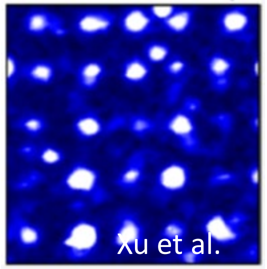
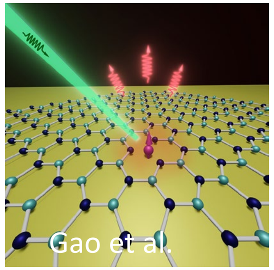
Yong P. Chen Group: Quantum Materials/Matters for Quantum Information/Technologies

(material/hardware platforms)

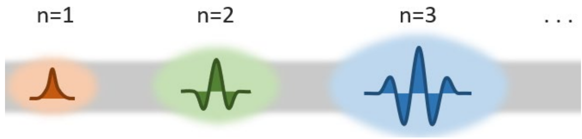
Semiconductor quantum Emitters (defects/excitons)

- Quantum photonics /communications/networking (distributing entanglement)
- Quantum sensing
- Quantum transduction


Xu et al.


Gao et al.

Defects in *h-BN*



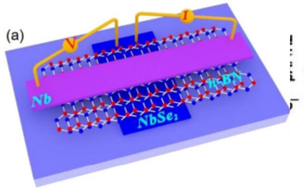
Excitons/ Rydbergs (*Cu_2O; TMDCs*)

Superconductors /Josephson Junctions

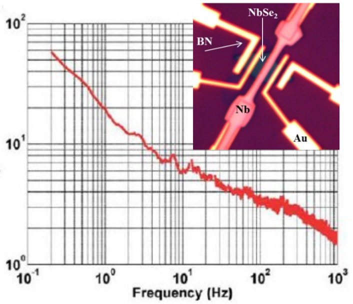
- (better) Qubits for quantum computing
- Quantum sensing

[of quantum materials]

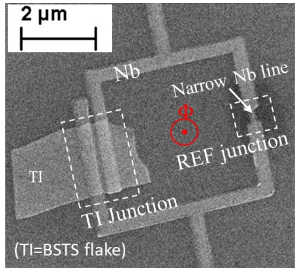
***h-BN* Junction**

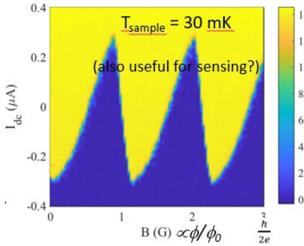


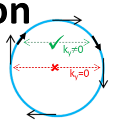
Tian et al.



***Topological* superconductor/junction**



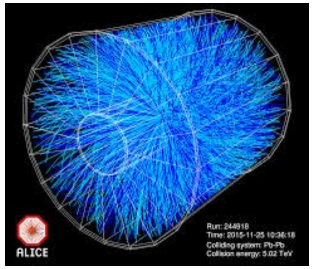


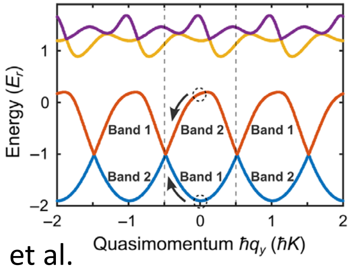


Kayyalha et al.

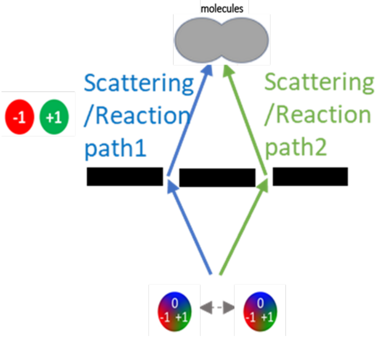
Atoms/Molecules

- Quantum Simulation
- Quantum Control
- Quantum Chemistry

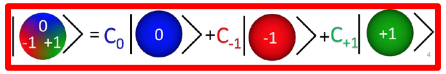




Li et al.



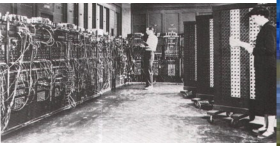
Blasing et al.



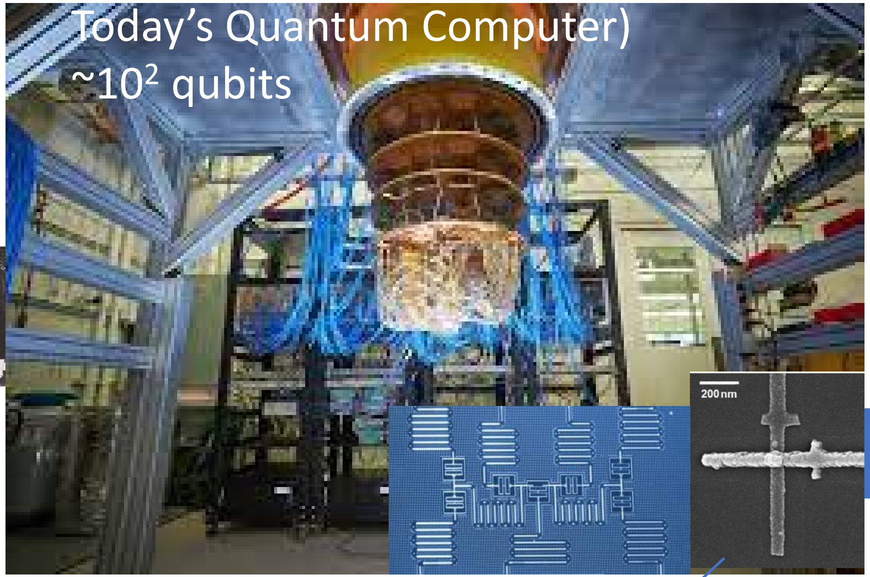
yongchen@purdue.edu

(materials) challenge: decoherence/scaling-up

Example: (superconductor) quantum computing

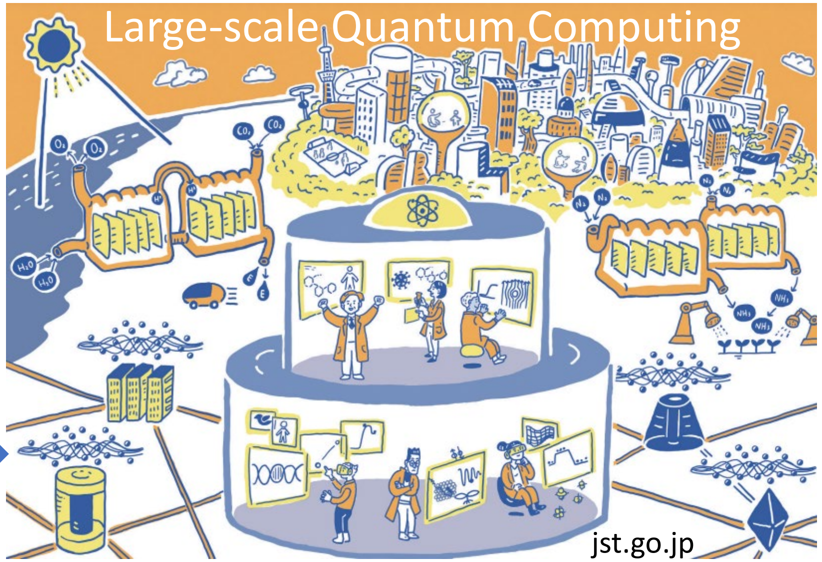


ENIAC-like?



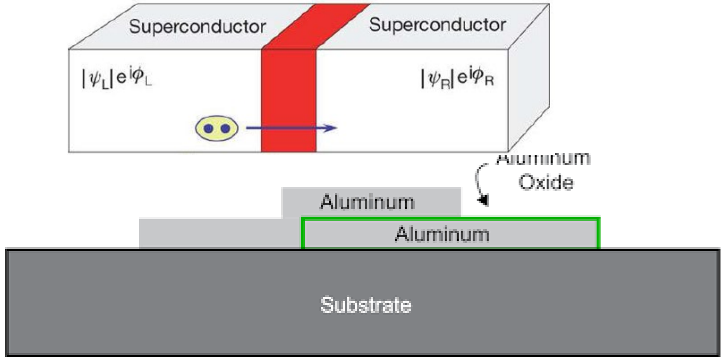
<u>What material</u> will be used for future large-scale *<u>fault-tolerant</u>* quantum computers (>~10^6 qubits?)

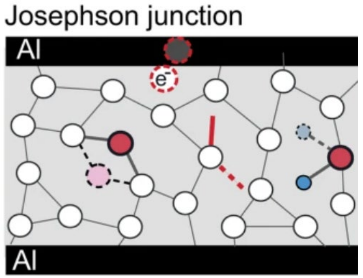
?



jst.go.jp

What is the "silicon" (material) for quantum computing?





Lisenfeld et al. Sci.Rep.'16

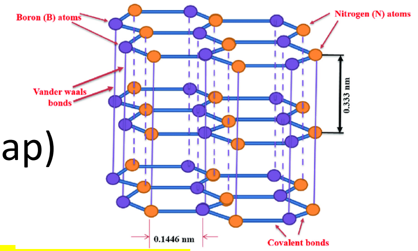
Common sources of decoherence in Superconductor Josephson Junction qubits:

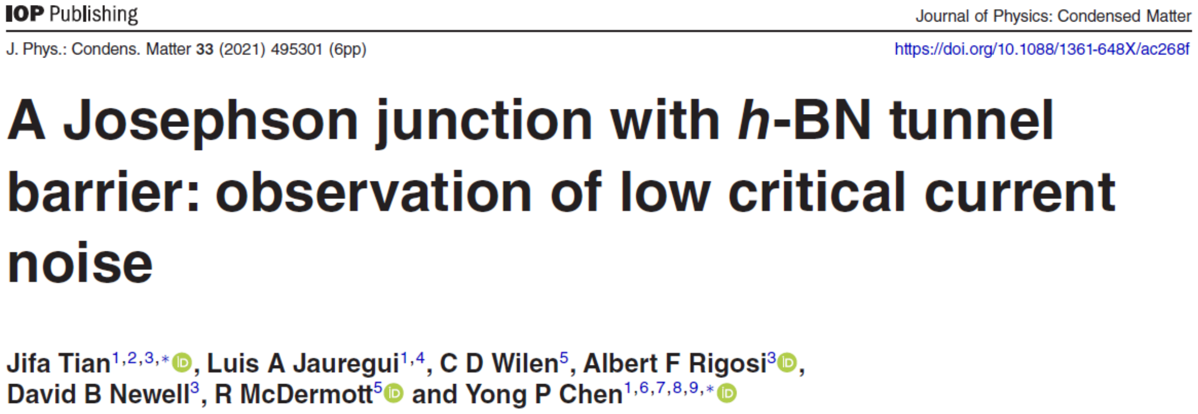
- Phonons (less at very low T)
- Non-uniformity (tunnel barrier oxide)
- 2-level defects (fluctuating states) in (amorphous) oxide (AlOx)
- (low T) adsorbed O_2 molecules on superconductor (Al) surface ……

Martinis, McDermott, Yu et al.

h-BN as "clean dielectric" to reduce noise in devices: superconductor Josephson Junctions/qubits

Highly crystalline
& insulating (6eV gap)




IOP Publishing Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter 33 (2021) 495301 (6pp) https://doi.org/10.1088/1361-648X/ac268f

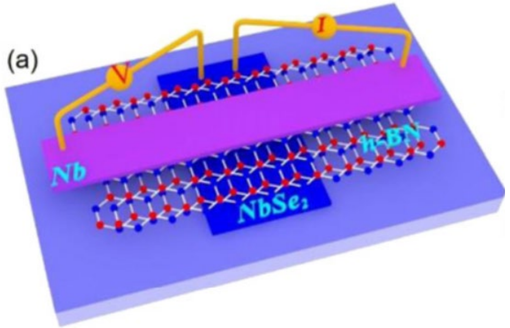
A Josephson junction with *h*-BN tunnel barrier: observation of low critical current noise

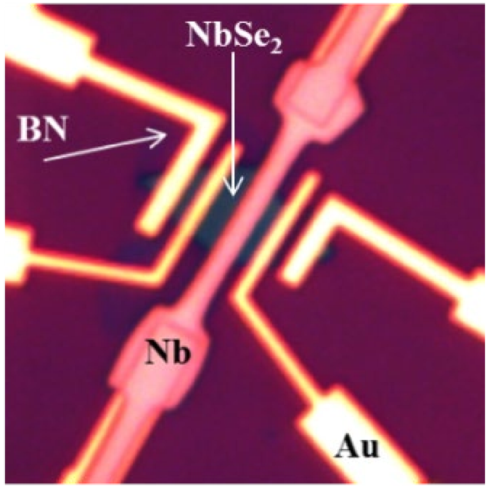
Jifa Tian[1,2,3,*], Luis A Jauregui[1,4], C D Wilen[5], Albert F Rigosi[3], David B Newell[3], R McDermott[5] and Yong P Chen[1,6,7,8,9,*]

