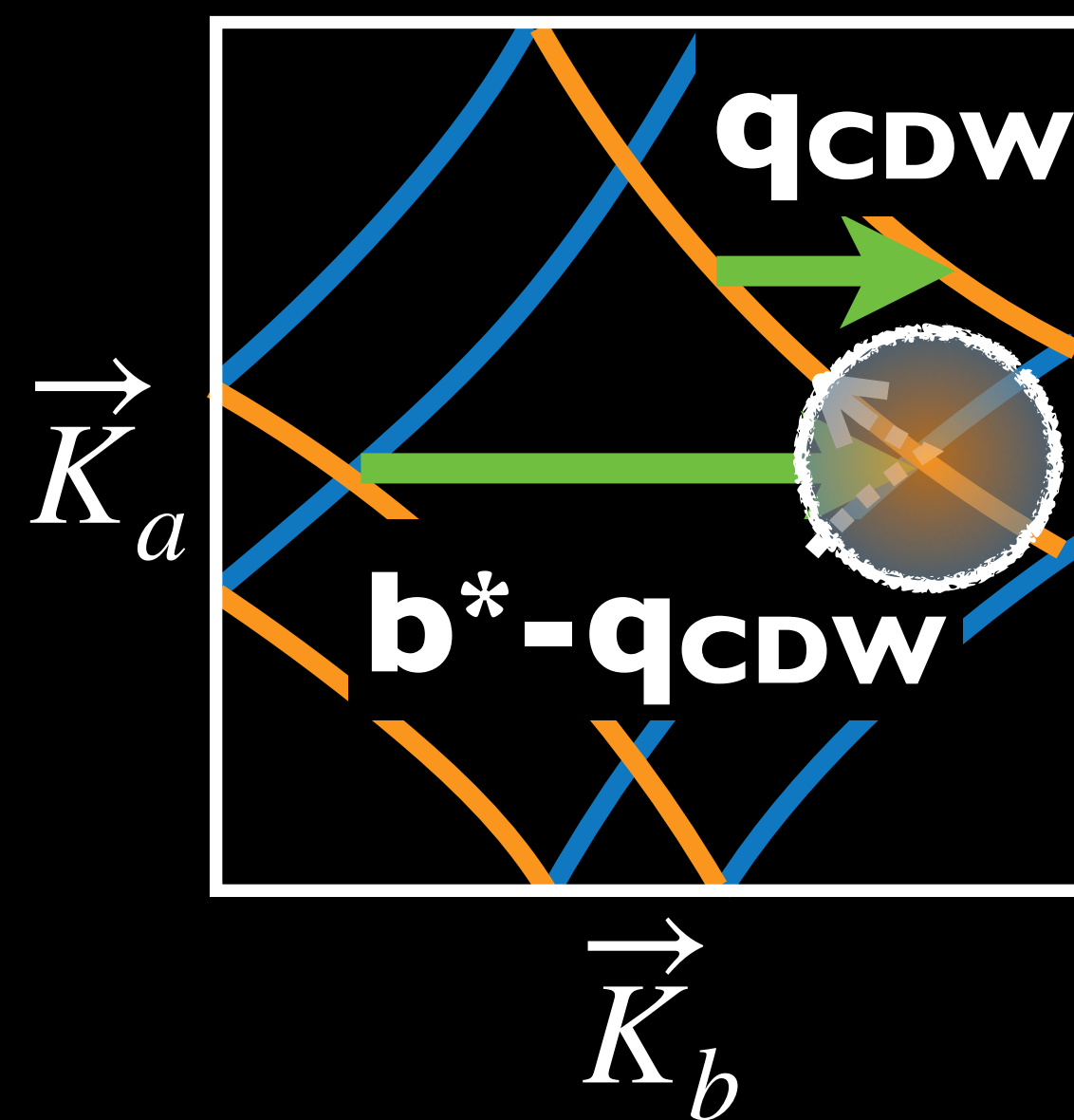
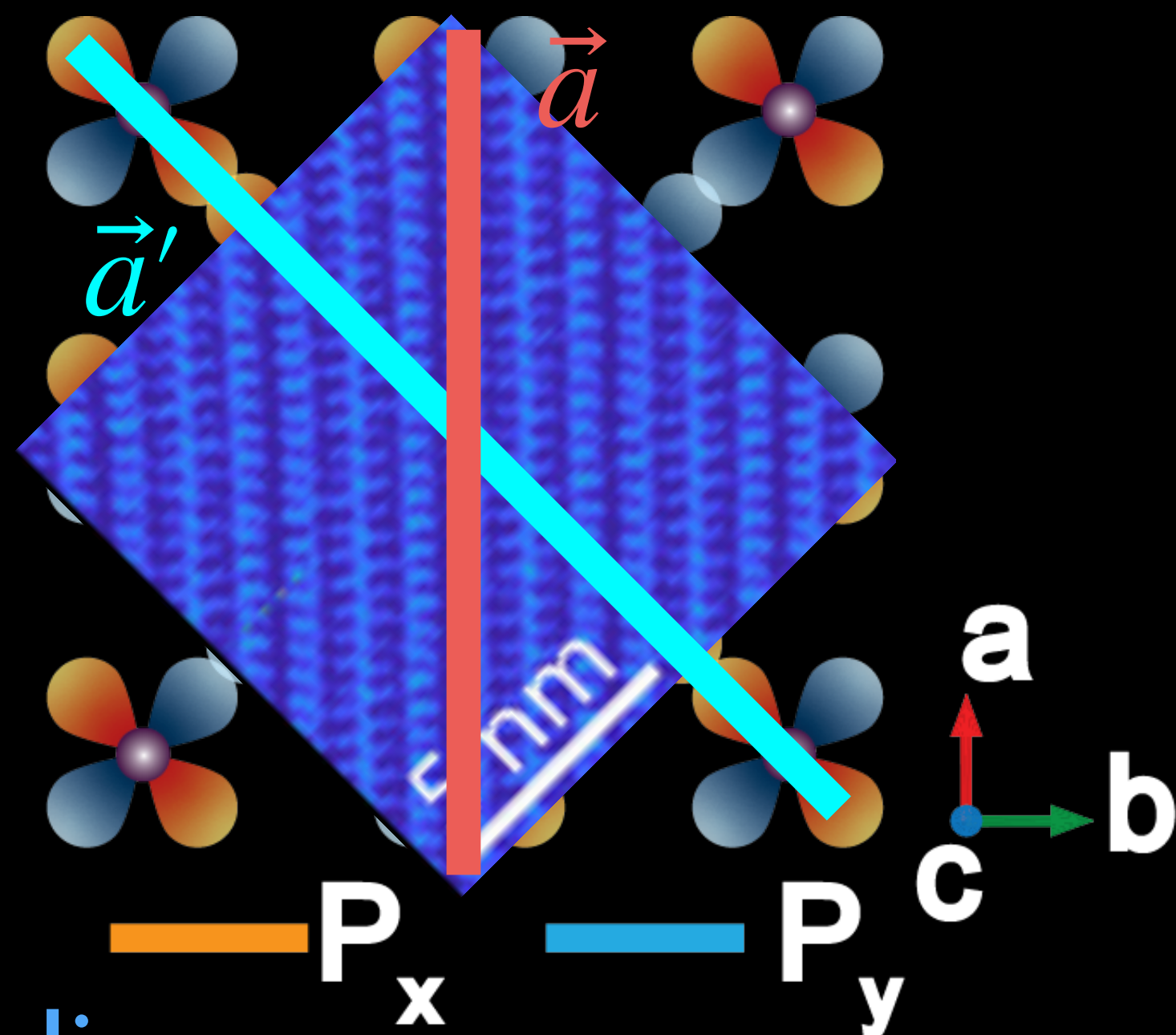
$$\hat{O} = f(\hat{\rho} \cdot \hat{\rho}) \rightarrow \text{electrons}$$

PRB 13, 169 (1976)

Proc. Phys. Soc. 86, 699 (1965)

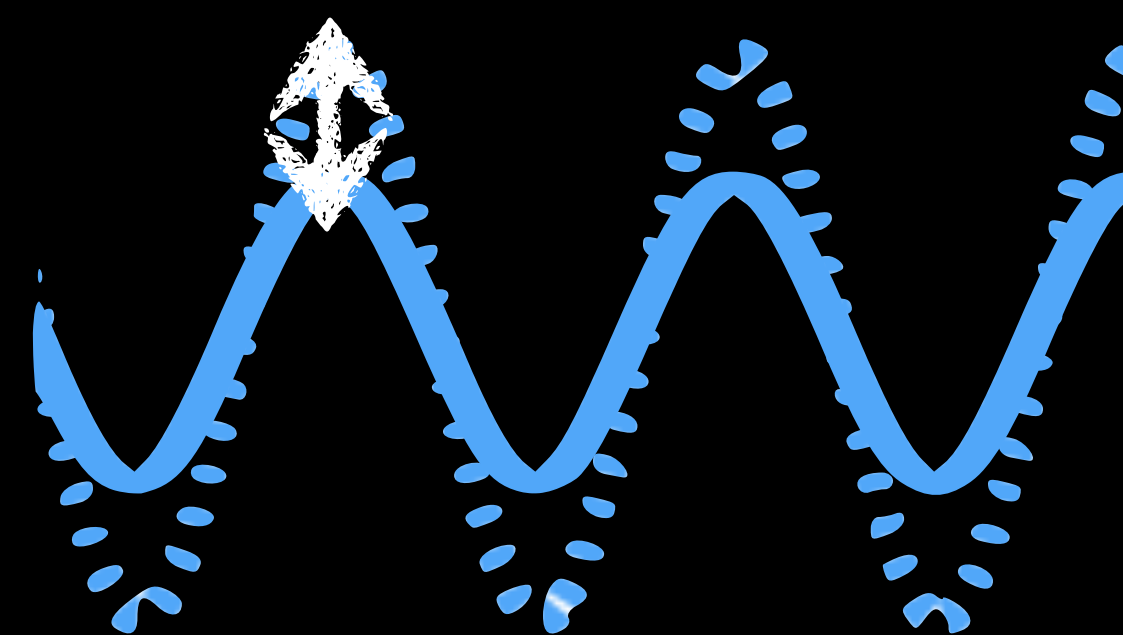
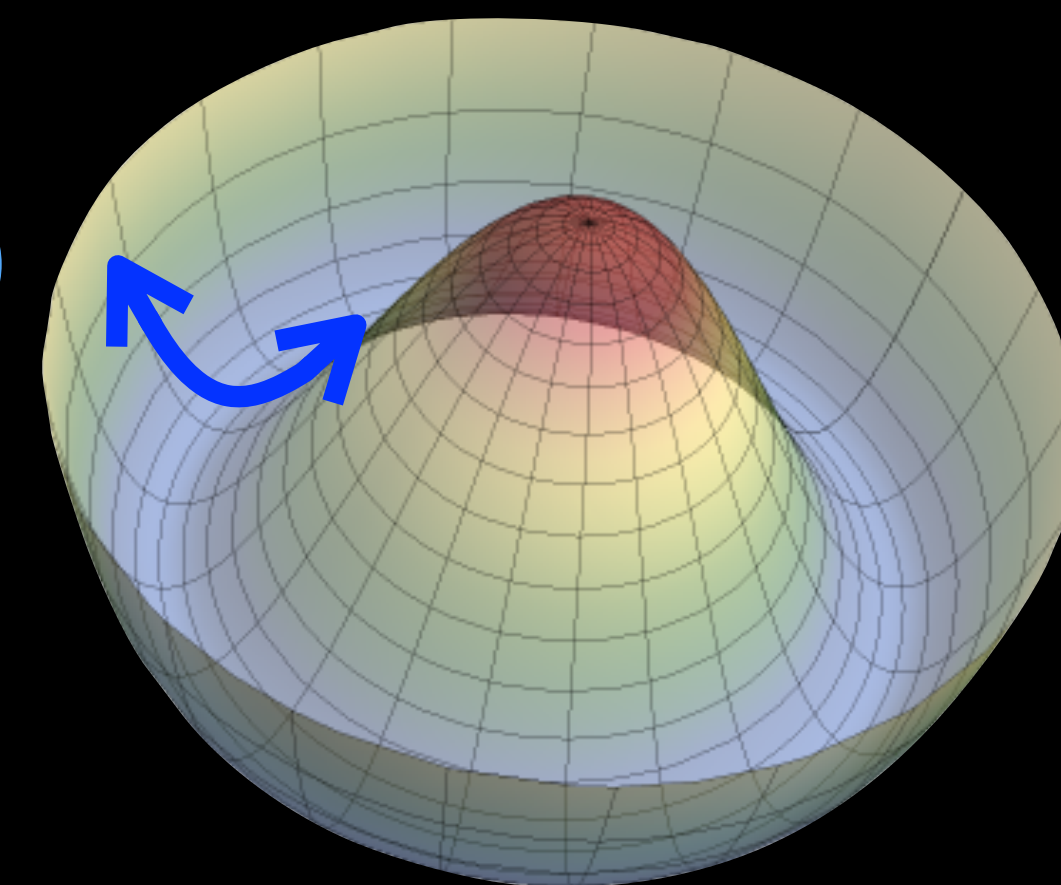
T. Devereaux and R. Hackl Rev. Mod Phys. 79, 175 (2007)

# FerroAxial CDW

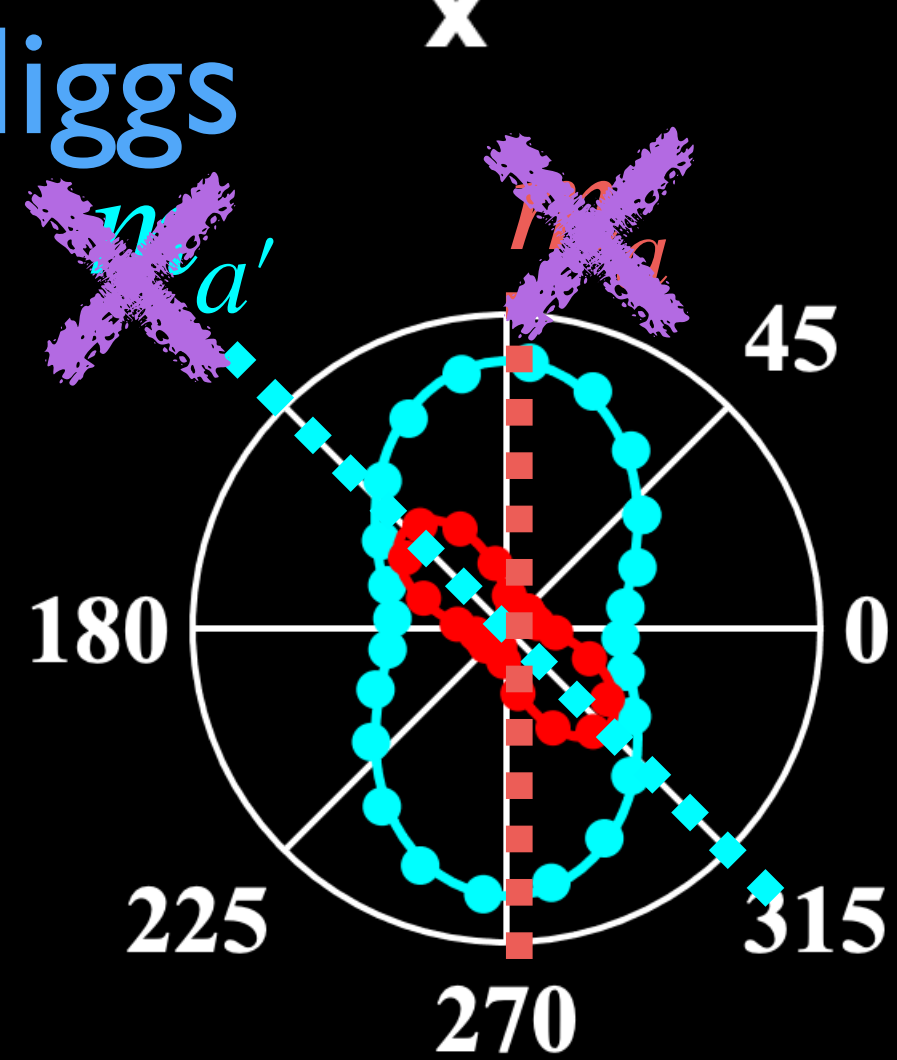


TEM - Incommensurate CDW  
E. DiMasi, M. Aronson, et al  
PRB 52, 14516, (1995)

Higgs  
(Amplitudon)



T Dependence:  
R. V. Yusupov, et al (PRL 2008)  
M. Lavagnini, et al (PRB 81, 081101 2010)  
Y. Chen, et al (APL 115, 151905 2019)  
XX vs. YY:  