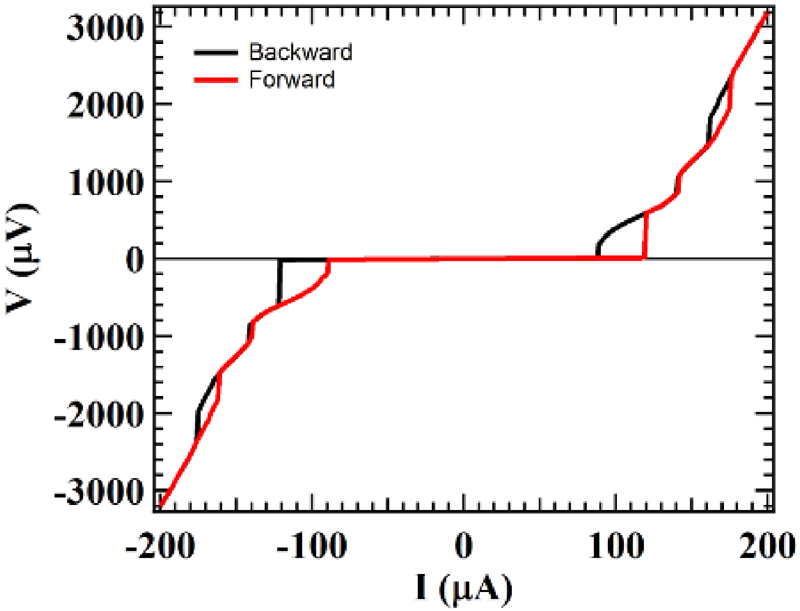
h-BN dielectric promises better Josephson junctions (?!):
- 2D atomic crystal – near perfect lattice and crystallinity
- Ultralow defects -- (shown to be "best" dielectric)
- Clean interface with other 2D material superconductors

→ Better qubit (lower decoherence) & sensor (lower noise)

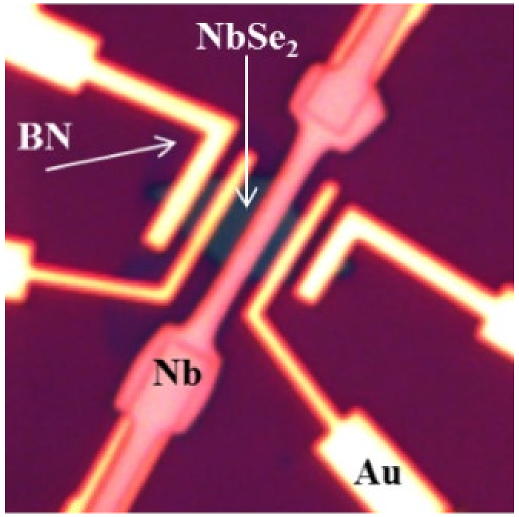
Postdoc Jifa Tian
(now faculty @Wyoming)

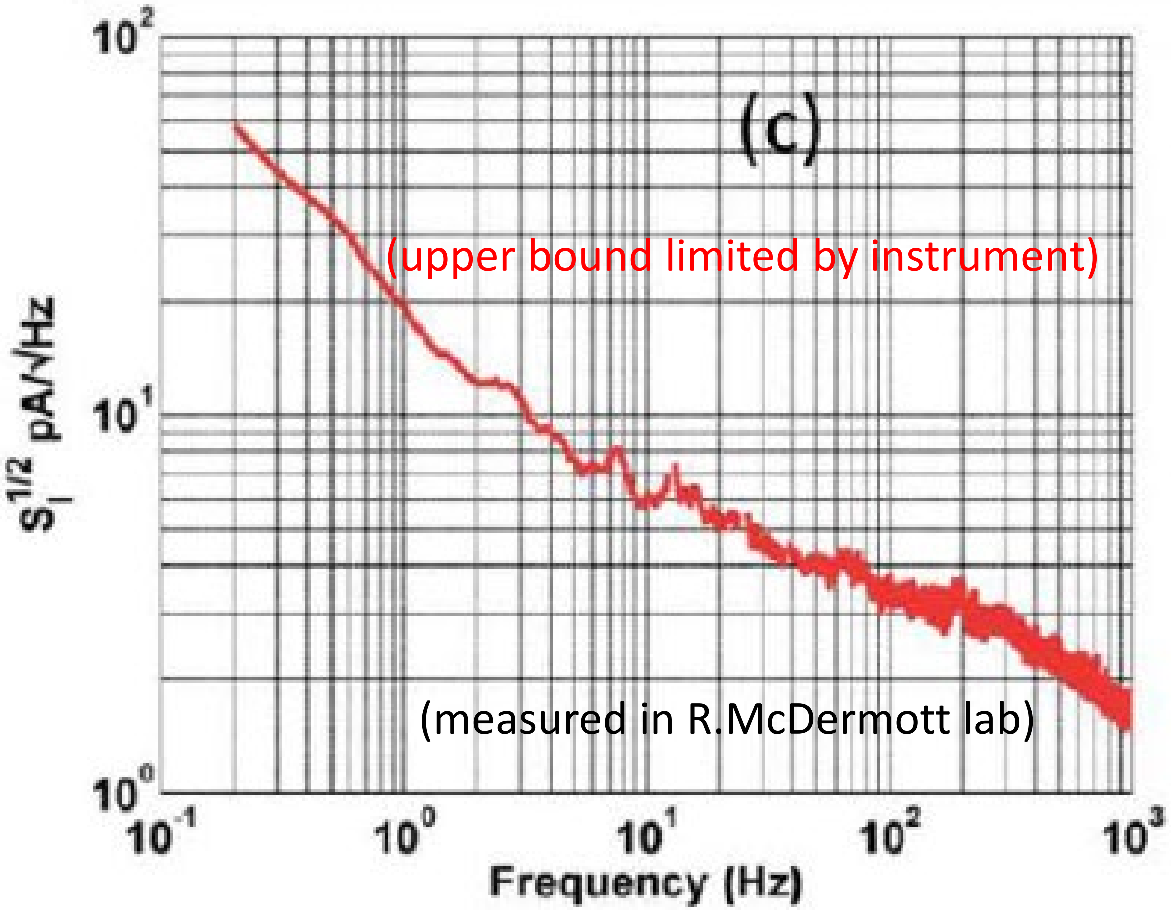






h-BN as dielectric tunnel barrier in Josephson Junctions : reduced noise





(upper bound limited by instrument)

(measured in R.McDermott lab)

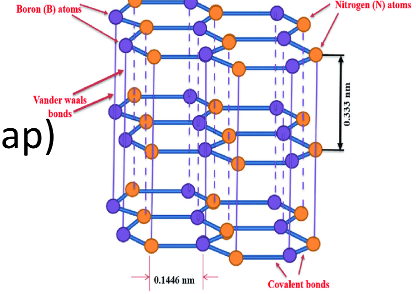
Already at least 4X lower noise than traditional Al/AlOx/Al Junctions!

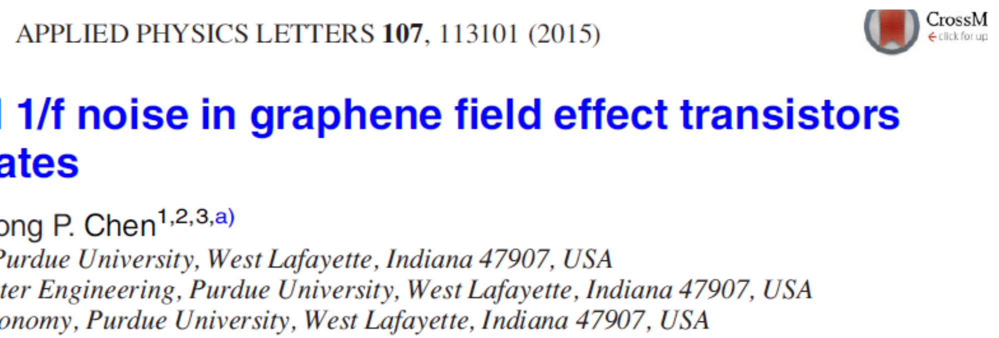
→ Promise to:

- **reduce decoherence in SC qubits?**
- *better SQUIDs?*

h-BN as “clean dielectric” to reduce noise in devices:
graphene FET and electrodes

Highly crystalline
& insulating (6eV gap)

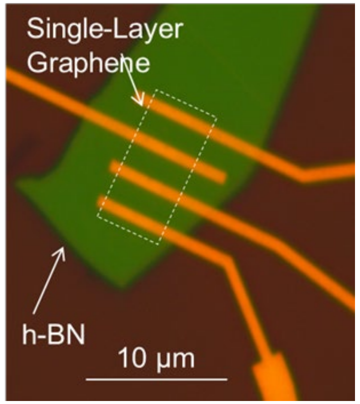


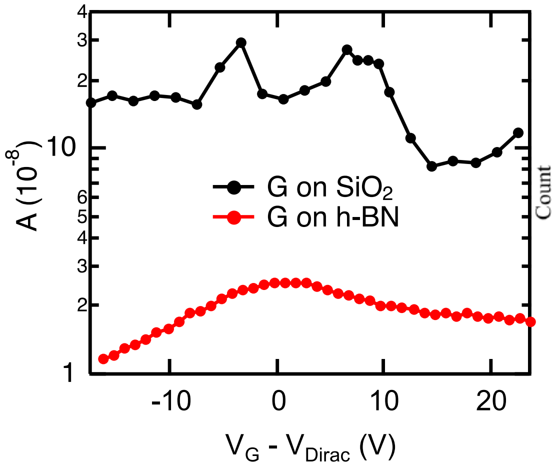

APPLIED PHYSICS LETTERS **107**, 113101 (2015)

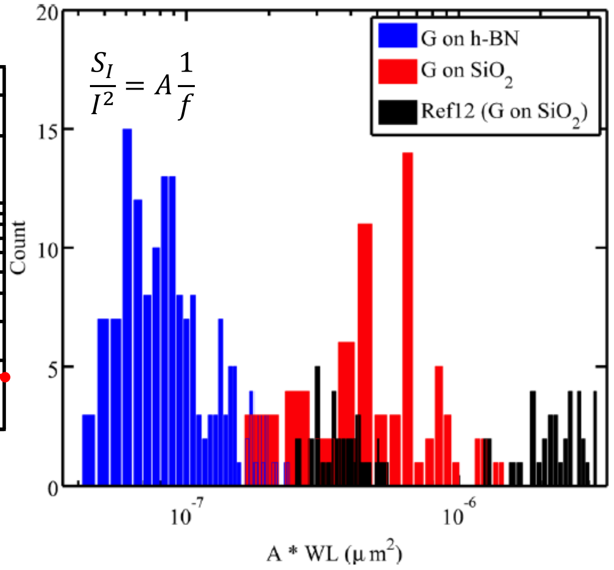
Observation of reduced 1/f noise in graphene field effect transistors on boron nitride substrates

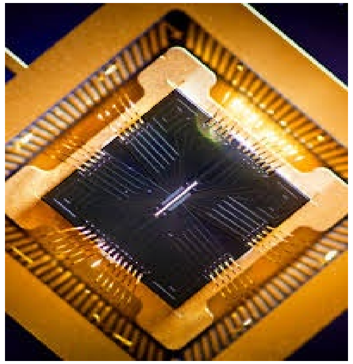
Morteza Kayyalha[1,2] and Yong P. Chen[1,2,3,a)]
[1]Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA
[2]School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, USA
[3]Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA


PhD Morteza Kayyalha
(->now faculty
@Penn State EE)







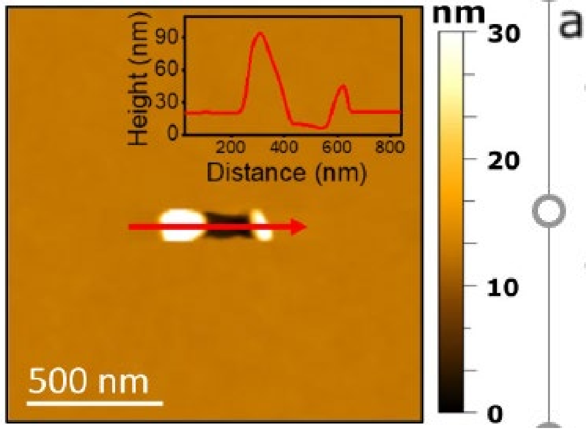

(might help ion trap electrodes....)