H.-M. Eiter, T. Devereaux, L. Degiorgi et al (PNAS - 2013)

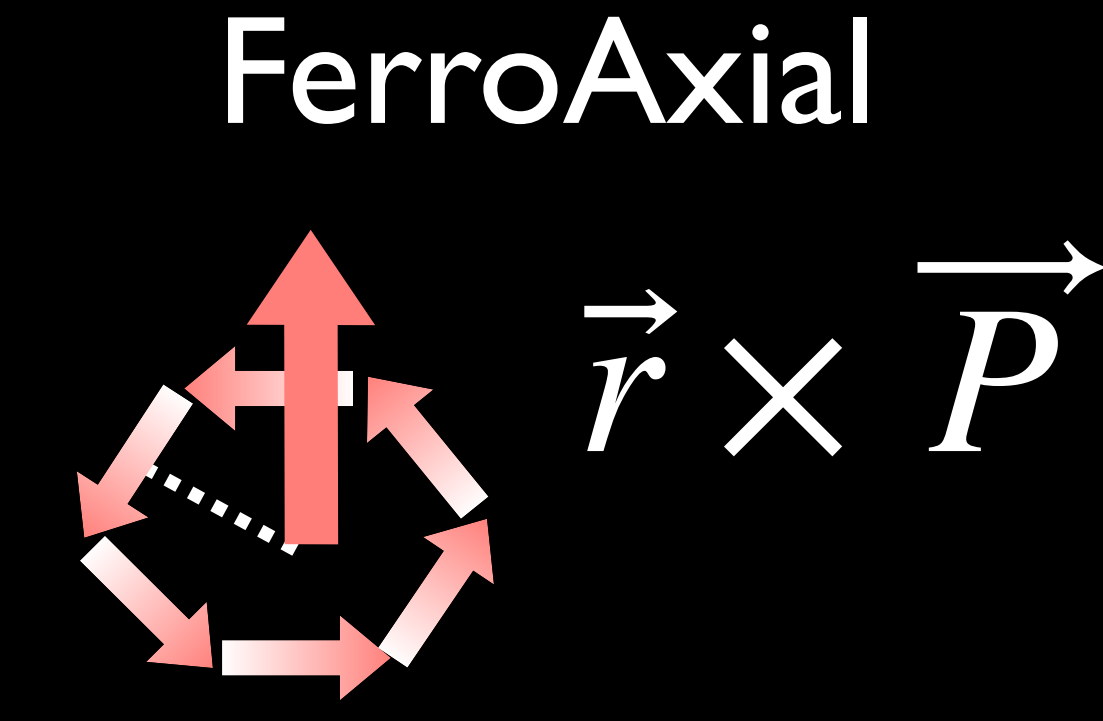
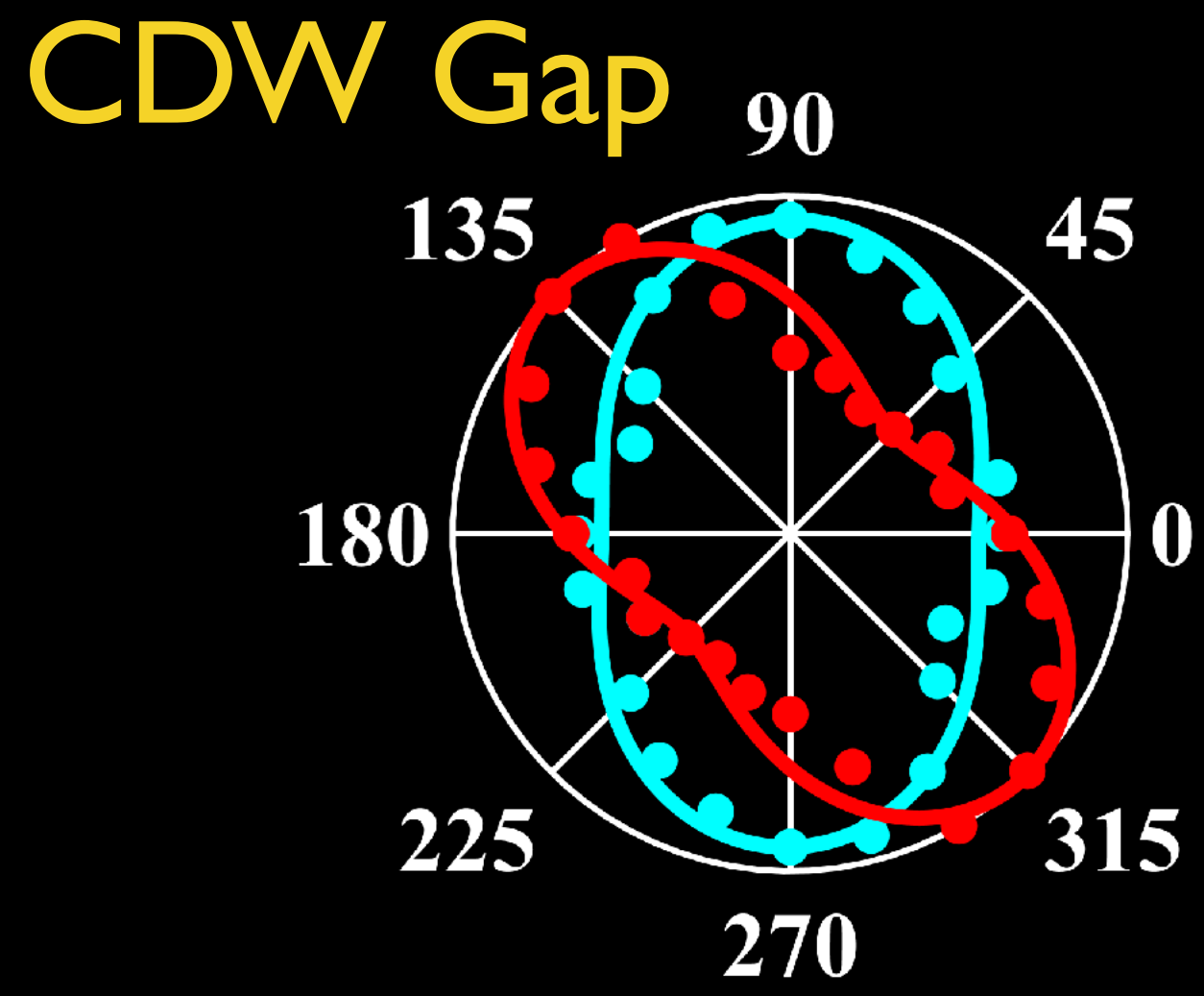
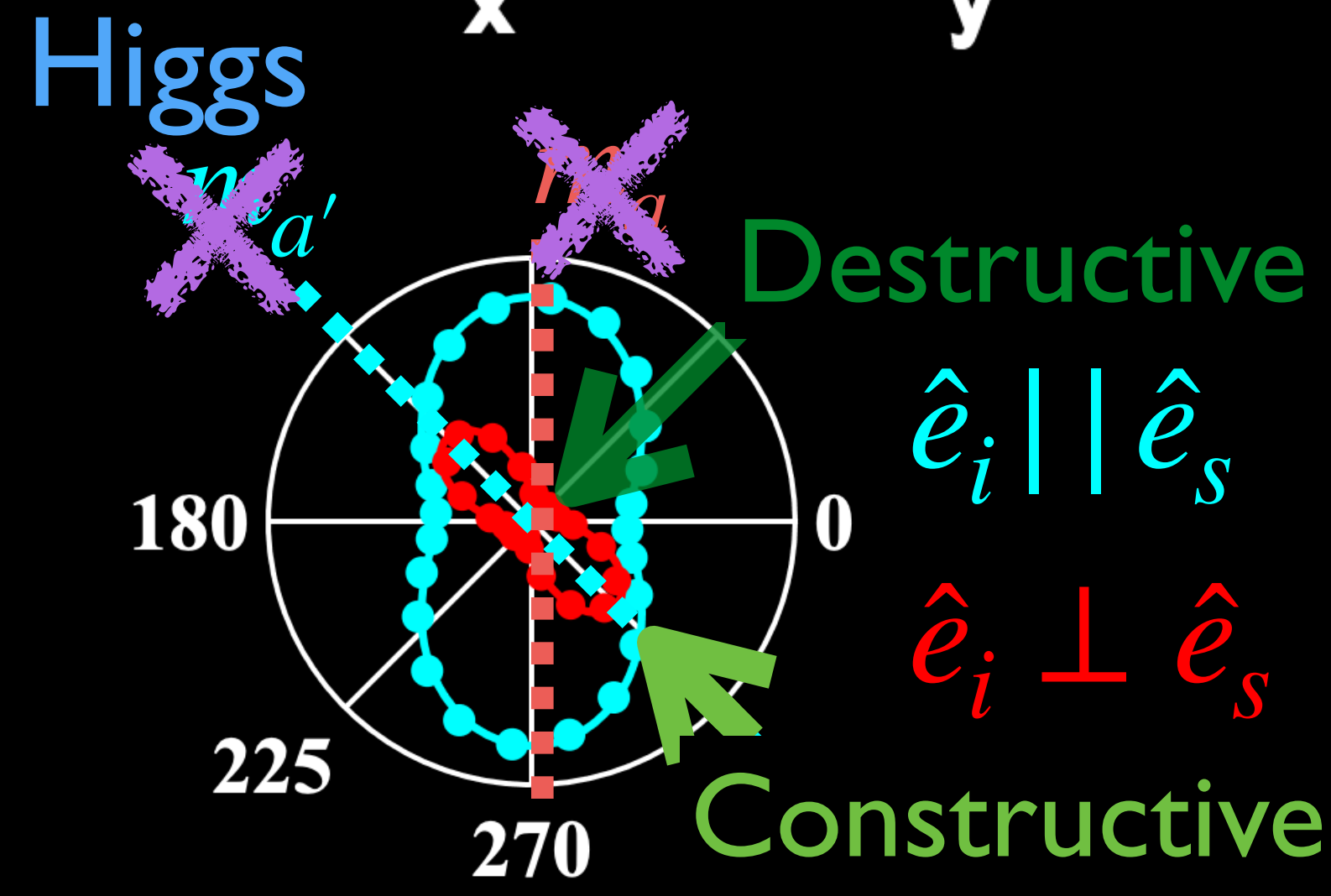
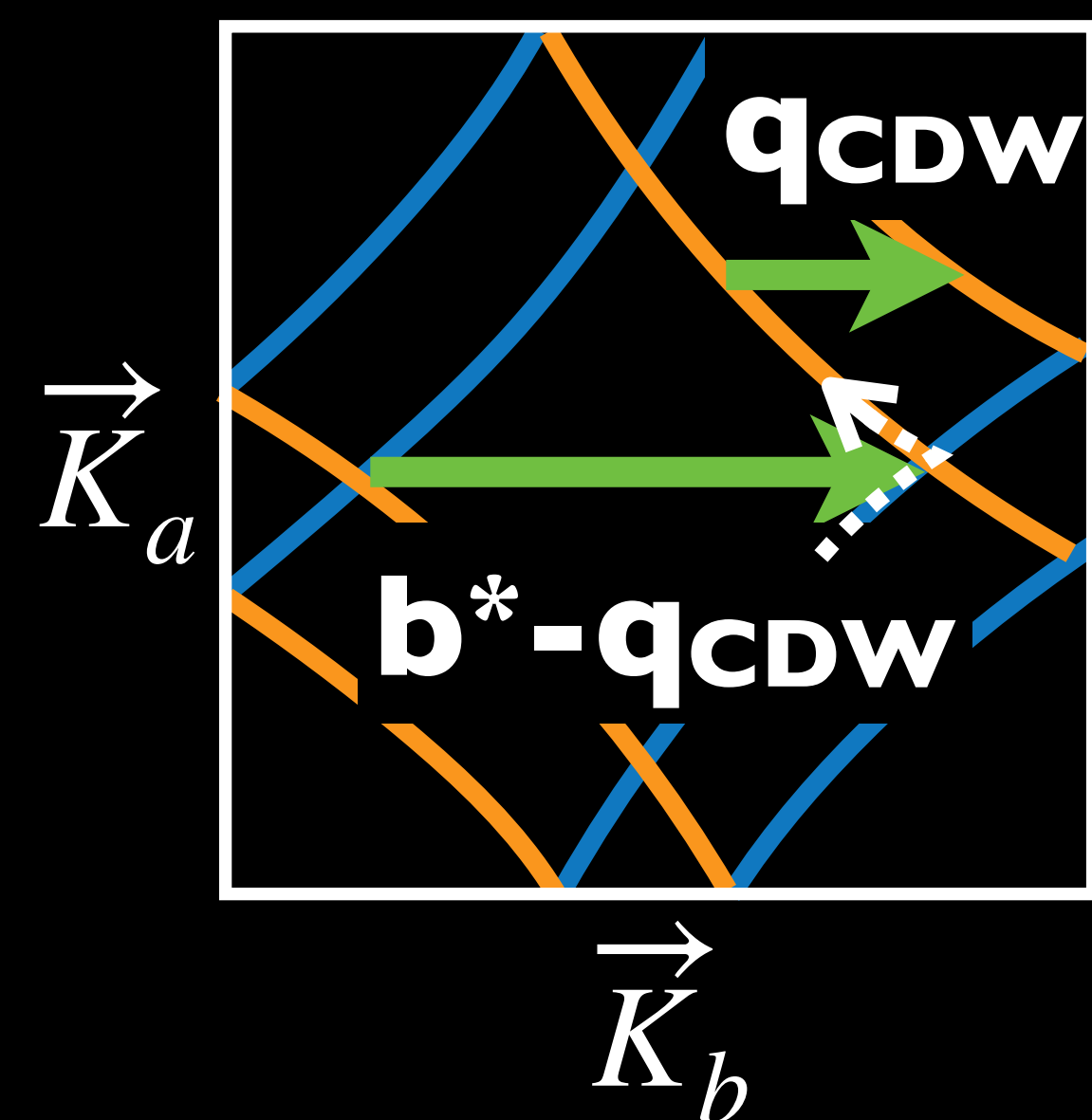
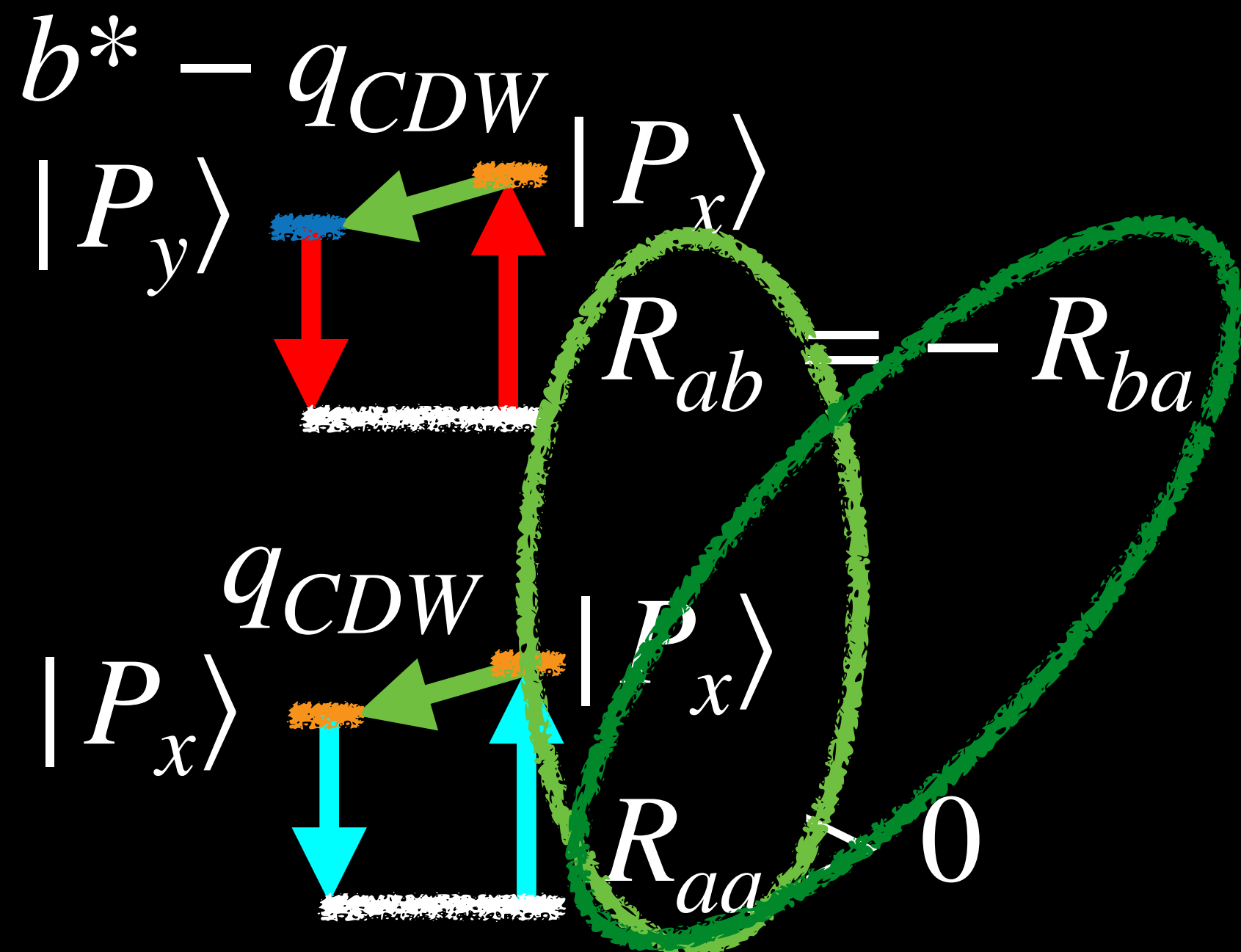
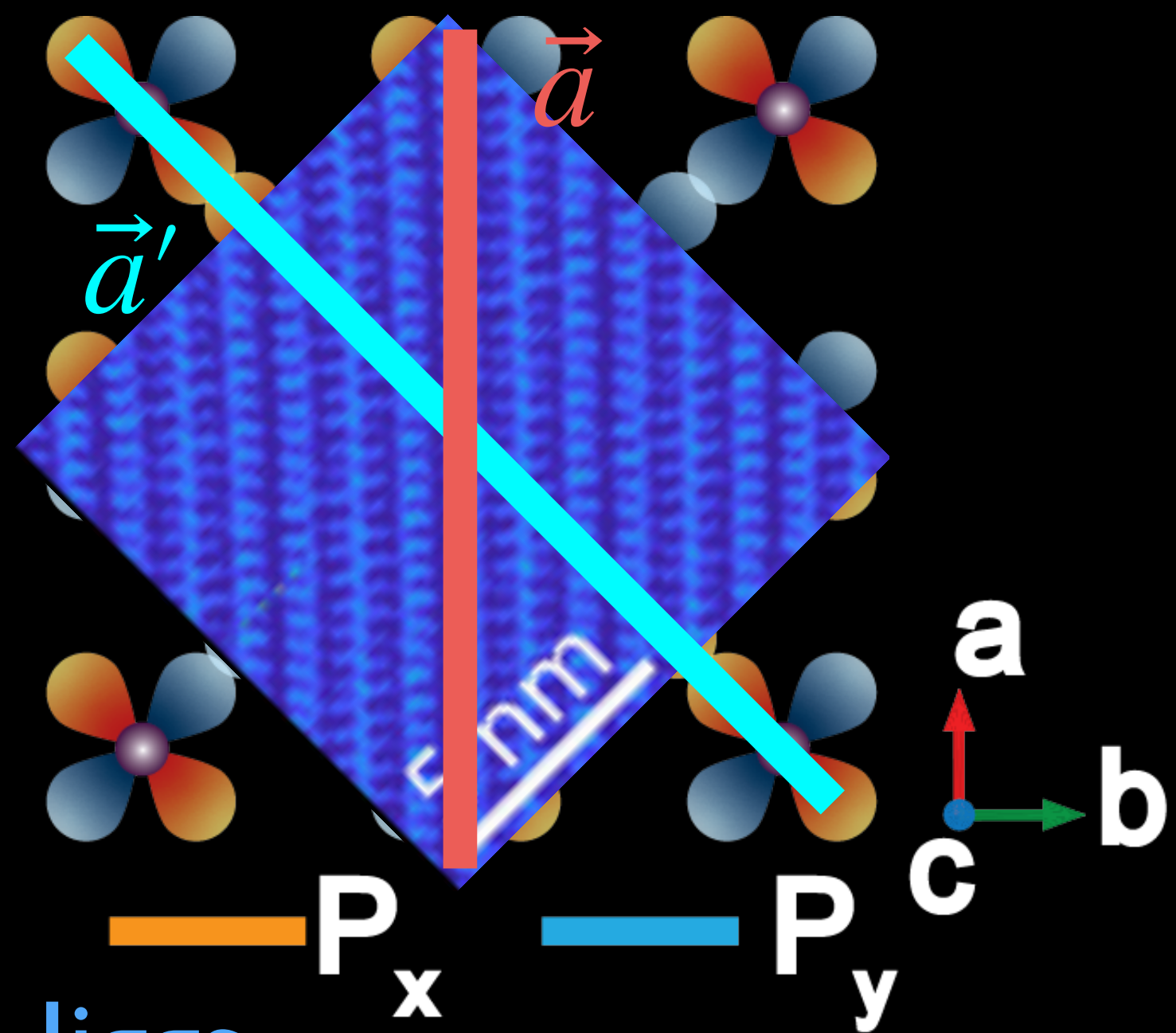


$\hat{e}_i \parallel \hat{e}_s$   
 $\hat{e}_i \perp \hat{e}_s$



● Raman

# FerroAxial CDW



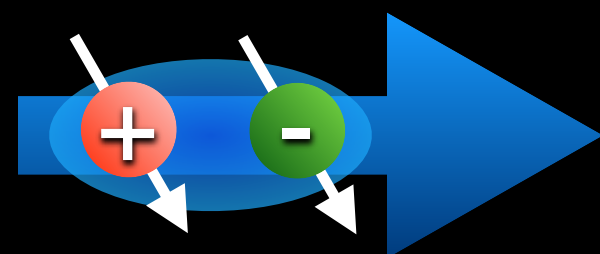
Measure Phase?

Y. Wang, L. Schoop, KSB et al (Nature - 2022)  
B. Singh, KSB et al (Nature Phys - 2025)

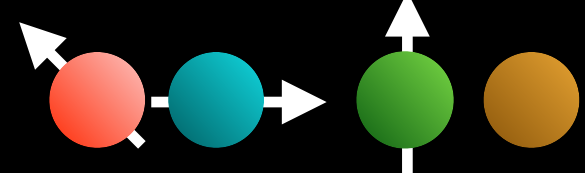
● Raman

A. Kitaev, Annals of Physics 321, 2 (2006)

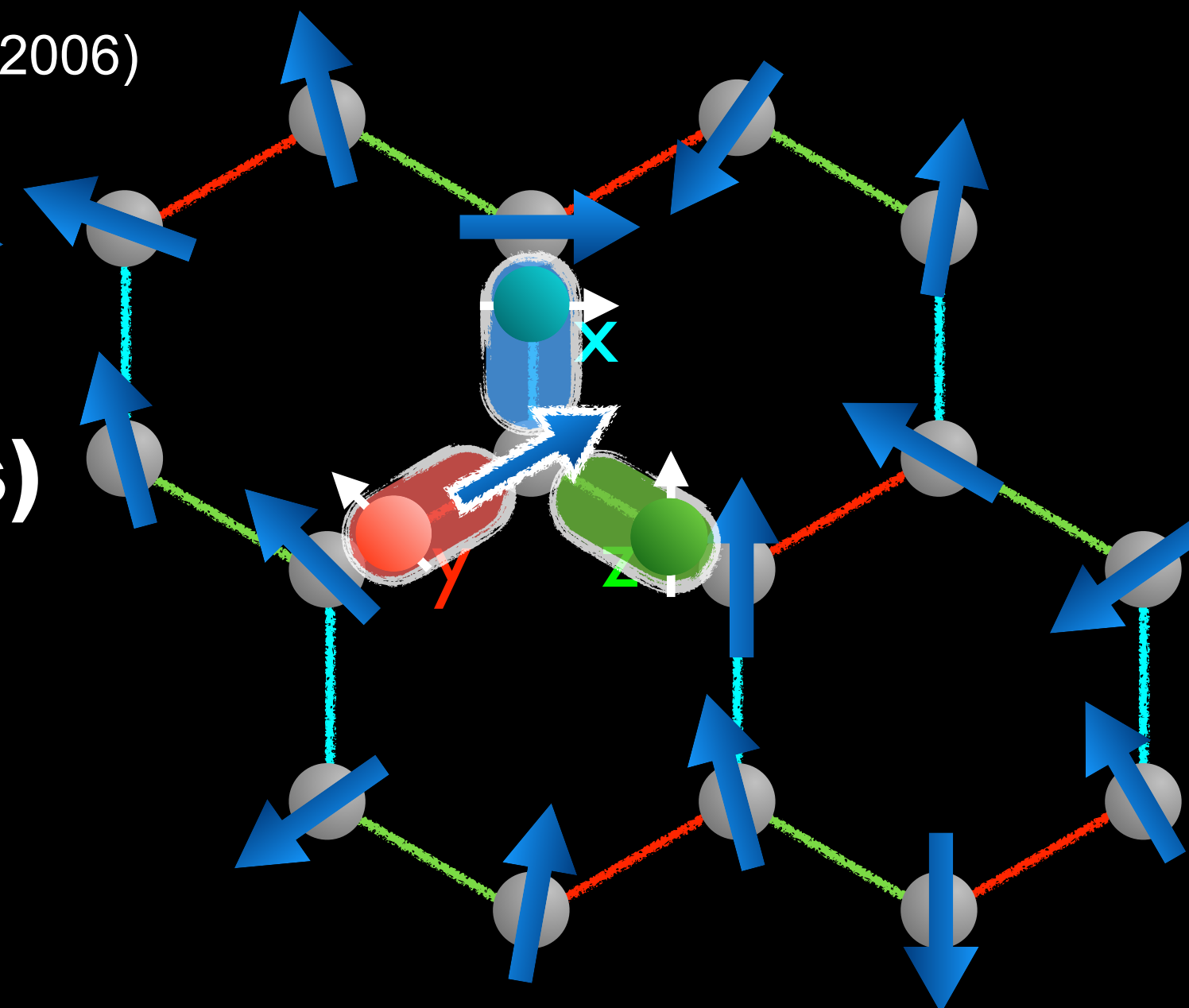
**Bosons**



**Fermions (spinons)**



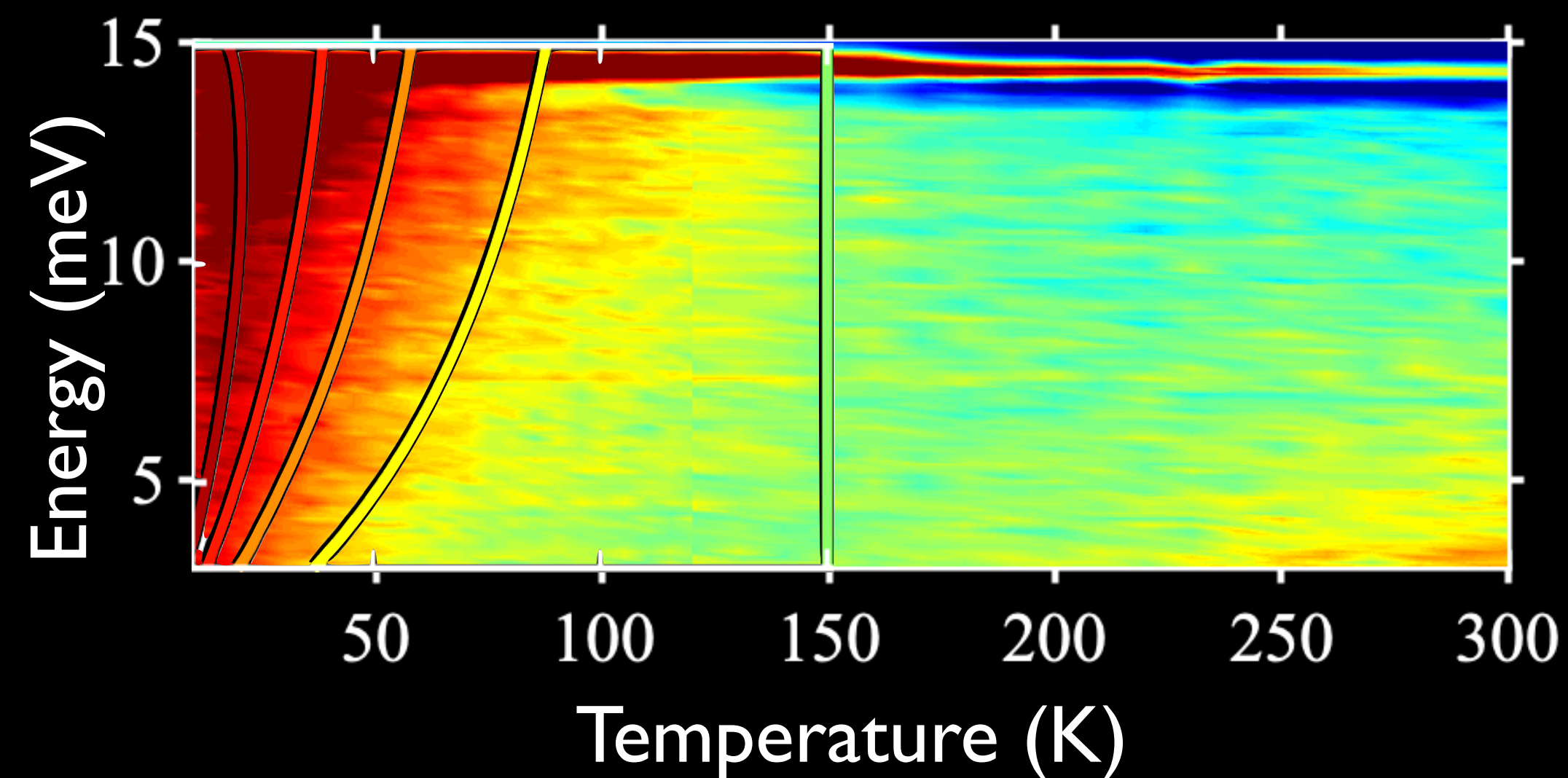
**Majorana**



$$H = -J_x \sum_{j,k=\text{cyan}} \sigma_j^x \sigma_k^x - J_y \sum_{j,k=\text{red}} \sigma_j^y \sigma_k^y - J_z \sum_{j,k=\text{green}} \sigma_j^z \sigma_k^z$$

**RuCl<sub>3</sub>**

$$\Delta\chi_{\text{Total}}(\omega, T) = \chi_{\text{Total}}(\omega, T) - \chi_{\text{Total}}(\omega, 150)$$



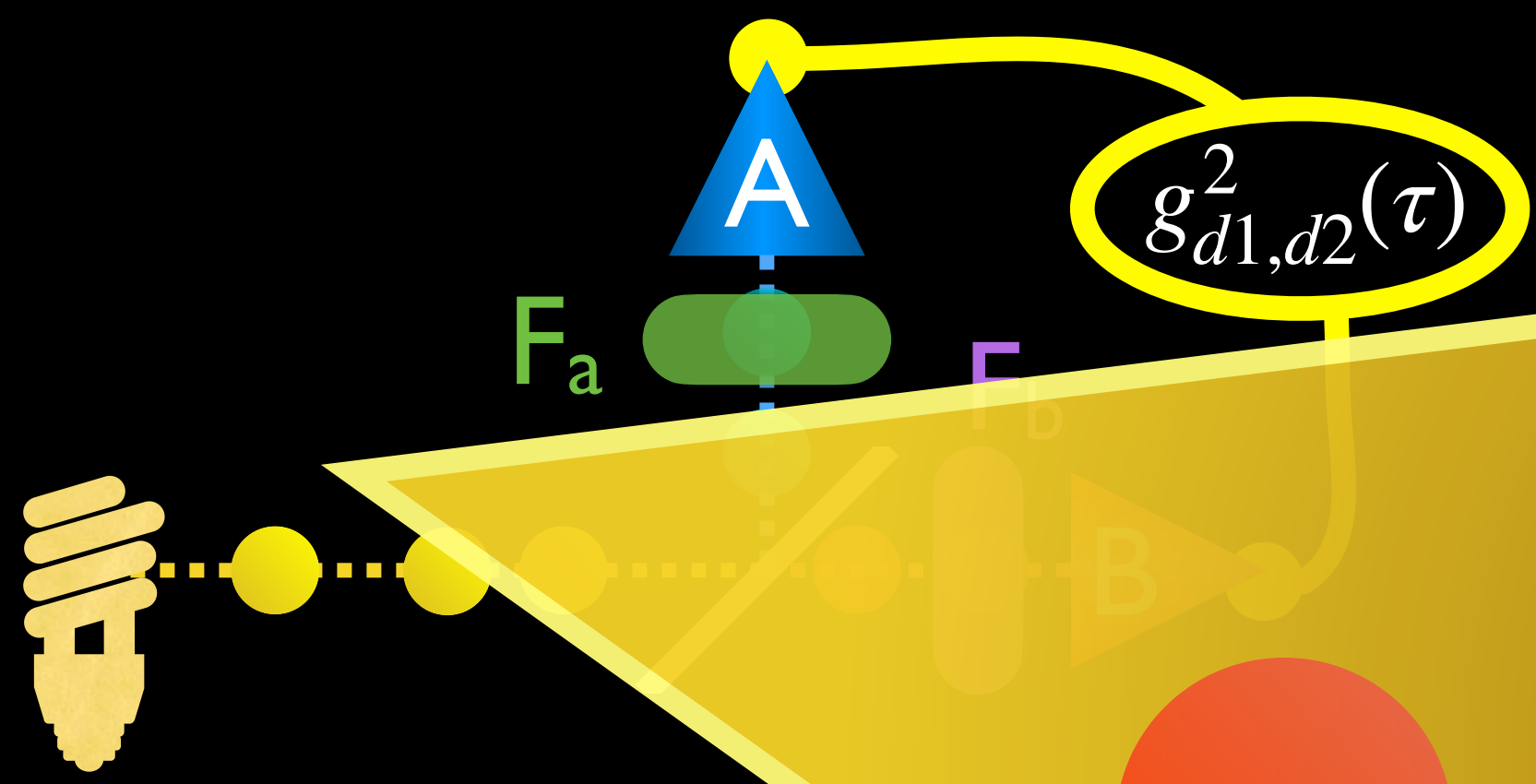
L. Sandilands, KSB et al, PRL 114, 147201 (2015)

Y. Wang, KSB, Nat. Quantum Materials (2020)

QuILS

# Detecting Entanglement

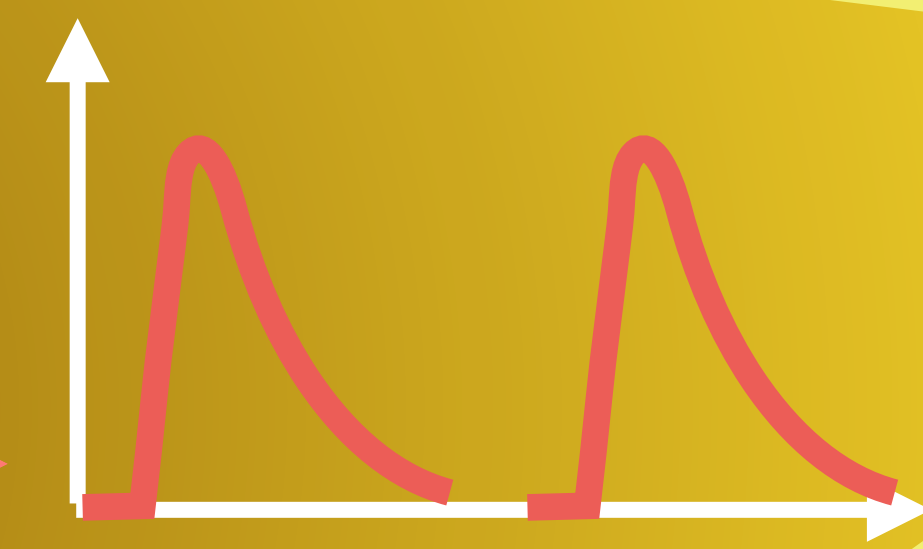
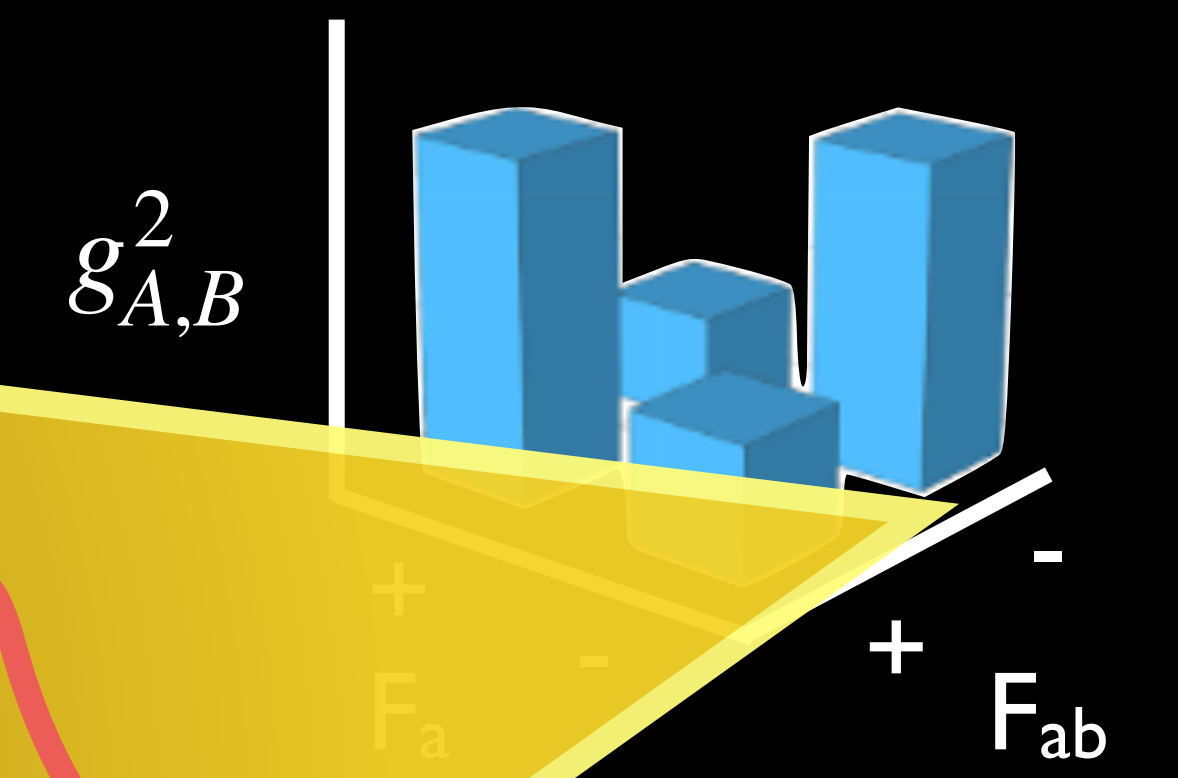
## Hanbury Brown-Twiss