Adding **Defects** (type 1) in h-BN: single photon **quantum emitters**

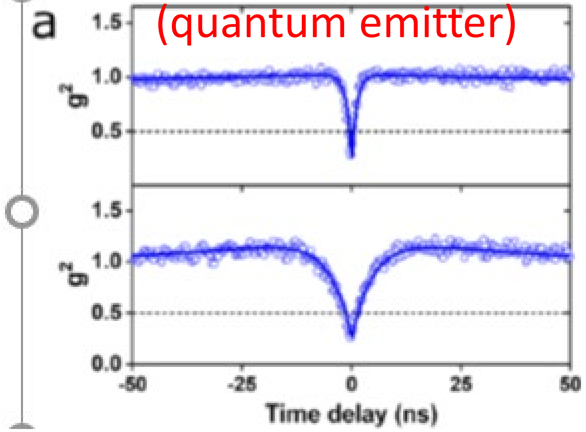
Xiaohui Xu, Zachariah O. Martin, Demid Sychev, Alexei S. Lagutchev, Yong P. Chen, Takashi Taniguchi, Kenji Watanabe, Vladimir M. Shalaev, Alexandra Boltasseva, "Creating Quantum Emitters in Hexagonal Boron Nitride Deterministically on Chip-Compatible Substrates", **Nano Lett.** (2021); doi:10.1021/acs.nanolett.1c02640

Xiaohui Xu
(Purdue)

depths less than or comparable to the hBN flake thickness → "pokes" hBN without deforming or damaging the substrate

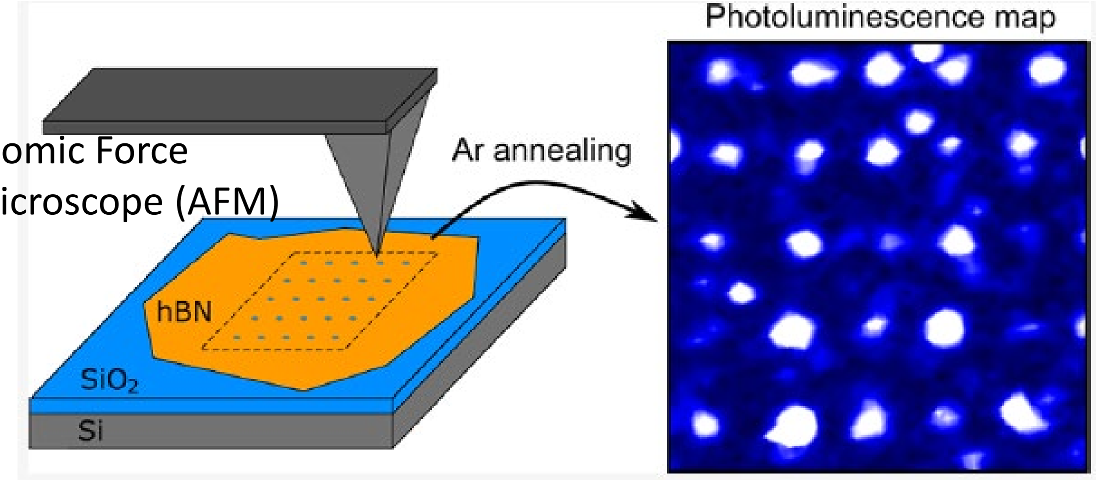


- Single photon source! (quantum emitter)

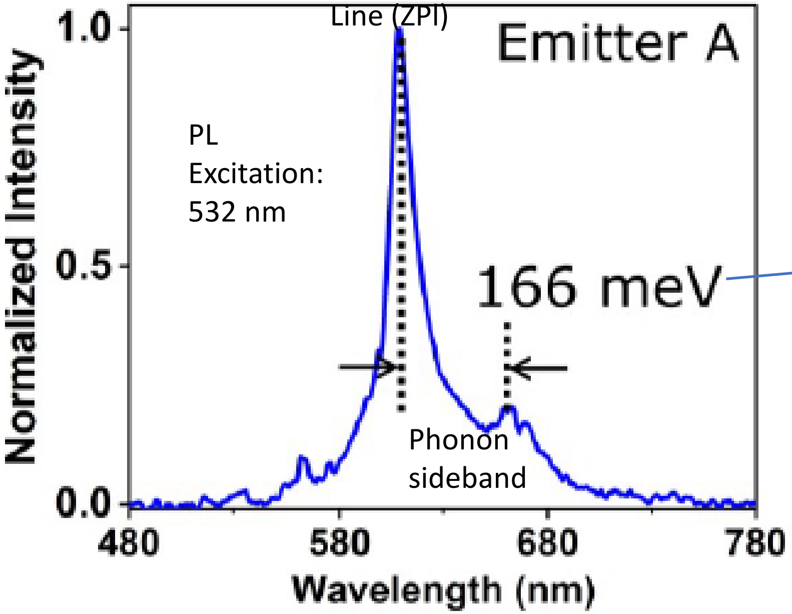


- NOT spin-sensitive

Atomic Force Microscope (AFM)



<~um spacing>



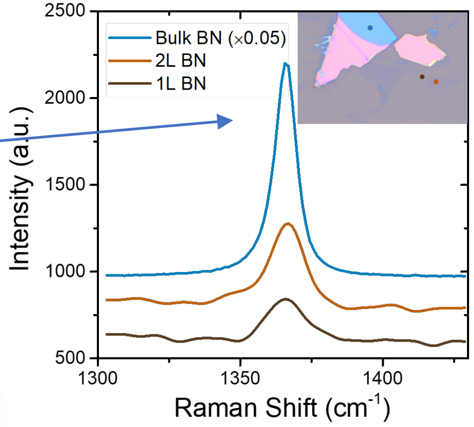
zero-phonon Line (ZPl)

PL Excitation: 532 nm

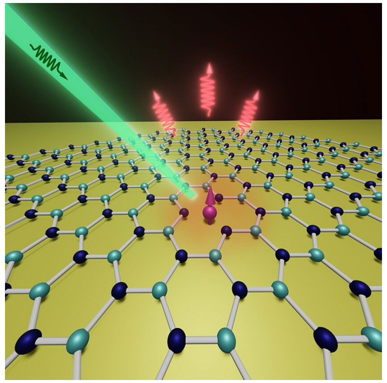
166 meV

Phonon sideband

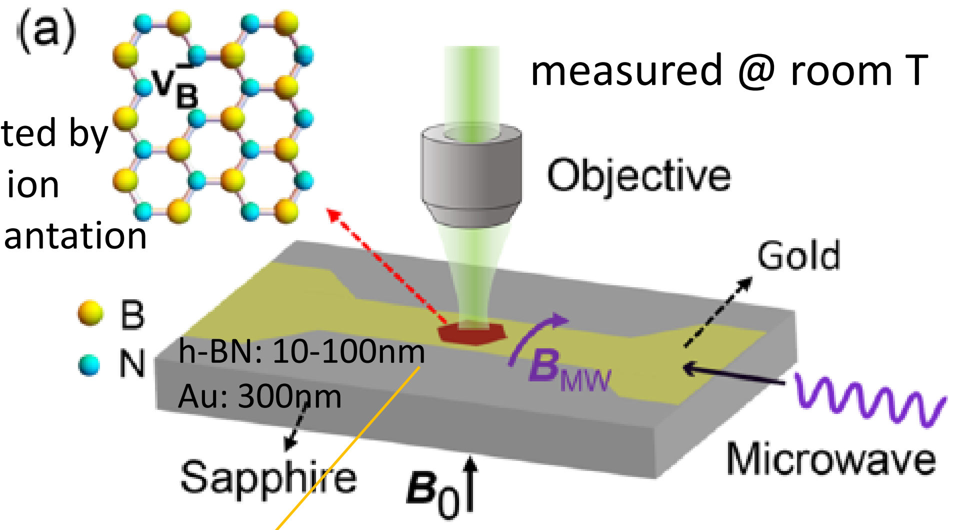
Consistent with Raman spectra of h-BN (example taken by Kimberly Hsieh, @AU-iNano)



Defect type-2 (V_B-) --- spin defects in hBN for quantum sensing and magnetometry



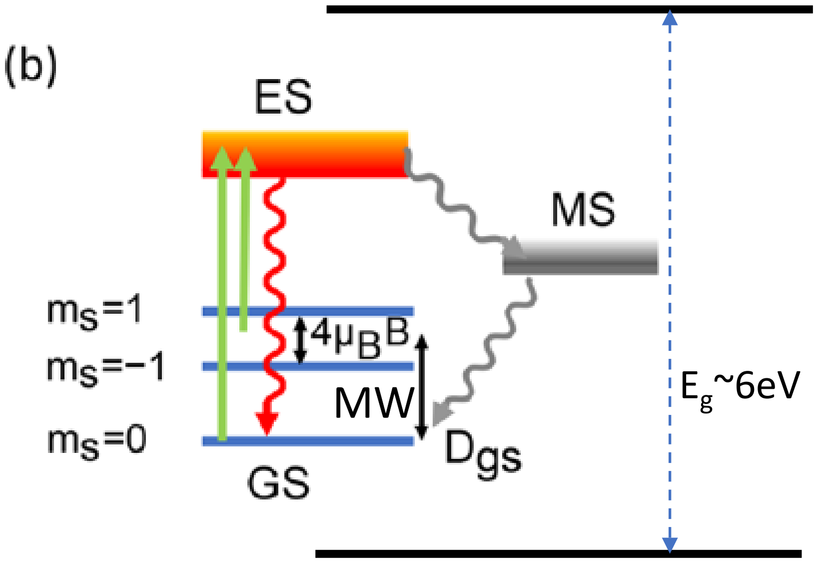
c.f. review by S. Vaidya et al. *Adv.Phys.X*, 8, 2206049 (2023).

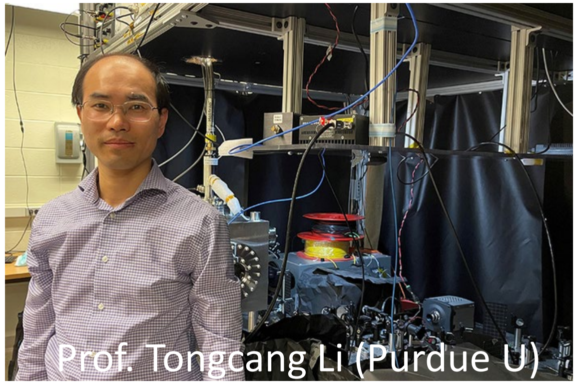


created by He+ ion implantation

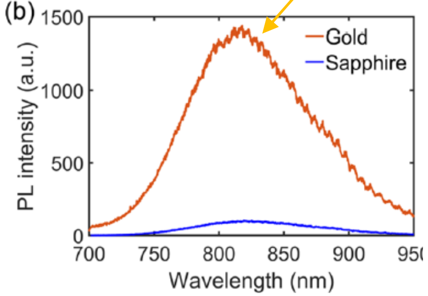
measured @ room T

h-BN: 10-100nm
Au: 300nm



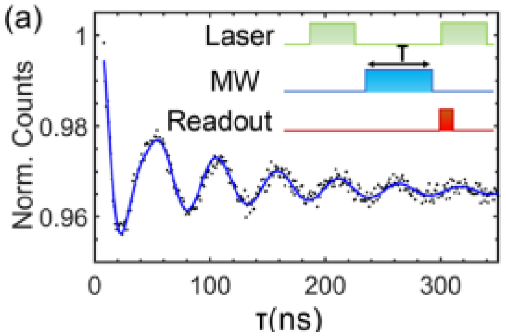


Prof. Tongcang Li (Purdue U)

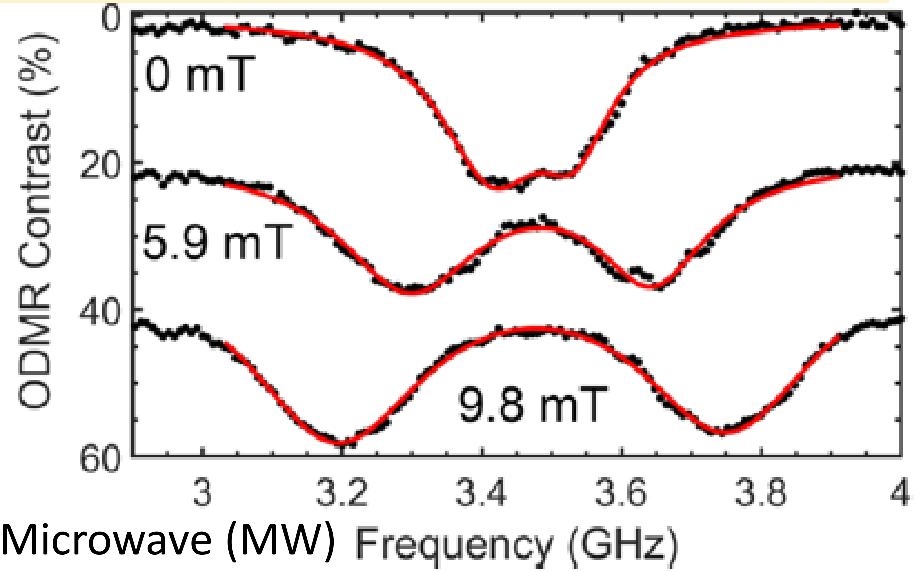


PL enhanced by Au (plasmonics)

Coherent Rabi Osc. (“atom-like object”)



Optically Detected Magnetic Resonance (ODMR)



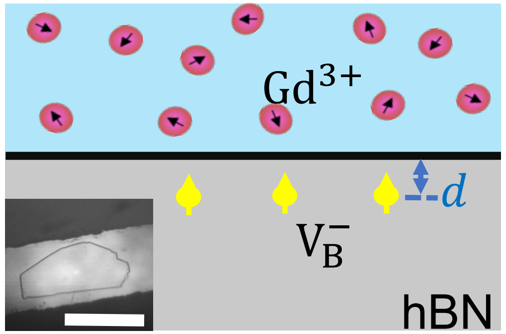
Xingyu Gao, Boyang Jiang, Andres E. Llacsahuanga Allcca, Kunhong Shen, Mohammad A. Sadi, Abhishek B. Solanki, Peng Ju, Zhujing Xu, Pramey Upadhyaya, Yong P. Chen, Sunil A. Bhave, Tongcang Li, "High-contrast plasmonic-enhanced shallow spin defects in hexagonal boron nitride for quantum sensing", **Nano Letters** 21, 7708 (2021)

Nuclear spin polarization and control in hexagonal boron nitride

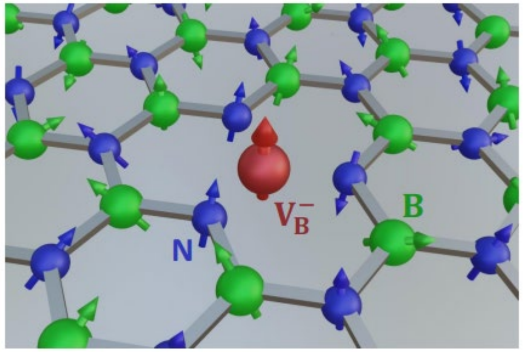
Nature Materials 21,1024 (2022)