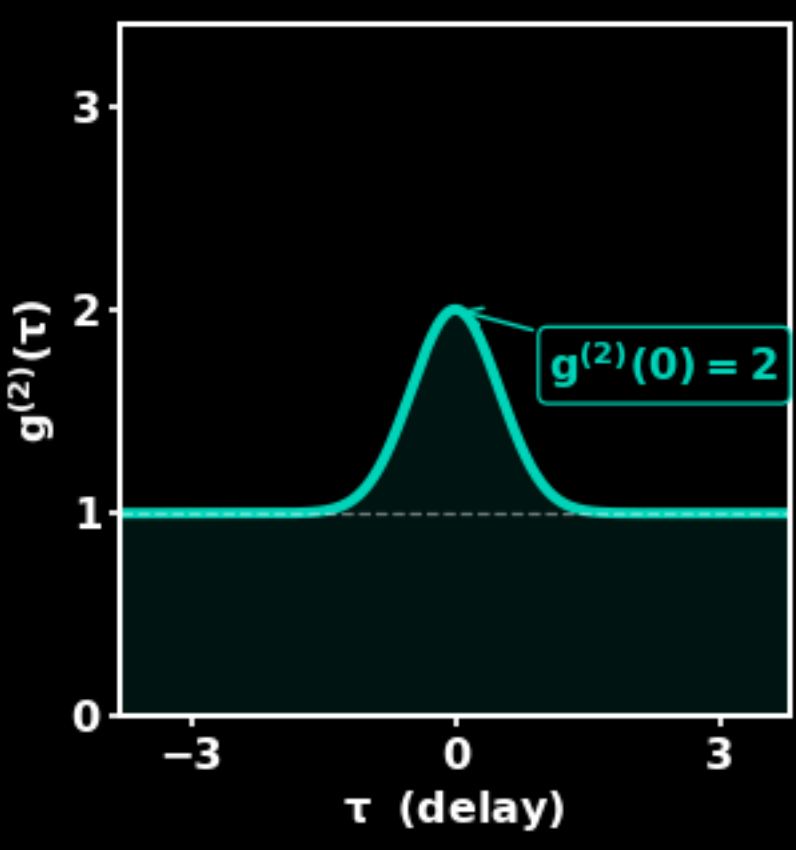
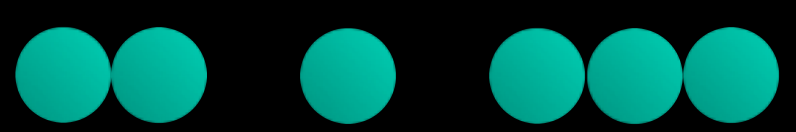
$$g_{A,B}^2(\tau) = \frac{\langle I_A(0)I_B(\tau) \rangle}{\langle I_A \rangle \langle I_B \rangle}$$

$$= \frac{\langle a_A(0)a_A^\dagger(0)a_B(\tau)a_B^\dagger(\tau) \rangle}{\langle I_A \rangle \langle I_B \rangle}$$

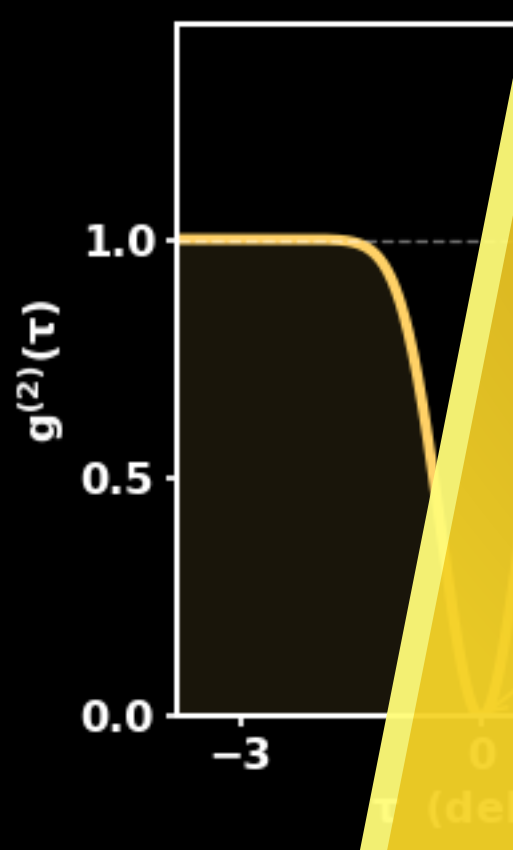
## Density Matrix



## Thermal

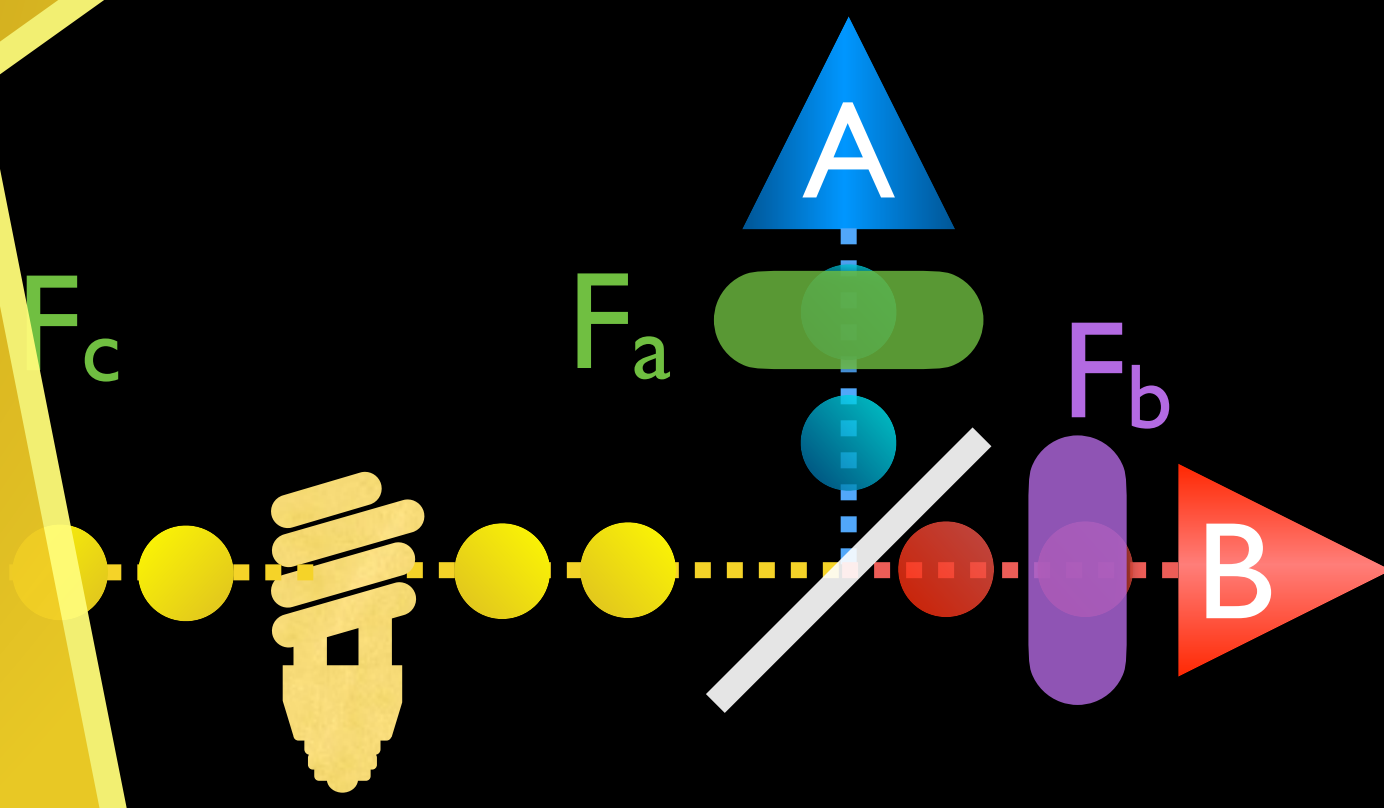


## Single Photon



# Single Photon Detector

## Bell Test



# Single Q.Particle Detector

## Correlation between the Stokes and anti-Stokes components in inelastic scattering of light

D. N. Klyshko

*M. V. Lomonosov State University, Moscow*  
(Submitted September 9, 1976)  
*Kvantovaya Elektron. (Moscow)* 4, 1341–1350 (June 1977)

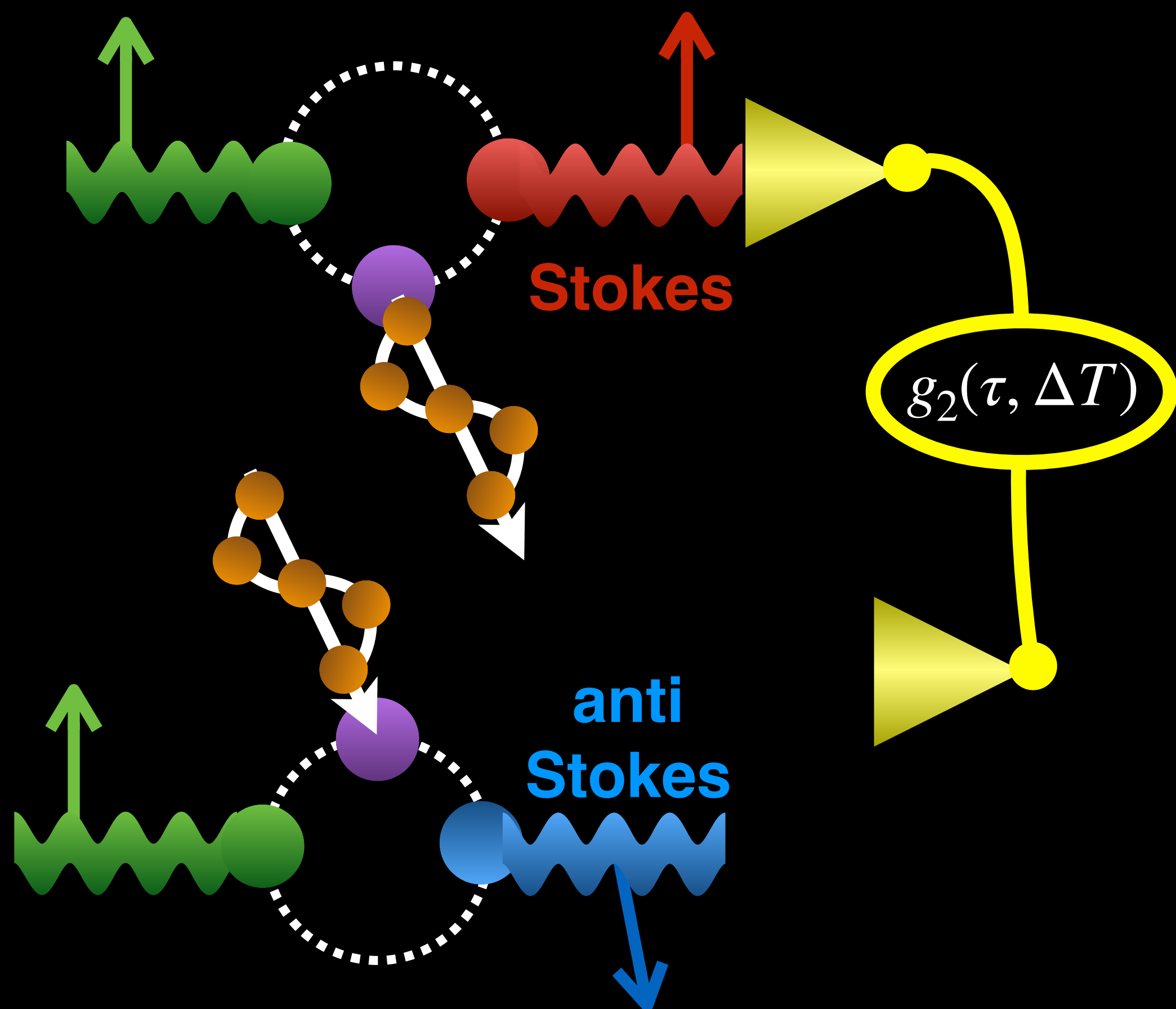
PRL 117, 243603 (2016)

PHYSICAL REVIEW LETTERS

week ending  
9 DECEMBER 2016

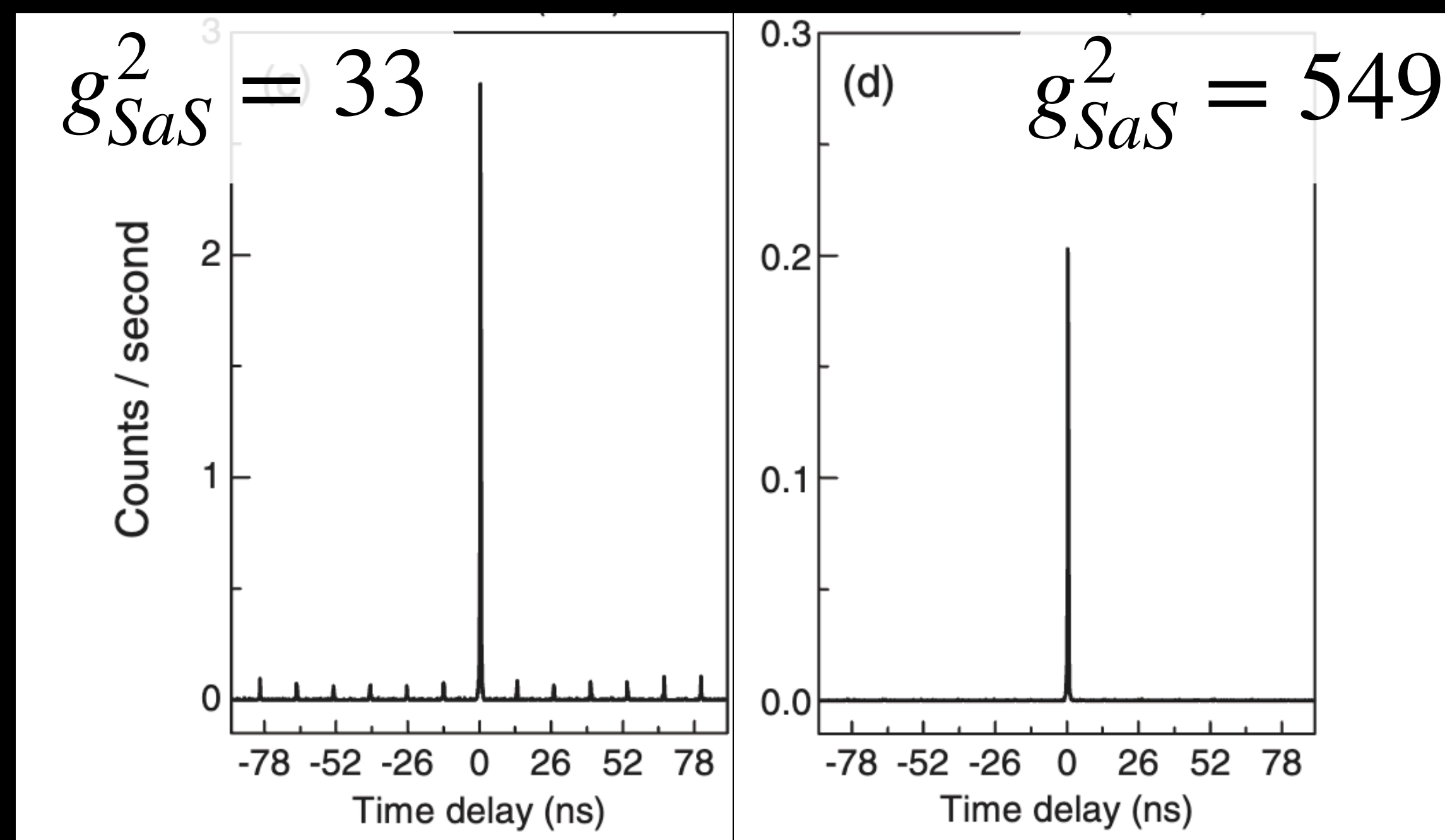
## Temporal Quantum Correlations in Inelastic Light Scattering from Water