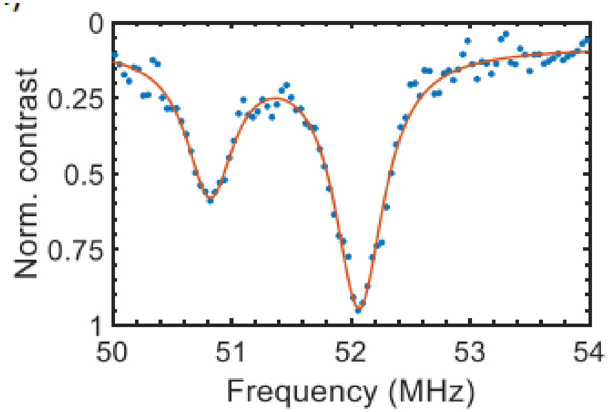
Xingyu Gao[1], Sumukh Vaidya[1], Kejun Li[2], Peng Ju[1], Boyang Jiang[3], Zhujing Xu[1], Andres E. Llacsahuanga Allcca[1], Kunhong Shen[1], Takashi Taniguchi[4], Kenji Watanabe[5], Sunil A. Bhave[3,6,7], Yong P. Chen[1,3,6,7,8], Yuan Ping[9] and Tongcang Li[1,3,6,7] ✉

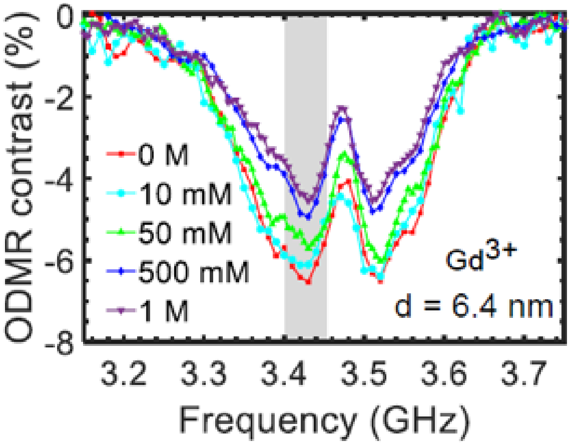
Sense Paramagnetic Spins (in liquid)

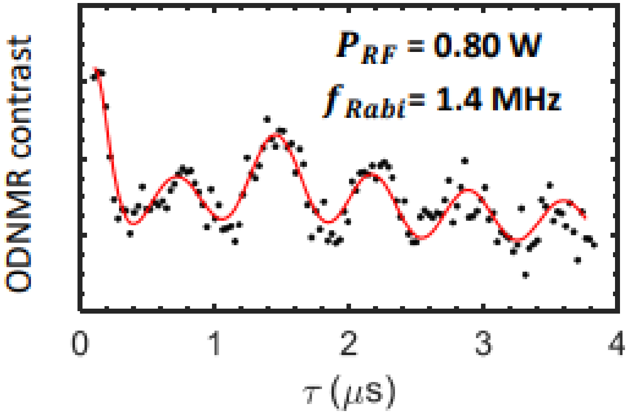


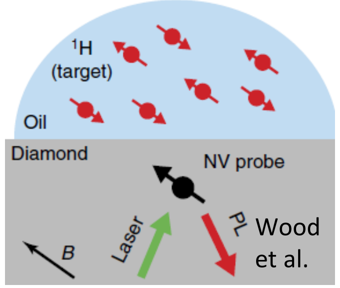
(a)





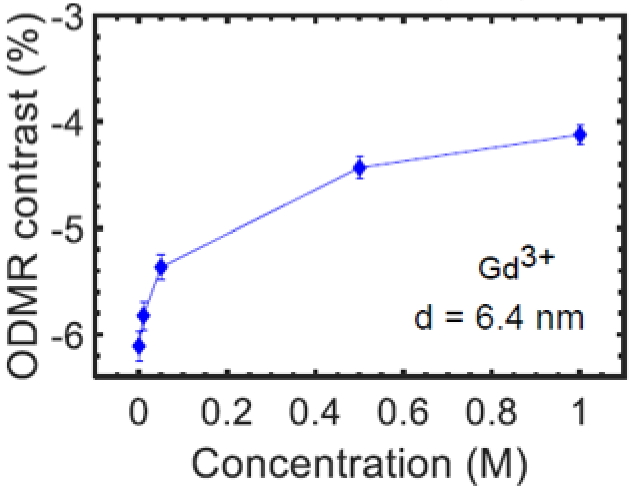






potential in developing **micro/nanoscale NMR**

Towards 2D material based NMR sensing!

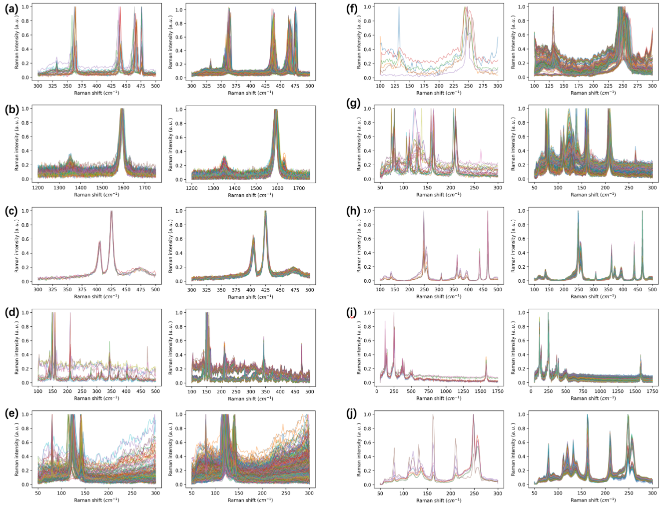


X. Gao, S. Vaidya, P. Ju, S. Dikshit, K. Shen, Y. P. Chen, T. Li. ACS Photonics (2023)

AI can help us find (better) materials

- Deep Learning Assisted Raman Spectroscopy for Rapid Identification of 2D Materials and stacked combinations.

➢ Identification of different classes of 2D materials



Y.Qi et al.
In prep'24

Figure 1. The 2D material Raman spectra before and after data augmentation using DDPM: (a) BP, (b) Graphene, (c) MoS_2, (d) ReS_2, (e) Te, (f) WSe_2, (g) WTe_2, (h) BP–WSe_2 stack, (i) Te-ReS_2-WSe_2-Graphene stack, and (j) Te-WSe_2-WTe_2 stack. The left side represents the original Raman spectra dataset, while the right represents the augmented Raman spectra dataset.

Method	Accuracy	Precision	Recall
CNN	0.988	0.945	0.937
DDPM-CNN	1.000	1.000	1.000
ANN	0.946	0.658	0.646
DDPM-ANN	1.000	1.000	1.000
RF	0.906	0.566	0.574
DDPM-RF	1.000	1.000	1.000
SVM	0.966	0.829	0.786
DDPM-SVM	1.000	1.000	1.000
KNN	0.953	0.826	0.770
DDPM-KNN	0.988	0.989	0.988
LR	0.960	0.731	0.711
DDPM-LR	1.000	1.000	1.000

Table 1: The average performance of ten-fold cross-validation comparisons between the proposed method vs. baselines.

Dr. Yaping "Joyce" Qi [AI-materials analysis]

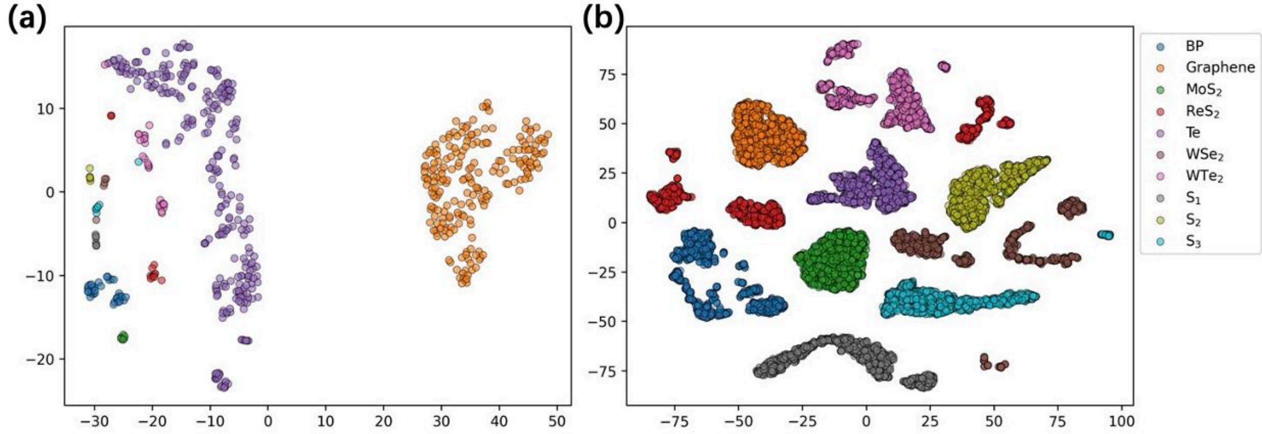
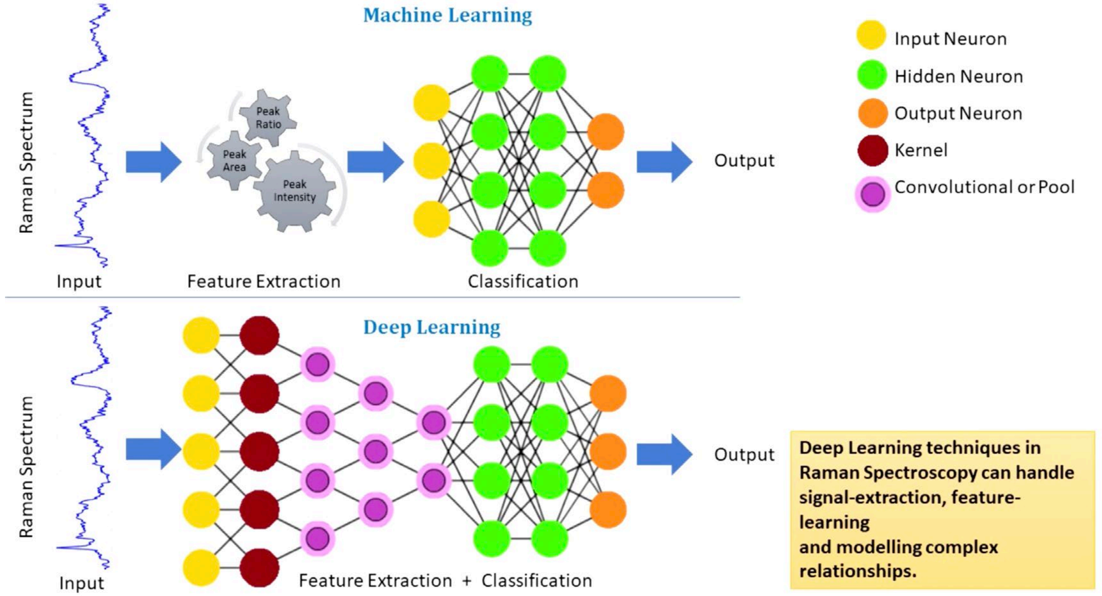


Figure 2. t-SNE plots for (a) the original and (b) the augmented dataset of different 2D materials. [S_1: BP–WSe_2 stack, S_2: Te-ReS_2-WSe_2-Graphene stack, S_3: Te-WSe_2-WTe_2 stack.]



Deep Learning techniques in Raman Spectroscopy can handle signal-extraction, feature-learning
and modelling complex relationships.

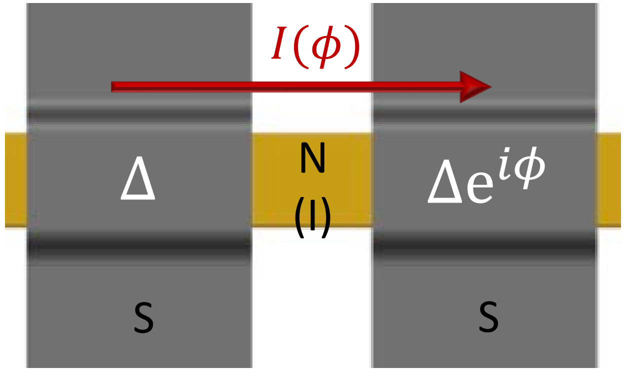
Y.Qi, D.Hu et al., "Recent Progresses in Machine Learning Assisted Raman Spectroscopy", **Advanced Optical Materials**, 2203104 (2023)

S/TI/S Josephson Junctions

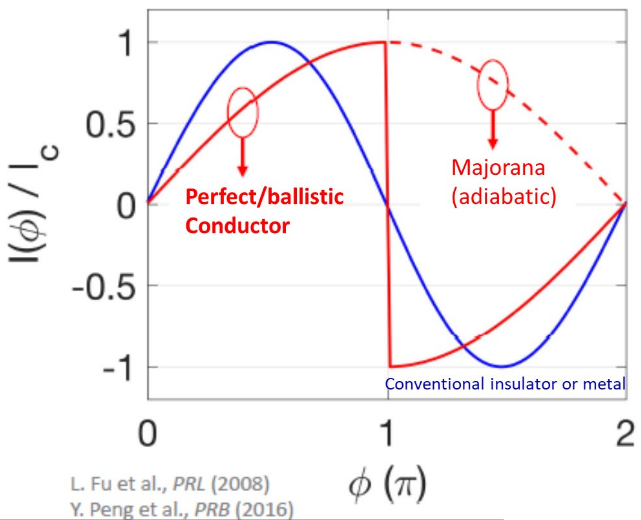
with L. Rokhinson et al. (PU)

$I = I(\phi)$ S/I/S Josephson junctions

$= I_c \sin(\phi)$ (also true if I replaced by Normal/conventional metal)

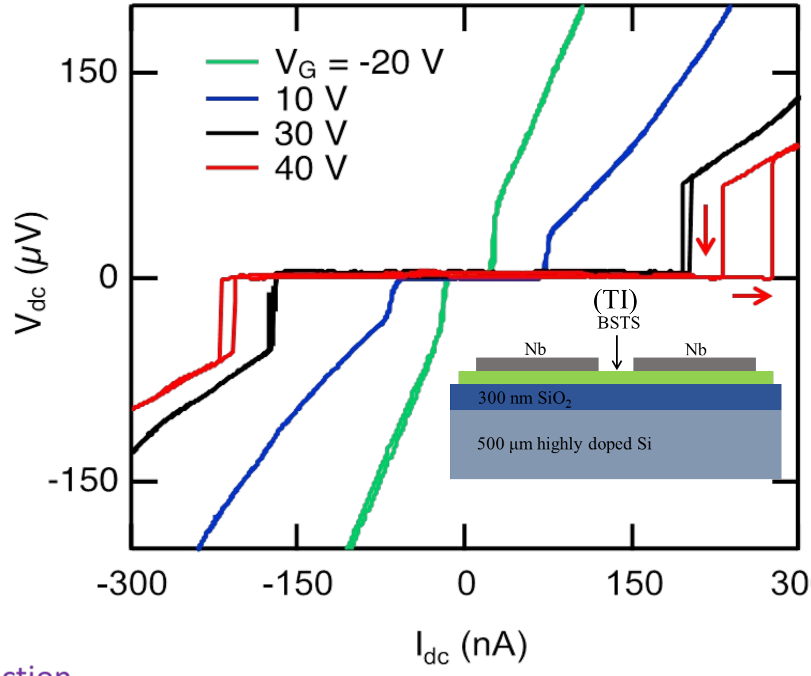


See also recent review by D.van Harlingren et al'21

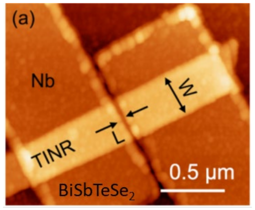


L. Fu et al., *PRL* (2008)
Y. Peng et al., *PRB* (2016)

Gate-tunable supercurrent in S/TI/S Junction

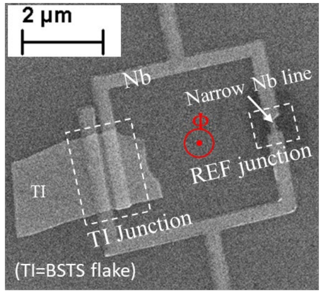


L.A. Jauregui (now UCI) & M. Kayyalha (now PSU) et al. APL'2018

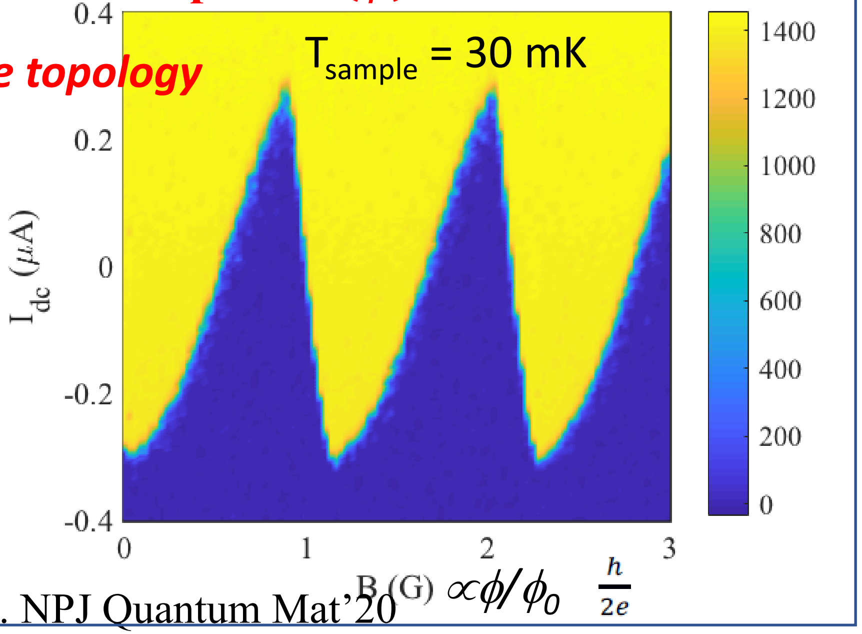


Unconventional current-phase $I(\phi)$ in S/TI/S Junction

--***probes k-space topology***

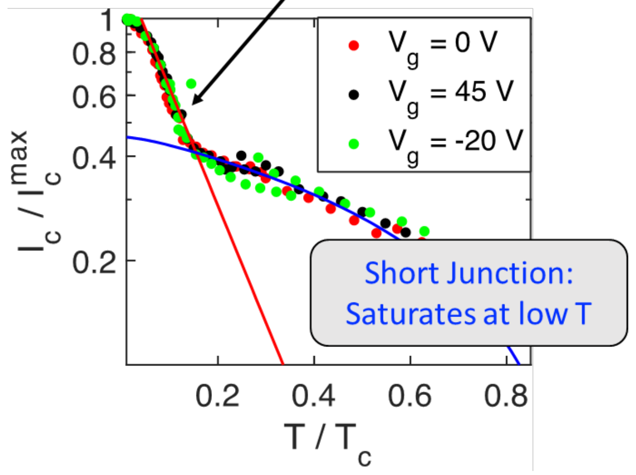


S/TI/S
SQUID

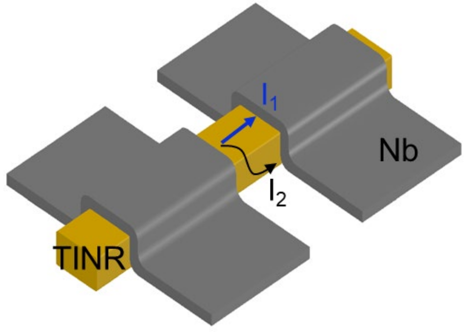


M. Kayyalha et al. NPJ Quantum Mat'20

Long junction
Probe low energy Andreev Bound States!



Short Junction: Saturates at low T



Evidence for supercurrent flowing on surface

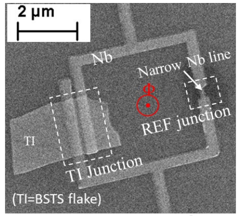
--***probes real-space topology***

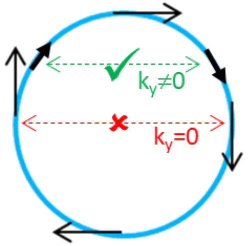
M. Kayyalha* et al., PRL 122, 047003 (2019)

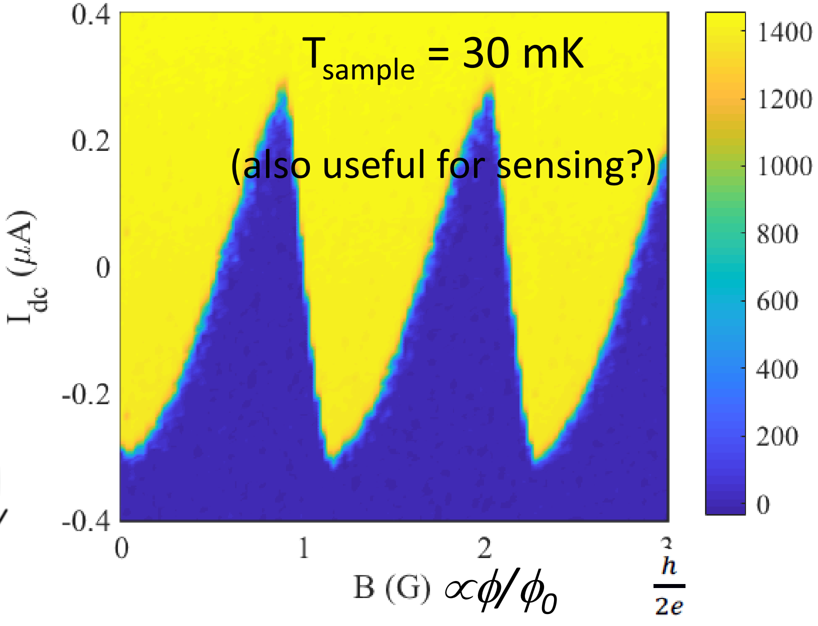
Potential applications: to protect SC qubits (reduce noise/decoherence)

*(using topology to) improve **conventional SC quantum computing** (not "topological QC")*

unconventional "skewed" current-phase relation (CPR)







->Protected by "topology"
(w/o even requiring more exotic physics "majorana anyons")

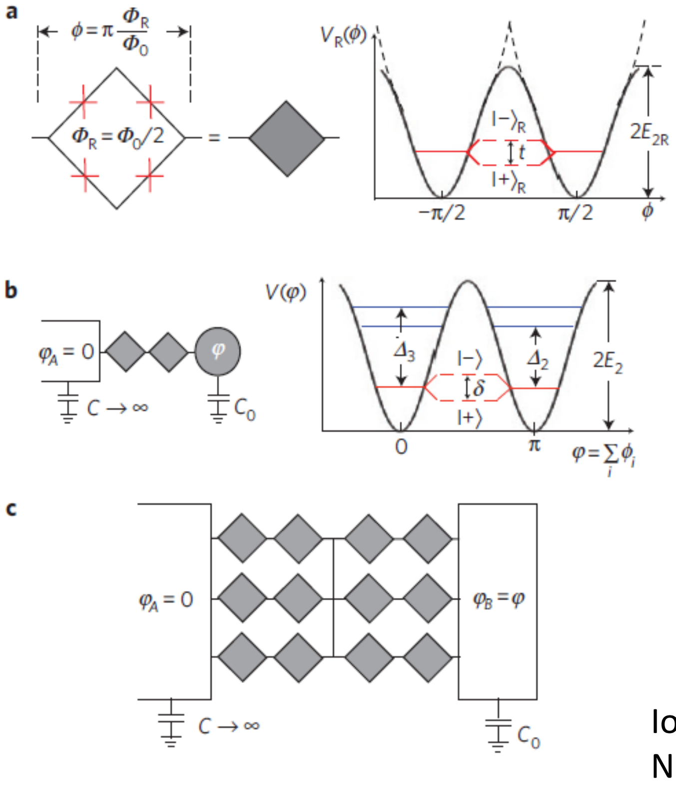
M. Kayyalha et al., NPJ QM 2020

$$I(\phi) = \sum_{n=1,2,\ldots} A_n \sin(n\phi)$$

Non-sinusoidal CPR
→
Higher harmonics
sin (nϕ) , n>1

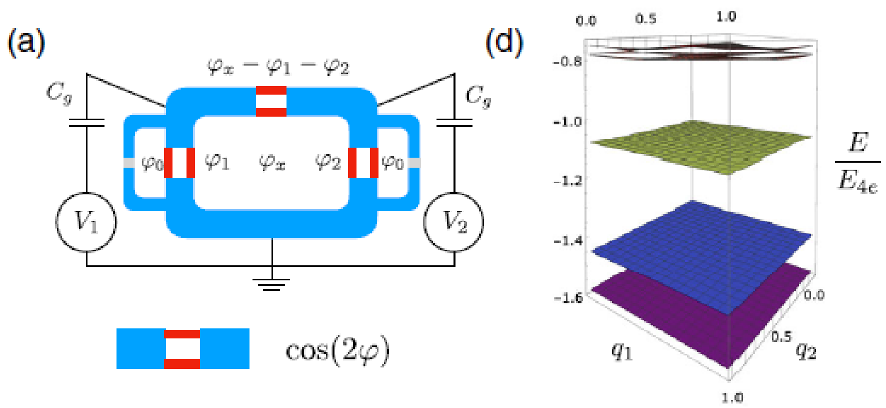
→ May enable more robust/error-resilient SC qubits (non-majorana)

L. Ioffe'01; ….



Ioffe, Gershensen,
Nature Physics 5 48–53 (2009)

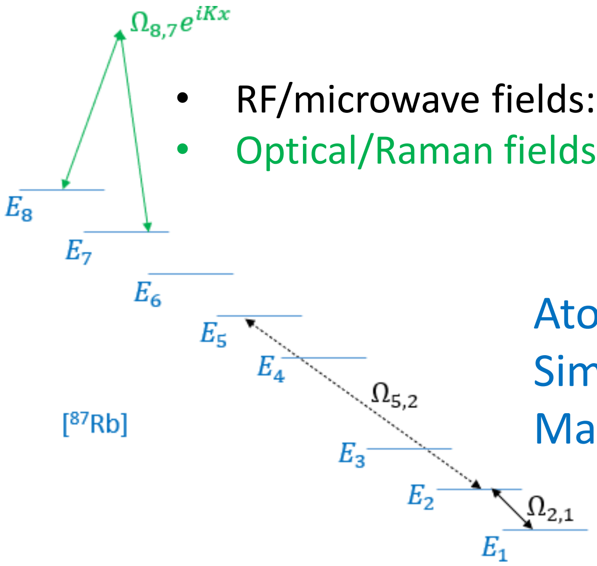
Figure 1 | Protected qubit based on 'cos(2ϕ)' Josephson elements.