Mark Kasperczyk,<sup>1</sup> Filomeno S. de Aguiar Júnior,<sup>2</sup> Cassiano Rabelo,<sup>3</sup> Andre Saraiva,<sup>4</sup>  
Marcelo F. Santos,<sup>4</sup> Lukas Novotny,<sup>1</sup> and Ado Jorio<sup>2,\*</sup>



Diamond

Water



PHYSICAL REVIEW A **108**, L051501 (2023)

Letter

## Microscopic origin of polarization-entangled Stokes–anti-Stokes photons in diamond

Tiago A. Freitas<sup>1,2,3</sup>, Paula Machado<sup>2,3</sup>, Lucas Valente<sup>2</sup>, Diego Sier<sup>2</sup>, Raul Corrêa<sup>2</sup>, Riichiro Saito<sup>4</sup>,  
Christophe Galland<sup>5</sup>, Marcelo F. Santos<sup>6</sup>, Carlos H. Monken<sup>2</sup> and Ado Jorio<sup>1,2</sup>

<sup>1</sup>Programa de Pós-Graduação em Engenharia Elétrica

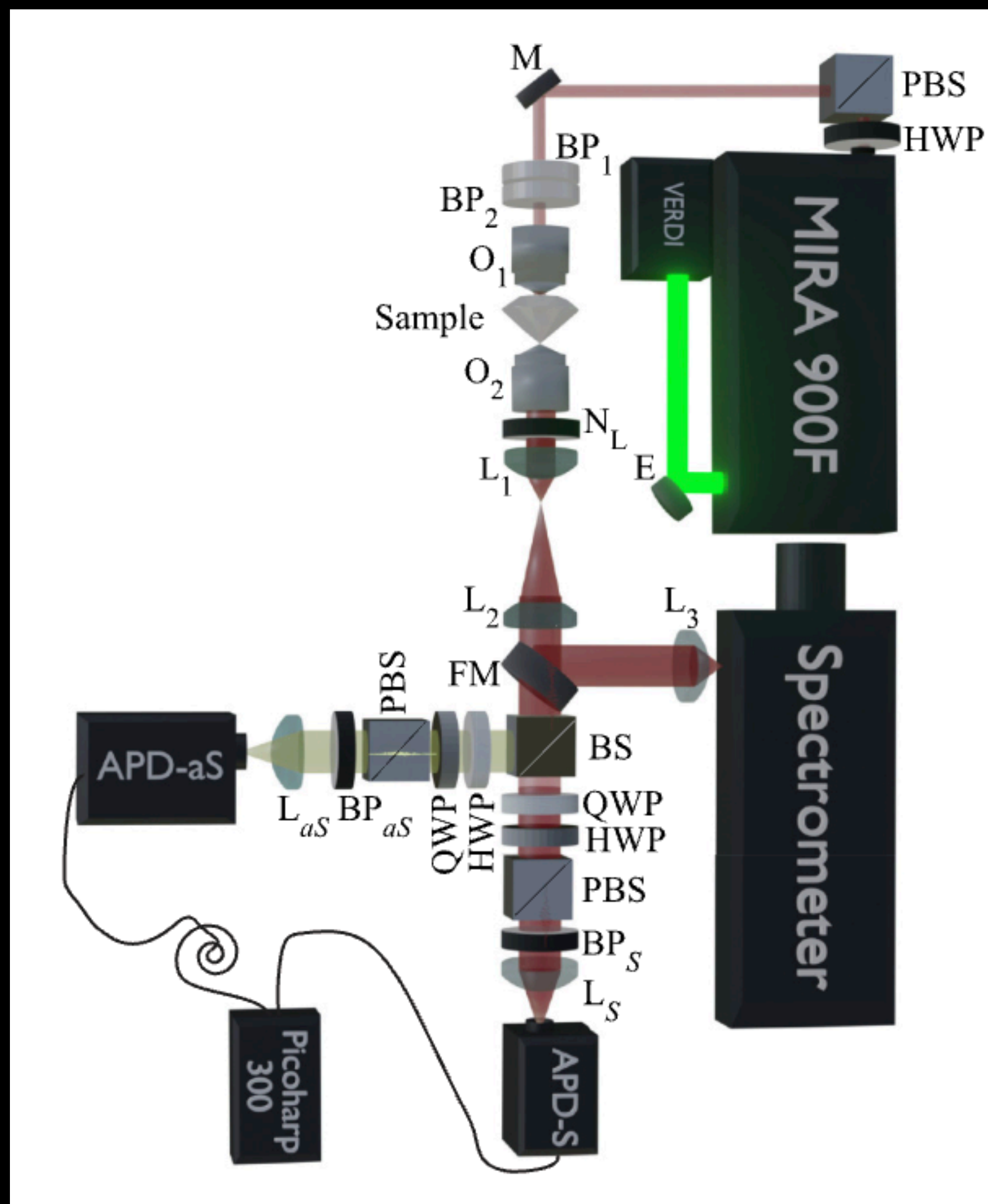
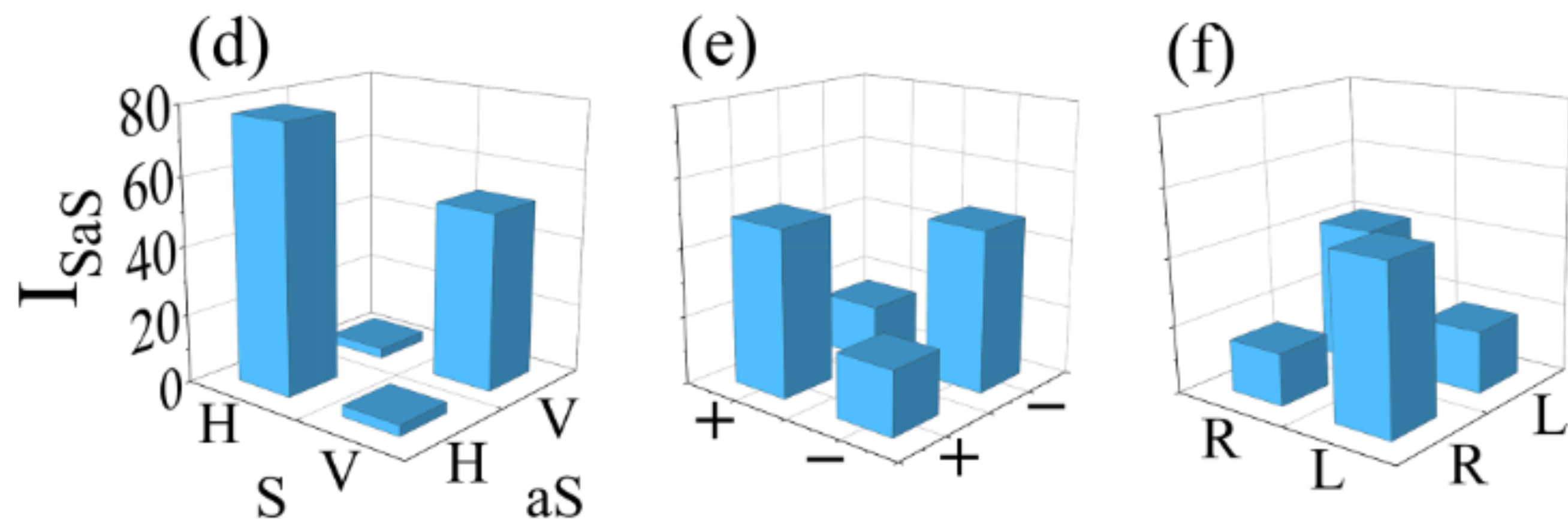
<sup>2</sup>Departamento de Física, Universidade Federal de Minas Gerais, Belo Horizonte, MG 30123-970, Brazil

<sup>3</sup>Instituto D'Or de Pesquisa e Ensino, Rio de Janeiro, RJ 22281-100, Brazil

<sup>4</sup>Department of Physics, National Taiwan Normal University, Taipei 106, Taiwan

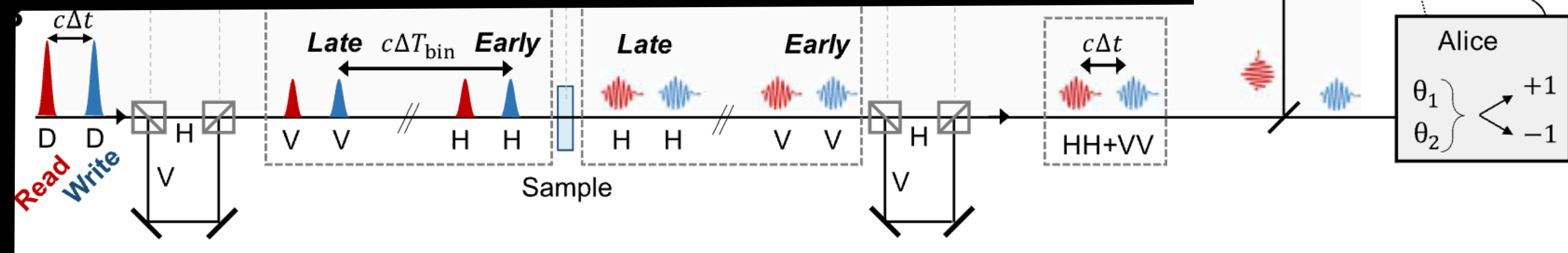
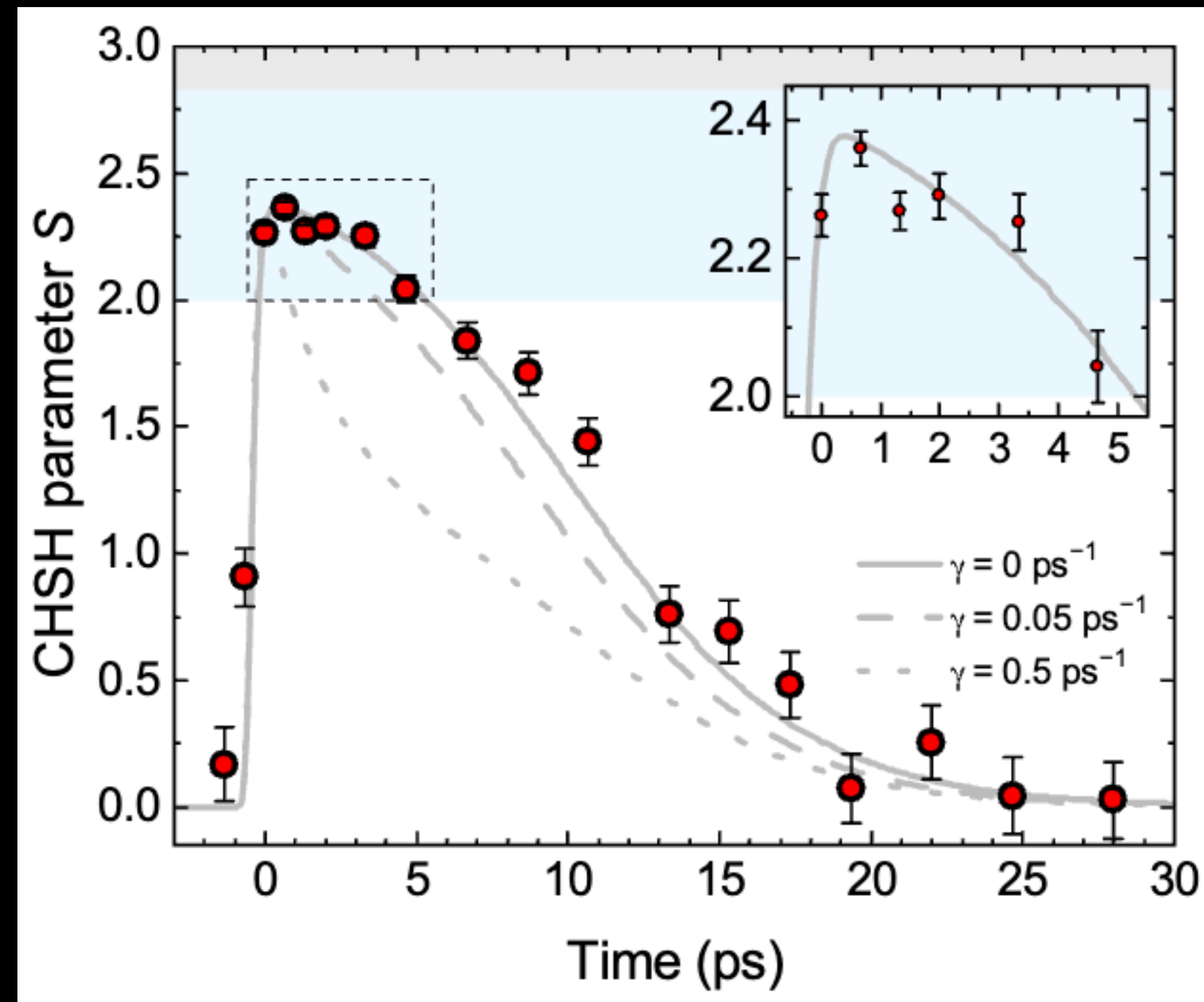
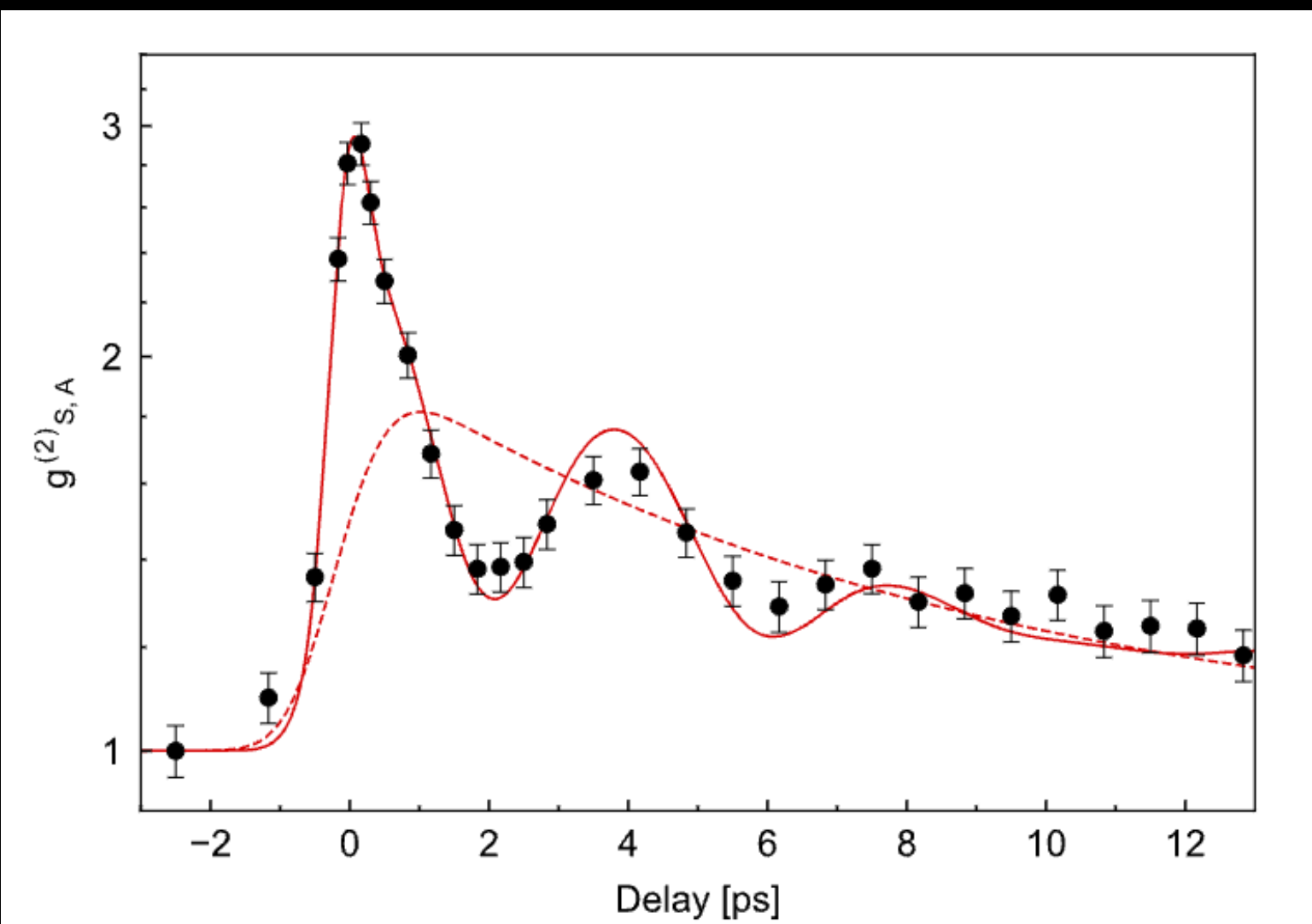
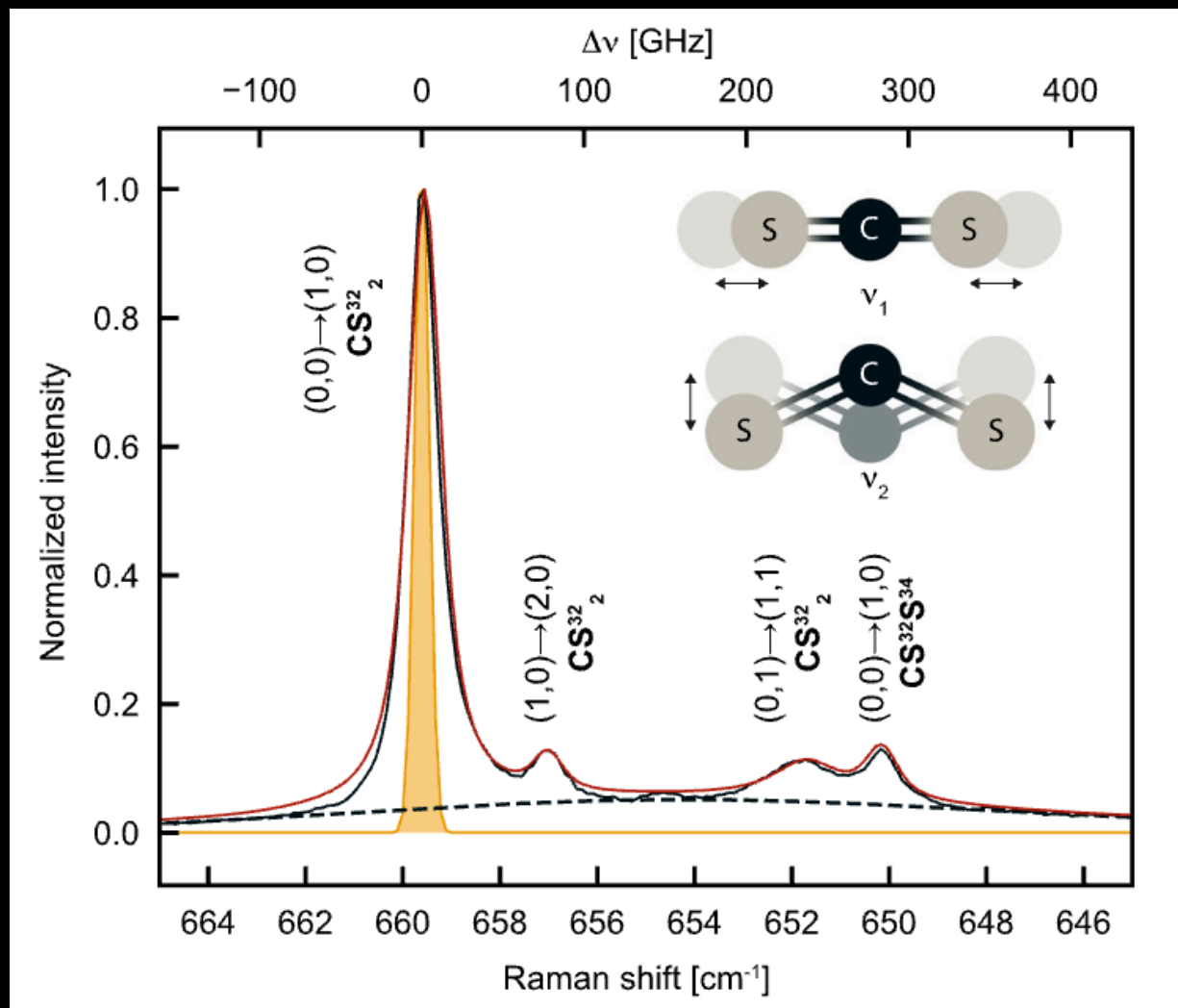
<sup>5</sup>Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

<sup>6</sup>Instituto de Física, UFRJ, Caixa Postal 68528, Rio de Janeiro, RJ 21941-972, Brazil



# Interference and Bell Tests

V. Vento et al, Nat. Comm 14, 2818 (2023)

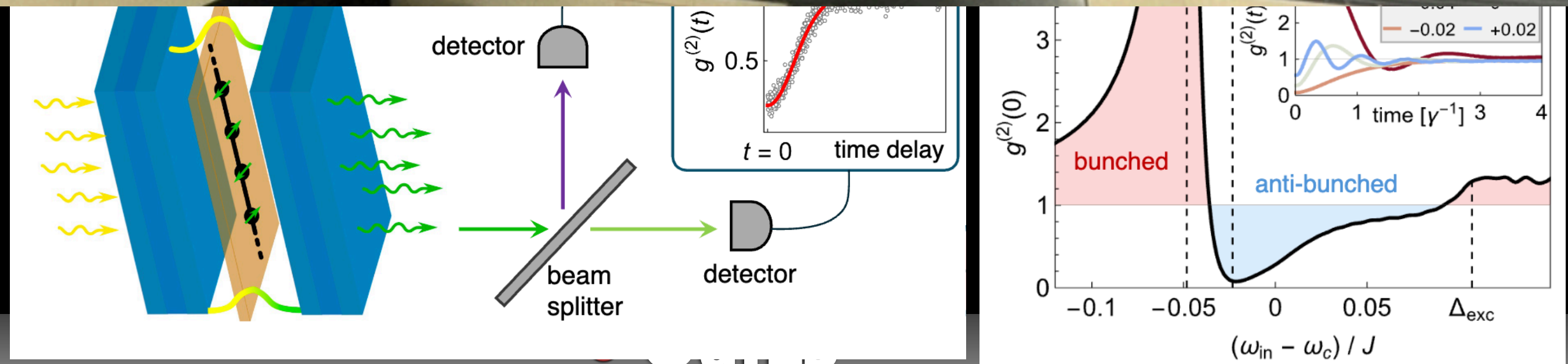
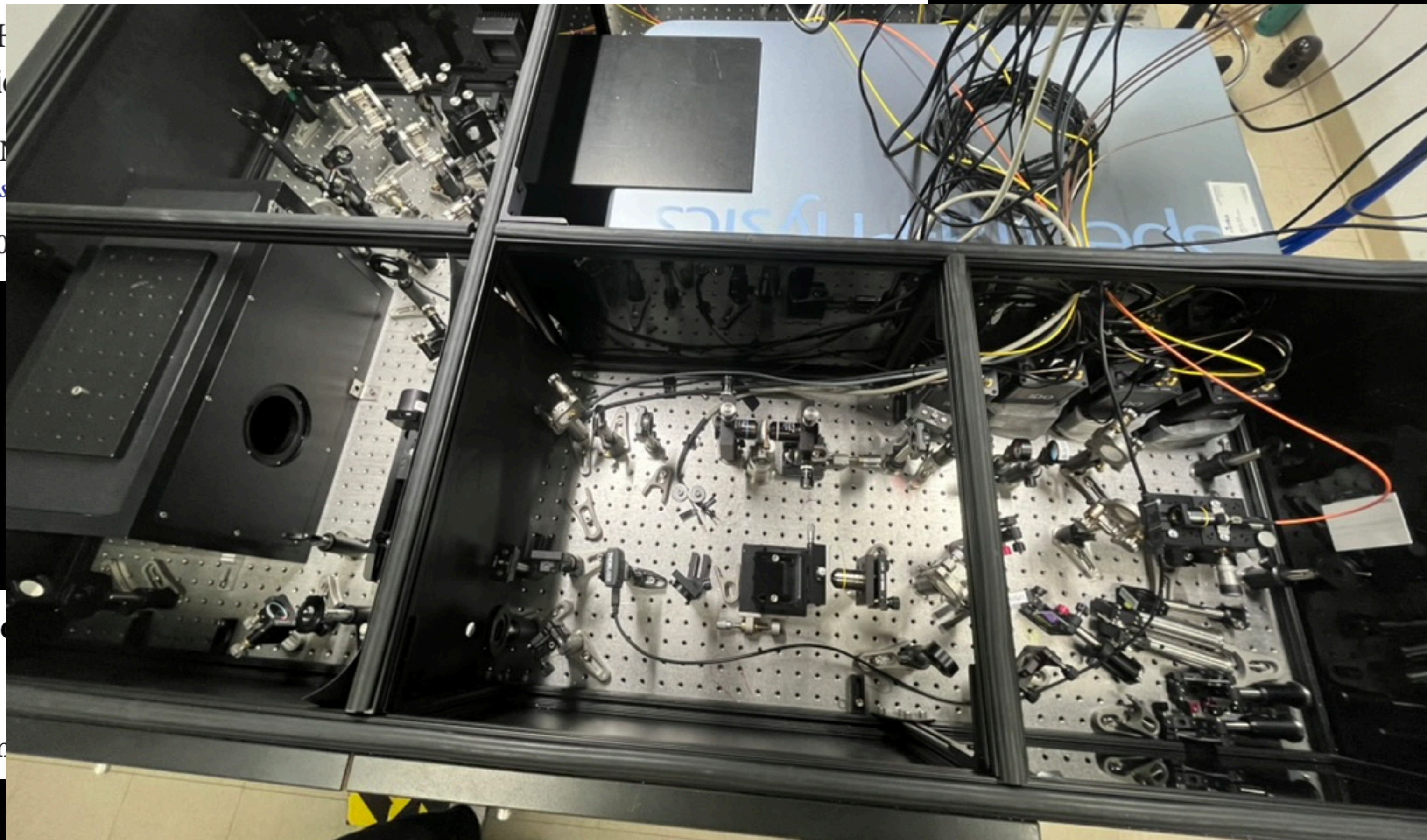


S.T. Valez et al, Science Advances 6, eabb0260 (2020)

- Two-Phonon?
- Spatial  $g^2$
- “Glue” (Magnons/Phonons)?
- Raman Phase
- Conditional Probability?
- Fractional Symmetries?
- Fractional Bell Test?
- New Photon Sources?