Enhanced Coherence in Superconducting Circuits via Band Engineering

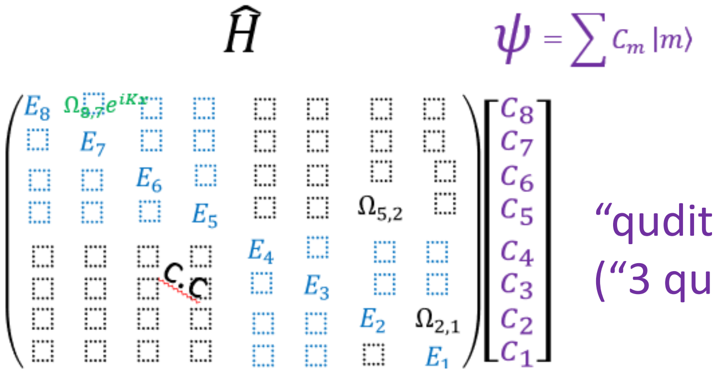
PRL 126, 187701 (2021) Luca Chirolli[1,2] and Joel E. Moore[1,3]

Coherent light-matter interaction with atoms: optical "dressing"



- RF/microwave fields: spin states
- Optical/Raman fields: spin-momentum states

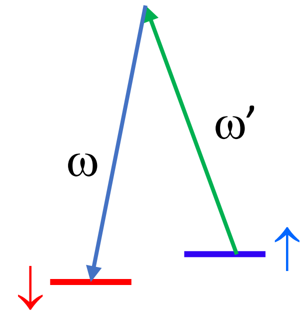
Atom (d-levels) + Light :
Simulating a (dxd)
Matrix-Hamiltonian

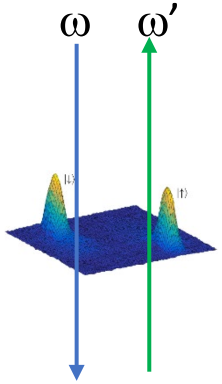


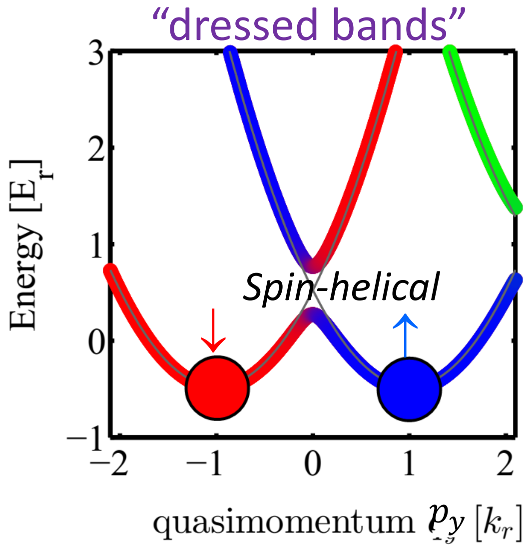
"qudit" (d=8)
("3 qubits = 2⊗2⊗2)

Synthetic "bandstructure"/spin-orbit coupling (SOC) by Raman (optical) dressing

$$\begin{array}{cc} \text{“matter”} & \text{“light”} \\ \left(\begin{array}{cc} \frac{\hbar^2}{2m}(p_y+k_r)^2 & \Omega \\ \Omega & \frac{\hbar^2}{2m}(p_y-k_r)^2 \end{array}\right) & \end{array}$$



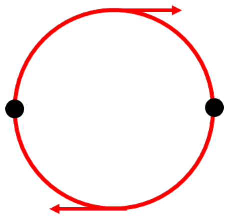




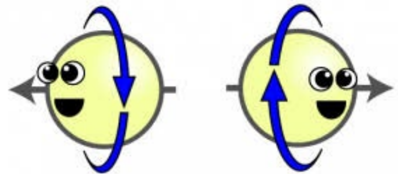
Eigenvalues E(Ω,p_y) and
Eigenstate ("dressed state")
[spin/momentum superposition]:

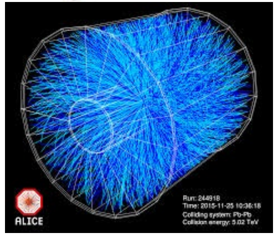
$\alpha(\Omega,p_y)|\downarrow,p_y+k_r\rangle+\beta(\Omega,p_y)|\uparrow,p_y-k_r\rangle$
dep on parameters (p, Ω)

c.f.Ding/YPC/S.Kai et al. "Spin-momentum entanglement in a Bose-Einstein condensate", Phys. Chem. Chem. Phys. 22, 25669 (2020)

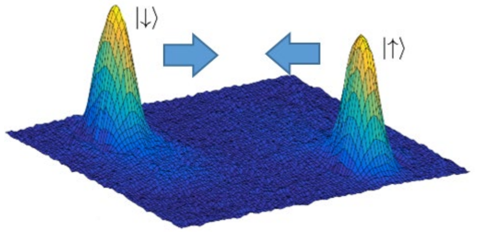


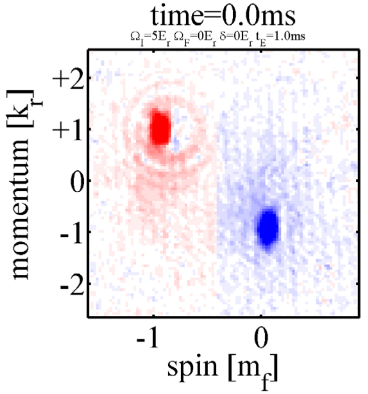
Quantum science & technologies based on "Spin-helical" particles



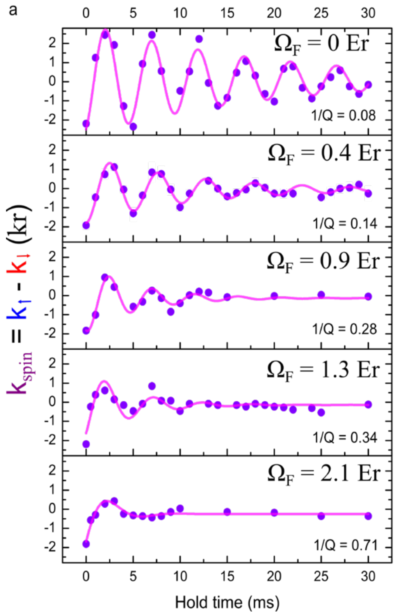


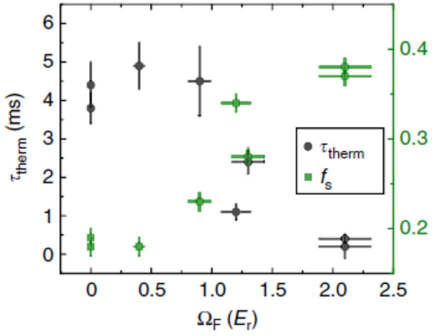
- Quantum simulation



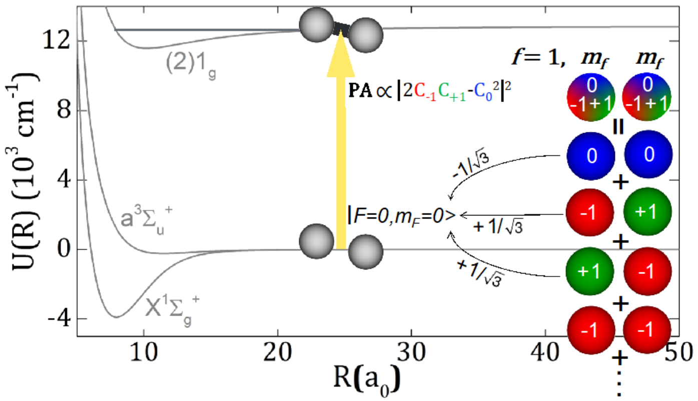


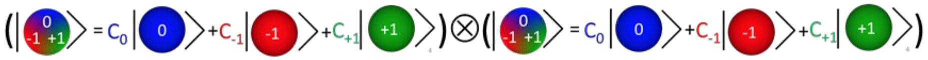
C. Li *et al.*, Nature Comm. 10, 375 (2019)



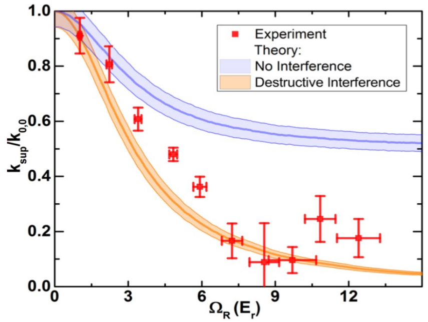


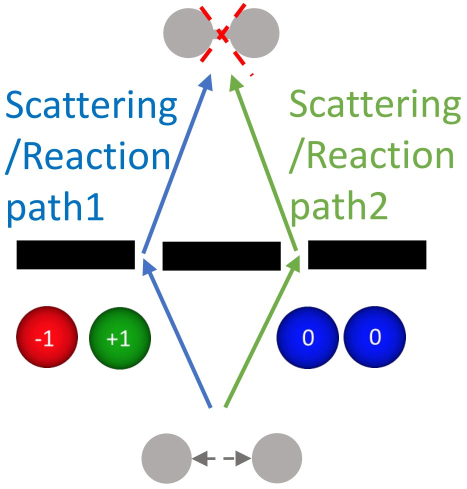
- (spin-based) quantum control/chemistry





D.Blasing *et al.* PRL 121, 073202 (2018)



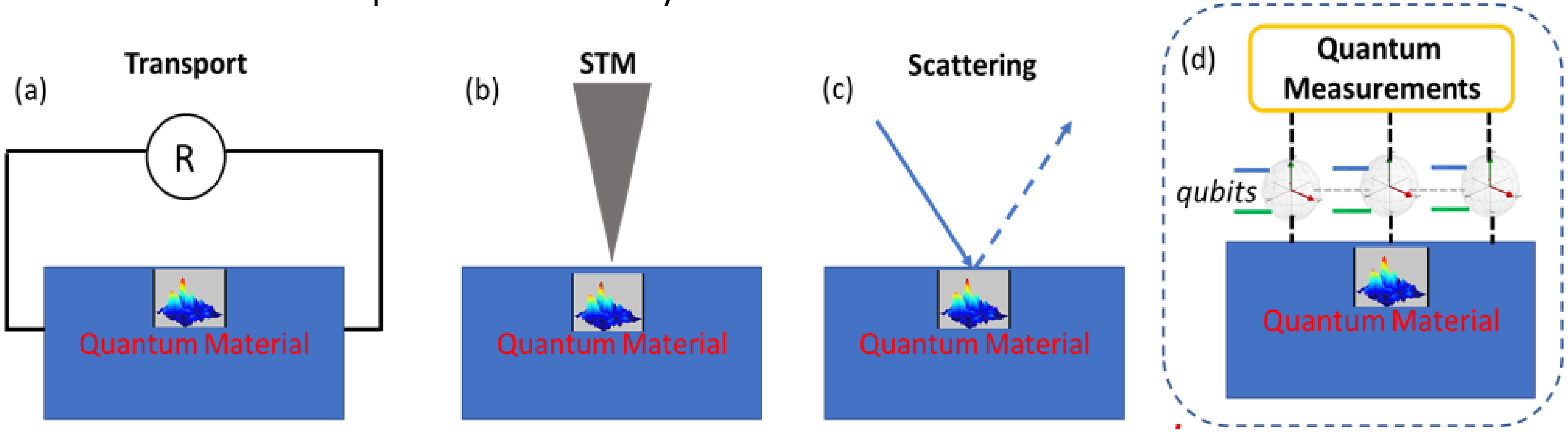


Scattering /Reaction path1

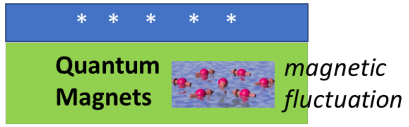
Scattering /Reaction path2

Develop new experimental methods: Quantum Sensing of quantum materials

<Traditional probes: 1 or 2-body correlation function>

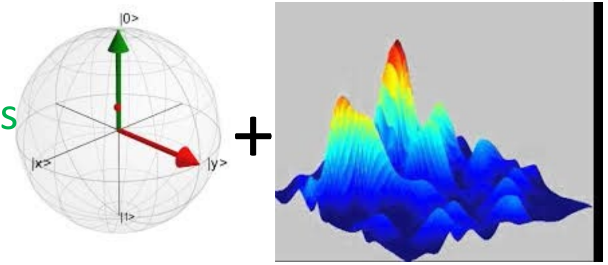


Want: **Array of Spin qubits** in h-BN



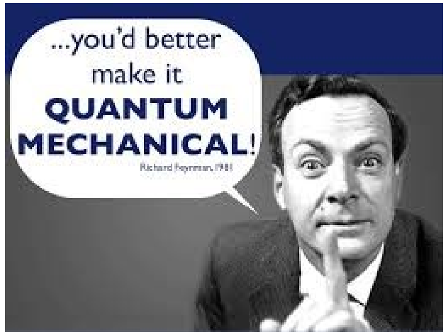
"Q+Q" -- quantum hybrid

Well-controlled "simple" quantum systems/sensors (e.g. "2-level system" -- qubits, q-beams)

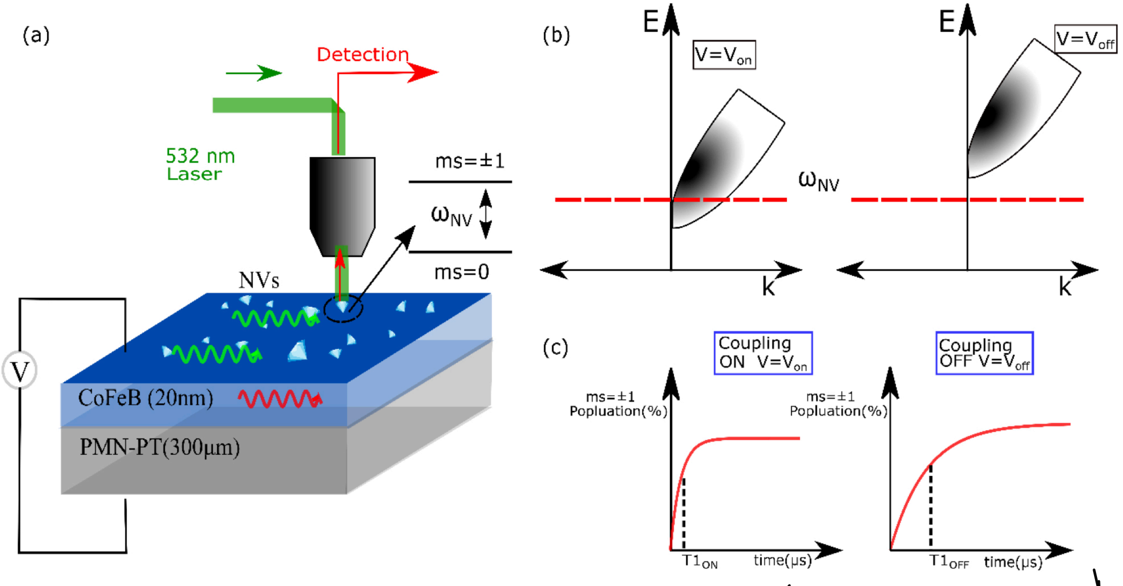


Complex, poorly-understood/controlled quantum systems (e.g. complex quantum materials)

→ More direct probe of "quantum" (many-body wavefunction/correlation/entanglement)…

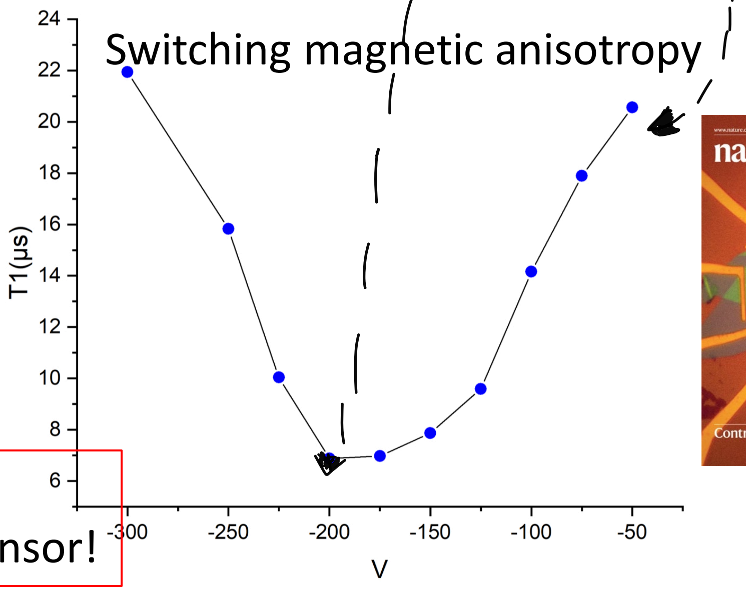


Quantum sensing of (Magnetic/Spintronic) Quantum Materials

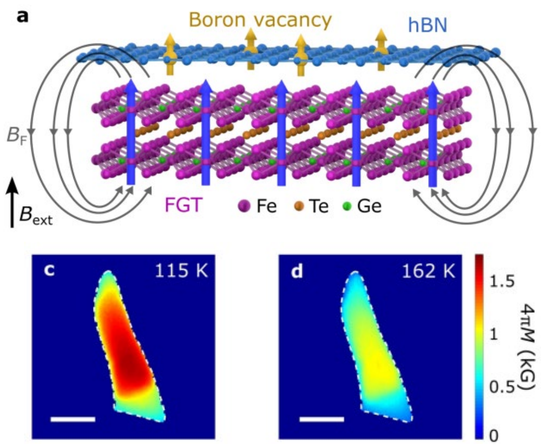


A. Solanki, S. I. Bogdanov, A.Rustagi, N.R. Dilley, T.Shen, M.Mushfiqur Rahman, W. Tong, P. Debashis, Z.Chen, J.Appenzeller, Y. P. Chen, V. M. Shalaev, and P. Upadhyaya. "Electric field control of interaction between magnons and quantum spindefects", **Phys. Rev. Res. 4, L012025 (2022)**

Switching magnetic anisotropy



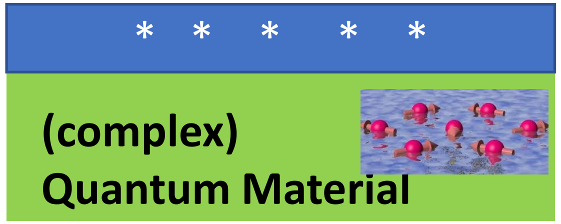
A "bad qubit",
but a good q-sensor!



See also: C. Du et al. (UCSD) arXiv'21

(decoherence or [many-body] *quantum optics* as a probe!)

Array of Spin defects

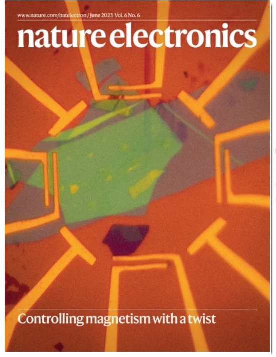


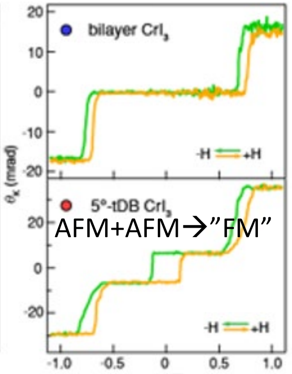
(complex) Quantum Material

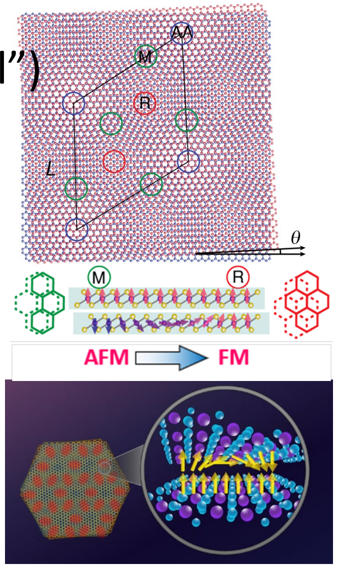
(the [many-body] *quantum measurement problem)*

Twisted/Moire magnets

(magnetic "metamaterial")



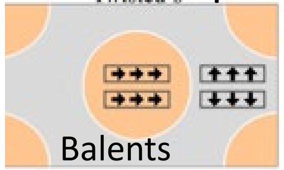




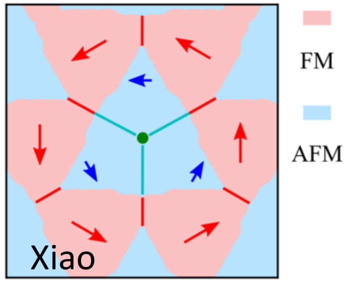
G. Cheng et al. Nat. Elect.'23

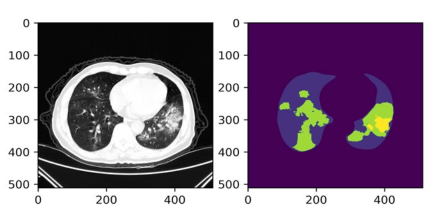
Also: Zhao, Xu, Mak/Shan et al.

Non-collinear phases



1D magnon network





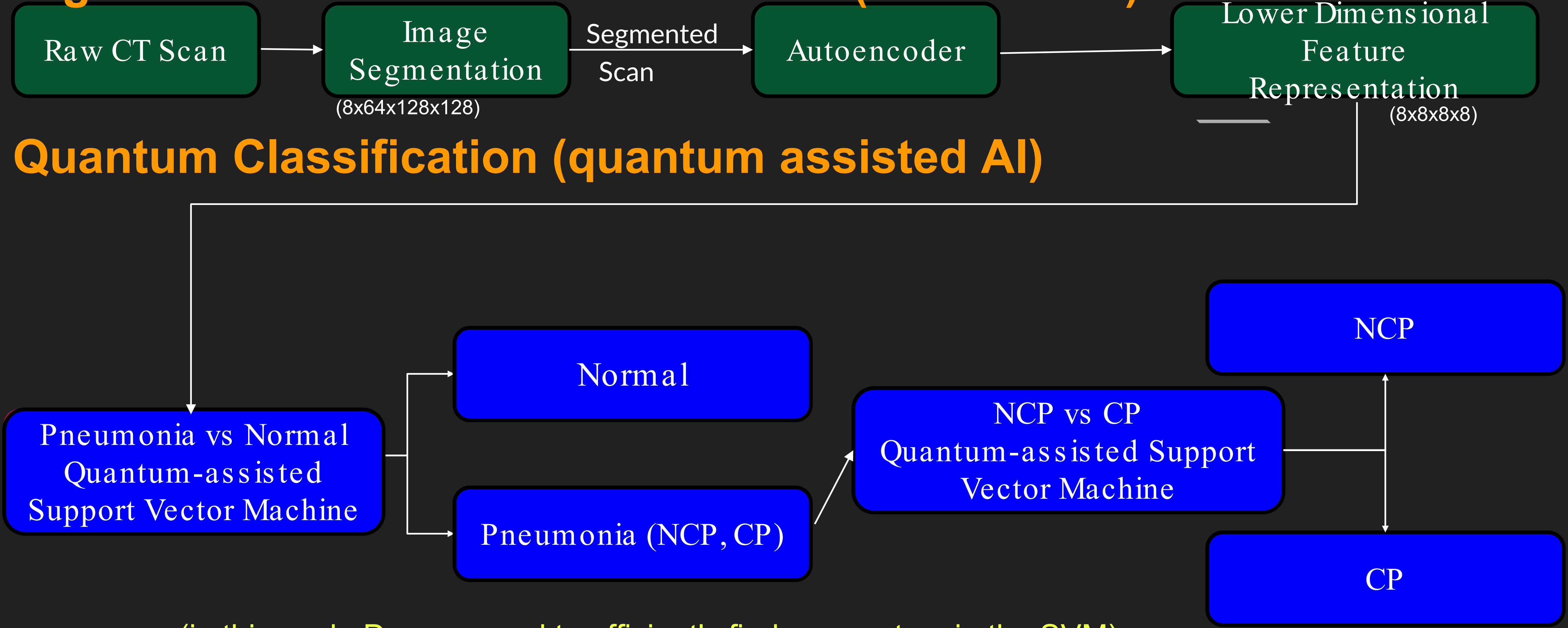
Zhang et al.

Gautham Umasankar (summer student), Y.Qi, K.Zhang et al.,

Exploration of quantum AI for COVID diagnosis

Original\Predicted	Normal	NCP	CP
Normal	93.9%	6.1%	0%
NCP	0%	100%	0%
CP	0%	9.76%	90.24%

Segmentation and Feature Extraction (classical AI)



Raw CT Scan

Image Segmentation

(8x64x128x128)

Segmented Scan

Autoencoder

Lower Dimensional Feature Representation

(8x8x8x8)

Quantum Classification (quantum assisted AI)

Pneumonia vs Normal Quantum-assisted Support Vector Machine

Normal

Pneumonia (NCP, CP)

NCP vs CP Quantum-assisted Support Vector Machine

NCP

CP

(in this work, D-wave used to efficiently find parameters in the SVM)

Community Input welcome to a **DOE QIS Applications Road-Mapping** Exercise

- yongchen@purdue.edu

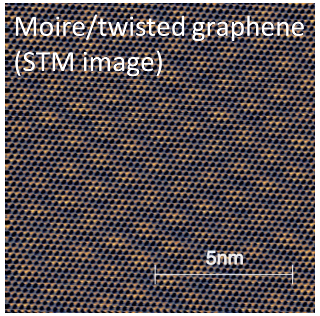
Physics; ECE; Purdue Quantum Science & Engineering Institute (PQSEI); Birck Nanotechnology Center (BNC); Quantum Science Center (QSC); Center for Quantum Technologies (CQT)

Yong P. Chen: Quantum Materials meets Quantum Information

(mostly 2D/topological materials)

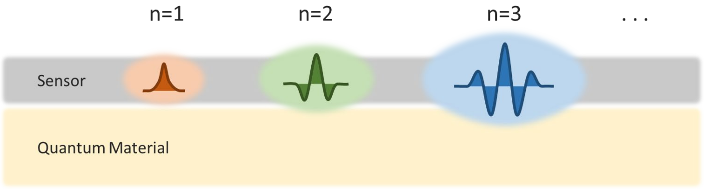
(quantum sensing/computing/photonics..)