PH  
**Diagnosing Electronic**  
 Gautam I  
*Joint Quantum Ins*  
 (Received 23 December 20

Many-B  
 Benjamin



LASE Team

**Yiping Wang (Columbia)**

**L. Sandilands (NRC)**

**G. McNamara (BU)**

**B. Singh**

**K.-M. Kim**

**M. Romanelli (UIUC)**

**P. Sakrikar**

V. Plisson

G. Osterhoudt (Thorlabs)

RuCl<sub>3</sub>

K. Plumb (Brown U.), Y.J. Kim (U.Toronto)

A. Banerjee (Purdue), J. Yan, S. Nagler, (ORNL), D. Mandrus (UTK)

Theory (RuCl<sub>3</sub>):

J. Knolle (TUM)

J. Nasu (Tohoku U.), Y. Motome (U.Tokyo)

RTe<sub>3</sub> (Princeton)

R. Singha (IITGuwahati), S. Lei (HKUST), L. Schoop

Theory (RTe<sub>3</sub>):

R.M. Fernandes (UIUC)

S. Alekseev, S.A.A. Ghorashi, J. Cano (SUNY-SB)

La<sub>2</sub>O<sub>3</sub>Mn<sub>2</sub>Se<sub>2</sub> (U.Utah)

C.-C. Wei, H. Ji

Theory

V. Williams B. Flebus (BC)

X. Xu, D. Qiu (Yale)

R. Fernandes (UIUC)

Neutrons (BYU)

S. Hatt

B. Frandsen

PL

S. Paul

V. Menon (CCNY)

M. Shehabeldin

Q. Ma (BC)



QRaman:

C. Galland (EPFL)

Y. Ran (BC)

F. Schlawin (TUM)

M. Claassen (UPenn)

Funding:



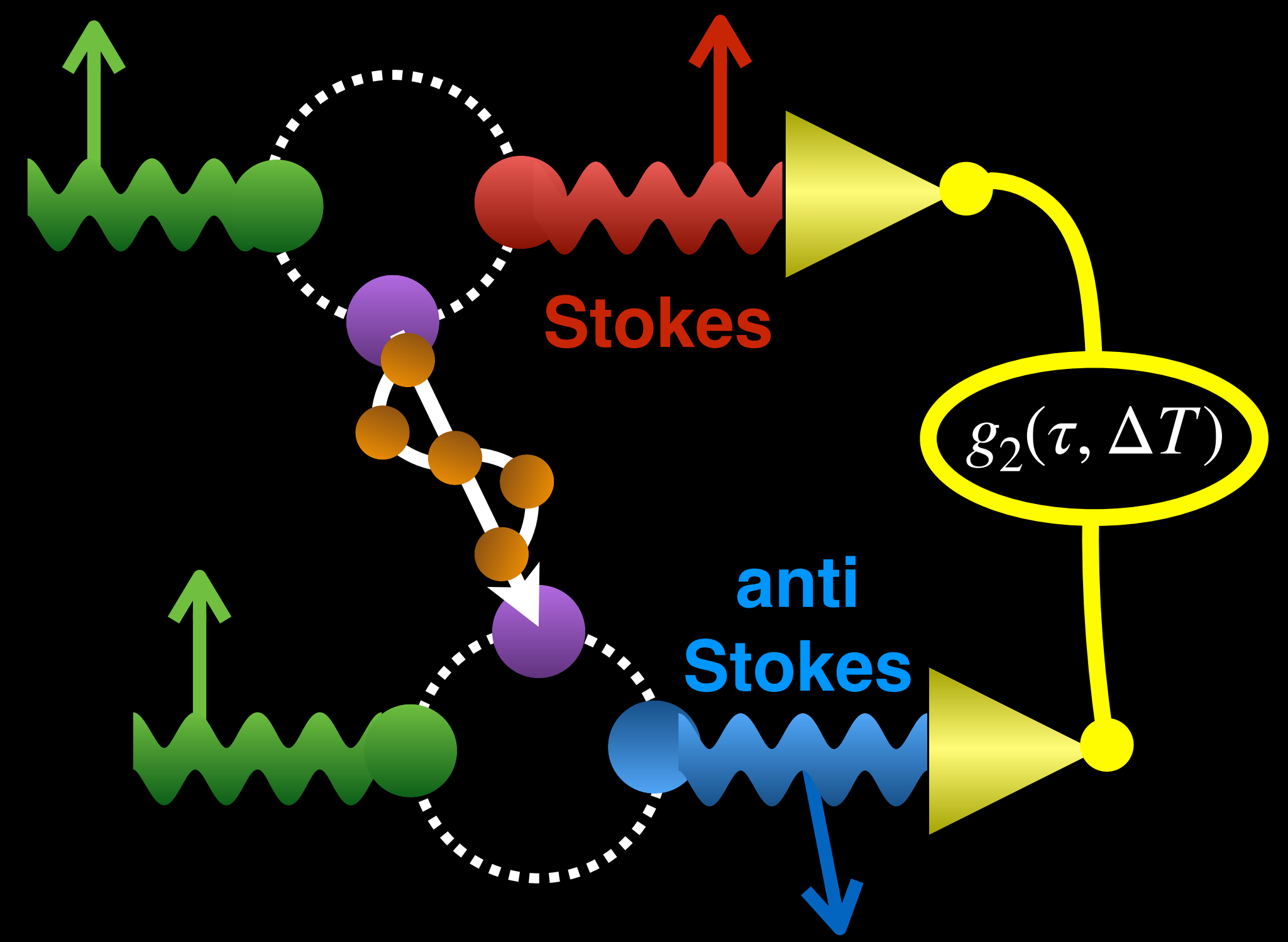
# Summary

[ks.burch@bc.edu](mailto:ks.burch@bc.edu)

## Challenge

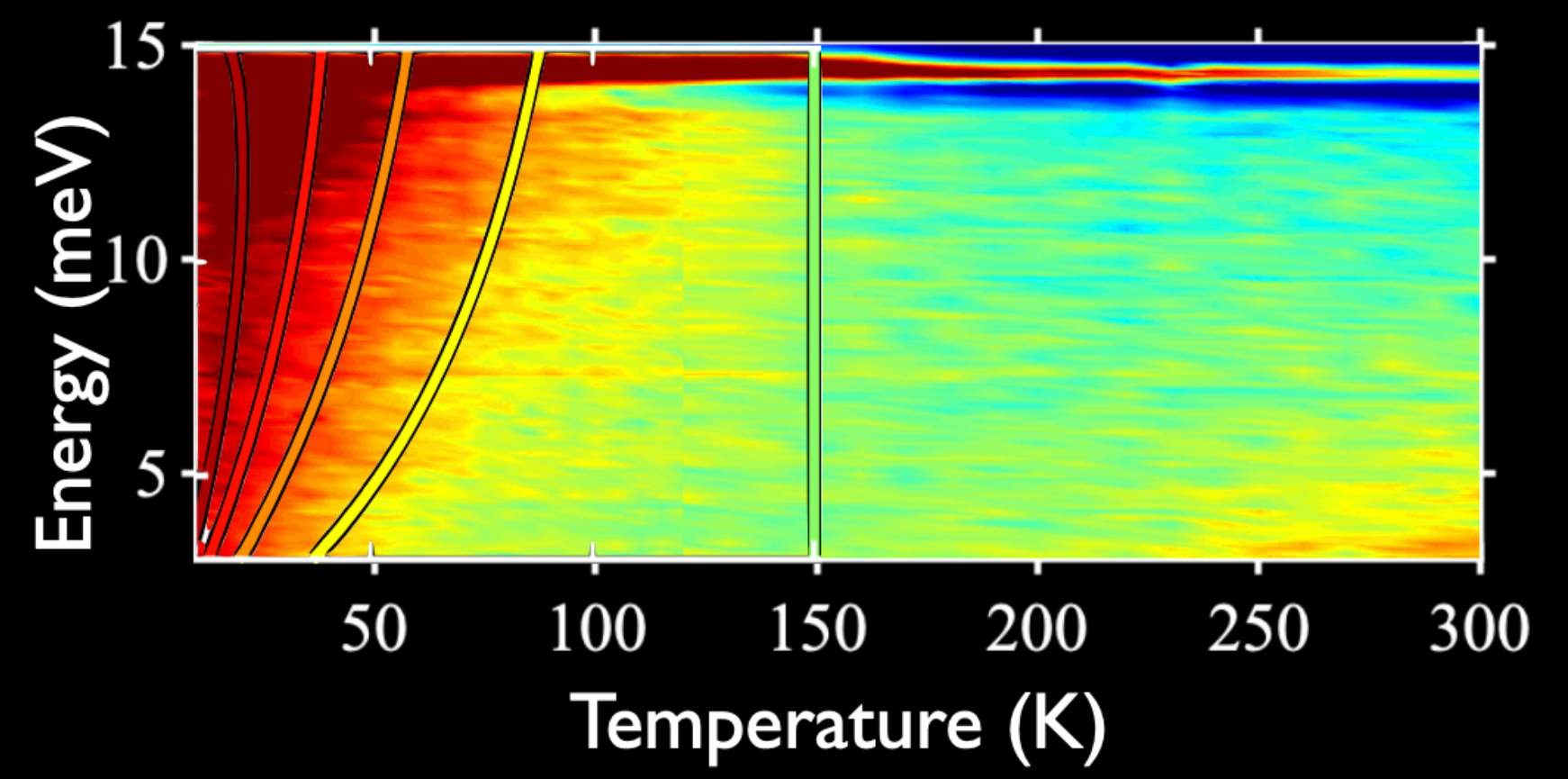


## QuILS



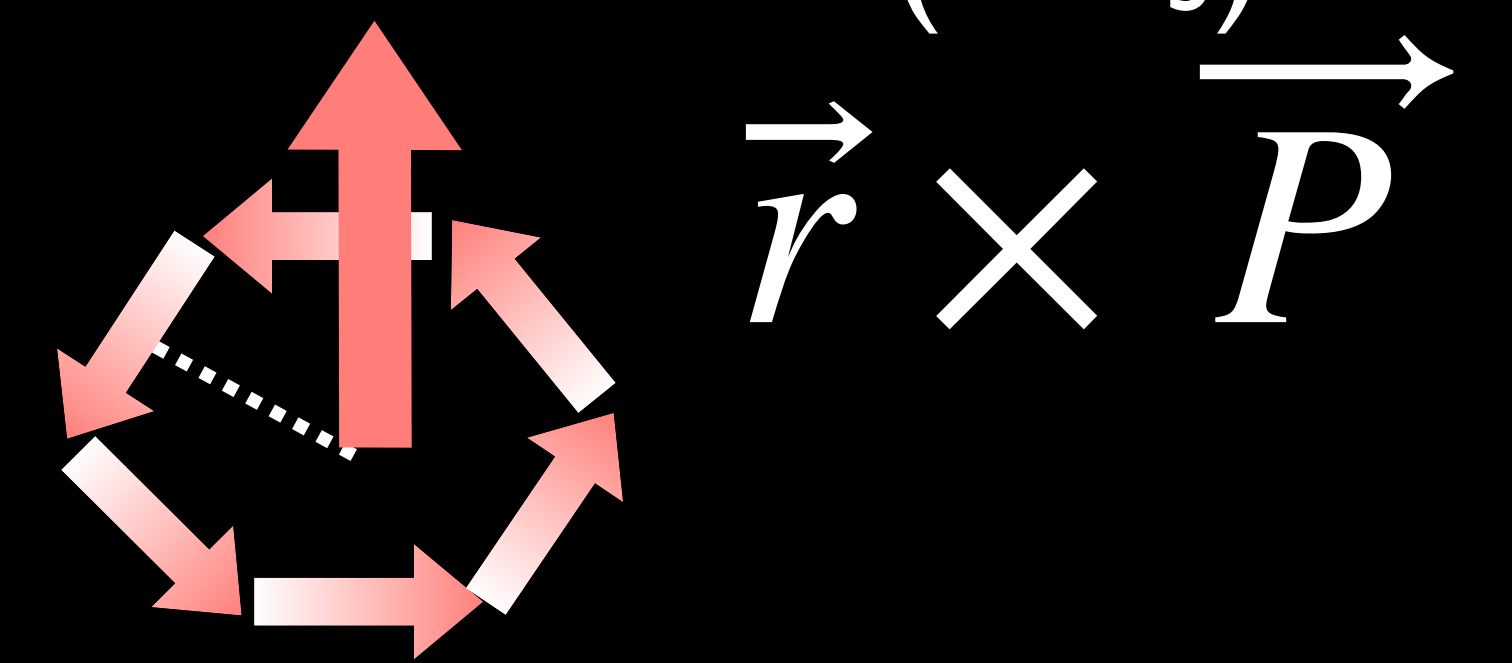
## Raman

Fermionic Response -  $\text{RuCl}_3$



L. Sandilands, KSB et al, PRL (2015)  
Y. Wang, KSB et al, NPJ Q. Mat (2020)

FerroAxial  
Orbital CDW ( $\text{RTe}_3$ )



Y. Wang, KSB et al, Nature (2022);  
B. Singh, KSB et al, Nature Physics (2025)

Backup

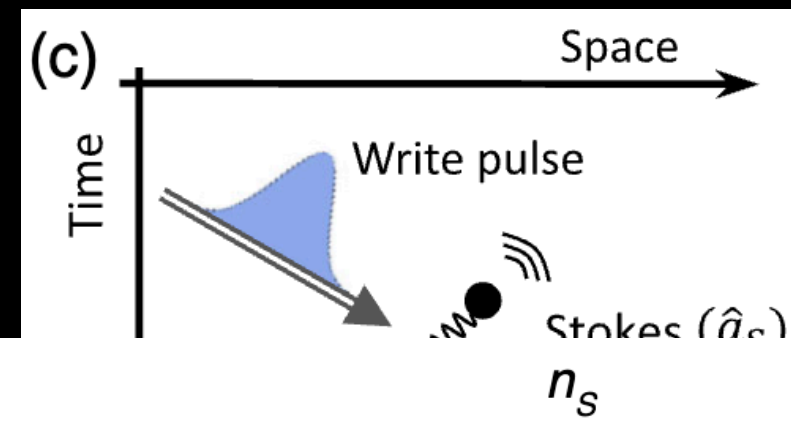
**Preparation and Decay of a Single Quantum of Vibration at Ambient Conditions**

Santiago Tarrago Velez,<sup>1</sup> Kilian Seibold,<sup>1</sup> Nils Kipfer,<sup>1</sup> Mitchell D. Anderson,<sup>1</sup>  
 Vivishek Sudhir,<sup>2,3</sup> and Christophe Galland<sup>1</sup>

<sup>1</sup>*Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland*

<sup>2</sup>*LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

<sup>3</sup>*Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*



$$g_{SS}^2 = 2$$

$$g_{aS1aS2}^2 \approx 2$$

$$\alpha \approx \frac{N_{aS1,aS2,S} N_S}{N_{d1,S} N_{d2,S}}$$