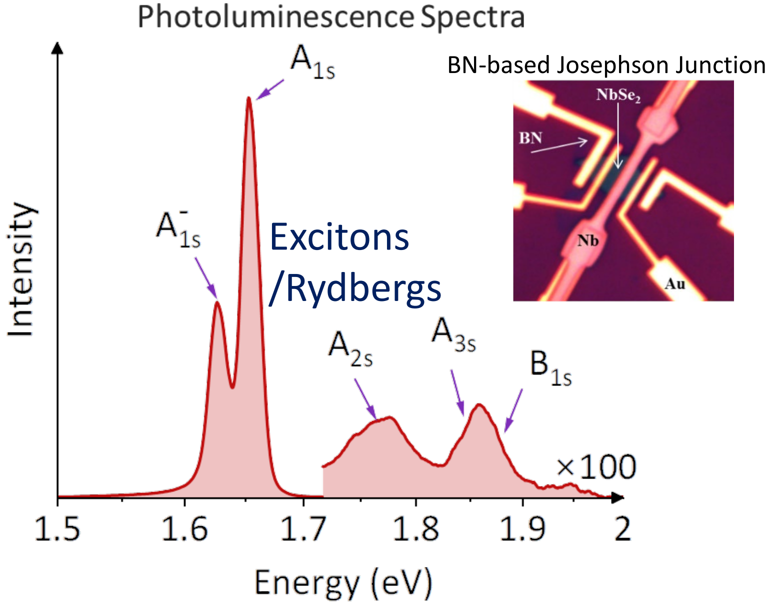
Graphene



Semiconductors/Insulators

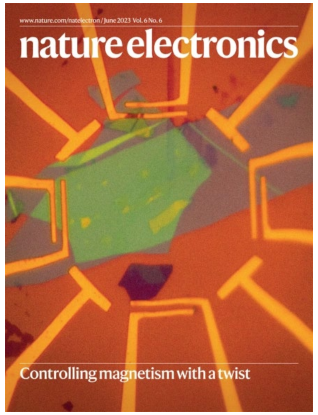
(TMDCs, h-BN, etc.)

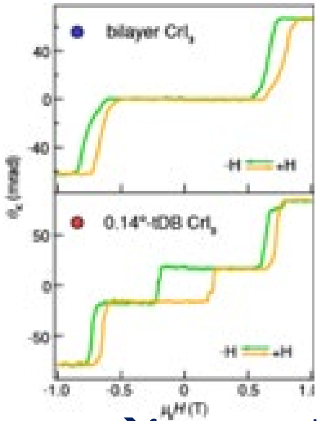




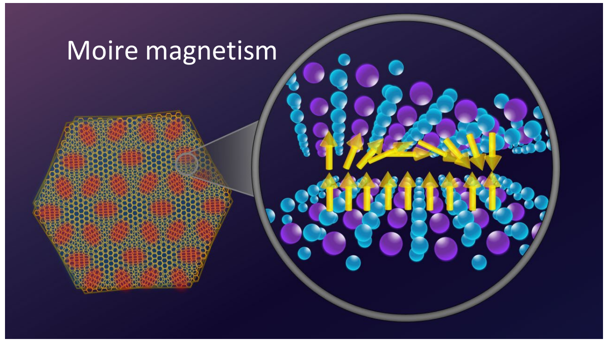
Quantum Magnets

(2D/twisted magnets, spin liquids)



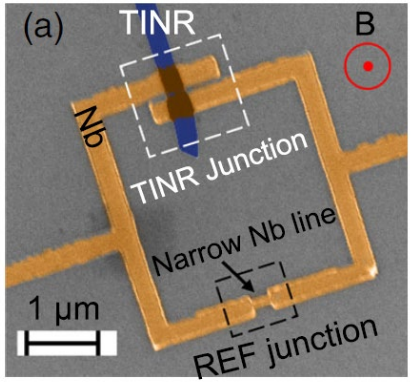


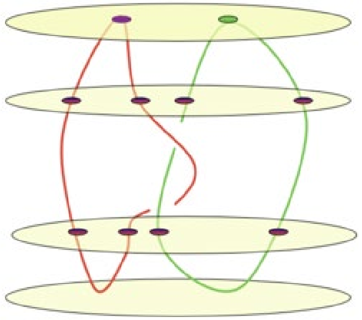
antiferromagnet+antiferromagnet➔ferromagnet!



Topological Insulators

/superconductors/semimetals





TI-based Josephson Junction & SQUID

(potential platform for more robust qubit & other “topological” quantum devices)

Research Themes and Major Goals:

1) Develop/study novel quantum materials promising better/newer quantum devices/technologies (qubits, sensing, photonics)
2) Apply ideas/techniques from quantum information (sensing/optics) to develop new methods to measure quantum materials

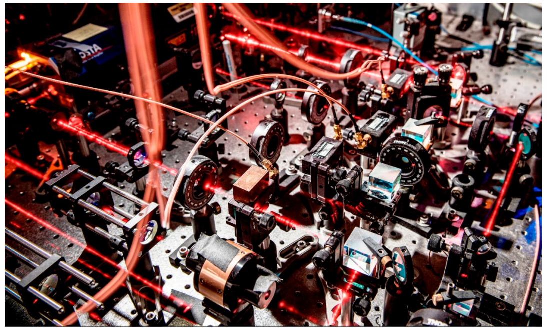
Research Methods/Tools: materials/device (nano) fabrication; device/transport + SPM or Optical (magneto-optical, Raman, PL) spectroscopy; quantum sensing/optics

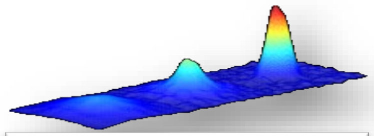
Group has/operates diverse experimental facilities locally (Physics + Birck Nano. Center/PQSEI) and off-campus (national labs; international – Denmark & Japan)

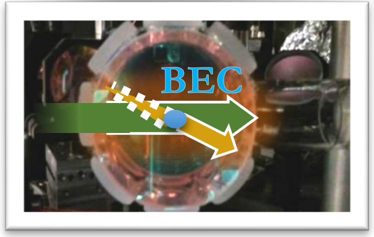
Quantum Simulation and Quantum Chemistry with Cold Atoms at QMD Lab (Yong P. Chen)

Cold atoms — “seeing” quantum mechanics & dynamics

We have an experimental system with laser-cooled atoms, where we can dynamically control the Hamiltonian to quantum simulate various novel quantum matter not easily realized in electronic materials.

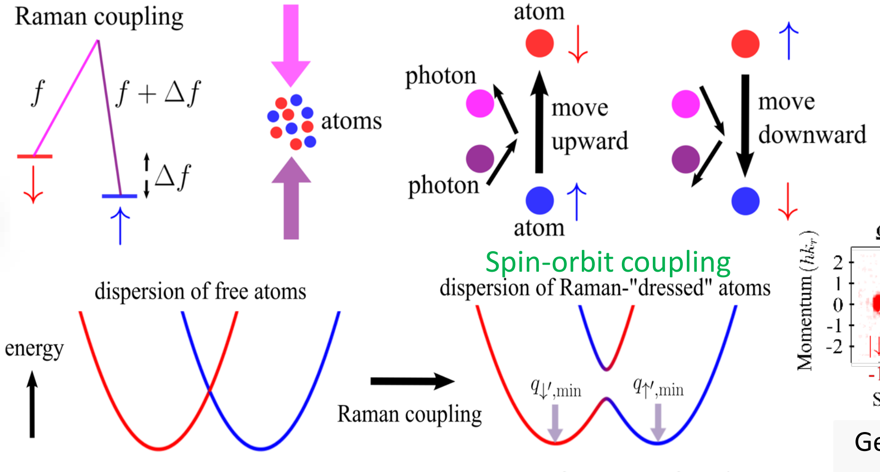






A.J. Olson *et al.*, *Phys. Rev. A* 87, 053613 (2013)

Coherent light-matter interaction — optical dressing to put atoms into quantum superposition states



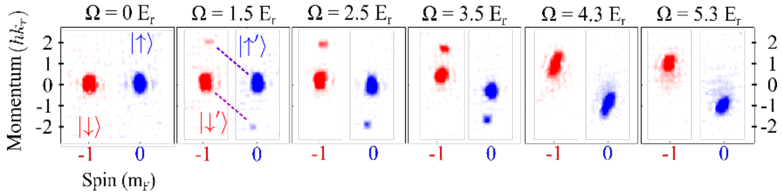
quasimomentum $\hbar q_y$

$E(q_y) = \hbar^2(q_y - q_{\sigma\,\min})^2/(2m^*)$

$\hat{H} = (\hat{p}_y - QA)^2/(2m_Q)$

“matter” “light”

$$H_{\mathrm{soc}} = \begin{pmatrix} \frac{\hbar^2}{2m}(q_y + k_r)^2 - \delta_R & \frac{\Omega}{2} \\ \frac{\Omega}{2} & \frac{\hbar^2}{2m}(q_y - k_r)^2 \end{pmatrix}$$



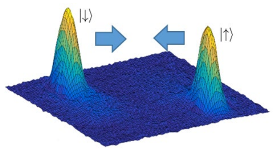
Generation of synthetic magnetic and electric fields

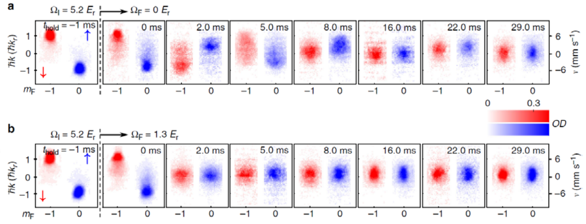
$$-\frac{\partial A_y(t)}{\partial t} = E_y \qquad \frac{\partial A_y(x)}{\partial x} = B_z$$

Atomtronic spintronics & quantum gas collider

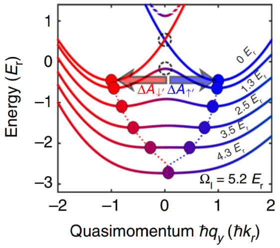
Spin current generation and relaxation

Quantum quench

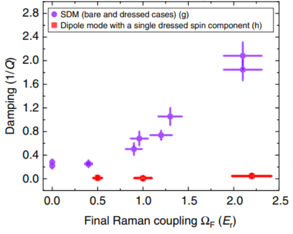




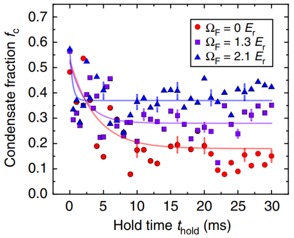
$\mathbf{E}_\sigma \approx -(\Delta A_\sigma / t_E)\hat{y}$



Damping

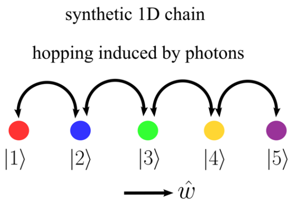


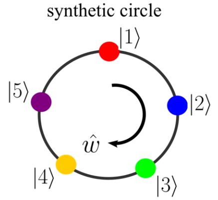
Thermalization

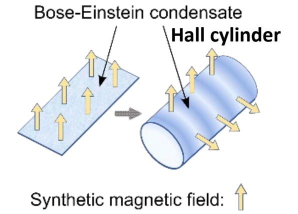


C.-H. Li *et al.*, *Nature Commun.* 10, 375 (2019)

Quantum matter in synthetic gauge fields & spaces

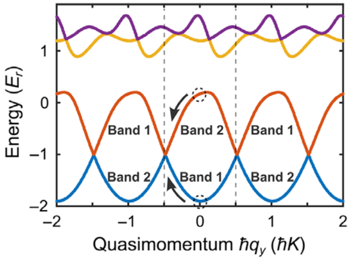


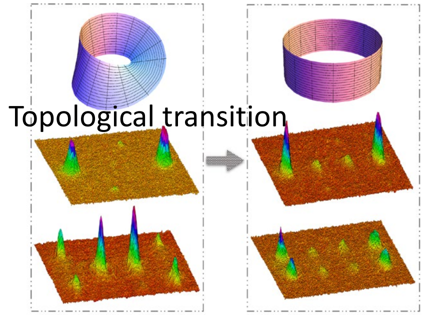




Synthetic magnetic field: ↑

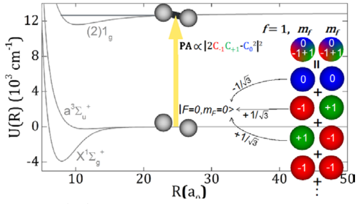
Topological band structure

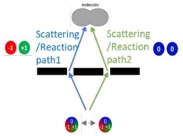


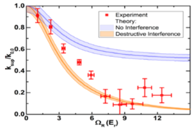


C.-H. Li *et al.*, *PRX Quantum* 3, 010316 (2022)

Quantum Control of (Photo)Chemical Reactions

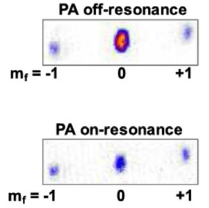


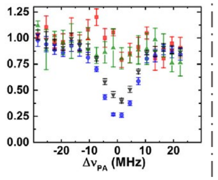




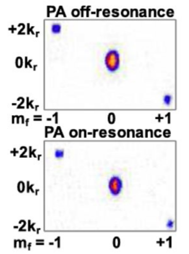
Quantum chemistry interferometer: controlling quantum interference between photochemical reaction (photoassociation) pathways

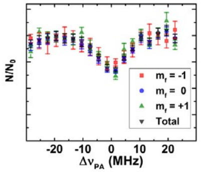
Spin Statistical Mixture





Spin-Momentum Superposition





D.B. Blasing *et al.*, *Phys.Rev. Lett.* 131, 0732020 (2018)